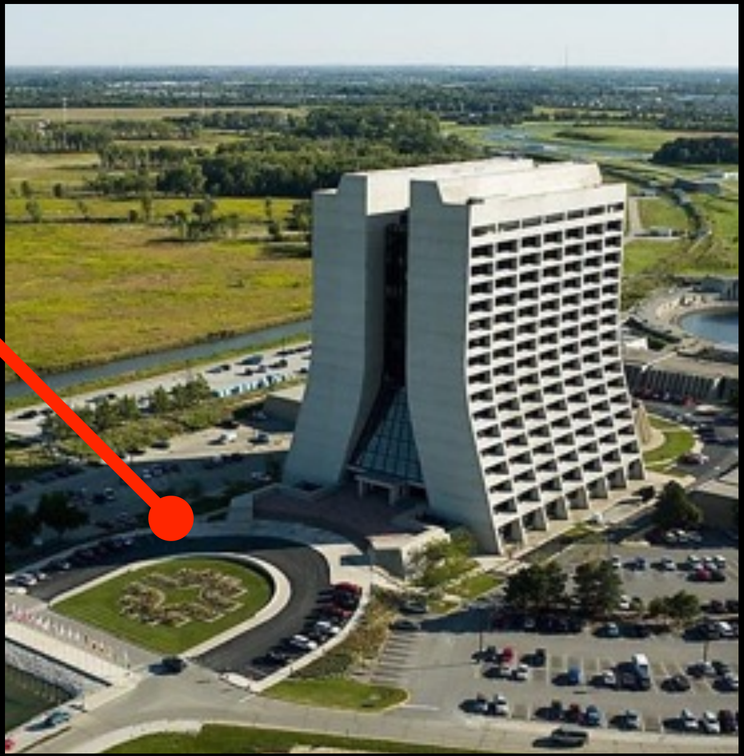
Direct dark matter searches: status and implications

Paolo Gondolo

University of Utah

Direct dark matter searches: status and implications



Paolo Gondolo
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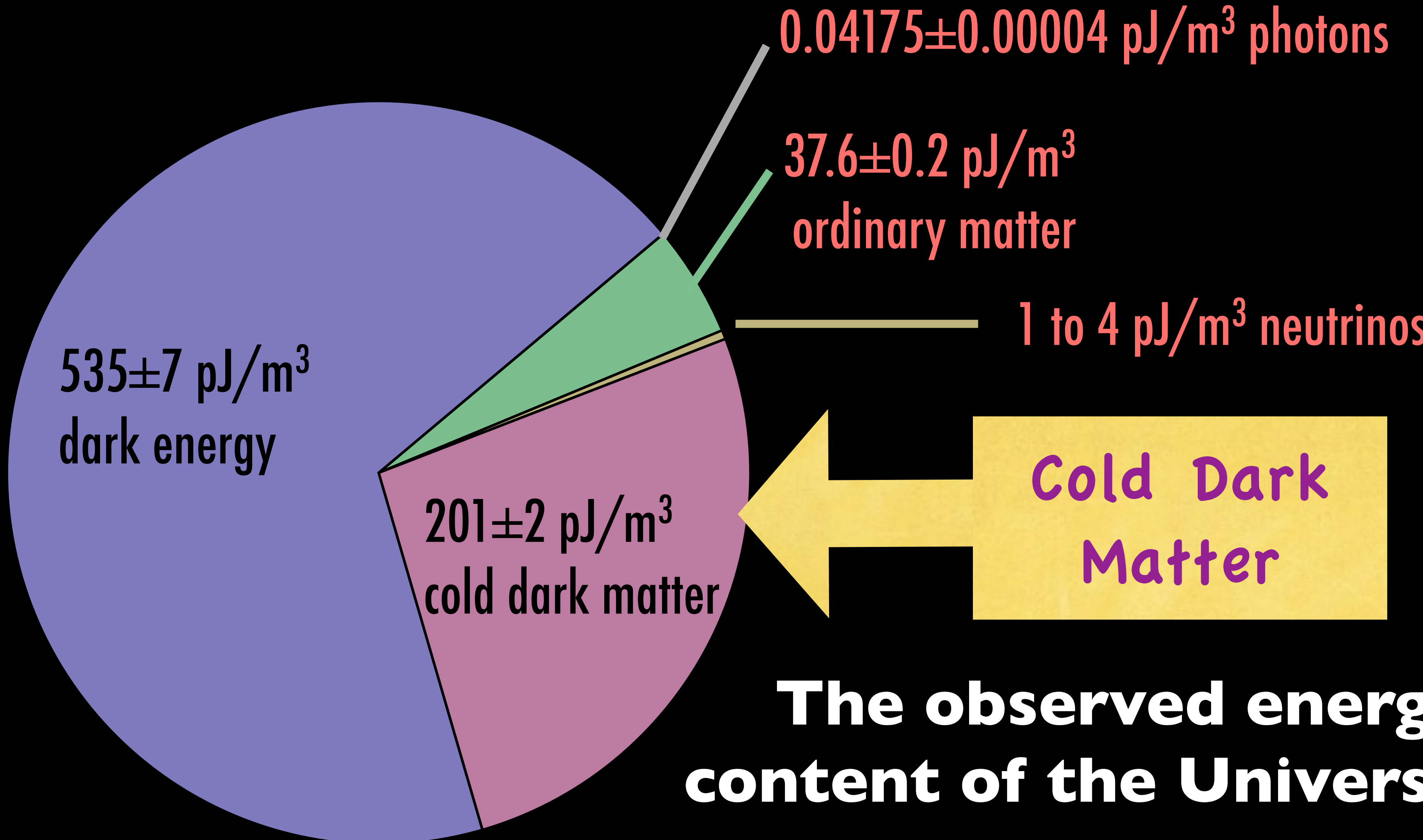
Direct WIMP searches

- Fifty shades of dark
- The forbidden fruit
- Confusion of the mind
- Treason and murder
- That which does not kill us makes us stronger

Fifty shades of dark

Evidence for cold dark matter



The observed energy content of the Universe

matter $p \ll \rho$

radiation $p=\rho/3$

vacuum $p=-\rho$

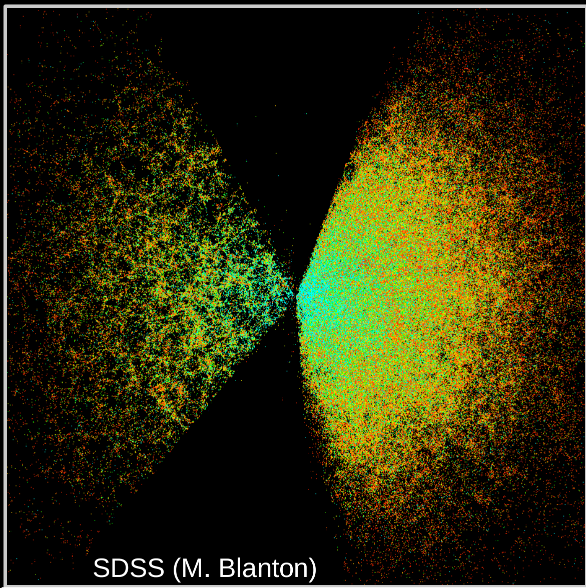
Planck (2015)
TT,TE,EE+lowP+lensing+ext

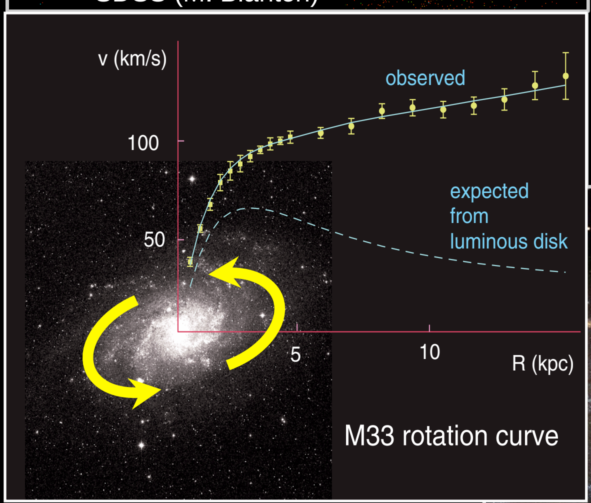
$1\ \mathrm{pJ} = 10^{-12}\ \mathrm{J}$

$\rho_{\mathrm{crit}}=1.68829\ h^2\ \mathrm{pJ/m^3}$

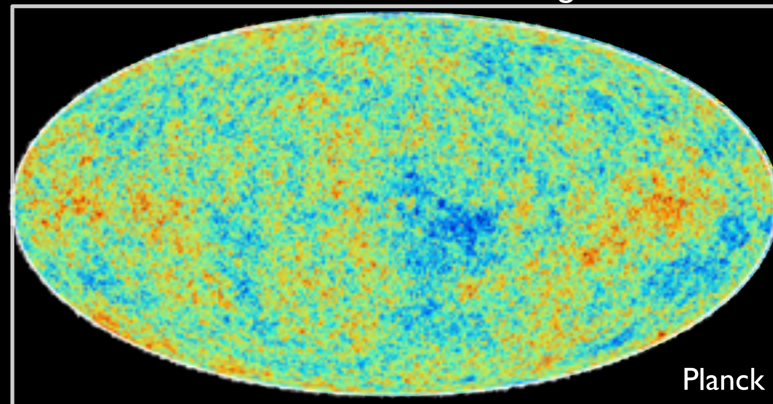
Evidence for cold dark matter

Large Scale Structure



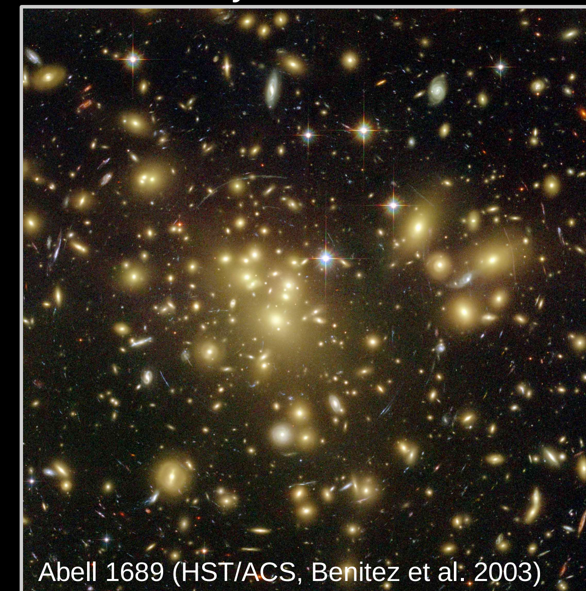


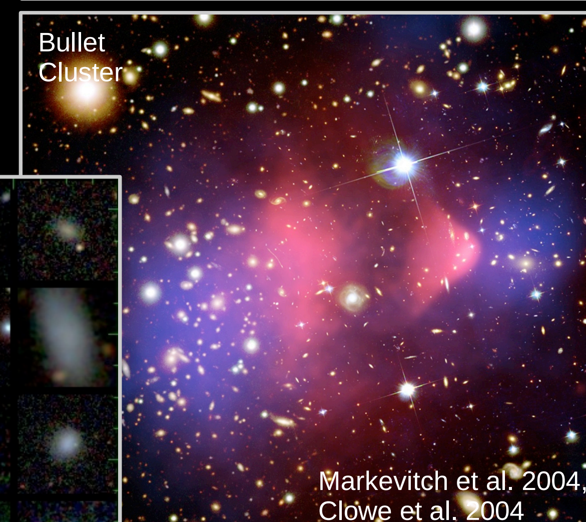
Cosmic Microwave Background



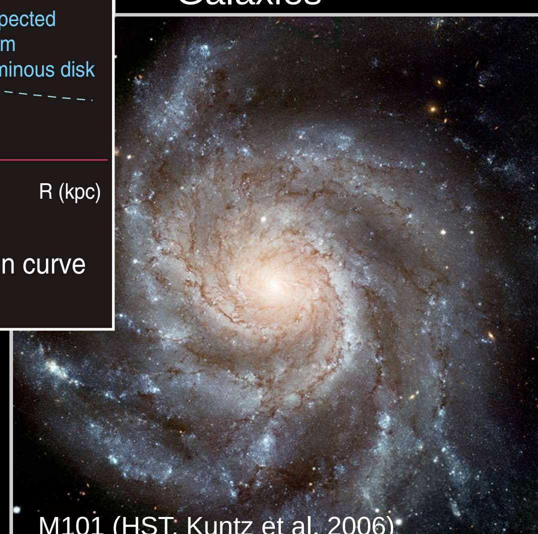
Supernovae

Galaxy Clusters

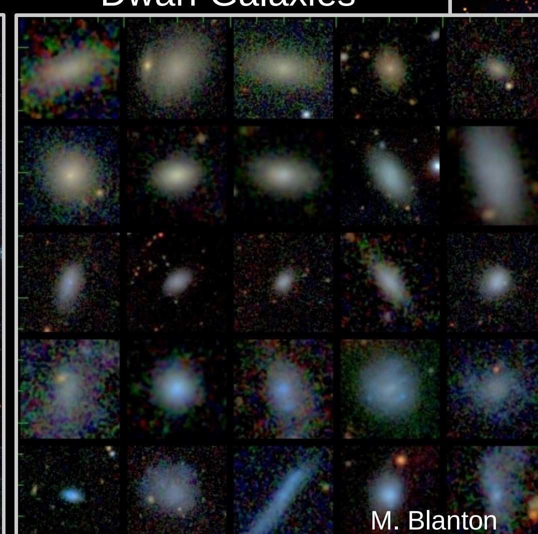




Galaxies

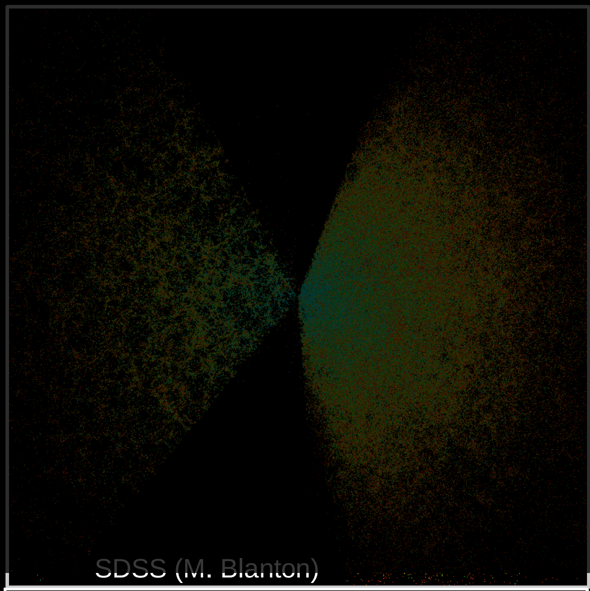


Dwarf Galaxies

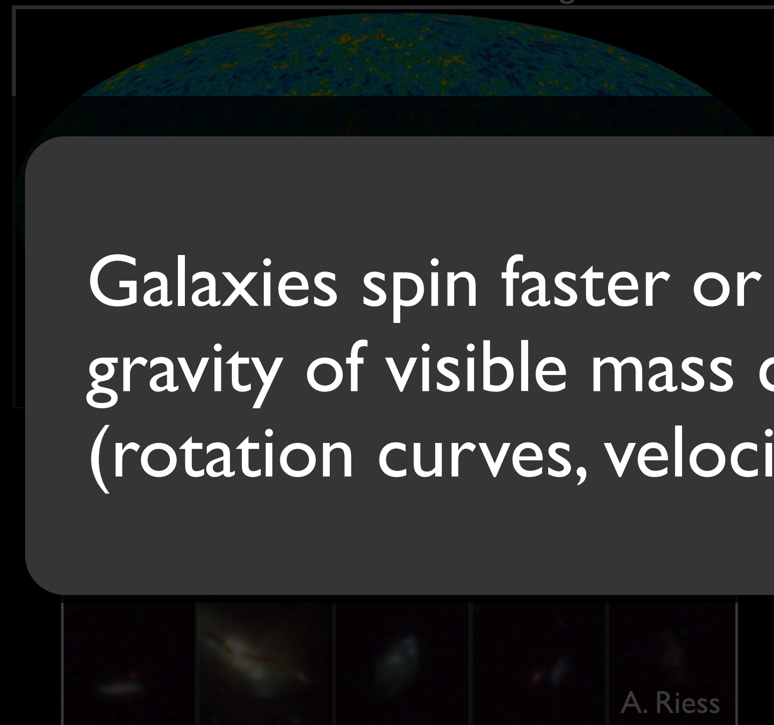


Evidence for cold dark matter

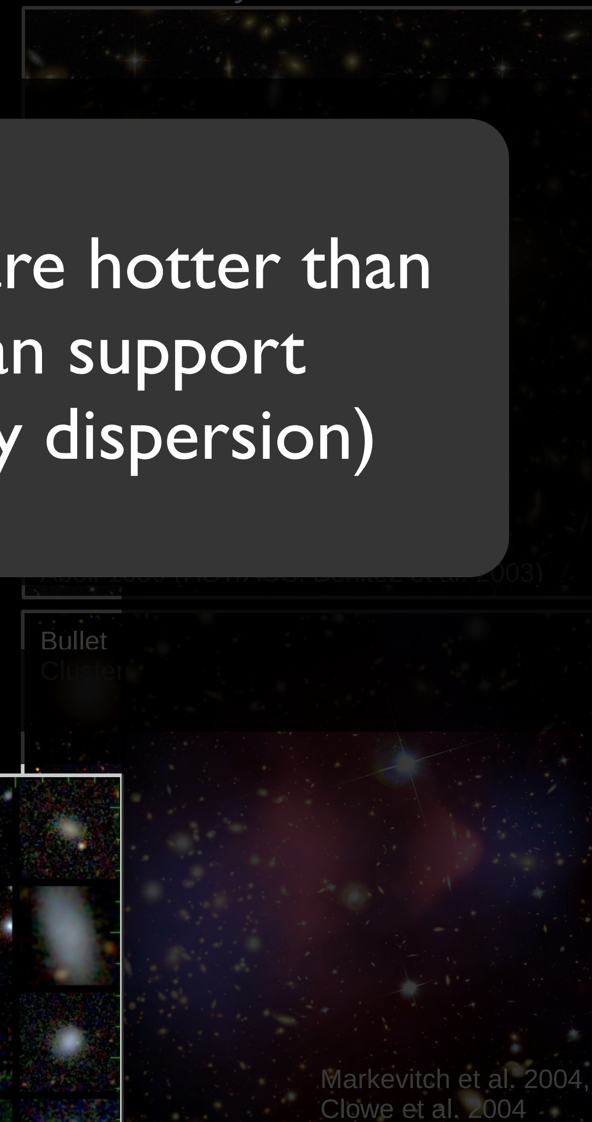
Large Scale Structure



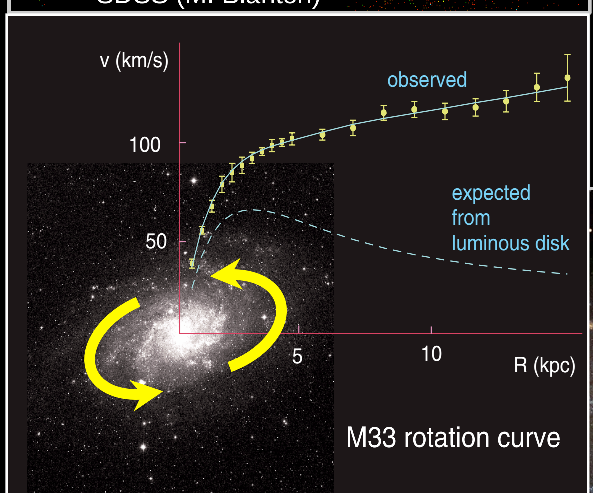
Cosmic Microwave Background



Galaxy Clusters

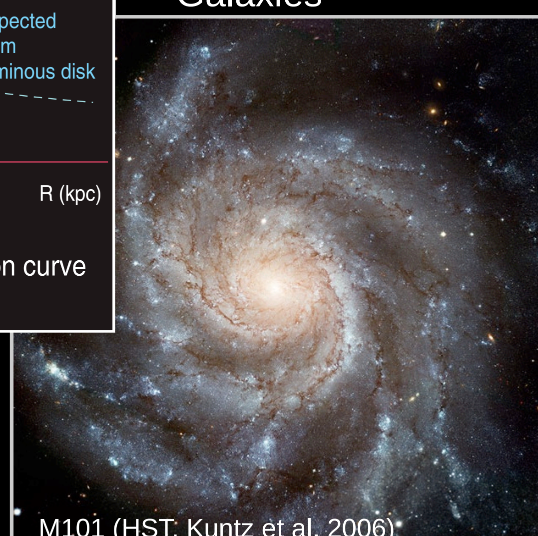


Galaxies spin faster or are hotter than gravity of visible mass can support (rotation curves, velocity dispersion)



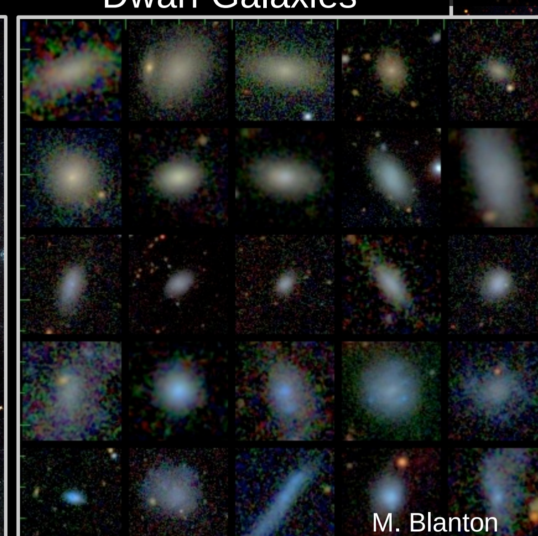
M33 rotation curve

Galaxies



M101 (HST; Kuntz et al. 2006)

Dwarf Galaxies



M. Blanton

Evidence for cold dark matter

Large Scale Structure

Cosmic Microwave Background

Galaxy clusters are mostly invisible mass (motion of galaxies, gas density and temperature, gravitational lensing)

