Astrophysics-Independent Analysis of Direct Detection Data

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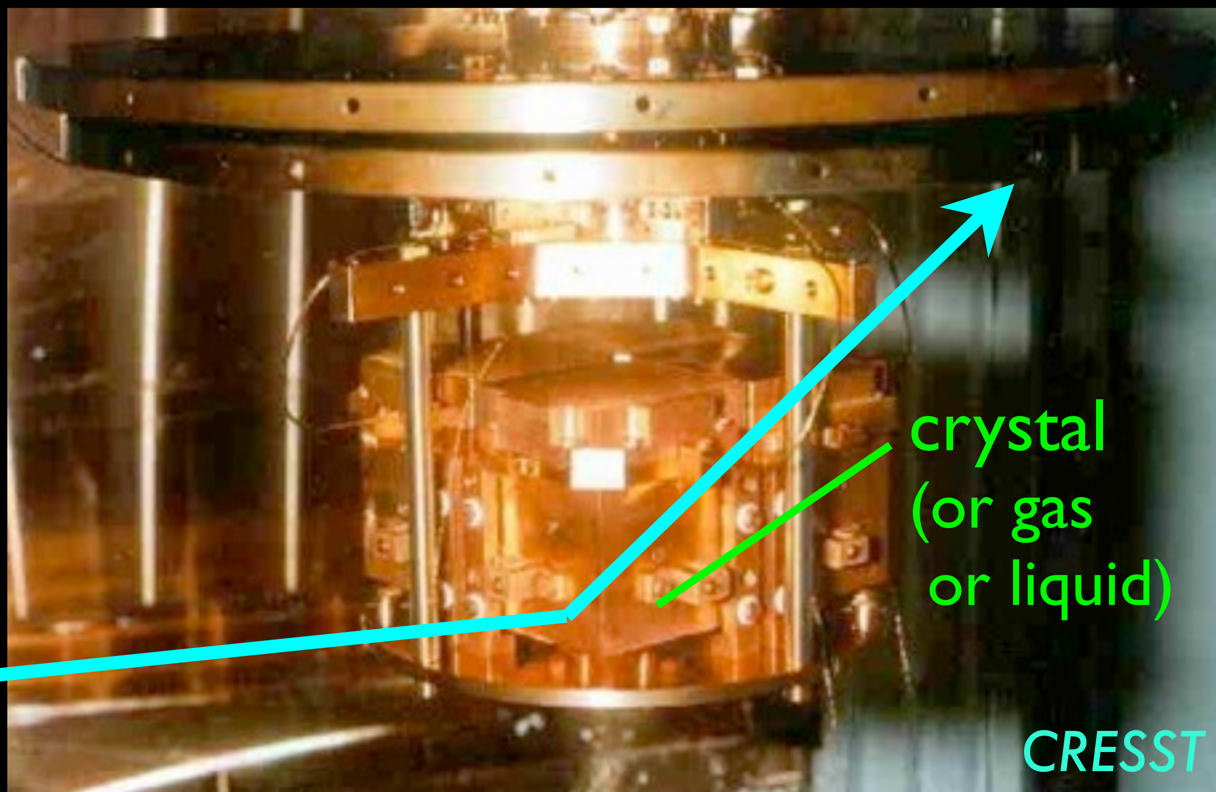
The principle of direct detection

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

Goodman, Witten 1985

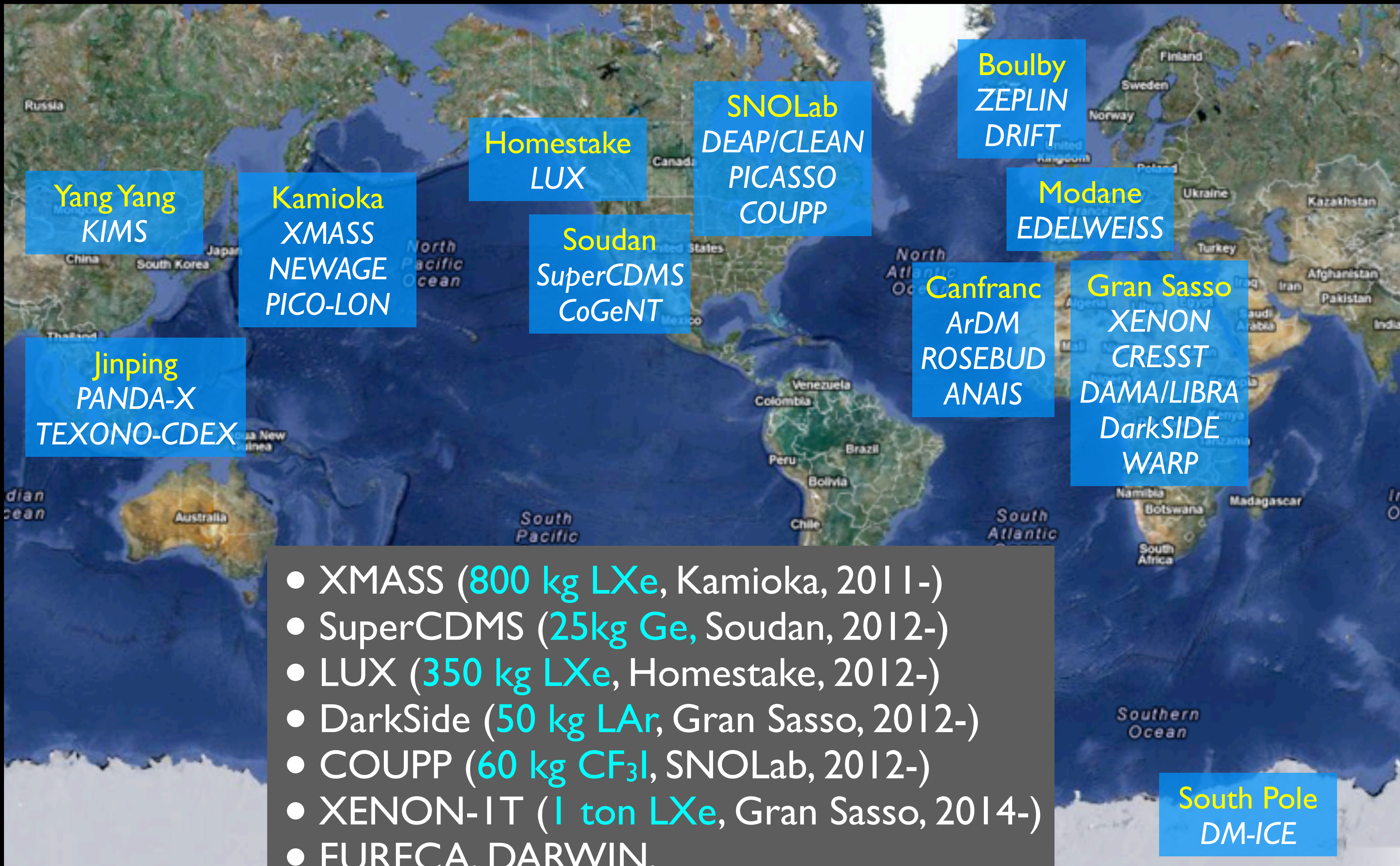
Dark matter particle



Low-background underground detector

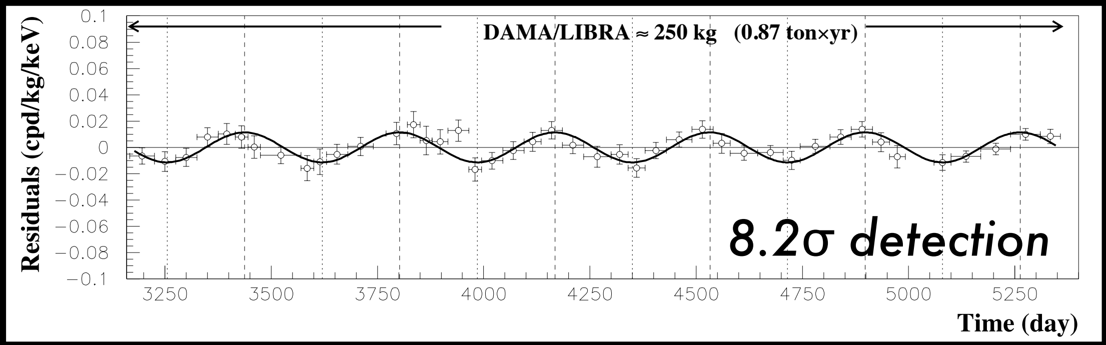
CDMS
EDELWEISS
DAMA
CRESST
KIMS
DRIFT
XENON
COUPP
CoGeNT
TARP
DMTPC
TEXONO
PANDA-X
.....

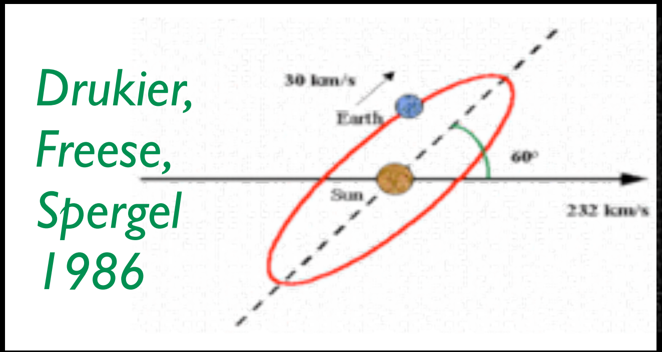
Direct dark matter searches (2013)



- 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, ...

