Theory and Phenomenology of Dark Matter

Paolo Gondolo

University of Utah

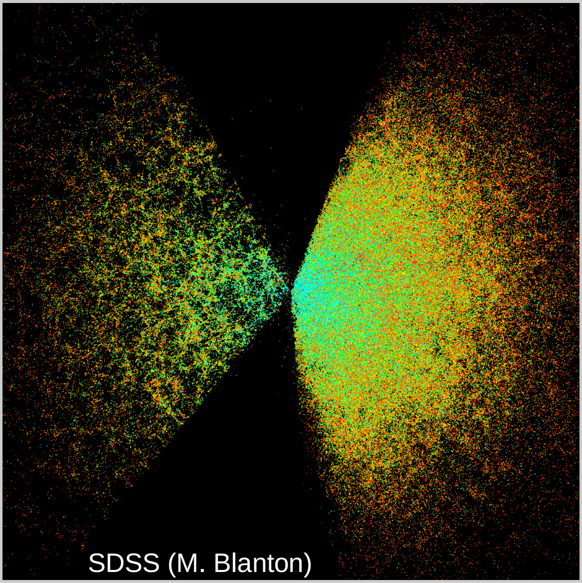
Overview

- Cosmological evidence for dark matter
- Particle candidates for dark matter
- Searches for particle dark matter

Cosmological evidence
for
dark matter

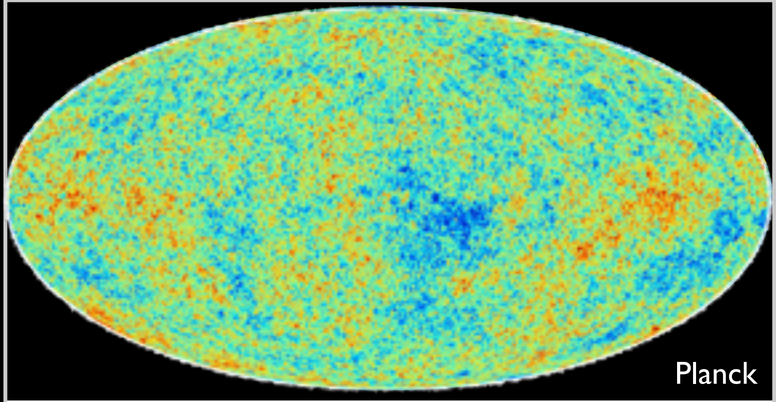
Evidence for cold dark matter

Large Scale Structure



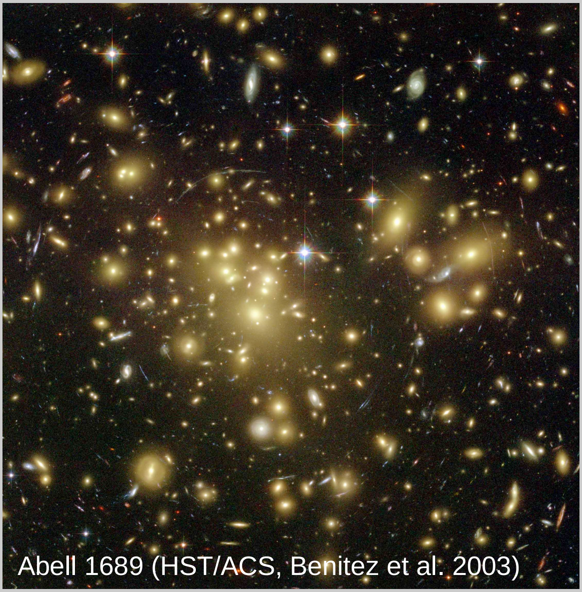
SDSS (M. Blanton)

Cosmic Microwave Background



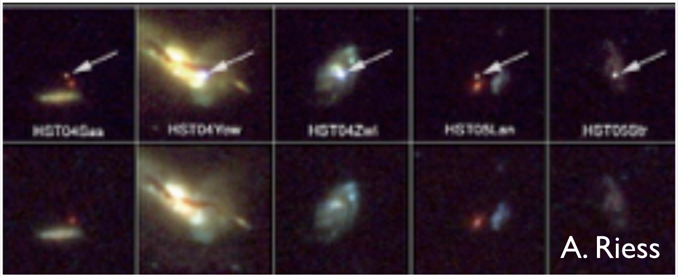
Planck

Galaxy Clusters

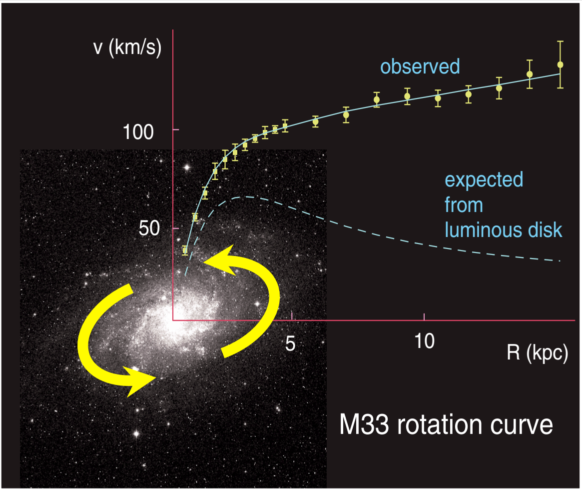


Abell 1689 (HST/ACS, Benitez et al. 2003)

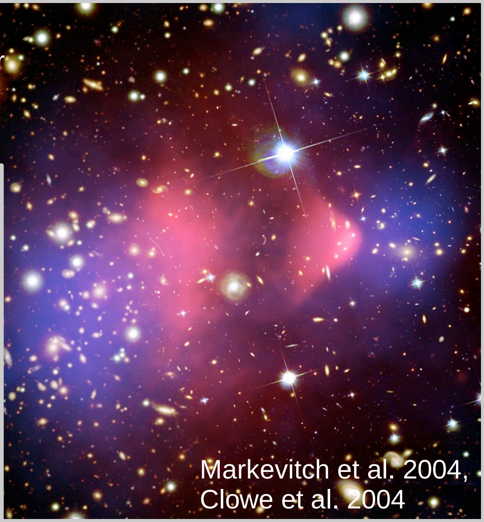
Supernovae



A. Riess



M33 rotation curve



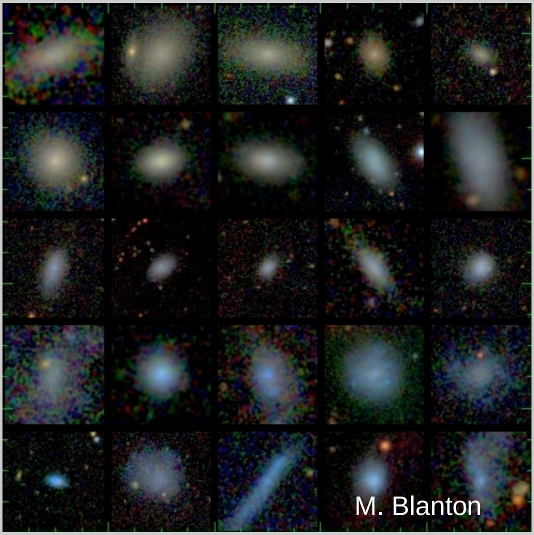
Bullet Cluster

Markevitch et al. 2004,
Clowe et al. 2004

Galaxies

M101 (HST, Kuntz et al. 2006)

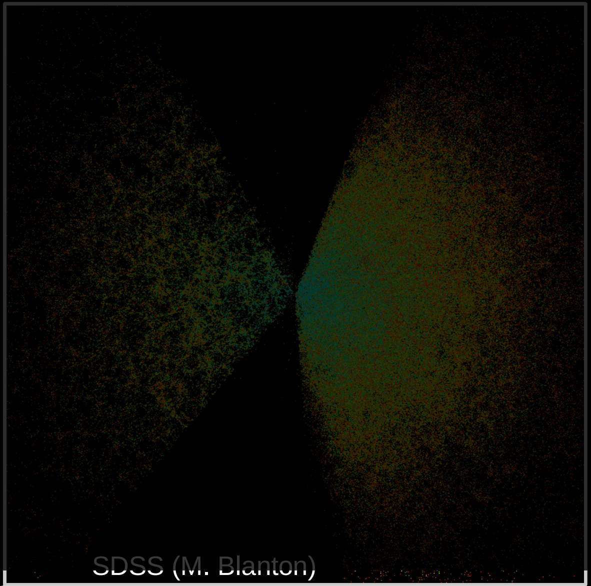
Dwarf Galaxies



M. Blanton

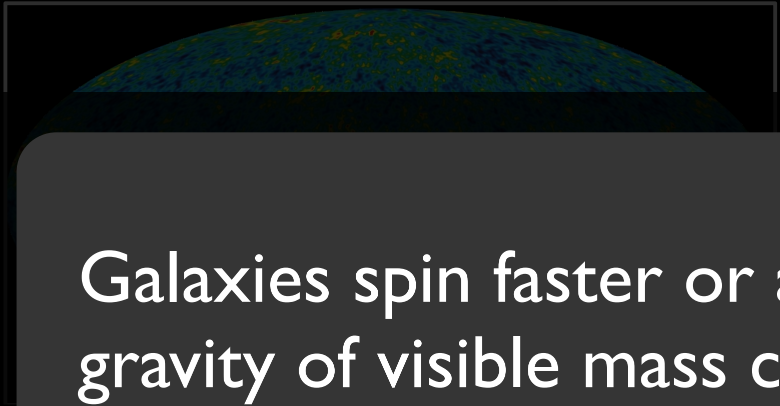
Evidence for cold dark matter

Large Scale Structure

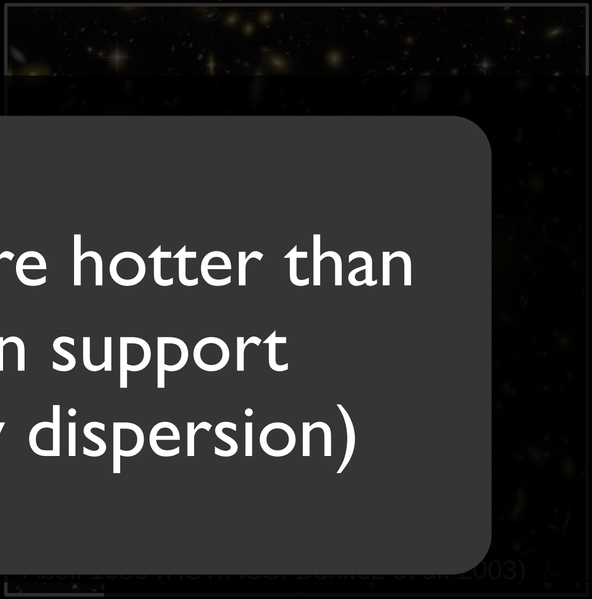


SDSS (M. Blanton)

Cosmic Microwave Background



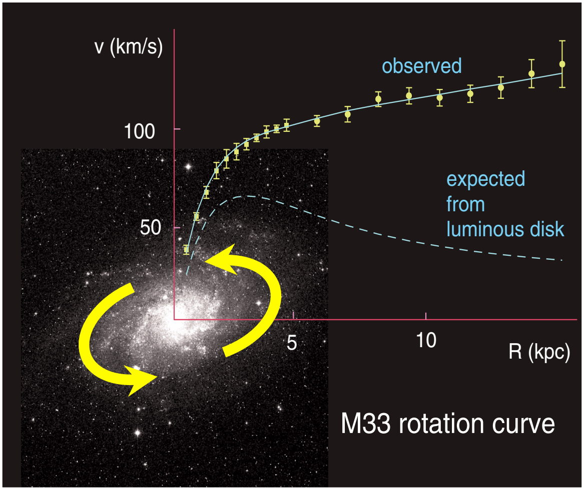
Galaxy Clusters



Abell 1689 (HST/ACS; Benítez et al. 2003)

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

A. Riess

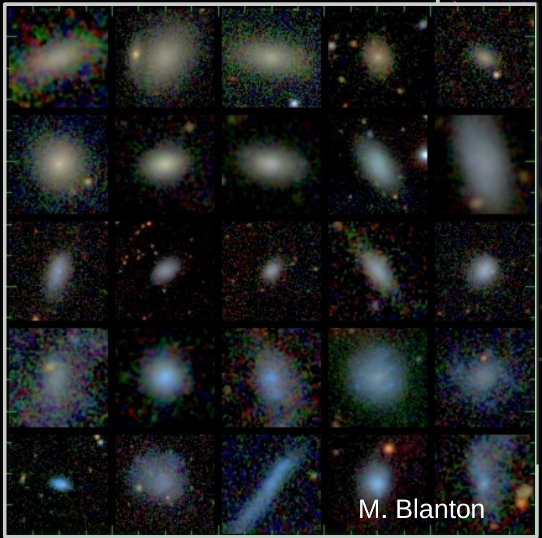


M33 rotation curve

Galaxies

M101 (HST; Kuntz et al. 2006)

Dwarf Galaxies



M. Blanton

Bullet Cluster

Markevitch et al. 2004,
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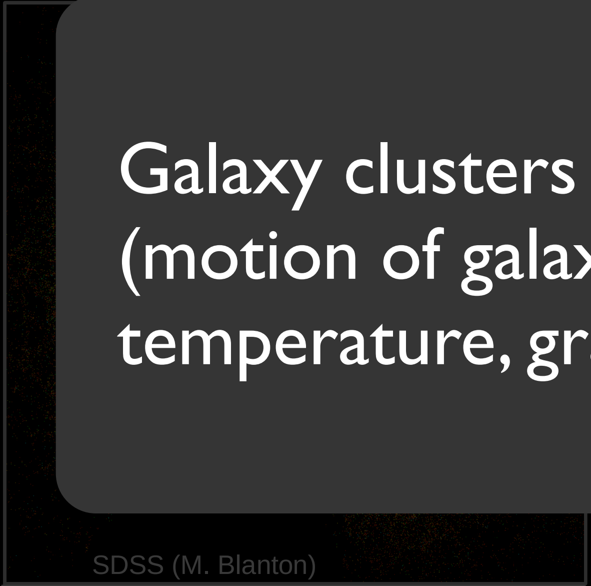
Evidence for cold dark matter

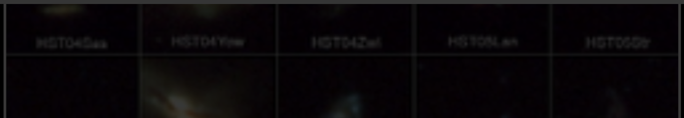
Large Scale Structure



SDSS (M. Blanton)

Cosmic Microwave Background

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



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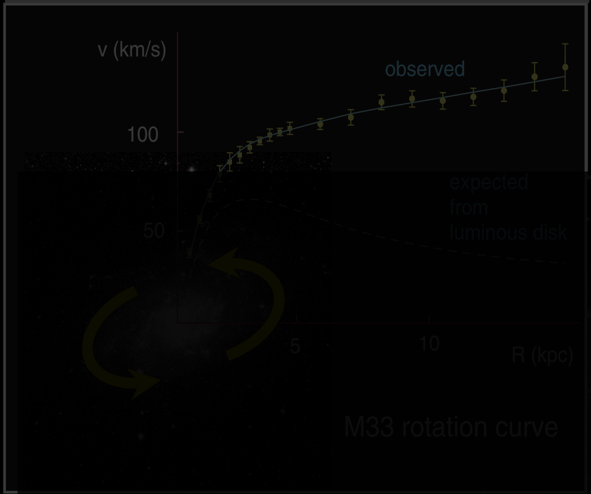
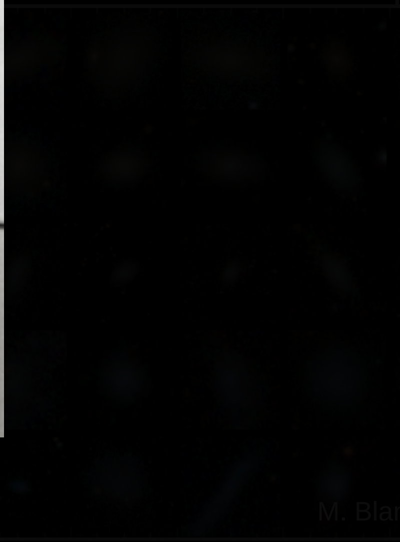


M33 rotation curve

Fritz Zwicky

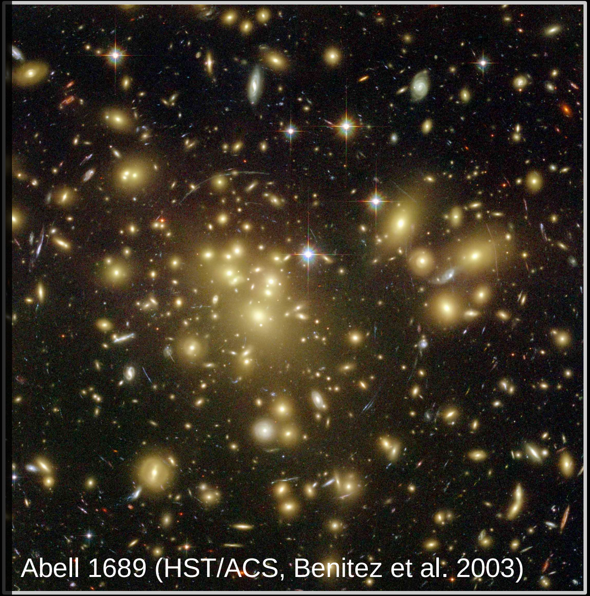
M101 (HST, Kuntz et al. 2006)

Dwarf Galaxies



M. Blanton

Galaxy Clusters



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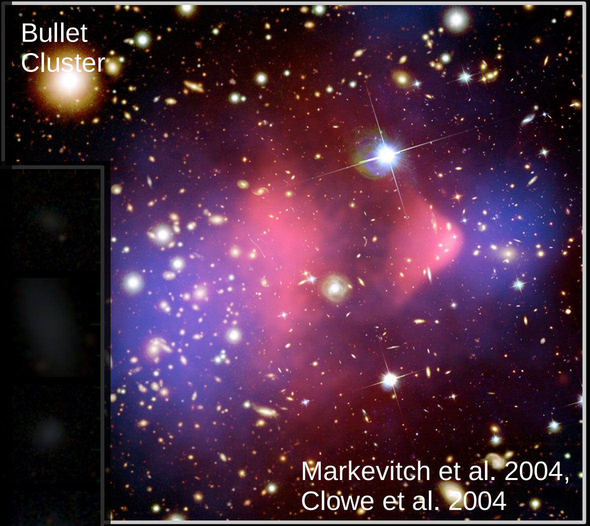
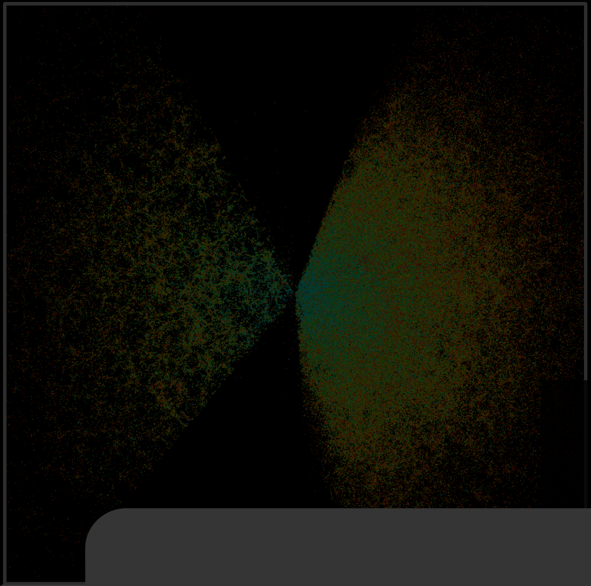


Bullet Cluster

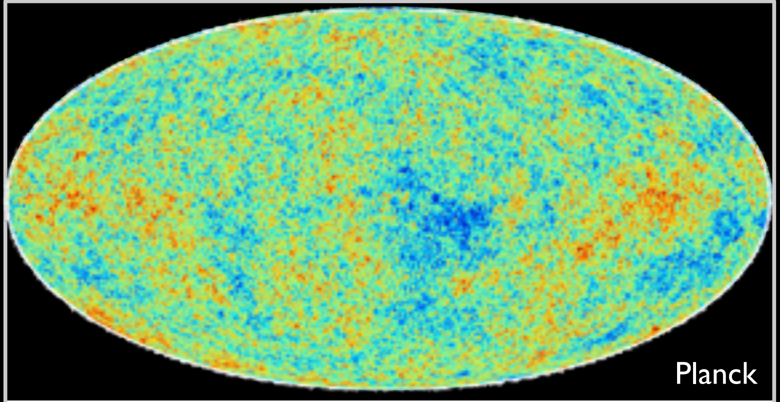
Markevitch et al. 2004, Clowe et al. 2004

Evidence for cold dark matter

Large Scale Structure

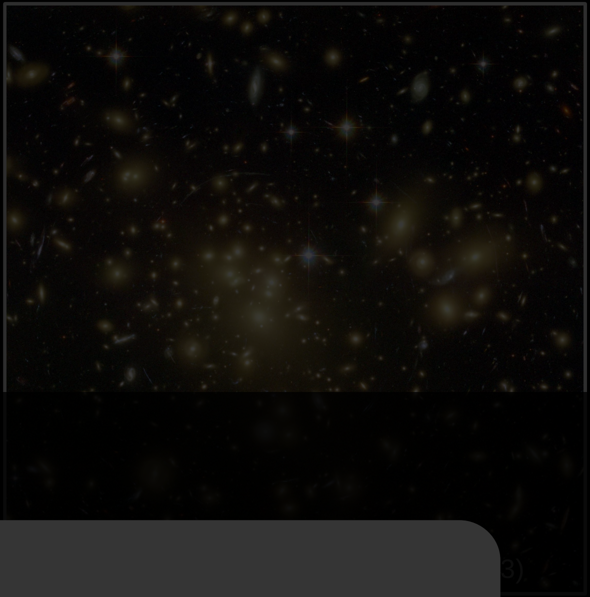


Cosmic Microwave Background

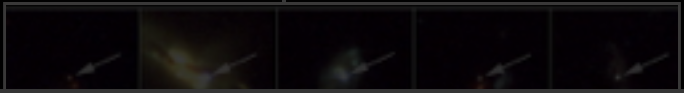


Planck

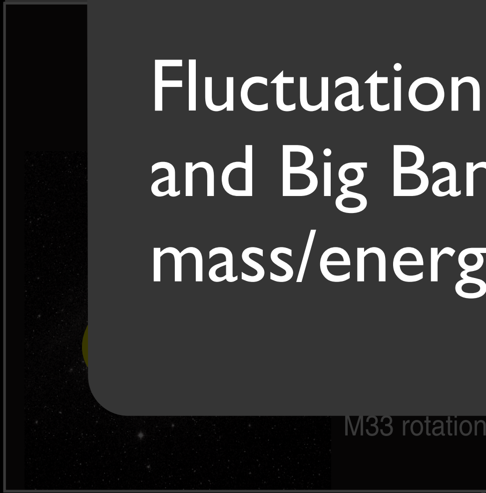
Galaxy Clusters



Supernovae



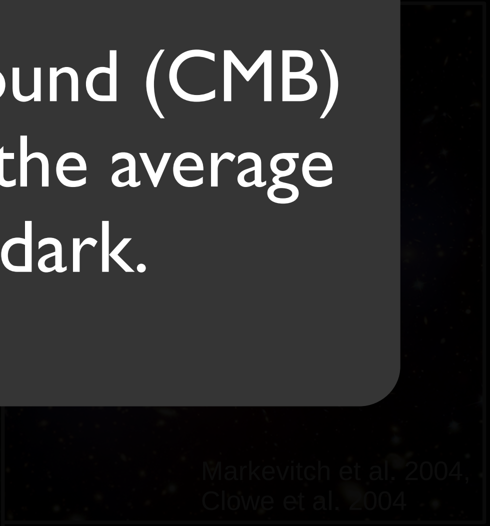
Fluctuations in the Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN) find that the average mass/energy content of the universe is mostly dark.



M33 rotation curve

M101 (HST; Kuntz et al. 2006)

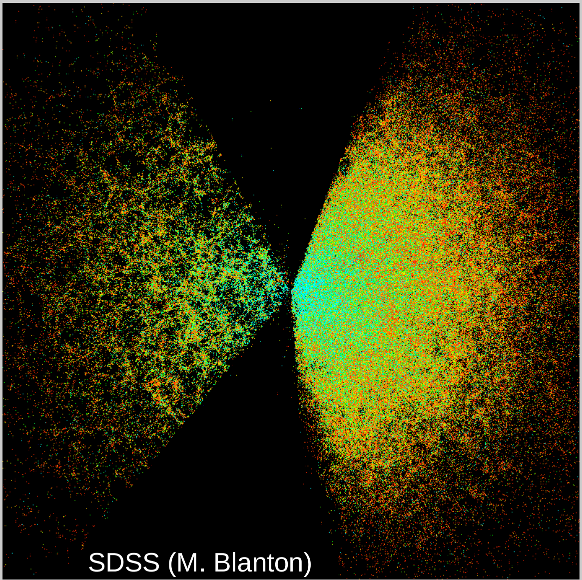
M. Blanton



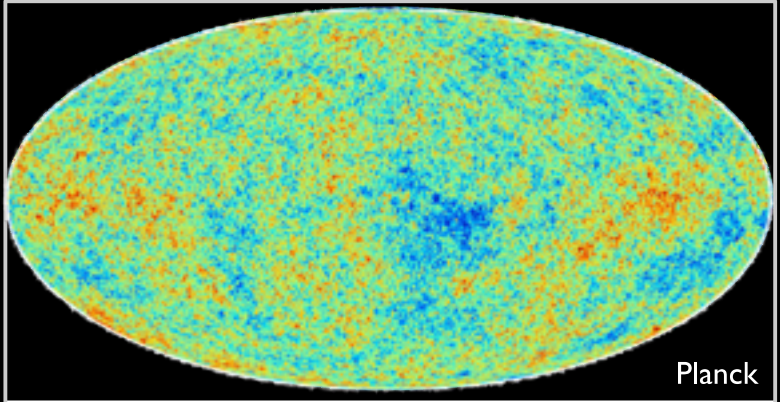
Markevitch et al. 2004,
Clowe et al. 2004

Evidence for cold dark matter

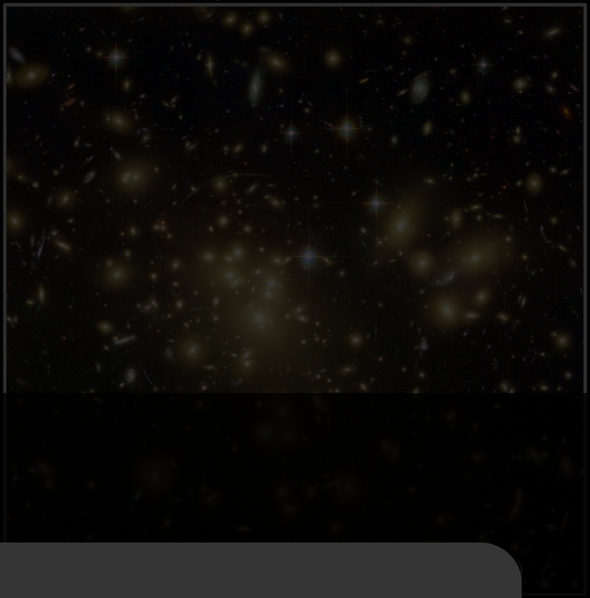
Large Scale Structure


SDSS (M. Blanton)

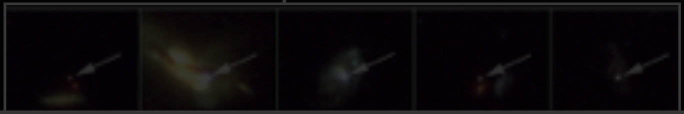
Cosmic Microwave Background

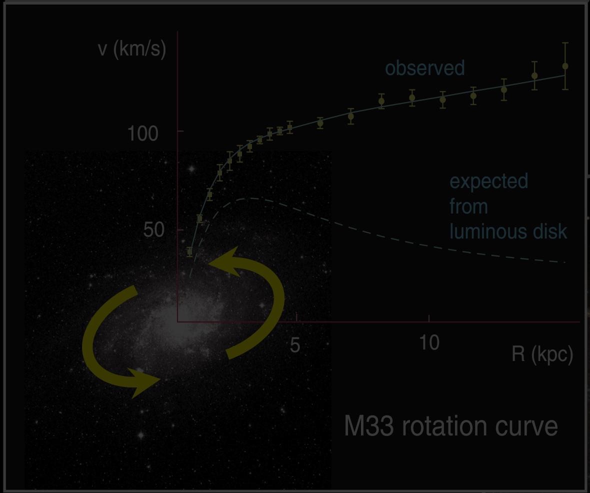

Planck

Galaxy Clusters



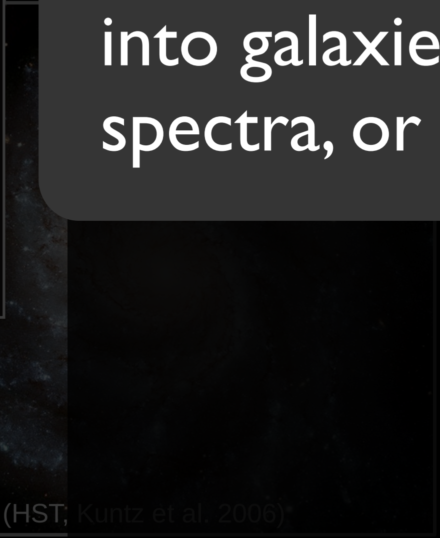
Supernovae

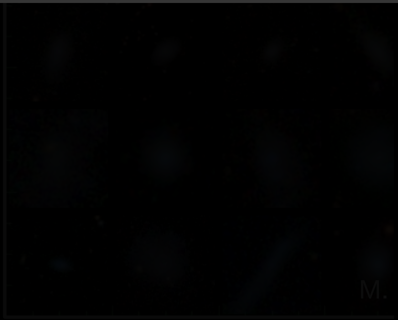




M33 rotation curve

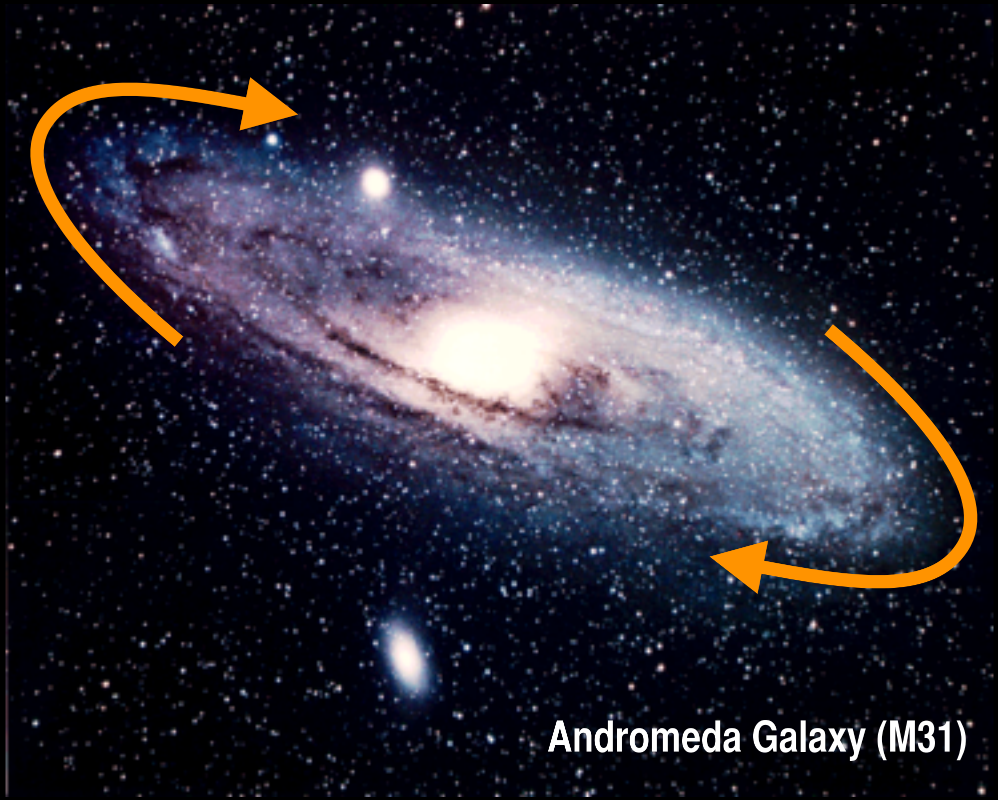
An invisible mass makes the Cosmic Microwave Background fluctuations grow into galaxies (CMB and matter power spectra, or correlation functions)


M101 (HST; Kuntz et al. 2006)


M.

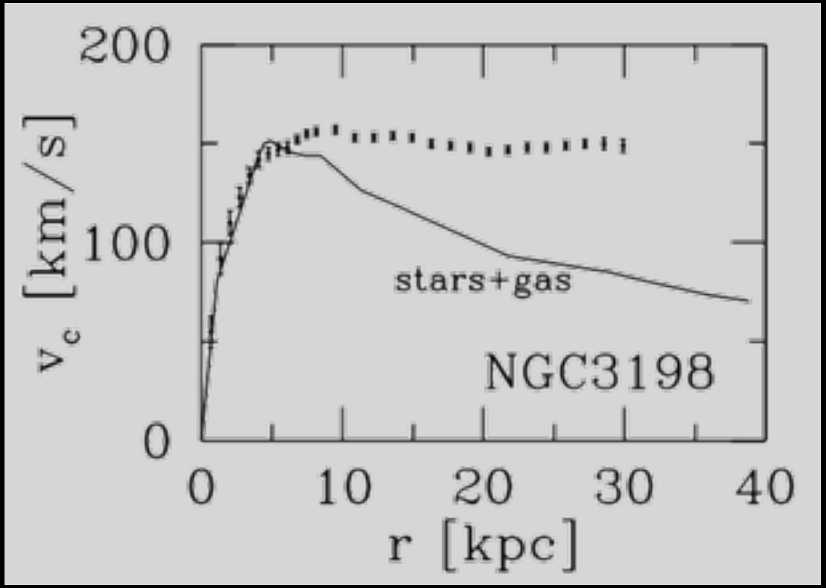
Galaxies

Galaxies



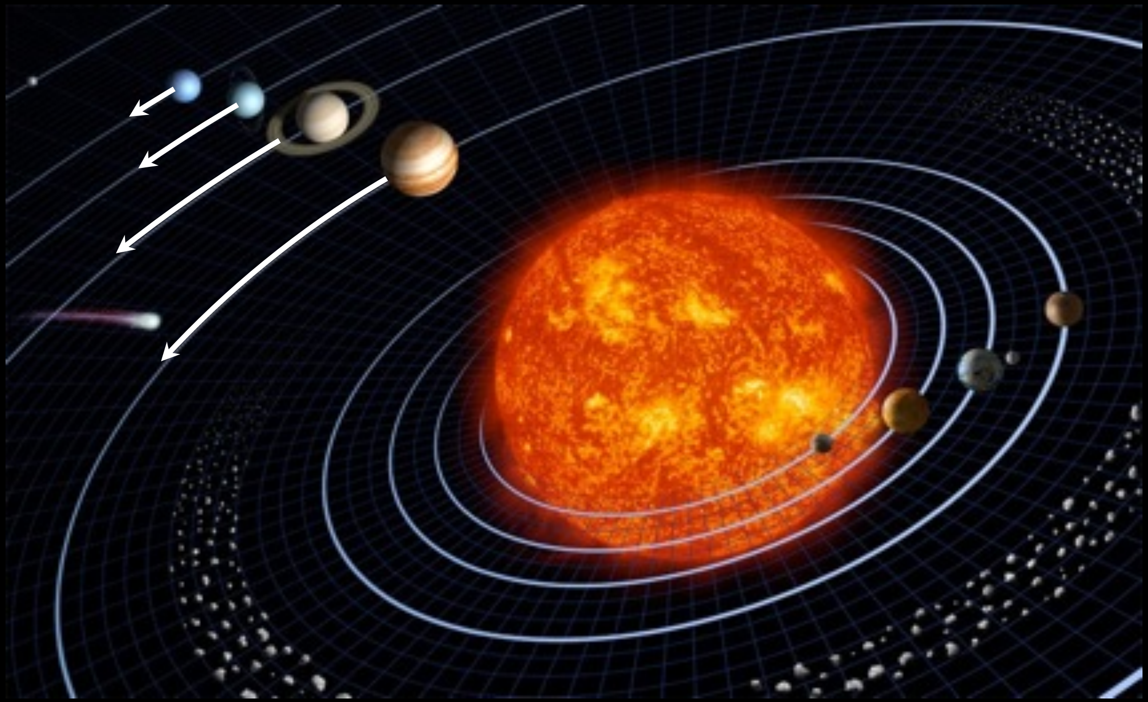
Andromeda Galaxy (M31)

Vera Rubin



Galaxies

The method: more mass, faster orbits

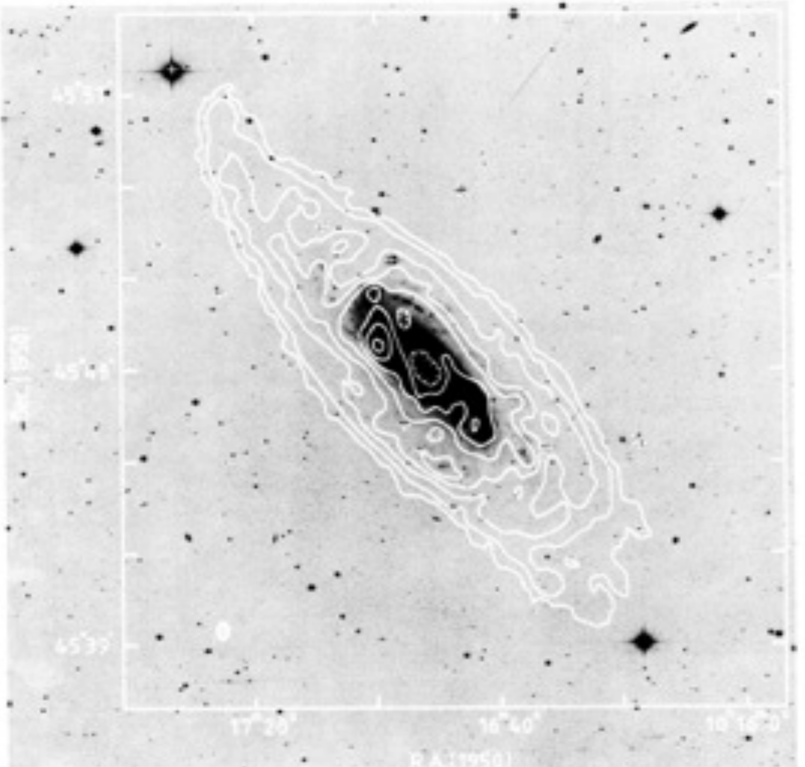


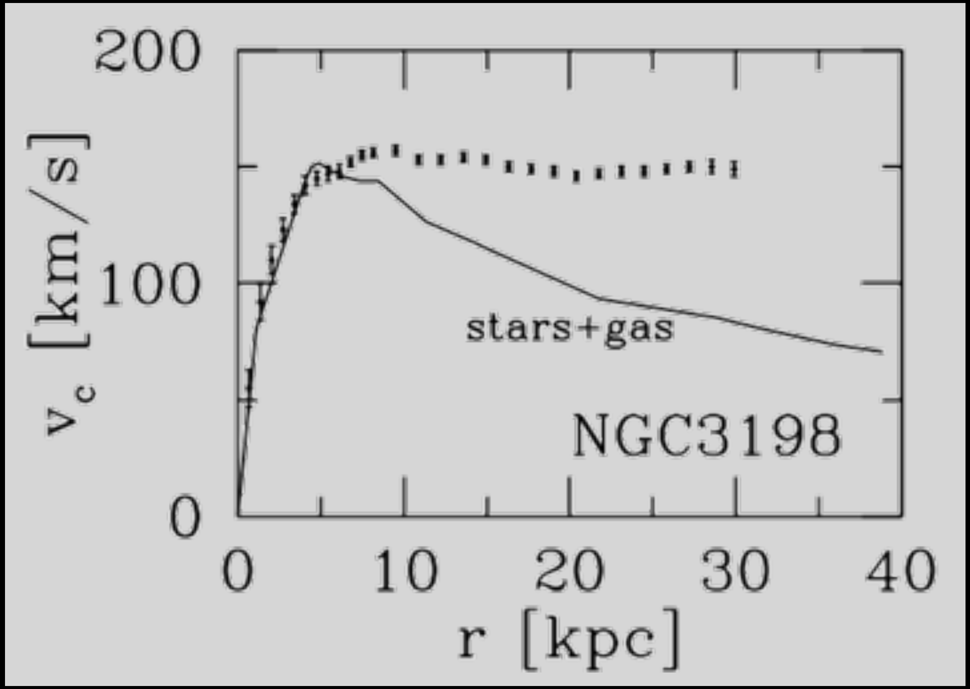
Gravity of sun keeps planets in orbit

$$\frac{GM}{r^2} = \frac{v^2}{r}$$

Galaxies

Galaxies spin faster than gravity of known matter can support





$$M = 1.6 \times 10^{11} M_{\odot} (r/30\,\mathrm{kpc})$$
$$M_{\mathrm{stars+gas}} = 0.4 \times 10^{11} M_{\odot}$$

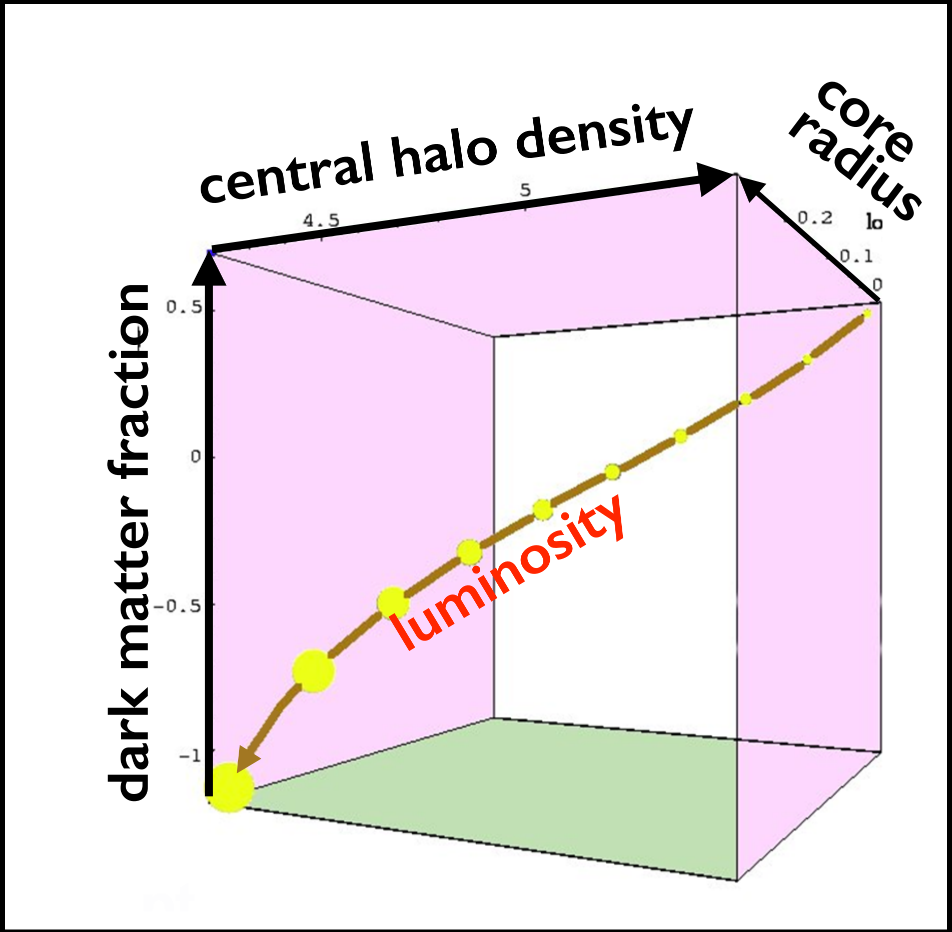
$$\frac{M_{\mathrm{total}}}{M_{\mathrm{visible}}} > 4$$

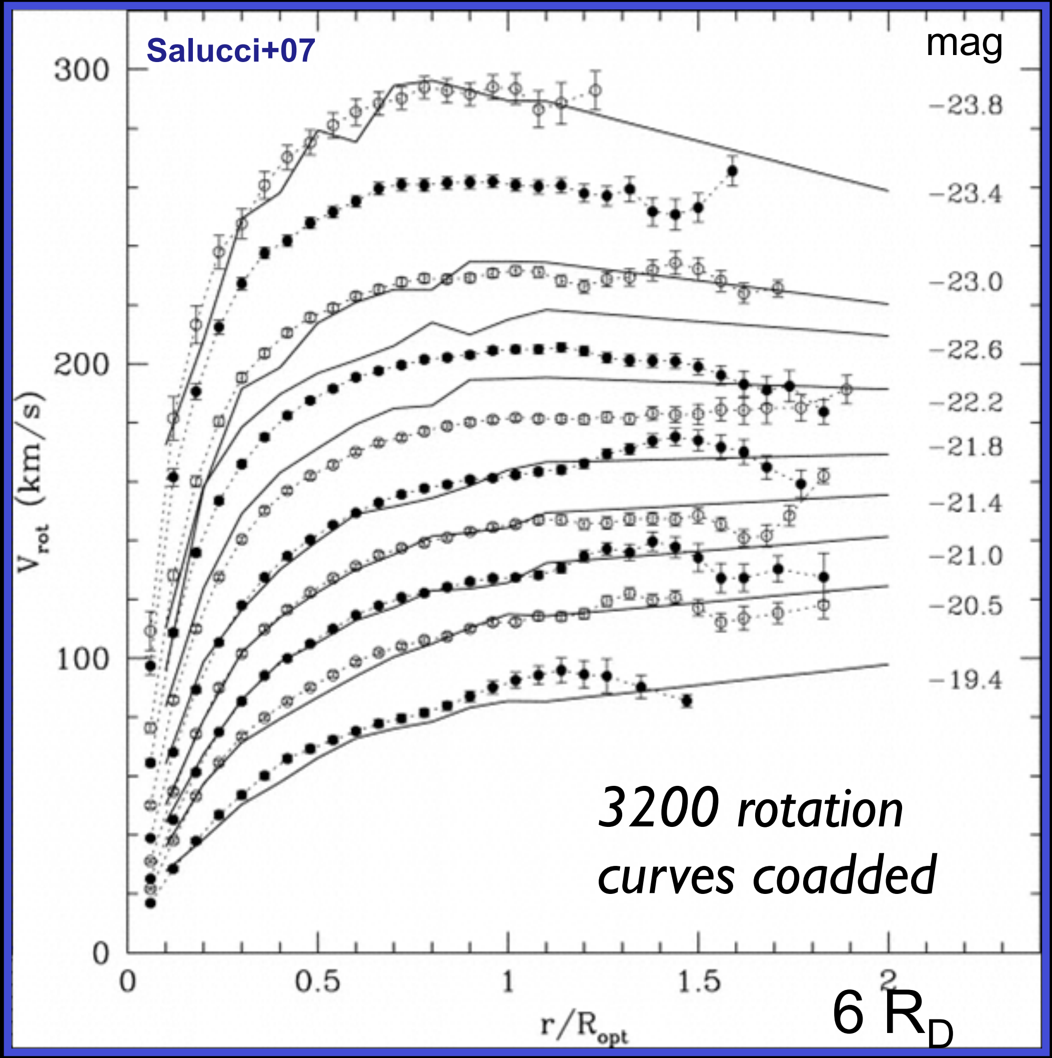
Dark matter

1 pc = 3.08×10^{16} m

Galaxies

Empirical correlations found from thousands of spiral galaxy rotation curves

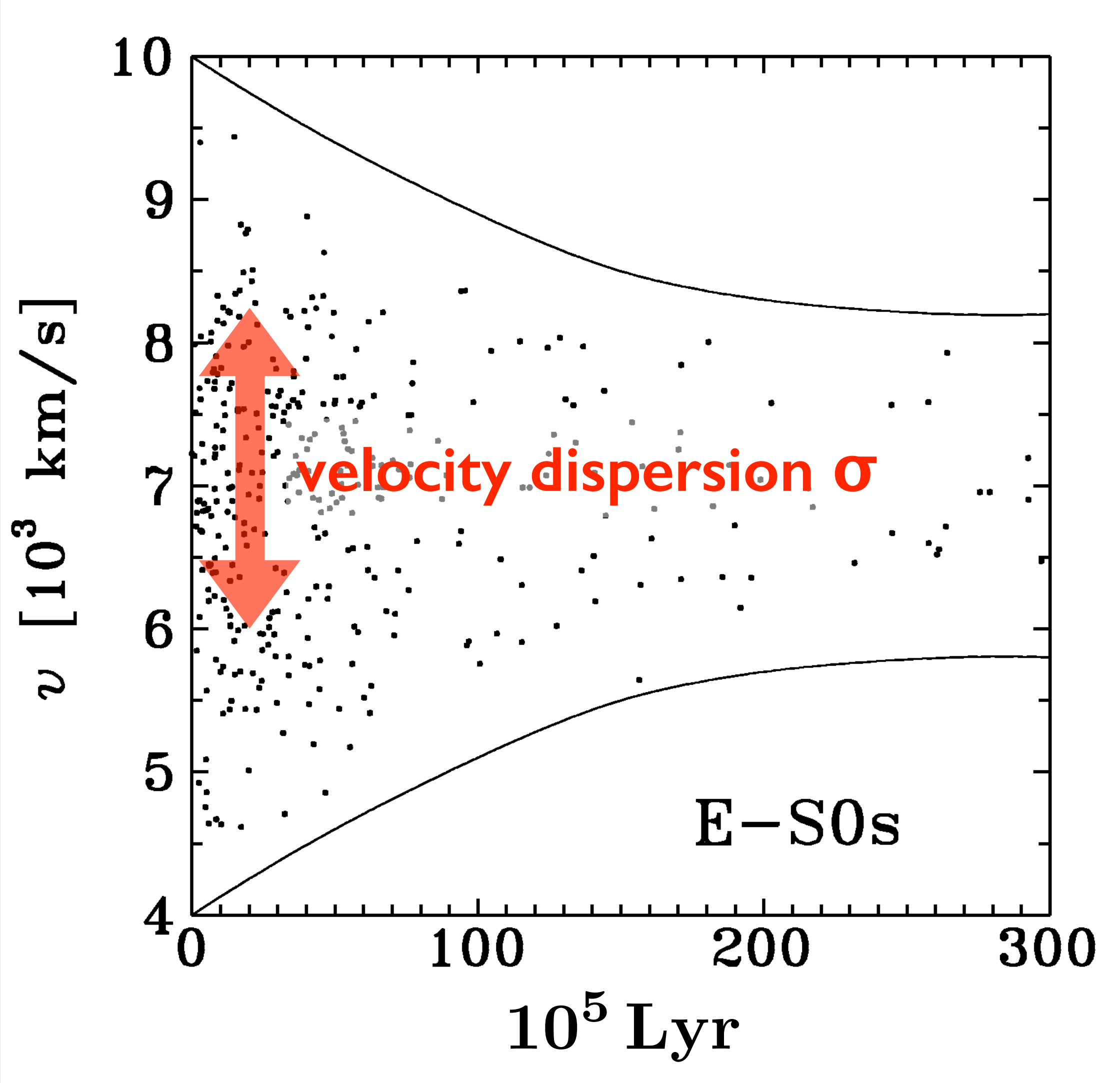




3200 rotation curves coadded

Salucci et al 2007

Galaxies



Lokas, Mamon 2003

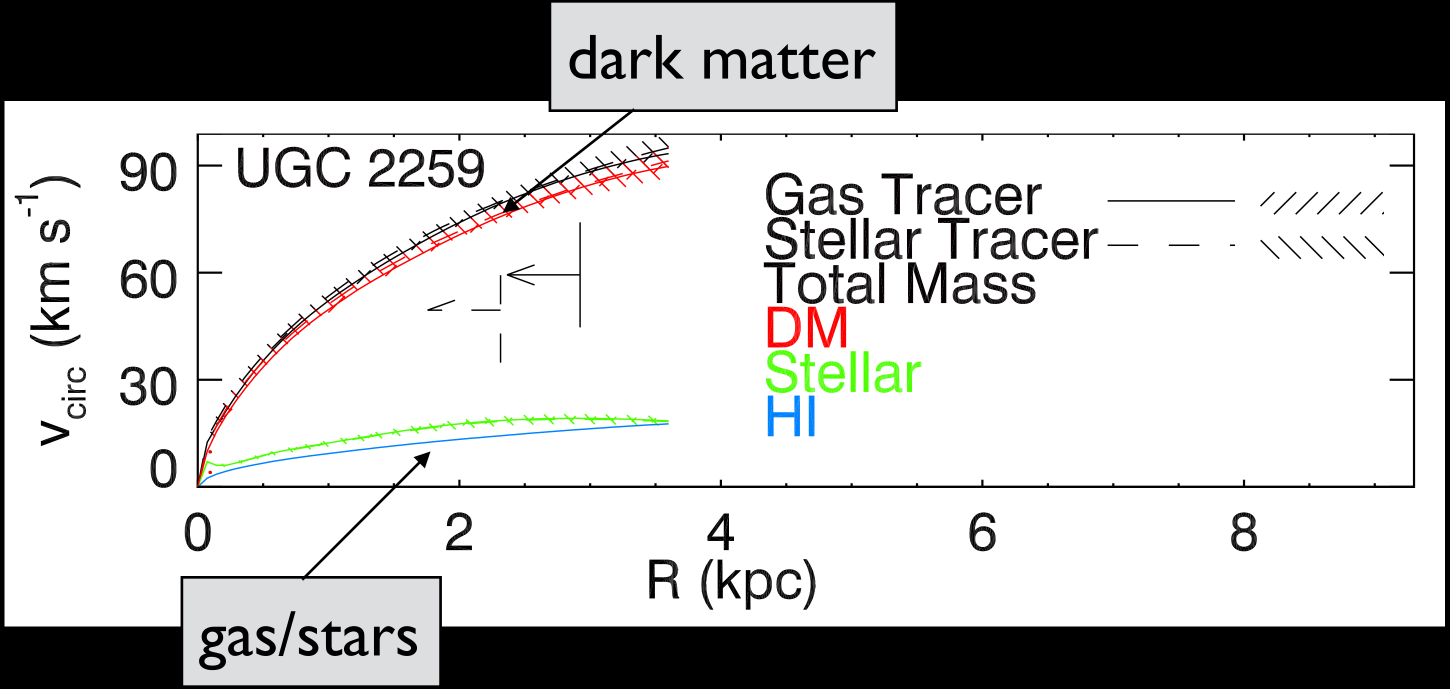
Velocity dispersion measurements reveal dark matter in elliptical galaxies

$$\sigma^2 \propto \frac{GM}{r}$$

$$M_{\rm dyn} \sim 10^{15}\, M_\odot$$

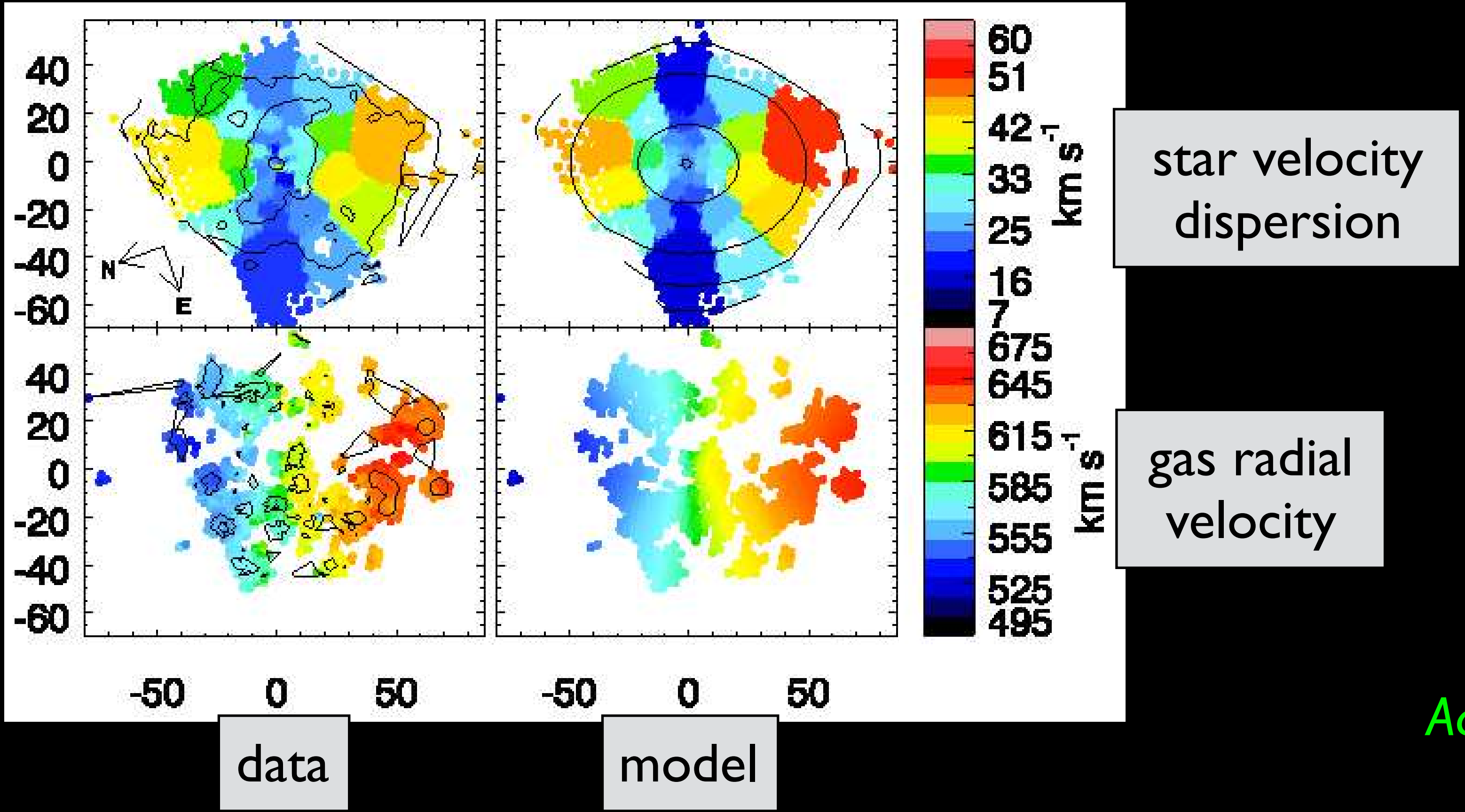
Galaxies

Dwarf galaxies are dominated by dark matter.