SDSS (M. Blanton)

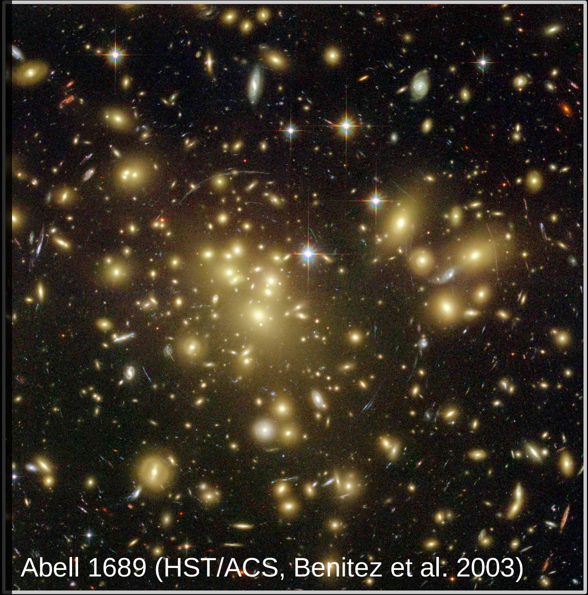
A. Riess

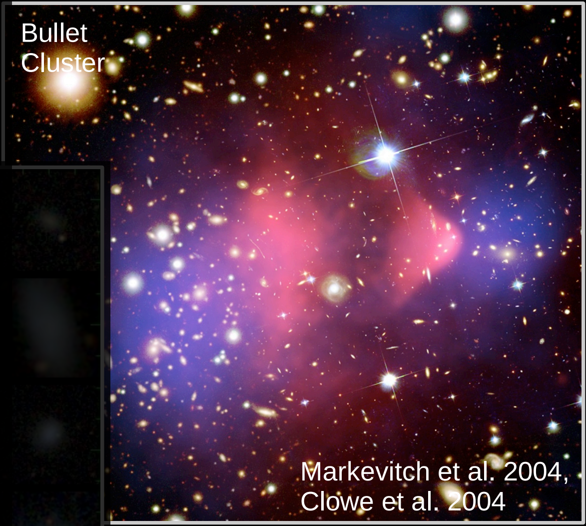
Dwarf Galaxies

M101 (HST, Kuntz et al. 2006)

M. Blanton

Galaxy Clusters

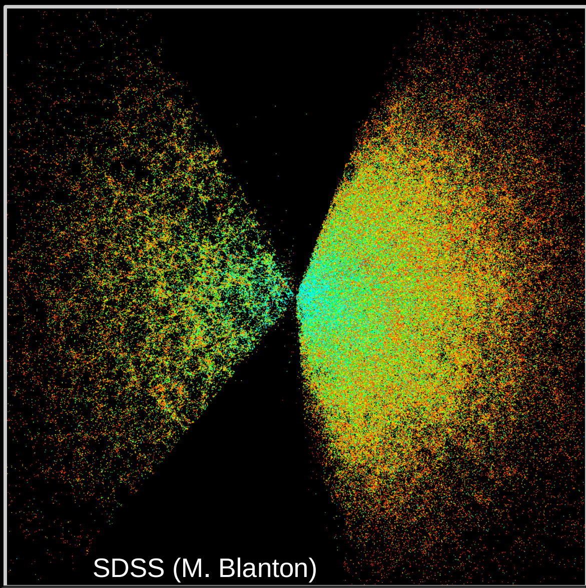

Abell 1689 (HST/ACS, Benitez et al. 2003)



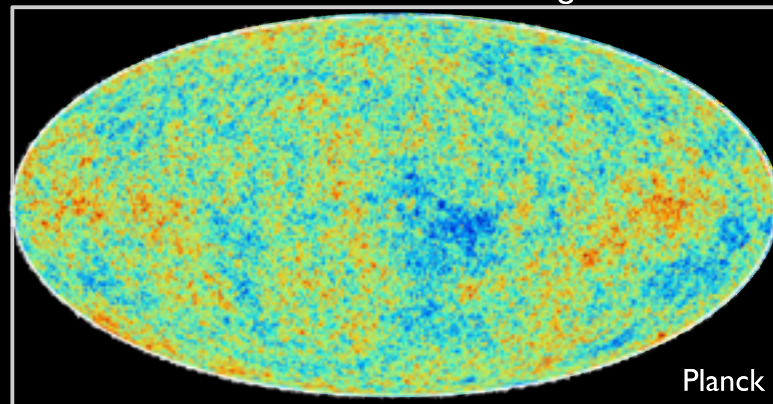
Markevitch et al. 2004, Clowe et al. 2004

Evidence for cold dark matter

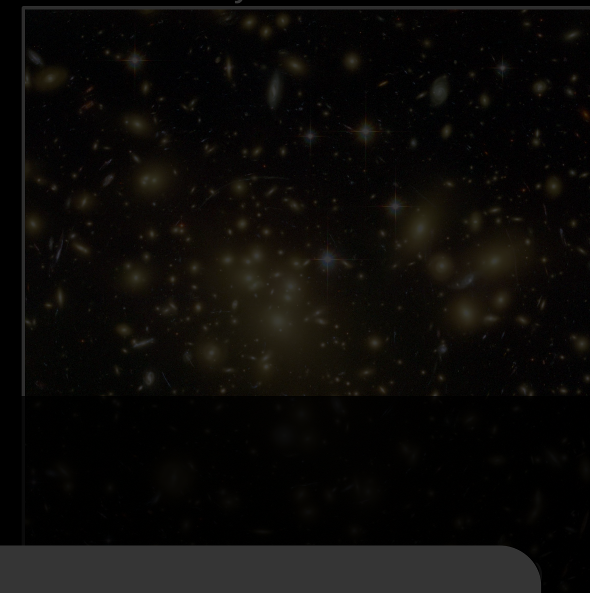
Large Scale Structure



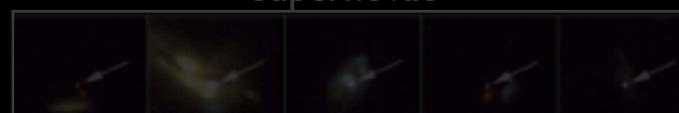
Cosmic Microwave Background

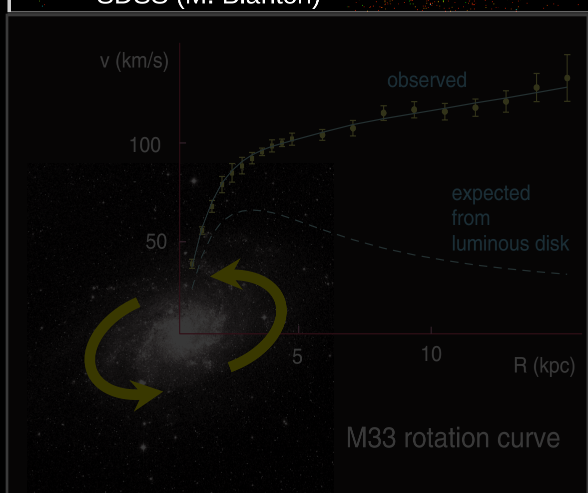


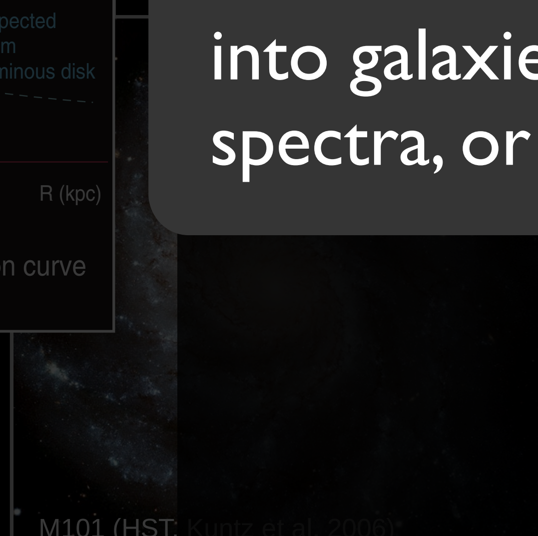
Galaxy Clusters



Supernovae

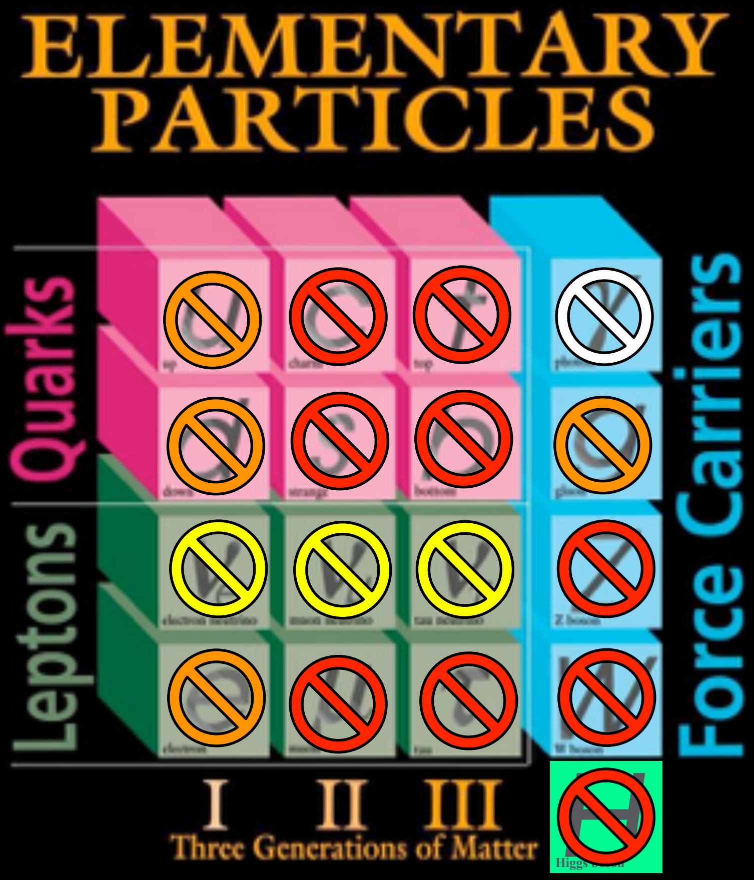






An invisible mass makes the Cosmic Microwave Background fluctuations grow into galaxies (CMB and matter power spectra, or correlation functions)

Is dark matter an elementary particle?



is the particle of light

couples to the plasma

disappears too quickly

is hot dark matter

No known particle can be cold dark matter!

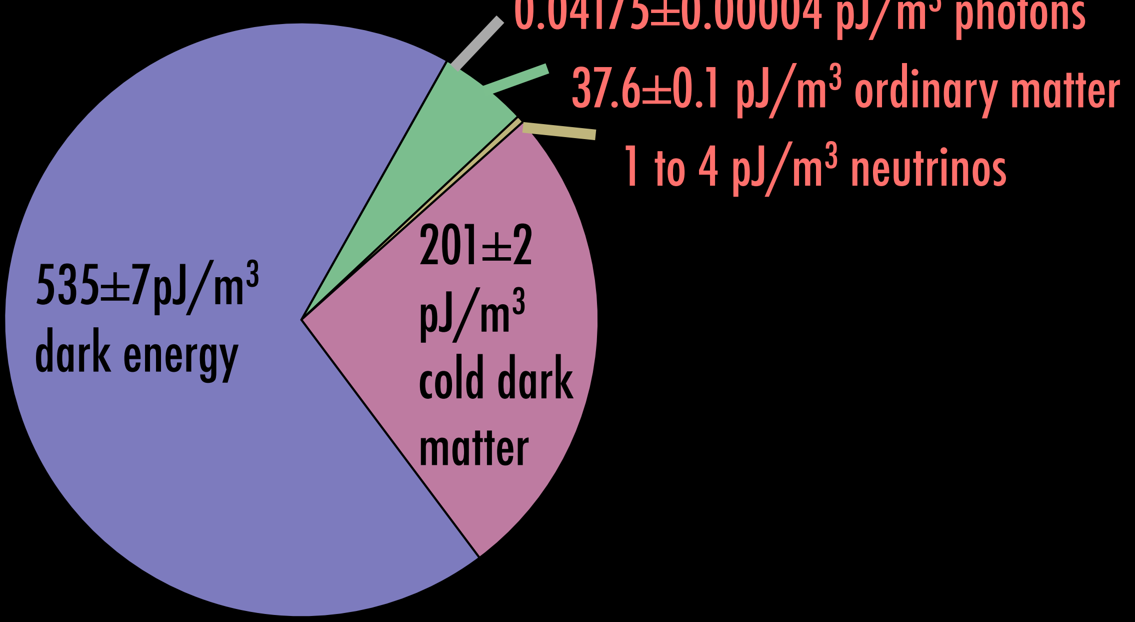
The simplest and most elegant idea

The Magnificent WIMP
(Weakly Interacting Massive Particle)

Lee, Weinberg; Vysotski, Dolgov, Zeldovich 1977

- One naturally obtains the right cosmic density of WIMPs

  Thermal production in hot primordial plasma.



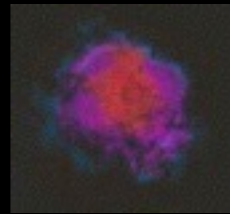
- One can experimentally test the WIMP hypothesis

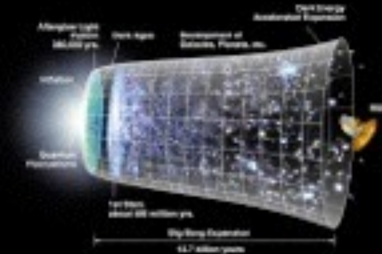
  The same physical processes that produce the right density of WIMPs make their detection possible

* wimp = a weak and cowardly person

The power of the WIMP

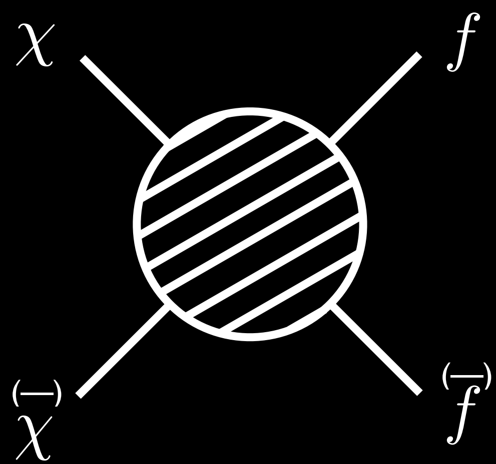
Indirect detection





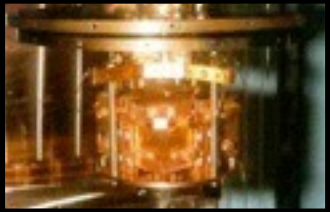
Cosmic density

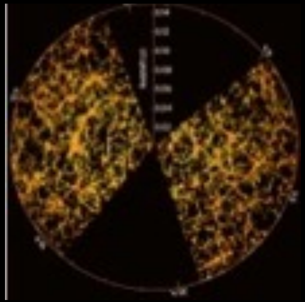
Annihilation $\chi\overline{\chi} \rightarrow f\overline{f}$



Scattering $f\chi \rightarrow f\chi$

Direct detection

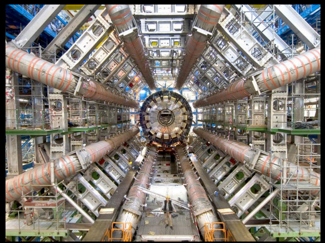


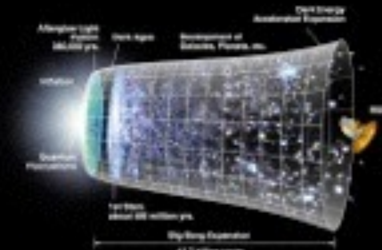


Large scale structure

Production $f\overline{f} \rightarrow \chi\overline{\chi}$

Colliders



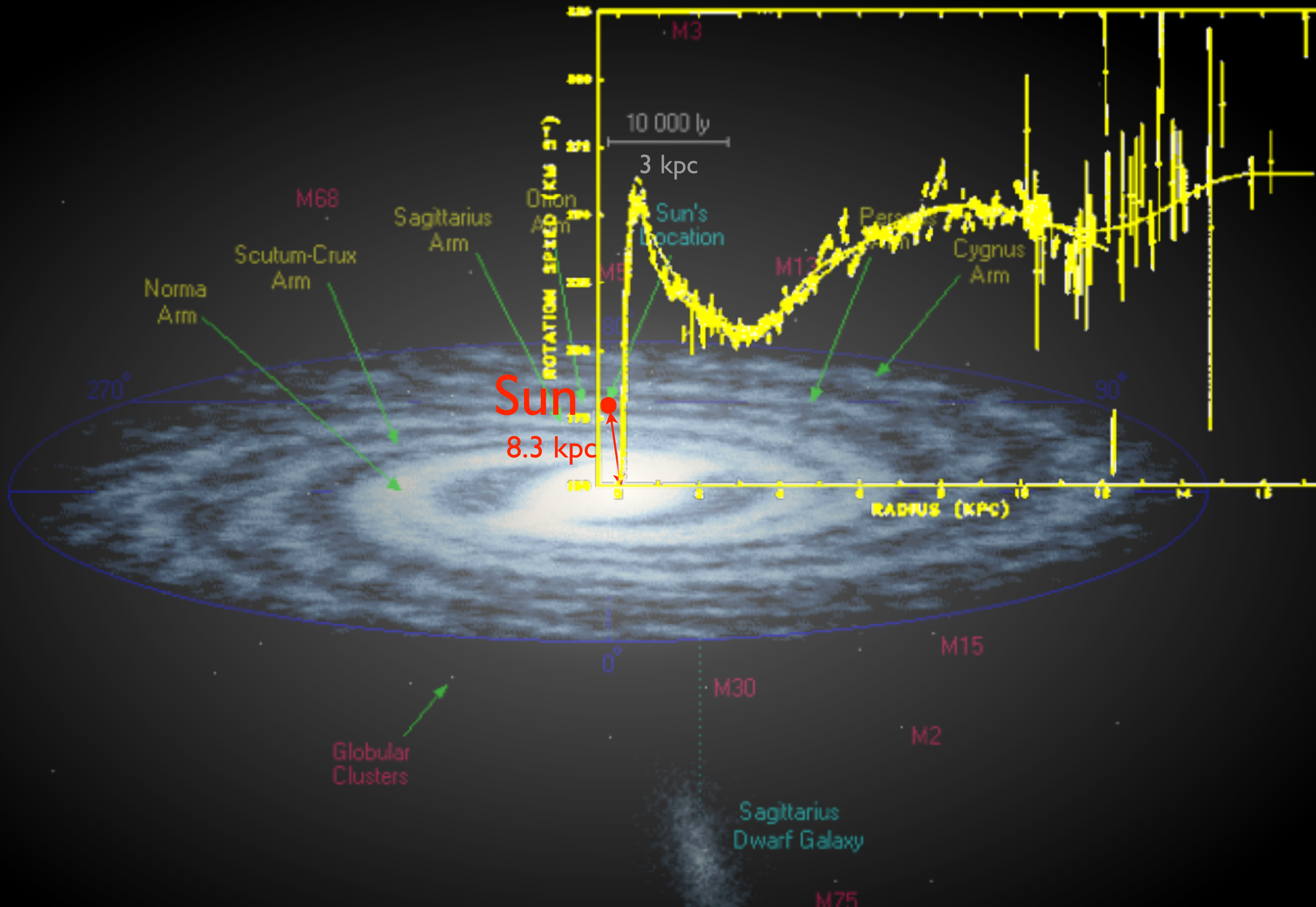


Cosmic density

The forbidden fruit

Galactic dark matter

Rotation curve (Clemens 1985)



