Particle Physics Models for Dark Matter

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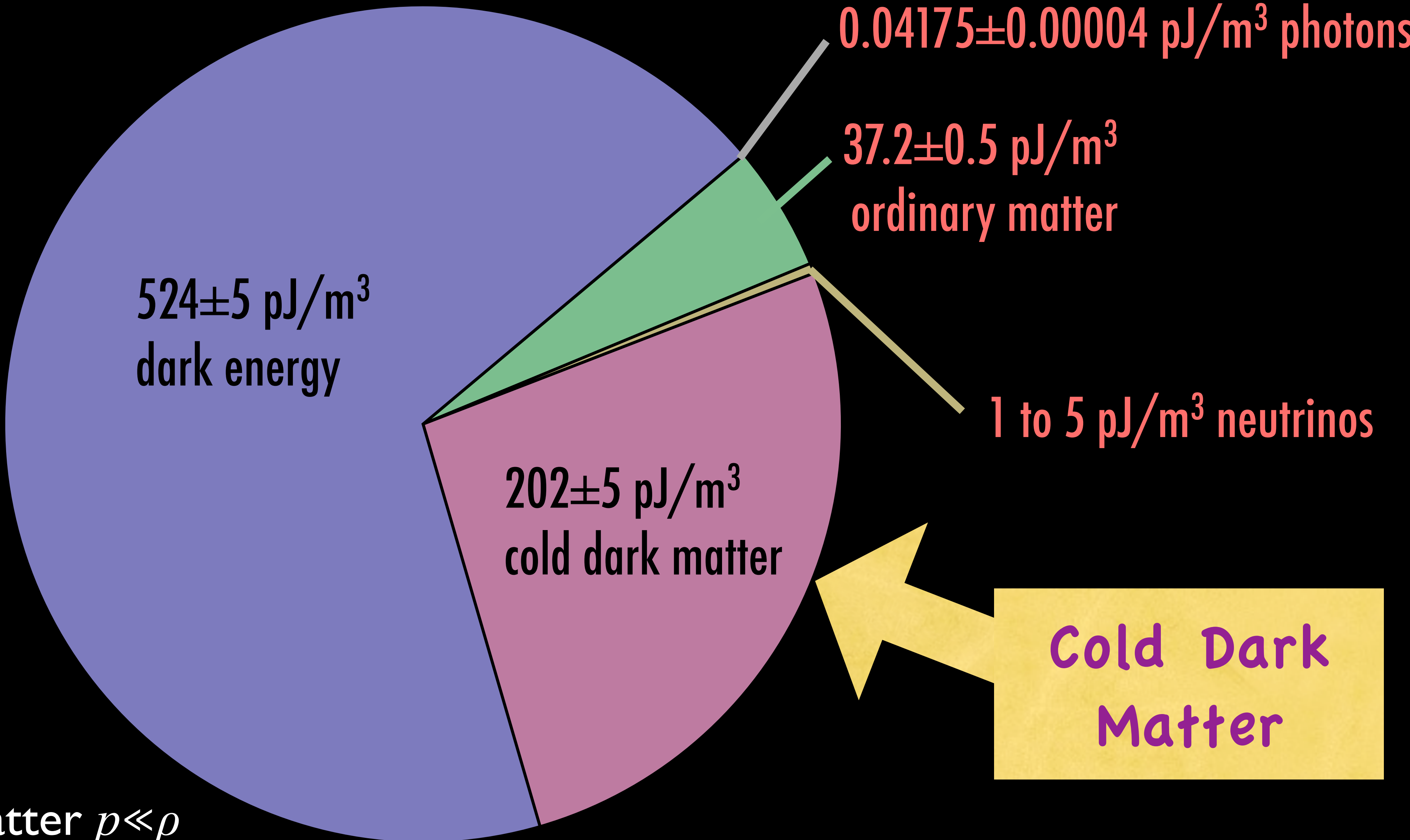
The observed content of the Universe



matter $p \ll \rho$

radiation $p = \rho/3$

vacuum $p = -\rho$

Planck (2013)

1 pJ = 10^{-12} J

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.)

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, *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 and matter power spectra

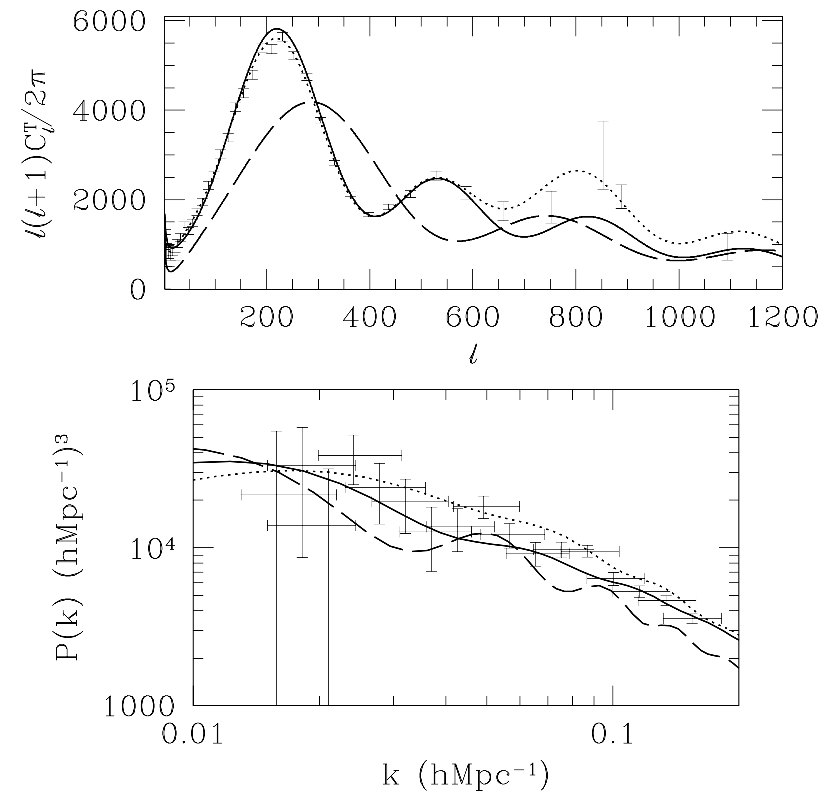
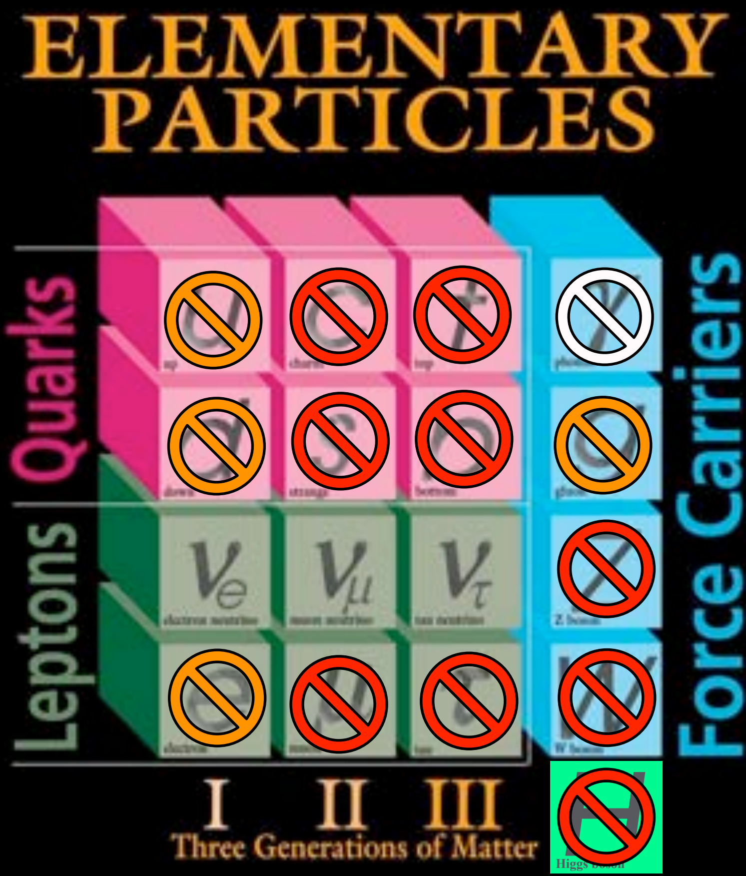


FIG. 4: The angular power spectrum of the CMB (top panel) and the power spectrum of the baryon density (bottom panel) for a MOND universe (with $a_0 \simeq 4.2\times10^{-8}cm/s^2$) with $\Omega_\Lambda = 0.78$ and $\Omega_\nu = 0.17$ and $\Omega_B = 0.05$ (solid line), for a MOND universe $\Omega_\Lambda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

Which particle is cold dark matter?



is the particle of light

couples to the plasma

disappears too quickly

Neutrinos exist!!!

INGRID LUCIA & THE FLYING NEUTRINOS

3 active neutrinos (ν_e, ν_μ, ν_τ)

Known active neutrinos

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

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

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 $\delta\rho_\nu$

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

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

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

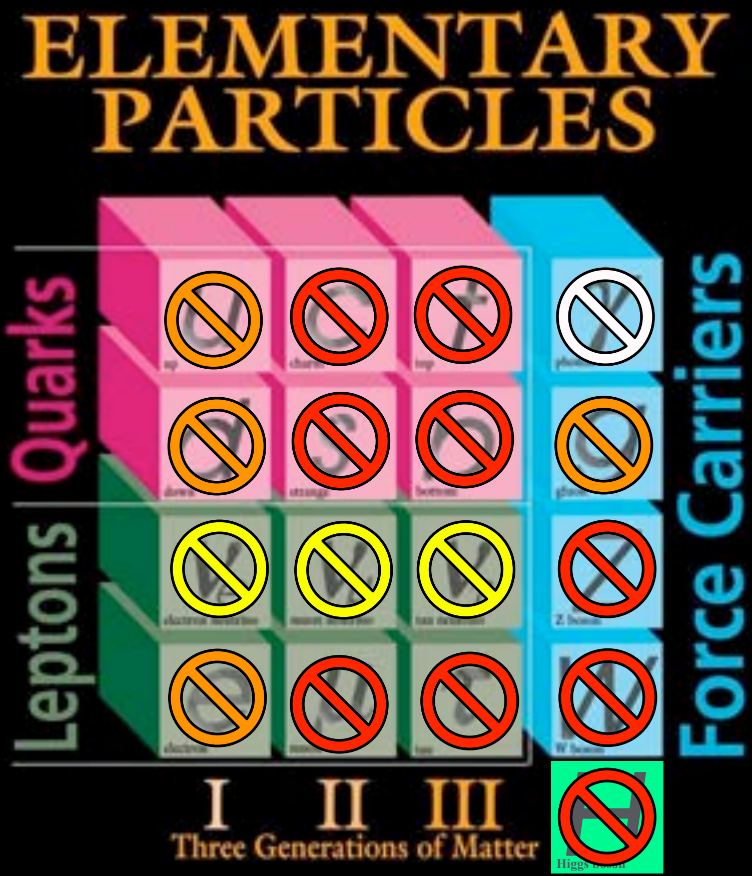
Known active neutrinos

- 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

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

- 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

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

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Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
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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.

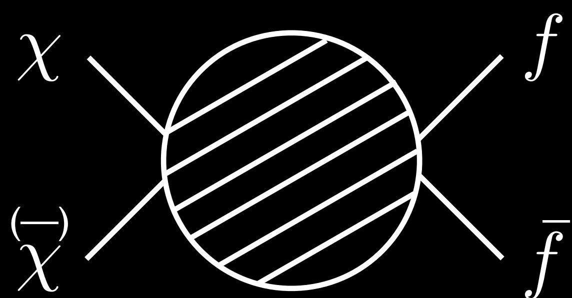
2 GeV/c^2 for Ω_c=1

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*].

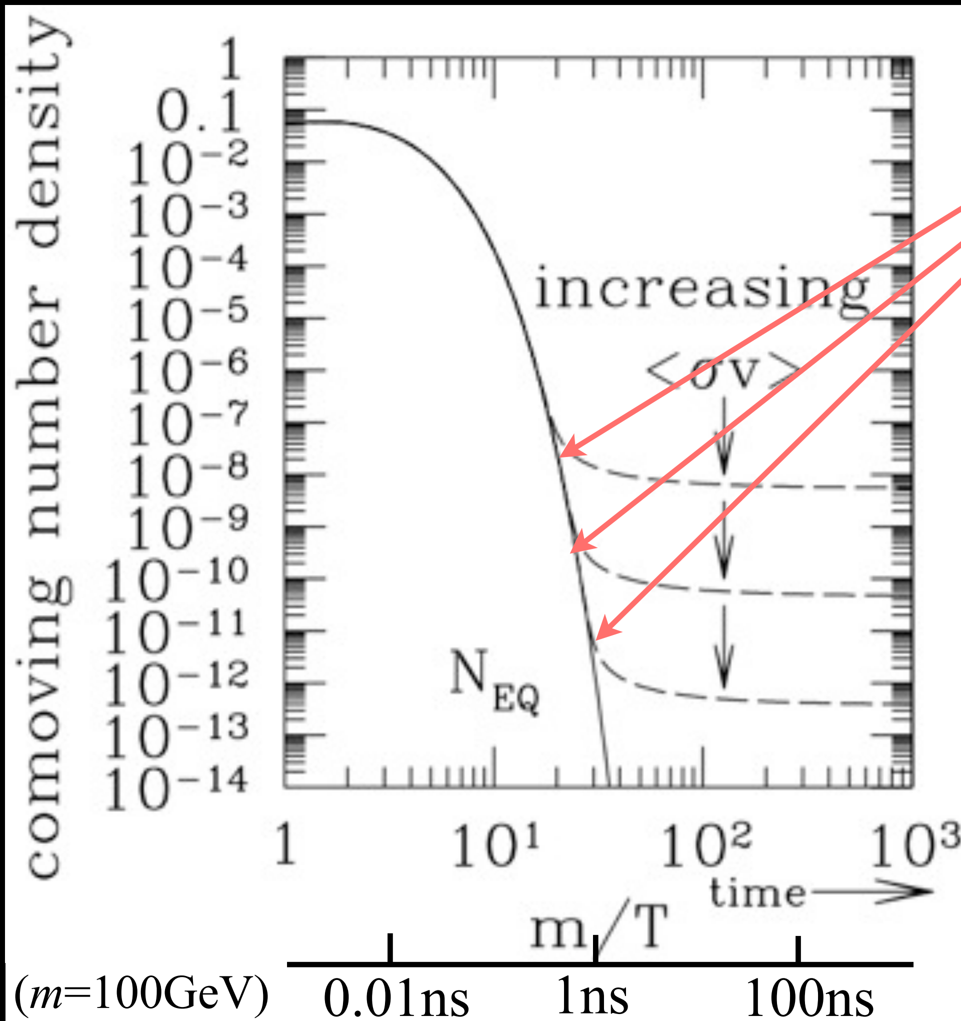
$$e^+ + e^-, \mu^+ + \mu^-, \text{etc.} \leftrightarrow \chi + \overset{(-)}{\chi}$$



- 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*

$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}{\rm cm}^3/{\rm s}}{\langle\sigma v\rangle_{\rm ann}}$$

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

for $\langle\sigma v\rangle_{\rm ann} \simeq 3\times 10^{-26}{\rm cm}^3/{\rm s}$

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)

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

Gondolo, Gelmini 1991

Cosmic density of heavy active neutrinos

Enqvist, Kainulainen, Maalampi 1989

DIrac neutrino in 4-th generation lepton doublet

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

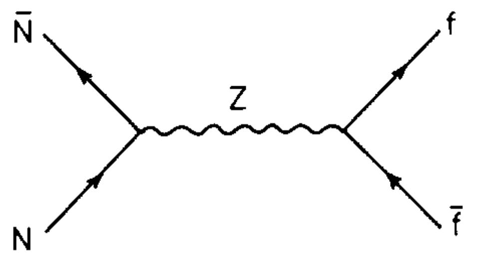
After electroweak symmetry breaking

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

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

Cosmic density of heavy active neutrinos

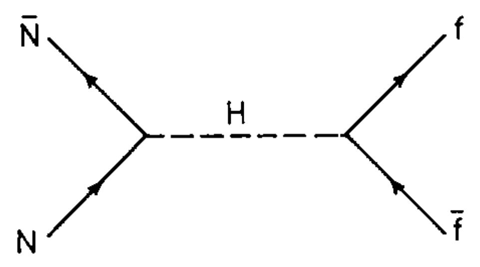
Enqvist, Kainulainen, Maalampi 1989



(a)

$$\sigma_Z(\bar{N}N \to \bar{f}f) = \frac{N_c}{4s}\frac{\pi\alpha^2}{x_W^2}\frac{\beta_f}{\beta_N}\frac{1}{16(1-x_W)^2}|D_Z|^2$$

$$\times\left[\tfrac{1}{2}\left(v_f^2+a_f^2\right)s^2\left(1+\tfrac{1}{3}\beta^2\right)+2\left(v_f^2-a_f^2\right)m_f^2\left(s-2m_N^2\right)\right]$$



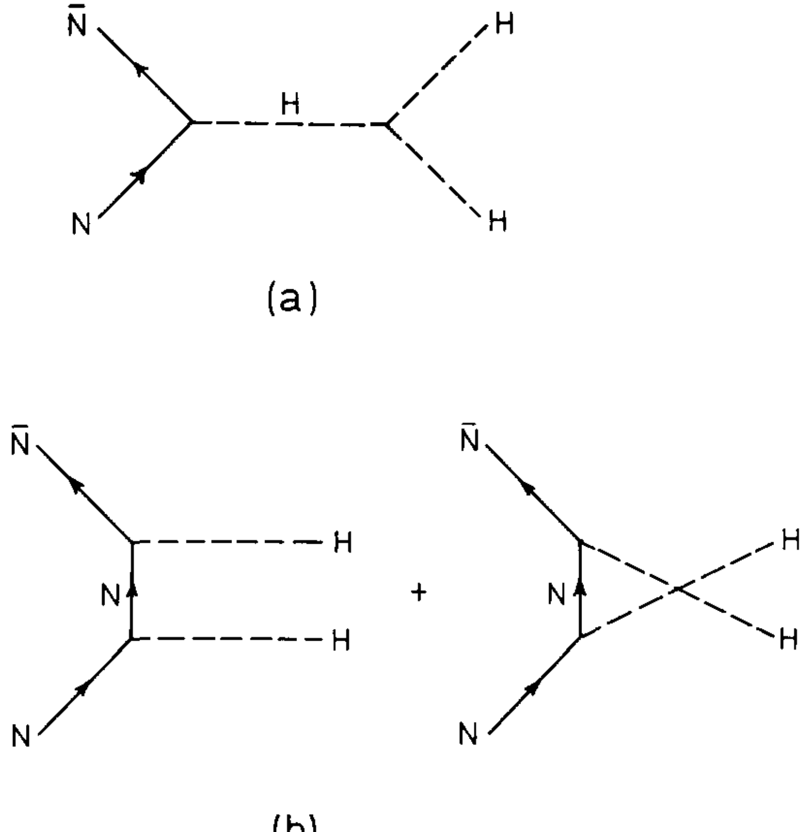
$$\sigma_H(N\bar{N} \to \bar{f}f) = N_c\frac{\pi\alpha^2}{4sx_W^2}\frac{\beta_f}{\beta_N}|D_H|^2\left(\frac{m_f m_N}{m_W^2}\right)^2 s^2\beta^2,$$

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

Cosmic density of heavy active neutrinos

Enqvist, Kainulainen, Maalampi 1989

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



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

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

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

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

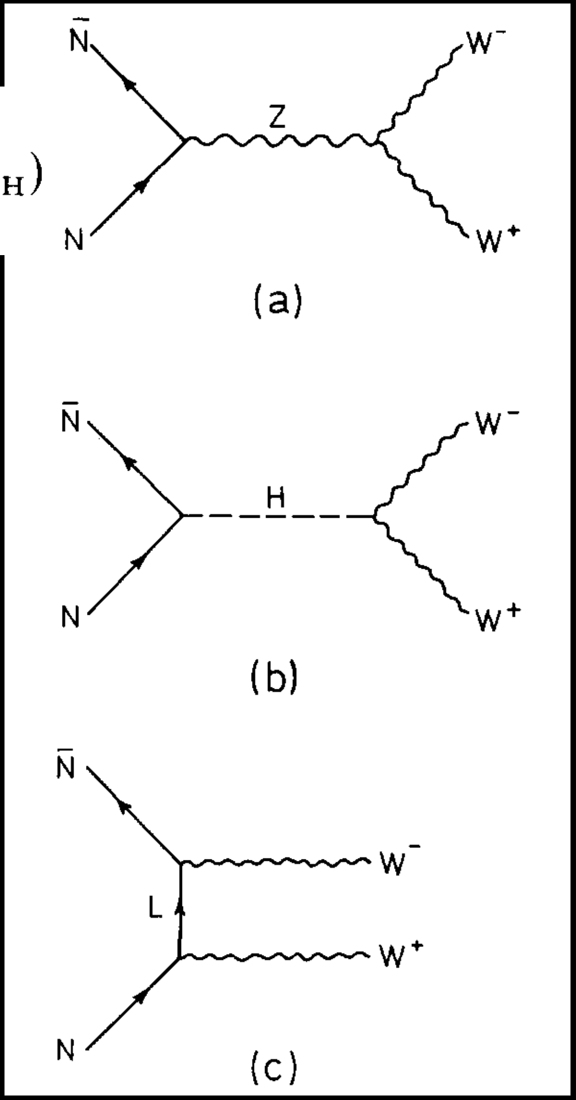
$$L \equiv -\frac{1}{2s\beta_\mathrm{N}\beta_\mathrm{H}}\ln\left(\frac{2m_\mathrm{H}^2 - s + s\beta_\mathrm{N}\beta_\mathrm{H}}{2m_\mathrm{H}^2 - s - s\beta_\mathrm{N}\beta_\mathrm{H}}\right) \qquad \beta_i = \left(1-\frac{4m_i^2}{s}\right)^{1/2} \quad (i=\mathrm{N},\mathrm{H}),$$

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

Cosmic density of heavy active neutrinos

Enqvist, Kainulainen, Maalampi 1989

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



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

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

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

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

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

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

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

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

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

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

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

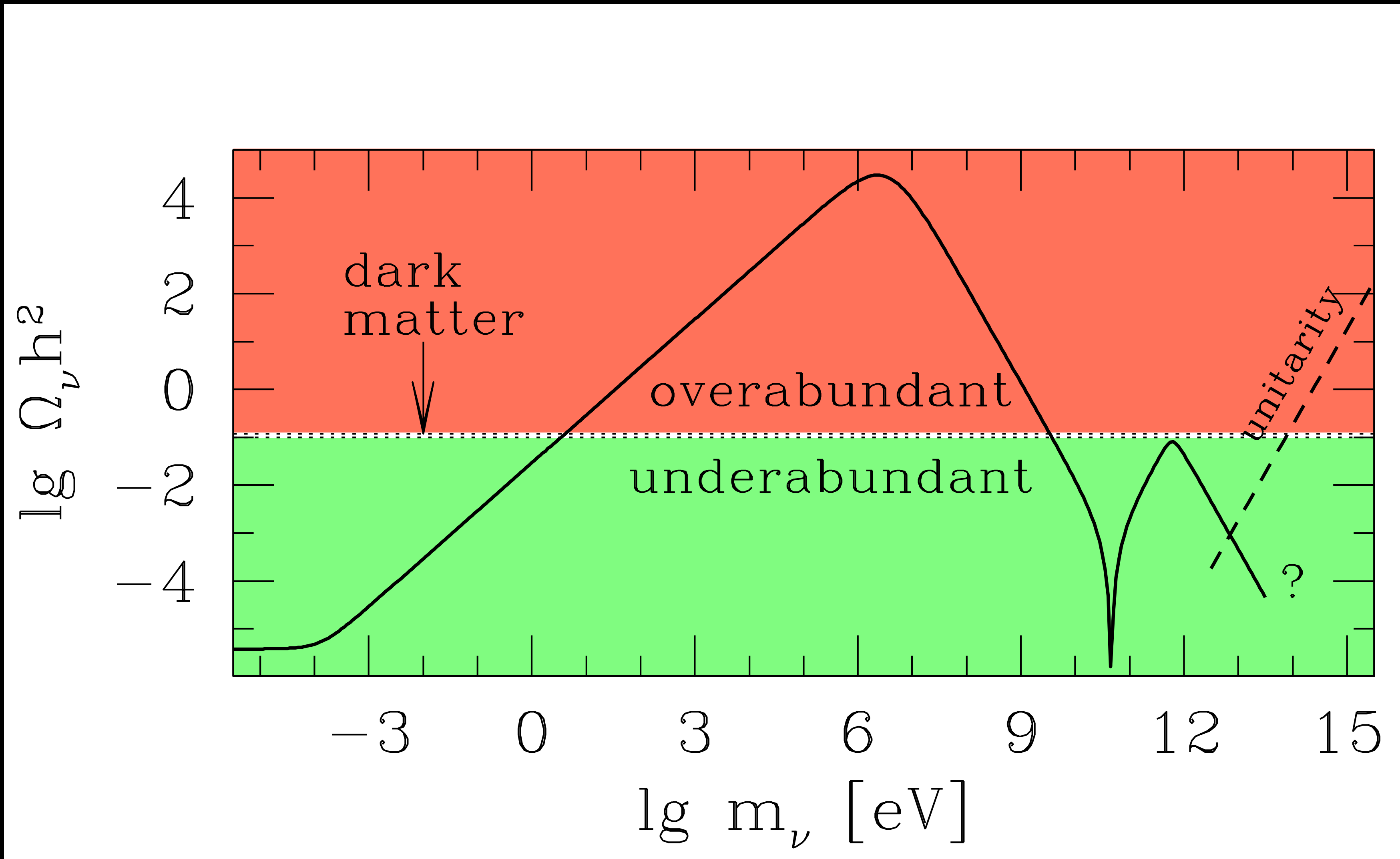
$$P_2 = 4\hat{s} - 5 + (2\hat{s} - 6)\hat{m}_\mathrm{N}^2 - 6\hat{m}_\mathrm{N}^4\,,$$

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

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

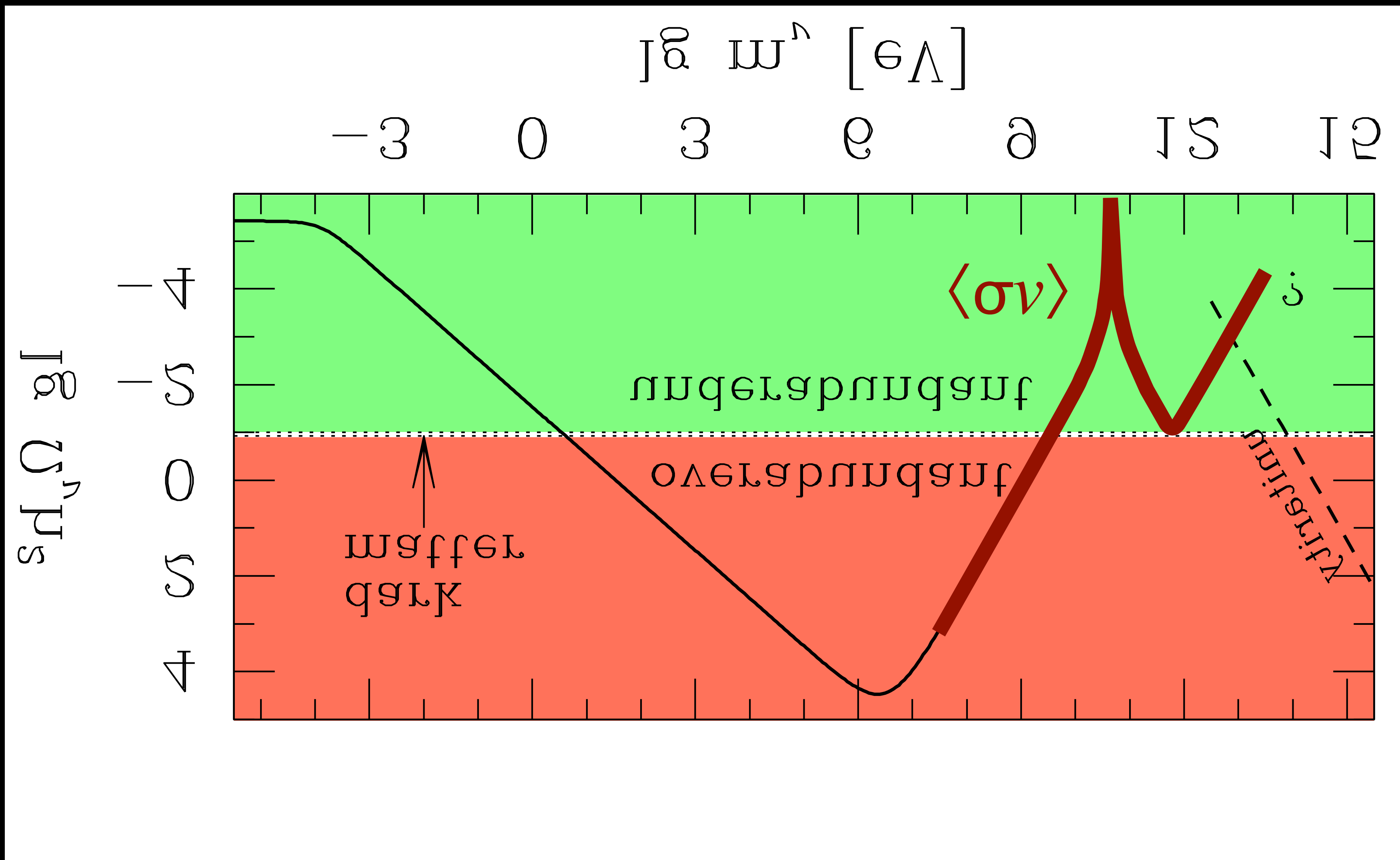
Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino



Cosmic density of massive neutrinos

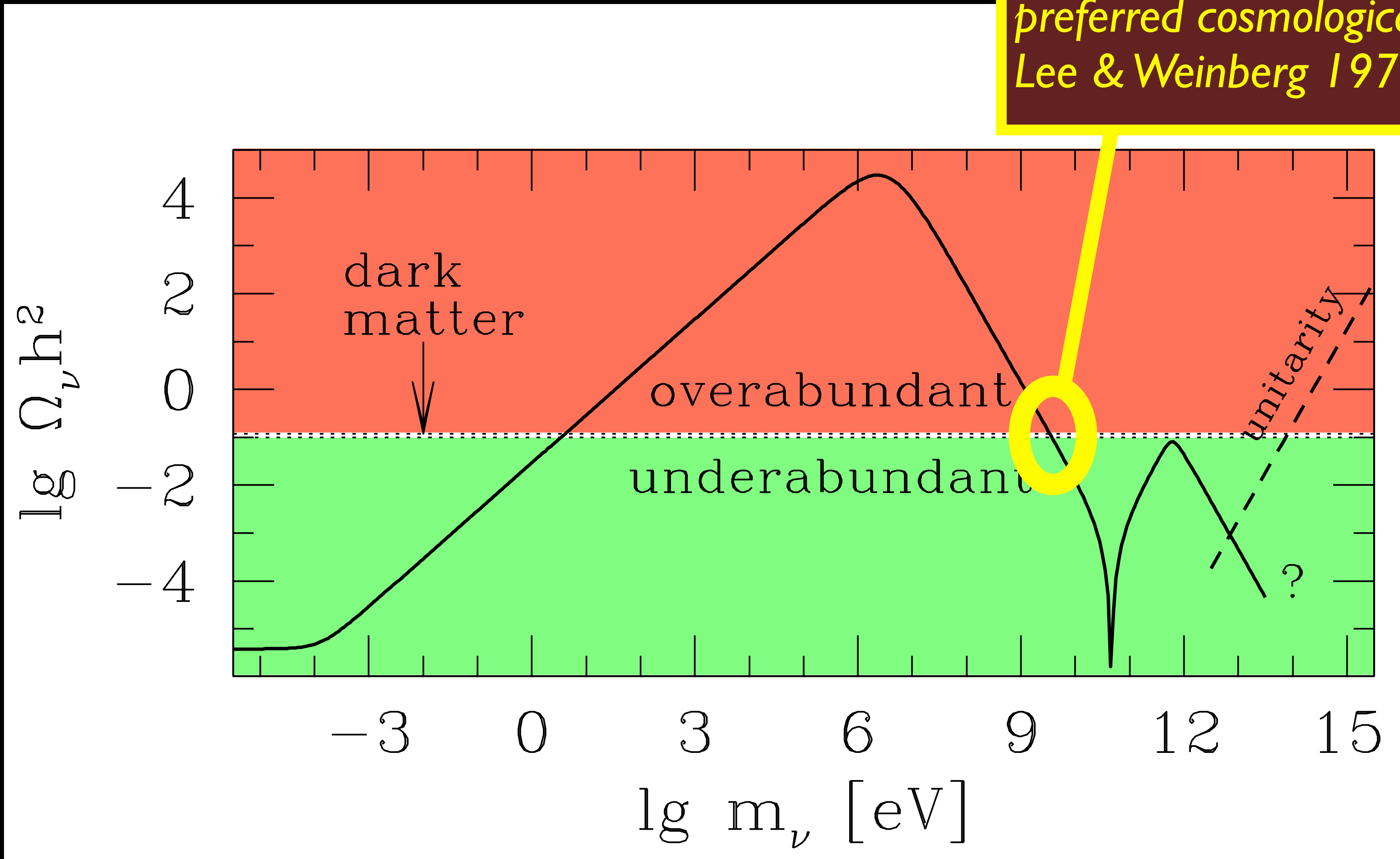
Fourth-generation Standard Model neutrino



Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino

~ few GeV
preferred cosmological mass
Lee & Weinberg 1977



Cosmic density of massive neutrinos

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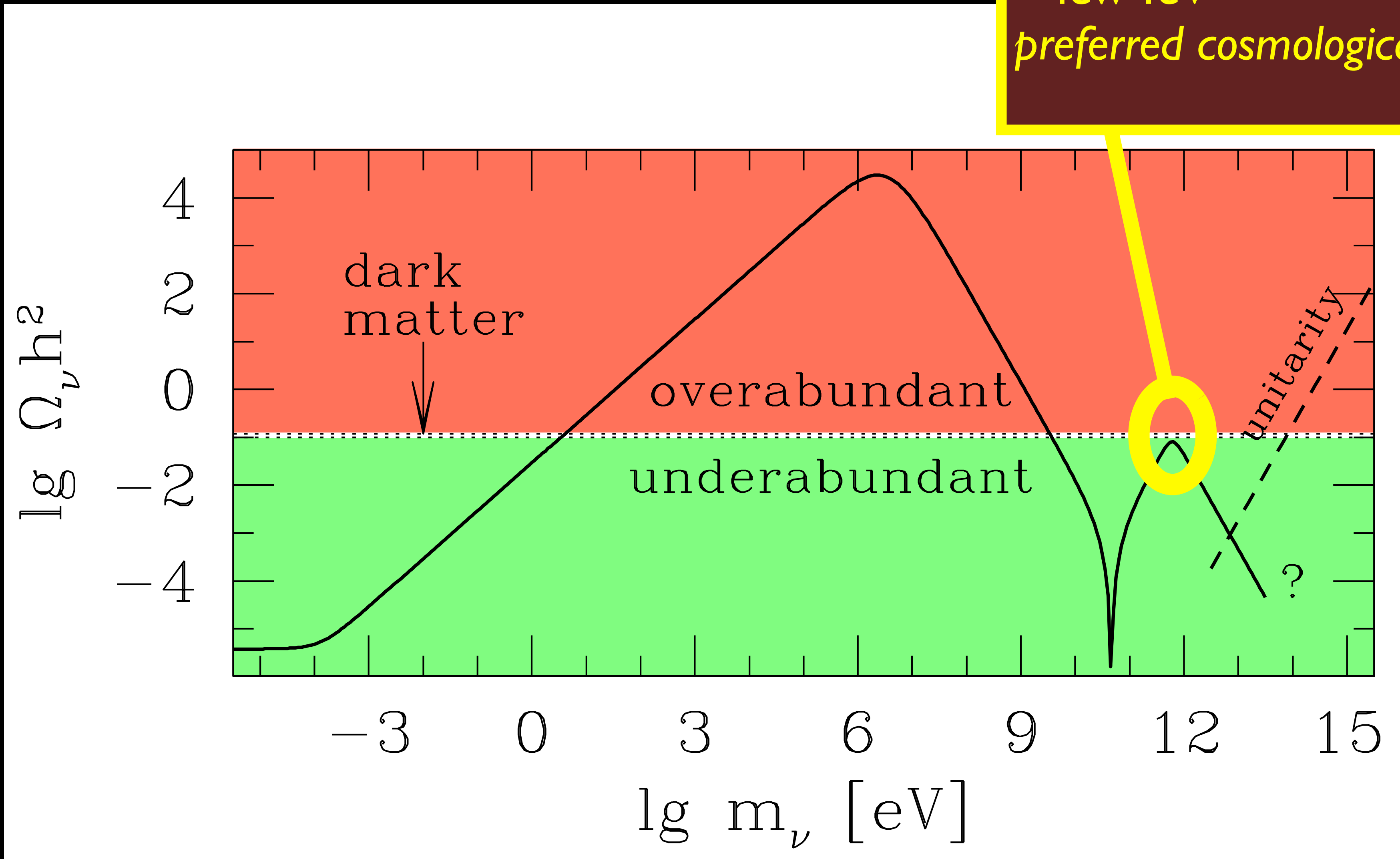
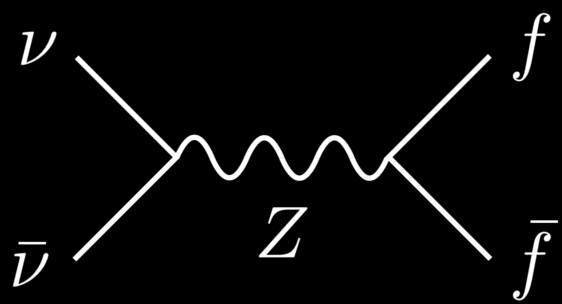


