Halo-Independent Analysis of Direct Dark Matter Experiments

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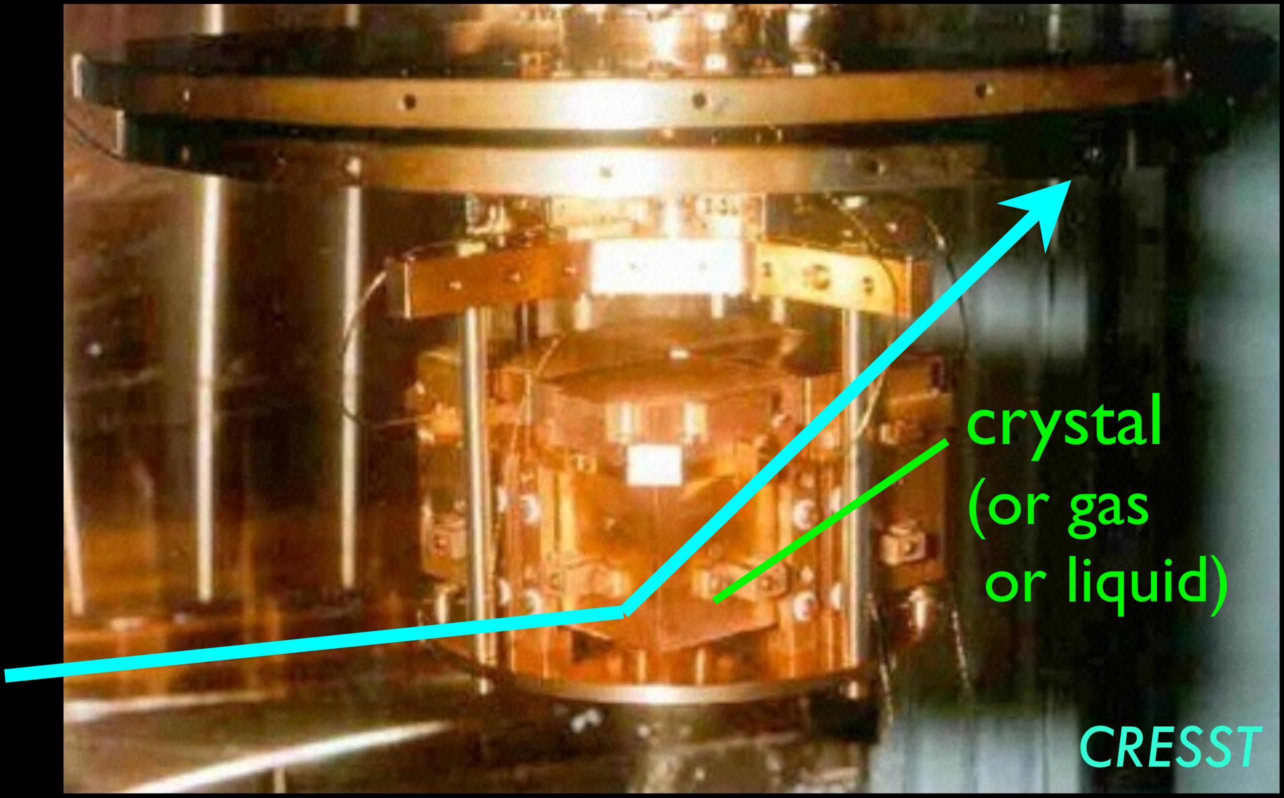
The principle of direct detection

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

Goodman,
Witten
1985



Low-background underground detector

Direct WIMP searches

Yang Yang
KIMS

Kamioka
XMASS
NEWAGE

Jinping
PANDA-X
CDEX

Homestake
LUX
LZ

Soudan
SuperCDMS
CoGeNT

SNOLab
DEAP
PICASSO
COUPP
SuperCDMS
PICO

Boulby
DRIFT

Modane
EDELWEISS
MIMAC

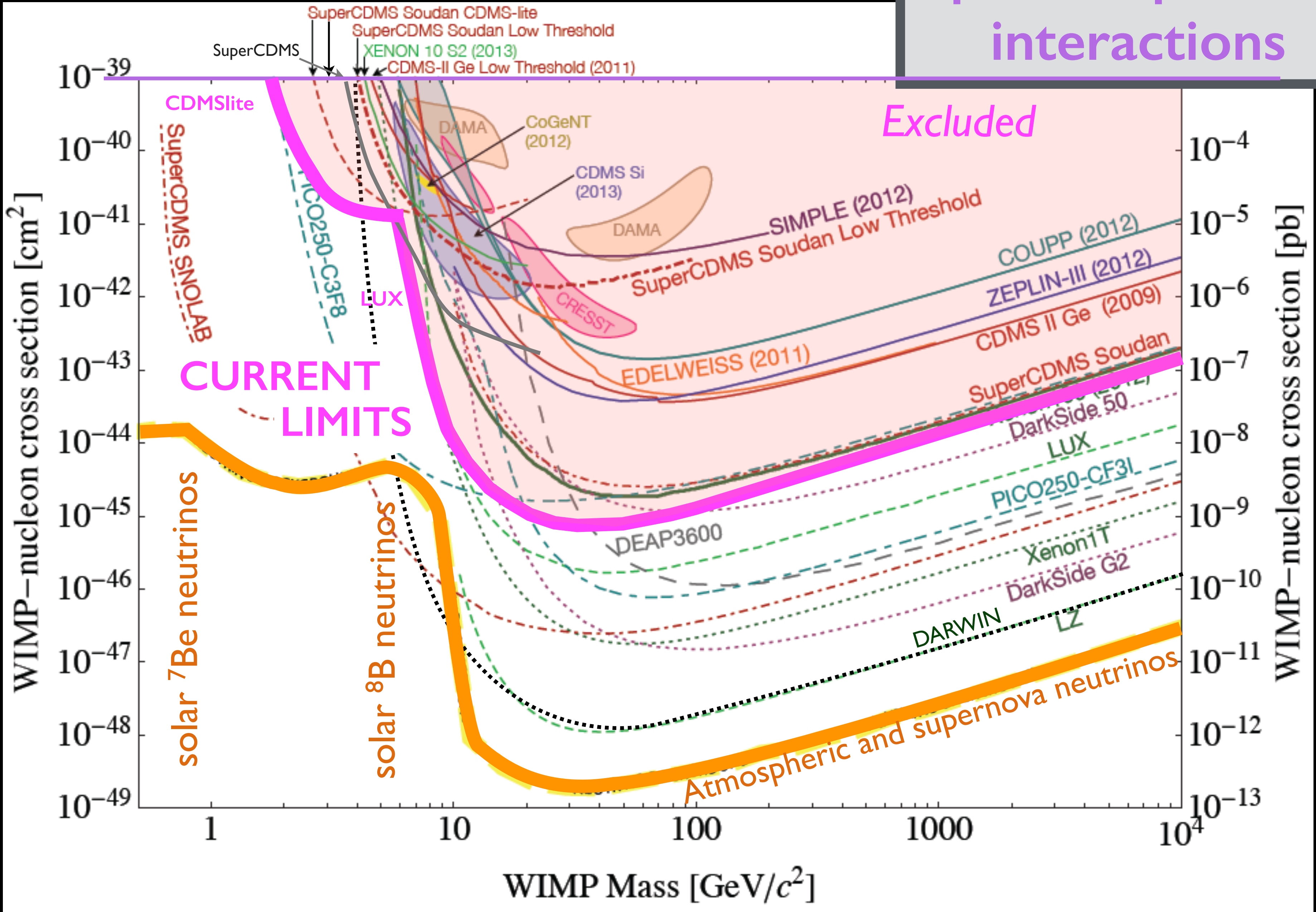
Canfranc
ArDM
ROSEBUD
ANAIS

Gran Sasso
XENON
CRESST
DAMA
DarkSIDE

South Pole
DM-ICE

Direct WIMP searches (2015)

Spin-independent interactions

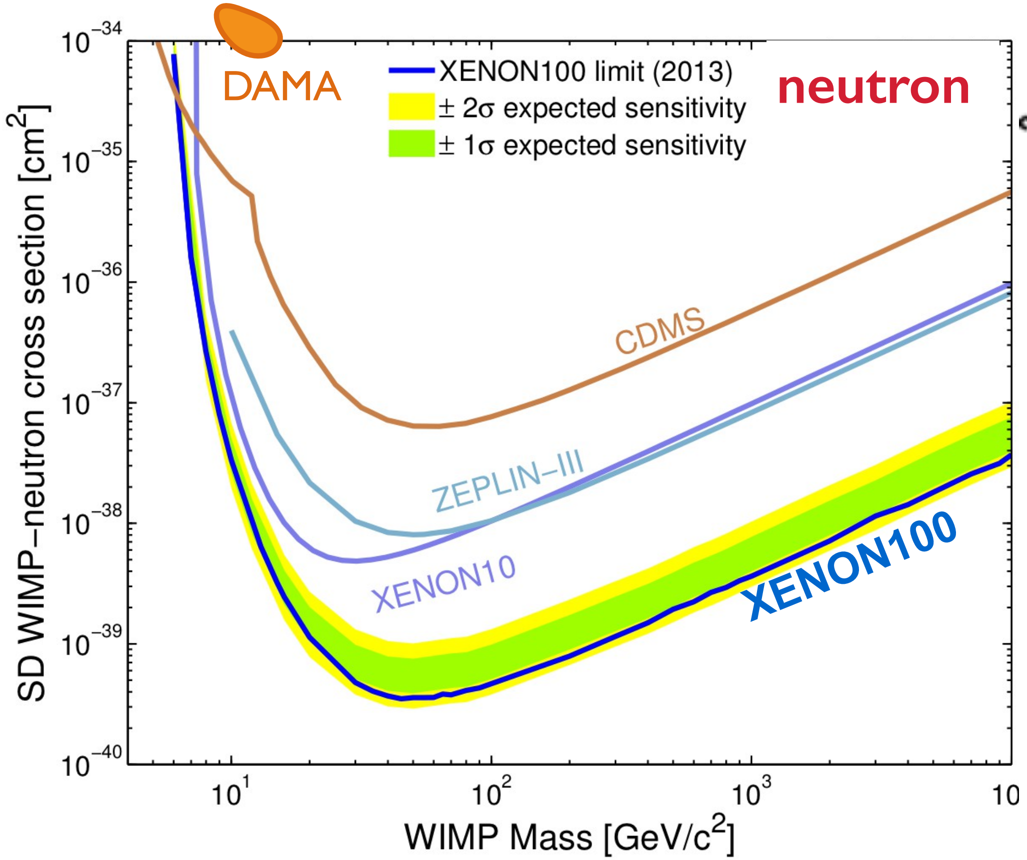


Billard et al 2013, Snowmass 2013, LUX 2013, CDMSlite 2015

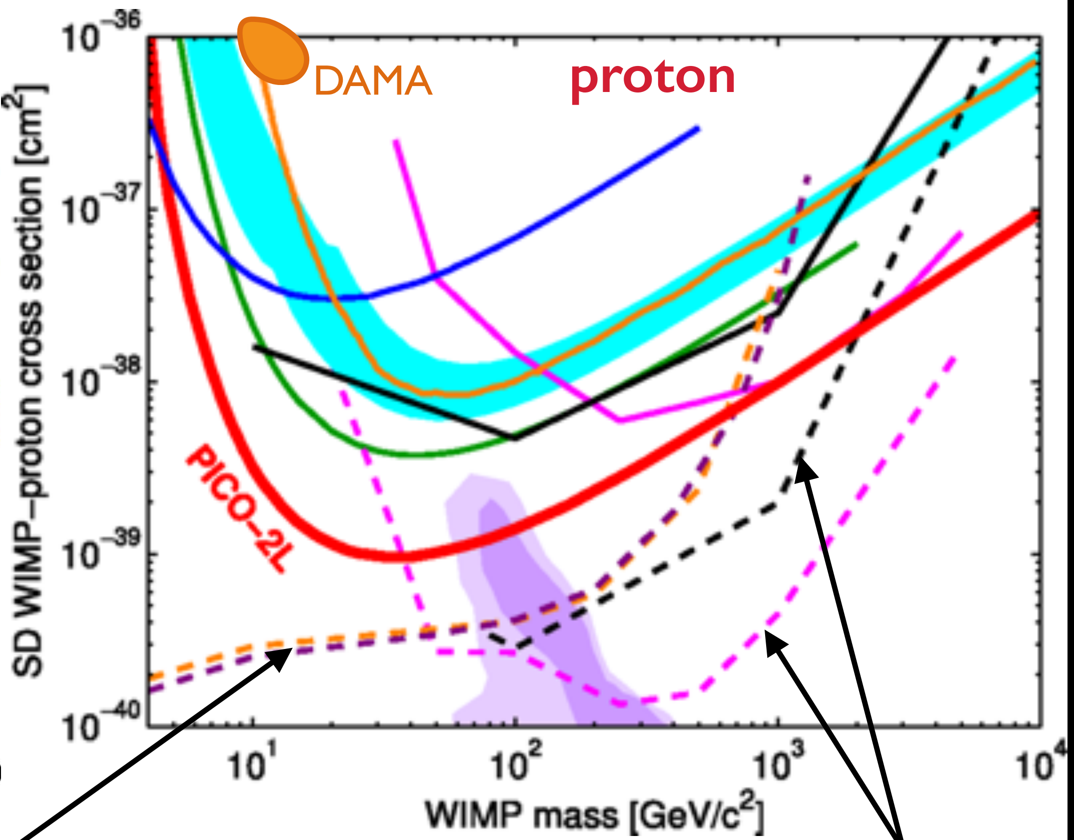
Direct WIMP searches (2015)

