WIMP Dark Matter

&

Halo-Independent Analysis of Direct Detection Data

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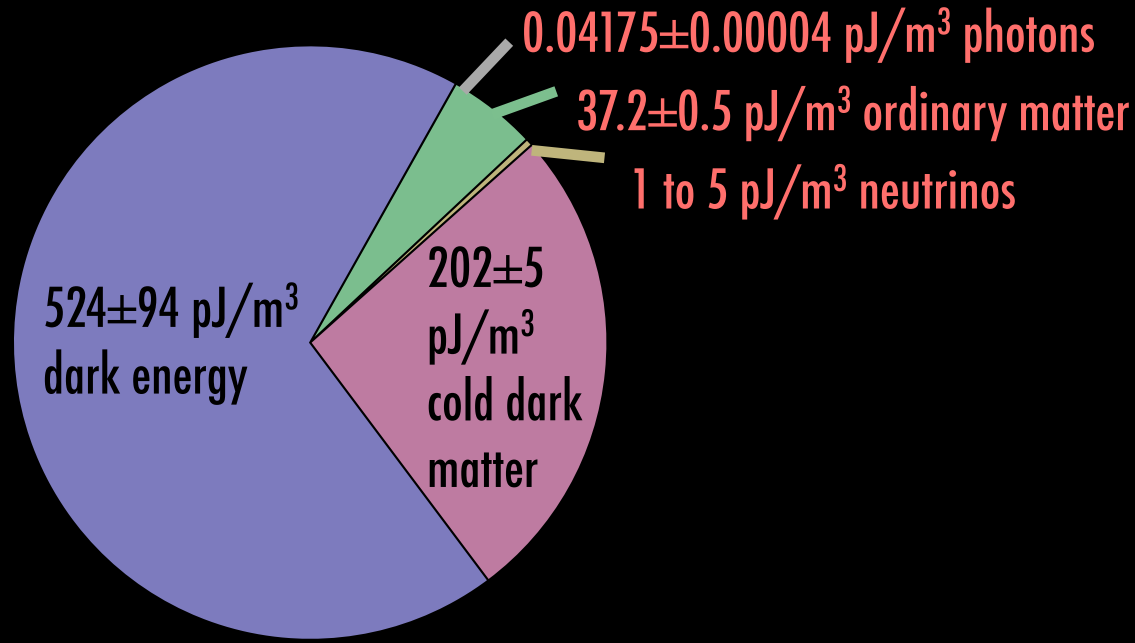
University of Utah

The Magnificent WIMP
(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

    Thermal production in hot primordial plasma.



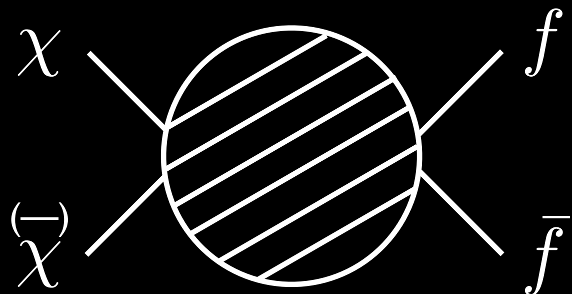
- One can experimentally test the WIMP hypothesis

    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*].

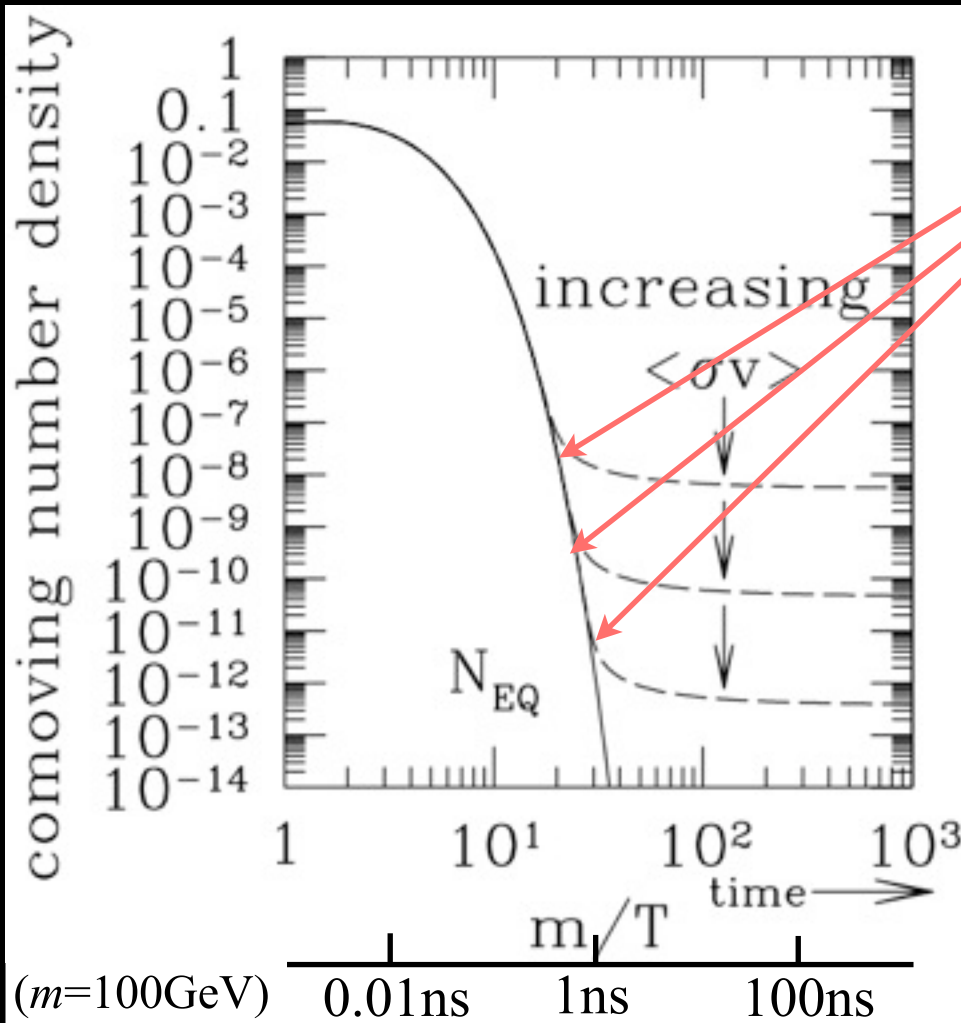
$$e^+ + e^-, \mu^+ + \mu^-, \text{etc.} \leftrightarrow \chi + \overset{(-)}{\chi}$$



- 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*

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

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

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

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

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

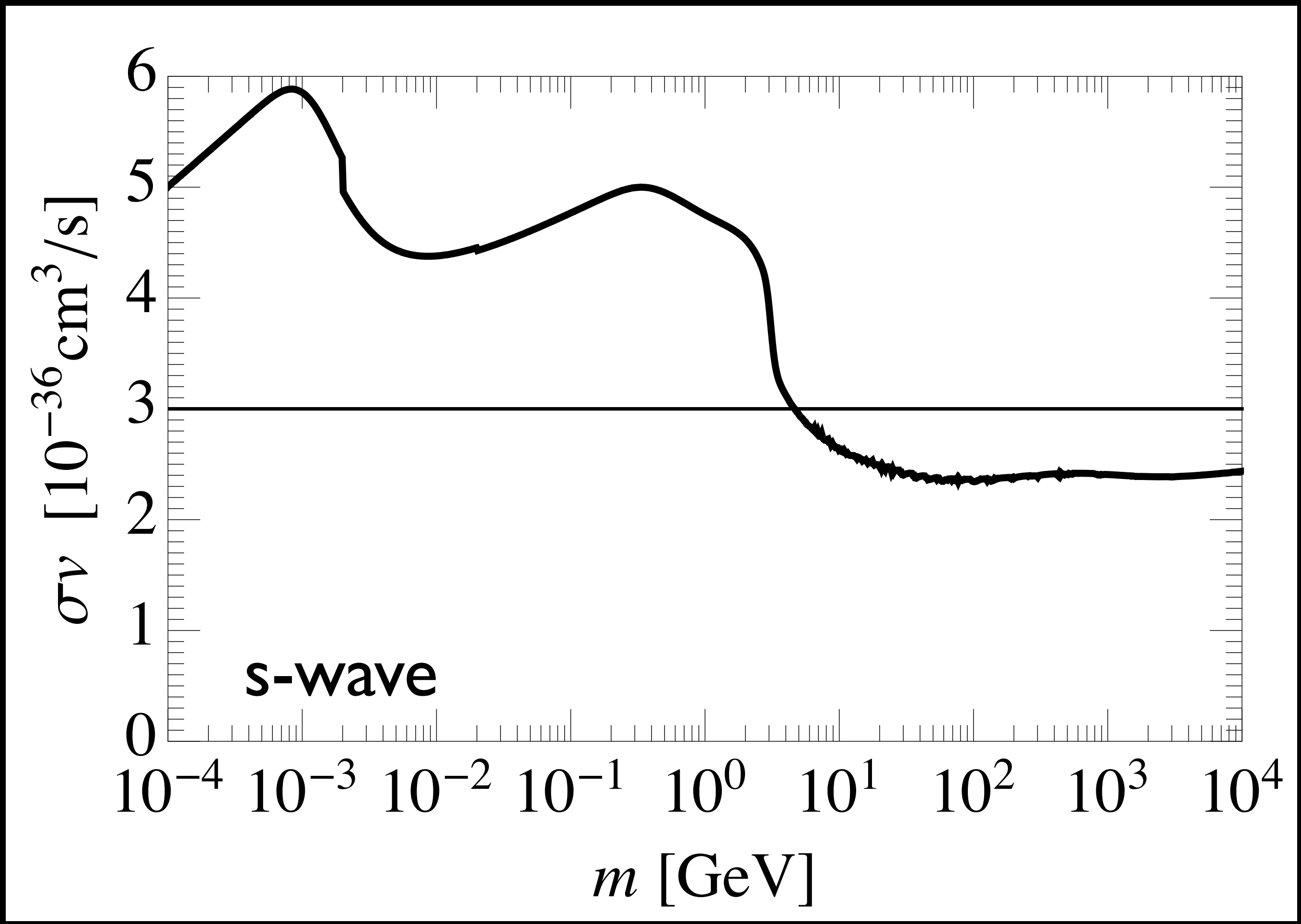
$$\langle \sigma v \rangle = a + b v^2 + \cdots \qquad \text{s-wave}$$

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

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

Cosmic density of thermal WIMPs

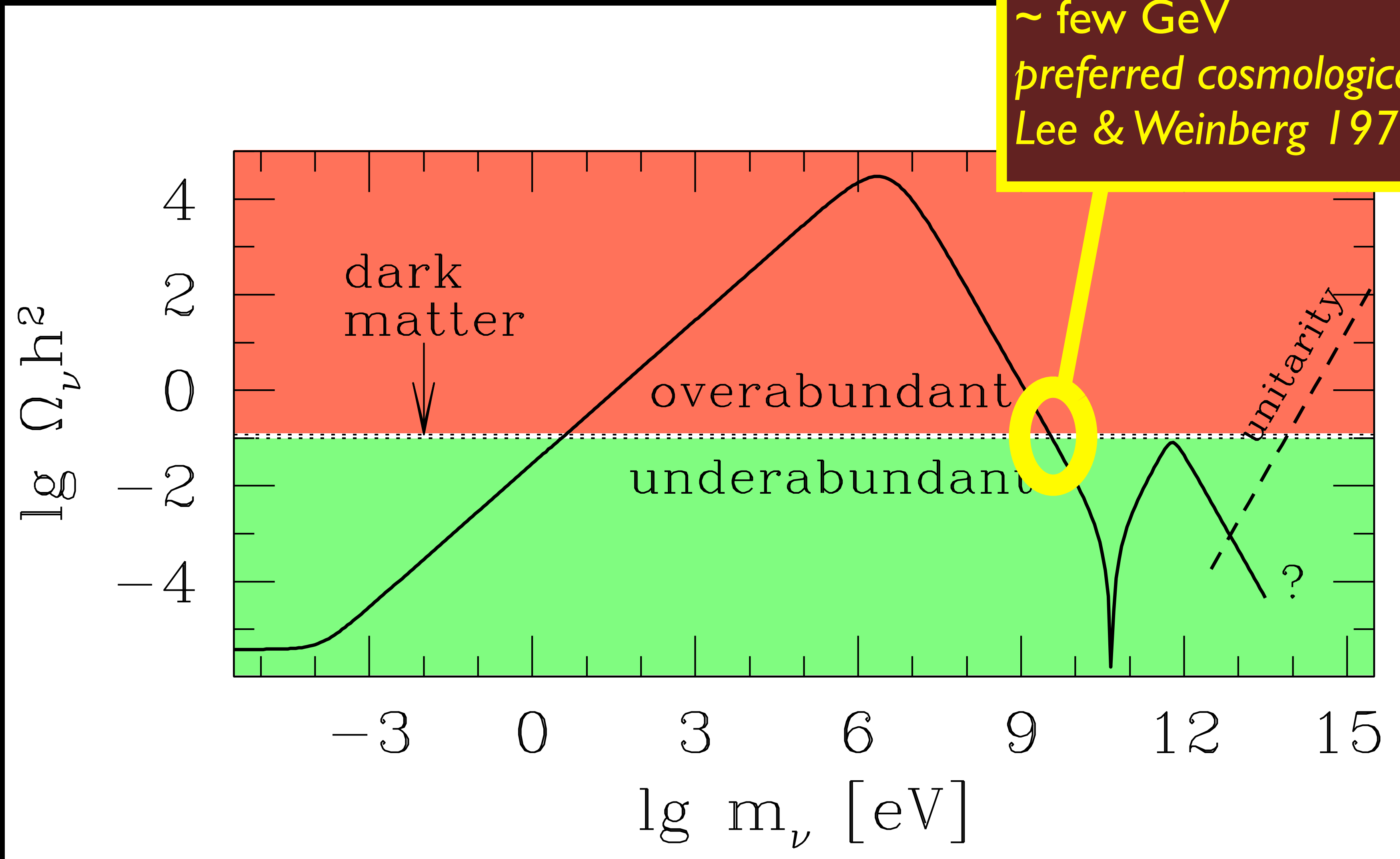
$\langle\sigma v\rangle$=const required for right cosmic density



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

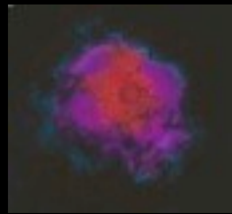
Cosmic density of thermal WIMPs

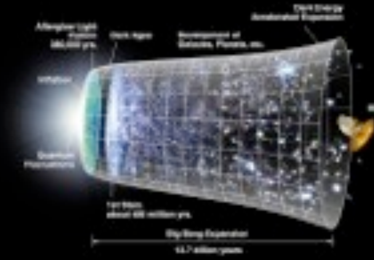
Fourth-generation Standard Model neutrino



~ few GeV
preferred cosmological mass
Lee & Weinberg 1977

Indirect detection

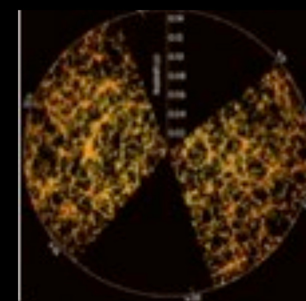




Cosmic density

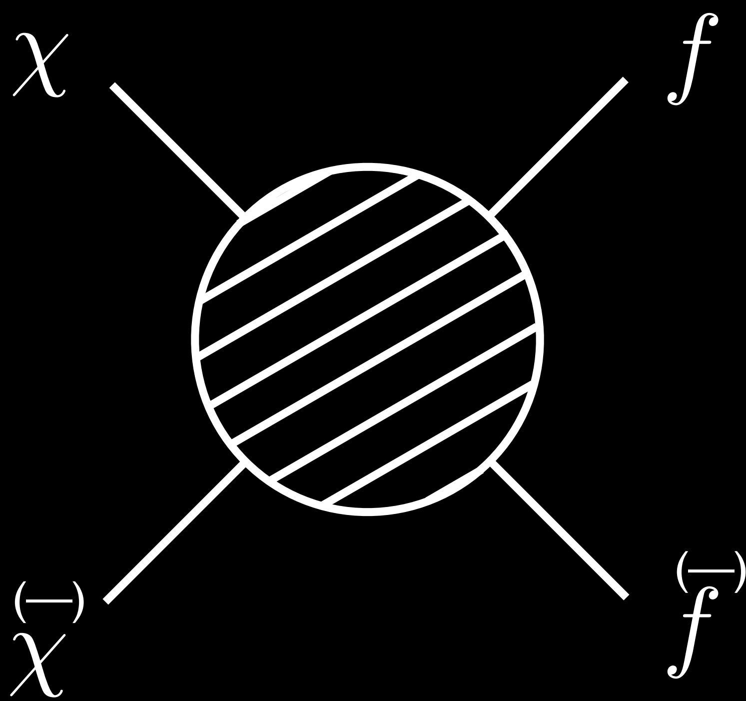
Annihilation $\longrightarrow$

Direct detection



Large scale structure

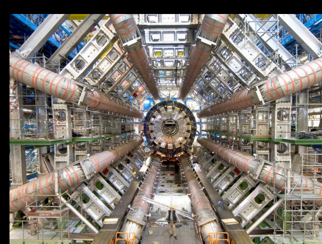
The power of the WIMP hypothesis

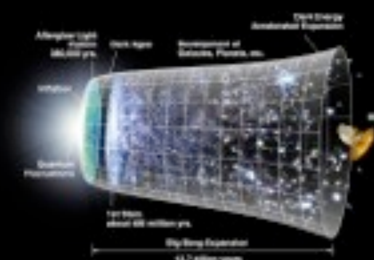


Scattering $\downarrow$

$\longleftarrow$ Production

Colliders

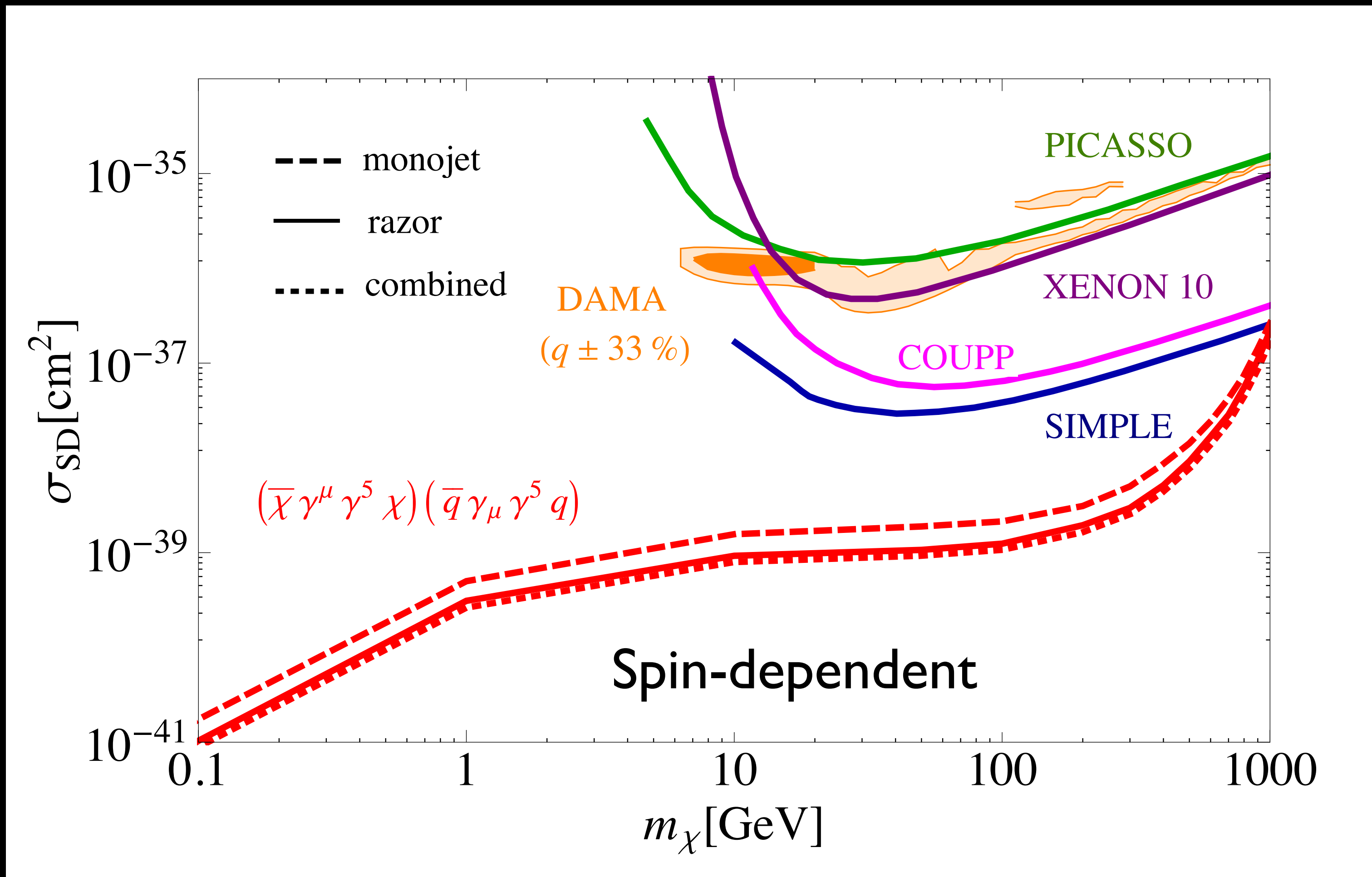




Cosmic density

Constraints on scattering cross section

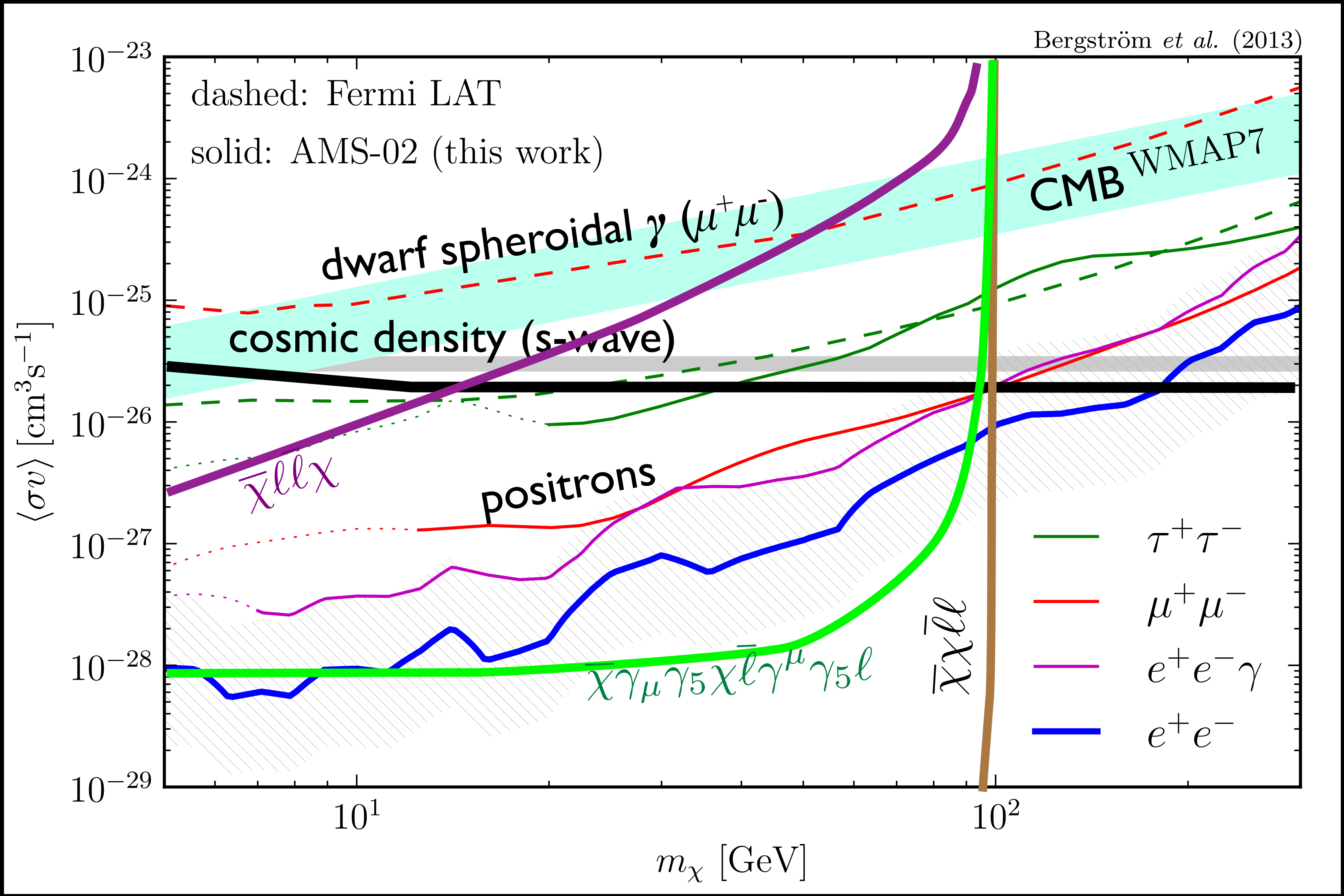
Direct detection and LHC



Fox et al 2012

Constraints on annihilation cross section

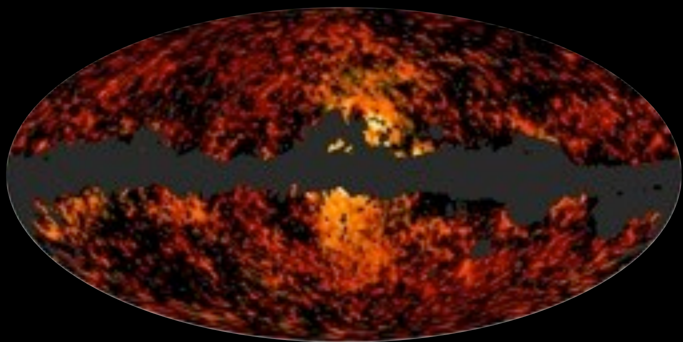
γ-rays, cosmological ionization, positrons, and LHC



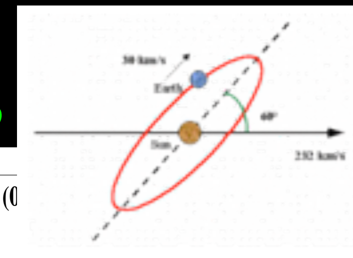
Kopp, Fox, Harnik, Tait 2011 & Bergstrom et al 2013

Evidence for WIMP dark matter?