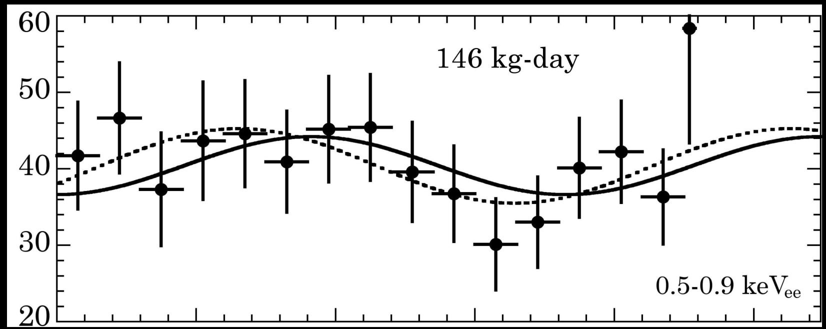
Evidence for light dark matter particles?





Bernabei et al (DAMA) 1997-10

Annually modulated.....

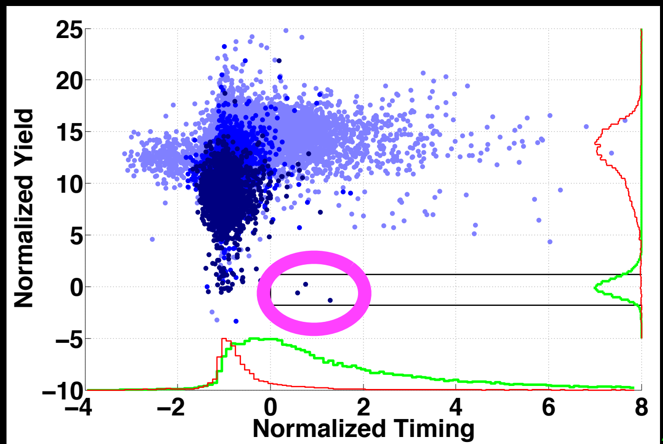


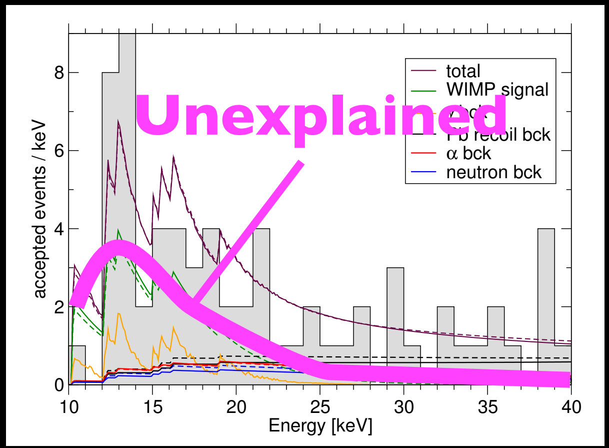
Aalseth et al (CoGeNT) 1106.0650

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

......and unmodulated

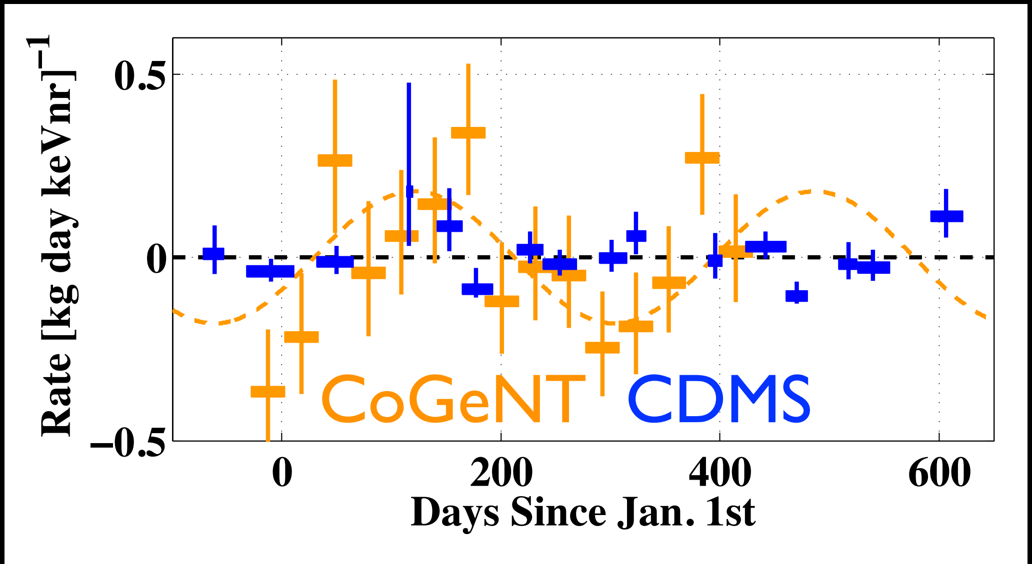
Agnese et al (CDMS) 2013





Anglehor et al (CRESST) 2011

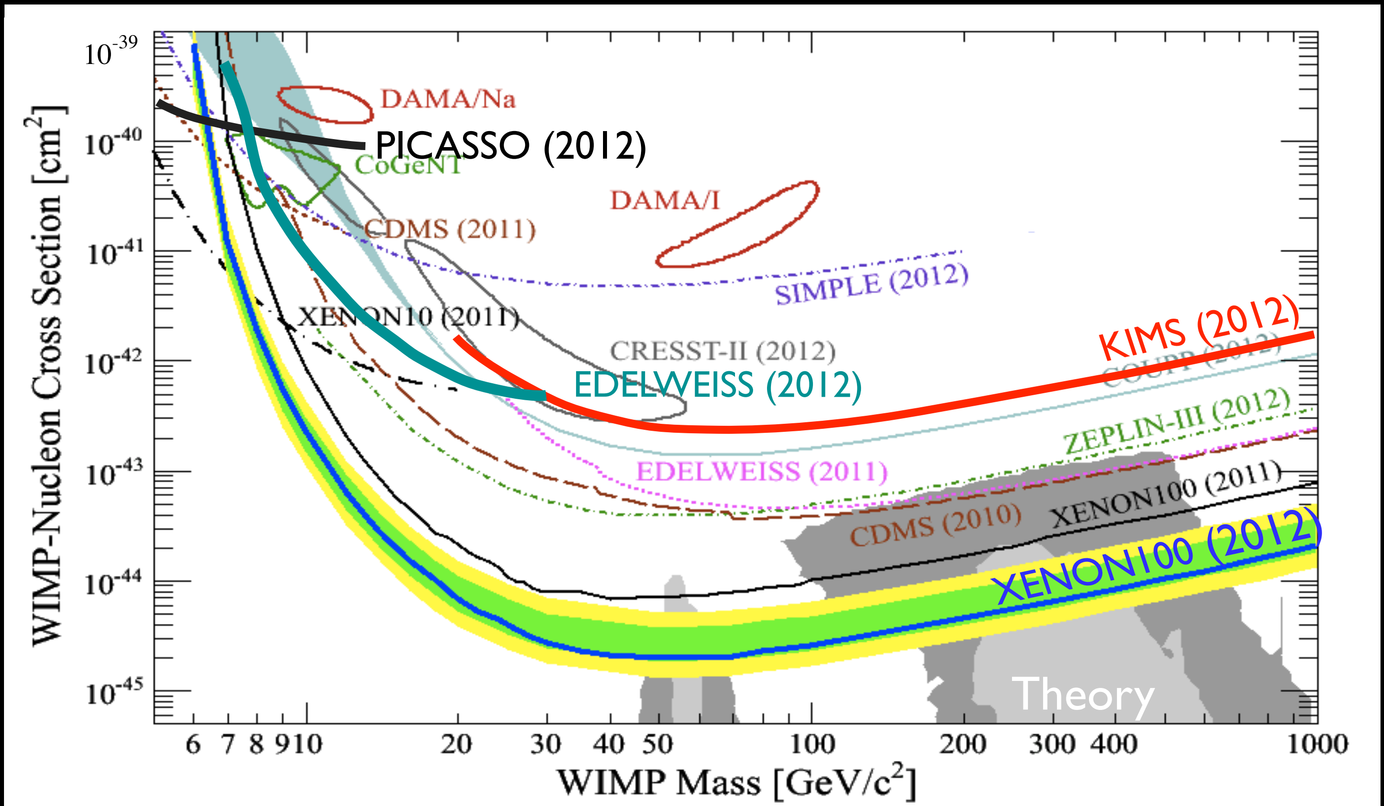
Evidence for light dark matter particles?



