Dark Matter

Leszek Roszkowski

National Centre for Nuclear Research, Warsaw, Poland,

and

Univ. of Sheffield, England

Two Universes

Two Universes

shining Universe

Two Universes

shining Universe

Two Universes

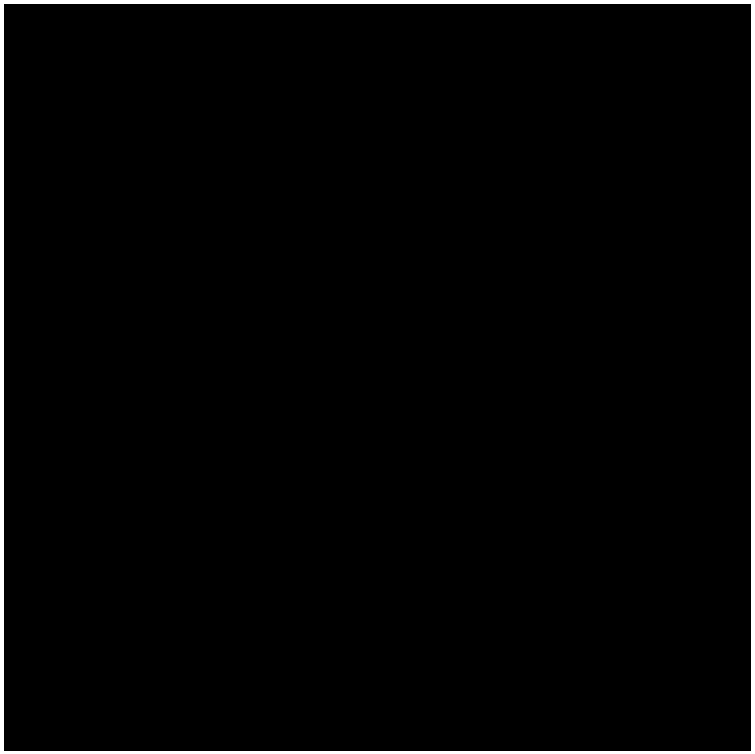
shining Universe

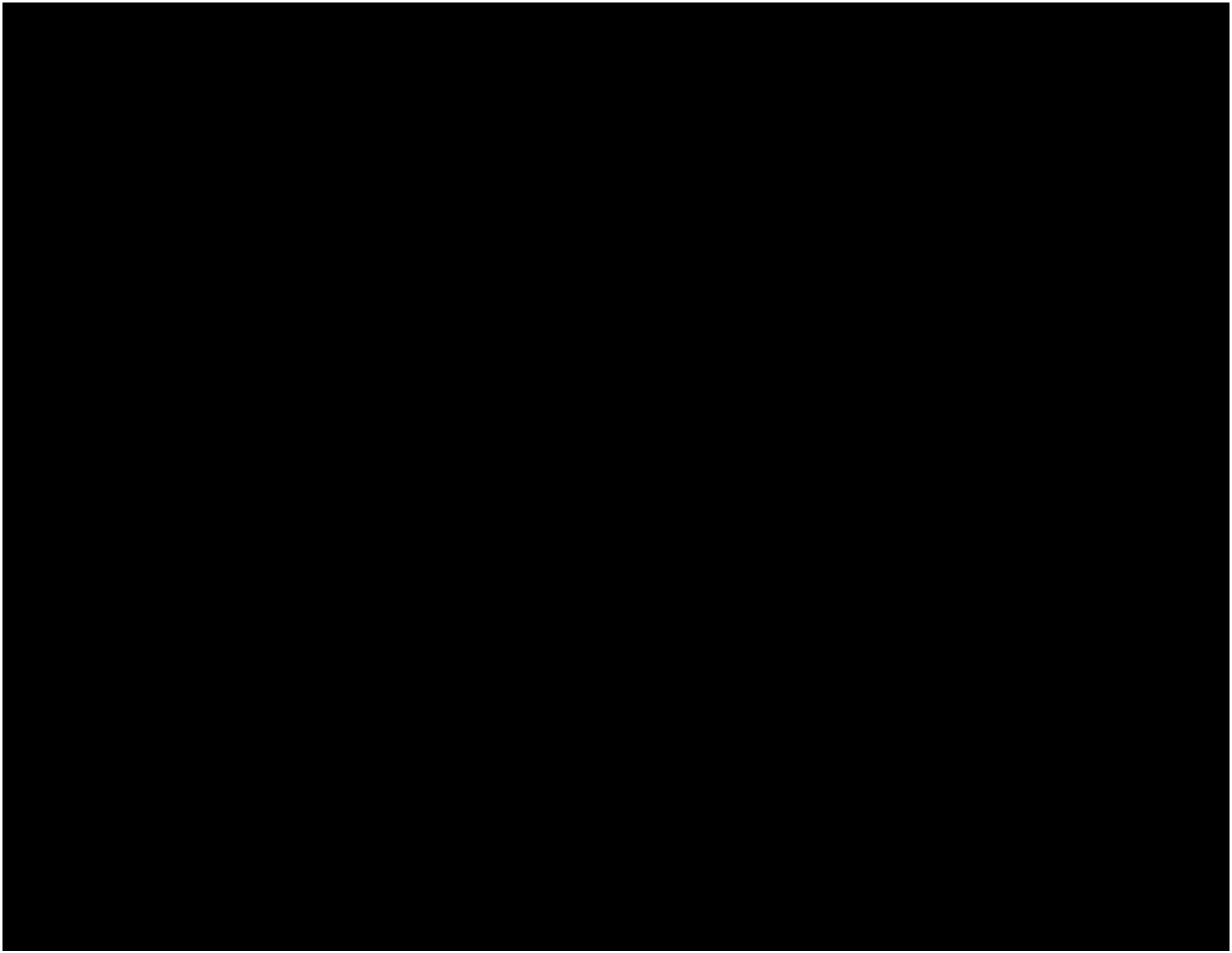
dark Universe

Two Universes

shining Universe

dark Universe





Outline

Outline

- evidence for DM

Outline

- evidence for DM
- DM candidates and particle physics models

Outline

- evidence for DM
- DM candidates and particle physics models
- direct detection of DM

Outline

- evidence for DM
- DM candidates and particle physics models
- direct detection of DM
  - SUSY neutralino - most popular candidate
  - recent hints of low-mass WIMP?

Outline

- evidence for DM
- DM candidates and particle physics models
- direct detection of DM
  - SUSY neutralino - most popular candidate
  - recent hints of low-mass WIMP?
- indirect detection of DM

Outline

- evidence for DM
- DM candidates and particle physics models
- direct detection of DM
  - SUSY neutralino - most popular candidate
  - recent hints of low-mass WIMP?
- indirect detection of DM
- DM and the Large Hadron Collider

Outline

- evidence for DM
- DM candidates and particle physics models
- direct detection of DM
  - SUSY neutralino - most popular candidate
  - recent hints of low-mass WIMP?
- indirect detection of DM
- DM and the Large Hadron Collider
- summary

Dark Matter - Evidence

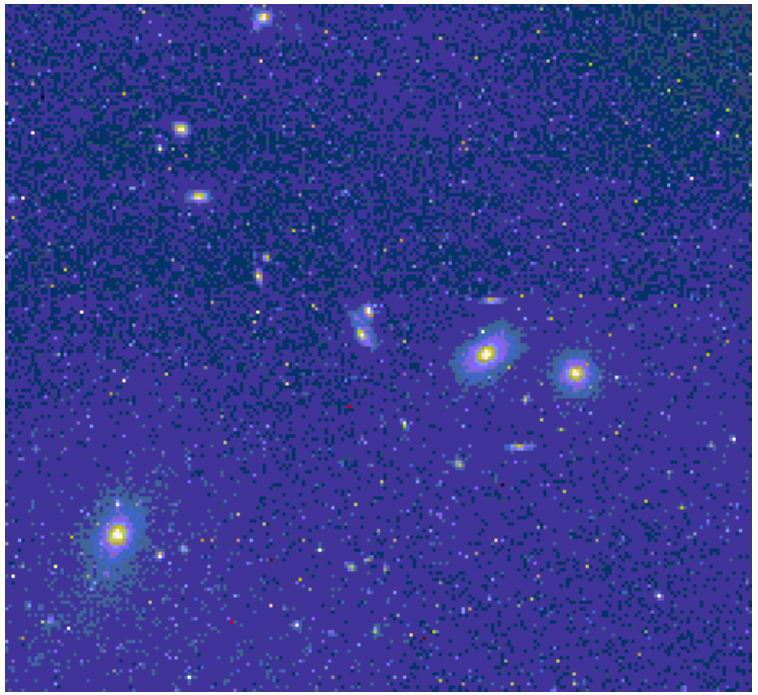
among the oldest puzzles in cosmology

Dark Matter - Evidence

among the oldest puzzles in cosmology

visible mass not enough to bound it

- Zwicky ('33): Coma cluster



Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky ('33): Coma cluster
- spiral galaxies

flat rotation curves

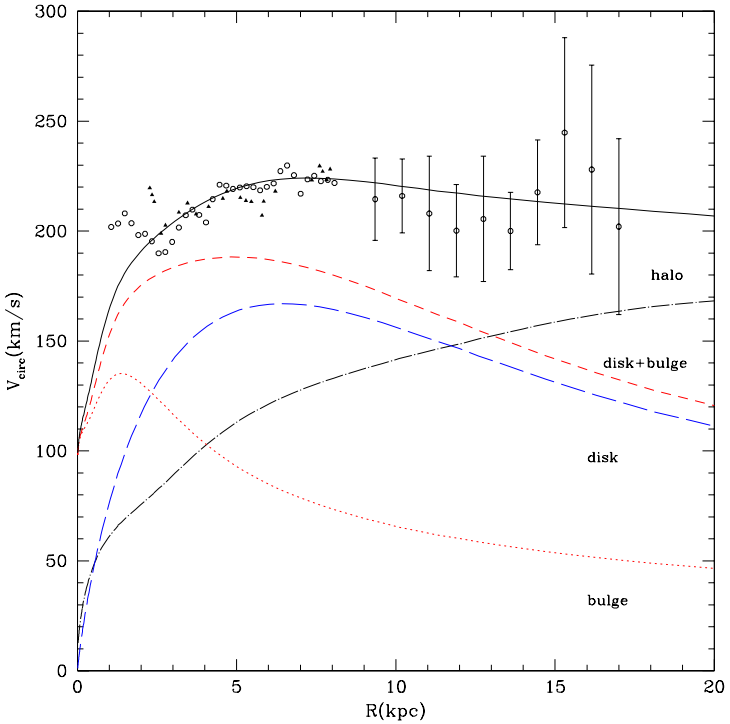
Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky ('33): Coma cluster
- spiral galaxies rotational velocity

$$\frac{mv^2}{r} = \frac{GMm}{r^2} \Rightarrow \boxed{v = \sqrt{G\frac{M}{r}}}$$

Milky Way (Klypin, et al.)

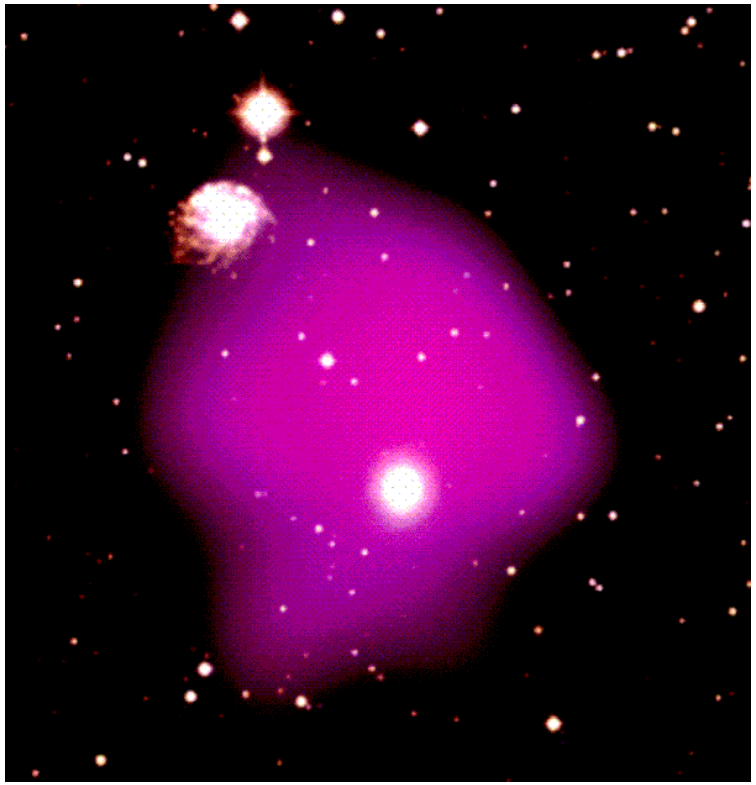


Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky ('33): Coma cluster
- spiral galaxies
- clusters of galaxies

hot gas, $\sim 10^8$ K

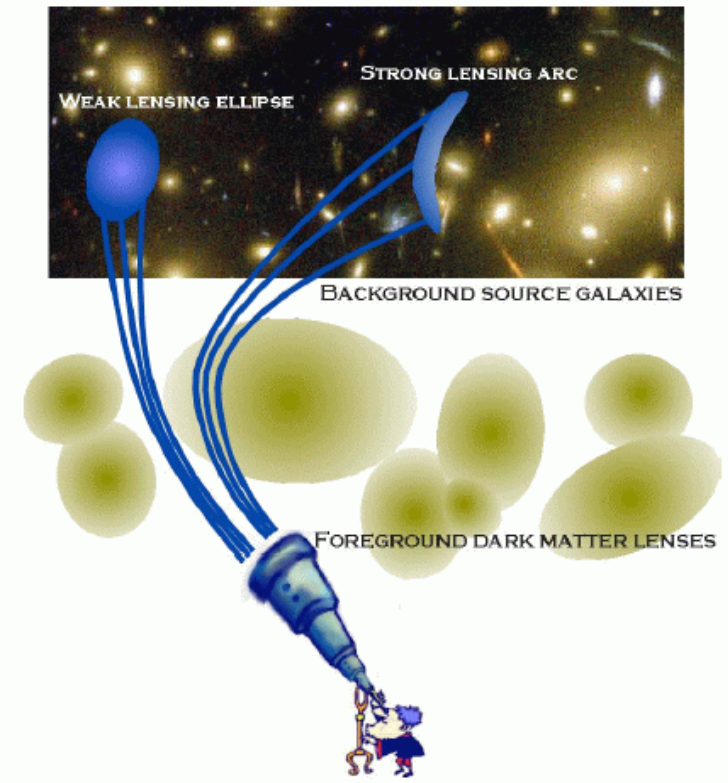


Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky ('33): Coma cluster
- spiral galaxies
- clusters of galaxies
- gravitational lensing

images of distant objects



Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky (’33): Coma cluster
- spiral galaxies
- clusters of galaxies
- gravitational lensing

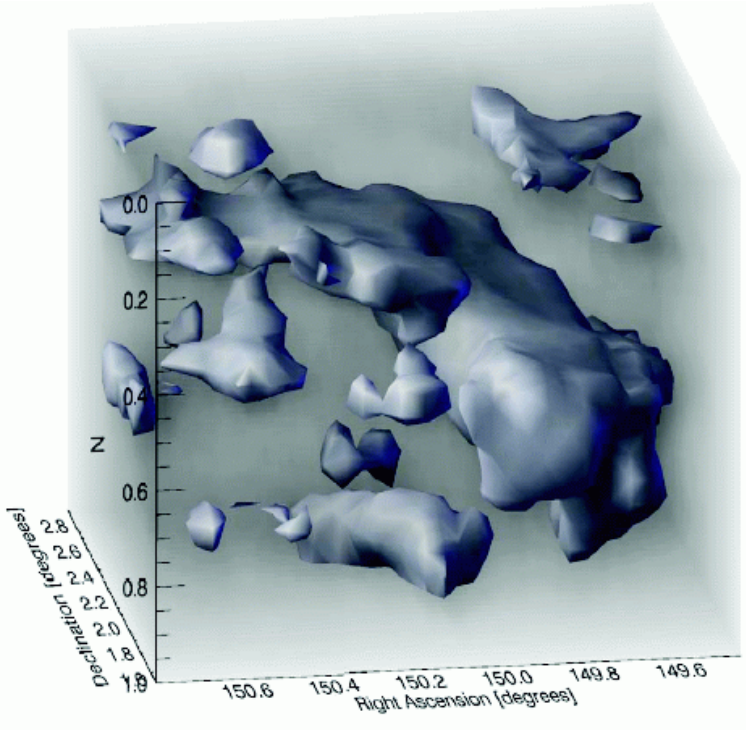
arc images of distant quasars

Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky (’33): Coma cluster
- spiral galaxies
- clusters of galaxies
- gravitational lensing

3dim DM distribution, (Massey, et al, ’07)

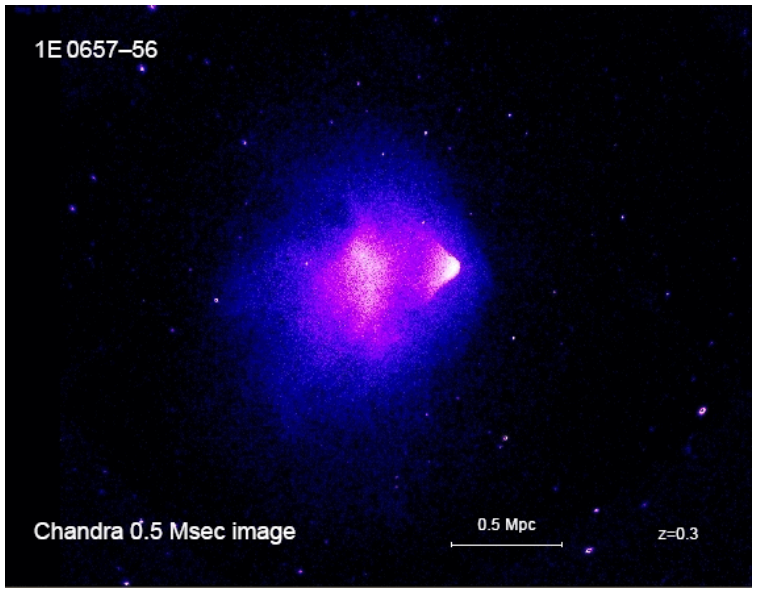


Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky (’33): Coma cluster
- spiral galaxies
- clusters of galaxies
- gravitational lensing
- colliding clusters: Bullet cluster

