Quantum Universe

Hitoshi Murayama (Berkeley, IPMU Tokyo)

臺灣大學 colloquium, June 7, 2011



IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE



2011年6月8日星期三



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How did the Universe begin?



How did the Universe begin?

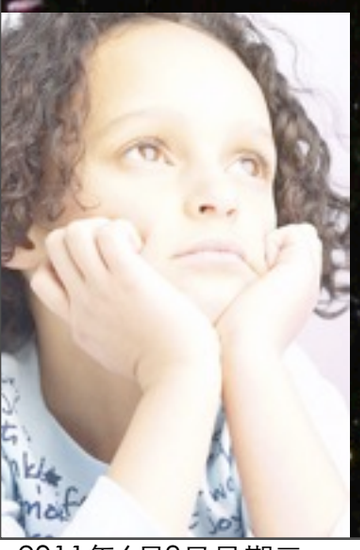
What is its fate?



How did the Universe begin?

What is its fate?

What is it made of?

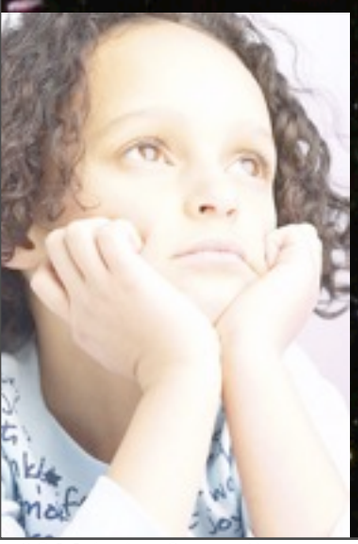


How did the Universe begin?

What is its fate?

What is it made of?

What are its fundamental laws?



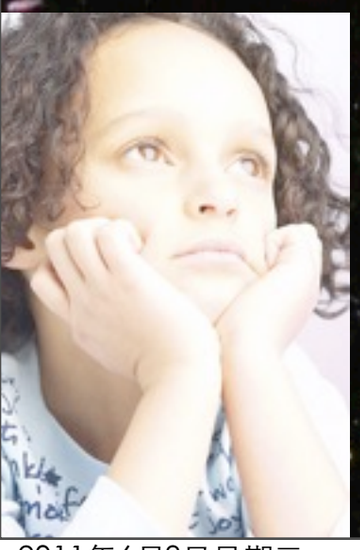
How did the Universe begin?

What is its fate?

What is it made of?

What are its fundamental laws?

Why do we exist?





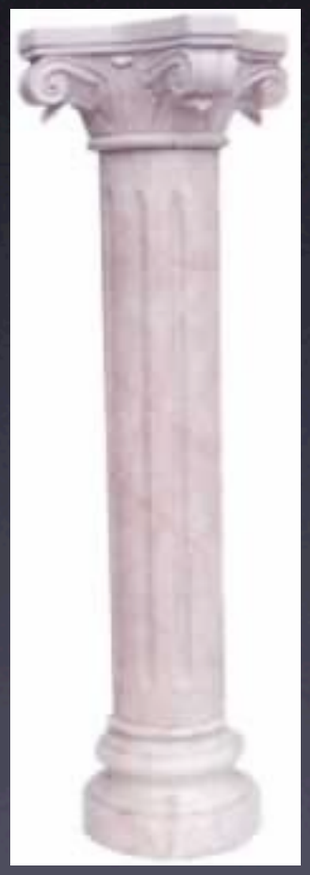
Galileo Galilei

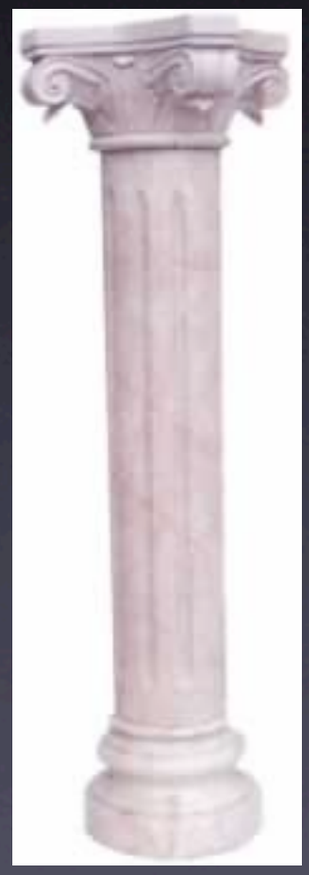
Philosophy is written in this grand book, the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and read the letters in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures without which it is humanly impossible to understand a single word of it.



Galileo Galilei

Two pillars





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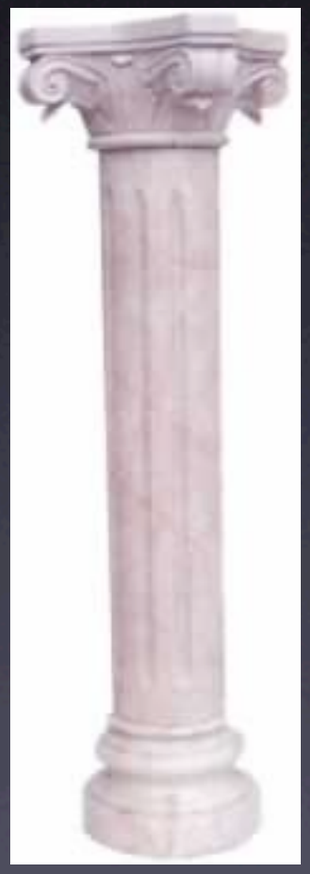
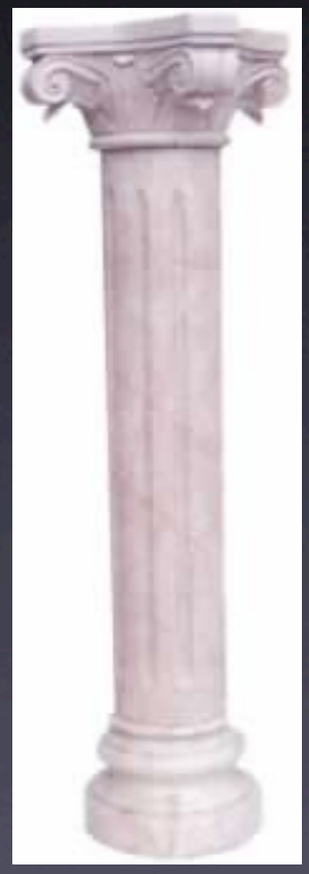
Two pillars

- Relativity
  - describes physics of the large
  - relies heavily on geometry





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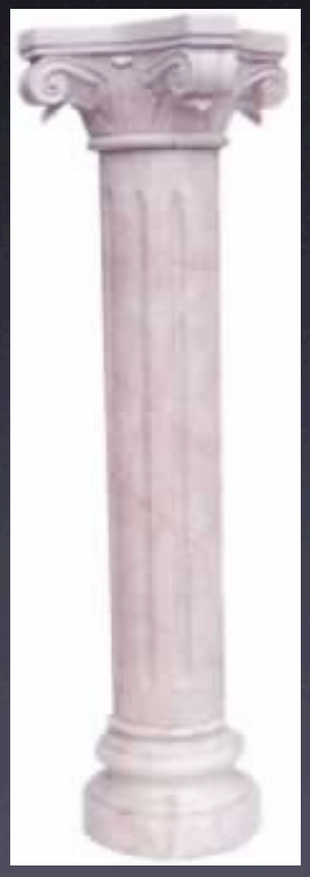
Two pillars



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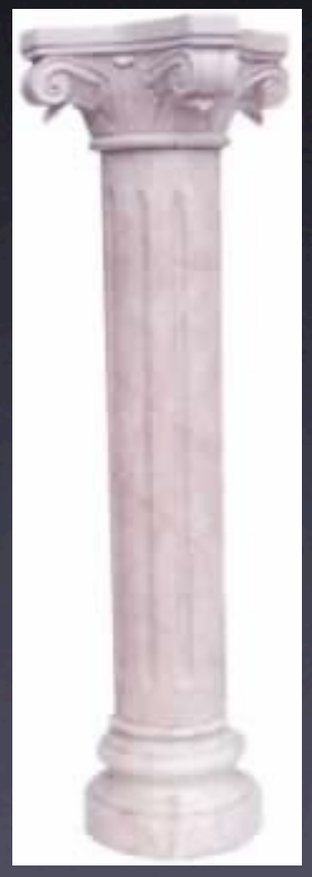
  - describes physics of the large
  - relies heavily on geometry
- Quantum Mechanics
  - describes physics of the small
  - relies heavily on algebra and analysis



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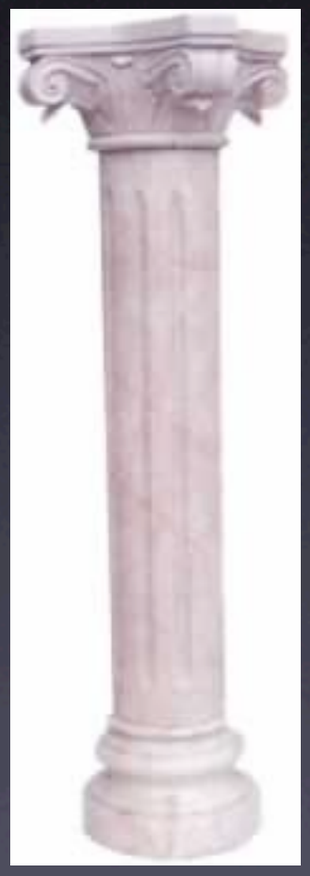

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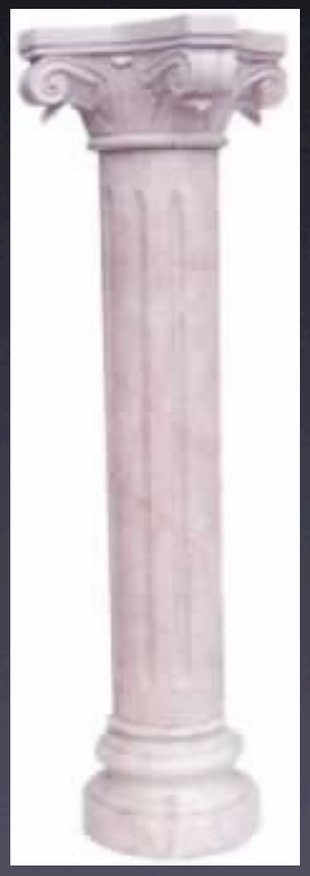
- Combination=Quantum Field Theory
  - relies on geometry and topology, too



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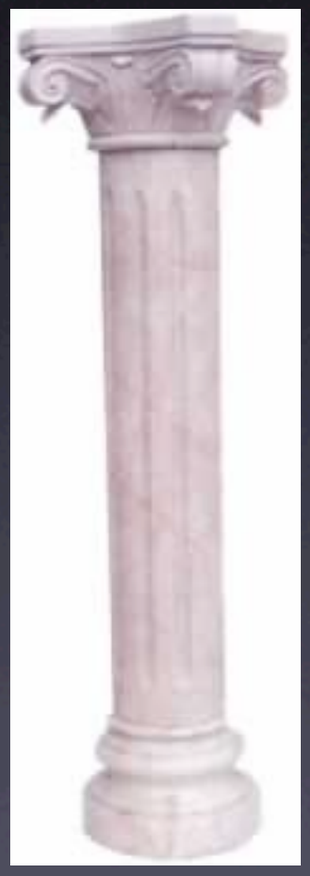

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  - describes physics of the large
  - relies heavily on geometry
- Quantum Mechanics
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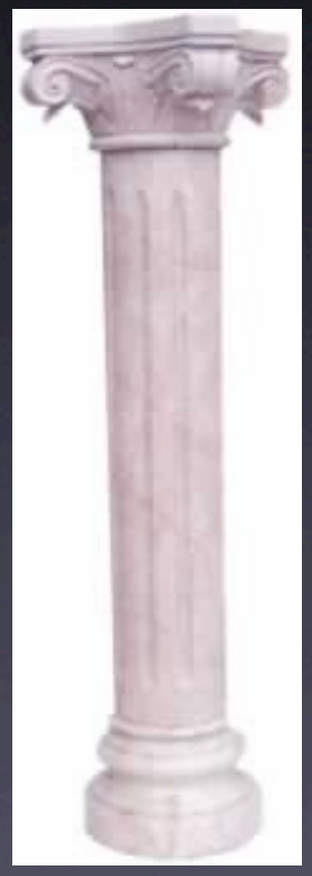
  - relies heavily on algebra and analysis
- Combination=Quantum Field Theory
  - relies on geometry and topology, too
- also important is computation, statistics



Third Birthday



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Full-time scientists paid by IPMU



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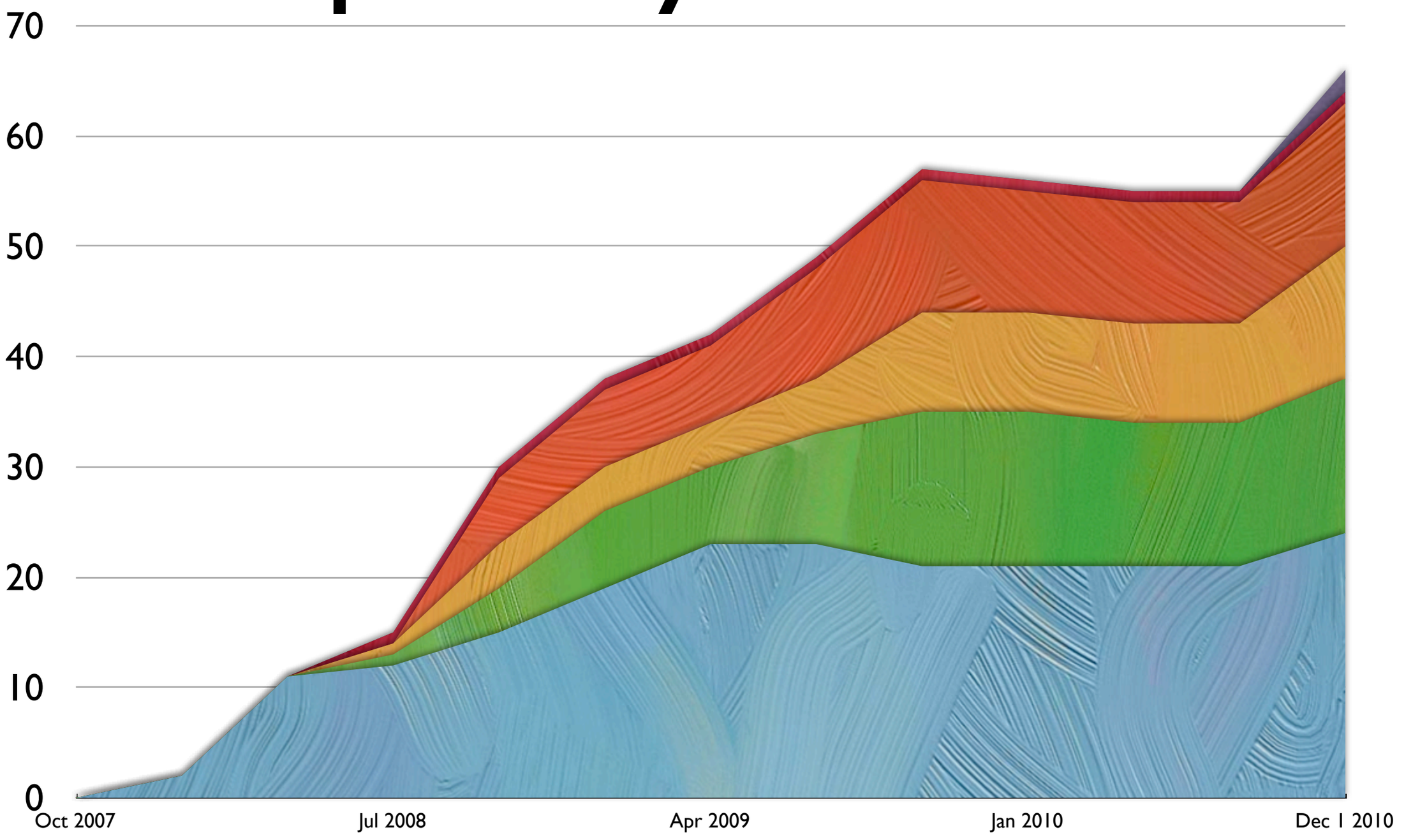
Full-time scientists paid by IPMU



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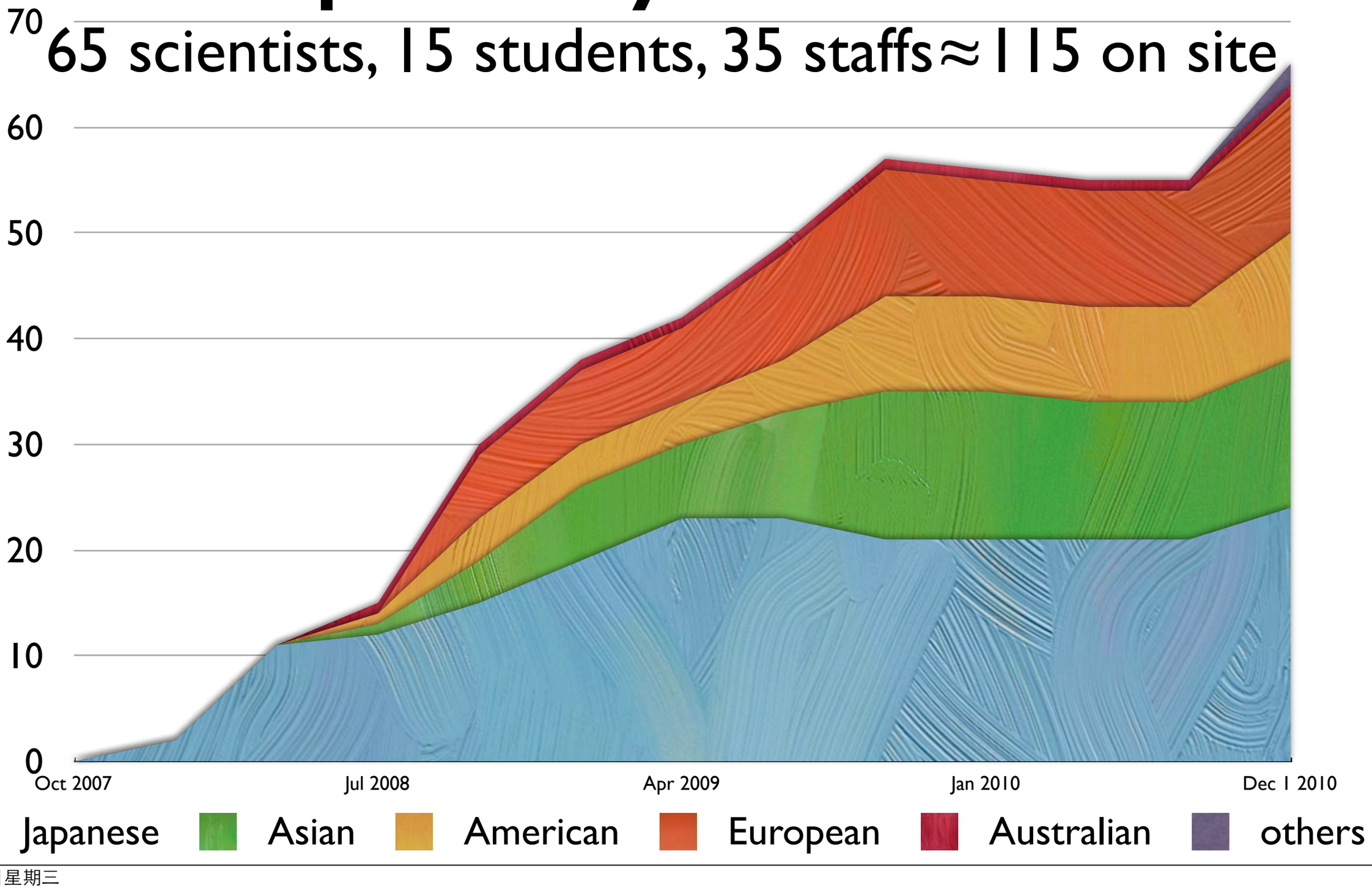


moved in on Jan 18, 2010

~5900 m^2



interaction area ~400m^2

like a European town square



interaction area ~400m^2

like a European town square



"obelisk"

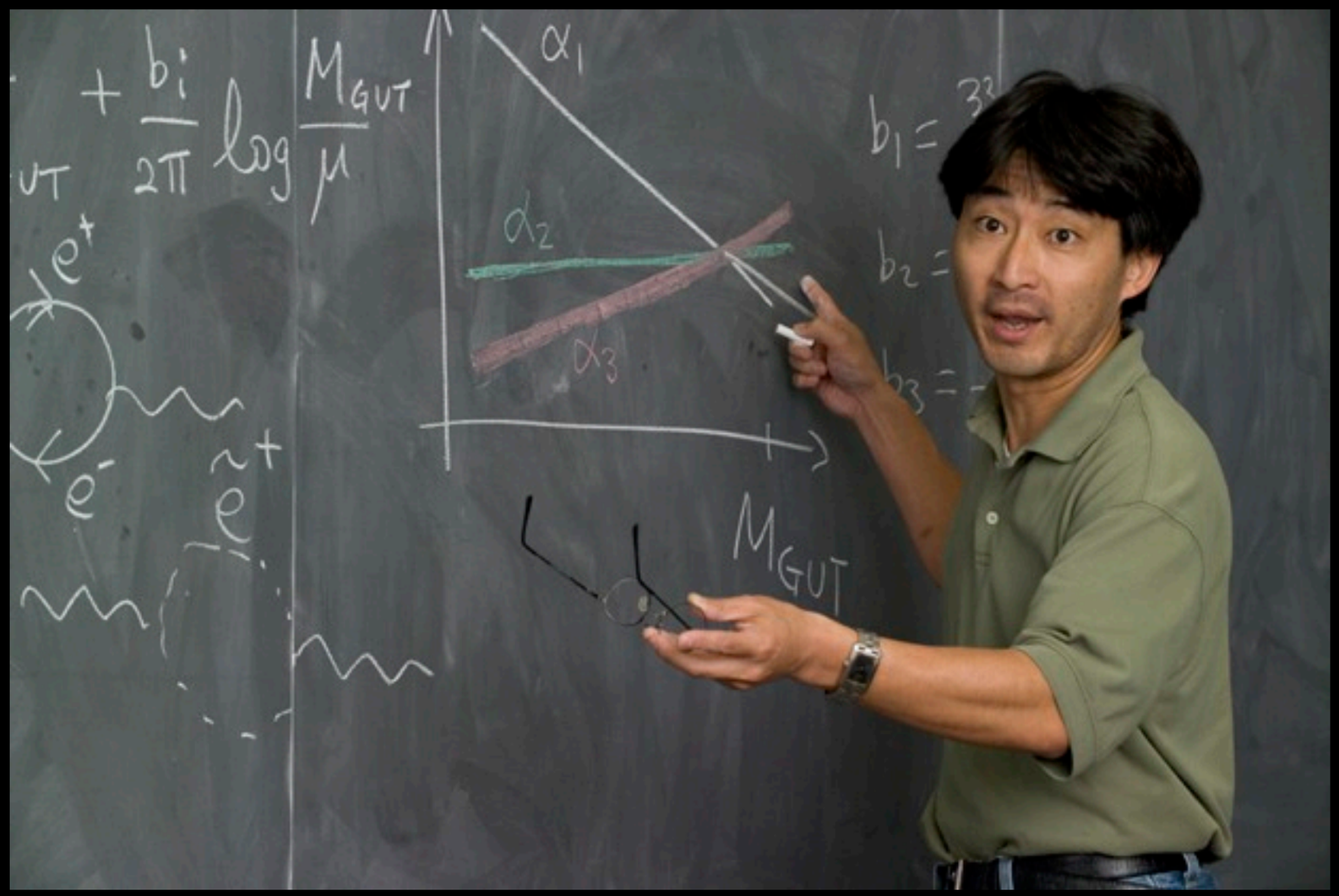
L'Universo é scritto in lingua matematica

Galileo Galilei

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

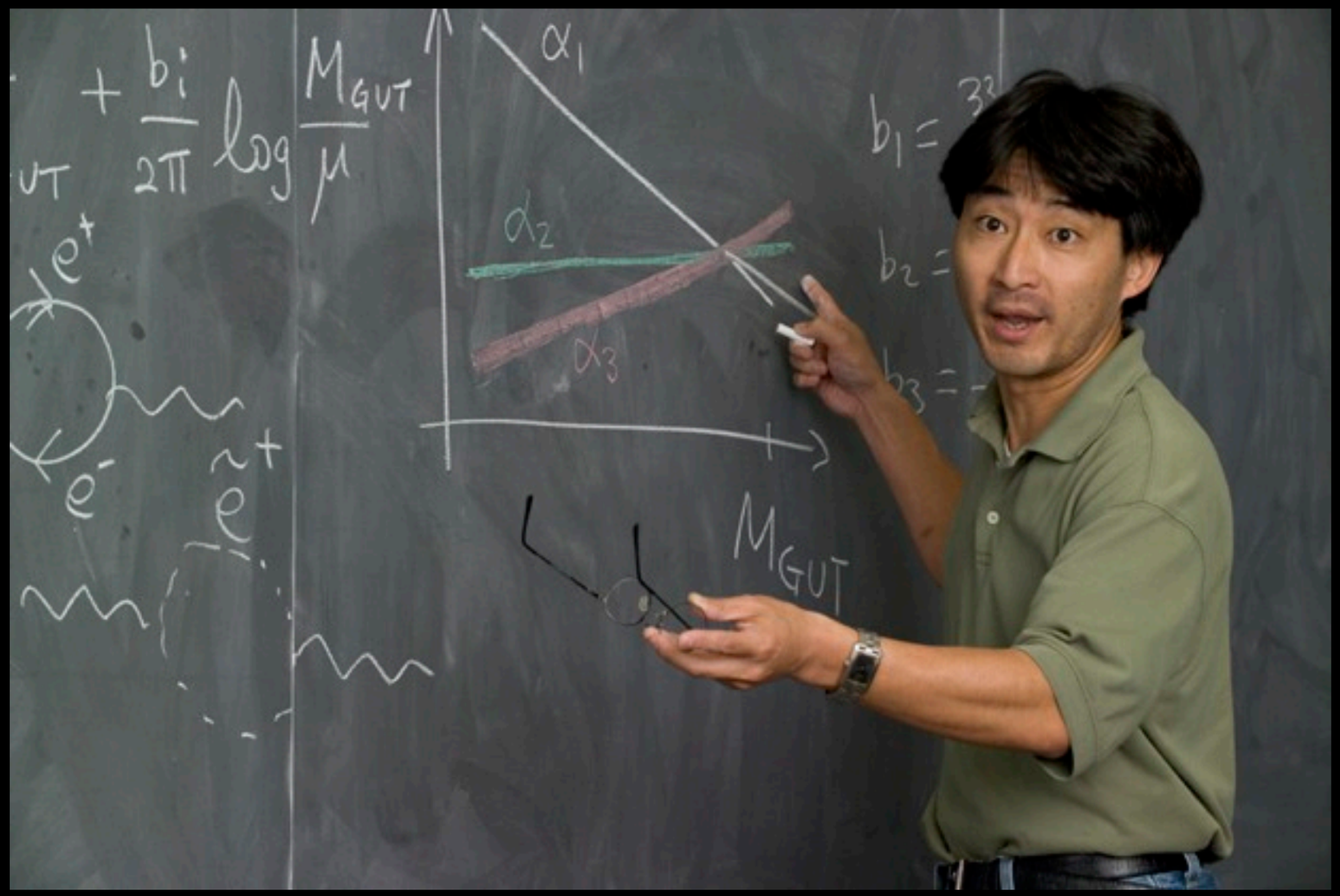
Director of the Institute for the Physics

and Mathematics of the Universe



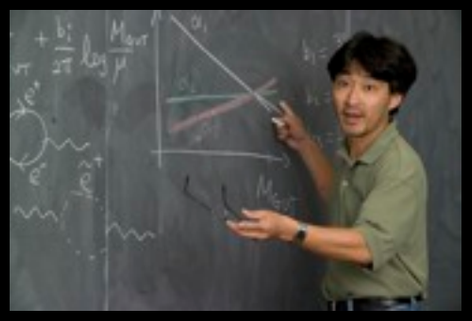
Director of the Universe

A lot of responsibility!



Director of the Universe

Not high enough authority



Director of the Universe

Not high enough authority

Voice of God





Director of the Universe

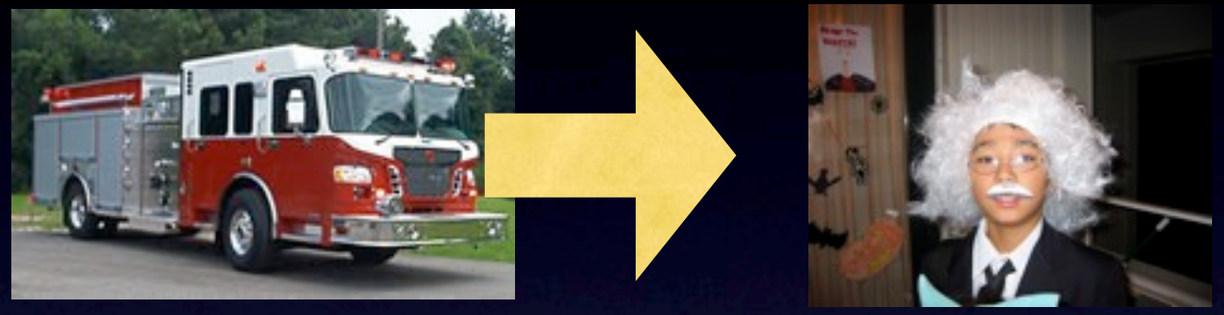
Big-Bang

Universe is expanding

- Approaching ambulance: higher key
- Moving-away ambulance: lower key

- Much the same way, moving-away stars: lower key (redder) in spectrum of light
- We see distant stars/ galaxies are redder

Universe is expanding



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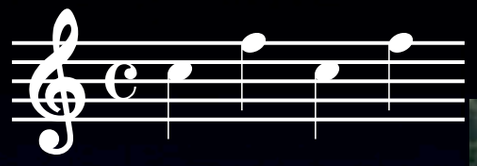





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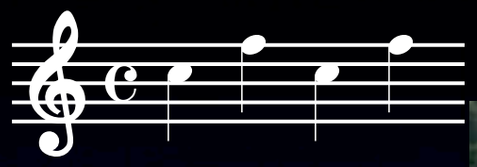





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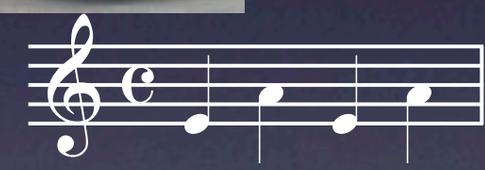

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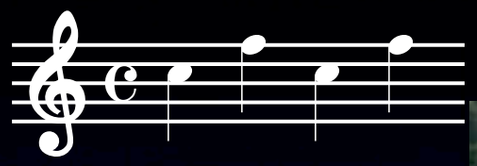

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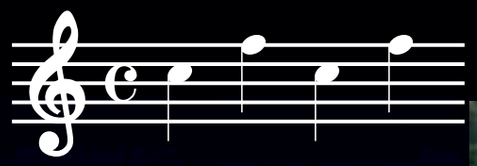

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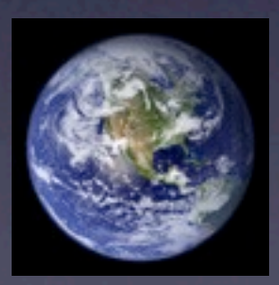
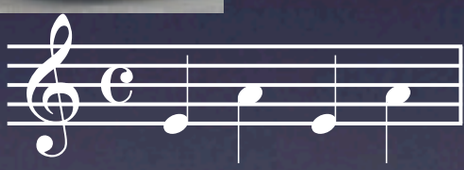
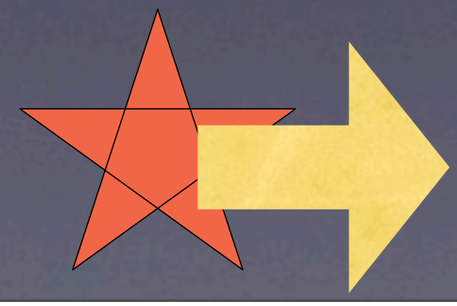




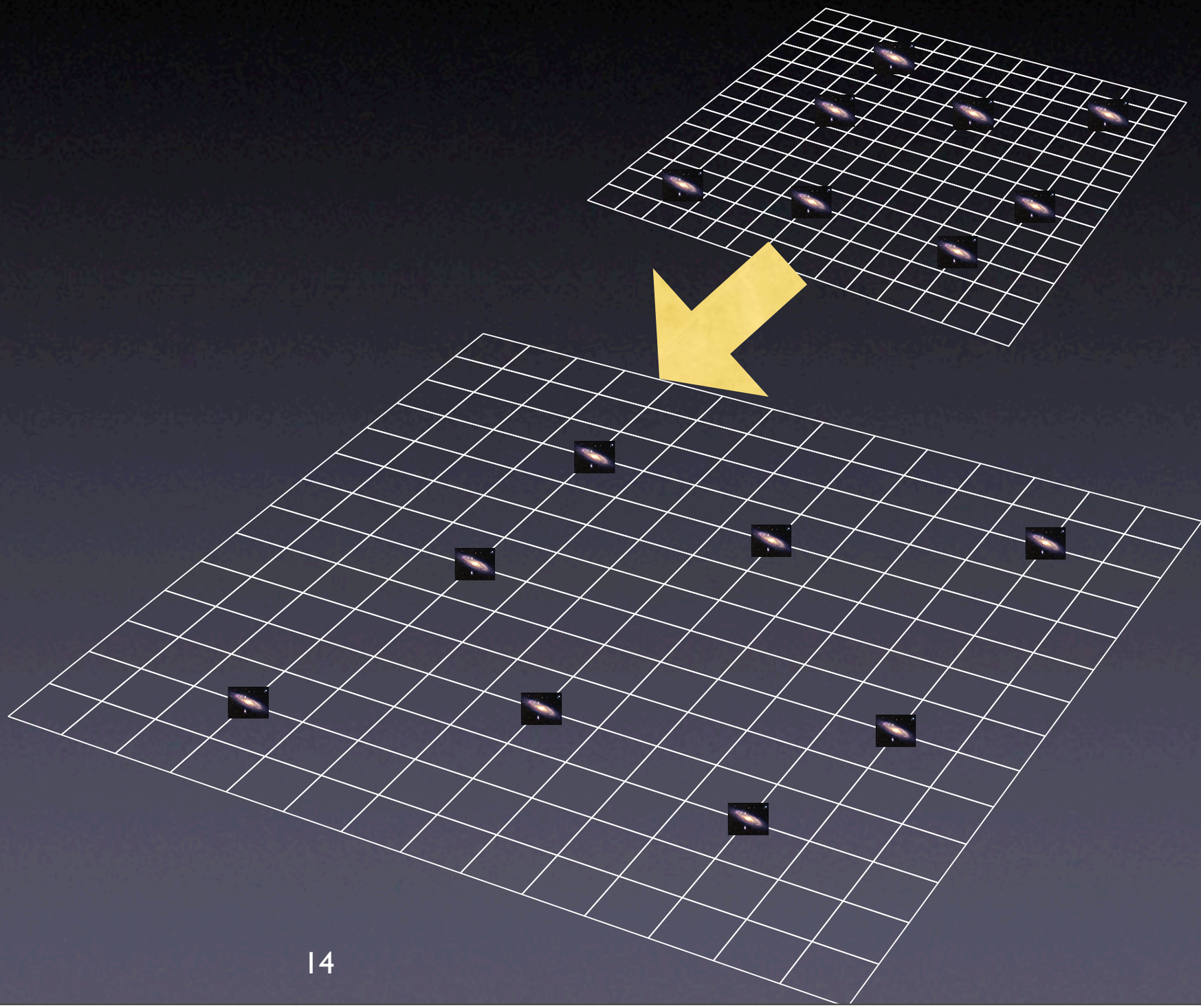






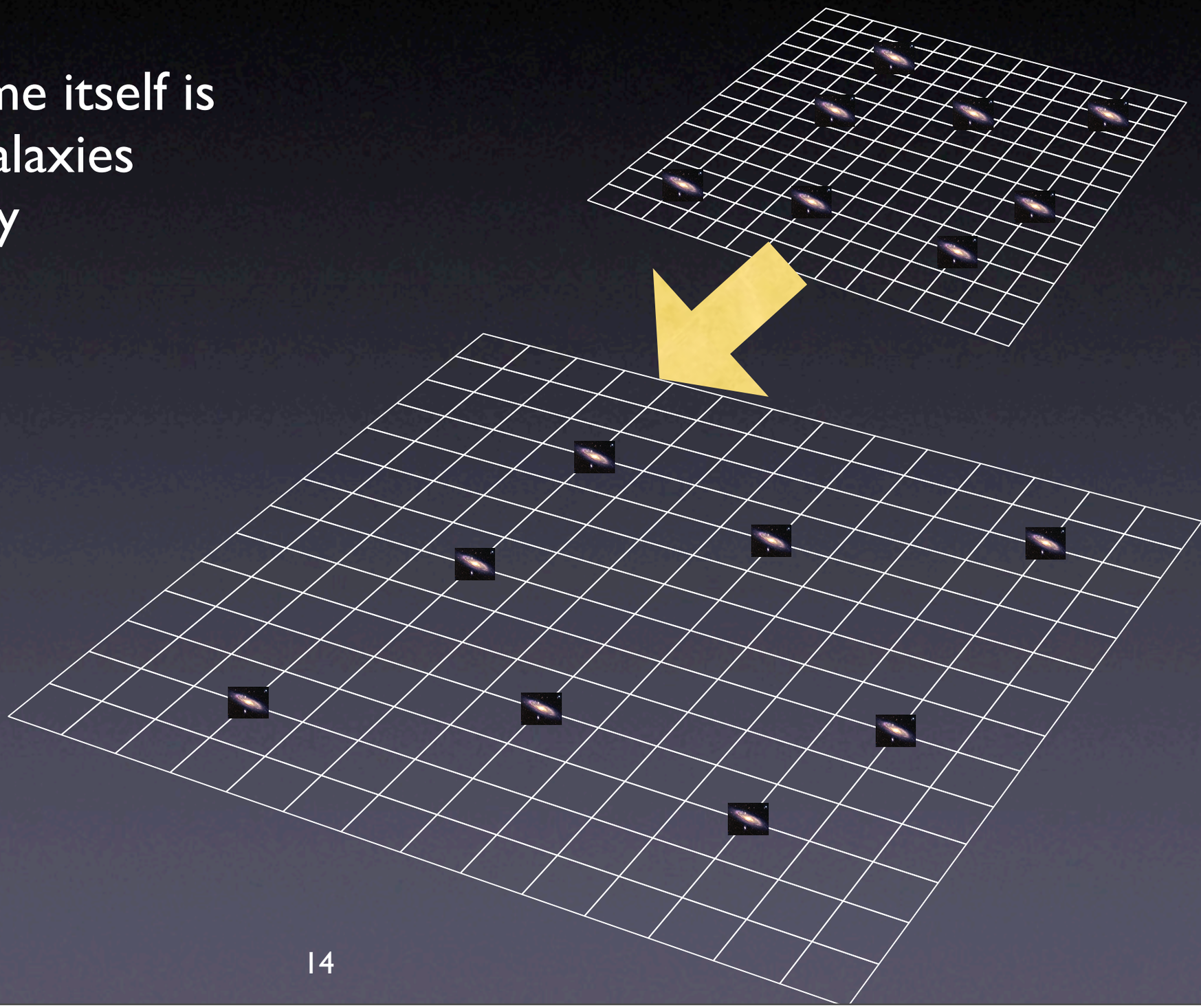


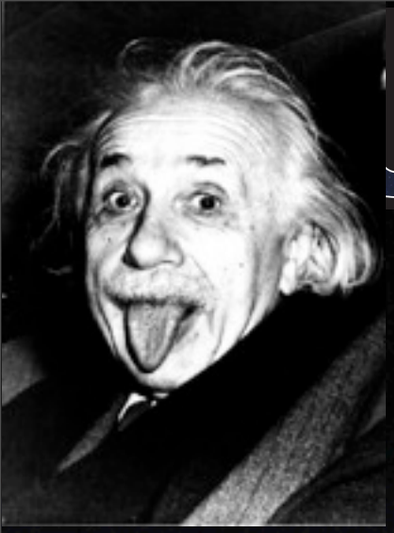
Expansion of Space



Expansion of Space

- The spacetime itself is stretching, galaxies dragged away





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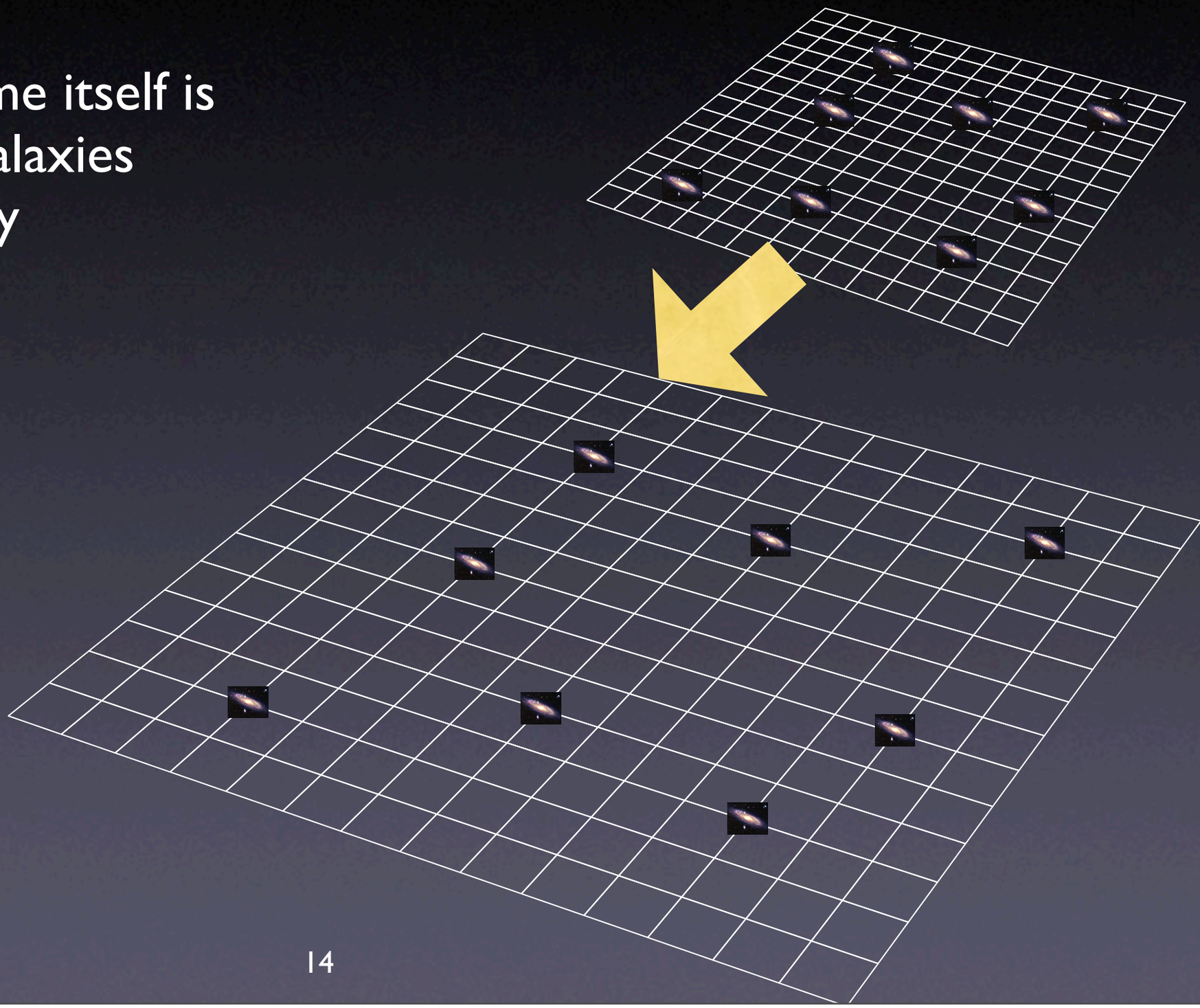
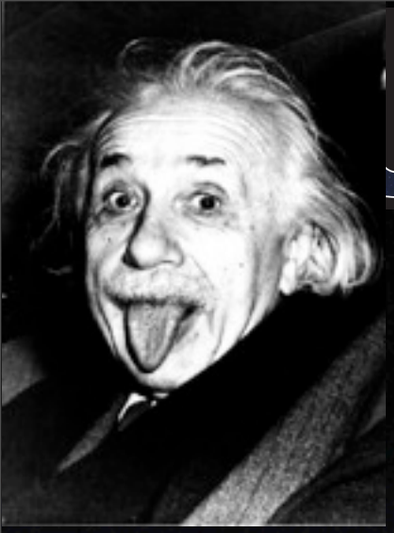
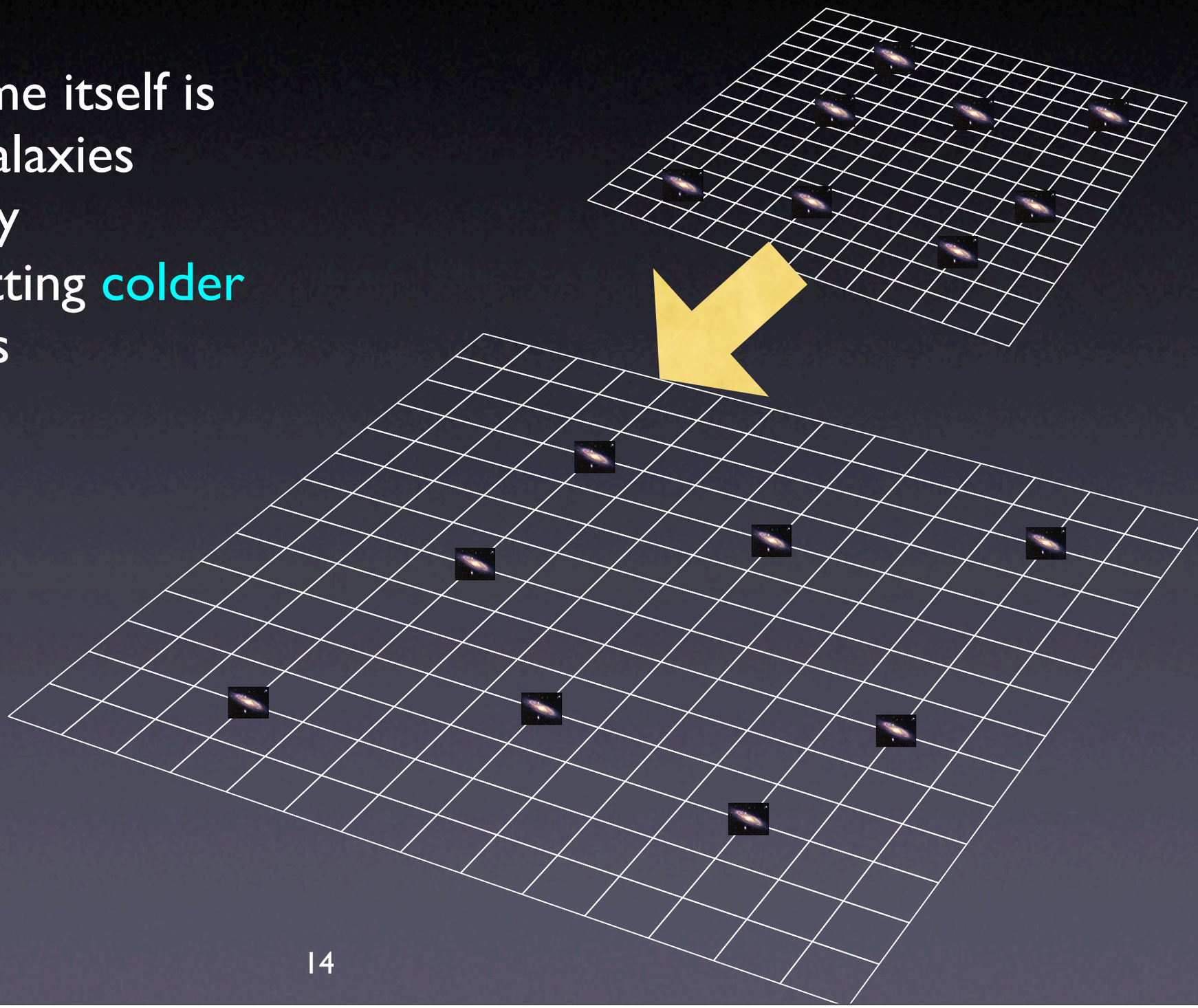
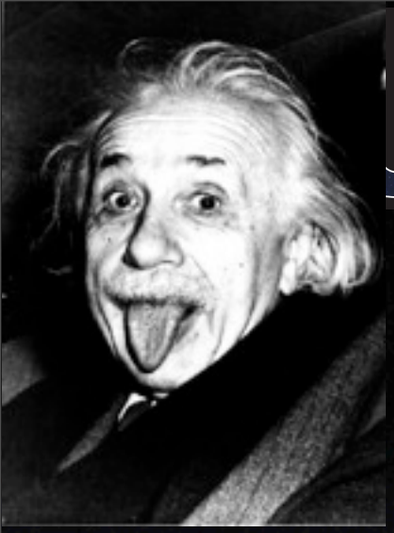




Expansion of Space

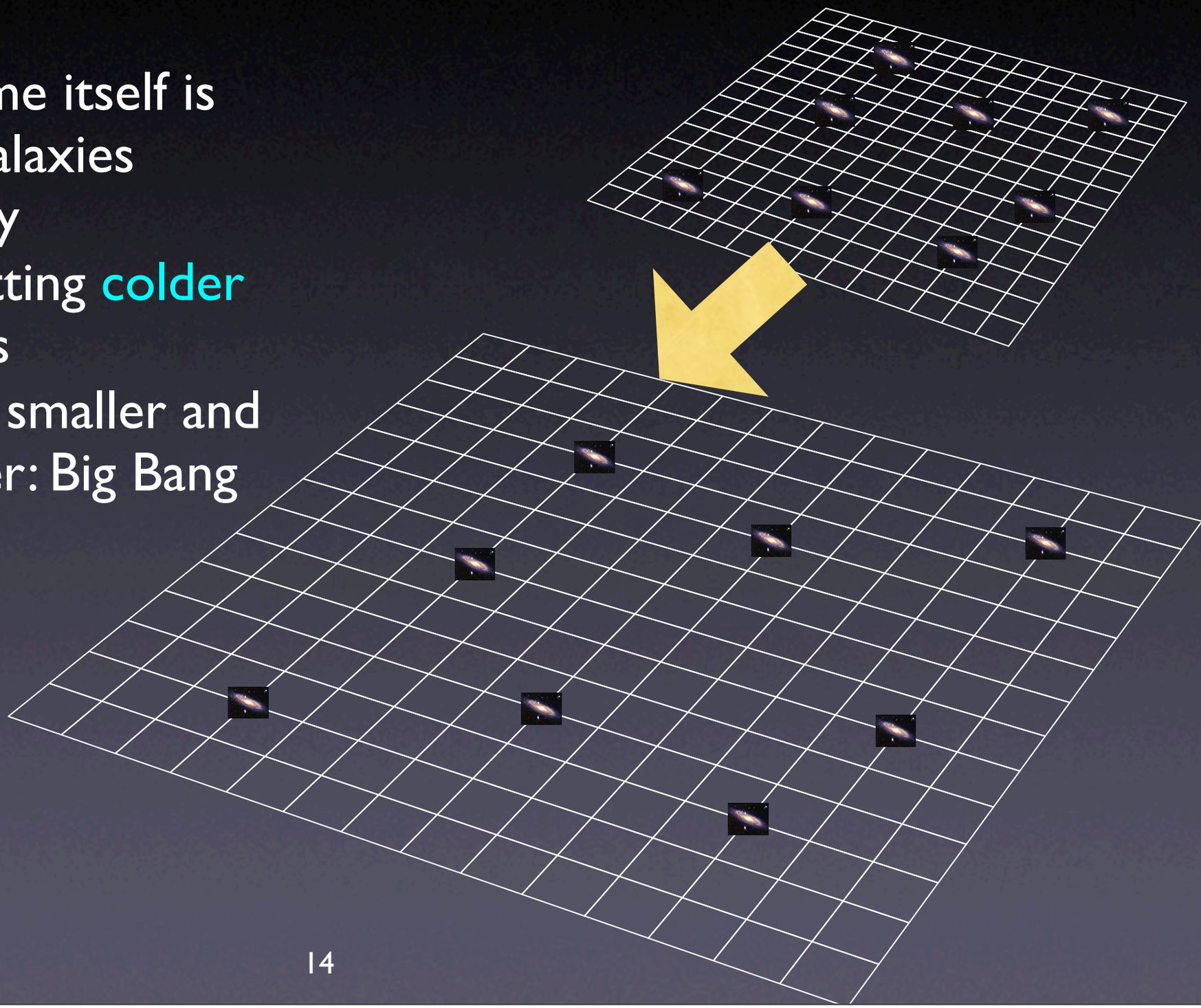
- The spacetime itself is stretching, galaxies dragged away
- Universe getting colder as it expands

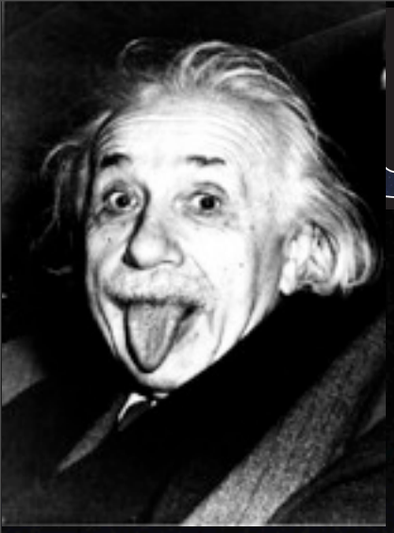




Expansion of Space

- The spacetime itself is stretching, galaxies dragged away
- Universe getting colder as it expands
- It was much smaller and hotter earlier: Big Bang





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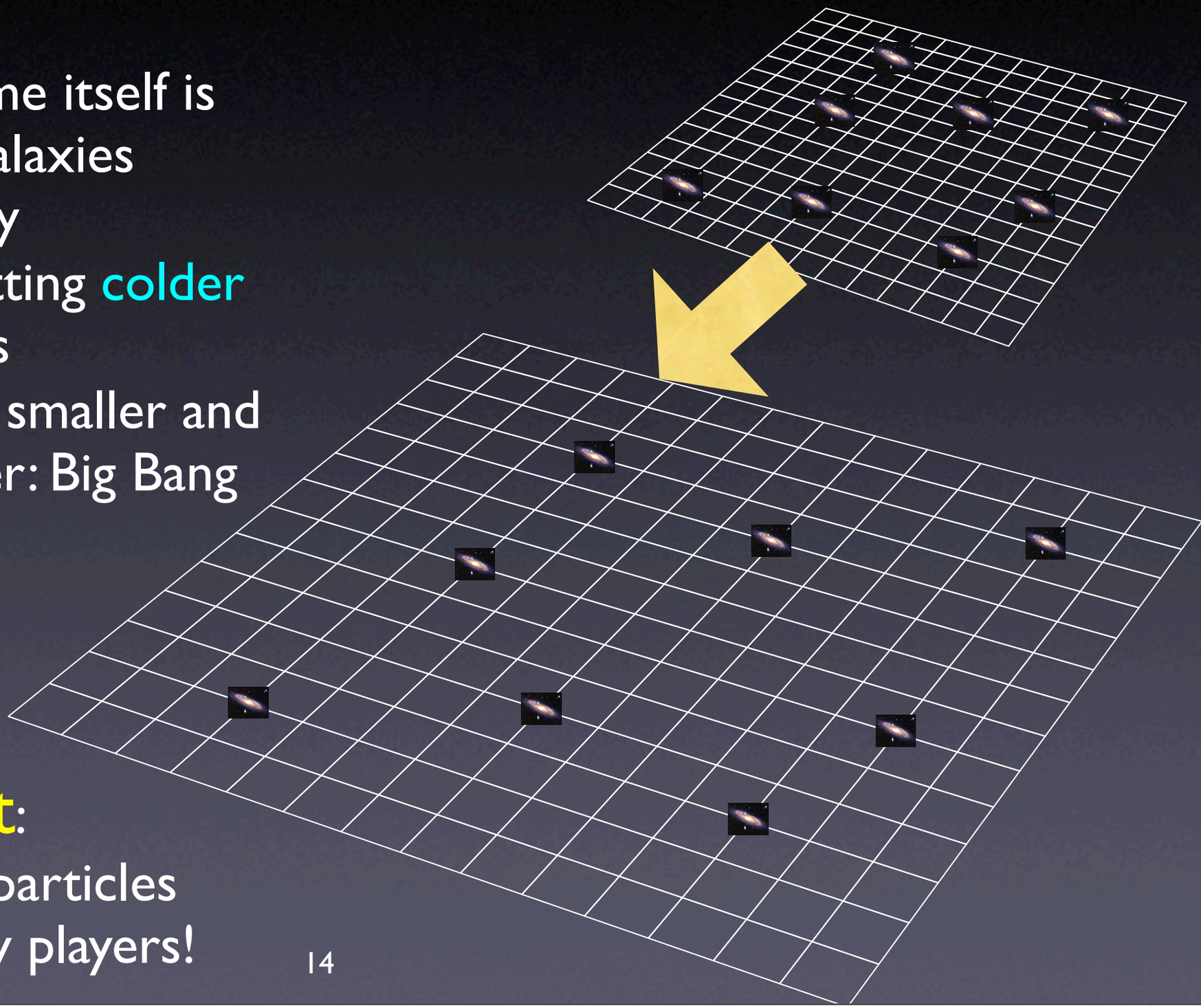


- small and hot: elementary particles were the key players!

George Smoot





John Mather

George Smoot

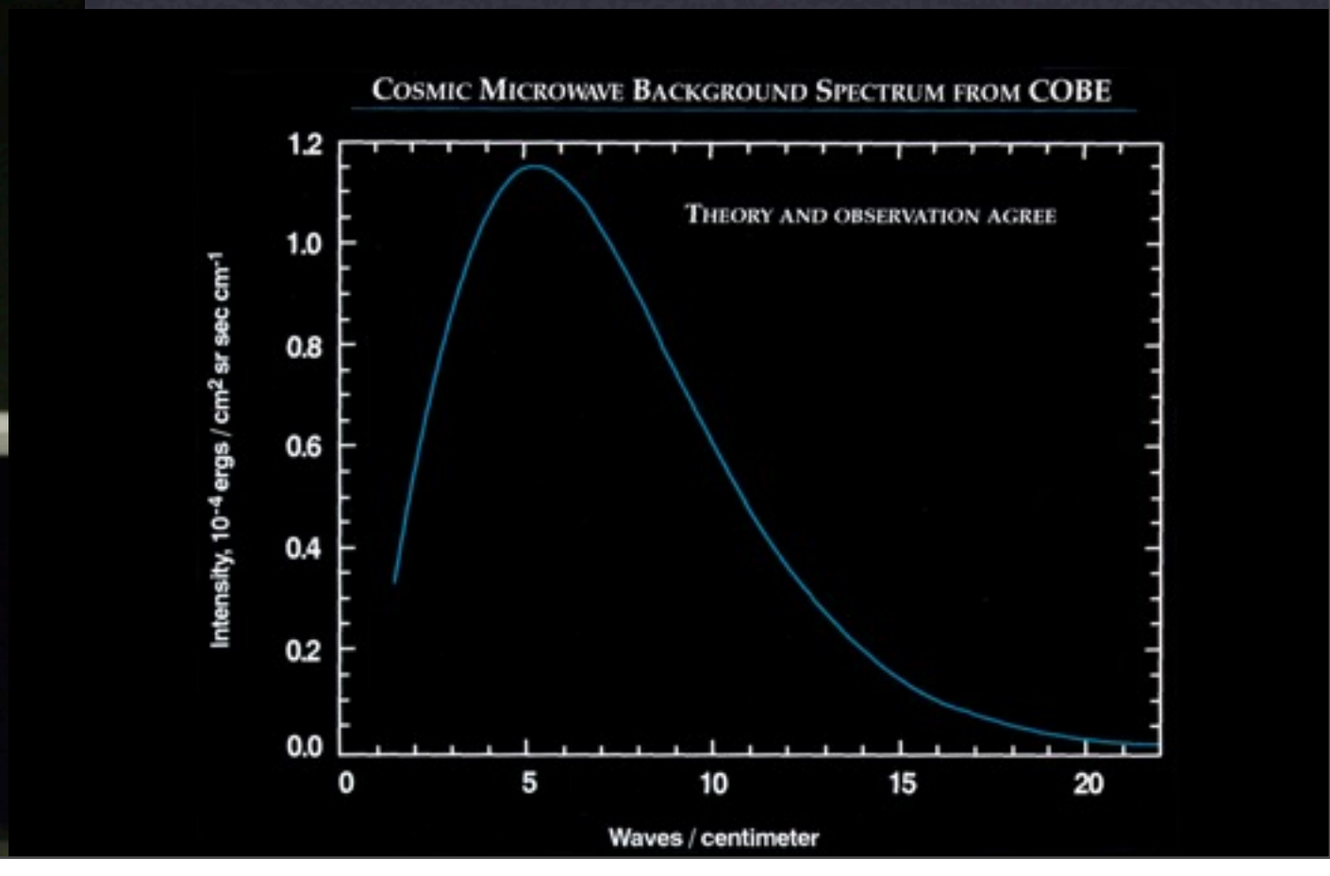




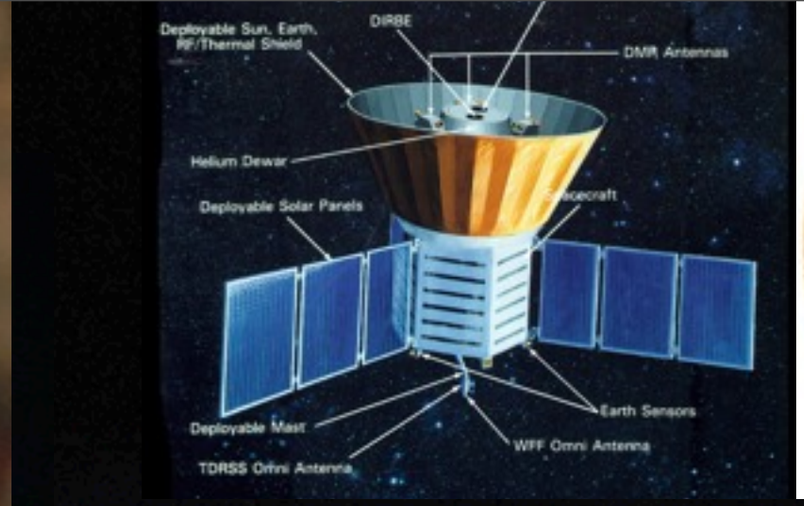


John Mather

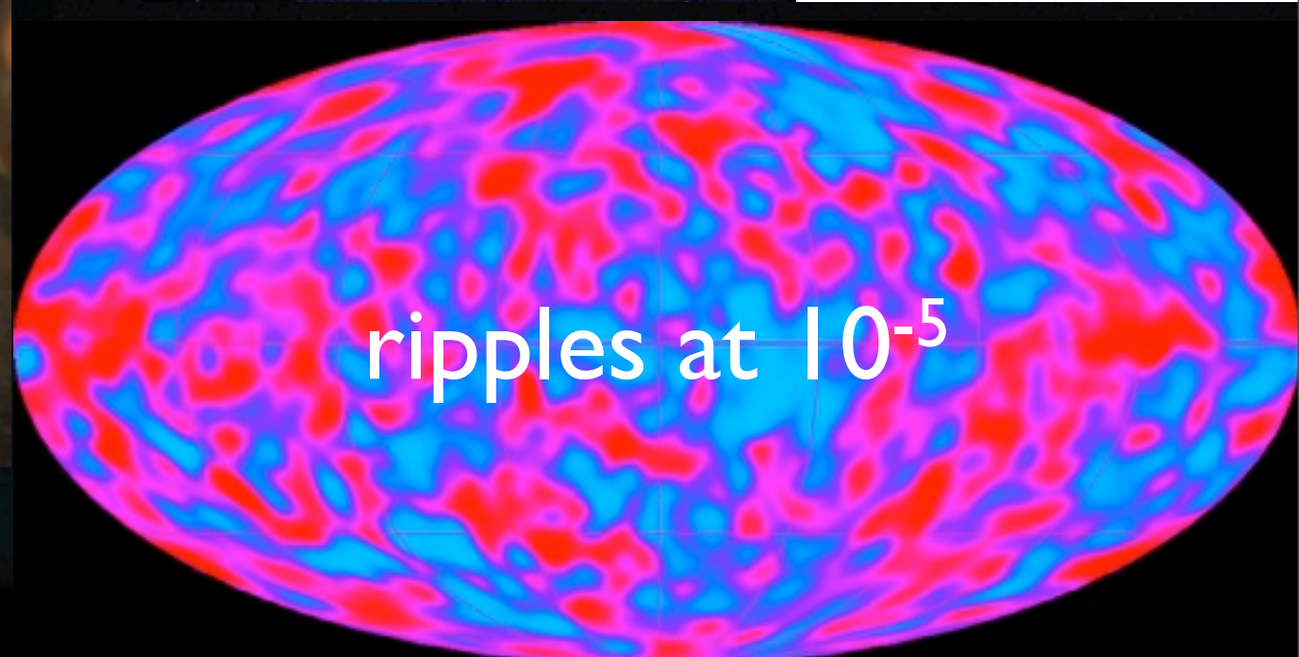




George Smoot

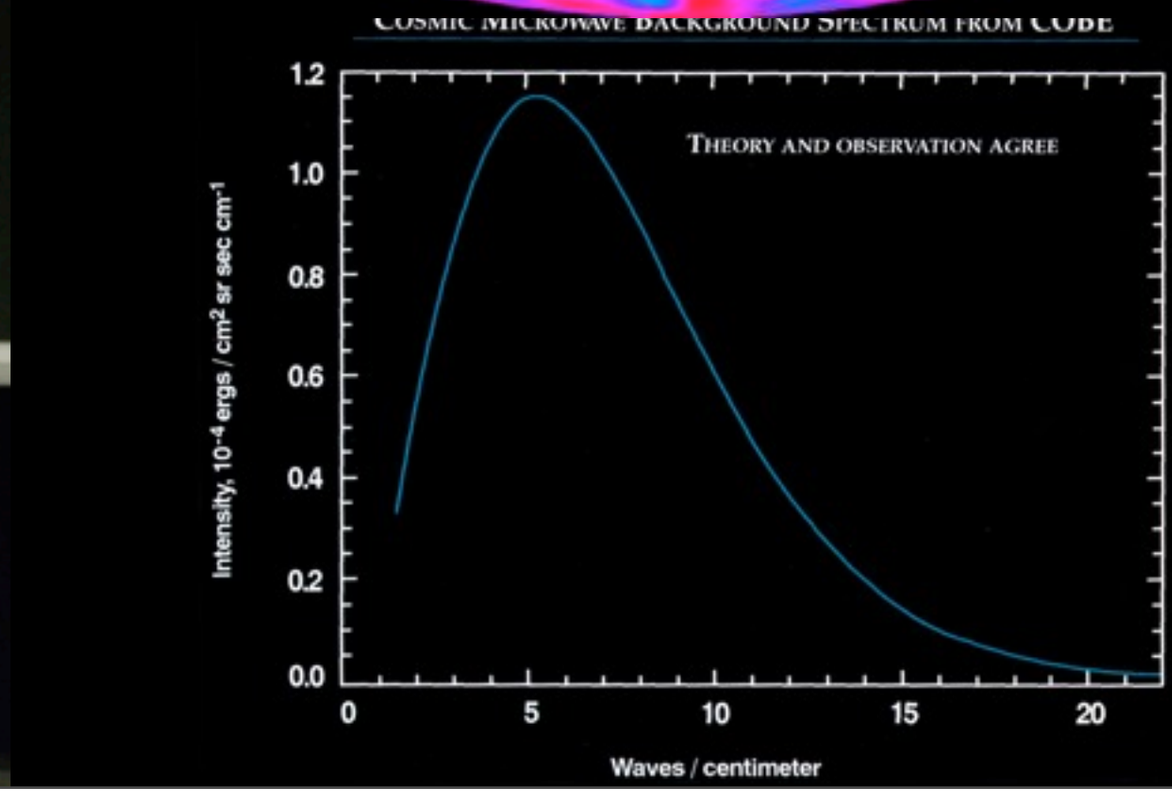




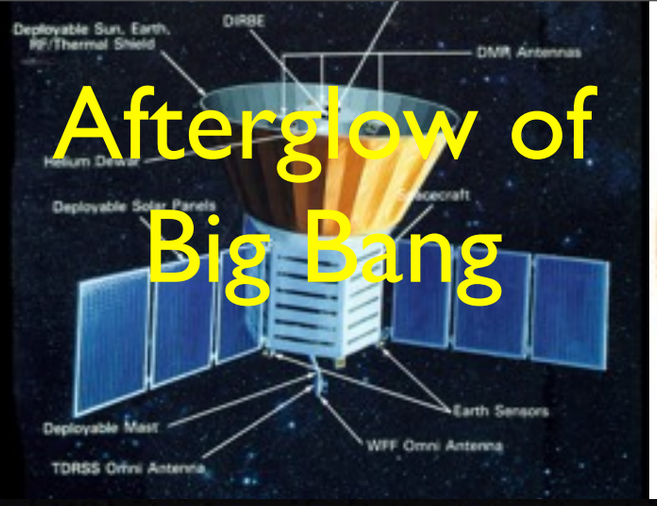


John Mather





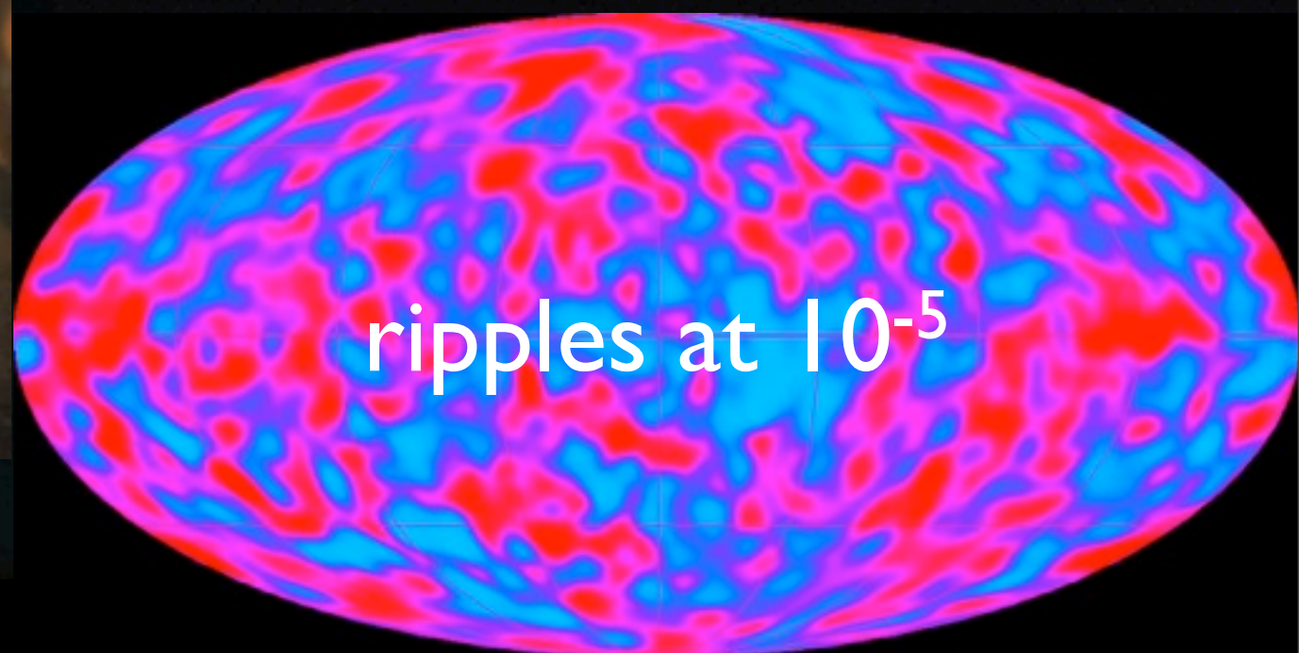
George Smoot



Afterglow of Big Bang

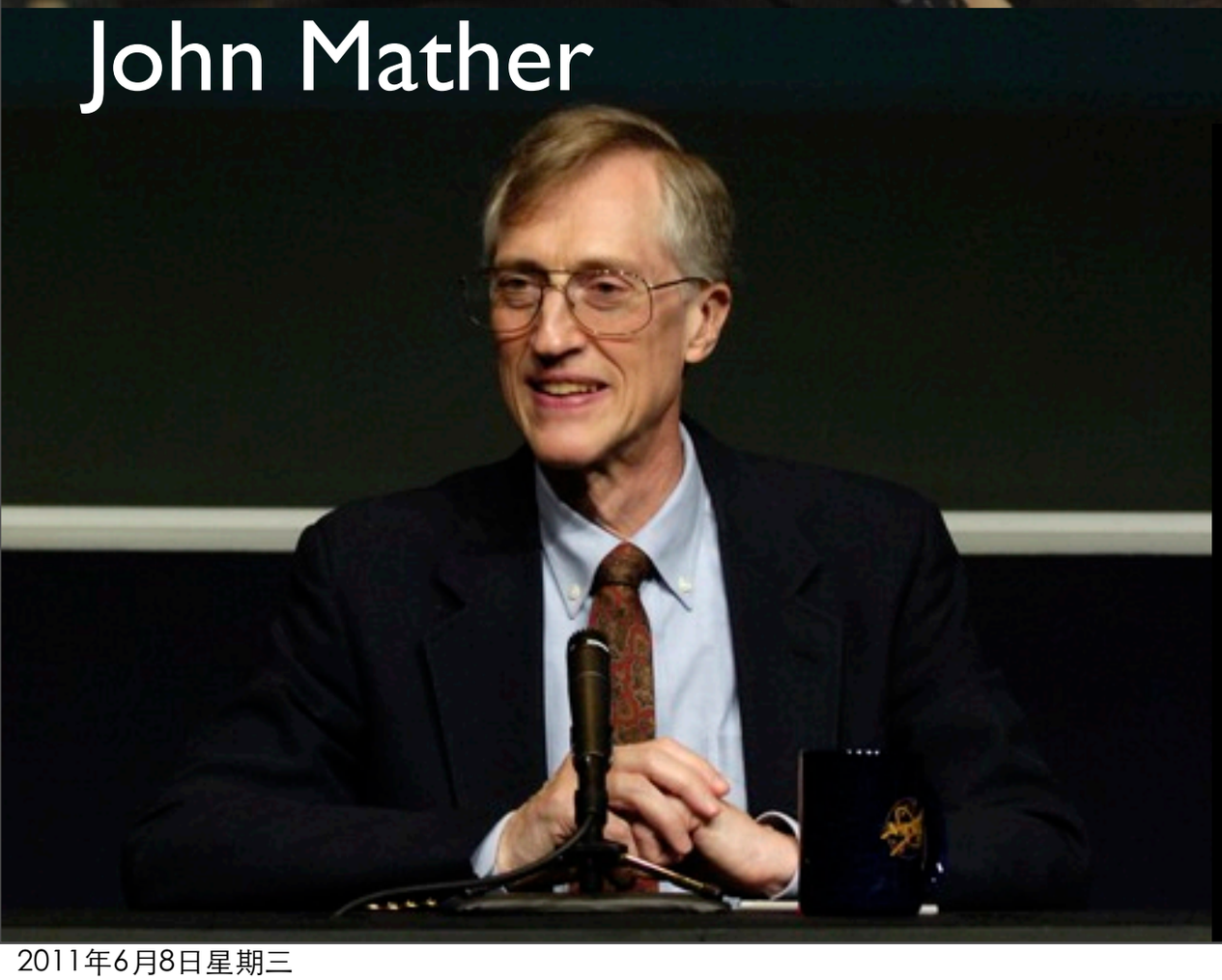


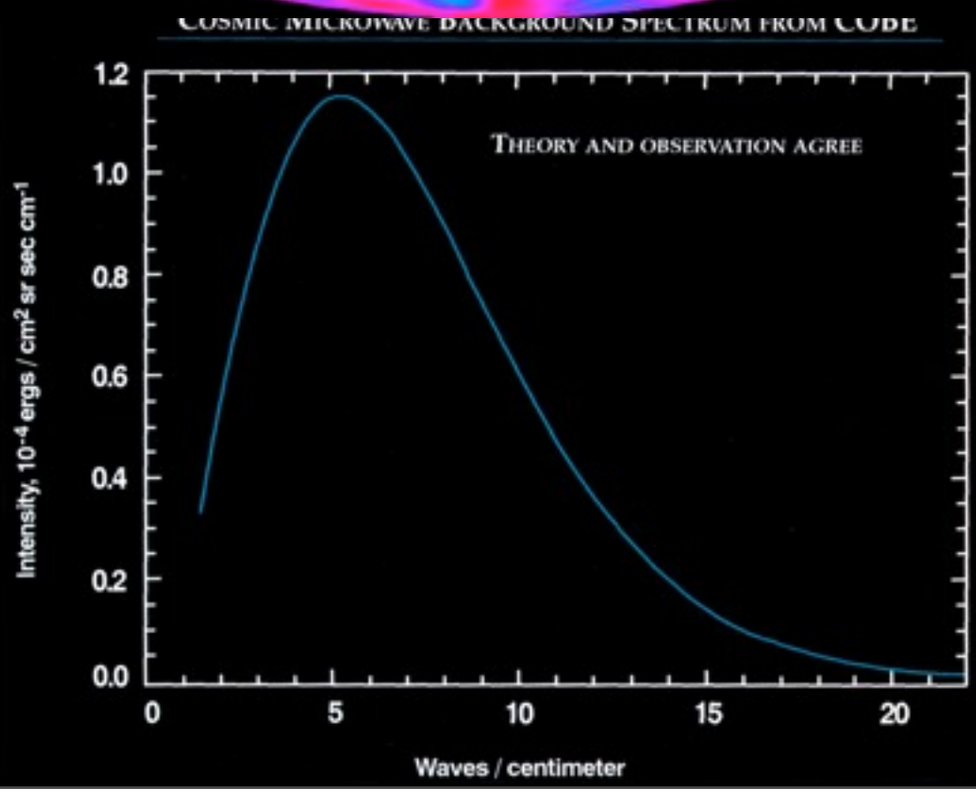
2006



ripples at 10^{-5}

John Mather





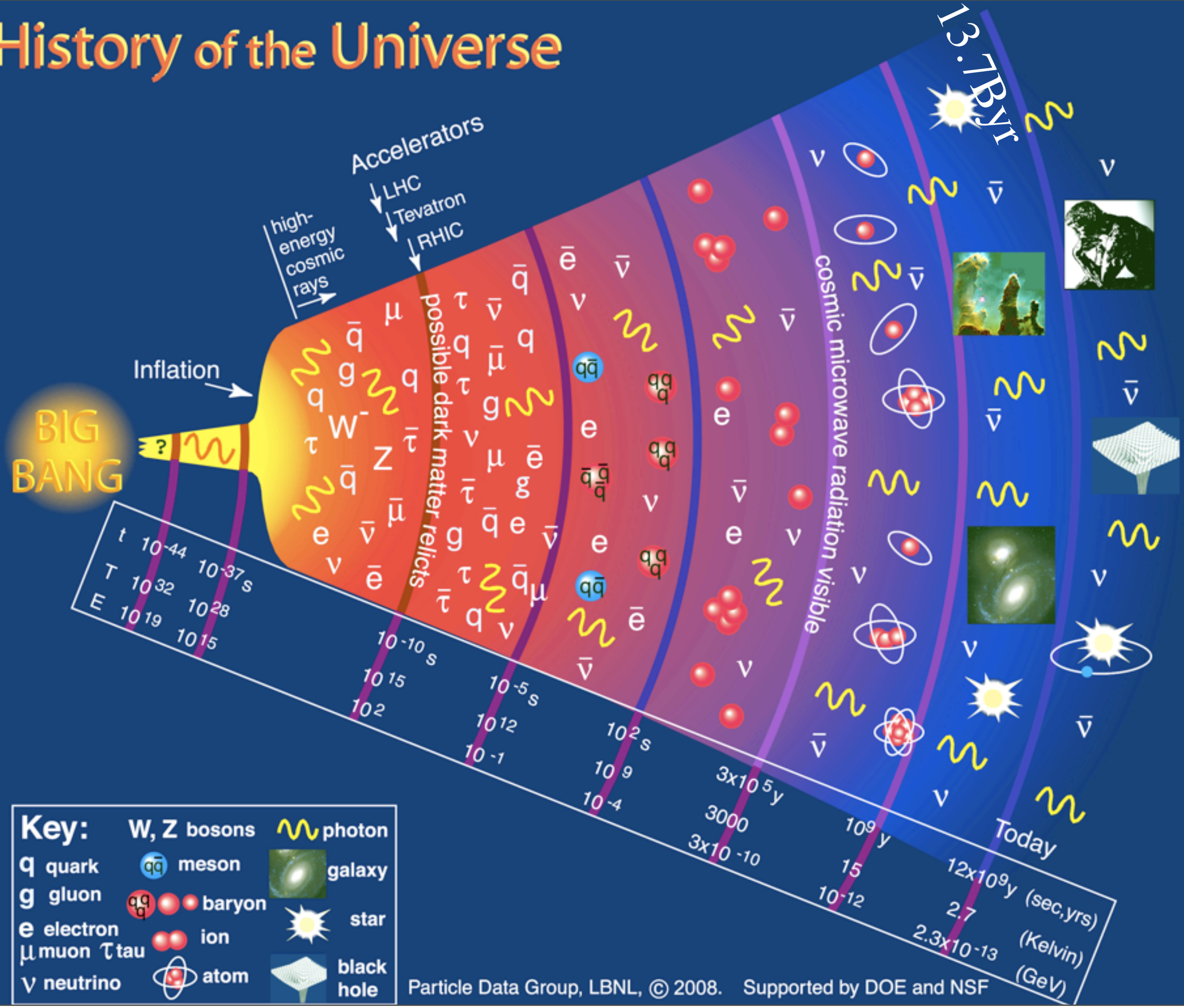
Big Bang enactment by Cal Band

Big Bang enactment by Cal Band



2011年6月8日星期三

History of the Universe



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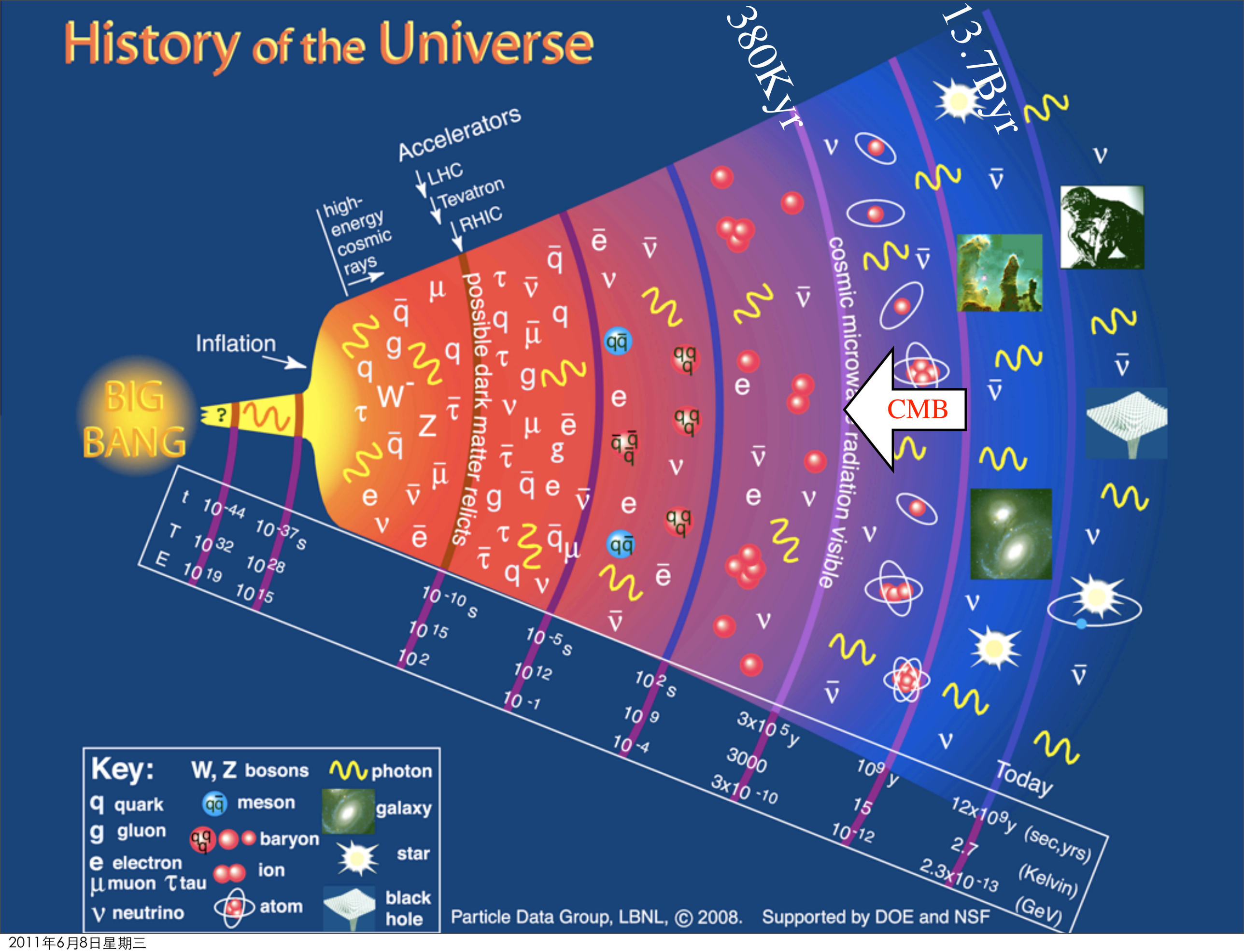

Dark Matter



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There are many
things we don't see

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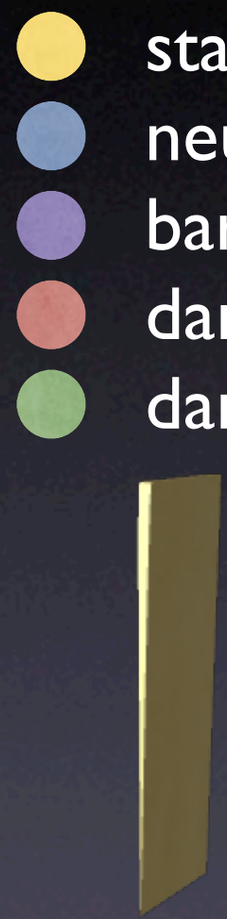
Energy Budget of the Universe

- stars
- neutrinos
- baryon
- dark matter
- dark energy

Energy Budget of the Universe

- Stars and galaxies are only ~0.5%



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Energy Budget of the Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%

stars
neutrinos
baryon
dark matter
dark energy



Energy Budget of the Universe

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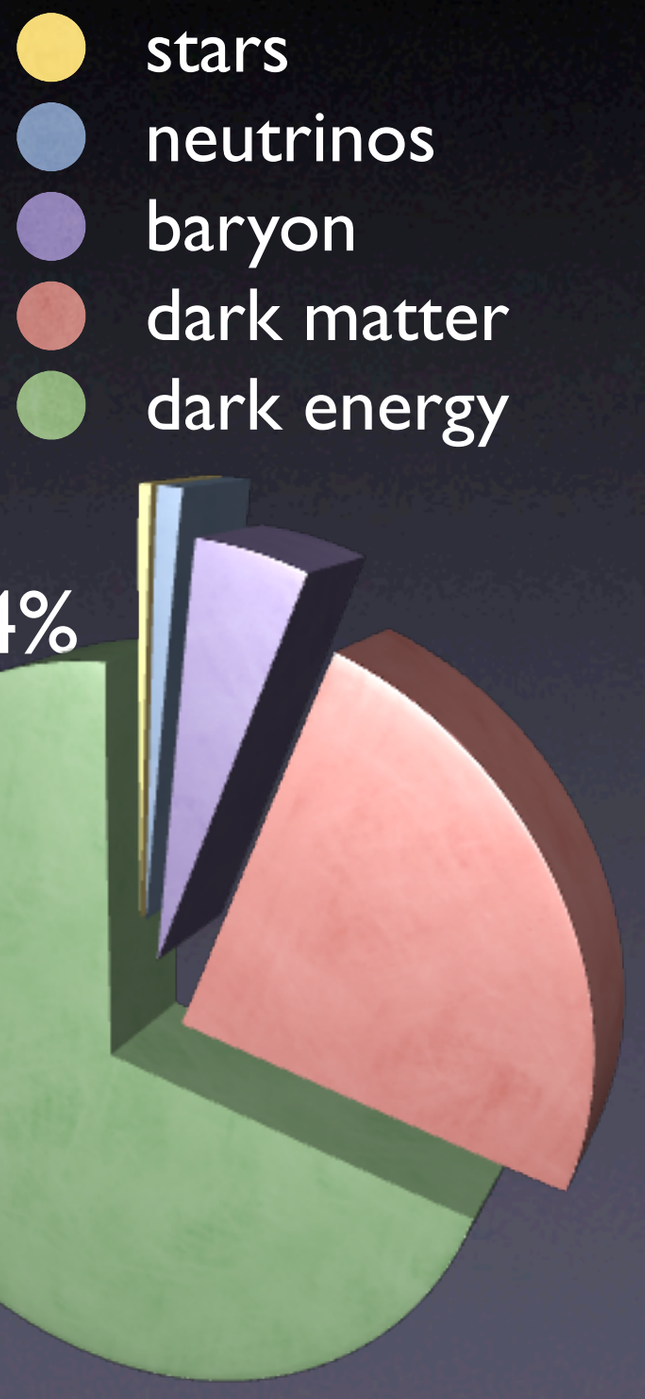