No significant modulation

Same target material

Ahmed et al (CDMS) 1203.1309



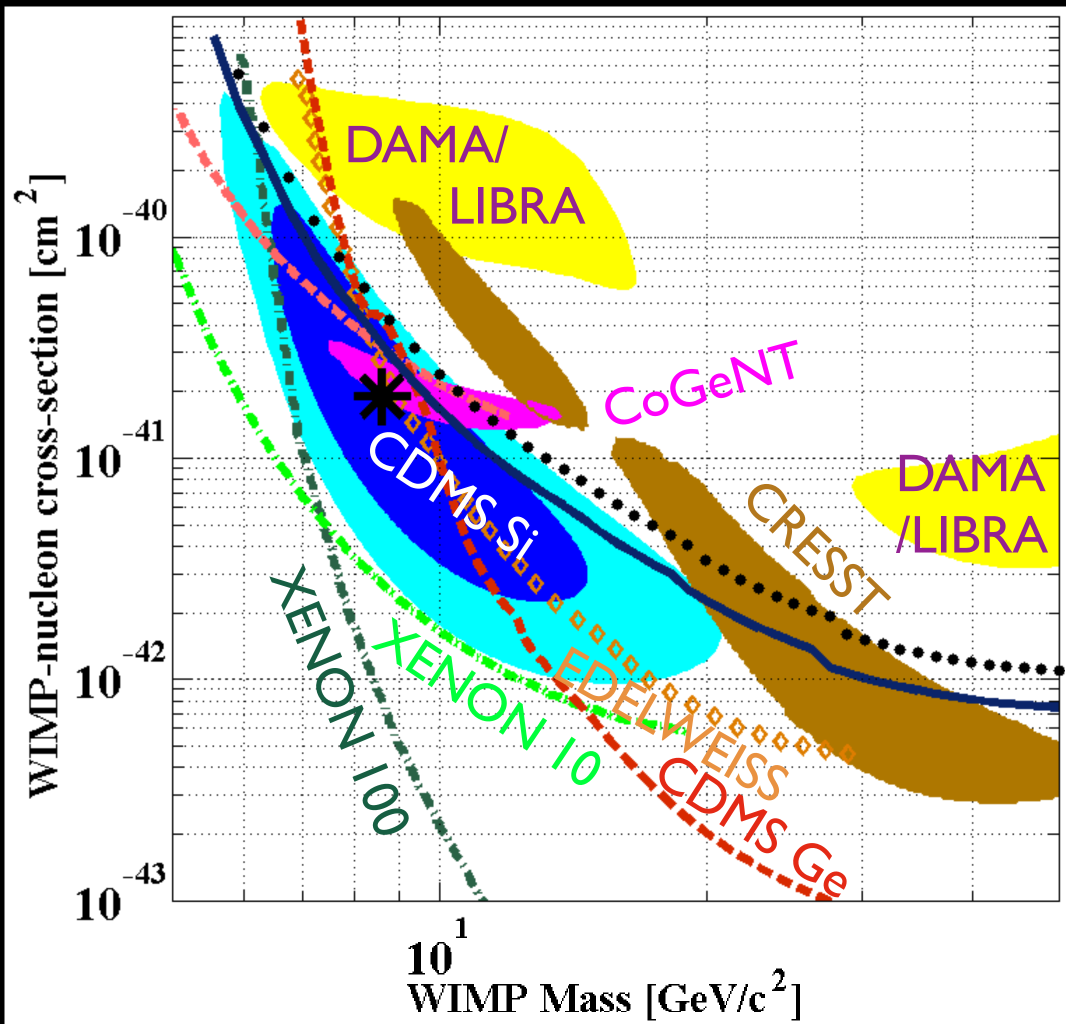
Not so many events

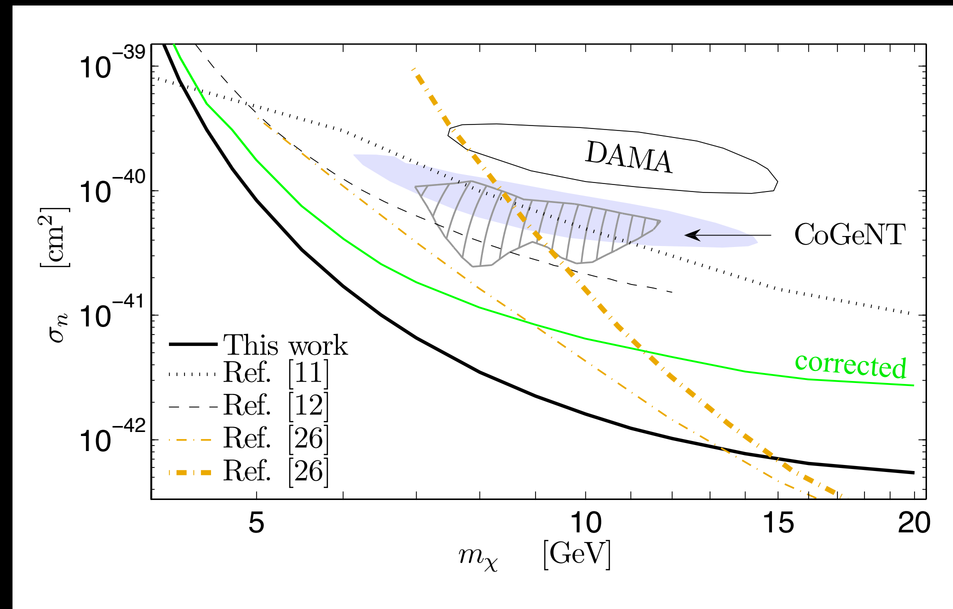
Adapted from Aprile et al (XENON-100) 2012

Evidence for light dark matter particles?

Angle et al (XENON10) 2013

3 events in CDMS-Si



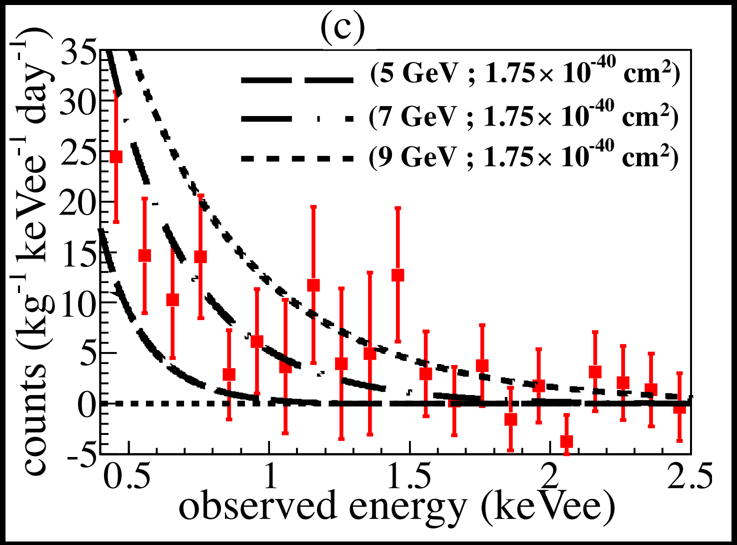


XENON10 bound weaker

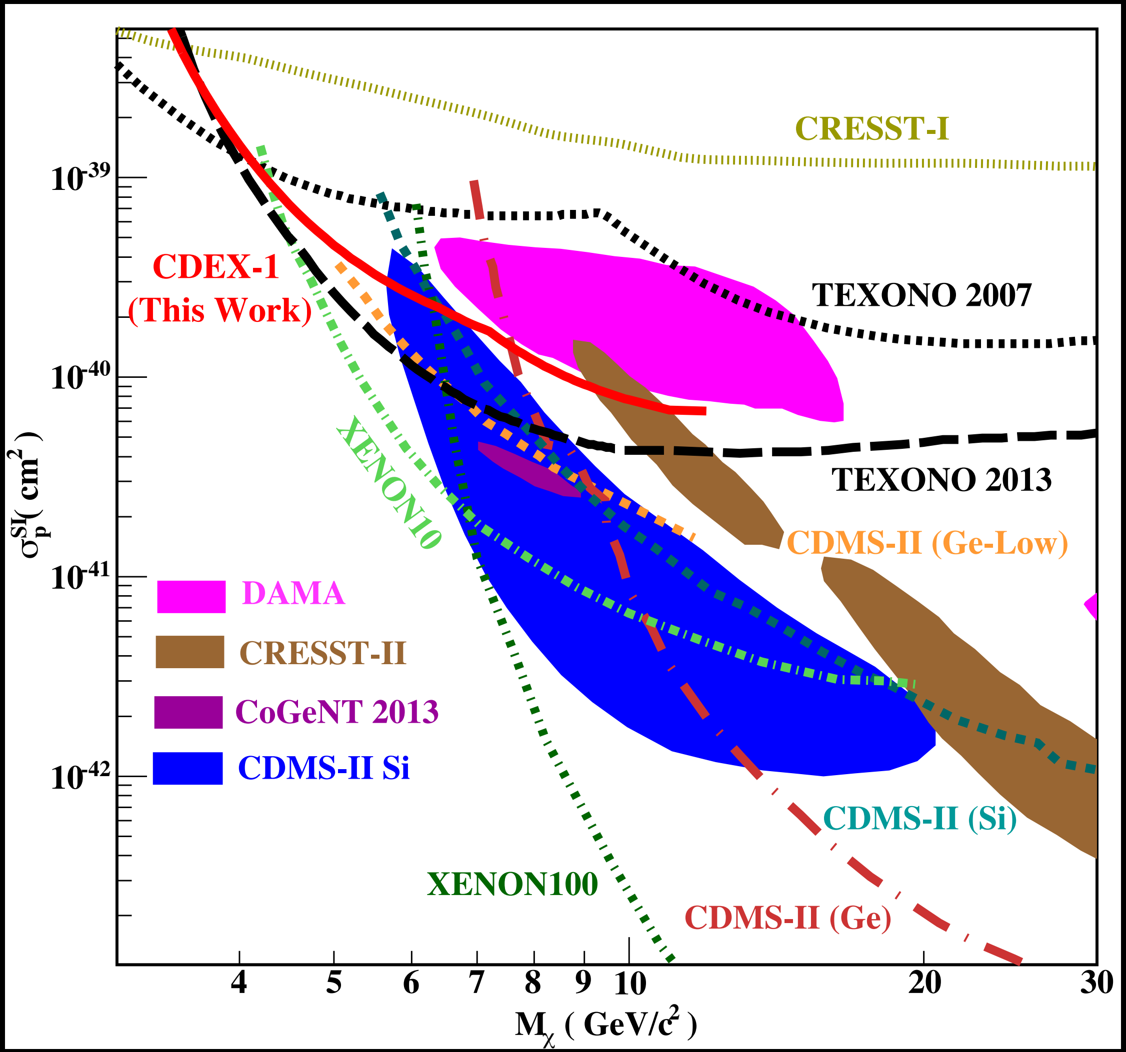
CDMS Si (2013)
CDMS Si (all)

