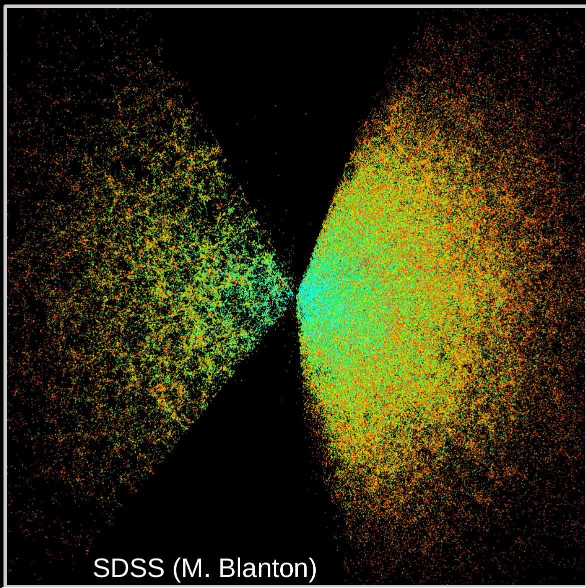
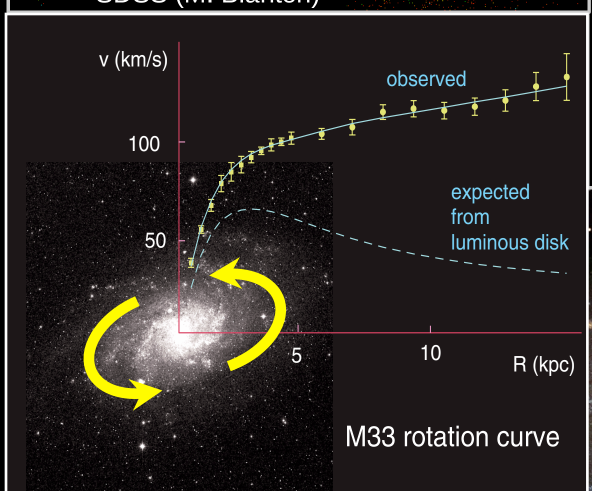
Dark Matter Theory

Paolo Gondolo
University of Utah

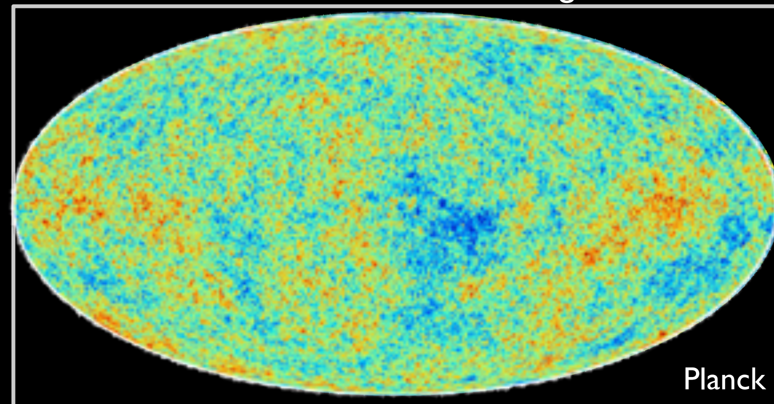
Evidence for cold dark matter

Large Scale Structure



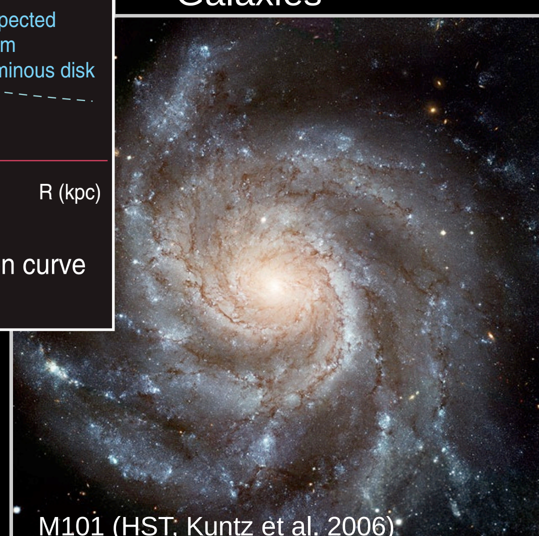


Cosmic Microwave Background

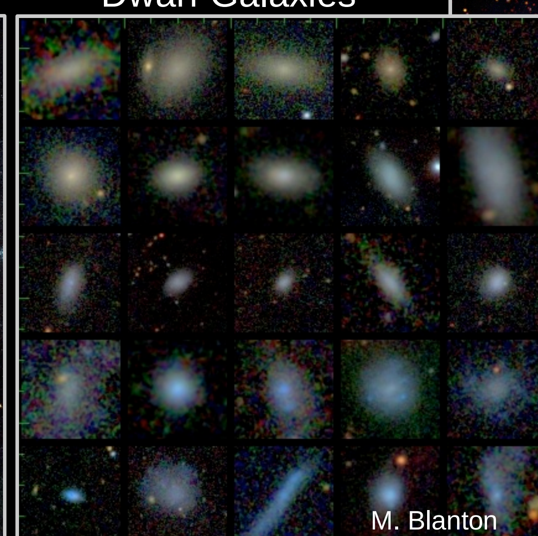


Supernovae

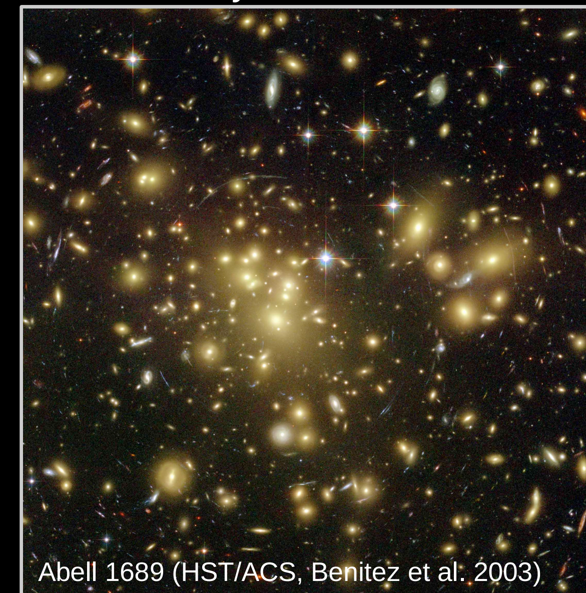
Galaxies

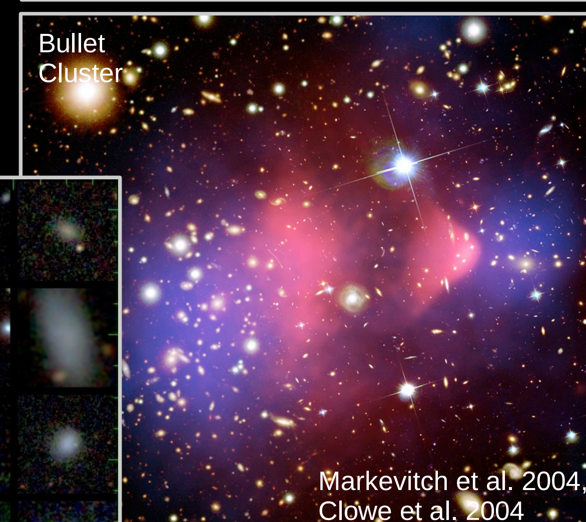


Dwarf Galaxies

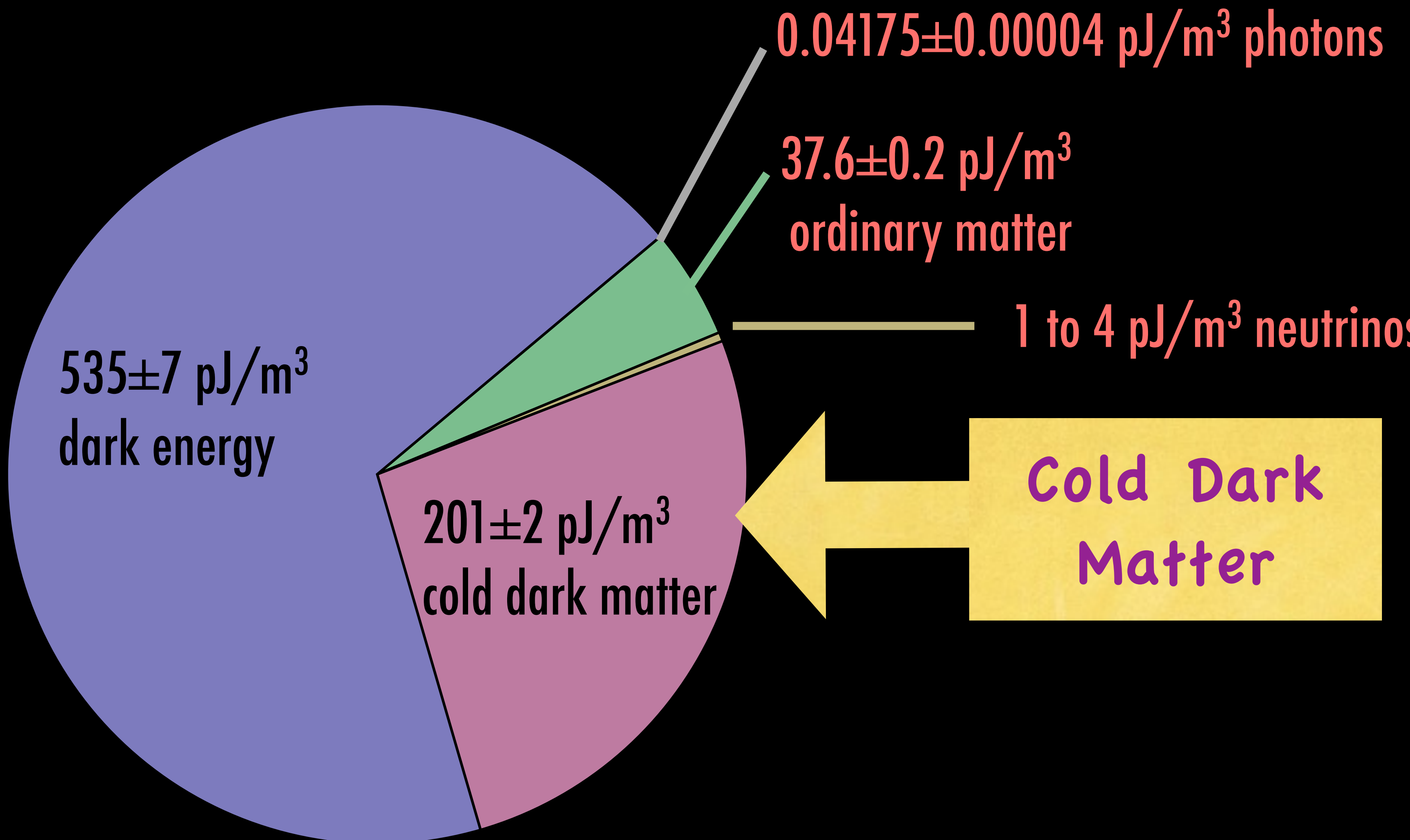


Galaxy Clusters





The observed energy content of the universe



matter $p \ll \rho$

radiation $p = \rho/3$

vacuum $p = -\rho$

Planck (2015)

TT,TE,EE+lowP+lensing+ext

1 pJ = 10^{-12} J

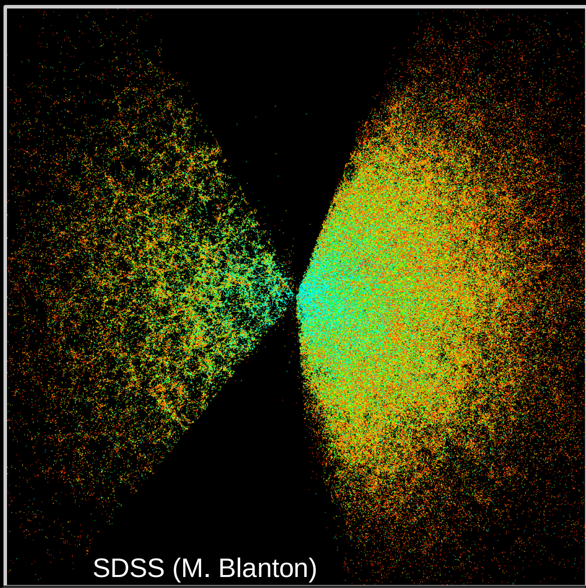
$\rho_{\mathrm{crit}} = 1.68829\, h^2$ pJ/m^3

From CMB fluctuations to galaxies

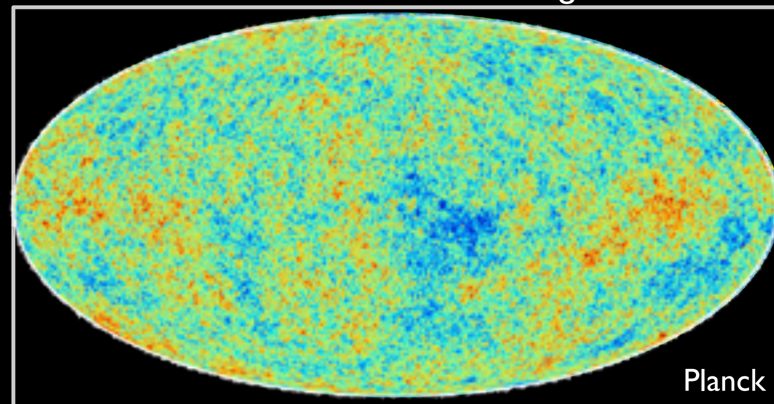
Galaxy formation

From CMB fluctuations to galaxies

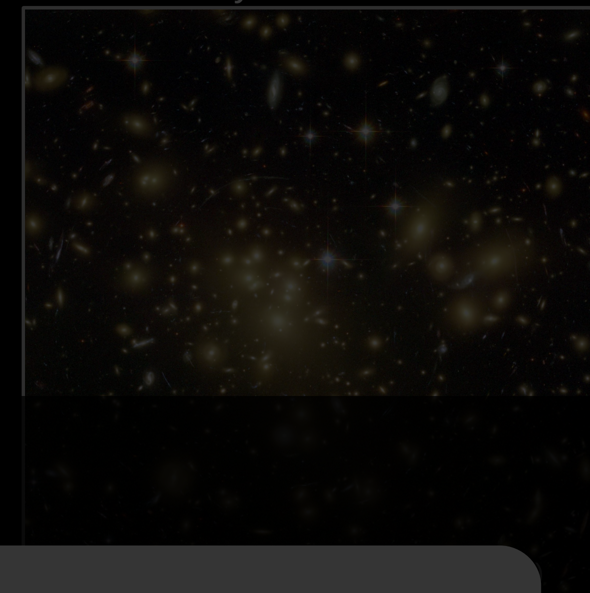
Large Scale Structure



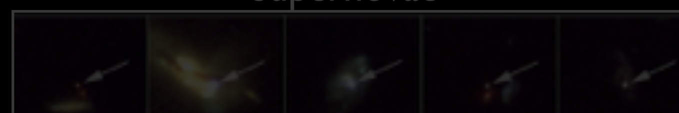
Cosmic Microwave Background

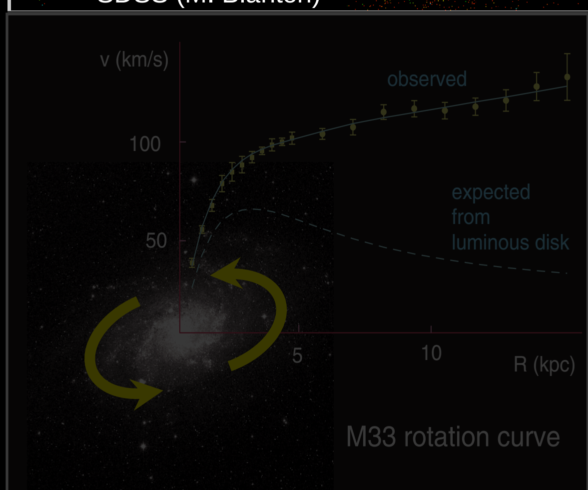


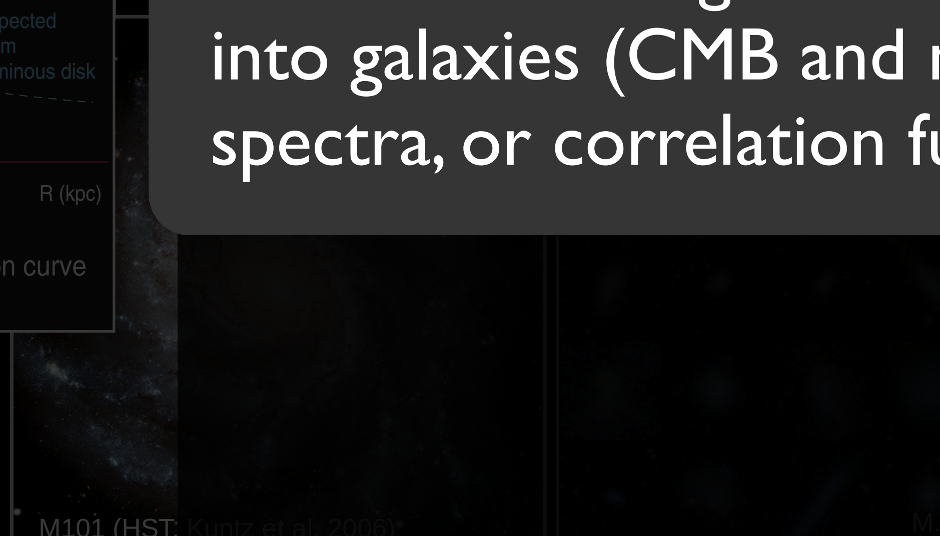
Galaxy Clusters



Supernovae



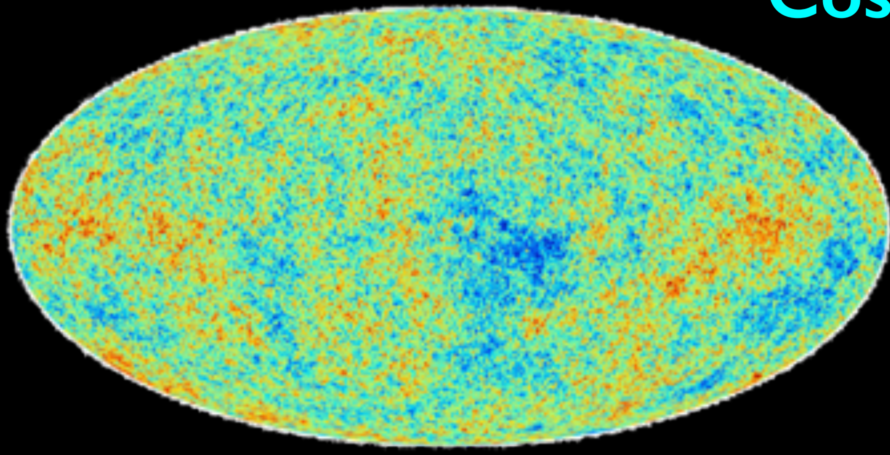


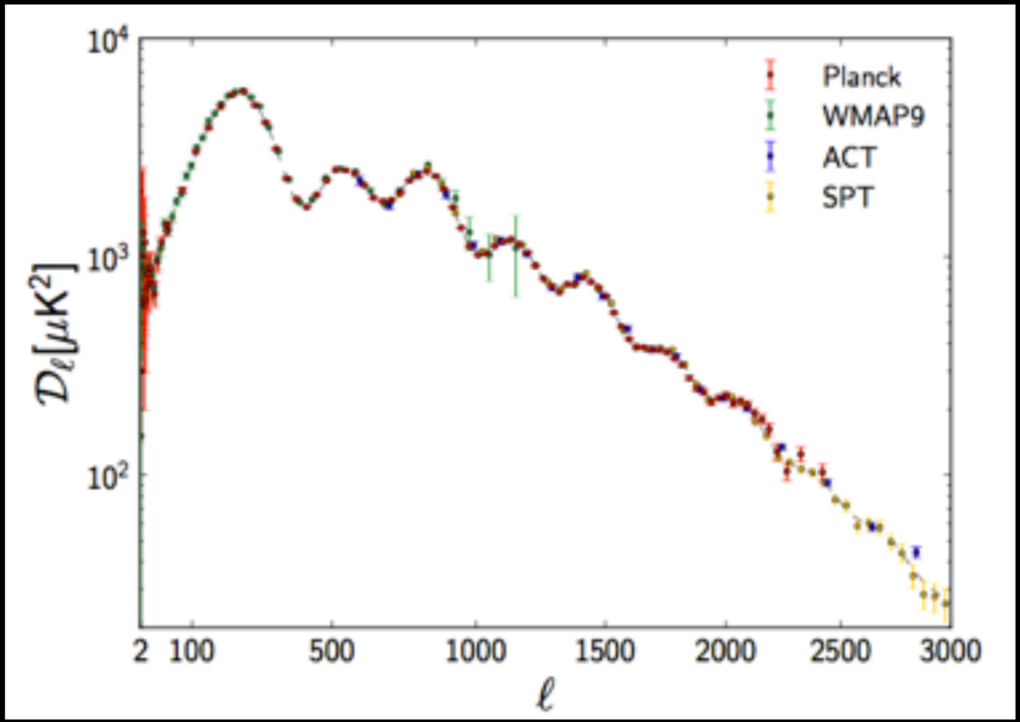


An invisible mass makes the Cosmic Microwave Background fluctuations grow into galaxies (CMB and matter power spectra, or correlation functions)

Evidence for cold dark matter

Cosmic Microwave Background fluctuations





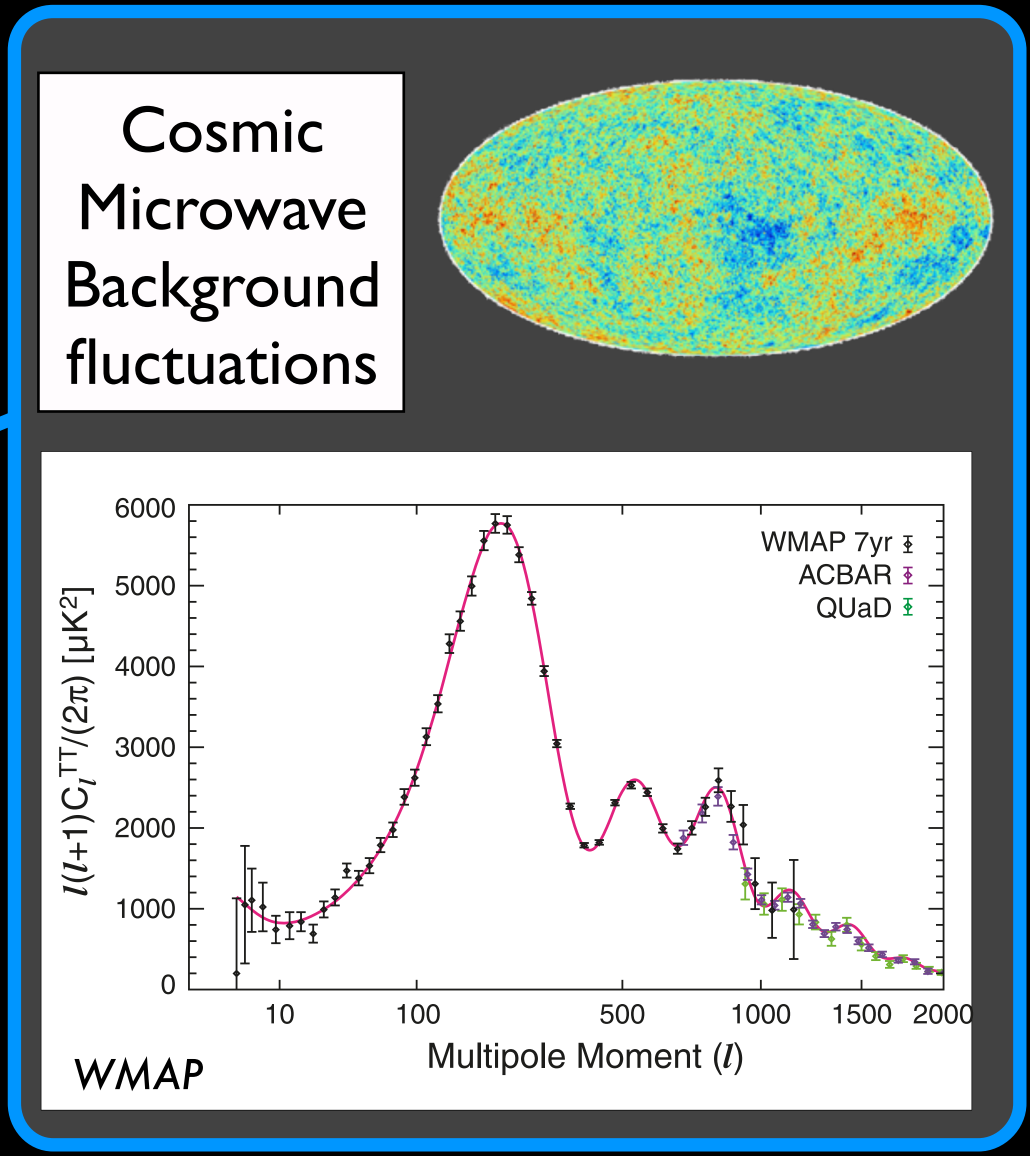
	Planck+WP+highL+BAO	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04148	1.04147 ± 0.00056
τ	0.0952	0.092 ± 0.013
n_s	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0973	3.091 ± 0.025
Ω_Λ	0.6914	0.692 ± 0.010
σ_8	0.8288	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

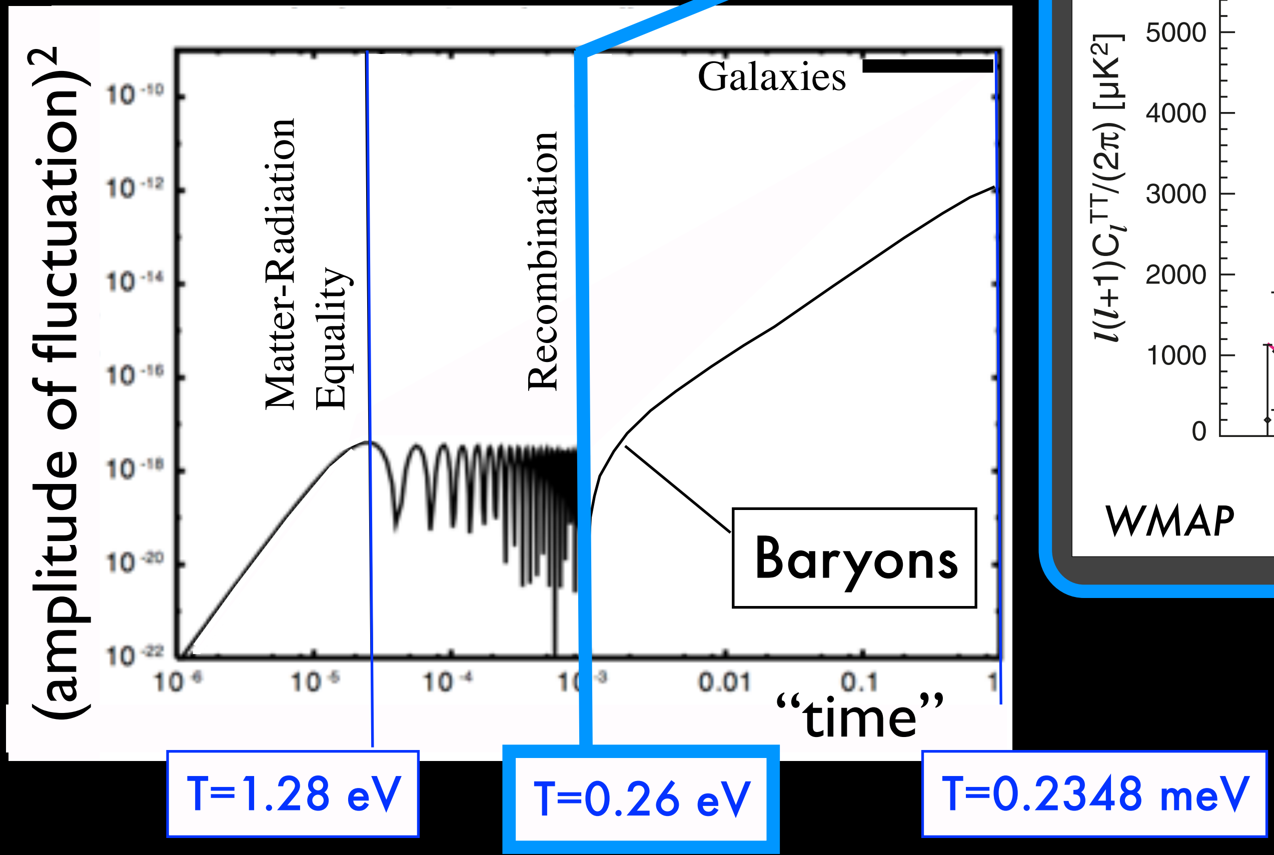
Planck (2013)

linear perturbation theory

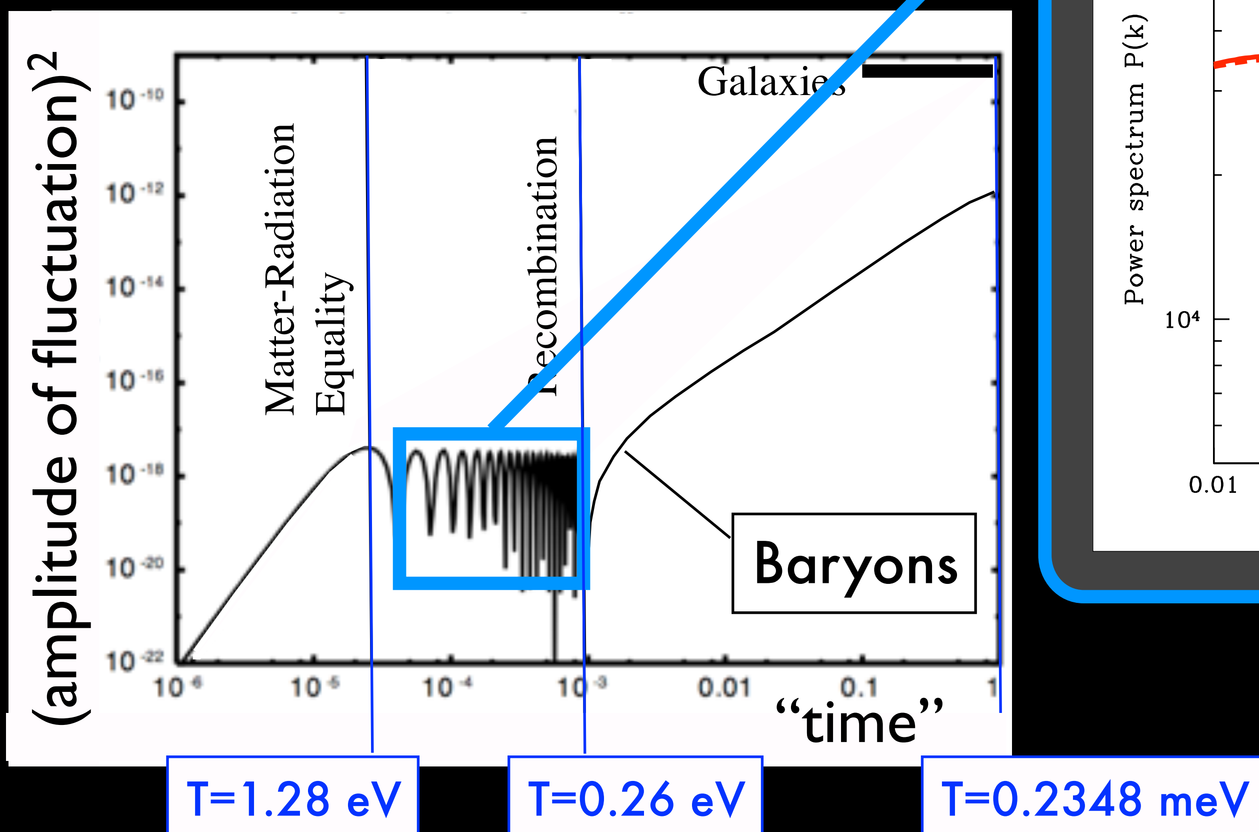
general relativity and statistical mechanics at 10^4 K ~ 1 eV/k

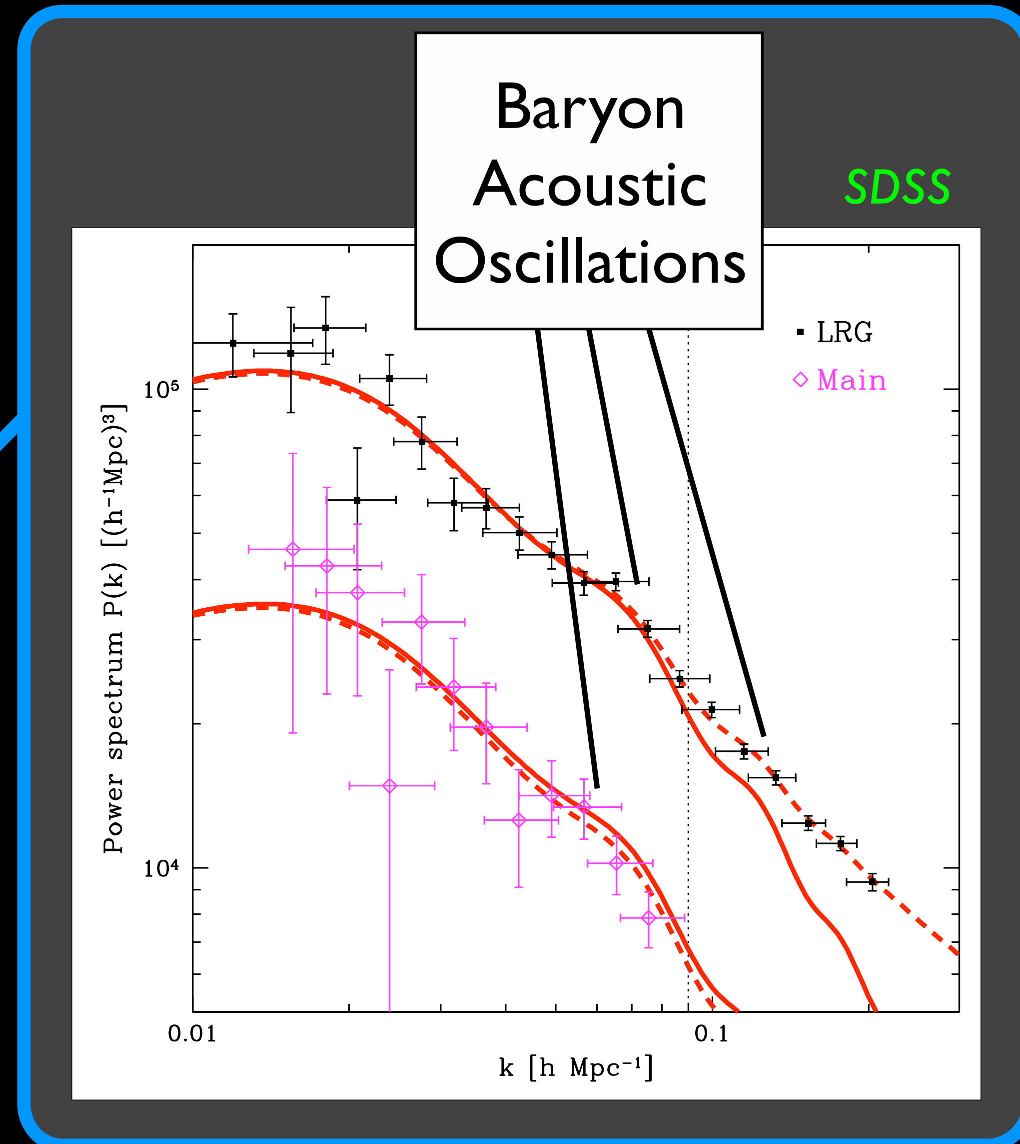
From CMB fluctuations to galaxies





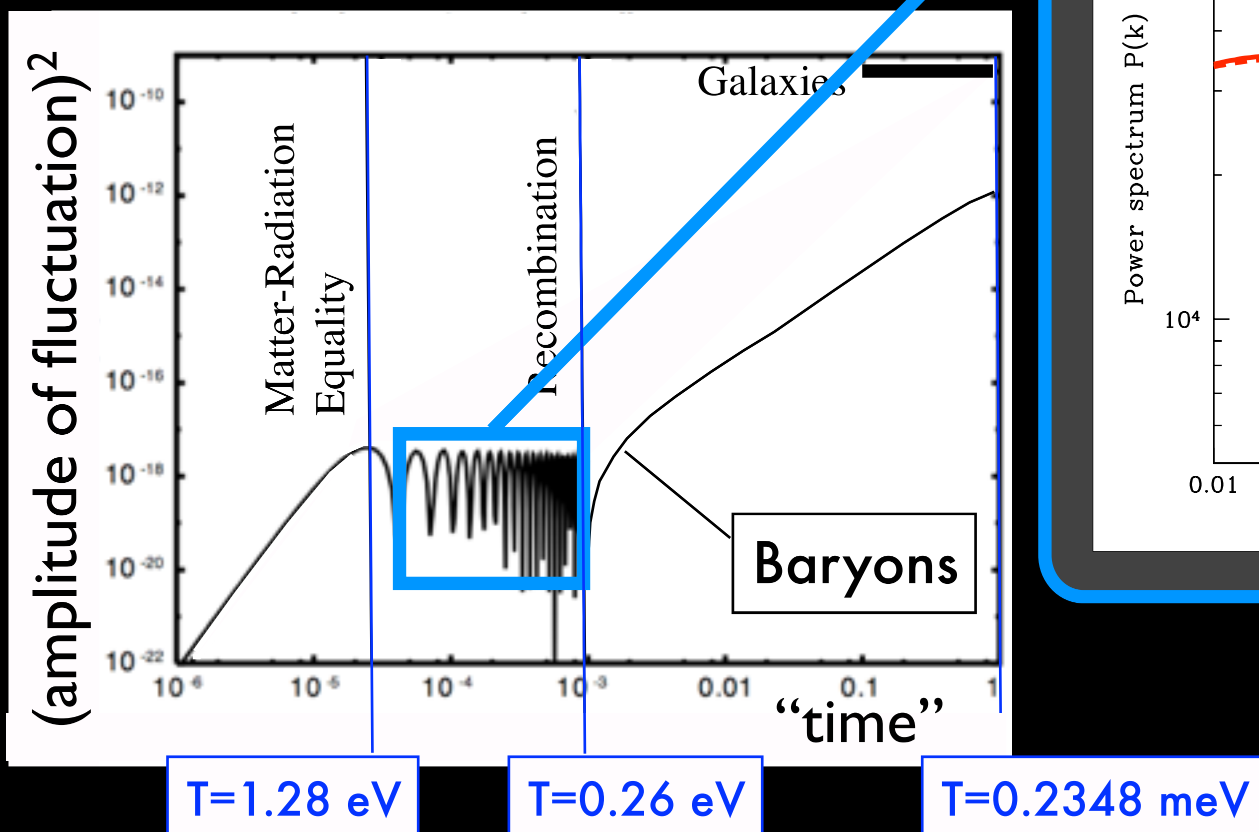
From CMB fluctuations to galaxies

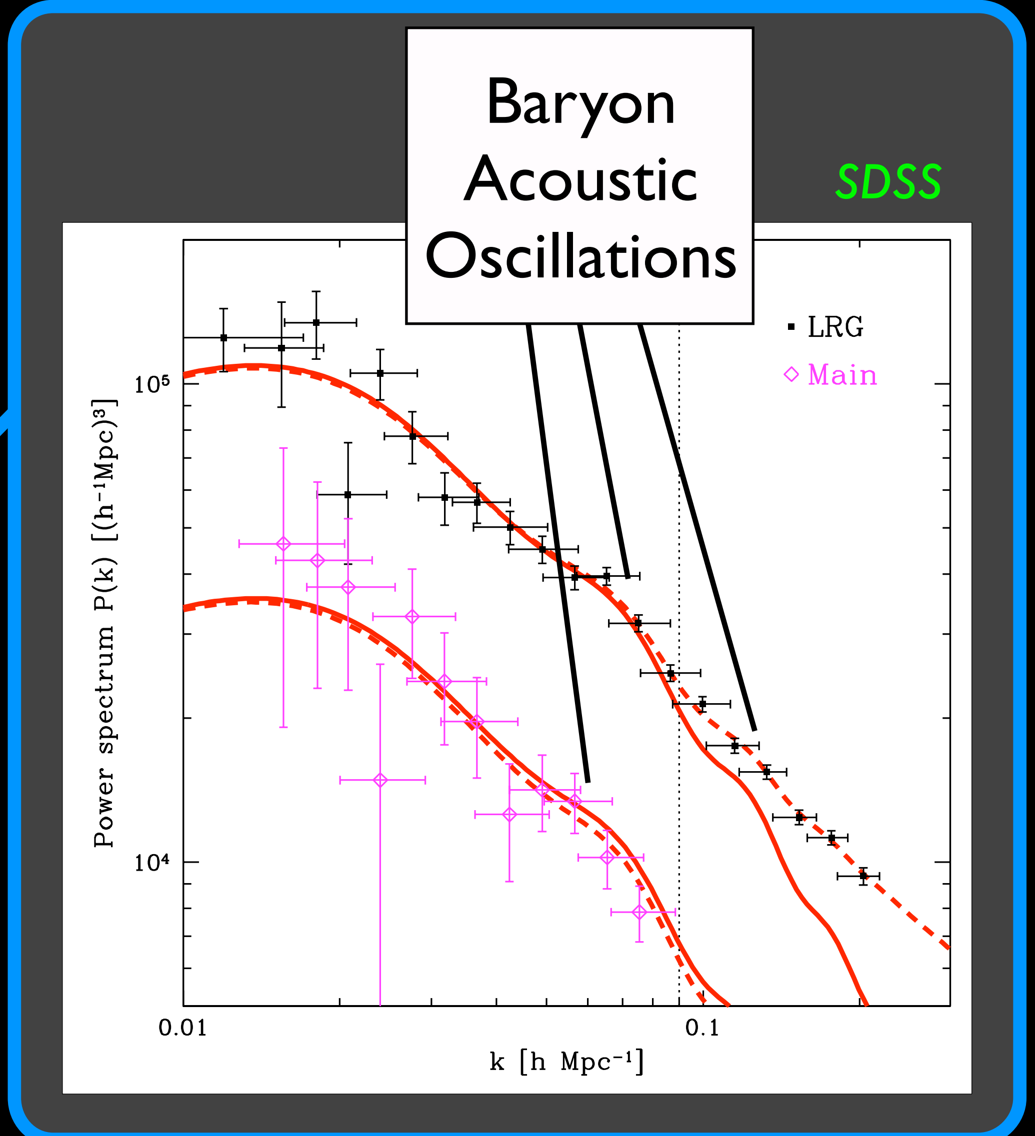




From CMB fluctuations to galaxies

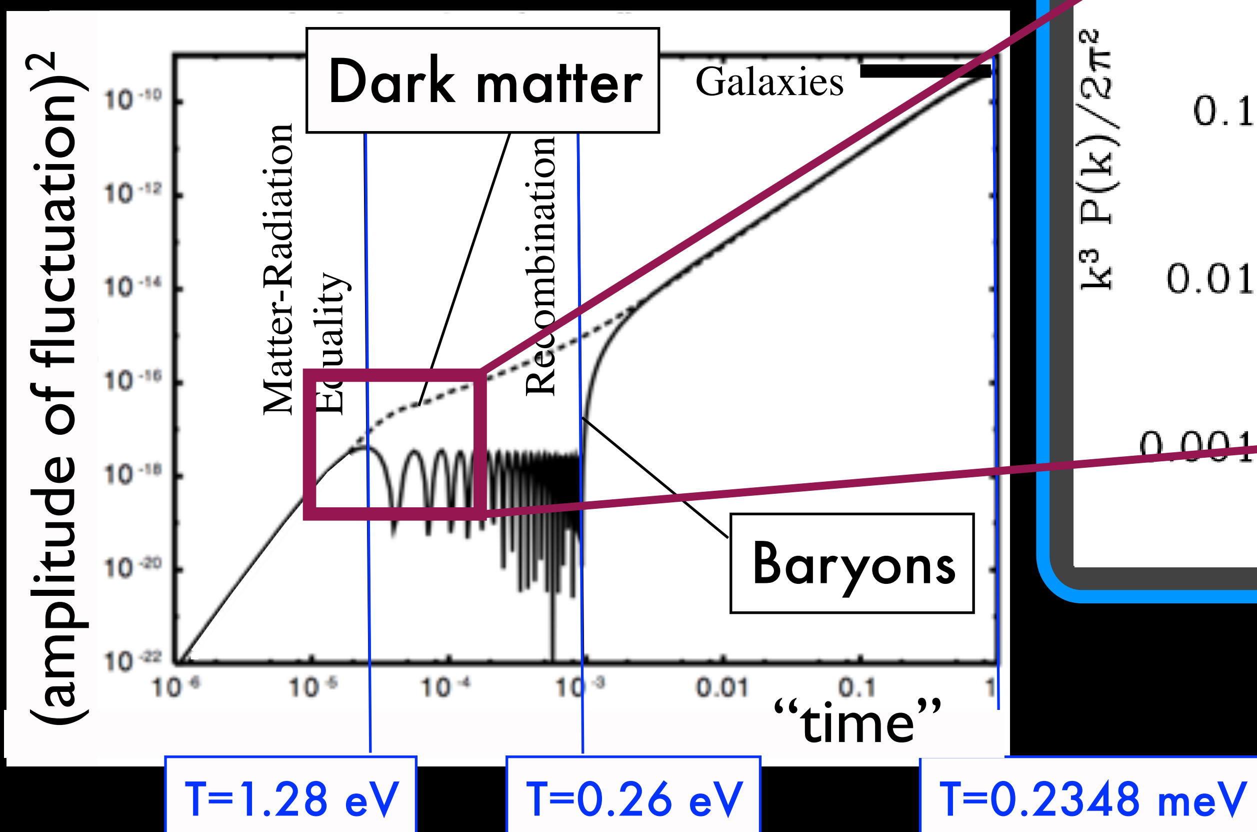
Fluctuations are too small to gravitationally grow into galaxies in the given 13 billion years.