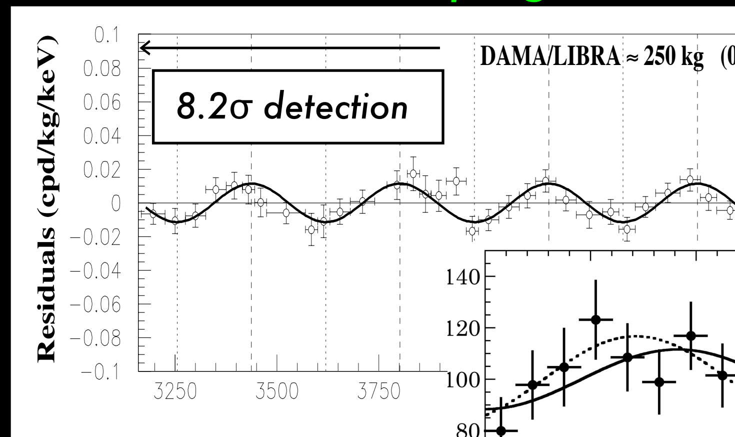
WMAP/Planck haze



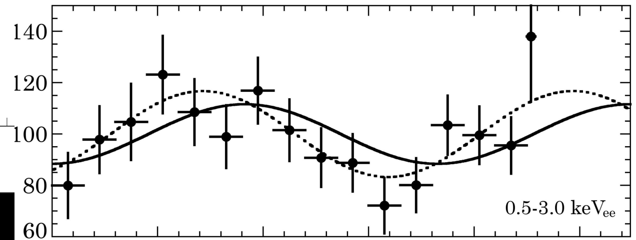
Annual modulation



Drukier, Freese, Spergel 1986

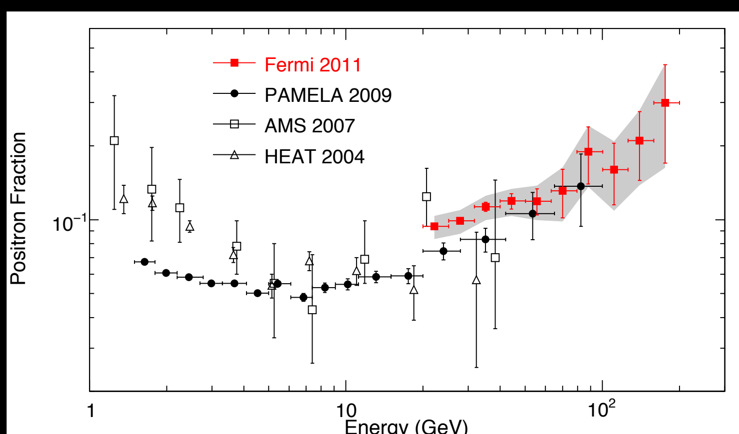


Bernabei et al 1997-2012



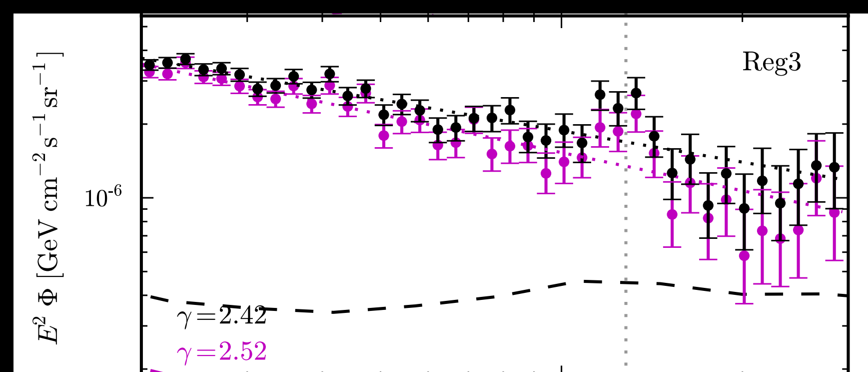
Aalseth et al 2011

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?

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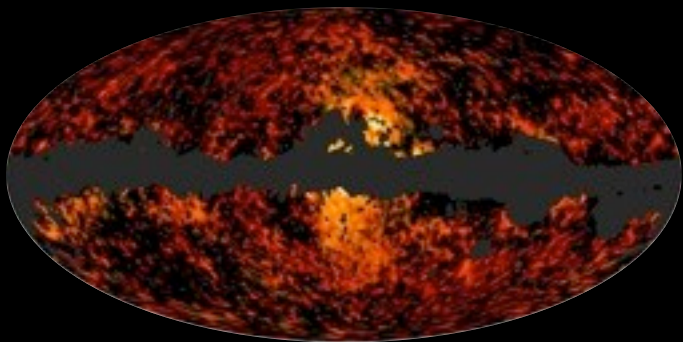
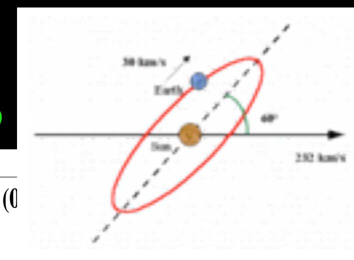
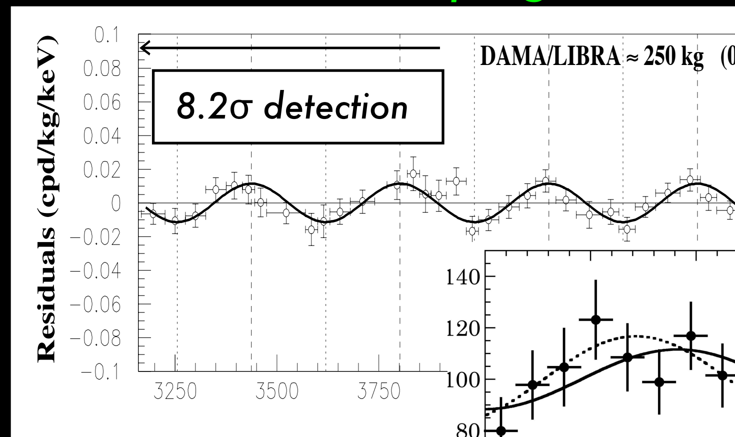


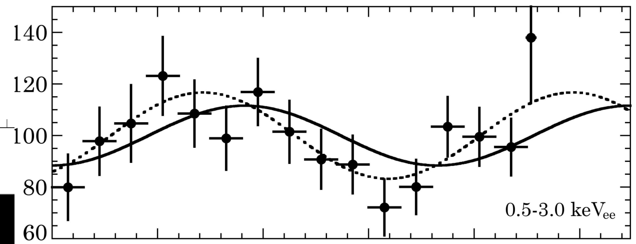
Annual modulation

Drukier, Freese, Spergel 1986



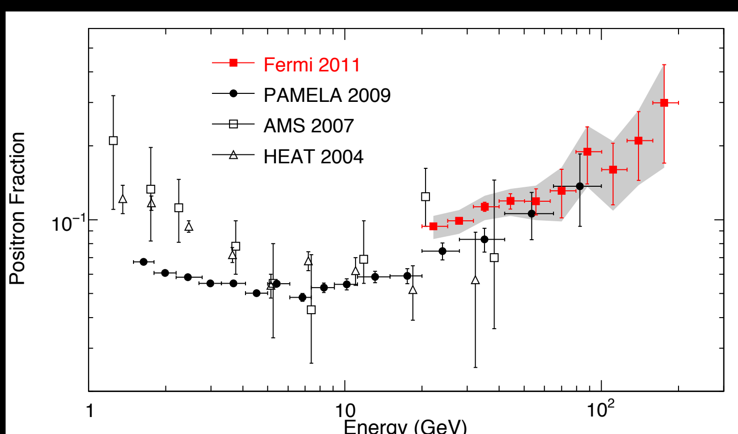


Bernabei et al 1997-2012



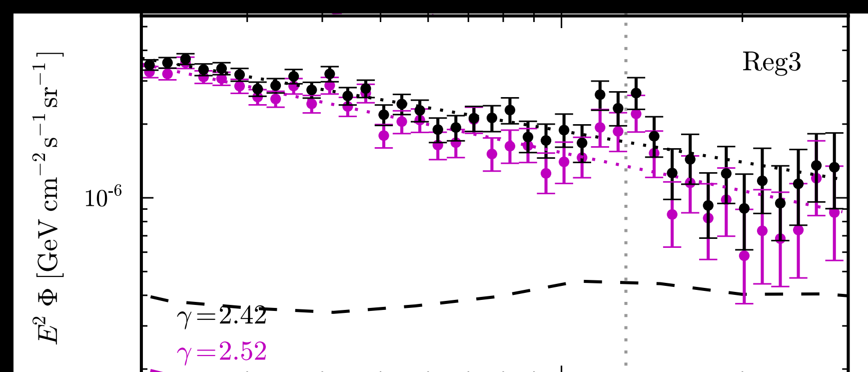
Aalseth et al 2011

Positron excess



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

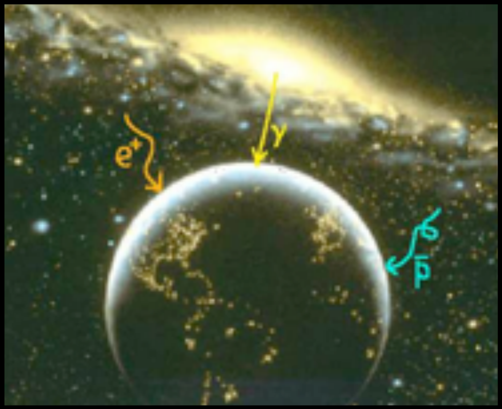
130 GeV γ-ray line

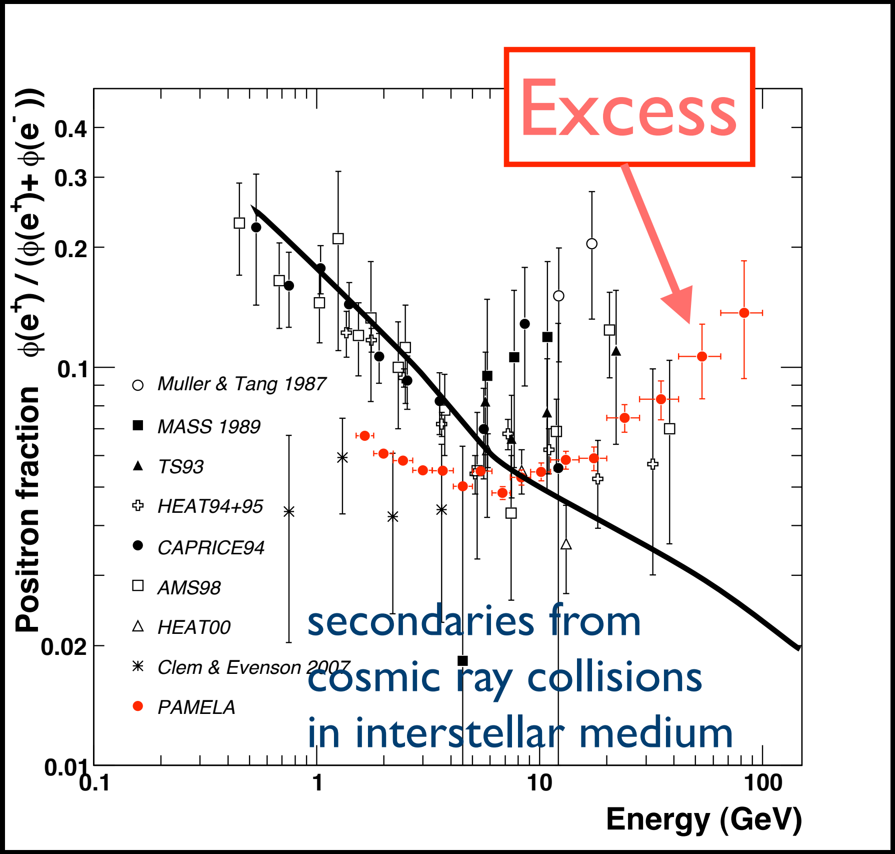


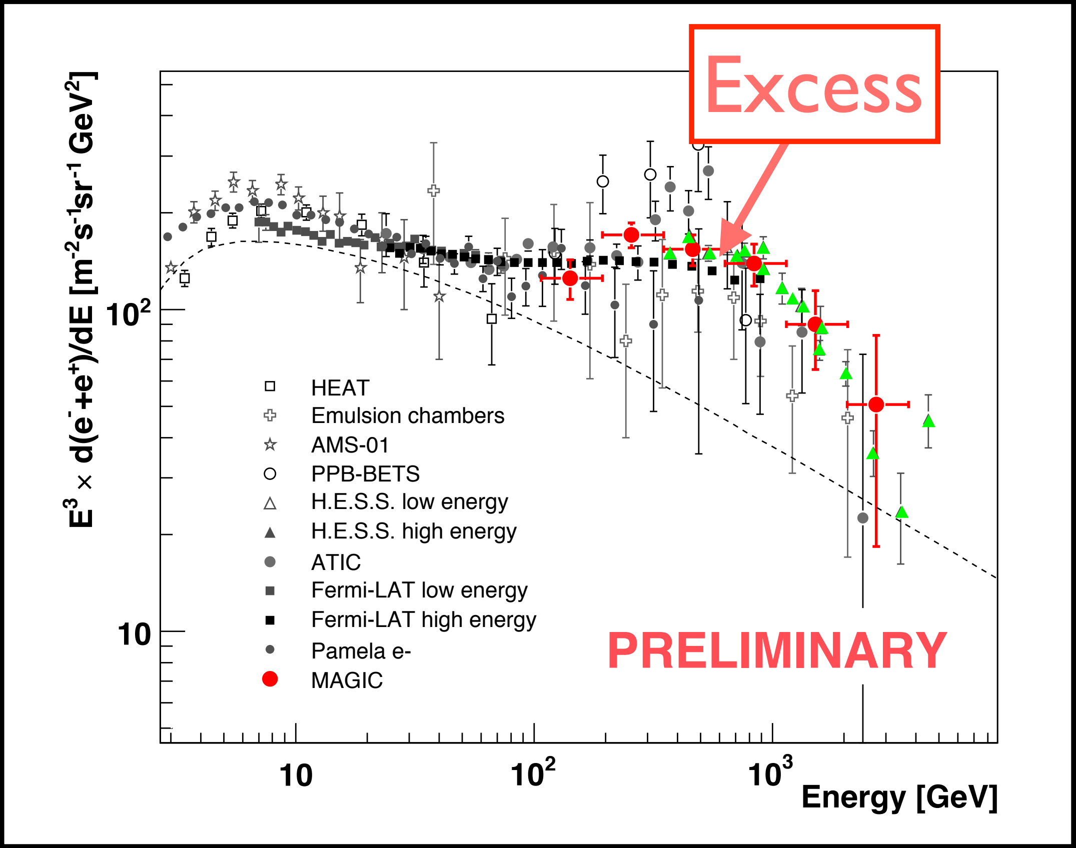
Weniger 2012

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

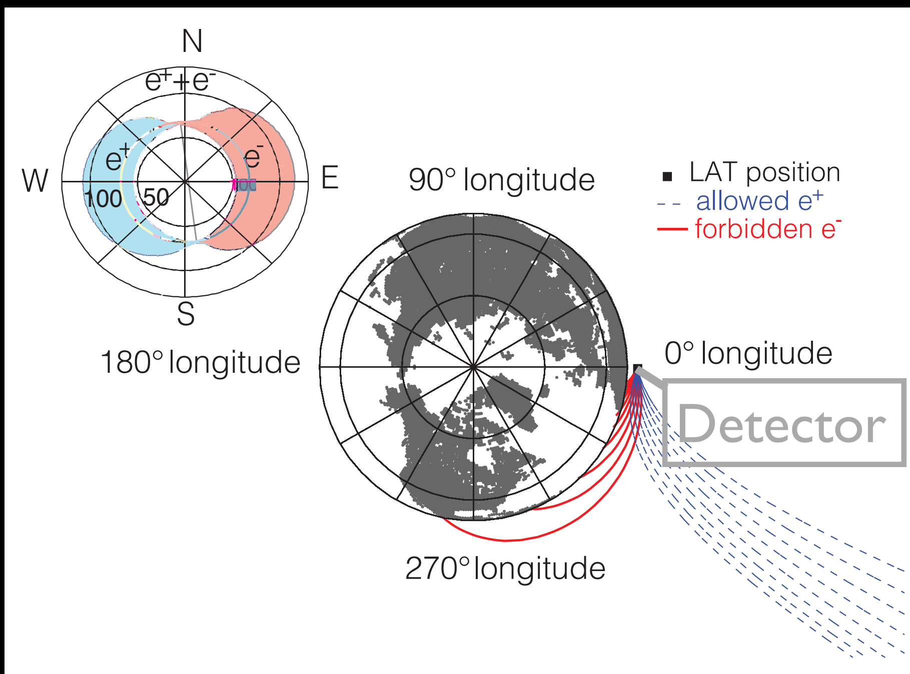
Cosmic ray positrons

Fermi-LAT confirms and extends the positron excess

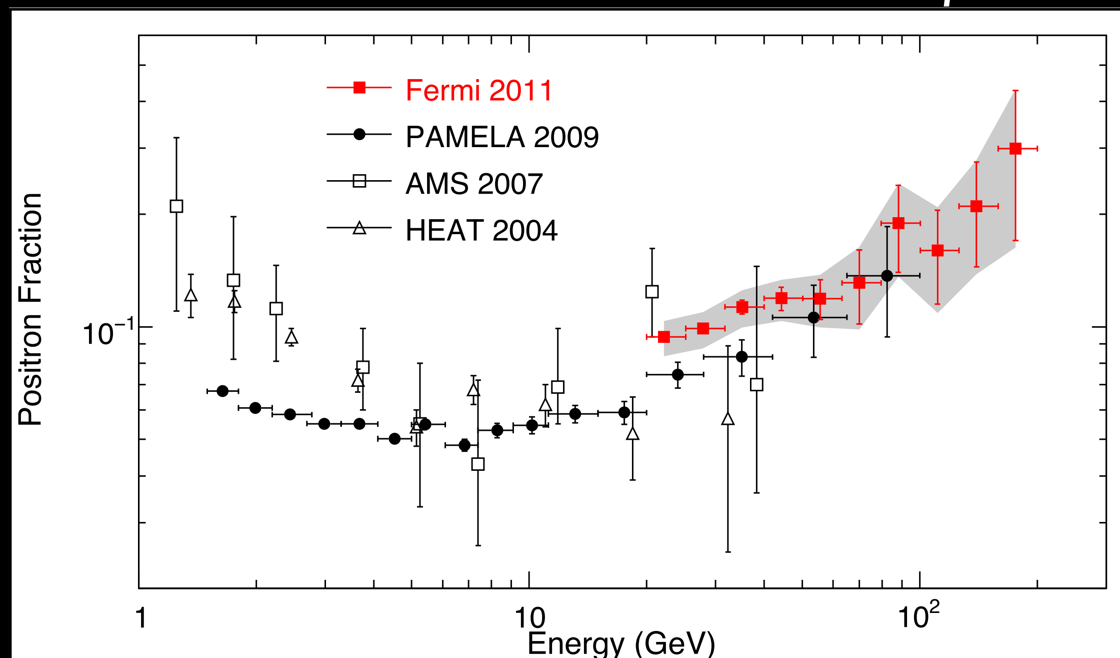
Ackernmann et al, 1109.0521

Use the biggest magnet on Earth: the geomagnetic field!

