Updated view on WIMP DM

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(My) Updated view on WIMP DM

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Particle dark matter

Hot dark matter

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

light neutrinos

Cold dark matter

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

neutralinos, axions, WIMPZILLAs, solitons

Warm dark matter

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

sterile neutrinos, gravitinos

Particle dark matter

Thermal relics

in thermal equilibrium in the early universe

neutrinos, neutralinos, other WIMPs, ...

Non-thermal relics

never in thermal equilibrium in the early universe

axions, WIMPZILLAs, solitons, ...

Particle dark matter

- 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

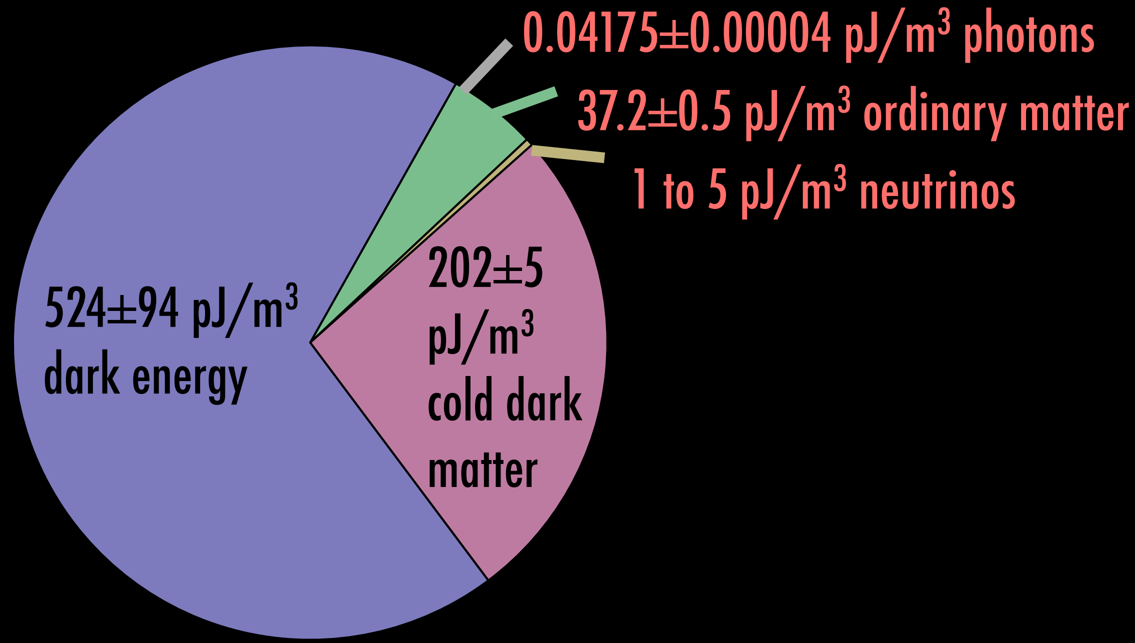
Interaction strength range

Only gravitational: wimpzillas
Strongly interacting: B-balls

The Magnificent WIMP
(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

  Thermal production in hot primordial plasma.



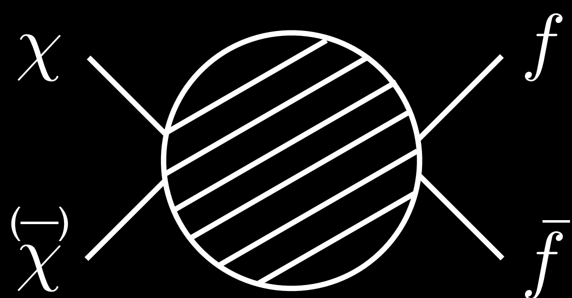
- One can experimentally test the WIMP hypothesis

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

Cosmic density of thermal WIMPs

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

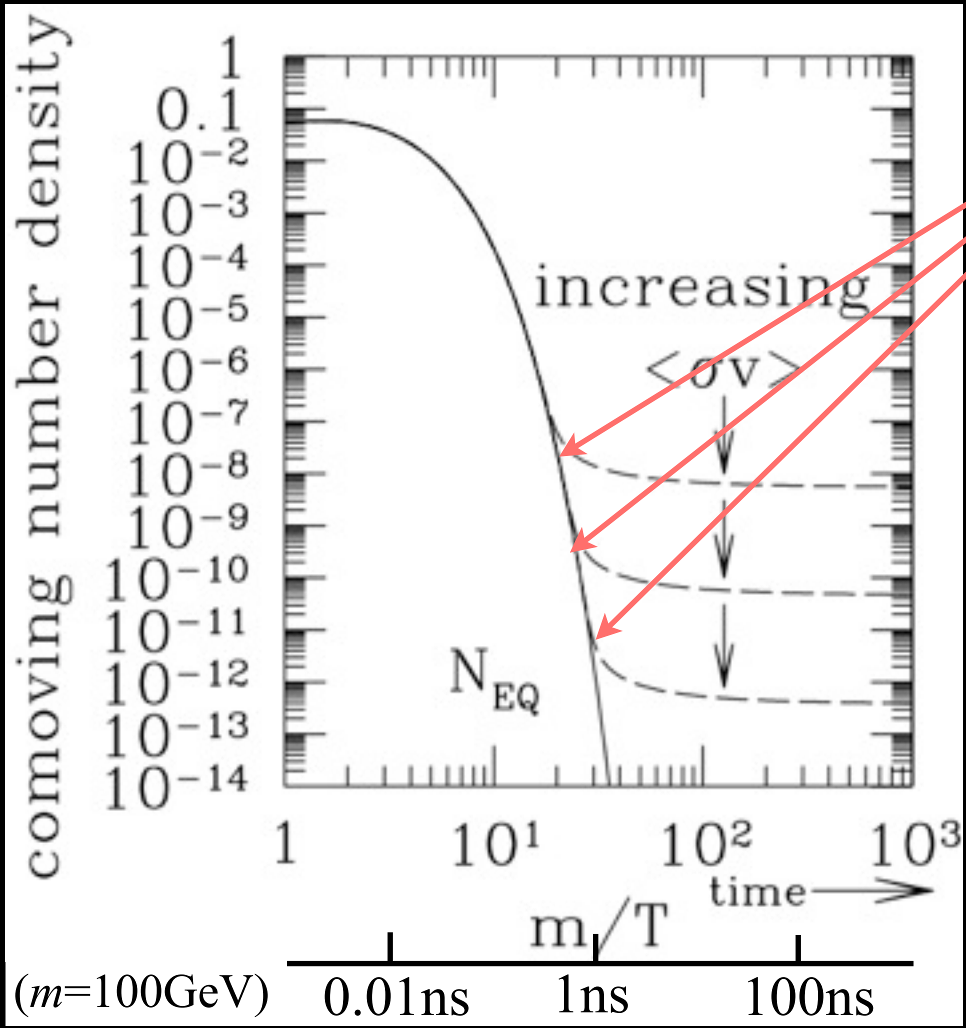
$$e^+ + e^-, \mu^+ + \mu^-, \text{etc.} \leftrightarrow \chi + \overset{(-)}{\chi}$$



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

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

Cosmic density of thermal WIMPs



freeze-out

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

annihilation rate *expansion rate*

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

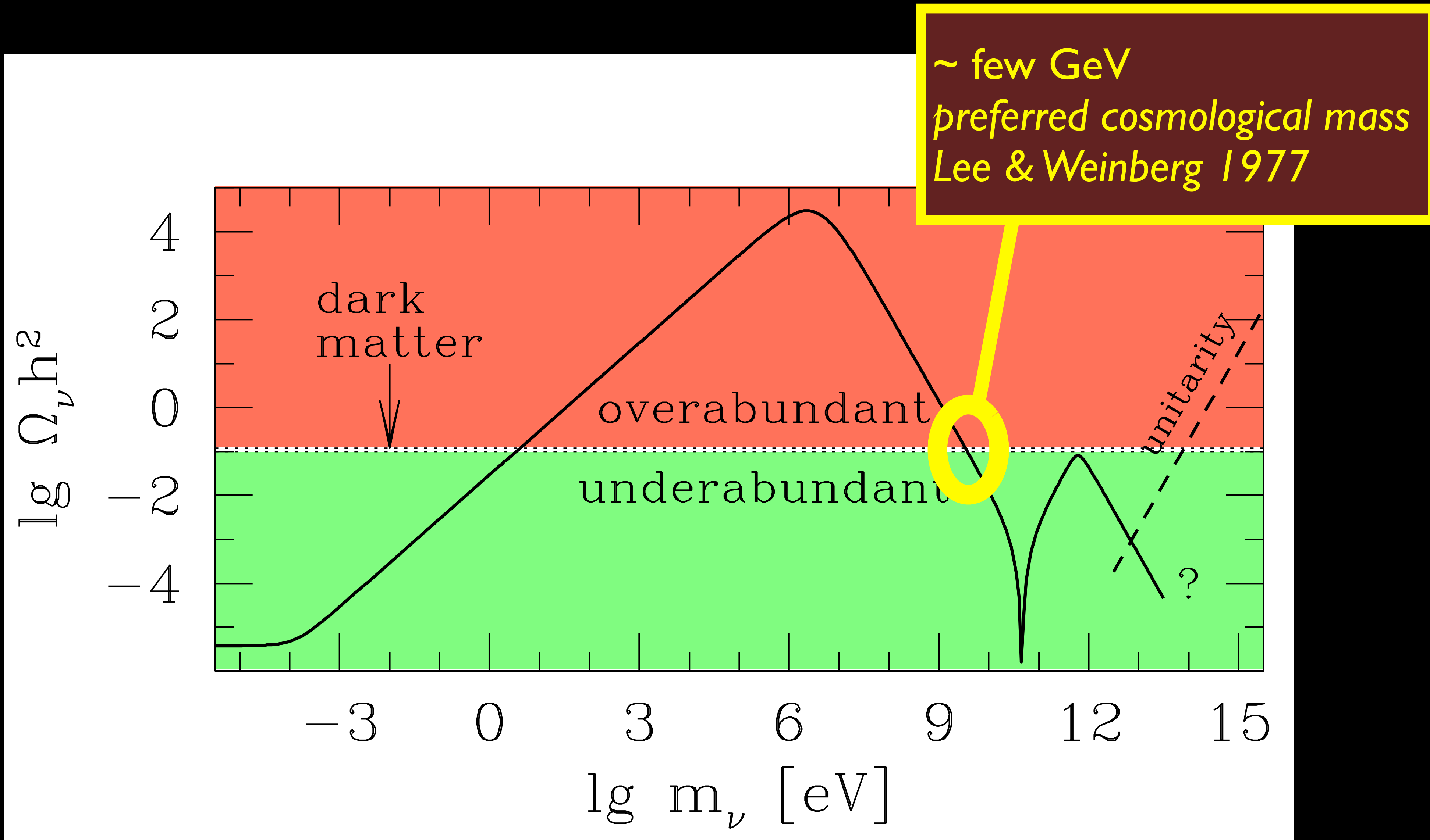
$$\Omega_\chi h^2 = \Omega_{\rm cdm} h^2 \simeq 0.1143$$

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

This is why they are called Weakly Interacting Massive Particles
(WIMPless candidates are WIMPs!)

Cosmic density of thermal WIMPs

Fourth-generation Standard Model neutrino



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

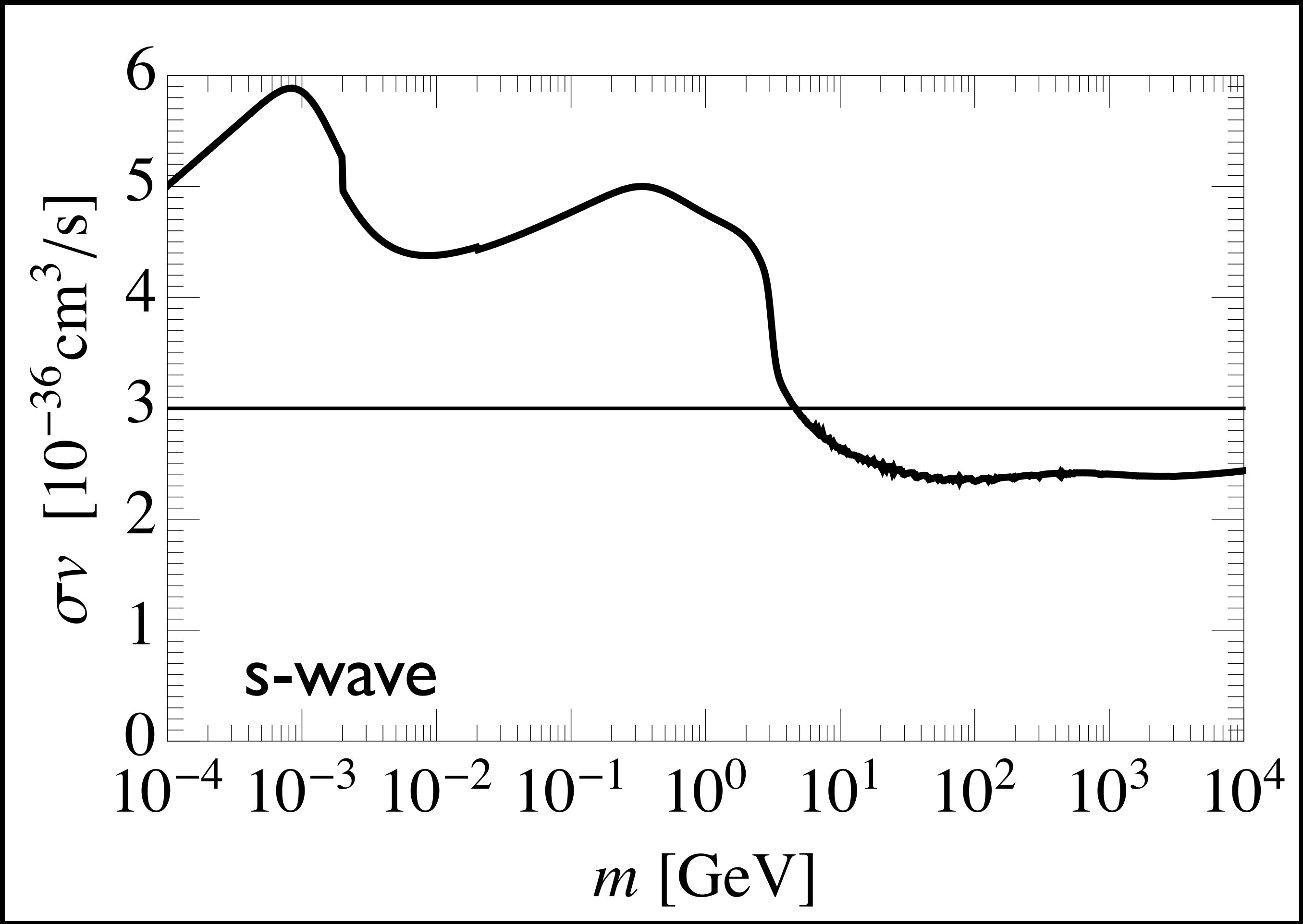
$$\langle \sigma v \rangle = a + b v^2 + \cdots \qquad \text{s-wave}$$

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

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

Cosmic density of thermal WIMPs

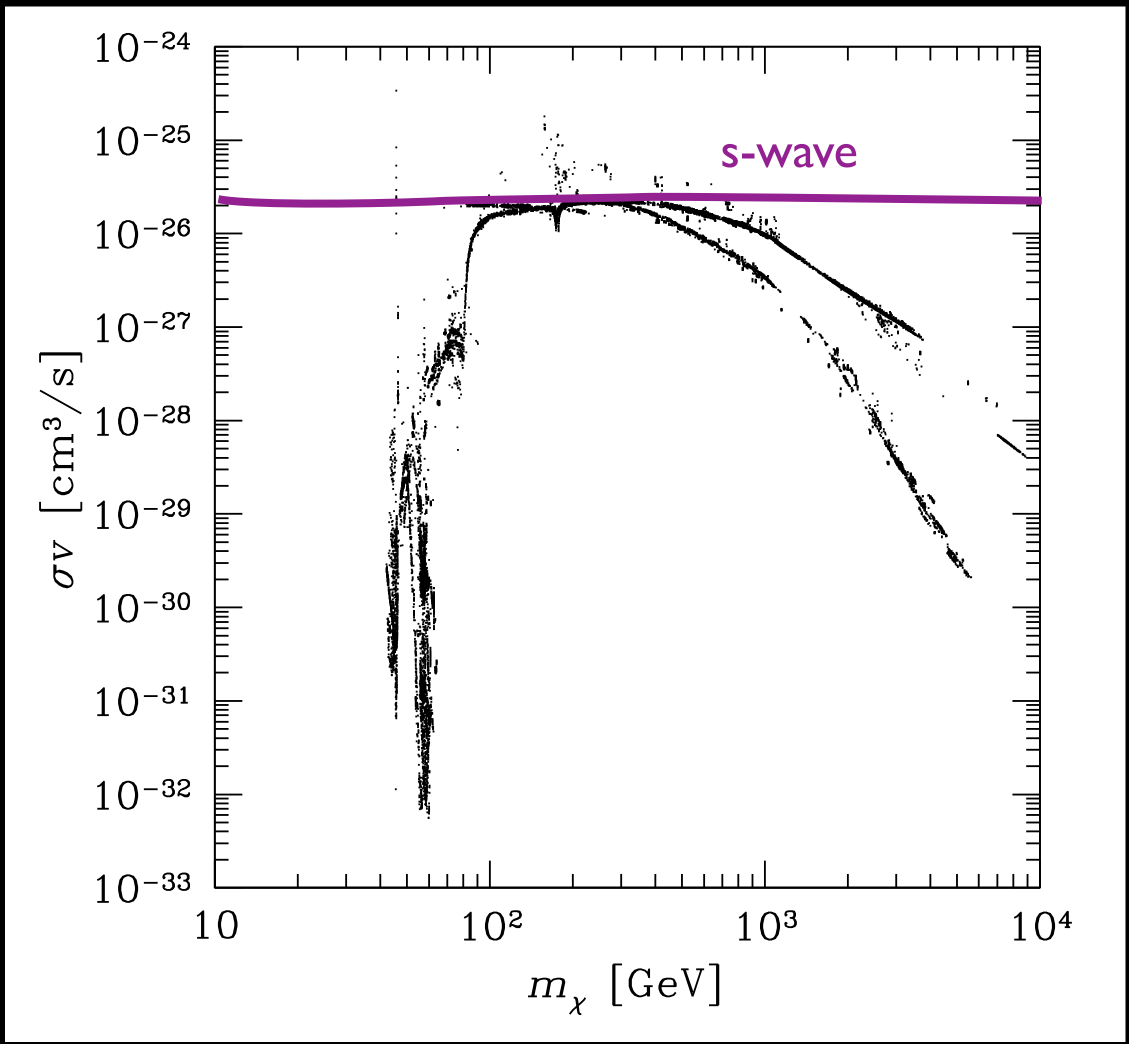
$\langle\sigma v\rangle$=const required for right cosmic density



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

Cosmic density of WIMPs: caveats

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



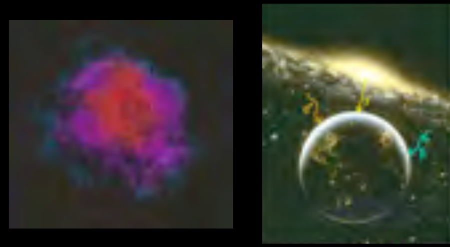
Example

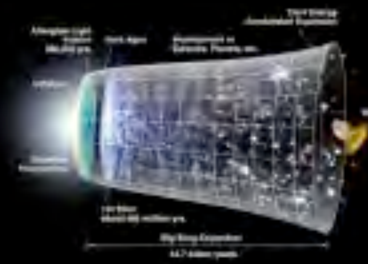
lightest neutralino in minimal supersymmetric standard model

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

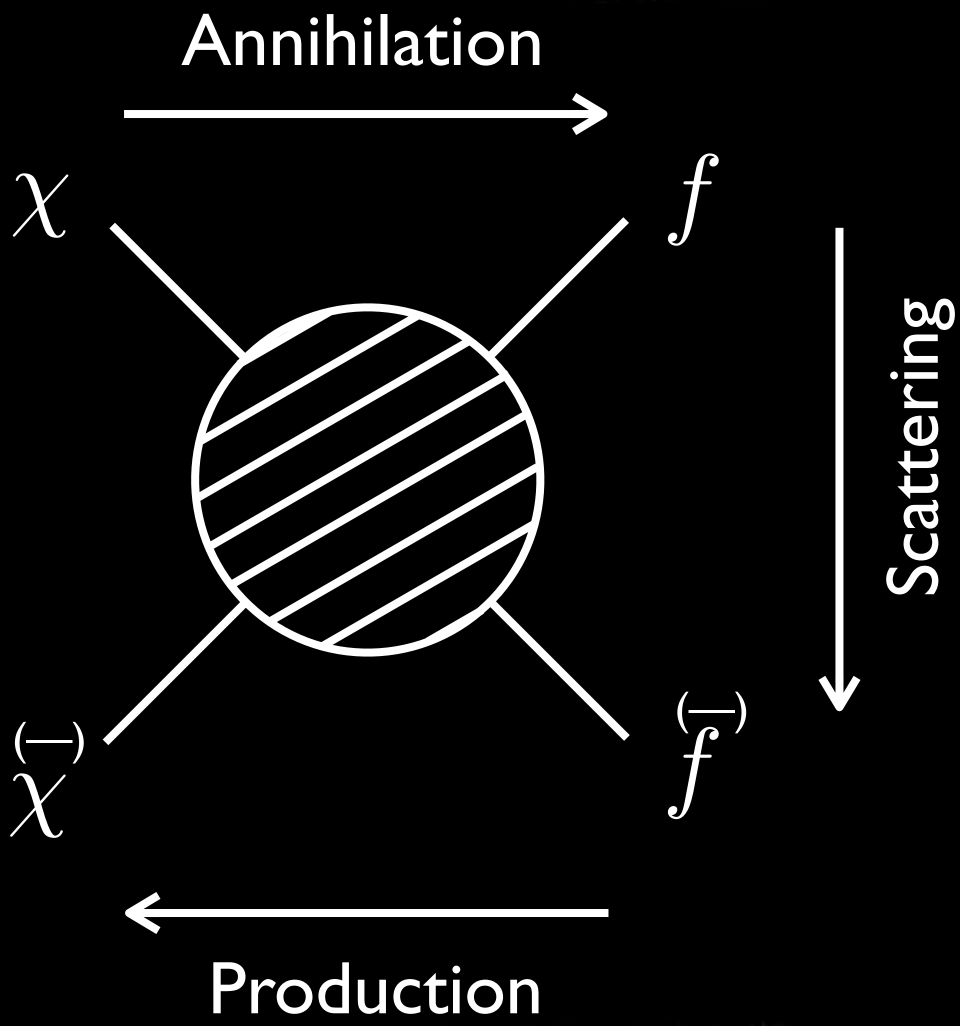
The power of the WIMP hypothesis

Indirect detection

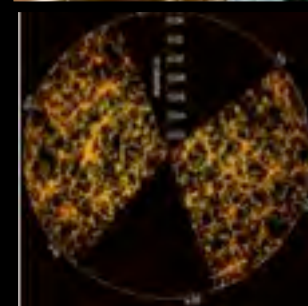




Cosmic density

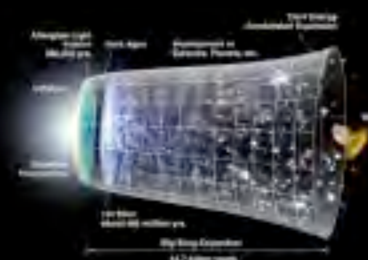


Direct detection



Large scale structure

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 ($S \rightarrow -S$)

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

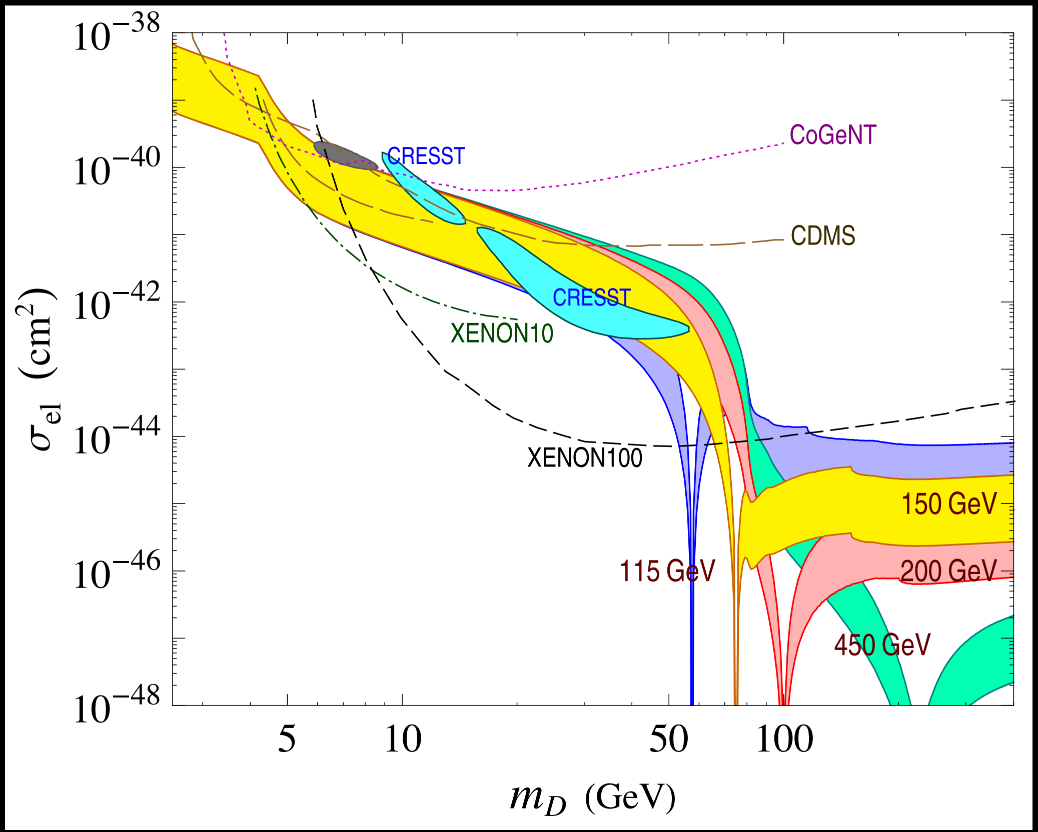
Silveira, Zee 1985

Andreas, Hambye, Tytgat 2008

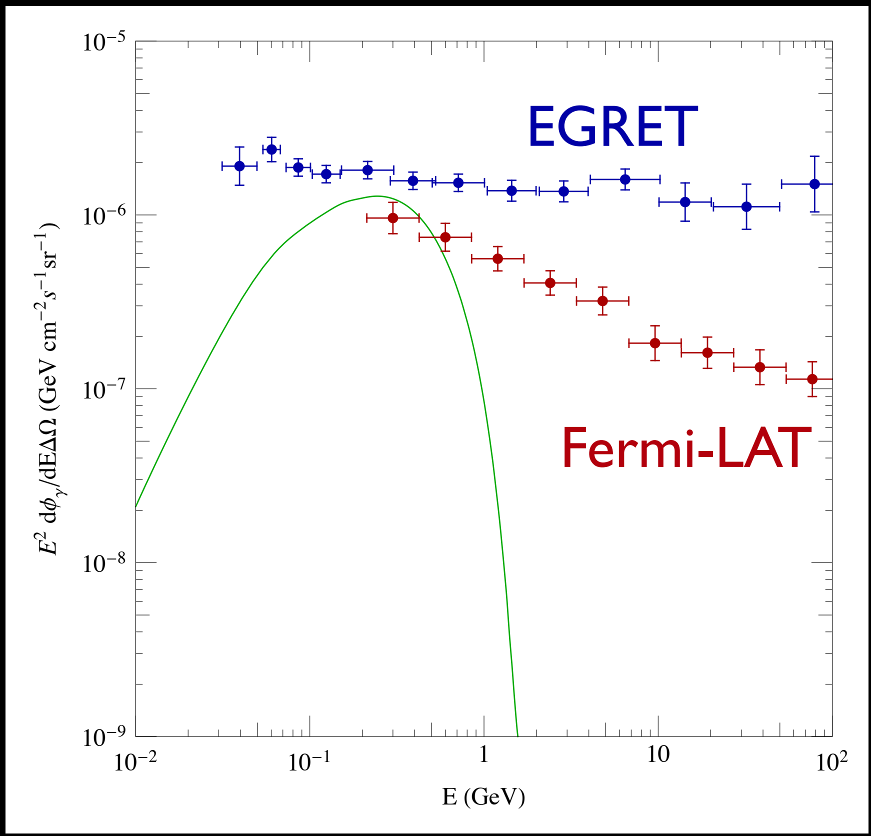
Minimalist dark matter

do not confuse with minimal dark matter

Andreas et al 2010; He, Tandean 2011



Arina, Tytgat 2010



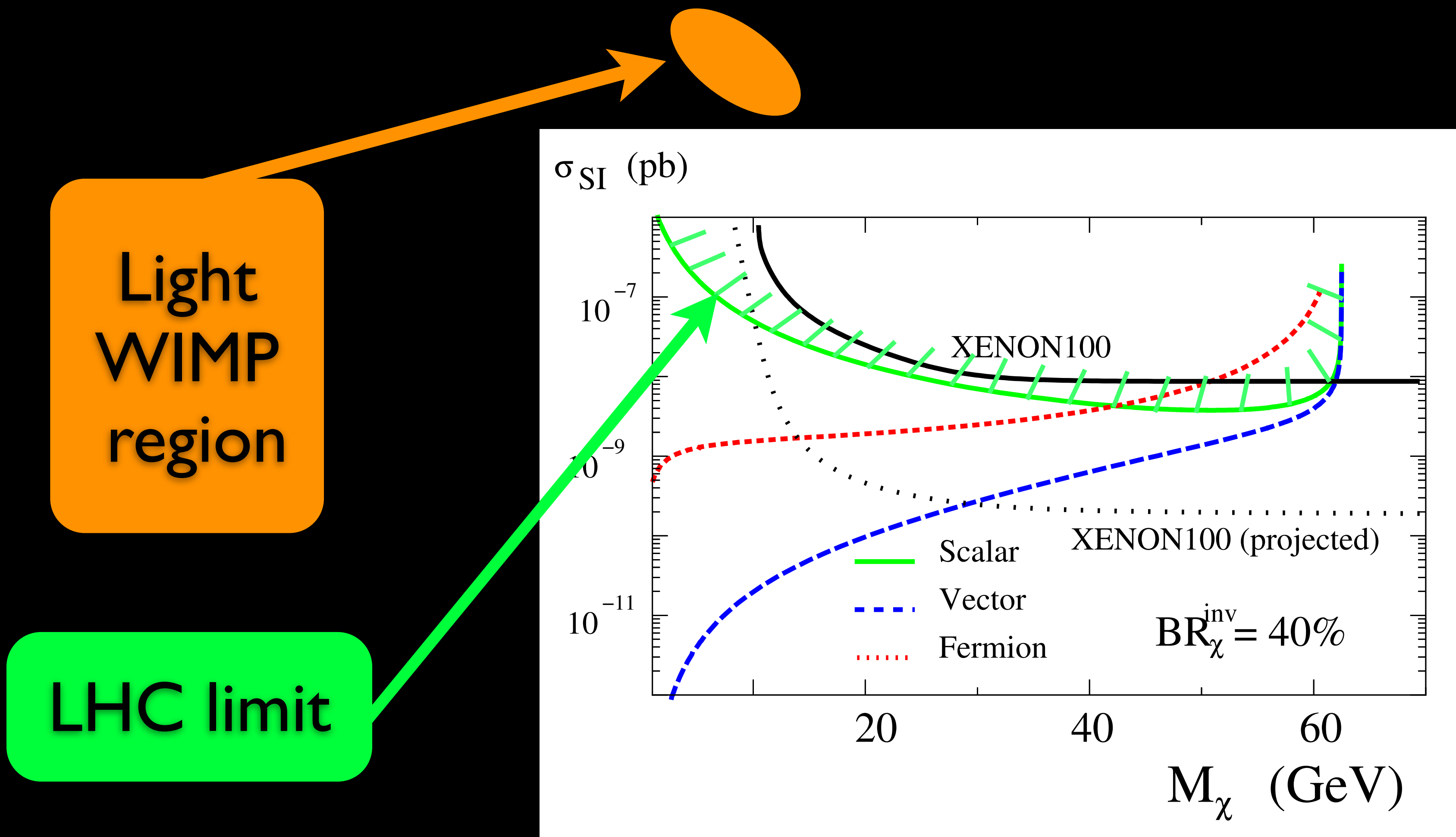
For DM, let Higgs mass > 115 GeV.