Spin-dependent interactions

Aprile et al (XENON100) 2013



Amole et al (PICO) 2015

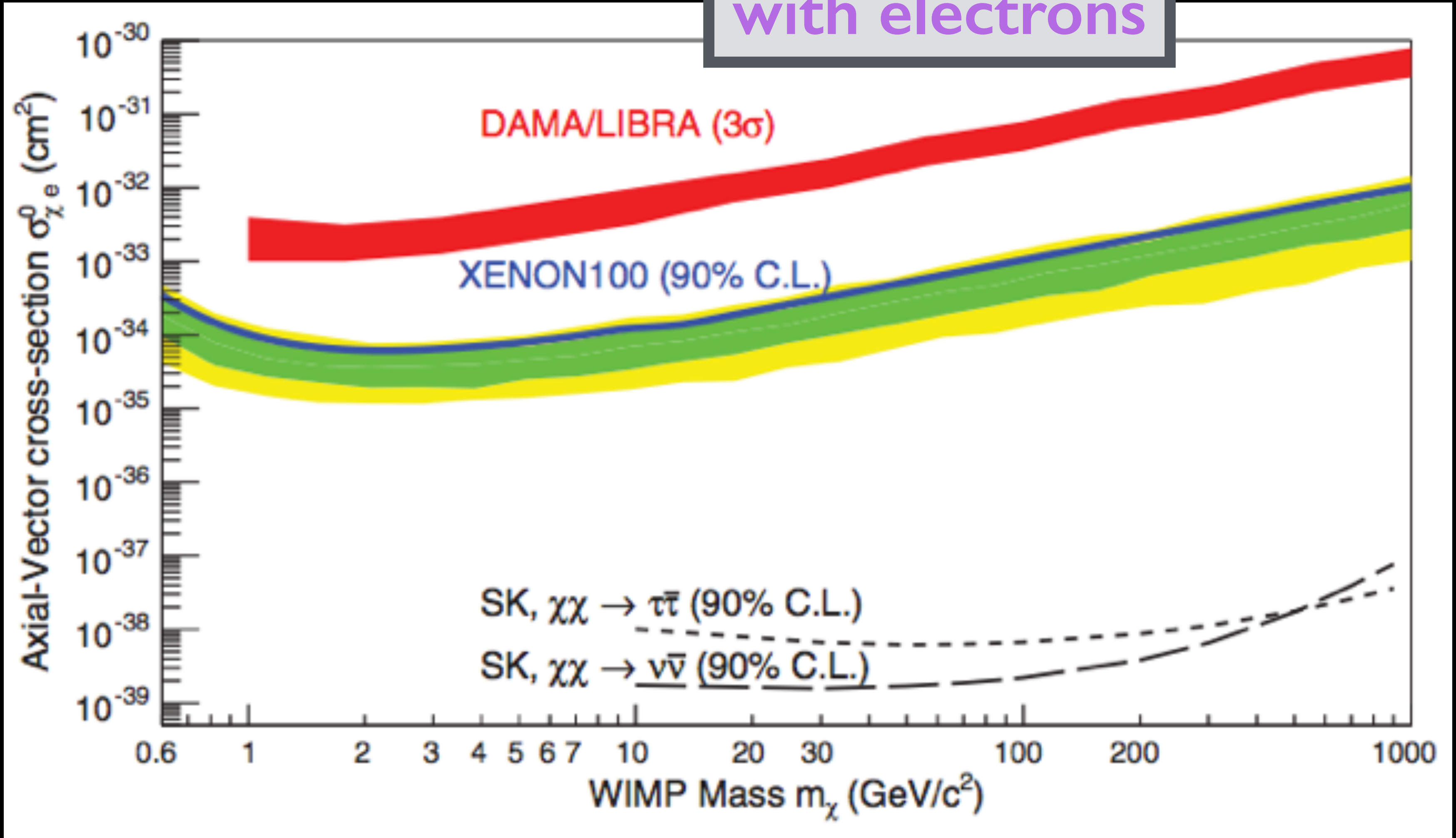


ATLAS and CMS
(WIMP production at the LHC)

IceCube and SuperK
(high-energy neutrinos from the Sun)

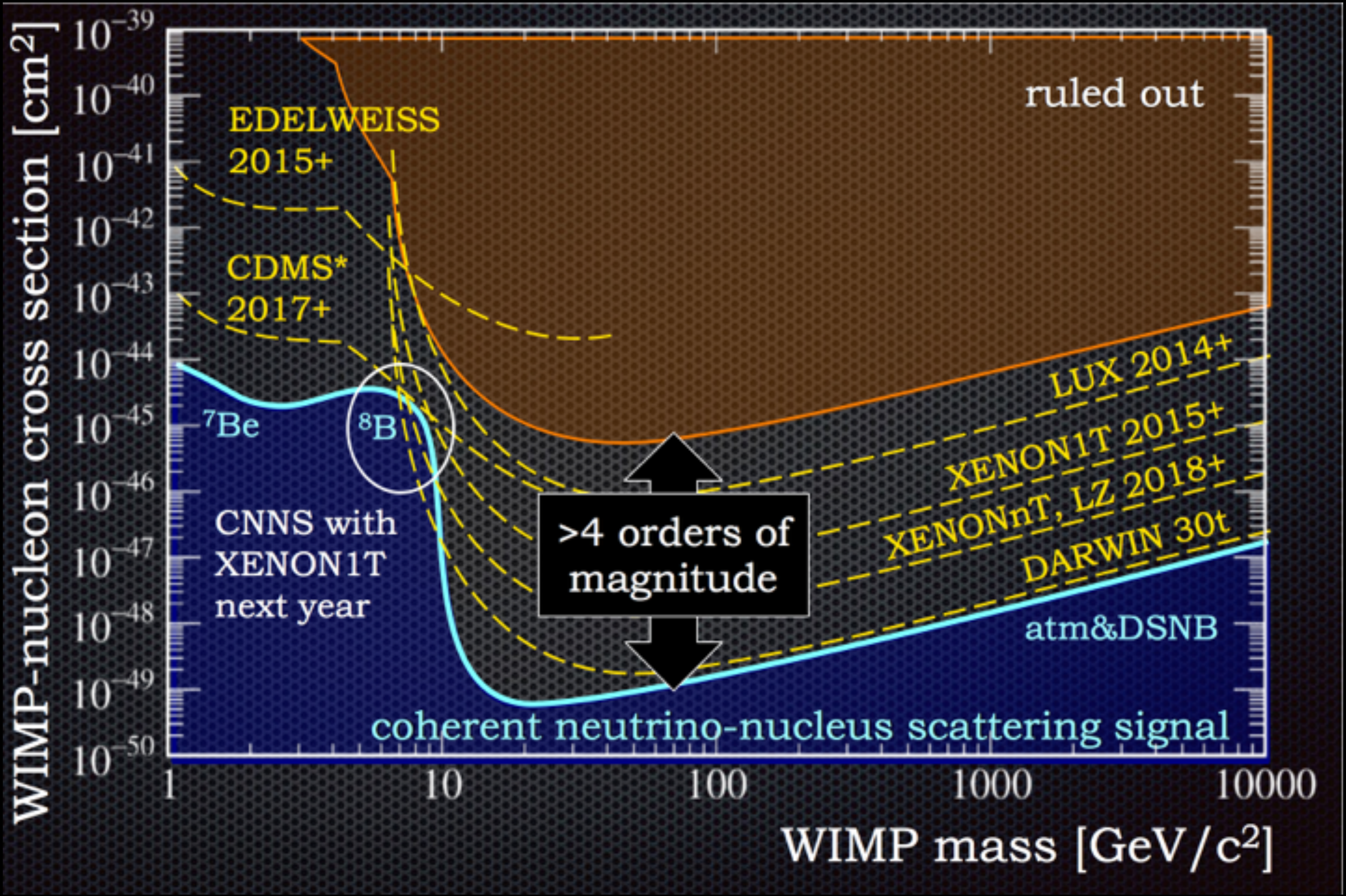
Direct WIMP searches (2015)

Interactions with electrons



Aprile et al (XENON100) 2015

Direct WIMP searches (near future)

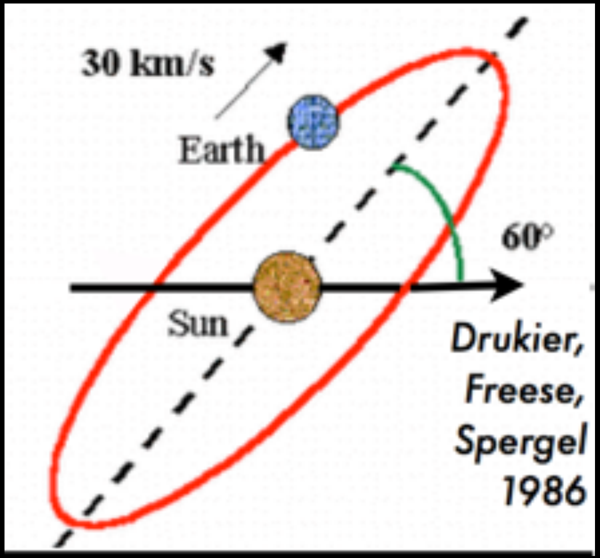


Summary by Elena Aprile 2015

Annual modulation in direct detection

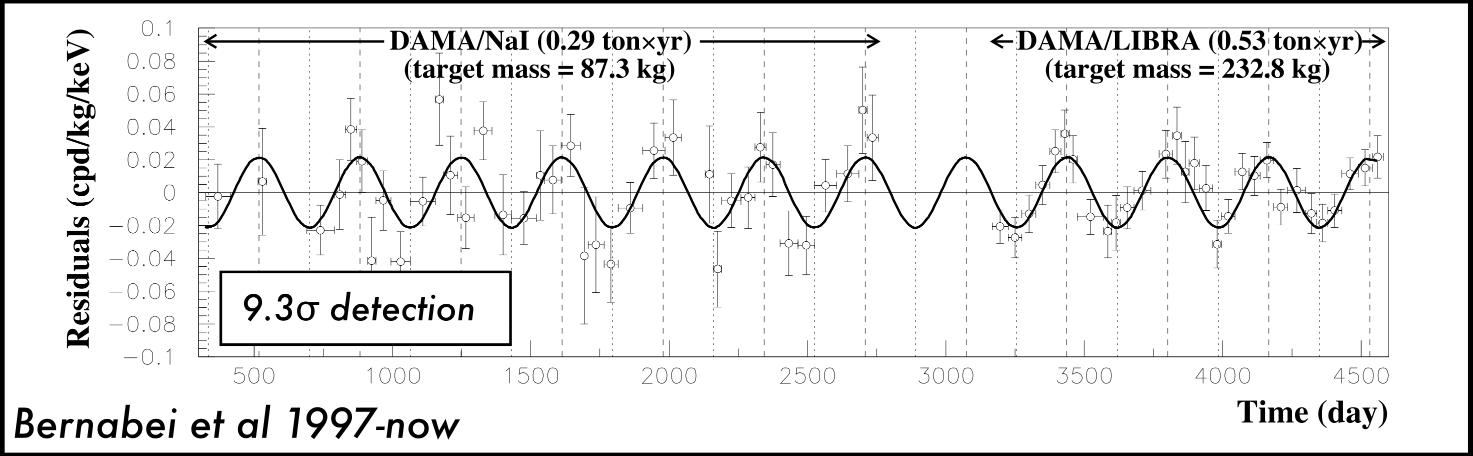
- The revolution of the Earth around the Sun modulates the WIMP event rate