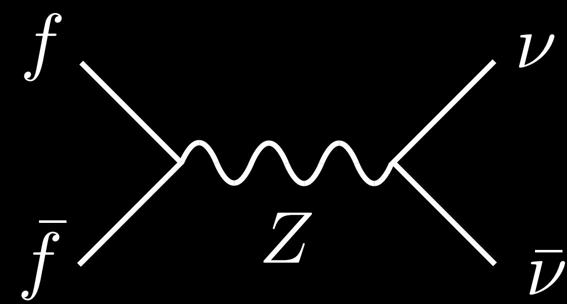
Connection to colliders

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

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



Inverse reaction

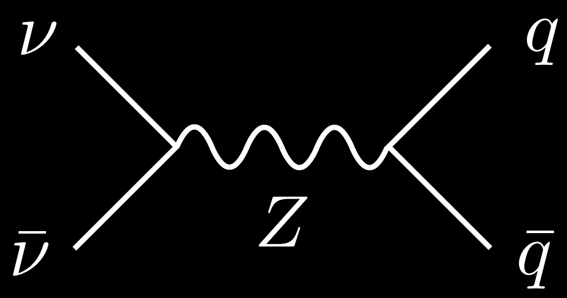


For example, a ~4 GeV/c^2 dark matter neutrino would be copiously produced in resonant Z boson decays

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

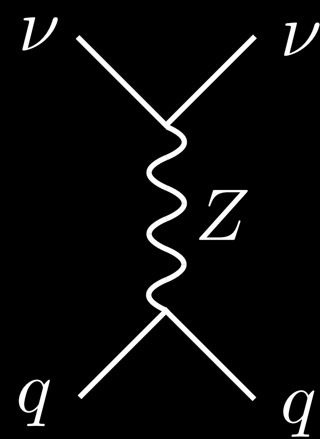
Connection to direct detection

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



Crossing

Scattering $\nu q \longrightarrow \nu q$

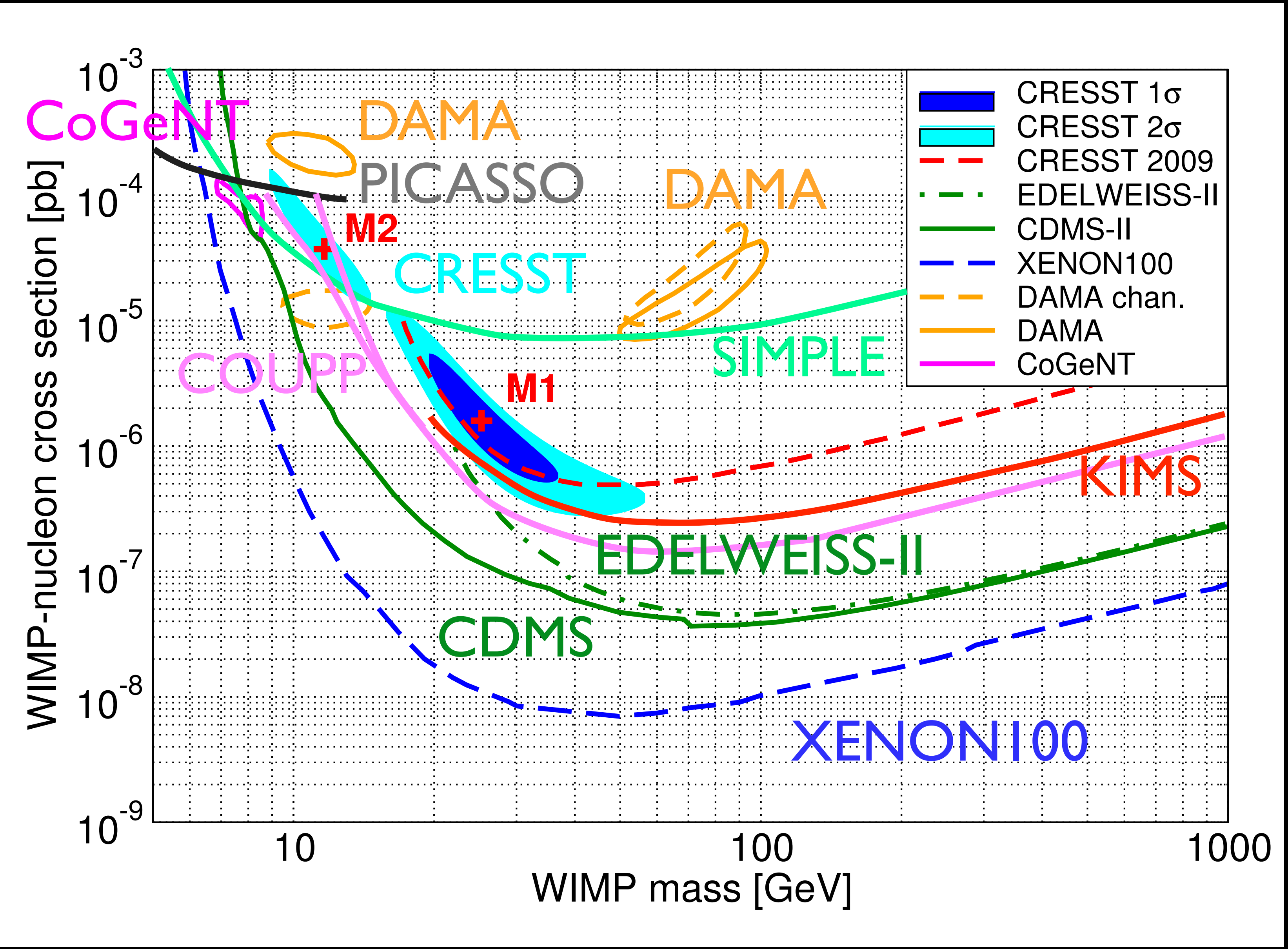


For example, for a ~4 GeV/c² dark matter neutrino, the scattering cross section is

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

Excluded by direct searches

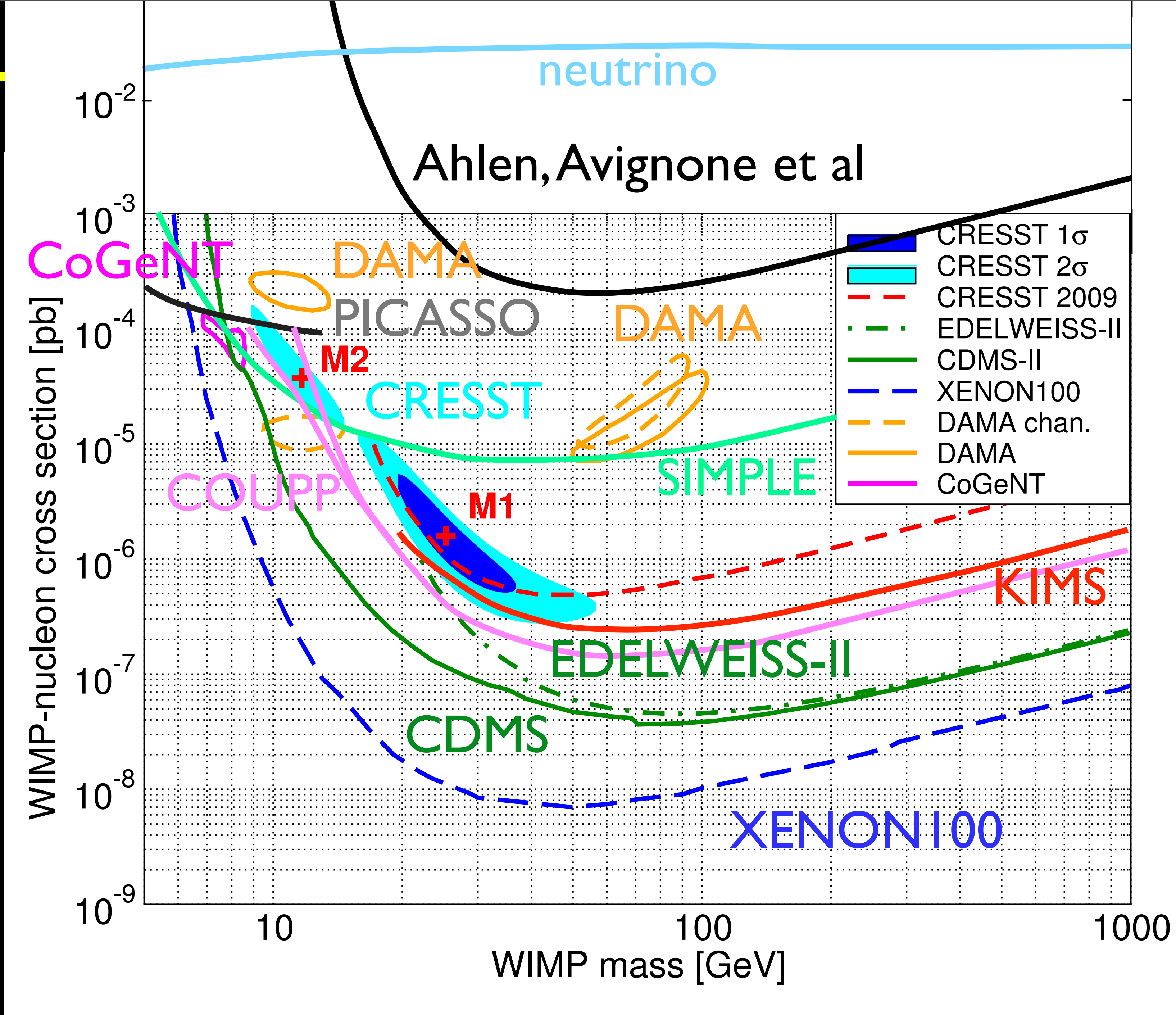
Spin-independent (June 2012)



Updated from Anglehor et al 2011

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

Spin-



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

Updated from Anglehor et al 2011

Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino

~ few GeV
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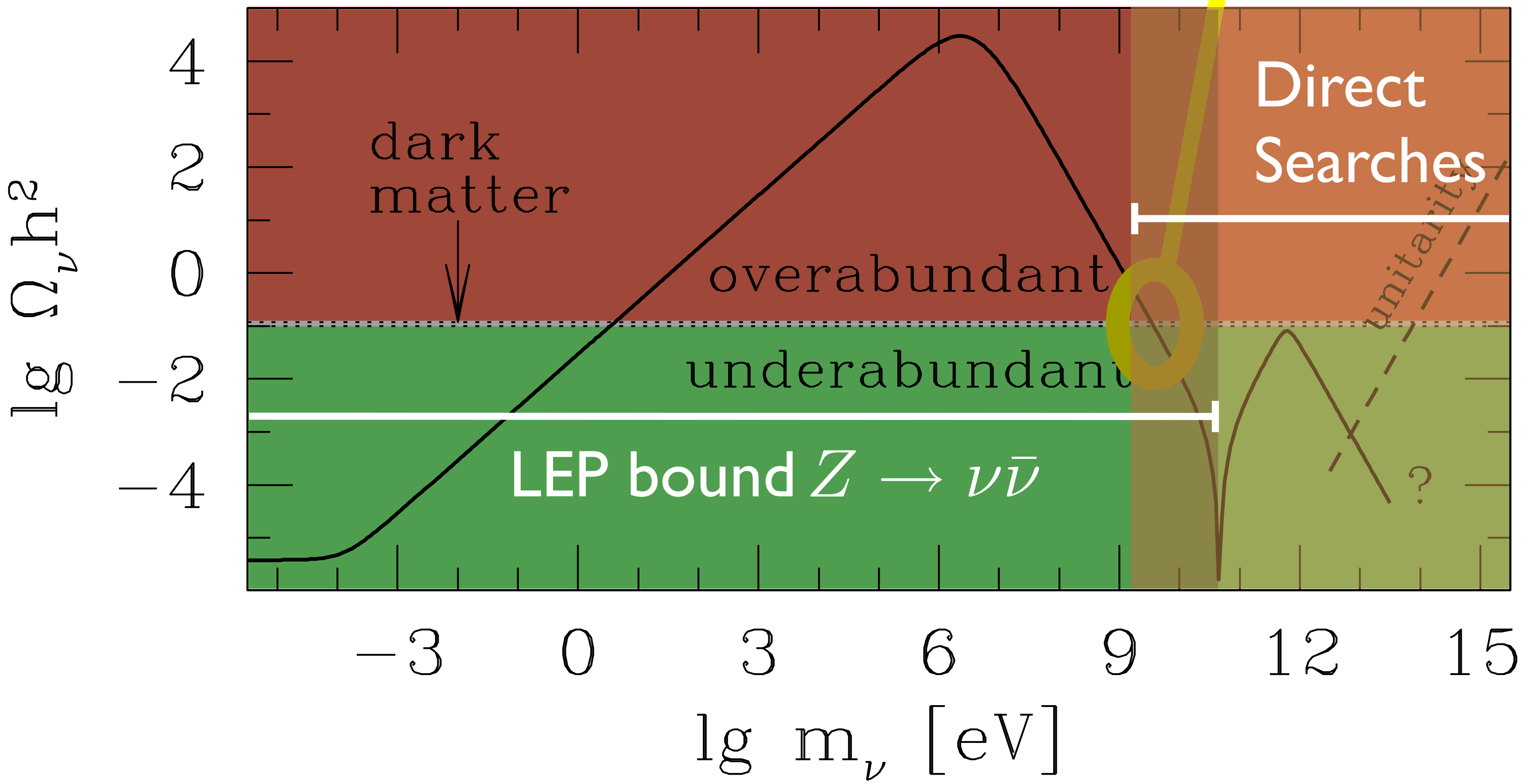
Lee & Weinberg 1977

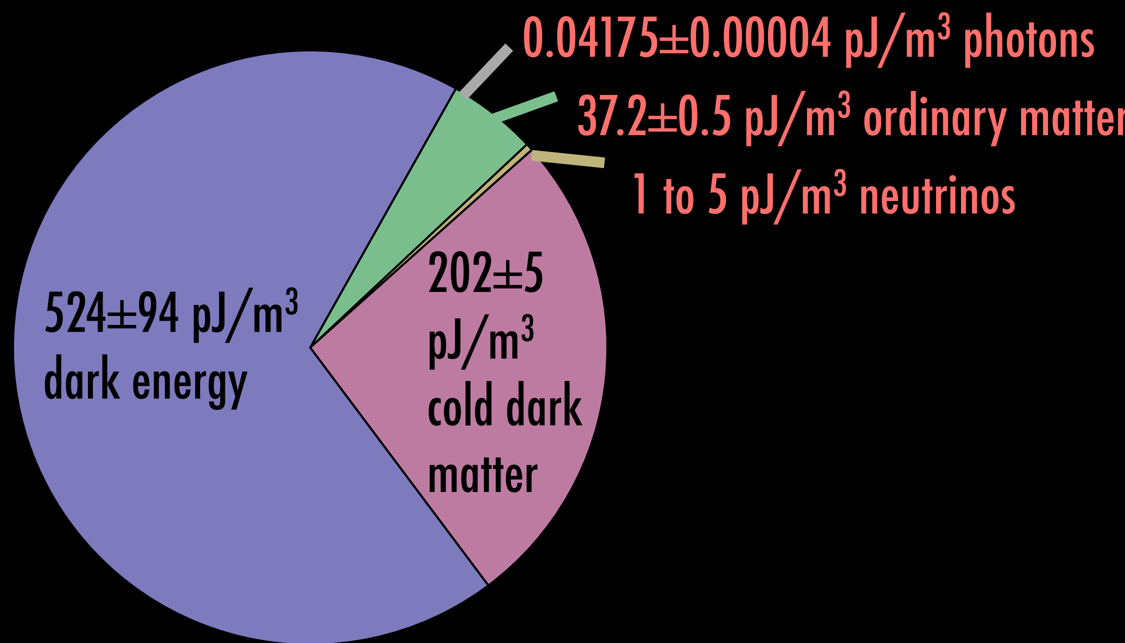
Excluded as dark matter (1991)



The Magnificent WIMP
(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

  Thermal production in hot primordial plasma.



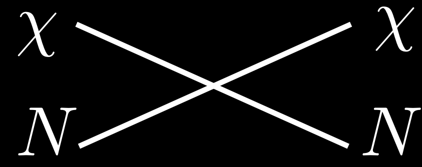
- One can experimentally test the WIMP hypothesis

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

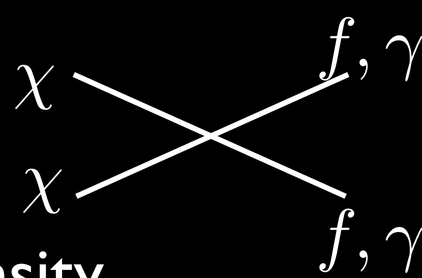
The magnificent WIMP

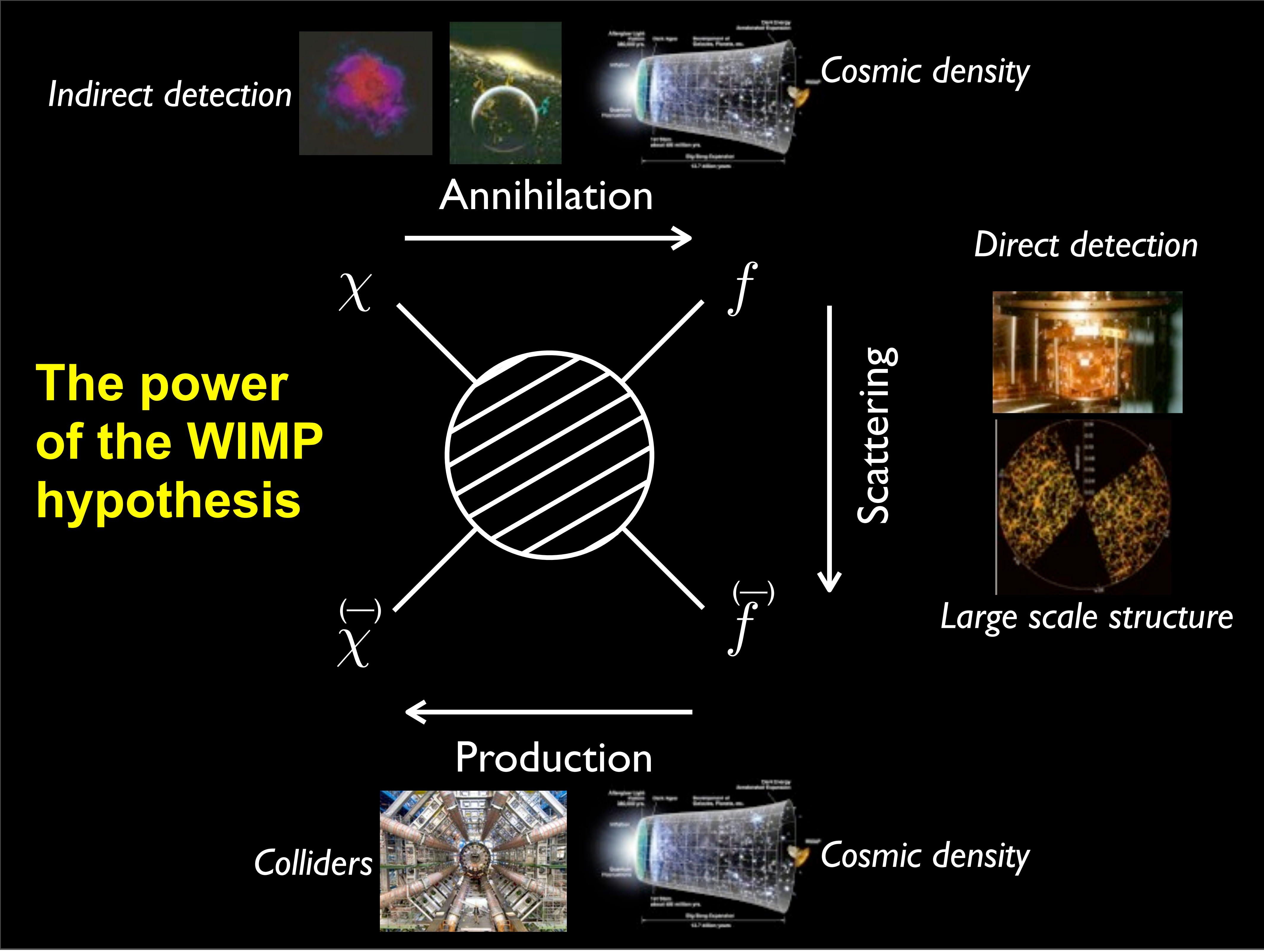
To first order, three quantities characterize a WIMP

- 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
Indirect detection
Cosmic density
Annihilation
Direct detection
χ
f
Scattering
$\overset{(-)}{\chi}$
$\overset{(-)}{f}$
Large scale structure
Production
Colliders
Cosmic density

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 ($S \rightarrow -S$)

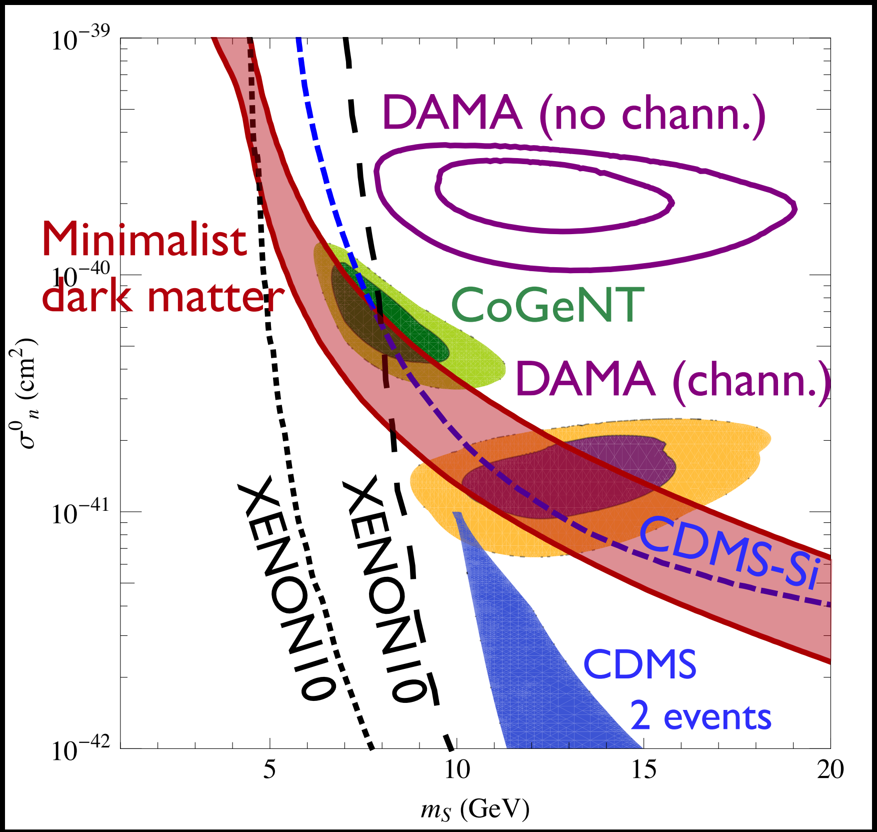
$$\mathcal{L}_S = \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 - \lambda_L H^\dagger H S^2$$

Silveira, Zee 1985

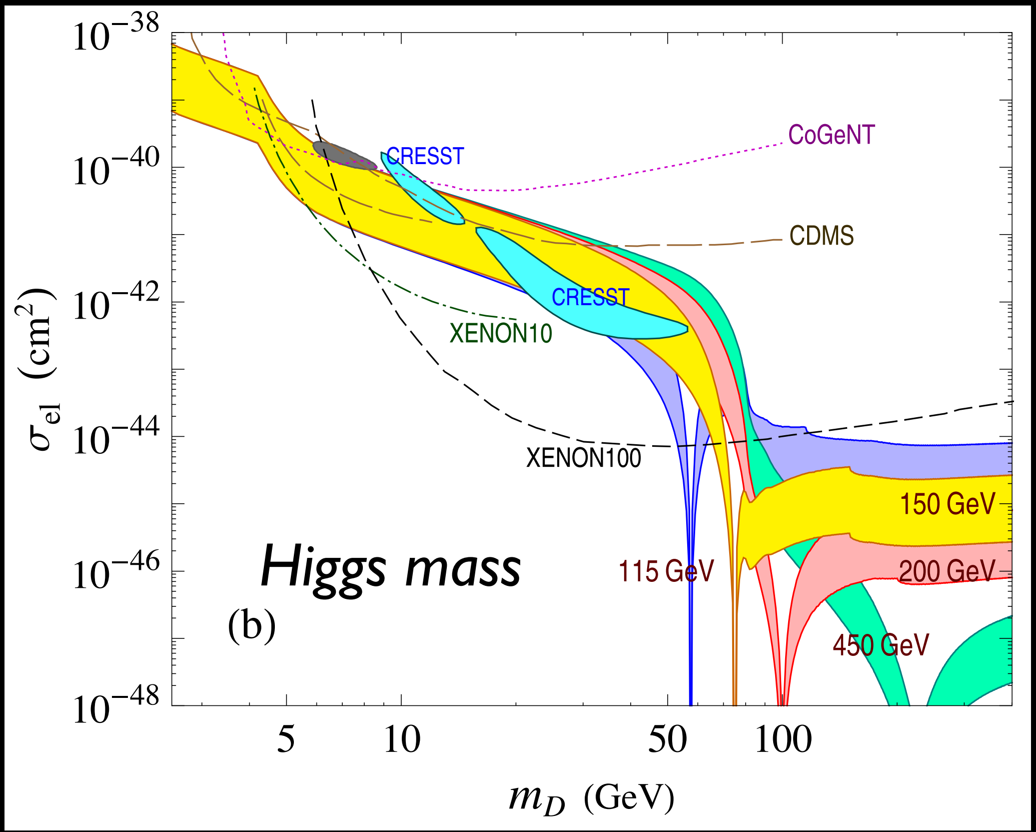
Andreas, Hambye, Tytgat 2008

Minimalist dark matter

do not confuse with minimal dark matter



Andreas, Arina, Hambye, Ling, Tytgat 2010



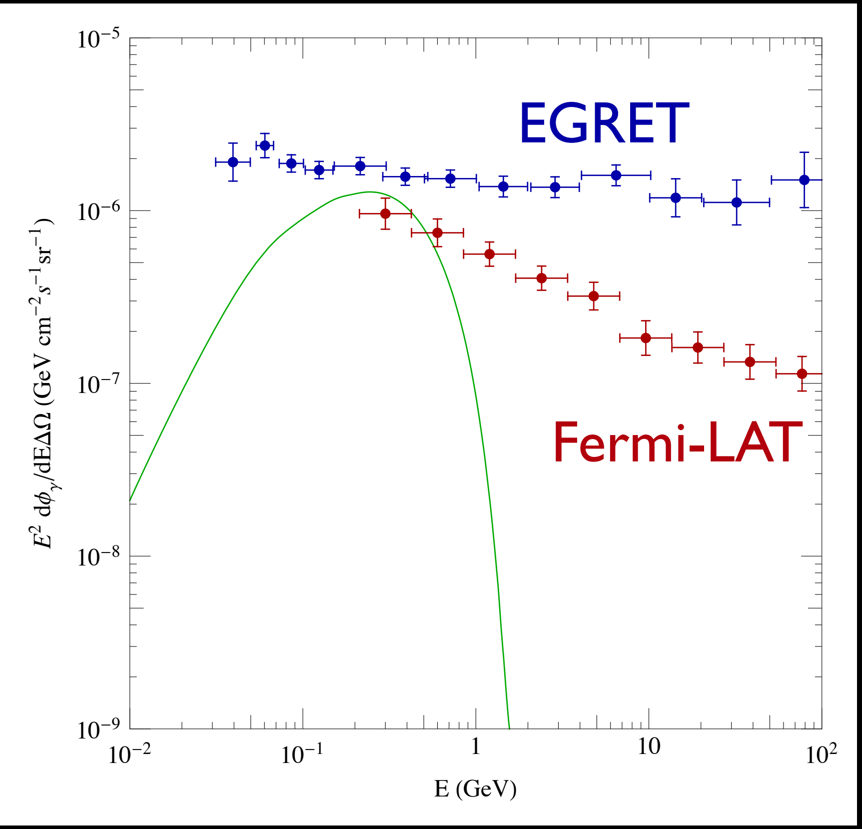
He, Tandean 2011

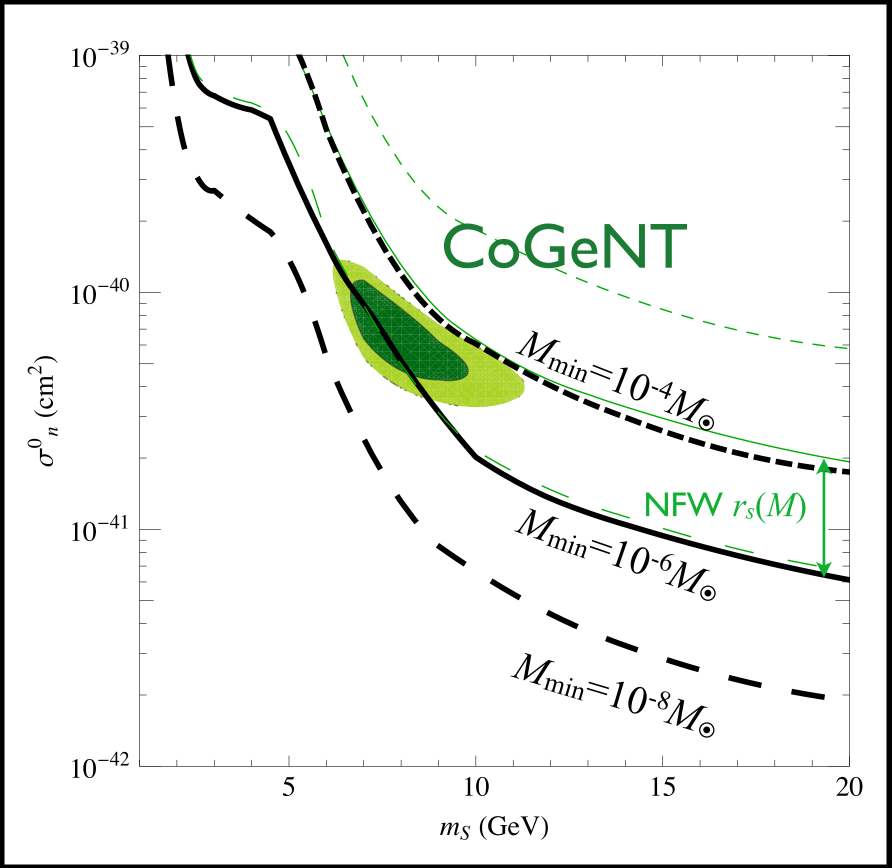
Minimalist dark matter

do not confuse with minimal dark matter

Constraints from diffuse Galactic gamma-rays

Very sensitive to unknown properties of small dark subhalos



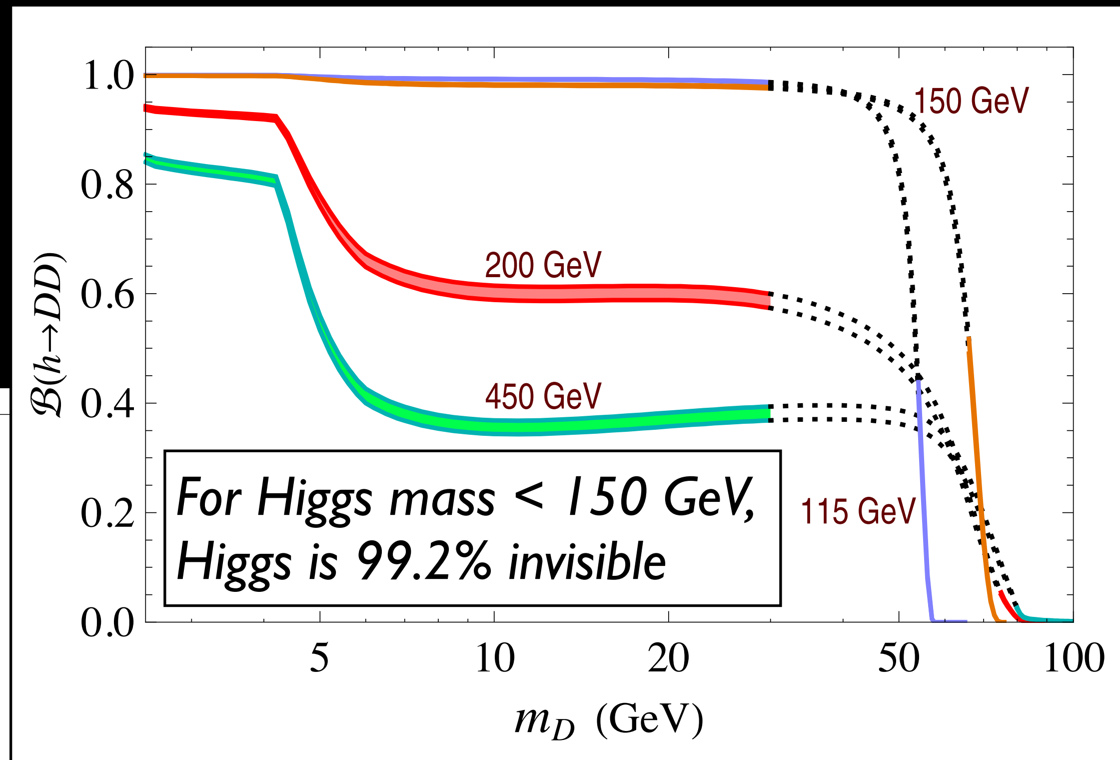


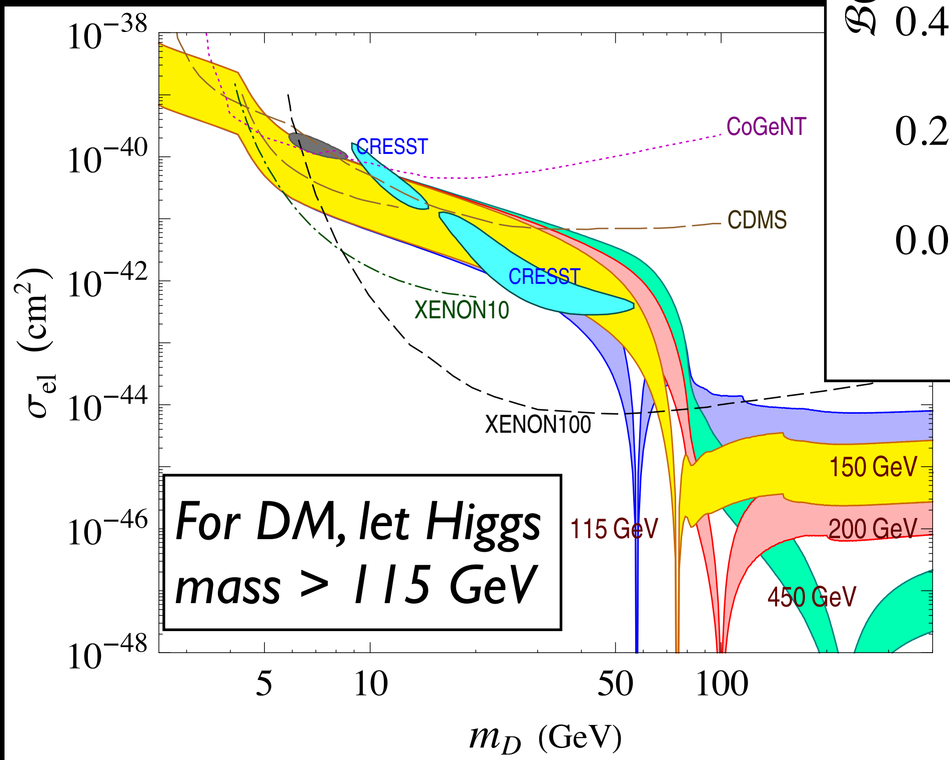
Arina, Tytgat 2010

Minimalist dark matter

do not confuse with minimal dark matter

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



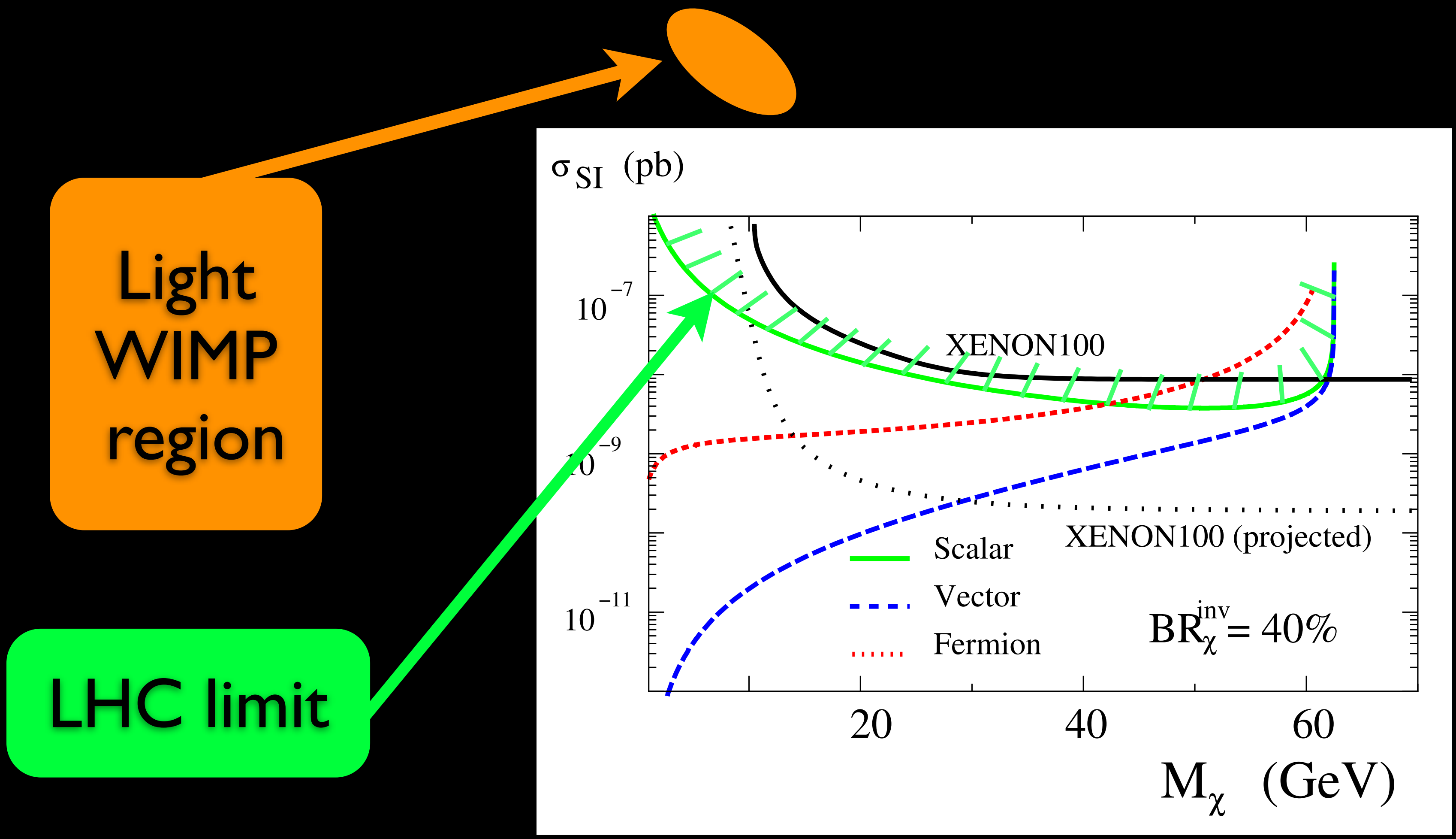


He, Tandean 2011

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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Department of Physics, McGill University, 3600 Rue University, Montréal, Québec, Canada H3A 2T8