If Higgs mass < 150 GeV, Higgs must be 99.2% invisible.

Minimalist dark matter

do not confuse with minimal dark matter

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

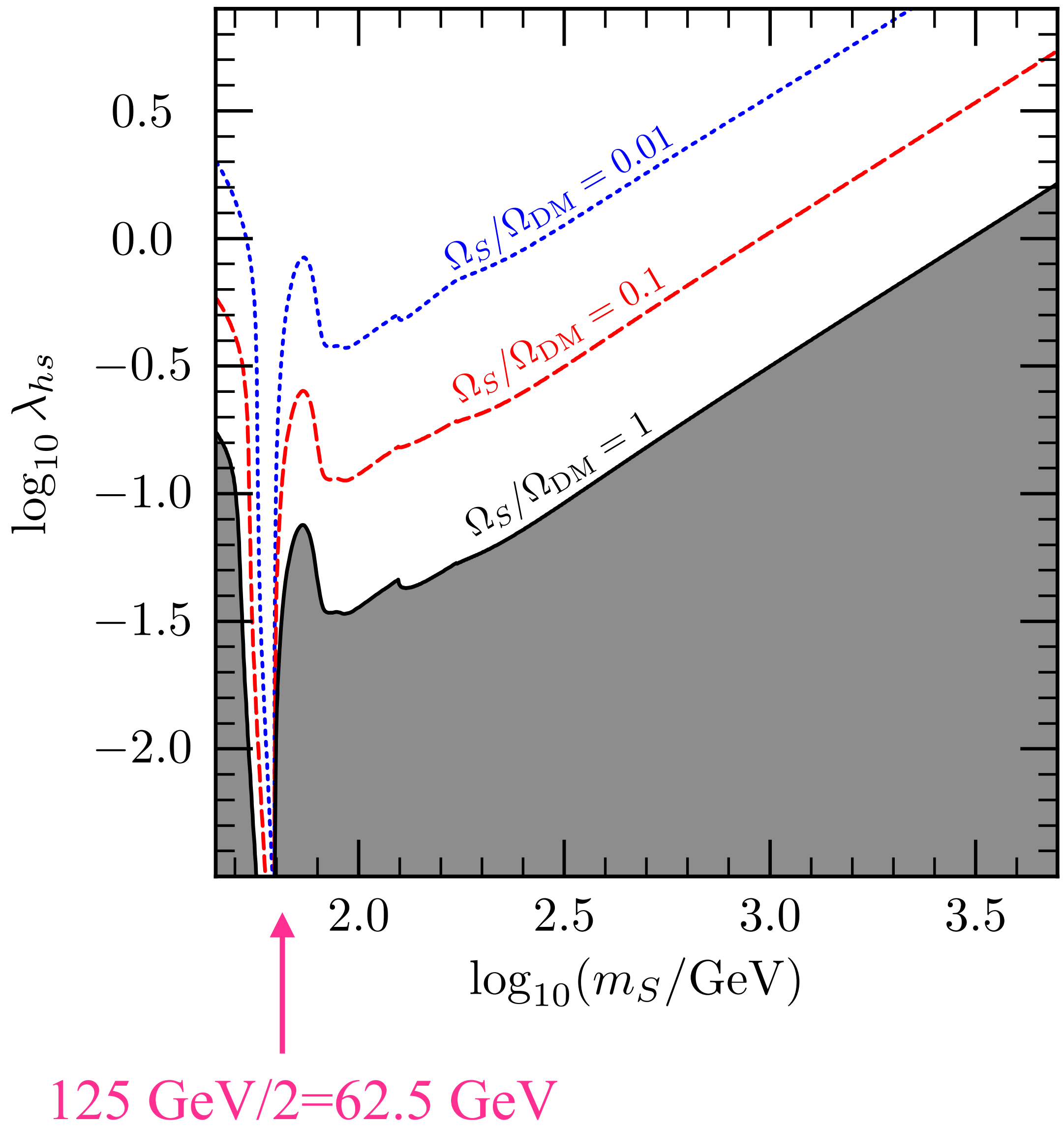


Djouadi, Falkowski, Mambrini, Quevillon 2012

Minimalist dark matter

Cline, Scott, Kainulainen, Weniger 2013

Cosmic density



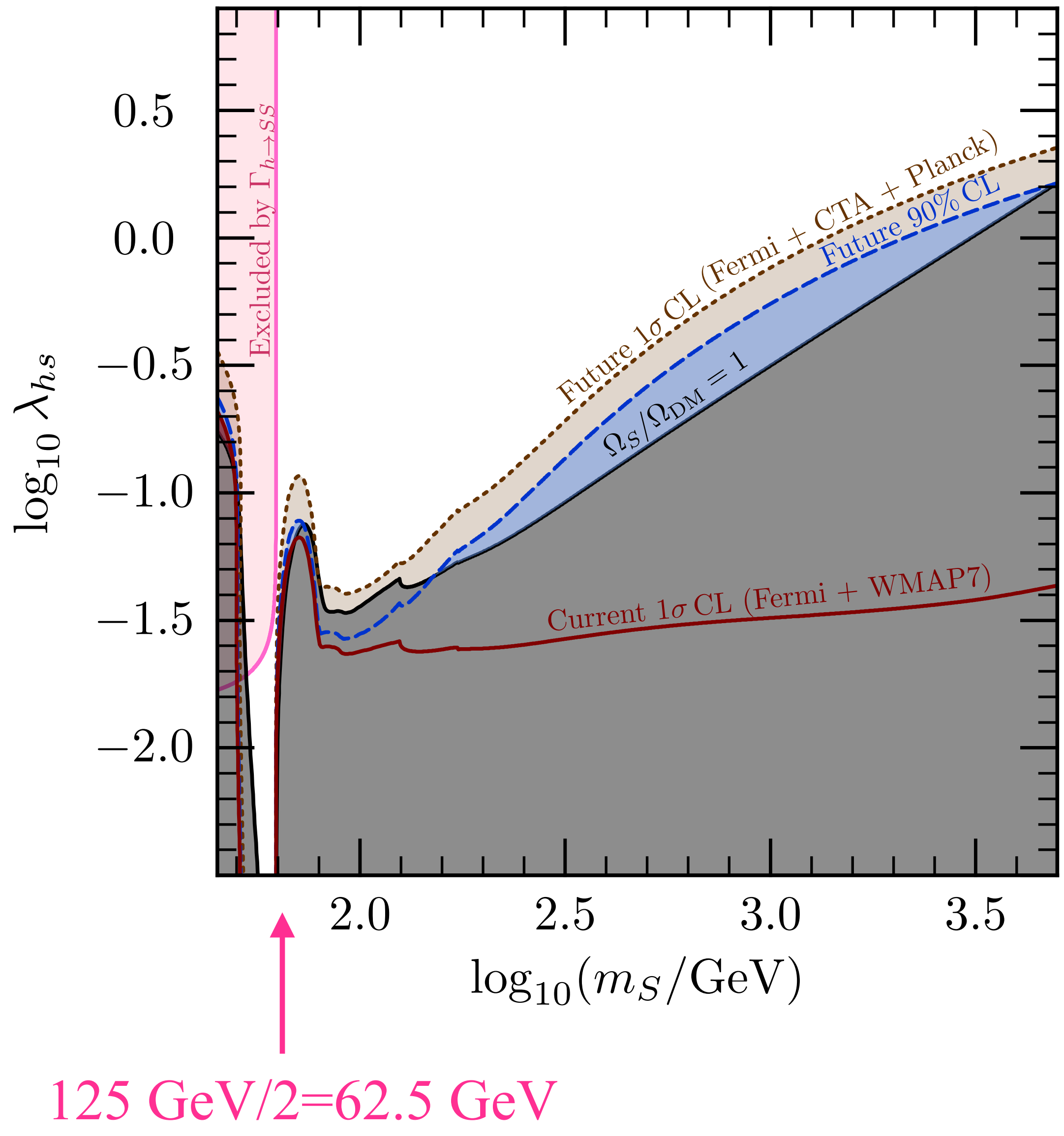
Minimalist dark matter

Cline, Scott, Kainulainen, Weniger 2013

Cosmic density

Invisible Higgs width

Indirect detection



Minimalist dark matter

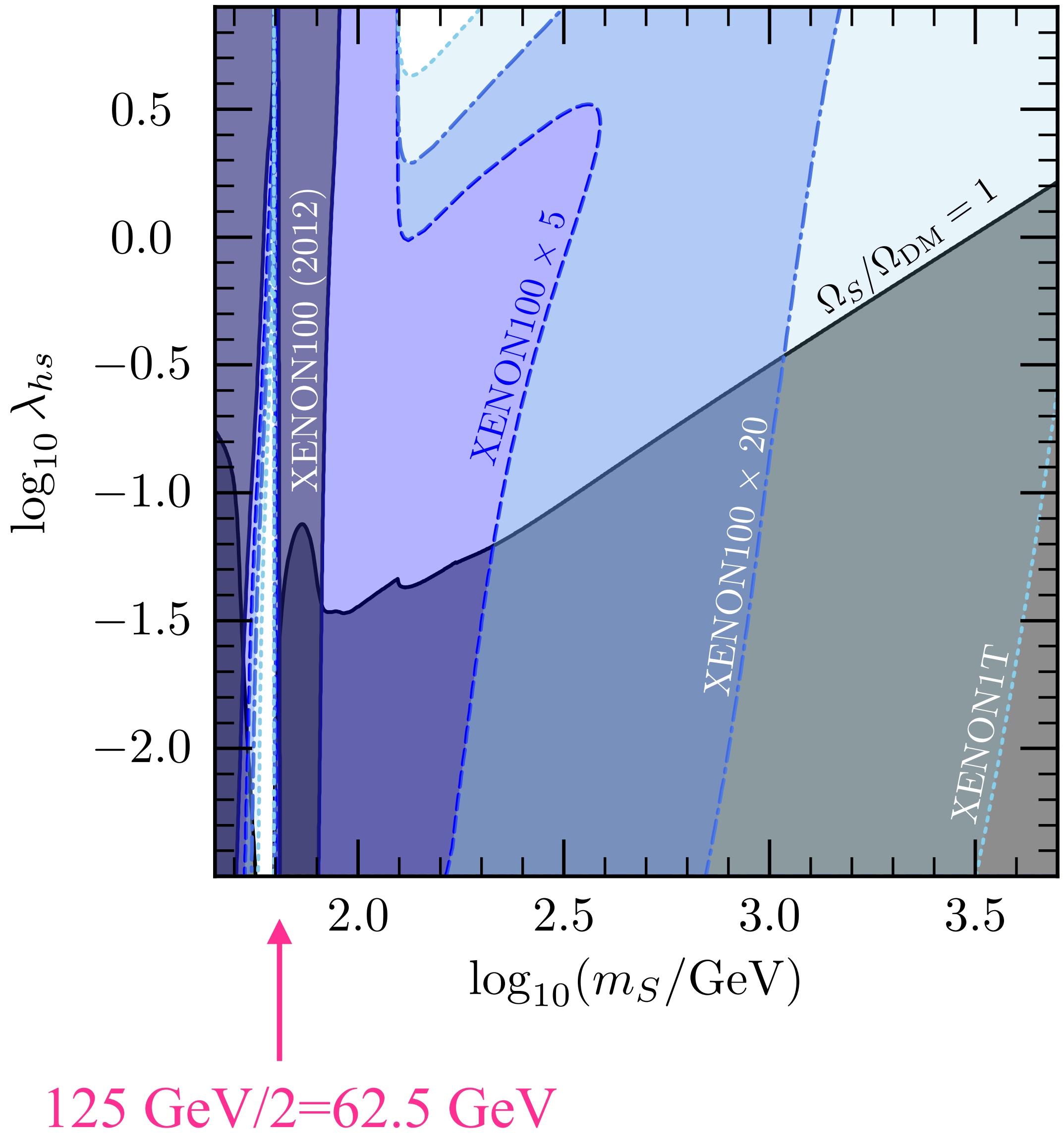
Cline, Scott, Kainulainen, Weniger 2013

Cosmic density

Invisible Higgs width

Indirect detection

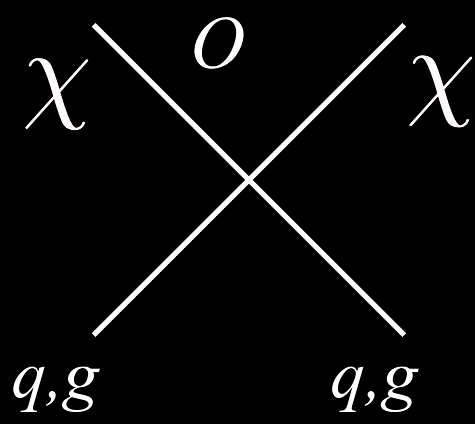
Direct detection



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

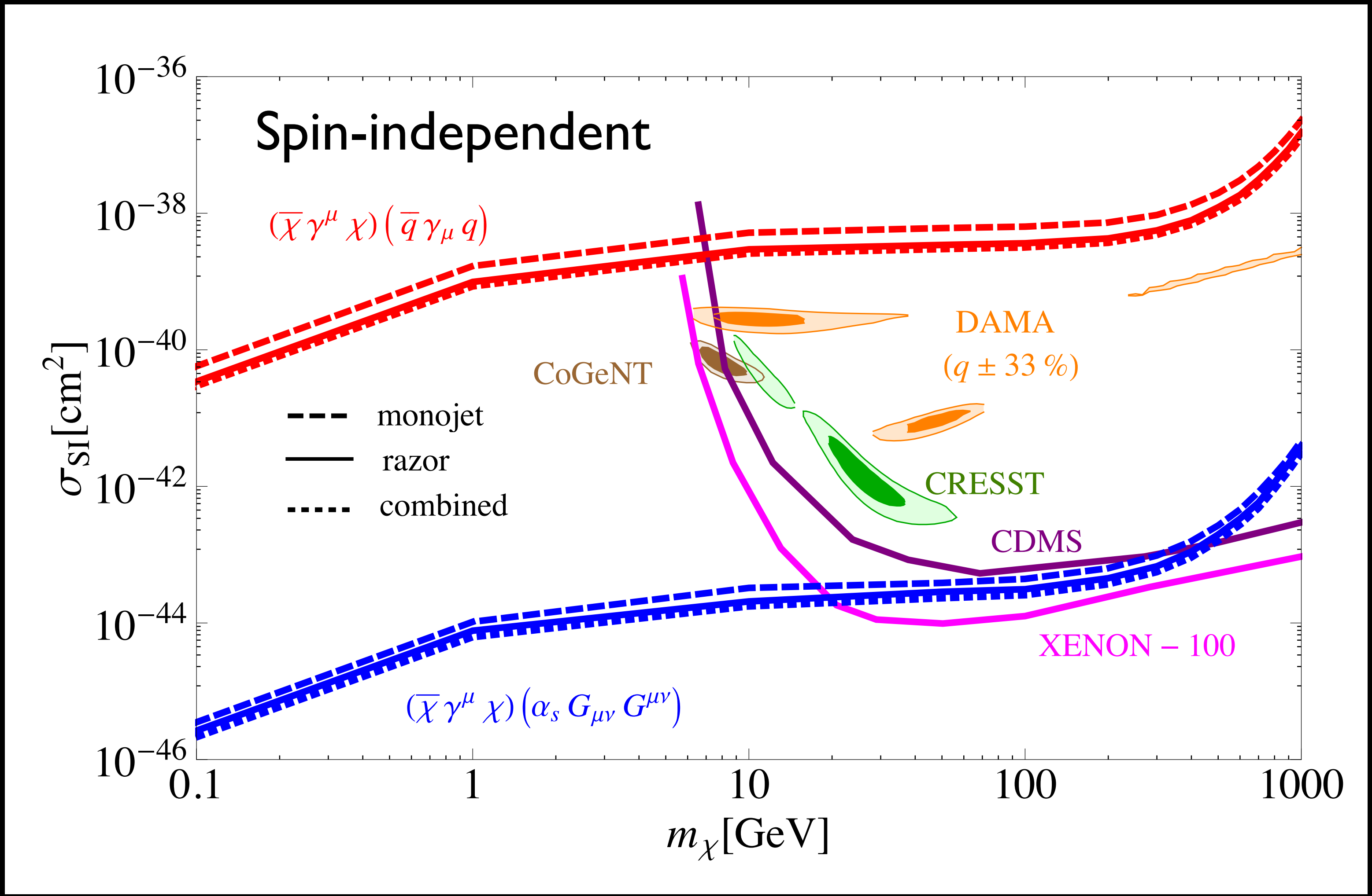
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$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

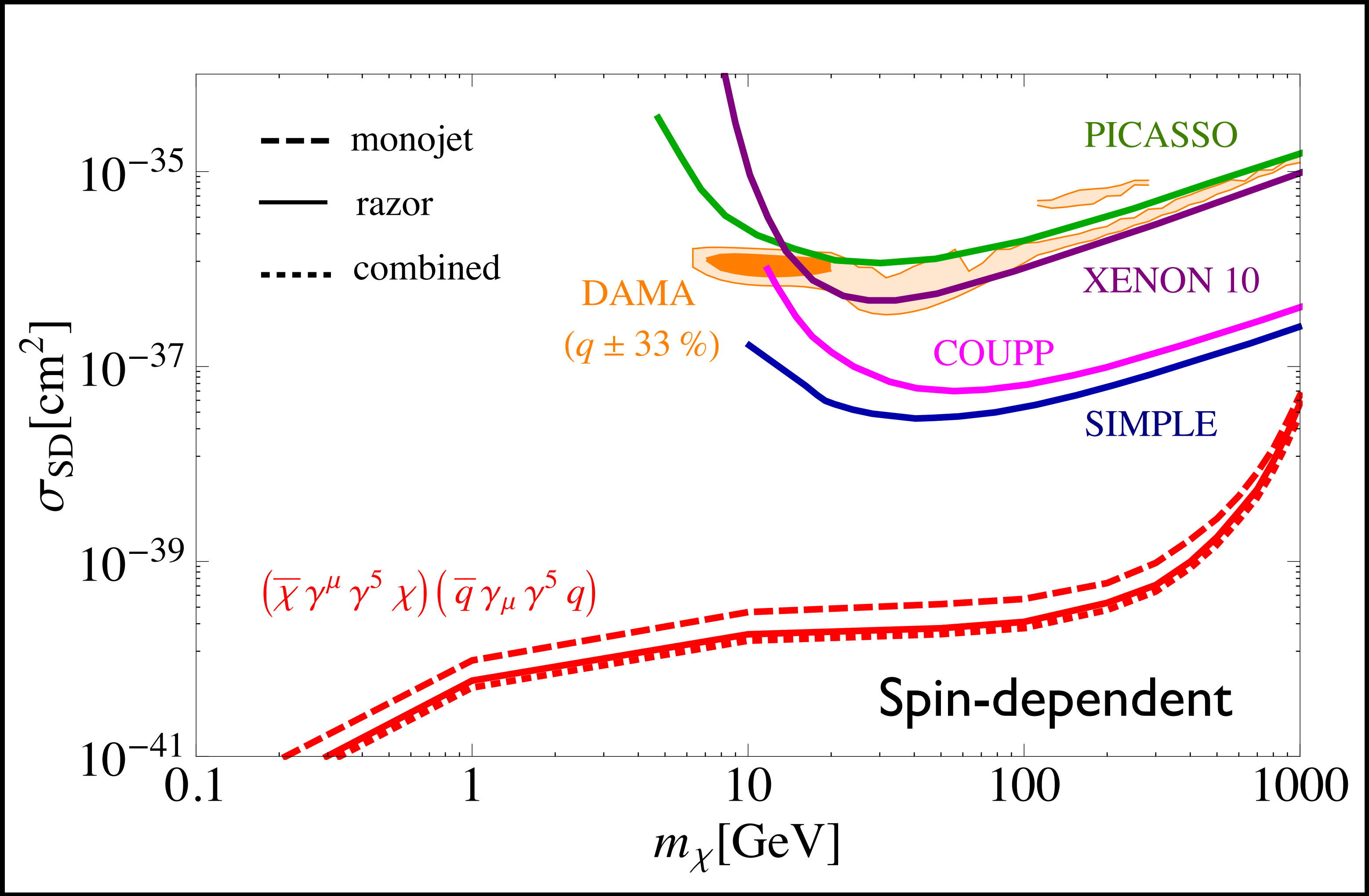
Direct detection and LHC



Fox, Harnik, Primulando, Yu 2012

Constraints on scattering cross section

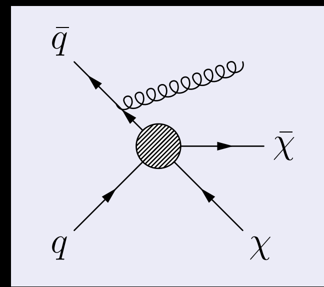
Direct detection and LHC

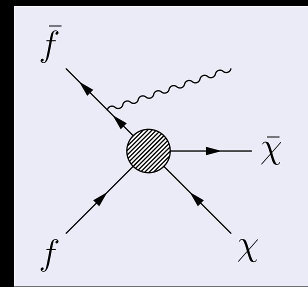


Fox, Harnik, Primulando, Yu 2012

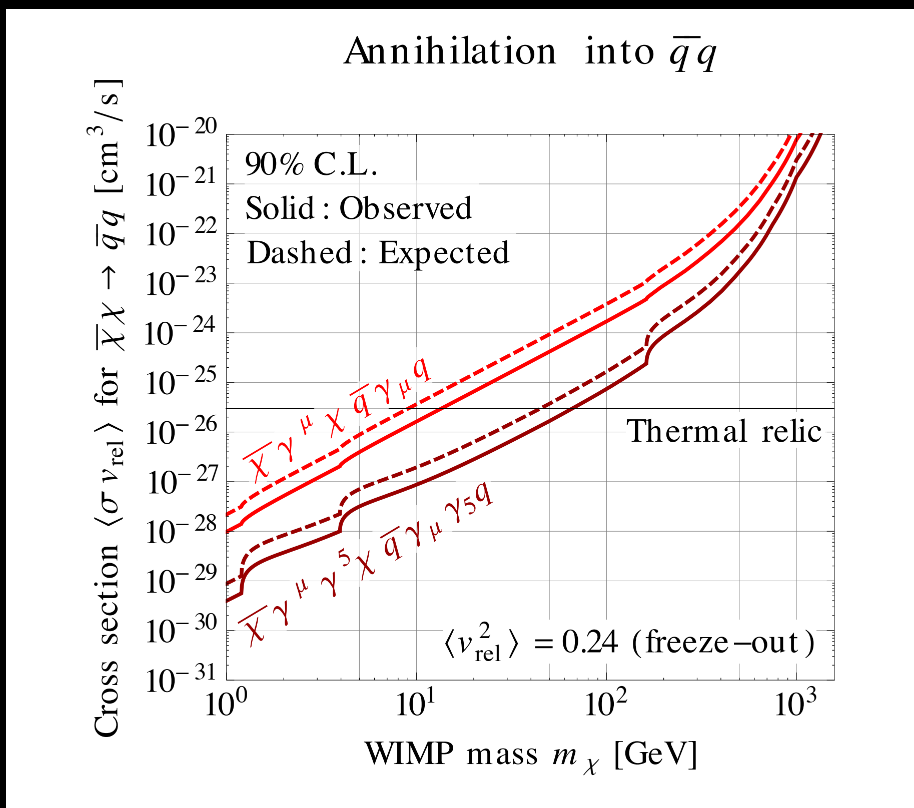
Effective operator approach

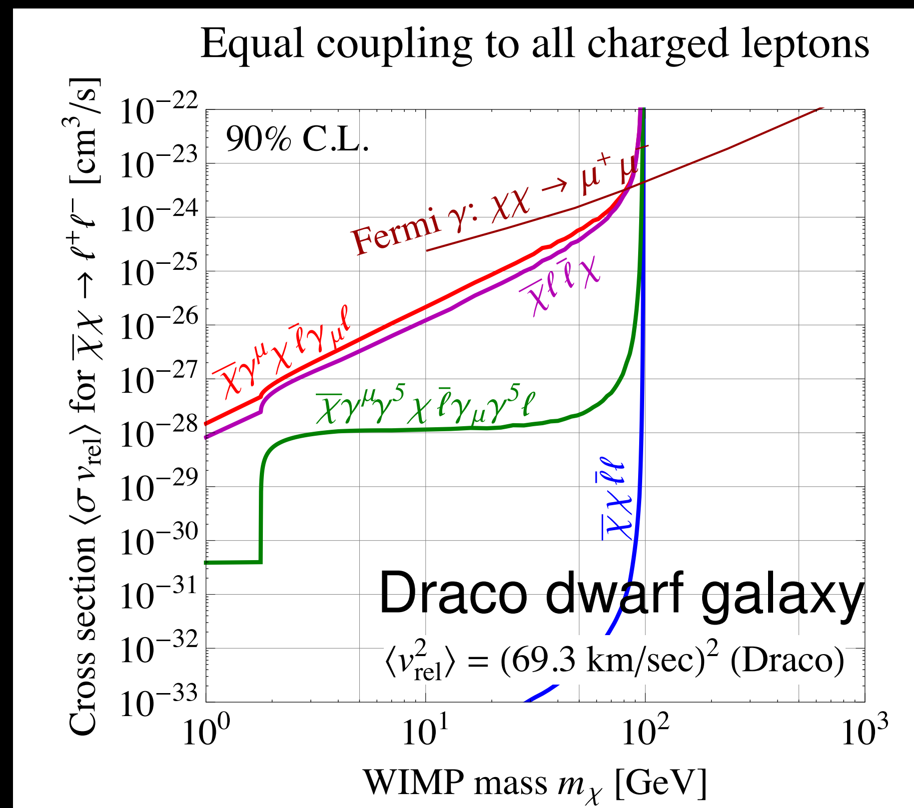
LHC limits and gamma-rays from dark matter