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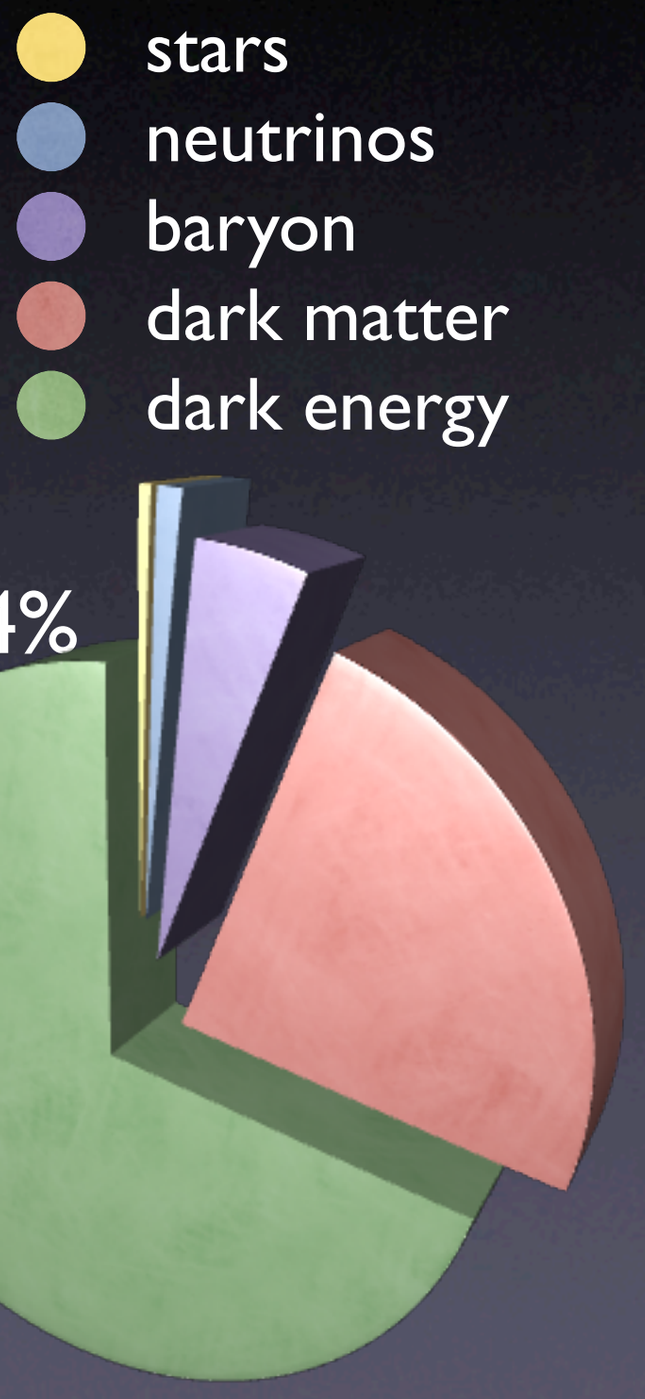

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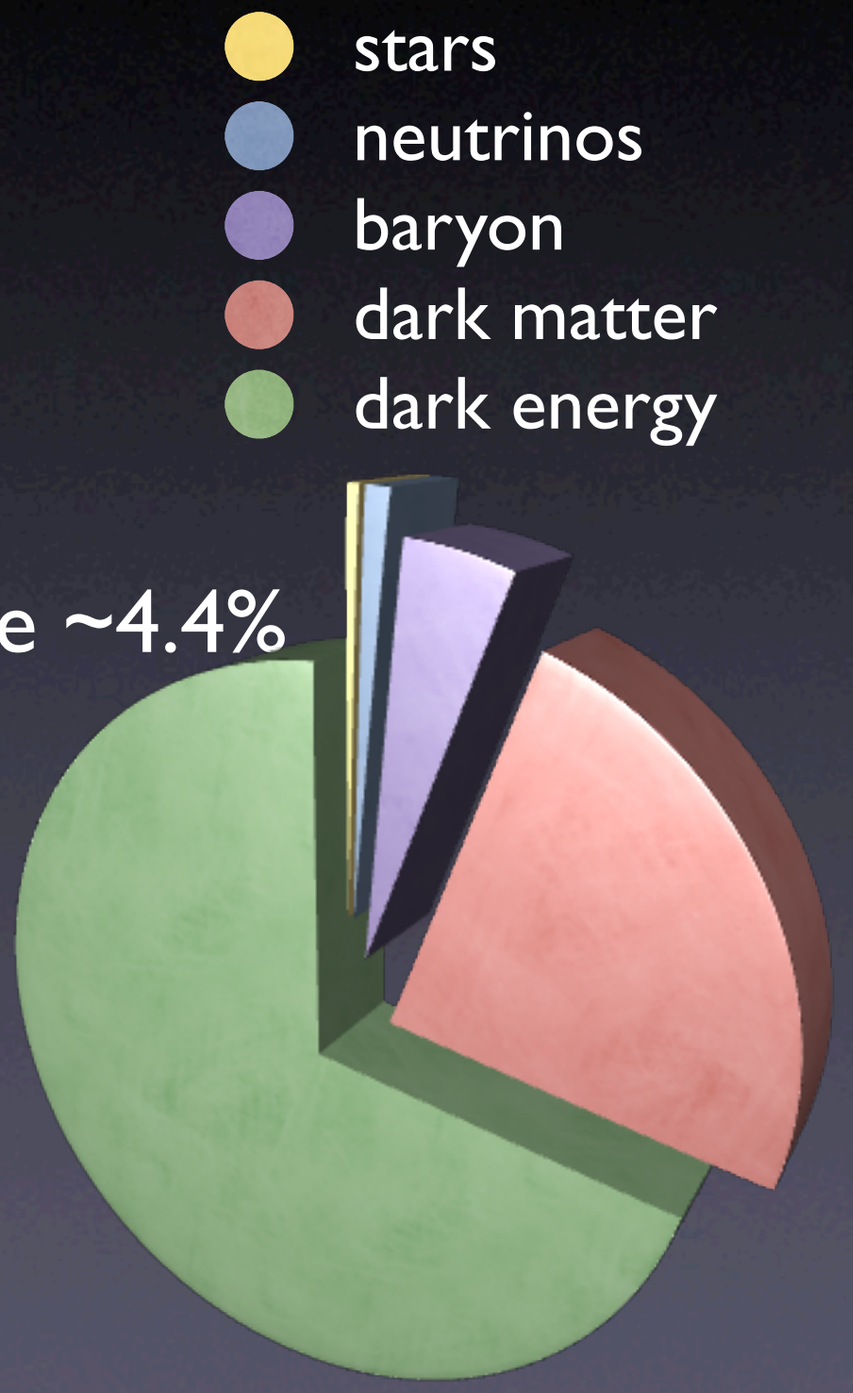

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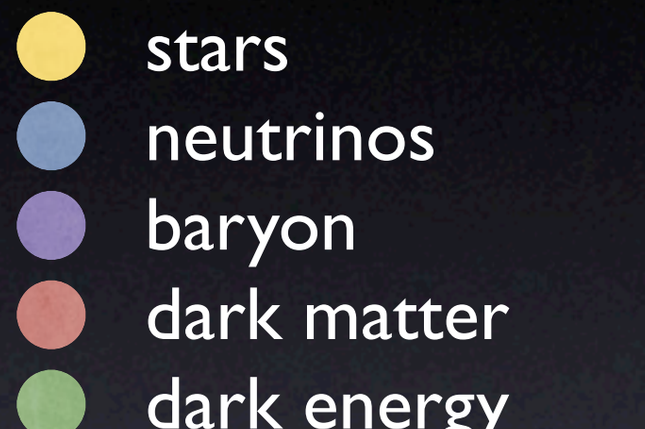
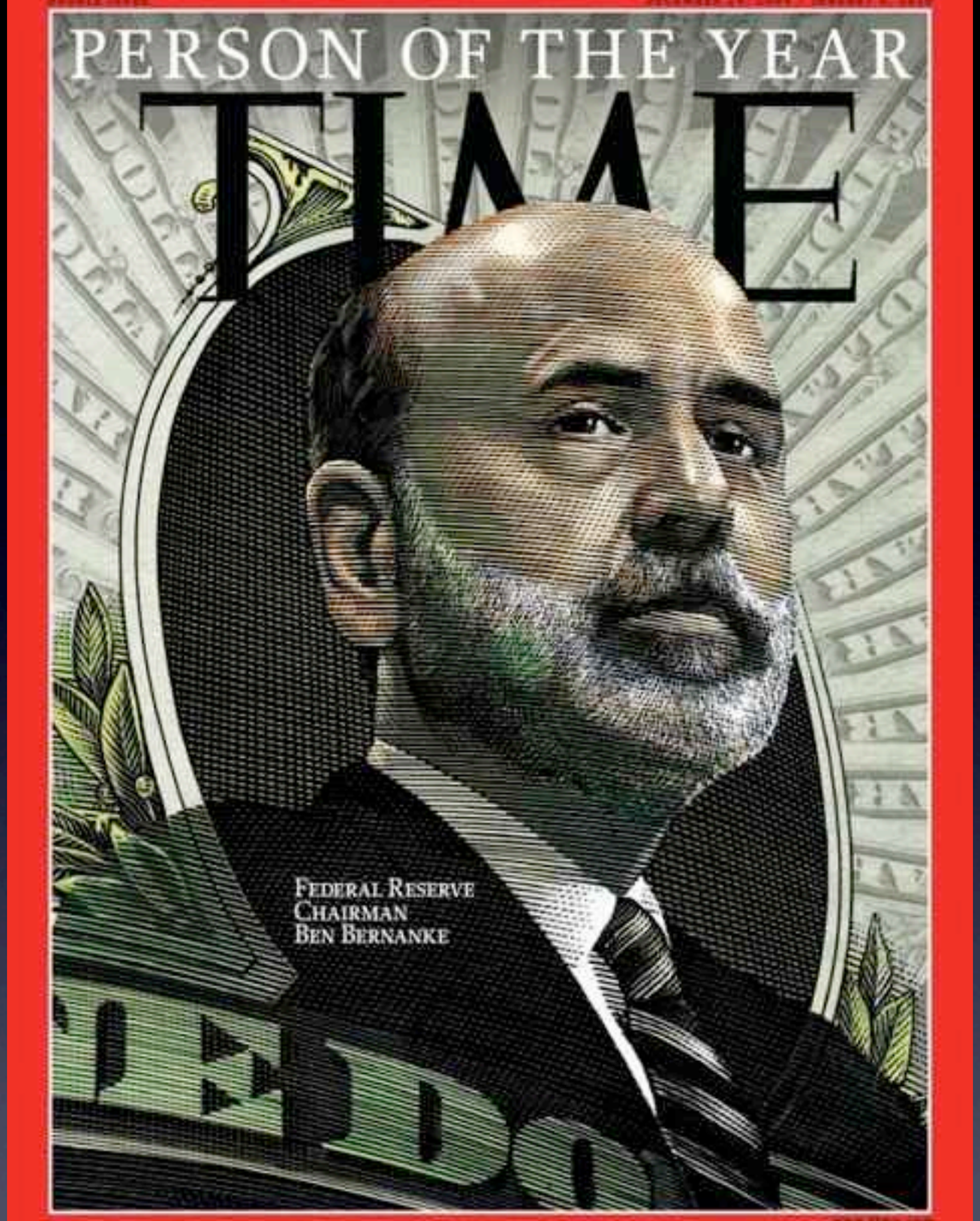
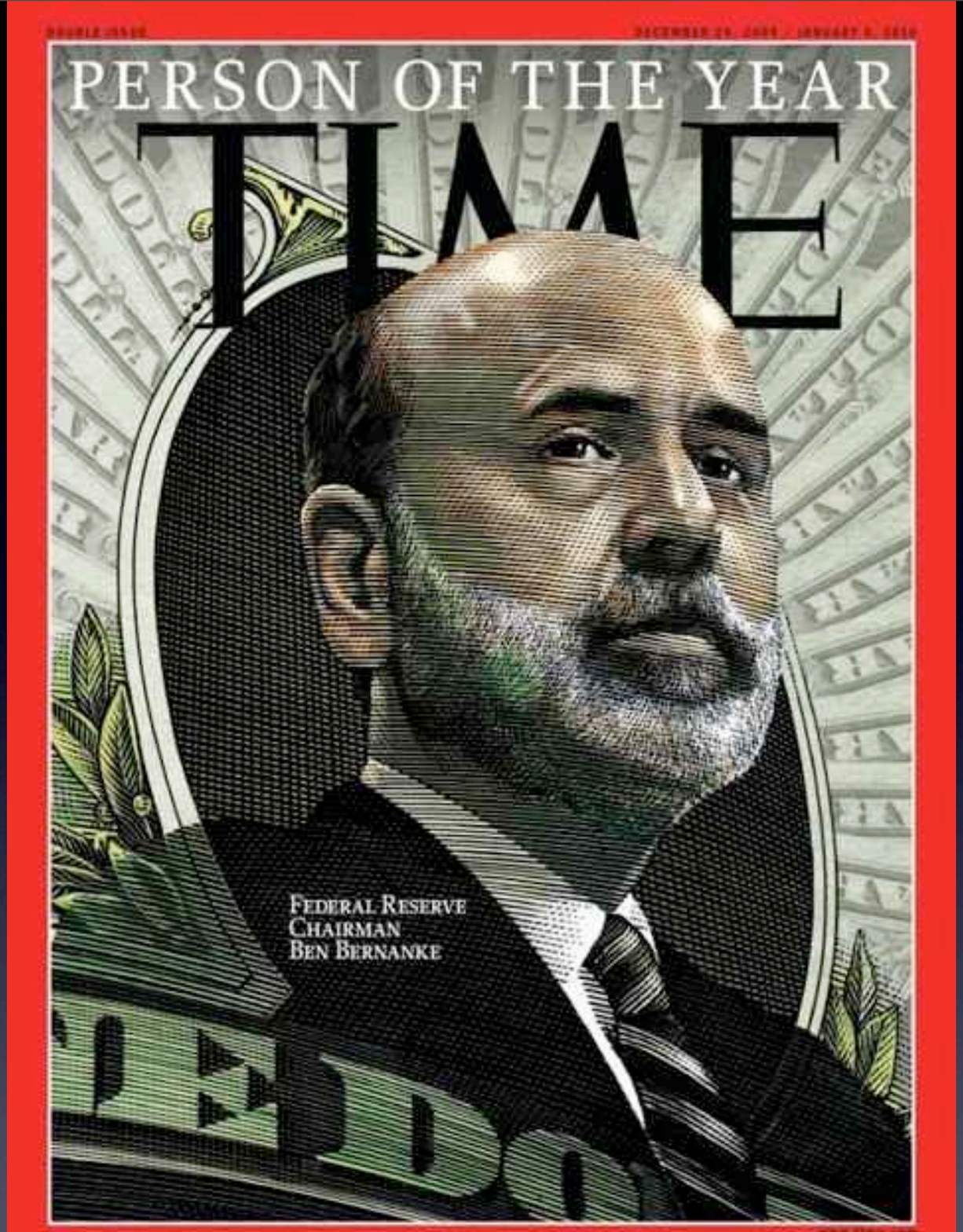



PERSON OF THE YEAR
TIME
FEDERAL RESERVE
CHAIRMAN
BEN BERNANKE

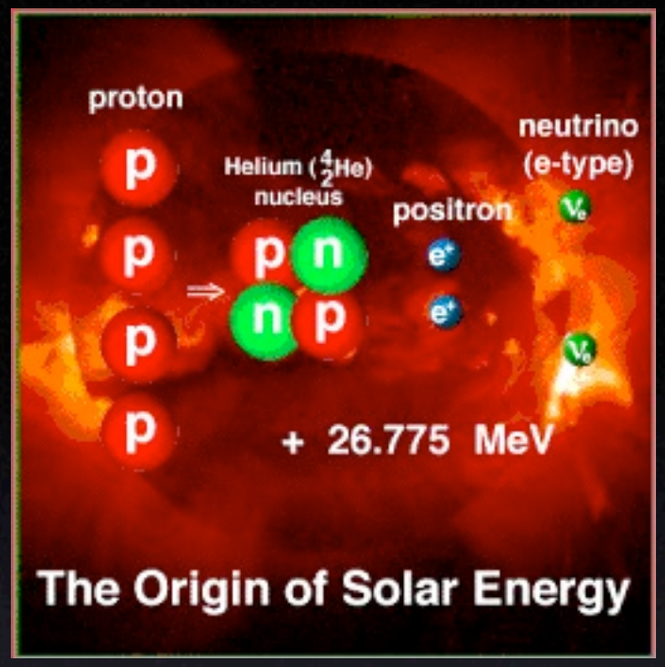


The prospective
increase in the budget deficit will
place risk at future living standards

Don’t be afraid of invisibles

Pauli regretted to have predicted neutrinos nobody can detect

Trillions of them go through our body every second



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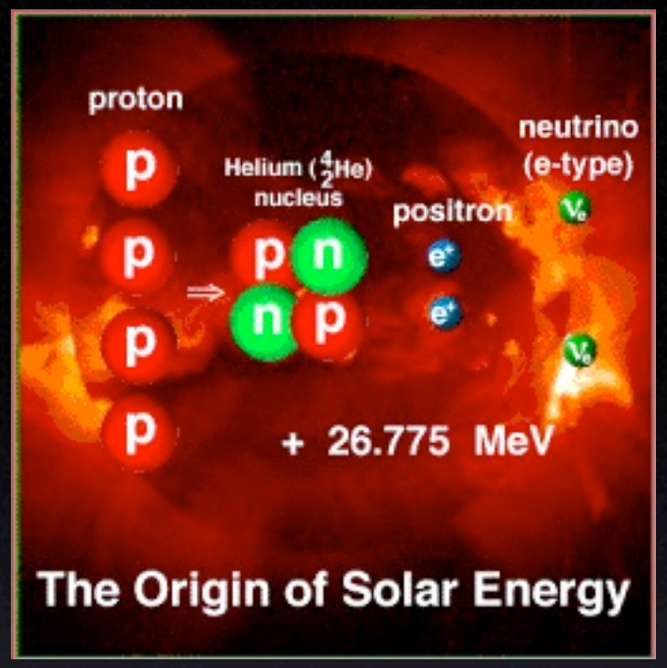

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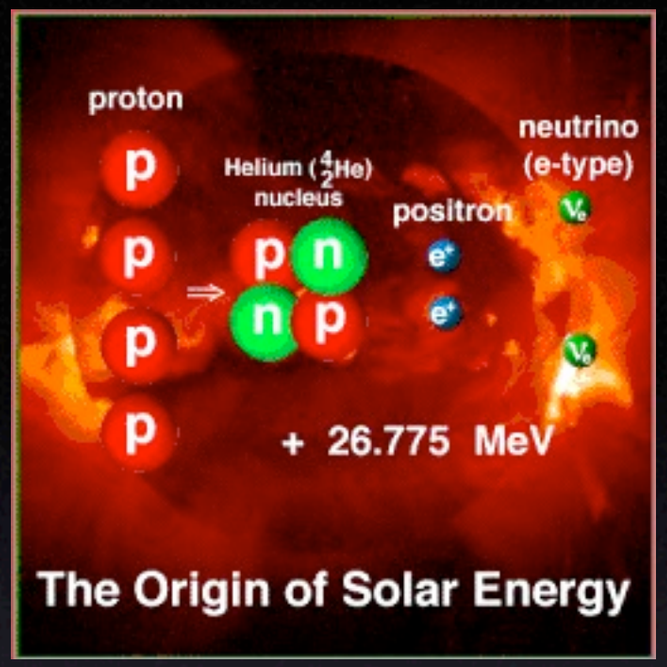

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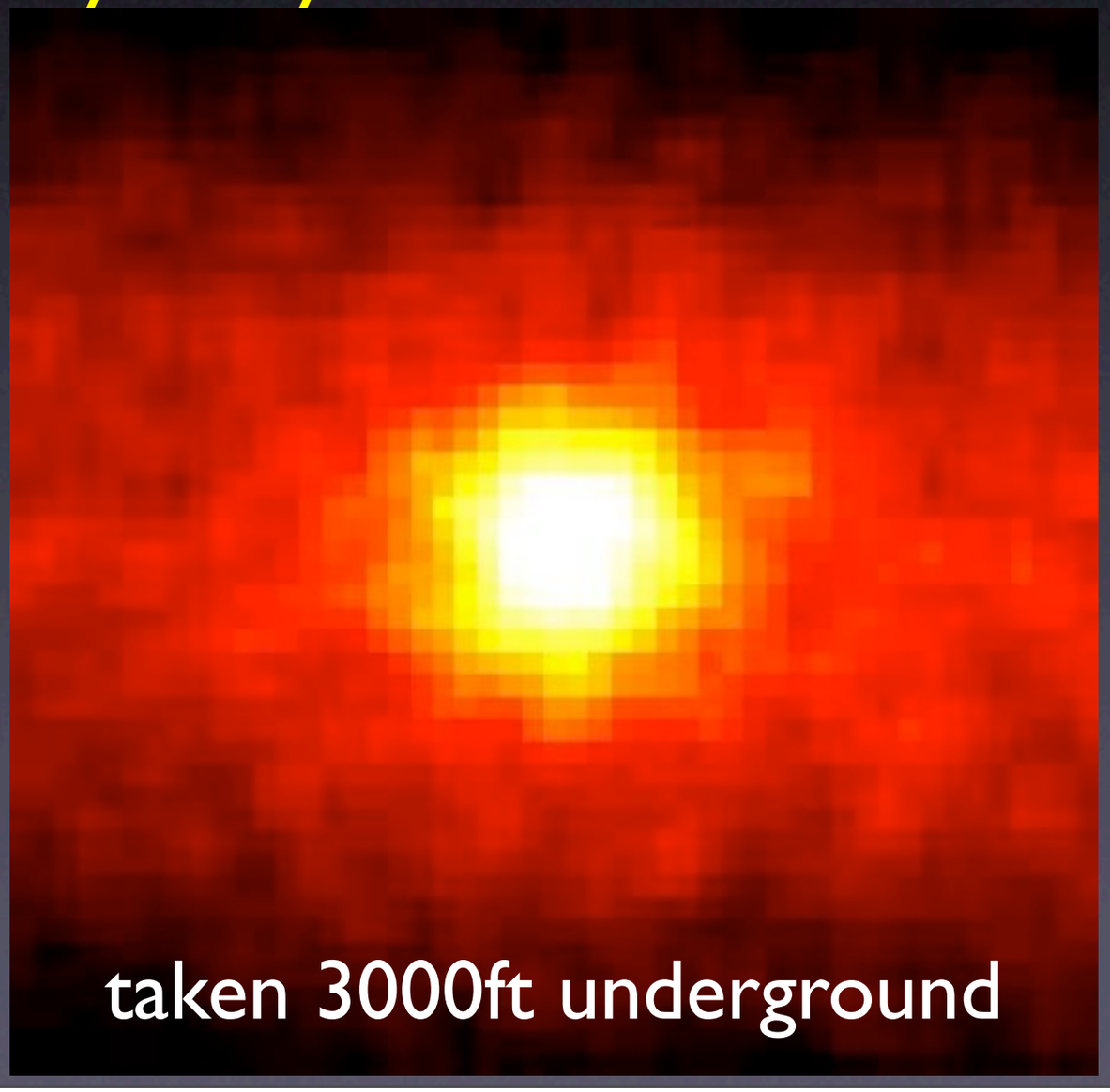
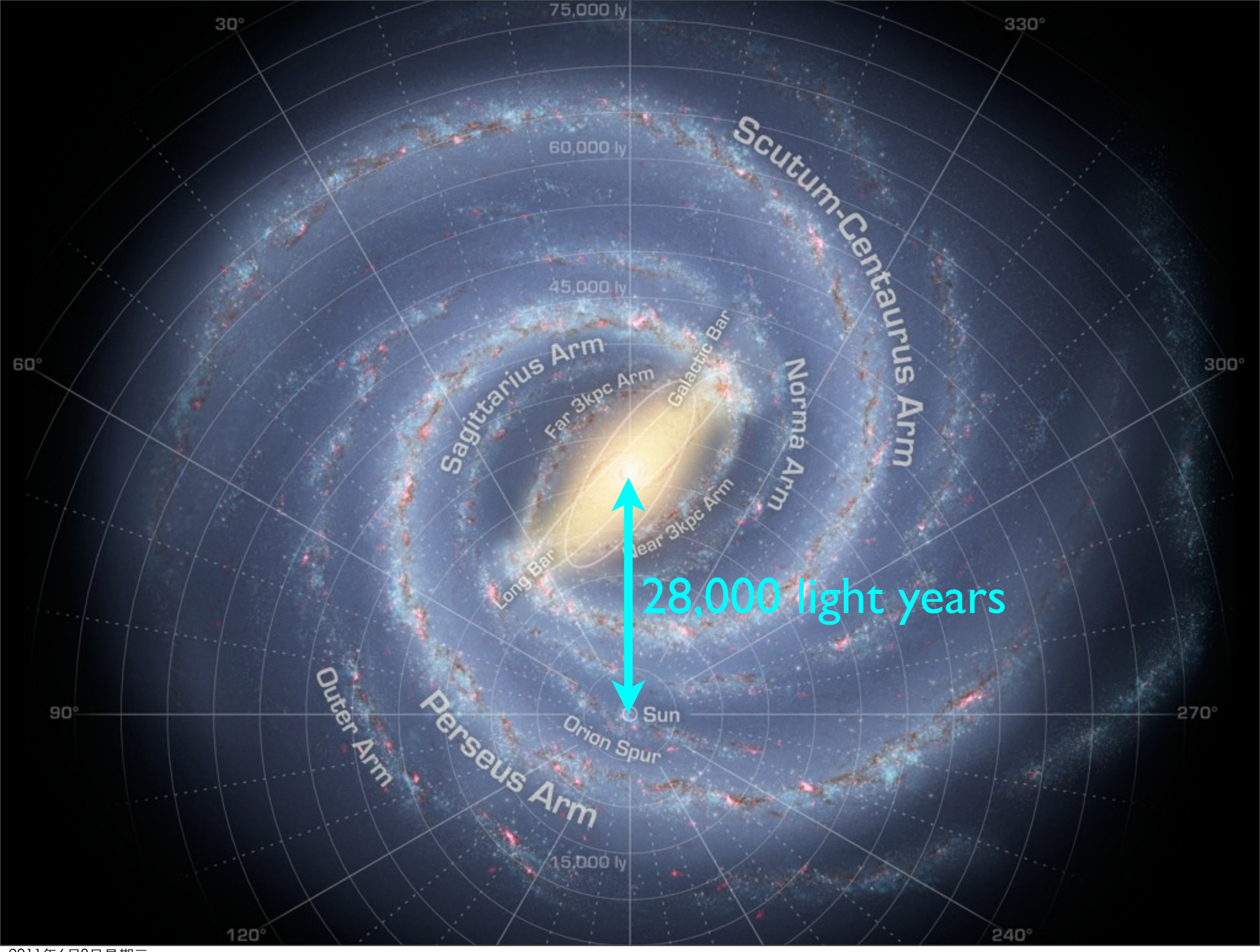


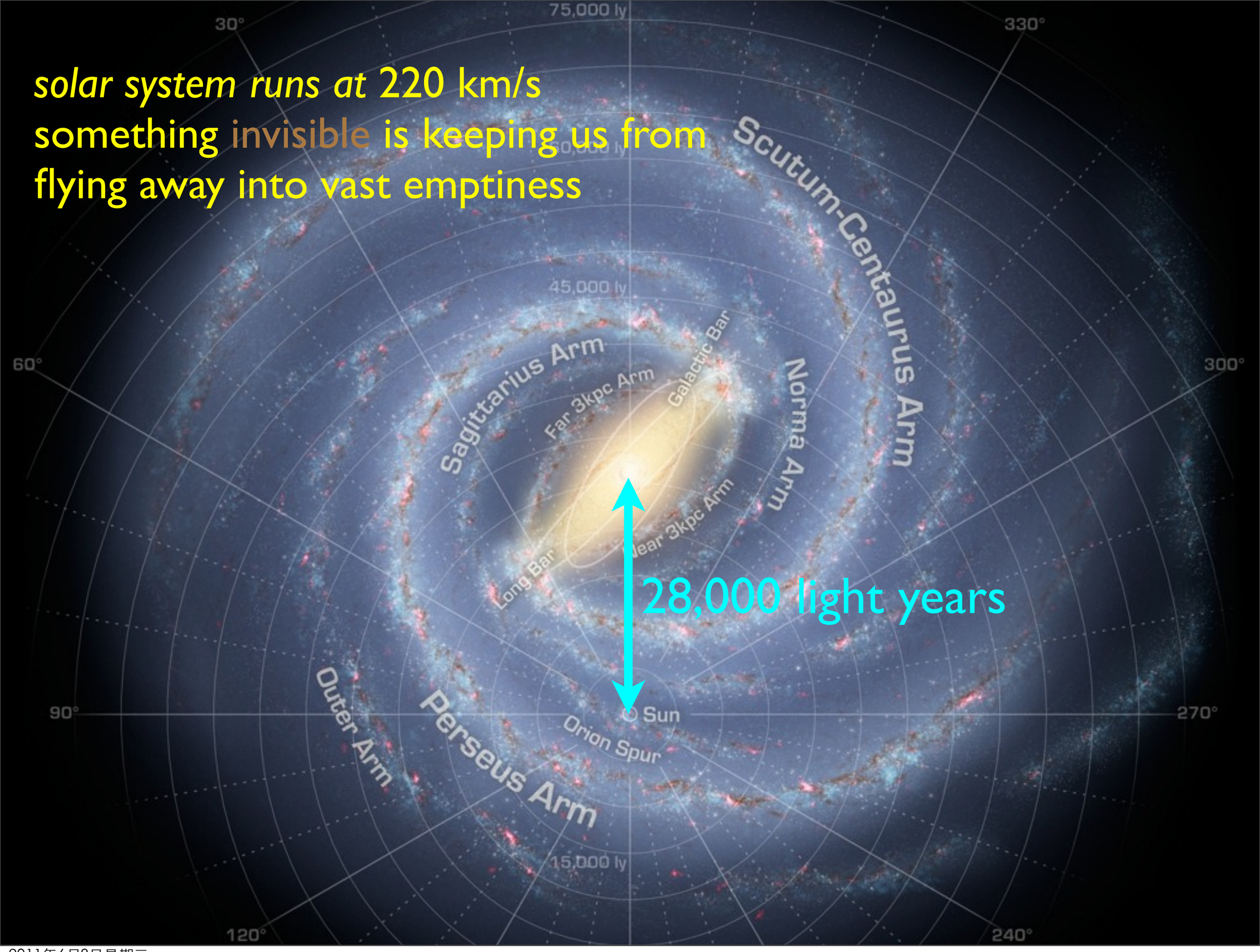
$$\nu$$



2011年6月8日星期三


75,000 ly
60,000 ly
45,000 ly
15,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
28,000 light years
Sun
Orion Spur
Perseus Arm
Outer Arm

solar system runs at 220 km/s
something invisible is keeping us from
flying away into vast emptiness



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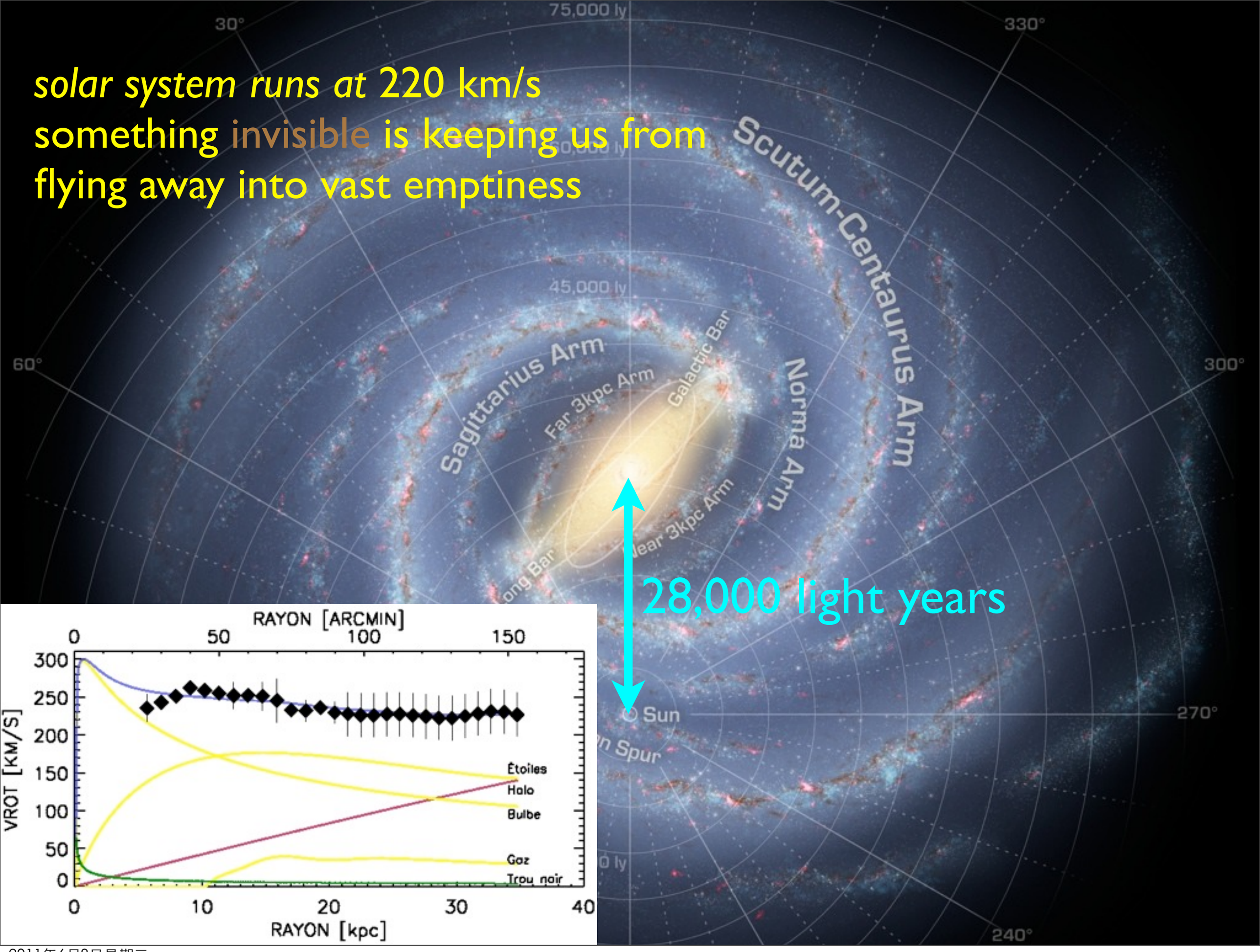
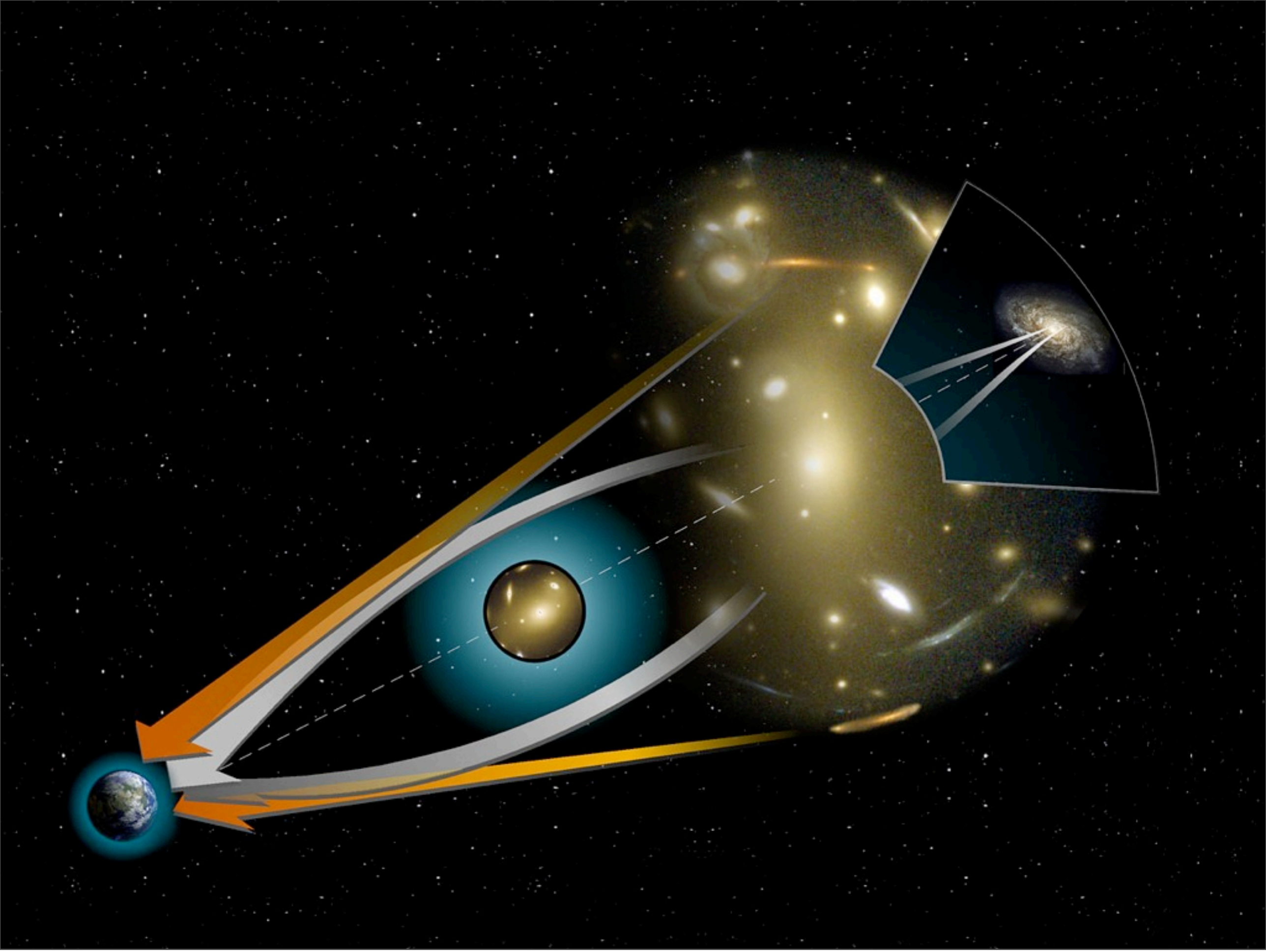


Cluster of galaxies



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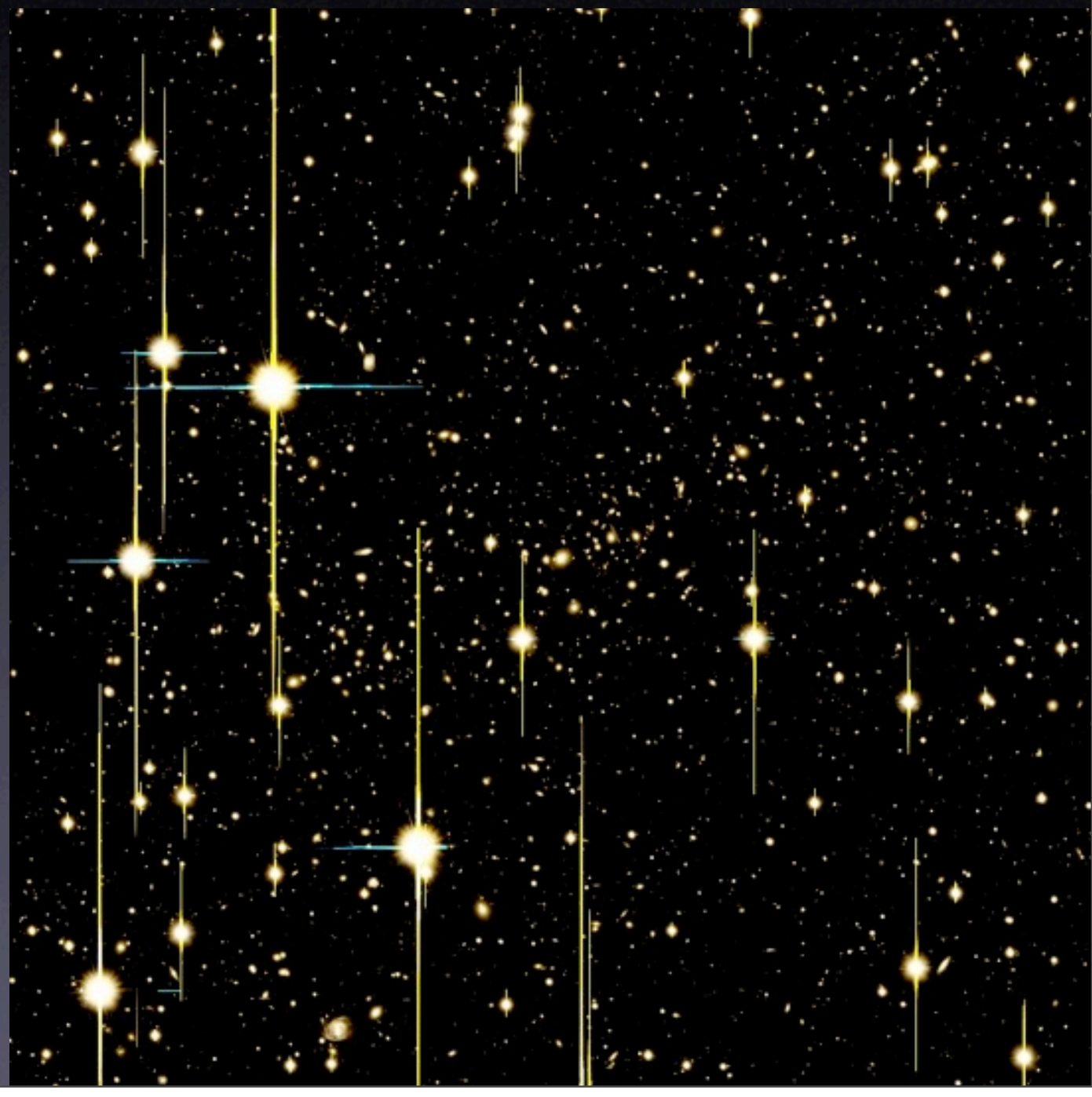
“Seeing” invisible dark matter

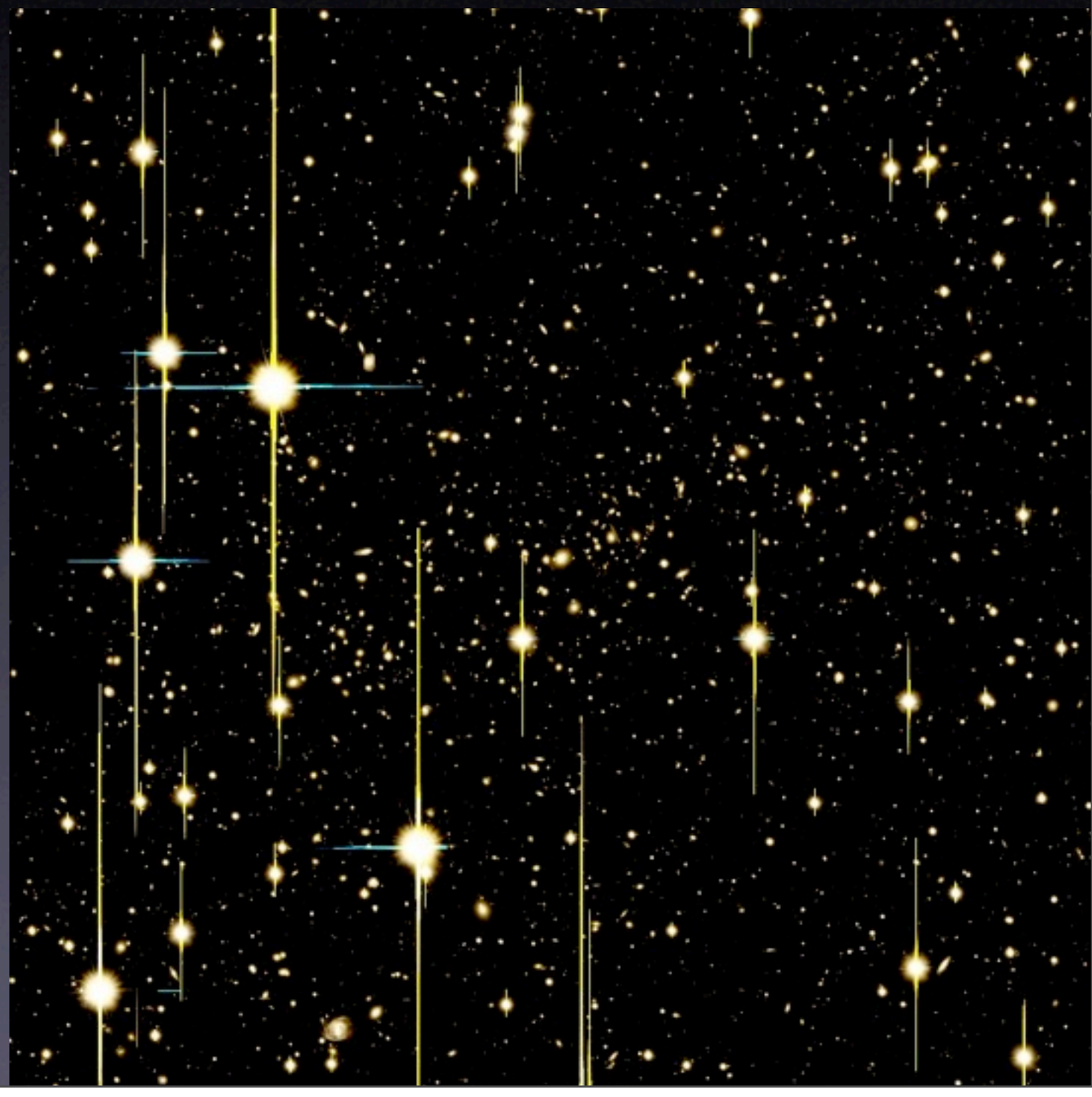




“Seeing” invisible dark matter



- light follows geodesics



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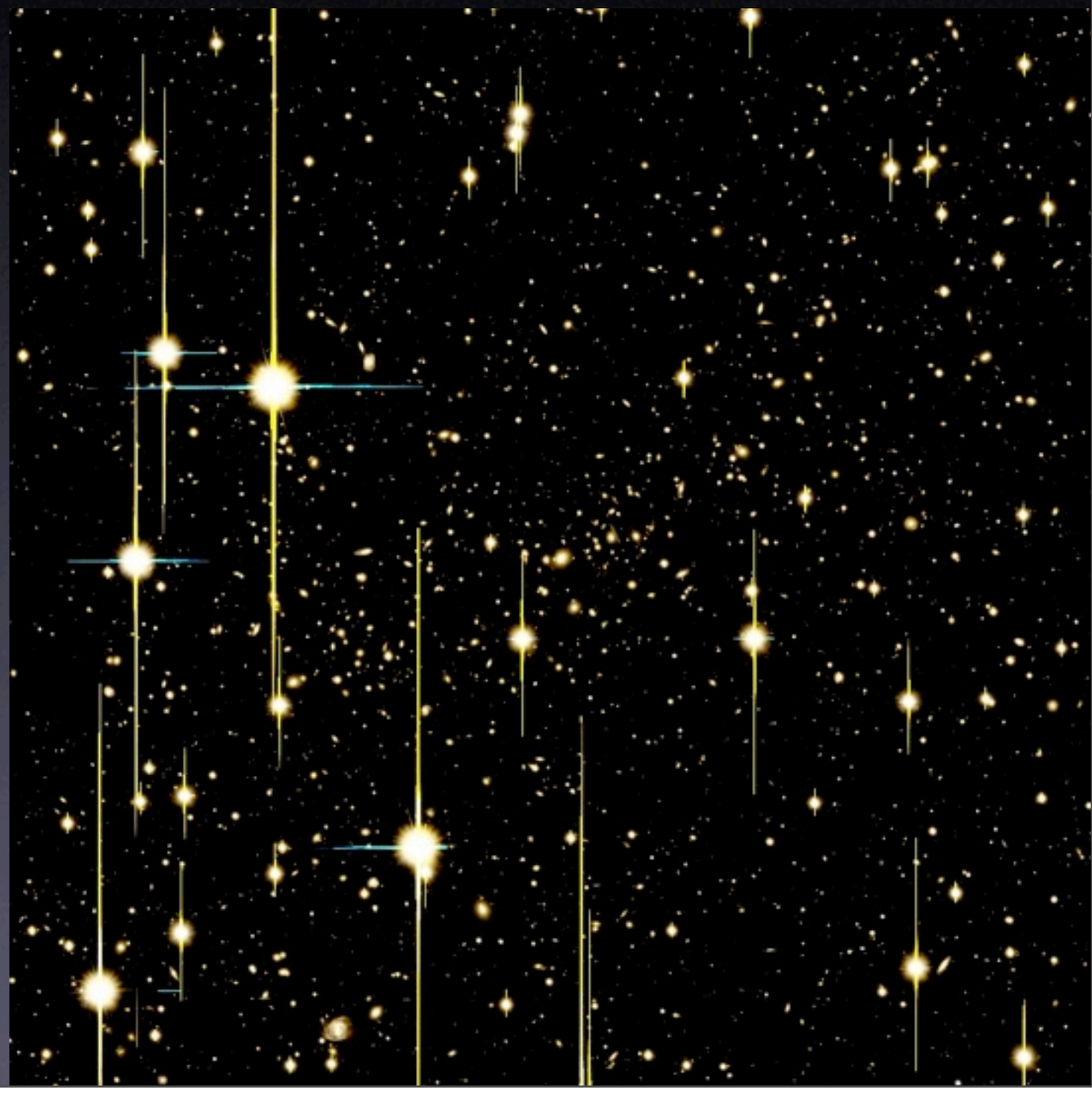

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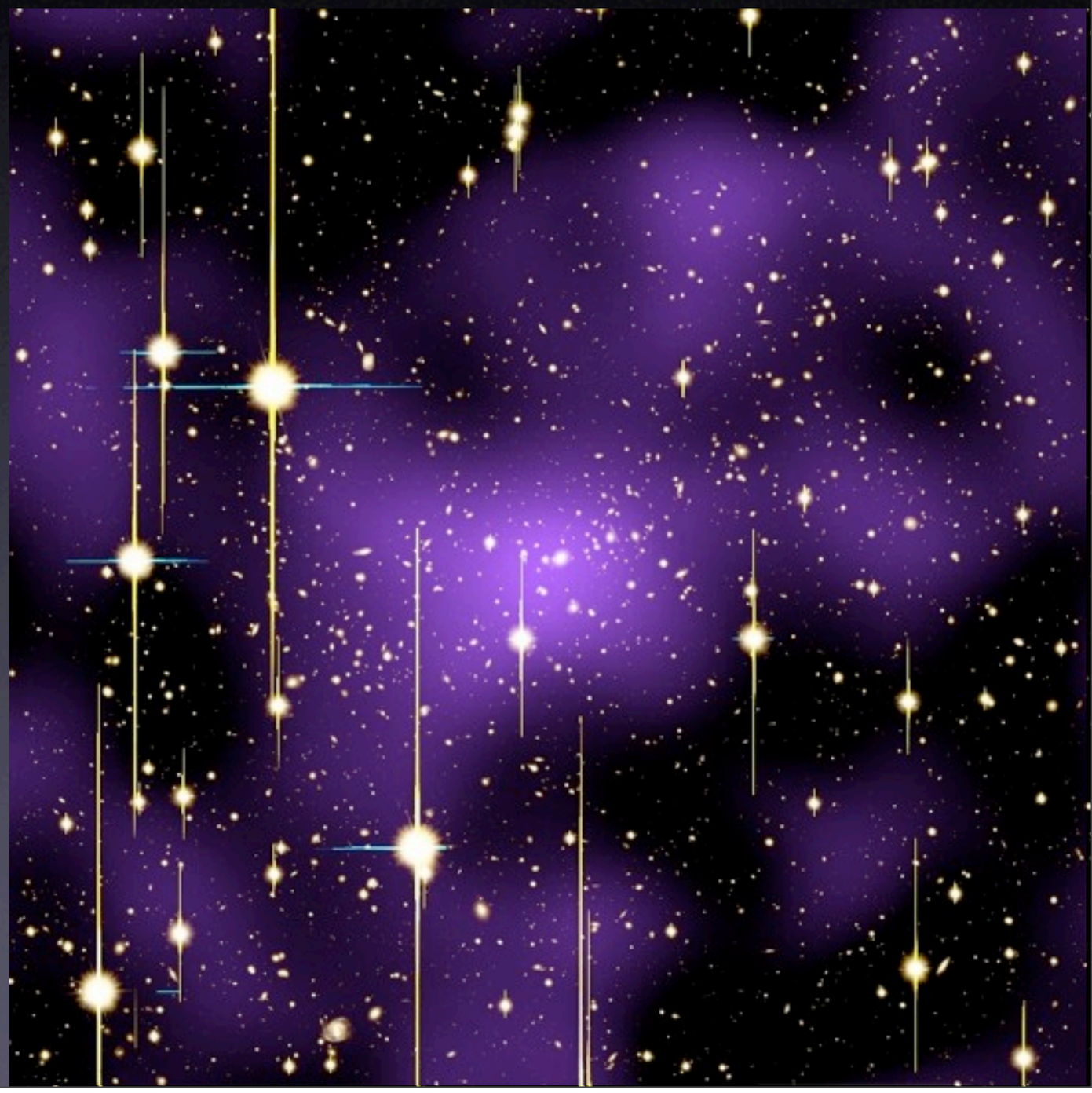
- map out invisible dark matter in clusters



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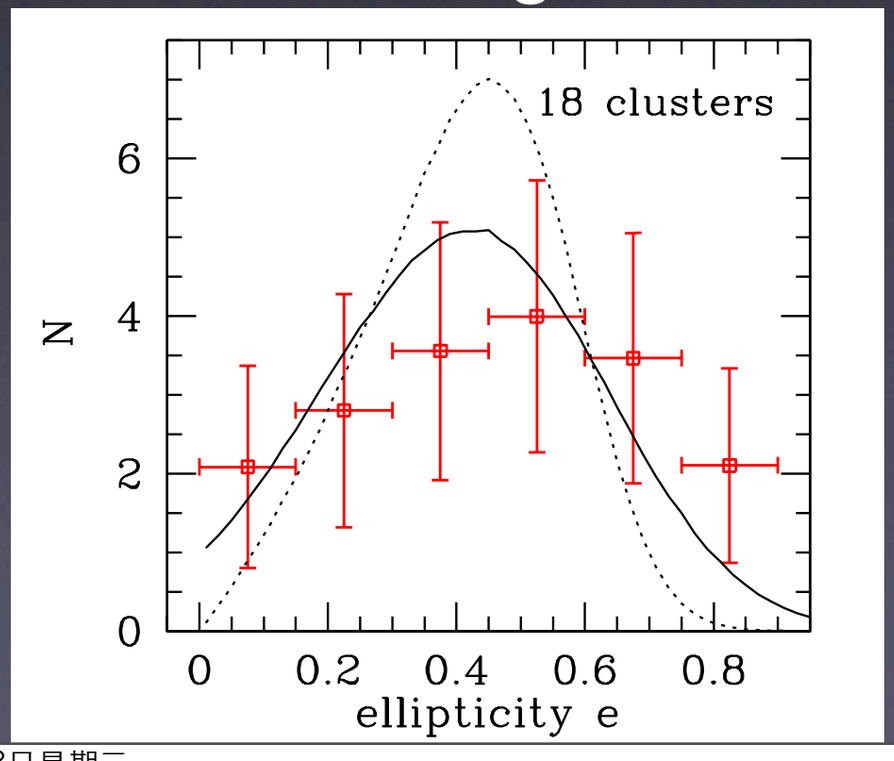
“Seeing” invisible dark matter

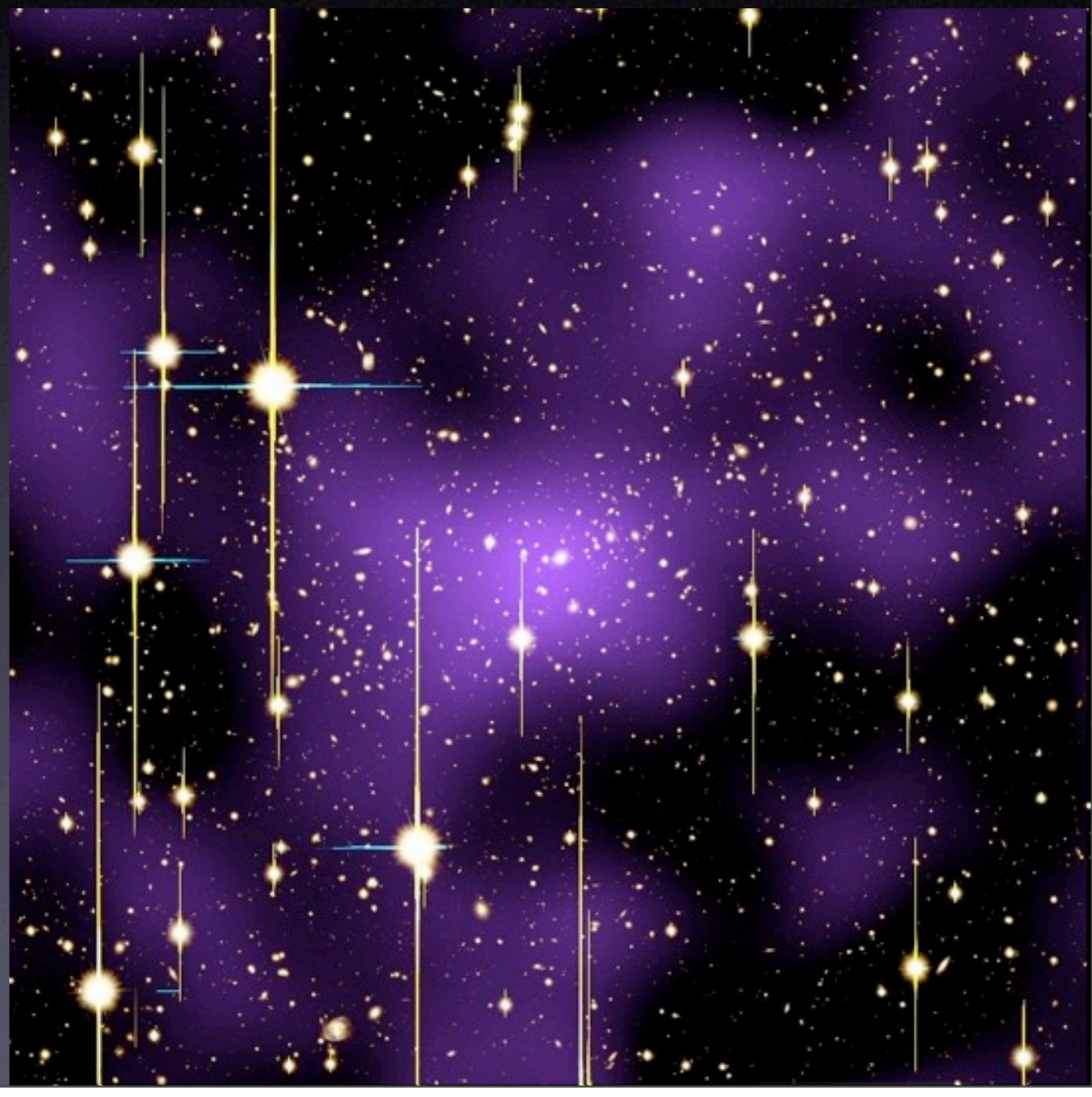


- light follows geodesics

➡ gravitational lensing

- map out invisible dark matter in clusters
- demonstrated that distribution is *elongated* with meaningful statistics





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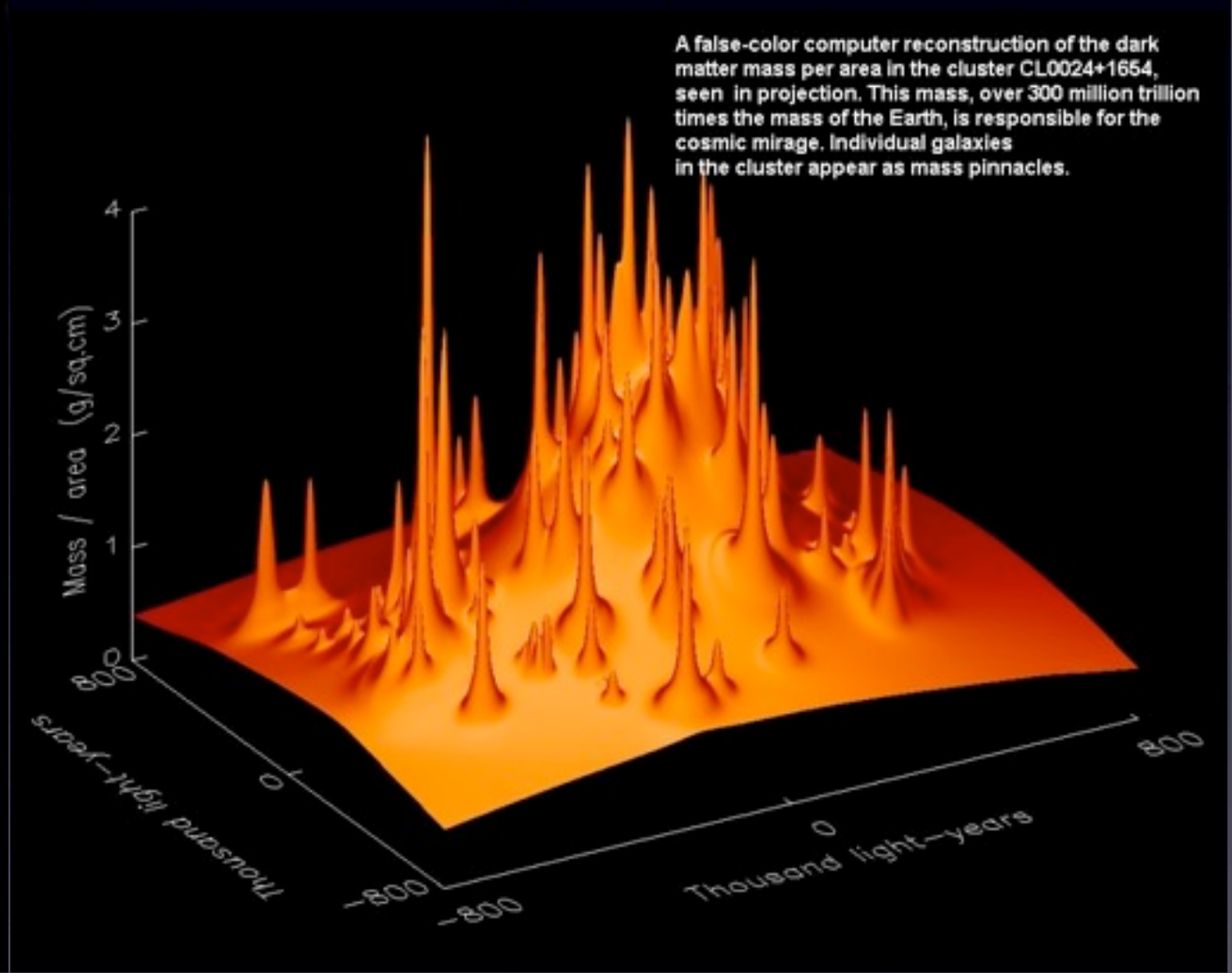
Cluster of galaxies





X

You don’t want to be there



You don't want to be there



You don't want to be there



You don't want to be there



We wouldn't exist without dark matter



w/o dark matter

with dark matter

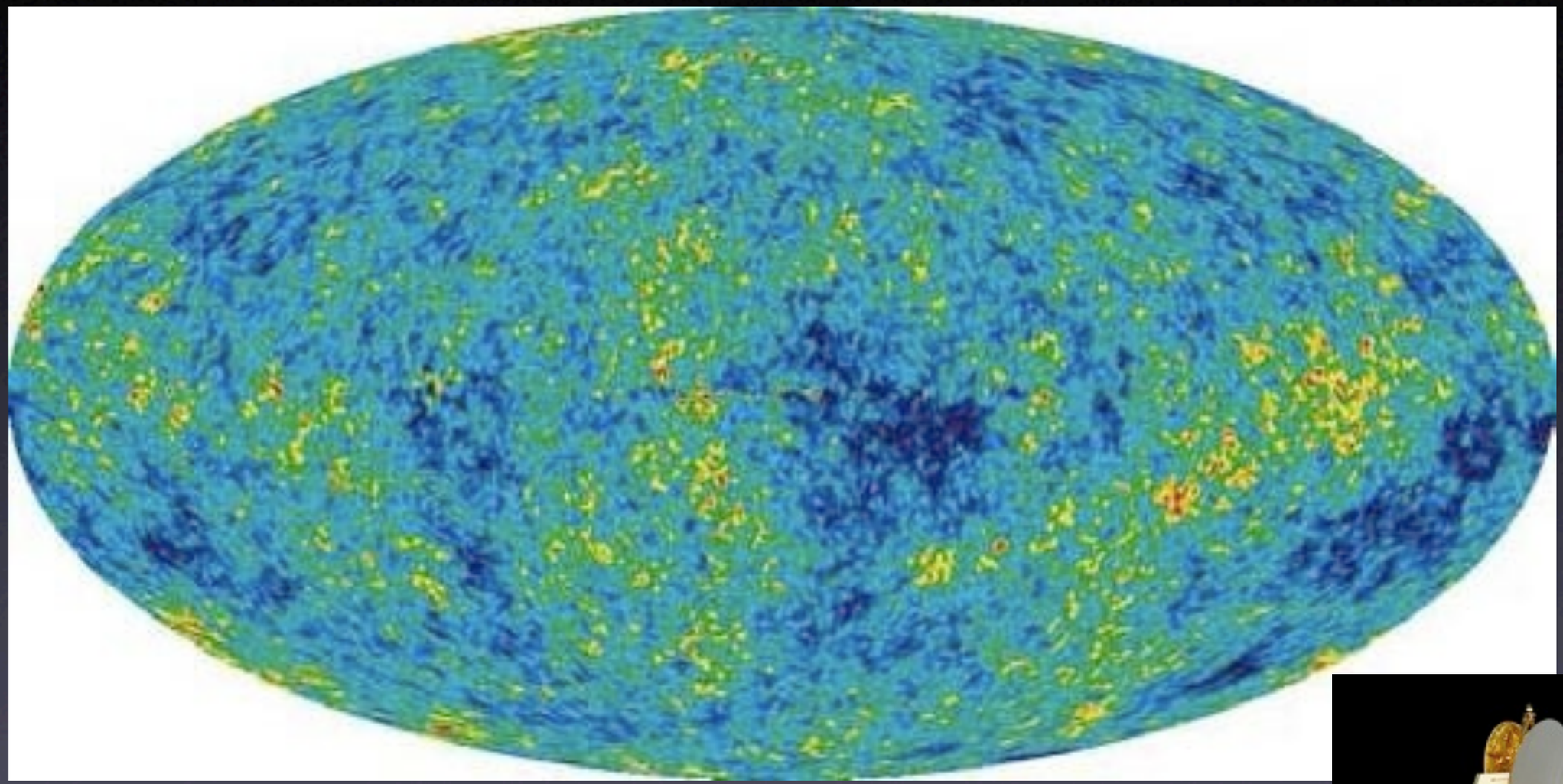
You don’t want to be there



You don't want to be there



Cosmological scales





X

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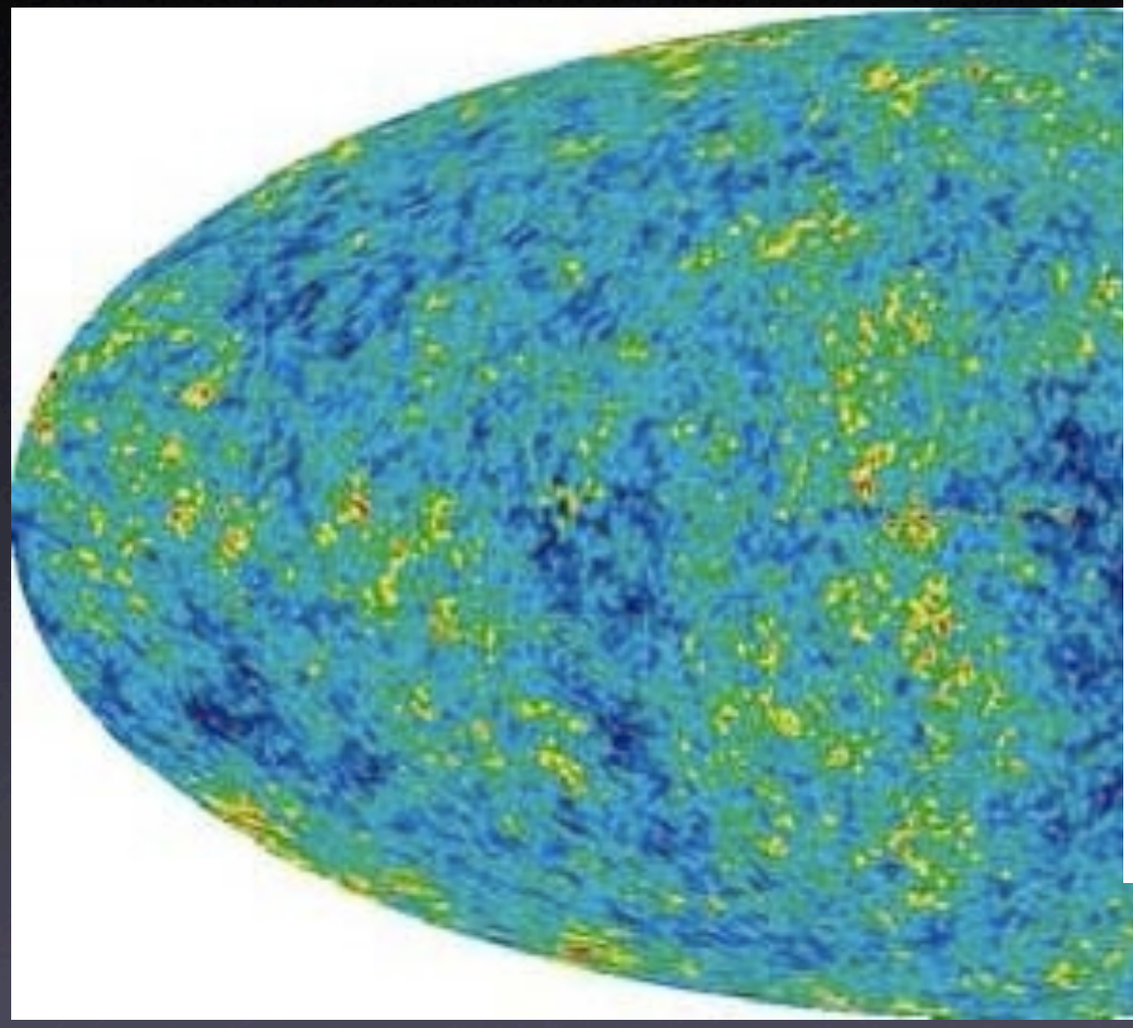

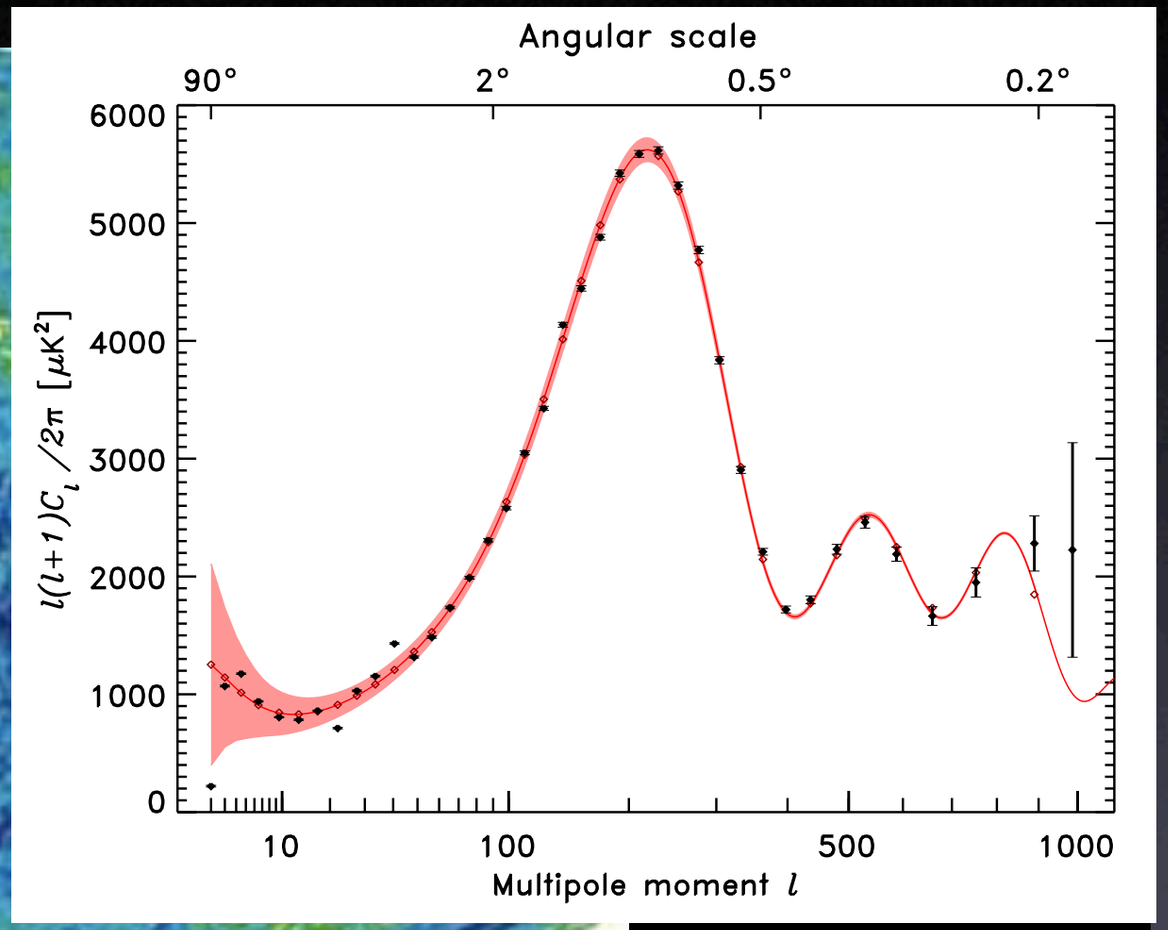



X

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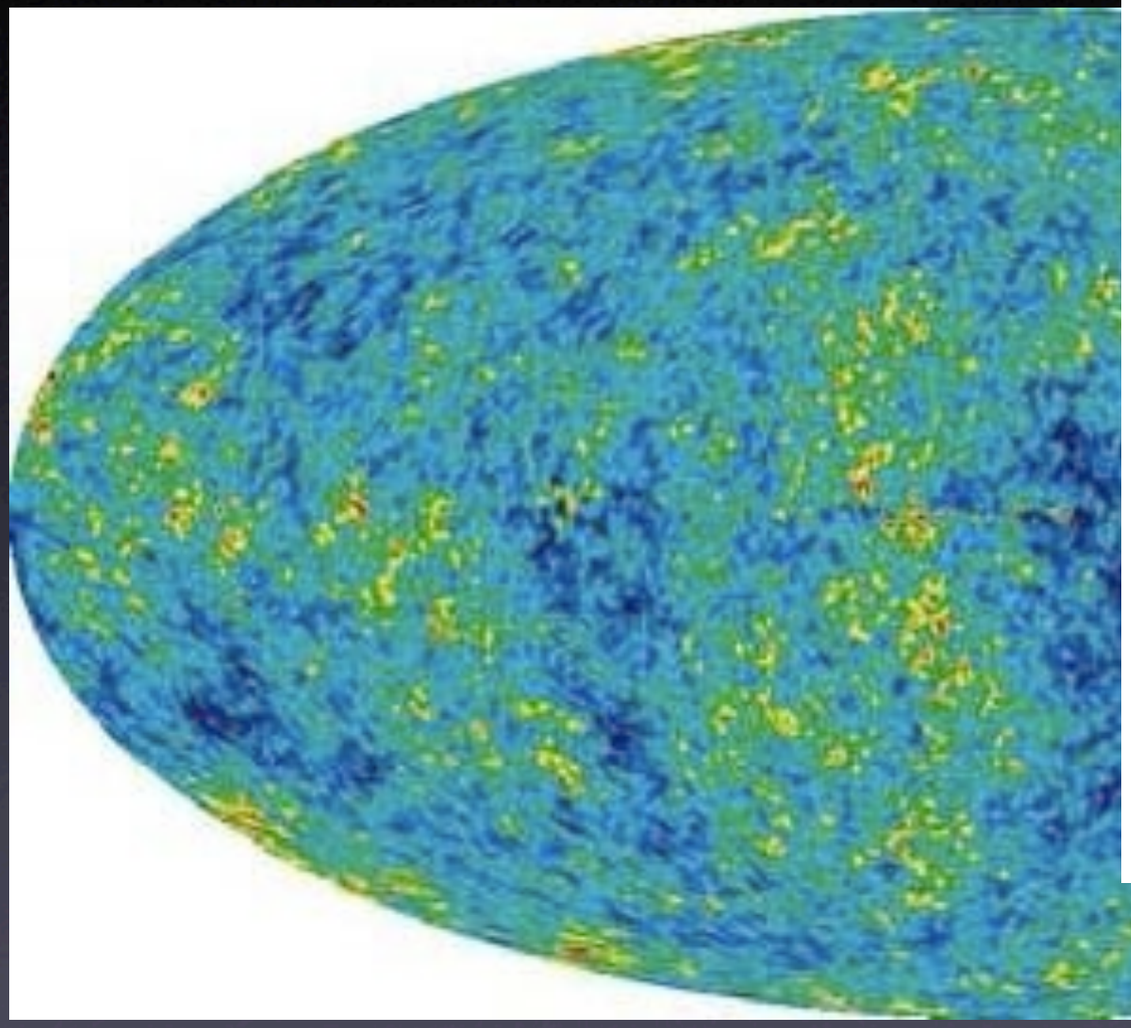

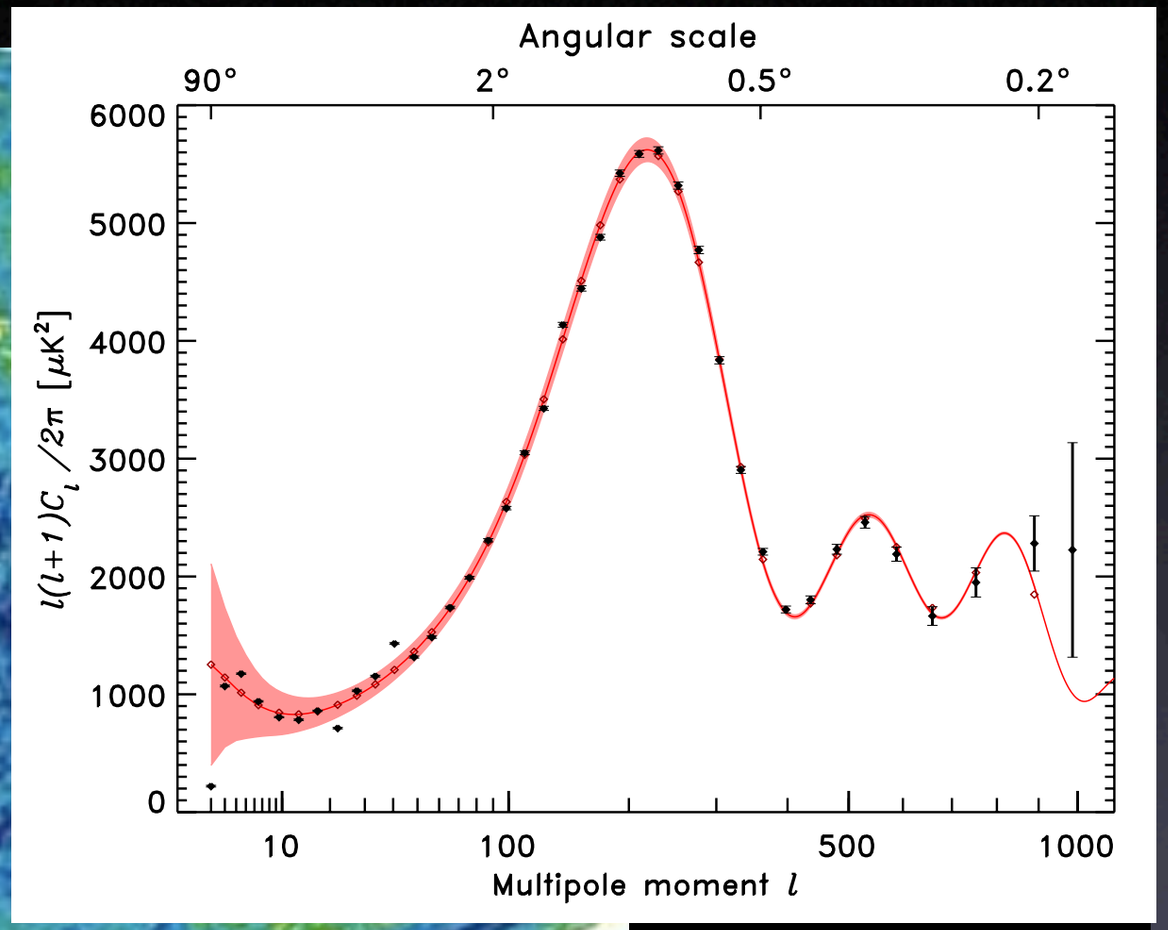

$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

x



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Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)



X

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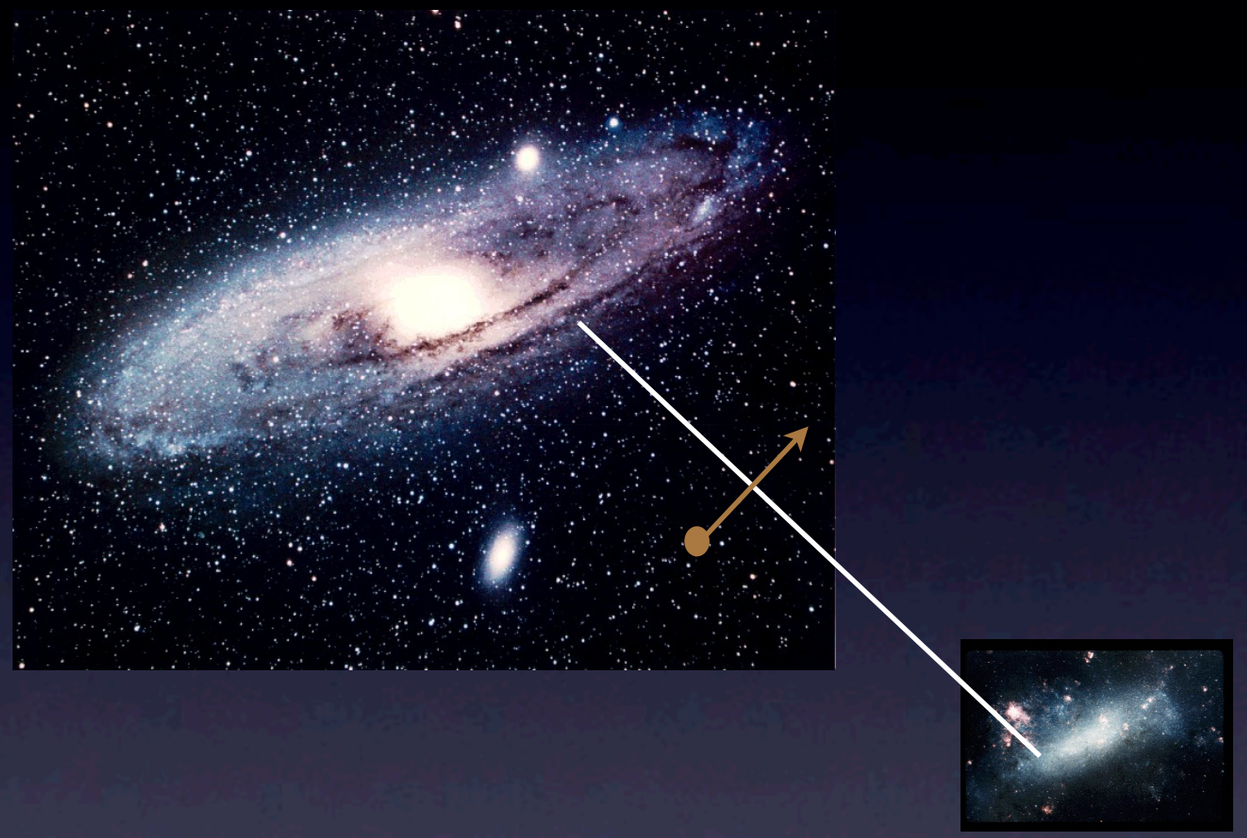

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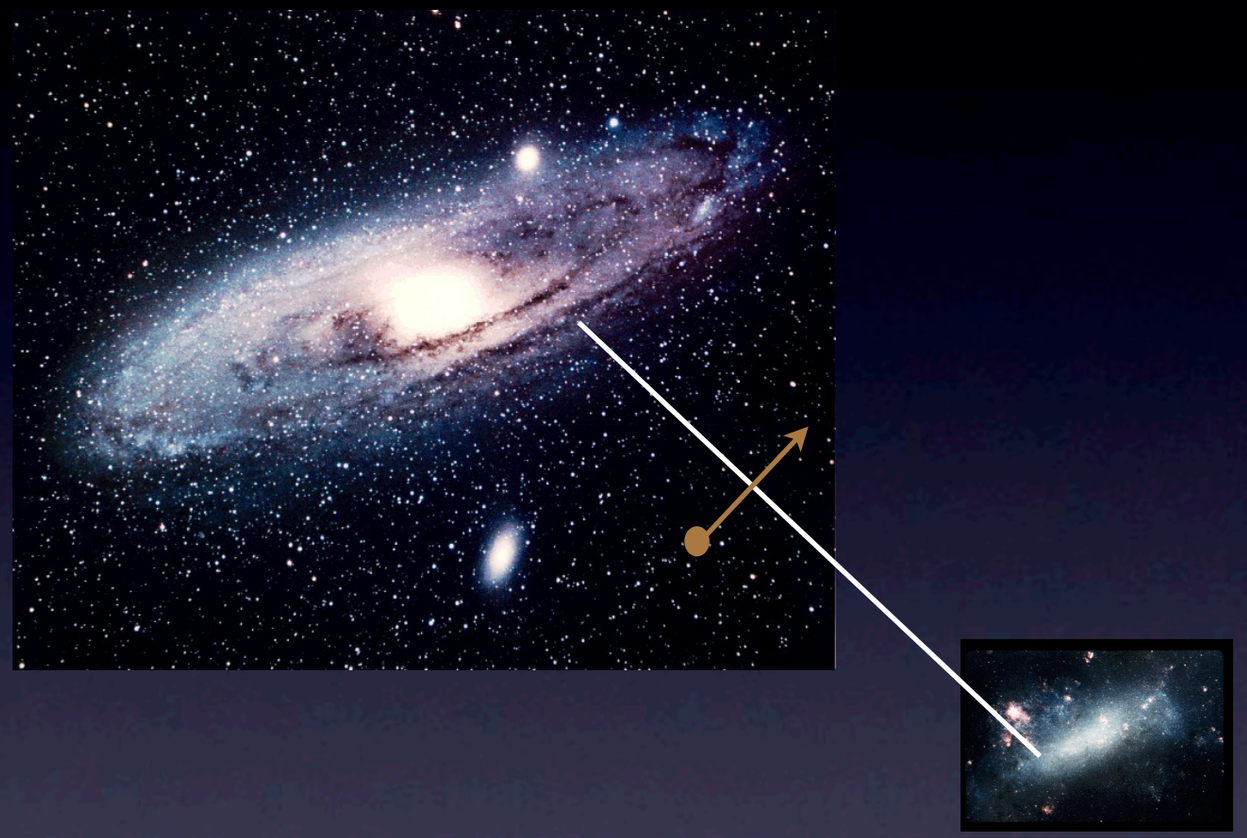

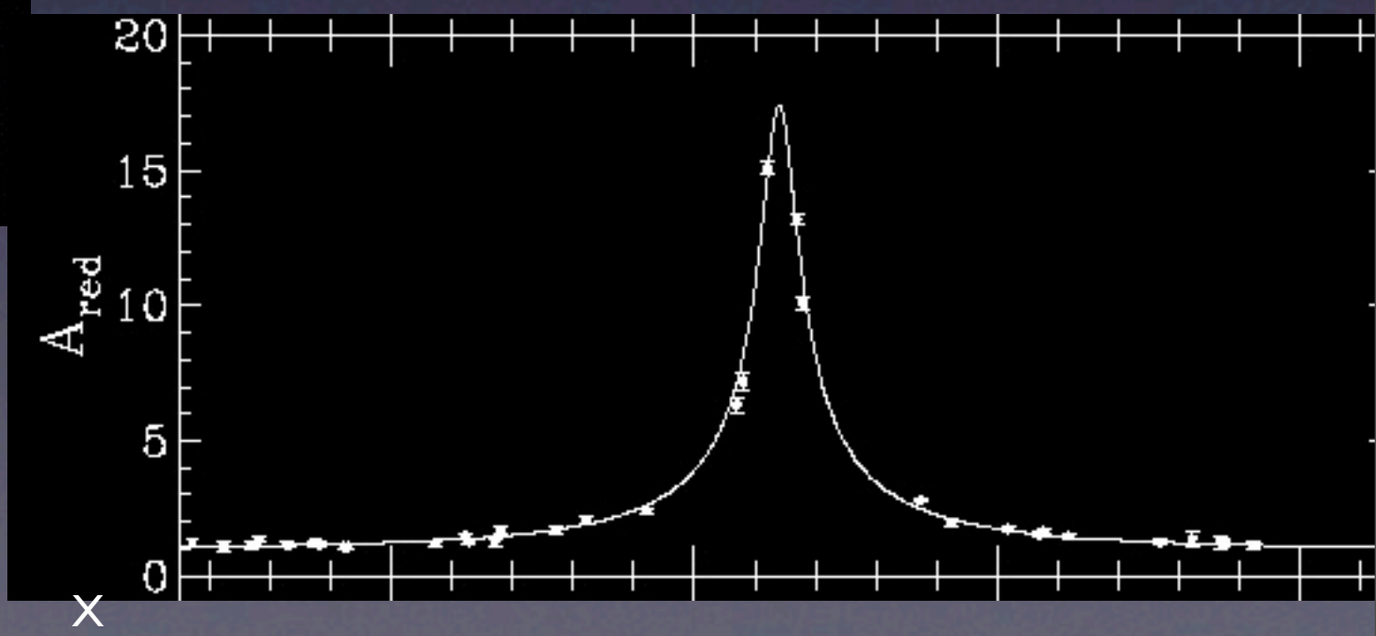

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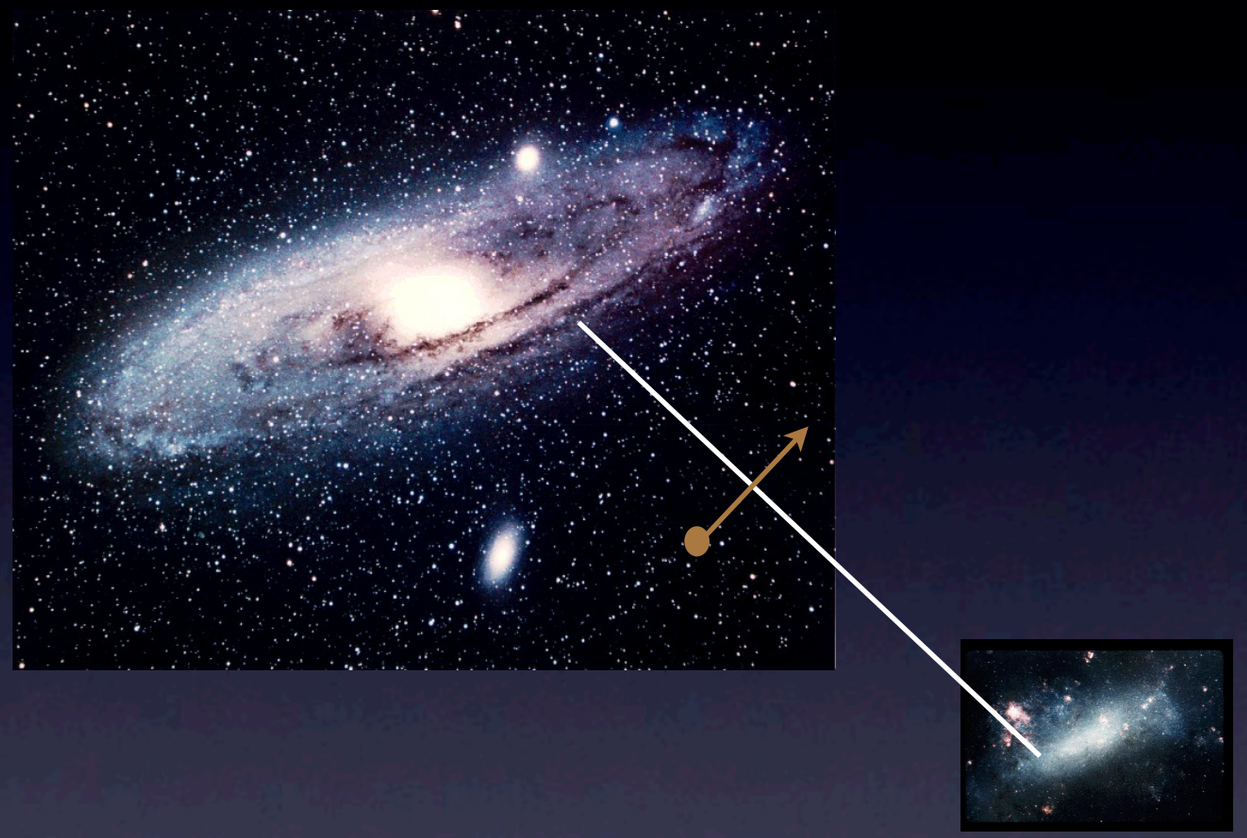

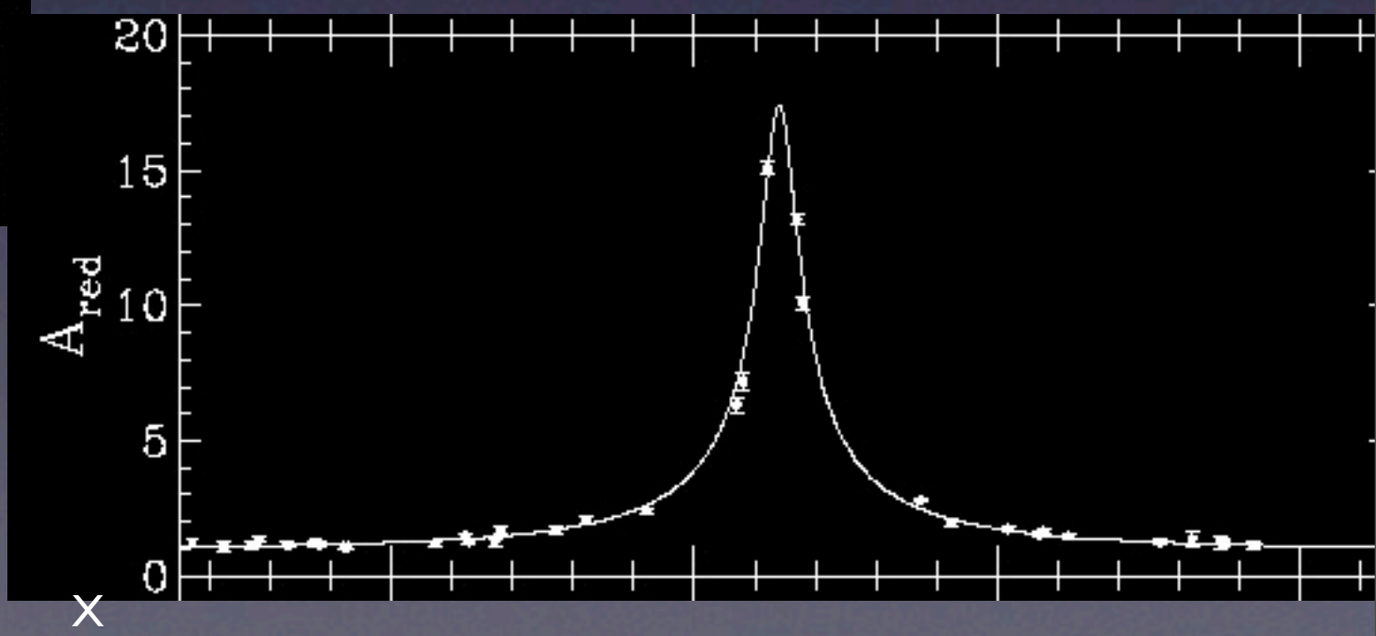

Not enough of them!