Daniel, Stephens 1965; Müller, Tang 1987

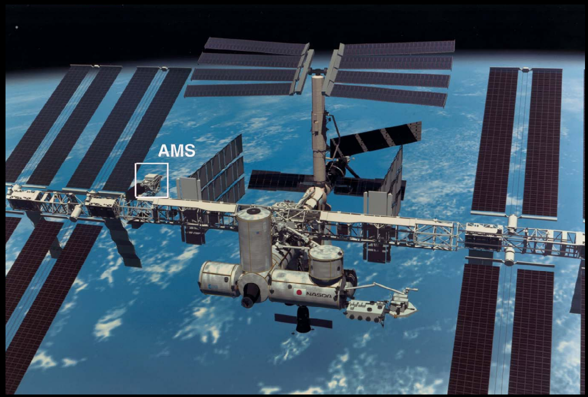


Positron fraction

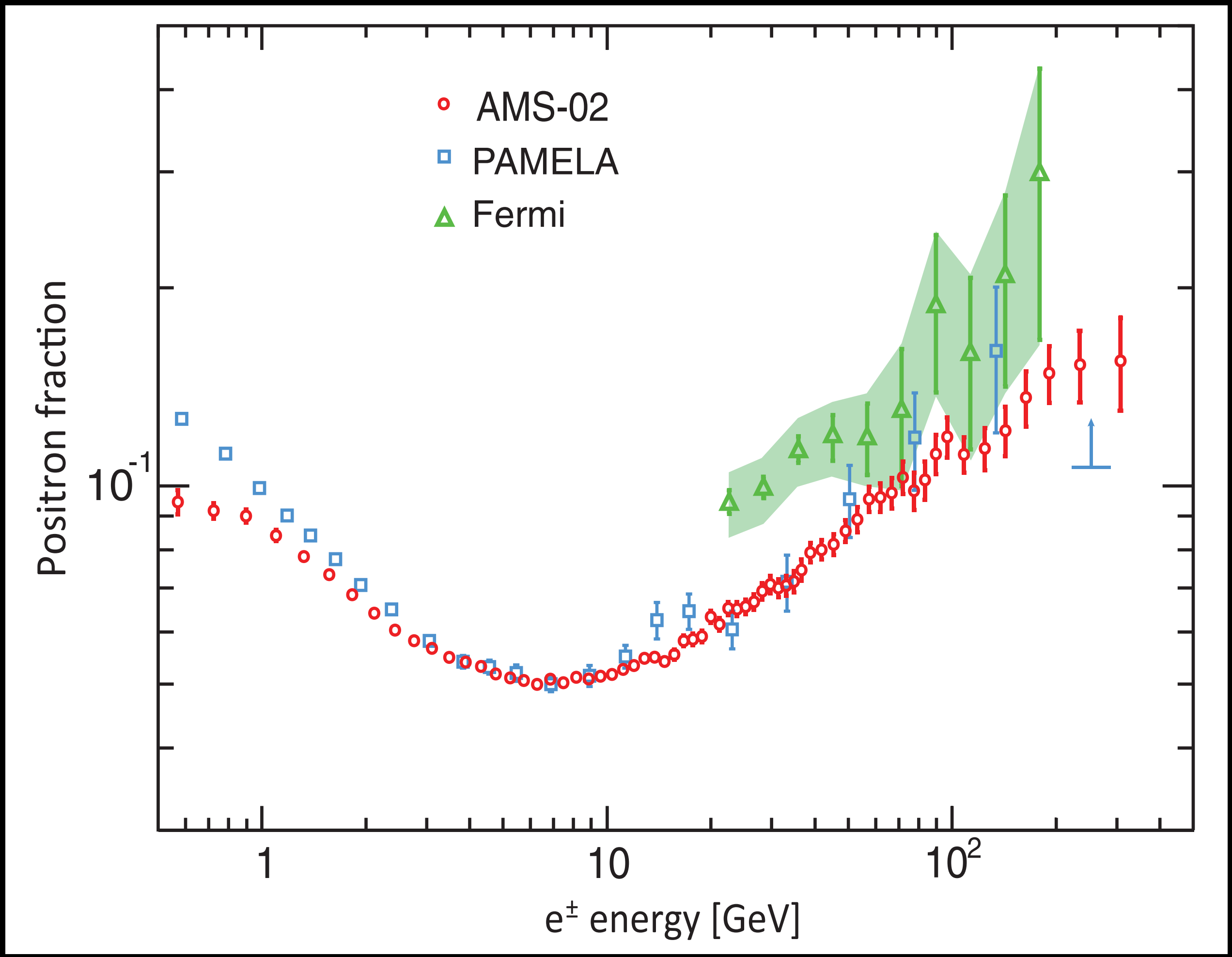


Excess in cosmic ray positrons

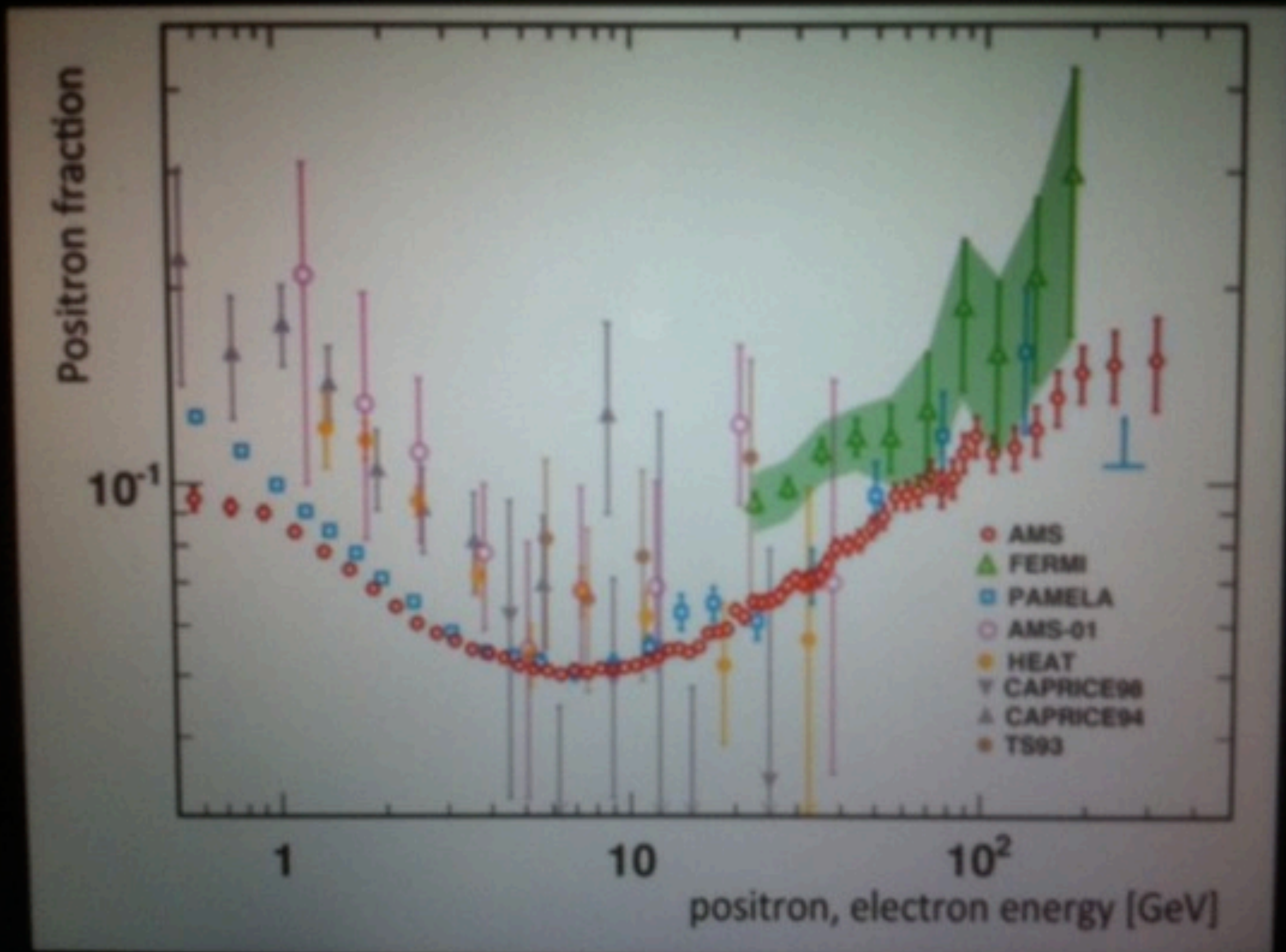
AMS-02 provides data with exquisite precision



Aguilar et al (AMS-02) 2013



Excess in cosmic ray positrons



Ting 2013

Excess in cosmic ray positrons

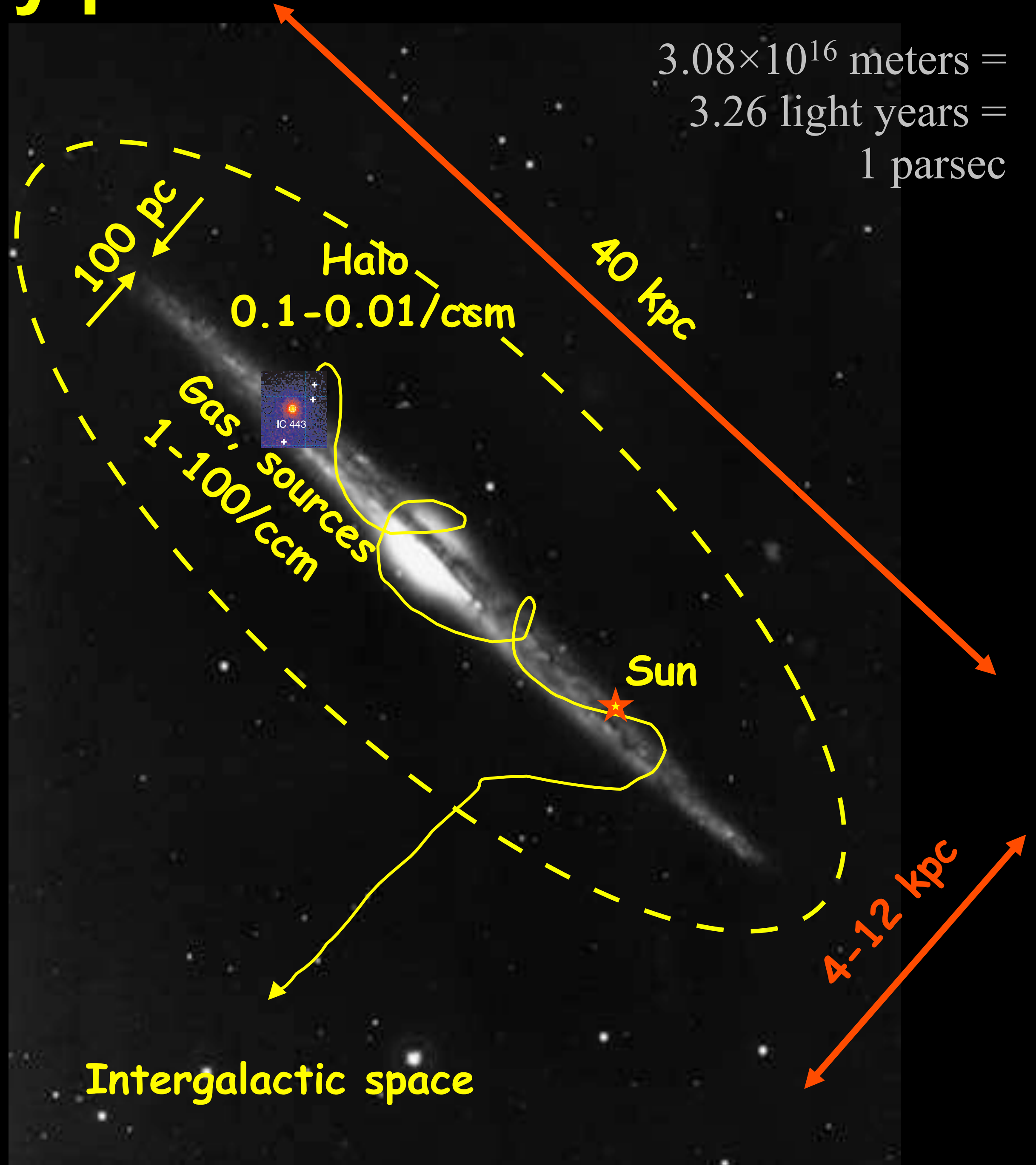
Galactic cosmic rays

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

First observational evidence Ackermann et al 2013

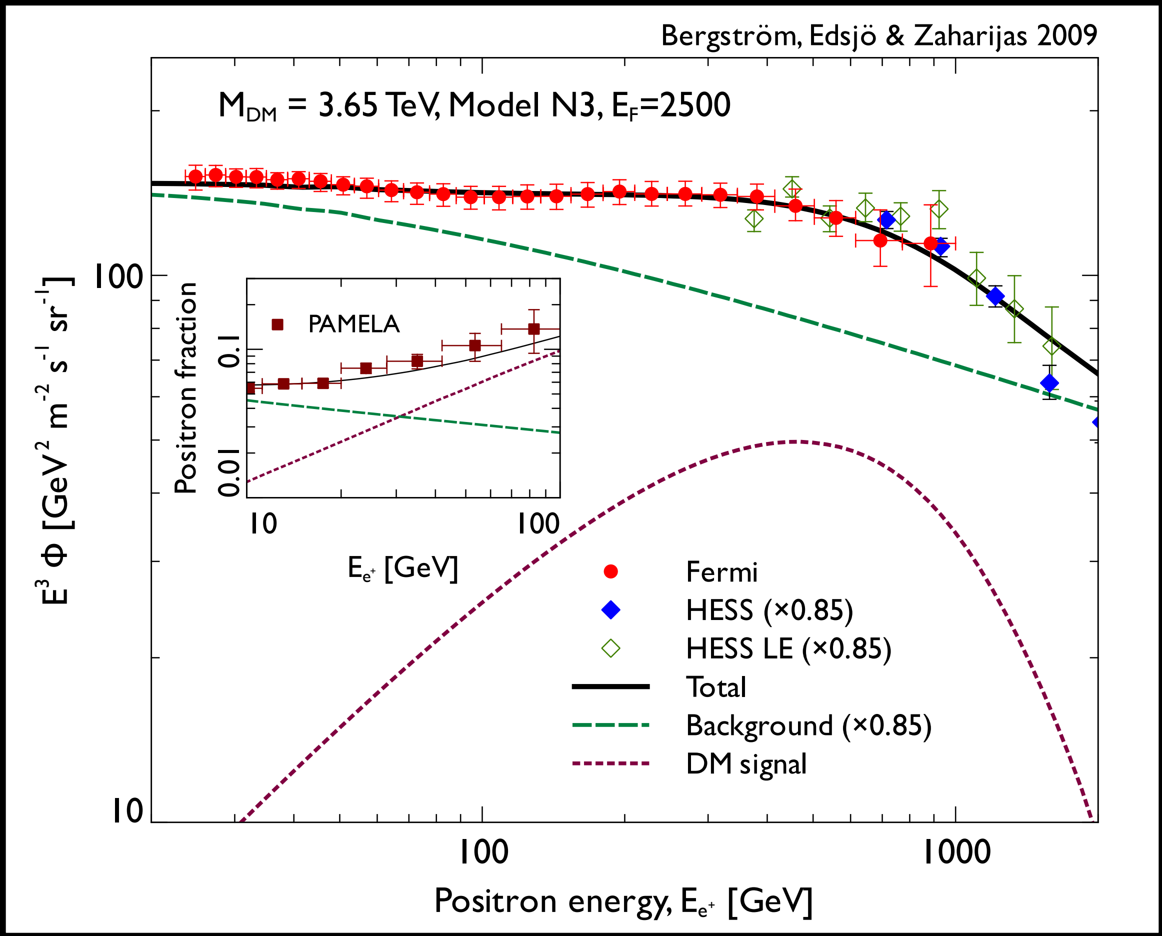
- Secondary cosmic rays (^{2}H, ^{3}He, ^{6,7}Li, ^{7,9,10}Be, ^{10,11}B, ..., ^{26}Al, ^{35}Cl, ^{54}Mn, ...) are produced in cosmic ray collisions with the interstellar medium (90% H, 10% He).

- Secondary to primary ratio carries information on astrophysical model.



Background graphics from Moskalenko 2005

Excess in cosmic ray positrons



Bergstrom, Edsjo, Zaharijas 2009

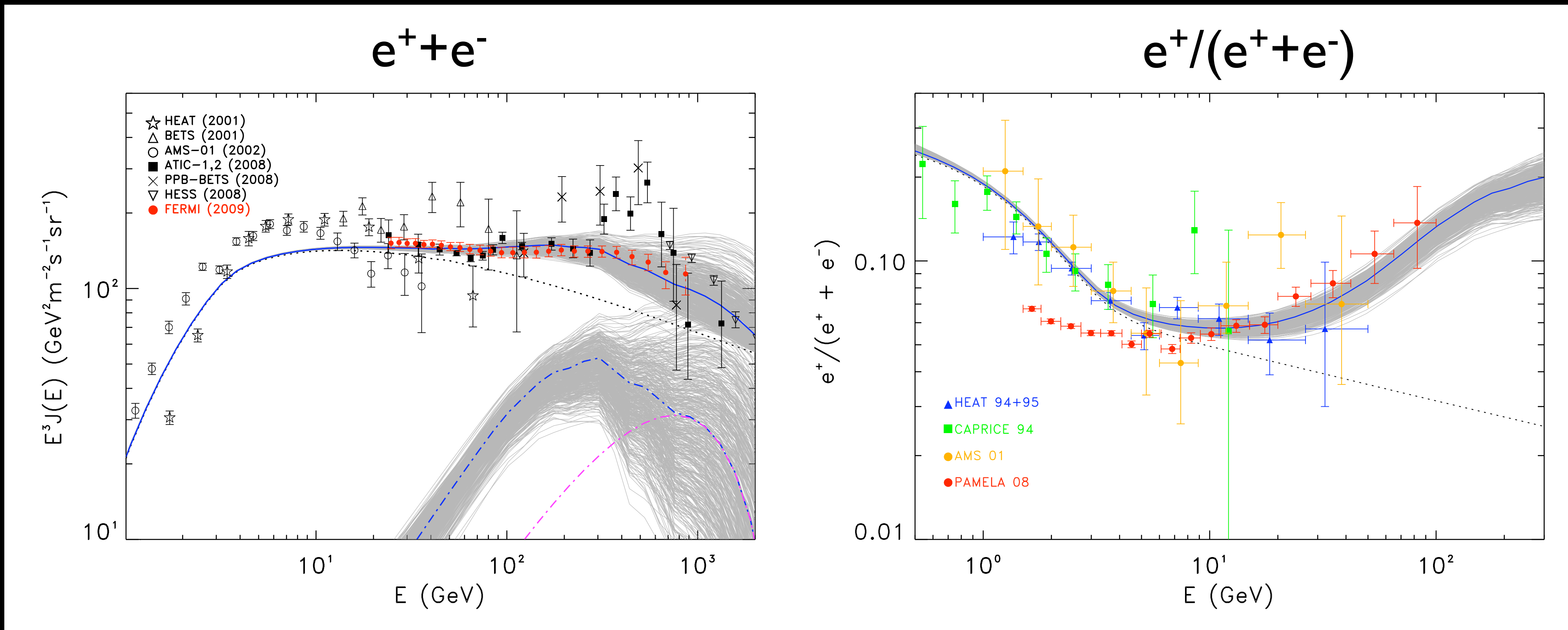
Nomura-Thaler model:

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

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

Excess in cosmic ray positrons

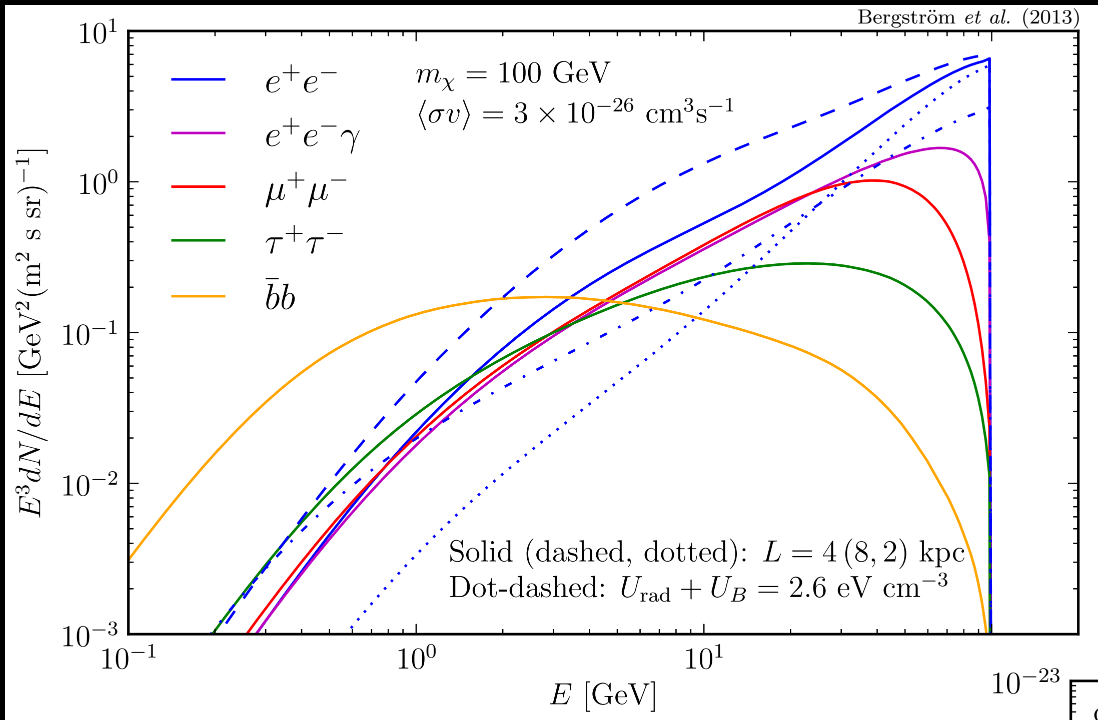
Pulsars



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

Many parameters and models to choose from.

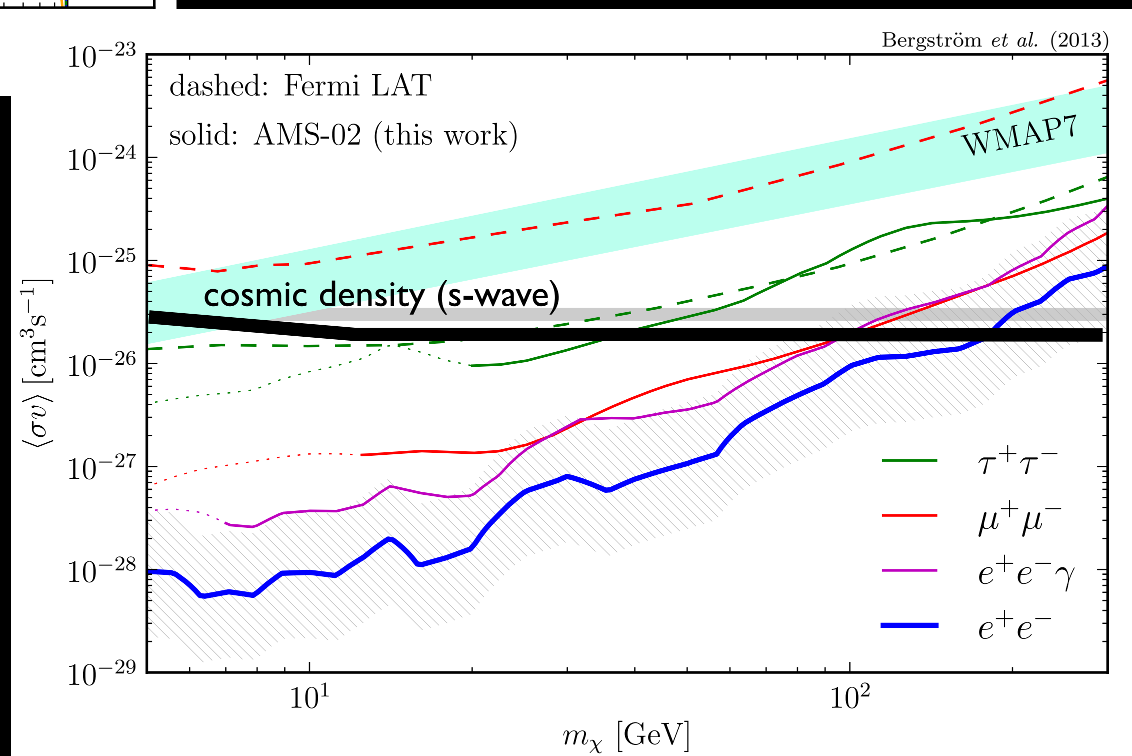
Excess in cosmic ray positrons



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

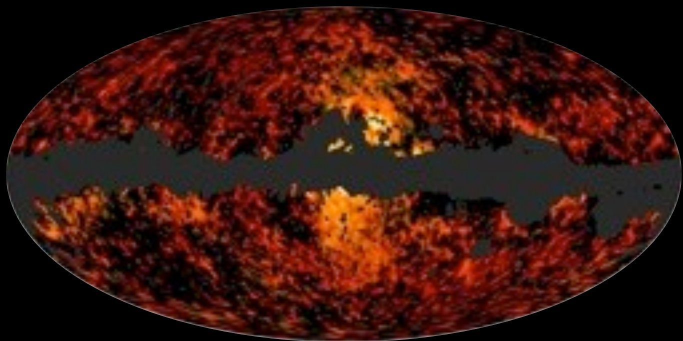
Bergstrom et al 2013

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



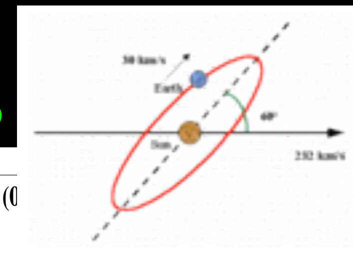
Evidence for cold dark matter particles?

