Astrophysics-Independent Analysis of Direct Detection Data

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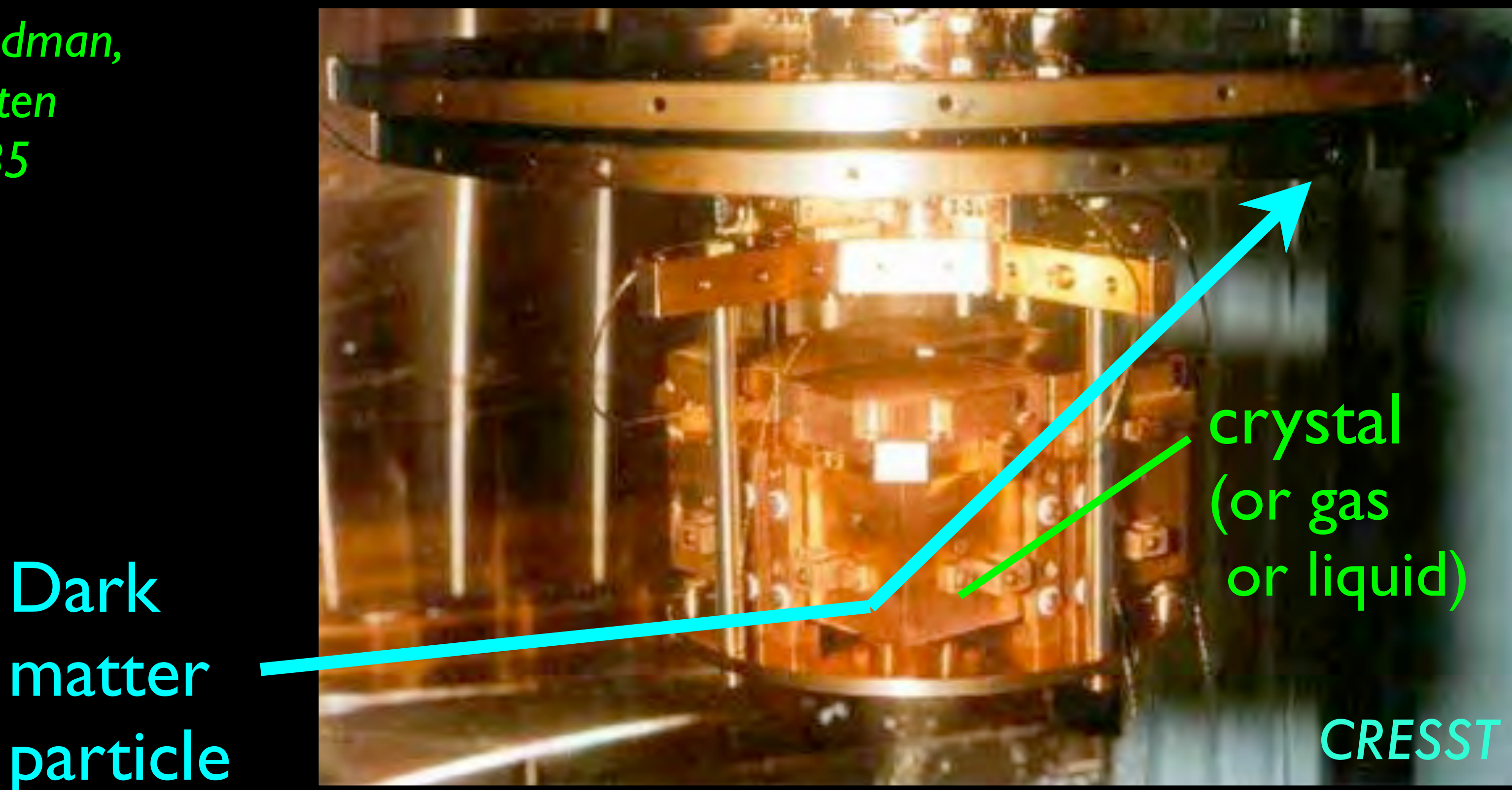
The principle of direct detection

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

Goodman, Witten 1985



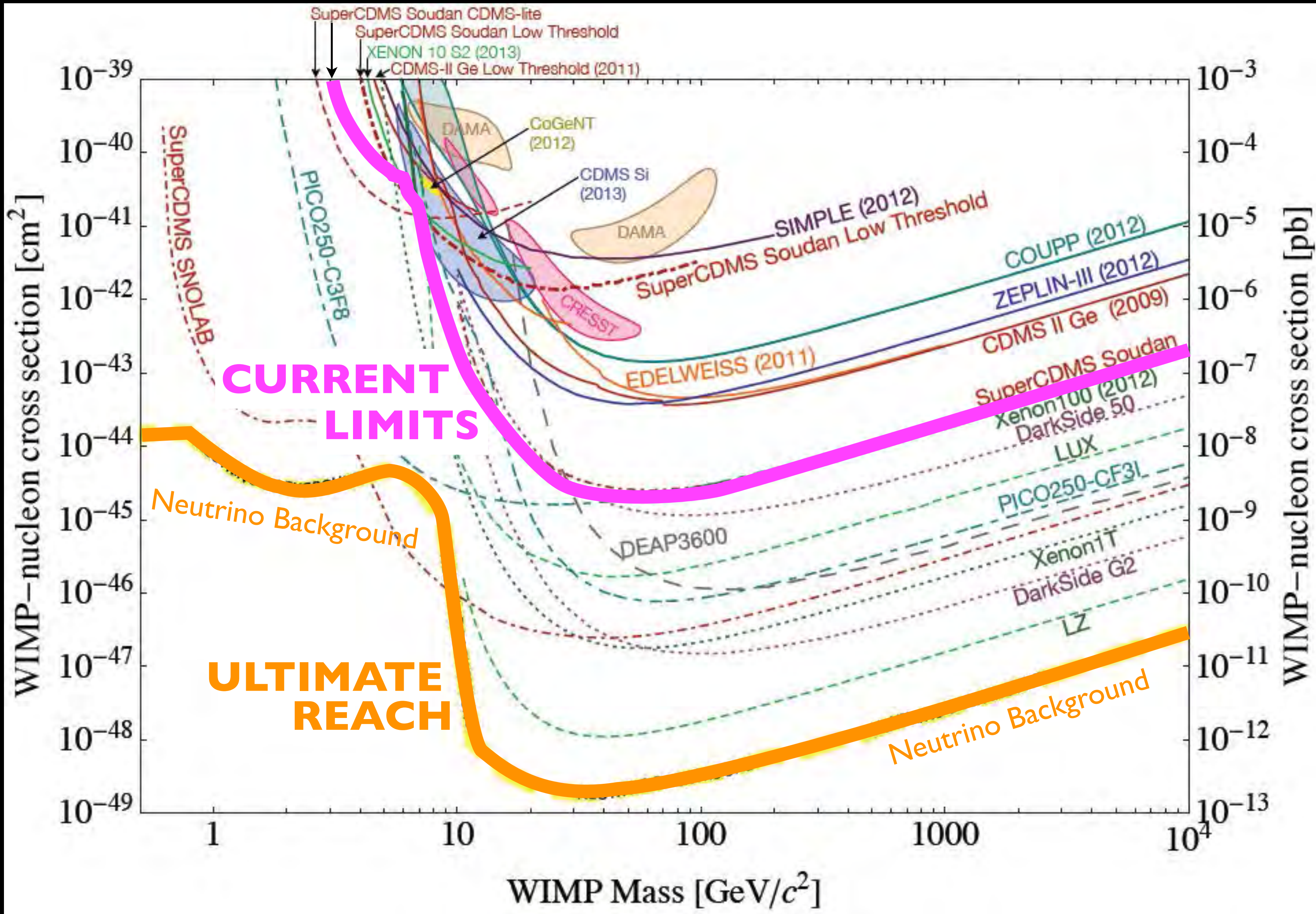
Low-background underground detector

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

Direct dark matter searches (2013)

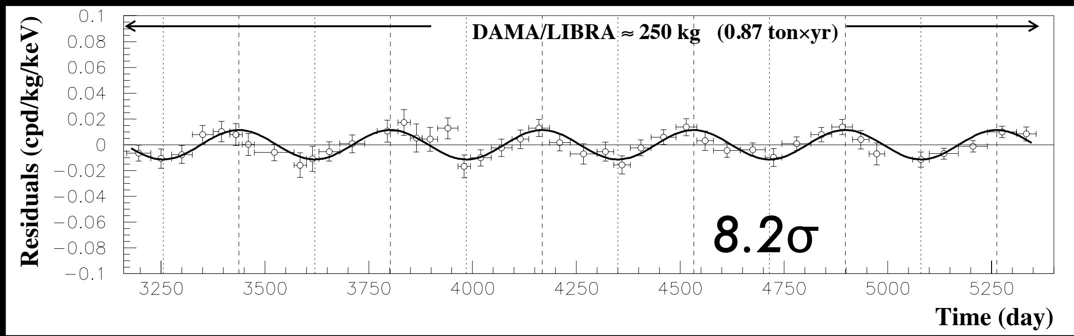
- XMASS (800 kg LXe, Kamioka, 2011-)
- SuperCDMS (25kg Ge, Soudan, 2012-)
- LUX (350 kg LXe, Homestake, 2012-)
- DarkSide (50 kg LAr, Gran Sasso, 2012-)
- COUPP (60 kg CF_3I, SNOLab, 2012-)
- XENON-1T (1 ton LXe, Gran Sasso, 2014-)
- EURECA, DARWIN, ...

Direct dark matter searches (2013)

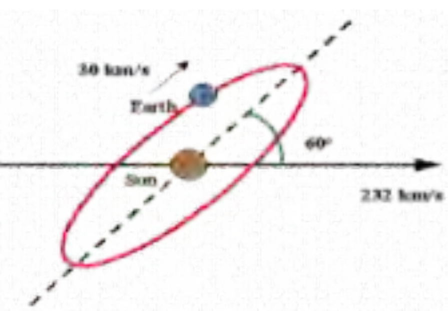


Billard, Strigari, Feliciano-Figueroa 2013 + Feng, Ritz(Snowmass 2013)

Evidence for light dark matter particles?

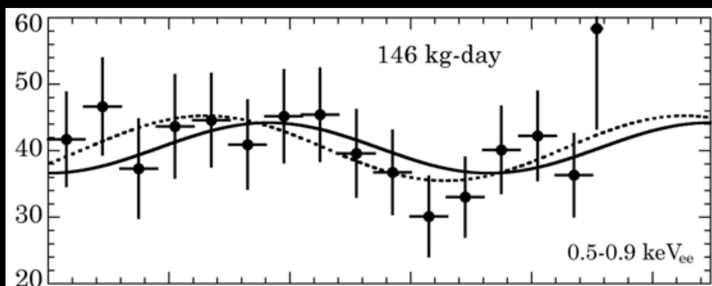


Drukier, Freese, Spergel 1986



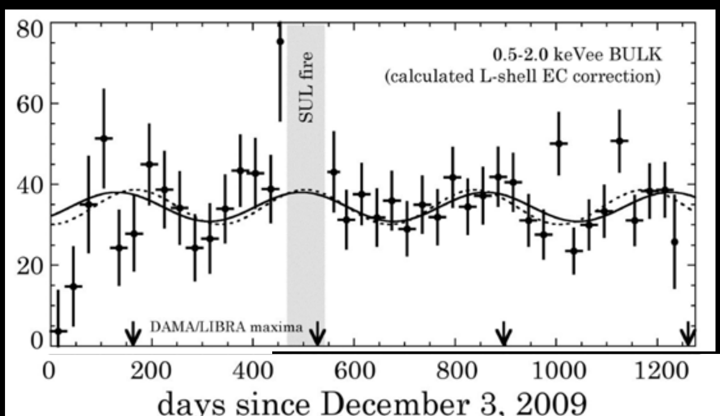
Bernabei et al (DAMA) 1997-10

Annually modulated.....