From CMB fluctuations to galaxies

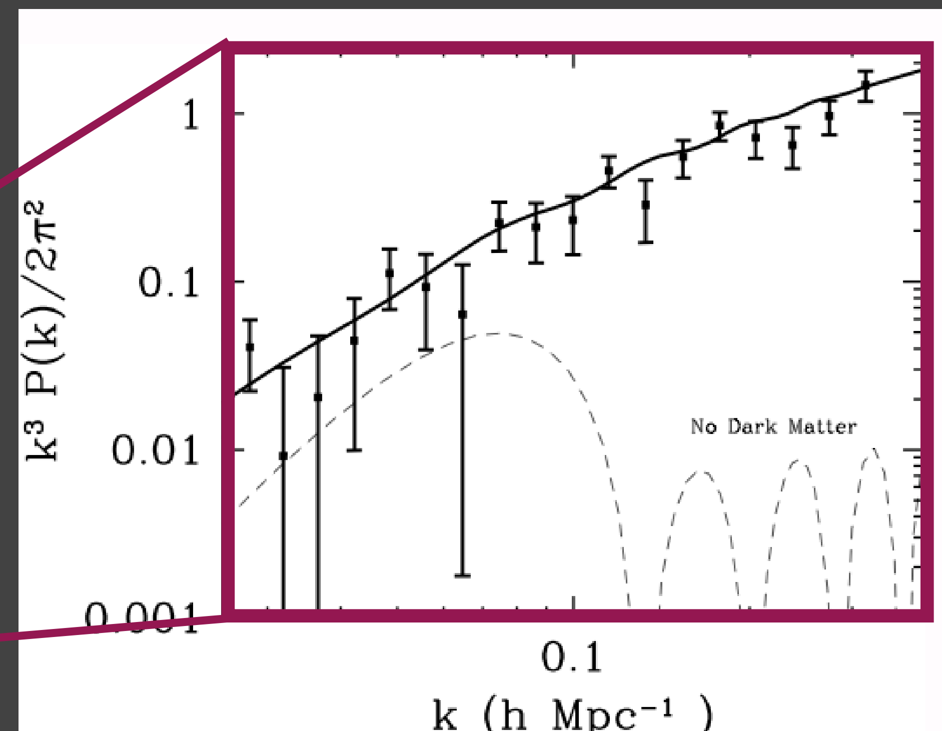
Fluctuation uncoupled to the plasma have enough time to grow



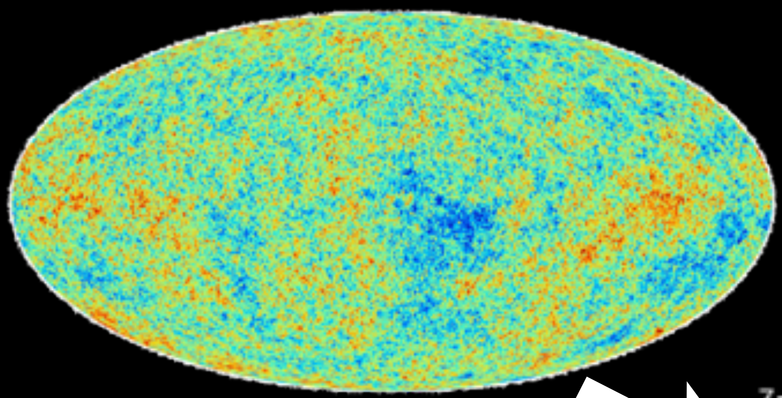
Dark matter is non-baryonic

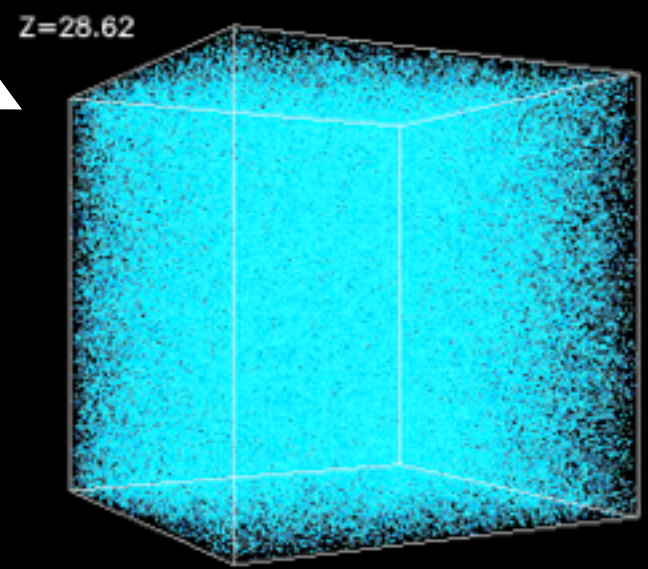
More than 80% of all matter does not couple to the primordial plasma!

SDSS

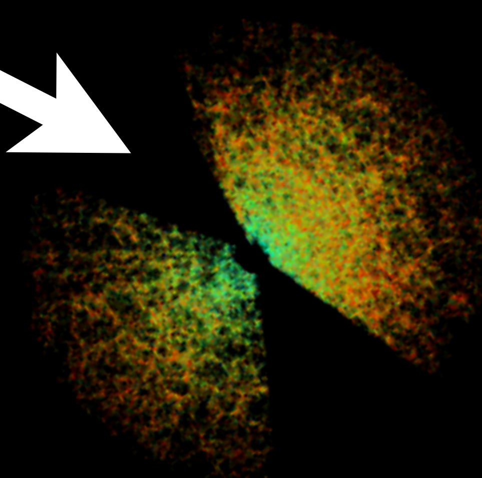


From CMB fluctuations to galaxies

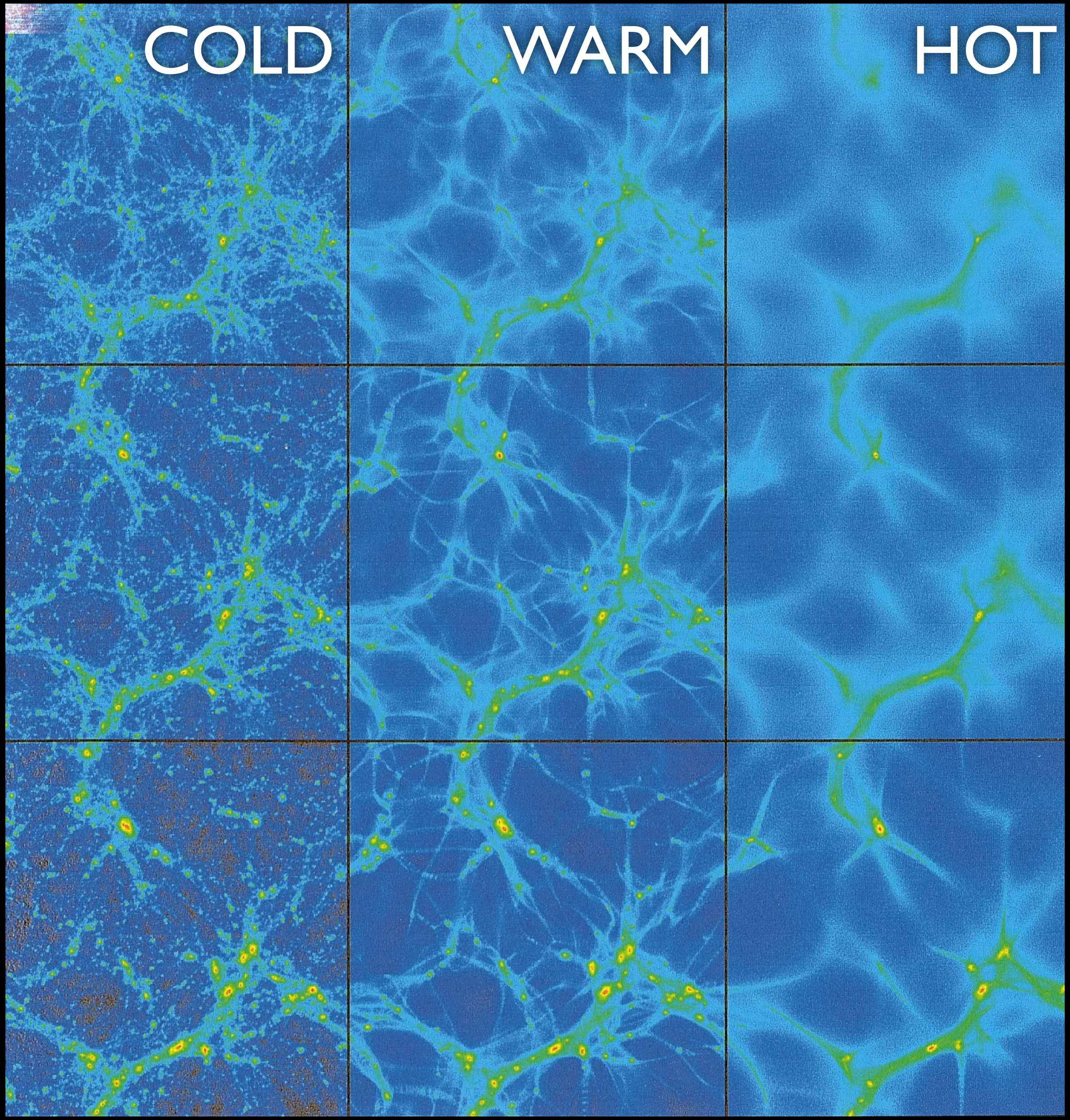




Kravtsov, Klypin

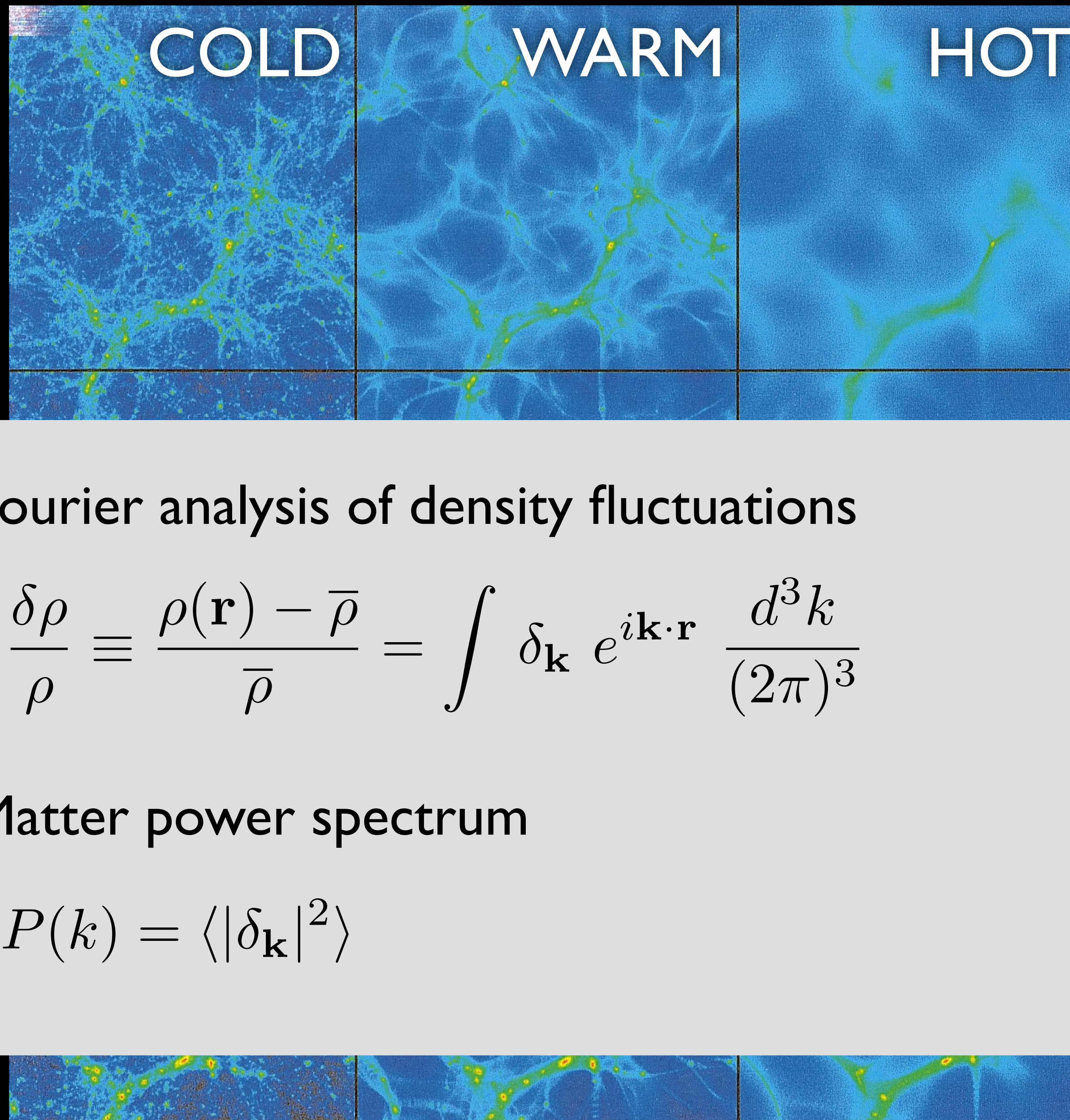


Cold/warm/hot dark matter



Bode et al 2001

Cold/warm/hot dark matter



Fourier analysis of density fluctuations

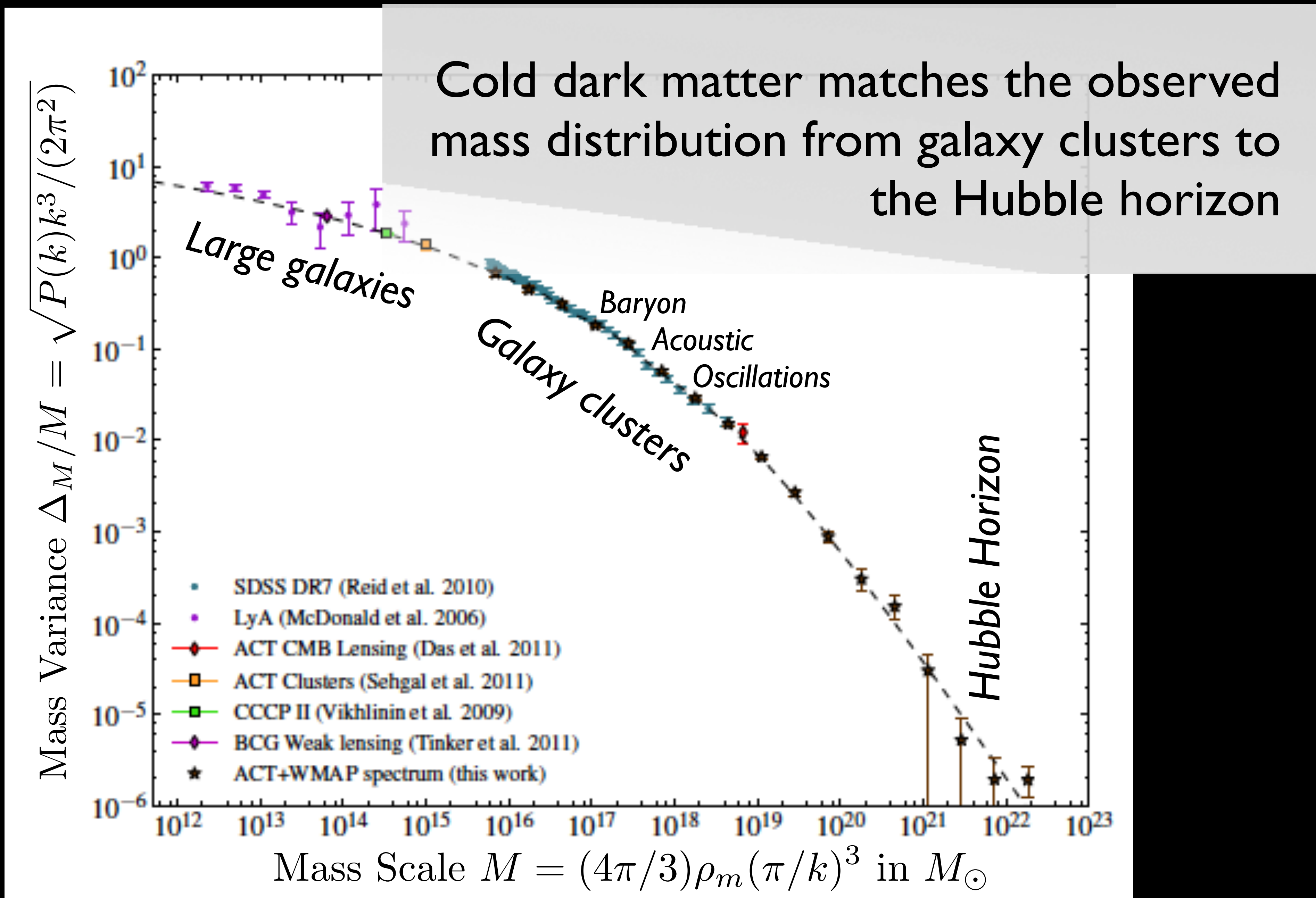
$$\frac{\delta\rho}{\rho} \equiv \frac{\rho(\mathbf{r}) - \overline{\rho}}{\overline{\rho}} = \int \delta_{\mathbf{k}}\ e^{i\mathbf{k}\cdot\mathbf{r}}\ \frac{d^3k}{(2\pi)^3}$$

Matter power spectrum

$$P(k) = \langle |\delta_{\mathbf{k}}|^2 \rangle$$

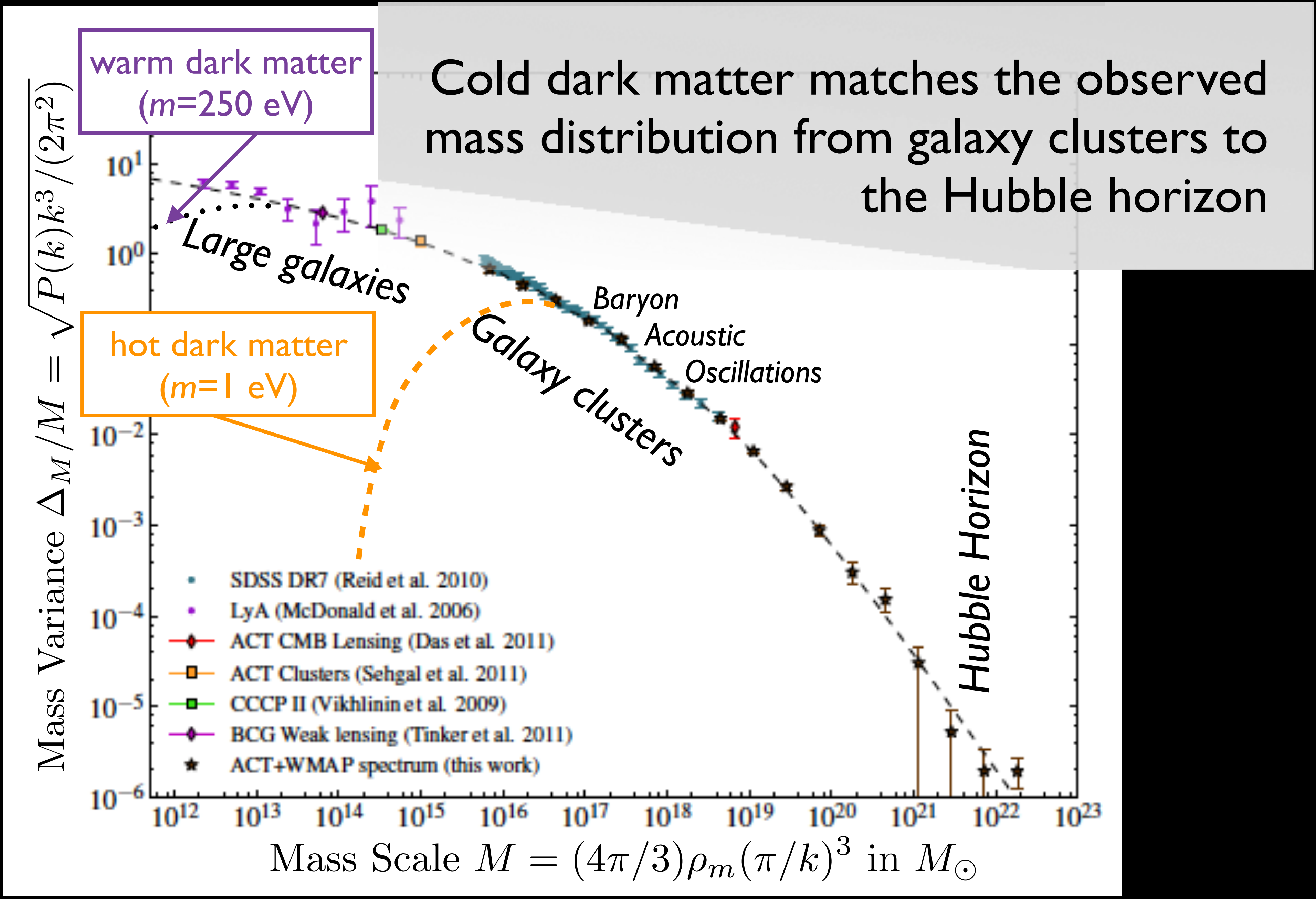
Bode et al 2001

From CMB fluctuations to galaxies



Hlozek et al 2012

Cold/warm/hot dark matter



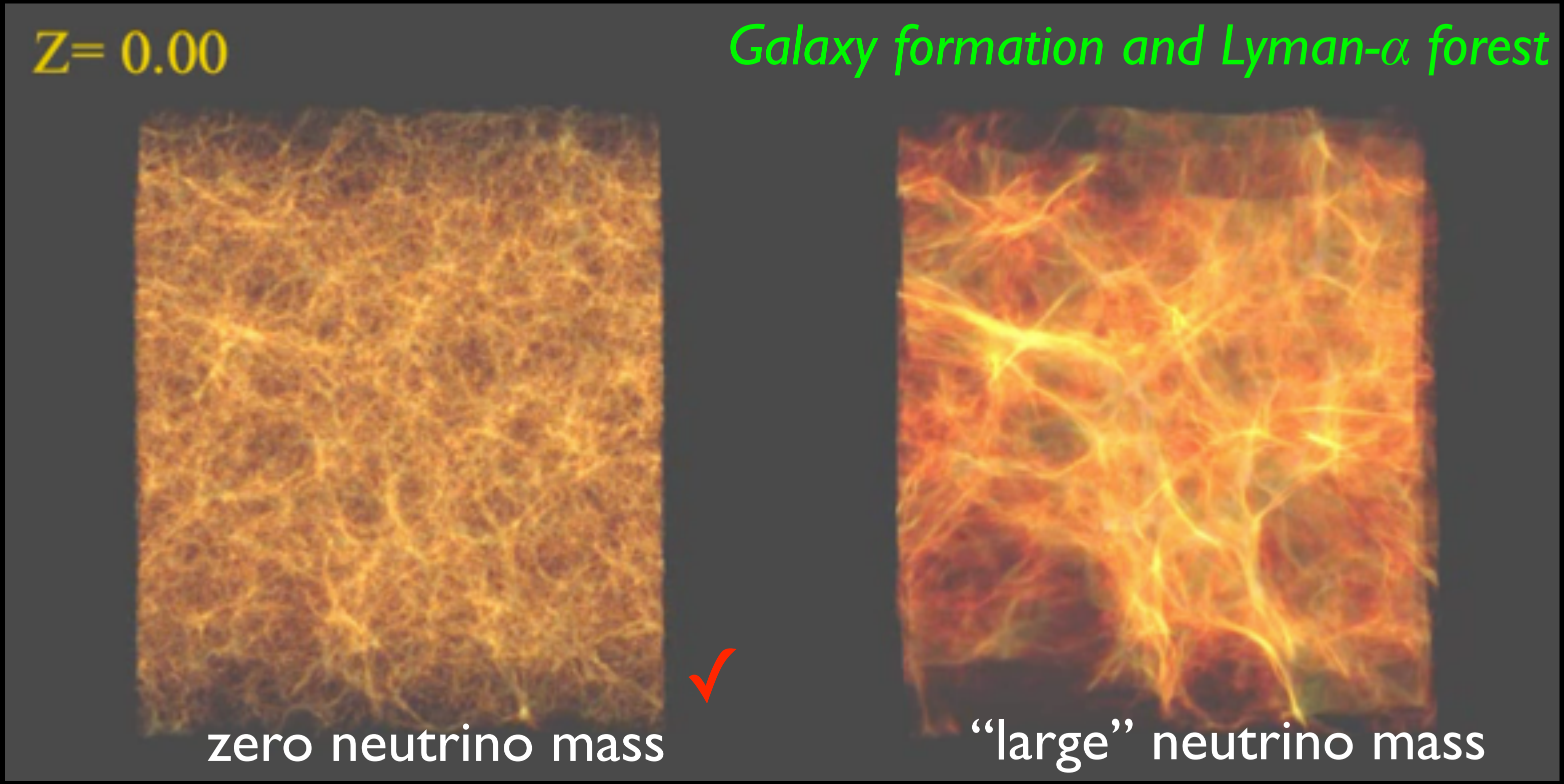
Hlozek et al 2012

Neutrinos as dark matter

Cosmology provides upper limits on neutrino masses

$\sum m < 0.23$ eV

Future reach
~ 0.06 eV



Neutrinos as dark matter

- Neutrino oscillations (largest Δm^2 from SK+K2K+MINOS) place a lower bound on one of the neutrino masses, $m_\nu > 0.048$ eV
- Cosmology (CMB+LRG+H_0) places an upper bound on the sum of the neutrino masses, $\sum m_\nu < 0.44$ eV
- Therefore neutrinos are *hot dark matter* ($m_\nu \ll T_{eq}$=1.28 eV) with density $0.0005 < \Omega_\nu h^2 < 0.0047$

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

Known neutrinos are hot dark matter

Neutrinos as dark matter

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720
(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

Recently there has been a resurgence of interest in the possibility that neutrinos may have a finite rest mass. These discussions have been in the context of weak-interaction theories,[1] possible decay of solar neutrinos,[2] and enumerating th... $K_L{}^0$ meson.[3]

and

$$n_{Bi} = \frac{2s_i+1}{2\pi^2\hbar^3}\int_0^\infty \frac{p^2dp}{\exp[E/kT(z_{eq})]-1}. \qquad (1b)$$

Here n_{Fi} is the number density of fermions of

Then m_ν<8 eV/c^2 from upper bound on ρ_ν

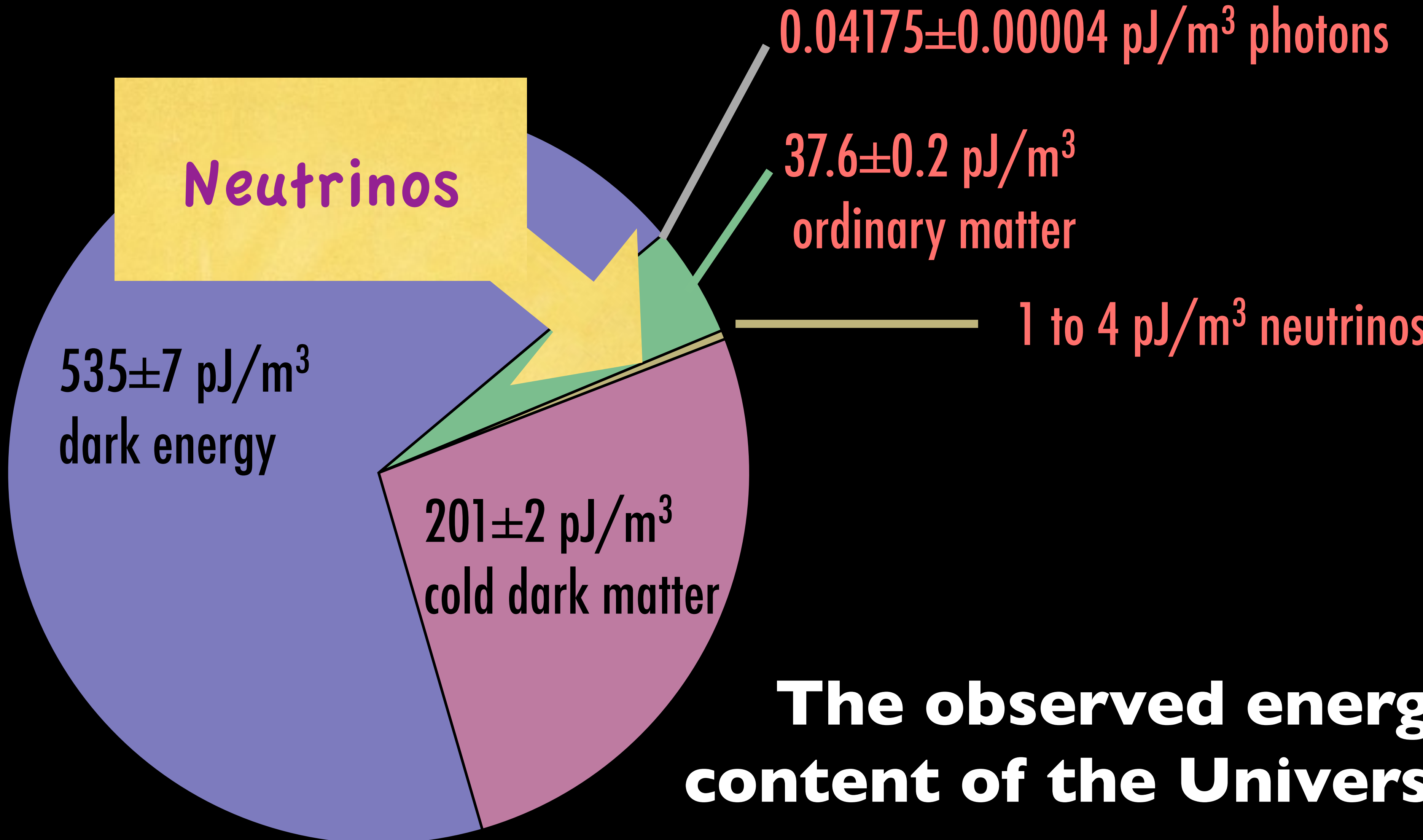
Now m_ν<0.44 eV/c^2 from upper bound on $\delta\rho_\nu$

$$\rho_\nu = \frac{3\zeta(3) g T_\nu^3 m_\nu}{8\pi^2} \qquad m_\nu \gtrsim T_\nu$$

$$\rho_\nu = \frac{7\pi^2 g T_\nu^4}{240} \qquad m_\nu \lesssim T_\nu$$

$$T_\nu = (4/11)^{1/3} T_{\rm CMB} = 168\mu{\rm eV}/k$$

Neutrinos as dark matter



The observed energy content of the Universe

matter $p \ll \rho$

radiation $p=\rho/3$

vacuum $p=-\rho$

Planck (2015)
TT,TE,EE+lowP+lensing+ext

$1\ \mathrm{pJ} = 10^{-12}\ \mathrm{J}$

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

The warning

"For any complex physical phenomenon there is a simple, elegant, compelling, wrong explanation."

Thomas Gold, 1920-2004, Austrian-born astronomer at Cambridge University and Cornell University

Cold dark matter or modified gravity?

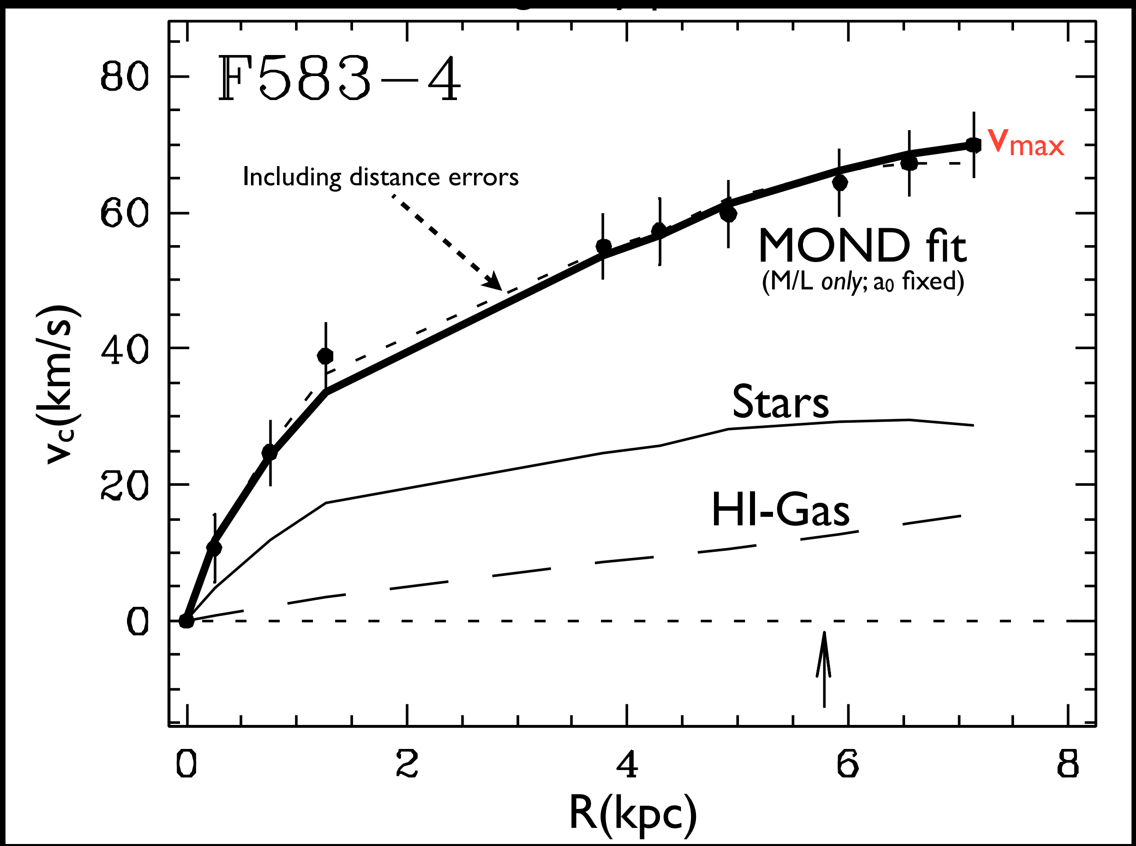
Cold dark matter or modified gravity?

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

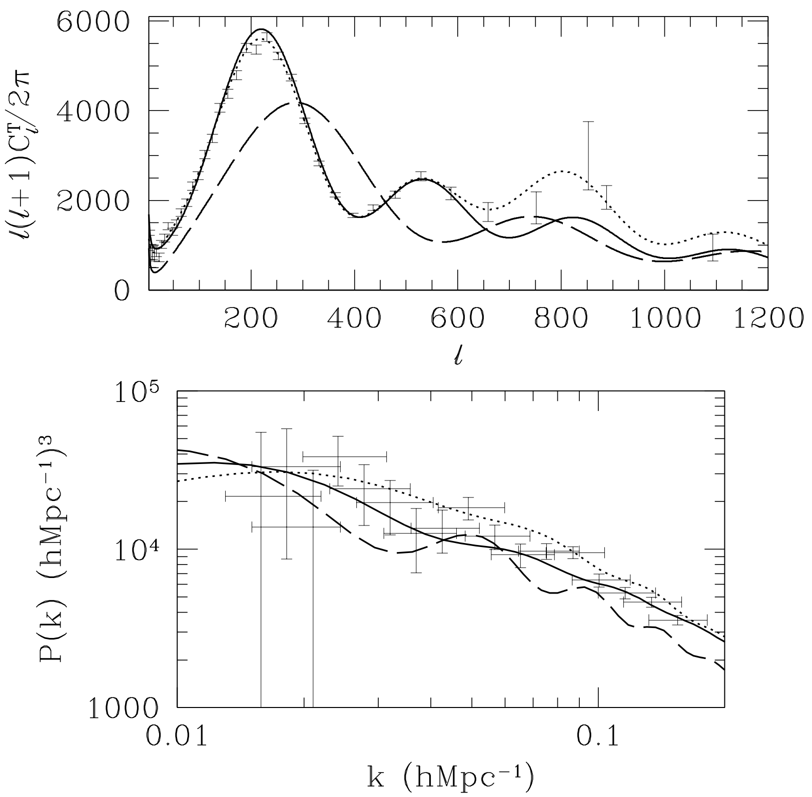
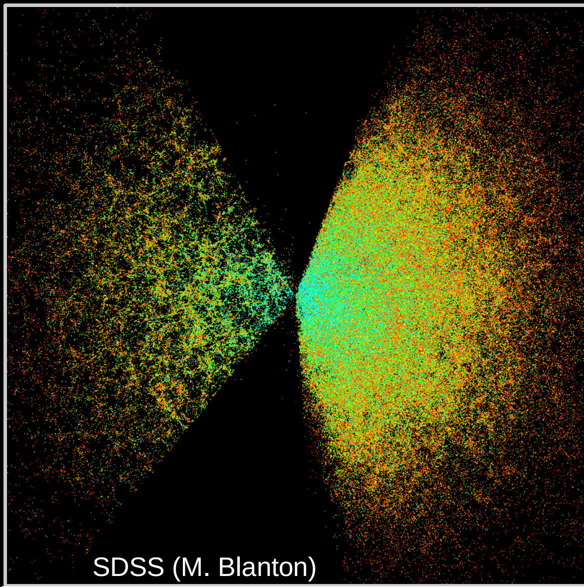


FIG. 4: The angular power spectrum of the CMB (top panel) and the power spectrum of the baryon density (bottom panel) for a MOND universe (with $a_0 \simeq 4.2\times10^{-8} cm/s^2$) with $\Omega_\Lambda = 0.78$ and $\Omega_\nu = 0.17$ and $\Omega_B = 0.05$ (solid line), for a MOND universe $\Omega_\Lambda = 0.95$ 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.

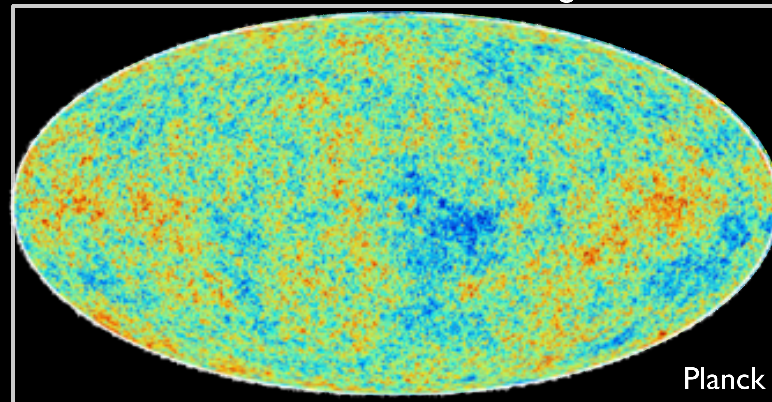
Skordis, Mota, Ferreira, Boehm 2005

Evidence for cold dark matter

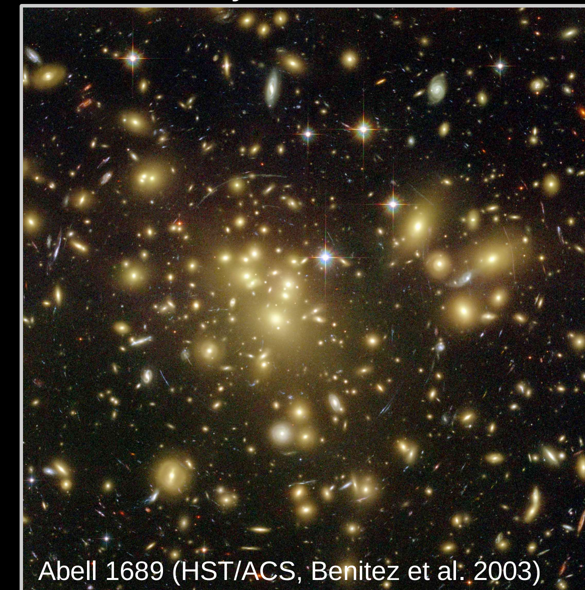
Large Scale Structure



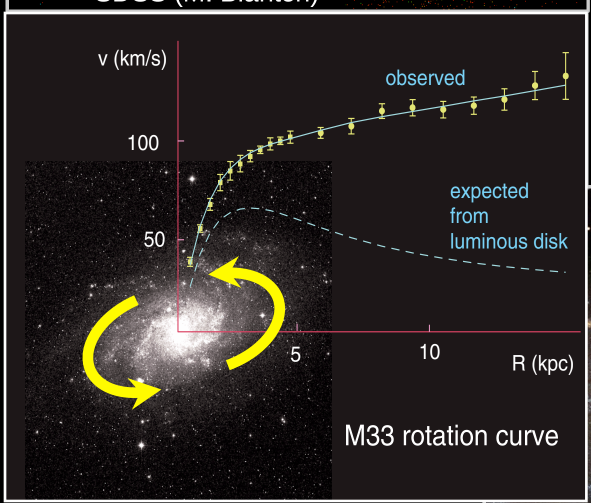
Cosmic Microwave Background

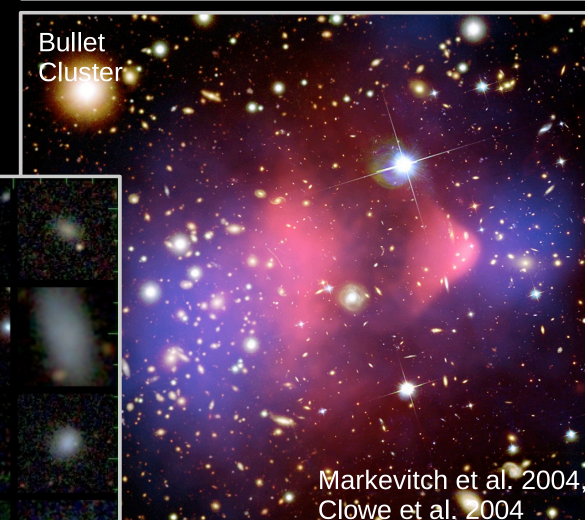


Galaxy Clusters

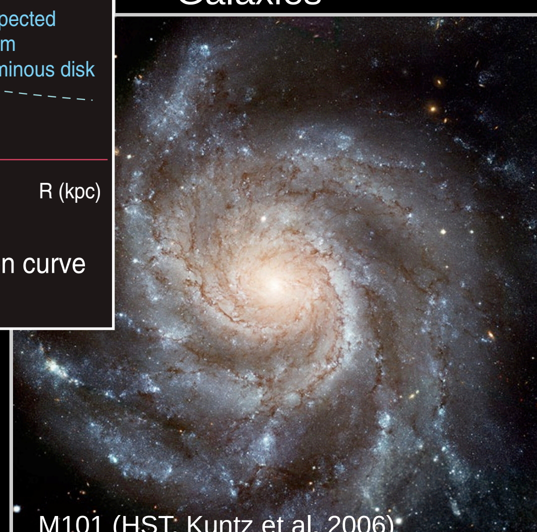


Supernovae

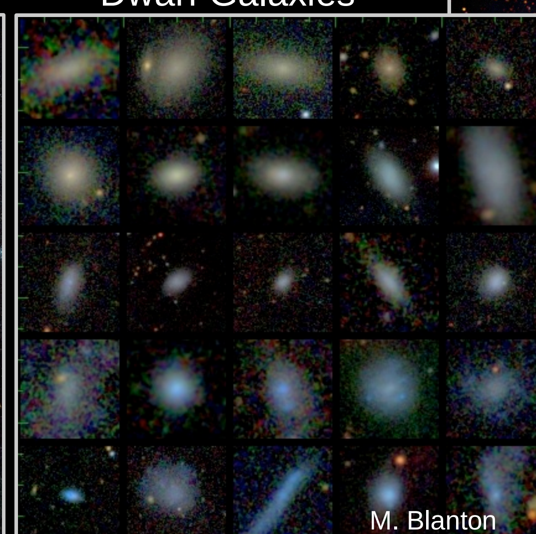




Galaxies



Dwarf Galaxies



Is cold dark matter an elementary particle?