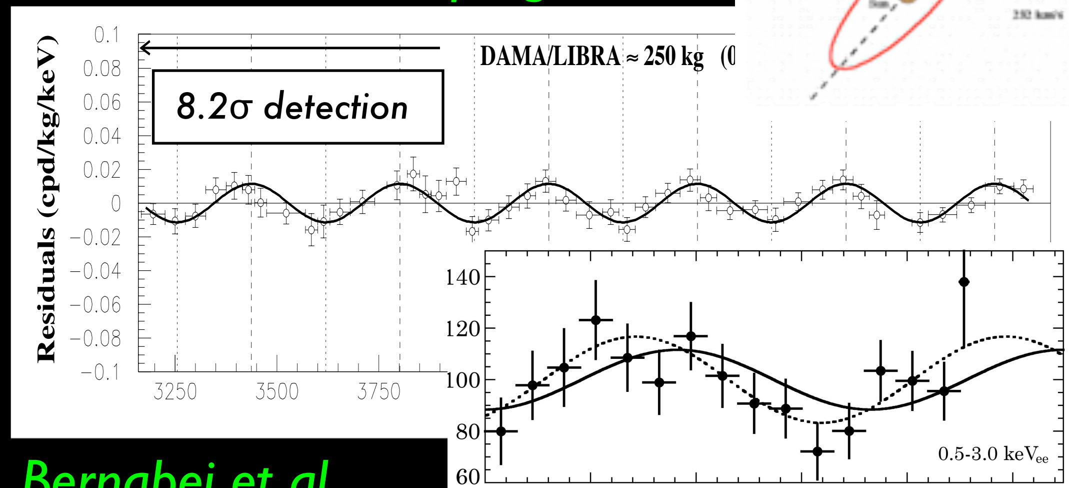
WMAP/Planck haze



Annual modulation

Drukier, Freese, Spergel 1986

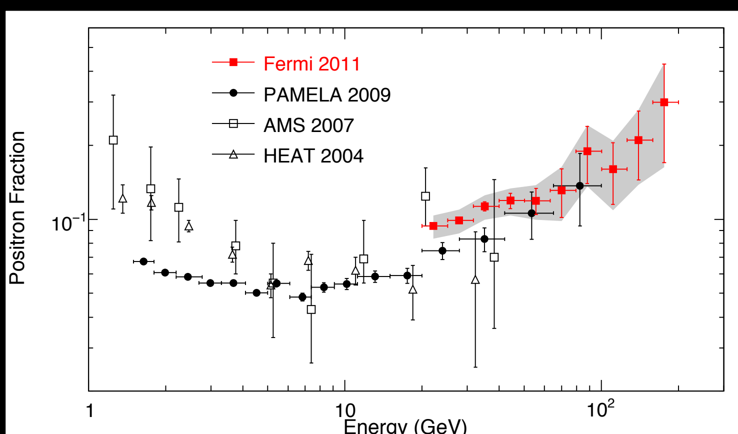




Bernabei et al 1997-2012

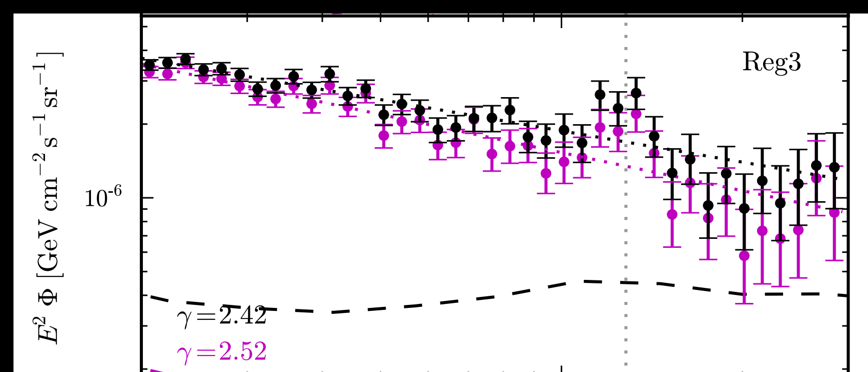
Aalseth et al 2011

Positron excess



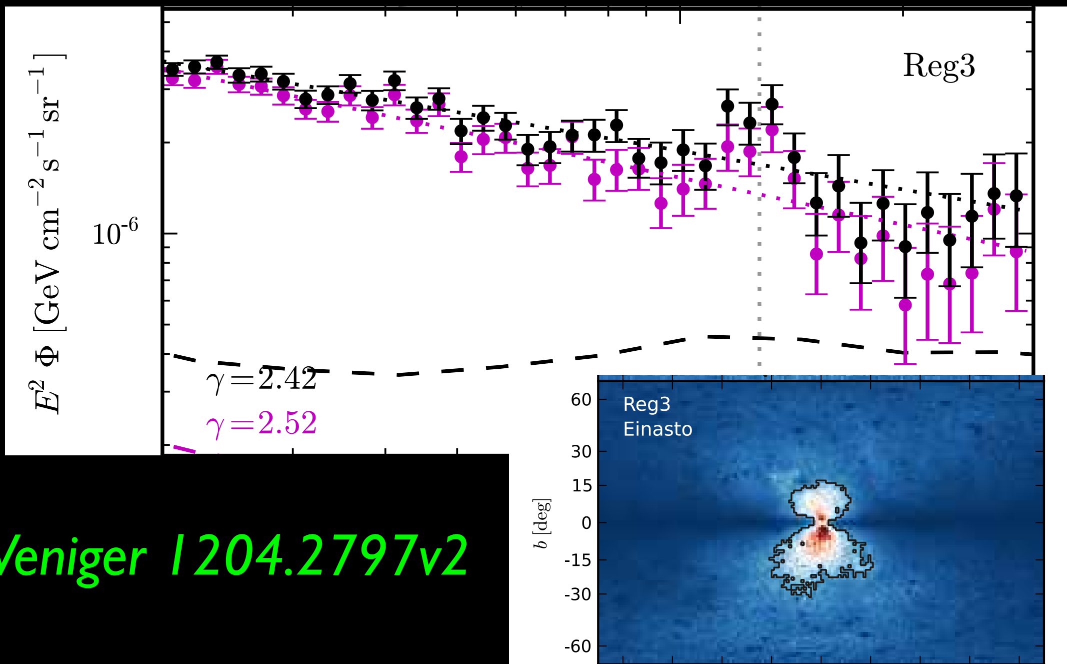
Adriani et al 2009;Ackerman et al 2011

130 GeV γ-ray line



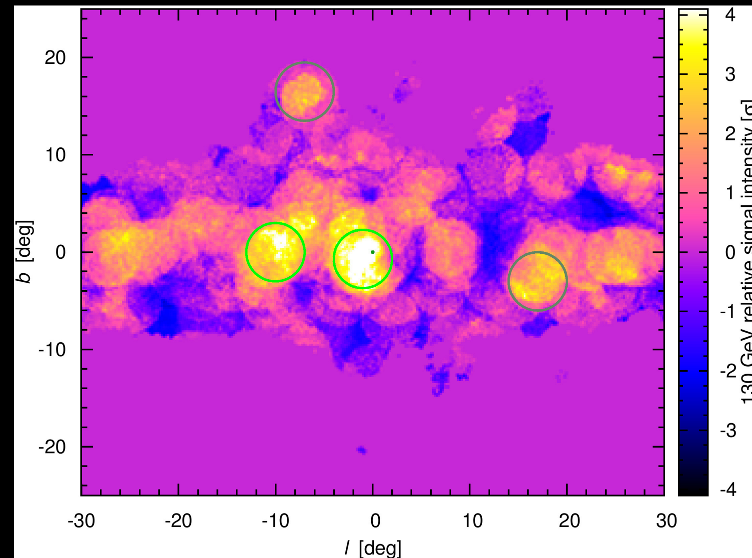
Weniger 2012

135 GeV gamma-ray line?



Weniger 1204.2797v2

found by others



Tempel, Hektor, Raidal 2012

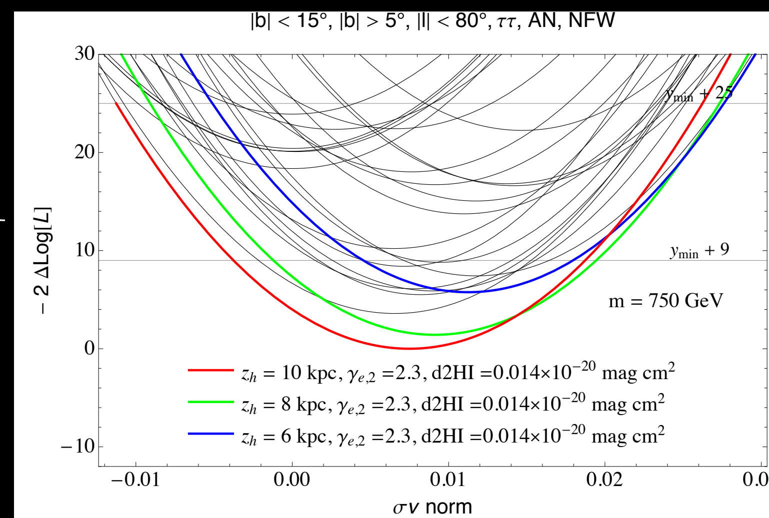
3.2σ effect based on 50 photons

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

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

HESS-2 will tell (July 2013?)

Fermi Collab. upper bounds

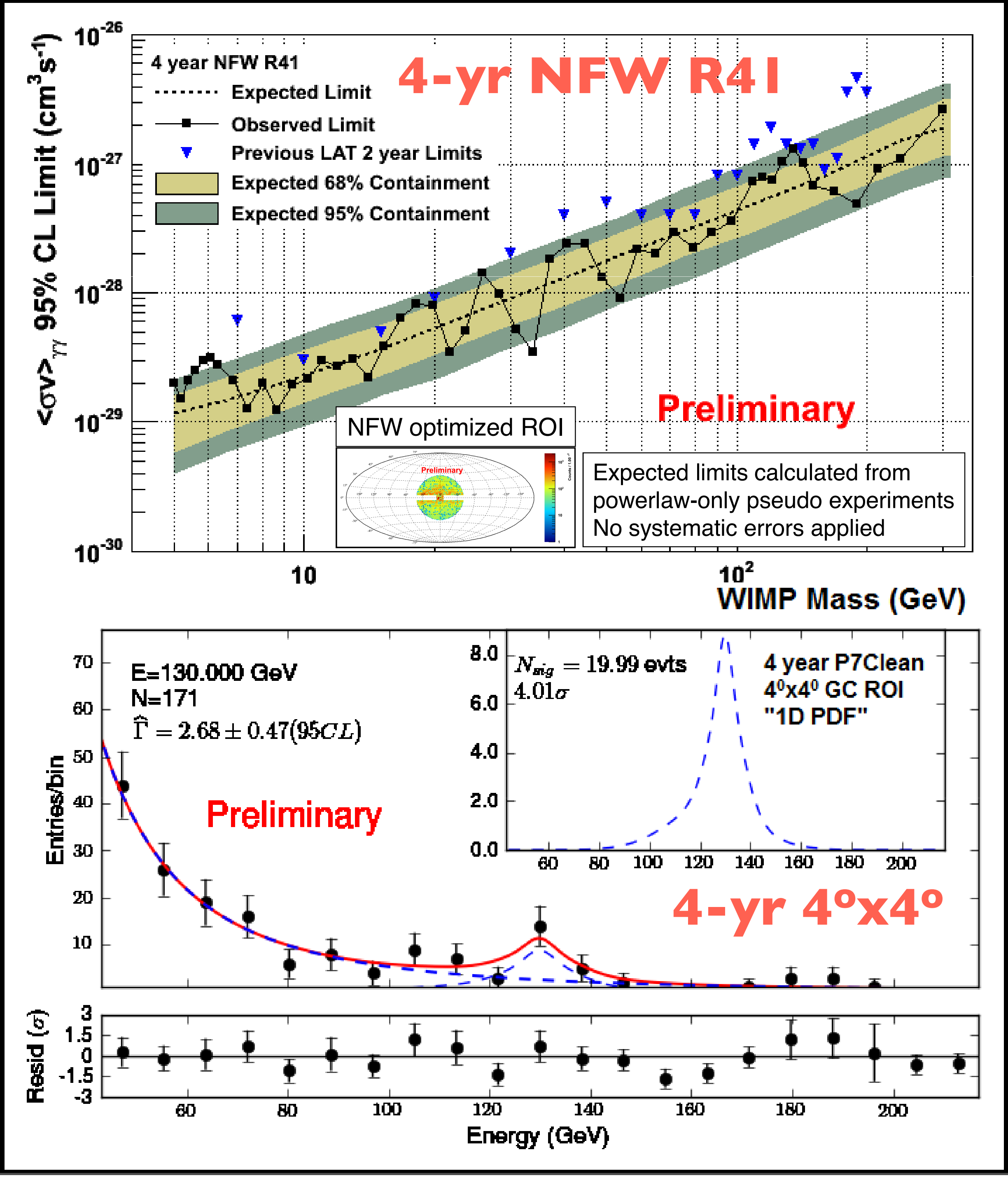


Ackerman et al (Fermi-LAT) 2012

135 GeV gamma-ray line?

Bloom et al (Fermi-LAT) 2012

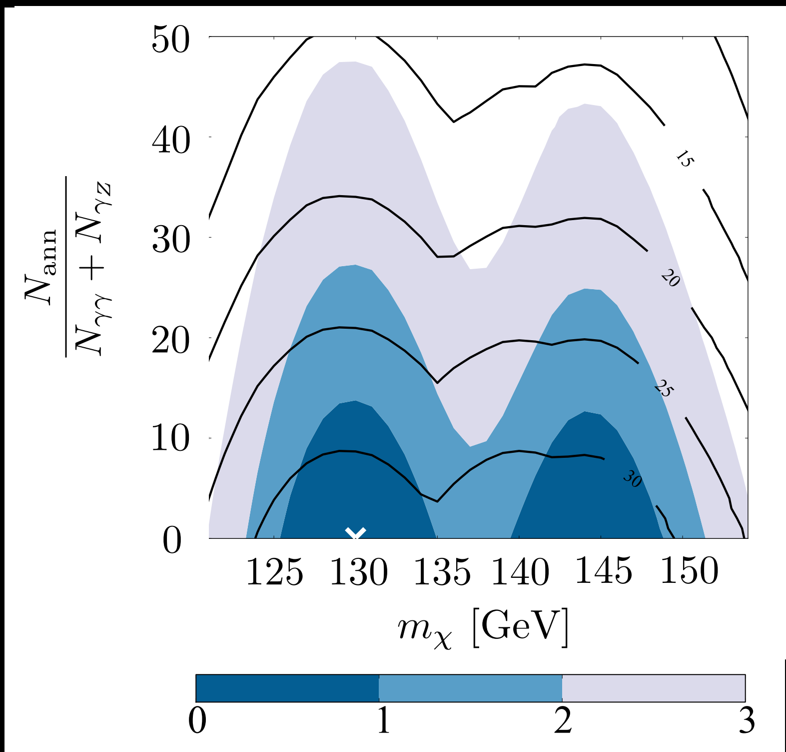
Albert et al (Fermi-LAT) 2012



135 GeV gamma-ray line?

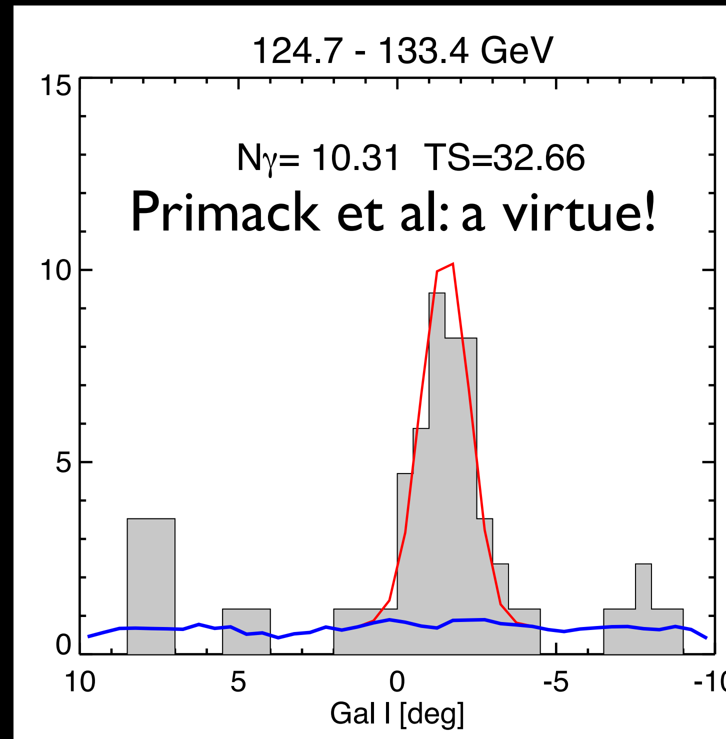
Difficulties......

suppressed continuum

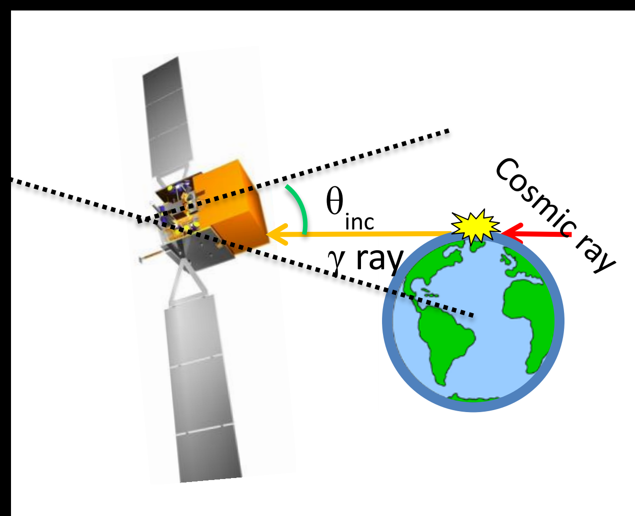


Cohen, Lisanti, Slatyer, Wacker 2012

off from Galactic Center



Su, Finkbeiner 2012



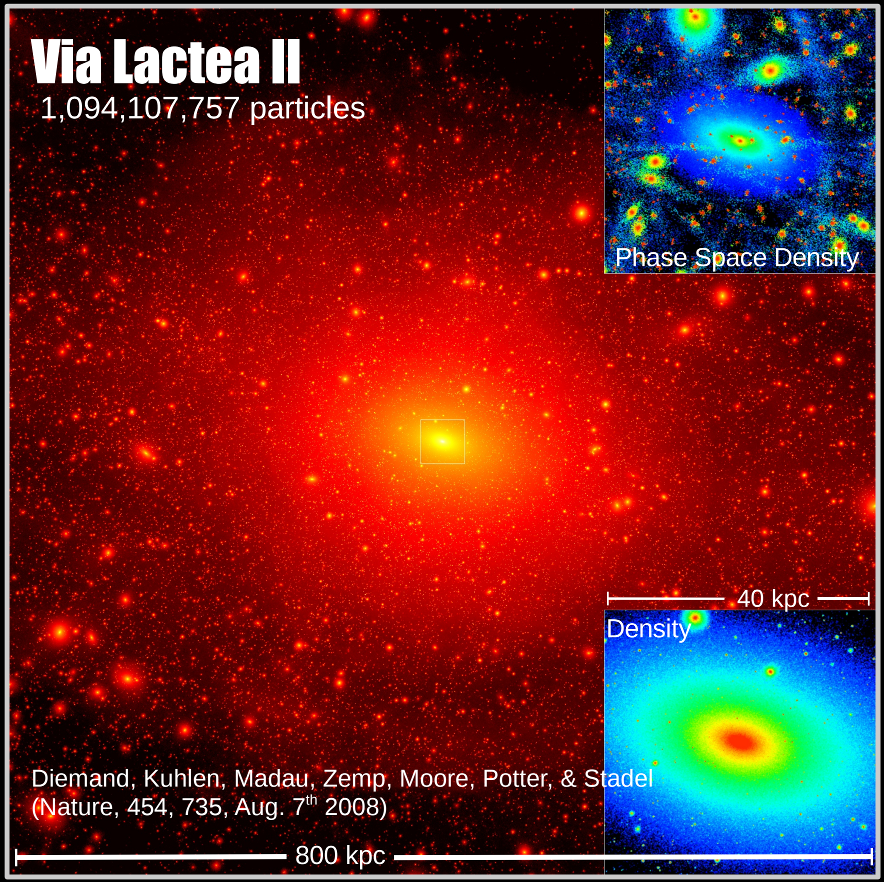
Earth limb data set shows pile-up at 130 GeV

135 GeV gamma-ray line: astrophysics

Intensity depends on halo clumpiness

Dark matter clumps, clouds, subhalos,
minihalos, microhalos, nanohalos, ...

$$\frac{d\Phi_\gamma}{dE} = \frac{\sigma v}{2m^2} \int \rho^2(\ell) \, \frac{dN_\gamma}{dE} \, d\ell$$



Boost factor

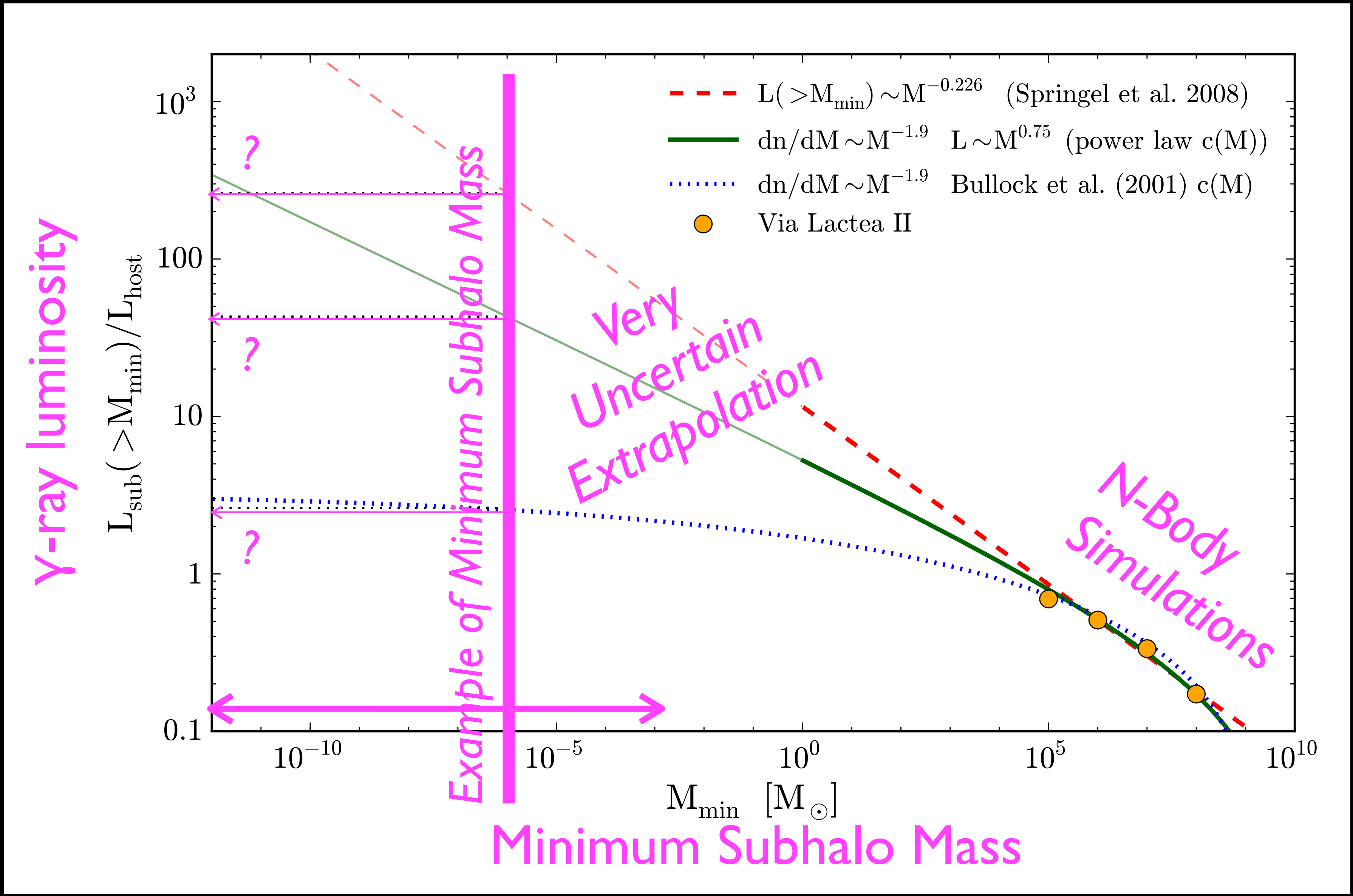
$$B = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

depends on position and on statistics (shape, mass) of subhalos

Not just for γ-rays: positrons, antiprotons, synchrotron, etc.

135 GeV gamma-ray line: astrophysics

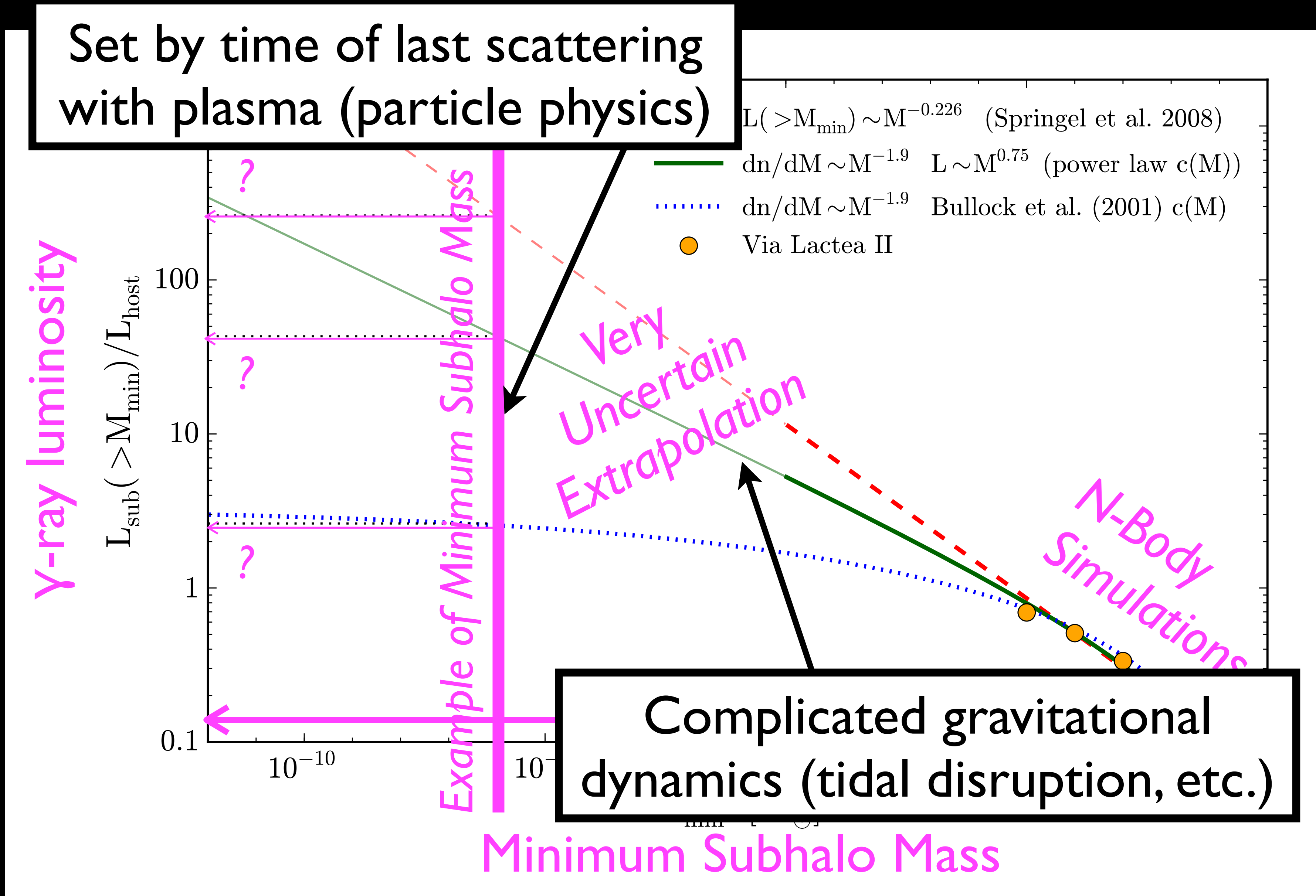
How small are cold dark matter halos?