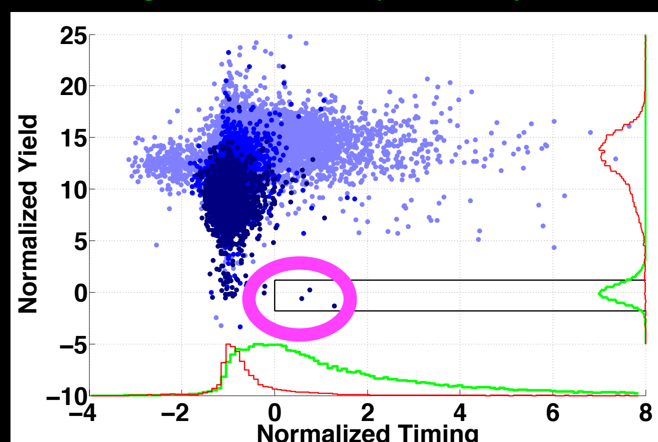
Aalseth et al (CoGeNT) 1106.0650

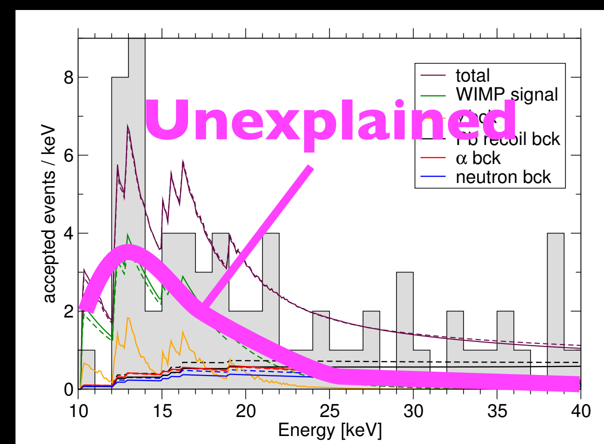
......and unmodulated



Collar (CoGeNT) 2013

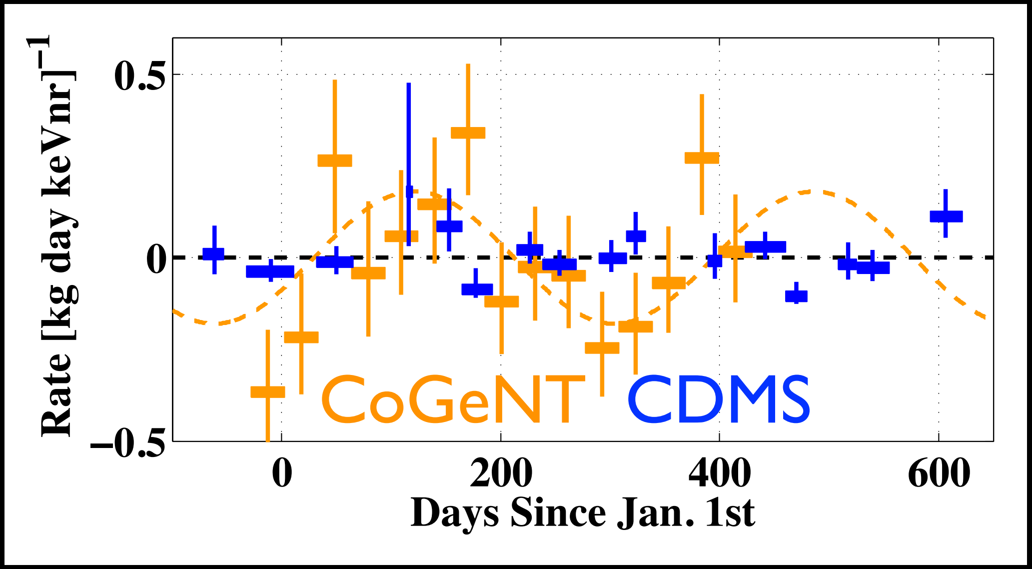
Agnese et al (CDMS) 2013





Anglehor et al (CRESST) 2011

Evidence for light dark matter particles?



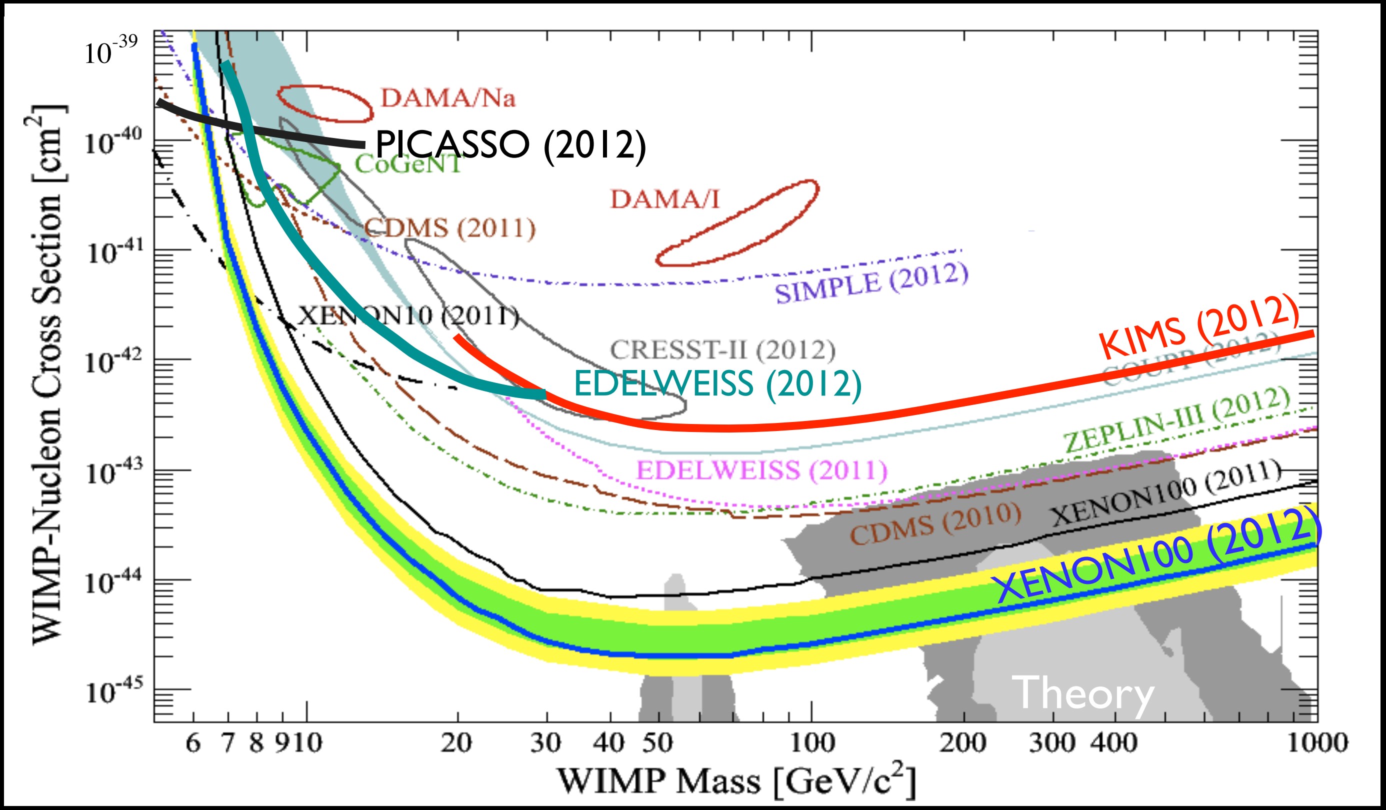
No significant modulation

Same target material

Ahmed et al (CDMS) 1203.1309

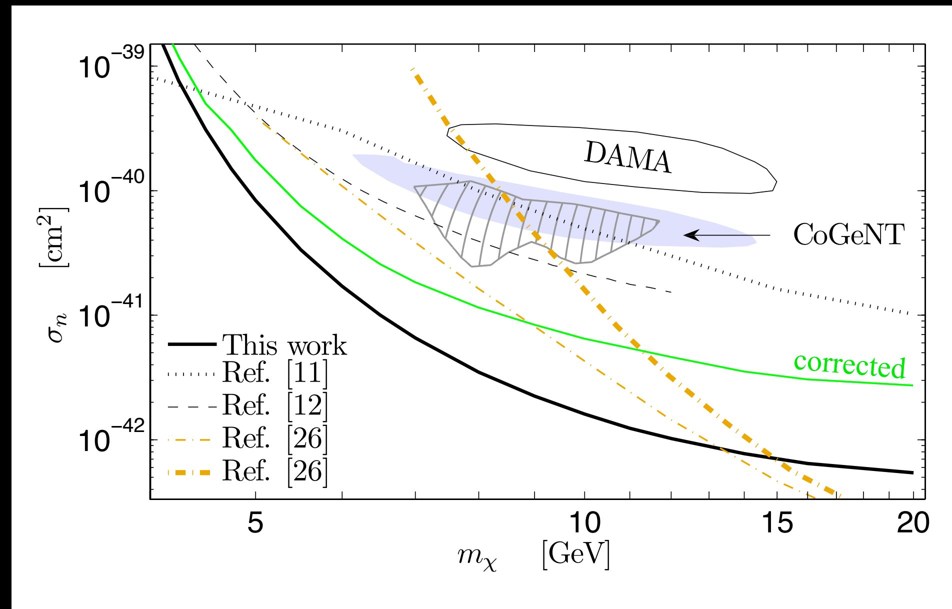
Not so many events

Adapted from Aprile et al (XENON-100) 2012

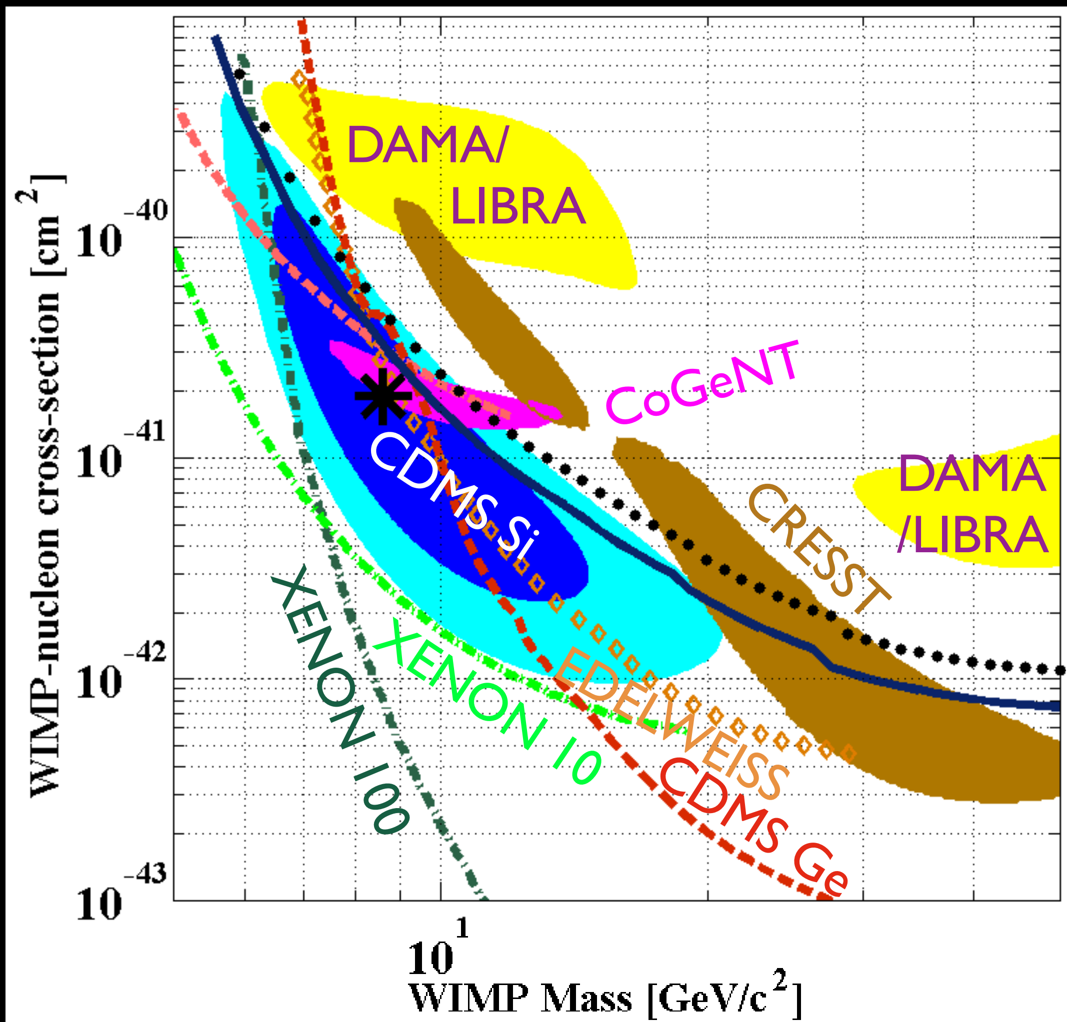


Evidence for light dark matter particles?