Mono-jet
Mono-gamma

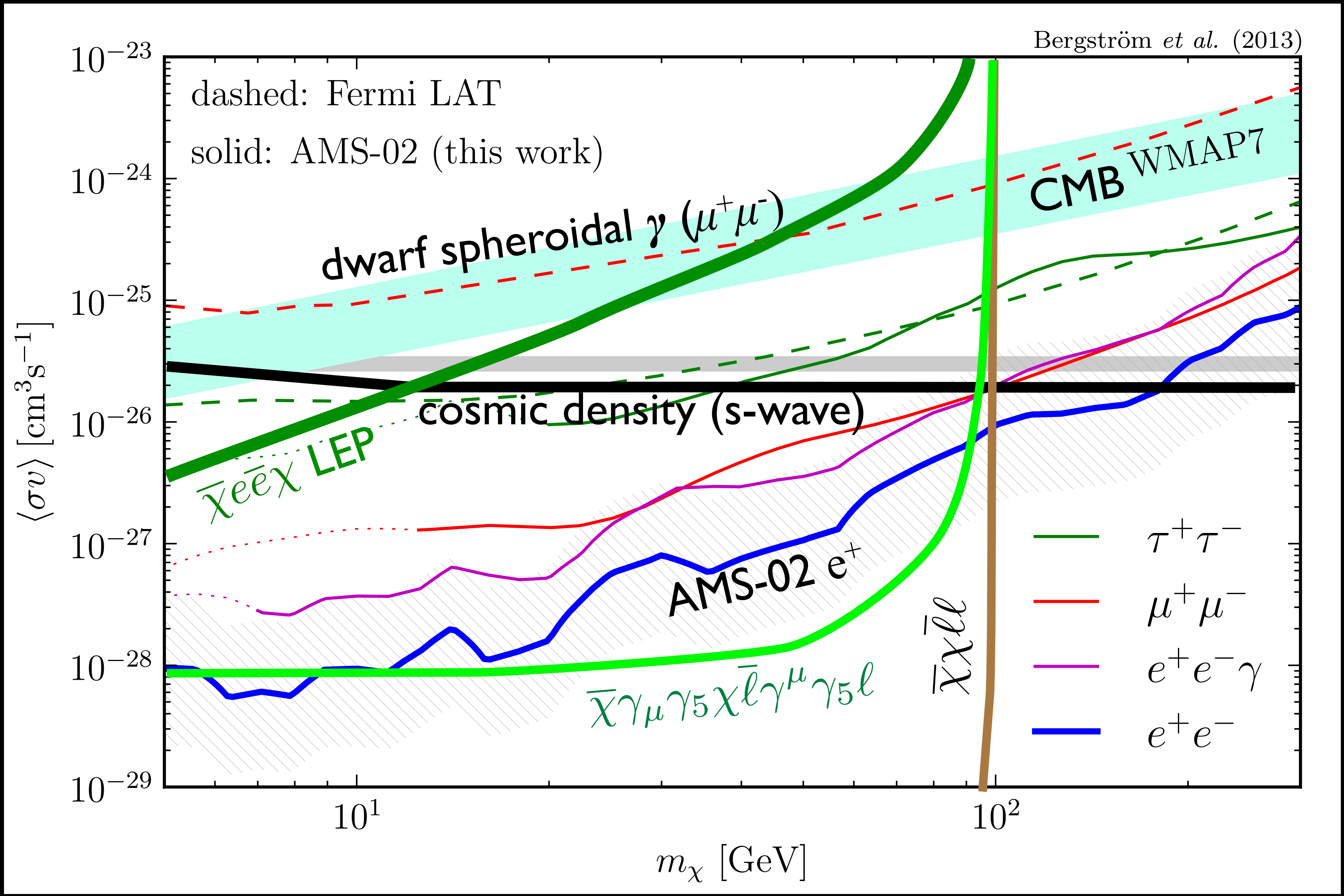




Kopp, Fox, Harnik, Tait 2011

Constraints on annihilation cross section

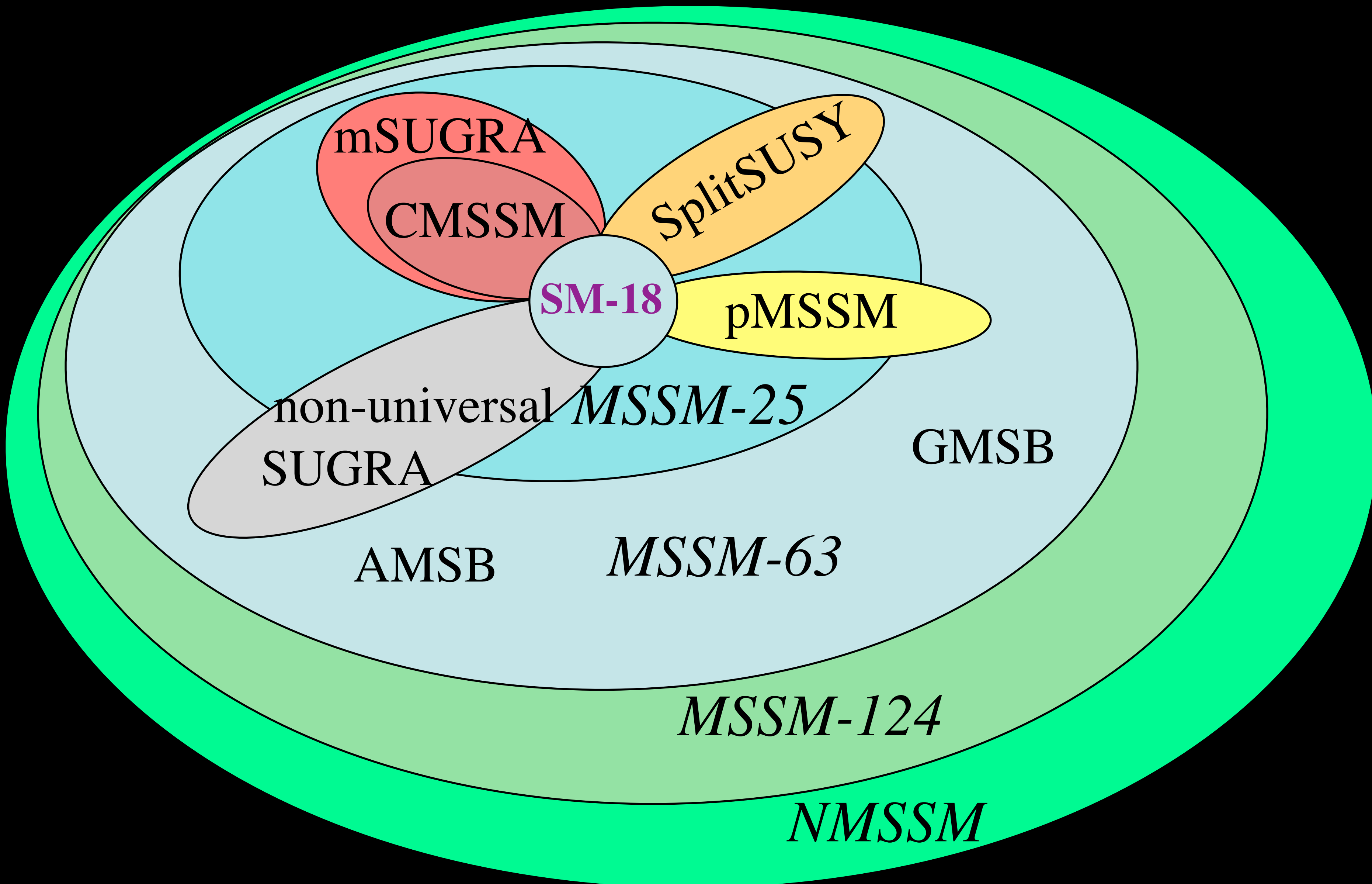
γ-rays, cosmological ionization, positrons, and LEP



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

Supersymmetric dark matter

Intersections of supersymmetric models



Supersymmetric dark matter

Neutralinos (the most fashionable/studied WIMP)

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

Sneutrinos (also WIMPs)

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

Gravitinos (SuperWIMPs)

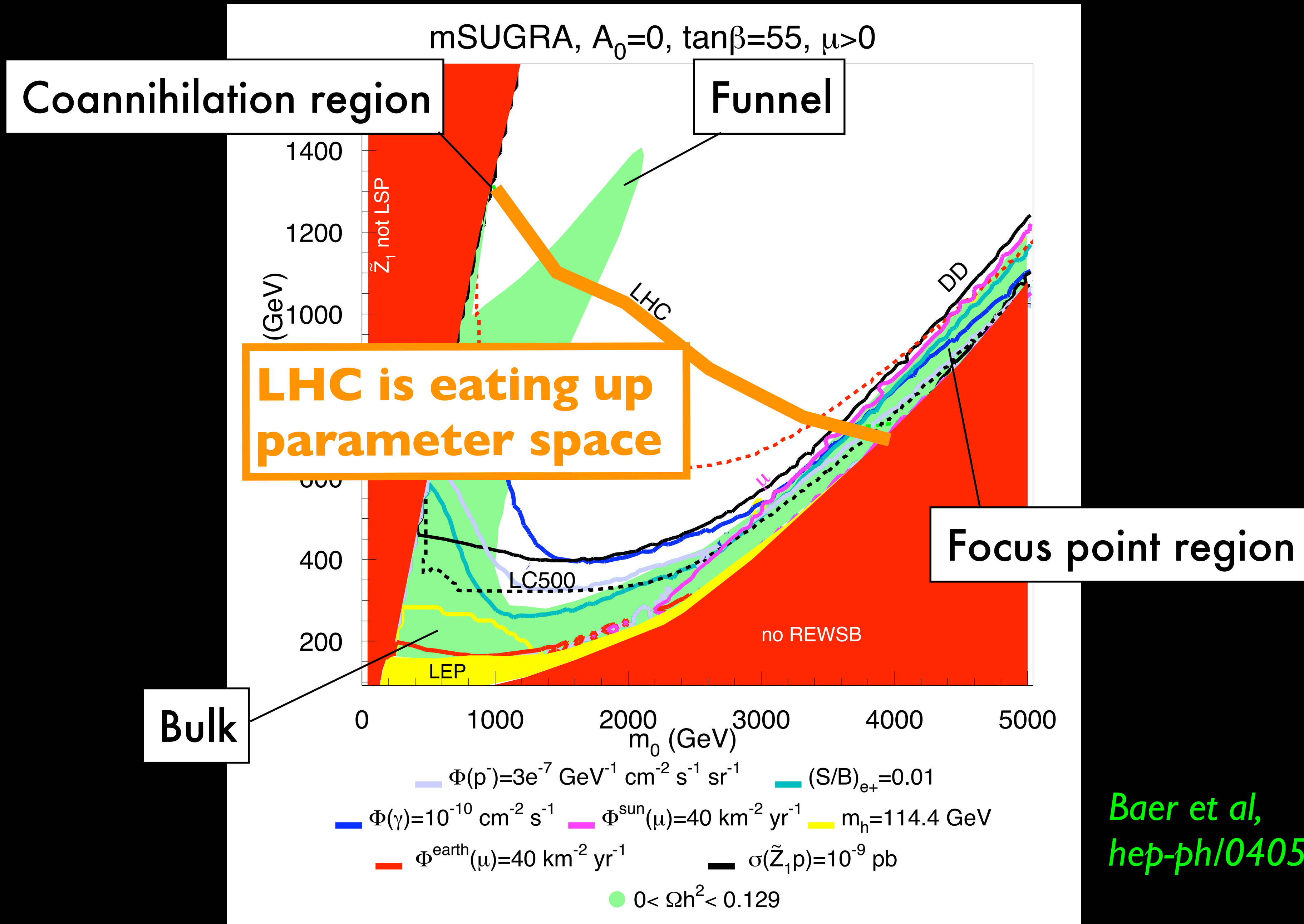
Feng, Rajaraman, Takayama 2003; Ellis, Olive, Santoso, Spanos 2004; Feng, Su, Takayama, 2004; etc.

Axinos (SuperWIMPs)

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

Neutralino dark matter: minimal supergravity

Only in special regions the density is not too large.



Baer et al, hep-ph/0405210

Neutralino dark matter: impact of LHC

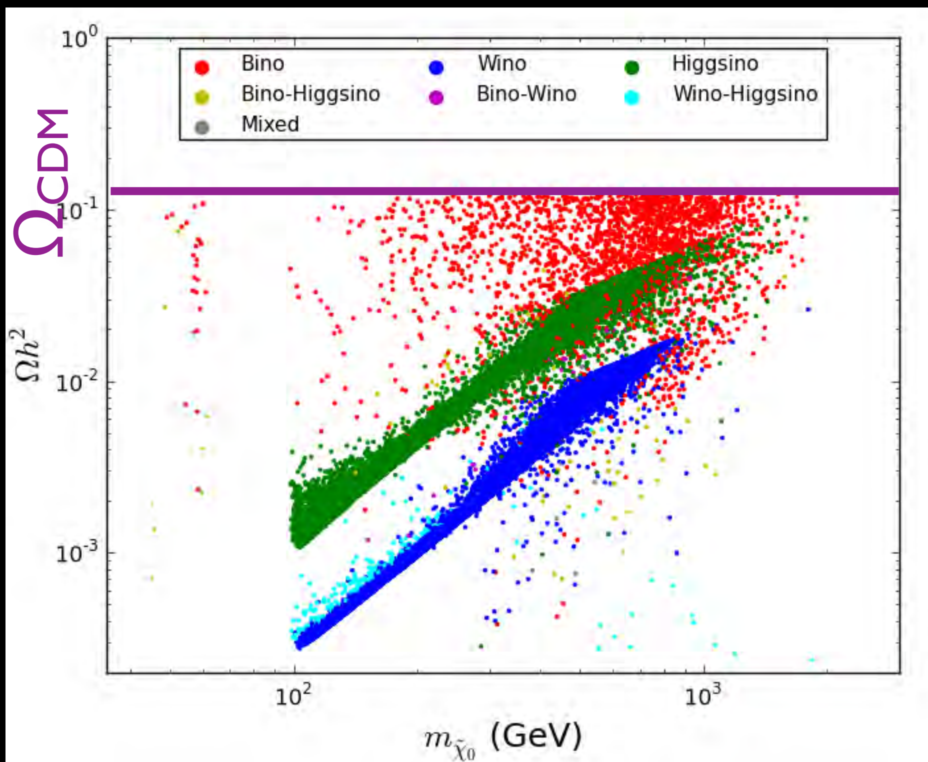
Cahill-Rowell et al 1305.6921

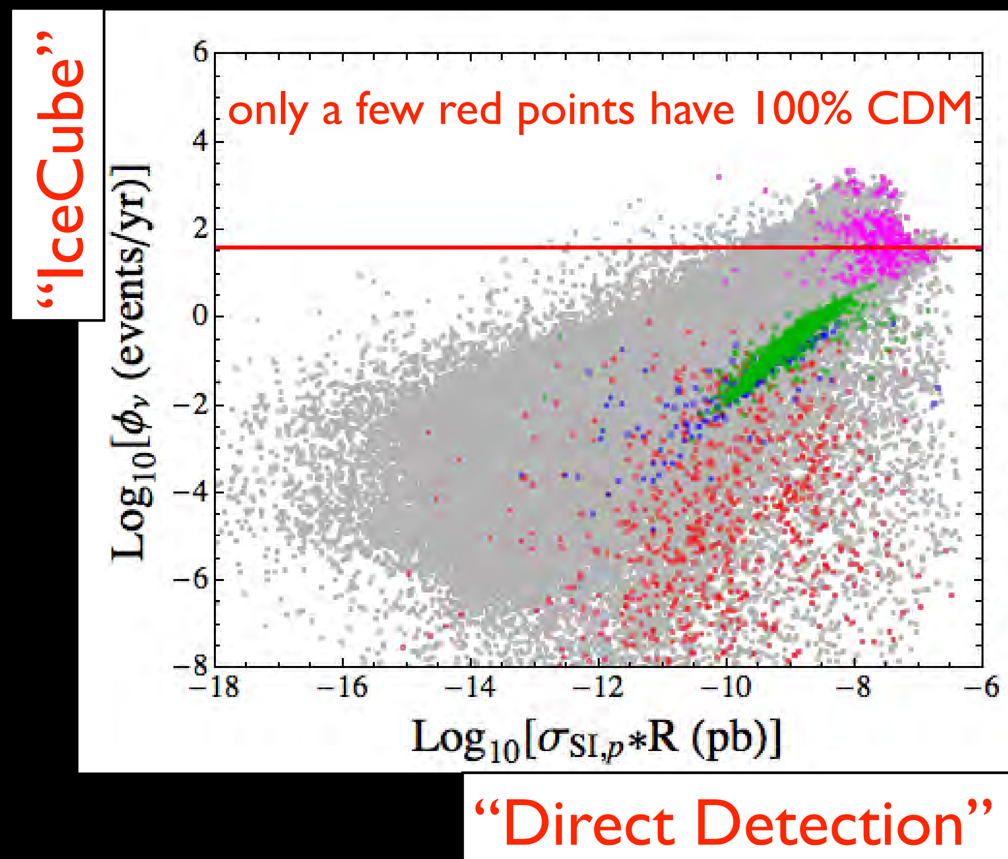
"the only pMSSM models remaining [with neutralino being 100% of CDM] are those with bino coannihilation"

pMSSM (phenomenological MSSM)

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

(19 parameters)

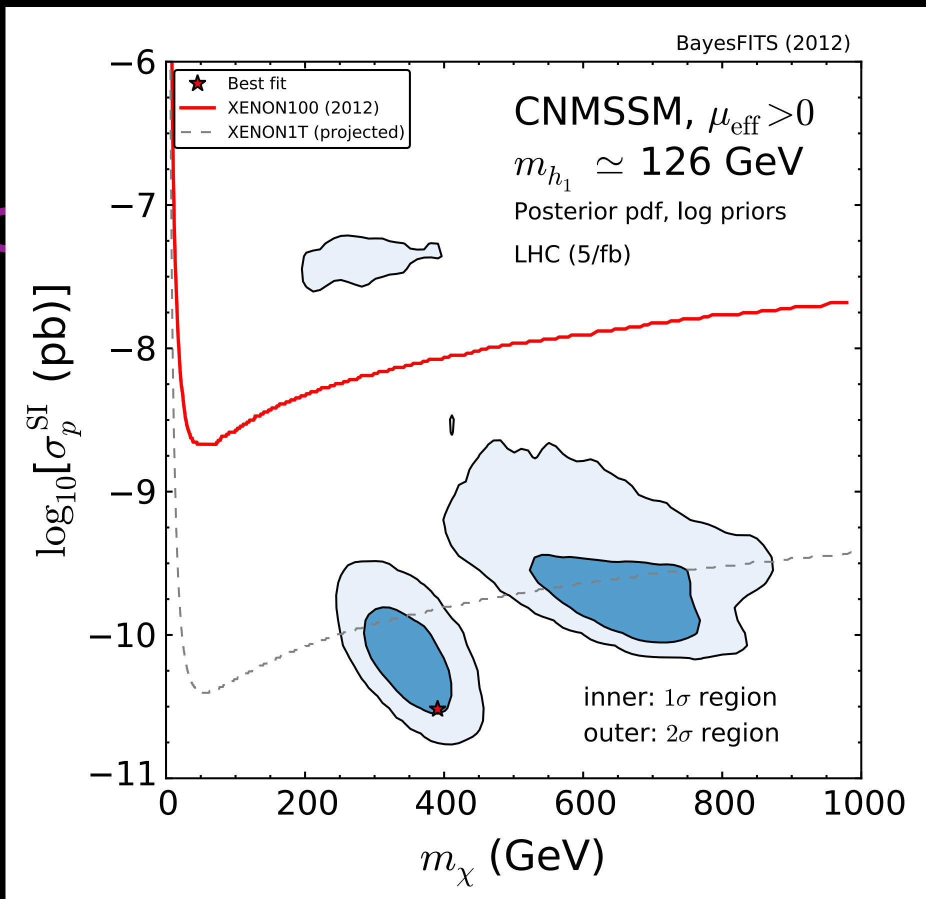




Neutralino dark matter: impact of LHC

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

CNMSSM: Alive and well!



NMSSM (Next-to-MSSM)

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

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

Constrained NMSSM

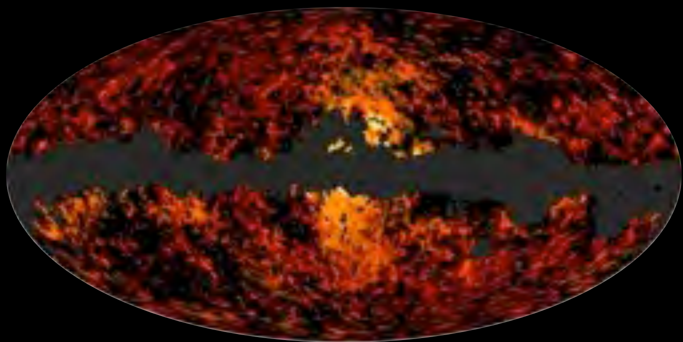
m_0, $m_{1/2}$, A_0, $\tan\beta$, λ, $\text{sgn}(\mu_{\rm eff})$,

GUT & radiative EWSB

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

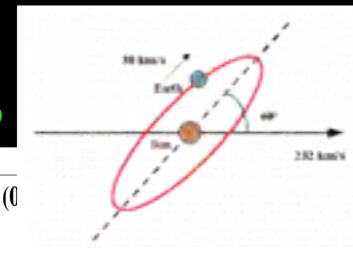
Evidence for WIMP dark matter?

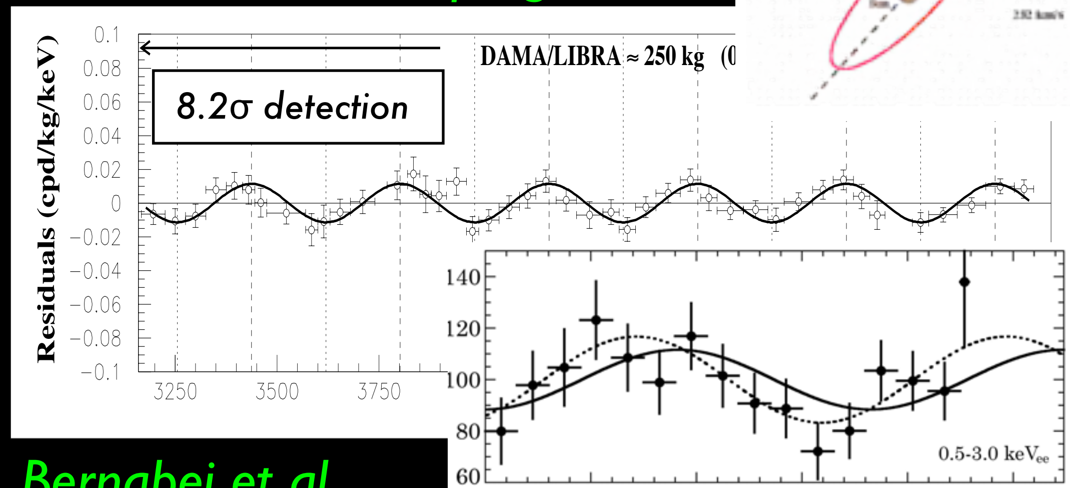
WMAP/Planck haze



Annual modulation

Drukier, Freese, Spergel 1986

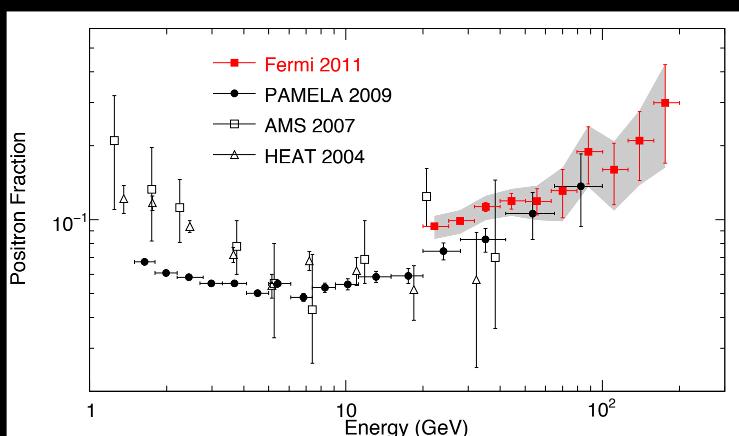




Bernabei et al 1997-2012

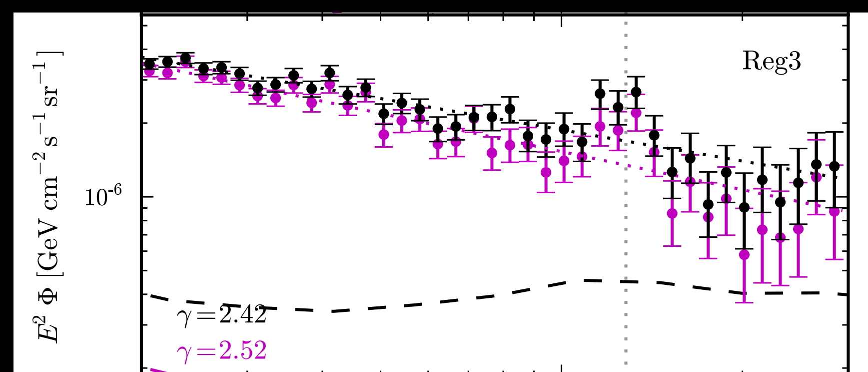
Aalseth et al 2011

Positron excess



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

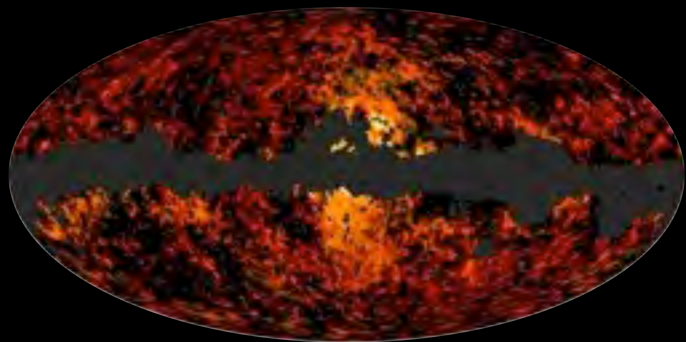
130 GeV γ-ray line



Weniger 2012

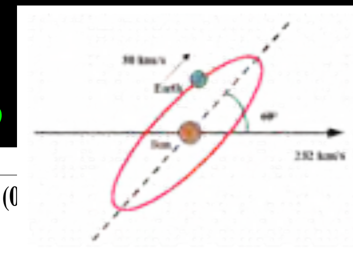
Evidence for WIMP dark matter?

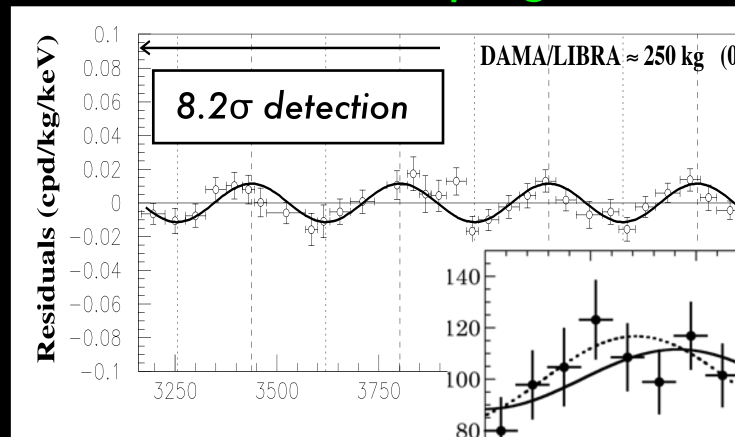
WMAP/Planck haze



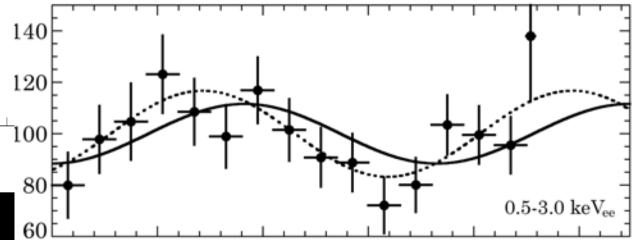
Annual modulation

Drukier, Freese, Spergel 1986



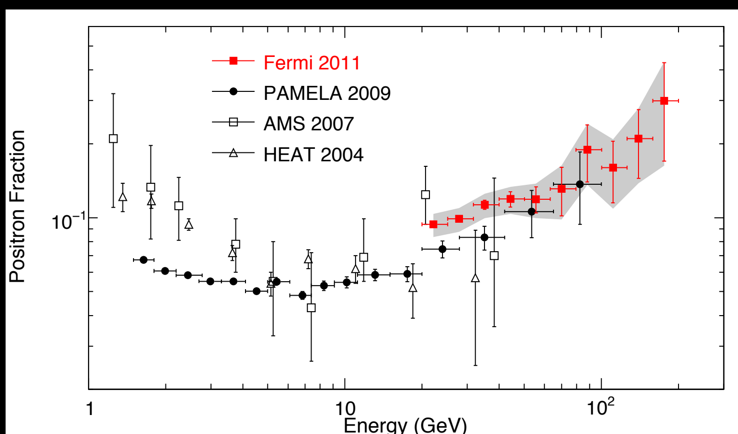


Bernabei et al 1997-2012



Aalseth et al 2011

Positron excess



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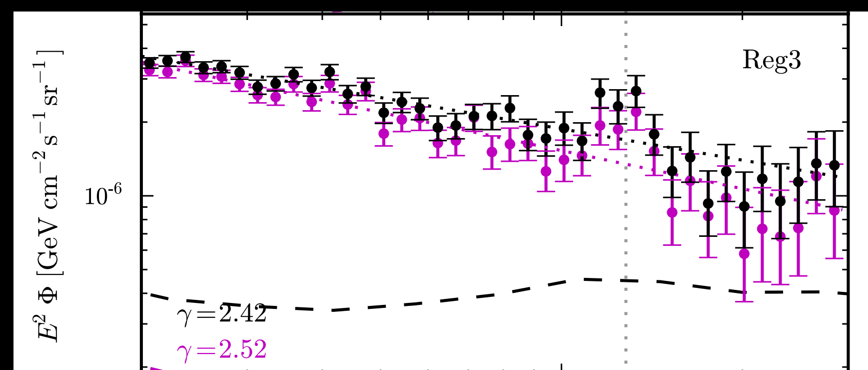
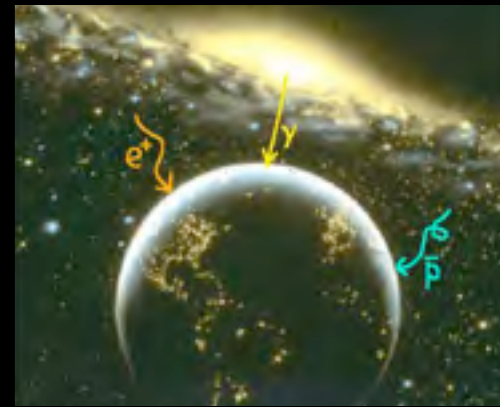
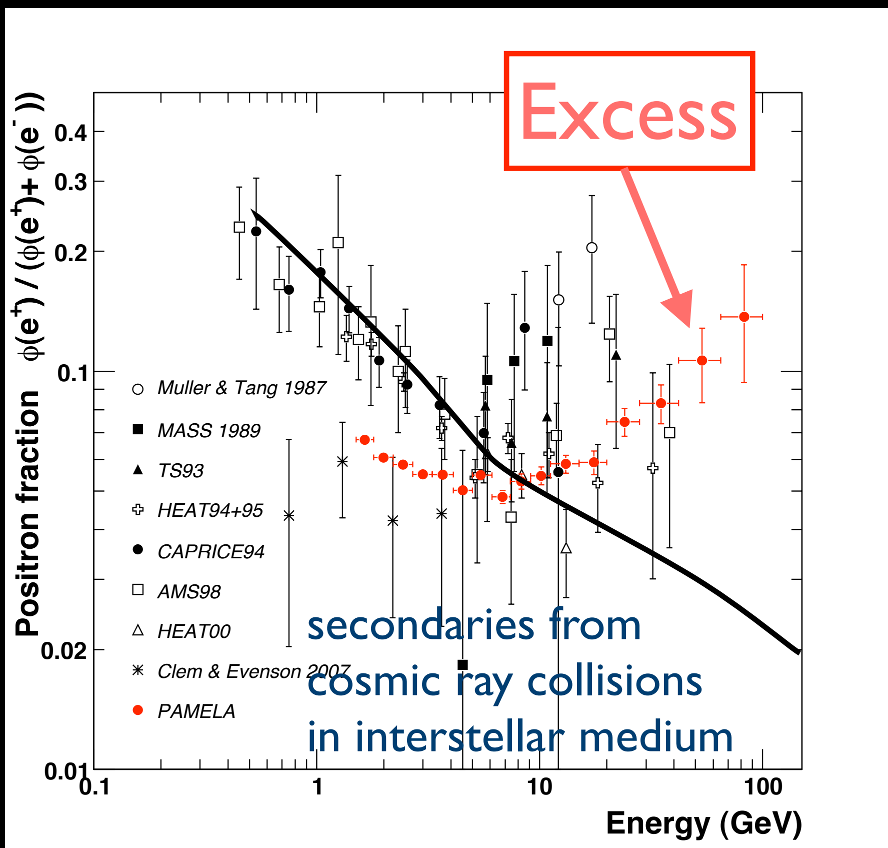