Bullet cluster, 2006

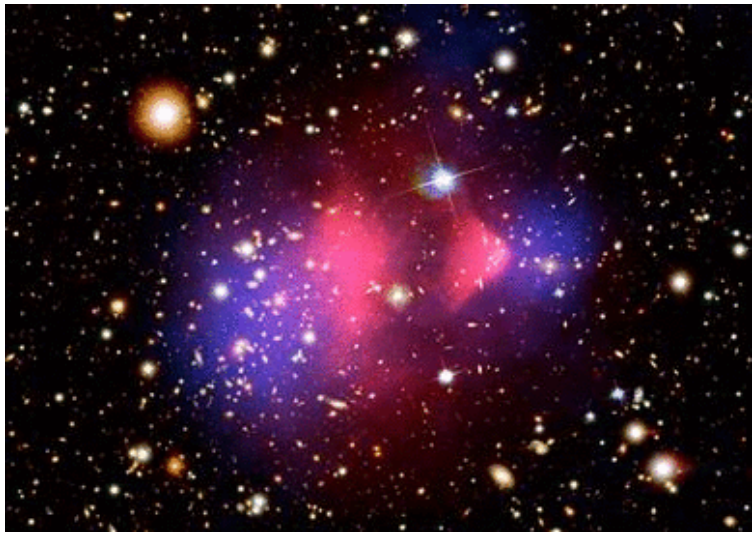


Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky (’33): Coma cluster
- spiral galaxies
- clusters of galaxies
- gravitational lensing
- colliding clusters: Bullet cluster

inferred DM distribution

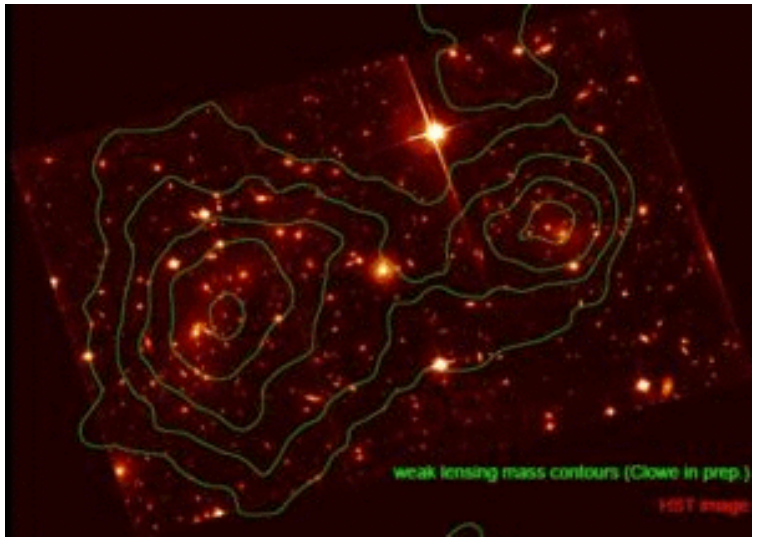


Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky (’33): Coma cluster
- spiral galaxies
- clusters of galaxies
- gravitational lensing
- colliding clusters: Bullet cluster

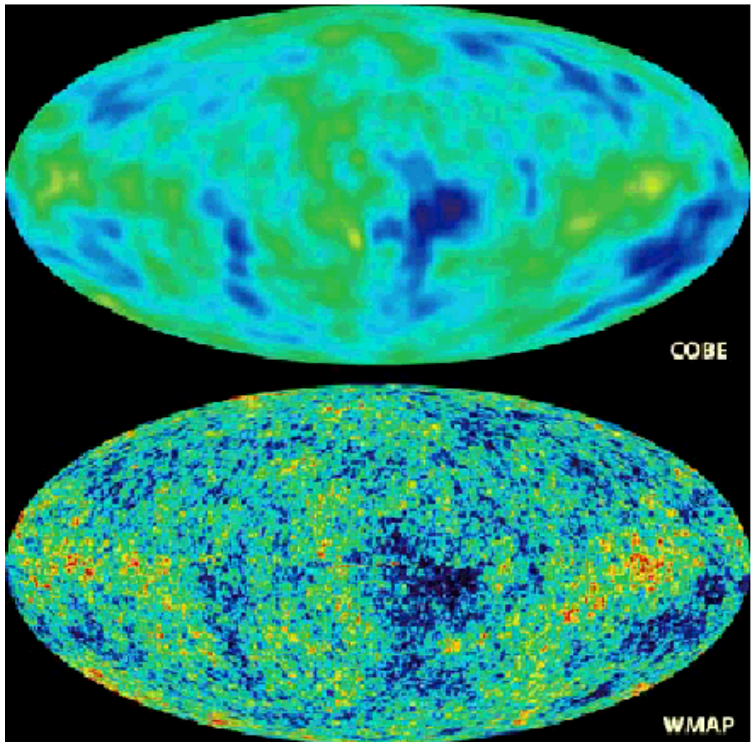
DM separated from baryons



Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky (’33): Coma cluster
- spiral galaxies
- clusters of galaxies
- gravitational lensing
- colliding clusters: Bullet cluster
- CMB: precision measurements



Knows and don't knows about DM

Knows and don't knows about DM

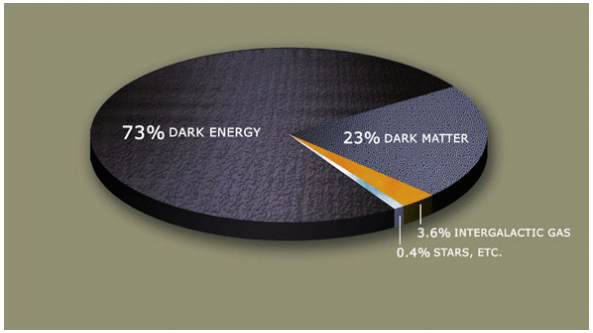
- evidence for dark matter is convincing

... but only through gravitational effects

Knows and don't knows about DM

- evidence for dark matter is convincing

... but only through gravitational effects



$$\Omega_i = \rho_i / \rho_{crit}$$

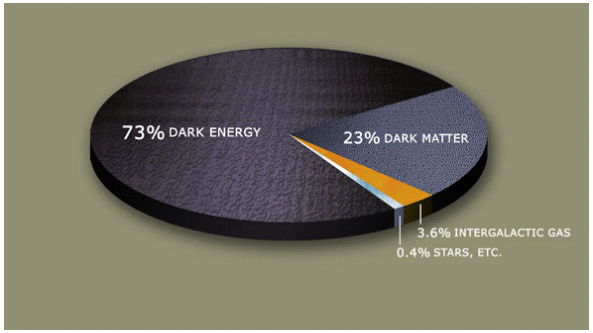
- concordance ΛCDM model works well
- main components: dark energy and cold dark matter

$$\boxed{\Omega_{\rm CDM} h^2 = 0.1120 \pm 0.0056}$$

Knows and don't knows about DM

- evidence for dark matter is convincing

... but only through gravitational effects



$$\Omega_i = \rho_i / \rho_{crit}$$

- concordance ΛCDM model works well
- main components: dark energy and cold dark matter

$$\boxed{\Omega_{\rm CDM} h^2 = 0.1120 \pm 0.0056}$$

What is the dark matter?

What is the DM?

What is the DM?

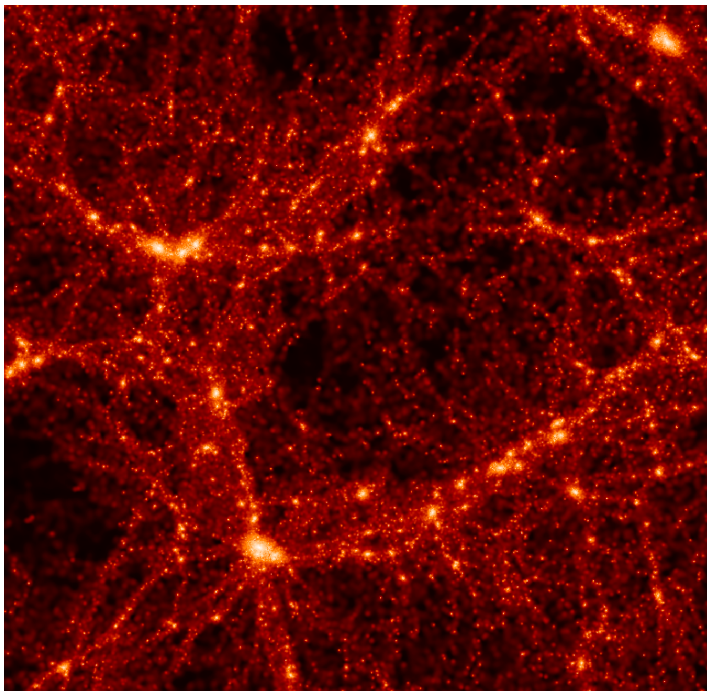
- non–baryonic

What is the DM?

- non–baryonic
- cold (CDM)

or possibly (?) warmish

numerical simulations of LSS



What is the DM?

- non–baryonic
- cold (CDM)

  or possibly (?) warmish
- no electric nor (preferably) color interactions
- limits on exotic elements

  (anomalous nuclei)
- DM is DARK

What is the DM?

- non–baryonic
- cold (CDM)

  or possibly (?) warmish
- no electric nor (preferably) color interactions
- relic from the Big Bang

What is the DM?

- non–baryonic
- cold (CDM)

  or possibly (?) warmish
- no electric nor (preferably) color interactions
- relic from the Big Bang
- element of some sensible particle theory

What is the DM?

- non–baryonic
- cold (CDM)

  or possibly (?) warmish
- no electric nor (preferably) color interactions
- relic from the Big Bang
- element of some sensible particle theory

plausible choice $\Rightarrow$ WIMP

(weakly interacting massive particle)

...a very broad class, not a single candidate

What is the DM?

- non–baryonic
- cold (CDM)

  or possibly (?) warmish
- no electric nor (preferably) color interactions
- relic from the Big Bang
- element of some sensible particle theory

plausible choice $\Rightarrow$ WIMP

(weakly interacting massive particle)

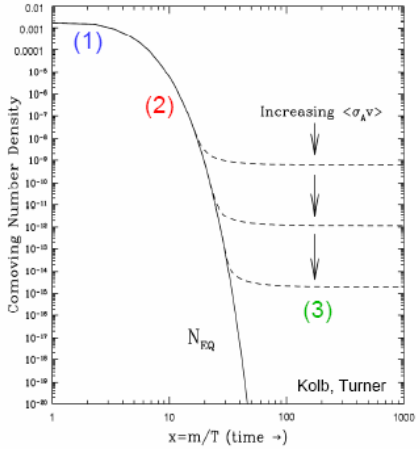
...a very broad class, not a single candidate

...How weak can weak be?

A simple, persuasive argument:

A simple, persuasive argument:

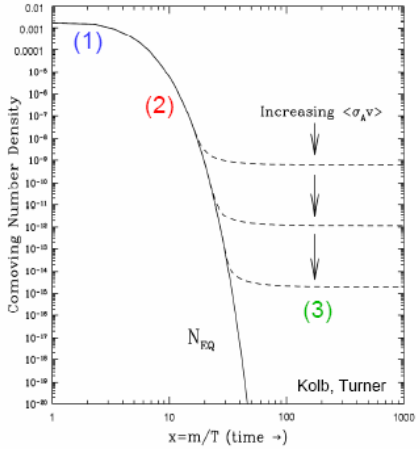
- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$



$$x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

A simple, persuasive argument:

- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$



WIMP relic abundance

$$\Omega h^2 \simeq \frac{1}{\left\langle \left(\frac{\sigma_{\rm ann}}{10^{-38}{\rm cm}^2}\right)\left(\frac{v/c}{0.1}\right)\right\rangle}$$

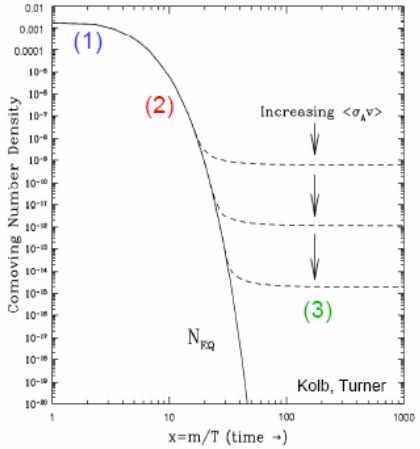
$$x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

$\sigma_{\rm ann}$ – c.s. for WIMP pair–annihilation in the early Universe

v – their relative velocity, $\langle \ldots \rangle$– thermal average

A simple, persuasive argument:

- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$



WIMP relic abundance

$$\Omega h^2 \simeq \frac{1}{\left\langle \left(\frac{\sigma_{\rm ann}}{10^{-38}{\rm cm}^2}\right)\left(\frac{v/c}{0.1}\right)\right\rangle}$$

$$x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

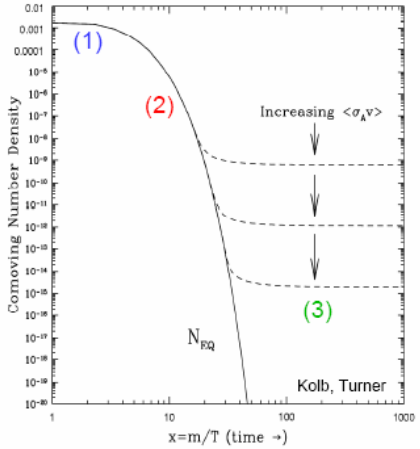
$\sigma_{\rm ann}$ – c.s. for WIMP pair–annihilation in the early Universe

v – their relative velocity, $\langle \ldots \rangle$– thermal average

$$\sigma_{\rm ann} \sim \sigma_{\rm weak} \sim 10^{-38}\,{\rm cm}^2 = 10^{-2}\,{\rm pb} \;\Rightarrow\; \Omega h^2 \sim 1$$

A simple, persuasive argument:

- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$



WIMP relic abundance

$$\Omega h^2 \simeq \frac{1}{\left\langle \left(\frac{\sigma_{\rm ann}}{10^{-38}{\rm cm}^2}\right)\left(\frac{v/c}{0.1}\right)\right\rangle}$$

$$x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

$\sigma_{\rm ann}$ – c.s. for WIMP pair–annihilation in the early Universe

v – their relative velocity, $\langle \ldots \rangle$– thermal average

$$\sigma_{\rm ann} \sim \sigma_{\rm weak} \sim 10^{-38}\,{\rm cm}^2 = 10^{-2}\,{\rm pb} \;\Rightarrow\; \Omega h^2 \sim 1$$

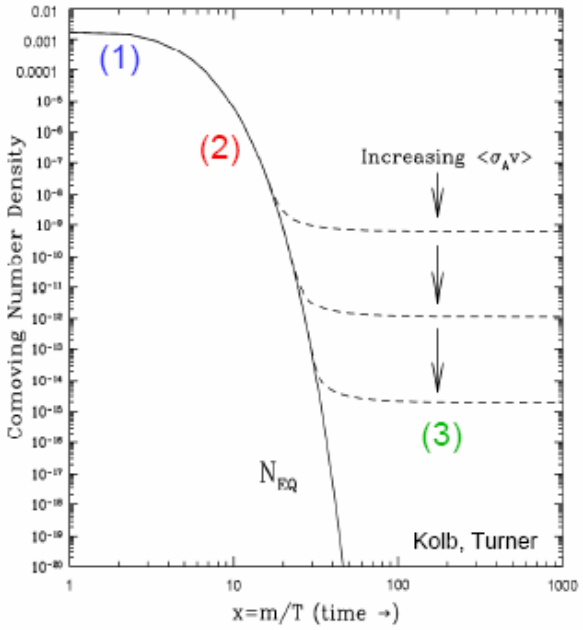
A hint? Possibly, but...

Thermal or non-thermal relic?

Thermal or non-thermal relic?

thermal

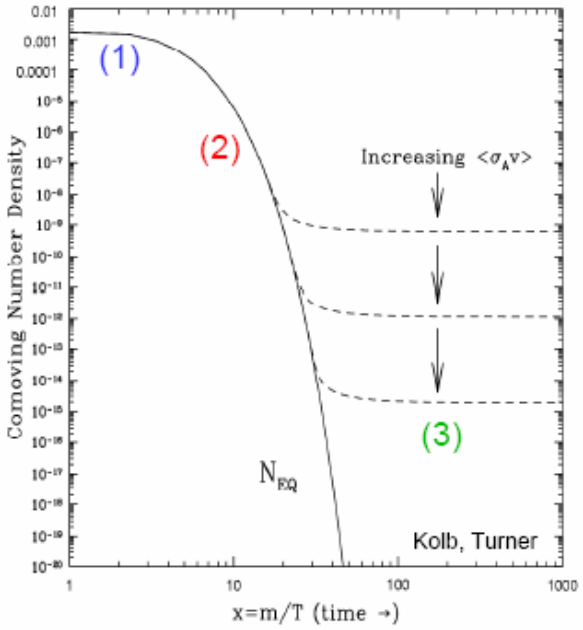
freeze-out



Thermal or non-thermal relic?

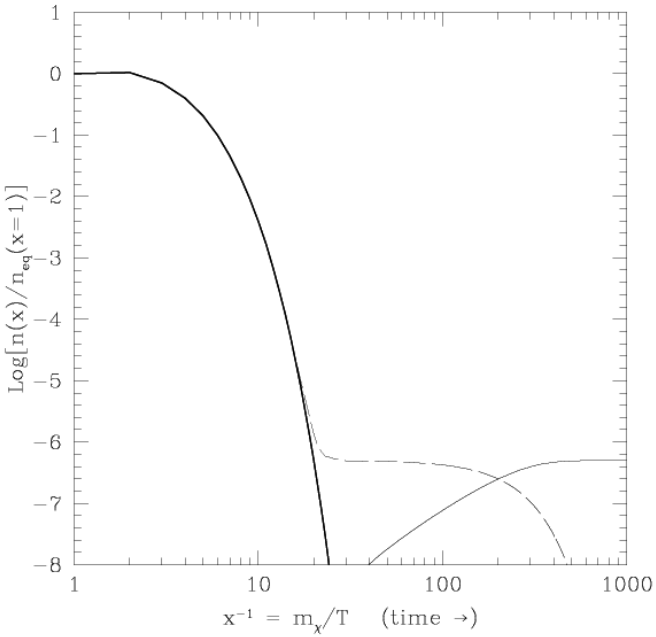
thermal

freeze-out



non-thermal

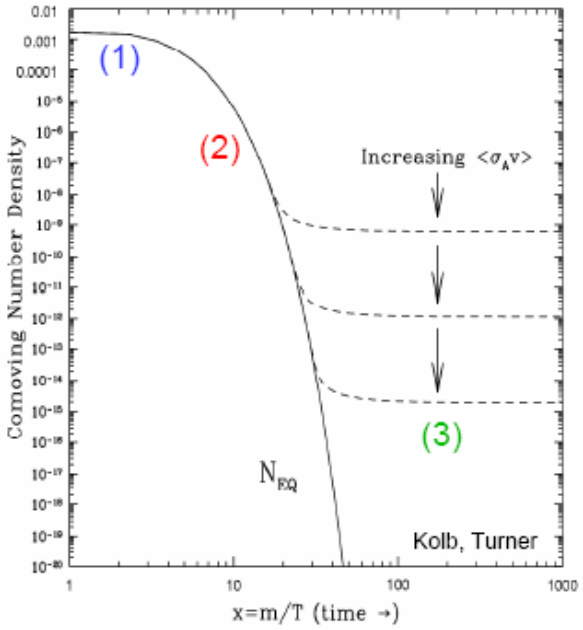
out-of-equilibrium, several mechanisms



Thermal or non-thermal relic?