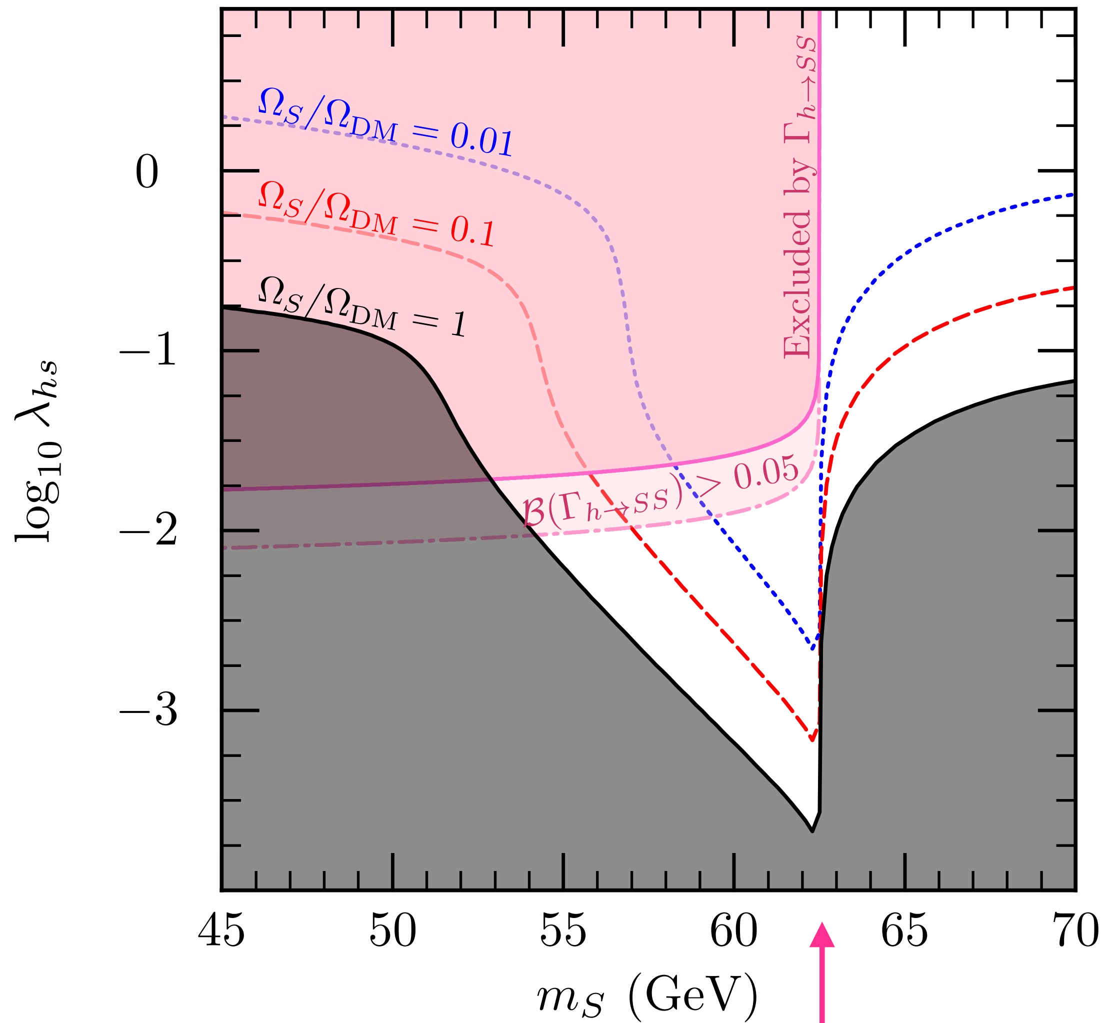
Kimmo Kainulainen‡
Department of Physics, P.O.Box 35 (YFL), FIN-40014 University of Jyväskylä, Finland and Helsinki Institute of Physics, P.O. Box 64, FIN-00014 University of Helsinki, Finland

Christoph Weniger§
GRAPPA Institute, University of Amsterdam, Science Park 904, 1098 GL Amsterdam, Netherlands

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.

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

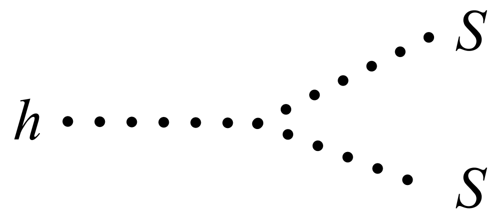
Minimalist dark matter



125 GeV/2=62.5 GeV

Invisible Higgs width

$h \to S + S$



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

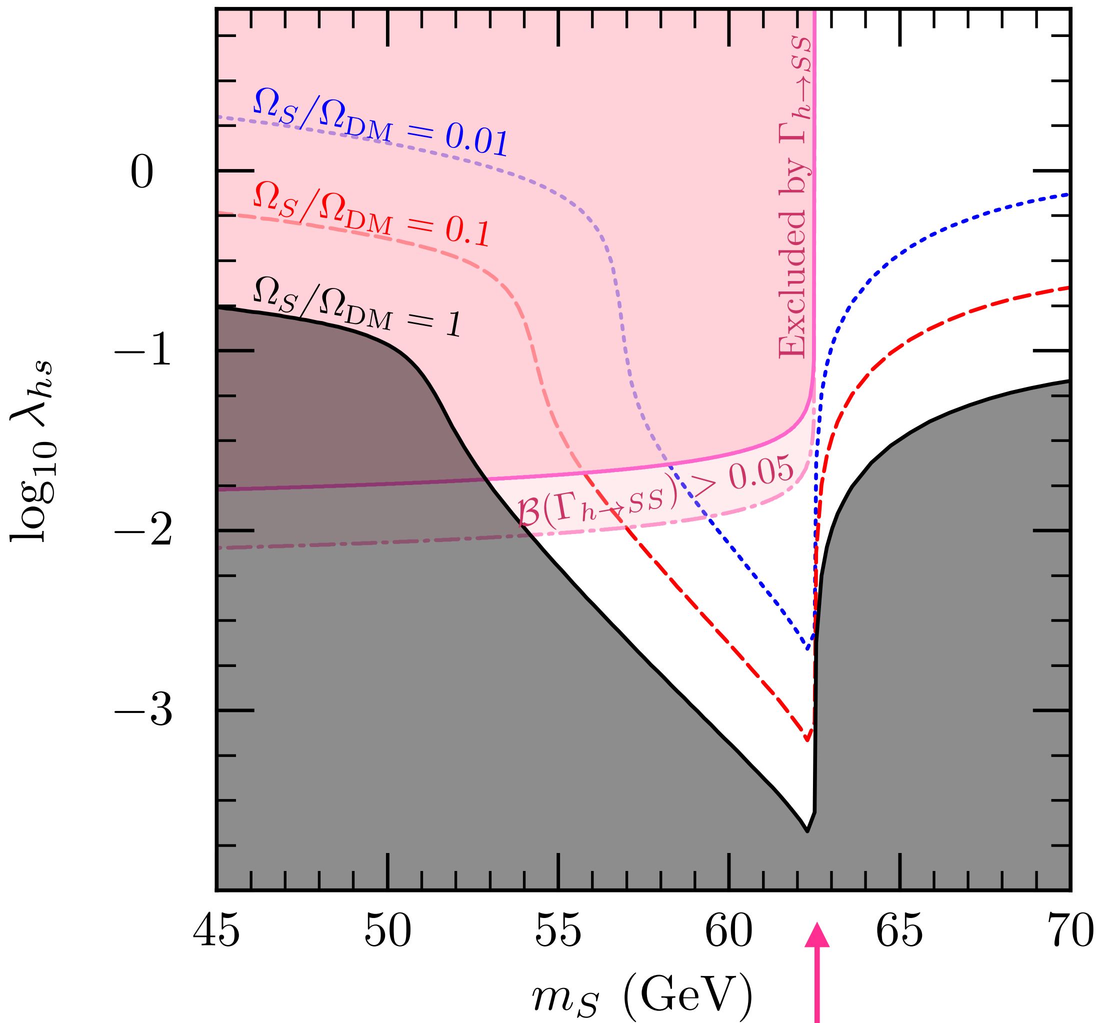
LHC

$\Gamma_{\rm vis}$=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)

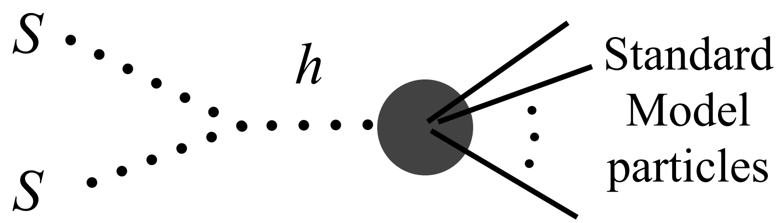
Minimalist dark matter



125 GeV/2=62.5 GeV

Cosmic density

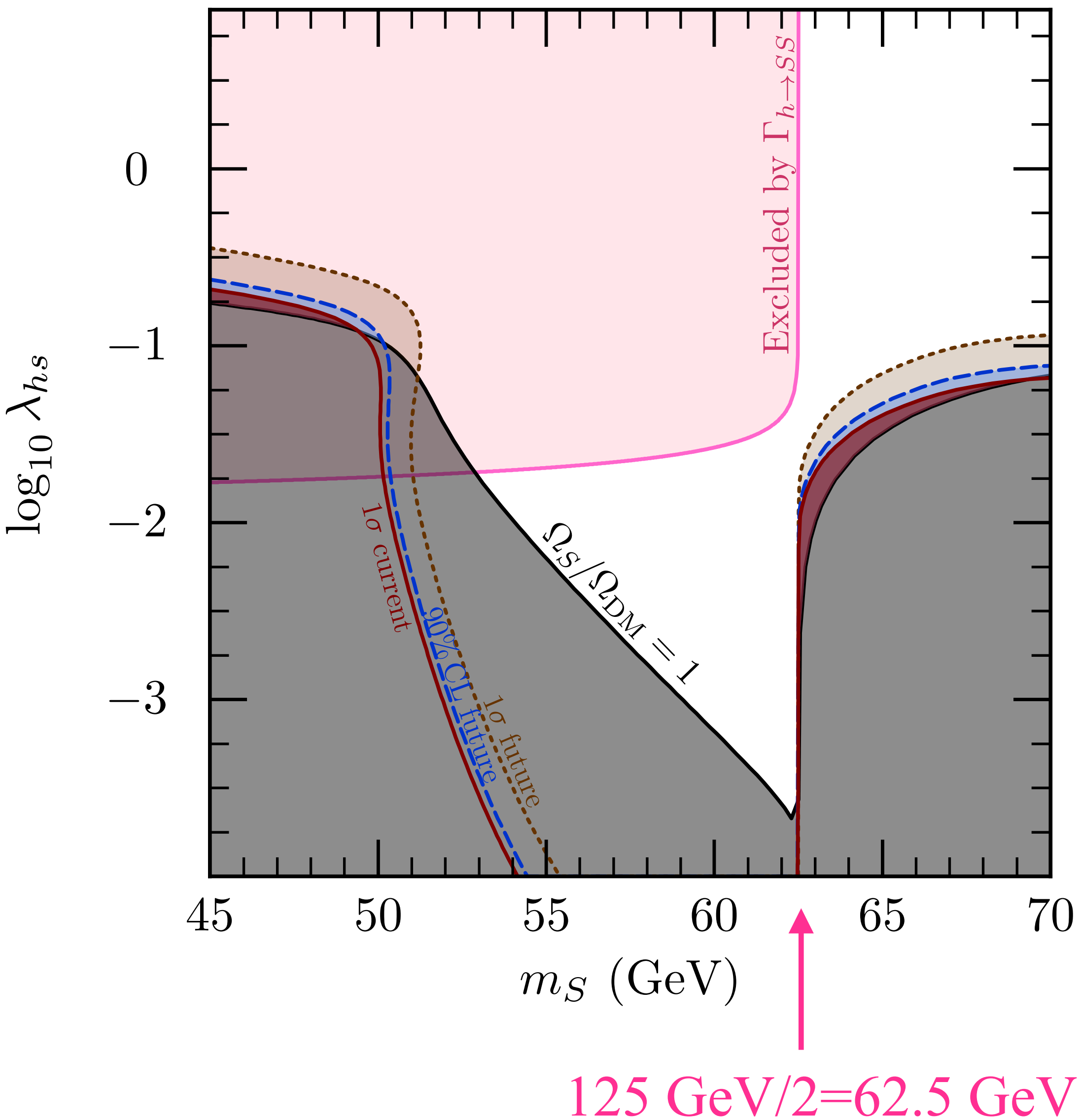
$S + S \to$ Standard Model particles



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

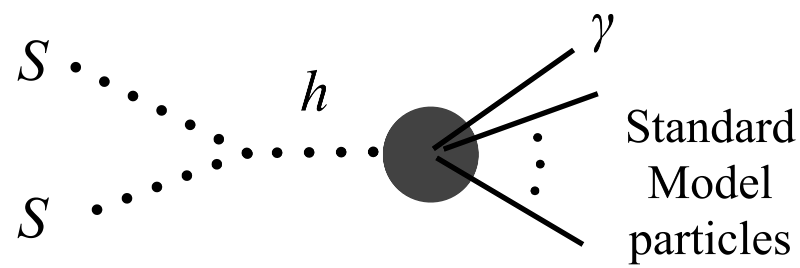
$$\langle \sigma v_{\rm rel} \rangle = \int_{4m_S^2}^{\infty} \frac{s\sqrt{s - 4m_S^2}\, K_1(\sqrt{s}/T)\, \sigma v_{\rm rel}}{16 T m_S^4\, K_2^2(m_S/T)}\, {\rm d}s$$

Minimalist dark matter



Indirect detection

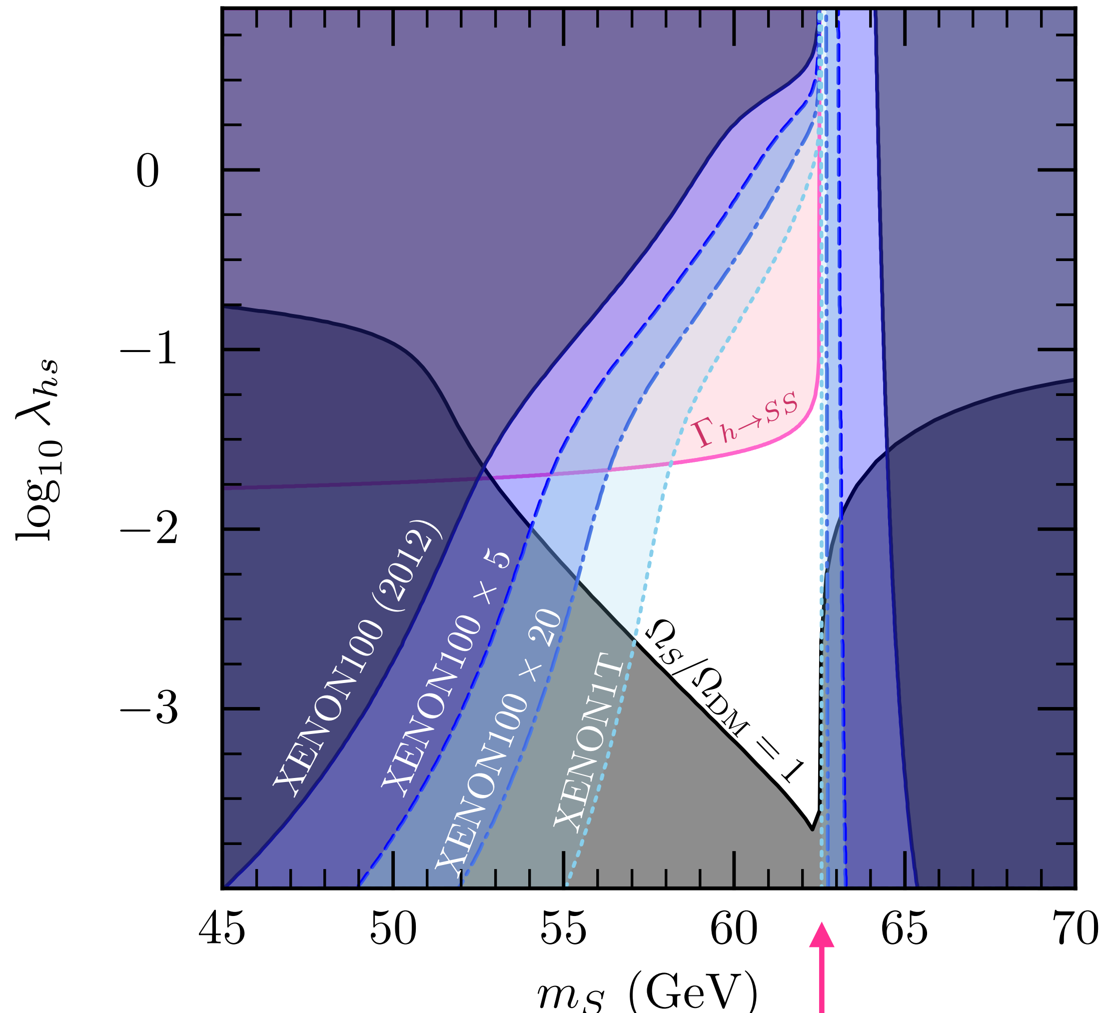
$S + S \to \gamma + \ldots.$



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

No gamma-rays in Fermi Observatory from dwarf spheroidal galaxies

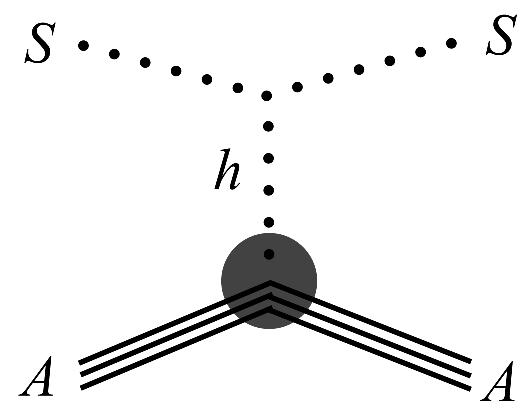
Minimalist dark matter



125 GeV/2=62.5 GeV

Direct detection

$S + A \rightarrow S + A$



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

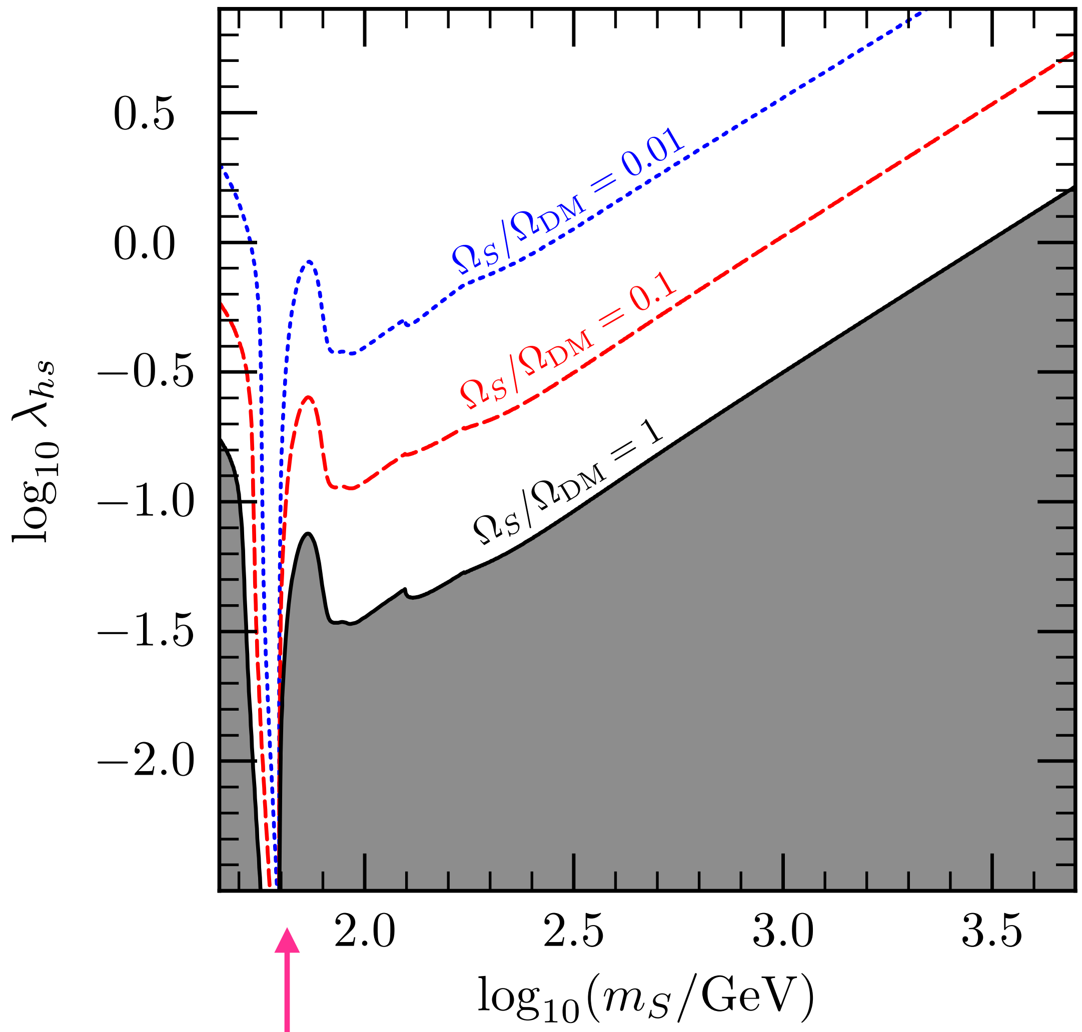
$$f_N = \sum_q f_q = \sum_q \frac{m_q}{m_N} \langle N|\bar{q}q|N\rangle$$

In the figure, limits from XENON experiments

Minimalist dark matter

Heavier masses

Cosmic density



125 GeV/2=62.5 GeV

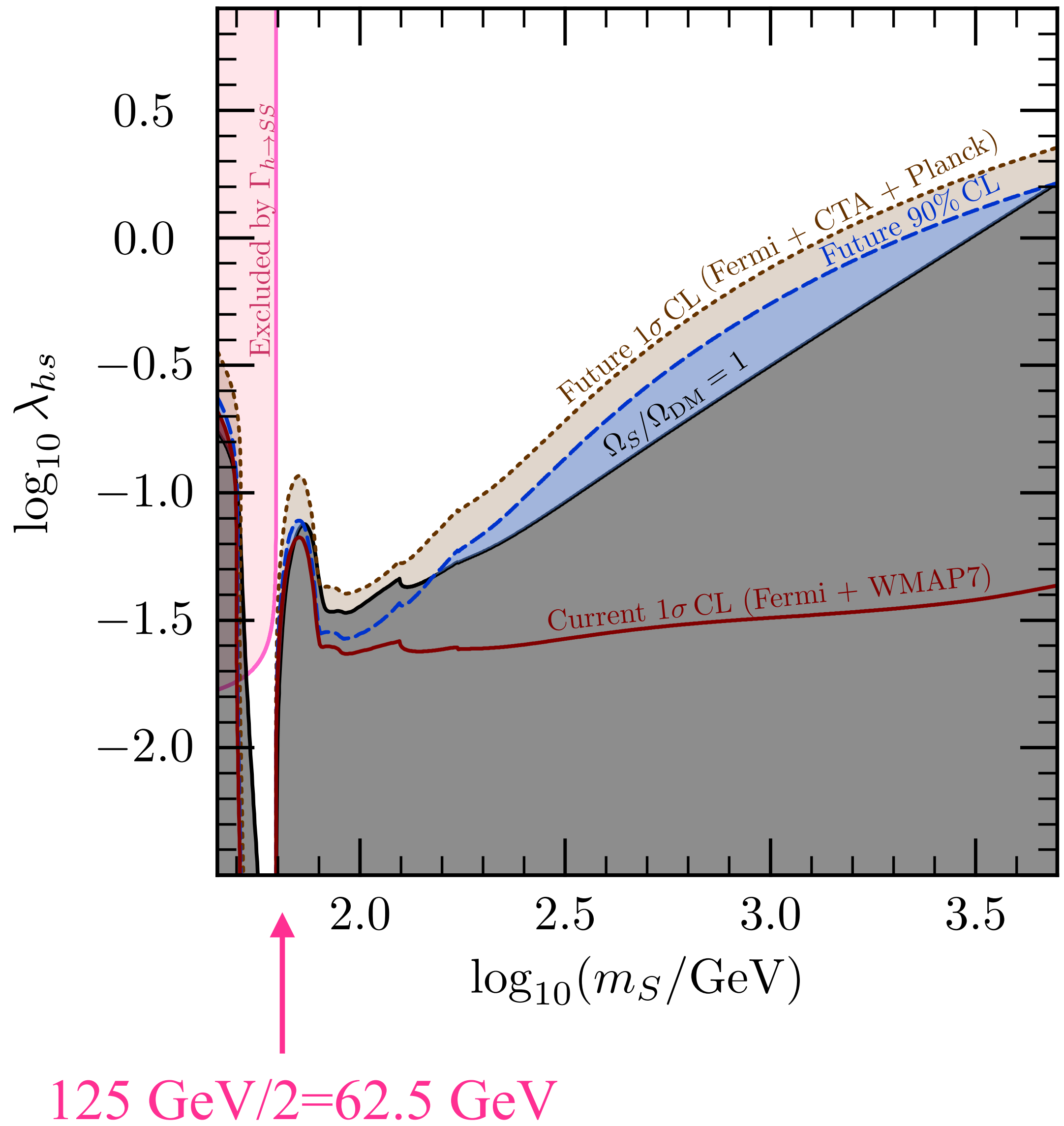
Minimalist dark matter

Heavier masses

Cosmic density

Invisible Higgs width

Indirect detection



Minimalist dark matter

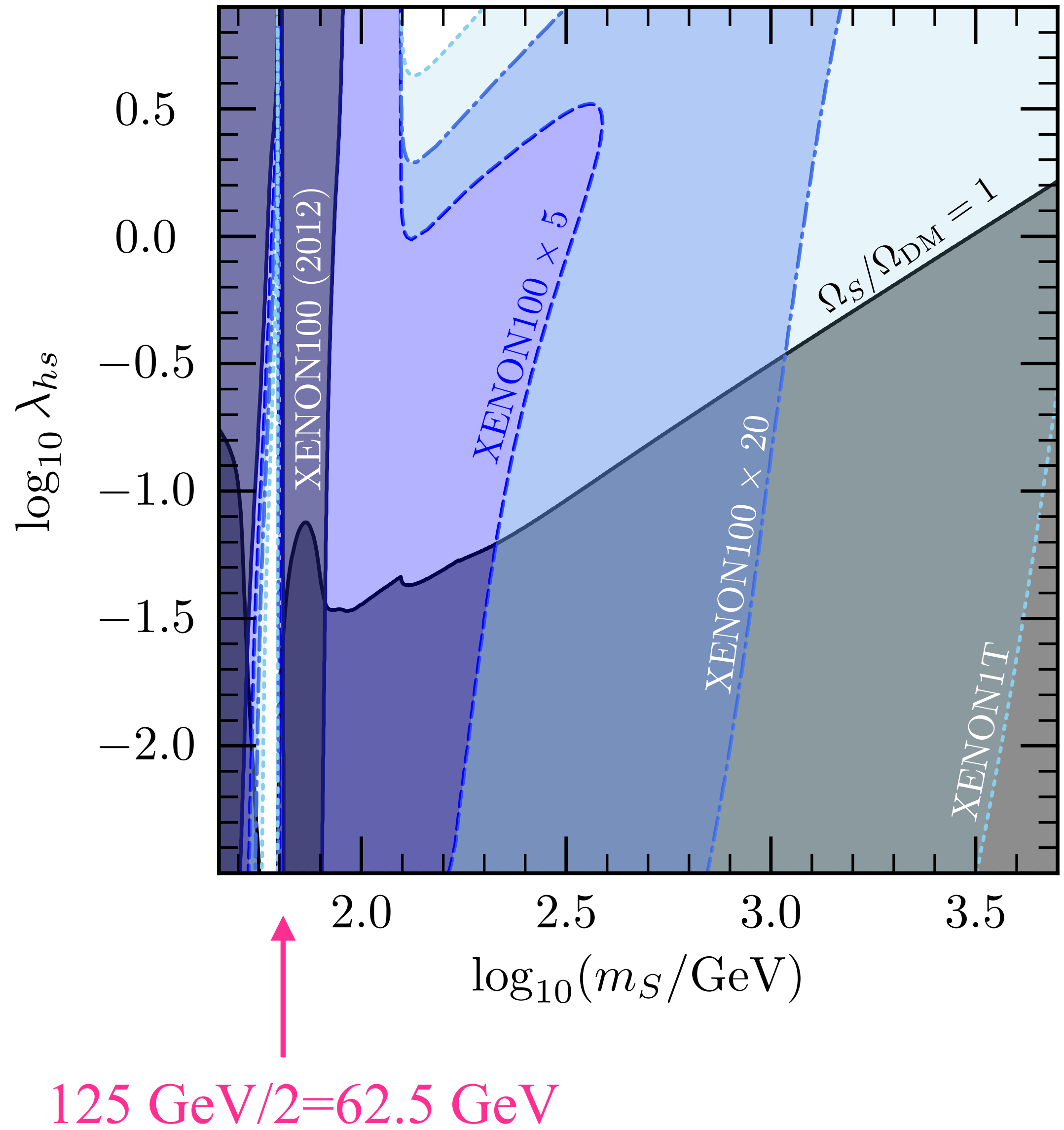
Heavier masses

Cosmic density

Invisible Higgs width

Indirect detection

Direct detection



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

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

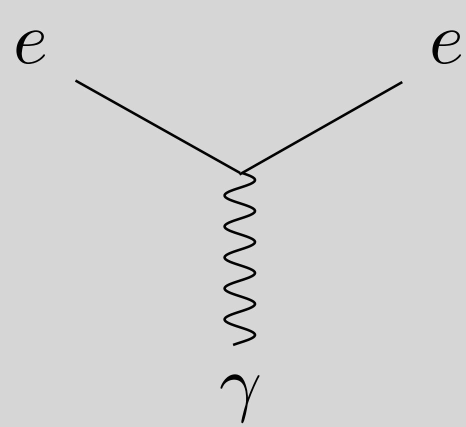
photon A^μ

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 $\tilde{e}_R$

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

Supersymmetric Quantum Electrodynamics

photon A^μ

left-handed electron e_L

right-handed electron e_R

photino λ

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

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

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

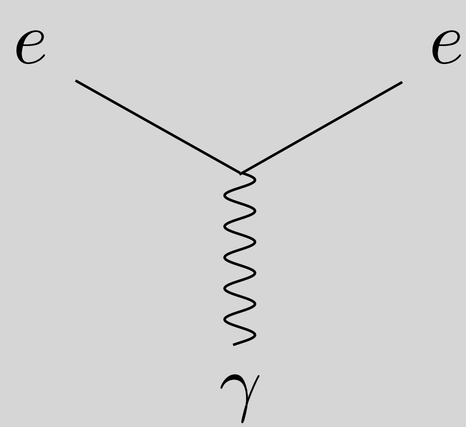
$$+ \partial^\mu\tilde{e}_L^*\partial_\mu\tilde{e}_L - m^2\tilde{e}_L^*\tilde{e}_L - iqA^\mu[\tilde{e}_L^*\partial_\mu\tilde{e}_L - \tilde{e}_L\partial_\mu\tilde{e}_L^*] + q^2A^\mu A_\mu\tilde{e}_L^*\tilde{e}_L$$

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

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

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

"spinor QED"



Supersymmetric Quantum Electrodynamics

photon A^μ

left-handed electron e_L

right-handed electron e_R

photino λ

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

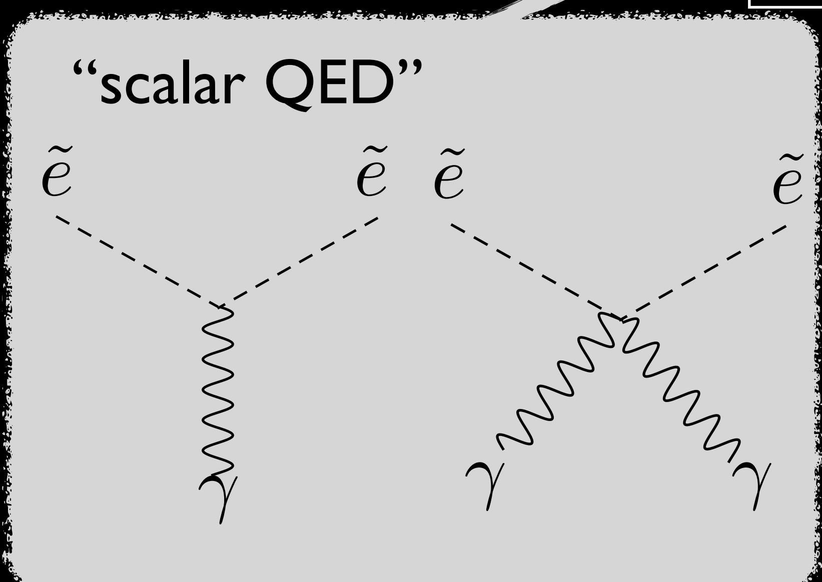
right-handed selectron $\tilde{e}_R$

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

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

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

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



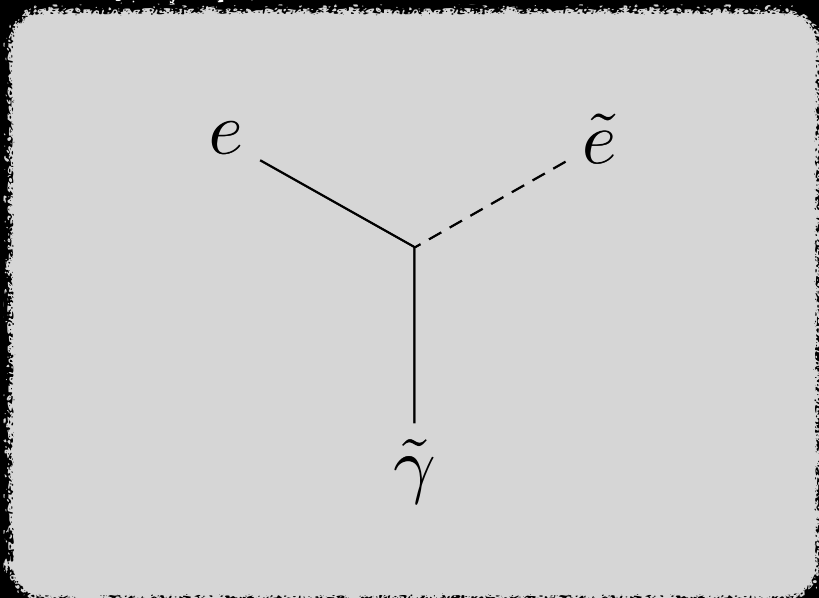
Supersymmetric Quantum Electrodynamics

photon A^μ

photino λ

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

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



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

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

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

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

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

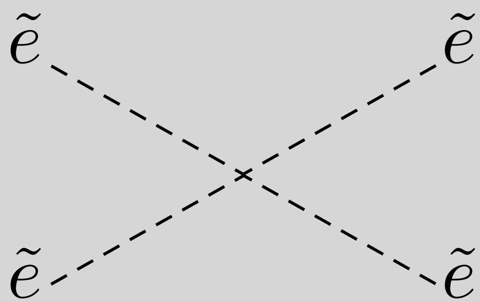
Supersymmetric Quantum Electrodynamics

photon A^μ … photino λ

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

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

“D-term”