Agnese et al (CDMS) 2013

Evidence for light dark matter particles?



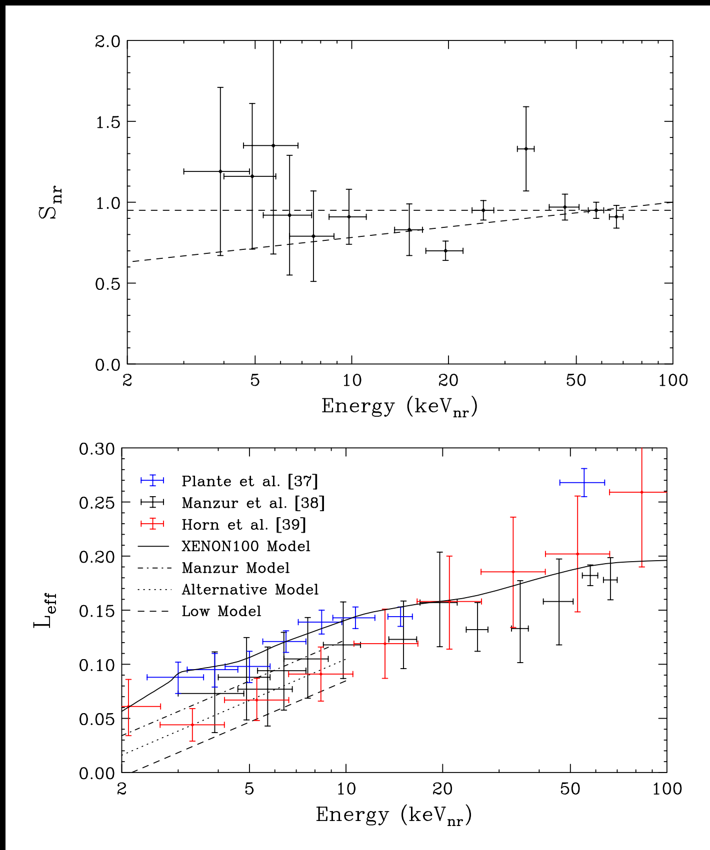
Zhao et al (CDEX) 2013



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

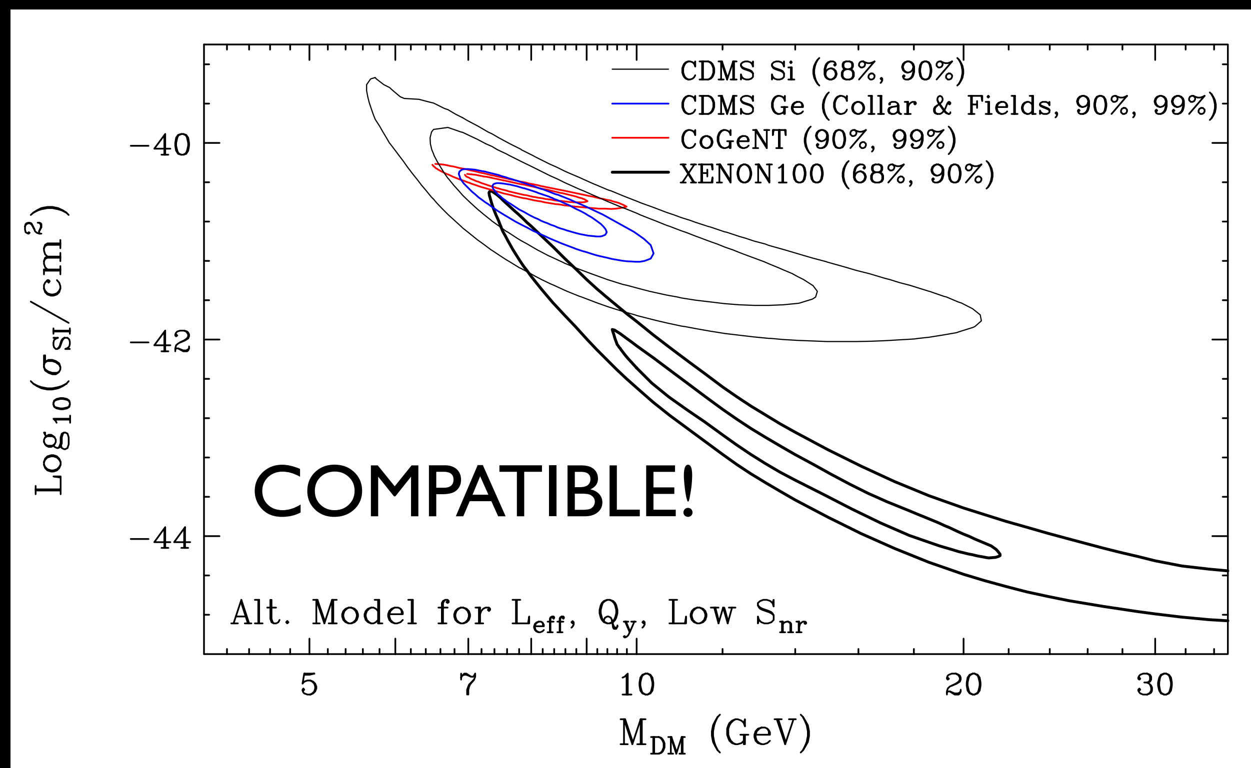
Evidence for light dark matter particles?

Hooper 2013



XENON100 detects events too!

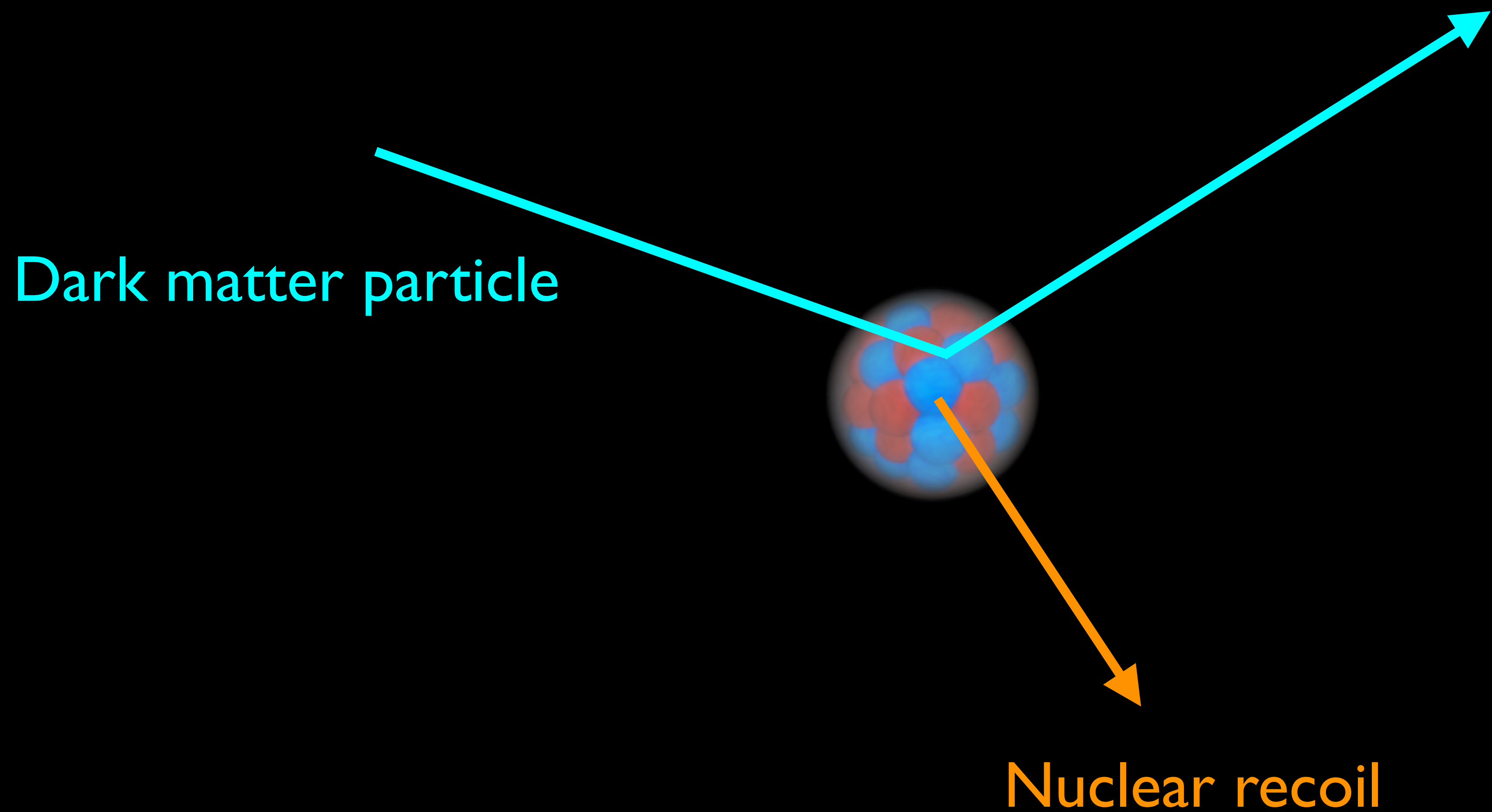
Is XENON100's sensitivity overestimated?



