Dark Matter Particle Candidates

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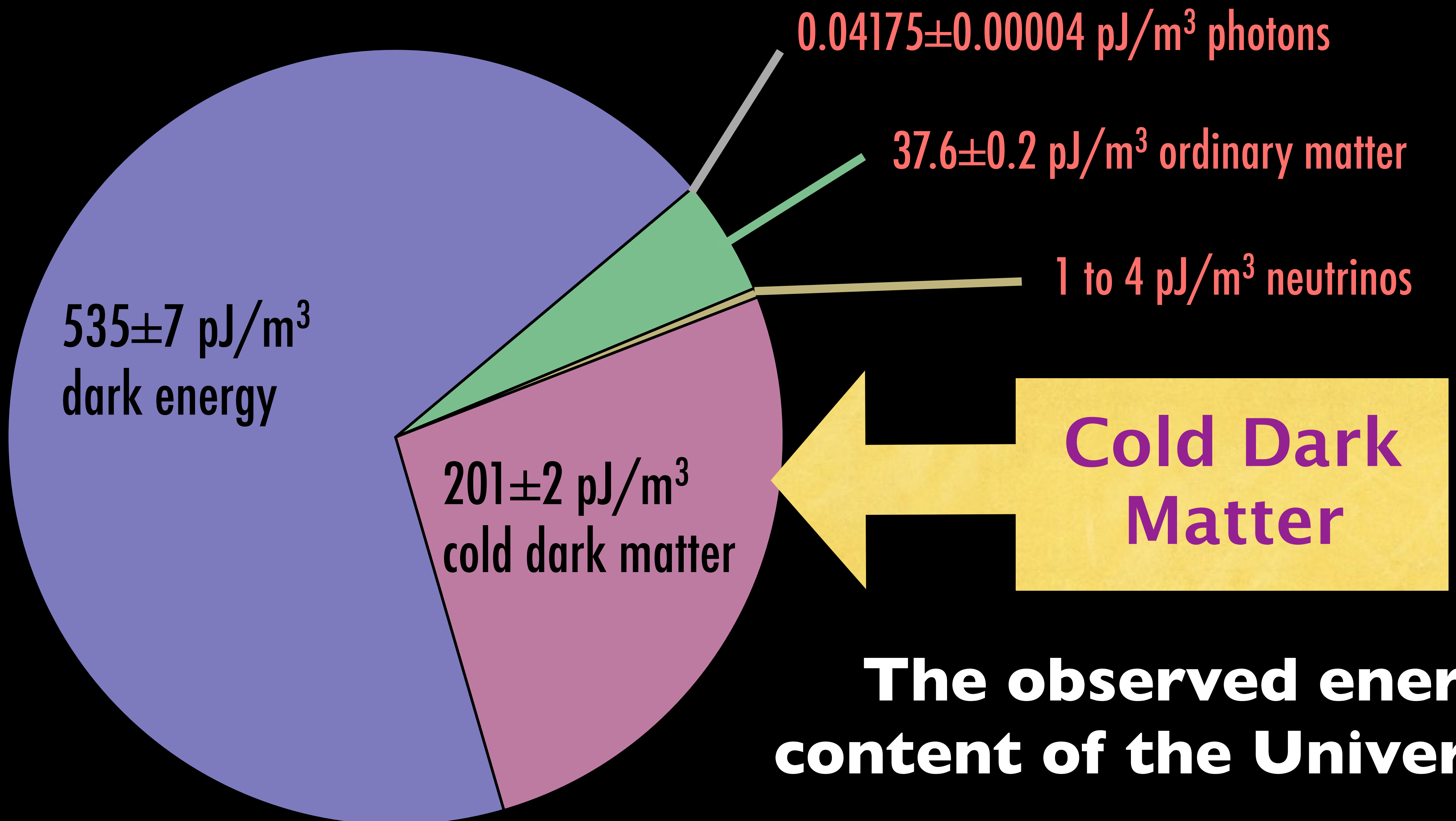
Evidence for cold dark matter



The observed energy content of the Universe

matter $p \ll \rho$

radiation $p=\rho/3$

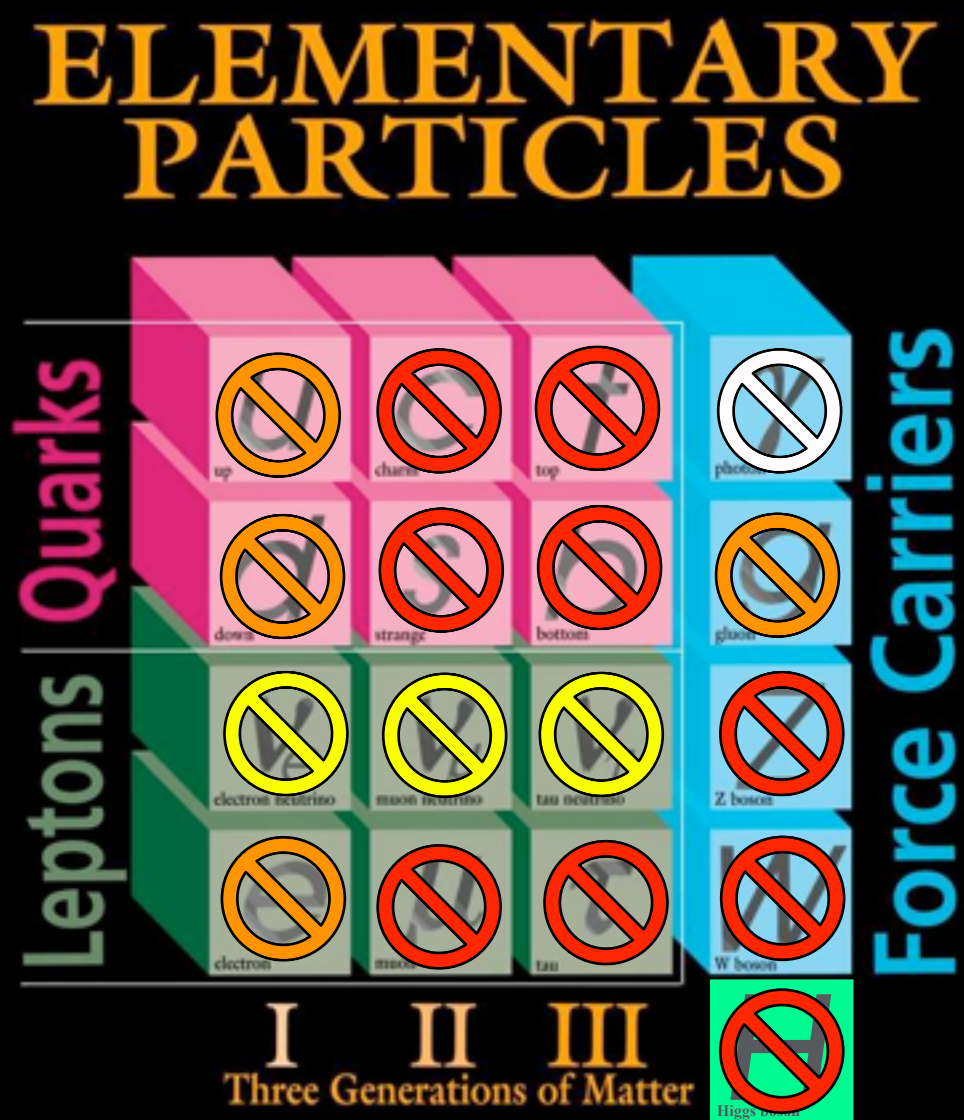
vacuum $p=-\rho$

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

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

$\rho_{\mathrm{crit}}=1688.29\ h^2\ \mathrm{pJ/m^3}$

Is cold dark matter an elementary particle?



- is the particle of light
- couples to the plasma
- disappears too quickly
- is hot dark matter

No known particle can be nonbaryonic cold dark matter!

What particle model for cold 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 claims of dark matter detection (annual modulation, positrons, X-ray line, γ-ray excess, etc.)

Particle dark matter

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

Mass range

10^{-22} eV (10^{-59}kg) B.E.C.s
10^{-8} $M_\odot$ (10^{+22}kg) axion clusters

Interaction strength range

Only gravitational: wimpzillas
Strongly interacting: B-balls

Particle dark matter

Hot dark matter

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

light neutrinos

Cold dark matter

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

neutralinos, axions, WIMPZILLAs, solitons

Warm dark matter

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

sterile neutrinos, gravitinos

Particle dark matter

Thermal relics

- in thermal equilibrium with the plasma in the early universe
- produced in collision of plasma particles
- insensitive to initial conditions

neutralinos, other WIMPs, ...

Non-thermal relics

- not in thermal equilibrium with the plasma in the early universe
- produced in decays of heavier particles or extended structures
- have a memory of initial conditions

axions, WIMPZILLAs, solitons, ...

Particle dark matter

DM production	- in plasma reactions - from decays of decoupled species - emitted from extended objects	collider searches cosmic density
DM-$\overline{\text{DM}}$ annihilation $\chi+\bar{\chi}\rightarrow$anything	- self-conjugate DM - asymmetric DM	indirect detection cosmic density
DM—SM scattering $\chi+\text{SM}\rightarrow\chi'+\text{SM}$	- elastic/inelastic scattering - short-/long-range interactions	hot/cold/warm halo (sub)structure direct detection
DM—DM scattering $\chi+\chi\rightarrow\chi+\chi$	- collisionless - self-interacting	dark halo structure
DM decay $\chi\rightarrow$anything	- stable - long-lived - ensemble of short-lived particles	indirect detection

Particle dark matter

Some factors affecting the particle dark matter cosmic density

— Production mechanism:

- produced in reactions of plasma (thermal) particles
  - reaching reaction equilibrium — *WIMP freeze-out, …*
  - not reaching reaction equilibrium — *FIMP freeze-in, …*
  - coannihilating with similar mass particles — *neutralinos, …*
- produced in decays of non-thermal particles — *gravitinos, …*
- emitted from extended objects — *axions, …*

— Dark matter-antimatter asymmetry:

- self-conjugate — *Majorana fermions, neutralinos, axions, gravitinos, …*
- not self-conjugate — *Dirac fermions, asymmetric dark matter, …*

— Hubble expansion rate before nucleosynthesis:

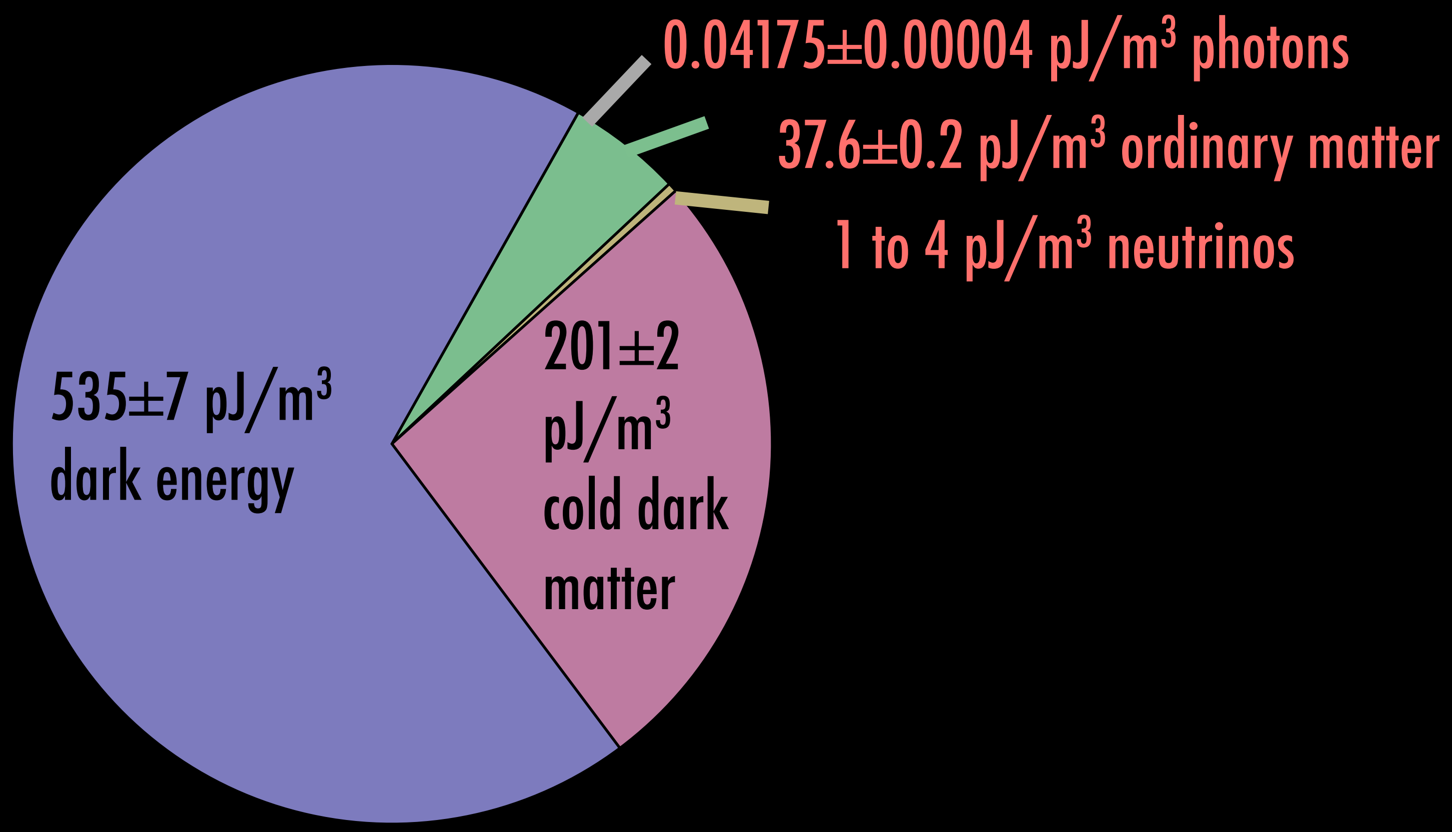
- standard vs nonstandard cosmology — *low temperature reheating, kination, …*

The magnificent WIMP

(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

    Thermal production in hot primordial plasma.