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?

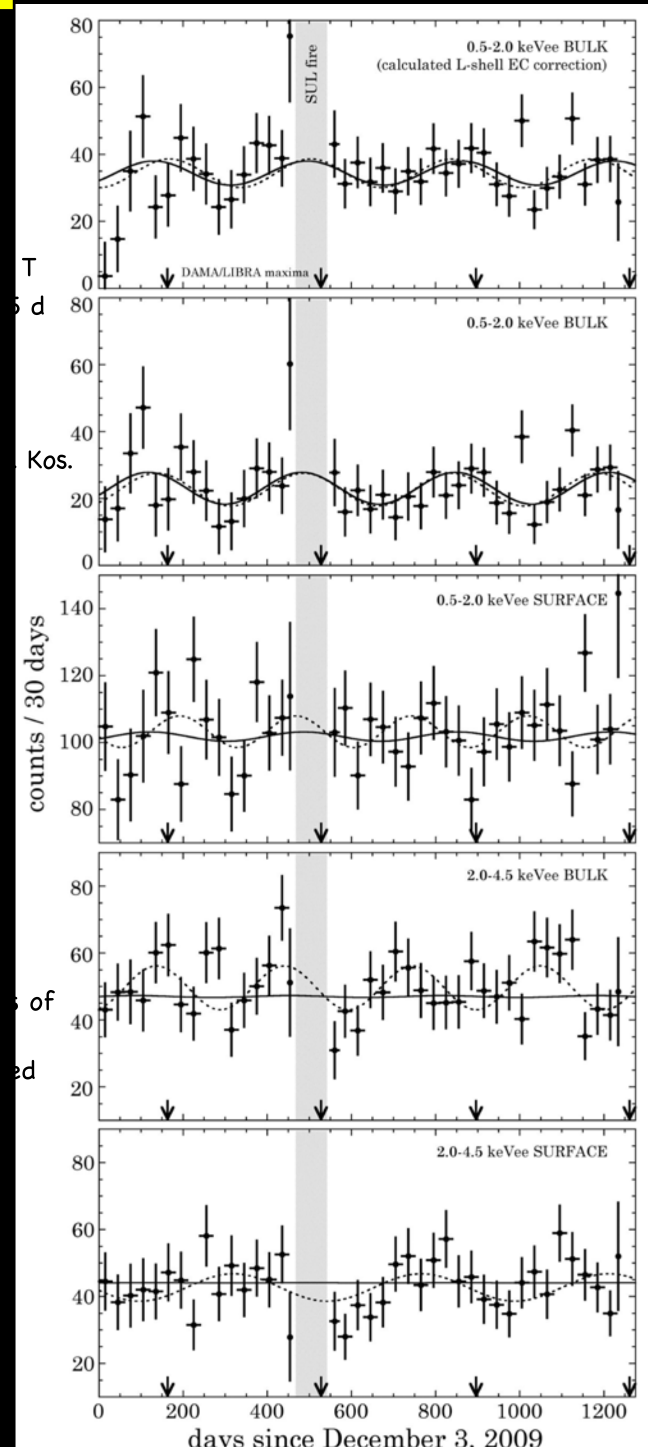
Annual modulation in 3.4 yr of CoGeNT

Annual modulation exclusively at low energy and for bulk events.

Best-fit phase consistent with DAMA/LIBRA

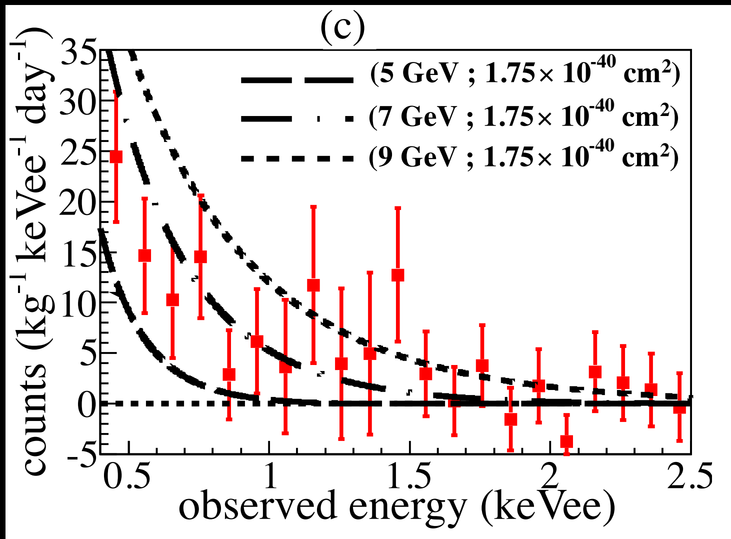
Unoptimized frequentist analysis yields ~2.2σ preference over null hypothesis

Modulation amplitude is 4-7 times larger than in the standard halo model

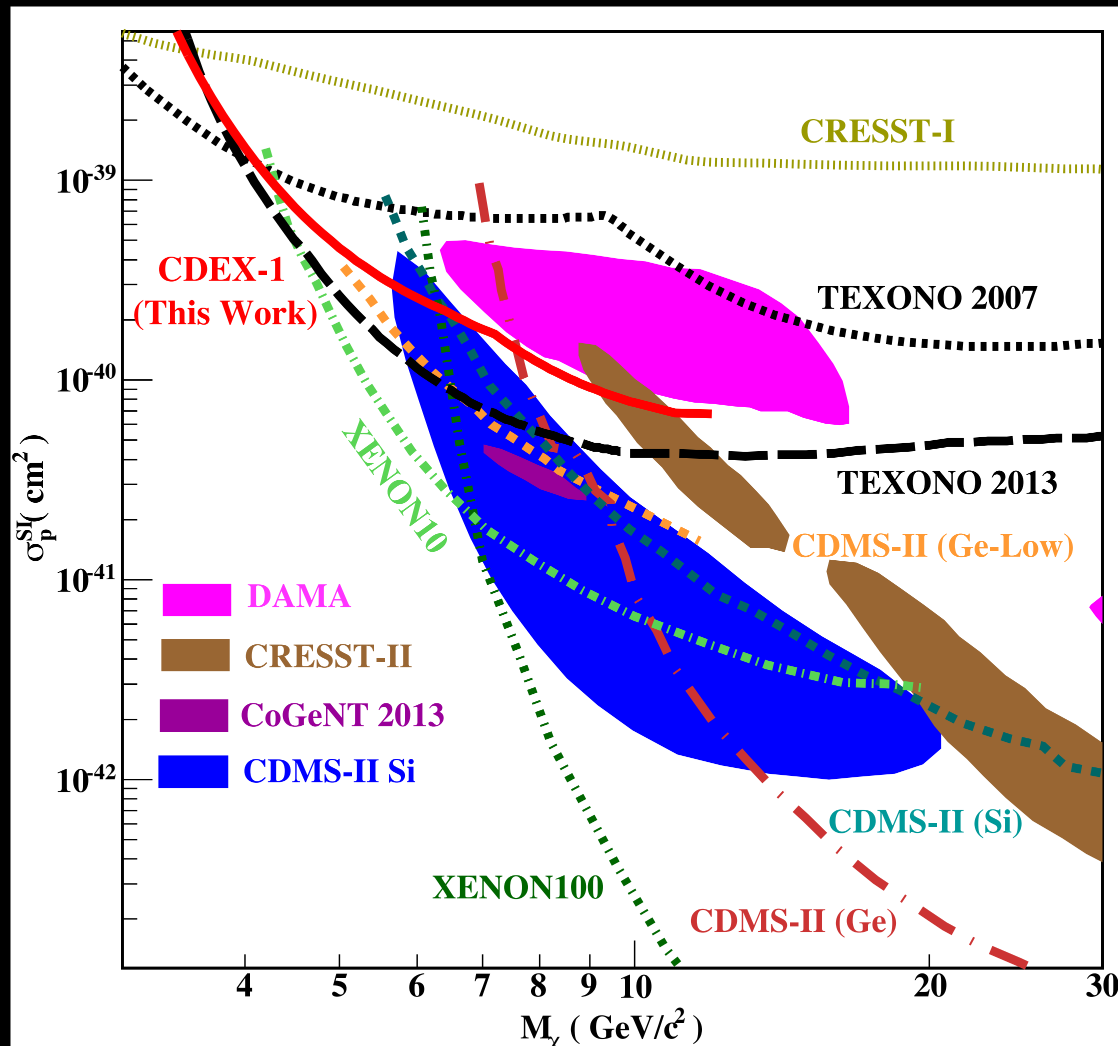


Collar (CoGeNT) at TAUP 2013

Evidence for light dark matter particles?