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

DM-nucleus elastic scattering

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



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

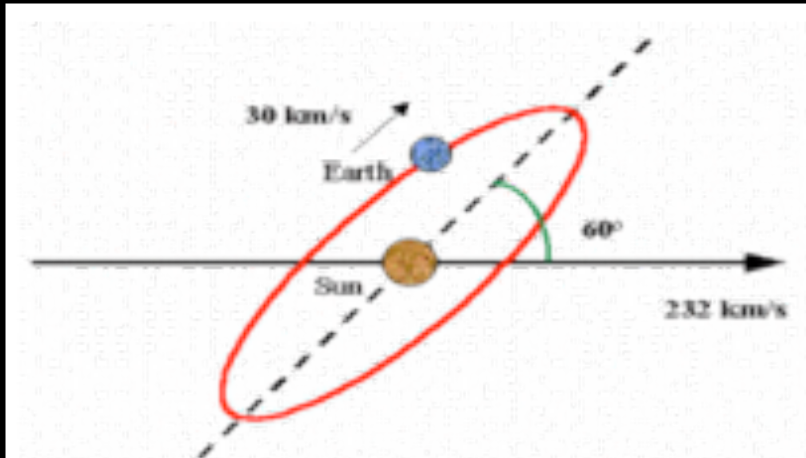
Velocity distribution

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

Minimum WIMP speed to impart recoil energy E_R

$$v_{\min} = (ME_R/\mu + \delta)/\sqrt{2ME_R}$$

Annual modulation



Drukier, Freese, Spergel 1986

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

$$\frac{dR}{dE} = \underbrace{S_0(E)}_{\text{Unmodulated signal}} + \underbrace{S_1(E)}_{\text{Modulation amplitude}}\ \cos(\omega t + \varphi)$$

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, $v^2\, d\sigma/dE_R$ = const × (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 $\tilde{\eta}(v_{\min}) = \frac{\sigma_{\chi p}}{m_\chi}\eta(v_{\min}) = \sigma_{\chi p}\frac{\rho_\chi}{m_\chi}\int_{v_{\min}}^{\infty}\frac{f(\mathbf{v})}{v}\, d^3v$

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.