dark matter

gas/stars



star velocity dispersion

gas radial velocity

data

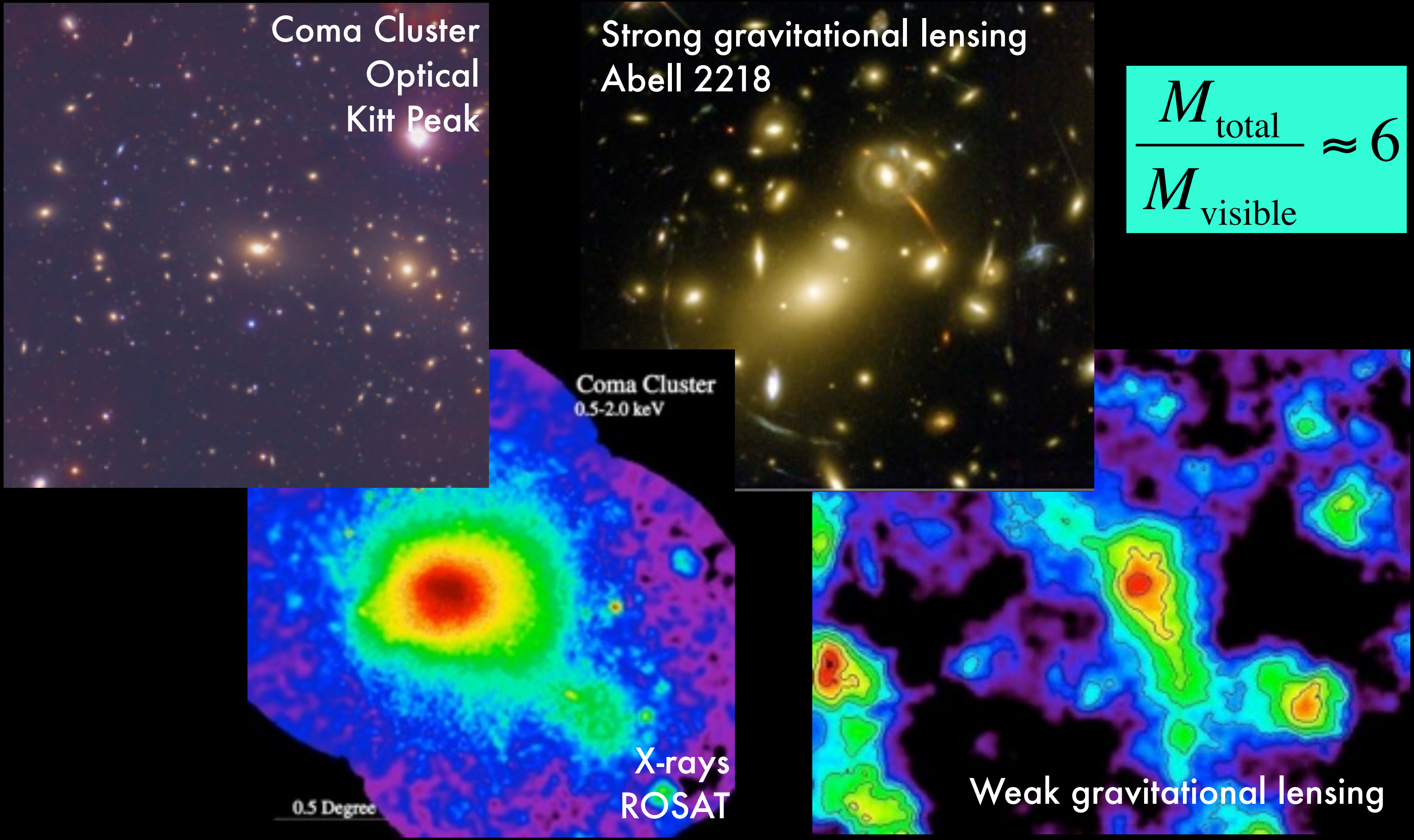
model

Adams et al 2014

Galaxy clusters

Galaxy clusters

Different methods lead to the same conclusion: dark matter



Coma Cluster
Optical
Kitt Peak

Strong gravitational lensing
Abell 2218

Coma Cluster
0.5-2.0 keV

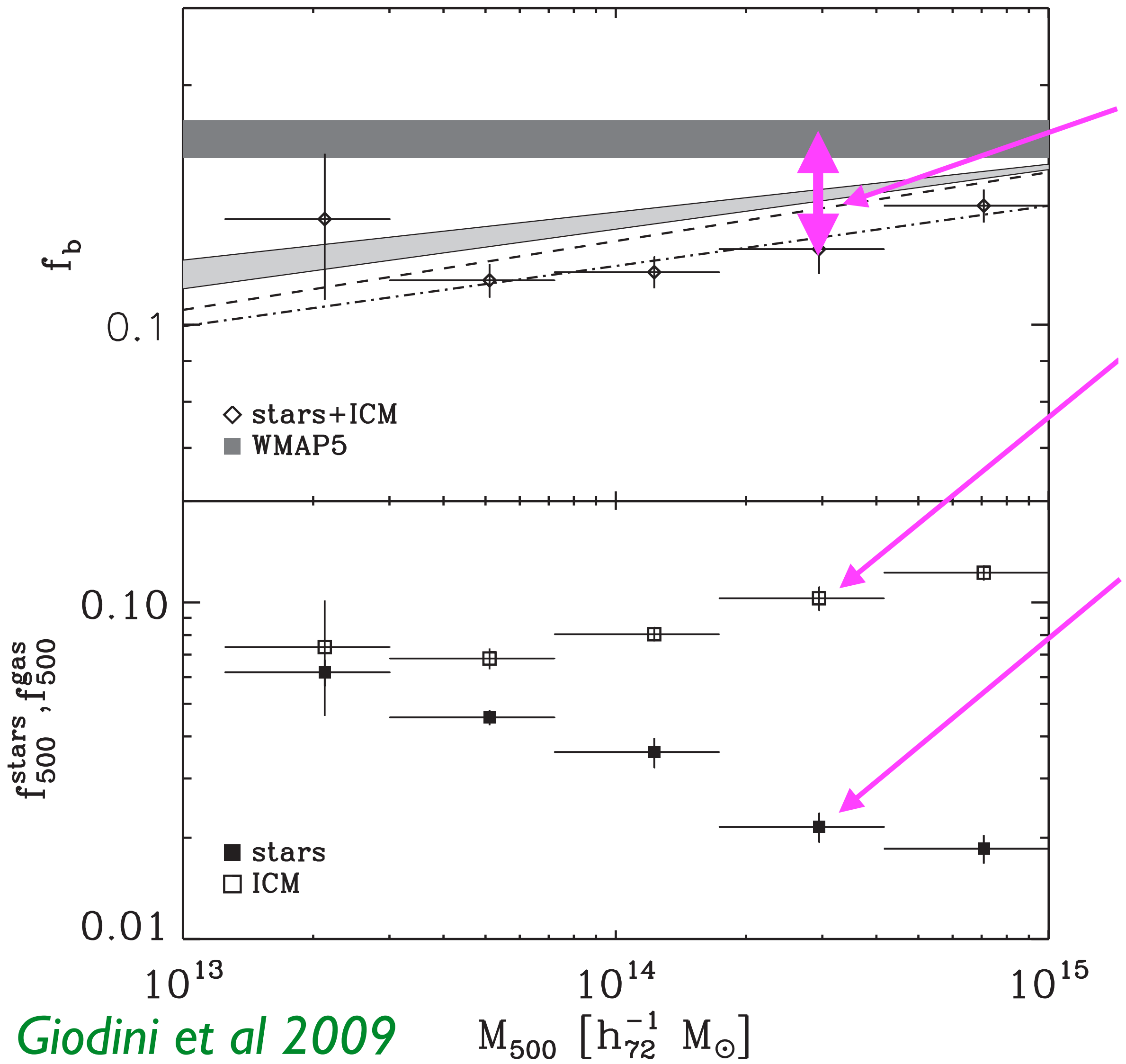
X-rays
ROSAT

Weak gravitational lensing

$$\frac{M_{\text{total}}}{M_{\text{visible}}} \approx 6$$

Galaxy clusters

Galaxy clusters are mostly dark matter with some gas and a sprinkle of galaxies



Giodini et al 2009

~5% of mass in missing baryons

10% of mass in gas

2% of mass in stars

83% of mass in non-baryonic dark matter

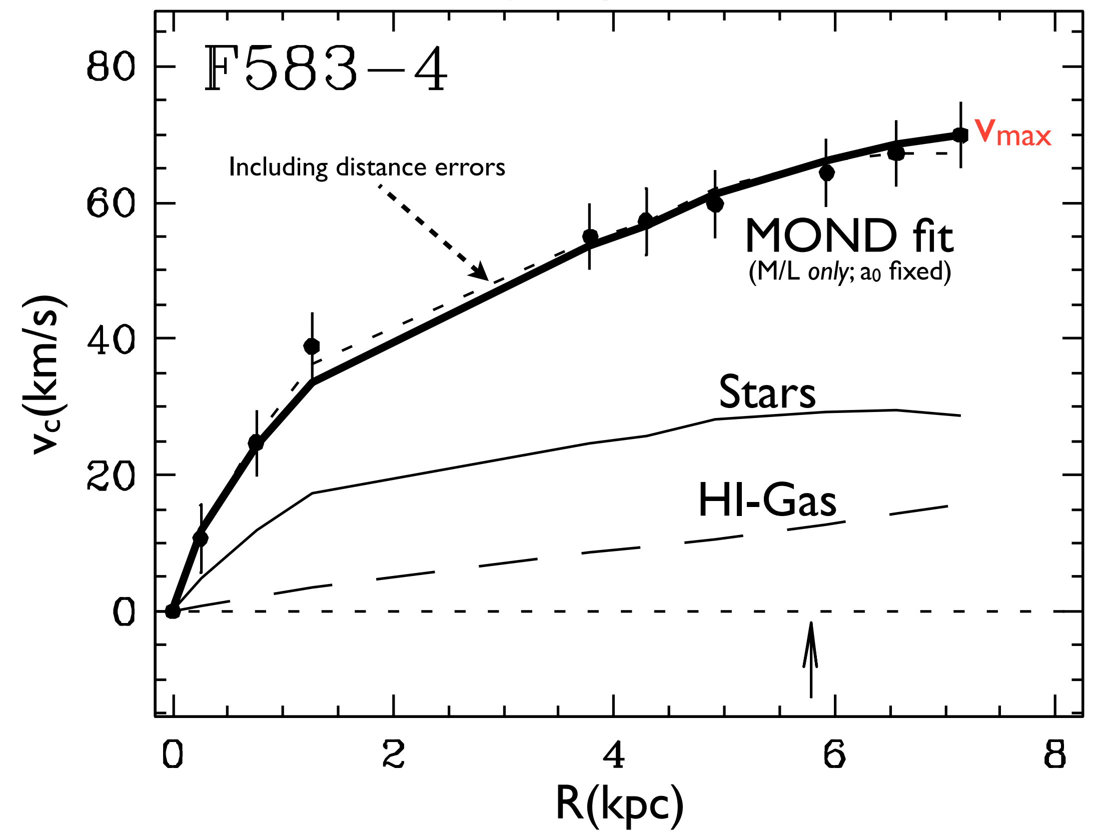
Cold dark matter or modified gravity?

Modified Newtonian Dynamics
or
MOND

New constant of nature:
universal acceleration a_0

$F=ma$ for $a \gg a_0$

$F=ma^2/a_0$ for $a \ll a_0$



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, *not* modified gravity

Bekenstein's TeVeS does not reproduce the CMB angular power spectrum not the matter power spectrum

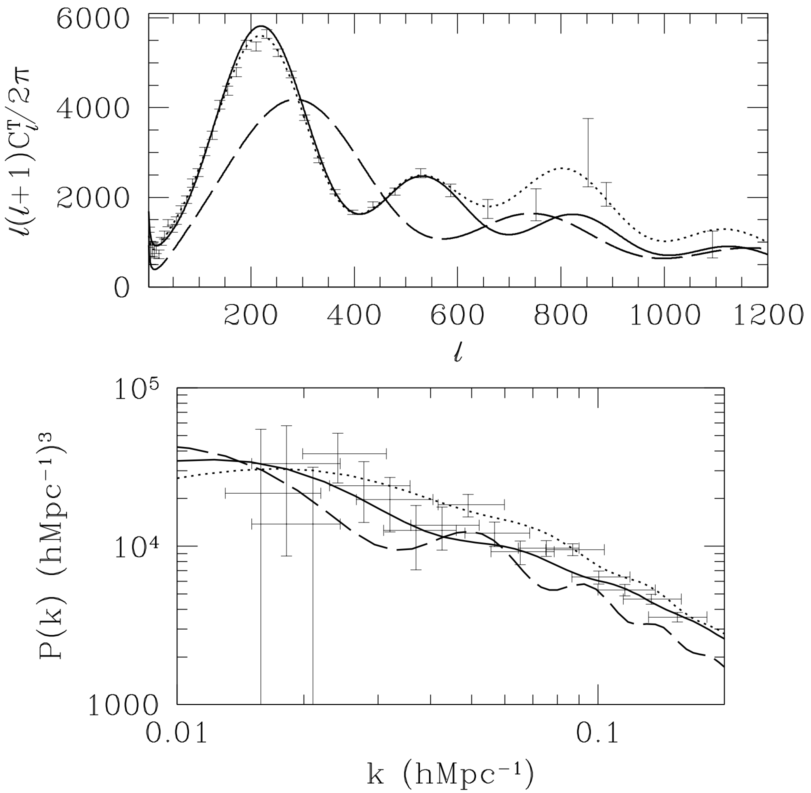


FIG. 4: The angular power spectrum of the CMB (top panel) and the power spectrum of the baryon density (bottom panel) for a MOND universe (with $a_0 \simeq 4.2\times10^{-8} cm/s^2$) with $\Omega_\Lambda = 0.78$ and $\Omega_\nu = 0.17$ and $\Omega_B = 0.05$ (solid line), for a MOND universe $\Omega_\Lambda = 0.95$ and $\Omega_B = 0.05$ (dashed line) and for the Λ-CDM model (dotted line). A collection of data points from CMB experiments and Sloan are overplotted.

Skordis, Mota, Ferreira, Boehm 2005

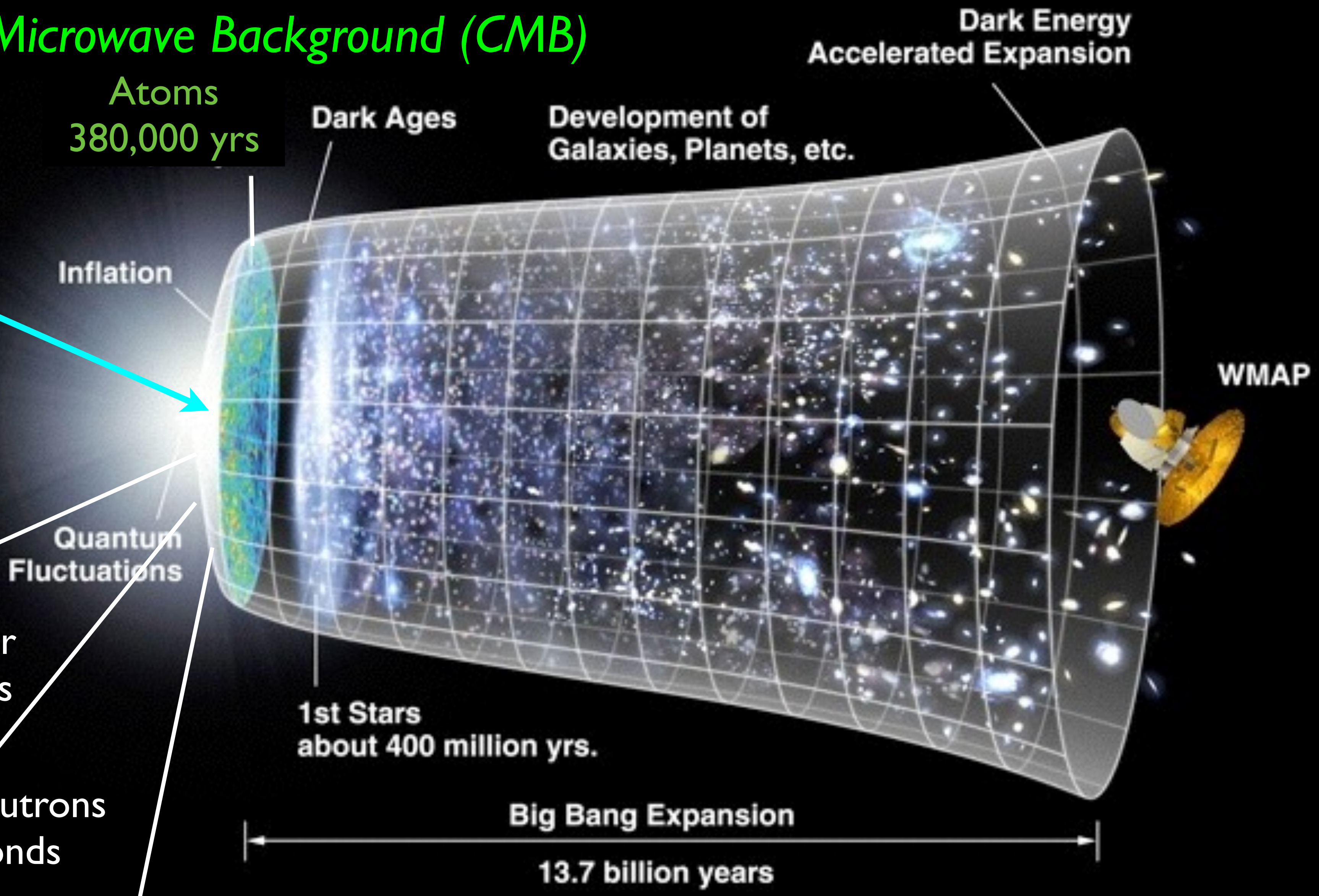
Early universe

Early universe

Cosmic Microwave Background (CMB)

Atoms
380,000 yrs

Primordial plasma



Cold dark matter
few nanoseconds

Protons and neutrons
few milliseconds

Atomic nuclei
few seconds — few minutes

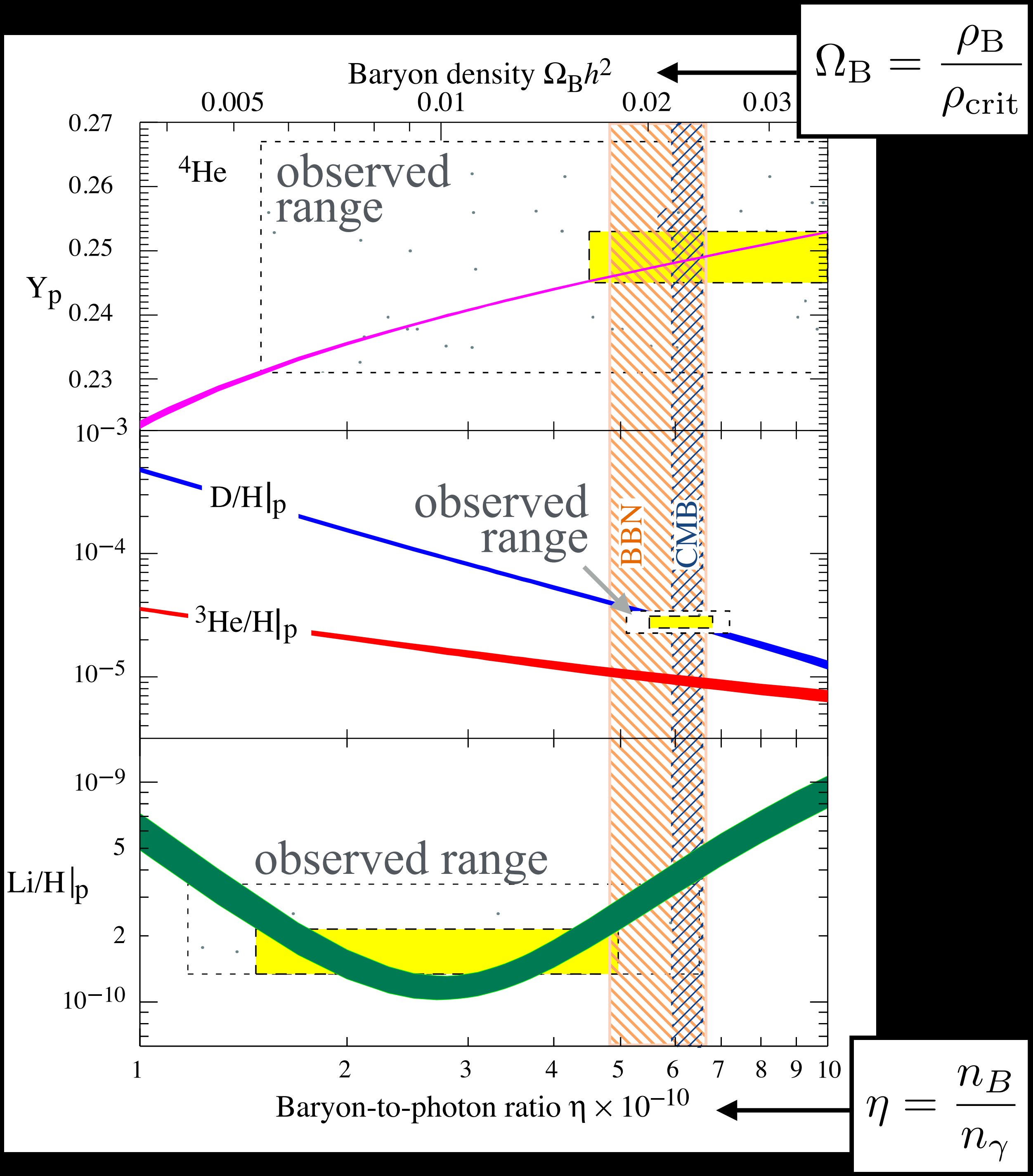
Big Bang Nucleosynthesis (BBN)

Early universe

Big Bang Nucleosynthesis

Nuclei formation rates depend on the density of baryons (strictly speaking, neutrons)

Agreement between CMB and BBN densities

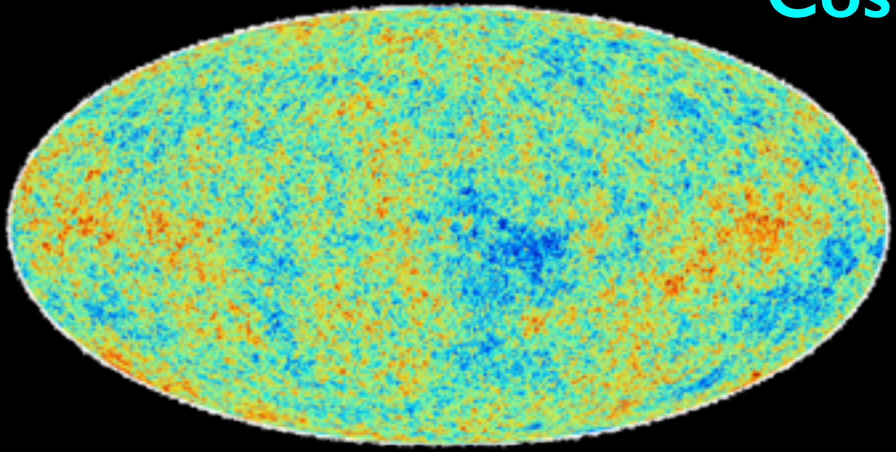


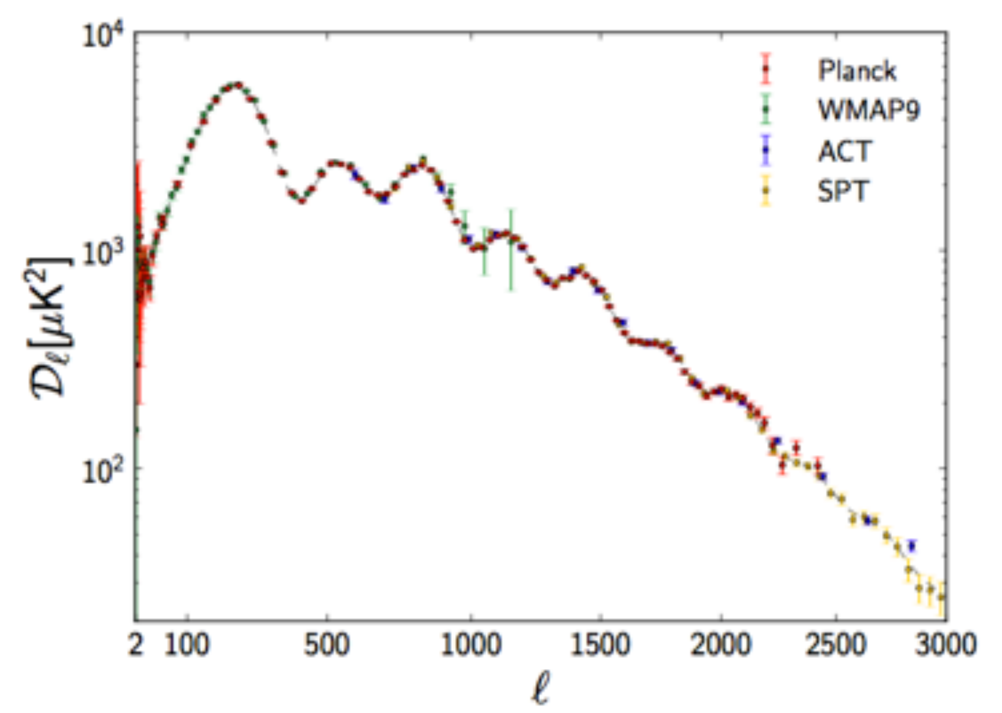
$$\Omega_B = \frac{\rho_B}{\rho_{\mathrm{crit}}}$$

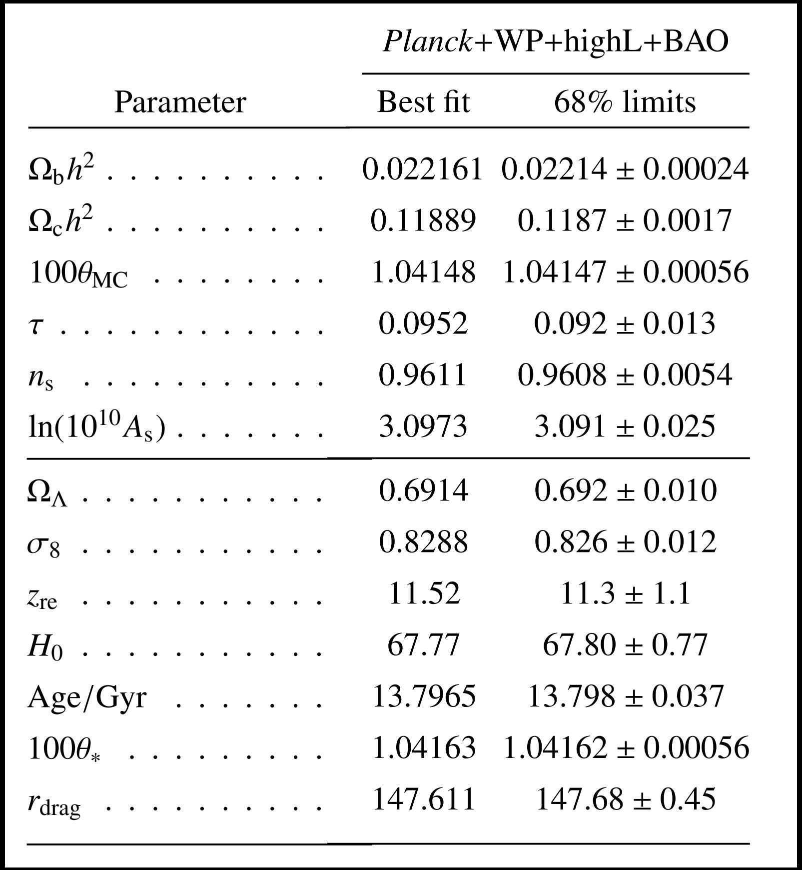
$$\eta = \frac{n_B}{n_\gamma}$$

Early universe

Cosmic Microwave Background fluctuations







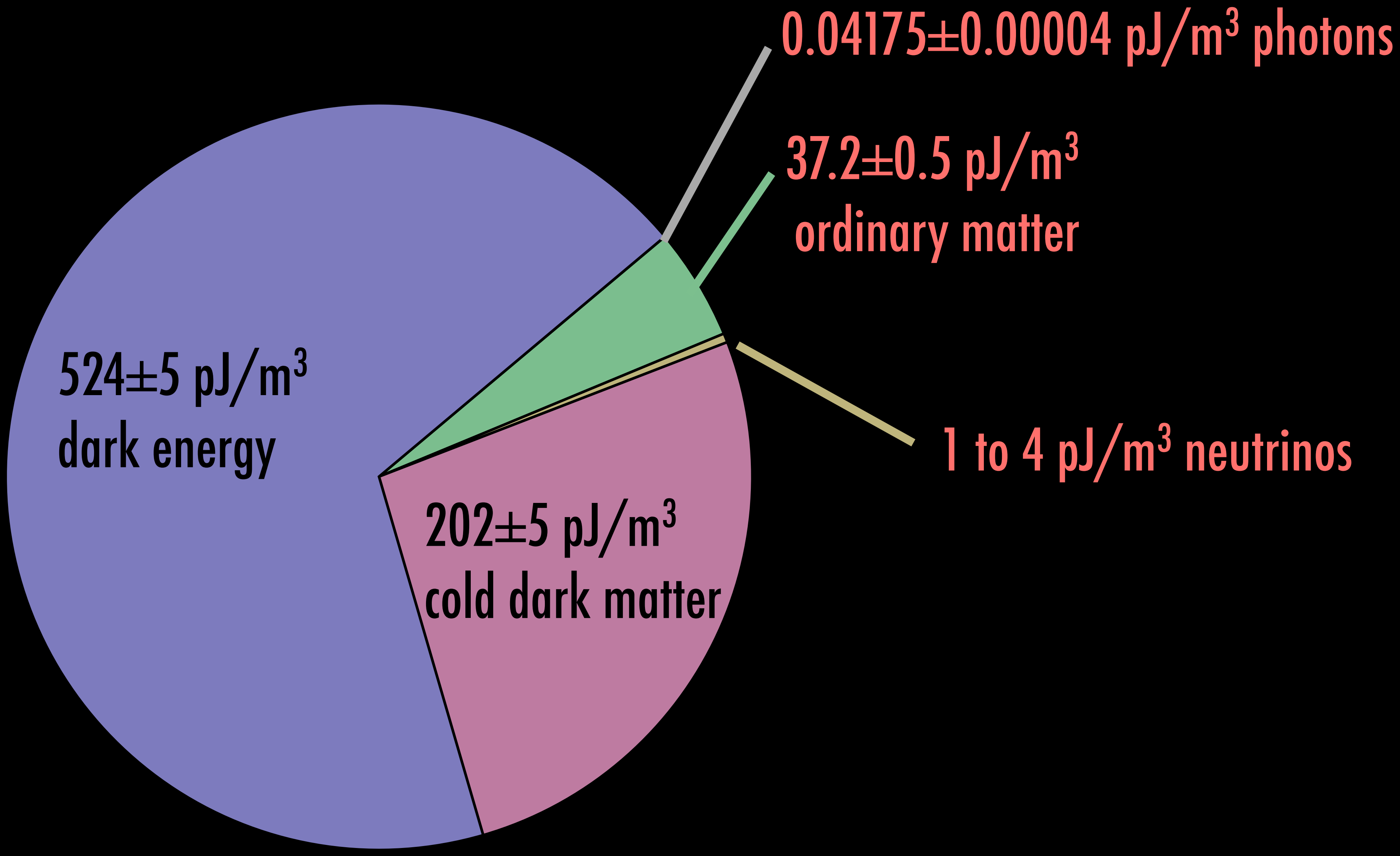
	Planck+WP+highL+BAO	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04148	1.04147 ± 0.00056
τ	0.0952	0.092 ± 0.013
n_s	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0973	3.091 ± 0.025
Ω_Λ	0.6914	0.692 ± 0.010
σ_8	0.8288	0.826 ± 0.012
z_{re}	11.52	11.3 ± 1.1
H_0	67.77	67.80 ± 0.77
Age/Gyr	13.7965	13.798 ± 0.037
$100\theta_*$	1.04163	1.04162 ± 0.00056
r_{drag}	147.611	147.68 ± 0.45

Planck (2013)

linear perturbation theory

general relativity and statistical mechanics at 10^4 K ~ 1 eV/k

The observed energy content of the Universe



matter $p \ll \rho$

radiation $p = \rho/3$

vacuum $p = -\rho$

Planck (2013)

1 pJ = 10^{-12} J

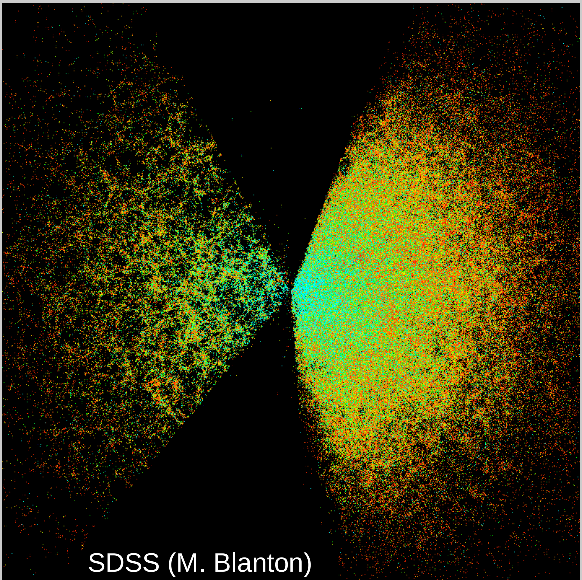
$\rho_{\mathrm{crit}} = 1.68829\, h^2$ pJ/m^3

From CMB fluctuations to galaxies

Galaxy formation

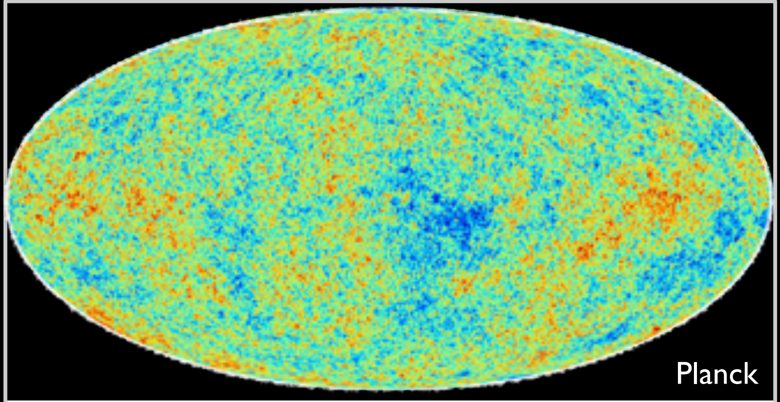
From CMB fluctuations to galaxies

Large Scale Structure



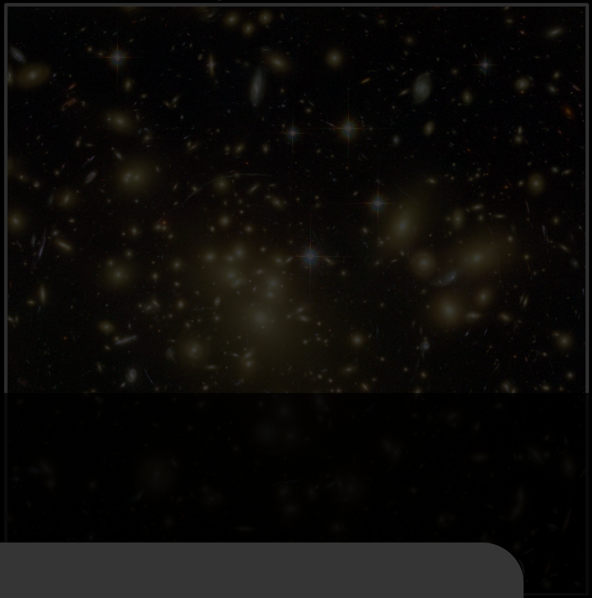
SDSS (M. Blanton)

Cosmic Microwave Background

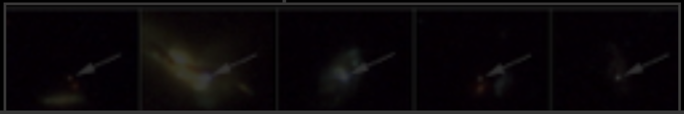


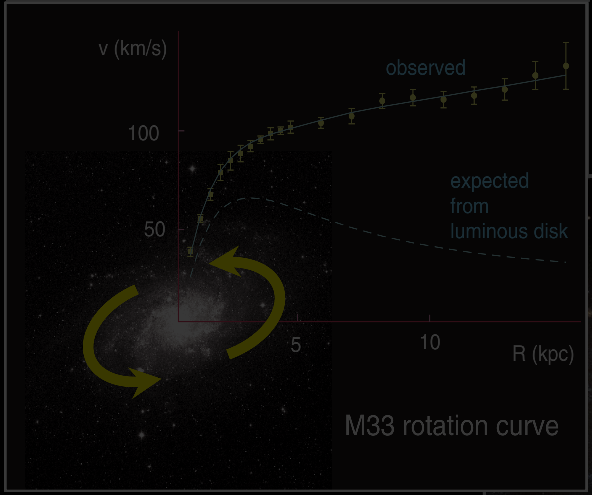
Planck

Galaxy Clusters



Supernovae





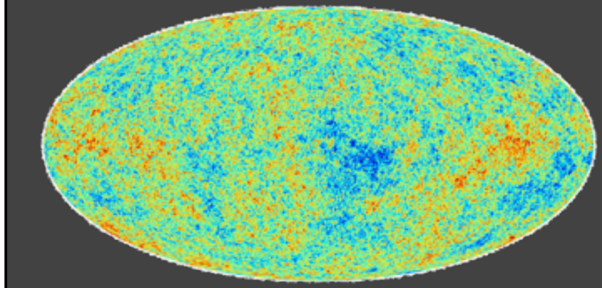
M33 rotation curve

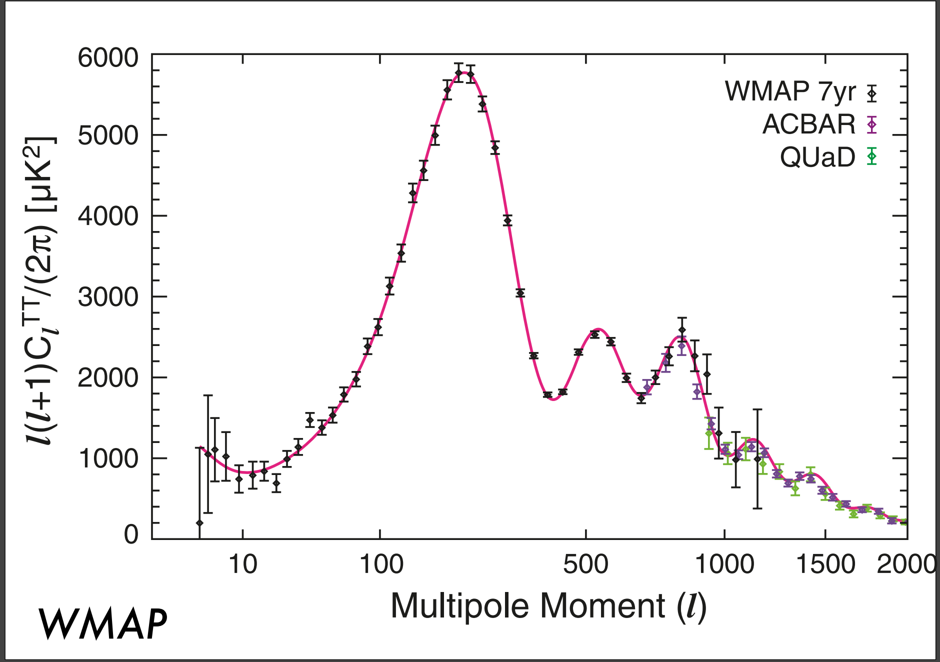
An invisible mass makes the Cosmic Microwave Background fluctuations grow into galaxies (CMB and matter power spectra, or correlation functions)

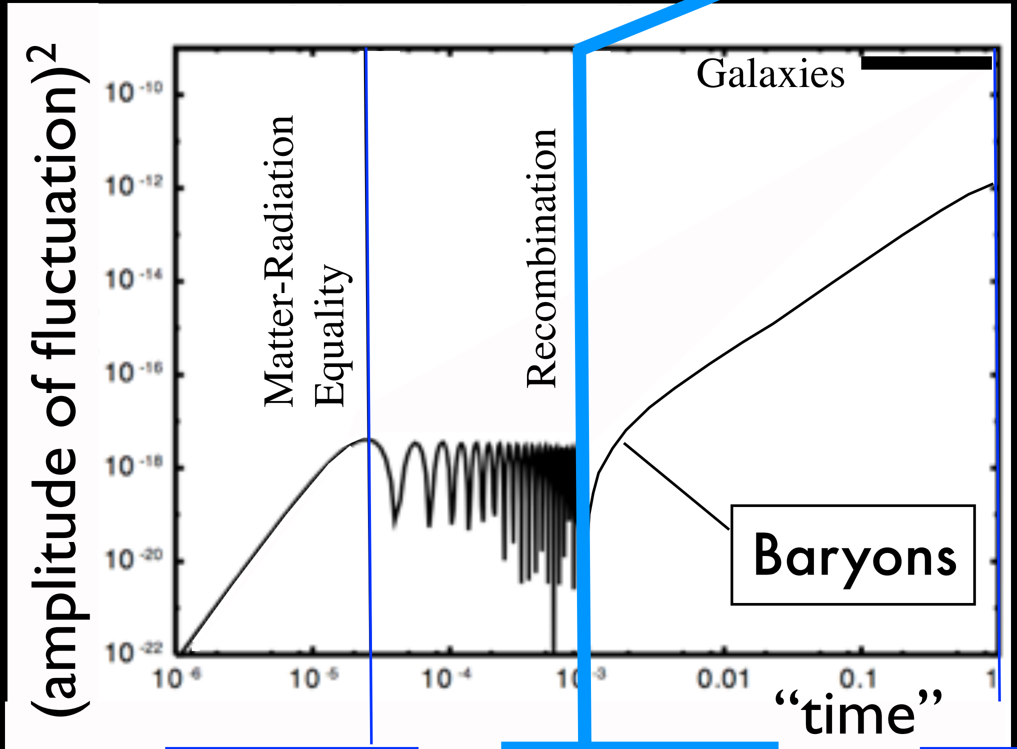
M101 (HST; Kuntz et al. 2006)

From CMB fluctuations to galaxies

Cosmic
Microwave
Background
fluctuations





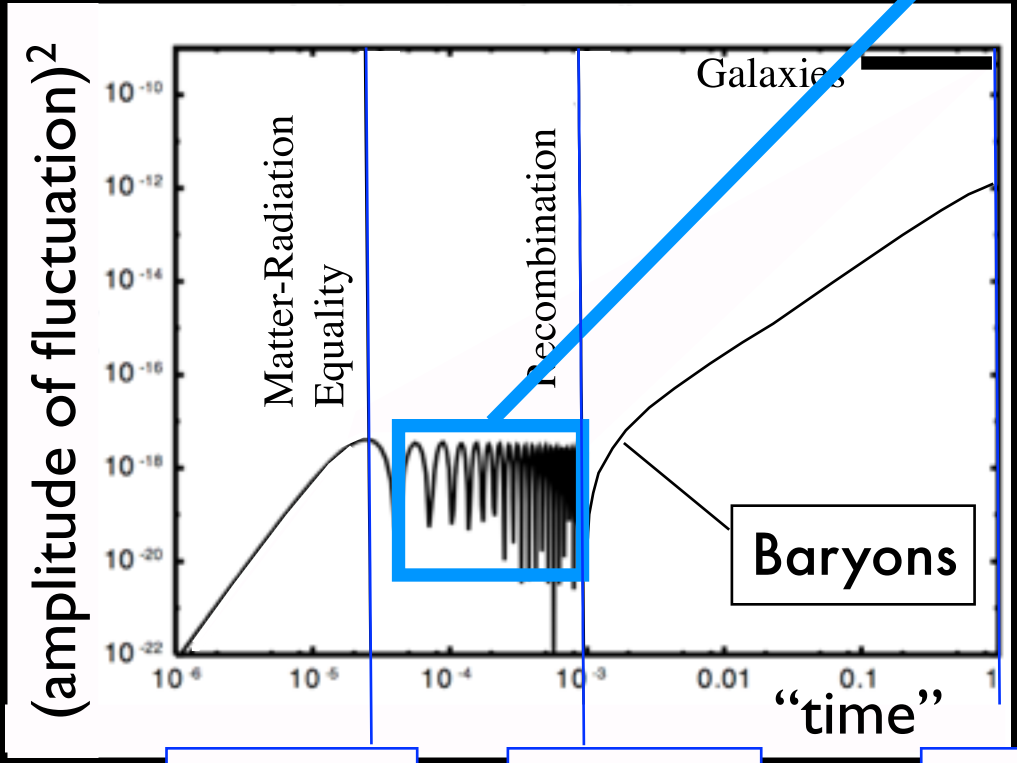


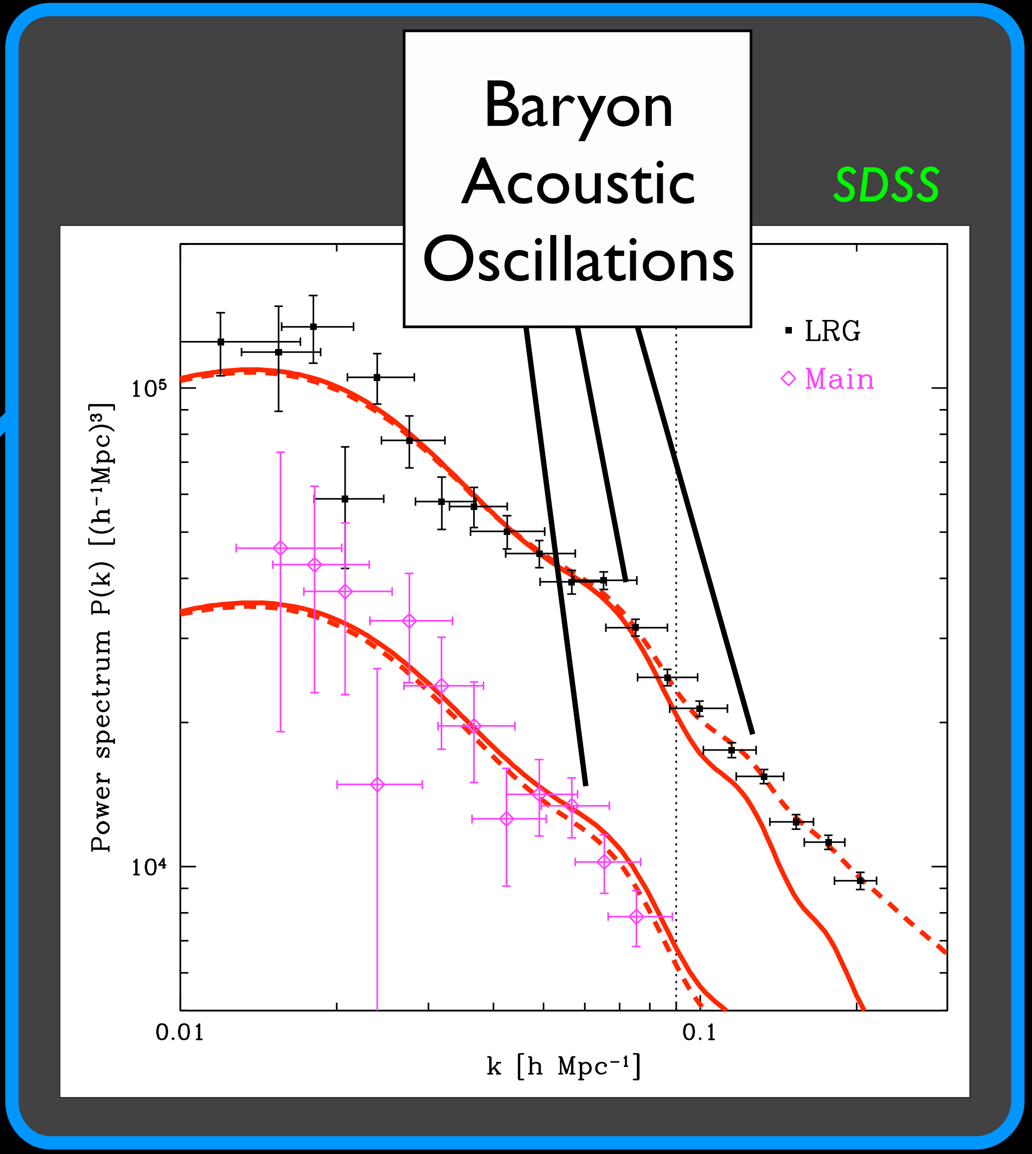
T=1.28 eV

T=0.26 eV

T=0.2348 meV

From CMB fluctuations to galaxies





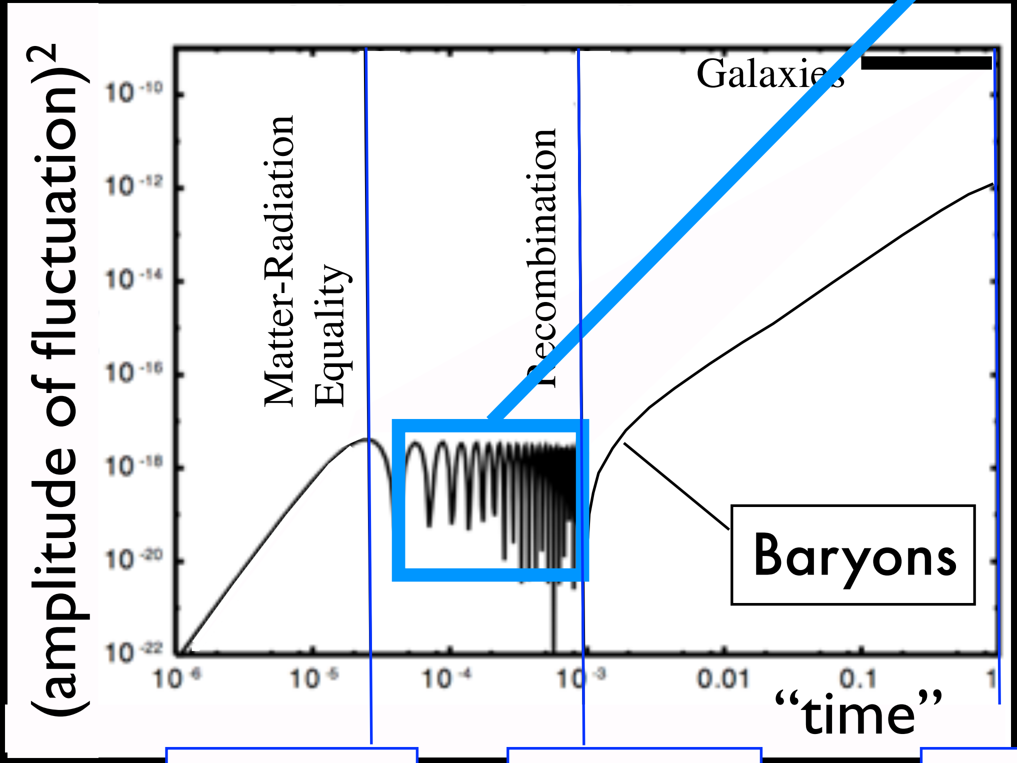
T=1.28 eV

T=0.26 eV

T=0.2348 meV

From CMB fluctuations to galaxies

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



T=1.28 eV

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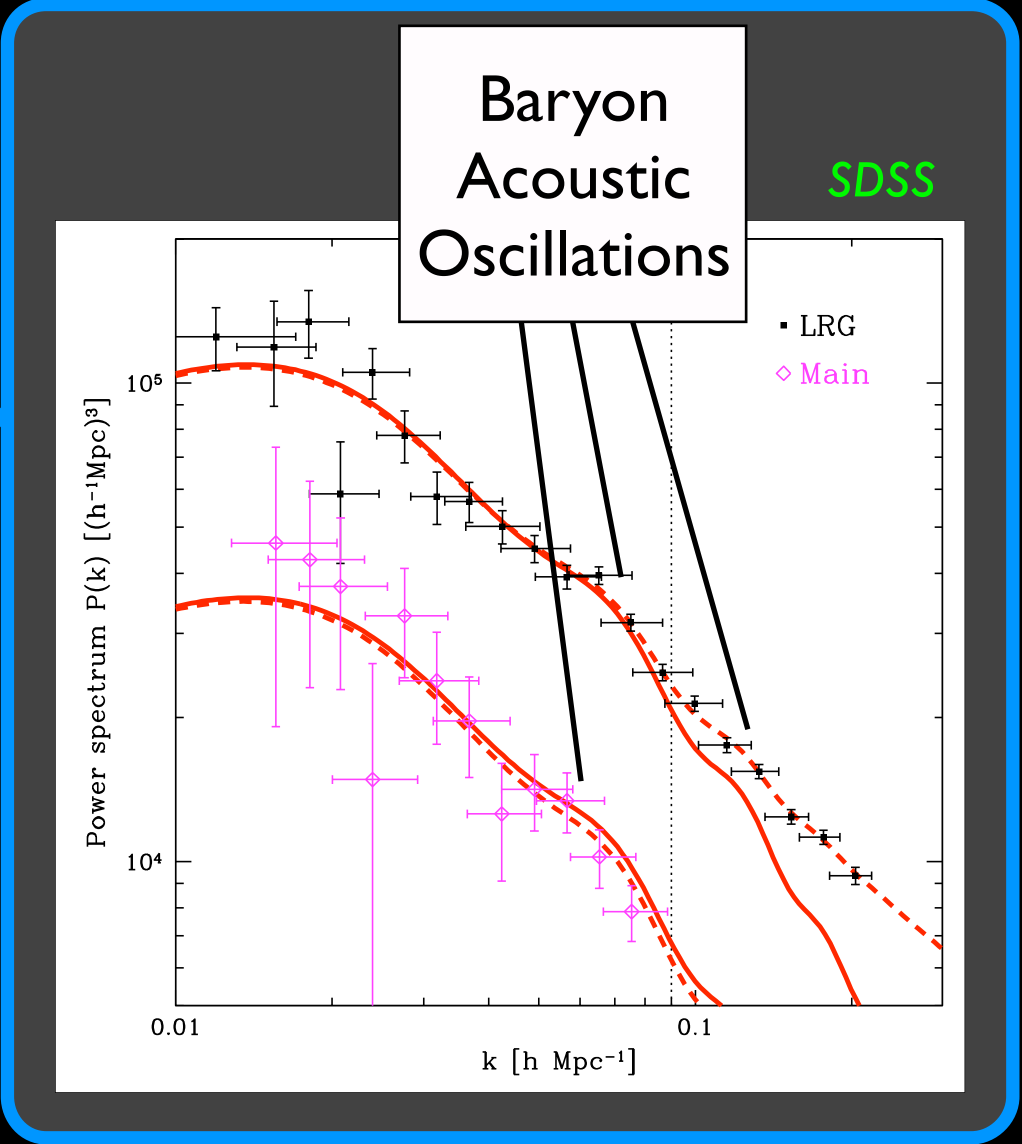


