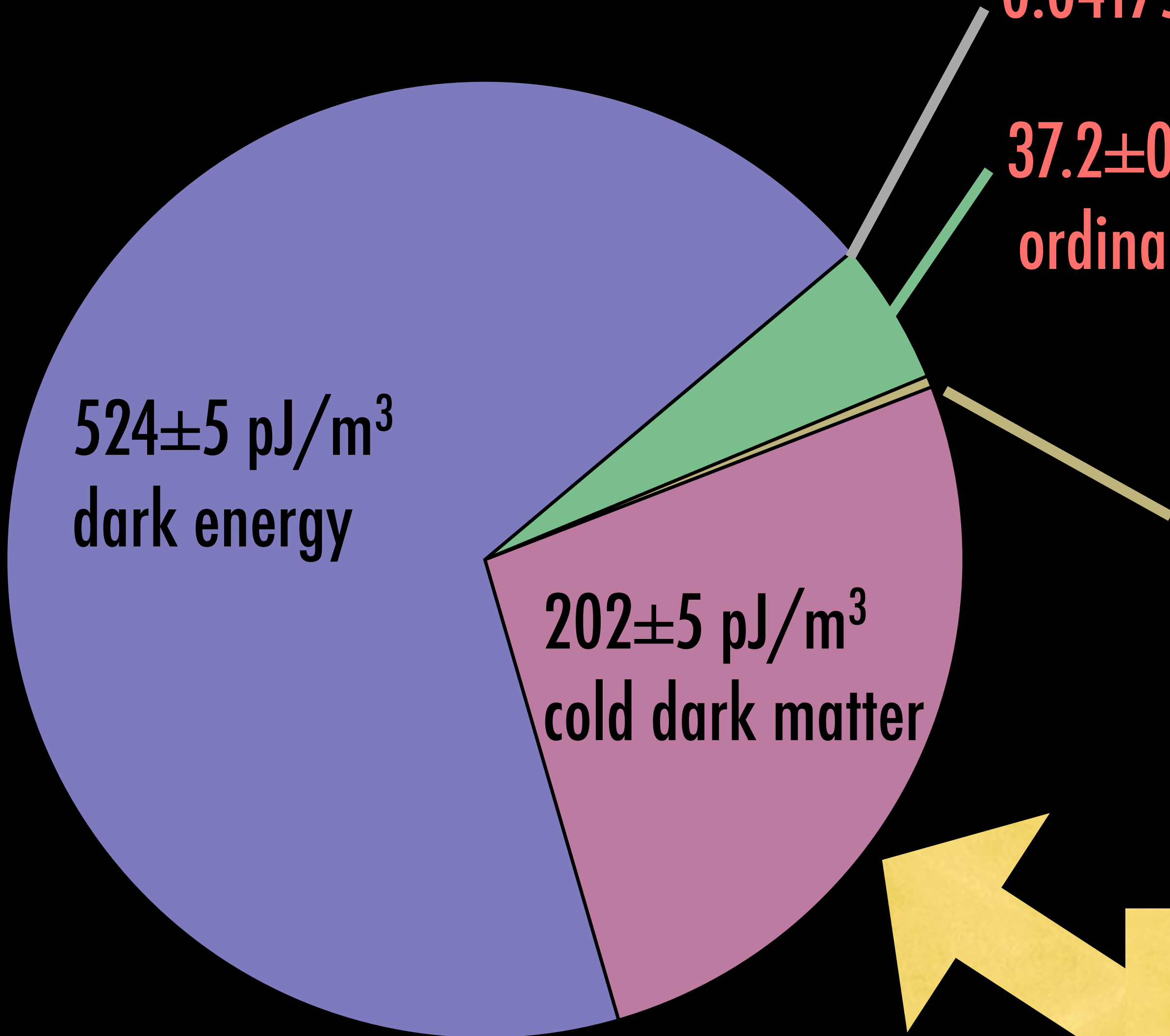
Review of Evidence for Dark Matter

Paolo Gondolo

University of Utah

Monday, May 12, 14

The observed content of the Universe



0.04175±0.00004 pJ/m^3 photons

37.2±0.5 pJ/m^3 ordinary matter

1 to 5 pJ/m^3 neutrinos

Cold Dark Matter

matter $p \ll \rho$

radiation $p = \rho/3$

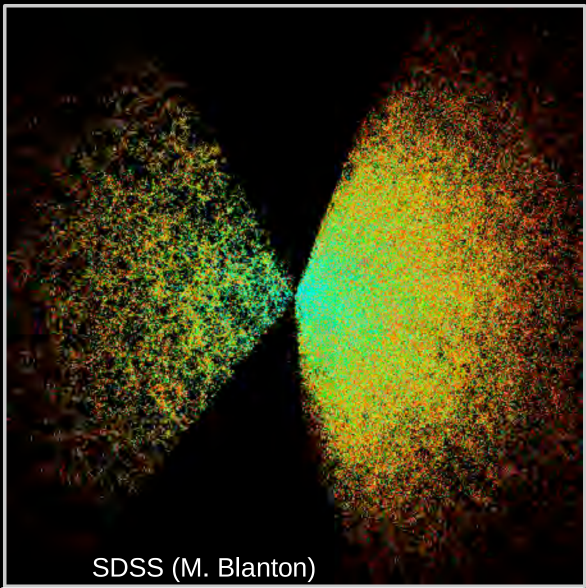
vacuum $p = -\rho$

Planck (2013)

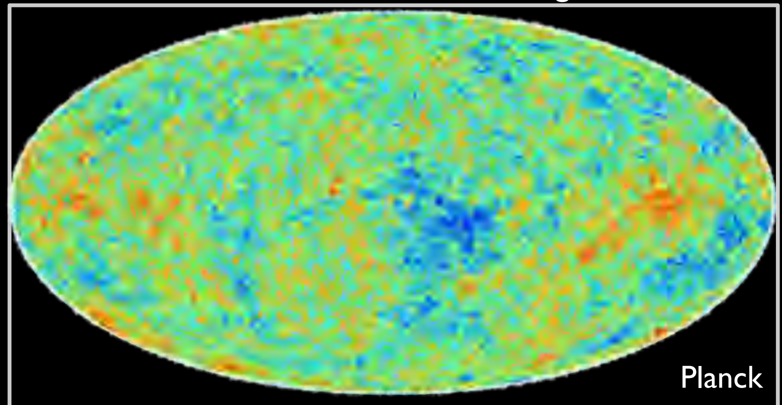
1 pJ = 10^{-12} J

Evidence for cold dark matter

Large Scale Structure

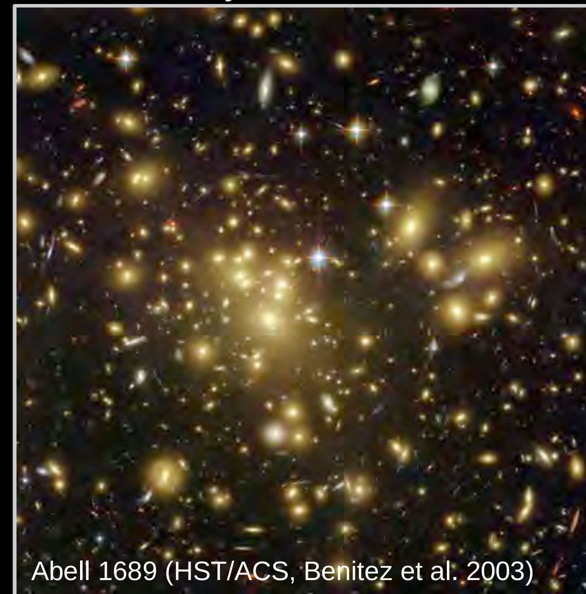


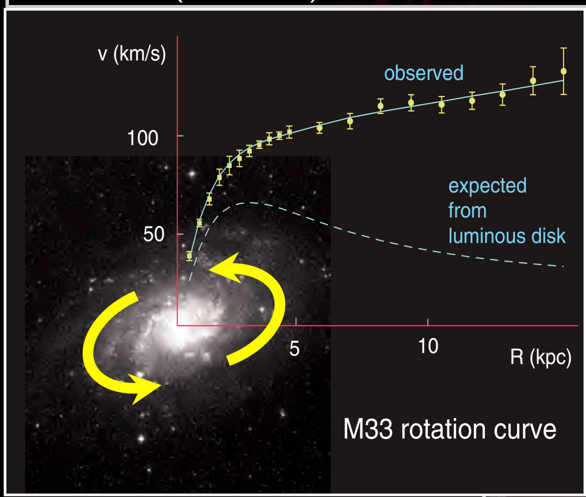
Cosmic Microwave Background

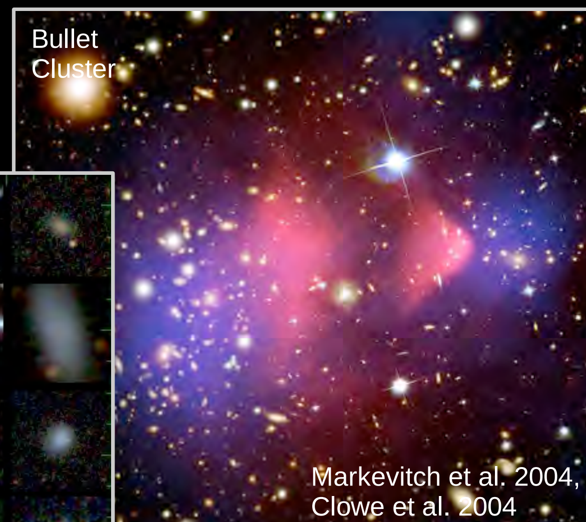


Supernovae

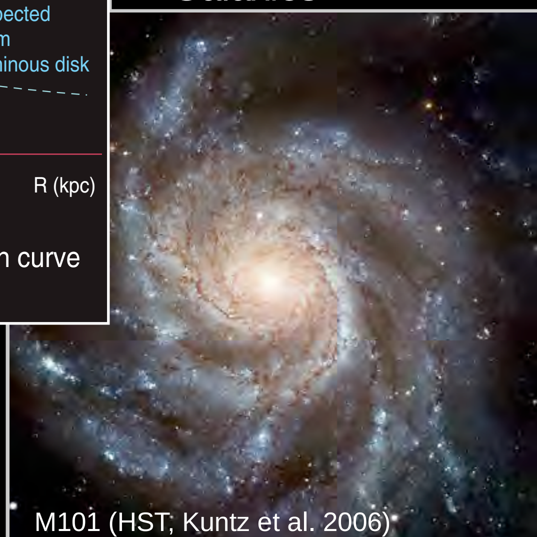
Galaxy Clusters



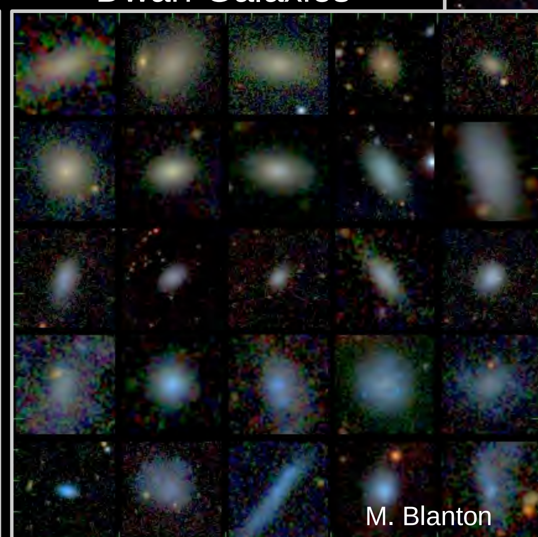




Galaxies

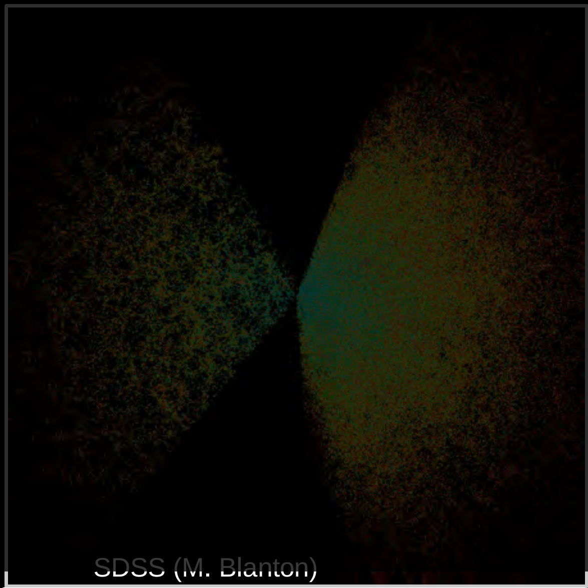


Dwarf Galaxies

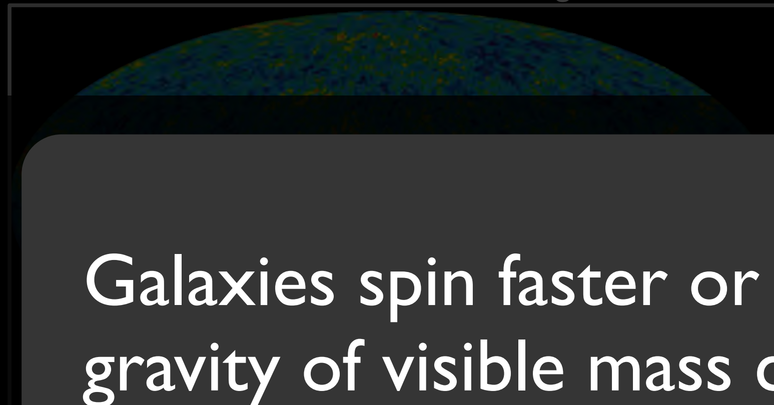


Evidence for cold dark matter

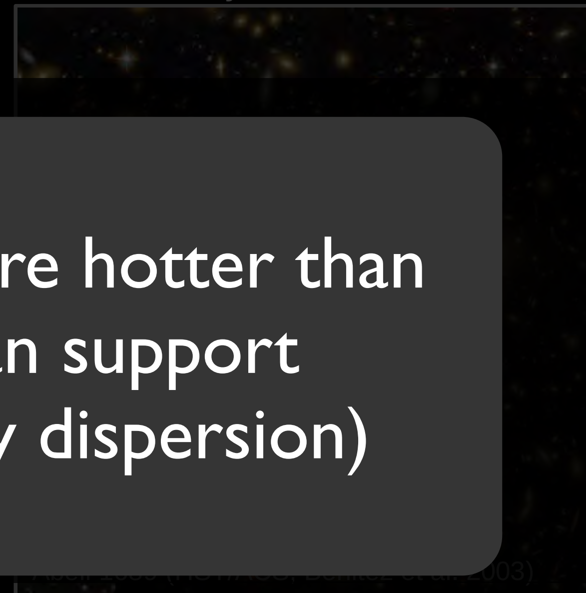
Large Scale Structure



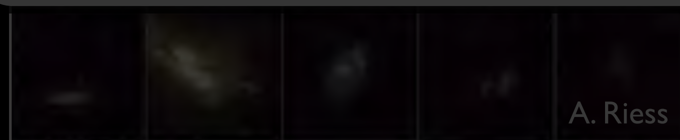
Cosmic Microwave Background

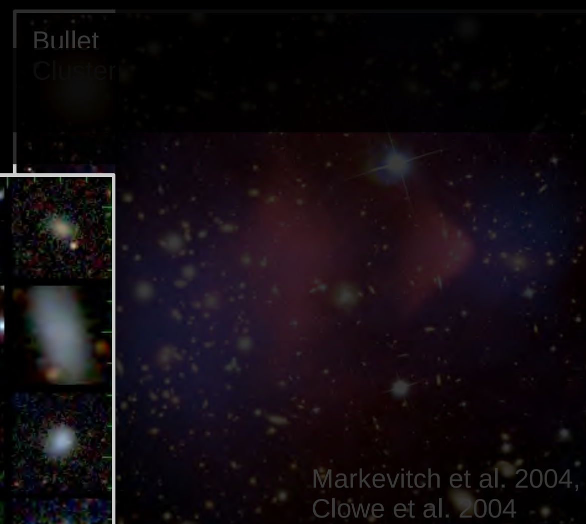


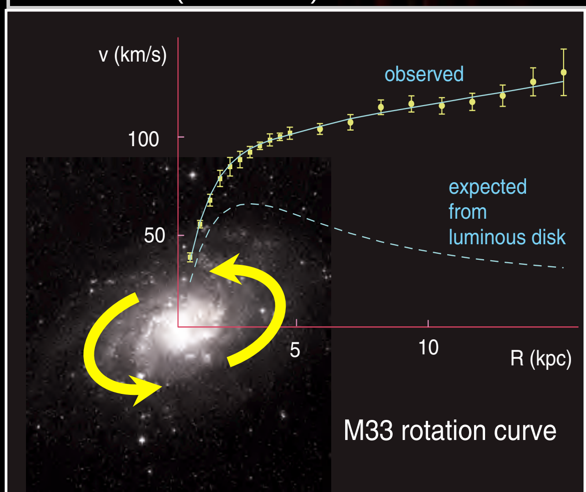
Galaxy Clusters



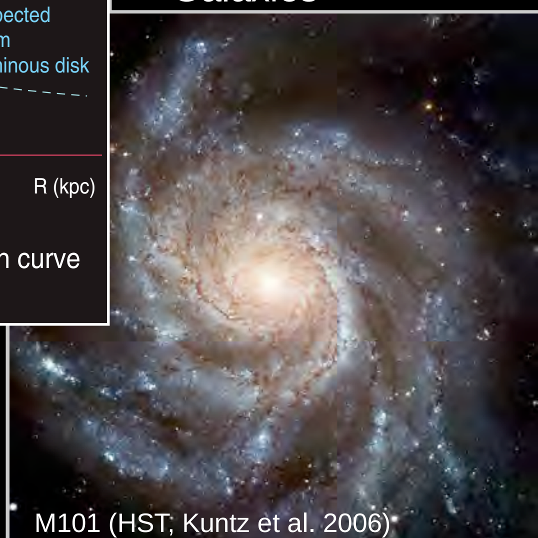
Galaxies spin faster or are hotter than gravity of visible mass can support (rotation curves, velocity dispersion)