Our galaxy is inside a halo of dark matter particles

1 kpc = 2.06×10^{11} AU

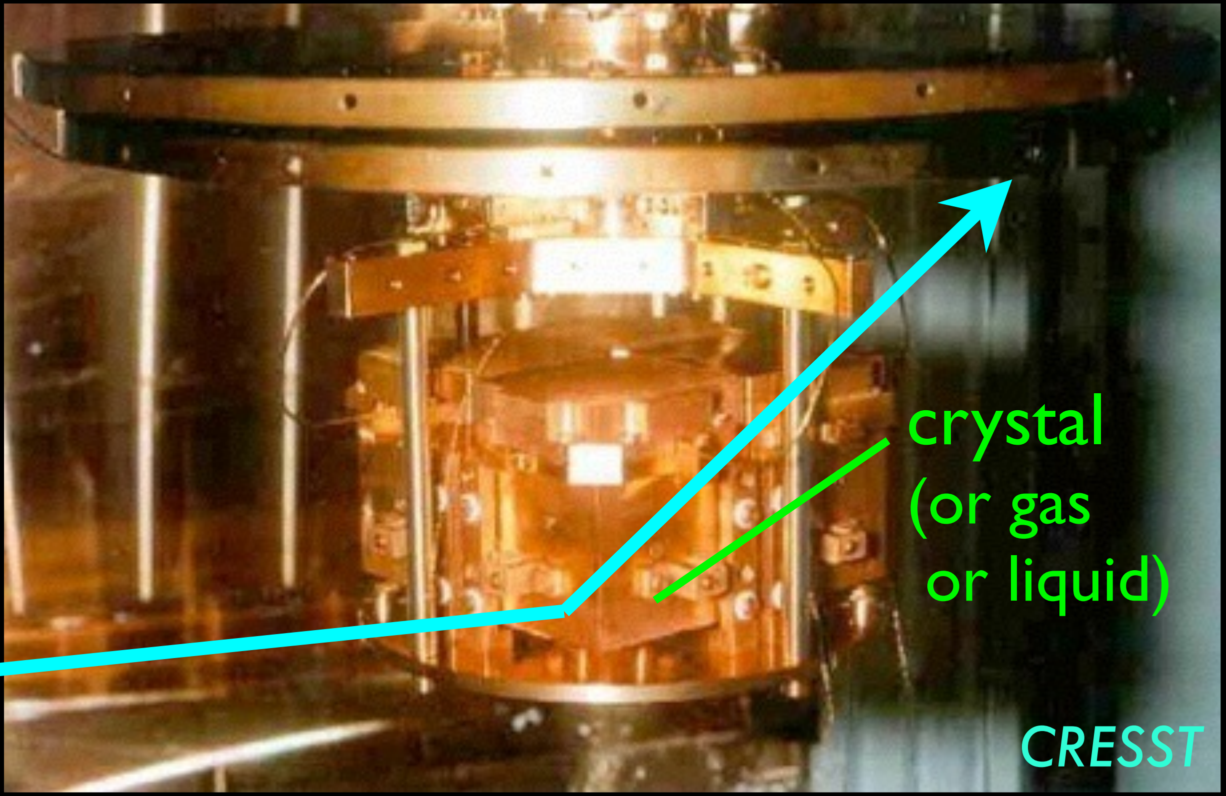
Image by R. Powell using DSS data

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

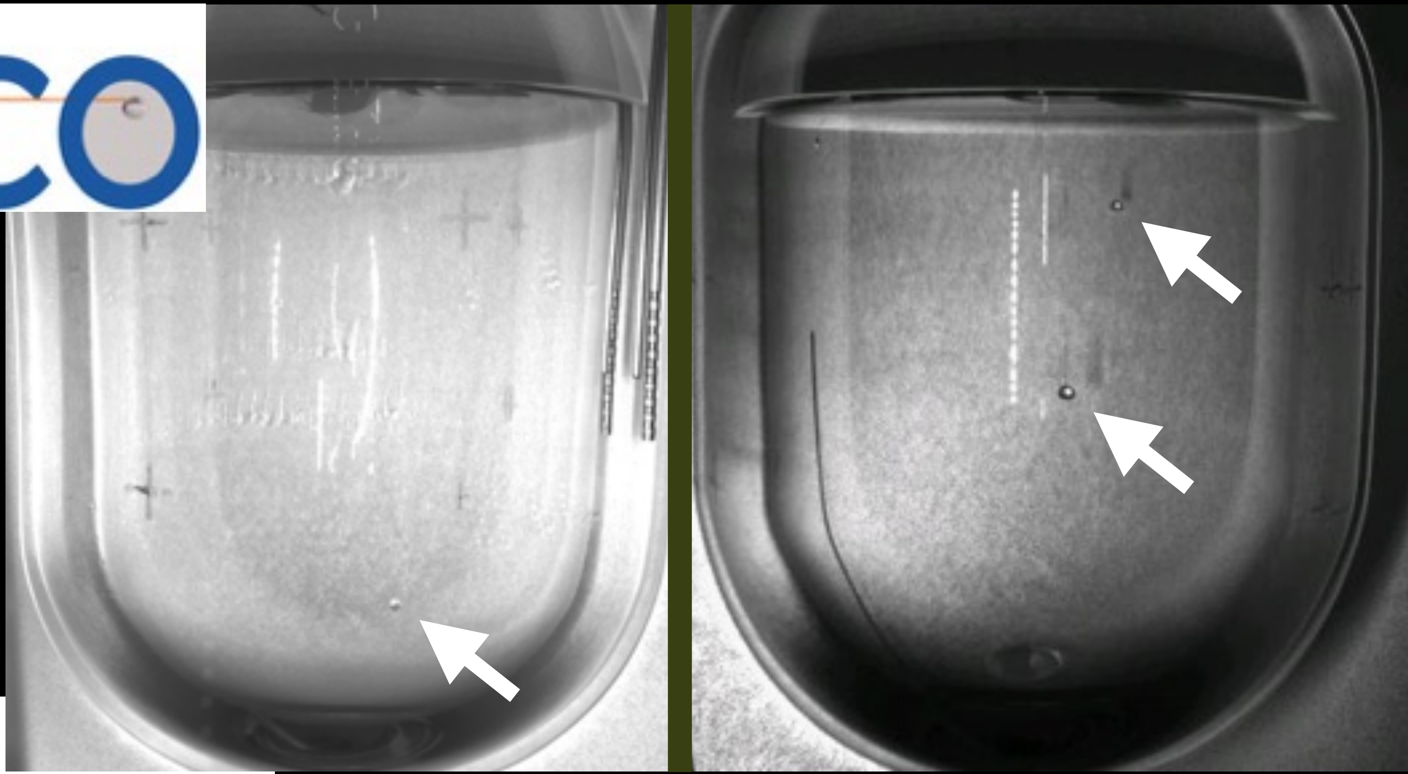
Direct dark matter searches

- LZ (7 ton LXe, Homestake)
- EURECA, DARWIN, ...

Direct dark matter searches

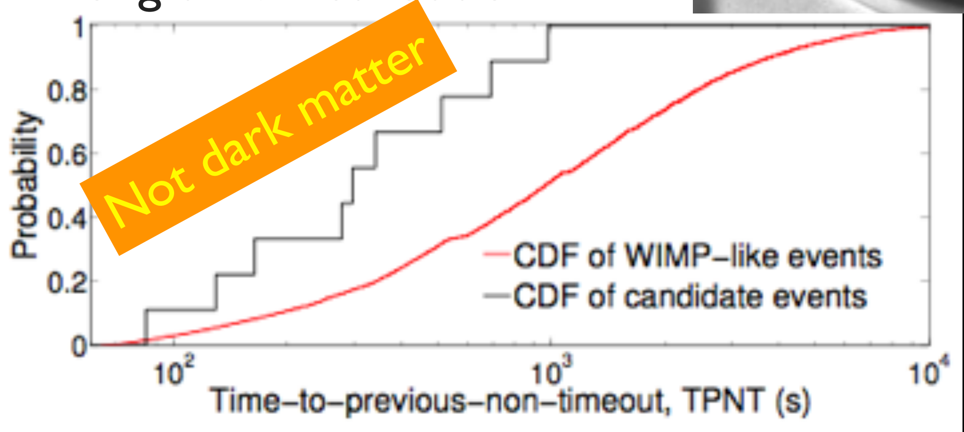
Platonic ideal: a simple binary indicator that only registers dark-matter-induced nuclear recoils and nothing else

PICO



single-bubble events in a C_3F_8 bubble chamber

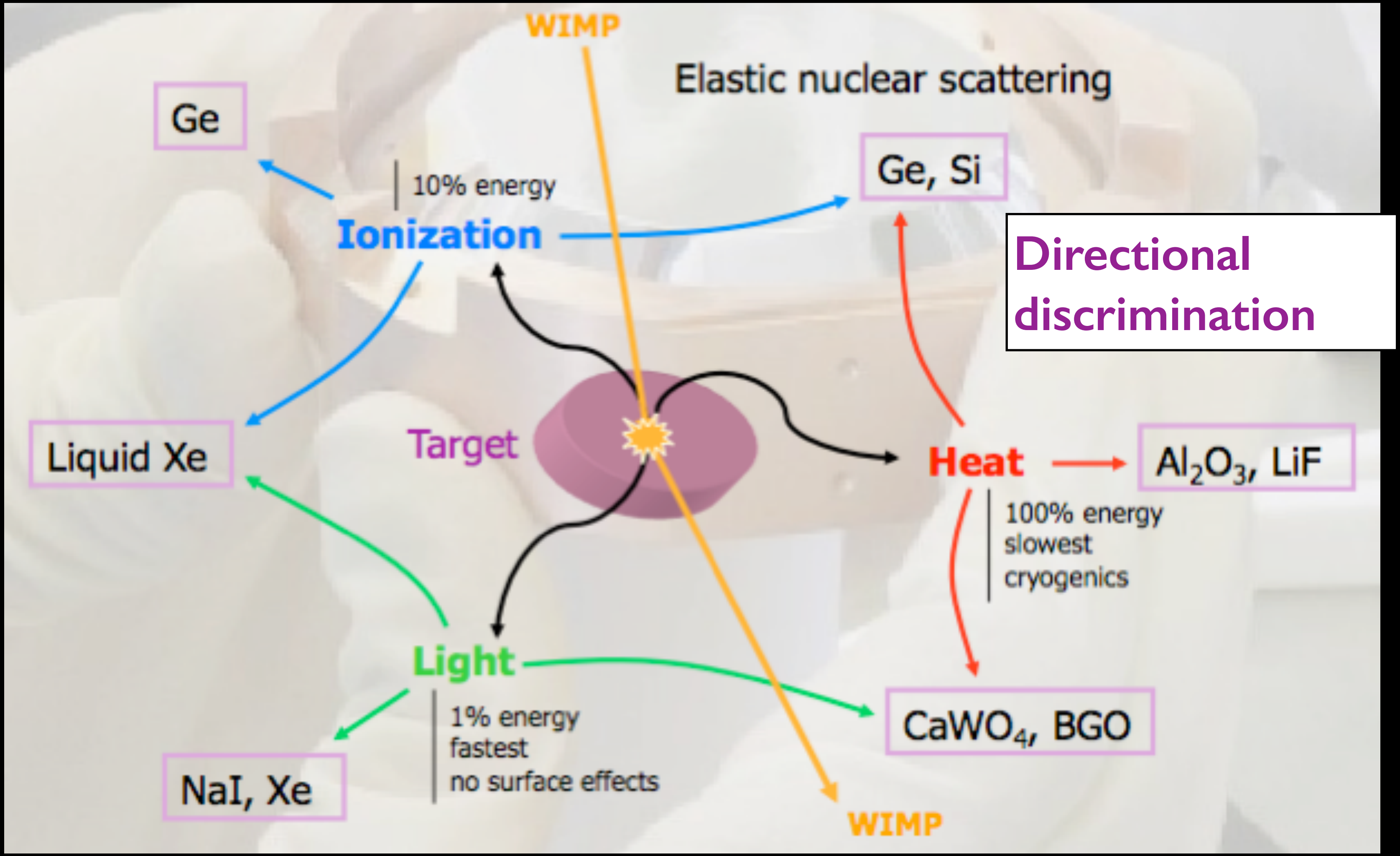
Wrong time distribution



Amole et al (PICO) 2/27/2015

Background discrimination

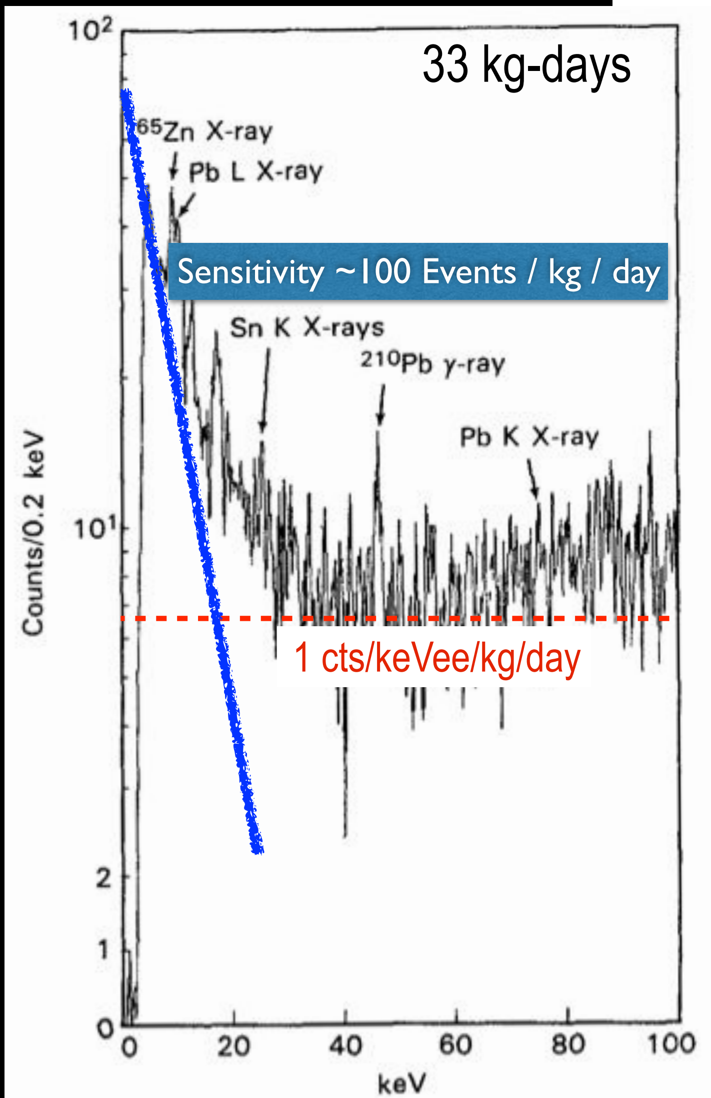
Finding the dark matter particles is a fight against background



From Sanglard 2005

Direct WIMP searches

First publication of an underground experimental search for WIMP cold dark matter (Ahlen et al 1987)



Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

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[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
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[e] *Applied Research Corp., 8201 Corporate Dr., Landover MD 20785, USA*
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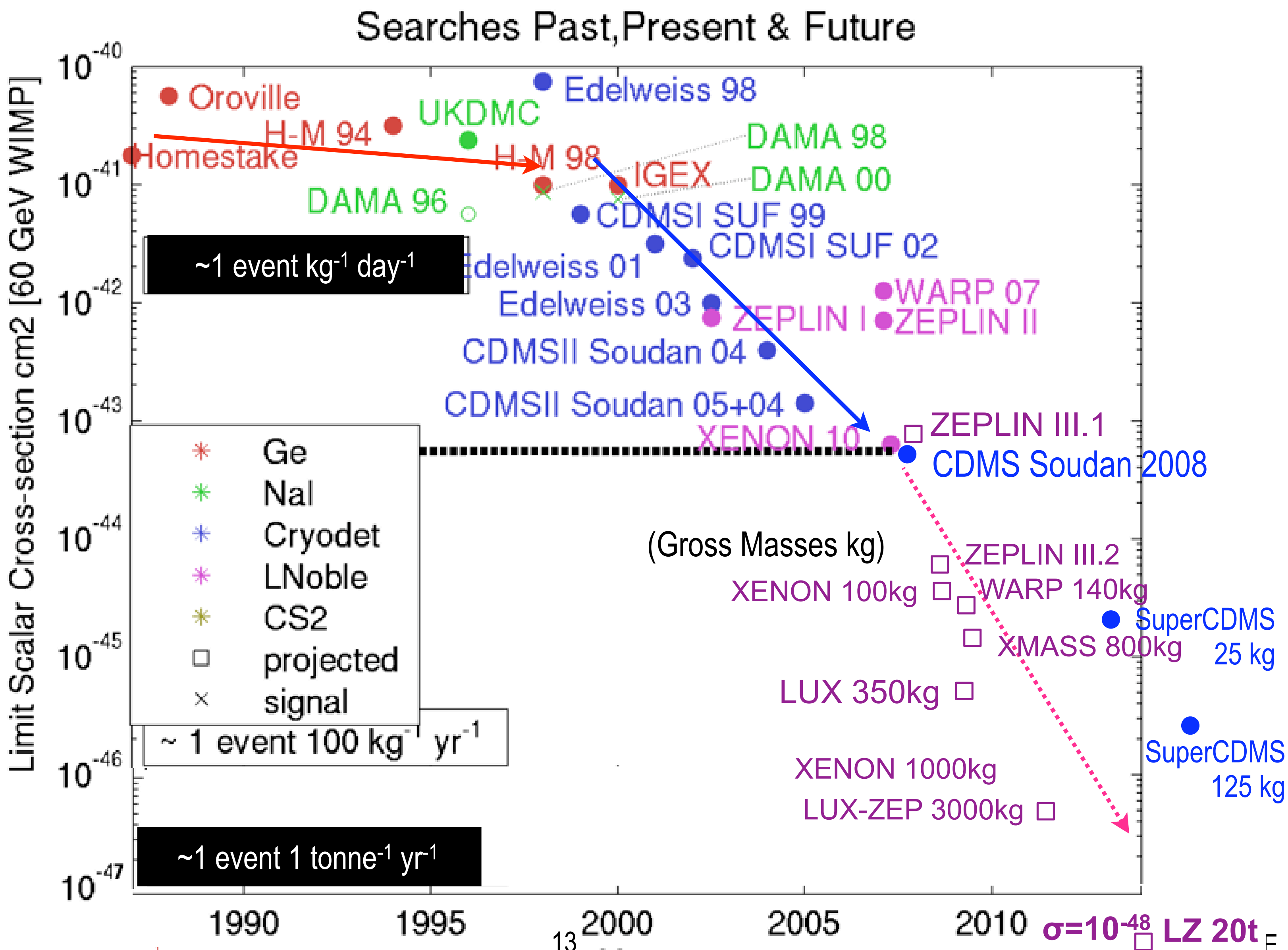
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2 5 TeV, at the 68% confidence level.

0.8 kg Ge ionization detector at Homestake Mine, SD

DM Direct Search Progress Over Time (2009)

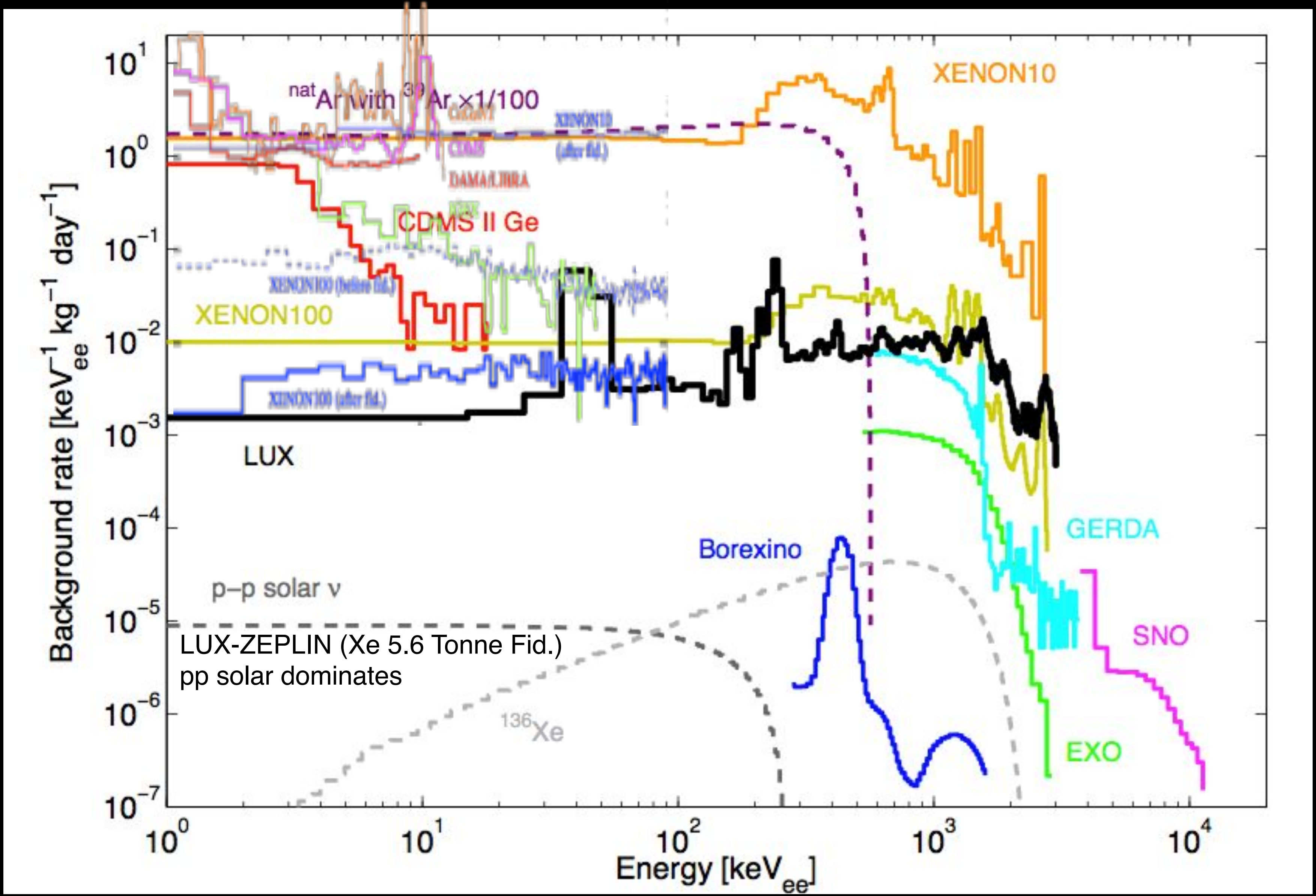


13

Gaitskell 2009

Direct dark matter searches

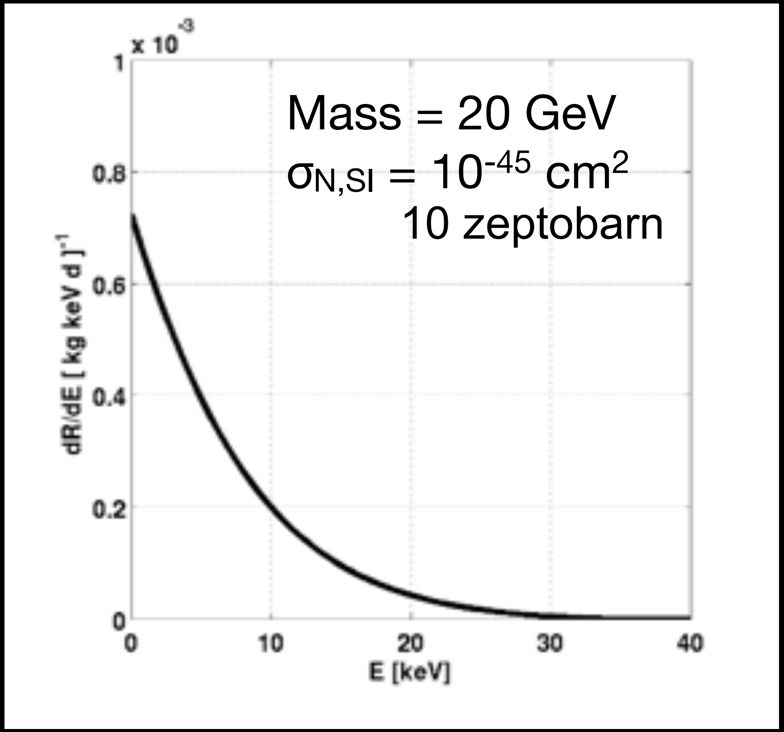
Background (electron recoil)