From Kuhlen, Vogelsberger, Angulo 2012

135 GeV gamma-ray line: astrophysics

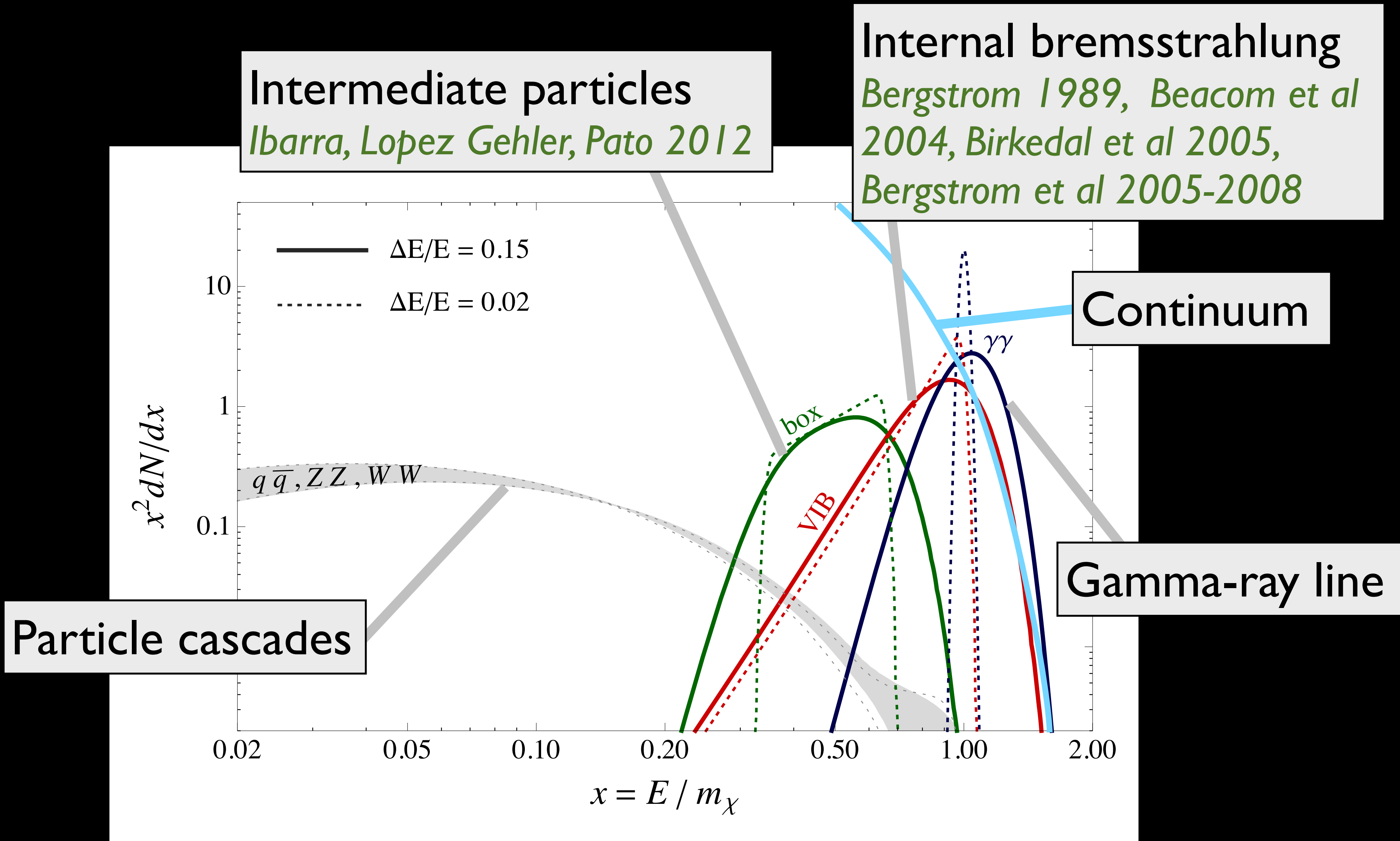
How small are cold dark matter halos?



From Kuhlen, Vogelsberger, Angulo 2012

135 GeV gamma-ray line: particle physics

Gamma-line chaperones



Bringman, Weniger 2012

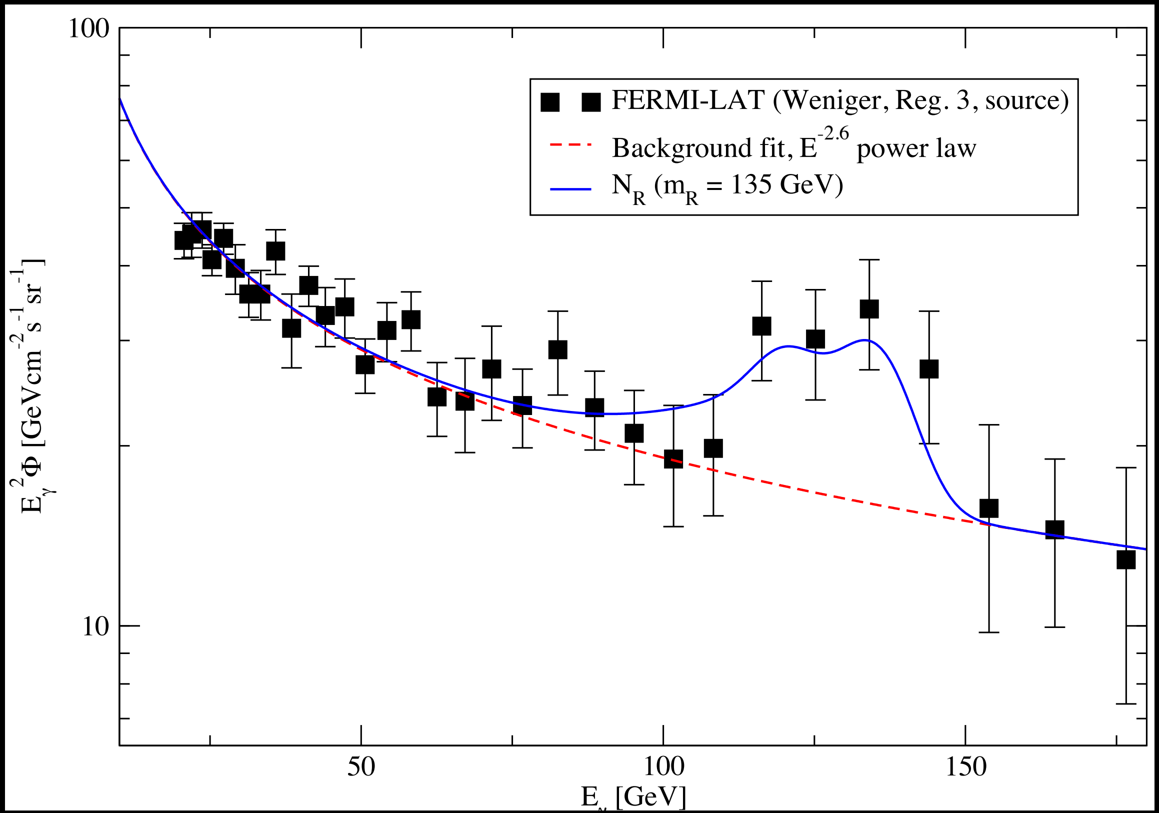
135 GeV gamma-ray line: particle physics

Highly incomplete list of suggested particle models

Models		References
SUSY	MSSM neutralino	*Acharya, Kane, Kumar, Lu, Zheng 1205.5789*
	beyond-MSSM neutralino	*Das, Ellwanger, Mitropoulos 1206.2639*
	sneutrino	*Choi, Seto 1205.3276*
decaying dark matter		*Kyee, Park 1205.4151; Buchmuller, Garny 1206.7056*
Extended Higgs sector		*Cline 1205.2688; Lee, Park, Park 1205.4675; Buckley, Hooper 1205.6811*
Minimalist dark matter		*Cheung, Tsai, Tseng, Yuan, Zee 1207.4930*
Extra U(1)’		*Dudas, Mambrini, Pokorski, Romagnoni 1205.1520*
Kinetically-mixed U(1)’		*Park, Park 1207.4981*
Dipole dark matter		*Weiner, Yavin 1206.2910; Heo, Kim 1207.1341; Cline, Moore, Frey 1208.2685*
Non-SUSY GUT		*Li, Maxin, Nanopoulos, Walker 1208.1999*
Leptonic dark matter		*Baltz, Bergstrom 2002; Bergstrom 1208.6082*
....		....

135 GeV gamma-ray line: particle physics

Leptonically-Interacting Massive Particles (LIMPs)



Baltz, Bergstrom 2002; Bergstrom 1208.6082

LIMPs predicted a gamma-ray line without a continuum

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

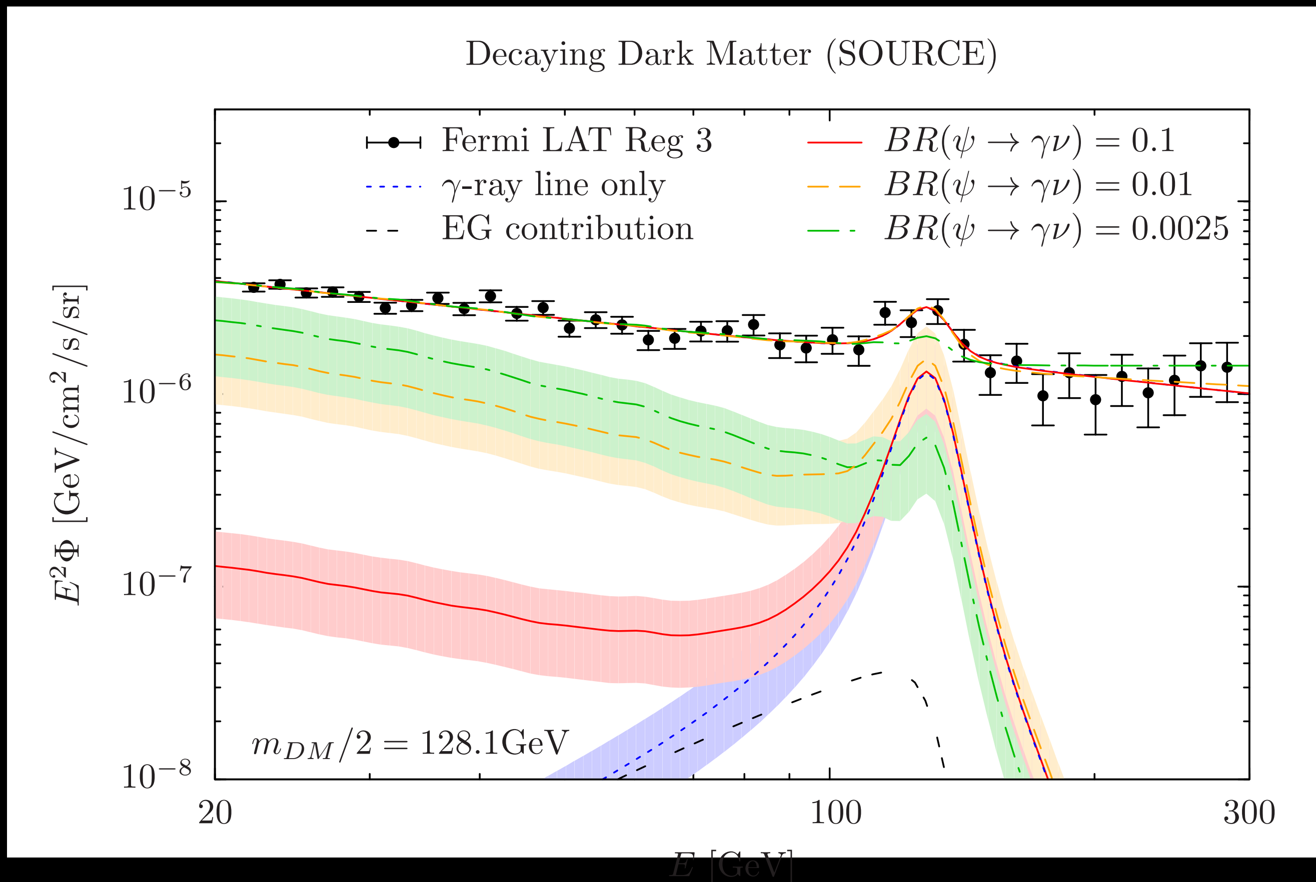
Zee 1980

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

Krauss, Nasri, Trodden 2002

270 GeV decaying dark matter?

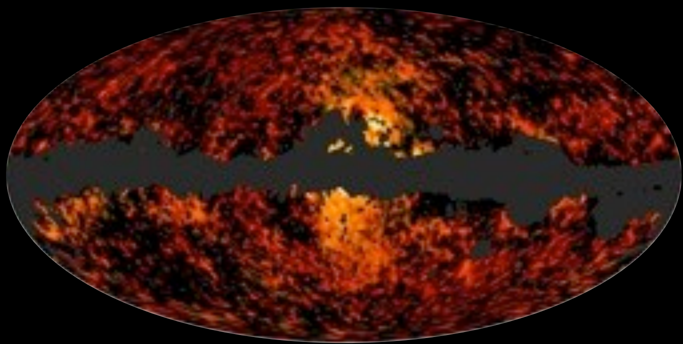
Kyae, Park 1205.4151; Buchmuller, Garny 1206.7056



Buchmuller, Garny 1206.7056

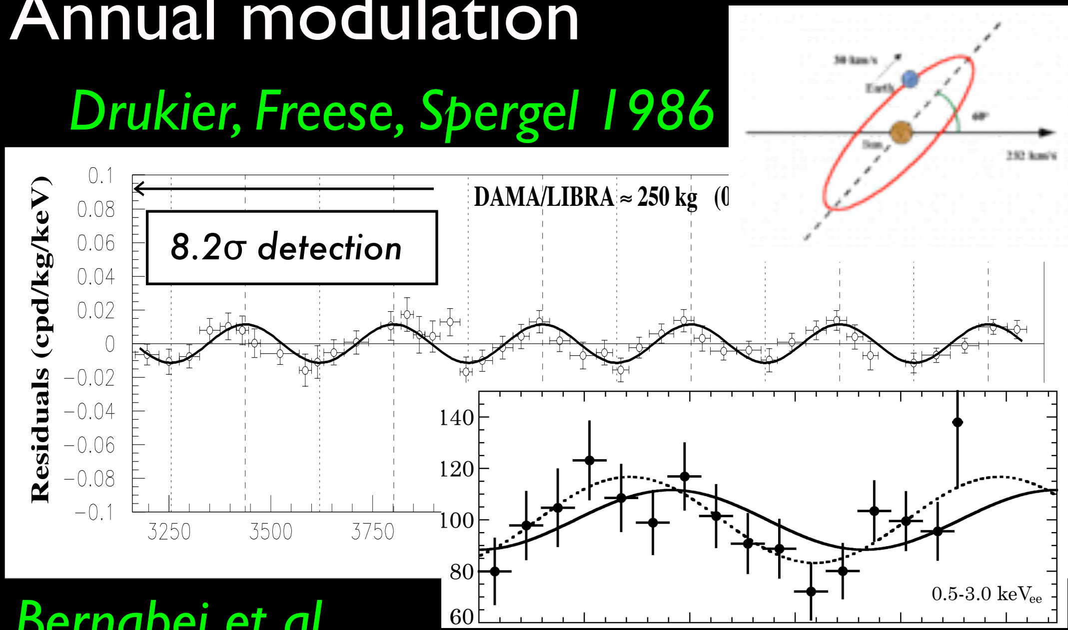
Evidence for cold dark matter particles?

WMAP/Planck haze



Annual modulation

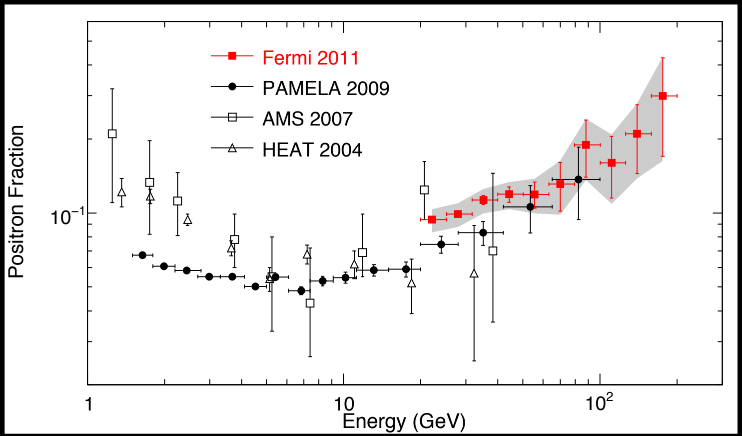
Drukier, Freese, Spergel 1986



Bernabei et al 1997-2012

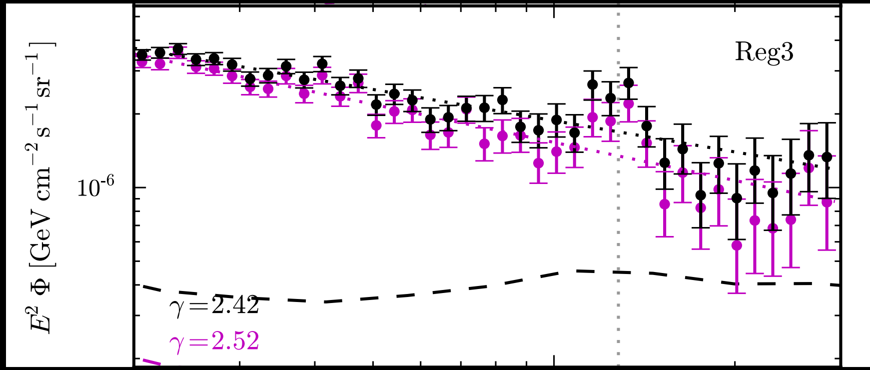
Aalseth et al 2011

Positron excess



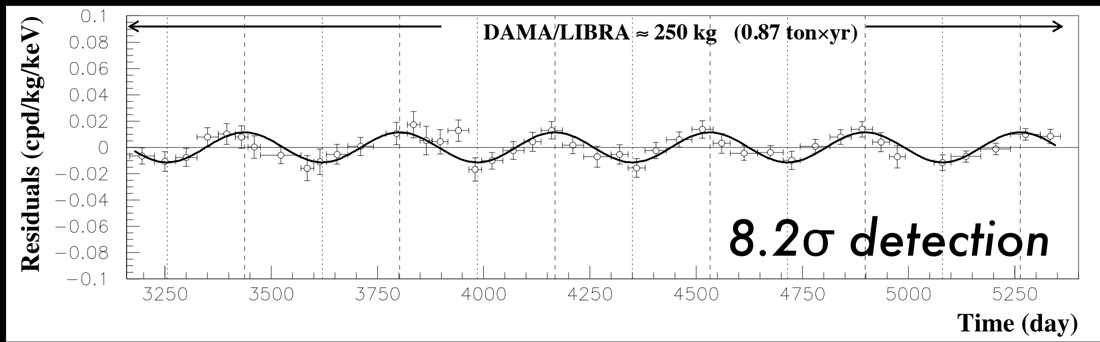
Adriani et al 2009; Ackerman et al 2011; Aguilar et al 2013

130 GeV γ-ray line

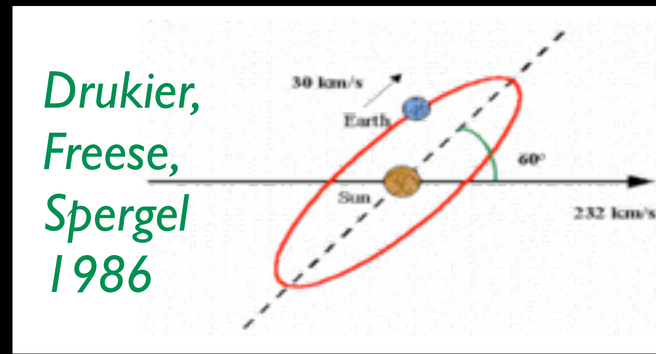


Weniger 2012

Evidence for light dark matter particles?

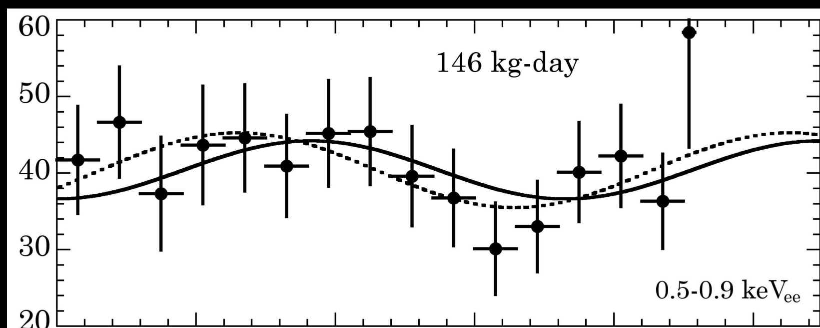


Bernabei et al (DAMA) 1997-10



Annually modulated.....

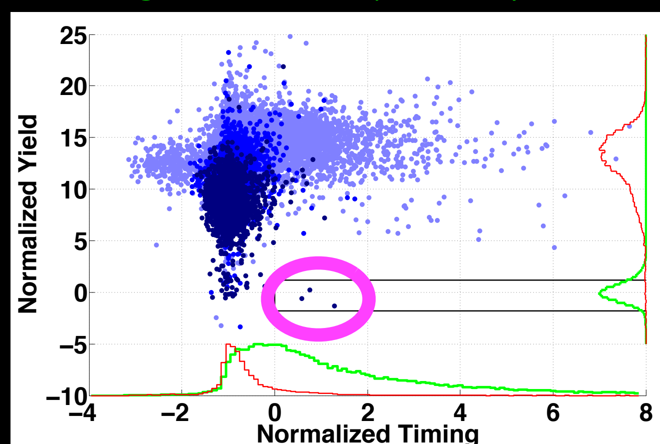
Aalseth et al (CoGeNT) 1106.0650

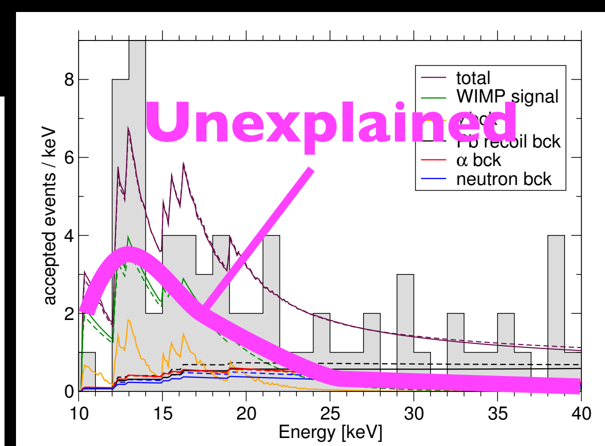


Caveat: "Rates look flatter on second year." Collar, IDM2012

......and unmodulated

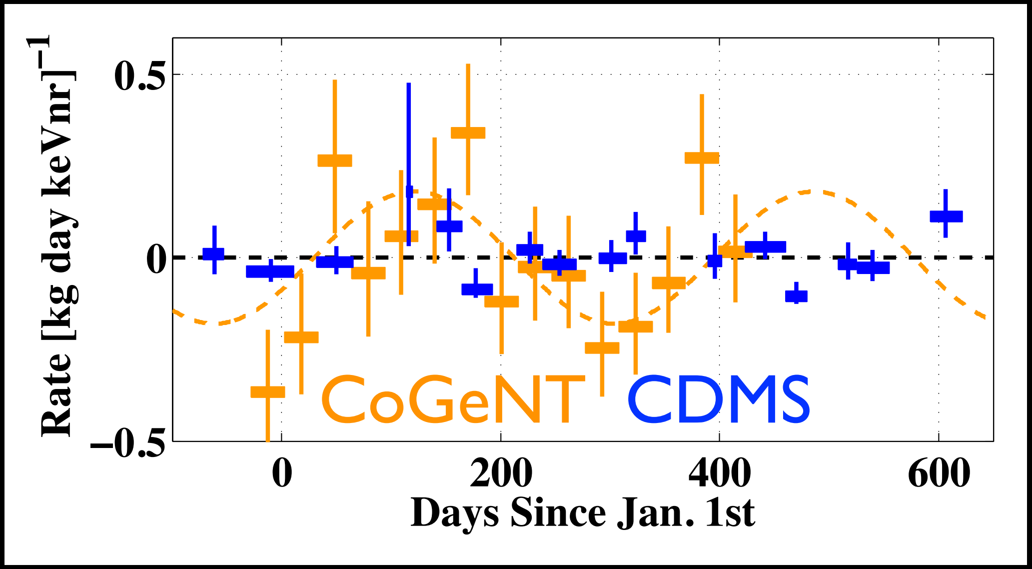
Agnese et al (CDMS) 2013





Anglehor et al (CRESST) 2011

Evidence for light dark matter particles?