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

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

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

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

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

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 $\tilde{e}_R$

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

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 $\tilde{e}_R$

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

Softly-broken superQED

Minimal Supersymmetric Standard Model

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

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

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

- Soft terms

$$\begin{aligned}V_{\mathrm{soft}} = \epsilon_{ij}&\left(-\tilde{\mathbf{e}}^*_{\mathrm{R}}\mathbf{A}_E\mathbf{Y}_E\tilde{\mathbf{l}}^i_{\mathrm{L}}H^j_1 - \tilde{\mathbf{d}}^*_{\mathrm{R}}\mathbf{A}_D\mathbf{Y}_D\tilde{\mathbf{q}}^i_{\mathrm{L}}H^j_1 + \tilde{\mathbf{u}}^*_{\mathrm{R}}\mathbf{A}_U\mathbf{Y}_U\tilde{\mathbf{q}}^i_{\mathrm{L}}H^j_2 - B\mu H^i_1H^j_2 + \mathrm{h.c.}\right)\\
&+ H^{i*}_1m^2_1H^i_1 + H^{i*}_2m^2_2H^i_2 + \tilde{\mathbf{q}}^{i*}_{\mathrm{L}}\mathbf{M}^2_Q\tilde{\mathbf{q}}^i_{\mathrm{L}} + \tilde{\mathbf{l}}^{i*}_{\mathrm{L}}\mathbf{M}^2_L\tilde{\mathbf{l}}^i_{\mathrm{L}} + \tilde{\mathbf{u}}^*_{\mathrm{R}}\mathbf{M}^2_U\tilde{\mathbf{u}}_{\mathrm{R}} + \tilde{\mathbf{d}}^*_{\mathrm{R}}\mathbf{M}^2_D\tilde{\mathbf{d}}_{\mathrm{R}}\\
&+ \tilde{\mathbf{e}}^*_{\mathrm{R}}\mathbf{M}^2_E\tilde{\mathbf{e}}_{\mathrm{R}} + \tfrac{1}{2}M_1\tilde{B}\tilde{B} + \tfrac{1}{2}M_2(\tilde{W}^3\tilde{W}^3 + 2\tilde{W}^+\tilde{W}^-) + \tfrac{1}{2}M_3\tilde{g}\tilde{g}.\end{aligned}$$

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

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

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

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

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

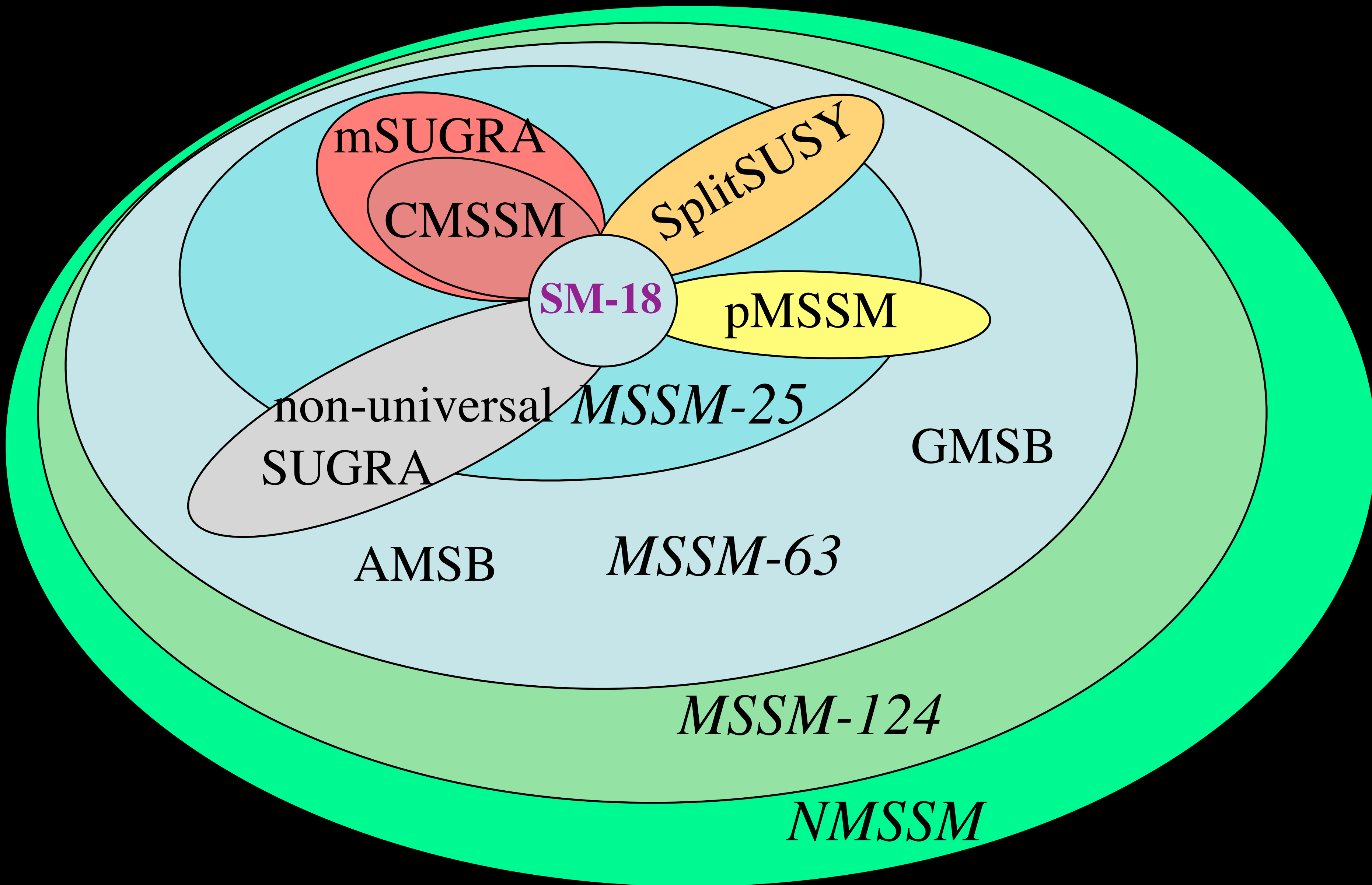
$$\mathcal{M}_{\tilde{\nu}}^2 = \mathbf{M}_L^2 + D_{LL}^{\nu} \mathbf{1}$$

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

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

$$D_{\mathrm{RR}}^f = m_Z^2 \cos(2\beta) e_f \sin^2\theta_W$$

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 ($f_{\rm PQ}$~10^{11}GeV)

thermally and non-thermally produced in early universe

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

scattering cross section with ordinary matter

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

Gravitino dark matter ($m_{\rm Pl}$~10^{19}GeV)

thermally and non-thermally produced in early universe

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

scattering cross section with ordinary matter

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

Neutralino dark matter

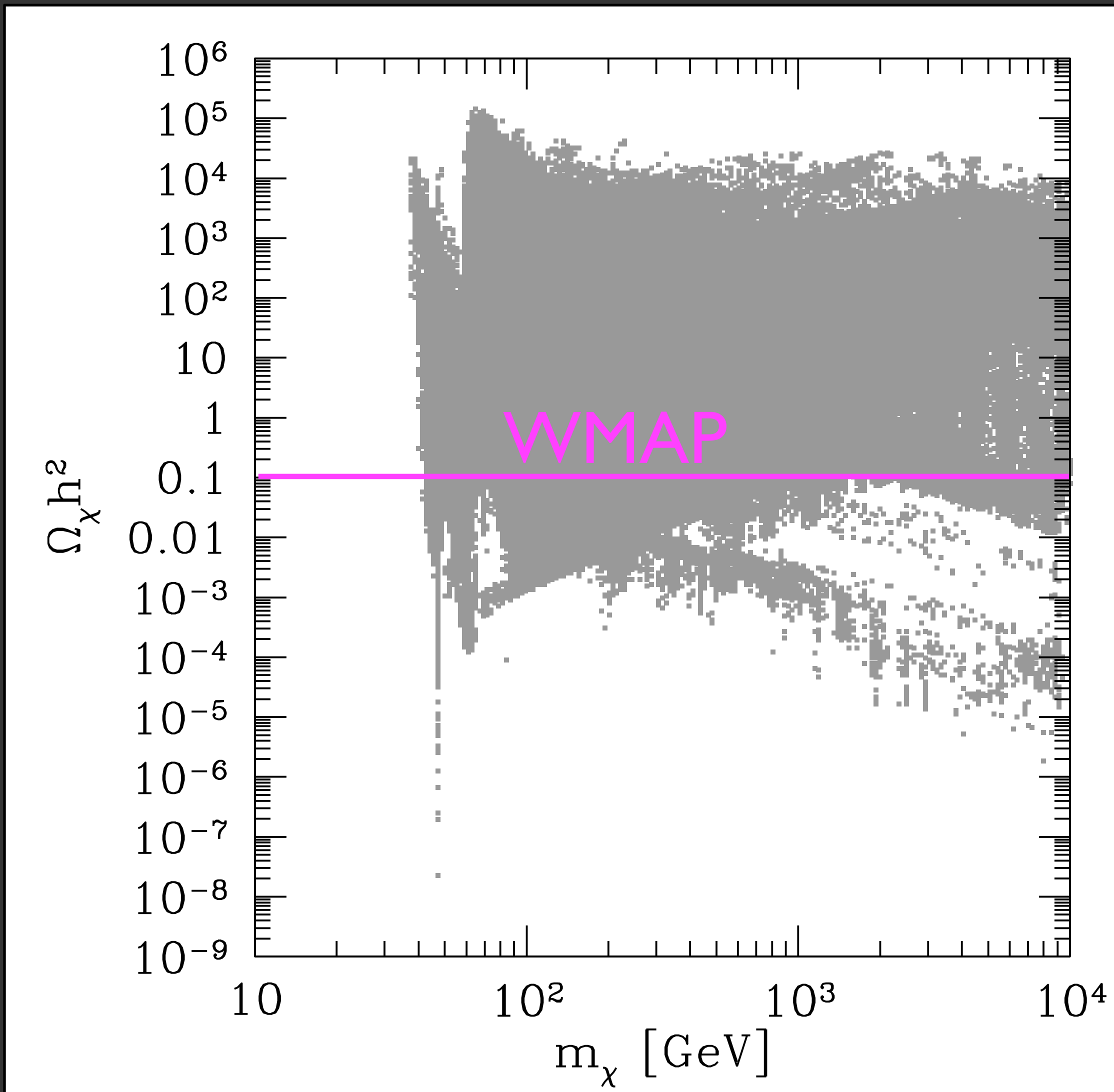
Process	Diagrams			
	s	t	u	p
$\chi_i^0\chi_j^0 \to B_m^0 B_n^0$	$H^0_{1,2,3}, Z$	χ_k^0	χ_l^0	
$\chi_i^0\chi_j^0 \to B_m^- B_n^+$	$H^0_{1,2,3}, Z$	χ_k^+	χ_l^+	
$\chi_i^0\chi_j^0 \to f\bar{f}$	$H^0_{1,2,3}, Z$	$\tilde{f}_{1,2}$	$\tilde{f}_{1,2}$	
$\chi_i^+\chi_j^0 \to B_m^+ B_n^0$	H^+, W^+	χ_k^0	χ_l^+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

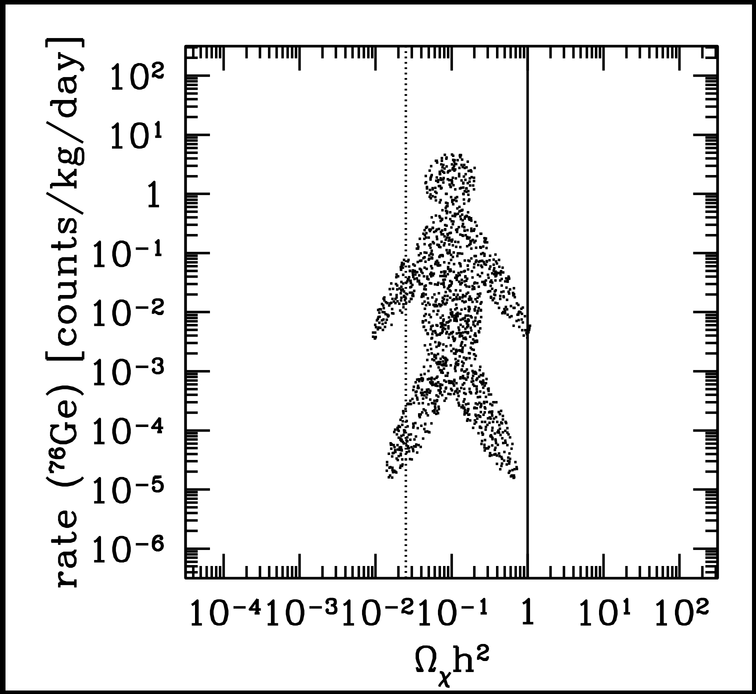


Range of $\Omega_\chi h^2$ for millions of points in minimal supergravity (mSUGRA)

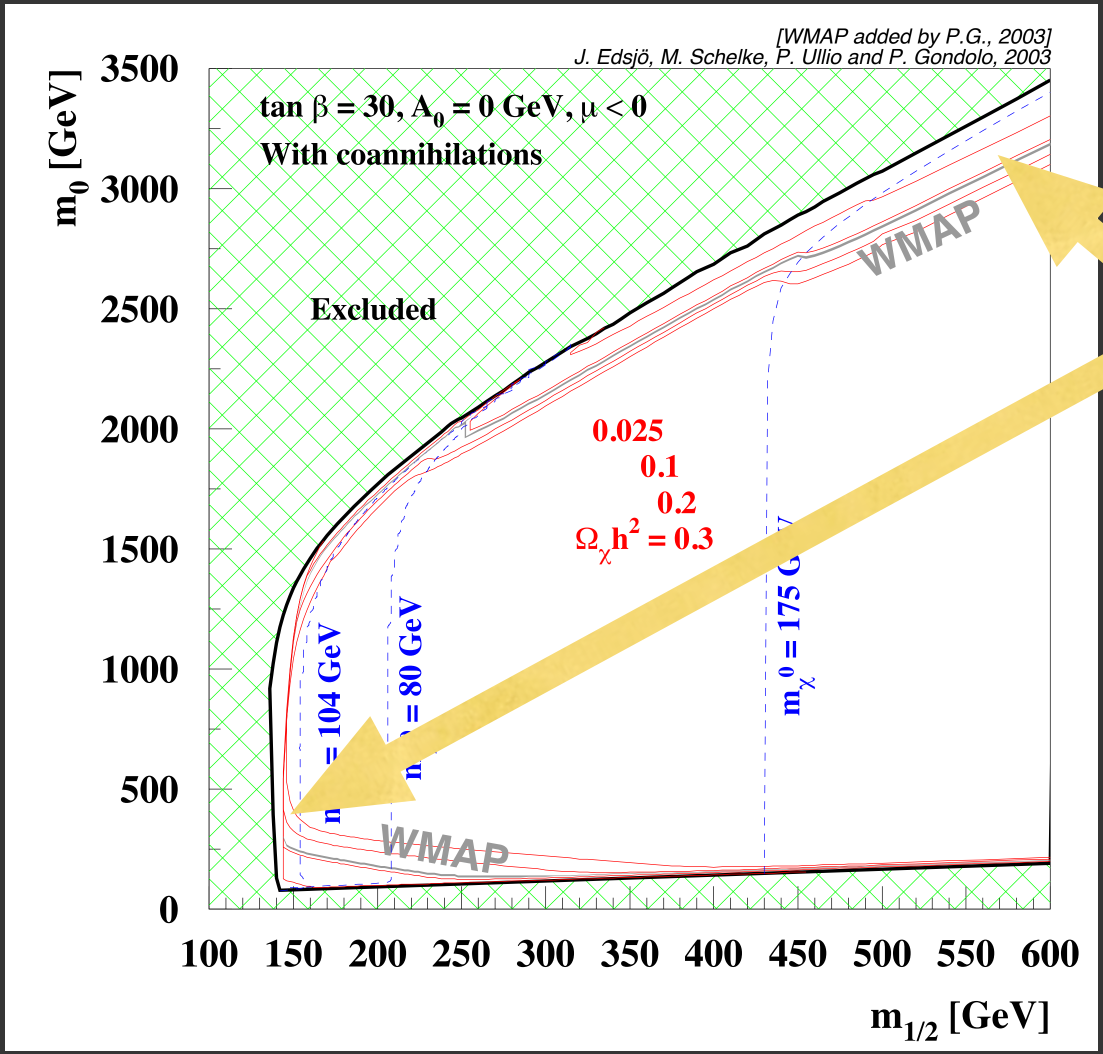
Ted Baltz 2005

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

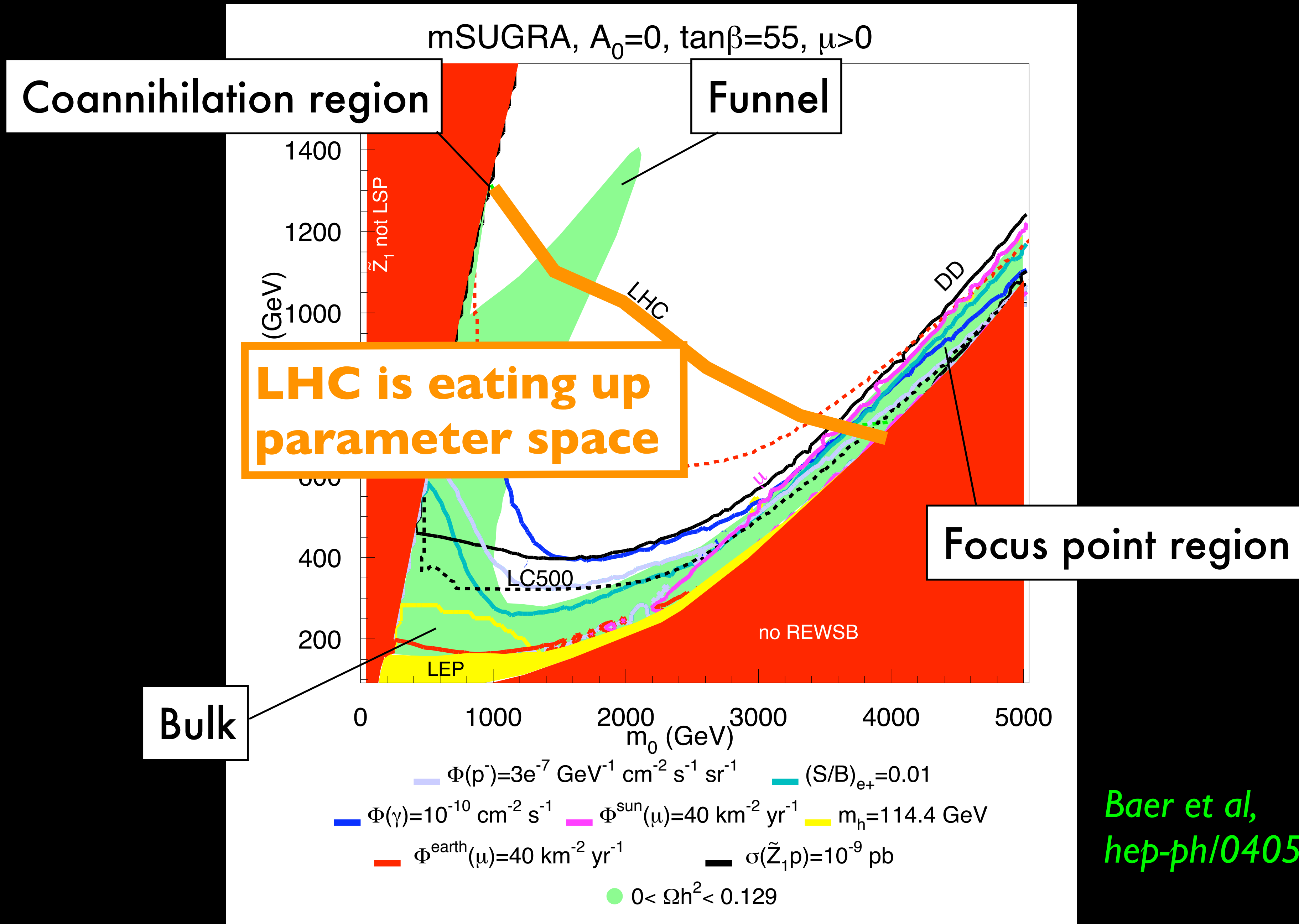


Narrow regions of $\Omega_\chi h^2$ within the WMAP range in minimal supergravity (mSUGRA)

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

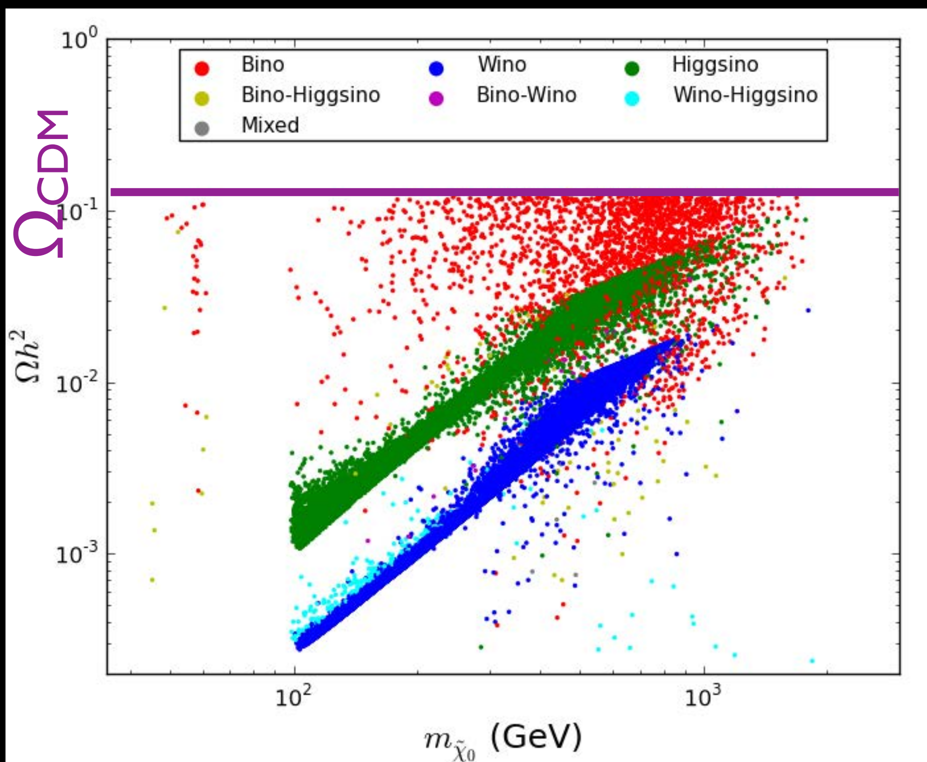
Cahill-Rowell et al 1305.6921

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

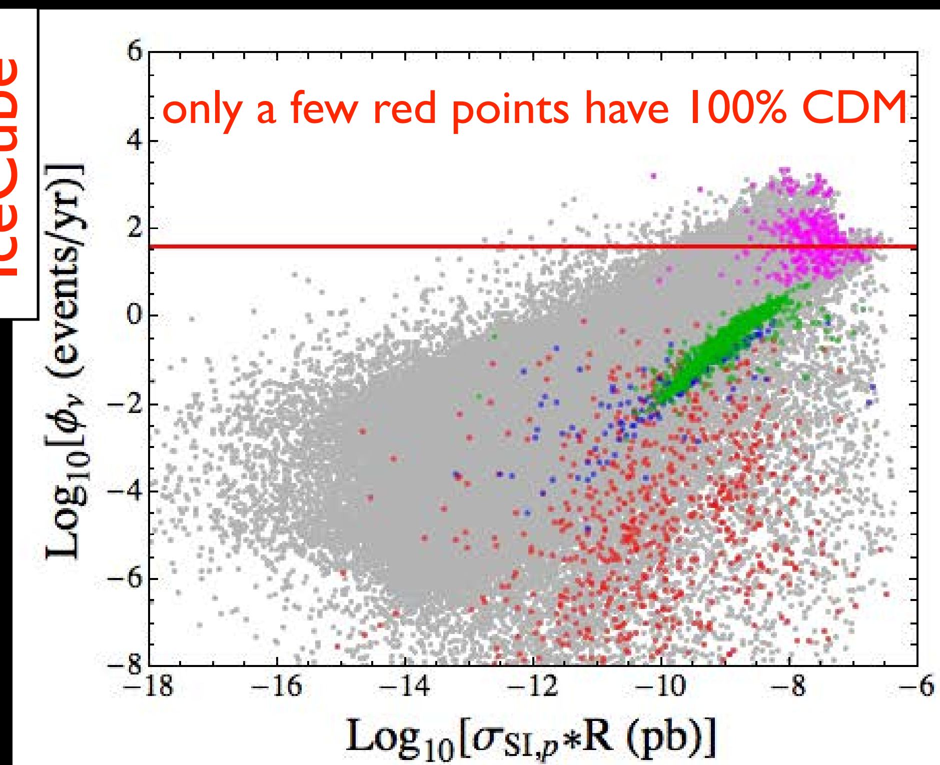
pMSSM (phenomenological MSSM)

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

(19 parameters)



"IceCube"

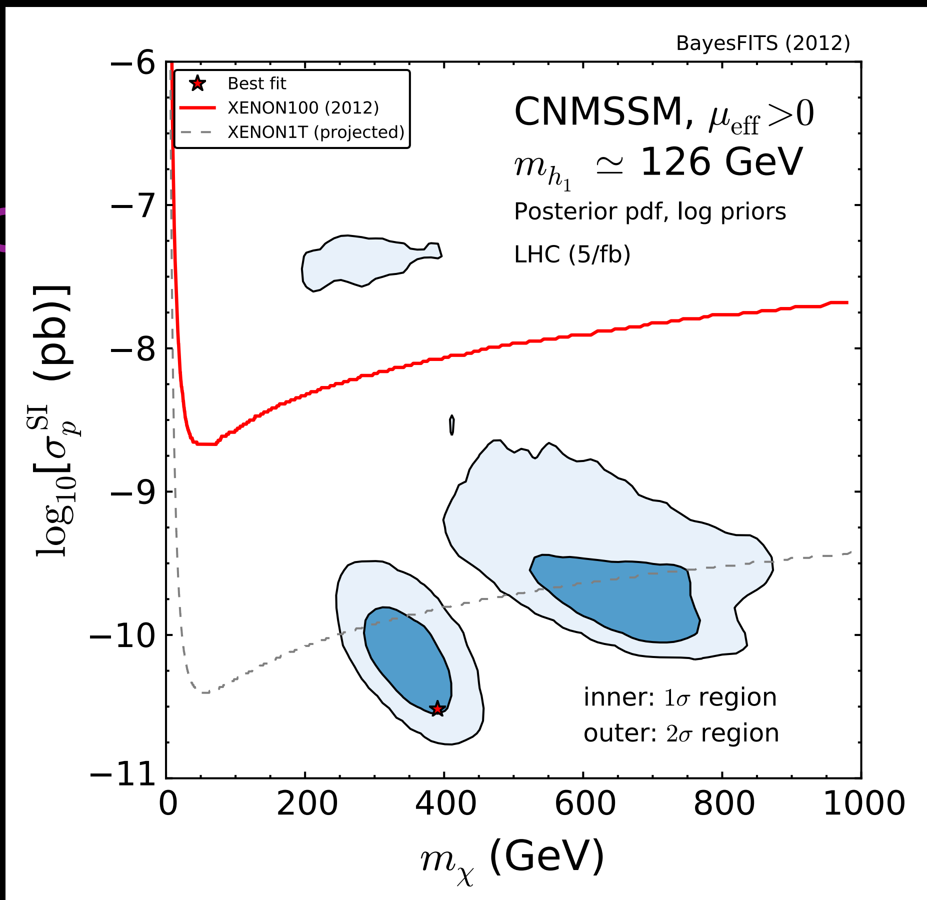


"Direct Detection"

Neutralino dark matter: impact of LHC

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

CNMSSM: Alive and well!



NMSSM (Next-to-MSSM)

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

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

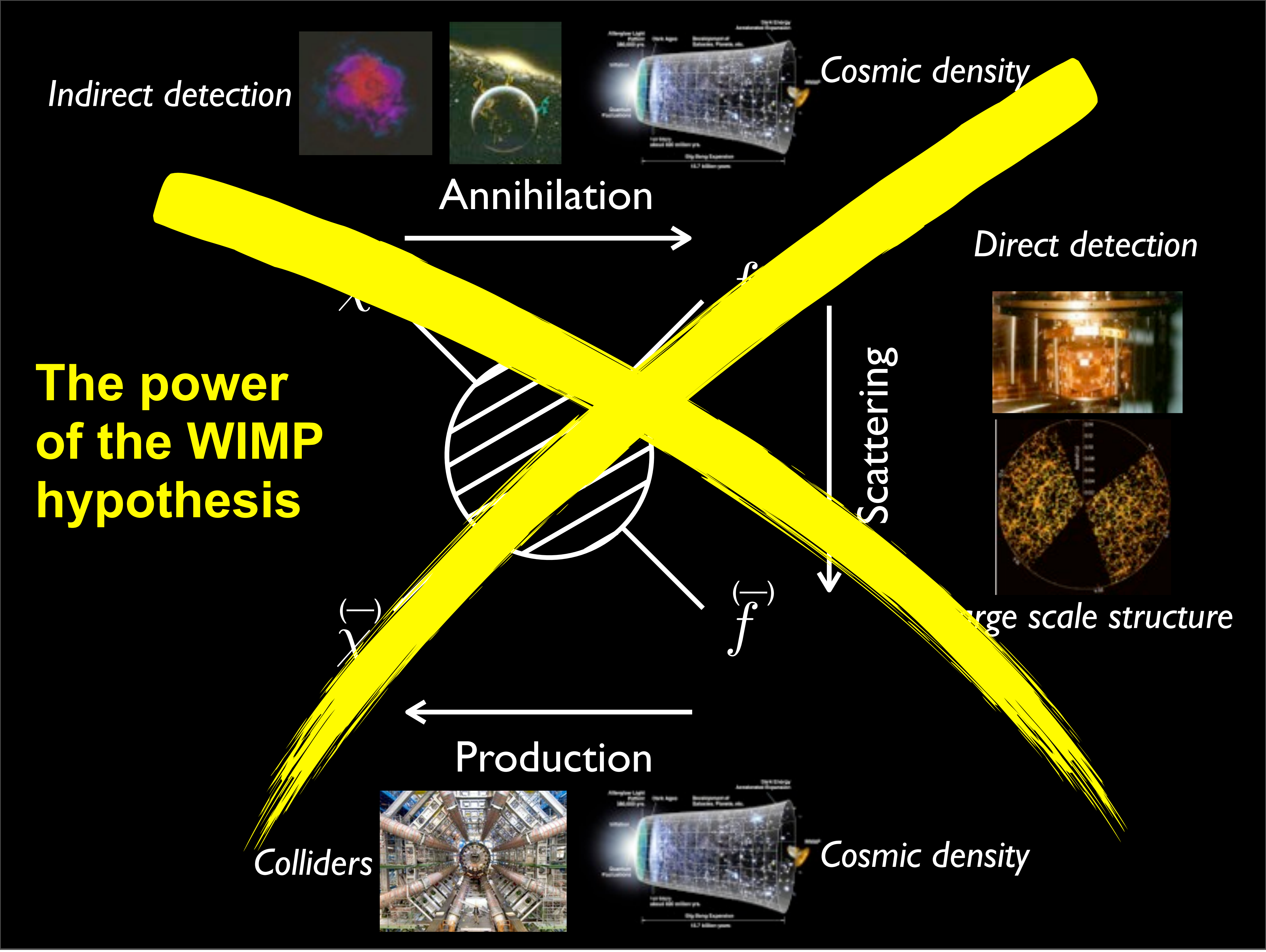
Constrained NMSSM

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

GUT & radiative EWSB

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

Axions


Indirect detection
Cosmic density
Annihilation
Direct detection
Scattering
The power
of the WIMP
hypothesis
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} $e\mathrm{cm}$, 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

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

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

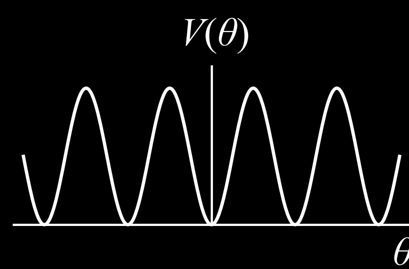
New lagrangian $\mathcal{L}_a = -\frac{1}{2}\partial^\mu a \partial_\mu a + \frac{a}{f_a}\frac{g^2}{32\pi^2}F_a^{\mu\nu}\tilde{F}_{a\mu\nu} + \mathcal{L}_{\rm int}(a)$

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

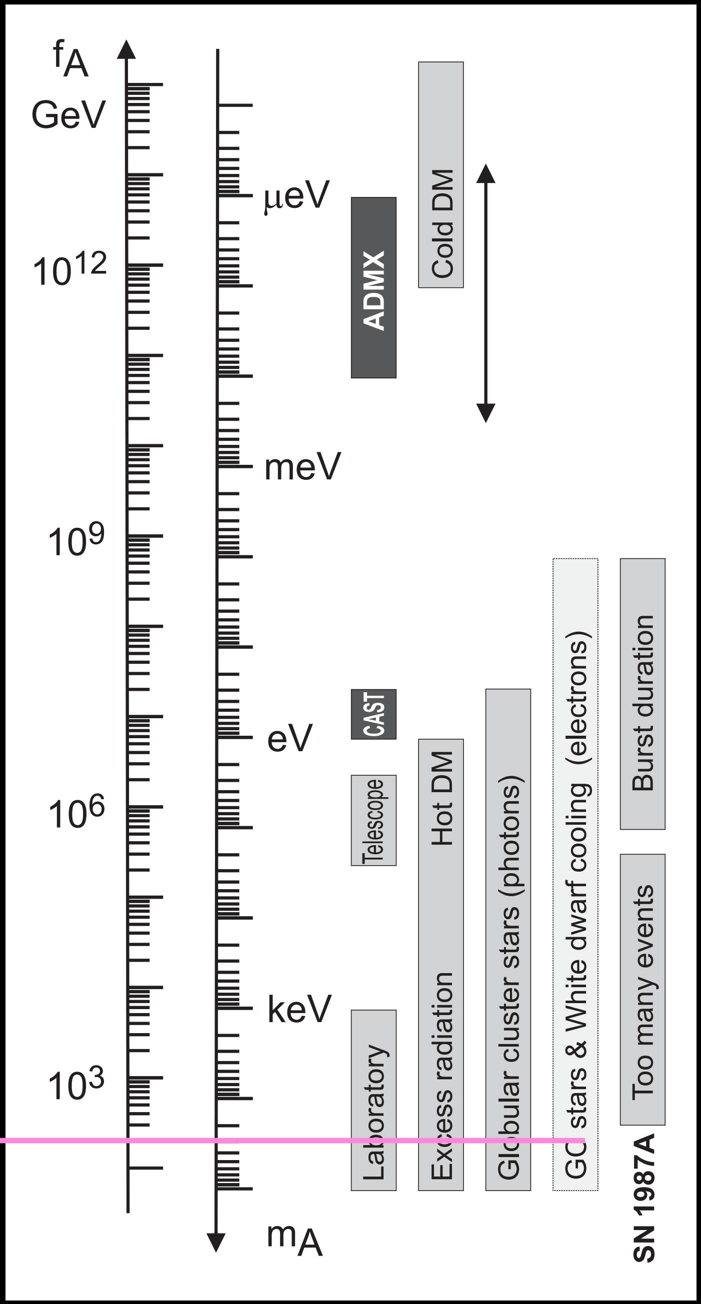
"Whenever you come up with a good idea, somebody tries to copy it."