IS HINCHLIFFE'S RULE TRUE? *

Boris Peon

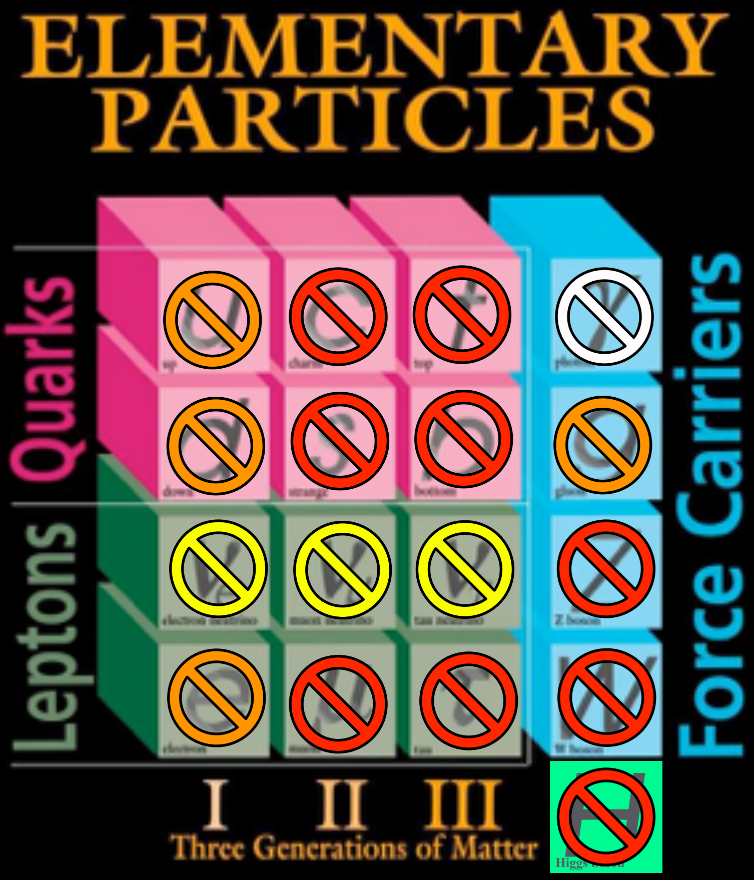
Abstract

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.

What particle model for dark matter?

- It should have the cosmic cold dark matter density
- It should be stable or very long-lived ($\gtrsim 10^{24}$ yr)
- It should be compatible with collider, astrophysics, etc. bounds
- Ideally, it would be possible to detect it in outer space and produce it in the laboratory
- For the believer, it would explain any claim of dark matter detection (annual modulation, positrons, gamma-ray line, etc.)

Which particle is cold dark matter?



is the particle of light

couples to the plasma

disappears too quickly

is hot dark matter

No known particle can be cold dark matter!

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

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

• SM neutrinos	(hot)	thermal relics
• lightest supersymmetric particle	(cold)	thermal relics
• lightest Kaluza-Klein particle	(cold)	thermal relics
• sterile neutrinos, gravitinos	(warm)	non-thermal relics
• Bose-Einstein condensates, axions, axion clusters	(cold)	non-thermal relics
• solitons (Q-balls, B-balls, ...)	(cold)	non-thermal relics
• supermassive wimpzillas	(cold)	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

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)

Type II All other candidates

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

Heavy active neutrinos (4-th generation)

PHYSICAL REVIEW LETTERS

VOLUME 39 | 25 JULY 1977 | NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

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.

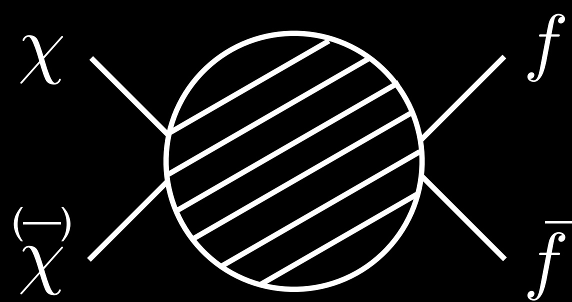
2 GeV/c^2 for Ω_c=1

Now 4 GeV/c^2 for Ω_c=0.25

Cosmic density of heavy active neutrinos

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

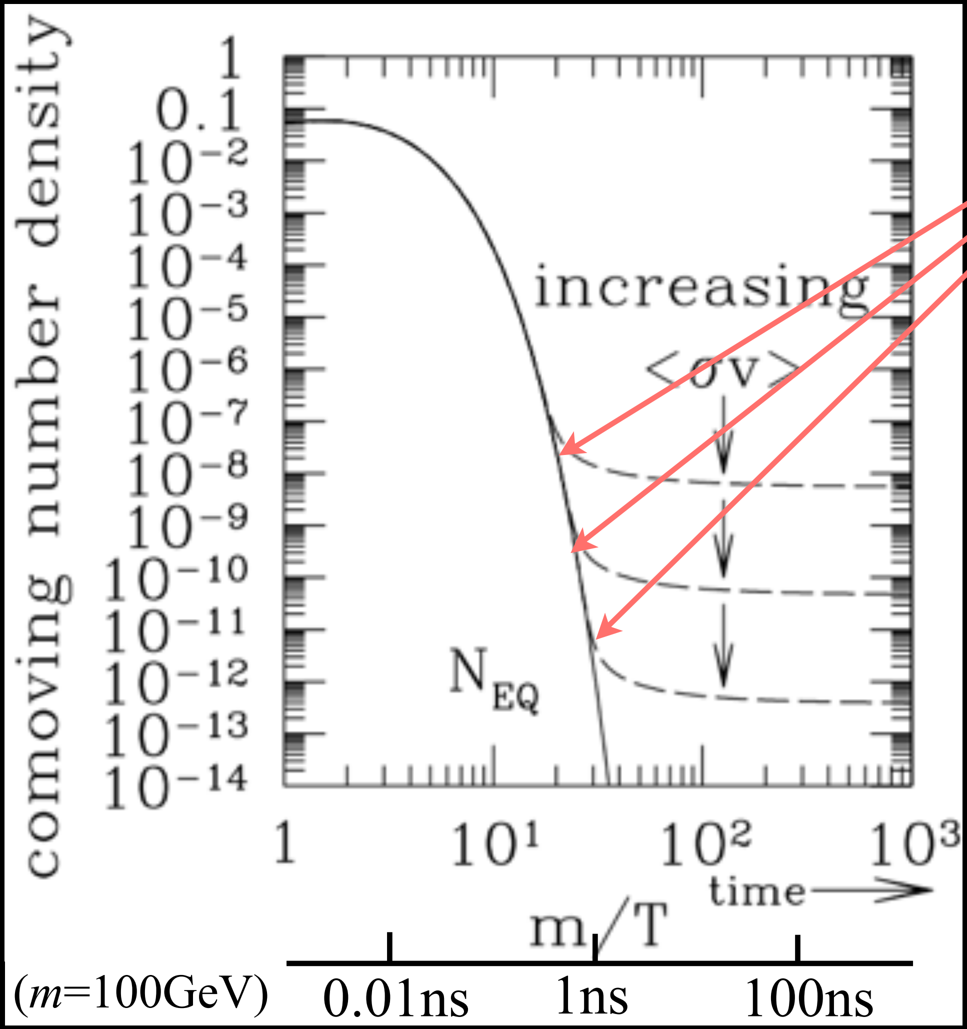
$$e^+ + e^-, \mu^+ + \mu^-, \text{etc.} \leftrightarrow \chi + \overset{(-)}{\chi}$$



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

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

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 heavy active neutrinos

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle_{\rm ann} \left(n^2 - n_{\rm eq}^2 \right)$$

density equation

("Boltzmann equation")

thermally averaged cross section times relative velocity

$$\langle \sigma v \rangle_{\rm ann} = \int_{4m^2}^{\infty} ds \, \frac{\sqrt{s - 4m^2} K_1(\sqrt{s}/T)}{16 m^4 T K_2^2(m/T)} \, W(s)$$

invariant annihilation rate (annihilations per unit time and unit volume)

$$W_{12\to\ldots}(s) = 4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} \, \sigma_{12\to\ldots}(s)$$

Gondolo, Gelmini 1991

Cosmic density of heavy active neutrinos

Enqvist, Kainulainen, Maalampi 1989

DIrac neutrino in 4-th generation lepton doublet

$$\mathcal{L} = y_e \bar{\ell}_L \phi e_R + y_\nu \bar{\ell}_L \tilde{\phi} \nu_R$$
$$= \begin{pmatrix} \bar{\nu}_L & \bar{e}_L \end{pmatrix} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R + \begin{pmatrix} \bar{\nu}_L & \bar{e}_L \end{pmatrix} \begin{pmatrix} \phi^0 \\ -\phi^- \end{pmatrix} \nu_R$$
$$= y_e \left(\bar{\nu}_L \phi^+ + \bar{e}_L \phi^0 \right) e_R + y_\nu \left(\bar{\nu}_L \phi^0 - \bar{e}_L \phi^- \right) \nu_R$$

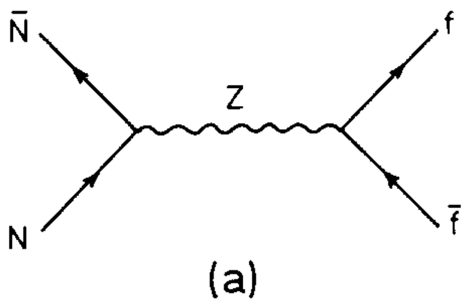
After electroweak symmetry breaking

$$\mathcal{L}_m = m_e \bar{e}_L e_R + m_\nu \bar{\nu}_L \nu_R$$

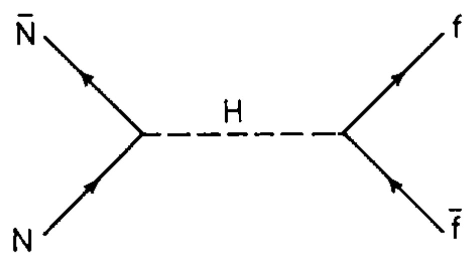
$$m_e = \frac{y_e v}{\sqrt{2}} \qquad m_\nu = \frac{y_\nu v}{\sqrt{2}}$$

Cosmic density of heavy active neutrinos

Enqvist, Kainulainen, Maalampi 1989



$$\sigma_Z(\bar{N}N \to \bar{f}f) = \frac{N_c}{4s}\frac{\pi\alpha^2}{x_W^2}\frac{\beta_f}{\beta_N}\frac{1}{16(1-x_W)^2}|D_Z|^2 \times \left[\tfrac{1}{2}\left(v_f^2+a_f^2\right)s^2\left(1+\tfrac{1}{3}\beta^2\right)+2\left(v_f^2-a_f^2\right)m_f^2\left(s-2m_N^2\right)\right]$$



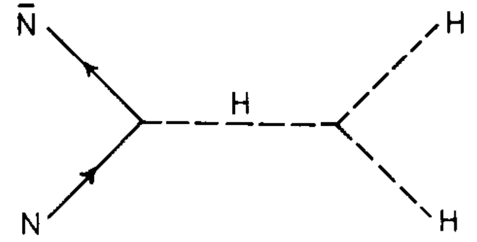
$$\sigma_H(N\bar{N} \to \bar{f}f) = N_c\frac{\pi\alpha^2}{4sx_W^2}\frac{\beta_f}{\beta_N}|D_H|^2\left(\frac{m_f m_N}{m_W^2}\right)^2 s^2\beta^2,$$

$$\beta_f = \left(1-\frac{4m_f^2}{s}\right)^{1/2}, \qquad \beta_N = \left(1-\frac{4m_N^2}{s}\right)^{1/2}. \qquad |D_H|^2 = \frac{1}{\left(s-m_H^2\right)^2+\Gamma_H^2 m_H^2}. \qquad |D_Z|^2 = \frac{1}{\left(s-m_Z^2\right)^2+\Gamma_Z^2 m_Z^2}.$$

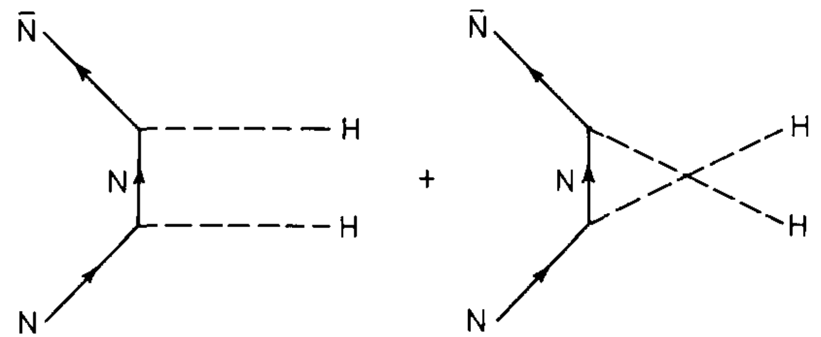
Cosmic density of heavy active neutrinos

Enqvist, Kainulainen, Maalampi 1989

$$\sigma(\bar{\mathrm{N}}\mathrm{N} \to \mathrm{H}^0\mathrm{H}^0) = \frac{g^4}{128\pi s}\frac{\beta_\mathrm{H}}{\beta_\mathrm{N}}\left(\frac{m_\mathrm{N}}{m_\mathrm{W}}\right)^4(\sigma_1+\sigma_2+\sigma_3+\sigma_4)$$



(a)



(b)

$$\sigma_1 = \left(\tfrac{1}{4}m_\mathrm{N}^2\left(s+4m_\mathrm{H}^2\right)-4m_\mathrm{N}^4\right)R+\left(\tfrac{1}{2}s-m_\mathrm{H}^2+4m_\mathrm{N}^2\right)L-\tfrac{1}{2},$$

$$\sigma_2 = \tfrac{9}{2}\left(\frac{m_\mathrm{H}}{m_\mathrm{N}}\right)^4|D_\mathrm{H}|^2m_\mathrm{N}^2s\beta_\mathrm{N}^2,$$

$$\sigma_3 = -\left(4m_\mathrm{N}^2s\beta_\mathrm{N}^2+m_\mathrm{H}^4\right)\frac{L}{2m_\mathrm{H}^2-s}-\tfrac{1}{4},$$

$$\sigma_4 = -3\left(\frac{m_\mathrm{H}}{m_\mathrm{N}}\right)^2\left(s-m_\mathrm{H}^2\right)|D_\mathrm{H}|^2m_\mathrm{N}^2\left[1+\left(2s\beta_\mathrm{N}^2+\left(2m_\mathrm{H}^2-s\right)\right)L\right].$$

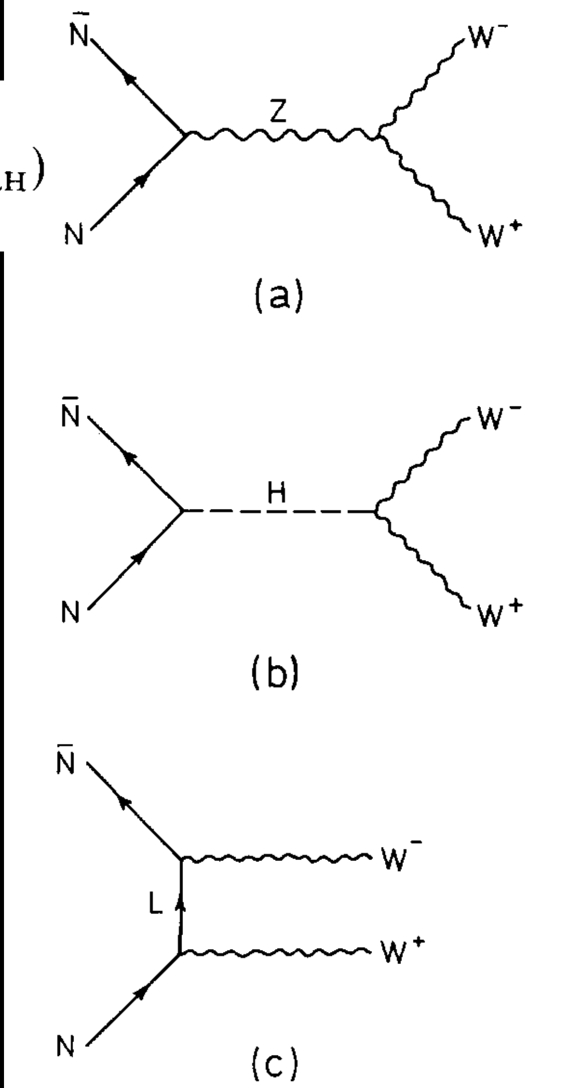
$$L \equiv -\frac{1}{2s\beta_\mathrm{N}\beta_\mathrm{H}}\ln\left(\frac{2m_\mathrm{H}^2-s+s\beta_\mathrm{N}\beta_\mathrm{H}}{2m_\mathrm{H}^2-s-s\beta_\mathrm{N}\beta_\mathrm{H}}\right) \qquad \beta_i=\left(1-\frac{4m_i^2}{s}\right)^{1/2} \quad (i=\mathrm{N},\mathrm{H}),$$

$$R \equiv \left[m_\mathrm{H}^4+m_\mathrm{N}^2s\beta_\mathrm{H}^2\right]^{-1}, \qquad |D_\mathrm{H}|^2=\frac{1}{\left(s-m_\mathrm{H}^2\right)^2+\Gamma_\mathrm{H}^2m_\mathrm{H}^2}.$$

Cosmic density of heavy active neutrinos

Enqvist, Kainulainen, Maalampi 1989

$$\sigma(\overline{\mathrm{N}}\mathrm{N} \to \mathrm{W}^+\mathrm{W}^-) = \frac{g^4}{128\pi s}\,\frac{\beta_{\mathrm{W}}}{\beta_{\mathrm{N}}}\left(\sigma_{\mathrm{LL}} + \sigma_{\mathrm{ZZ}} + \sigma_{\mathrm{HH}} + \sigma_{\mathrm{LZ}} + \sigma_{\mathrm{LH}}\right)$$



$$\sigma_{\mathrm{LL}} = G_{\mathrm{LL}},$$

$$\sigma_{\mathrm{ZZ}} = \tfrac{1}{8}|D_{\mathrm{Z}}|^2 m_{\mathrm{W}}^4 G_{\mathrm{ZZ}},$$

$$\sigma_{\mathrm{HH}} = \tfrac{1}{4}|D_{\mathrm{H}}|^2 m_{\mathrm{W}}^4 G_{\mathrm{HH}},$$

$$\sigma_{\mathrm{LZ}} = \tfrac{1}{2}(s - m_{\mathrm{Z}}^2)|D_{\mathrm{Z}}|^2 m_{\mathrm{W}}^2 G_{\mathrm{LZ}},$$

$$\sigma_{\mathrm{LH}} = \tfrac{1}{2}(s - m_{\mathrm{H}}^2)|D_{\mathrm{H}}|^2 m_{\mathrm{W}}^2 G_{\mathrm{LH}},$$

$$\begin{aligned} G_{\mathrm{LL}} = {} & \tfrac{1}{12}(\hat{s}^2 + 20\hat{s} - 24) + \left(\tfrac{1}{6}\hat{s} - \tfrac{5}{3}\right) m_{\mathrm{N}}^2 - \tfrac{3}{2}\hat{m}_{\mathrm{N}}^4 + P_1 \hat{L} \\ & - \tfrac{1}{2}(2 - \hat{m}_{\mathrm{N}}^2 - \hat{m}_{\mathrm{N}}^4)^2 \hat{R} - \hat{m}_{\mathrm{L}}^2\left[\tfrac{1}{2}\hat{s} - 1 - 3\hat{m}_{\mathrm{N}}^2 + 2P_2\hat{L} + \tfrac{1}{2}P_1\hat{R}\right] \\ & - \hat{m}_{\mathrm{L}}^4\left[\tfrac{3}{2} - 3(\hat{s} - 2 - 4\hat{m}_{\mathrm{N}}^2)\hat{L} - \tfrac{1}{2}P_2\hat{R}\right] \\ & + \hat{m}_{\mathrm{L}}^6\left[4\hat{L} - \left(\tfrac{1}{2}\hat{s} - 1 - 2\hat{m}_{\mathrm{N}}^2\right)\hat{R}\right] - \tfrac{1}{2}\hat{m}_{\mathrm{L}}^8\hat{R}, \end{aligned}$$

$$G_{\mathrm{ZZ}} = \tfrac{2}{3}(\hat{s} - \hat{m}_{\mathrm{N}}^2)(\hat{s}^3 + 16\hat{s}^2 - 68\hat{s} - 48), \qquad (\mathrm{A.13})$$

$$G_{\mathrm{HH}} = \hat{m}_{\mathrm{N}}^2(\hat{s} - 4\hat{m}_{\mathrm{N}}^2)(\hat{s}^2 - 4\hat{s} + 12), \qquad (\mathrm{A.14})$$

$$\begin{aligned} G_{\mathrm{LZ}} = {} & -\tfrac{1}{3}\left(\hat{s}^3 + 18\hat{s}^2 - 28\hat{s} - 24 - (\hat{s}^2 + 6\hat{s} + 8)\hat{m}_{\mathrm{N}}^2 - 6(\hat{s} - 2)\hat{m}_{\mathrm{N}}^4\right) \\ & + 4\left(8\hat{s} + 4 - (10\hat{s} + 4)\hat{m}_{\mathrm{N}}^2 + (\hat{s} + 2)\hat{m}_{\mathrm{N}}^4 + (\hat{s} - 2)\hat{m}_{\mathrm{N}}^6\right)\hat{L} \\ & + \hat{m}_{\mathrm{L}}^2\left[\hat{s}^2 - 4\hat{s} - 4 - (4\hat{s} - 8)\hat{m}_{\mathrm{N}}^2\right. \\ & \qquad \left. + 4\left(4\hat{s}^2 - 5\hat{s} - 6 + (\hat{s}^2 - 5\hat{s} - 2)\hat{m}_{\mathrm{N}}^2 - 3(\hat{s} - 2)\hat{m}_{\mathrm{N}}^4\right)\hat{L}\right] \\ & + \hat{m}_{\mathrm{L}}^4\left[2(\hat{s} - 2) - 4\left(\hat{s}(\hat{s} - 4) - 3(\hat{s} - 2)\hat{m}_{\mathrm{N}}^2\right)\hat{L}\right] - \hat{m}_{\mathrm{L}}^6\left[(4\hat{s} - 8)\hat{L}\right], \qquad (\mathrm{A.15}) \end{aligned}$$

$$\begin{aligned} G_{\mathrm{LH}} = {} & \hat{m}_{\mathrm{N}}^2\left\{-\hat{s}^2 + 2\hat{s} - 8 + 2(\hat{s} + 2)\hat{m}_{\mathrm{N}}^2 + 4\left(2\hat{s} - 4 - (3\hat{s} - 2)\hat{m}_{\mathrm{N}}^2 + (\hat{s} + 2)\hat{m}_{\mathrm{N}}^4\right)\hat{L}\right. \\ & + \hat{m}_{\mathrm{L}}^2\left[-2(\hat{s} + 2) + 4\left(\hat{s}^2 - \hat{s} + 2 - (2\hat{s} + 4)\hat{m}_{\mathrm{N}}^4\right)\hat{L}\right] \\ & \left. + \hat{m}_{\mathrm{L}}^4\left[(4\hat{s} + 8)\hat{L}\right]\right\}, \end{aligned}$$

$$P_1 = 4(\hat{s} - 2) + 4\hat{s}\hat{m}_{\mathrm{N}}^2 + (\hat{s} - 6)\hat{m}_{\mathrm{N}}^4 - 4\hat{m}_{\mathrm{N}}^6,$$

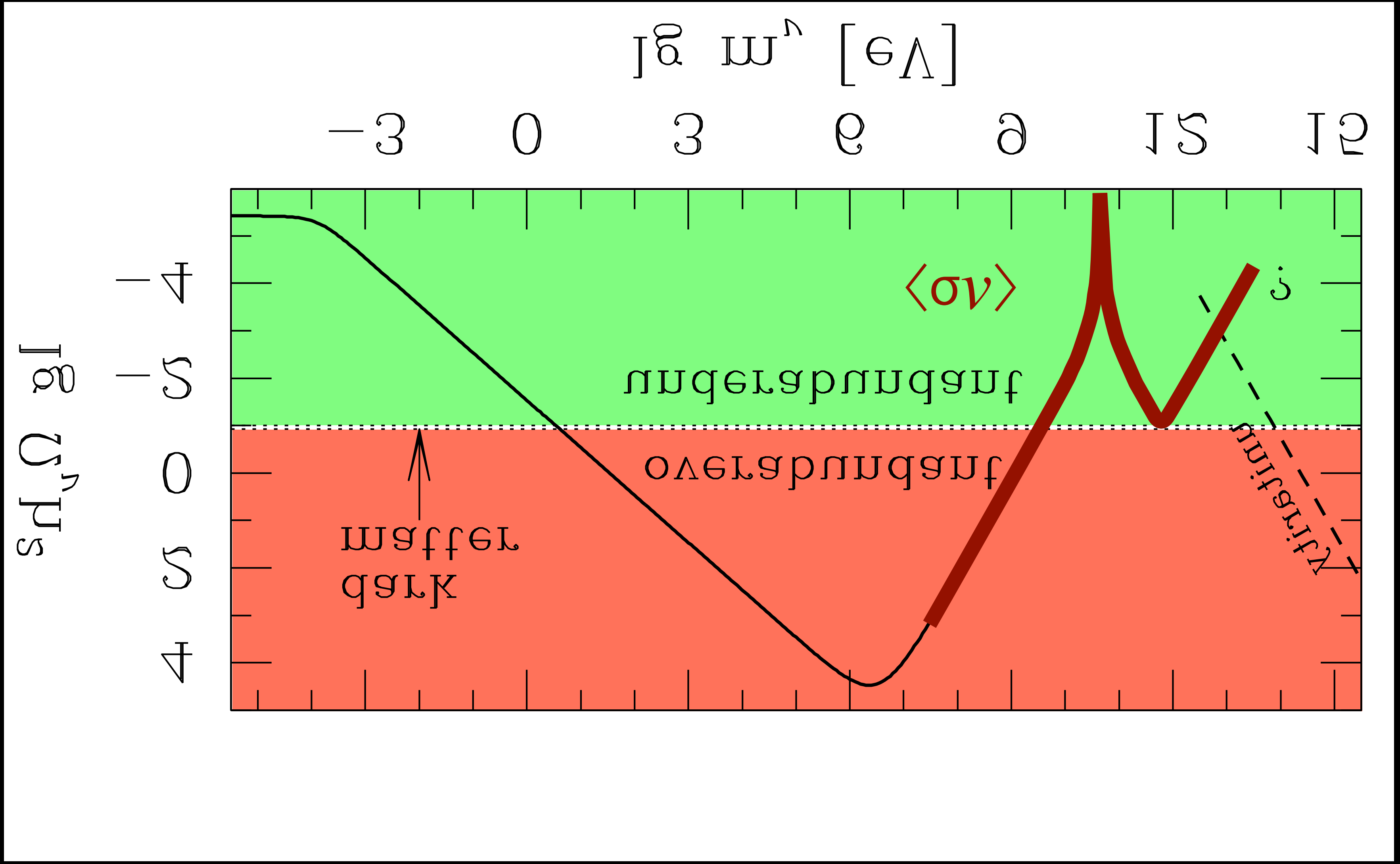
$$P_2 = 4\hat{s} - 5 + (2\hat{s} - 6)\hat{m}_{\mathrm{N}}^2 - 6\hat{m}_{\mathrm{N}}^4,$$

$$\hat{L} \equiv -\frac{1}{2\hat{s}\beta_{\mathrm{N}}\beta_{\mathrm{W}}}\ln\left(\frac{2 - \hat{s} + 2\hat{m}_{\mathrm{N}}^2 - 2\hat{m}_{\mathrm{L}}^2 + \hat{s}\beta_{\mathrm{N}}\beta_{\mathrm{W}}}{2 - \hat{s} + 2\hat{m}_{\mathrm{N}}^2 - 2\hat{m}_{\mathrm{L}}^2 - \hat{s}\beta_{\mathrm{N}}\beta_{\mathrm{W}}}\right),$$

$$\hat{R} \equiv \left[(1 - \hat{m}_{\mathrm{N}}^2)^2 - \hat{m}_{\mathrm{L}}^2(2 - \hat{s} + 2\hat{m}_{\mathrm{N}}^2) + \hat{m}_{\mathrm{L}}^4\right]^{-1}.$$

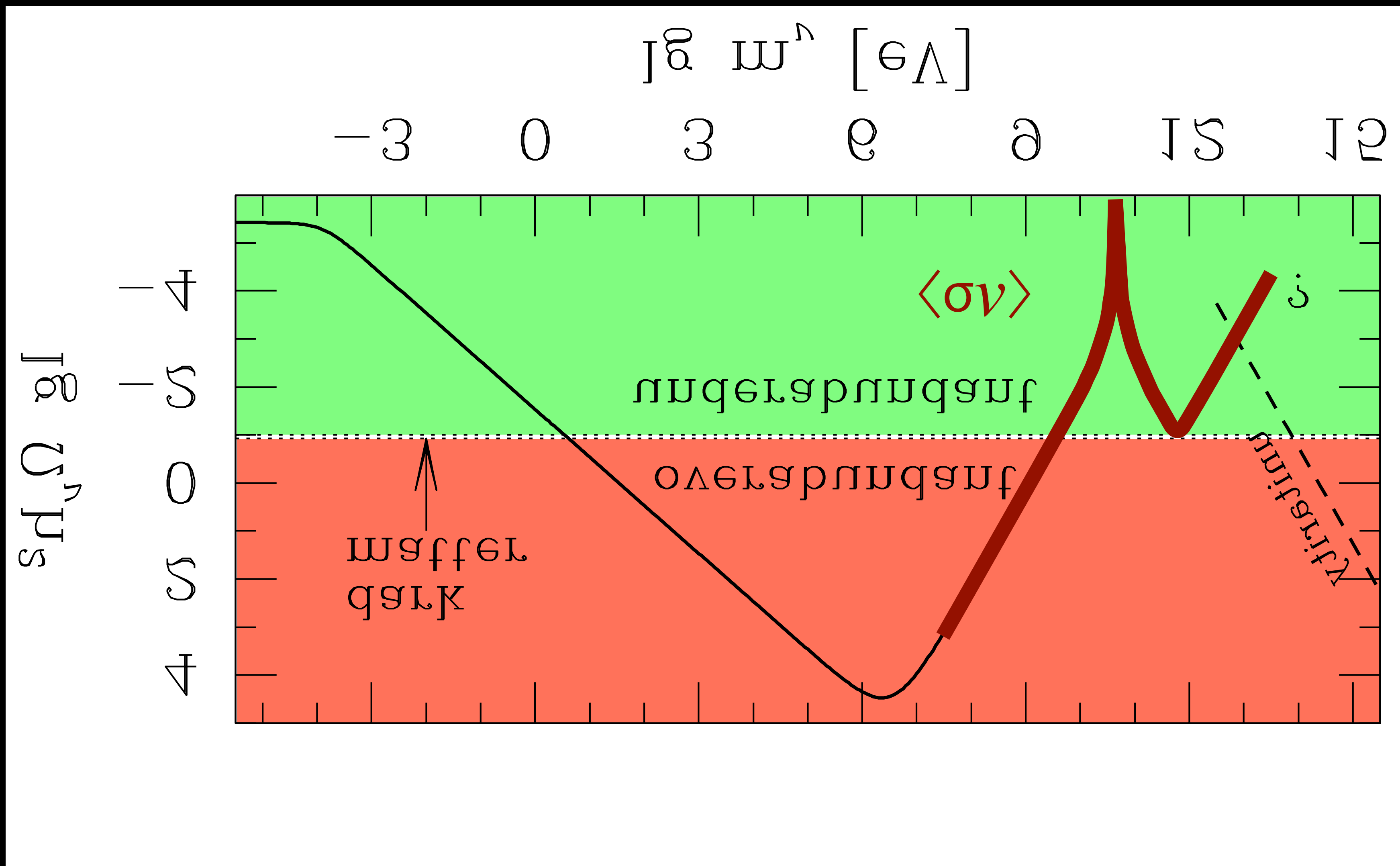
Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino



Cosmic density of massive neutrinos

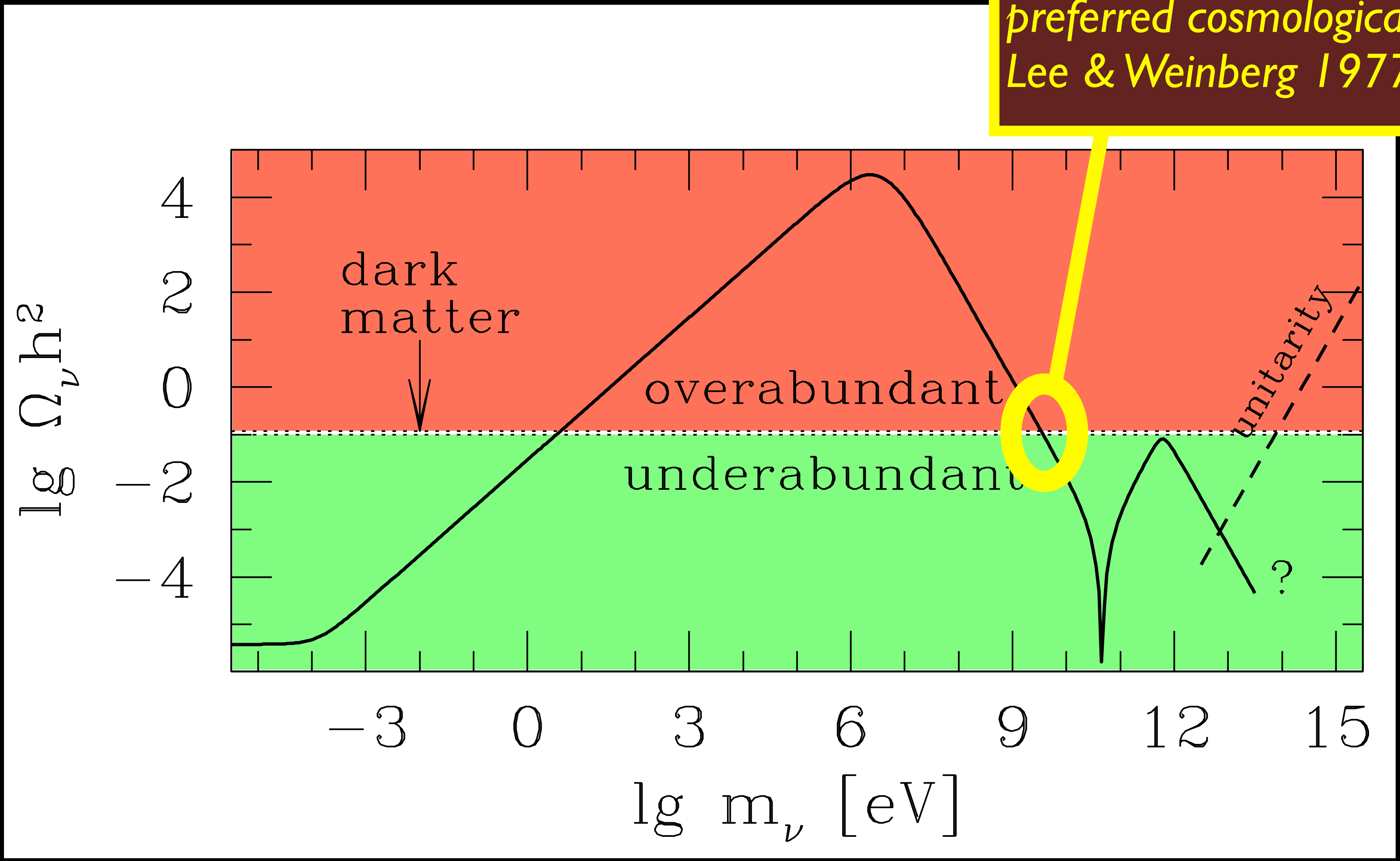
Fourth-generation Standard Model neutrino



Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrin

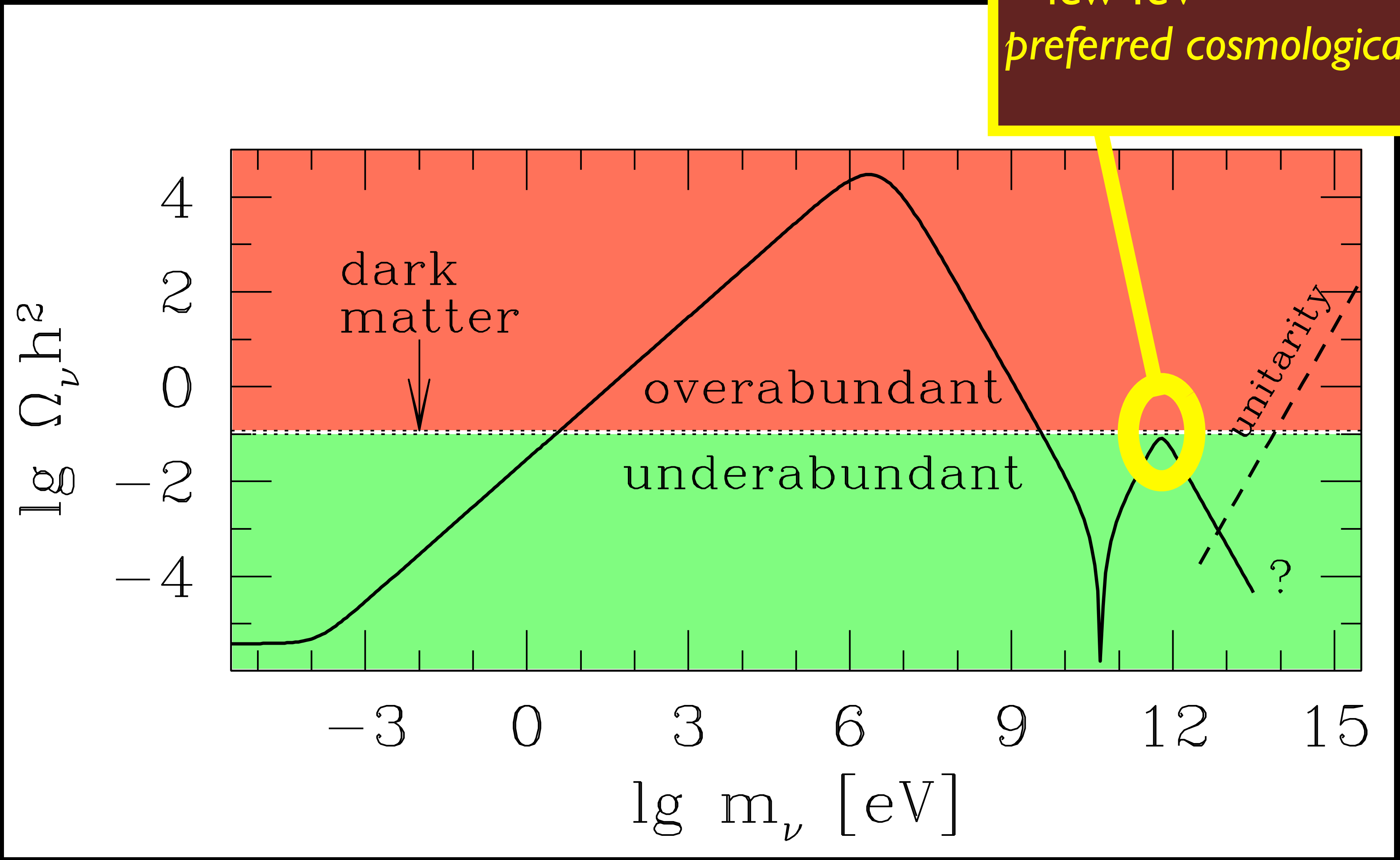
~ few GeV
preferred cosmological mass
Lee & Weinberg 1977



Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino

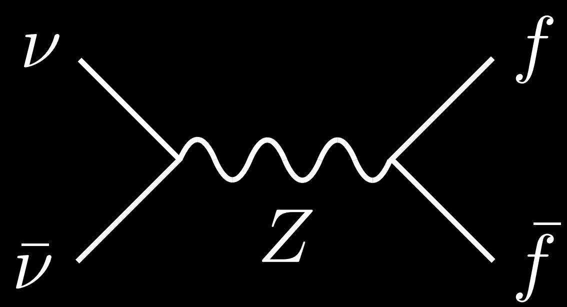
~ few TeV
preferred cosmological mass



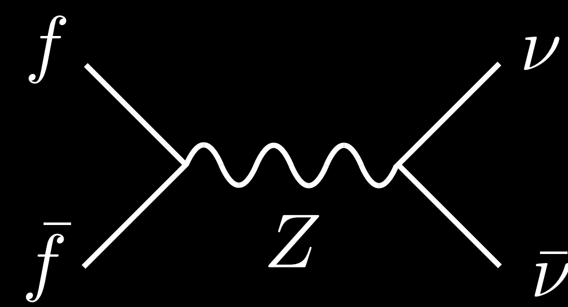
Connection to colliders

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

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



Inverse reaction



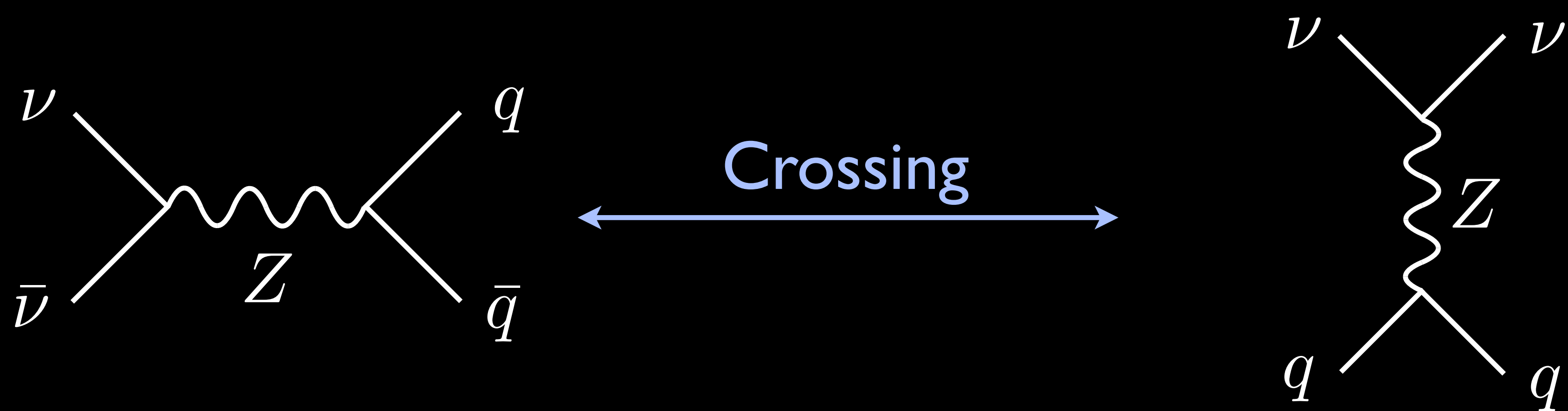
For example, a ~4 GeV/c^2 dark matter neutrino would be copiously produced in resonant Z boson decays

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

Connection to direct detection

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

Scattering $\nu q \to \nu q$

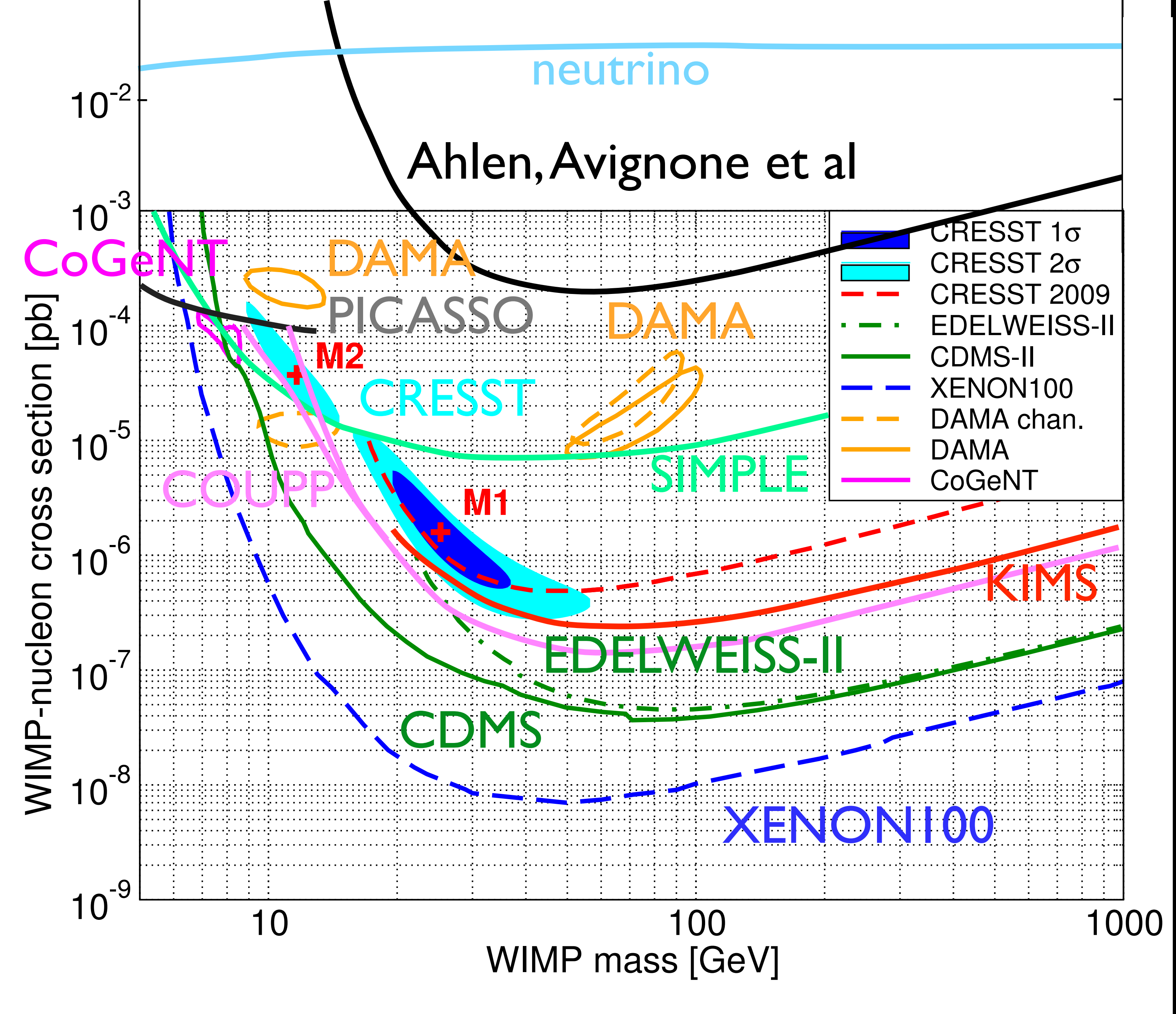


For example, for a ~4 GeV/c^2 dark matter neutrino, the scattering cross section is

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

Excluded by direct searches

Spin-



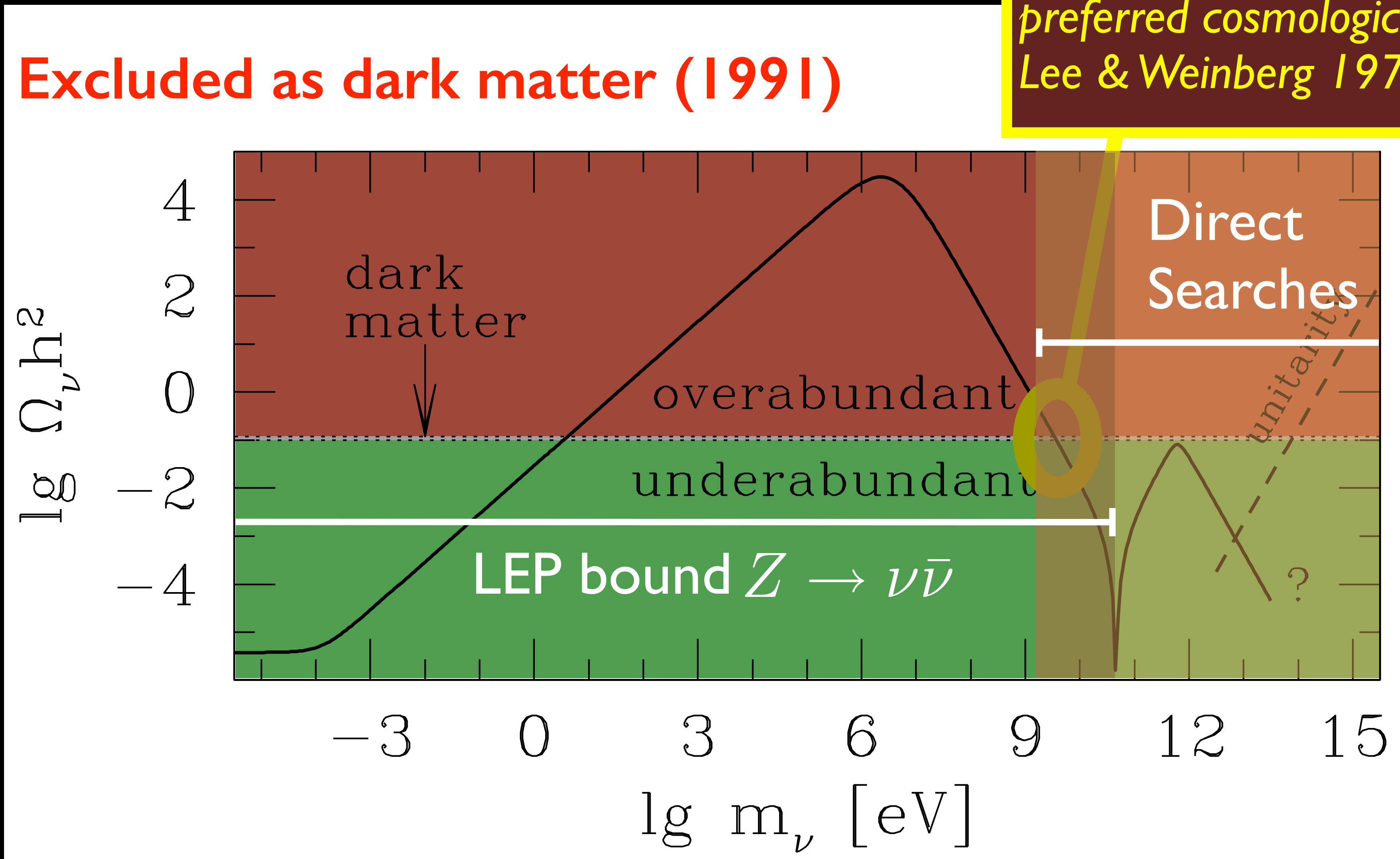
Updated from Anglehor et al 2011

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

Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrin

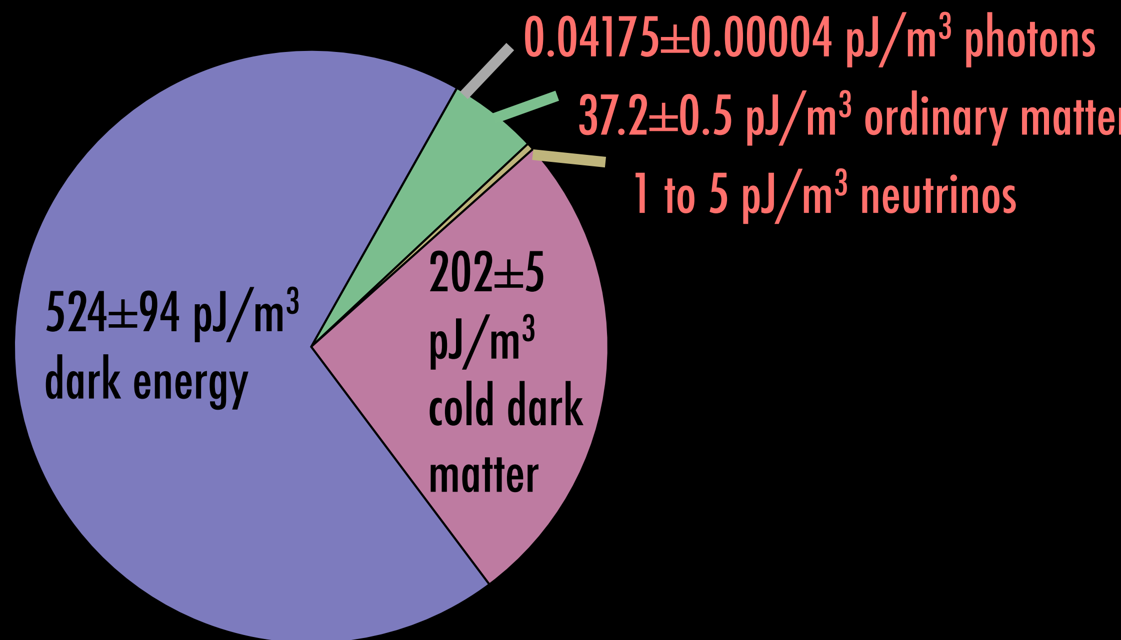
~ few GeV
preferred cosmological mass
Lee & Weinberg 1977



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

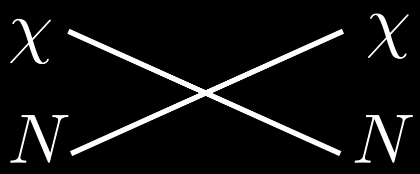
  The same physical processes that produce the right density of WIMPs make their detection possible

The magnificent WIMP

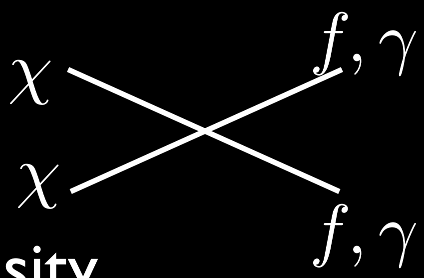
To first order, three quantities characterize a WIMP

- Mass *m*
  - Simplest models relate mass to cosmic density: $1-10^4$ GeV/c^2

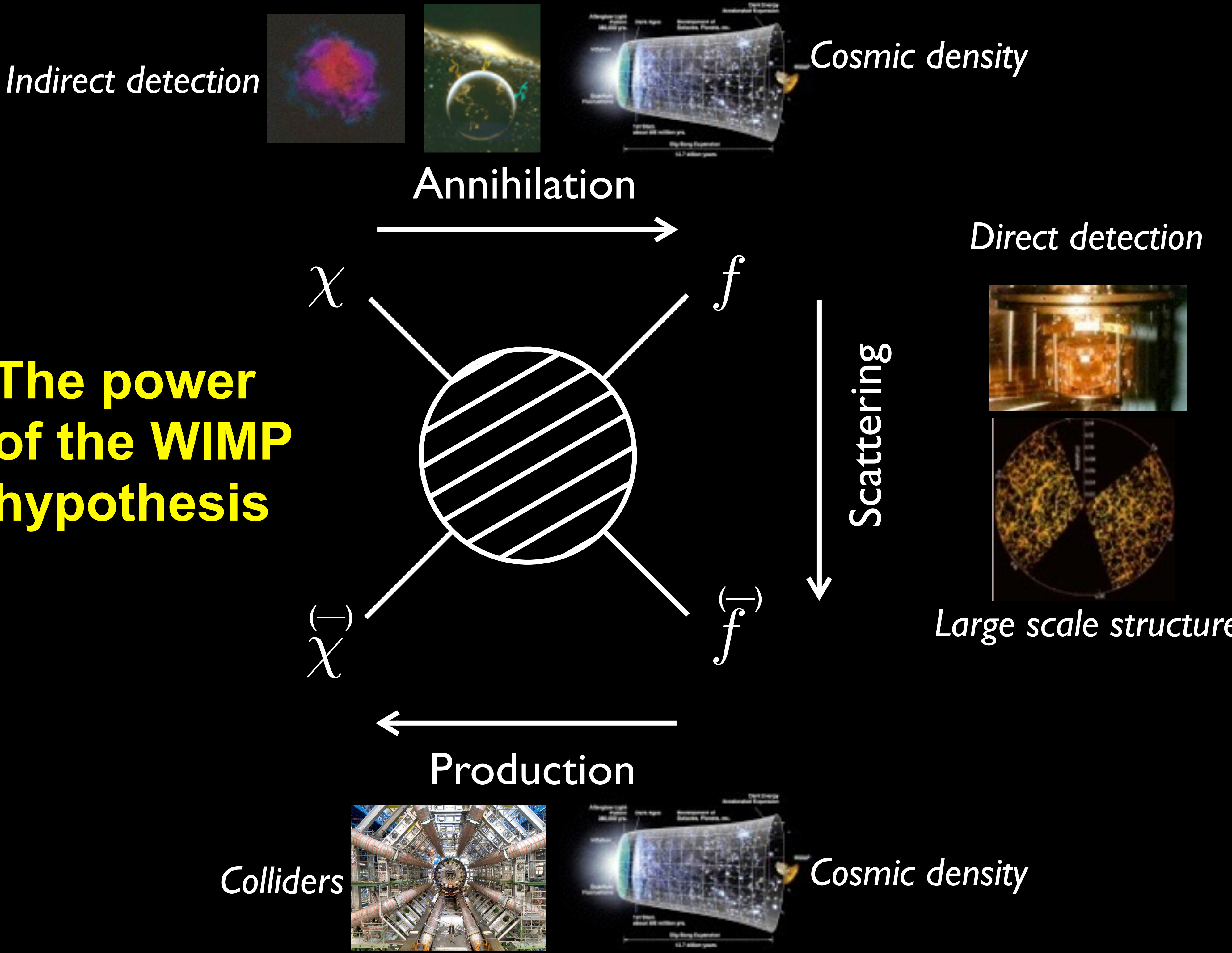
- Scattering cross section off nucleons σ_{XN}
  - Usually different for protons and neutrons
  - Spin-dependent or spin-independent governs scaling to nuclei



- Annihilation cross section into ordinary particles
  - $\sigma \simeq \text{const}/v$ at small v, so use σv
  - Simplest models relate cross section to cosmic density



The power of the WIMP hypothesis



Minimalist dark matter

Minimalist dark matter

do not confuse with minimal dark matter

"Higgs portal scalar dark matter"

Gauge singlet scalar field S, stabilized by Z_2 symmetry ($S \to -S$)

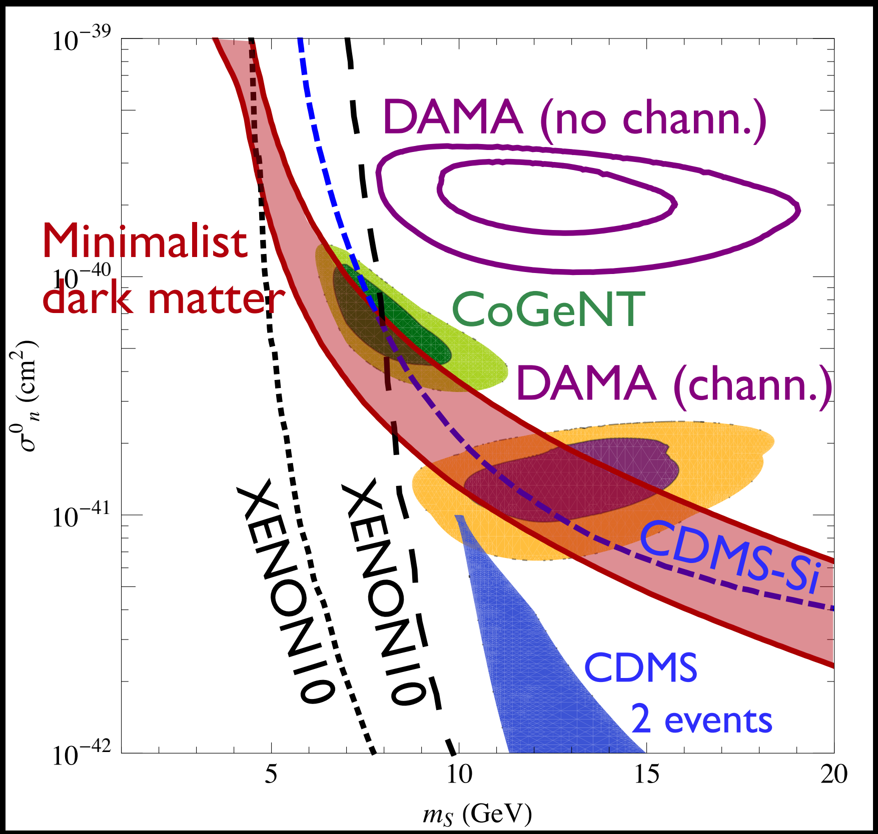
$$\mathcal{L}_S = \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 - \lambda_L H^\dagger H S^2$$

Silveira, Zee 1985

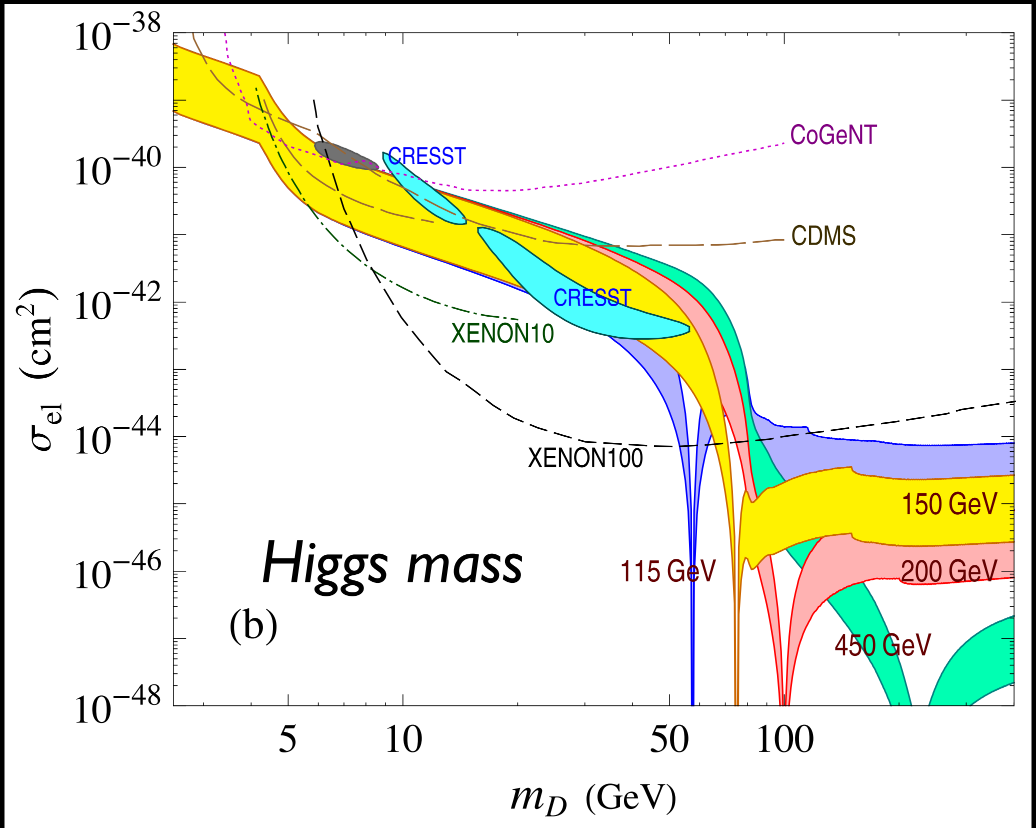
Andreas, Hambye, Tytgat 2008

Minimalist dark matter

do not confuse with minimal dark matter



Andreas, Arina, Hambye, Ling, Tytgat 2010



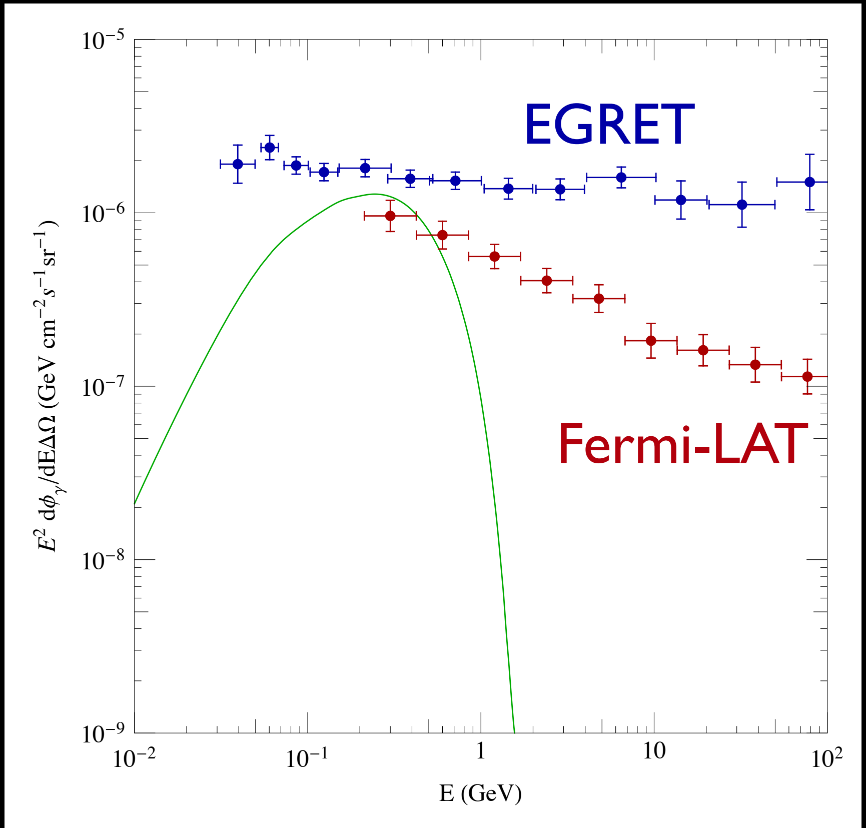
He, Tandean 2011

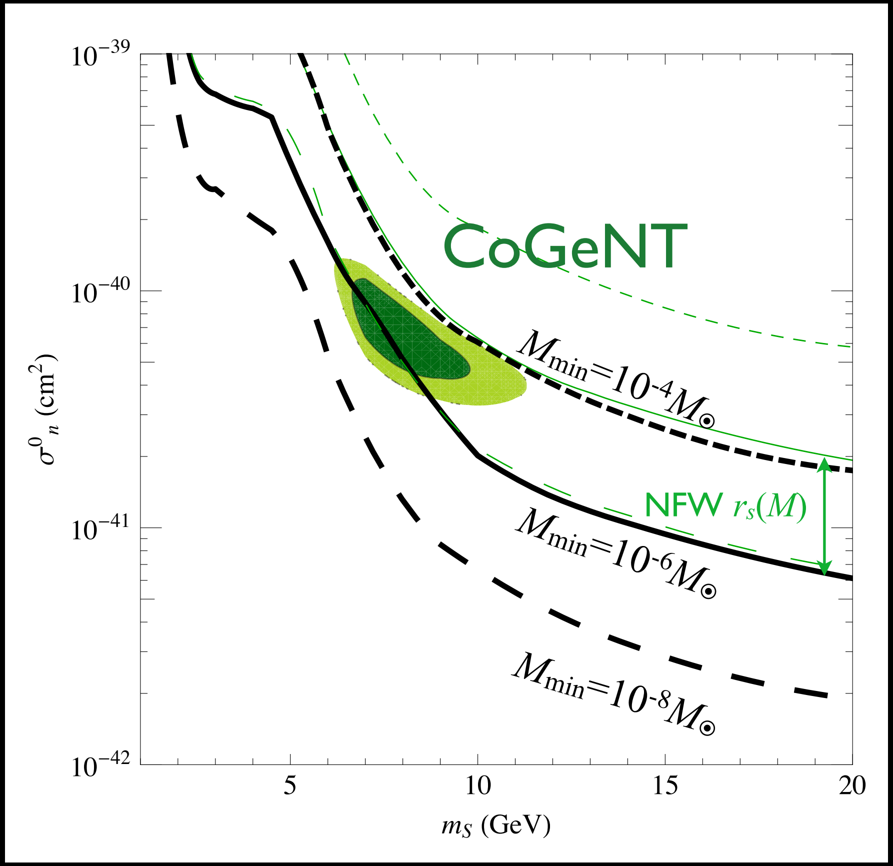
Minimalist dark matter

do not confuse with minimal dark matter

Constraints from diffuse Galactic gamma-rays

Very sensitive to unknown properties of small dark subhalos



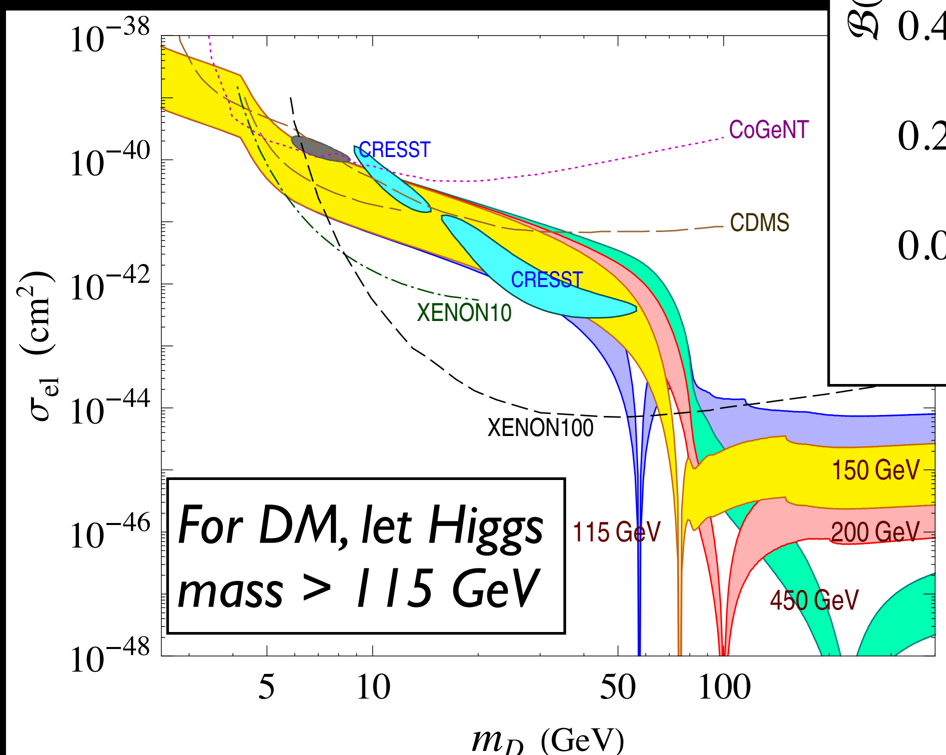


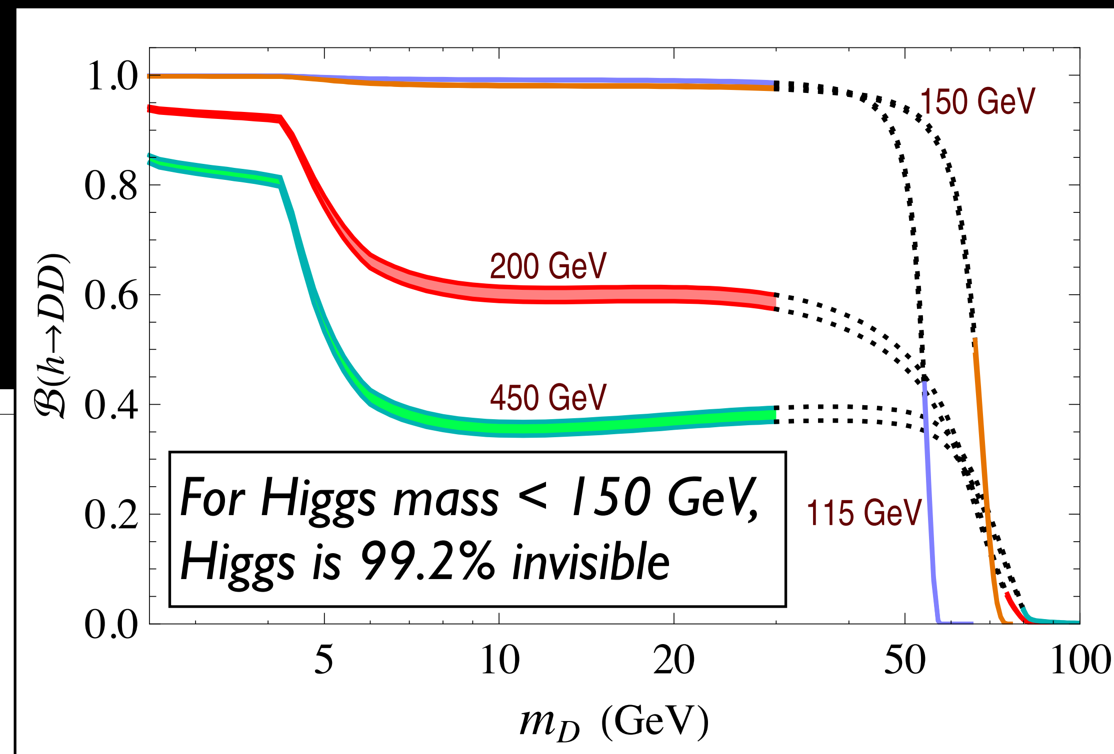
Arina, Tytgat 2010

Minimalist dark matter

do not confuse with minimal dark matter

Constraints from the LHC: a 125 Higgs is not 99.2% invisible



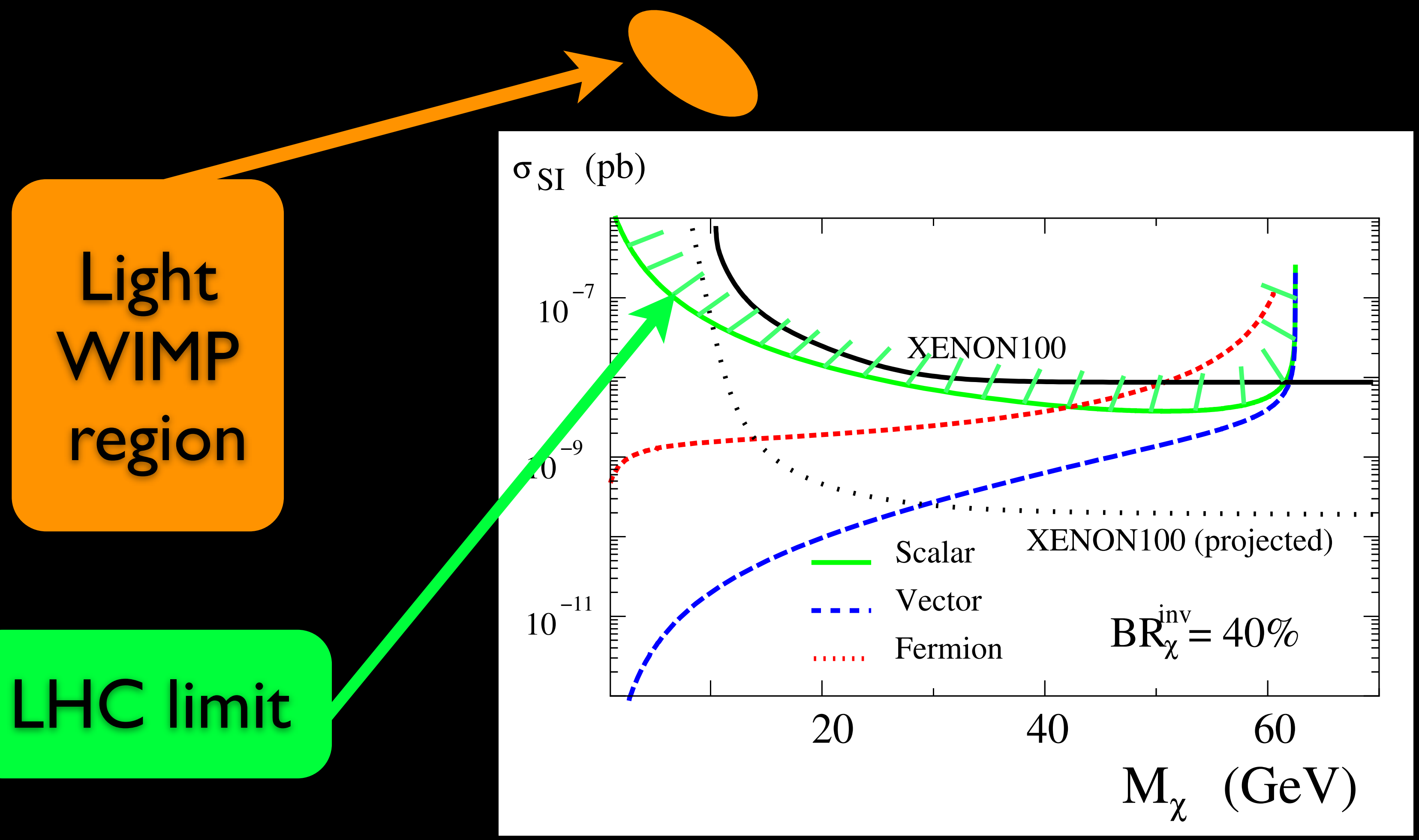


He, Tandean 2011

Minimalist dark matter

do not confuse with minimal dark matter

Constraints from the LHC: a 125 GeV Higgs is not 99.2% invisible



Djouadi, Falkowski, Mambrini, Quevillon 2012

Minimalist dark matter

arxiv:1306.4710

Update on scalar singlet dark matter

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Christoph Weniger§
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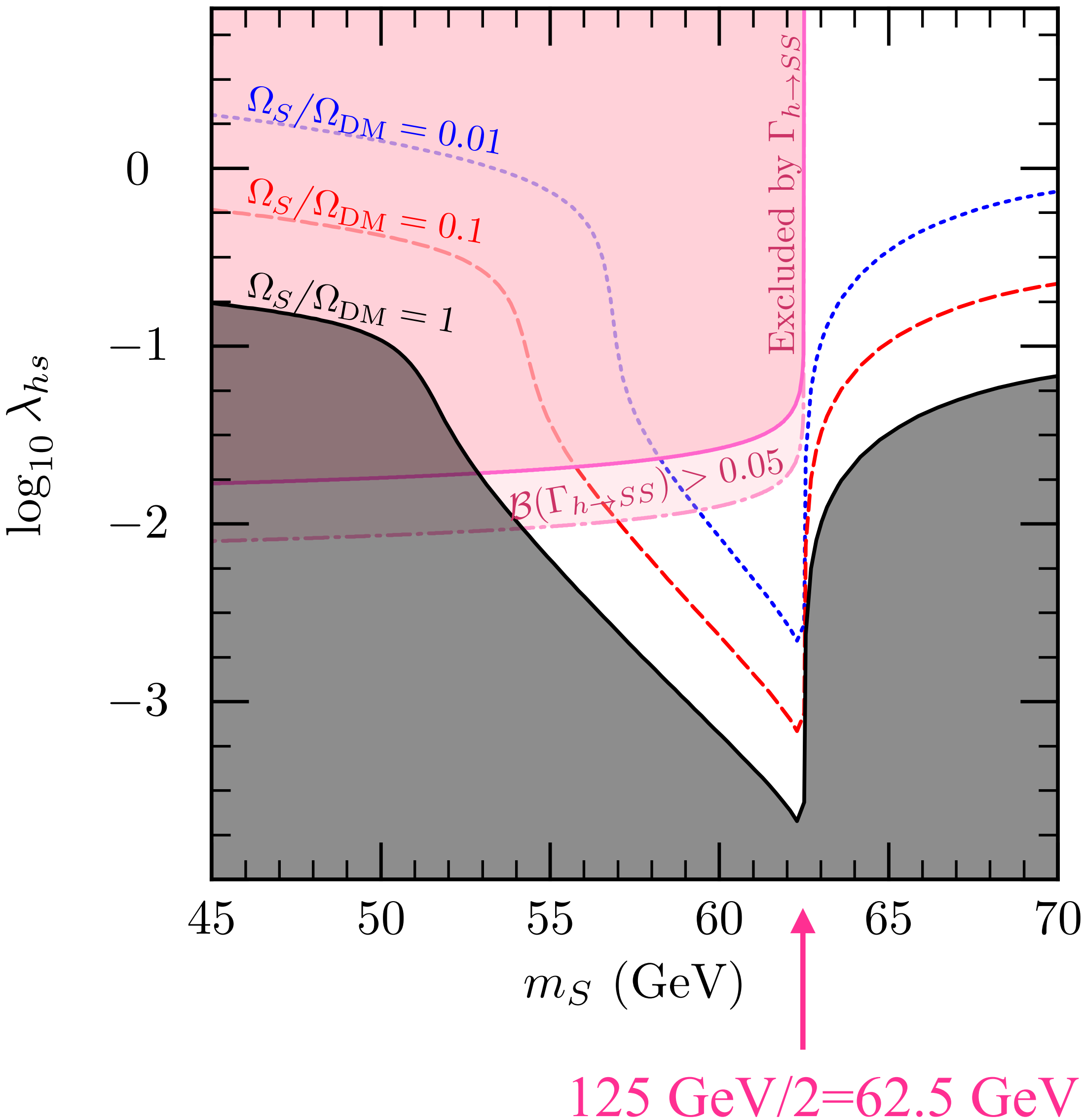
One of the simplest models of dark matter is that where a scalar singlet field S comprises some or all of the dark matter, and interacts with the standard model through an $|H|^2 S^2$ coupling to the Higgs boson. We update the present limits on the model from LHC searches for invisible Higgs decays, the thermal relic density of S, and dark matter searches via indirect and direct detection. We point out that the currently allowed parameter space is on the verge of being significantly reduced with the next generation of experiments. We discuss the impact of such constraints on possible applications of scalar singlet dark matter, including a strong electroweak phase transition, and the question of vacuum stability of the Higgs potential at high scales.