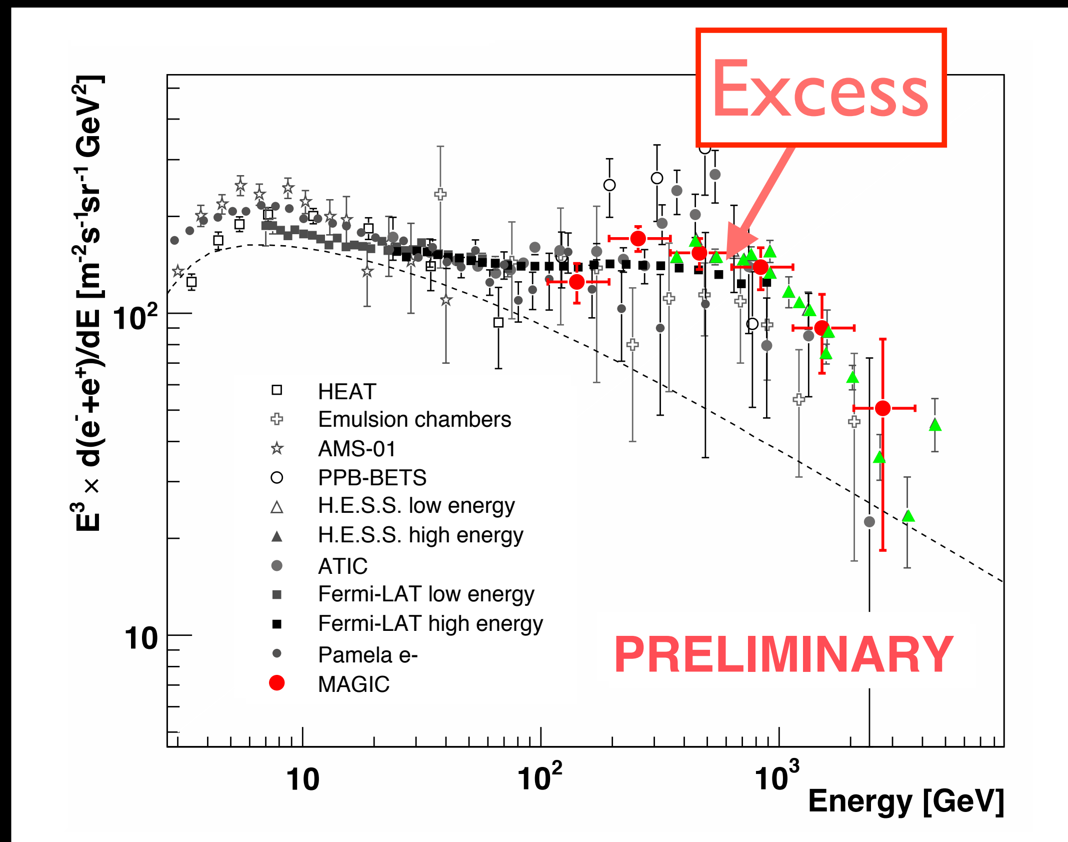
Weniger 2012

Excess in cosmic ray positrons

High energy cosmic ray positrons
are more than expected







Adriani et al. [PAMELA], arXiv: 0810.4995

Borla Tridon et al [MAGIC], arXiv: 1110.4008

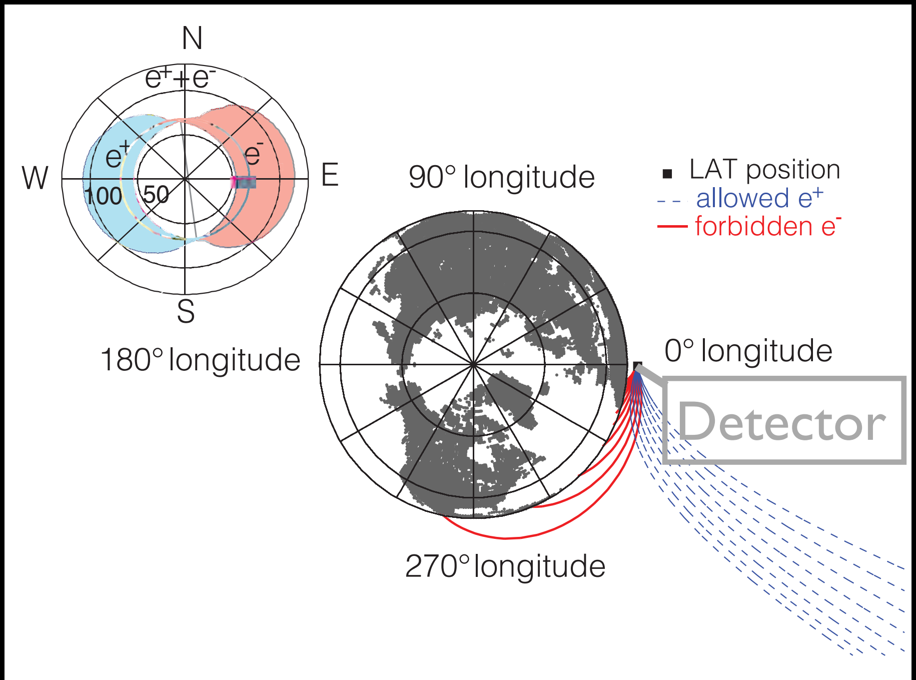
Cosmic ray positrons

Fermi-LAT confirms and extends the positron excess

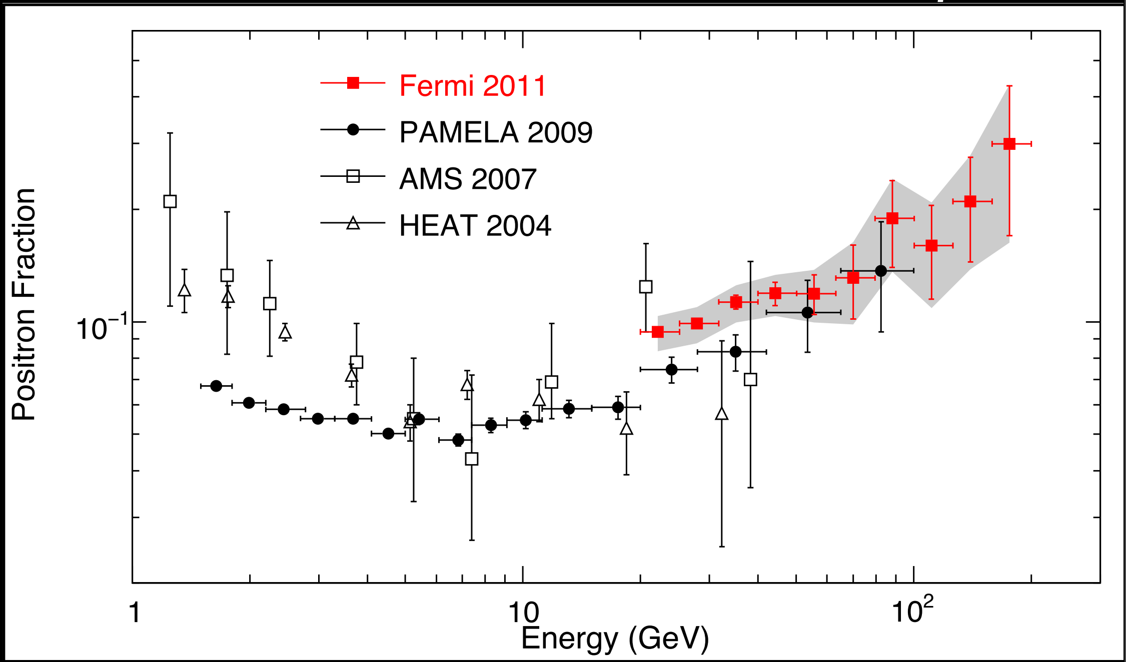
Ackernmann et al, 1109.0521

Use the biggest magnet on Earth: the geomagnetic field!

Daniel, Stephens 1965; Müller, Tang 1987

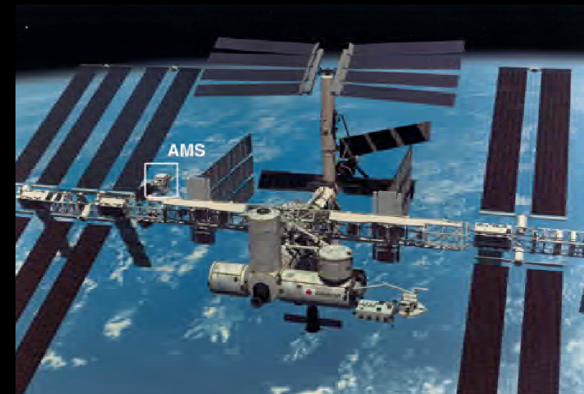


Positron fraction

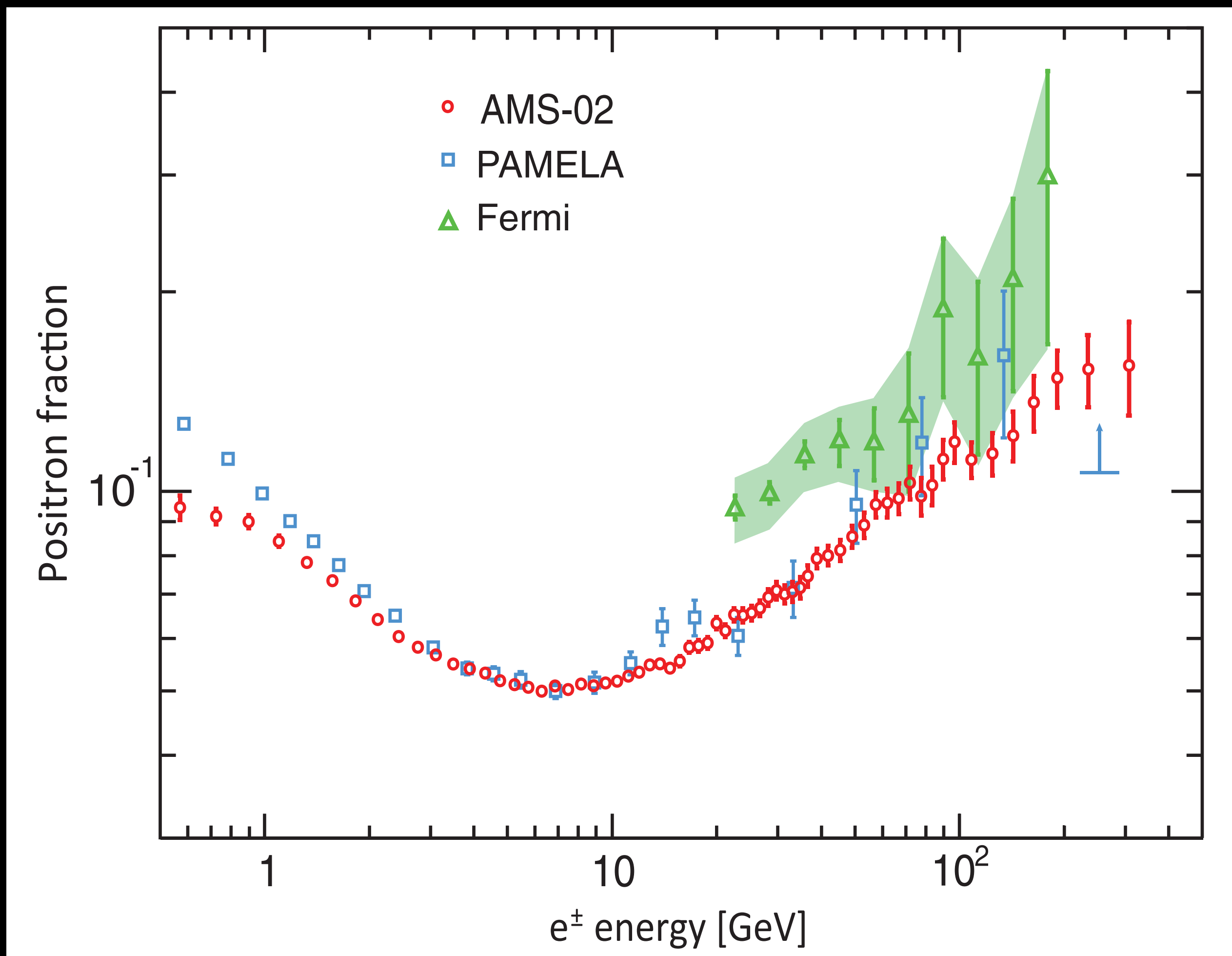


Excess in cosmic ray positrons

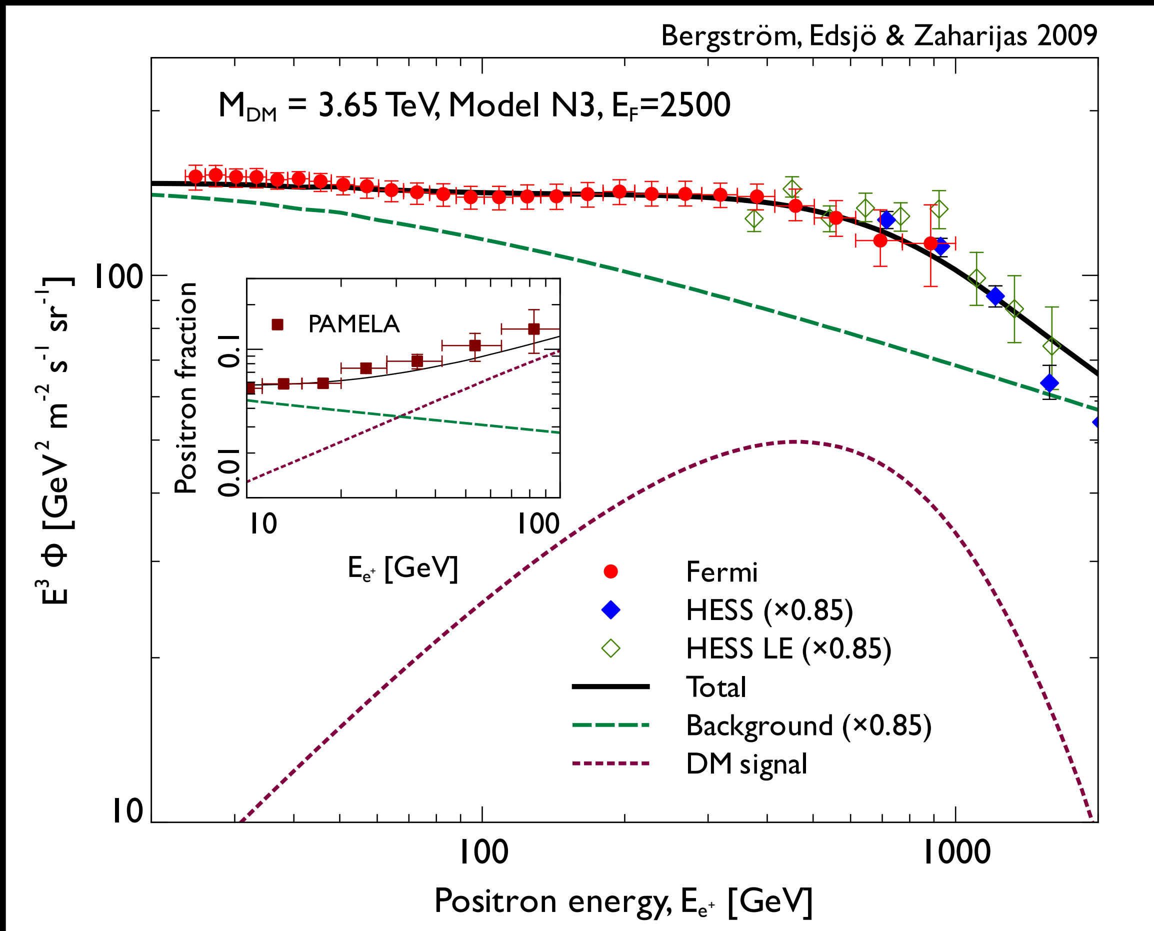
AMS-02 provides data with exquisite precision



Aguilar et al (AMS-02) 2013



Excess in cosmic ray positrons



Bergstrom, Edsjo, Zaharijas 2009

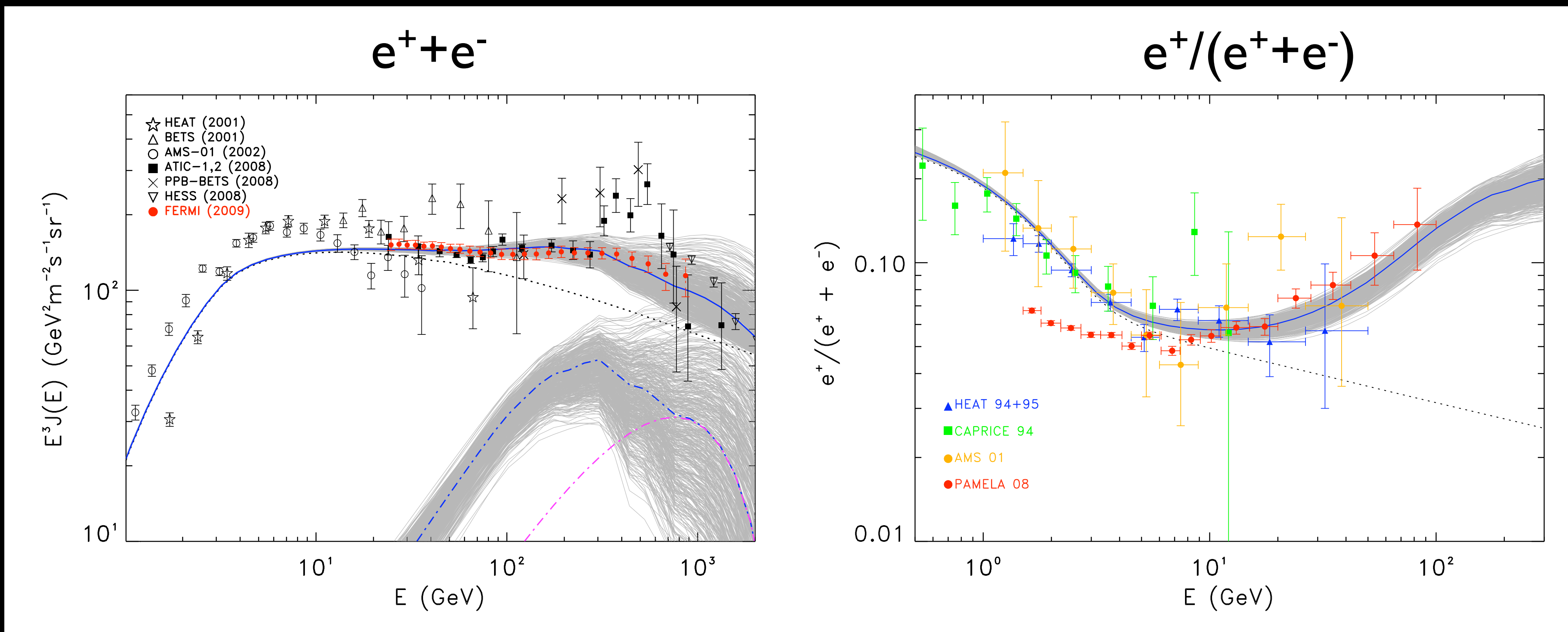
Nomura-Thaler model:

$$DM + DM \to s + a,\ s \to a + a,\ a \to \mu^+\mu^-$$

$$m_s = 20\ \text{GeV} \qquad m_a = 0.5\ \text{GeV}$$

Excess in cosmic ray positrons

Pulsars



Grasso et al [Fermi-LAT], arXiv: 0905.0636

Many parameters and models to choose from.

Excess in cosmic ray positrons

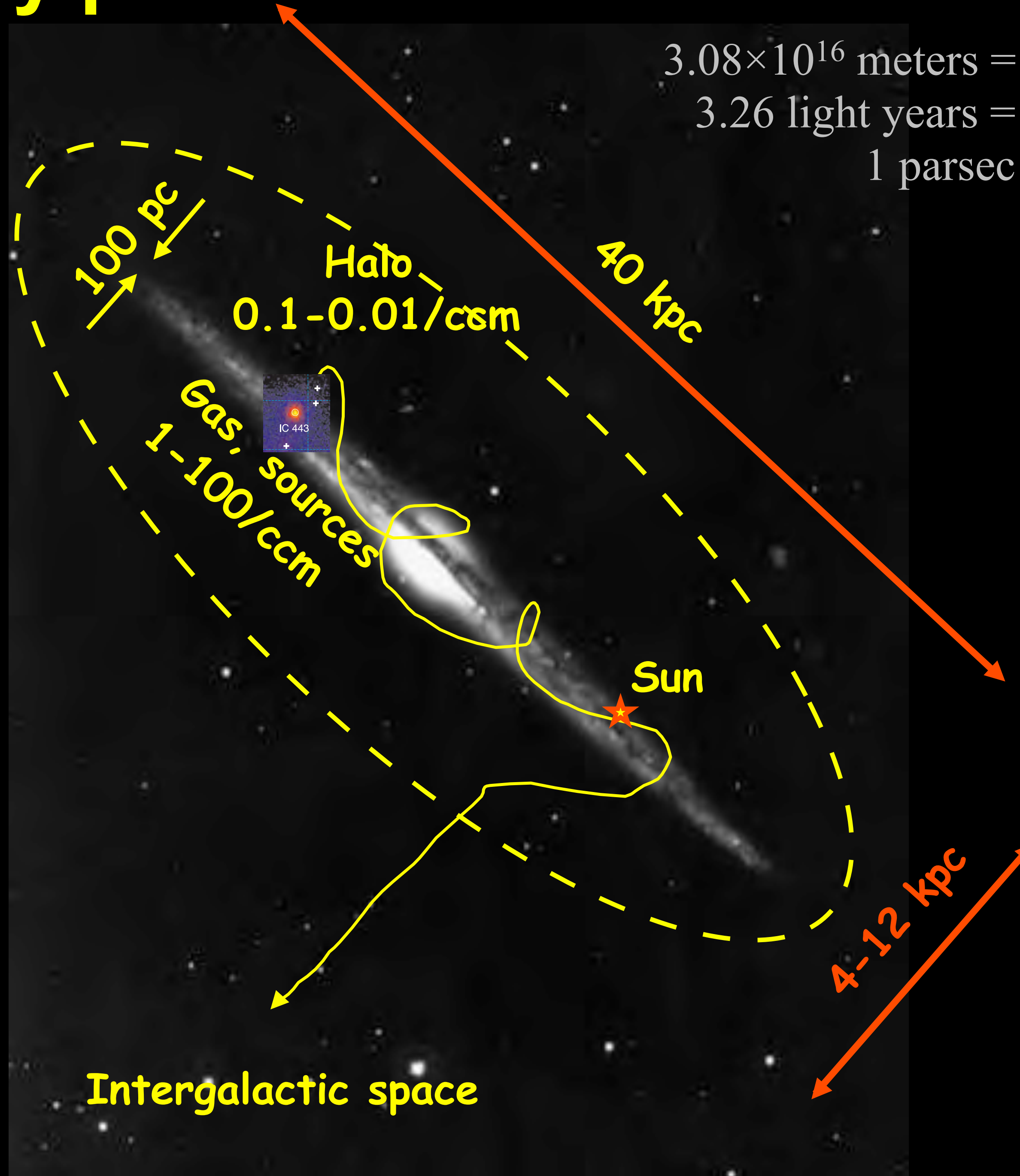
Galactic cosmic rays

- Primary cosmic rays (p, ^{4}He, C, N, O, ..., Fe, ^{64}Ni) are produced in supernova remnants.

First observational evidence Ackermann et al 2013

- Secondary cosmic rays (^{2}H, ^{3}He, ^{6,7}Li, ^{7,9,10}Be, ^{10,11}B, ..., ^{26}Al, ^{35}Cl, ^{54}Mn, ...) are produced in cosmic ray collisions with the interstellar medium (90% H, 10% He).

- Secondary to primary ratio carries information on astrophysical model.



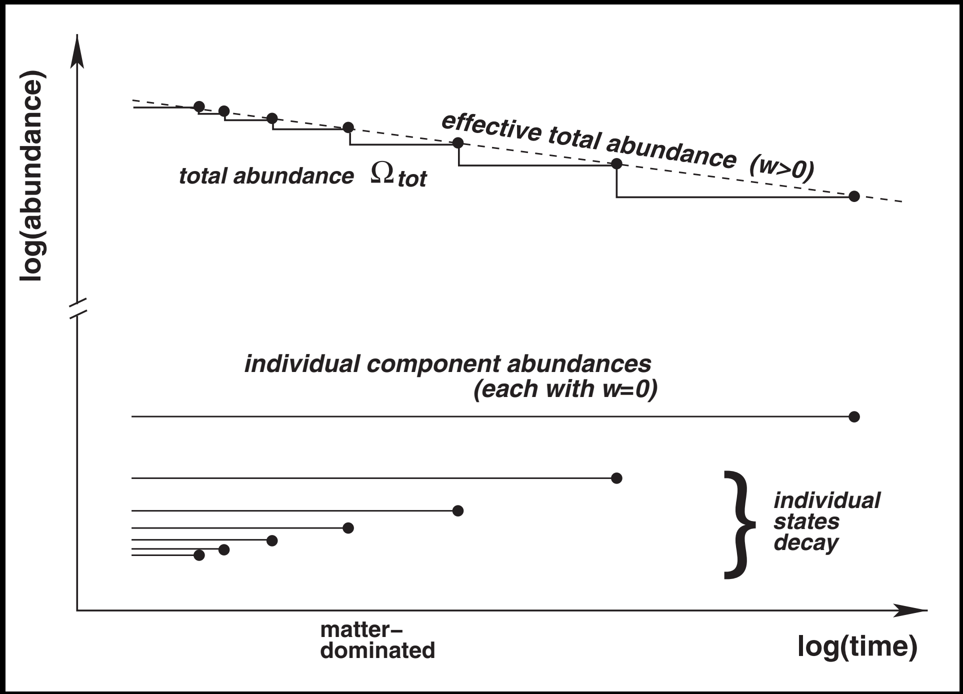
Background graphics from Moskalenko 2005

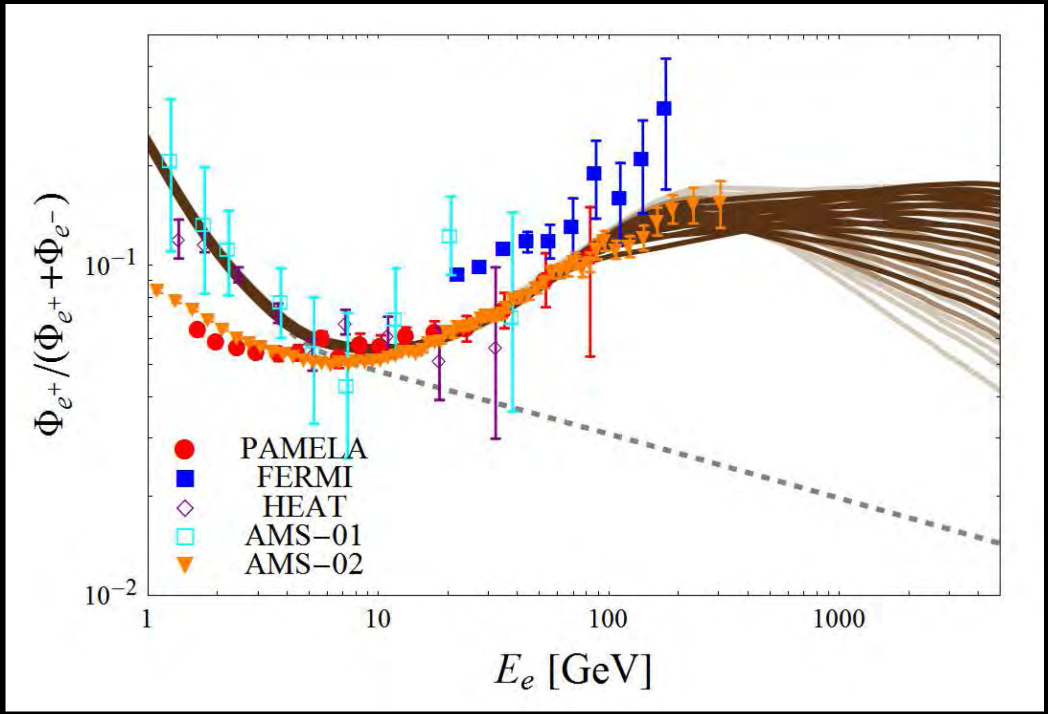
Dynamical dark matter

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



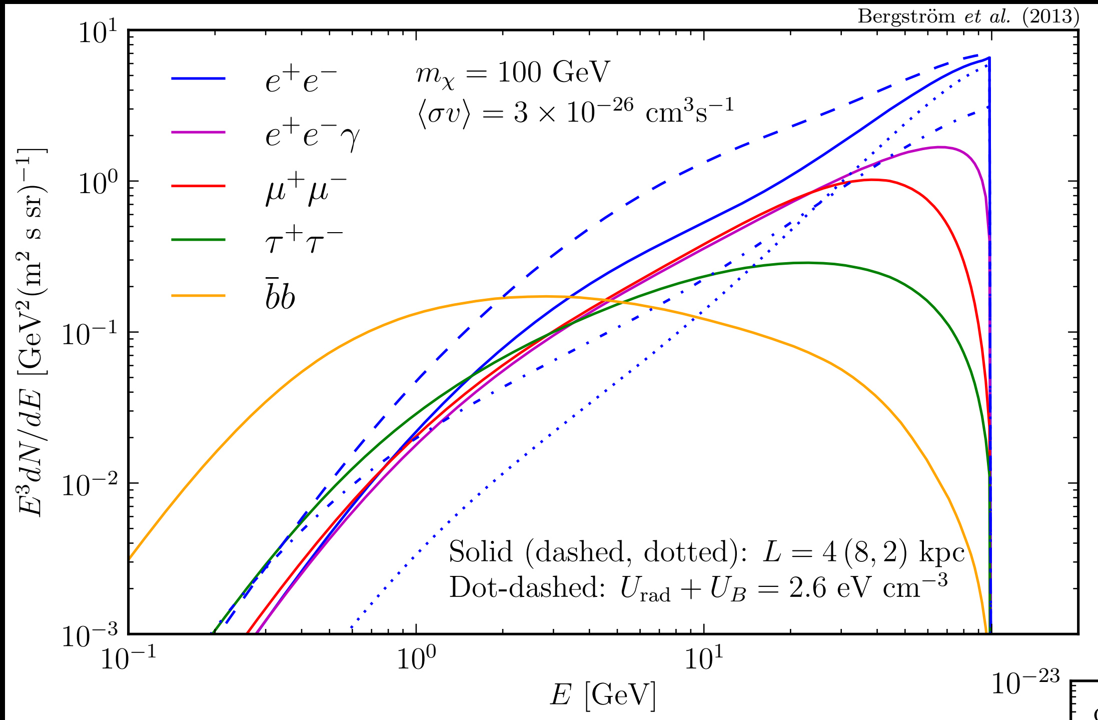


Phenomenology obtained through scaling laws

$$m_n = m_0 + n^\delta \Delta m,$$

$$\rho_n \sim m_n^\alpha,\ \tau_n \sim m_n^{-\gamma}$$

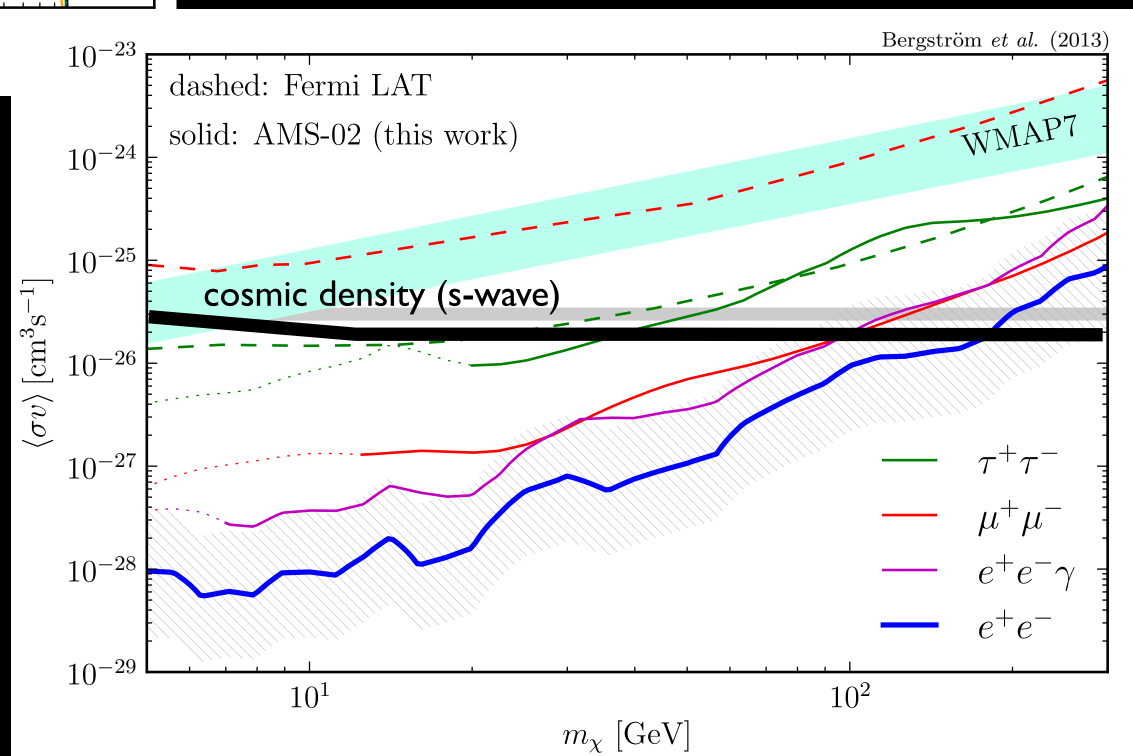
Excess in cosmic ray positrons



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

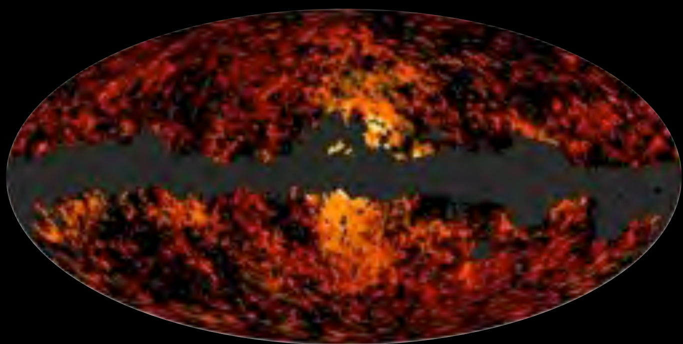
Bergstrom et al 2013

Spectral features in e^+e^- spectrum lead to limits on annihilation cross section



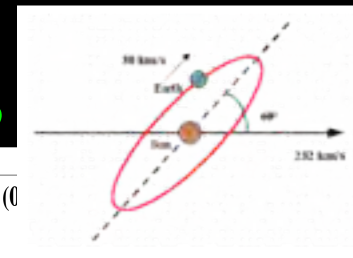
Evidence for cold dark matter particles?