David Malling, Uwe Oberlack

Expected event rate is small

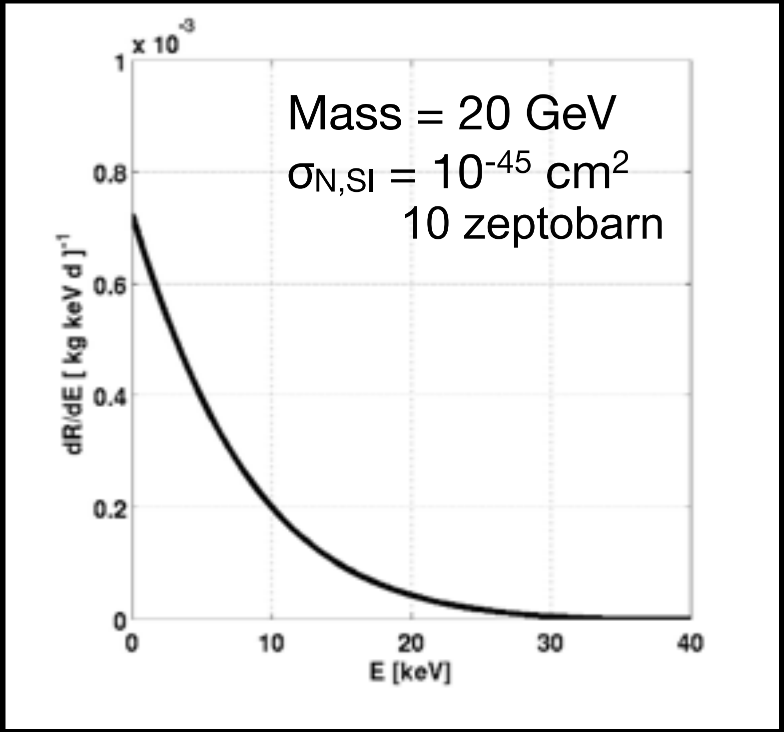
Expected
WIMP spectrum



~1 event/kg/year
(nuclear recoils)

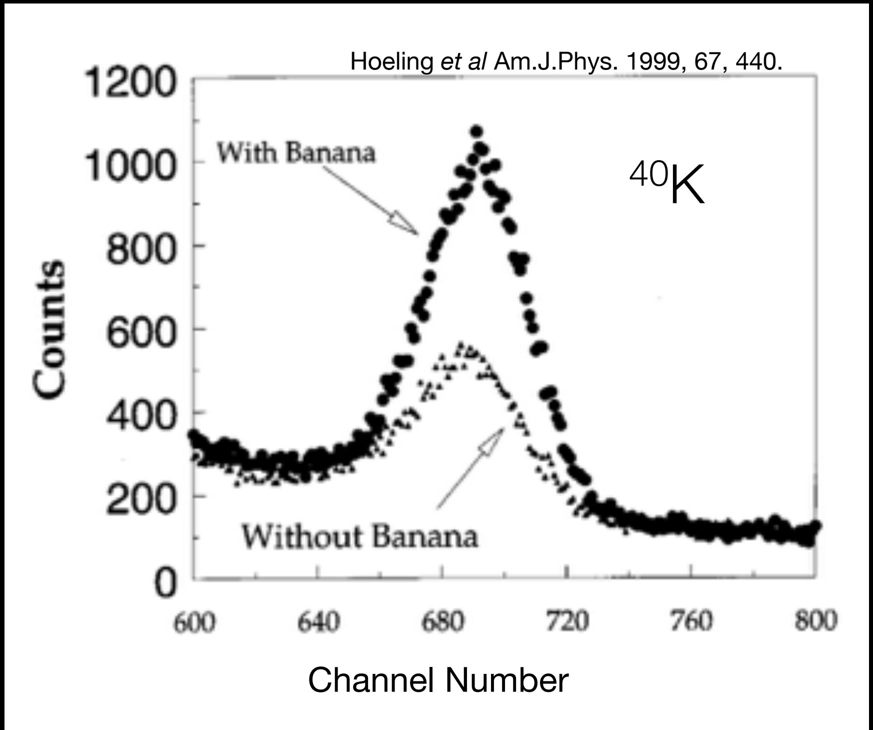
Expected event rate is small

Expected
WIMP spectrum



~1 event/kg/year
(nuclear recoils)

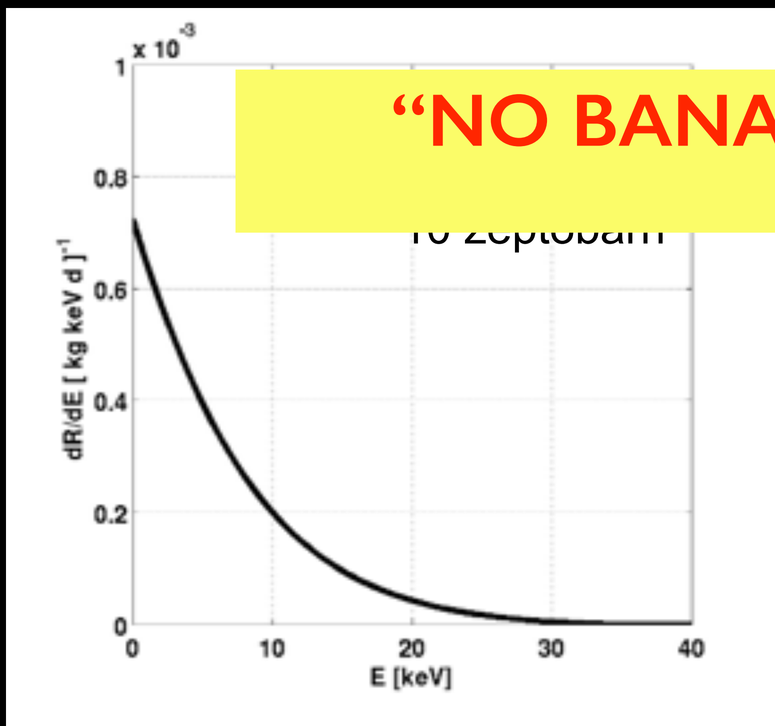
Measured
banana spectrum



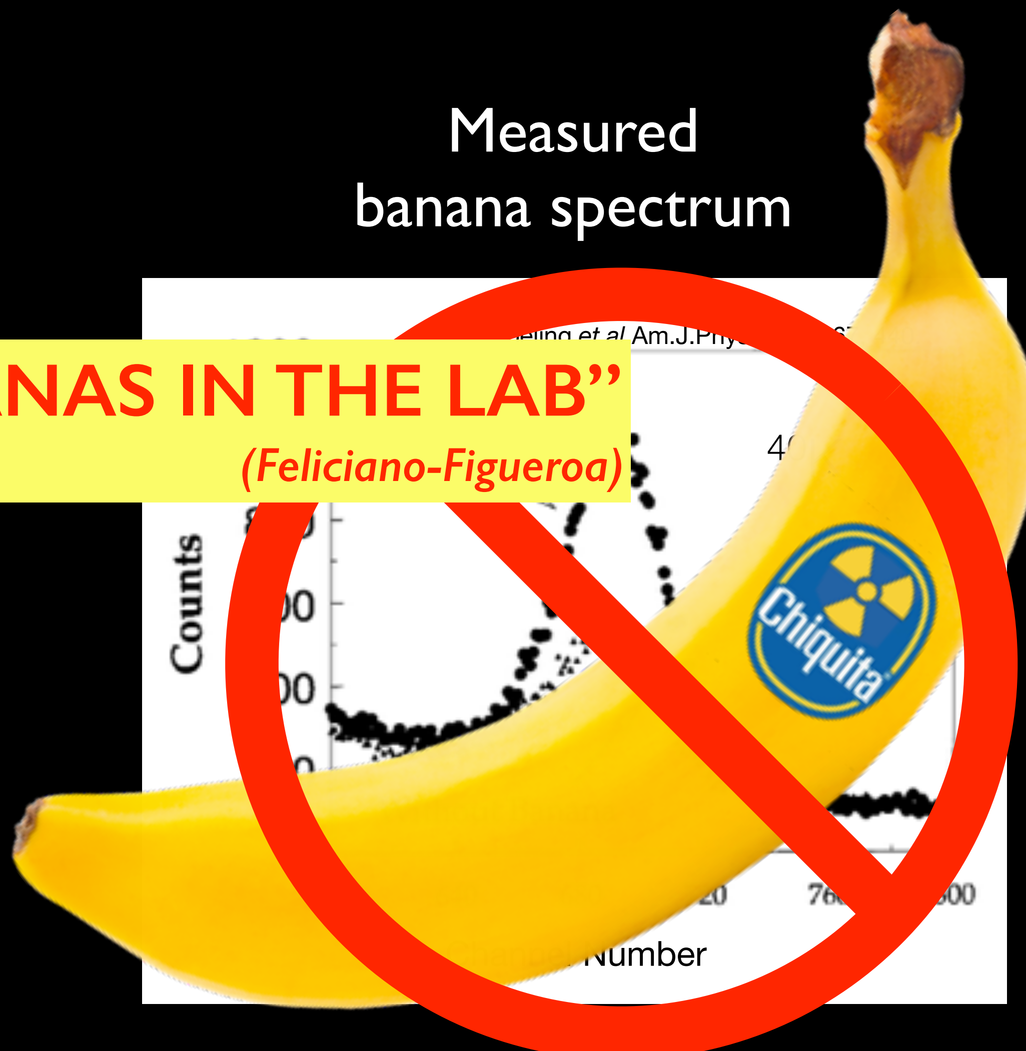
~100 events/kg/second
(electron recoils)

Expected event rate is small

Expected
WIMP spectrum



Measured
banana spectrum



"NO BANANAS IN THE LAB"

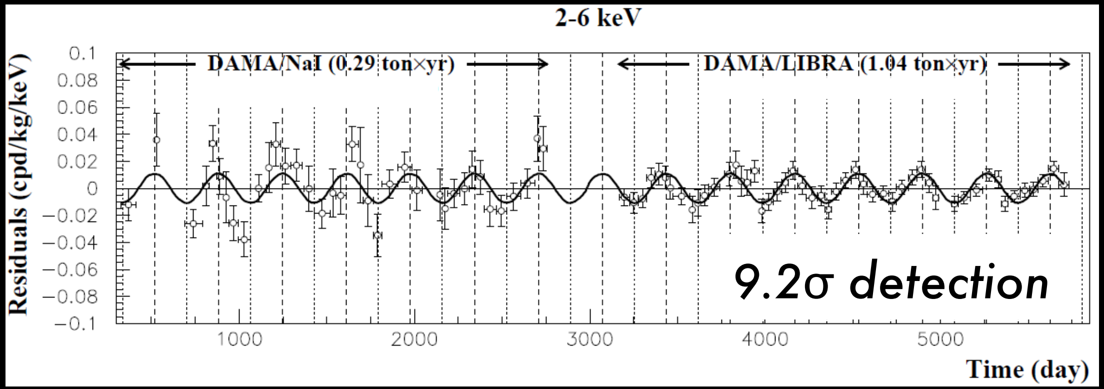
(Feliciano-Figueroa)

~1 event/kg/year
(nuclear recoils)

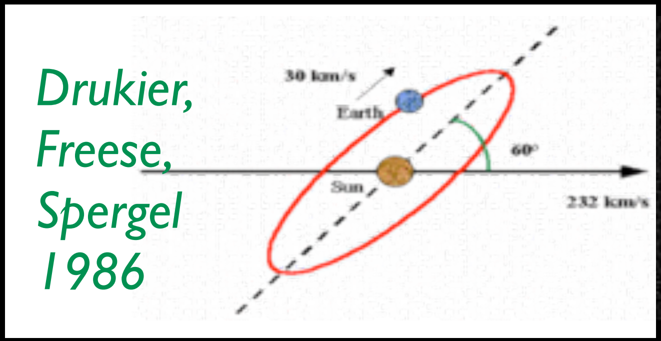
~100 events/kg/second
(electron recoils)

Confusion of the mind

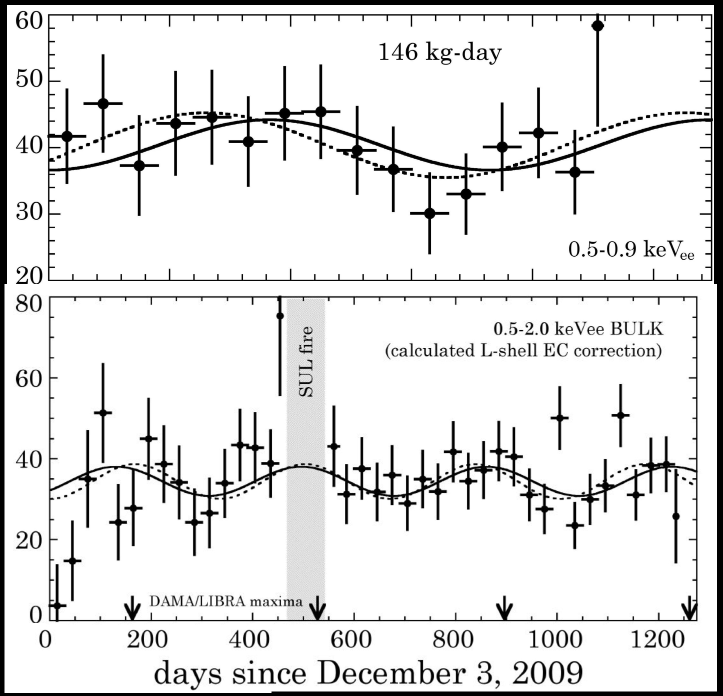
Evidence for light dark matter particles?



Bernabei et al (DAMA) 1997-15



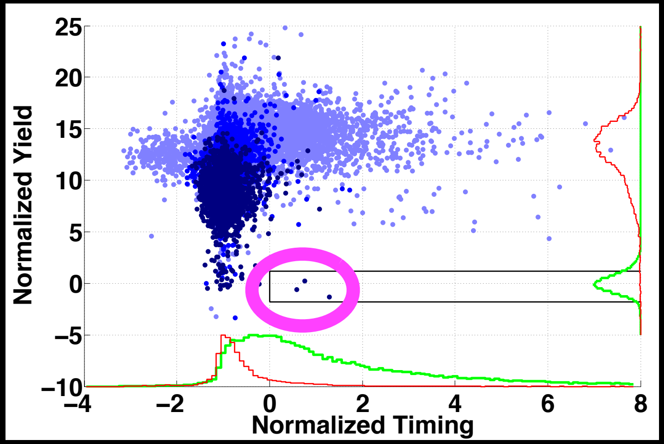
Annually modulated.....

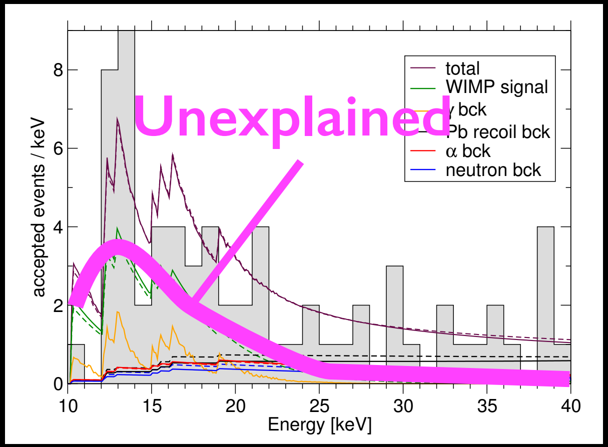


Aalseth et al (CoGeNT) 2011-2013

......and unmodulated

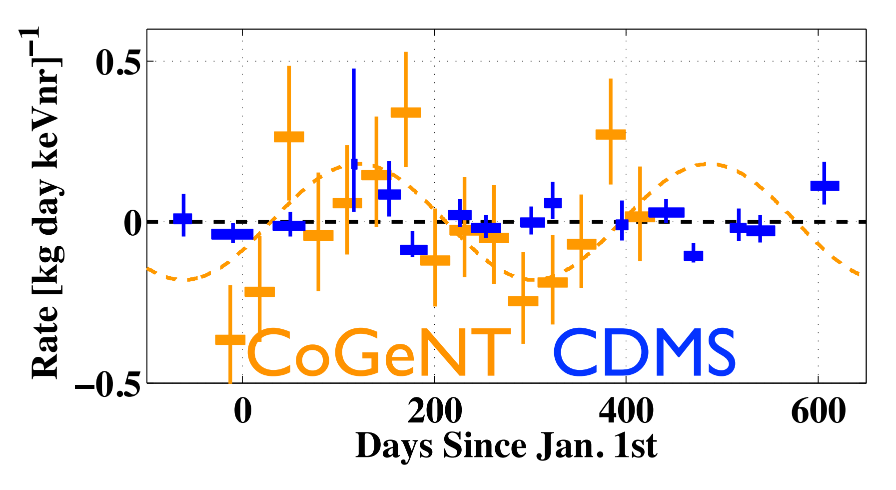
Agnese et al (CDMS) 2013





Anglehor et al (CRESST) 2011

Evidence for light dark matter particles?



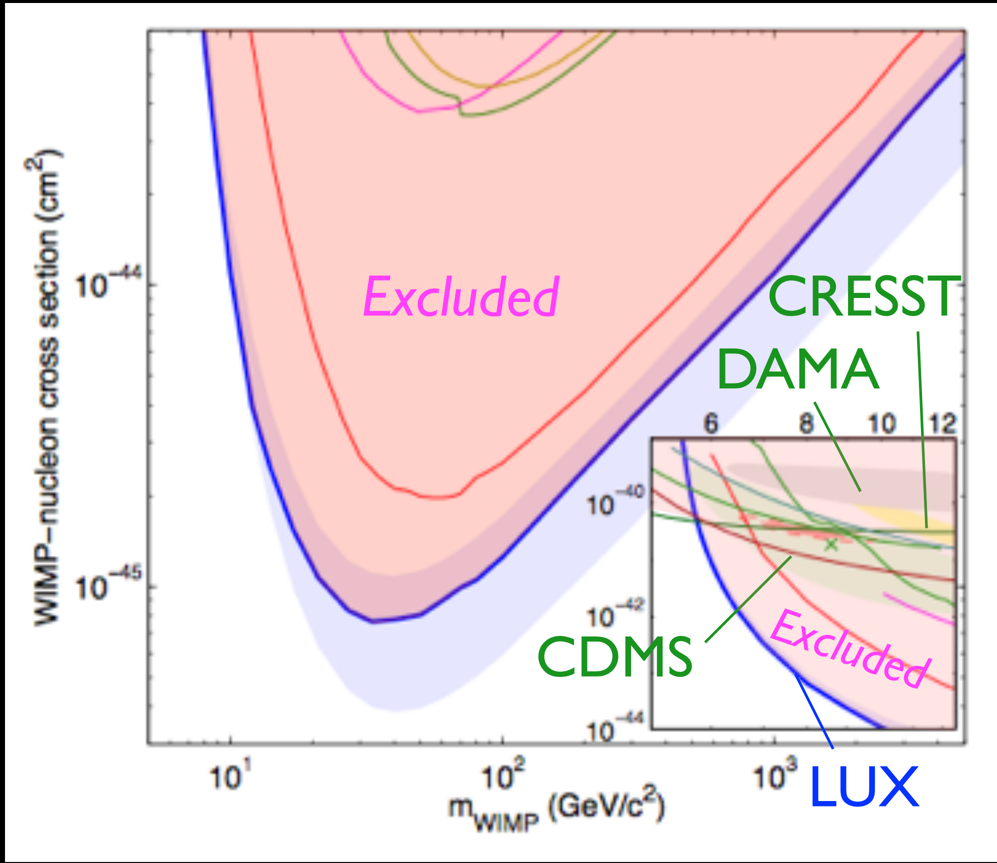
No significant modulation

Same target material

Ahmed et al (CDMS) 1203.1309

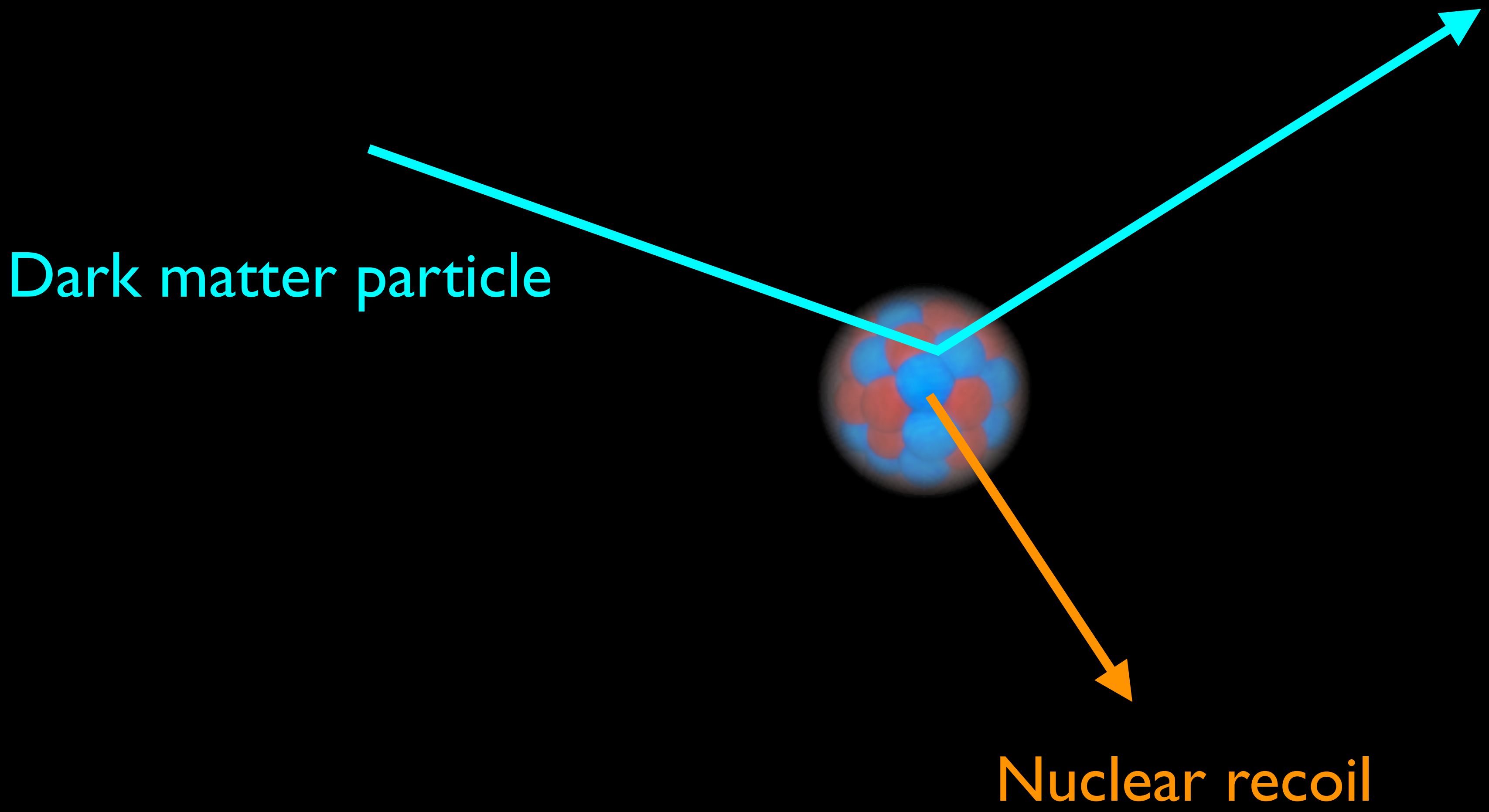
Not so many events

Akerib et al (LUX) 2013



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 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.