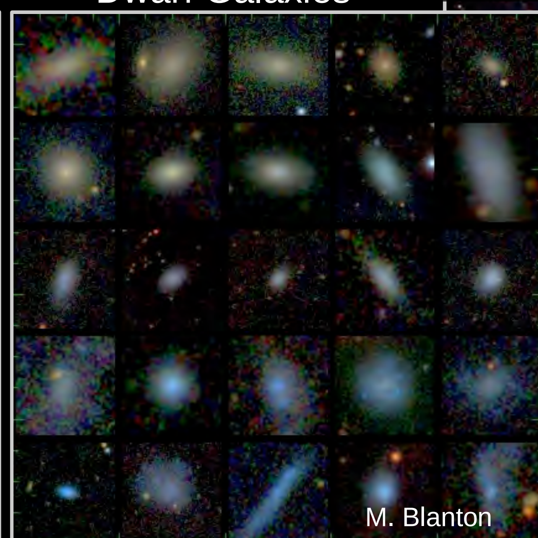




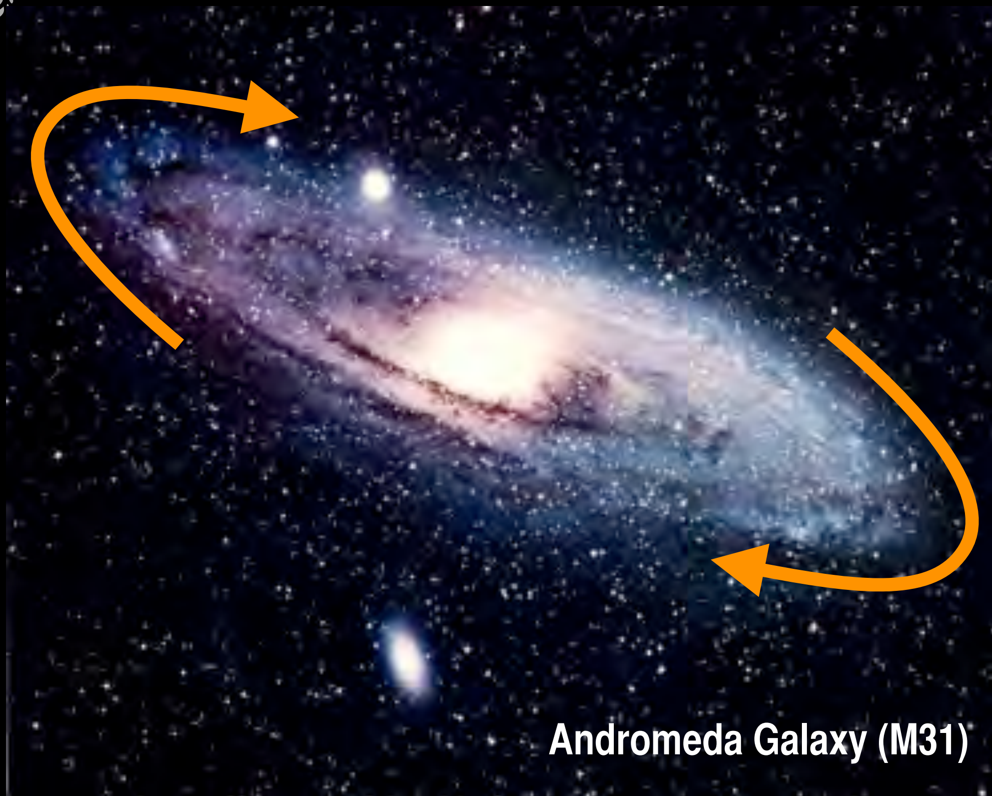
Galaxies

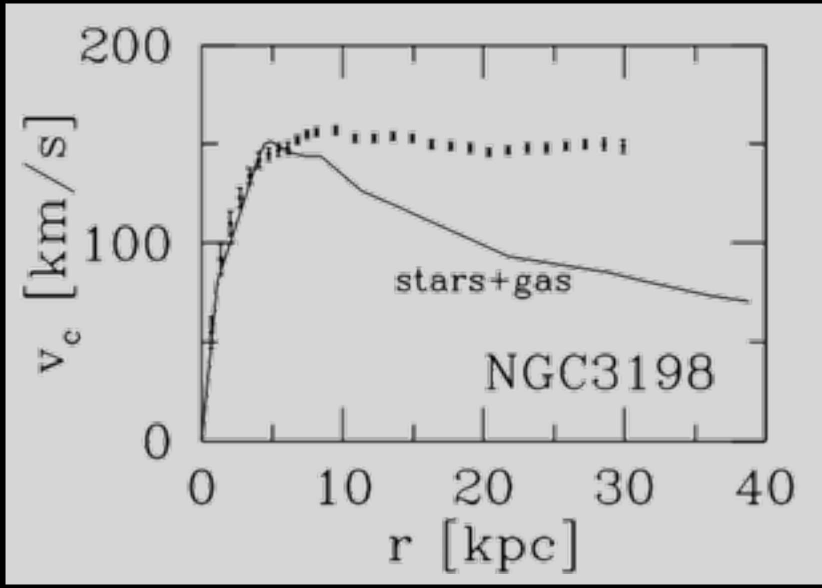


Dwarf Galaxies



Evidence for cold dark matter





Gravity of visible mass is not enough to keep the gas in orbit.

Evidence for cold dark matter

Large Scale Structure

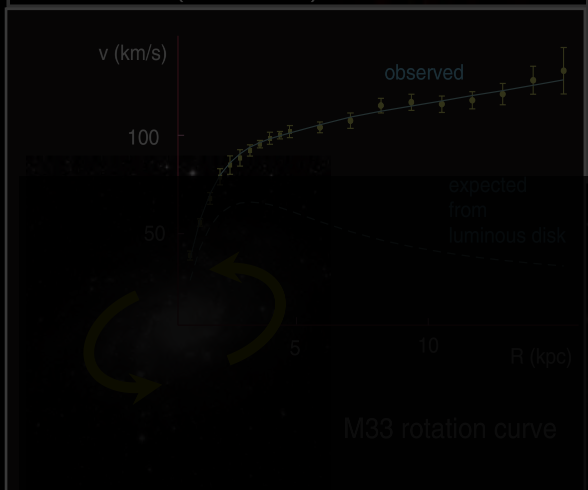
Cosmic Microwave Background

Galaxy Clusters

Galaxy clusters are mostly invisible mass (motion of galaxies, gas density and temperature, gravitational lensing)


Abell 1689 (HST/ACS, Benitez et al. 2003)

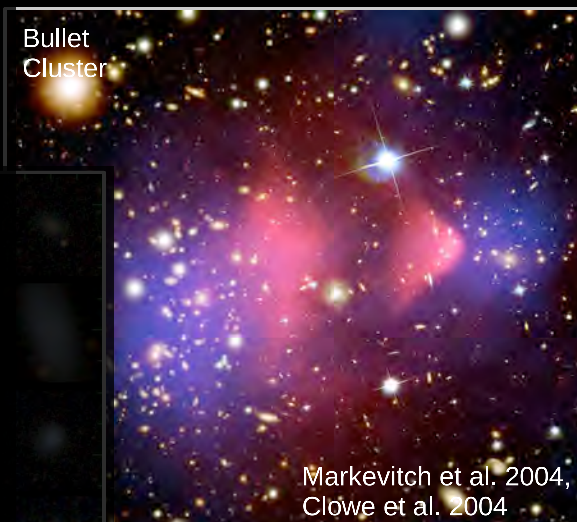
SDSS (M. Blanton)



M33 rotation curve

A. Riess

Dwarf Galaxies


Bullet Cluster

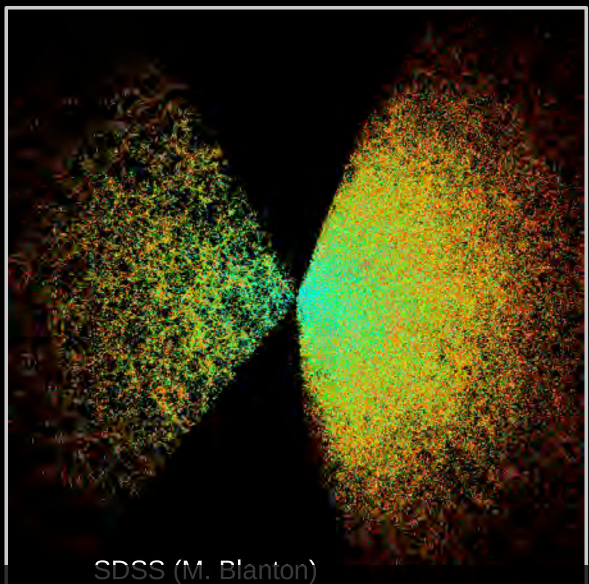
Markevitch et al. 2004, Clowe et al. 2004

M101 (HST; Kuntz et al. 2006)

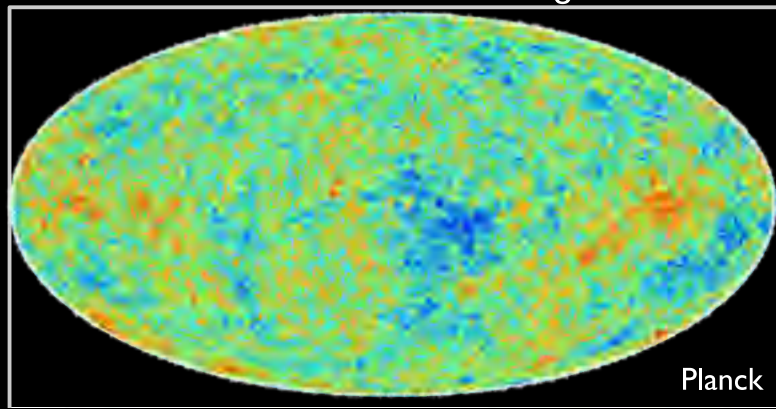
M. Blanton

Evidence for cold dark matter

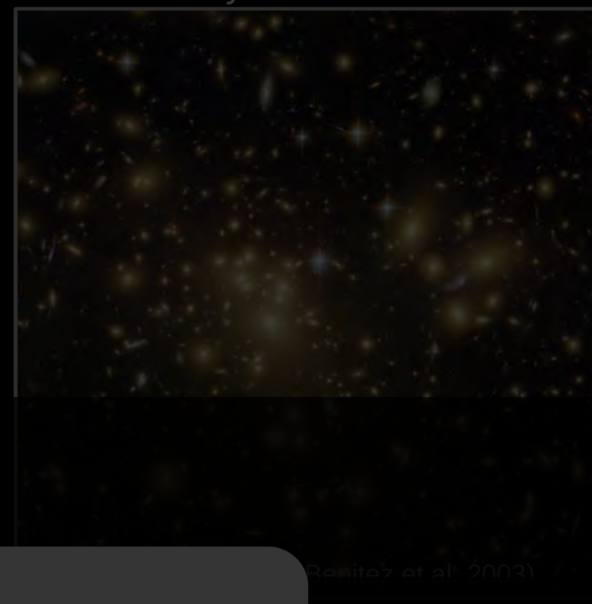
Large Scale Structure



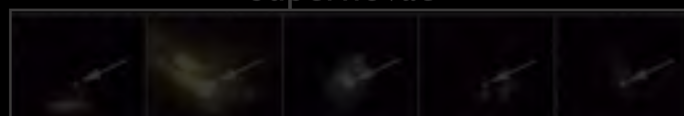
Cosmic Microwave Background

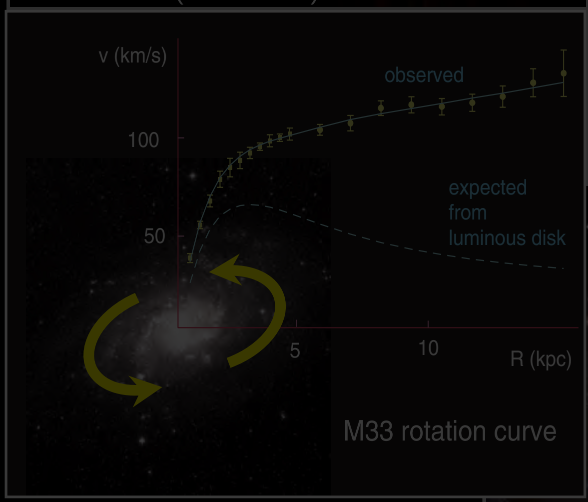


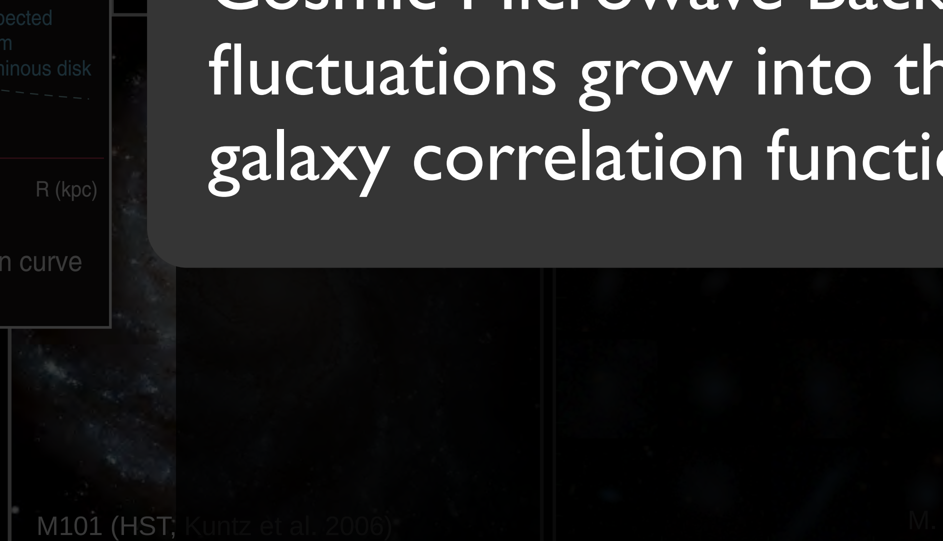
Galaxy Clusters



Supernovae

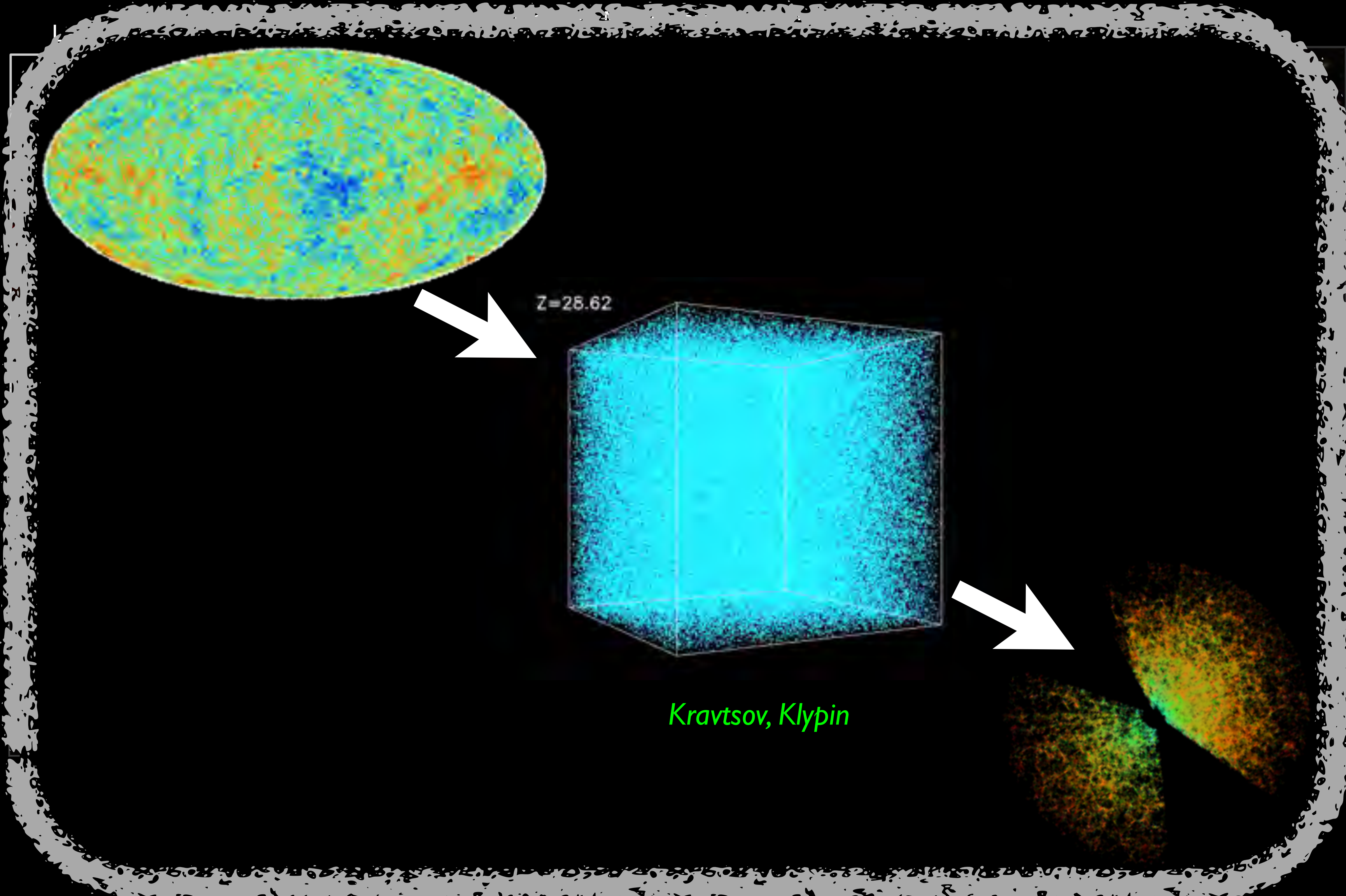






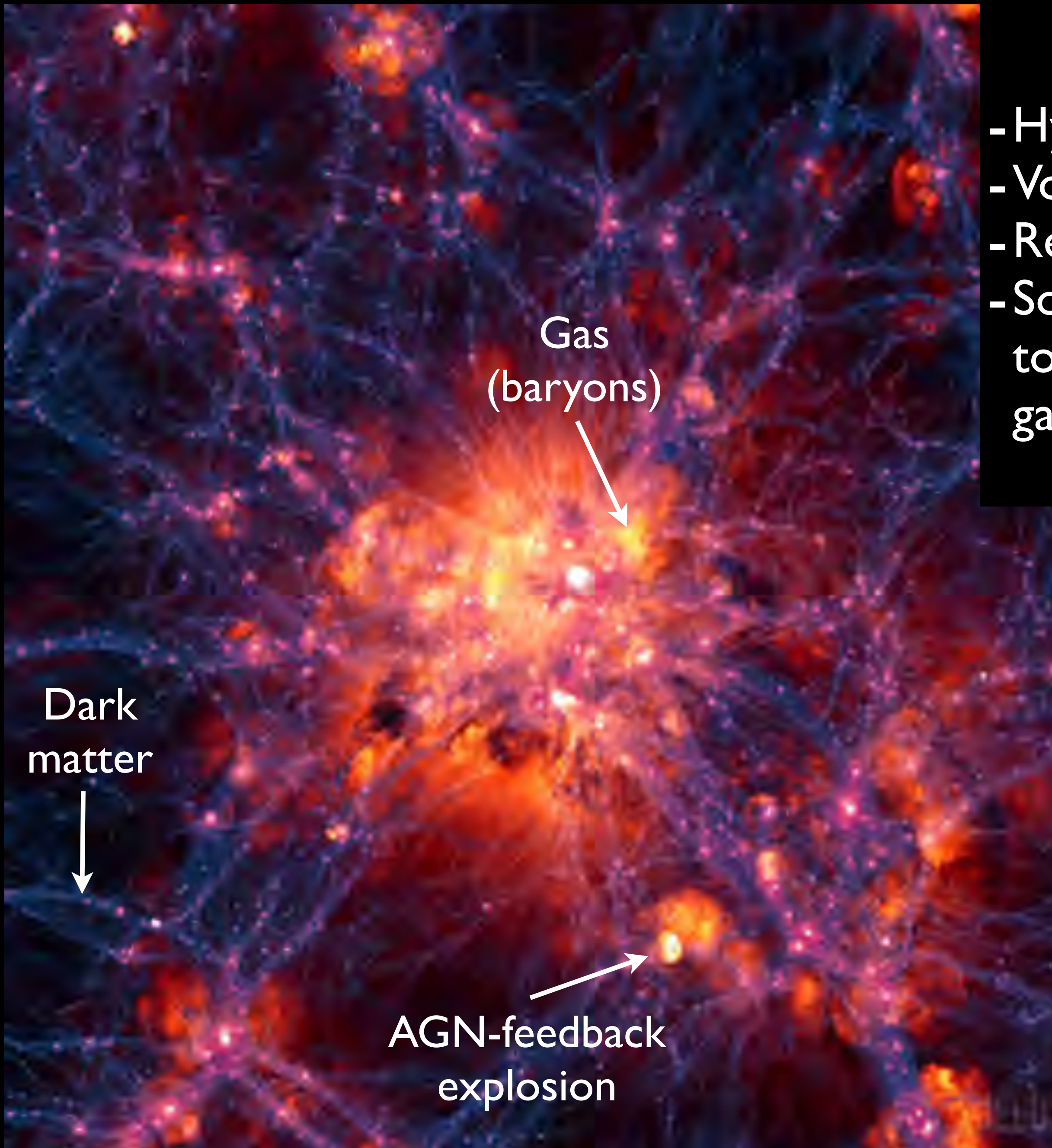
An invisible mass makes the Cosmic Microwave Background fluctuations grow into the galaxy-galaxy correlation function.