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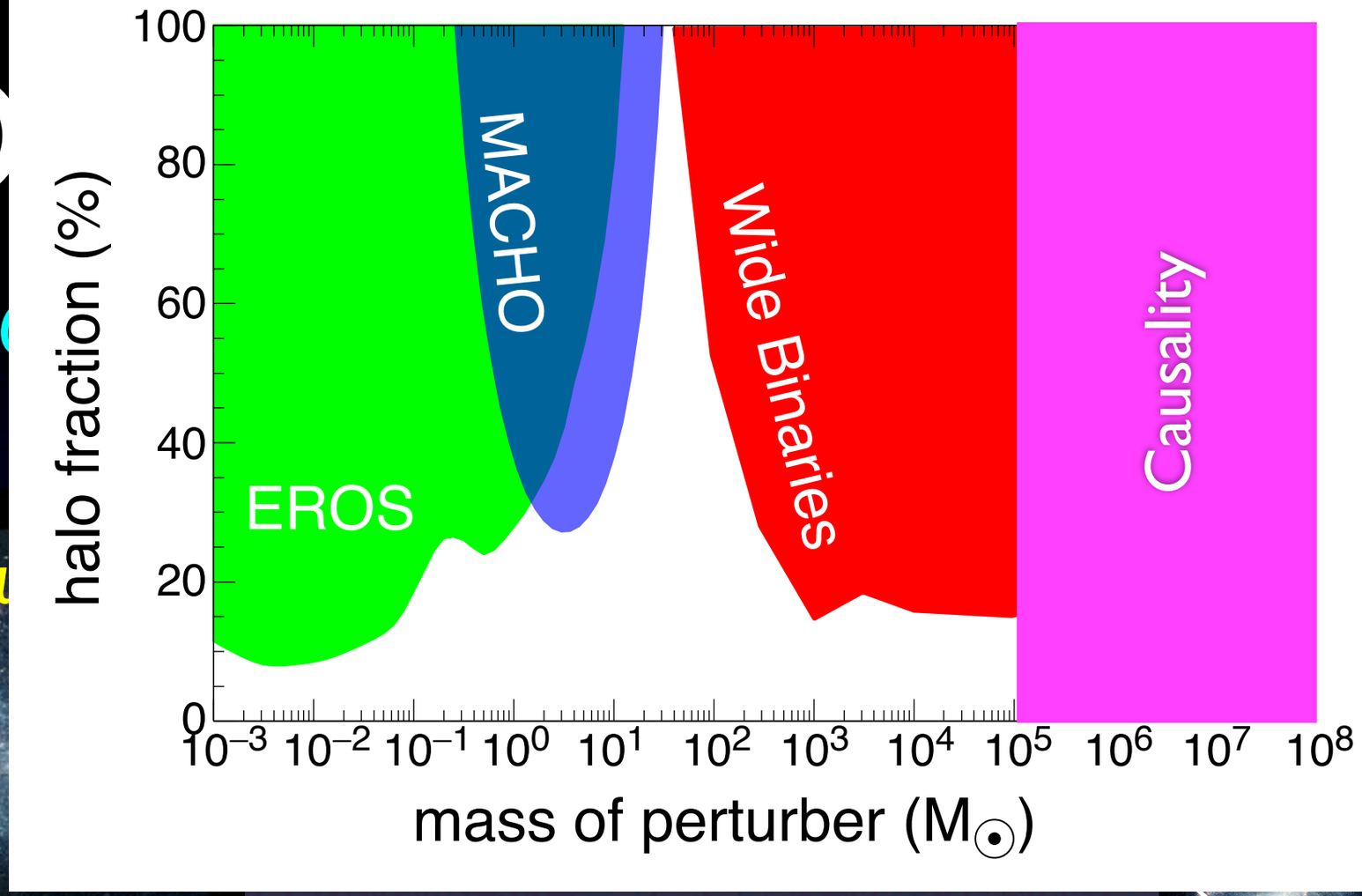
D

Search for MACH

(Massive Compact Halo





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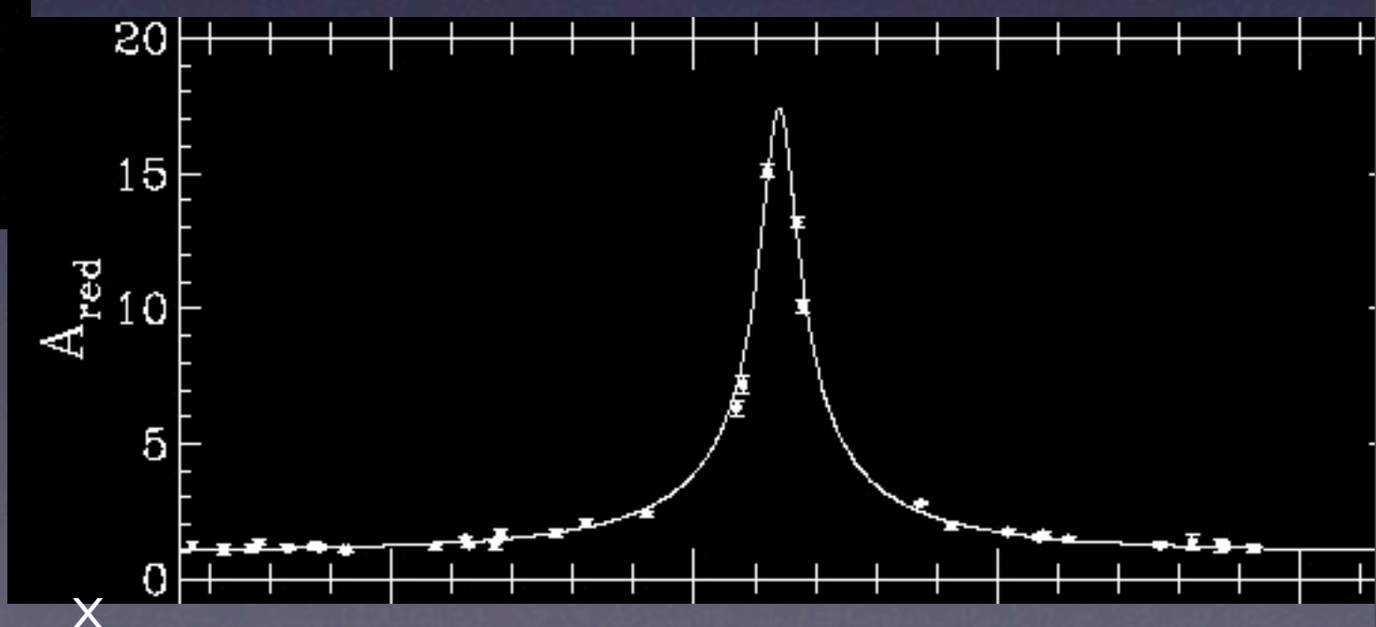

X

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Mass Limits

Mass Limits

- less than 10^{-7} M_{sun}

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- moves in $V = G_N \frac{Mm}{r}$

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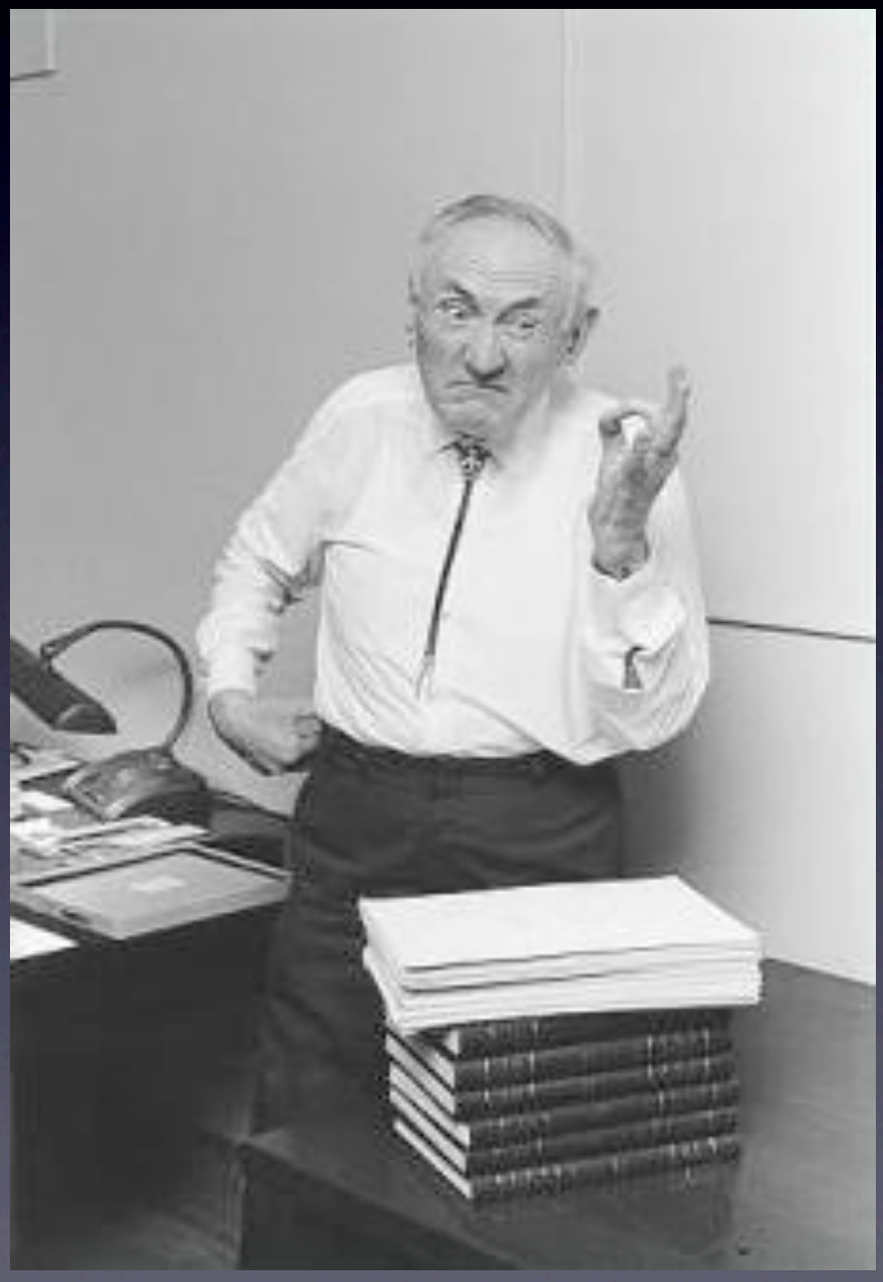
- narrowed it down to within 81 orders of magnitude
- a big progress in 70 years since Zwicky



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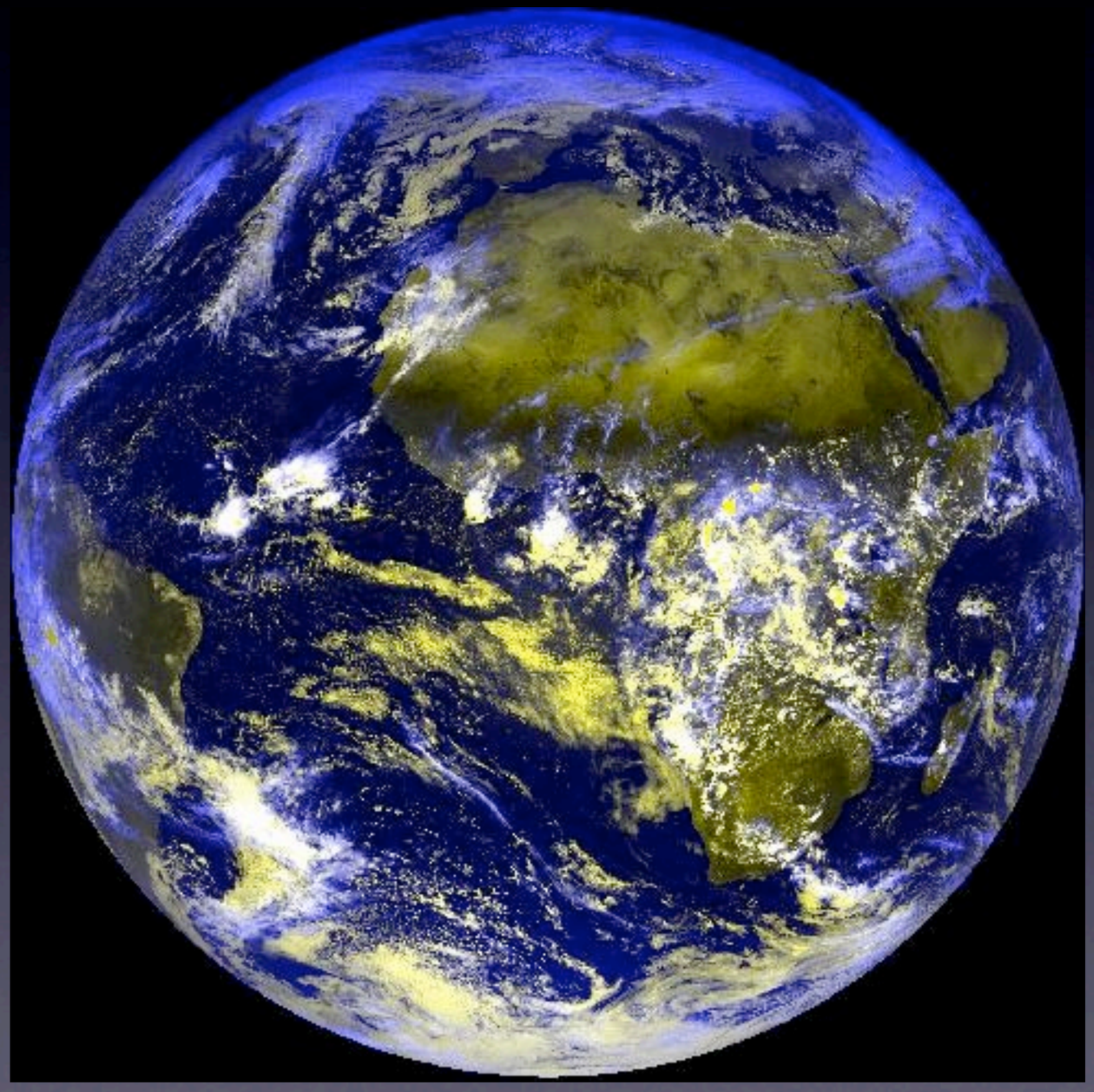
WIMP



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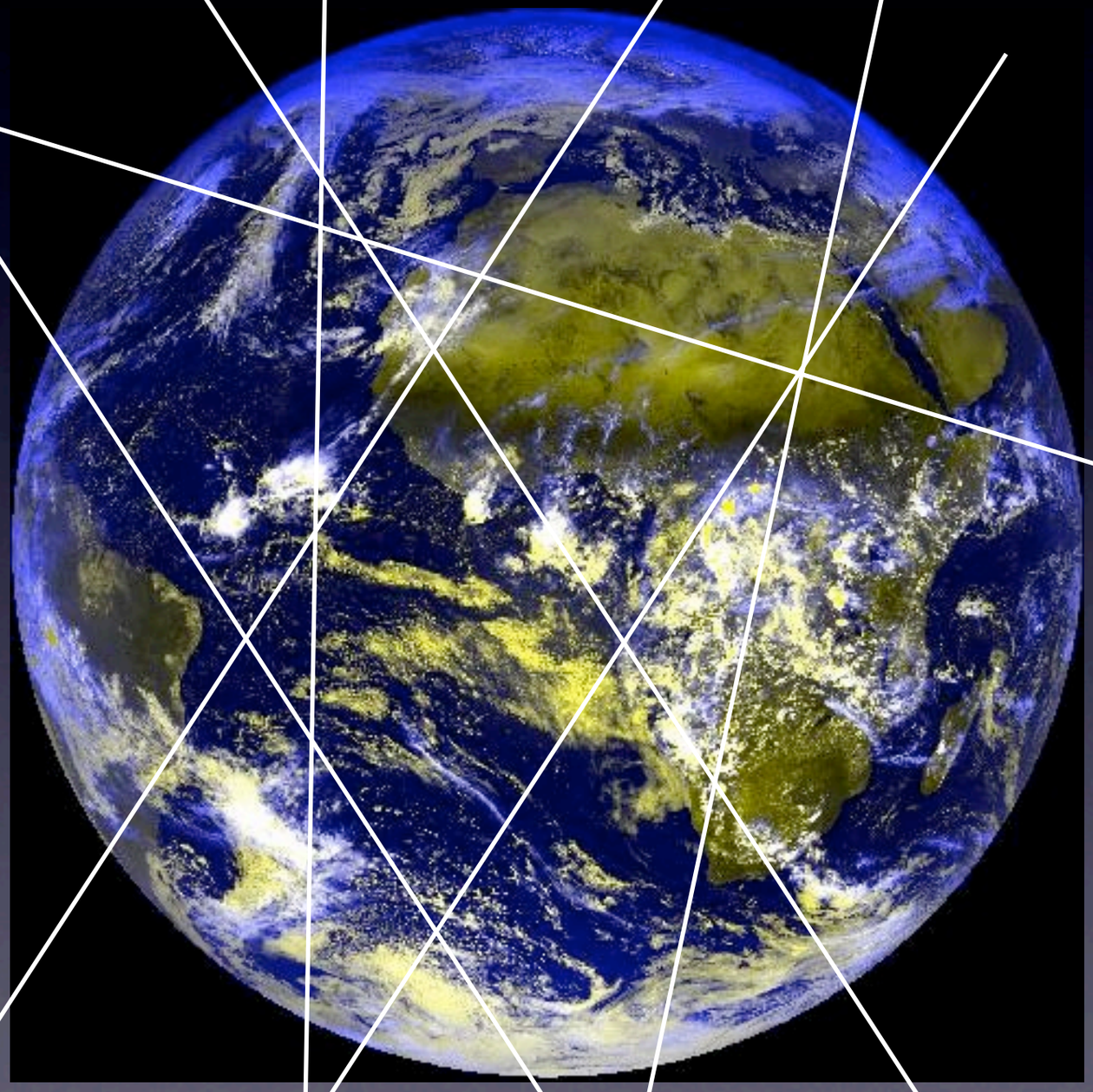

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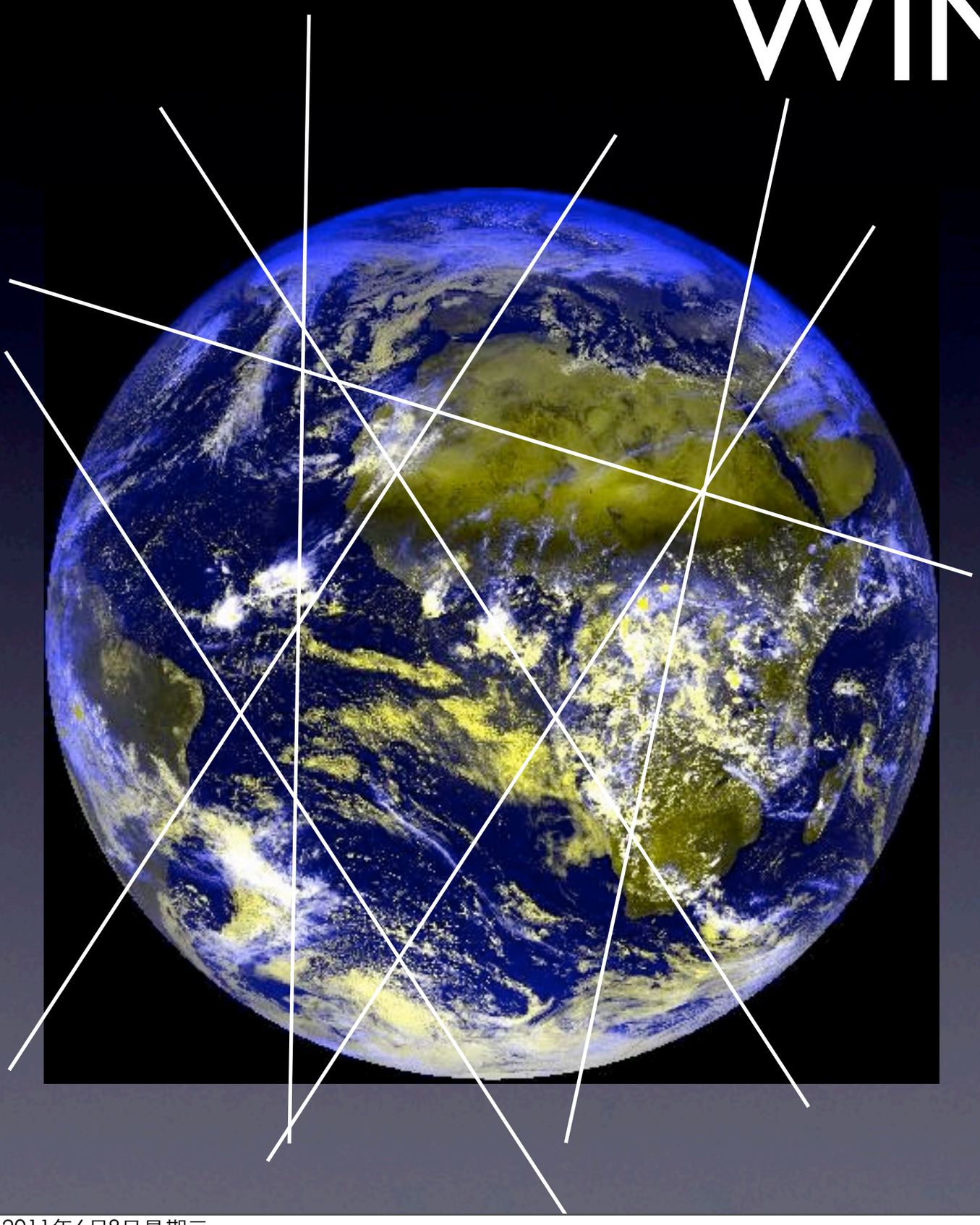
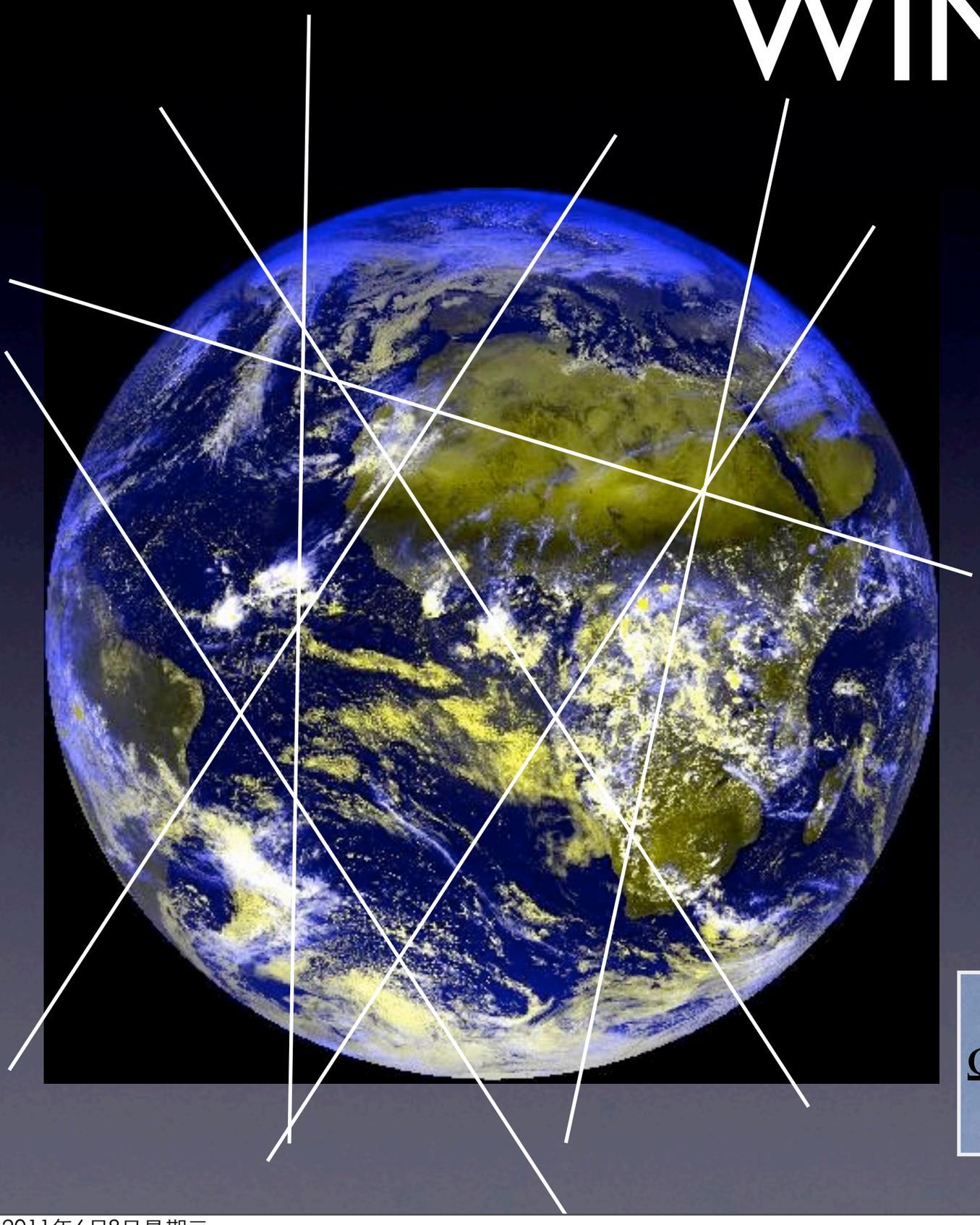


- *The dominant paradigm: WIMP (Weakly Interacting Massive Particle)*
- *Stable heavy particle produced in early Universe, left-over from near-complete annihilation*

WIMP



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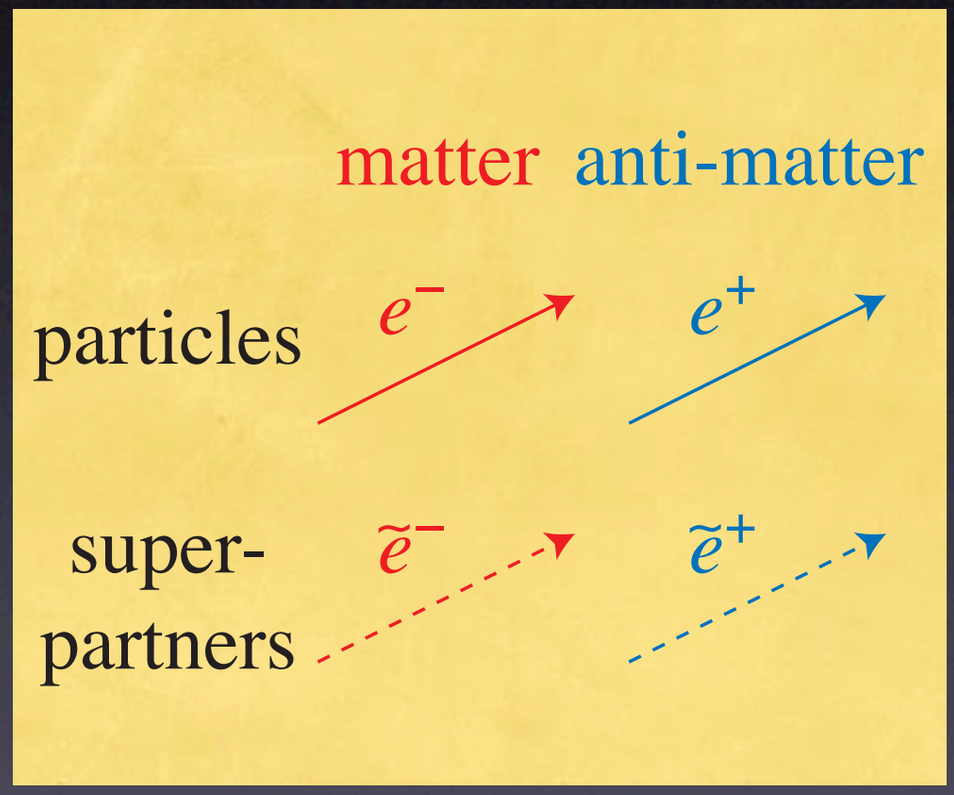
$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

Quantum Dimension

- every particle has anti-matter counterpart: doubled the number
- Nature may do it again
- suggested by string theory: supersymmetry
- The lightest superparticle is stable, neutral, weakly interacting

⇒ Dark Matter candidate



Supersymmetry

- extension of Poincaré symmetry of Minkowski space
  - P: spacetime translation
  - M: SO(3,1)
  - Q: supersymmetry
- theorem: only possible space-time symmetries of quantum theory

$$[P_\mu, Q^i_\alpha] = 0$$

$$[M^{\mu\nu}, Q^i_\alpha] = \frac{1}{2}(\sigma^{\mu\nu})_\alpha{}^\beta Q^i_\beta$$

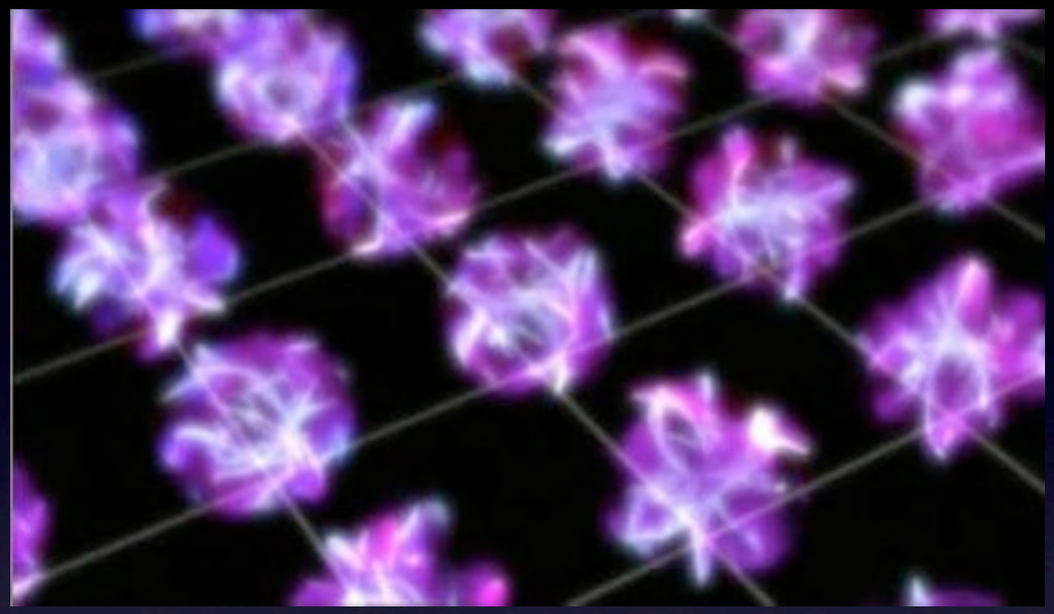
$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2P_\mu(\sigma^\mu)_{\alpha\dot\beta}\delta^{ij}$$

$$\{Q^i_\alpha, Q^j_\beta\} = \varepsilon_{\alpha\beta}C^{ij}$$

Connections to
- Morse theory
- index theorem
- integrable systems

x

Extra Dimensions



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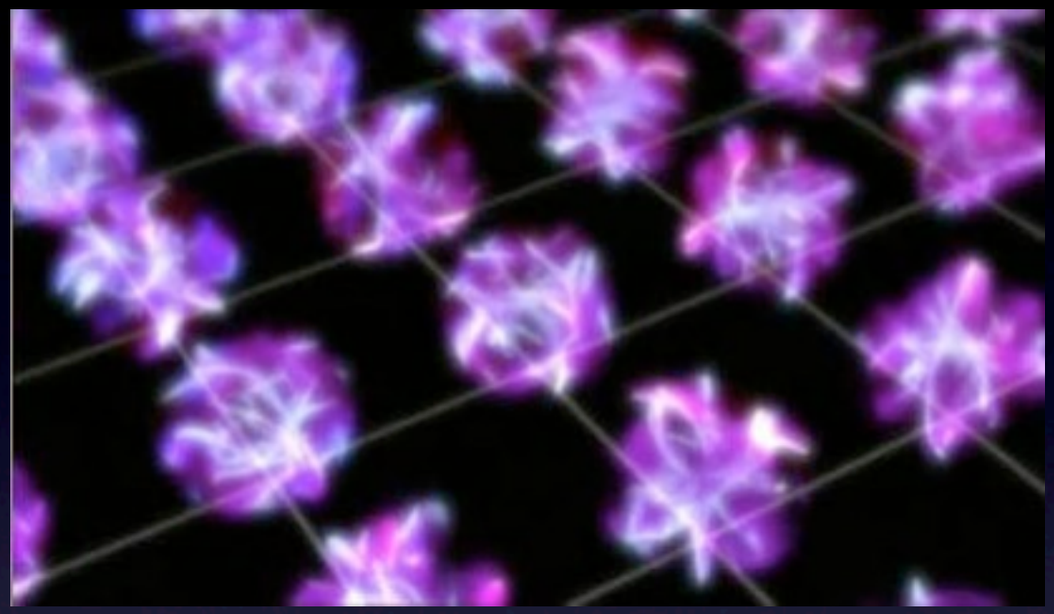
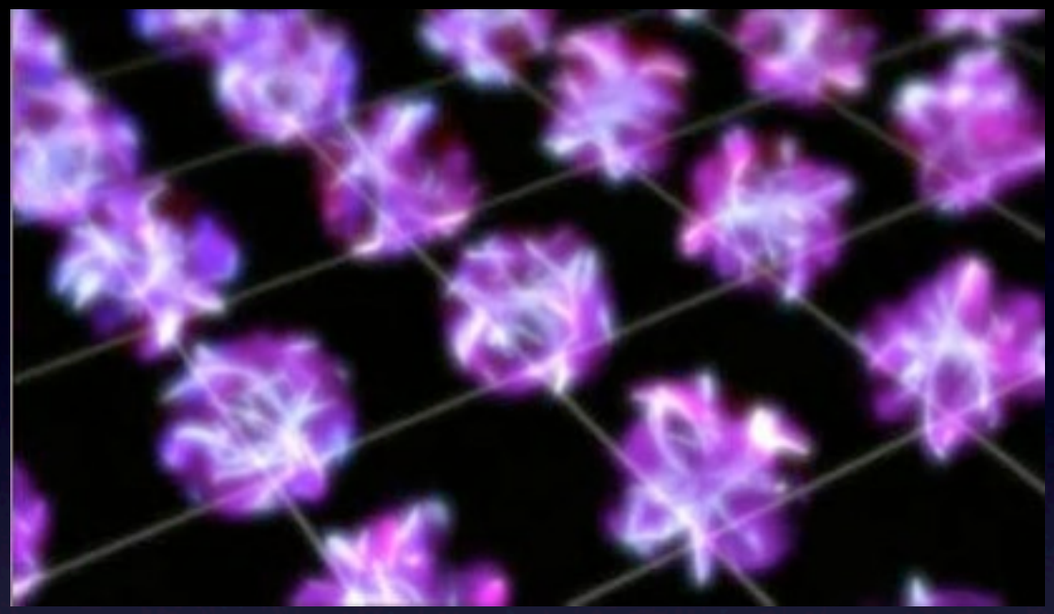


- Our spacetime is a direct product with a compact manifold

Extra Dimensions



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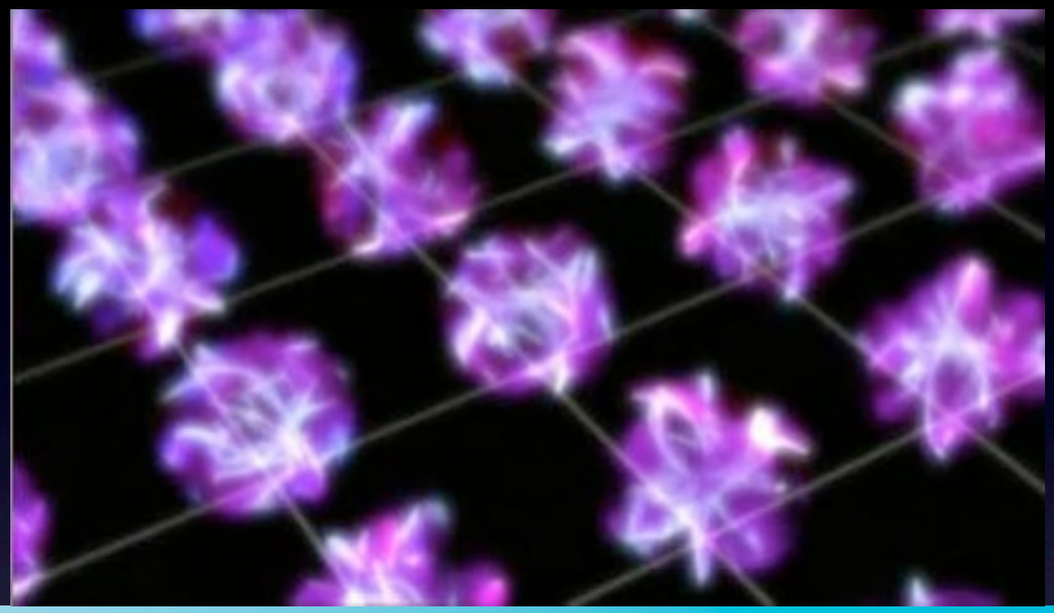

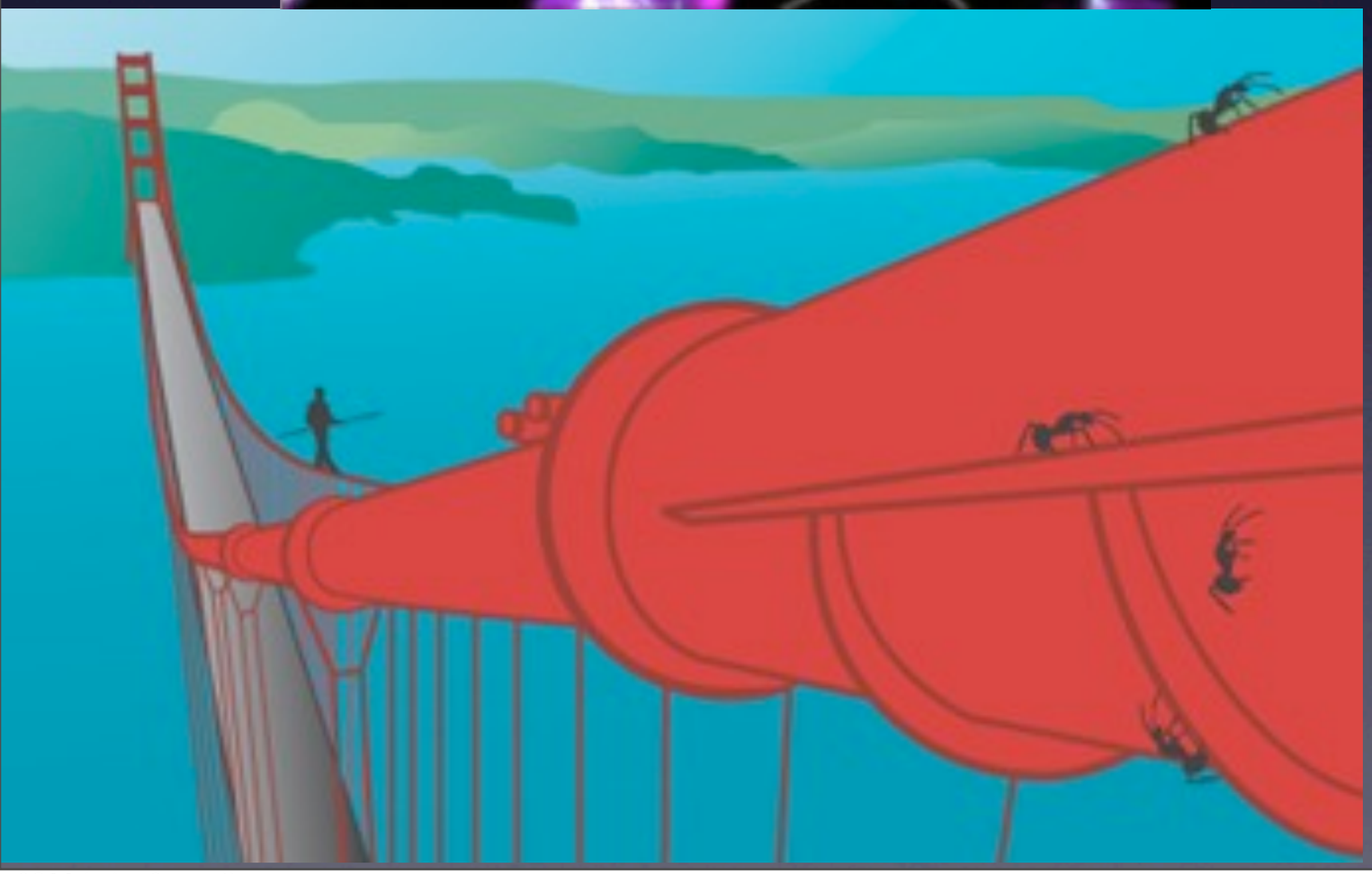

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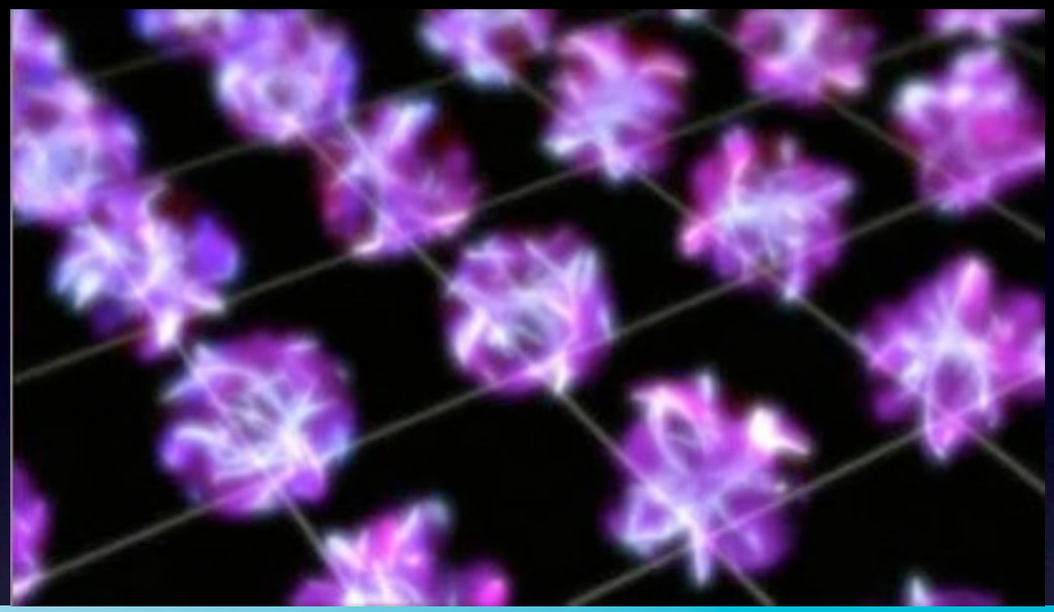

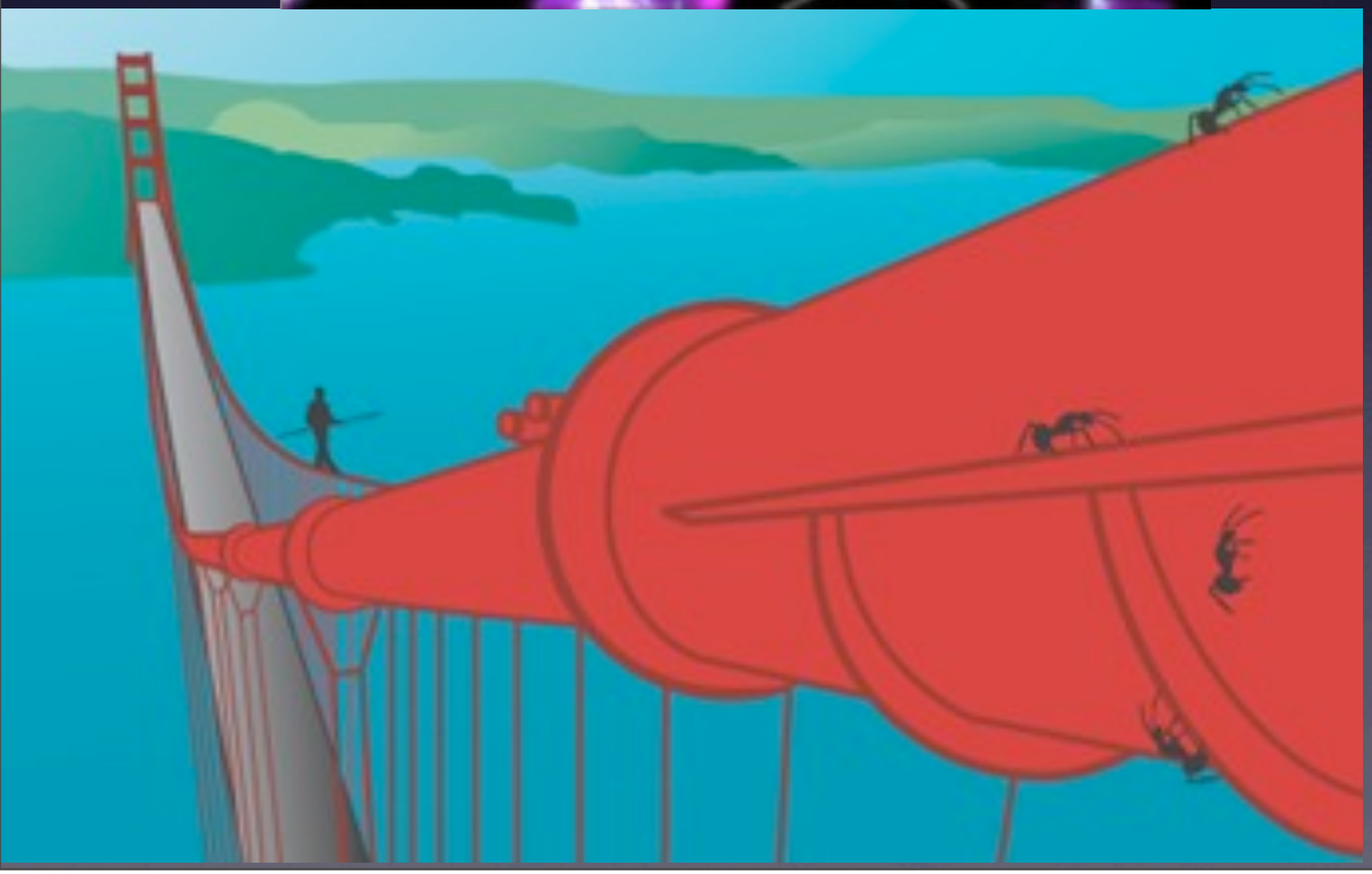

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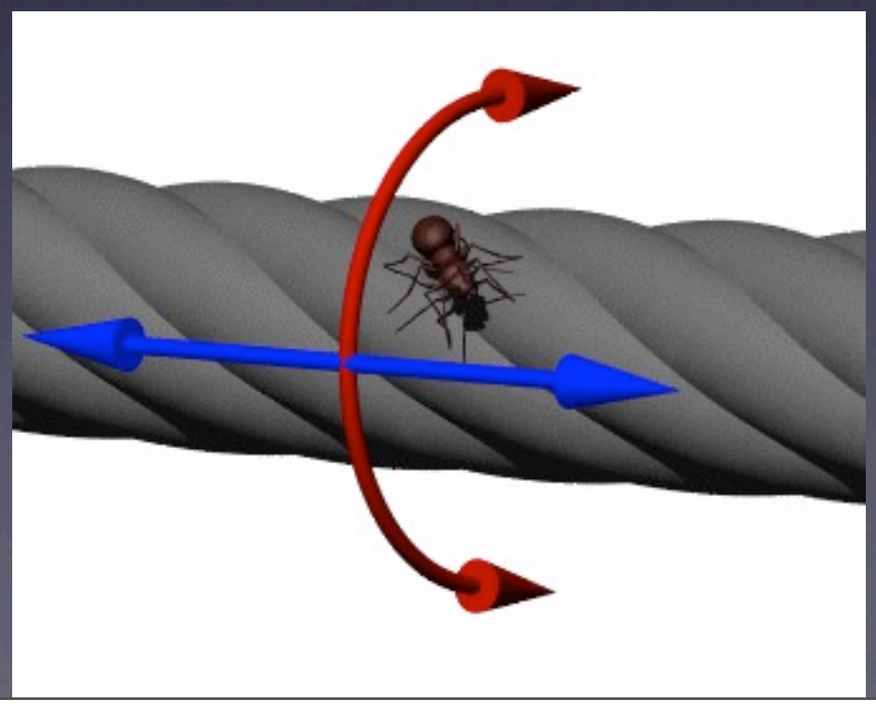

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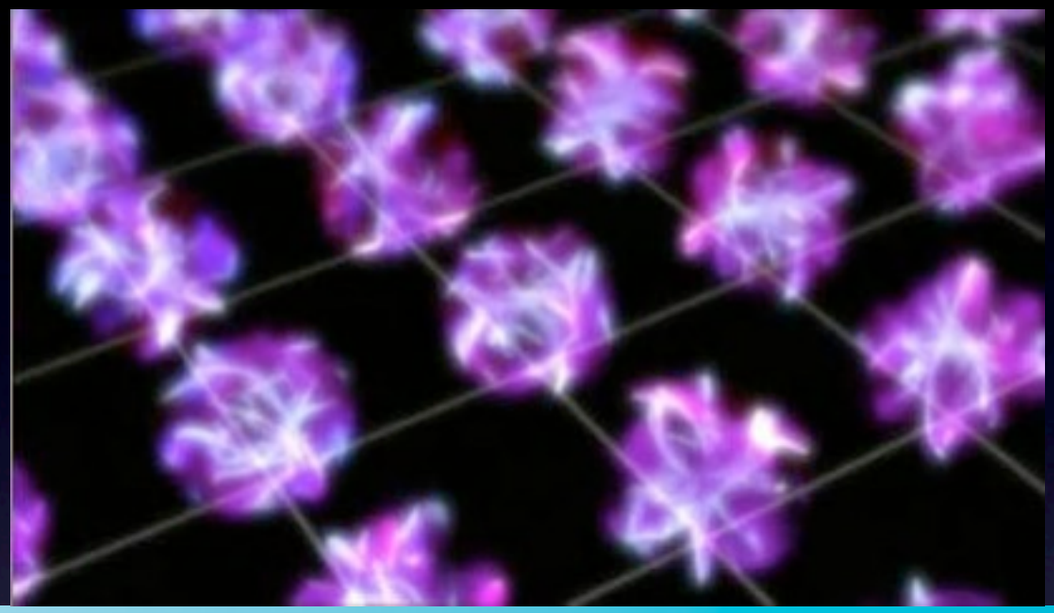

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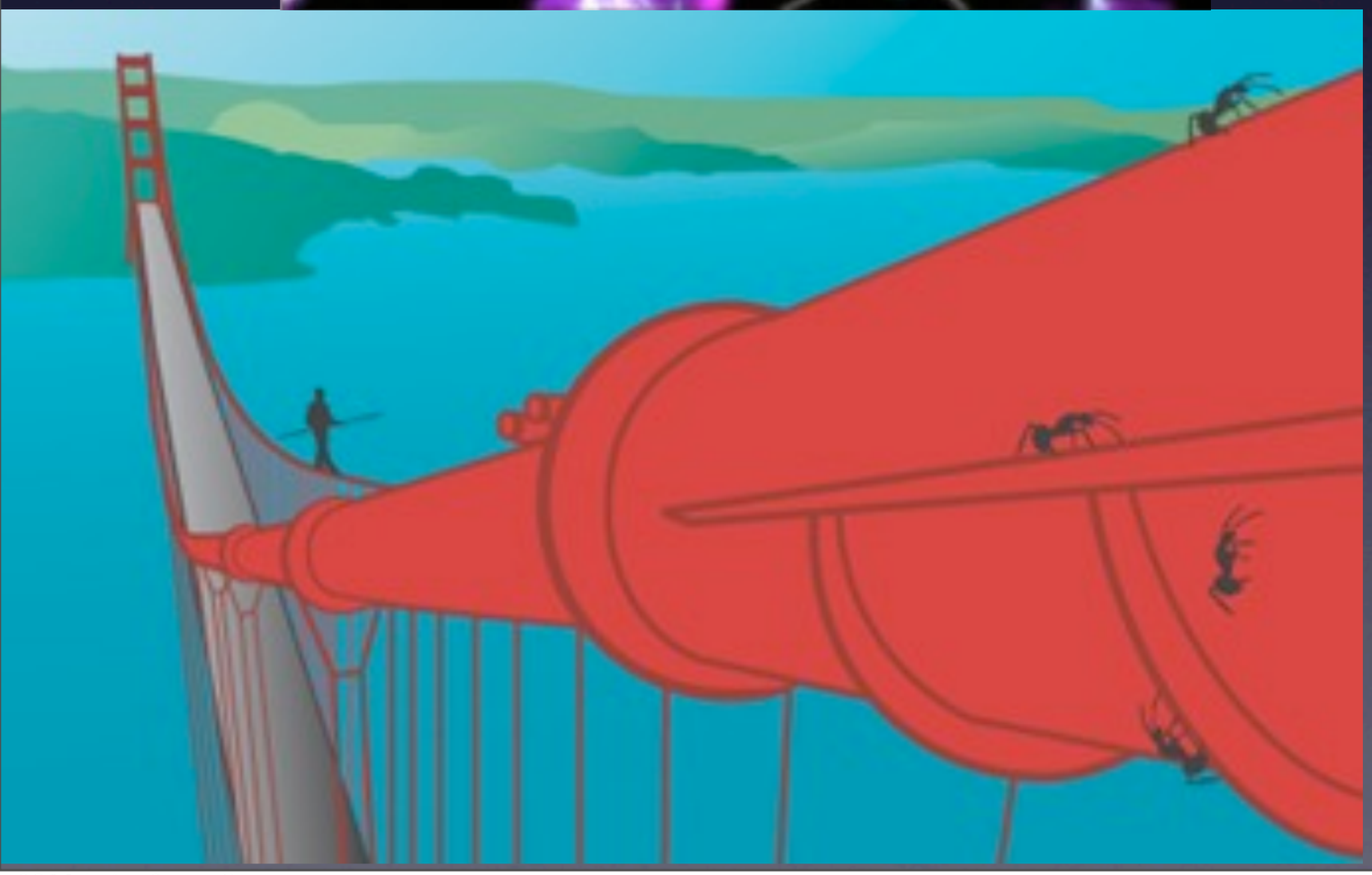

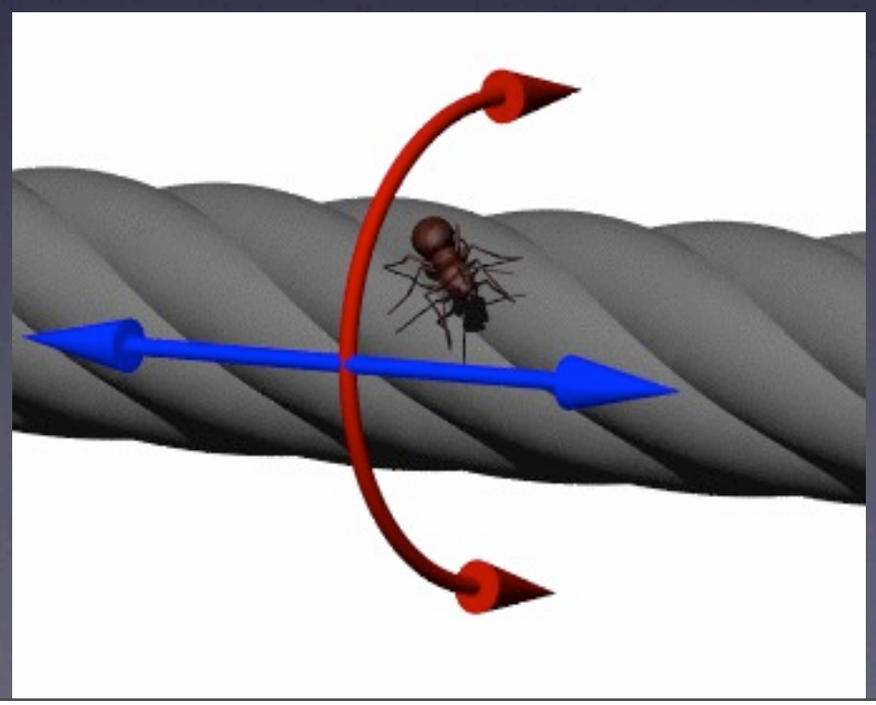

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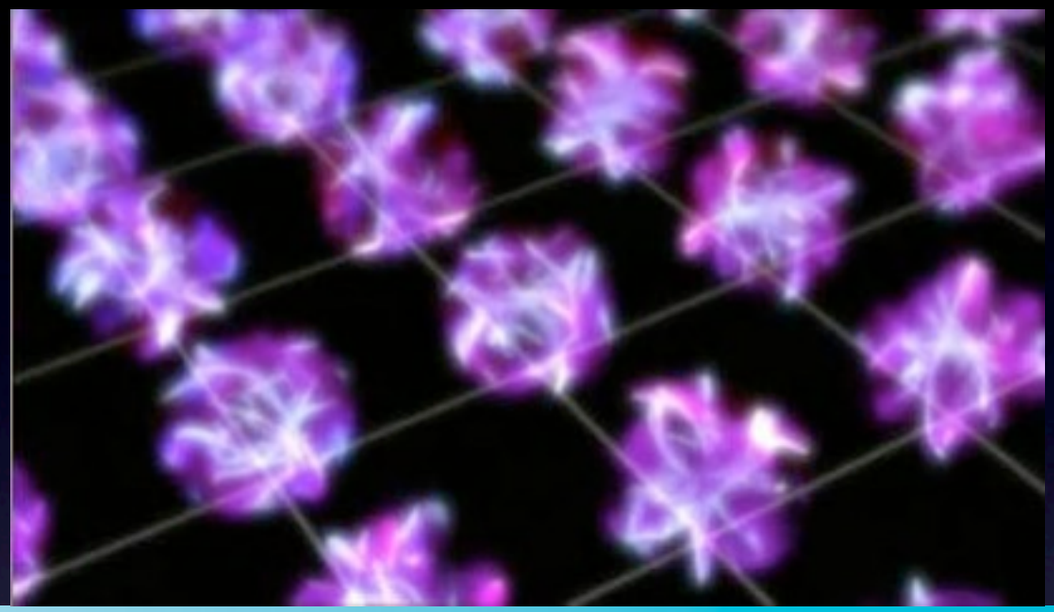

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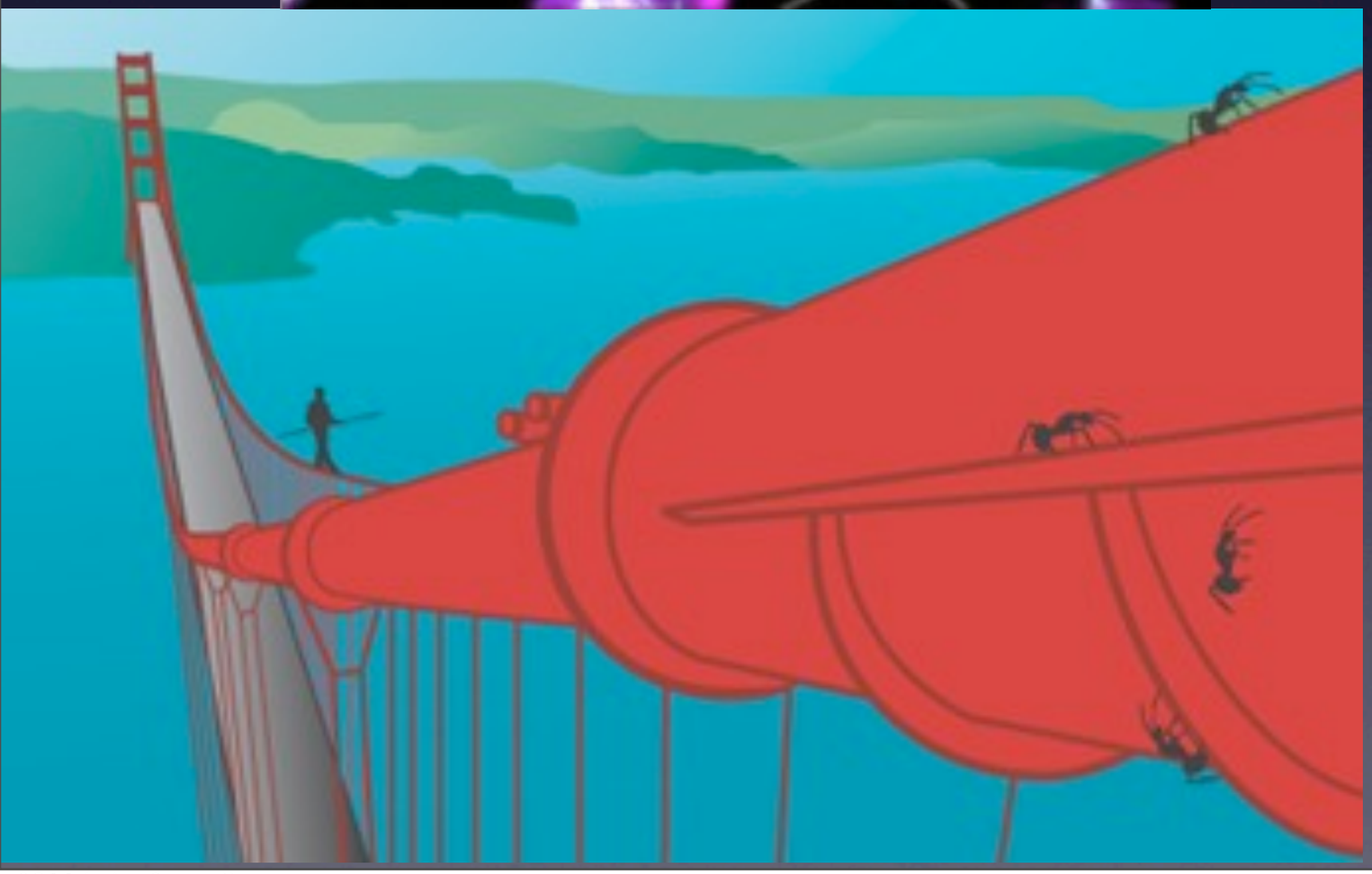

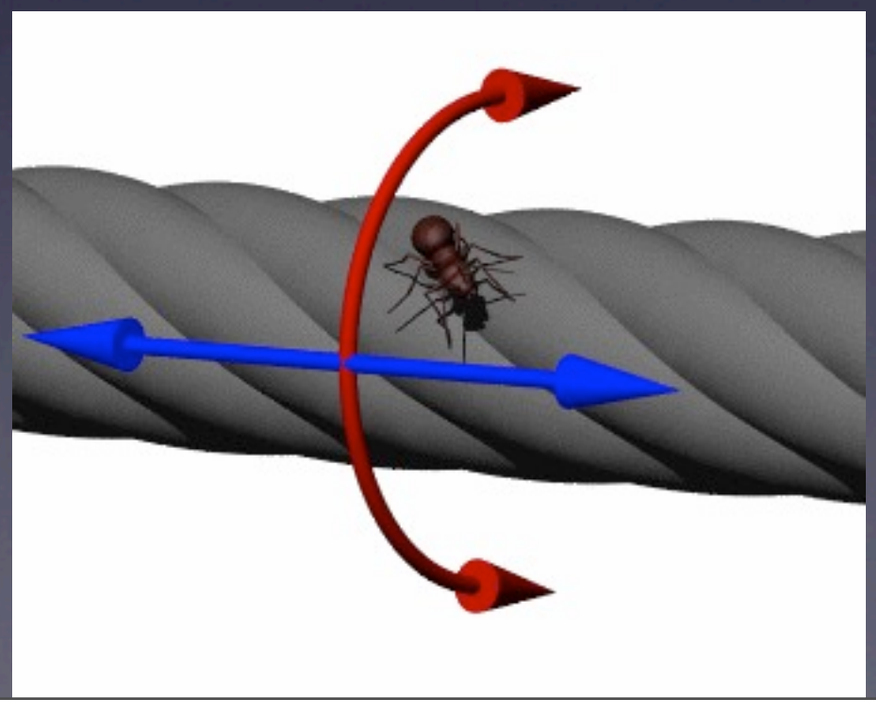

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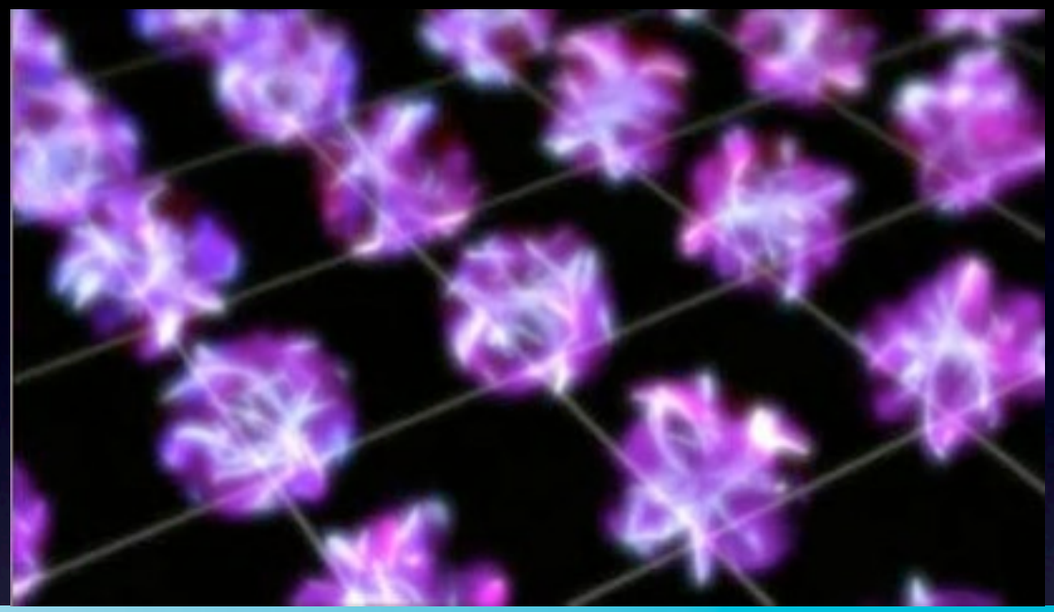

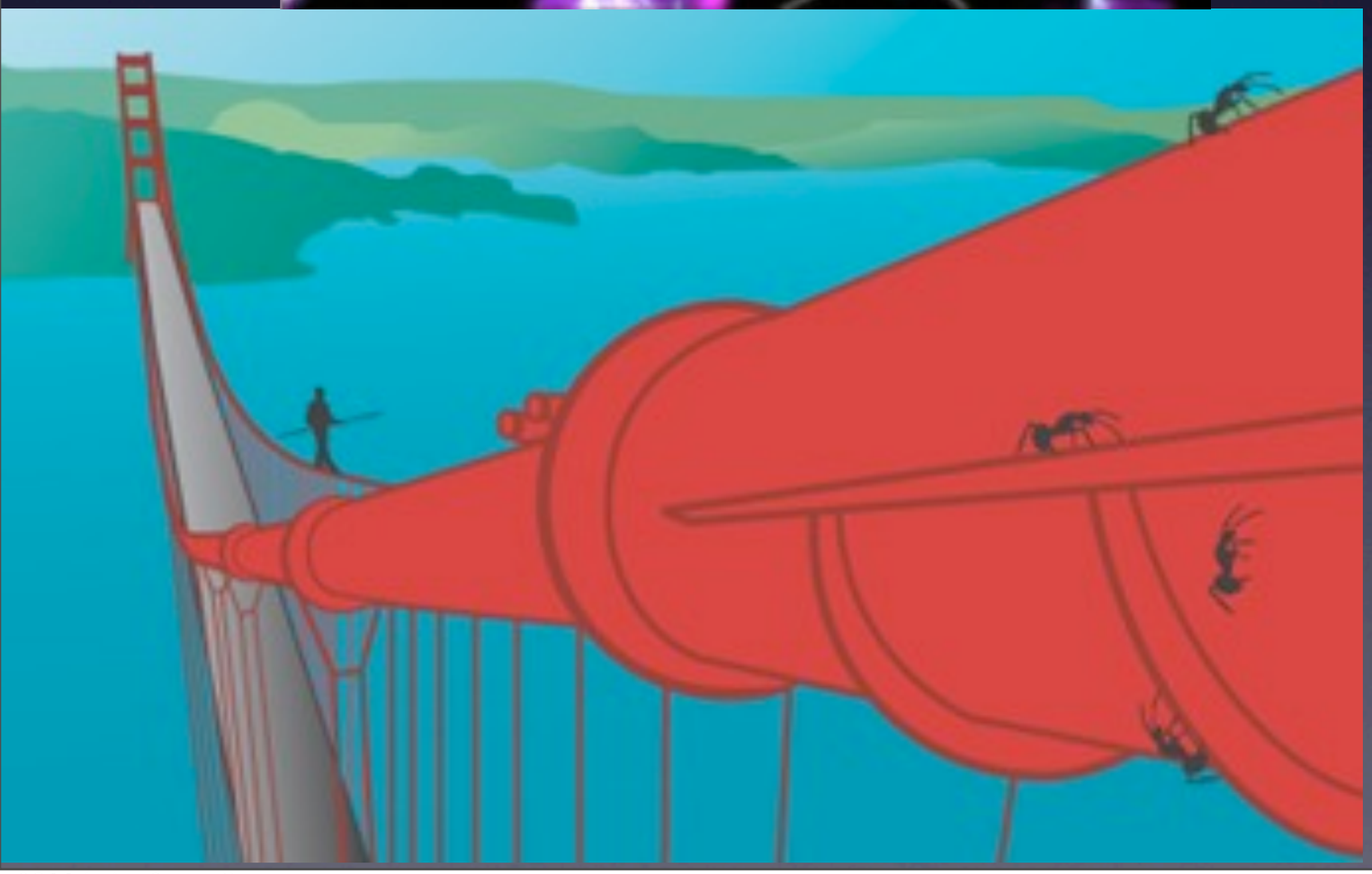

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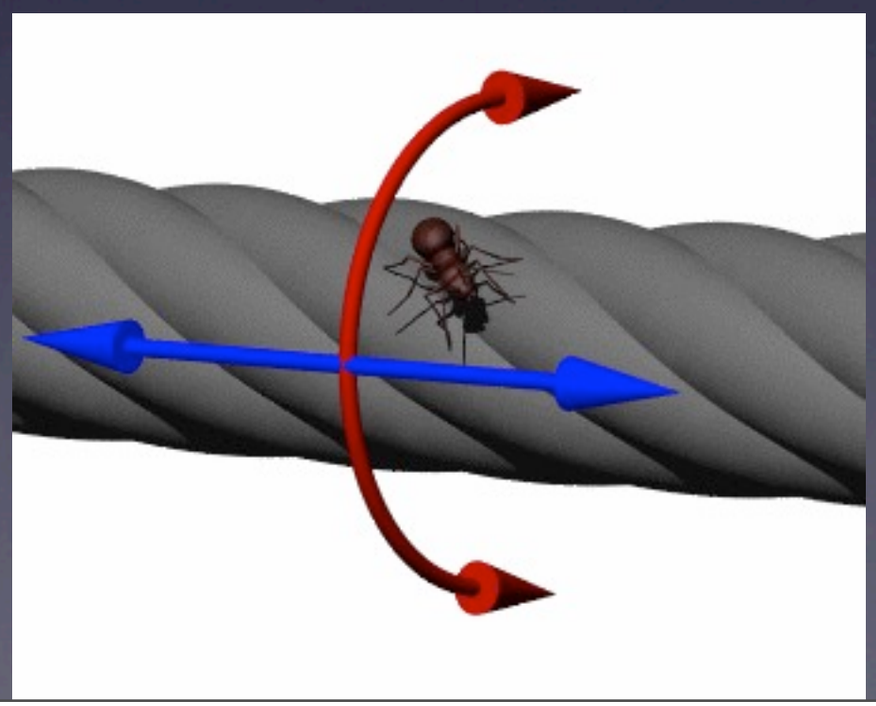

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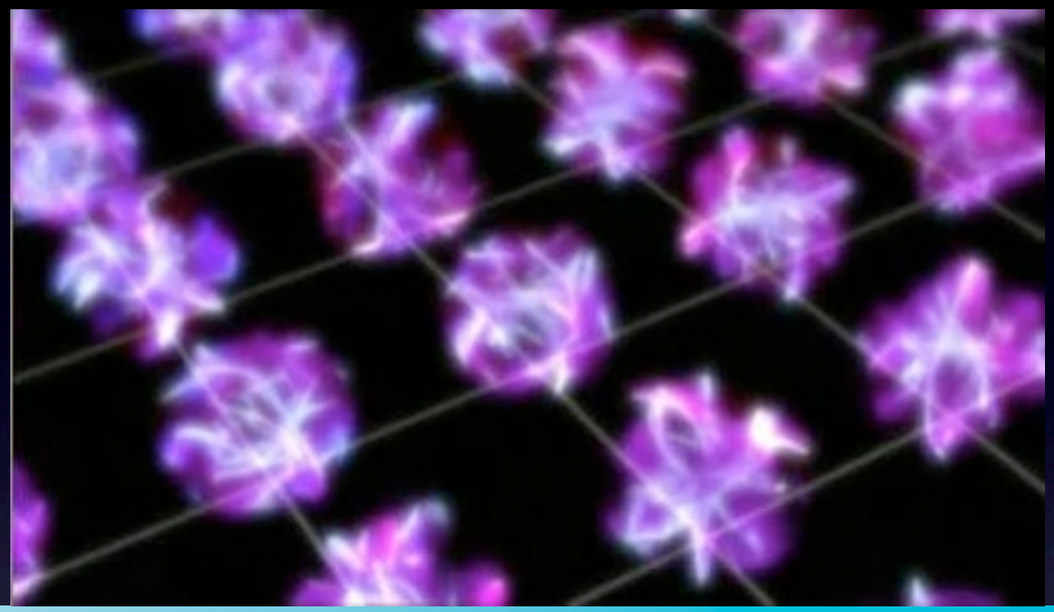

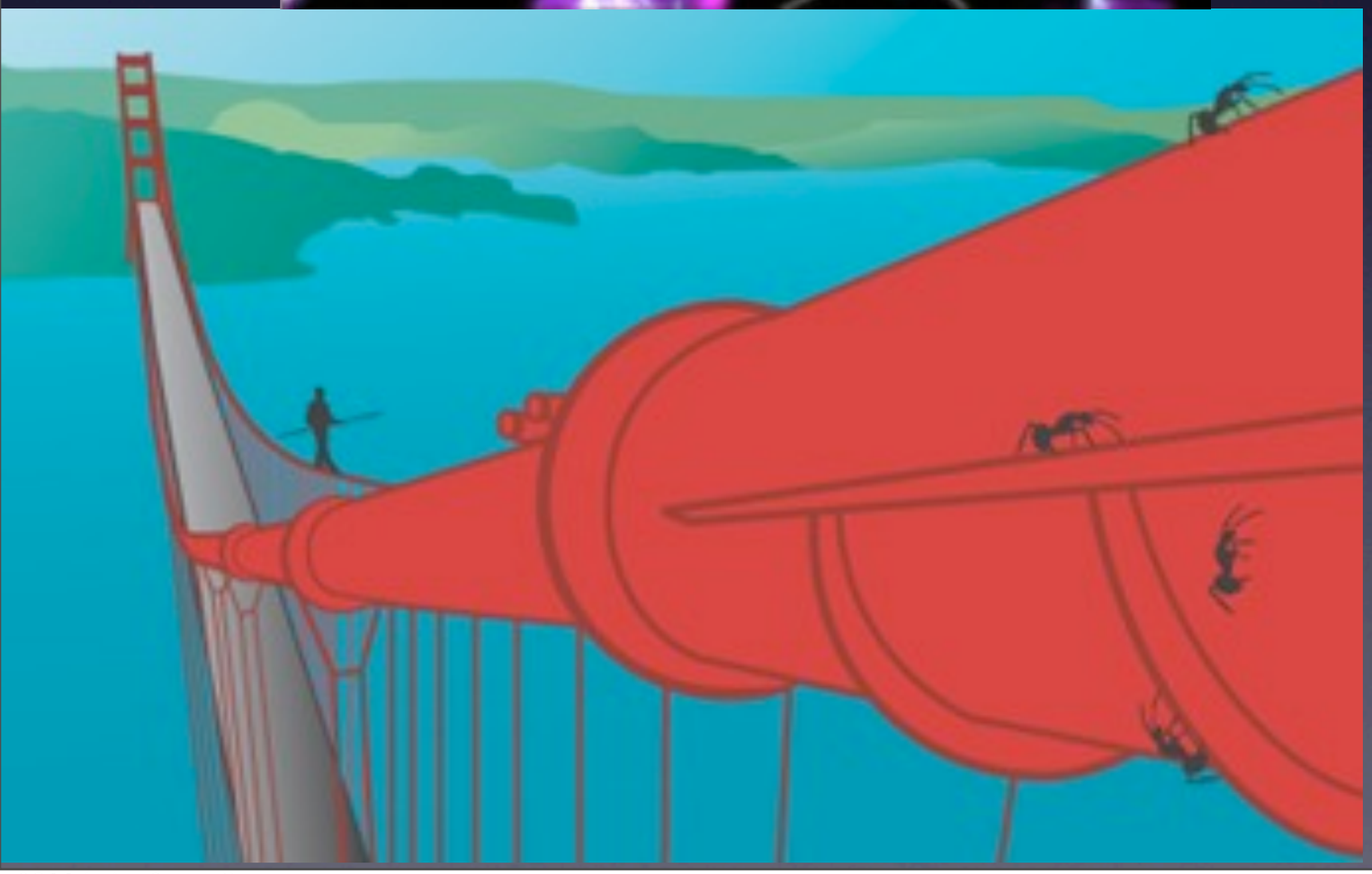

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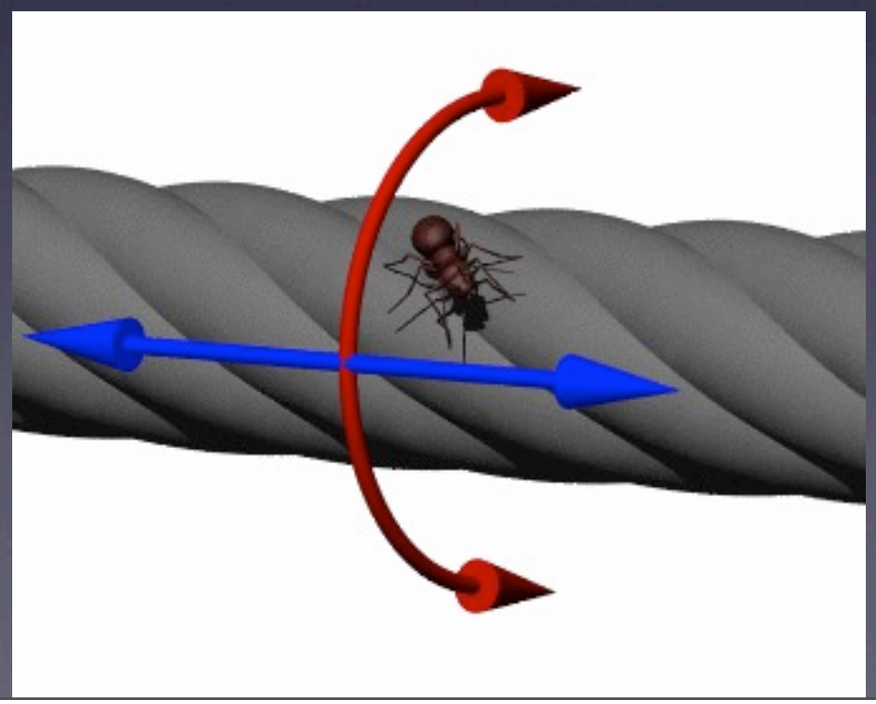
- each harmonic mode is a particle $\Delta\varphi_i=-m_i^2\varphi_i$
- *How do we reconstruct geometry?*



Evolution of massive galaxies and their AGNs with the SDSS-III/BOSS survey

October 25 - 28, 2010

Institute for the Physics and Mathematics of the Universe
(IPMU)
The University of Tokyo

This workshop aims to bring together individuals from the BOSS community with a strong interest in studies of luminous galaxies and/or AGNs (+QSOs) in order to foster collaborative efforts across these disciplines. The format of the meeting will involve a mixture of science presentations, working group sessions and ample time for interaction and discussion. Topics will include the following:

- Mass function of luminous galaxies
- Environmental drivers of galaxy evolution
- Stellar populations

- Active Galactic Nuclei in luminous galaxies
- QSOs: mass/luminosity function, Eddington ratio distributions, clustering





John Silverman

IPMU@UTokyo

屋形船の予約・
お問い合わせはこちら
TEL：03-3644-1344

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Massless particle

- Specialize to P_μ=E(1,0,0,1)
- helicity: $h = \varepsilon_{0ijk} P^i M^{jk}/2P^0 = M^{12}$

$$P^\mu = E(1,0,0,1)$$

$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2P_\mu(\sigma^\mu)_{\alpha\dot\beta}\delta^{ij} = 2E\begin{pmatrix}2 & \\ & 0\end{pmatrix}\delta^{ij}$$