Drukier, Freese, Spergel 1986



Drukier, Freese, Spergel 1986

- DAMA observes such kind of modulation



9.3σ detection

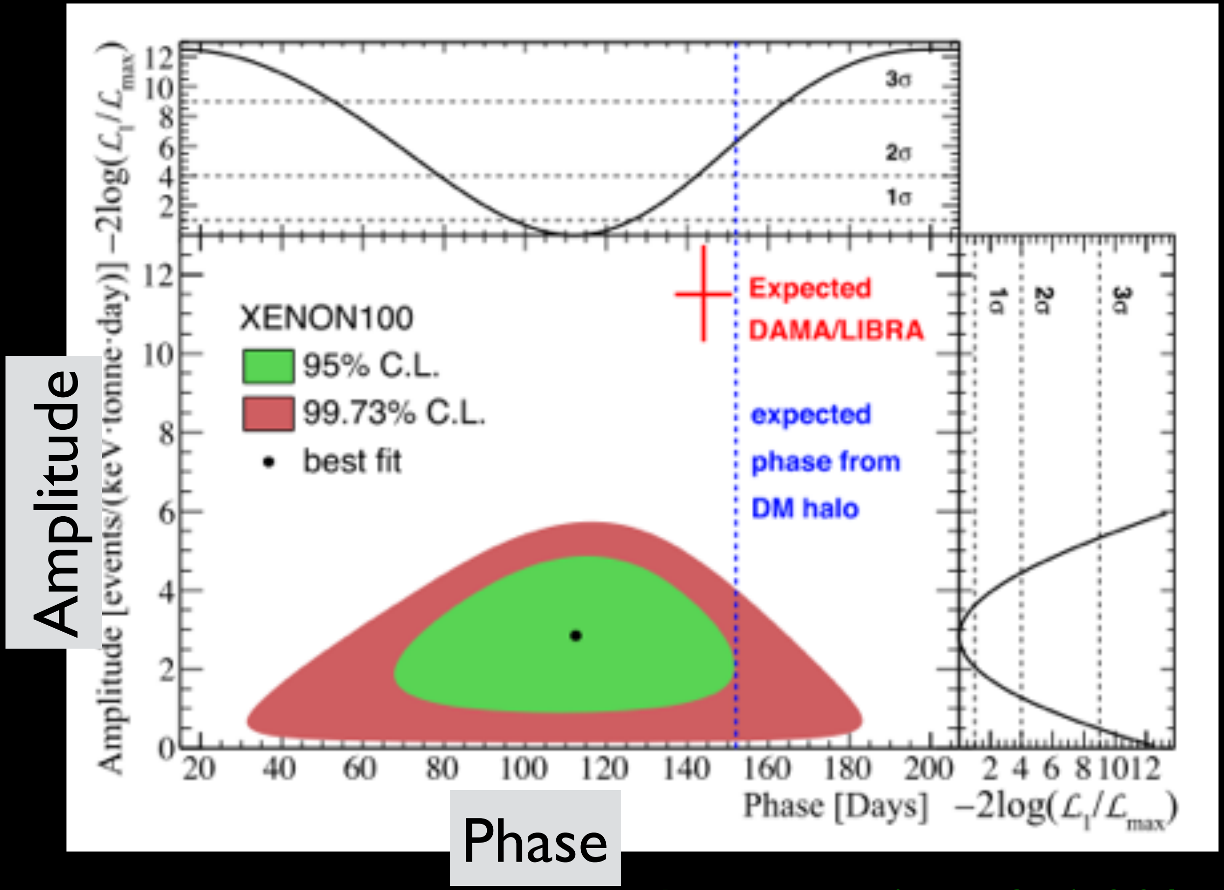
Bernabei et al 1997-now

Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments

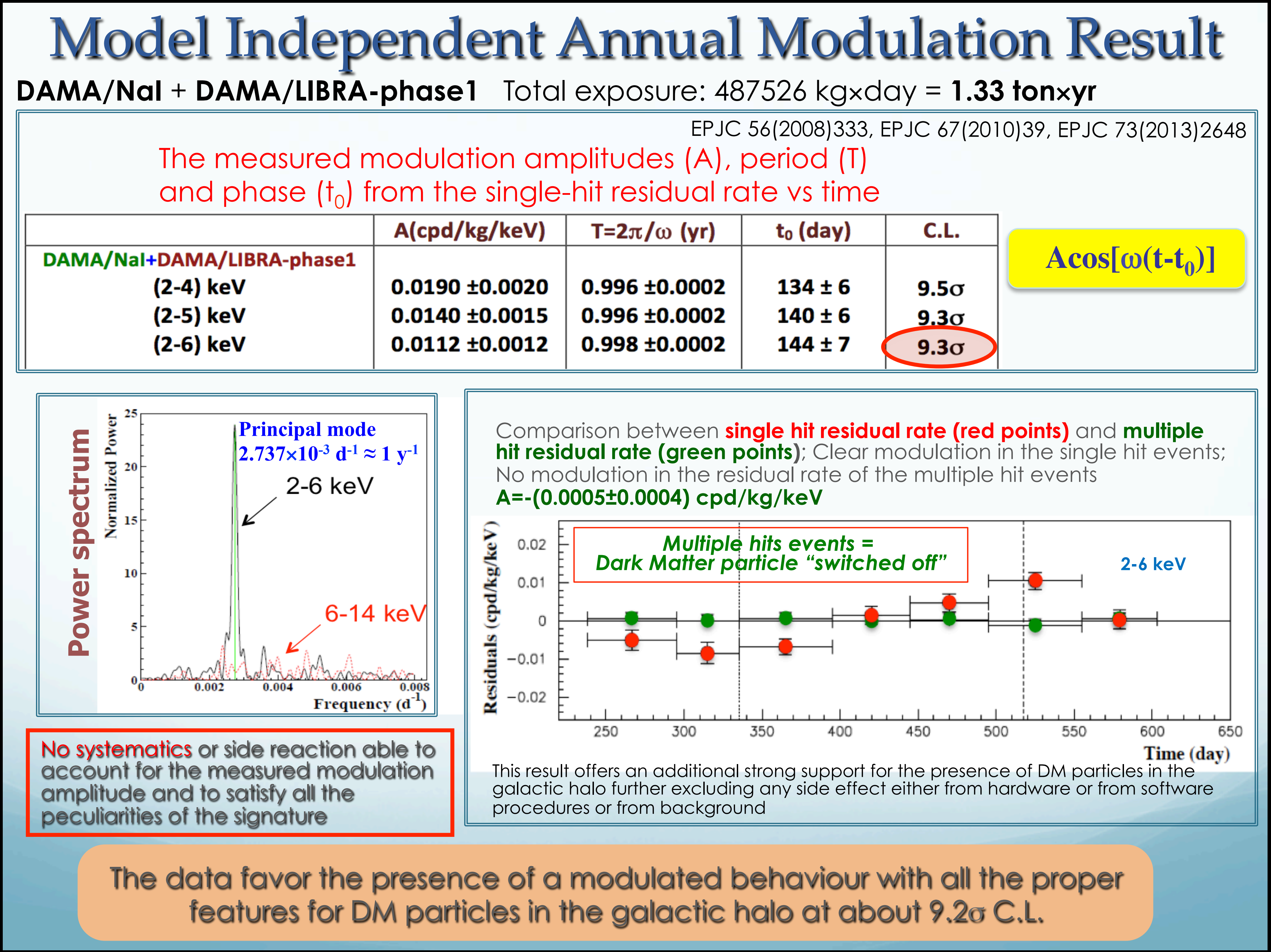
XENON100 finds an annual modulation in single- and multiple-electron scattering events

NOT due to dark matter
NOT compatible with DAMA's



Aprile et al (XENON) 2015

DAMA modulation



Model Independent Annual Modulation Result

DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

The measured modulation amplitudes (A), period (T) and phase (t_0) from the single-hit residual rate vs time

	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	0.0190 ±0.0020	0.996 ±0.0002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.0002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.0002	144 ± 7	9.3σ

$A\cos[\omega(t-t_0)]$

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

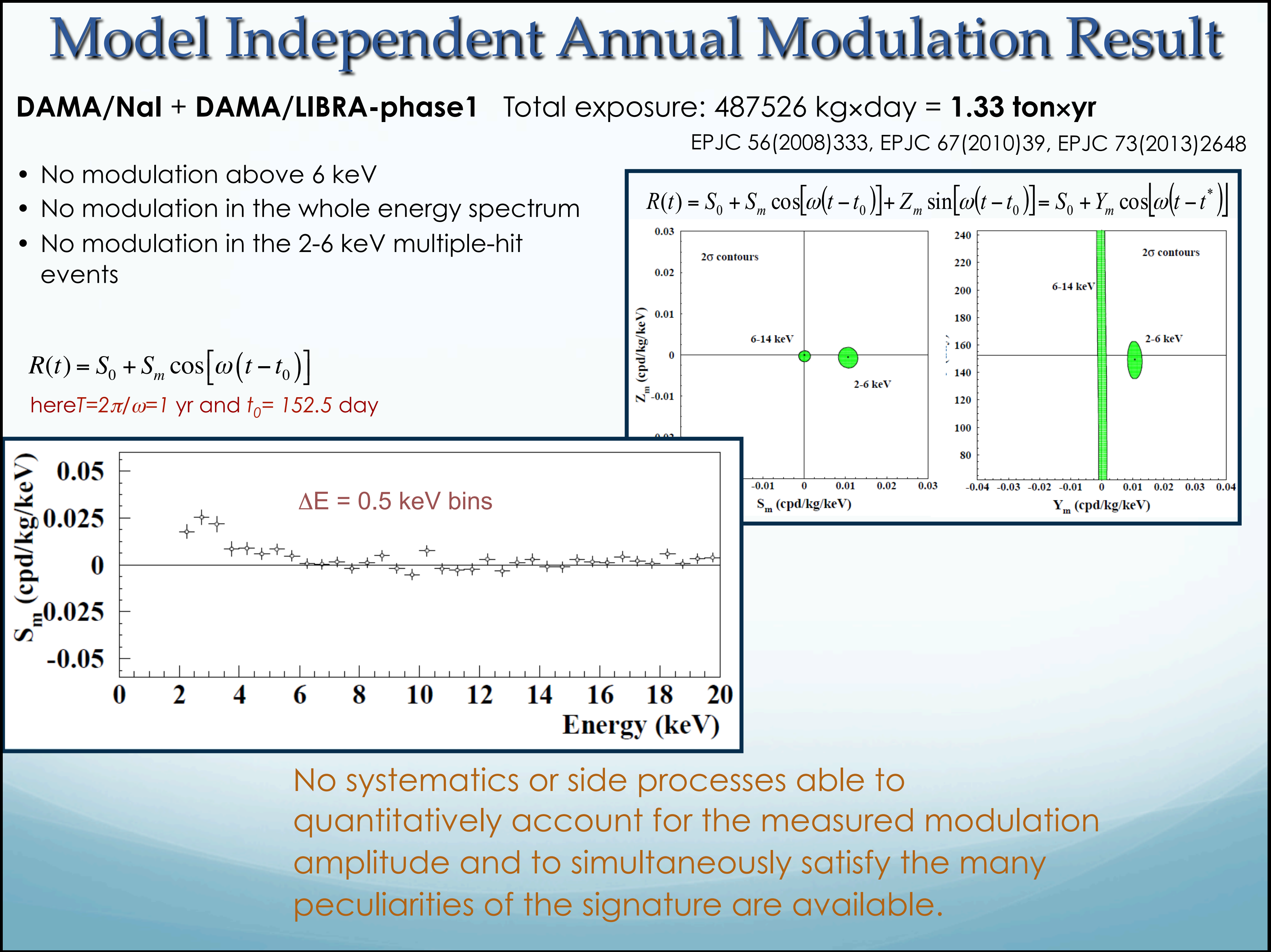
Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events **A=-(0.0005±0.0004) cpd/kg/keV**

This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.

Belli, IDM2014

DAMA modulation



Model Independent Annual Modulation Result

DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

$$R(t)=S_0+S_m\cos[\omega(t-t_0)]+Z_m\sin[\omega(t-t_0)]=S_0+Y_m\cos[\omega(t-t^*)]$$

$$R(t)=S_0+S_m\cos\left[\omega\left(t-t_0\right)\right]$$

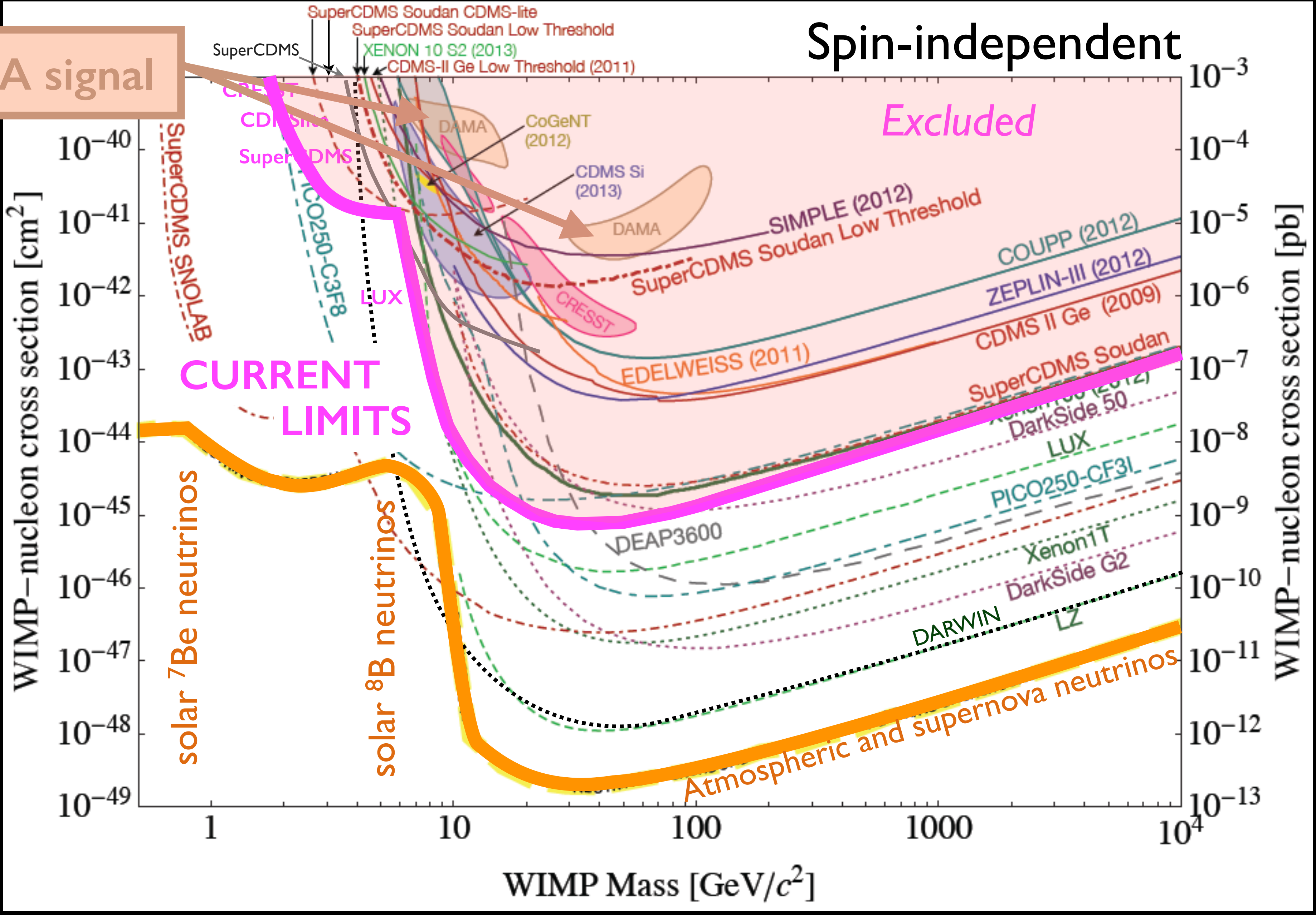
here$T=2\pi/\omega=1$ yr and t_0= 152.5 day

No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy the many peculiarities of the signature are available.

Belli, IDM2014

Direct evidence for dark matter particles?