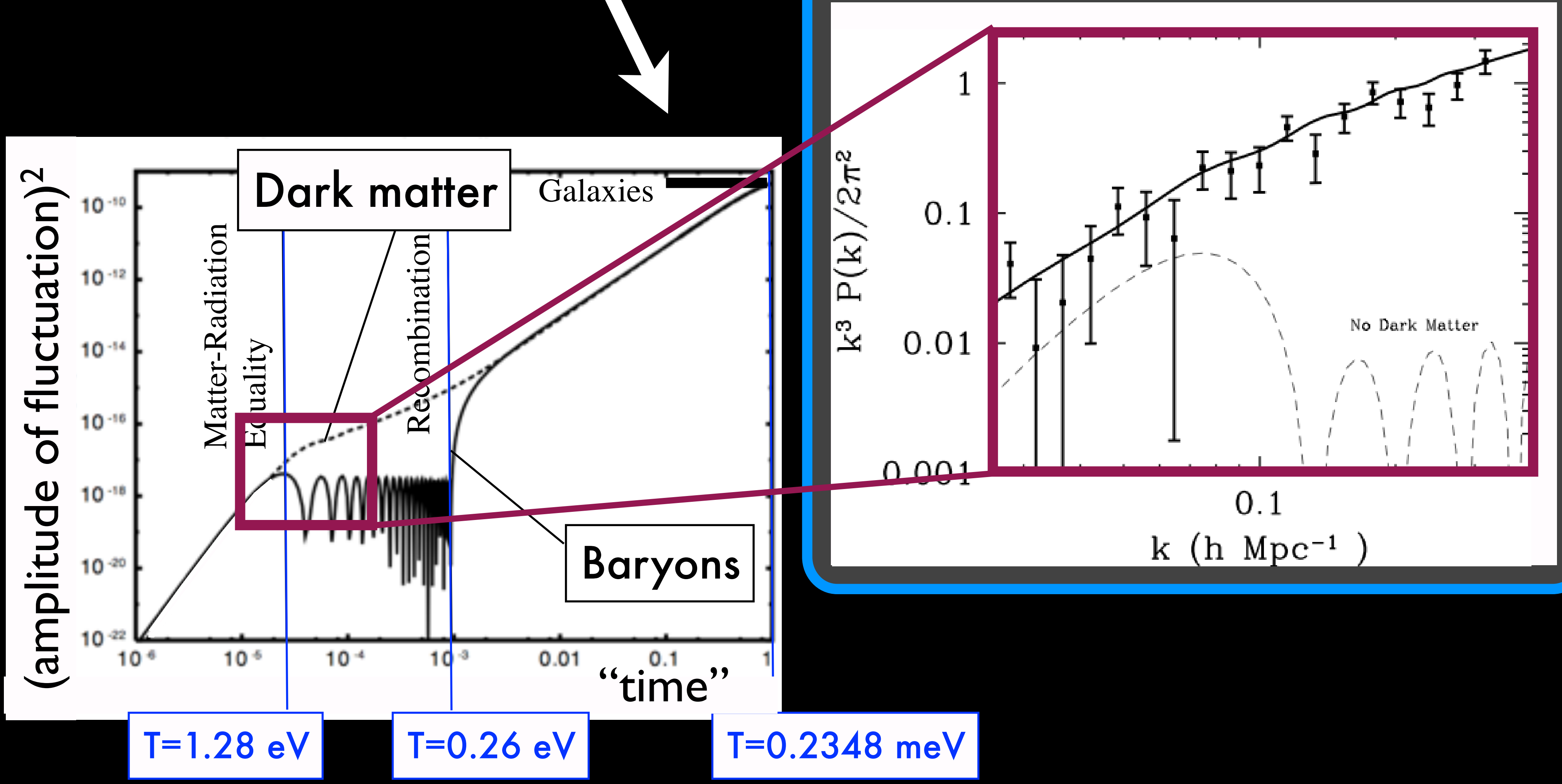
From CMB fluctuations to galaxies

Fluctuation uncoupled to the plasma have enough time to grow

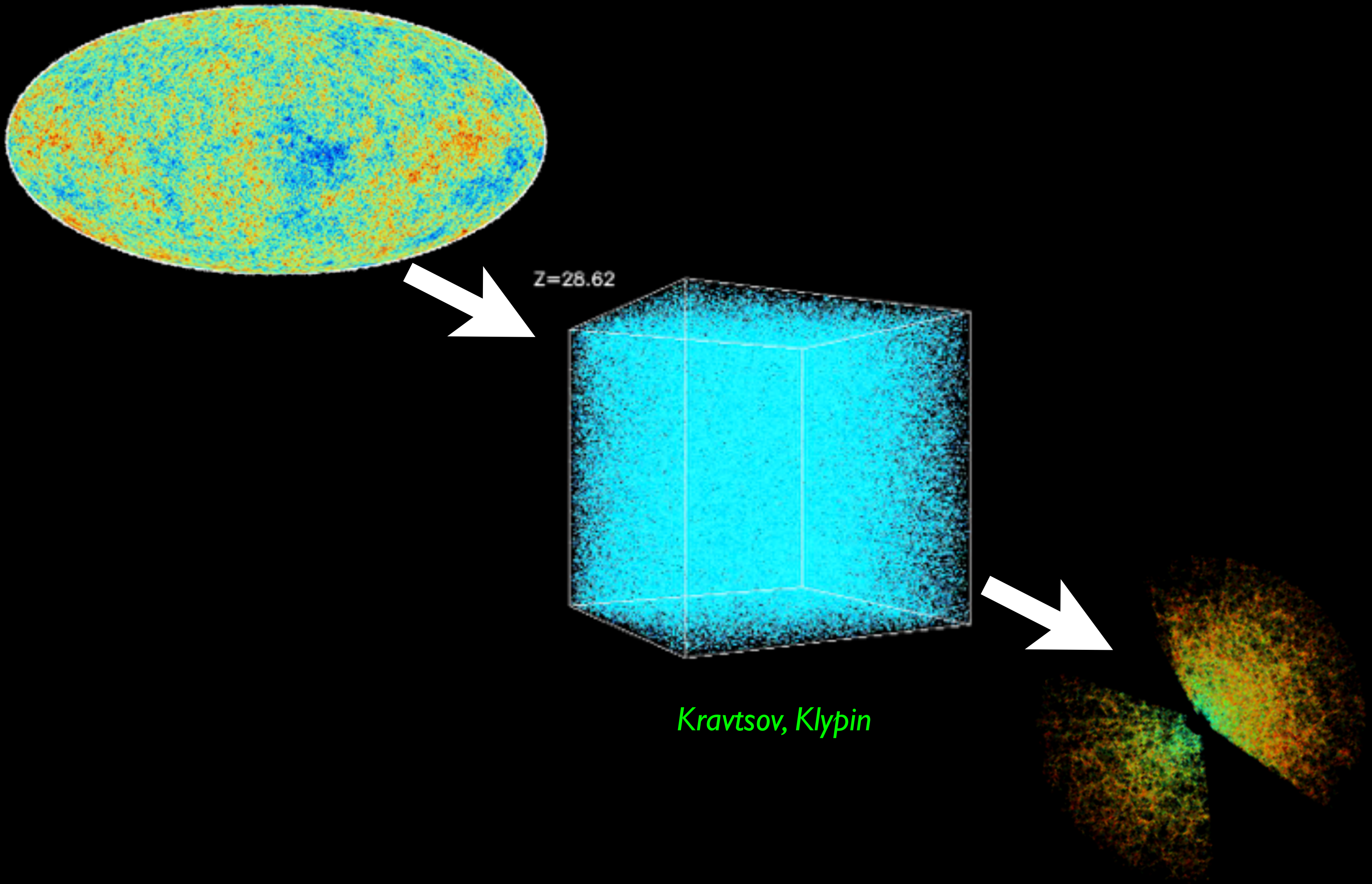
Dark matter is non-baryonic

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

SDSS

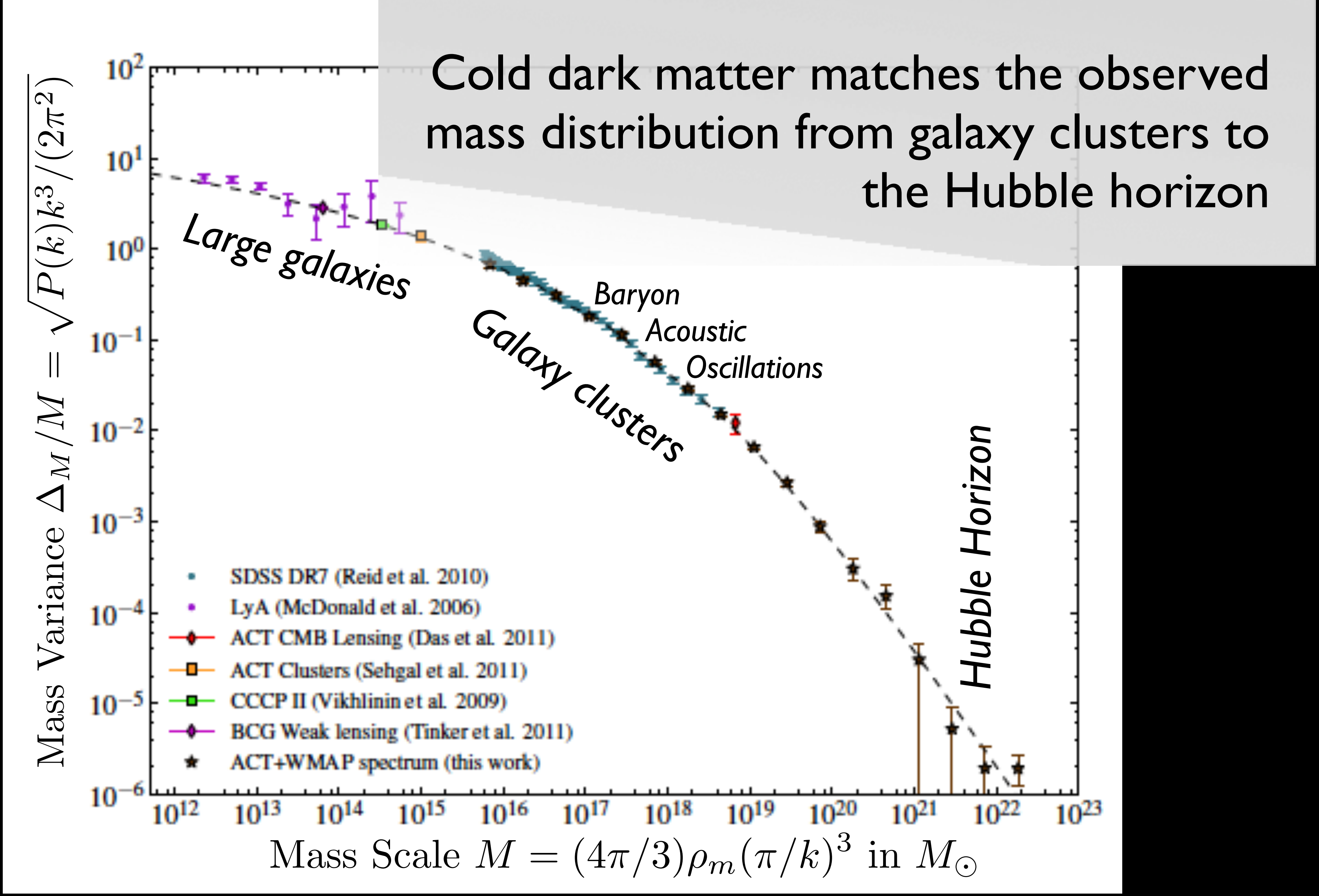


From CMB fluctuations to galaxies



Kravtsov, Klypin

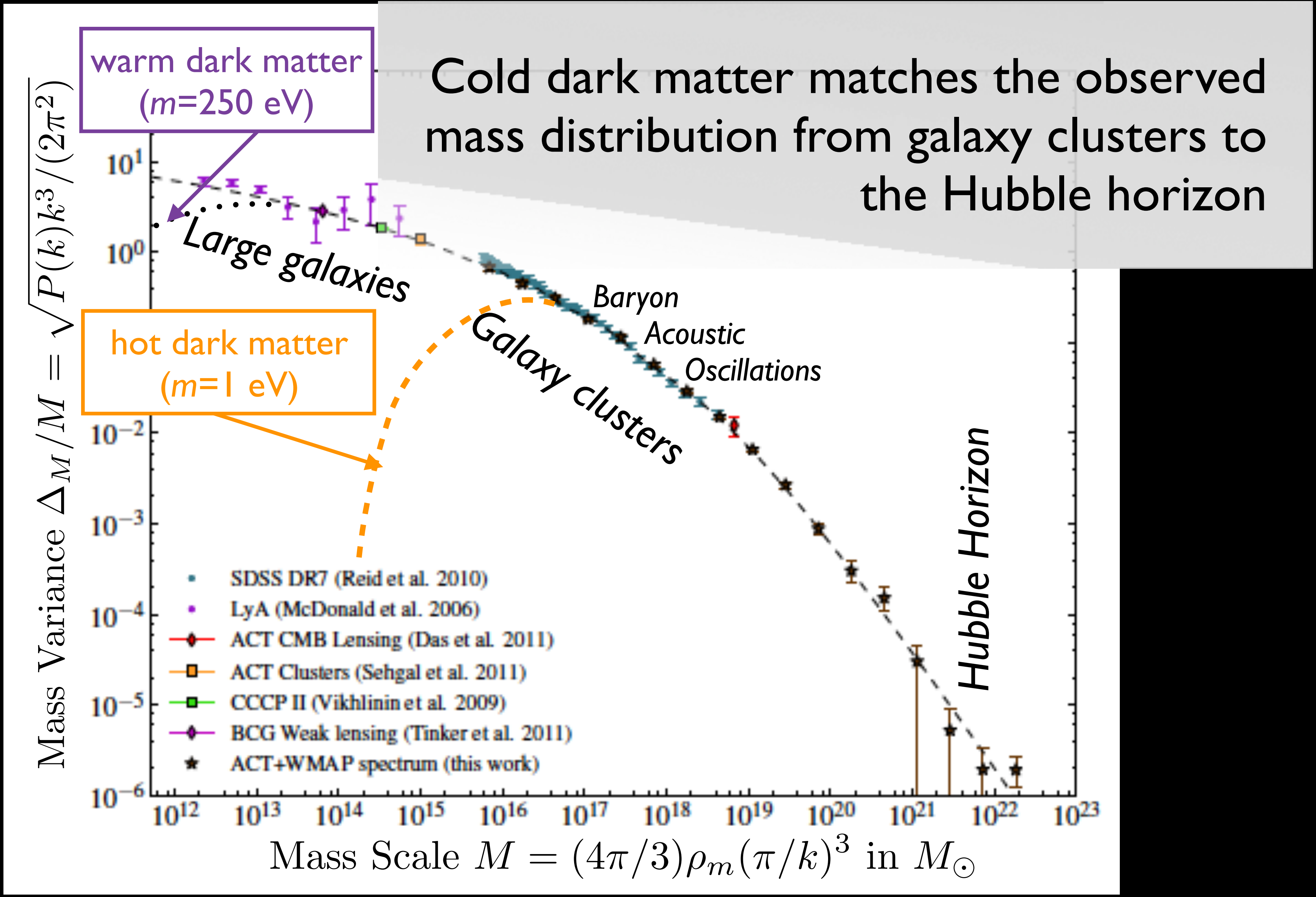
From CMB fluctuations to galaxies



Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon

Hlozek et al 2012

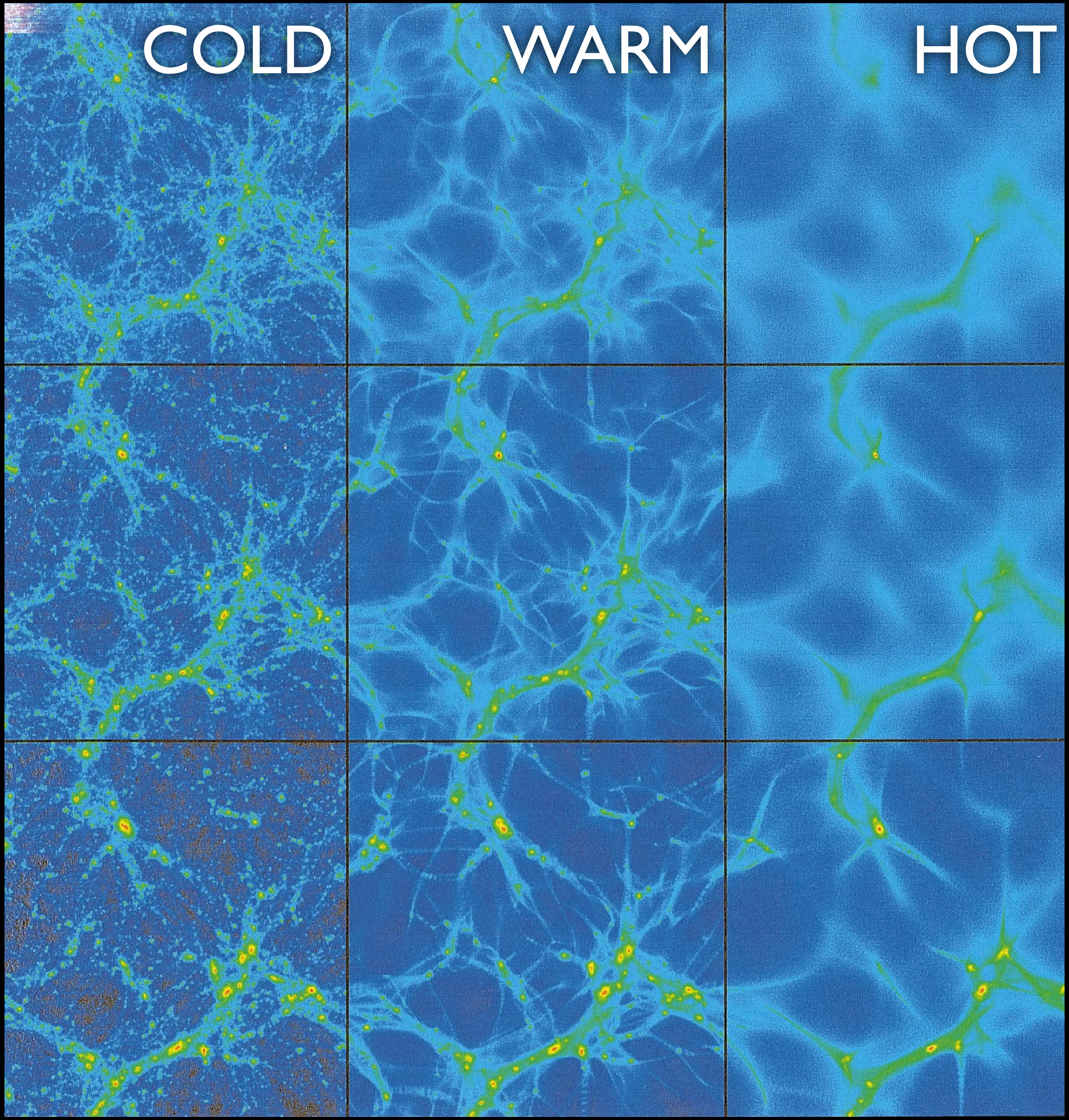
Cold/warm/hot dark matter



Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon

Hlozek et al 2012

Cold/warm/hot dark matter



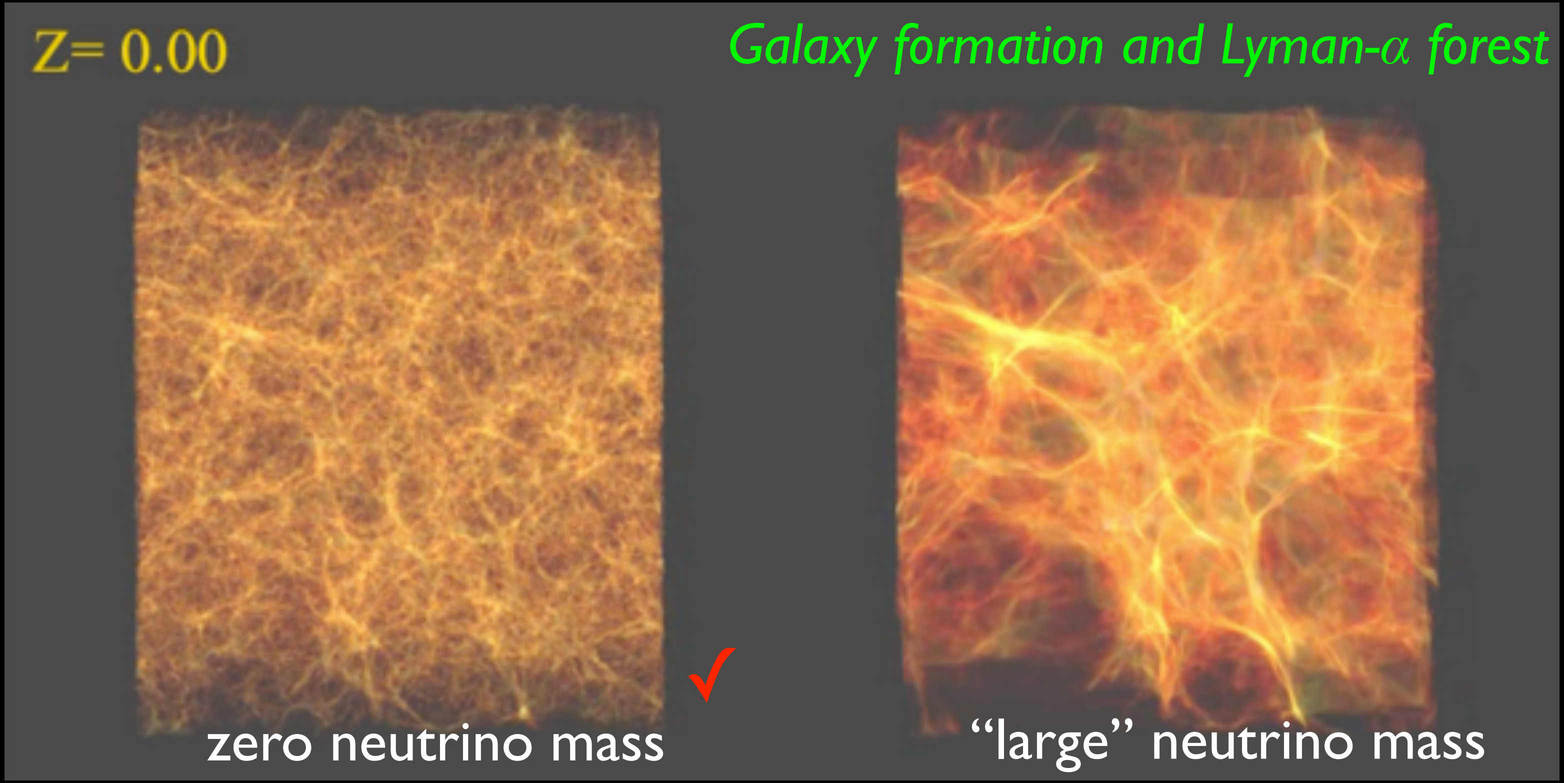
Bode et al 2001

Neutrinos as dark matter

Cosmology provides upper limits on neutrino masses

$\sum m < 0.23$ eV

Future reach
~ 0.06 eV



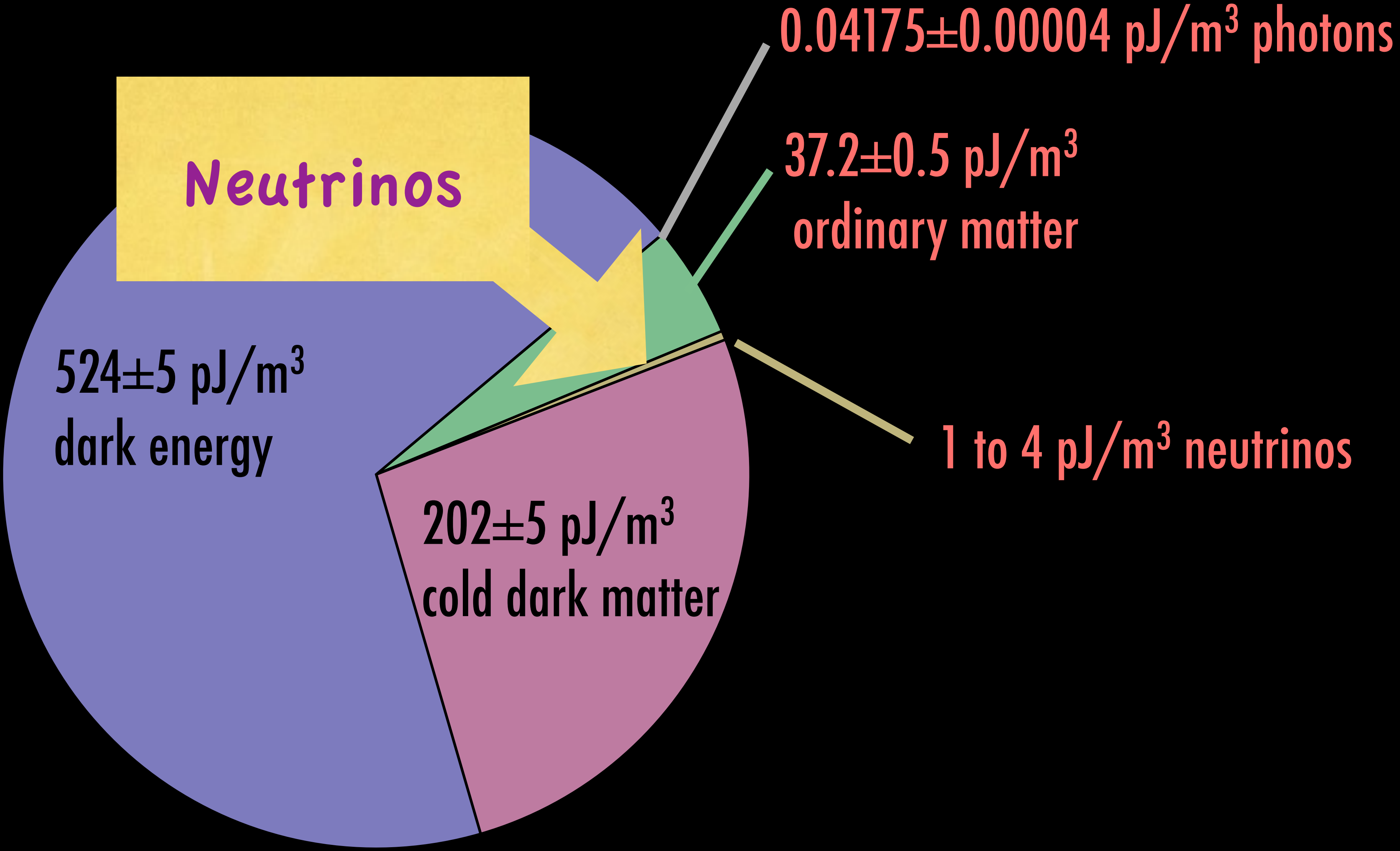
Galaxy formation and Lyman-α forest

Neutrinos as dark matter

- Neutrino oscillations (largest Δm^2 from SK+K2K+MINOS) place a lower bound on one of the neutrino masses, $m_\nu > 0.086$ eV *Gonzalez-Garcia et al 2012*
- Cosmology places an upper bound on the sum of the neutrino masses, $\sum m_\nu < 0.23$ eV *Planck+WP+ACT/SPT+BAO 2013*
- Therefore neutrinos are *hot dark matter* ($m_\nu \ll T_{eq}=1.28$ eV) with density $0.0009 < \Omega_\nu h^2 < 0.0025$

Detecting this Cosmic Neutrino Background (CNB) is a big challenge

The observed energy content of the Universe



0.04175±0.00004 pJ/m^3 photons

37.2±0.5 pJ/m^3
ordinary matter

1 to 4 pJ/m^3 neutrinos

524±5 pJ/m^3
dark energy

202±5 pJ/m^3
cold dark matter

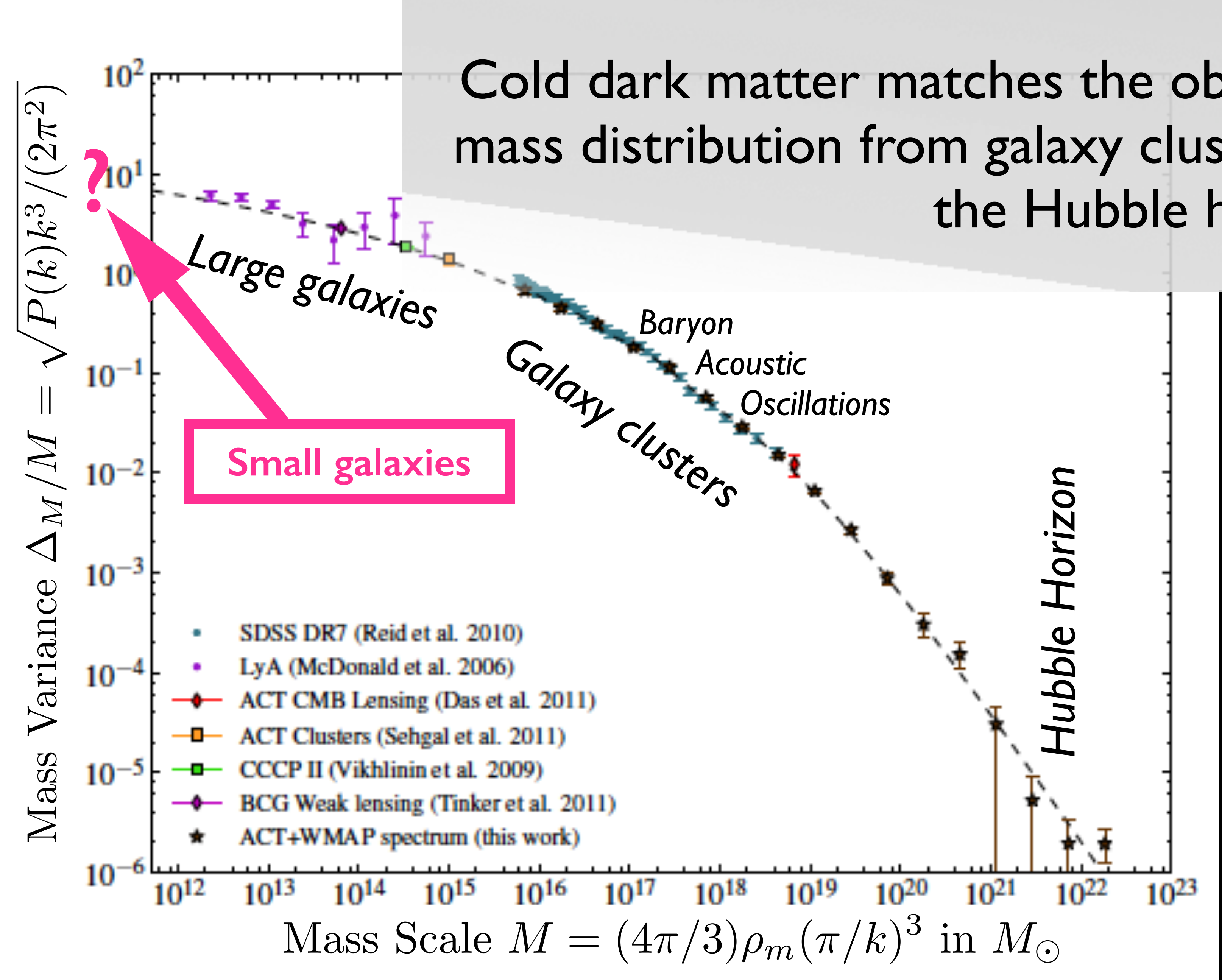
Neutrinos

matter $p \ll \rho$
radiation $p = \rho/3$
vacuum $p = -\rho$

Planck (2013)

1 pJ = 10^{-12} J
$\rho_{\rm crit} = 1.68829\, h^2$ pJ/m^3

Small galaxies and dark subhalos

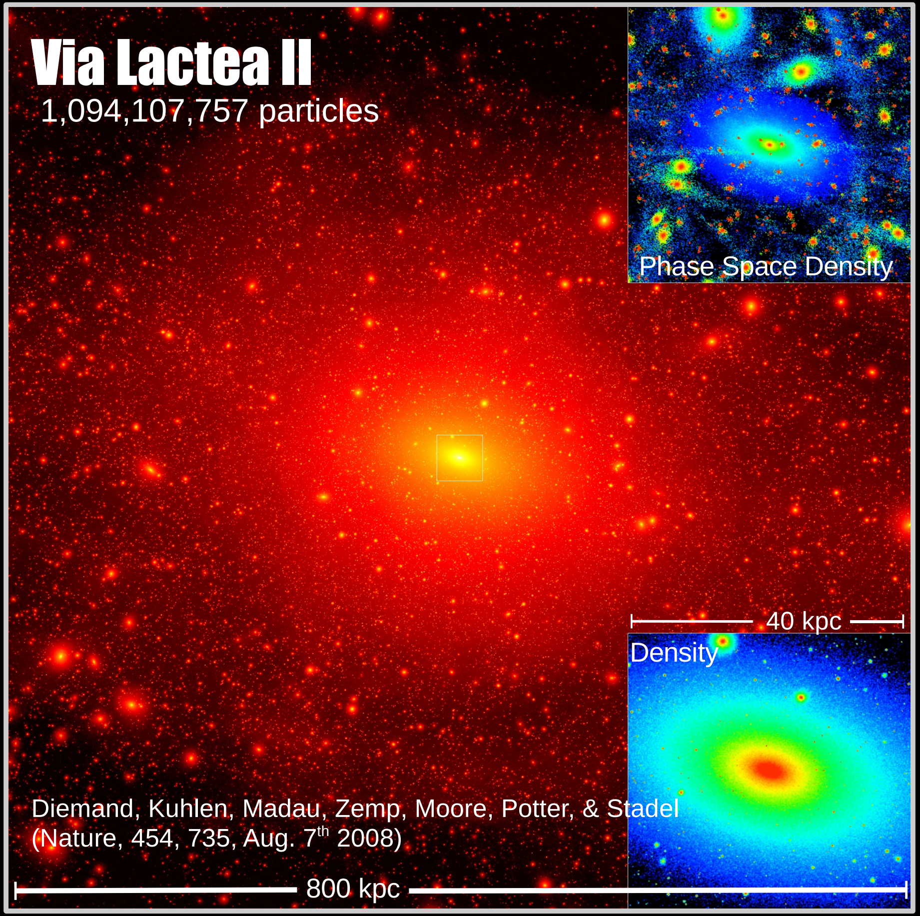


Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon

Hlozek et al 2012

Small galaxies and dark subhalos

Dark-matter-only simulations do not match observations at small scales (~kpc)



Diemand, Kuhlen, Madau, Zemp, Moore, Potter, & Stadel (Nature, 454, 735, Aug. 7th 2008)

They incorrectly predict:

- Too many galactic bulges (too much low angular momentum gas)
- Steep density profiles in dwarf galaxies (cusp/core problem)
- Too dense subhalos/satellites ("too big to fail" problem)
- Too many subhalos/satellites

Small galaxies and dark subhalos

Including baryons in the universe can significantly alter the results from structure formation simulations:

- Triaxial halos ➠ Oblate/round halos.
- Cuspy dark matter profiles ➠ Cored dark matter profiles.
- Cored halos are more easily tidally disrupted ➠ Fewer satellites.
- An existing stellar disk ➠ An accreted dark disk.

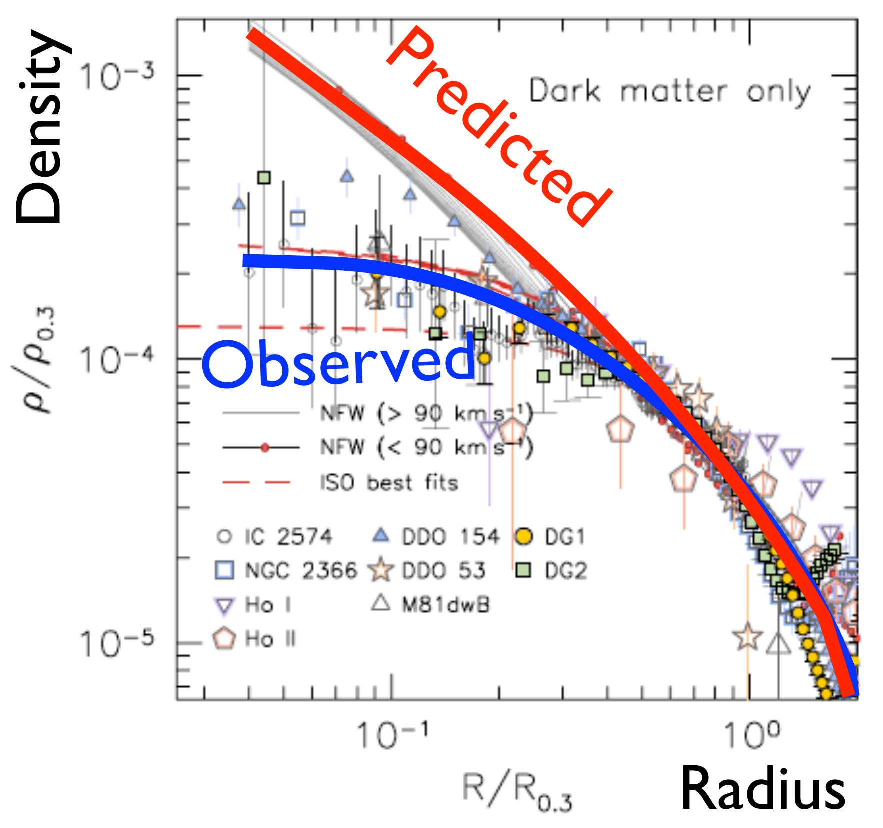
	Baryons	WDM	SIDM
Bulge-less disk galaxies	✓		
The Cusp/ Core Problem	✓		✓
Too Big to Fail	✓	✓	✓
Missing Satellites	✓	✓	

Brooks 2014

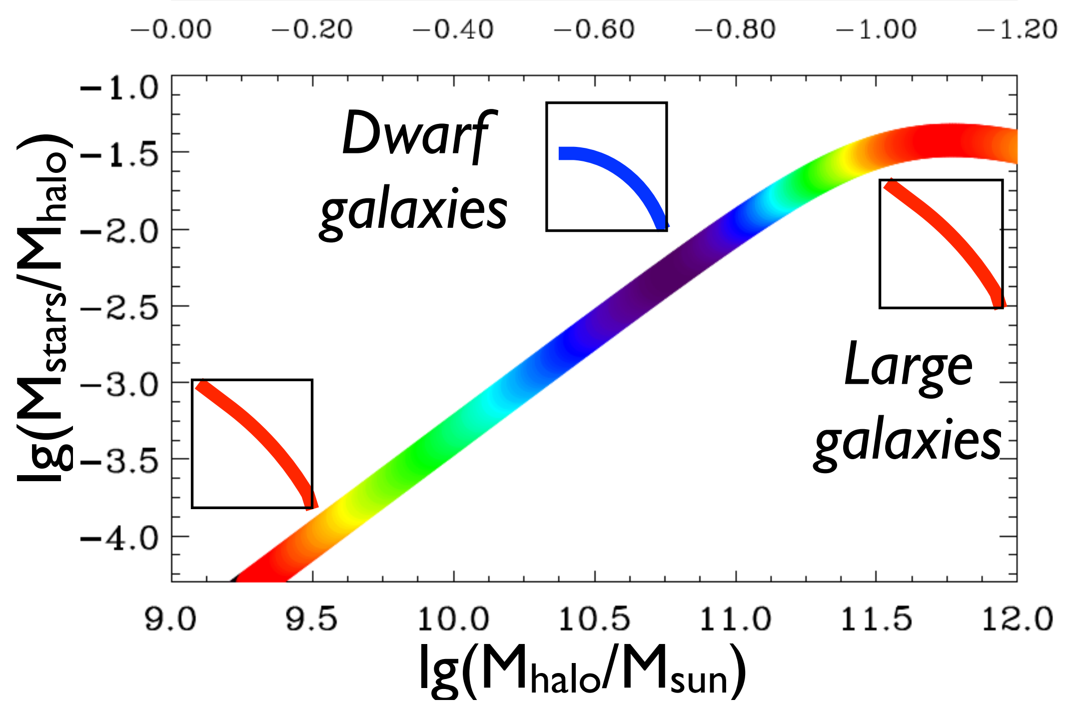
Small galaxies and dark subhalos

Cusp/core problem

Observed density profiles in dwarf galaxies are shallower than predicted with DM only



Oh et al 2011

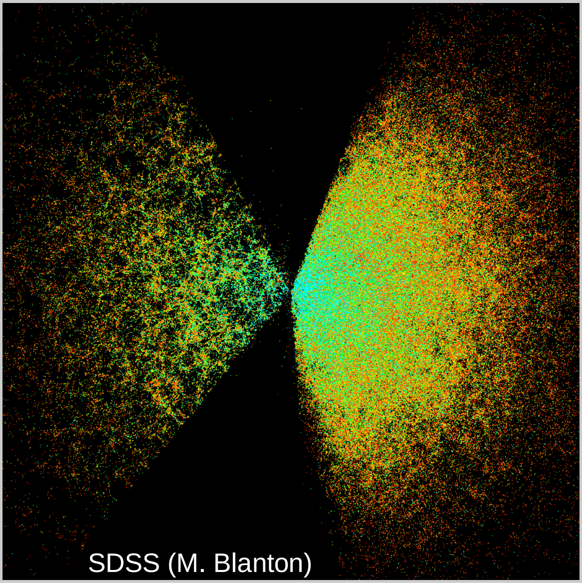


di Cintio et al 2014

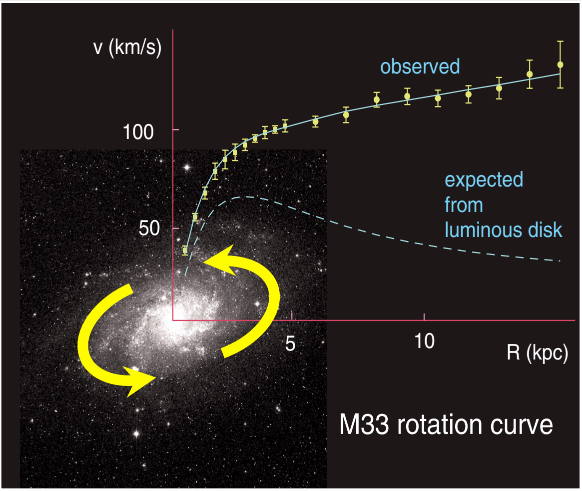
With baryons, density profiles appear to match observations

Evidence for cold dark matter

Large Scale Structure

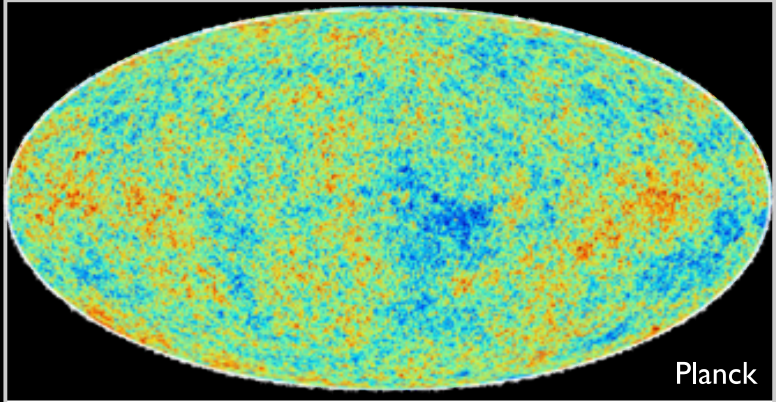


SDSS (M. Blanton)



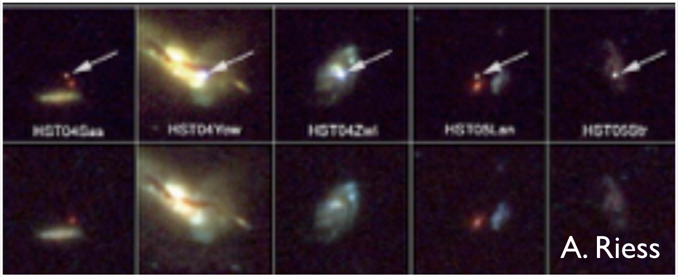
M33 rotation curve

Cosmic Microwave Background



Planck

Supernovae

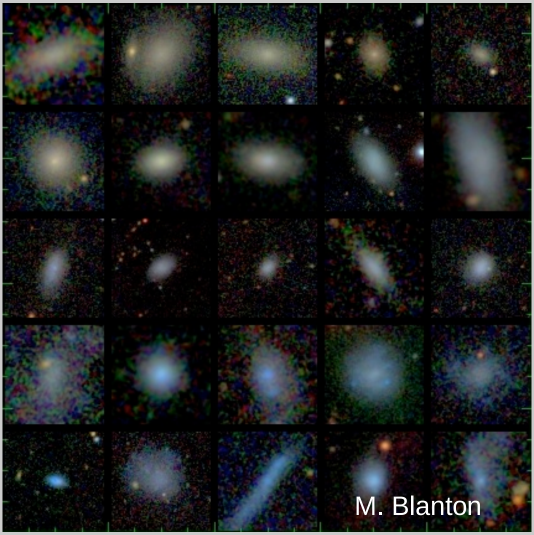


A. Riess

Galaxies

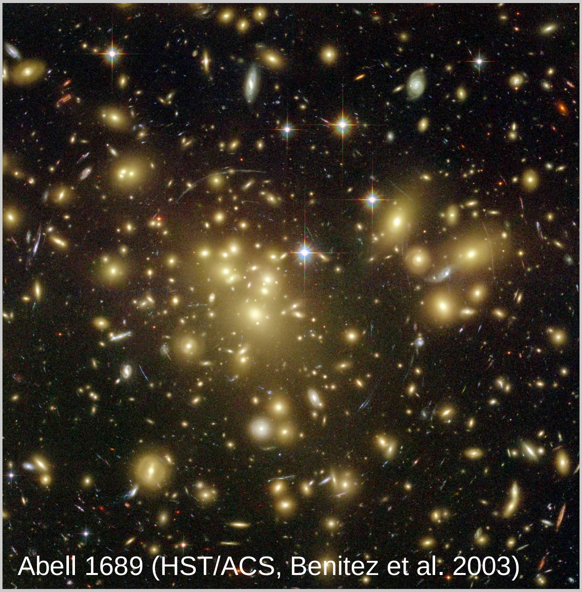
M101 (HST; Kuntz et al. 2006)

Dwarf Galaxies

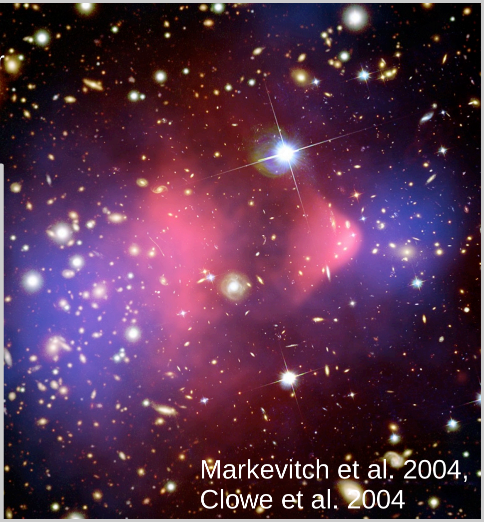


M. Blanton

Galaxy Clusters



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

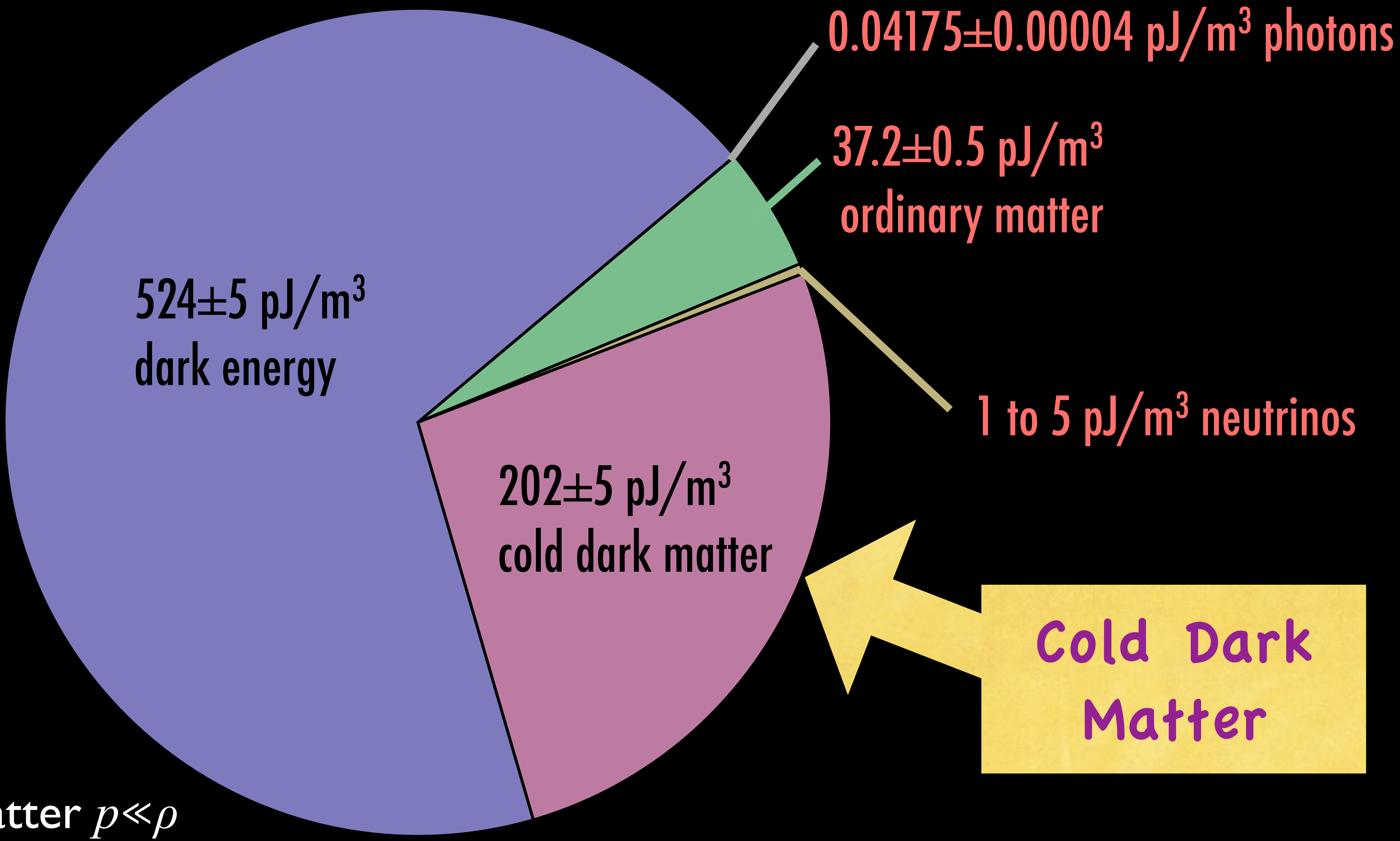


Bullet Cluster

Markevitch et al. 2004,
Clowe et al. 2004

Particle candidates
for
dark matter

The observed content of the Universe



Cold Dark Matter

matter $p \ll \rho$

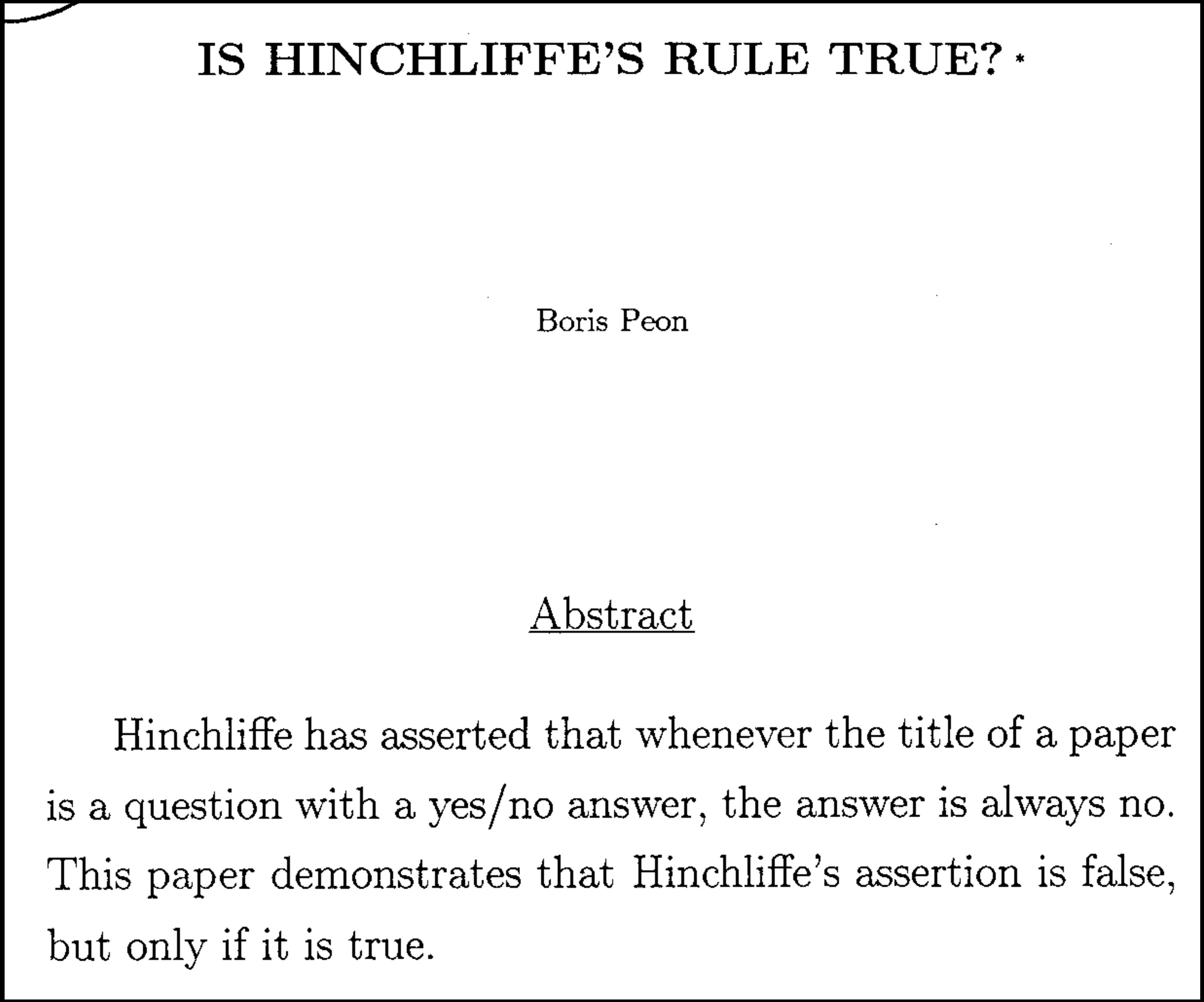
radiation $p = \rho/3$

vacuum $p = -\rho$

Planck (2013)

1 pJ = 10^{-12} J

Is dark matter an elementary particle?



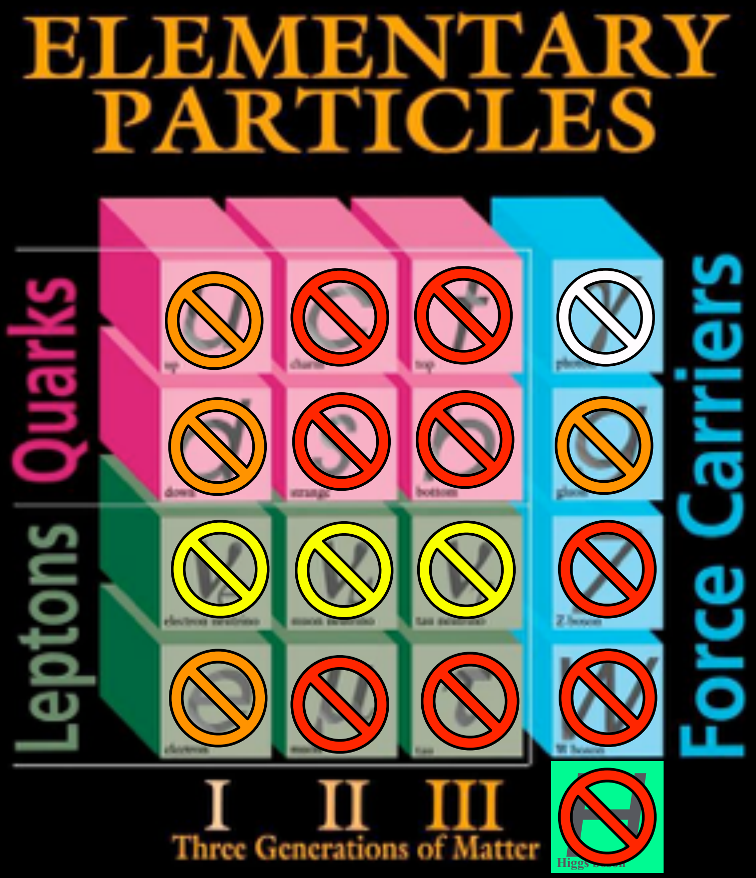
IS HINCHLIFFE'S RULE TRUE?[*]

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

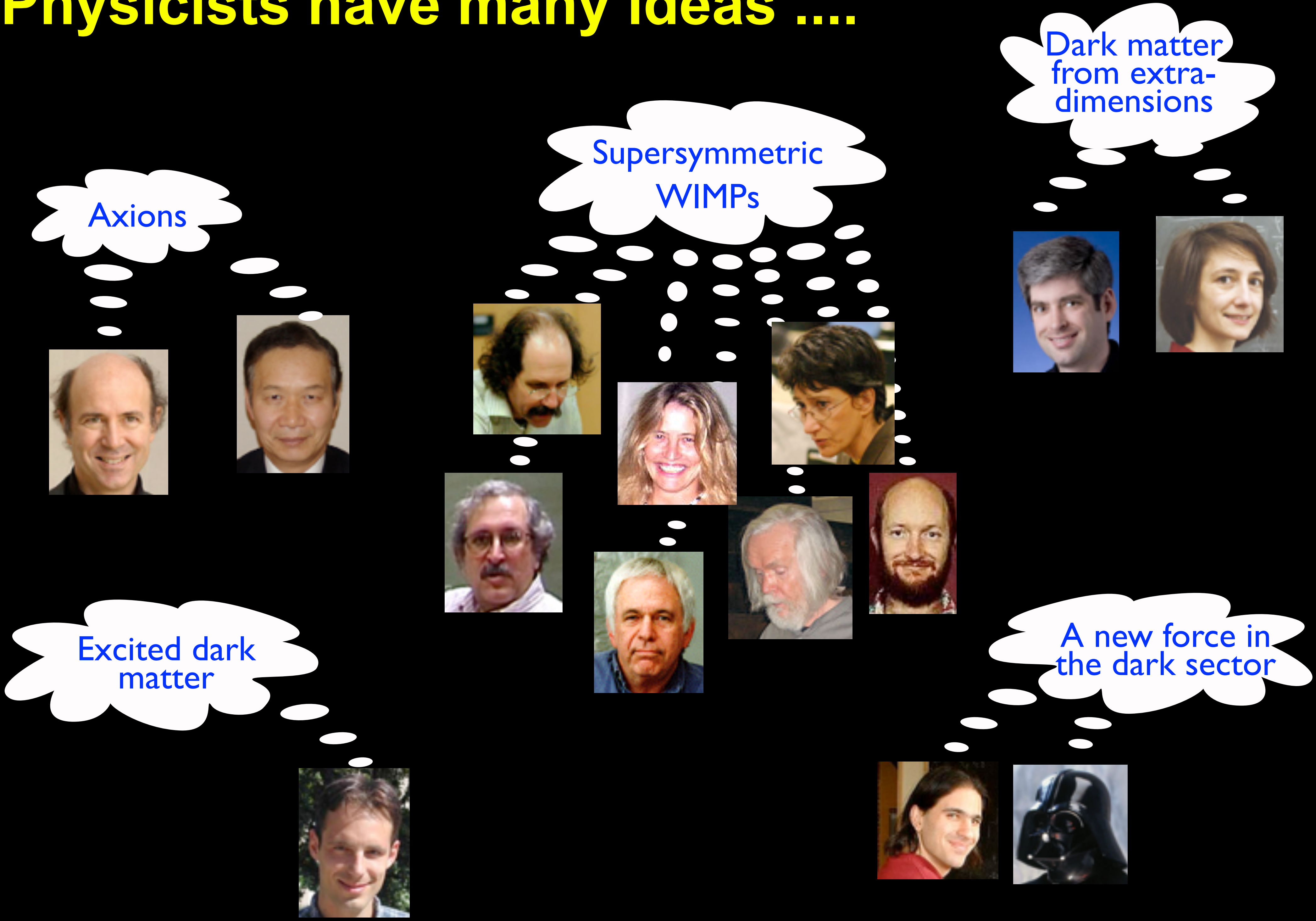
🚫 couples to the plasma

🚫 disappears too quickly

🚫 are hot dark matter

No known particle can be cold dark matter!