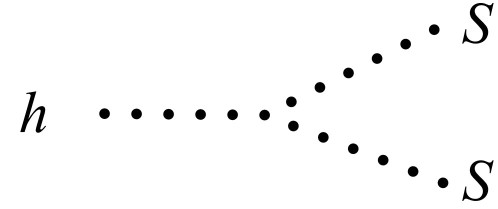
$$V = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 \, . \qquad m_S = \sqrt{\mu_S^2 + \frac{1}{2}\lambda_{hS} v_0^2} \, ,$$

Minimalist dark matter



Invisible Higgs width

$h \to S + S$



$$\Gamma_{\rm inv} = \frac{\lambda_{hs}^2 v_0^2}{32\pi m_h}\left(1 - 4m_S^2/m_h^2\right)^{1/2}$$

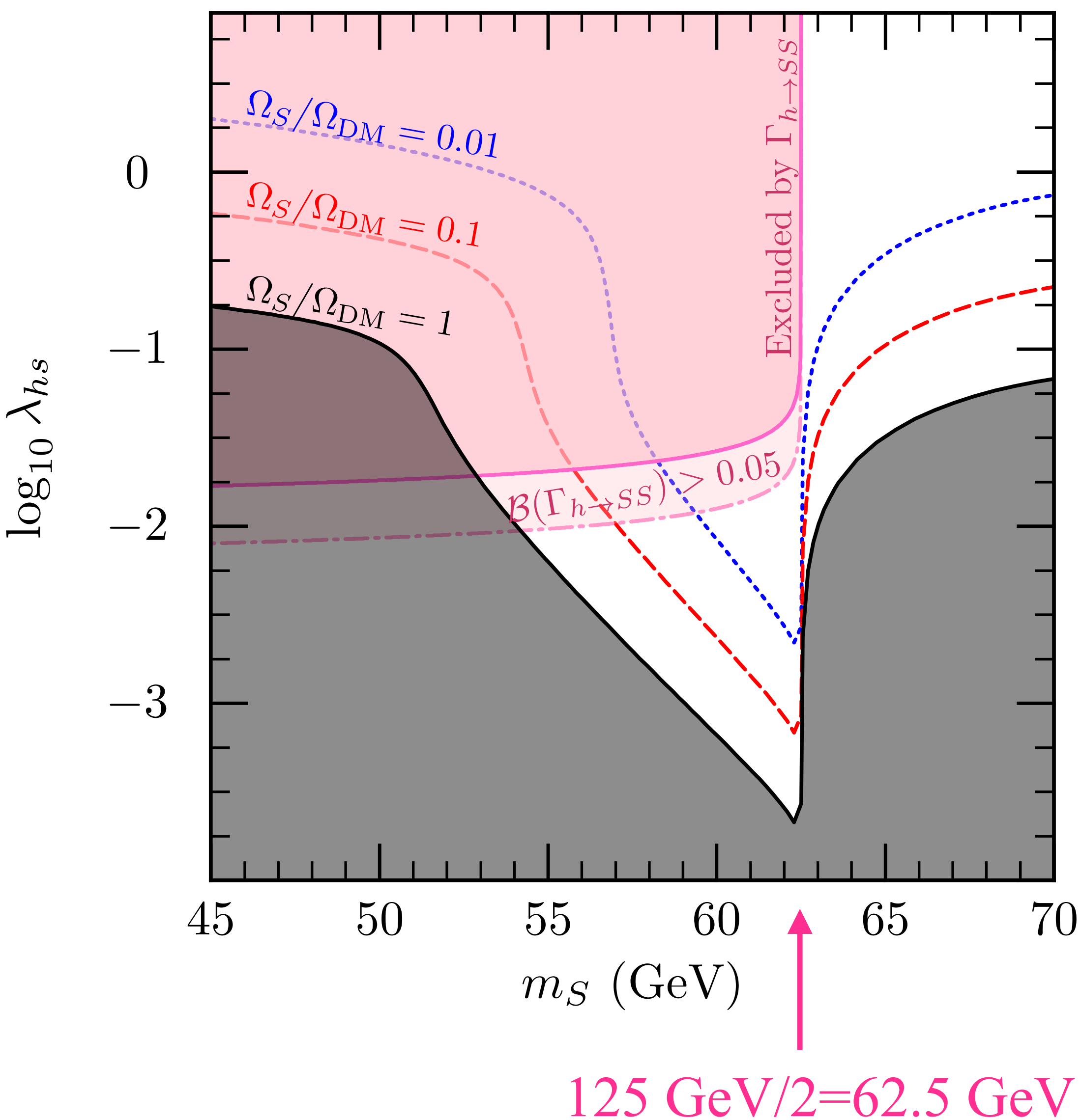
LHC

$\Gamma_{\rm vis}$=4.07 MeV m_h=125 GeV

$$\mathcal{B}(\Gamma_{h\to SS}) = \frac{\Gamma_{\rm inv}}{\Gamma_{\rm vis} + \Gamma_{\rm inv}} < 0.19$$

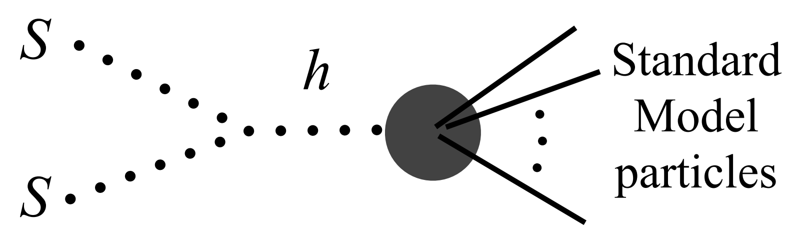
(2σ)

Minimalist dark matter



Cosmic density

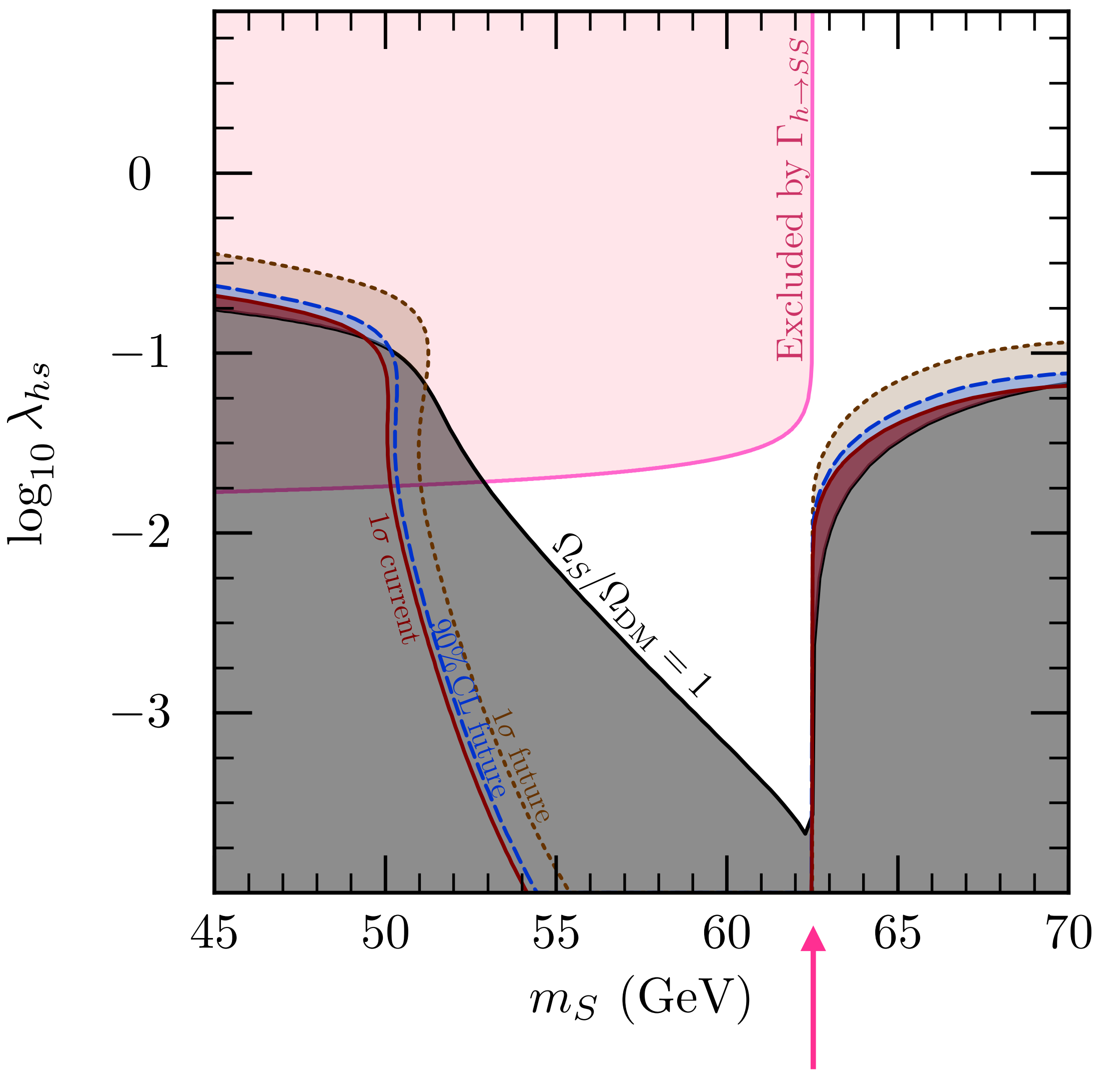
$S + S \to$ Standard Model particles



$$\sigma v_{\rm rel} = \frac{2\lambda_{hS}^2 v_0^2}{\sqrt{s}} \frac{\Gamma_h(\sqrt{s})}{(s-m_h^2)^2 + m_h^2\Gamma_h^2(m_h)}$$

$$\langle \sigma v_{\rm rel}\rangle = \int_{4m_S^2}^{\infty} \frac{s\sqrt{s-4m_S^2}\,K_1(\sqrt{s}/T)\,\sigma v_{\rm rel}}{16 T m_S^4\, K_2^2(m_S/T)}\,{\rm d}s$$

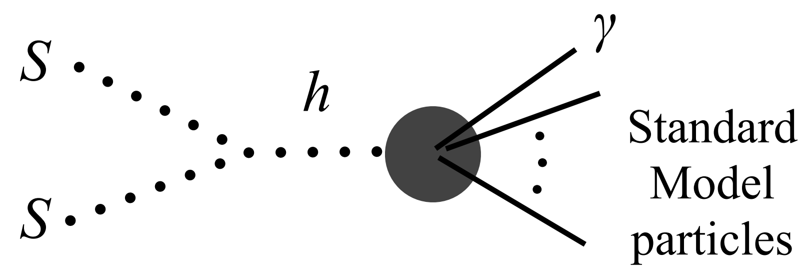
Minimalist dark matter



125 GeV/2=62.5 GeV

Indirect detection

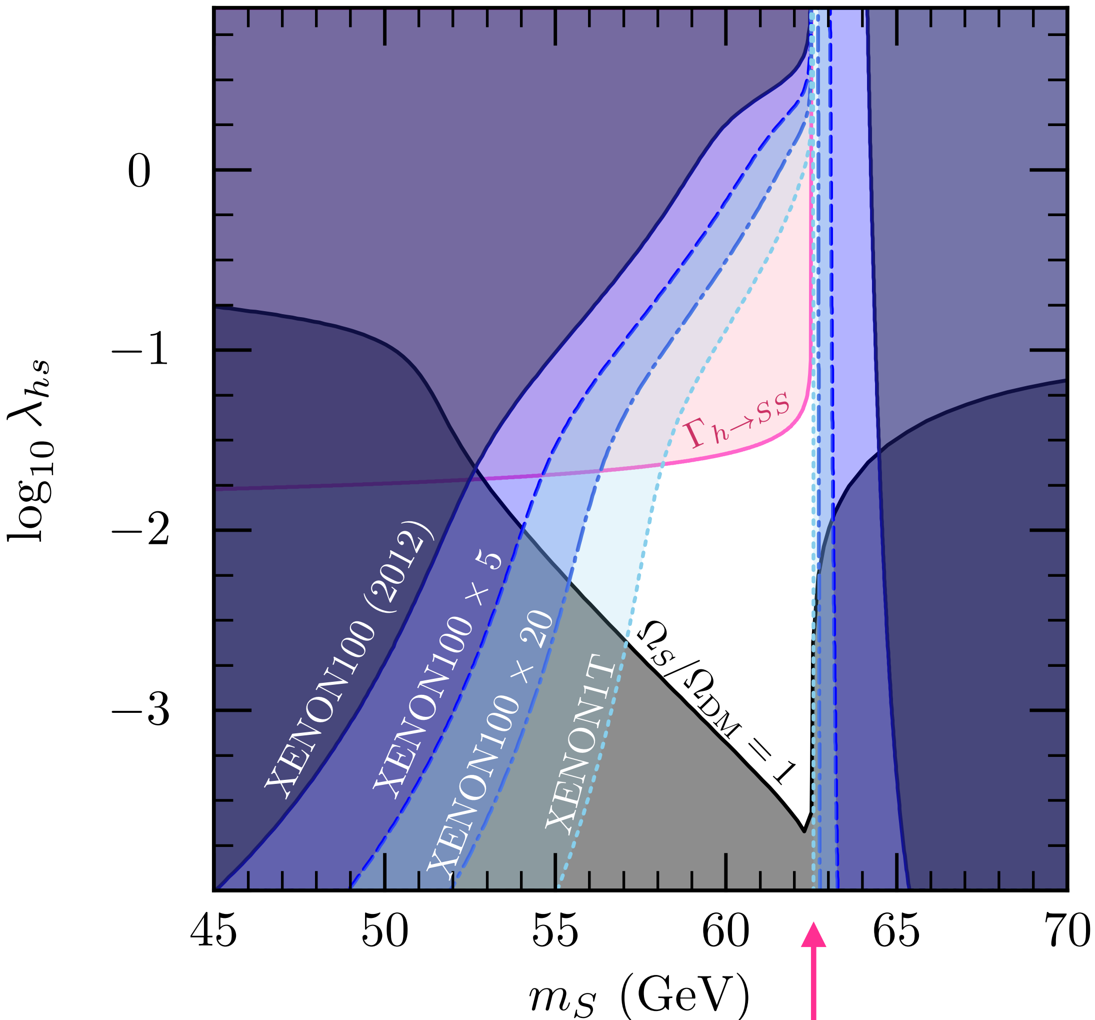
$S + S \to \gamma + \ldots.$



$$\frac{d\phi}{dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_S^2} \frac{dN_\gamma}{dE} \underbrace{\int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} ds \rho^2}_{\equiv J}$$

No gamma-rays in Fermi Observatory from dwarf spheroidal galaxies

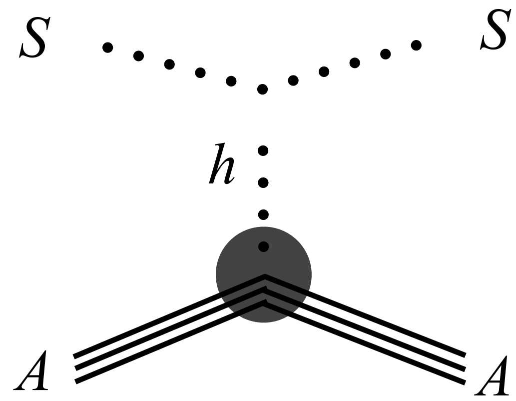
Minimalist dark matter



125 GeV/2=62.5 GeV

Direct detection

$S + A \to S + A$



$$\sigma_{\rm SI} = \frac{\lambda_{hS}^2 f_N^2}{4\pi} \frac{\mu^2 m_n^2}{m_h^4 m_s^2}$$

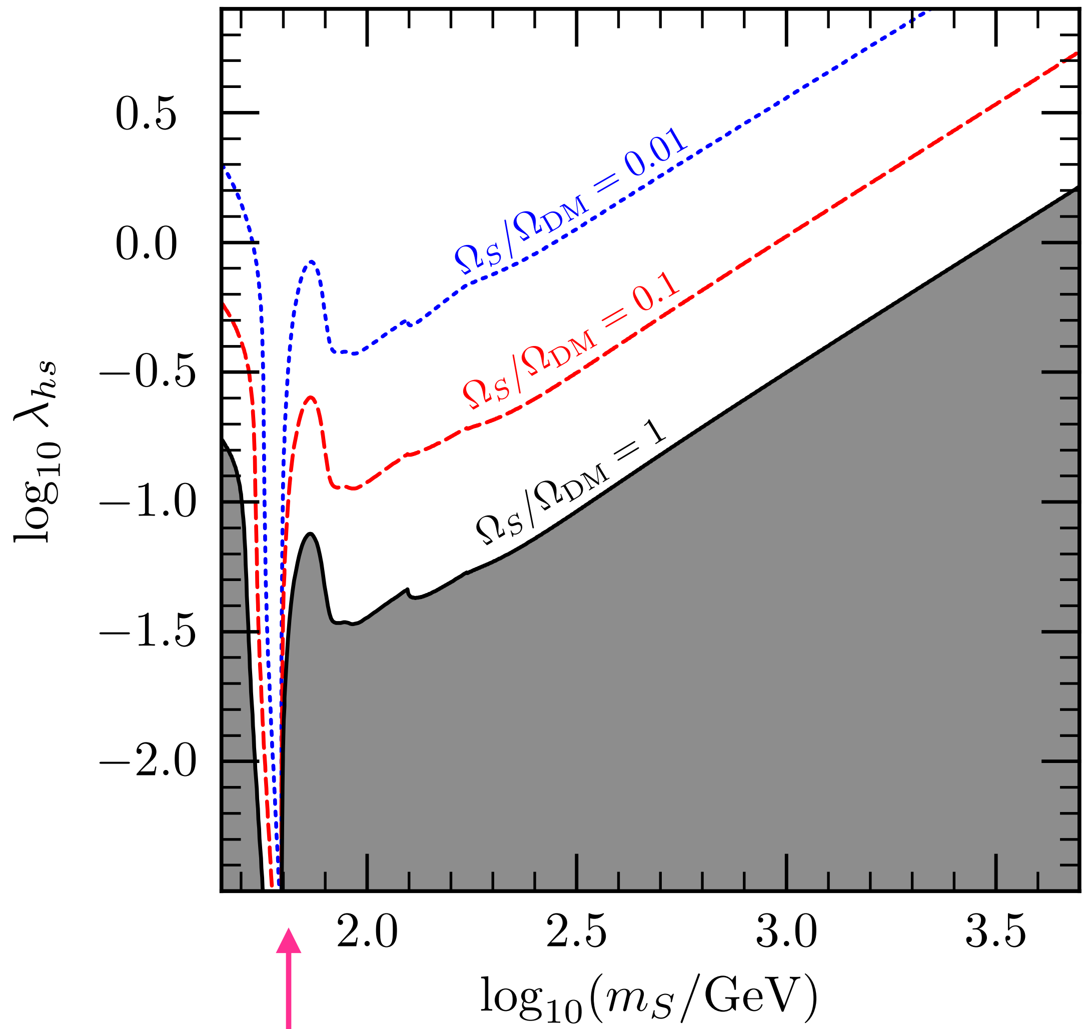
$$f_N = \sum_q f_q = \sum_q \frac{m_q}{m_N} \langle N|\bar{q}q|N\rangle$$

In the figure, limits from XENON experiments

Minimalist dark matter

Heavier masses

Cosmic density



125 GeV/2=62.5 GeV

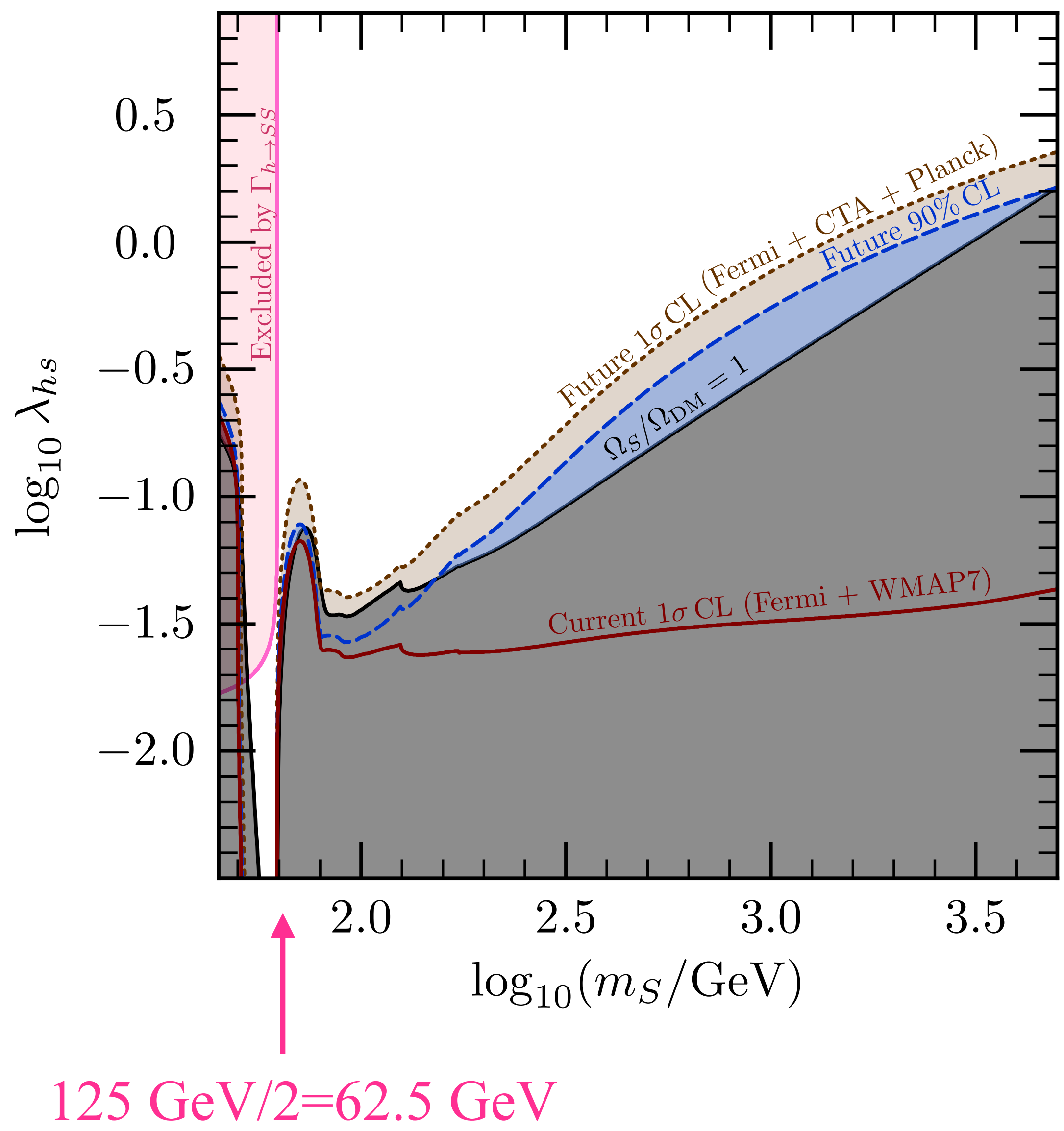
Minimalist dark matter

Heavier masses

Cosmic density

Invisible Higgs width

Indirect detection



Minimalist dark matter

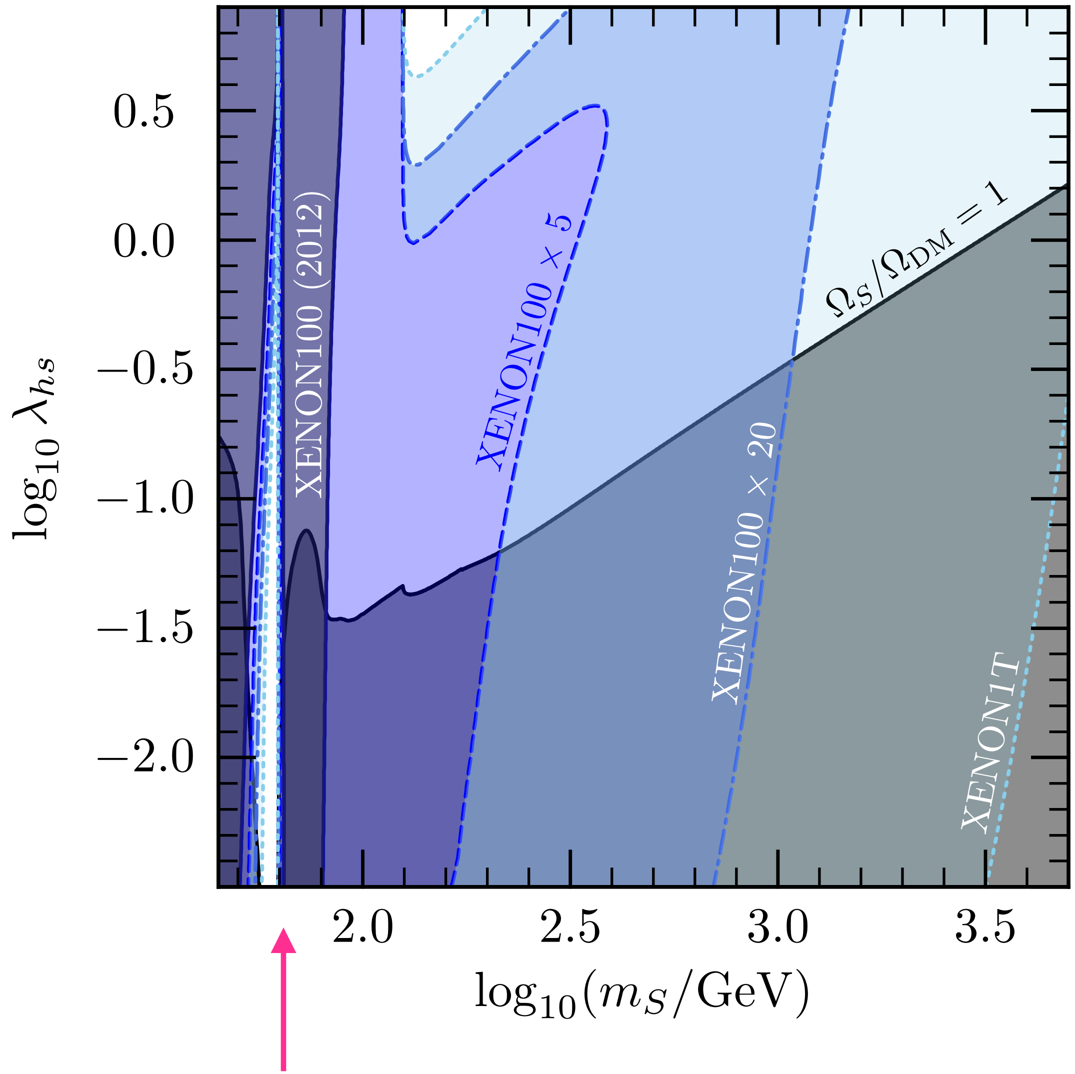
Heavier masses

Cosmic density

Invisible Higgs width

Indirect detection

Direct detection



125 GeV/2=62.5 GeV

Particle Dark Matter

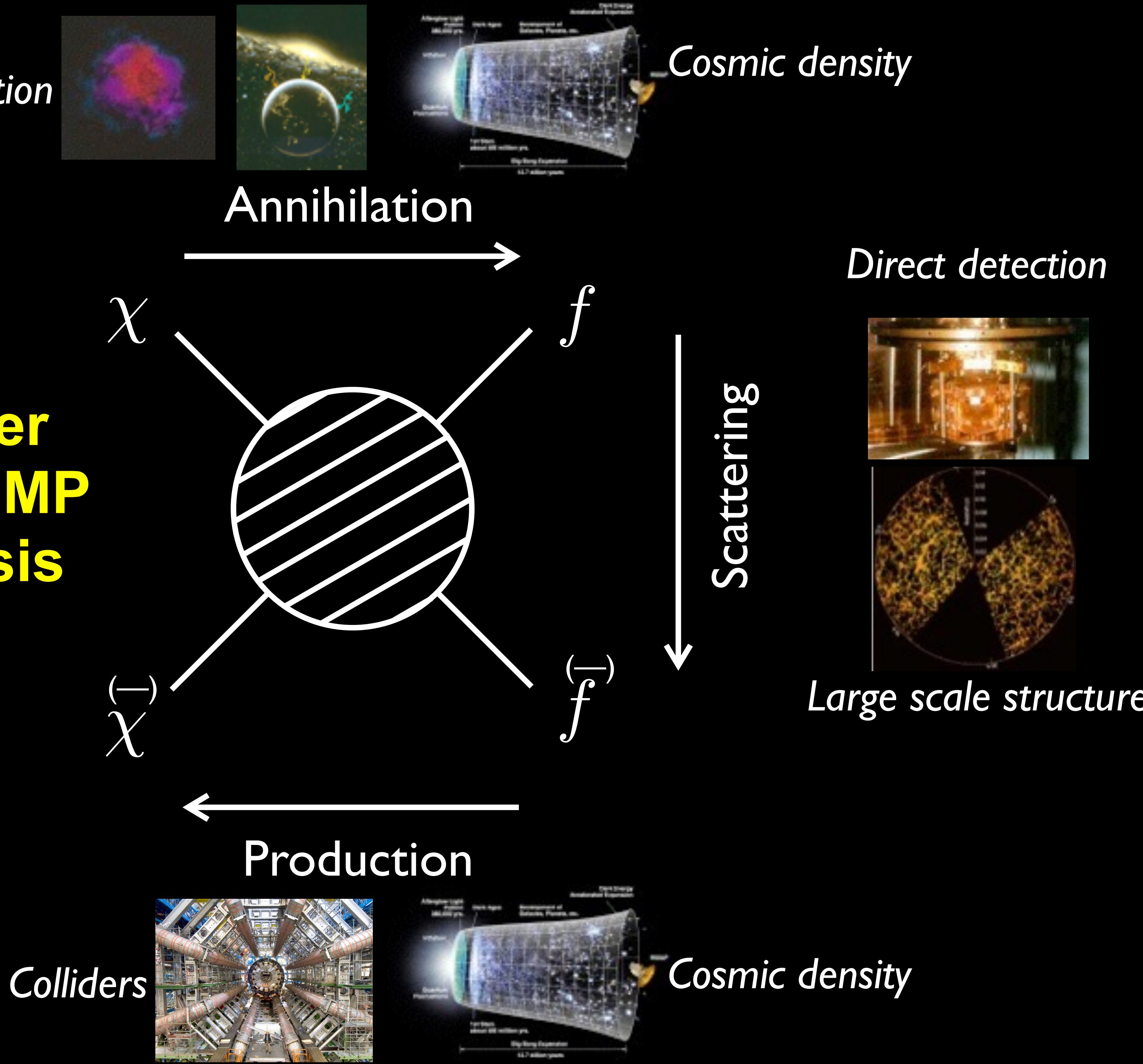
Type Ia Candidates that exist

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

The power of the WIMP hypothesis



Supersymmetric dark matter

Supersymmetry

A supersymmetric transformation Q turns a bosonic state into a fermionic state, and viceversa.

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$
$$Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = P_\mu \sigma^\mu_{\alpha\dot\alpha},\ \{Q_\alpha, Q_\beta\} = \{Q^\dagger_{\dot\alpha}, Q^\dagger_{\dot\beta}\} = 0,\ [P^\mu, Q_\alpha] = [P^\mu, Q^\dagger_{\dot\alpha}] = 0$$

A supersymmetric theory is invariant under supersymmetry transformations

- bosons and fermions come in pairs of equal mass
- the interactions of bosons and fermions are related

Supersymmetric Quantum Electrodynamics

Start with non-supersymmetric QED

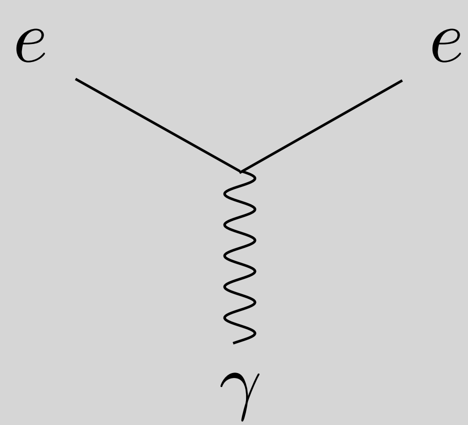
photon A^μ

left-handed electron e_L

right-handed electron e_R

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}i\gamma^\mu\partial_\mu e - m\bar{e}e - q\bar{e}\gamma^\mu e A_\mu$$

"spinor QED"



Supersymmetric Quantum Electrodynamics

photon A^μ	photino λ
left-handed electron e_L	left-handed selectron $\tilde{e}_L$
right-handed electron e_R	right-handed selectron $\tilde{e}_R$

Supersymmetric Quantum Electrodynamics

photon A^μ

left-handed electron e_L

right-handed electron e_R

photino λ

left-handed selectron $\tilde{e}_L$

right-handed selectron $\tilde{e}_R$

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}i\gamma^\mu\partial_\mu e - m\bar{e}e - q\bar{e}\gamma^\mu e A_\mu \\ &+ \partial^\mu \tilde{e}_L^*\partial_\mu\tilde{e}_L - m^2\tilde{e}_L^*\tilde{e}_L - iqA^\mu[\tilde{e}_L^*\partial_\mu\tilde{e}_L - \tilde{e}_L\partial_\mu\tilde{e}_L^*] + q^2A^\mu A_\mu\tilde{e}_L^*\tilde{e}_L \\ &+ \partial^\mu \tilde{e}_R^*\partial_\mu\tilde{e}_R - m^2\tilde{e}_R^*\tilde{e}_R - iqA^\mu[\tilde{e}_R^*\partial_\mu\tilde{e}_R - \tilde{e}_R\partial_\mu\tilde{e}_R^*] + q^2A^\mu A_\mu\tilde{e}_R^*\tilde{e}_R \\ &+ \frac{1}{2}\overline{\lambda}i\gamma^\mu\partial_\mu\lambda - \sqrt{2}q\left(\tilde{e}_L^*\overline{\lambda}e_L - \tilde{e}_R^*\overline{\lambda}e_R + \text{h.c.}\right) \\ &- \frac{1}{2}q^2\left(\tilde{e}_L^*\tilde{e}_L - \tilde{e}_R^*\tilde{e}_R\right)^2\end{aligned}$$

Supersymmetric Quantum Electrodynamics

photon A^μ	photino λ
left-handed electron e_L	left-handed selectron $\tilde{e}_L$
right-handed electron e_R	right-handed selectron $\tilde{e}_R$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}i\gamma^\mu\partial_\mu e - m\bar{e}e \boxed{- q\bar{e}\gamma^\mu e A_\mu}$$

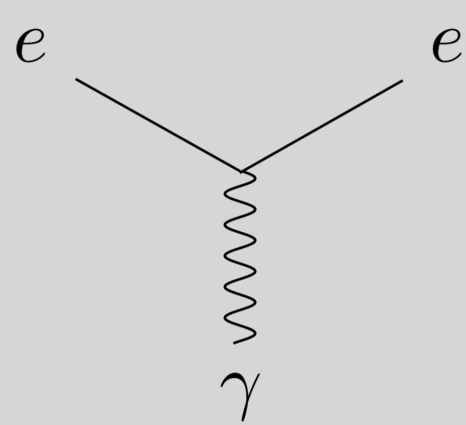
$$+ \partial^\mu\tilde{e}_L^*\partial_\mu\tilde{e}_L - m^2\tilde{e}_L^*\tilde{e}_L - iqA^\mu[\tilde{e}_L^*\partial_\mu\tilde{e}_L - \tilde{e}_L\partial_\mu\tilde{e}_L^*] + q^2A^\mu A_\mu\tilde{e}_L^*\tilde{e}_L$$

$$+ \partial^\mu\tilde{e}_R^*\partial_\mu \ldots {}_R - \tilde{e}_R\partial_\mu\tilde{e}_R^*] + q^2A^\mu A_\mu\tilde{e}_R^*\tilde{e}_R$$

$$+ \frac{1}{2}\bar{\lambda}i\gamma^\mu\partial_\mu \ldots + \text{h.c.})$$

$$- \frac{1}{2}q^2\left(\tilde{e}_L^* \ldots\right.$$

"spinor QED"



Supersymmetric Quantum Electrodynamics

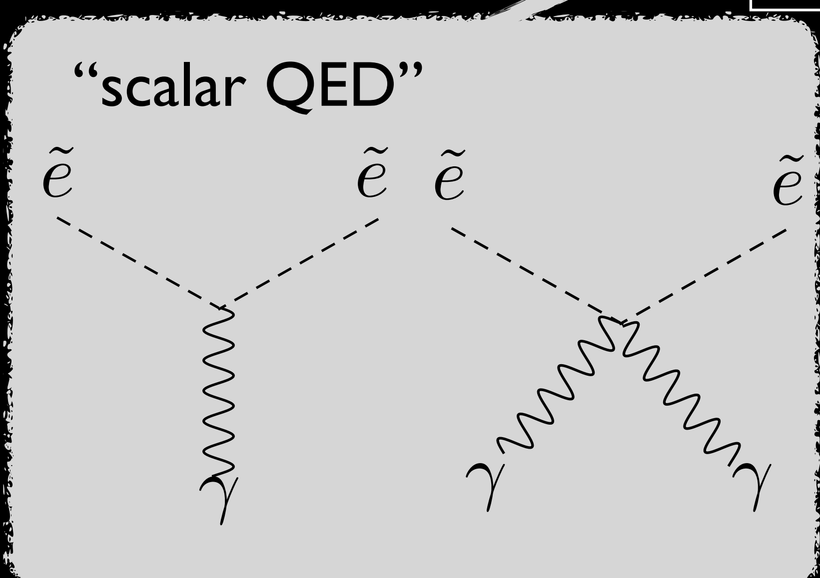
photon A^μ | photino λ
left-handed electron e_L | left-handed selectron $\tilde{e}_L$
right-handed electron e_R | right-handed selectron $\tilde{e}_R$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}i\gamma^\mu\partial_\mu e - m\bar{e}e - q\bar{e}\gamma^\mu e A_\mu$$

$$+ \partial^\mu \tilde{e}_L^* \partial_\mu \tilde{e}_L - m^2 \tilde{e}_L^* \tilde{e}_L - iqA^\mu[\tilde{e}_L^*\partial_\mu\tilde{e}_L - \tilde{e}_L\partial_\mu\tilde{e}_L^*] + q^2 A^\mu A_\mu \tilde{e}_L^* \tilde{e}_L$$

$$+ \partial^\mu \tilde{e}_R^* \partial_\mu \tilde{e}_R - m^2 \tilde{e}_R^* \tilde{e}_R - iqA^\mu[\tilde{e}_R^*\partial_\mu\tilde{e}_R - \tilde{e}_R\partial_\mu\tilde{e}_R^*] + q^2 A^\mu A_\mu \tilde{e}_R^* \tilde{e}_R$$

$$\ldots {}_L - \tilde{e}_R^* \overline{\lambda} e_R + \mathrm{h.c.})$$



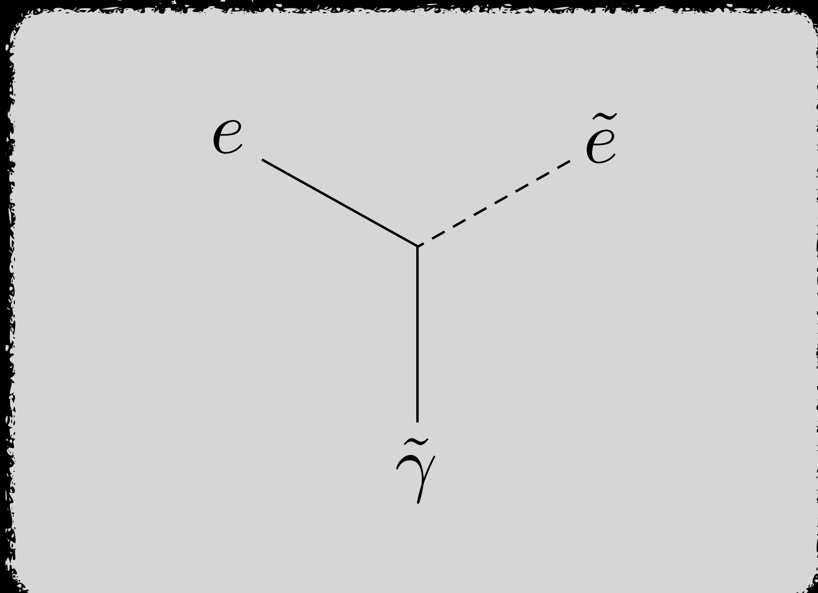
Supersymmetric Quantum Electrodynamics

photon A^μ

photino λ

left-handed selectron $\tilde{e}_L$

right-handed selectron $\tilde{e}_R$



$$\mathcal{L} \ldots m\bar{e}e - q\bar{e}\gamma^\mu e A_\mu$$

$$\ldots qA^\mu[\tilde{e}_L^*\partial_\mu\tilde{e}_L - \tilde{e}_L\partial_\mu\tilde{e}_L^*] + q^2 A^\mu A_\mu \tilde{e}_L^*\tilde{e}_L$$

$$+ \partial^\mu\tilde{e}_R^*\partial_\mu\tilde{e}_R - m^2\tilde{e}_R^*\tilde{e}_R - iqA^\mu[\tilde{e}_R^*\partial_\mu\tilde{e}_R - \tilde{e}_R\partial_\mu\tilde{e}_R^*] + q^2 A^\mu A_\mu \tilde{e}_R^*\tilde{e}_R$$

$$+ \frac{1}{2}\bar{\lambda}i\gamma^\mu\partial_\mu\lambda \boxed{- \sqrt{2}q\left(\tilde{e}_L^*\bar{\lambda}e_L - \tilde{e}_R^*\bar{\lambda}e_R + \text{h.c.}\right)}$$

$$- \frac{1}{2}q^2\left(\tilde{e}_L^*\tilde{e}_L - \tilde{e}_R^*\tilde{e}_R\right)^2$$

Supersymmetric Quantum Electrodynamics

photon A^μ

left-h…

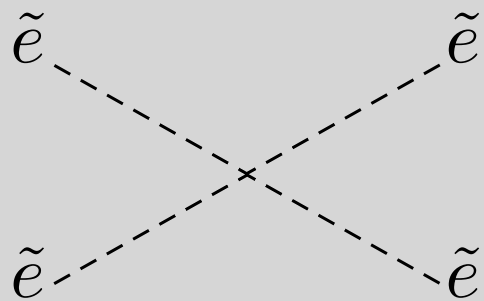
right-…

photino λ

left-handed selectron $\tilde{e}_L$

right-handed selectron $\tilde{e}_R$

"D-term"



$$\mathcal{L} = -\frac{1}{4} \ldots q\bar{e}\gamma^\mu e A_\mu$$

$$+ \partial^\mu \tilde{e}^*_L \ldots \partial_\mu \tilde{e}_L - \tilde{e}_L \partial_\mu \tilde{e}^*_L] + q^2 A^\mu A_\mu \tilde{e}^*_L \tilde{e}_L$$

$$+ \partial^\mu \tilde{e}^*_R \ldots \partial_\mu \tilde{e}_R - \tilde{e}_R \partial_\mu \tilde{e}^*_R] + q^2 A^\mu A_\mu \tilde{e}^*_R \tilde{e}_R$$

$$+ \frac{1}{2}\overline{\lambda} i\gamma^\mu \partial_\mu \lambda \ldots 2q\left(\tilde{e}^*_L \overline{\lambda} e_L - \tilde{e}^*_R \overline{\lambda} e_R + \text{h.c.}\right)$$

$$-\frac{1}{2} q^2 \left(\tilde{e}^*_L \tilde{e}_L - \tilde{e}^*_R \tilde{e}_R\right)^2$$

Supersymmetric Quantum Electrodynamics

photon A^μ

left-handed electron e_L

right-handed electron e_R

photino λ

left-handed selectron $\tilde{e}_L$

right-handed selectron $\tilde{e}_R$

$$\begin{aligned}
\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}i\gamma^\mu\partial_\mu e - m\bar{e}e - q\bar{e}\gamma^\mu e A_\mu \\
&+ \partial^\mu \tilde{e}_L^* \partial_\mu \tilde{e}_L - m^2 \tilde{e}_L^* \tilde{e}_L - iqA^\mu[\tilde{e}_L^*\partial_\mu\tilde{e}_L - \tilde{e}_L\partial_\mu\tilde{e}_L^*] + q^2 A^\mu A_\mu \tilde{e}_L^*\tilde{e}_L \\
&+ \partial^\mu \tilde{e}_R^* \partial_\mu \tilde{e}_R - m^2 \tilde{e}_R^* \tilde{e}_R - iqA^\mu[\tilde{e}_R^*\partial_\mu\tilde{e}_R - \tilde{e}_R\partial_\mu\tilde{e}_R^*] + q^2 A^\mu A_\mu \tilde{e}_R^*\tilde{e}_R \\
&+ \frac{1}{2}\overline{\lambda}i\gamma^\mu\partial_\mu\lambda - \sqrt{2}q\left(\tilde{e}_L^*\overline{\lambda}e_L - \tilde{e}_R^*\overline{\lambda}e_R + \text{h.c.}\right) \\
&- \frac{1}{2}q^2\left(\tilde{e}_L^*\tilde{e}_L - \tilde{e}_R^*\tilde{e}_R\right)^2
\end{aligned}$$

Supersymmetric Quantum Electrodynamics

photon A^μ

left-handed electron e_L

right-handed electron e_R

photino λ

left-handed selectron $\tilde{e}_L$

right-handed selectron $\tilde{e}_R$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}i\gamma^\mu\partial_\mu e - m\bar{e}e - q\bar{e}\gamma^\mu e A_\mu$$
$$+ \partial^\mu\tilde{e}_L^*\partial_\mu\tilde{e}_L - m^2\tilde{e}_L^*\tilde{e}_L - iqA^\mu[\tilde{e}_L^*\partial_\mu\tilde{e}_L - \tilde{e}_L\partial_\mu\tilde{e}_L^*] + q^2A^\mu A_\mu\tilde{e}_L^*\tilde{e}_L$$
$$+ \partial^\mu\tilde{e}_R^*\partial_\mu\tilde{e}_R - m^2\tilde{e}_R^*\tilde{e}_R - iqA^\mu[\tilde{e}_R^*\partial_\mu\tilde{e}_R - \tilde{e}_R\partial_\mu\tilde{e}_R^*] + q^2A^\mu A_\mu\tilde{e}_R^*\tilde{e}_R$$
$$+ \frac{1}{2}\overline{\lambda}i\gamma^\mu\partial_\mu\lambda - \sqrt{2}q\left(\tilde{e}_L^*\overline{\lambda}e_L - \tilde{e}_R^*\overline{\lambda}e_R + \text{h.c.}\right)$$
$$- \frac{1}{2}q^2\left(\tilde{e}_L^*\tilde{e}_L - \tilde{e}_R^*\tilde{e}_R\right)^2 \boxed{-m_L^2\tilde{e}_L^*\tilde{e}_L - m_R^2\tilde{e}_R^*\tilde{e}_R - \frac{1}{2}M\overline{\lambda}\lambda}$$

"soft supersymmetry-breaking terms"

