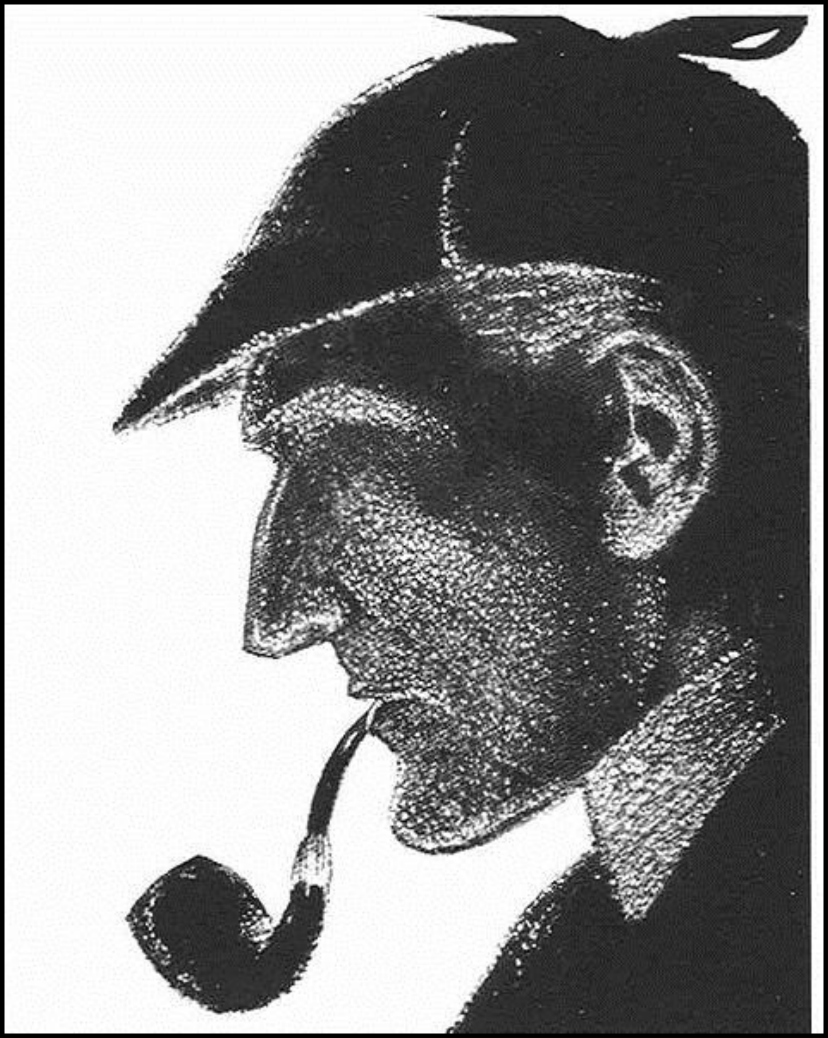
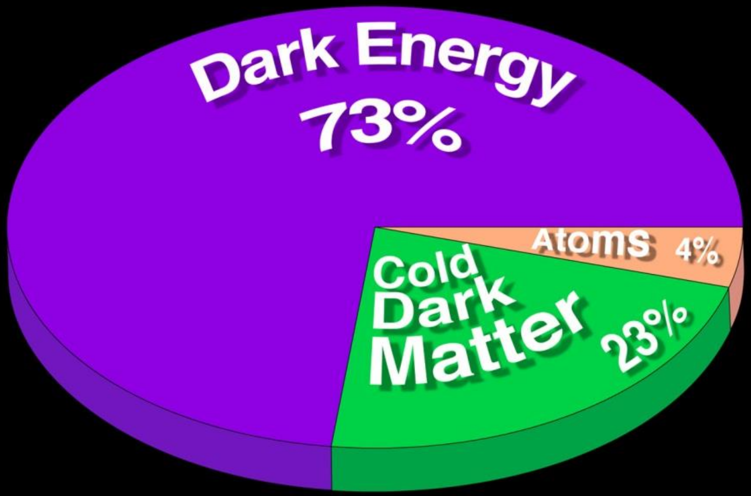


What is the Universe Made Of?

The case for Dark Matter and Dark Energy, and for what they might be

Cliff Burgess

What is the Universe Made Of?



From best fits to the ‘Concordance Cosmology’

Courtesy: Ned Wright’s Cosmology Page

What is the Universe Made Of?

Why Not Modify Gravity Instead?

From best fits to the 'Concordance Cosmology'

Courtesy: Ned Wright's Cosmology Page

1905 – A Big Year for Einstein

- Photo-electric Effect
  - “On a Heuristic Point of View concerning the Production and Transformation of Light.” rcd Mar 18, pub Jun 9
- Brownian Motion
  - “On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat.” *rcd May 11, pub Jul 18*
- Special Relativity
  - “On the Electrodynamics of Moving Bodies.” rcd Jun 30, pub 26 Sep
- Size of Molecules
  - “A New Determination of Molecular Dimensions.” *rcd Aug 19, pub Feb 8*
- Mass-Energy Equivalence
  - “Does the Inertia of a Body Depend upon Its Energy Content?” rcd Sep 27, pub Nov 21

Albert Einstein

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Albert Einstein

* *PhD Thesis and most cited*

Outline

- Dark Cosmology
  - *The Hot Big Bang*
- Dark Matter
  - *Evidence for Dark Matter*
  - *Dark stuff or modified gravity?*
- Dark Energy
  - *Why doesn't the vacuum gravitate?*
  - *Dark Energy as vacuum energy*

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Part I

Dark Cosmology

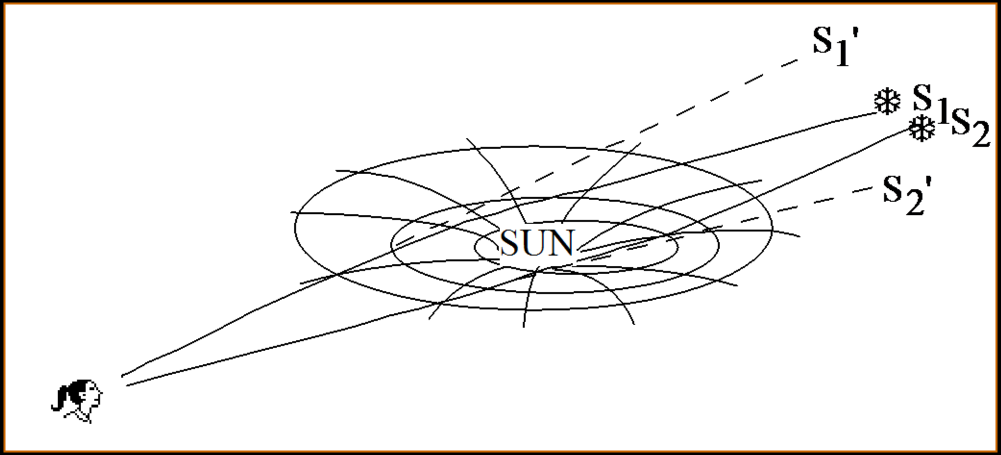
“It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.”

Sherlock Holmes in *A Scandal in Bohemia*

The Hot Big Bang

Dark Cosmology

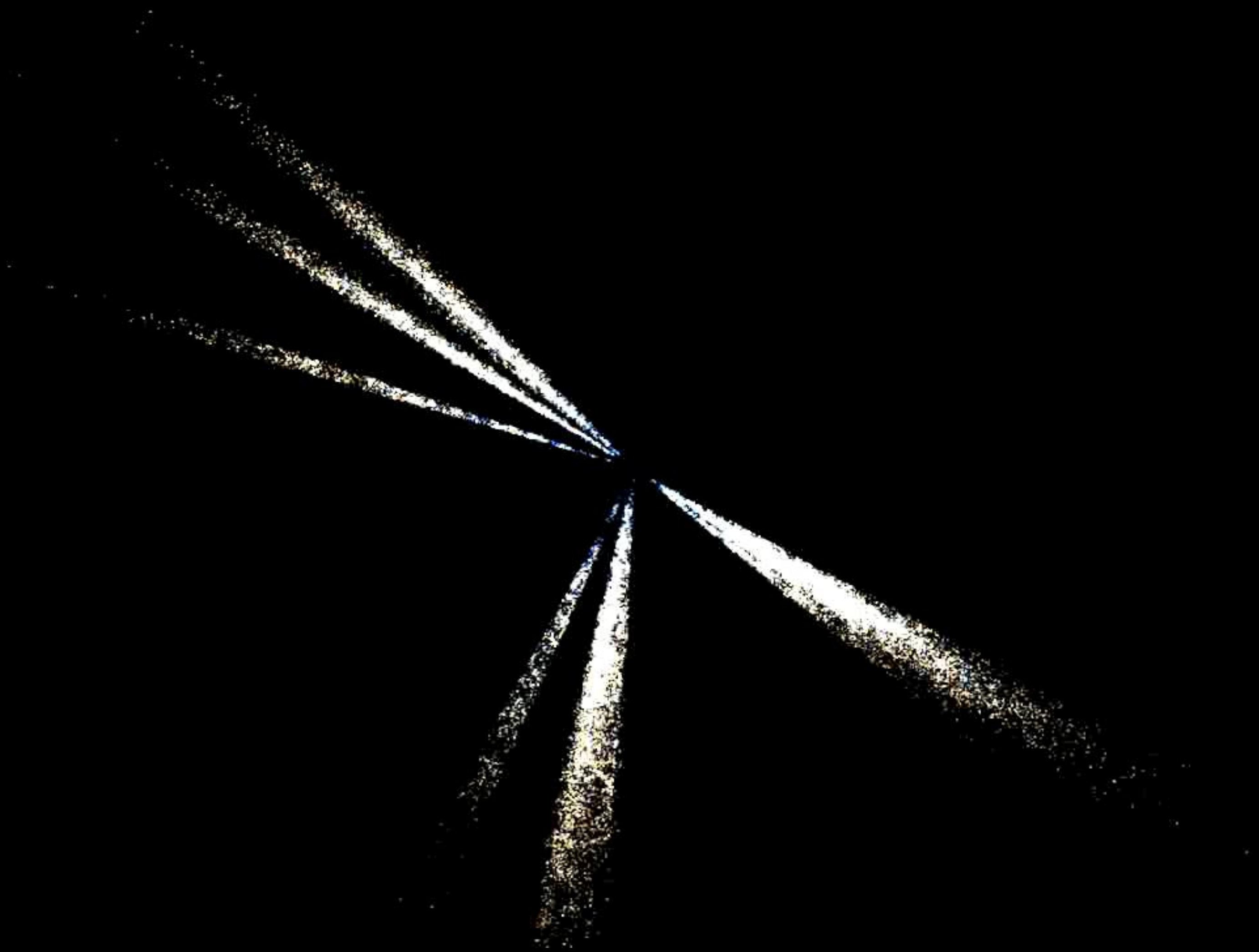
Gravity, Matter & Geometry



- According to Einstein gravity is really the response of space and time to the presence of matter.
  - The presence of energy curves space and time.
  - The curvature of space changes how objects move.
- *Knowing how matter is distributed over large scales tells us the shape and evolution of the Universe.*