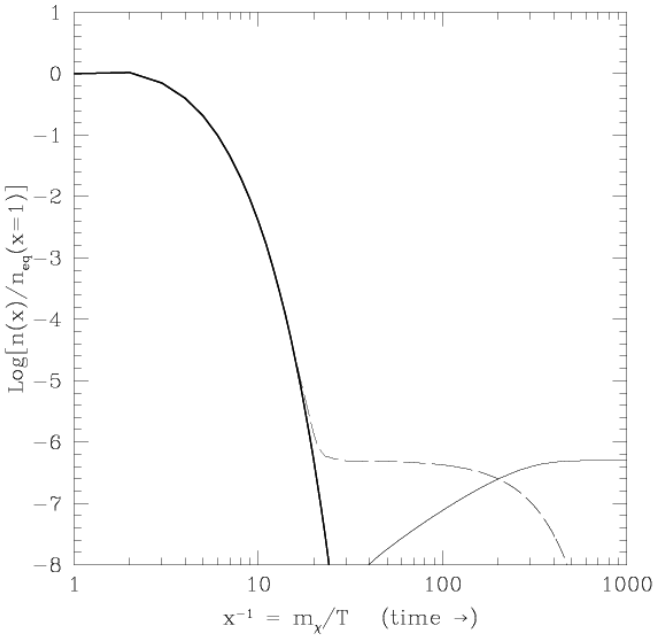
thermal

freeze-out



non-thermal

out-of-equilibrium, several mechanisms

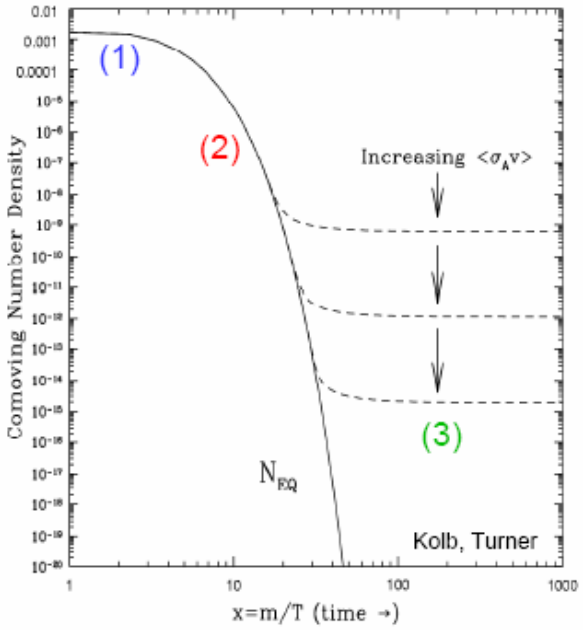


- thermal production (TP): robust

Thermal or non-thermal relic?

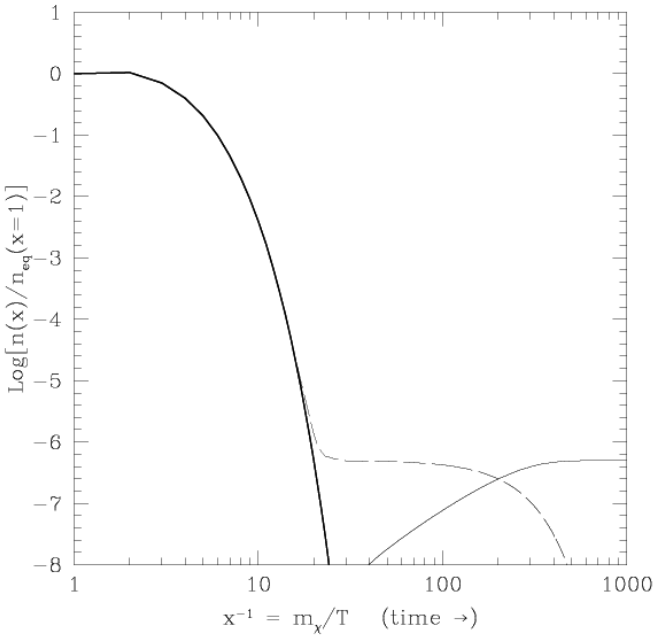
thermal

freeze-out



non-thermal

out-of-equilibrium, several mechanisms



- thermal production (TP): robust
- non-thermal production (NTP): more model-/mechanism- dependent, can be dominant, opens up new possibilities

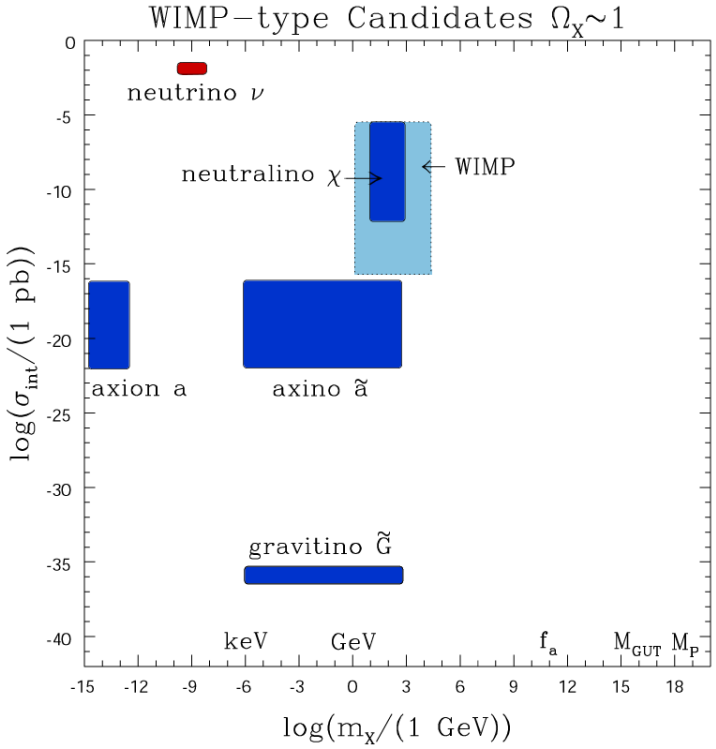
DM: The Big Picture

* – not invented to solve the DM problem

*well–motivated** particle candidates with $\Omega \sim 0.1$

DM: The Big Picture

L.R. (2000), hep-ph/0404052



- neutrino ν – hot DM
- neutralino χ
- "generic" WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$

- vast ranges of interactions and masses
- different production mechanisms in the early Universe (thermal, non-thermal)
- need to go beyond the Standard Model
- WIMP candidates testable at present/near future
- axino, gravitino EWIMPs/superWIMPs not directly testable, but some hints from LHC

Some WIMP candidates for Cold DM

No shortage of ideas...

...but few good ones, ...and even fewer longer-lasting

Some WIMP candidates for Cold DM

No shortage of ideas... ...but few good ones, ...and even fewer longer-lasting

- lightest neutralino χ of supersymmetry

Some WIMP candidates for Cold DM

No shortage of ideas... ...but few good ones, ...and even fewer longer-lasting

- lightest neutralino χ of supersymmetry
- lightest Kałuża-Klein (KK) state from warped/universal extra dimensions

Some WIMP candidates for Cold DM

No shortage of ideas... ...but few good ones, ...and even fewer longer-lasting

- lightest neutralino χ of supersymmetry
- lightest Kałuża-Klein (KK) state from warped/universal extra dimensions
- massive (almost) sterile neutrino ν_R or sneutrino $\tilde{\nu}_R$

Some WIMP candidates for Cold DM

No shortage of ideas... ...but few good ones, ...and even fewer longer-lasting

- lightest neutralino χ of supersymmetry
- lightest Kałuża-Klein (KK) state from warped/universal extra dimensions
- massive (almost) sterile neutrino ν_R or sneutrino $\tilde{\nu}_R$
- axion a

Some WIMP candidates for Cold DM

No shortage of ideas... ...but few good ones, ...and even fewer longer-lasting

- lightest neutralino χ of supersymmetry
- lightest Kałuża-Klein (KK) state from warped/universal extra dimensions
- massive (almost) sterile neutrino ν_R or sneutrino $\tilde{\nu}_R$
- axion a
- axino $\widetilde{a}$, gravitino $\widetilde{G}$

extremely-weakly interacting relics

not necessarily stable

- add your own...

Some WIMP candidates for Cold DM

No shortage of ideas... ...but few good ones, ...and even fewer longer-lasting

- lightest neutralino χ of supersymmetry
- lightest Kałuża-Klein (KK) state from warped/universal extra dimensions
- massive (almost) sterile neutrino ν_R or sneutrino $\tilde{\nu}_R$
- axion a
- axino $\widetilde{a}$, gravitino $\widetilde{G}$

extremely-weakly interacting relics

not necessarily stable

- add your own...

several other interesting candidates: well-tempered neutralino, multiple DM, little Higgs DM, mirror DM, shadow DM, sequestered DM, secluded DM, flaxino DM, Higgs portal DM, inflation and DM, modulus DM, asymmetric DM, inelastic DM, etc etc. – no nonsense but not superior either

It is fairly easy to invent a DM relic

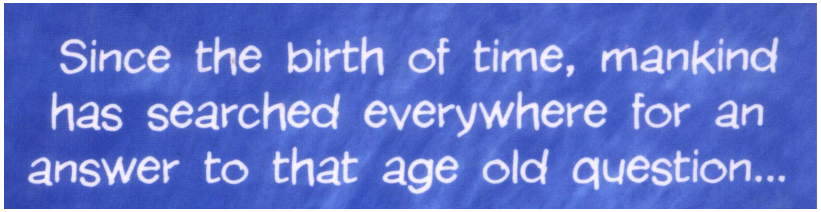
It is fairly easy to invent a DM relic

it is much (!) harder to invent a (lasting) model of ‘new physics’

WIMP Detection

Where to find the WIMP?

Where to find the WIMP?



Where to find the WIMP?

Since the birth of time, mankind has searched everywhere for an answer to that age old question...

Where to find the WIMP?

Since the birth of time, mankind has searched everywhere for an answer to that age old question...

...go underground!

Strategies for WIMP Detection

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

- indirect detection (ID):

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape
  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

    from within a few kpc

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape
  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

    from within a few kpc
  - gamma rays from WIMP pair-annihilation in the Galactic center

    depending on DM distribution in the GC

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape
  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

    from within a few kpc
  - gamma rays from WIMP pair-annihilation in the Galactic center

    depending on DM distribution in the GC
  - other ideas: traces of WIMP annihilation in dwarf galaxies, in rich clusters, etc

    more speculative

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape
  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

    from within a few kpc
  - gamma rays from WIMP pair-annihilation in the Galactic center

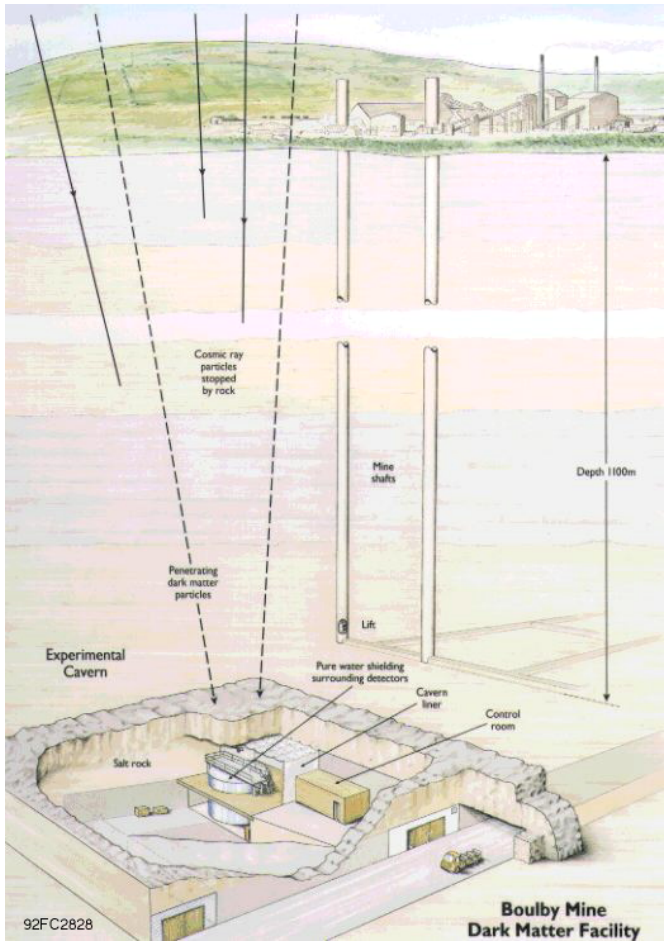
    depending on DM distribution in the GC
  - other ideas: traces of WIMP annihilation in dwarf galaxies, in rich clusters, etc