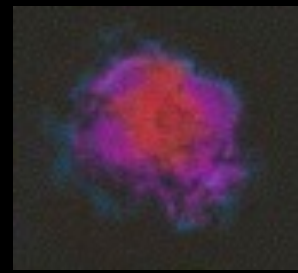


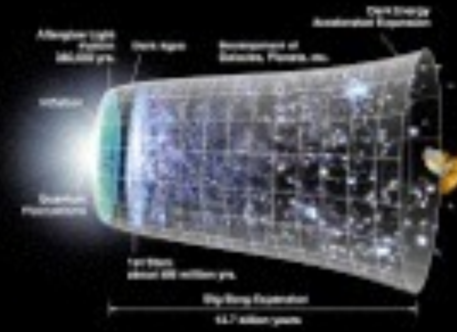
- One can experimentally test the WIMP hypothesis

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

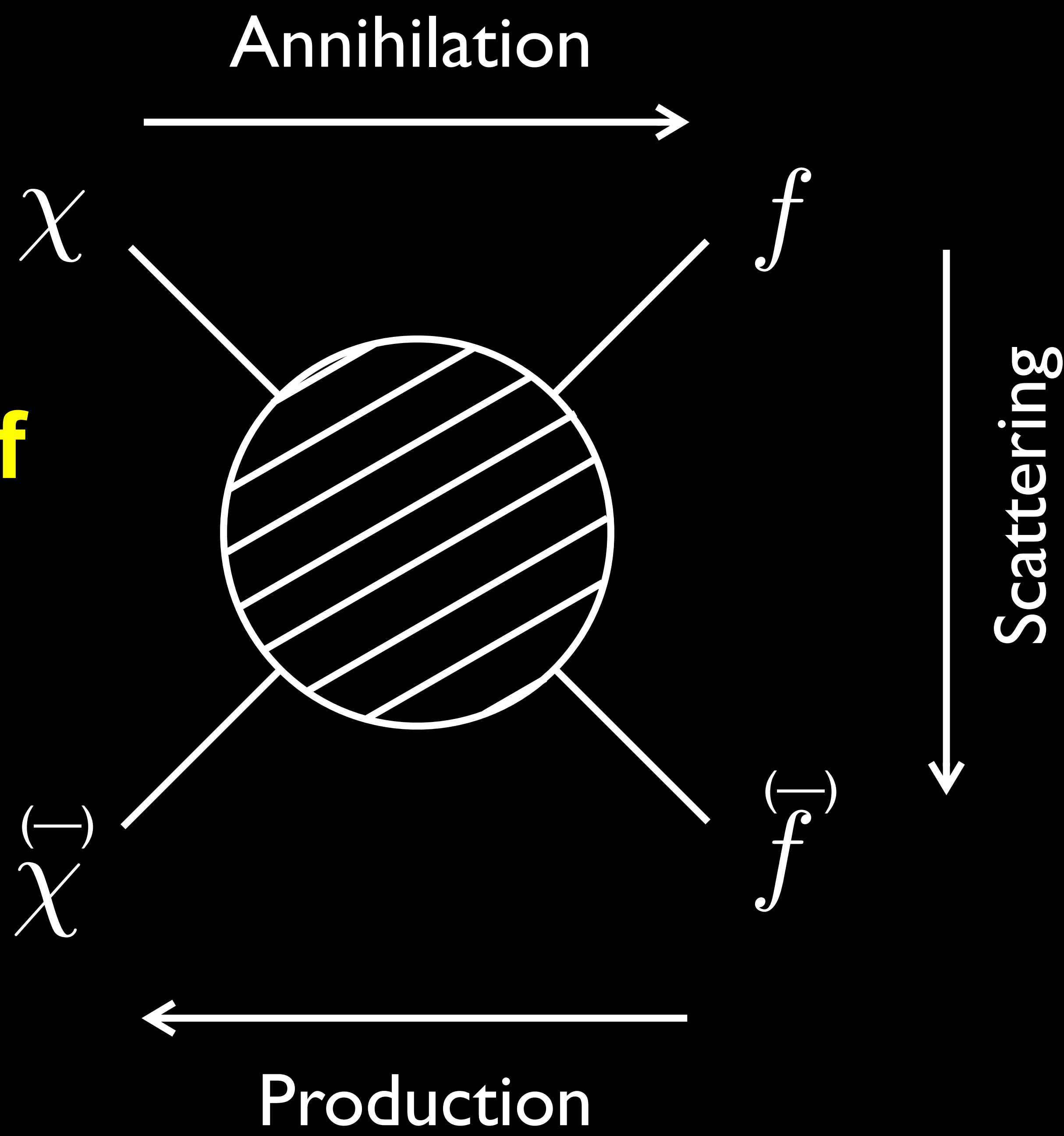
The power of the WIMP

Indirect detection

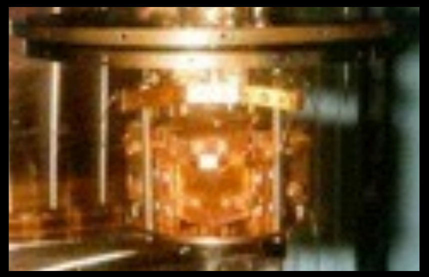


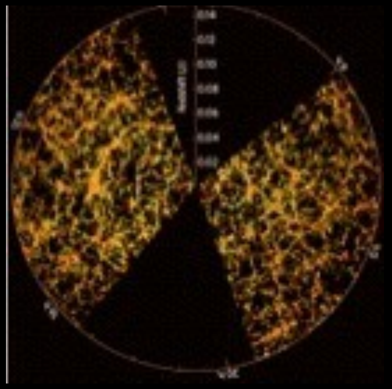


Cosmic density



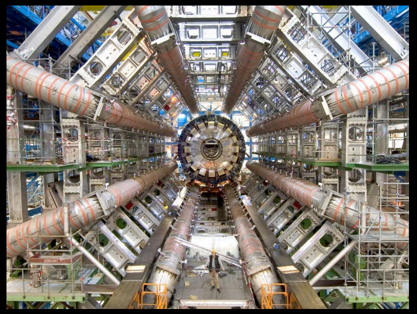
Direct detection

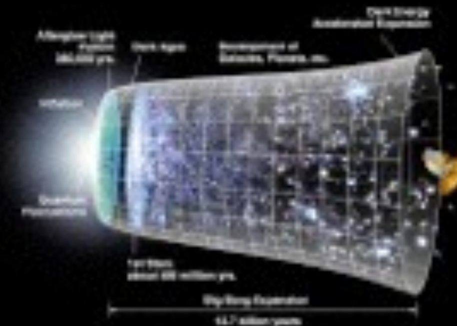




Large scale structure

Colliders



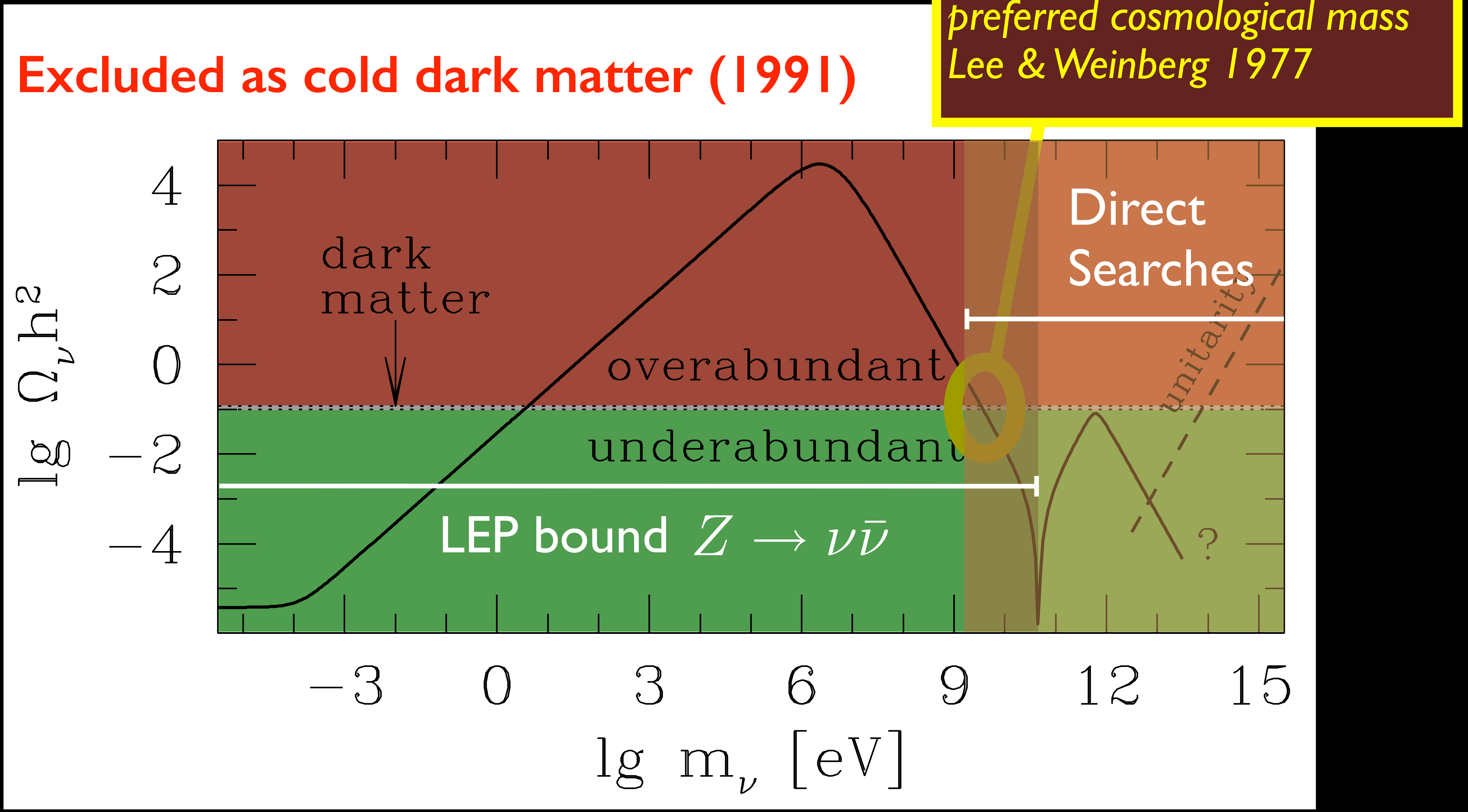


Cosmic density

Neutrinos

Cosmic density of massive neutrinos

Active neutrinos



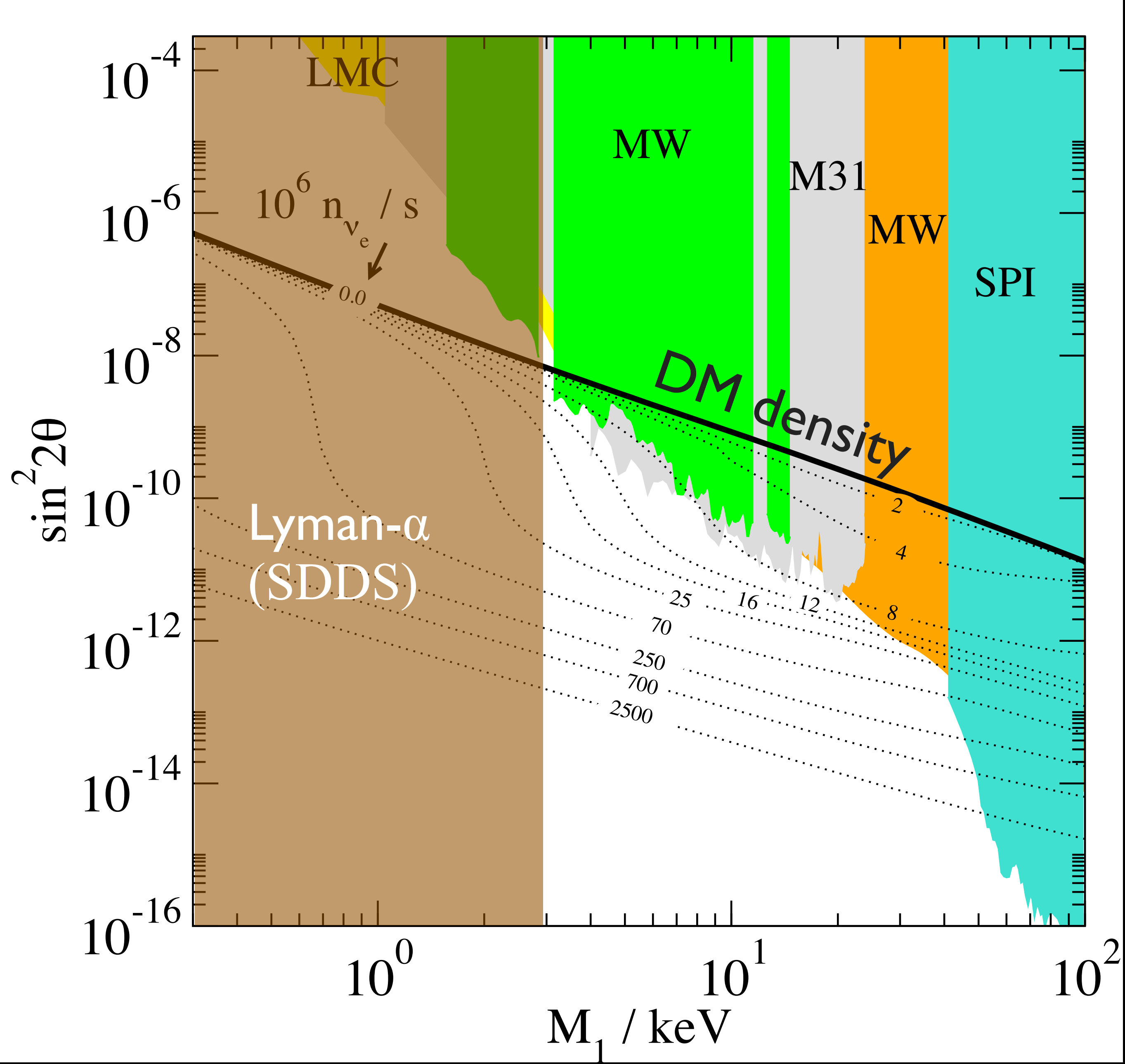
Sterile neutrino dark matter

Standard model + right-handed neutrinos

Active and sterile neutrinos oscillate into each other.