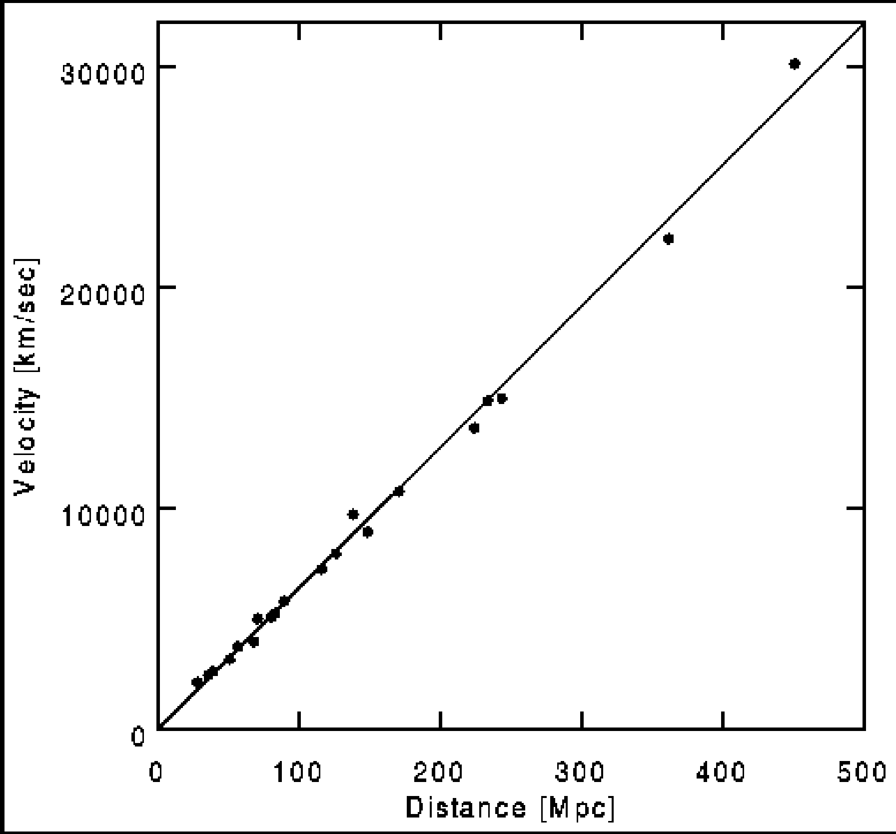
Matter Distribution

Courtesy: Sloan Digital Sky Survey
WMAP



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae

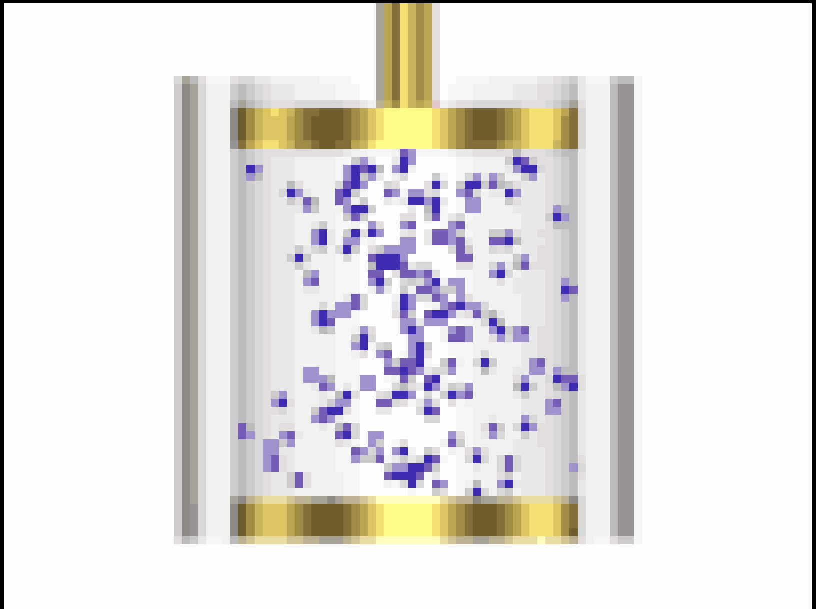


$$v = H_0 d$$

Courtesy: Ned Wright's Cosmology Page

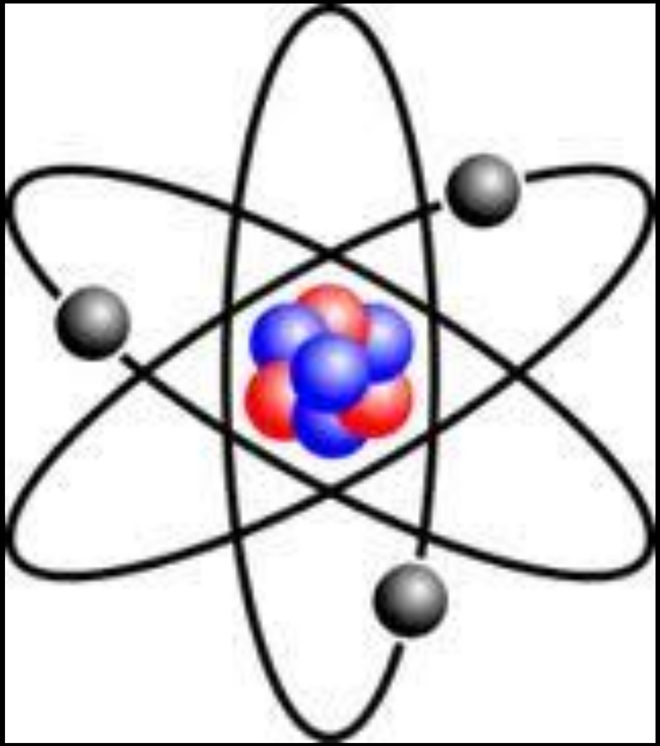
Hot Big Bang

- Assume Universe once a hot soup of elementary particles
- Seek relics of earlier hotter epochs
- *Use:* at high temperatures particles get broken to their constituents. As universe cools, bound states form



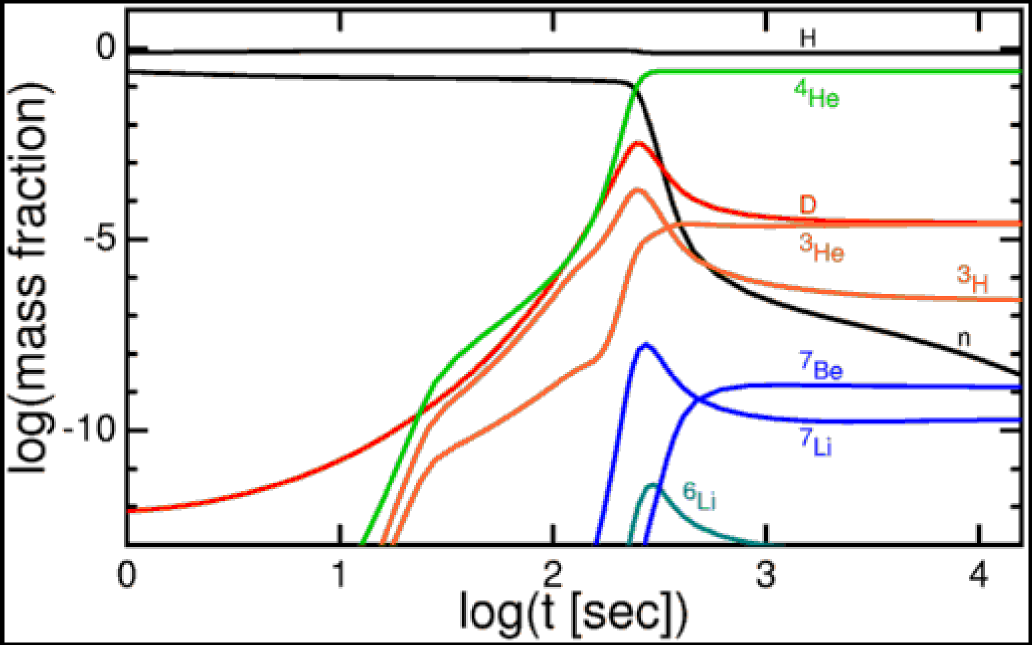
Hot Big Bang

- Atoms form below 1000 degrees
  - electrons and nuclei combine into neutral atoms.
- Nuclei form below 10^{10} degrees.
  - Protons and neutrons combine into nuclei.



Evidence for a Hot Big Bang

- *Primordial element abundances*
- The cosmic microwave background
- T_{CMB} vs distance



Burles, Nolette & Turner, 1999

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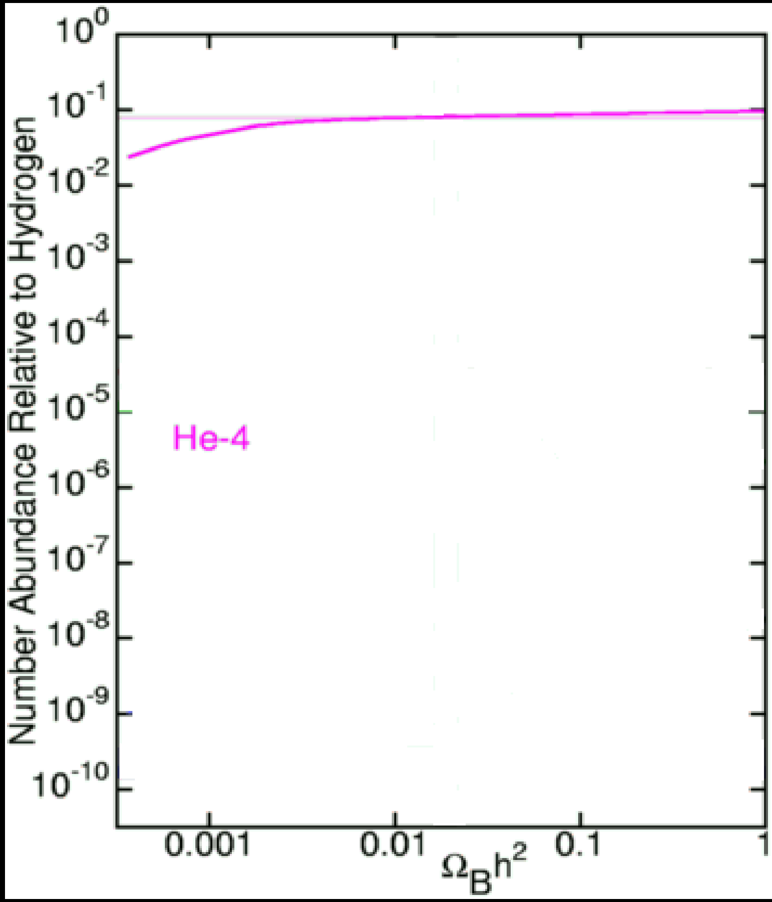

Total Mass Density of Atoms

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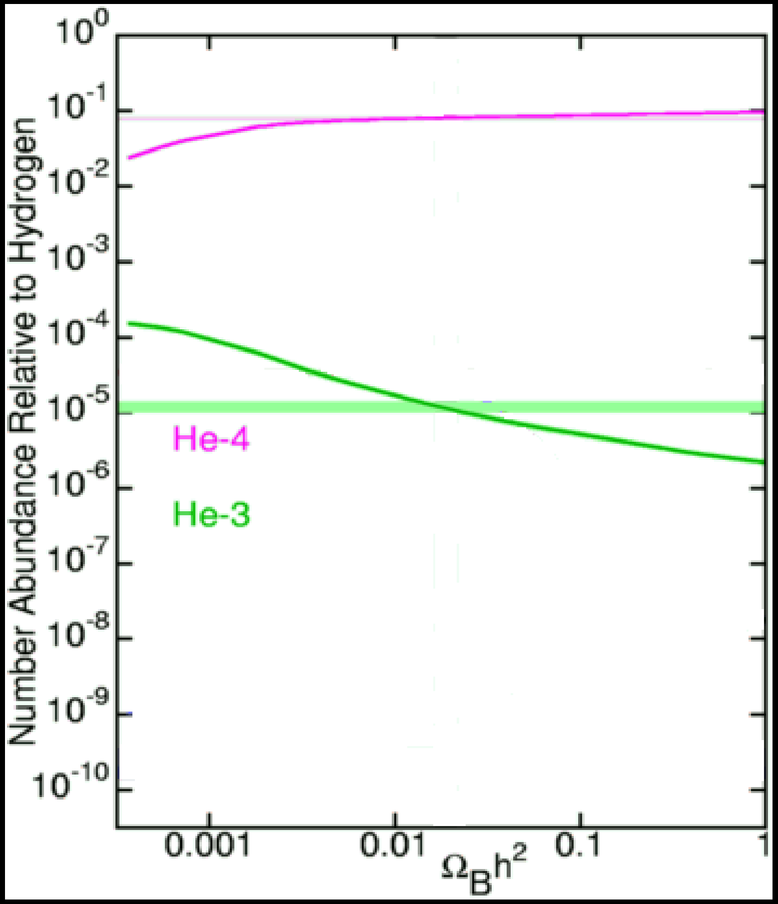