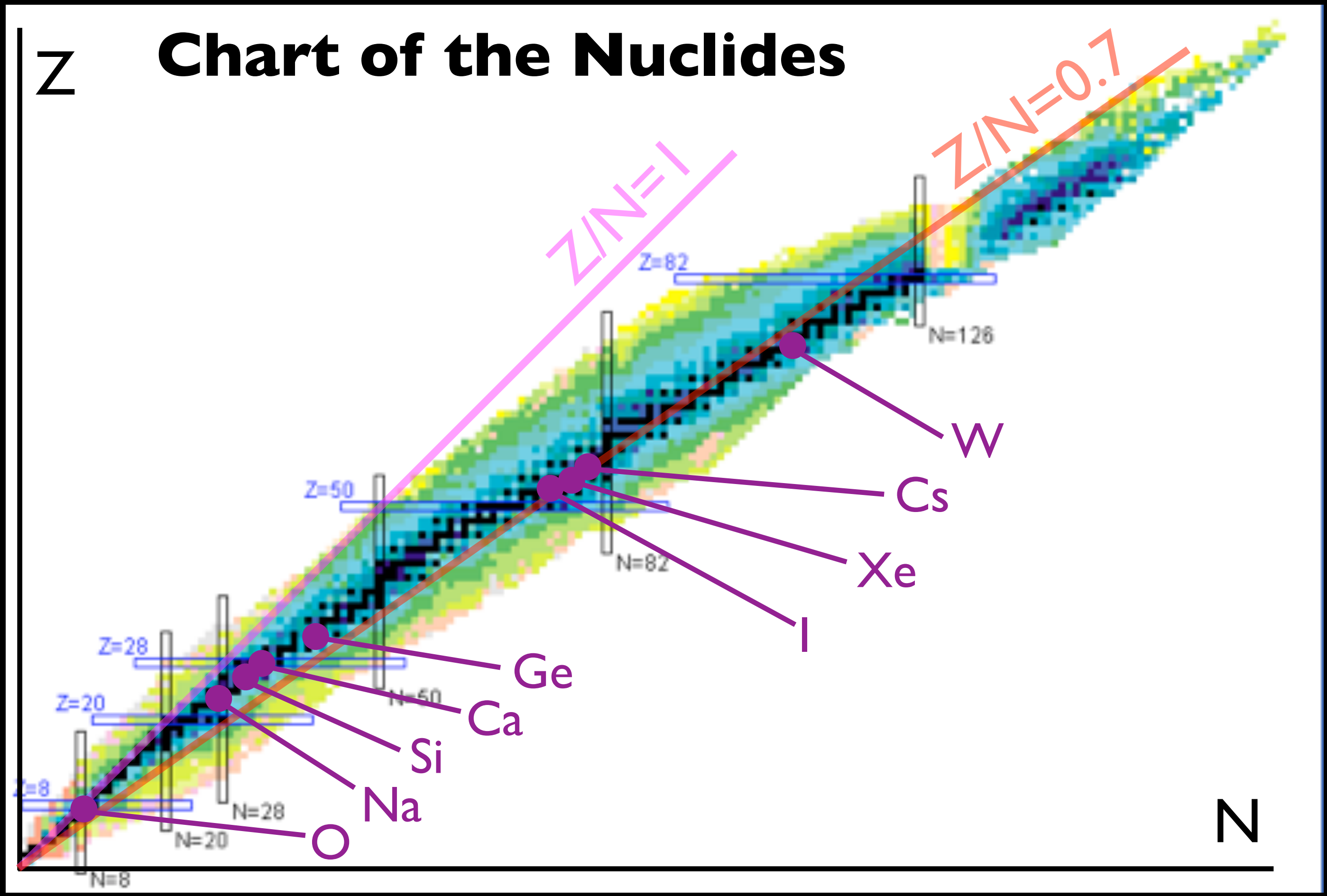
Isospin-violating dark matter

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

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



Particle physics model

Energy and/or velocity dependent scattering cross sections

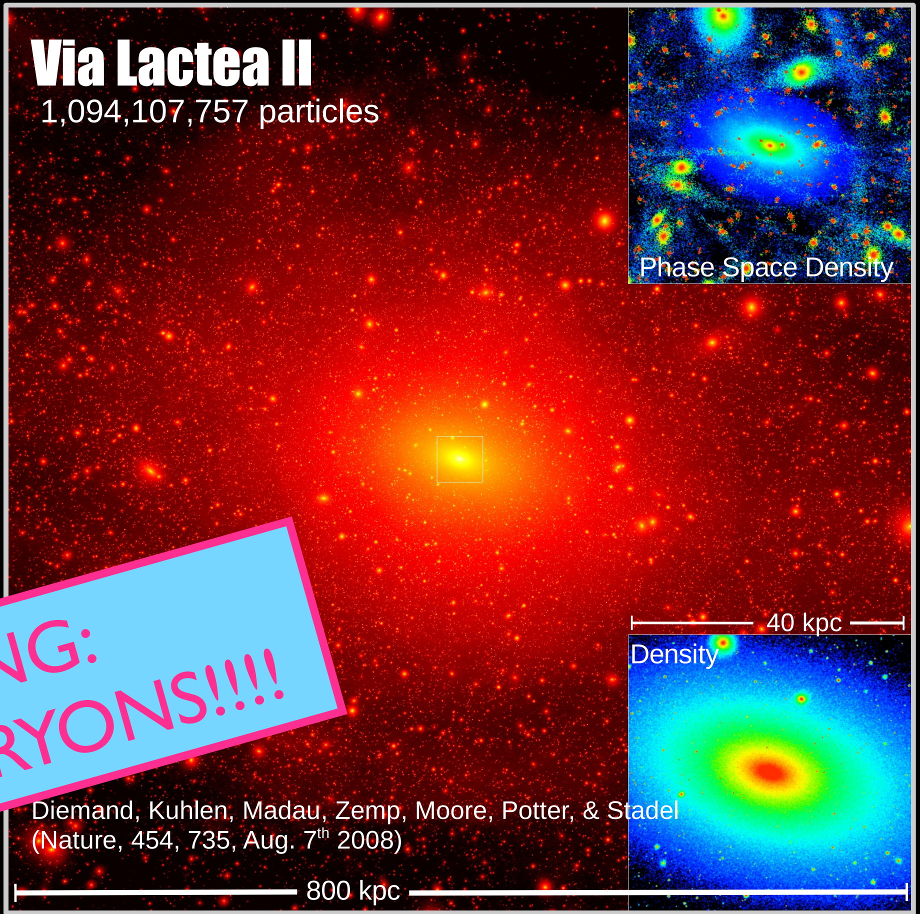
nucleus	DM	$v^2\, d\sigma/dE_R$	
		light mediator	heavy mediator
"charge"	*"charge"*	$1/E_R^2$	$1/M^4$
"charge"	*dipole*	$1/E_R$	E_R/M^4
dipole	*dipole*	$\mathrm{const} + E_R/v^2$	E_R^2/M^4

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

Astrophysics model: velocity distribution

We know very little about the dark matter velocity distribution



WARNING: NO BARYONS!!!!

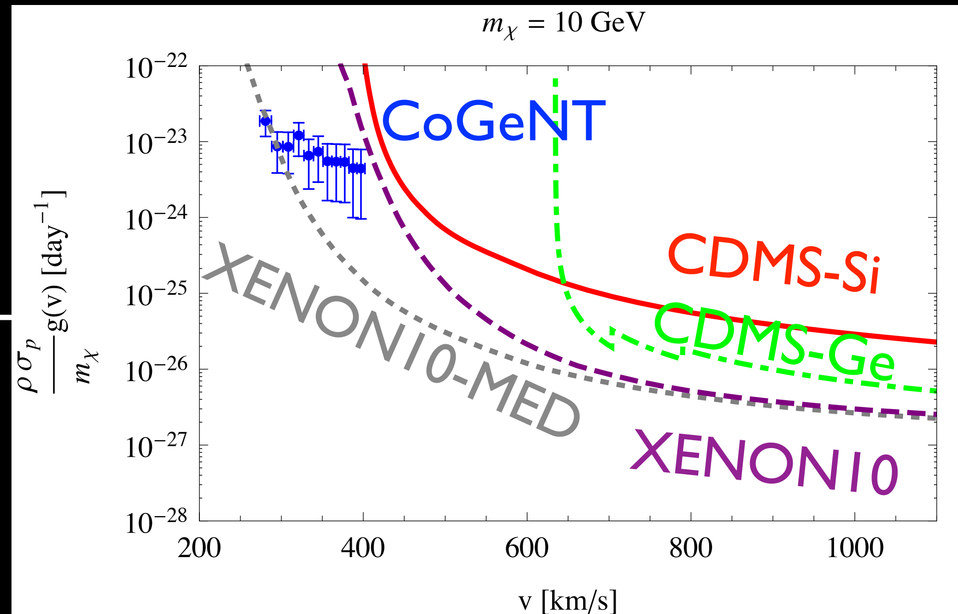
Cosmological N-Body simulations including baryons are challenging

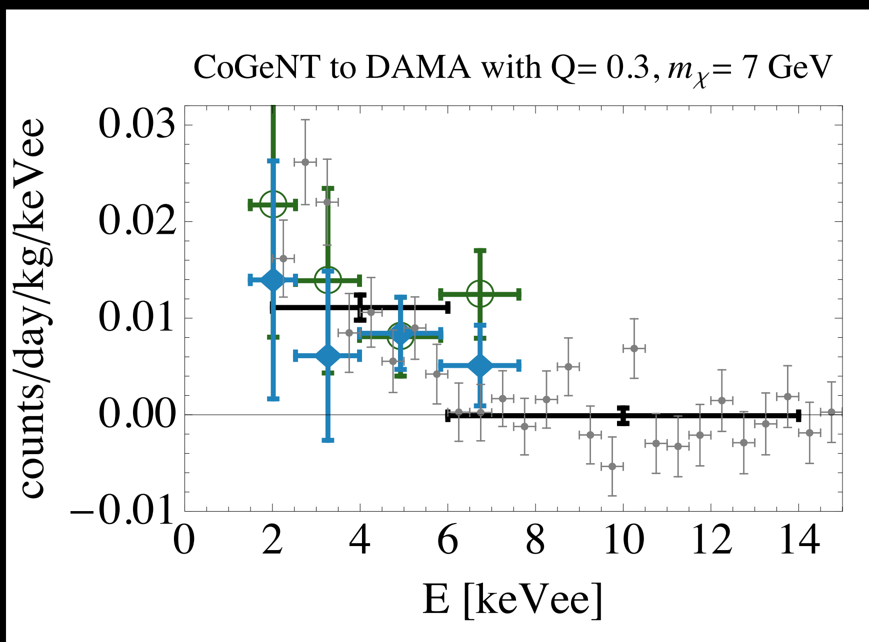
Astrophysics-independent approach

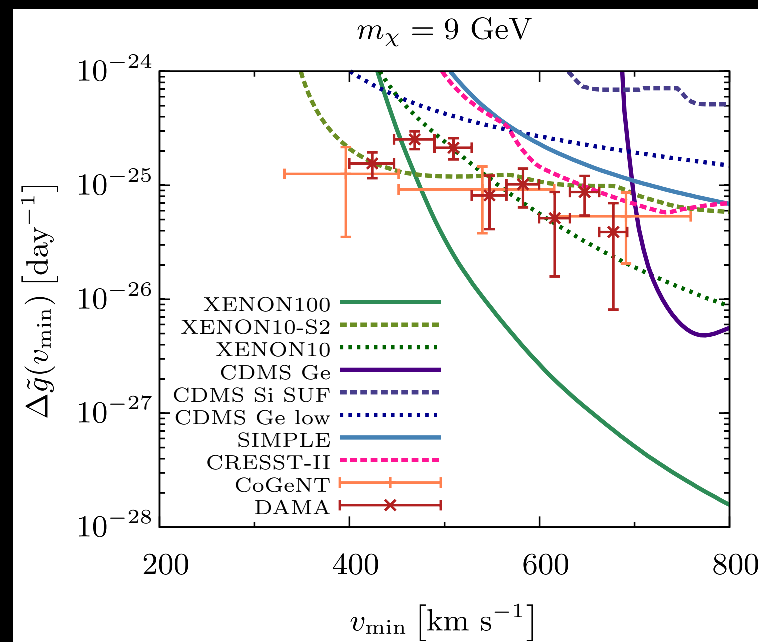
Fox, Liu, Weiner 2011

Rescaled astrophysics factor

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







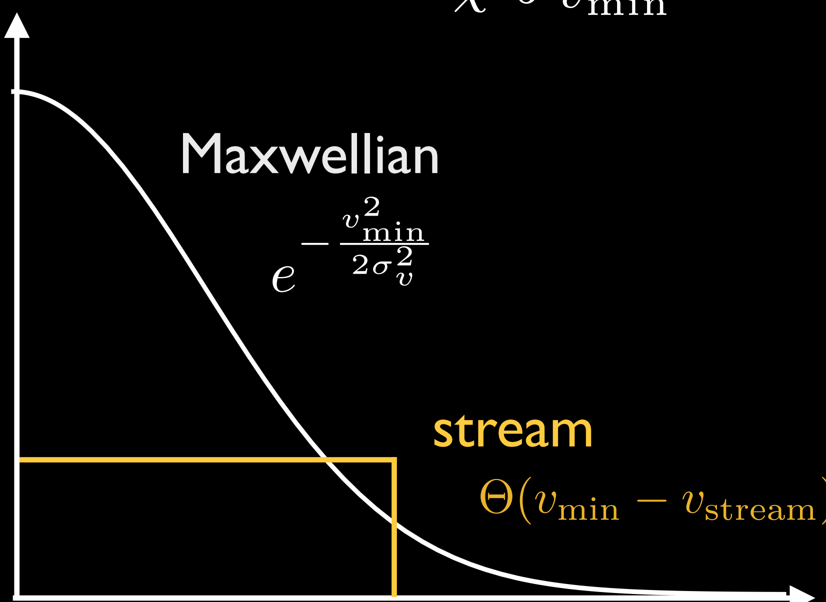
Fox, Kopp, Lisanti, Weiner 2011

Frandsen et al 2011

Astrophysics-independent approach

Rescaled astrophysics factor common to all experiments

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



Minimum WIMP speed to impart recoil energy E_R

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

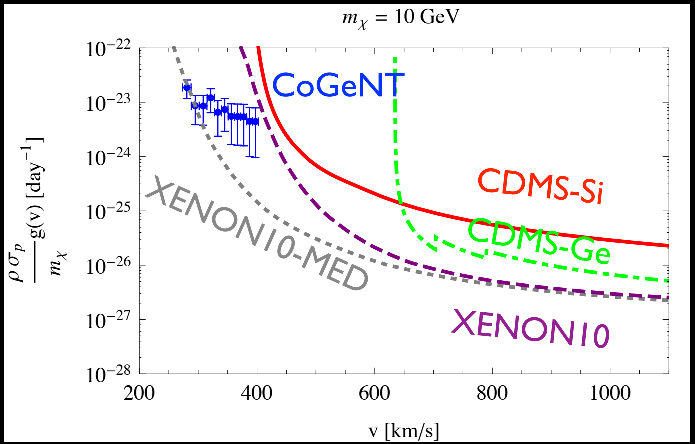
Recoil energy

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.