Detector response model

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

A common model for $\mathcal{G}(E, E_R)$ is a Gaussian with mean value

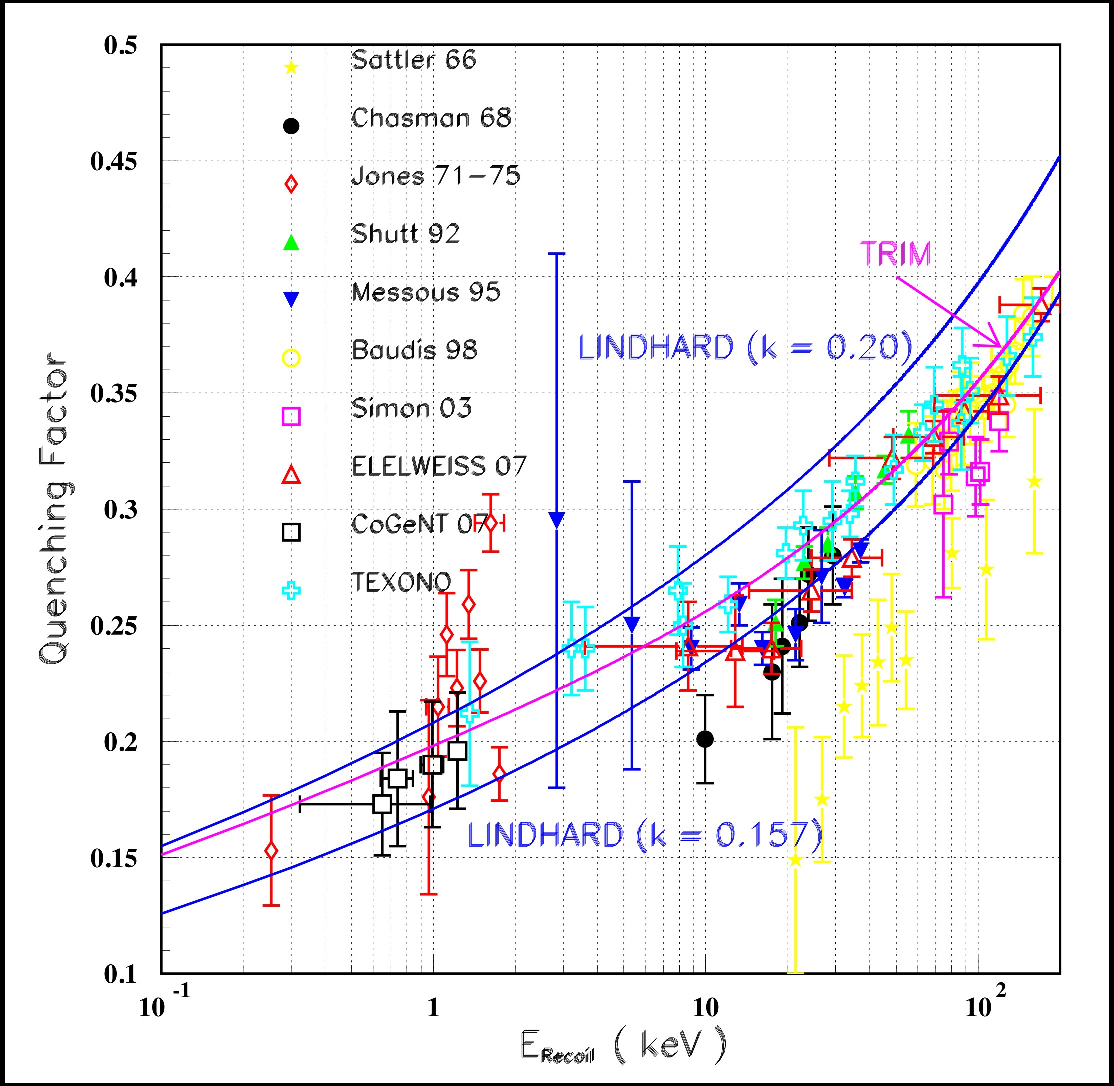
$$E = \boxed{Q} E_R$$

Quenching factor

and standard deviation equal to the energy resolution
(but there are exceptions, e.g., the XENON experiments)

Detector response model

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



Compilation of measurements of the quenching factor *Q* in germanium

New efforts to measure quenching factors

Lin et al (TEXONO) 2007

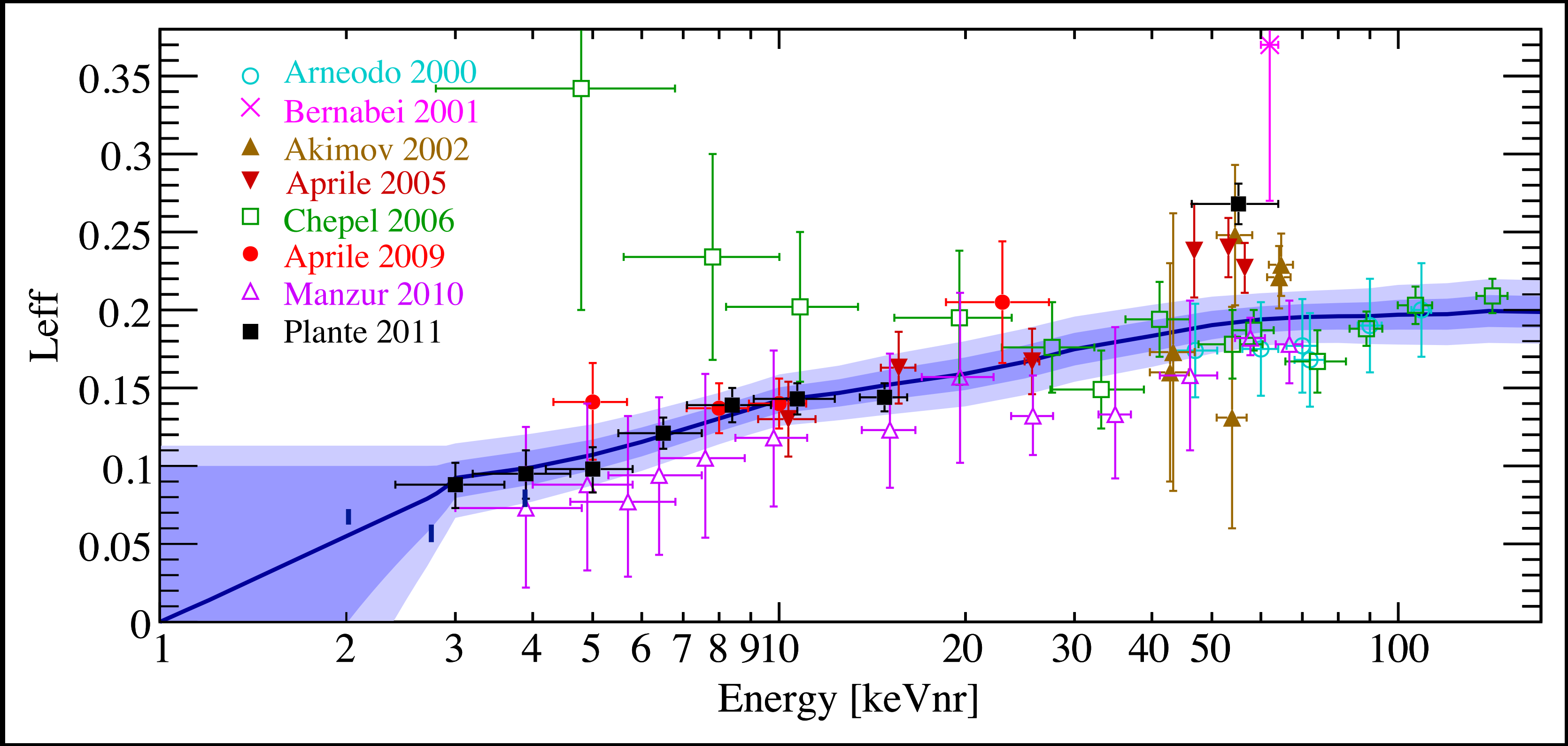
Detector response model

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

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

$$Q = (S_{\rm nr}/S_{\rm ee})L_{\rm eff}$$

New efforts to measure efficiency at low recoil energy



Aprile et al (XENON100), 1104.2549

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

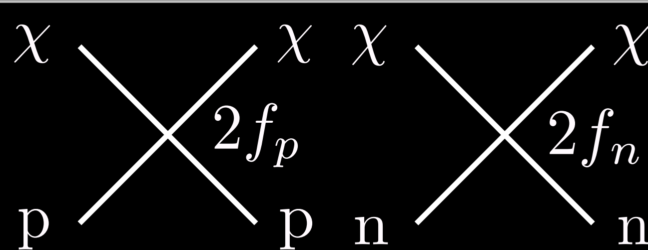
Particle physics model

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

Spin-independent

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

Effective four-particle vertices



Nuclear density form factor

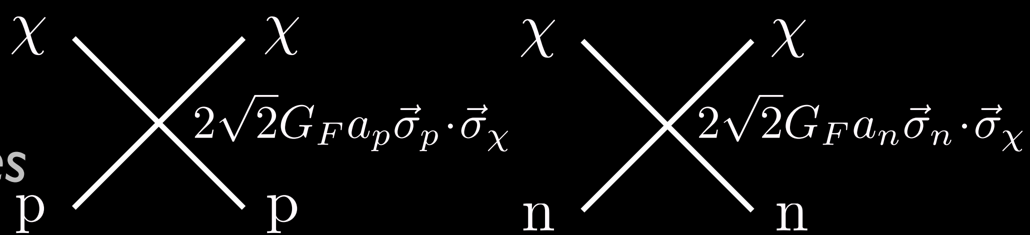
Particle physics model

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

Spin-dependent

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

Effective four-particle vertices



Nuclear spin structure functions

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

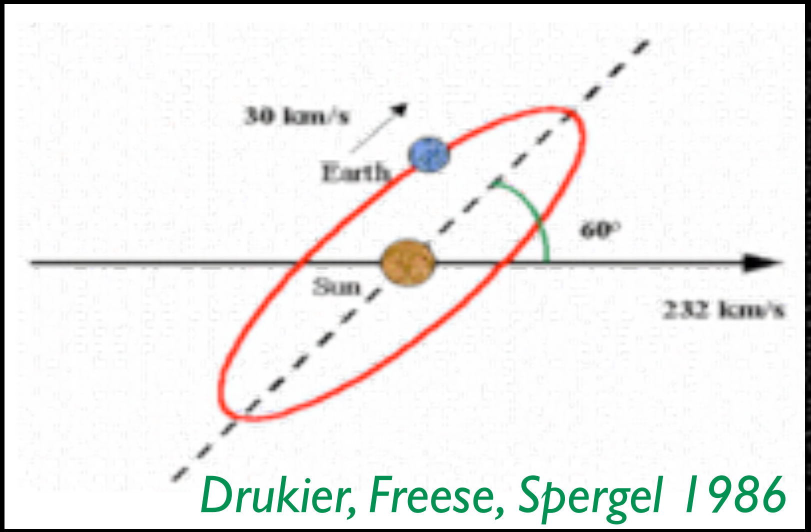
Local halo density

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

Minimum WIMP speed to impart recoil energy E_R

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

Annual modulation



Drukier, Freese, Spergel 1986

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

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

Astrophysics model: velocity distribution

Standard Halo Model

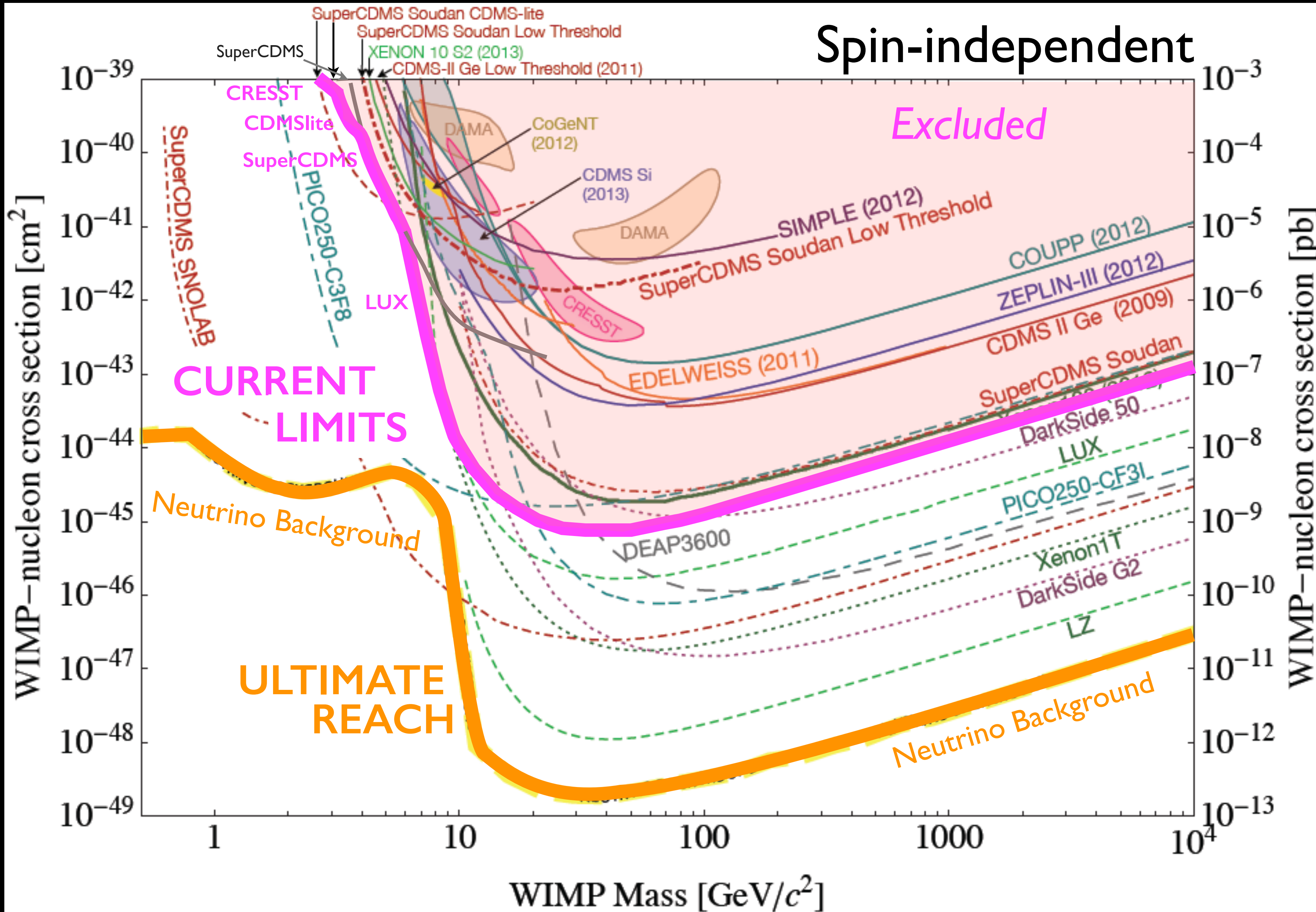
truncated Maxwellian

$$f(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}\pi^{3/2}\bar{v}_0^3} e^{-|\mathbf{v}+\mathbf{v}_{\rm obs}|/\bar{v}_0^2} & |\mathbf{v}| < v_{\rm esc} \\ 0 & \text{otherwise} \end{cases}$$

The spherical cow of direct WIMP searches

(Gelmini)

Direct dark matter searches (2014)



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

Treason and murder

DAMA modulation

Model Independent Annual Modulation Result

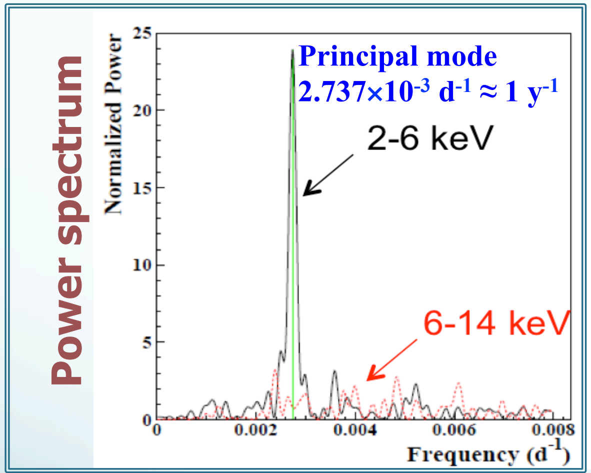
DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

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

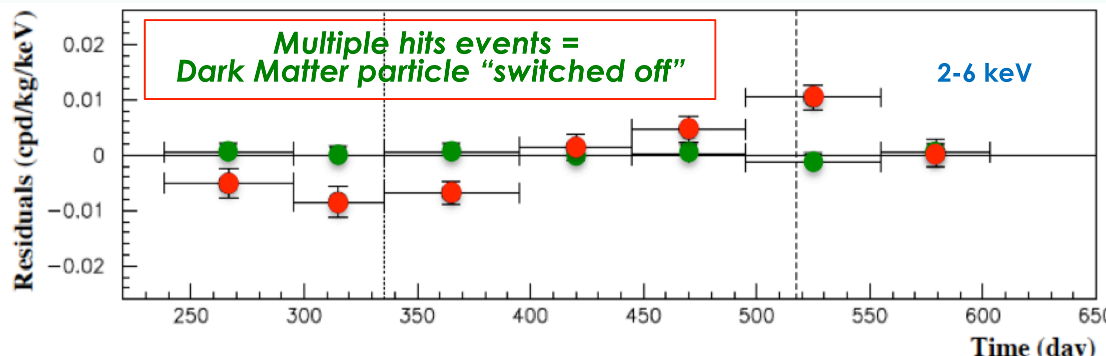
	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	**0.0190 ±0.0020**	**0.996 ±0.0002**	**134 ± 6**	**9.5σ**
(2-5) keV	**0.0140 ±0.0015**	**0.996 ±0.0002**	**140 ± 6**	**9.3σ**
(2-6) keV	**0.0112 ±0.0012**	**0.998 ±0.0002**	**144 ± 7**	**9.3σ**

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



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

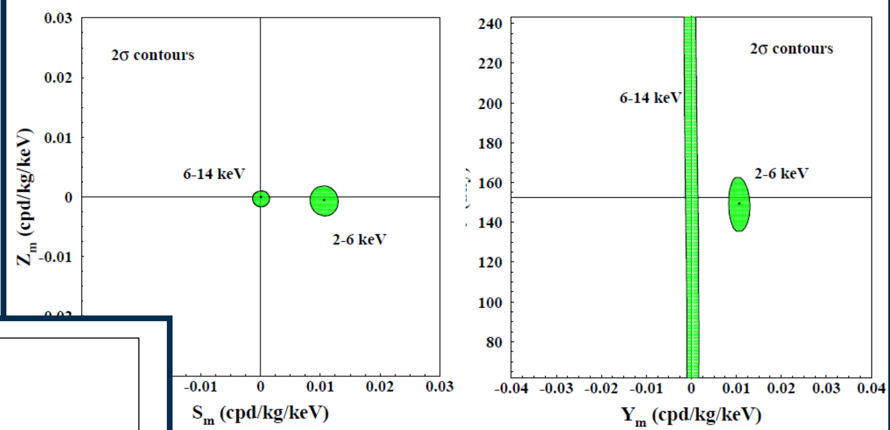
Model Independent Annual Modulation Result

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

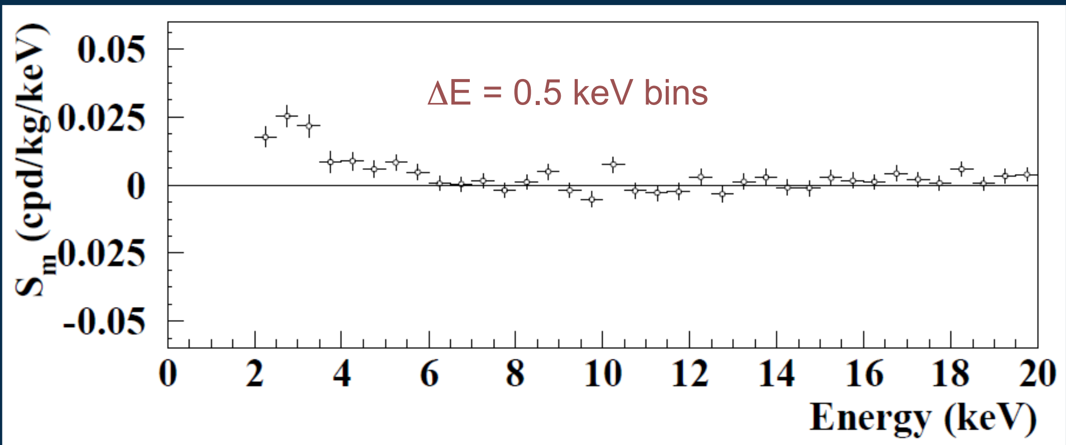
- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

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



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

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

DAMA modulation

Model Independent Annual Modulation Result

“Public?
What does it mean?”