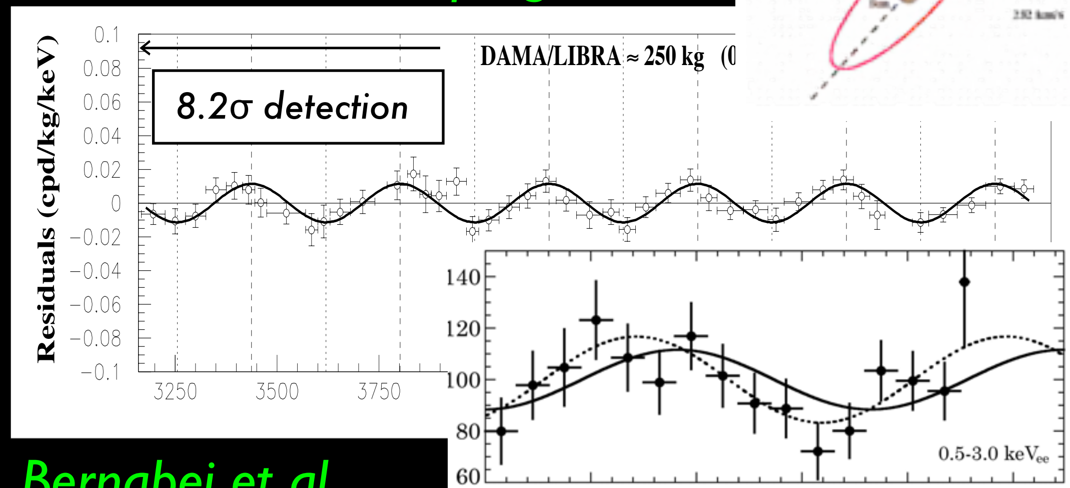
WMAP/Planck haze



Annual modulation

Drukier, Freese, Spergel 1986

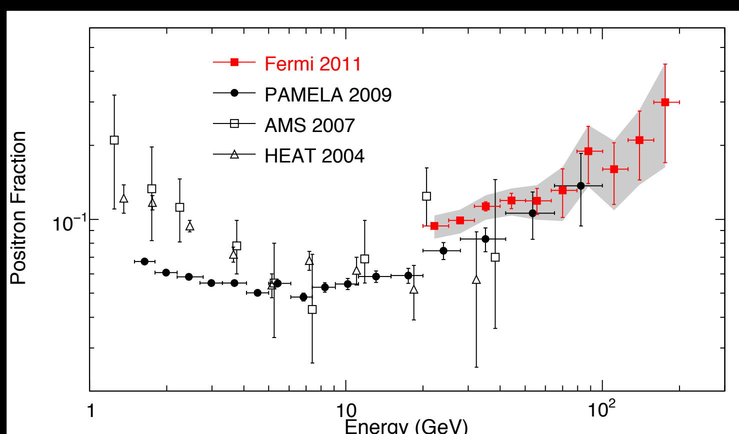




Bernabei et al 1997-2012

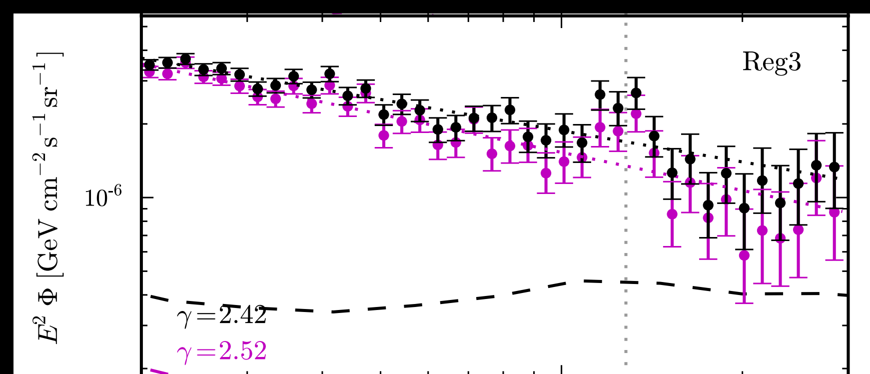
Aalseth et al 2011

Positron excess



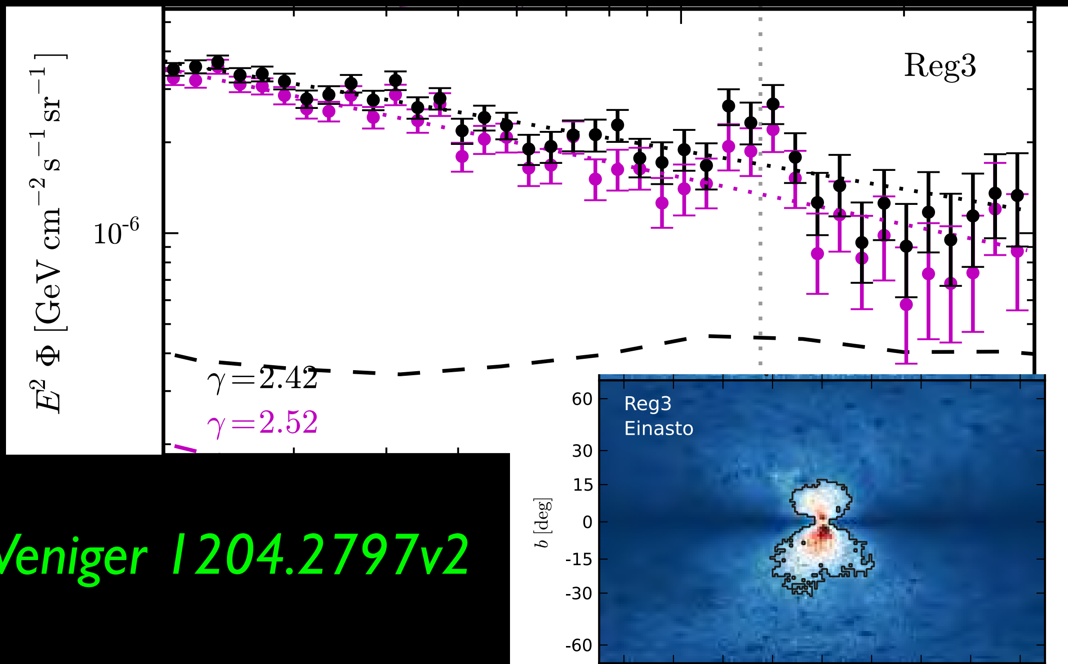
Adriani et al 2009;Ackerman et al 2011

130 GeV γ-ray line



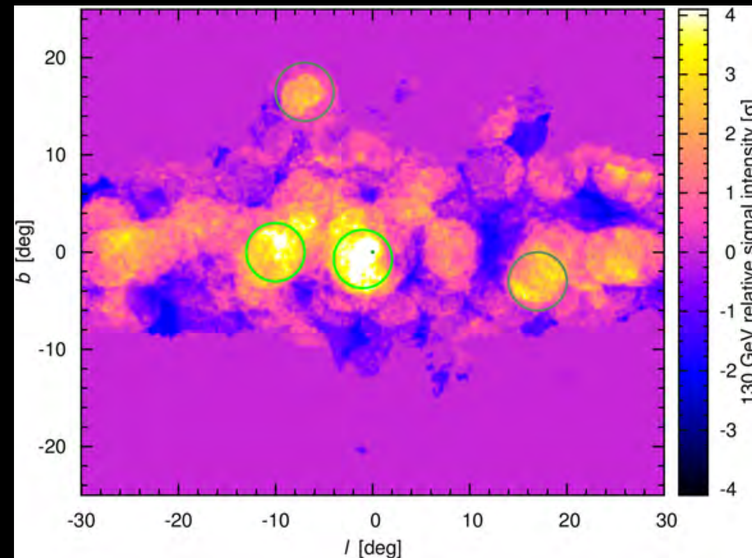
Weniger 2012

135 GeV gamma-ray line?



Weniger 1204.2797v2

found by others



Tempel, Hektor, Raidal 2012

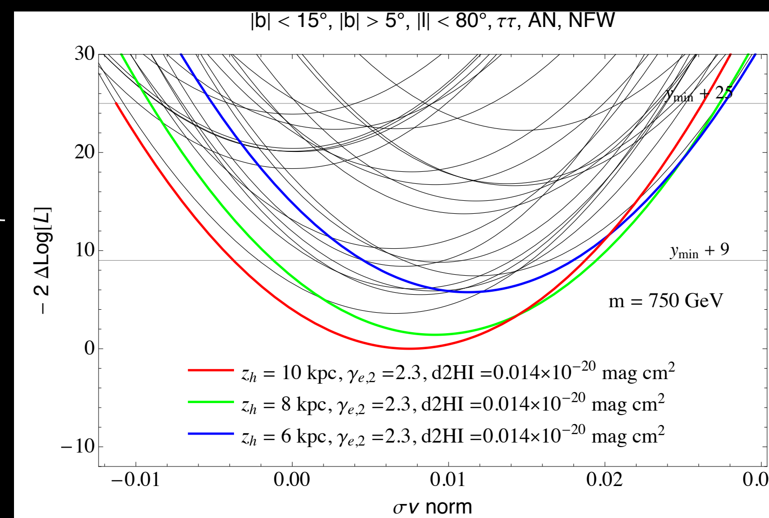
3.2σ effect based on 50 photons

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

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

HESS-2 will tell (when?)

Fermi Collab. upper bounds

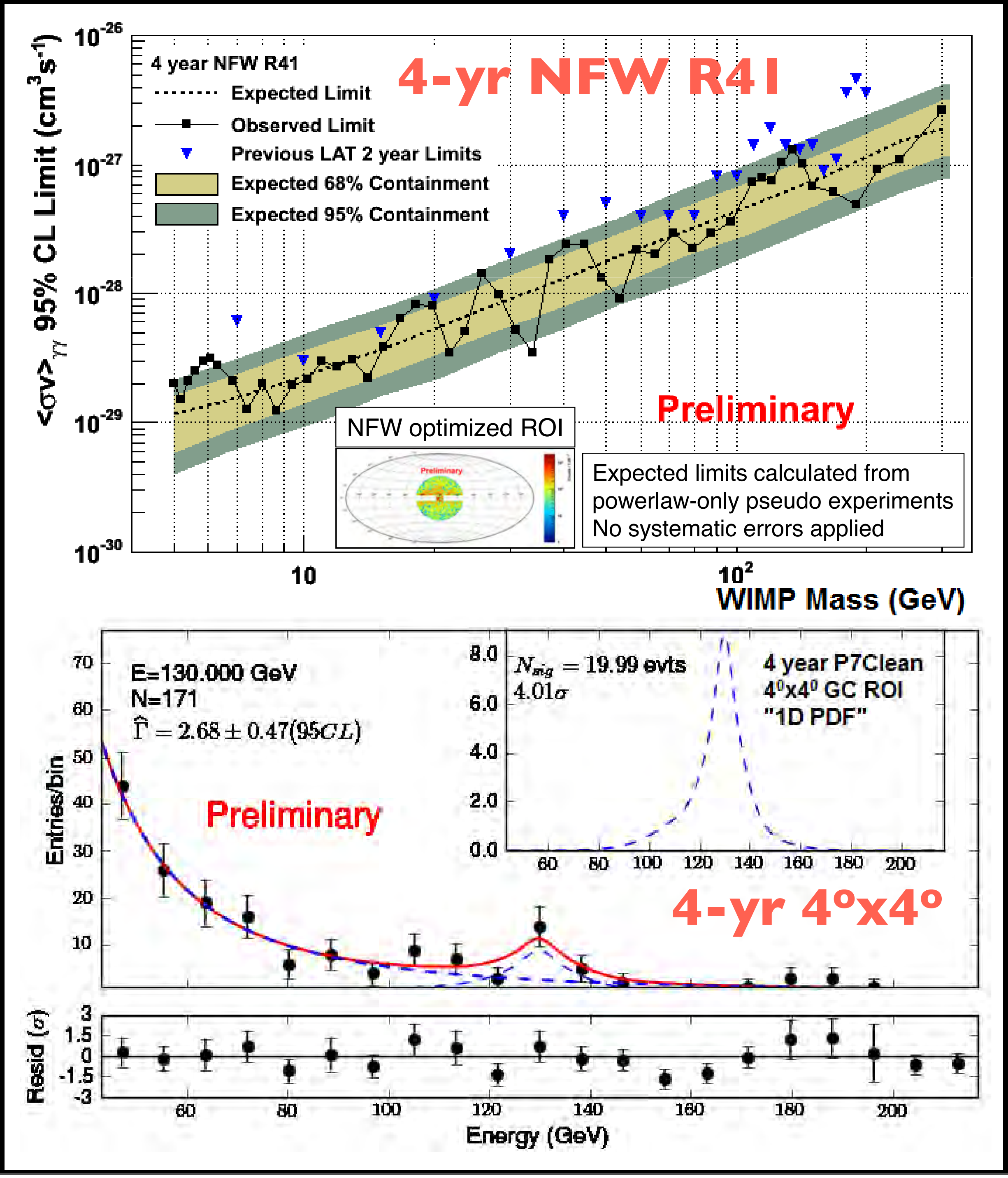


Ackerman et al (Fermi-LAT) 2012

135 GeV gamma-ray line?

Bloom et al (Fermi-LAT) 2012

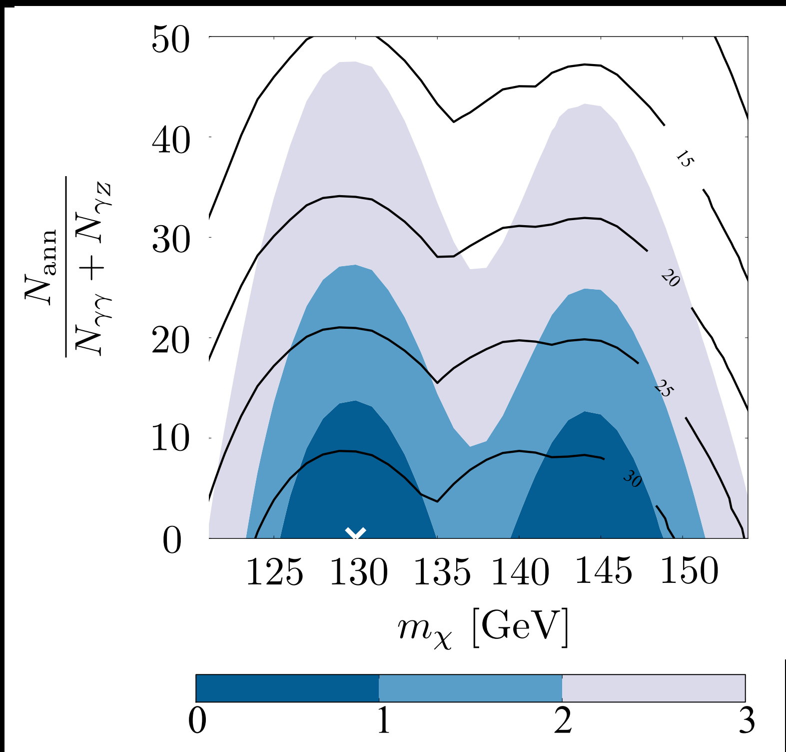
Albert et al (Fermi-LAT) 2012



135 GeV gamma-ray line?

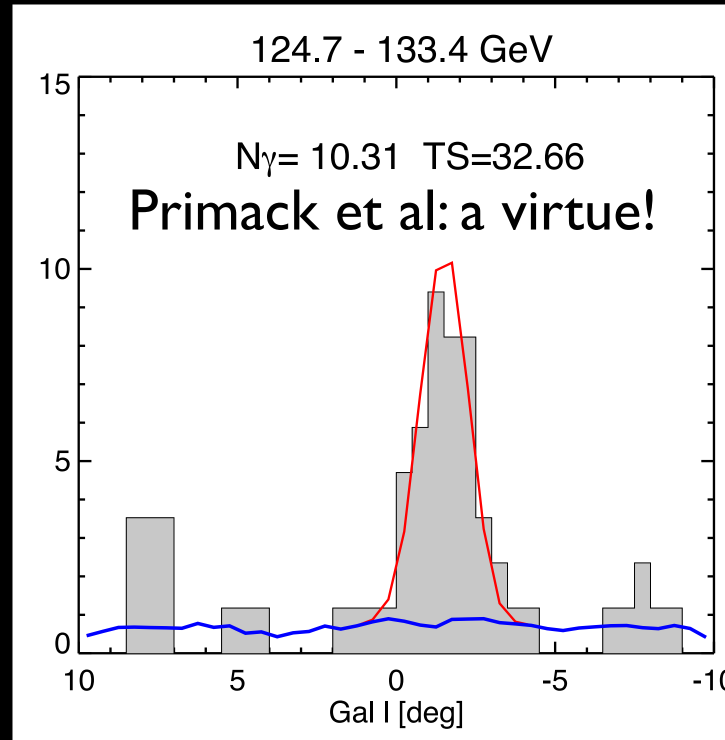
Difficulties......

suppressed continuum

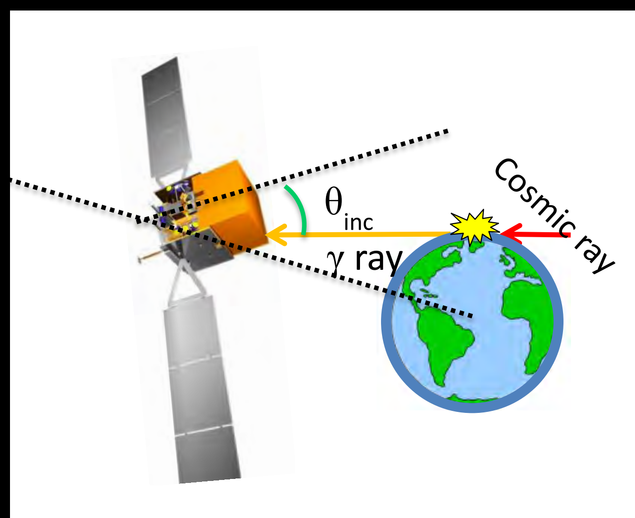


Cohen, Lisanti, Slatyer, Wacker 2012

off from Galactic Center



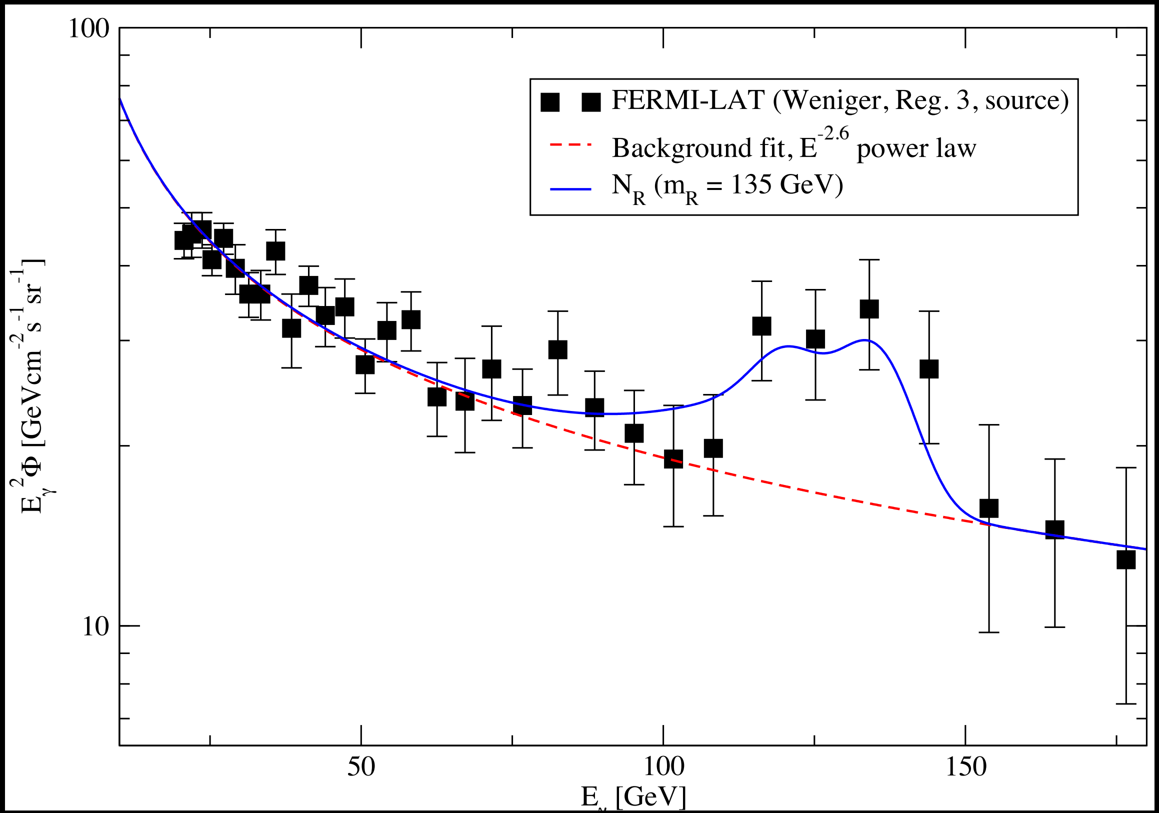
Su, Finkbeiner 2012



Earth limb data set shows pile-up at 130 GeV

135 GeV gamma-ray line: particle physics

Leptonically-Interacting Massive Particles (LIMPs)



Baltz, Bergstrom 2002; Bergstrom 1208.6082

LIMPs predicted a gamma-ray line without a continuum

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

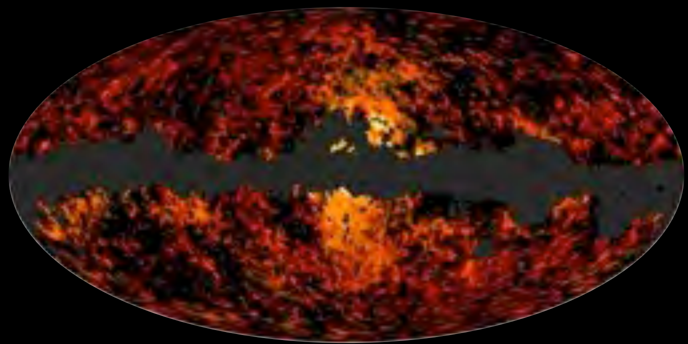
Zee 1980

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

Krauss, Nasri, Trodden 2002

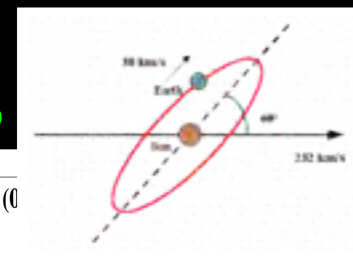
Evidence for cold dark matter particles?