$$\underbrace{\frac{dR}{dE}}_{\text{Measured energy}} = \int_0^\infty \underbrace{\mathcal{G}(E, E_R)}_{\text{Effective energy response function}} \underbrace{\frac{dR}{dE_R}}_{\text{Recoil energy}} \, dE_R$$

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

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

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.

$$\underbrace{R}_{\text{Measured rate}} = \int_0^\infty dv\, \underbrace{\mathcal{R}(v)}_{\text{Response function}}\, \underbrace{\tilde{\eta}(v)}_{\text{Rescaled astrophysics factor}}$$

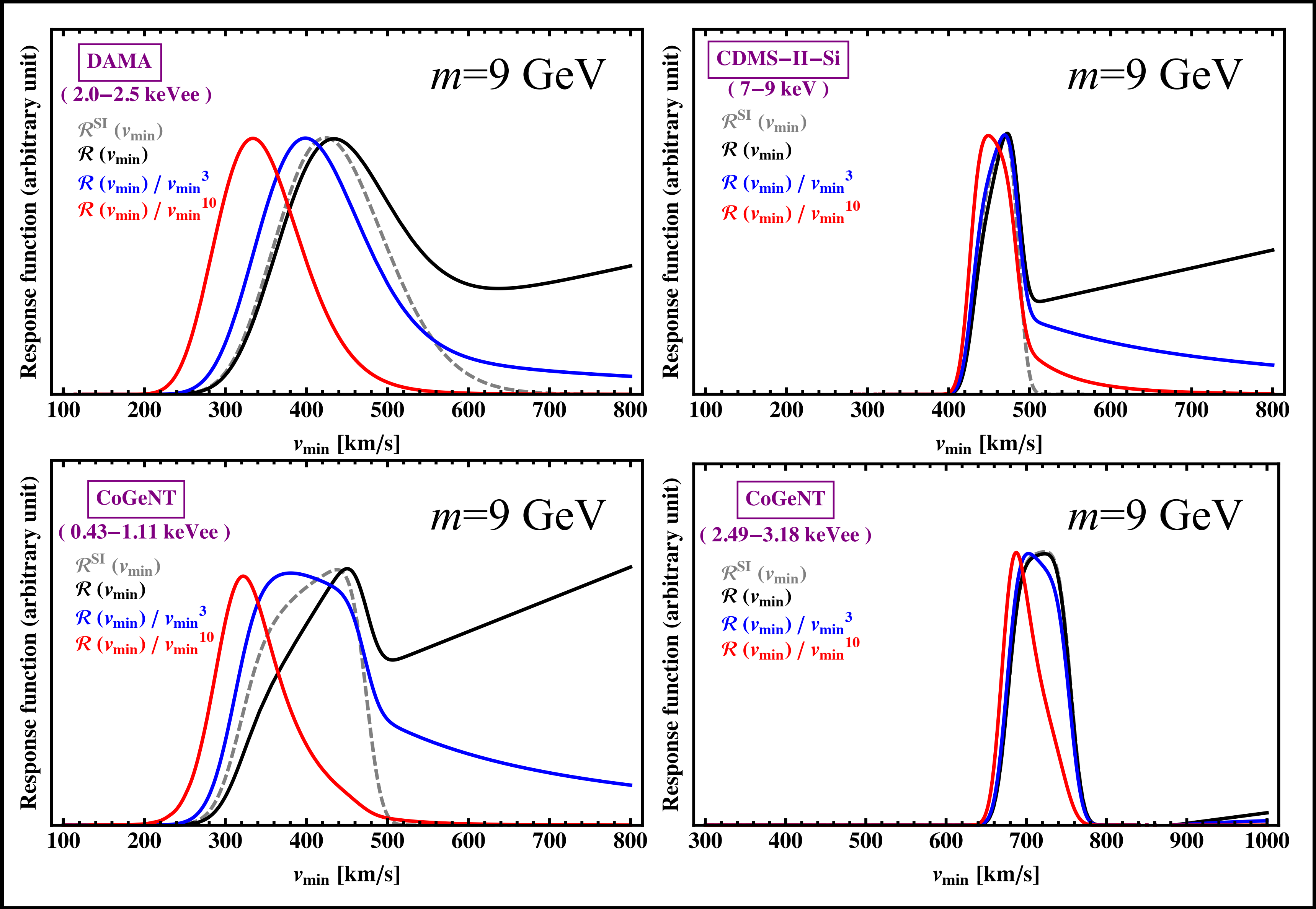
- Every experiment is sensitive to a "window in velocity space" given by the response function.

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

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

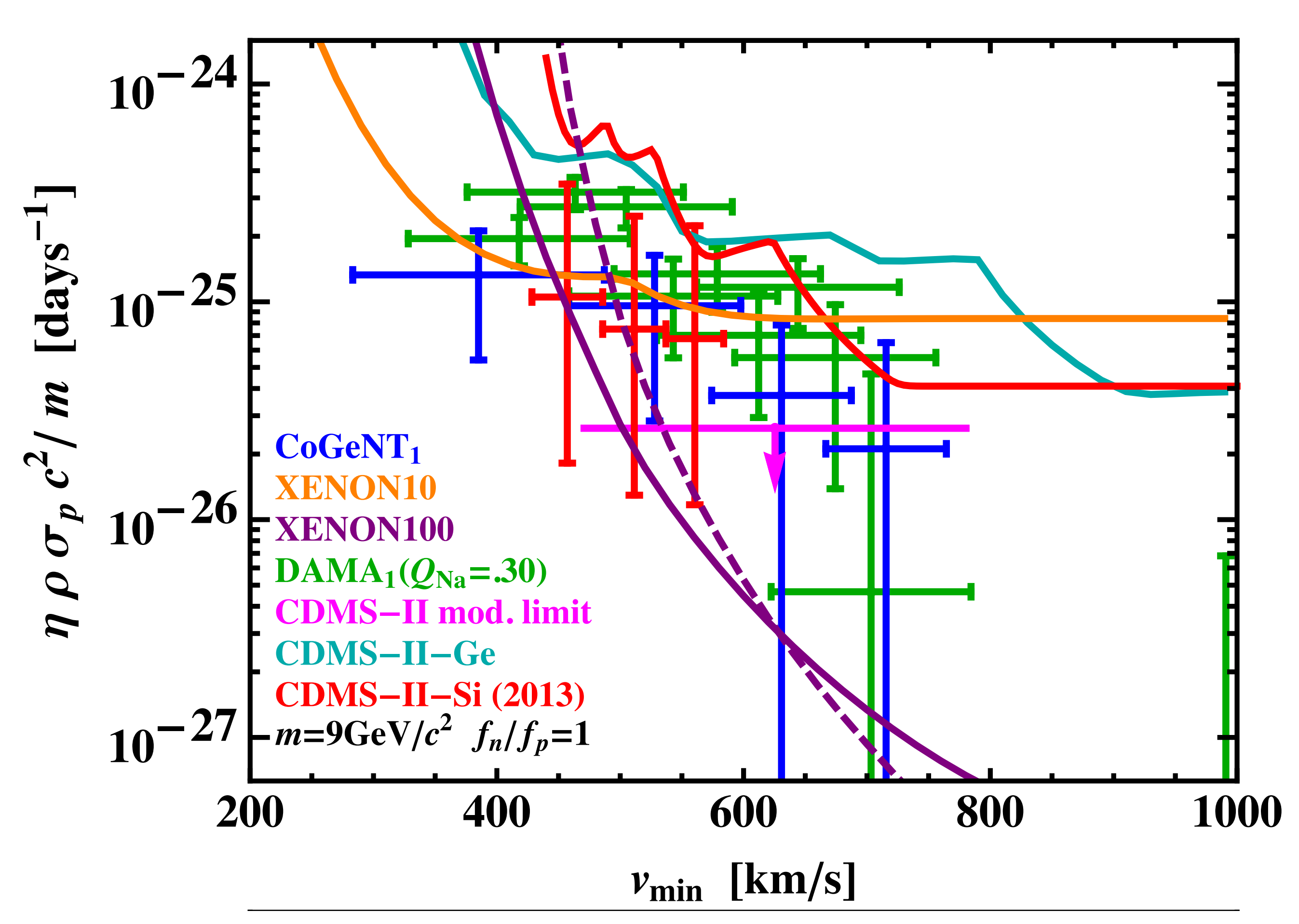
Measure or bound astrophysics factor in velocity interval $[v_1, v_2]$