Physicists have many ideas ....



Axions

Supersymmetric WIMPs

Dark matter from extra-dimensions

Excited dark matter

A new force in the dark sector

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

Particle dark matter

Hot dark matter

- relativistic at kinetic decoupling (start of free streaming)
- big structures form first, then fragment

light neutrinos

Cold dark matter

- non-relativistic at kinetic decoupling
- small structures form first, then merge

neutralinos, axions, WIMPZILLAs, solitons

Warm dark matter

- semi-relativistic at kinetic decoupling
- smallest structures are erased

sterile neutrinos, gravitinos

Particle dark matter

Thermal relics

in thermal equilibrium in the early universe

neutrinos, neutralinos, other WIMPs, ...

Non-thermal relics

never in thermal equilibrium in the early universe

axions, WIMPZILLAs, solitons, ...

Particle Dark Matter

Type Ia Candidates that exist

Type Ib Candidates in well-motivated frameworks

Type II All other candidates

Particle Dark Matter

Type Ia Candidates that exist

Type Ib Candidates in well-motivated frameworks

- have been proposed to solve genuine particle physics problems, a priori unrelated to dark matter
- have interactions and masses specified within a well-defined particle physics model

Type II All other candidates

Particle Dark Matter

Type Ia Candidates that exist

standard neutrinos

Type Ib Candidates in well-motivated frameworks

heavy neutrinos, axion, lightest supersymmetric particle (neutralino, sneutrino, gravitino, axino), lightest Kaluza-Klein particle

Type II All other candidates

maverick WIMP, WIMPZILLA, B-balls, Q-balls, self-interacting dark matter, string-inspired dark matter, string-perspired dark matter, etc.

Axions

Axions as solution to the strong CP problem

The strong CP problem

In QCD, the *neutron electric dipole moment* d_n should be ~10^{-16} $e\mathrm{cm}$, but experimentally it is $d_n < 1.1 \times 10^{-26}\, e\mathrm{cm}$

The Peccei-Quinn solution

Introduce a new $U(1)_{PQ}$ symmetry and break it spontaneously at some energy scale f_a. The neutron e.d.m. is proportional to the vacuum phase (the axion*), which can dynamically be driven to zero.

At the QCD scale (~200 MeV), instantons generate an axion potential and an axion mass.

* *Wilczek introduced the name "axion" after a famous laundry detergent*

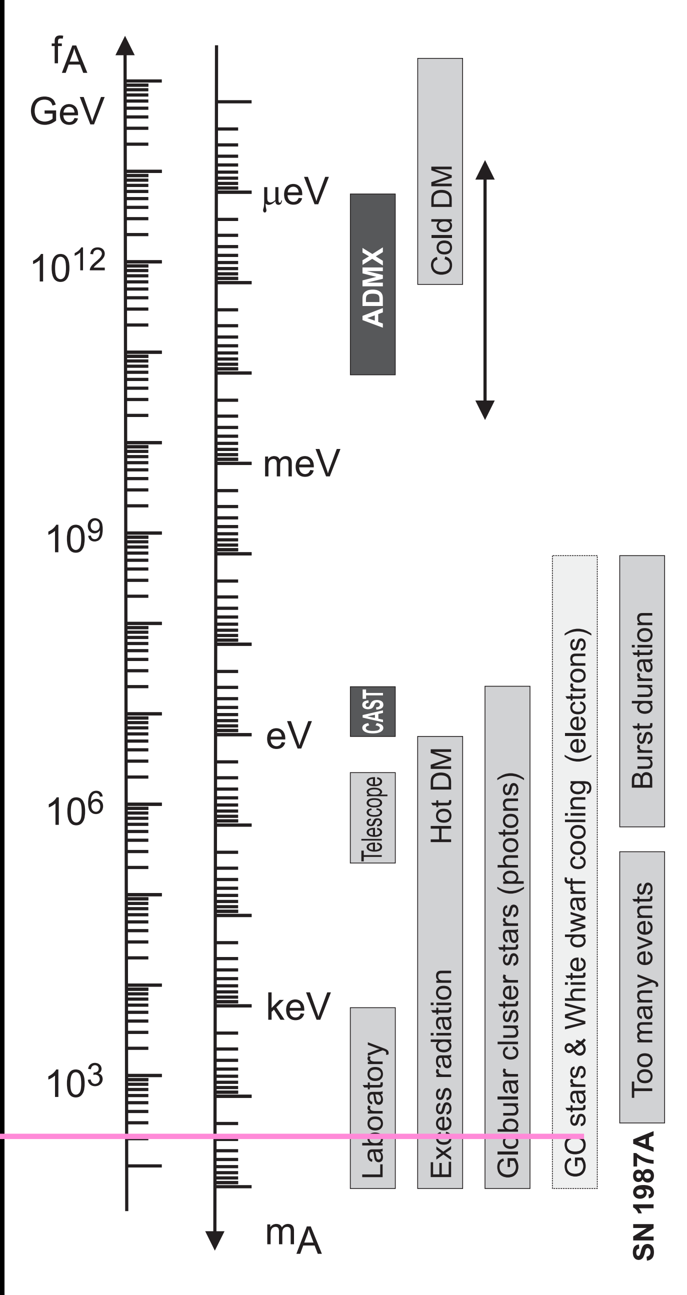
Axions

“Whenever you come up with a good idea,
somebody tries to copy it.”
(Axion Commercial with Arthur Godfrey, 1968)

Axions as solution to the strong CP problem

Constraints from laboratory searches and astrophysics

Peccei & Quinn had $f_a \sim 200\,\mathrm{GeV}$ (electroweak), with large axion-quark couplings quickly excluded by laboratory searches



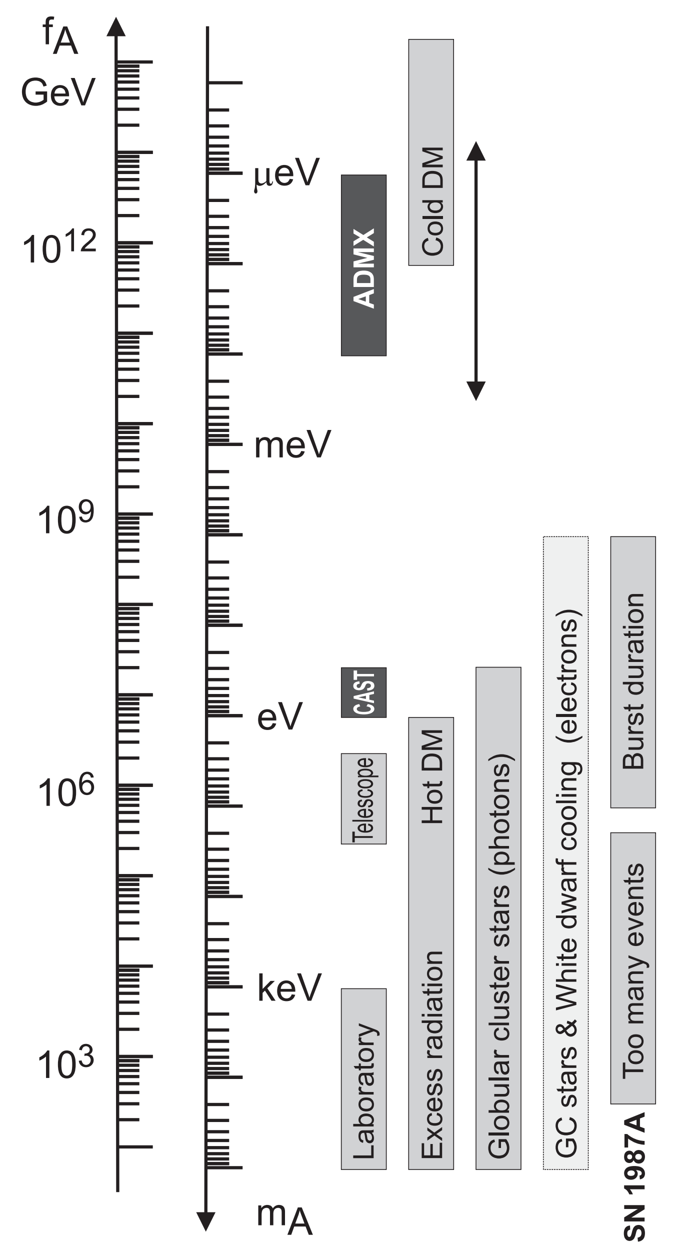
Raffelt, Rosenberg 2012

Axions as solution to the strong CP problem

Constraints from laboratory searches and astrophysics

Other models with much higher PQ scale f_a and suppressed axion-quark couplings were quickly found ("invisible axions")

Kim (1979)
Shifman, Vainshtein, Zakharov (1980)
Zhitnistki (1980)
Dine, Fischler, Srednicki (1981)



Raffelt, Rosenberg 2012

Axions as dark matter

Hot

Produced thermally in early universe

Important for $m_a > 0.1 eV$ $(f_a < 10^8)$*, mostly excluded by astrophysics*

Cold

Produced by coherent field oscillations around mimimum of $V(\theta)$

(Vacuum realignment)

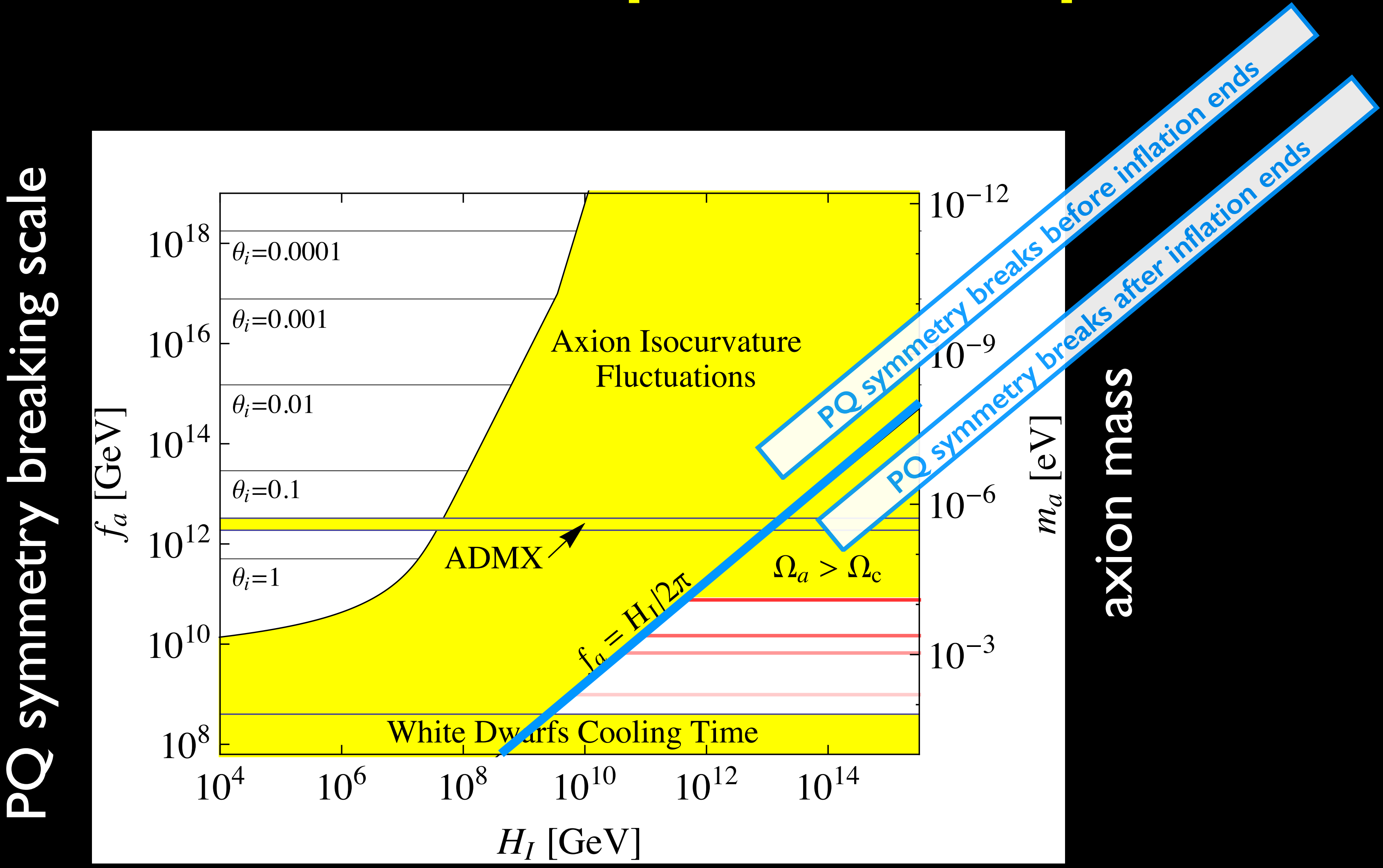
Produced by decay of topological defects

(Axionic string decays)

Still a very complicated and uncertain calculation!

e.g. Harimatsu et al 2012

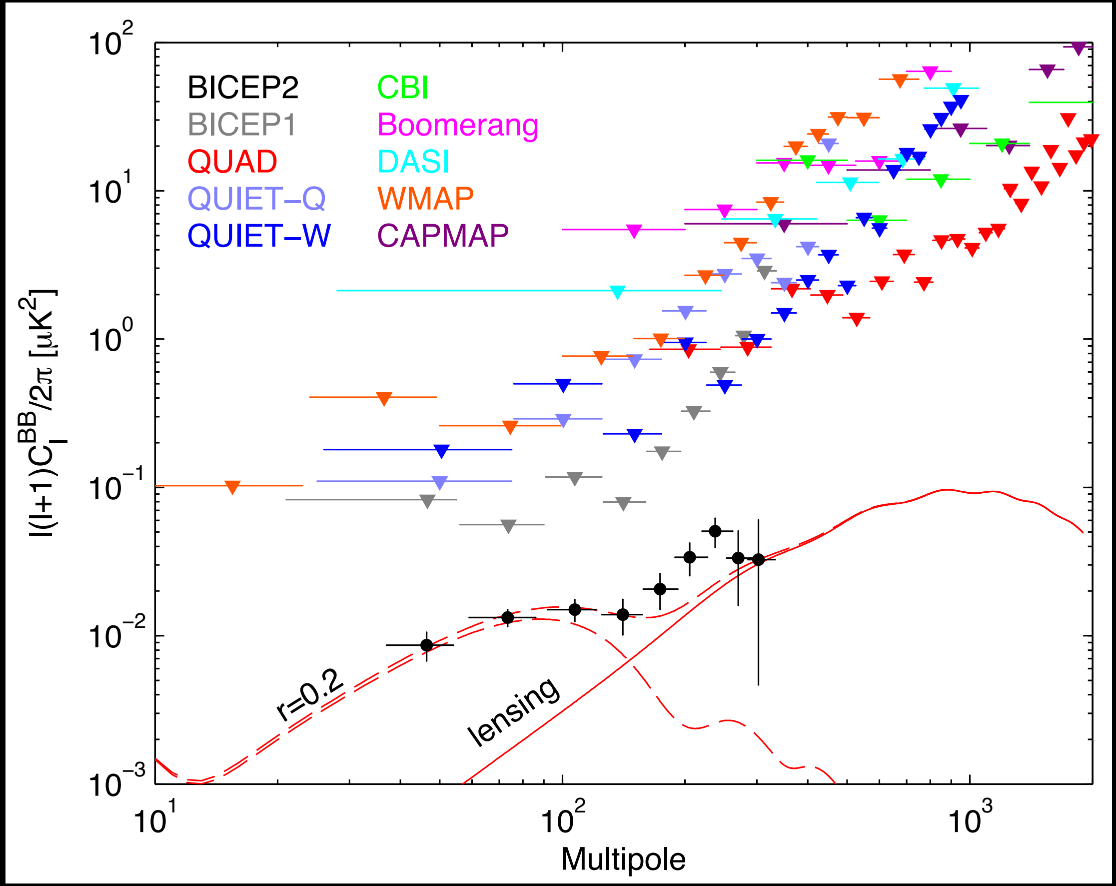
Axion cold dark matter parameter space



Expansion rate at end of inflation

Visinelli, Gondolo 2009 + updates

Gravitational waves from inflation?

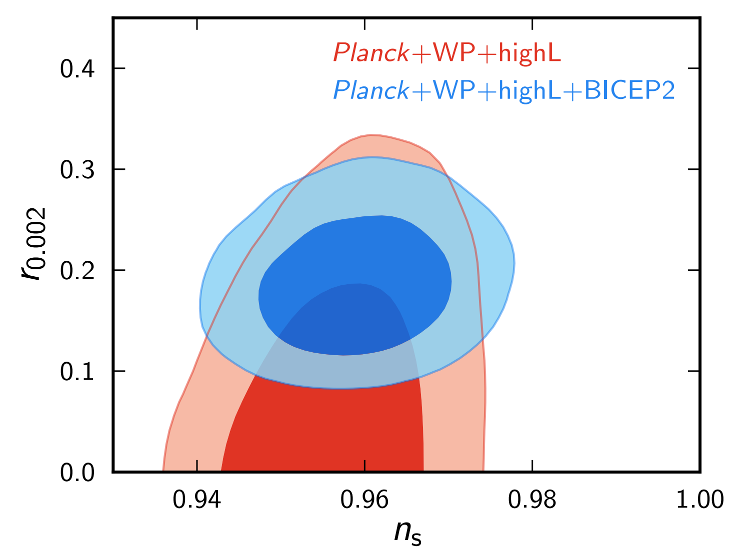


Ade et al (BICEP2) 1403.3985

CMB polarization measurements exhibit the divergence-free pattern typical of gravitational modes

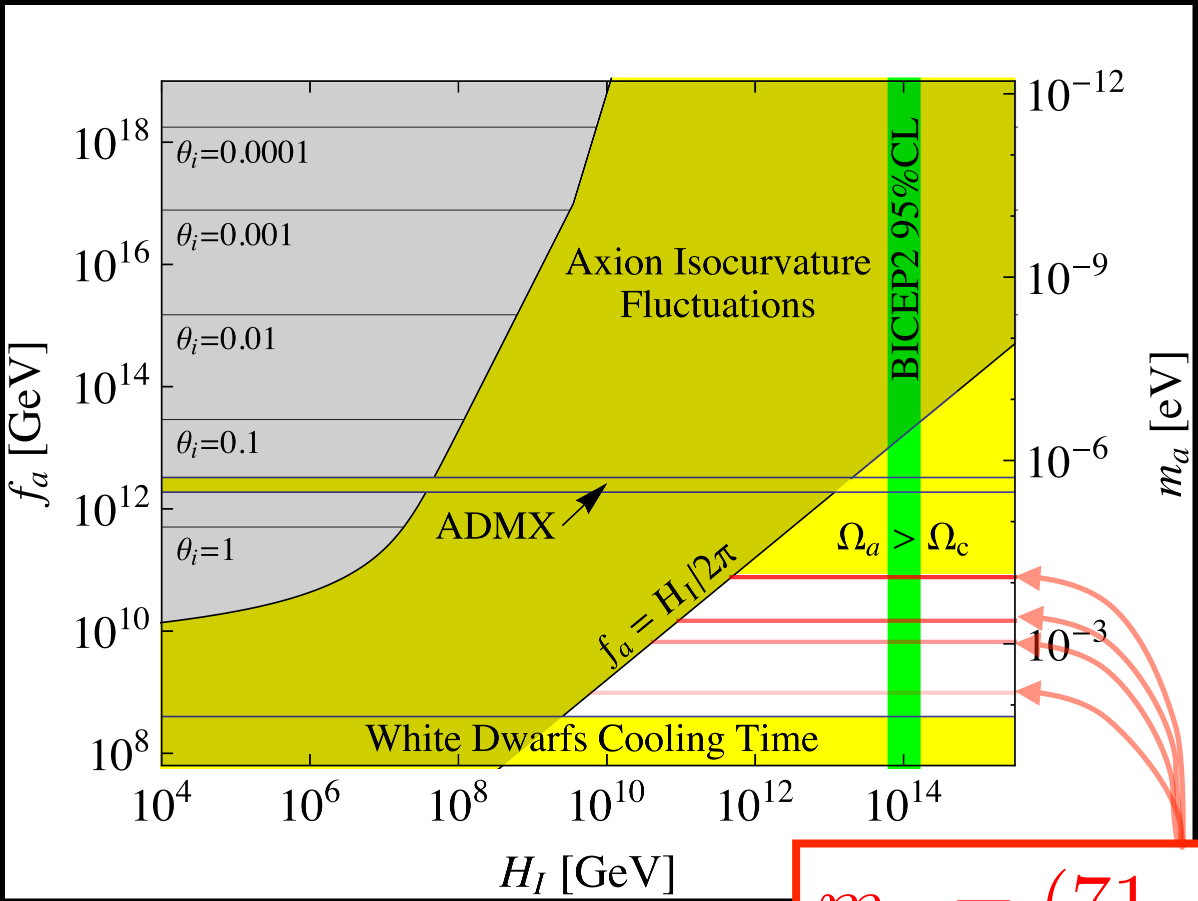
Tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$

Inflation scale $H_I = 1.1\times10^{14}$ GeV



Axion dark matter in view of BICEP2

Visinelli, Gondolo 2014



If BICEP2 has detected gravitational waves from inflation, then "half" of the axion dark matter parameter space is ruled out.

BICEP2 may have detected nothing more than dust

(Planck paper yesterday; joint analysis under way)

Adam et al 1409.5738

$$\boxed{m_a = (71 \pm 2)\,\mu\text{eV}\,(\alpha^{\text{dec}} + 1)^{6/7}}$$

See also Higaki et al 1403.4186, Marsh et al 1403.4216

Weakly Interacting Massive Particles

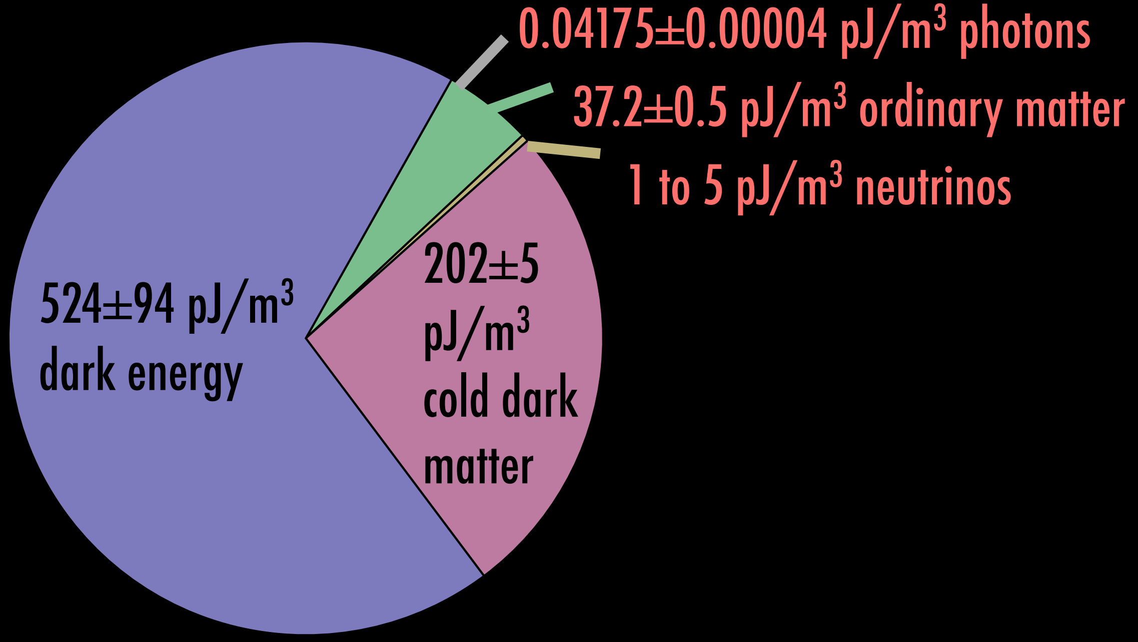
A whole class of particles

The magnificent WIMP

(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

  Thermal production in hot primordial plasma.



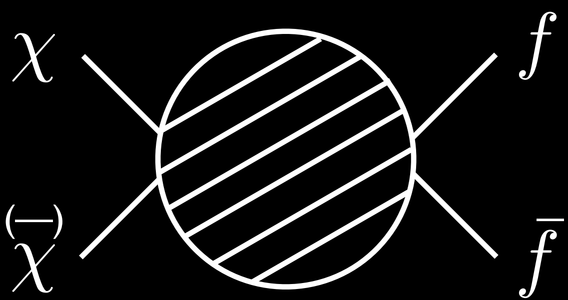
- One can experimentally test the WIMP hypothesis

  The same physical processes that produce the right density of WIMPs make their detection possible

Cosmic density of thermal WIMPs

- At early times, WIMPs are produced in e^+e^-, $\mu^+\mu^-$, etc collisions in the hot primordial soup [*thermal production*].

$$e^+ + e^-, \mu^+ + \mu^-, \text{etc.} \leftrightarrow \chi + \overset{(-)}{\chi}$$

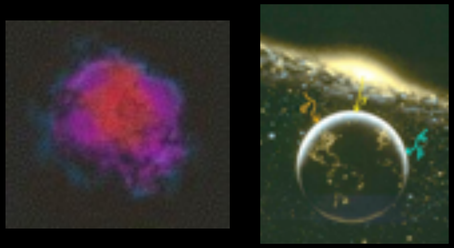


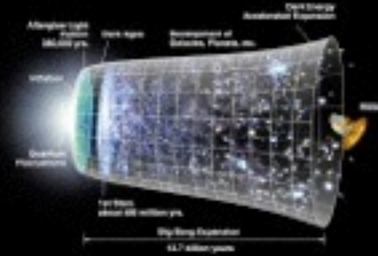
- WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate [*freeze-out*].

- After freeze-out, there is a constant number of WIMPs in a volume expanding with the universe.

The power of the WIMP

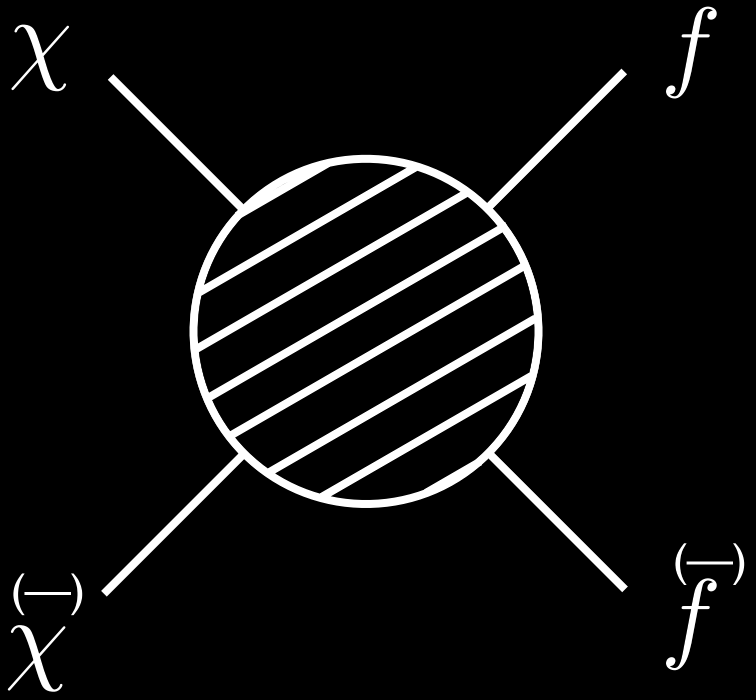
Indirect detection





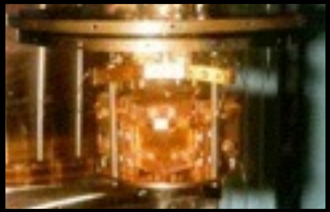
Cosmic density

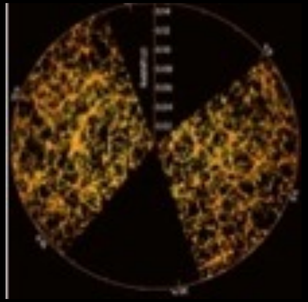
Annihilation



Scattering

Direct detection

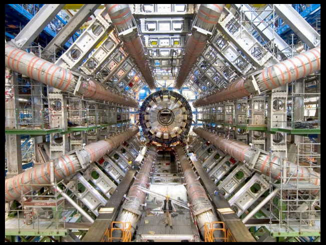


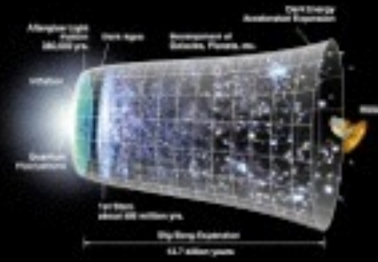


Large scale structure

Production

Colliders





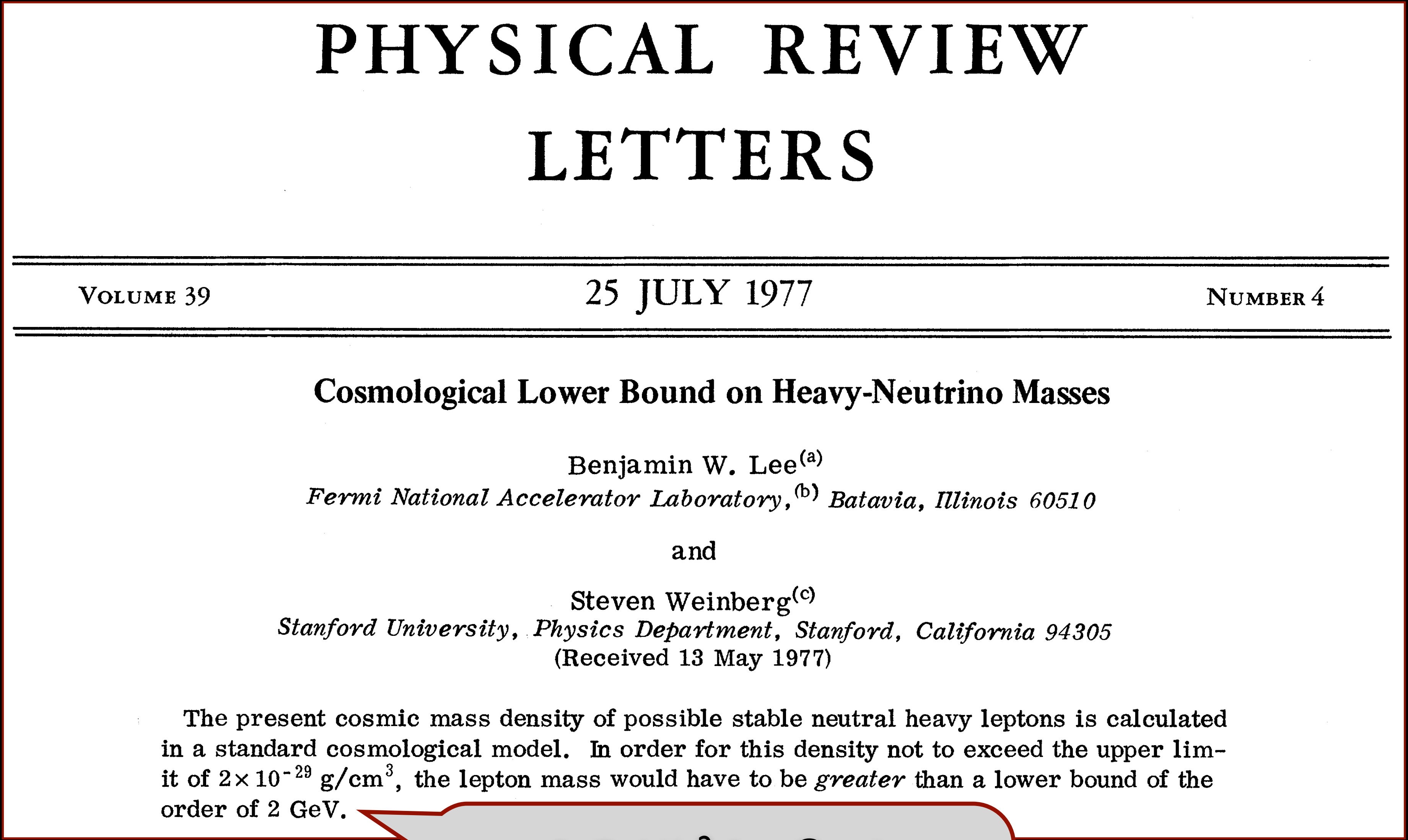
Cosmic density

Neutrinos

Active neutrinos

Excluded as cold dark matter but of pedagogical and historical importance

Heavy active neutrinos



PHYSICAL REVIEW
LETTERS

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Cosmological Lower Bound on Heavy-Neutrino Masses

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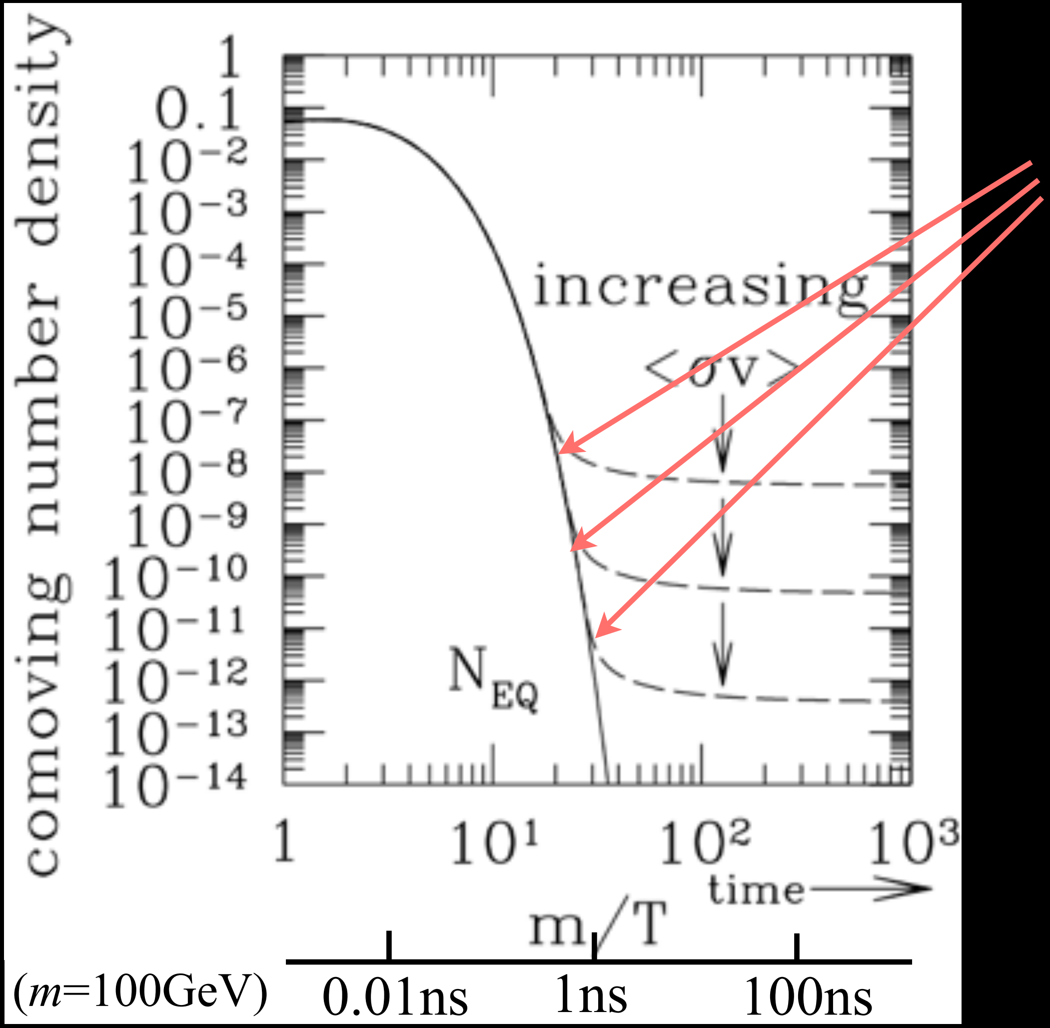
The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

2 GeV/c^2 for $\Omega_c=1$

Now 4 GeV/c^2 for $\Omega_c=0.25$

Cosmic density of heavy active neutrinos



freeze-out

$$\Gamma_{\rm ann} \equiv n\langle\sigma v\rangle \sim H$$

annihilation rate *expansion rate*

$$\Omega_\chi h^2 \simeq \frac{3\times10^{-27}{\rm cm}^3/{\rm s}}{\langle\sigma v\rangle_{\rm ann}}$$

$$\Omega_\chi h^2 = \Omega_{\rm cdm}h^2 \simeq 0.1143$$

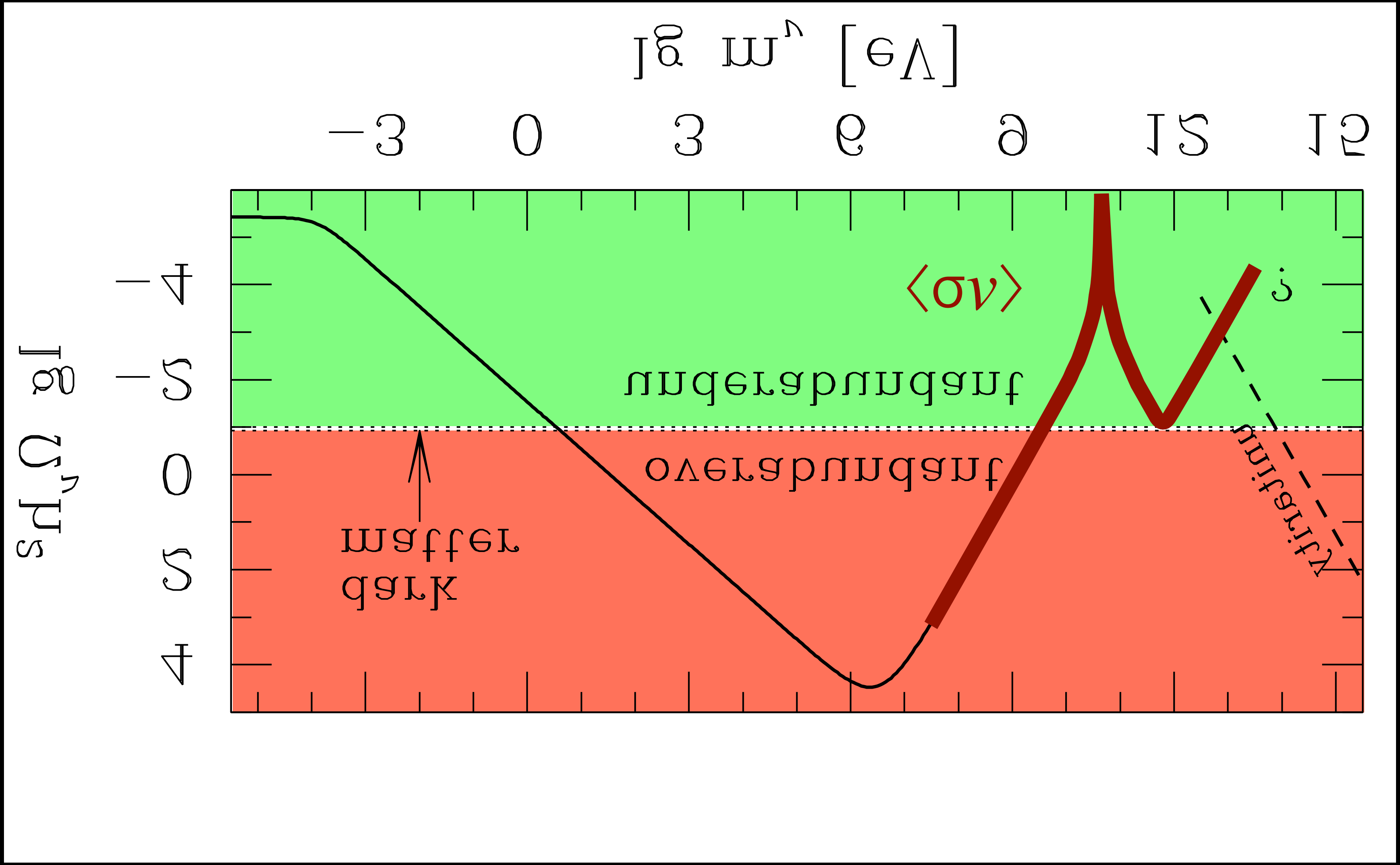
for $\langle\sigma v\rangle_{\rm ann} \simeq 3\times10^{-26}{\rm cm}^3/{\rm s}$

This is why they are called Weakly Interacting Massive Particles

(WIMPless candidates are WIMPs!)

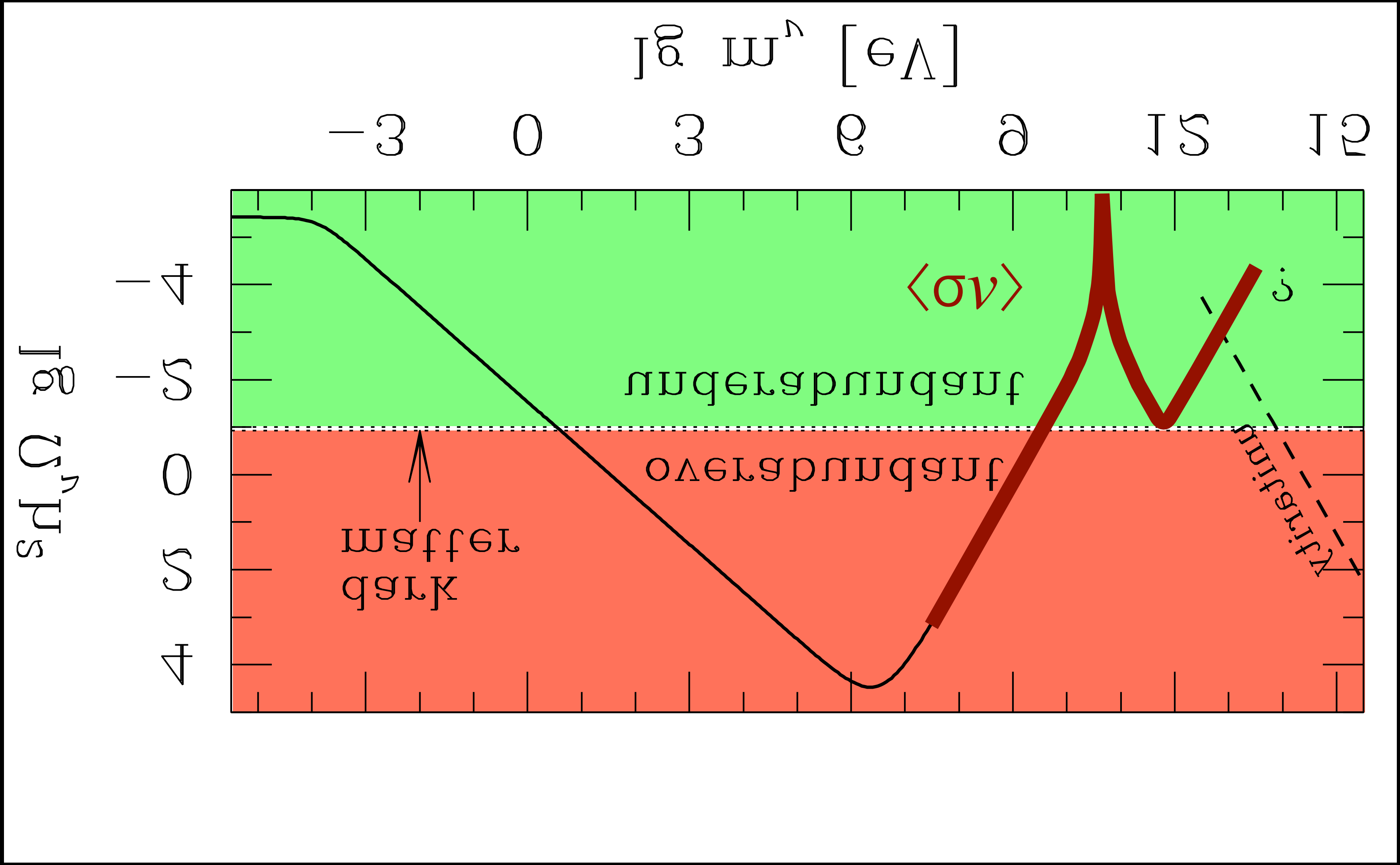
Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino



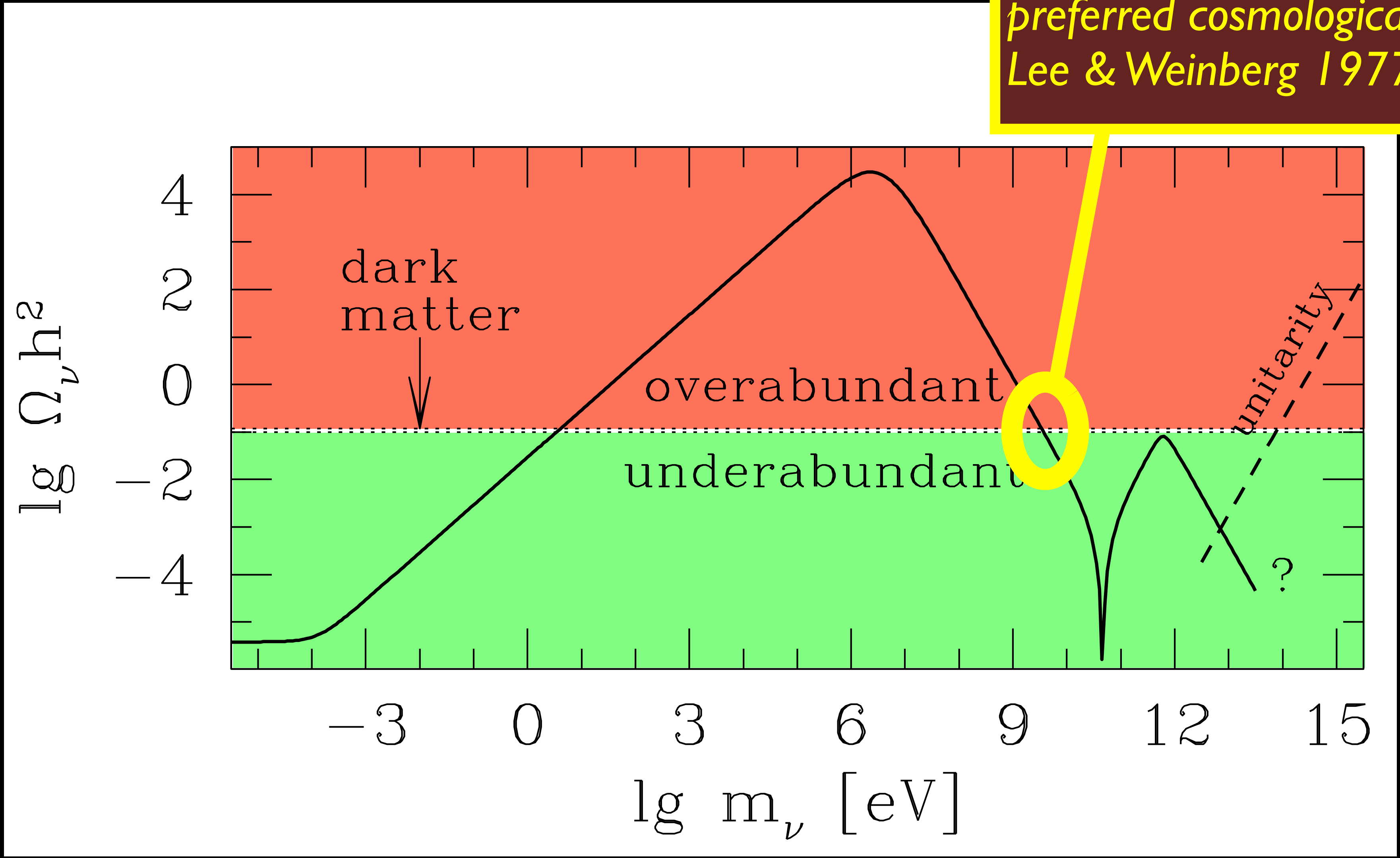
Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino



Cosmic density of massive neutrinos

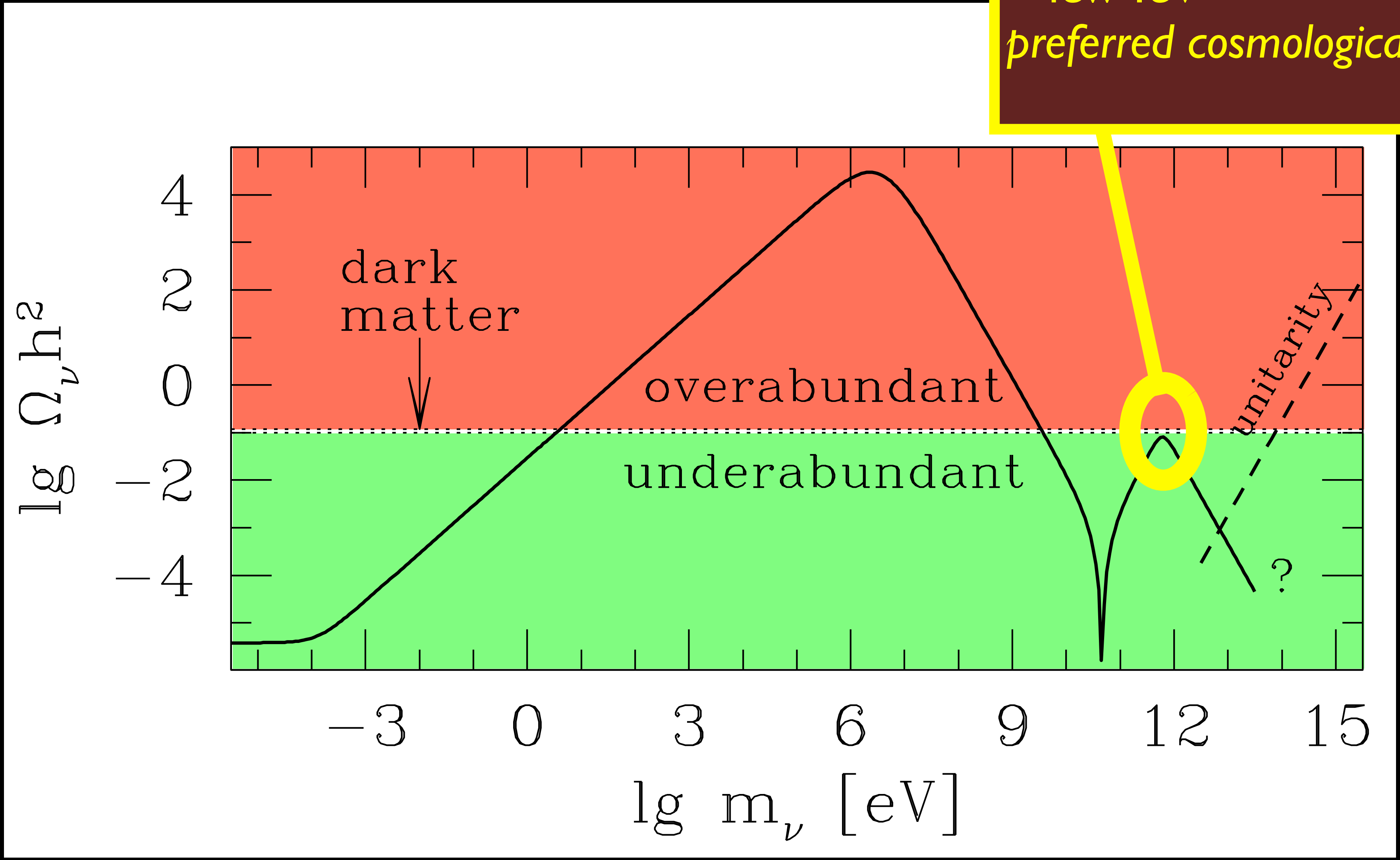
Fourth-generation Standard Model neutrin



~ few GeV
preferred cosmological mass
Lee & Weinberg 1977

Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrin

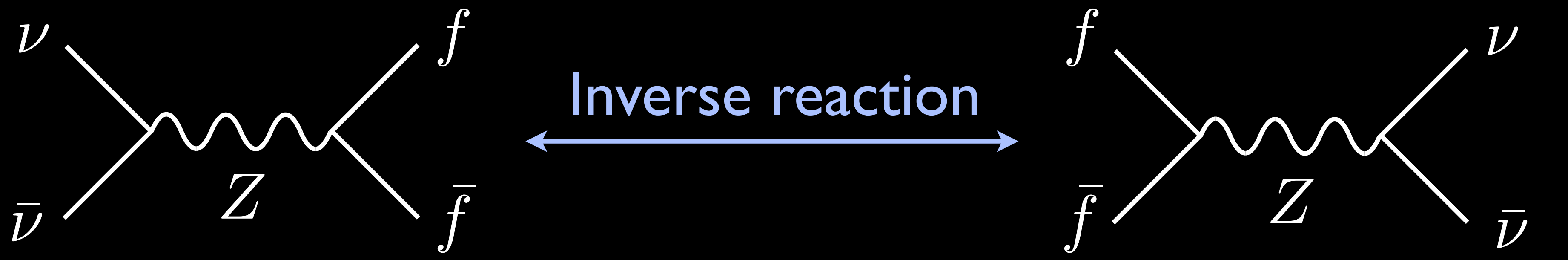


~ few TeV
preferred cosmological mass

Connection to colliders

Annihilation $\nu\bar{\nu} \to f\bar{f}$

Production $f\bar{f} \to \nu\bar{\nu}$



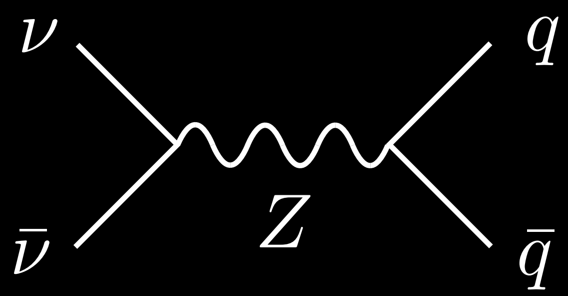
Inverse reaction

For example, a ~4 GeV/c² dark matter neutrino would be copiously produced in resonant Z boson decays