    more speculative
- the LHC

Go underground/–ice/–water

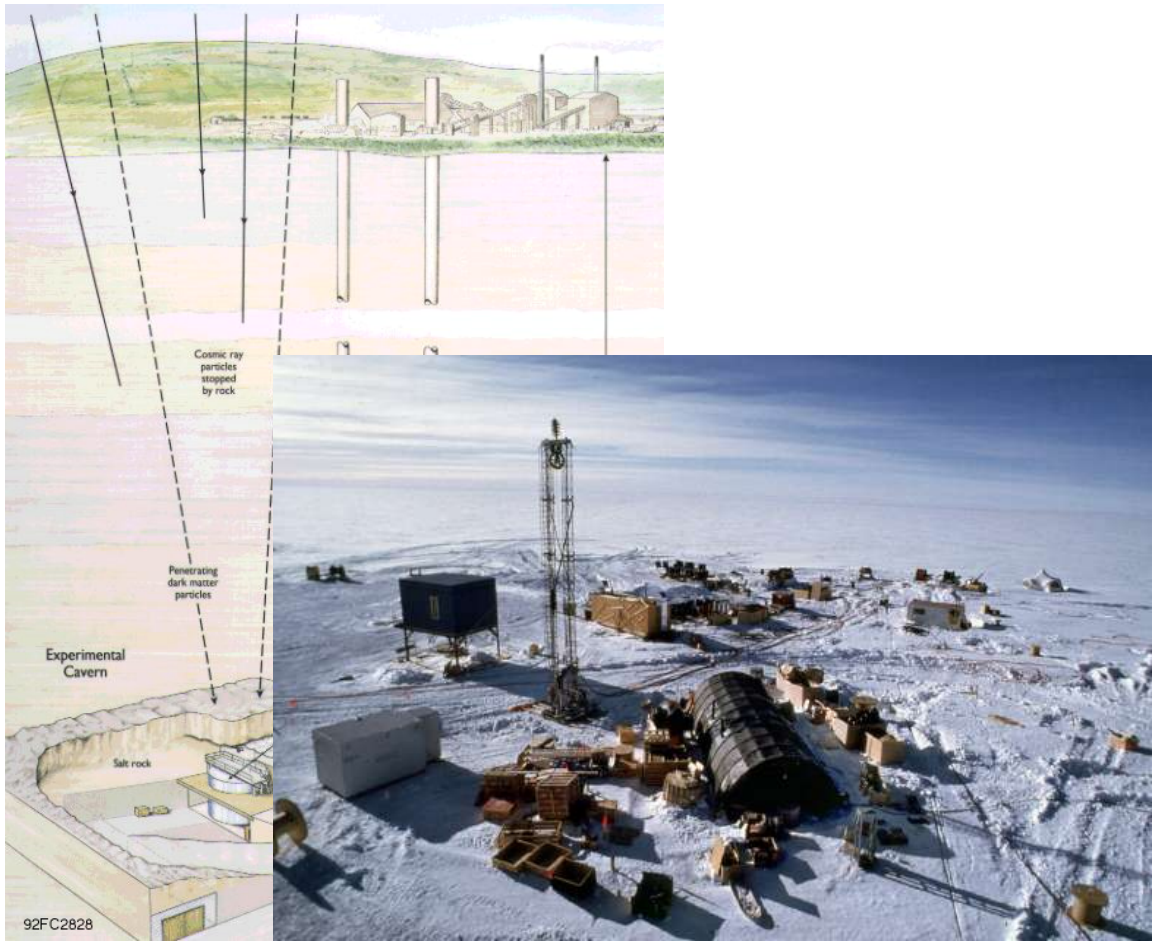
... or to space

Go underground/–ice/–water



... or to space

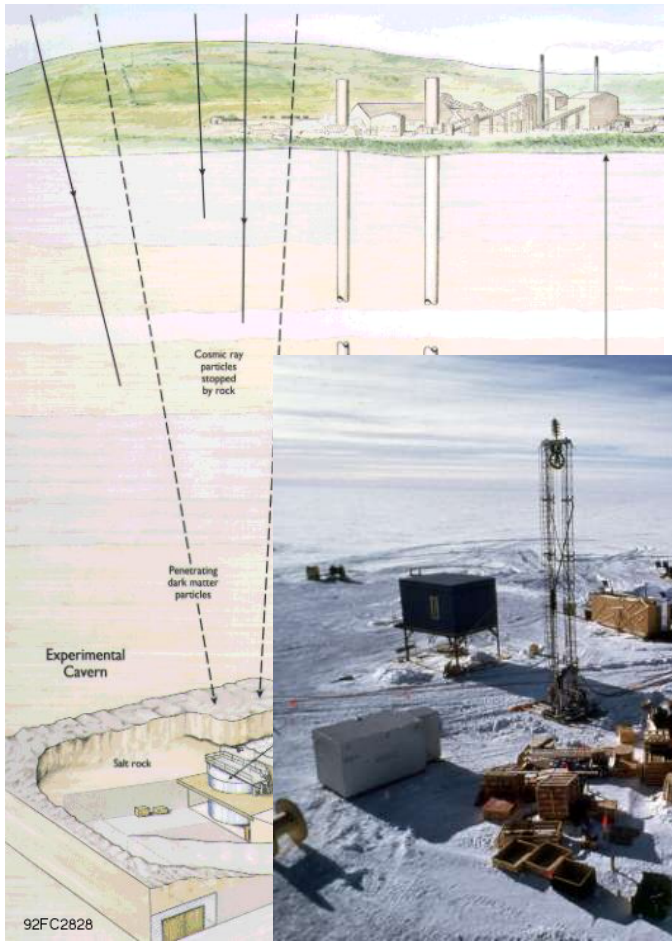
Go underground/–ice/–water

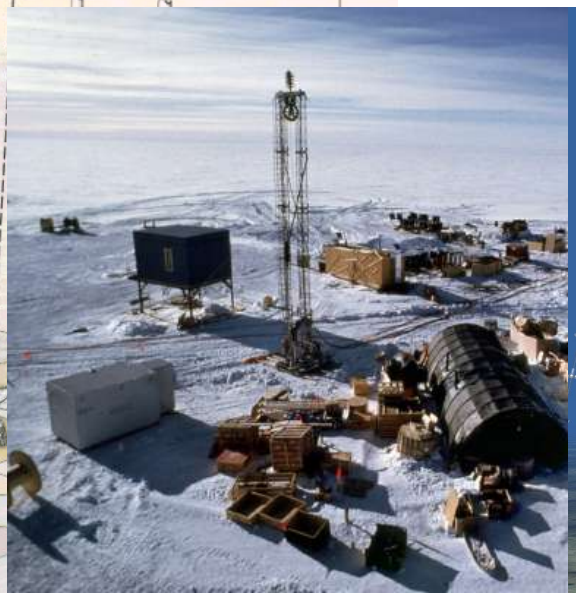


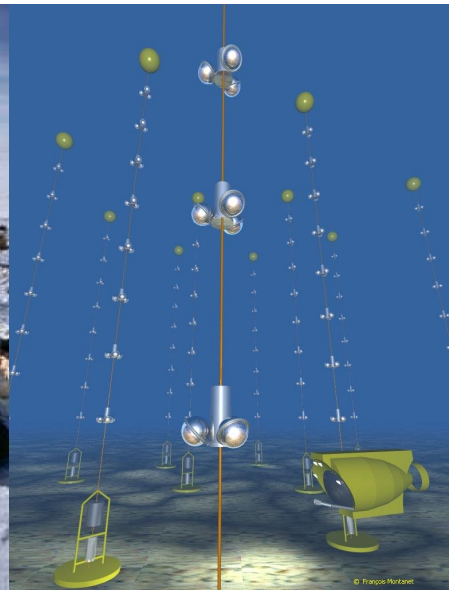
... or to space

Go underground/–ice/–water

... or to space

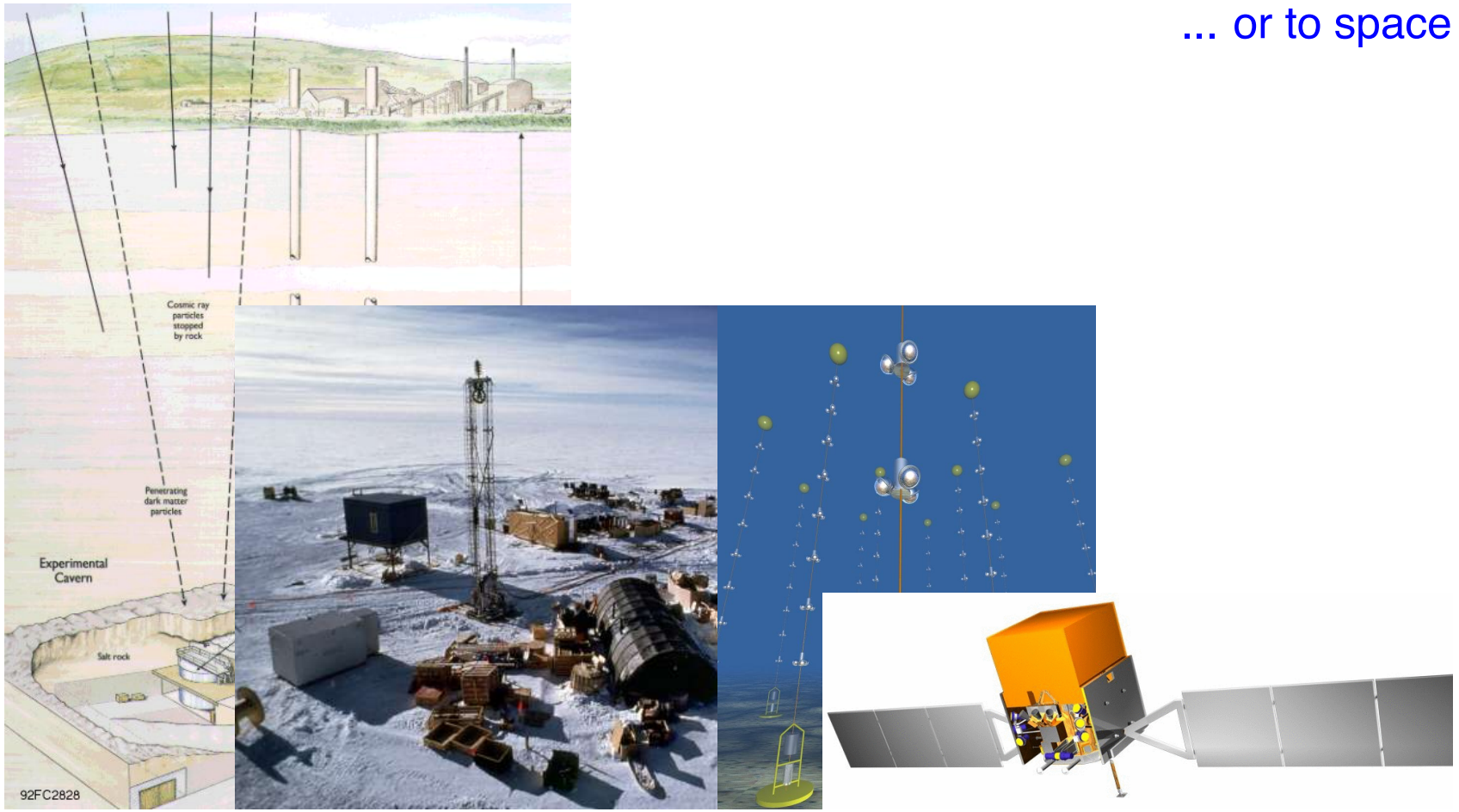






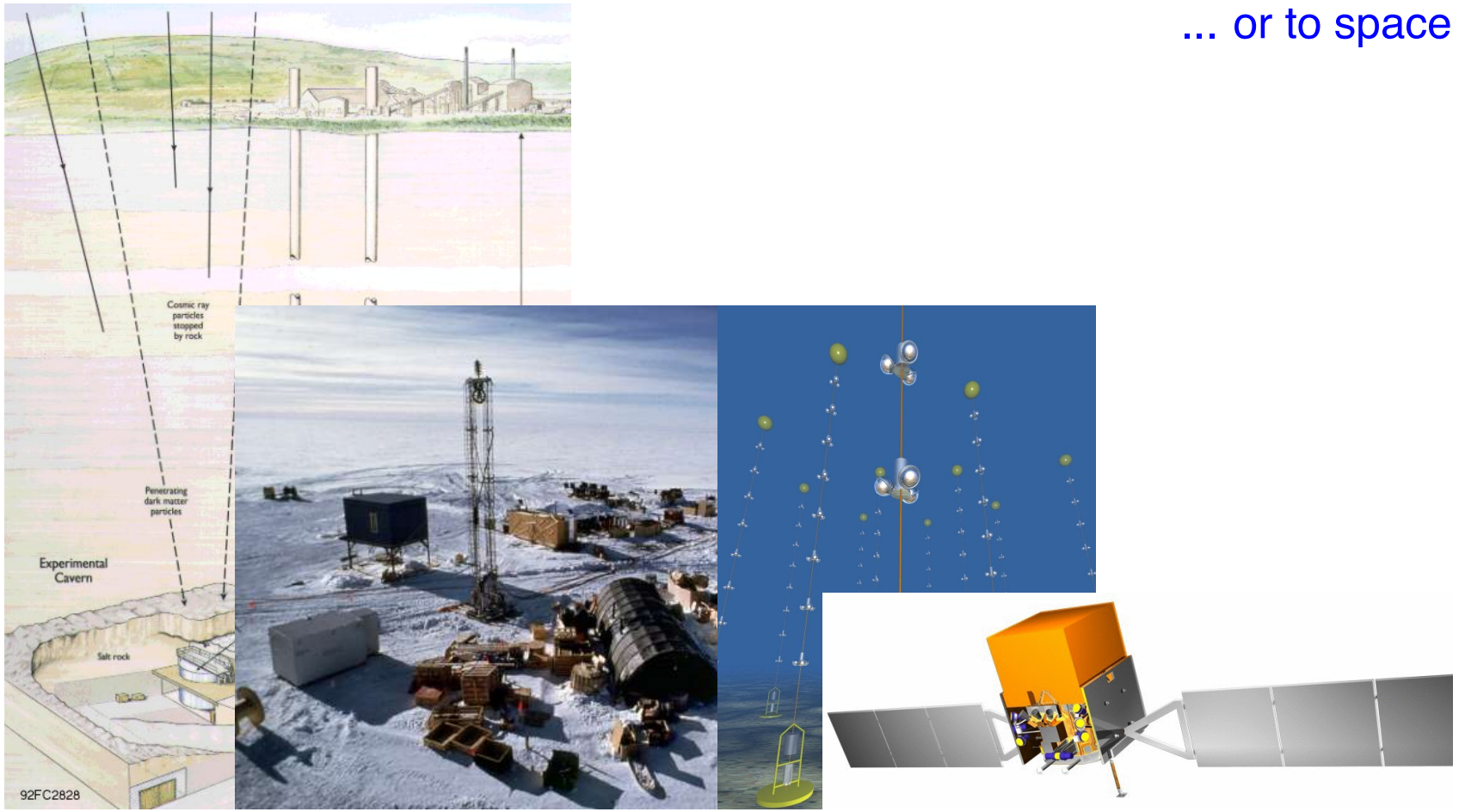
Go underground/–ice/–water

... or to space



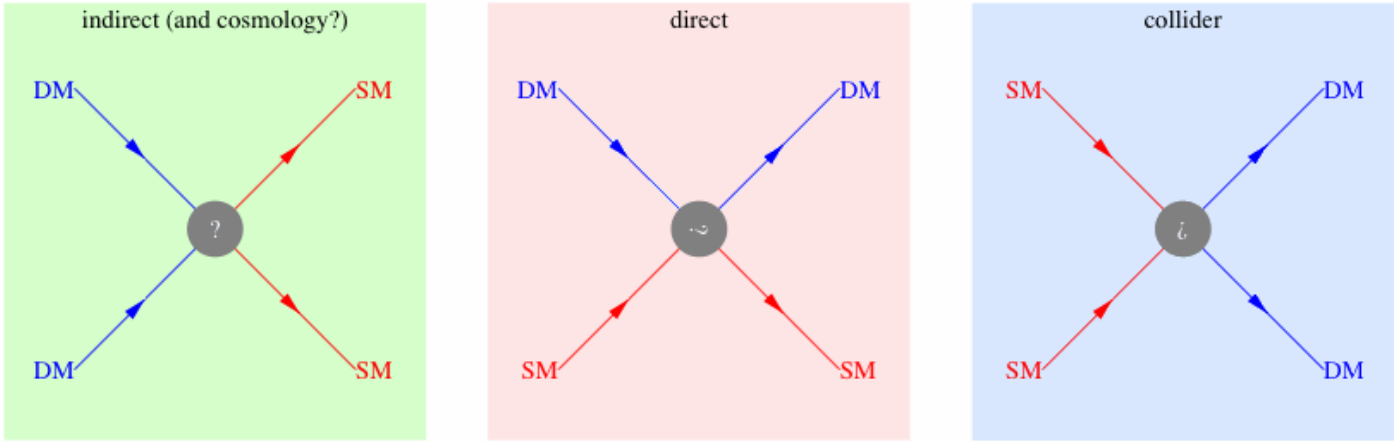
Go underground/–ice/–water

... or to space



impressive experimental effort

Indirect, direct, collider



(figure from Strumia)

but... usually NO crossing symmetry to help

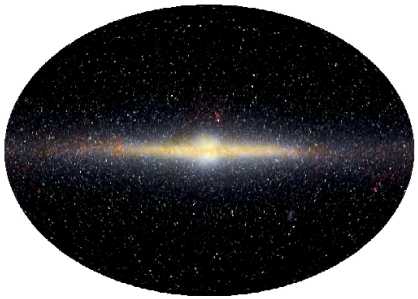
reason: in each case different diagrams dominate

- DD: XENON, CDMS, CoGeNT, ...
- ID: Fermi, Pamela, ACT, ...
- colliders: LHC

Direct detection

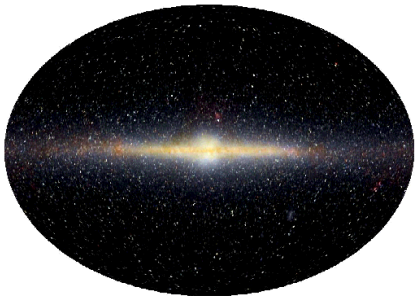
Direct detection

MW is immersed in a halo of WIMPs



Direct detection

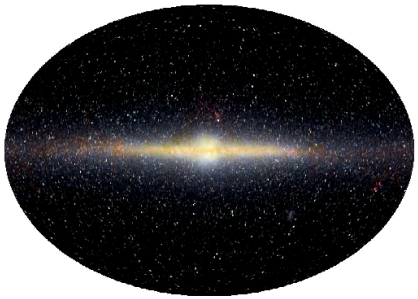
MW is immersed in a halo of WIMPs



- local density: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- velocity $v \sim 270\,\mathrm{km/sec}$, Maxwellian

Direct detection

MW is immersed in a halo of WIMPs

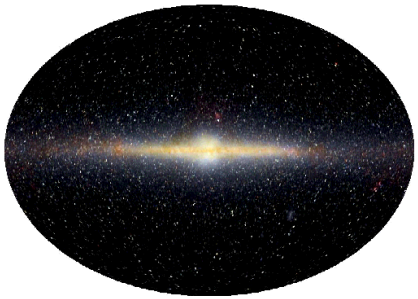


- local density: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- velocity $v \sim 270\,\mathrm{km/sec}$, Maxwellian
- flux

$$\Phi = n_\chi v = 10^{10}\,\frac{\mathrm{WIMPs}}{\mathrm{m^2 sec}}\left(\frac{\rho_\chi}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{270\,\mathrm{km/sec}}\right)$$

Direct detection

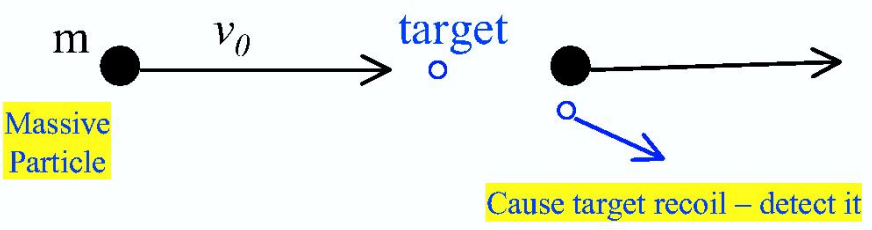
MW is immersed in a halo of WIMPs



- local density: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- velocity $v \sim 270\,\mathrm{km/sec}$, Maxwellian
- flux

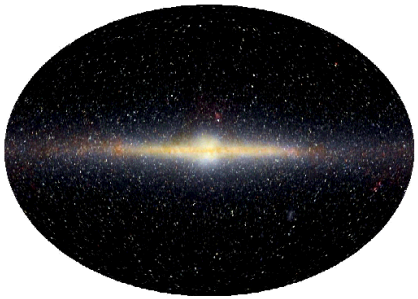
$$\Phi = n_\chi v = 10^{10}\,\frac{\text{WIMPs}}{\text{m}^2\text{sec}}\left(\frac{\rho_\chi}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{270\,\mathrm{km/sec}}\right)$$

- energy deposit $\sim m_\chi v^2/2 \sim 10 - 100\,\mathrm{keV}$ tiny!!!



Direct detection

MW is immersed in a halo of WIMPs



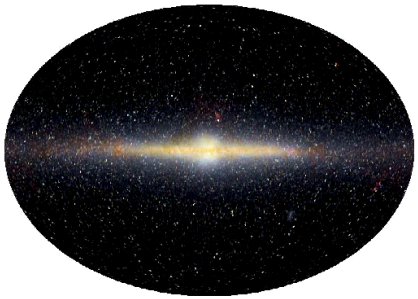
- local density: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- velocity $v \sim 270\,\mathrm{km/sec}$, Maxwellian
- flux

$$\Phi = n_\chi v = 10^{10}\,\frac{\text{WIMPs}}{\text{m}^2\text{sec}}\left(\frac{\rho_\chi}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{270\,\mathrm{km/sec}}\right)$$

- energy deposit $\sim m_\chi v^2/2 \sim 10 - 100\,\mathrm{keV}$ tiny!!!
- detection cross section $\frac{d\sigma}{dq} = G_F^2 \frac{C}{\pi v^2} F^2(q)$ $F(q)$– nuclear form factor

Direct detection

MW is immersed in a halo of WIMPs



- local density: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- velocity $v \sim 270\,\mathrm{km/sec}$, Maxwellian
- flux

$$\Phi = n_\chi v = 10^{10}\,\frac{\text{WIMPs}}{\text{m}^2\text{sec}}\left(\frac{\rho_\chi}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{270\,\mathrm{km/sec}}\right)$$

- energy deposit $\sim m_\chi v^2/2 \sim 10 - 100\,\mathrm{keV}$ tiny!!!
- detection cross section $\frac{d\sigma}{dq} = G_F^2 \frac{C}{\pi v^2} F^2(q)$ $F(q)$– nuclear form factor

Non-relat. Majorana WIMP: effectively two types of interactions:

- spin independent (SI, or scalar)

target: nucleus X_Z^A

$$\boxed{\frac{d\sigma^{\mathrm{SI}}}{dq} \propto A^2} \Leftarrow \text{coherent enhancement} \quad \boxed{q \to 0: \quad \sigma_p^{\mathrm{SI}}}$$

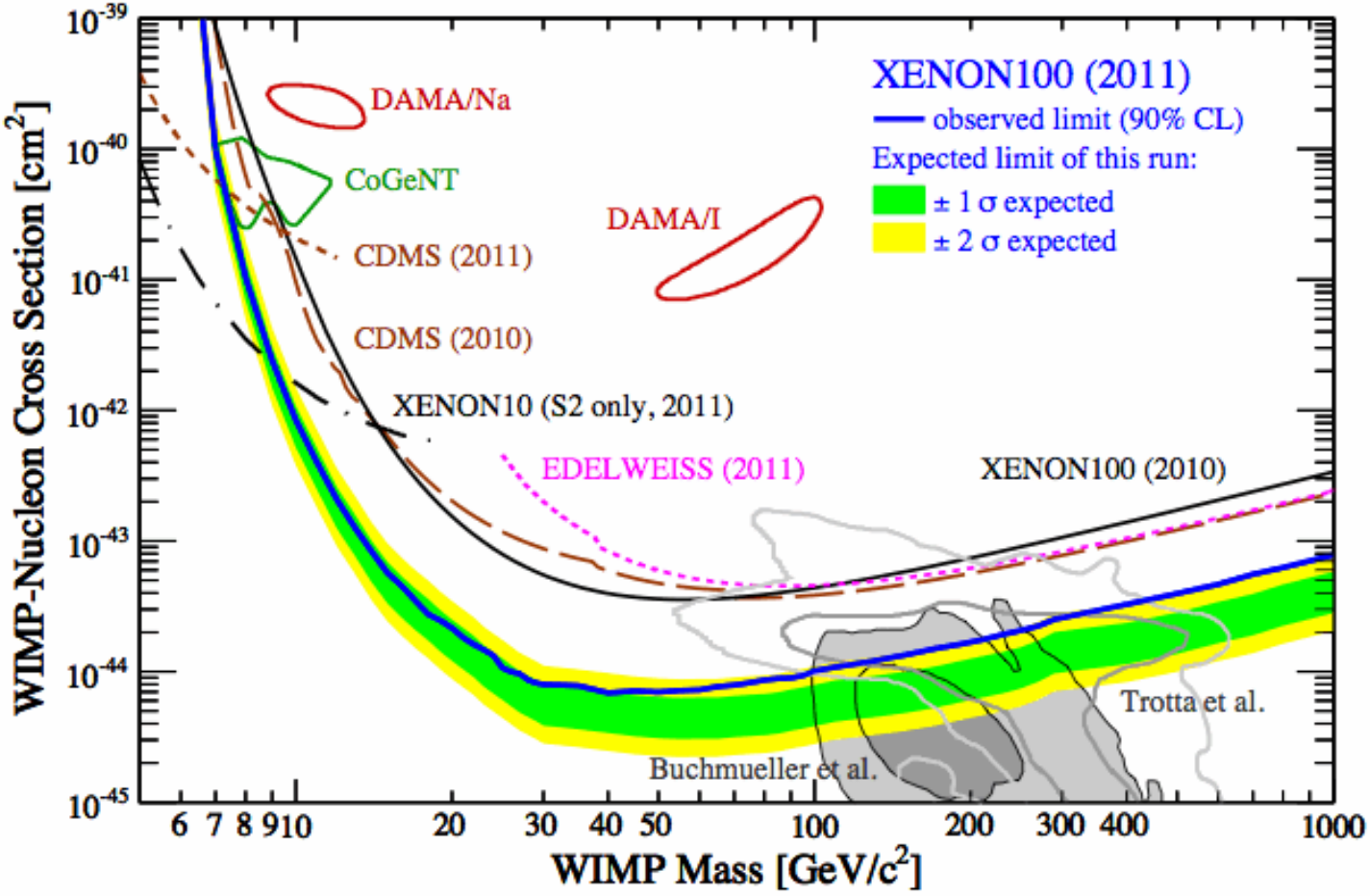
- spin dependent (SD, or axial)

$$\boxed{\frac{d\sigma^{\mathrm{SD}}}{dq} \propto J} \qquad \boxed{q \to 0: \quad \sigma_p^{\mathrm{SD}}, \sigma_n^{\mathrm{SD}}}$$