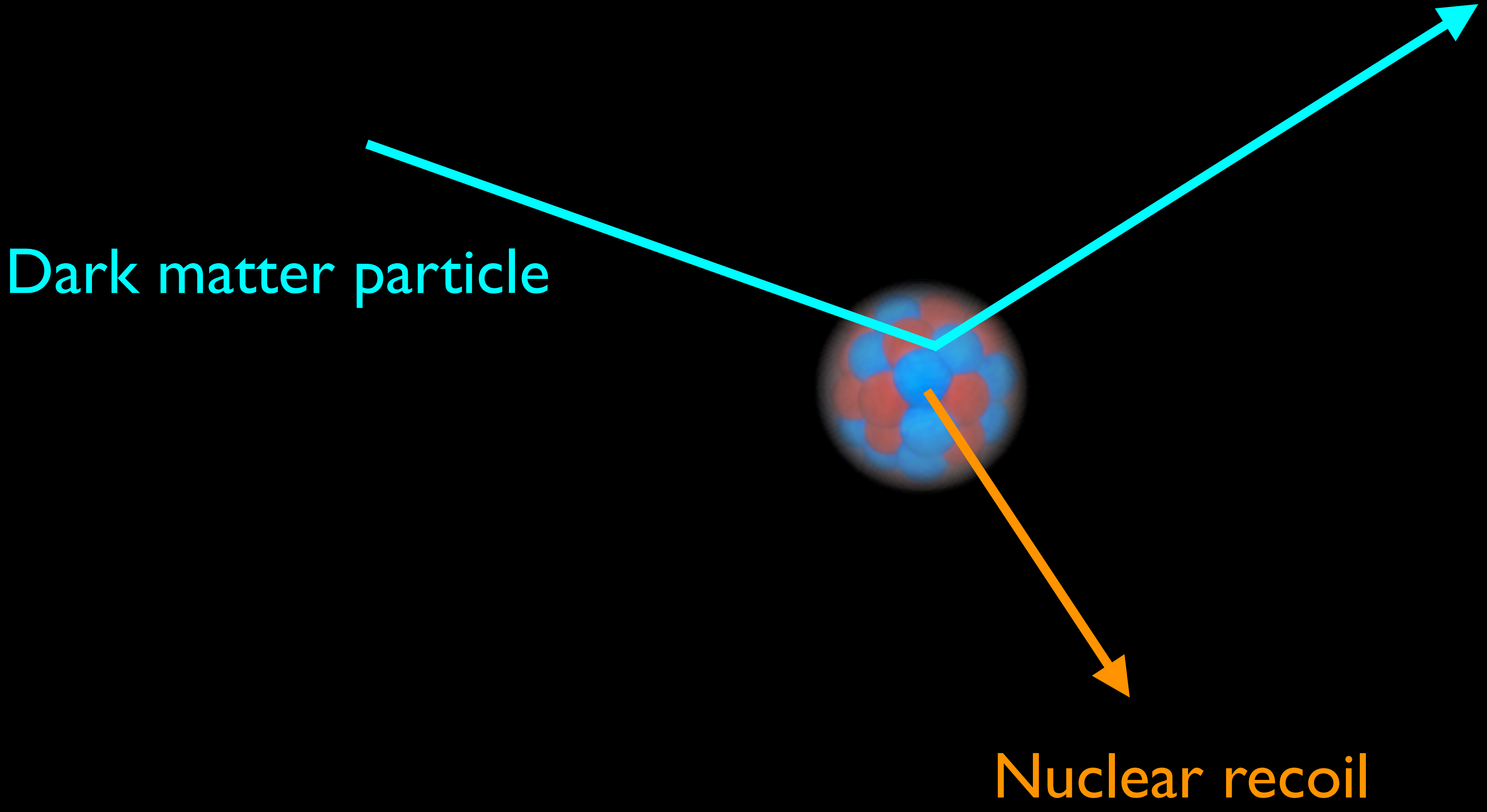
The DAMA signal seems incompatible with other experiments



Billard et al 2013, Snowmass 2013, LUX 2013, SuperCDMS 2014

DM-nucleus elastic scattering

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



Detector response

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

Is a nuclear recoil detectable?

Counting efficiency, energy resolution, scintillation response, etc.

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

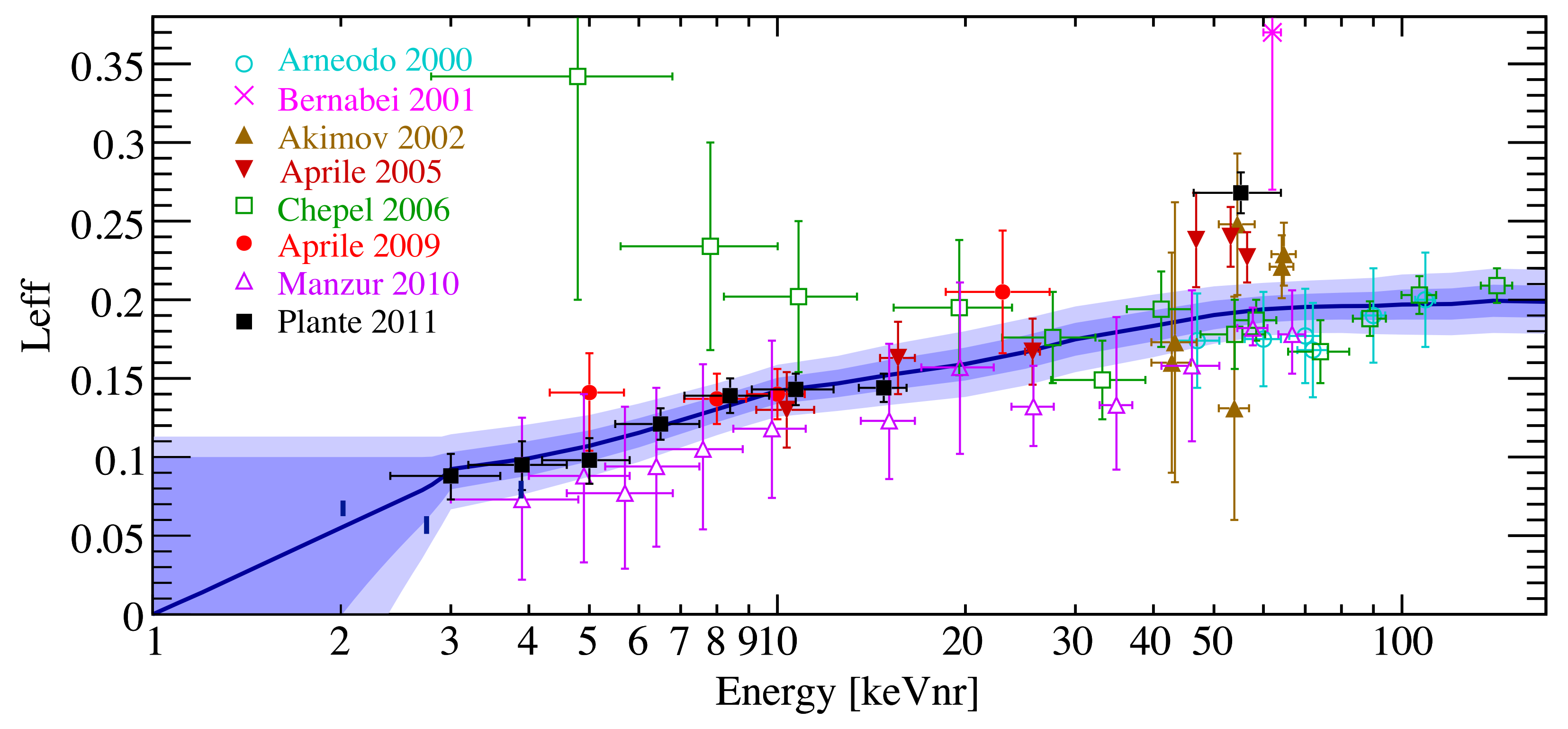
Probability of detecting an event with energy (or number of photoelectrons) E, given an event occurred with recoil energy E_R.

Detector response

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

Compilation of measurements of the light efficiency factor L_{eff} in liquid xenon

New efforts to measure efficiency at low recoil energy



Aprile et al (XENON100), 1104.2549

Detector response

The scattering rate per unit target mass (recoil spectrum)

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

The event rate per unit target mass (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

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

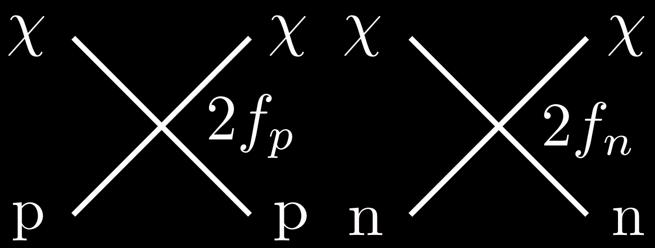
Particle physics model

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

Spin-independent

$$\frac{d\sigma_{SI}}{dE_R} = \frac{2m}{\pi v^2}\left|Zf_p+(A-Z)f_n\right|^2\left|F(E_R)\right|^2$$

Effective four-particle vertices



Nuclear density form factor

Isoscalar $f_p=f_n$

- inspired by neutralino
- used in most exclusion plots

Non-isoscalar $f_p \neq f_n$

- destructive interference in $Zf_p + Nf_n$
- f_n/f_p=-0.7 suppresses coupling to Xe

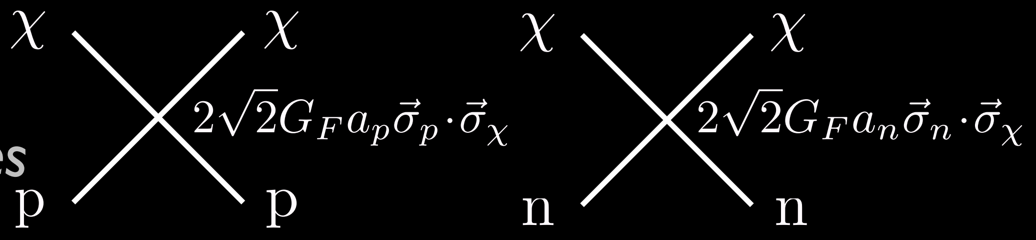
Particle physics model

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

Spin-dependent

$$\frac{d\sigma_{SD}}{dE_R} = \frac{16mG_F^2}{(2J+1)v^2}\left[a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q)\right]$$

Effective four-particle vertices



Nuclear spin structure functions

Particle physics model

Velocity and/or transfer energy dependence in scattering cross sections

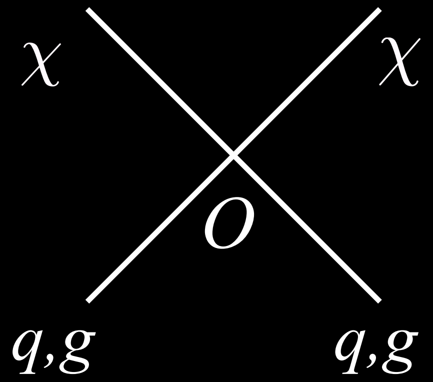
nucleus	DM	$v^2\, d\sigma/dE_R$	
		light mediator	heavy mediator
"charge"	*"charge"*	$1/E_R^2$	$1/M^4$
"charge"	*dipole*	$1/E_R$	E_R/M^4
dipole	*dipole*	$\mathrm{const} + E_R/v^2$	E_R^2/M^4

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

Particle physics model

Four-particle effective operators



All non-relativistic short-distance operators to second order in v, q

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

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

Fitzpatrick et al 2012

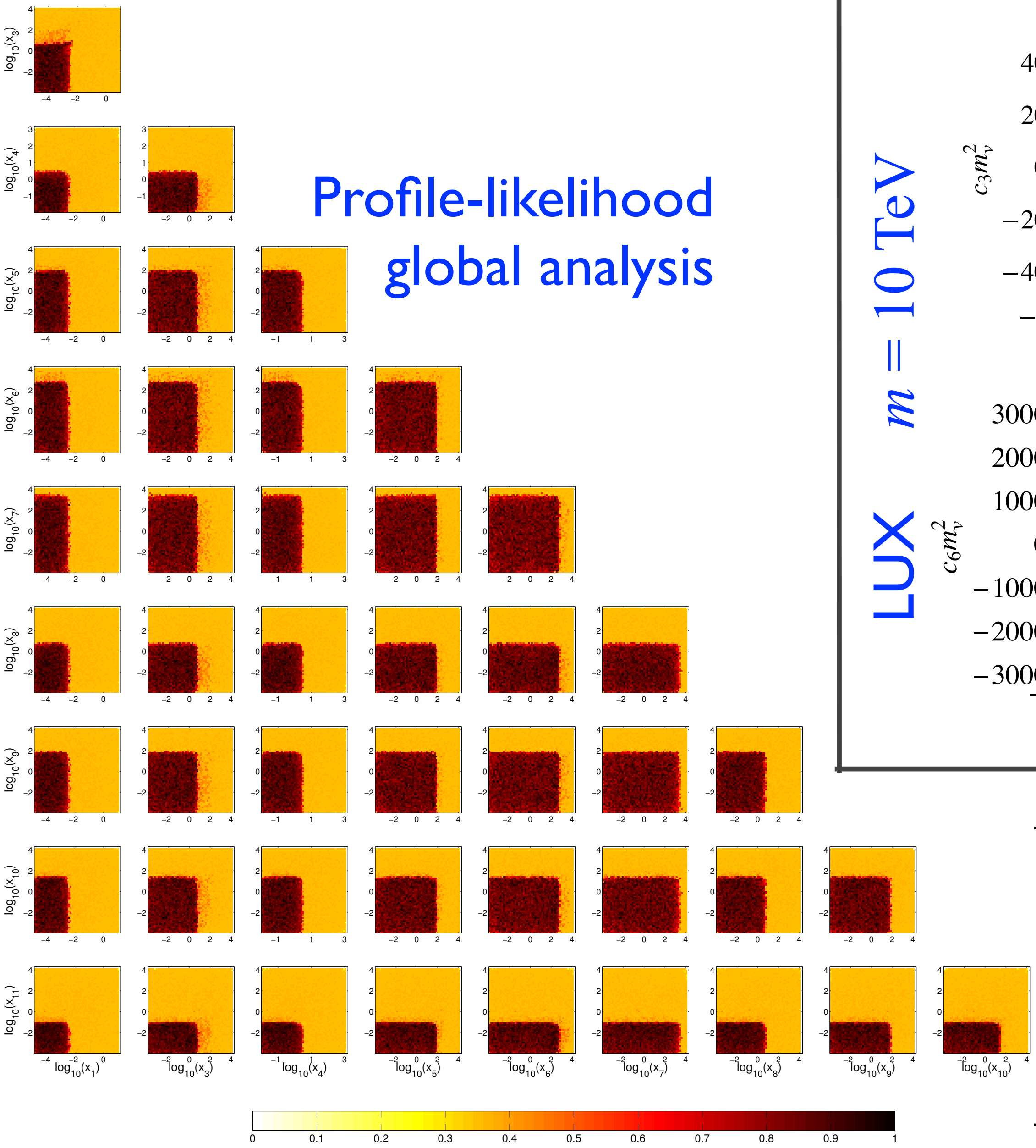
Long-distance interactions are not included.

Interference is important although often, but not always, neglected.