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

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



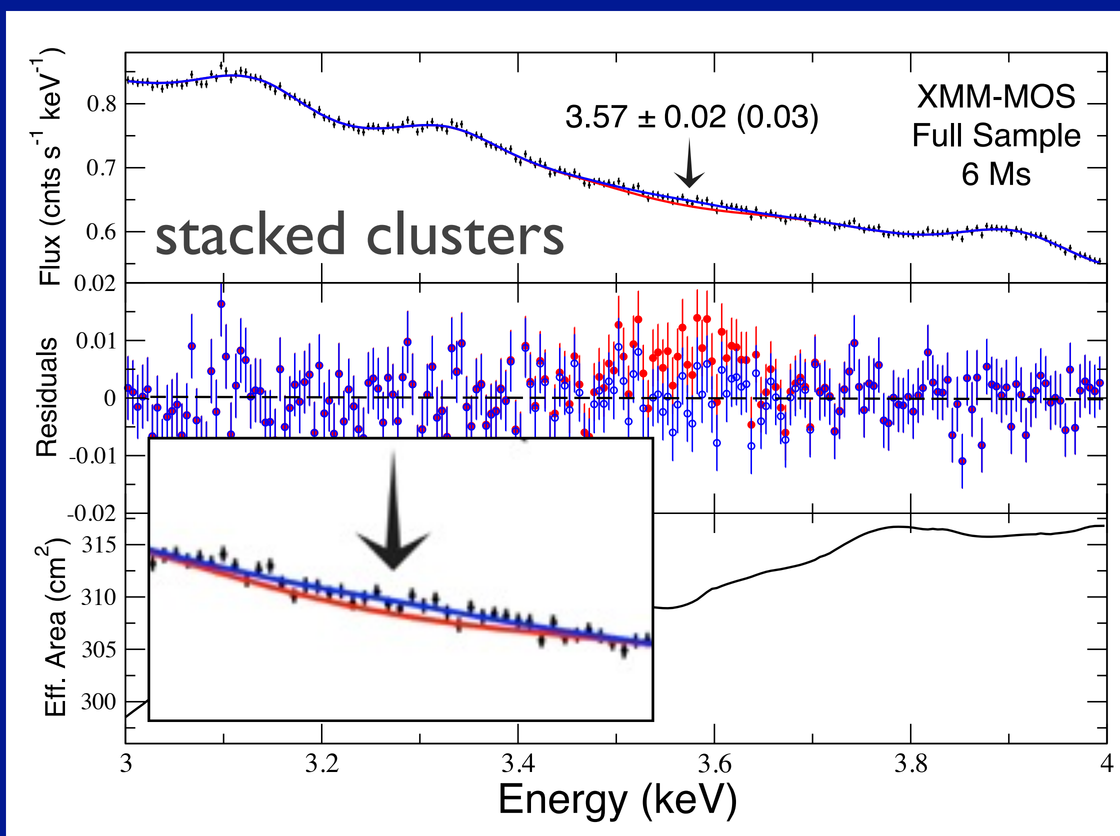
νMSM

Laine, Shaposhnikov 2008

Sterile neutrino dark matter

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

Bulbul et al 2014; Boyarski et al 2014; Iakubovskyi et al 2015

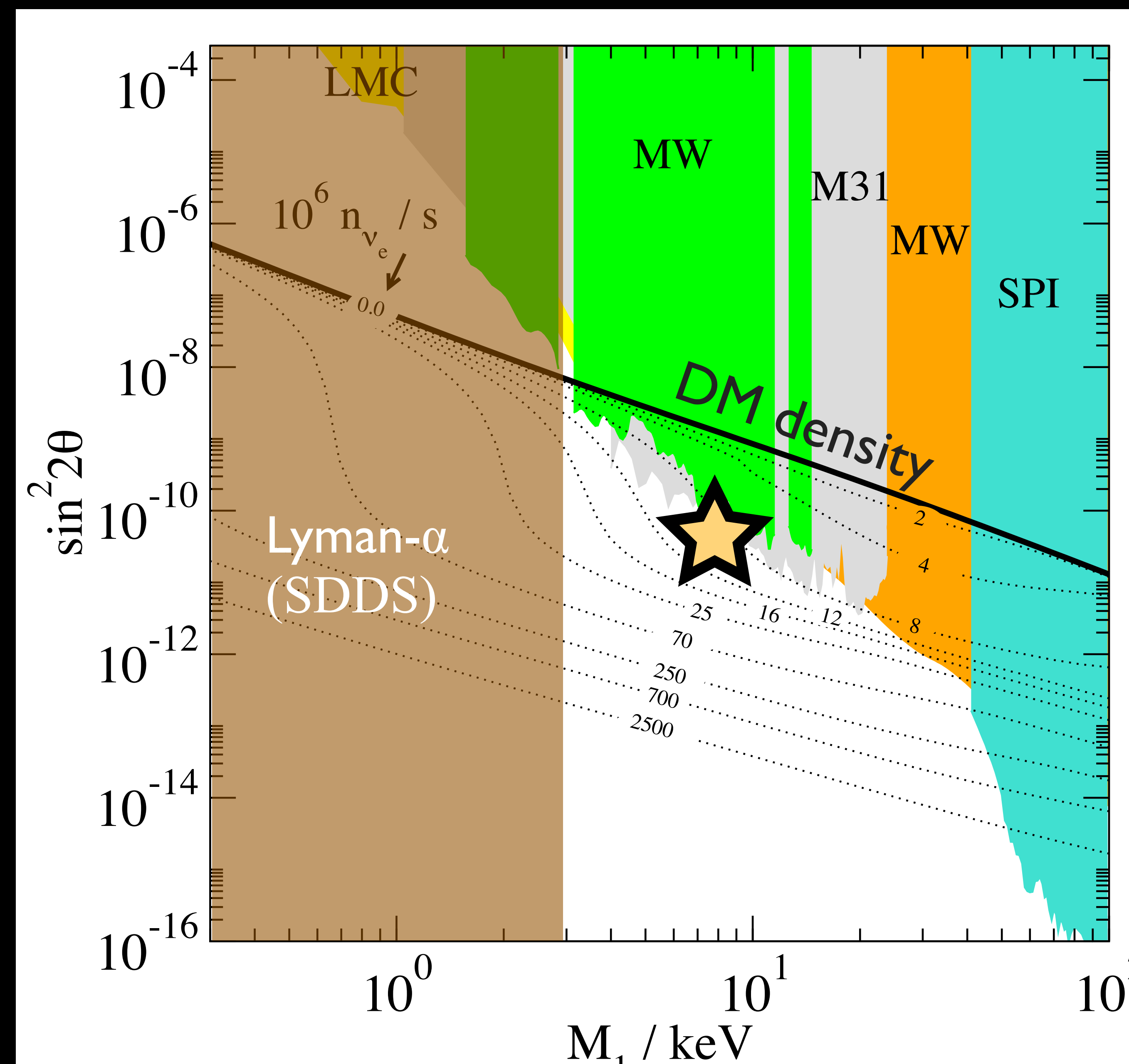


Fuller, Lowenstein, Jeltema, Kusenko, Abazajian, Smith (Thursday)