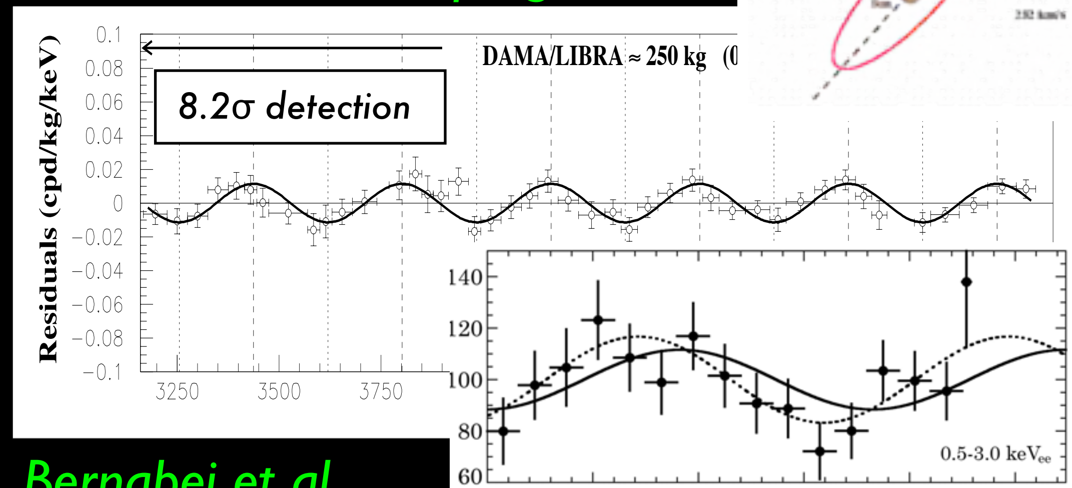
WMAP/Planck haze



Annual modulation

Drukier, Freese, Spergel 1986

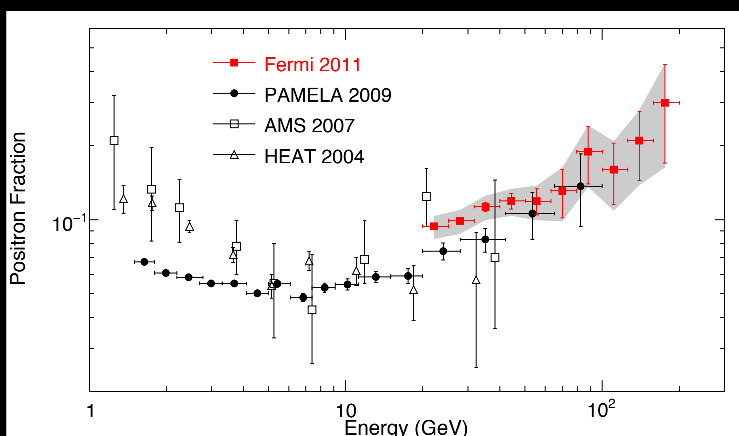




Bernabei et al 1997-2012

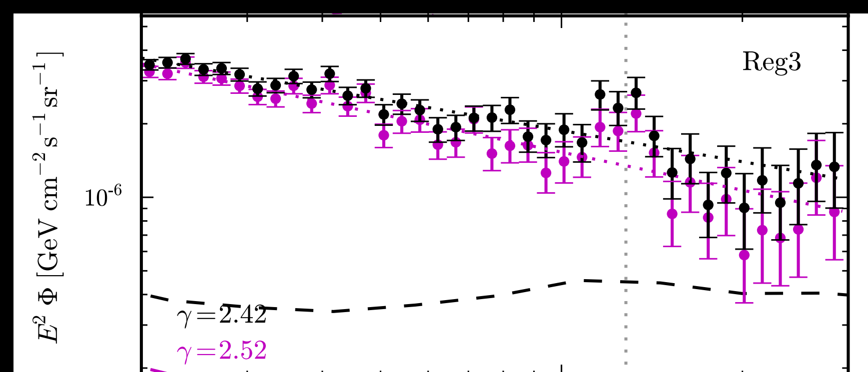
Aalseth et al 2011

Positron excess



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

130 GeV γ-ray line



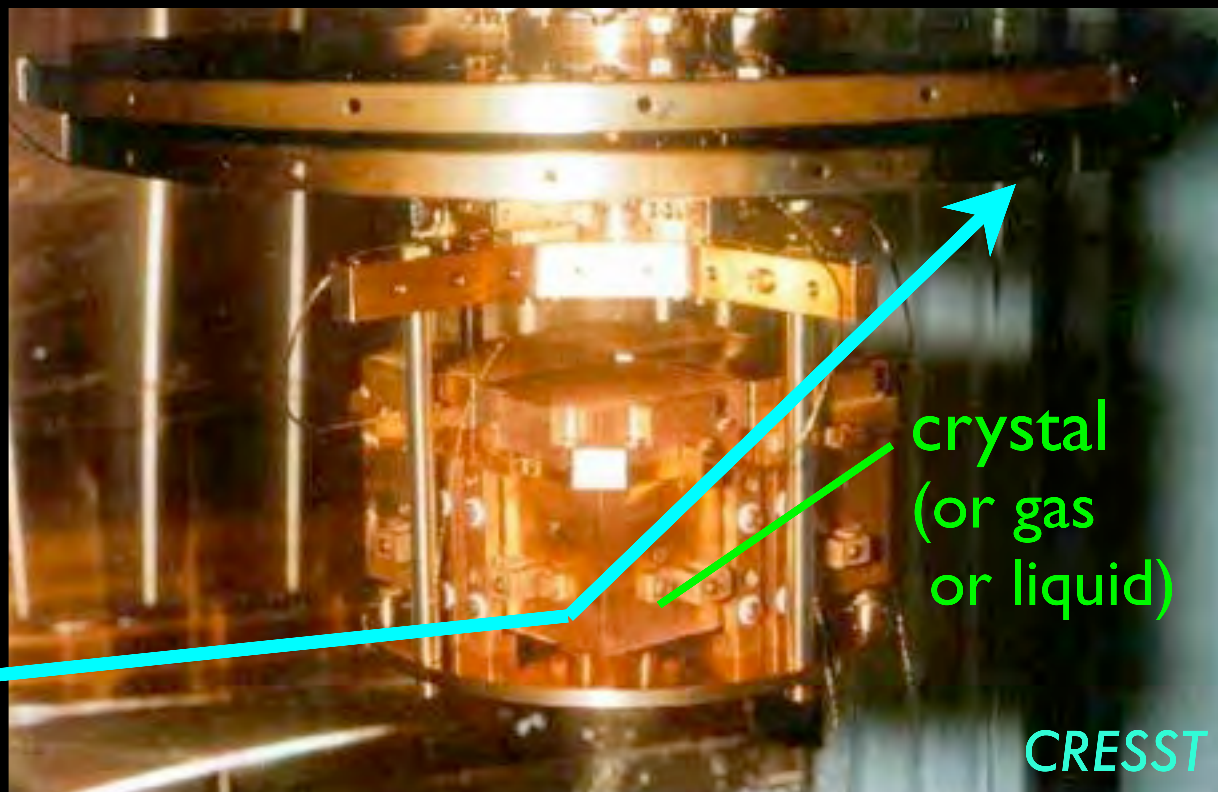
Weniger 2012

The principle of direct detection

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

Goodman, Witten 1985

Dark matter particle



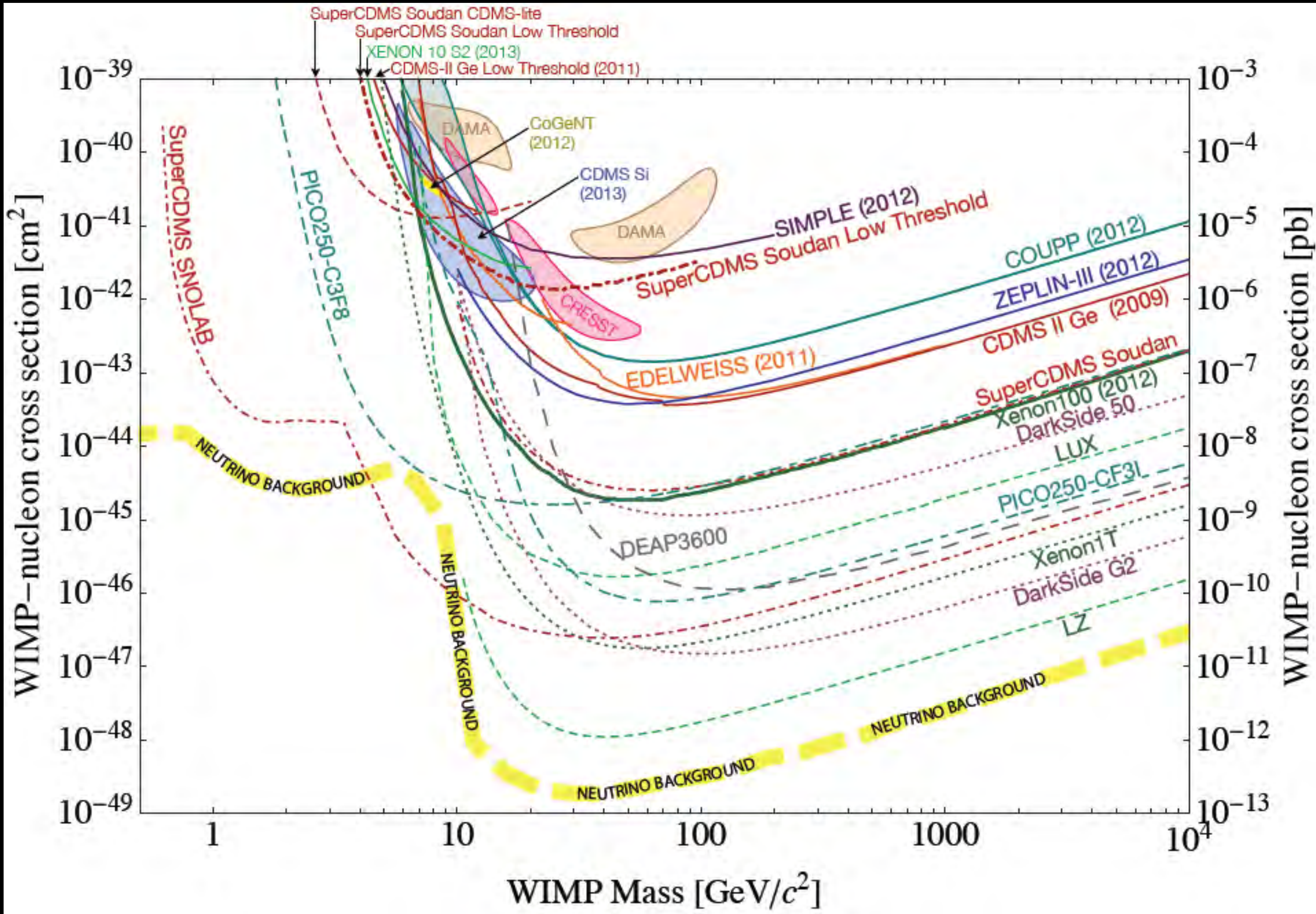
Low-background underground detector

CDMS
EDELWEISS
DAMA
CRESST
KIMS
DRIFT
XENON
COUPP
CoGeNT
TARP
DMTPC
TEXONO
PANDA-X
.....

Direct dark matter searches (2013)

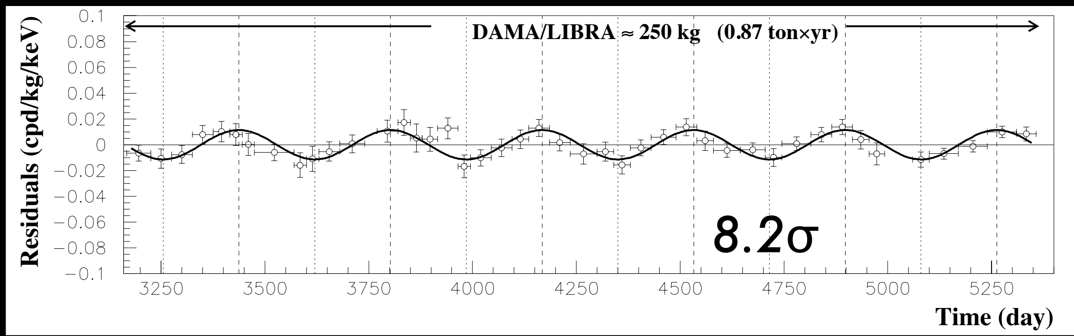
- XMASS (800 kg LXe, Kamioka, 2011-)
- SuperCDMS (25kg Ge, Soudan, 2012-)
- LUX (350 kg LXe, Homestake, 2012-)
- DarkSide (50 kg LAr, Gran Sasso, 2012-)
- COUPP (60 kg CF_3I, SNOLab, 2012-)
- XENON-1T (1 ton LXe, Gran Sasso, 2014-)
- EURECA, DARWIN, ...

Direct dark matter searches (2013)

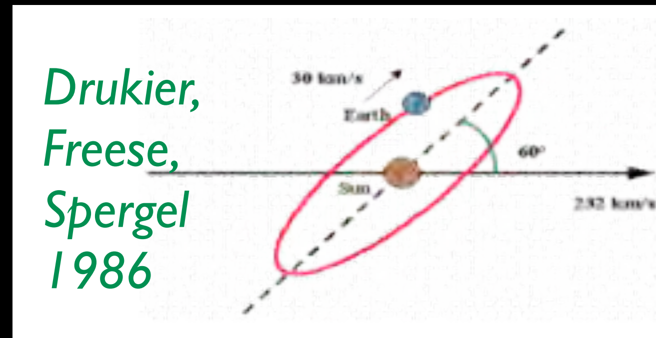


Billard, Strigari, Feliciano-Figueroa 2013 + Feng, Ritz(Snowmass 2013)

Evidence for light dark matter particles?

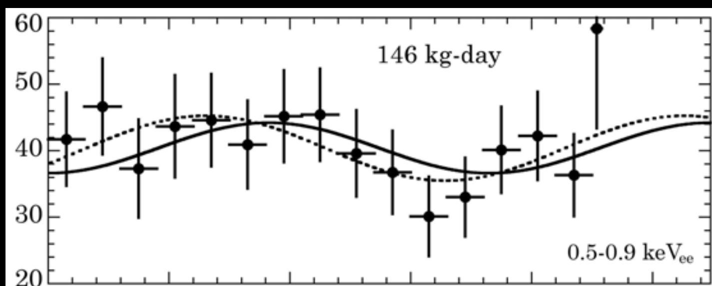


Bernabei et al (DAMA) 1997-10

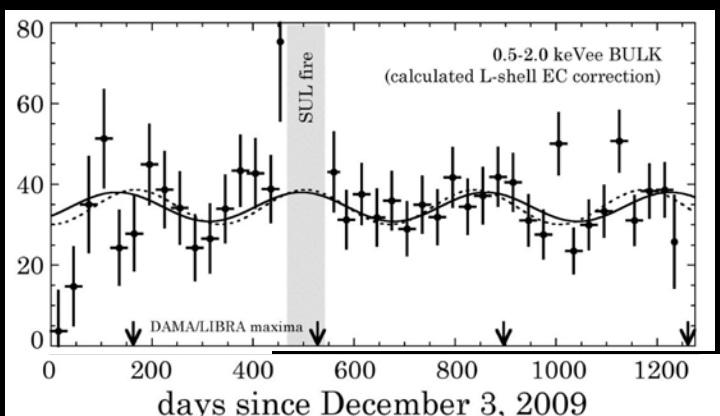


Drukier, Freese, Spergel 1986

Annually modulated.....



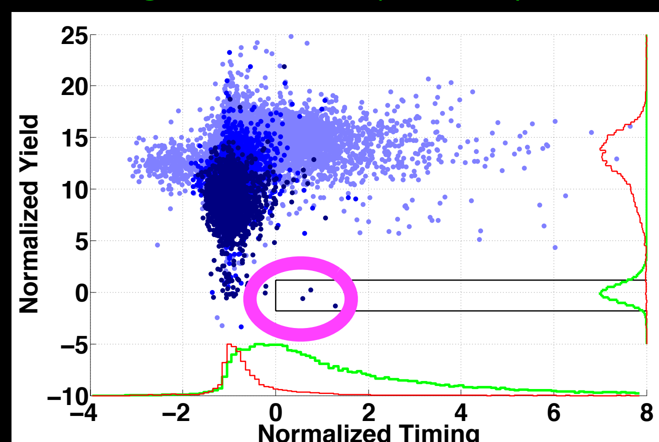
Aalseth et al (CoGeNT) 1106.0650

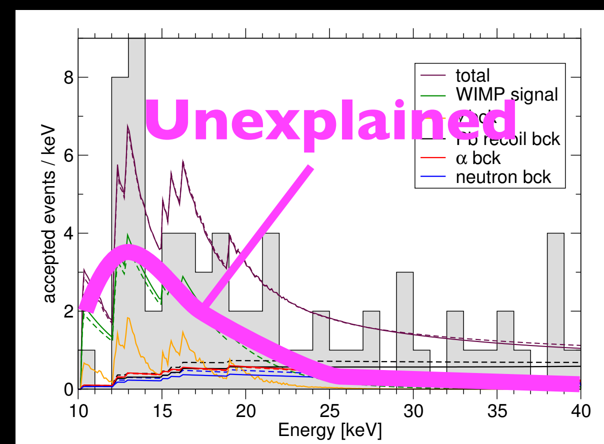


Collar (CoGeNT) 2013

......and unmodulated

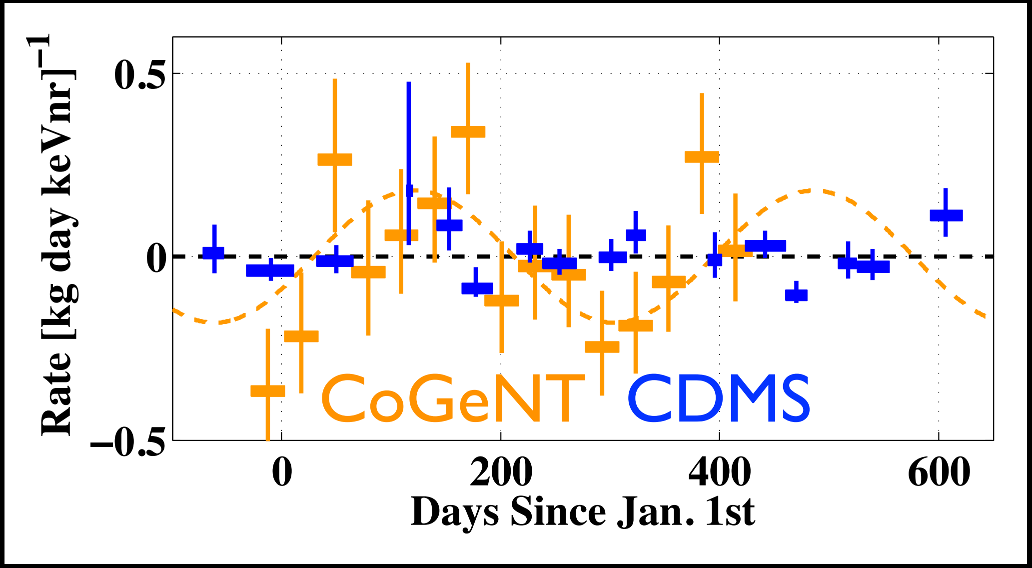
Agnese et al (CDMS) 2013





Anglehor et al (CRESST) 2011

Evidence for light dark matter particles?



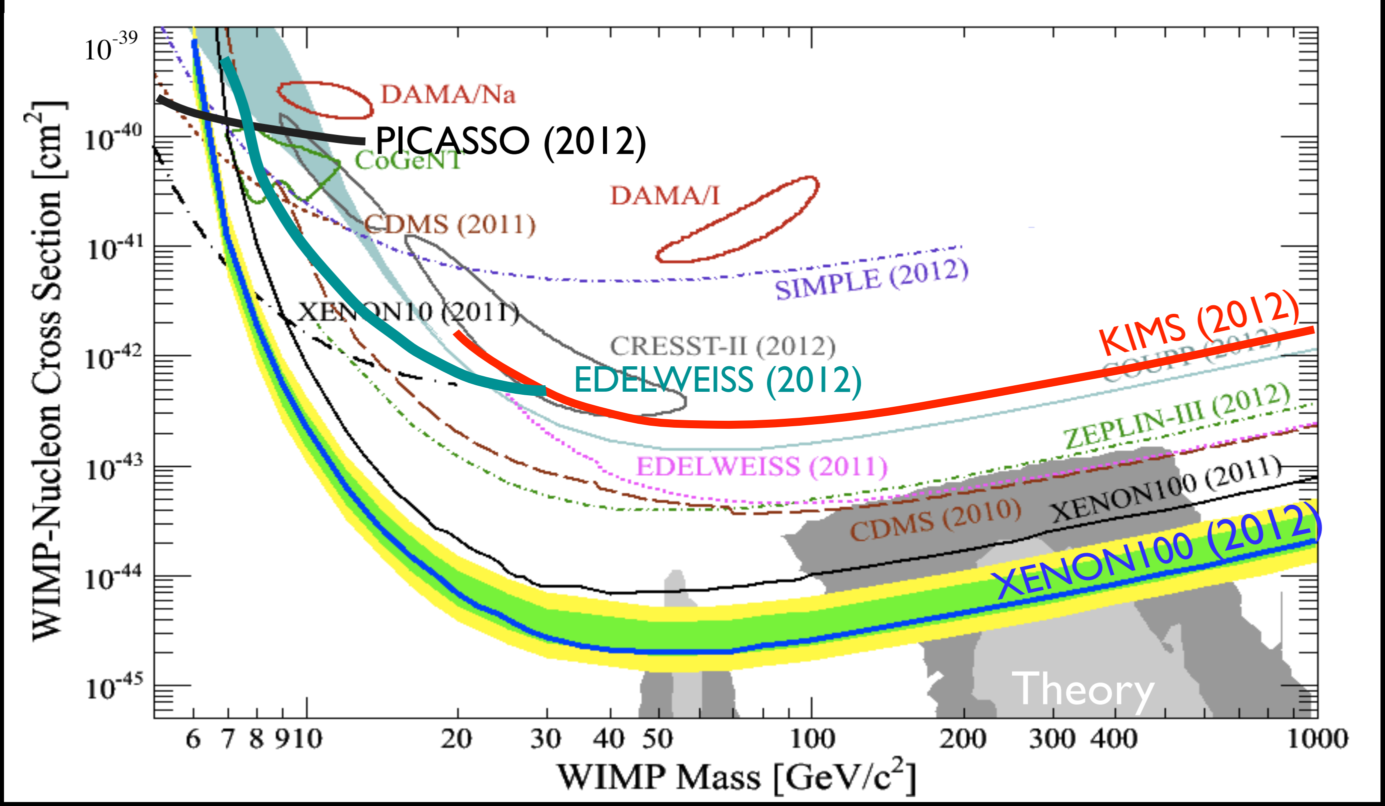
No significant modulation

Same target material

Ahmed et al (CDMS) 1203.1309

Not so many events

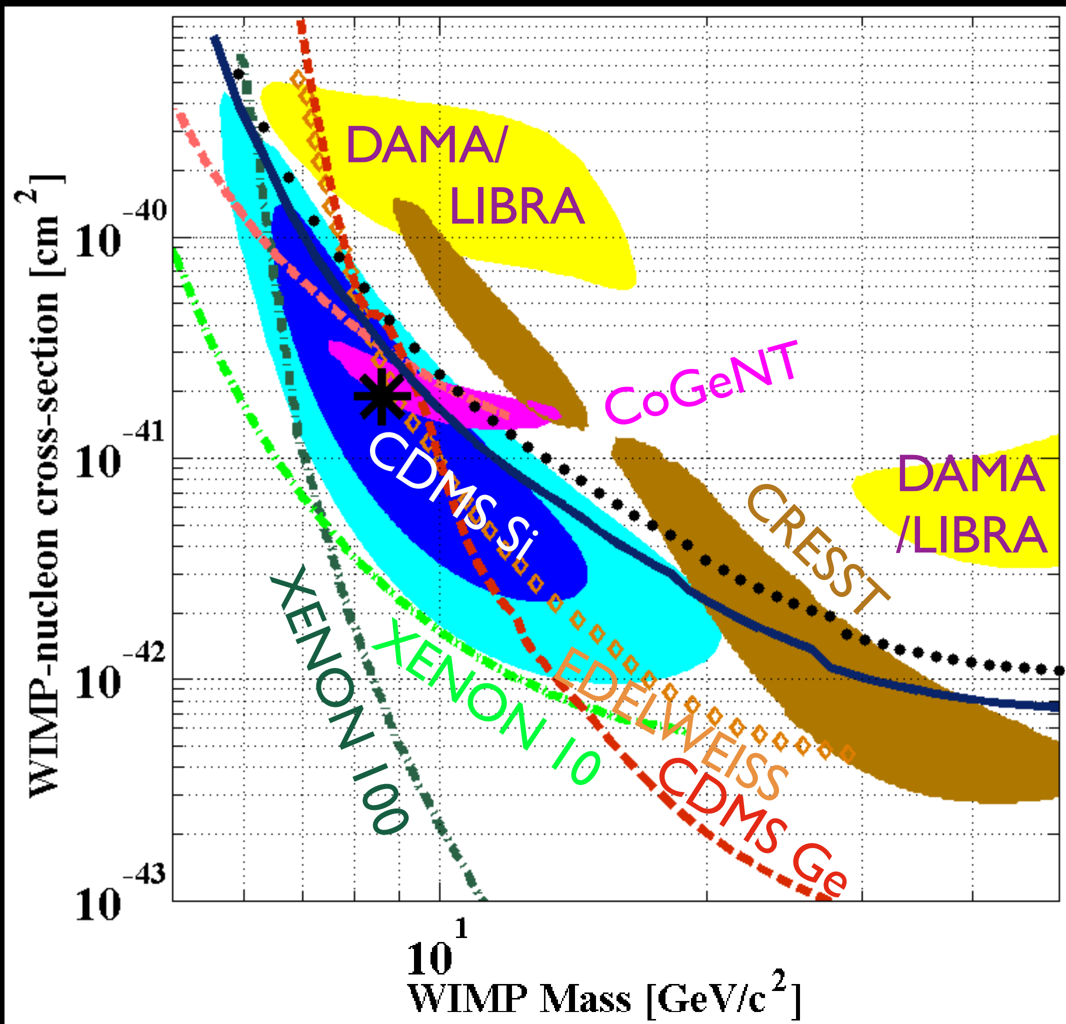
Adapted from Aprile et al (XENON-100) 2012

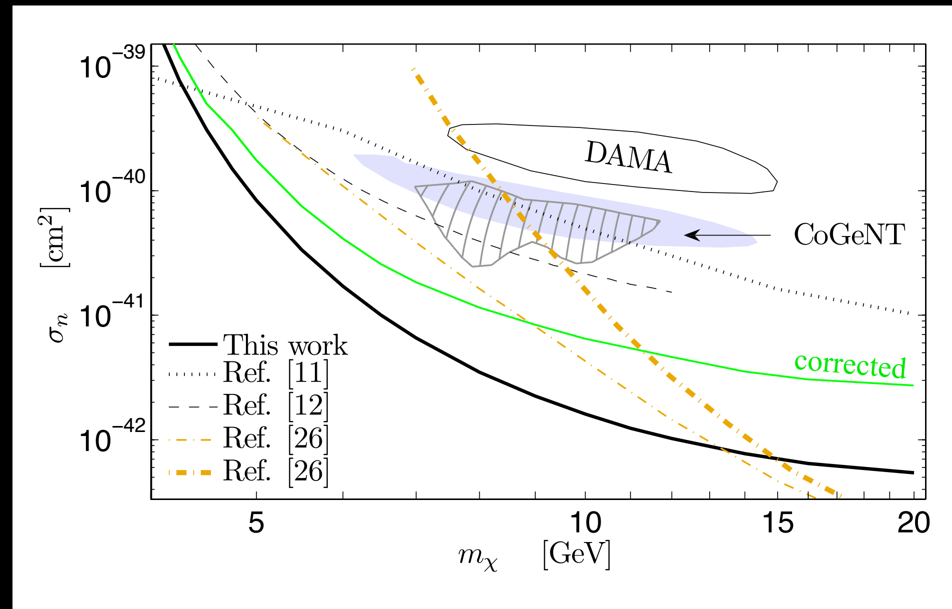


Evidence for light dark matter particles?

Angle et al (XENON10) 2013

3 events in CDMS-Si





CDMS Si (2013)
CDMS Si (all)

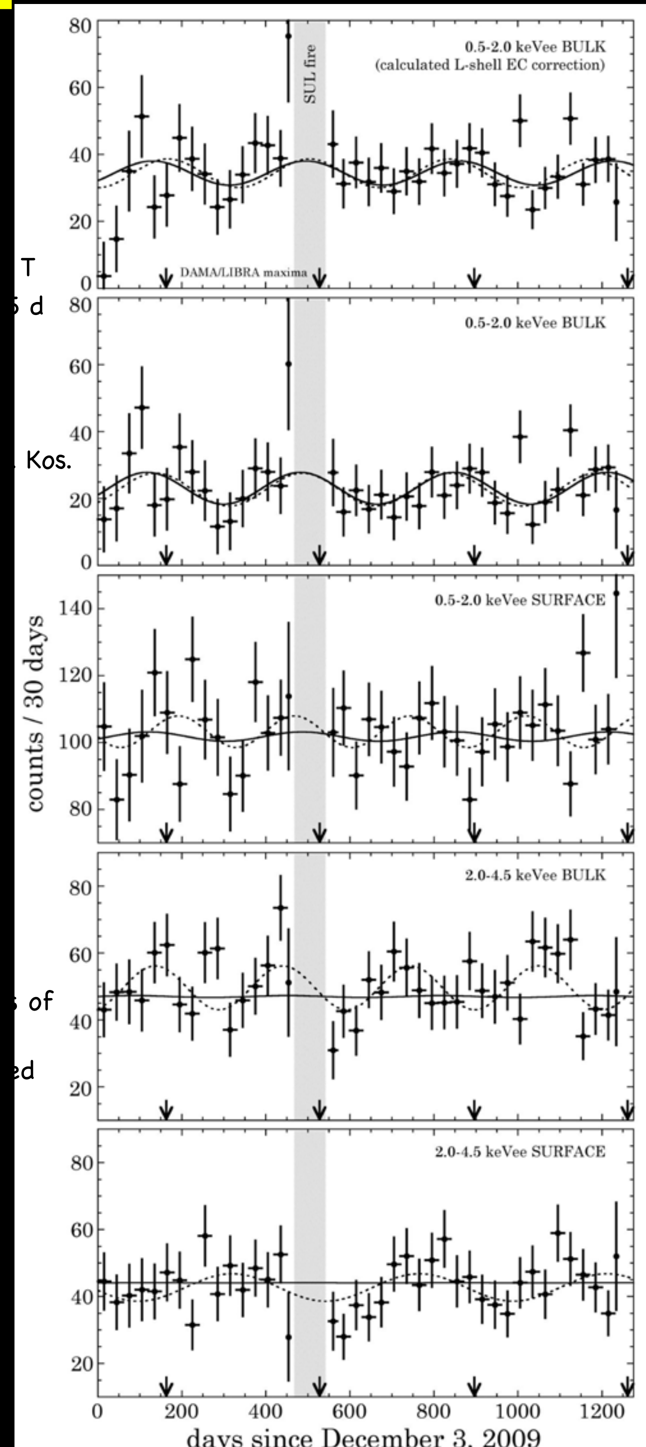
XENON10 bound weaker

Agnese et al (CDMS) 2013

Evidence for light dark matter particles?

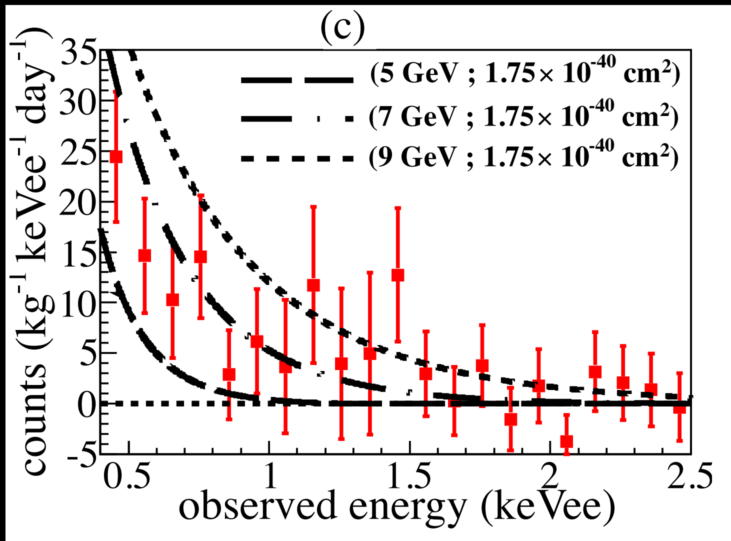
Annual modulation in 3.4 yr of CoGeNT

- Annual modulation exclusively at low energy and for bulk events.
- Best-fit phase consistent with DAMA/LIBRA
- Unoptimized frequentist analysis yields ~2.2σ preference over null hypothesis
- Modulation amplitude is 4-7 times larger than in the standard halo model

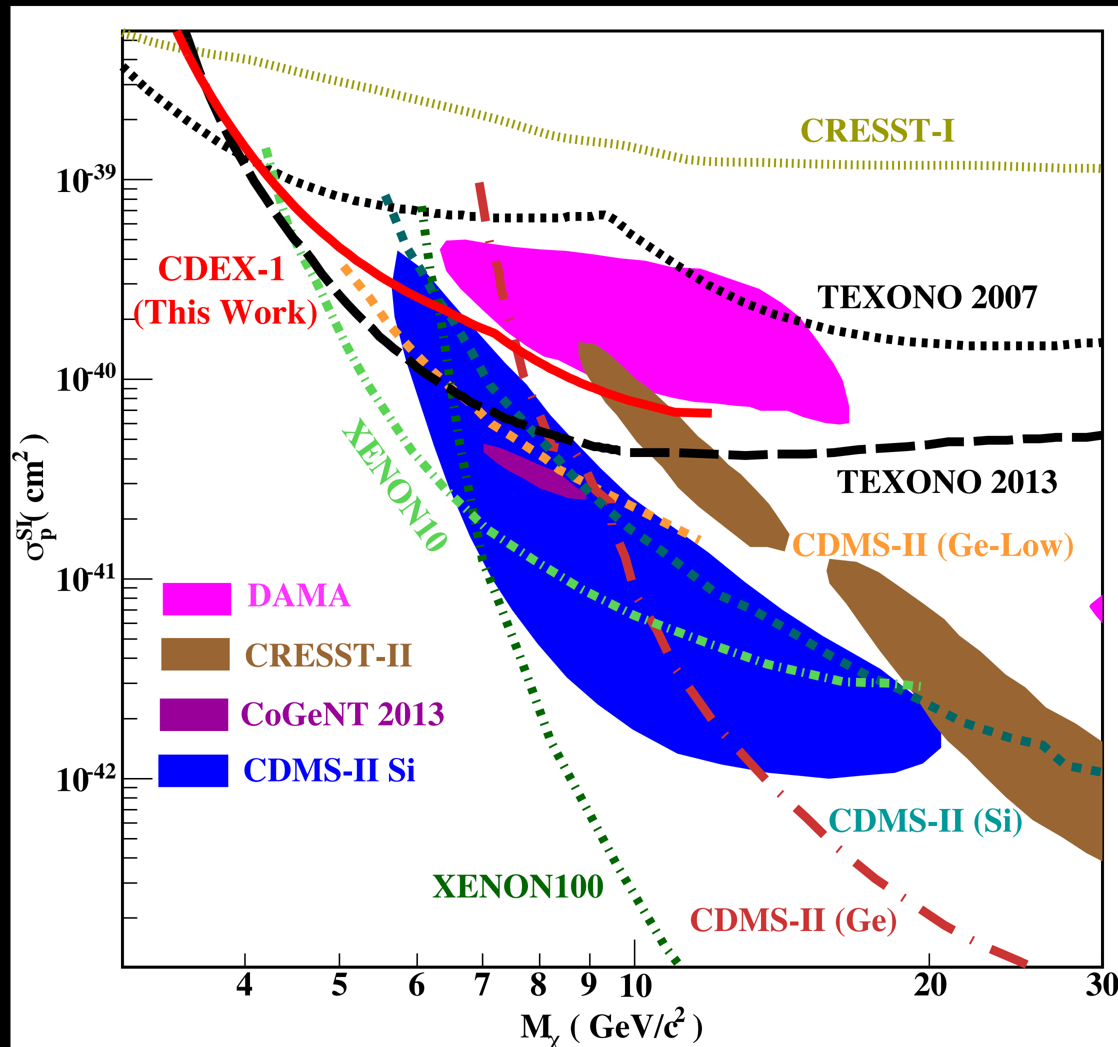


Collar (CoGeNT) at TAUP 2013

Evidence for light dark matter particles?