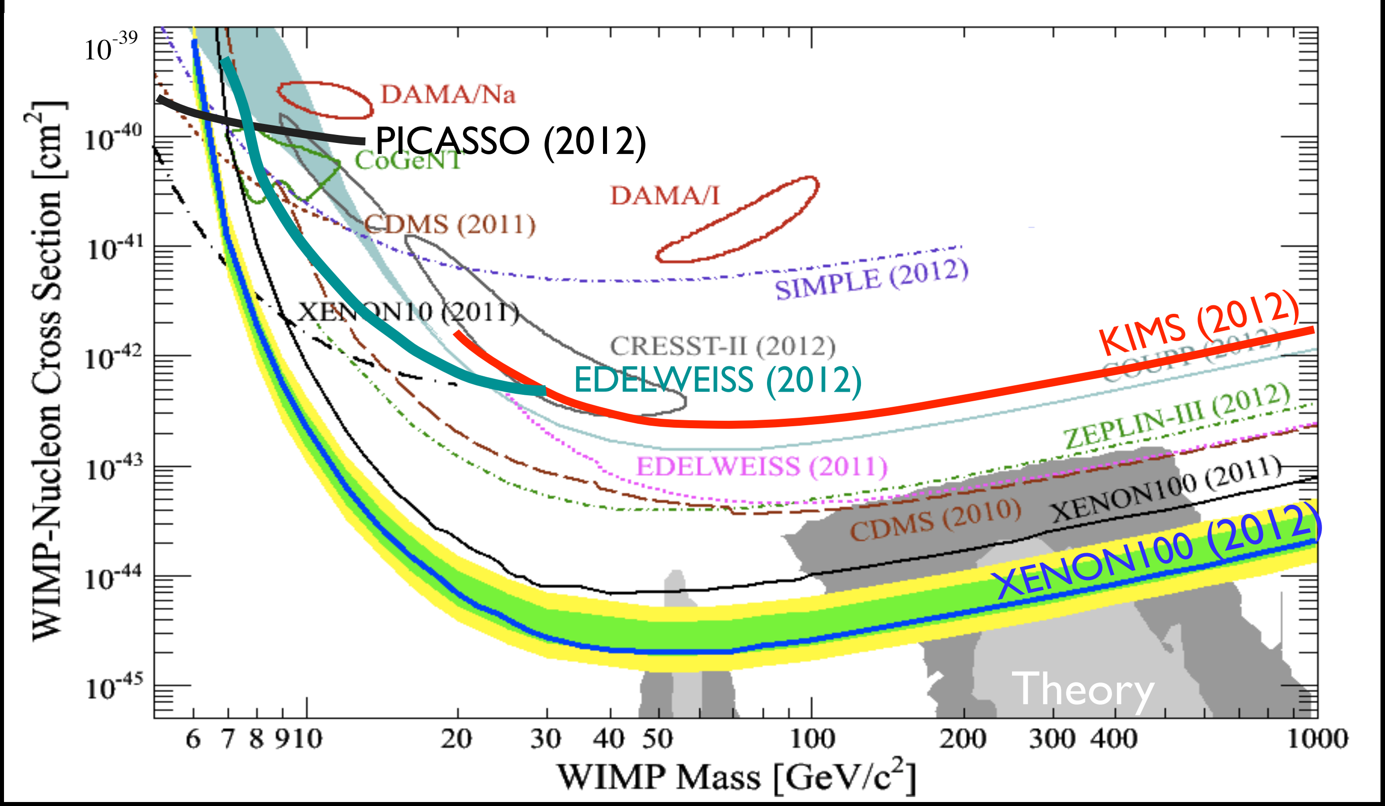
No significant modulation

Same target material

Ahmed et al (CDMS) 1203.1309

Not so many events

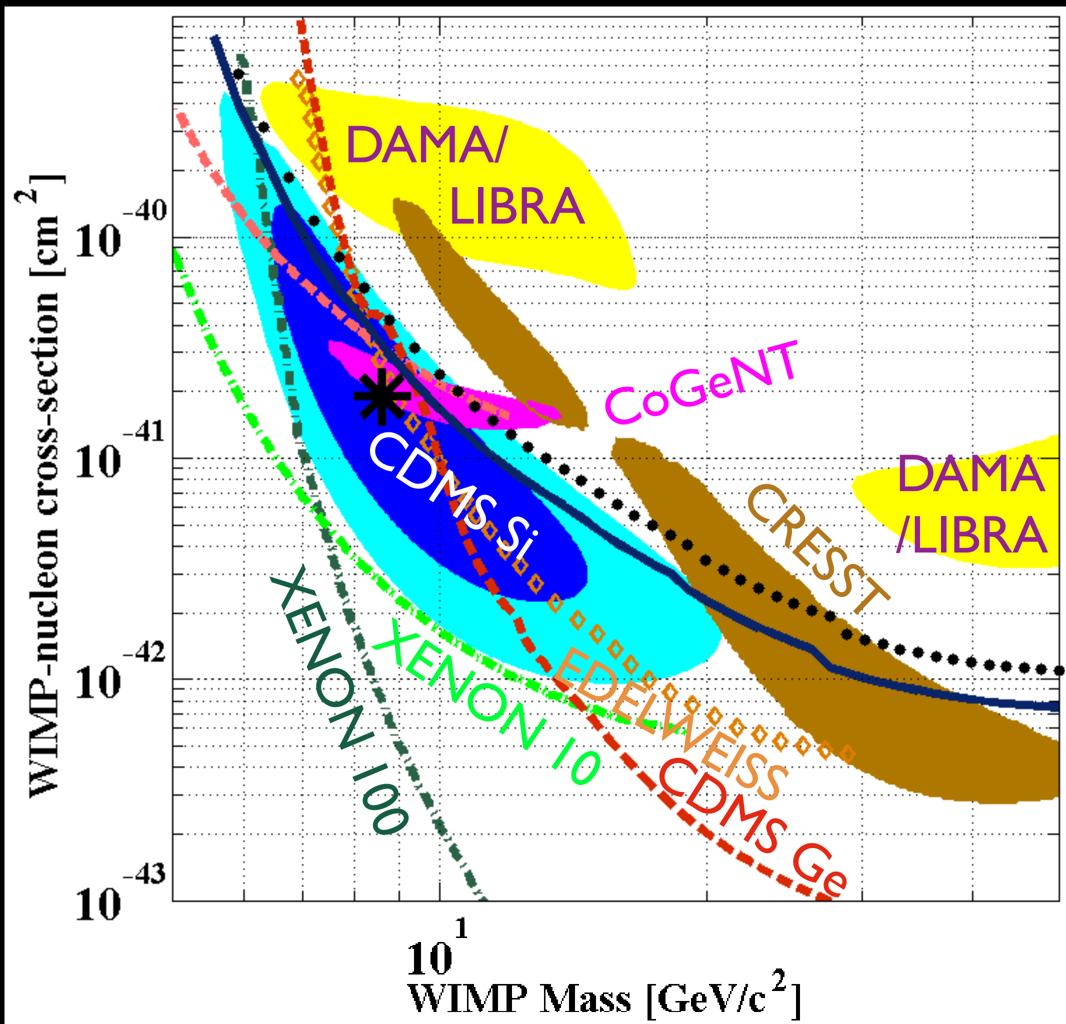
Adapted from Aprile et al (XENON-100) 2012



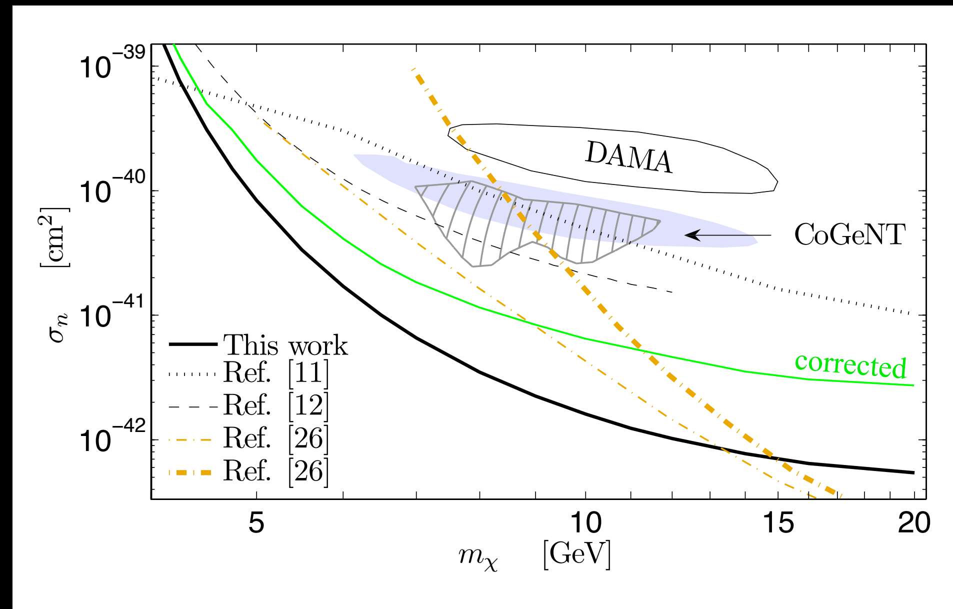
Evidence for light dark matter particles?

Angle et al (XENON10) 2013

3 events in CDMS-Si



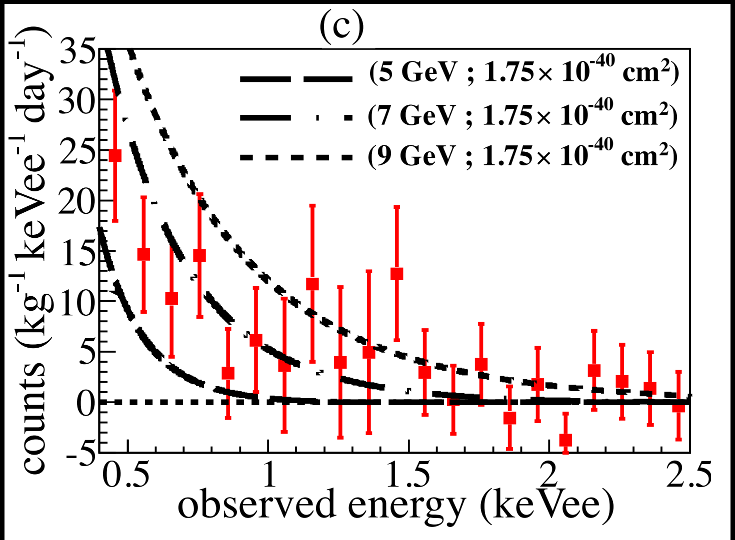
CDMS Si (2013)
CDMS Si (all)



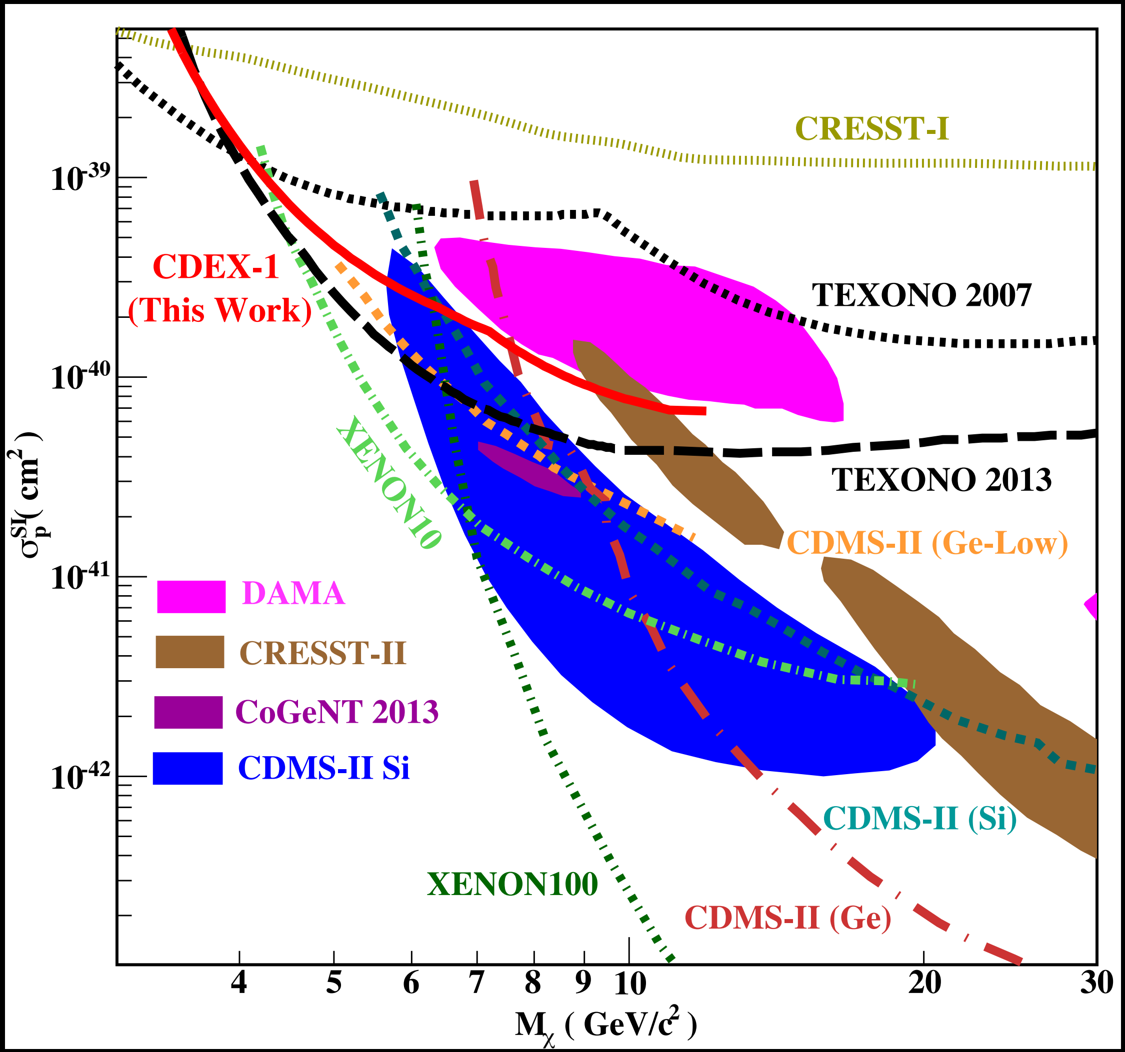
XENON10 bound weaker

Agnese et al (CDMS) 2013

Evidence for light dark matter particles?



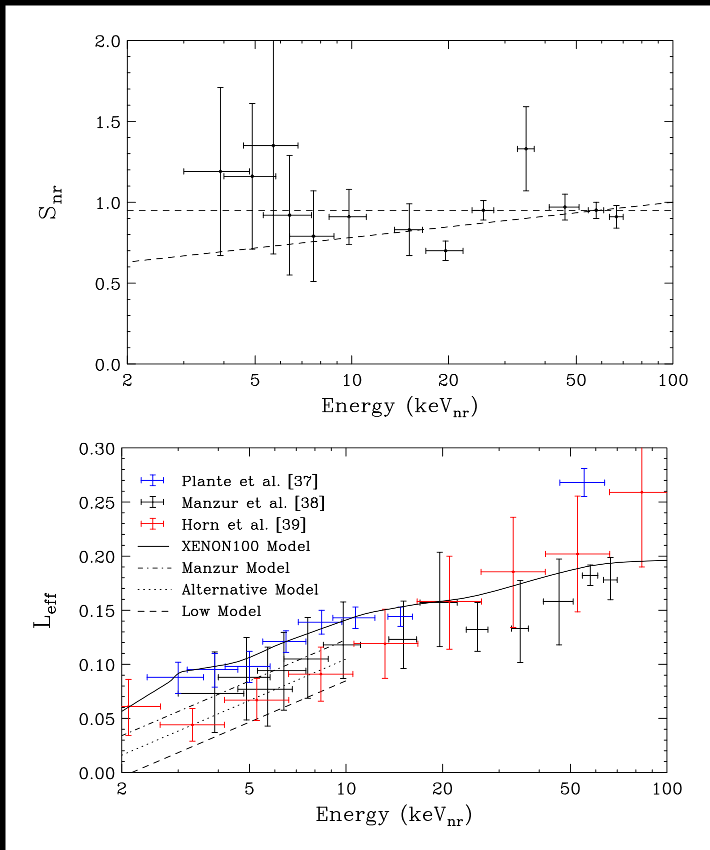
Zhao et al (CDEX) 2013



No events in CDEX (same target as CoGeNT and CDMS-Ge)

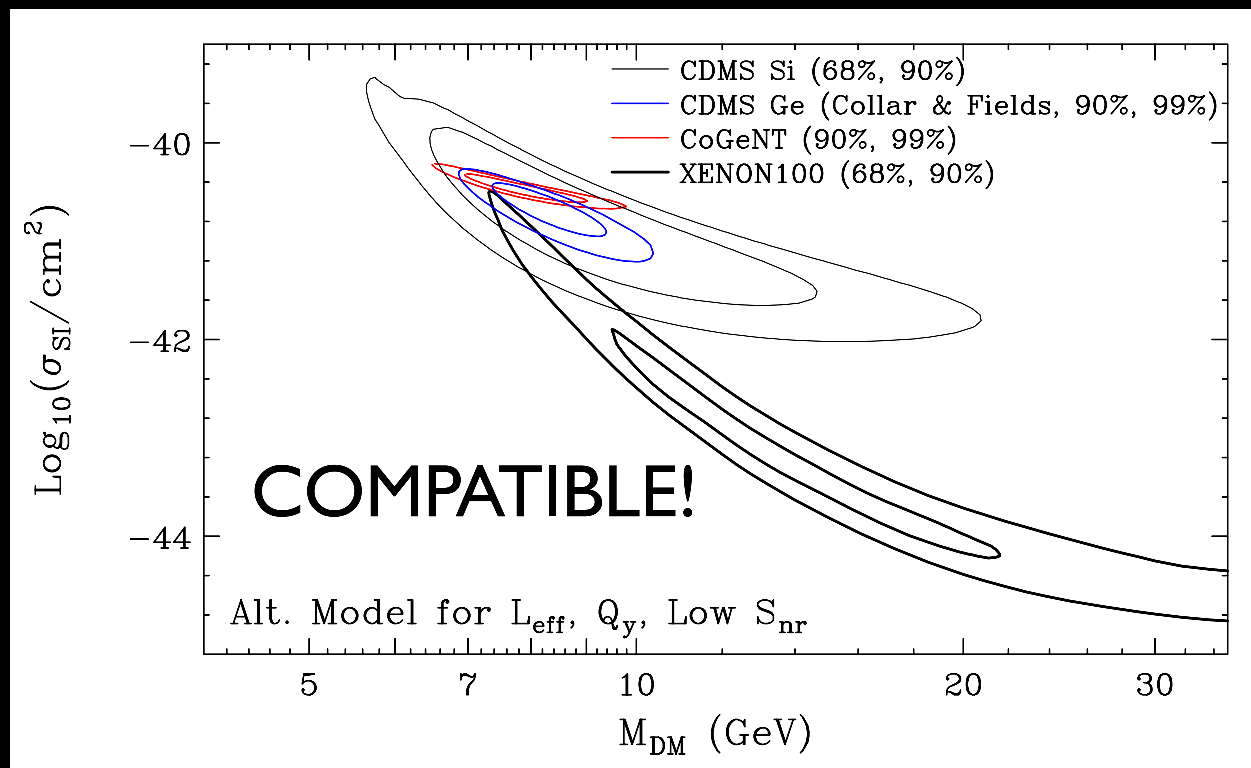
Evidence for light dark matter particles?

Hooper 2013



XENON100 detects events too!

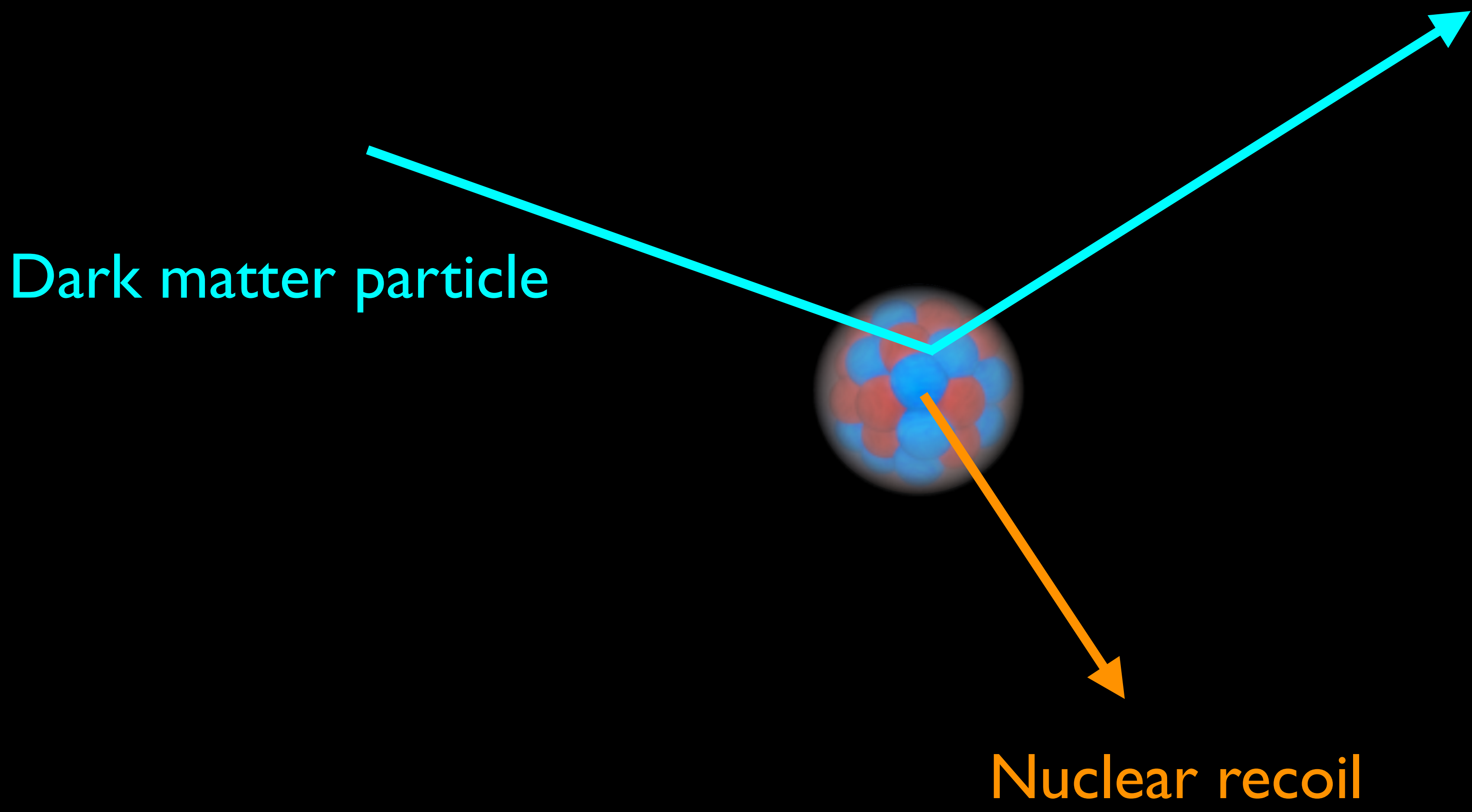
Is XENON100's sensitivity overestimated?



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

DM-nucleus elastic scattering

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



Particle physics model

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

What force couples dark matter to nuclei?

Coupling to either nucleon number density or nucleon spin density

Spin-independent and spin-dependent cross sections

$$\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} = \frac{\sigma_{SI}(E) + \sigma_{SD}(E)}{2m\mu^2}$$

Reduced mass $\mu = mM/(m+M)$

$$\sigma(E) = E_{\max}\frac{d\sigma}{dE} = \frac{2\mu^2 v^2}{m}\frac{d\sigma}{dE}$$

Particle physics model

1-10 GeV WIMP; very incomplete

Models		References
SUSY	MSSM neutralino	*Goldberg 1983; Griest 1988; Gelmini, Gondolo, Roulet 1989; Griest, Roszkowski 1991; Bottino et al 2002-11; ~~Kuflik, Pierce, Zurek 2010~~; ~~Feldman et al 2010~~; ~~Cumberbatch et al 2011~~; Belli et al 2011; .....*
SUSY	beyond-MSSM neutralino	*Flores, Olive, Thomas 1990; Gunion, Hooper, McElrath 2005; Belikov, Gunion, Hooper, Tait 2011; Belanger, Kraml, Lessa 1105.4878; ......*
SUSY	sneutrino	*.....; An, Dev, Cai, Mohapatra 1110.1366; Cerdeno, Huh, Peiro, Seto 1108.0978; .....*
minimalist dark matter (real singlet scalar with Z_2)		*Silveira, Zee 1985; Veltman, Ydnurain 1989; McDonald 1994; Burgess, Pospelov, ter Veldhuis 2000; Davoudiasl, Kitano, Li, Murayama 2004; Andreas et al 2008-10; He, Tandean 1109.1267; .....*
technicolor and alike		*....; Lewis, Pica, Sannino 1109.3513; .....*
kinetically-mixed U(1)' (Higgs portal)		*.....; Foot 2003-10; Kaplan et al 1105.2073; An, Gao 1108.3943; Fornengo, Panci, Regis 1108.4661; Andreas, Goodsell, Ringwald 1109.2869; Andreas 1110.2636; Feldman, Perez, Nath 1109.2901; ......*
baryonic U(1)'		*Gondolo, Ko, Omura ; Cline, Frey 1109.4639; ......*
....		....