J – total spin of target nucleus

Direct Detection of Dark Matter

Direct Detection of Dark Matter



Neutralino of SUSY – Prime Suspect

Neutralino of SUSY – Prime Suspect

neutralino χ = lightest mass eigenstate
of neutral gauginos $\widetilde{B}$ (bino), $\widetilde{W}_3^0$ (wino) and neutral higgsinos $\widetilde{H}_t^0$, $\widetilde{H}_b^0$
Majorana fermion ($\chi^c = \chi$)

most popular candidate

Neutralino of SUSY – Prime Suspect

neutralino χ = lightest mass eigenstate
of neutral gauginos $\widetilde{B}$ (bino), $\widetilde{W}_3^0$ (wino) and neutral higgsinos $\widetilde{H}_t^0$, $\widetilde{H}_b^0$
Majorana fermion ($\chi^c = \chi$)

most popular candidate

- part of a well-defined and well-motivated framework of SUSY
- calculable
- relic density: $\Omega_\chi h^2 \sim 0.1$ from freeze-out (...more like $10^{-4} - 10^3$)
- stable with some discrete symmetry (e.g., R-parity or baryon parity)
- testable with today's experiments (DD, ID, LHC)
- ...no obviously superior competitor (both to SUSY and to χ) exists

Neutralino of SUSY – Prime Suspect

neutralino χ = lightest mass eigenstate
of neutral gauginos $\widetilde{B}$ (bino), $\widetilde{W}_3^0$ (wino) and neutral higgsinos $\widetilde{H}_t^0$, $\widetilde{H}_b^0$
Majorana fermion ($\chi^c = \chi$)

most popular candidate

- part of a well-defined and well-motivated framework of SUSY
- calculable
- relic density: $\Omega_\chi h^2 \sim 0.1$ from freeze-out (...more like $10^{-4} - 10^3$)
- stable with some discrete symmetry (e.g., R-parity or baryon parity)
- testable with today's experiments (DD, ID, LHC)
- ...no obviously superior competitor (both to SUSY and to χ) exists

Don't forget:

- multitude of SUSY-based models: general MSSM, CMSSM, split SUSY, MNMSSM, $SO(10)$ GUTs, string inspired models, etc, etc
- neutralino properties often differ widely from model to model

Neutralino of SUSY – Prime Suspect

neutralino χ = lightest mass eigenstate
of neutral gauginos $\widetilde{B}$ (bino), $\widetilde{W}_3^0$ (wino) and neutral higgsinos $\widetilde{H}_t^0$, $\widetilde{H}_b^0$
Majorana fermion ($\chi^c = \chi$)

most popular candidate

- part of a well-defined and well-motivated framework of SUSY
- calculable
- relic density: $\Omega_\chi h^2 \sim 0.1$ from freeze-out (...more like $10^{-4} - 10^3$)
- stable with some discrete symmetry (e.g., R-parity or baryon parity)
- testable with today's experiments (DD, ID, LHC)
- ...no obviously superior competitor (both to SUSY and to χ) exists

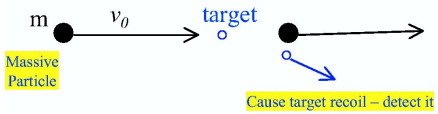
Don't forget:

- multitude of SUSY-based models: general MSSM, CMSSM, split SUSY, MNMSSM, $SO(10)$ GUTs, string inspired models, etc, etc
- neutralino properties often differ widely from model to model

neutralino = stable, weakly interacting, massive $\Rightarrow$ WIMP

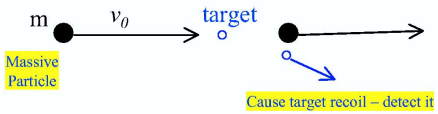
SUSY: Prospects for direct detection

Bayesian analysis, MCMC scan of 8 params (4 SUSY+4 SM)

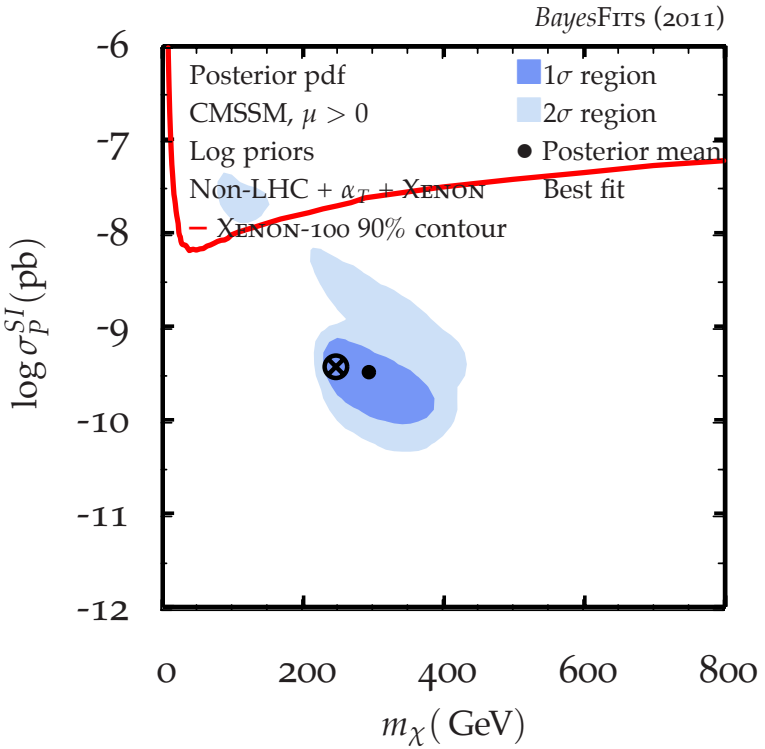


SUSY: Prospects for direct detection

Bayesian analysis, MCMC scan of 8 params (4 SUSY+4 SM)



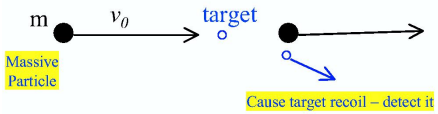
Constrained MSSM: global scan



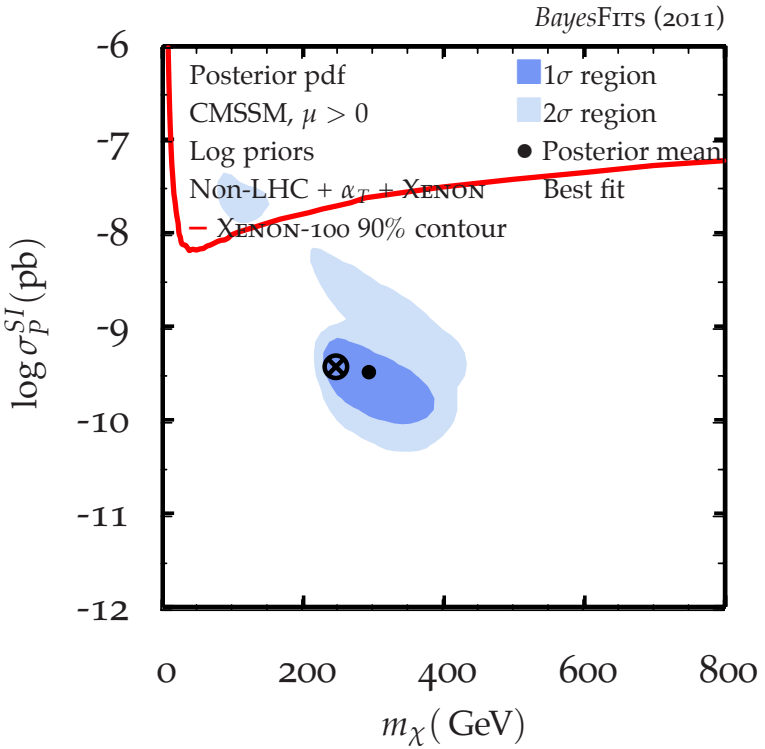
internal (external): 68% (95%) region

SUSY: Prospects for direct detection

Bayesian analysis, MCMC scan of 8 params (4 SUSY+4 SM)



Constrained MSSM: global scan



limit from XENON100

$$\sigma_p^{\mathrm{SI}} \lesssim 10^{-8}\ \mathrm{pb}$$

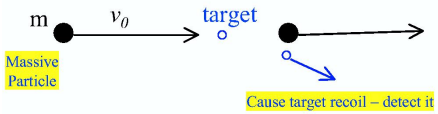
$\Rightarrow$ still above most favored region

reason: new LHC limits on SUSY

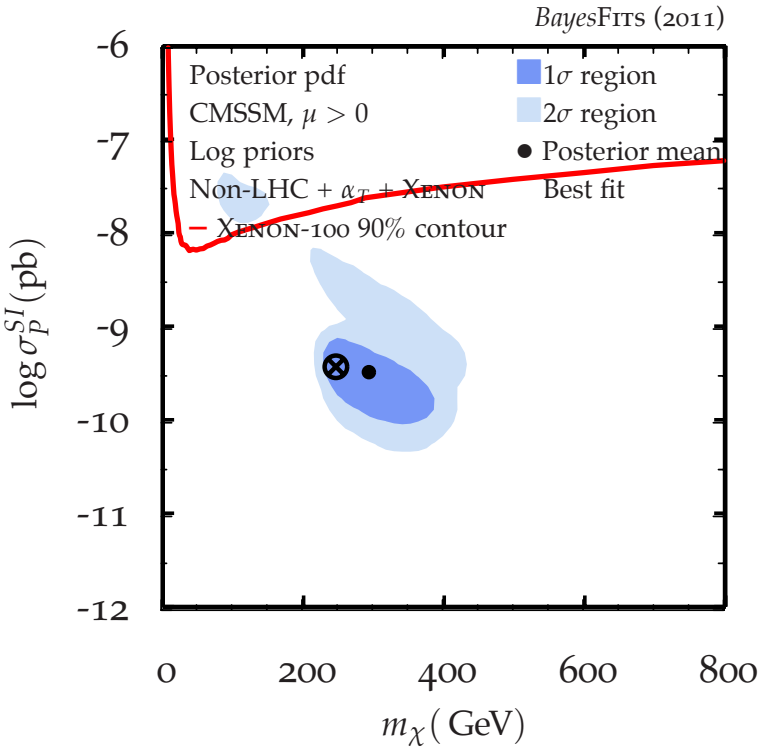
internal (external): 68% (95%) region

SUSY: Prospects for direct detection

Bayesian analysis, MCMC scan of 8 params (4 SUSY+4 SM)



Constrained MSSM: global scan



limit from XENON100

$$\sigma_p^{\mathrm{SI}} \lesssim 10^{-8}\ \mathrm{pb}$$

$\Rightarrow$ still above most favored region

reason: new LHC limits on SUSY

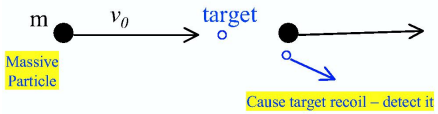
internal (external): 68% (95%) region

$\Rightarrow$ next: XENON100 - sensitivity reach $\sim 10^{-9}$ pb — next year?

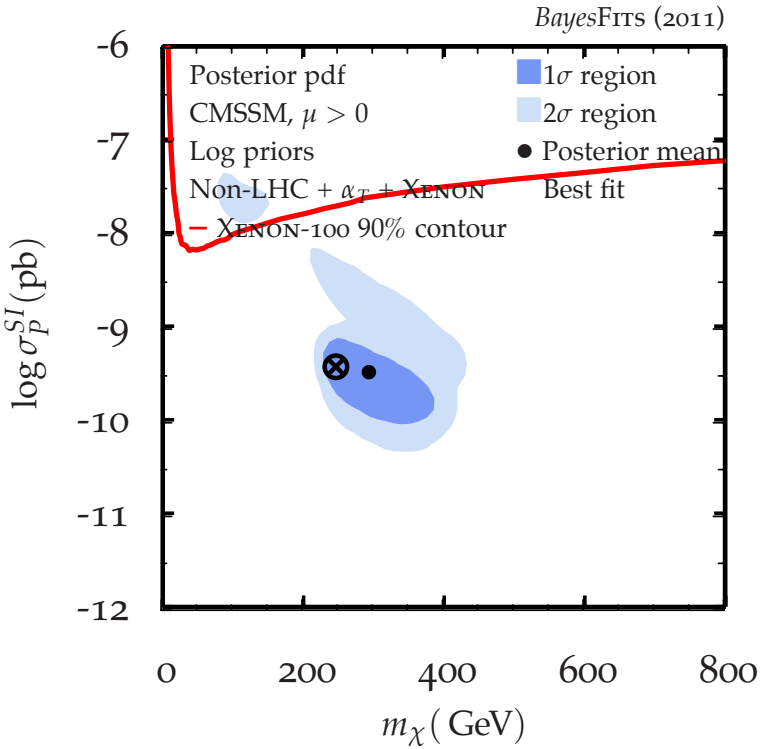
$\Rightarrow$ future: 1 tonne detectors - sensitivity reach $\sim 10^{-10}$ pb — in a few years

SUSY: Prospects for direct detection

Bayesian analysis, MCMC scan of 8 params (4 SUSY+4 SM)



Constrained MSSM: global scan



internal (external): $\mathbf{68\%}$ ($\mathbf{95\%}$) region

limit from XENON100

$$\sigma_p^{\mathrm{SI}} \lesssim 10^{-8}\ \mathrm{pb}$$

$\Rightarrow$ still above most favored region

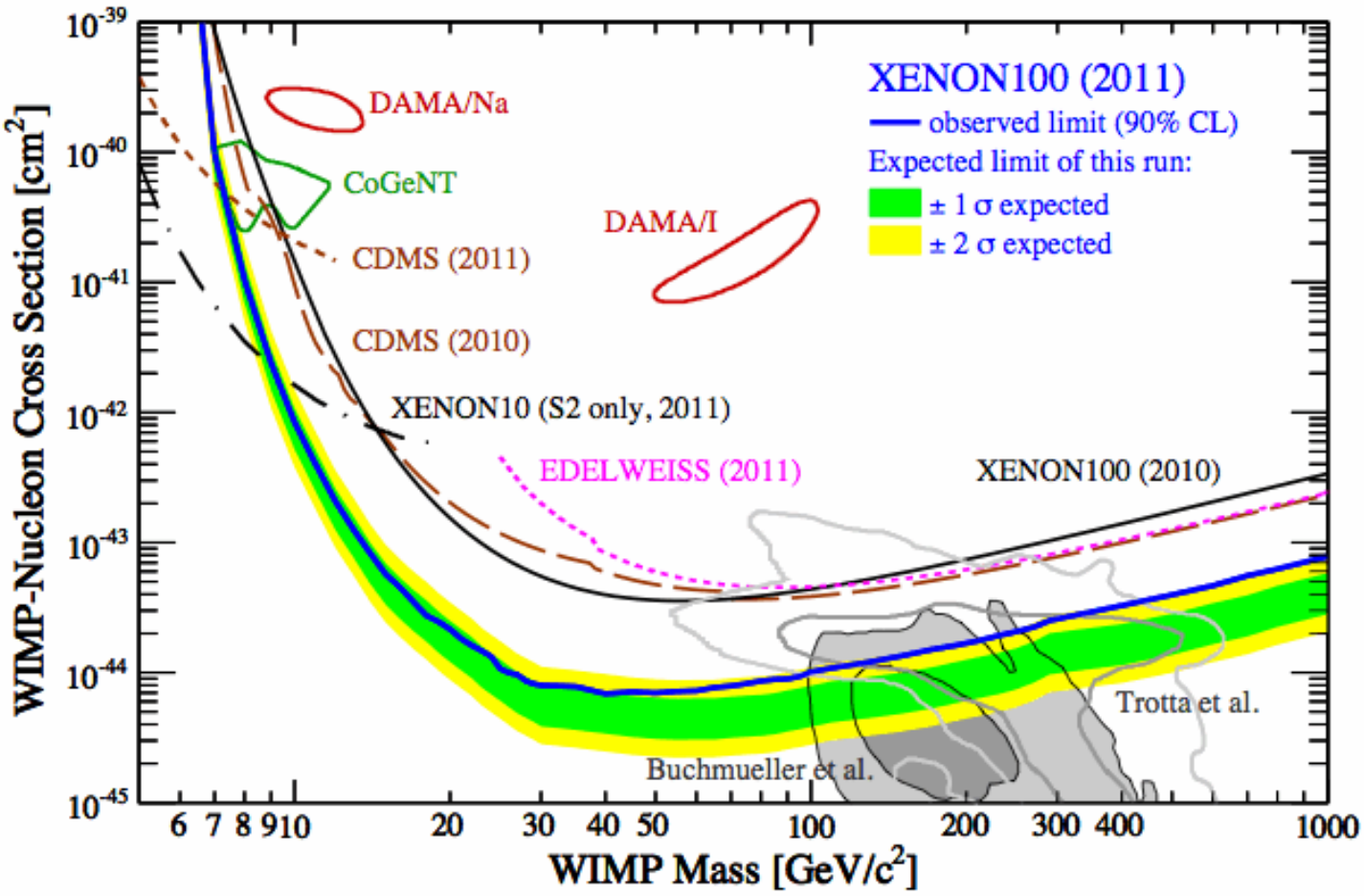
reason: new LHC limits on SUSY

$\Rightarrow$ direct detection: prospects look very good

...in a few years

Direct Detection of Dark Matter

Direct Detection of Dark Matter



Hints of low-mass WIMP?

Hints of low-mass WIMP?