Evidence for cold dark matter



Kravtsov, Klypin

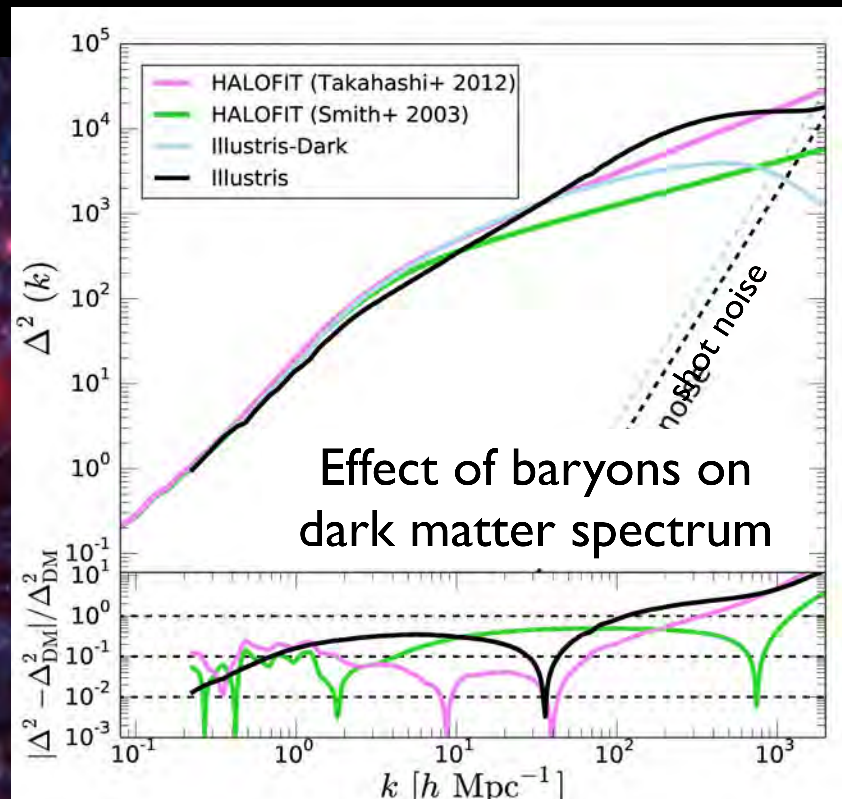
Evidence for cold dark matter



Illustris Collaboration 2014

Illustris Simulation

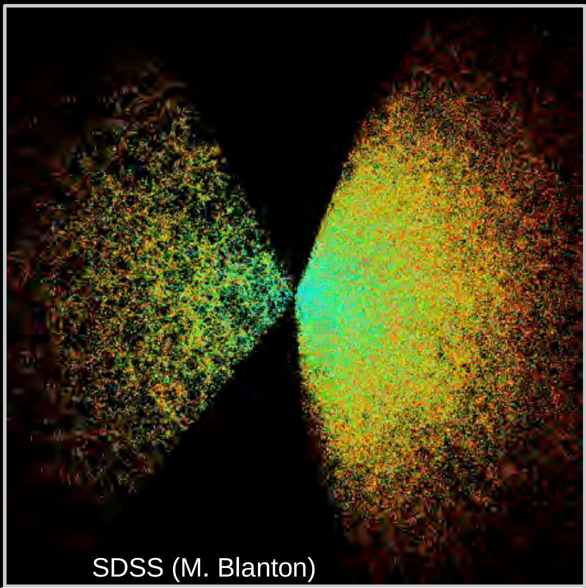
- Hydrodynamical simulation
- Volume: (106.5 Mpc)^3
- Resolution: 710 pc (DM)/48 pc (gas)
- Solves `missing satellite' and `too big-to-fail' problems. Produces observed galaxy shapes and metallicity.



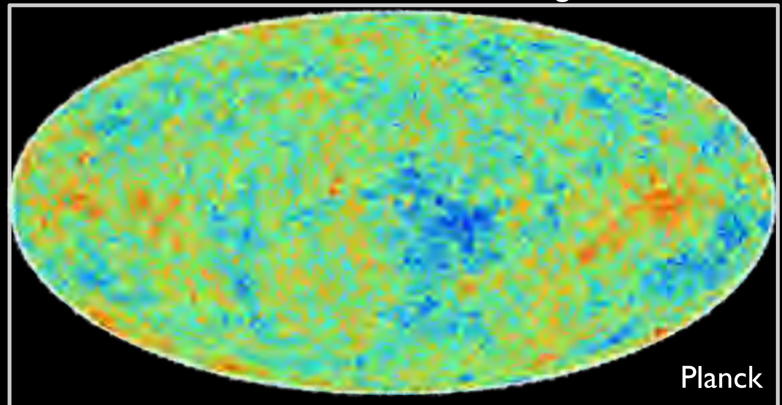
Vogelsberger et al 2014

Evidence for cold dark matter

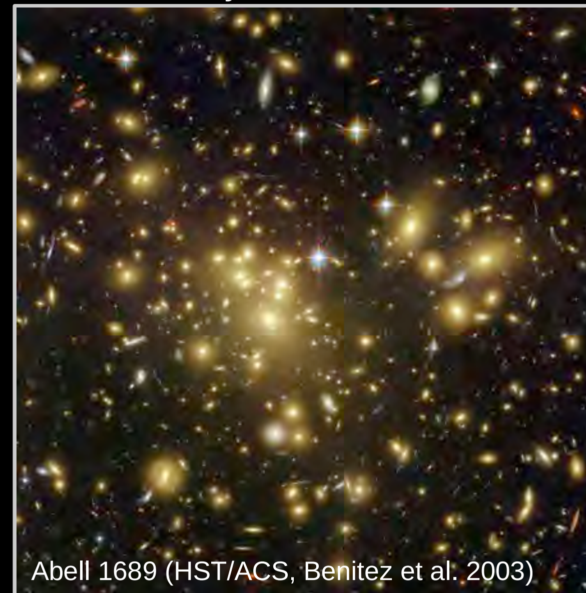
Large Scale Structure



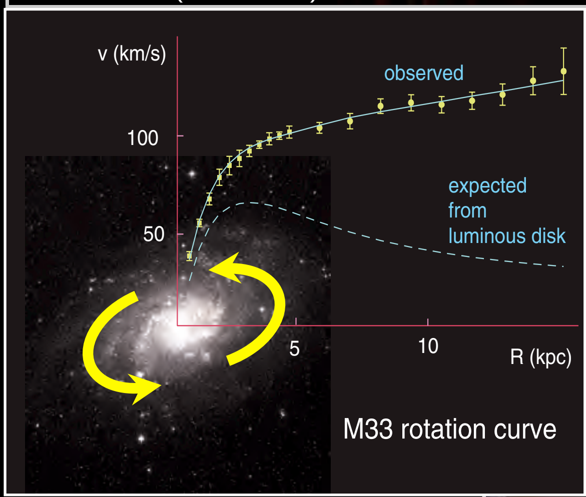
Cosmic Microwave Background

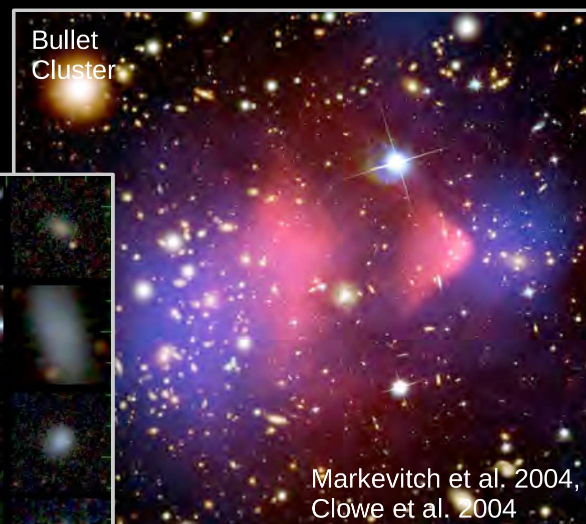


Galaxy Clusters

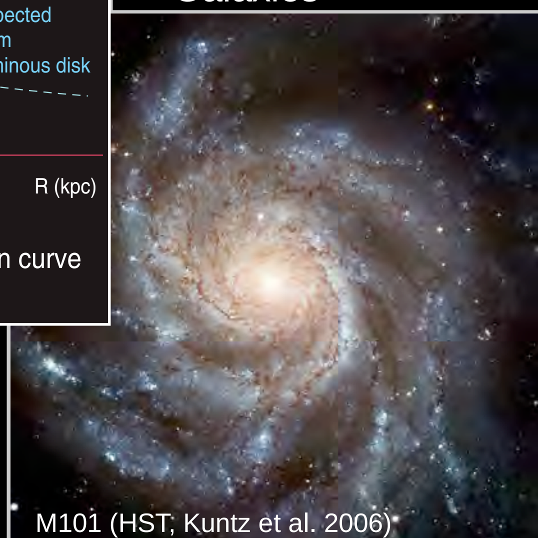


Supernovae

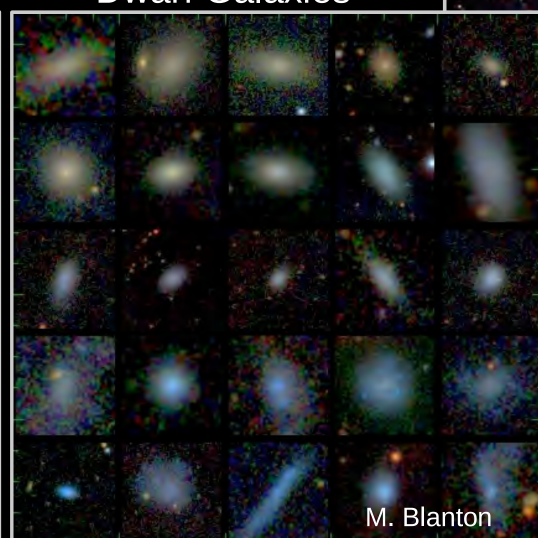




Galaxies



Dwarf Galaxies



What is cold dark matter?

Cold dark matter or modified gravity?

- MOND ($F=ma^2/a_0$ for a<universal a_0) is only non-relativistic and so cannot be tested on cosmological scales

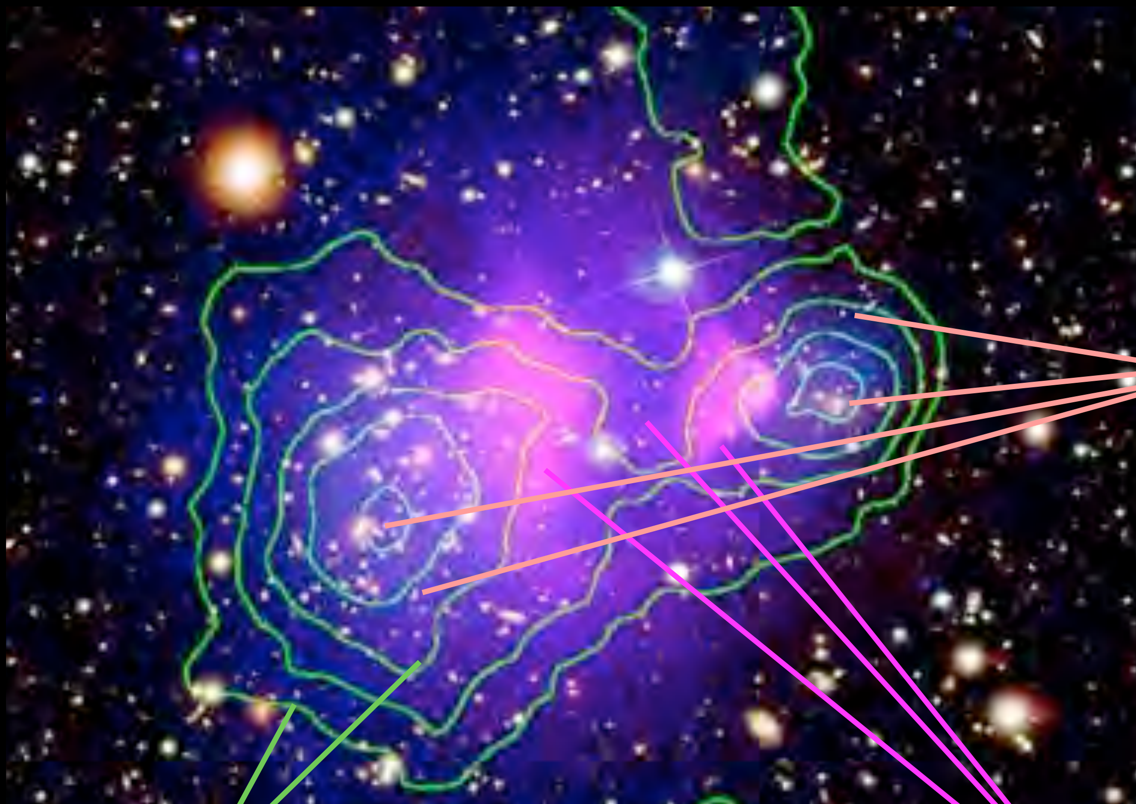
- TeVeS, MOND's generalization, contains new fields that could be interpreted as cold dark matter interacting only gravitationally. It does not reproduce the pattern of CMB peaks.

- There are other ideas, like conformal gravity, but are less studied

Cold dark matter, *not* modified gravity

The Bullet Cluster

Symmetry argument: gas is at center, but potential has two wells.

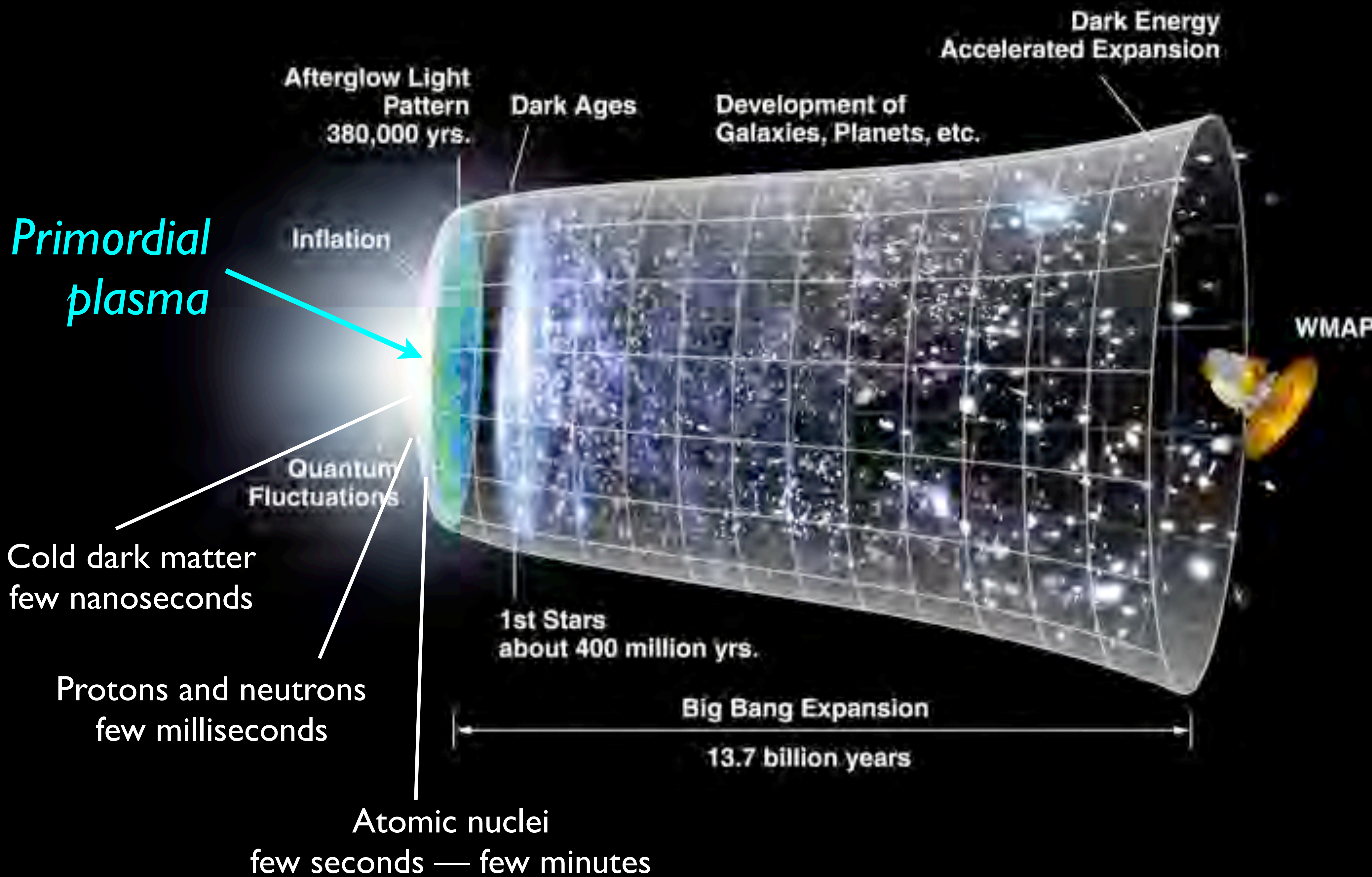


Galaxies in optical (Hubble Space Telescope)

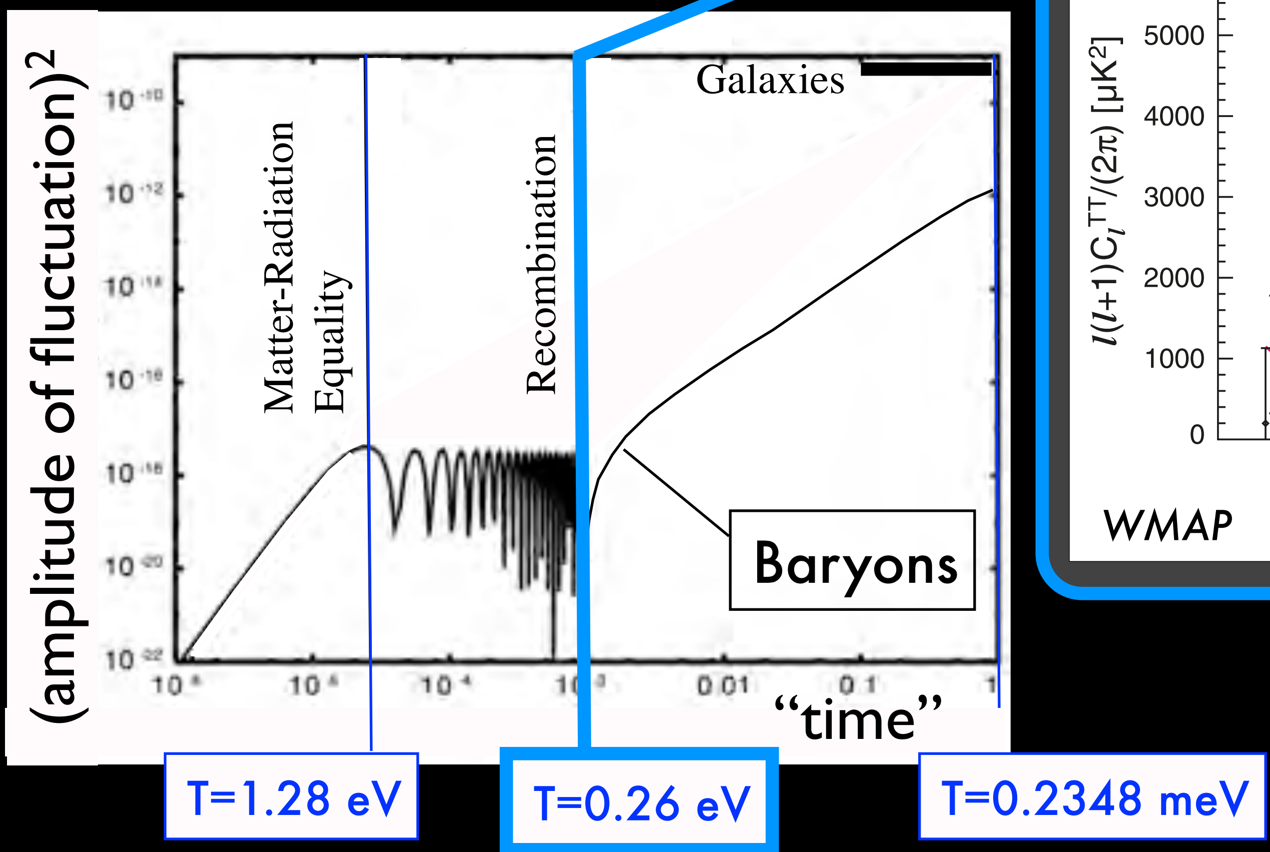
X-ray emitting hot gas (Chandra)