Excluded by LEP bound $Z \to \nu\bar{\nu}$

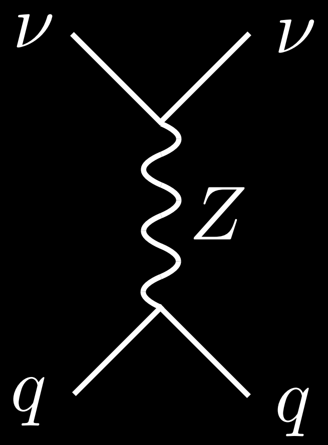
Connection to direct detection

Annihilation $\nu\bar{\nu} \longrightarrow q\bar{q}$



Crossing ↔

Scattering $\nu q \longrightarrow \nu q$

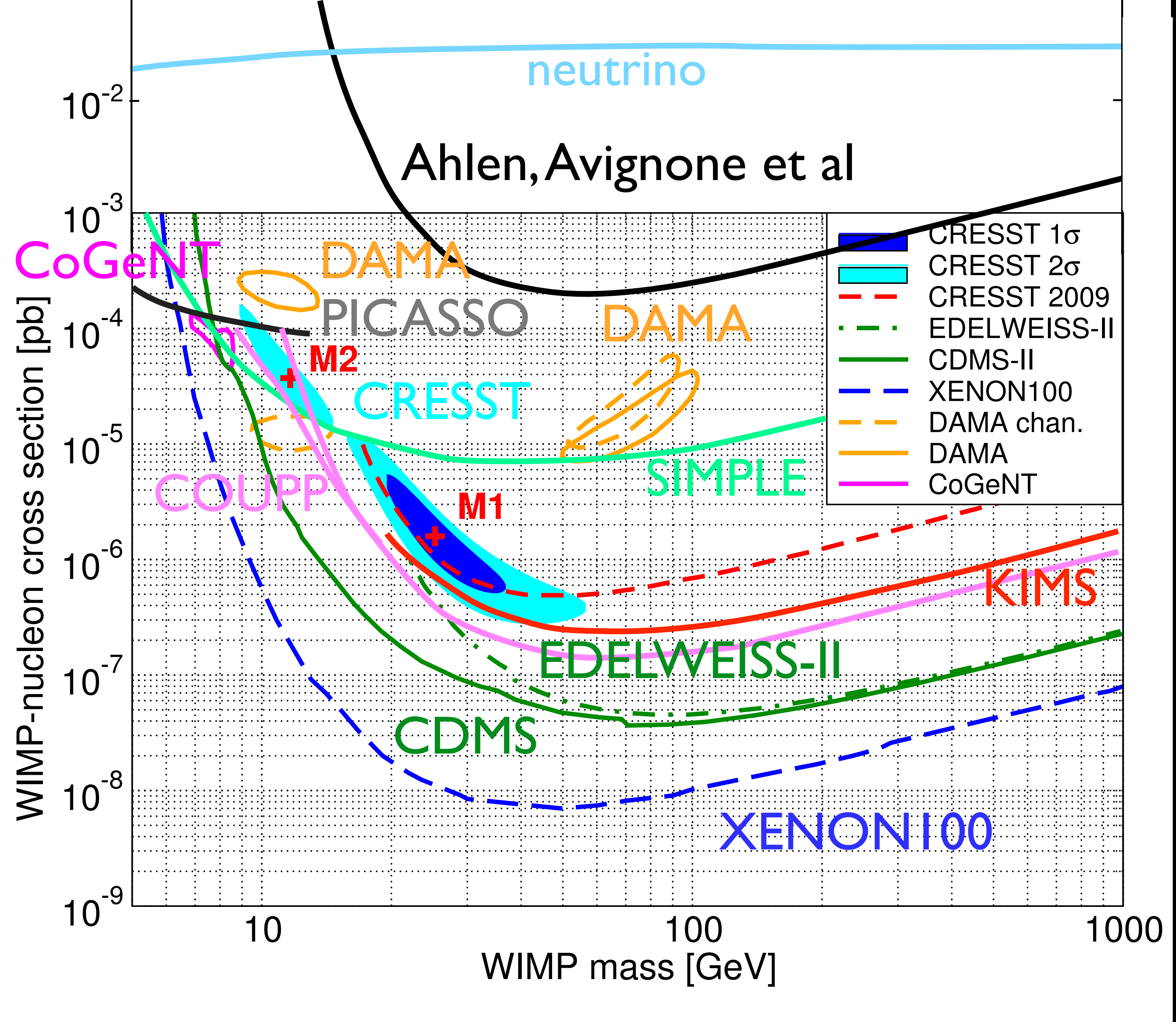


For example, for a ~4 GeV/c² dark matter neutrino, the scattering cross section is

$$\sigma_{\nu n} \simeq 0.01 \frac{\langle \sigma v \rangle}{c} \simeq 10^{-38}\,\mathrm{cm}^2$$

Excluded by direct searches

Spin-



1pb = 10^{-36} cm^2

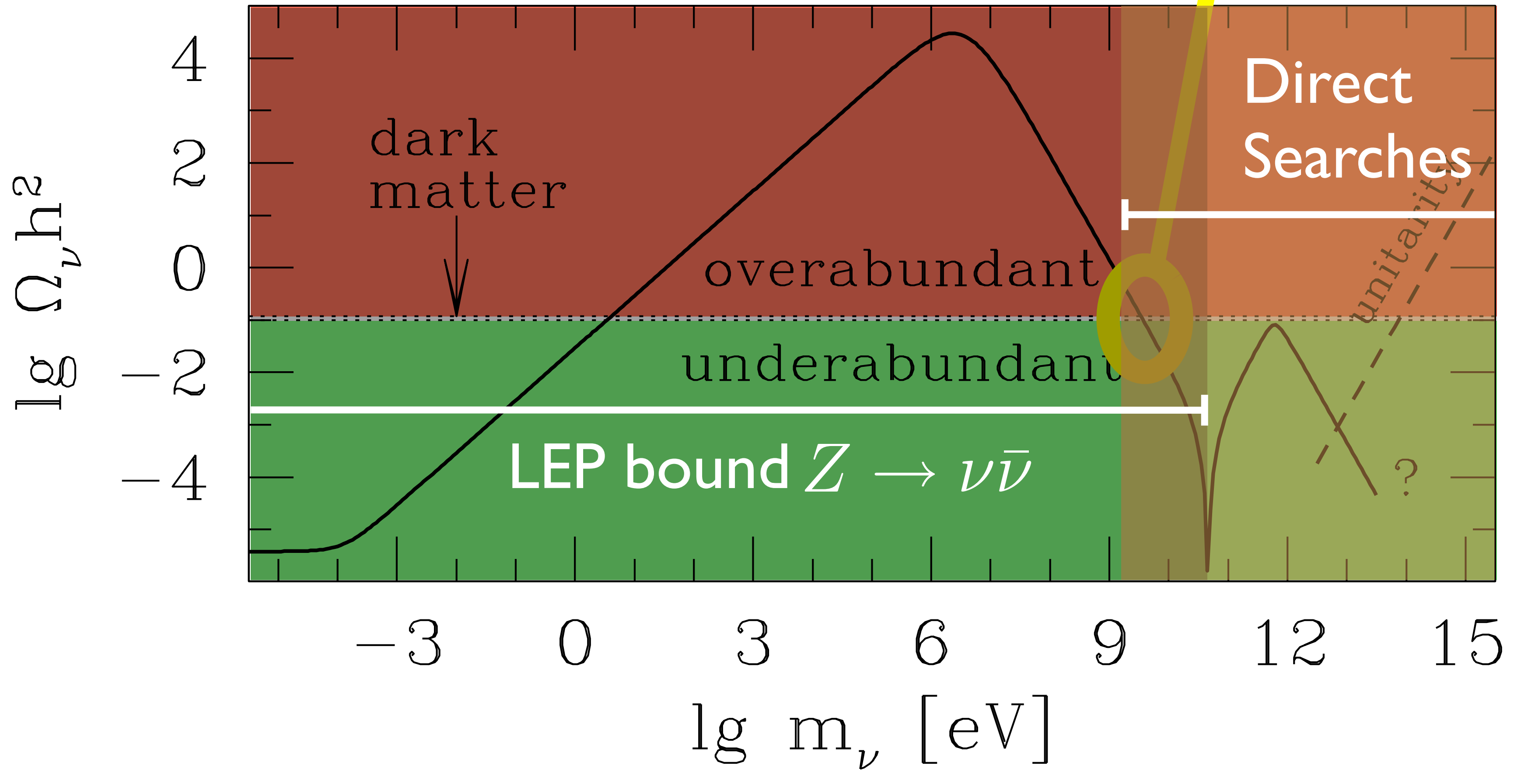
Updated from Anglehor et al 2011

Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrin

~ few GeV
preferred cosmological mass
Lee & Weinberg 1977

Excluded as dark matter (1991)



Sterile neutrinos

Neutrino oscillations

Neutrino flavors

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

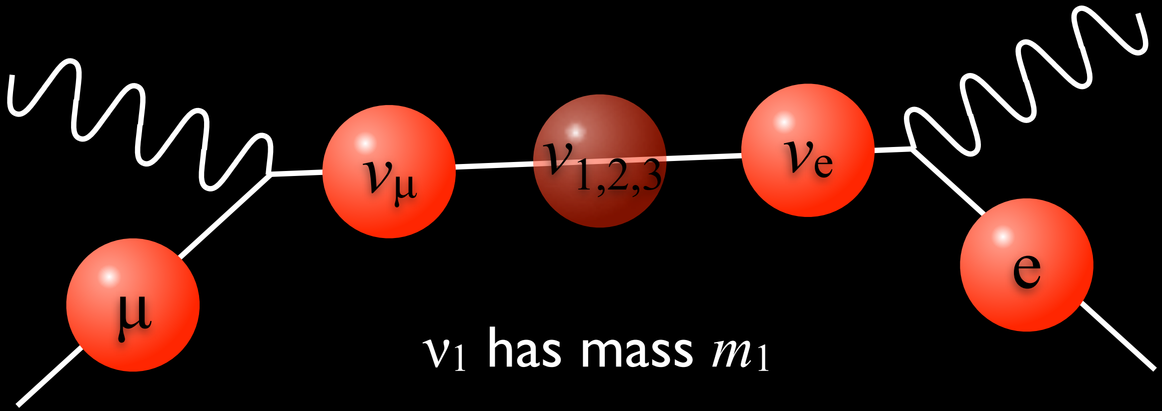
Electron-neutrinos are interaction partners of electrons

Muon-neutrinos are interaction partners of muons

Tau-neutrinos are interaction partners of taus

The neutrino flavor changes as the neutrino propagates

First suggested purely theoretically by Bruno Pontecorvo 1957



ν_1 has mass m_1

ν_2 has mass m_2

ν_3 has mass m_3

Sterile neutrino dark matter

Standard model + right-handed neutrinos

Neutrino mass eigenstates are obtained by diagonalization

$$\begin{cases} \nu_a = \cos\theta\,\nu_L - \sin\theta\,\nu_R^c \\ \nu_s = \sin\theta\,\nu_L + \cos\theta\,\nu_R^c \end{cases}$$

mixing angle θ

Active neutrinos ν_a are left-handed and have electroweak charges
Sterile neutrinos ν_s are right-handed and have no electroweak charge

Active and sterile neutrinos oscillate into each other.

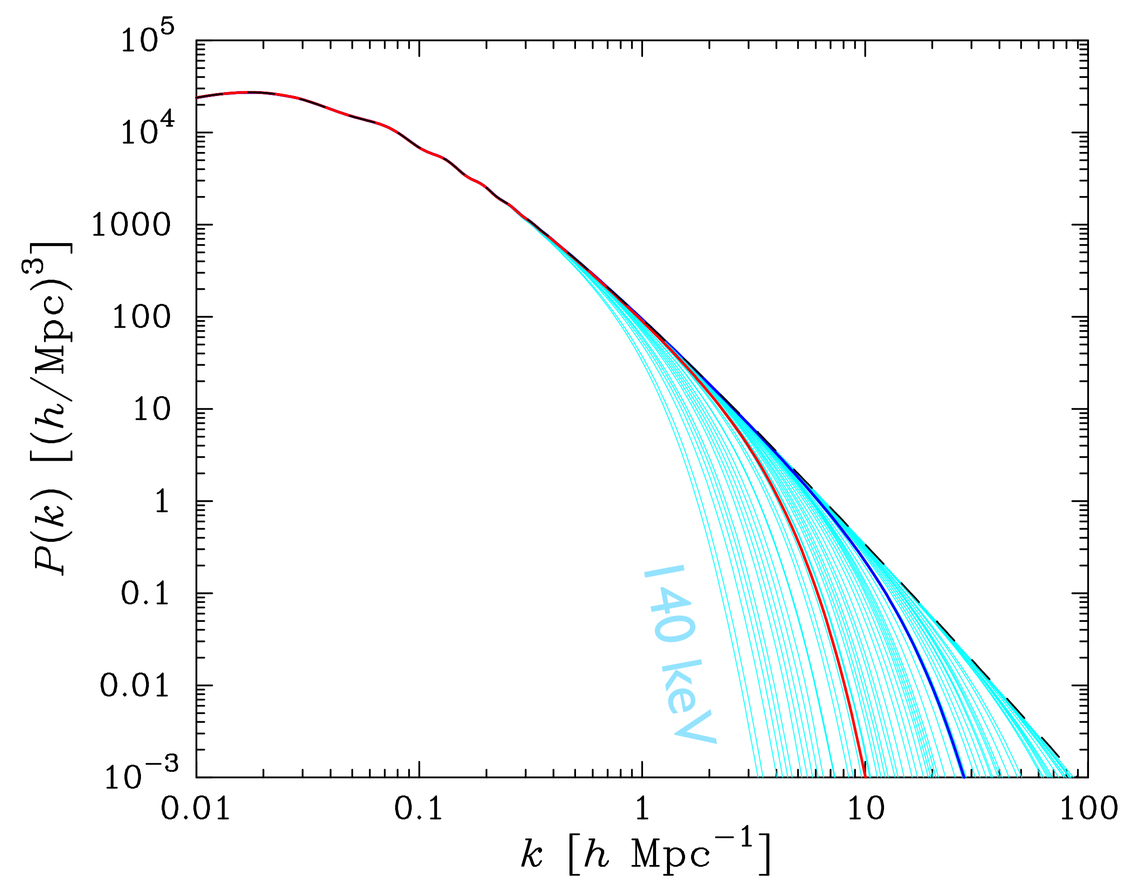
Sterile neutrinos can be warm dark matter (mass > 0.3 keV)

Dodelson, Widrow 1994; Shi, Fuller 1999; Laine, Shaposhnikov 2008

Limits on sterile neutrino dark matter

Sterile neutrinos are warm dark matter

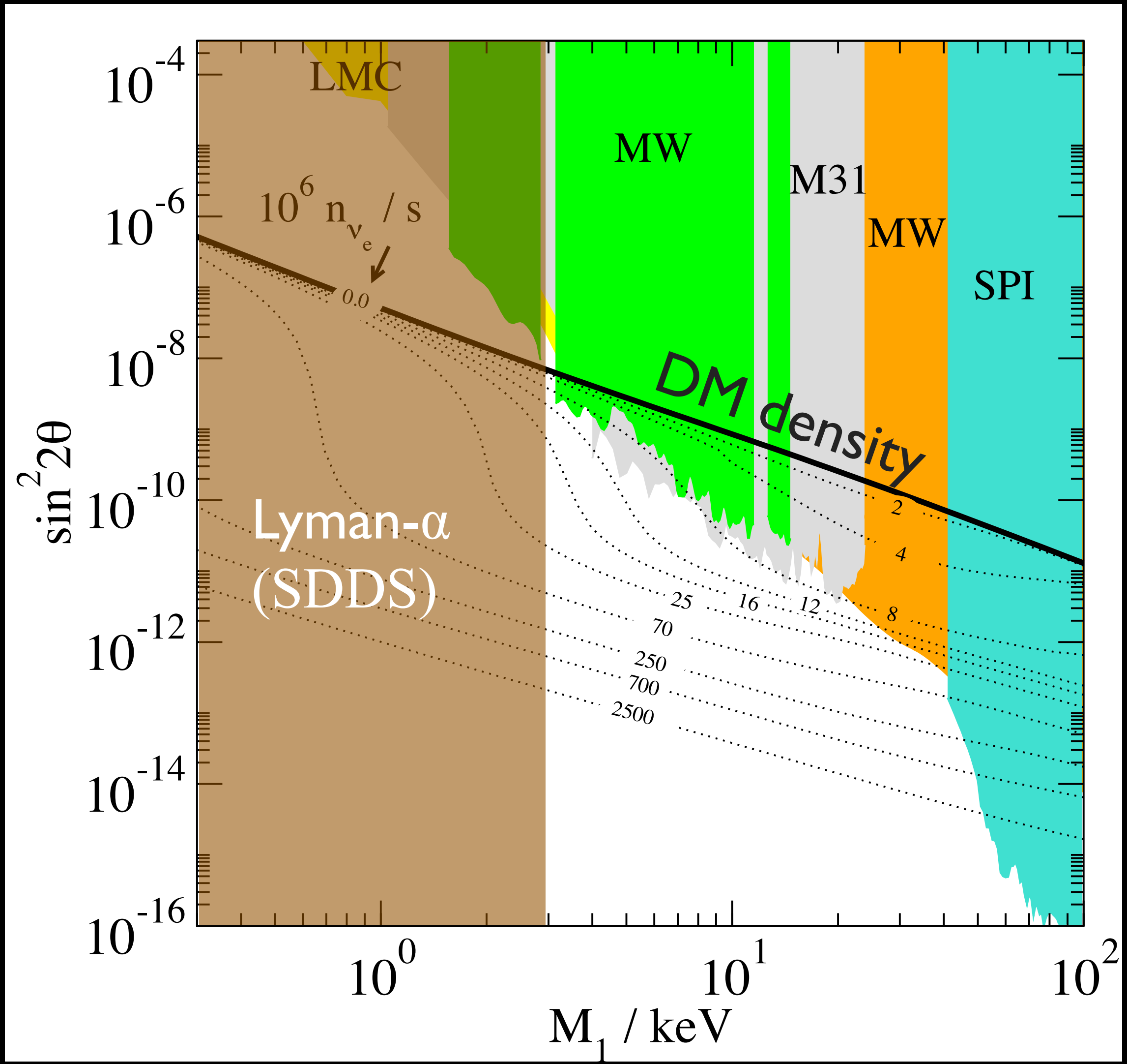
Small scale structure is erased



Abazajian 2005

Limits on sterile neutrino dark matter

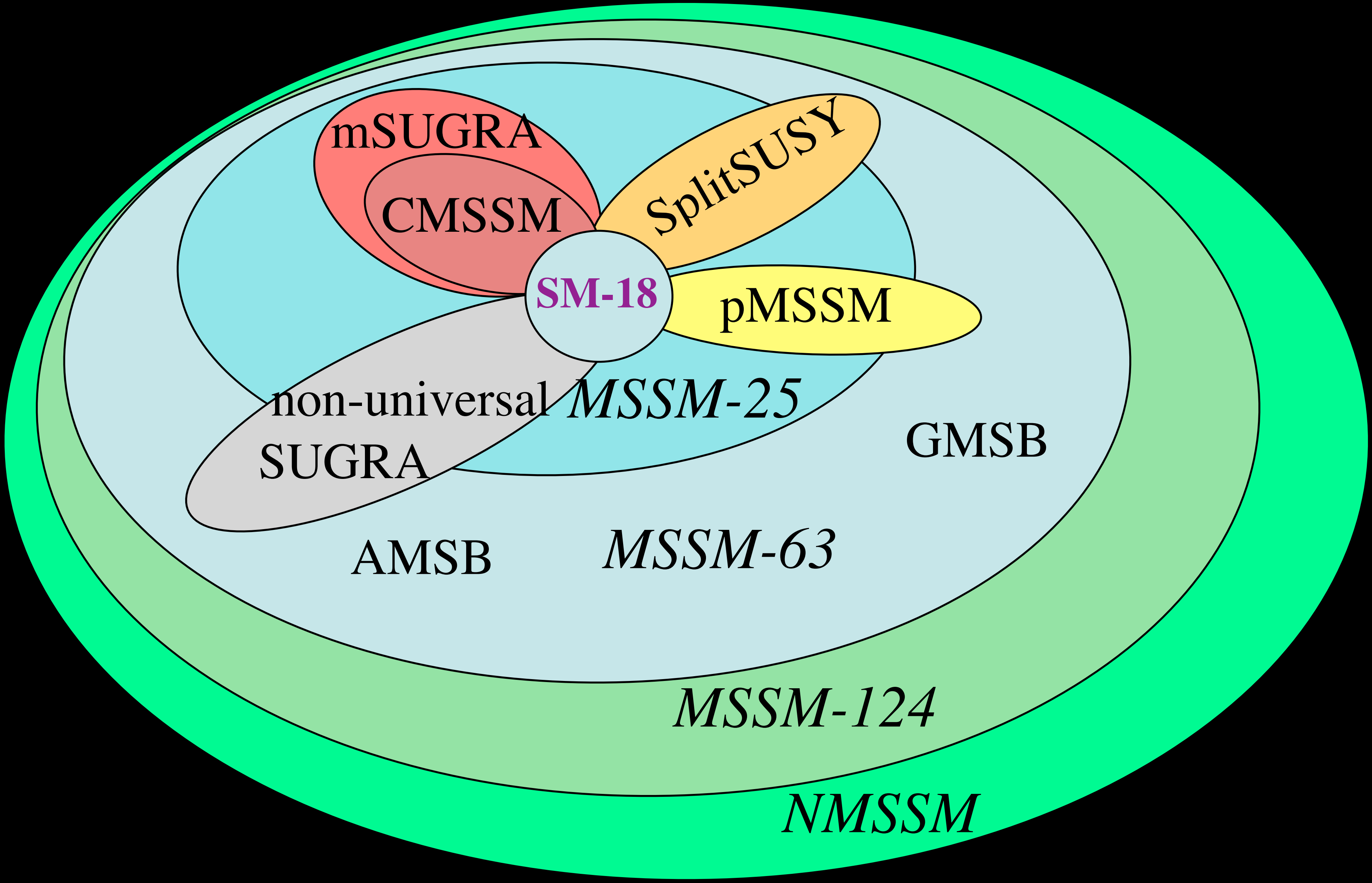
Compilation of limits on sterile neutrino dark matter in a model with three generations of sterile neutrinos (*ν*MSM)



Laine, Shaposhnikov 2008

Supersymmetric dark matter

Intersections of supersymmetric models



Supersymmetric dark matter

Neutralinos (the most fashionable/studied WIMP)

Goldberg 1983; Ellis, Hagelin, Nanopoulos, Olive, Srednicki 1984; etc.

Sneutrinos (also WIMPs)

Falk, Olive, Srednicki 1994; Asaka, Ishiwata, Moroi 2006; McDonald 2007; Lee, Matchev, Nasri 2007; Deppisch, Pilaftsis 2008; Cerdeno, Munoz, Seto 2009; Cerdeno, Seto 2009; etc.

Gravitinos (SuperWIMPs)

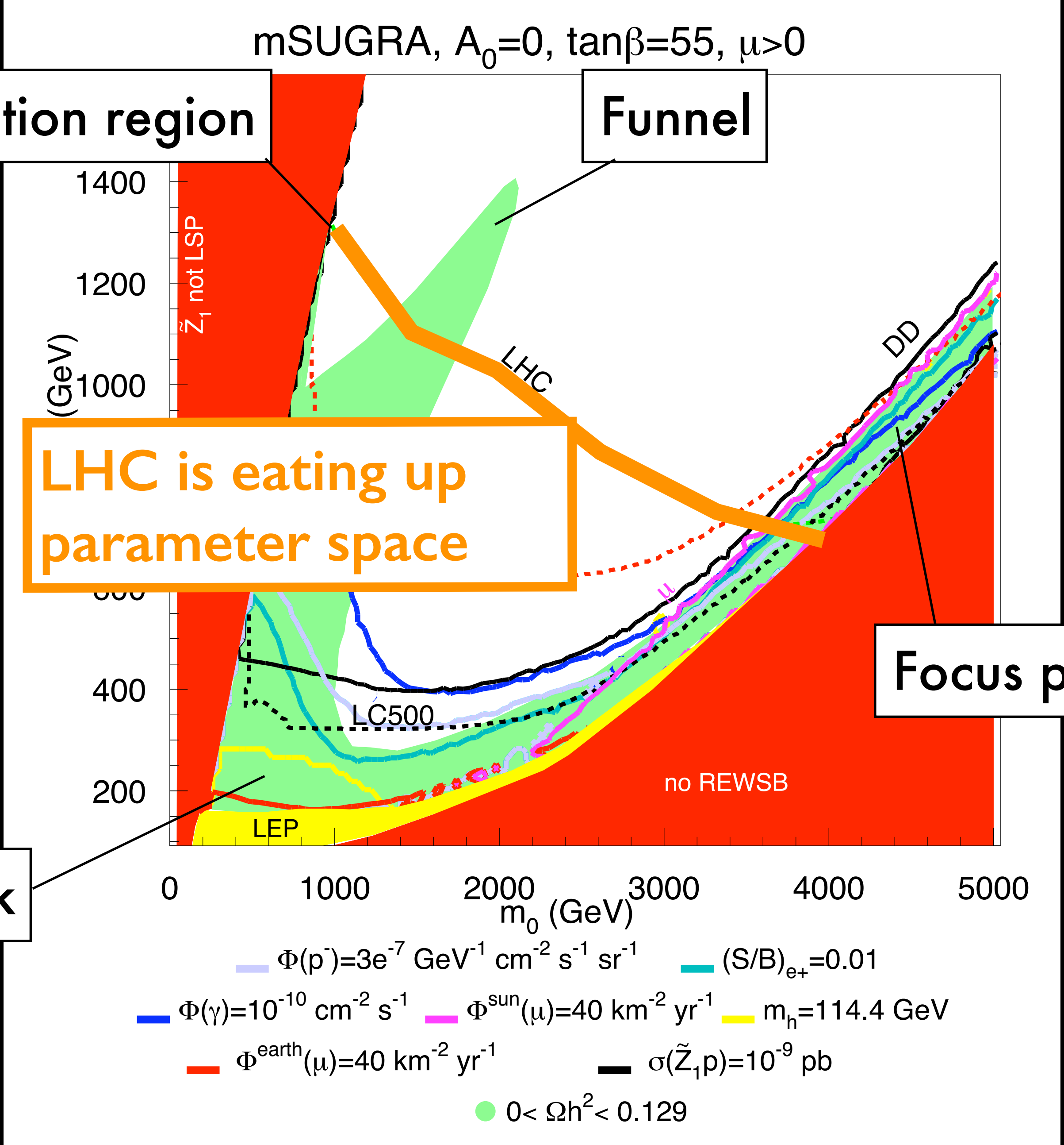
Feng, Rajaraman, Takayama 2003; Ellis, Olive, Santoso, Spanos 2004; Feng, Su, Takayama, 2004; etc.

Axinos (SuperWIMPs)

Tamvakis, Wyler 1982; Nilles, Raby 1982; Goto, Yamaguchi 1992; Covi, Kim, Kim, Roszkowski 2001; Covi, Roszkowski, Ruiz de Austri, Small 2004; etc.

Neutralino dark matter: minimal supergravity

Only in special regions the density is not too large.



Coannihilation region

Funnel

LHC is eating up parameter space

Focus point region

Bulk

Baer et al, hep-ph/0405210

Neutralino dark matter: impact of LHC

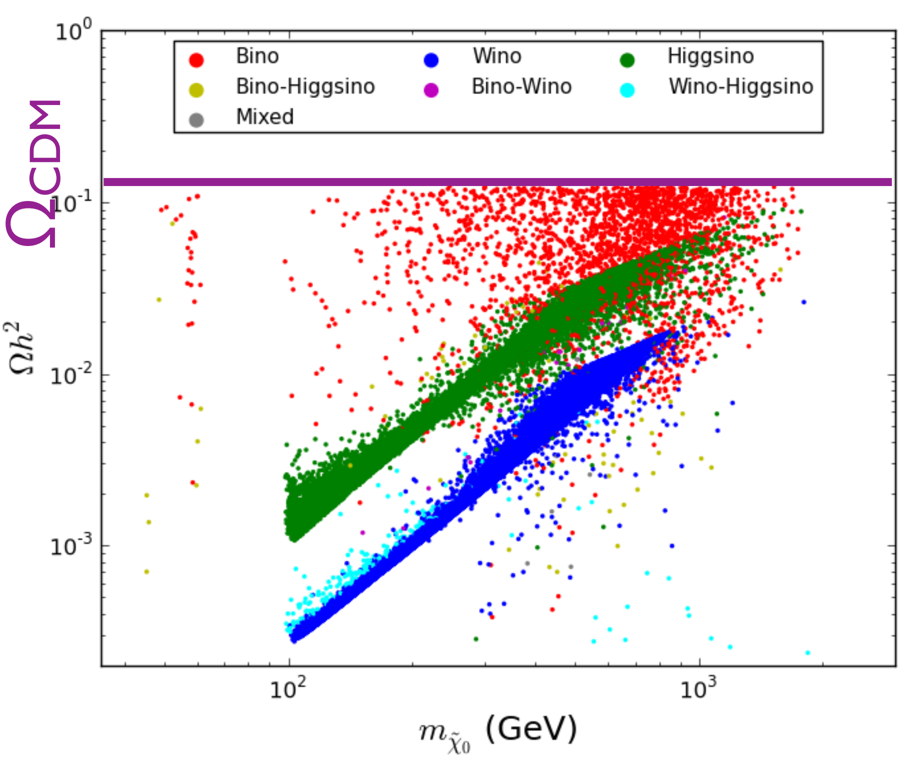
Cahill-Rowell et al 1305.6921

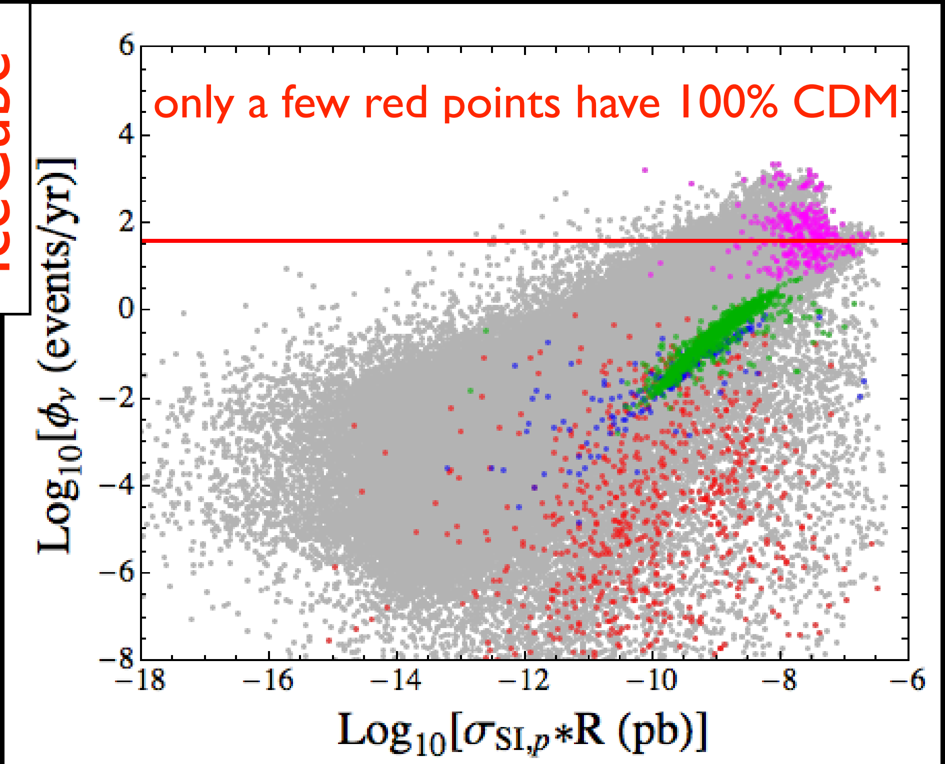
"the only pMSSM models remaining [with neutralino being 100% of CDM] are those with bino coannihilation"

pMSSM (phenomenological MSSM)

$$\mu, m_A, \tan\beta, A_b, A_t, A_\tau, M_1, M_2, M_3,$$
$$m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3},$$
$$m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}$$

(19 parameters)





only a few red points have 100% CDM

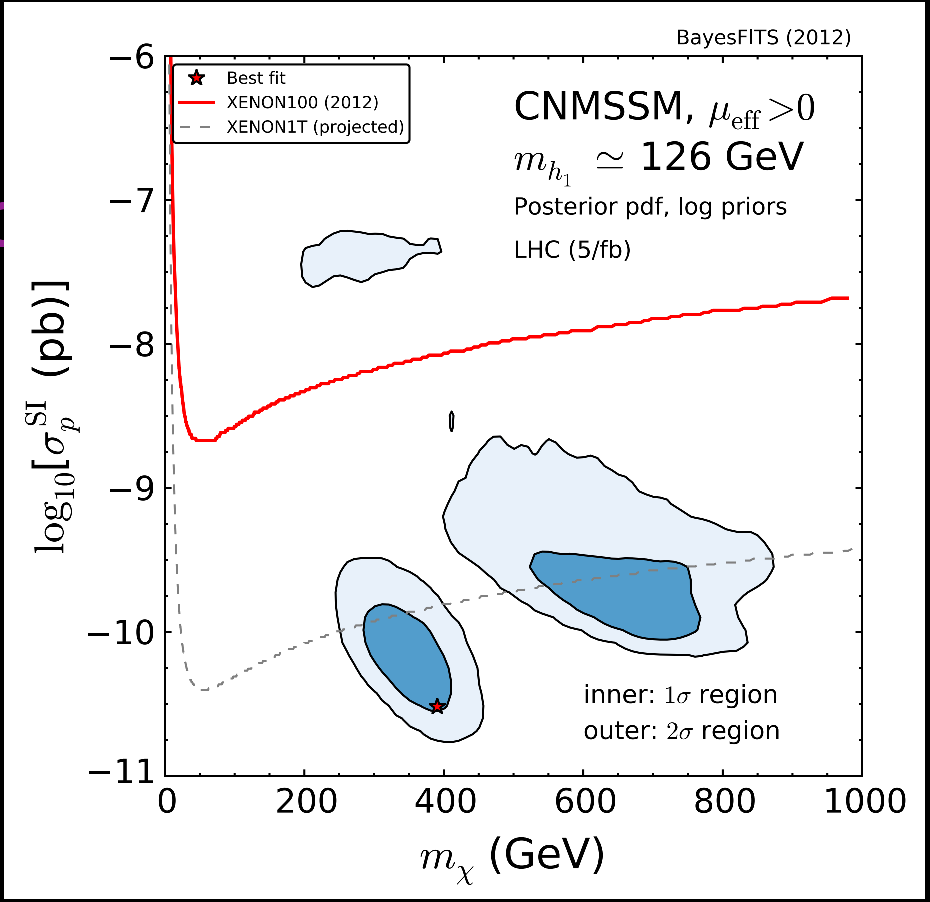
"IceCube"

"Direct Detection"

Neutralino dark matter: impact of LHC

Kowalska et al 1211.1693 [PRD 87(2013)115010]

CNMSSM: Alive and well!



NMSSM (Next-to-MSSM)

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 + (\text{MSSM Yukawa terms}),$$

$$V_{\rm soft} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{H.c.}\right),$$

Constrained NMSSM

$m_0, m_{1/2}, A_0, \tan\beta, \lambda, \text{sgn}(\mu_{\rm eff})$,

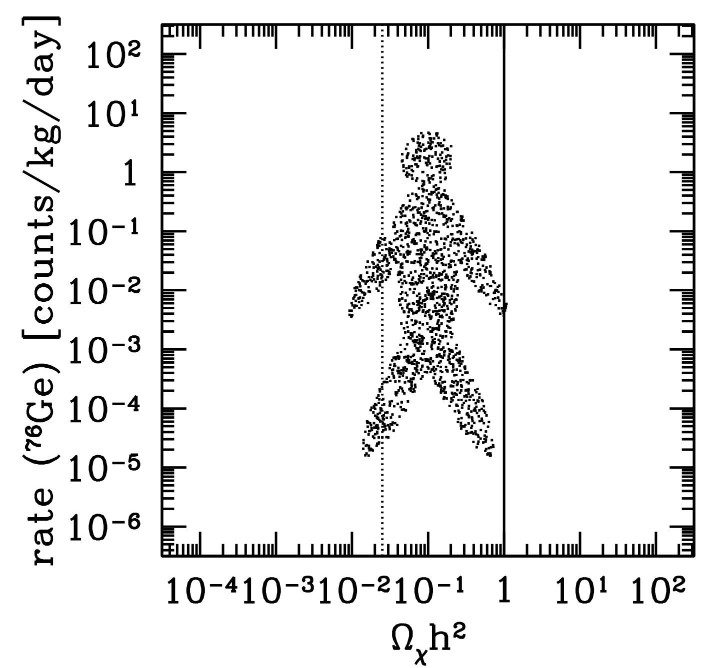
GUT & radiative EWSB

Marginalized 2D posterior PDF of global analysis including LHC, WMAP, $(g\text{-}2)_\mu$, $B_s \to \mu^+\mu^-$ etc.

The density of points in parameter space

- Density of points depends on priors in parameters
- Priors describe our beliefs in the value of the model parameters
- What is a sensible prior for M_2, say?
  - Flat in M_2? Flat in $\log(M_2)$? Exponential in $\arctan(M_2)$?

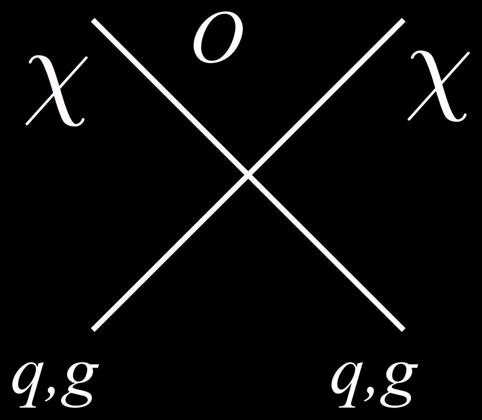
- Example: a scan in parameter space using an anthropic prior



Effective operator approach (maverick WIMP)

For the agnostics and the uncommitted

Effective operator approach



if mediator mass ≫ LHC energy scale

LHC limits on WIMP-quark and WIMP-gluon interactions are competitive with direct searches

Beltran et al, Agrawal et al., Goodman et al., Bai et al., 2010; Goodman et al., Rajaraman et al. Fox et al., 2011; Cheung et al., Fitzptrick et al., March-Russel et al., Fox et al., 2012.......

These bounds do not apply to SUSY, etc.

Complete theories contain sums of operators (interference) and not-so-heavy mediator (Higgs)

Effective operator approach

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

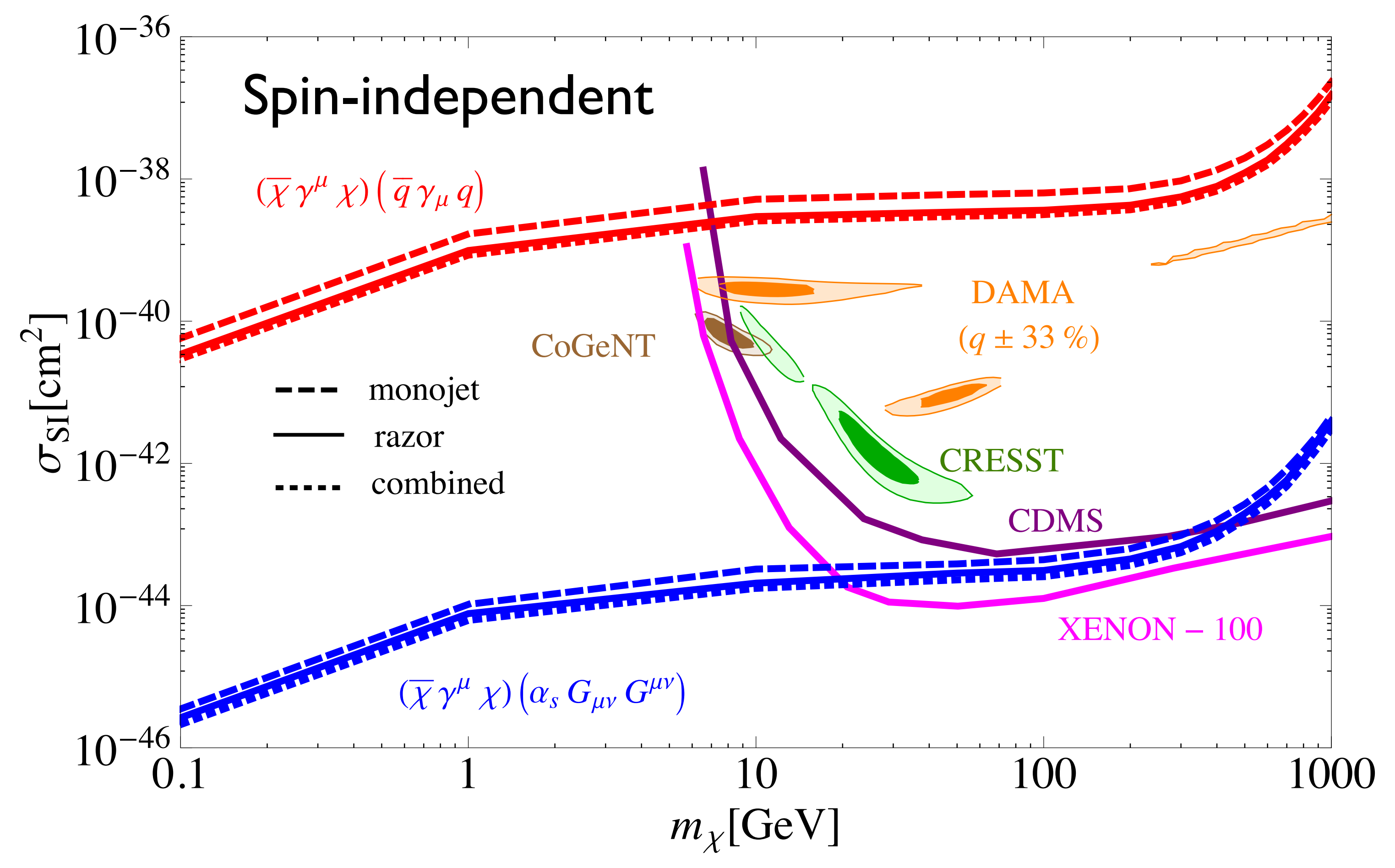
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Table of effective operators relevant for the collider/direct detection connection

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2010

Constraints on scattering cross section

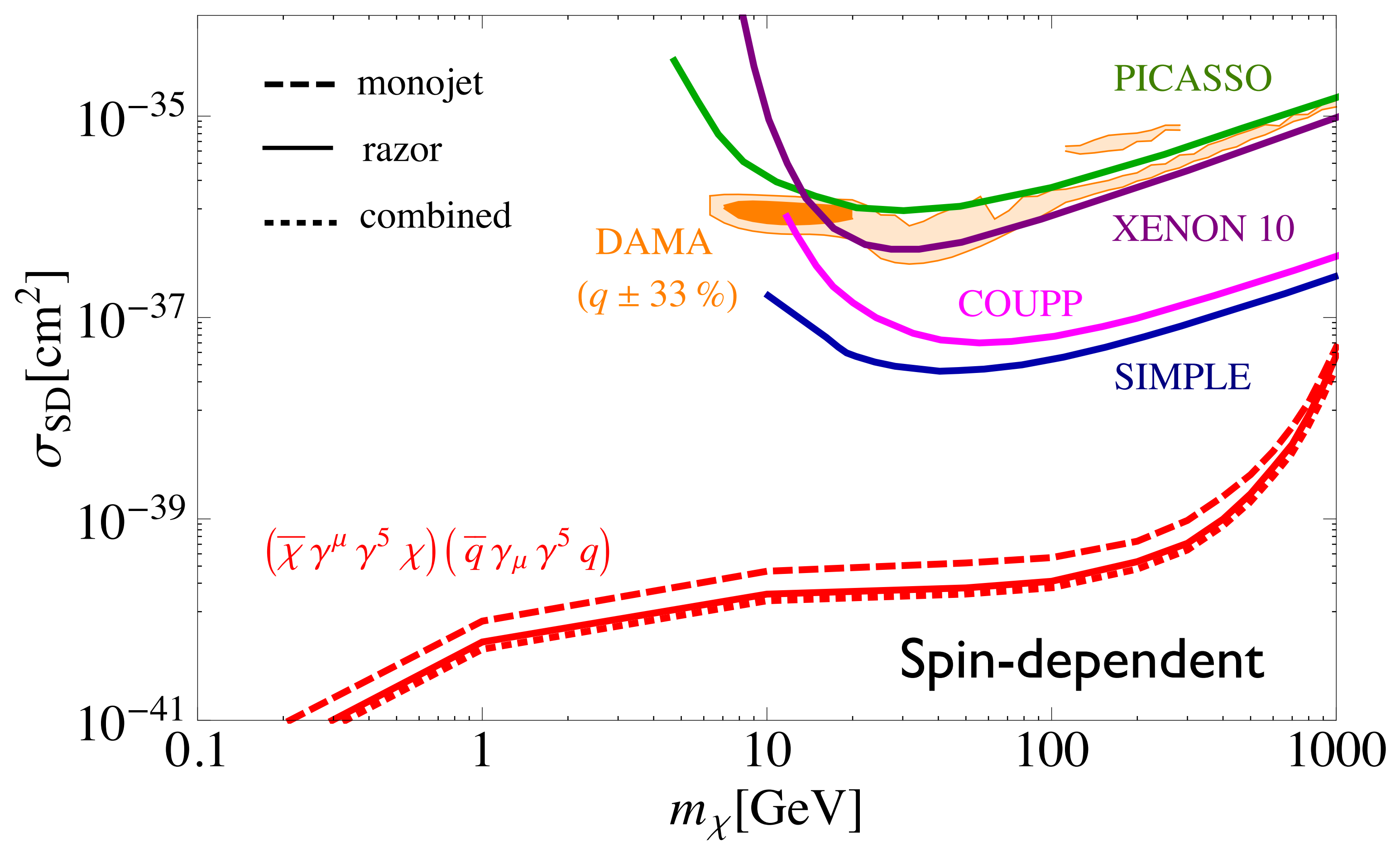
Direct detection and LHC



Fox, Harnik, Primulando, Yu 2012

Constraints on scattering cross section

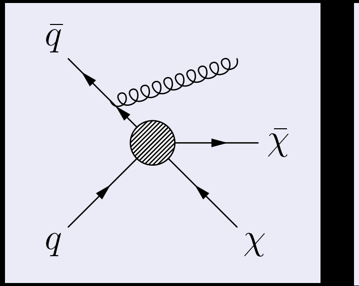
Direct detection and LHC

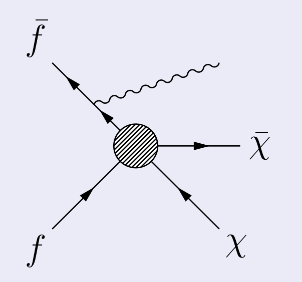


Fox, Harnik, Primulando, Yu 2012

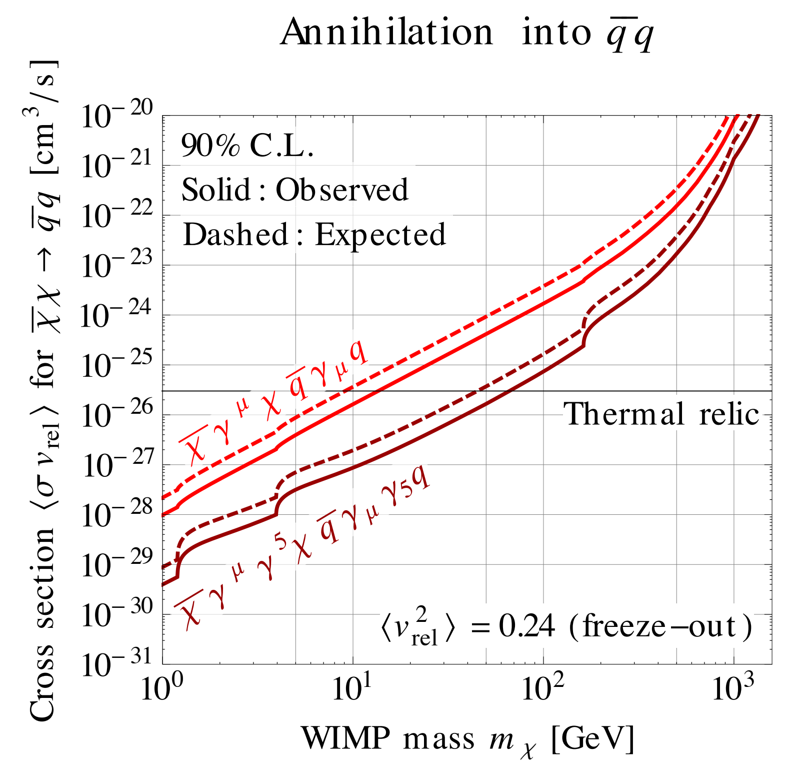
Effective operator approach

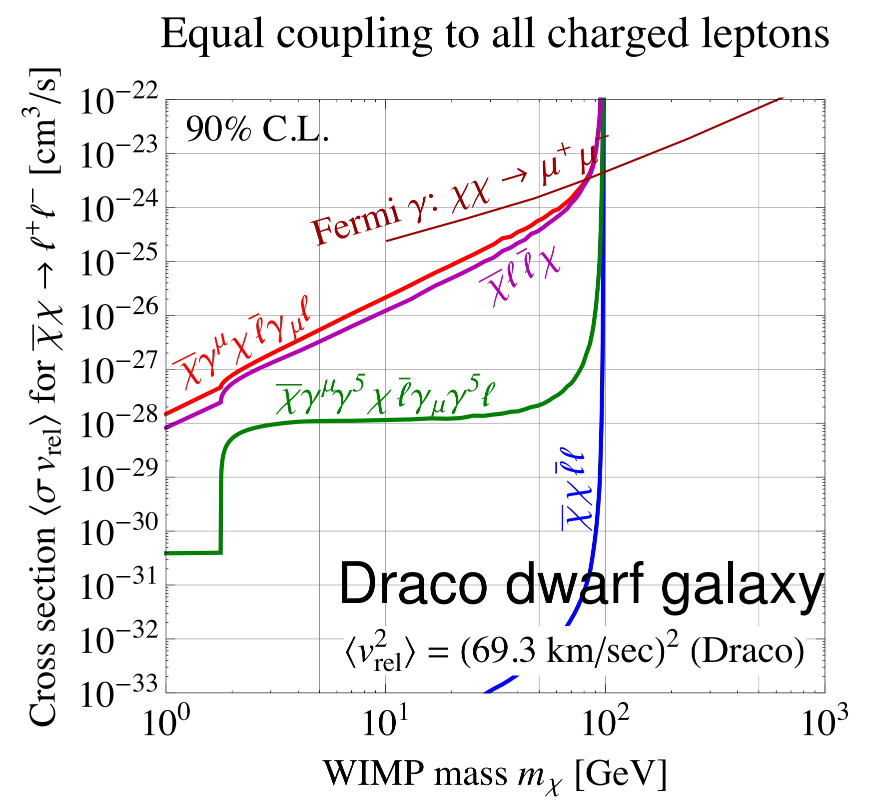
LHC limits and gamma-rays from dark matter