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

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

Astrophysics-independent approach

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

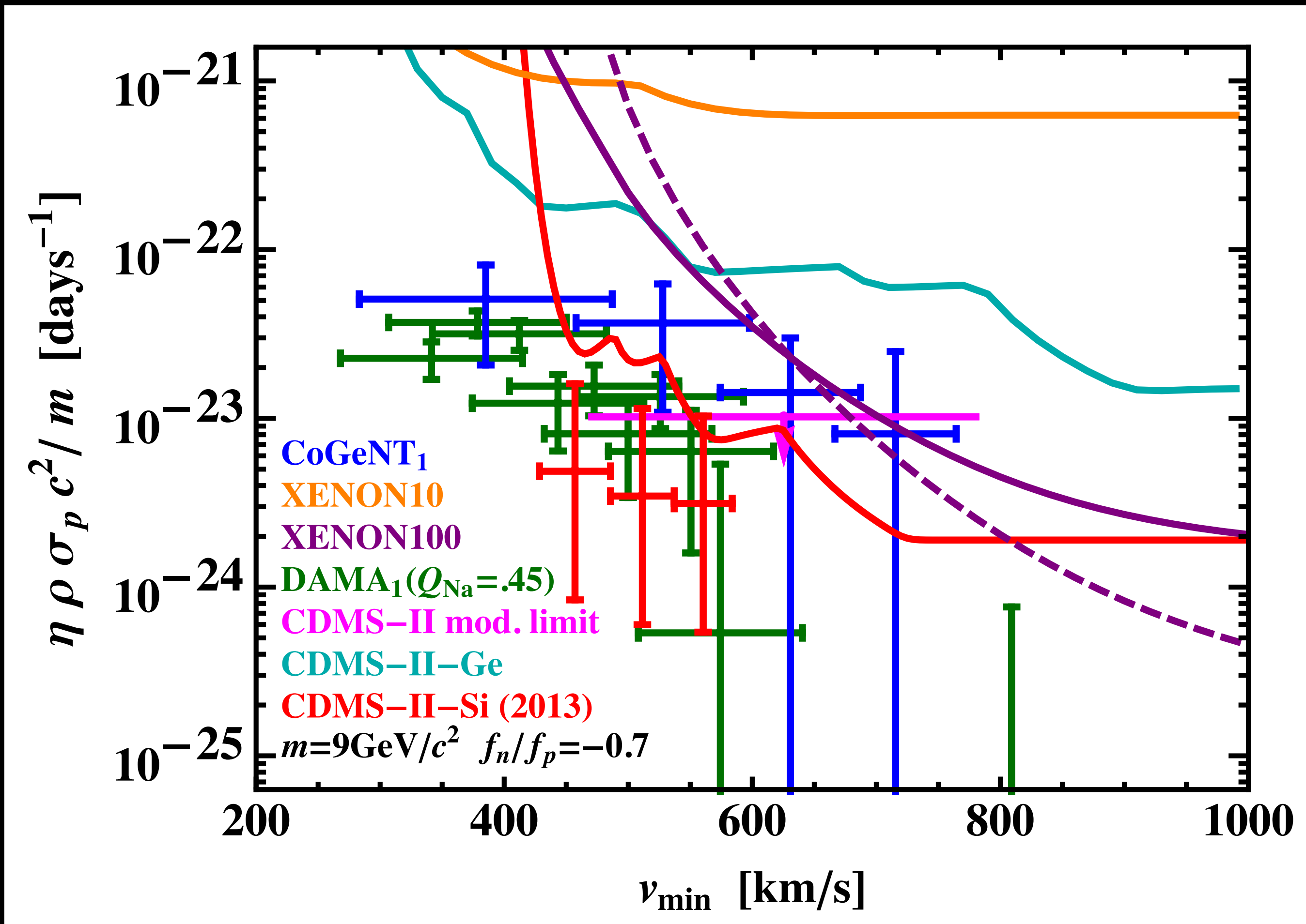
CDMS-Si event rate is similar to annual modulated rates

Del Nobile, Gelmini, Gondolo, Huh 2013

Still depends on particle model

Astrophysics-independent approach

Isospin-violating dark matter



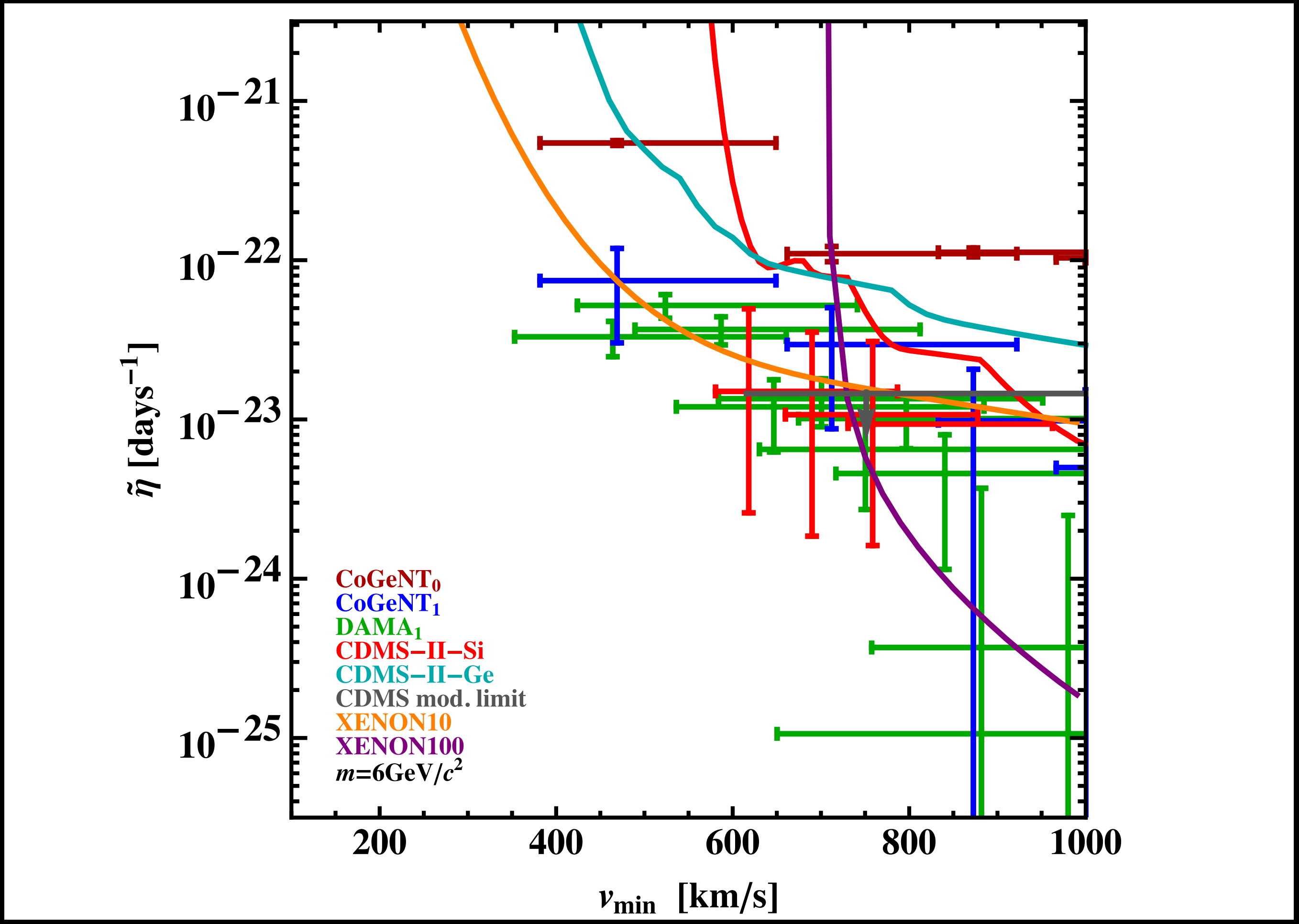
Dark matter coupled differently to protons and neutrons may have a chance

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



Del Nobile, Gelmini, Gondolo, Huh 2013

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

CDMS-Si event rate is similar to yearly modulated rates

Still depends on particle model

Conclusions

- New generalized astrophysics-independent method to analyze direct detection data.
- Results depend on particle model: mass and type of interaction.
- Tension between XENON upper limits and CoGeNT/DAMA modulation amplitudes
- General tension: CDMS-Si events occur at a rate comparable to the DAMA and CoGeNT annual modulation amplitudes (large modulation?)