Particle physics model

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

Energy and/or velocity dependent scattering cross sections

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

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

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

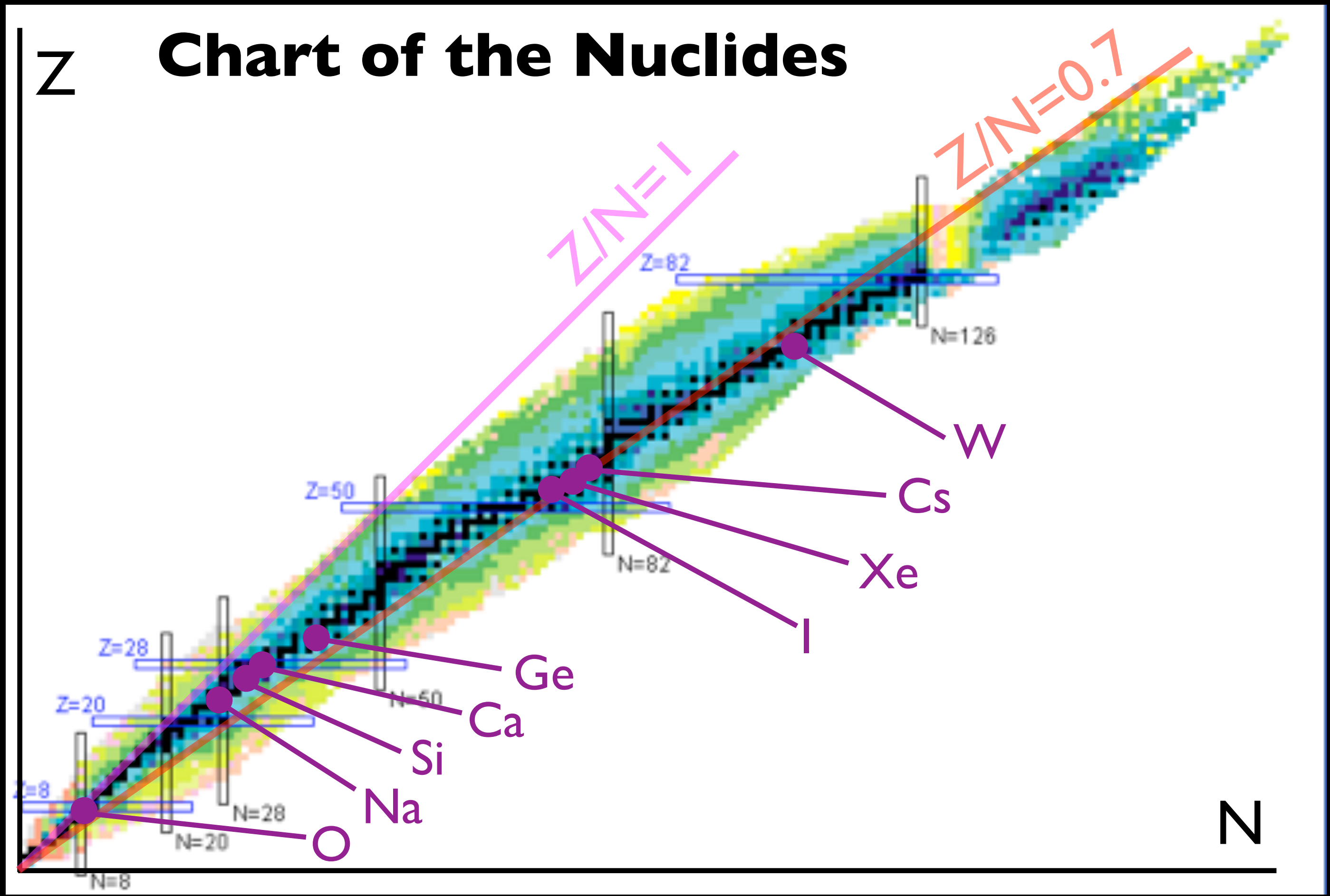
Isospin-violating dark matter

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

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



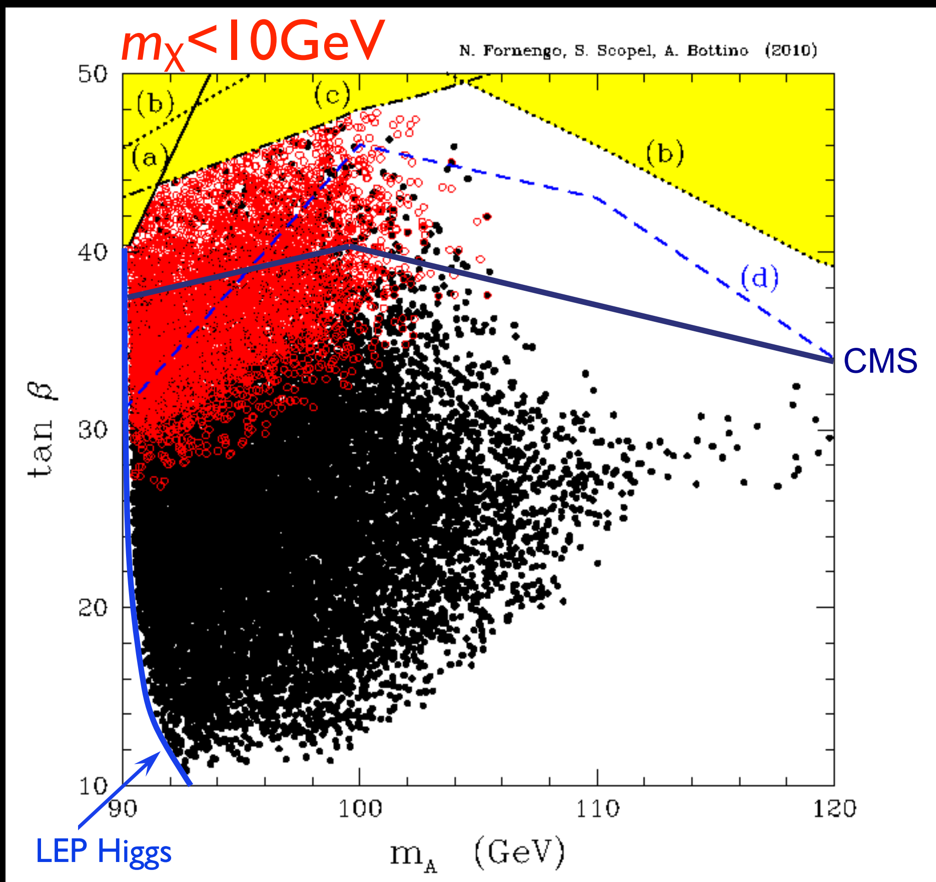
Light neutralinos in the MSSM

Bottino, Donato, Fornengo, Scopel 2003-2011   *Non-GUT MSSM*

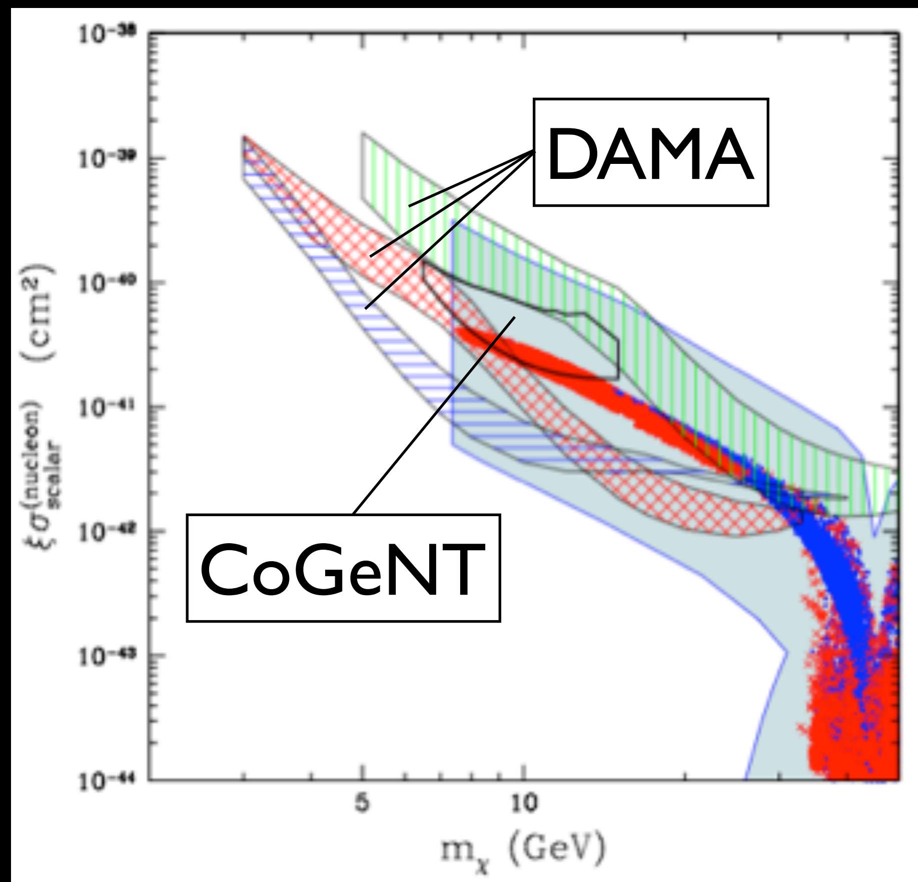
~10 GeV neutralinos may account for DAMA, CoGeNT, and CRESST

"light" Higgs (~90 GeV) — enhanced couplings (large $\tan\beta$*)*

Fornengo at TAUP 2011



Belli et al 1106.4667



Light neutralinos in the MSSM

Bottino, Donato, Fornengo, Scopel 2003-2011 Non-GUT MSSM

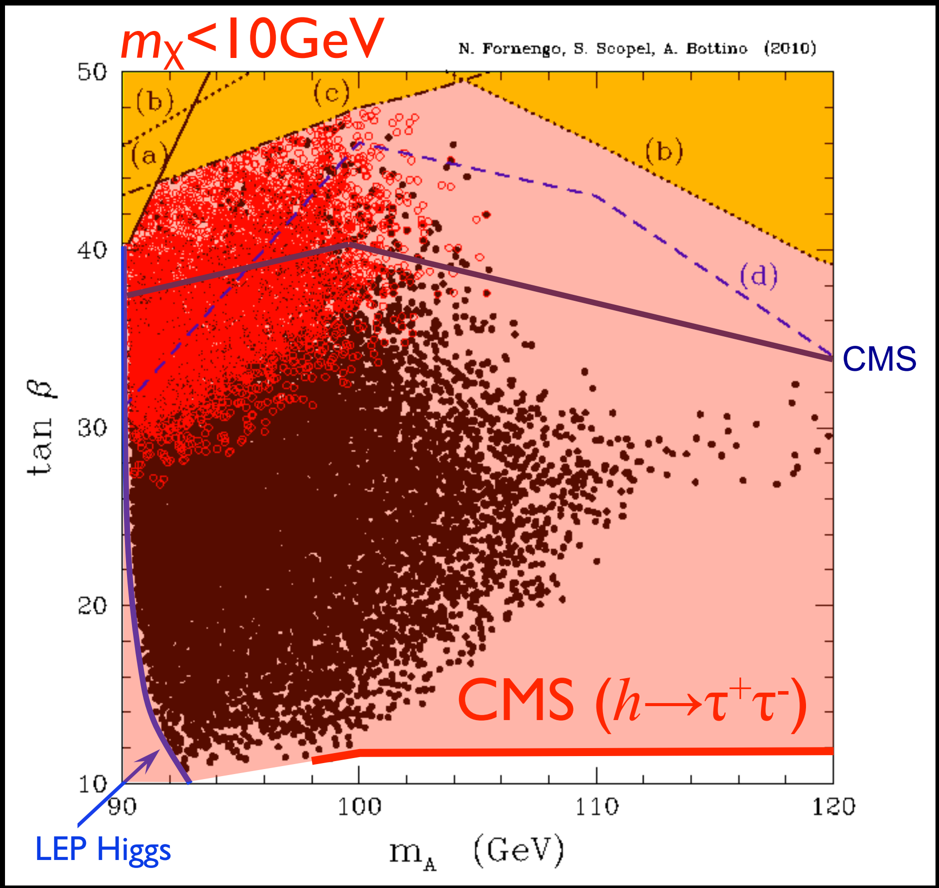
~10 GeV neutralinos may account for DAMA, CoGeNT, and CRESST

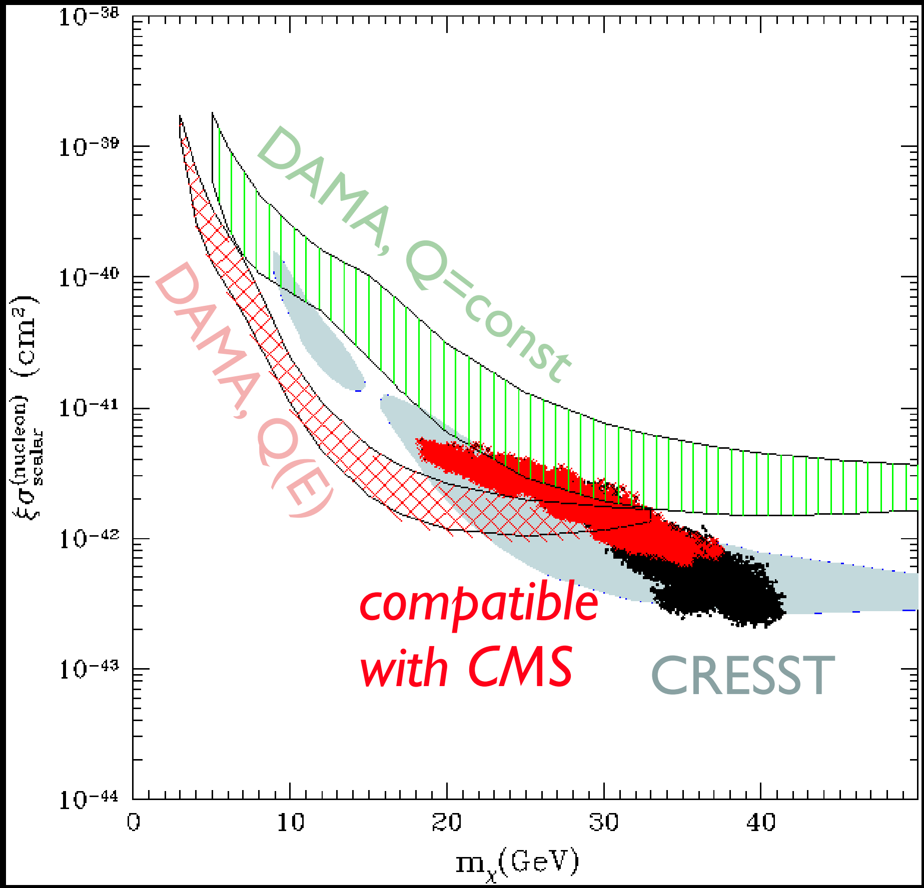
negative LHC Higgs searches impose $m_\chi > 18$ GeV

(see also Kuflik, Pierce, Zurek 2010)

Fornengo at TAUP 2011

Bottino et al 1112.5666





Minimalist dark matter

do not confuse with minimal dark matter

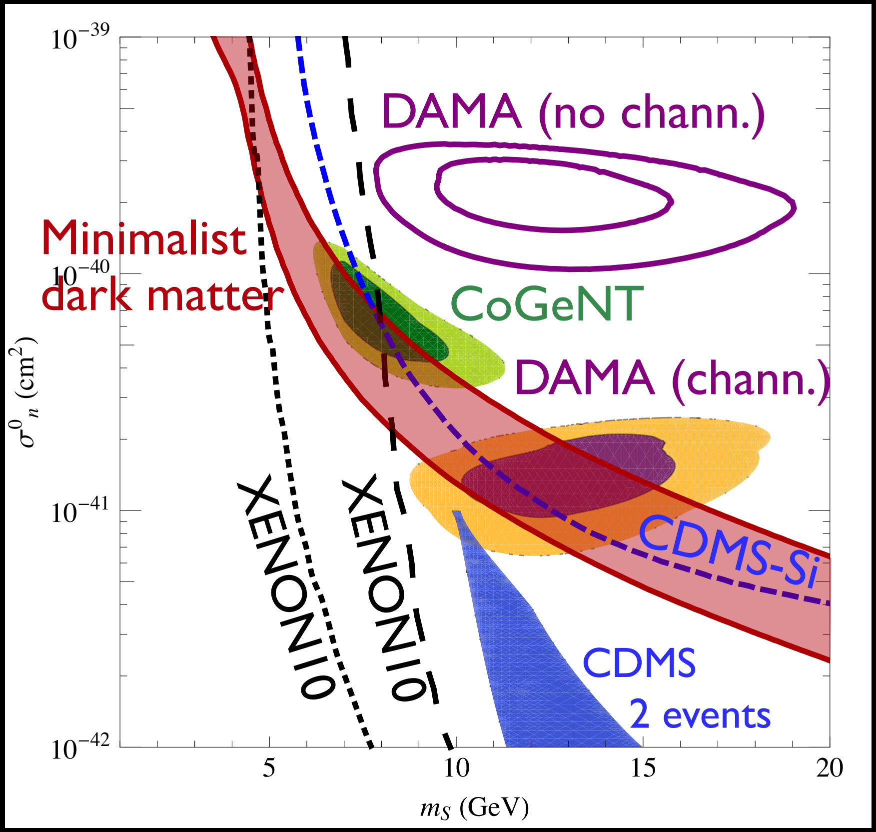
Gauge singlet scalar field S, stabilized by Z_2 symmetry

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

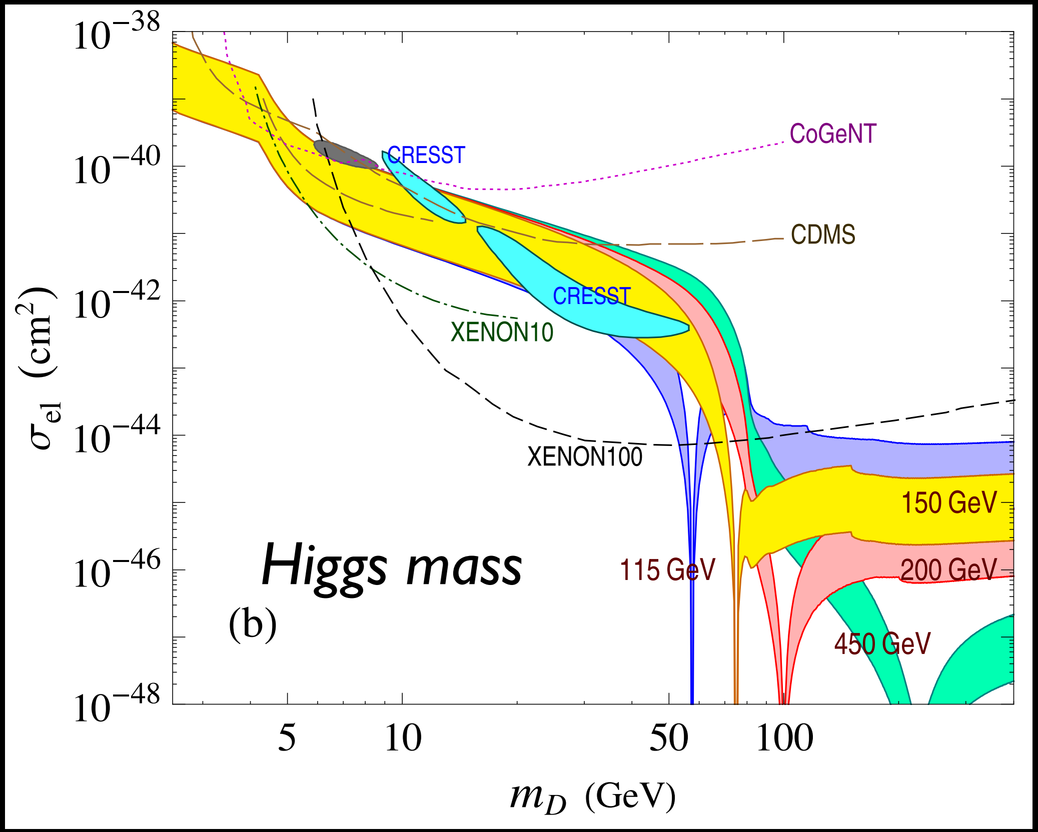
Silveira, Zee 1985

"Higgs portal scalar dark matter"

Andreas, Hambye, Tytgat 2008



Andreas, Arina, Hambye, Ling, Tytgat 2010



He, Tandean 2011

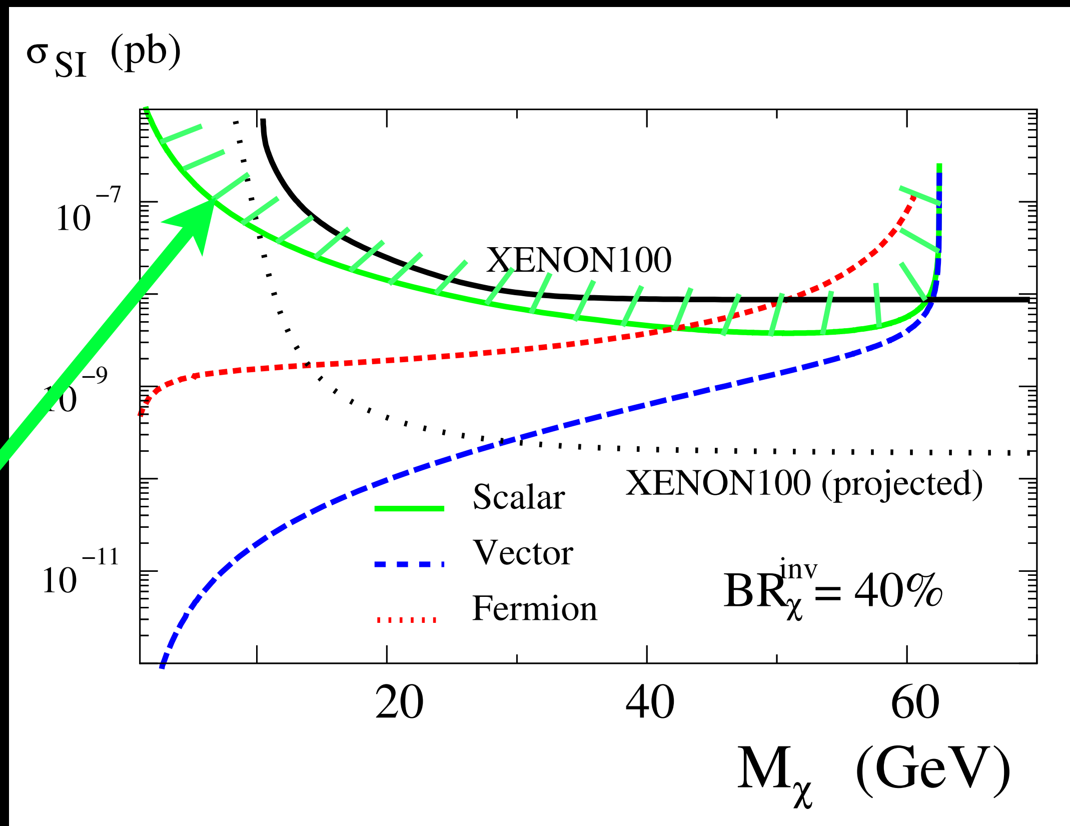
Minimalist dark matter

do not confuse with minimal dark matter

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

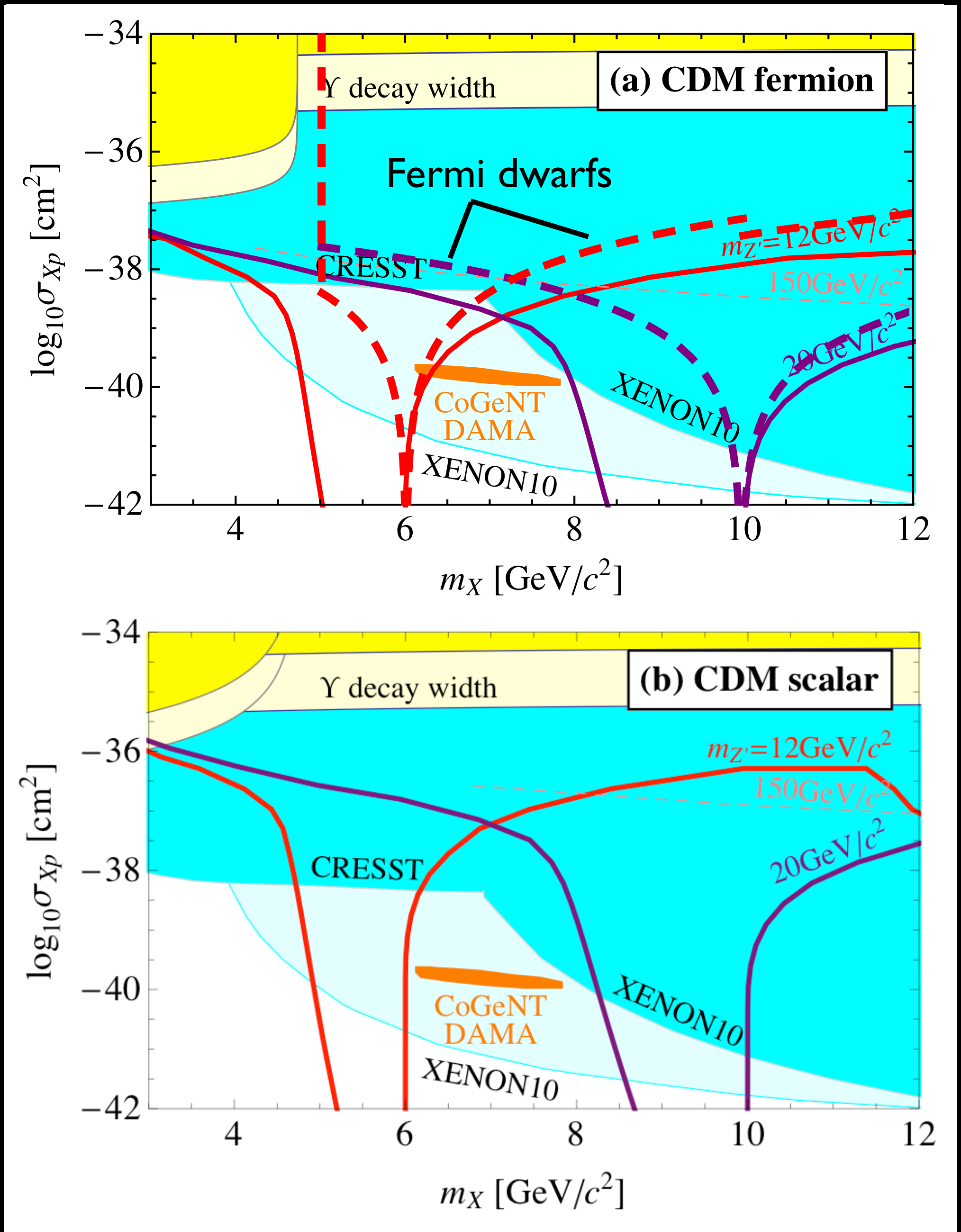
Light WIMP region

LHC limit



Djouadi, Falkowski, Mambrini, Quevillon 2012

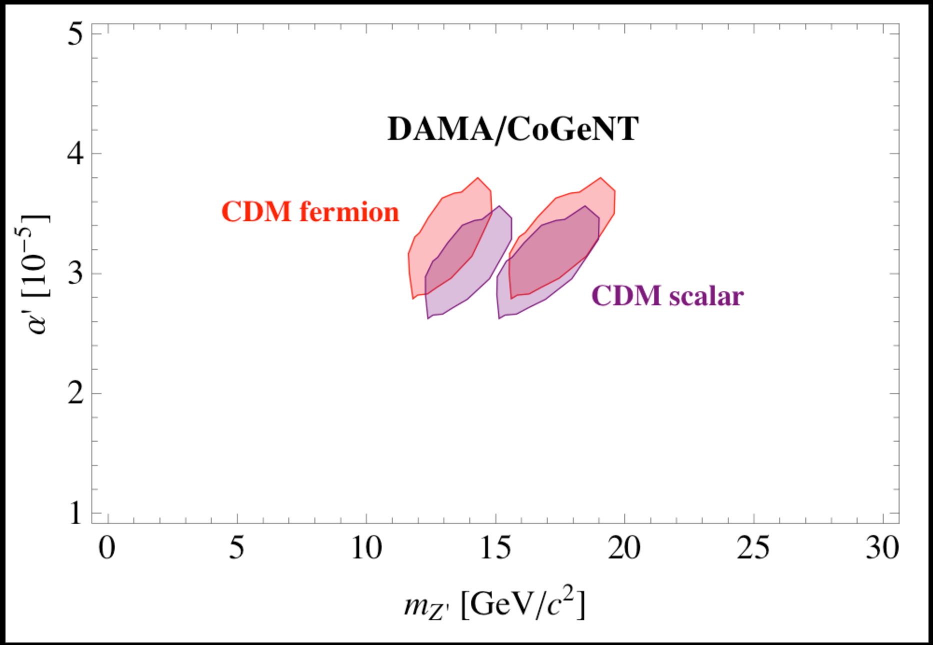
Light WIMPs with light Z' boson



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

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

How much dark matter comes to Earth?