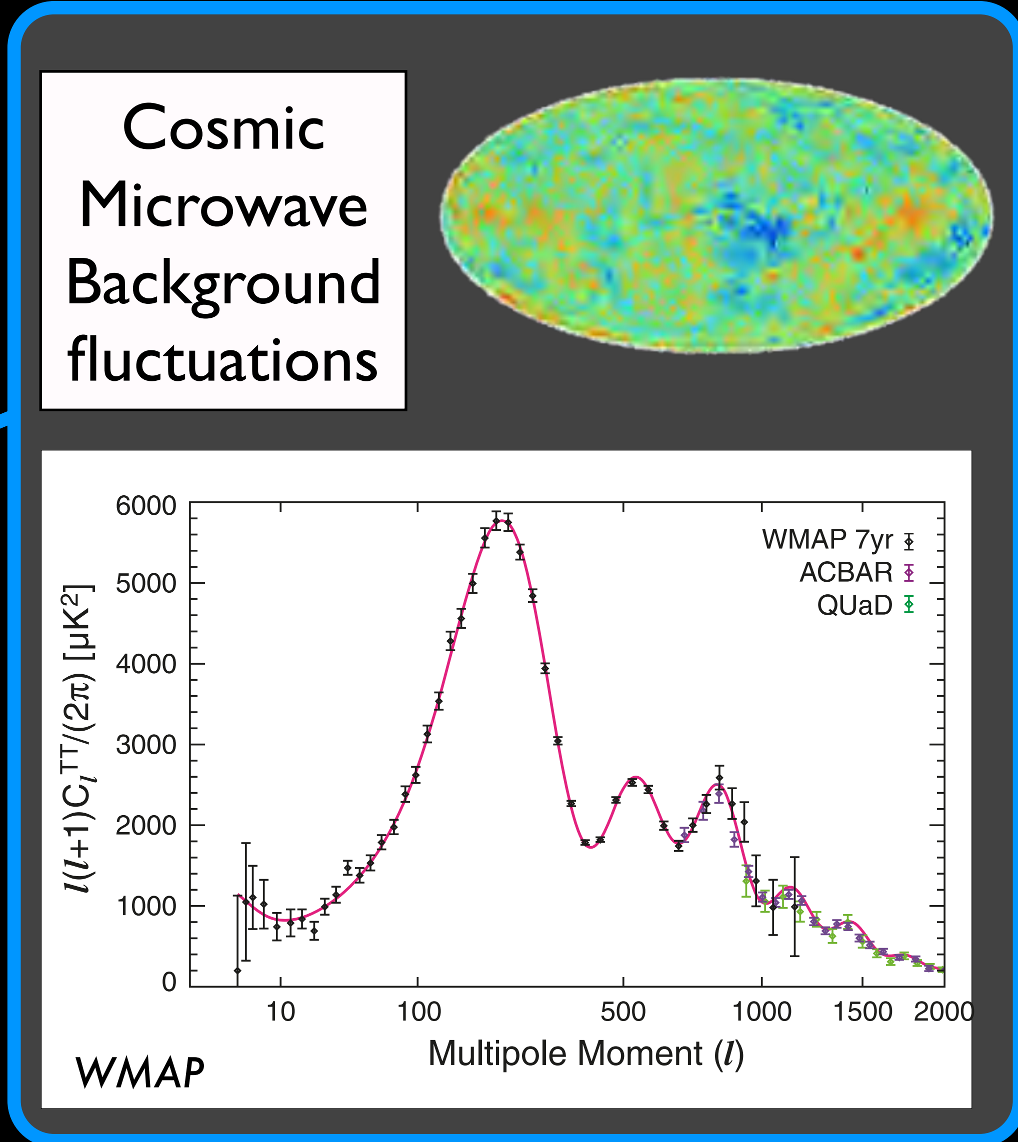
Gravitational potential from weak lensing

Cold dark matter is *non-baryonic*



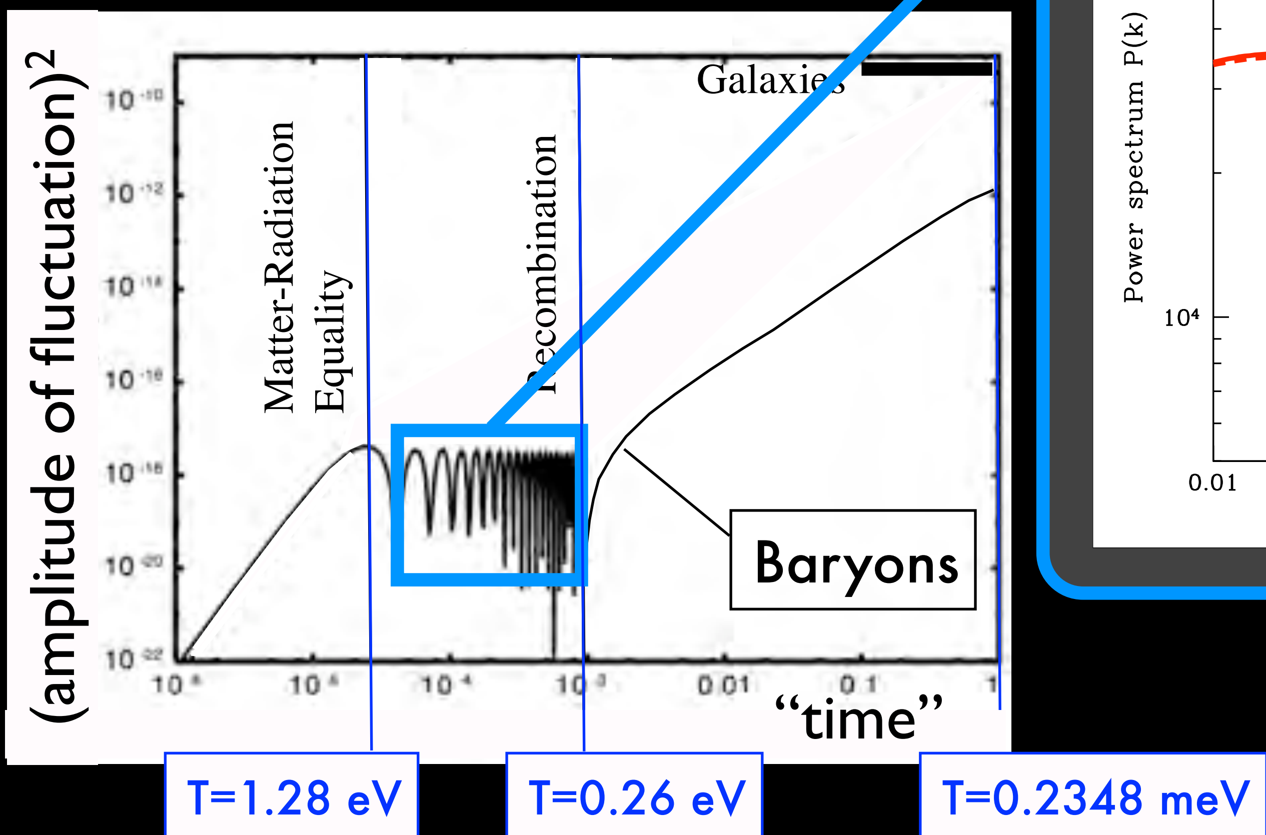
Cold dark matter is *non-baryonic*

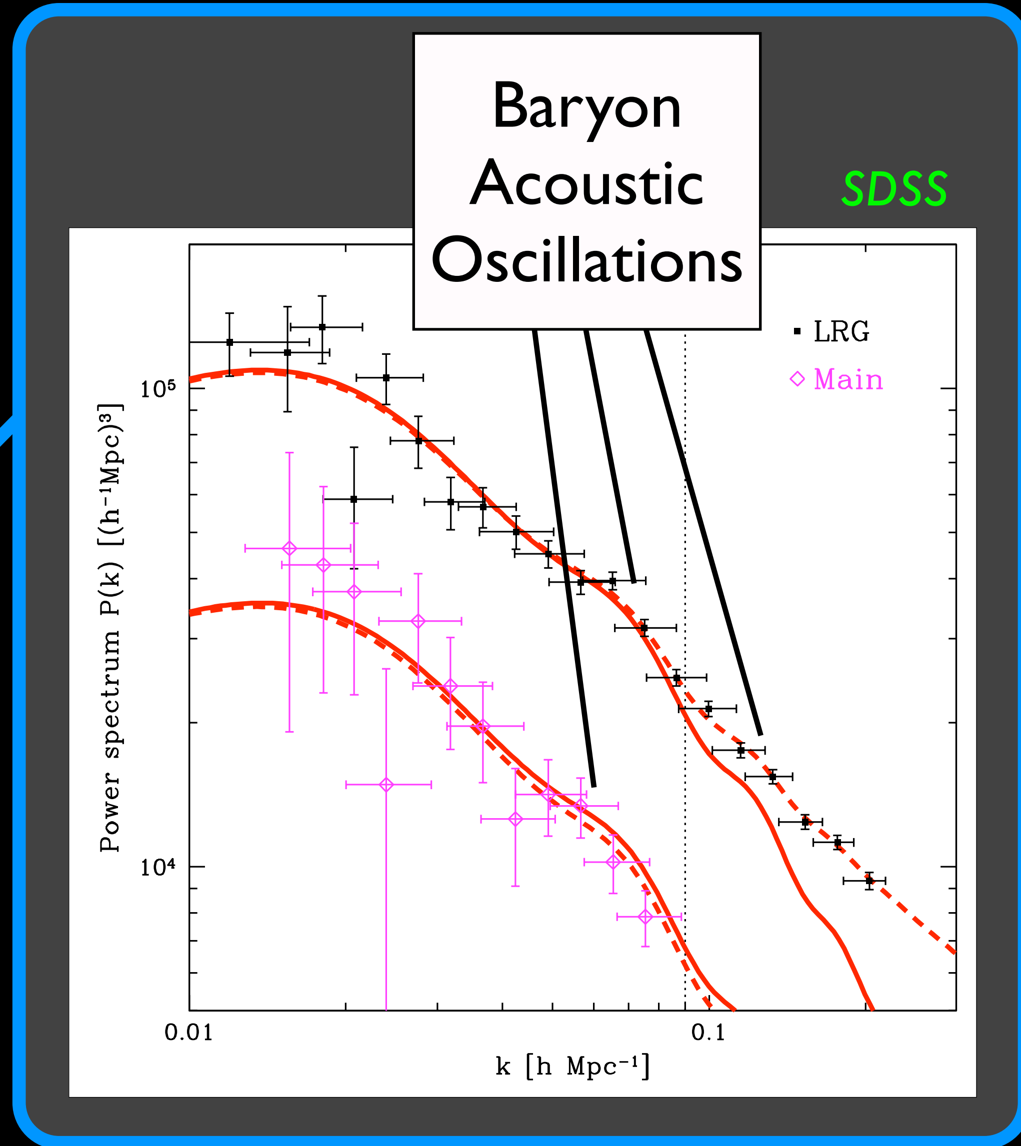




Cold dark matter is *non-baryonic*

Fluctuations are too small to gravitationally grow into galaxies in the given 13 billion years.

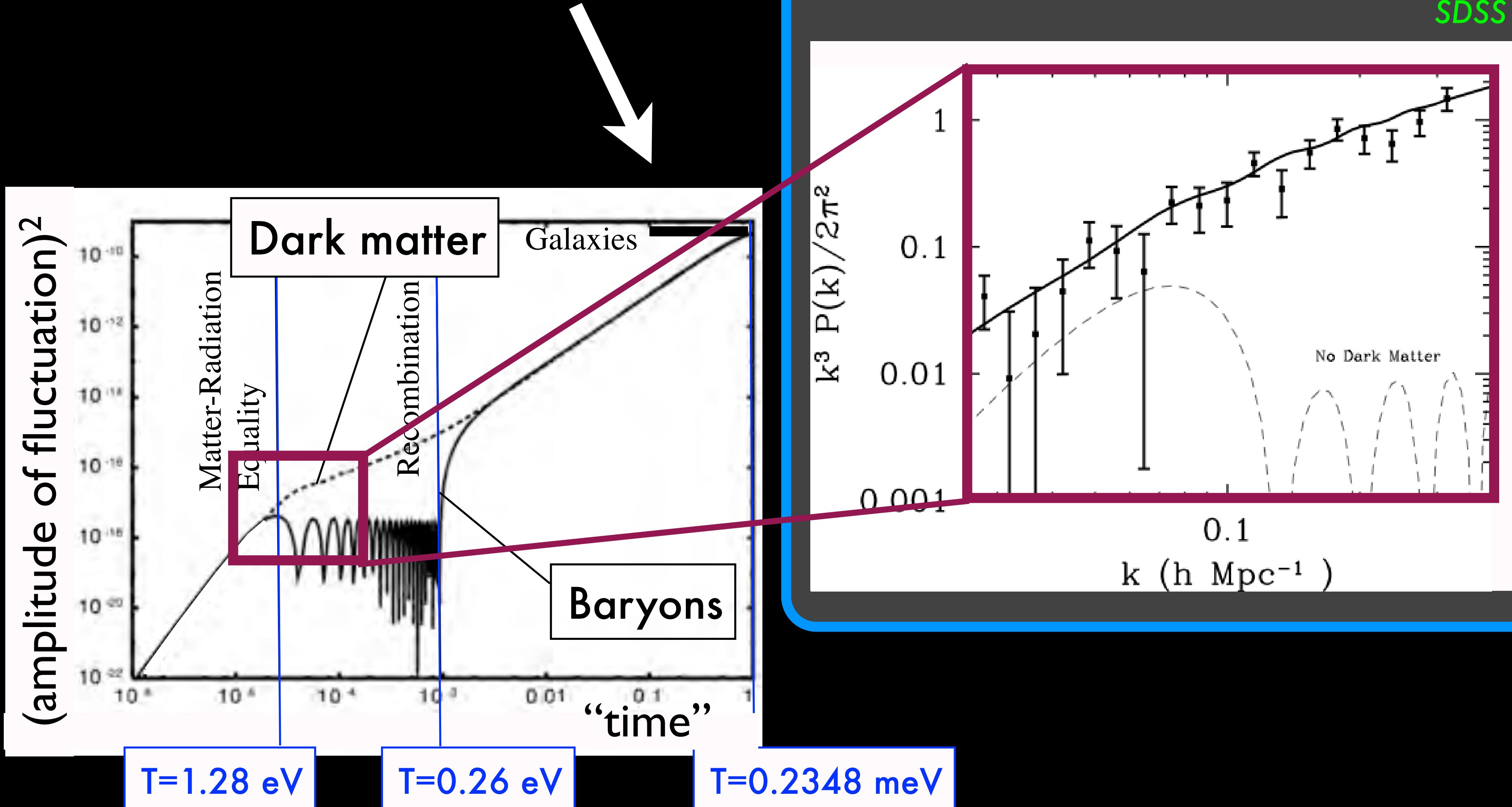




Cold dark matter is *non-baryonic*

Fluctuation uncoupled to the plasma have enough time to grow

More than 80% of all matter does not couple to the primordial plasma!



Is dark matter an elementary particle?

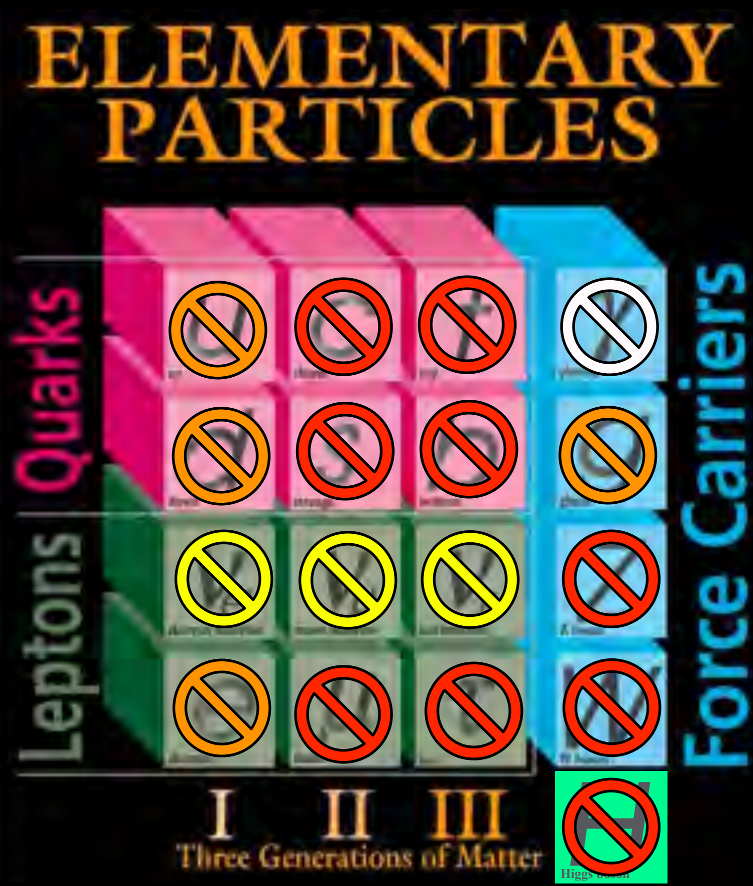
IS HINCHLIFFE'S RULE TRUE? *

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

Is dark matter an elementary particle?



- ⃠ is the particle of light
- ⃠ couples to the plasma
- ⃠ disappears too quickly
- ⃠ is too scarce

No known particle can be cold dark matter!

Particle dark matter

- neutrinos (hot)
- sterile neutrinos, gravitinos (warm)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

} thermal relics

- Bose-Einstein condensates, axions, axion clusters
- solitons (Q-balls, B-balls, ...)
- supermassive wimpzillas

} non-thermal relics

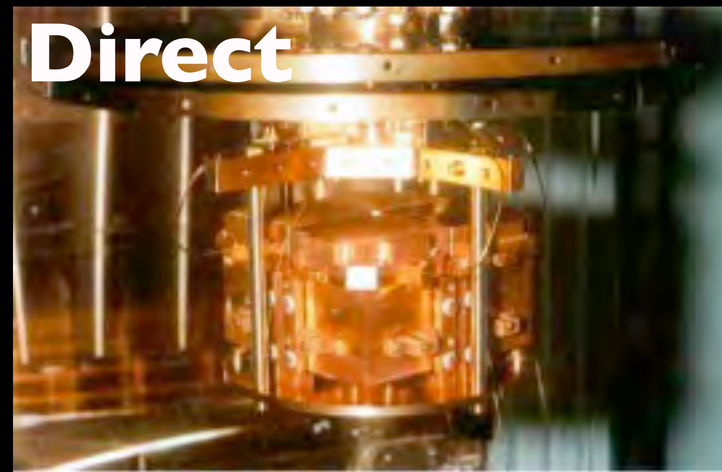
Mass range

10^{-22} eV (10^{-56}g) B.E.C.s
10^{-8} $M_\odot$ (10^{+25}g) axion clusters

Interaction strength range

Only gravitational: wimpzillas
Strongly interacting: B-balls

Searches for particle dark matter



Evidence for cold dark matter particles?