Particle physics model

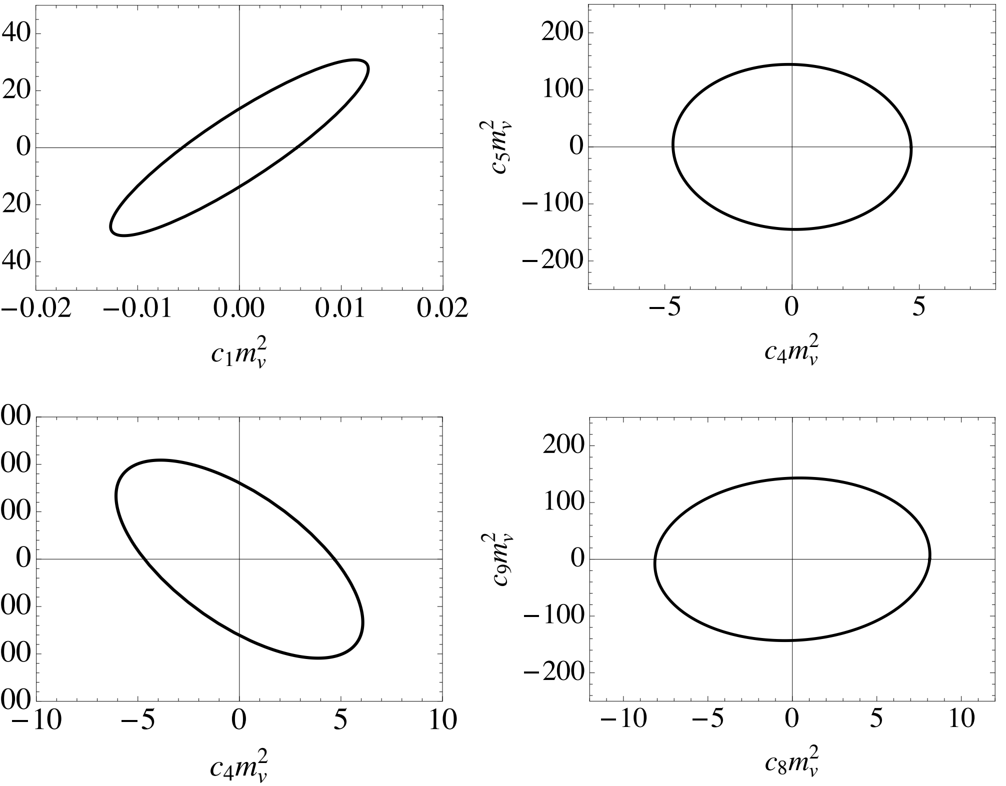
Combined analysis of short-distance operators

Catena, Gondolo 2014



Profile-likelihood global analysis

LUX $m = 10$ TeV



$$\mathcal{O}_1 = 1_\chi 1_N \qquad \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp_{\chi N}$$

$$\mathcal{O}_3 = -i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right) \qquad \mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp_{\chi N}$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \qquad \mathcal{O}_9 = -i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

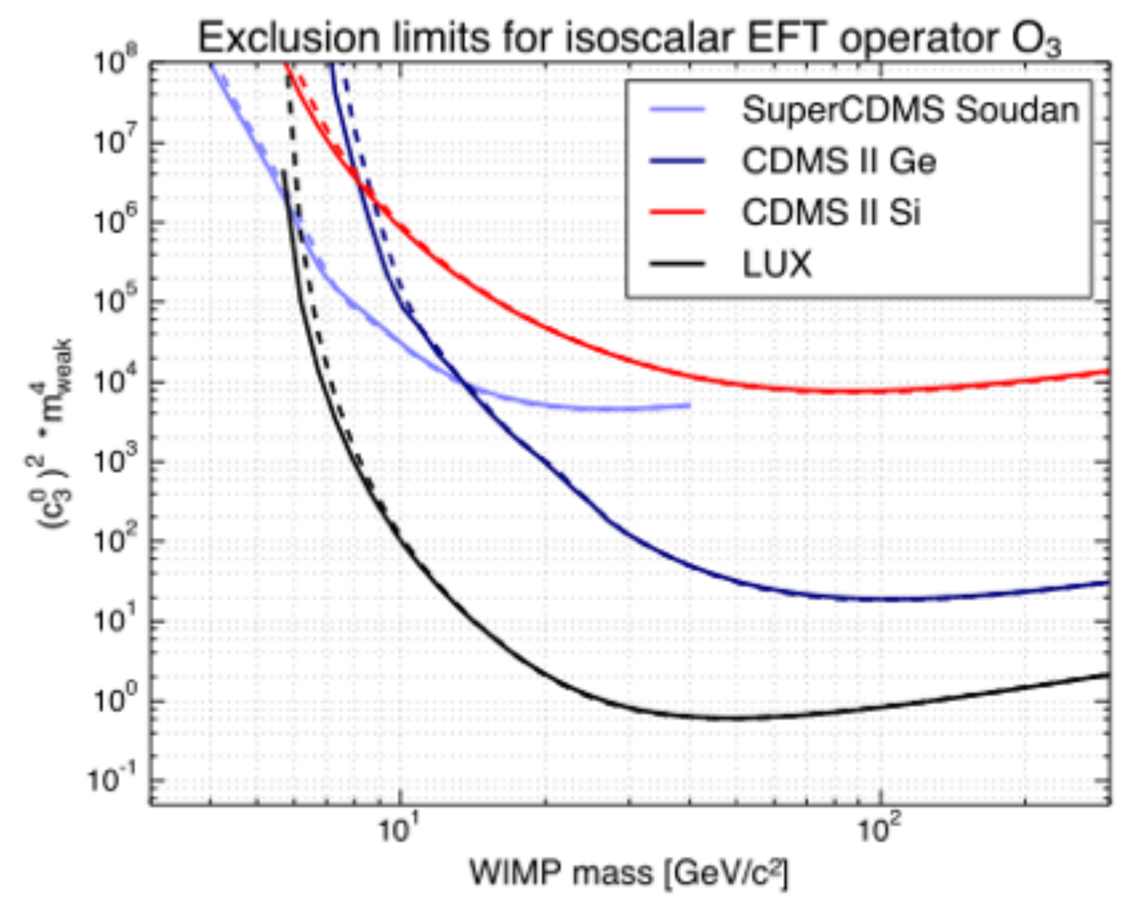
$$\mathcal{O}_5 = -i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right) \qquad \mathcal{O}_{10} = -i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

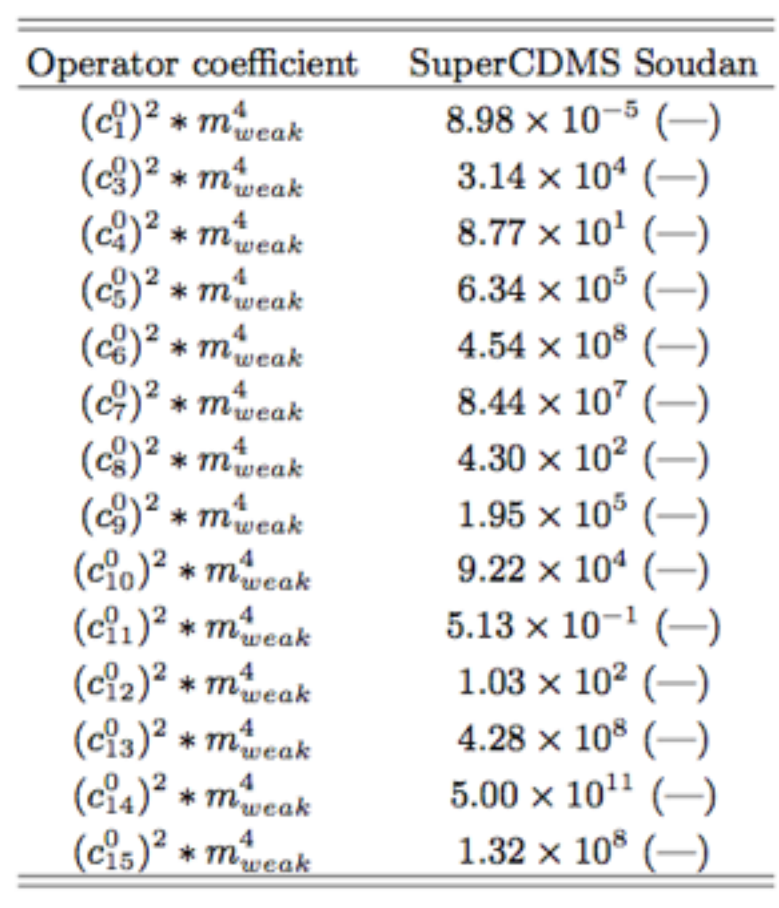
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right) \qquad \mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

Particle physics model

Experimental limits on single operators…

Schneck et al (SuperCDMS) 2015





Operator coefficient	SuperCDMS Soudan
$(c_1^0)^2 * m_{weak}^4$	8.98×10^{-5} (—)
$(c_3^0)^2 * m_{weak}^4$	3.14×10^{4} (—)
$(c_4^0)^2 * m_{weak}^4$	8.77×10^{1} (—)
$(c_5^0)^2 * m_{weak}^4$	6.34×10^{5} (—)
$(c_6^0)^2 * m_{weak}^4$	4.54×10^{8} (—)
$(c_7^0)^2 * m_{weak}^4$	8.44×10^{7} (—)
$(c_8^0)^2 * m_{weak}^4$	4.30×10^{2} (—)
$(c_9^0)^2 * m_{weak}^4$	1.95×10^{5} (—)
$(c_{10}^0)^2 * m_{weak}^4$	9.22×10^{4} (—)
$(c_{11}^0)^2 * m_{weak}^4$	5.13×10^{-1} (—)
$(c_{12}^0)^2 * m_{weak}^4$	1.03×10^{2} (—)
$(c_{13}^0)^2 * m_{weak}^4$	4.28×10^{8} (—)
$(c_{14}^0)^2 * m_{weak}^4$	5.00×10^{11} (—)
$(c_{15}^0)^2 * m_{weak}^4$	1.32×10^{8} (—)

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

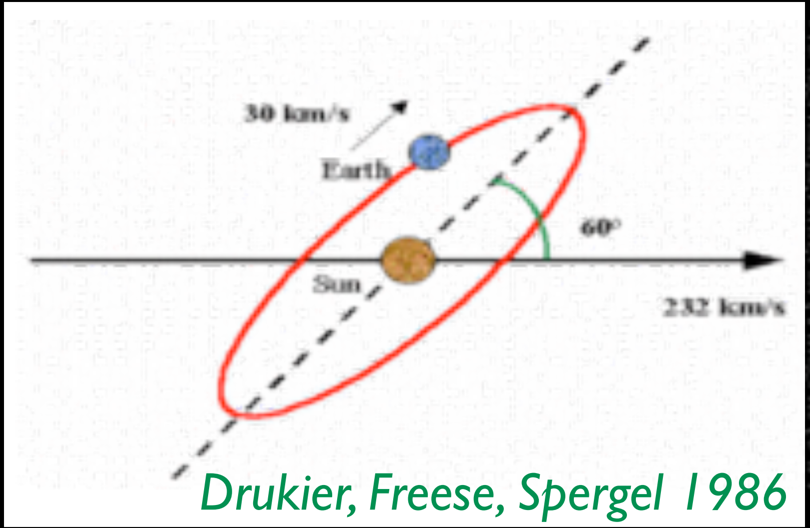
Velocity distribution

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

Minimum WIMP speed to impart recoil energy E_R

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

Astrophysics model: annual modulation



Drukier, Freese, Spergel 1986

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

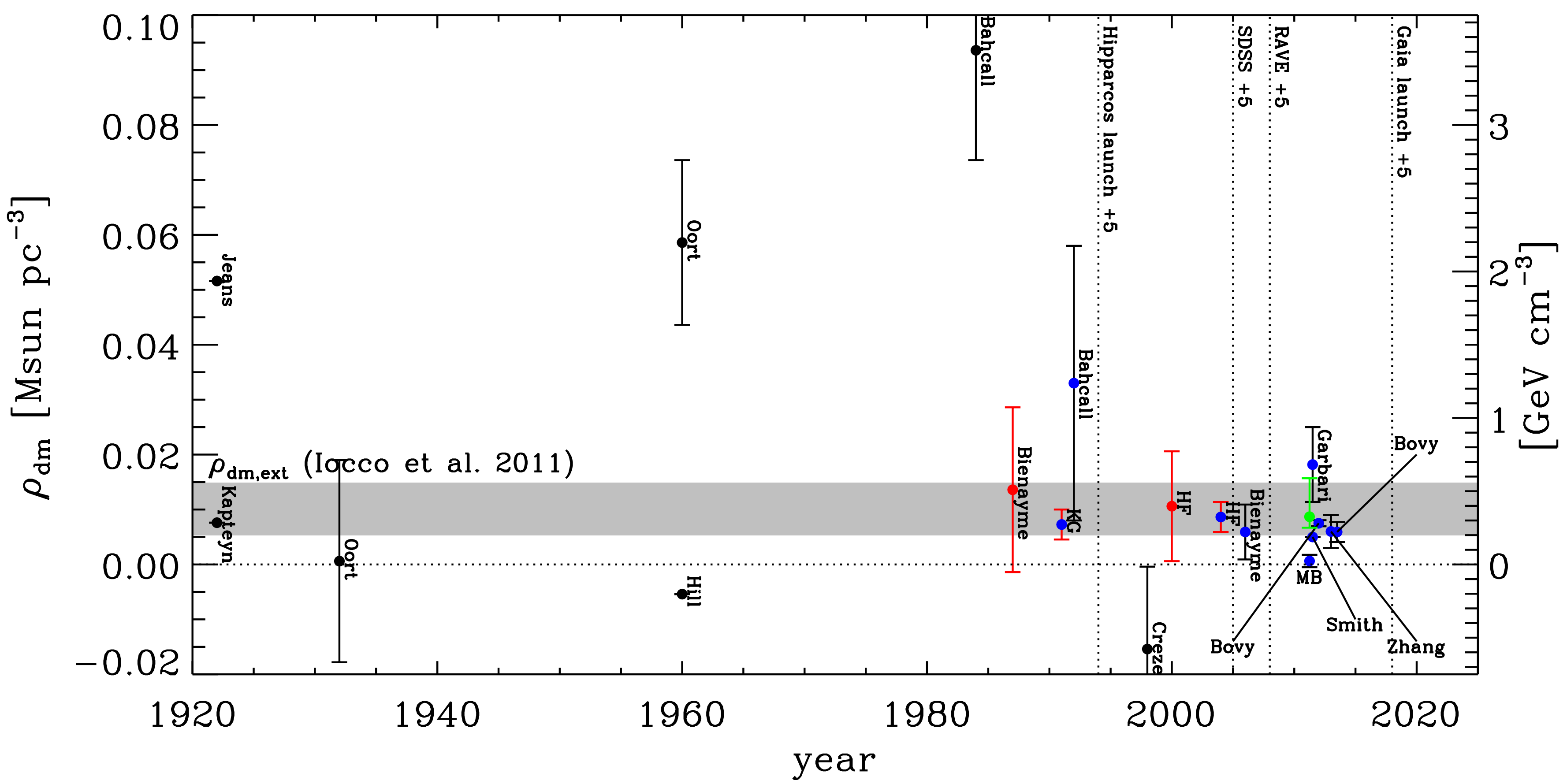
$$\frac{dR}{dE} = S_0(E) + S_1(E) \, \cos(\omega t + \varphi)$$