(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

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

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

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

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

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

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
$H_{\rm I}$	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, $H_{\rm I}$ and one constraint Ω_a=$\Omega_{\rm CDM}$

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 $T < \Lambda \approx \Lambda_{QCD}$

- 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) $\bar{r} = \frac{1-\beta}{3\beta-1} \ln(t_1/\delta)$

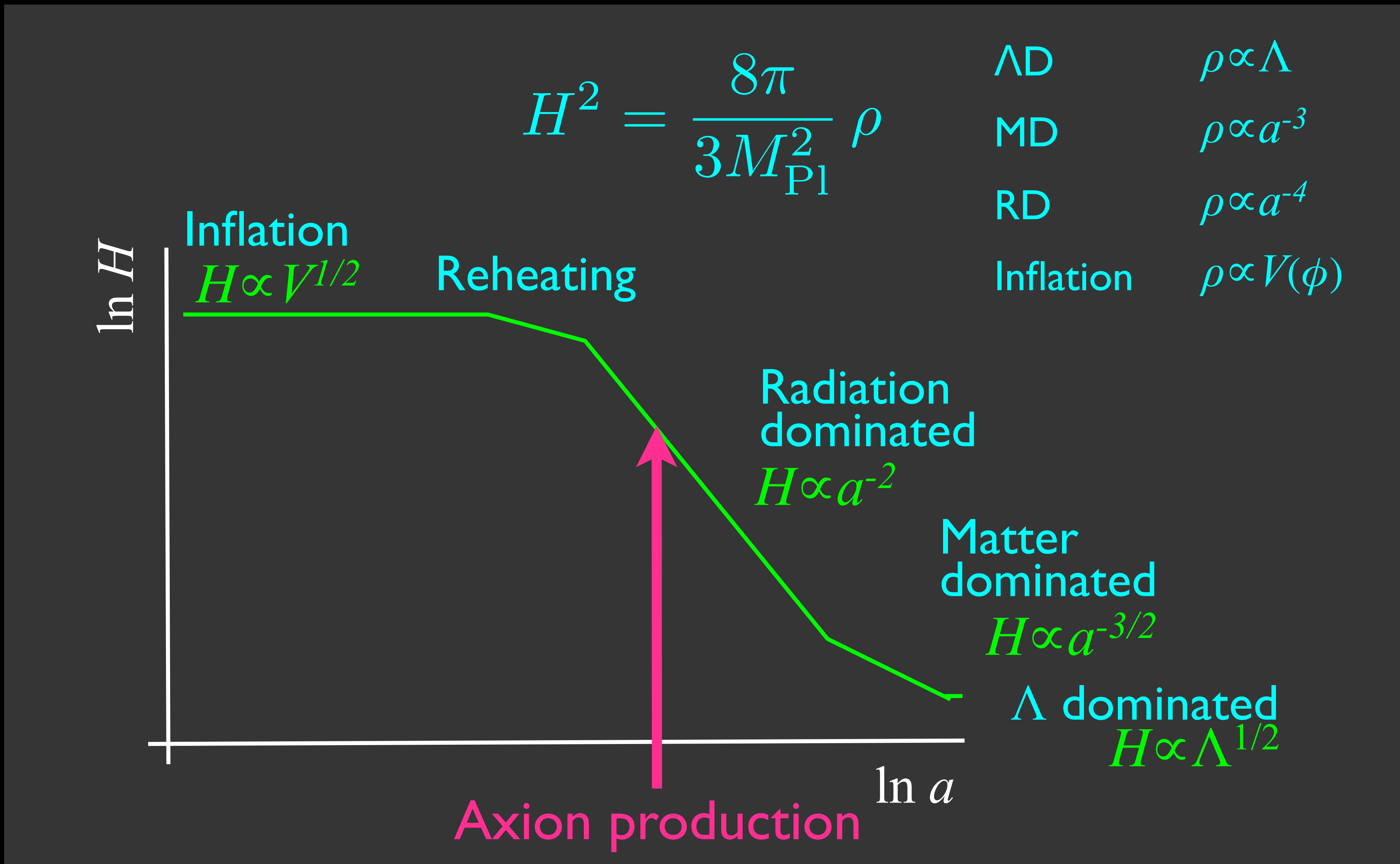
Fast-oscillating strings (Harari-Hagmann-Chang-Sikivie) $\bar{r} = \frac{1-\beta}{3\beta-1} 0.8$

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

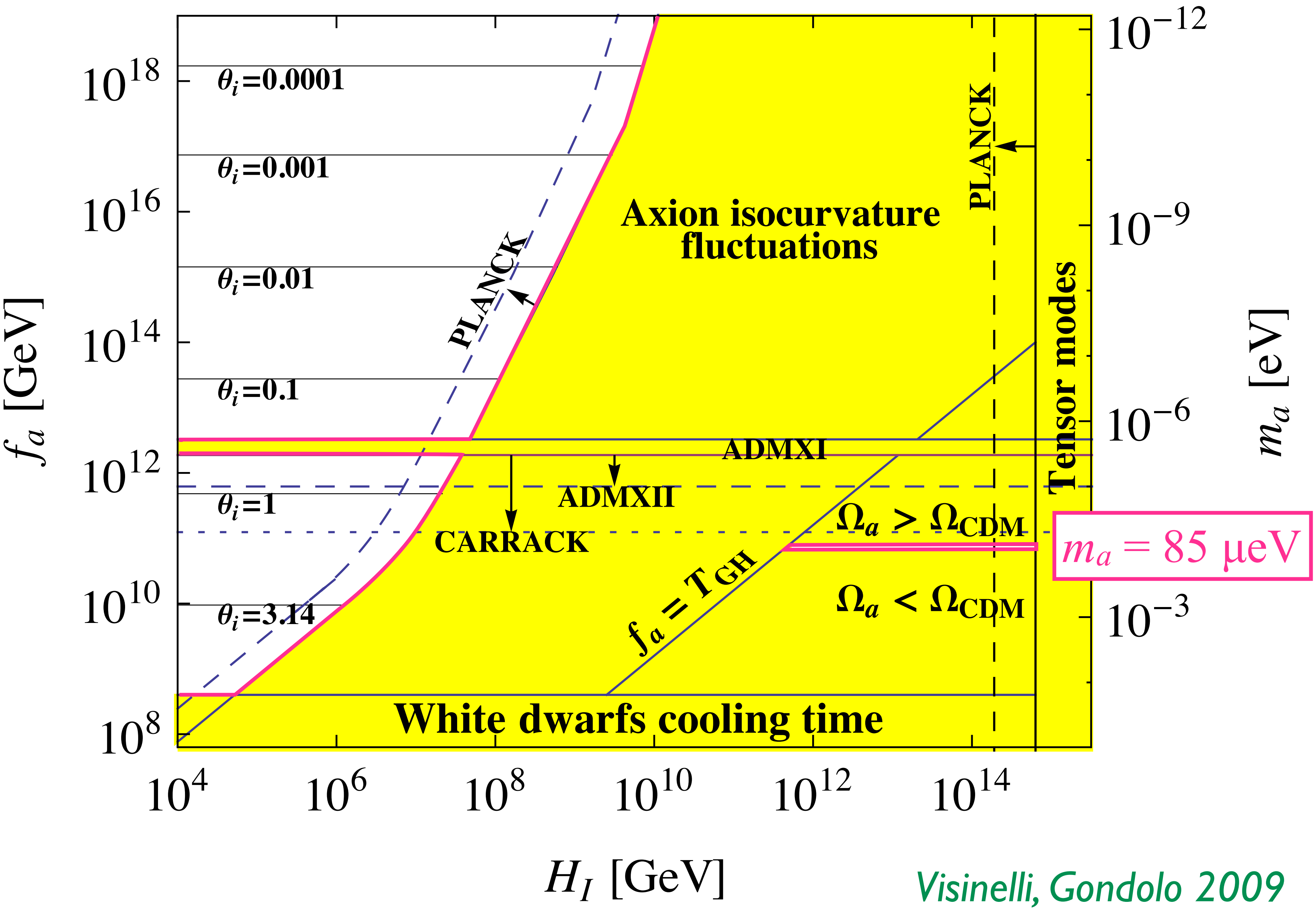
with $a(t) \propto t^\beta$

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

Standard cosmology



Axion CDM - Standard cosmology



Visinelli, Gondolo 2009

Axion condensate

Sikivie, Yang 2009; Sikivie, Banik 2013

- *Axions thermalize due to gravitational interactions*
- *An axionic Bose-Einstein condensate is formed at*

$$T_\gamma \sim 500 \text{ eV} \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{1/2}$$

- *Dark halos are vortices of axion BEC*
- *The baryon angular momentum distributions are better explained than in standard CDM*

Bose-Einstein Condensate

If (identical bosons,
high phase-space density,
conserved total number,
thermalized)

then

{most of them go to
the lowest energy state}

Caveats on cosmic density

"If you want to lie and not be caught,
testify about far away things."

Cosmic density: caveats

- Velocity dependence of cross section
  - p-waves, resonances, Sommerfeld enhancement
- Non-thermal production of dark matter particles
  - from decay of heavy particles
- Non-standard expansion before nucleosynthesis
  - low-temperature reheating, kination

Cosmic density of thermal WIMPs

- In general, $\langle\sigma v\rangle$ is a complicated function of the WIMP mass m and the WIMP velocity v, including resonances, thresholds, and coannihilations.
- At small v, $\langle\sigma v\rangle$ can be expanded as

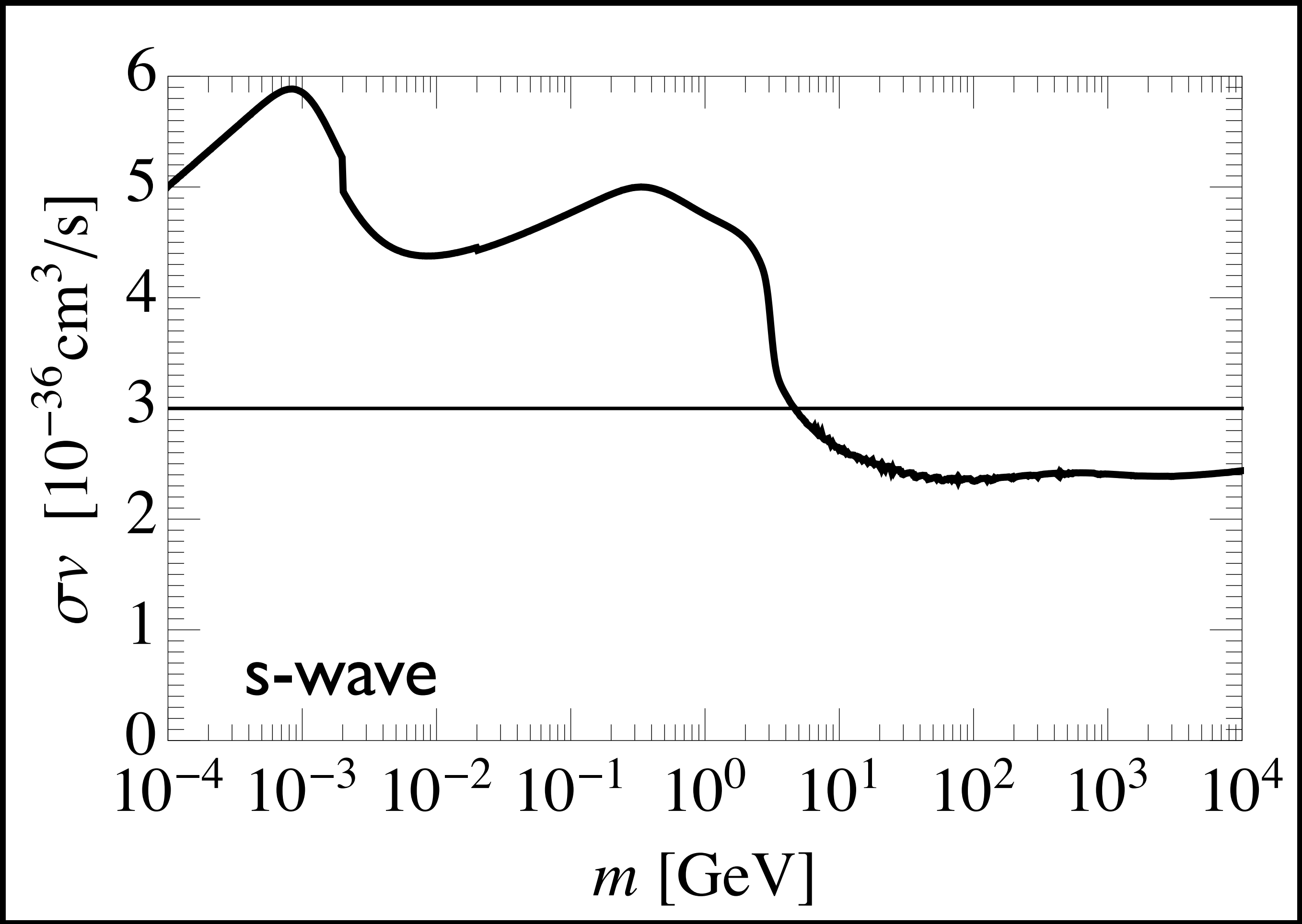
$$\langle\sigma v\rangle = a + bv^2 + \cdots \qquad \text{s-wave}$$

$$\langle\sigma v\rangle = bv^2 + cv^4 + \cdots \qquad \text{p-wave}$$

(These expansions are not good near a resonance or threshold.)

Cosmic density of thermal WIMPs

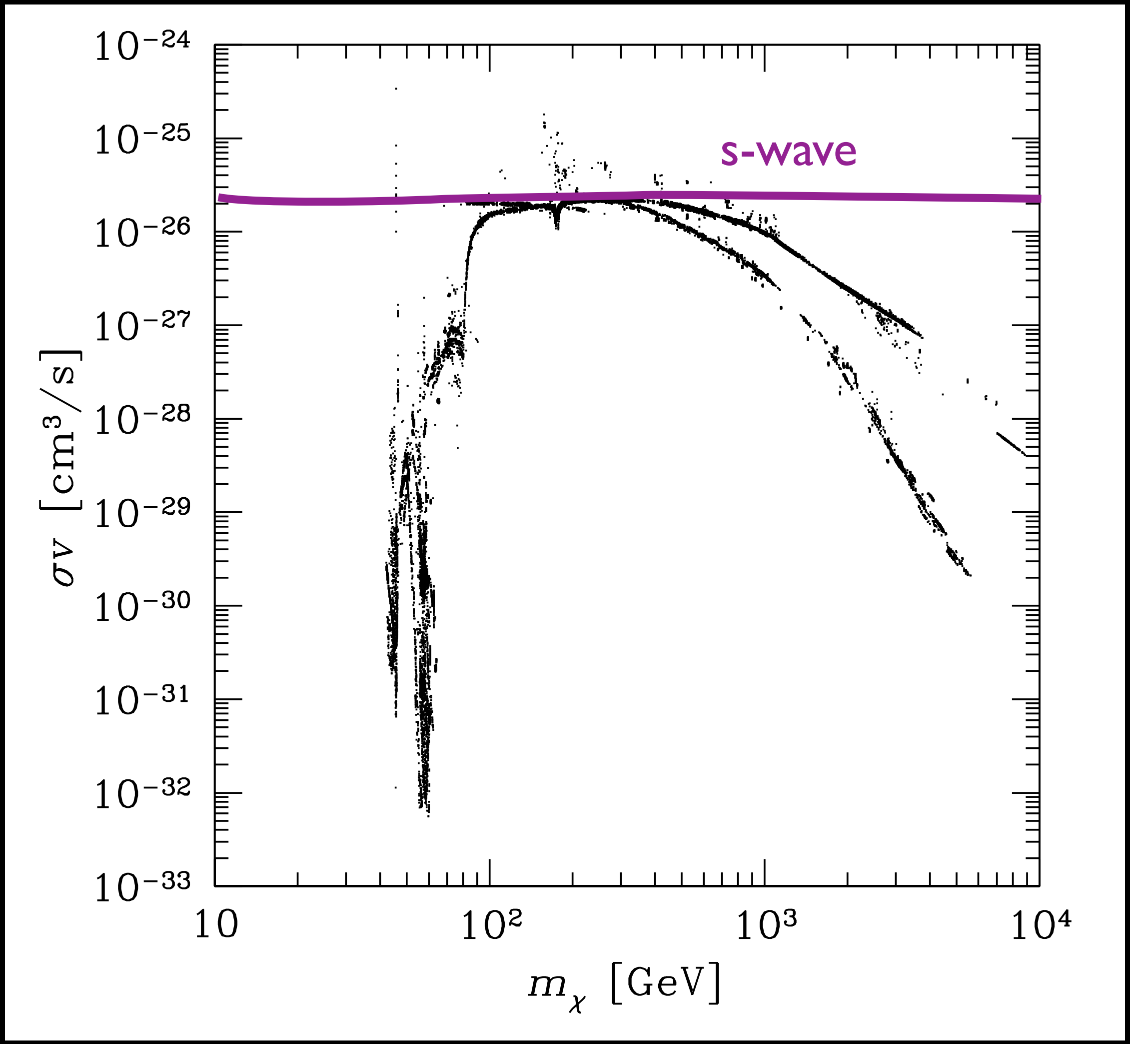
$\langle\sigma v\rangle$=const required for right cosmic density



Steigman, Dasgupta, Beacom 2012
Gondolo, Steigman (in prep.)

Cosmic density of WIMPs: caveats

σv in galaxies (entering gamma-ray predictions) may be different from $\sigma v \simeq 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$



Example

lightest neutralino in minimal supersymmetric standard model

Resonances, p-waves, coannihilations brake simplest relation between cosmic density and annihilation cross section

Cosmic density: caveats

- Velocity dependence of cross section
  - p-waves, resonances, Sommerfeld enhancement
- Non-standard expansion before nucleosynthesis
  - low-temperature reheating, kination
- Non-thermal production of dark matter particles
  - from decay of heavy particles

The expansion of the Universe

The Friedman equation governs the evolution of the scale factor a

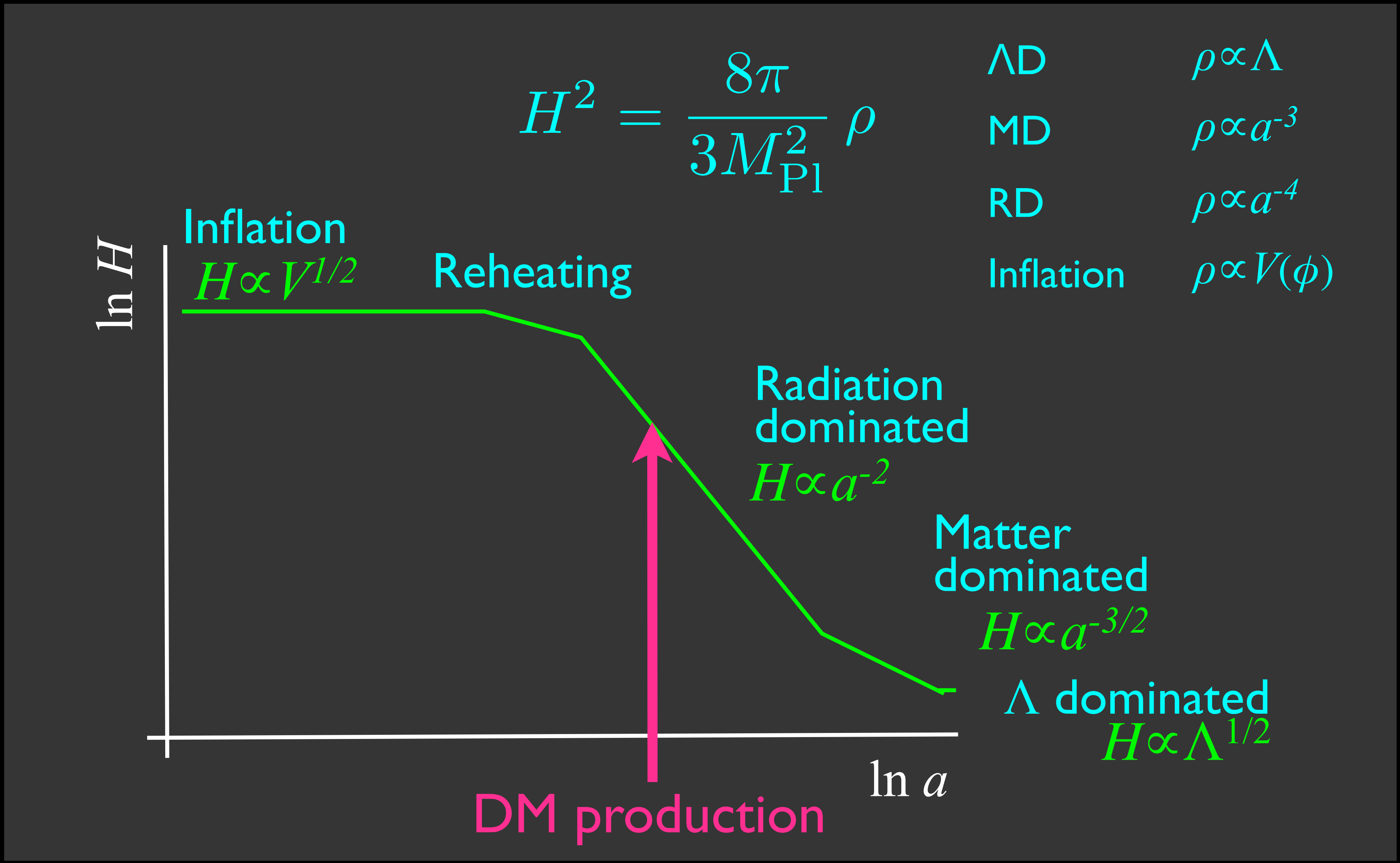
$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\,\rho$$

$H = \dot{a}/a =$ Hubble parameter = expansion rate

$\rho =$ total energy density

Dominant dependence of ρ on a determines the expansion rate

Standard cosmology



Non-standard cosmology

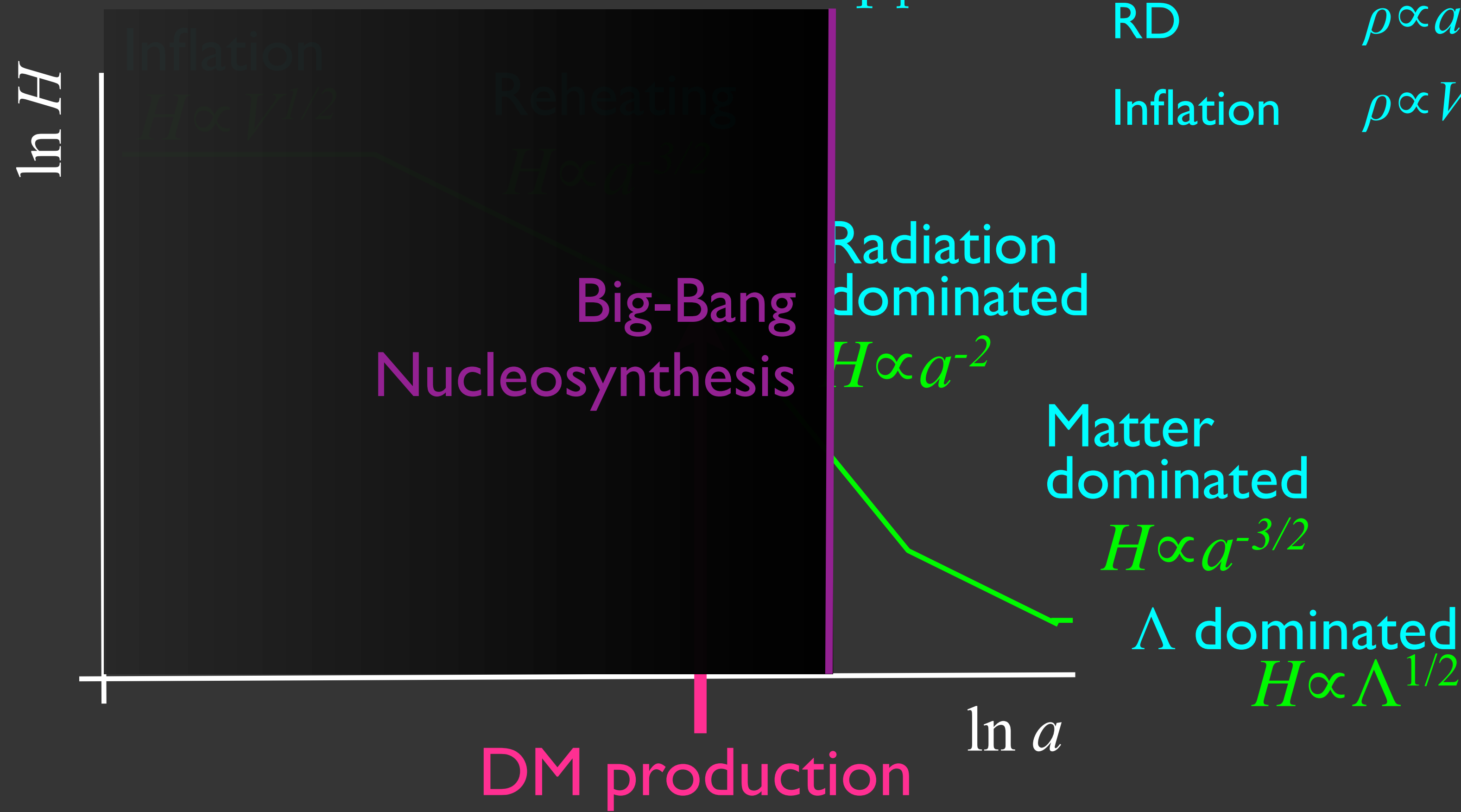
$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\,\rho$$

ΛD $\rho \propto \Lambda$

MD $\rho \propto a^{-3}$

RD $\rho \propto a^{-4}$

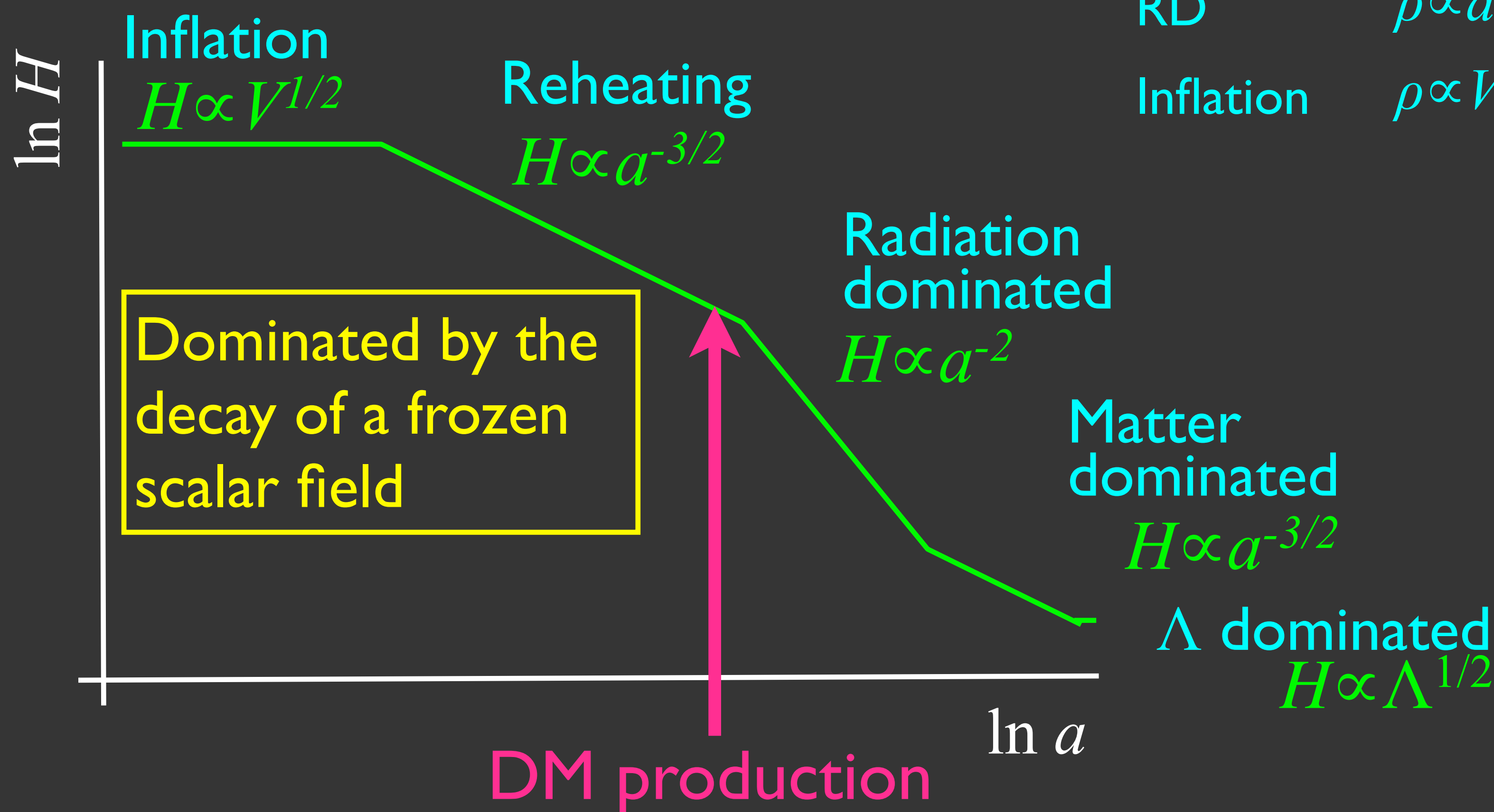
Inflation $\rho \propto V(\phi)$



Low Temperature Reheating cosmology

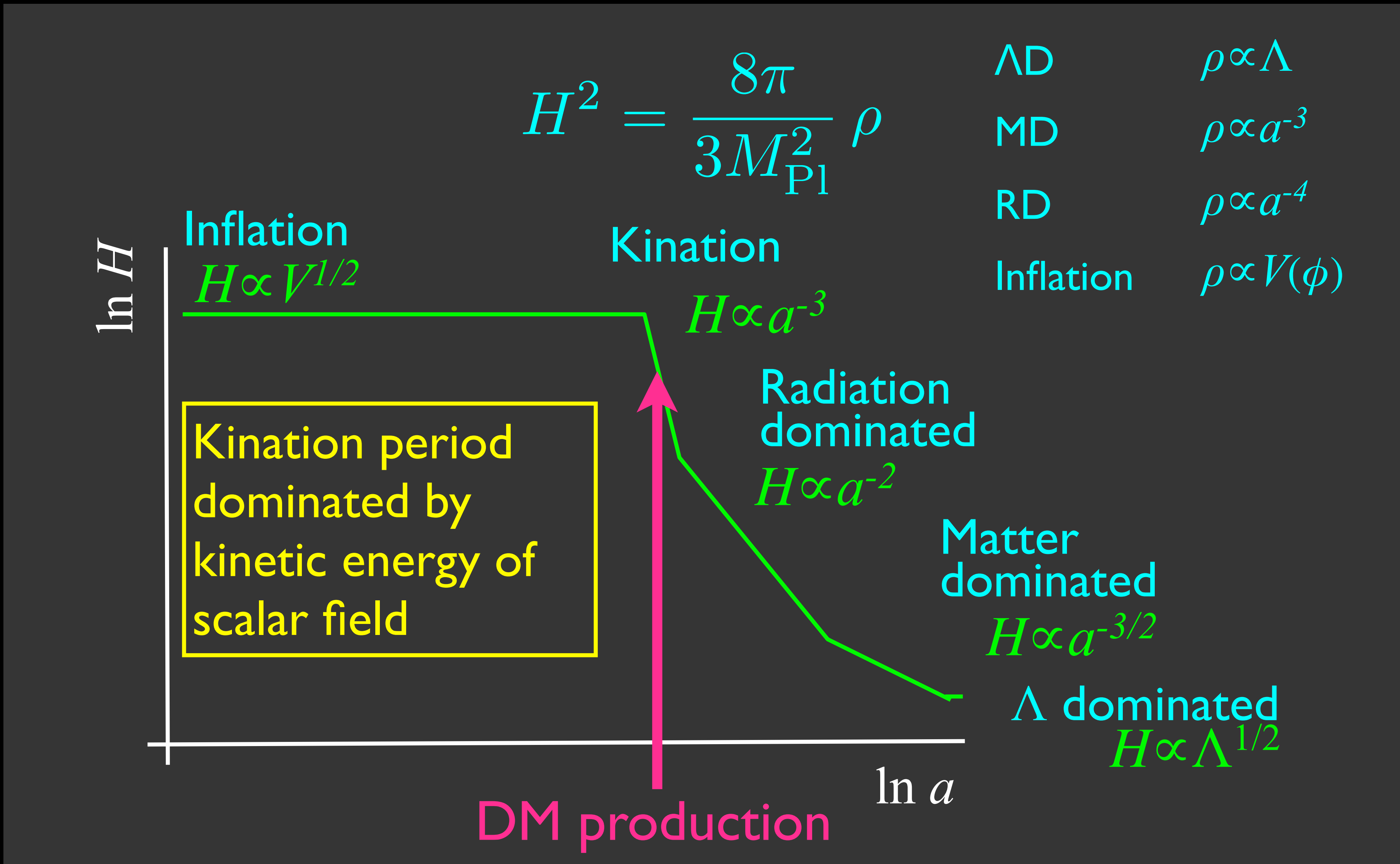
$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\rho$$

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



Turner 1983, Scherrer, Turner 1983, Dine, Fischler 1983

Kination cosmology



Ford 1987

How to get a non-standard abundance

- ***Decrease*** the DM density by producing photons after freeze-out [*entropy dilution*].

  We only measure the ratio of DM and photon densities at the present cosmological epoch, so increasing the number of photons is tantamount to decreasing the DM density

How to get a non-standard abundance

- ***Decrease*** the DM density by producing photons after freeze-out [*entropy dilution*].
- ***Increase*** the density by creating DM from particle decays (or topological defects) [*non-thermal production*], or by increasing the expansion rate at freeze-out [*quintessence, etc.*].

Freeze-out occurs when the annihilation rate equals the expansion rate. Since the annihilation rate is proportional to the particle density, a higher expansion rate means a higher annihilation rate, which means a higher density.

How to get a non-standard abundance

- ***Decrease*** the DM density by producing photons after freeze-out [*entropy dilution*].

- ***Increase*** the density by creating DM from particle decays (or topological defects) [*non-thermal production*], or by increasing the expansion rate at freeze-out [*quintessence, etc.*].

..... Barrow 1982; Kamionkowski, Turner 1990; McDonald 1991; Jeannerot, Zhang, Brandenberger 1999; Chung, Kolb, Riotto 1999; Lin et al 2000; Moroi, Randall 2000; Giudice, Kolb, Riotto 2001; Salati 2002; Fornengo, Kolb, Scopel 2002; Allahverdi, Drees 2002, 2004; Fujii, Hamaguchi 2002; Fujii, Ibe 2003; Profumo, Ullio 2003; Pallis 2004; Catena et al 2004, 2007; Okada, Seto 2004; Gelmini, Gondolo 2006; Gelmini et al. 2006, 2007; Donato et al 2007; Drees et al 2006, 2007; .....

Decrease the DM density

- Produce entropy after dark matter freeze-out
  - add massive particles that decay or annihilate late (e.g. NLSP, ...)