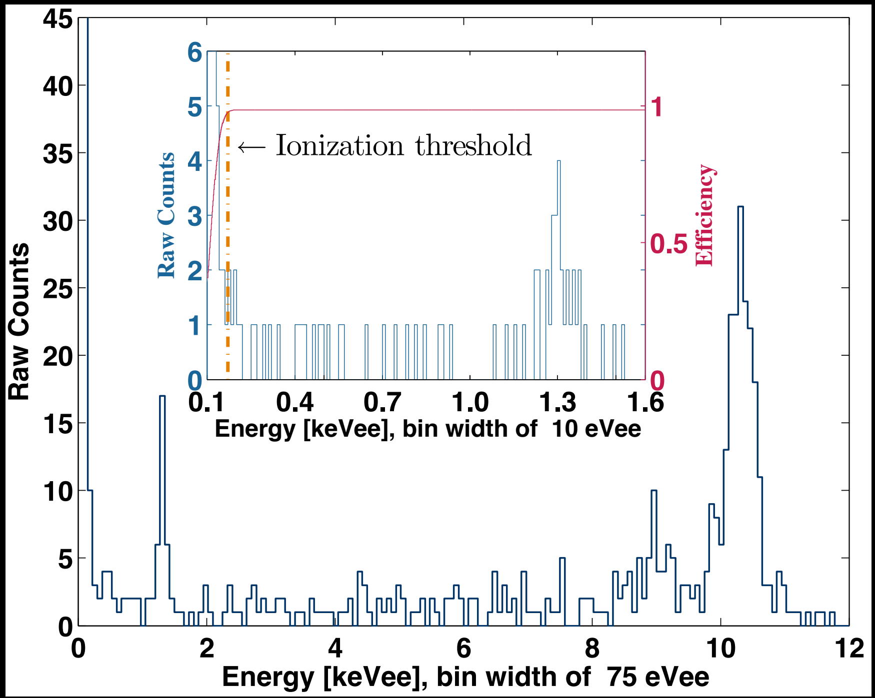
Zhao et al (CDEX) 2013

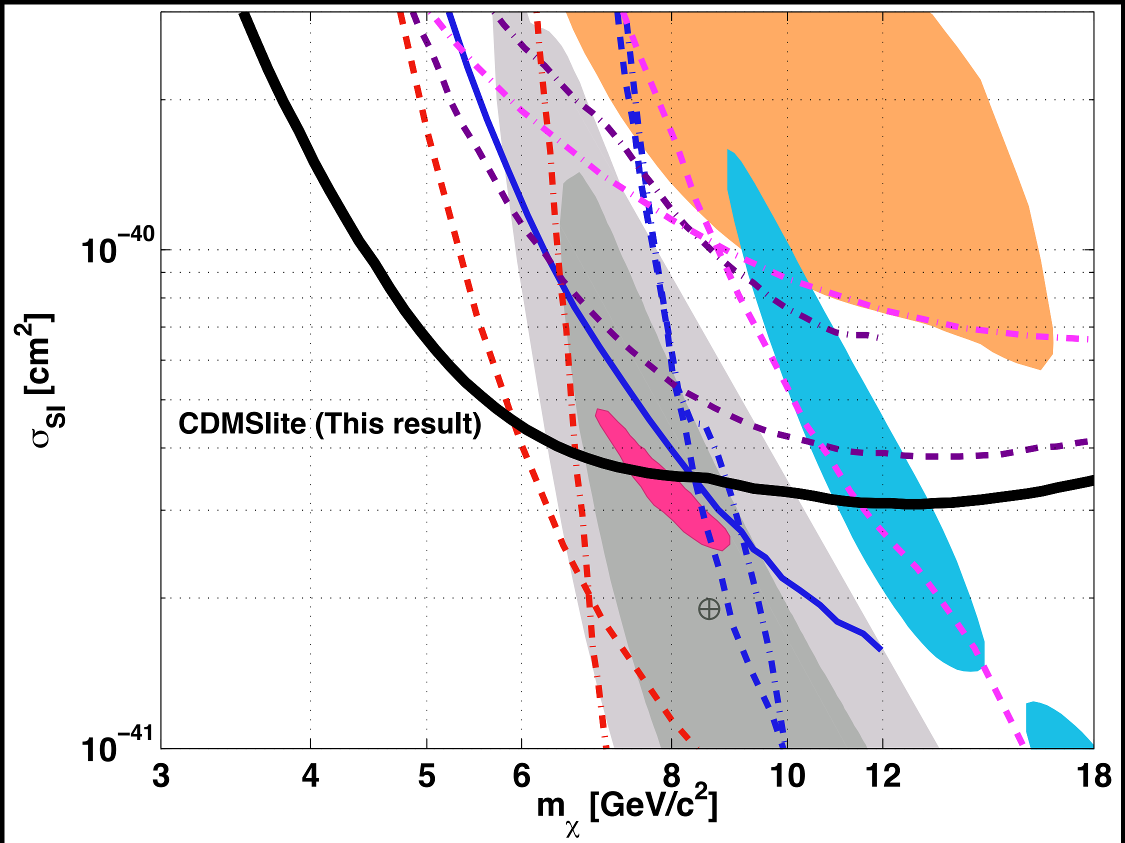


Upper bound from CDEX (same target as CoGeNT and CDMS-Ge)

Evidence for light dark matter particles?

Upper bound from CDMSlite (low ionization threshold experiment)

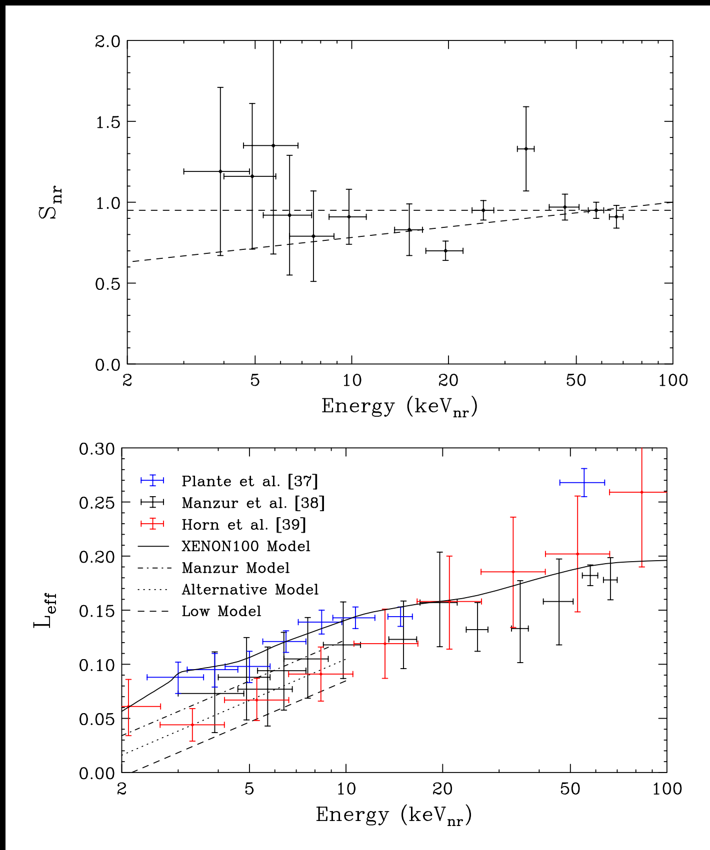




Hall at TAUP2013
Agnese et al (CDMS) 1309.3259

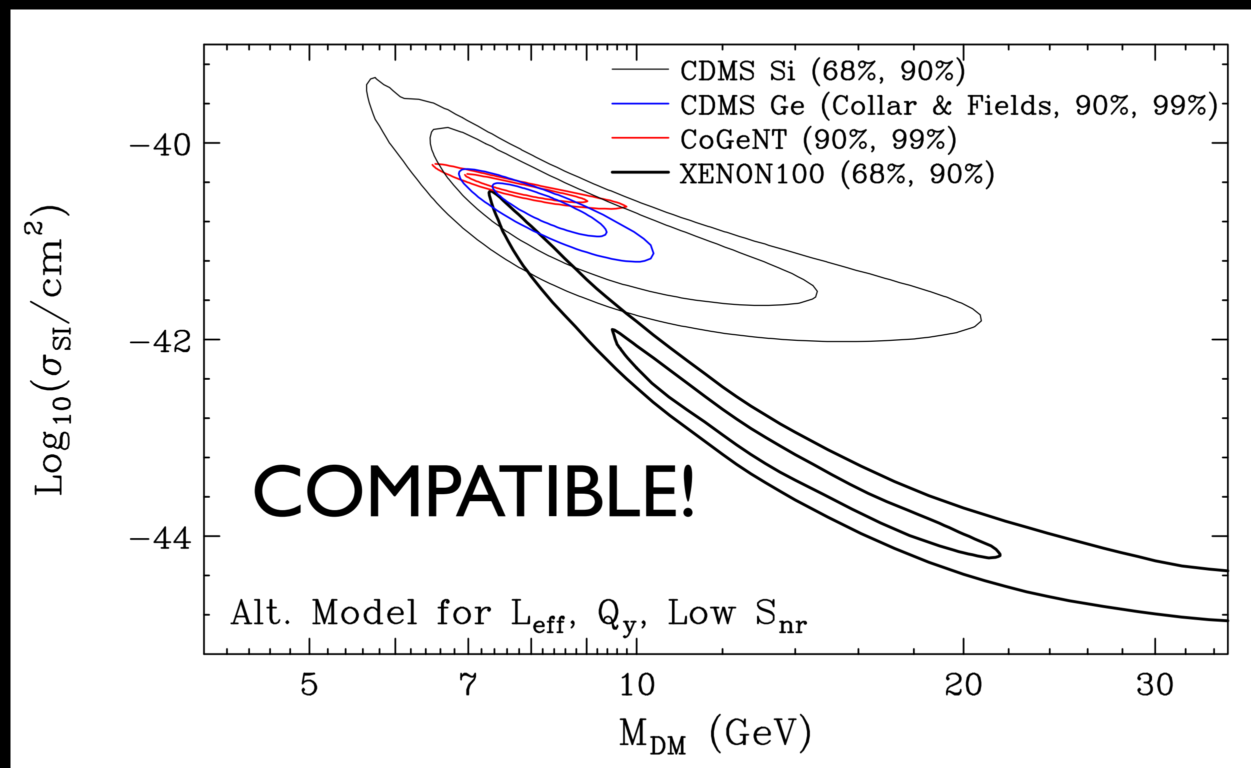
Evidence for light dark matter particles?

Hooper 2013



XENON100 detects events too!

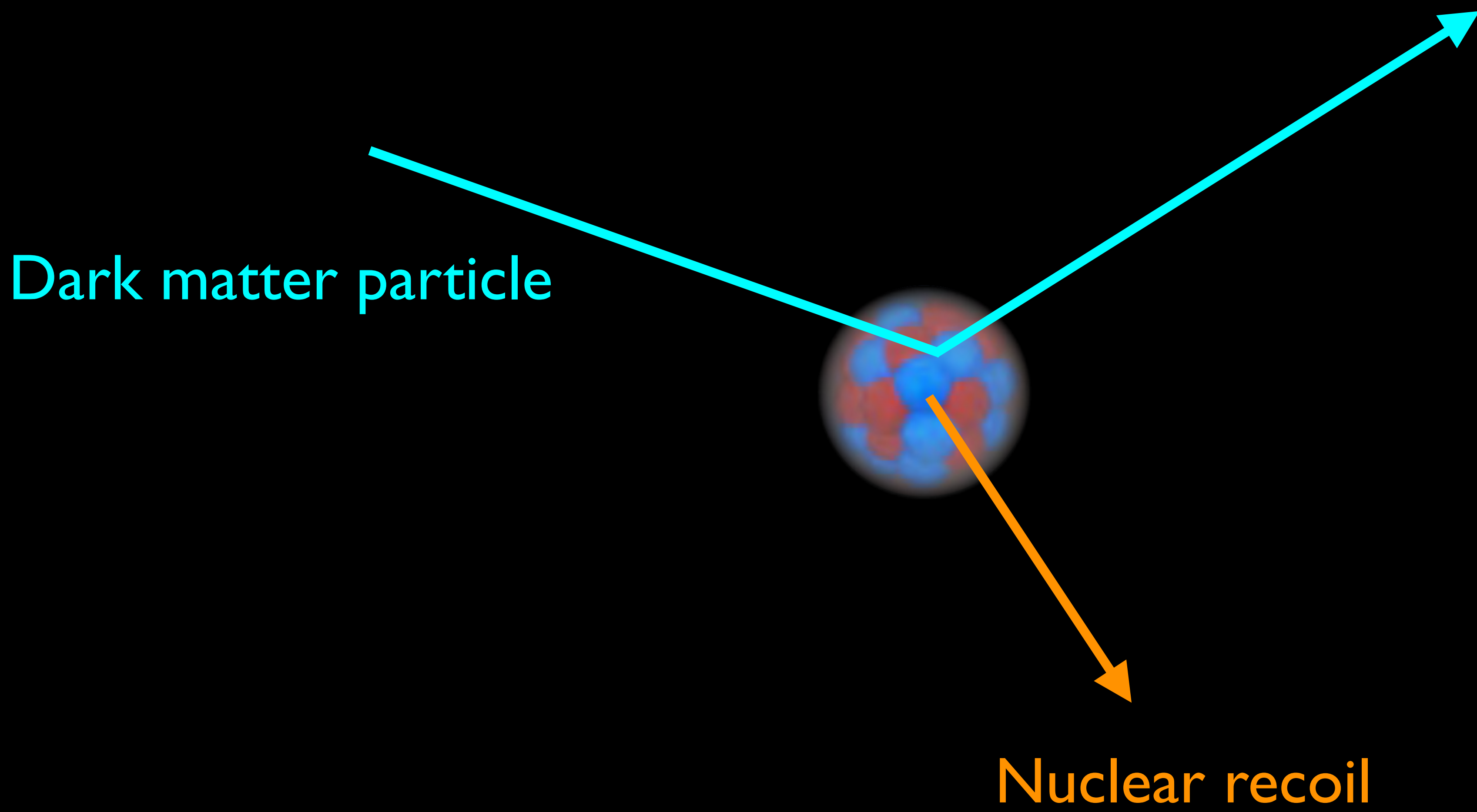
Is XENON100's sensitivity overestimated?



"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?