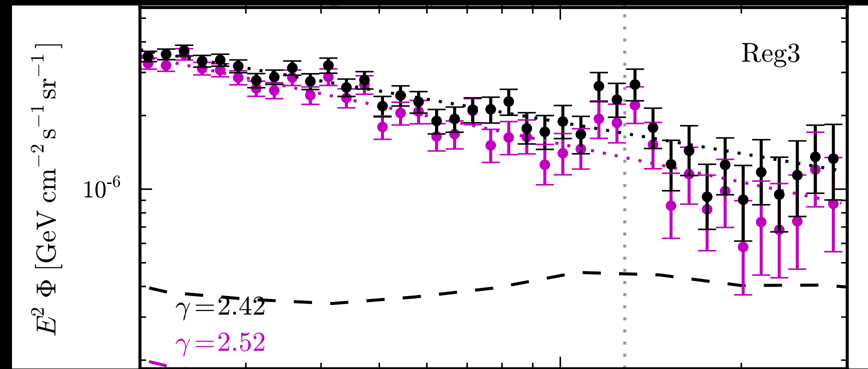
GeV γ-rays

Hooper et al 2009-14

3.5 keV X-ray line

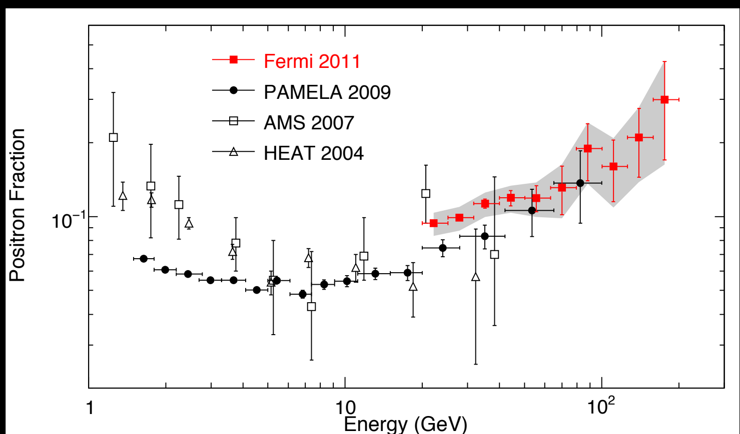
Bulbul et al 2014

135 GeV γ-ray line



Weniger 2012

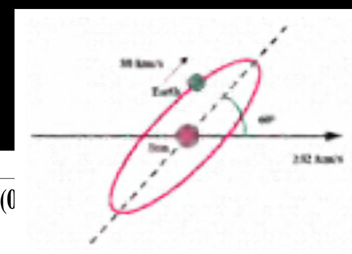
Positron excess

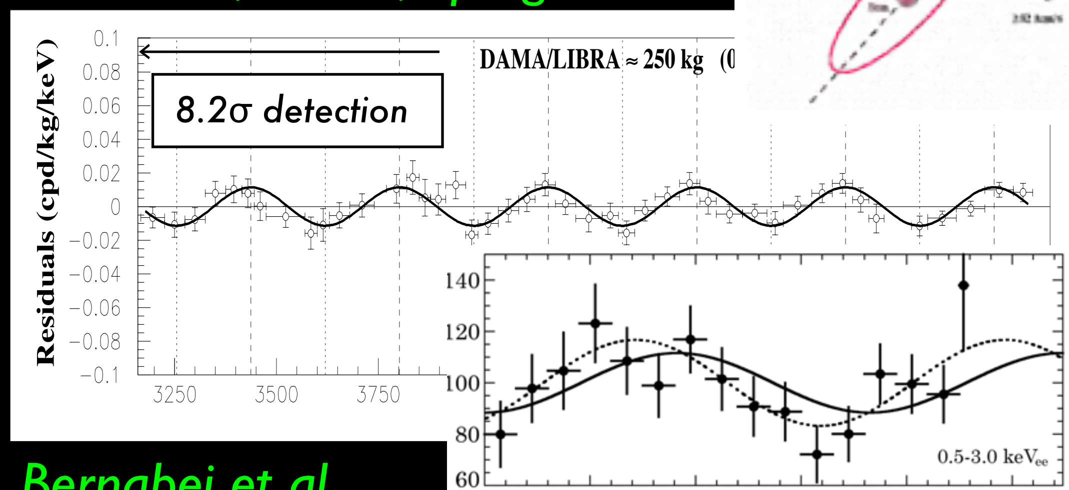


Adriani et al 2009;Ackerman et al 2011; Aguilar et al 2013

Annual modulation

Drukier, Freese, Spergel 1986





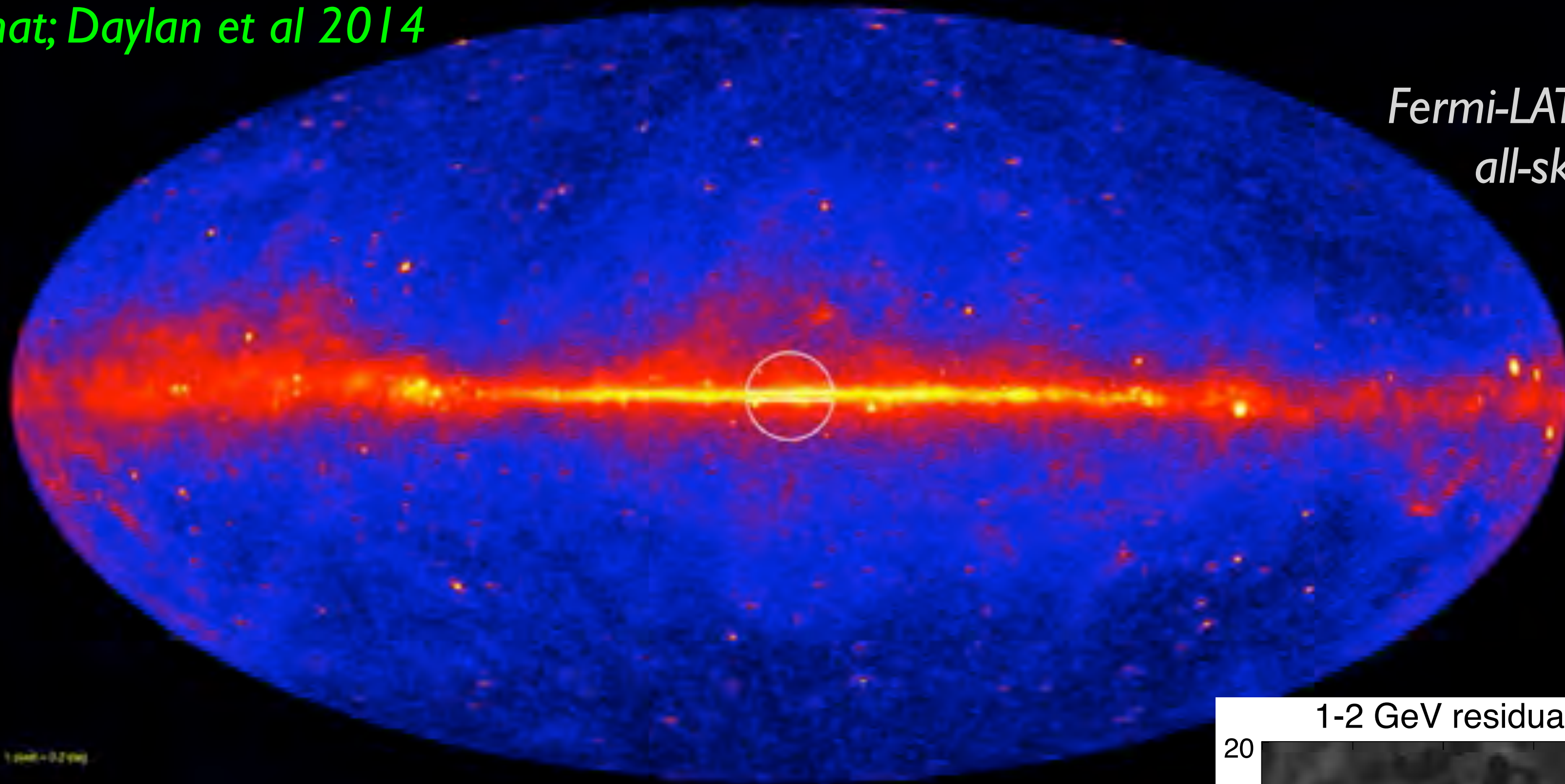
Bernabei et al 1997-2012

Aalseth et al 2011

1 GeV gamma-ray excess?

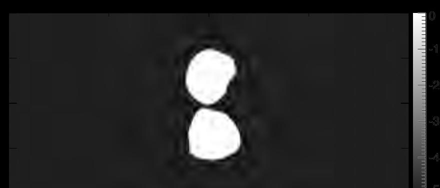
1 GeV gamma-ray excess?

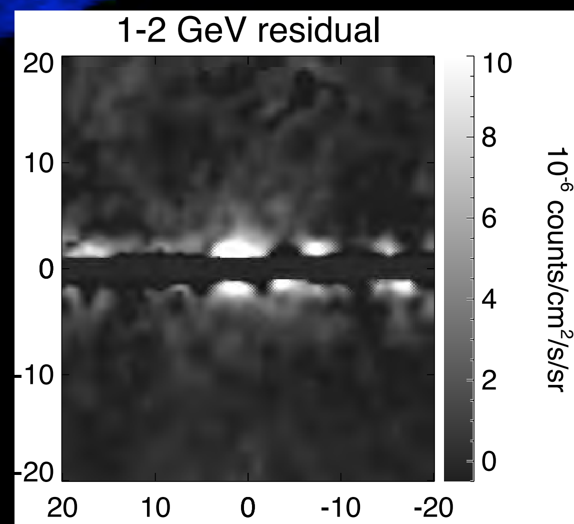
Goodenough, Hooper 2009; Hooper, Goodenough; Boyarsky, Malyshev, Ruchayskiy; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon, Macias 2013; Abazajian, Canac, Horiuchi, Kaplinghat; Daylan et al 2014



Fermi-LAT all-sky map

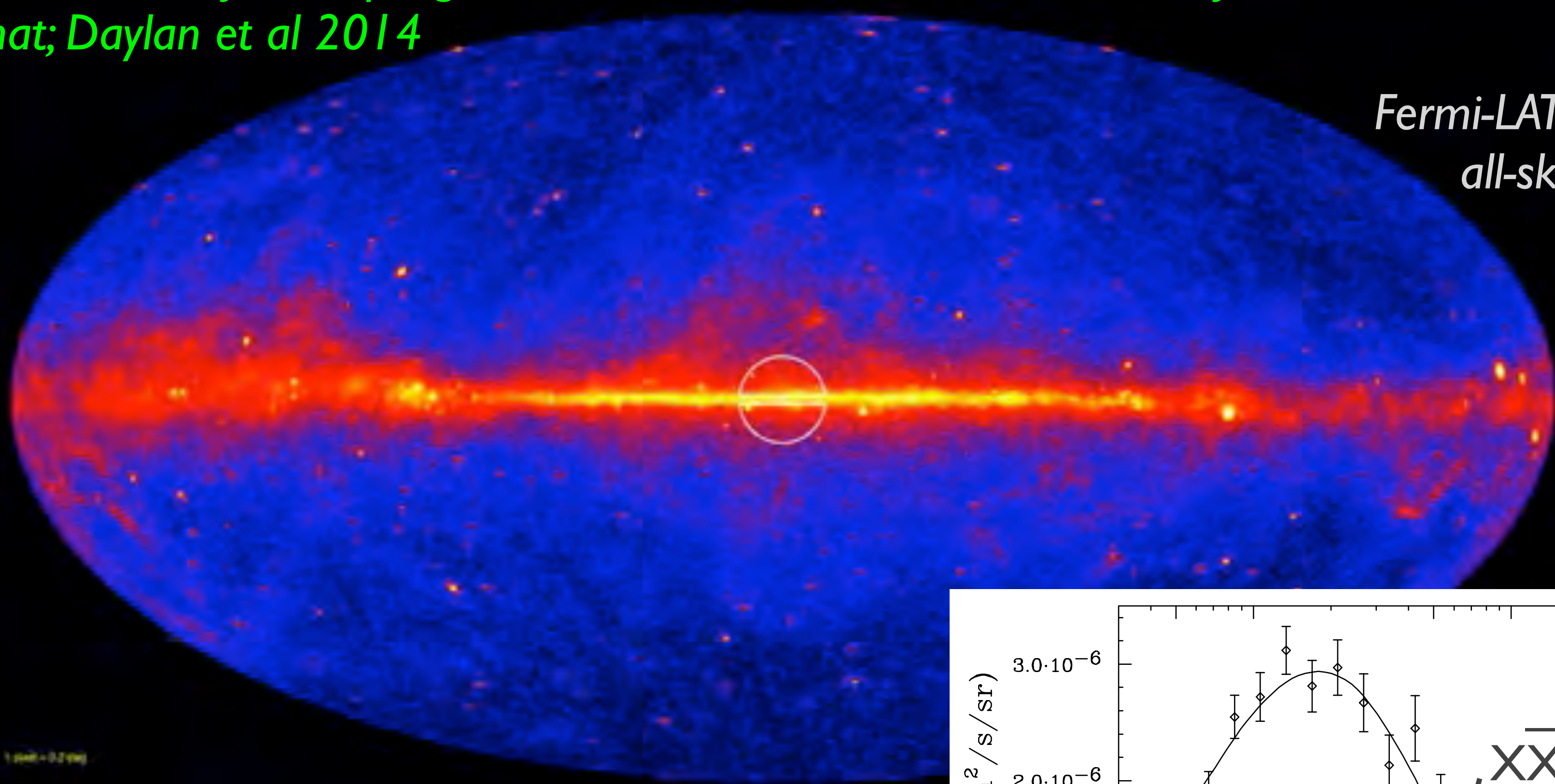
Fit diffuse + Fermi-bubble, find residual





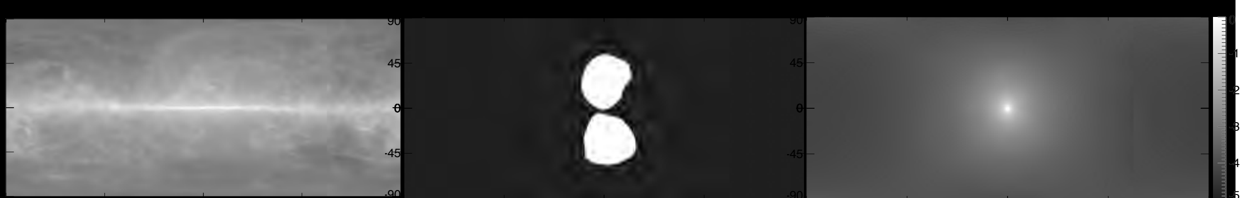
1 GeV gamma-ray excess?

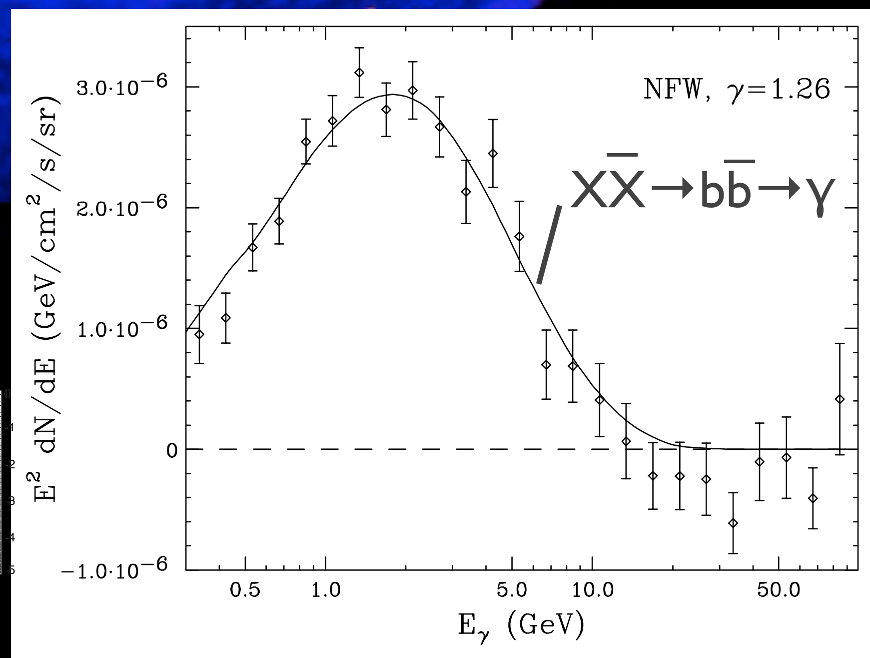
Goodenough, Hooper 2009; Hooper, Goodenough; Boyarsky, Malyshev, Ruchayskiy; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon, Macias 2013; Abazajian, Canac, Horiuchi, Kaplinghat; Daylan et al 2014



Fermi-LAT all-sky map

Fit diffuse + Fermi-bubble + dark matter





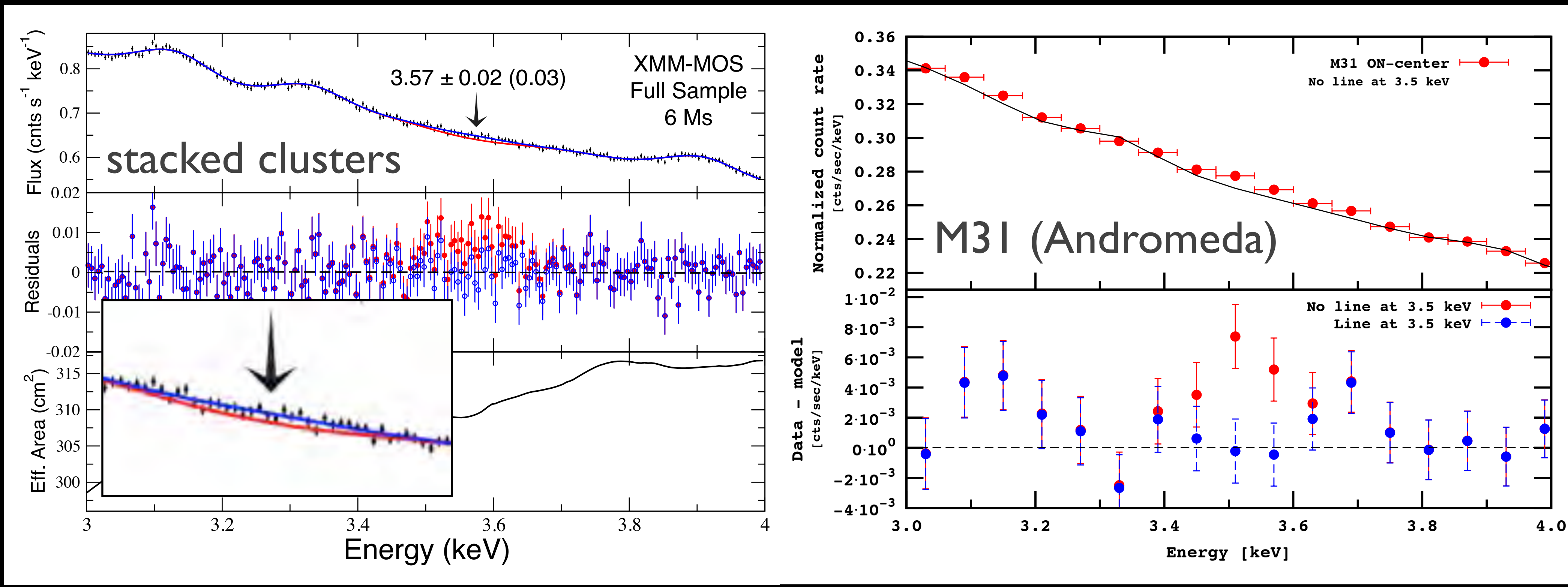
3.5 keV X-ray line?