Supersymmetric Quantum Electrodynamics

photon A^μ

left-handed electron e_L

right-handed electron e_R

photino λ

left-handed selectron $\tilde{e}_L$

right-handed selectron $\tilde{e}_R$

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}i\gamma^\mu\partial_\mu e - m\bar{e}e - q\bar{e}\gamma^\mu e A_\mu \\
& + \partial^\mu \tilde{e}_L^*\partial_\mu \tilde{e}_L - m^2 \tilde{e}_L^*\tilde{e}_L - iqA^\mu[\tilde{e}_L^*\partial_\mu\tilde{e}_L - \tilde{e}_L\partial_\mu\tilde{e}_L^*] + q^2A^\mu A_\mu \tilde{e}_L^*\tilde{e}_L \\
& + \partial^\mu \tilde{e}_R^*\partial_\mu \tilde{e}_R - m^2 \tilde{e}_R^*\tilde{e}_R - iqA^\mu[\tilde{e}_R^*\partial_\mu\tilde{e}_R - \tilde{e}_R\partial_\mu\tilde{e}_R^*] + q^2A^\mu A_\mu \tilde{e}_R^*\tilde{e}_R \\
& + \frac{1}{2}\overline{\lambda}i\gamma^\mu\partial_\mu\lambda - \sqrt{2}q\left(\tilde{e}_L^*\overline{\lambda}e_L - \tilde{e}_R^*\overline{\lambda}e_R + \text{h.c.}\right) \\
& - \frac{1}{2}q^2\left(\tilde{e}_L^*\tilde{e}_L - \tilde{e}_R^*\tilde{e}_R\right)^2 - m_L^2\tilde{e}_L^*\tilde{e}_L - m_R^2\tilde{e}_R^*\tilde{e}_R - \frac{1}{2}M\overline{\lambda}\lambda
\end{aligned}
$$

Softly-broken superQED

Minimal Supersymmetric Standard Model

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \;\; \widetilde{W}^0$	$W^\pm \;\; W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

From Martin hep-ph/9709356

Minimal Supersymmetric Standard Model

- Gauge interactions (covariant derivatives + D-terms)

- Superpotential (Yukawa terms + F-terms)

$$W = \epsilon_{ij}(-\hat{\mathbf{e}}^*_{\rm R}\mathbf{Y}_E\hat{\mathbf{l}}^i_{\rm L}\hat{H}^j_1 - \hat{\mathbf{d}}^*_{\rm R}\mathbf{Y}_D\hat{\mathbf{q}}^i_{\rm L}\hat{H}^j_1 + \hat{\mathbf{u}}^*_{\rm R}\mathbf{Y}_U\hat{\mathbf{q}}^i_{\rm L}\hat{H}^j_2 - \mu\hat{H}^i_1\hat{H}^j_2)$$

$$\mathcal{L}_{\rm Yuk} = -\frac{1}{2}\frac{\partial^2 W}{\partial\phi_i\partial\phi_j}\,\overline{\psi}_i\,\psi_j \qquad \mathcal{L}_{\text{F-terms}} = \left|\frac{\partial W}{\partial\phi_i}\right|^2$$

- Soft terms

$$\begin{aligned} V_{\rm soft} = \epsilon_{ij}(&-\tilde{\mathbf{e}}^*_{\rm R}\mathbf{A}_E\mathbf{Y}_E\tilde{\mathbf{l}}^i_{\rm L}H^j_1 - \tilde{\mathbf{d}}^*_{\rm R}\mathbf{A}_D\mathbf{Y}_D\tilde{\mathbf{q}}^i_{\rm L}H^j_1 + \tilde{\mathbf{u}}^*_{\rm R}\mathbf{A}_U\mathbf{Y}_U\tilde{\mathbf{q}}^i_{\rm L}H^j_2 - B\mu H^i_1H^j_2 + \text{h.c.}) \\ &+ H^{i*}_1 m^2_1 H^i_1 + H^{i*}_2 m^2_2 H^i_2 + \tilde{\mathbf{q}}^{i*}_{\rm L}\mathbf{M}^2_Q\tilde{\mathbf{q}}^i_{\rm L} + \tilde{\mathbf{l}}^{i*}_{\rm L}\mathbf{M}^2_L\tilde{\mathbf{l}}^i_{\rm L} + \tilde{\mathbf{u}}^*_{\rm R}\mathbf{M}^2_U\tilde{\mathbf{u}}_{\rm R} + \tilde{\mathbf{d}}^*_{\rm R}\mathbf{M}^2_D\tilde{\mathbf{d}}_{\rm R} \\ &+ \tilde{\mathbf{e}}^*_{\rm R}\mathbf{M}^2_E\tilde{\mathbf{e}}_{\rm R} + \tfrac{1}{2}M_1\tilde{B}\tilde{B} + \tfrac{1}{2}M_2(\tilde{W}^3\tilde{W}^3 + 2\tilde{W}^+\tilde{W}^-) + \tfrac{1}{2}M_3\tilde{g}\tilde{g}. \end{aligned}$$

124 parameters (cfr. 18 in SM)

From Martin hep-ph/9709356

Minimal Supersymmetric Standard Model

Neutralinos are linear combinations of neutral gauginos and higgsinos

$$\tilde{\chi}_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0,$$

$$\mathcal{M}_{\tilde{\chi}^0_{1,2,3,4}} = \begin{pmatrix} M_1 & 0 & -\frac{g'v_1}{\sqrt{2}} & +\frac{g'v_2}{\sqrt{2}} \\ 0 & M_2 & +\frac{gv_1}{\sqrt{2}} & -\frac{gv_2}{\sqrt{2}} \\ -\frac{g'v_1}{\sqrt{2}} & +\frac{gv_1}{\sqrt{2}} & \delta_{33} & -\mu \\ +\frac{g'v_2}{\sqrt{2}} & -\frac{gv_2}{\sqrt{2}} & -\mu & \delta_{44} \end{pmatrix}$$

Charginos are linear combinations of charged gauginos and higgsinos

$$\tilde{\chi}_i^- = U_{i1}\tilde{W}^- + U_{i2}\tilde{H}_1^-,$$
$$\tilde{\chi}_i^+ = V_{i1}\tilde{W}^+ + V_{i2}\tilde{H}_2^+.$$

$$\mathcal{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & gv_2 \\ gv_1 & \mu \end{pmatrix},$$

Minimal Supersymmetric Standard Model

Squarks and sleptons are linear combinations of interaction eigenstates

$$\tilde{f}_{\mathrm{L}a} = \sum_{k=1}^{6} \tilde{f}_k \mathbf{\Gamma}_{FL}^{*ka},$$

$$\tilde{f}_{\mathrm{R}a} = \sum_{k=1}^{6} \tilde{f}_k \mathbf{\Gamma}_{FR}^{*ka}.$$

$$\mathcal{M}_{\tilde{\mathrm{u}}}^2 = \begin{pmatrix} \mathbf{M}_Q^2 + \mathbf{m}_{\mathrm{u}}^\dagger \mathbf{m}_{\mathrm{u}} + D_{\mathrm{LL}}^{\mathrm{u}} \mathbf{1} & \mathbf{m}_{\mathrm{u}}^\dagger (\mathbf{A}_U^\dagger - \mu^* \cot\beta) \\ (\mathbf{A}_U - \mu \cot\beta) \mathbf{m}_{\mathrm{u}} & \mathbf{M}_U^2 + \mathbf{m}_{\mathrm{u}} \mathbf{m}_{\mathrm{u}}^\dagger + D_{\mathrm{RR}}^{\mathrm{u}} \mathbf{1} \end{pmatrix},$$

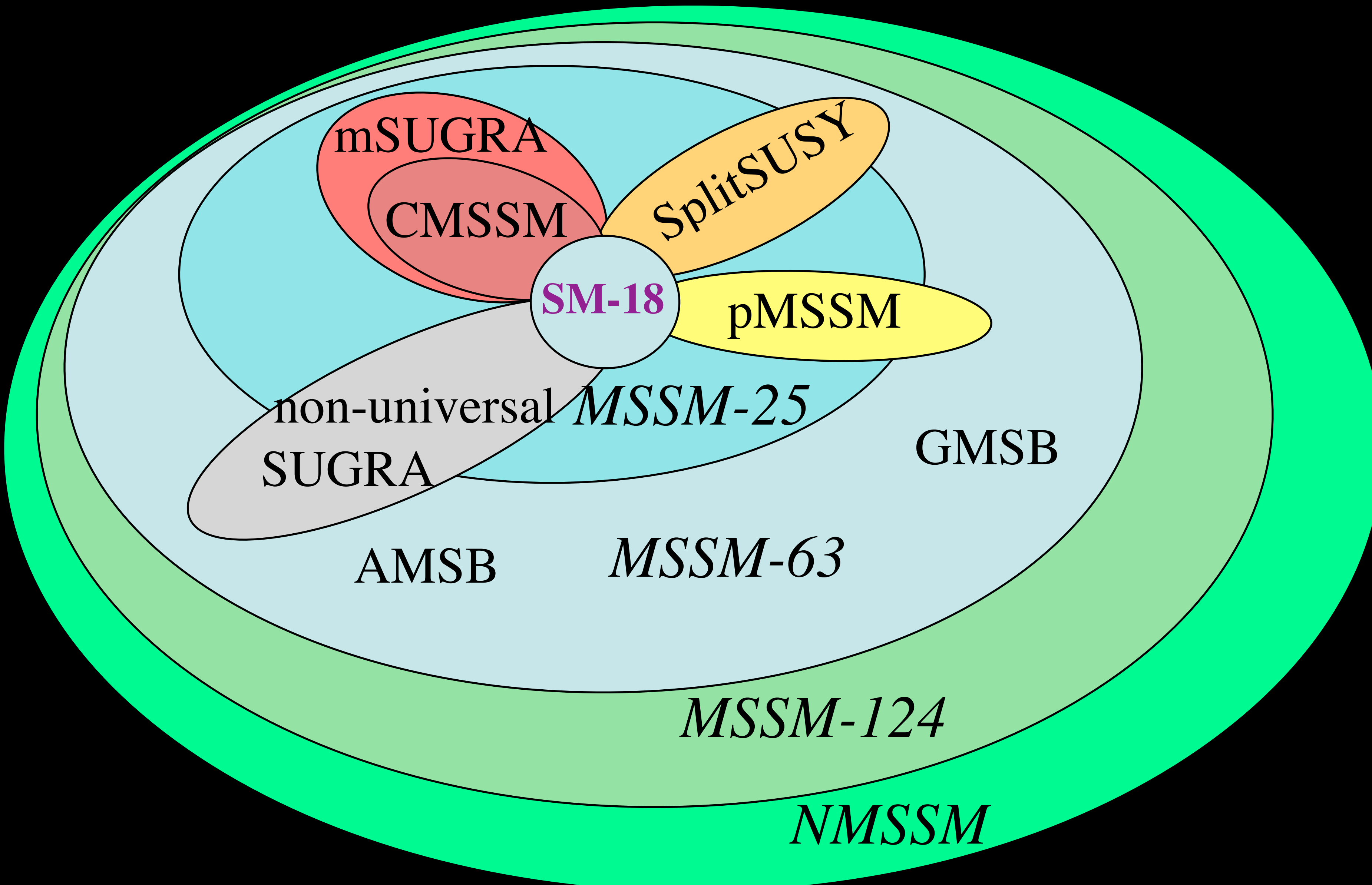
$$\mathcal{M}_{\tilde{\mathrm{d}}}^2 = \begin{pmatrix} \mathbf{K}^\dagger \mathbf{M}_Q^2 \mathbf{K} + \mathbf{m}_{\mathrm{d}} \mathbf{m}_{\mathrm{d}}^\dagger + D_{\mathrm{LL}}^{\mathrm{d}} \mathbf{1} & \mathbf{m}_{\mathrm{d}}^\dagger (\mathbf{A}_D^\dagger - \mu^* \tan\beta) \\ (\mathbf{A}_D - \mu \tan\beta) \mathbf{m}_{\mathrm{d}} & \mathbf{M}_D^2 + \mathbf{m}_{\mathrm{d}}^\dagger \mathbf{m}_{\mathrm{d}} + D_{\mathrm{RR}}^{\mathrm{d}} \mathbf{1} \end{pmatrix}.$$

$$\mathcal{M}_{\tilde{\nu}}^2 = \mathbf{M}_L^2 + D_{LL}^{\nu} \mathbf{1}$$

$$\mathcal{M}_{\tilde{\mathrm{e}}}^2 = \begin{pmatrix} \mathbf{M}_L^2 + \mathbf{m}_{\mathrm{e}} \mathbf{m}_{\mathrm{e}}^\dagger + D_{\mathrm{LL}}^{\mathrm{e}} \mathbf{1} & \mathbf{m}_{\mathrm{e}}^\dagger (\mathbf{A}_E^\dagger - \mu^* \tan\beta) \\ (\mathbf{A}_E - \mu \tan\beta) \mathbf{m}_{\mathrm{e}} & \mathbf{M}_E^2 + \mathbf{m}_{\mathrm{e}}^\dagger \mathbf{m}_{\mathrm{e}} + D_{\mathrm{RR}}^{\mathrm{e}} \mathbf{1} \end{pmatrix}.$$

$$D_{\mathrm{LL}}^{f} = m_Z^2 \cos 2\beta (T_{3f} - e_f \sin^2\theta_W),$$
$$D_{\mathrm{RR}}^{f} = m_Z^2 \cos(2\beta) e_f \sin^2\theta_W$$

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.

Supersymmetric superWIMPs

Interaction scale with ordinary matter suppressed by large mass scale

Axino dark matter ($f_{\mathrm{PQ}} \sim 10^{11}\,\mathrm{GeV}$)

thermally and non-thermally produced in early universe

$$m_{\tilde{a}} \gtrsim 0.1 \text{ MeV}$$

scattering cross section with ordinary matter

$$\sigma \approx (m_W / f_{PQ})^2 \sigma_{\text{weak}} \approx 10^{-18} \sigma_{\text{weak}} \approx 10^{-56} \text{ cm}^2$$

Gravitino dark matter ($m_{\mathrm{Pl}} \sim 10^{19}\,\mathrm{GeV}$)

thermally and non-thermally produced in early universe

$$m_{3/2} \approx 1 \text{ GeV–}700 \text{ GeV}$$

scattering cross section with ordinary matter

$$\sigma \approx 10^{-72} \text{ cm}^2$$

Neutralino dark matter

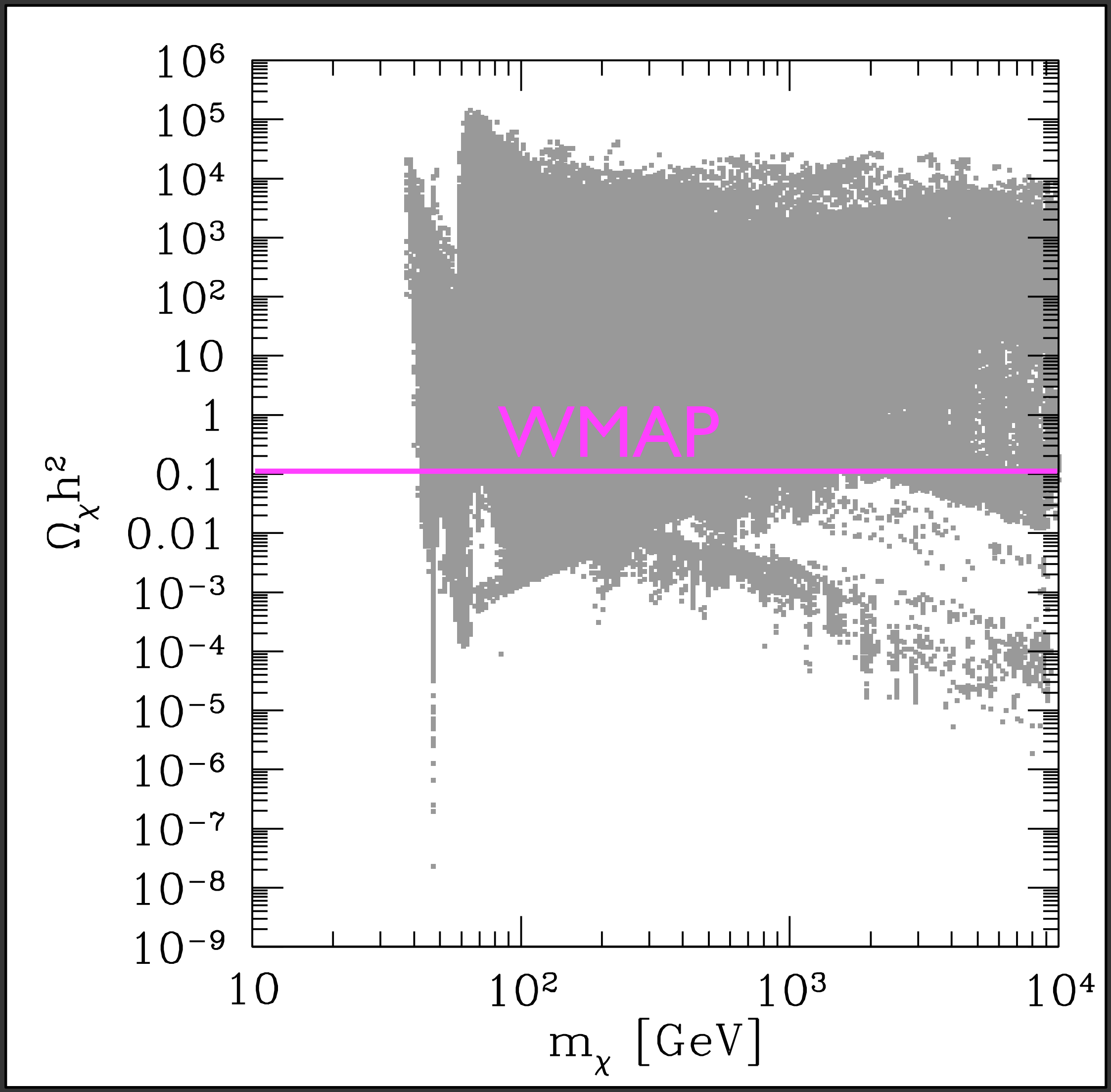
Process	Diagrams s	t	u	p
$\chi_i^0\chi_j^0 \to B_m^0 B_n^0$	$H_{1,2,3}^0, Z$	χ_k^0	χ_l^0	
$\chi_i^0\chi_j^0 \to B_m^- B_n^+$	$H_{1,2,3}^0, Z$	χ_k^+	χ_l^+	
$\chi_i^0\chi_j^0 \to f\bar{f}$	$H_{1,2,3}^0, Z$	$\tilde{f}_{1,2}$	$\tilde{f}_{1,2}$	
$\chi_i^+\chi_j^0 \to B_m^+ B_n^0$	H^+, W^+	χ_k^0	χ_l^+	
$\chi_i^+\chi_j^0 \to f_\mathrm{u}\bar{f}_\mathrm{d}$	H^+, W^+	$\tilde{f}'_{\mathrm{d}_{1,2}}$	$\tilde{f}'_{\mathrm{u}_{1,2}}$	
$\chi_i^+\chi_j^- \to B_m^0 B_n^0$	$H_{1,2,3}^0, Z$	χ_k^+	χ_l^+	
$\chi_i^+\chi_j^- \to B_m^+ B_n^-$	$H_{1,2,3}^0, Z, \gamma$	χ_k^0		
$\chi_i^+\chi_j^- \to f_\mathrm{u}\bar{f}_\mathrm{u}$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}'_{\mathrm{d}_{1,2}}$		
$\chi_i^+\chi_j^- \to \bar{f}_\mathrm{d} f_\mathrm{d}$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}'_{\mathrm{u}_{1,2}}$		
$\chi_i^+\chi_j^+ \to B_m^+ B_n^+$		χ_k^0	χ_l^0	
$\tilde{f}_i\chi_j^0 \to B^0 f$	f	$\tilde{f}_{1,2}$	χ_l^0	
$\tilde{f}_{\mathrm{d}_i}\chi_j^0 \to B^- f_\mathrm{u}$	f_d	$\tilde{f}_{\mathrm{u}_{1,2}}$	χ_l^+	
$\tilde{f}_{\mathrm{u}_i}\chi_j^0 \to B^+ f_\mathrm{d}$	f_u	$\tilde{f}_{\mathrm{d}_{1,2}}$	χ_l^+	
$\tilde{f}_{\mathrm{d}_i}\chi_j^+ \to B^0 f_\mathrm{u}$	f_u	$\tilde{f}_{\mathrm{d}_{1,2}}$	χ_l^+	
$\tilde{f}_{\mathrm{u}_i}\chi_j^+ \to B^+ f_\mathrm{u}$		$\tilde{f}_{\mathrm{d}_{1,2}}$	χ_l^0	
$\tilde{f}_{\mathrm{d}_i}\chi_j^+ \to B^+ f_\mathrm{d}$	f_u		χ_l^0	
$\tilde{f}_{\mathrm{u}_i}\chi_j^- \to B^0 f_\mathrm{d}$	f_d	$\tilde{f}_{\mathrm{u}_{1,2}}$	χ_l^+	
$\tilde{f}_{\mathrm{u}_i}\chi_j^- \to B^- f_\mathrm{u}$	f_d		χ_l^0	
$\tilde{f}_{\mathrm{d}_i}\chi_j^- \to B^- f_\mathrm{d}$		$\tilde{f}_{\mathrm{u}_{1,2}}$	χ_l^0	
$\tilde{f}_{\mathrm{d}_i}\tilde{f}^*_{\mathrm{d}_j} \to B_m^0 B_n^0$	$H_{1,2,3}^0, Z, g$	$\tilde{f}_{\mathrm{d}_{1,2}}$	$\tilde{f}_{\mathrm{d}_{1,2}}$	p
$\tilde{f}_{\mathrm{d}_i}\tilde{f}^*_{\mathrm{d}_j} \to B_m^- B_n^+$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}_{\mathrm{u}_{1,2}}$		p
$\tilde{f}_{\mathrm{d}_i}\tilde{f}'^*_{\mathrm{d}_j} \to f''_\mathrm{d}\bar{f}'''_\mathrm{d}$	$H_{1,2,3}^0, Z, \gamma, g$	$\chi_k^0, \tilde{g}$		
$\tilde{f}_{\mathrm{d}_i}\tilde{f}'^*_{\mathrm{d}_j} \to f''_\mathrm{u}\bar{f}'''_\mathrm{u}$	$H_{1,2,3}^0, Z, \gamma, g$	χ_k^+		
$\tilde{f}_{\mathrm{d}_i}\tilde{f}'_{\mathrm{d}_j} \to f_\mathrm{d} f'_\mathrm{d}$		$\chi_k^0, \tilde{g}$	$\chi_l^0, \tilde{g}$	
$\tilde{f}_{\mathrm{u}_i}\tilde{f}^*_{\mathrm{d}_j} \to B_m^+ B_n^0$	H^+, W^+	$\tilde{f}_{\mathrm{d}_{1,2}}$	$\tilde{f}_{\mathrm{u}_{1,2}}$	p
$\tilde{f}_{\mathrm{u}_i}\tilde{f}'^*_{\mathrm{d}_j} \to f''_\mathrm{u}\bar{f}'''_\mathrm{d}$	H^+, W^+	$\chi_k^0, \tilde{g}$		
$\tilde{f}_{\mathrm{u}_i}\tilde{f}'_{\mathrm{d}_j} \to f''_\mathrm{u} f'''_\mathrm{d}$		$\chi_k^0, \tilde{g}$	χ_l^+	

Cosmic density

Thousands of annihilation (and coannihilation) processes

Use publicly-available computer codes, e.g. DarkSUSY, micrOMEGAs

Neutralino dark matter: minimal supergravity

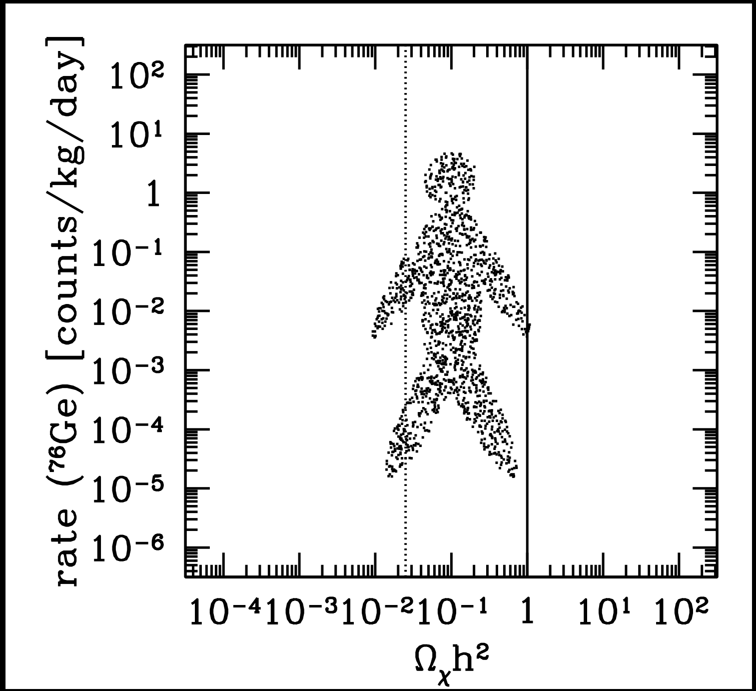


Range of $\Omega_\chi h^2$ for millions of points in minimal supergravity (mSUGRA)

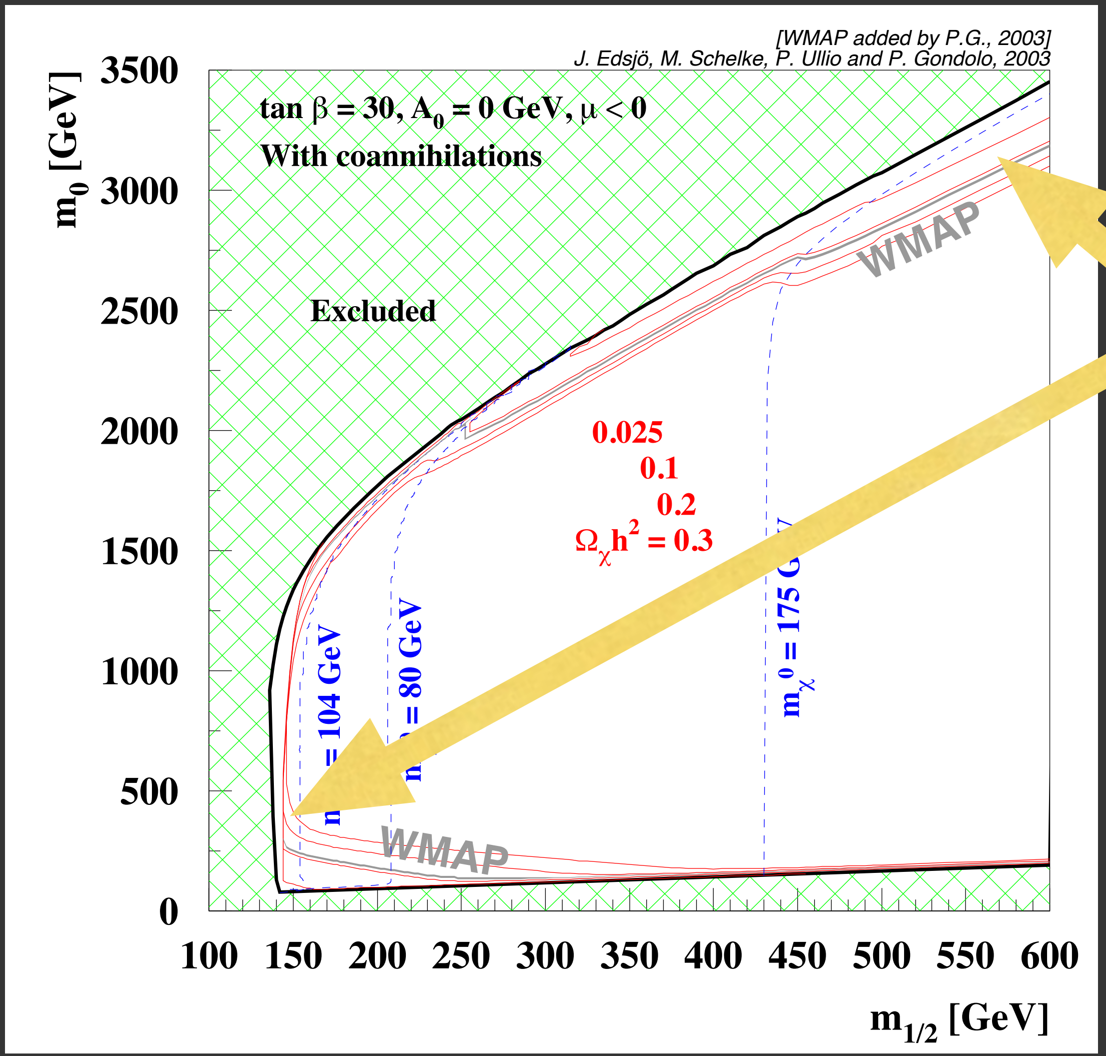
Ted Baltz 2005

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



Neutralino dark matter: minimal supergravity

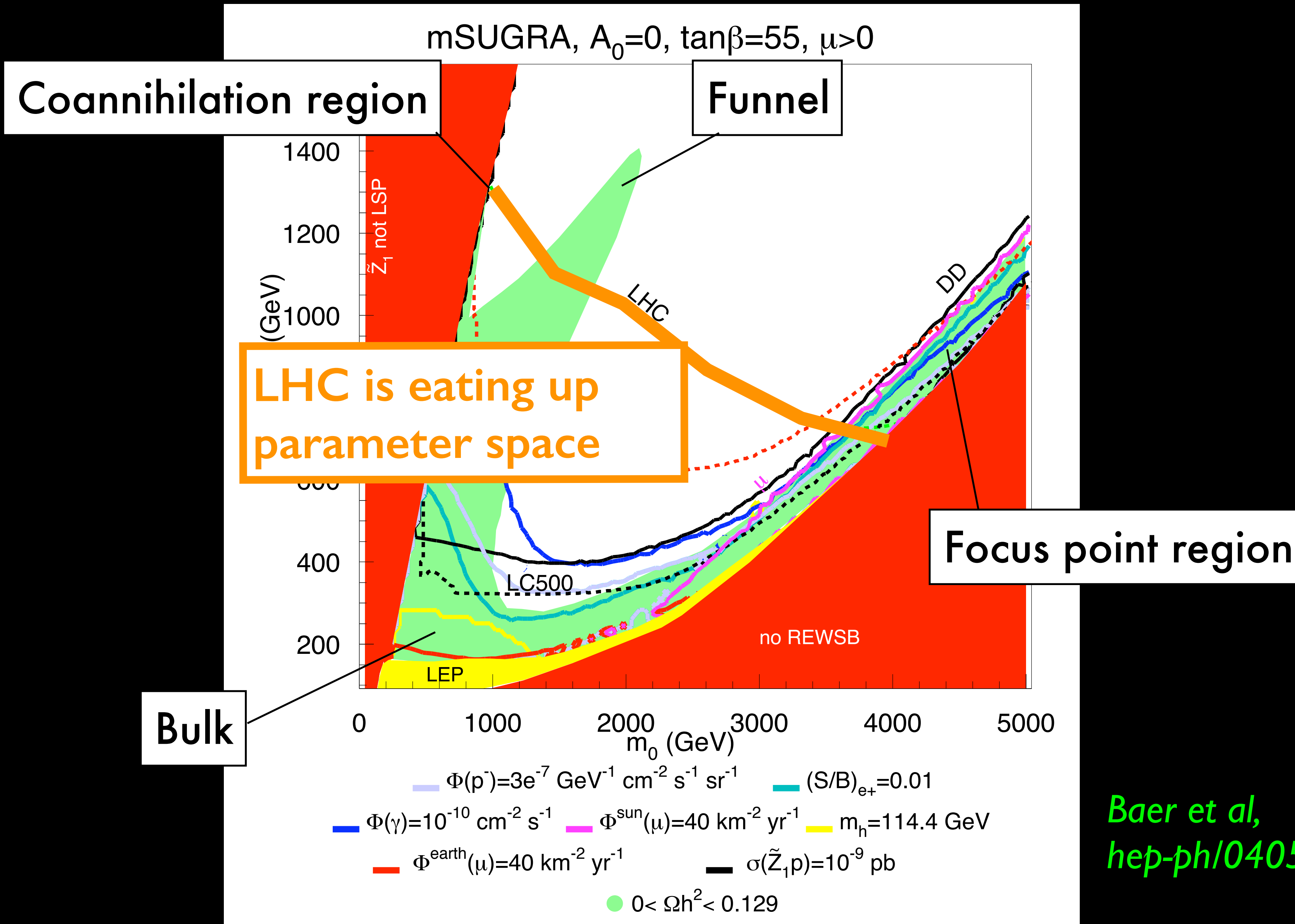


Narrow regions of $\Omega_\chi h^2$ within the WMAP range in minimal supergravity (mSUGRA)

Edsjo et al 2003

Neutralino dark matter: minimal supergravity

Only in special regions the density is not too large.



Baer et al, hep-ph/0405210

Neutralino dark matter: impact of LHC

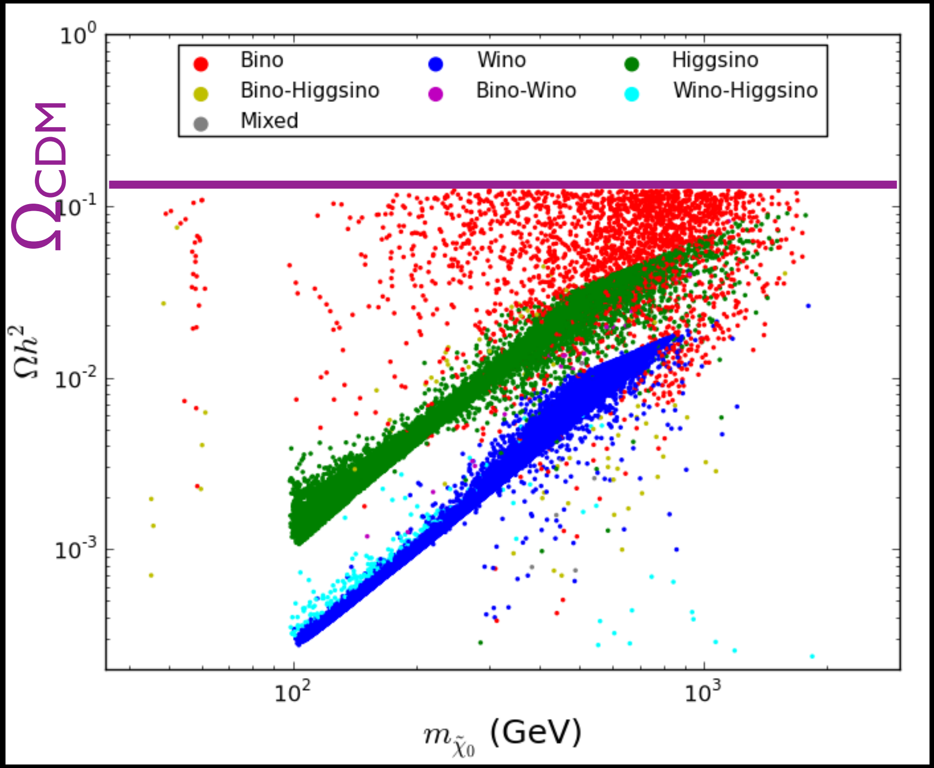
Cahill-Rowell et al 1305.6921

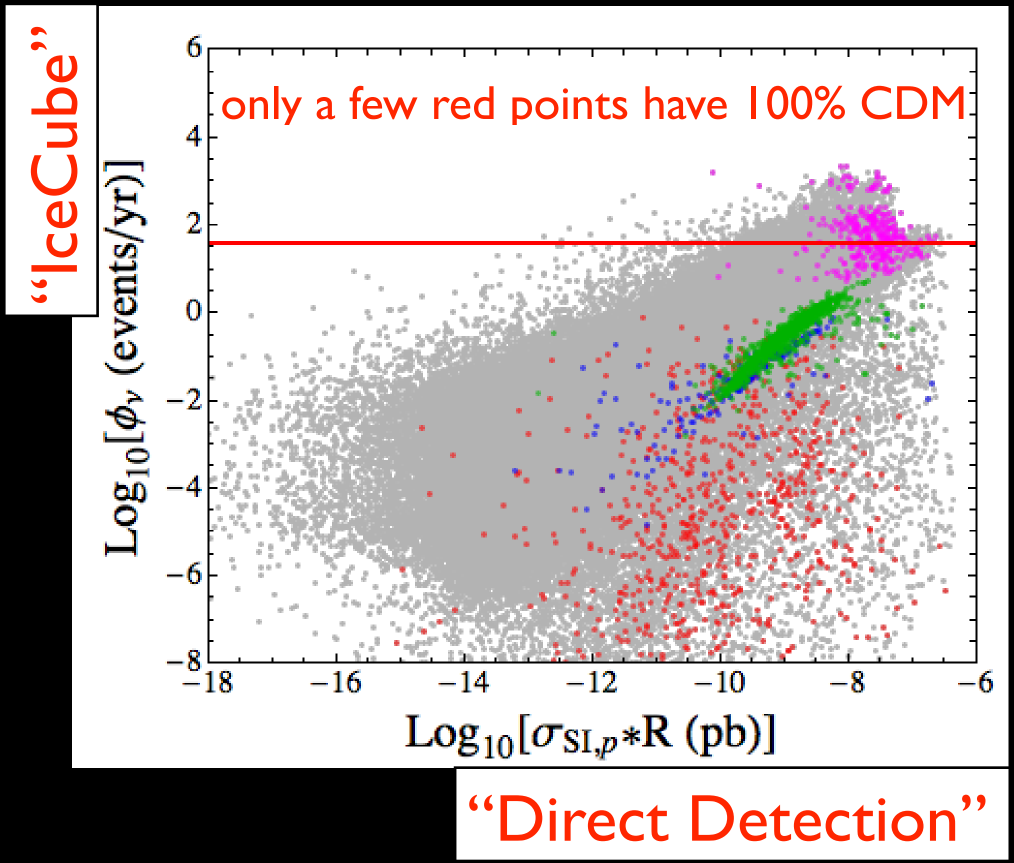
"the only pMSSM models remaining [with neutralino being 100% of CDM] are those with bino coannihilation"

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)

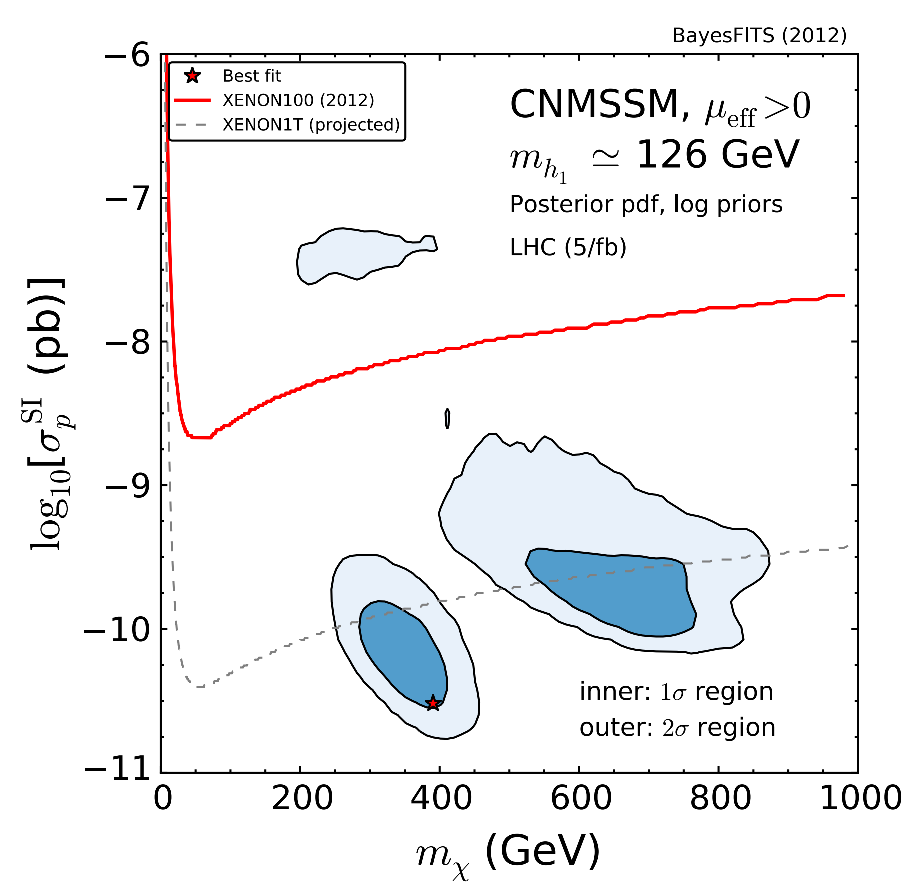




Neutralino dark matter: impact of LHC

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

CNMSSM: Alive and well!



NMSSM (Next-to-MSSM)

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

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

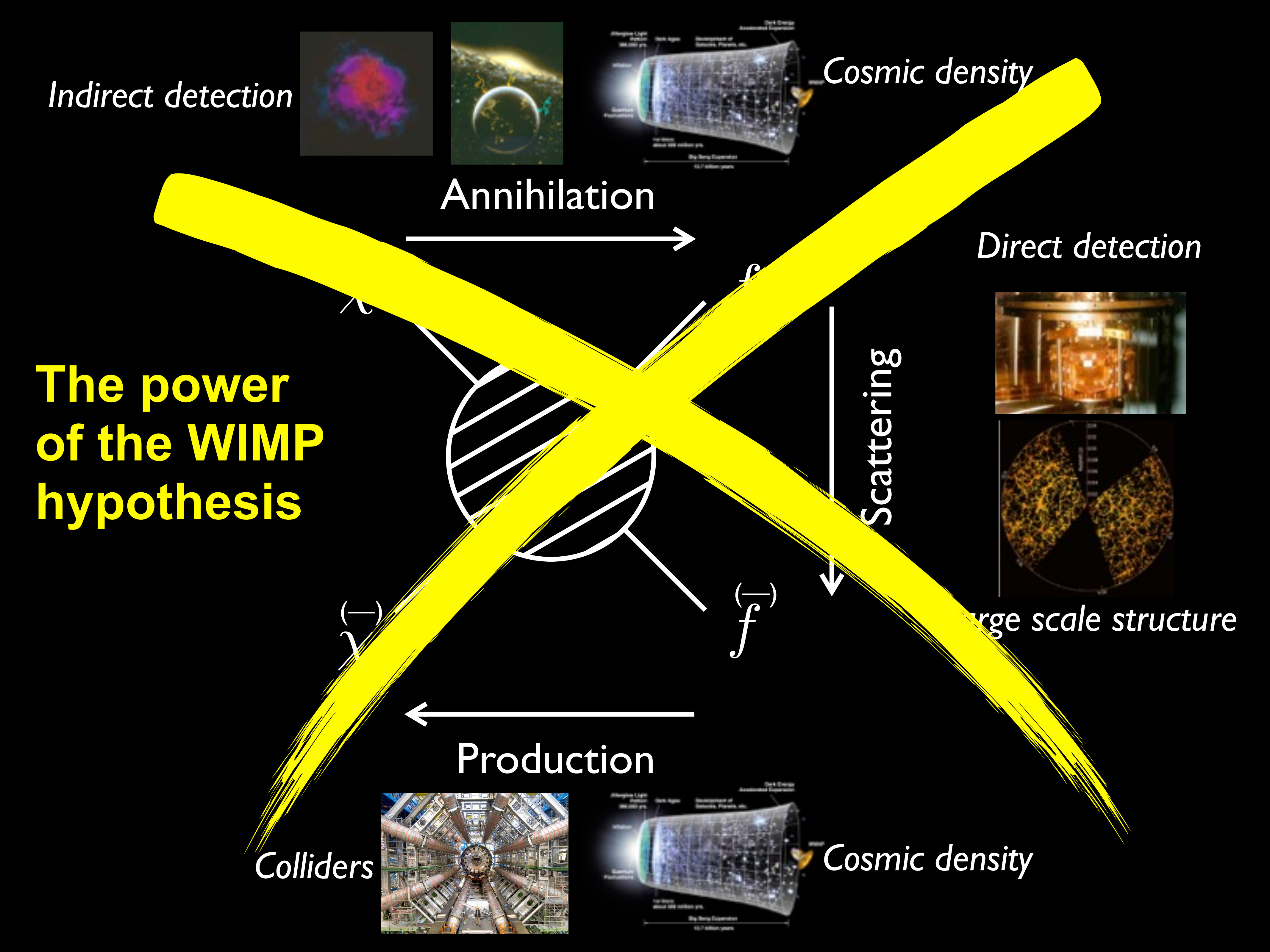
Constrained NMSSM

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

GUT & radiative EWSB

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

Axions


The power of the WIMP hypothesis
Indirect detection
Cosmic density
Annihilation
Direct detection
Scattering
rge scale structure
Production
Colliders
Cosmic density

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} $e$cm, but experimentally $d_n < 1.1 \times 10^{-26}\, e\mathrm{cm}$

The Peccei-Quinn solution

Introduce a new $U(1)_{PQ}$ symmetry and a new field to break it spontaneously. The remaining pseudoscalar Goldstone boson is the axion. It acquires mass through QCD instanton effects.