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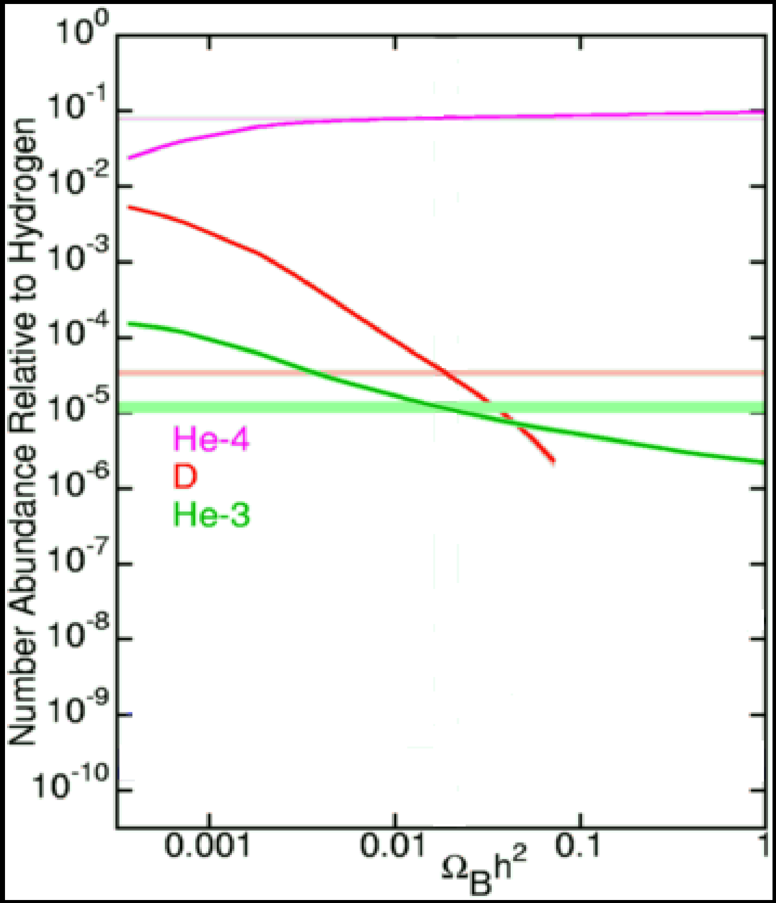

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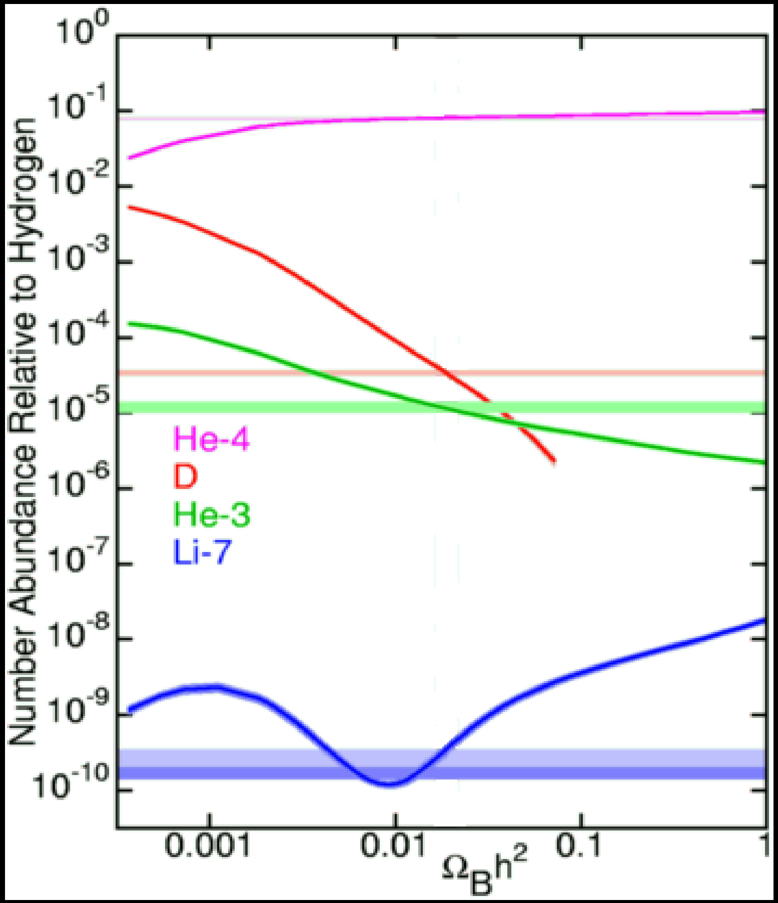

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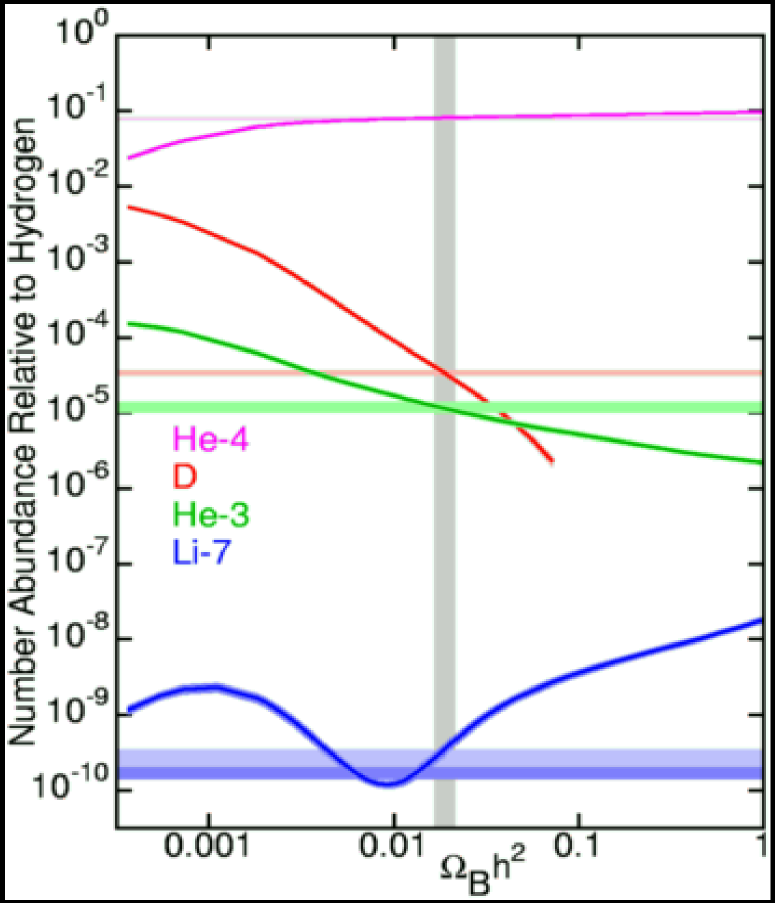

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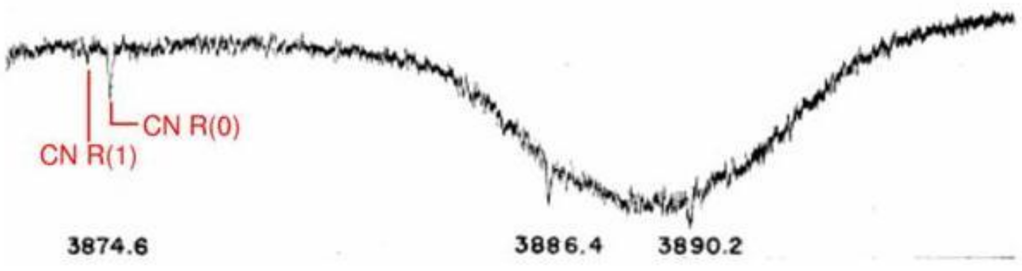


Plate 3 of Adams (1941, ApJ, 93, 11-23)

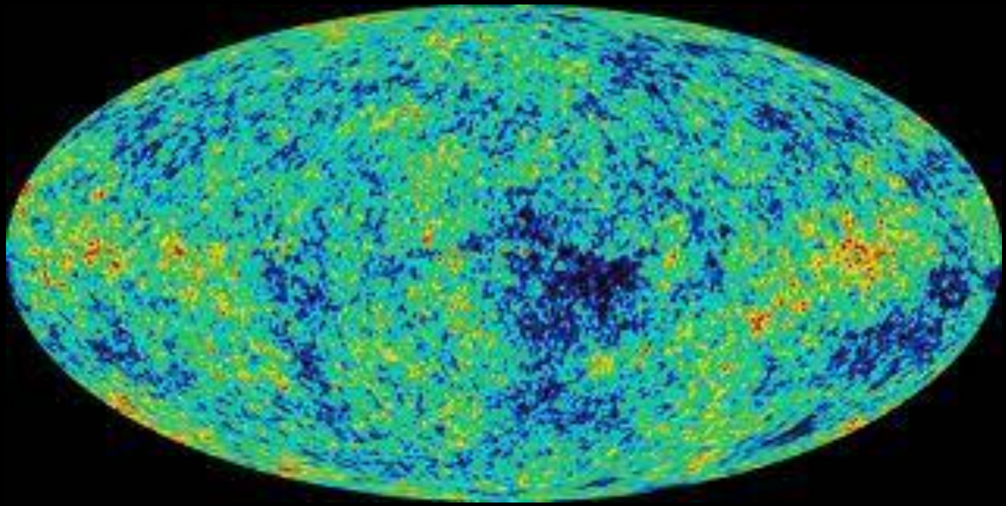
Herzberg (1950) in *Spectra of Diatomic Molecules*, p 496:

"From the intensity ratio of the lines with K=0 and K=1 a rotational temperature of 2.3° K follows, which has of course only a **very restricted meaning**."

Evidence for a Hot Big Bang

- Primordial element abundances
- *The cosmic microwave background*
- T_{CMB} vs distance

CMB Temperature vs Direction



WMAP collaboration

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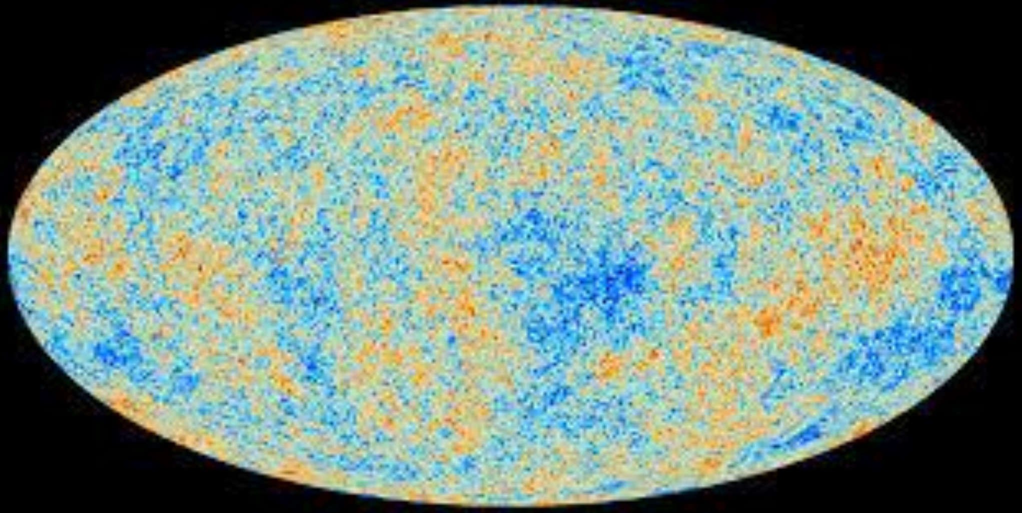

Planck collaboration

Part II

DARK MATTER

"Circumstantial evidence is a very tricky thing," answered Holmes thoughtfully.
"It may seem to point very straight to one thing, but if you shift your own point of view a little, you may find it pointing in an equally uncompromising manner to something entirely different."

Sherlock Holmes in *The Boscombe Valley Mystery*

The evidence for it

Dark stuff or modified gravity?