Analogous to $e^+ + e^- \longrightarrow \gamma + \gamma$ at $T \sim 1$ MeV,
which increases the photon temperature and entropy,
while the neutrino temperature is unaffected,

$$T_\nu = (4/11)^{1/3}\, T_\gamma.$$

This decreases the neutrino density with respect to the photon density,

$$n_\nu = (4/11)\, n_\gamma\,.$$

Increase the DM density

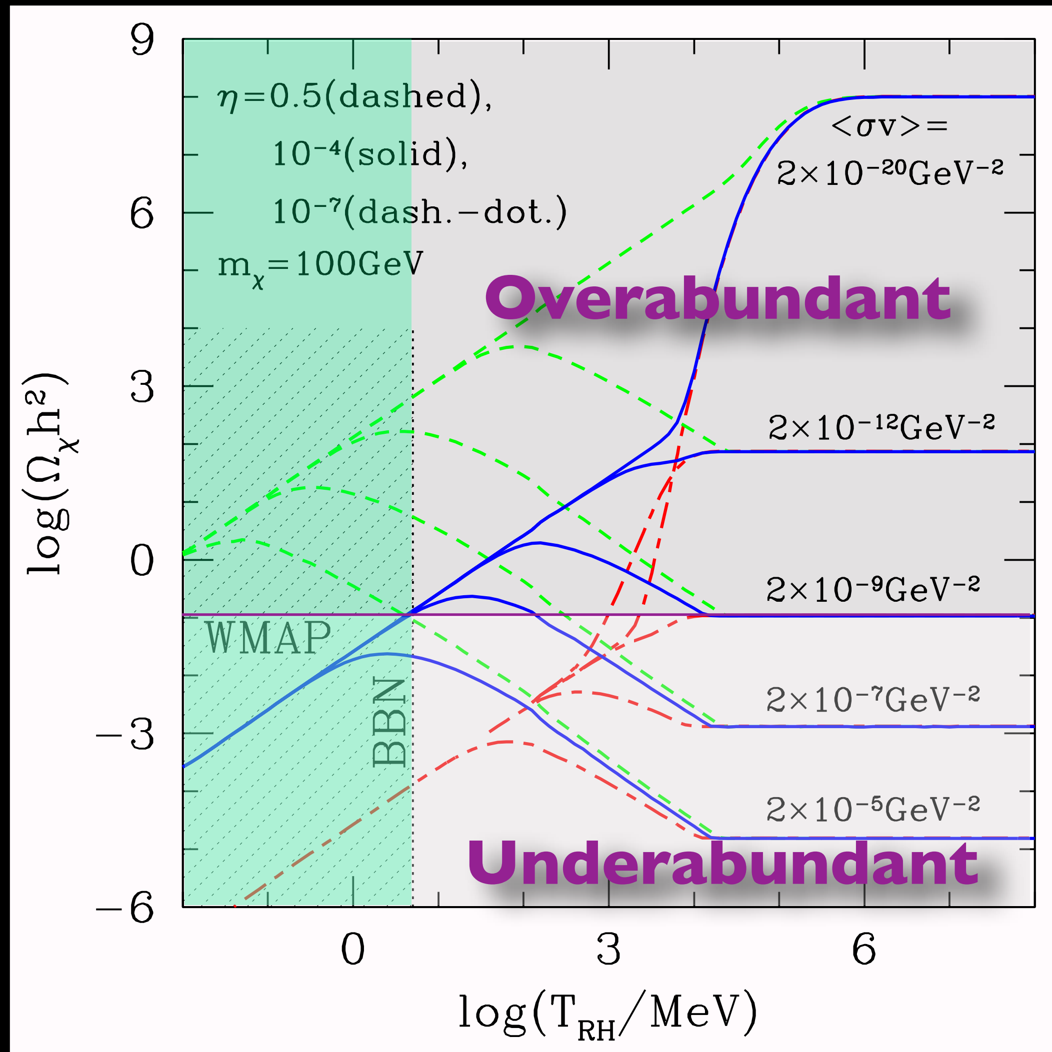
- Increase the expansion rate at freeze-out
  by adding more energy to the Universe
    - add a scalar field, e.g. scalar-tensor gravity, quintessence, inflation
- or by modifying the Friedmann equation
    - add extra dimensions, e.g. braneworld models
      like Randall-Sundrum II
- Alternatively, produce DM from decays of heavier particles

Cosmic density of WIMPs: caveats

There are multiple ways to produce and destroy WIMPs

Example

neutralinos in low reheating temperature cosmologies can always have the correct cosmic density



Gelmini, Gondolo 2006

Cosmic density of WIMPs: caveats

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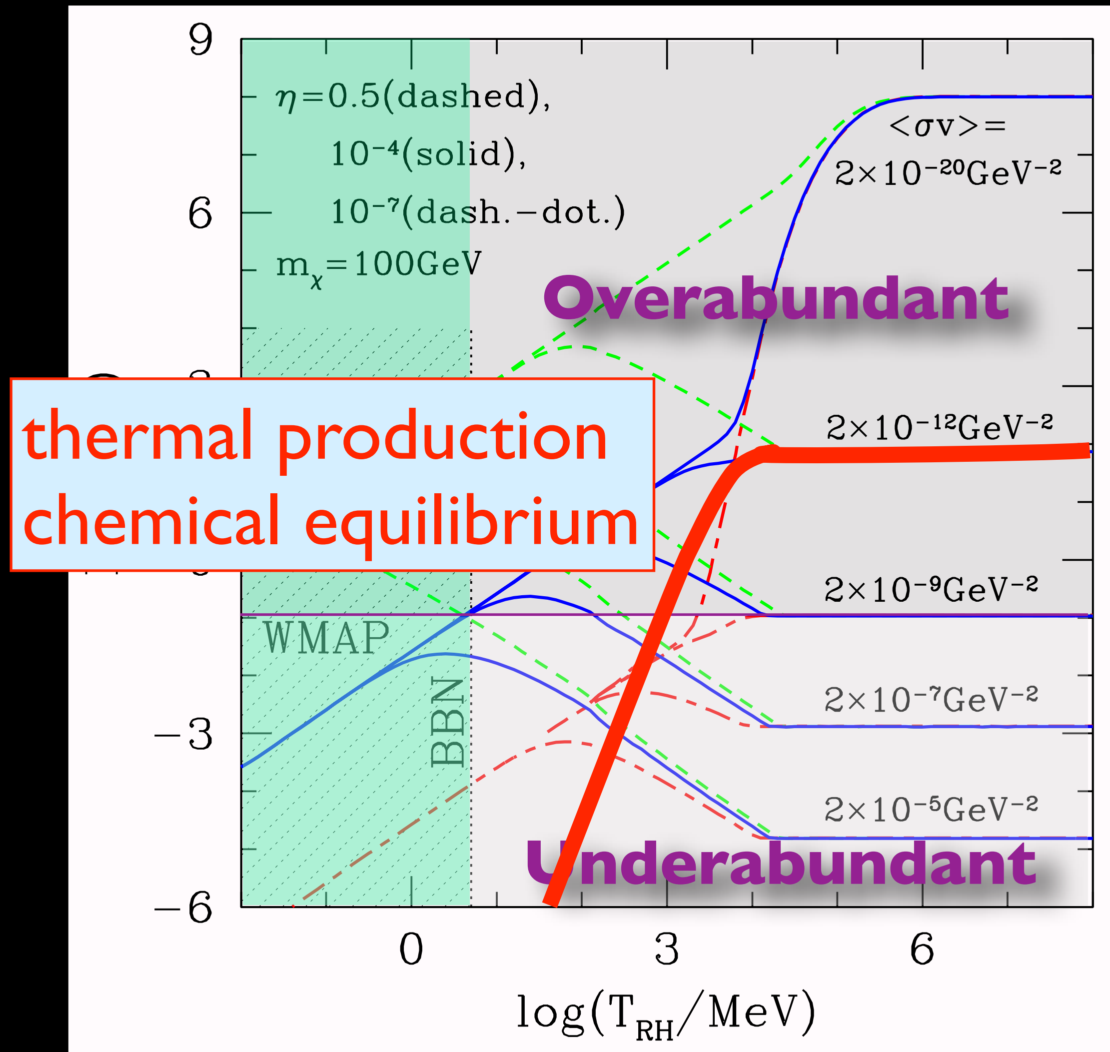
Gelmini, Gondolo 2006



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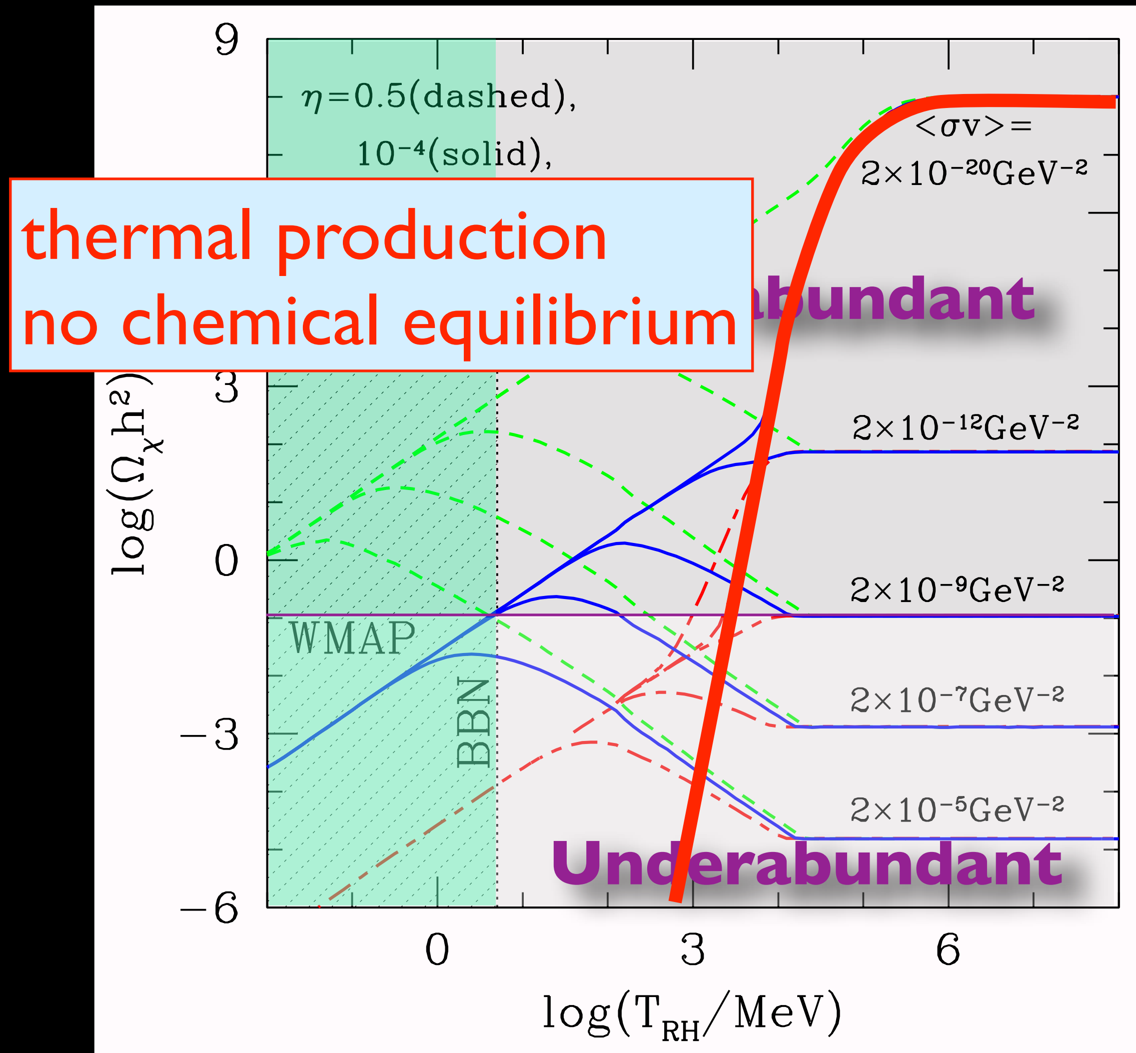

Cosmic density of WIMPs: caveats

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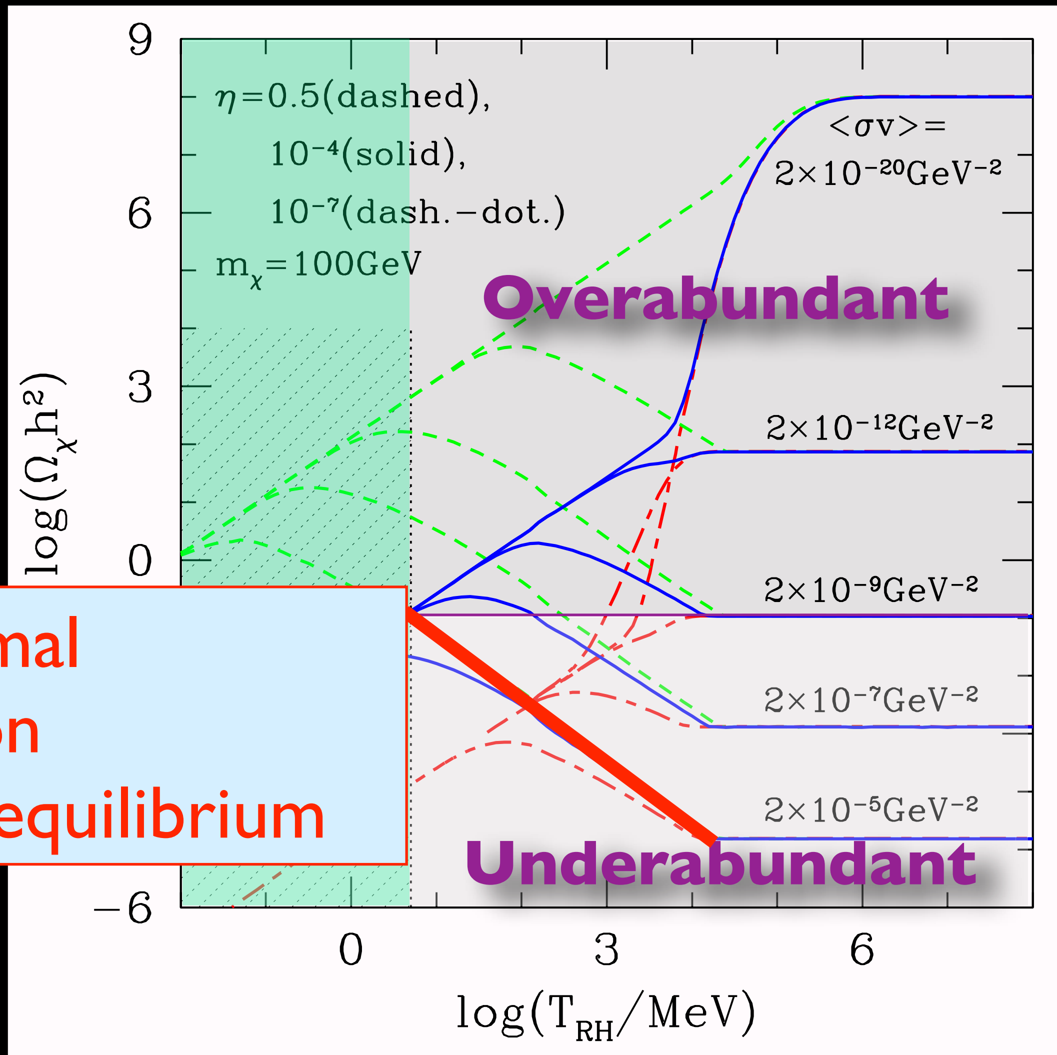


non-thermal production
chemical equilibrium

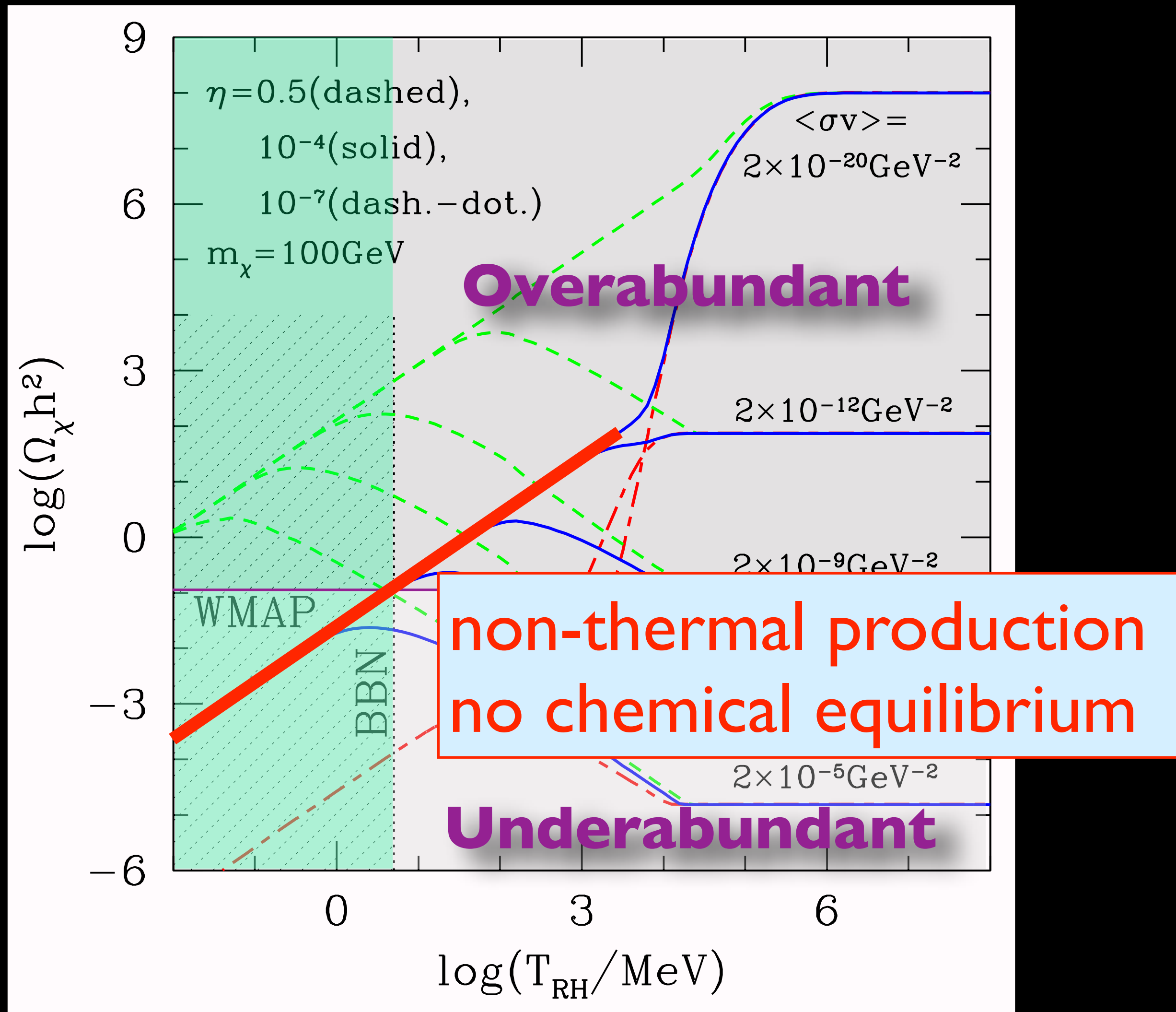
Gelmini, Gondolo 2006

Cosmic density of WIMPs: caveats

There are multiple ways to produce and destroy WIMPs

Example

neutralinos in low reheating temperature cosmologies can always have the correct cosmic density



Gelmini, Gondolo 2006

Non-thermal supersymmetric singlet

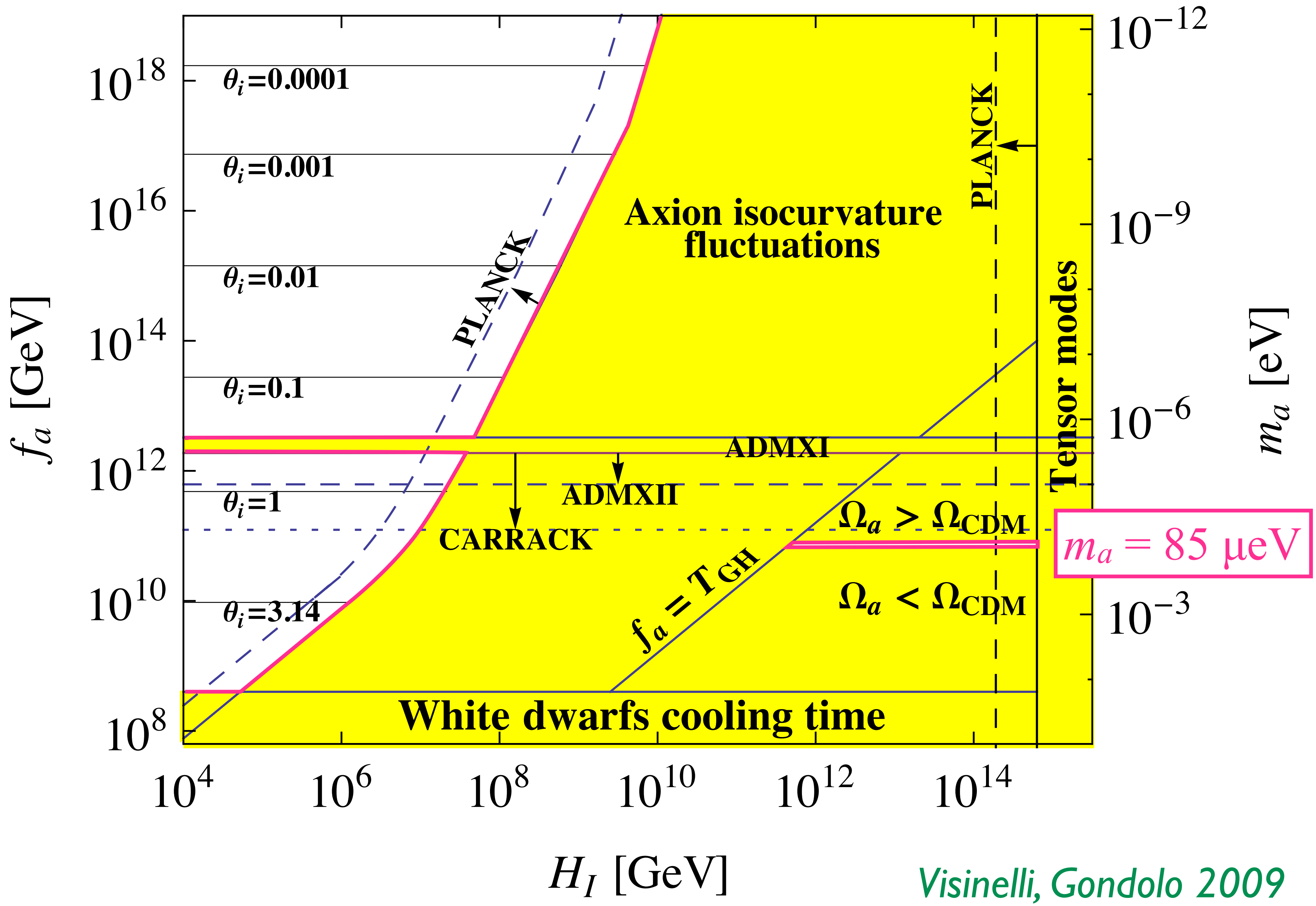
Allahverdi, Dutta, Mohapatra, Sinha 2013

MSSM + singlet superfield + isosinglet color-triplet superfields

Dark matter and baryon asymmetry generated in moduli decays at low reheating temperatures

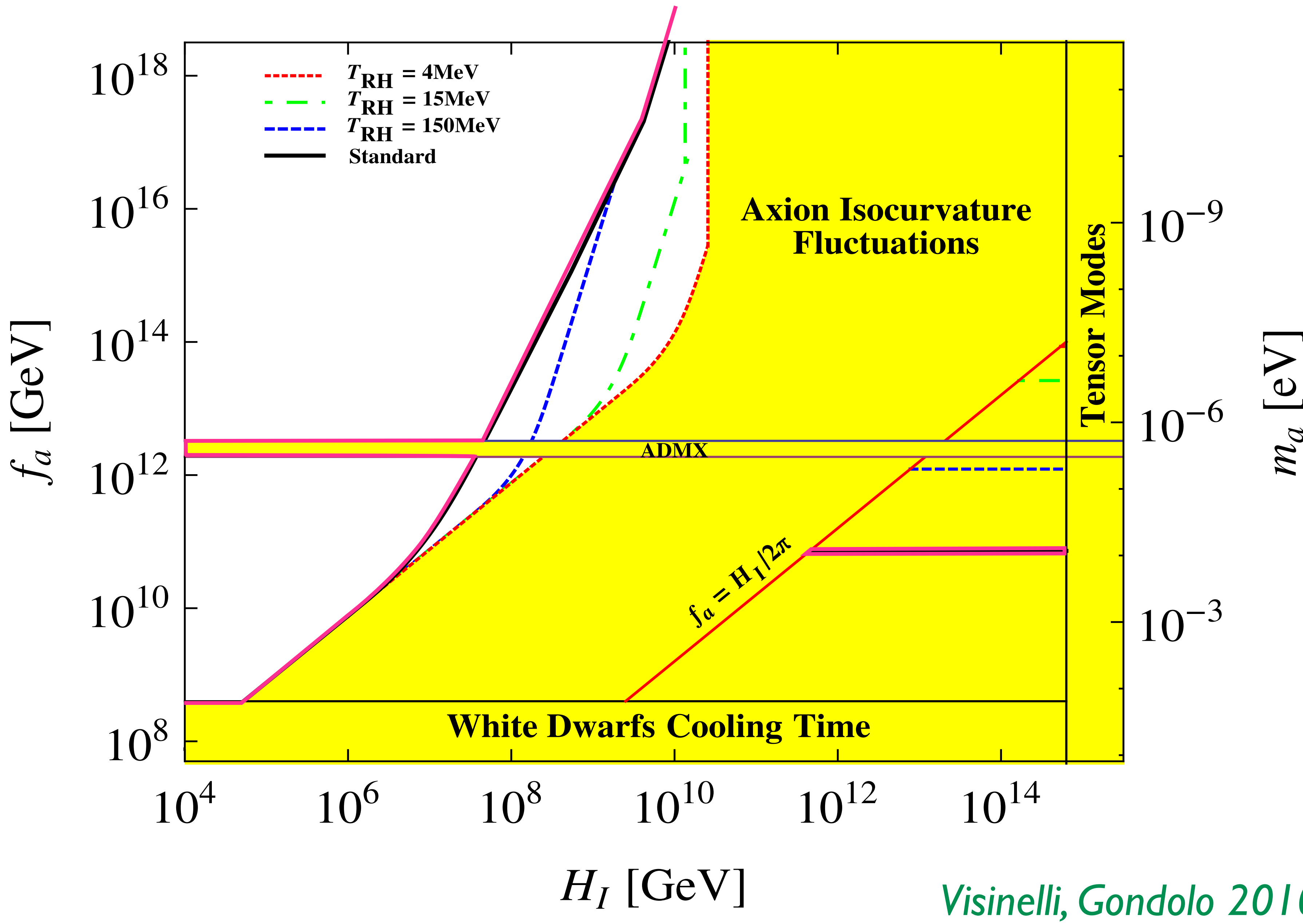
Model can accommodate light WIMPs as in CDMS-Si, etc.

Axion CDM - Standard cosmology



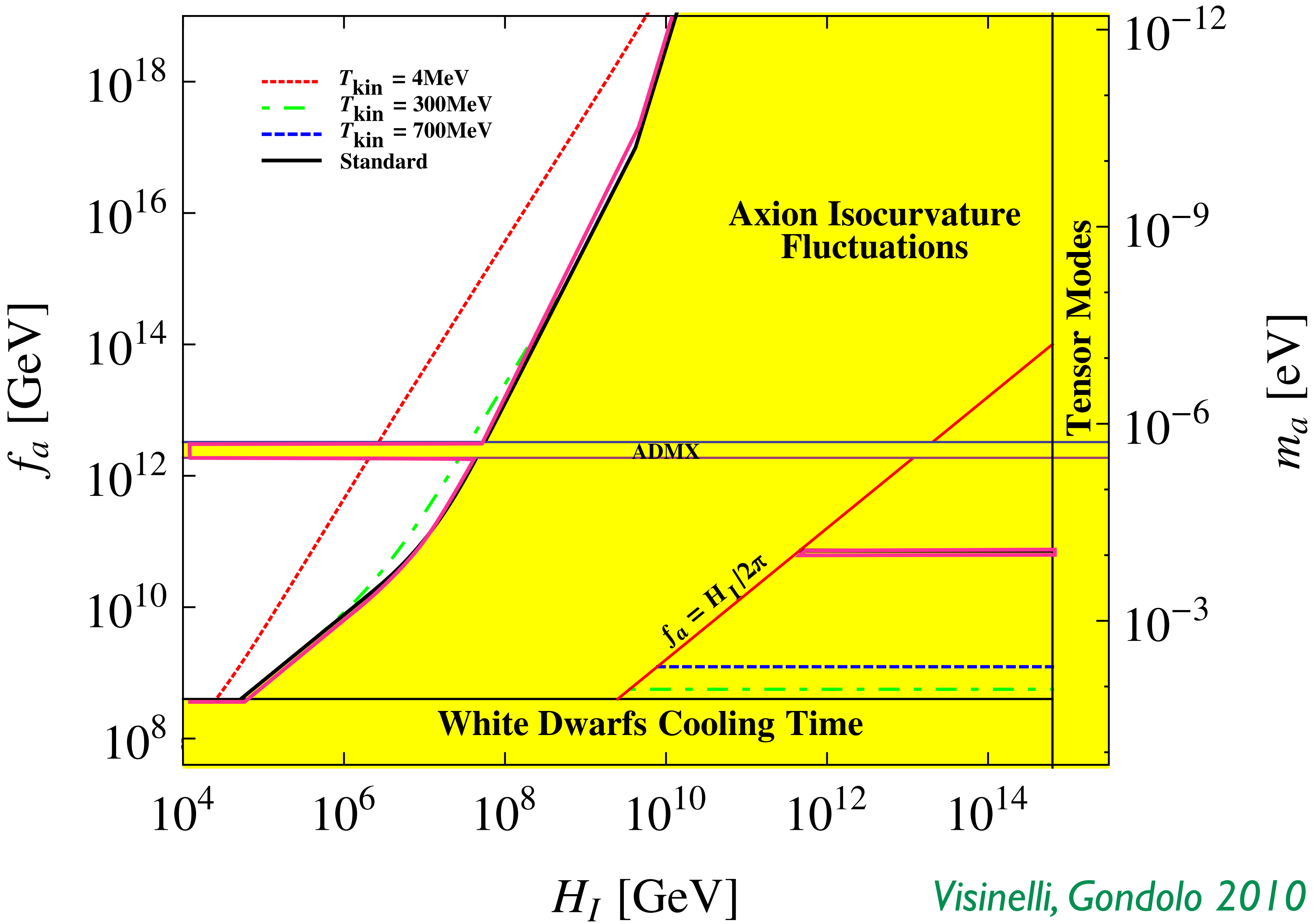
Visinelli, Gondolo 2009

Axion CDM - Low Temp. Reheating cosmology



Visinelli, Gondolo 2010

Axion CDM - Kination cosmology



Visinelli, Gondolo 2010

Sterile neutrinos

Active-sterile neutrino mixing

Standard model + right-handed neutrinos

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

Neutrino mass eigenstates are obtained by diagonalization

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

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

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)

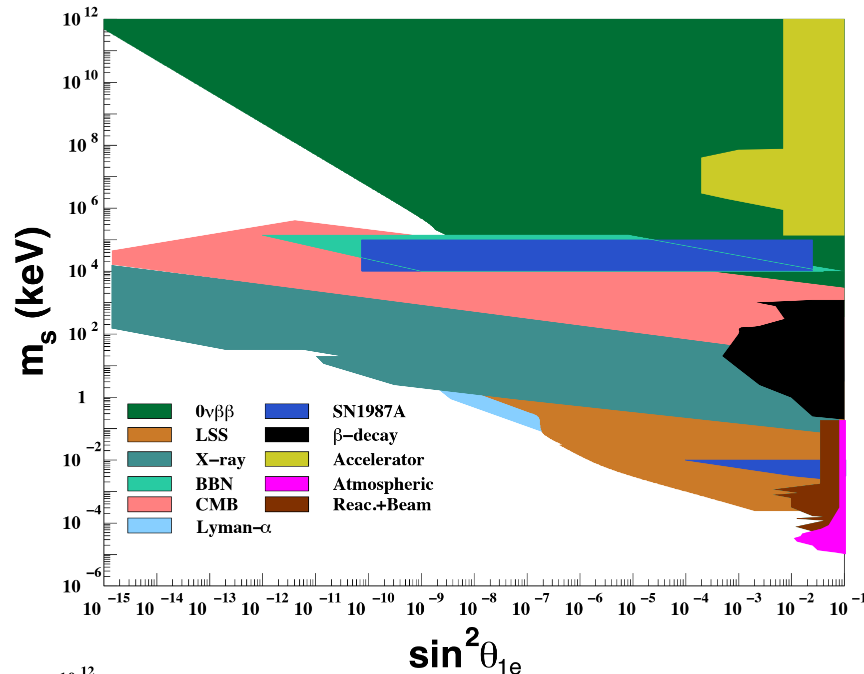
Neutrinos produced in weak interactions are left-handed, while mass eigenstates contain a (tiny) right-handed component

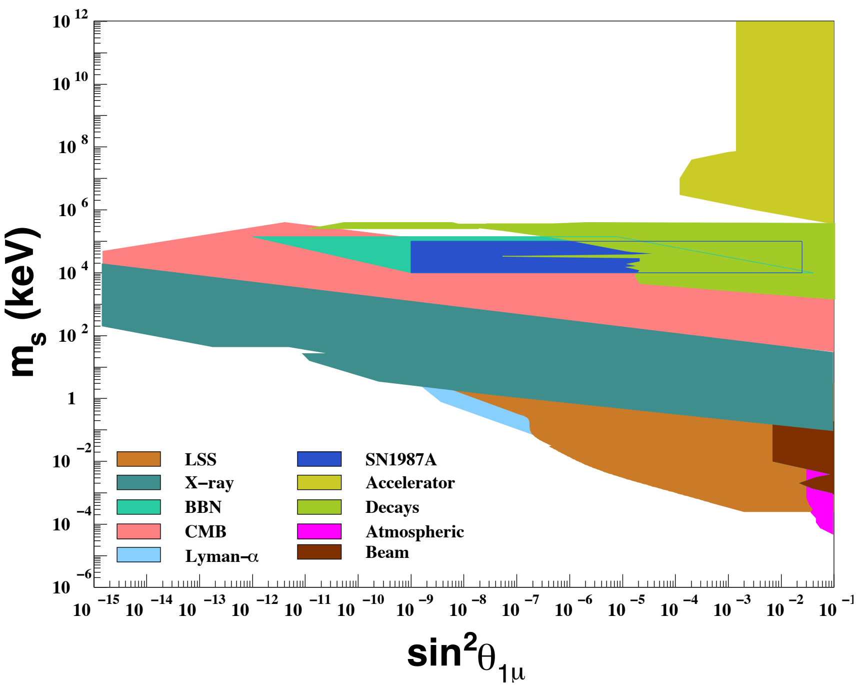
Oscillations between active and sterile neutrinos