Pierluigi Belli at IDM2014

peculiarities of the signature are available.

Belli, IDM2014

CoGeNT made their data public

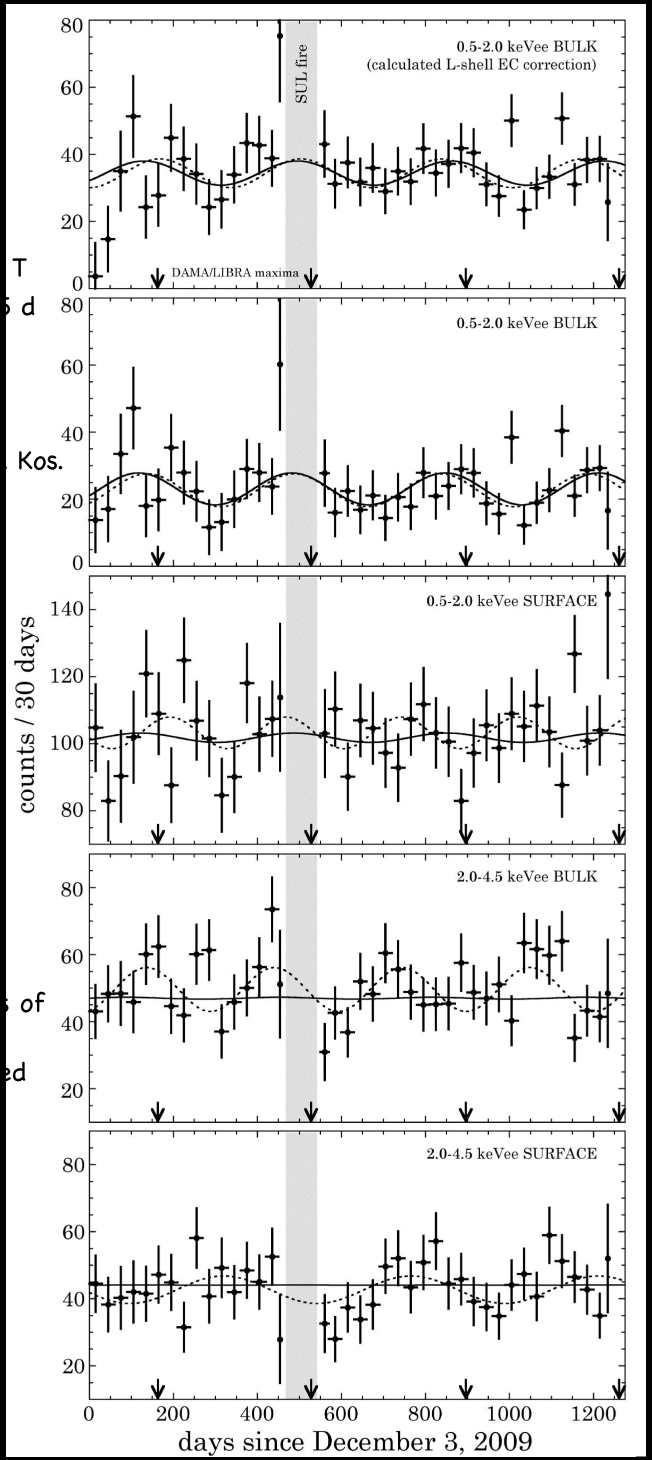
Annual modulation in 3.4 yr of CoGeNT

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

CoGeNT made their data public

CoGeNT decided to publish energy and time of their events

Independent groups reanalyzed the CoGeNT data

Pulse-shape discrimination of surface/bulk events

No significant modulation found

The CoGeNT region of interest results from a biased analysis, and has no statistical meaning.

Davis, McCabe, Boehm 1405.0495

The likelihood gets worse when including a WIMP component either as a standard halo or Sagittarius like stream

Bellis, Collar, Field, Kelso at IDM2014

CoGeNT made their data public

CoGeNT decided to publish energy and time of their events

Maximum Likelihood Signal Extraction Method Applied to 3.4 years of CoGeNT Data

C.E. Aalseth,[1] P.S. Barbeau,[2,*] J. Colaresi,[3] J.I. Collar,[2] J. Diaz Leon,[4] J.E. Fast,[1] N.E. Fields,[2] T.W. Hossbach,[1] A. Knecht,[4,†] M.S. Kos,[1,‡] M.G. Marino,[4,§] H.S. Miley,[1] M.L. Miller,[4,¶] J.L. Orrell,[1] and K.M. Yocum[3]
(CoGeNT Collaboration)

arXiv:1401.6234v1 24 Jan 2014

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arXiv:1401.6234v2 27 Jan 2014

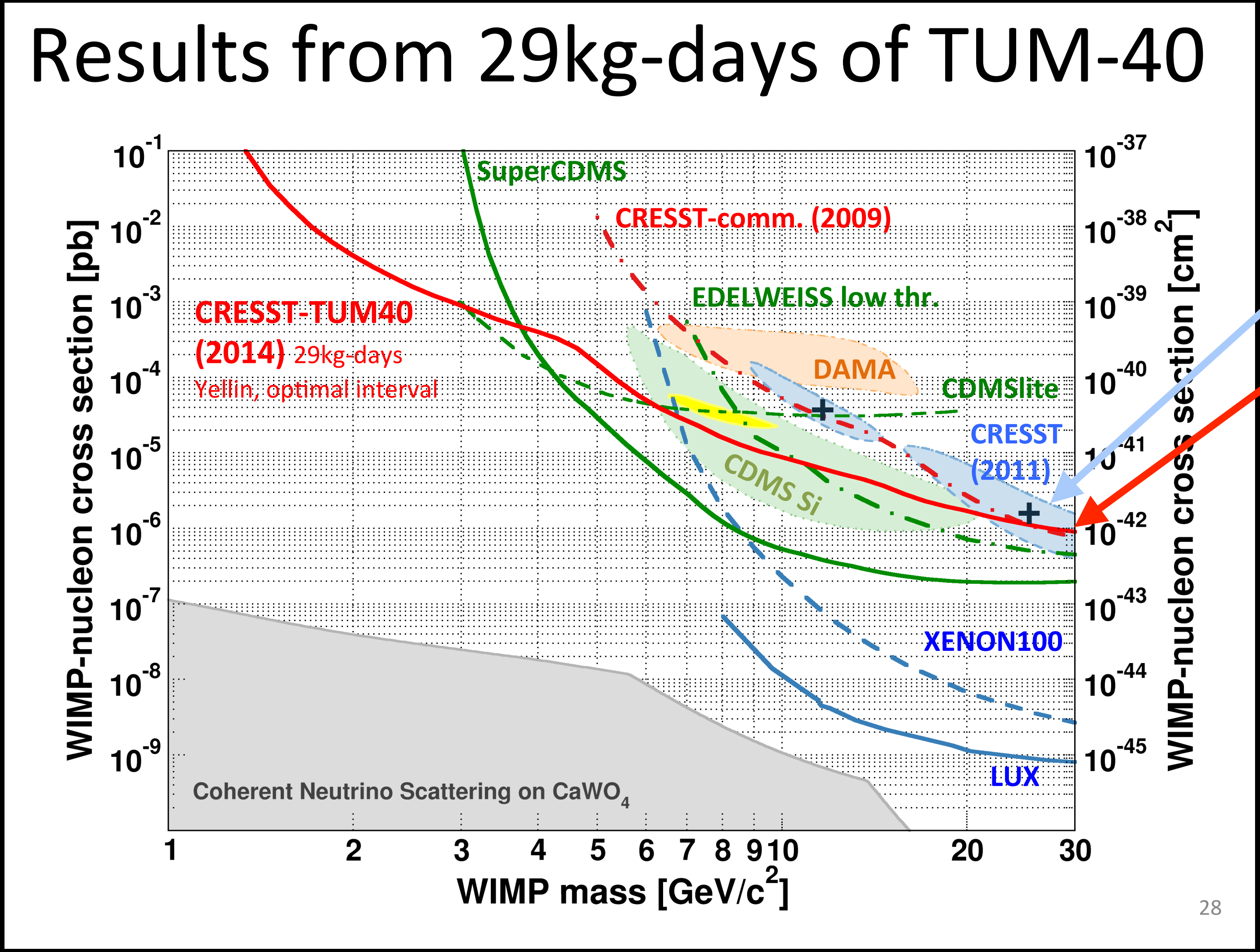
The likelihood gets worse when including a WIMP component either as a standard halo or Sagittarius like stream

Bellis, Collar, Field, Kelso at IDM2014

CoGeNT leader

News from CRESST

The CRESST-TUM40 upgrade rules out
the CRESST low-mass WIMP solution



CRESST

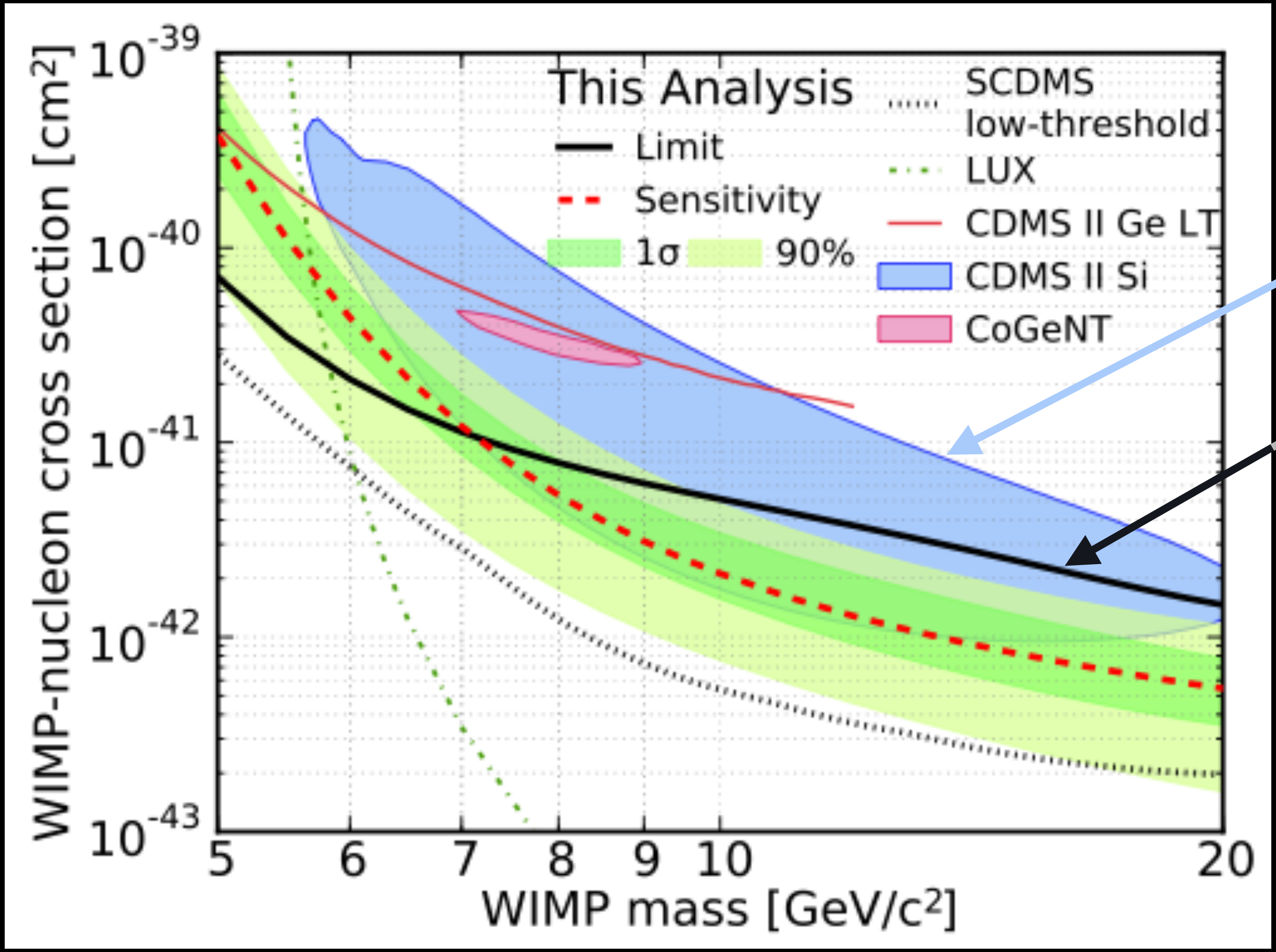
CRESST-TUM40
upper limit

Strauss at IDM2014

News from CDMS II

CDMS II Ge rules out
the CDMS II Si low-mass WIMP solution

Agnese et al (CDMS) 2014



CDMS II Si

CDMS II Ge
upper limit

That which does not kill us makes us stronger

All particle physics models

Write down and analyze
all possible WIMP-nucleus currents

Recoil spectrum

The recoil spectrum (scattering rate per unit target mass)

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

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

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 $v^2 \, d\sigma/dE_R$

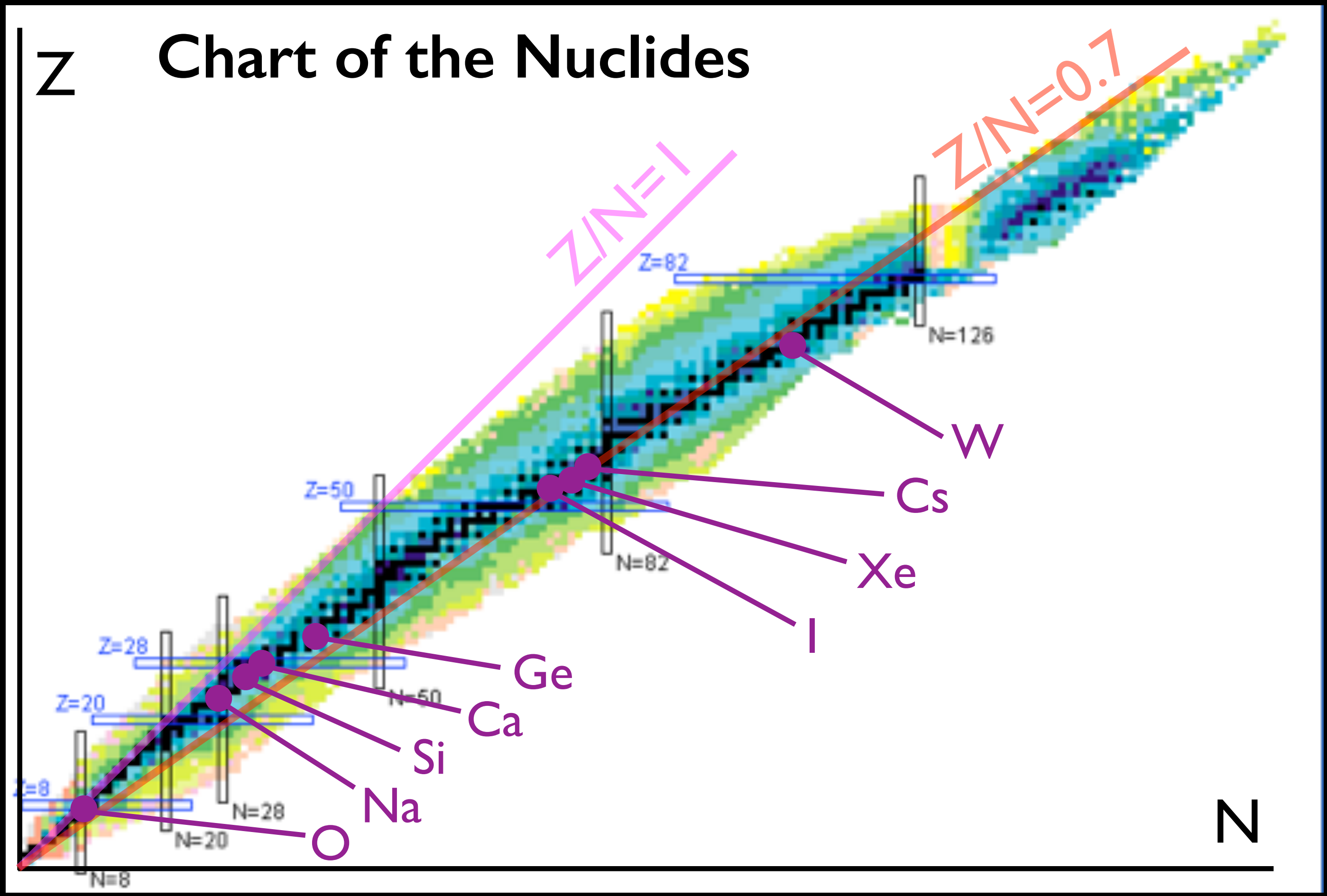
Isospin-violating (nonisoscalar) dark matter

Spin-independent couplings to protons stronger than to neutrons may 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"*	$1/E_R$	$1/M^4$
"charge"	*dipole*	$1/E_R$	E_R/M^4
dipole	*dipole*	$\text{const} + E_R/v^2$	E_R^2/M^4

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

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

All particle physics models

All short-distance operators classified

Fitzpatrick et al 2012

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

All nuclear form factors classified

Response $\times\left[\frac{4\pi}{2J_i+1}\right]^{-1}$	Leading Multipole	Long-wavelength Limit	Response Type
$\sum_{J=0,2,...}^{\infty}\lvert\langle J_i\lvert\lvert M_{JM}\rvert\rvert J_i\rangle\rvert^2$	$M_{00}(q\vec{x}_i)$	$\frac{1}{\sqrt{4\pi}}1(i)$	M_{JM} : Charge
$\sum_{J=1,3,...}^{\infty}\lvert\langle J_i\lvert\lvert\Sigma''_{JM}\rvert\rvert J_i\rangle\rvert^2$	$\Sigma''_{1M}(q\vec{x}_i)$	$\frac{1}{2\sqrt{3\pi}}\sigma_{1M}(i)$	L^5_{JM} : Axial Longitudinal
$\sum_{J=1,3,...}^{\infty}\lvert\langle J_i\lvert\lvert\Sigma'_{JM}\rvert\rvert J_i\rangle\rvert^2$	$\Sigma'_{1M}(q\vec{x}_i)$	$\frac{1}{\sqrt{6\pi}}\sigma_{1M}(i)$	$T^{\mathrm{el}5}_{JM}$: Axial Transverse Electric
$\sum_{J=1,3,...}^{\infty}\lvert\langle J_i\lvert\lvert\frac{q}{m_N}\Delta_{JM}\rvert\rvert J_i\rangle\rvert^2$	$\frac{q}{m_N}\Delta_{1M}(q\vec{x}_i)$	$-\frac{q}{2m_N\sqrt{6\pi}}\ell_{1M}(i)$	T^{mag}_{JM} : Transverse Magnetic
$\sum_{J=0,2,...}^{\infty}\lvert\langle J_i\lvert\lvert\frac{q}{m_N}\Phi''_{JM}\rvert\rvert J_i\rangle\rvert^2$	$\frac{q}{m_N}\Phi''_{00}(q\vec{x}_i)$	$-\frac{q}{3m_N\sqrt{4\pi}}\vec{\sigma}(i)\cdot\vec{\ell}(i)$	L_{JM} : Longitudinal
	$\frac{q}{m_N}\Phi''_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{30\pi}}[x_i\otimes(\vec{\sigma}(i)\times\frac{1}{i}\vec{\nabla})_1]_{2M}$	
$\sum_{J=2,4,...}^{\infty}\lvert\langle J_i\lvert\lvert\frac{q}{m_N}\tilde{\Phi}'_{JM}\rvert\rvert J_i\rangle\rvert^2$	$\frac{q}{m_N}\tilde{\Phi}'_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{20\pi}}[x_i\otimes(\vec{\sigma}(i)\times\frac{1}{i}\vec{\nabla})_1]_{2M}$	T^{el}_{JM} : Transverse Electric

nuclear oscillator model

Fitzpatrick et al 2012

All particle physics models

Combined analysis of short-distance operators

Catena, Gondolo 2014

$$\mathcal{H} = \sum_i \left(c_i^0 + c_i^1 \tau_3\right) \mathcal{O}_i$$

$$\frac{d\sigma}{dE_R} = \frac{m_T}{2\pi v^2} P_{\rm tot}(v^2, q^2)$$

$\mathcal{O}_1 = 1_\chi 1_N$	$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp_{\chi N}$
$\mathcal{O}_3 = -i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$	$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp_{\chi N}$
$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_9 = -i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$
$\mathcal{O}_5 = -i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$	$\mathcal{O}_{10} = -i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$	$\mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

$$\begin{aligned}
P_{\rm tot}(v^2, q^2) \;=\; & \frac{4\pi}{2j_N+1} \sum_{\tau=0,1} \sum_{\tau'=0,1} \Bigg\{ \Bigg[R_M^{\tau\tau'}\Big(v^{\perp 2}_{\chi T}, \frac{q^2}{m_N^2}\Big)\, W_M^{\tau\tau'}(y) \\
& + R_{\Sigma''}^{\tau\tau'}\Big(v^{\perp 2}_{\chi T}, \frac{q^2}{m_N^2}\Big)\, W_{\Sigma''}^{\tau\tau'}(y) + R_{\Sigma'}^{\tau\tau'}\Big(v^{\perp 2}_{\chi T}, \frac{q^2}{m_N^2}\Big)\, W_{\Sigma'}^{\tau\tau'}(y) \Bigg] \\
& + \frac{q^2}{m_N^2} \Bigg[R_{\Phi''}^{\tau\tau'}\Big(v^{\perp 2}_{\chi T}, \frac{q^2}{m_N^2}\Big)\, W_{\Phi''}^{\tau\tau'}(y) + R_{\Phi'' M}^{\tau\tau'}\Big(v^{\perp 2}_{\chi T}, \frac{q^2}{m_N^2}\Big)\, W_{\Phi'' M}^{\tau\tau'}(y) \\
& + R_{\tilde{\Phi}'}^{\tau\tau'}\Big(v^{\perp 2}_{\chi T}, \frac{q^2}{m_N^2}\Big)\, W_{\tilde{\Phi}'}^{\tau\tau'}(y) + R_{\Delta}^{\tau\tau'}\Big(v^{\perp 2}_{\chi T}, \frac{q^2}{m_N^2}\Big)\, W_{\Delta}^{\tau\tau'}(y) \\
& + R_{\Delta\Sigma'}^{\tau\tau'}\Big(v^{\perp 2}_{\chi T}, \frac{q^2}{m_N^2}\Big)\, W_{\Delta\Sigma'}^{\tau\tau'}(y) \Bigg] \Bigg\} .
\end{aligned}$$