Velocity distribution

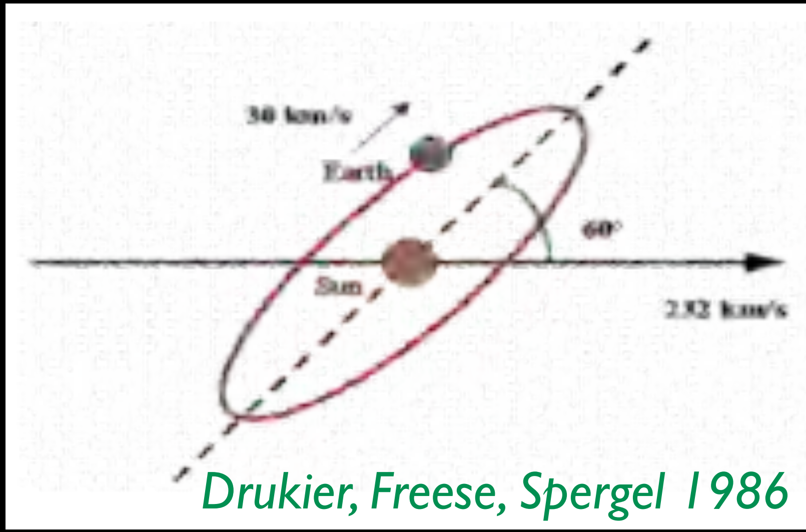
Local halo density

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

Minimum WIMP speed to impart recoil energy E_R

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

Annual modulation



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

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

Unmodulated signal

Modulation amplitude

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.

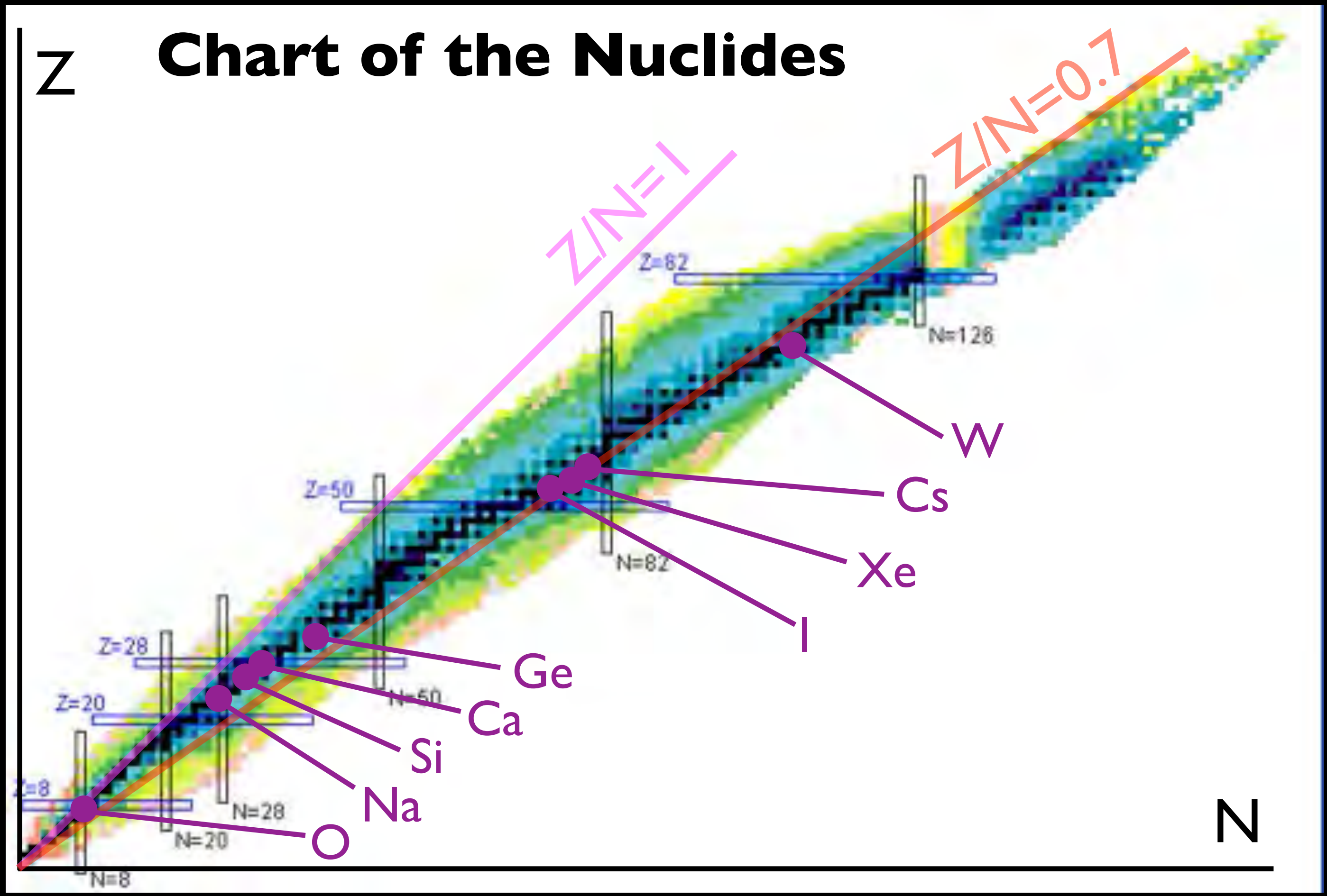
Isospin-violating dark matter

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

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



Particle physics model

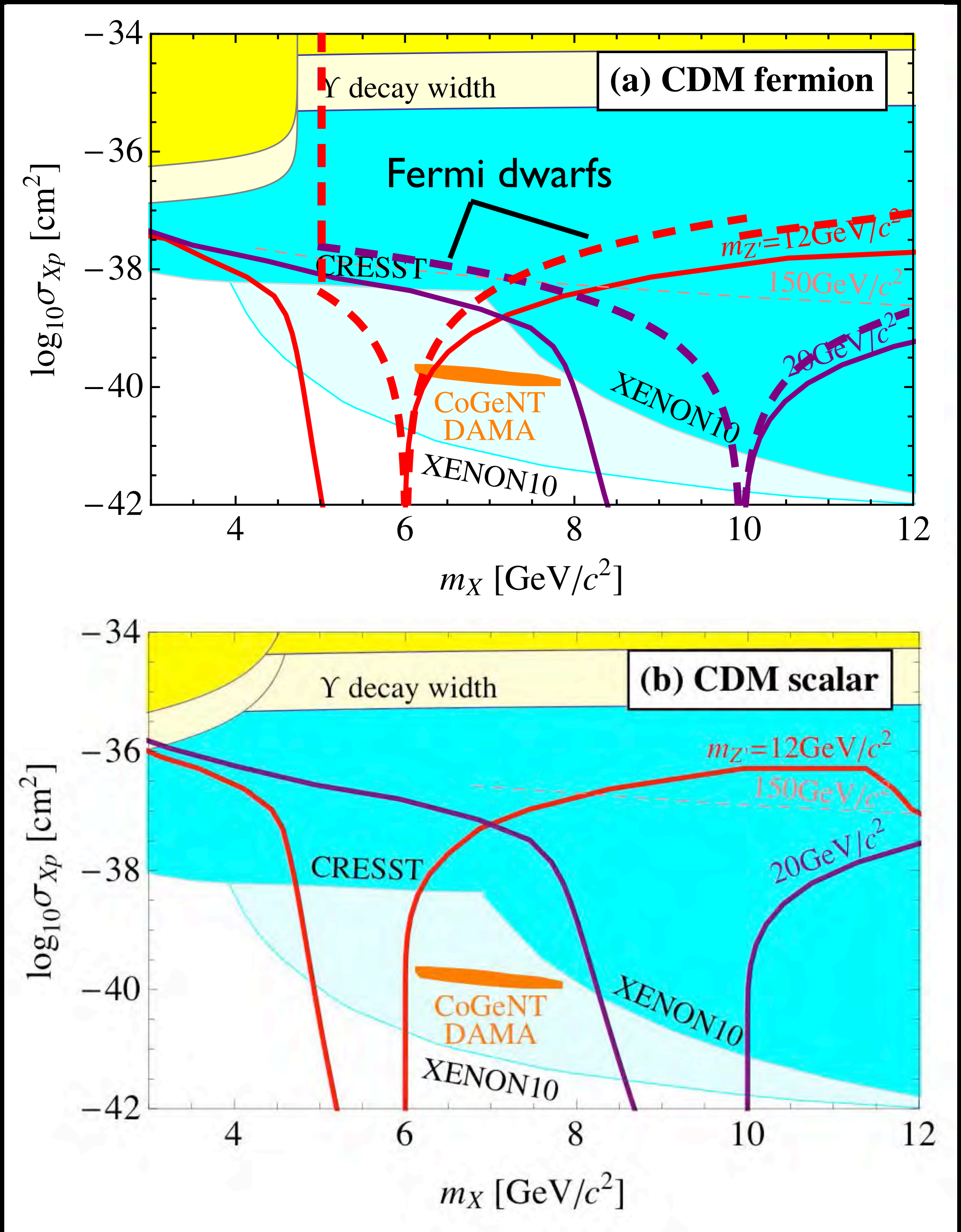
Energy and/or velocity dependent scattering cross sections