Sterile neutrino dark matter

An unidentified 3.5 keV X-ray line has been reported in stacked images of 73 galaxy clusters and in the Andromeda galaxy

Bulbul et al 2014

Boyarsky et al 2014



Sterile neutrino dark matter

The main decay mode of keV sterile neutrinos ($\nu_s \rightarrow 3\nu$) is undetectable

Radiative decay of sterile neutrinos $\nu_s \rightarrow \gamma\nu_a$

X-ray line

$$E_\gamma = \frac{1}{2} m_s$$

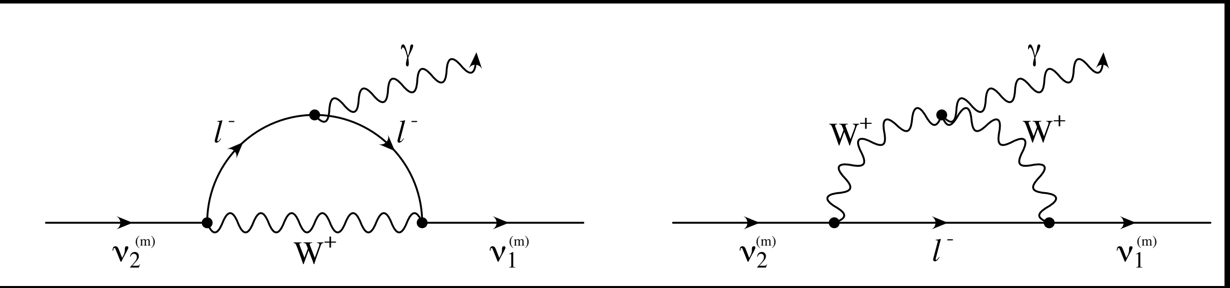


Figure from Kusenko 0906.2968

$$\Gamma_{\nu_s \rightarrow \gamma\nu_a} = \frac{9}{256\pi^4} \alpha_{\rm EM} \, G_F^2 \, \sin^2\theta \, m_s^5$$

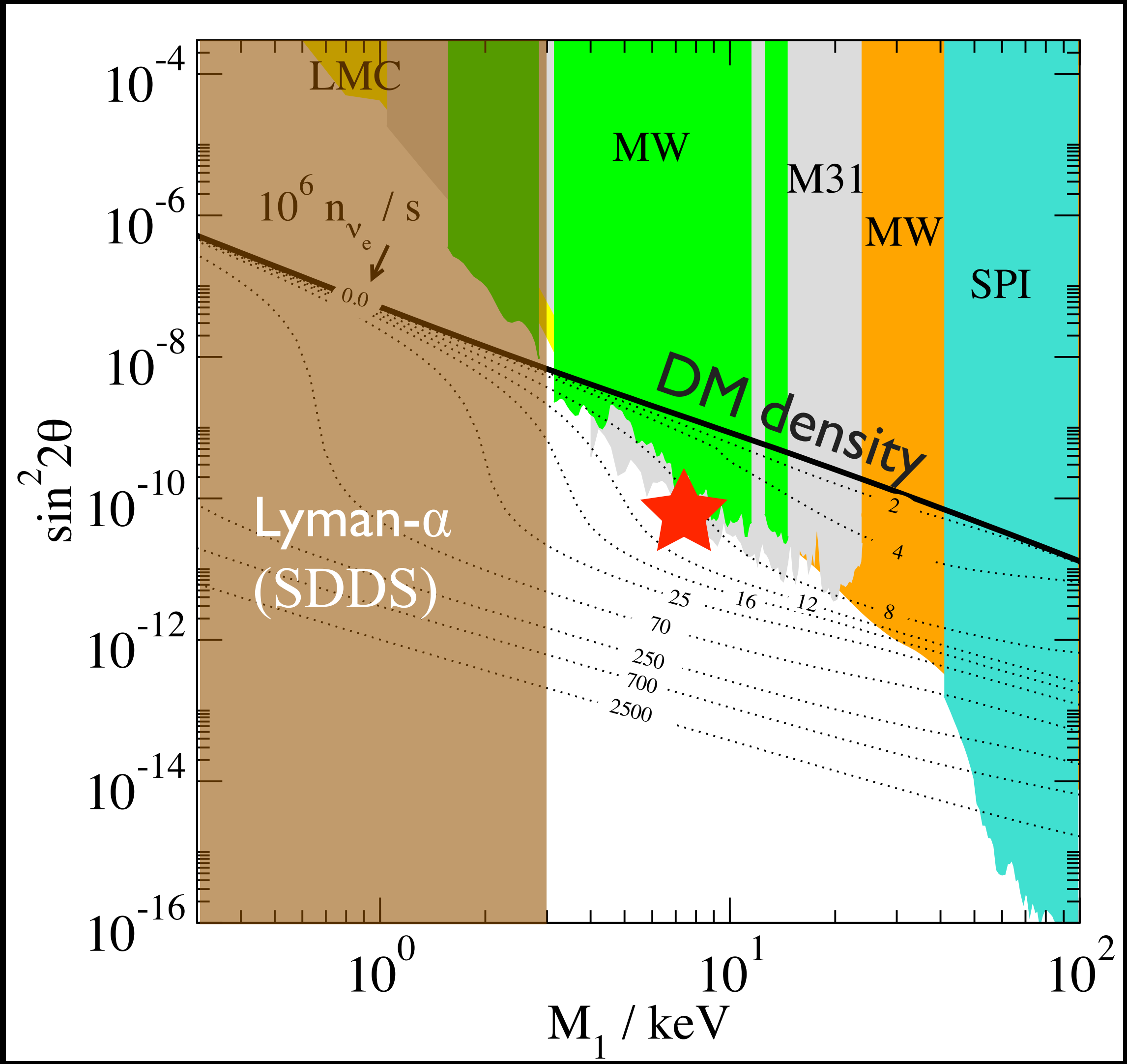
$$= \frac{1}{1.8 \times 10^{21} {\rm s}} \sin^2\theta \left(\frac{m_s}{\rm keV}\right)^5$$

Sterile neutrino dark matter

νMSM

$m_\nu = 7.1$ keV

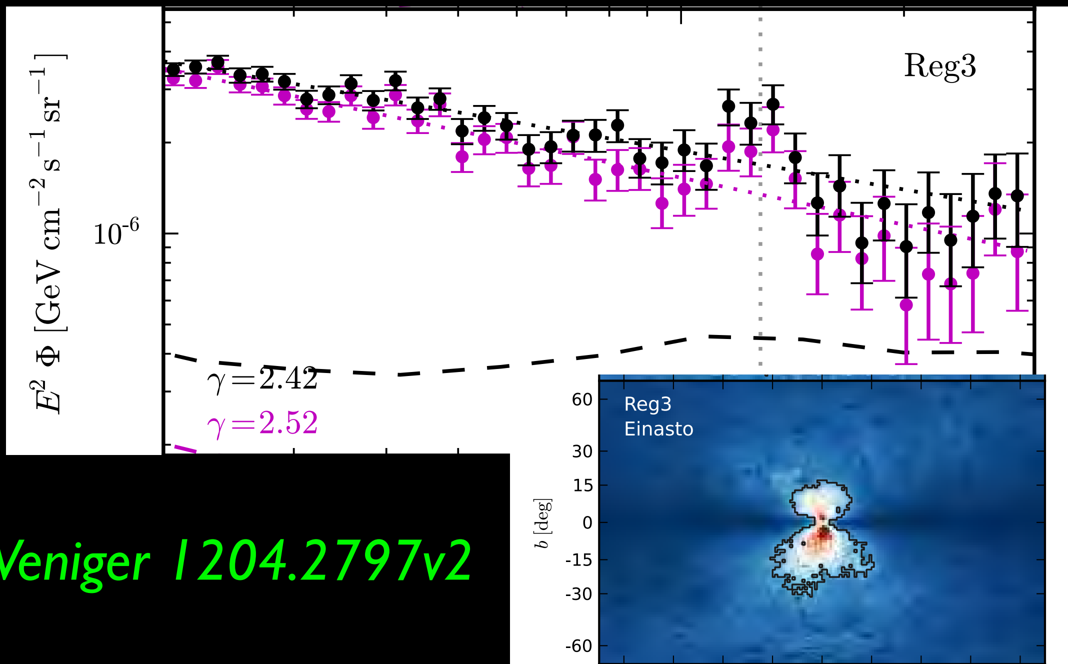
$\sin^2(2\theta) = 7\times10^{-11}$



Laine, Shaposhnikov 2008

135 GeV gamma-ray line?

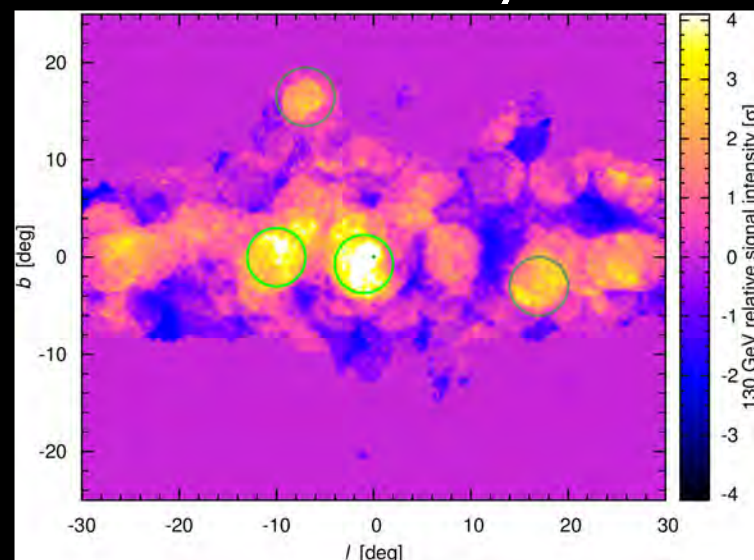
135 GeV gamma-ray line?



Weniger 1204.2797v2

$$\chi + \chi \to \gamma + \gamma$$

found by others



Tempel, Hektor, Raidal 2012

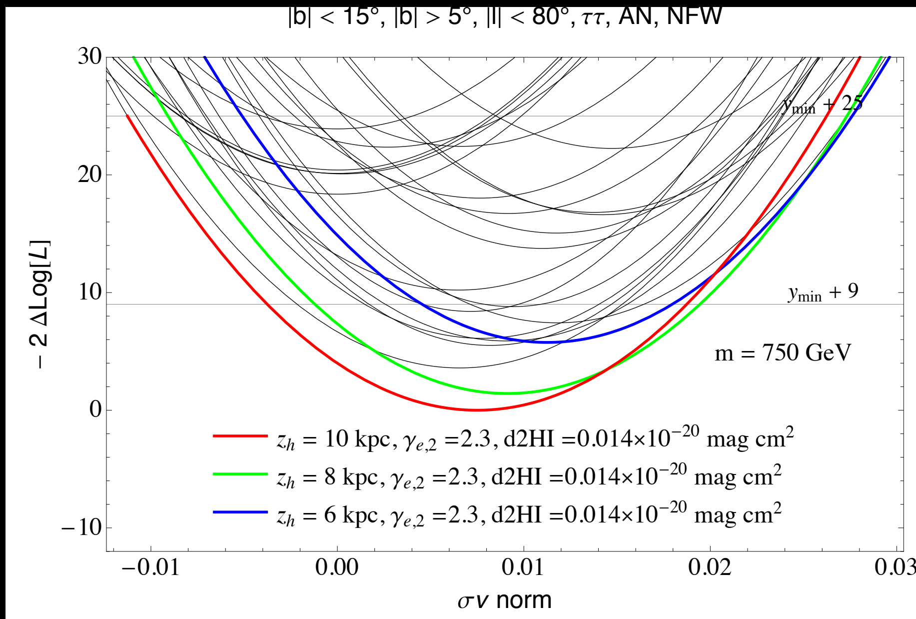
3.2σ effect based on 50 photons

$$m = 129.8 \pm 2.4^{+7}_{-13}\ \mathrm{GeV}$$

$$\langle \sigma v \rangle_{\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm^3 s^{-1}}$$

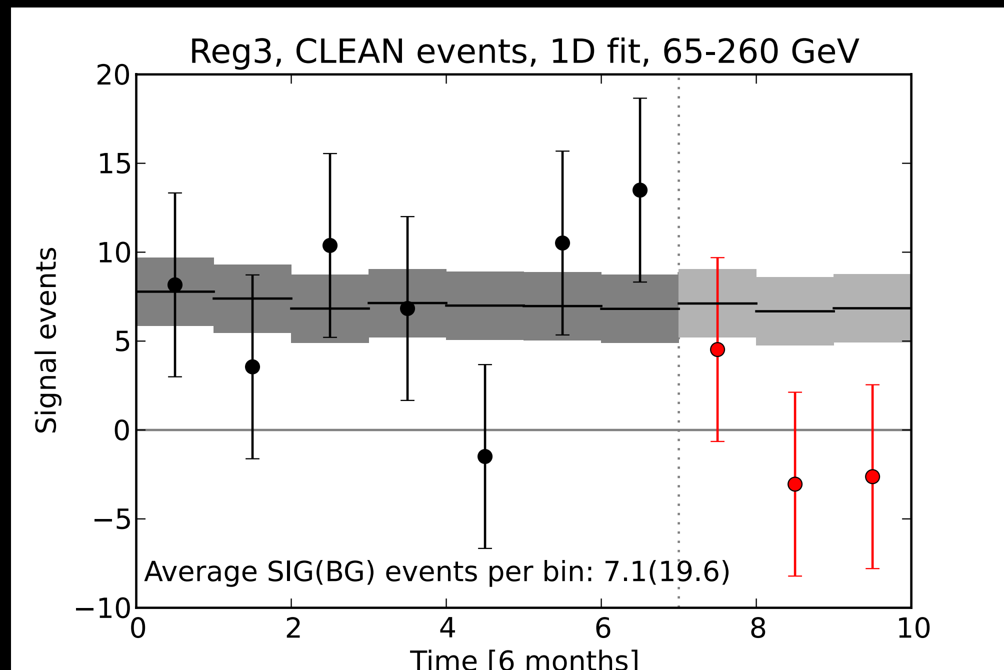
135 GeV gamma-ray line?

Fermi Collab. upper bounds



Ackerman et al (Fermi-LAT) 2012

The evidence for a 135 GeV γ-ray line may be disappearing



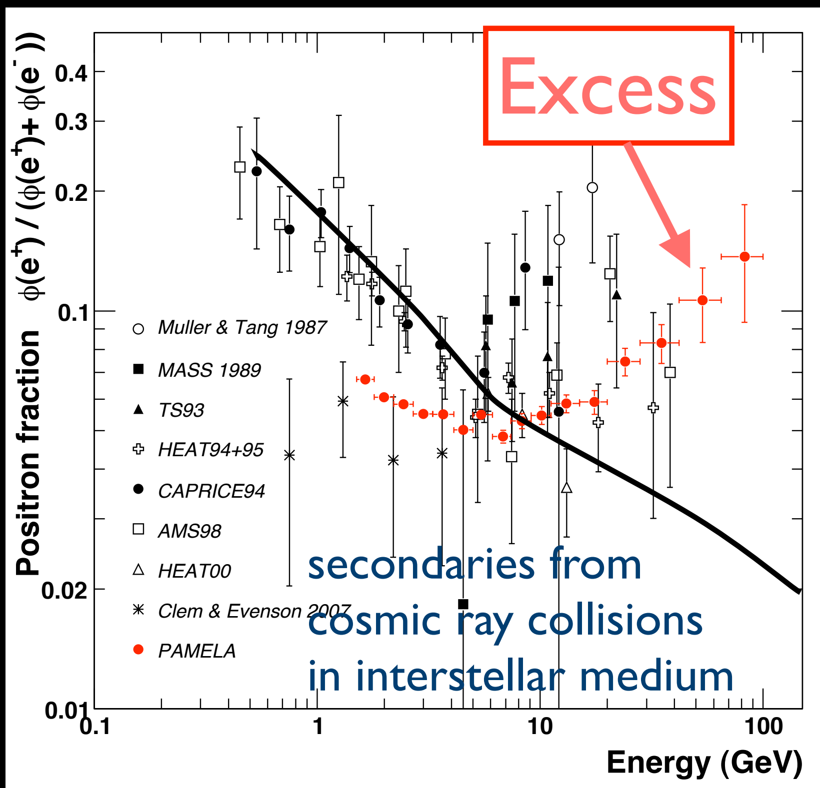
Courtesy C.Weniger 2014

HESS-2 may tell

Positron excess

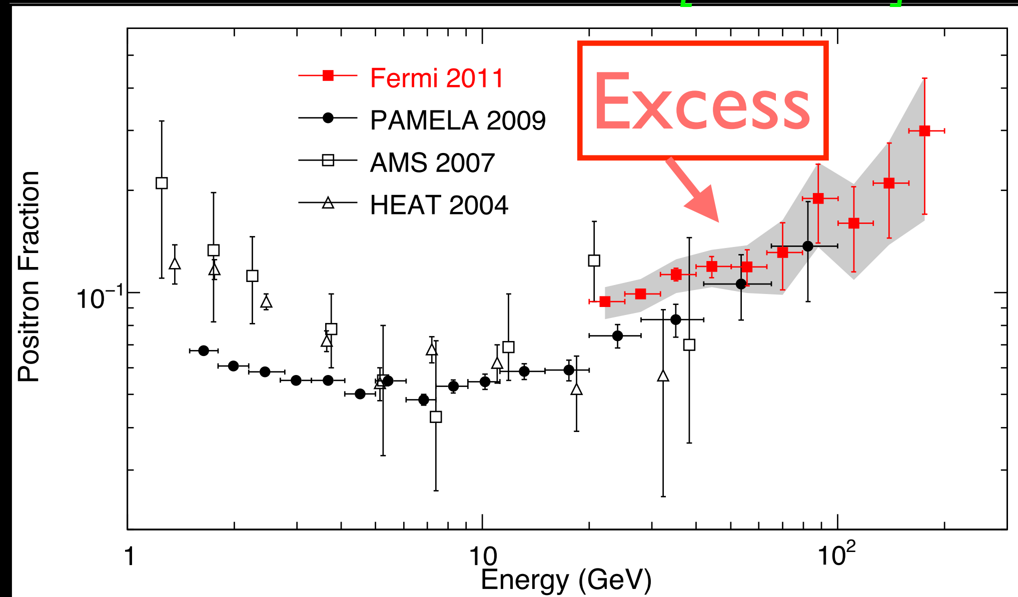
Excess in cosmic ray positrons

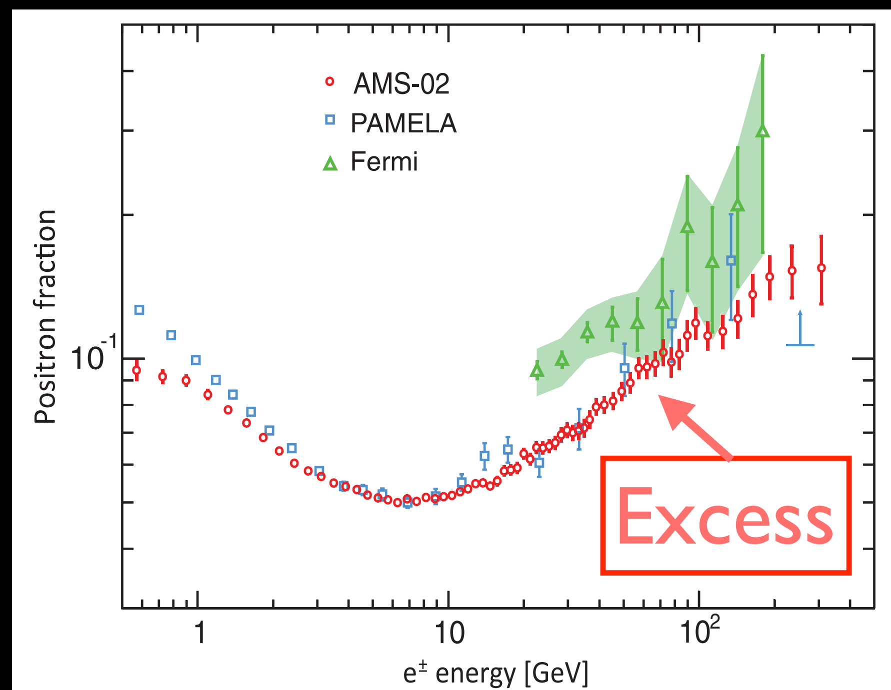
High energy cosmic ray positrons are more than expected