- CoGeNT (Feb 2010): signal at $m_\chi \sim 10\,\mathrm{GeV}$ and $\sigma_p^{\mathrm{SI}} \sim 10^{-4}$ pb?

arXiv:1002.4703

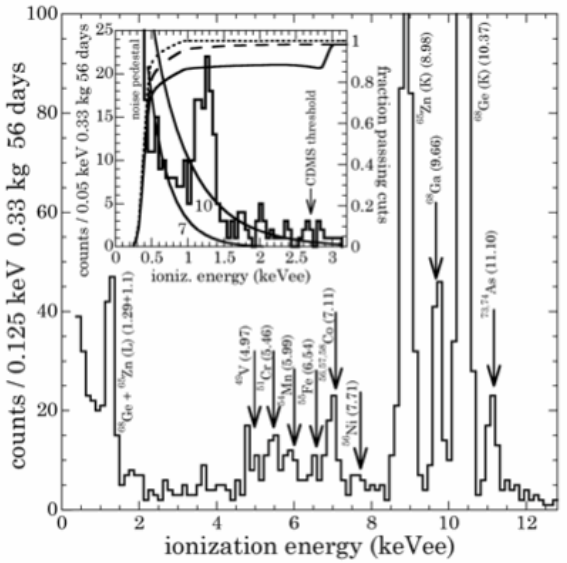


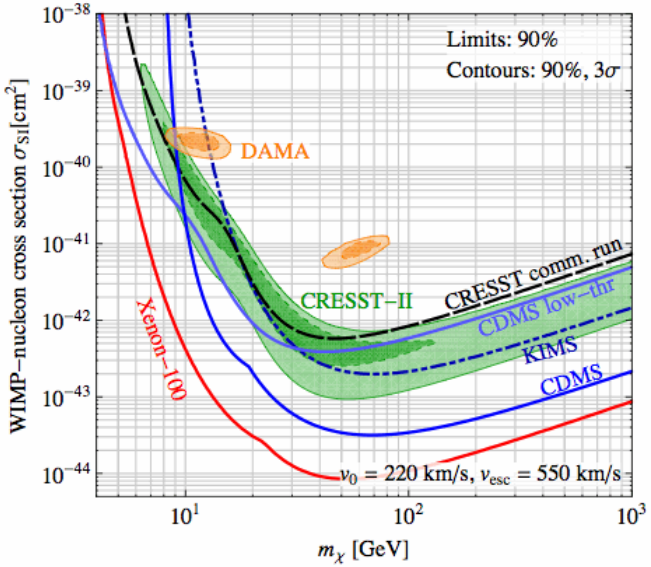
FIG. 3: Low-energy spectrum after all cuts, prior to efficiency corrections. Arrows indicate expected energies for all viable cosmogenic peaks (see text). *Inset:* Expanded threshold region, showing the ^{65}Zn and ^{68}Ge L-shell EC peaks. Overlapped on the spectrum are the sigmoids for triggering efficiency (dotted), trigger + microphonic PSD cuts (dashed) and trigger + PSD + rise time cuts (solid), obtained via high-statistics electronic pulser calibrations. Also shown are reference signals (exponentials) from 7 GeV/c^2 and 10 GeV/c^2 WIMPs with spin-independent coupling $\sigma_{SI} = 10^{-4}$pb.

Hints of low-mass WIMP?

- CoGeNT (Feb 2010): signal at $m_\chi \sim 10\,\mathrm{GeV}$ and $\sigma_p^{\mathrm{SI}} \sim 10^{-4}$ pb?

- consistent with expt?

Kopp, et al, 1110.2721



Hints of low-mass WIMP?

- CoGeNT (Feb 2010): signal at $m_\chi \sim 10\,\mathrm{GeV}$ and $\sigma_p^{\mathrm{SI}} \sim 10^{-4}$ pb?

- consistent with expt?

- consistent with theory?

  lots of papers: Hooper et al (6!), Belanger, et al, Kopp, et al

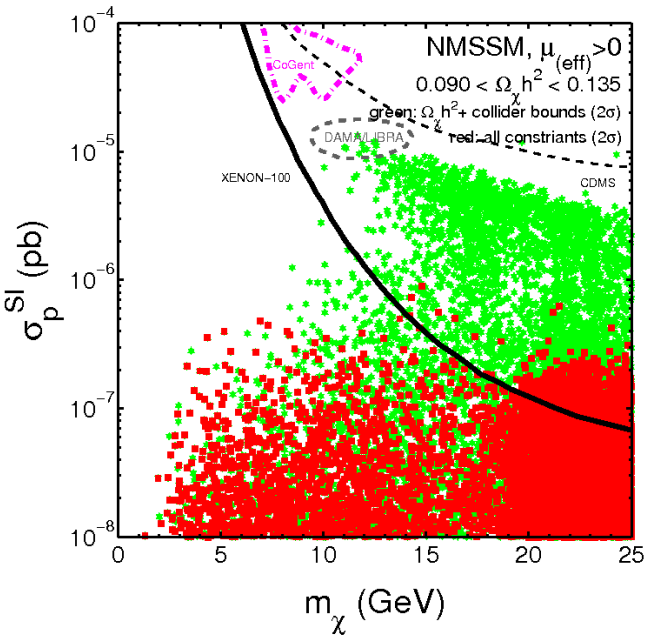
Hints of low-mass WIMP?

- CoGeNT (Feb 2010): signal at $m_\chi \sim 10\,\mathrm{GeV}$ and $\sigma_p^{\mathrm{SI}} \sim 10^{-4}$ pb?
- consistent with expt?
- consistent with theory?

  lots of papers: Hooper et al (6!), Belanger, et al, Kopp, et al

  - plain vanilla, tailored-to-fit: yes
  - neutralino: only with much fine-tuning

Cumberbatch, et al, 1107.1604



Hints of low-mass WIMP?

- CoGeNT (Feb 2010): signal at $m_\chi \sim 10\,\mathrm{GeV}$ and $\sigma_p^{\mathrm{SI}} \sim 10^{-4}$ pb?

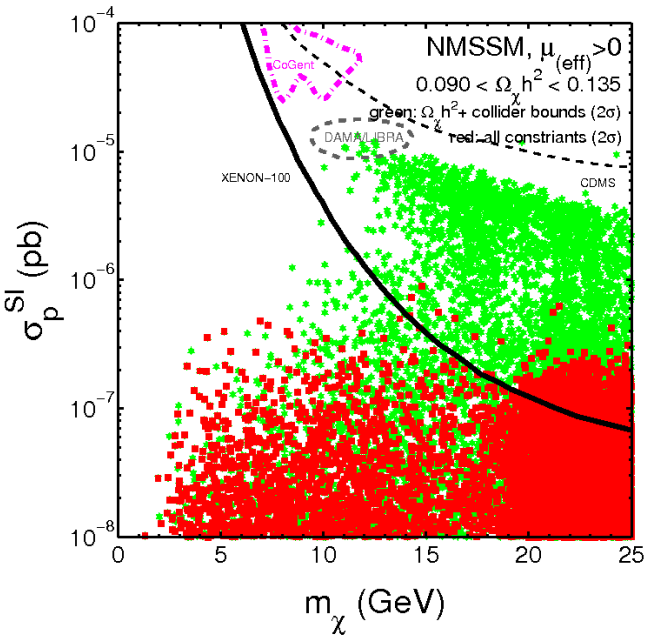
- consistent with expt?

- consistent with theory?

  lots of papers: Hooper et al (6!), Belanger, et al, Kopp, et al

  - plain vanilla, tailored-to-fit: yes
  - neutralino: only with much fine-tuning

Cumberbatch, et al, 1107.1604

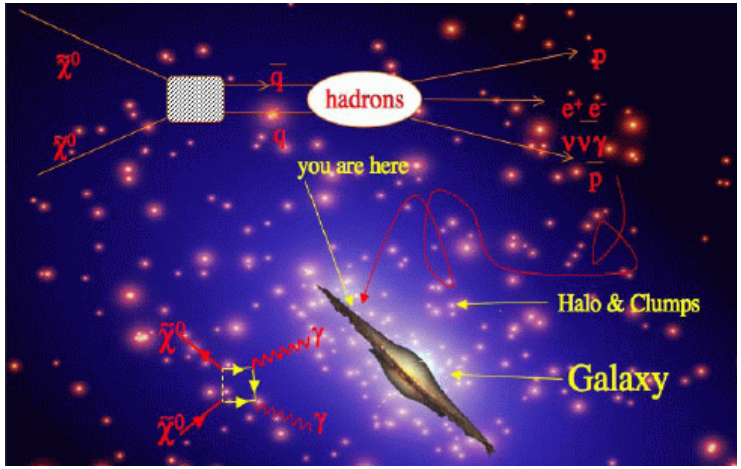


Genuine signal unlikely but more data coming.

...more data from CoGeNT, CRESST-II, XENON, ...

Indirect detection

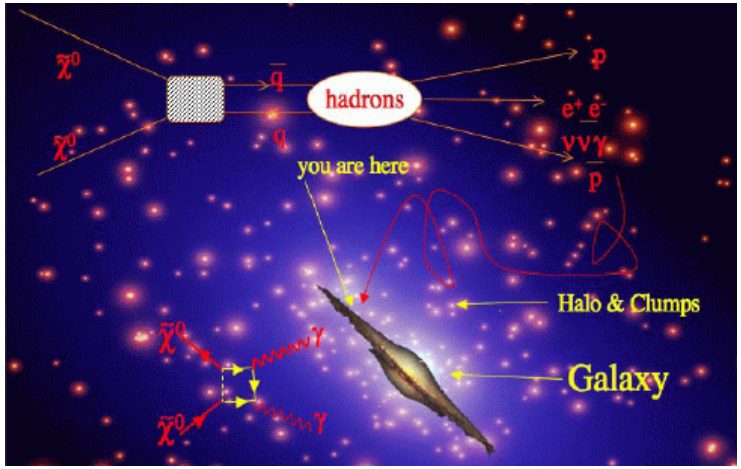
Indirect detection



- look for traces of WIMP annihilation in the MW halo (γ's, e^+'s, $\bar{p}$, ...)
- detection prospects often strongly depend on astrophysical uncertainties (halo models, astro bgnd, ...)

Much activity:

Indirect detection

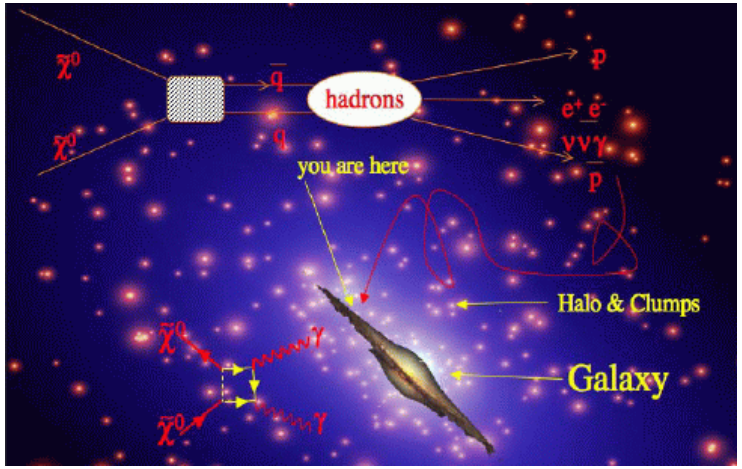


- look for traces of WIMP annihilation in the MW halo (γ's, e^+'s, $\bar{p}$, ...)
- detection prospects often strongly depend on astrophysical uncertainties (halo models, astro bgnd, ...)

Much activity:

- PAMELA

Indirect detection

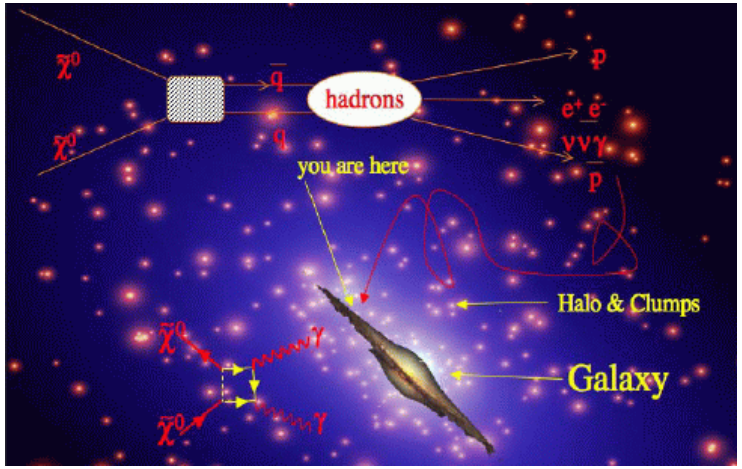


- look for traces of WIMP annihilation in the MW halo (γ's, e^+'s, $\bar{p}$, ...)
- detection prospects often strongly depend on astrophysical uncertainties (halo models, astro bgnd, ...)

Much activity:

- PAMELA
- Fermi

Indirect detection



- look for traces of WIMP annihilation in the MW halo (γ's, e^+'s, $\bar{p}$, ...)
- detection prospects often strongly depend on astrophysical uncertainties (halo models, astro bgnd, ...)

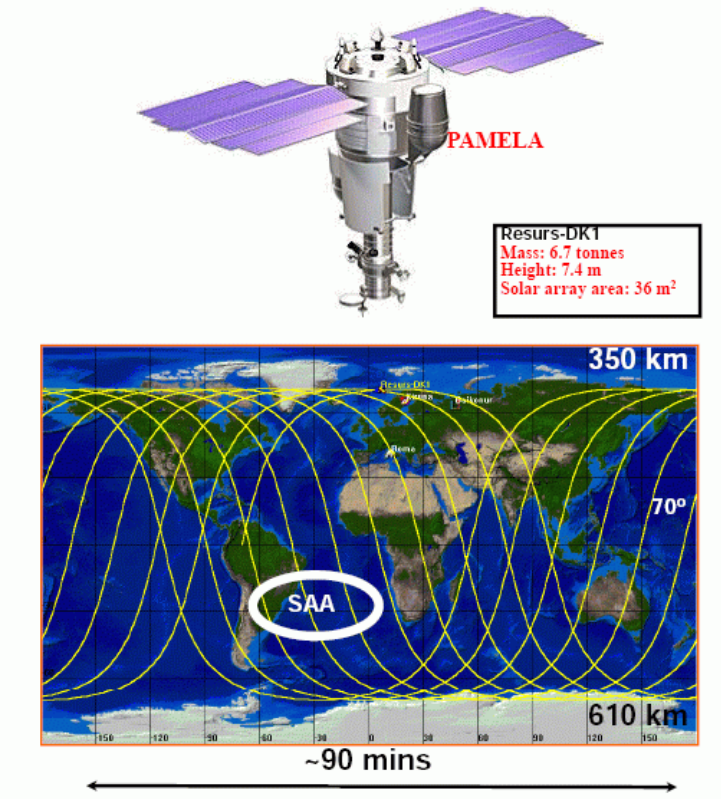
Much activity:

- PAMELA
- Fermi
- neutrino telescopes, ATCs, ...

e^+ data from PAMELA & DM

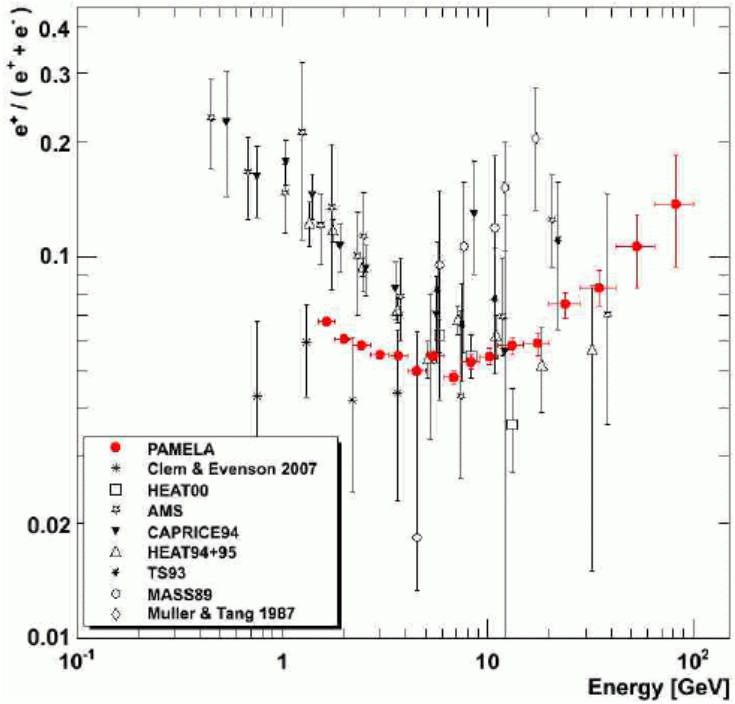
e^+ data from PAMELA & DM

PAMELA satelite (since 2007)



e^+ data from PAMELA & DM

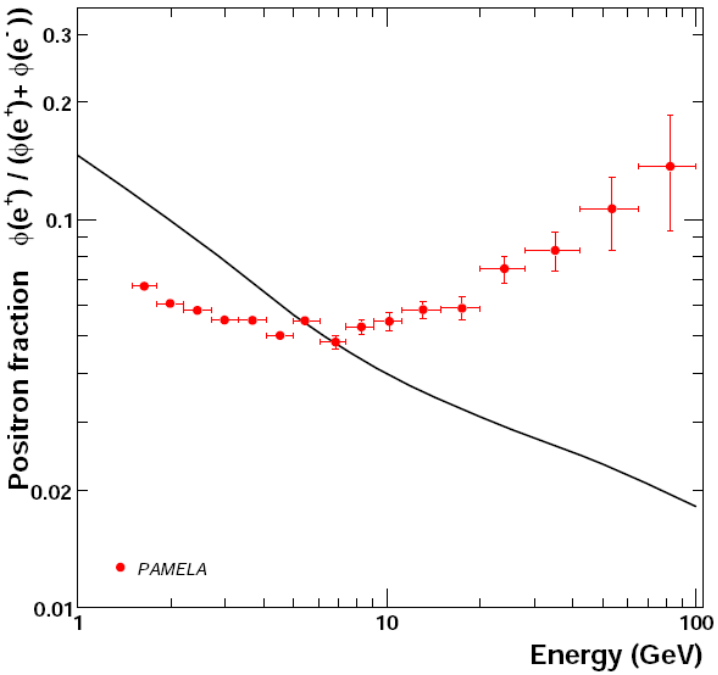
$e^+/(e^+ + e^-)$ ratio, $\bar{p}$ flux, ...



O. Adriani et al., arXiv:0810.4995

e^+ data from PAMELA & DM

- no excess in $\bar{p}$ flux
- puzzling: growth at large e^+ energy

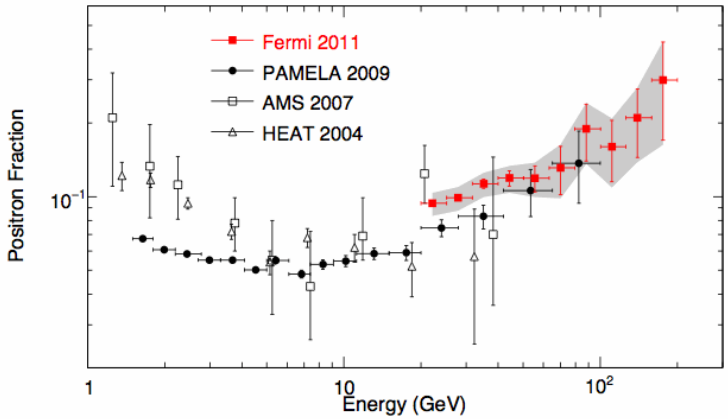


O. Adriani et al., arXiv:0810.4995

e^+ data from PAMELA & DM

- no excess in $\bar{p}$ flux
- puzzling: growth at large e^+ energy

recently confirmed by Fermi



1109.0521

e^+ data from PAMELA & DM

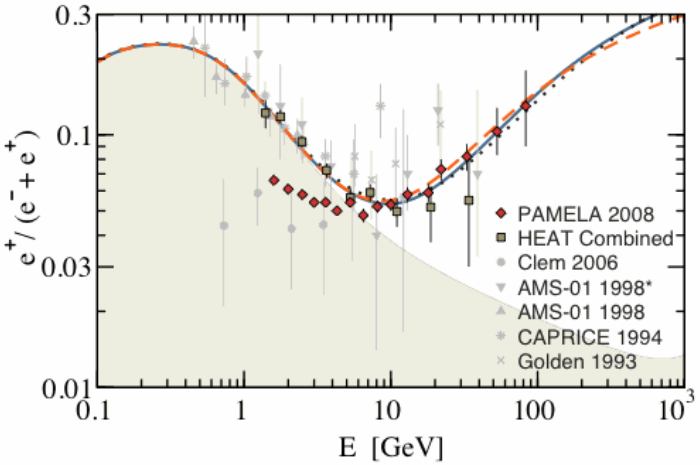
- no excess in $\bar{p}$ flux
- puzzling: growth at large e^+ energy

If excess genuine, explanations:

- pulsars

  Hooper et al, Profumo, Yuksel et al, ...