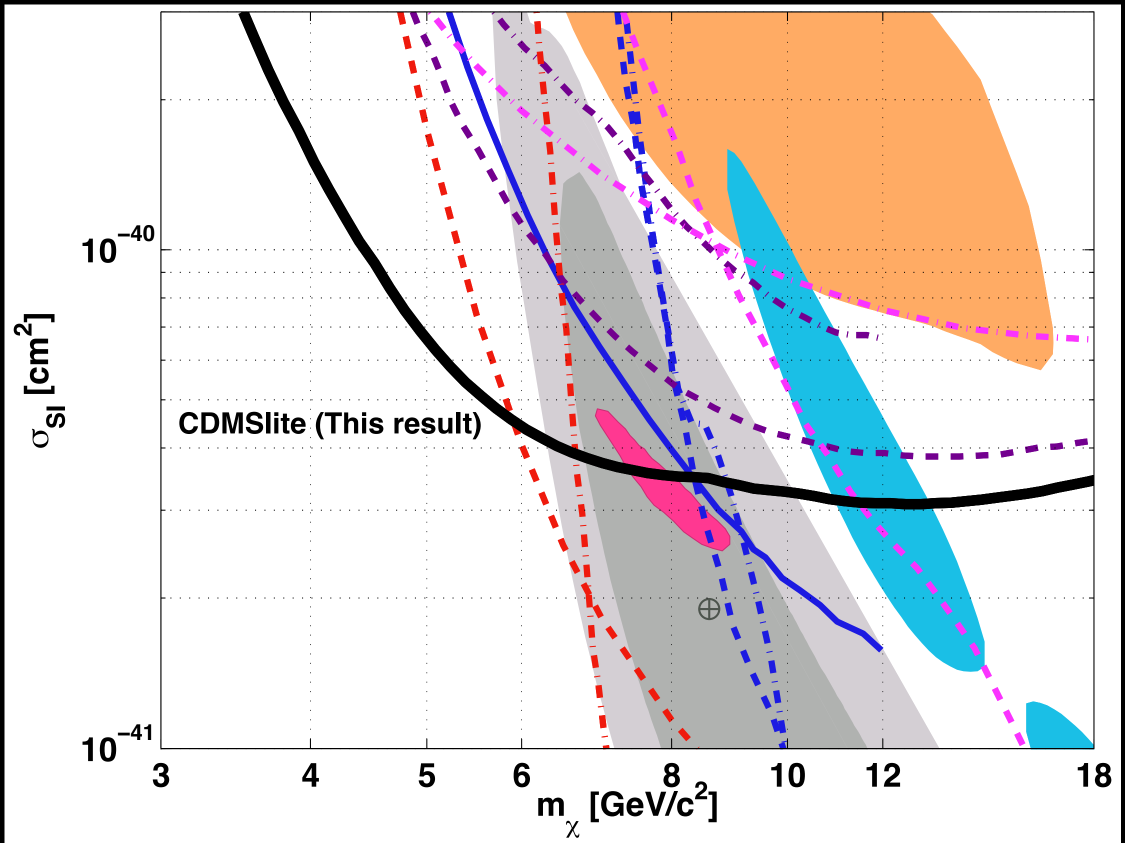
Zhao et al (CDEX) 2013

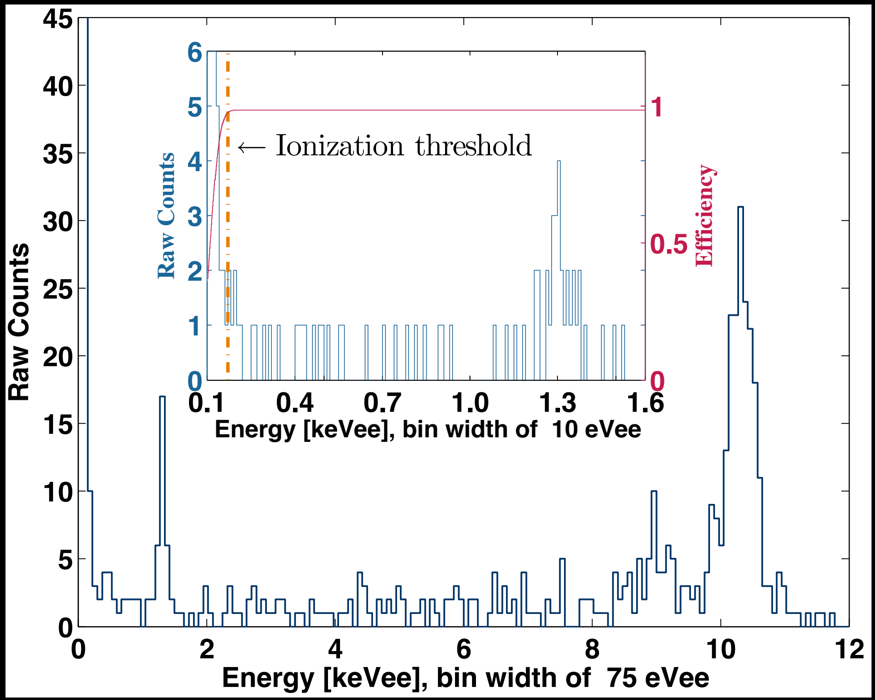


Upper bound from CDEX (same target as CoGeNT and CDMS-Ge)

Evidence for light dark matter particles?

Upper bound from CDMSlite (low ionization threshold experiment)

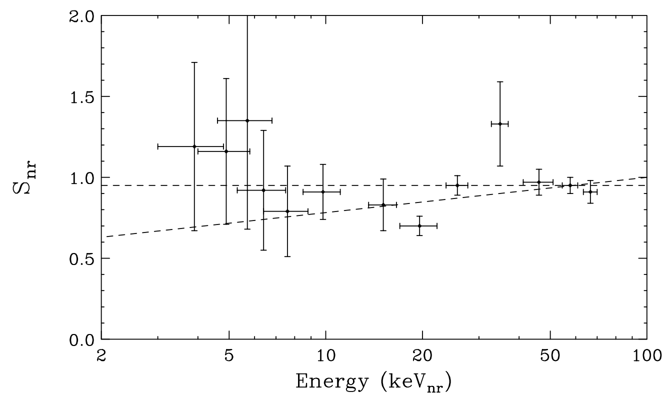




Hall at TAUP2013
Agnese et al (CDMS) 1309.3259

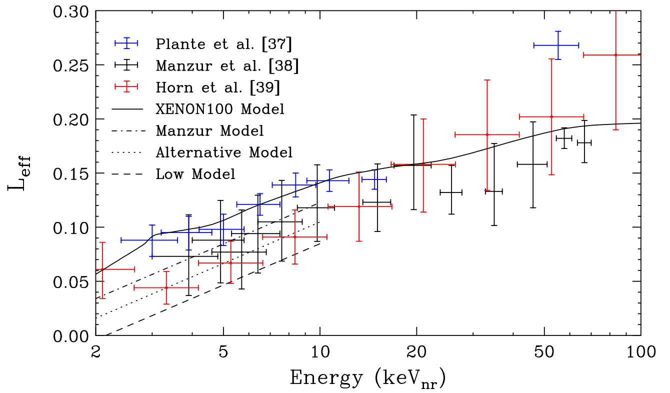
Evidence for light dark matter particles?

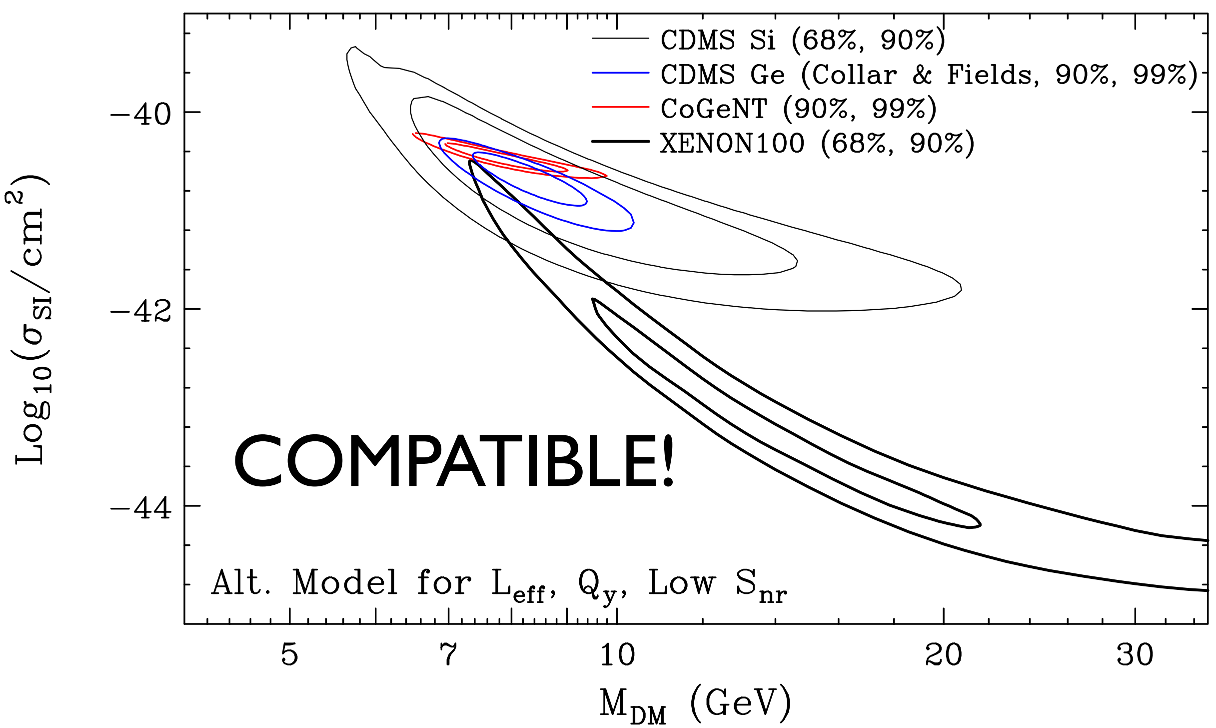
Hooper 2013



XENON100 detects events too!

Is XENON100's sensitivity overestimated?

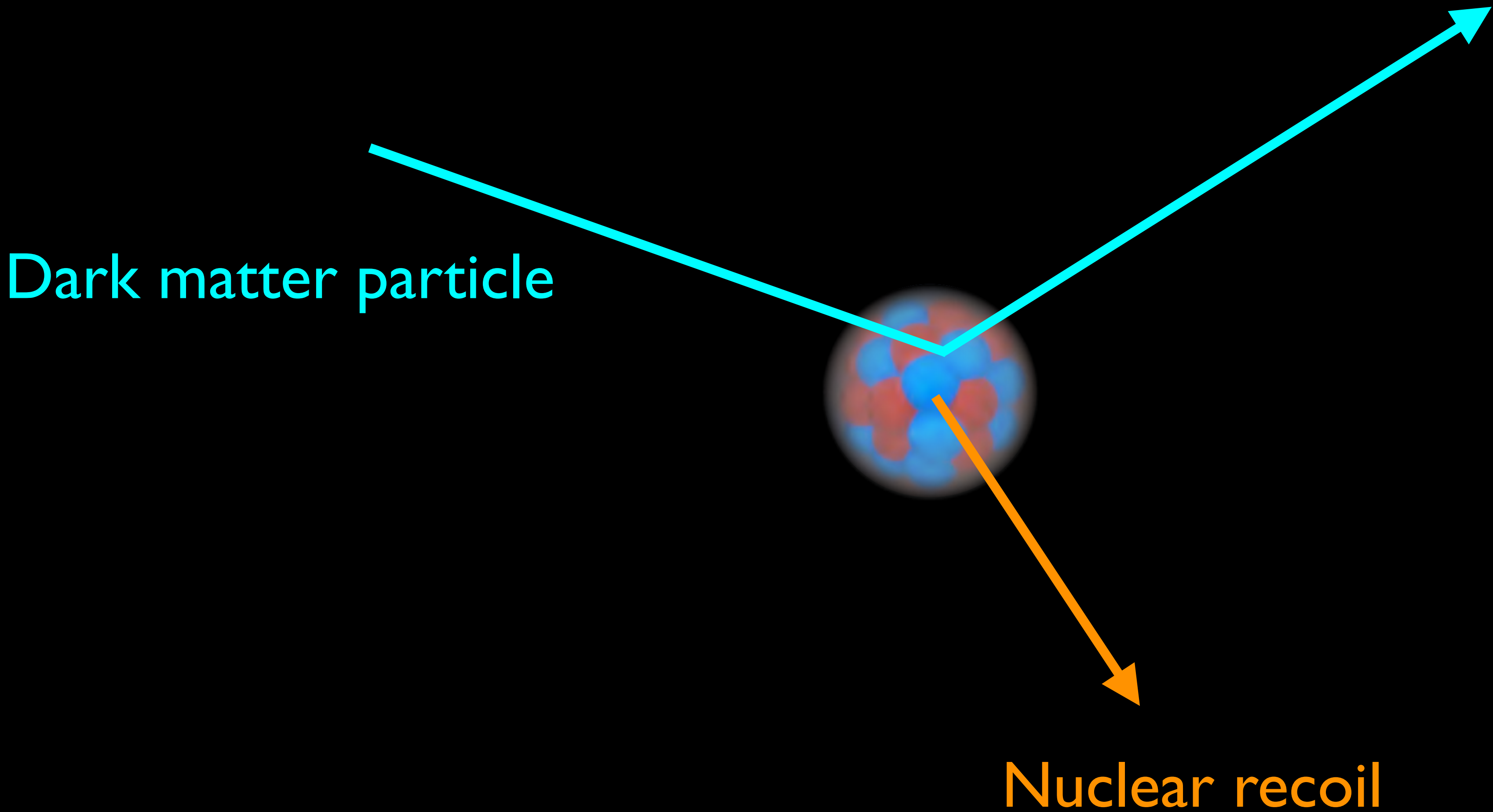




"We consider DAMA/LIBRA and CRESST-II more difficult to interpret at this time"

DM-nucleus elastic scattering

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



Particle physics model

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

Is a nuclear recoil detectable?

Counting efficiency, energy resolution, scintillation response, etc.

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

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

Particle physics model

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

What force couples dark matter to nuclei?

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

WIMP speed

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

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

WIMP mass

Nucleus recoil energy

Astrophysics model

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

How much dark matter comes to Earth?

Local halo density

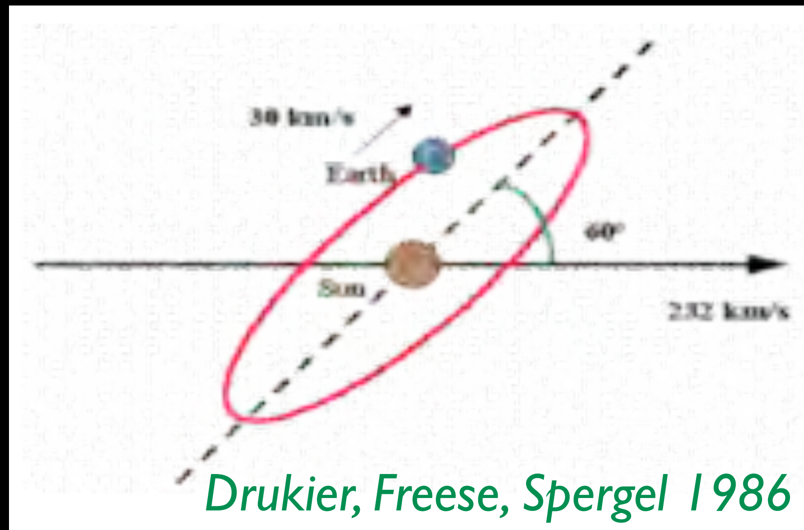
Velocity distribution

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

Minimum WIMP speed to impart recoil energy E_R

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

Annual modulation



Drukier, Freese, Spergel 1986

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

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

Unmodulated signal ($S_0(E)$)

Modulation amplitude ($S_1(E)$)

Recoil spectrum

The recoil spectrum (scattering rate per unit target mass)

$$\frac{dR}{dE_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}} v^2 \frac{d\sigma}{dE_R}\,\frac{f(\mathbf{v})}{v}\,d^3\mathbf{v}$$

Recoil spectrum

The recoil spectrum (scattering rate per unit target mass)

$$\frac{dR}{dE_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}} v^2 \frac{d\sigma}{dE_R}\frac{f(\mathbf{v})}{v}\, d^3\mathbf{v}$$

Traditionally, $v^2\, d\sigma/dE_R = \text{const} \times (\text{nuclear form factor})$, with the same coupling to protons and neutrons (spin-independent case)

$$\frac{dR}{dE_R} = \frac{A^2 F^2(E_R)}{2\mu_{\chi p}^2}\,\tilde{\eta}(v_{\min})$$

with $\tilde{\eta}(v_{\min}) = \frac{\sigma_{\chi p}}{m_\chi}\eta(v_{\min}) = \sigma_{\chi p}\frac{\rho_\chi}{m_\chi}\int_{v_{\min}}^{\infty}\frac{f(\mathbf{v})}{v}\, d^3 v$

Recoil spectrum

The recoil spectrum (scattering rate per unit target mass)

$$\frac{dR}{dE_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}} v^2 \frac{d\sigma}{dE_R}\frac{f(\mathbf{v})}{v}\, d^3\mathbf{v}$$

In trying to explain the data, modify the cross section

– set different couplings to neutrons and protons (“isospin-violating”)

– put additional velocity or energy dependence in $v^2\, d\sigma/dE_R$

or modify the velocity distribution.

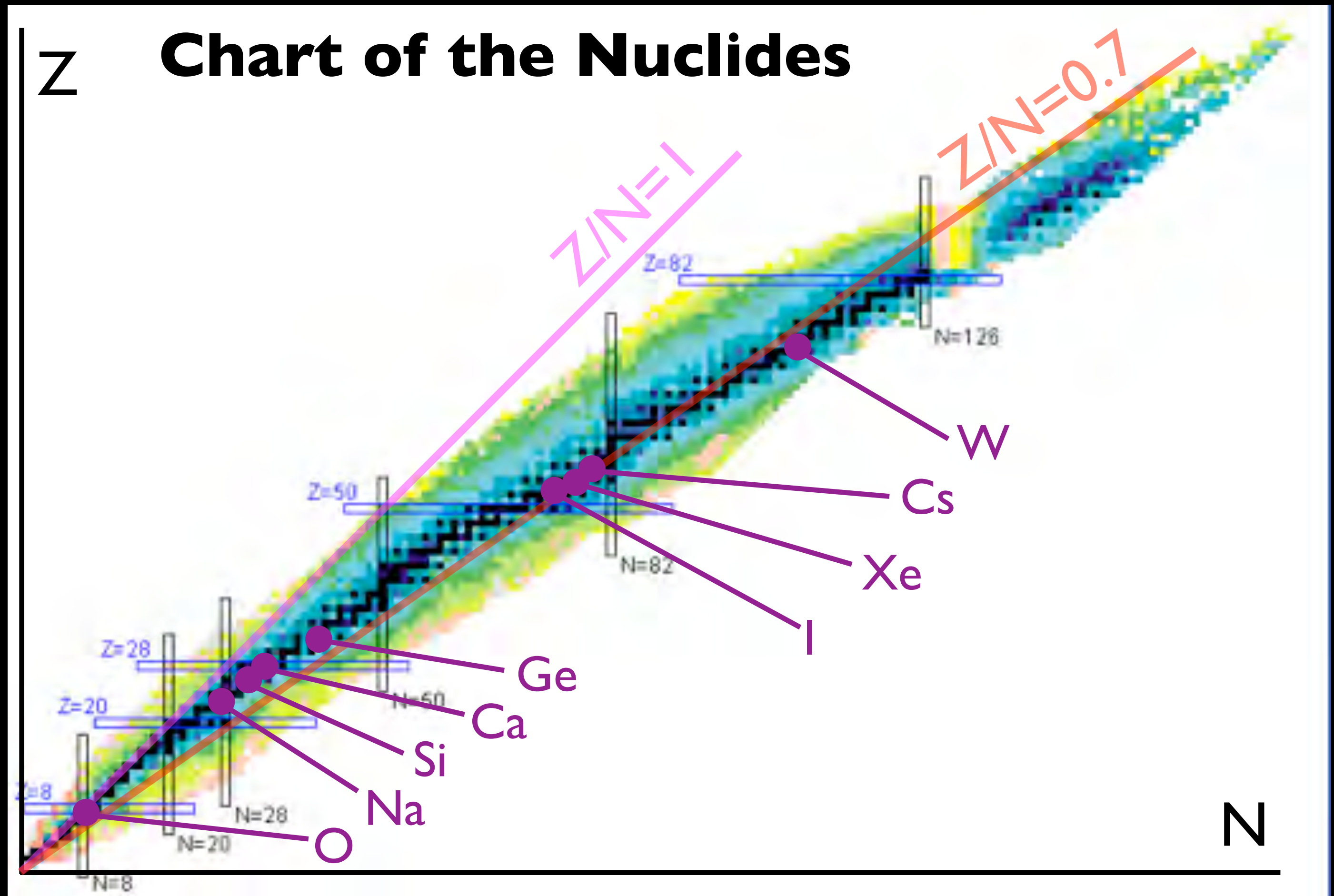
Isospin-violating dark matter

Spin-independent couplings to protons stronger than to neutrons allow modulation signals compatible with other null searches

Kurylov, Kamionkowski 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010; Feng et al 2011; Del Nobile et al 2011; .....

coupling $Nf_n + Zf_p \approx 0$ for $f_n/f_p \approx -Z/N$

Why f_n/f_p=-0.7 suppresses the coupling to Xe



Particle physics model

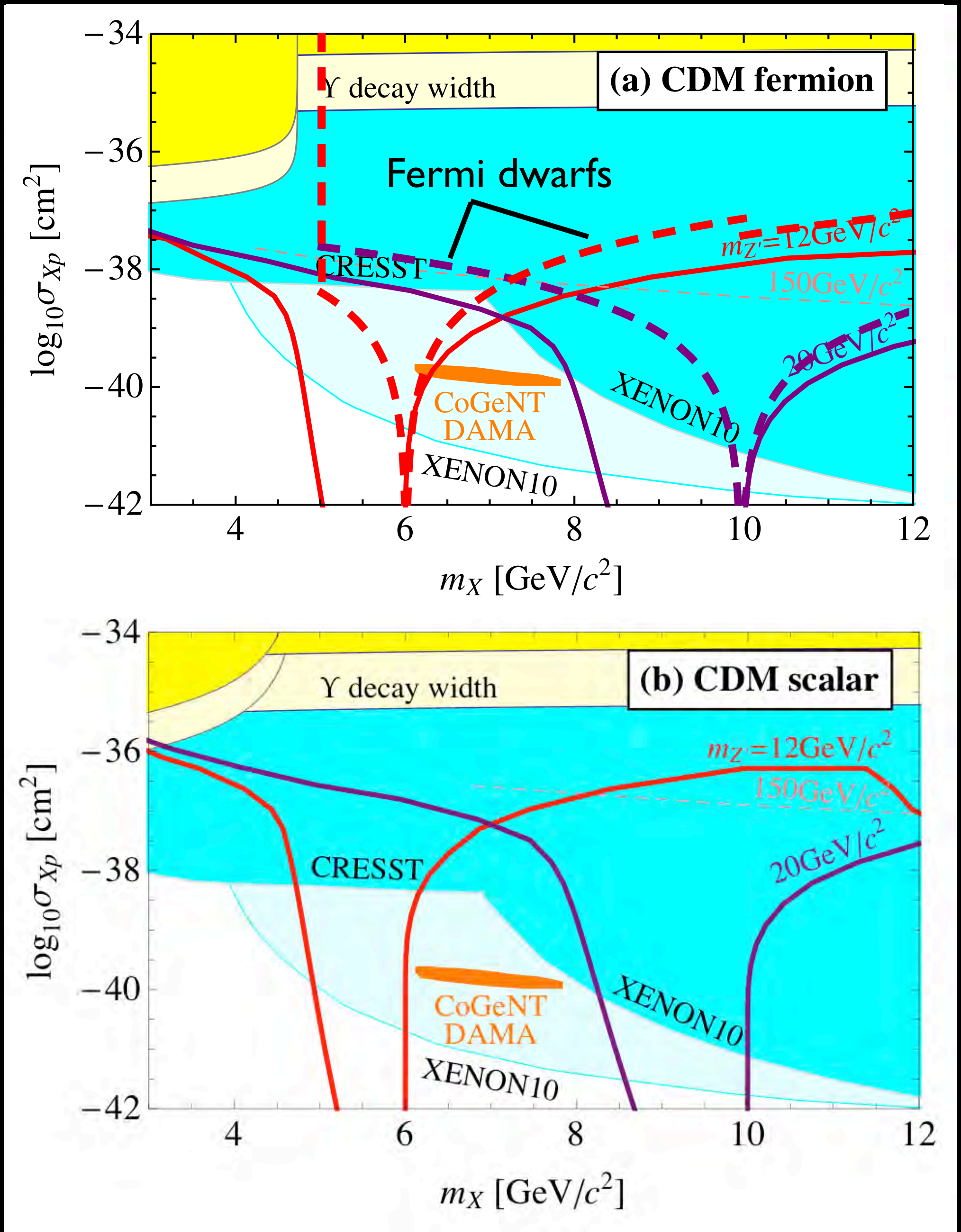
Energy and/or velocity dependent scattering cross sections

nucleus	DM	$v^2\, d\sigma/dE_R$	
		light mediator	heavy mediator
"charge"	*"charge"*	$1/E_R^2$	$1/M^4$
"charge"	*dipole*	$1/E_R$	E_R/M^4
dipole	*dipole*	$\text{const} + E_R/v^2$	E_R^2/M^4

All terms may be multiplied by nuclear or DM form factors $F(E_R)$

See e.g. Barger, Keung, Marfatia 2010; Fornengo, Panci, Regis 2011; An et al 2011

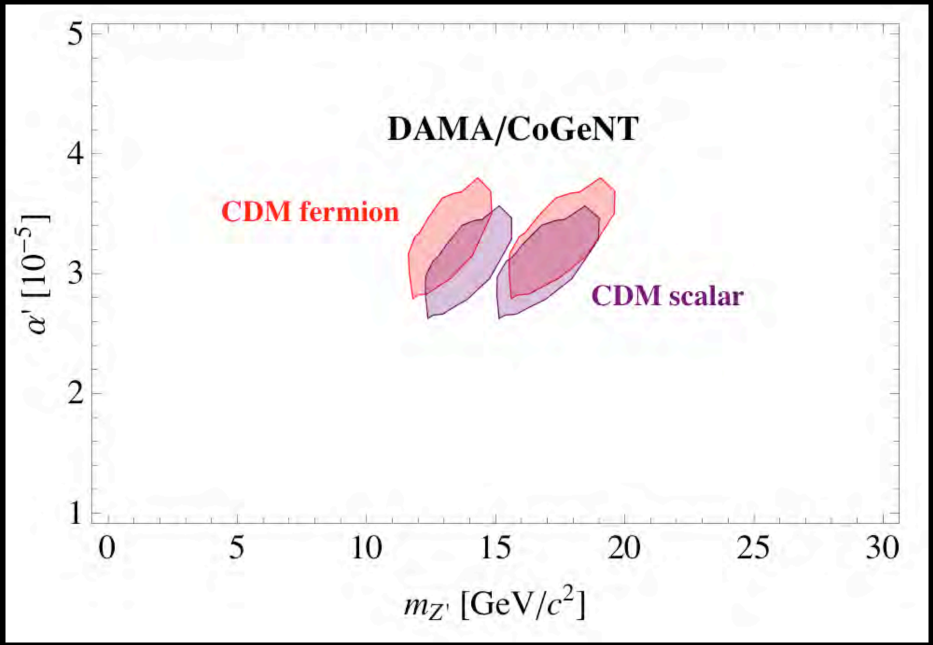
Light WIMPs with light Z′ boson



Example: Leptophobic Z’

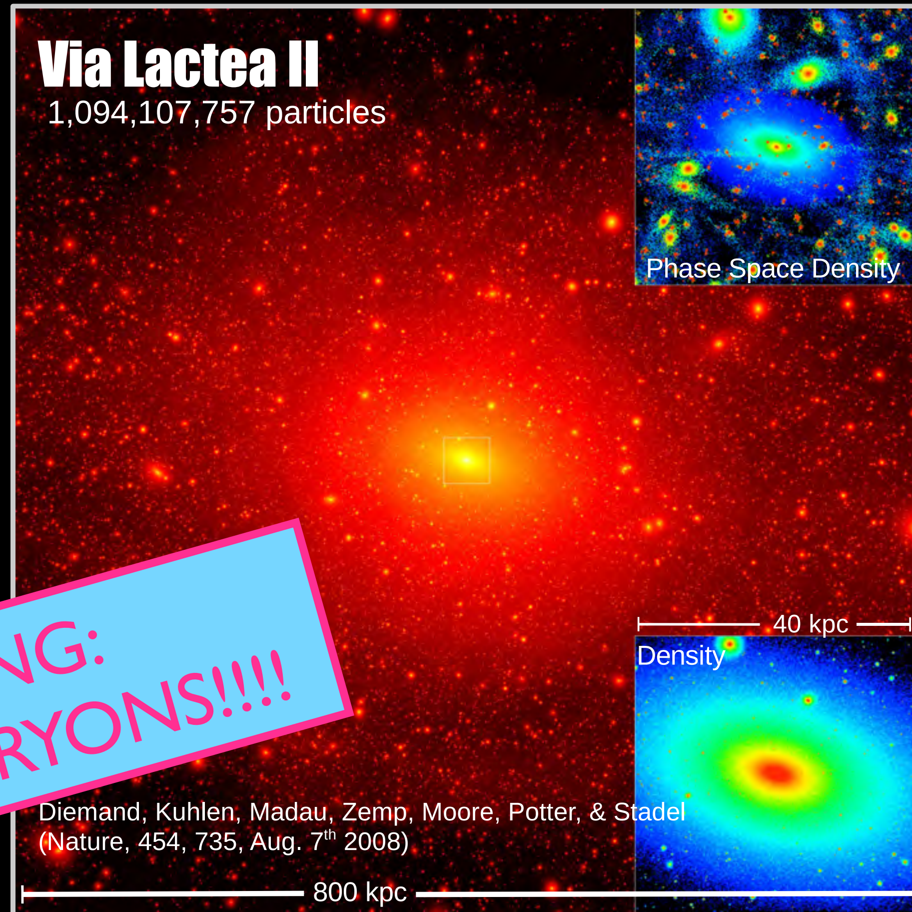
- An extra U(1) gauge boson Z’ coupled to quarks but no leptons, with no significant kinetic mixing
- Works for $m_{Z'}$~10-20 GeV and α’~10^{-5}

Gondolo, Ko, Omura 2011



Astrophysics model: velocity distribution

We know very little about the dark matter velocity distribution



WARNING:
NO BARYONS!!!!