Local halo density

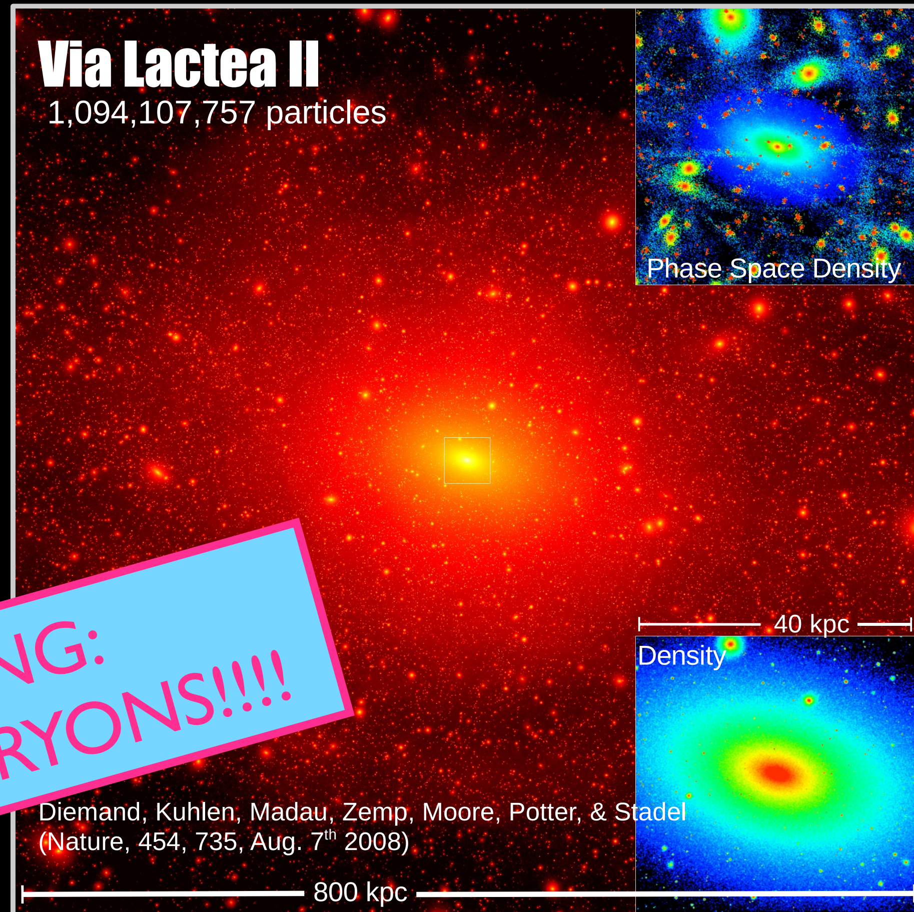
Velocity distribution

$$(\text{astrophysics}) = \rho \int_{v > v_{\min}(E)} \frac{f(\vec{v}, t)}{v} \, \mathrm{d}^3 v$$

Minimum speed to impart energy E, $v_{\min}(E) = (ME/\mu + \delta)/\sqrt{2ME}$

Astrophysics model: velocity distribution

We know very little about the dark matter velocity distribution



WARNING: NO BARYONS!!!!

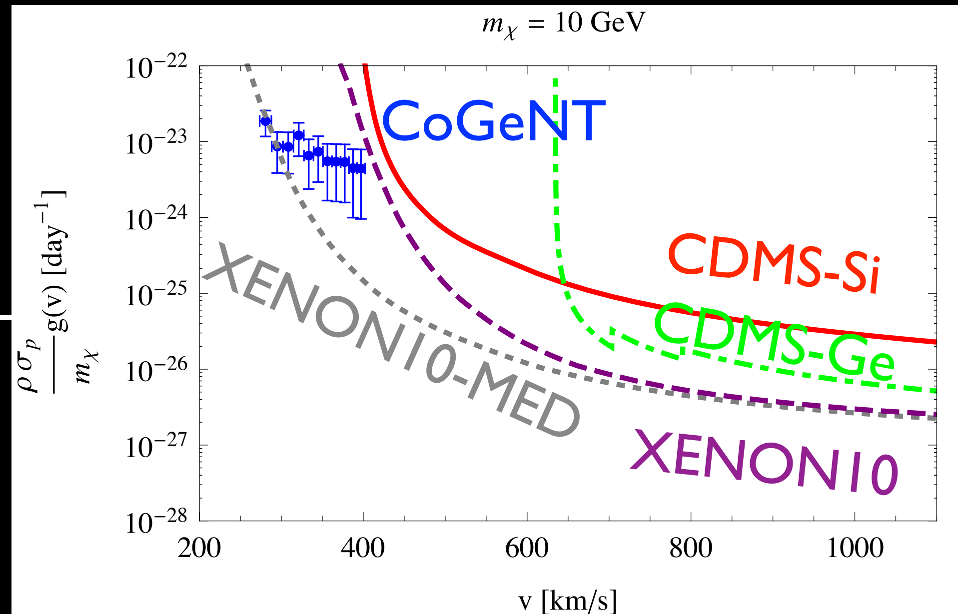
Cosmological N-Body simulations including baryons are challenging

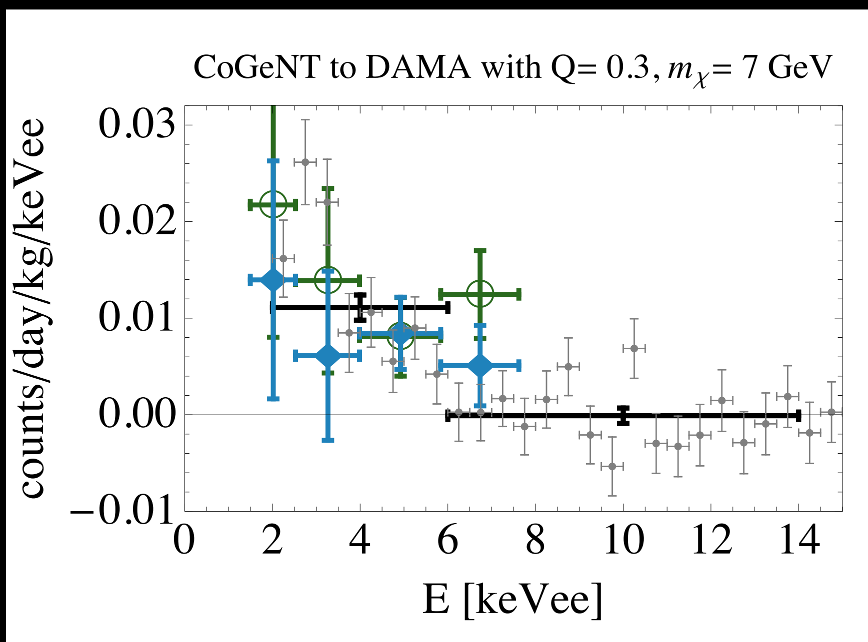
Astrophysics-independent approach

Fox, Liu, Weiner 2011

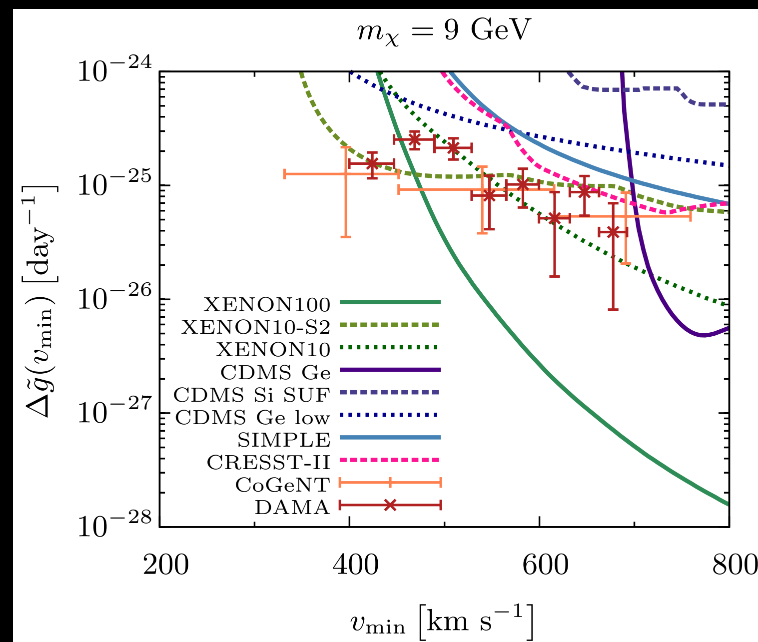
Astrophysics factor

$$\frac{\rho_\chi \sigma_{\chi p} c^2}{m_\chi} \int_v^\infty \frac{f(v')}{v'} dv'$$





Fox, Kopp, Lisanti, Weiner 2011



Frandsen et al 2011

Astrophysics-independent approach

Include energy dependence of efficiency and energy response function.

Gondolo Gelmini 1202.6359

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

Measured energy

Effective energy response function

Recoil energy

Change variables:

$$v_{\rm min} = \sqrt{\frac{m_T E}{2\mu^2}}$$

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

Minimum WIMP speed to impart recoil energy E

Halo-independent factor accessible to experiments

Astrophysics-independent approach

Include energy dependence of efficiency and energy response function.

Gondolo Gelmini 1202.6359

Expected rate in energy interval $[E_1, E_2]$

$$R_{[E'_1,E'_2]} = \int_0^\infty \mathcal{R}_{[E'_1,E'_2]}(v_{\min})\ \tilde{\eta}(v_{\min})\ dv_{\min}$$

Response function

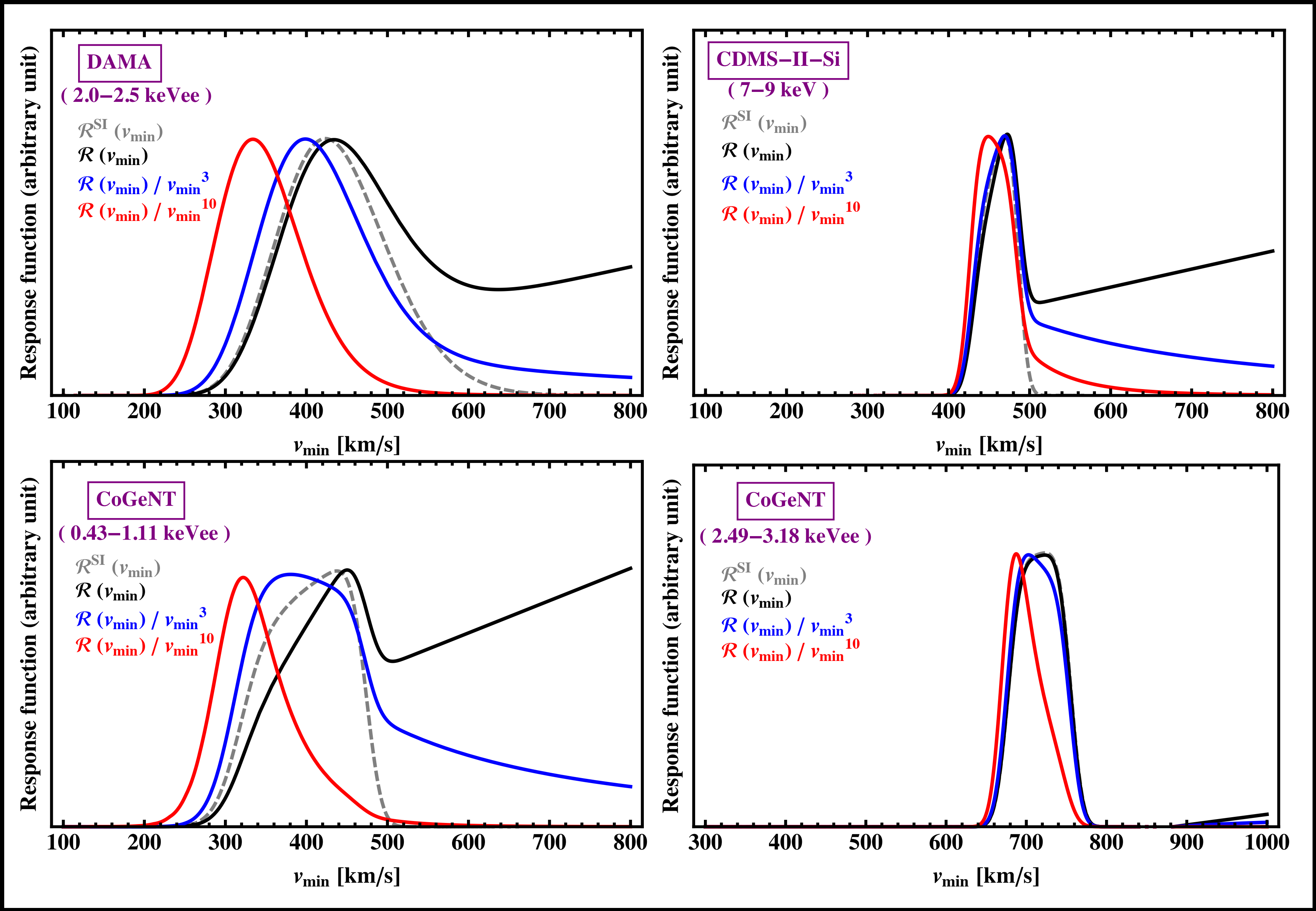
Estimate of halo-independent factor in velocity interval $[v_1, v_2]$

$$\bar{\tilde{\eta}}_{[v_1,v_2]} = \frac{R^{\text{measured}}_{[E'_1,E'_2]}}{\int_0^\infty \mathcal{R}_{[E'_1,E'_2]}(v_{\min})\, dv_{\min}}$$

$$\tilde{\eta}(v) < \frac{R^{\text{upper limit}}_{[E'_1,E'_2]}}{\int_0^v \mathcal{R}_{[E'_1,E'_2]}(v_{\min})\, dv_{\min}}$$

Astrophysics-independent approach

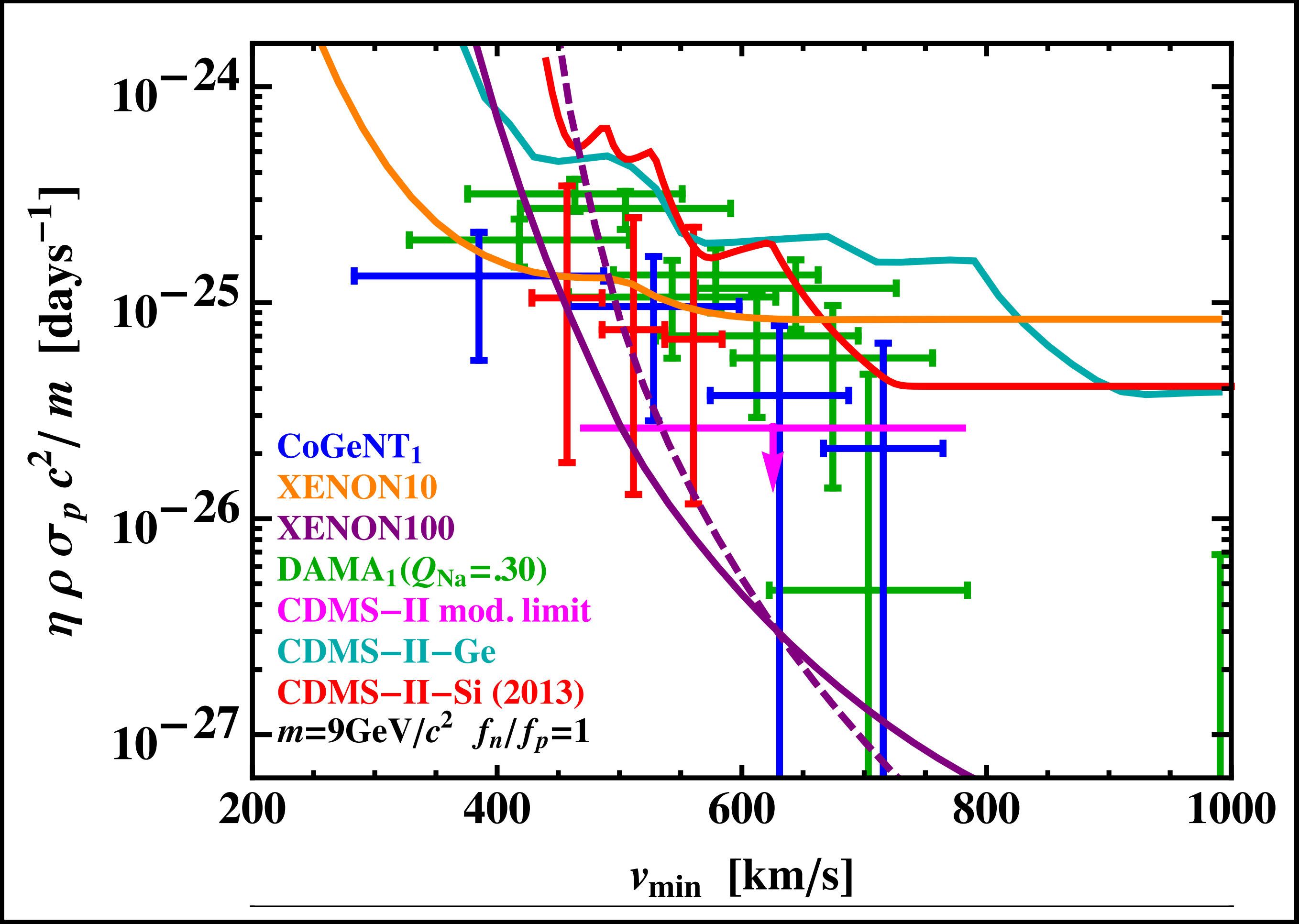
Include energy dependence of efficiency and energy response function.



Del Nobile, Gelmini, Gondolo, Huh 2013

Astrophysics-independent approach

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



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

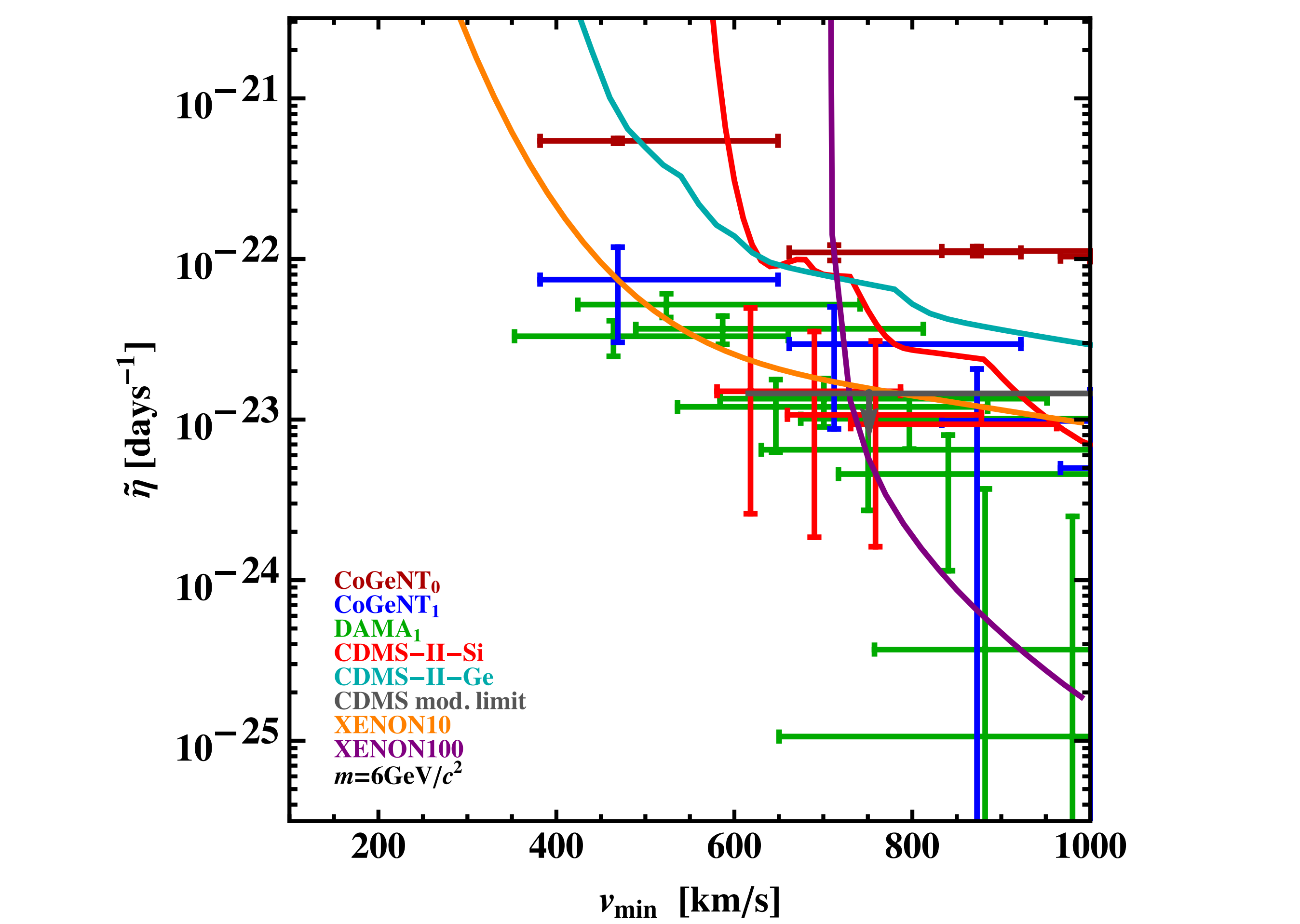
CDMS-Si event rate is similar to annual modulated rates

Del Nobile, Gelmin, Gondolo, Huh 2013

Still depends on particle model

Astrophysics-independent approach

Anomalous magnetic moment dark matter



Del Nobile, Gelmin, Gondolo, Huh 2013

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

CDMS-Si event rate is similar to annual modulated rates

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 ~10 GeV thermal WIMPs.
  - Light supersymmetric particles may still be possible beyond the MSSM. Non-supersymmetric models include a 10-20 GeV Z' boson coupled to quarks but not leptons.