Unmodulated signal

Modulation amplitude

Astrophysics model: local density

The dark matter density near the Solar System
is known reasonably well



$$\rho_{\rm dm} = 0.33^{+0.26}_{-0.075}\,{\rm GeV\,cm}^{-3}$$

[volume complete; G12*;R14]

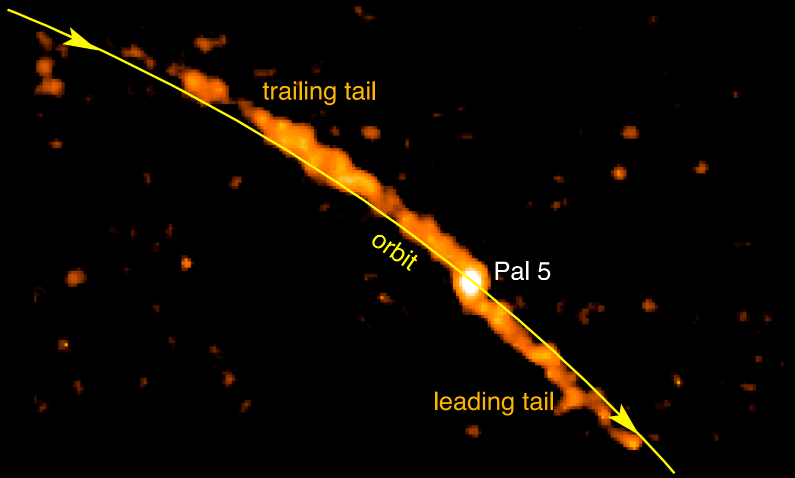
$$\rho_{\rm dm} = 0.25 \pm 0.09\,{\rm GeV\,cm}^{-3}$$

[SDSS; Z13]

Read at IDM 2014

Astrophysics model: velocity distribution

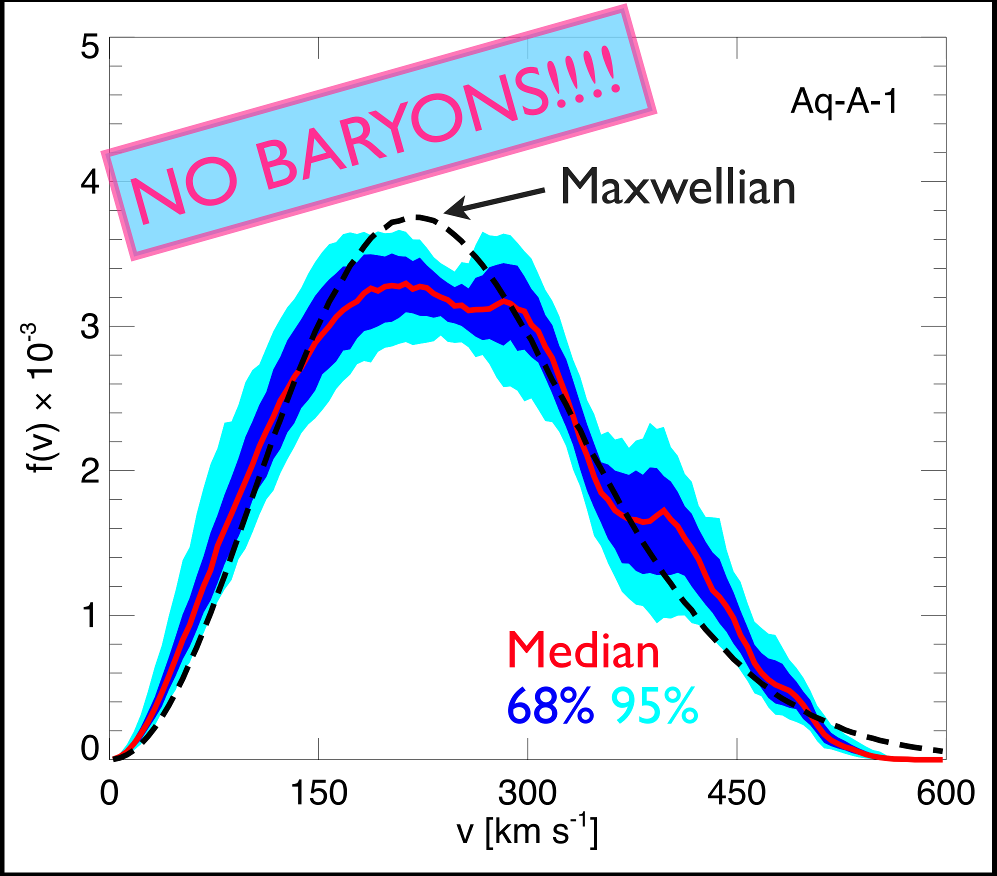
We know very little about the dark matter velocity distribution near the Sun



Odenkirchen et al 2002 (SDSS)

Streams of stars have been observed in the galactic halo

SDSS, 2MASS, SEGUE,…….



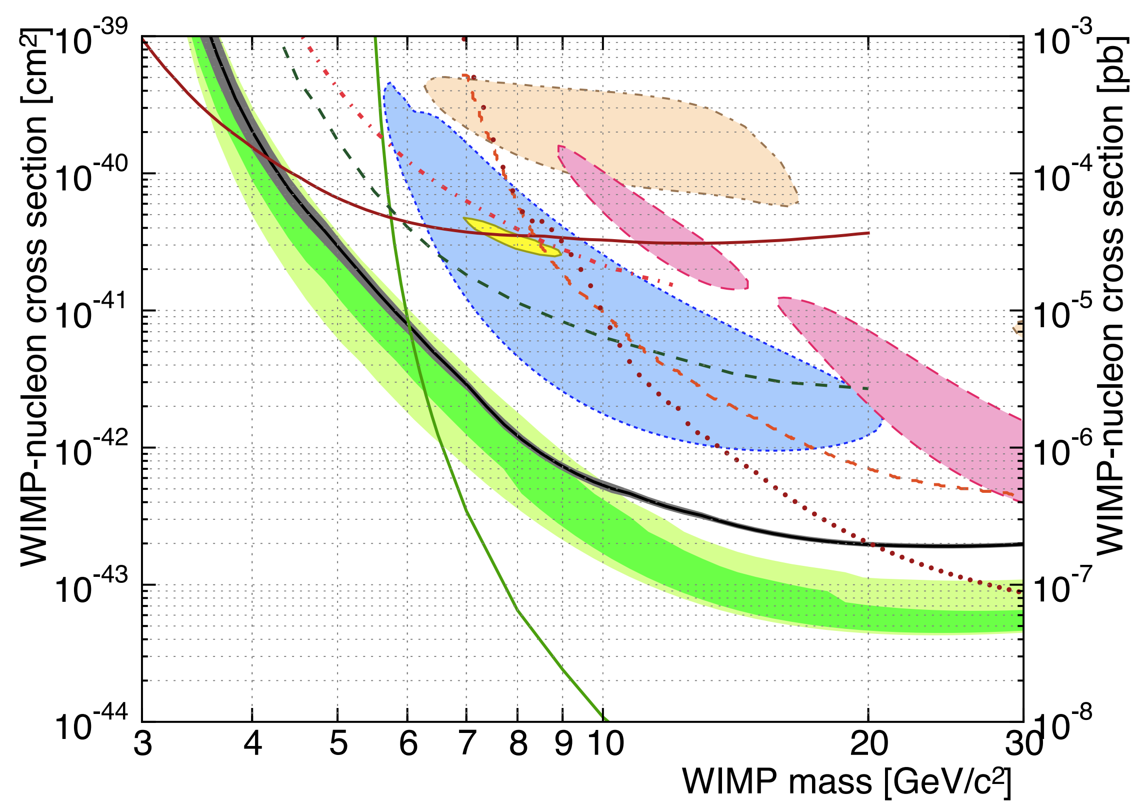
Vogelsberger et al 2009

Cosmological N-Body simulations including baryons are challenging but underway

Astrophysics model: velocity distribution

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

FIXED FIXED



Agnese et al (SuperCDMS) 2014

Standard Halo Model

truncated Maxwellian

$$f(\vec{v}) = C\, e^{-|\vec{v}+\vec{v}_{\rm obs}|/\bar{v}_0^2}\, \Theta(v - v_{\rm esc})$$

The spherical cow of direct WIMP searches

Gelmini

Astrophysics-independent approach

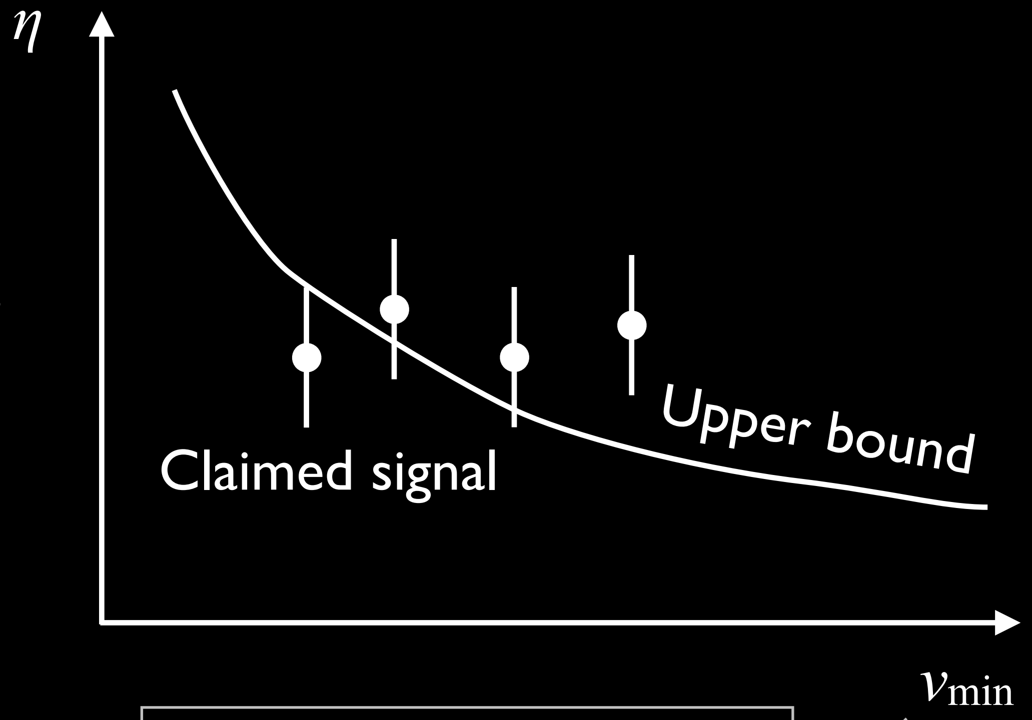
$$\begin{pmatrix}\text{event}\\\text{rate}\end{pmatrix} = \begin{pmatrix}\text{detector}\\\text{response}\end{pmatrix} \times \boxed{\begin{pmatrix}\text{particle}\\\text{physics}\end{pmatrix}} \times \boxed{(\text{astrophysics})}$$

FIXED

ARBITRARY

Rescaled astrophysics factor common to all experiments

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



Minimum WIMP speed to impart recoil energy E_R

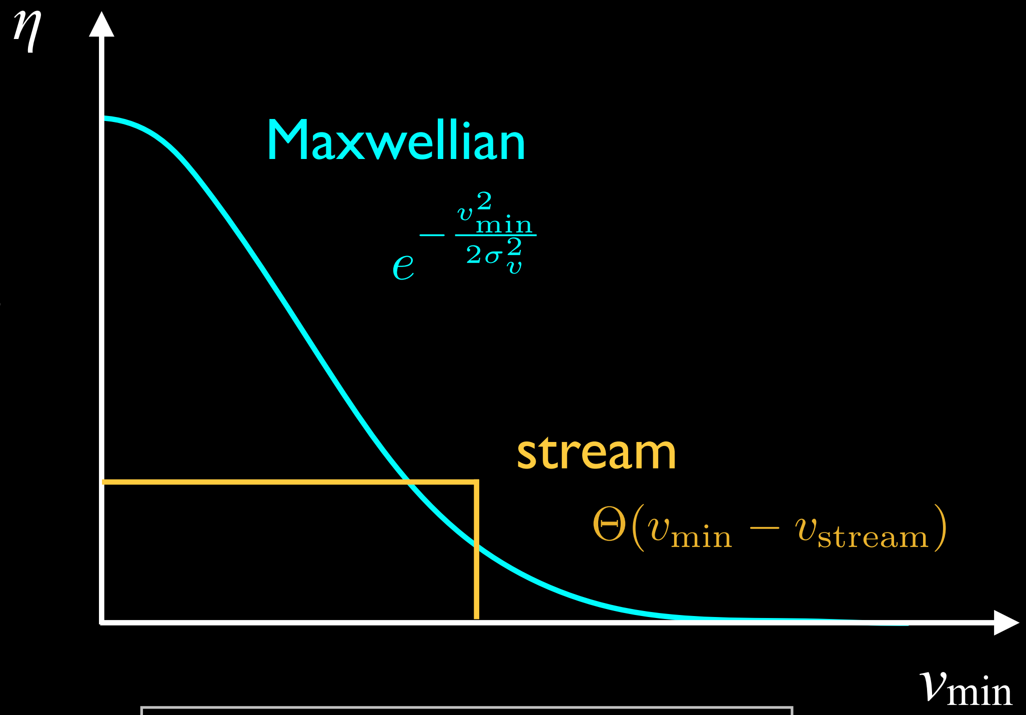
Fox, Liu, Wiener 2011; Gondolo, Gelmini 2012; Del Nobile, Gelmini, Gondolo, Huh 2013-14

Astrophysics-independent approach

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

Rescaled astrophysics factor common to all experiments

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



Minimum WIMP speed to impart recoil energy E_R

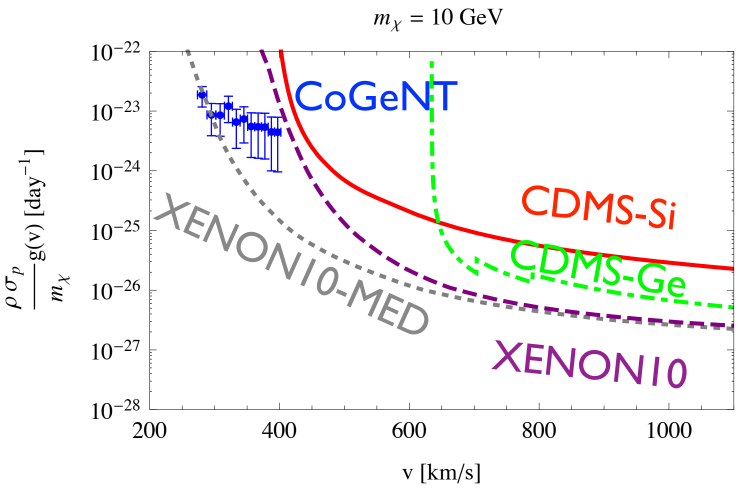
Fox, Liu, Wiener 2011; Gondolo, Gelmini 2012; Del Nobile, Gelmini, Gondolo, Huh 2013-14