Axions as solution to the strong CP problem

The strong CP problem

Vacuum potentials $A_\mu = i\Omega\partial_\mu\Omega^{-1}$ with $\Omega \to e^{2\pi i n}$ as $r \to \infty$

Vacuum state $|\theta\rangle = \sum_n e^{-in\theta} |0\rangle$

New term in lagrangian $\mathcal{L}_\theta = \theta \, \frac{g^2}{32\pi^2} F_a^{\mu\nu} \, \tilde{F}_{a\mu\nu}$

$\mathcal{L}_\theta$ violates P and T but conserves C, thus produces a *neutron electric dipole moment* $d_n \approx e(m_q/M_n^2)\theta$

Experimentally $d_n < 1.1 \times 10^{-26} \, e\mathrm{cm}$ so $\theta < 10^{-9}$–10^{-10}

Why θ should be so small is the strong CP problem

Axions as solution to the strong CP problem

The Peccei-Quinn solution

Introducing a $U(1)_{PQ}$ symmetry replaces

axion

$$\theta_{\text{total}} = \theta + \arg\det M_{\text{quark}} \quad \Rightarrow \quad \theta(x) = a(x)/f_a$$

static CP-violating angle *dynamic CP-conserving field*

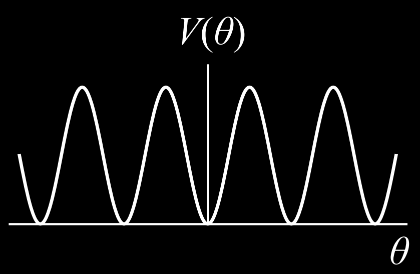
New lagrangian $\mathcal{L}_a = -\frac{1}{2}\partial^\mu a \partial_\mu a + \frac{a}{f_a}\frac{g^2}{32\pi^2} F_a^{\mu\nu}\tilde{F}_{a\mu\nu} + \mathcal{L}_{\text{int}}(a)$

Before QCD phase transition, $\langle\theta\rangle$ can be anything

After QCD phase transition, instanton effects generate

$$V(\theta) = m_a^2 f_a^2 (1 - \cos\theta)$$

and $\langle\theta\rangle = 0$ dynamically



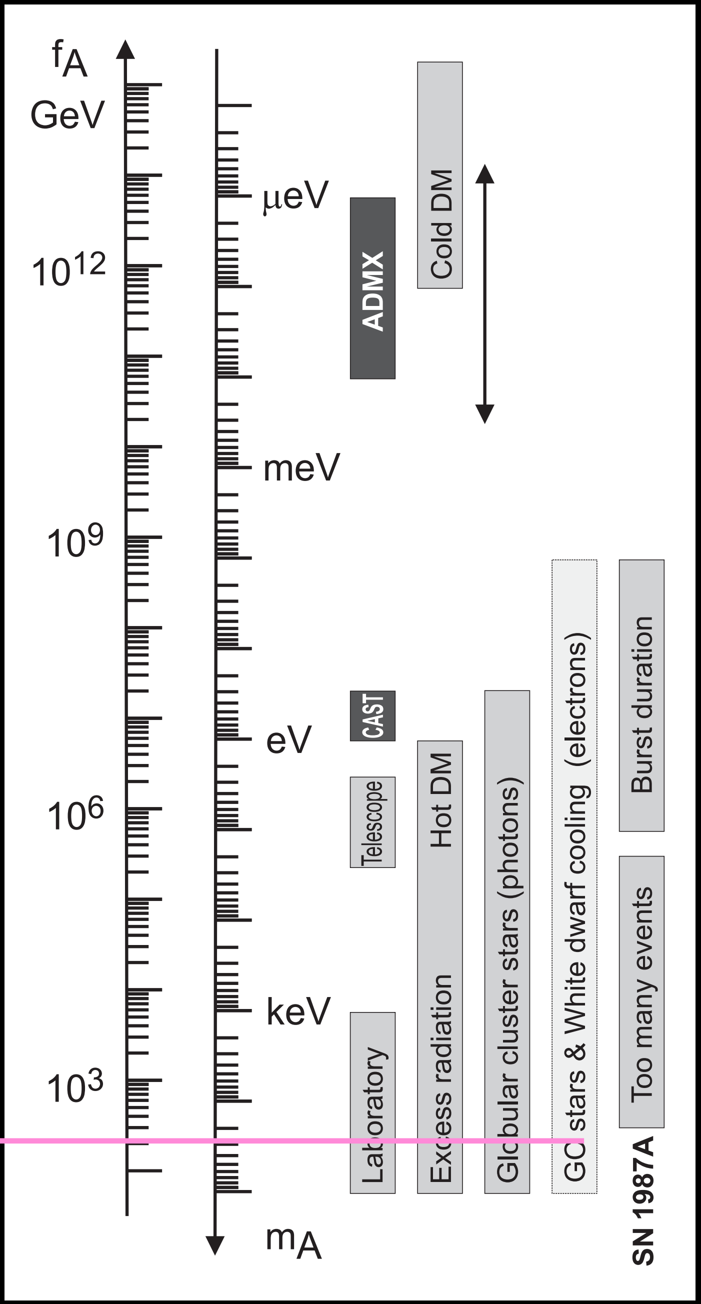
Wilczek realized this leads to a very light pseudoscalar particle he called the "axion" after the name of a famous laundry detergent

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 2 Higgs doublets and $f_a \sim 200\,\mathrm{GeV}$ (electroweak), with an axion-quark coupling too high and quickly excluded by laboratory searches

Raffelt, Rosenberg 2012

Axions as solution to the strong CP problem

Beyond Peccei-Quinn: the invisible axion

Kim (1979)
Shifman, Vainshtein, Zakharov (1980)

1 Higgs doublets, 1 Higgs singlet,
1 exotic quark (*$SU(2)_W$-singlet $SU(3)_C$-triplet*)

$$\mathfrak{L}_y = f\bar{Q}_L\sigma Q_R + f^*\bar{Q}_R\sigma^* Q_L$$

Judicious choice of $U(1)_{PQ}$ charges

$$V(\varphi,\sigma) = -\mu_\varphi^2\varphi^+\varphi - \mu_\sigma^2\sigma^*\sigma + \lambda_\varphi(\varphi^+\varphi)^2 + \lambda_\sigma(\sigma^*\sigma)^2 + \lambda_{\varphi\sigma}\varphi^+\varphi\sigma^*\sigma.$$

Axion not coupled to quarks at tree level

Zhitnistki (1980)
Dine, Fischler, Srednicki (1981)

2 Higgs doublets, 1 Higgs singlet

$$\mathcal{L}_Y = G_u(\bar{u}\bar{d})_L\phi_u u_R + G_d(\bar{u}\bar{d})_L\phi_d d_R + \text{h.c.}$$

Judicious choice of $U(1)_{PQ}$ charges

$$V(\phi,\phi_u,\phi_d) = \lambda_u(|\phi_u|^2 - V_u^2)^2 + \lambda_d(|\phi_d|^2 - V_d^2)^2 + \lambda(|\phi|^2 - V^2)^2 + (a|\phi_u|^2 + b|\phi_d|^2)|\phi|^2 + c(\phi_u^i\epsilon_{ij}\phi_d^j\phi^2 + \text{h.c.}) + d|\phi_u^i\epsilon_{ij}\phi_d^j|^2 + e|\phi_u^*\phi_d|^2 . \quad (5)$$

Axion-quark couplings suppressed by $200\ \text{GeV}/\langle\phi\rangle \ll 1$

Axions as solution to the strong CP problem

Beyond Peccei-Quinn: the invisible axion

Model-dependent axion-photon coupling

$$L_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}(C - C')a\mathbf{E}\cdot\mathbf{B}$$

$$C' = \frac{2}{3}\frac{m_u m_d + 4 m_d m_s + m_s m_u}{m_u m_d + m_d m_s + m_s m_u} = 1.93 \pm 0.04$$

$$C_{\mathrm{DFSZ}} = \frac{8}{3}$$

$$C_{\mathrm{KSVZ}} = 6Q^2$$

Model-dependent axion-fermion coupling

$$\mathcal{L}_{Aff} = \frac{C_f}{2f_A}\,\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f\partial_\mu\phi$$

$$C_e^{\mathrm{DFSZ}} = \frac{\cos^2\beta}{3}$$

$$C_e^{\mathrm{KSVZ}} \ll 1$$

See e.g. Srednicki hep-th/0210172, Review of Particle Properties

Axions as dark matter

Hot

Produced thermally in early universe

Important for $m_a > 0.1eV$ ($f_a < 10^8$), 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

f_a	Peccei-Quinn symmetry breaking scale
N	Peccei-Quinn color anomaly
N_d	Number of degenerate QCD vacua
Kim-Shifman-Vainshtein-Zakharov Dine-Fischler-Srednicki-Zhitnistki	Couplings to quarks, leptons, and photons
H_I	Expansion rate at end of inflation
θ_i	Initial misalignment angle
Harari-Hagmann-Chang-Sikivie Davis-Battye-Shellard	Axionic string parameters

Assume $N = N_d = 1$ *and show results for KSVZ and HHCS string network*

Thus 3 free parameters f_a, θ_i, H_I *and one constraint* $\Omega_a = \Omega_\mathrm{CDM}$

Cold axion production in cosmology

Vacuum realignment

- Initial misalignment angle θ_i
- Coherent axion oscillations start at temperature T_1

$$3H(T_1)=m(T_1)$$

Hubble expansion parameter
non-standard expansion histories differ in the function $H(T)$

T-dependent axion mass
axions acquire mass through instanton effects at $T < \Lambda \approx \Lambda_{\rm QCD}$

- Density at T_1 is $n_a(T_1) = \frac{1}{2} m_a(T_1) f_a^2 \chi \langle \theta_i^2 f(\theta_i) \rangle$

Anharmonicity correction $f(\theta)$
axion field equation has anharmonic terms $\ddot{\theta} + 3H(T)\dot{\theta} + m_a^2(T)\sin\theta = 0$

- Conservation of comoving axion number gives present density Ω_a

Cold axion production in cosmology

Axionic string decays

- Energy density ratio (string decay/misalignment)

(String stretching rate)$^{-2}$

Density enhancement from string decays

$$\alpha \equiv \frac{\rho_a^{\rm str}}{\rho_a^{\rm mis}} = \frac{\xi \bar{r} N_d^2}{\zeta}$$

Uncertainty in axion spectrum

Slow-oscillating strings (Davis-Battye-Shellard) $\bar{r} = \frac{1-\beta}{3\beta-1}\ \ln(t_1/\delta)$

Fast-oscillating strings (Harari-Hagmann-Chang-Sikivie) $\bar{r} = \frac{1-\beta}{3\beta-1}\ 0.8$

$$\xi = \frac{1}{4c^2}\left(2 - 3\beta + \sqrt{(4c+0)\beta^2 - 12\beta + 4}\right)^2$$

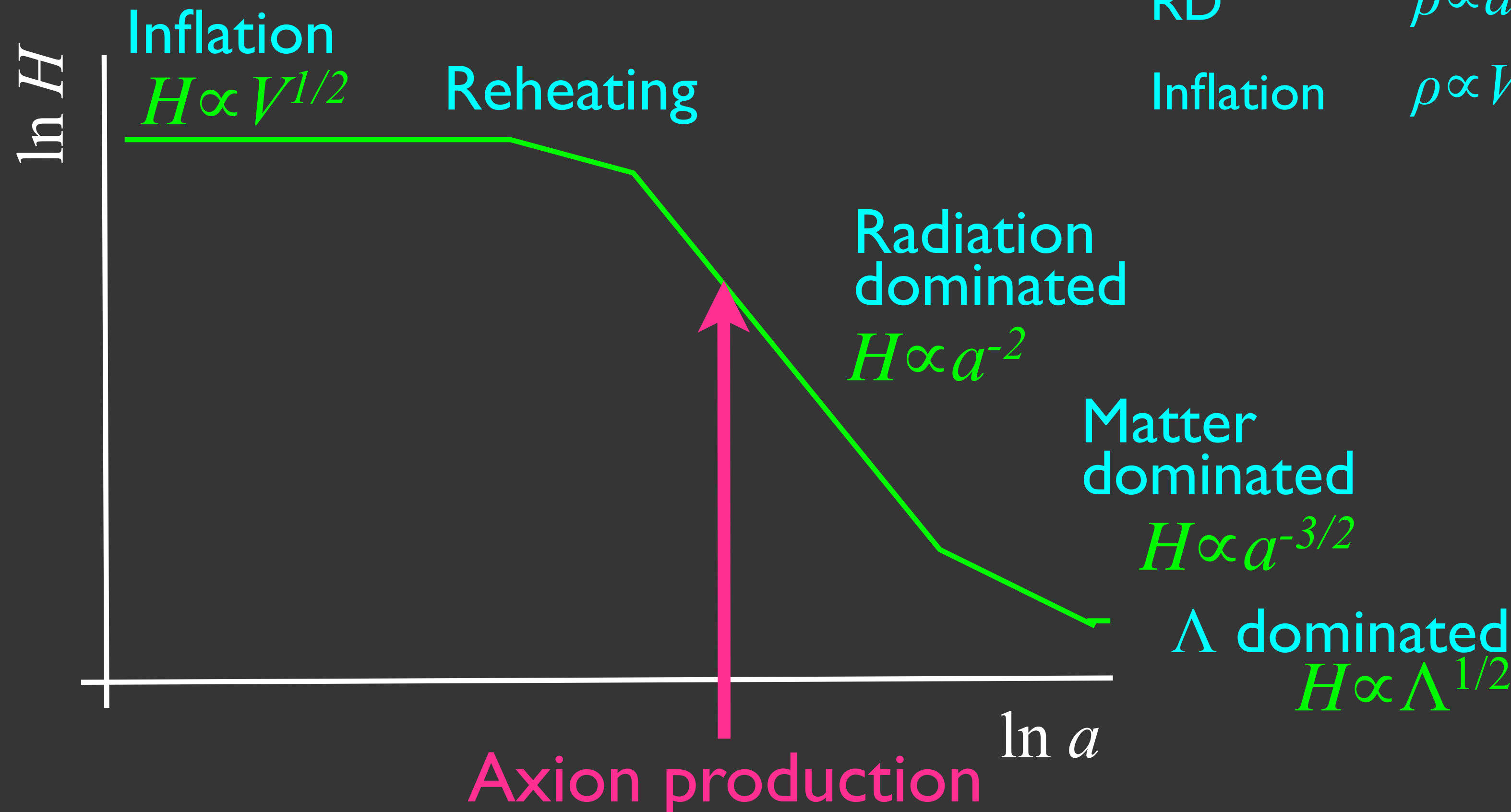
with $a(t) \propto t^{\beta}$

$$c = (1 + 2\sqrt{\xi^{\rm std}})/(4\xi^{\rm std})$$

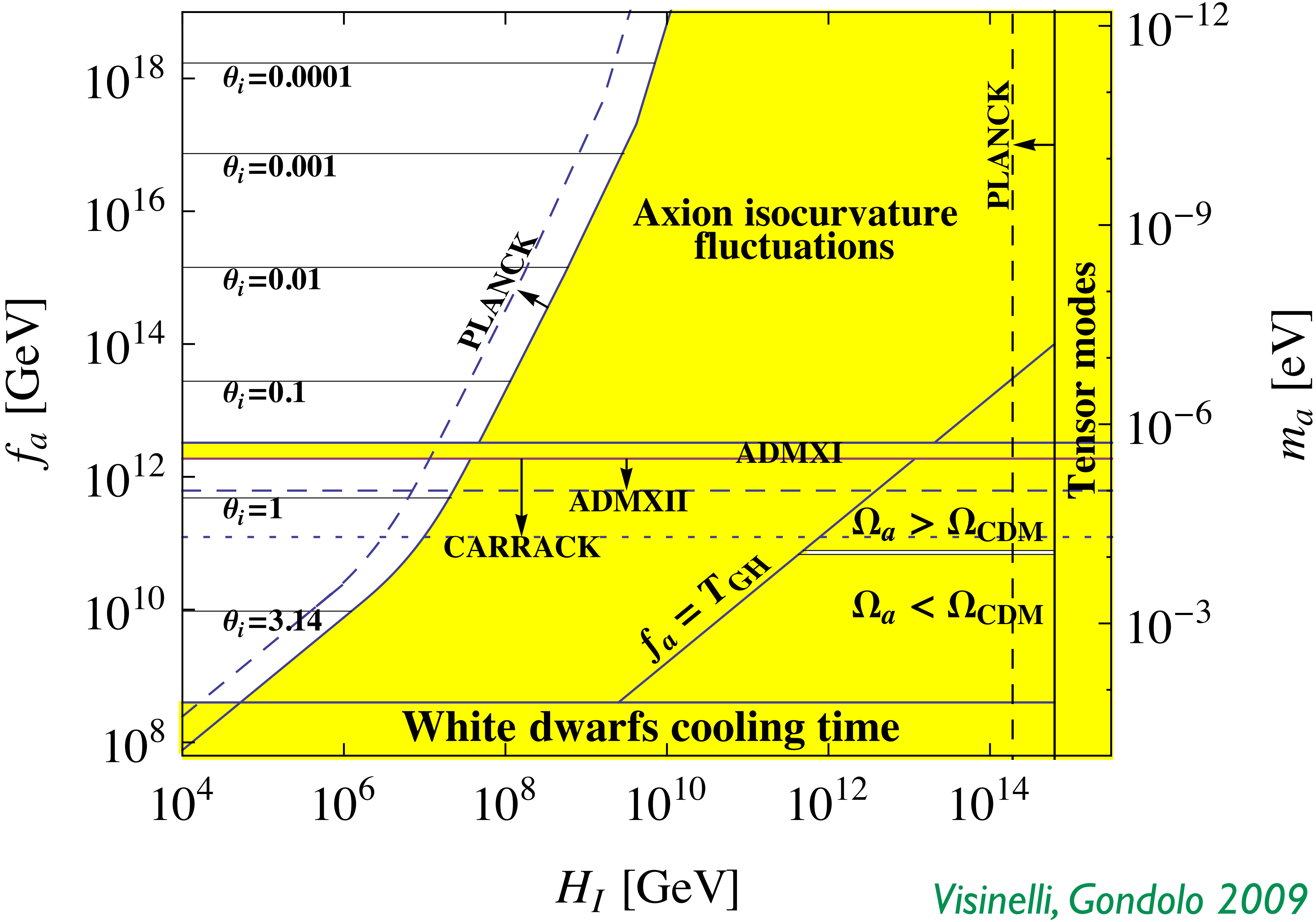
Standard cosmology

$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\rho$$

ΛD	$\rho \propto \Lambda$
MD	$\rho \propto a^{-3}$
RD	$\rho \propto a^{-4}$
Inflation	$\rho \propto V(\phi)$

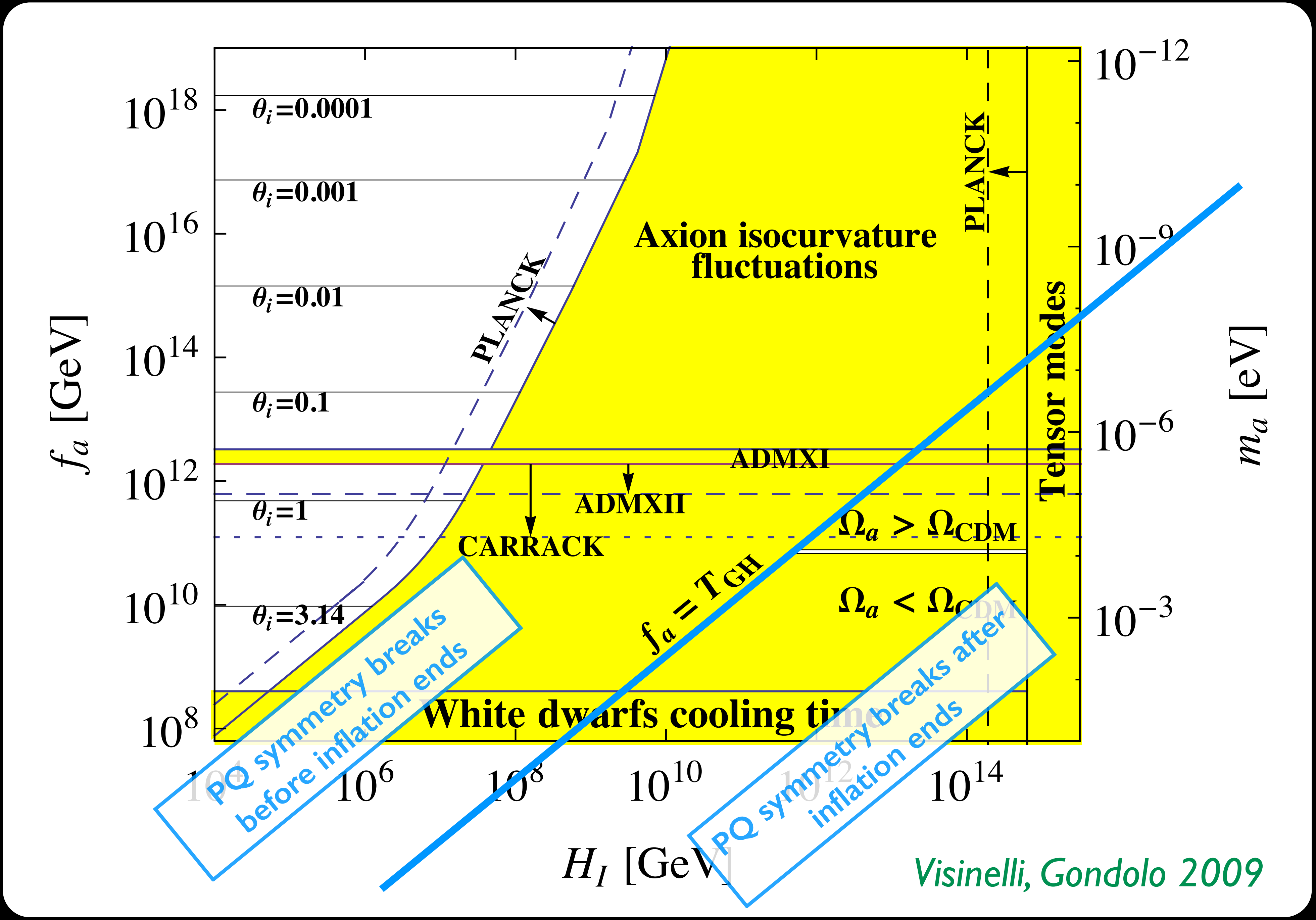


Axion CDM - Standard cosmology



Visinelli, Gondolo 2009

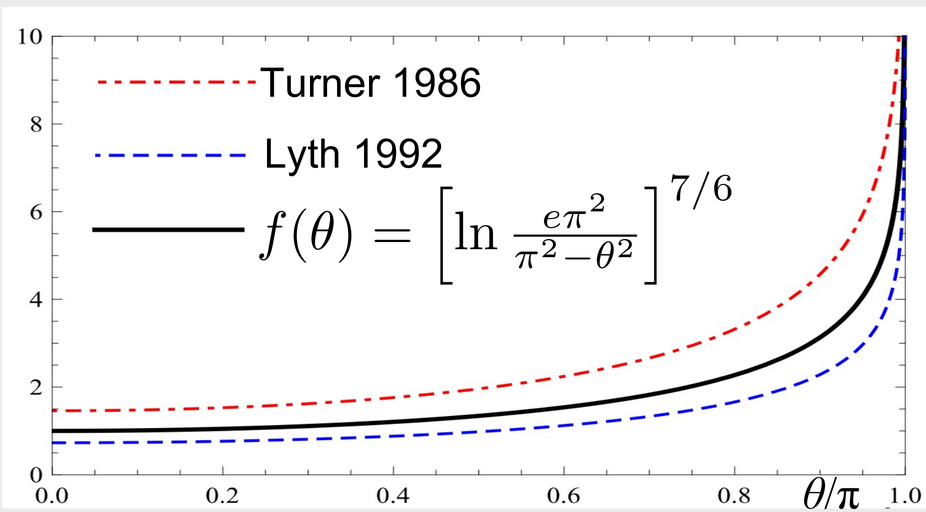
Axion CDM - Standard cosmology



Axion CDM - Standard cosmology

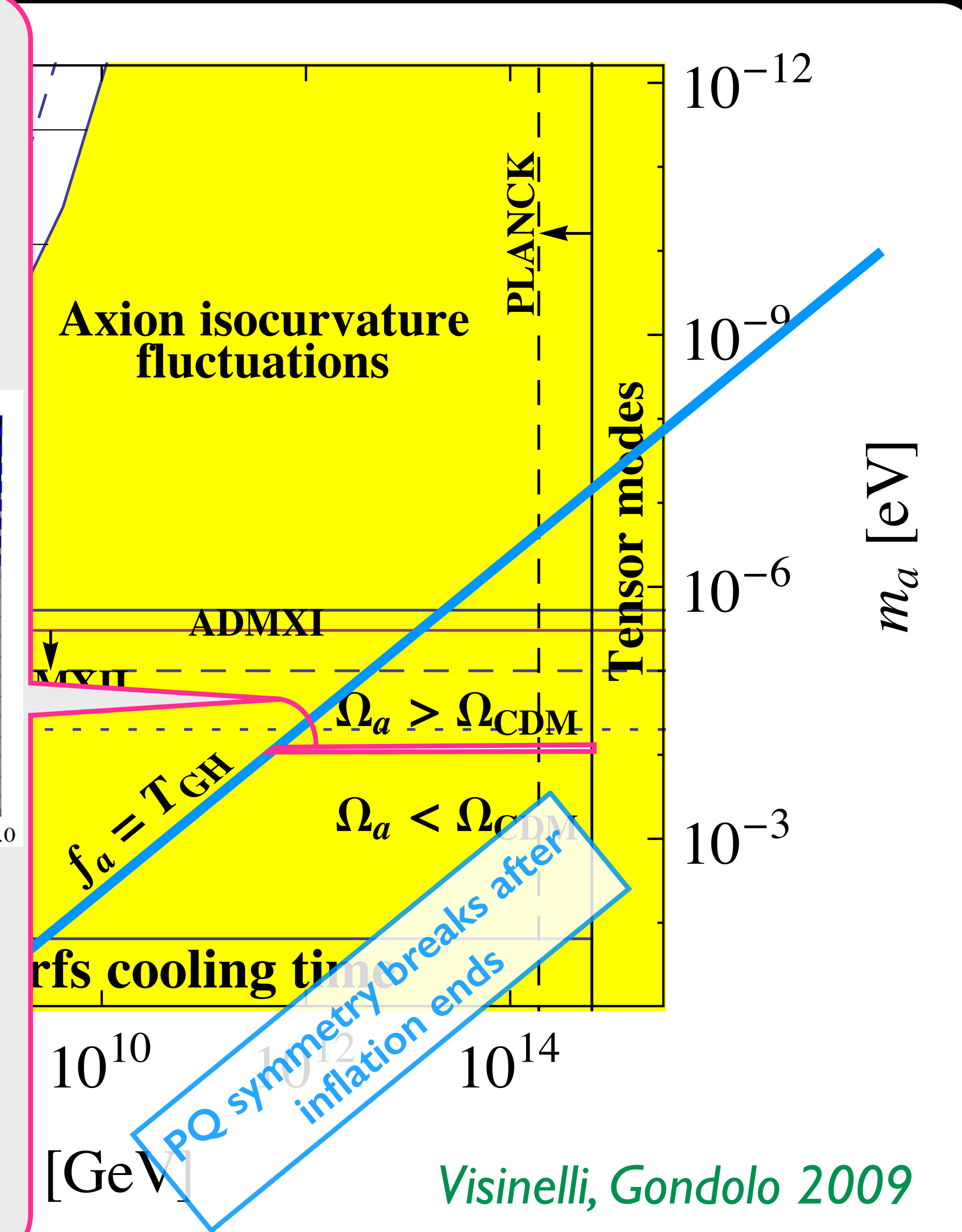
PQ symmetry breaks after inflation ends

- Average θ_i over Hubble volume
- Anharmonicities are important



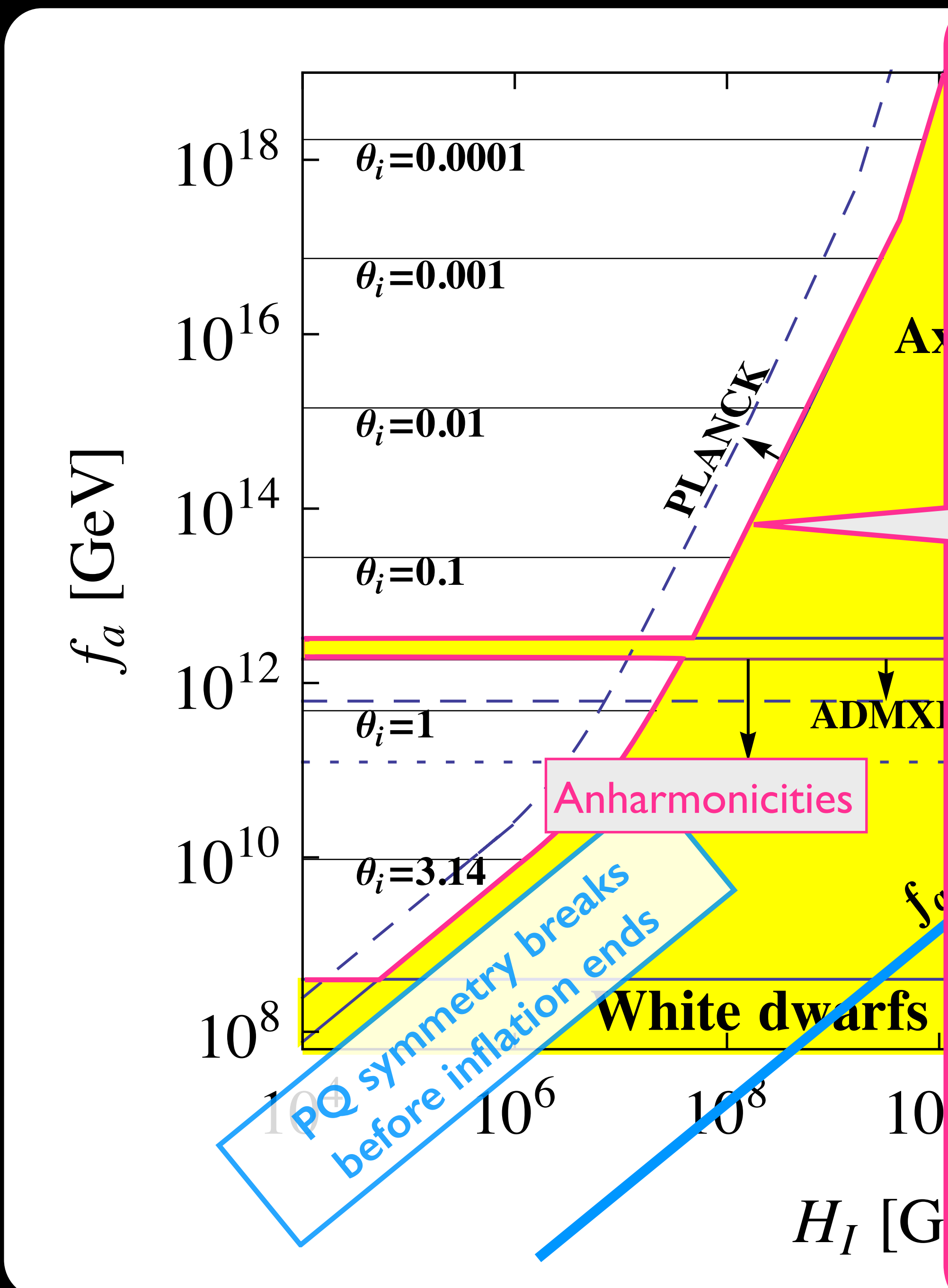
$$\langle \theta_i^2 f(\theta_i) \rangle = (2.96)^2$$

- String decay contribution is ~16% of vacuum realignment



Visinelli, Gondolo 2009

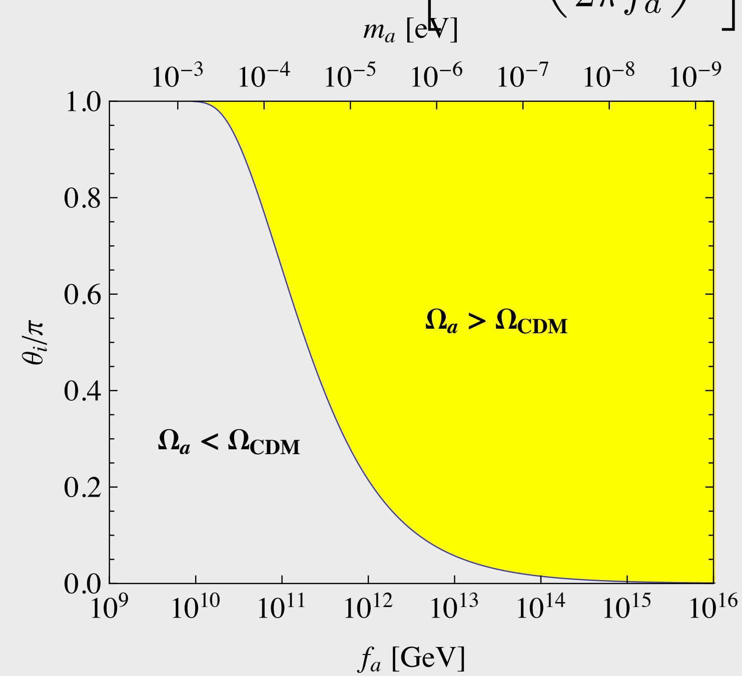
Axion CDM - Standard cosmology



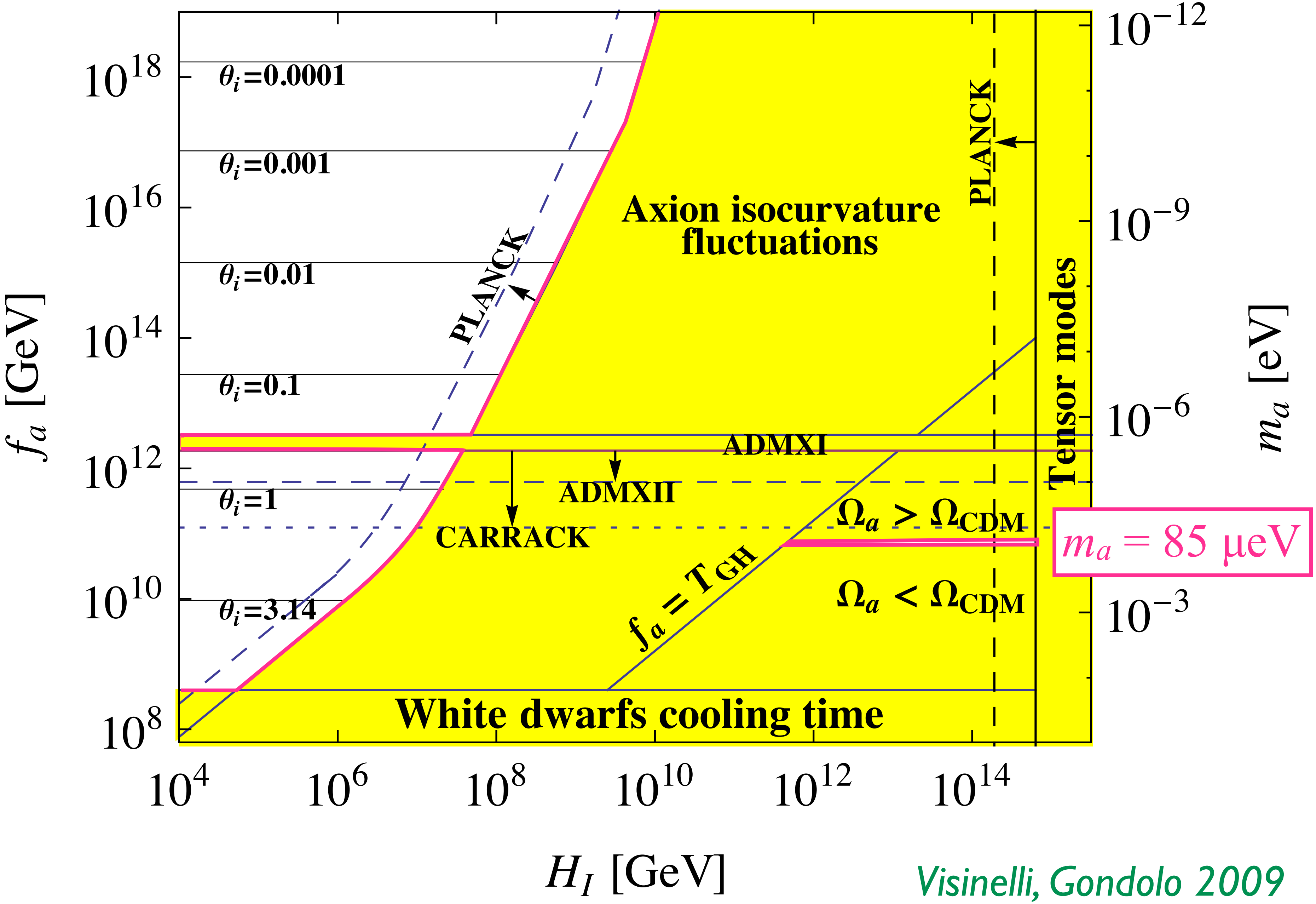
PQ symmetry breaks before inflation ends

- Constrained by non-adiabatic fluctuations $\frac{H_I}{\theta_i f_a} < 4.2 \times 10^{-5}$ *WMAP7 96%CL*
- Single value of θ_i throughout Hubble volume

$$\langle \theta_i^2 f(\theta_i) \rangle = \left[\theta_i^2 + \left(\frac{H_I}{2\pi f_a} \right)^2 \right] f(\theta_i)$$



Axion CDM - Standard cosmology



Visinelli, Gondolo 2009

Sterile neutrinos

Active-sterile neutrino mixing

Standard model + right-handed neutrinos

$$-\mathcal{L}_m = y_\nu v \overline{\nu}_L \nu_R + \frac{1}{2} M \, \overline{\nu_R^c} \nu_R + \text{h.c.} = \frac{1}{2} \begin{bmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{bmatrix} \begin{bmatrix} 0 & y_\nu v \\ y_\nu v & M \end{bmatrix} \begin{bmatrix} \overline{\nu_L} \\ \overline{\nu_R^c} \end{bmatrix} + \text{h.c.}$$

Neutrino mass eigenstates are obtained by diagonalization

$$-\mathcal{L}_m = \frac{1}{2} m_a \overline{\nu}_a \nu_a + \frac{1}{2} m_s \overline{\nu}_s \nu_s$$

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

mixing angle θ

Active-sterile neutrino mixing

If $y_\nu v \ll M$, then $m_s \simeq M, \quad m_a \simeq \frac{y_\nu^2 v^2}{M} \ll M, \quad \theta \simeq \frac{y_\nu v}{M} \ll 1$

seesaw mechanism

ν_a are ≈LH, light, with tree-level couplings (active neutrinos)
ν_s are ≈RH, heavy, with no tree-level coupling (sterile neutrinos)

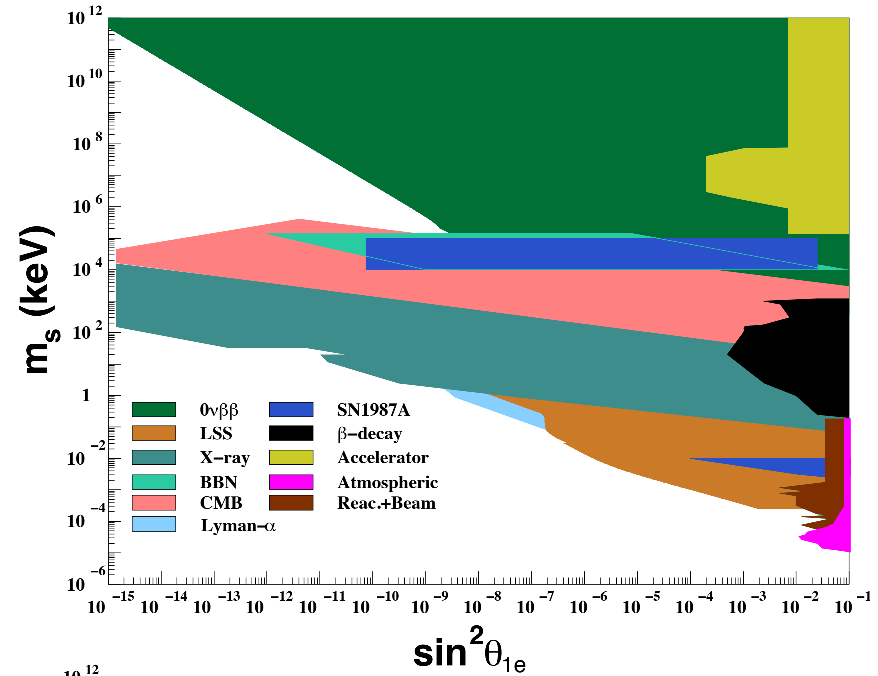
Neutrinos produced in weak interactions are left-handed, while mass eigenstates contain a (tiny) right-handed component

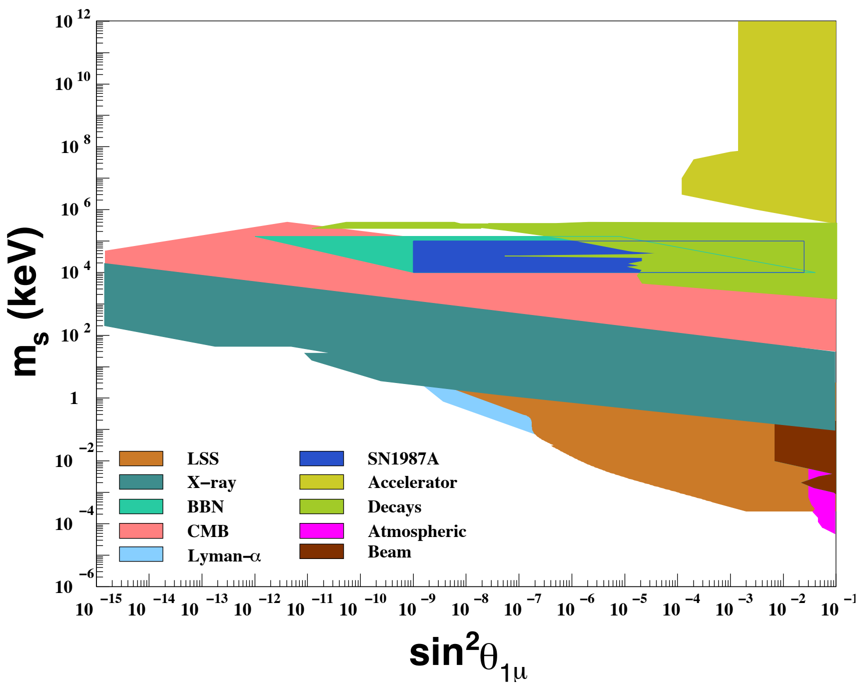
Oscillations between active and sterile neutrinos