DARK MATTER

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Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation

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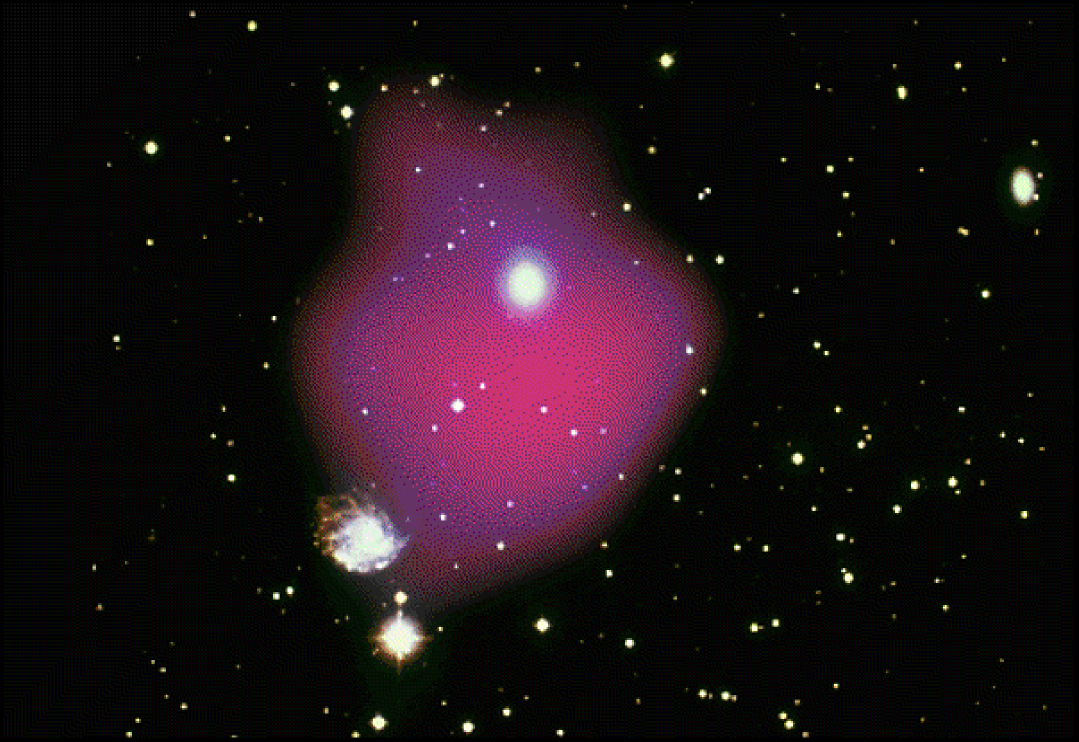

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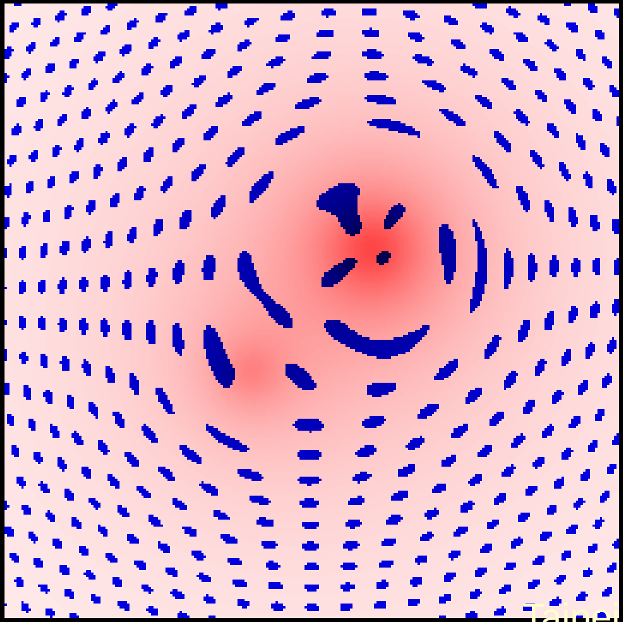

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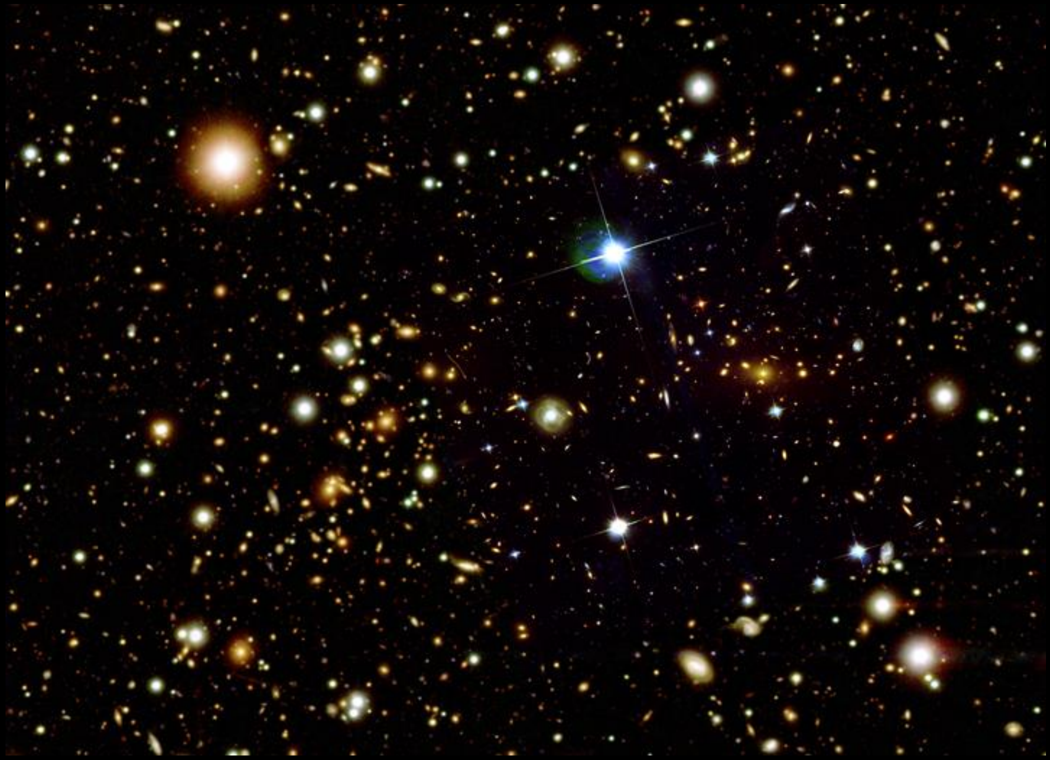

The Bullet Cluster: Separating Dark and Visible Matter

Evidence for Dark Matter

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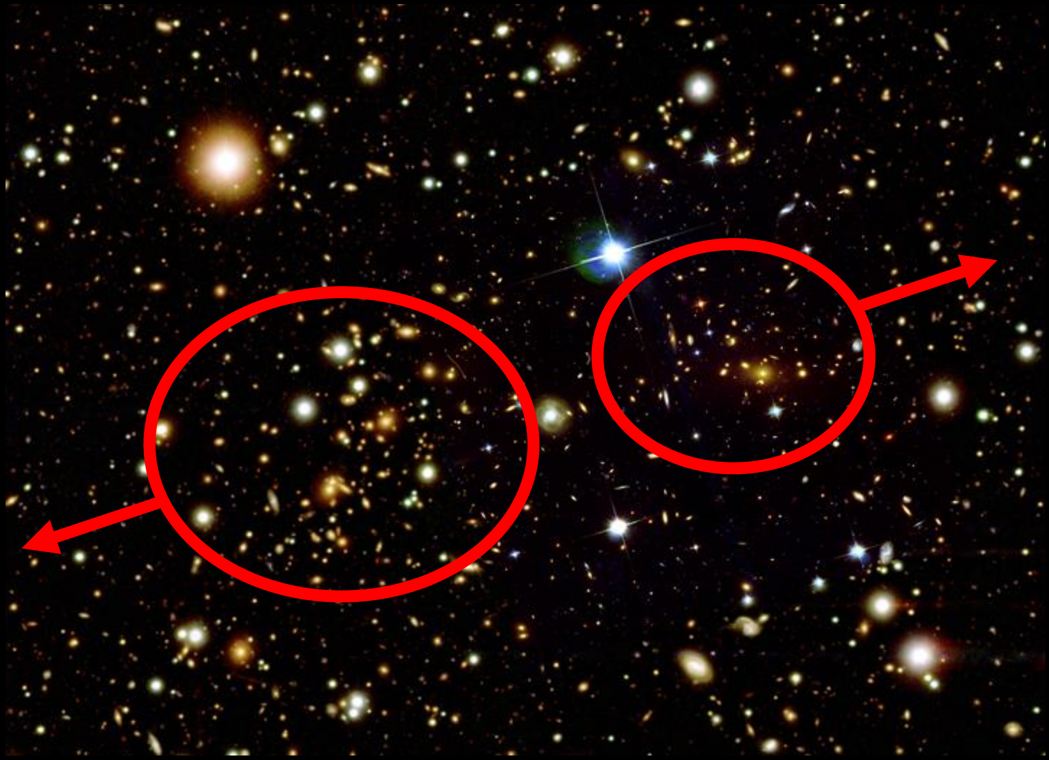
Colliding galaxy clusters



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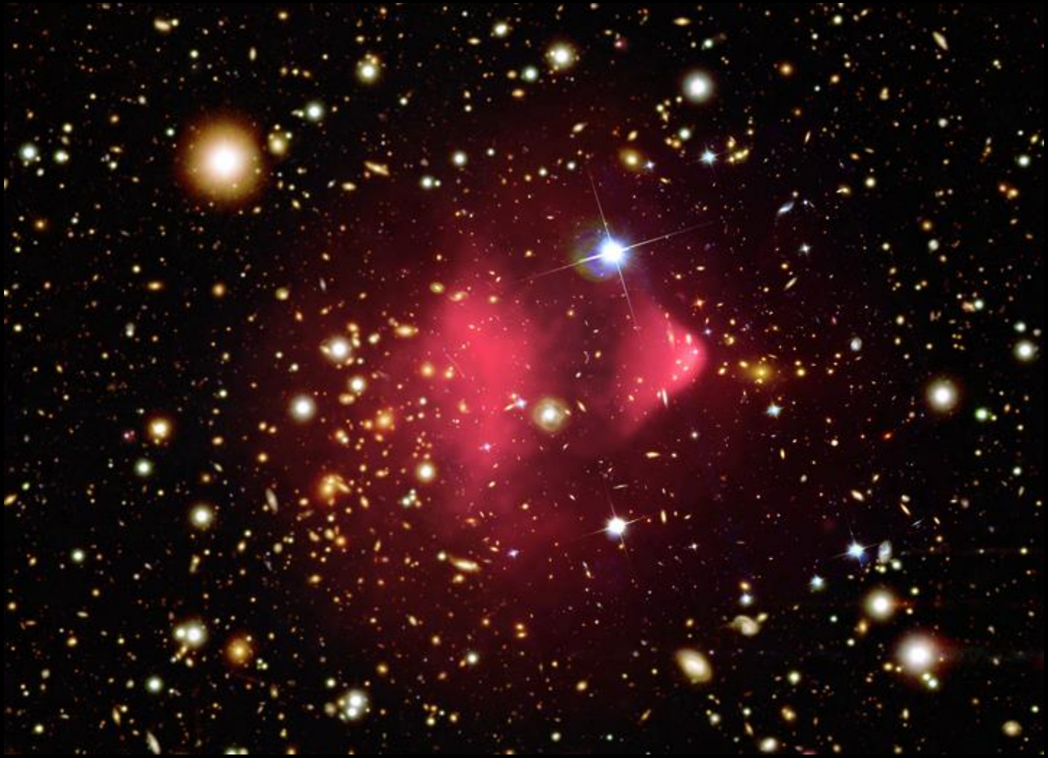
Hot intra-cluster gas



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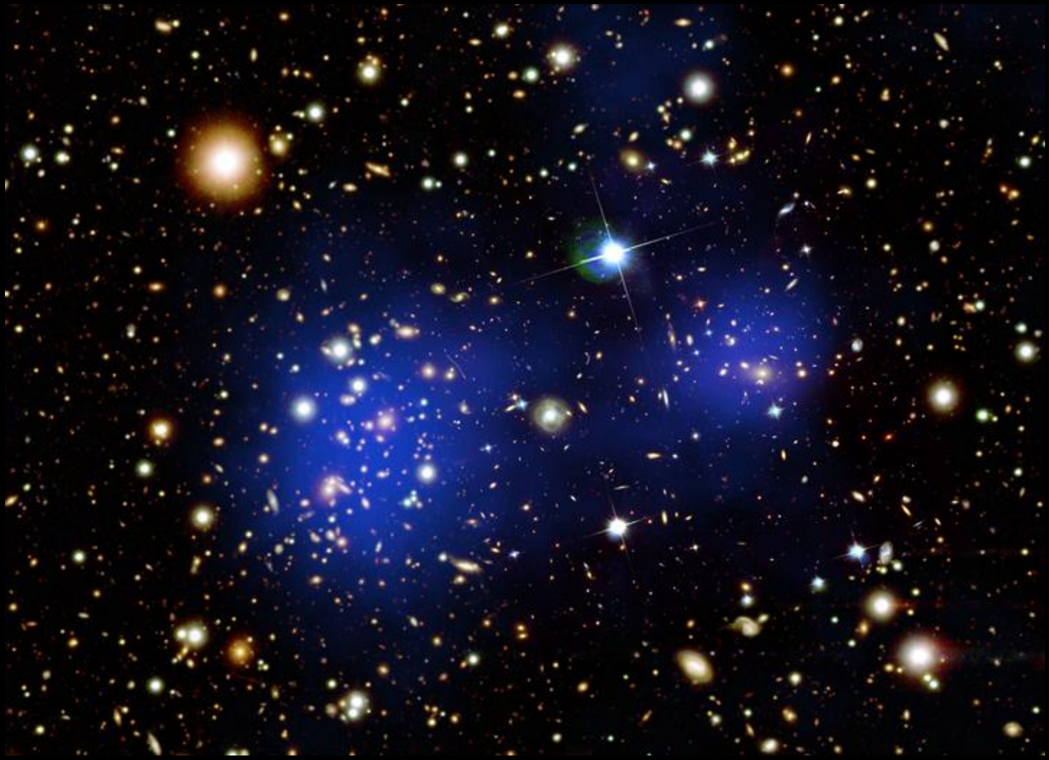
Mass measured by lensing