Astrophysics-independent approach

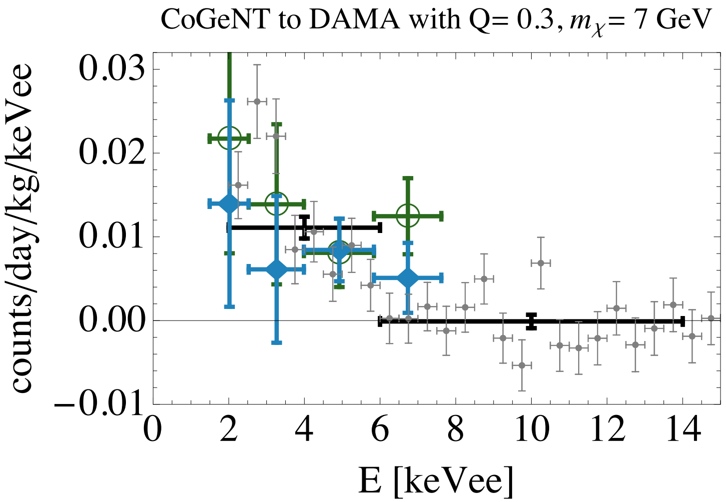
Isoscalar spin-independent case *same coupling to protons and neutrons*

Fox, Liu, Weiner 2011

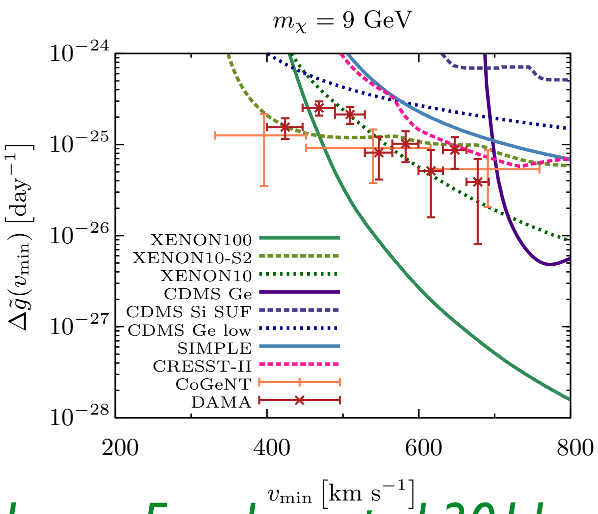
$$\frac{dR}{dE_R} = \frac{A^2 F^2(E_R)}{2\mu_{\chi p}^2}\,\tilde{\eta}(v_{\min}) \quad \Rightarrow \quad \tilde{\eta}(v_{\min}) = \frac{2\mu_{\chi p}^2}{A^2 F^2(E_R)}\,\frac{dR}{dE_R}$$



Fox, Liu, Weiner 2011



Fox, Kopp, Lisanti, Weiner 2011



Frandsen et al 2011

Astrophysics-independent approach

The original idea applies to specific interactions only, and refers 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

Generalize to all interactions and use quantities accessible to experiments, i.e., include effective energy response function.

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

Astrophysics-independent approach

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

Change variables:

Minimum WIMP speed to impart recoil energy E_R

$$v_{\min} = \sqrt{\frac{(m_T E_R + \mu_T \delta)^2}{2 m_T E_R \mu_T^2}}$$

Constant reference cross section

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

Astrophysics factor, same for all direct detection experiments

Astrophysics-independent approach

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

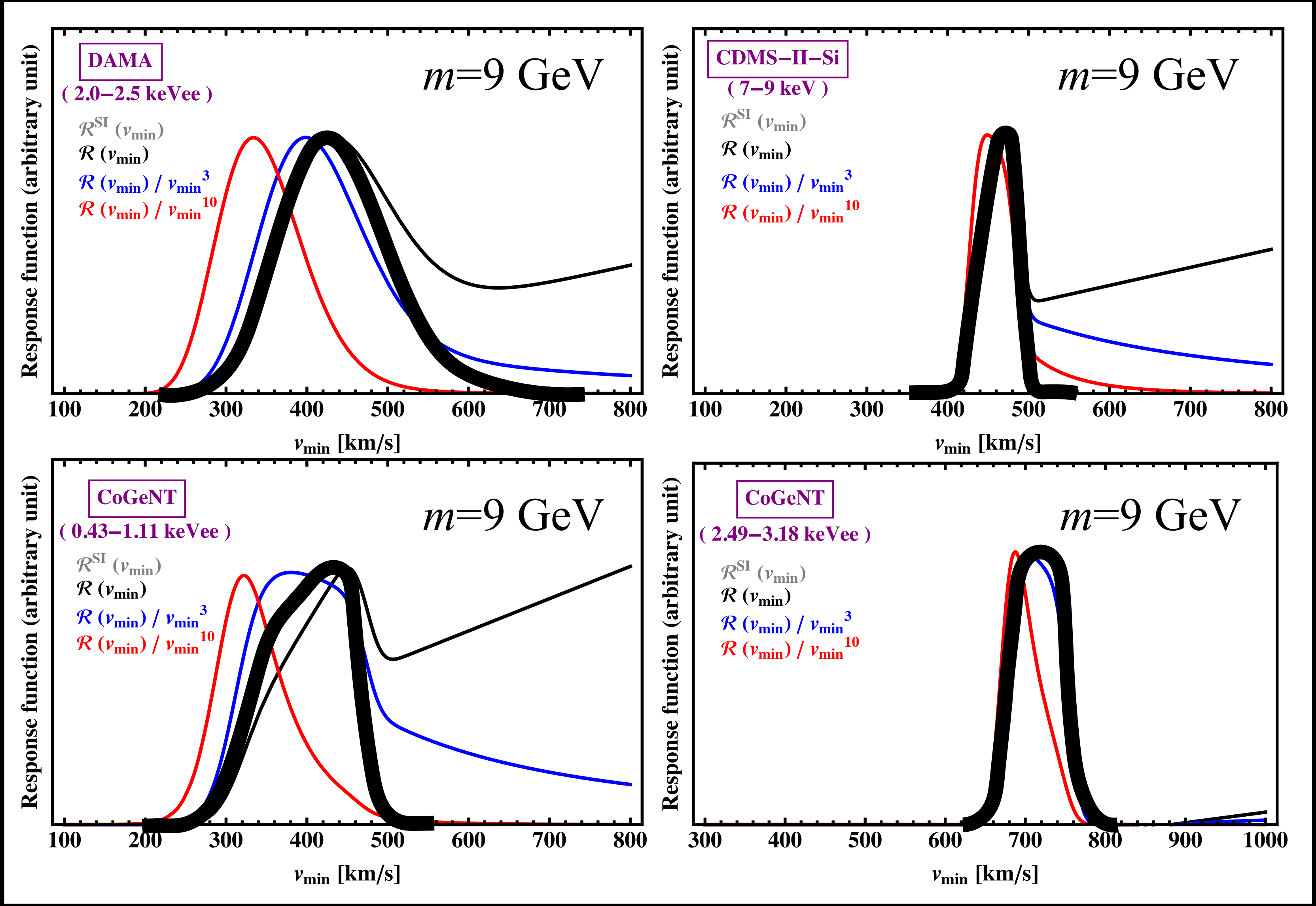
- Every experiment is sensitive to a "window in velocity space" given by the response function.

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

Astrophysics-independent approach

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

Examples of response functions ("windows in velocity space")



Del Nobile, Gelmini, Gondolo, Huh 2013

Astrophysics-independent approach

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

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

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

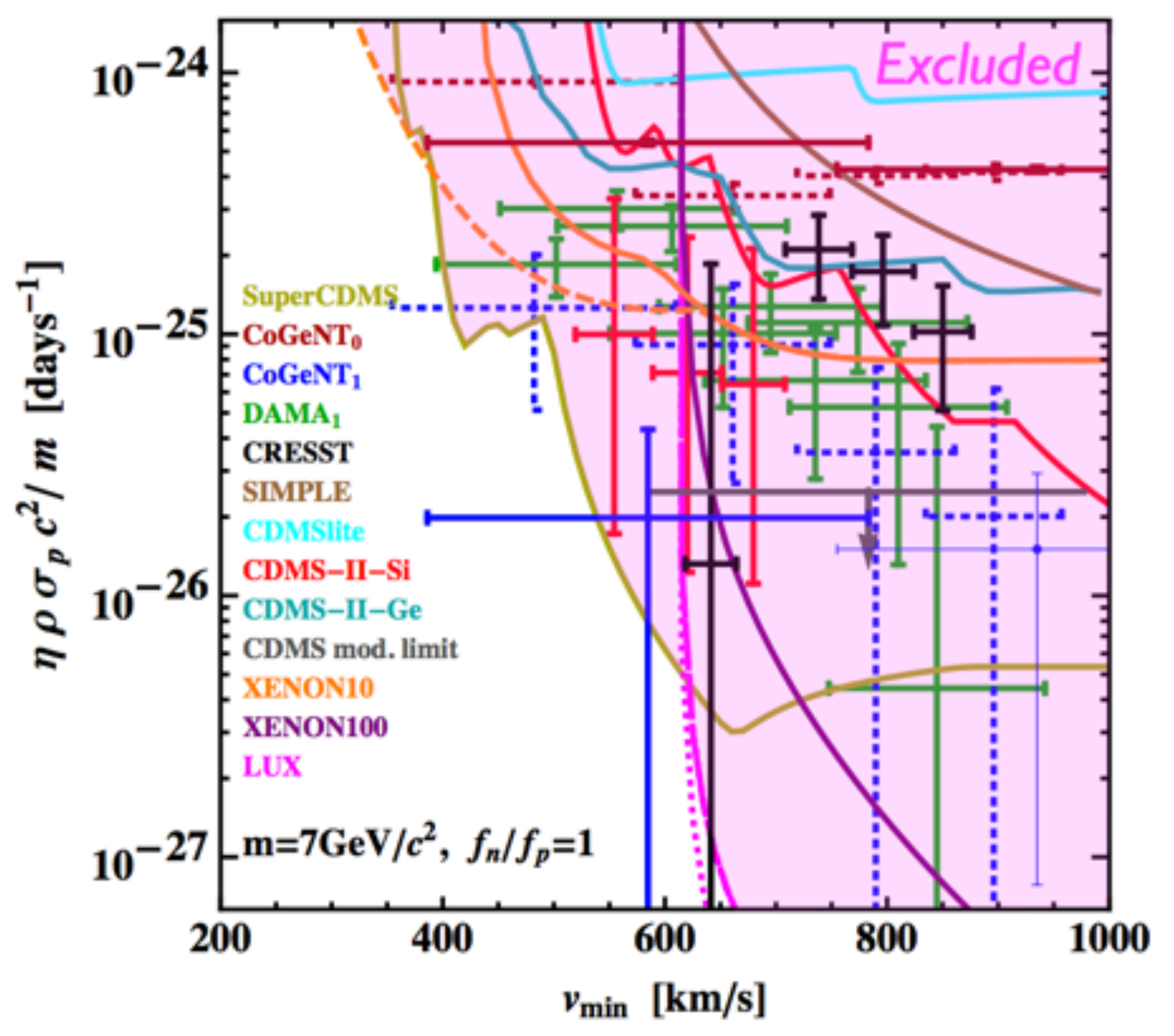
$$\tilde{\eta}(v) < \frac{R^{\text{upper limit}}_{[E_1,E_2]}}{\int_0^v \mathcal{R}_{[E_1,E_2]}(v_{\rm min})\, dv_{\rm min}}$$

Binned or unbinned

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

Spin-independent isoscalar interactions

$$\frac{d\sigma}{dE_R} = \frac{2m}{\pi v^2} A^2 f_p^2 F^2(E_R)$$



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

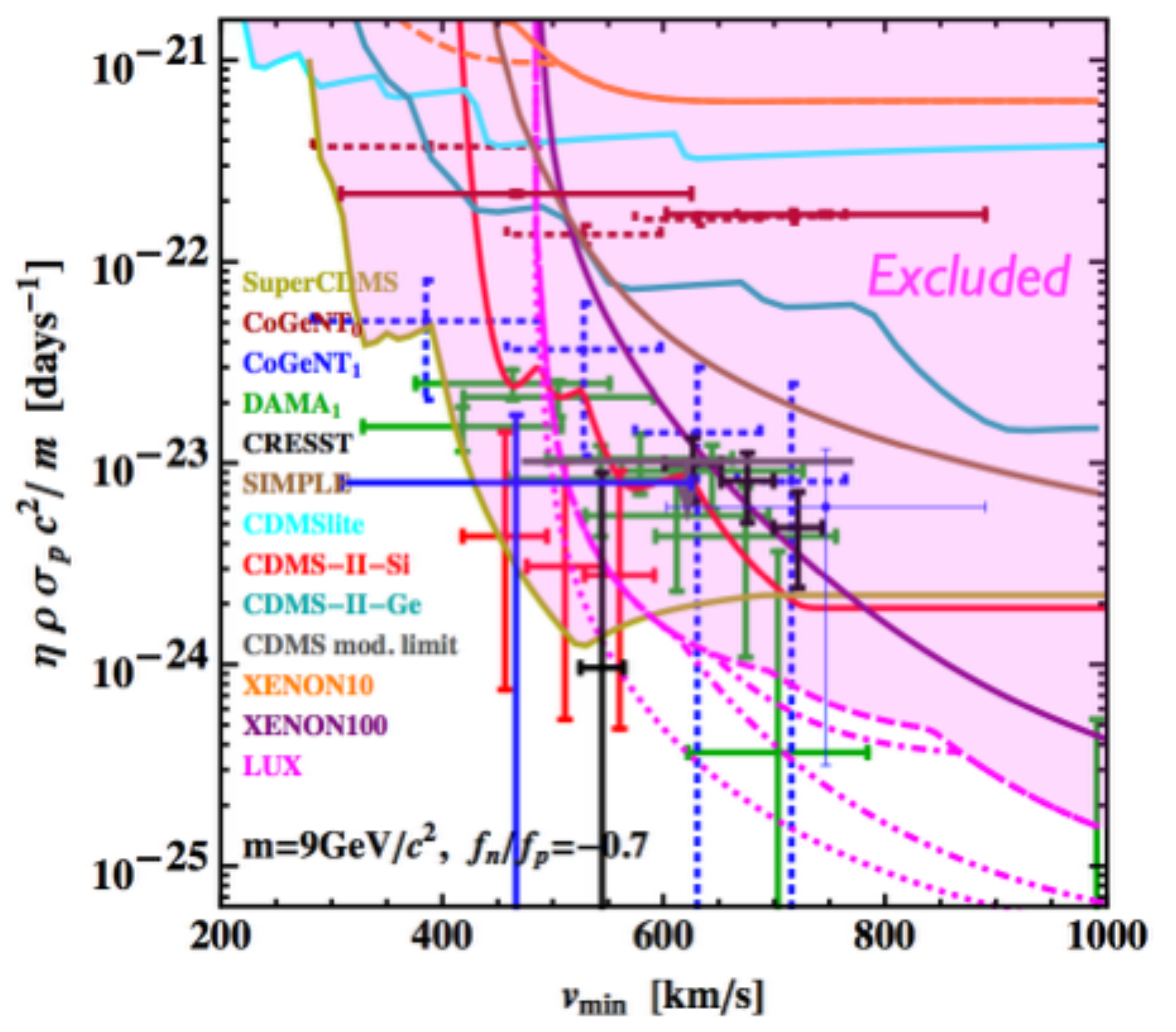
CDMS-Si event rate is similar to yearly modulated rates