Mono-jet
Mono-gamma

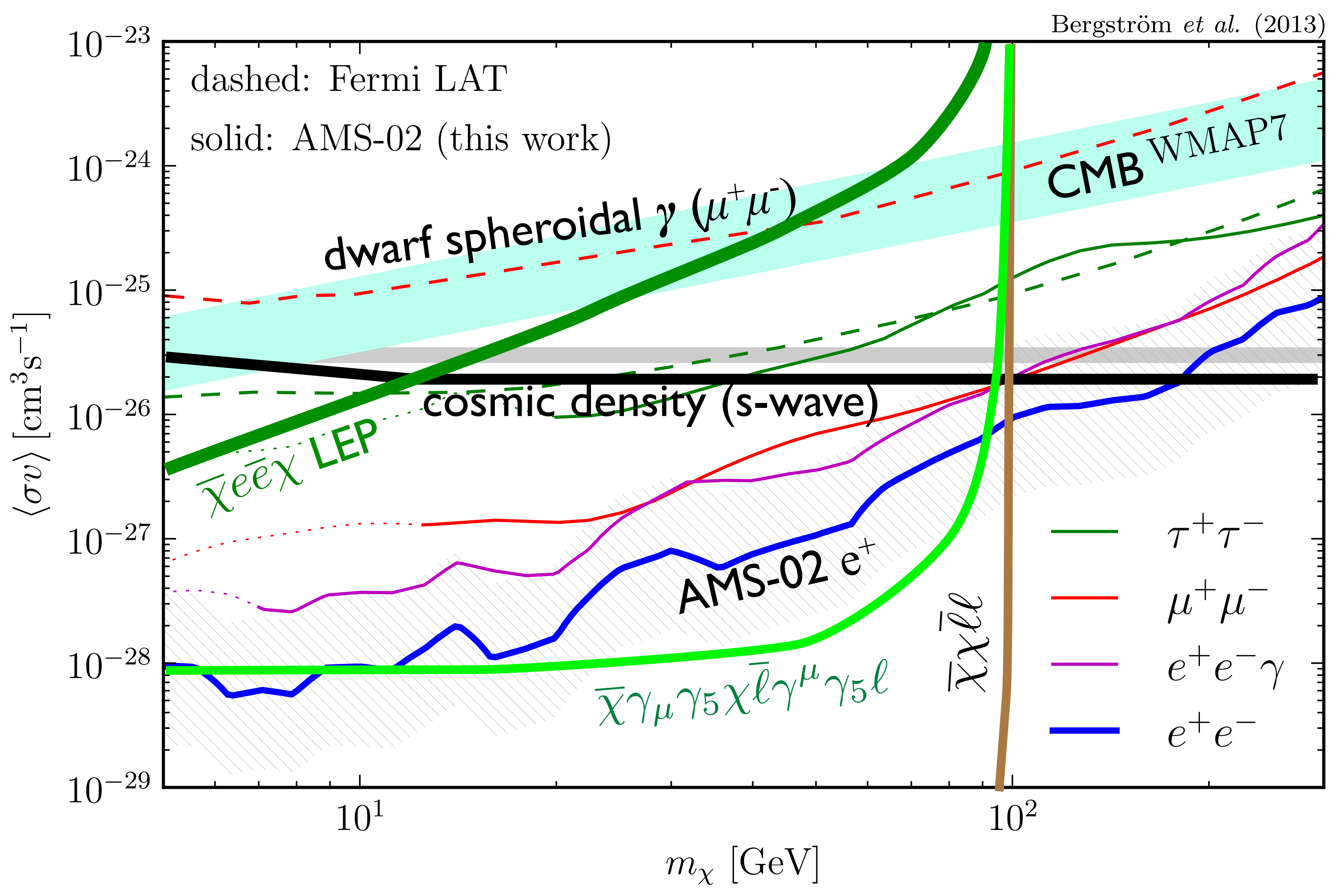




Kopp, Fox, Harnik, Tait 2011

Constraints on annihilation cross section

γ-rays, cosmological ionization, positrons, and LEP



Fox,Harnik,Kopp,Tsai 2011 & Bergstrom,Bringmann,Cholis,Hooper,Weniger 2013

Particle dark matter flowchart

A NEW AND DEFINITIVE META-COSMOLOGY THEORY

T. R. Lauer
T. S. Statler
B. S. Ryden
D. H. Weinberg

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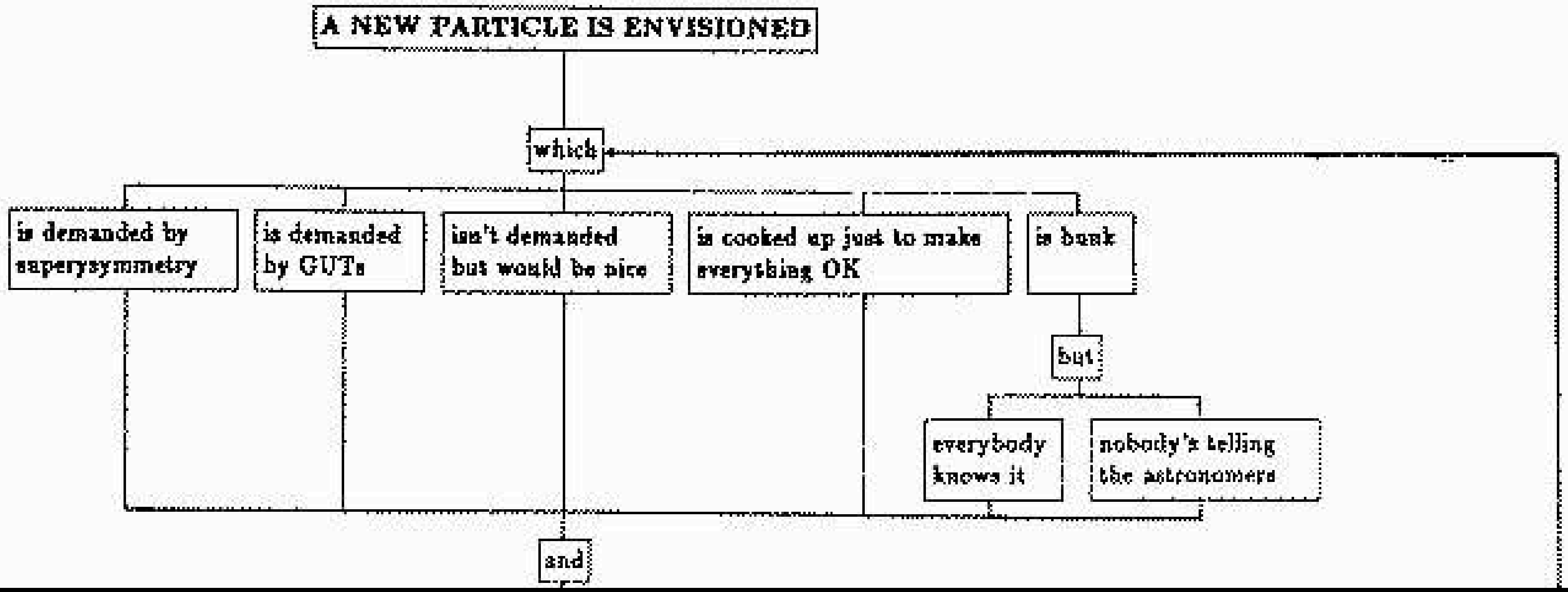
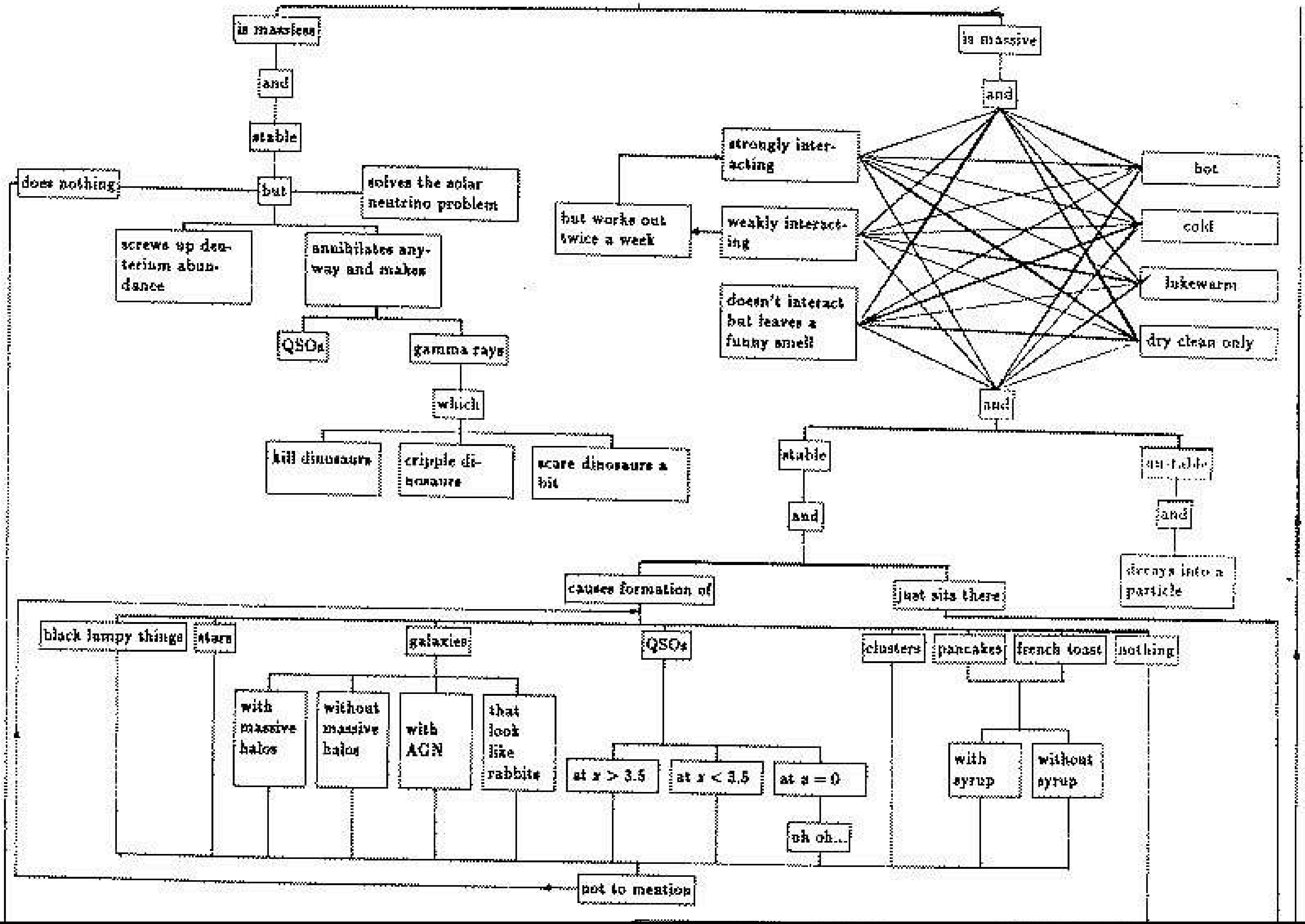
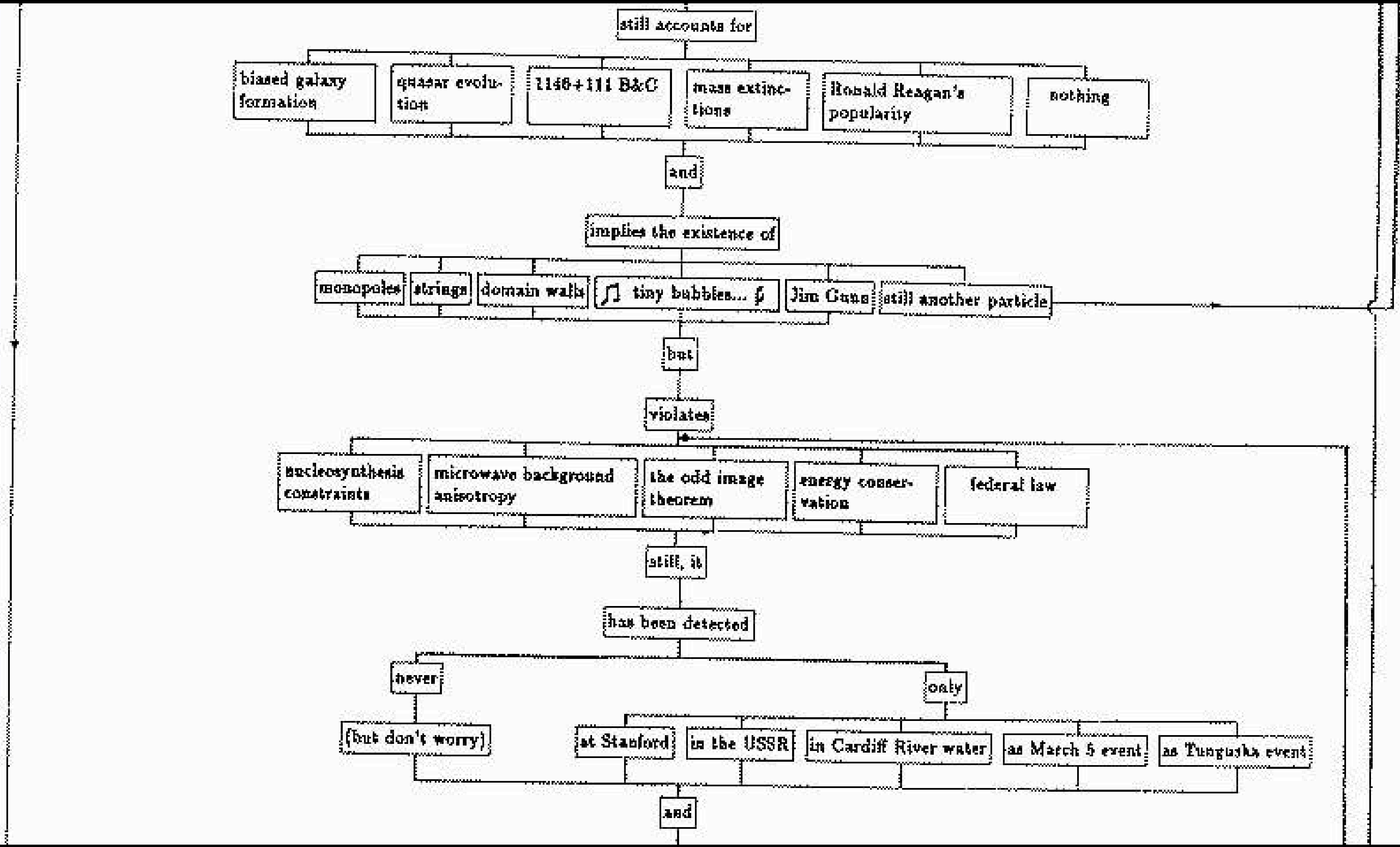
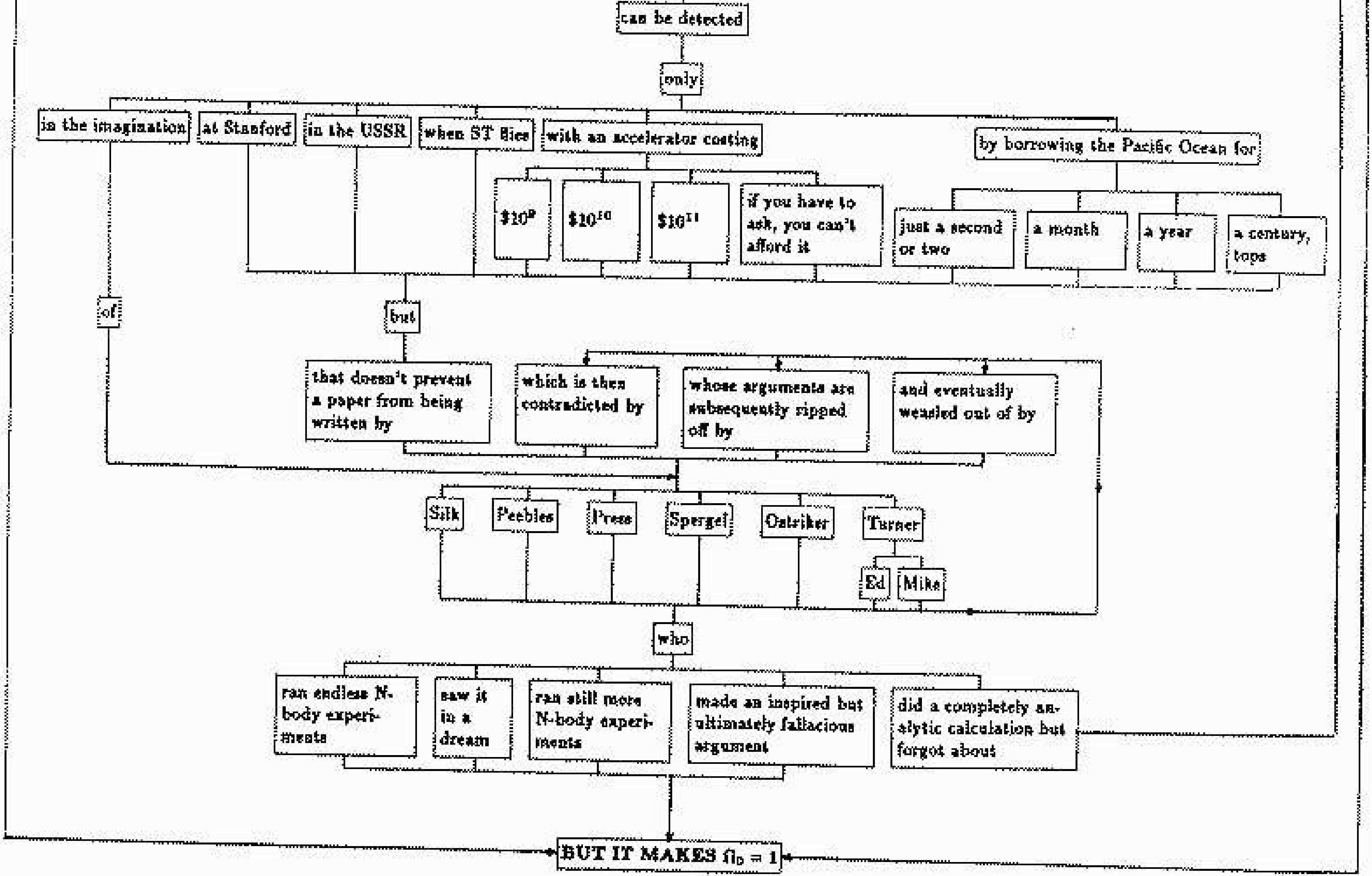
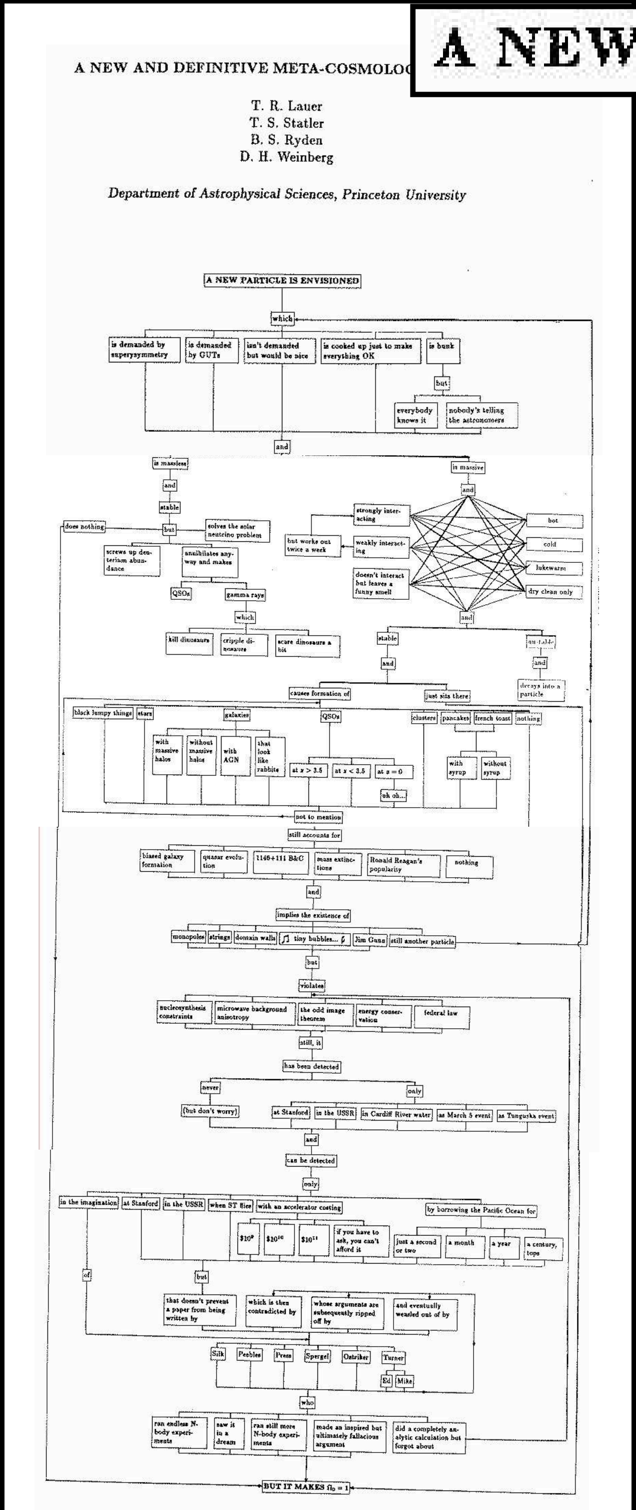



is massless
and
stable
but
does nothing
solves the solar neutrino problem
screws up deuterium abundance
annihilates anyway and makes
QSOs
gamma rays
which
kill dinosaurs
cripple dinosaurs
scare dinosaurs a bit
is massive
and
strongly interacting
weakly interacting
doesn't interact but leaves a funny smell
but works out twice a week
hot
cold
lukewarm
dry clean only
and
stable
unstable
and
and
decays into a particle
causes formation of
just sits there
black lumpy things
stars
galaxies
QSOs
clusters
pancakes
french toast
nothing
with massive halos
without massive halos
with AGN
that look like rabbits
at $z > 3.5$
at $z < 3.5$
at $z = 0$
oh oh...
with syrup
without syrup
not to mention


still accounts for
biased galaxy formation
quasar evolution
1146+111 B&C
mass extinctions
Ronald Reagan's popularity
nothing
and
implies the existence of
monopoles
strings
domain walls
♫ tiny bubbles... ♫
Jim Gunn
still another particle
but
violates
nucleosynthesis constraints
microwave background anisotropy
the odd image theorem
energy conservation
federal law
still, it
has been detected
never
only
(but don't worry)
at Stanford
in the USSR
in Cardiff River water
as March 5 event
as Tunguska event
and


can be detected
only
in the imagination
at Stanford
in the USSR
when ST flies
with an accelerator costing
by borrowing the Pacific Ocean for
$\$10^{9}$
$\$10^{10}$
$\$10^{11}$
if you have to ask, you can't afford it
just a second or two
a month
a year
a century, tops
of
but
that doesn't prevent a paper from being written by
which is then contradicted by
whose arguments are subsequently ripped off by
and eventually weaseled out of by
Silk
Peebles
Press
Spergel
Ostriker
Turner
Ed
Mike
who
ran endless N-body experiments
saw it in a dream
ran still more N-body experiments
made an inspired but ultimately fallacious argument
did a completely analytic calculation but forgot about
BUT IT MAKES $\Omega_0 = 1$

A NEW AND DEFINITIVE META-COSMOLOGY THEORY



A NEW AND DEFINITIVE META-COSMOLOG

T. R. Lauer
T. S. Statler
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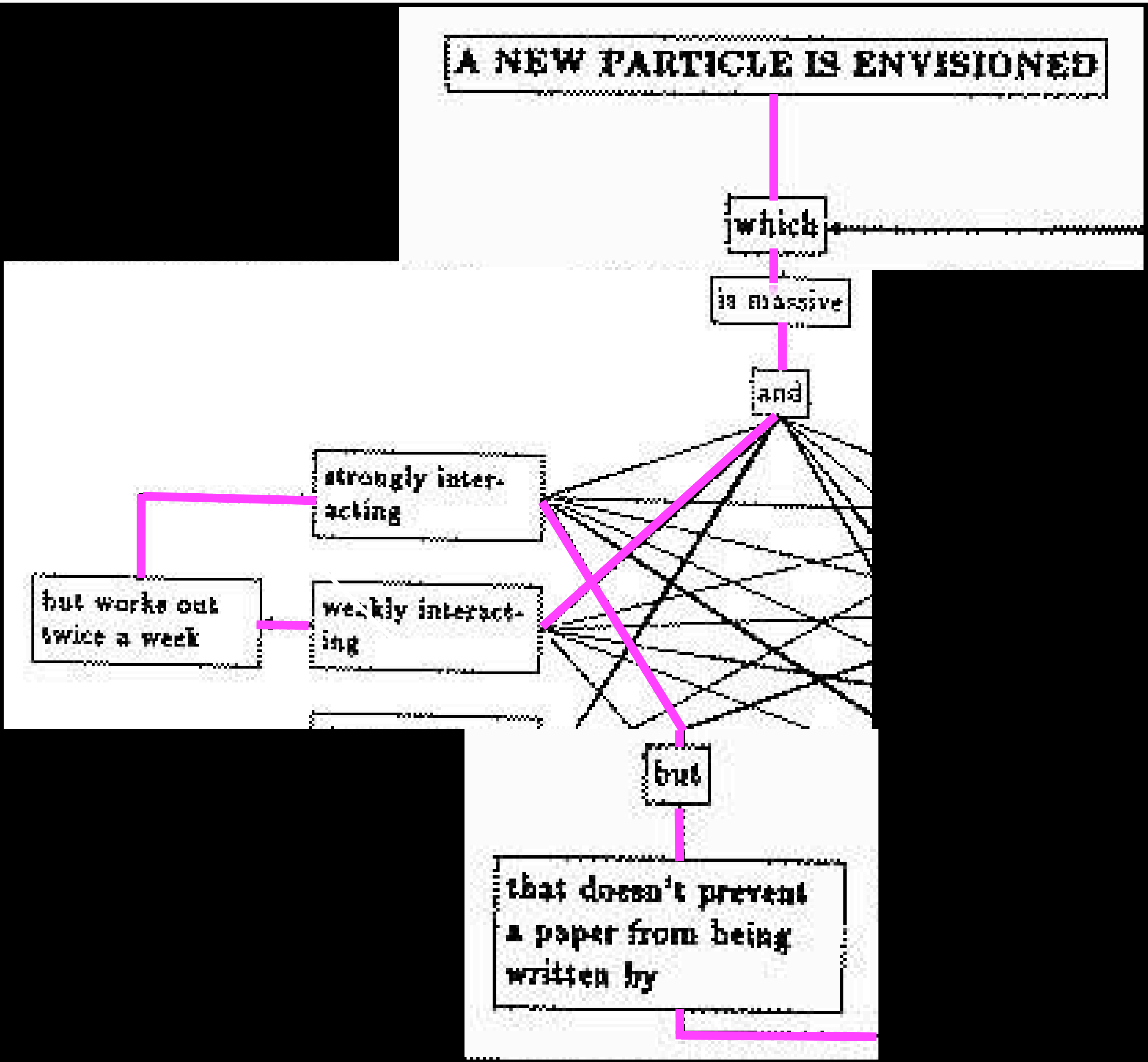
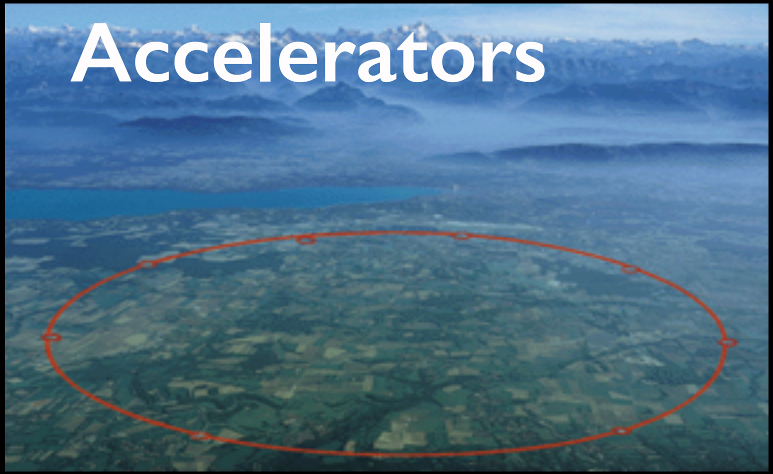
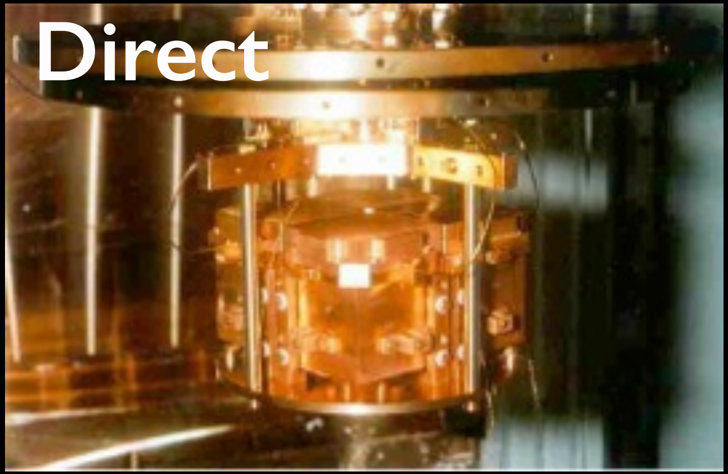


Searches
for
particle dark matter

Searches for particle dark matter

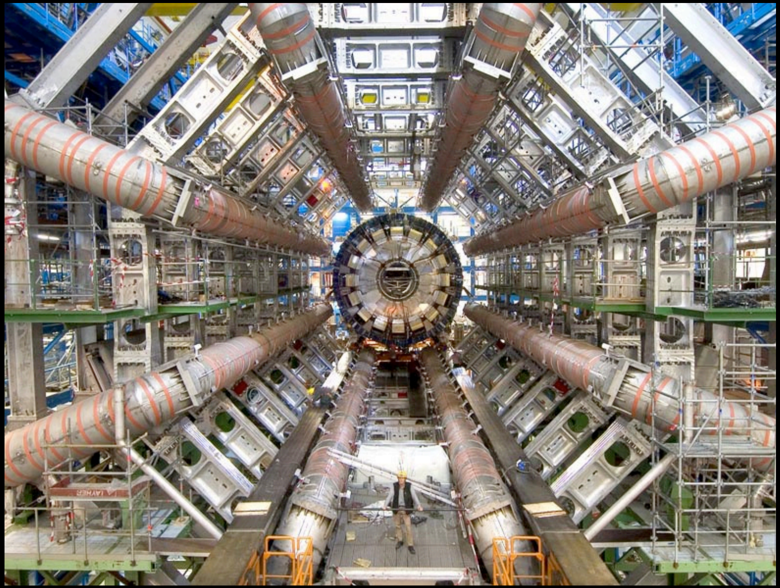




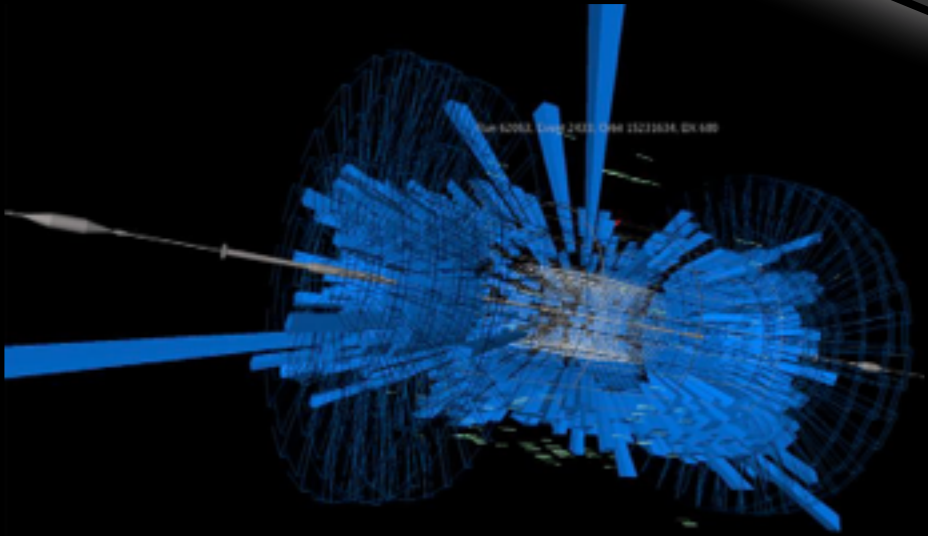
Dark matter creation with particle accelerators

Searching for the conversion
protons → energy → dark matter

$E=mc^2$ in action



The ATLAS detector

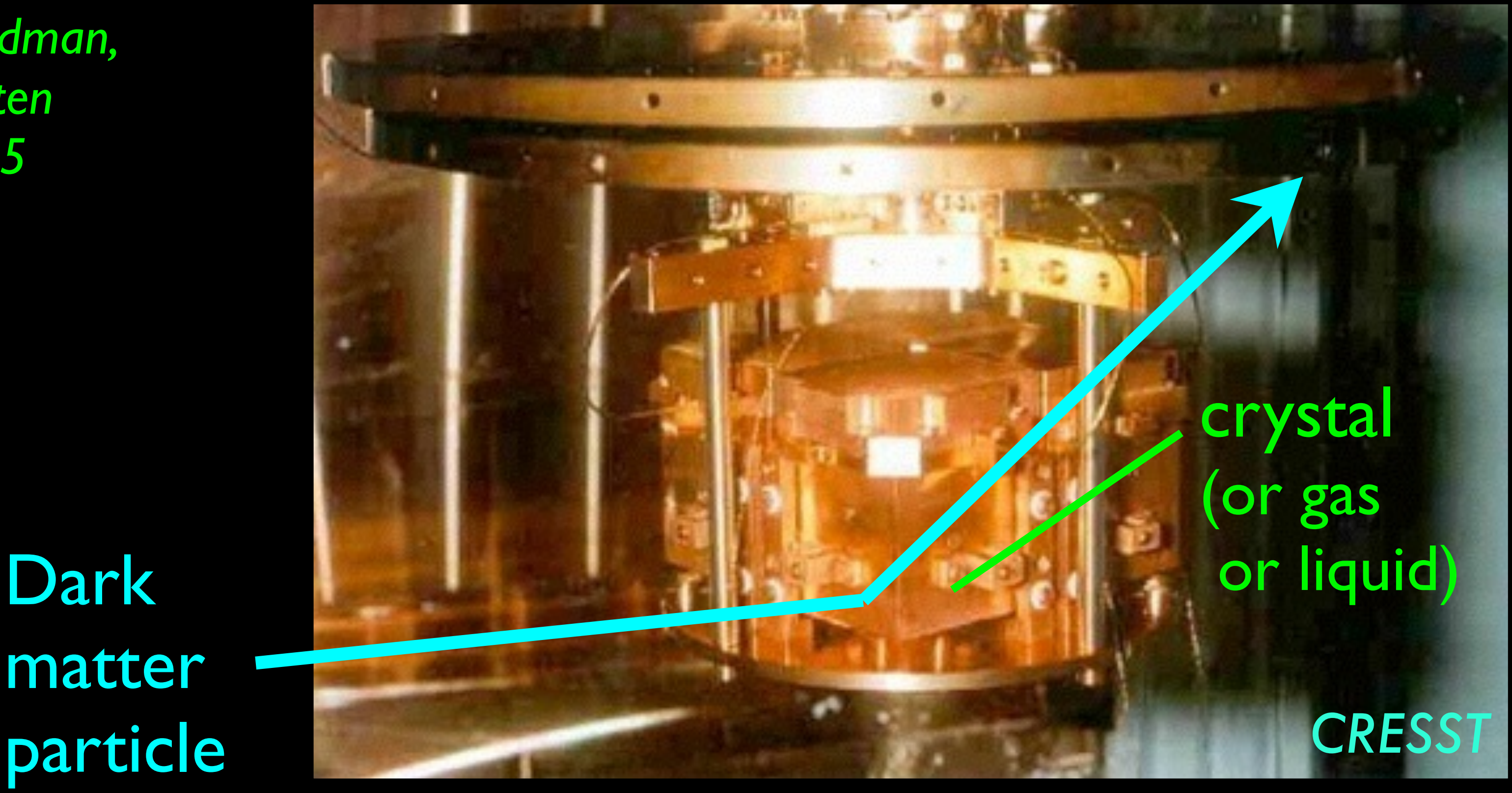


Particle production at the Large Hadron Collider

The principle of direct detection

Dark matter particles that arrive on Earth scatter off nuclei in a detector

Goodman,
Witten
1985



Low-background underground detector

Indirect detection of particle dark matter

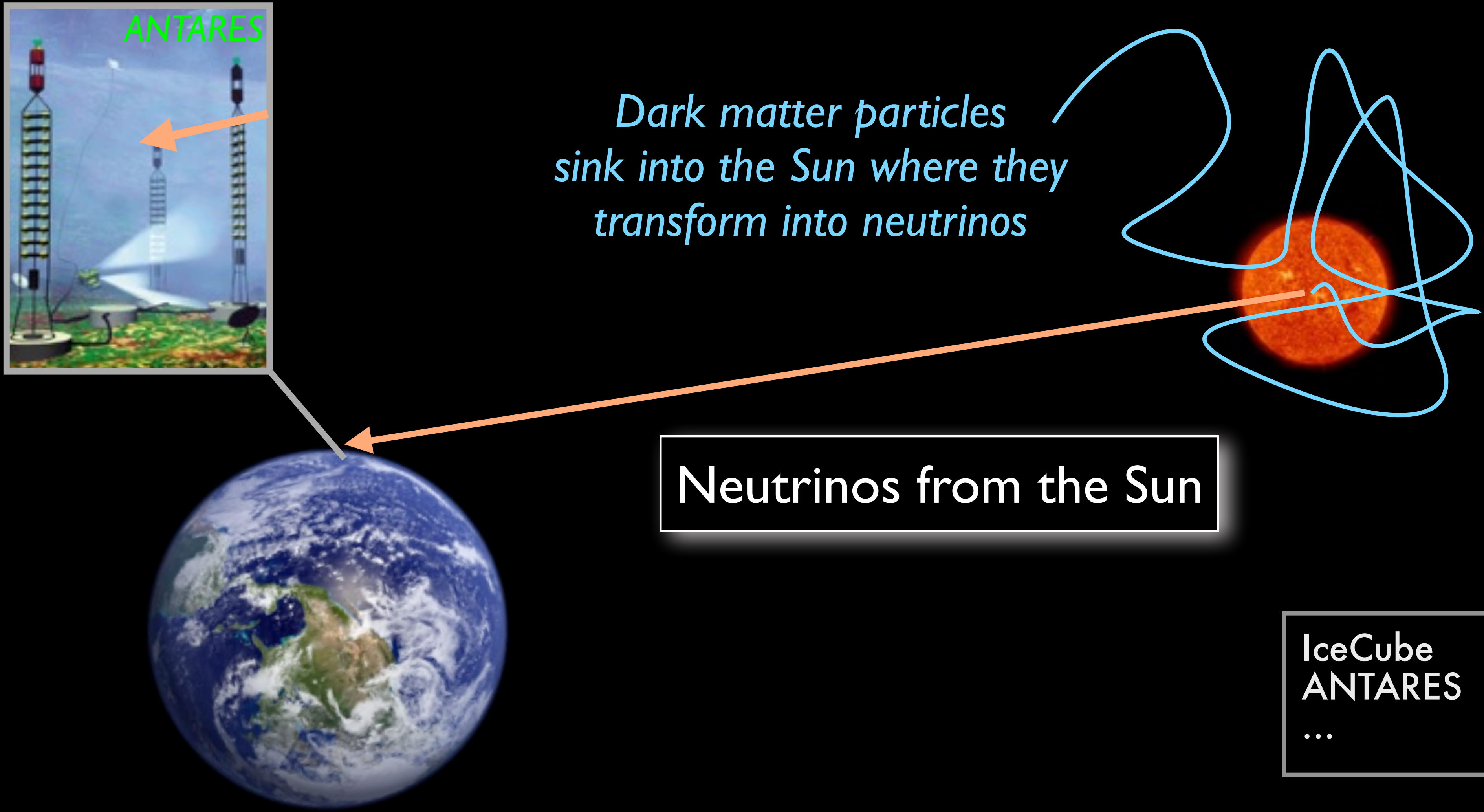
The principle

Dark matter particles transform into ordinary particles, which are then detected or inferred

Indirect detection of particle dark matter

The principle

Dark matter particles transform into ordinary particles, which are then detected or inferred



Dark matter particles sink into the Sun where they transform into neutrinos

Neutrinos from the Sun

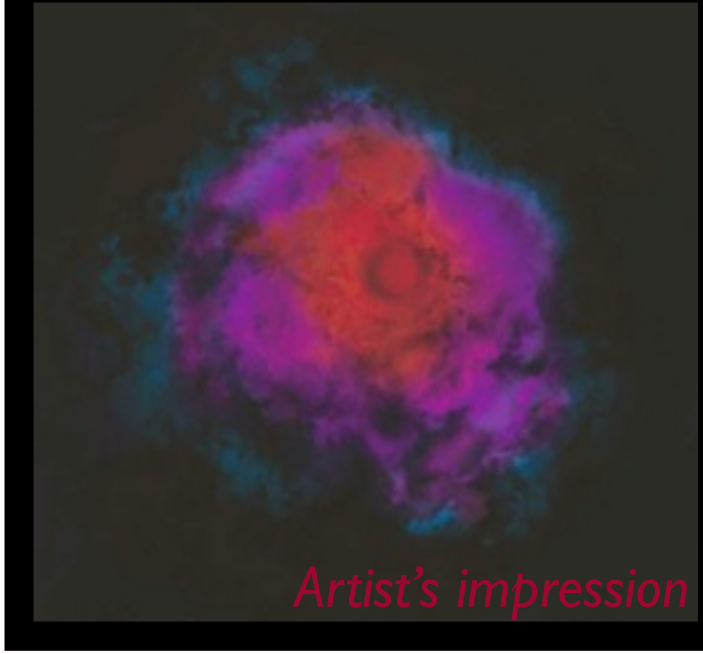
IceCube
ANTARES
…

Indirect detection of particle dark matter

The principle

Dark matter particles transform into ordinary particles, which are then detected or inferred

The first stars to form in the universe may have been powered by dark matter instead of nuclear fusion.



They were *dark-matter powered stars* or for short

Dark Stars

- Explain chemical elements in old halo stars
- Explain origin of supermassive black holes in early quasars

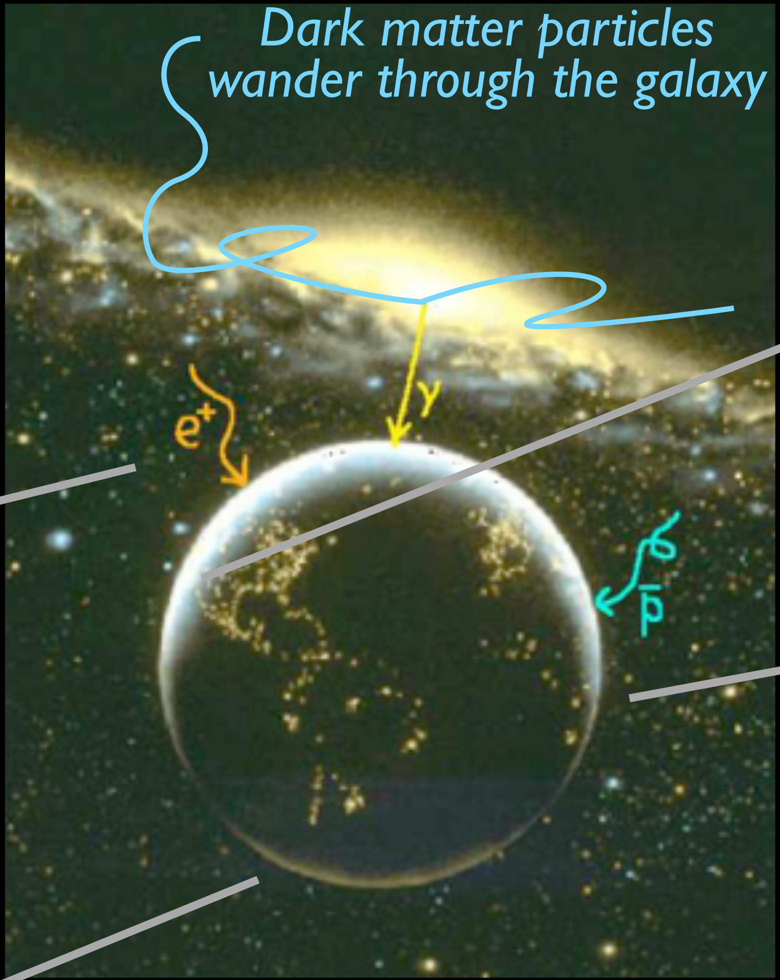
Spolyar, Freese, Gondolo 2007-2008

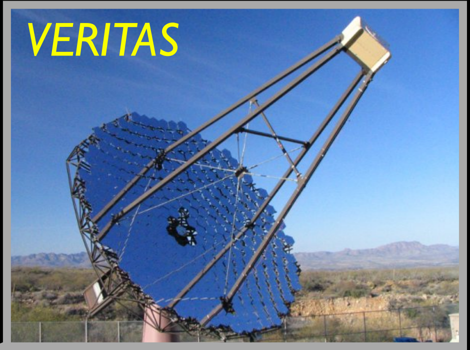
Indirect detection of particle dark matter

The principle

Dark matter particles transform into ordinary particles, which are then detected or inferred

Gunn, Lee, Lerche, Schramm, Steigman 1978; Stecker 1978



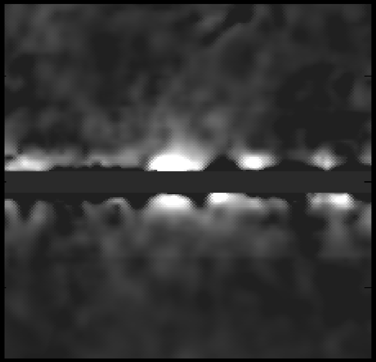


- HEAT
- BESS
- PAMELA
- AMS
- GAPS
- EGRET
- HESS
- MAGIC
- VERITAS
- GLAST
- STACEE
- CTA
- …

Gamma-rays, positrons, antiprotons from our galaxy and beyond

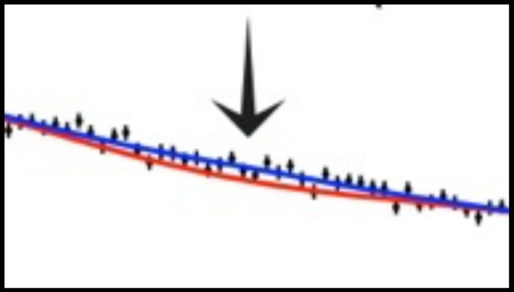
Evidence for cold dark matter particles?

GeV γ-rays



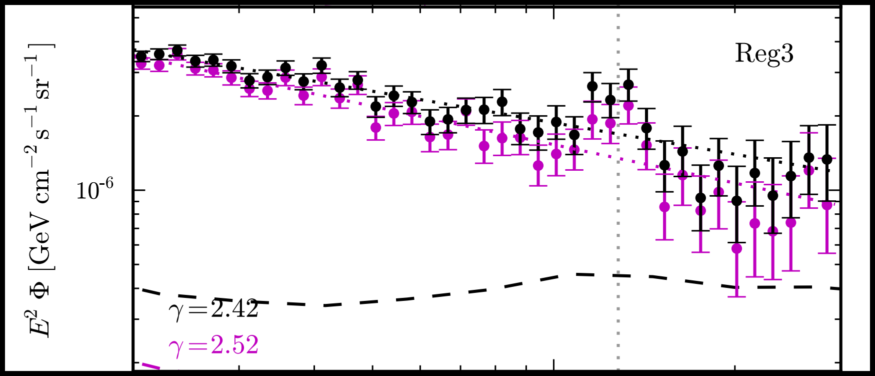
Hooper et al 2009-14

3.5 keV X-ray line



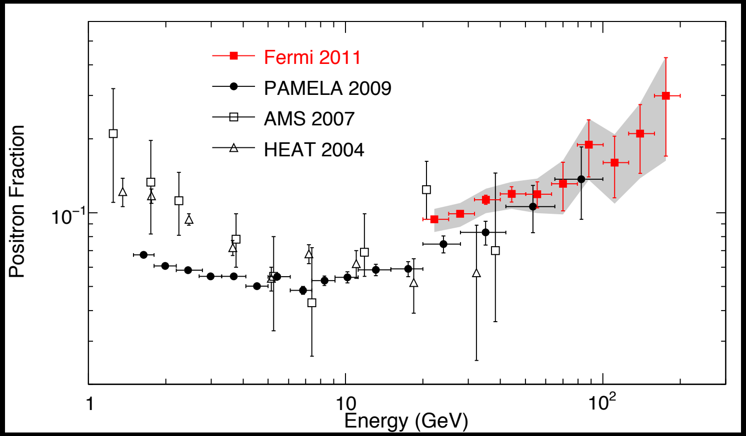
Bulbul et al 2014

135 GeV γ-ray line



Weniger 2012

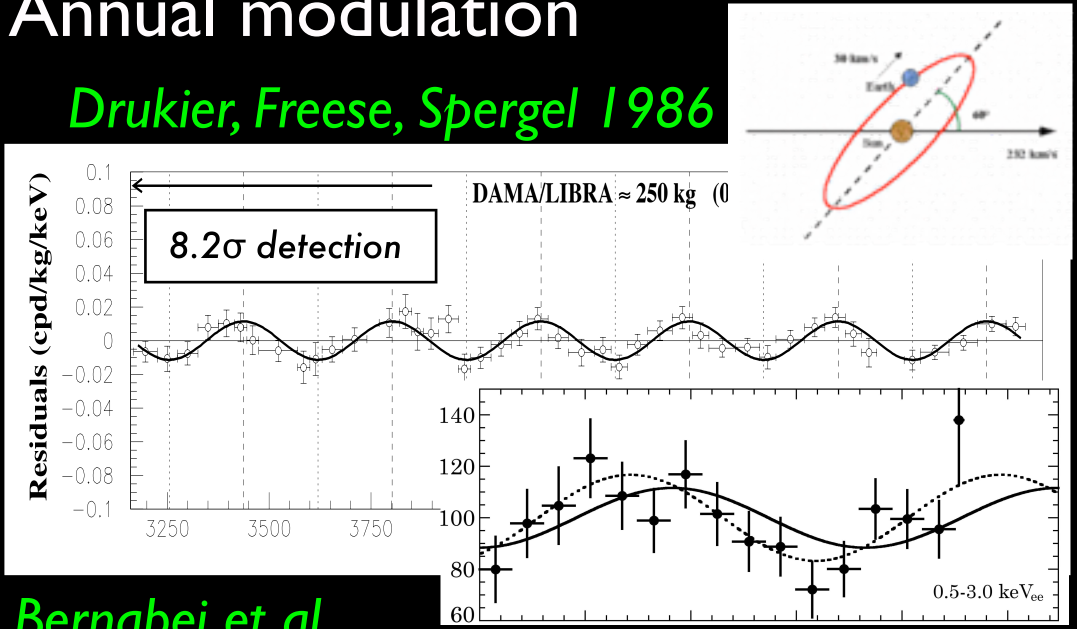
Positron excess



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

The bane

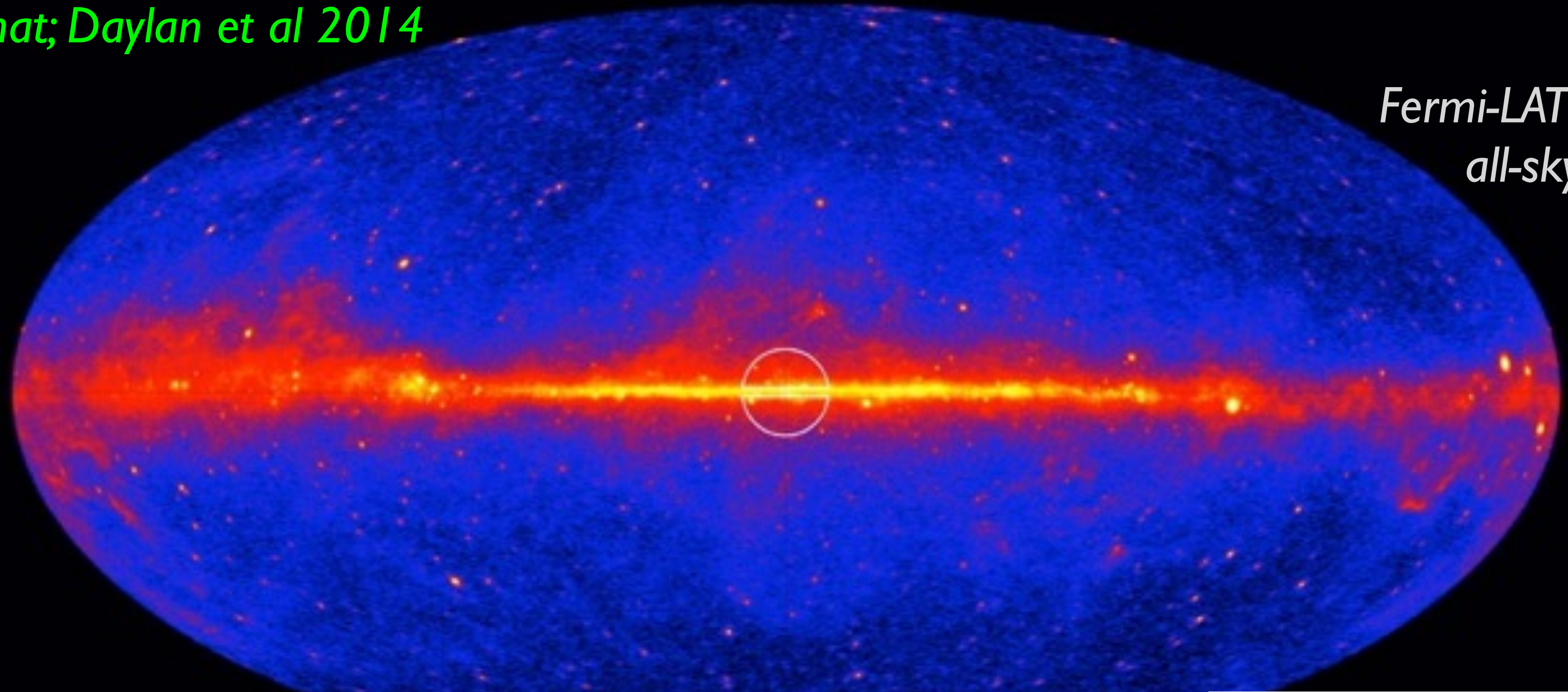
Roderick O. Redman, 1905-1975, Professor of Astronomy at Cambridge University

“Any competent theoretician can fit any theory to any given set of facts.”

1 GeV gamma-ray excess?

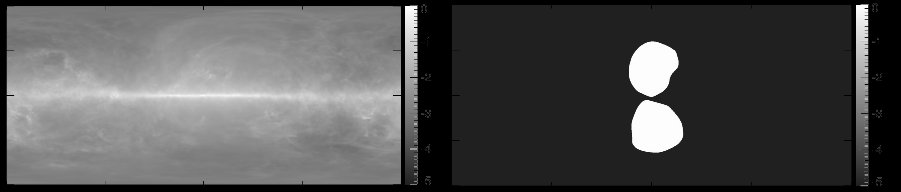
1 GeV gamma-ray excess?

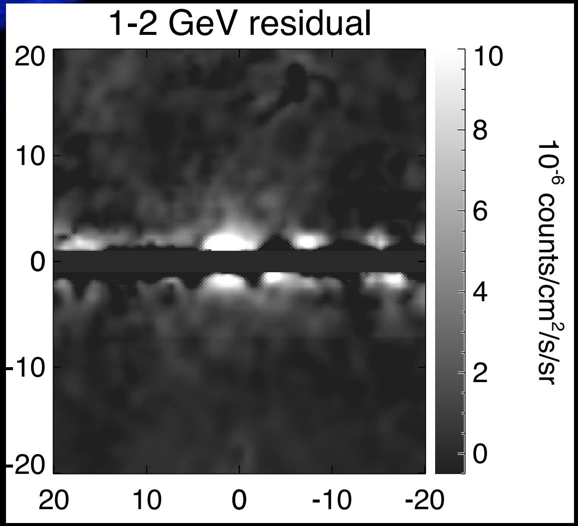
Goodenough, Hooper 2009; Hooper, Goodenough; Boyarsky, Malyshev, Ruchayskiy; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon, Macias 2013; Abazajian, Canac, Horiuchi, Kaplinghat; Daylan et al 2014



Fermi-LAT all-sky map

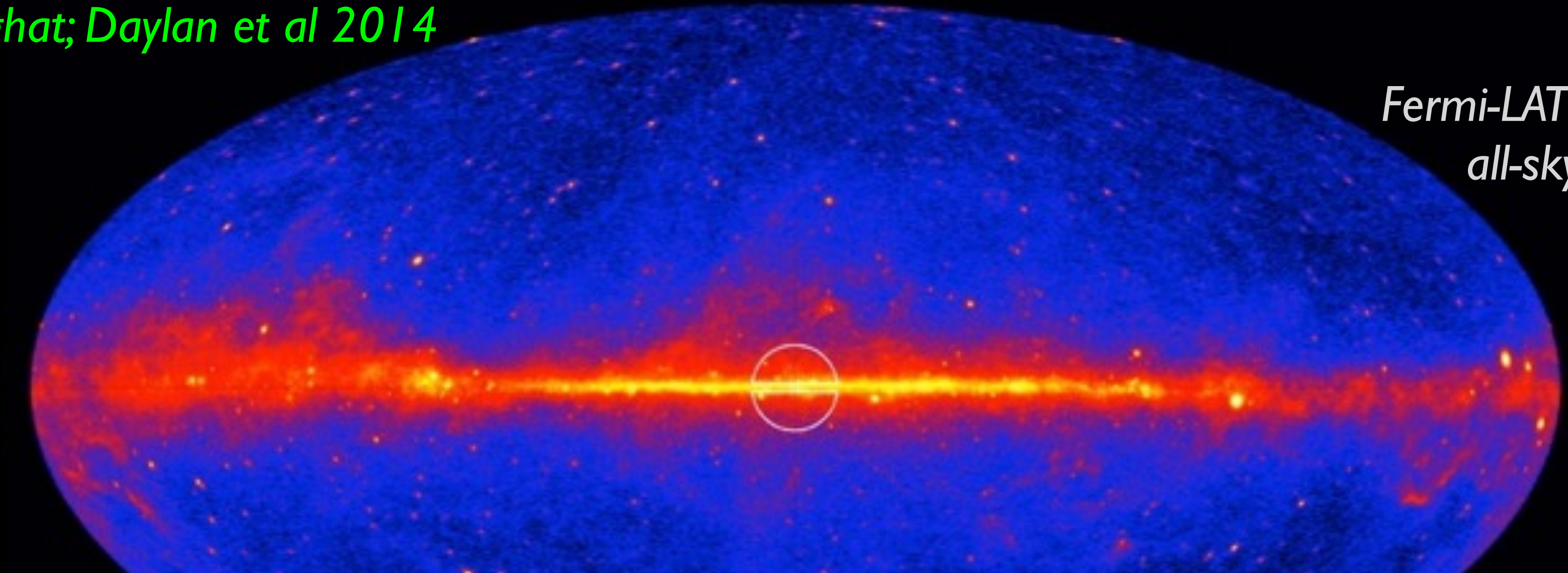
Fit diffuse + Fermi-bubble, find residual





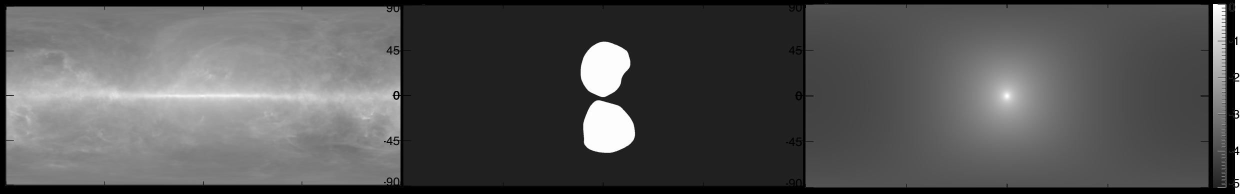
1 GeV gamma-ray excess?

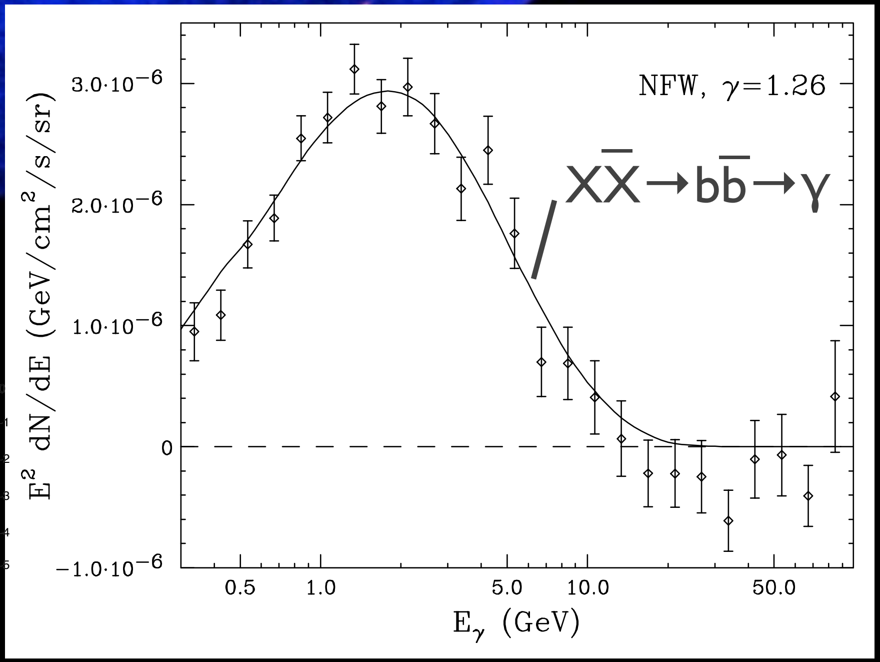
Goodenough, Hooper 2009; Hooper, Goodenough; Boyarsky, Malyshev, Ruchayskiy; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon, Macias 2013; Abazajian, Canac, Horiuchi, Kaplinghat; Daylan et al 2014



Fermi-LAT all-sky map

Fit diffuse + Fermi-bubble + dark matter



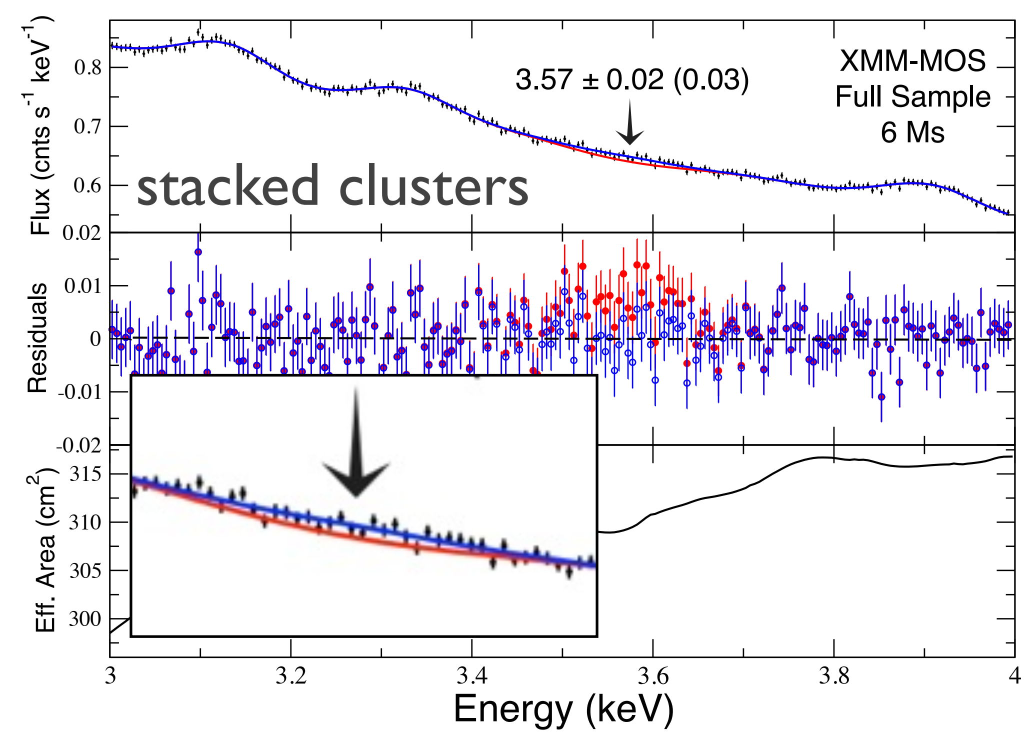


3.5 keV X-ray line?