...seems sufficient



e.g., Geminga pulsar

Yuksel+Kistler+Stanev, 0810.2784

e^+ data from PAMELA & DM

- no excess in $\bar{p}$ flux
- puzzling: growth at large e^+ energy

If excess genuine, explanations:

- pulsars

  Hooper et al, Profumo, Yuksel et al, ...

...seems sufficient

- DM (stable or not)

  many theoretical speculations: leptophilic DM, decaying DM, ...

  no compelling DM candidate

e^+ data from PAMELA & DM

- no excess in $\bar{p}$ flux
- puzzling: growth at large e^+ energy

If excess genuine, explanations:

- pulsars

  Hooper et al, Profumo, Yuksel et al, ...

...seems sufficient

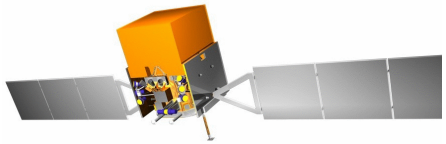
- DM (stable or not)

  many theoretical speculations: leptophilic DM, decaying DM, ...

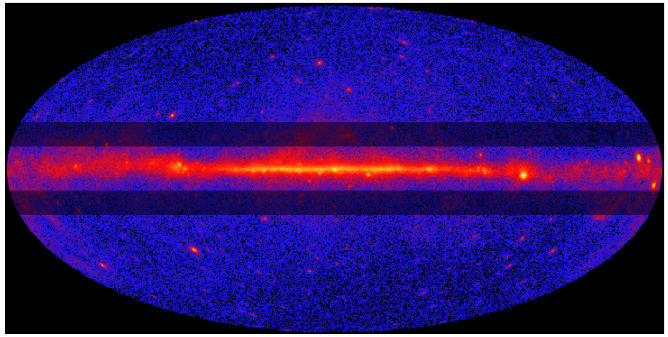
  no compelling DM candidate

$\Rightarrow$ DM origin of e^+ excess unlikely

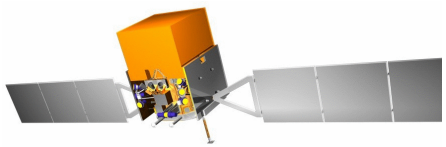
Fermi



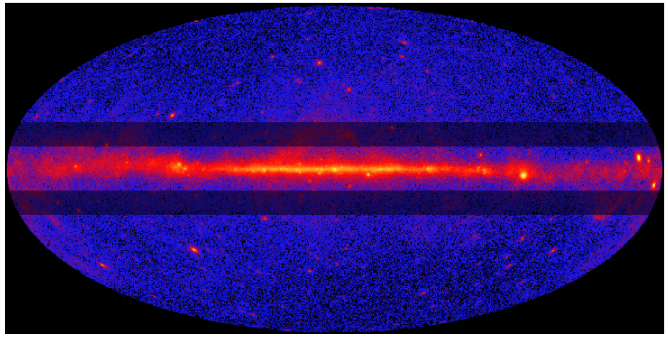
in orbit since 2008



Fermi



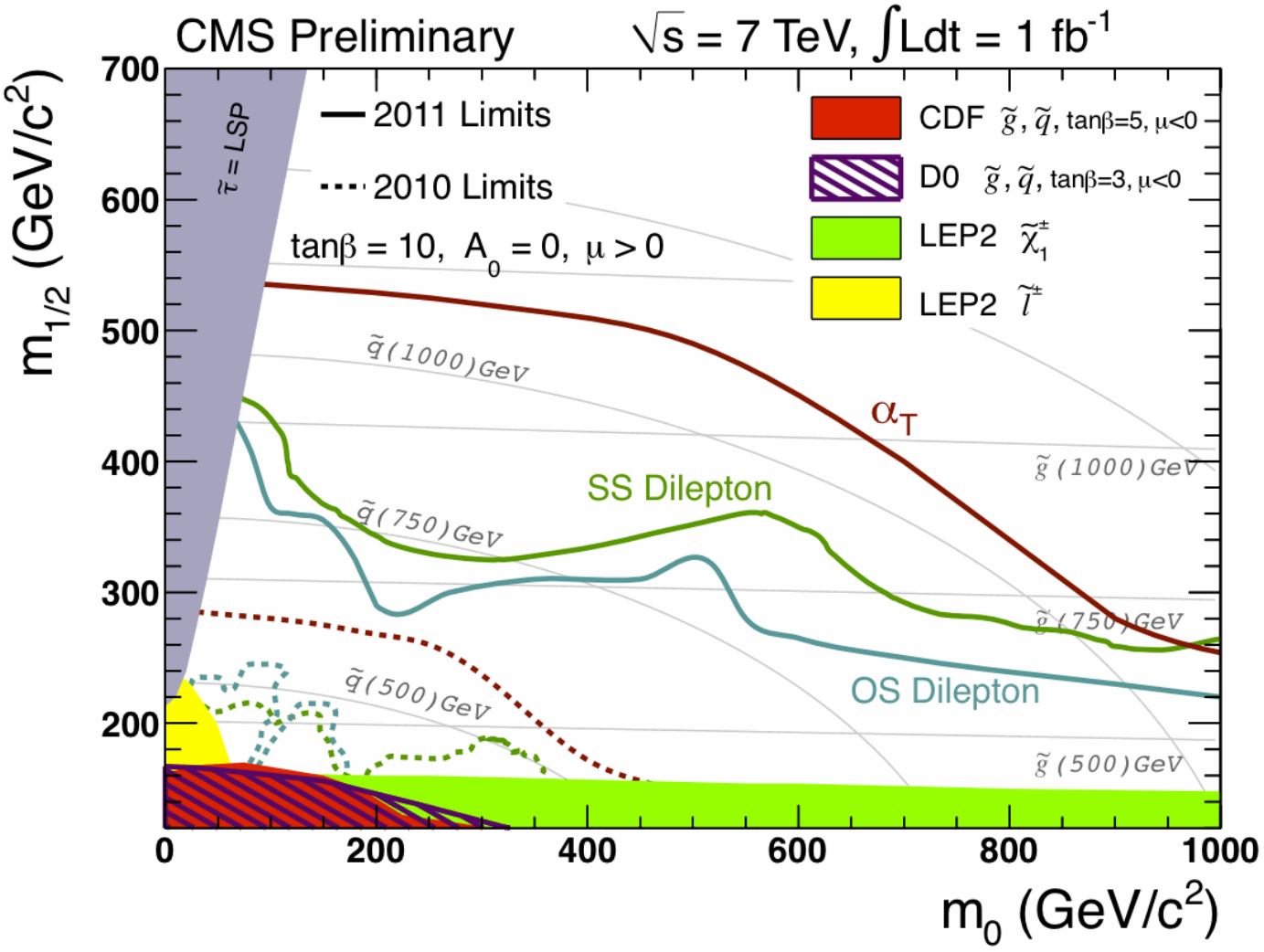
in orbit since 2008



- full sky map in γ-ray spectrum, $\sim \mathbf{20\,MeV}$ to $\sim \mathbf{300\,GeV}$
- superior energy and angular resolution
- improve accuracy/energy range of EGRET by an order of magnitute
- 1st year LAT data released in August '09, more coming
- mid-latitude LAT data on diffuse γ-radiation $\Rightarrow$ little room for DM
- most interesting (and difficult): Galactic Center – still being analyzed

The LHC

The LHC


CMS Preliminary
$\sqrt{s}$ = 7 TeV, $\int$Ldt = 1 fb^{-1}
$\tilde{\tau}$ = LSP
2011 Limits
2010 Limits
tanβ = 10, A$_0$ = 0, μ > 0
CDF $\tilde{g}, \tilde{q}$, tanβ=5, μ<0
D0 $\tilde{g}, \tilde{q}$, tanβ=3, μ<0
LEP2 $\tilde{\chi}_1^{\pm}$
LEP2 $\tilde{l}^{\pm}$
$\tilde{q}$(1000)GeV
$\tilde{g}$(1000)GeV
α_T
SS Dilepton
$\tilde{q}$(750)GeV
$\tilde{g}$(750)GeV
OS Dilepton
$\tilde{q}$(500)GeV
$\tilde{g}$(500)GeV
m$_{1/2}$ (GeV/c^2)
m$_0$ (GeV/c^2)
700
600
500
400
300
200
0
200
400
600
800
1000

Gazing into a crystal ball...

Gazing into a crystal ball...

Gazing into a crystal ball...

Gazing into a crystal ball...

THE SUNDAY TIMES · SEPTEMBER 21, 2003

There's a black hole in the middle of our finances

Gazing into a crystal ball...

Niels Bohr

Prediction is very difficult,

Gazing into a crystal ball...

Niels Bohr

Prediction is very difficult,
especially if it's about the future.

Dark Matter and the LHC

Dark Matter and the LHC

In elucidating the nature of dark matter, the role of the LHC will not be just helpful, or complimentary.

It will be absolutely essential!

Dark Matter and the LHC

In elucidating the nature of dark matter, the role of the LHC will not be just helpful, or complimentary.

It will be absolutely essential!

...depending on the outcome

Gazing into a crystal ball...

Gazing into a crystal ball...

Let's assume that DM signal is measured in direct detection...

What shall we learn from this?

- WIMP elastic scat. cross section

Gazing into a crystal ball...

Let's assume that DM signal is measured in direct detection...

What shall we learn from this?

- WIMP elastic scat. cross section

...within an order of magnitude, or so

Gazing into a crystal ball...

Let's assume that DM signal is measured in direct detection...

What shall we learn from this?

- WIMP elastic scat. cross section

...within an order of magnitude, or so

- WIMP mass

...within a factor of two, or so
signal in more than one detector with different targets will help a lot

(Drees+Shan, Green, 2008,...)

Gazing into a crystal ball...

Let's assume that DM signal is measured in direct detection...

What shall we learn from this?

- WIMP elastic scat. cross section

...within an order of magnitude, or so

- WIMP mass

...within a factor of two, or so
signal in more than one detector with different targets will help a lot

(Drees+Shan, Green, 2008,...)

$\Rightarrow$ The nature of DM WIMP would remain a mystery

Gazing into a crystal ball...

Let's assume that DM signal is measured in direct detection...

What shall we learn from this?

- WIMP elastic scat. cross section

...within an order of magnitude, or so

- WIMP mass

...within a factor of two, or so
signal in more than one detector with different targets will help a lot

(Drees+Shan, Green, 2008,...)

$\Rightarrow$ The nature of DM WIMP would remain a mystery

...need info from colliders

Gazing into a crystal ball...

Let's assume that DM signal is measured in direct detection...

What shall we learn from this?

- WIMP elastic scat. cross section

...within an order of magnitude, or so

- WIMP mass

...within a factor of two, or so
signal in more than one detector with different targets will help a lot

(Drees+Shan, Green, 2008,...)

$\Rightarrow$ The nature of DM WIMP would remain a mystery

...need info from colliders

(...indirect detection: too many astrophysical uncertainties)

Dark matter at colliders

Dark matter at colliders

- direct WIMP production $pp \to \chi\chi +$ hadronic debris: undetectable

Dark matter at colliders

- direct WIMP production $pp \to \chi\chi +$ hadronic debris: undetectable

only missing energy, nothing to tag on

Dark matter at colliders

- direct WIMP production $pp \to \chi\chi +$ hadronic debris: undetectable

only missing energy, nothing to tag on

- DM WIMP is expected to be part of "new physics" at/above EW scale

like neutralino and SUSY

Dark matter at colliders

- direct WIMP production $pp \to \chi\chi +$ hadronic debris: undetectable

only missing energy, nothing to tag on

- DM WIMP is expected to be part of "new physics" at/above EW scale

like neutralino and SUSY

- LHC will probe "new physics" up to a few TeV

Dark matter at colliders

- direct WIMP production $pp \to \chi\chi +$ hadronic debris: undetectable

only missing energy, nothing to tag on

- DM WIMP is expected to be part of "new physics" at/above EW scale

like neutralino and SUSY

- LHC will probe "new physics" up to a few TeV
- one will need to measure several processes, perform detailed spectroscopy,...

likely to be a very long process

Standard SUSY at the LHC

with neutralino χ as LSP

Standard SUSY at the LHC

with neutralino χ as LSP

$\sqrt{s} = 7\,\mathrm{TeV}\ \ (\rightarrow 14\,\mathrm{TeV}),\ \int\ \mathcal{L} \gtrsim 1\,\mathrm{fb}^{-1}$

ATLAS, CMS

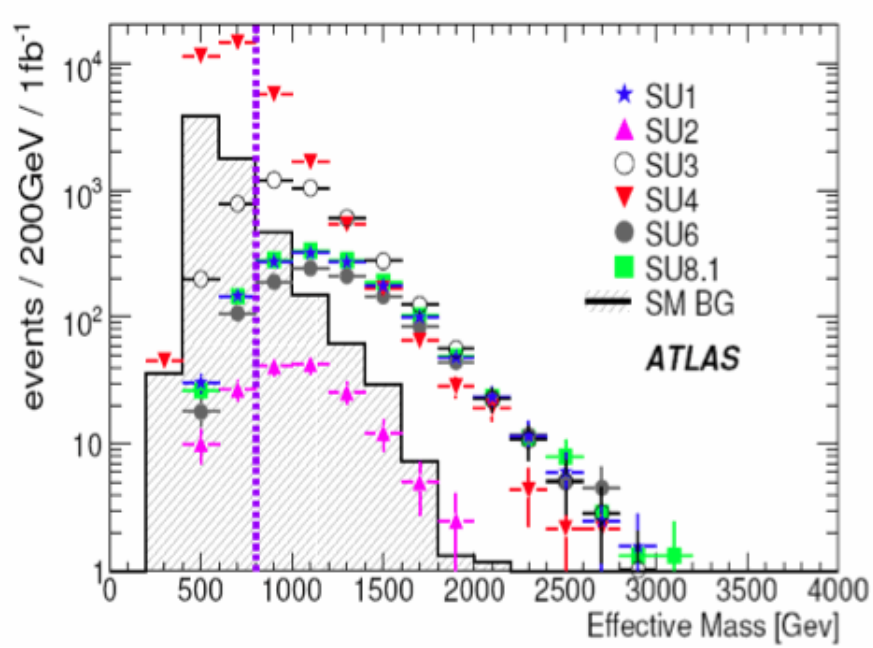
Standard SUSY at the LHC

with neutralino χ as LSP

$\sqrt{s} = 7\,\mathrm{TeV}\ \ (\rightarrow 14\,\mathrm{TeV}),\ \int \mathcal{L} \gtrsim 1\,\mathrm{fb}^{-1}$

ATLAS, CMS

e.g.: 4 jet + p_T^{miss} distribution

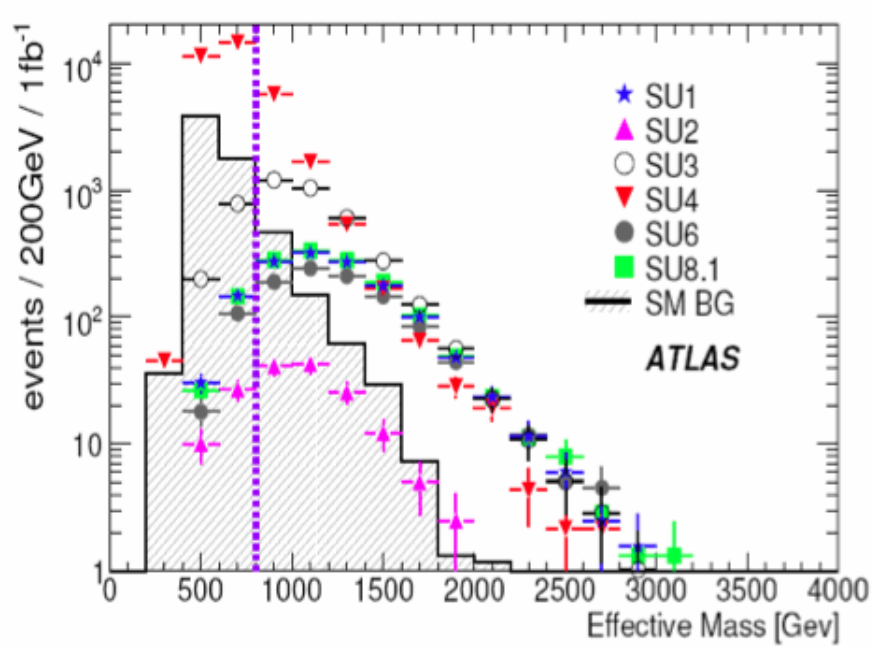


Standard SUSY at the LHC

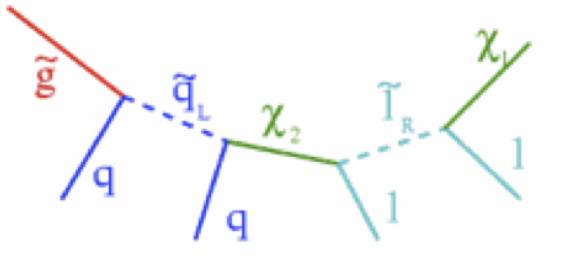
with neutralino χ as LSP

$\sqrt{s} = 7\,\mathrm{TeV}\ \ (\rightarrow 14\,\mathrm{TeV}),\ \int \mathcal{L} \gtrsim 1\,\mathrm{fb}^{-1}$ ATLAS, CMS

e.g.: 4 jet + p_T^{miss} distribution



e.g.: $\tilde{g}$ cascade decay



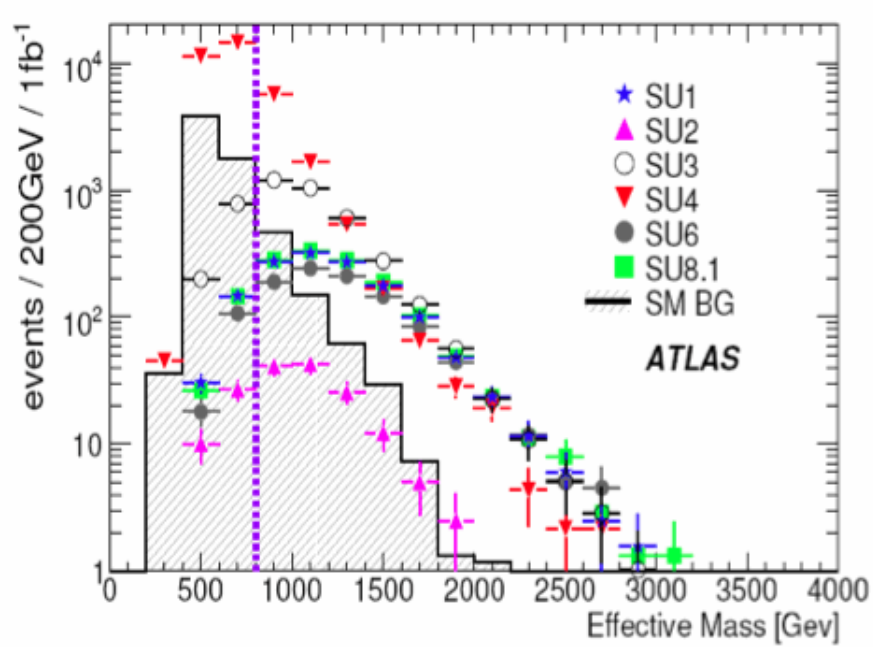
- use end-point, E_T^{miss}, etc, to work out m_χ
- LHC: m_χ up to some $400 - 500\,\mathrm{GeV}$