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

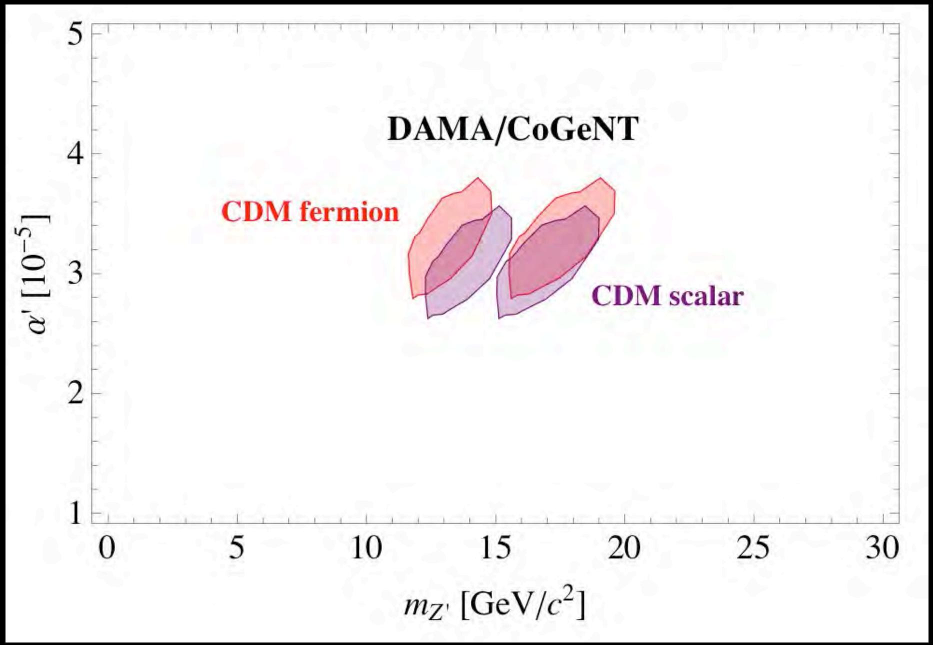
Light WIMPs with light Z' boson



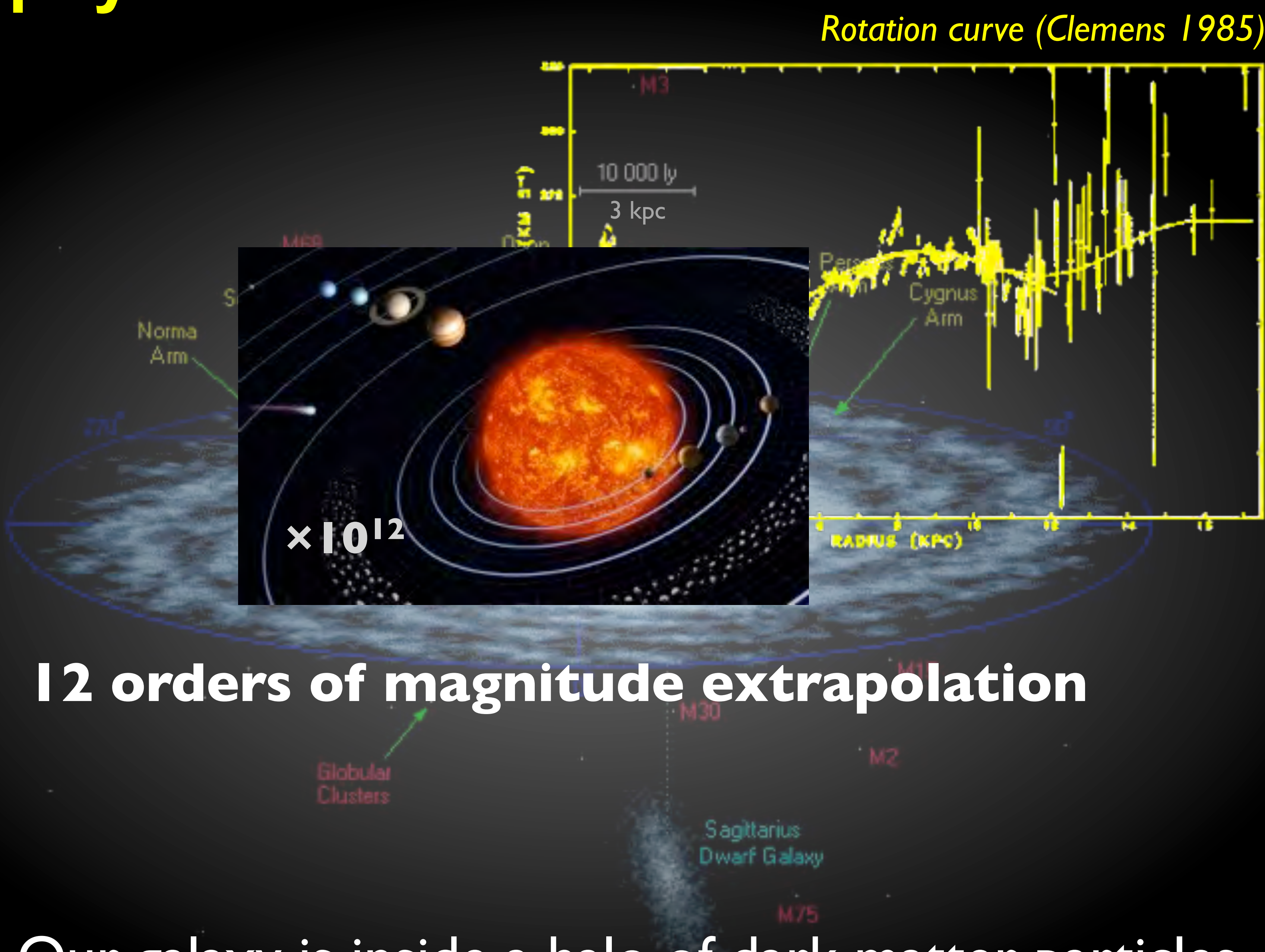
Example: Leptophobic Z'

- 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



12 orders of magnitude extrapolation

Our galaxy is inside a halo of dark matter particles

1 kpc = 2.06×10^{11} AU

Image by R. Powell using DSS data

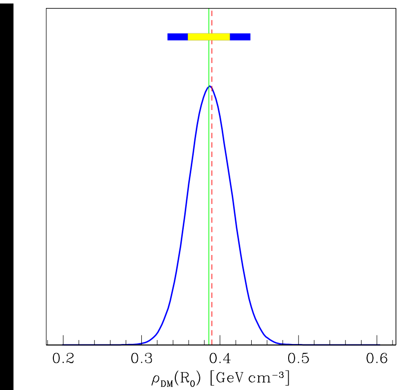
Astrophysics model: local density

$$\rho_\odot = \left(0.430 \pm 0.113_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\mathrm{GeV}}{\mathrm{cm}^3}\,.$$

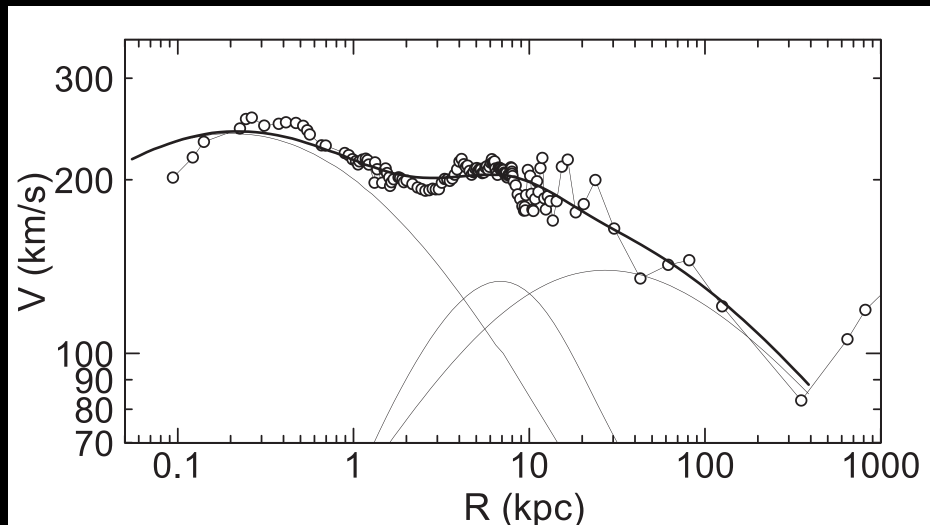
Salucci et al 2010

$$\rho_{DM}(R_0) = 0.385 \pm 0.027\,\mathrm{GeV\ cm^{-3}}$$

Ullio, Catena 2009

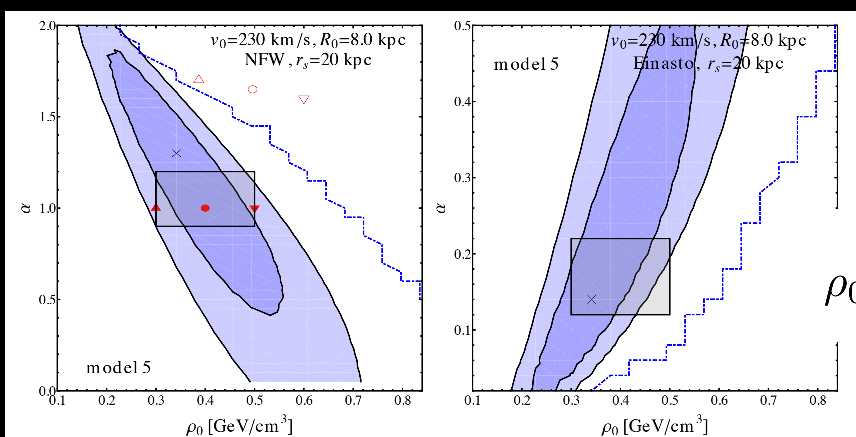


Local density from galactic modeling



Sofue 2011

$$\rho_0^\odot = 0.235 \pm 0.030\ \mathrm{GeV\ cm^{-3}}$$



$$\rho_0 = 0.20 - 0.55\ \mathrm{GeV/cm^3}$$

Iocco, Pato, Bertone, Jetzer 2010

Astrophysics model: local density

$$\rho_\odot = \left(0.430 \pm 0.113_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\mathrm{GeV}}{\mathrm{cm}^3}\,.$$

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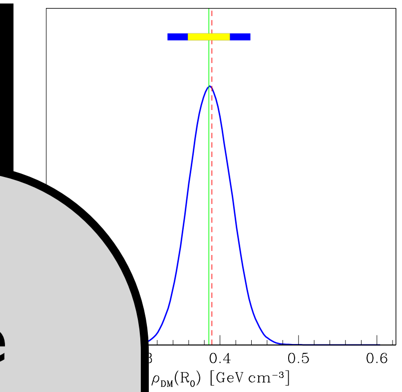


Lo

gal

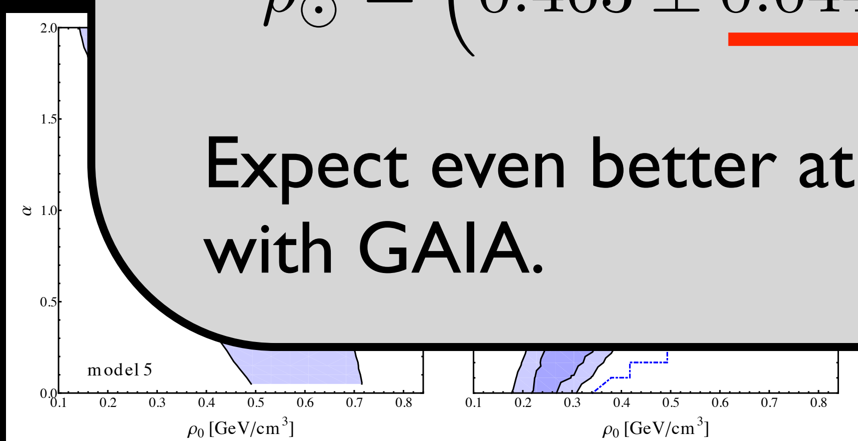
The most direct method, requiring only local measurements of the disk contribution and the slope of rotation curve at the Sun's distance.
Now even more precise with preliminary VERA:

Honma at Neutrinos and Dark Matter 2012

$$\rho_\odot = \left(0.463 \pm 0.044_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Expect even better at VERA completion and with GAIA.

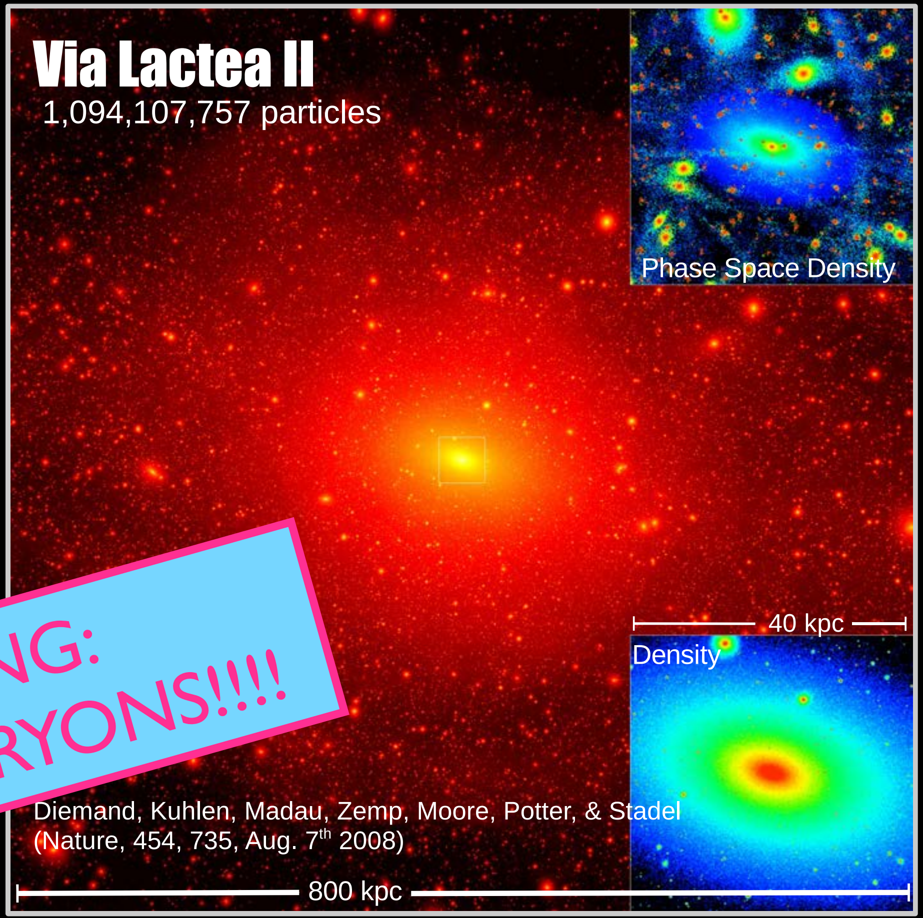
cm^{-3}



Iocco, Pato, Bertone, Jetzer 2010

Astrophysics model: velocity distribution

We know very little about the dark matter velocity distribution



WARNING:
NO BARYONS!!!!