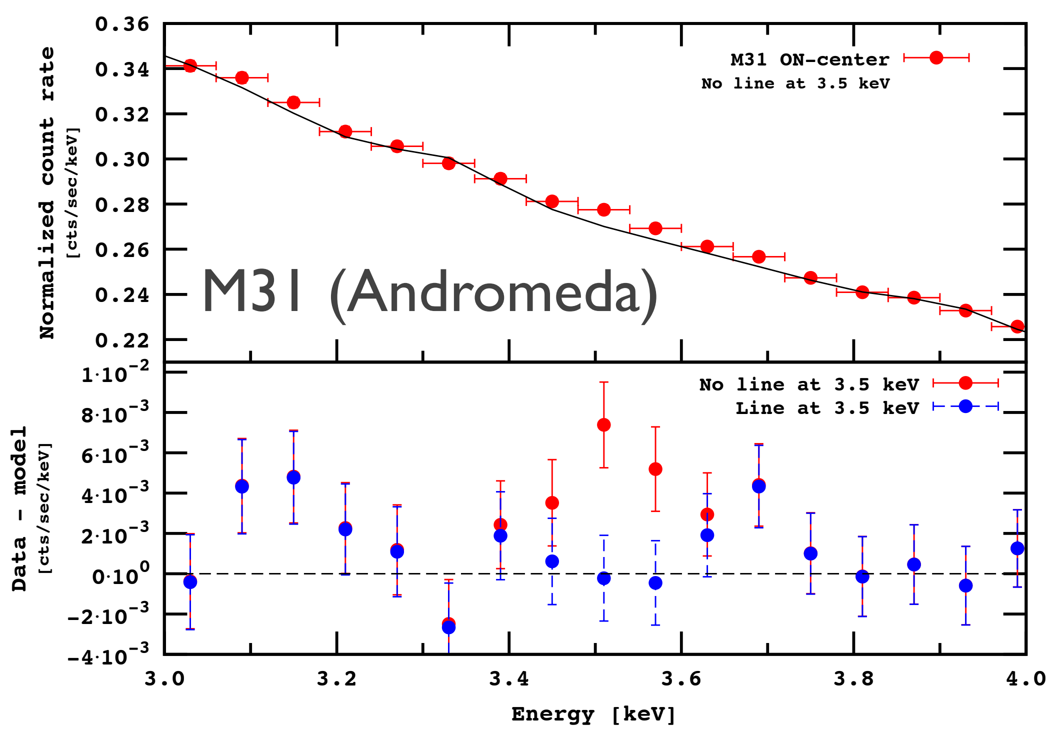
Sterile neutrino dark matter

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 $\nu_s \to \gamma\nu_a$

X-ray line

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

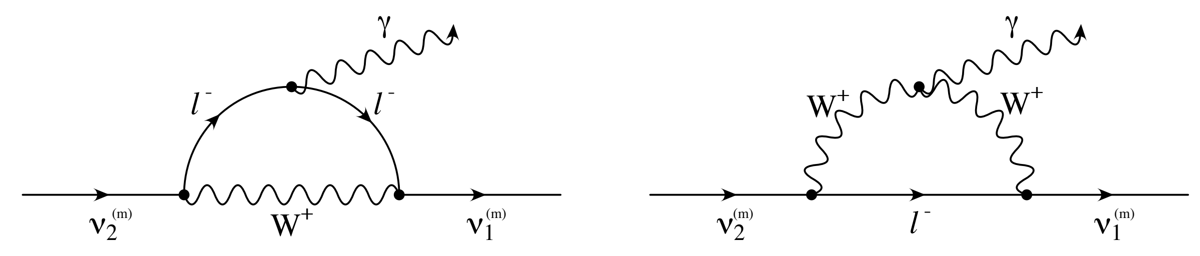


Figure from Kusenko 0906.2968

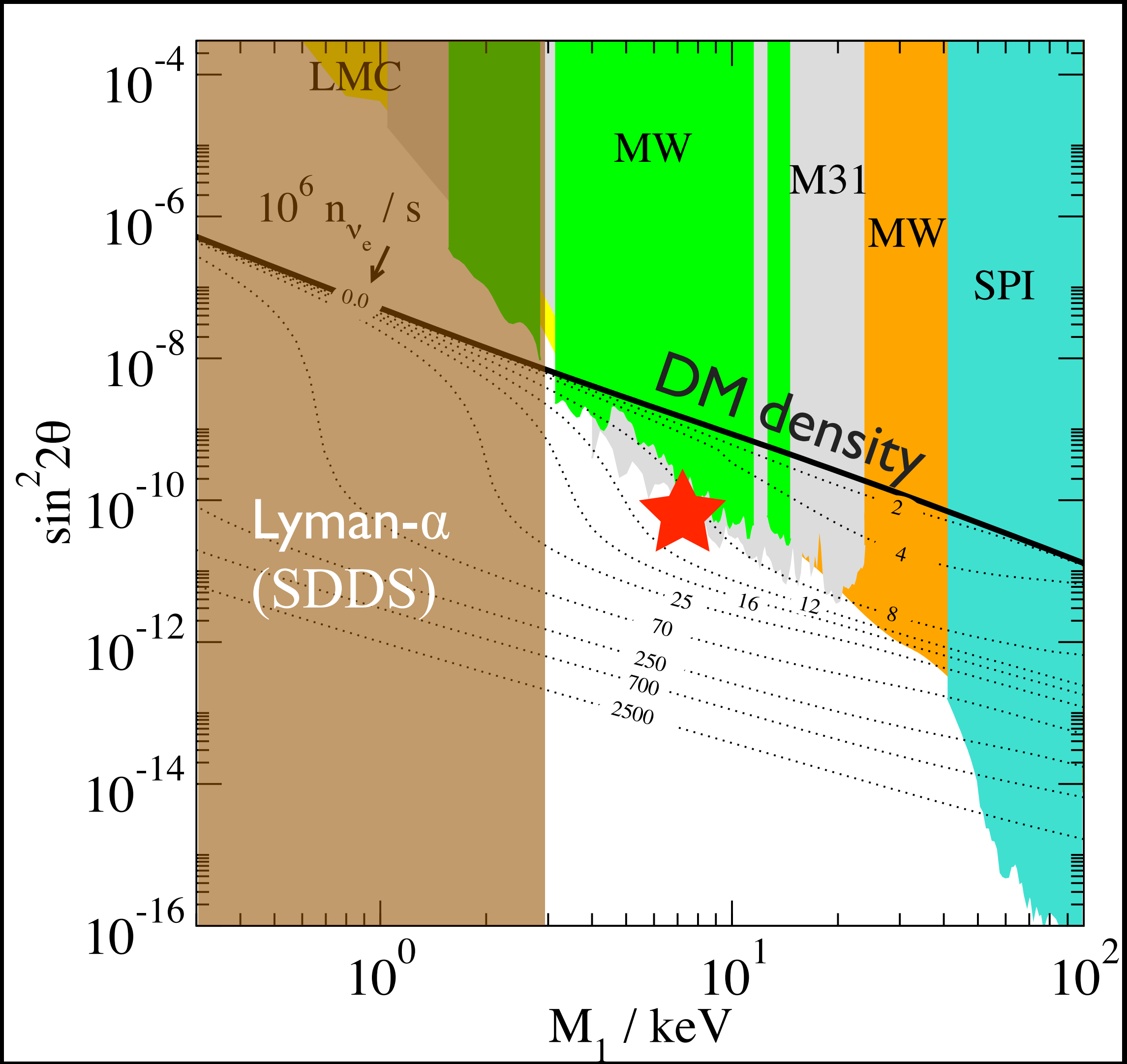
$$\begin{aligned}\Gamma_{\nu_s\to\gamma\nu_a} &= \frac{9}{256\pi^4}\,\alpha_{\rm EM}\,{\rm G}_{\rm F}^2\,\sin^2\theta\, m_{\rm s}^5\\ &= \frac{1}{1.8\times 10^{21}{\rm s}}\,\sin^2\theta\,\left(\frac{m_{\rm s}}{\rm keV}\right)^5\end{aligned}$$

Sterile neutrino dark matter

νMSM

$m_\nu = 7.1$ keV

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

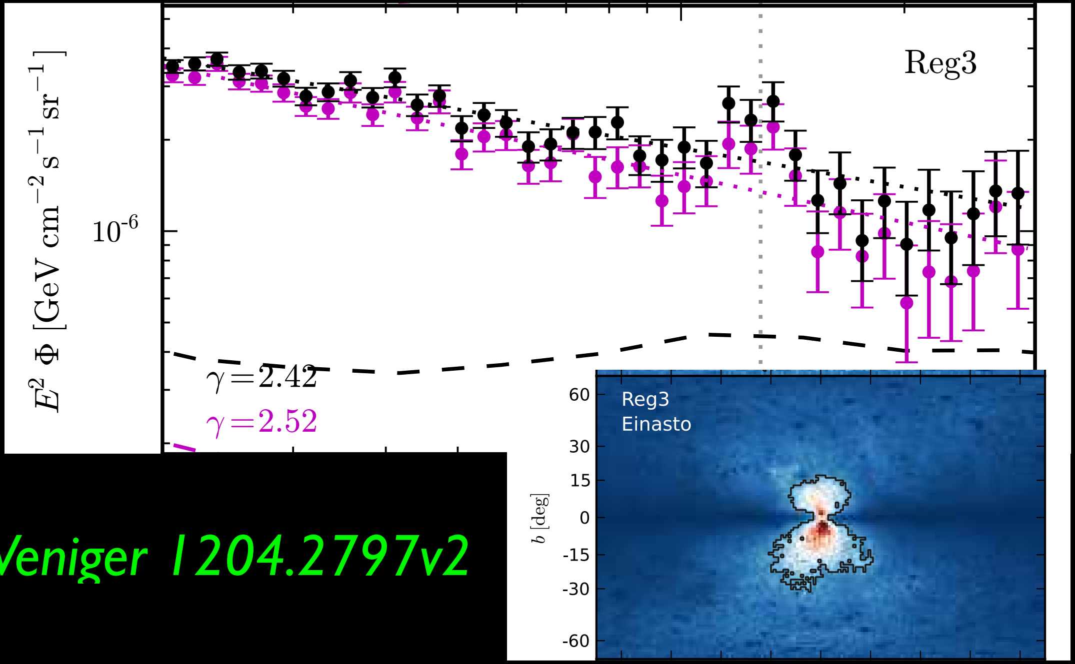


Laine, Shaposhnikov 2008

135 GeV gamma-ray line?

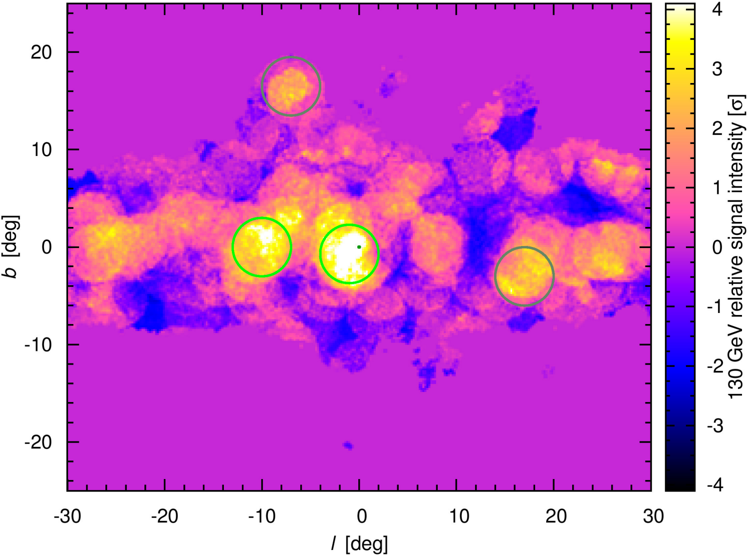
135 GeV gamma-ray line?

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



Weniger 1204.2797v2

found by others



Tempel, Hektor, Raidal 2012

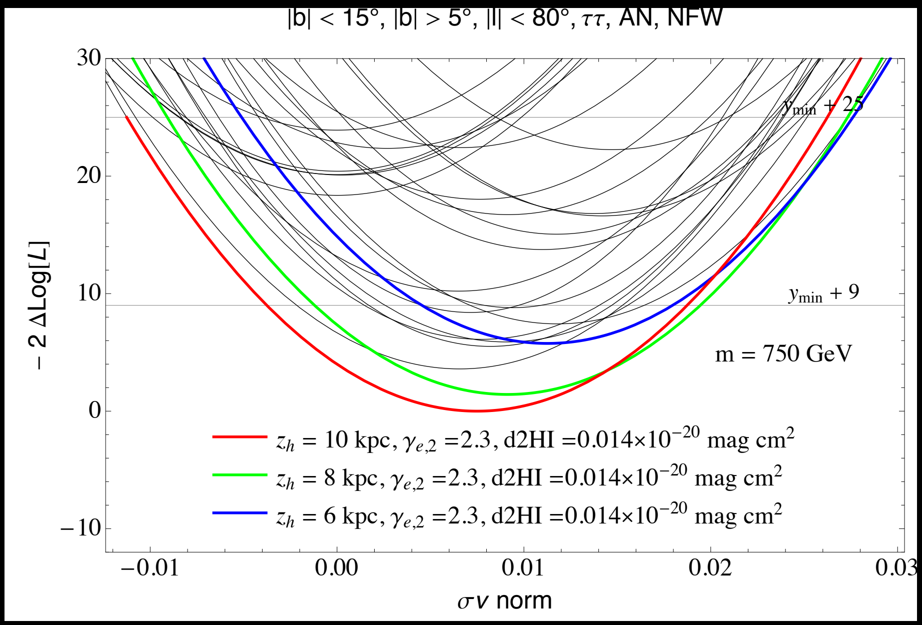
3.2σ effect based on 50 photons

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

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

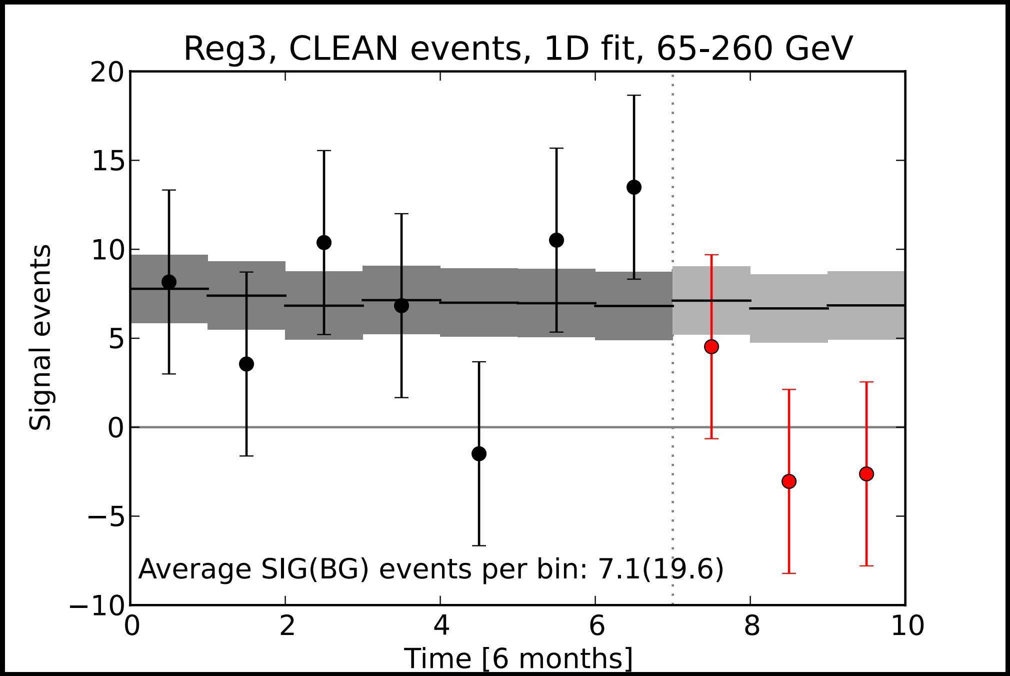
135 GeV gamma-ray line?

Fermi Collab. upper bounds



Ackerman et al (Fermi-LAT) 2012

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

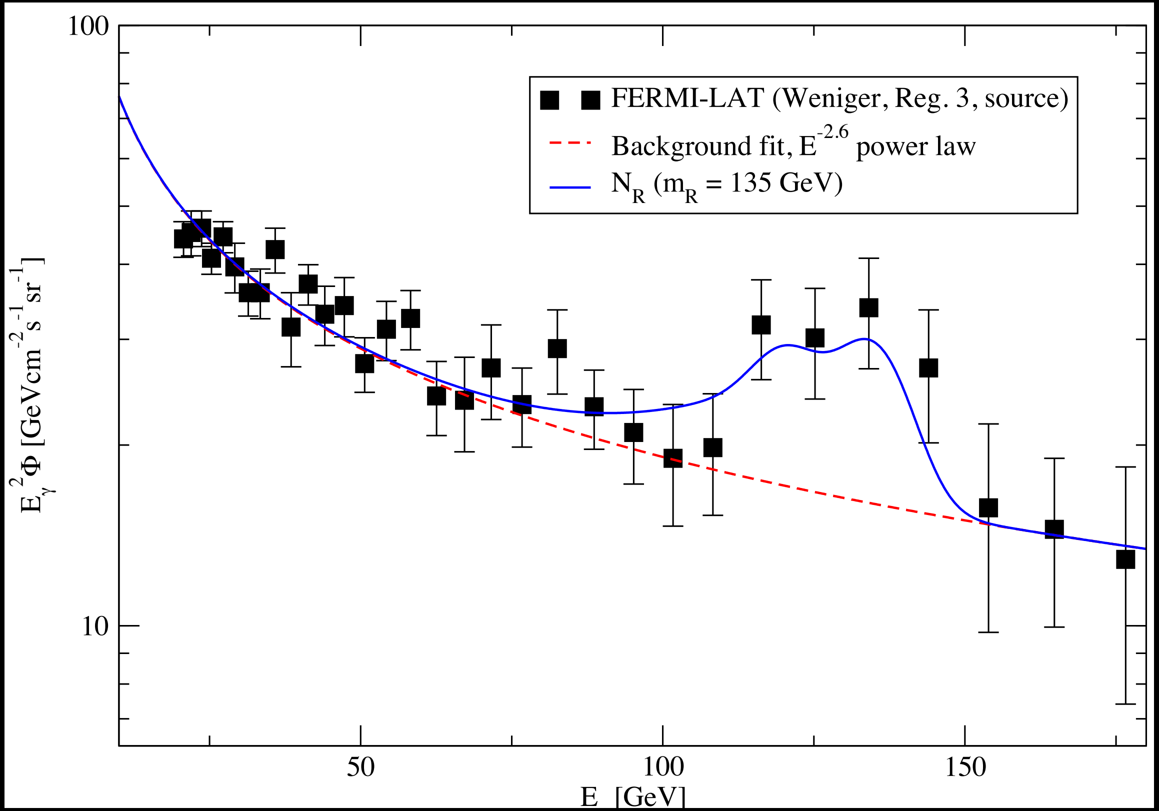


Courtesy C.Weniger 2014

HESS-2 may tell

135 GeV gamma-ray line: particle physics

Leptonically-Interacting Massive Particles (LIMPs)



Baltz, Bergstrom 2002;
Bergstrom 1208.6082

LIMPs predicted a gamma-ray line without a continuum

$$\mathcal{L}_{\rm Zee} = f_{\alpha\beta} L_\alpha^T C i\tau_2 L_\beta S^+ + \mu \Phi_1^T i\tau_2 \Phi_2 S^- + \text{h.c.}$$

Zee 1980

$$\begin{aligned}\mathcal{L}_{\rm KNT} \; = \; & f_{\alpha\beta} L_\alpha^T C i\tau_2 L_\beta S_1^+ + g_\alpha N_R S_2^+ l_{\alpha R} \\ & + M_R N_R^T C N_R + V(S_1, S_2) + \text{h.c.} \; ,\end{aligned}$$

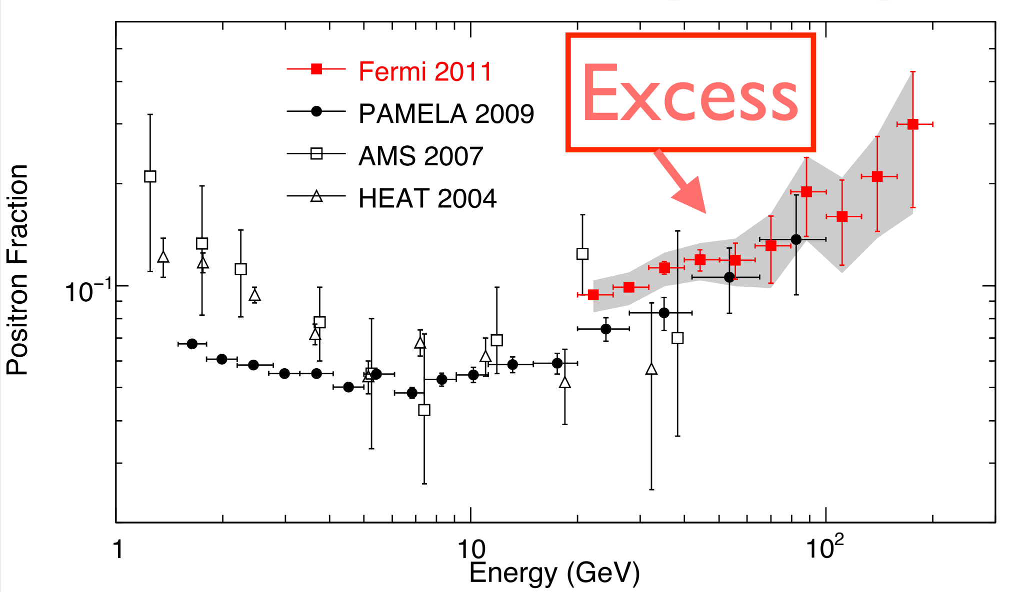
Krauss, Nasri, Trodden 2002

Positron excess

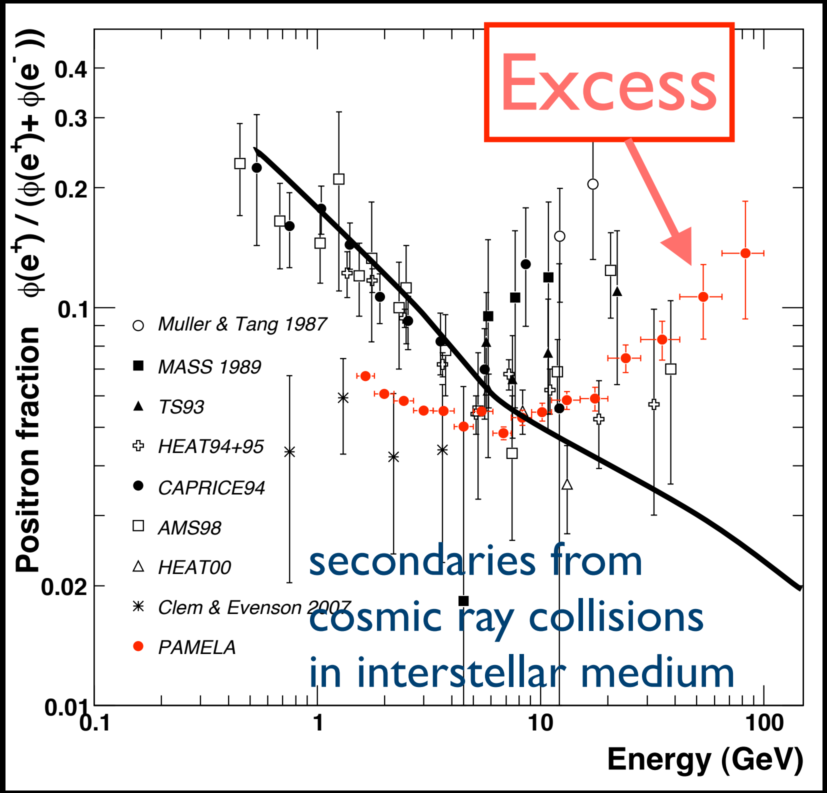
Excess in cosmic ray positrons

High energy cosmic ray positrons are more than expected

Ackernmann et al [Fermi-LAT] 2011



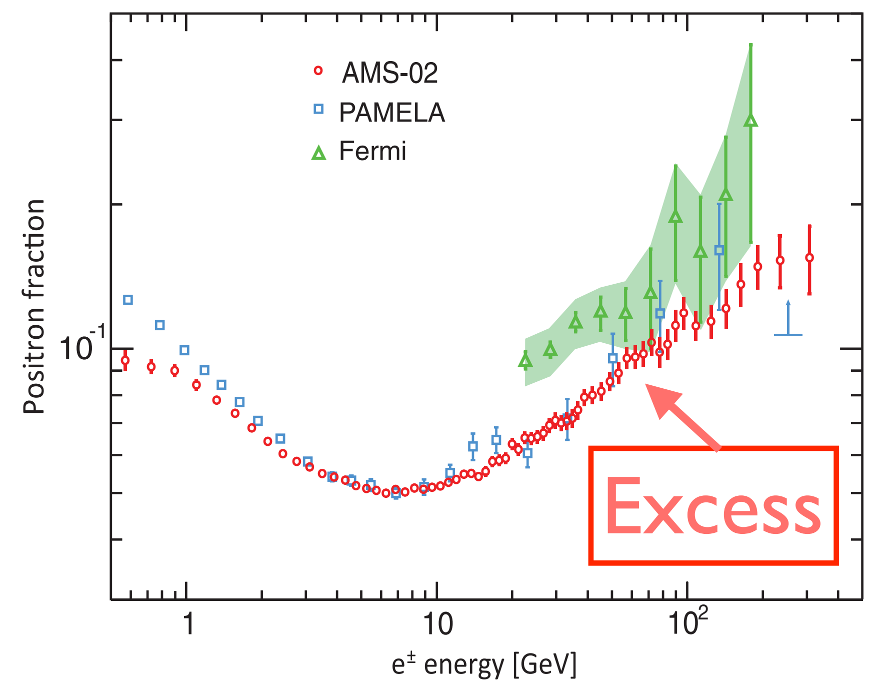
Excess



Excess

secondaries from cosmic ray collisions in interstellar medium

Adriani et al. [PAMELA ,2008



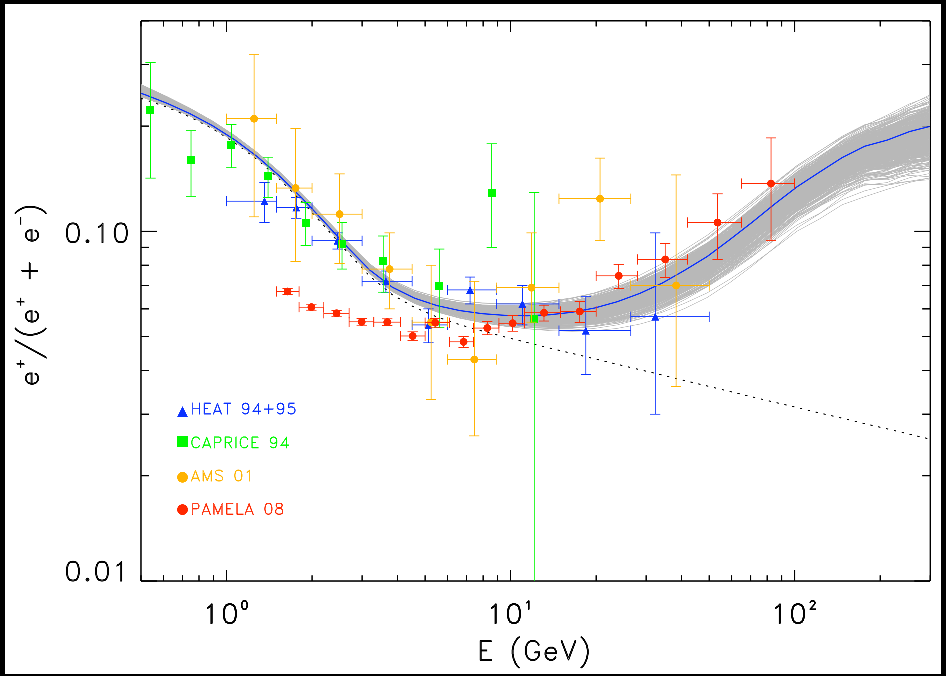
Excess

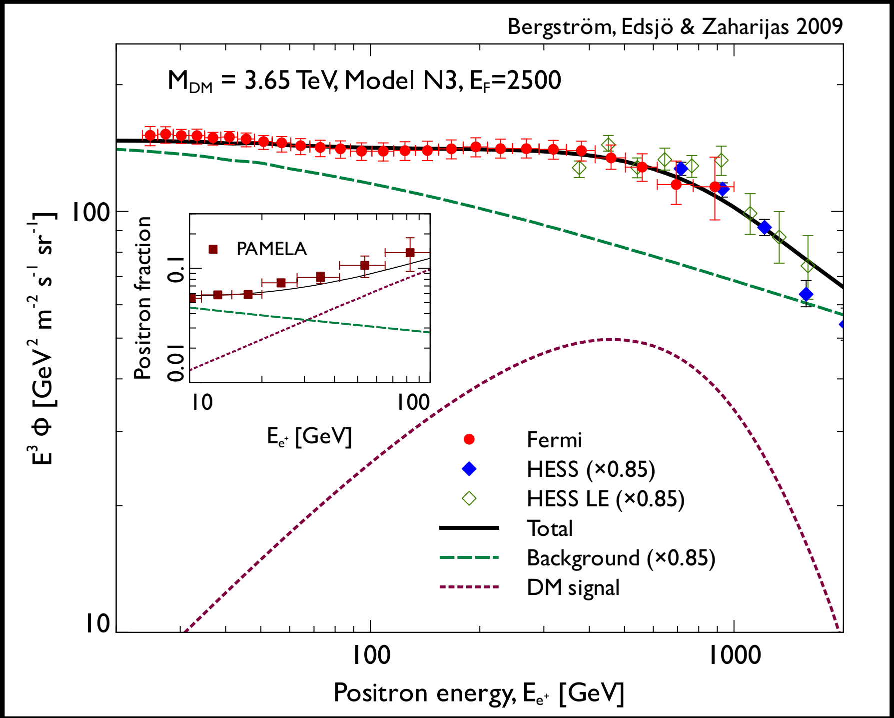
Aguilar et al [AMS-02] 2013

Excess in cosmic ray positrons

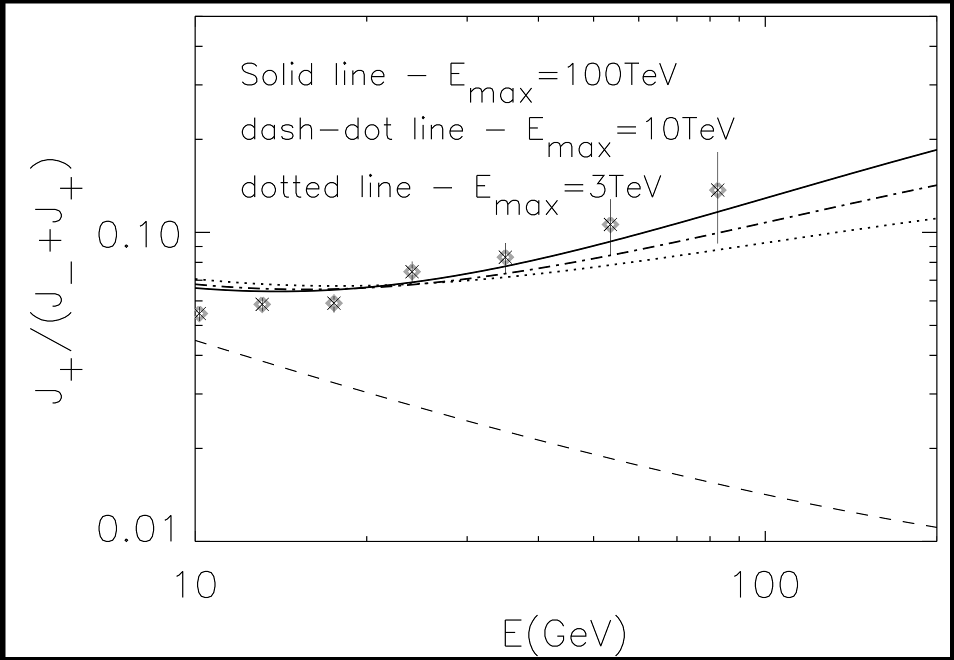
Dark matter?
Pulsars?
Acceleration near source?

Grasso et al [Fermi-LAT] 2009





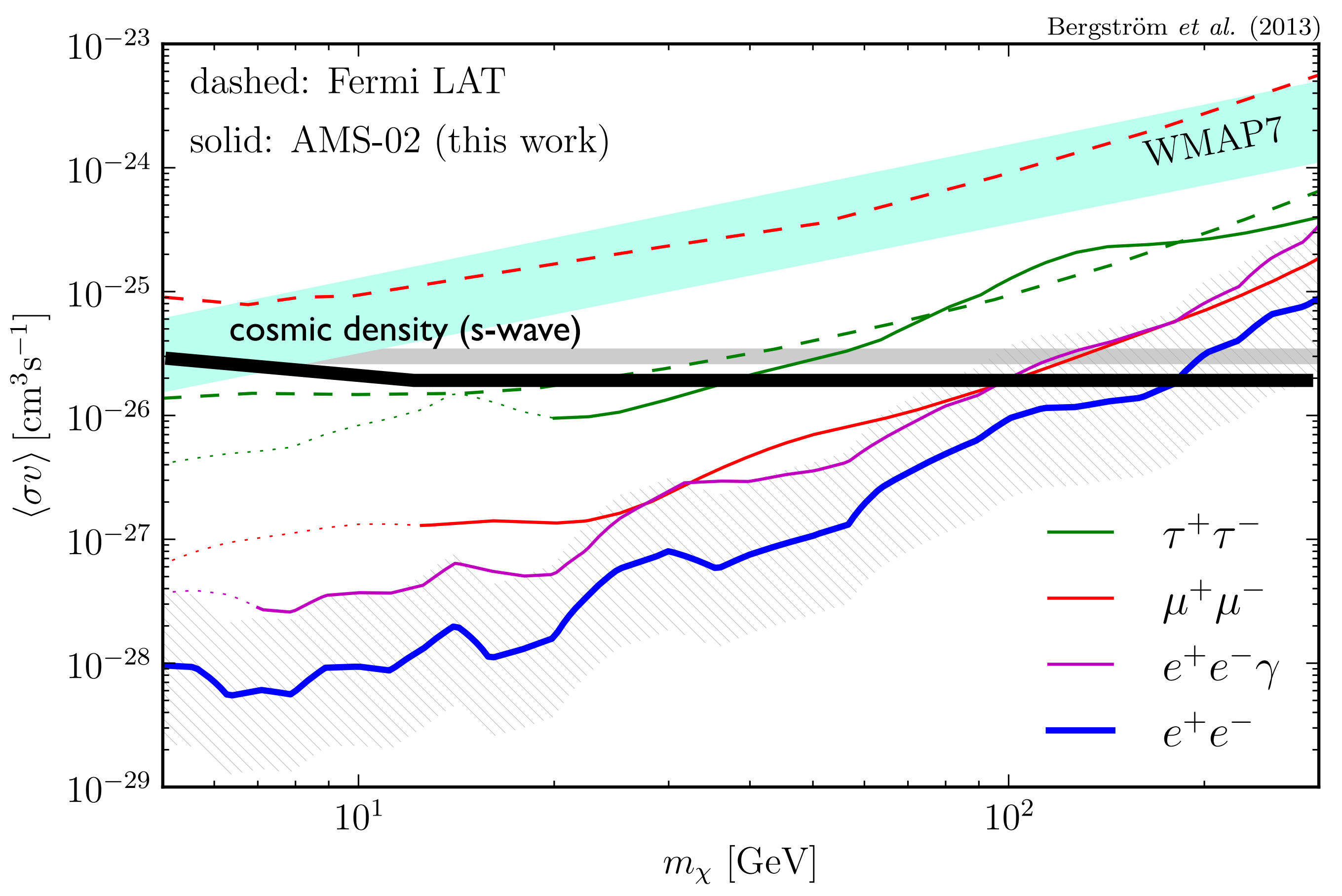
Bergstrom, Edsjo, Zaharijas 2009



Blasi 2009

Excess in cosmic ray positrons

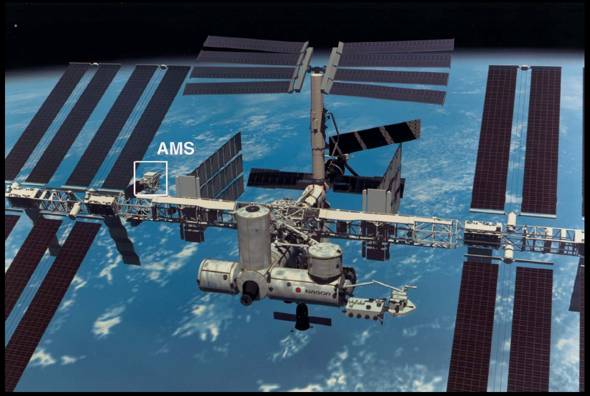
The safe way: use the AMS spectrum purely as upper limit on positrons from WIMP dark matter.

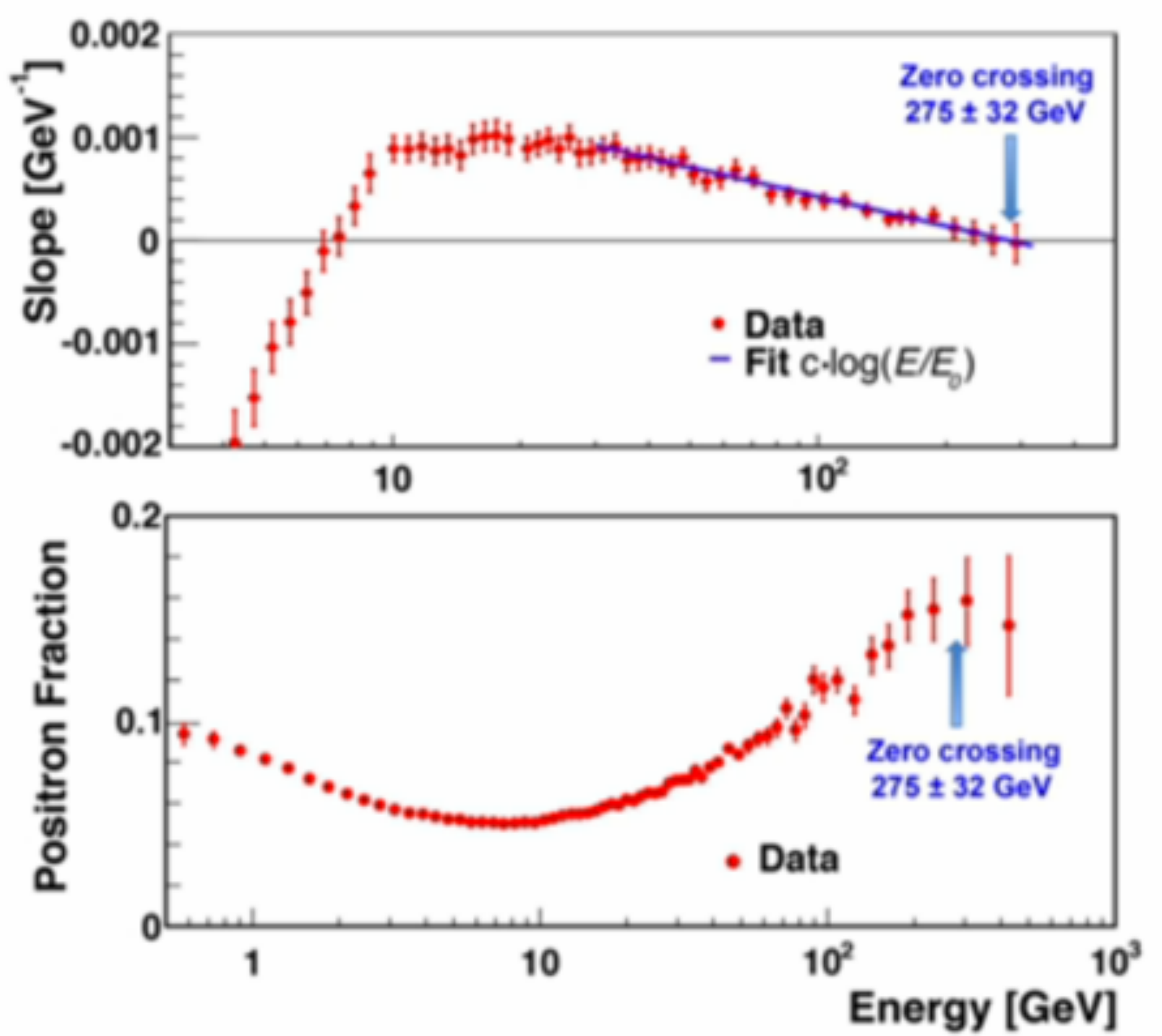


Bergstrom et al 2013

Excess in cosmic ray positrons

AMS-02 provides data with exquisite precision





Accardo et al [AMS] 2014

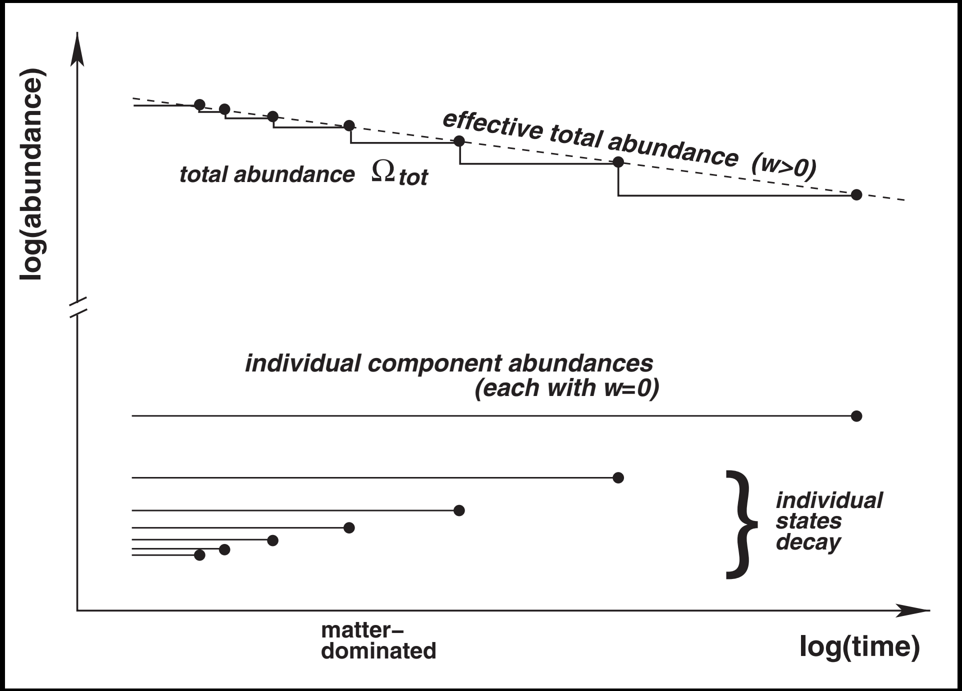
*New result
(4 days ago)*

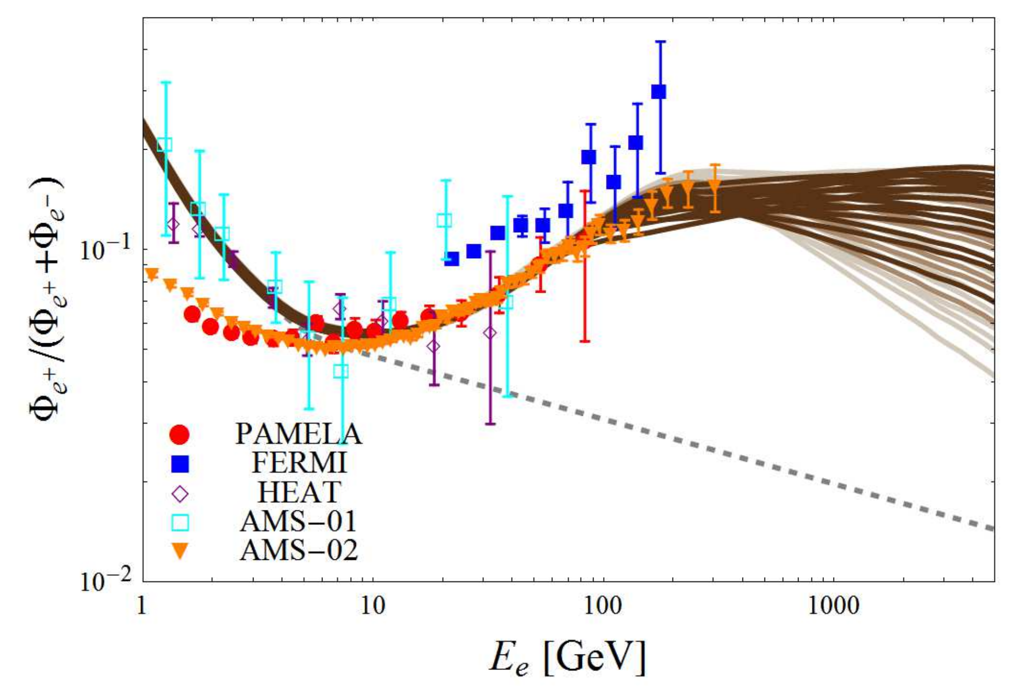
Dynamical dark matter

Dienes, Thomas 2011, 2012
Dienes, Kumar, Thomas 2012, 2013

A vast ensemble of fields decaying one into another

Example: Kaluza-Klein tower of axions in extra-dimensions



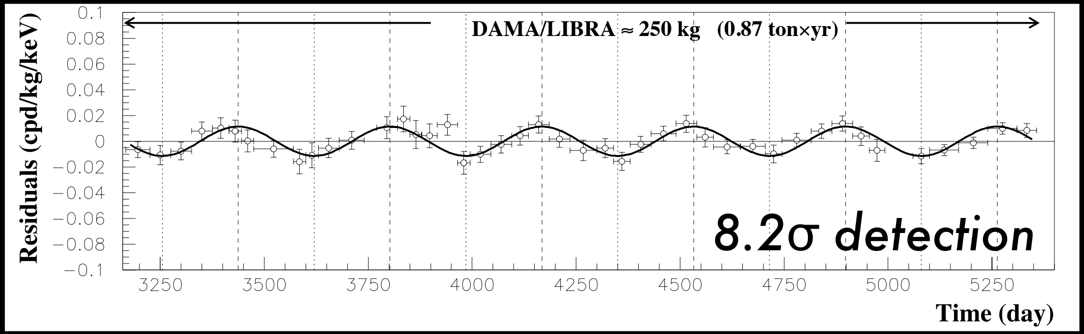


Phenomenology obtained through scaling laws

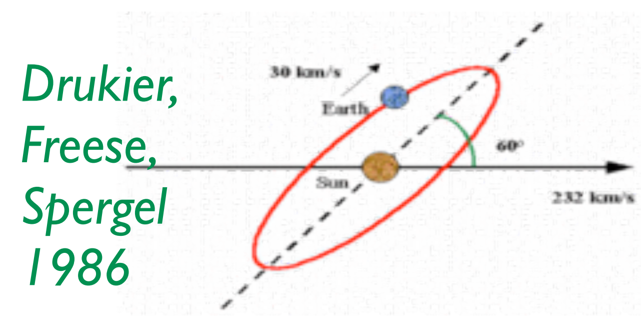
$$m_n = m_0 + n^\delta \Delta m,$$
$$\rho_n \sim m_n^\alpha,\ \tau_n \sim m_n^{-\gamma}$$

Direct detection

Evidence for light dark matter particles?



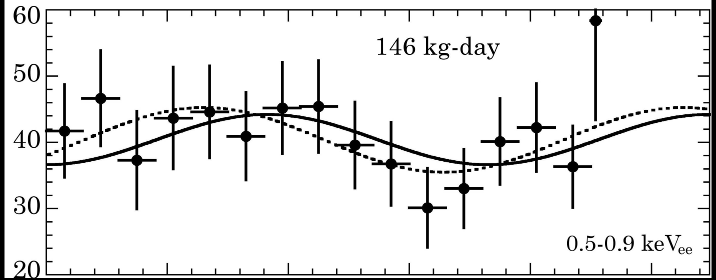
8.2σ detection



Drukier, Freese, Spergel 1986

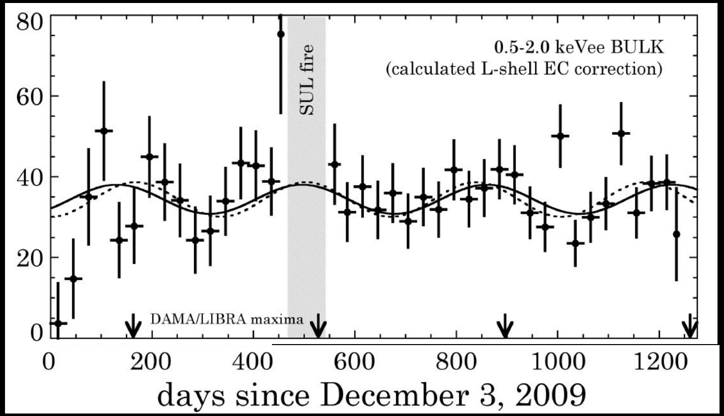
Bernabei et al (DAMA) 1997-10

Annually modulated.....



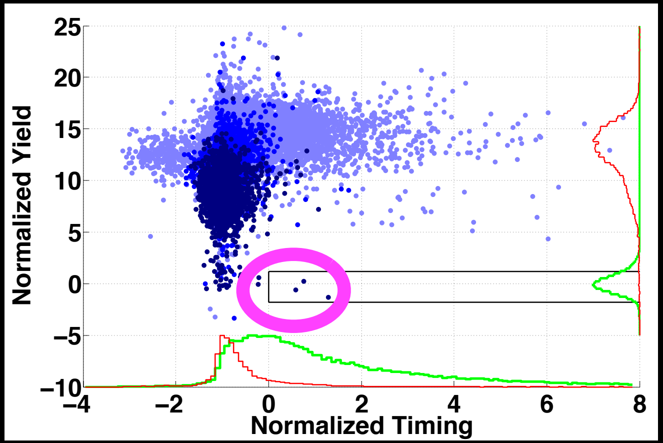
Aalseth et al (CoGeNT) 1106.0650

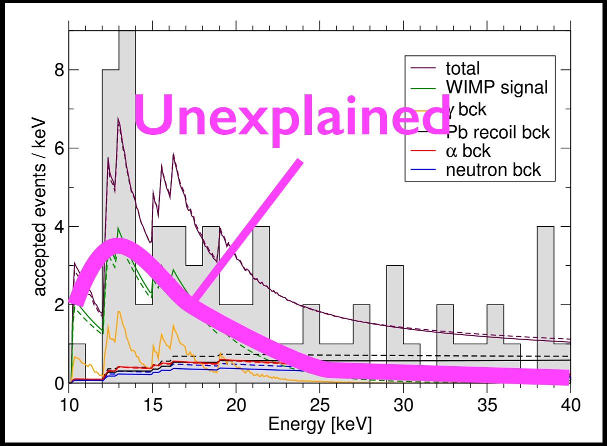
......and unmodulated



Collar (CoGeNT) 2013

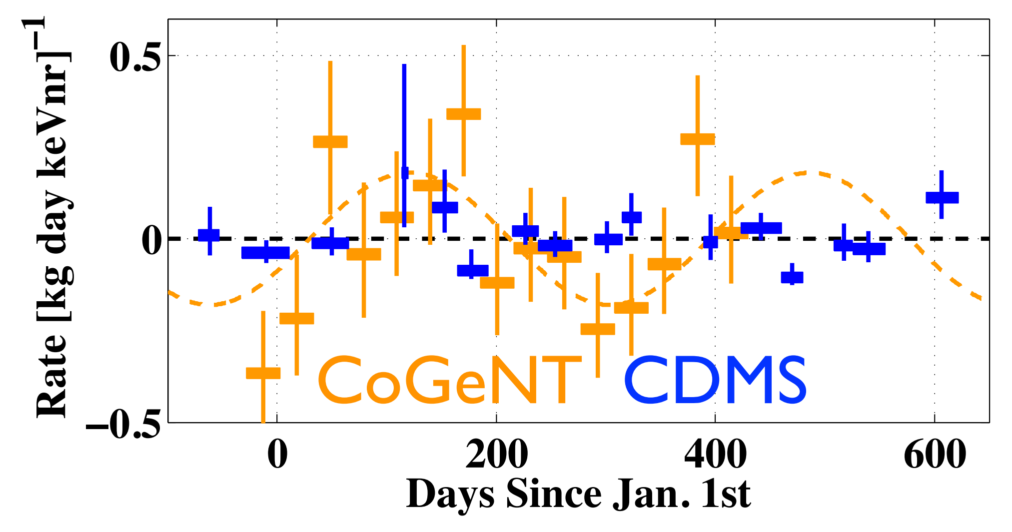
Agnese et al (CDMS) 2013





Anglehor et al (CRESST) 2011

Evidence for light dark matter particles?



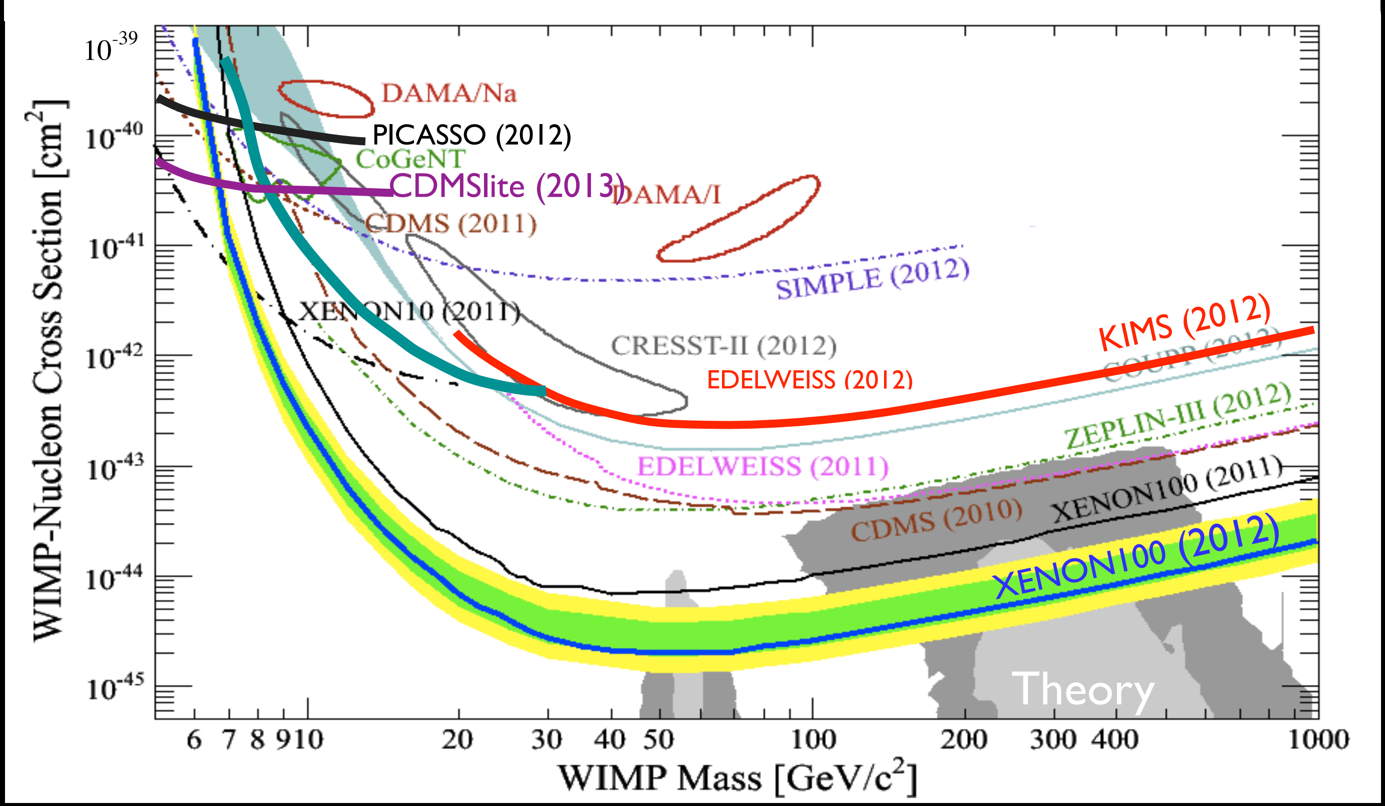
No significant modulation

Same target material

Ahmed et al (CDMS)
1203.1309

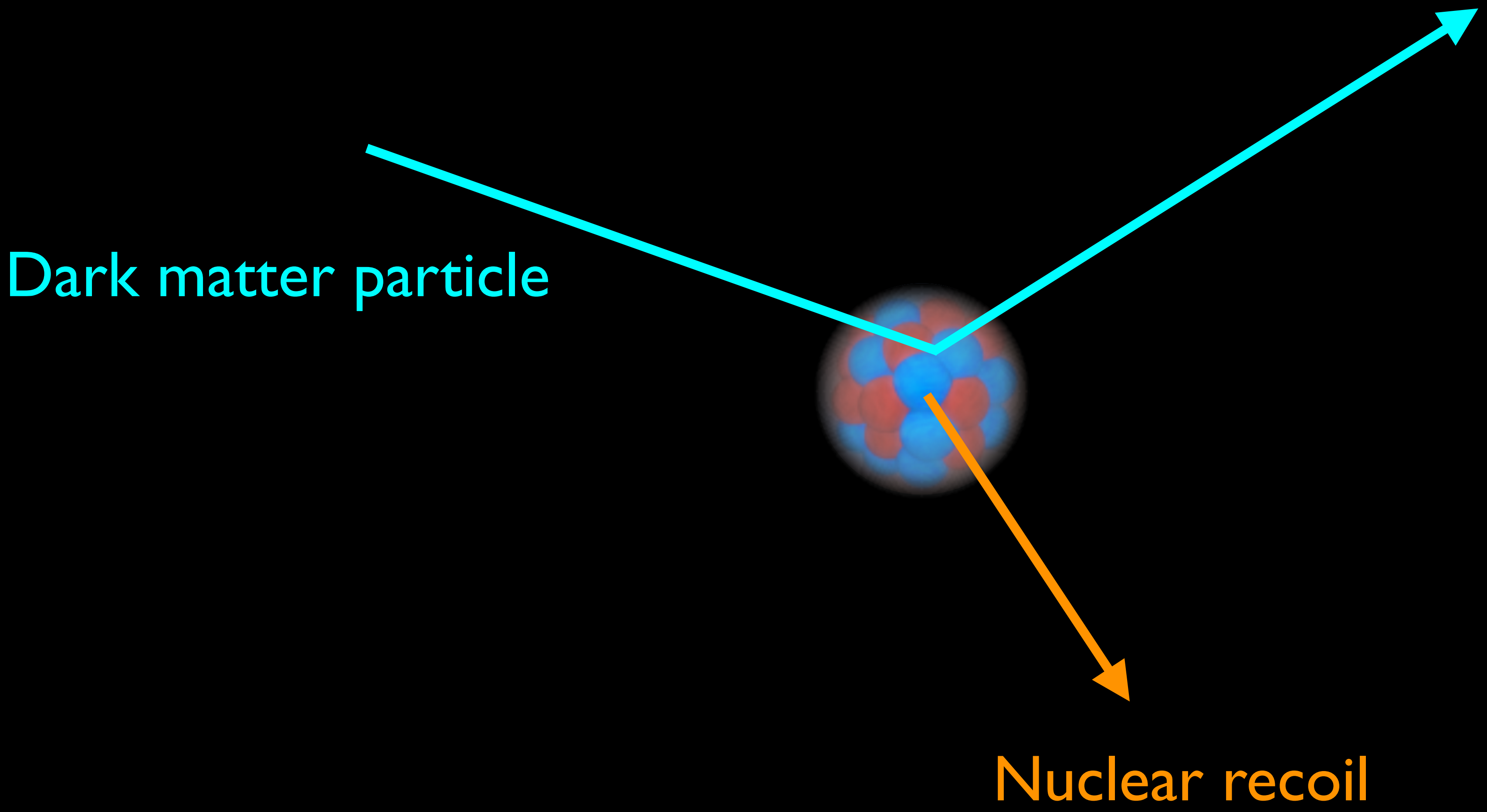
Not enough events

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



DM-nucleus elastic scattering

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



Detector response model

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

Is a nuclear recoil detectable?