Standard SUSY at the LHC

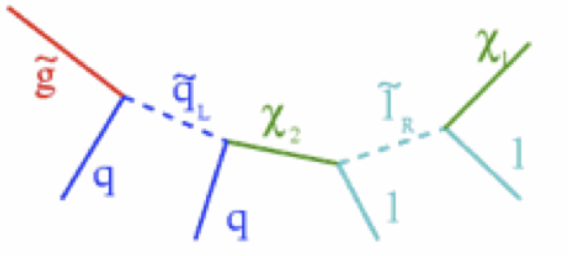
with neutralino χ as LSP

$\sqrt{s} = 7\,\mathrm{TeV}\ \ (\rightarrow 14\,\mathrm{TeV}),\ \int \mathcal{L} \gtrsim 1\,\mathrm{fb}^{-1}$ ATLAS, CMS

e.g.: 4 jet + p_T^{miss} distribution



e.g.: $\tilde{g}$ cascade decay



- use end-point, E_T^{miss}, etc, to work out m_χ
- LHC: m_χ up to some $400 - 500\,\mathrm{GeV}$

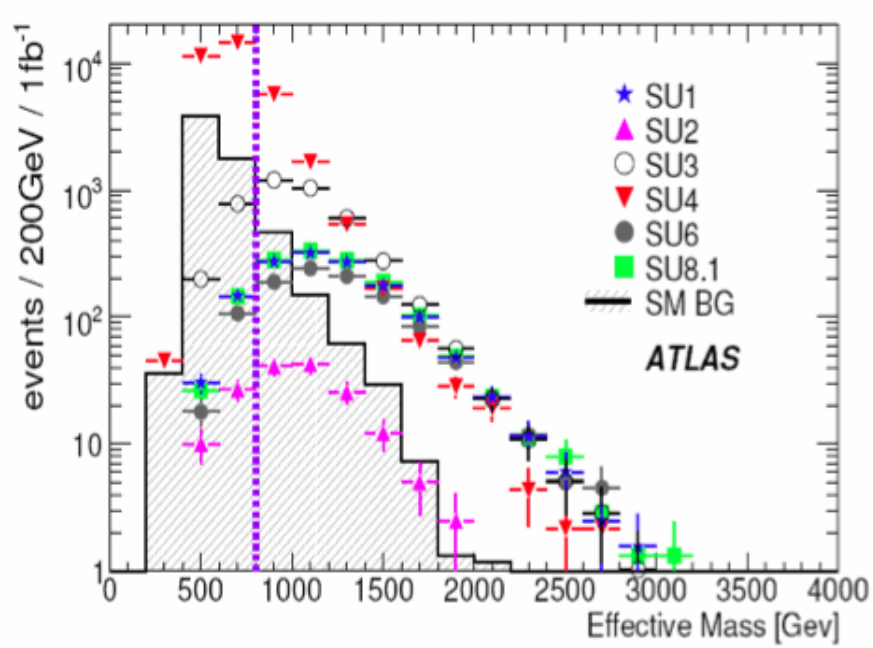
Standard SUSY at the LHC

with neutralino χ as LSP

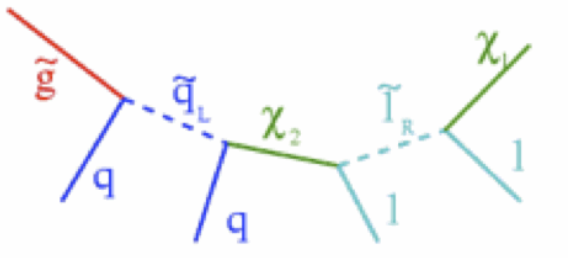
$\sqrt{s} = 7\,\mathrm{TeV}\ \ (\rightarrow 14\,\mathrm{TeV}),\ \int \mathcal{L} \gtrsim 1\,\mathrm{fb}^{-1}$

ATLAS, CMS

e.g.: 4 jet + p_T^{miss} distribution



e.g.: $\tilde{g}$ cascade decay



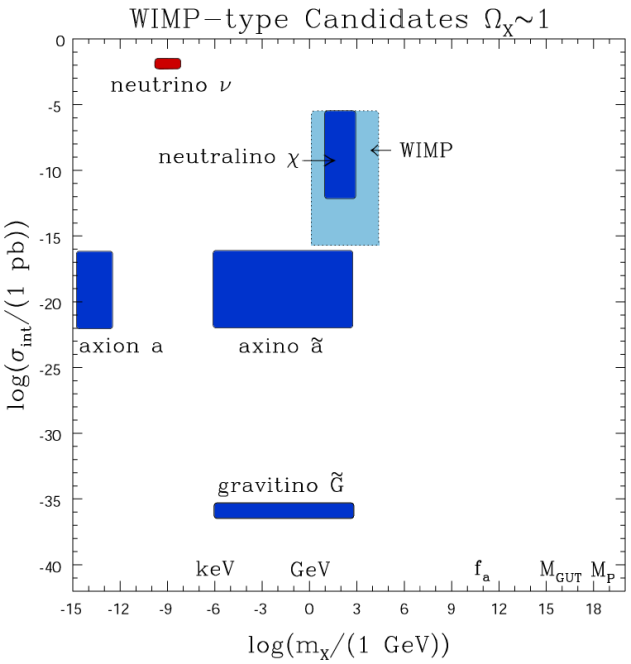
- use end-point, E_T^{miss}, etc, to work out m_χ
- LHC: m_χ up to some $400 - 500\,\mathrm{GeV}$

will be essential to cross-check WIMP mass with DM searches

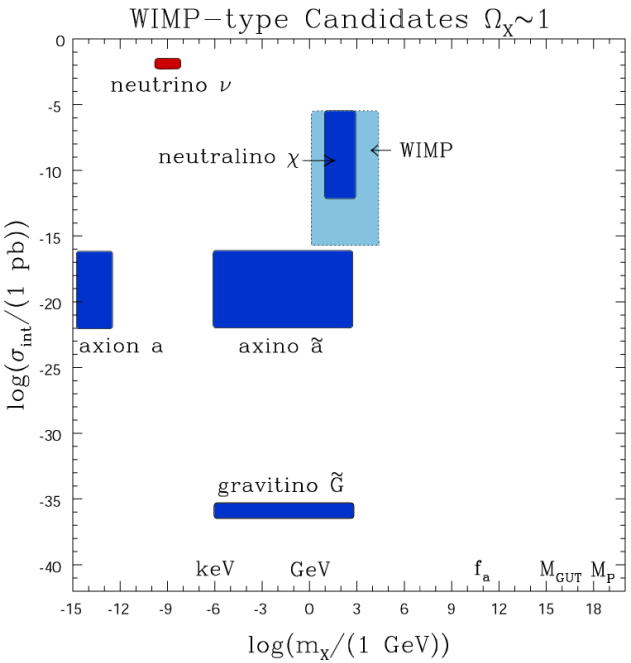
$\Rightarrow$ Would be great triumph of the standard WIMP paradigm

Gazing into a crystal ball...

Gazing into a crystal ball...



Gazing into a crystal ball...

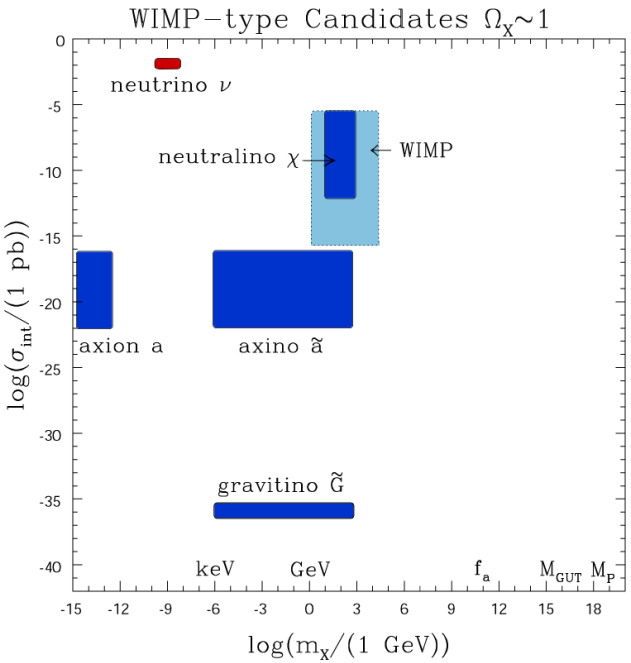


	DD	ID	LHC
χ	Yes	Yes (?)	Yes*
$\widetilde{G}$	No	No	cannonball†
$\widetilde{a}$	No	No	$E_T^{\rm miss}$ or cannonball

*: if $m_\chi \lesssim 400\ {\rm GeV}$

†: charged, massive, seemingly stable particle

Gazing into a crystal ball...



	DD	ID	LHC
χ	Yes	Yes (?)	Yes*
$\widetilde{G}$	No	No	cannonball†
$\widetilde{a}$	No	No	$E_T^{\rm miss}$ or cannonball

*: if $m_\chi \lesssim 400\,\mathrm{GeV}$

†: charged, massive, seemingly stable particle

$\Rightarrow$ LHC: watch out for non-standard signatures

...may give a hint at physics with σ <<<<<<<< $\sigma_{\rm weak}$

Cannonball at the LHC

Cannonball at the LHC

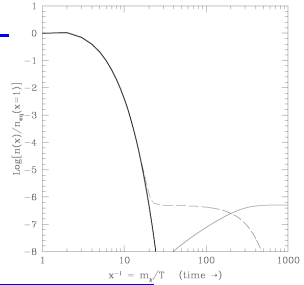
With axino or gravitino as true LSP WIMP: DM searches hopeless

Cannonball at the LHC

With axino or gravitino as true LSP WIMP: DM searches hopeless

- if next lightest SUSY particle is super-tau (stau $\widetilde{\tau}$):

$\widetilde{G}$ LSP: $\tau(\widetilde{\tau}_{\mathbf{R}} \to \tau\, \widetilde{G}) \sim 6 \times 10^8\,\mathbf{sec} \left(\frac{100\,\mathbf{GeV}}{m_{\widetilde{\tau}}}\right)^5 \left(\frac{m_{\widetilde{G}}}{100\,\mathbf{GeV}}\right)^2$



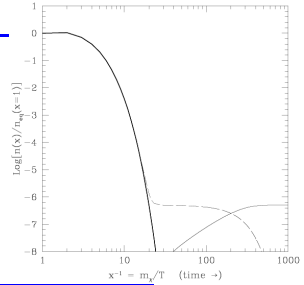
$\widetilde{a}$ LSP: $\tau(\widetilde{\tau}_{\mathbf{R}} \to \tau\, \widetilde{a}) \sim 5\,\mathbf{sec} \left(\frac{100\,\mathbf{GeV}}{m_{\widetilde{\tau}}}\right) \left(\frac{f_a}{10^{11}\,\mathbf{GeV}}\right)^2 \left(\frac{100\,\mathbf{GeV}}{m_{\widetilde{B}}}\right)^2$

Cannonball at the LHC

With axino or gravitino as true LSP WIMP: DM searches hopeless

- if next lightest SUSY particle is super-tau (stau $\widetilde{\tau}$):

$$\widetilde{G}\text{ LSP:}\quad \tau(\widetilde{\tau}_{\mathbf{R}} \to \tau\,\widetilde{G}) \sim 6\times 10^{8}\,\mathbf{sec}\left(\frac{100\,\mathbf{GeV}}{m_{\widetilde{\tau}}}\right)^{5}\left(\frac{m_{\widetilde{G}}}{100\,\mathbf{GeV}}\right)^{2}$$



$$\widetilde{a}\text{ LSP:}\quad \tau(\widetilde{\tau}_{\mathbf{R}} \to \tau\,\widetilde{a}) \sim 5\,\mathbf{sec}\left(\frac{100\,\mathbf{GeV}}{m_{\widetilde{\tau}}}\right)\left(\frac{f_a}{10^{11}\,\mathbf{GeV}}\right)^{2}\left(\frac{100\,\mathbf{GeV}}{m_{\widetilde{B}}}\right)^{2}$$

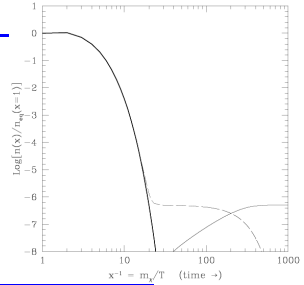
$\Rightarrow$ charged, massive, effectively stable at the LHC

Cannonball at the LHC

With axino or gravitino as true LSP WIMP: DM searches hopeless

- if next lightest SUSY particle is super-tau (stau $\widetilde{\tau}$):

$\widetilde{G}$ LSP: $\quad \tau(\widetilde{\tau}_{\mathrm{R}} \to \tau\, \widetilde{G}) \sim 6 \times 10^8\,\mathrm{sec} \left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{\tau}}}\right)^5 \left(\frac{m_{\widetilde{G}}}{100\,\mathrm{GeV}}\right)^2$



$\widetilde{a}$ LSP: $\quad \tau(\widetilde{\tau}_{\mathrm{R}} \to \tau\, \widetilde{a}) \sim 5\,\mathrm{sec} \left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{\tau}}}\right) \left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{B}}}\right)^2$

$\Rightarrow$ charged, massive, effectively stable at the LHC

if mass $\lesssim 400\,\mathrm{GeV}$ $\Rightarrow$ spectacular signature at the LHC

LHC: may provide unique hint for EWIMP-type DM

Summary

- dark matter: many possible WIMP candidates, few well motivated
- neutralino of unified SUSY: most attractive and well-motivated candidate
- best prospects for revealing the nature of DM: direct detection + LHC

...but one-tonne detectors likely needed

- some odd experimental results
  - low-mass WIMPs of a few GeV? (CoGeNT, DAMA/LIBRA, CRESST-II...)
  - CR positron flux (Pamela, ...)

...not convincing as DM signatures

- much activity in experiment: DD, Fermi, neutrino telescopes, CRs, ...
- LHC: still early days... but data already coming!
- ...be open to possible surprises

Gazing into a crystal ball...

Gazing into a crystal ball...

DM WIMP will be detected

Gazing into a crystal ball...

DM WIMP will be detected

- within a year

Gazing into a crystal ball...

DM WIMP will be detected

- within a year
- or decade

Gazing into a crystal ball...

DM WIMP will be detected

- within a year
- or decade
- or century
- or ...

Gazing into a crystal ball...

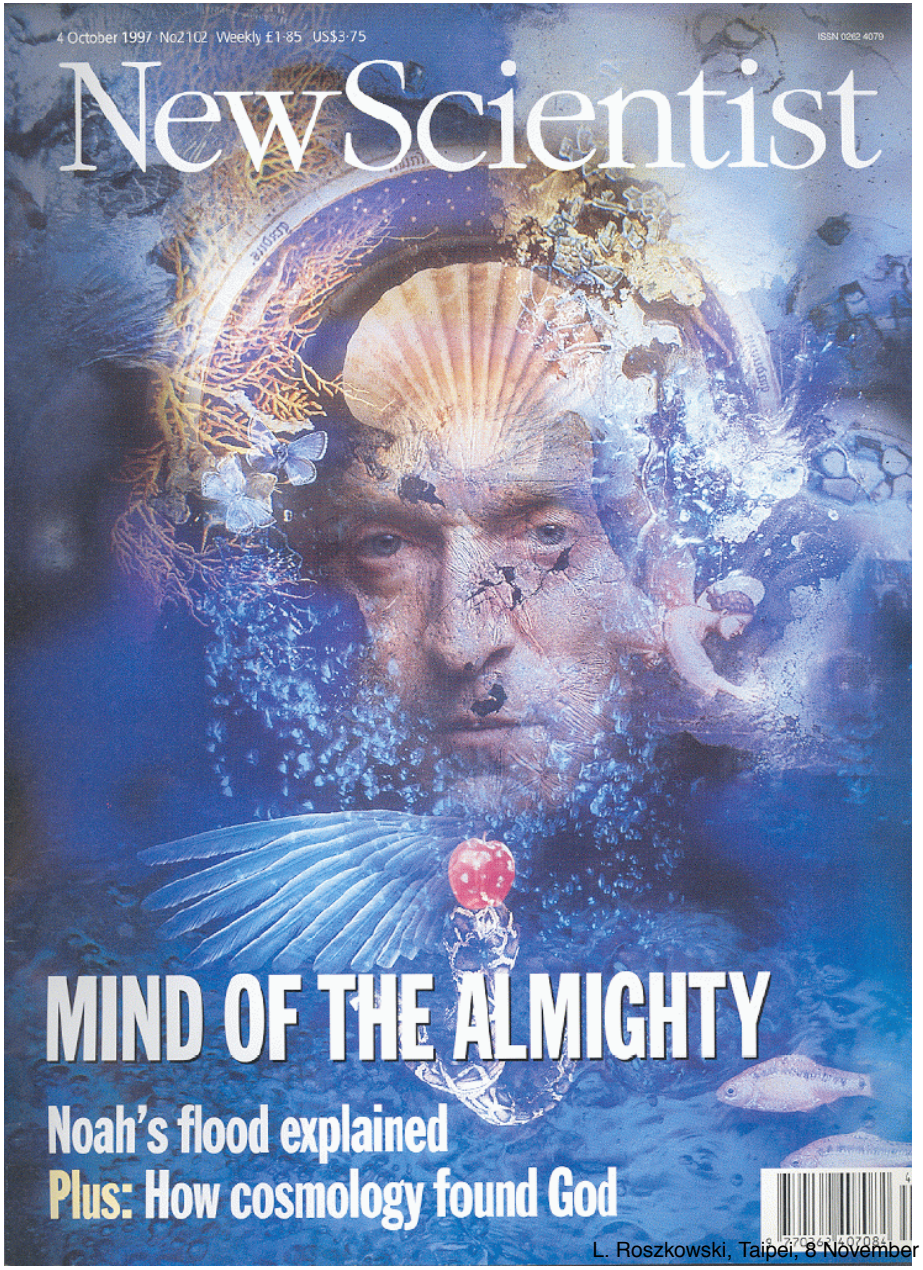
DM WIMP will be detected

- within a year
- or decade
- or century
- or ...

FOR SURE!

Gazing into a crystal ball...

DM WIMP will be detected

- within a year
- or decade
- or century
- or ...

FOR SURE!