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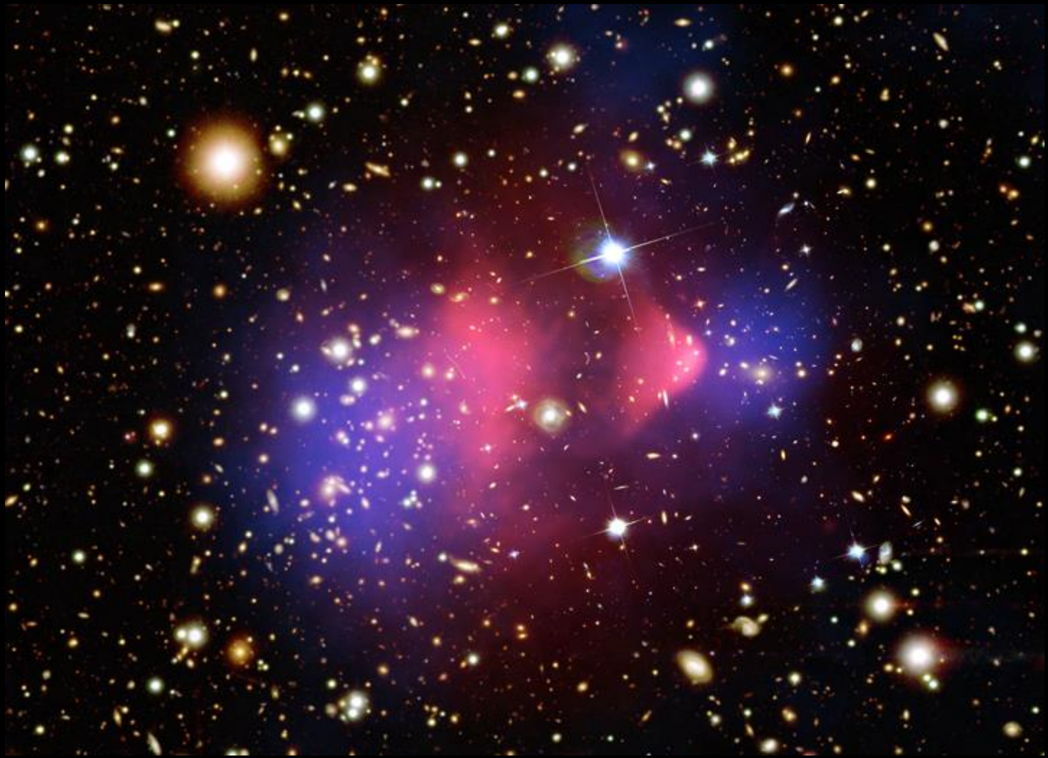

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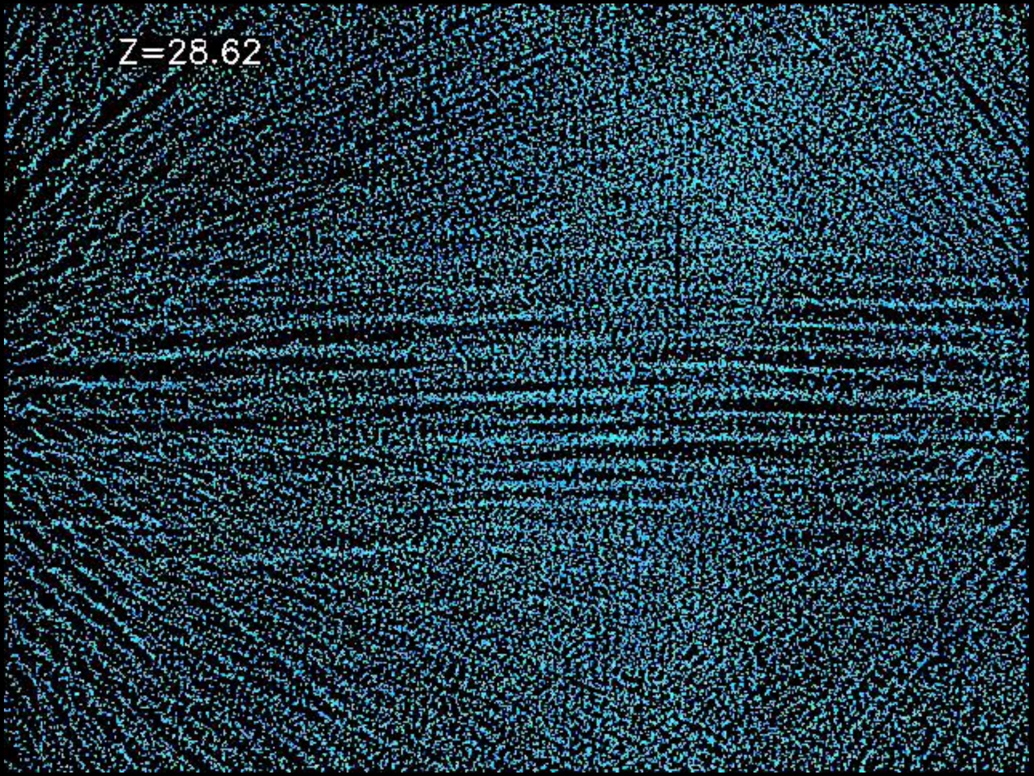

Time available for structure formation

Evidence for Dark Matter

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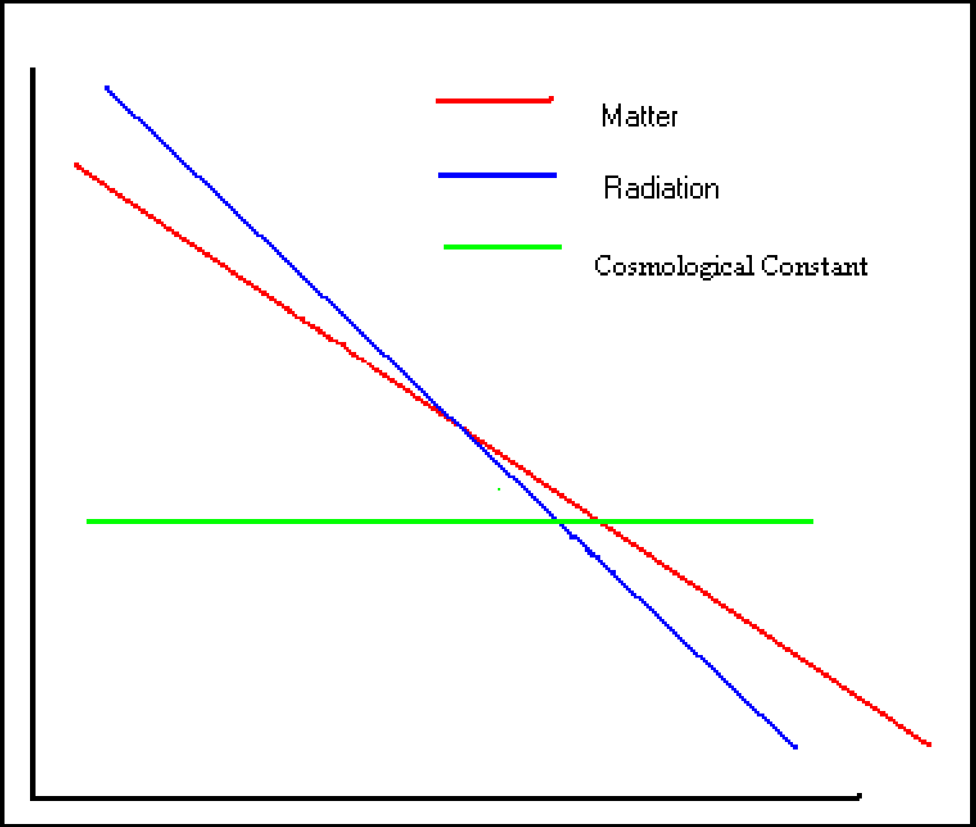
log ρ



log a

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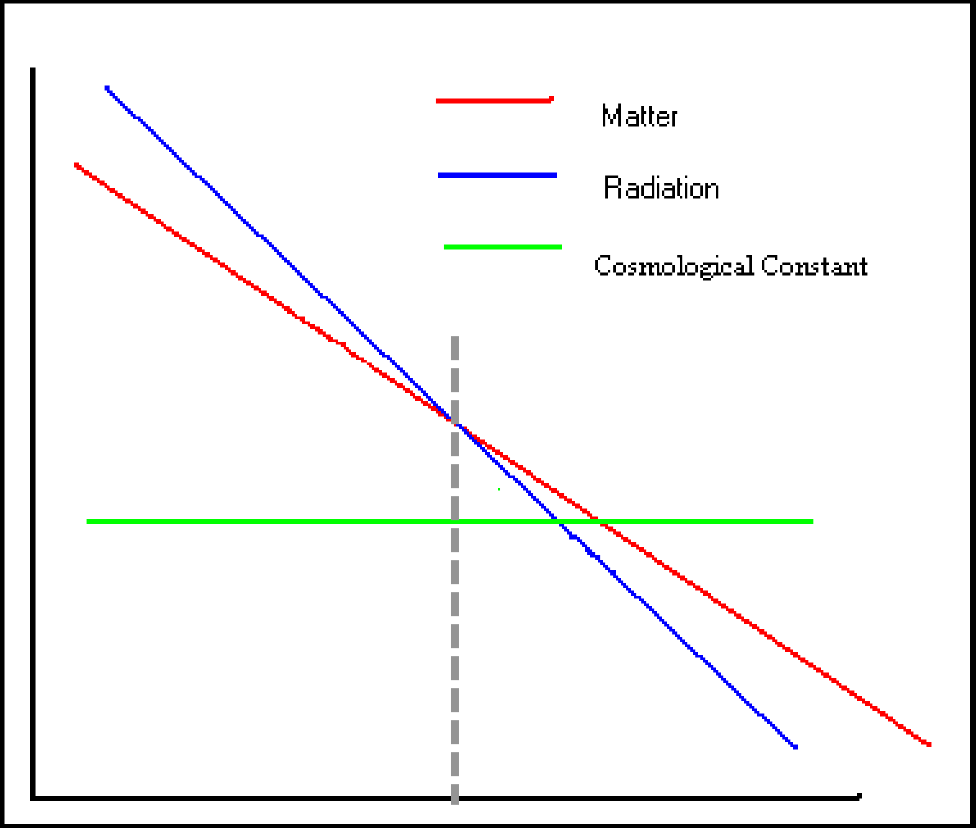

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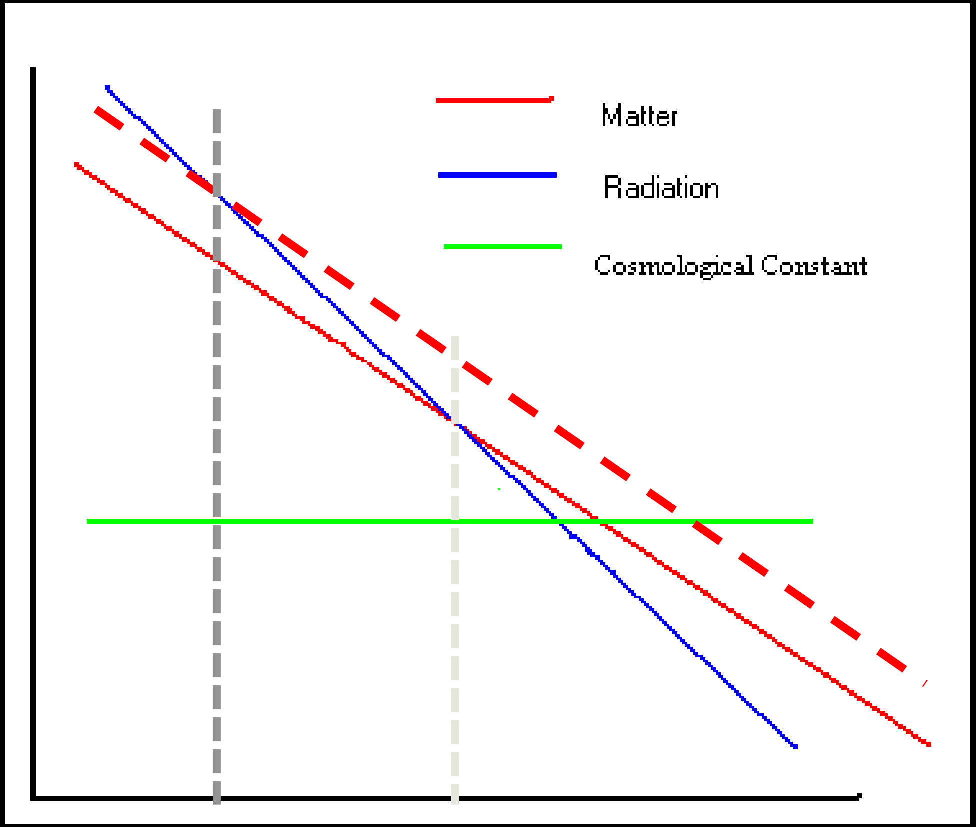

log a

Time available for structure formation

What is the Dark Matter?