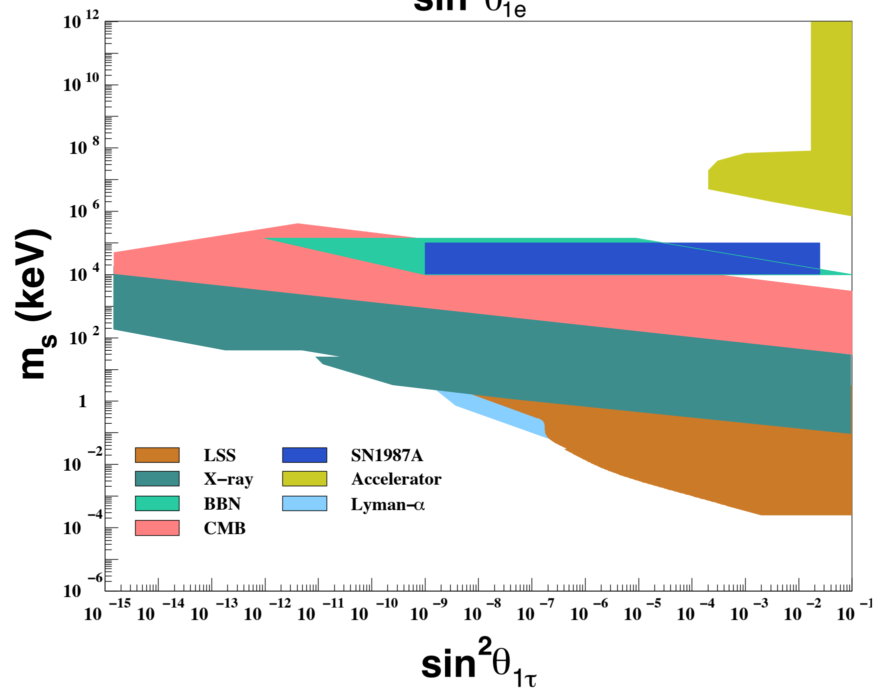
Neutrino mixing

Limits on sterile neutrino mixing with ν_e, ν_μ, ν_τ

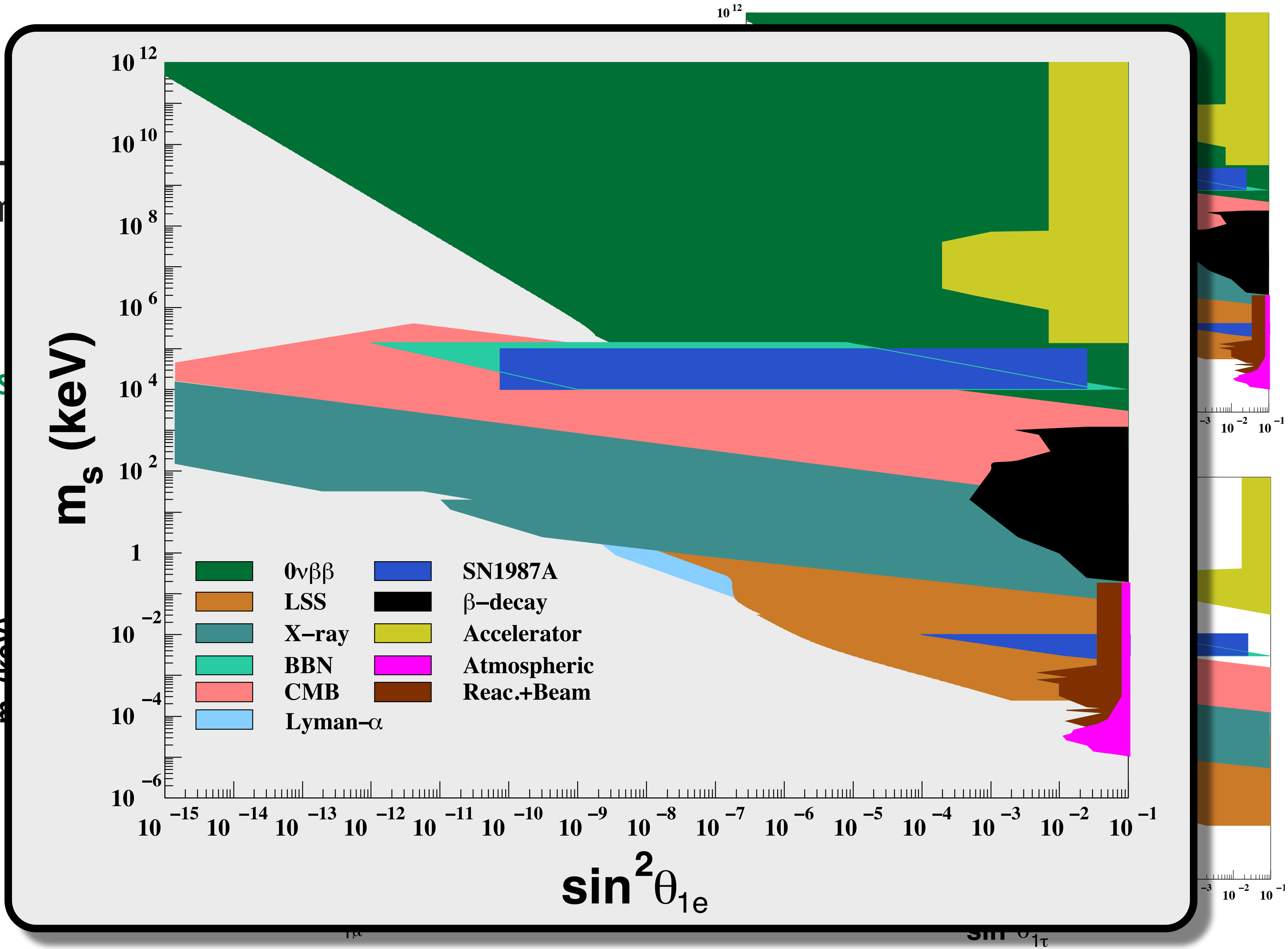
Kusenko 0906.2968





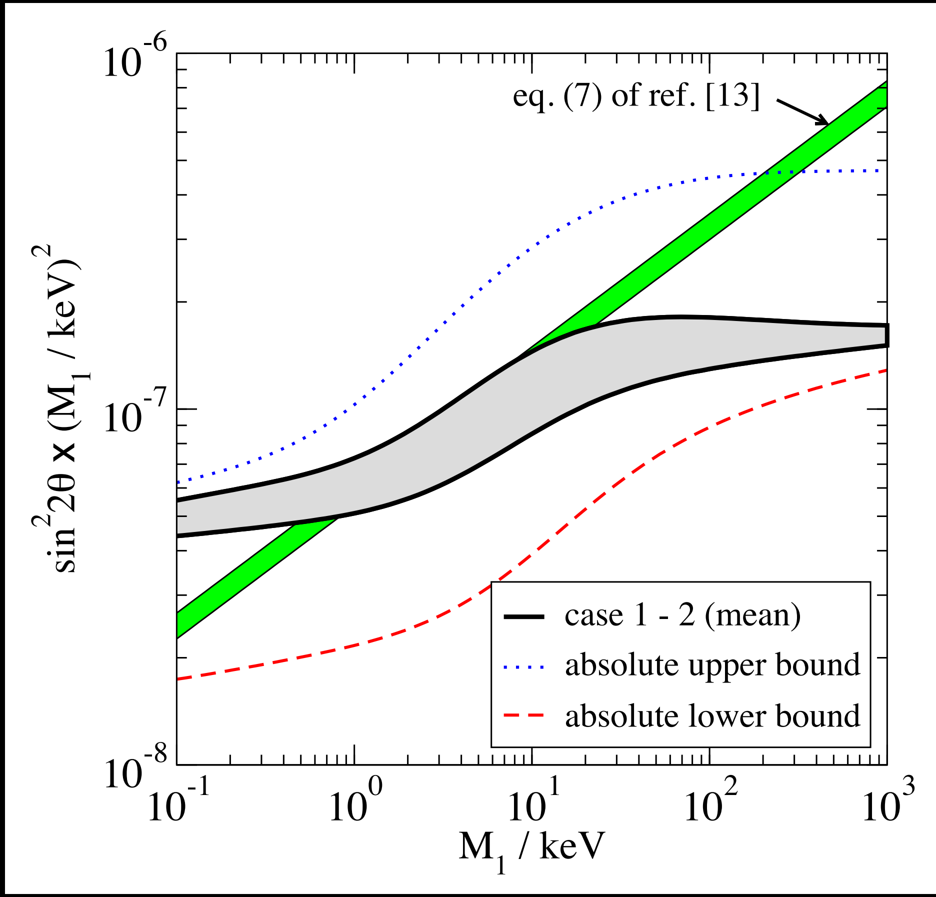


Neutrino mixing



Sterile neutrino dark matter

- Mass > 0.3 keV (Tremaine-Gunn bound)
- Sterile neutrinos are produced from oscillations of active neutrinos in the early universe (*T*~100 MeV) *Dodelson, Widrow 1994*
- In the presence of a large lepton asymmetry, oscillation production is enhanced *Shi, Fuller 1999*
- In a model with three generations of sterile neutrinos (νMSM), decay of the two heavy neutrinos can generate a lepton asymmetry then converted to baryon asymmetry, and the light sterile neutrino can be the dark matter
  Laine, Shaposhnikov 2008



Asaka, Laine, Shaposhnikov 2007

Limits on sterile neutrino dark matter

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

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

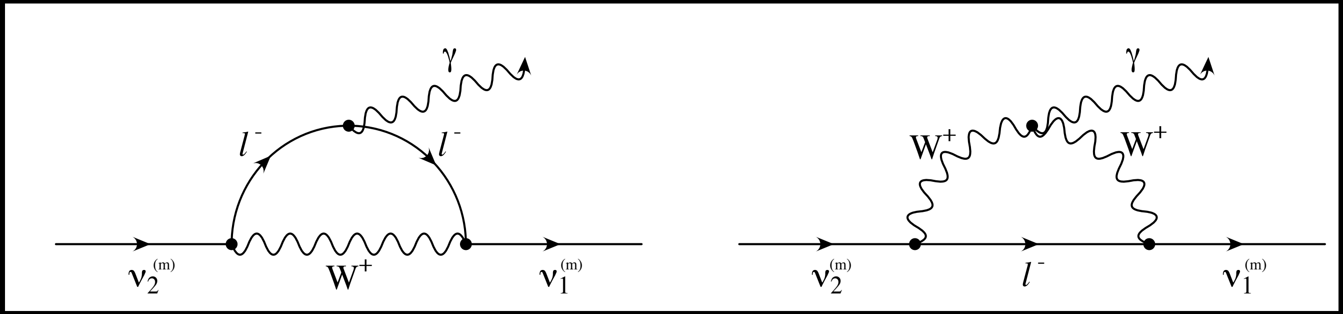


Figure from Kusenko 0906.2968

X-ray line

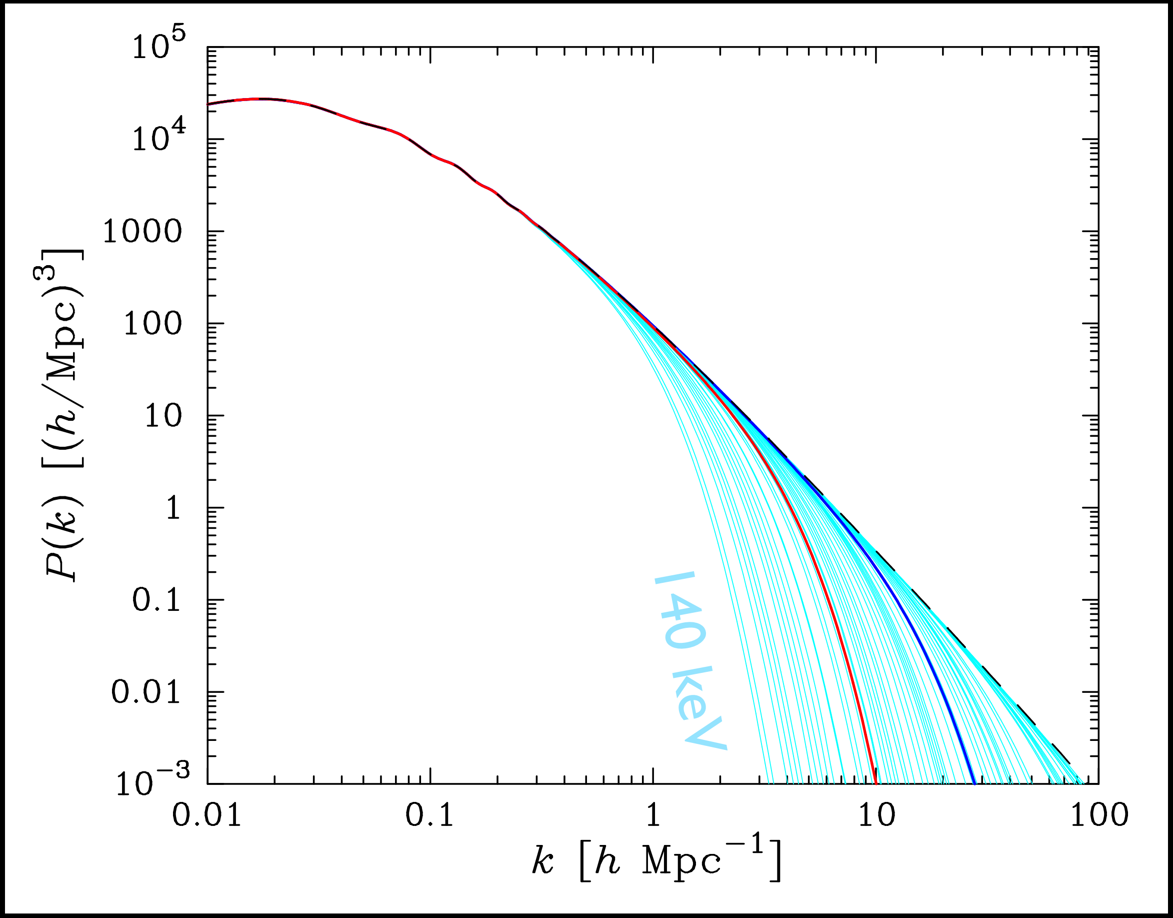
$$E_\gamma = \frac{1}{2} m_s$$

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

Limits on sterile neutrino dark matter

Sterile neutrinos are warm dark matter

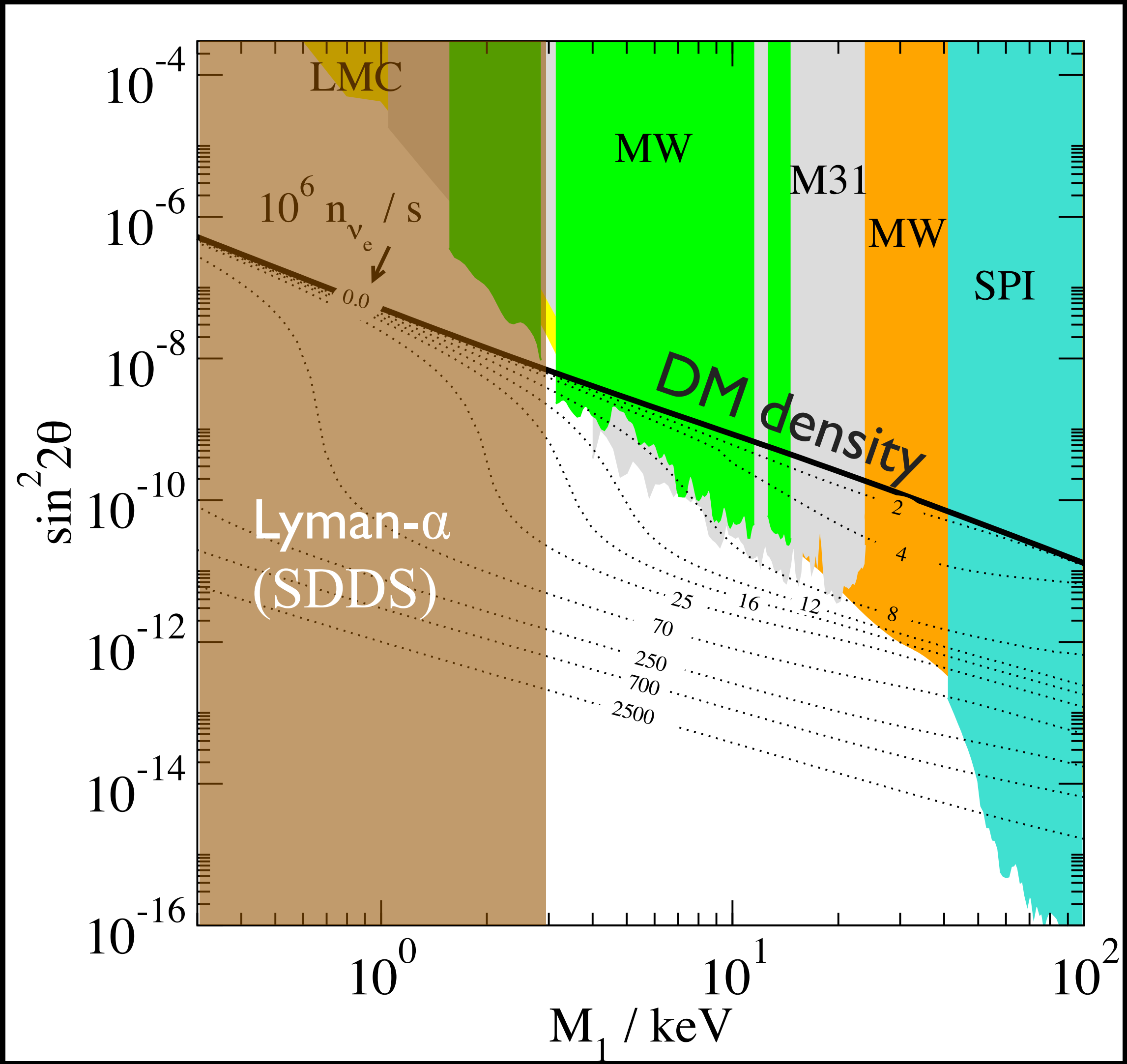
Small scale structure is erased



Abazajian 2005

Limits on sterile neutrino dark matter

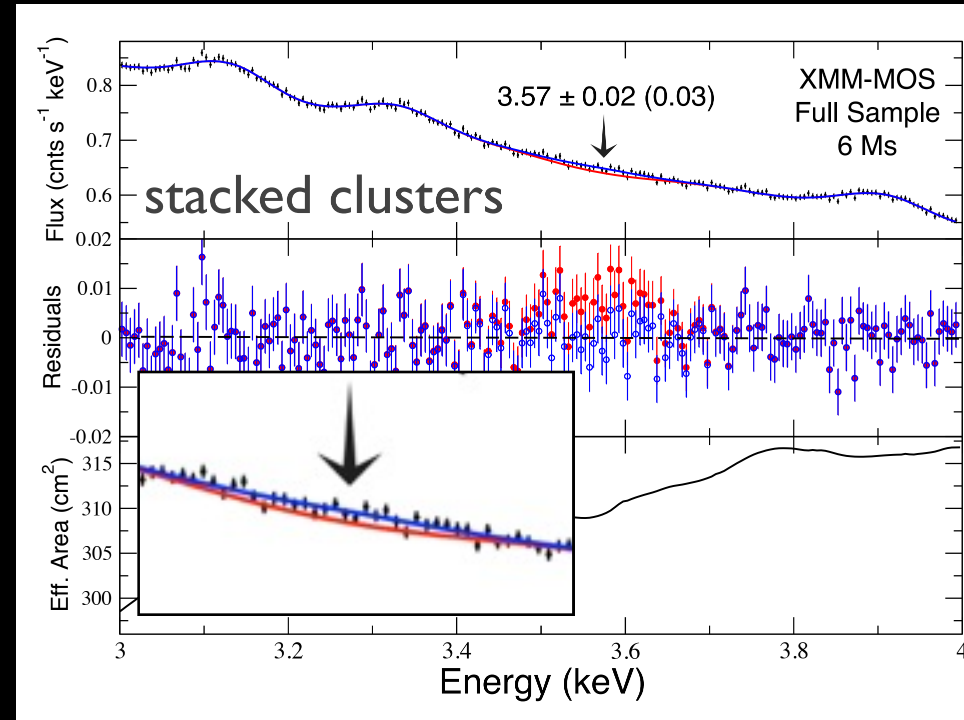
νMSM



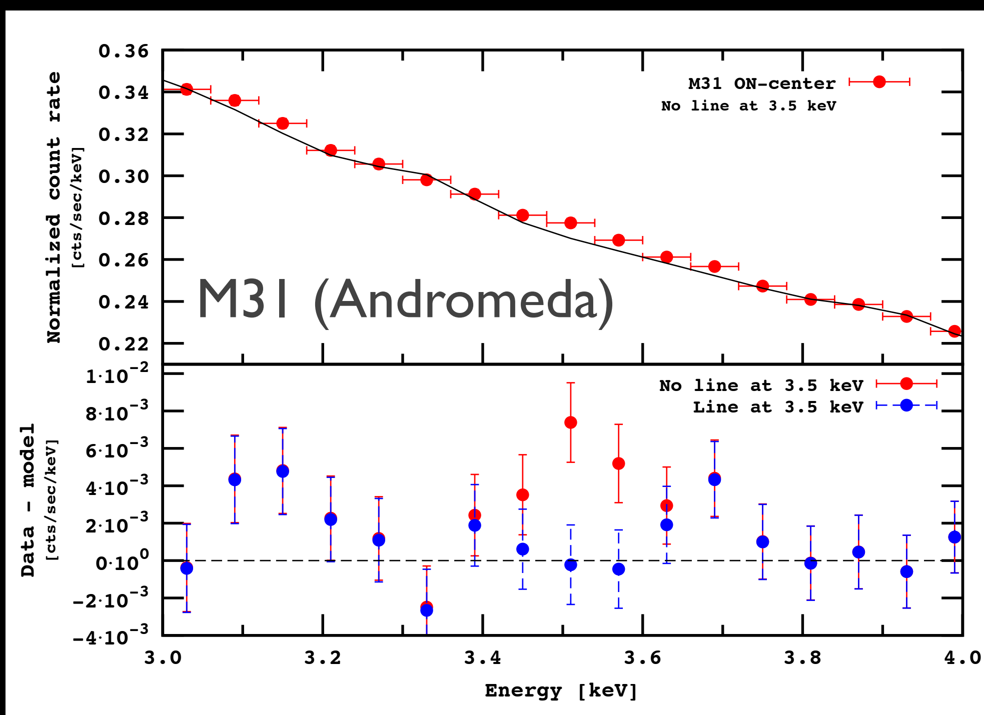
Laine, Shaposhnikov 2008

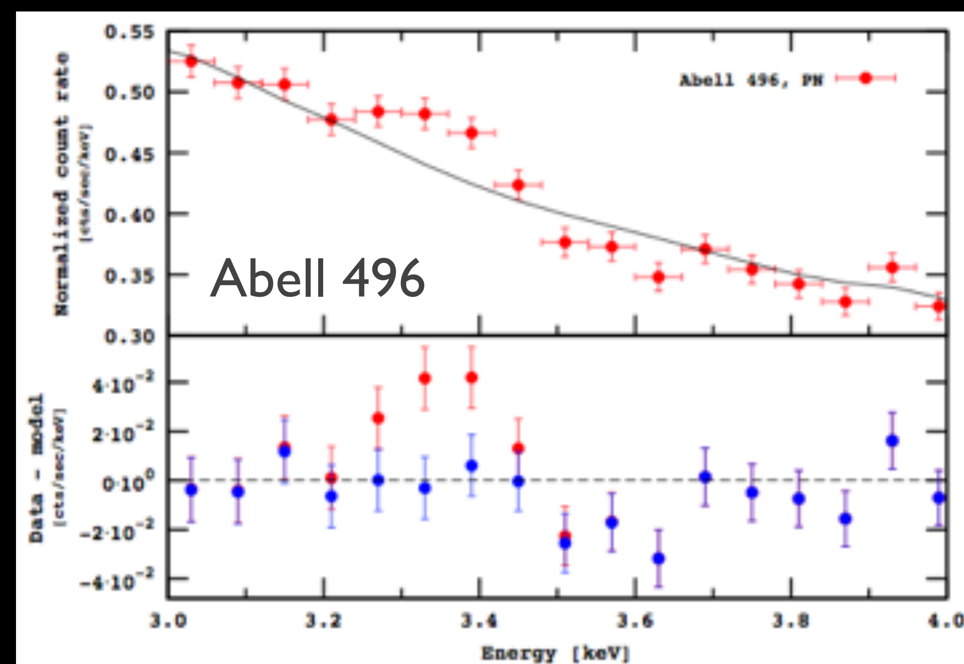
X-rays from dark matter?

Bulbul et al 2014



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





Boyarsky et al 2014

Iakubovskyi et al 2015

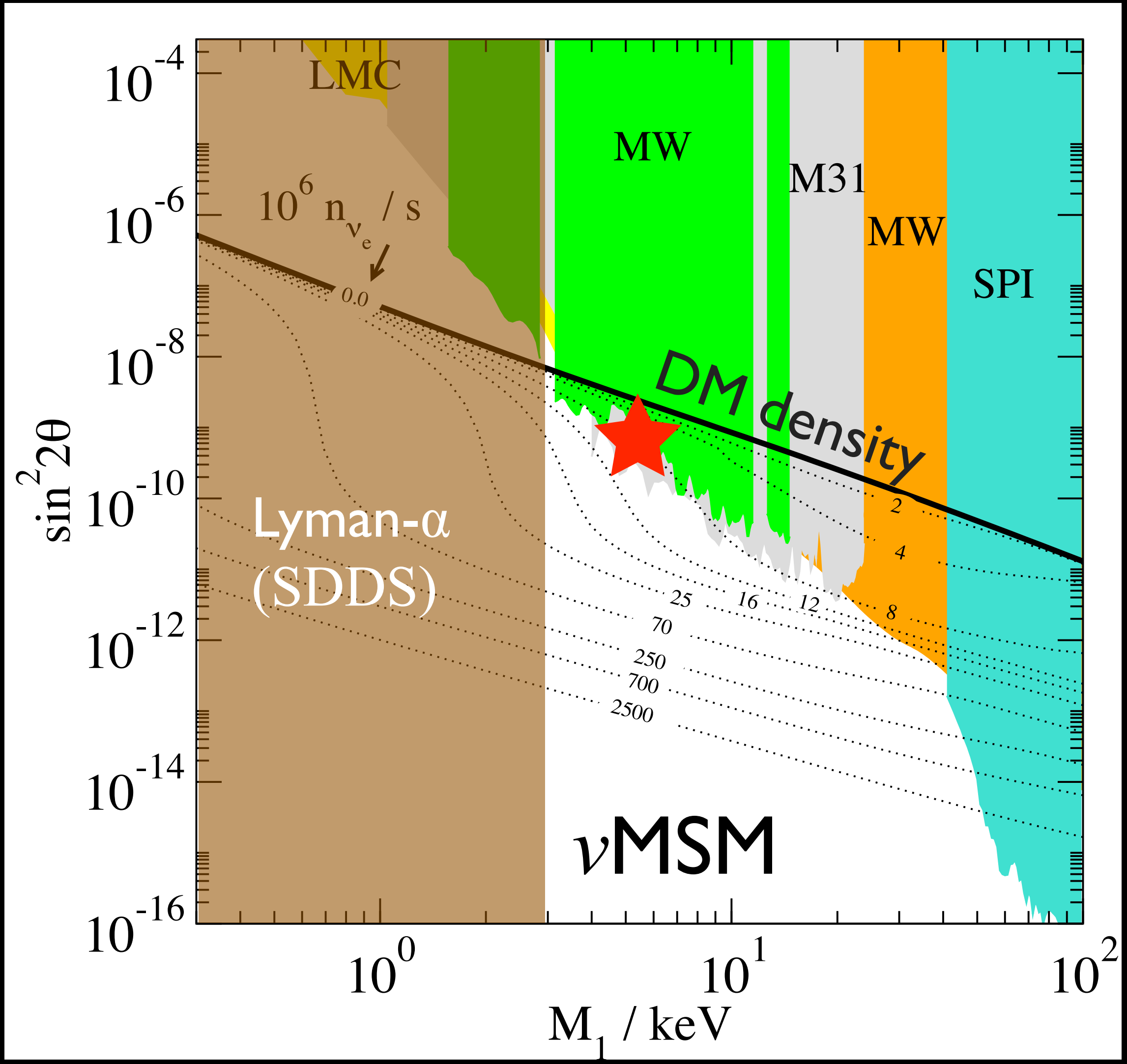
X-rays from dark matter?

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

X-ray line $E_\gamma = \frac{1}{2} m_s$

m_ν = 7.1 keV

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



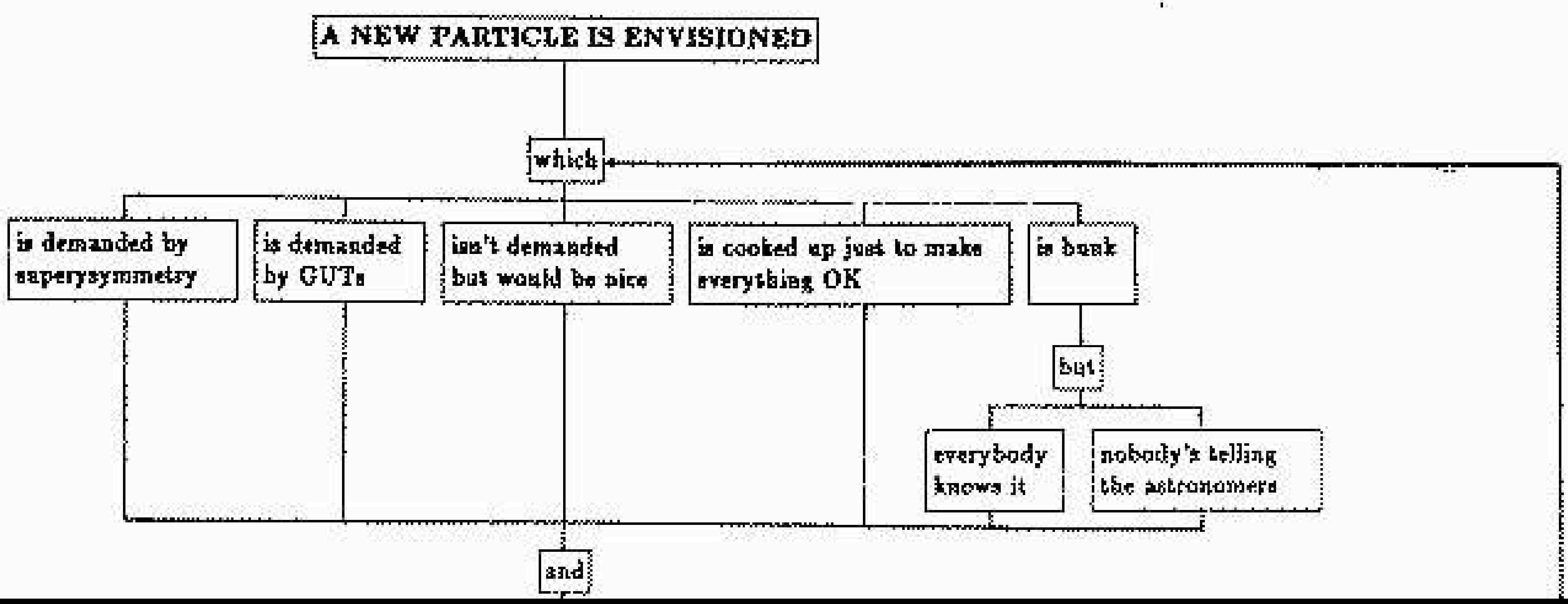
Laine, Shaposhnikov 2008

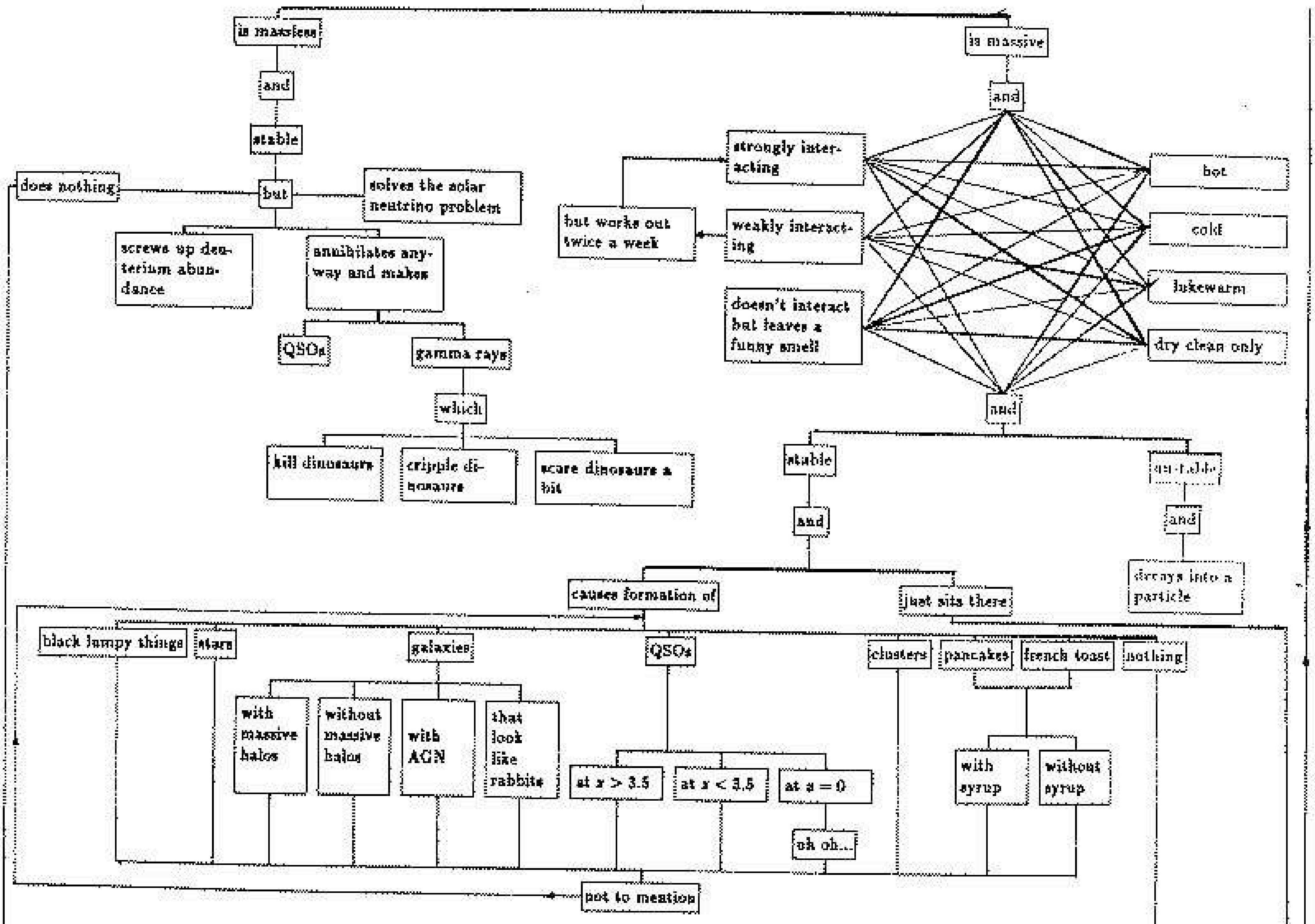
Particle dark matter flowchart

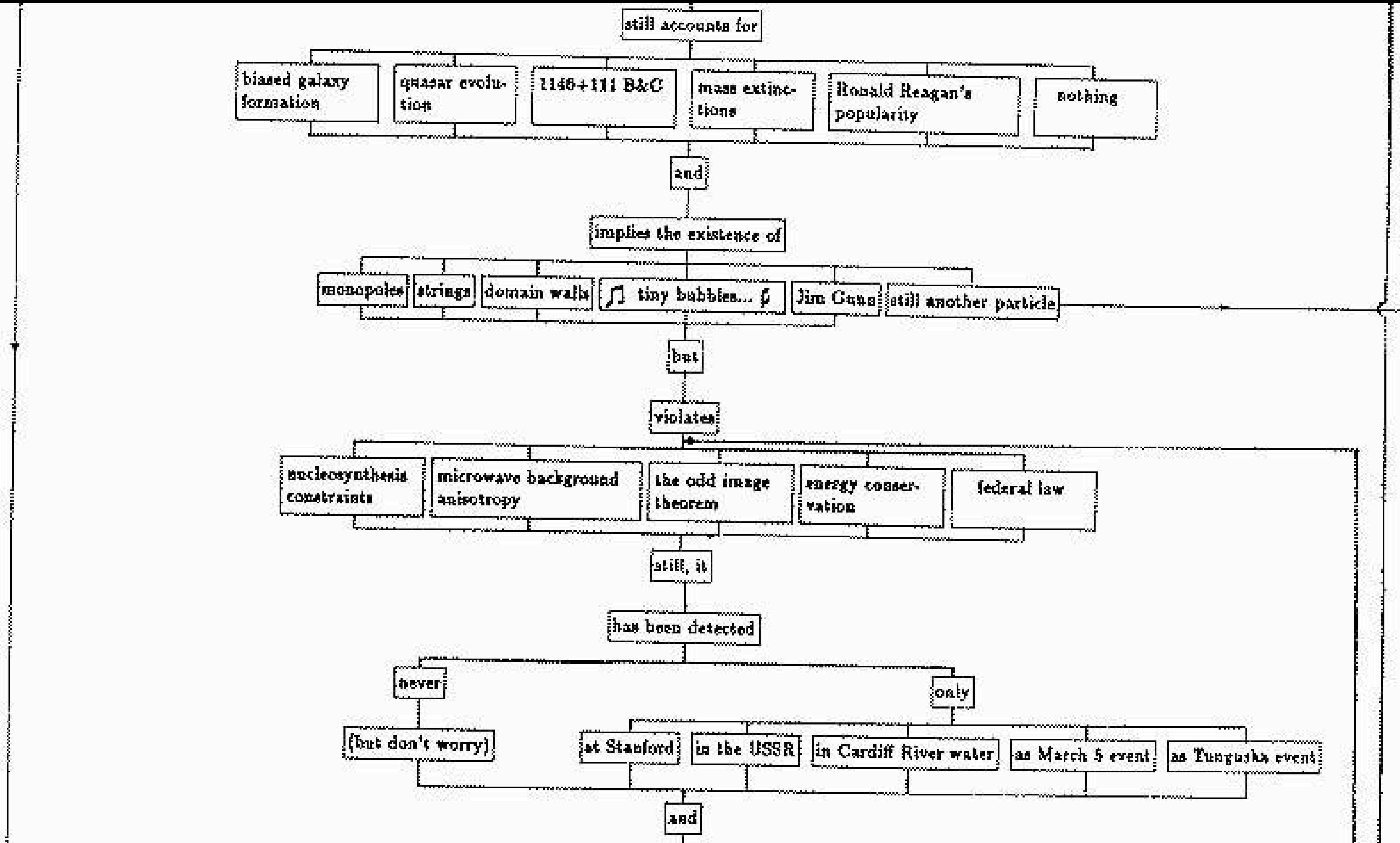
A NEW AND DEFINITIVE META-COSMOLOGY THEORY

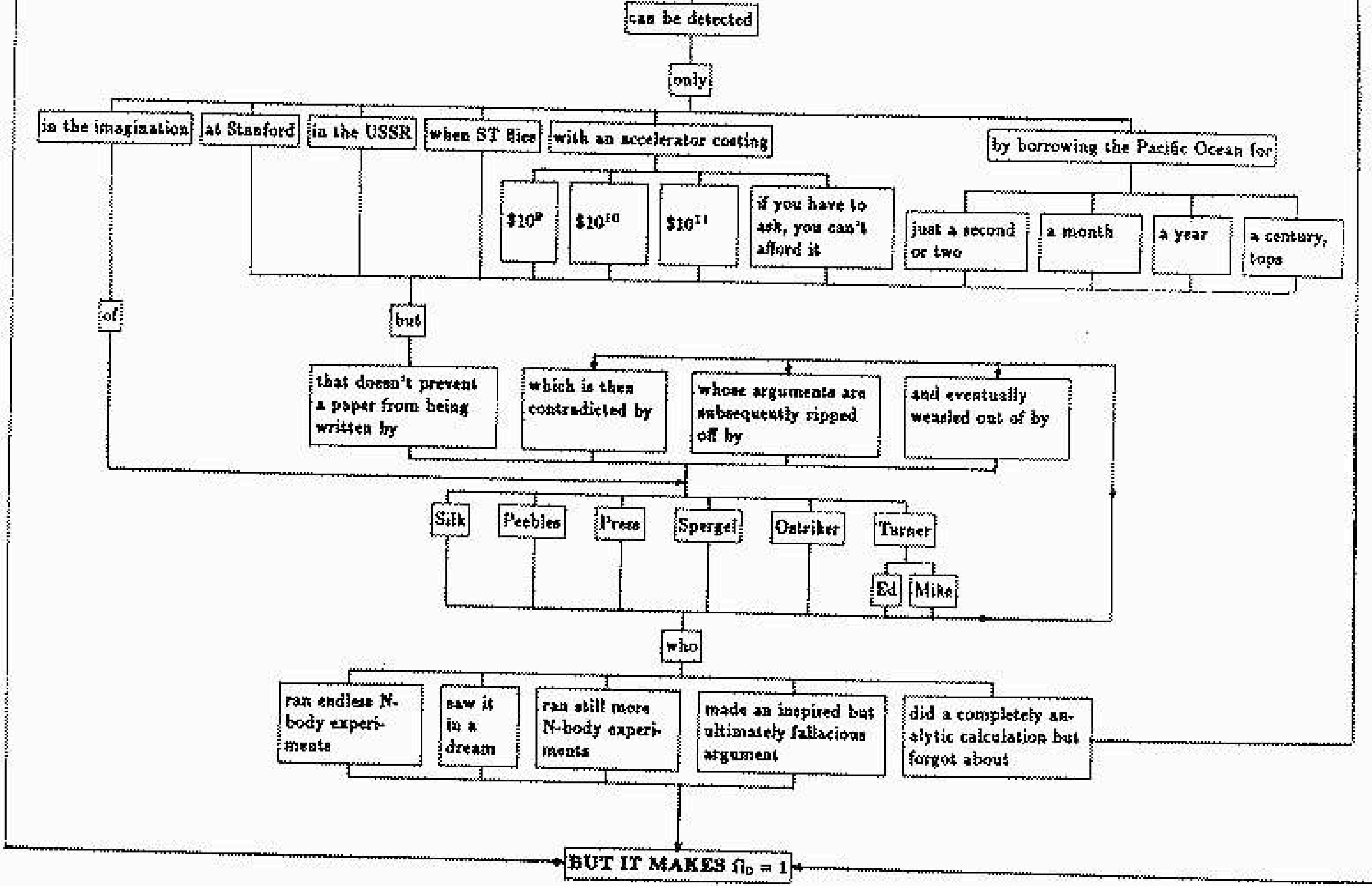
T. R. Lauer
T. S. Statler
B. S. Ryden
D. H. Weinberg

Department of Astrophysical Sciences, Princeton University




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
decays into a particle
and
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
$\$10^9$
$\$10^{10}$
$\$10^{11}$
if you have to ask, you can't afford it
by borrowing the Pacific Ocean for
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