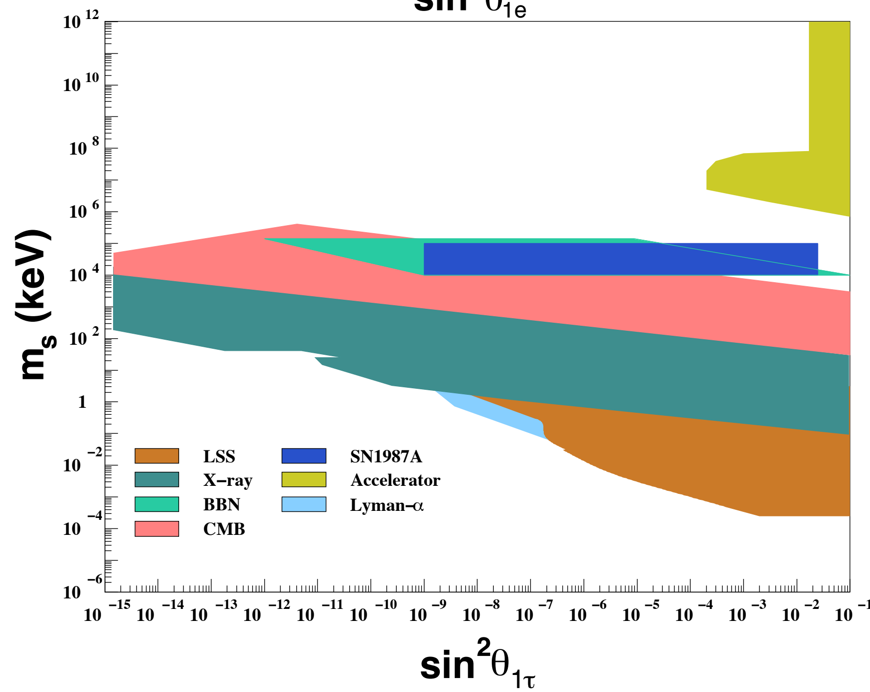
Neutrino mixing

Limits on sterile neutrino mixing with ν_e, ν_μ, ν_τ

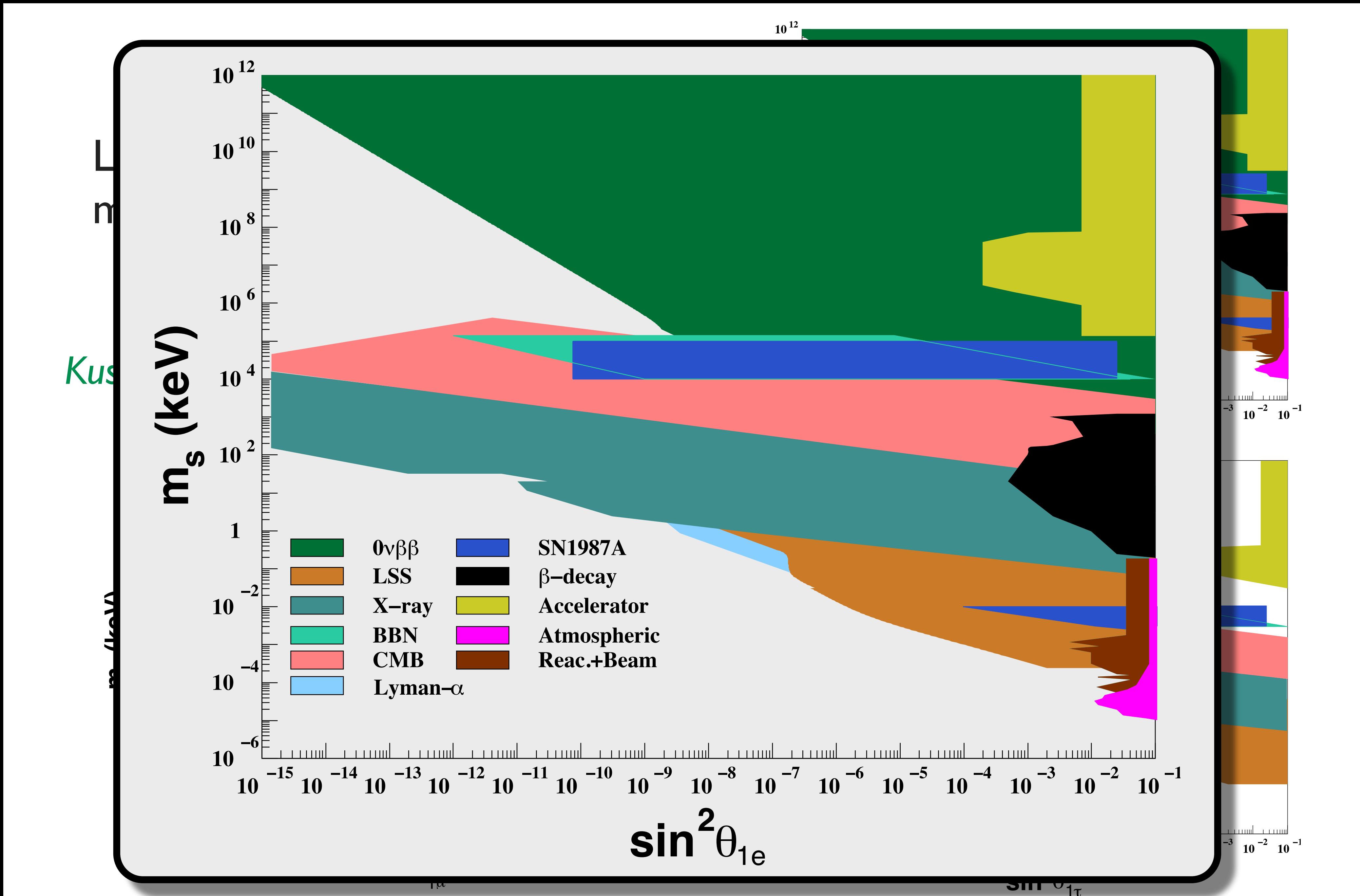
Kusenko 0906.2968





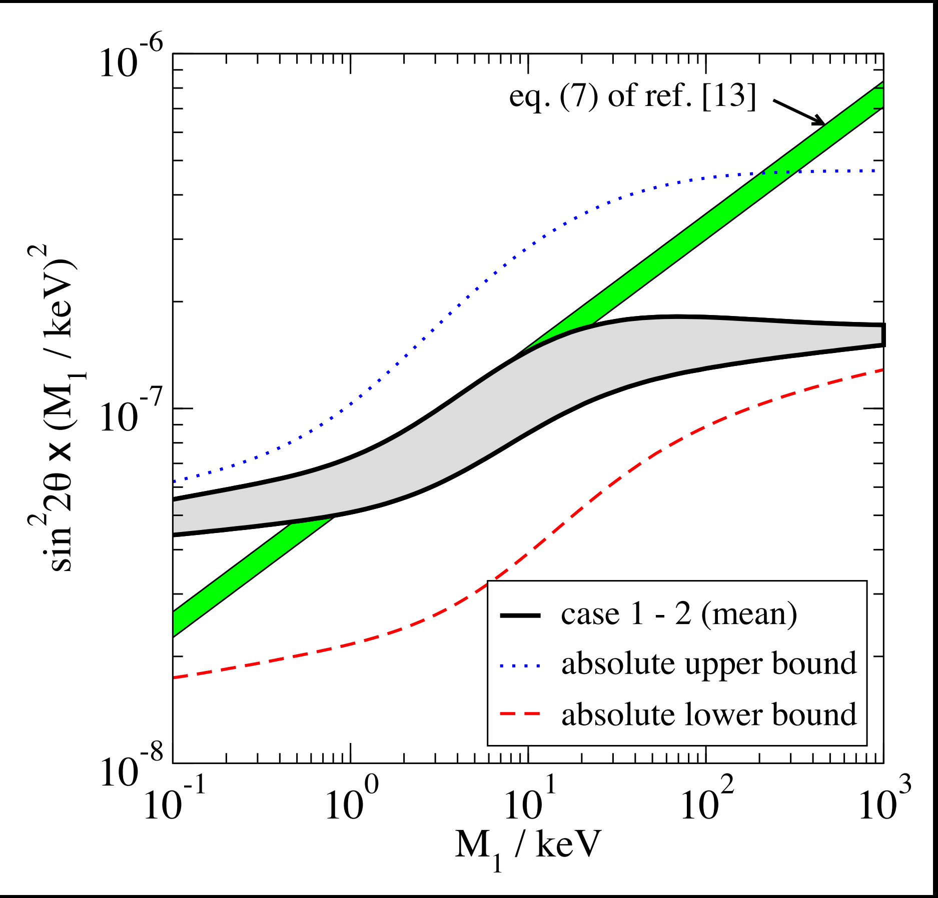


Neutrino mixing



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 $\nu_s \to \gamma\nu_a$

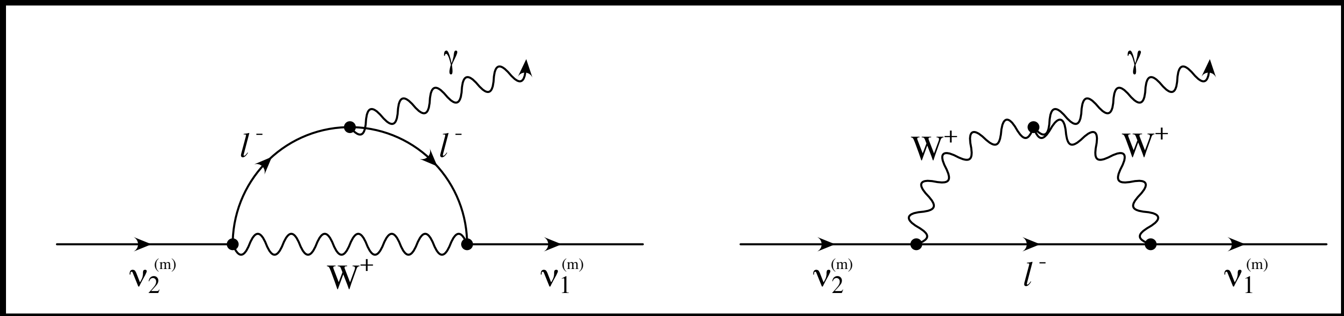


Figure from Kusenko 0906.2968

X-ray line

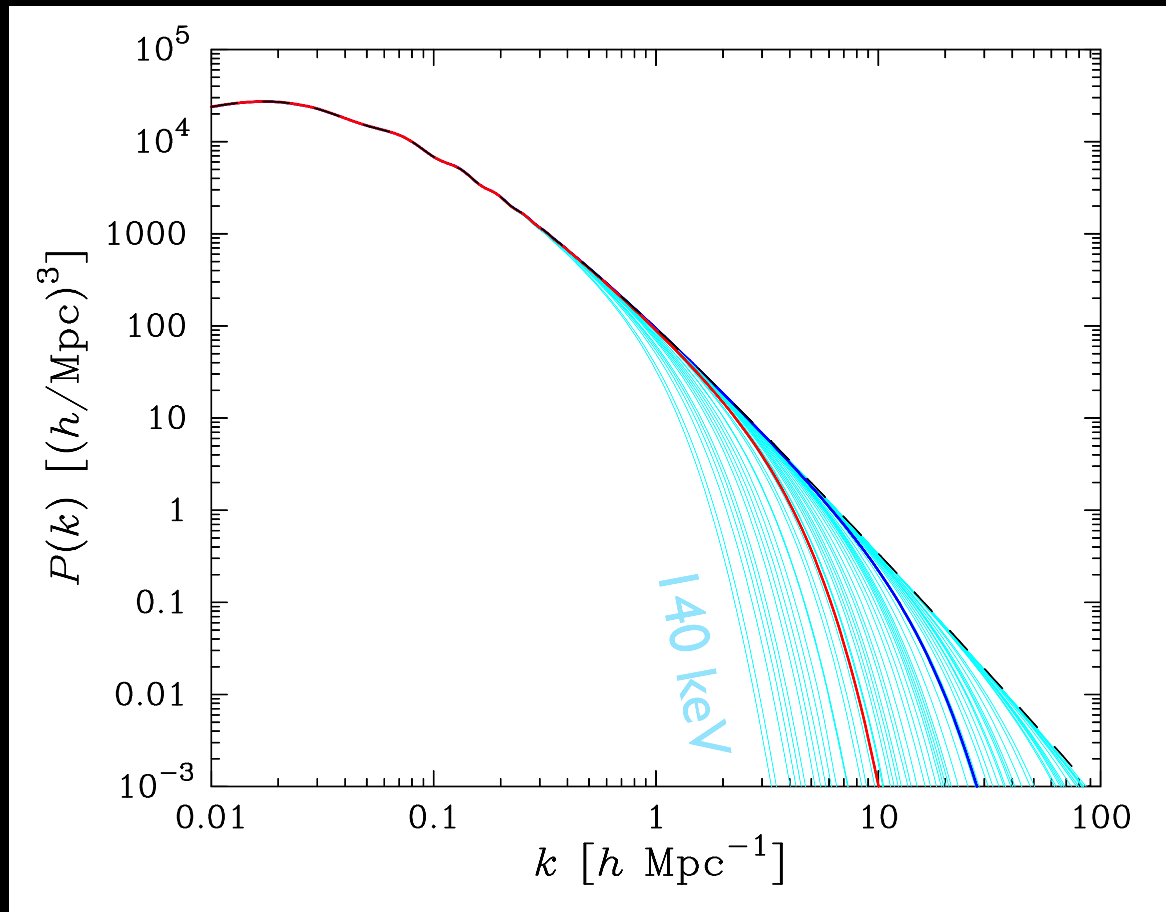
$$E_\gamma = \frac{1}{2} m_s$$

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

Limits on sterile neutrino dark matter

Sterile neutrinos are warm dark matter

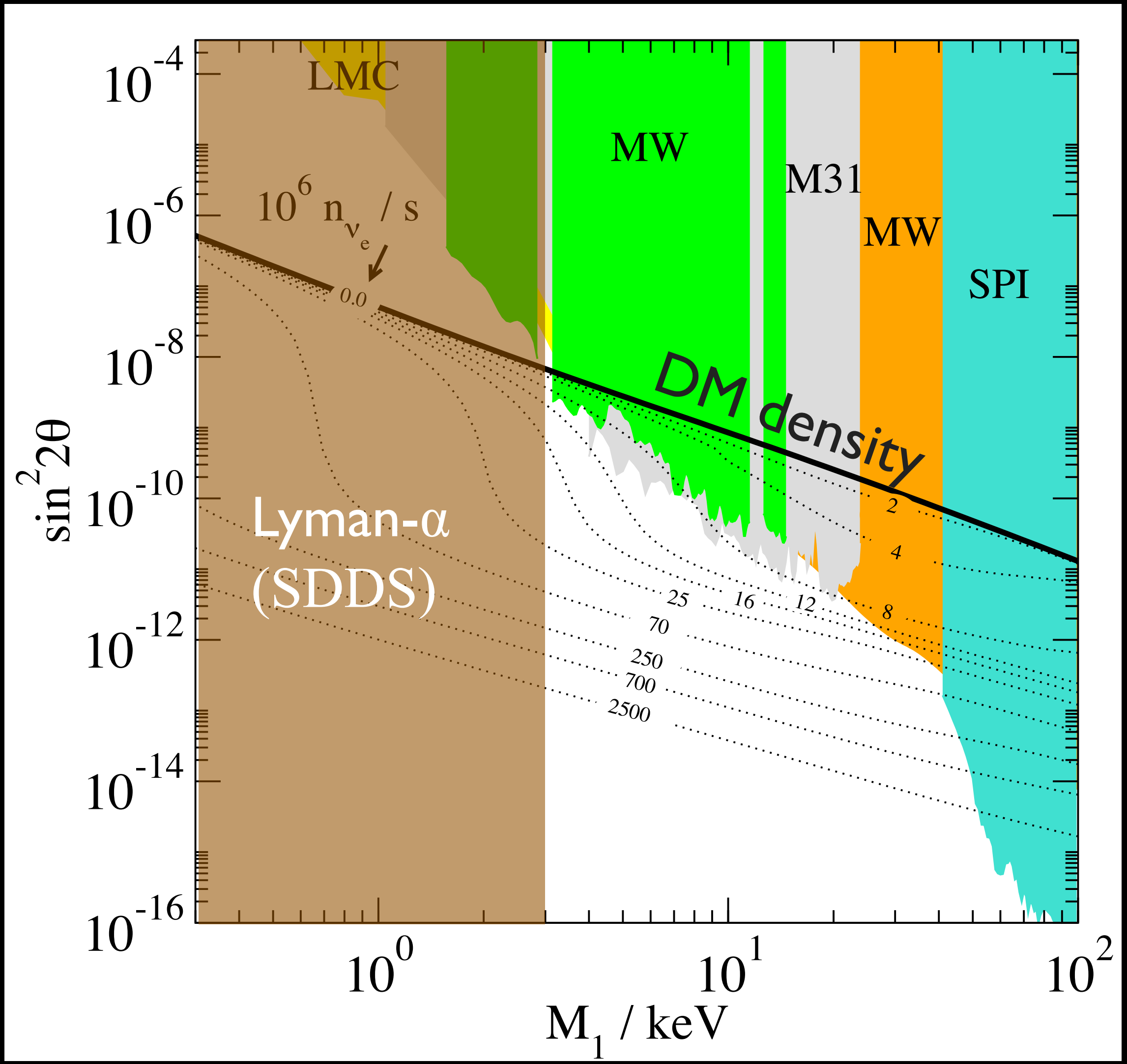
Small scale structure is erased



Abazajian 2005

Limits on sterile neutrino dark matter

νMSM



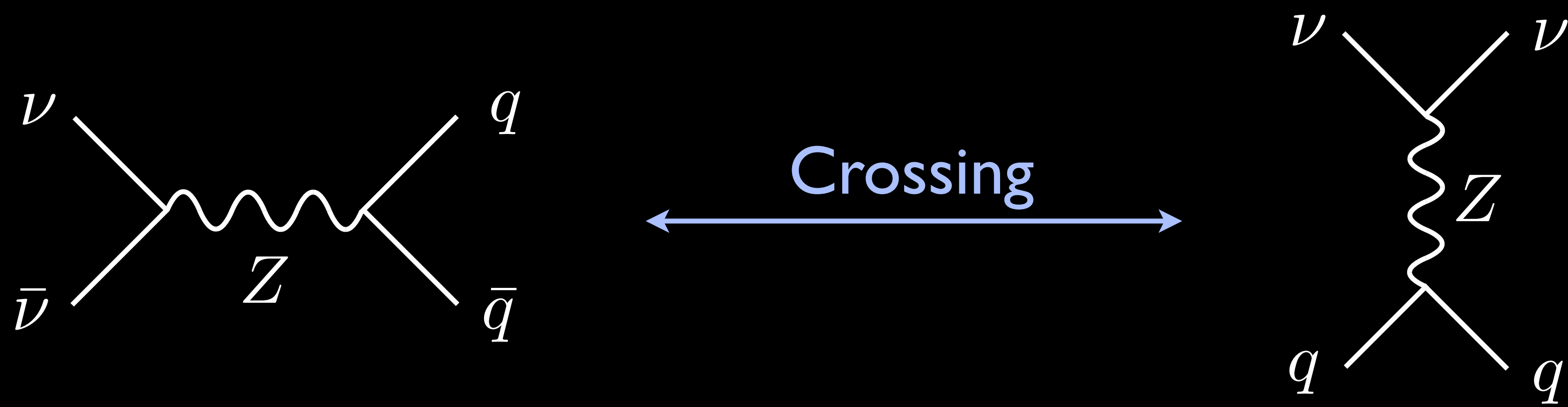
Laine, Shaposhnikov 2008

Light WIMPs with light Z' bosons

Break the annihilation/scattering relation

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

Scattering $\nu q \to \nu q$

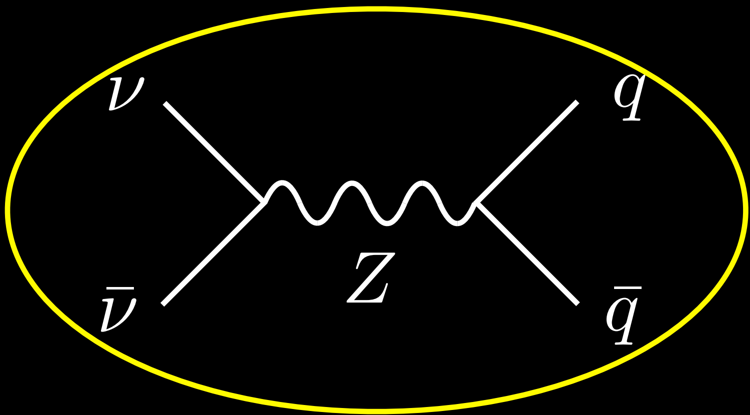


For example, for a ~4 GeV/c² dark matter neutrino, the scattering cross section is

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

Break the annihilation/scattering relation

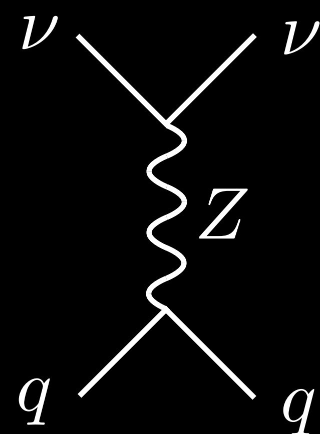
Annihilation $\nu\bar{\nu} \to q\bar{q}$



Resonant when $m_\nu \approx m_Z/2$

Crossing

Scattering $\nu q \to \nu q$



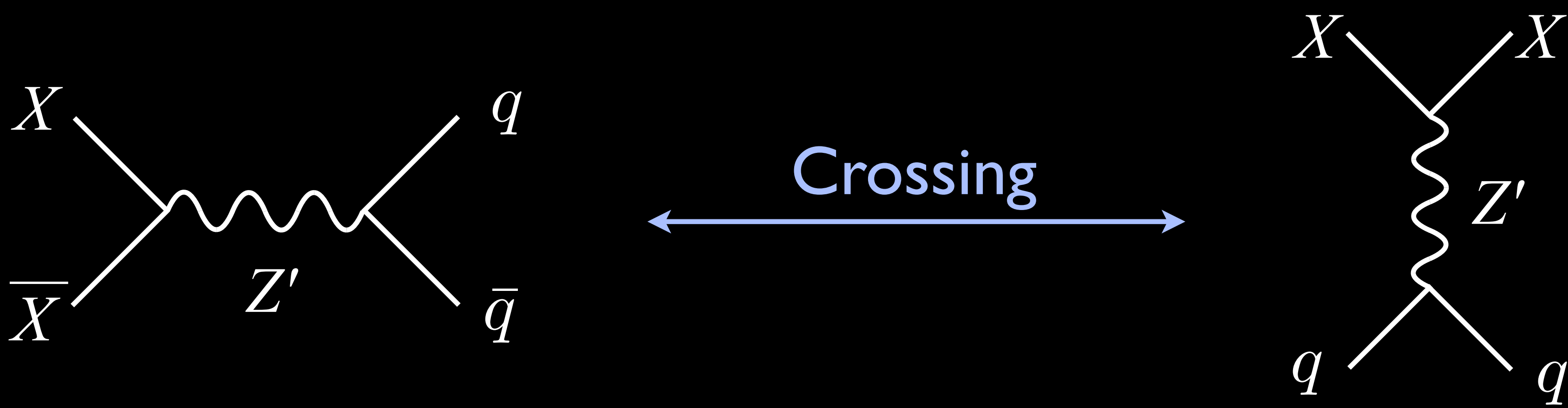
$$\sigma_{\nu n} \simeq \frac{0.02}{1 + m_n/m_\nu} \left(1 - \frac{4m_\nu^2}{m_Z^2}\right)^2 \frac{\langle \sigma v \rangle}{c}$$

$\sigma_{\nu n}$ would perhaps match DAMA/CoGeNT if m_Z were $\approx 2m_\nu$

Try a new particle X and a new vector boson Z'

A new particle *X* and a new gauge boson *Z'*

Annihilation $X\overline{X} \to q\bar{q}$ Scattering $Xq \to Xq$



Leptophobic Z'

Gondolo, Ko, Omura 2011

no coupling to leptons to avoid stringent LEP and Tevatron bounds

Scalar X or Dirac X

but could be something else

Elastic scattering

Conserved vector current

nucleus-Z' interaction term $\quad g' Q'_N Z'_\mu \overline{N} \gamma^\mu N$

$$Q'_N = ZQ'_p + (A-Z)Q'_n \qquad Q'_p = 2Q'_u + Q'_d \qquad Q'_n = Q'_u + 2Q'_d$$

Scattering cross section

$$\sigma_{XN} = \frac{16\pi\alpha'^2}{m_{Z'}^4} Q'^2_X Q'^2_N \left(\frac{m_X m_N}{m_X + m_N}\right)^2$$

Once m_X and σ_{Xp} are determined in direct dark matter detection experiments, this expression directly constrains $m_{Z'}/g'$.
Q'_N=1, Q'_X~1, m_X~7GeV, σ_{Xp}~10^{-40}cm^2 leads to $m_{Z'}/g'$~1TeV.

Relic density

X-anti$X$ pairs annihilate to quarks and Z' pairs

$$\sigma_{\rm ann} = \sum_f \sigma_{X\overline{X}\to f\overline{f}} + \sigma_{X\overline{X}\to Z'Z'}$$

Relic density calculation using DarkSUSY for non-SUSY model

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

invariant rate $W = 8Ep\sigma_{\rm ann}$

Solve $\Omega(\alpha',m_{Z'},m_X)=\Omega_{\rm cdm}$ for α', and plug into $\sigma_{XN}(\alpha',m_{Z'},m_X)$

Scalar *X*, leptophobic *Z'*

Standard Model plus X, Z', and extra Higgs φ

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}'_{\rm scalar}$$

$$\begin{aligned}\mathcal{L}'_{\rm scalar} = & D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X - \frac{\lambda_X}{4}(X^\dagger X)^2 \\ & + D_\mu \varphi^\dagger D^\mu \varphi - m_\varphi^2 \varphi^\dagger \varphi - \frac{\lambda_\varphi}{4}(\varphi^\dagger \varphi)^2 \\ & - \frac{\lambda_{HX}}{2} X^\dagger X H^\dagger H - \frac{\lambda_{X\varphi}}{2} \varphi^\dagger \varphi X^\dagger X \\ & - \frac{\lambda_{H\varphi}}{2} \varphi^\dagger \varphi H^\dagger H - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}\end{aligned}$$

$$D_\mu = D_\mu^{\rm SM} - iQ' g' Z'_\mu$$

Scalar *X*, leptophobic *Z'*

- This type of model has been studied by Wise et al for $U(1)'=U(1)_B$ and Q'_X fixed by a Yukawa coupling that allows non-SM charged particles to decay.
- Stability of X requires $\langle X\rangle=0$ to avoid e.g. $X\rightarrow H^{*}H$ arising from $\lambda_{HX}\langle X\rangle\, X\, H^{\dagger}H$.
- Terms like $X\phi^{-Q'_X/Q'_\phi}$ arise from one-loop and non-renormalizable corrections.
  - $Q'_X=\pm 2Q'_f,\ 3Q'_f$ forbids renormalizable terms,
  - non-renormalizable terms cannot be completely forbidden but can be made such that the DM particle is very long lived

Scalar *X*, leptophobic *Z'*

XX^* pairs annihilate to quarks and Z' pairs

$$\sigma_{XX^*\to f\bar{f}} = \frac{8\pi Q_X'^2 Q_f'^2 \alpha'^2 \beta\beta' (2E^2 + m_f^2)}{(4E^2 - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2}$$

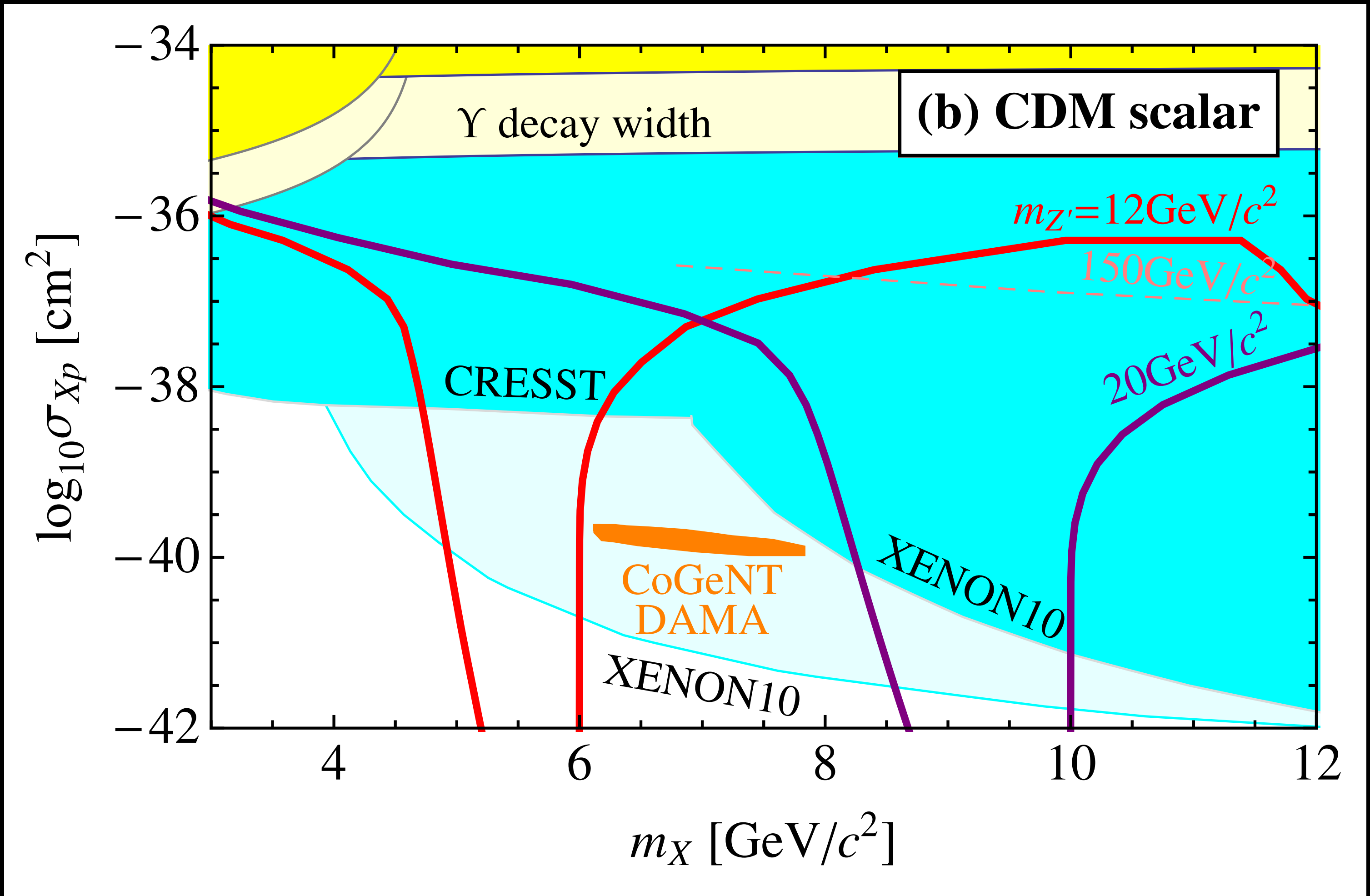
p-wave

$$\sigma_{XX^*\to Z'Z'} = \frac{\pi Q_X'^4 \alpha'^2}{E^2} \frac{w}{v} \left[\frac{32 - 24z^2 + 5z^4 + 16v^2}{4 - 4z^2 + z^4 + 4v^2} - \frac{16 - 8z^2 - z^4 + 16v^2(2 - z^2)}{4vw(1 + v^2 + w^2)} \ln \frac{1 + (v+w)^2}{1 + (v-w)^2} \right]$$

We neglect H exchange contributions on the basis that H is heavy or its couplings $\lambda_{X\phi}$ and λ_{HX} are small.

$$\Gamma_{Z'} = \frac{\alpha'}{m_{Z'}} \sum_f Q_f'^2 (m_{Z'}^2 + 2m_f^2) \sqrt{1 - \frac{4m_f^2}{m_{Z'}^2}} + \frac{\alpha'}{12 m_{Z'}} Q_X'^2 (m_{Z'}^2 - 4m_X^2) \sqrt{1 - \frac{4m_X^2}{m_{Z'}^2}}$$

Scalar *X*, leptophobic *Z'*



Gondolo, Ko, Omura 2011

Dirac *X*, leptophobic *Z'*

Standard Model plus X, Z', and extra Higgs φ

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}'_{\rm Dirac}$$

$$\begin{aligned}\mathcal{L}'_{\rm Dirac} = \overline{\psi}_X \left(i\partial\!\!\!/ + g' Q'_X Z\!\!\!/' - m_X \right) \psi_X \\ + D_\mu \varphi^\dagger D^\mu \varphi - m_\varphi^2 \varphi^\dagger \varphi - \frac{\lambda_\varphi}{4} (\varphi^\dagger \varphi)^2 \\ - \frac{\lambda_{H\varphi}}{2} \varphi^\dagger \varphi H^\dagger H - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}\end{aligned}$$

$$D_\mu = D_\mu^{\rm SM} - iQ' g' Z'_\mu$$

Dirac *X*, leptophobic *Z'*

XX* pairs annihilate to quarks and Z' pairs

$$\sigma_{X\overline{X}\to f\overline{f}} = \frac{4\pi Q'^2_X Q'^2_f \alpha'^2}{E^2}\frac{\beta'}{\beta}\frac{(2E^2+m_f^2)(2E^2+m_X^2)}{(4E^2-m_{Z'}^2)^2+m_{Z'}^2\Gamma_{Z'}^2}$$

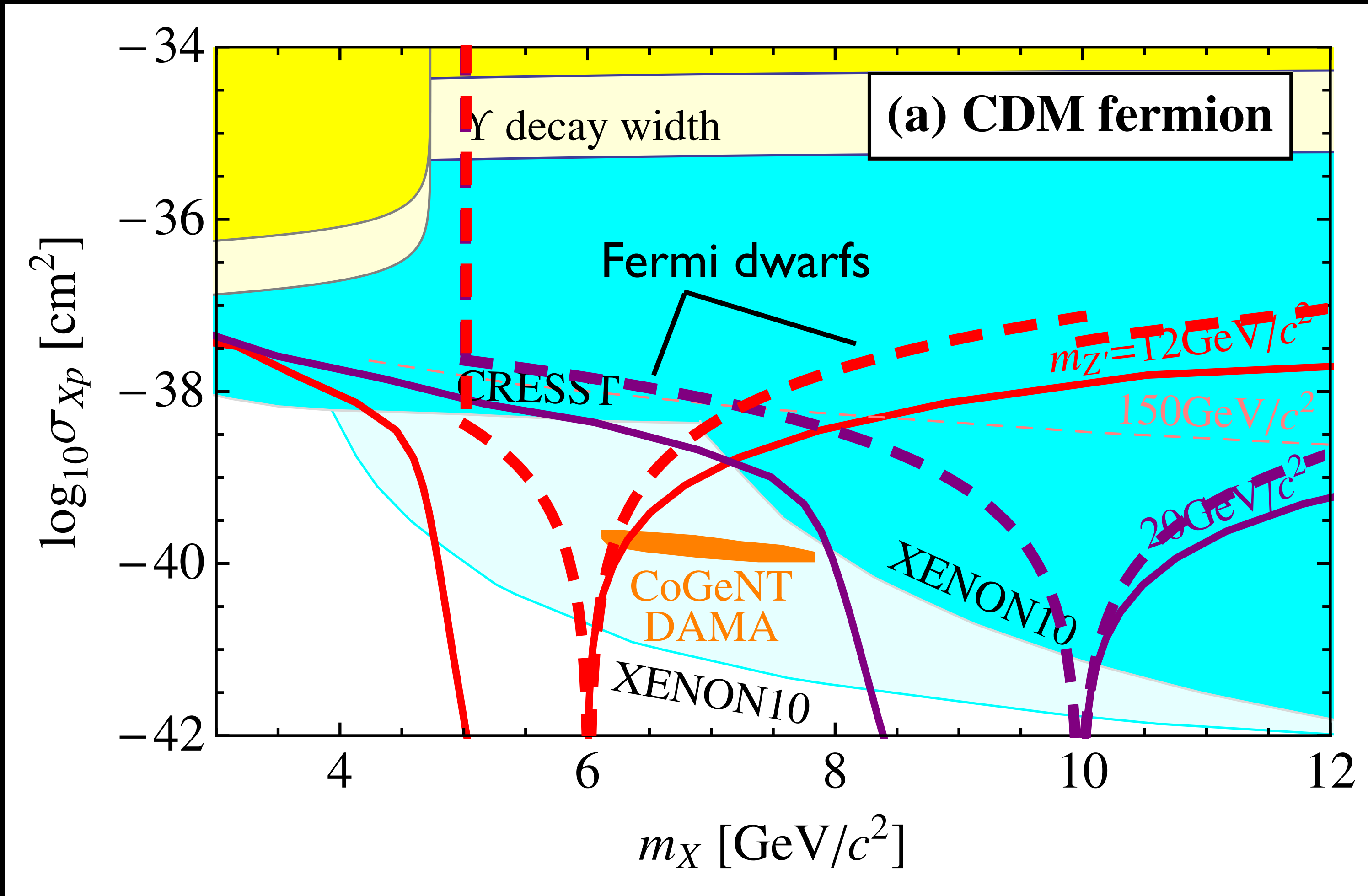
s-wave

$$\sigma_{X\overline{X}\to Z'Z'} = \frac{\pi Q'^4_X \alpha'^2}{E^2}\frac{w}{v}\left[-1-\frac{(2+z^2)^2}{(1+v^2+w^2)^2-4vw}\right.$$
$$\left.+\frac{6-2z^2+z^4+12v^2+4v^4}{2vw(1+v^2+w^2)}\ln\frac{1+(v+w)^2}{1+(v-w)^2}\right]$$

There is no H exchange contribution because kinetic mixing is negligible.

$$\Gamma_{Z'} = \frac{\alpha'}{m_{Z'}}\sum_f Q'^2_f(m_{Z'}^2+2m_f^2)\sqrt{1-\frac{4m_f^2}{m_{Z'}^2}}$$
$$+\frac{\alpha'}{12m_{Z'}}Q'^2_X(m_{Z'}^2+2m_X^2)\sqrt{1-\frac{4m_X^2}{m_{Z'}^2}}$$

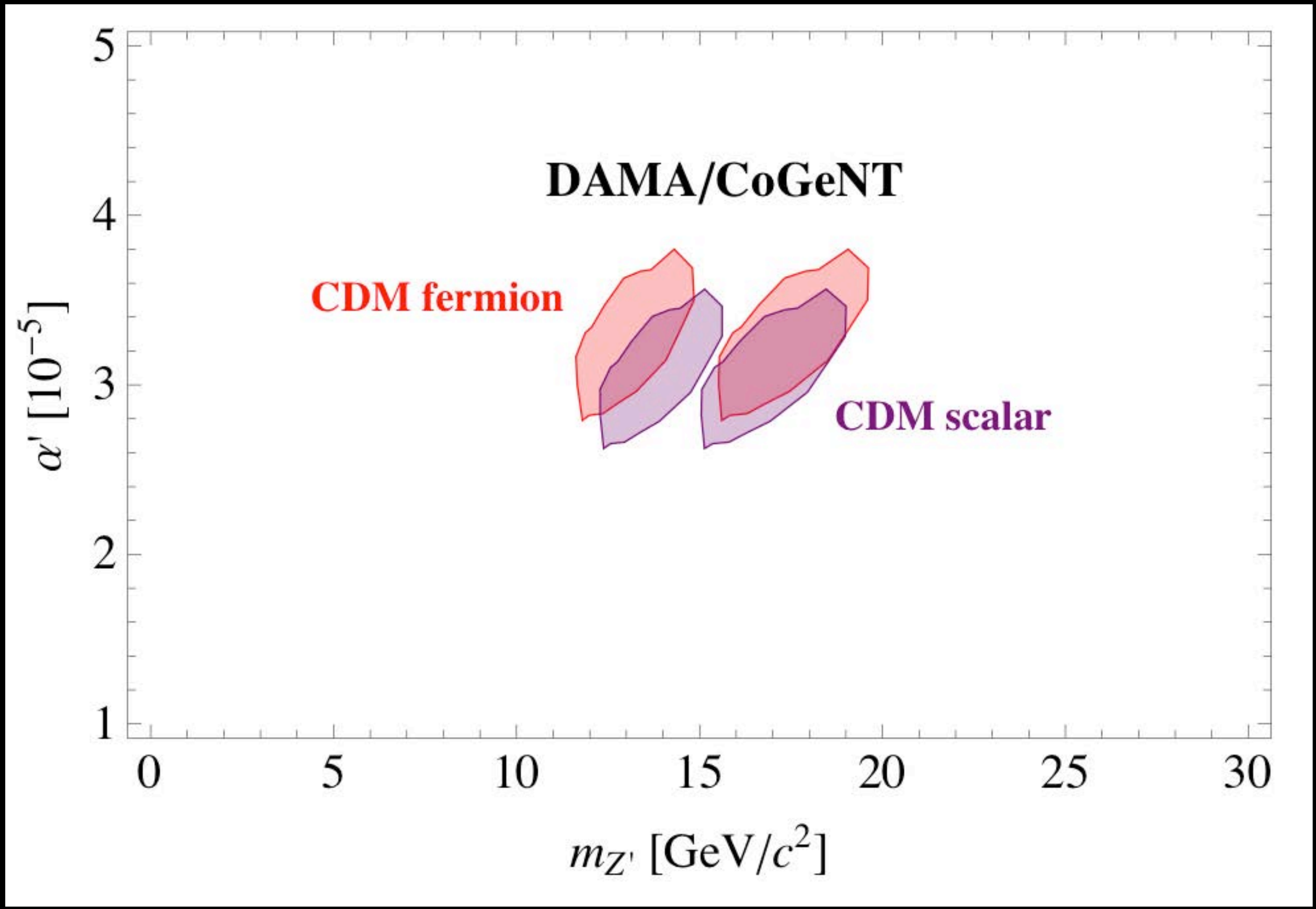
Dirac *X*, leptophobic *Z'*



Gondolo, Ko, Omura 2011 and in prep.