Data used:

CDMS-Ge
CDMS-low-thr
CMDSlite
SuperCDMS
XENON-10
XENON-100
LUX
COUPP
SIMPLE
DAMA
CoGeNT

All particle physics models

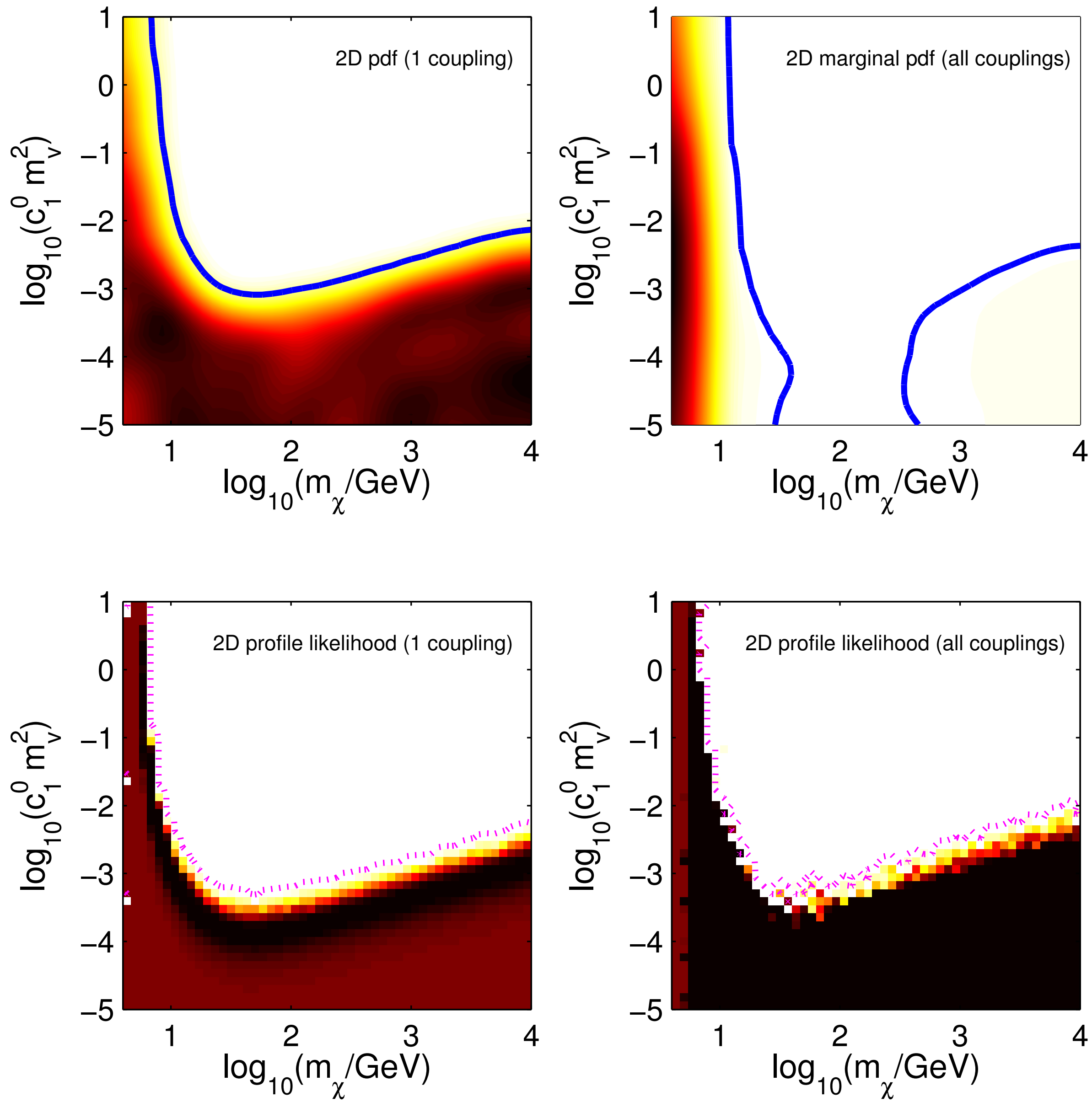
Combined analysis of short-distance operators

Catena, Gondolo 2014

$$\mathcal{O}_1 = 1_\chi 1_N$$

marginalization (Bayesian)

profile likelihood (frequentist)

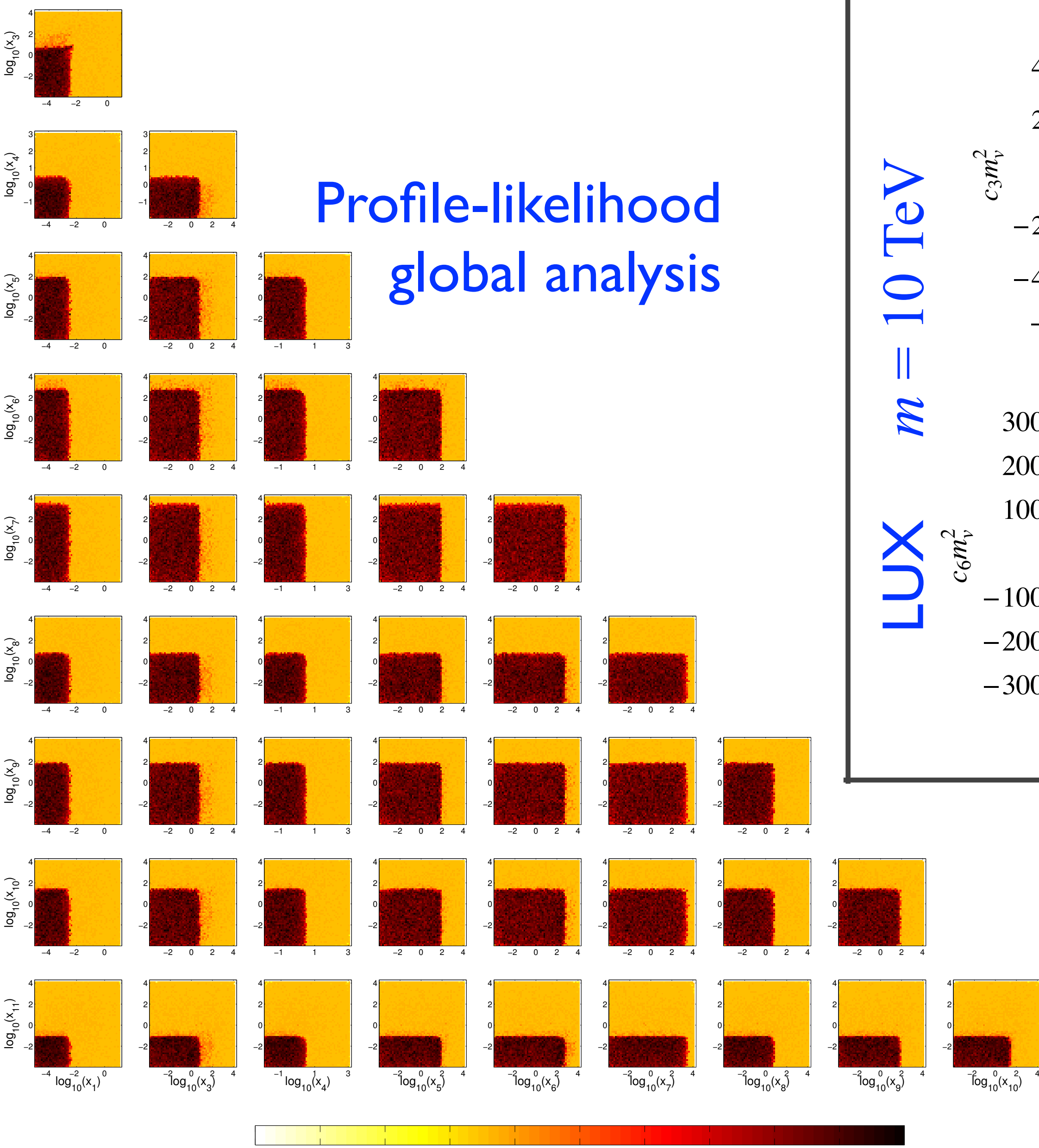


still not enough data, so large dependence on prior

All particle physics models

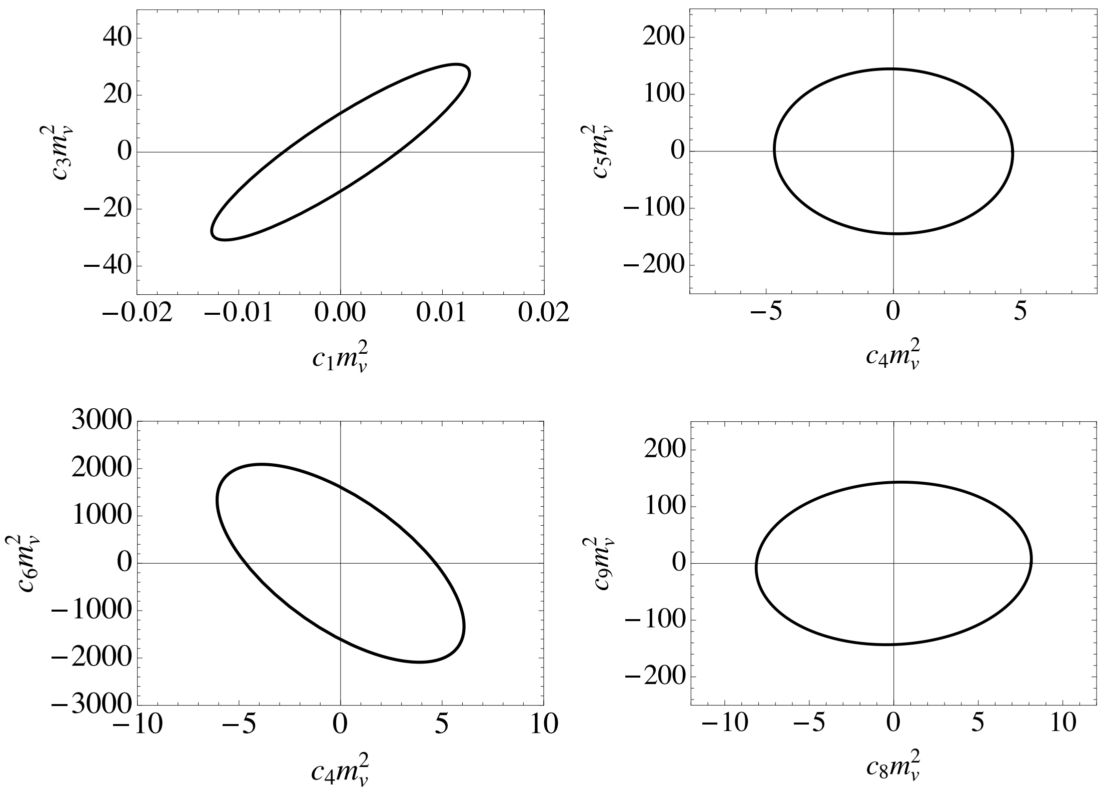
Combined analysis of short-distance operators

Catena, Gondolo 2014



Profile-likelihood global analysis

LUX $m = 10$ TeV

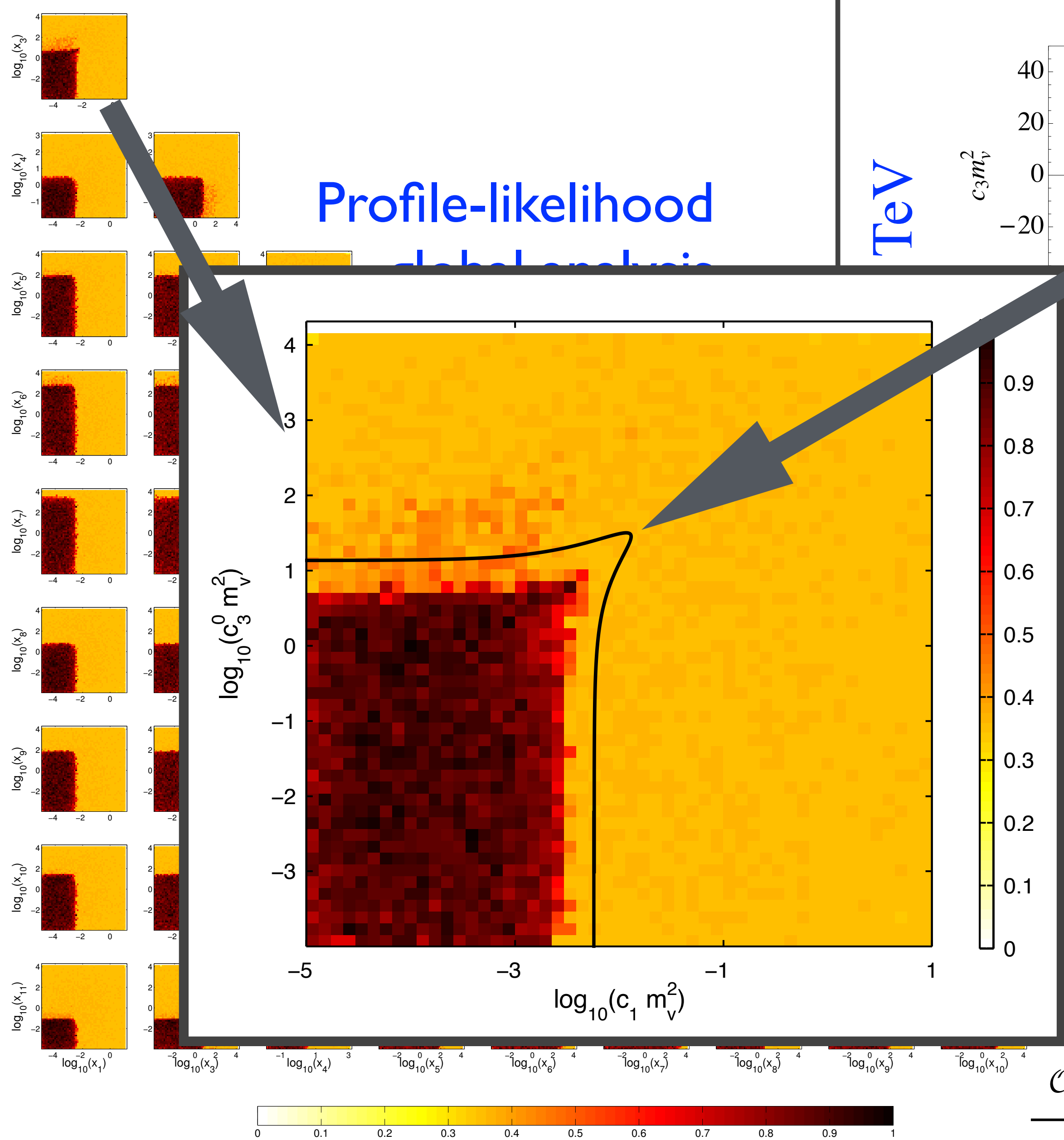


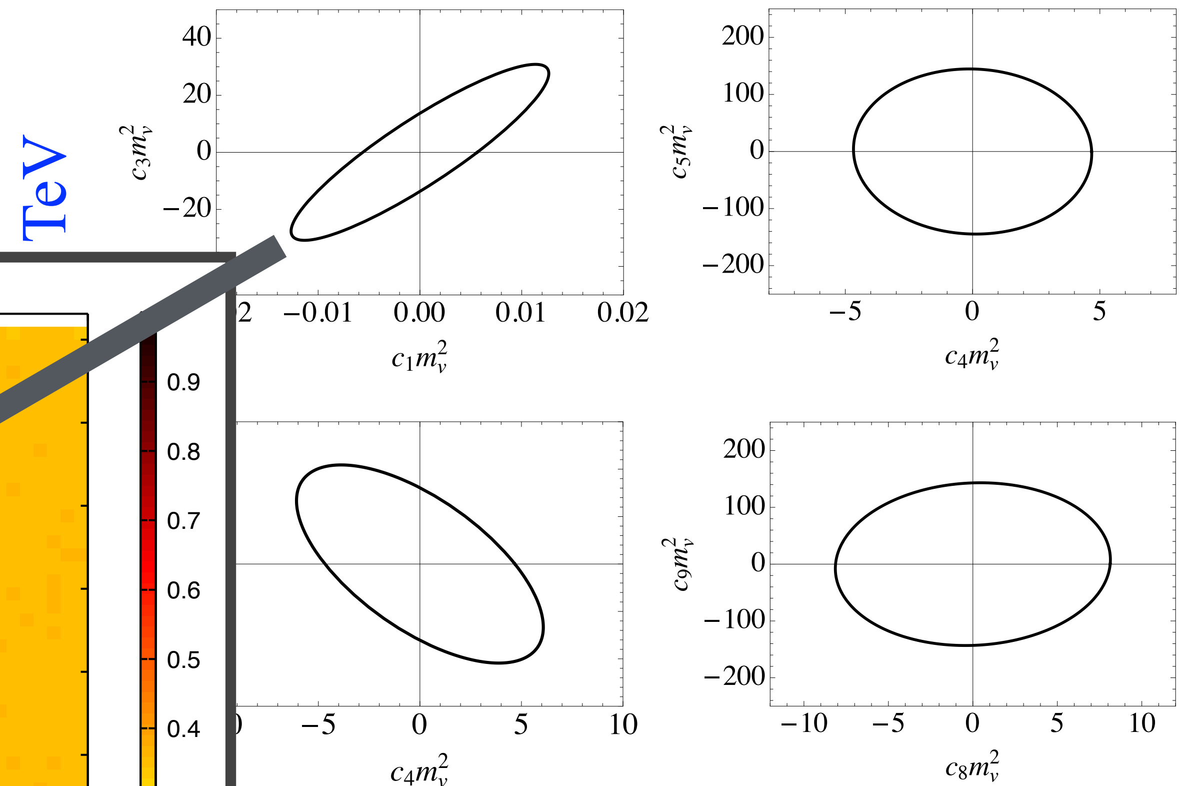
$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = -i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = -i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp_{\chi N}$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp_{\chi N}$$
$$\mathcal{O}_9 = -i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_{10} = -i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

All particle physics models

Combined analysis of short-distance operators

Catena, Gondolo 2014





$\mathcal{O}_1 = 1_\chi 1_N$

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

$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

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

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

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

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp_{\chi N}$

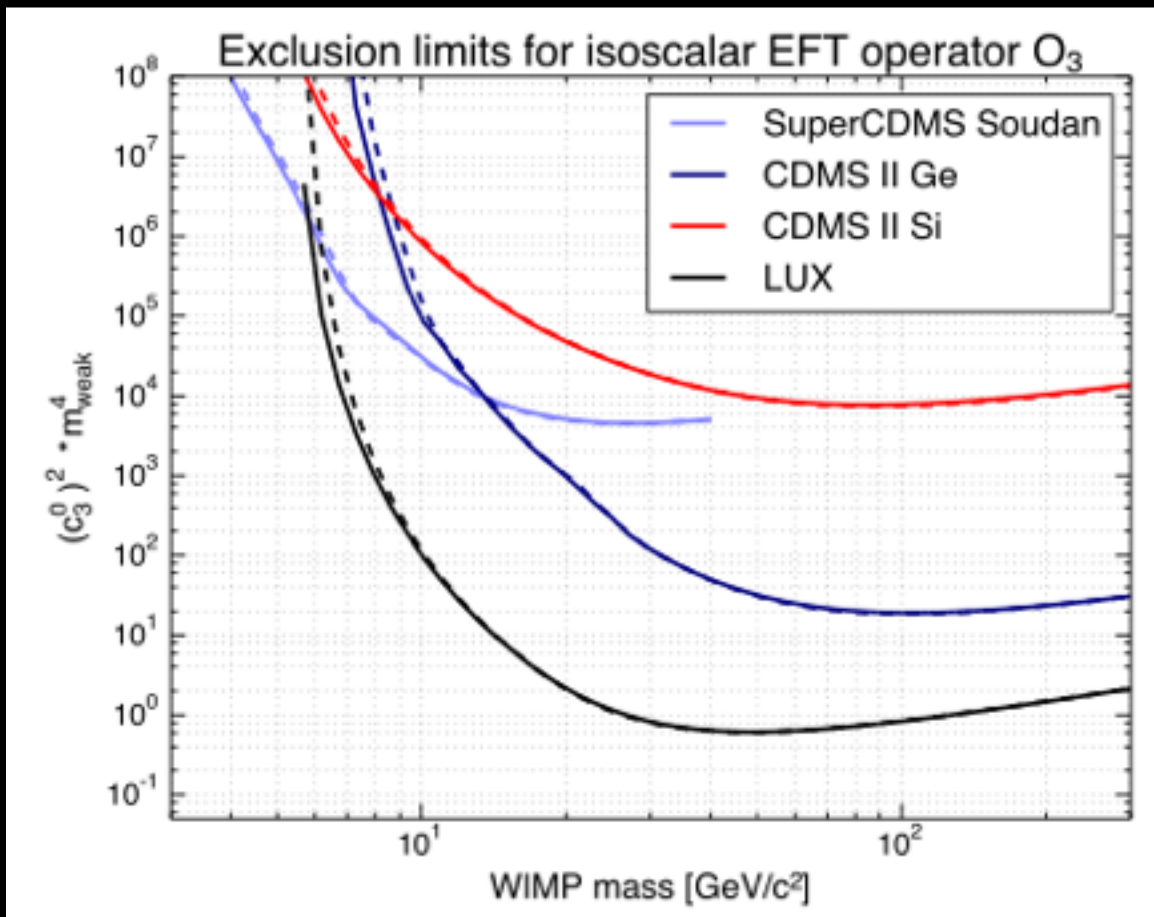
$\mathcal{O}_9 = -i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$