Radiative decay of sterile neutrinos

$$\nu_s \to \gamma \nu_a \qquad E_\gamma = m_s/2$$

$$m_\nu = 7.1 \text{ keV} \qquad \sin^2(2\theta) = 7\times10^{-11}$$



νMSM

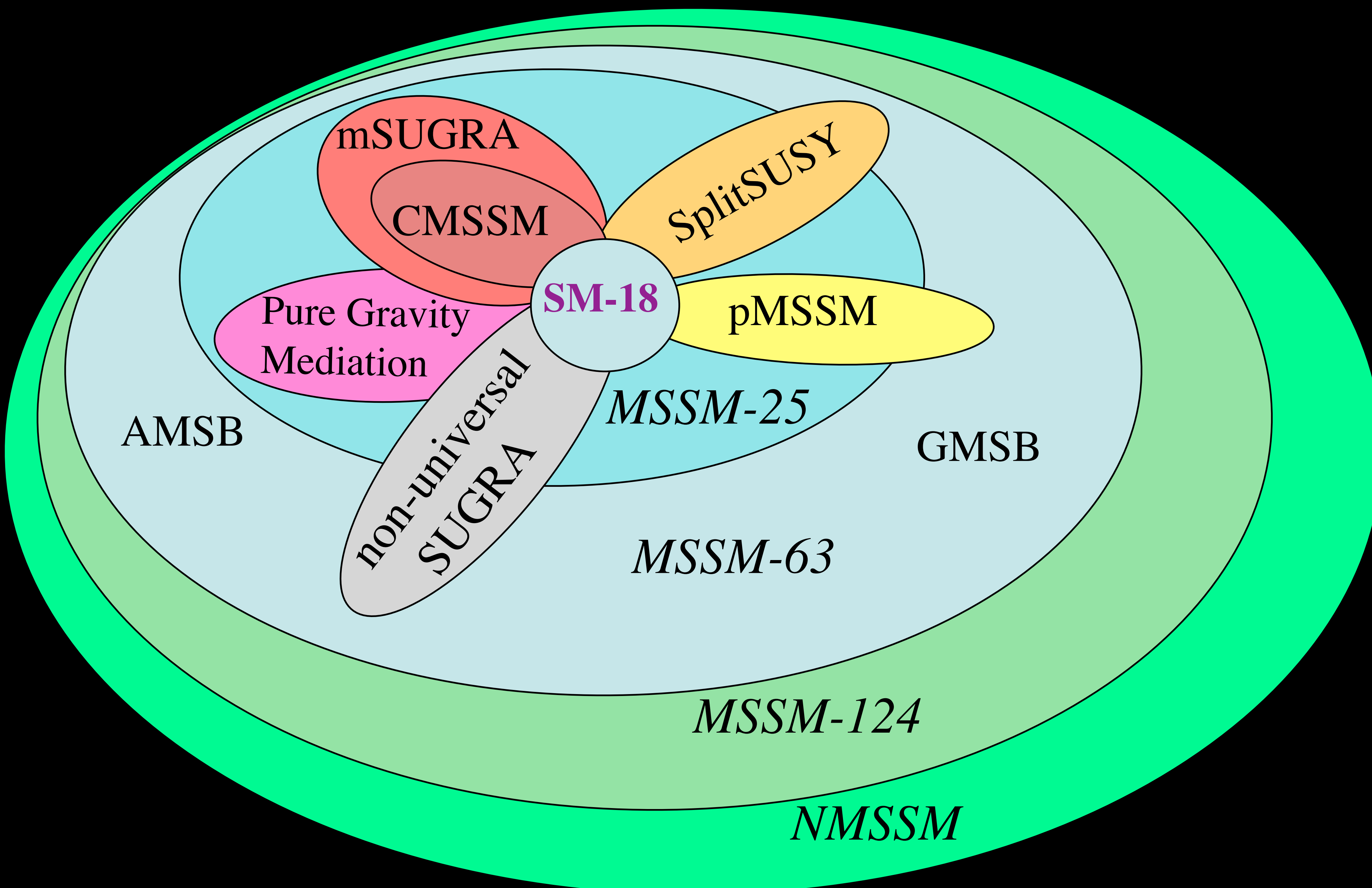
haposhnikov 2008

Neutralinos

Supersymmetric models

The CMSSM* is in dire straights, but there are many supersymmetric models

**Constrained Minimal Supersymmetric Standard Model*



Neutralino dark matter: impact of LHC

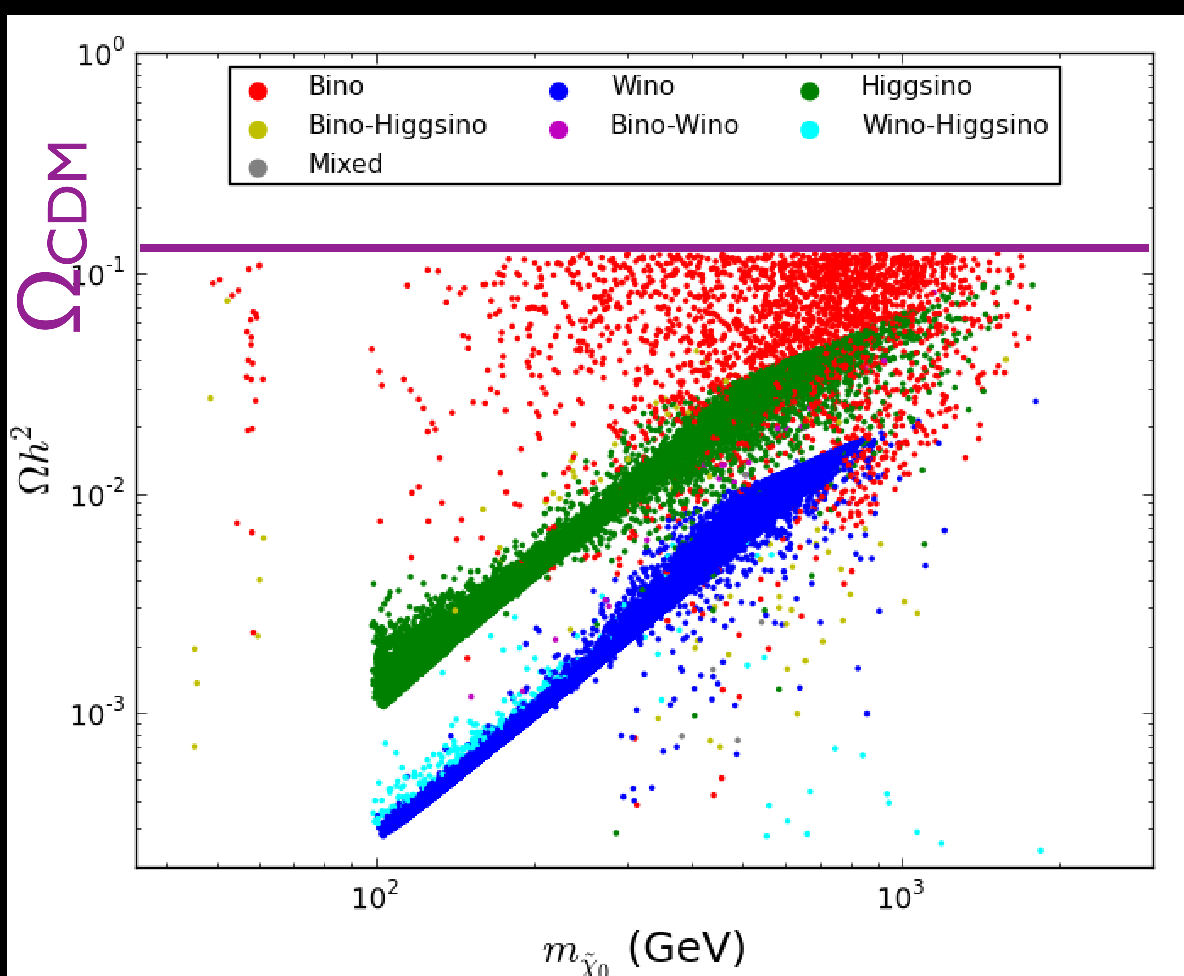
Cahill-Rowell et al 1305.6921

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

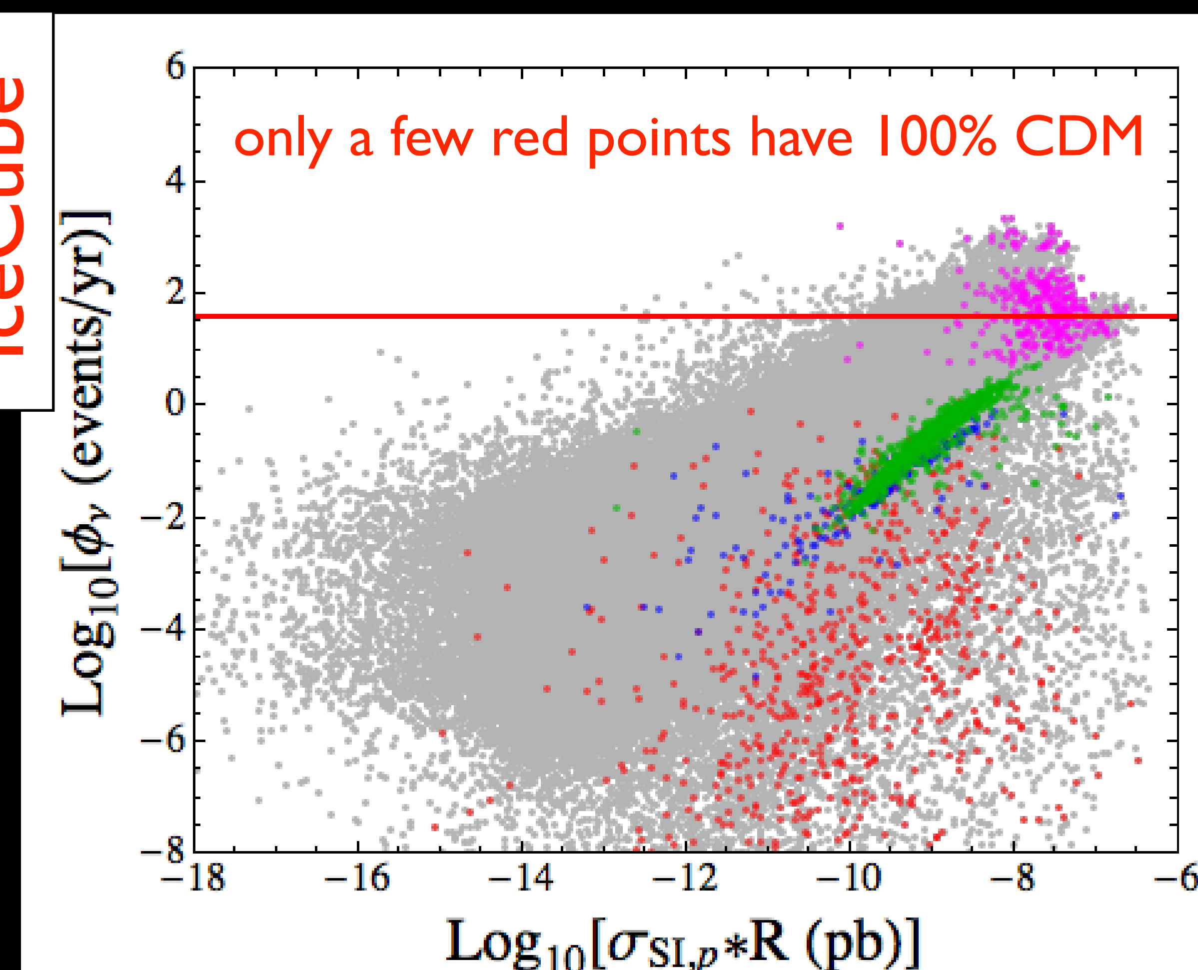
pMSSM (phenomenological MSSM)

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

(19 parameters)



“IceCube”

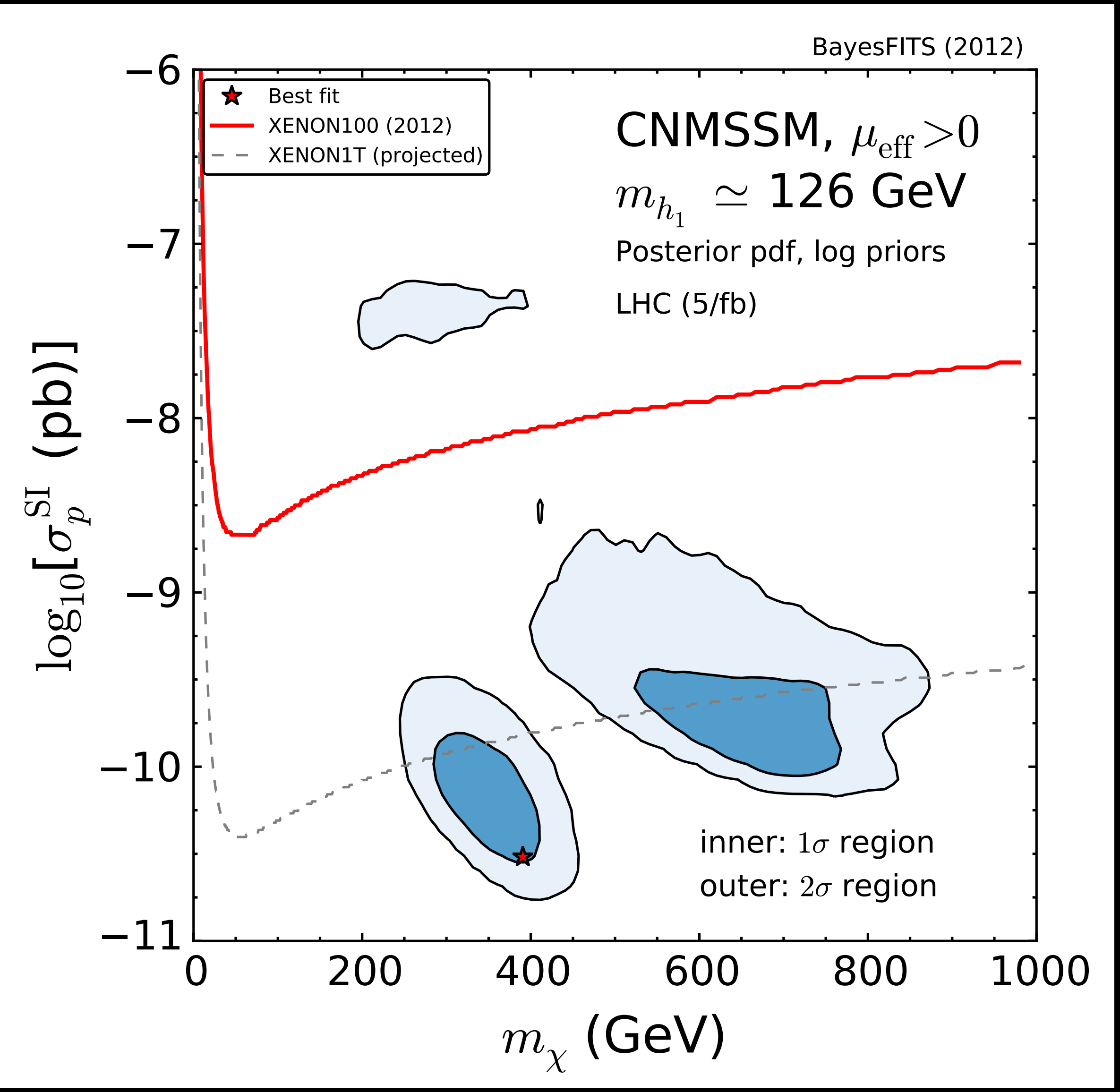


“Direct Detection”

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

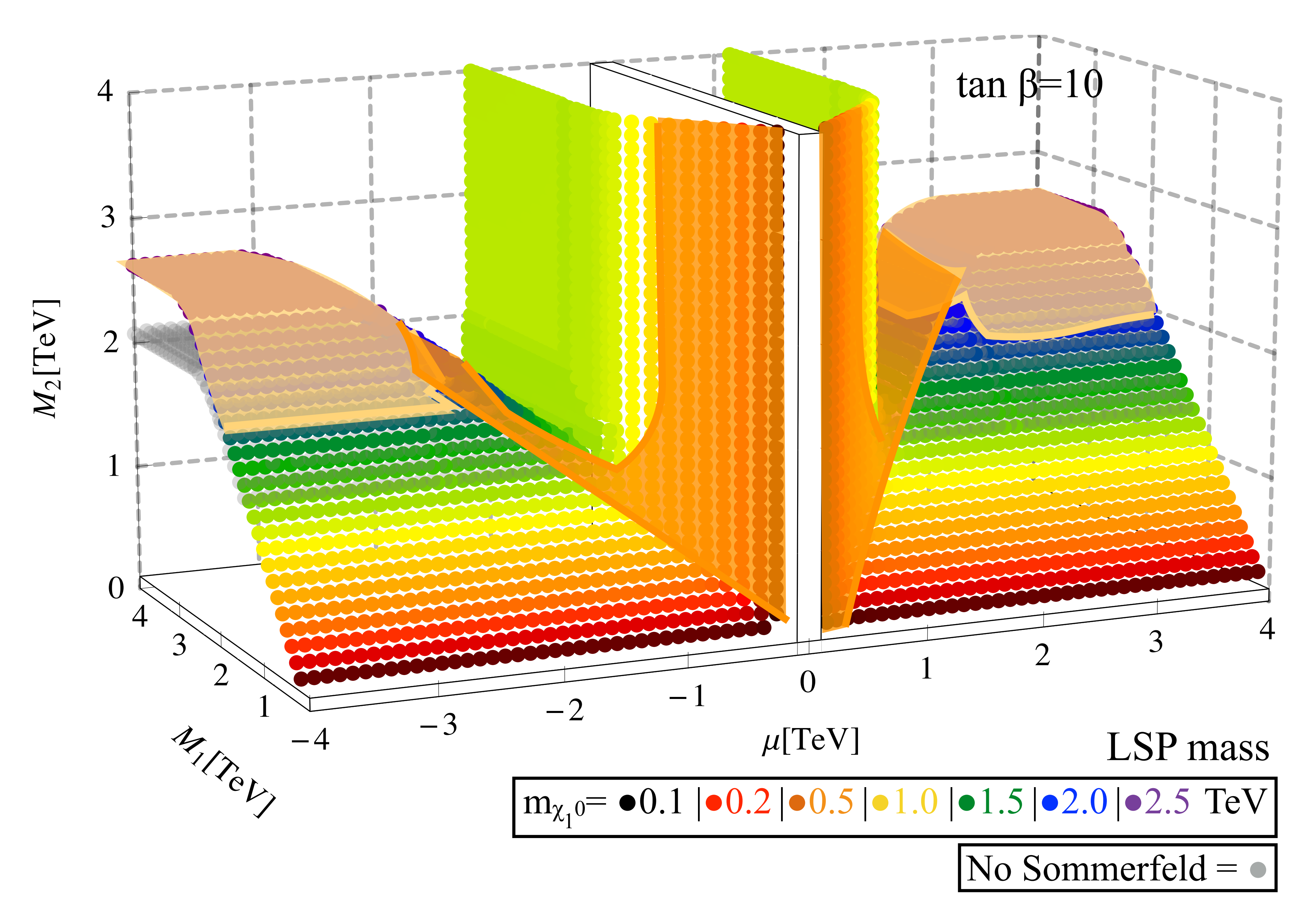
m_0, $m_{1/2}$, A_0, $\tan\beta$, λ, $\text{sgn}(\mu_{\rm eff})$,

GUT & radiative EWSB

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

Neutralino dark matter

Neutralino dark matter with decoupled (heavy) sfermions



Bramante, Desai, Fox, Martin, Ostdiek, Plehn 2015

Excluded by LEP, HESS, LUX

All can be tested by LZ, CTA, and a 100-TeV pp collider

Baer, Nanopoulos (Thursday)

QCD axions

QCD 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 minimum of the axion potential

(Vacuum realignment)