- creation/annihilation operators (C^{ij}=0)

$$b^i = Q^i_1/\sqrt{4E}, \quad b^{i\dagger} = \bar{Q}^i_1/\sqrt{4E}$$

$$\{b^i, b^{j\dagger}\} = \delta^{ij}$$

$$[h, b^i] = -\frac{1}{2}b^i$$

$$[h, b^{i\dagger}] = \frac{1}{2}b^{i\dagger}$$

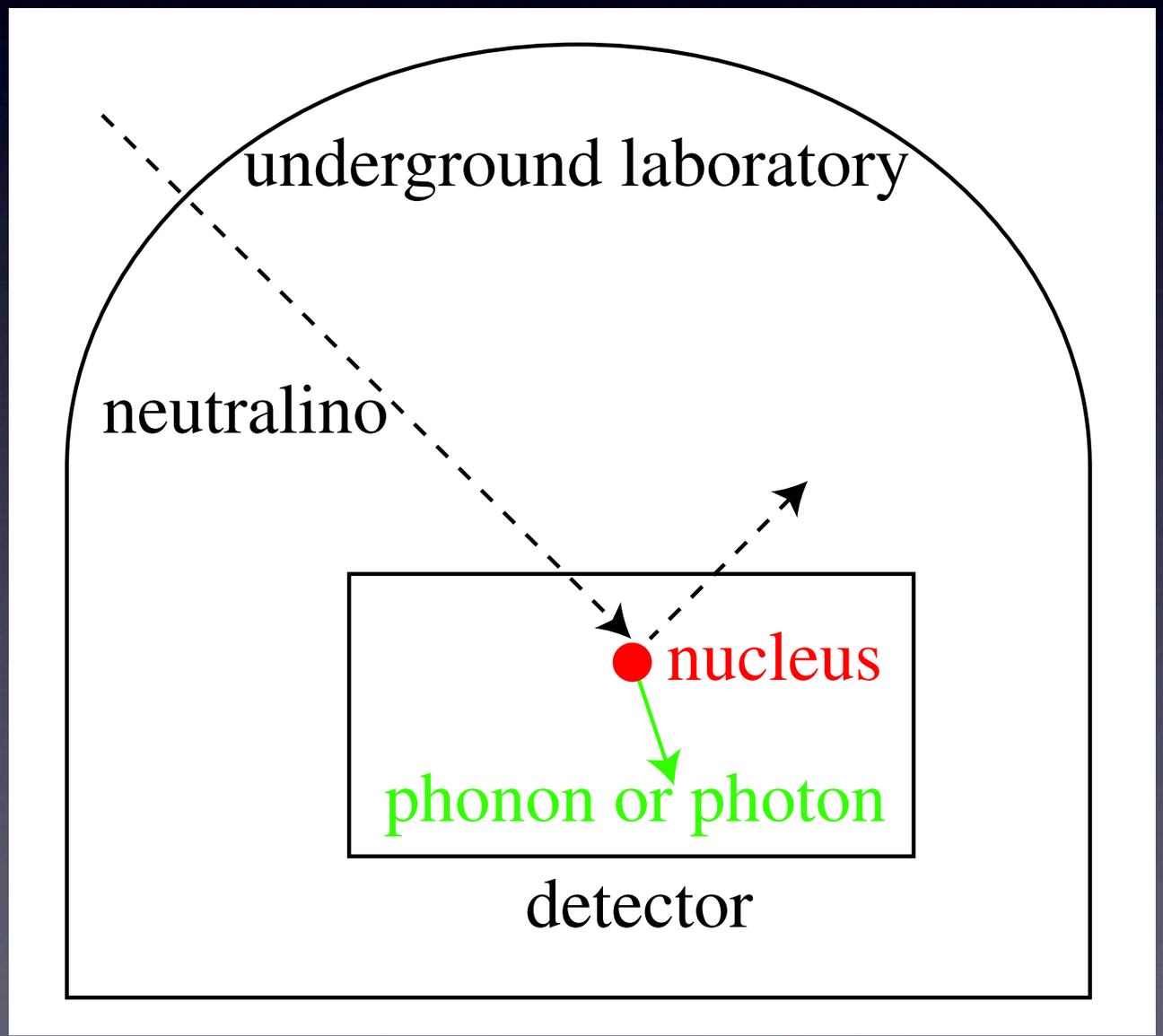
x

N=1 multiplets

- Restrict $|h| \leq 1$ for renormalizability
- Multiplet structure: $\{|0\rangle, b^\dagger|0\rangle\}$
- chiral multiplet: pick $h|0\rangle = 0$ or $-1/2$
  - $h = \{0, 1/2\}$ (anti-chiral) or $\{-1/2, 0\}$ (chiral)
  - i.e., spin 1/2 and spin 0 particles
- vector multiplet: pick $h|0\rangle = 1/2|0\rangle$ or -1
  - $h = \{1/2, 1\}$ or $\{-1, -1/2\}$
  - i.e, spin 1/2 and spin 1 particles
  - must be in adjoint (real) rep ⇒ non-chiral

Finding Dark Matter

Direct method



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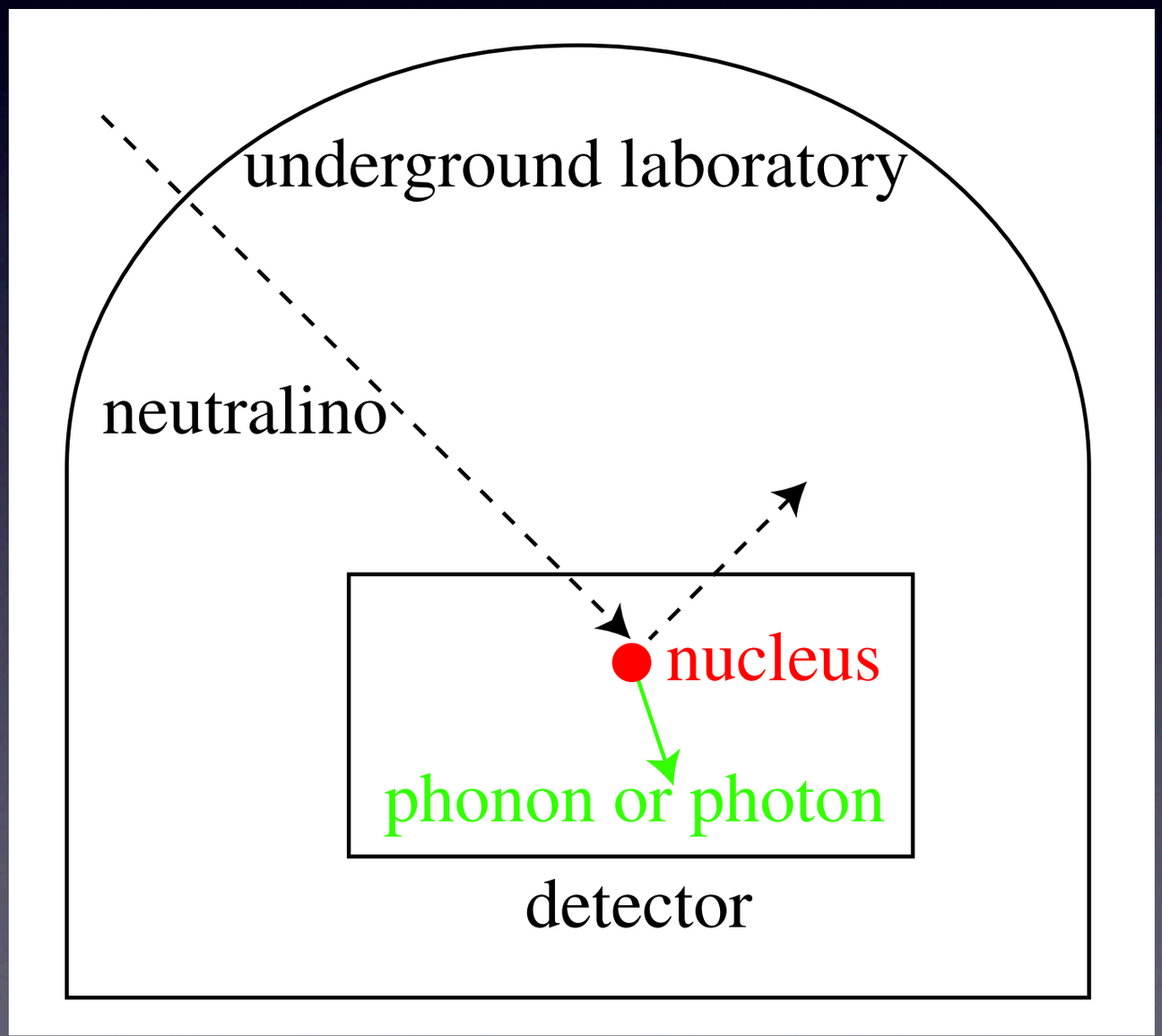

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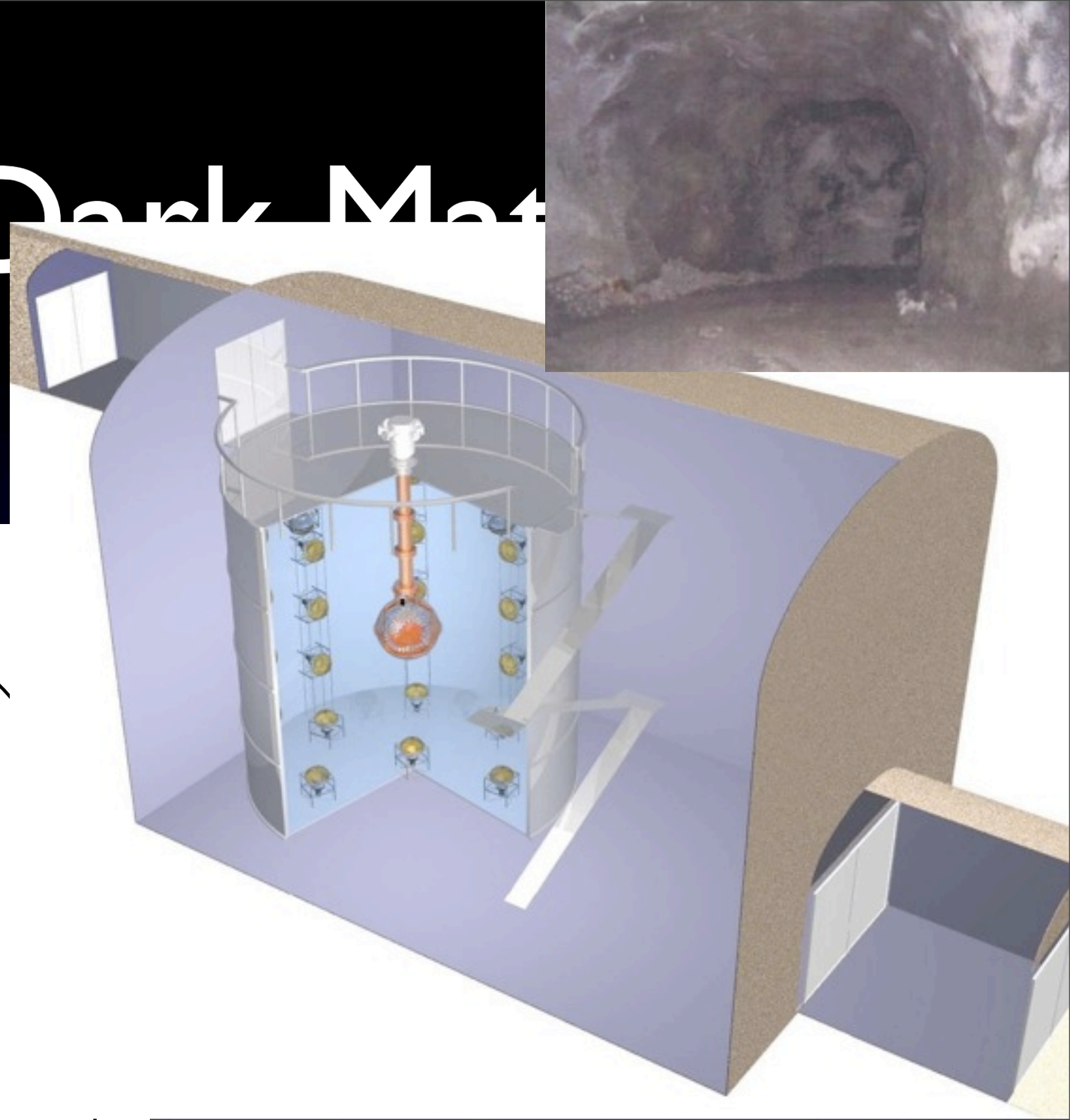
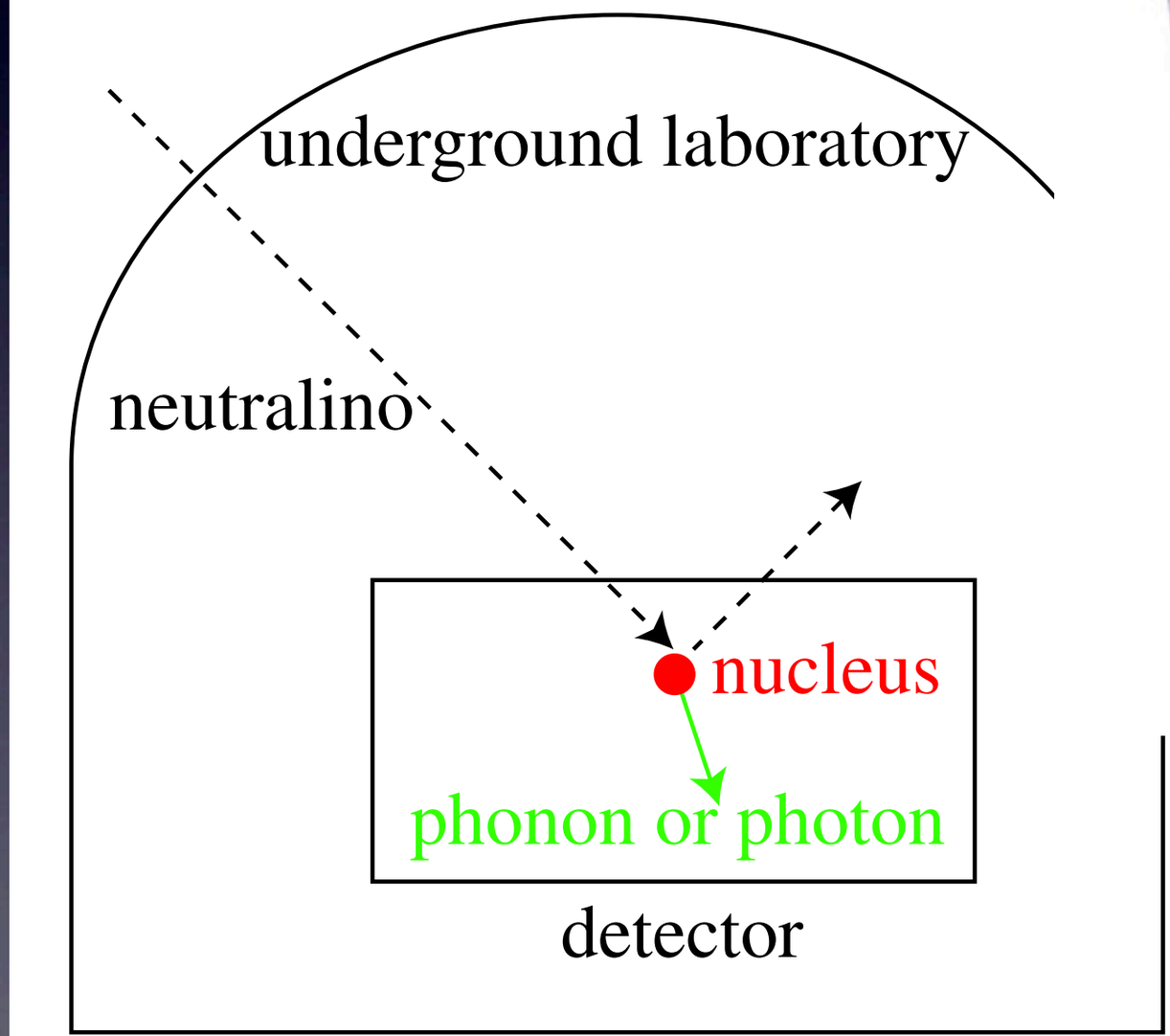


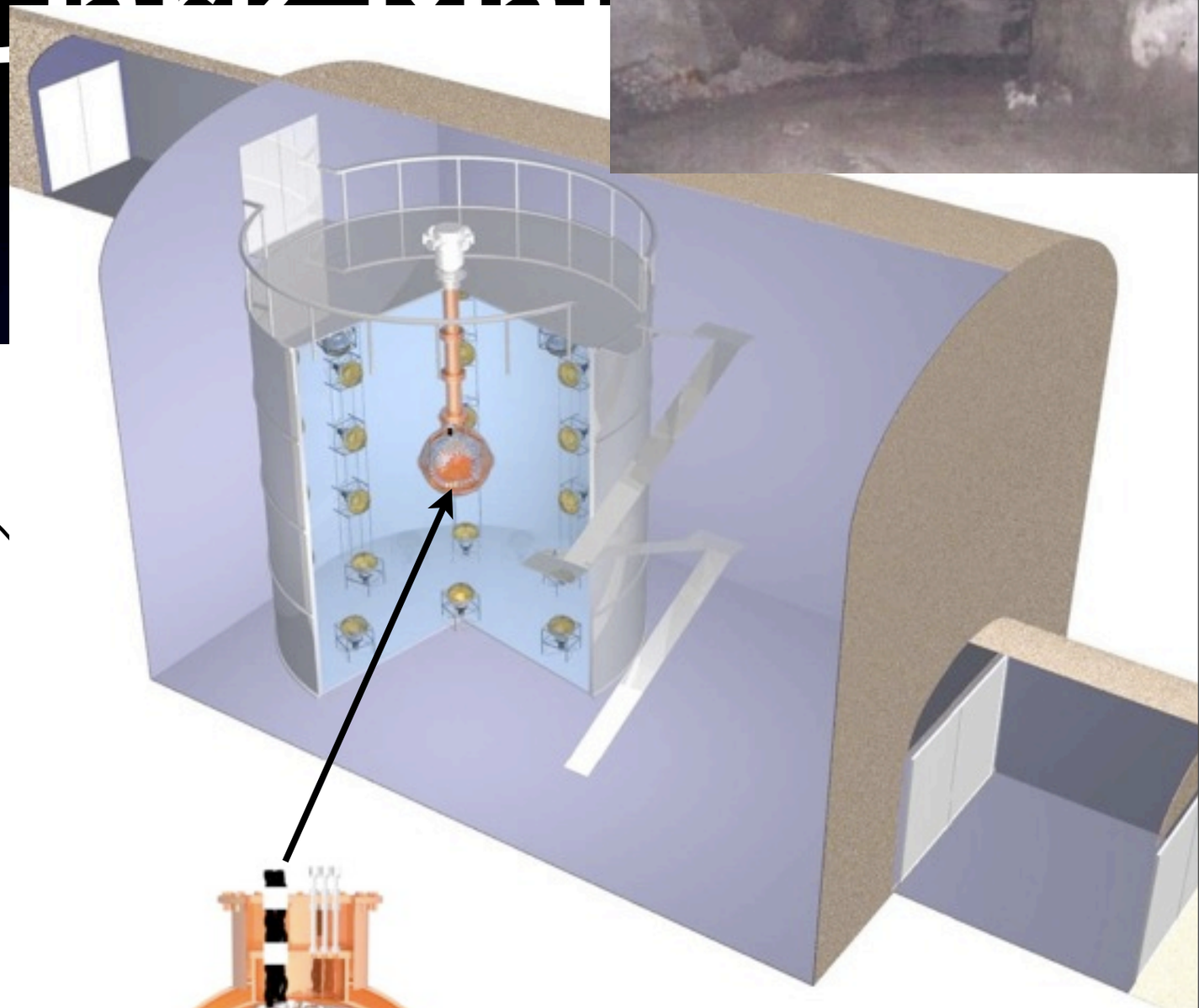


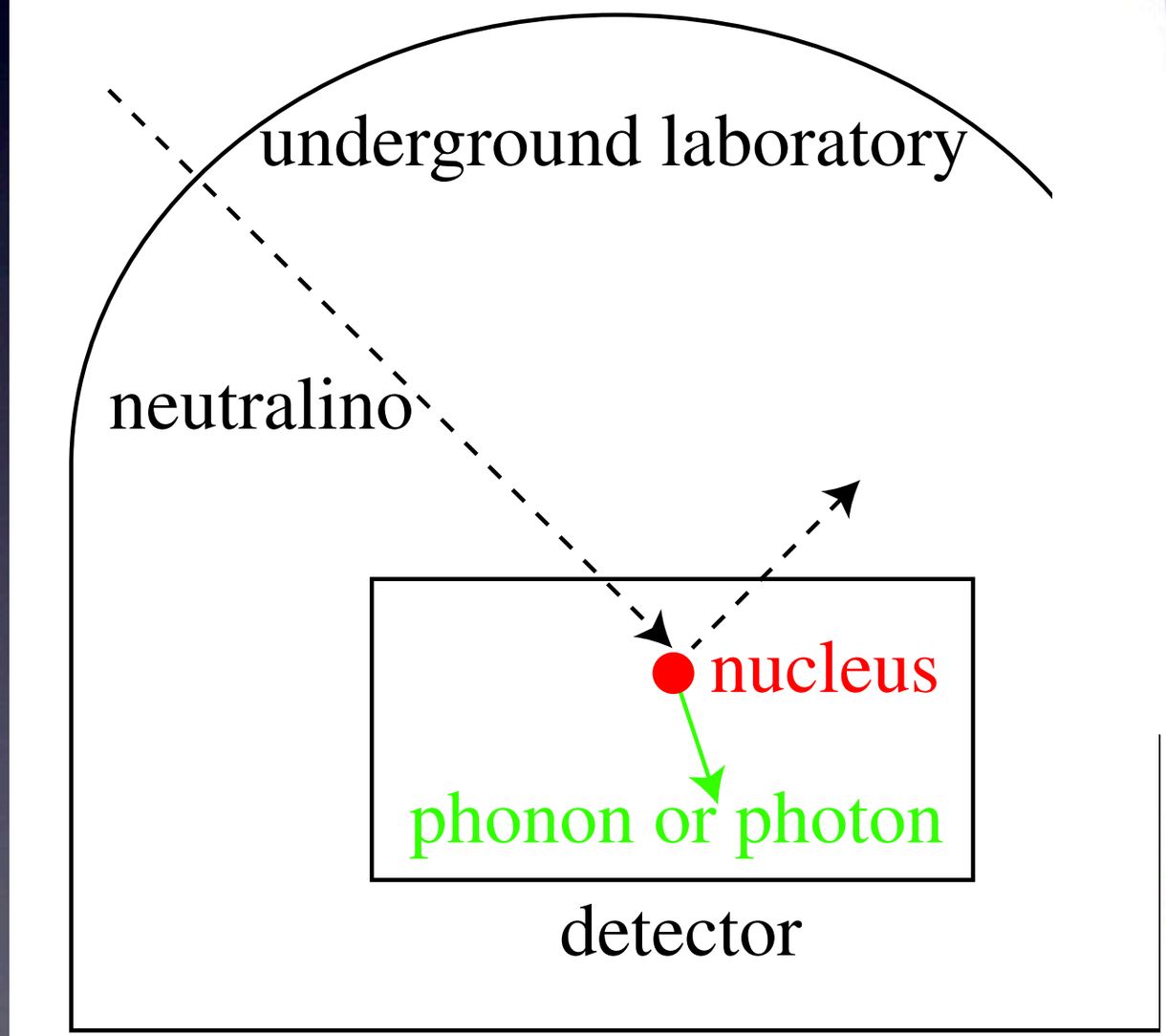
IPMU

Finding Dark Mat



Direct method







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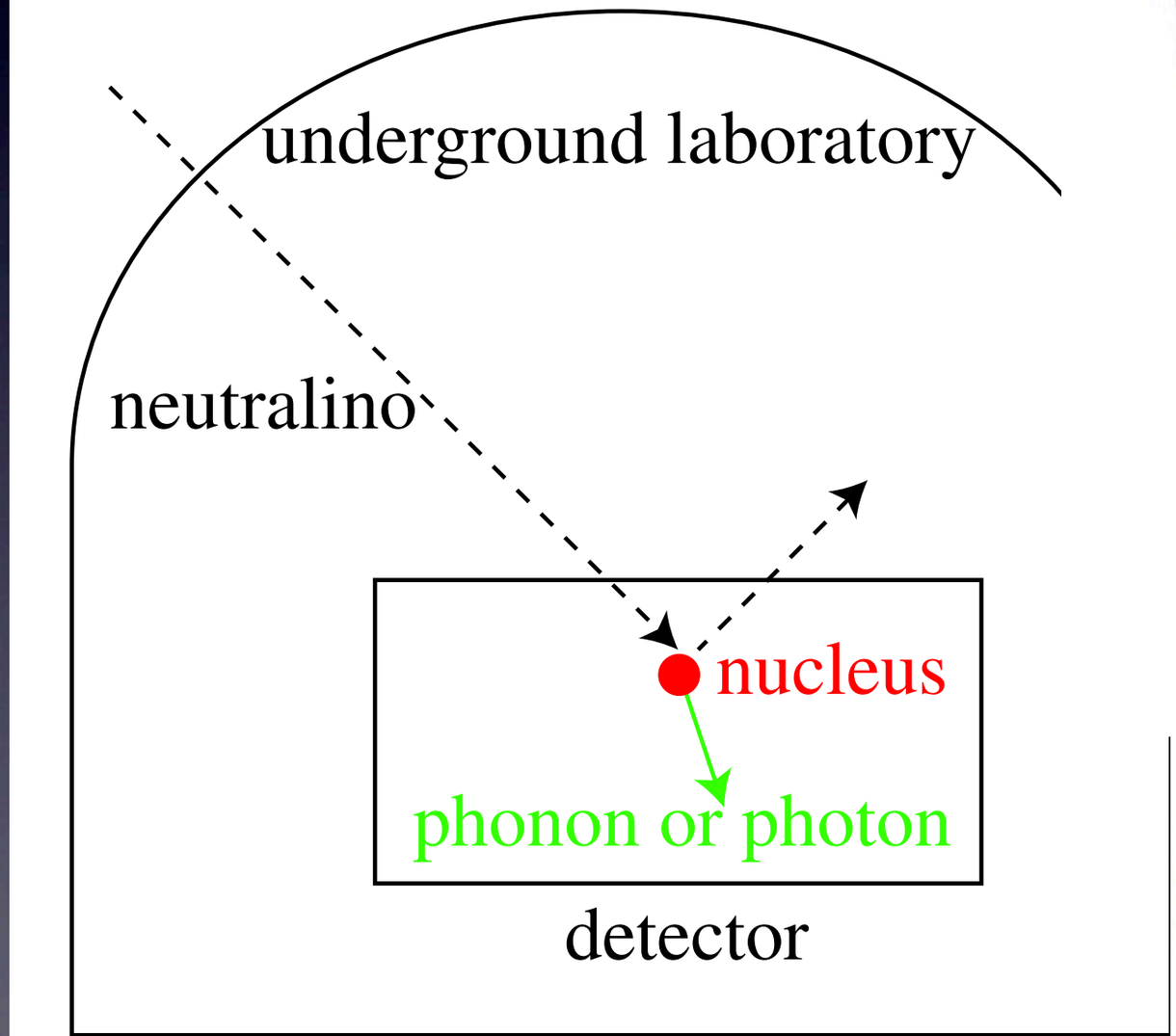
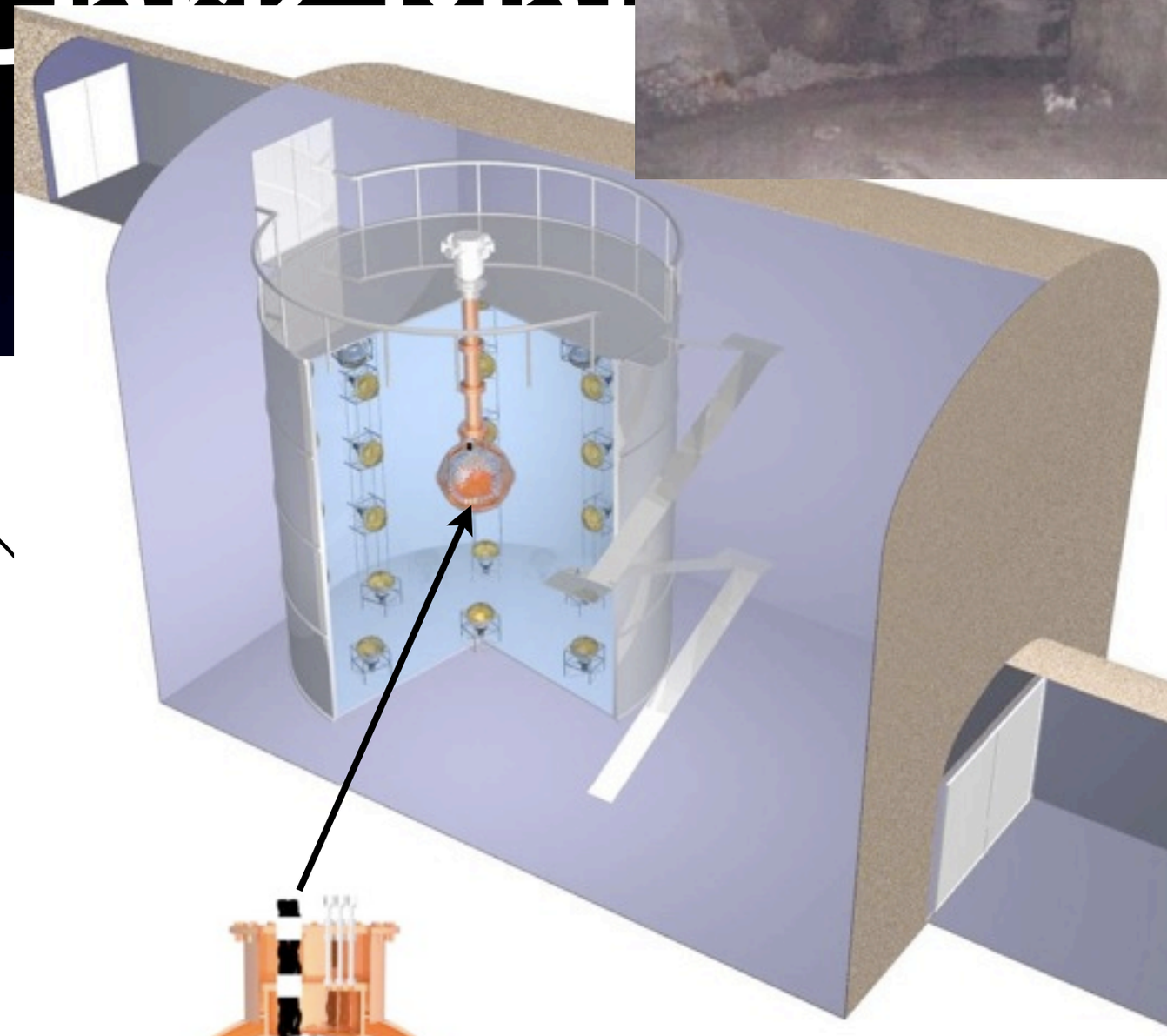
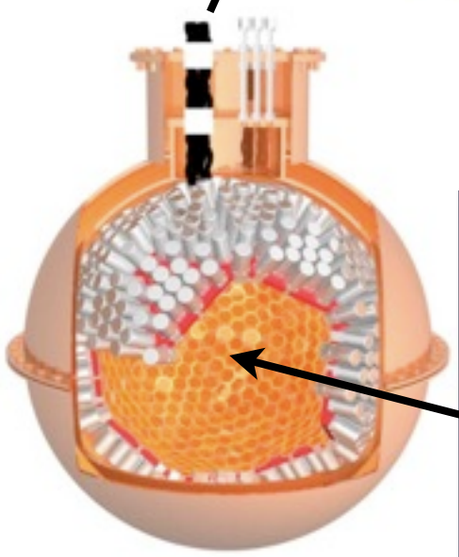










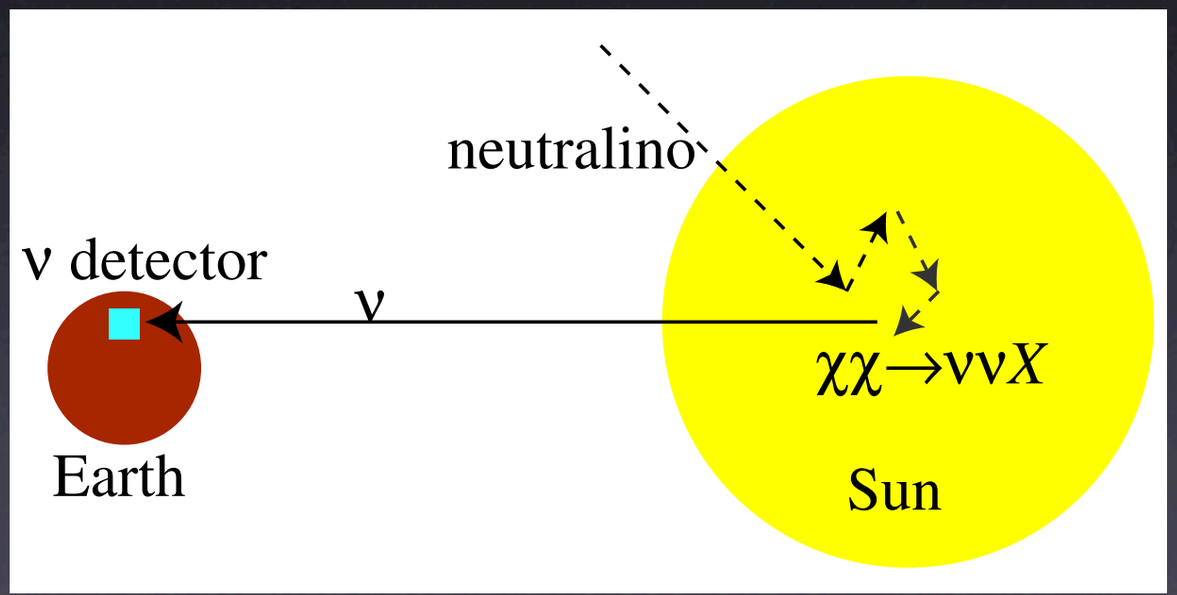
Completed!

commissioning started



Finding Dark Matter

Indirect method



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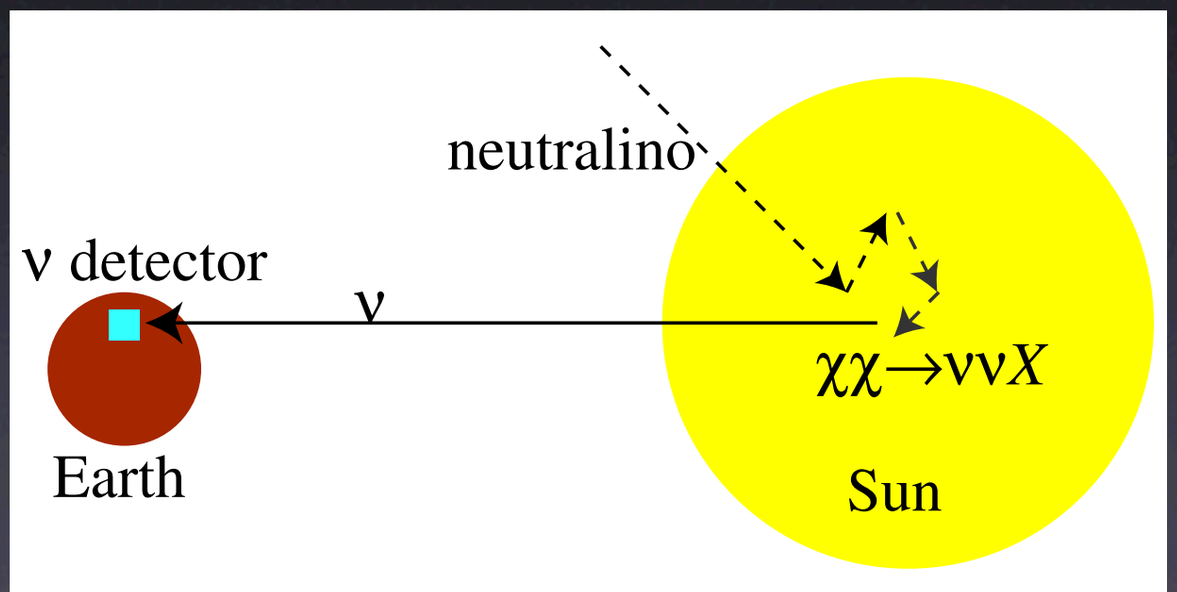

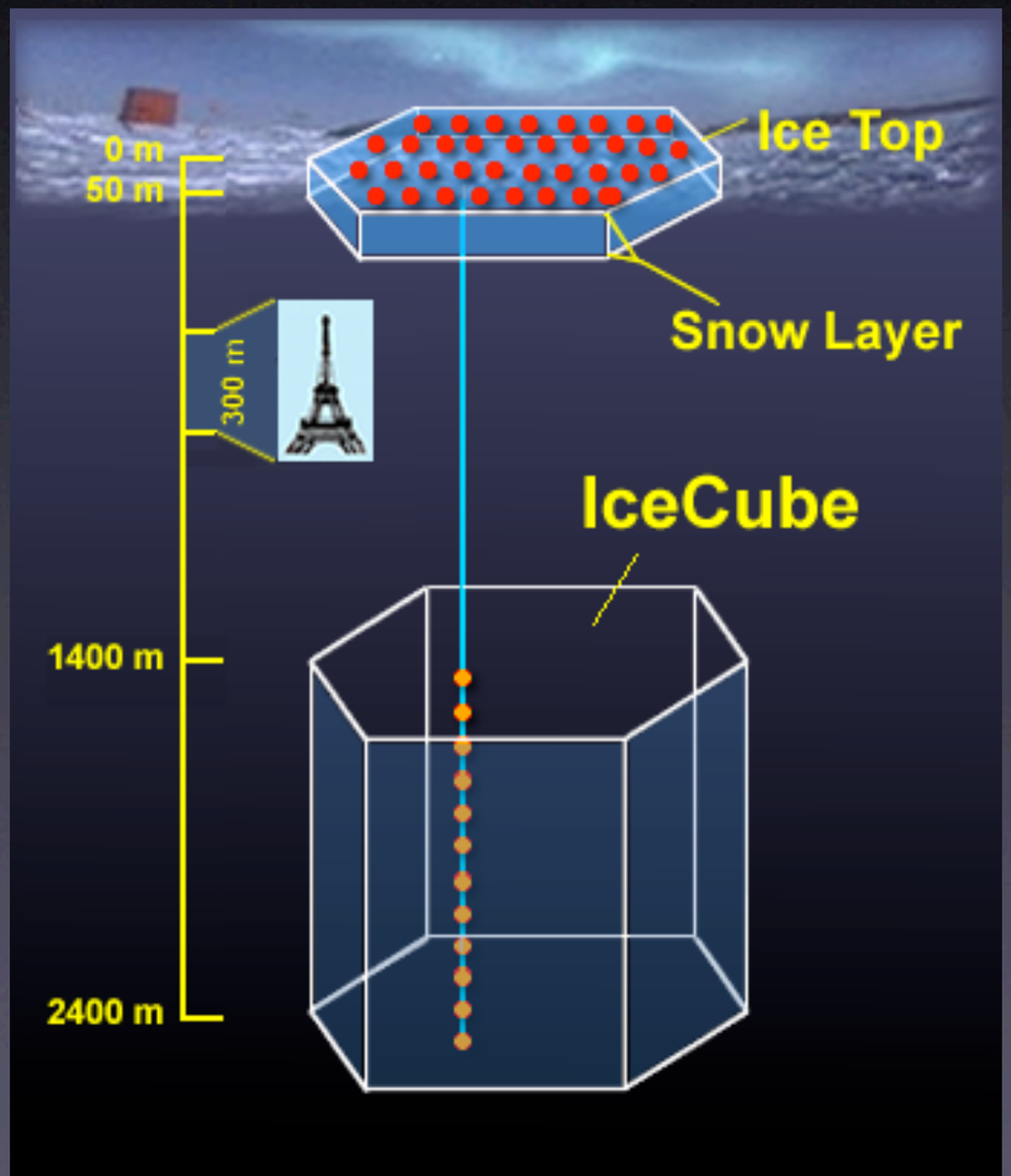

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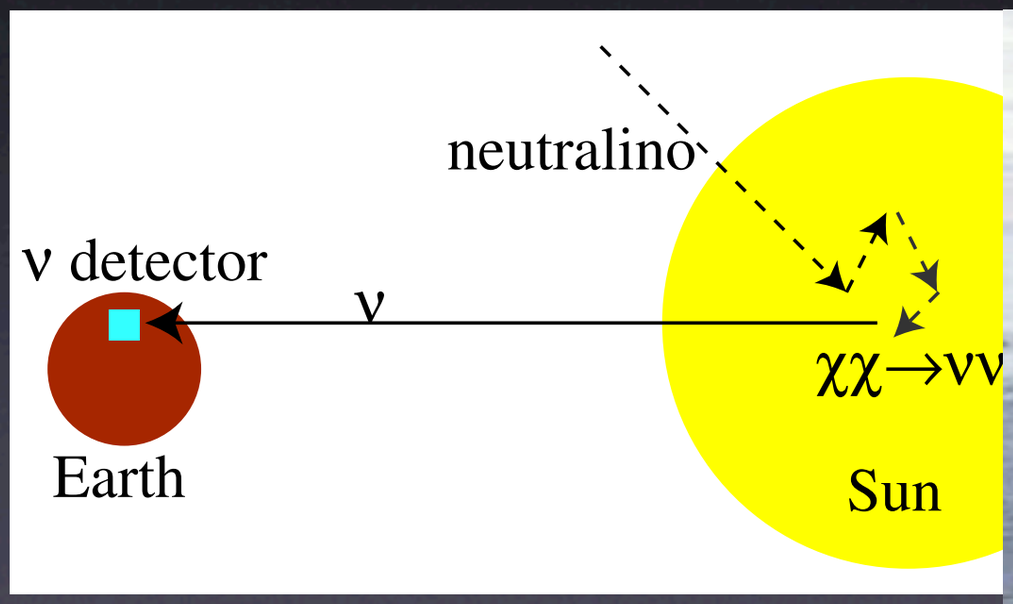




Large Hadron Collider (LHC)

Recreating Big Bang



Large Hadron Collider (LHC)

Recreating Big Bang



adron Collider (LHC)

Recreating Big Bang

BERKELEY CENTER FOR THEORETICAL PHYSICS

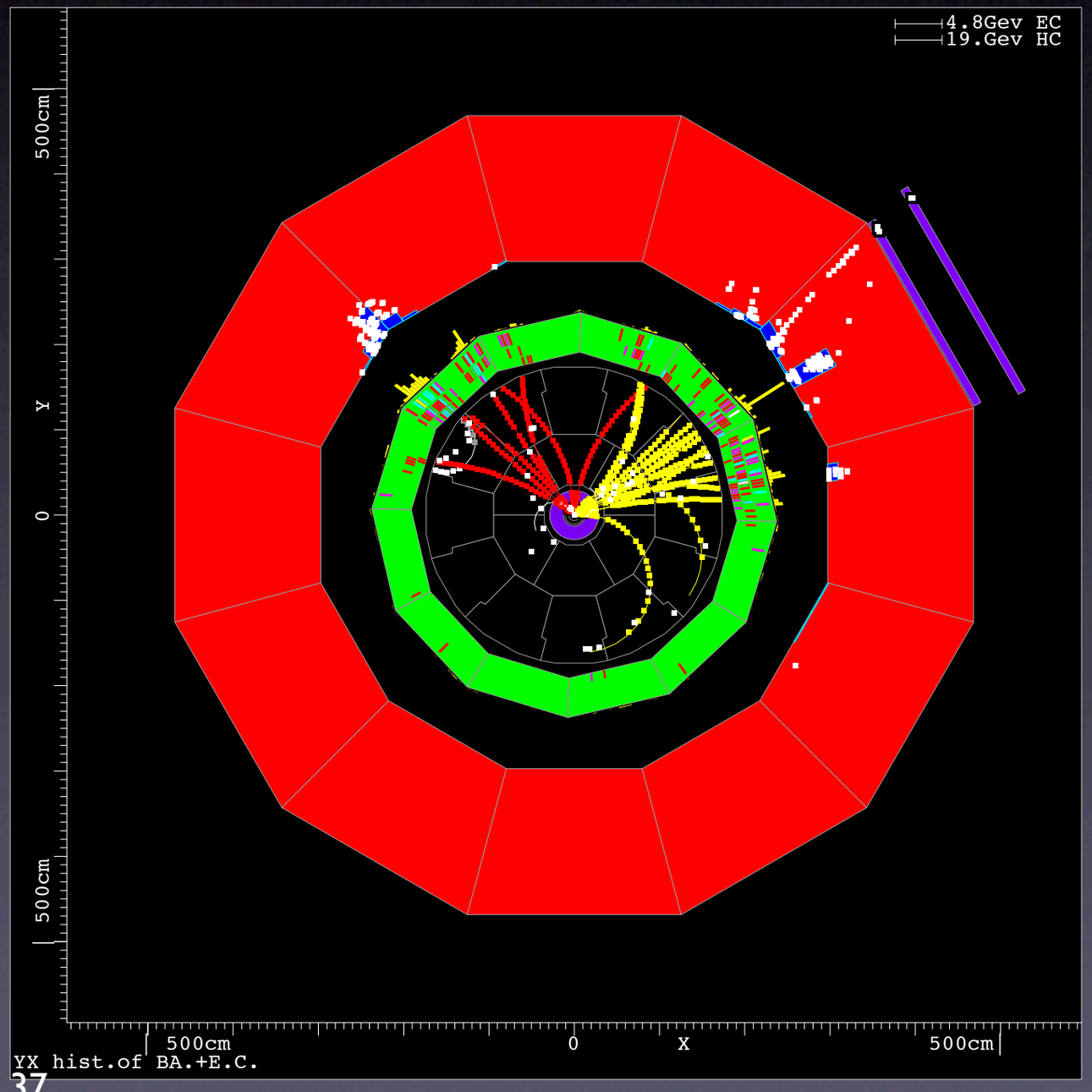
Producing Dark Matter in the laboratory

- Mimic Big Bang in the lab
- Hope to create invisible Dark Matter particles
- Look for events where energy and momenta are unbalanced

"missing energy" E_{miss}

- Something is escaping the detector

⇒Dark Matter!?



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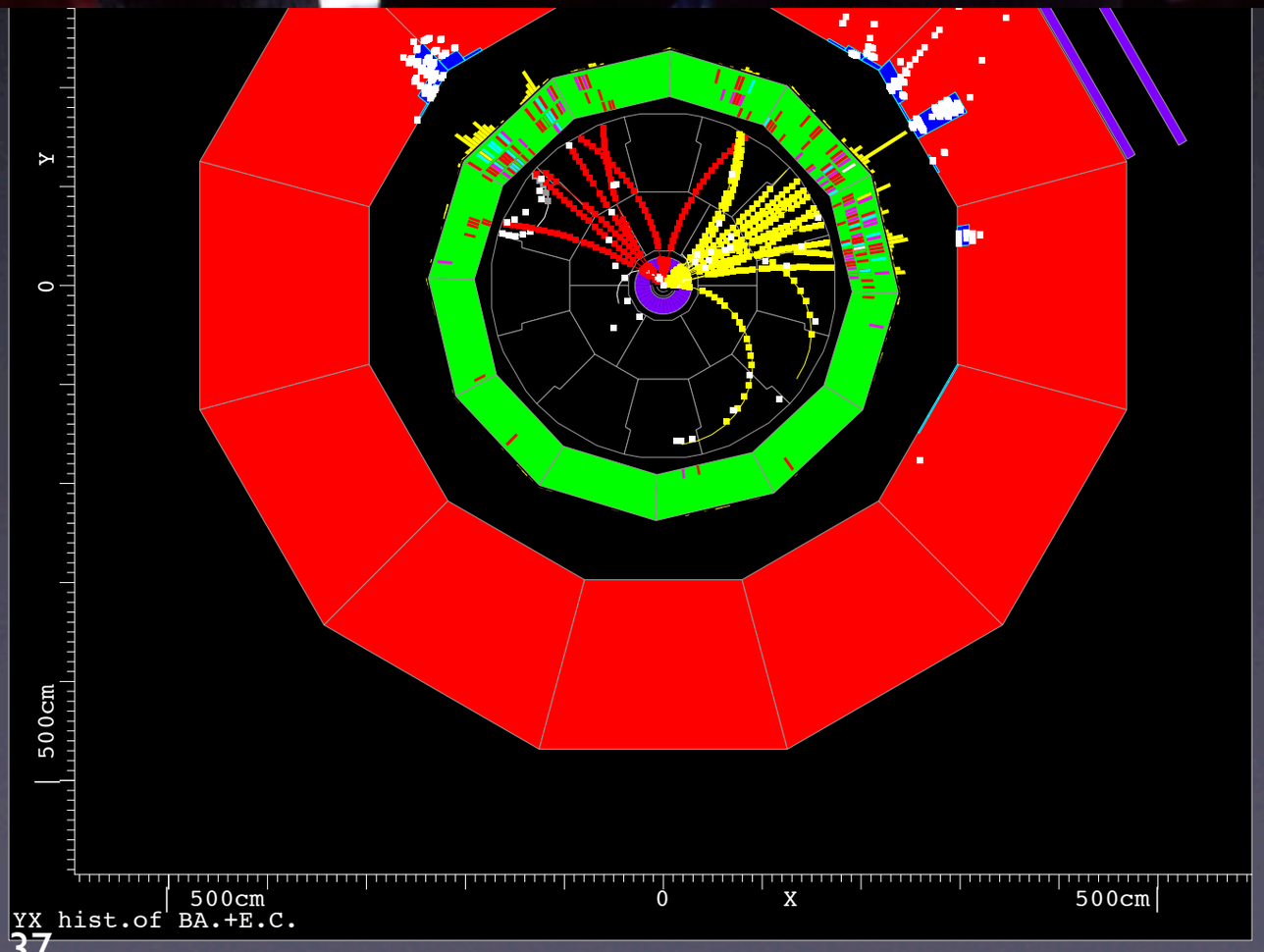
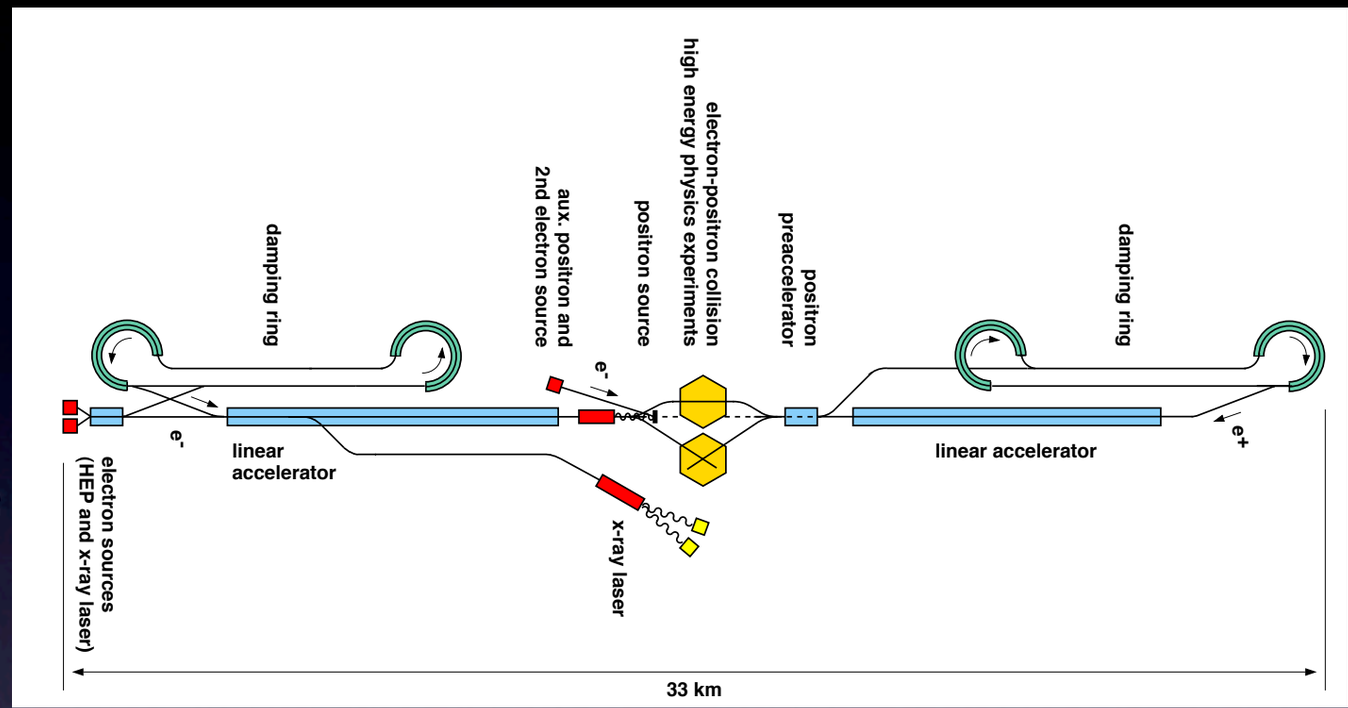


Linear Collider

- Electron-positron collider
- Super-high-tech machine
- Accelerate the beam over ten miles
- Focus beam down to a few nanometers and make them collide
- Precisely measure the dark matter properties



International Linear Collider (ILC)



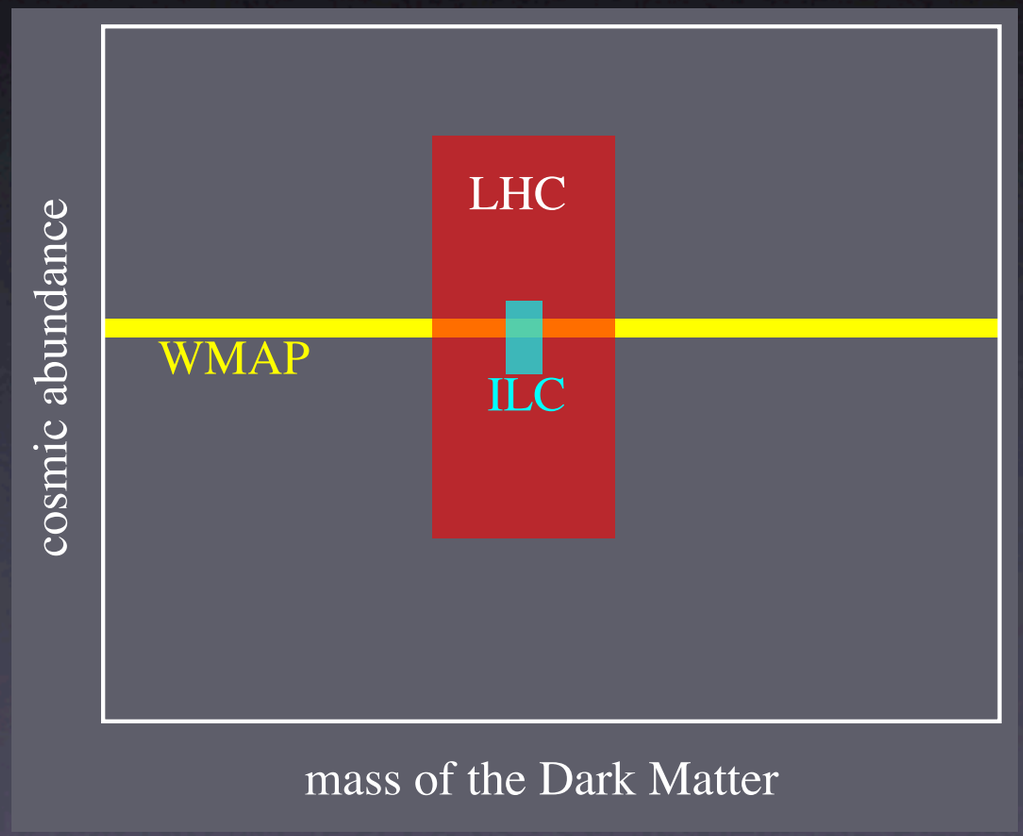
X

How do we know what Dark Matter *is*?

- cosmological measurement of dark matter
  - abundance $\propto \sigma_{ann}^{-1}$
- detection experiments
  - scattering cross section
- production at colliders
  - mass, couplings
  - can calculate cross sections
- If they agree with each other:

$\Rightarrow$ Will know *what Dark Matter is*

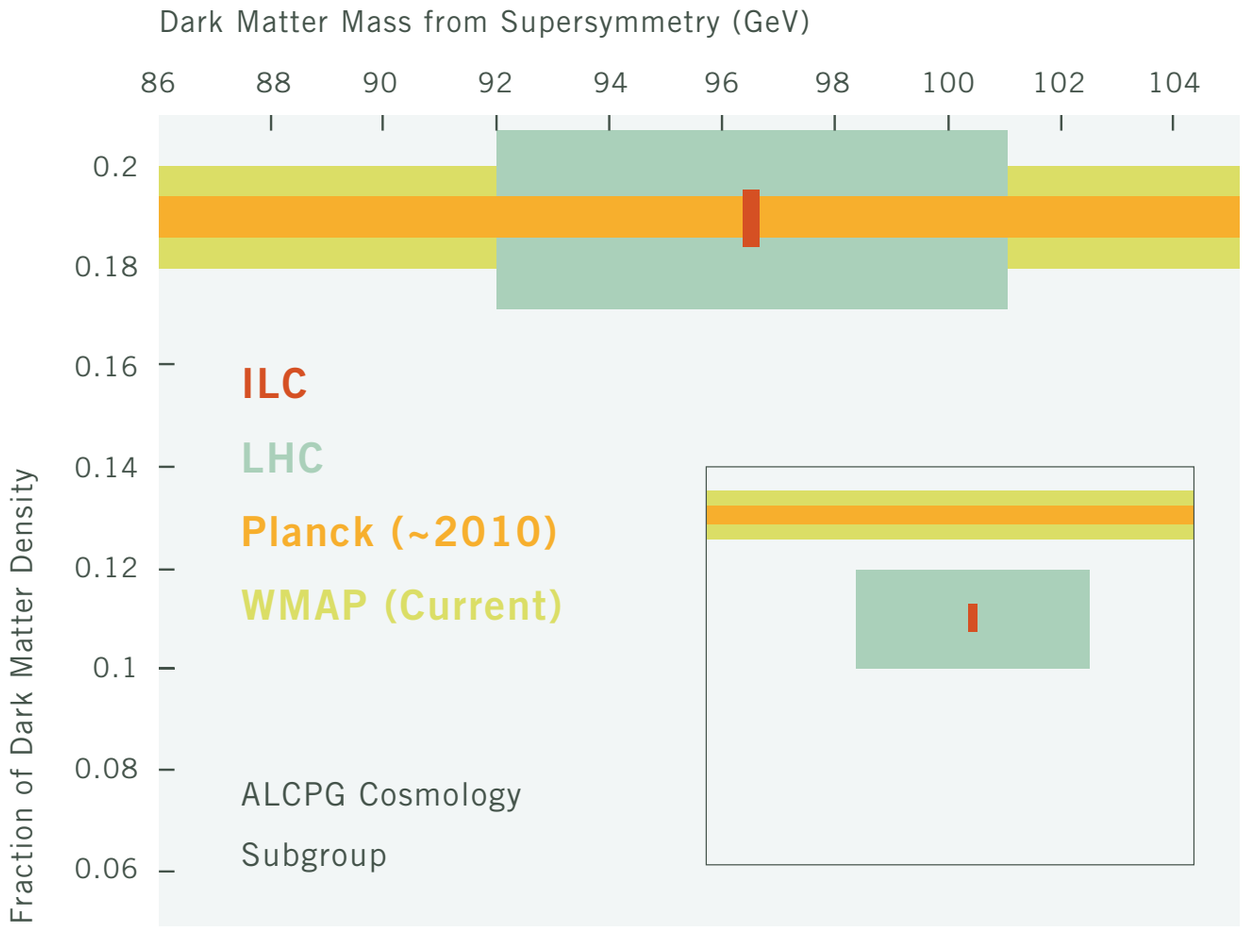
$\Rightarrow$ Will understand universe back to $t \sim 10^{-10}$ sec



Dark Matter

abundance

direct detection cross section



Dark Matter

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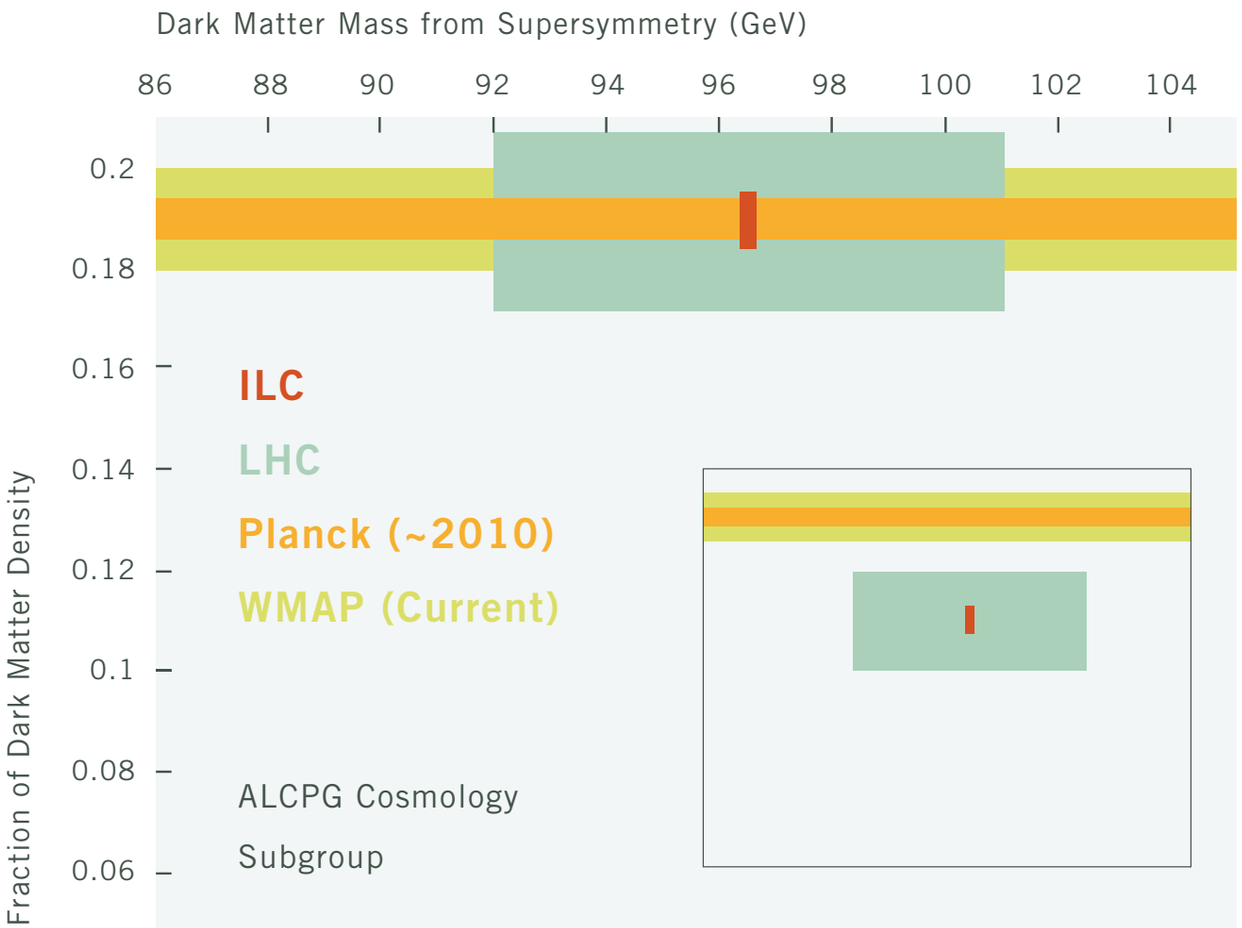

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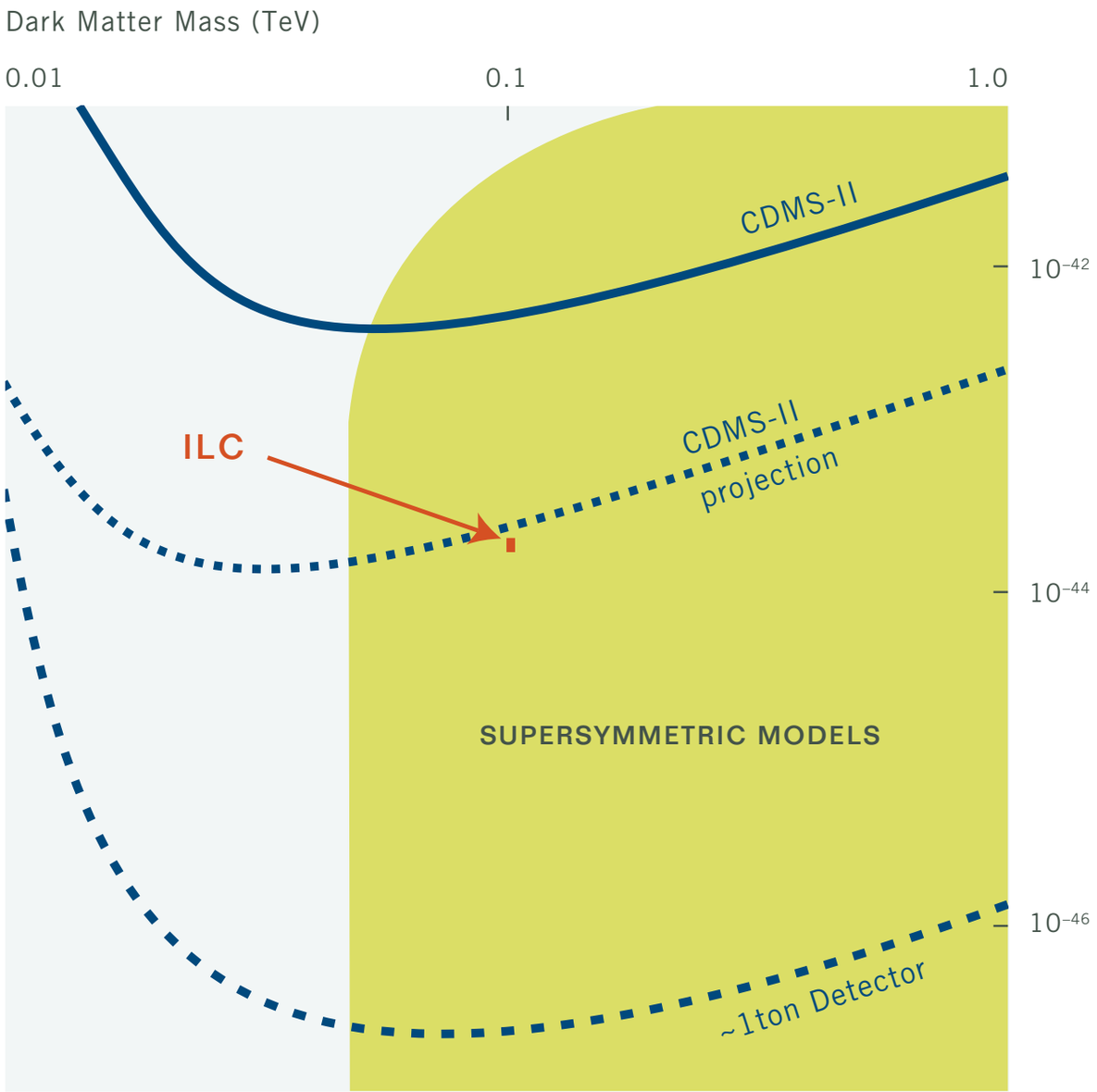
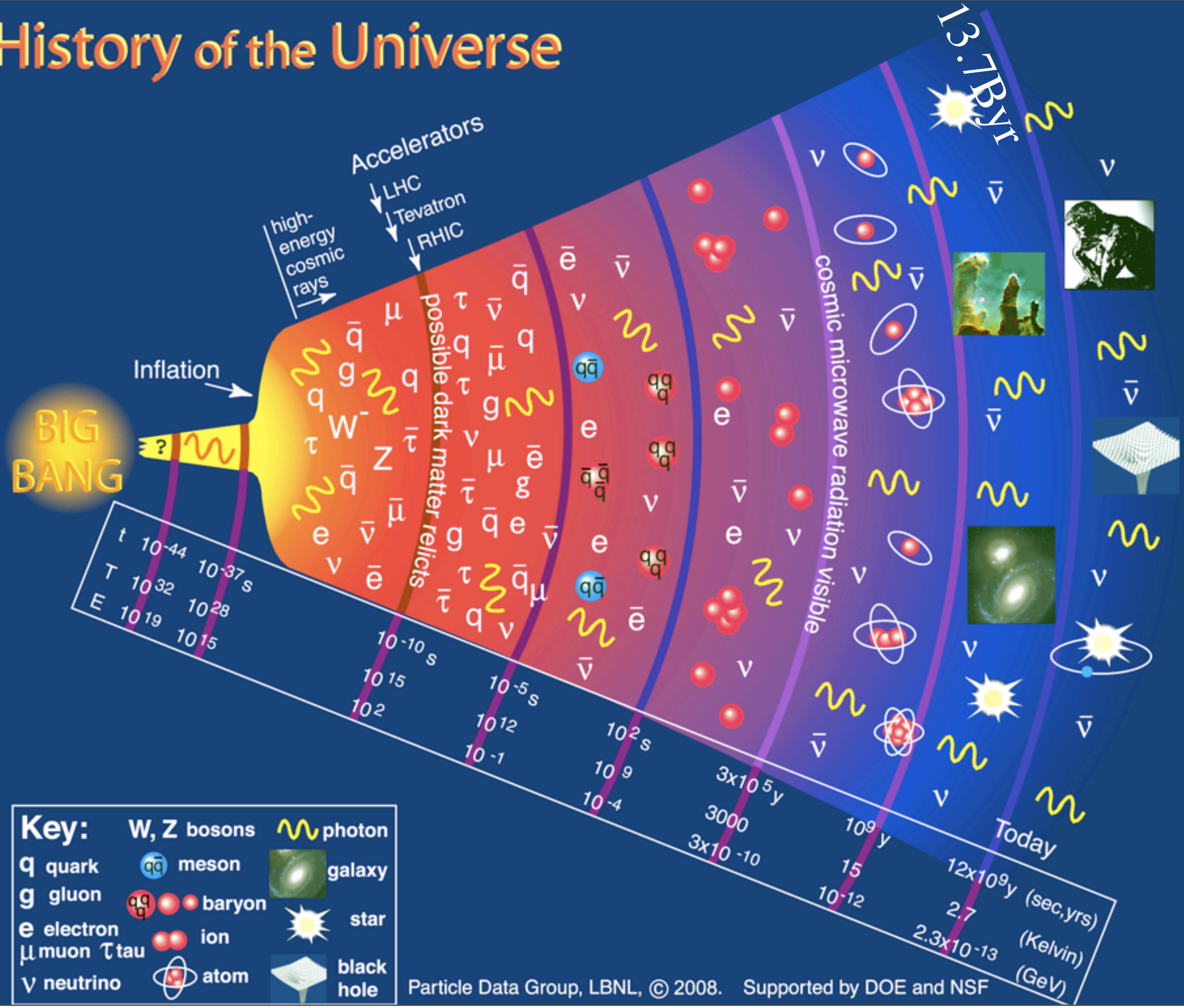


History of the Universe



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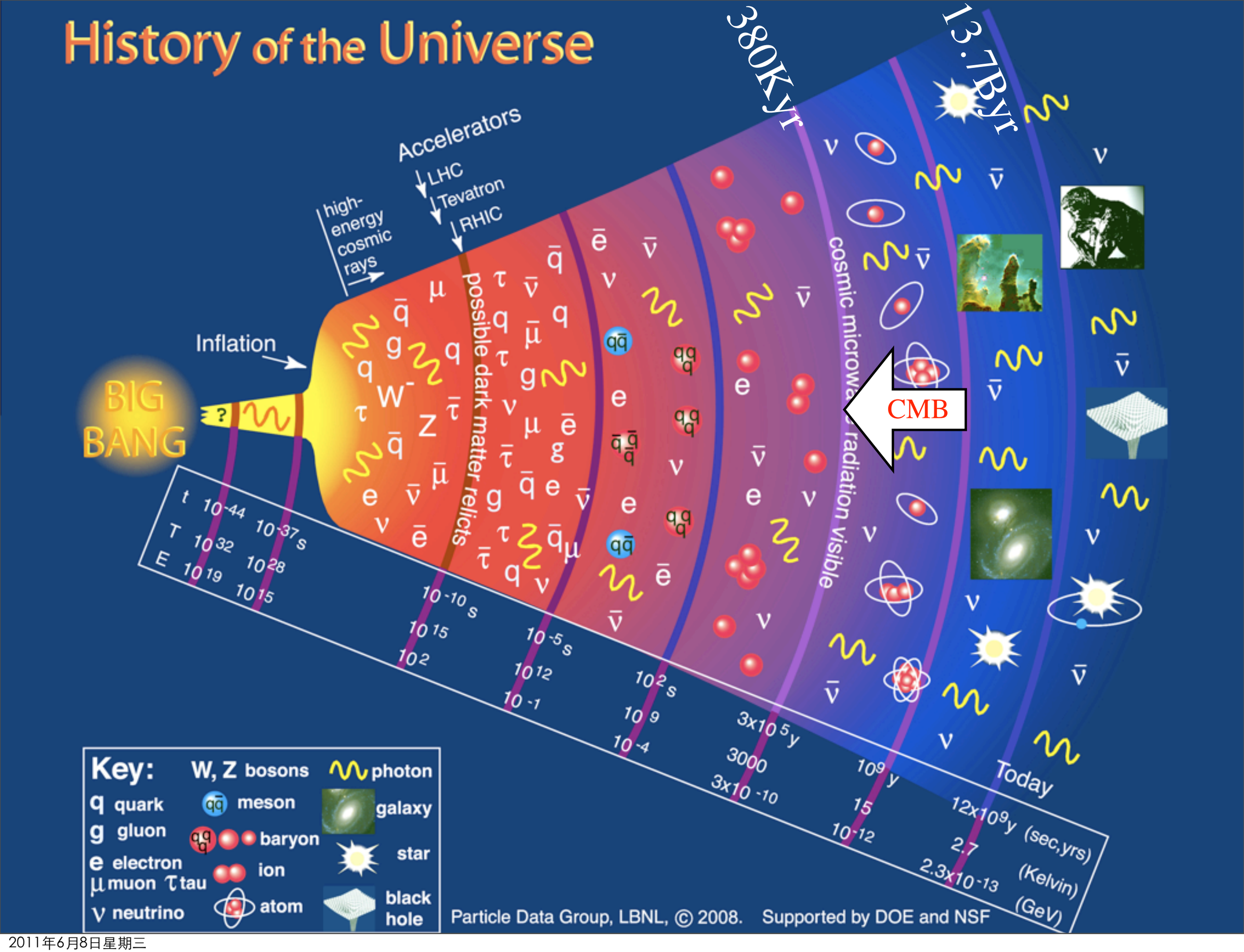

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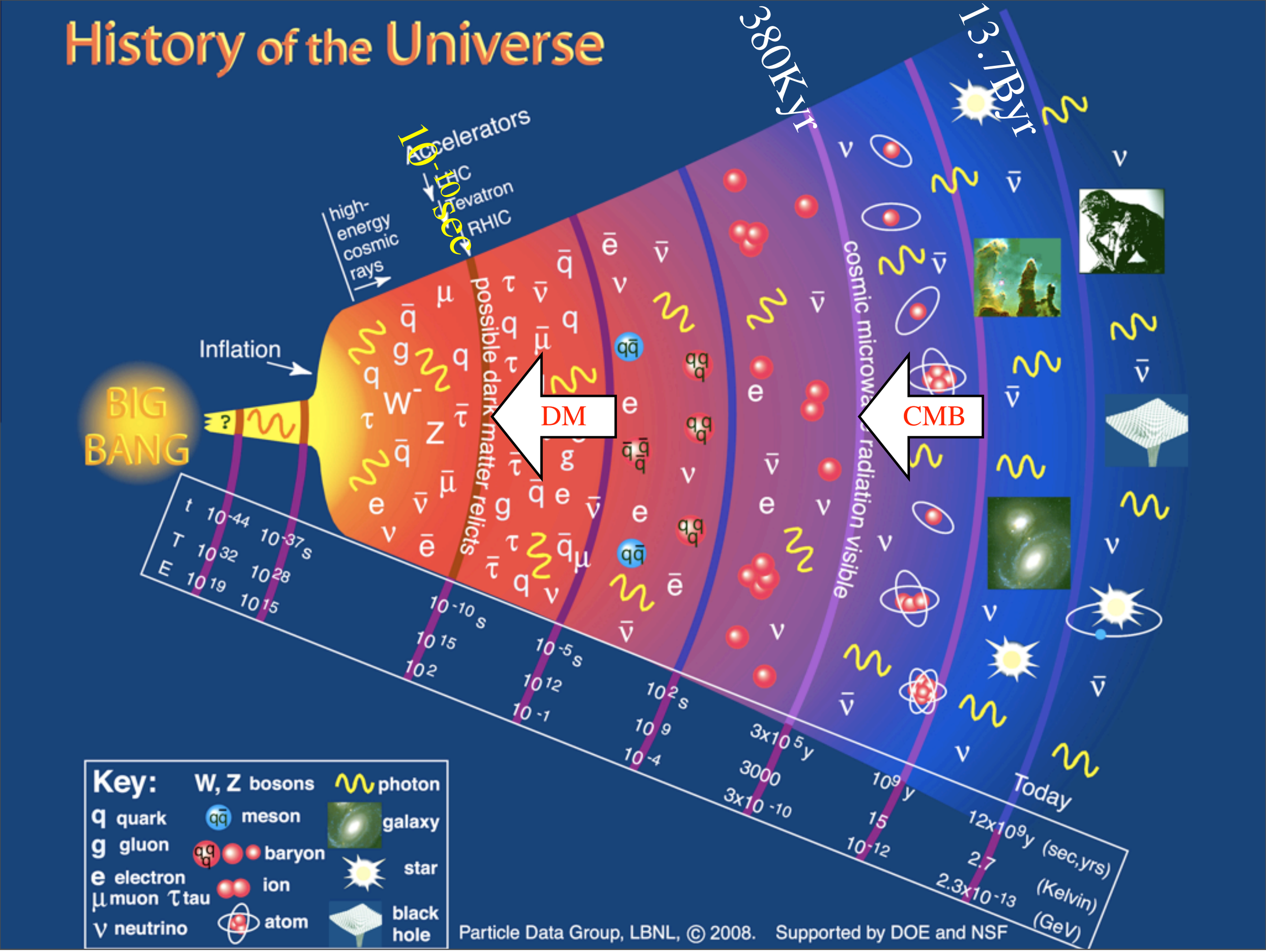


Why do we exist?