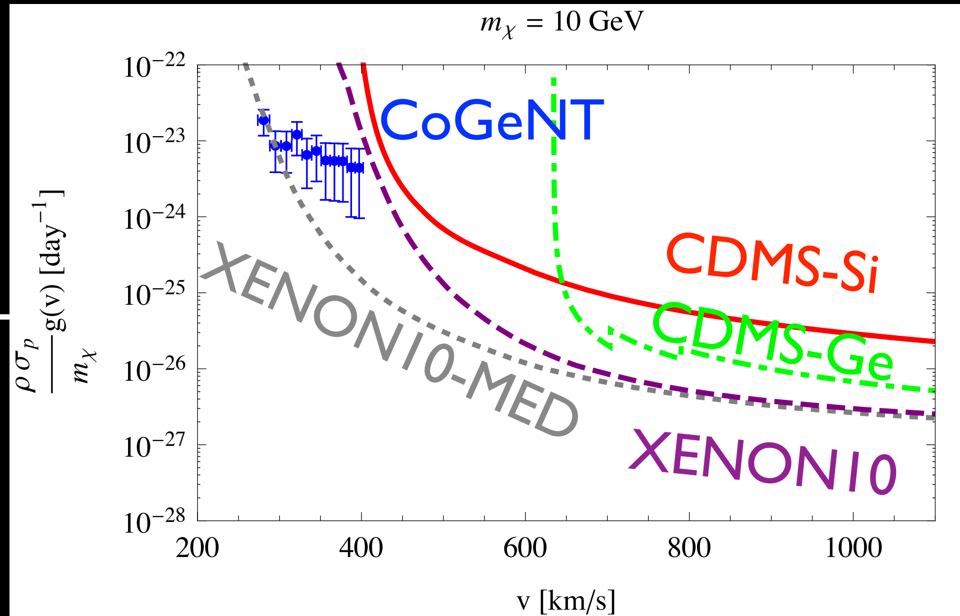
Cosmological N-Body simulations including baryons are challenging

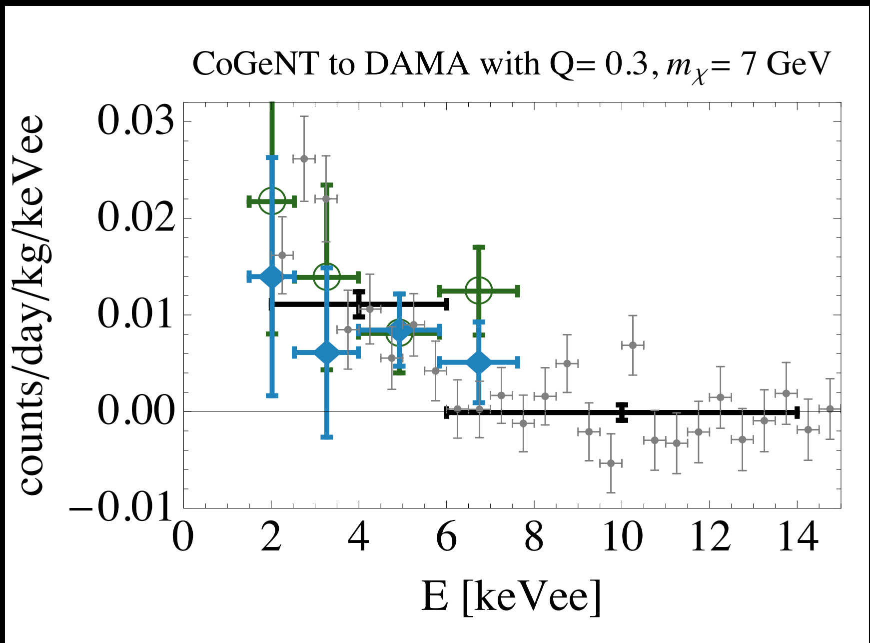
Astrophysics-independent approach

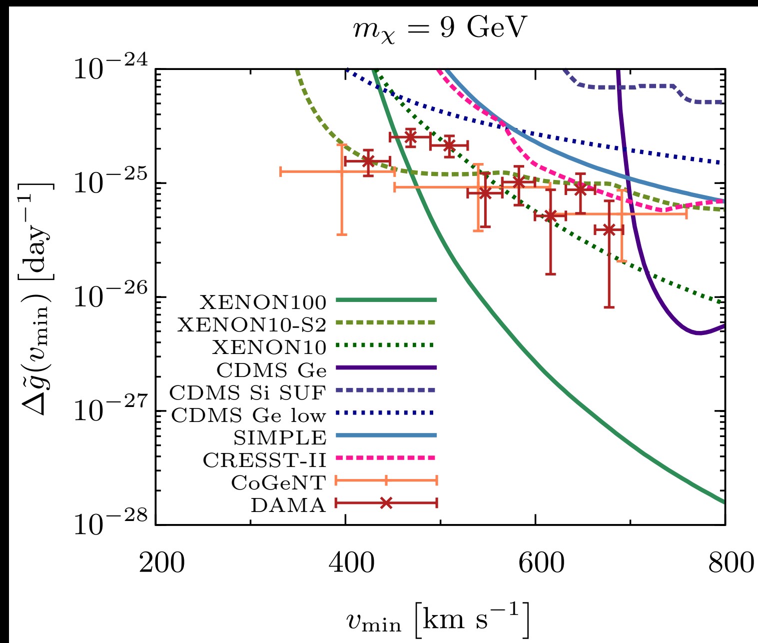
Fox, Liu, Weiner 2011

Rescaled astrophysics factor

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







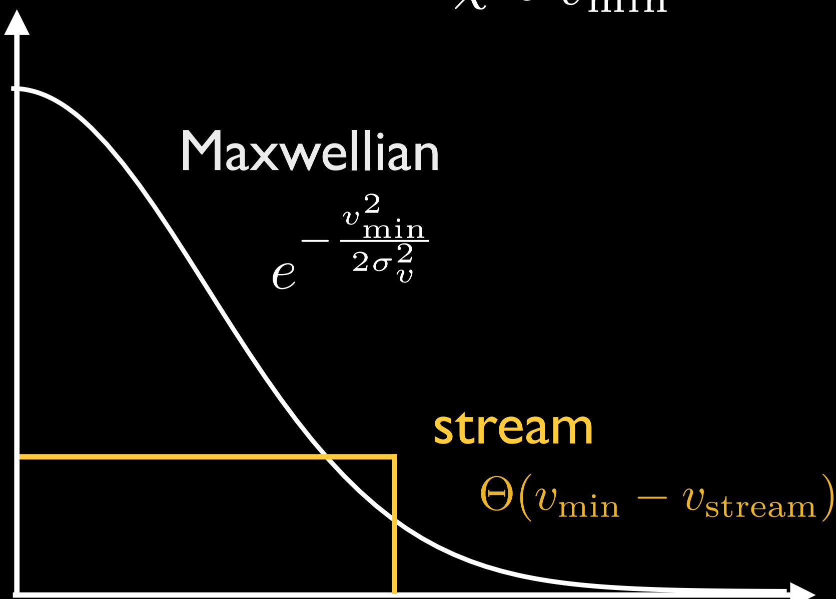
Fox, Kopp, Lisanti, Weiner 2011

Frandsen et al 2011

Astrophysics-independent approach

Rescaled astrophysics factor common to all experiments

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



Minimum WIMP speed to impart recoil energy E_R

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

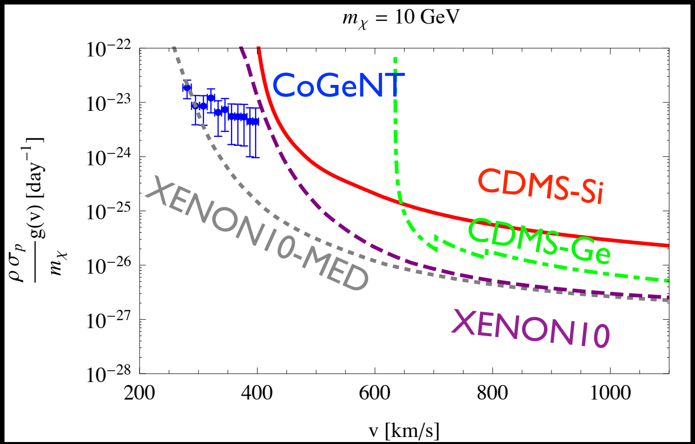
Recoil energy

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.

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

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:

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

Minimum WIMP speed to impart recoil energy E_R

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

Constant reference cross section

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*

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

Response function

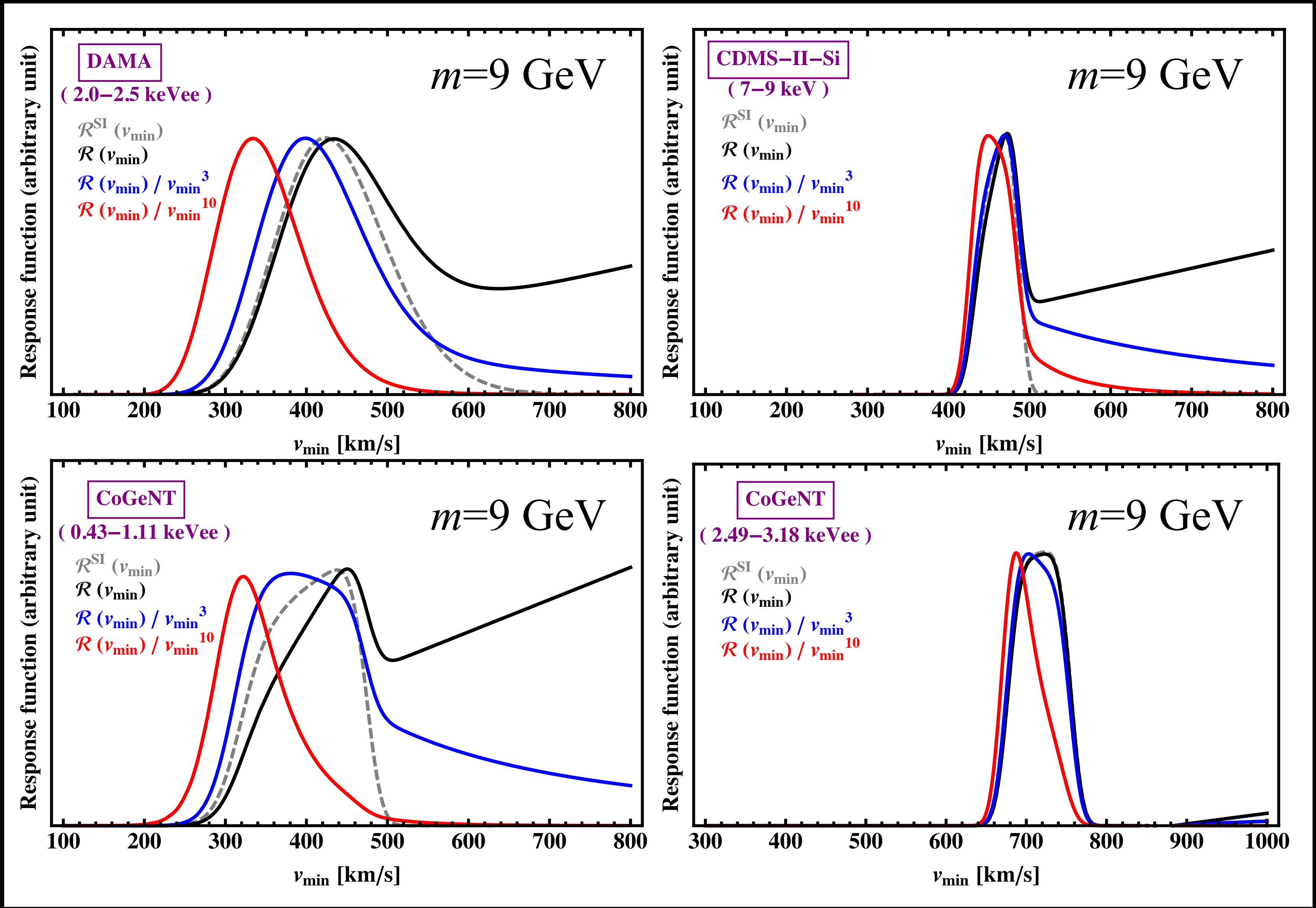
- Every experiment is sensitive to a "window in velocity space" given by the response function.