Counting efficiency, energy resolution, scintillation response, etc.

$$\begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} = \mathcal{G}(E, E_R)$$

Probability of detecting an event with energy (or number of photoelectrons) E, given an event occurred with recoil energy E_R.

Particle physics model

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

What force couples dark matter to nuclei?

Coupling to nucleon number density, nucleon spin density, ...

WIMP speed

WIMP-nucleus cross section:
spin-independent, spin-dependent,
electric, magnetic, ...

$$\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} = \frac{v^2}{m}\frac{d\sigma}{dE_R}$$

WIMP mass

Nucleus recoil energy

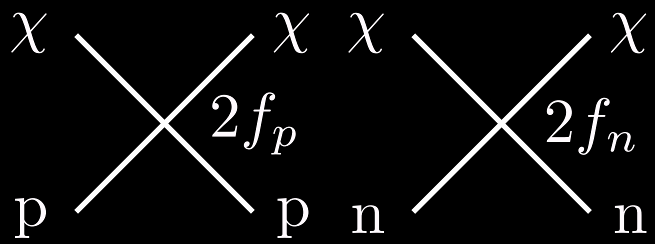
Particle physics model

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

Spin-independent

$$\frac{d\sigma_{SI}}{dE_R} = \frac{2m}{\pi v^2}\left|Zf_p + (A-Z)f_n\right|^2 \left|F(E_R)\right|^2$$

Effective four-particle vertices



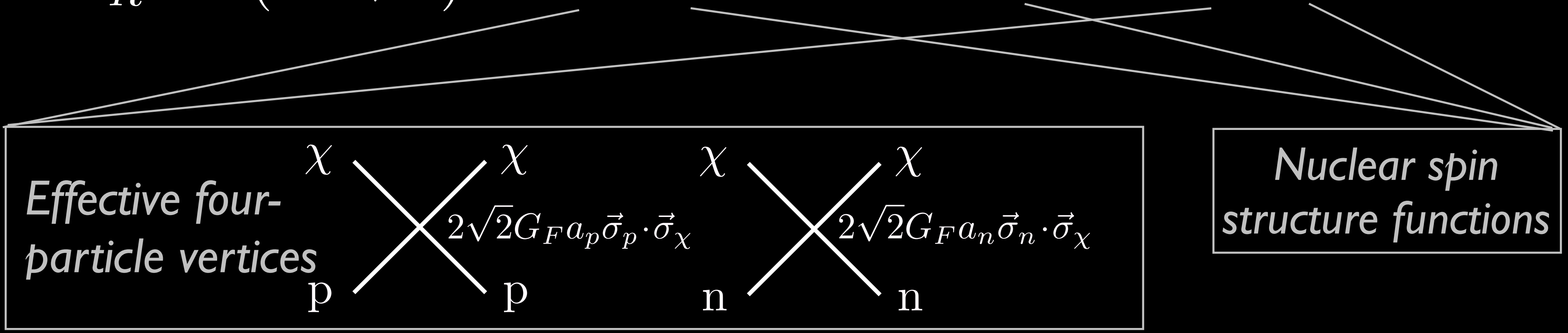
Nuclear density form factor

Particle physics model

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

Spin-dependent

$$\frac{d\sigma_{SD}}{dE_R} = \frac{16mG_F^2}{(2J+1)v^2}\left[a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q)\right]$$



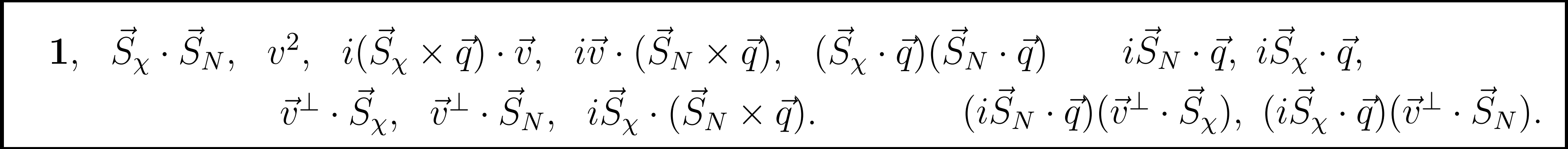
Effective four-particle vertices

Nuclear spin structure functions

All particle physics models

All short-distance operators classified

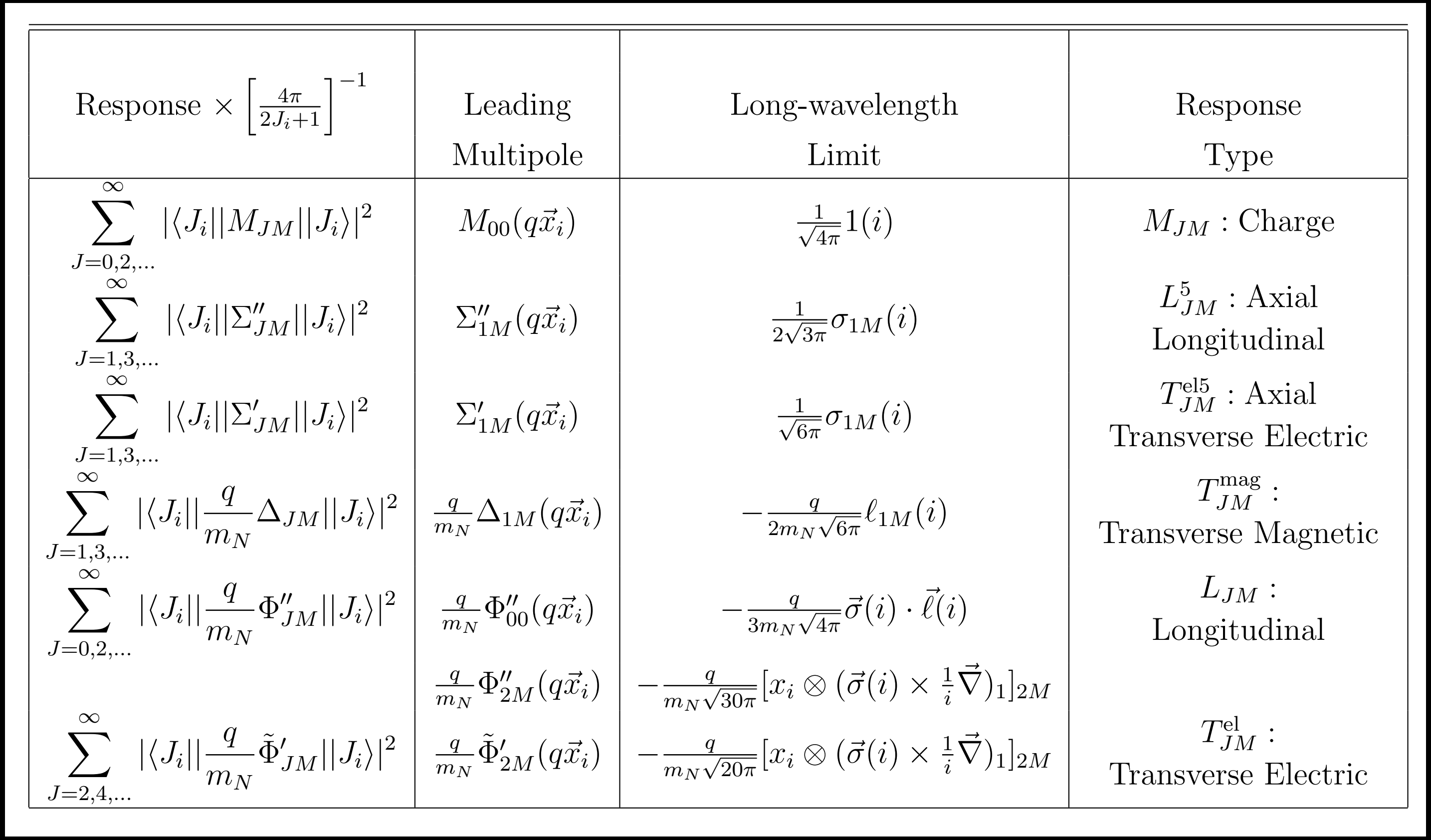
Fitzpatrick et al 2012



$$\mathbf{1},\quad \vec{S}_\chi \cdot \vec{S}_N,\quad v^2,\quad i(\vec{S}_\chi \times \vec{q}) \cdot \vec{v},\quad i\vec{v} \cdot (\vec{S}_N \times \vec{q}),\quad (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}) \qquad i\vec{S}_N \cdot \vec{q},\; i\vec{S}_\chi \cdot \vec{q},$$

$$\vec{v}^\perp \cdot \vec{S}_\chi,\quad \vec{v}^\perp \cdot \vec{S}_N,\quad i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q}). \qquad (i\vec{S}_N \cdot \vec{q})(\vec{v}^\perp \cdot \vec{S}_\chi),\; (i\vec{S}_\chi \cdot \vec{q})(\vec{v}^\perp \cdot \vec{S}_N).$$

All nuclear form factors classified



Response $\times \left[\frac{4\pi}{2J_i+1}\right]^{-1}$	Leading Multipole	Long-wavelength Limit	Response Type
$\sum_{J=0,2,\ldots}^{\infty} \lvert\langle J_i \vert\vert M_{JM} \vert\vert J_i\rangle\rvert^2$	$M_{00}(q\vec{x}_i)$	$\frac{1}{\sqrt{4\pi}} 1(i)$	M_{JM} : Charge
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \vert\vert \Sigma''_{JM} \vert\vert J_i\rangle\rvert^2$	$\Sigma''_{1M}(q\vec{x}_i)$	$\frac{1}{2\sqrt{3\pi}} \sigma_{1M}(i)$	L^5_{JM} : Axial Longitudinal
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \vert\vert \Sigma'_{JM} \vert\vert J_i\rangle\rvert^2$	$\Sigma'_{1M}(q\vec{x}_i)$	$\frac{1}{\sqrt{6\pi}} \sigma_{1M}(i)$	T^{el5}_{JM} : Axial Transverse Electric
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \vert\vert \frac{q}{m_N} \Delta_{JM} \vert\vert J_i\rangle\rvert^2$	$\frac{q}{m_N} \Delta_{1M}(q\vec{x}_i)$	$-\frac{q}{2m_N\sqrt{6\pi}} \ell_{1M}(i)$	T^{mag}_{JM} : Transverse Magnetic
$\sum_{J=0,2,\ldots}^{\infty} \lvert\langle J_i \vert\vert \frac{q}{m_N} \Phi''_{JM} \vert\vert J_i\rangle\rvert^2$	$\frac{q}{m_N} \Phi''_{00}(q\vec{x}_i)$	$-\frac{q}{3m_N\sqrt{4\pi}} \vec{\sigma}(i) \cdot \vec{\ell}(i)$	L_{JM} : Longitudinal
	$\frac{q}{m_N} \Phi''_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{30\pi}} [x_i \otimes (\vec{\sigma}(i) \times \frac{1}{i}\vec{\nabla})_1]_{2M}$	
$\sum_{J=2,4,\ldots}^{\infty} \lvert\langle J_i \vert\vert \frac{q}{m_N} \tilde{\Phi}'_{JM} \vert\vert J_i\rangle\rvert^2$	$\frac{q}{m_N} \tilde{\Phi}'_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{20\pi}} [x_i \otimes (\vec{\sigma}(i) \times \frac{1}{i}\vec{\nabla})_1]_{2M}$	T^{el}_{JM} : Transverse Electric

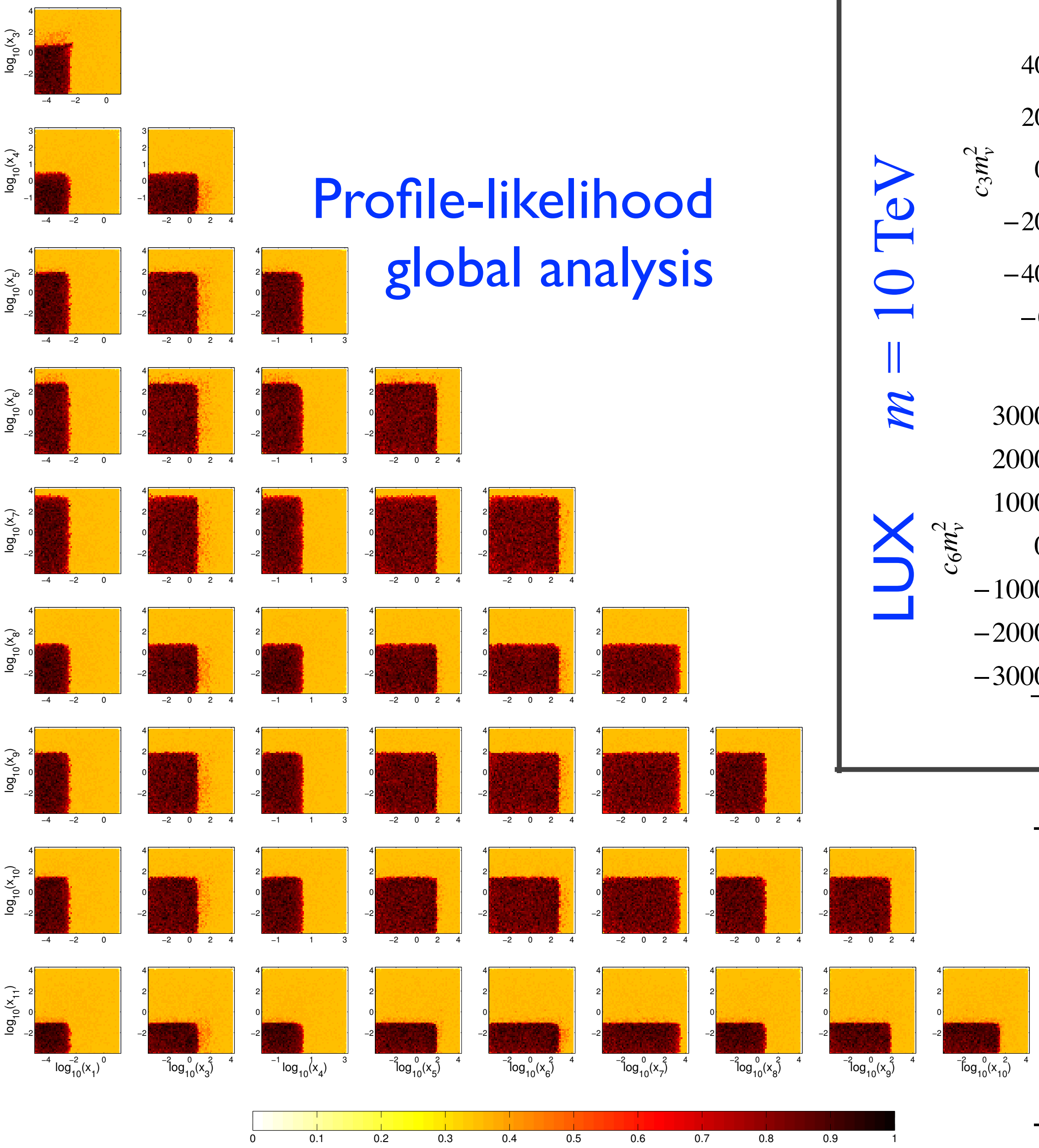
nuclear
oscillator
model

Fitzpatrick et al 2012

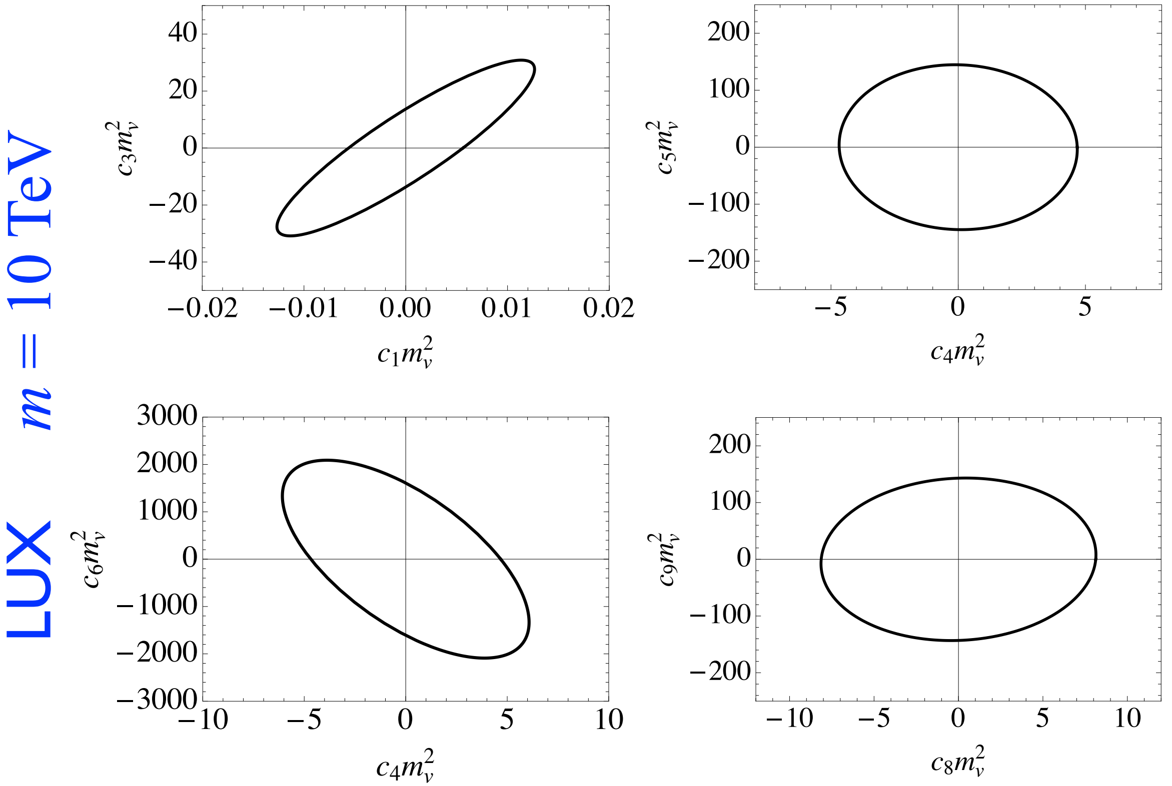
All particle physics models

Combined analysis of short-distance operators

Catena, Gondolo 2014



Profile-likelihood global analysis



$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = -i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = -i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$$

$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp_{\chi N}$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp_{\chi N}$$

$$\mathcal{O}_9 = -i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_{10} = -i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

Astrophysics model

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

How much dark matter comes to Earth?

Local halo density

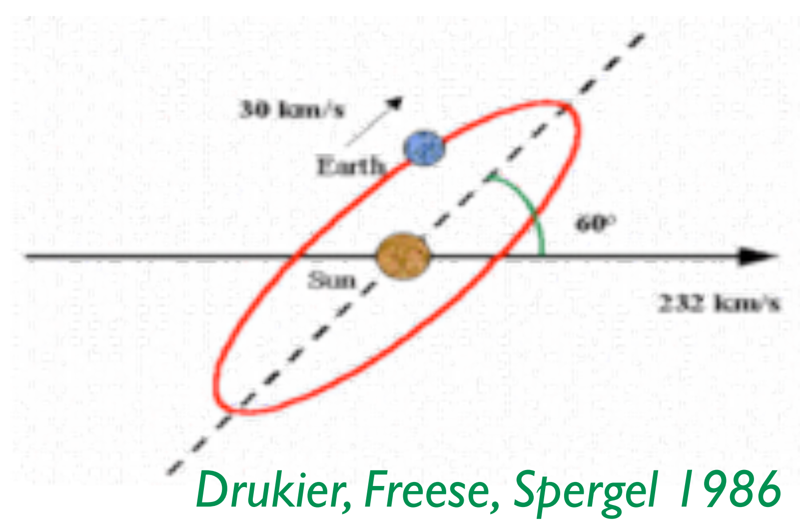
Velocity distribution

$$(\text{astrophysics}) = \eta(v_{\min}, t) \equiv \rho_\chi \int_{v > v_{\min}} \frac{f(\mathbf{v}, t)}{v}\, \mathrm{d}^3 v$$

Minimum WIMP speed to impart recoil energy E_R

$$v_{\min} = (M E_R/\mu + \delta)/\sqrt{2 M E_R}$$

Annual modulation



Drukier, Freese, Spergel 1986

$$\eta(v_{\min}, t) = \eta_0(v_{\min}) + \eta_1(v_{\min})\ \cos(\omega t + \varphi)$$

$$\frac{dR}{dE} = S_0(E) + S_1(E)\ \cos(\omega t + \varphi)$$

Unmodulated signal

Modulation amplitude

Astrophysics model: velocity distribution

Standard Halo Model

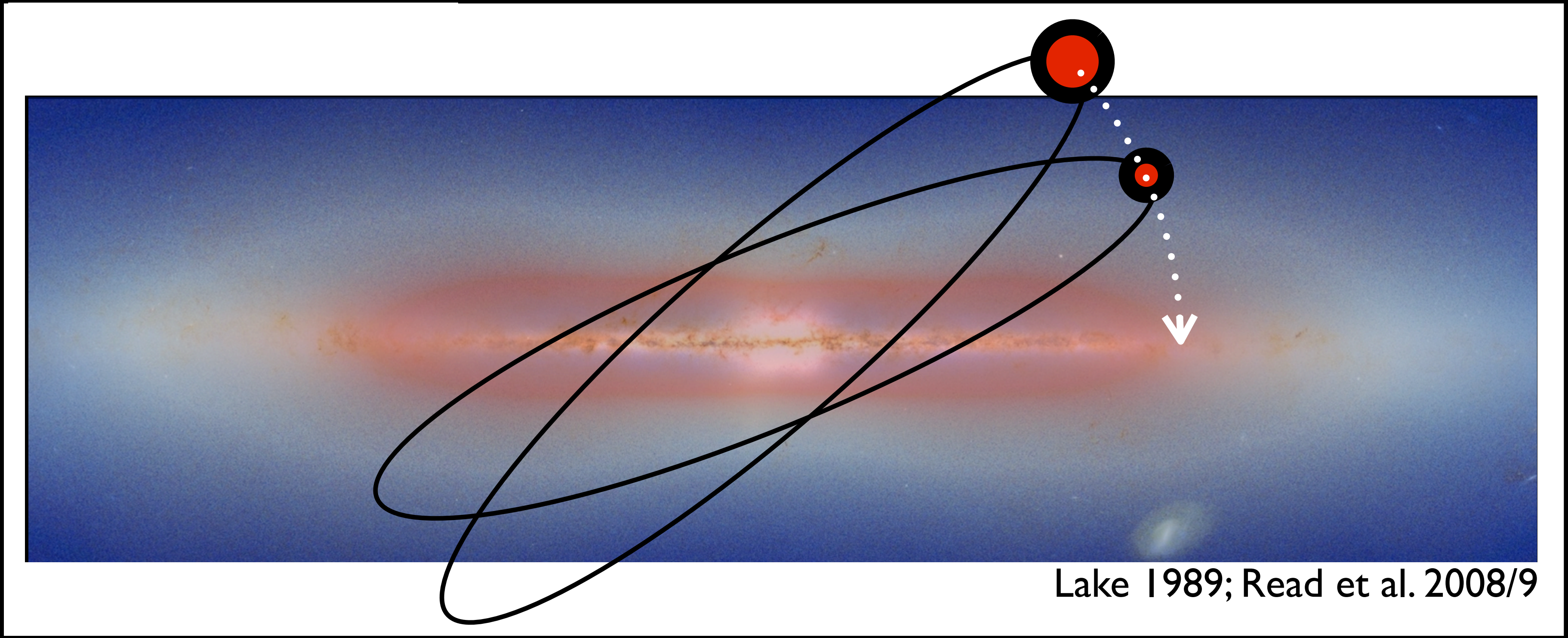
truncated Maxwellian

$$f(\mathbf{v}) = \begin{cases} \frac{1}{N_{\mathrm{esc}} \pi^{3/2} \bar{v}_0^3} e^{-|\mathbf{v}+\mathbf{v}_{\mathrm{obs}}|/\bar{v}_0^2} & |\mathbf{v}| < v_{\mathrm{esc}} \\ 0 & \mathrm{otherwise} \end{cases}$$

The spherical cow of direct WIMP searches

Galactic dark matter

Dark disks arise from dynamical friction on accreted satellites



Lake 1989; Read et al. 2008/9

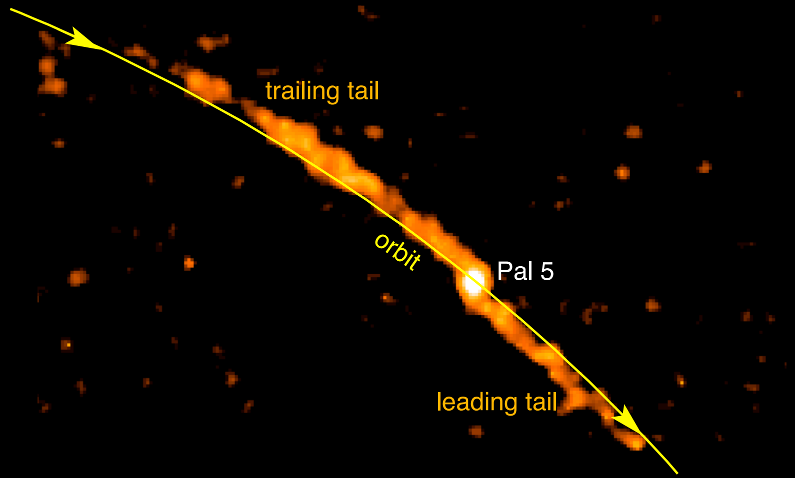
Our galaxy had no recent major merger, thus no significant dark disk.

Galactic dark matter

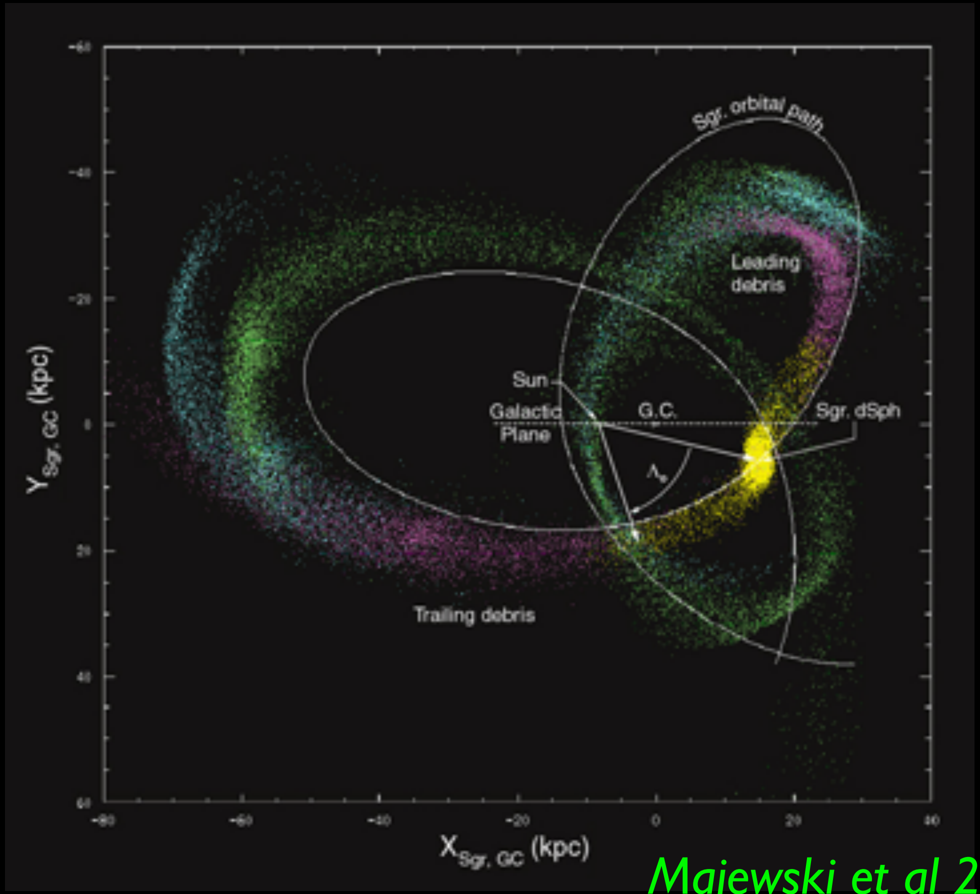
Tidal forces can destroy subhalos and generate tidal streams

Streams of stars have been observed in the galactic halo

SDSS, 2MASS, SEGUE,…….



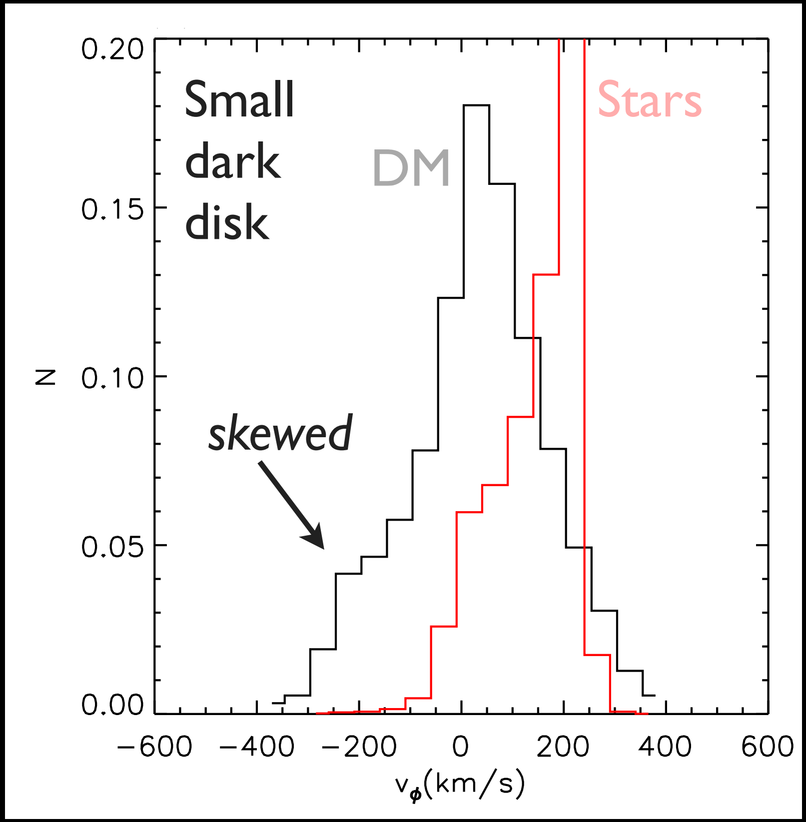
Odenkirchen et al 2002 (SDSS)



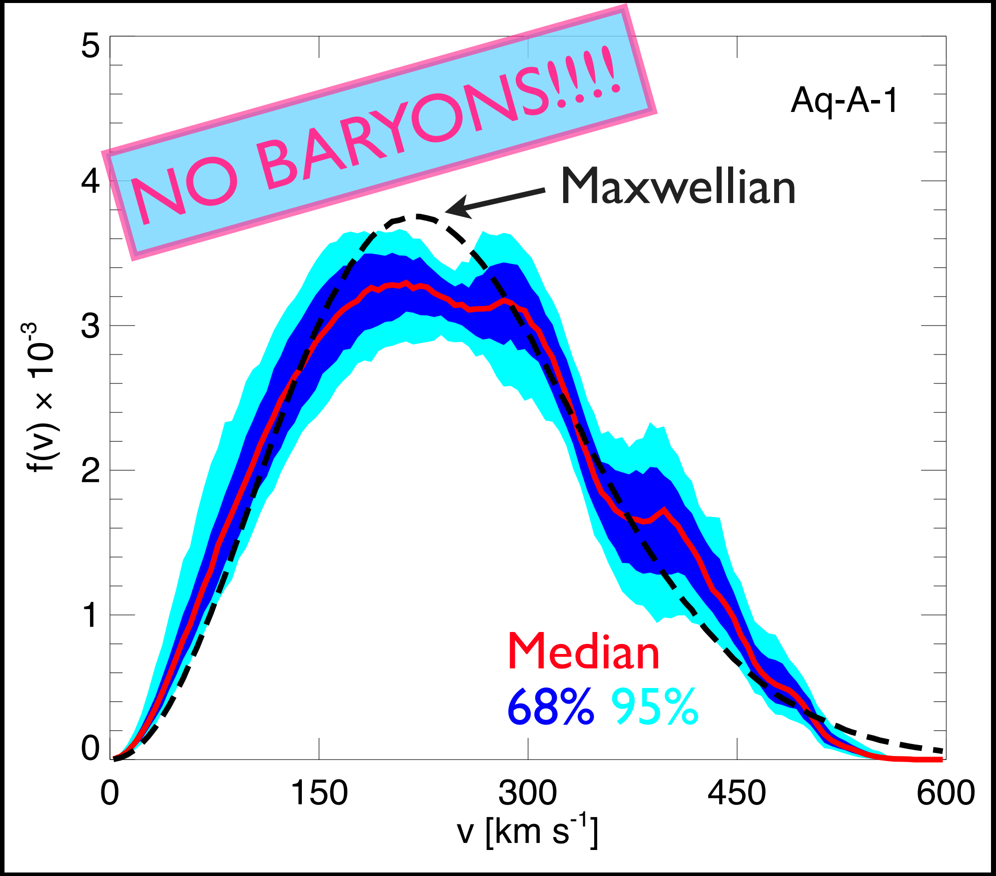
Majewski et al 2013 (2MASS)

Galactic dark matter

We know very little about the dark matter velocity distribution near the Sun



Read et al 2009

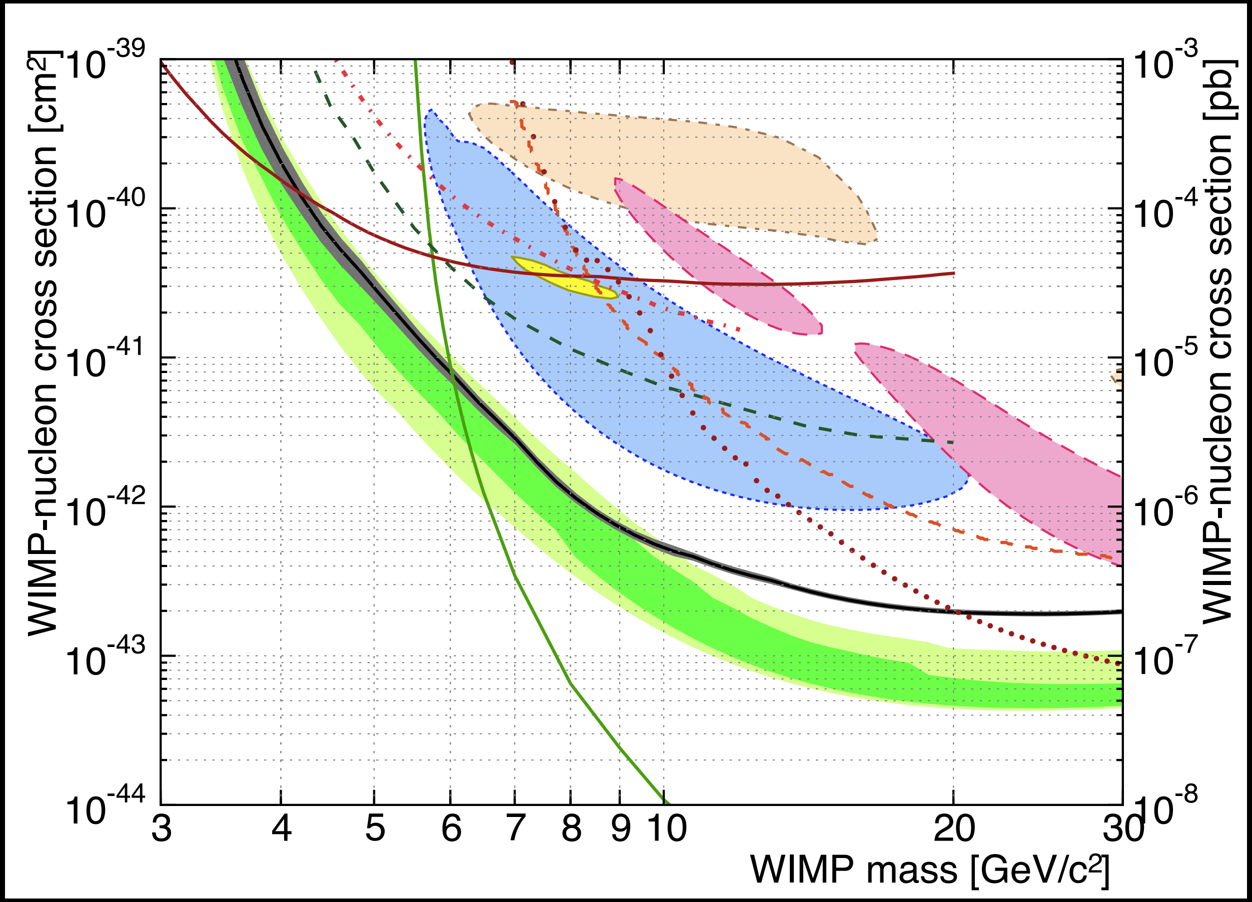


Vogelsberger et al 2009

Cosmological N-Body simulations including baryons are challenging

DM-nucleus elastic scattering

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

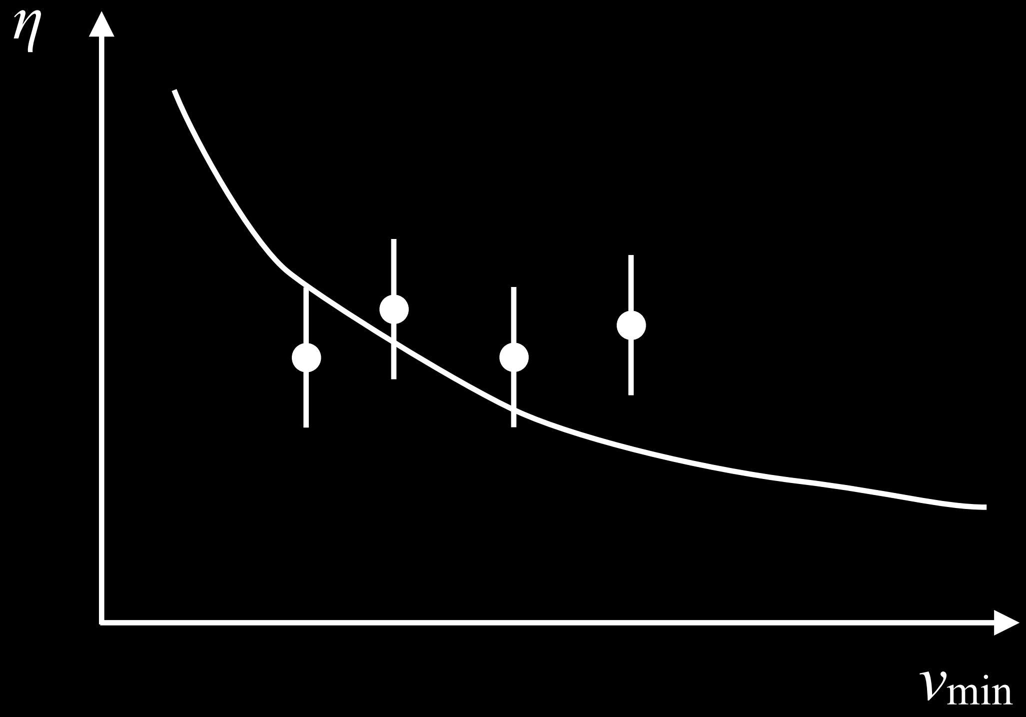


Agnese et al (SuperCDMS) 2014

Astrophysics-independent approach

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

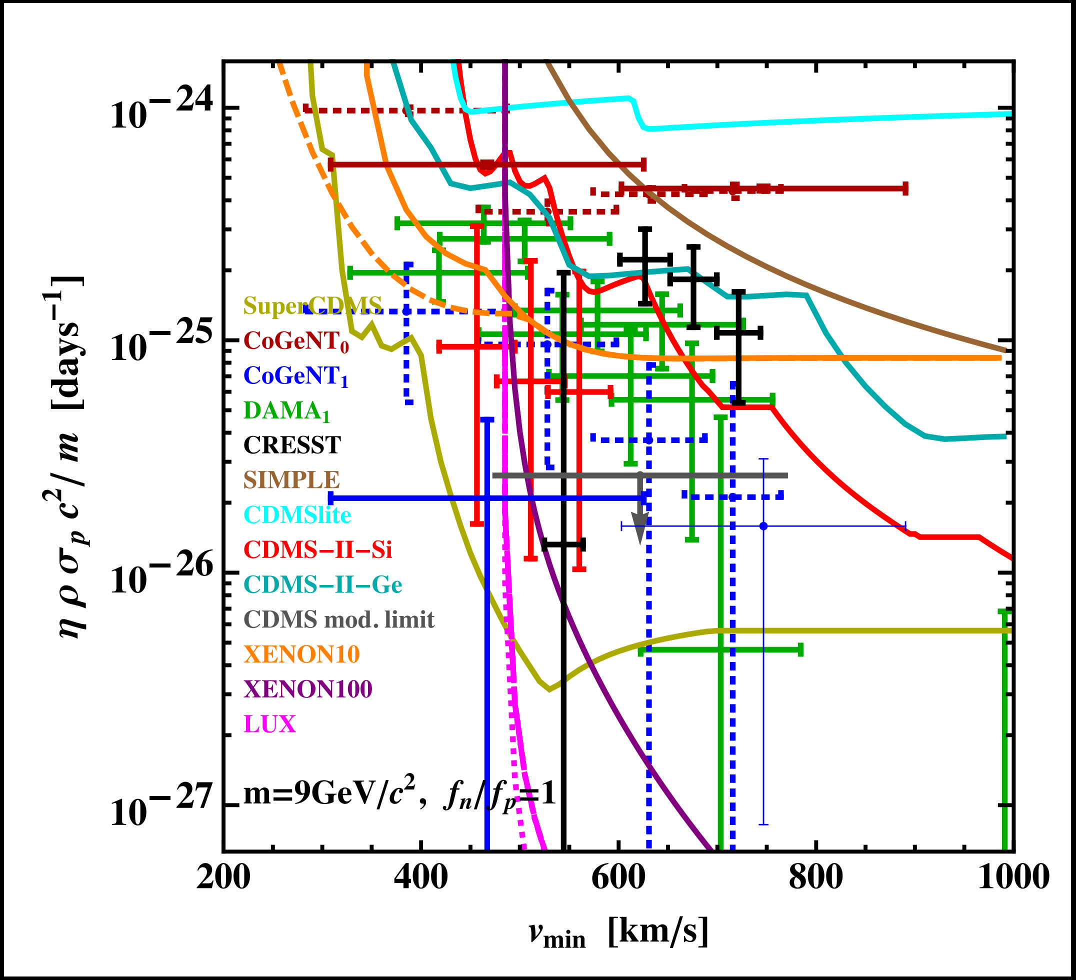
$$\eta(v_{\rm min}) = \int_{v_{\rm min}}^{\infty} \frac{f(\mathbf{v})}{v}\, d^3v$$



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

Astrophysics-independent approach

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



Del Nobile, Gelmini, Gondolo, Huh 2013-14

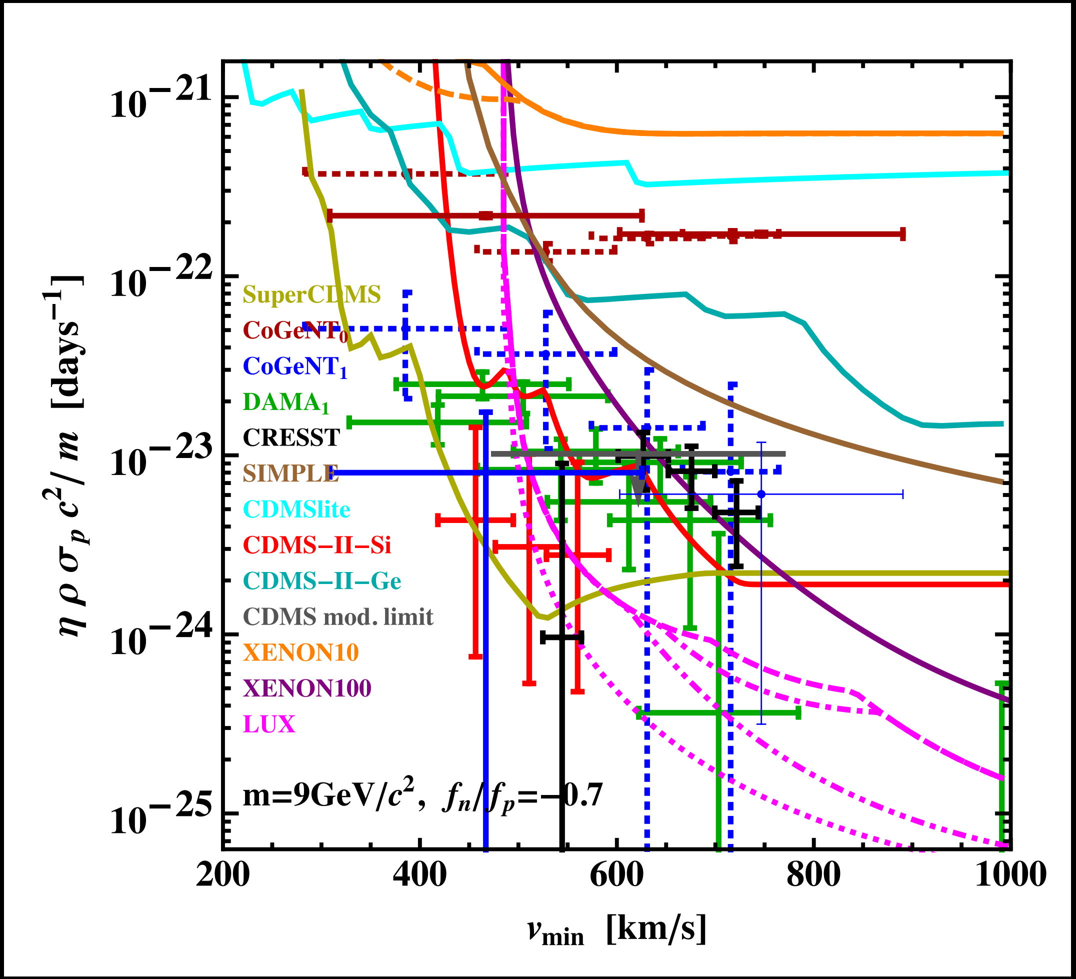
Halo modifications alone cannot save the SI signal regions from the bounds

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

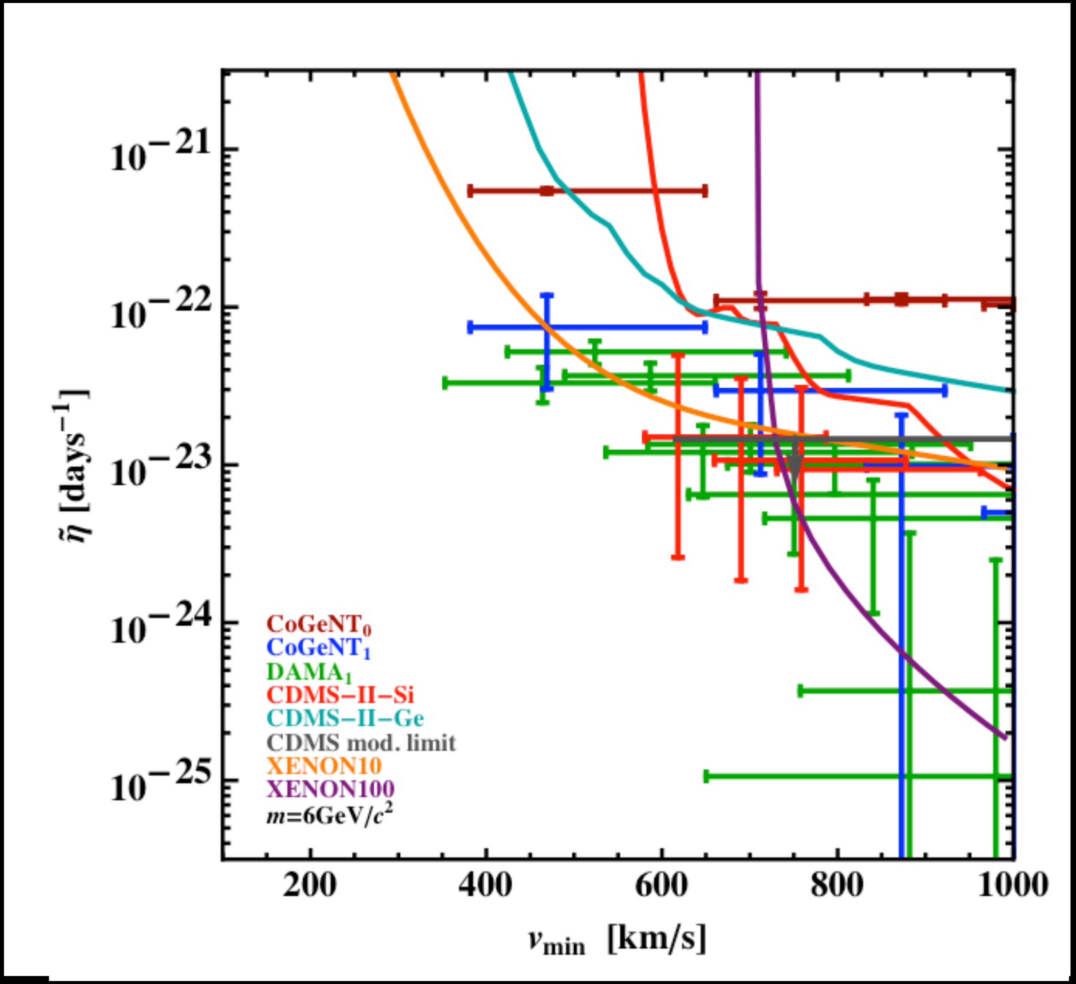
Dark matter coupled differently to protons and neutrons may have a (tiny) chance

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

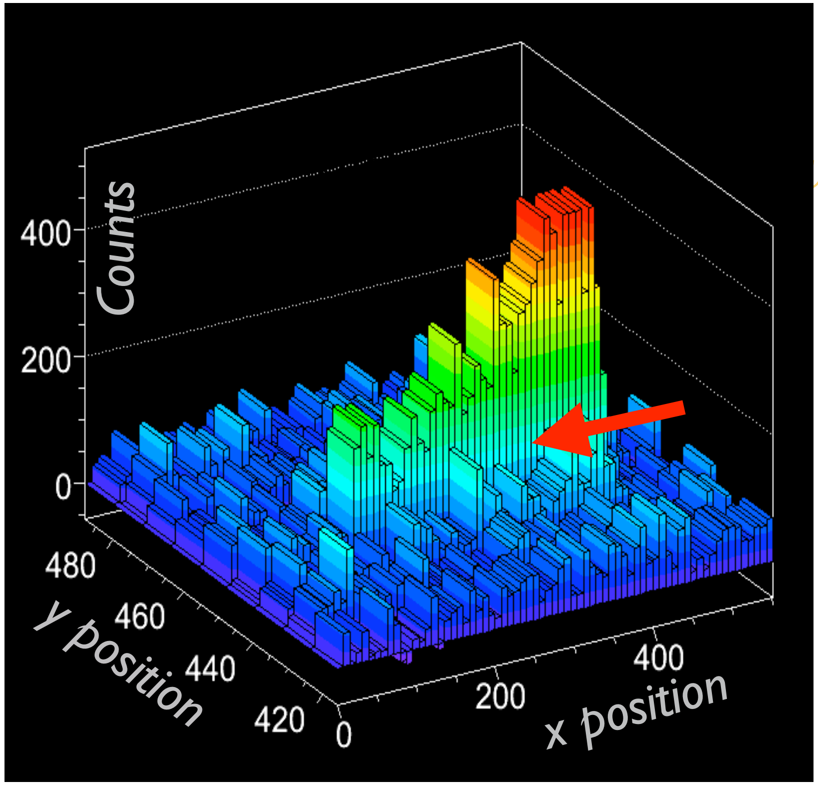
CDMS-Si event rate is similar to annually modulated rates

Still depends on particle model

Toward WIMP astronomy

- Directional direct detection
  - measure direction of nuclear recoil

- Several R&D efforts
  - DRIFT
  - Dark Matter TPC
  - NEWAGE
  - MIMAC
  - D3
  - Emulsion Dark Matter Search
  - Columnar recombination



DMTPC

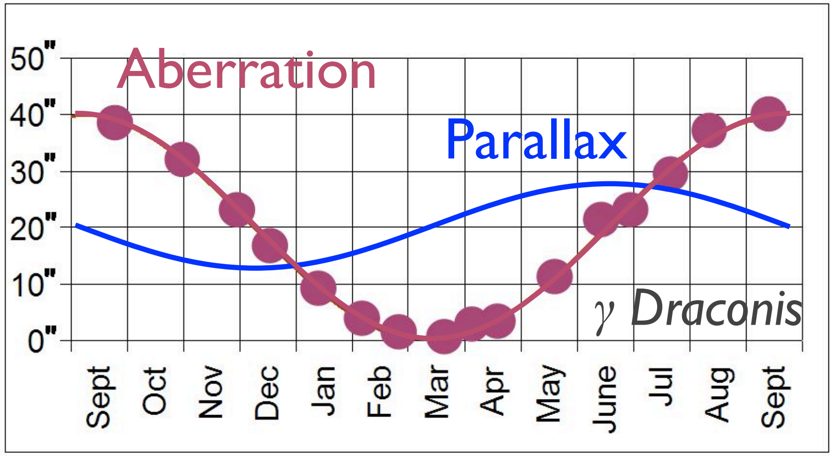
Only ~10 events needed to confirm extraterrestrial signal

Toward WIMP astronomy

Aberration of WIMPs

Photon arrival direction

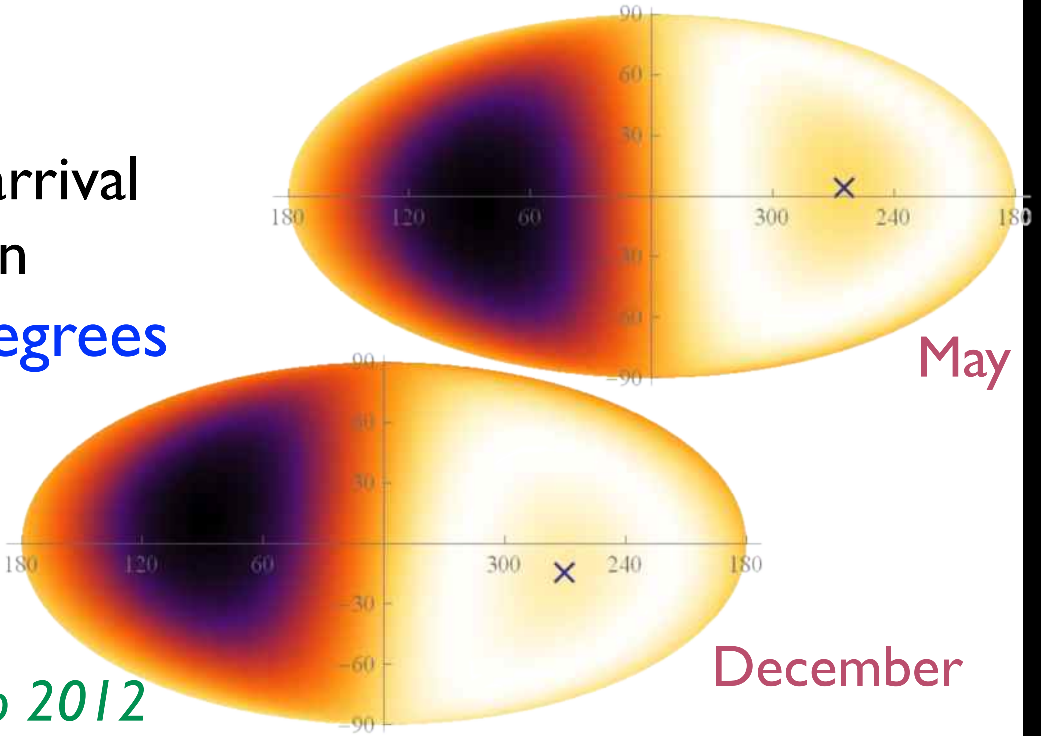
20 arcsec



Bradley 1725

WIMP arrival direction

10 degrees



Bozorgnia, Gelmini, Gondolo 2012

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.