Scalar or Dirac *X* and light leptophobic *Z'*

Reasonable values for Z' mass and α' coupling constant

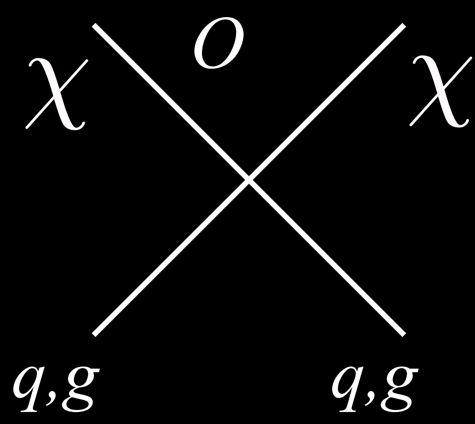


Gondolo, Ko, Omura 2011

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

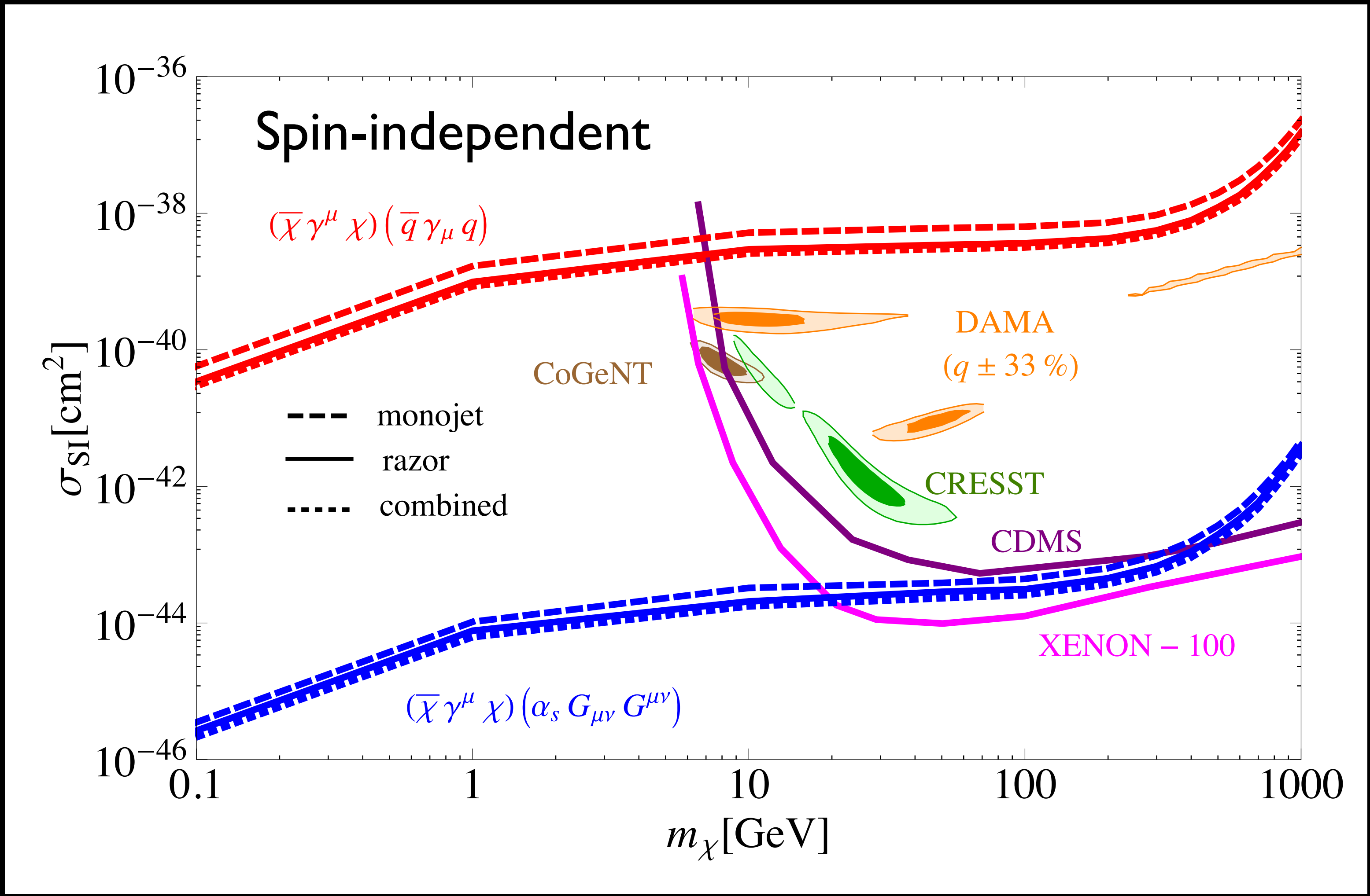
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$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

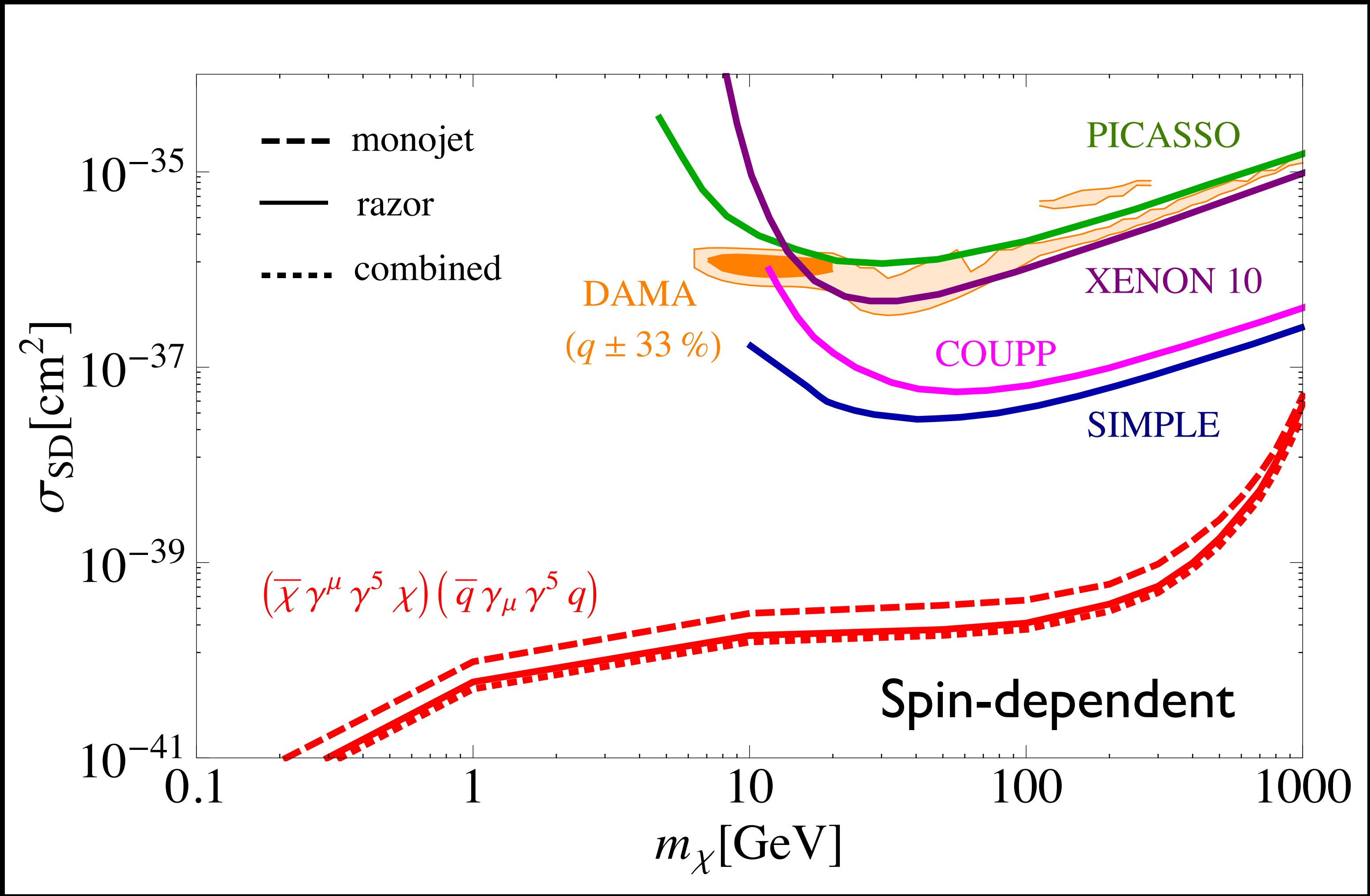
Direct detection and LHC



Fox, Harnik, Primulando, Yu 2012

Constraints on scattering cross section

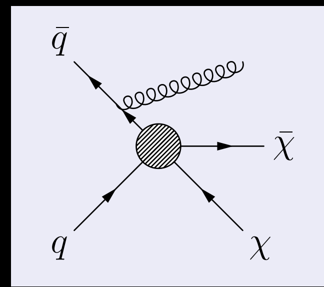
Direct detection and LHC

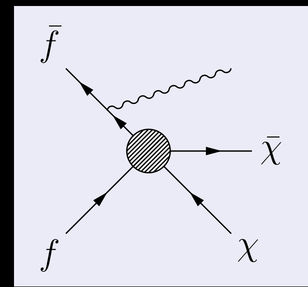


Fox, Harnik, Primulando, Yu 2012

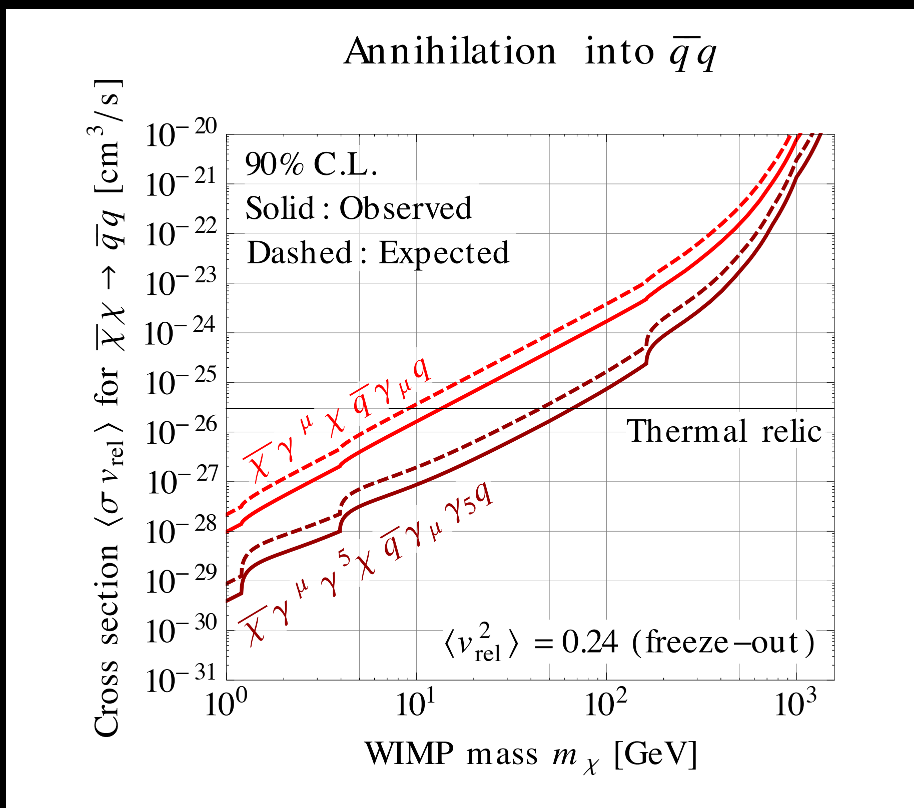
Effective operator approach

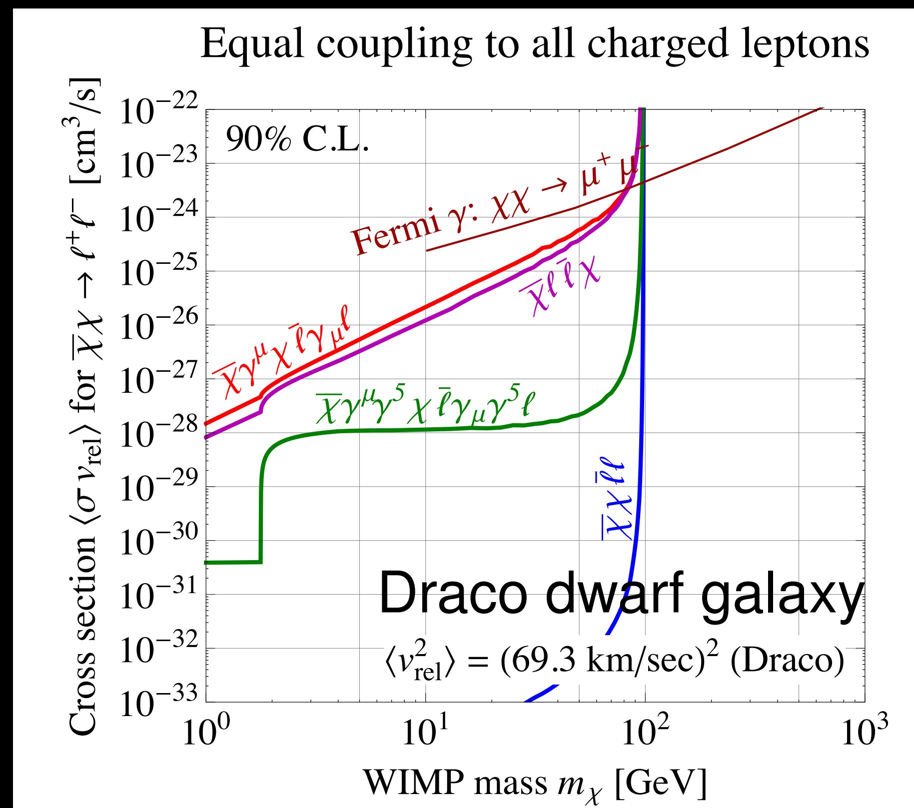
LHC limits and gamma-rays from dark matter





Mono-jet
Mono-gamma

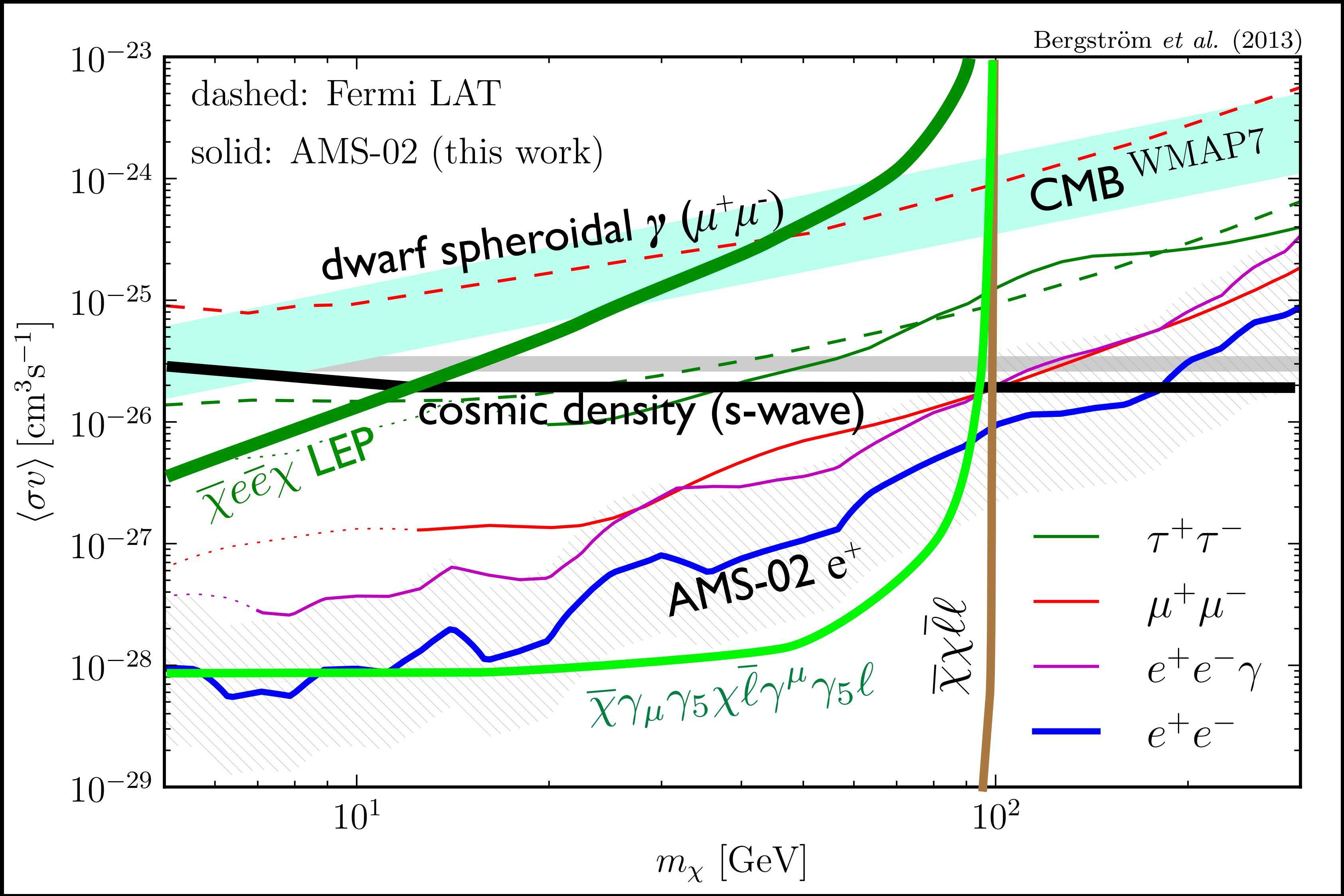




Kopp, Fox, Harnik, Tait 2011

Constraints on annihilation cross section

γ-rays, cosmological ionization, positrons, and LEP



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

Asymmetric dark matter

- Dark matter in a hidden mirror sector ("dark sector")
- Dark matter asymmetry similar to baryon asymmetry, generated by similar mechanisms

$$n_\chi \approx n_{\rm p}$$

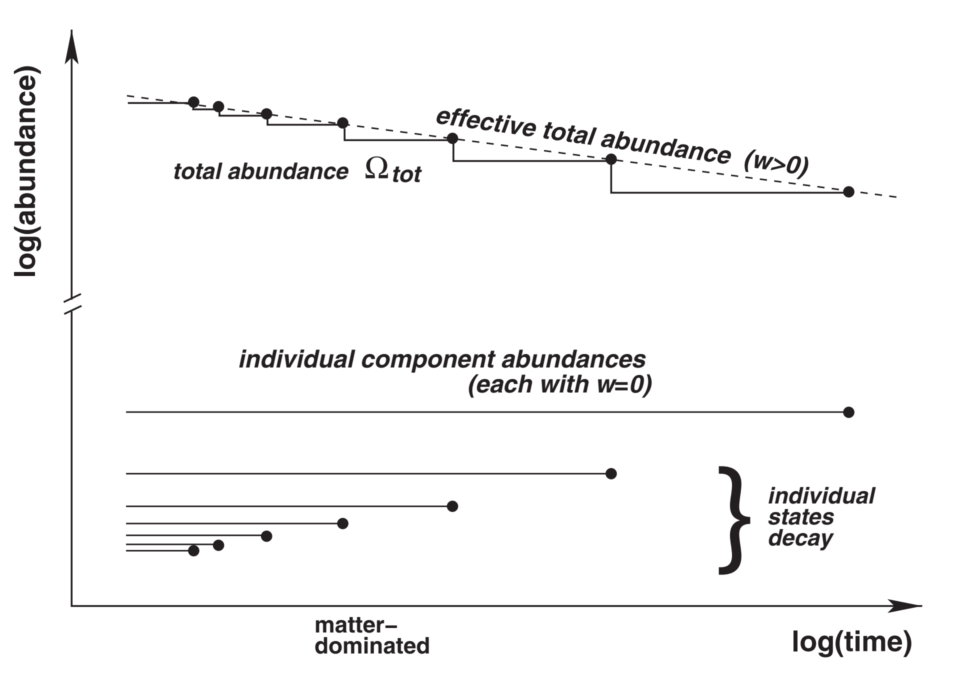
- Dark matter mass is a few times the proton mass

$$\Omega_\chi \approx \frac{m_\chi}{m_p}\,\Omega_{\rm p} \approx (\text{a few})\,\Omega_{\rm p}$$

Nussinov 1985; Graciela, Hall, Lin 1986; Hooper, March-Russell, West 2008; Kouvaris 2008; Kaplan, Luty, Zurek 2009; Hall, March-Russell, West 2010; Buckley, Randall 2010; Dutta, Kumar 2011; Cohen, Phalen, Pierce, Zurek 2010; Falkowski, Ruderman, Volansky 2011; Frandsen, Sarkar, Schmidt-Hoberg 2011; etc.

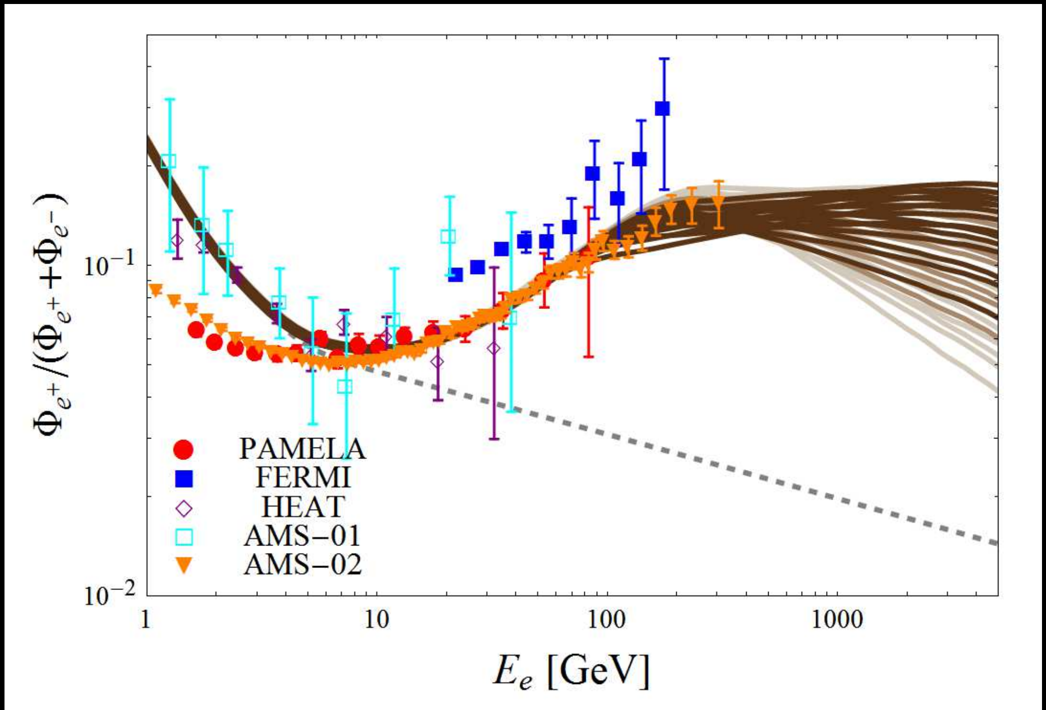
Dynamical dark matter

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

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

Conclusions

A NEW AND DEFINITIVE META-COSMOLOGY THEORY

T. R. Lauer
T. S. Statler
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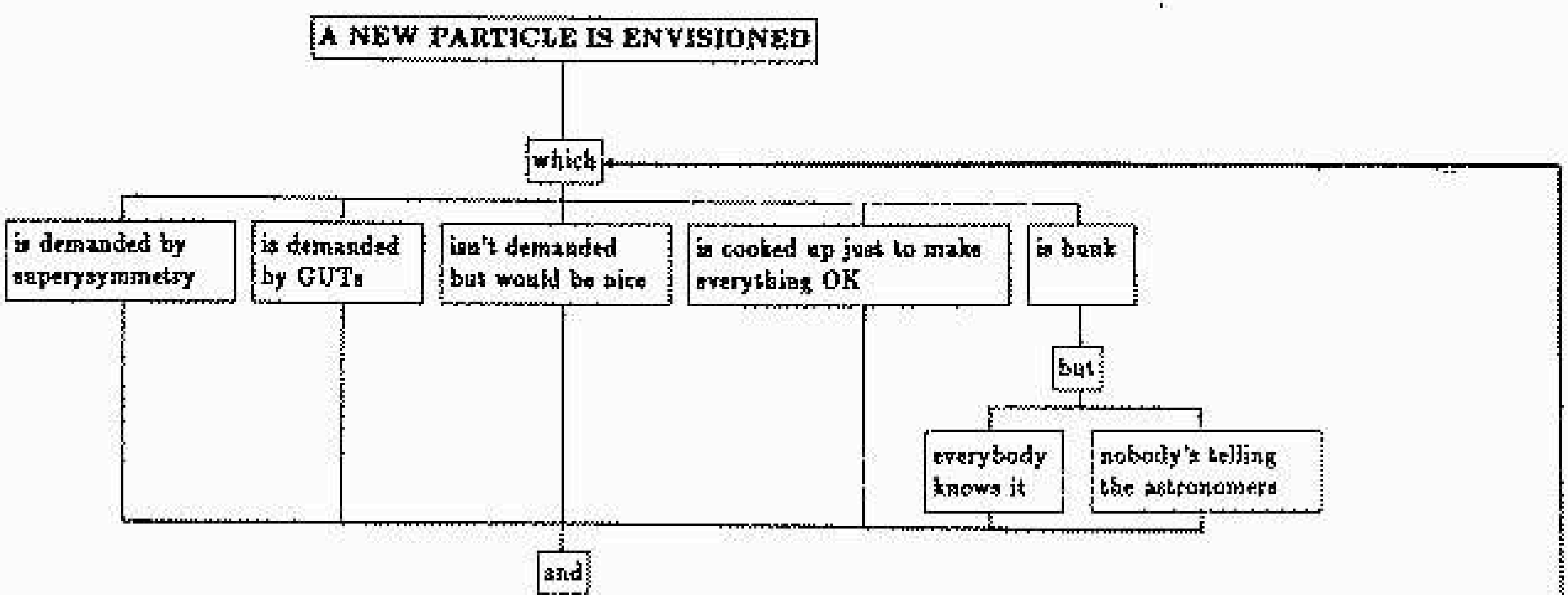
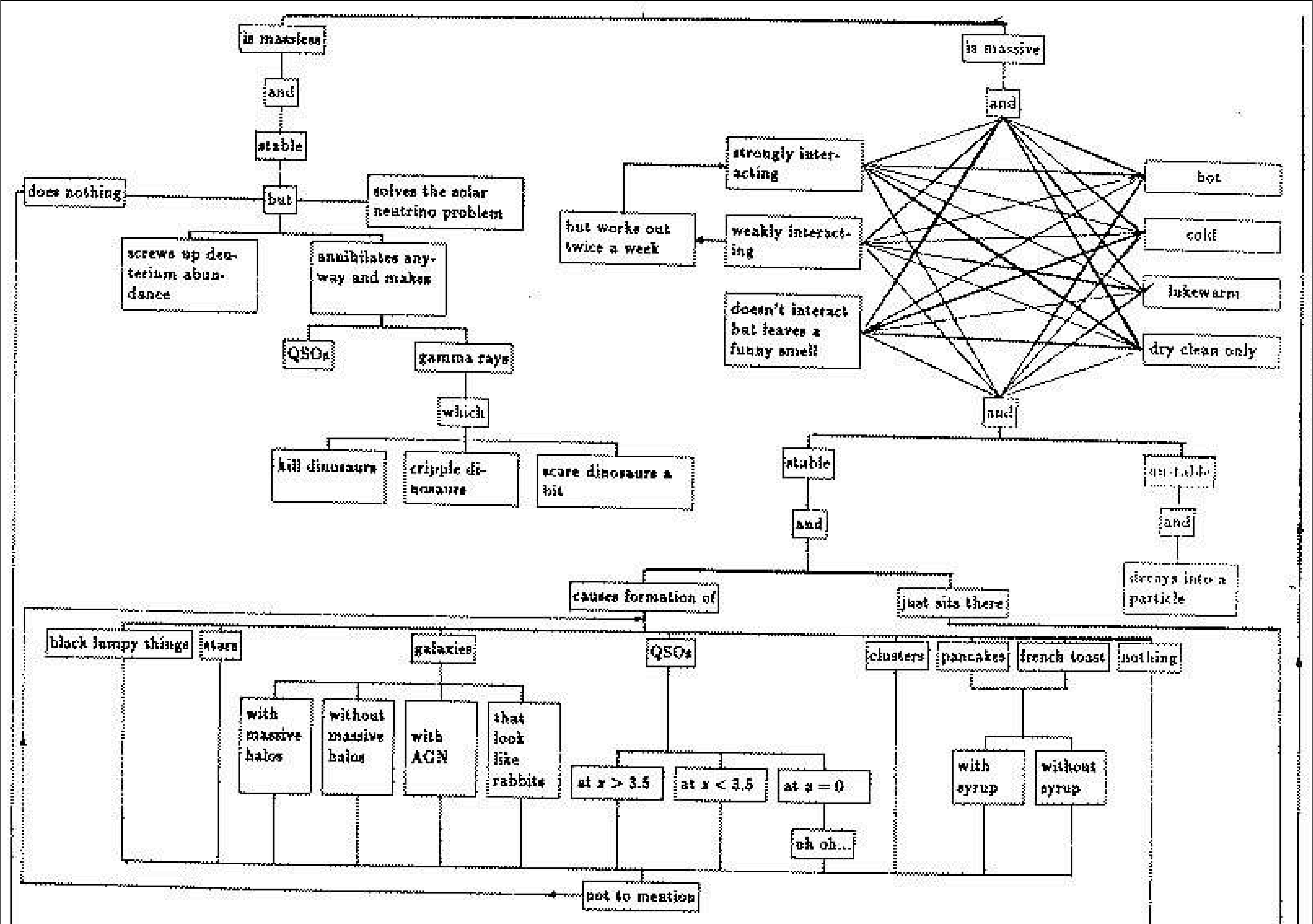
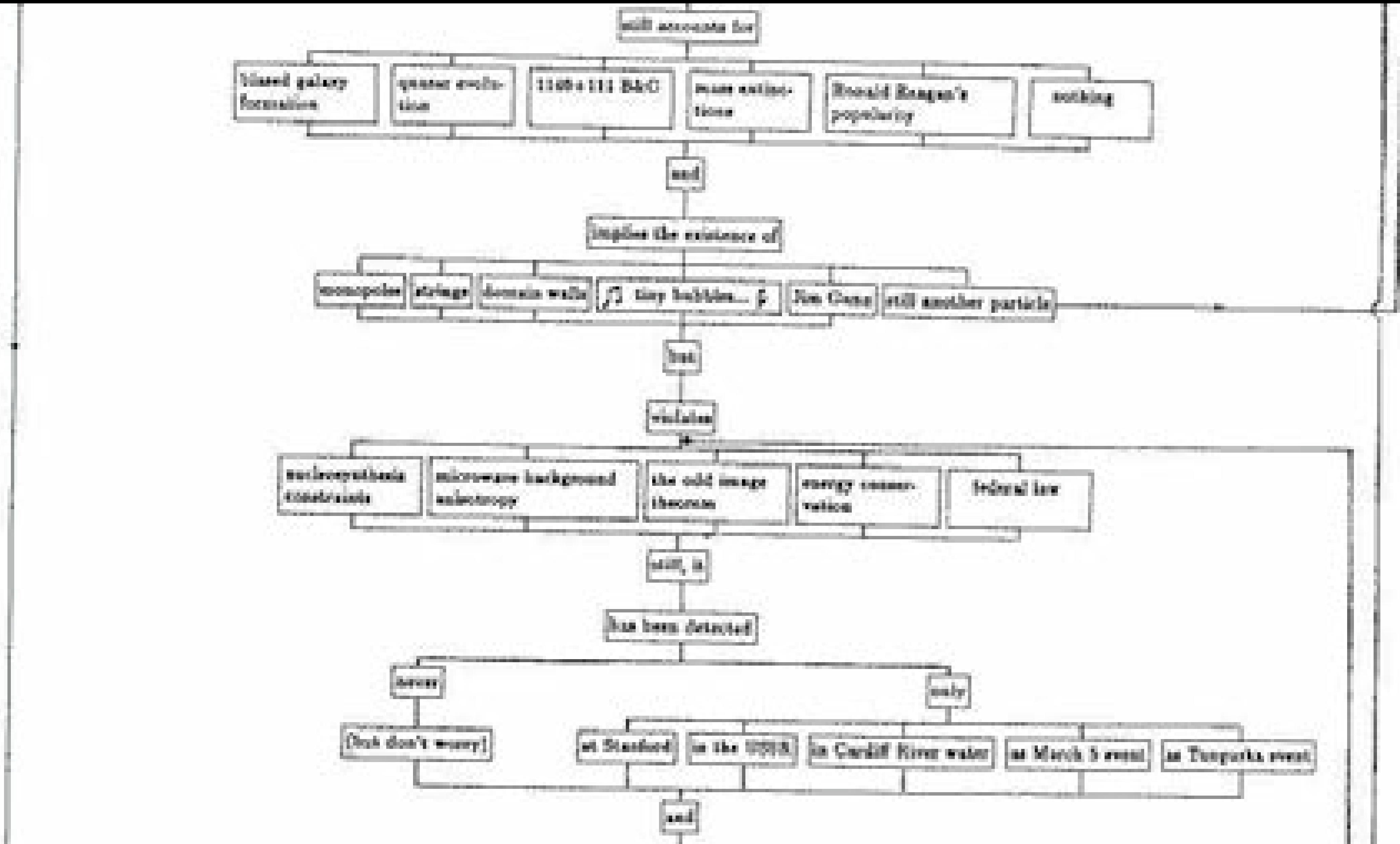
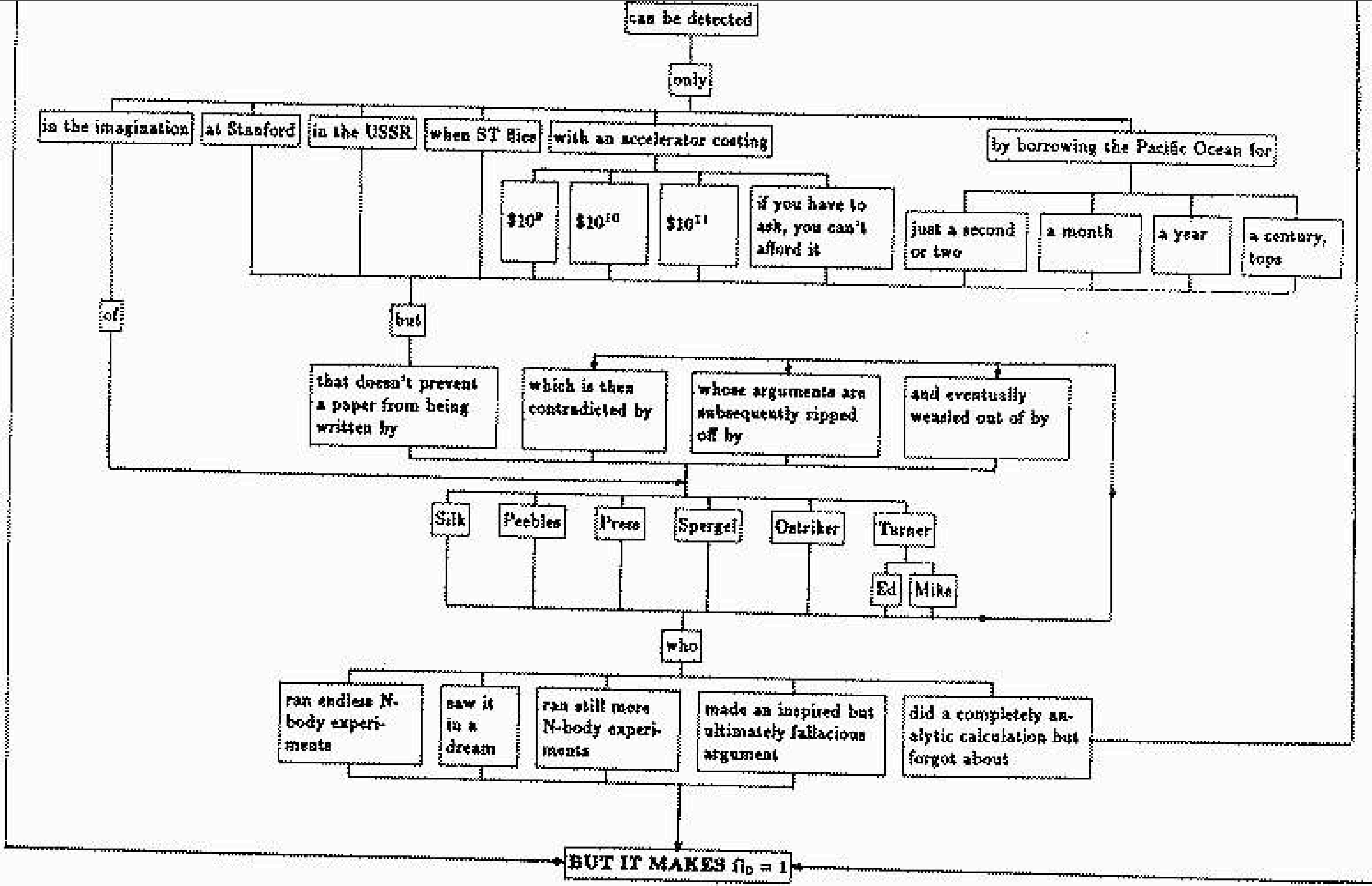
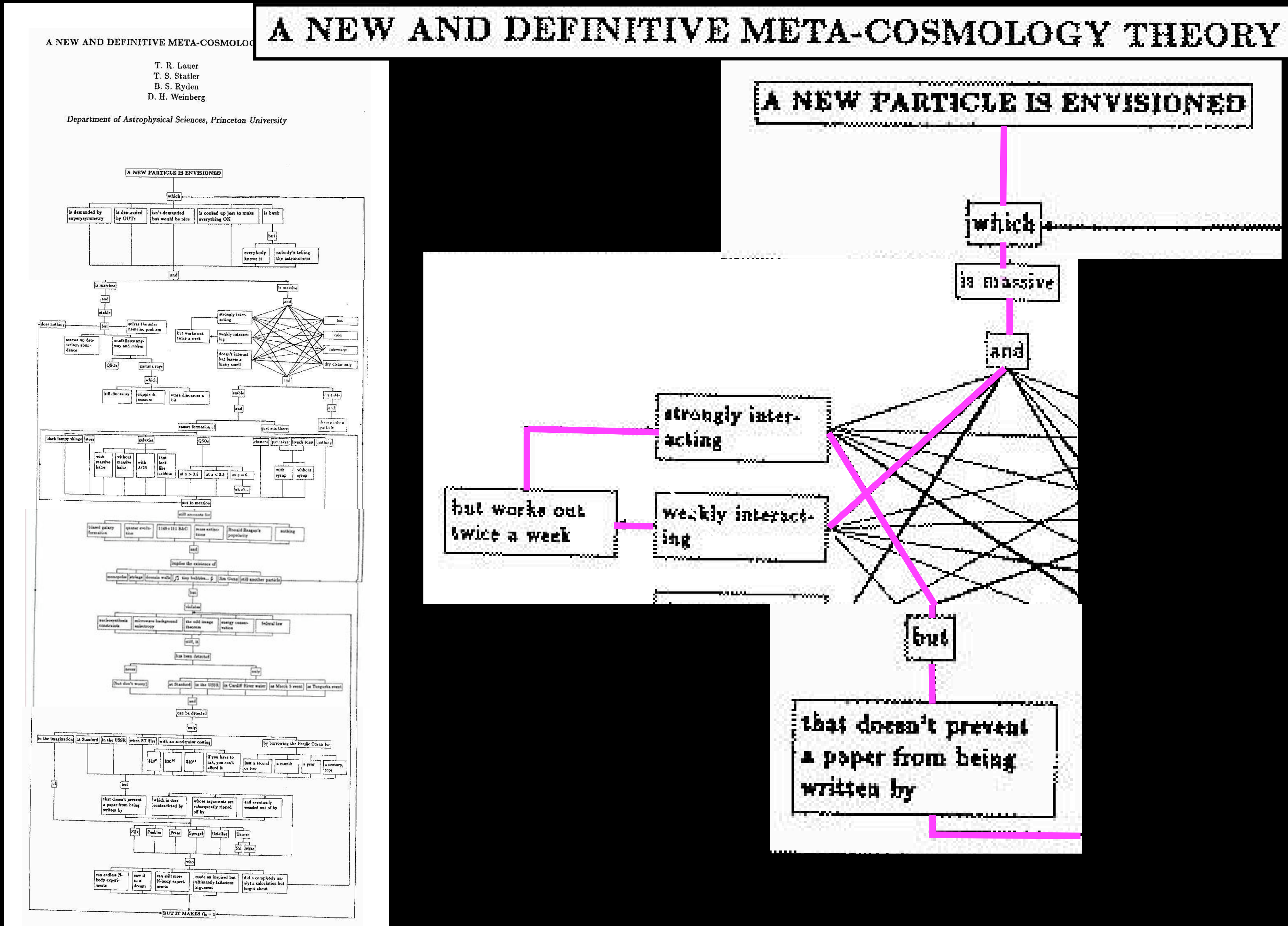
Department of Astrophysical Sciences, Princeton University




is massless
and
stable
does nothing
but
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
and
causes formation of
just sits there
and
decays into a particle
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
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
at March 5 event
at 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 weasled 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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D. H. Weinberg
Department of Astrophysical Sciences, Princeton University
A NEW PARTICLE IS ENVISIONED
which
is massive
and
strongly inter-
acting
but works out
twice a week
weakly interact-
ing
but
that doesn't prevent
a paper from being
written by