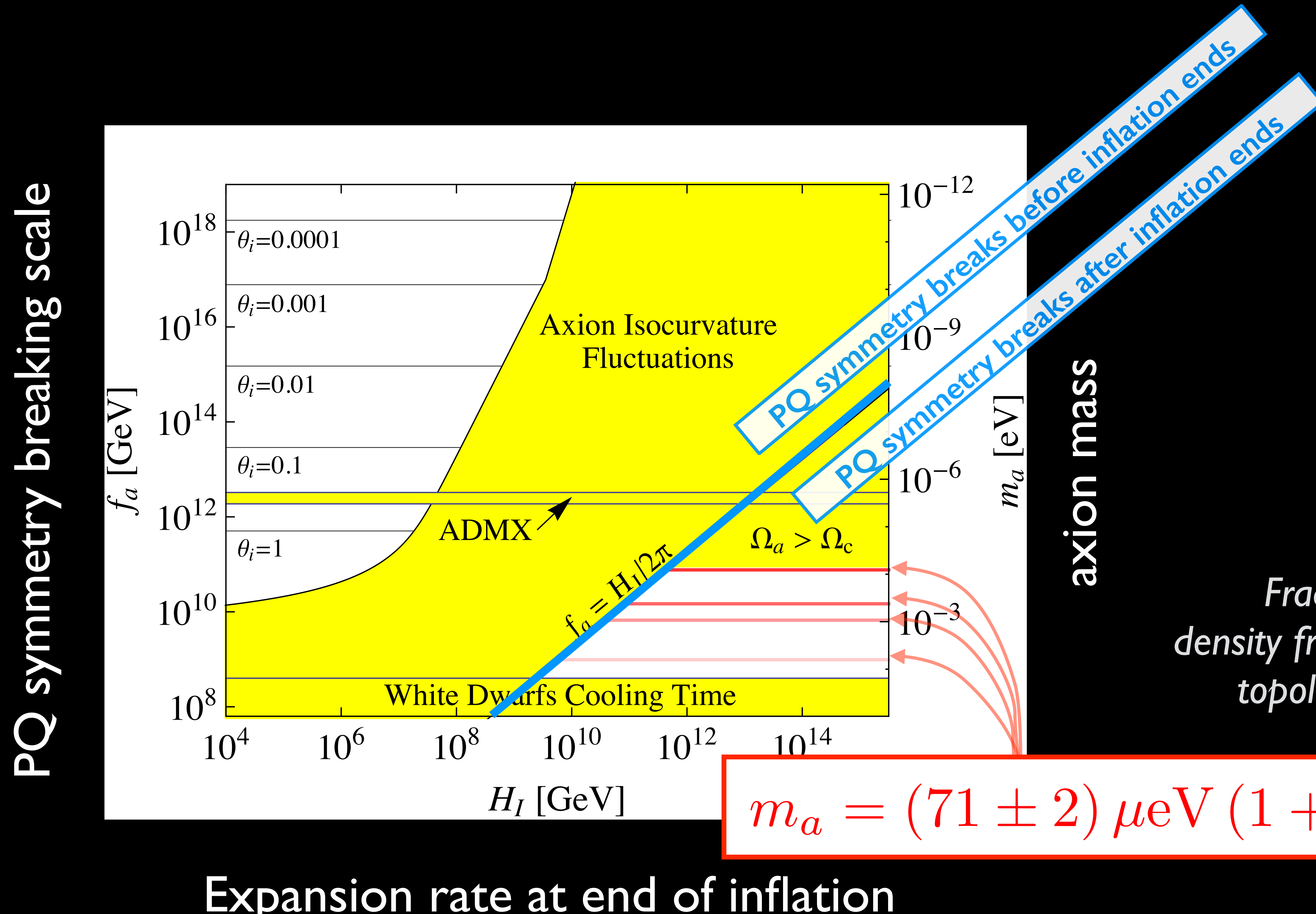
Produced by decay of topological defects

(Axionic string decays)

Still a very complicated and uncertain calculation!

e.g. Hiramatsu et al 2012

QCD axions as cold dark matter



Fraction of axion density from decays of topological defects

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

Visinelli, Gondolo 2009, 2014

Sikivie (today),
Carosi, Brubaker, Baer
(Thursday)

Anapole dark matter

Anapole dark matter

The anapole moment is a C and P violating,
but CP-conserving, electromagnetic moment *Zeldovich 1957*

First measured experimentally in Cesium atoms *Wood et al 1997*

Anapole dark matter

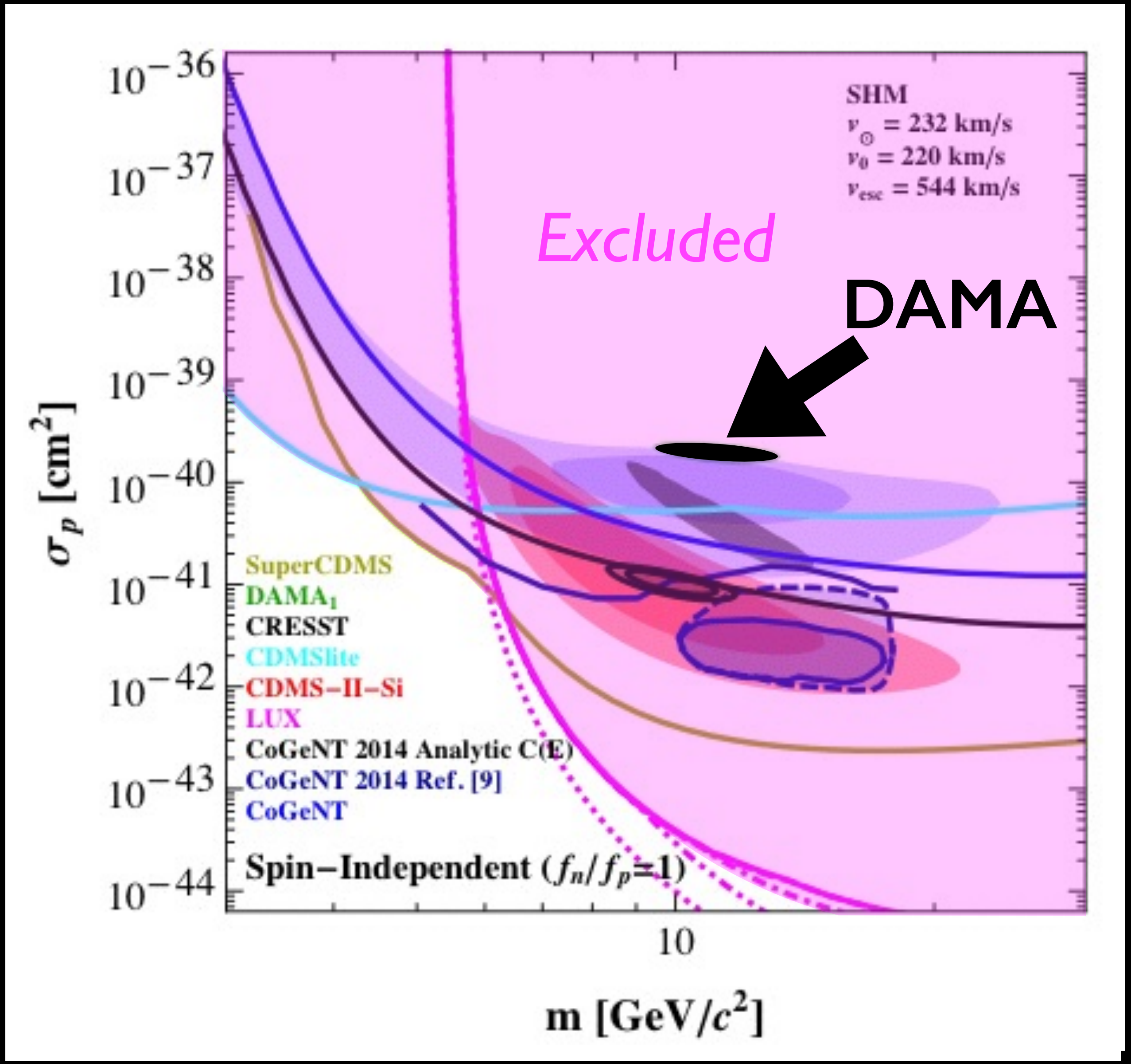
spin-1/2 Majorana fermion

$$\mathcal{L} = \frac{g}{2\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$

$$H = -\frac{g}{\Lambda^2}\,\vec{\sigma}\cdot\vec{\nabla}\times\vec{B}$$

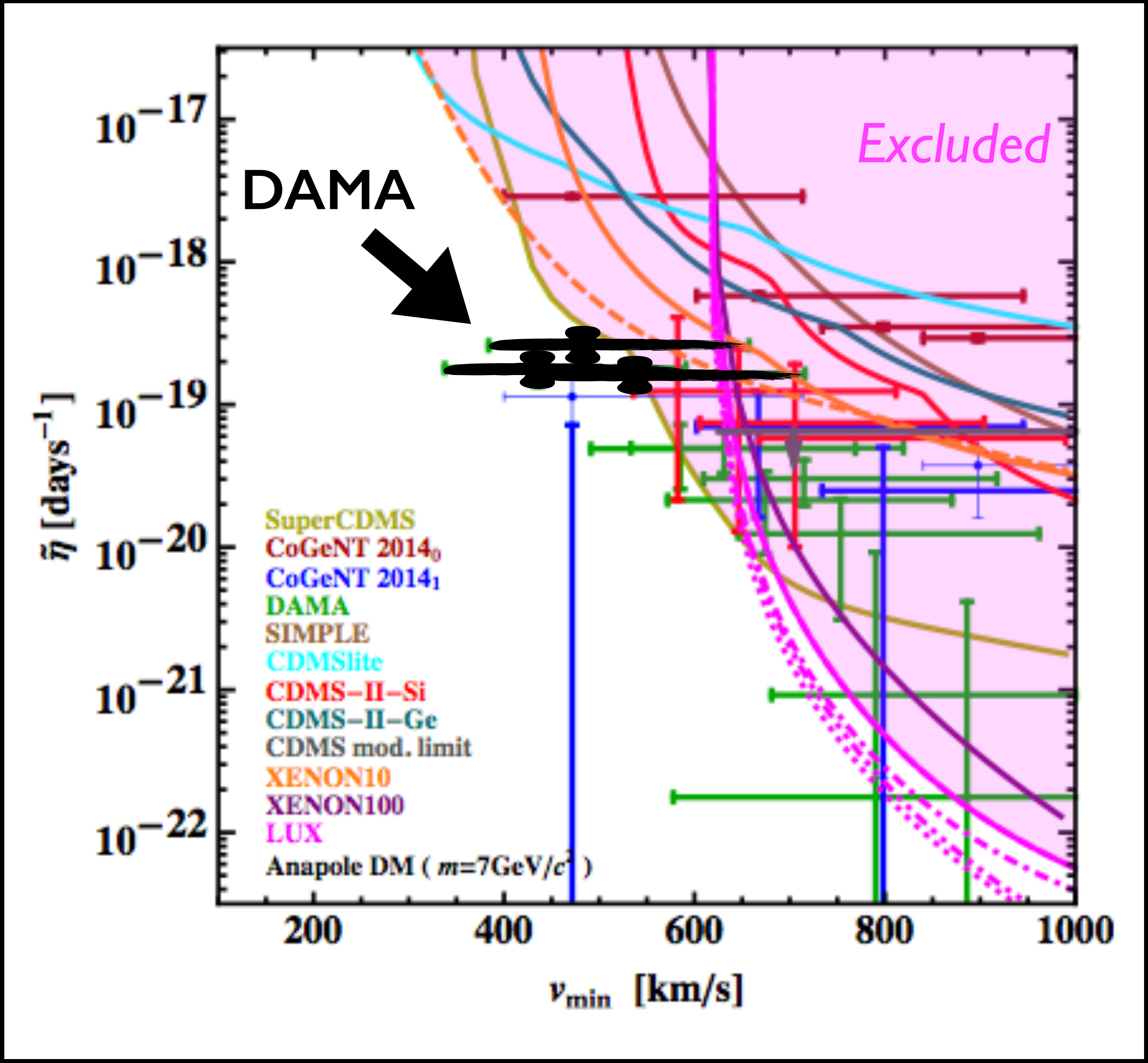
Direct detection limits
with standard dark halo

Del Nobile, Gelmini, Gondolo, Huh 2014



Anapole dark matter

$$\frac{d\sigma}{dE_R} = \frac{2m}{\pi v^2}\frac{e^2 g^2}{\Lambda^2}\left[\left(v^2 - v_{\min}^2\right)F_L^2(E_R) + F_T^2(E_R)\right]$$



For anapole dark matter, the lowest DAMA bins may be compatible with null searches

The modulation amplitude would need to be large

Del Nobile, Gelmini, Gondolo, Huh 2014

Scalar phantoms

Scalar phantom dark matter

"Gauge singlet scalar dark matter"
"Singlet scalar dark matter"
"Scalar singlet dark matter"
"Scalar Higgs-portal dark matter"
"The minimal model of dark matter"