- Ordinary atoms?
- Modifications to the Law of Gravity?
- New kind of particles?

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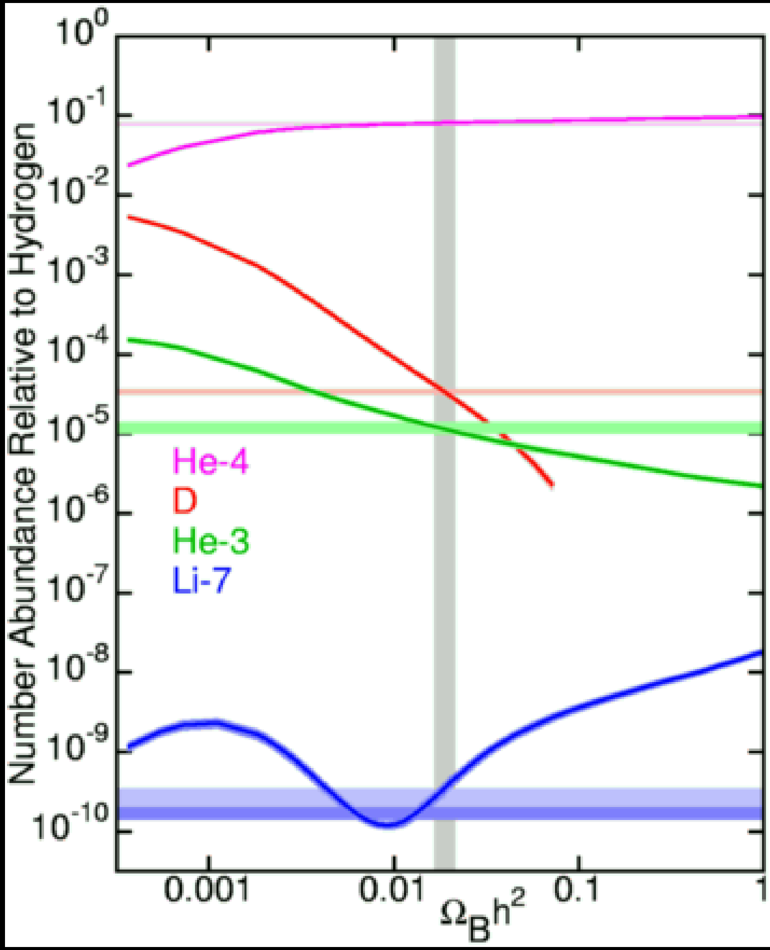

Burles, Nolette & Turner, 1999

Courtesy: Ned Wright's Cosmology Page

What is the Dark Matter?

- Ordinary atoms?
- *Modifications to the Law of Gravity?*
- New kind of particles?

The devil is in the details:

No proposals yet succeed for galaxies and *clusters* and *the CMB.*

Very difficult to modify gravity at long distances without having problems with fundamental principles.

What is the Dark Matter?

- Ordinary atoms? ~~~~
- Modifications to the Law of Gravity? ~~~~
- *New kind of particles?*

Weakly Interacting Particles arise in most theories of microscopic physics.

Their residual cosmic abundance is naturally the right size to agree with the observed amount of Dark Matter.

Part III

DARK ENERGY

"How often have I said to you that when you have eliminated the impossible, whatever remains, *however improbable*, must be the truth?"

Sherlock Holmes in *The Sign of the Four*

Evidence for Dark Energy

The Cosmological Constant Problem

DARK ENERGY

Evidence for Dark Energy

- Brightness of very distant supernovae
- Flatness of the universe as a whole

Evidence for Dark Energy

- *Brightness of very distant supernovae*
- Flatness of the universe as a whole

Very distant objects should not precisely follow Hubble's Law because gravitational attraction should decelerate the universal expansion.

This can be tested by looking for deviations from Hubble's Law for very distant supernovae.

Evidence for Dark Energy

- *Brightness of very distant supernovae*

- Flatness of the universe as a whole

Evidence for Dark Energy

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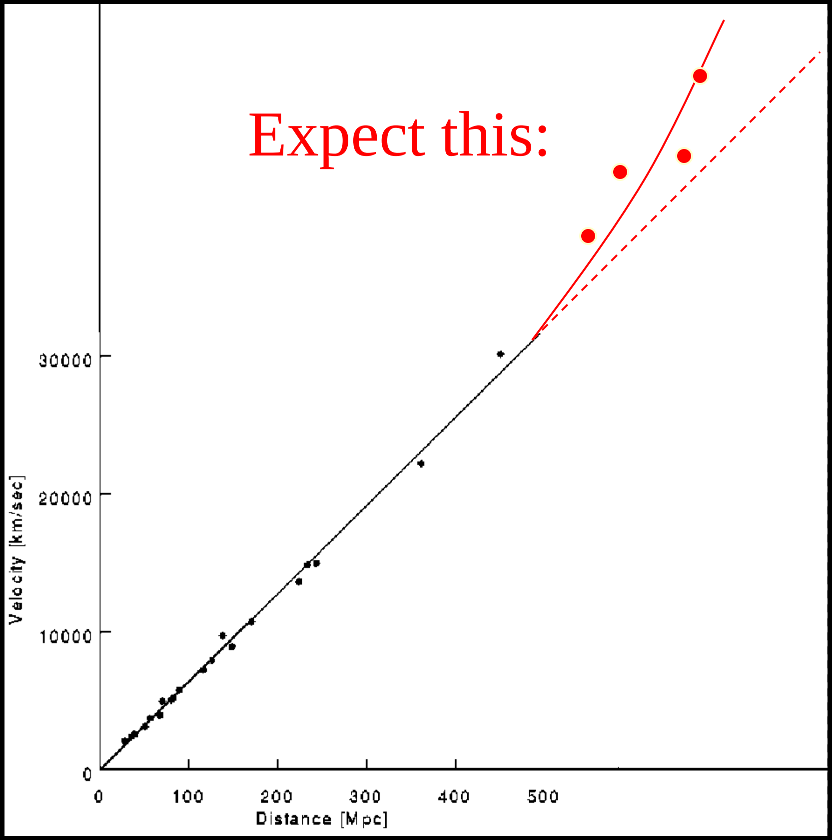

The universal expansion should be decelerating due to gravitational attraction

Evidence for Dark Energy

Tonrey et.al., 2003

- *Brightness of very distant supernovae*
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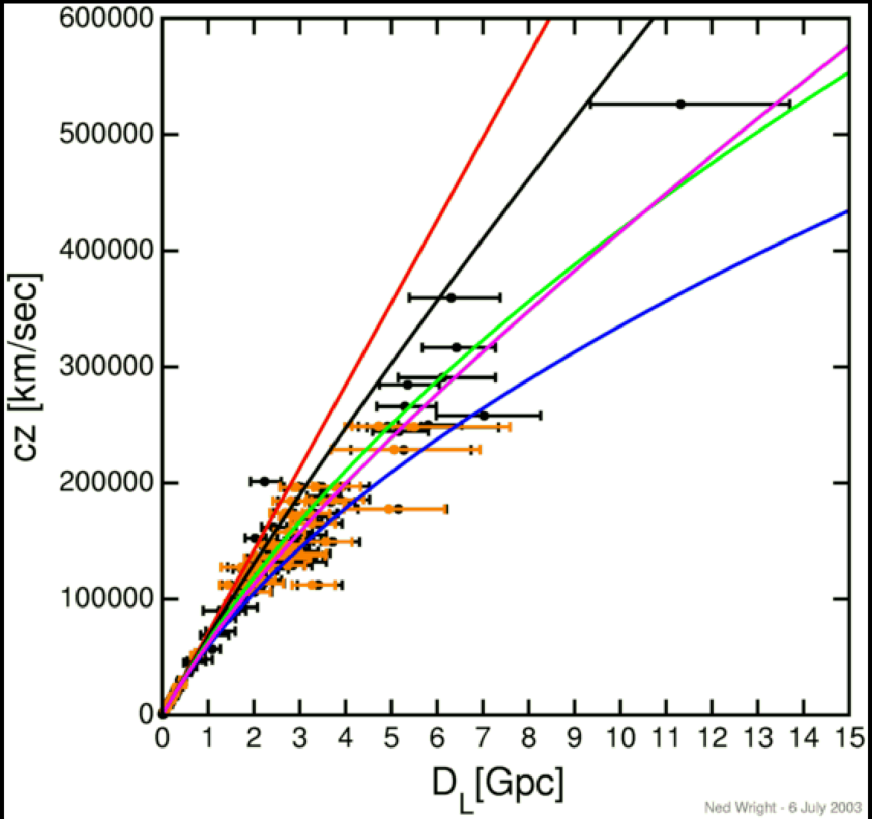

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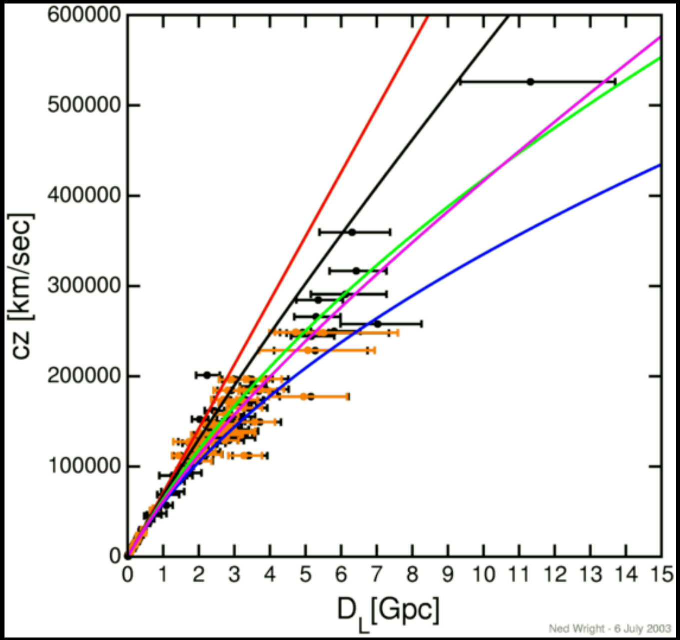
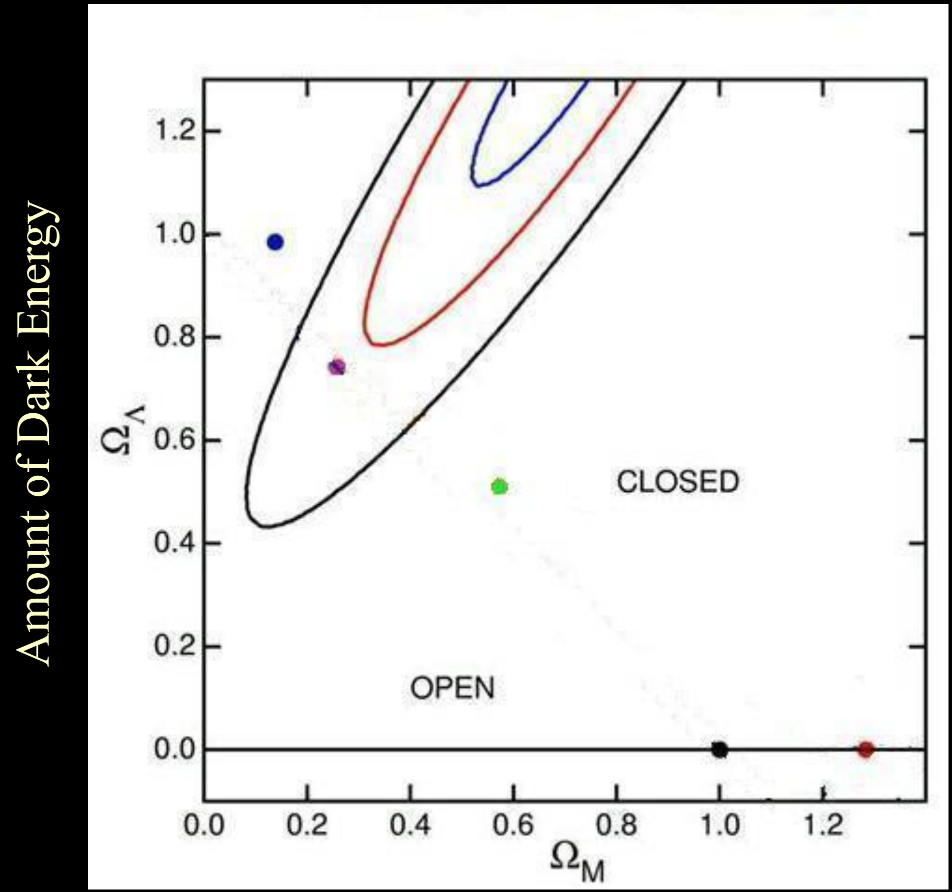