–Anti-Matter–



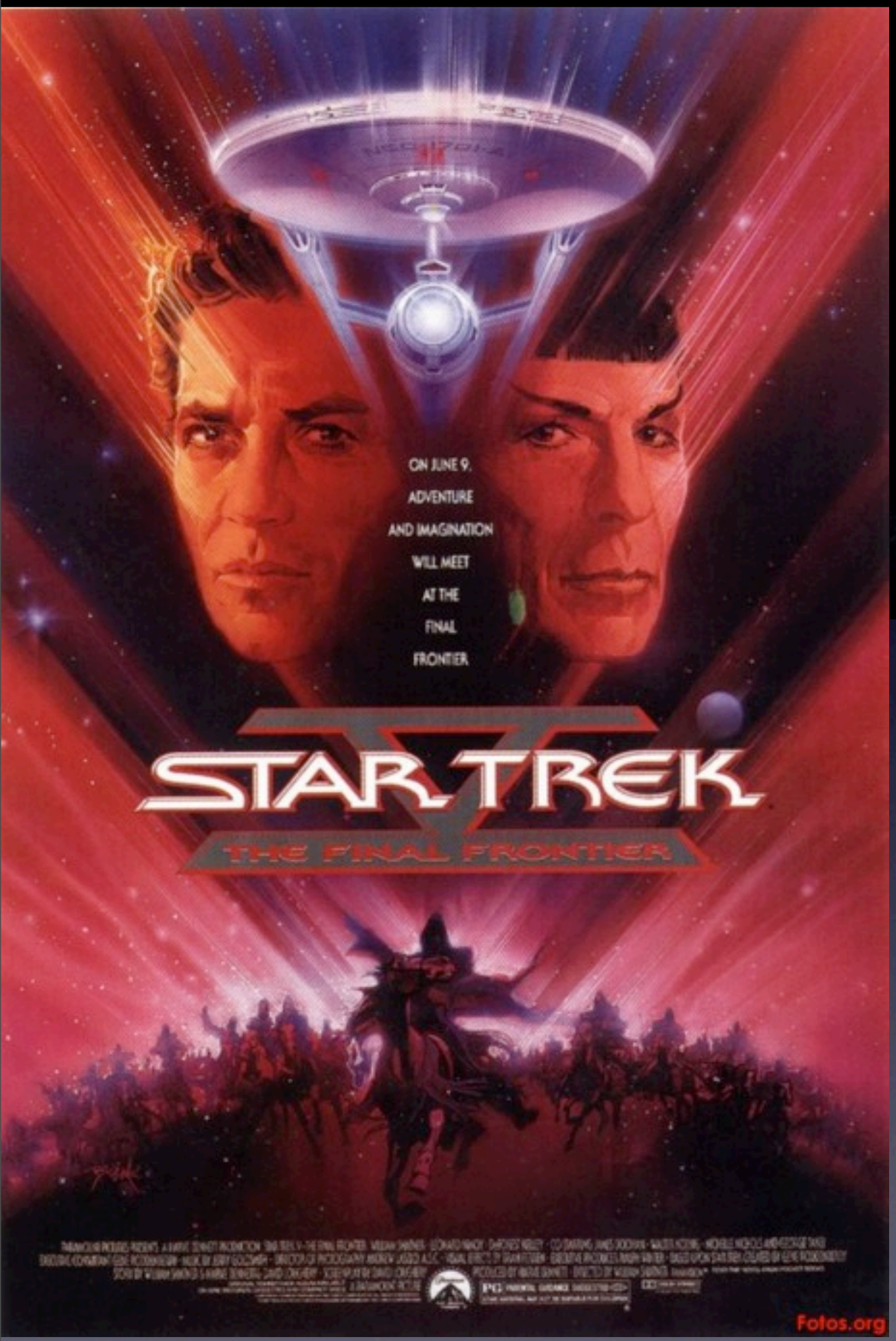






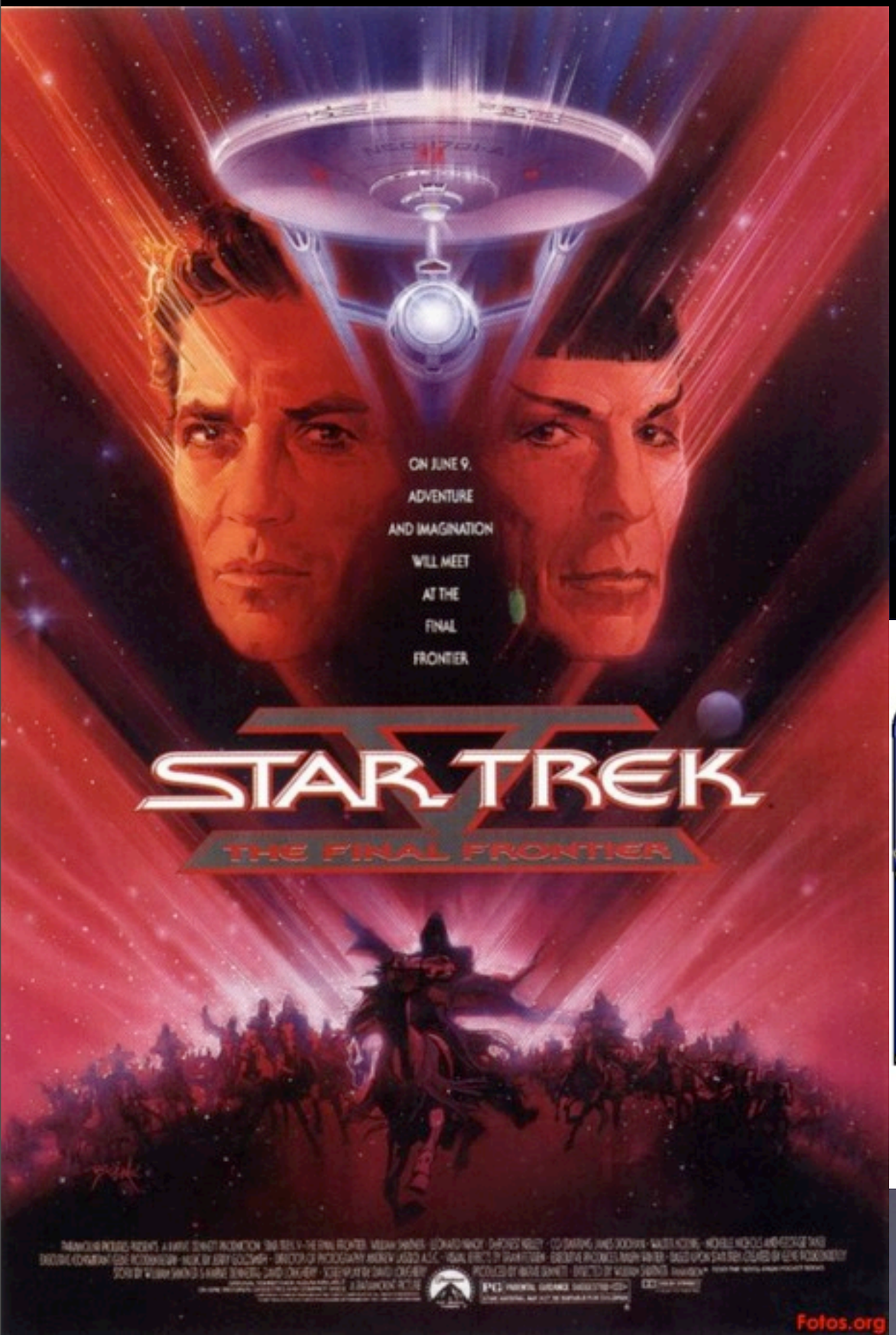
1955
anti-proton
in Berkeley



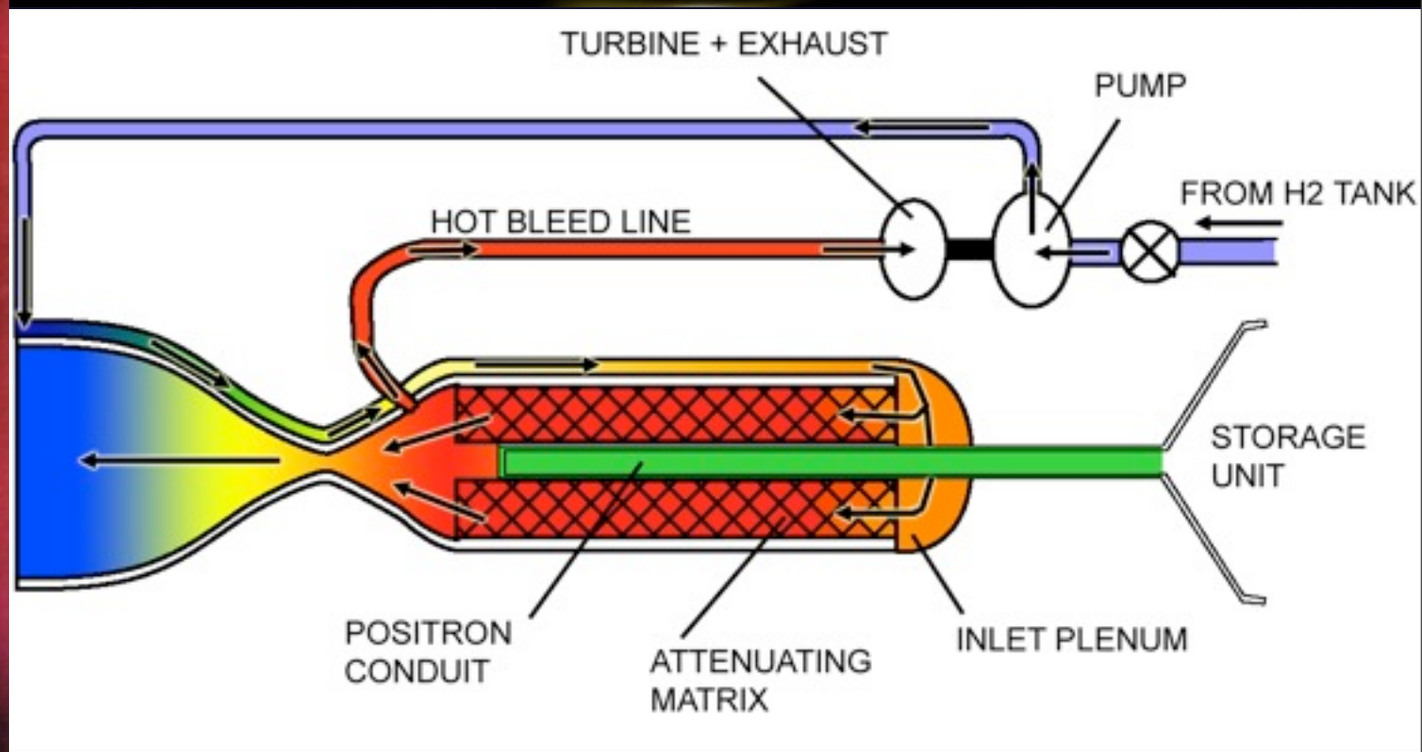


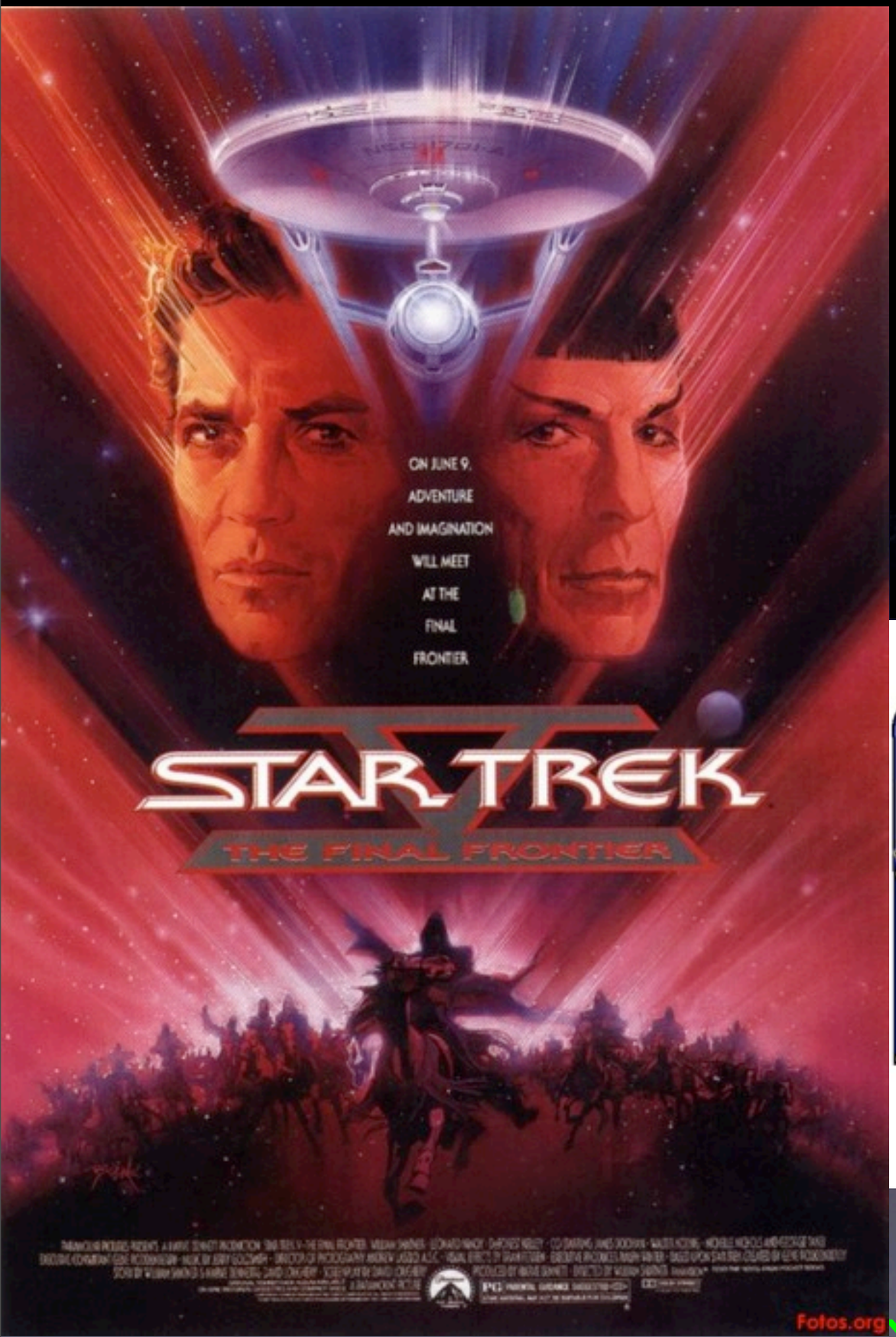


2011年6月8日星期三

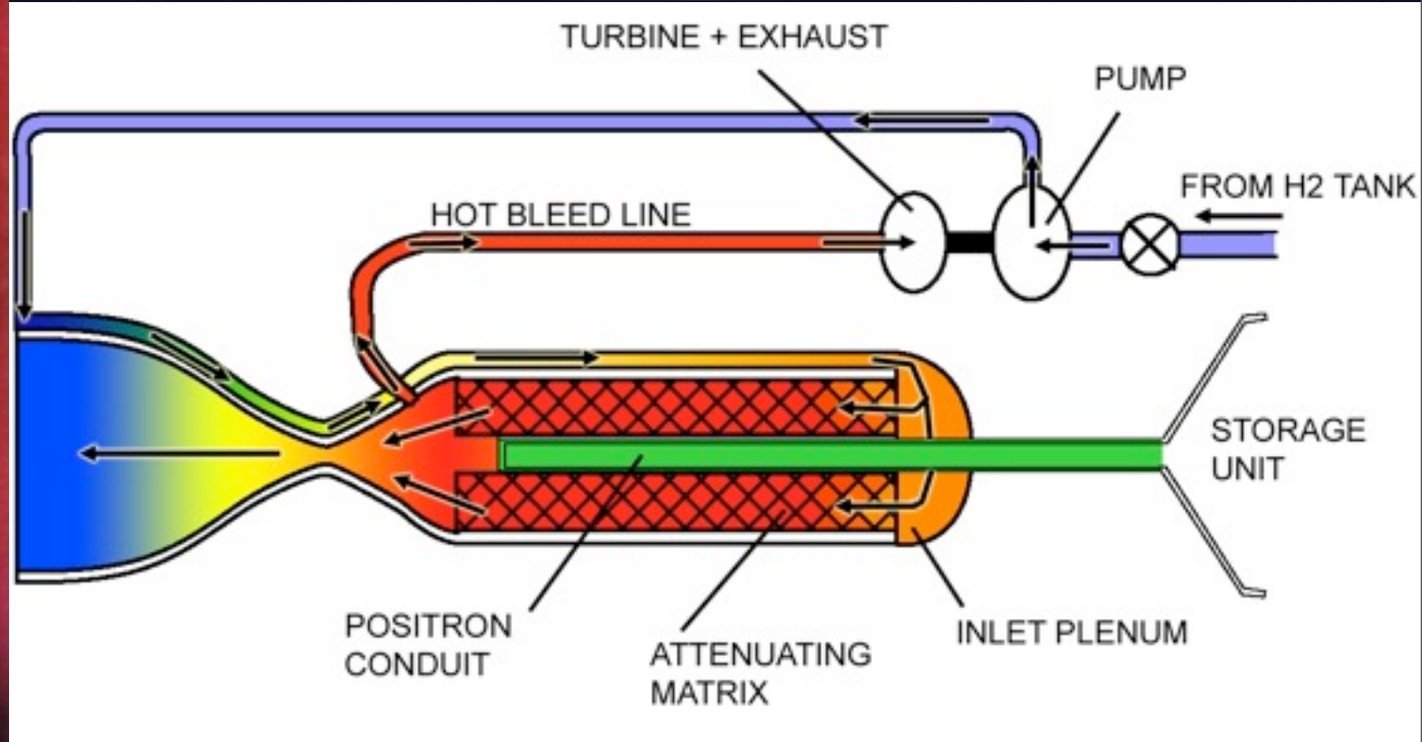

ON JUNE 9,
ADVENTURE
AND IMAGINATION
WILL MEET
AT THE
FINAL
FRONTIER
STAR TREK V
THE FINAL FRONTIER
Fotos.org


NCC-1701


TURBINE + EXHAUST
PUMP
FROM H2 TANK
HOT BLEED LINE
STORAGE
UNIT
POSITRON
CONDUIT
ATTENUATING
MATRIX
INLET PLENUM

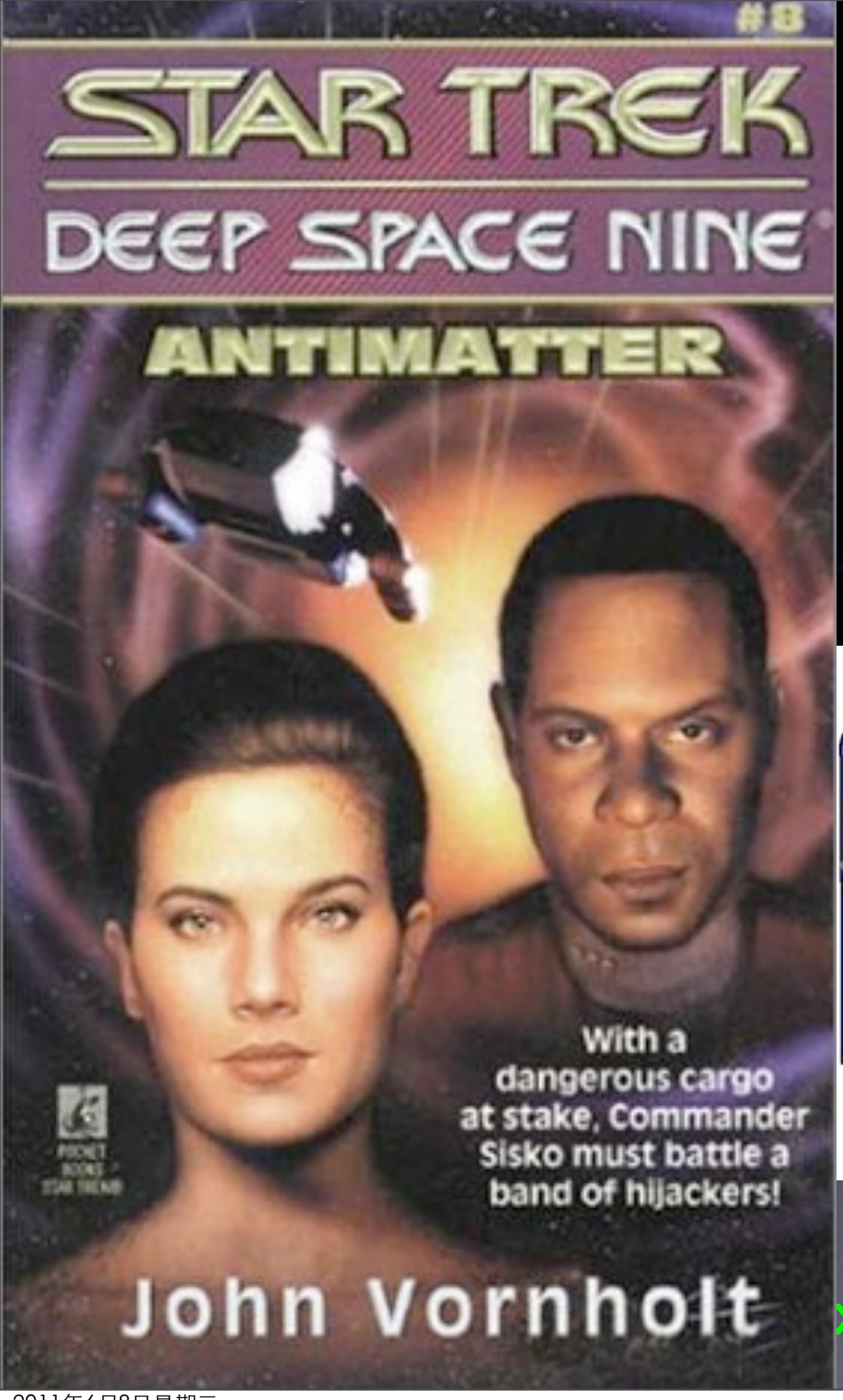




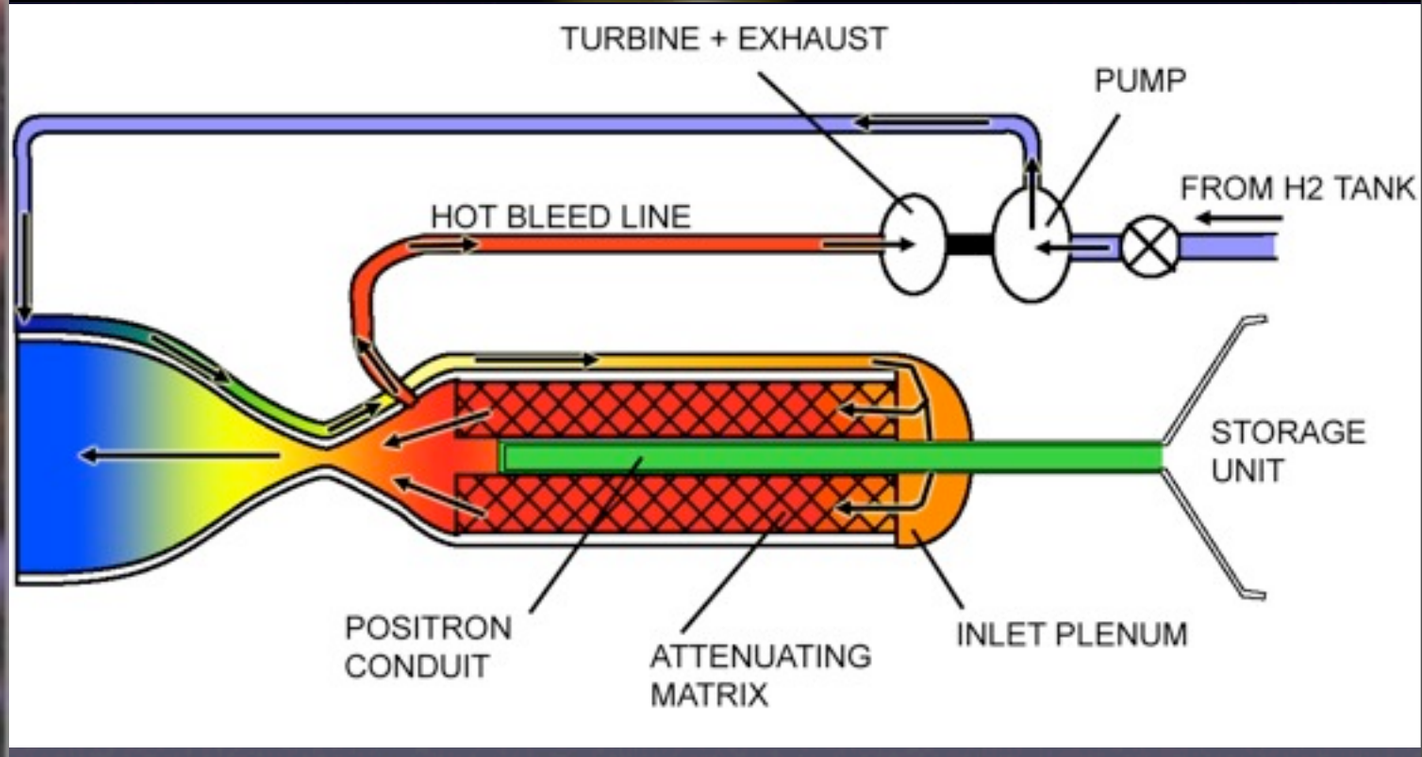


$E=mc^2$

x2billion more efficient than gasoline







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TOM HANKS
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Matter and Anti-Matter Early Universe

1,000,000,002

1,000,000,000

matter

anti-matter

x

Matter and Anti-Matter Current Universe

2

us

matter *anti-matter*

The Great Annihilation

x

Beginning of Universe

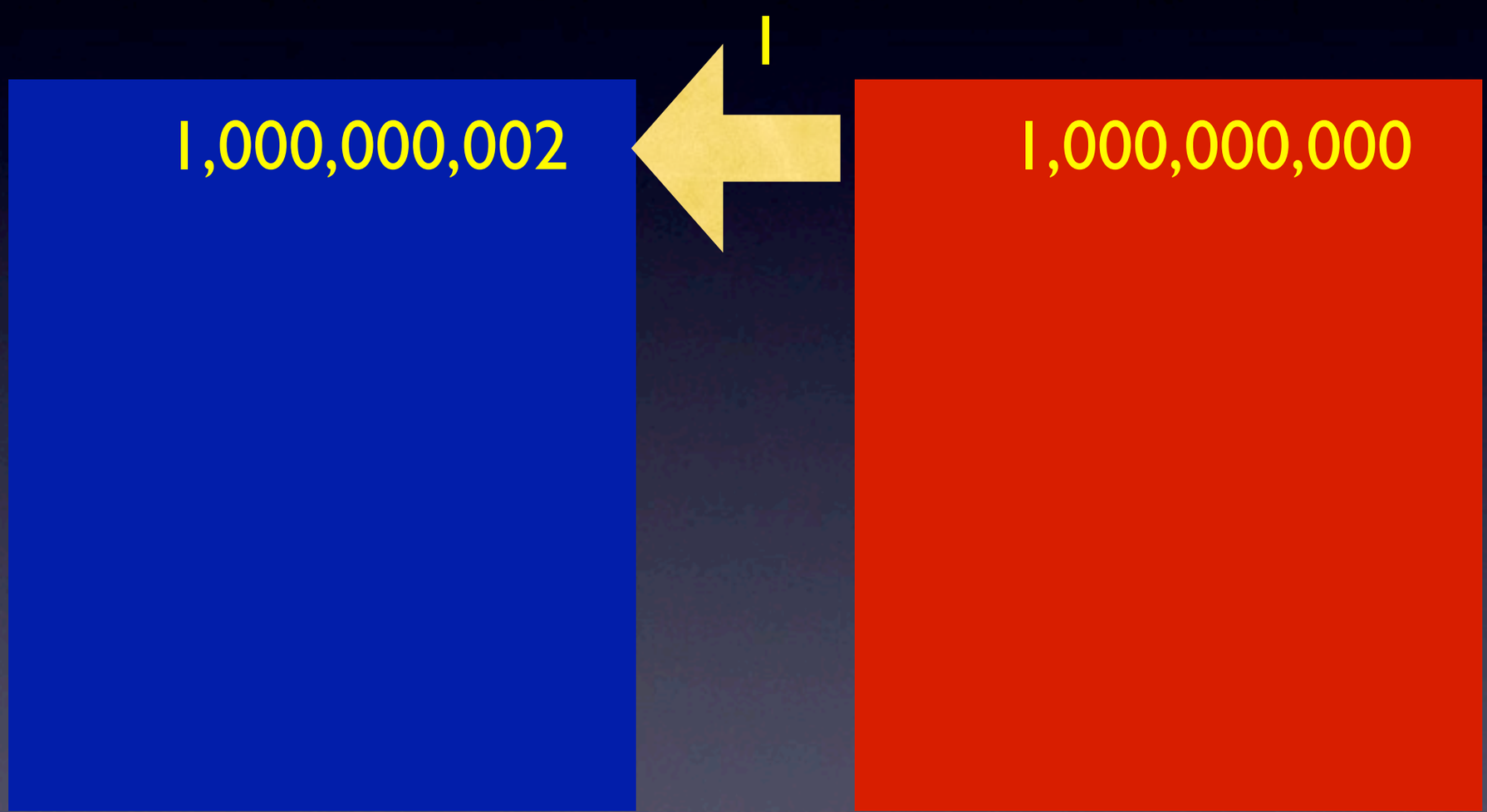
1,000,000,001

1,000,000,001

matter

anti-matter

fraction of second later



turned a billionth of anti-matter to matter

Universe Now

2

•

us

matter *anti-matter*

This must be how we survived the Big Bang!

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CP Violation

X

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CP Violation

- Is anti-matter the exact mirror of matter?

X

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1964 discovery of CP violation

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- But only one system, hard to tell what is going on.

X

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2001, 2002 Two new CP-violating phenomena

X

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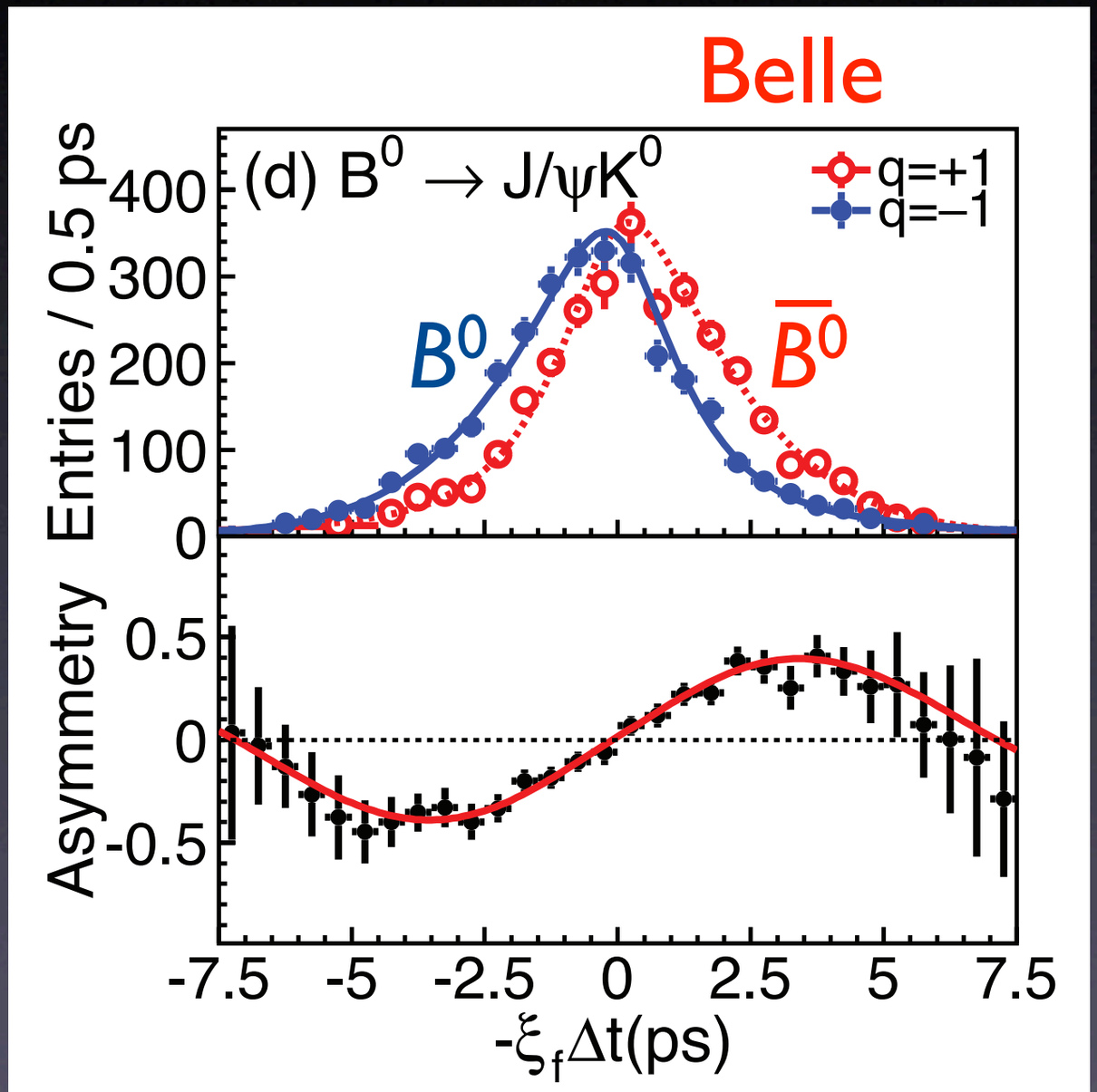

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CP Violation

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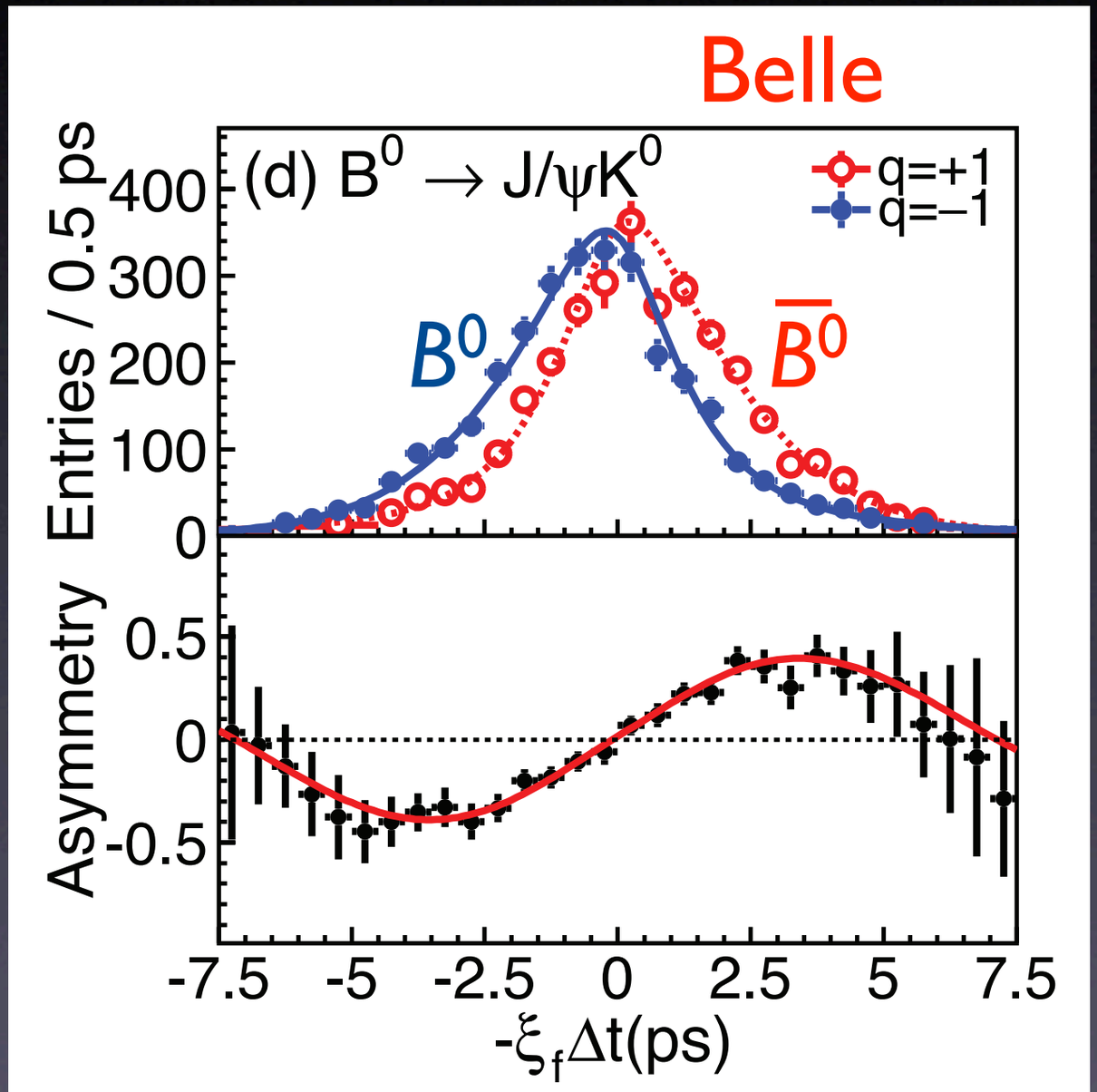

X

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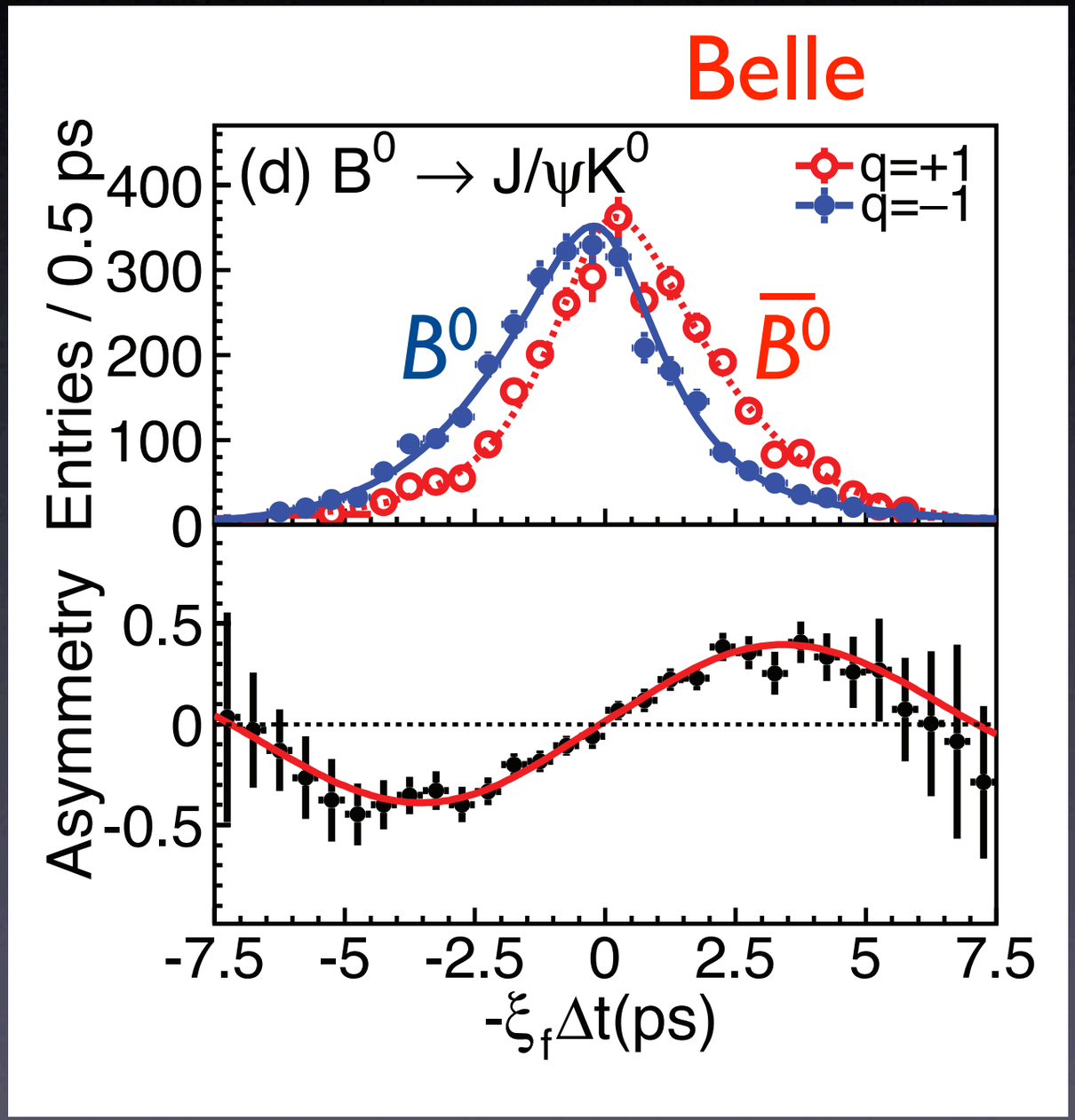
1964 discovery of CP violation

- But only one system, hard to tell what is going on.

2001, 2002 Two new CP-violating phenomena

- But CP violation observed so far is too small by a factor of 10^{-16} to explain the absence of anti-matter
- doesn't look like quarks are important here



x

Maybe Neutrinos!

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- Neutrinos are special
  because no electric charge

X

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- *did neutrinos reshuffle*
  matter and anti-matter?

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X

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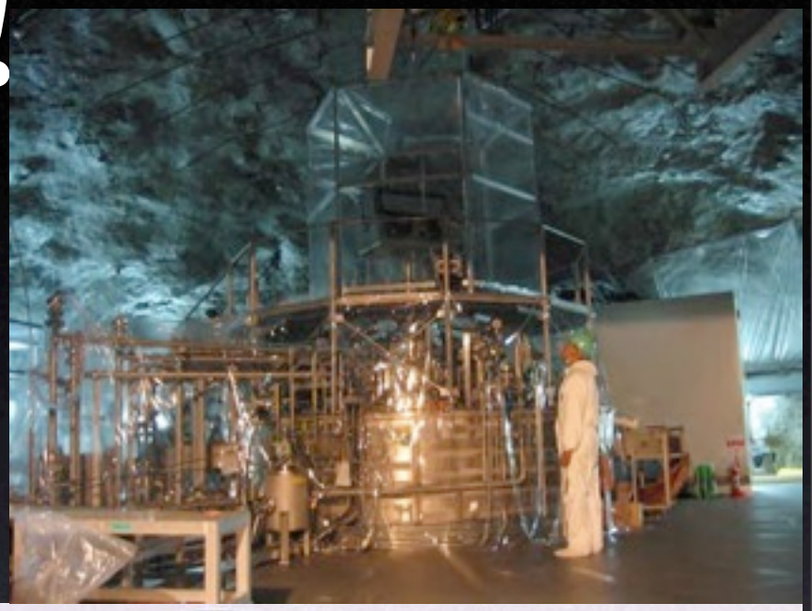

- Neutrinos are special because no electric charge
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- possible by topology of gauge fields
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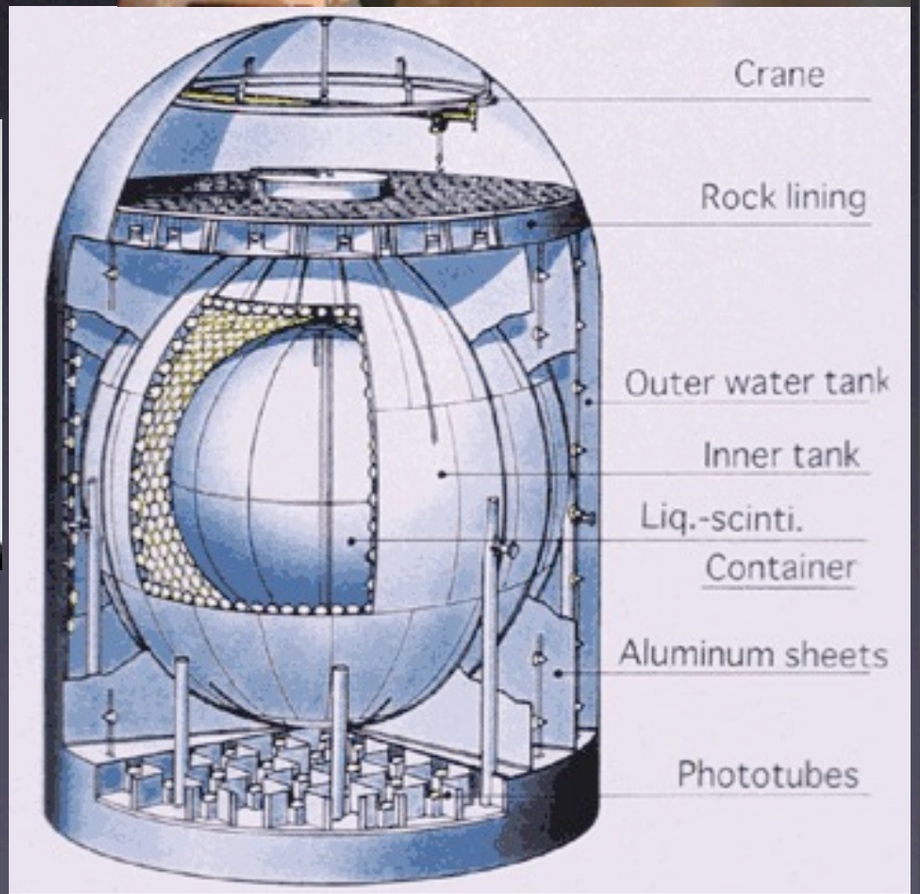
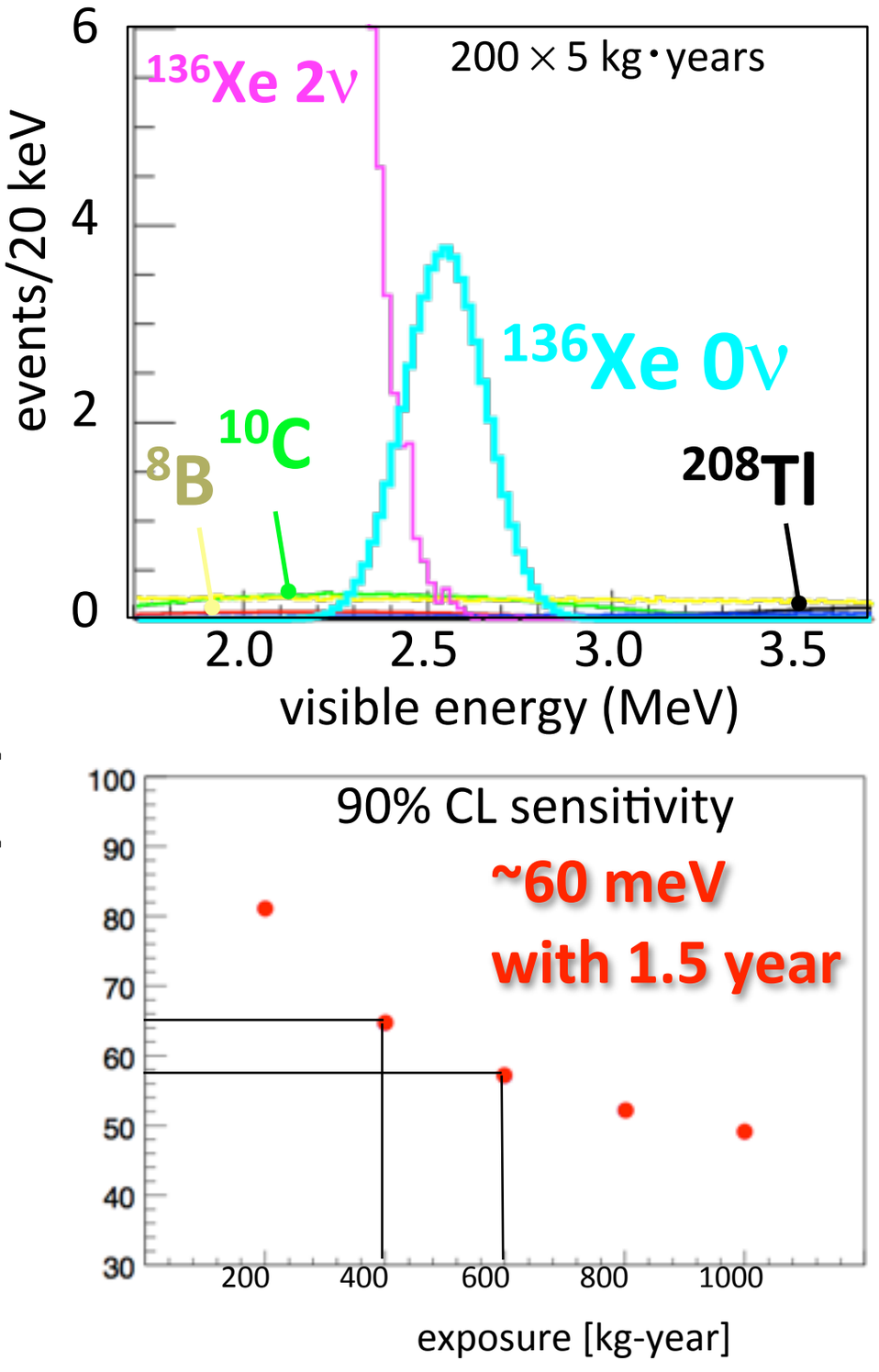


x KamLAND=1000t

XeN



$\langle m_\nu \rangle$=0.15 eV (min KKDC)
($T_{1/2}$ (0ν) =9.8×10^{25} y)

($T_{1/2}$ (2ν) =1.0×10^{22} y)

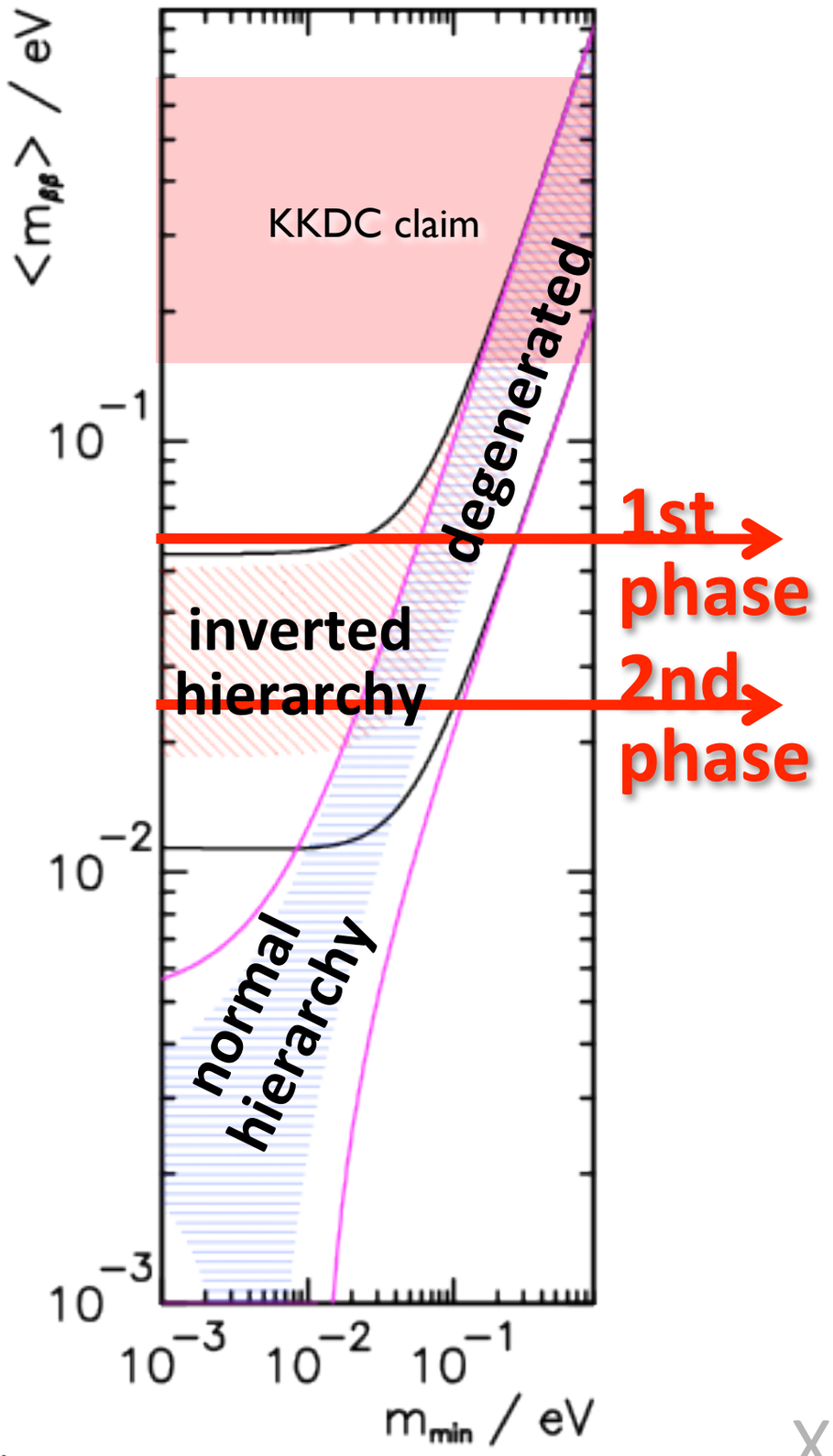
$t_{balloon}$=25 μm,
$R_{balloon}$=1.35 m

^{232}Th,^{238}U = 10^{-13} g/g

^{10}C 95% tag

1st phase:
2011~12

2nd phase:
2013 <



2nd phase ⟶ inverted hierarchy

Target sensitivity of the 2nd phase is ~25 meV with 5 years.

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Leptogenesis

- Neutrinos have mass (1998-2002)
- Neutrinos may be their own anti-particles
- They can transform matter to anti-matter and vice versa
- Maybe they are responsible for our existence! (Fukugita, Yanagida)

X

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Shoot the beams over thousands of kilometers to see CP violation in neutrinos



X

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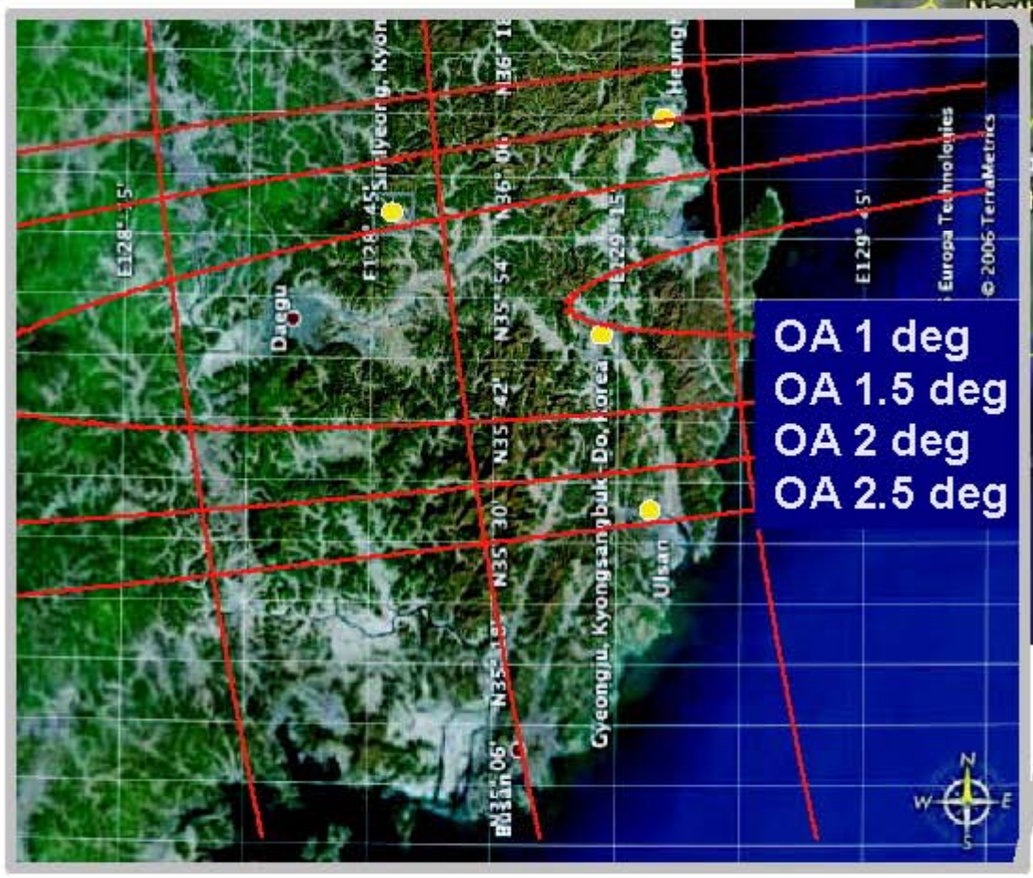
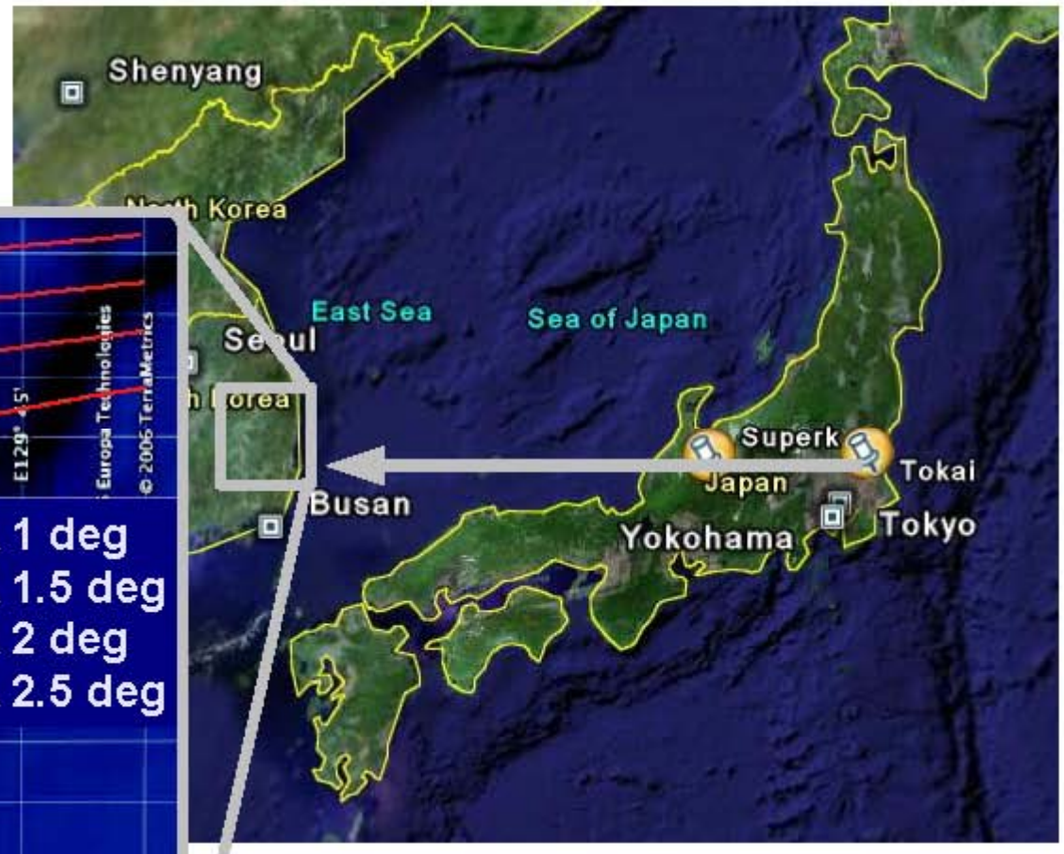
T2KK (T2K to Korea)

Detecting neutrinos from T2K in Korea → T2KK





Studied OA from 1.0º to 2.5º in Korea
(Kamioka fixed at 2.5º)

09/16/06 Fanny Dufour, Boston University 6/32

see

os



x

2011年6月8日星期三

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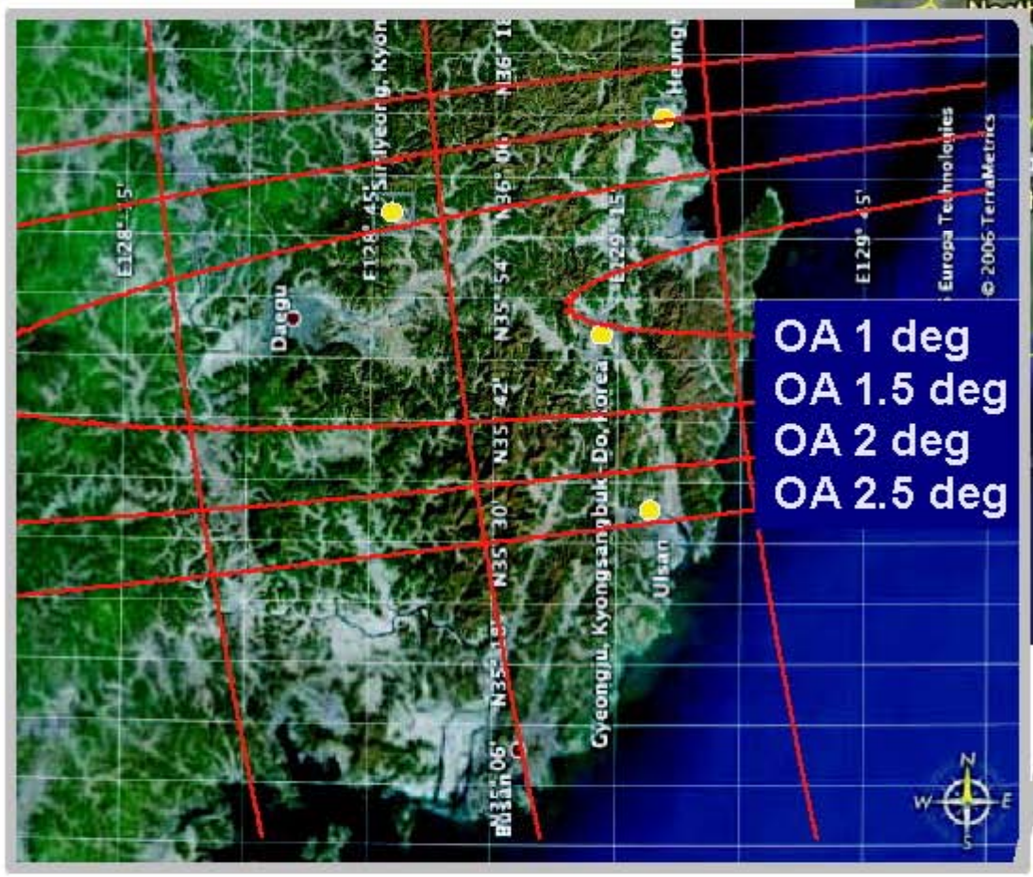

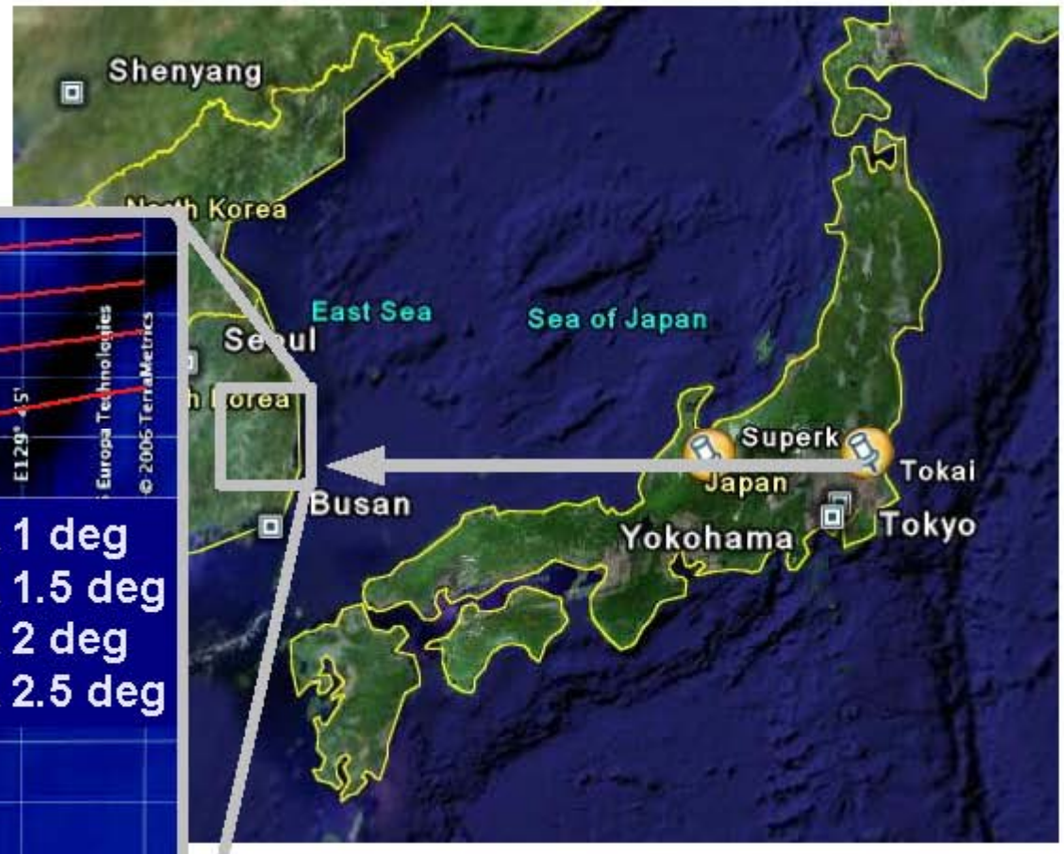

Studied OA from 1.0º to 2.5º in Korea
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09/16/06 Fanny Dufour, Boston University 6/32

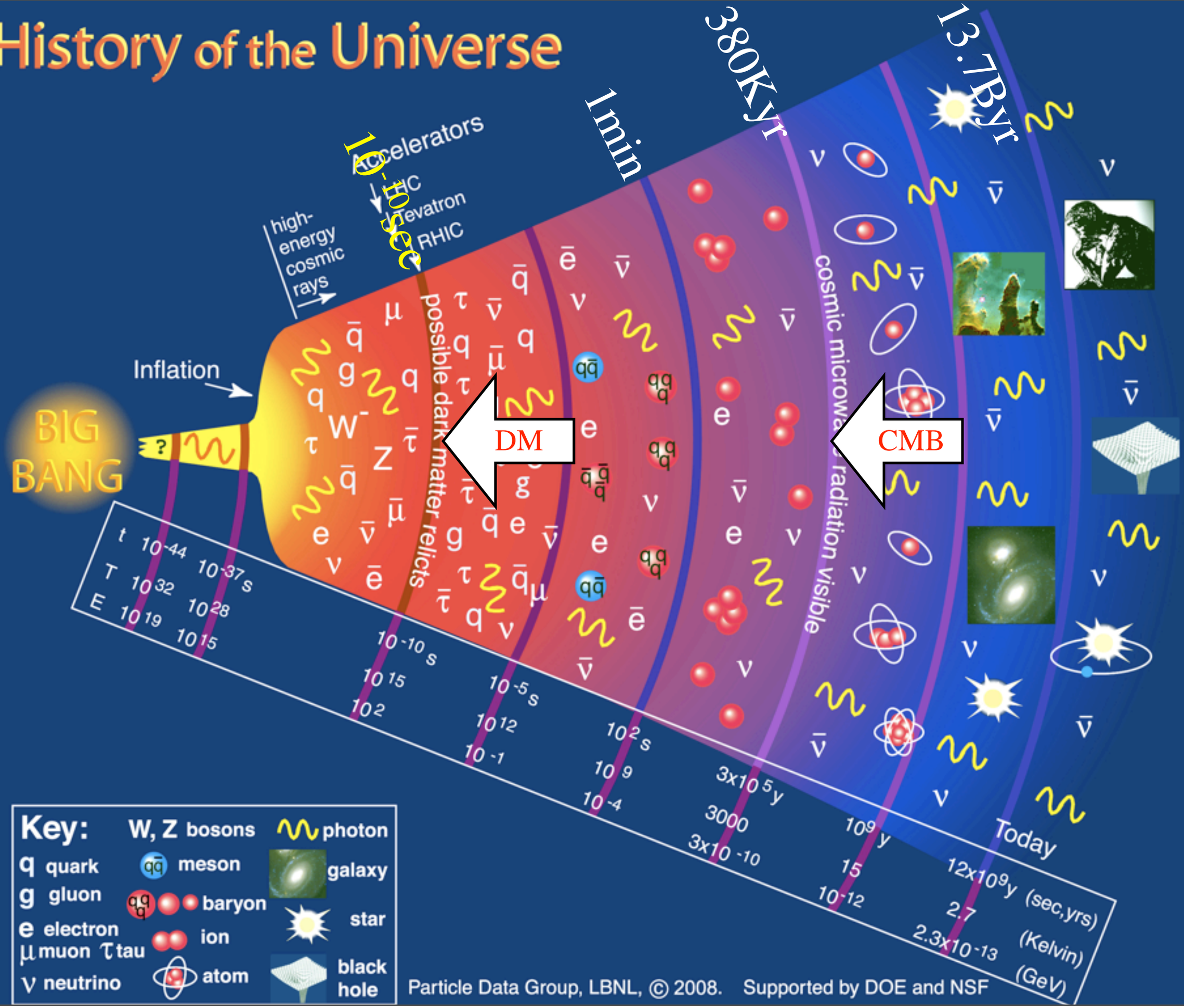
o see
os



First beam last night!

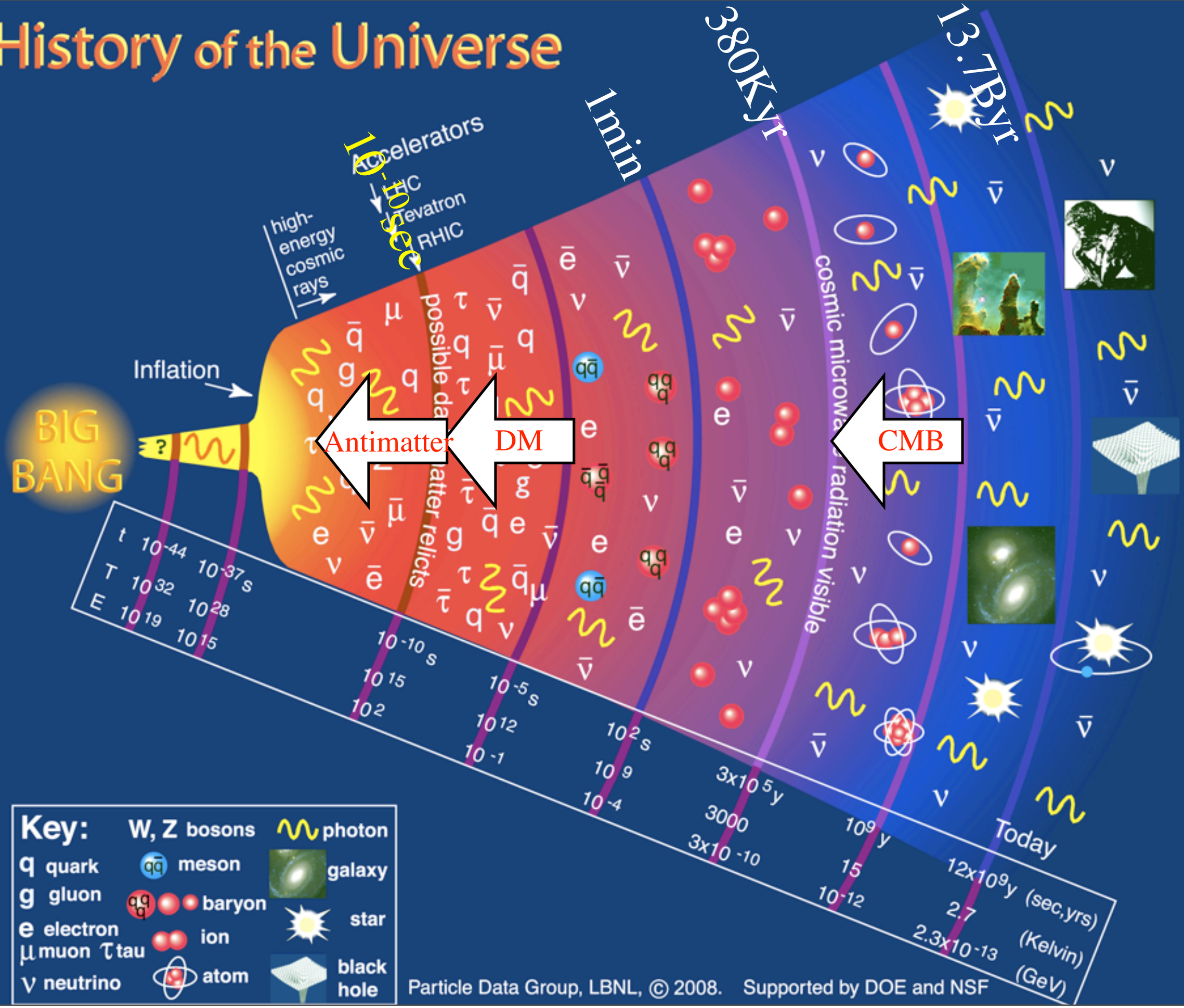
2011年6月8日星期三

History of the Universe



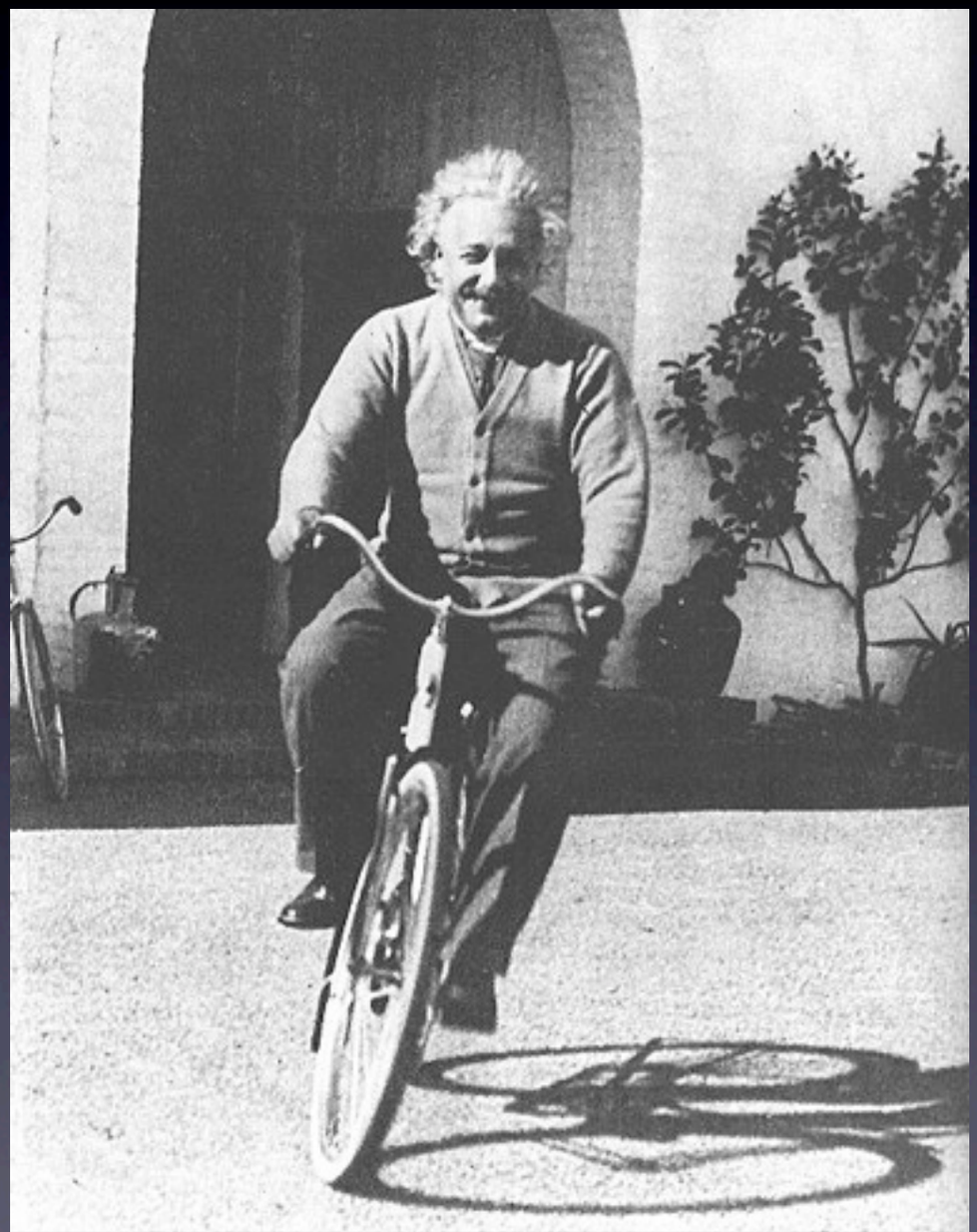
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

History of the Universe



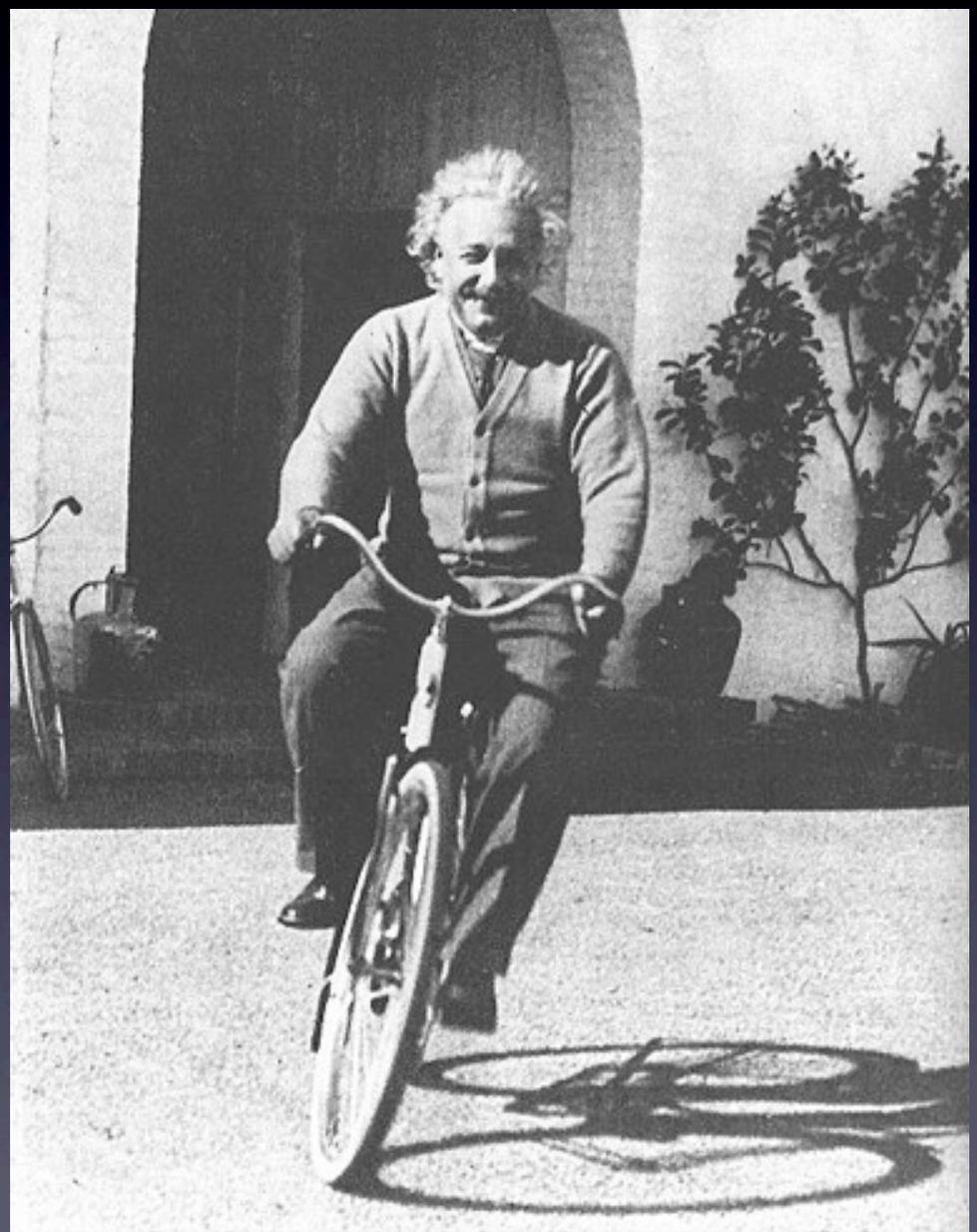
Quantum Field

Einstein's Dream



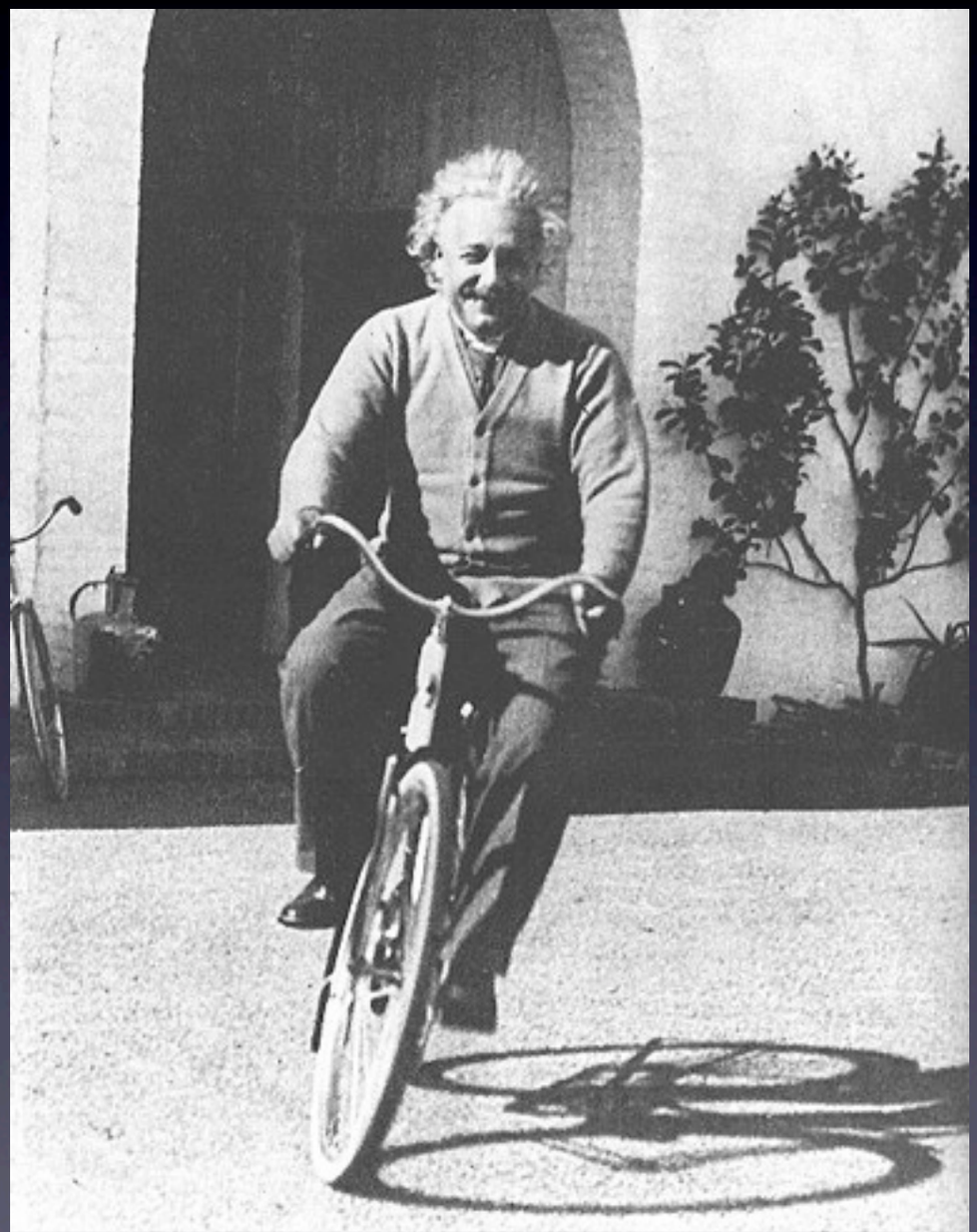
Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?



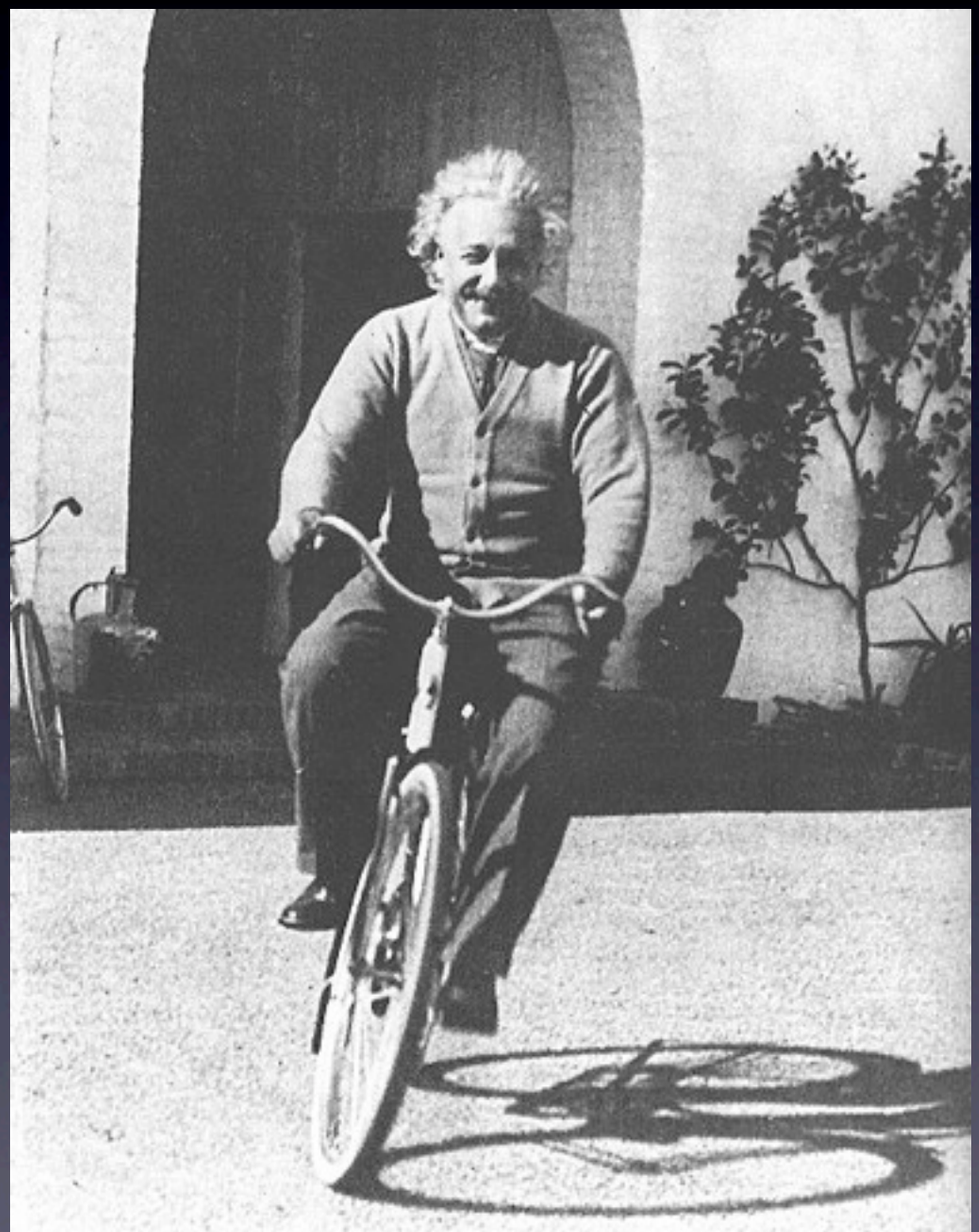
Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description



Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description
- But he failed to unify electromagnetism and gravity (GR)

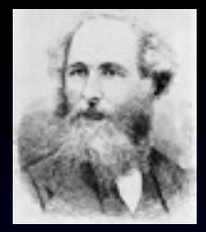


History of Unification



planets *apple*

gravity *mechanics*



electric *magnetic*

electromagnetism

atoms

Quantum mechanics

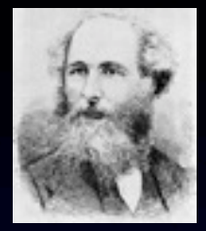
γ-*decay*

β-*decay*

α-*decay*

History of Unification





electric *magnetic*

atoms

planets *apple*

electromagnetism

Quantum mechanics

gravity *mechanics*



Special relativity

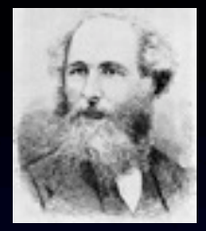
γ-*decay*

β-*decay*

α-*decay*

History of Unification





electric *magnetic*

atoms

planets *apple*

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Quantum mechanics

gravity *mechanics*



Special relativity

γ-decay

GR

β-decay

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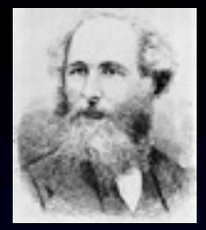
History of Unification







planets *apple* *gravity* *mechanics* *GR*

electric *magnetic* *electromagnetism*

Special relativity

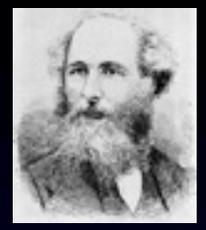
atoms *Quantum mechanics*

Quantum ElectroDynamics

γ-decay *β-decay* *α-decay*

History of Unification









planets apple

gravity mechanics

GR

electric magnetic

electromagnetism

Special relativity

Quantum ElectroDynamics

atoms

Quantum mechanics

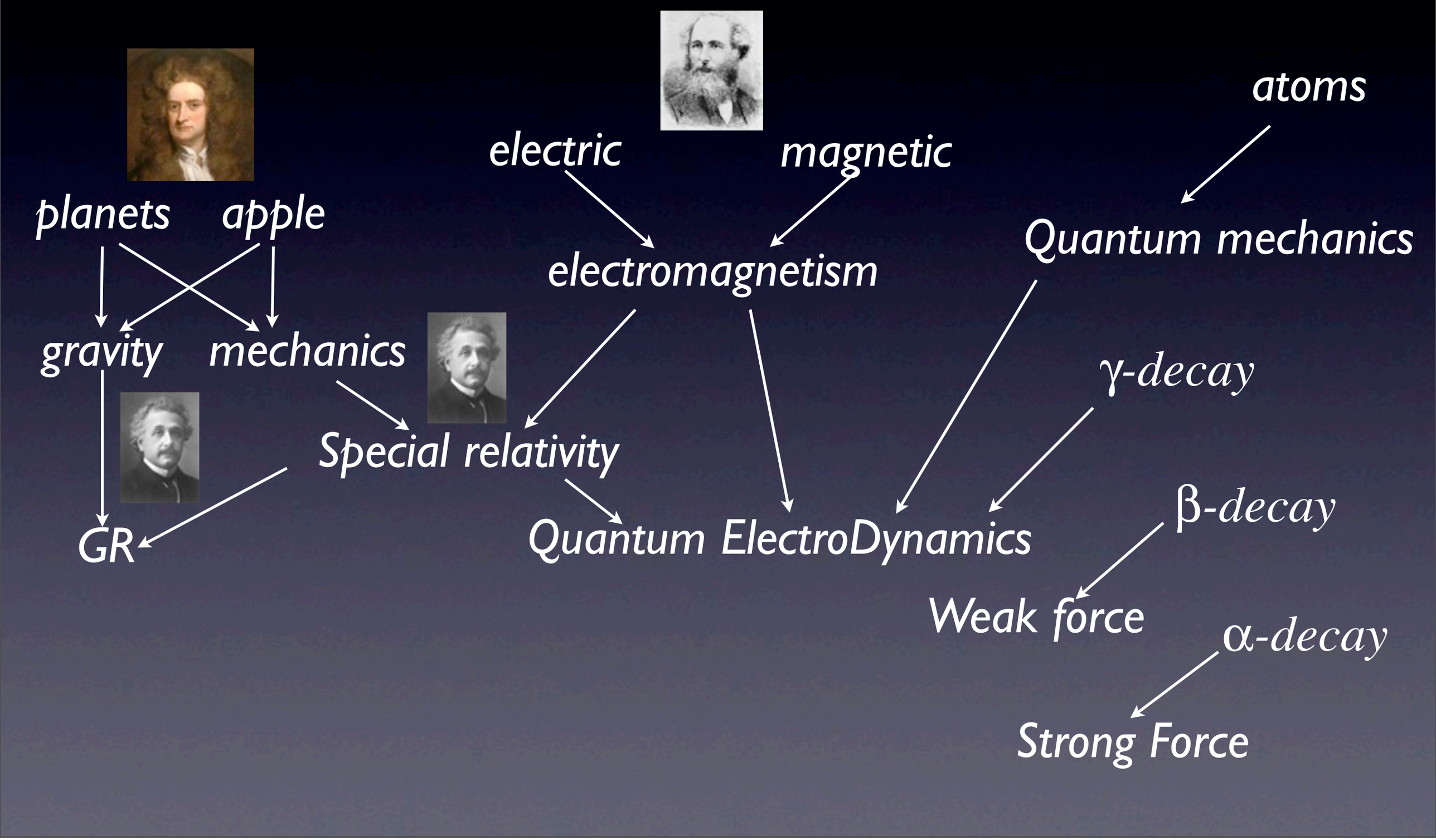
γ-decay

β-decay

Weak force

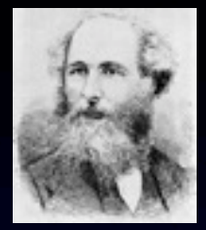
α-decay

History of Unification



History of Unification







planets apple gravity mechanics GR

electric magnetic electromagnetism

Special relativity

Quantum ElectroDynamics

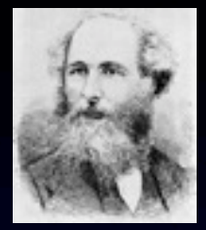
Electroweak theory

atoms Quantum mechanics

γ-decay β-decay Weak force α-decay Strong Force

History of Unification







planets *apple* *electric* *magnetic* *atoms*

gravity *mechanics* *electromagnetism* *Quantum mechanics*

Special relativity *γ-decay*

GR *Quantum ElectroDynamics* *β-decay*

Weak force

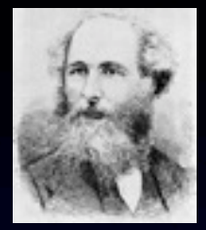
Electroweak theory *α-decay*

Strong Force

Grand Unification?

History of Unification







planets apple gravity mechanics

electric magnetic electromagnetism

atoms Quantum mechanics

γ-decay

Special relativity

GR

Quantum ElectroDynamics

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Weak force

Electroweak theory

α-decay

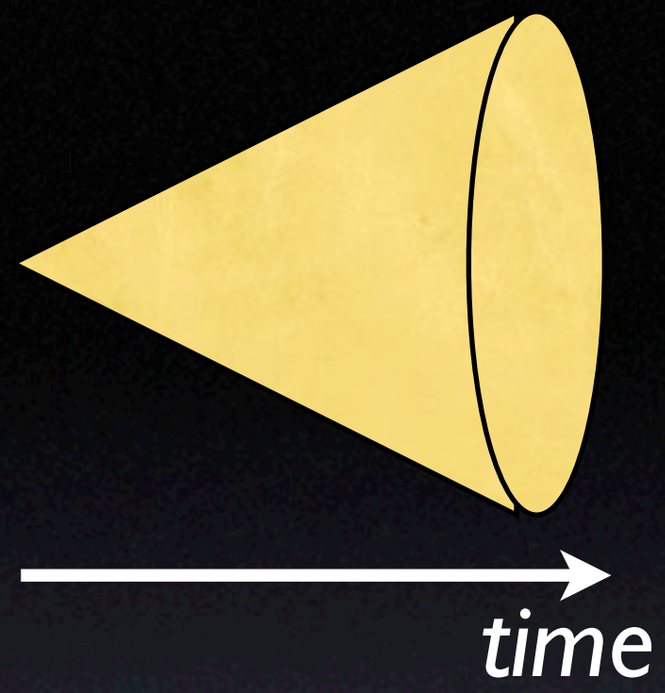
Strong Force

String theory? Grand Unification?