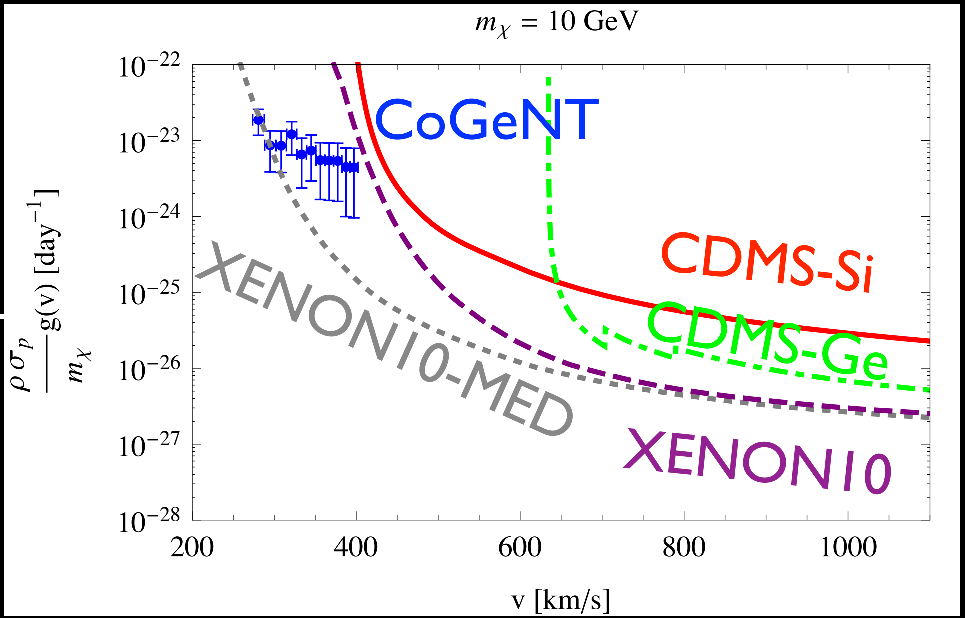
Cosmological N-Body simulations including baryons are challenging

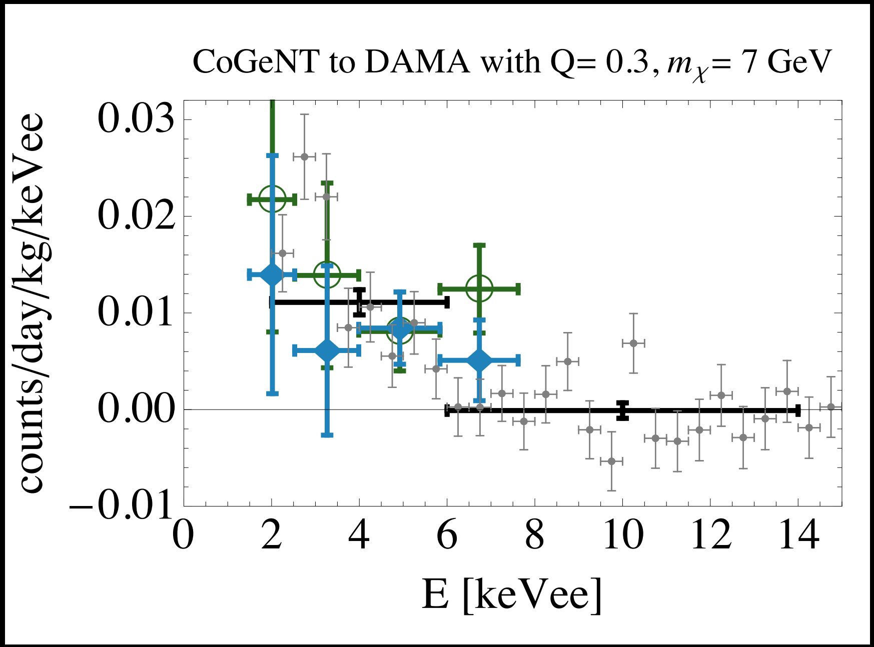
Astrophysics-independent approach

Fox, Liu, Weiner 2011

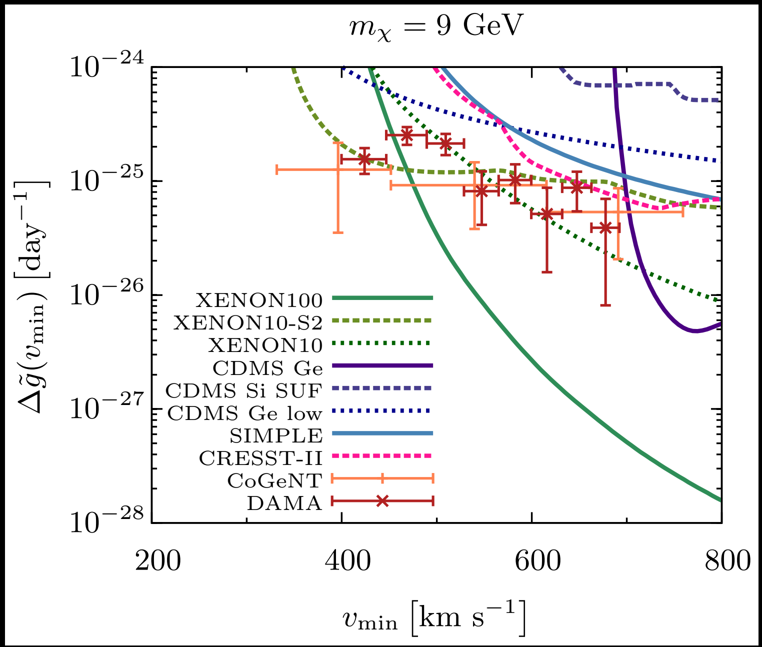
Rescaled astrophysics factor

$$\frac{\rho_\chi \sigma_{\chi p}}{m_\chi} \int_{v_{\min}}^{\infty} \frac{f(\mathbf{v})}{v} dv$$





Fox, Kopp, Lisanti, Weiner 2011

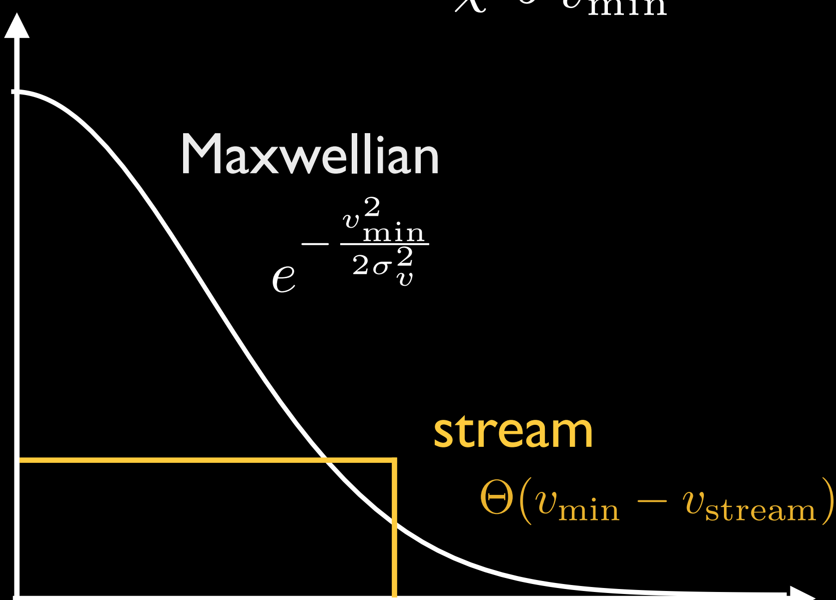


Frandsen et al 2011

Astrophysics-independent approach

Rescaled astrophysics factor common to all experiments

$$\tilde{\eta}(v_{\rm min}) = \sigma_{\chi p} \frac{\rho_\chi}{m_\chi} \int_{v_{\rm min}}^{\infty} \frac{f(\mathbf{v})}{v} \, d^3 v$$



Minimum WIMP speed to impart recoil energy E_R

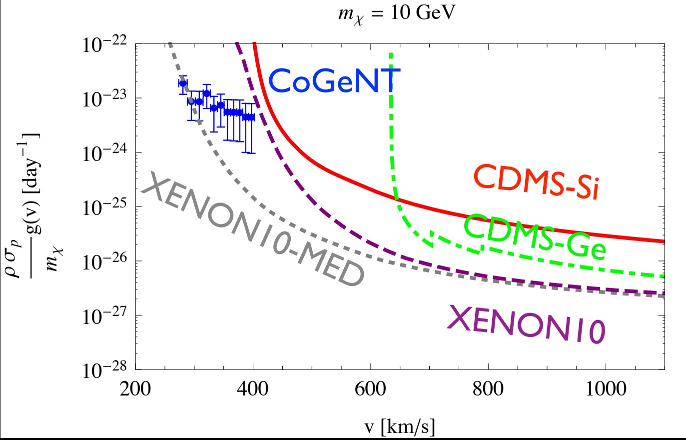
$$v_{\rm min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}}$$

Recoil energy

Astrophysics-independent approach

Extract $\tilde{\eta}(v_{\rm min})$ from dR/dE_R (both measurements and upper limits).

Fox, Liu, Weiner 2011



$$\tilde{\eta}(v_{\rm min}) = \frac{2\mu_{\chi p}^2}{A^2 F^2(E_R)} \frac{dR}{dE_R}$$

Alternative approach: solve the recoil rate equation for $f(\mathbf{v})$

Fox, Kribs, Tait 2010

$$\frac{dR}{dE_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\rm min}} v^2 \frac{d\sigma}{dE_R}\frac{f(\mathbf{v})}{v}\, d^3\mathbf{v}$$

Requires derivatives of experimentally measured dR/dE_R, which is a notoriously unstable procedure.

Astrophysics-independent approach

All these ideas refer to the recoil spectrum dR/dE_R, which is not accessible to experiments because of energy-dependent efficiencies and energy resolution, and the fact that often only part of the recoil energy is actually measured.

$$\frac{dR}{dE} = \int_0^\infty \mathcal{G}(E, E_R)\, \frac{dR}{dE_R}\, dE_R$$

Measured energy | *Effective energy response function* | *Recoil energy*

Use quantities accessible to experiments, i.e., include effective energy response function.

Gondolo Gelmini 1202.6359

Astrophysics-independent approach

Include effective energy response function.

Gondolo Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo, Huh 1304.6183,1306.5273

Change variables:

Constant reference cross section

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}} \qquad \tilde{\eta}(v_{\min}) = \sigma_{\text{ref}} \frac{\rho_\chi}{m_\chi} \int_{v_{\min}}^{\infty} \frac{f(\mathbf{v})}{v} d^3v$$

Minimum WIMP speed to impart recoil energy E_R

Astrophysics factor, same for all direct detection experiments

And integrate over measured energy intervals:

$$R_{[E_1,E_2]} = \int_{E_1}^{E_2} dE \frac{dR}{dE}$$

Astrophysics-independent approach

Include effective energy response function.

Gondolo Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo, Huh 1304.6183,1306.5273

- The measured rate is a "weighted average" of the astrophysical factor.

Measured rate — *Rescaled astrophysics factor* — *Response function*

$$R = \int_0^\infty dv\, \mathcal{R}(v)\, \tilde{\eta}(v)$$

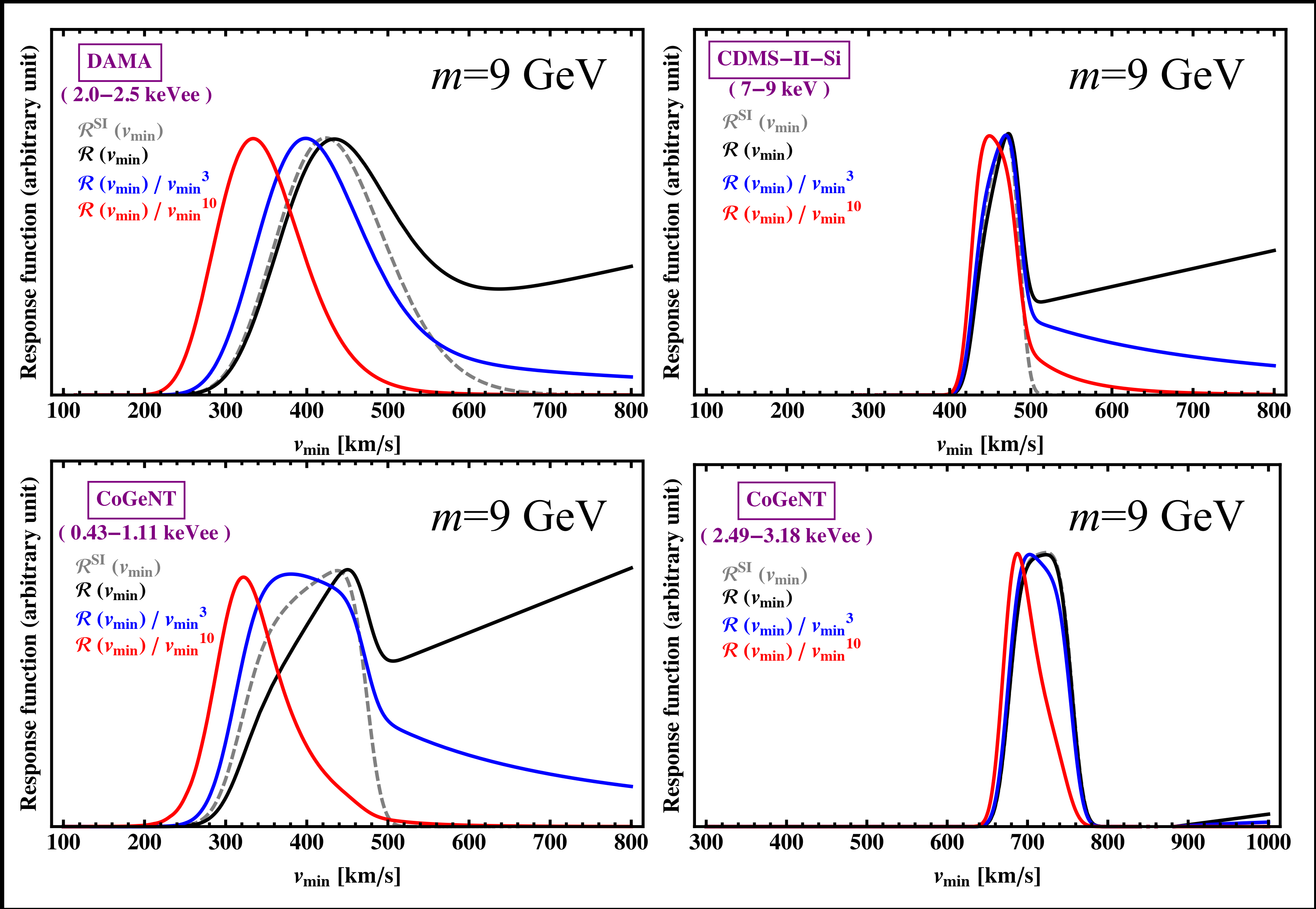
- Every experiment is sensitive to a "window in velocity space" given by the response function.

$$\mathcal{R}_{[E_1,E_2]}(v) = \int_{E_1}^{E_2} dE\, \frac{\partial}{\partial v} \int_0^{2\mu_T^2 v^2/m_T} dE_R\, \mathcal{G}(E, E_R)\, \frac{v^2}{\sigma_{\rm ref} m_T} \frac{d\sigma}{dE_R}$$

Astrophysics-independent approach

Examples of response functions

Del Nobile, Gelmini, Gondolo, Huh 2013



Astrophysics-independent approach

Include effective energy response function.

Gondolo Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo, Huh 1304.6183,1306.5273

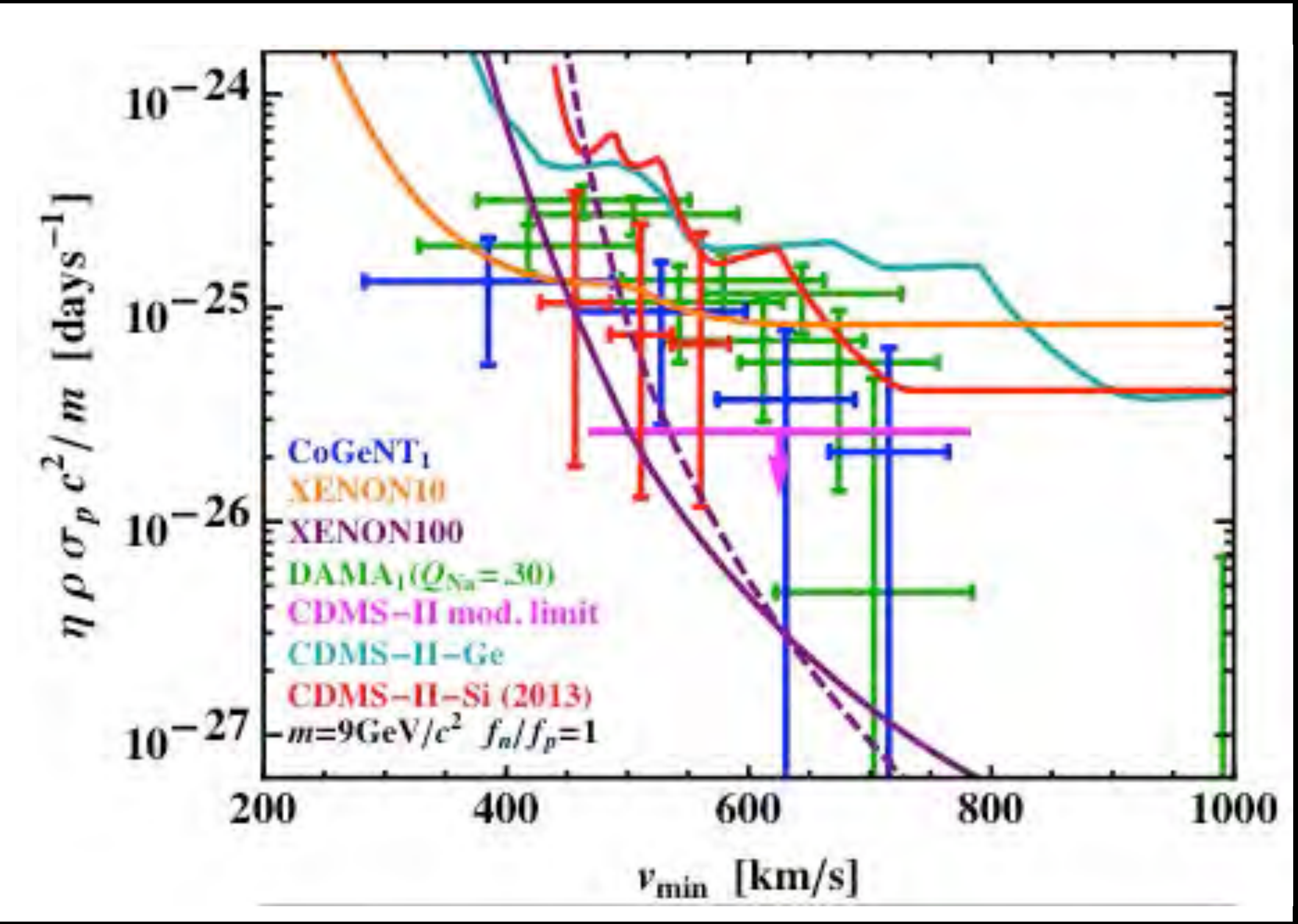
Measure or bound astrophysics factor in velocity interval $[v_1, v_2]$

$$\bar{\tilde{\eta}}_{[v_1,v_2]} = \frac{R^{\text{measured}}_{[E_1,E_2]}}{\int_0^\infty \mathcal{R}_{[E_1,E_2]}(v_{\text{min}})\, dv_{\text{min}}}$$

$$\tilde{\eta}(v) < \frac{R^{\text{upper limit}}_{[E_1,E_2]}}{\int_0^v \mathcal{R}_{[E_1,E_2]}(v_{\text{min}})\, dv_{\text{min}}}$$

Astrophysics-independent approach

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



Del Nobile, Gelmini, Gondolo, Huh 2013

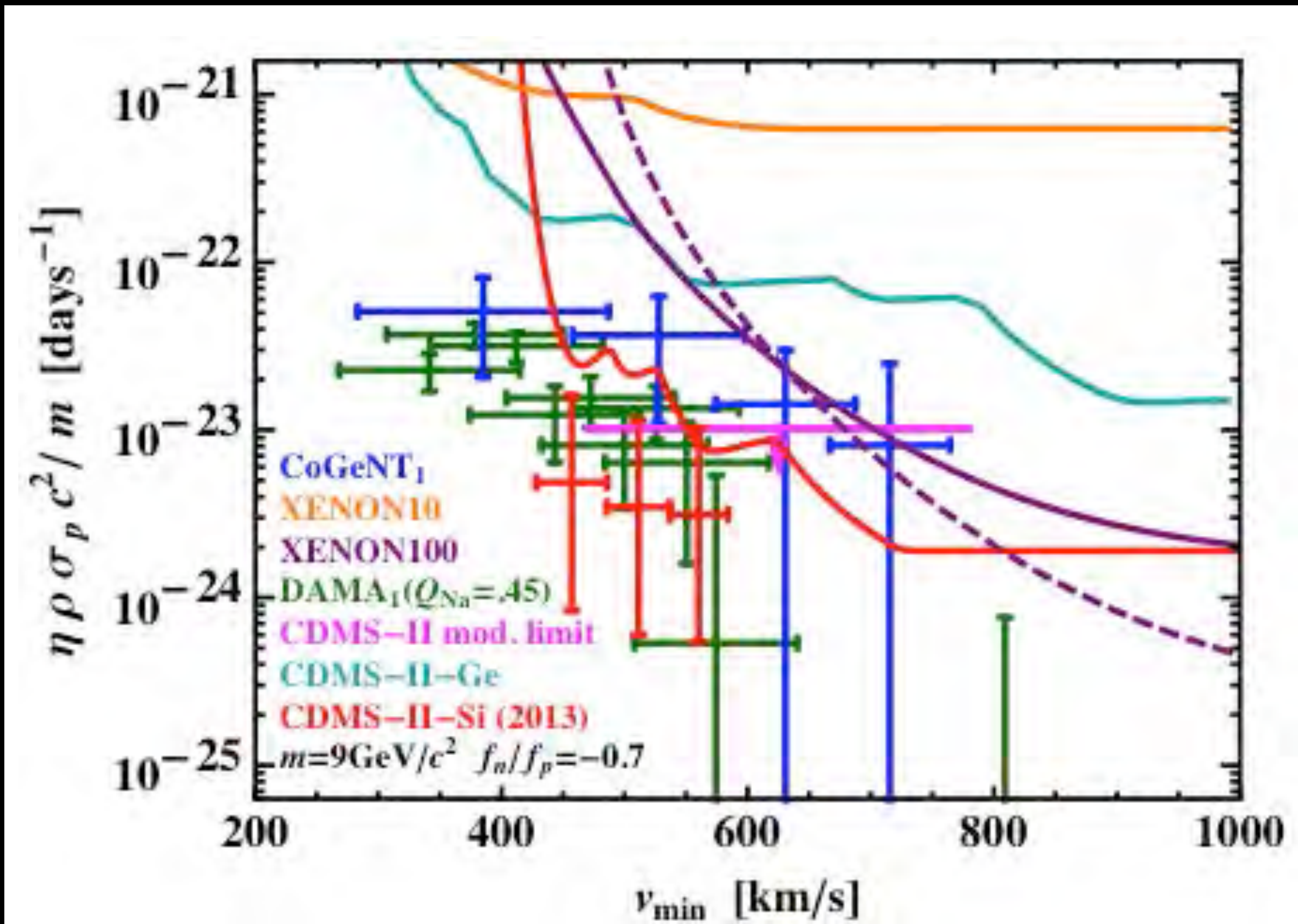
Halo modifications alone cannot save the SI signal regions from the Xe bounds

CDMS-Si event rate is similar to annual modulated rates

Still depends on particle model

Astrophysics-independent approach

Isospin-violating dark matter



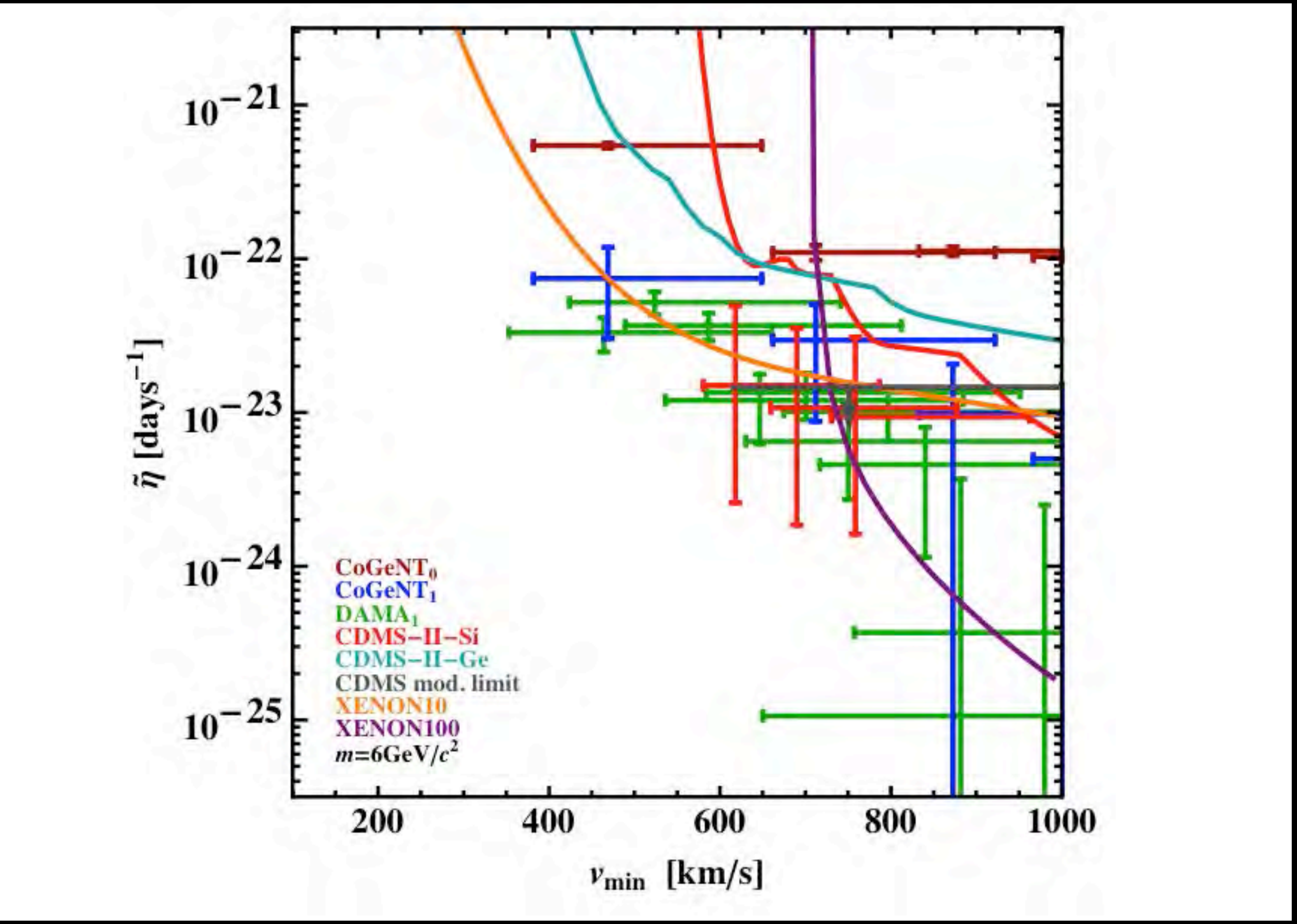
Dark matter coupled differently to protons and neutrons may have a chance

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

Del Nobile, Gelmini, Gondolo, Huh 2013

Astrophysics-independent approach

Anomalous magnetic moment dark matter



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

CDMS-Si event rate is similar to yearly modulated rates

Del Nobile, Gelmini, Gondolo, Huh 2013

Still depends on particle model

Summary

- The thermal WIMP hypothesis is under strong scrutiny, especially at masses ~10 GeV (light dark matter).
- Controversial evidence for direct detection of light dark matter particles (maybe be backgrounds).
  - Halo-independent analyses show that recent CDMS-Si events occur at a rate smaller than the CoGeNT/DAMA modulation amplitudes.
- LHC and indirect searches (γ, CMB, e^+) place strong contraints on models of thermal WIMPs.
  - Light supersymmetric particles may still be possible beyond the MSSM. Non-supersymmetric models include minimalist dark matter (>60 GeV), and dark matter coupled to leptophobic light Z' bosons (~10 GeV).