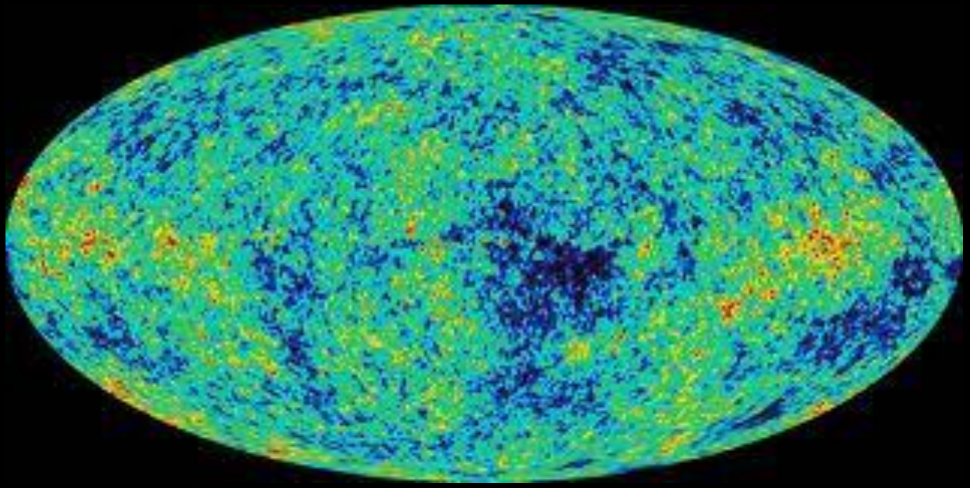


Amount of Dark Matter

Courtesy: Ned Wright's Cosmology Page

Evidence for Dark Energy

- Brightness of very distant supernovae
- *Flatness of the universe as a whole*



WMAP collaboration

Small temperature variations, at the level of one part in 100,000, are visible in the CMB

Evidence for Dark Energy

- Brightness of very distant supernovae
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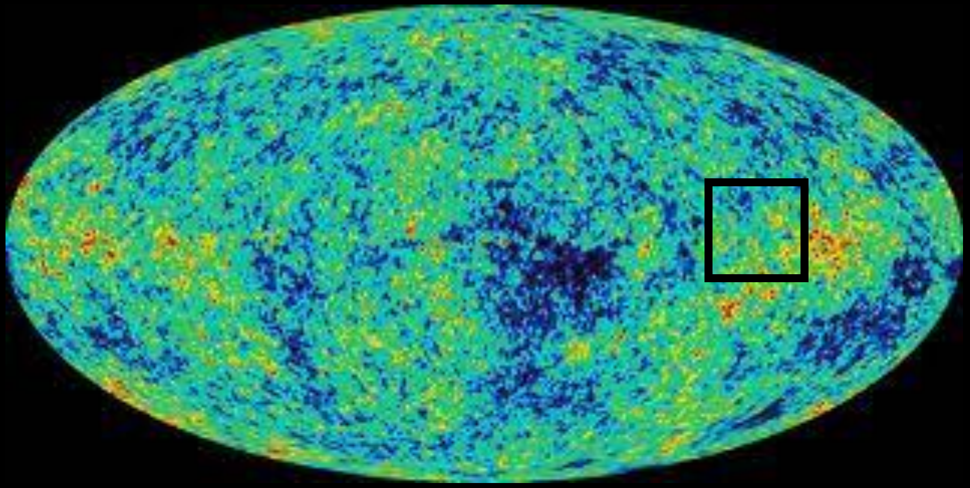

WMAP collaboration

These are due to sound waves in the primordial gas which emitted this light.

Evidence for Dark Energy

- Brightness of very distant supernovae

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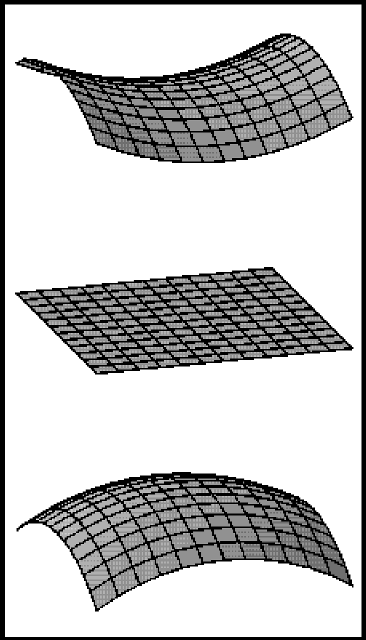

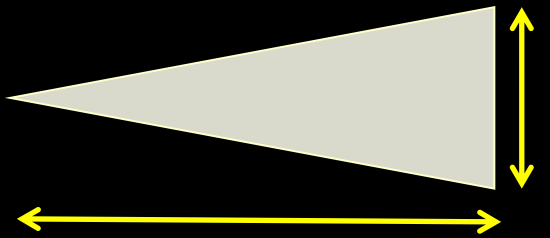

The CMB allows the inference of the properties of the later universe through which these photons pass.

Evidence for Dark Energy

- Brightness of very distant supernovae

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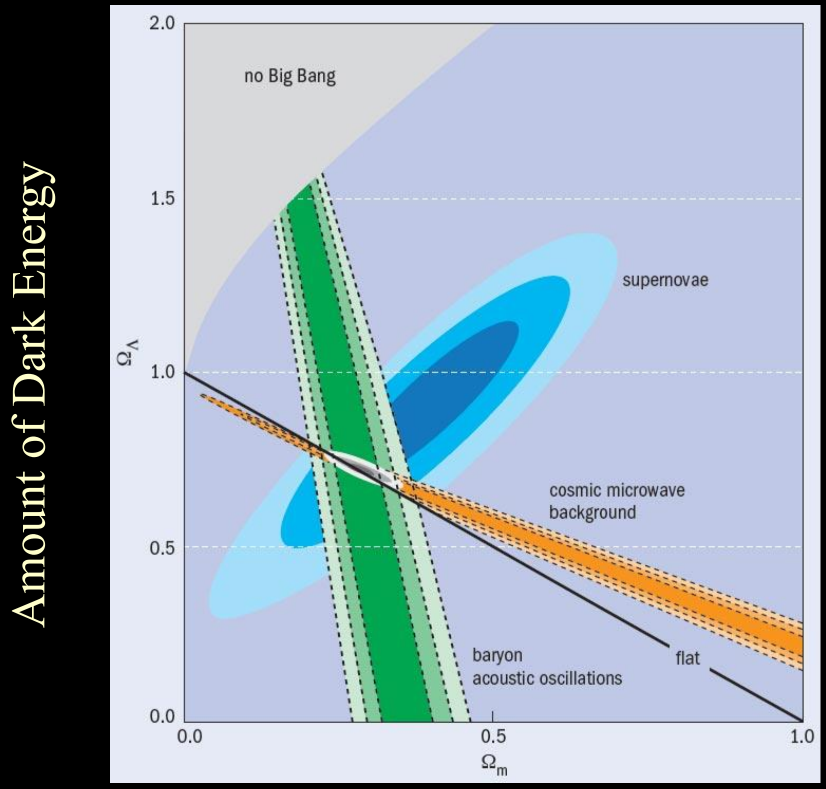
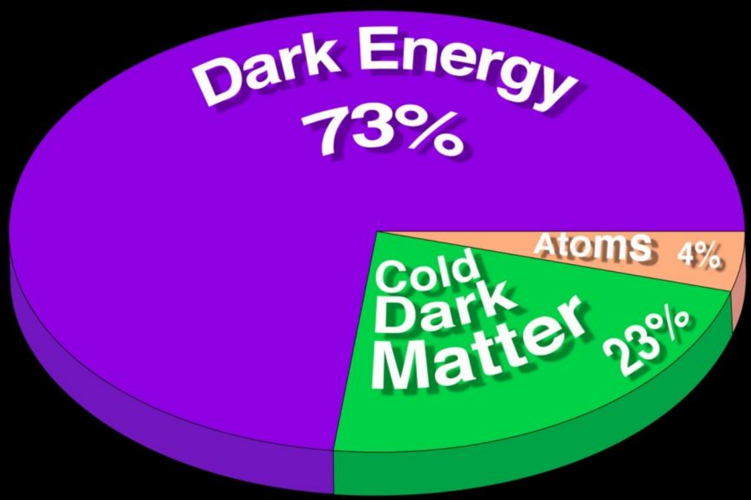
Courtesy: Ned Wright's Cosmology Page



Amount of Dark Matter

Measurements of CMB and Dark Matter and universal expansion and acceleration are consistent

Concordance Cosmology



Can also count ordinary atoms even if they cannot be seen!