Big Bang

X

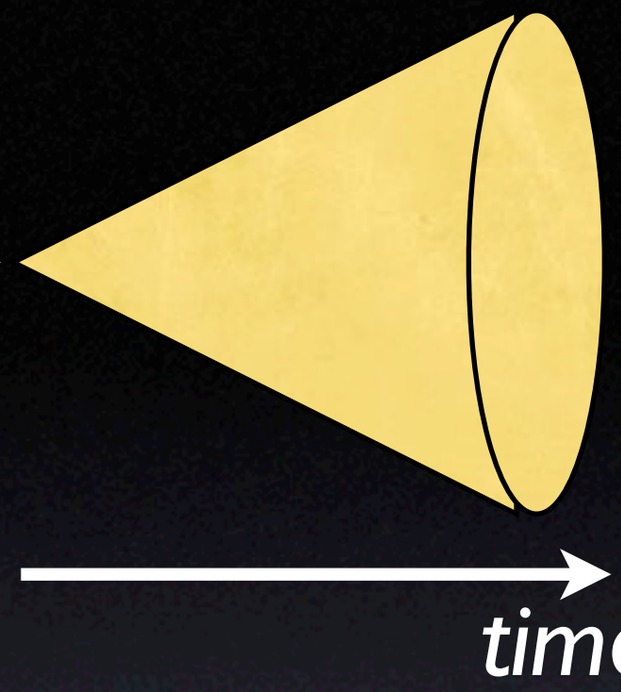
Big Bang



x

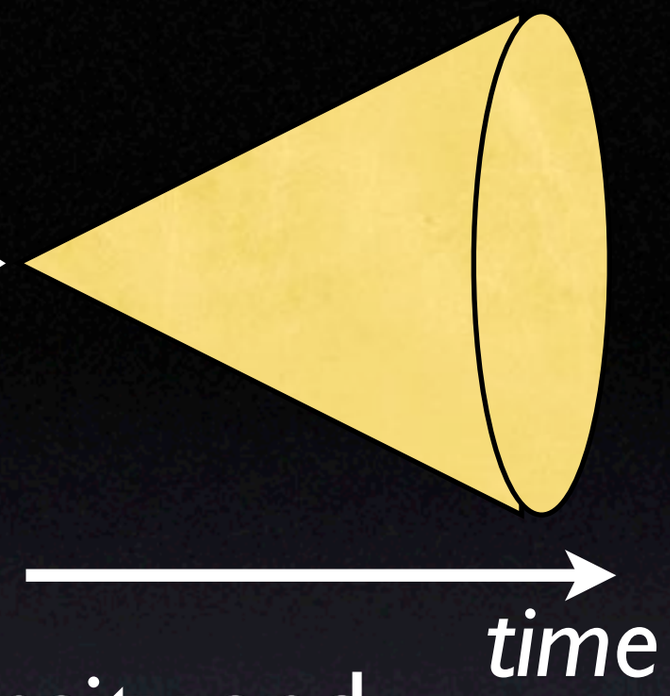
IPMU

Big Bang



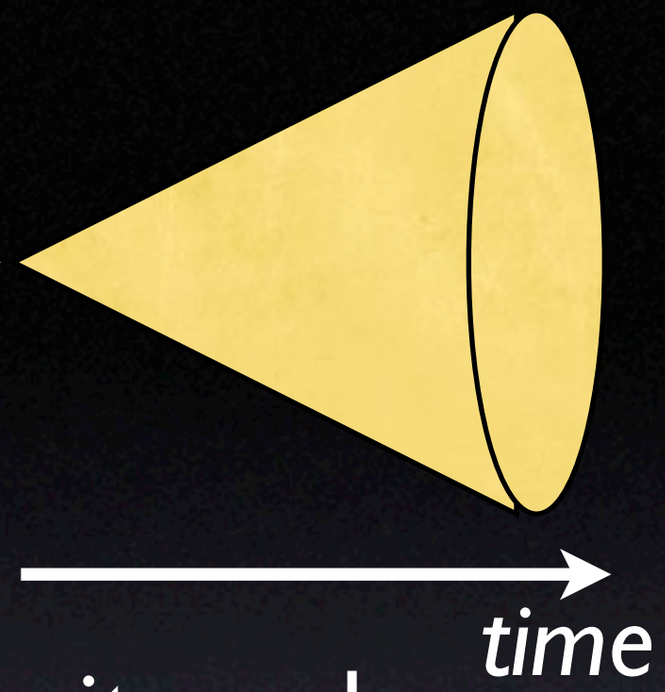
X

Big Bang



- Universe with infinite energy density and curvature: space-like singularity

Big Bang

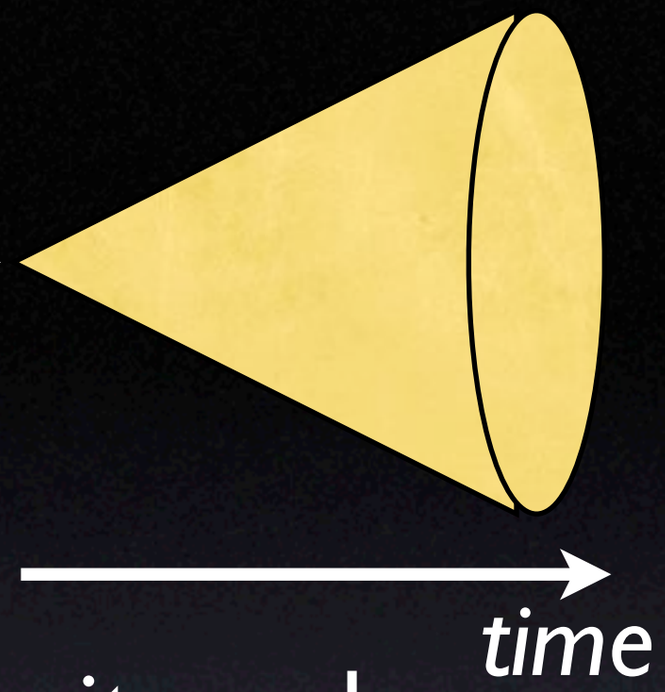


- Universe with infinite energy density and curvature: space-like singularity

- *All known laws of physics break down*

x

Big Bang



- Universe with infinite energy density and curvature: space-like singularity

- *All known laws of physics break down*

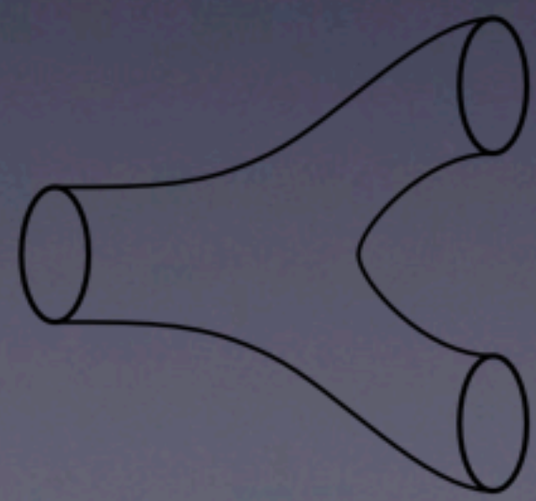
- need theory that brings quantum theory and gravity together ⇒ string theory

String theory

- replace point particles by strings (open & closed)
- Map($\Sigma \to M$)
- "sum" over all maps
- D-branes on which strings can end

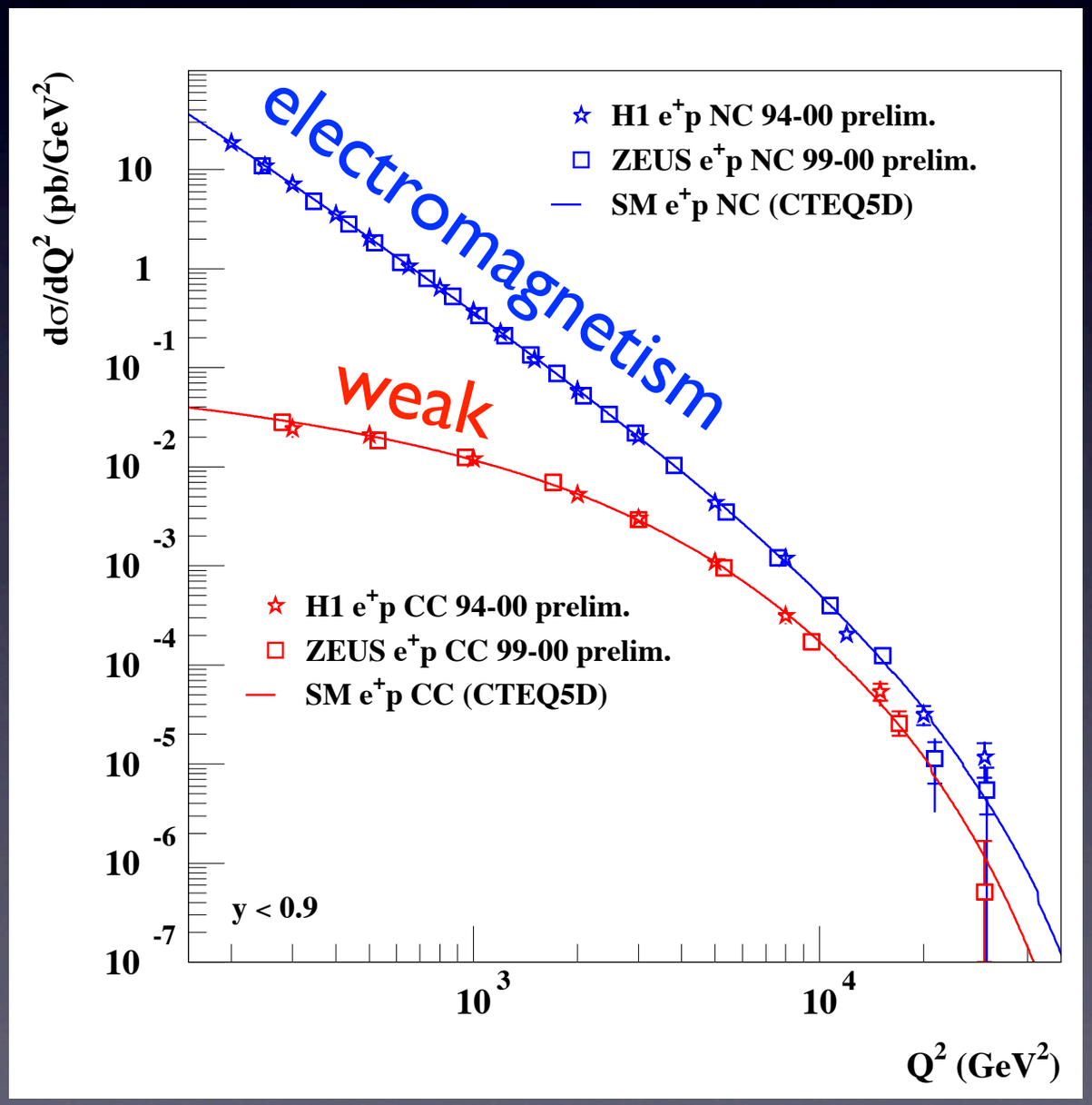


- strong synergy with mathematics
  - Calabi-Yau manifolds, mirror symmetry
  - D-branes, derived categories
  - infinite-dimensional Lie algebras
  - integrable systems



We are just about to achieve another layer of unification

HERA ep collider



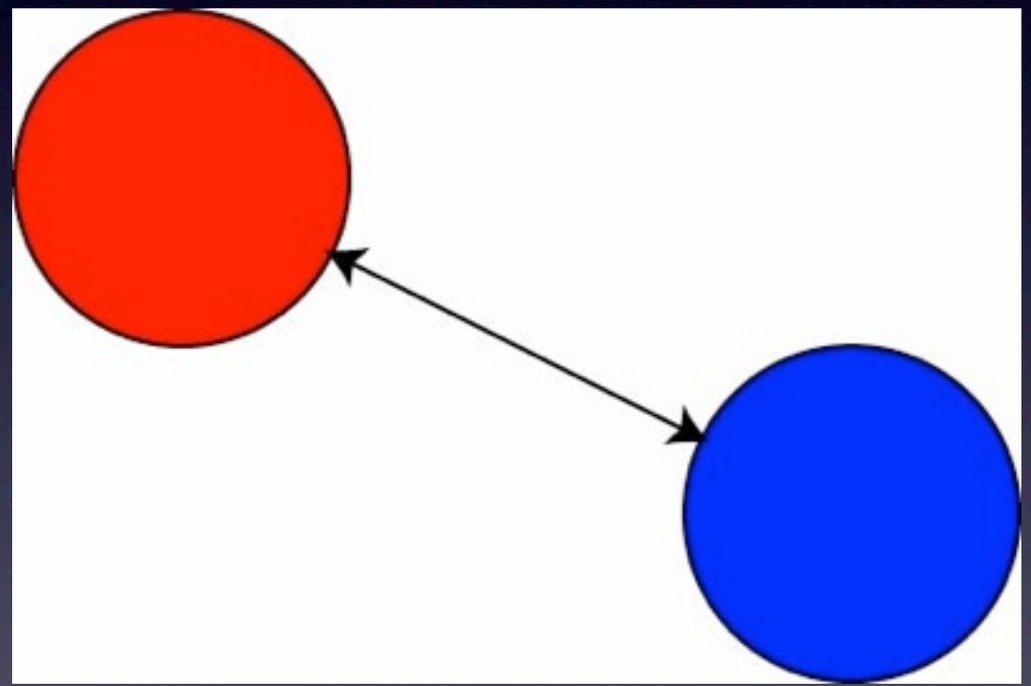
- Unification of electromagnetic and weak forces

⇒ standard model

- Long-term goal since ‘60s
- We are getting there!
- The missing link: the Dark Field = Higgs

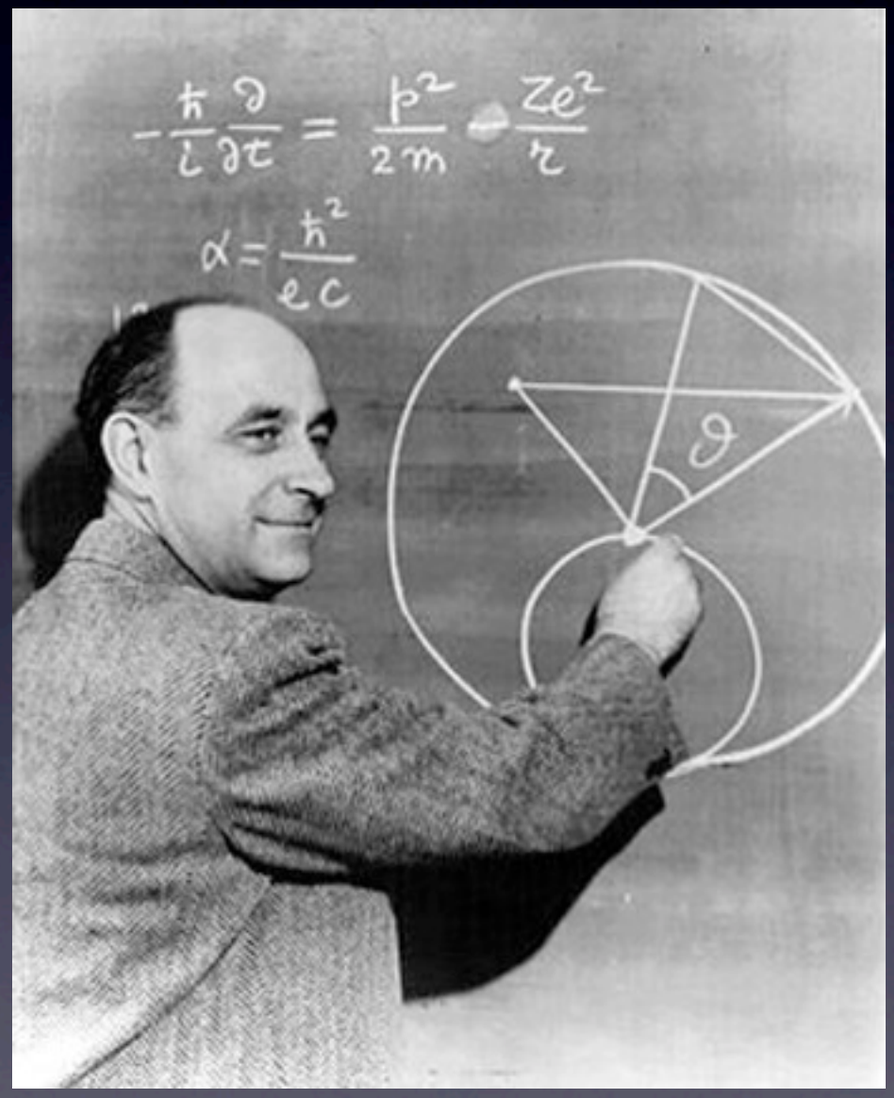
Mystery of the weak force

- Gravity pulls two massive bodies (long-ranged)
- Electric force repels two like charges (long-ranged)
- Weak force pulls protons and electrons (short-ranged) acts only over 0.000000001 nanometer
- We know the energy scale: ~0.3 TeV



Fermi's dream era

- Fermi formulated the first theory of the weak force (1932)

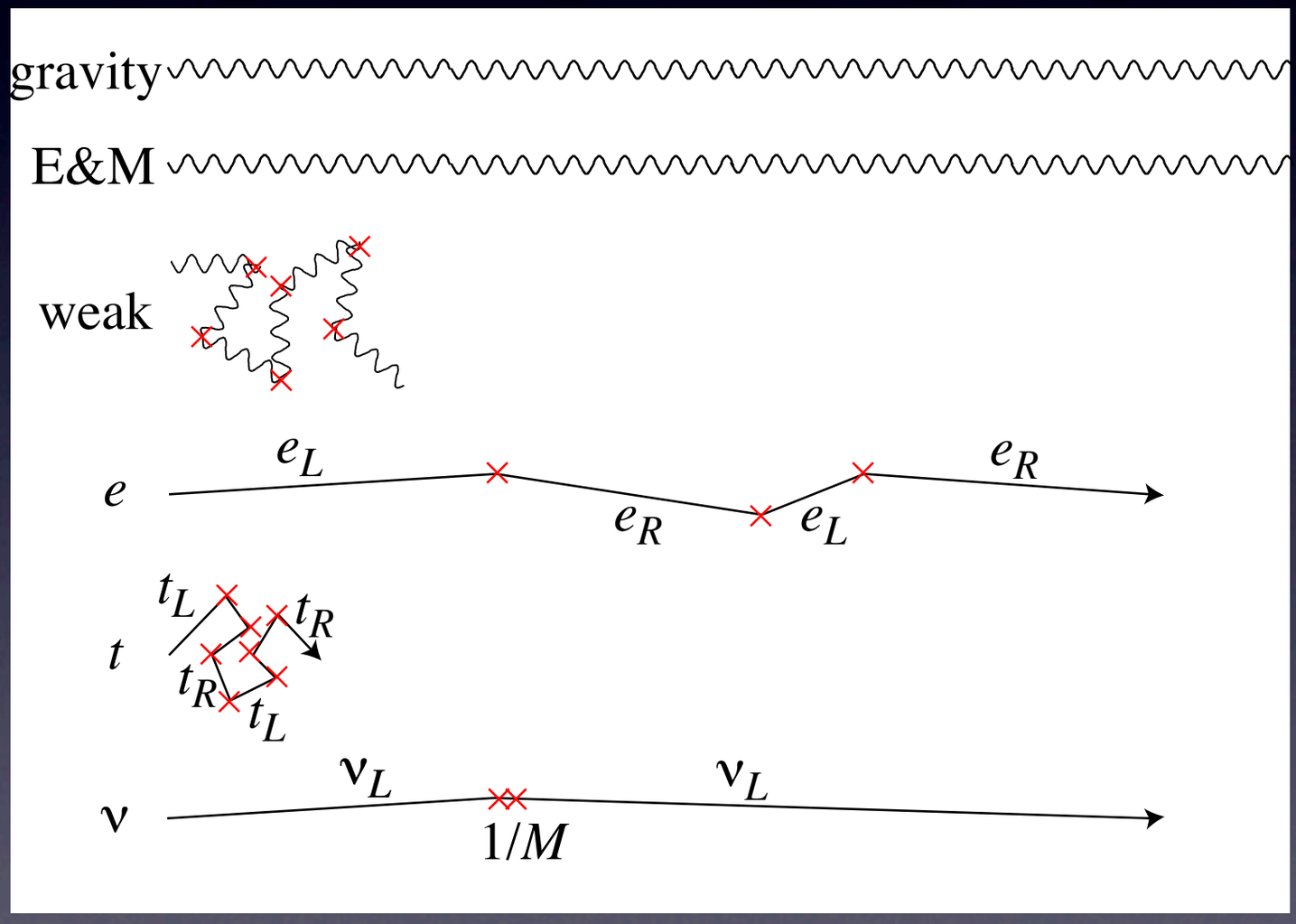


- *The required energy scale to study the problem known since then: ~TeV*

- We are finally getting there!

We are swimming in Dark Field

- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- otherwise no atoms!
- What is it??



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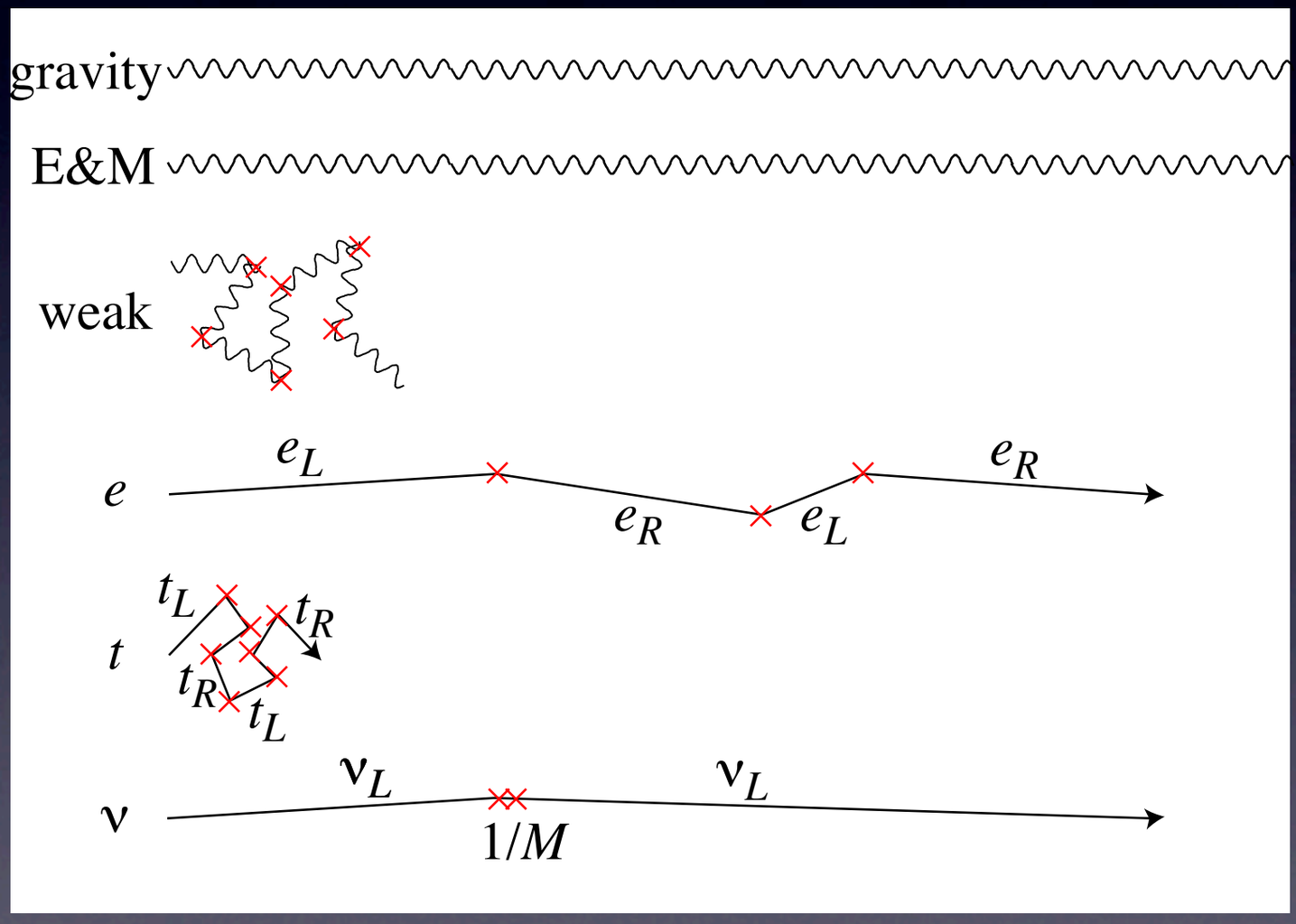


Cosmic Superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"

  ⇒ Magnetic field is short-ranged!



- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her "Universe"
  - But doesn't know what the condensate is, nor why it condenses
  - Doesn't have enough energy (gap) to break up Cooper pairs

That's the stage where we are!

testing unification



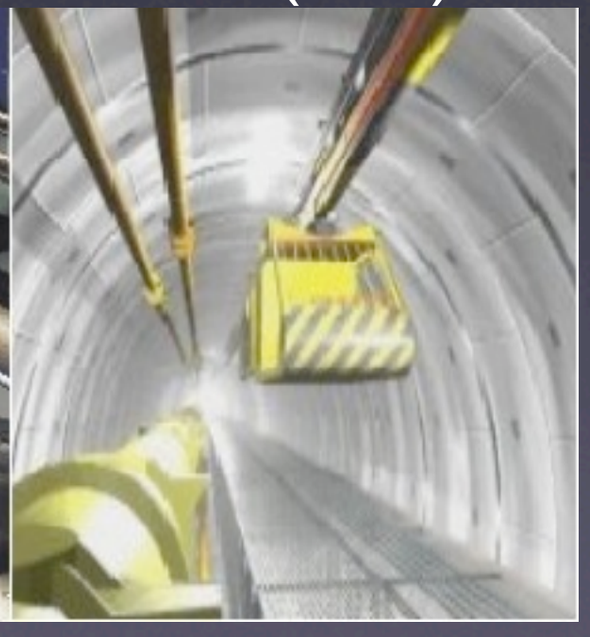
Tevatron

Large Hadron Collider (LHC)

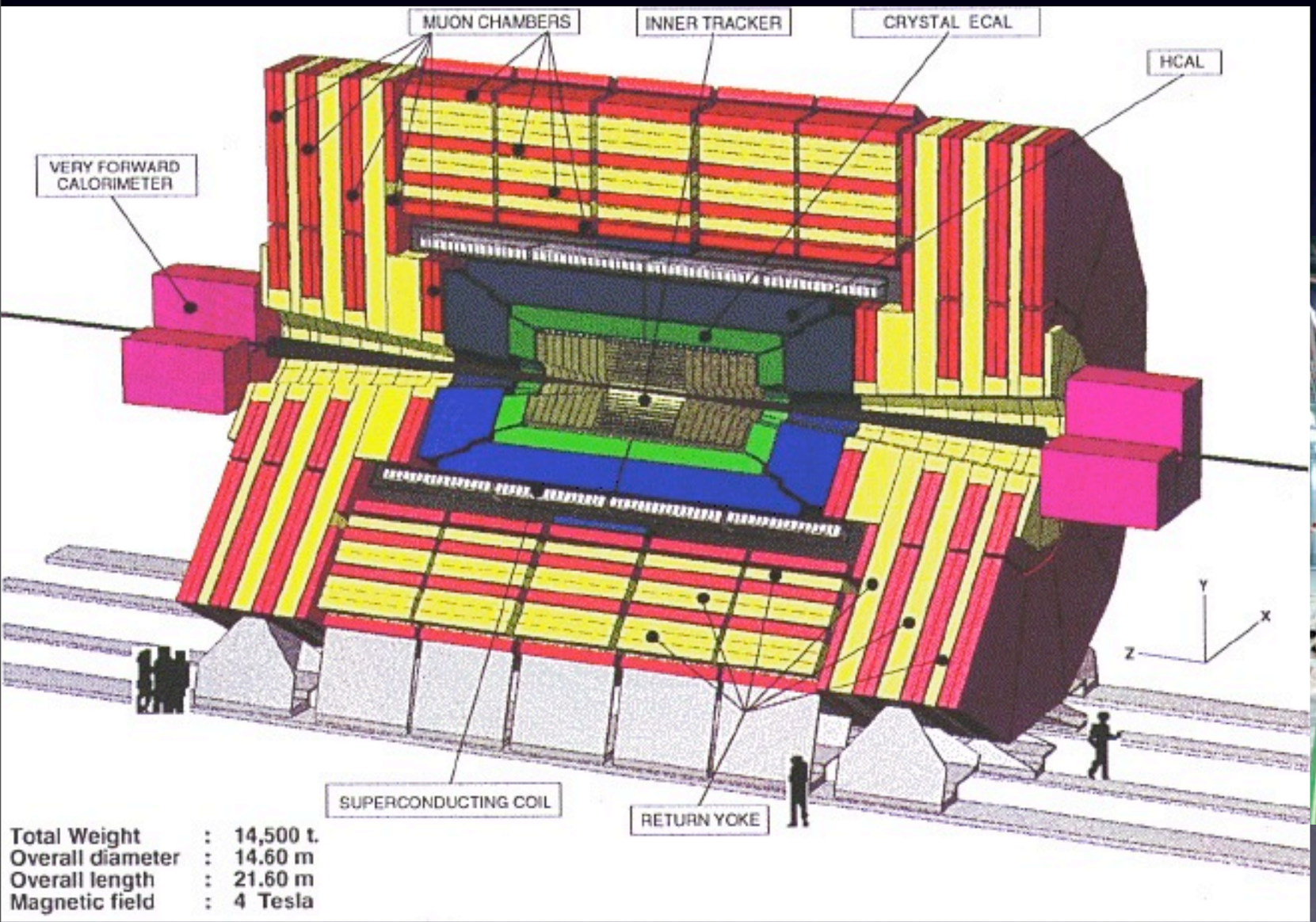


International Linear Collider (ILC)



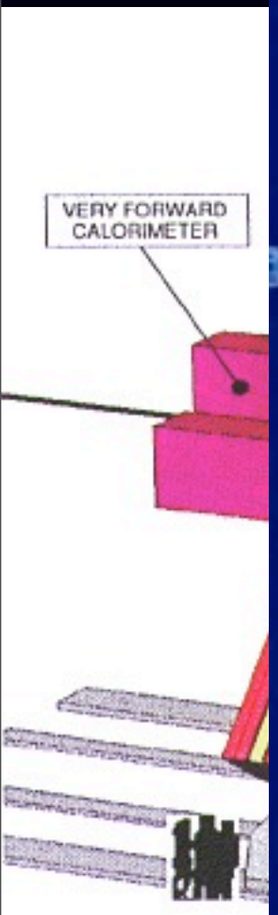


Higgs at CMS


MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Y
X
Z
Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla



IPM


VERY FORWARD
CALORIMETER
Total Weight :
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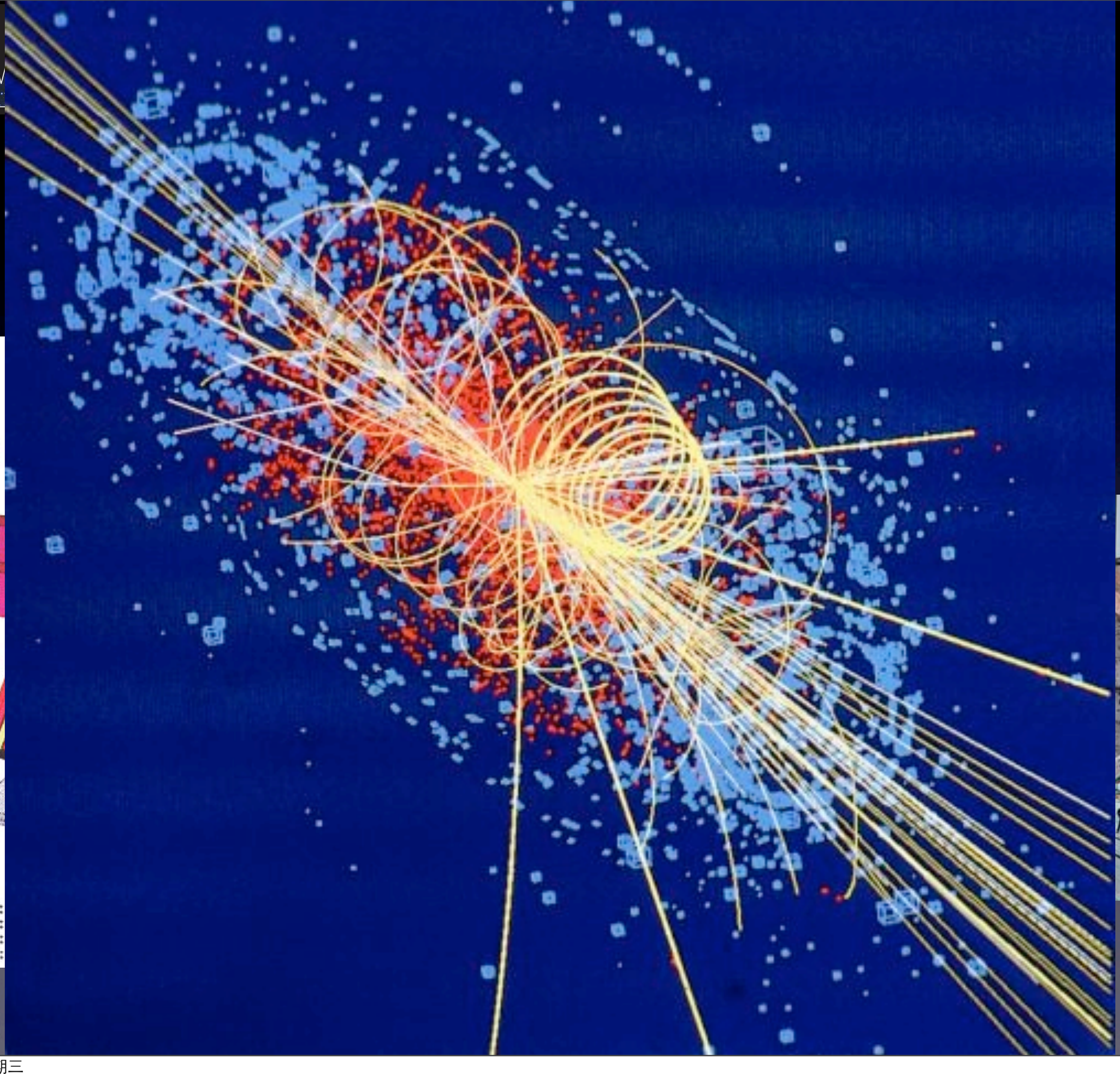
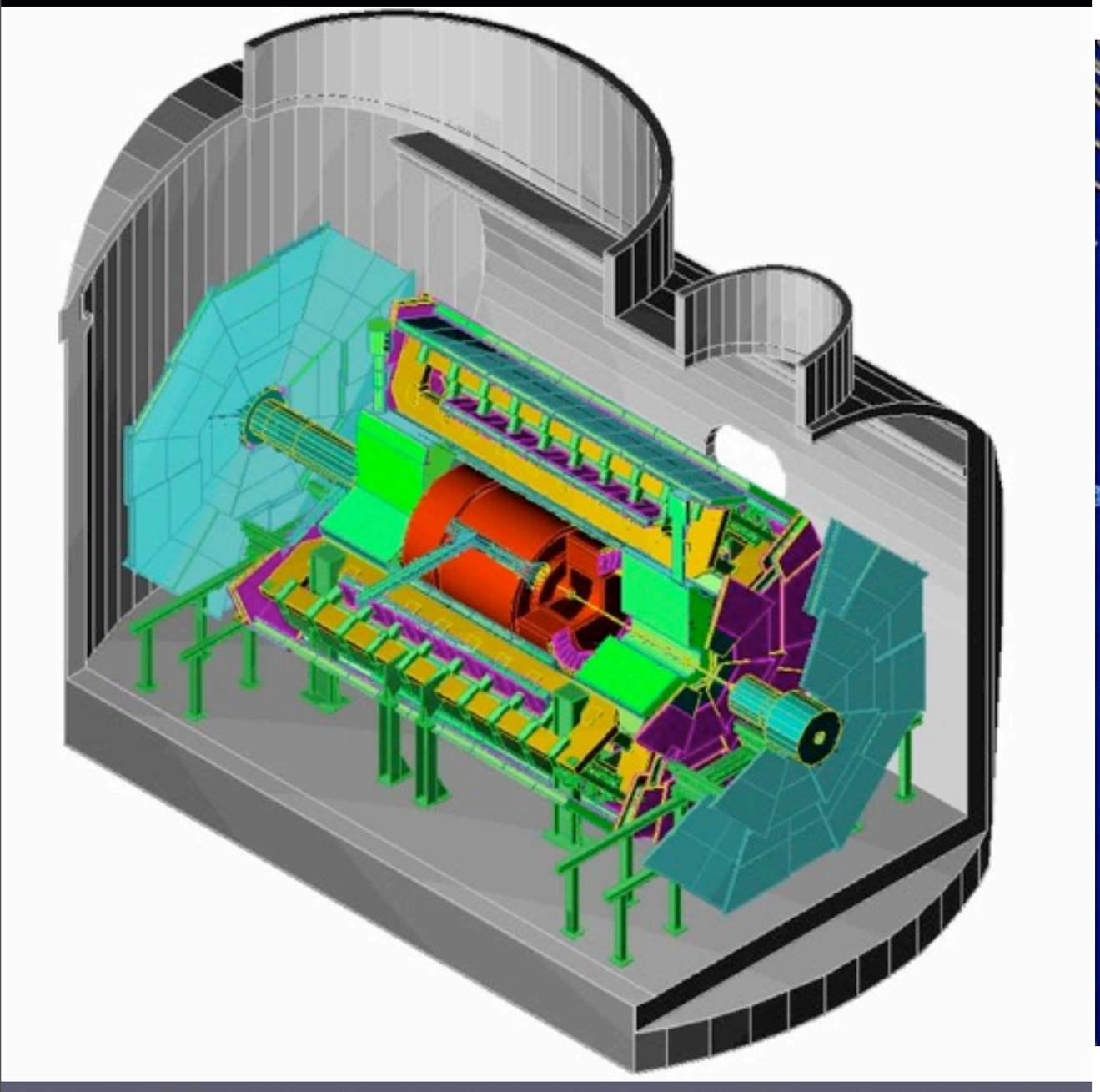
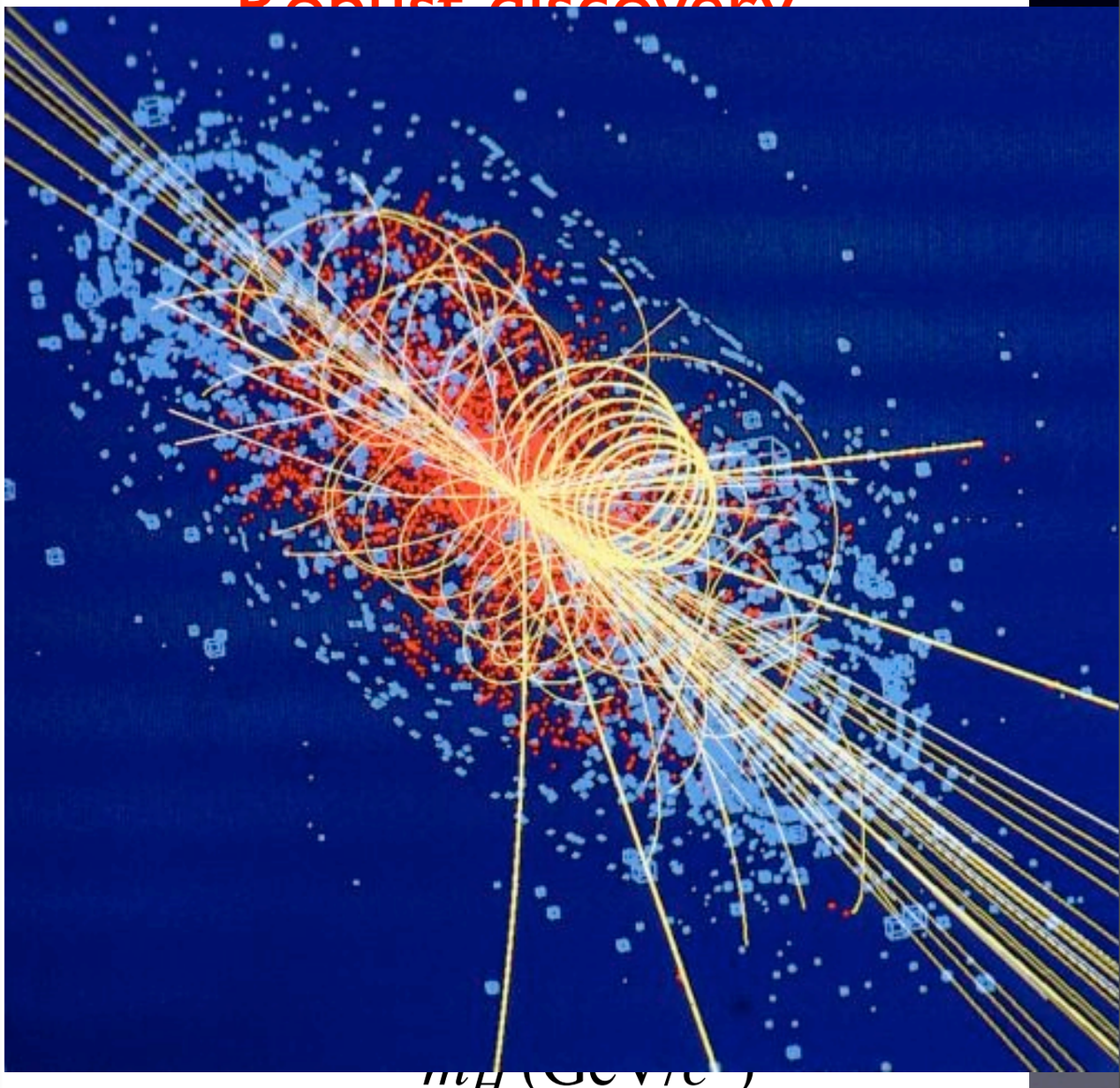




Higgs at ATLAS



Robust discovery



m_H (GeV/c^2)

Post-Higgs Problem

- We see "what" is condensed
- But we still don't know "why"
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation ~TeV<<M_{Pl}=10^{15}TeV
- Explanation most likely to be at ~TeV scale because this is the relevant energy scale

Three Directions

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History repeats itself

- Crisis with electron solved by anti-matter
- Double #particles again ⇒ supersymmetry

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Learn from Cooper pairs

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- Higgs boson may be fermion-pair composite
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  ⇒ technicolor

Physics as we know it ends at TeV

- Ultimate scale of physics: quantum gravity
- May have quantum gravity at TeV
  ⇒ hidden dimensions (0.1 mm to 10^{-17} cm)

More Directions

- Higgs boson as a Pseudo-Nambu-Goldstone boson (Little Higgs)
- Higgs boson as an extra-dimensional gauge boson (Gauge-Higgs Unification)
- Fat Higgs (Composite)
- Higgsless and $W^{\pm}$ as Kaluza-Klein boson
- technicolorful supersymmetry

techni-color

topcolor

Randall Sundrum II

EXTRA DIMENSION

SUSY

Scherk - schwarz

mSUGRA

composite

anomaly med

+ SUGRA

+ non-decoupling

Randall-Sundrum I

large extra dim

$\delta=2$

$\delta=3$

$\delta=4$

$\delta=5$

$\delta=6$

$\delta=7$ M theory

+ R_p

G

U

T

gauge med

gaugino med

Z'_{LR}

Z'_ψ

Z'_{SM}

Z'_χ

Z'_η

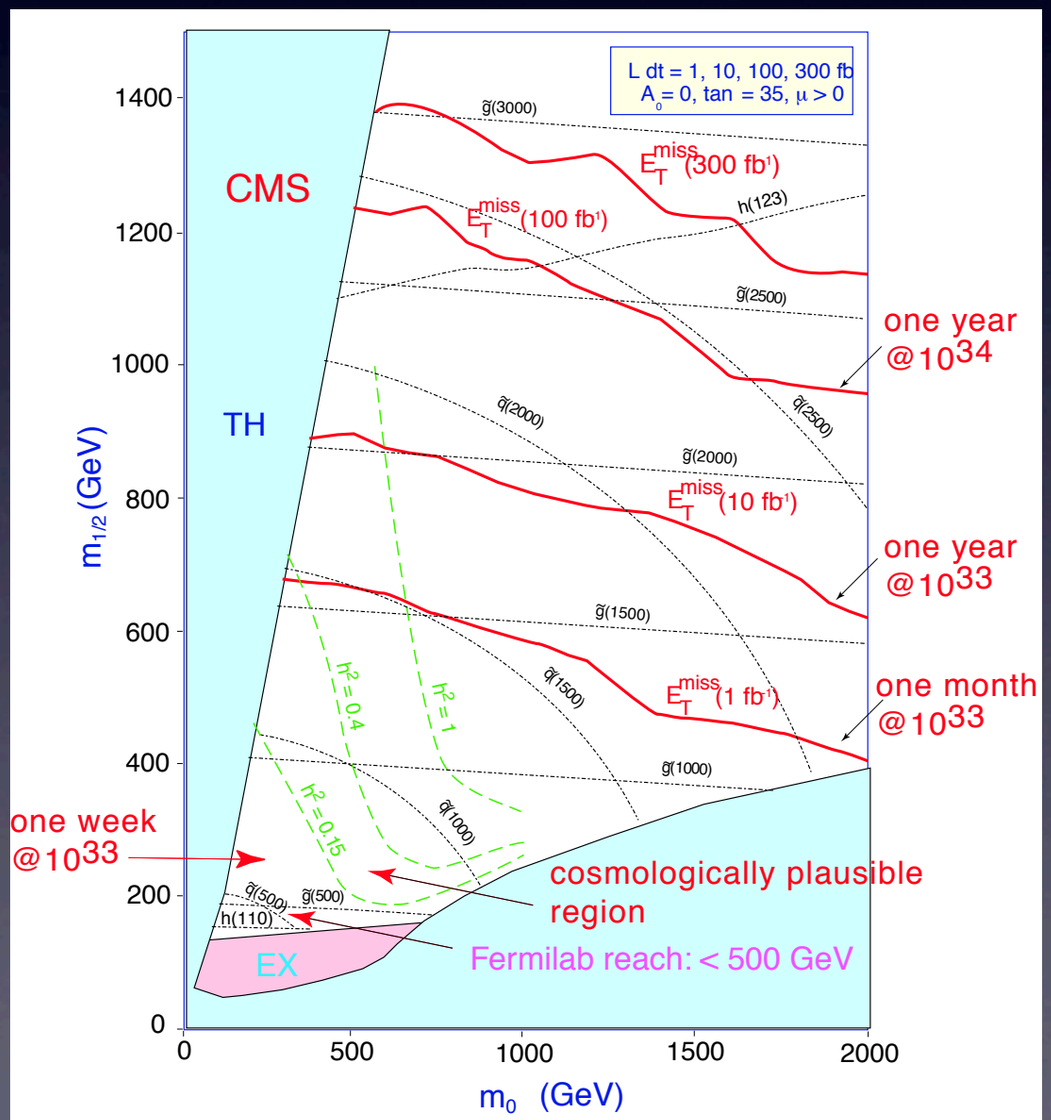
qk



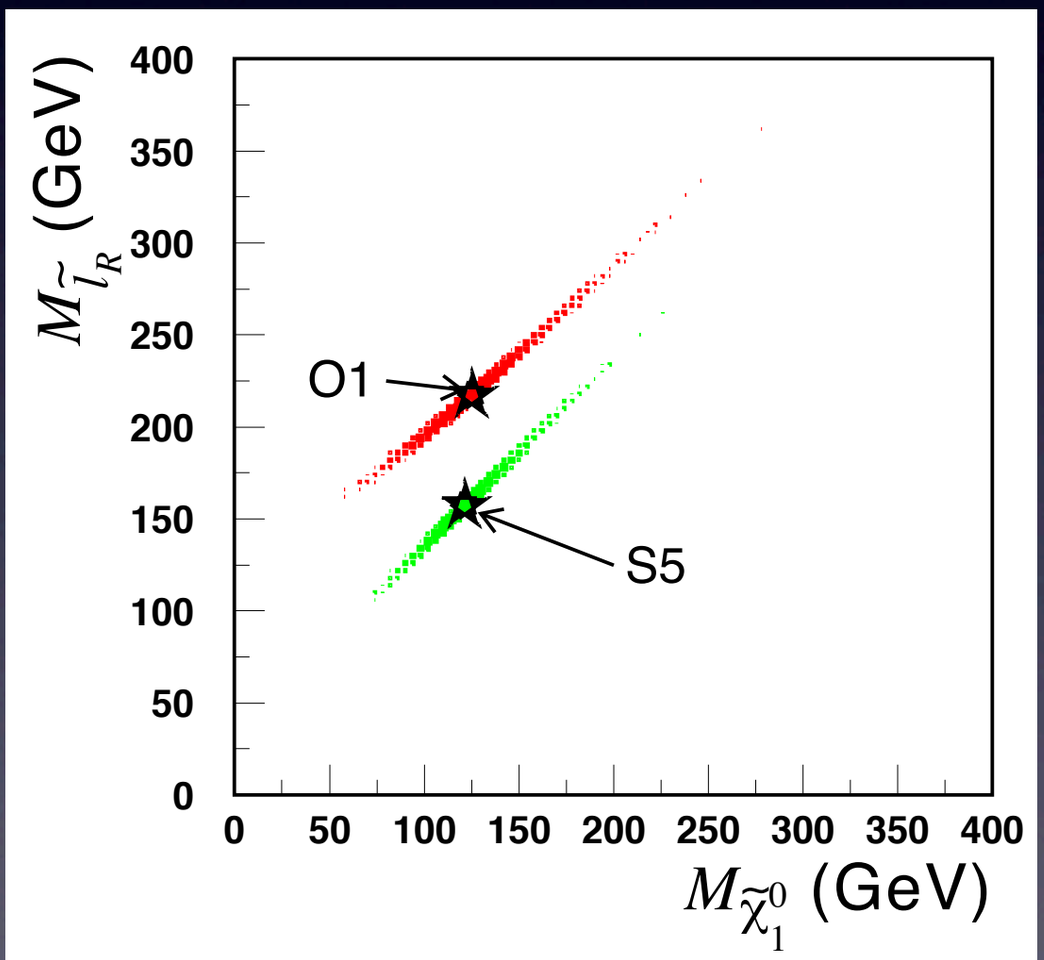
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
bosonic TC
TC-TC
composite Higgs
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
6th gen
5th gen
4th gen
S,T,U
vector-like family
lepto quark
heavy Majorana ν
sterile ν
fractionally charged
milli-charged
mono-pole
X Y
MSSM +νR
NNMSSM
NMSSM
effective SUSY
SUSY
ununified SM
axigluon
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
Weinberg's 3HD
milli-weak
Majoron
axion
familon
NGB
saxion
axino
quintessence
k-ssence
composite W,Z
contact int.
string
heterotic
matrix M
IIB
IIA
F
I
N=2
N=4
N=8
Extra dim
worm-hole

Supersymmetry

Tevatron/LHC will discover supersymmetry

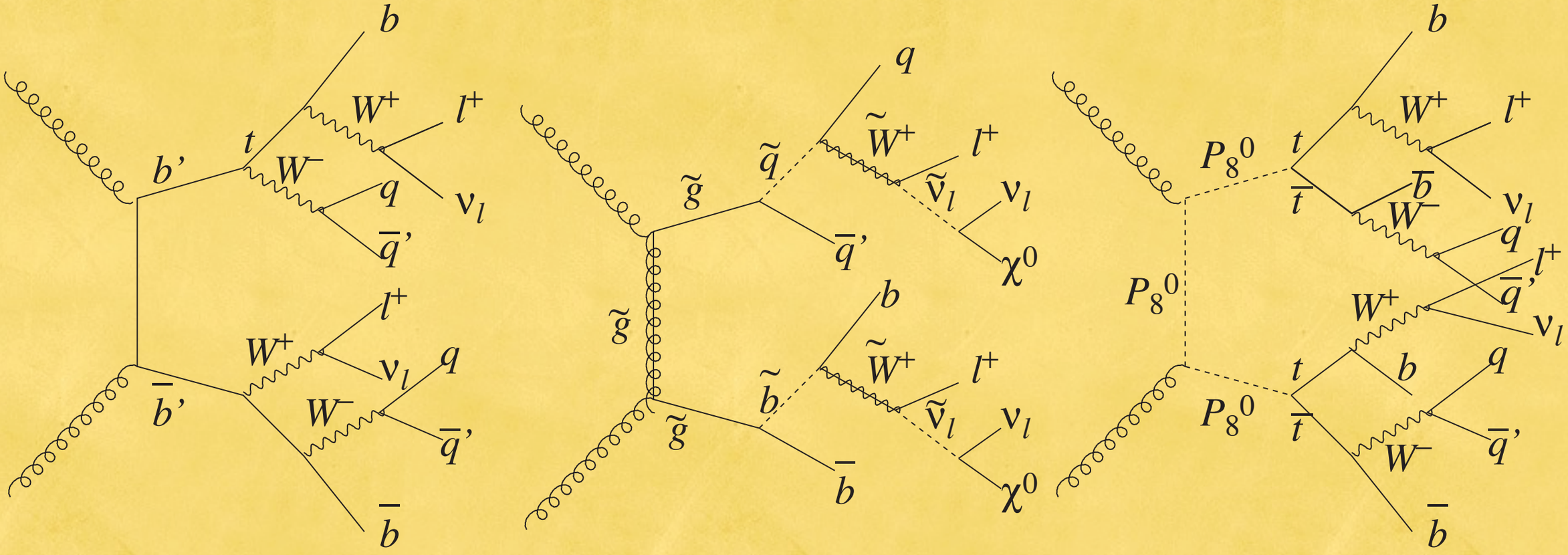


Can do many measurements at LHC



New physics looks alike

missing E_T, multiple jets, b-jets, (like-sign) di-leptons



4th generation SUSY technicolor

+Universal extra dimension, little Higgs with T-parity

Need absolute confidence

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As an example, supersymmetry

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"New-York Times level" confidence



The New York Times

July 23, 2008

The Other Half of the World Discovered

Geneva, Switzerland

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"We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

Prove Superpartners

- *Discovery at Tevatron Run II and/or LHC*
- *Test they are really superpartners*
  - *Spins differ by 1/2*
  - *Same SU(3)×SU(2)×U(1) quantum numbers*
  - *Supersymmetric couplings*

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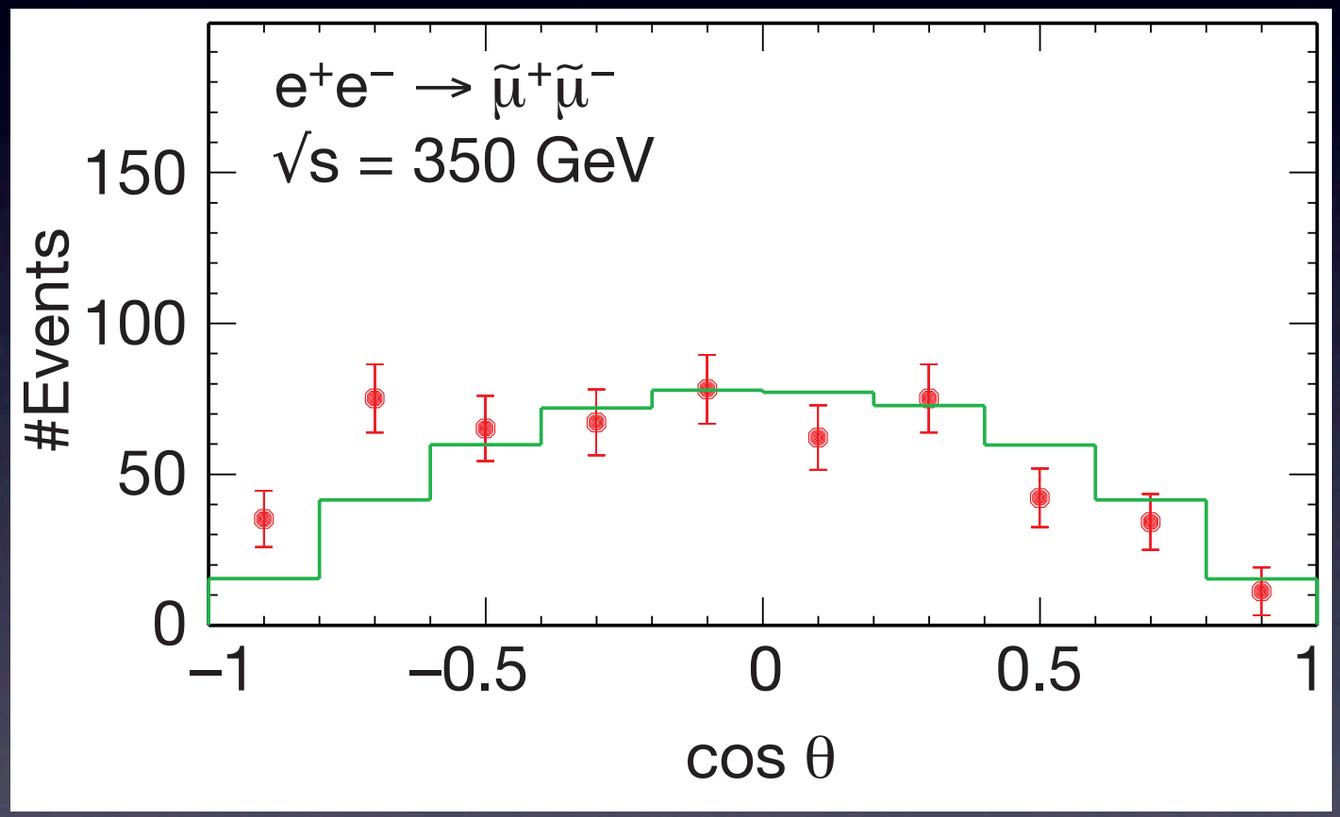


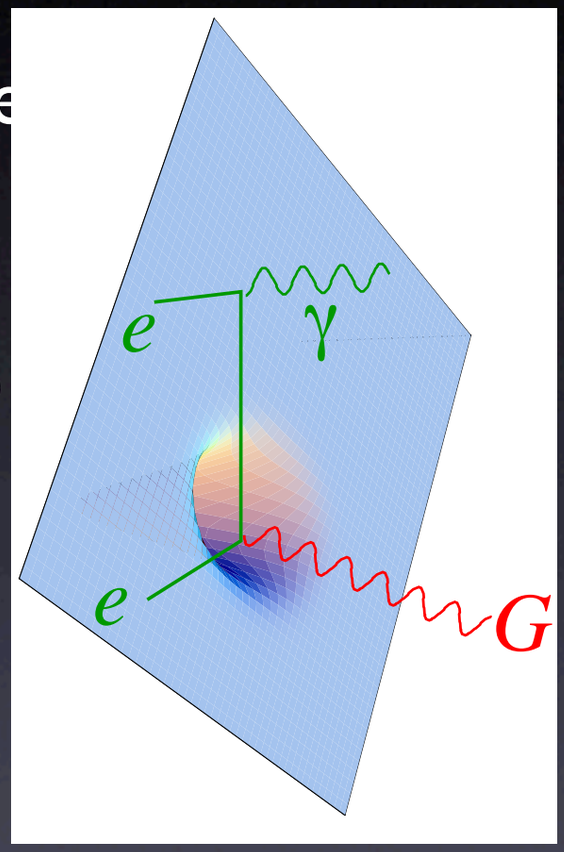
Tsukamoto, Fujii, HM, Yamaguchi, Okada

Extra Dimensions

- Extra dimensions hidde
from us

- Can emit graviton into
the bulk

- Events with apparent
energy imbalance



⇒How many extra dimensions are there? What are their shapes?

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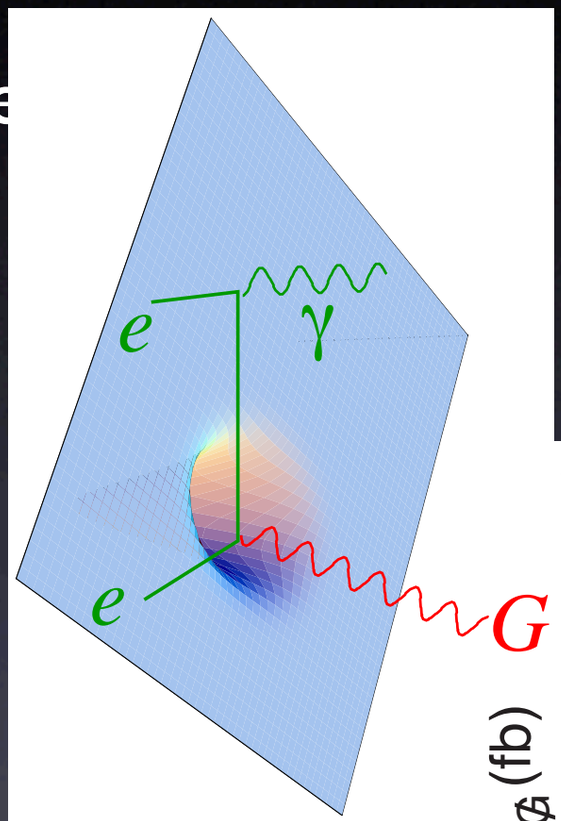

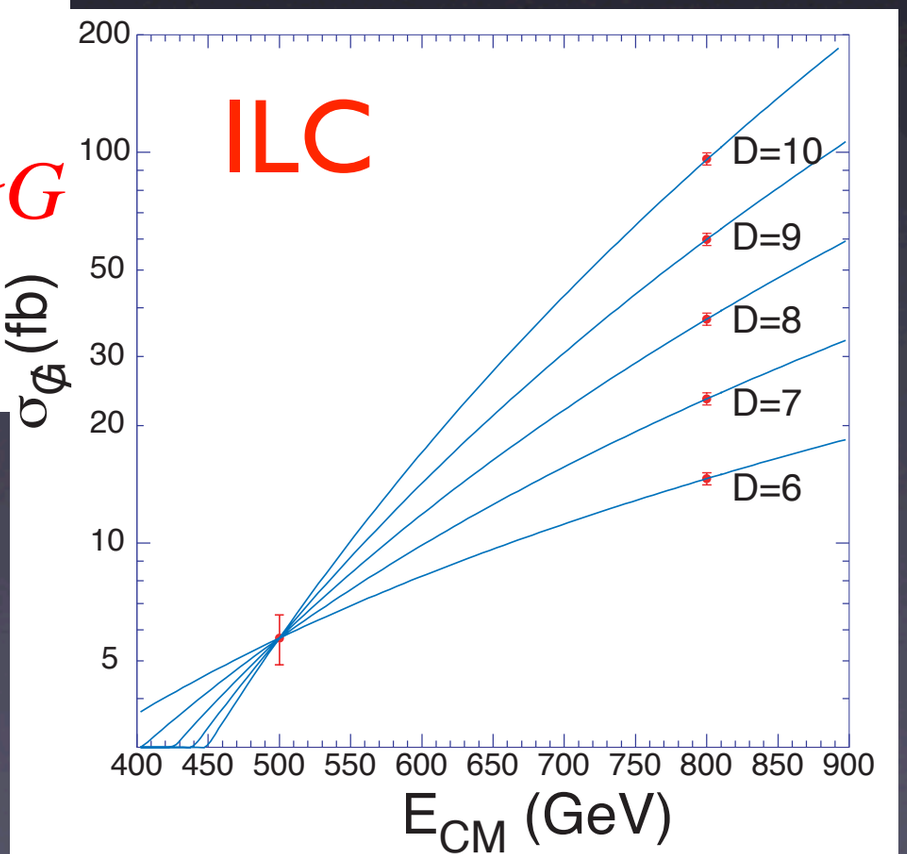

Superpartners as probe

- Most exciting thing about superpartners beyond existence:

They carry information of small-distance physics to something we can measure

"Are forces unified?"

approach laws of physics at the birth of the Universe

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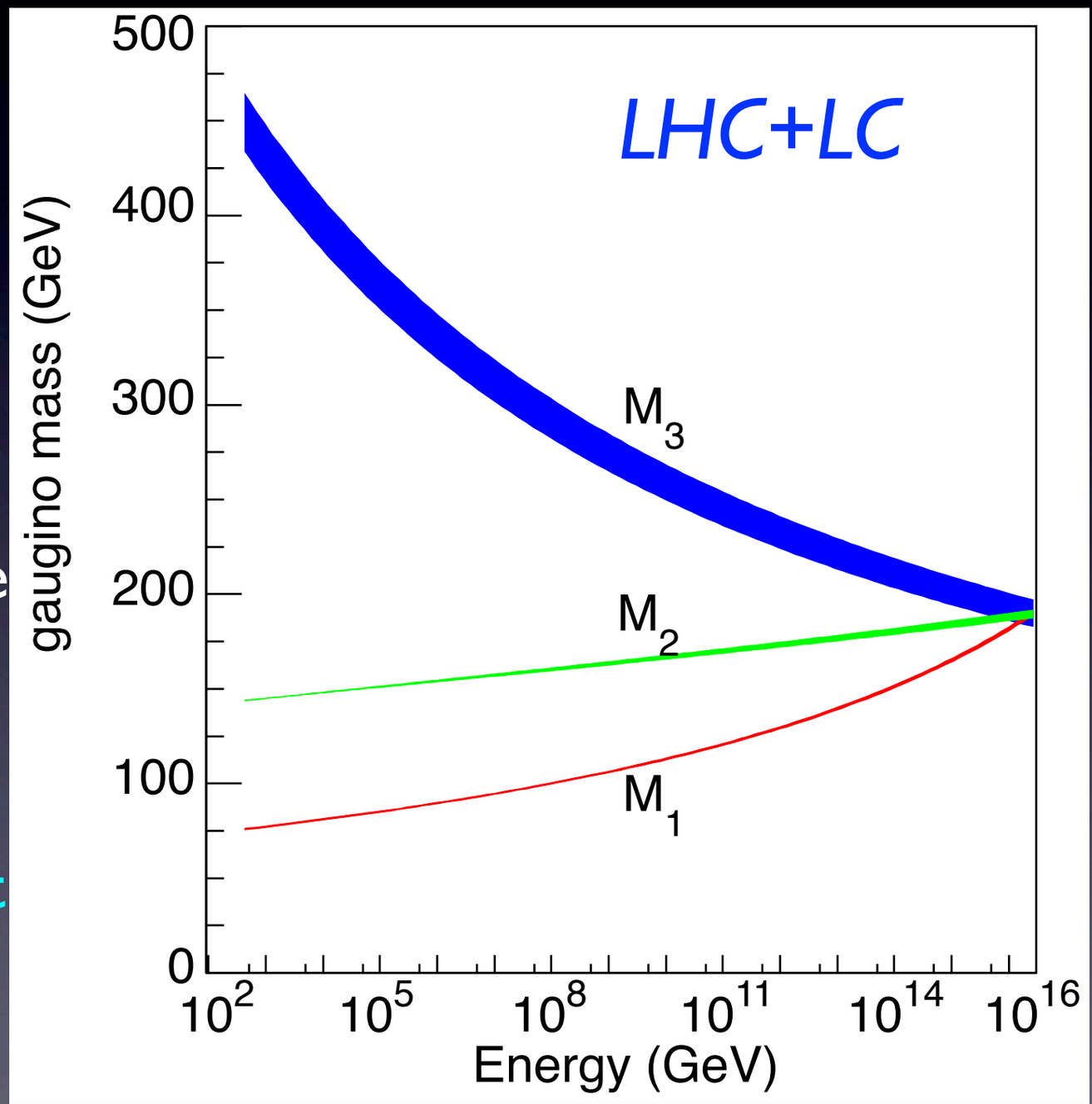
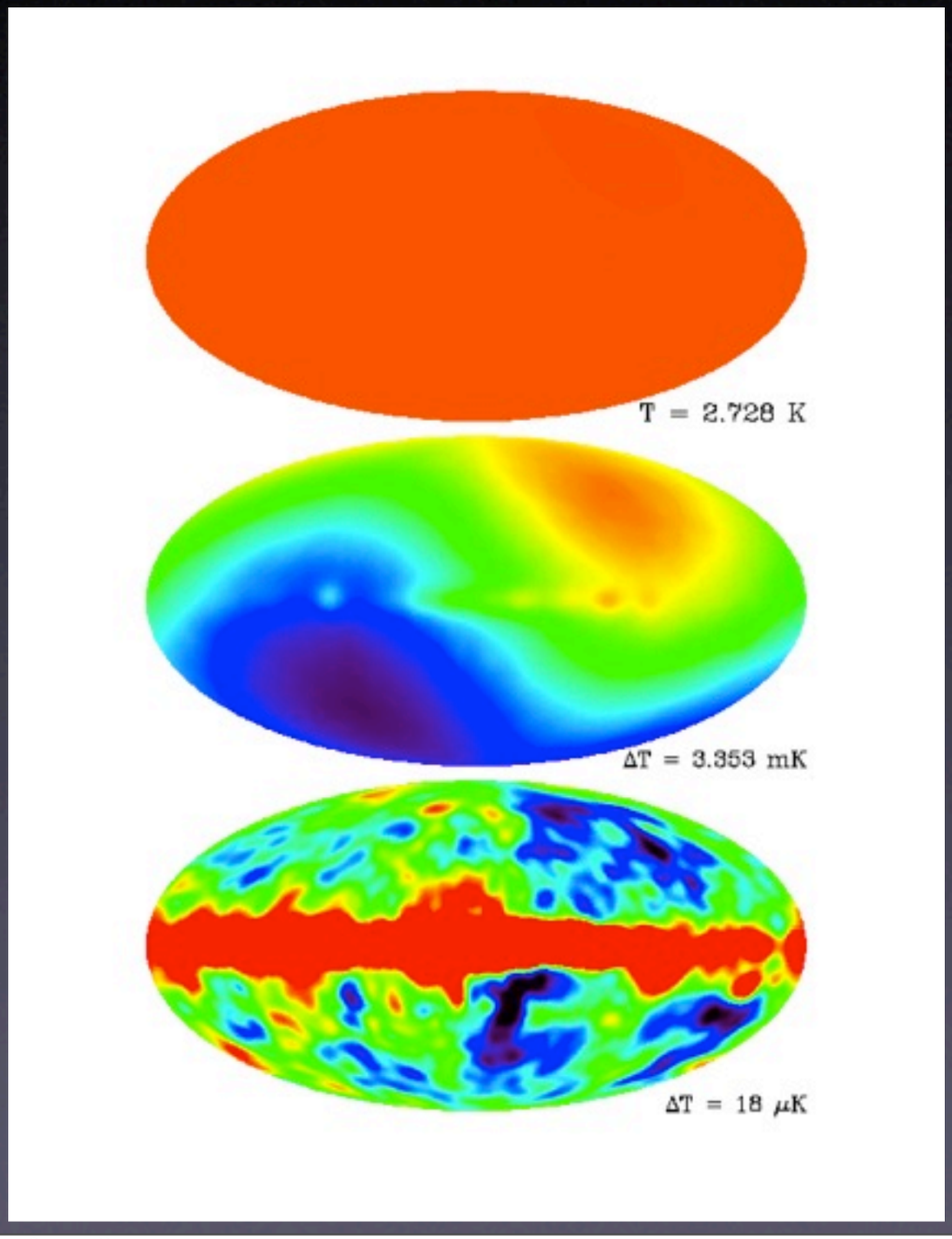


Inflation

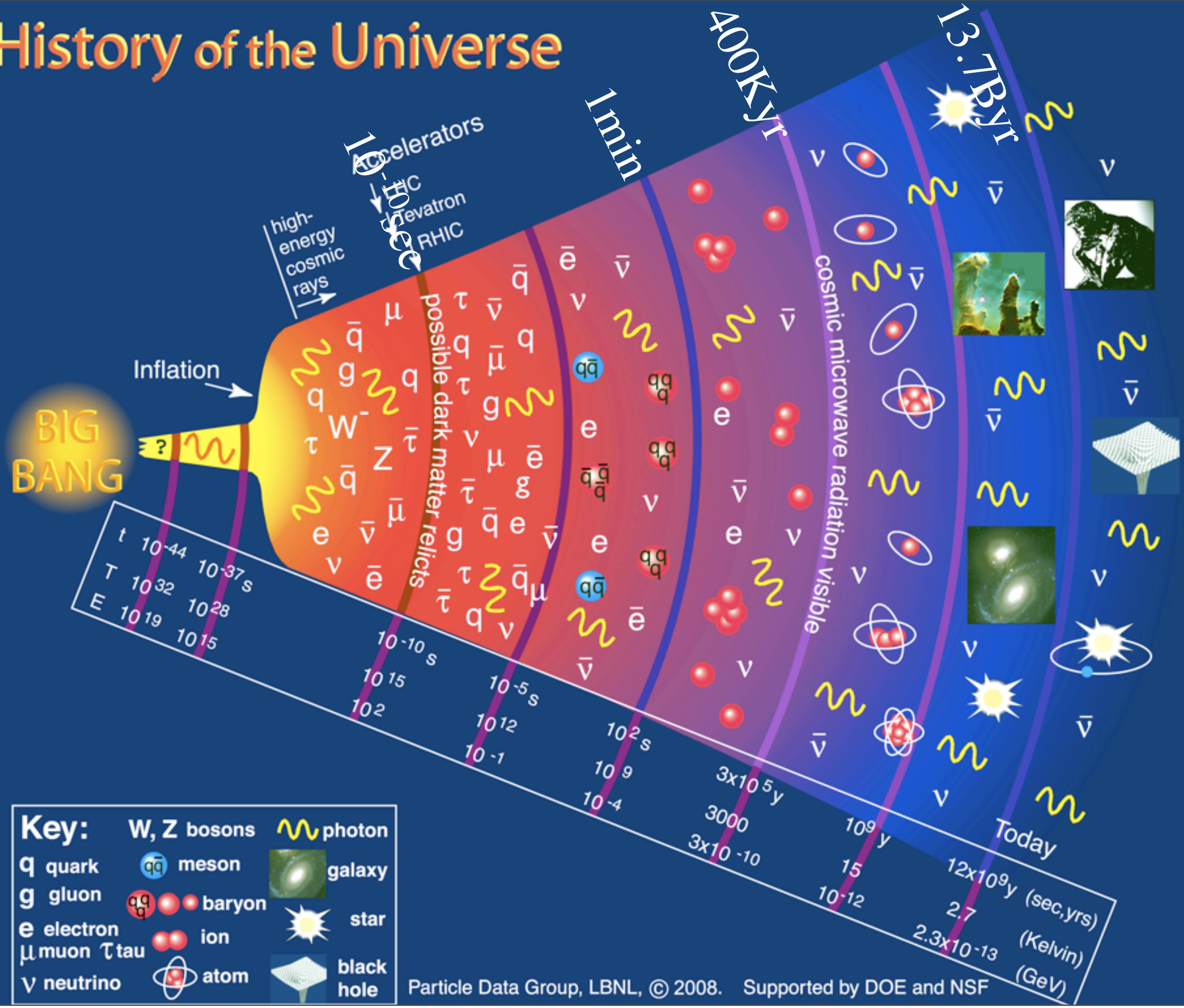
Why do they all look the same?



- Like having discovered two remote islands in very different parts of the world, speaking the same language
- even the accents are nearly the same: one part in 100,000
- we suspect they had communication

Guth, Sato

History of the Universe



IPMU

BERKELEY CENTER FOR THEORETICAL PHYSICS

Big endorsement



x

IPMU

BERKELEY CENTER FOR THEORETICAL PHYSICS

Big endorsement

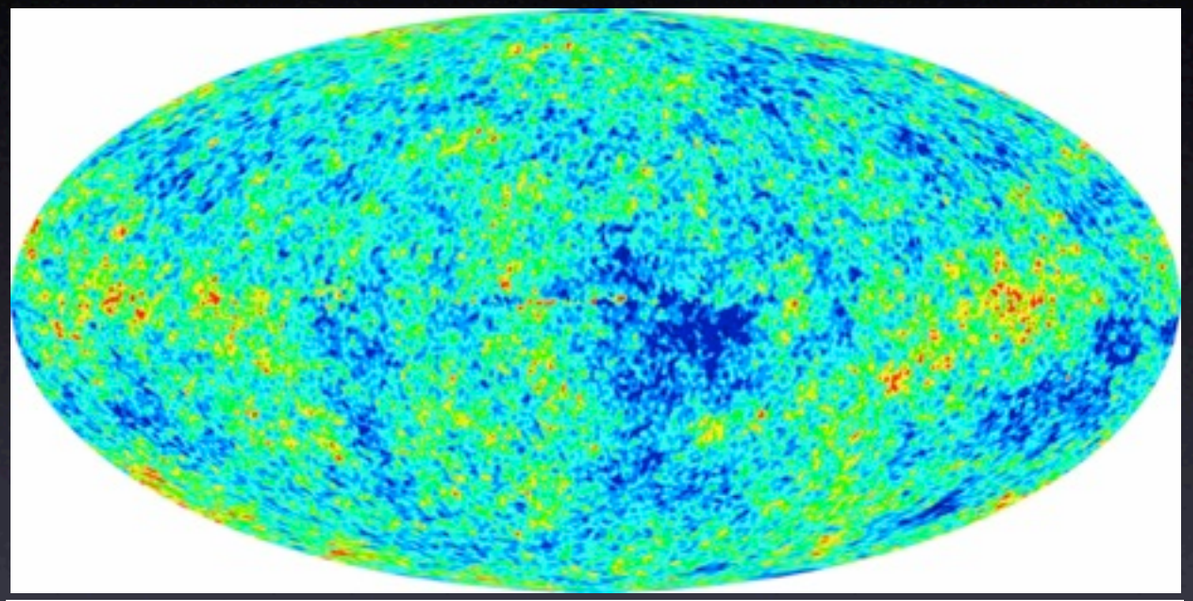


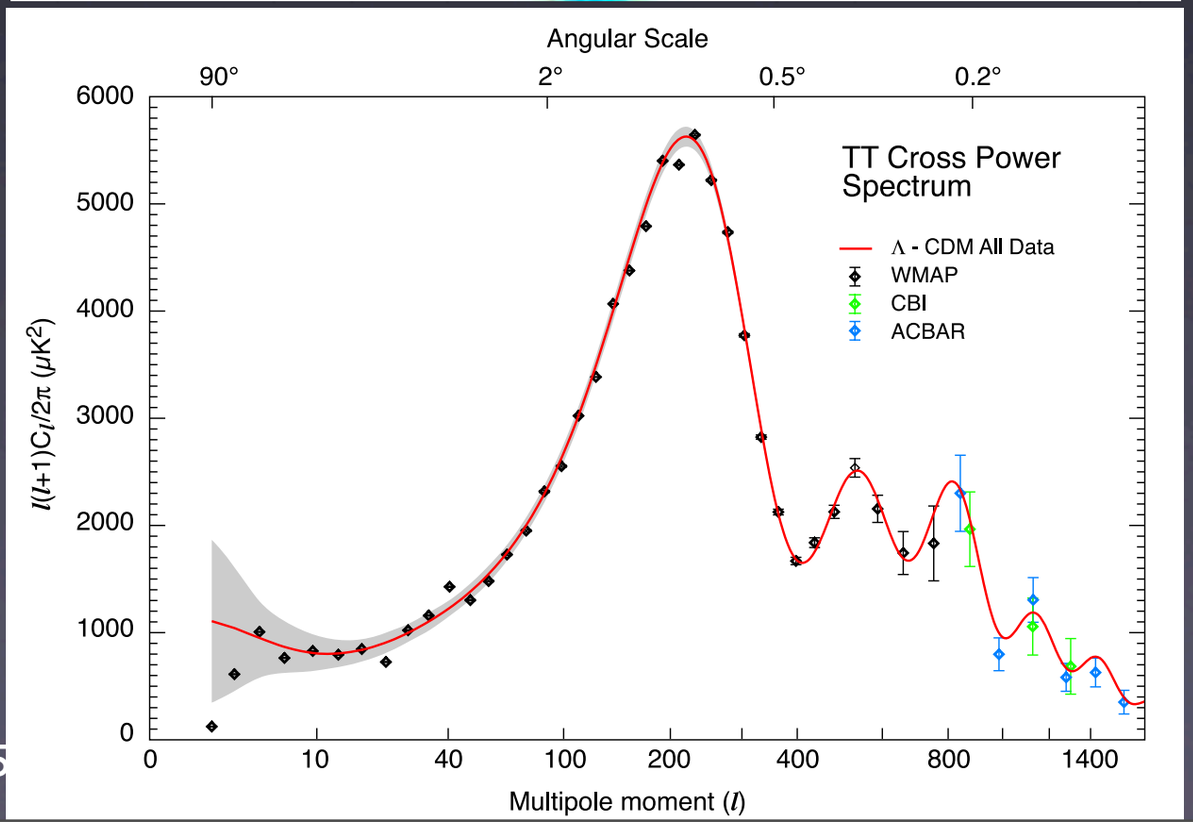
"A brief period of inflation is inevitable"

x

Seeds for structure

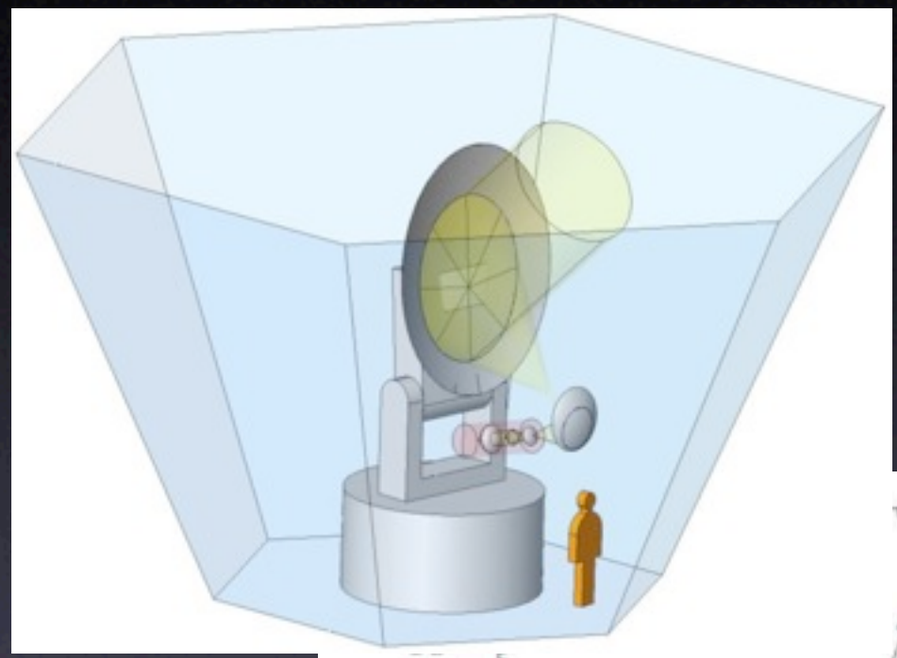
- Cosmic Inflation stretched the new-born microscopic space to our entire visible universe
- Observed structure originates from quantum fluctuation of inflaton
- Large-Scale Structure, CMB E-mode polarization consistent with this picture

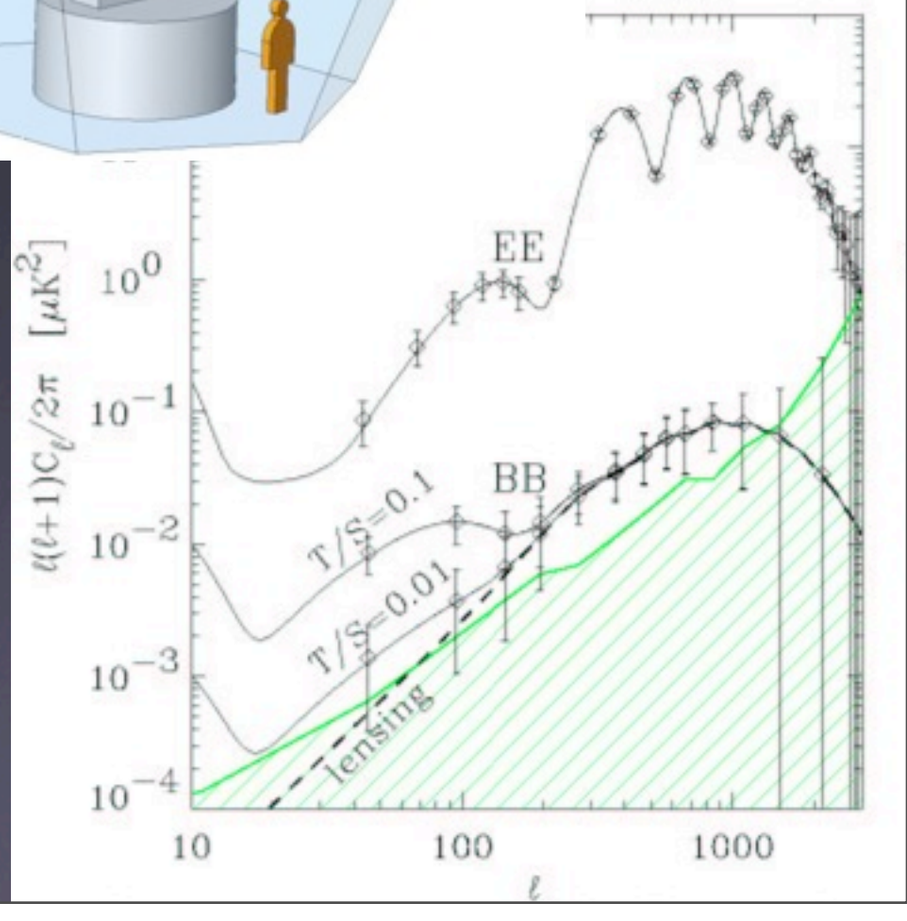




How do we know it really happened?

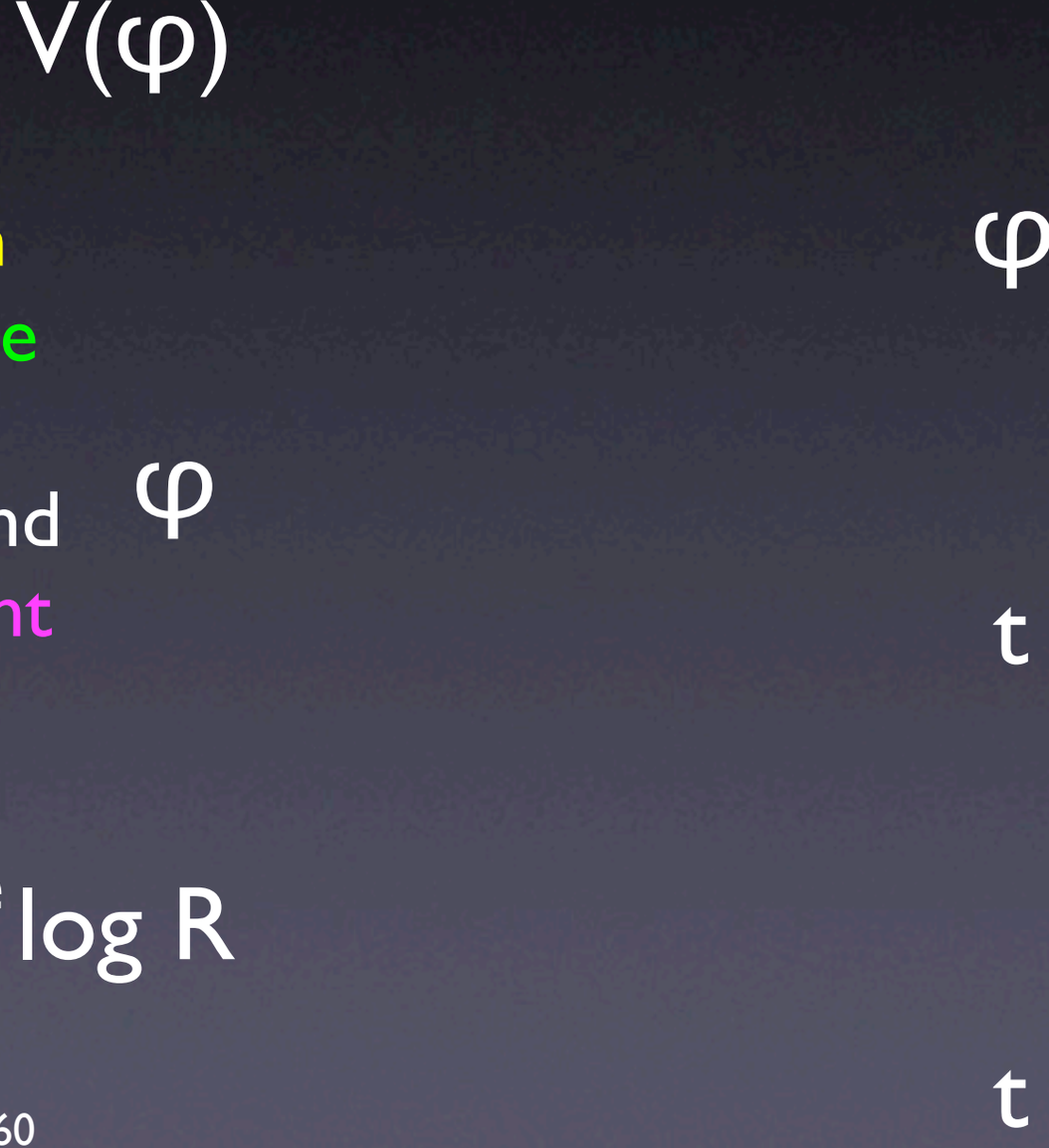
- everything gets quantum fluctuation, including gravitons
- Gravitons from quantum fluctuation gives B-mode polarization in CMB
- The size is directly proportional to the inflationary energy scale
  ⇒ e.g., POLARBEAR, Quiet





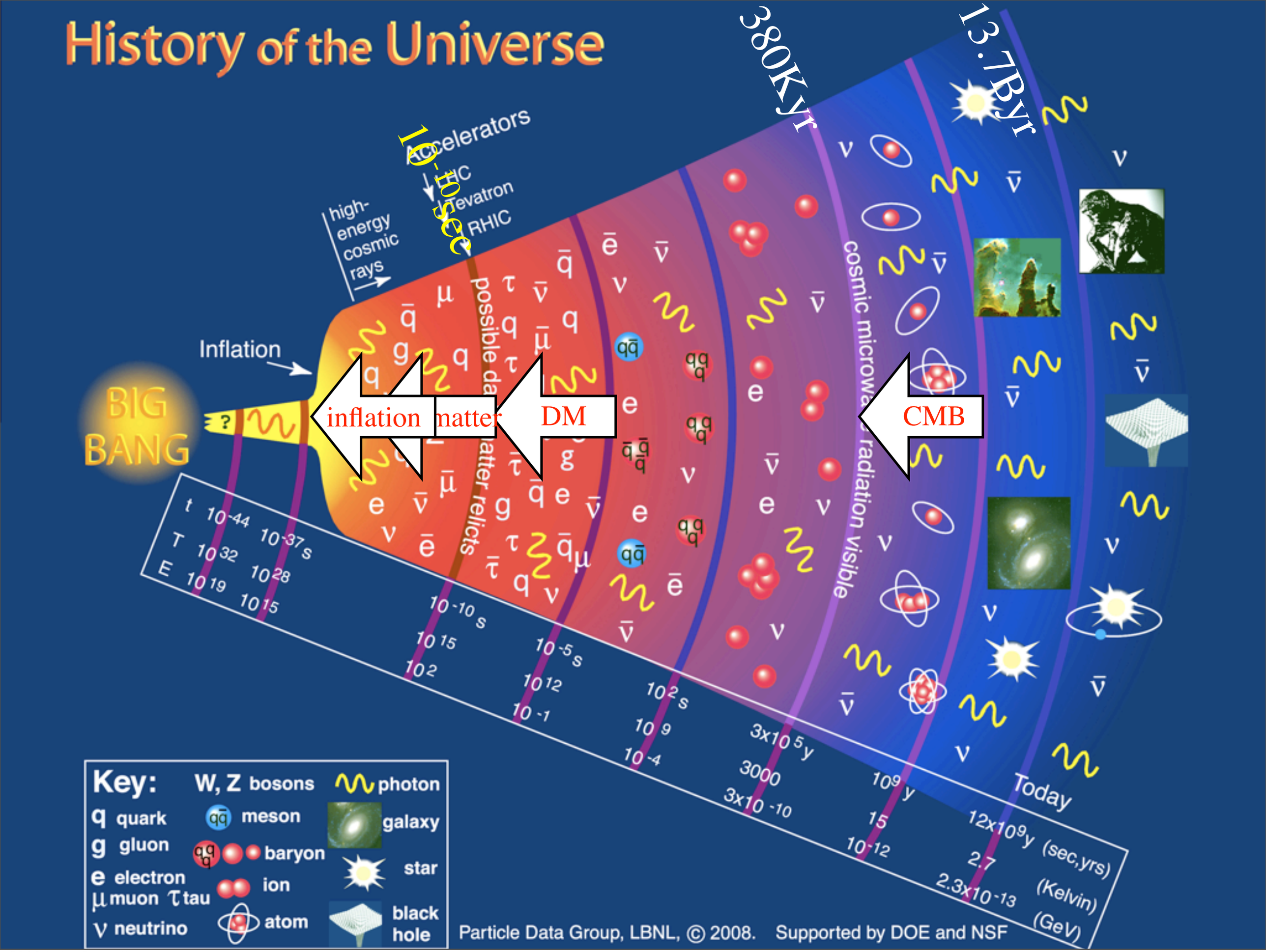
Putting them together

- Superpartner of a heavy neutrino
- displaced from the minimum at the beginning
- rolls down slowly: inflation
- quantum fluctuation source of later structure
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter



HM, Suzuki, Yanagida, Yokoyama

History of the Universe



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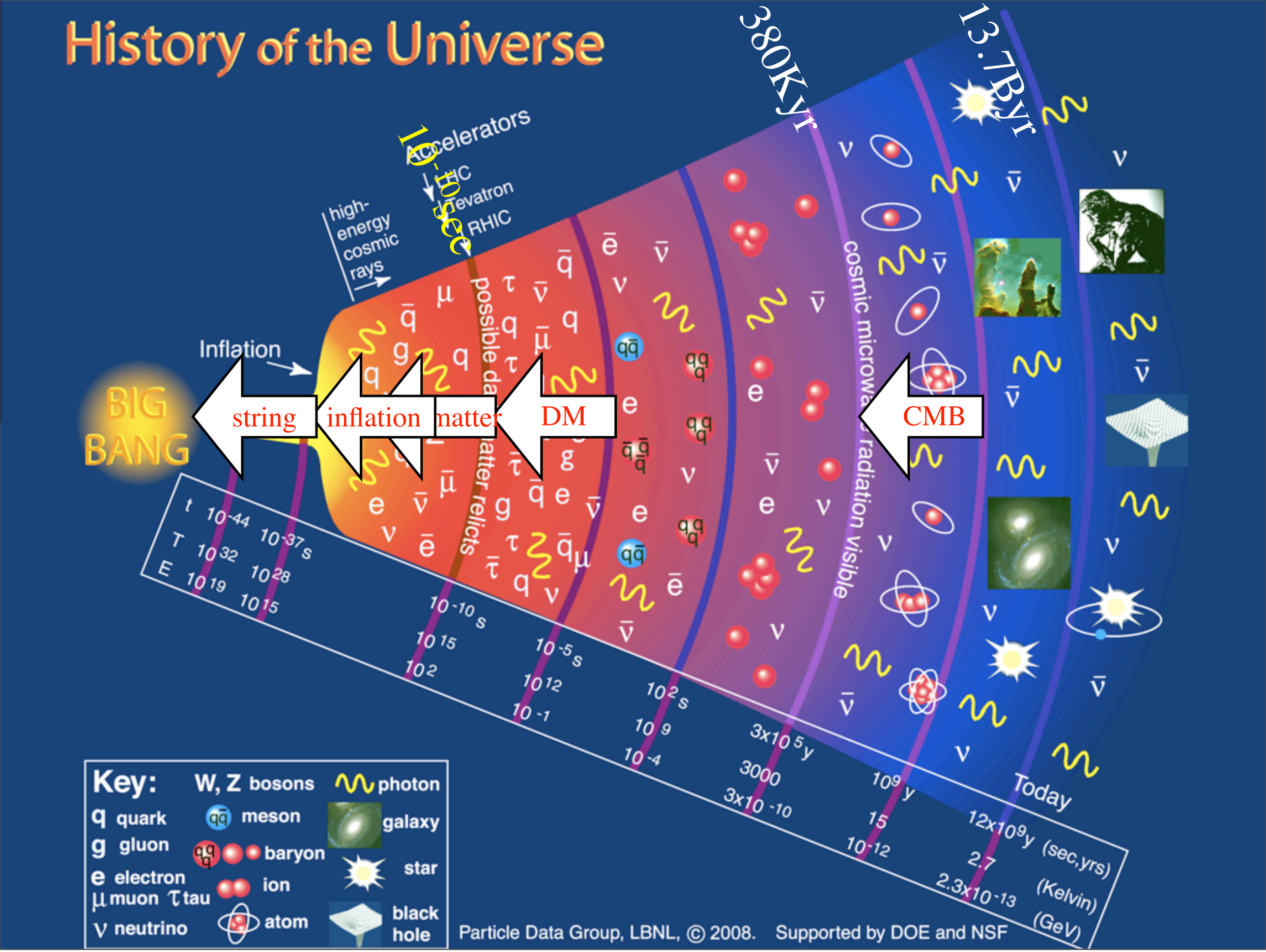
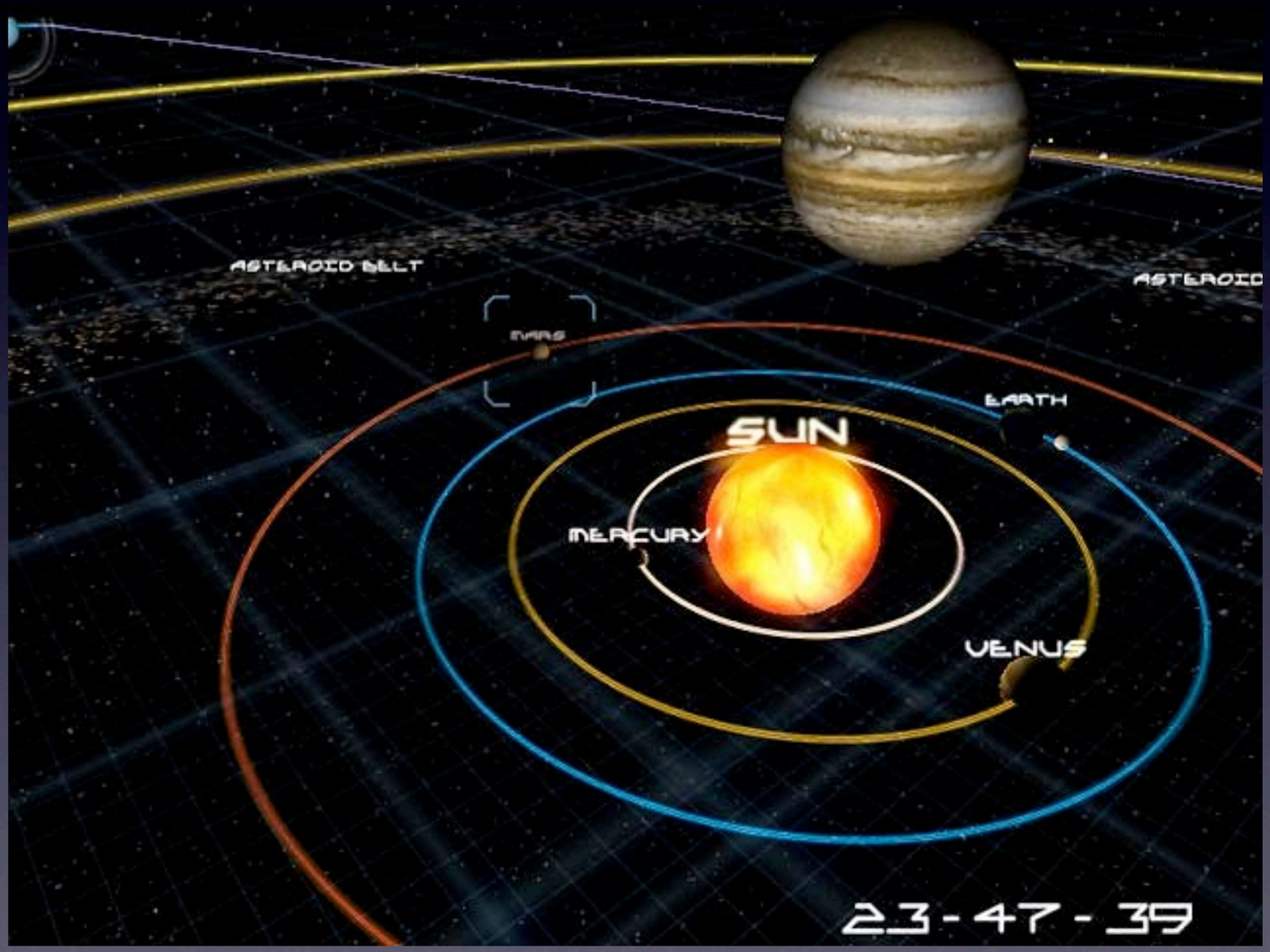


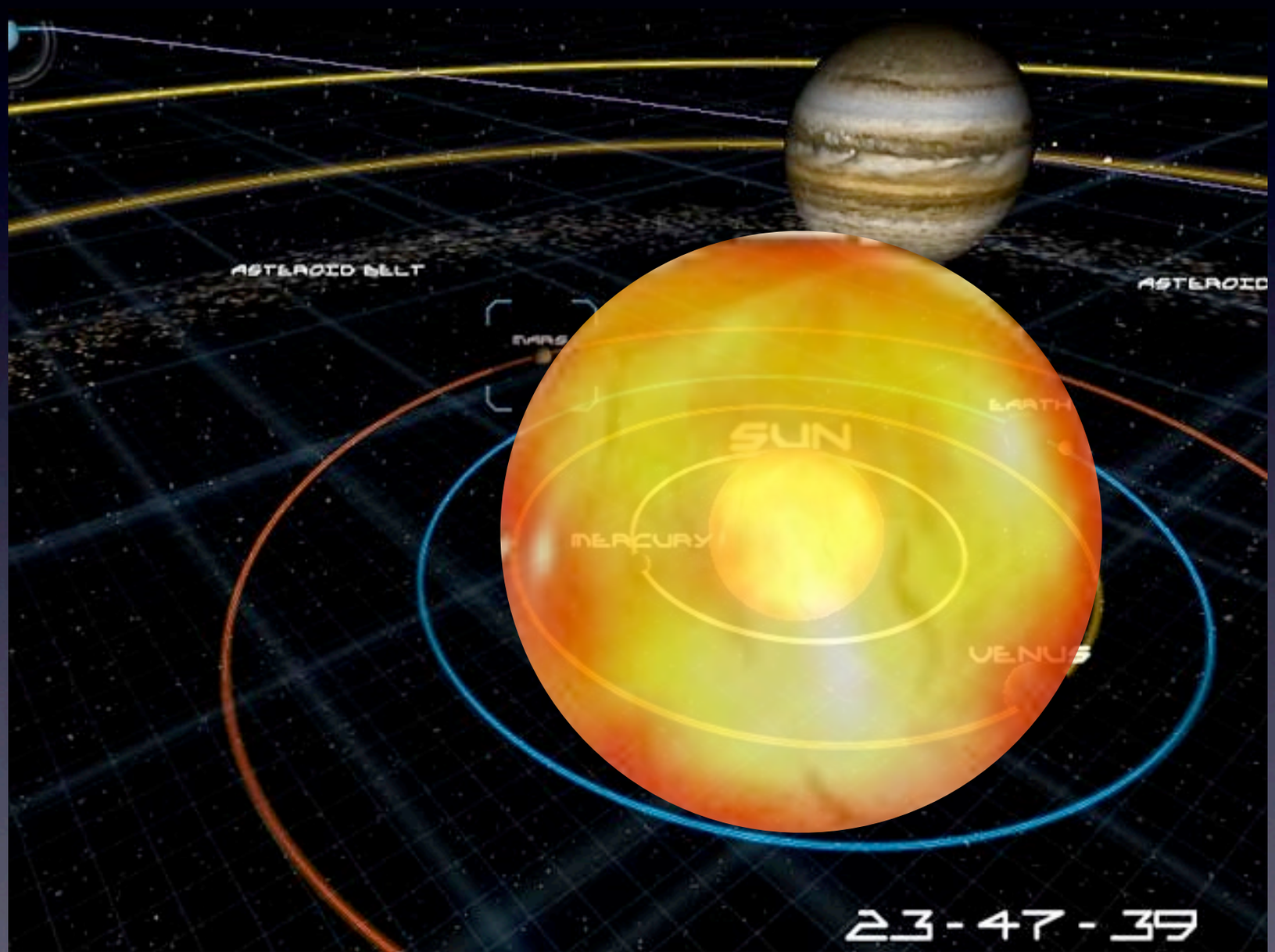
What is its fate?