Minimalist dark matter

do not confuse with minimal dark matter

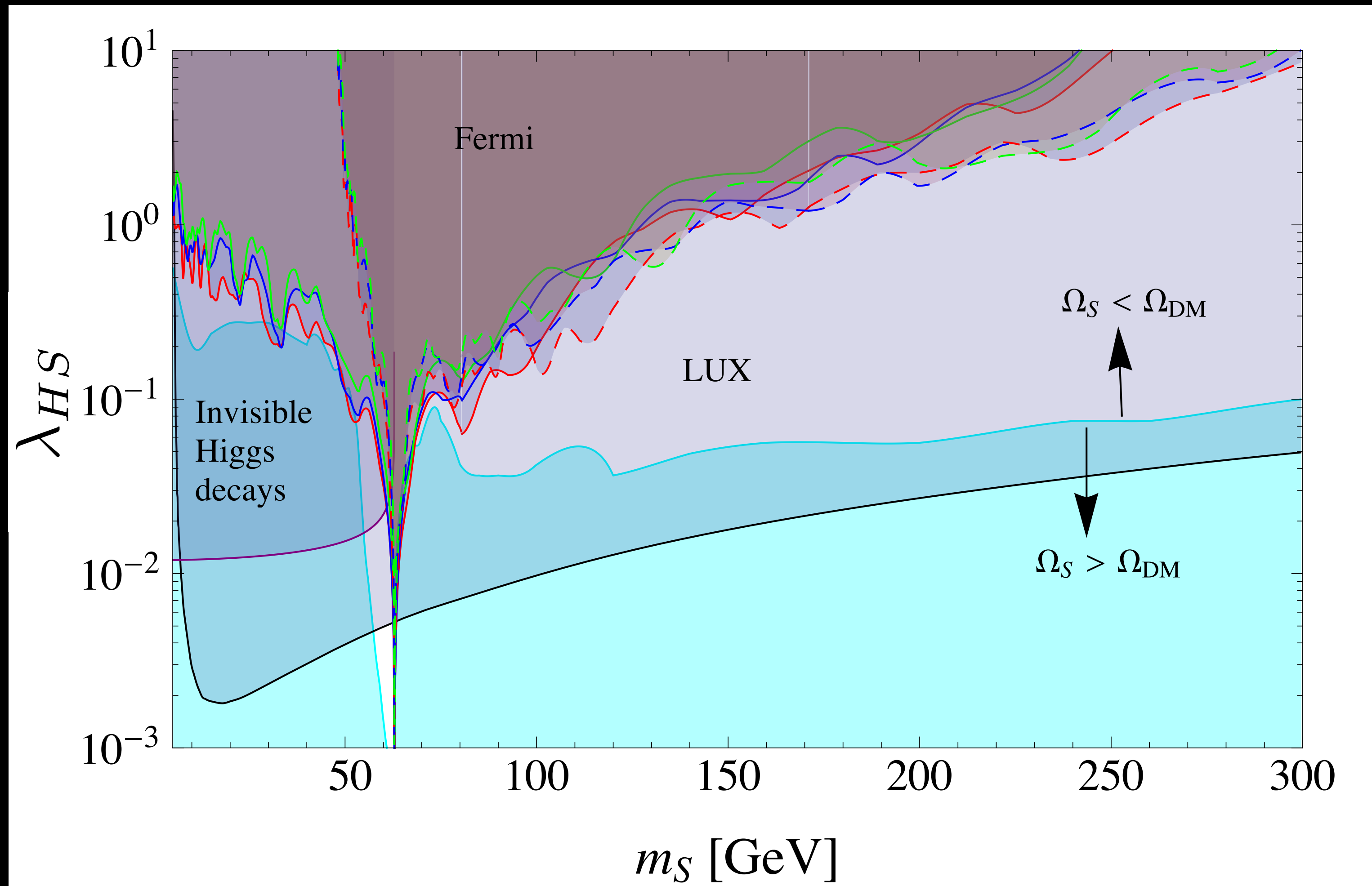
Gauge singlet scalar field S stabilized by a Z_2 symmetry ($S \to -S$)

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

Silveira, Zee 1985
Andreas, Hambye, Tytgat 2008
Djouadi, Falkowksi, Mambrini, Quevillon 2012
Cline, Scott, Kainulainen, Weniger 2013

"Scalar phantom" is the original 1985 name

Scalar phantom dark matter



Not excluded by LUX at $m_S \approx 60$ GeV and $m_S > 1$ TeV
No density rescaling

Feng, Profumo, Ubaldi 2015

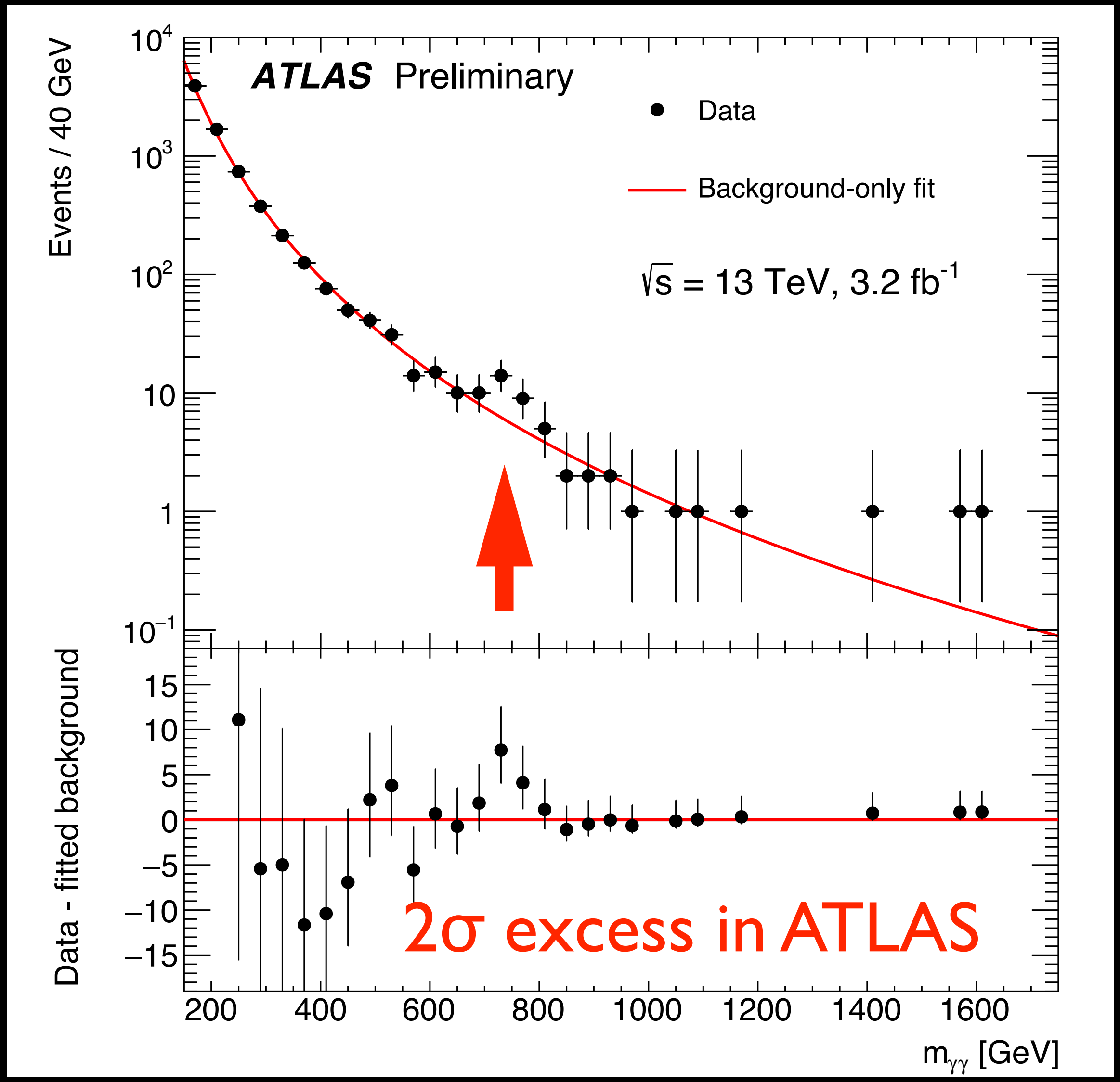
If density is rescaled according to Ω_S, LUX and FERMI exclusion regions are very different

Cline, Scott, Kainulainen, Weniger 2013

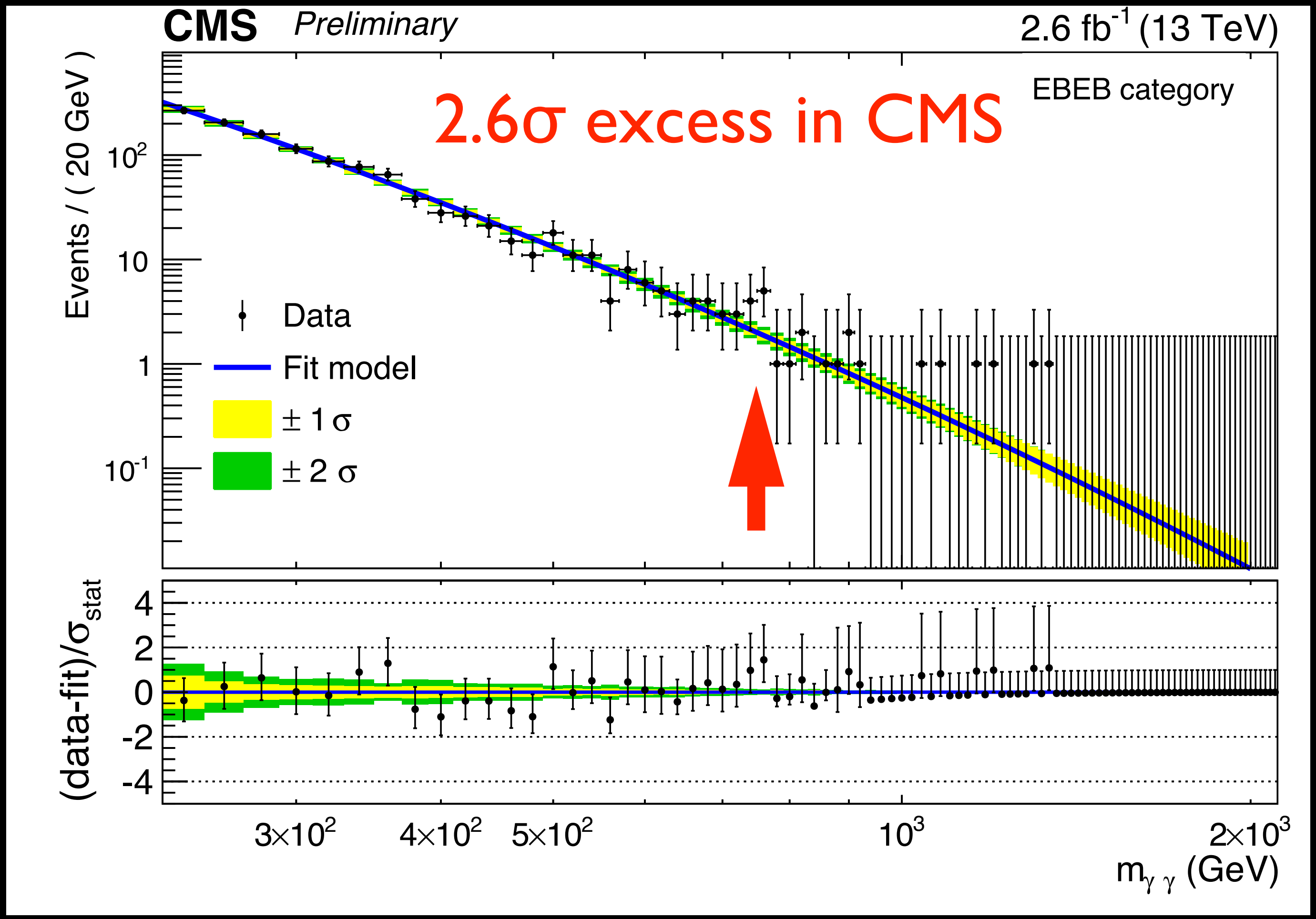
750-GeV portal

The 750-GeV resonance at the LHC

A possible spin-0 resonance decaying into a pair of photons



ATLAS note CONF-2015-081 (2015/12/15)



CMS PAS EXO-15-004 (2015/12/18)

There are many models and analyses relating the 750-GeV resonance to dark matter, too numerous to list here.

750-GeV portal with Majorana dark matter

D'Eramo, de Vries, Panci 1601.01571

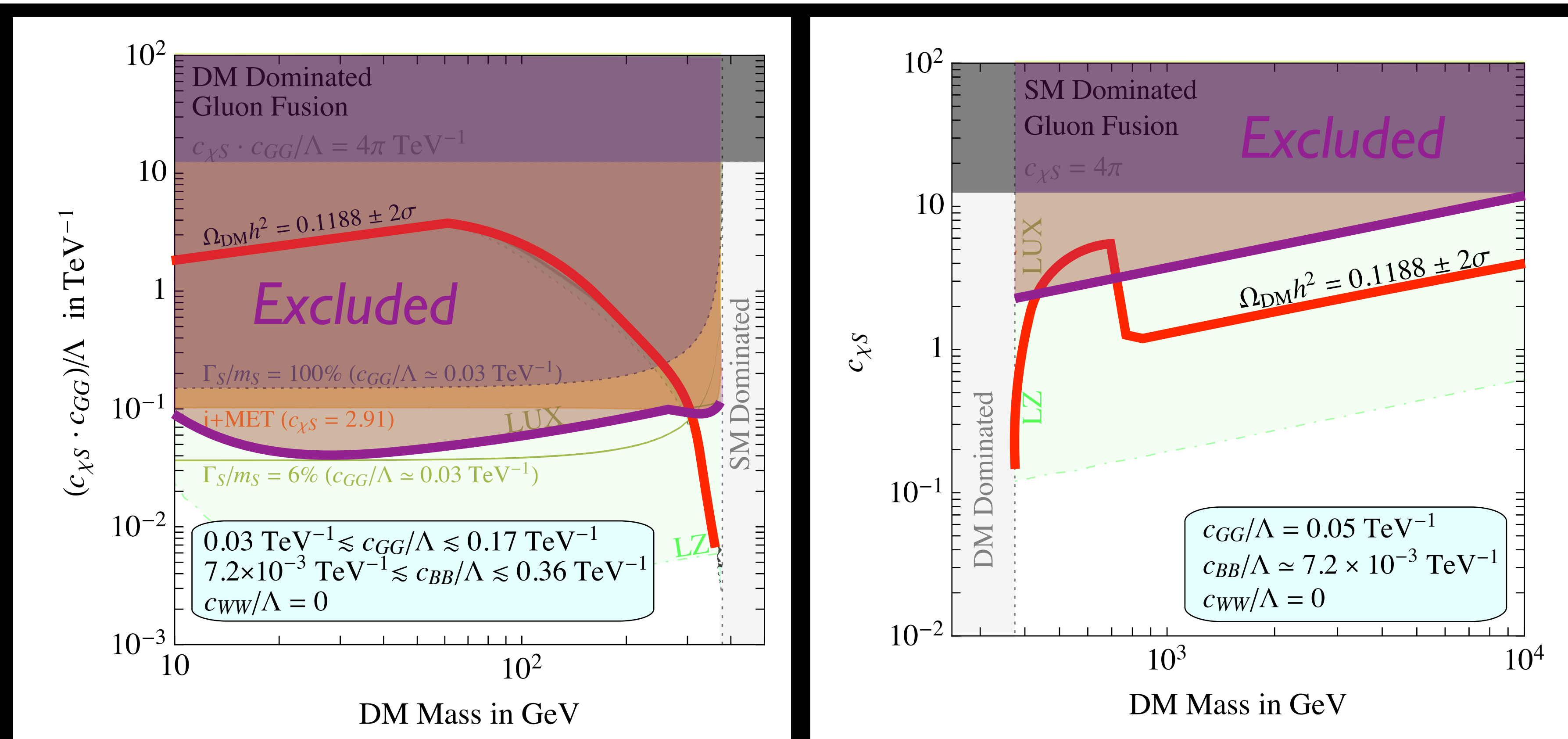
Scalar resonance

$$gg \to S \to \gamma\gamma$$

$$c_{\chi S} S \bar{\chi}\chi + \frac{c_{GG}}{\Lambda} S G^{a}_{\mu\nu} G^{\mu\nu}_{a}$$