Adriani et al. [PAMELA ,2008

Ackernmann et al [Fermi-LAT] 2011



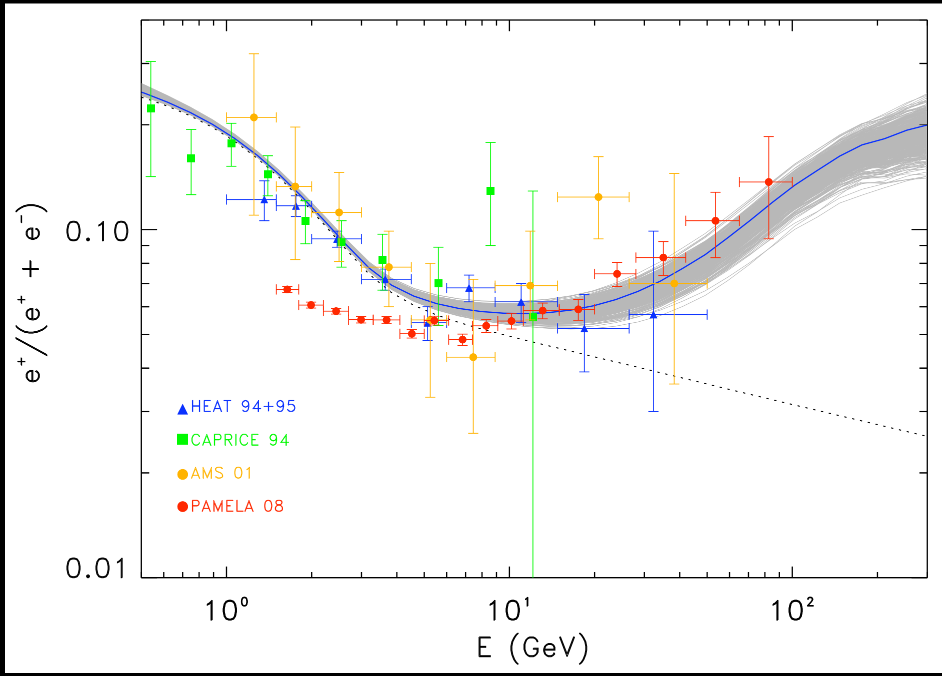


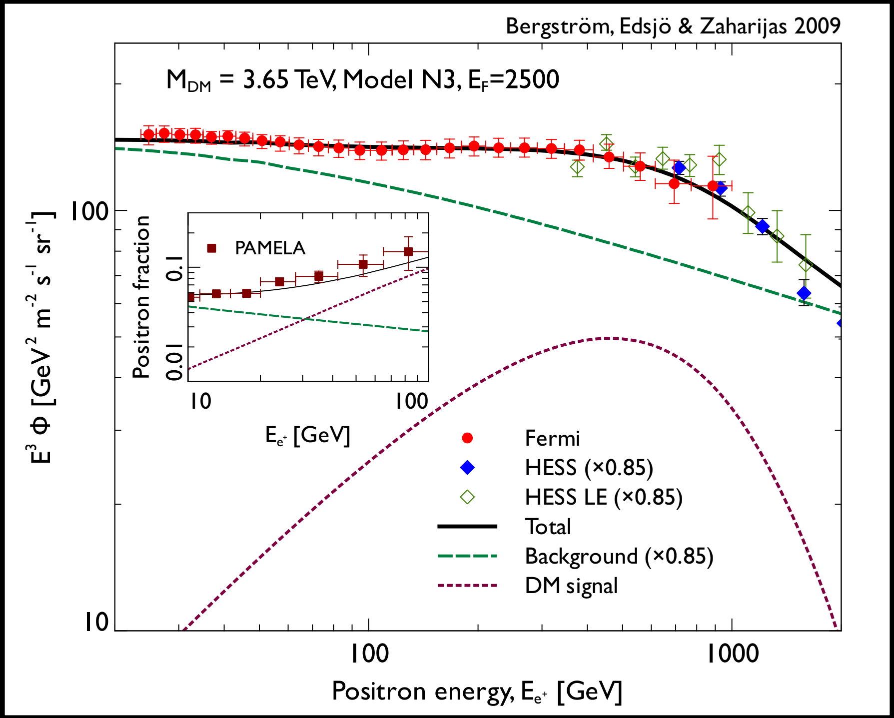
Aguilar et al [AMS-02] 2013

Excess in cosmic ray positrons

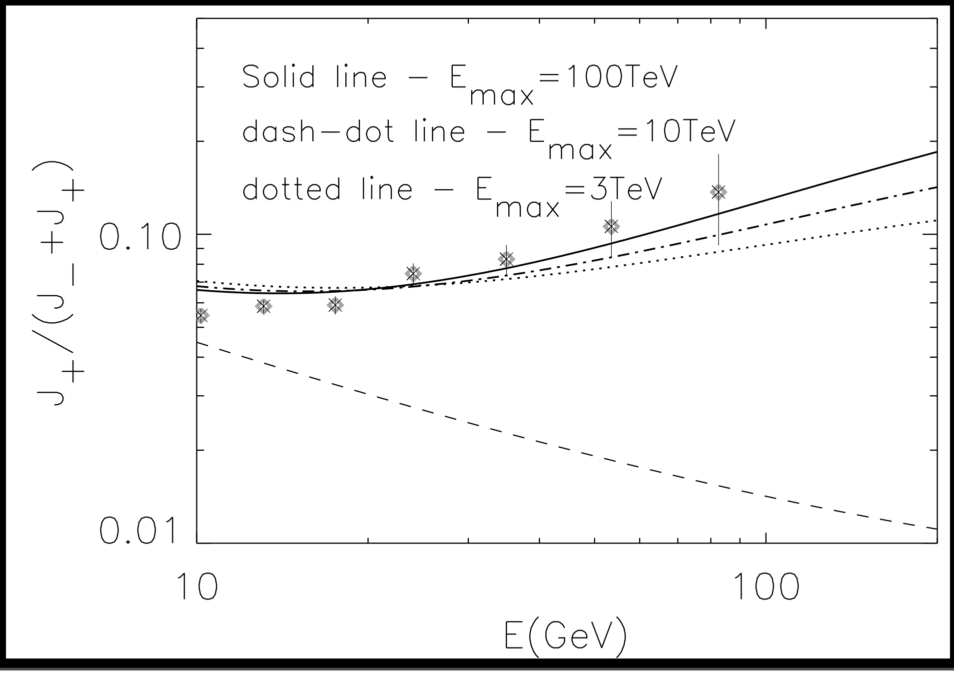
Dark matter?
Pulsars?
Acceleration near source?

Grasso et al [Fermi-LAT] 2009





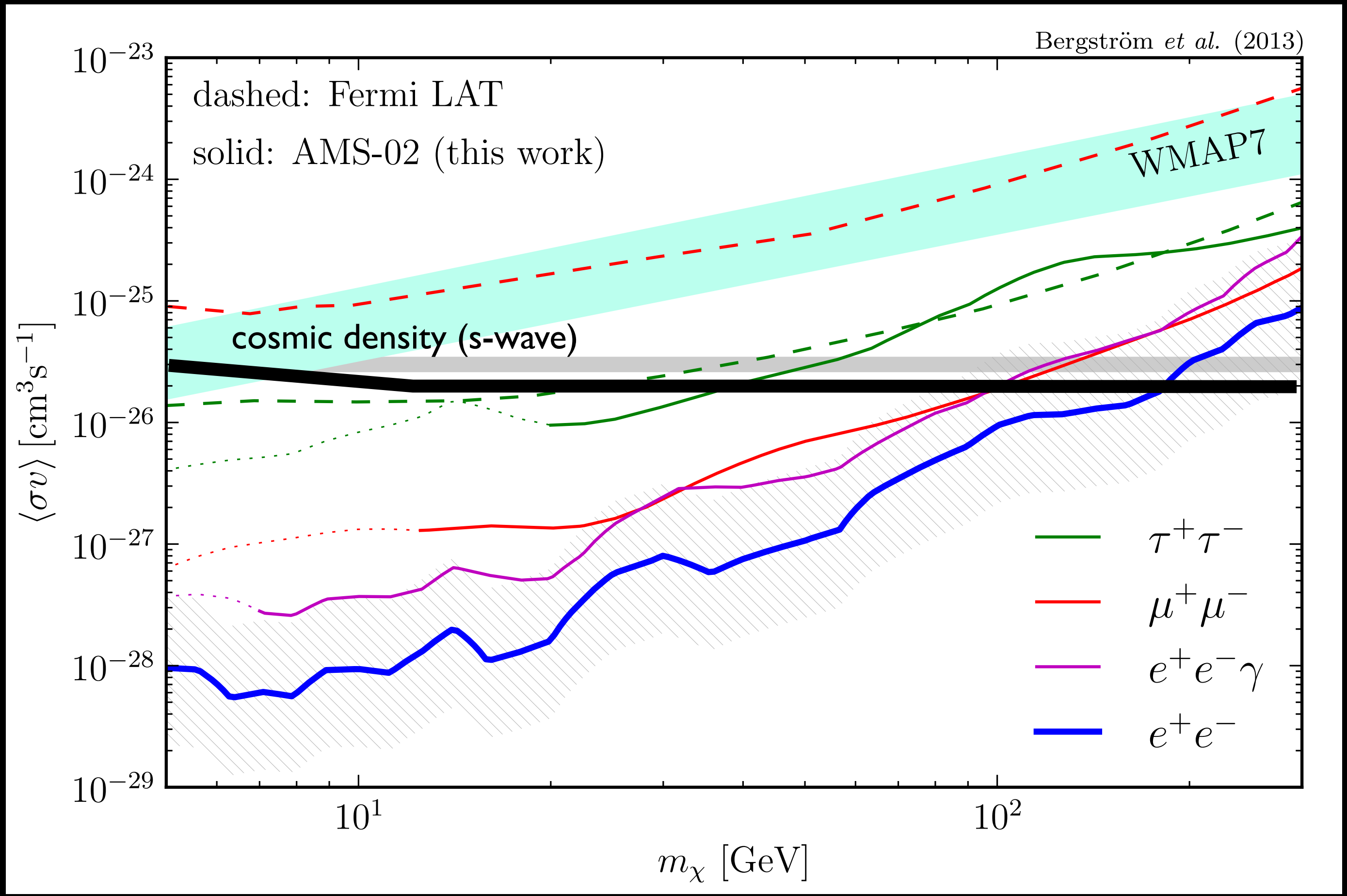
Bergstrom, Edsjo, Zaharijas 2009



Blasi 2009

Excess in cosmic ray positrons

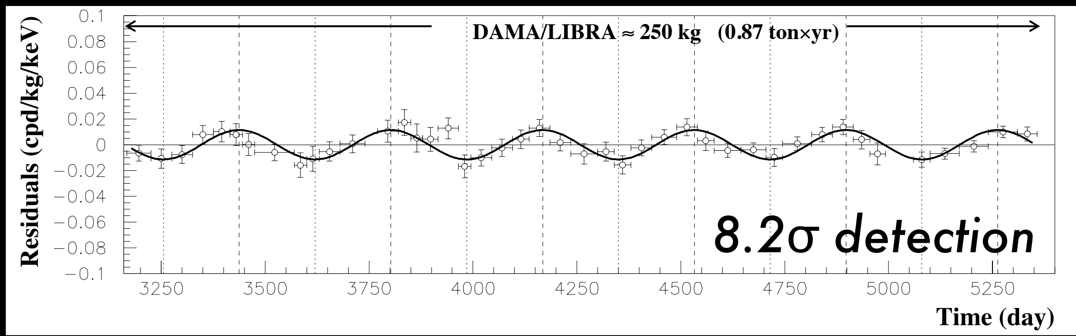
The safe way: use the AMS spectrum purely as upper limit on positrons from WIMP dark matter.

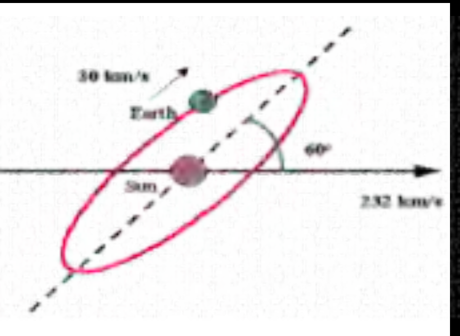


Bergstrom et al 2013

Direct detection

Evidence for light dark matter particles?

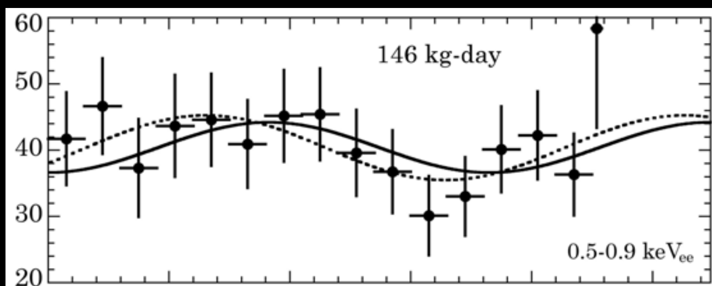




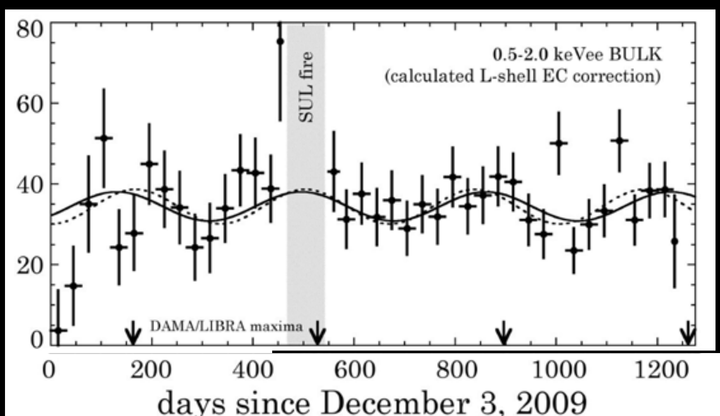
Drukier, Freese, Spergel 1986

Bernabei et al (DAMA) 1997-10

Annually modulated.....



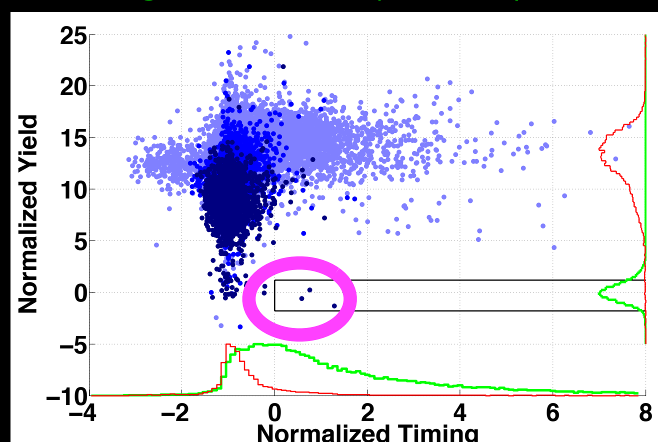
Aalseth et al (CoGeNT) 1106.0650

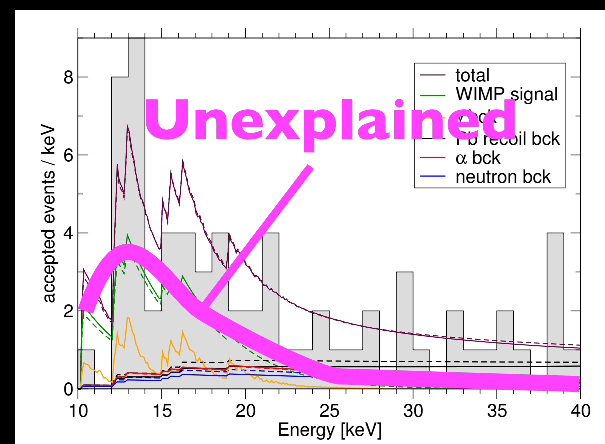


Collar (CoGeNT) 2013

......and unmodulated

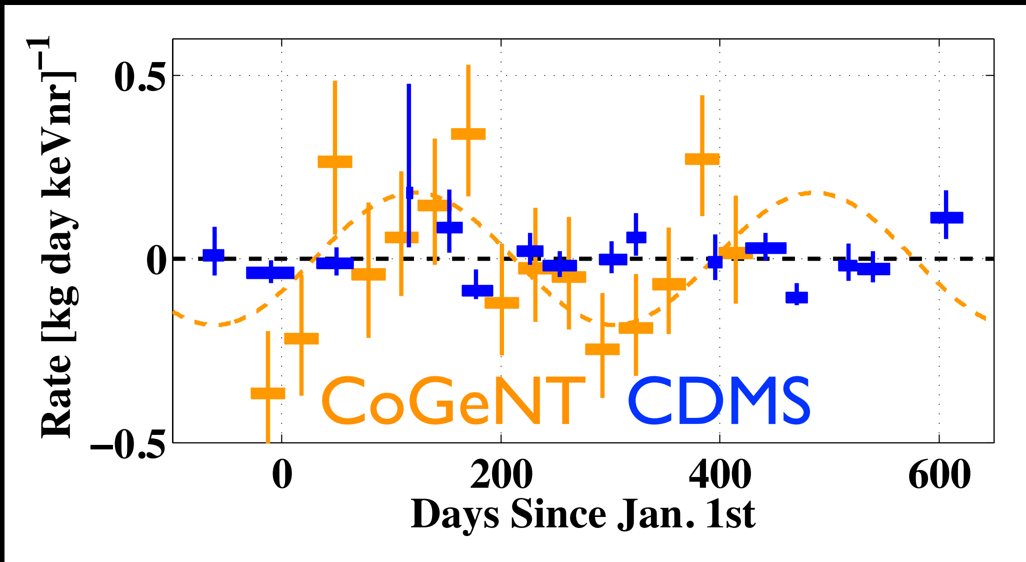
Agnese et al (CDMS) 2013





Anglehor et al (CRESST) 2011

Evidence for light dark matter particles?