–Dark Energy–

Fate of the Earth



Fate of the Earth





2011年6月8日星期三



2011年6月8日星期三


Dark Energy
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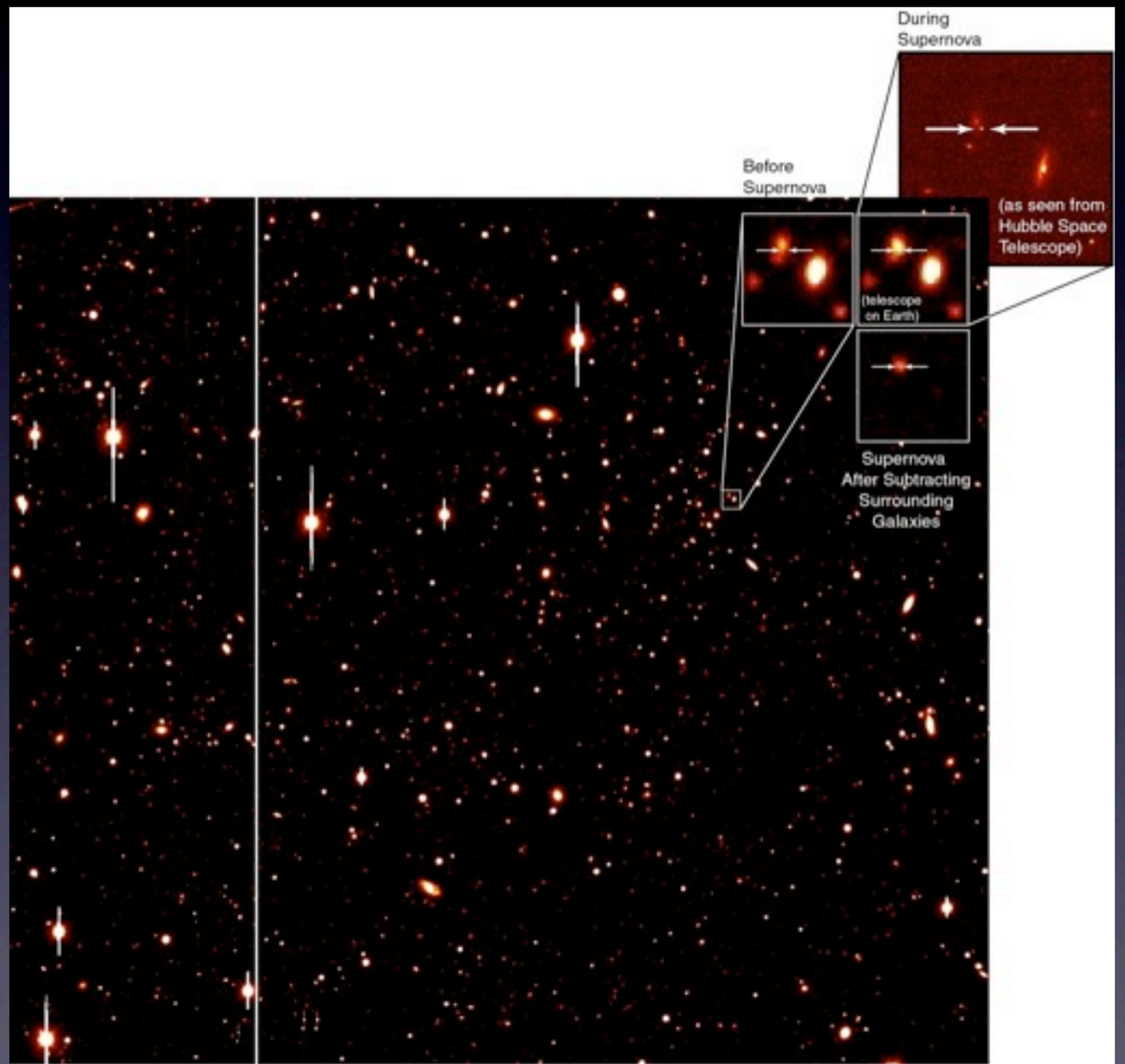
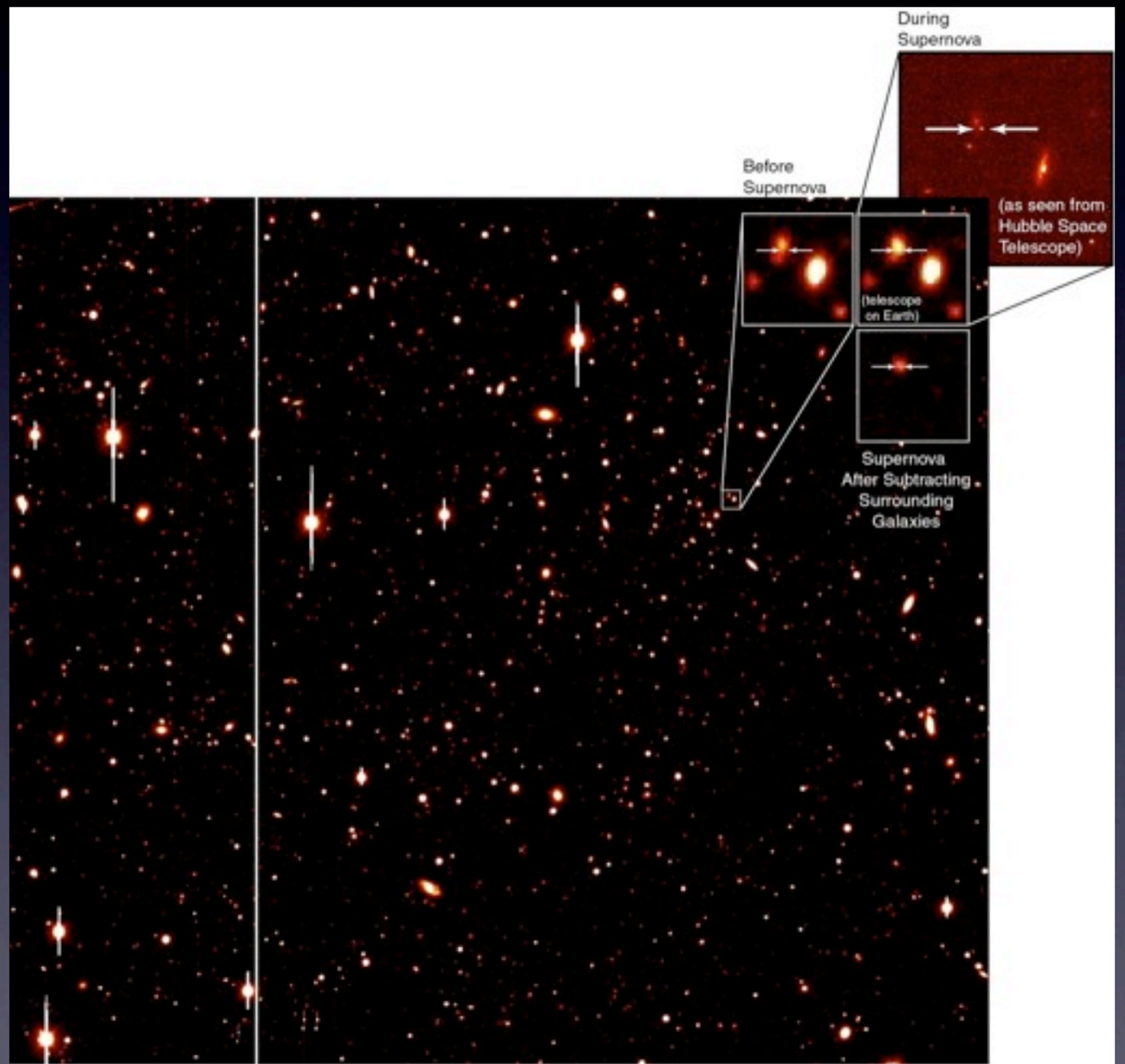
Type-Ia supernovae



Type-Ia supernovae

- Type-Ia supernova becomes brighter than the whole galaxy





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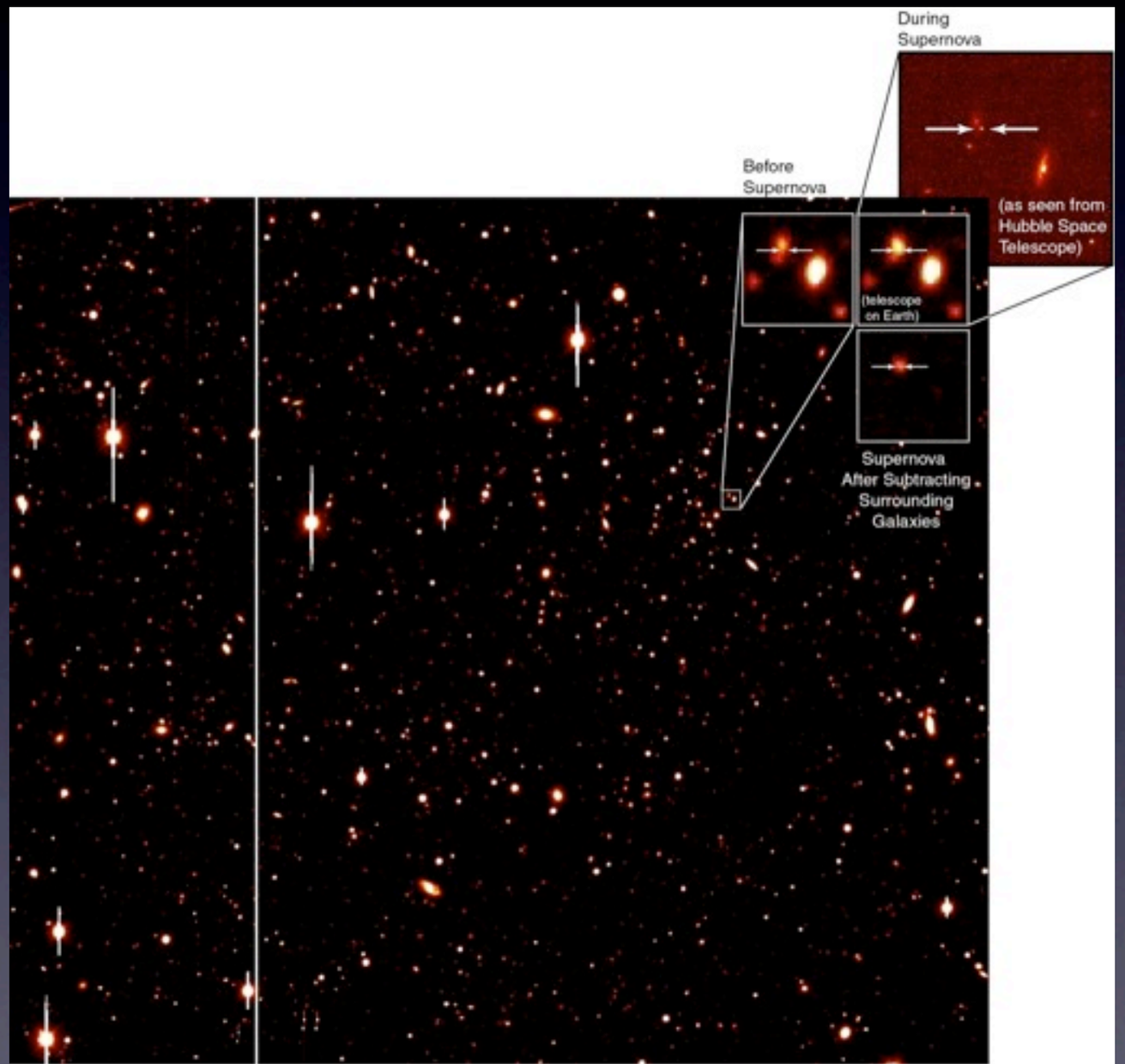



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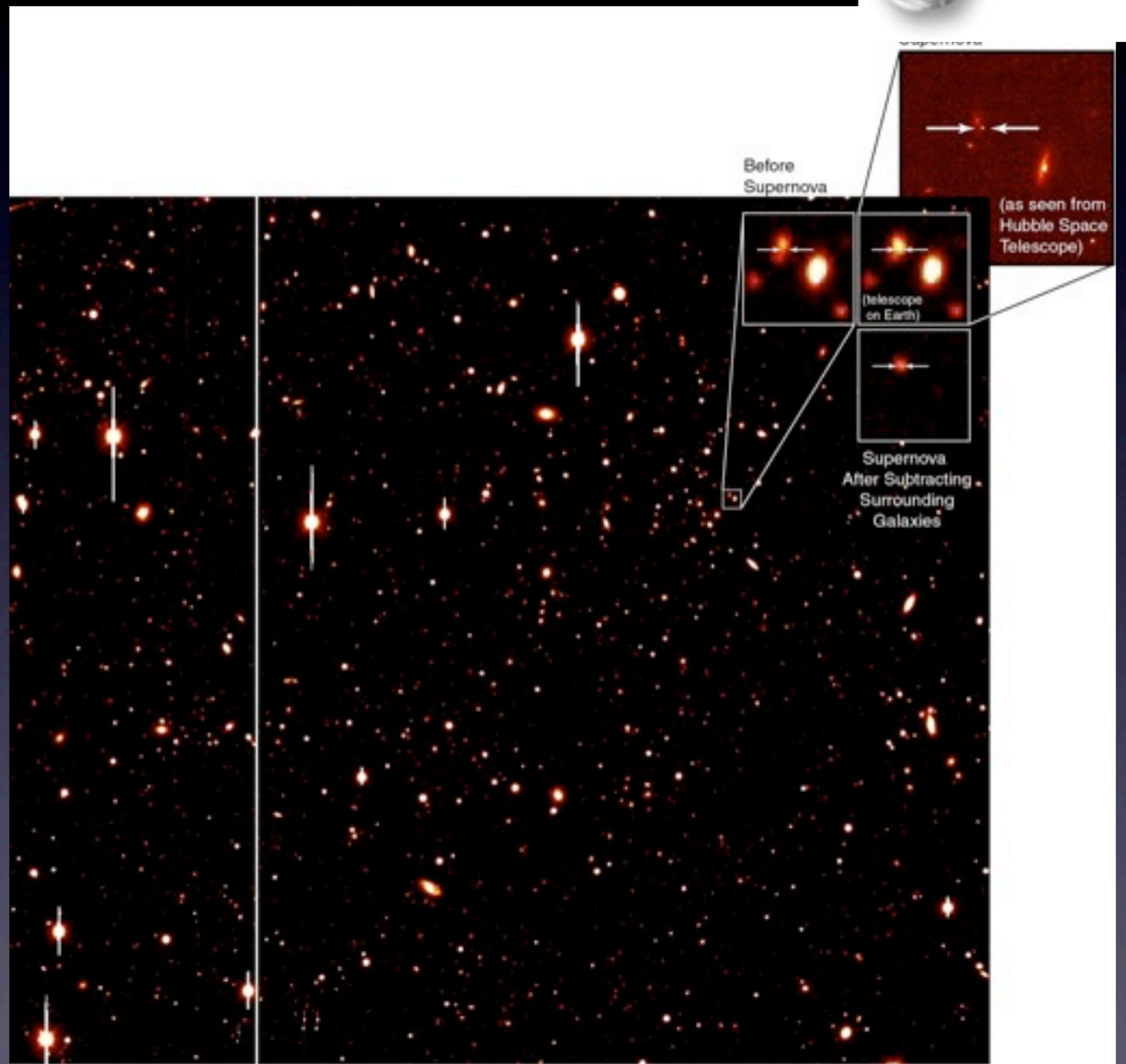
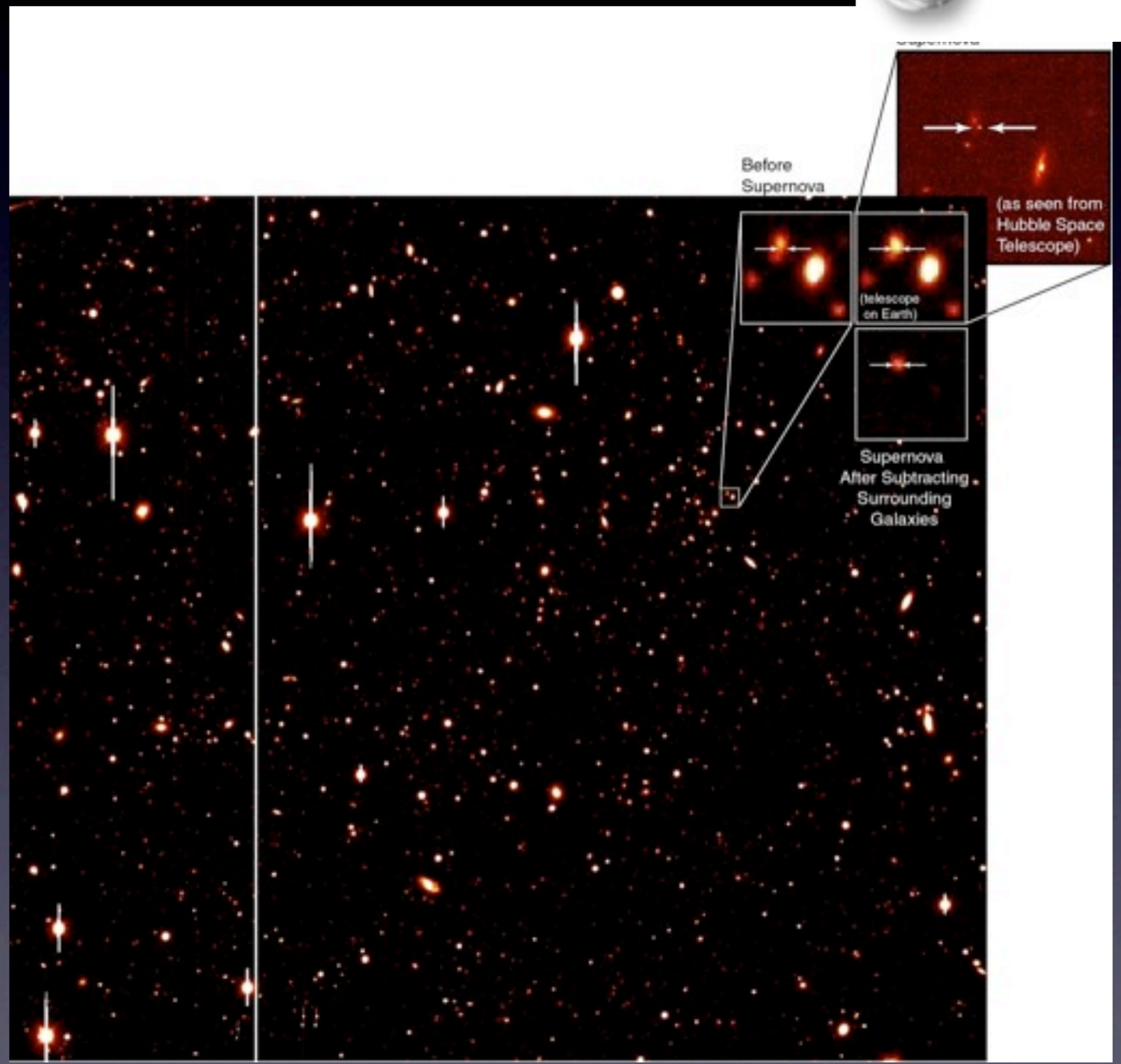




Type-Ia supernovae



- Type-Ia supernova becomes brighter than the whole galaxy
- *How bright it looks*
  ⇒ How far away
  ⇒ How far back in time



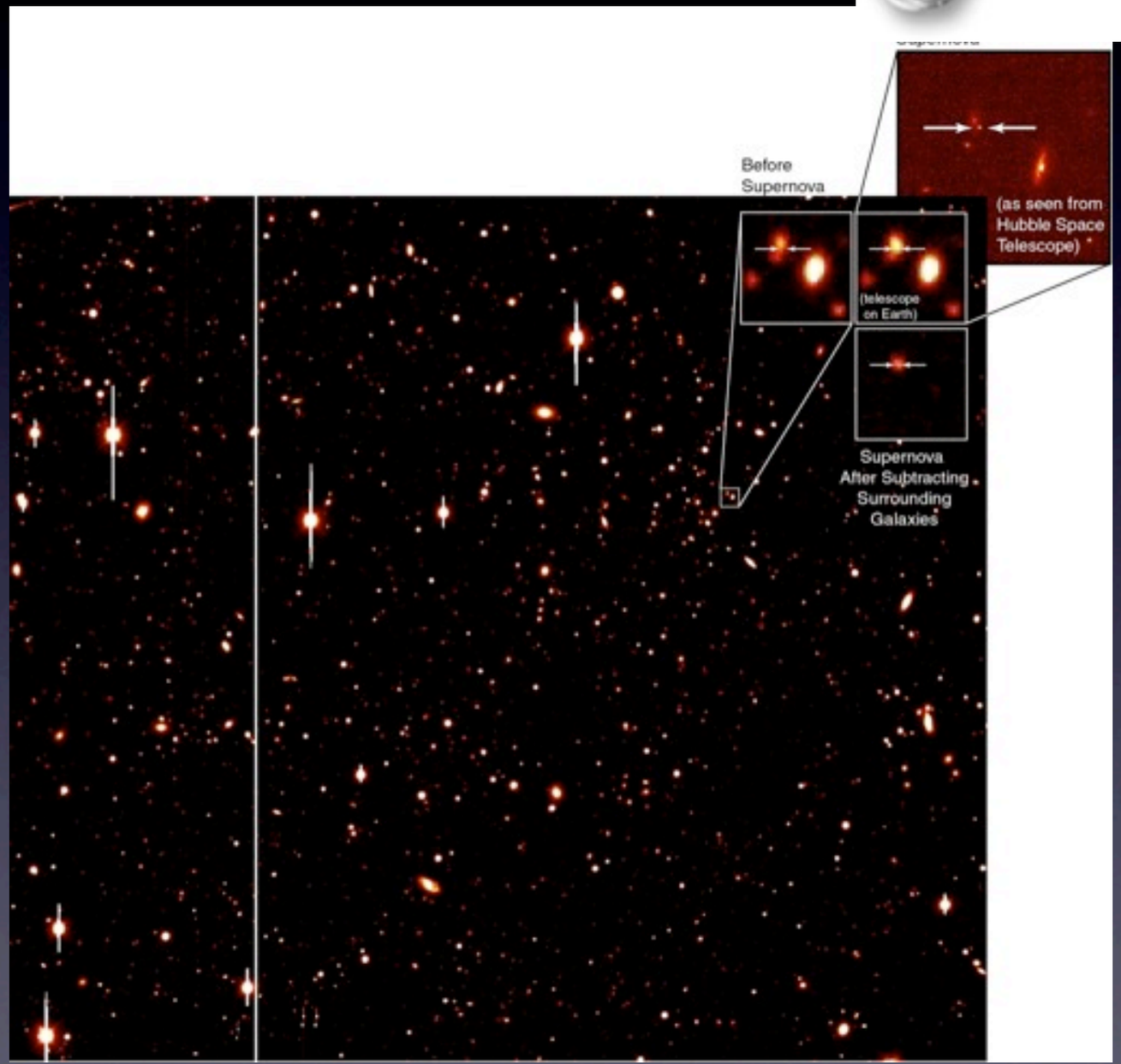


Type-Ia supernovae



- Type-Ia supernova becomes brighter than the whole galaxy
- *How bright it looks*
  ⇒ How far away

  ⇒ How far back in time
- *How red it looks*
  ⇒ How much expansion

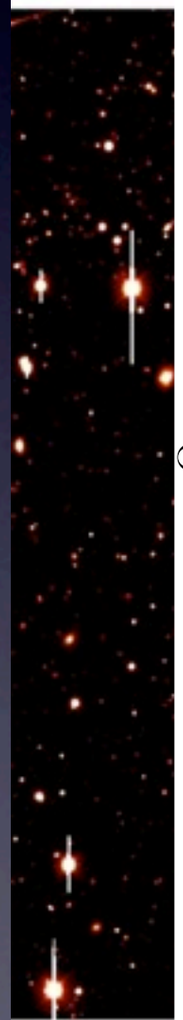


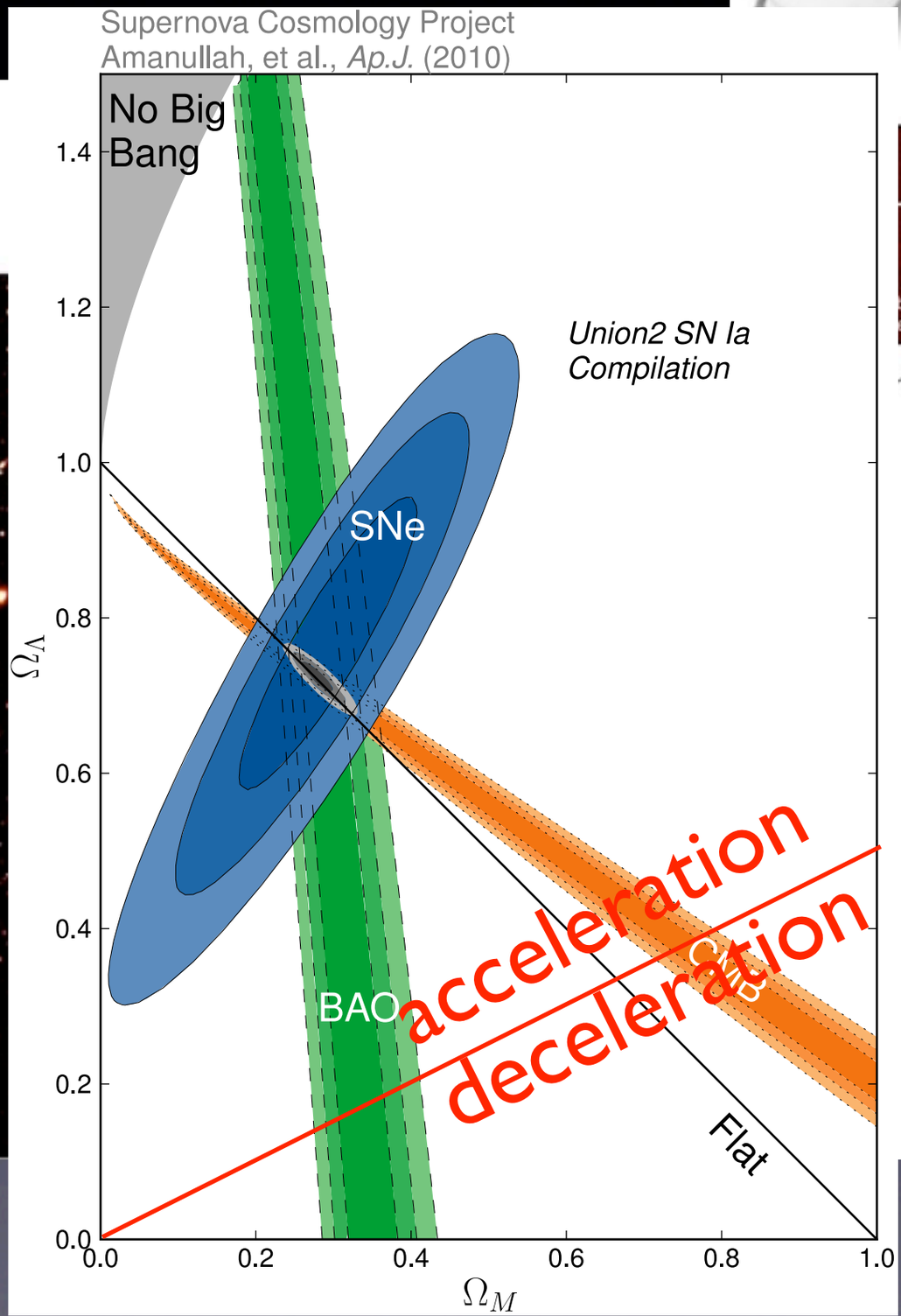


Type-Ia supernovae



- Type-Ia supernova becomes brighter than the whole galaxy
- *How bright it looks*
  ⇒ How far away
  ⇒ How far back in time
- *How red it looks*
  ⇒ How much expansion







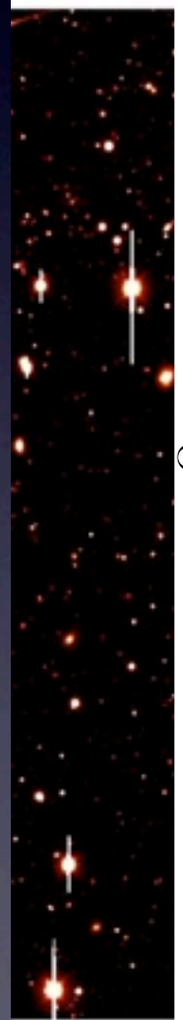


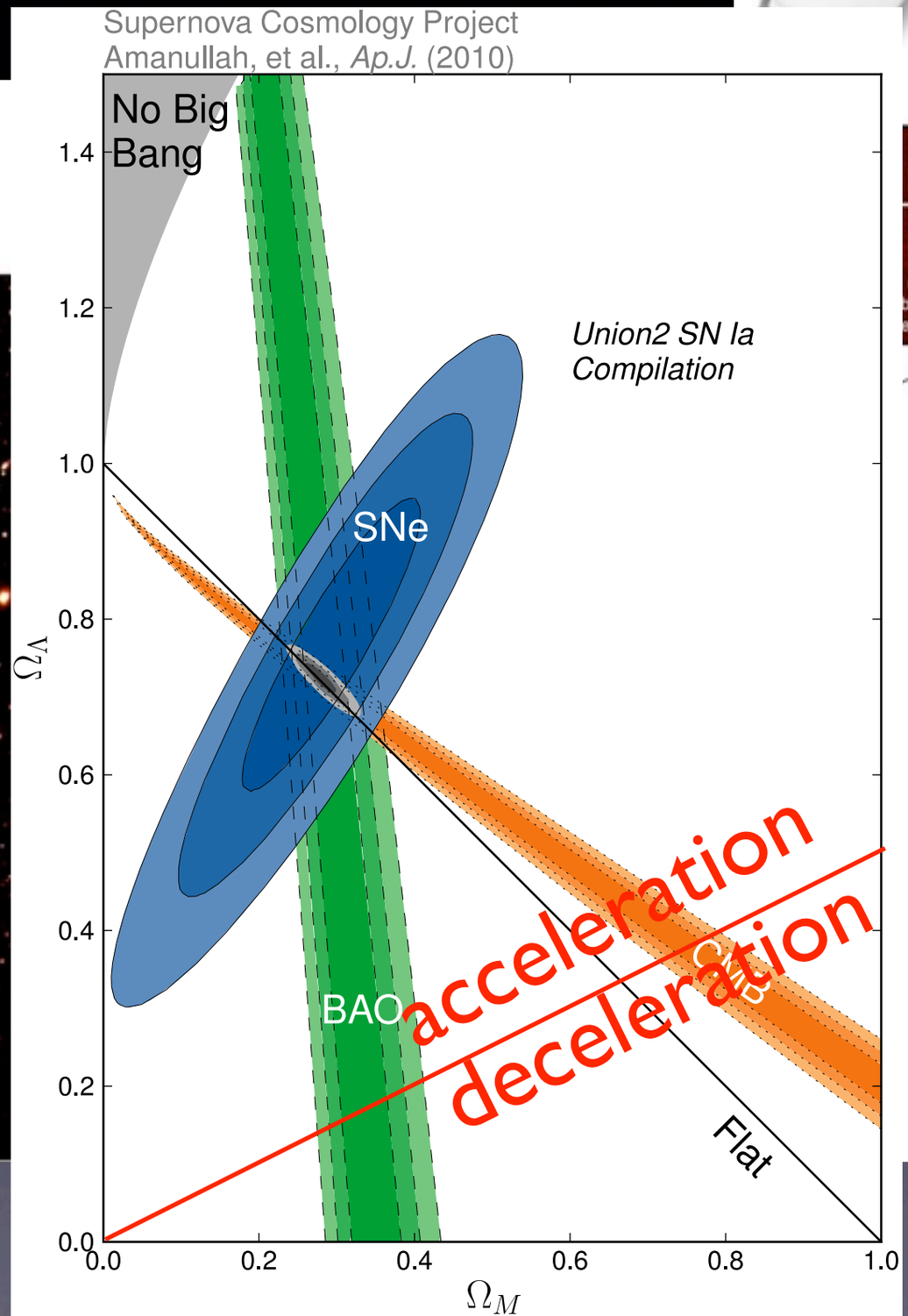
Type-Ia supernovae



- Type-Ia supernova becomes brighter than the whole galaxy
- *How bright it looks*
  ⇒ How far away

  ⇒ How far back in time
- *How red it looks*
  ⇒ How much expansion
- Expansion of the Universe is getting faster!

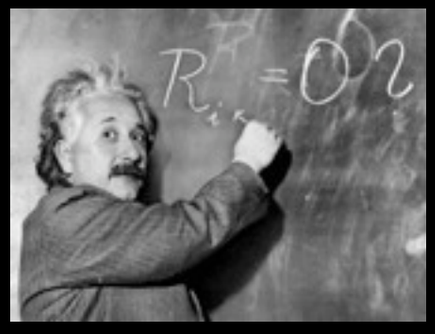






expansion

expansion



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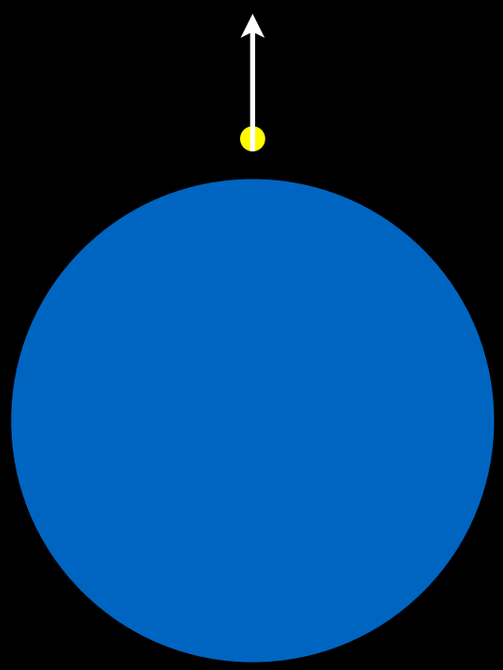

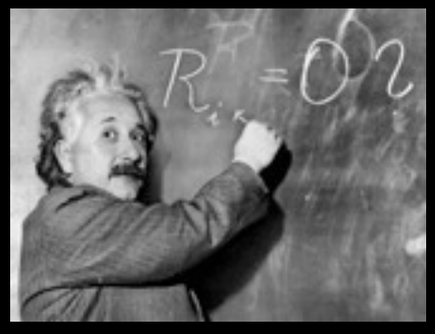

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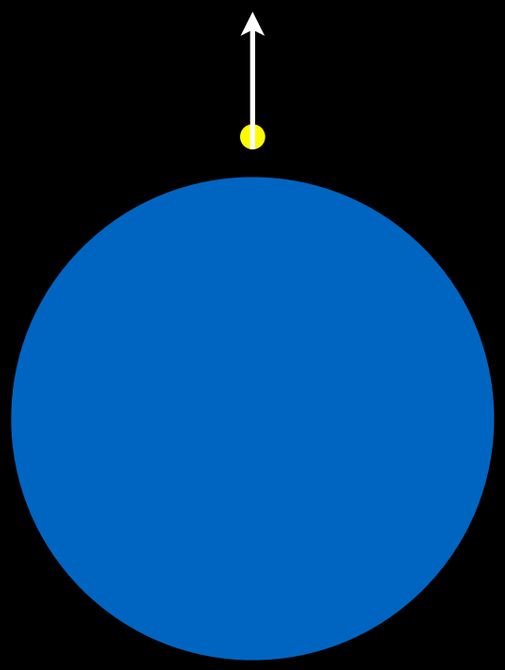
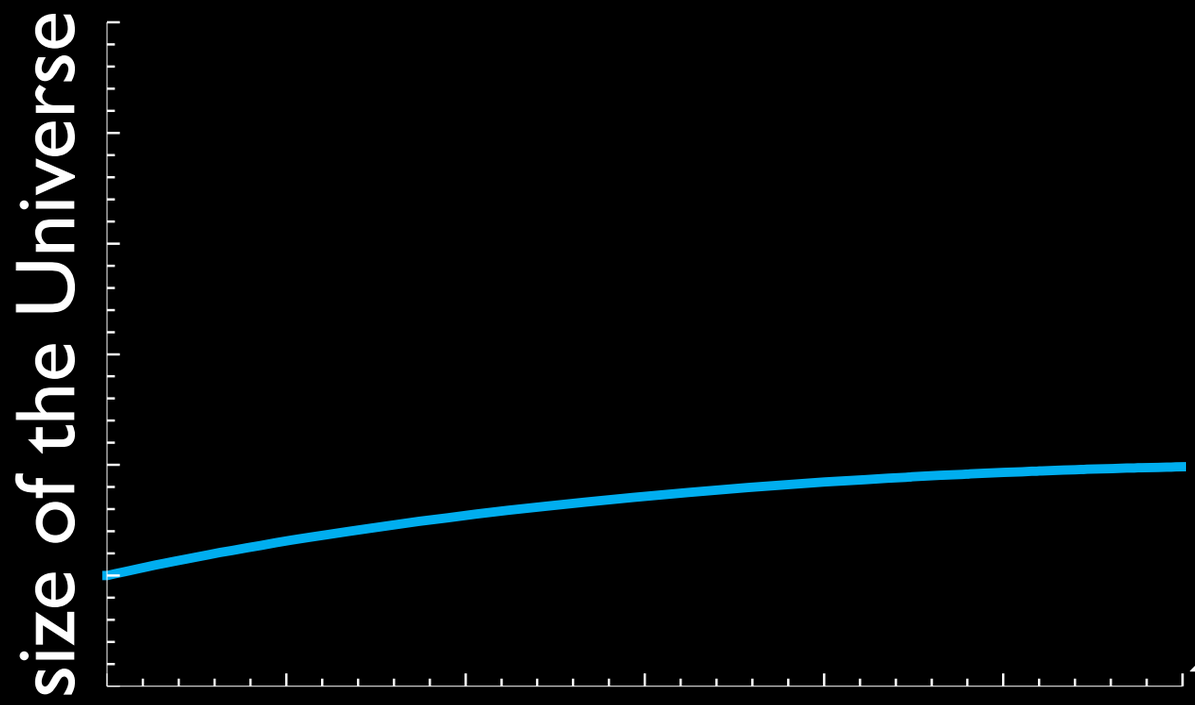
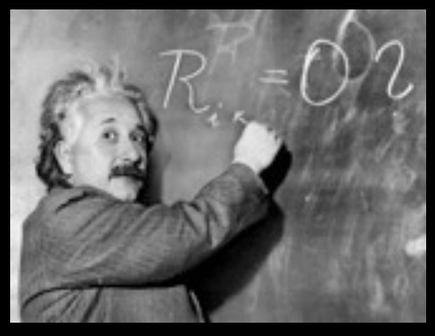




should slow down



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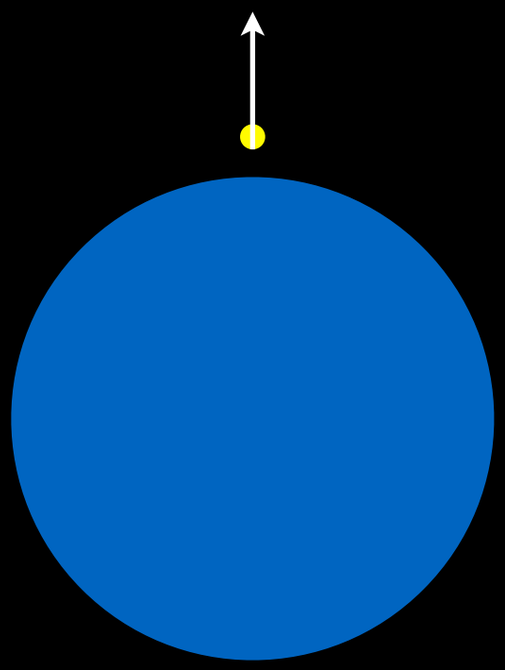
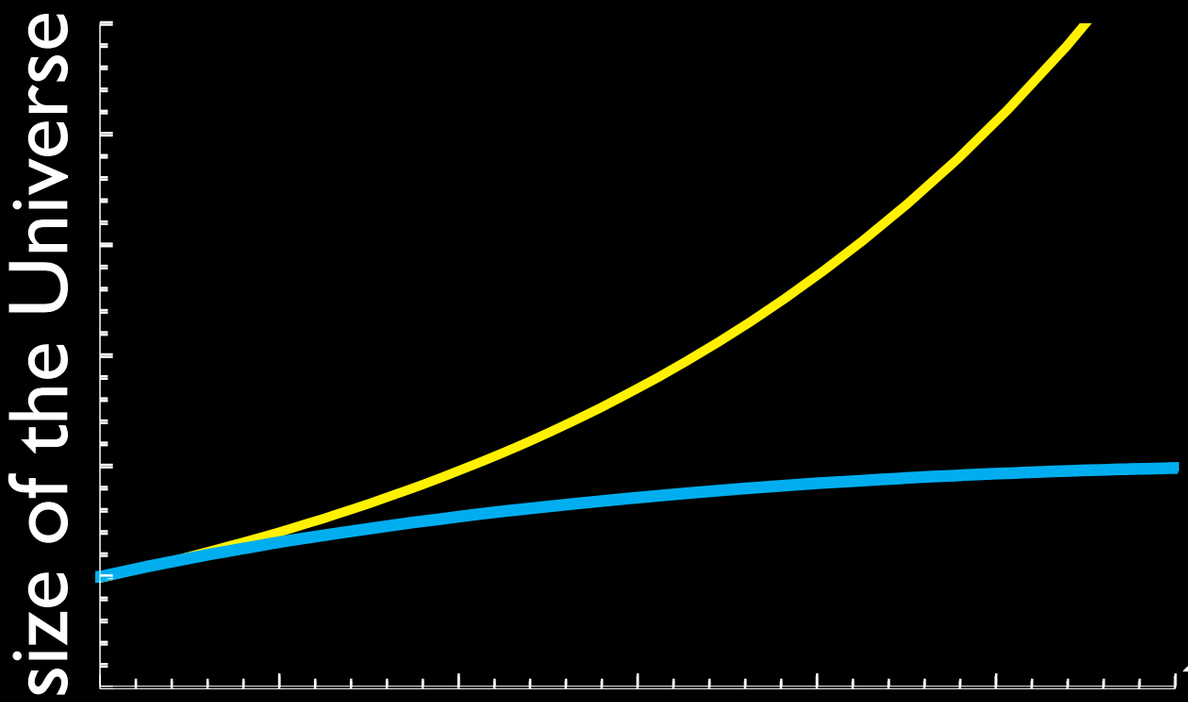
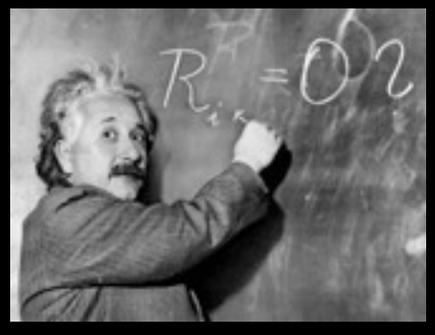




speeding up!

~~should slow down~~



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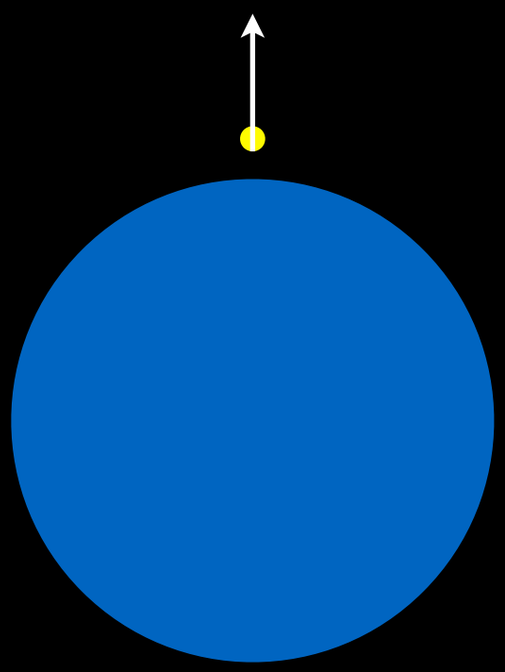

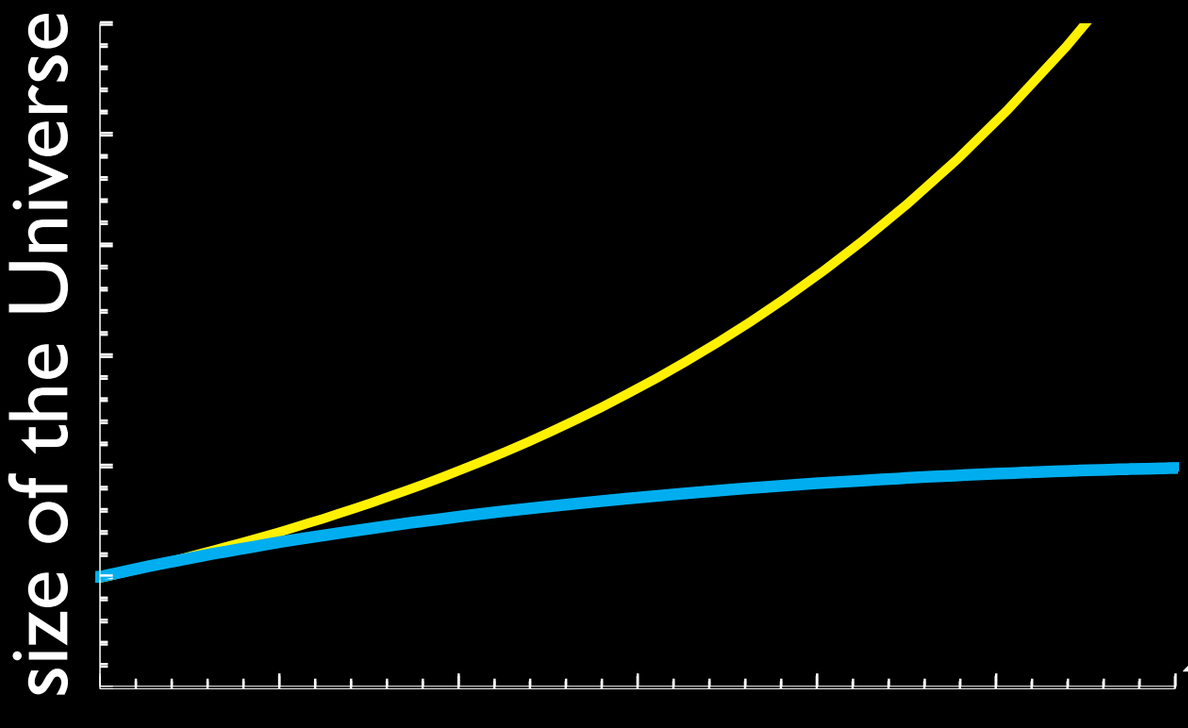

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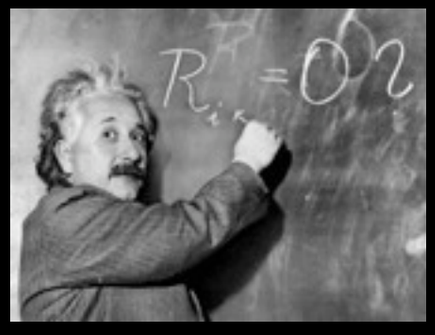

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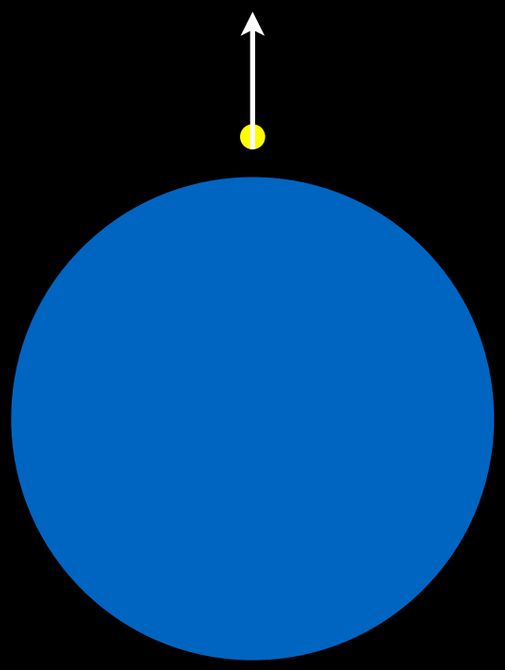

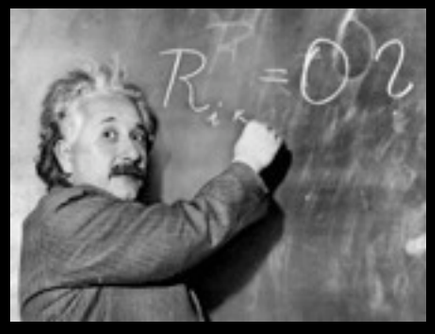

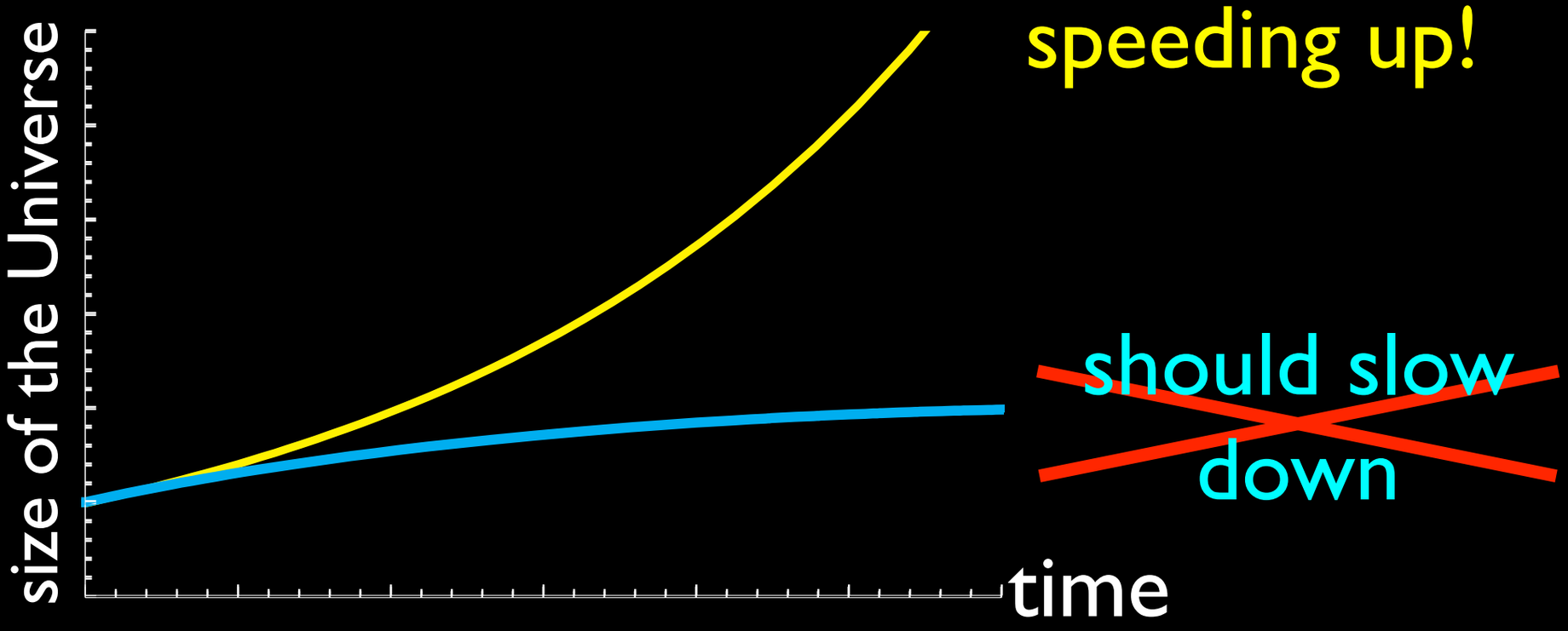

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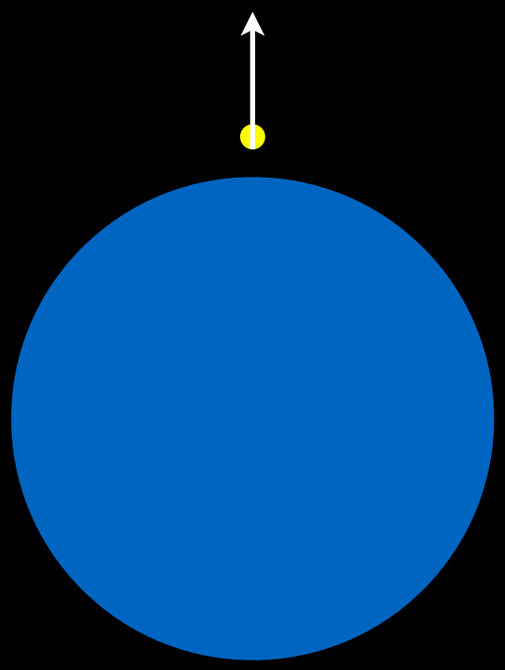
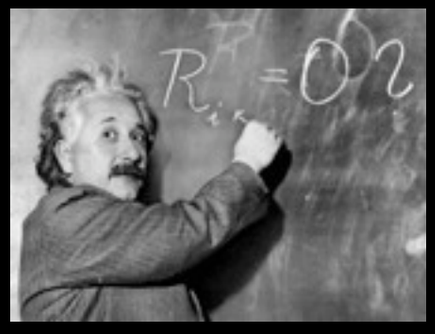
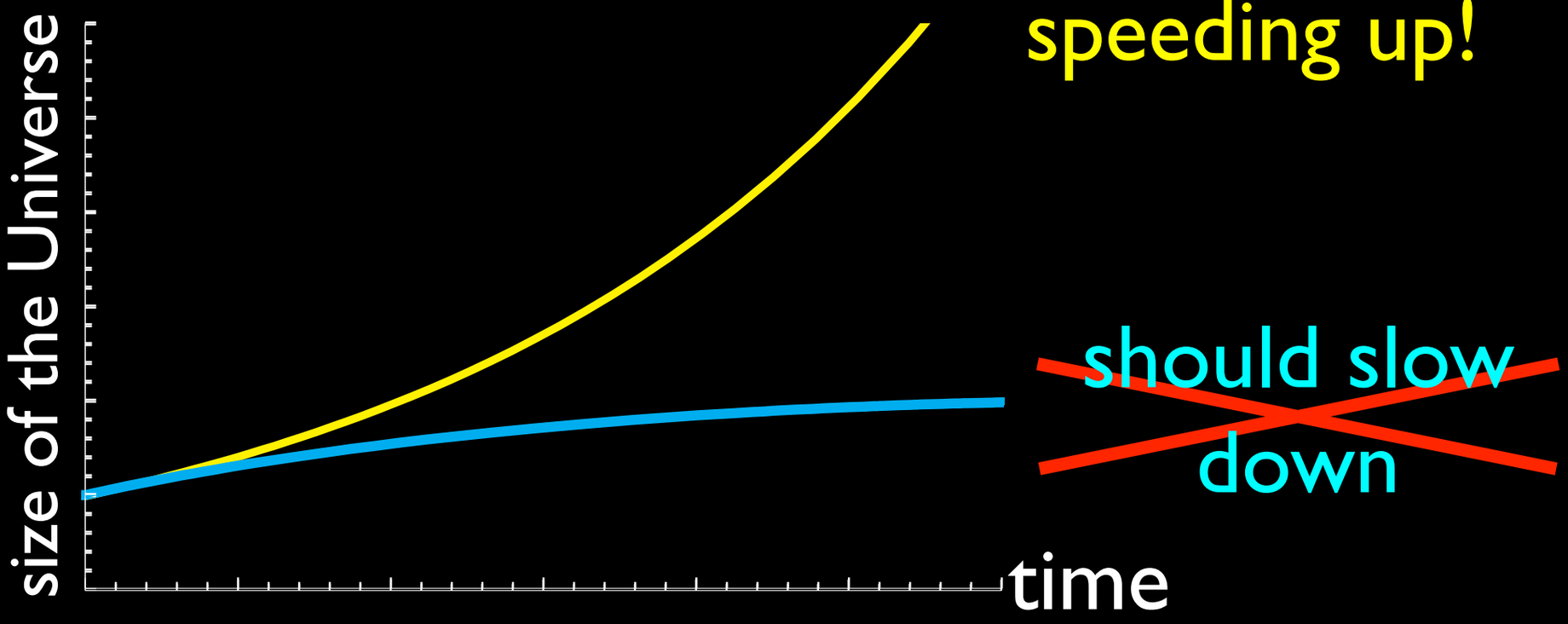
- energy is increasing!

expansion







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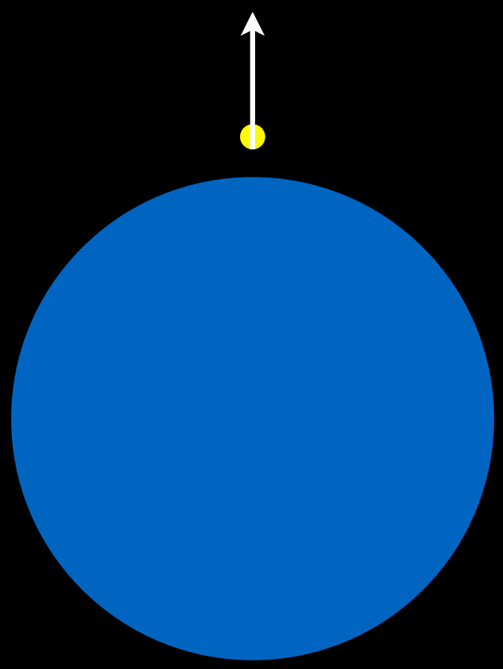

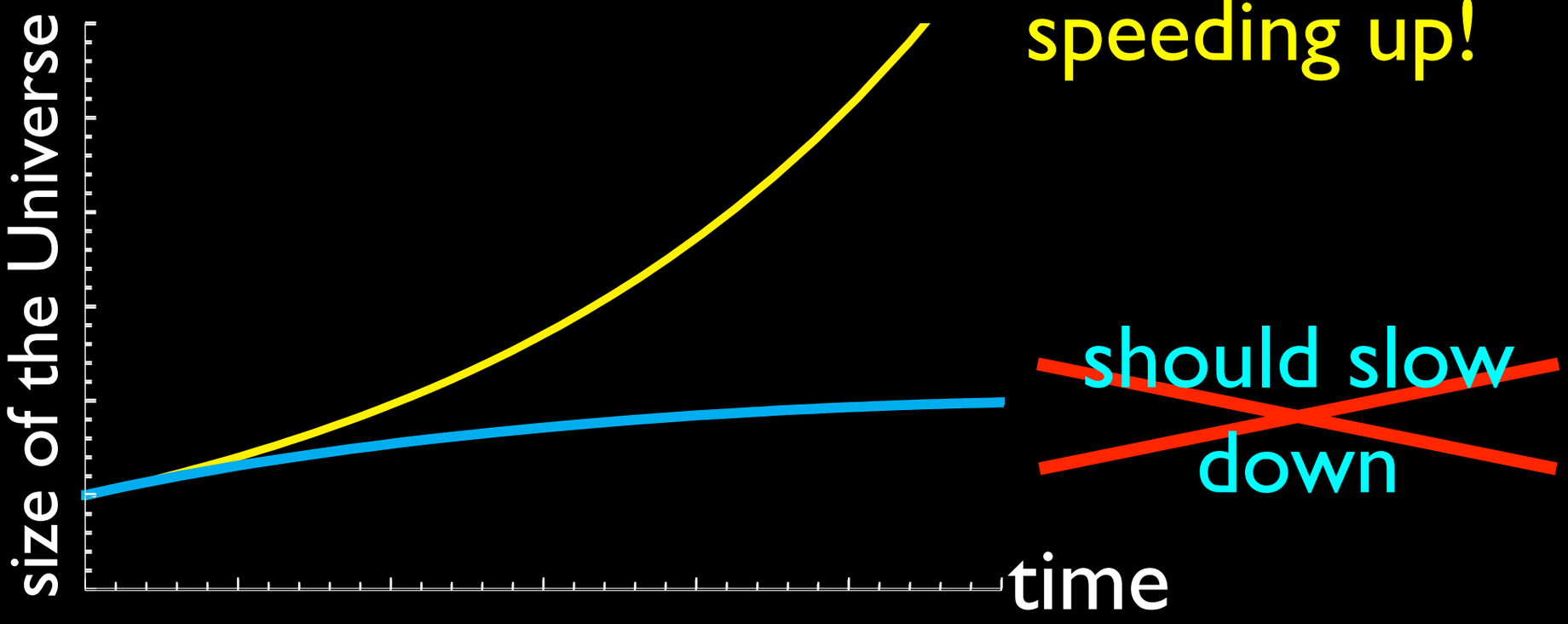

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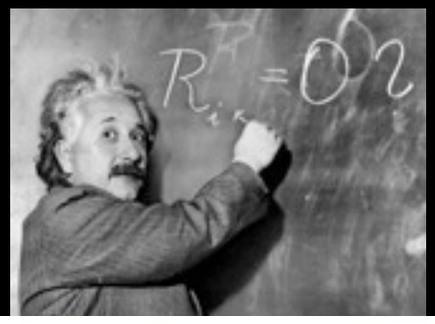

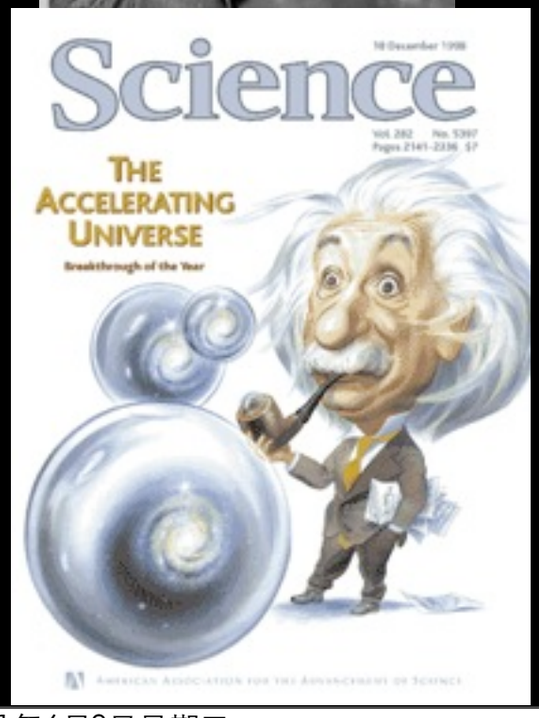

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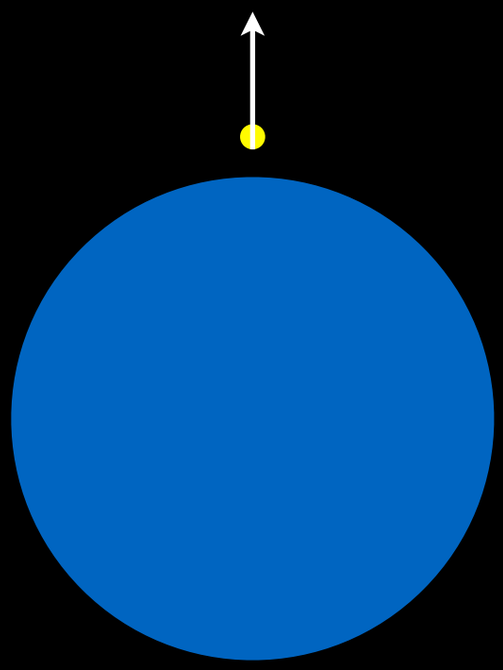

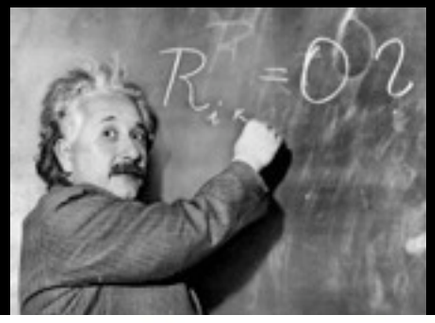

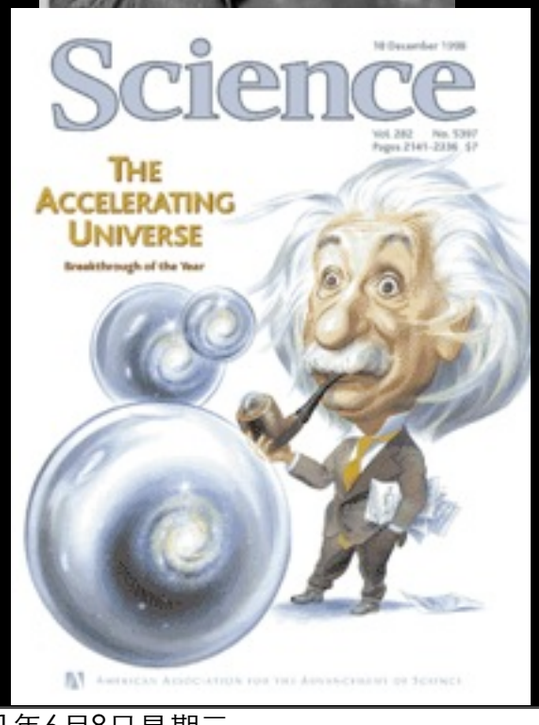

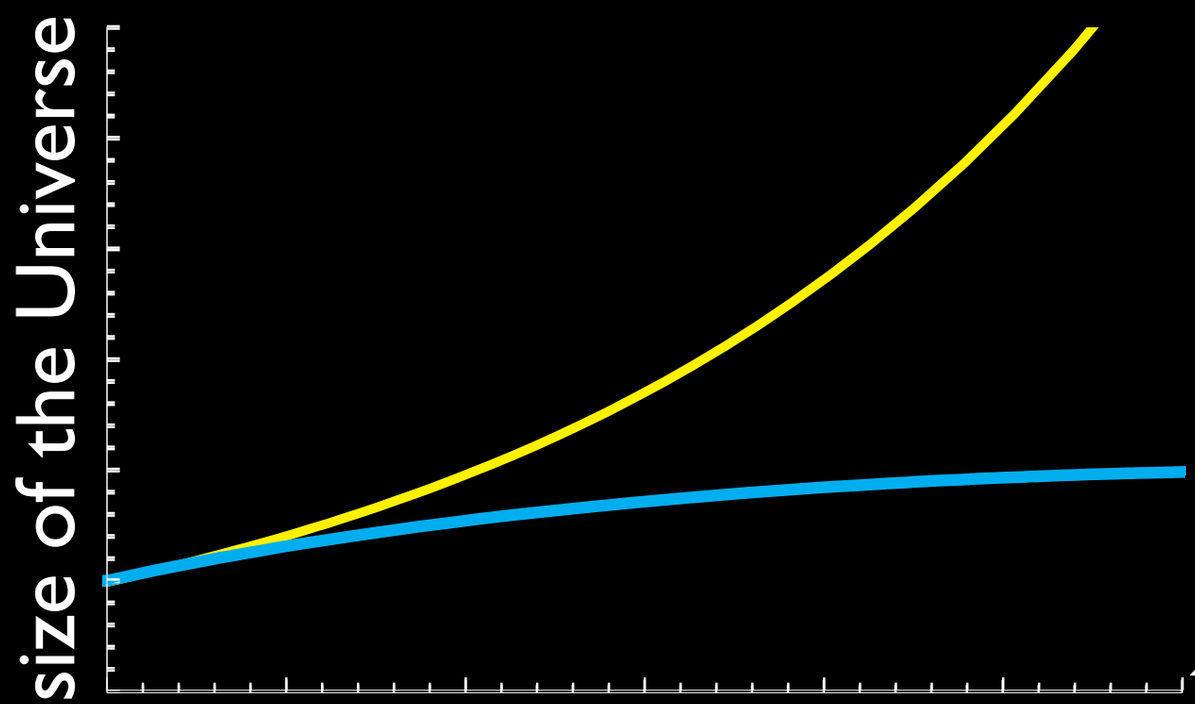

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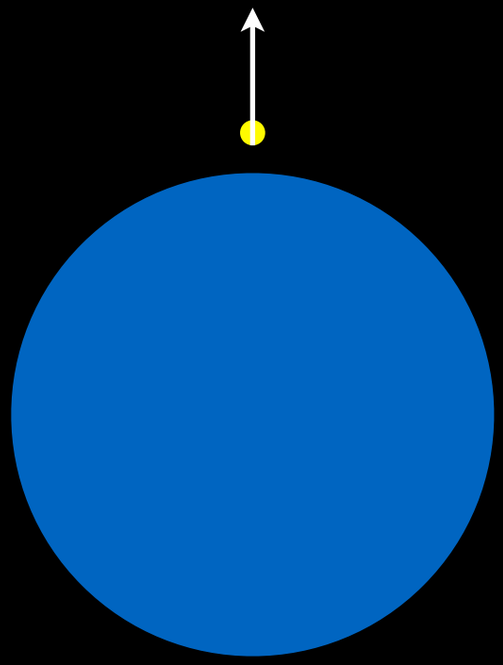

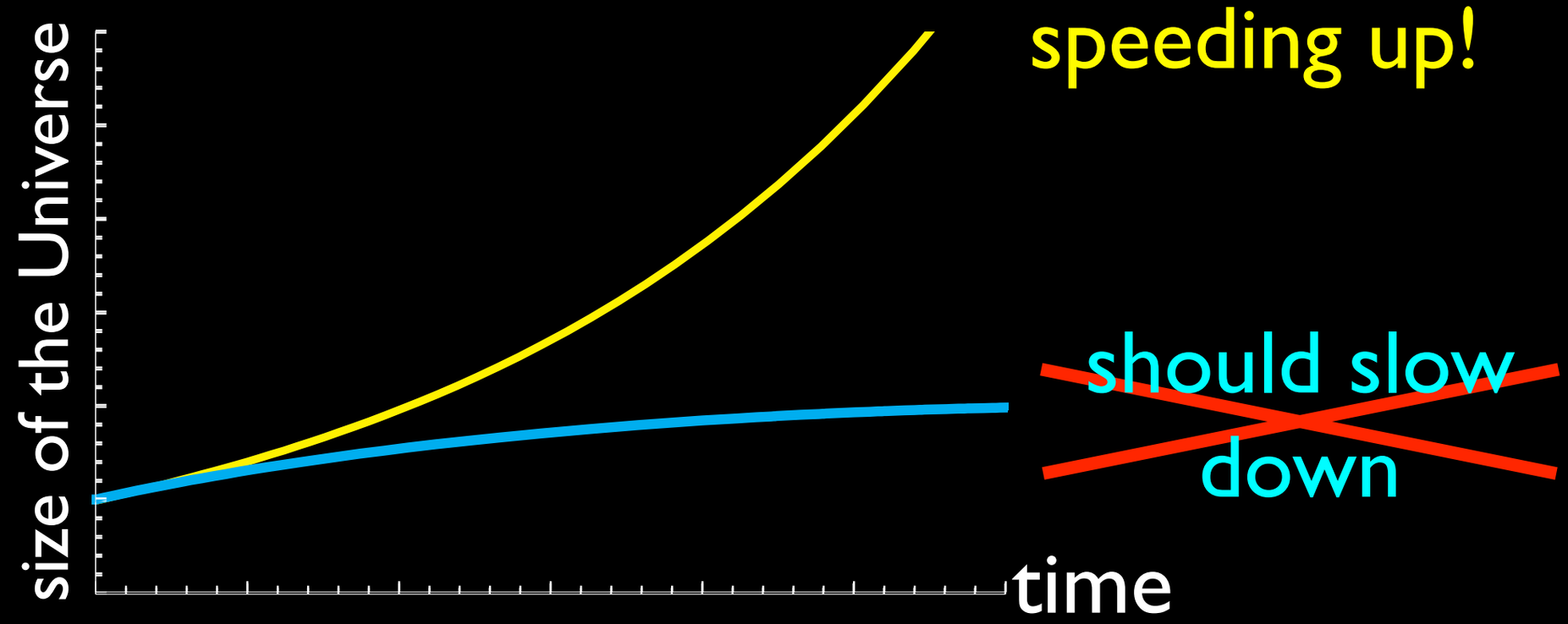

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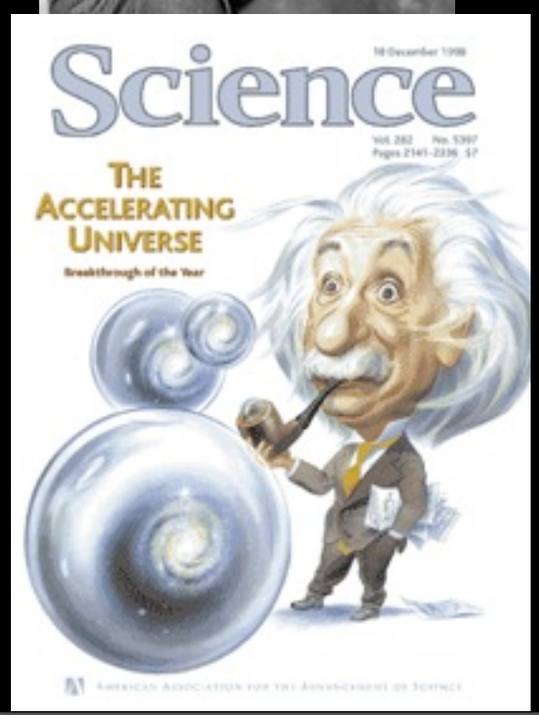



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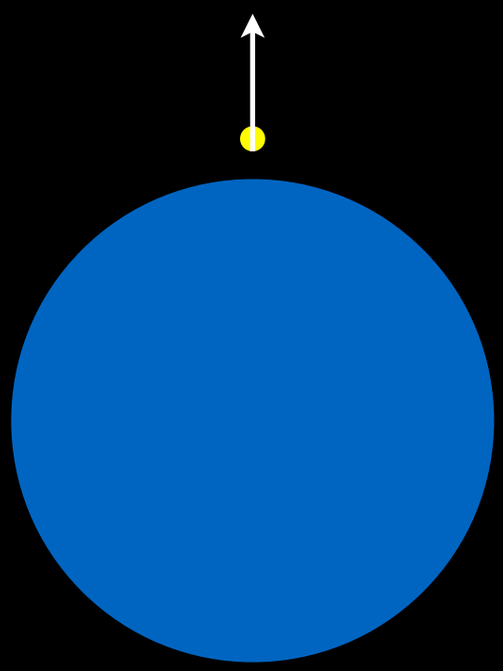

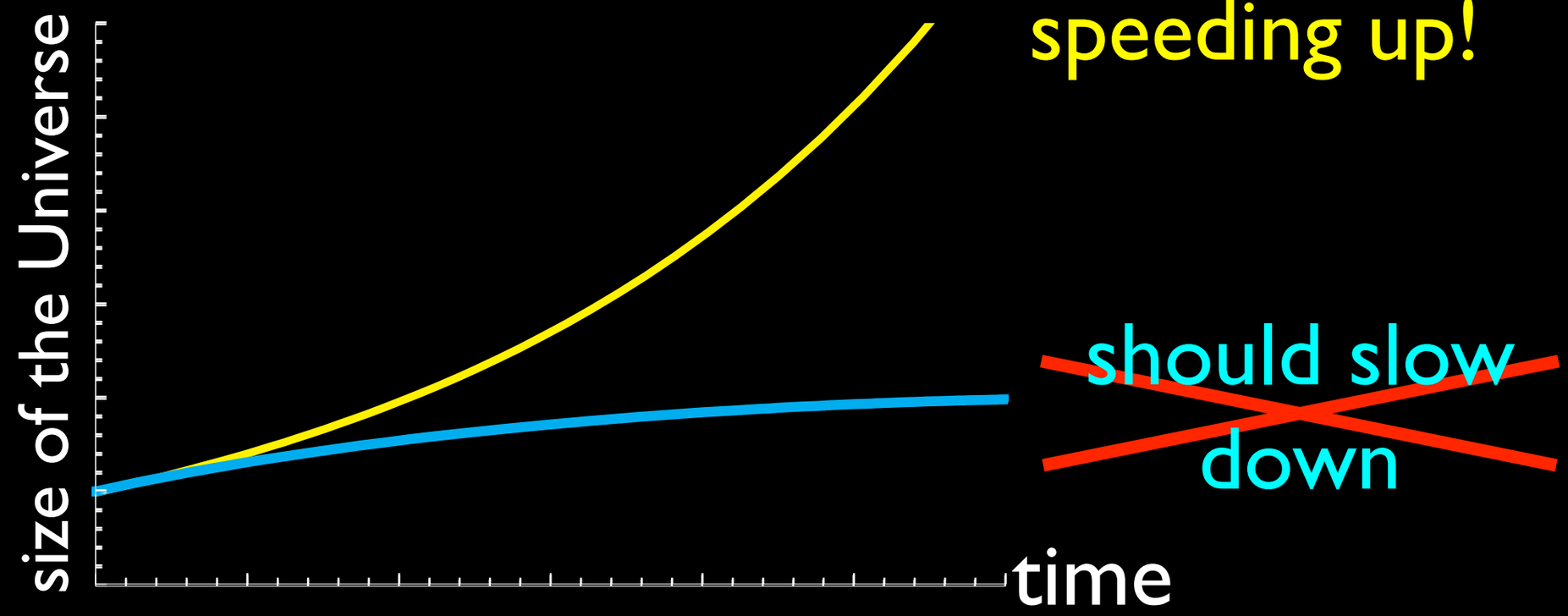

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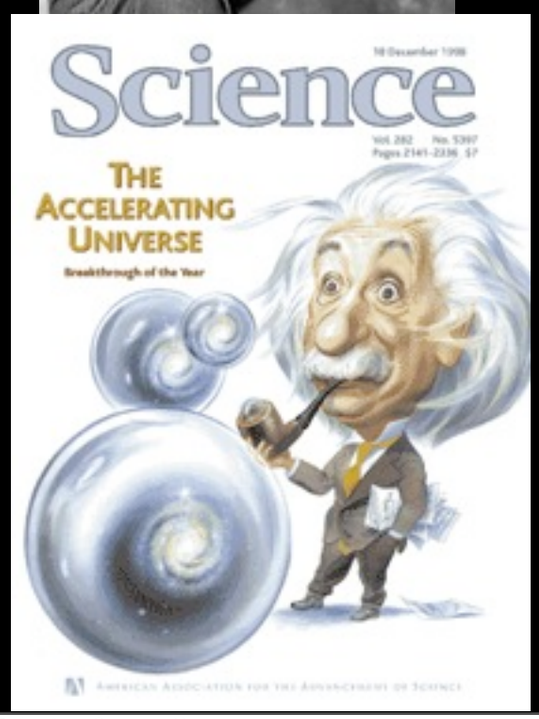



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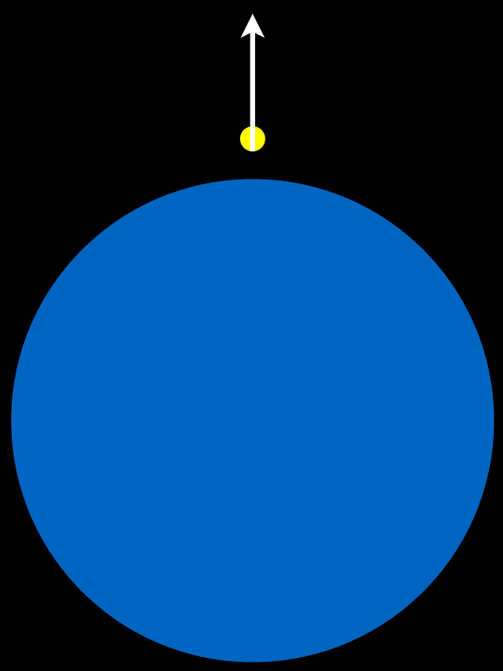

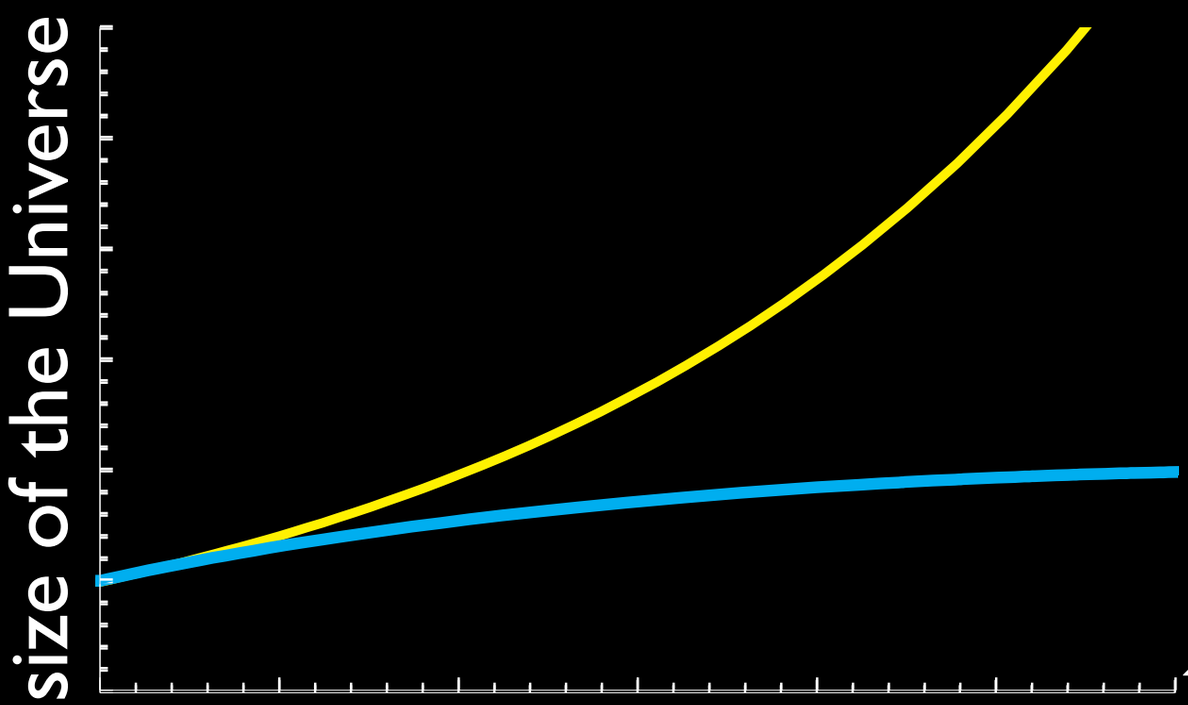

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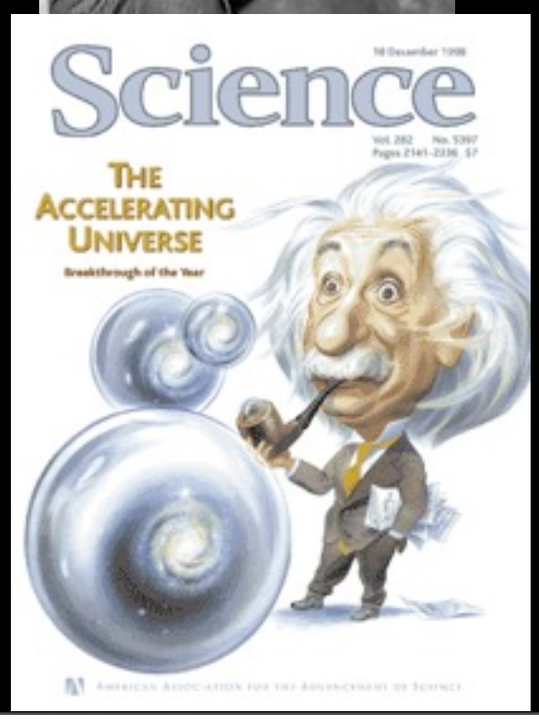



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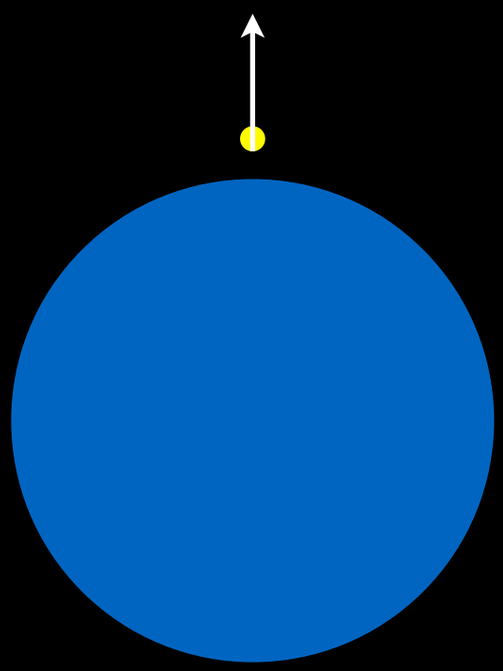

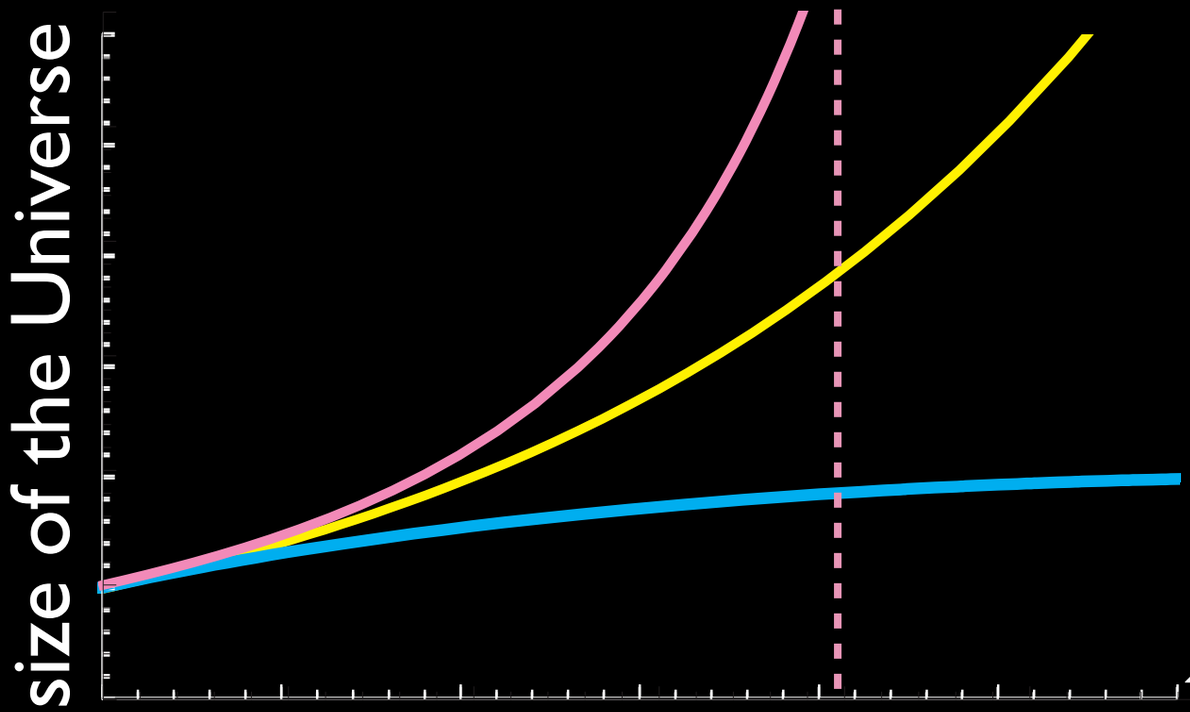

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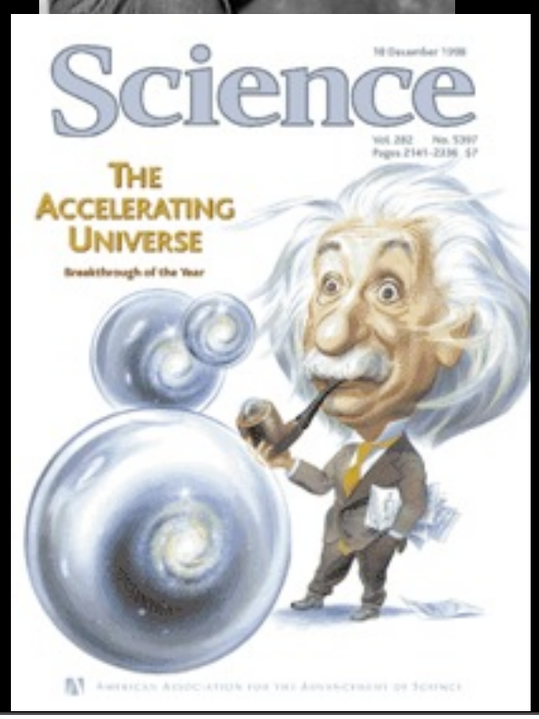



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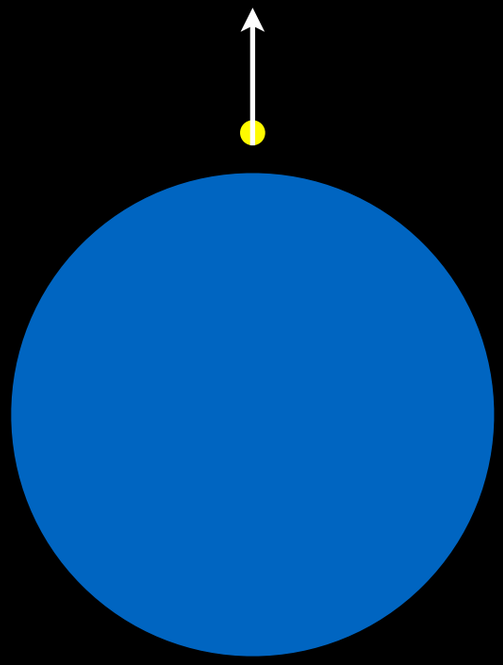

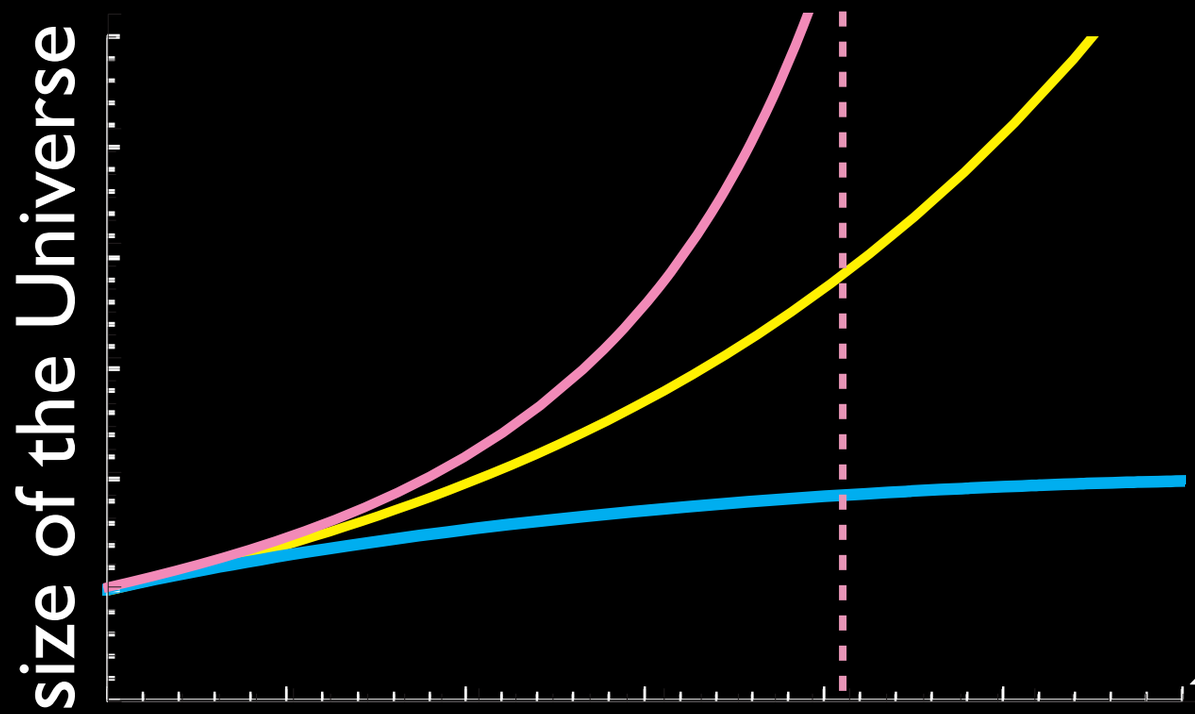

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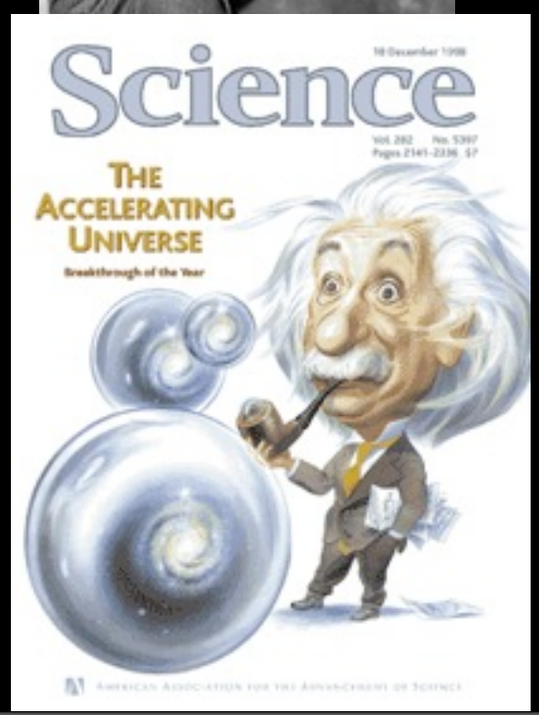
- Need to measure the rate of energy increase!