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

Spin-independent nonisoscalar interactions

$$\frac{d\sigma_{\chi A}}{dE_R} = \frac{2m}{\pi v^2}\left[Z f_p + (A-Z) f_n\right]^2 F^2(E_R)$$



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

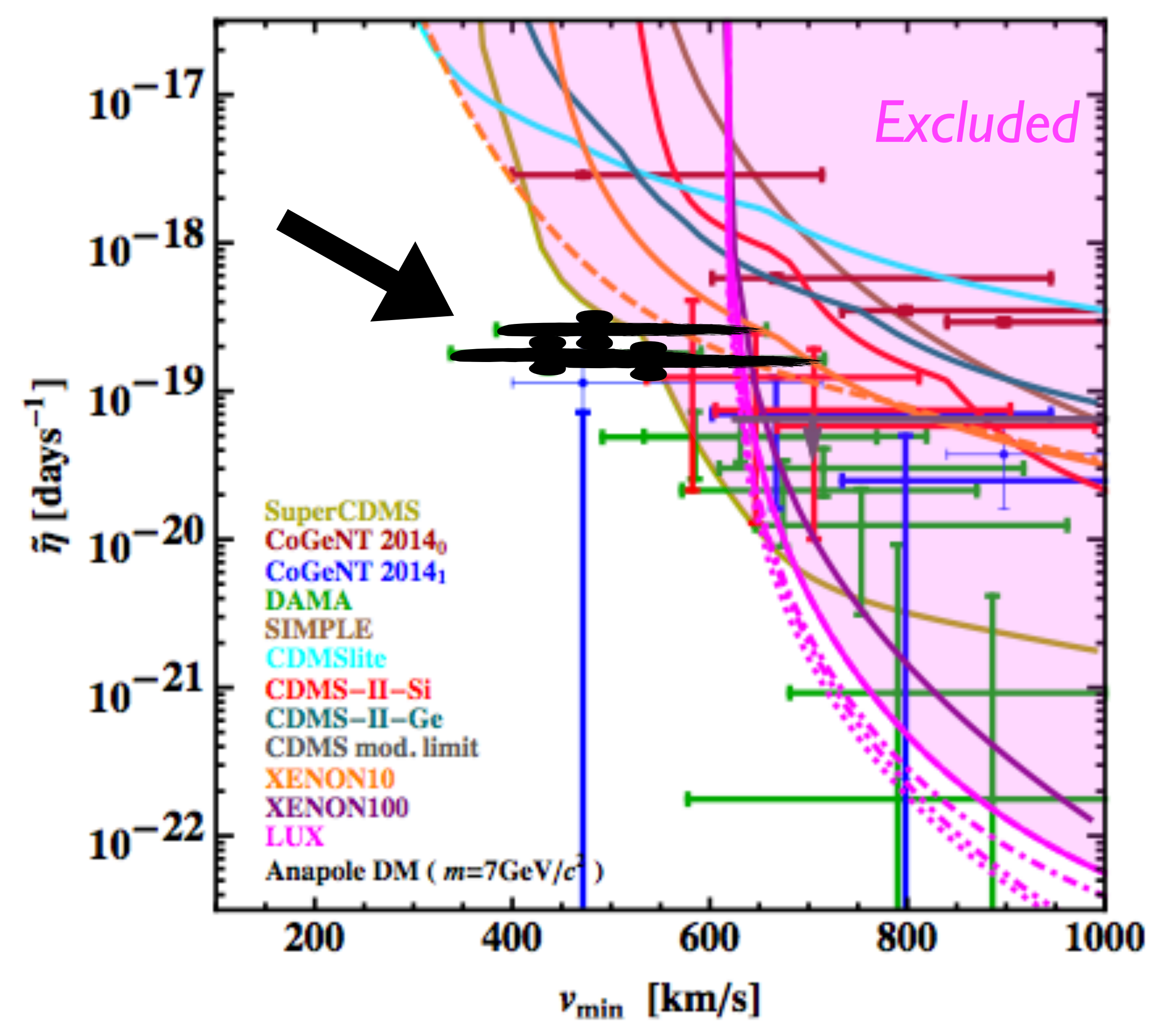
The CDMS-Si events lie “below” the CoGeNT/DAMA modulation amplitudes

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

Anapole dark matter

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



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

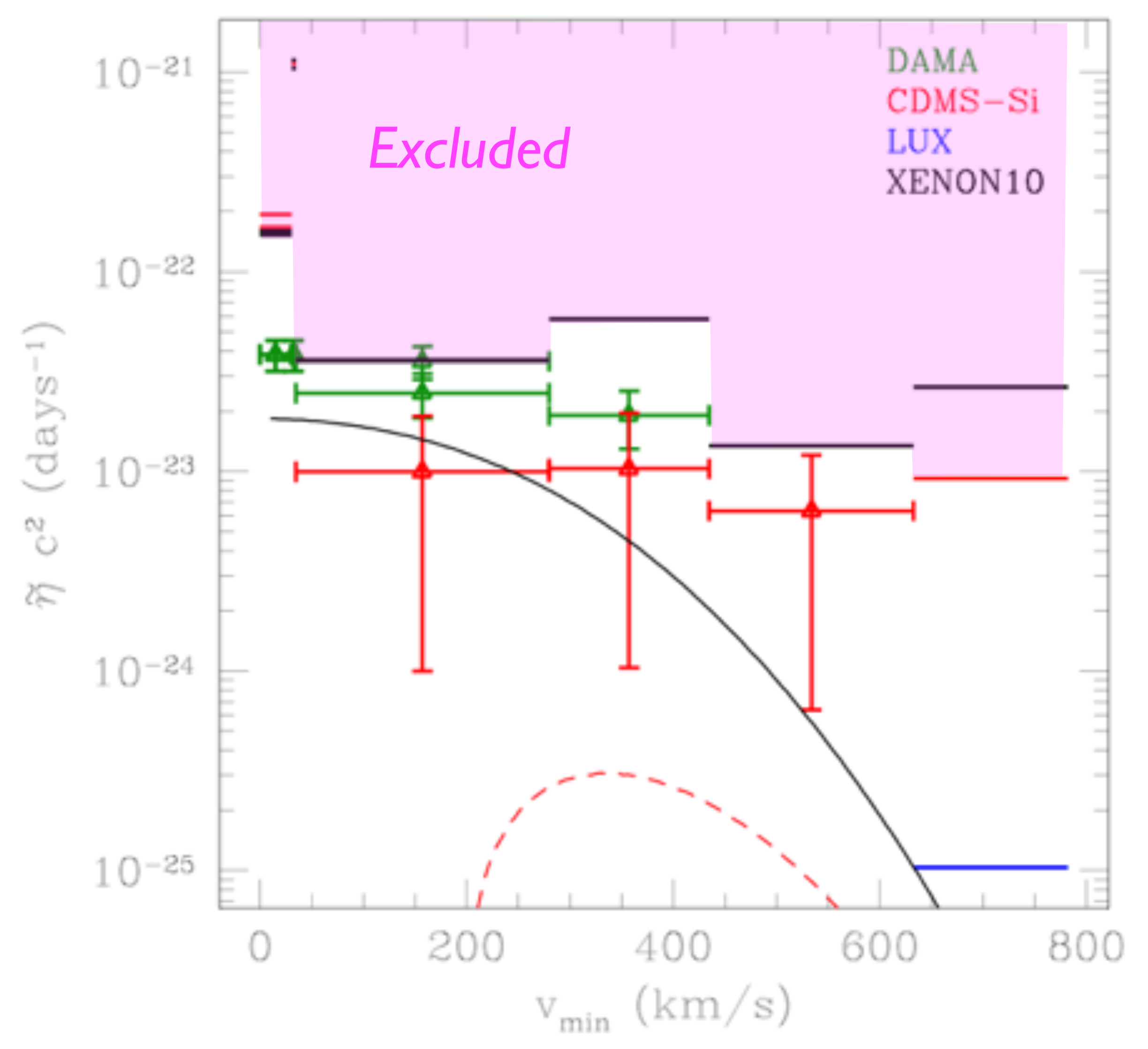
The modulation amplitude would need to be large

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

Exothermic nonisoscalar scattering

$$\frac{d\sigma_{\chi A}}{dE_R} = \frac{2m}{\pi v^2}\left[Zf_p + (A-Z)f_n\right]^2 F^2(E_R)$$



For light exothermic nonisoscalar scattering, the DAMA modulation can be compatible with other experiments

$m = 3\ \mathrm{GeV}/c^2$
$\delta = -70\ \mathrm{keV}$
$f_n/f_p = -0.79$

Still depends on particle model

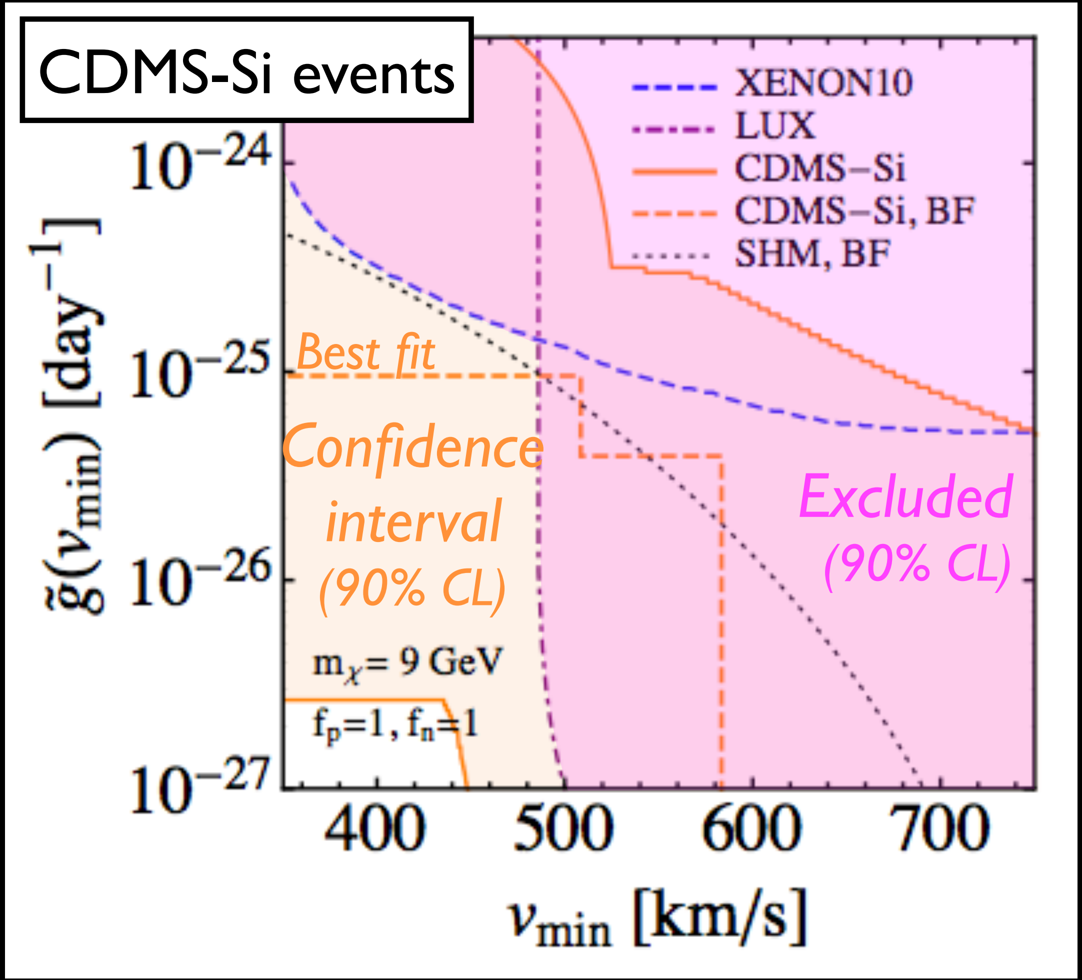
Scopel, Yoon 2014

Astrophysics-independent approach

Unbinned likelihood analysis

$$\mathcal{L} = \frac{e^{-\int_{E_{\min}}^{E_{\max}} \frac{dR}{dE}\, dE}}{N!} \prod_{i=1}^{N} \frac{dR}{dE}\bigg|_{E=E_i}$$

Fox, Kahn, McCullough (2015) show that for reasonable energy response functions $G(E,E_R)$, the likelihood is maximized when the astrophysics factor $\eta(v)$ is a sequence of $\leq N$ downward steps.



Fox, Kahn, McCullough 2015

Conclusions

- Halo-independent methods for direct WIMP searches are a powerful way to compare claimed signals with null searches.
- The results depend on the particle model: mass and type of interaction.
- There is tension between upper limits and claimed signals.
- The statistical interpretation of halo-independent methods is getting understood.