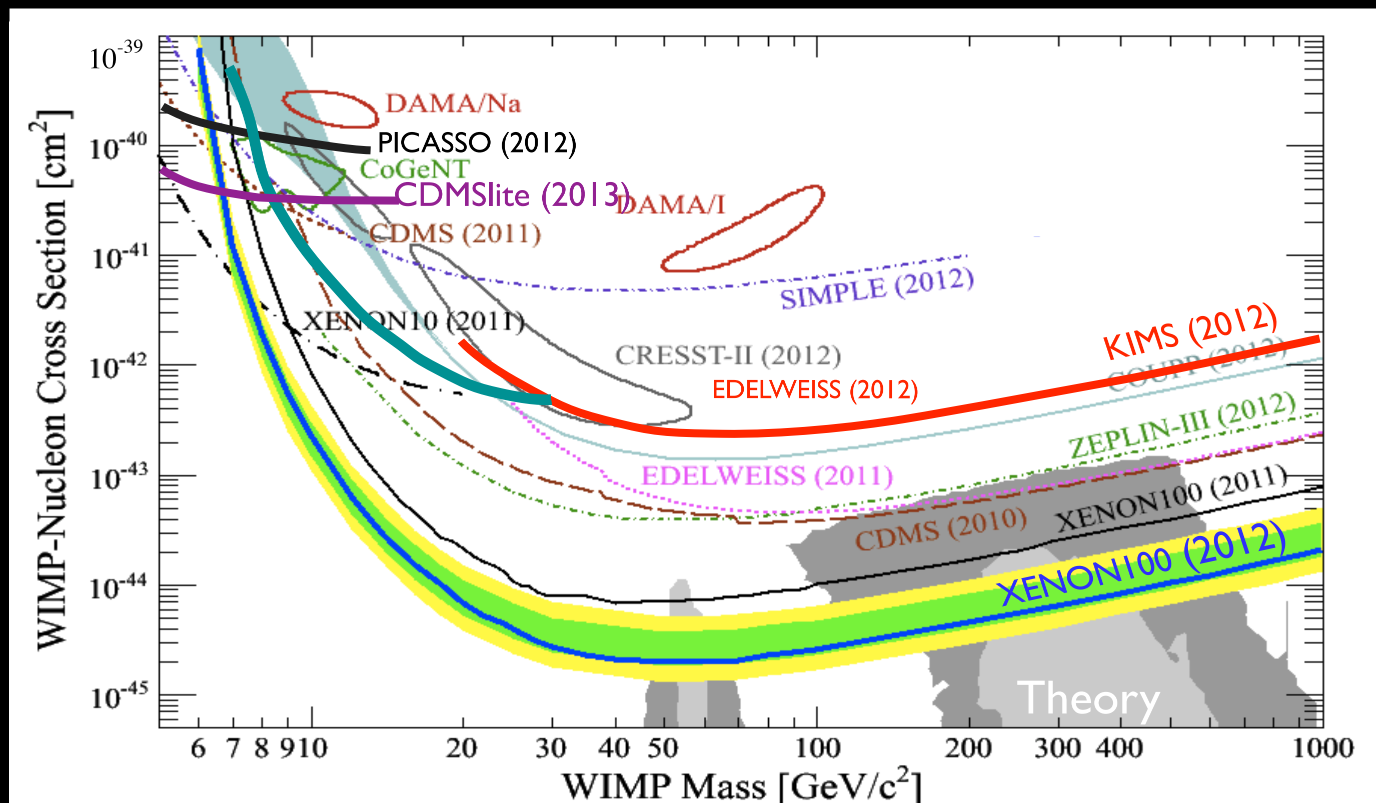
No significant modulation

Same target material

Ahmed et al (CDMS) 1203.1309

Not enough events

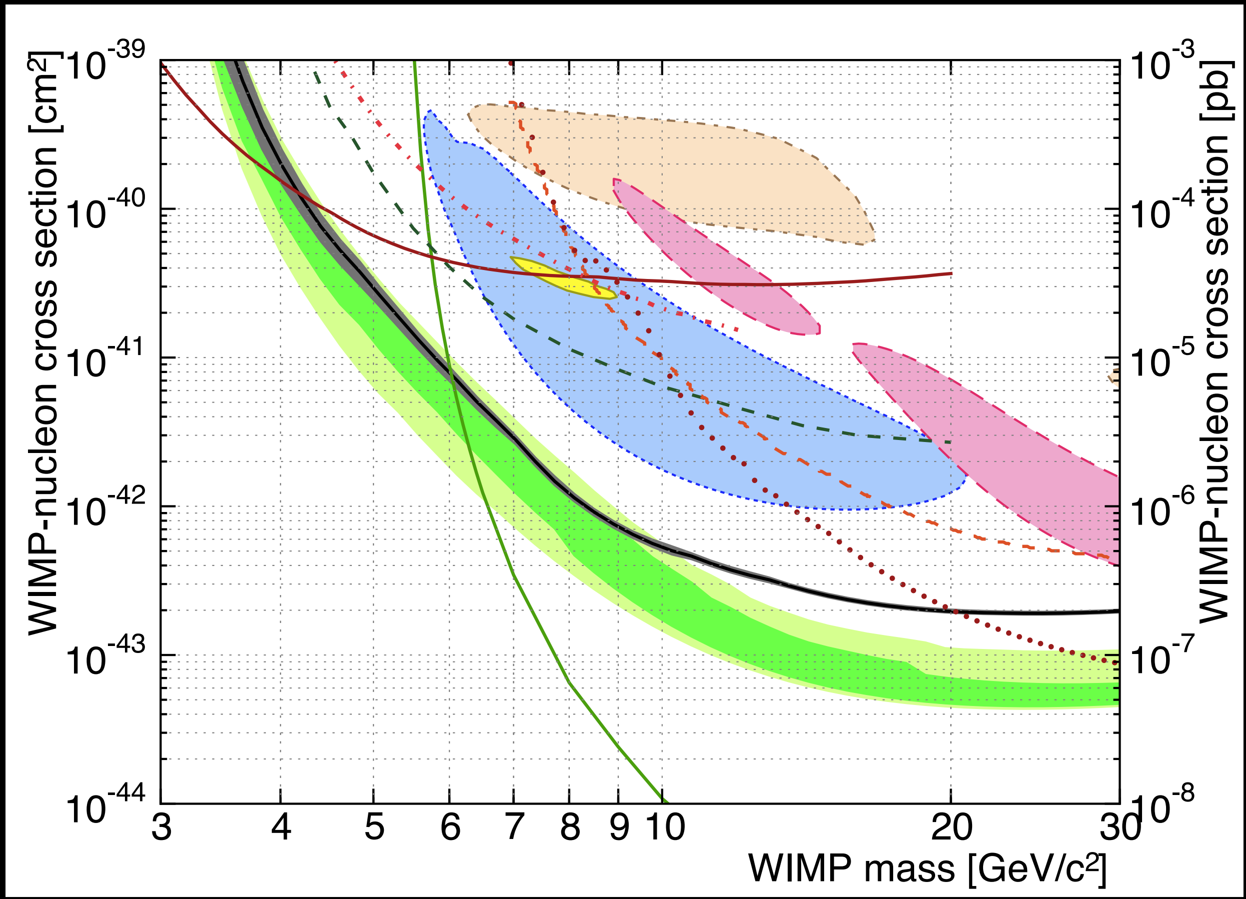
Aprile et al (XENON100) 2012
Agnese et al (CDMSlite) 2013



DM-nucleus elastic scattering

$$\begin{pmatrix}\text{event}\\\text{rate}\end{pmatrix} = \begin{pmatrix}\text{detector}\\\text{response}\end{pmatrix} \times \begin{pmatrix}\text{particle}\\\text{physics}\end{pmatrix} \times \left(\text{astrophysics}\right)$$

FIXED FIXED



Agnese et al (SuperCDMS) 2014

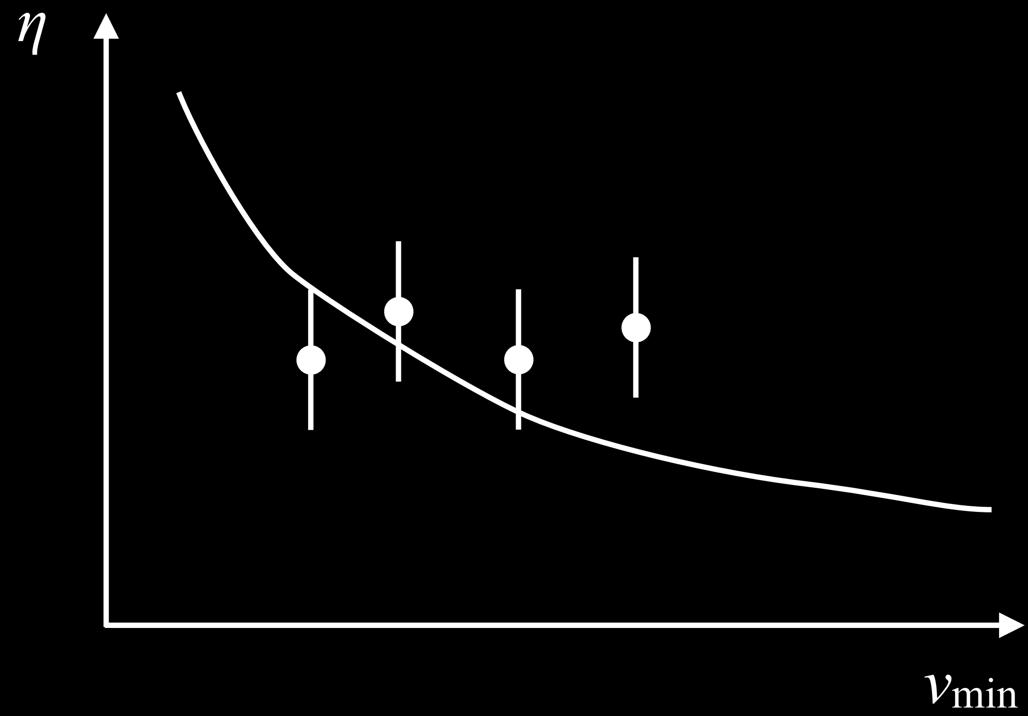
Astrophysics-independent approach

$$\begin{pmatrix}\text{event}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} \times \begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} \times (\text{astrophysics})$$

FIXED

ARBITRARY

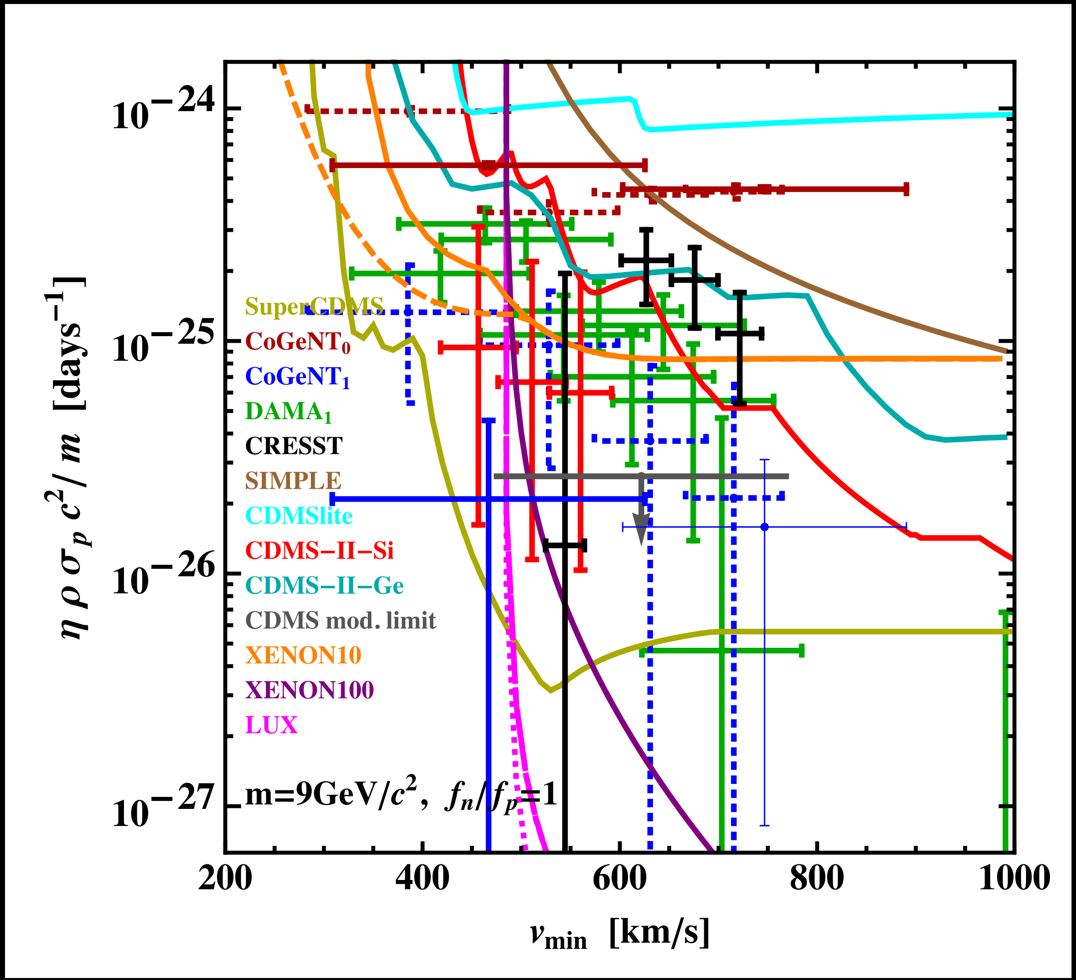
$$\eta(v_{\min}) = \int_{v_{\min}}^{\infty} \frac{f(\mathbf{v})}{v}\, d^3v$$



Fox, Liu, Wiener 2011; Gondolo, Gelmini 2012; Del Nobile, Gelmini, Gondolo, Huh 2013-14

Astrophysics-independent approach

Spin-independent interactions $\sigma_{\chi A} = A^2 \sigma_{\chi \mathrm{p}} \mu_{\chi A}^2 / \mu_{\chi \mathrm{p}}^2$



Del Nobile, Gelmini, Gondolo, Huh 2013-14

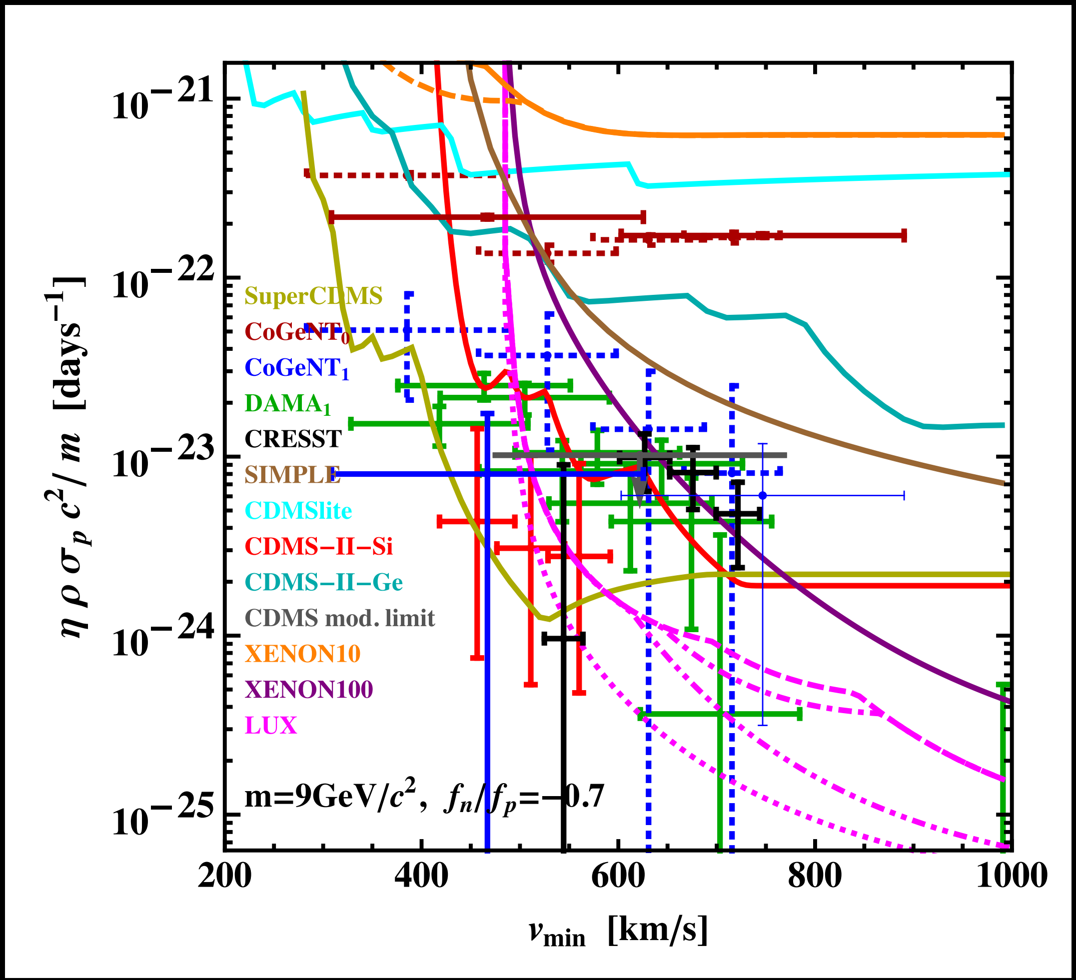
Halo modifications alone cannot save the SI signal regions from the bounds

CDMS-Si event rate is similar to annually modulated rates

Still depends on particle model

Astrophysics-independent approach

Isospin-violating dark matter



Del Nobile, Gelmini, Gondolo, Huh 2013-14

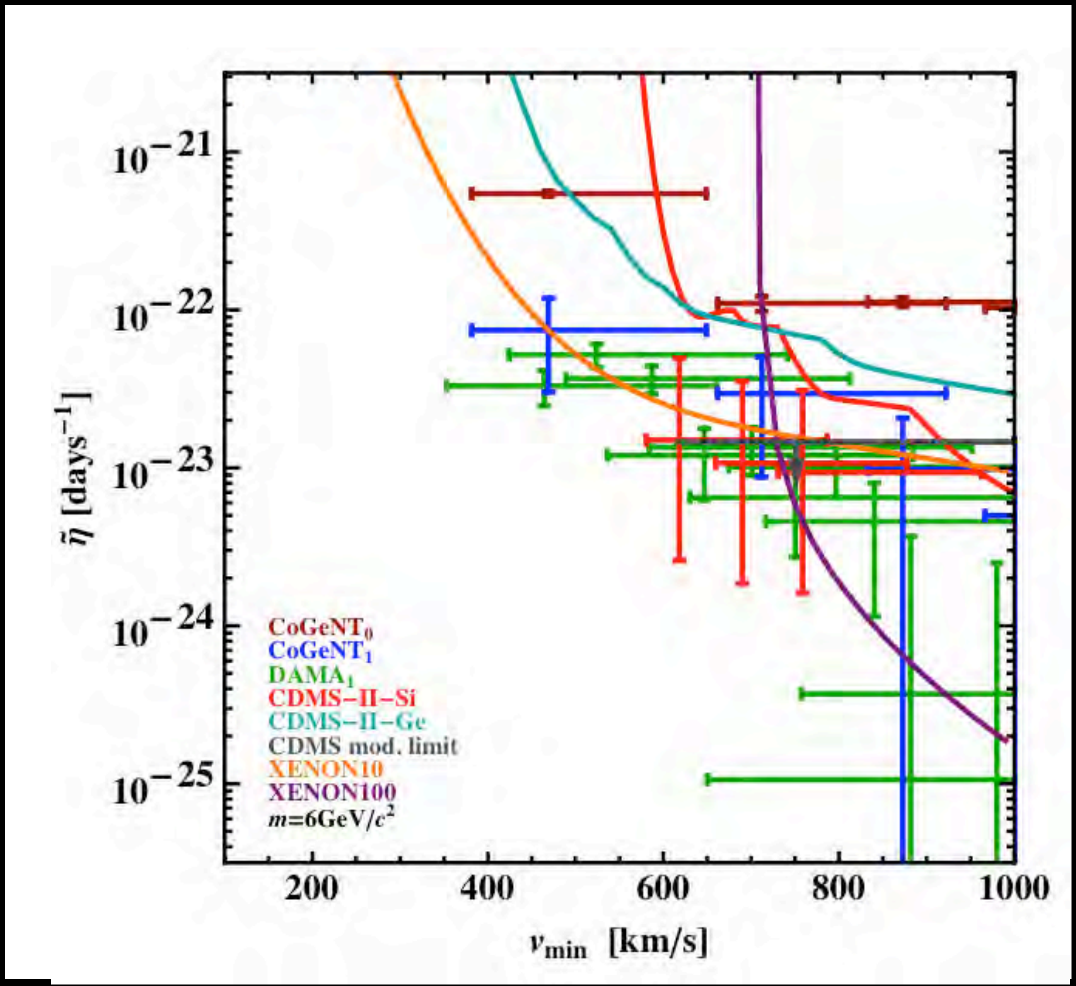
Dark matter coupled differently to protons and neutrons may have a (tiny) chance

Notice that the CDMS-Si events lie "below" the CoGeNT/DAMA modulation amplitudes

Still depends on particle model

Astrophysics-independent approach

Anomalous magnetic moment dark matter



Del Nobile, Gelmini, Gondolo, Huh 2013-14

Halo modifications alone cannot save the MDM signal regions from the Xe bounds

CDMS-Si event rate is similar to annually modulated rates

Still depends on particle model

Conclusions

Conclusions

- The astrophysical evidence for cold dark matter is overwhelming. From dwarf galaxies to spirals and ellipticals, to clusters of galaxies and the overall geometry of the universe.

- The evidence for particle dark matter is yet unsatisfactory. Indirect signals in X-rays, γ-rays, and positrons are arguable. Signals and bounds in direct detection are in apparent contradiction.

- More work is necessary to figure out the nature of cold dark matter.