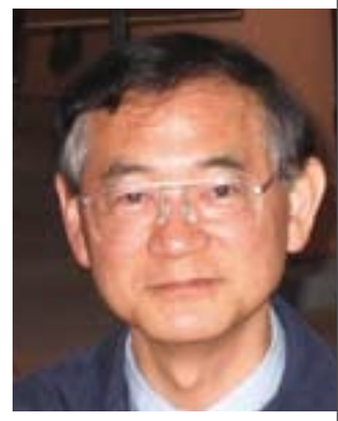






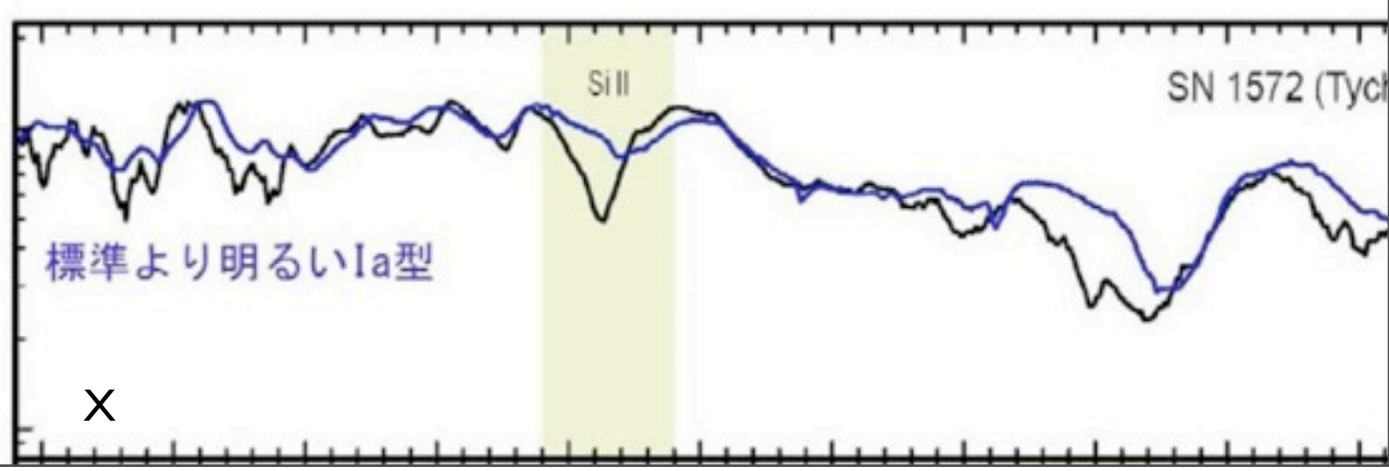


Echo of Tycho's supernova *Nature*, 456 (2008) 617



- Tycho's supernova observed in 1572
- not known its type
- Nomoto (PI) and collaborators observed its *echo* due to reflection by dust cloud, spectral analysis by Subaru telescope
- determined to be Type-IA, the kind used to discover Dark Energy





Embarrassment

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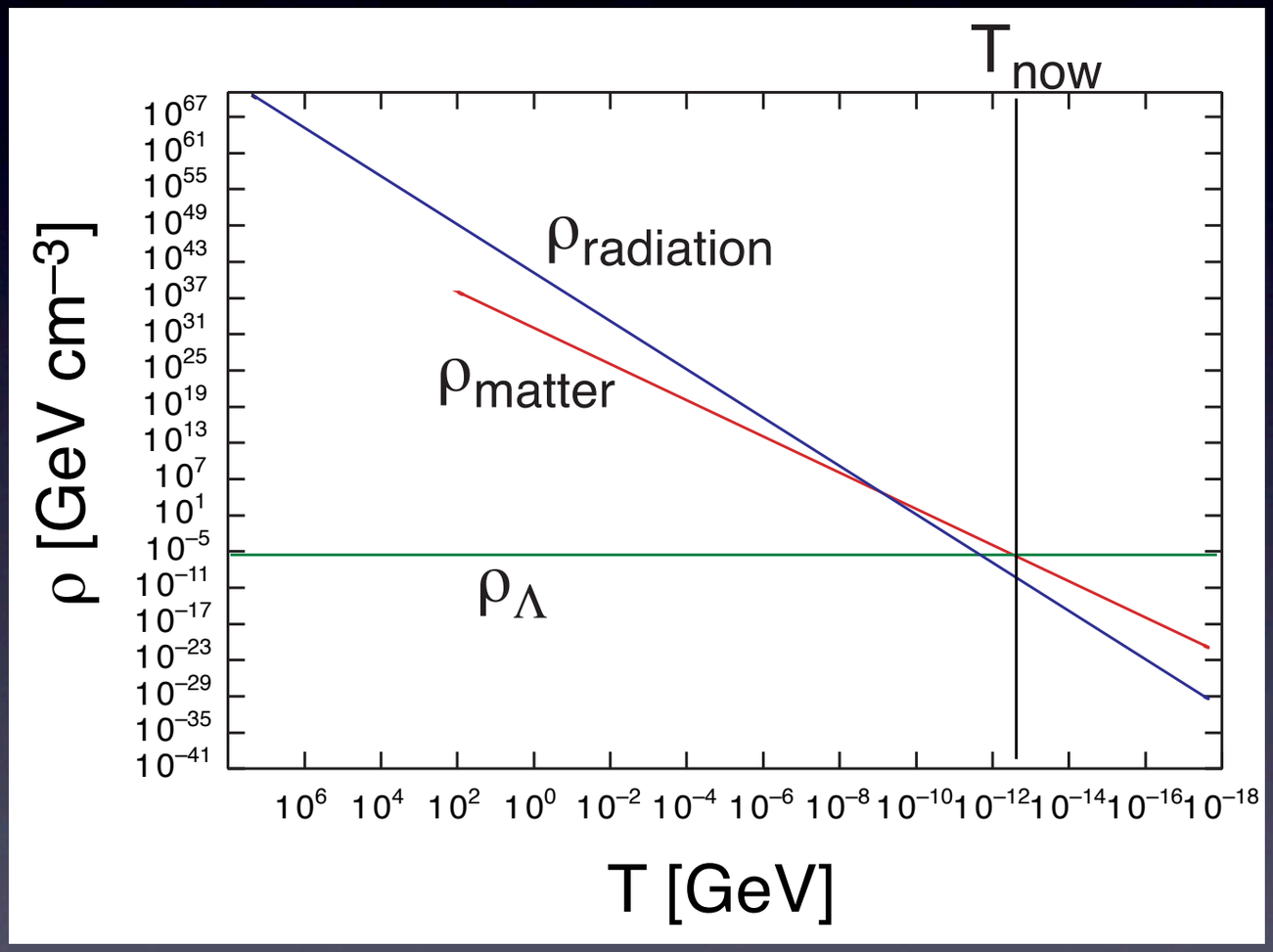
The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero
- But now it seems finite???

Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- *Actually a triple coincidence problem including the radiation*
- If there is a deep reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, coincidence natural



Arkani-Hamed, Hall, Kolda, HM

Does the Universe end?

- If $w<-1$, the Universe ends in a Big Rip
- Expansion becomes so fast that galaxies, stars, eventually atoms and even nuclei get ripped apart
- Universe ends with an infinite speed and empty!
- We need to know the equation of state



2011年6月8日星期三





2011年6月8日星期三

We can study cosmology only now.

Need funding ASAP.







SuMIRe

Subaru

- Major study of dark energy
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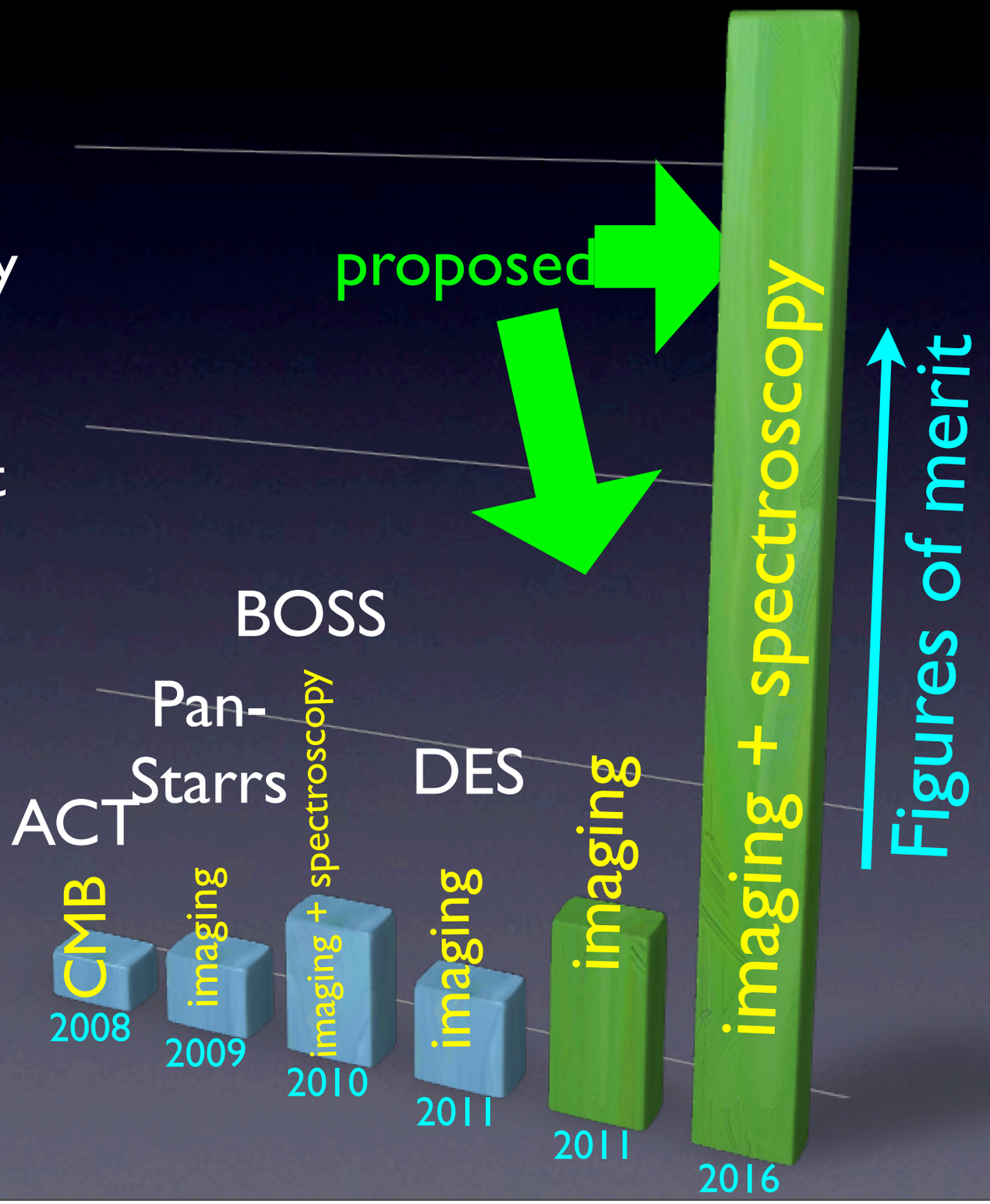



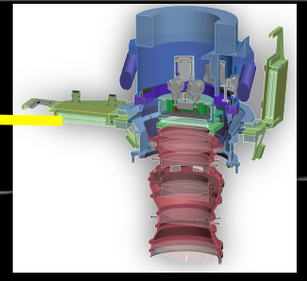

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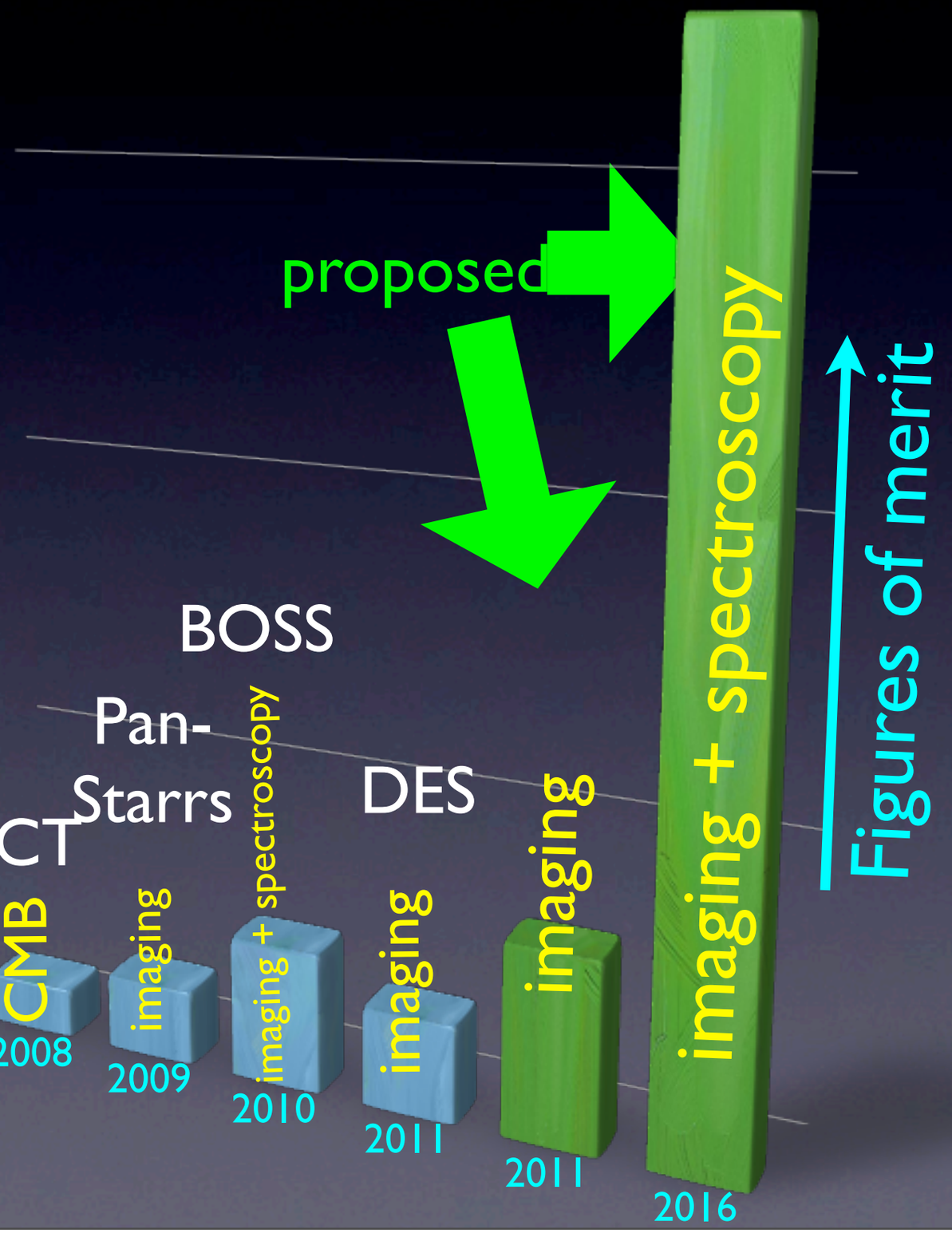



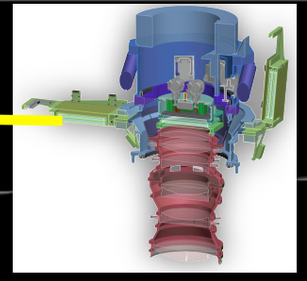

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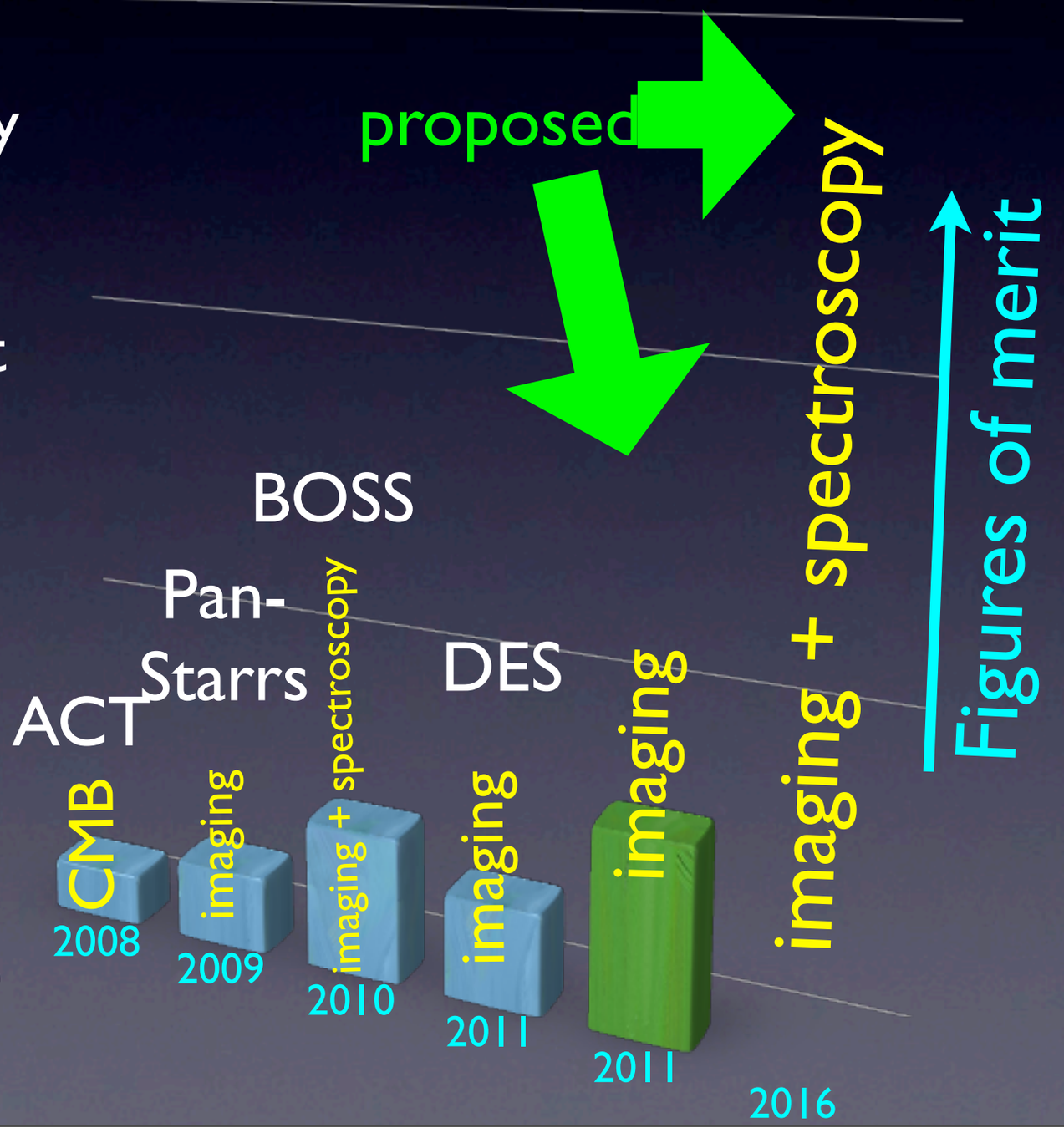



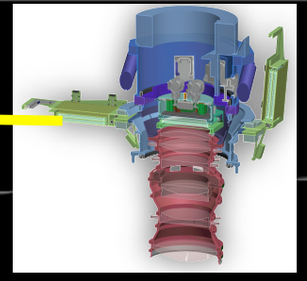

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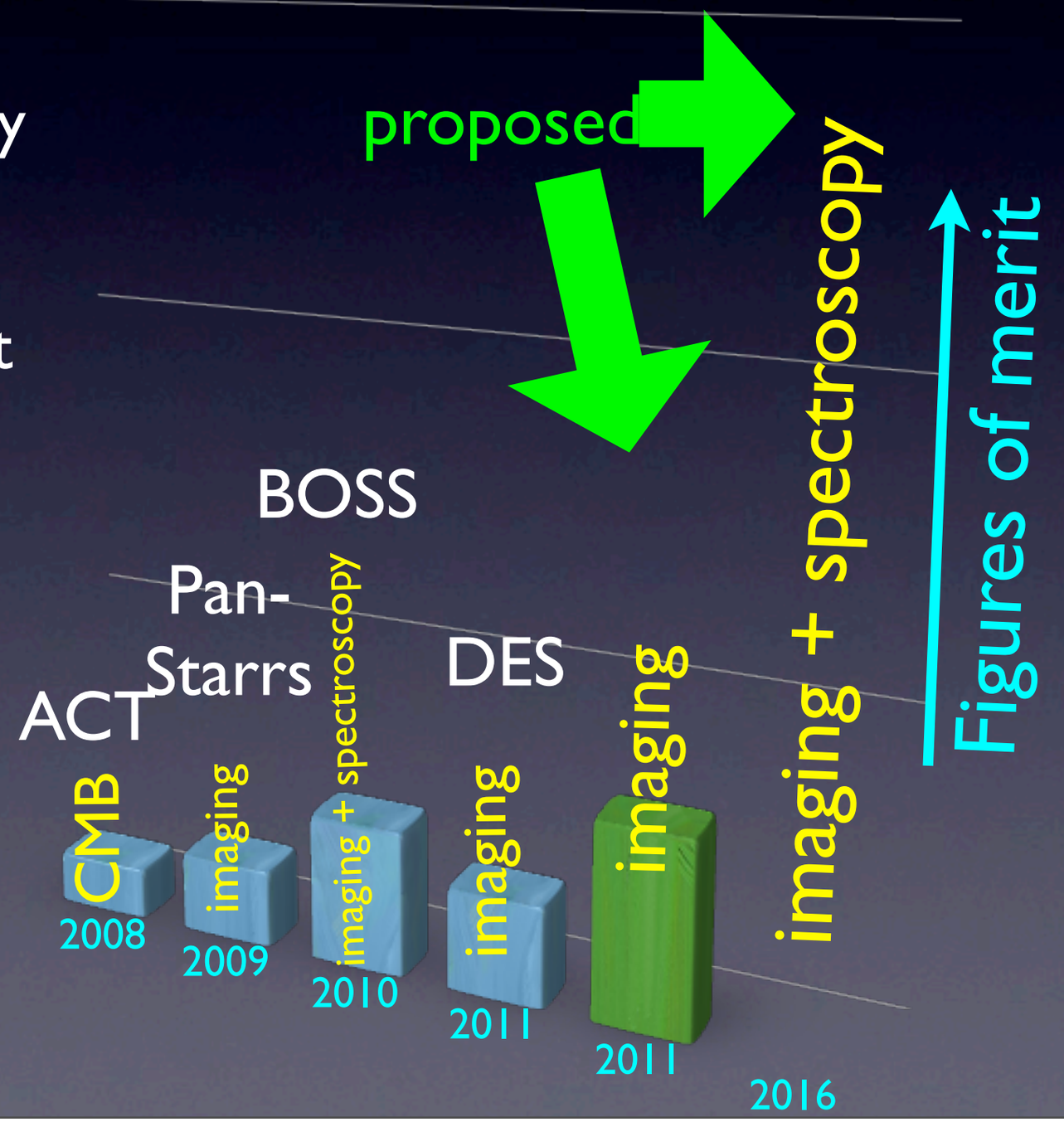

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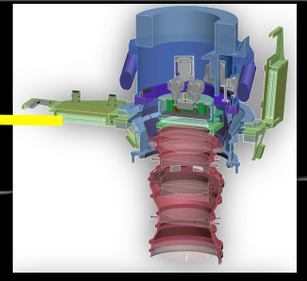

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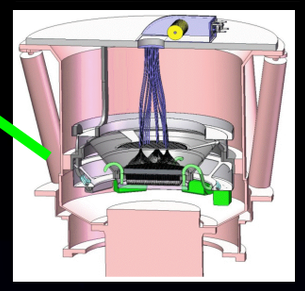

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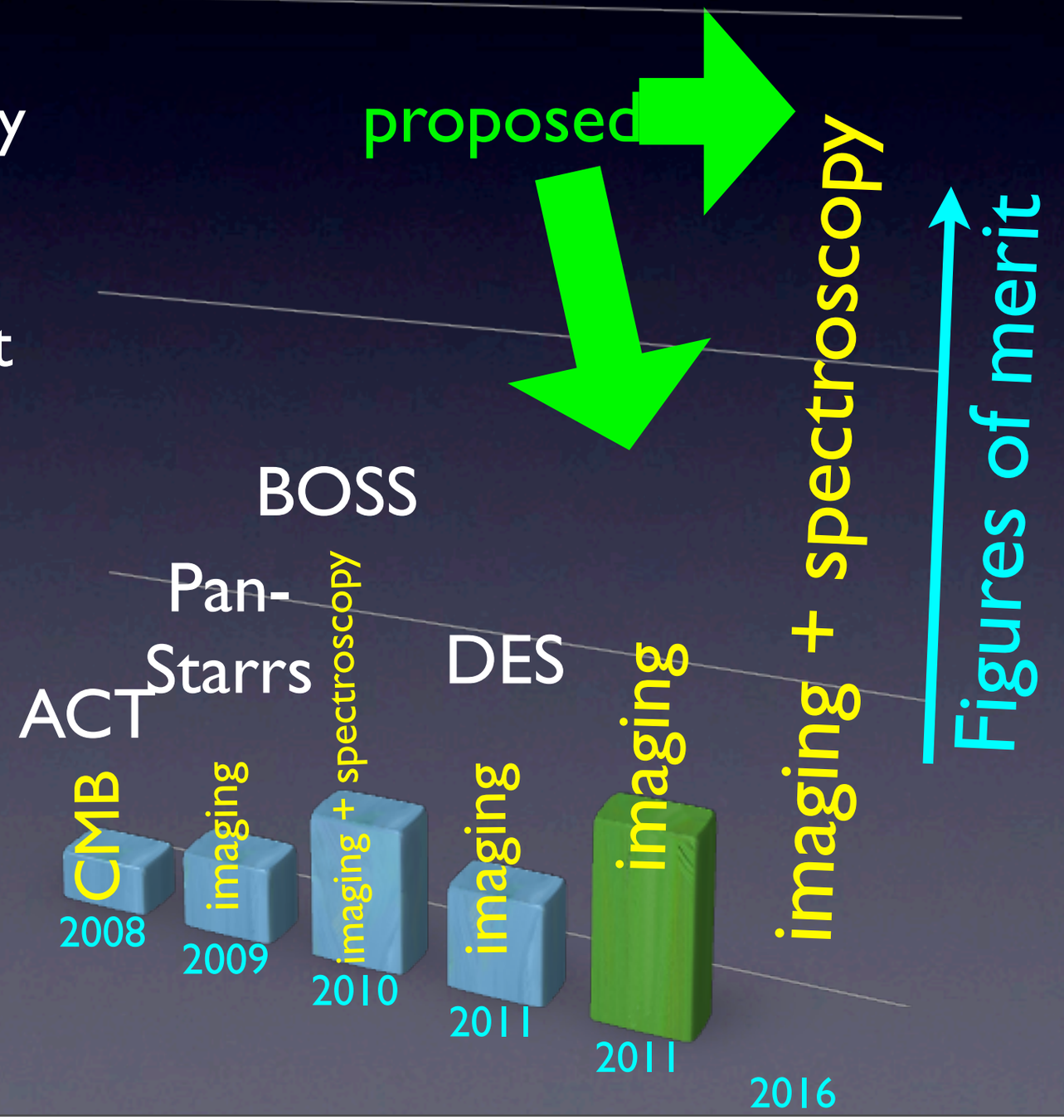

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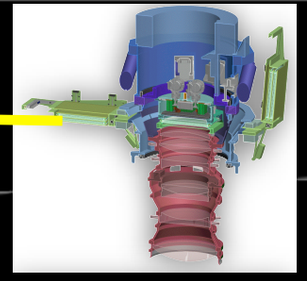

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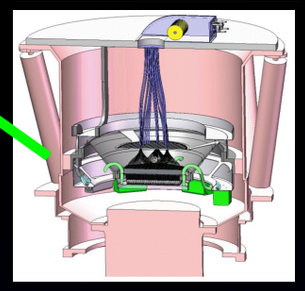

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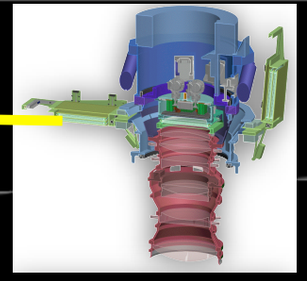

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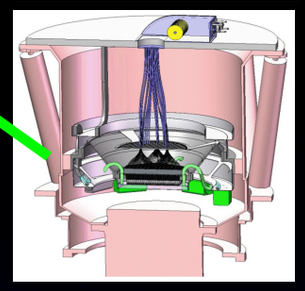

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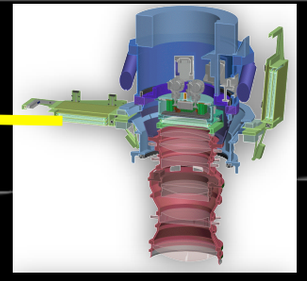

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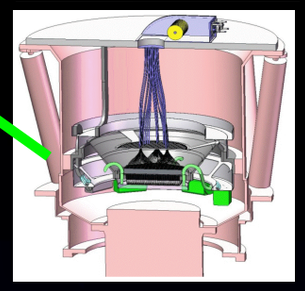

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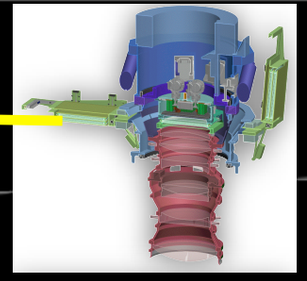

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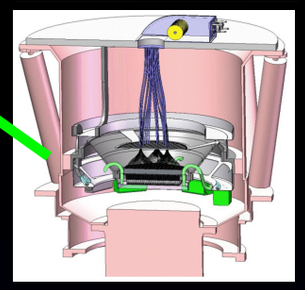

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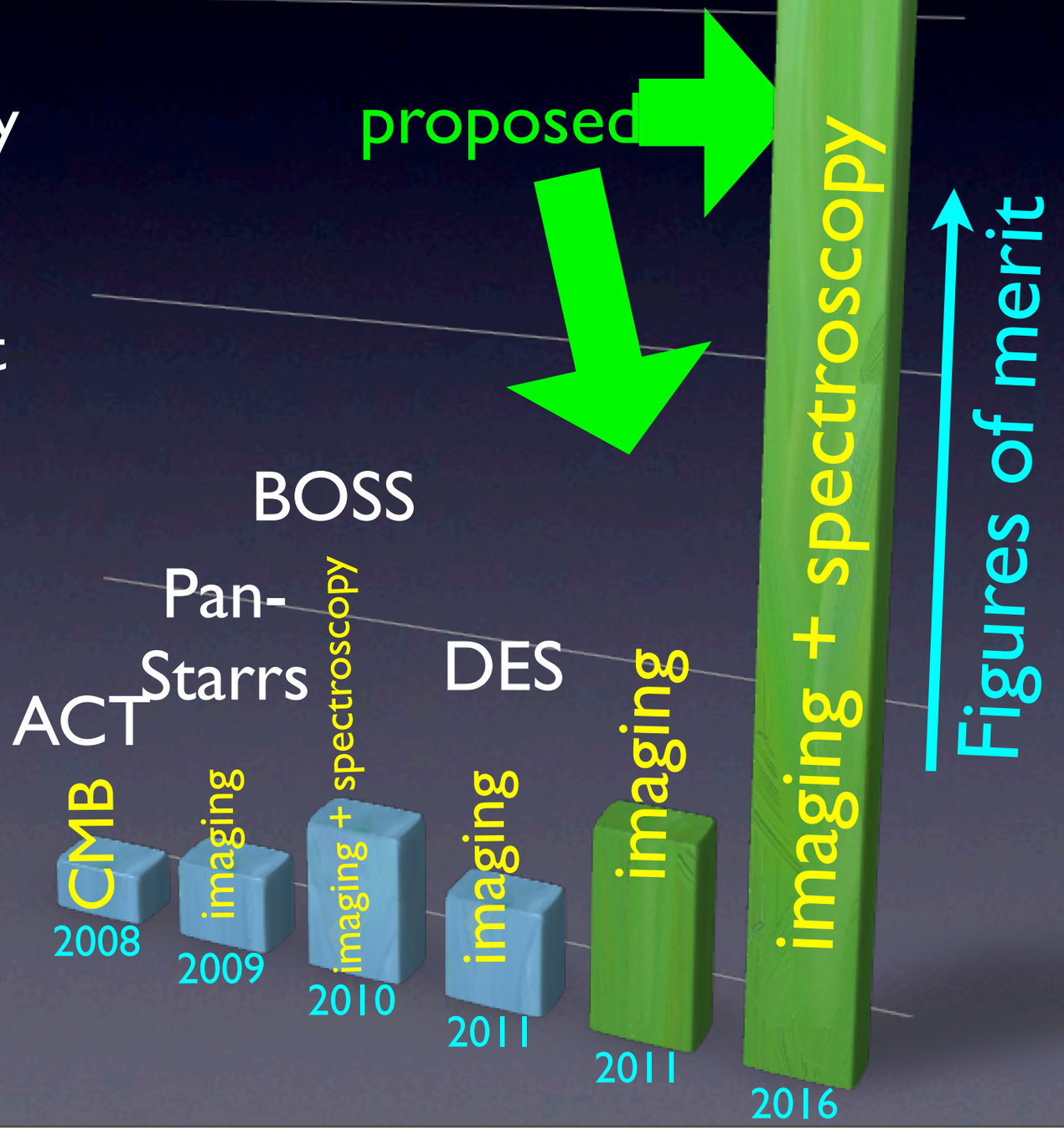



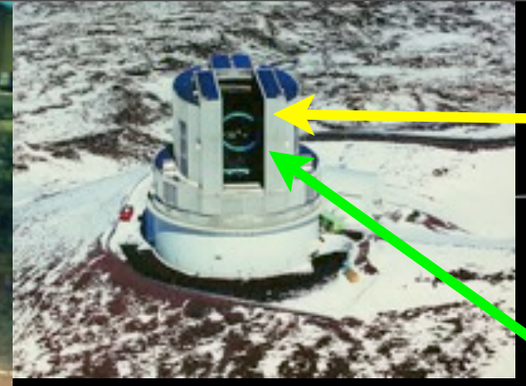

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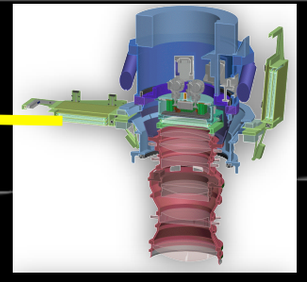

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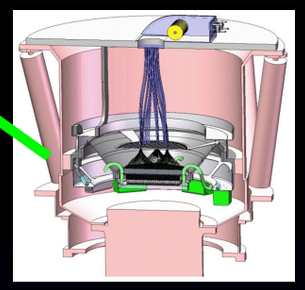

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Are all supernovae really the same?





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- some individualities in how quickly spectral features evolve



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- found strong evidence that it depends on which side you look at



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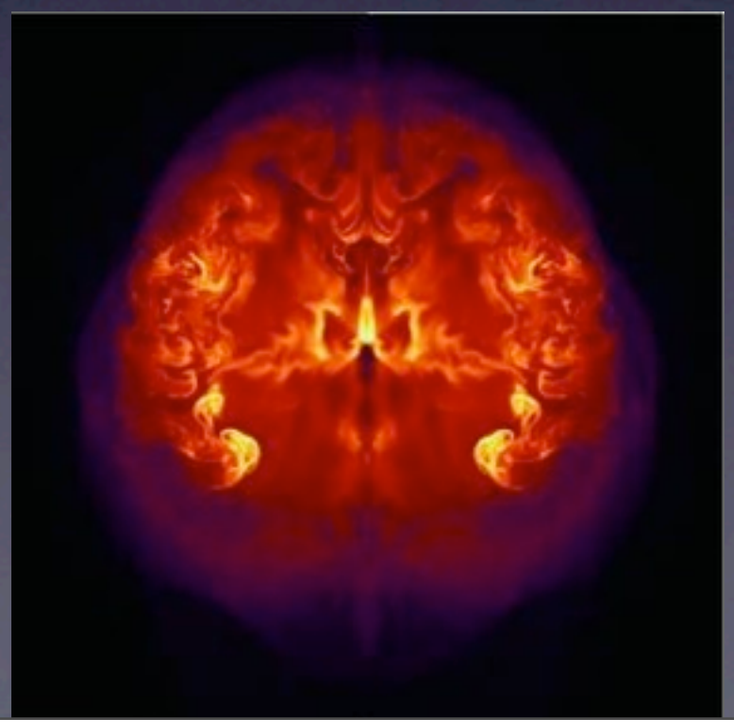



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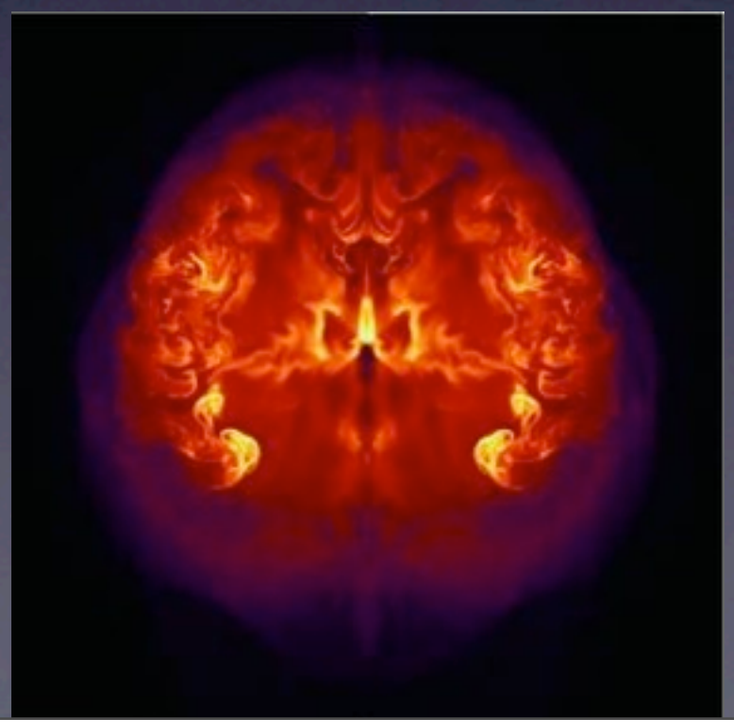
- Can we look at a supernova from all directions?







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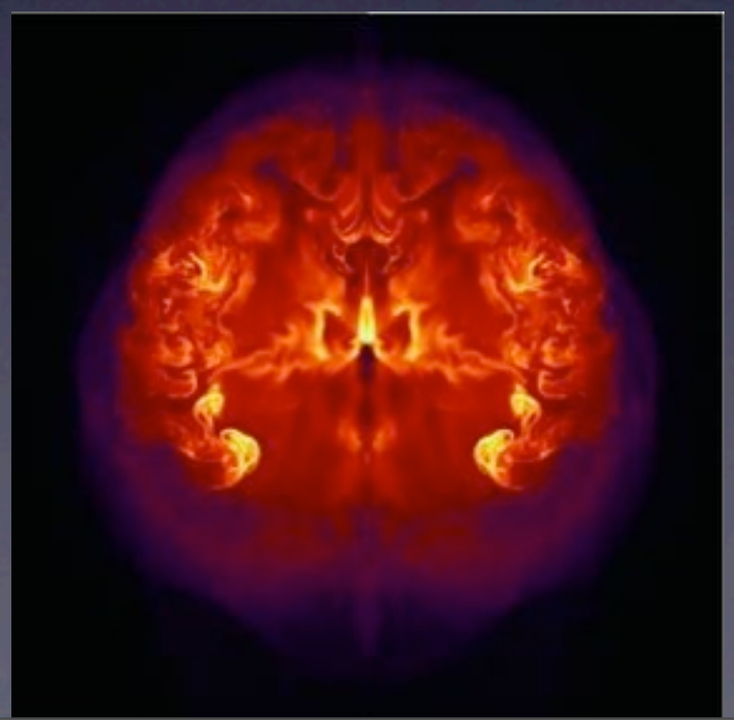



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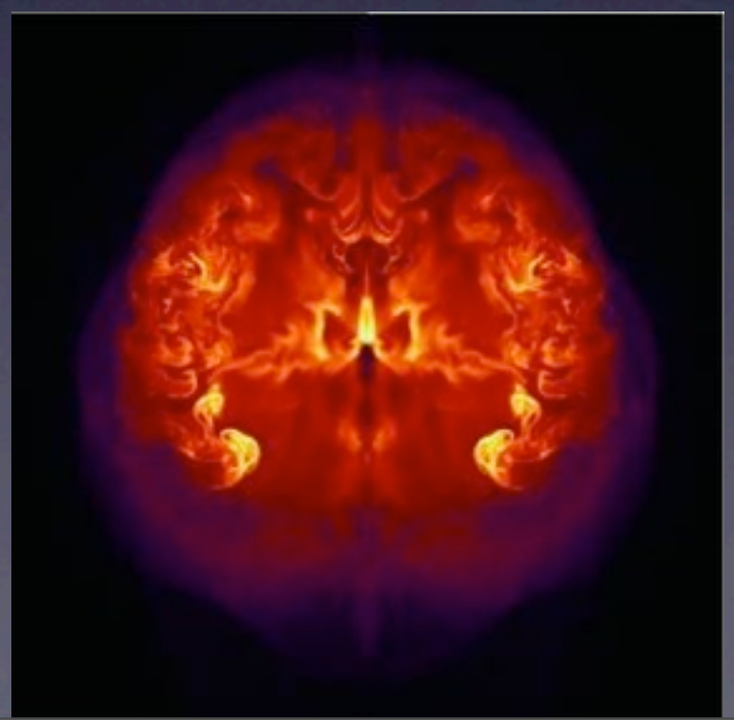

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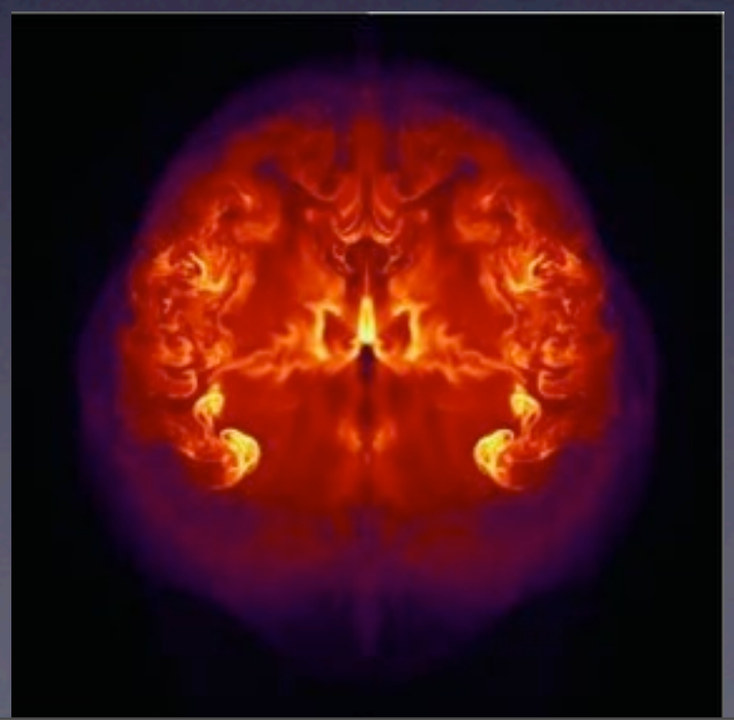

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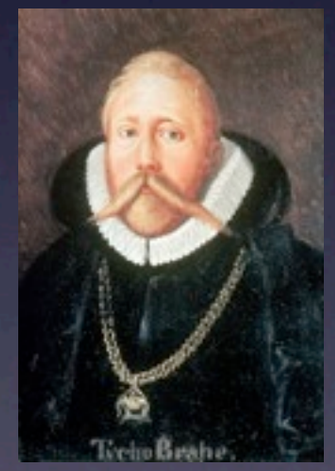



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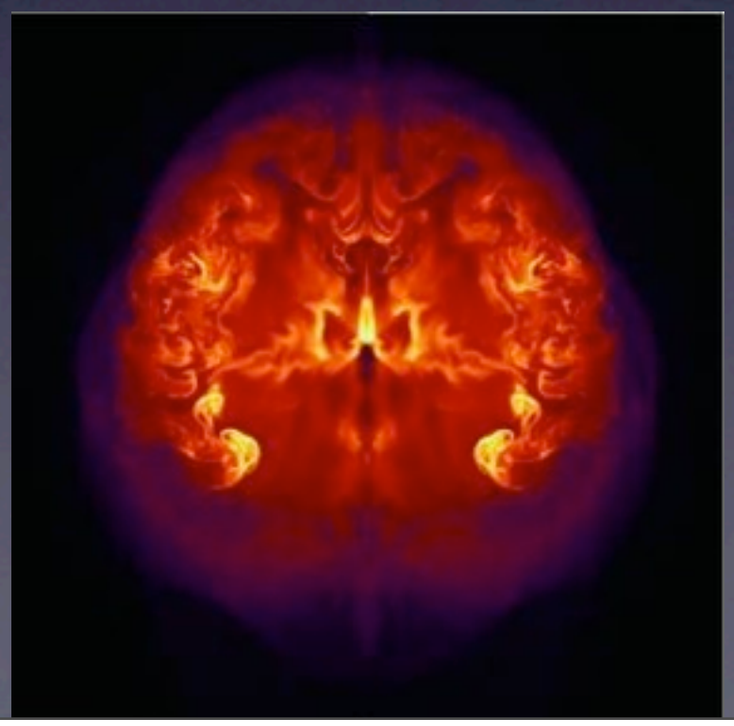

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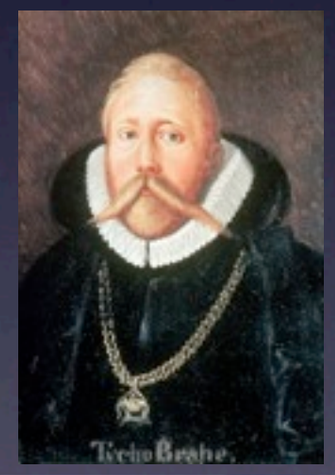





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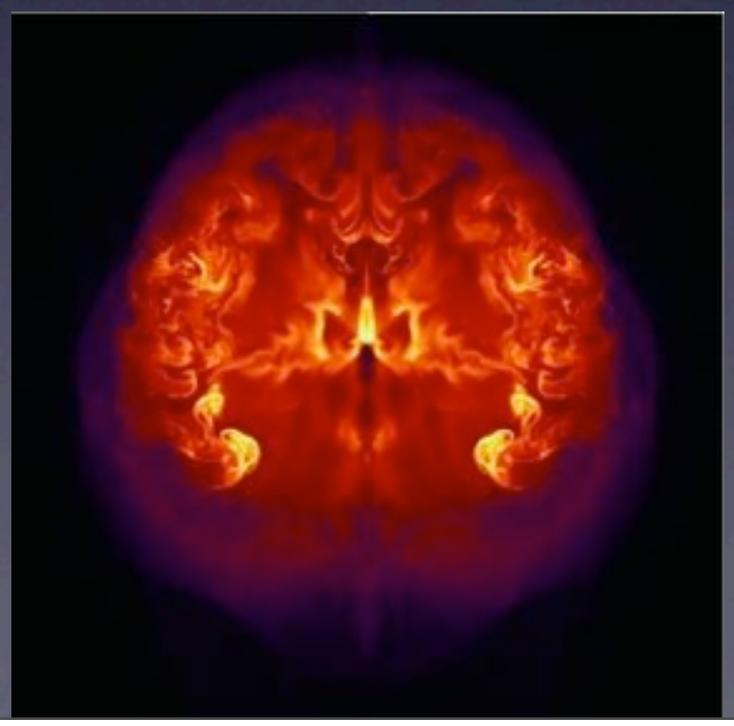

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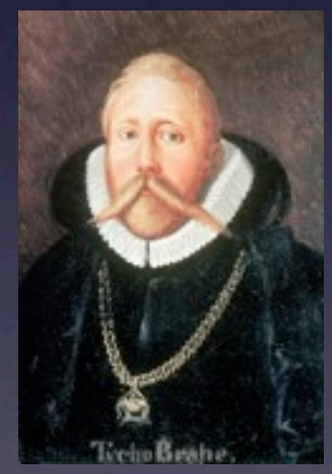
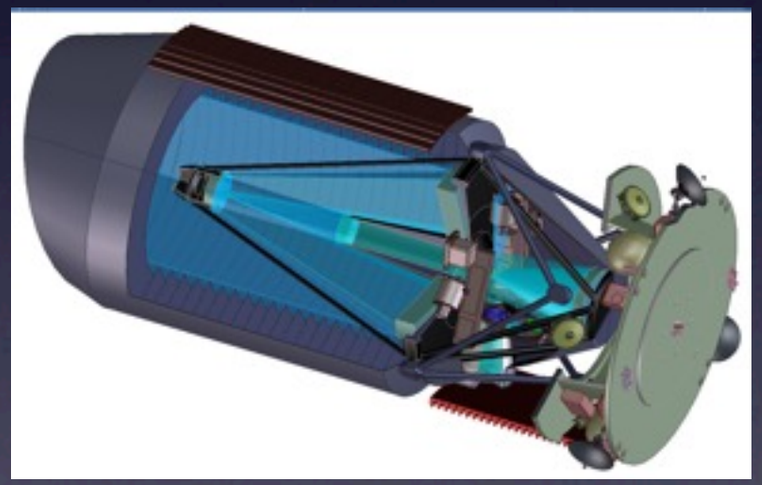




What is Dark Energy?

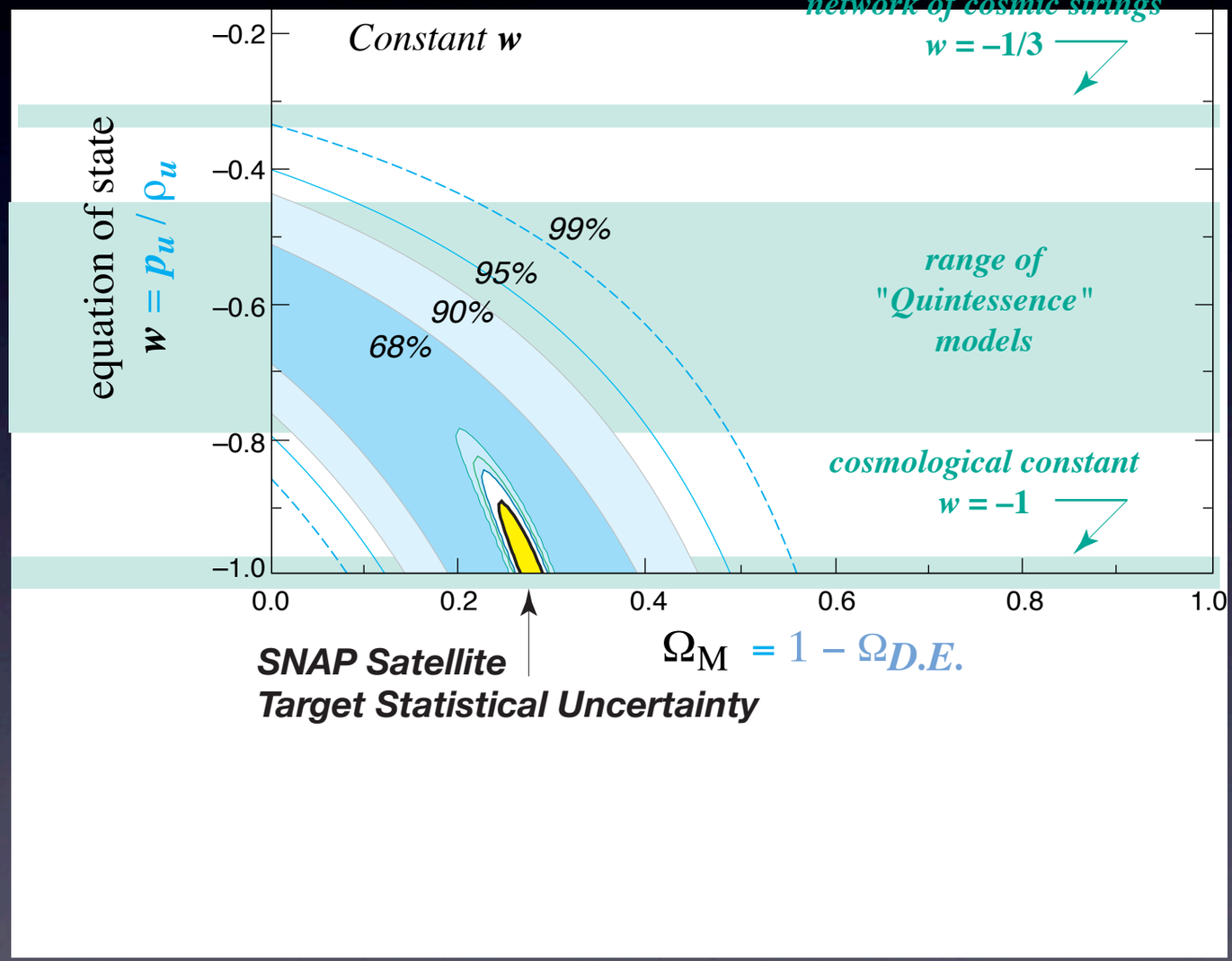
Supernova Cosmology Project
Perlmutter *et al.* (1999)

- We have to measure w
- For example with a dedicated satellite experiment



SNAP

- or on the ground: DES, BOSS, LSST, etc



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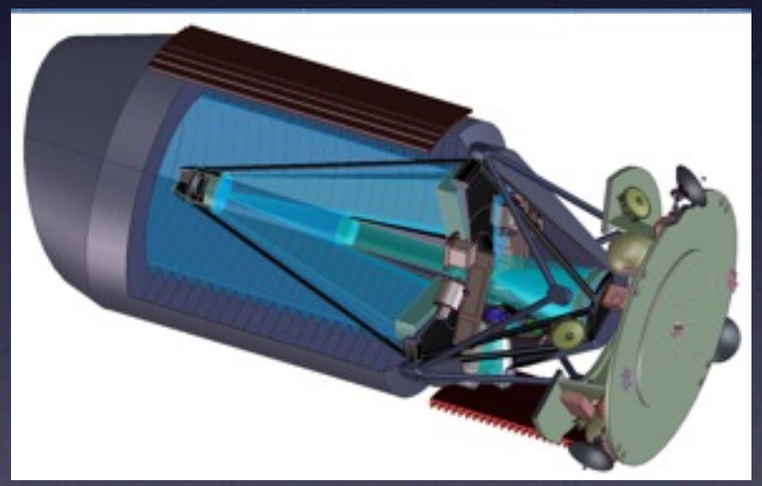

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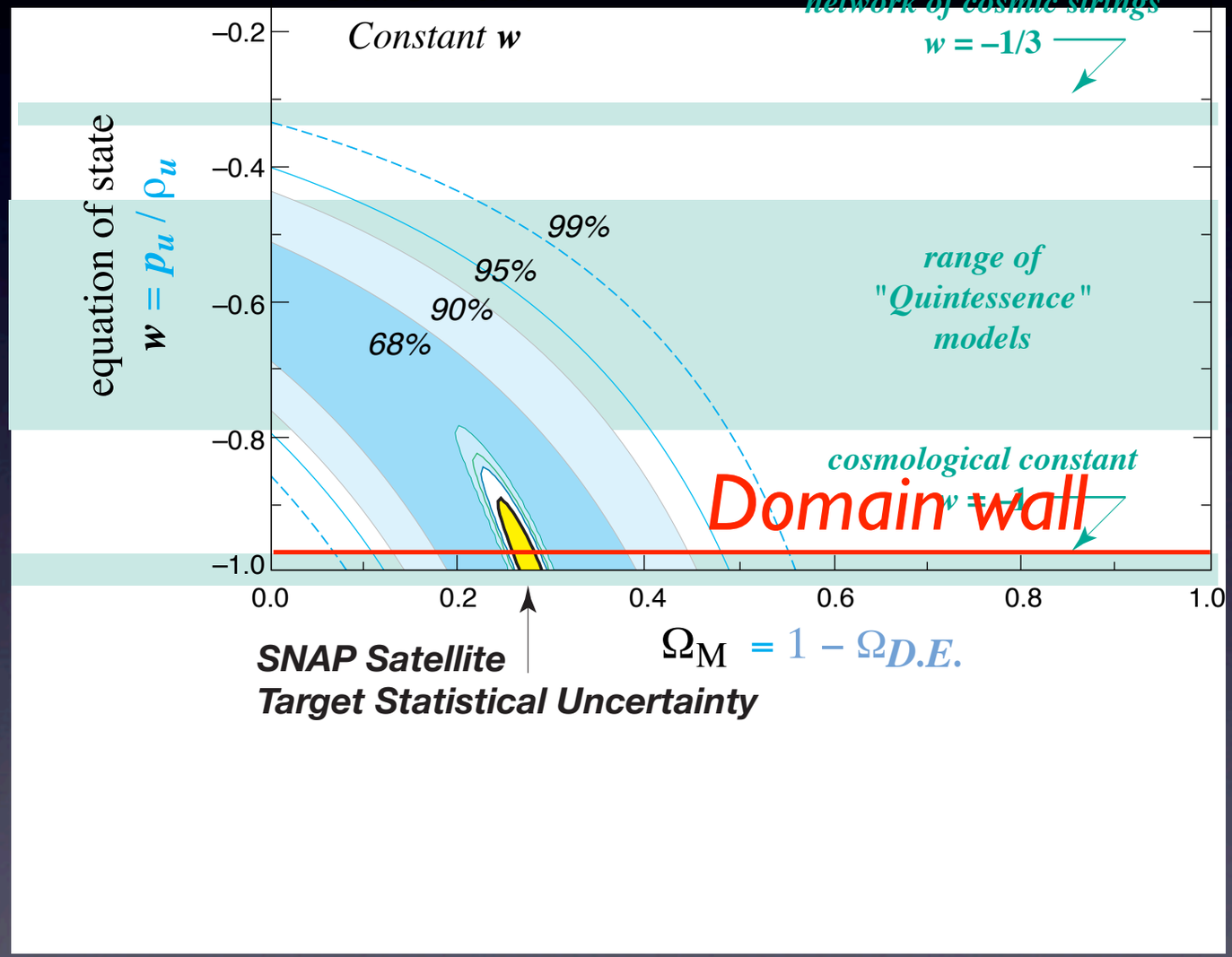
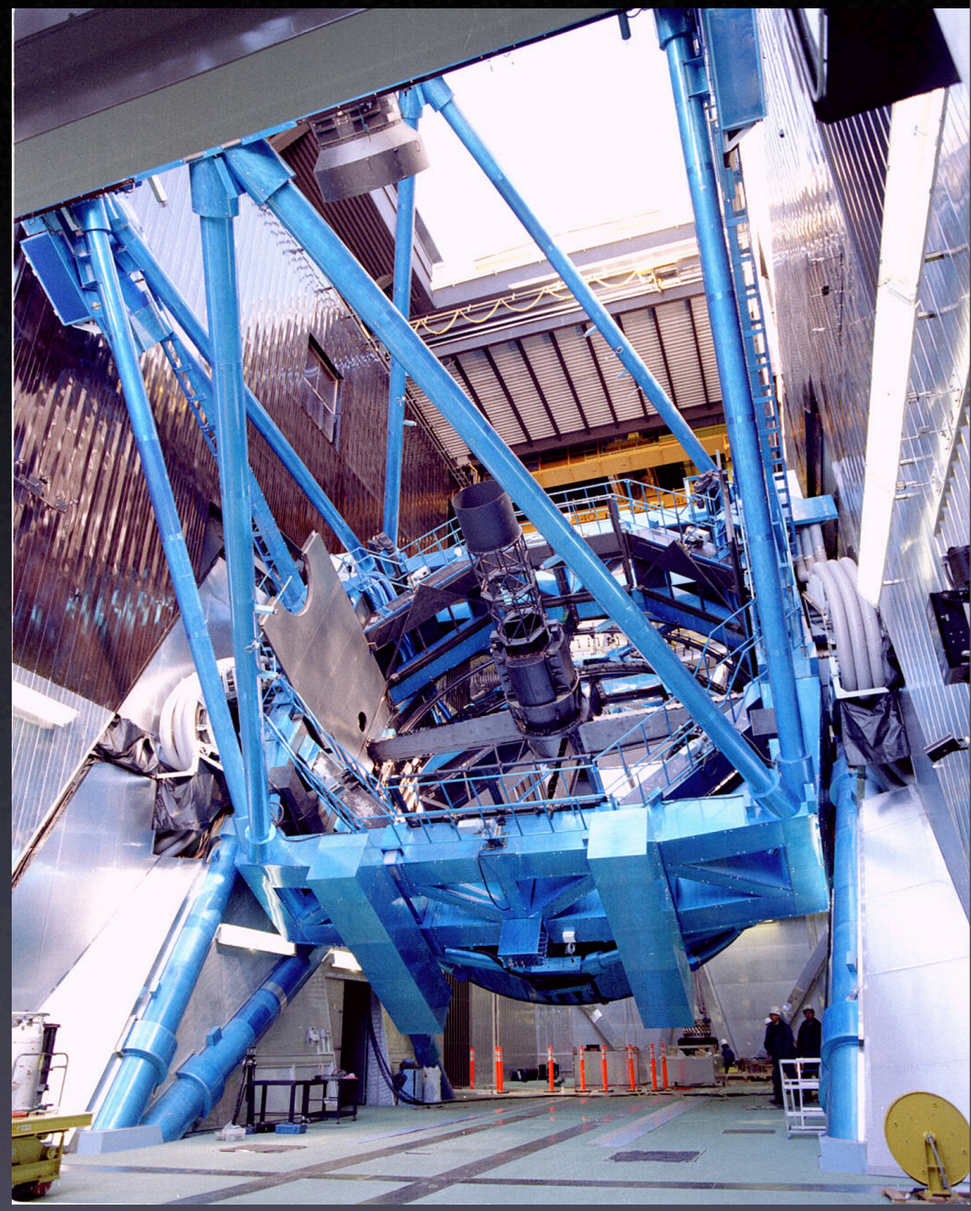


Friedland, HM, Perelstein

HyperSuprimeCam

- New camera at Subaru
- IPMU, NAOJ, KEK, Princeton
- IPMU leads the design (Aihara)
- IPMU leads the analysis team (Takada, Yoshida)
- map out distribution of dark matter
- constrain dark energy properties



X

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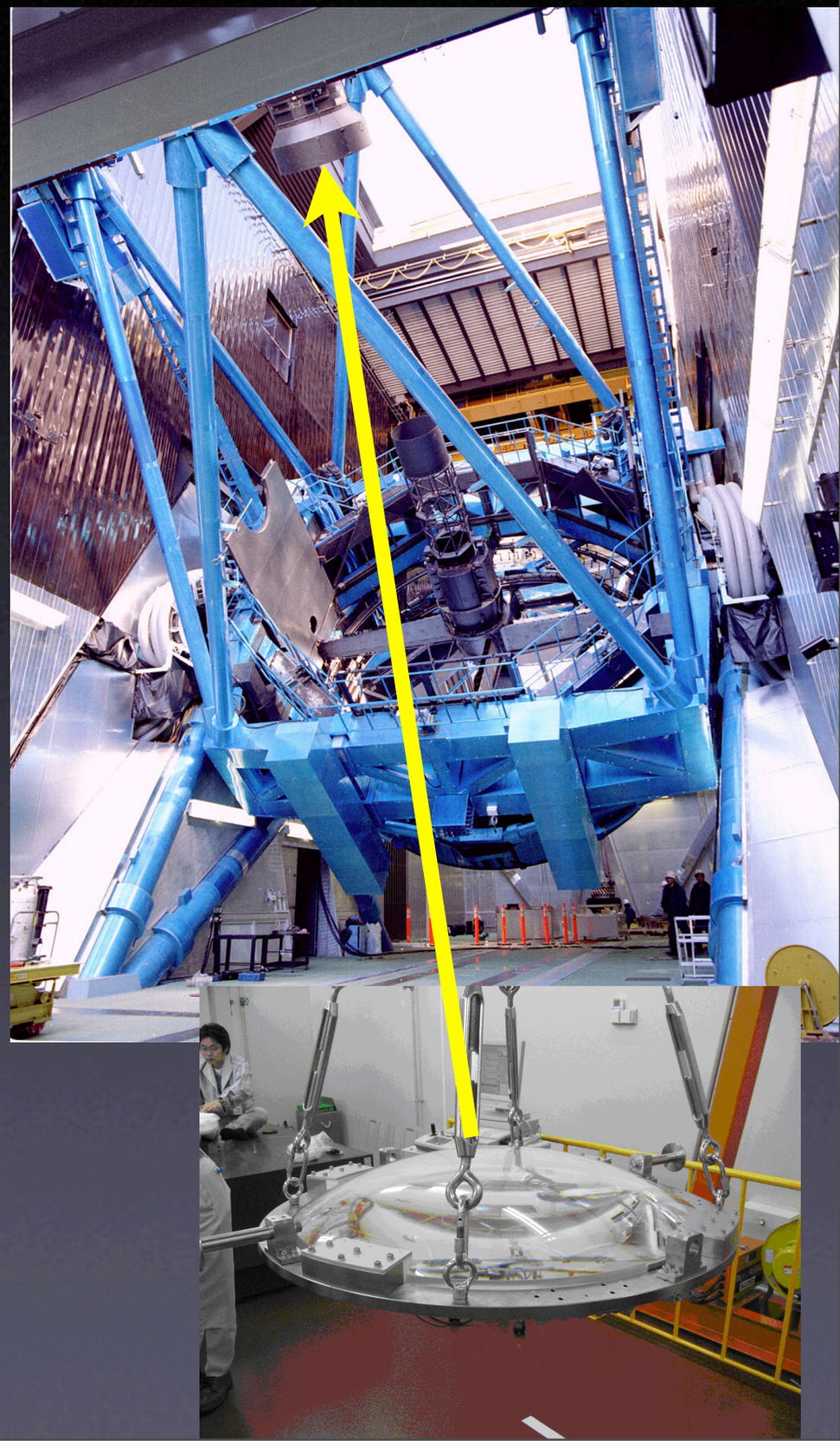

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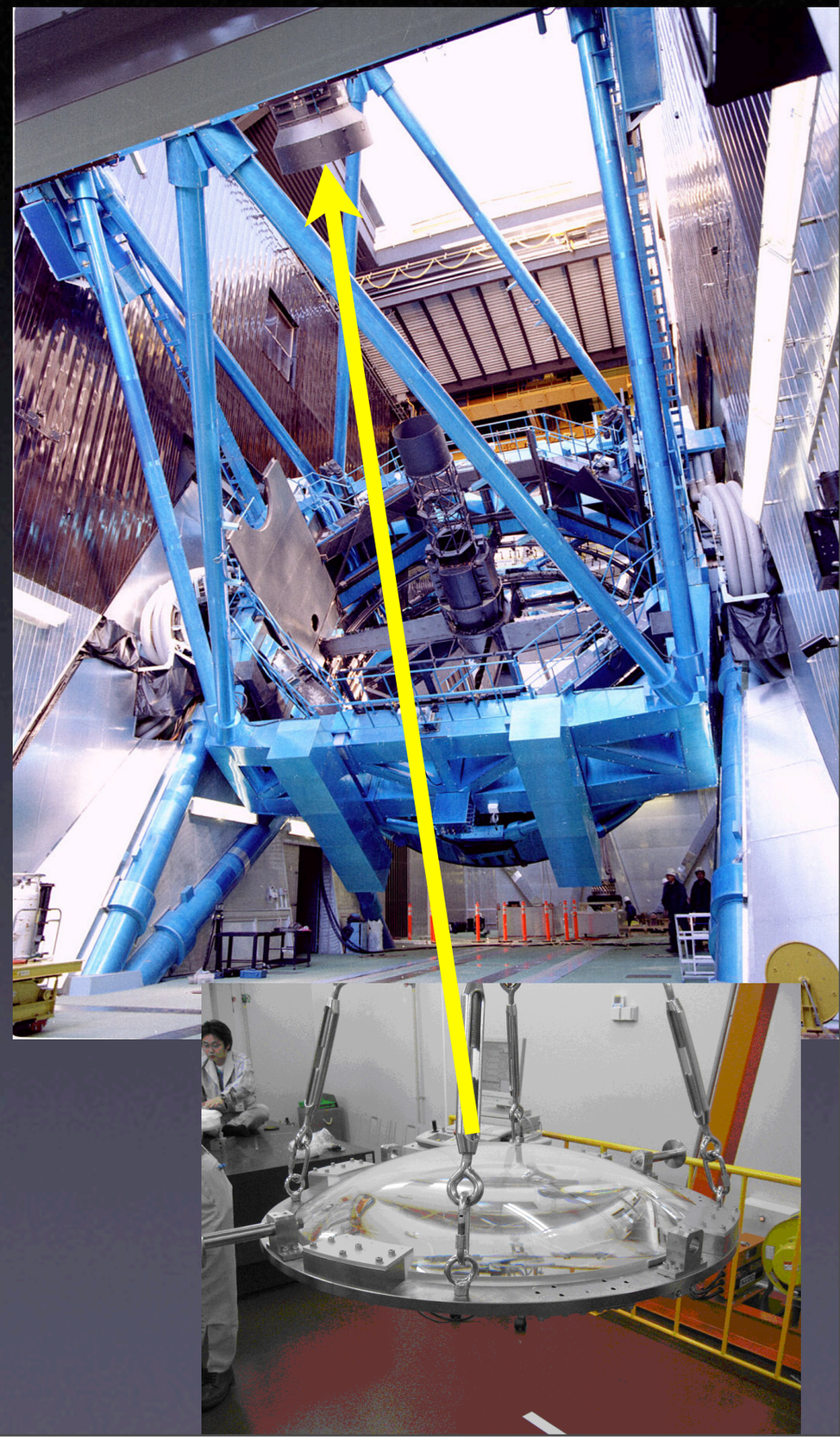
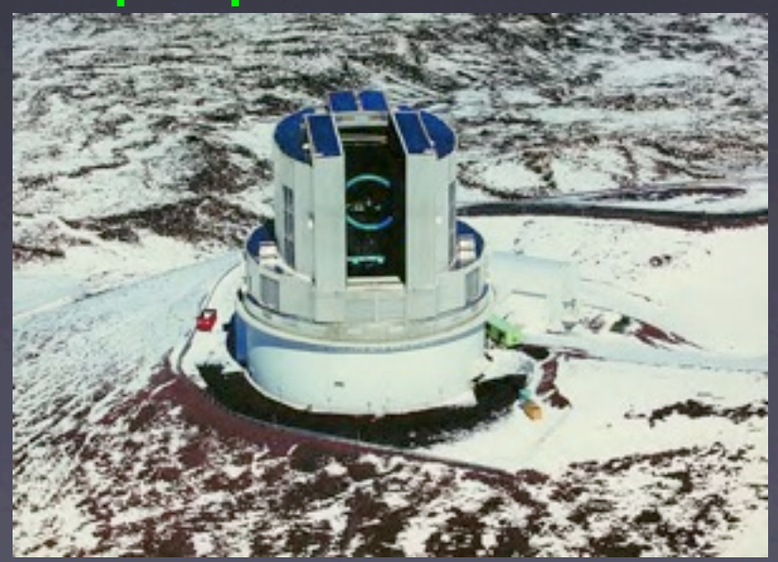




Subaru (NAOJ) x

SDSS-III

- need data ASAP to attract the best astrophysicists
- we also need to nurture observational cosmology in Japan
- Sloan Digital Sky Survey III
- Build 3D map of galaxies
- constrain properties of the dark energy

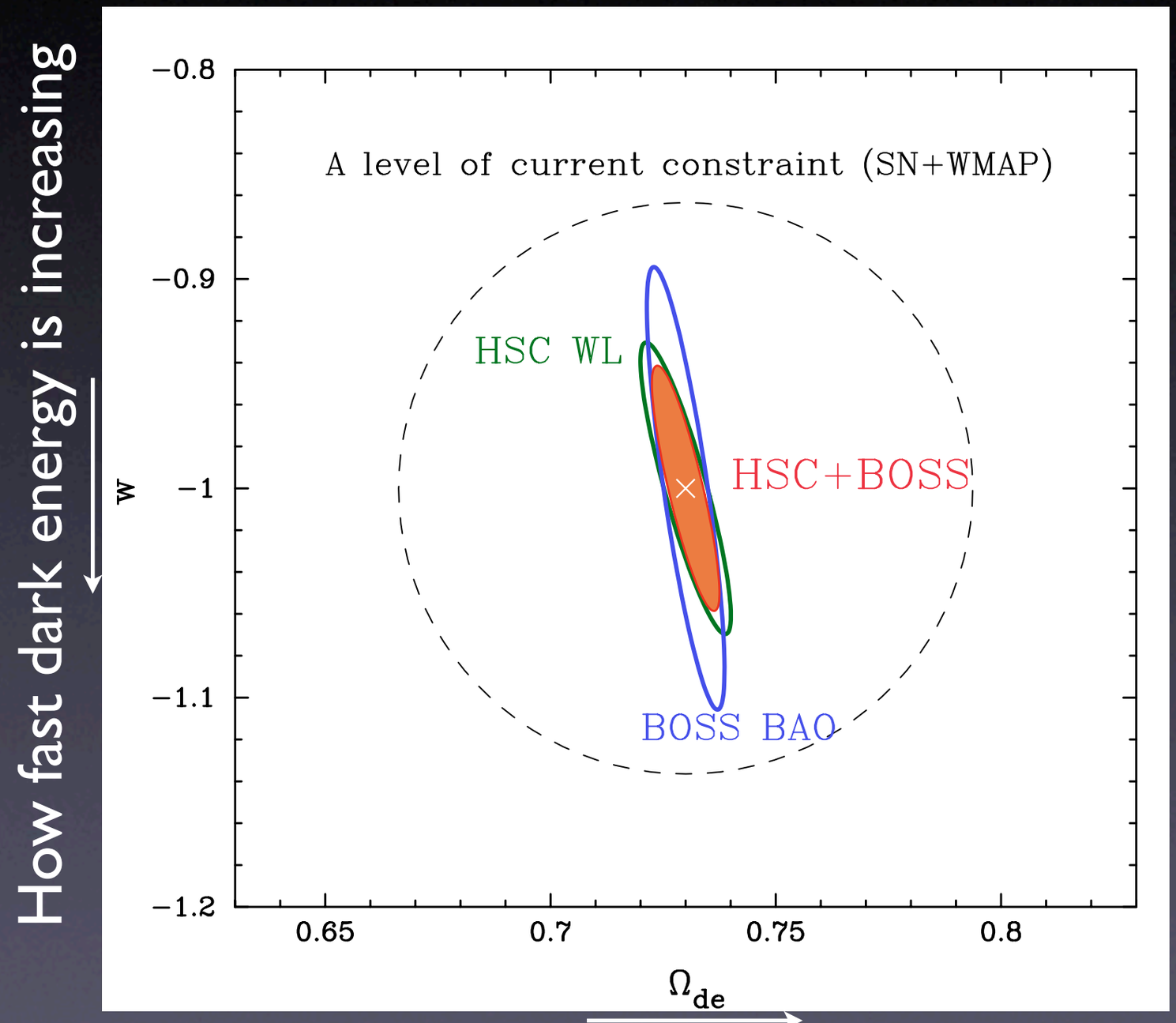


Takada, Yoshida, Fukugita, Spergel

X

What to look for

- *How fast is dark energy creating energy?*
- *Is dark energy "alive"?* (w>-1)
- *Will there be Big Rip?* (w<-1)



How fast dark energy is increasing

x How much dark energy there is

string theory and dark energy

- again getting a lot of help from mathematics
- moduli space of Calabi-Yau threefold
- intersection number of cocycles
- conformal field theories

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Conclusions

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- Consistent picture of the universe emerged

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- What is Dark Field? Why is it there?
- Universe emerged from quantum physics
- New experiments gearing up to solve these puzzles



2011年6月8日星期三

Interactive Physicists' and Mathematicians' Utopia

TeV: rich energy scale?

- *Dark Matter*

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(\mathrm{TeV})^2}{\sigma_{ann}}$$

- *Fermi (Higgs) scale*

$G_F^{-1/2}$=0.3TeV

- *Dark Energy*

$\rho_\Lambda \sim (2\mathrm{meV})^4$ *vs* $(\mathrm{TeV})^2/M_{Pl} \sim 0.5\mathrm{meV}$

- *Neutrino*

$(\Delta m^2_{LMA})^{1/2} \sim 7\mathrm{meV}$ *vs* $(\mathrm{TeV})^2/M_{Pl} \sim 0.5\mathrm{meV}$

TeV-scale physics likely to be rich

We are now getting there!