Nucleosynthesis

Properties of the CMB

Courtesy: Ned Wright's Cosmology Page

The cosmological term

- *Einstein's equations as initially written preclude the existence of a static Universe*

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

- *This conclusion can be avoided if they are modified to include a 'cosmological term' which acts as a repulsive counterforce to gravity's attraction*

$$G_{\mu\nu} + \lambda\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

- *The requirement for the cosmological term was removed once the Universe was found to be expanding.*

Cosmological term as Dark Energy

- *The cosmological term provides an excellent description of the Dark Energy, since its repulsive nature can drive the observed cosmological acceleration*

$$8\pi G\, T_{\mu\nu} = -\lambda\, g_{\mu\nu}$$

- *Interpreted as a stress-energy the cosmological term looks like constant positive energy density and negative pressure*

$$-p = \rho = \frac{\lambda}{8\pi G}$$

Einstein's error

- *Was Einstein's greatest error introducing the cosmological term, or discarding it before Dark Energy was discovered?*

- *Modern point of view: Neither! His error was to believe he gets to choose...*

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu} - \lambda\, g_{\mu\nu} = 8\pi G\, (T_{\mu\nu} + \, t_{\mu\nu})$$

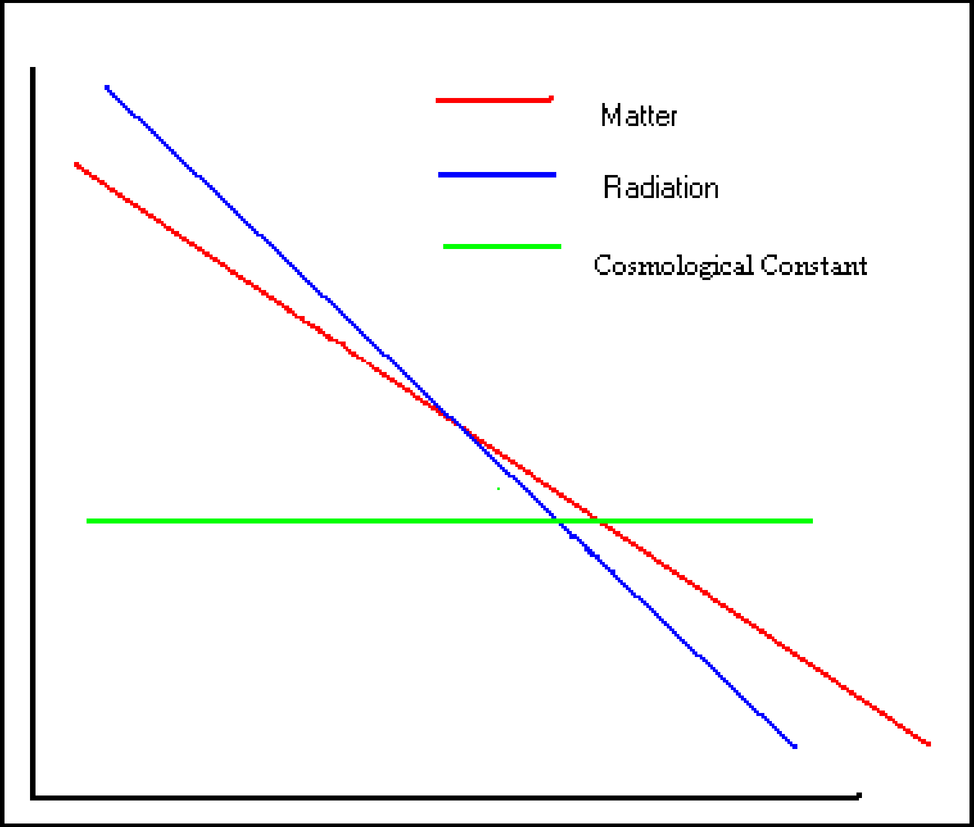
- *The cosmological term is precisely what a vacuum energy,* $t_{\mu\nu}$*, would look like, and we should be able to compute its properties if we understand the vacuum.*

Vacuum Energy as Dark Energy

- The success of special relativity requires the vacuum energy density to be constant and its pressure to be negative, as required to be Dark Energy.
  - Negative pressure keeps the vacuum energy density constant as the universe expands.

$$\rho = -p = \lambda > 0$$

log ρ



log a

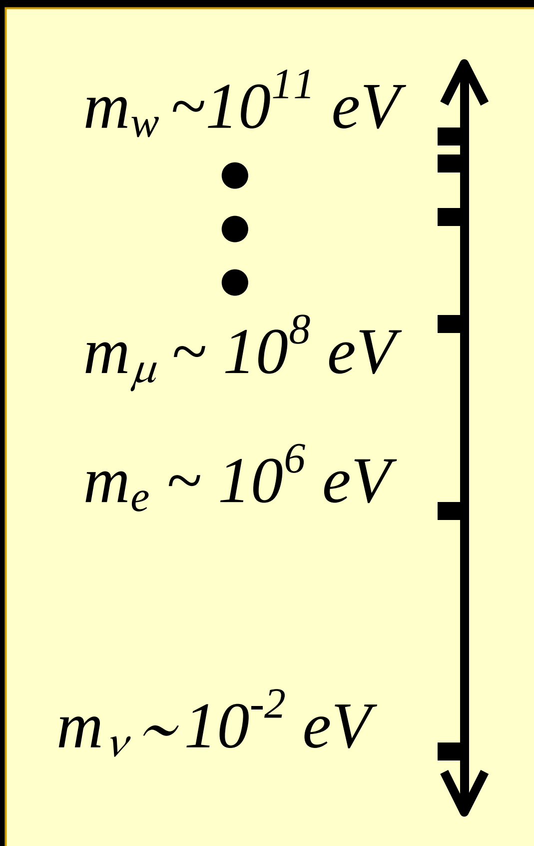
The Cosmological Constant Problem

- The vacuum energy is *calculable* within any theory of elementary particles, such as the Standard Model of particle physics, and the observed vacuum energy is the sum of a classical energy and an *enormous* quantum energy

$$\rho_{vac} = \lambda + \sum \frac{m^4}{(4\pi)^2}$$

- *So what? Can always choose classical λ to ensure the Universe accelerates by the right amount, even if ρ_{vac} is much smaller than m^4*

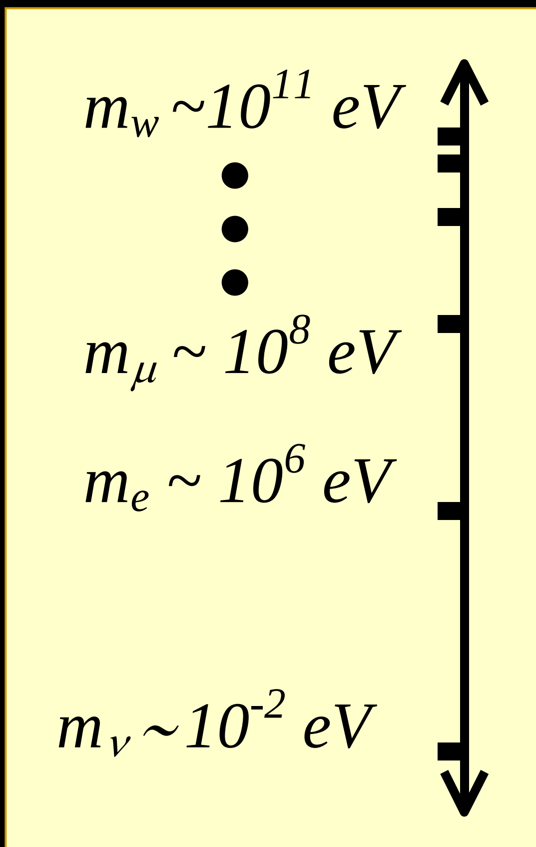
Hierarchy problems



Modern picture: no unique 'classical' theory; instead many 'effective' theories

$$\rho_{vac} = \lambda_0 + k_\upsilon m_\upsilon^4$$

Hierarchy problems

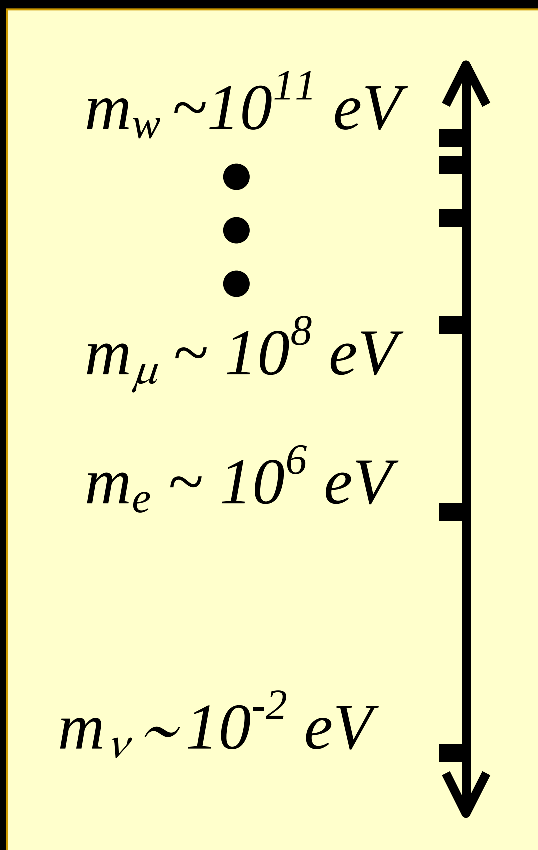
- 

Modern picture: no unique ‘classical’ theory; instead many ‘effective’ theories

- $$\rho_{vac} = \lambda_1 + k_e m_e^4 + k_\nu m_\nu^4$$

$$\rho_{vac} = \lambda_0 + k_\nu m_\nu^4$$

Hierarchy problems



Modern picture: no unique ‘classical’ theory; instead many ‘effective’ theories

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$$\rho_{vac} = \lambda_0 + k_\nu m_\nu^4$$

Must cancel to 32 decimal places!!

What We’re Looking For

- Our picture of the physics of ordinary particles must already be wrong at energies higher than 1 eV, or distances shorter than 1 micron.
    - *Whatever the change is, it must change gravity in such a way as to produce a small response to the vacuum energy.*
    - *It must not alter other interactions.*

- Is this possible? Party line says “no”.

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- Our picture of the physics of ordinary particles must already be wrong at energies higher than 1 eV, or distances shorter than 1 micron.
  - *Whatever the change is, it must change gravity in such a way as to produce a small response to the vacuum energy.*
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- Is this possible? Party line says "no".
  - *Remarkably, it may be!*

Helpful extra dimensions

- The Problem:
  - Einstein's equations make a lorentz-invariant vacuum energy *(which is generically large)* an obstruction to a close-to-flat spacetime *(which we see around us)*

$$T_{\mu\nu} = \lambda \, g_{\mu\nu}$$

$$G_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

Helpful extra dimensions

Arkani-Hamed et al
Kachru et al
Carroll & Guica
Aghababaie et al

- The Problem:
  - Einste
    energy
    a close

But this need not be true if there are more than 4 dimensions!!

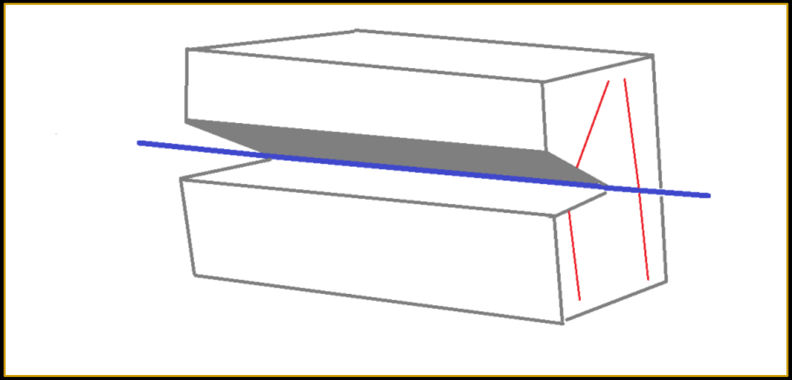
$$T_{\mu\nu} = \lambda \, g_{\mu\nu}$$

$$G_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

Helpful extra dimensions

Vilenkin et al

- *Why not?*
  - Extra dimensions need not be lorentz invariant
  - *Vacuum energy might curve extra dimensions, rather than the ones we see in cosmology*

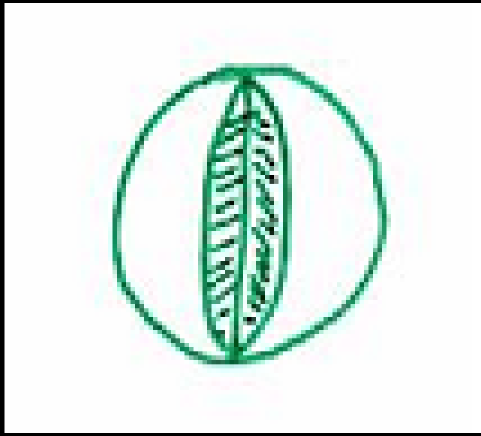


e.g. gravitational field of a cosmic string

Helpful extra dimensions

Carroll & Guica
Aghababaie et al

- A higher-dimensional analog:
  - Similar *(classical)* examples also with a 4D brane in two extra dimensions: *e.g. the rugby ball and related solutions*



Opportunities & Concerns

- If true, many striking implications:
  - Micron deviations from inverse square law
  - *Missing energy at the LHC and in astrophysics: requires M_g > 10 TeV*
  - ✓ *Probably a vanilla SM Higgs*
  - Excited string states (or QG) at LHC below 10 TeV
  - ✓ *Low energy SUSY without the MSSM*
  - Very light Brans-Dicke-like scalars
  - Sterile neutrinos from the bulk?

“…when you have eliminated the impossible, whatever remains, however improbable, must be the truth.”

A. Conan Doyle

Outlook

- Cosmological observations are now redundantly testing the Hot Big Bang model.
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  - Observations support the ‘Concordance Cosmology’.
- The concordance involves several lines of independent evidence for both Dark Matter and Dark Energy.
  - Neither can be dark forms of ordinary atoms.
- Dark Matter likely new particle types, but Dark Energy is harder (until recently thought impossible).
  - If so we’ll know from a variety of observational tests.