Strongest constraints from invisible width, jets, and LUX

Can be fully probed by LZ



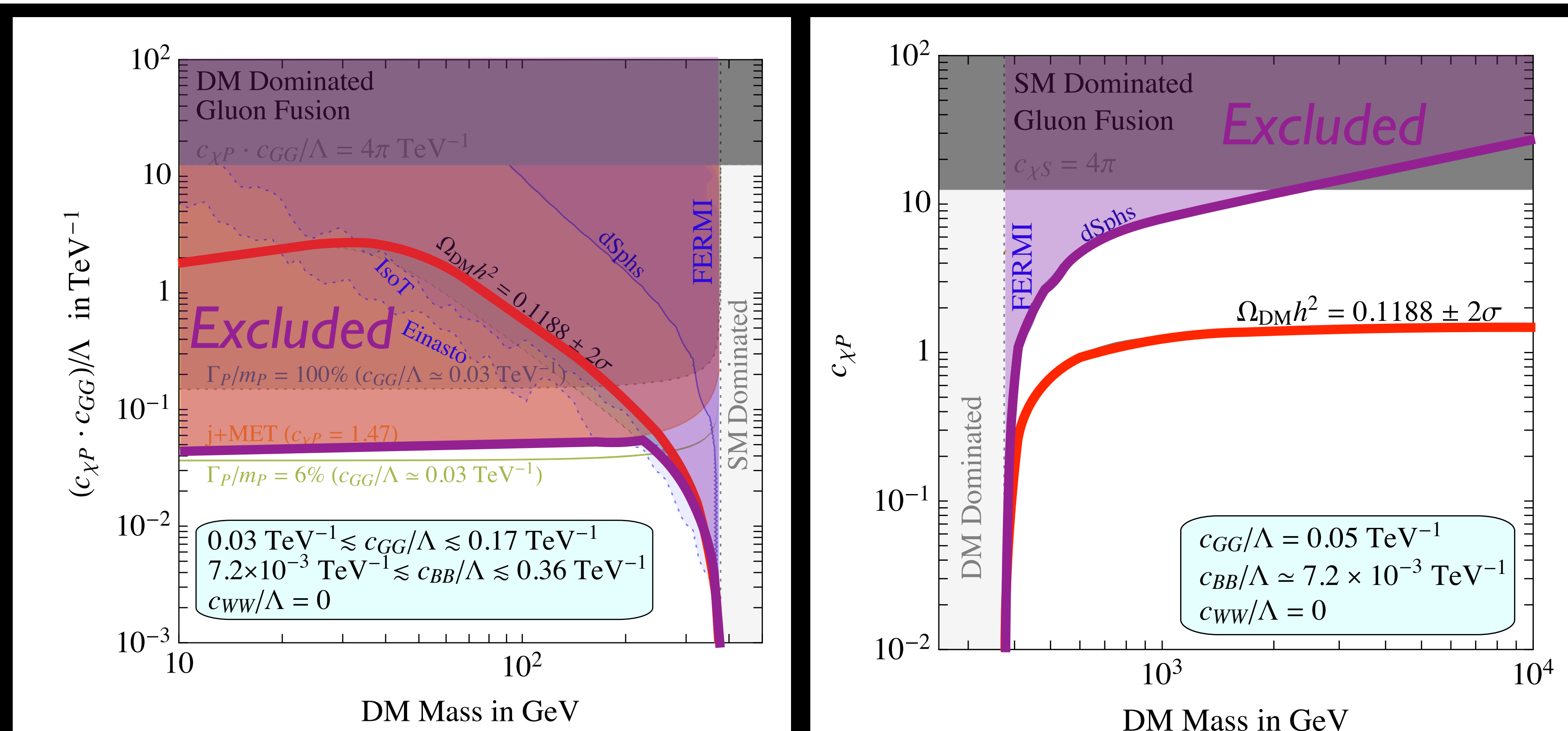
Pseudoscalar resonance

$$gg \to P \to \gamma\gamma$$

$$c_{\chi P} P \bar{\chi} i\gamma_5 \chi + \frac{\tilde{c}_{GG}}{\Lambda} P G^{a}_{\mu\nu} G^{\mu\nu}_{a}$$

Strongest constraints from invisible width and FERMI

Hard to probe > 350 GeV



Self-interacting dark matter

Self-interacting dark matter

Proposed as solution to 'cusp vs core' and 'too big to fail' puzzles in collisionless dark matter simulations. *Spergel, Steinhardt 1999*

Tested on cluster and galaxy collisions

$\sigma/m < 0.7\ \mathrm{cm^2/g}$ mass loss in Bullet Cluster *Randall et al 2008*

$\sigma/m < 0.47\ \mathrm{cm^2/g}$ 72 cluster collisions *Harvey et al 2015*

$\sigma/m = (1.7 \pm 0.7) \times 10^{-4}\ \mathrm{cm^2/g}$ in Abell 3827 (?) *Massey et al 2015*

Several particle models exist

Light mediator *Feng, Kaplinghat, Yu; Buckley, Fox 2009; Tulin, Yu, Zurek 2013*

Hidden vector dark matter (HVDM) *Hambye 2008*

Dark matter is 3 gauge bosons of a hidden SU(2) group spontaneously broken by a hidden Higgs doublet coupled to the SM Higgs.
Allowed in some regimes *Bernal et al 2015*

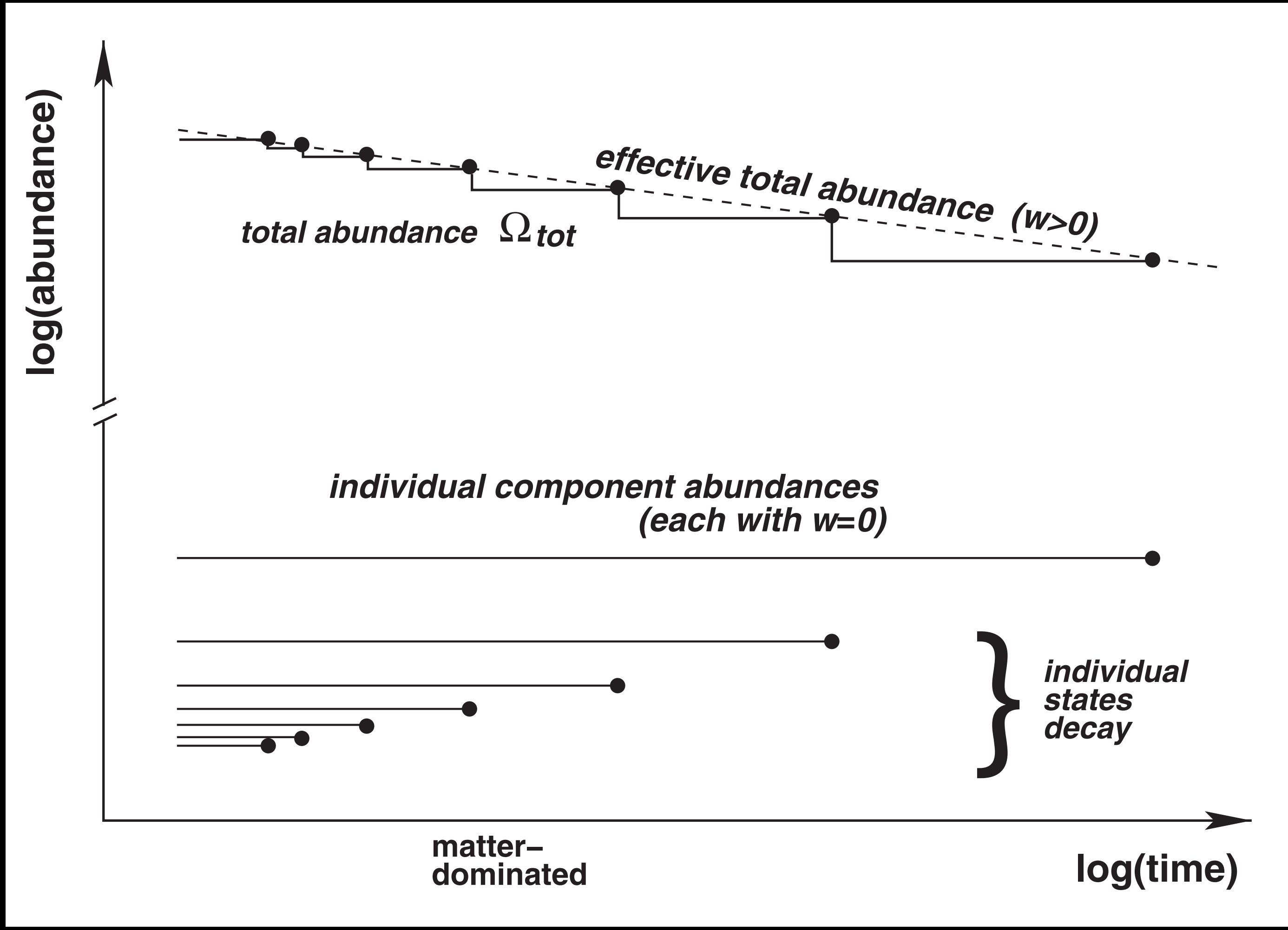
Yu, Bullock, Boddy
(Thursday)

$1\ \mathrm{barn/GeV} = 0.6\ \mathrm{cm^2/g}$

Dynamical dark matter

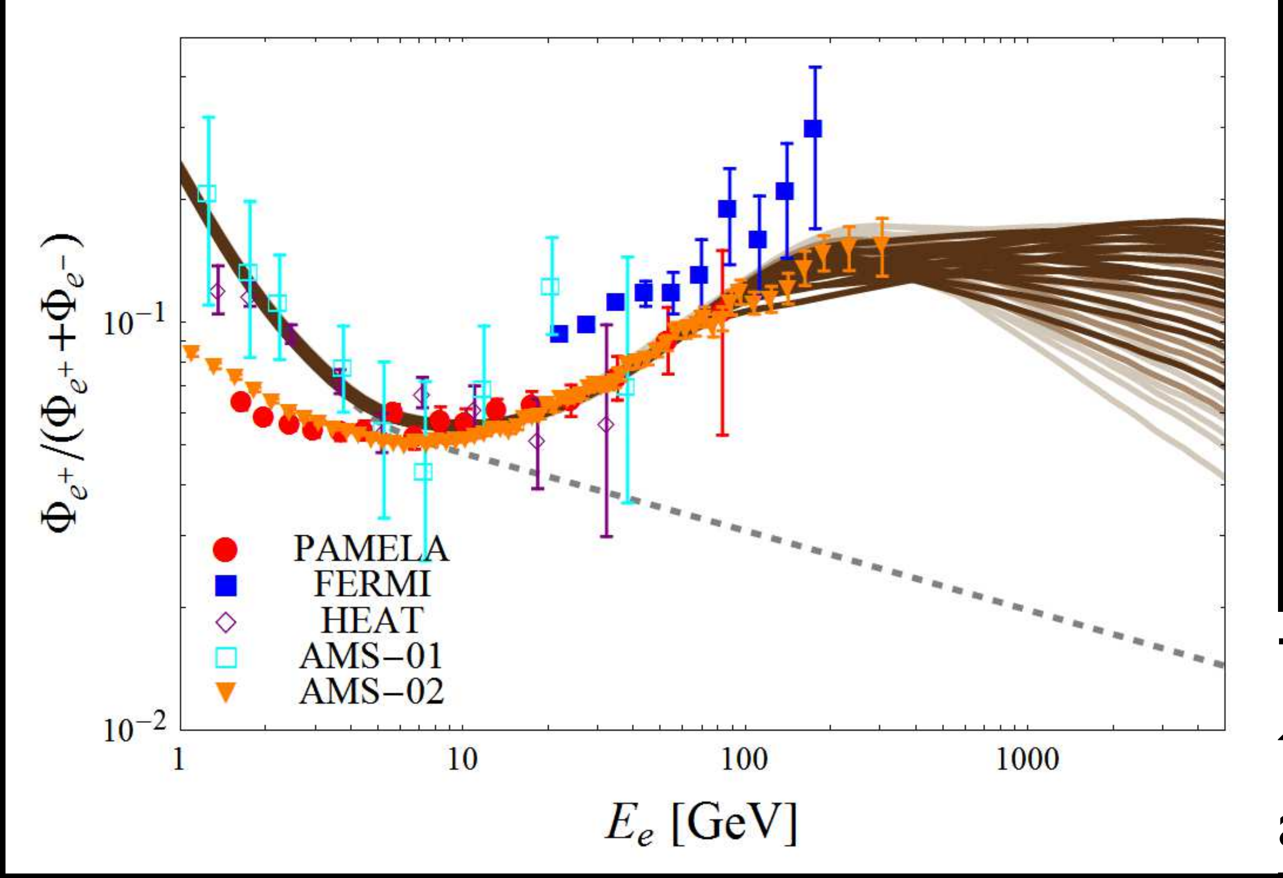
Dynamical dark matter

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



A vast ensemble of fields decaying from one to another

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



Phenomenology obtained through scaling laws

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

This model can fit the positron excess and has no cut off.