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

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

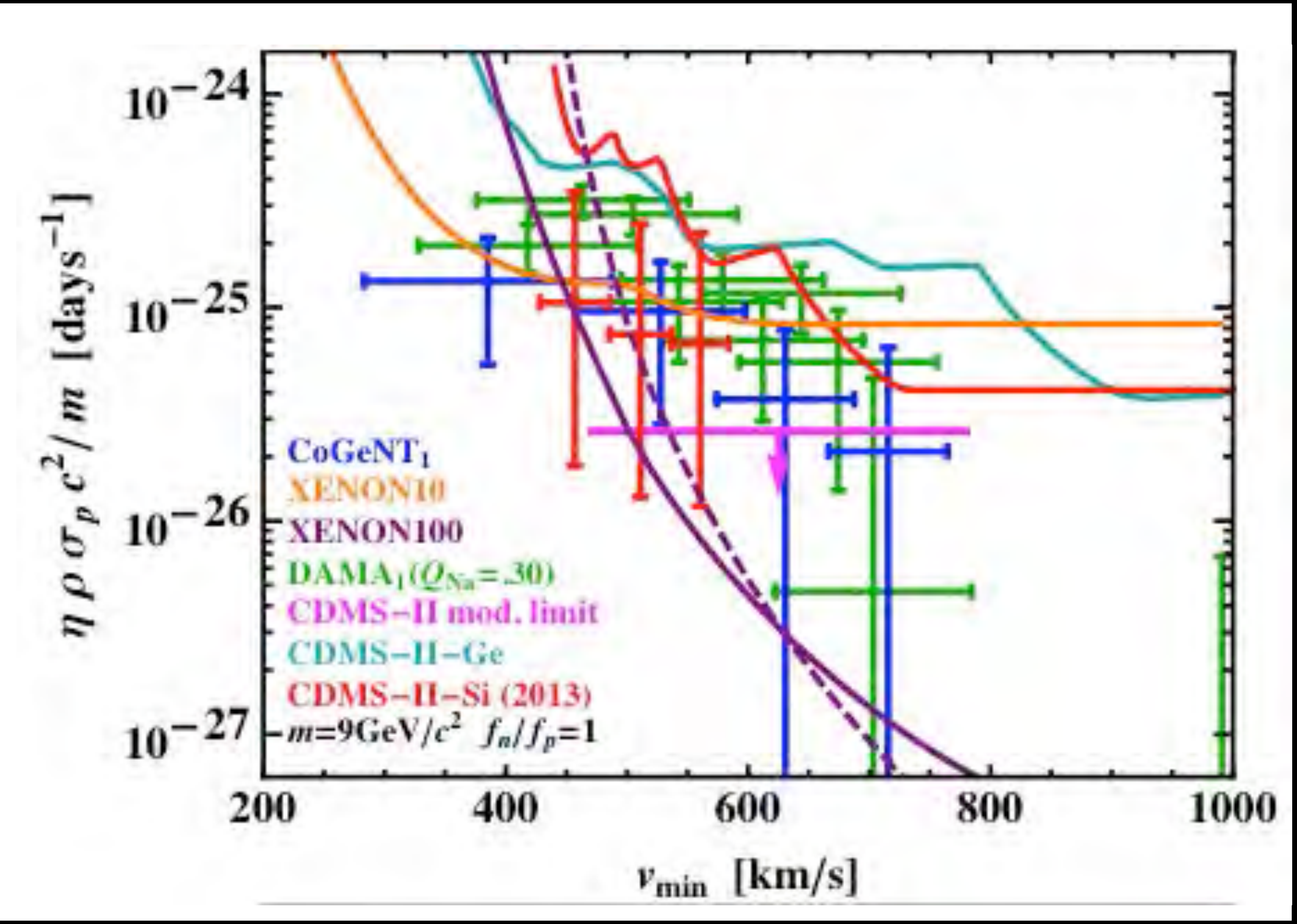
Measure or bound astrophysics factor in velocity interval $[v_1, v_2]$

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

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

Astrophysics-independent approach

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



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

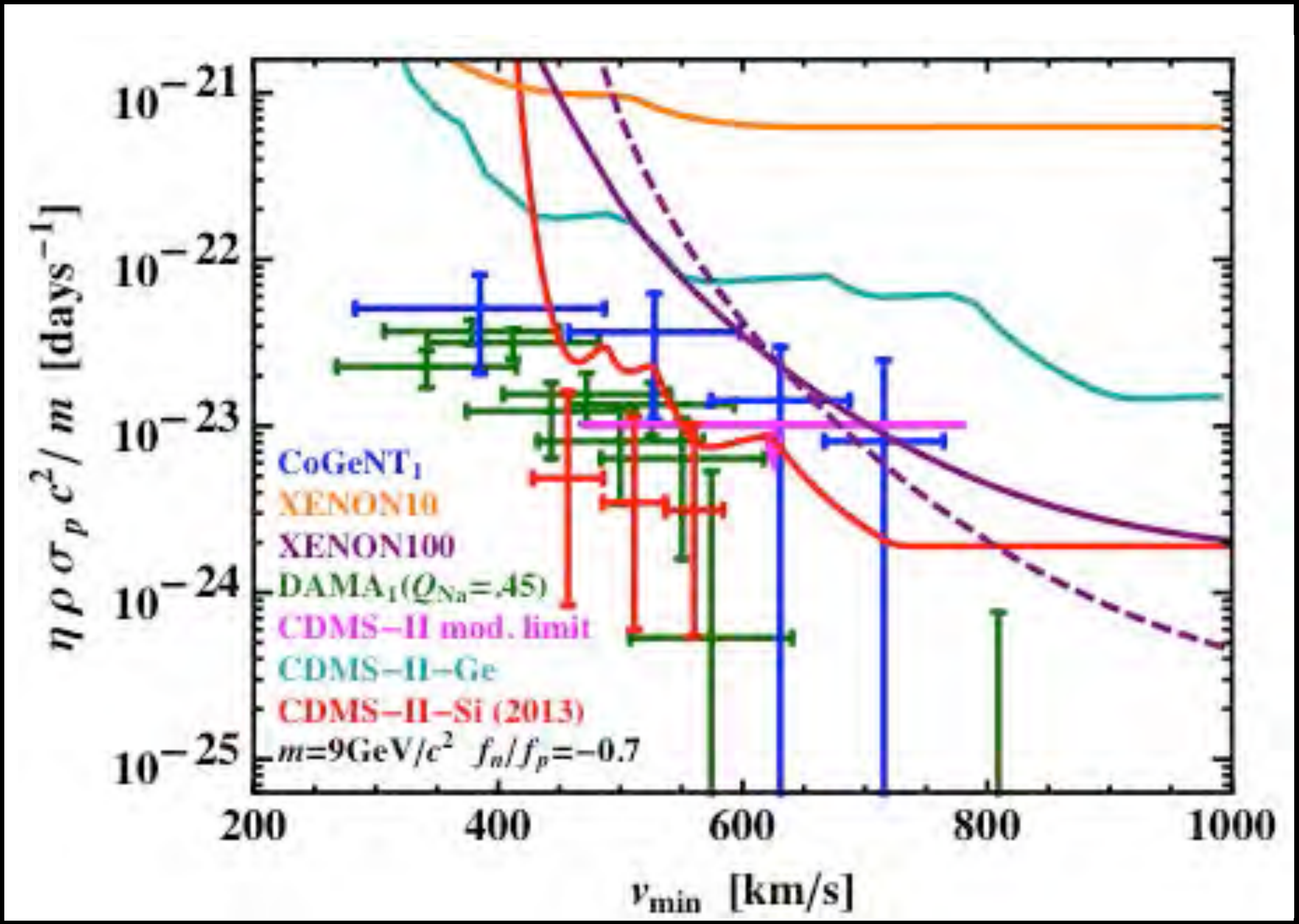
CDMS-Si event rate is similar to annual modulated rates

Del Nobile, Gelmini, Gondolo, Huh 2013

Still depends on particle model

Astrophysics-independent approach

Isospin-violating dark matter



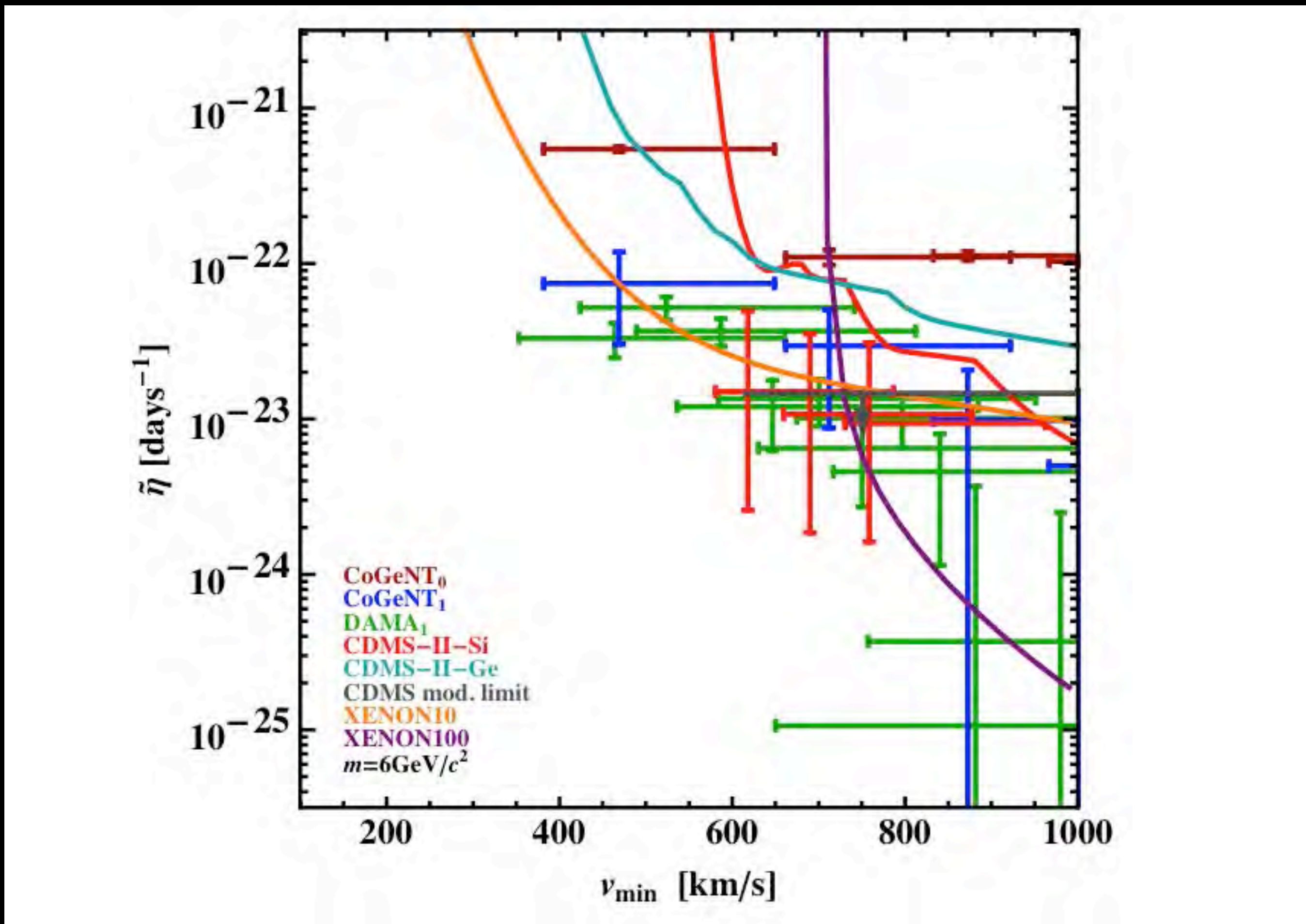
Dark matter coupled differently to protons and neutrons may have a chance

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



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

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?)