Asymmetric dark matter

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

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

Nussinov 1985; Gelmini, 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.

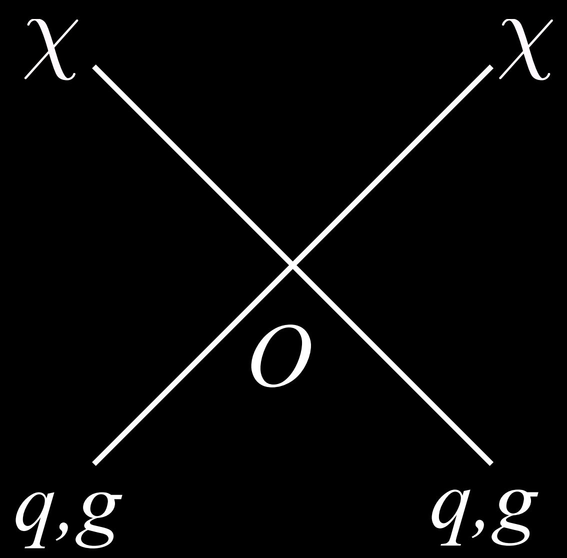
Model-agnostic dark matter

All particle physics models

- Consider all possible interactions between dark matter and standard model particles
- This program has been carried out in some limits (e.g., contact interactions, non-relativistic kinematics)

Four-particle effective operators

(mediator mass ≫ exchanged energy)



There are many possible operators.
Interference is important although often neglected.
Long-distance interactions are often not included.

Effective operators: LHC & direct detection

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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

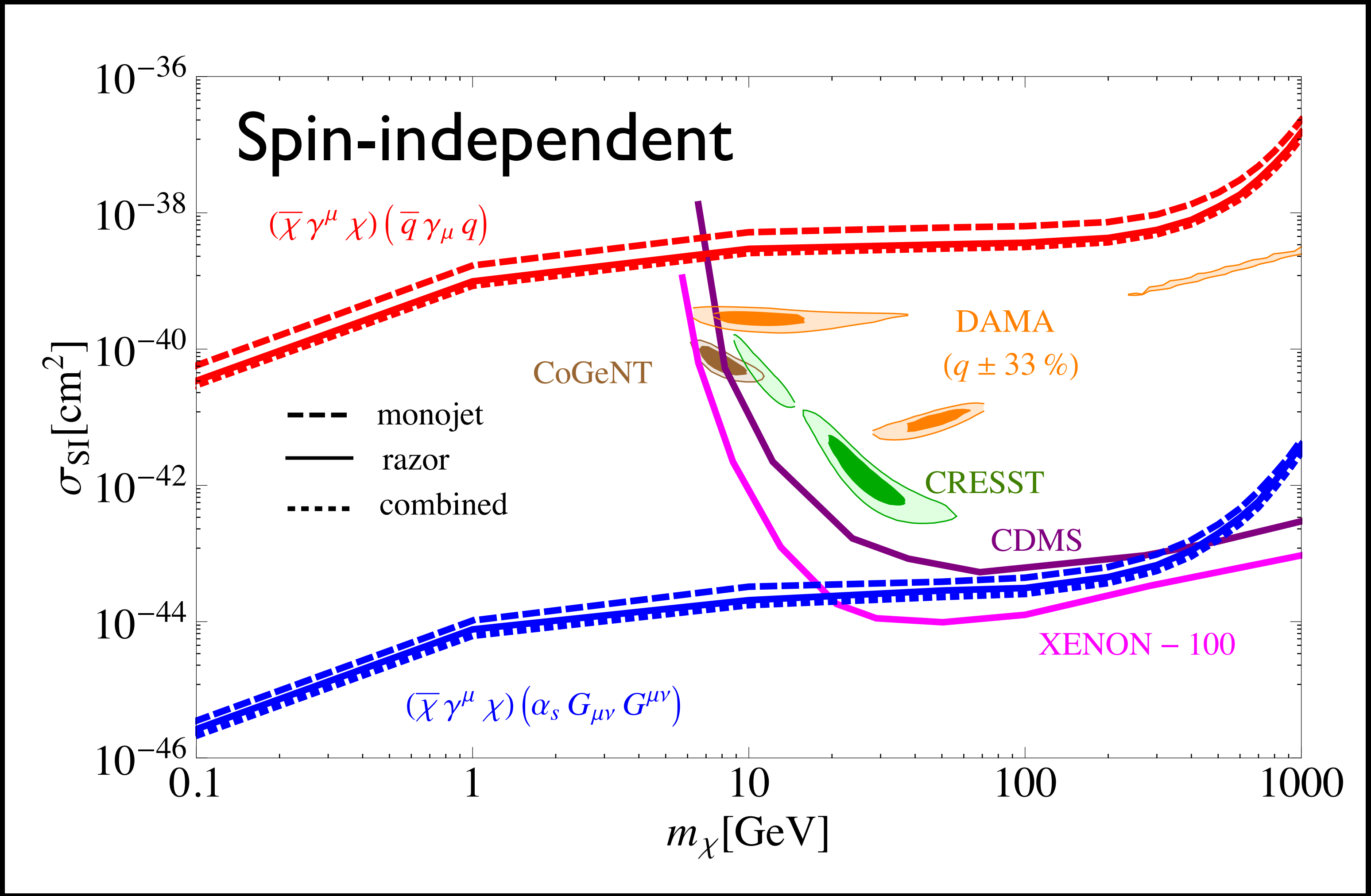
Table of effective operators relevant for the collider/direct detection connection

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

Effective operators: LHC & direct detection

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.......



Fox, Harnik, Primulando, Yu 2012

These bounds do not apply to SUSY, etc.

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

Effective operators: direct detection

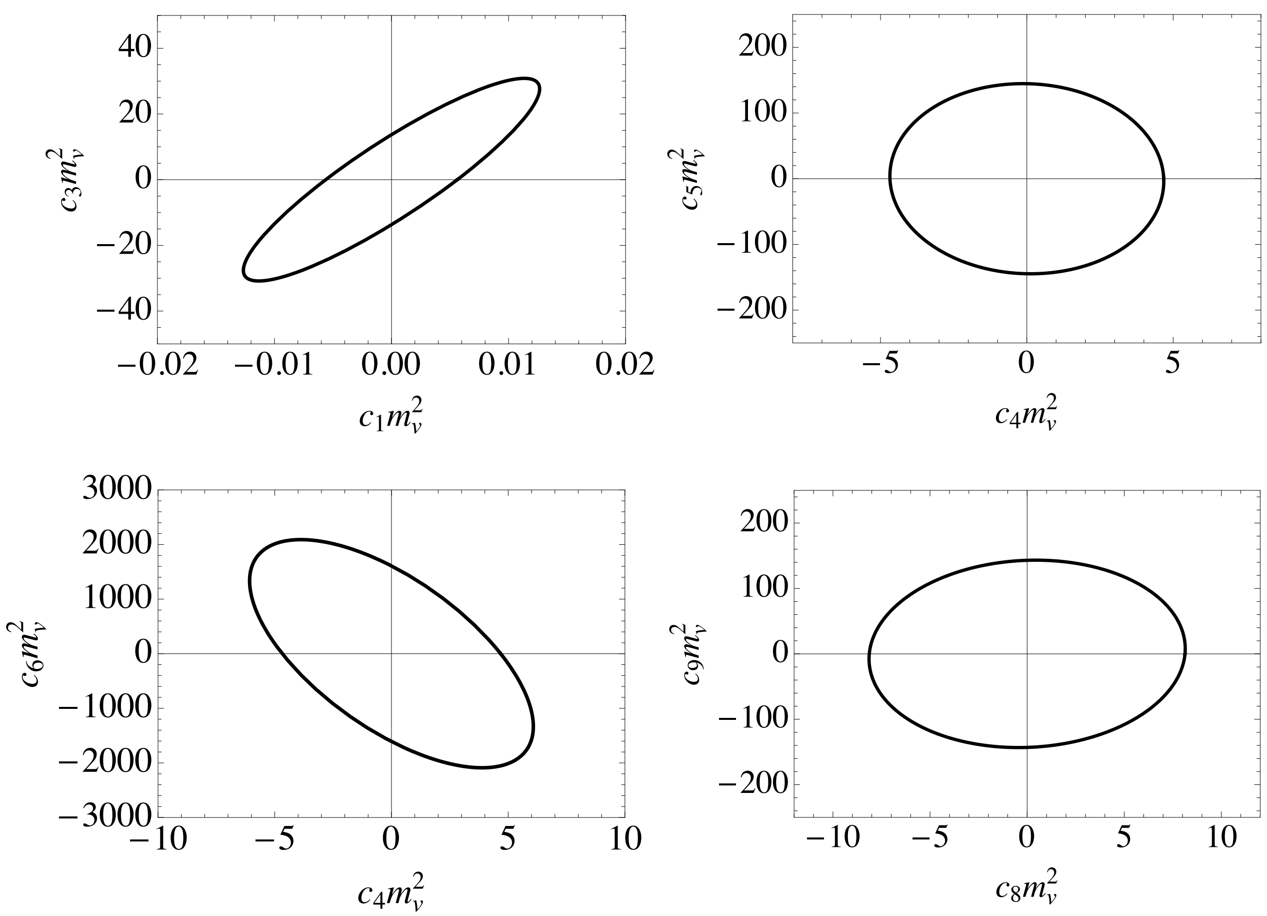
All non-relativistic contact operators classified — *Fitzpatrick et al. 2012*

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

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

Global analysis

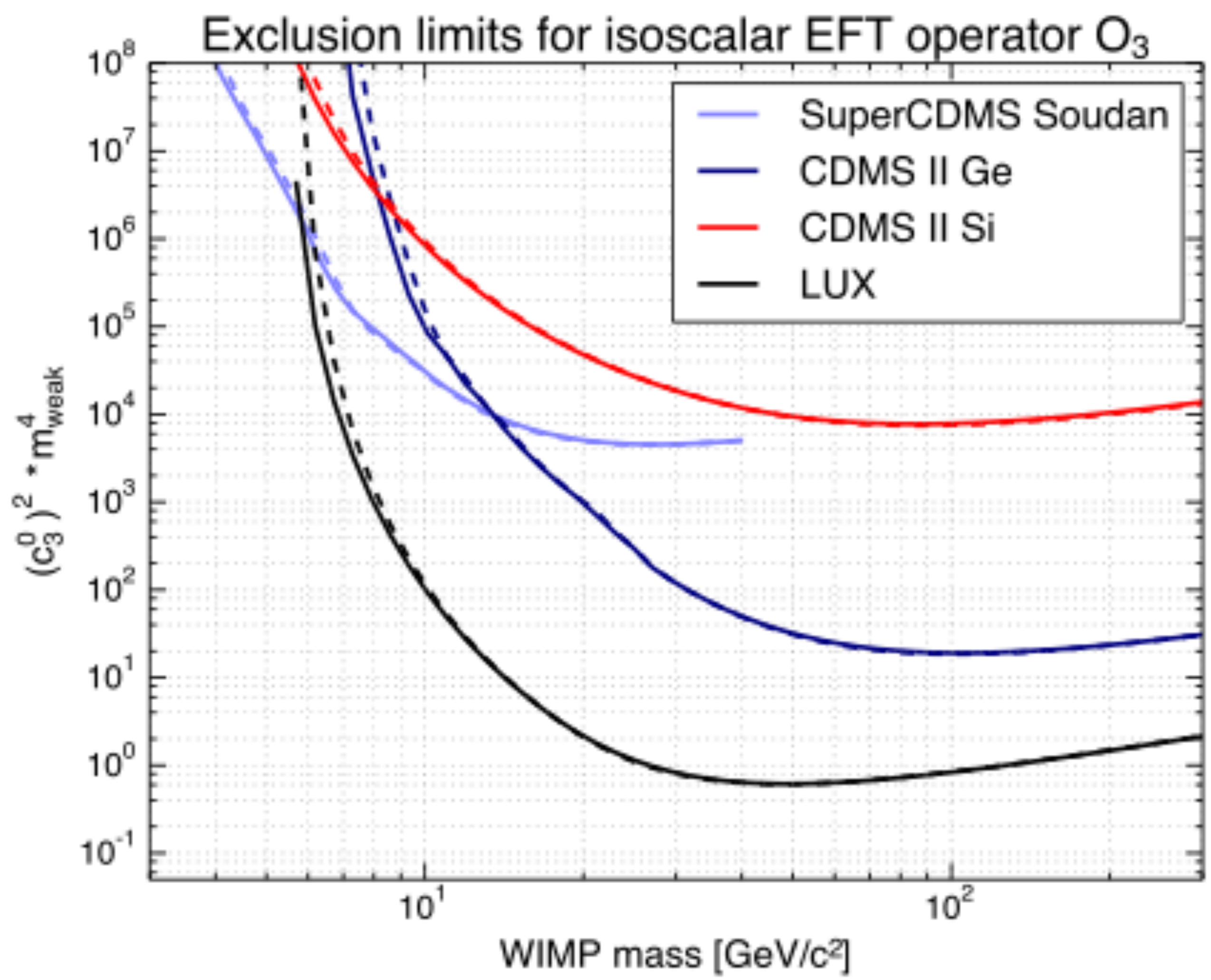
Catena, Gondolo 2014



LUX $\quad m = 10$ TeV

Experimental limits

Schneck et al. (SuperCDMS) 2015



Summary

- There have been many candidates for nonbaryonic dark matter over the years. There seem to be even more now.
- Particle physicists do not lack ideas and are able to escape stronger and stronger experimental constraints.
- The time is ripe for experiments to conclusively find a particle of dark matter.