$\mathcal{O}_{10} = -i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$

$\mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

All particle physics models

Experimental limits on single operators… *Schneck et al (SuperCDMS) 3/11/2015*

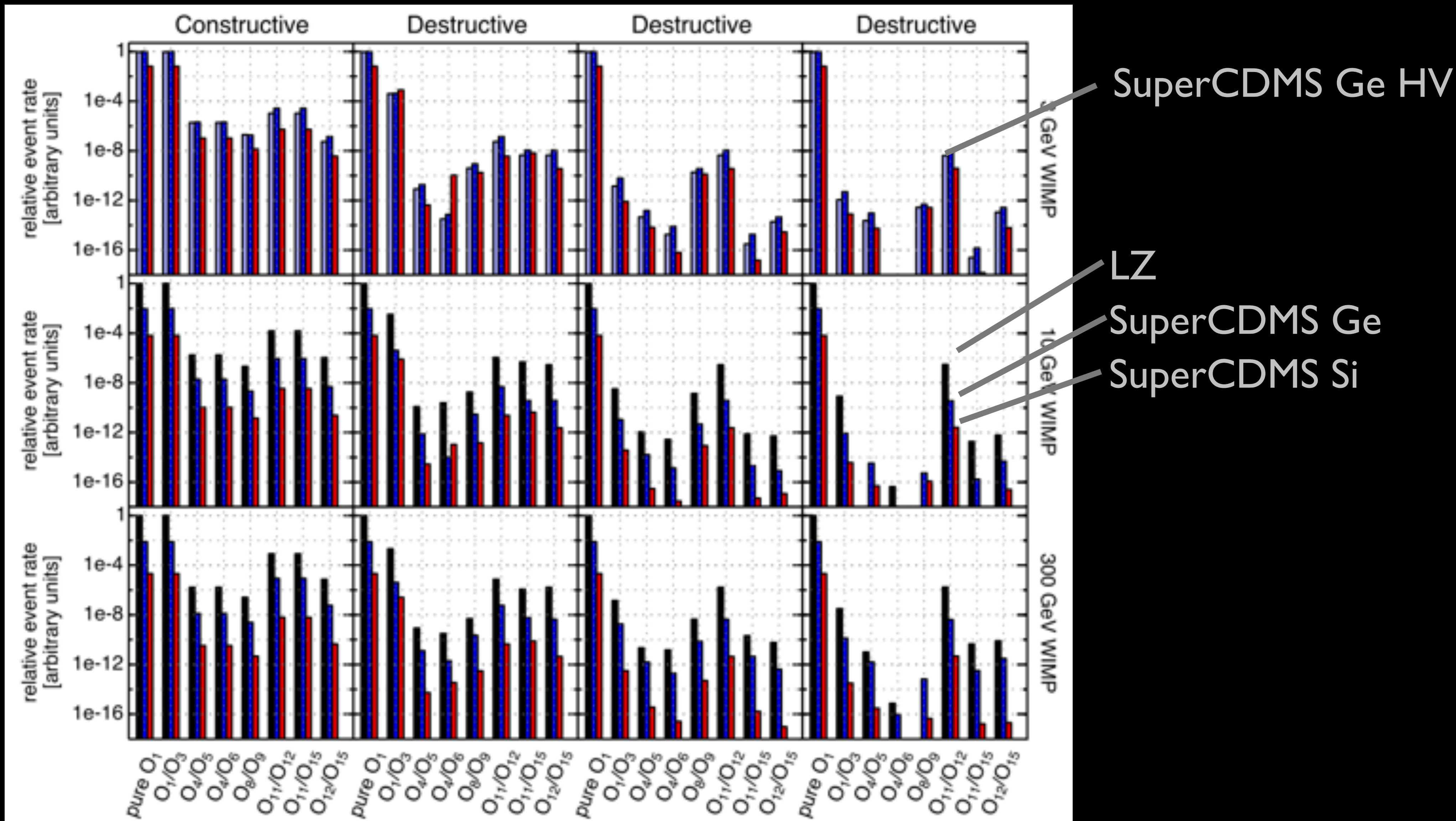


Operator coefficient	SuperCDMS Soudan
$(c_1^0)^2 * m_{weak}^4$	8.98×10^{-5} (—)
$(c_3^0)^2 * m_{weak}^4$	3.14×10^{4} (—)
$(c_4^0)^2 * m_{weak}^4$	8.77×10^{1} (—)
$(c_5^0)^2 * m_{weak}^4$	6.34×10^{5} (—)
$(c_6^0)^2 * m_{weak}^4$	4.54×10^{8} (—)
$(c_7^0)^2 * m_{weak}^4$	8.44×10^{7} (—)
$(c_8^0)^2 * m_{weak}^4$	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} (—)

All particle physics models

… and sensitivity of different targets

Schneck et al (SuperCDMS) 3/11/2015

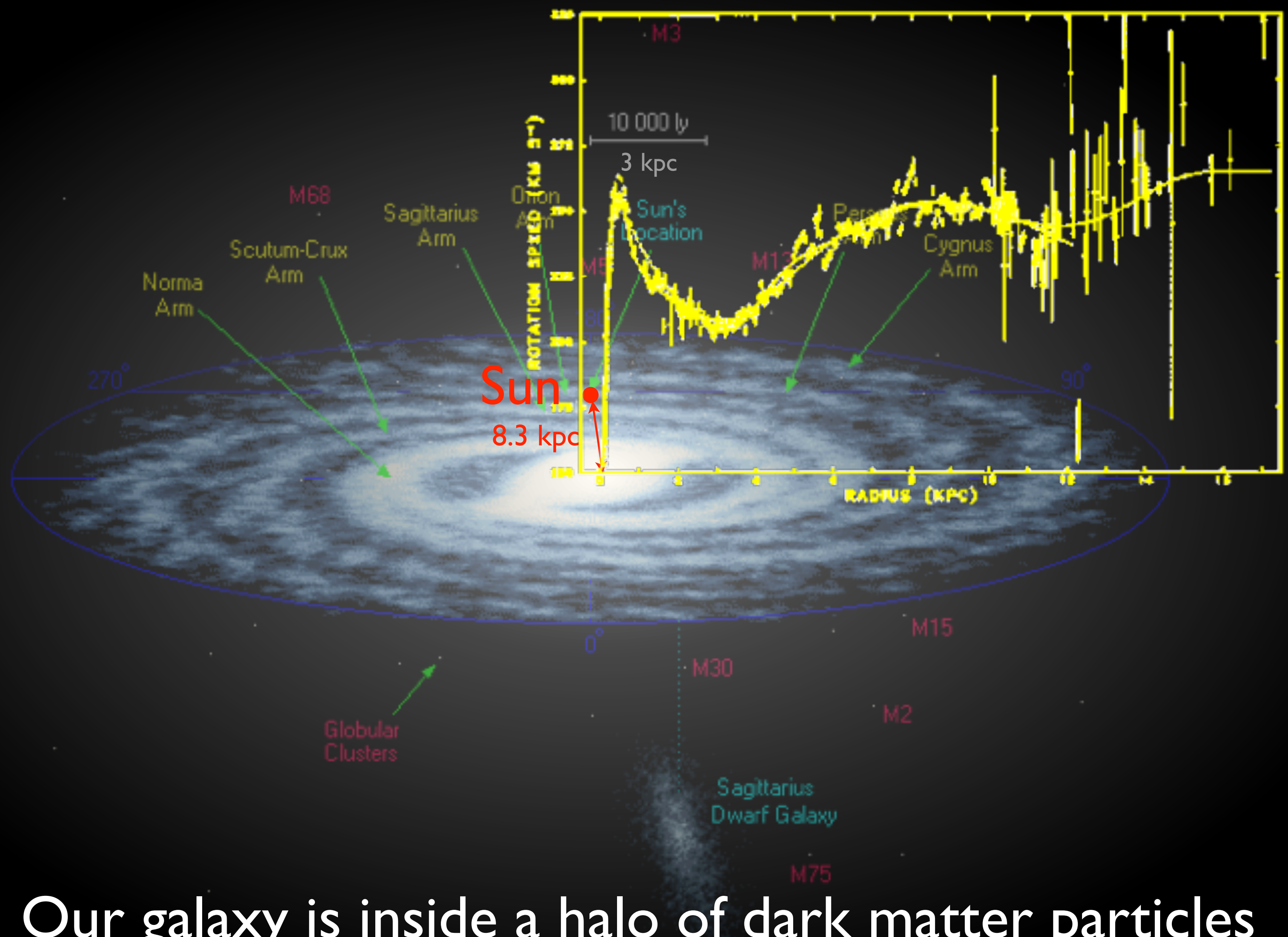


Astrophysics-independent approach

Compare experiments without assuming a local WIMP density or velocity distribution

Astrophysics model

Rotation curve (Clemens 1985)

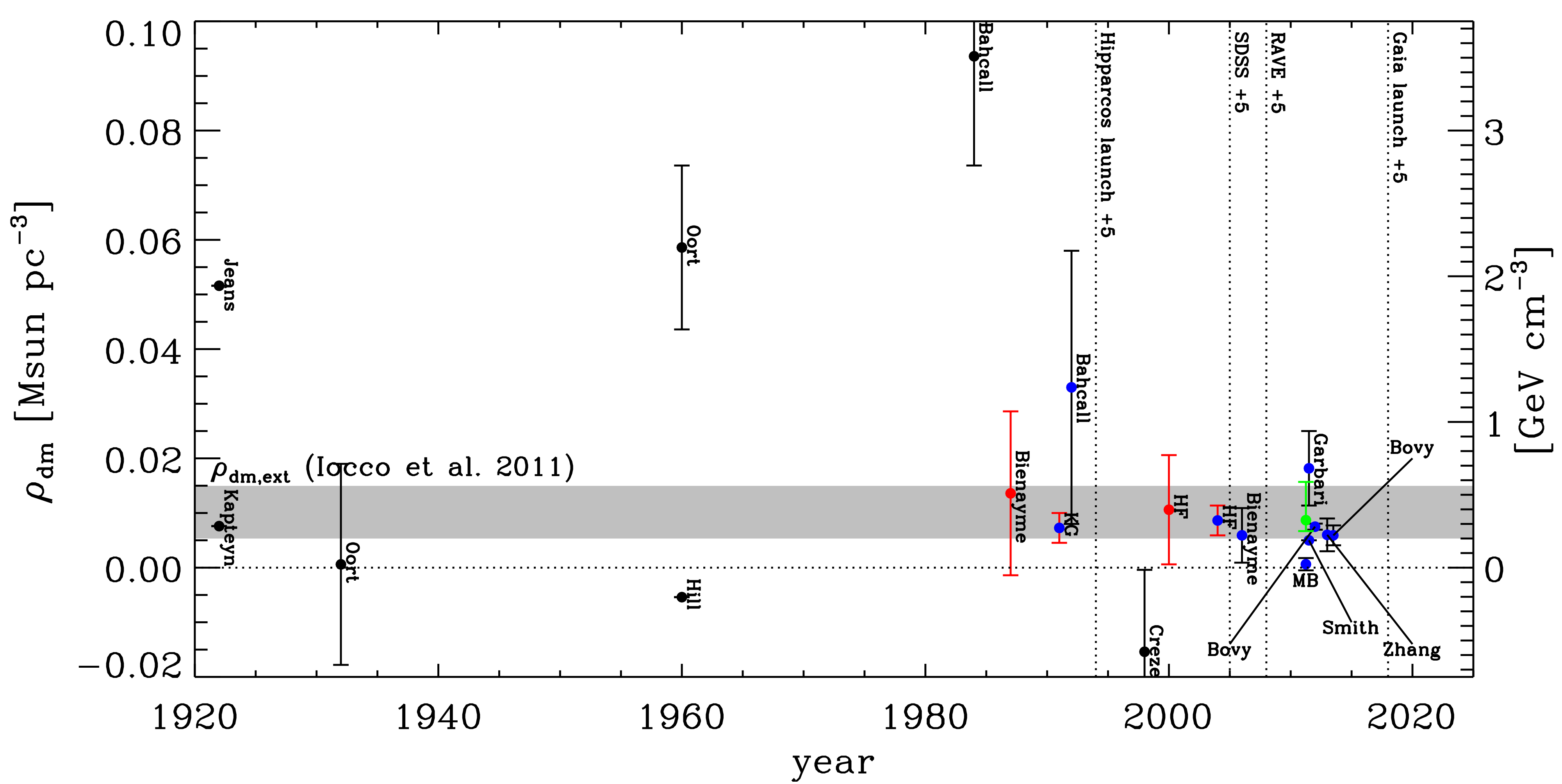


Our galaxy is inside a halo of dark matter particles

1 kpc = 2.06×10^{11} AU

Image by R. Powell using DSS data

Astrophysics model: local density



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

[volume complete; G12*;R14]

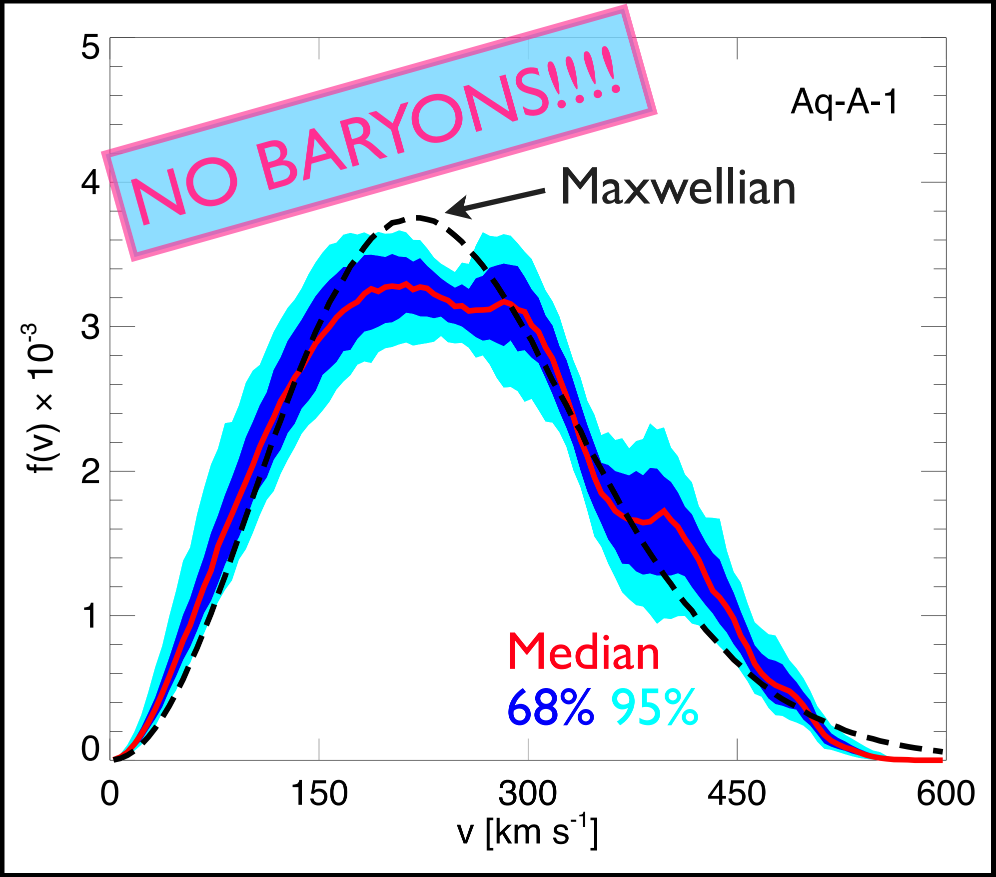
$$\rho_{\rm dm} = 0.25 \pm 0.09\,{\rm GeV\,cm^{-3}}$$

[SDSS; Z13]

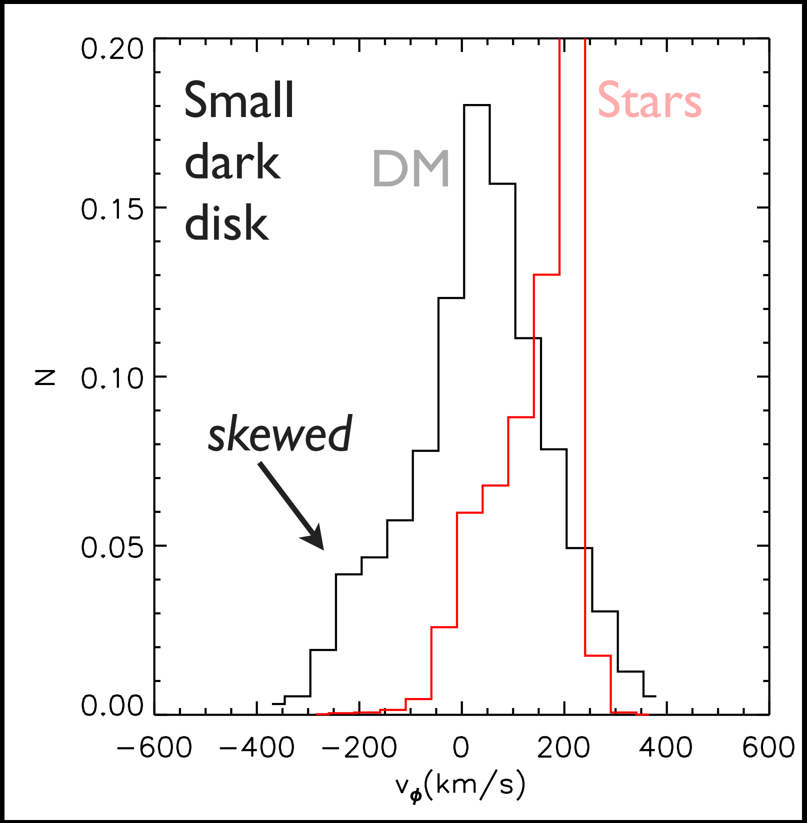
Read at IDM 2014

Astrophysics model: velocity distribution

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



Vogelsberger et al 2009

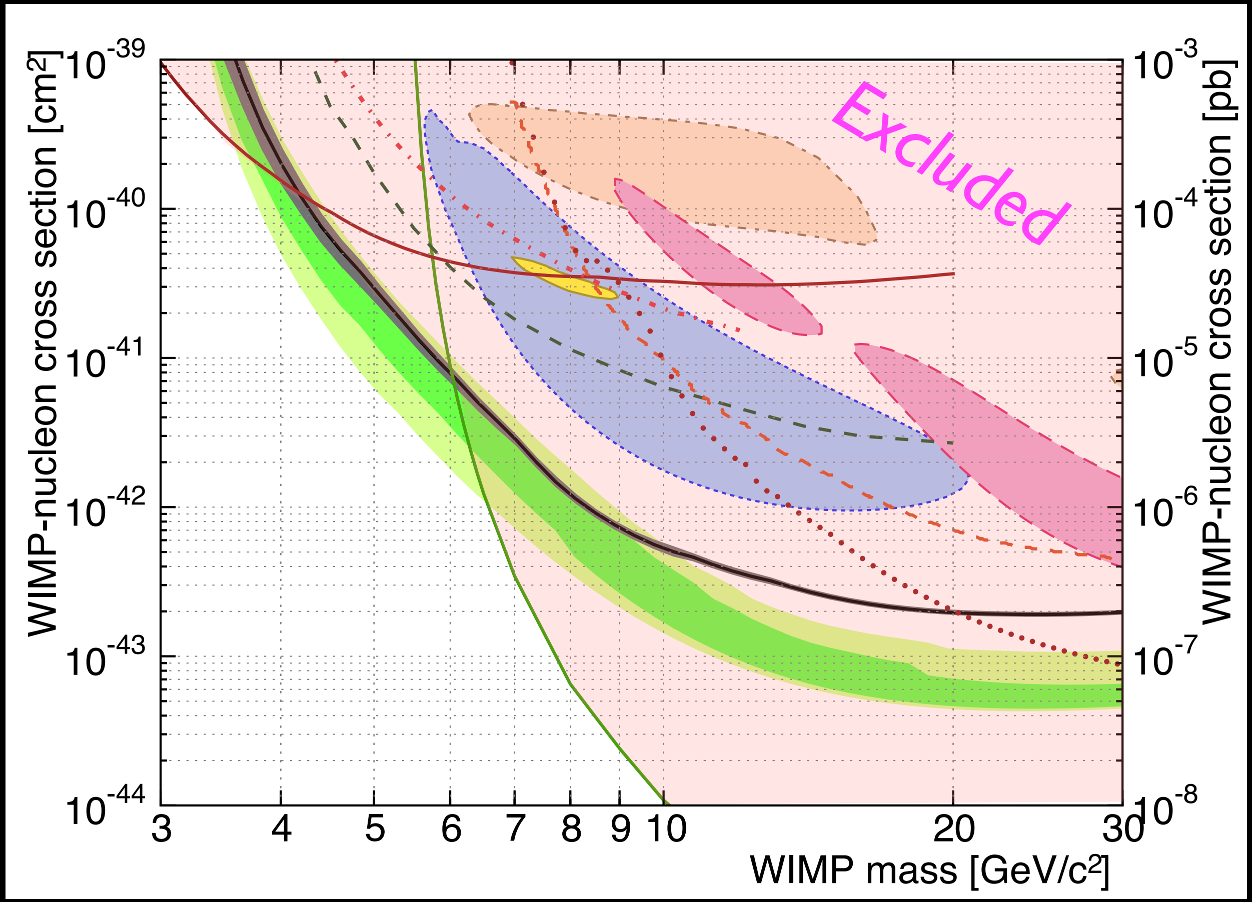


Read et al 2009

Cosmological N-Body simulations including baryons are challenging

The usual approach

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



Agnese et al (SuperCDMS) 2014

Astrophysics-independent approach

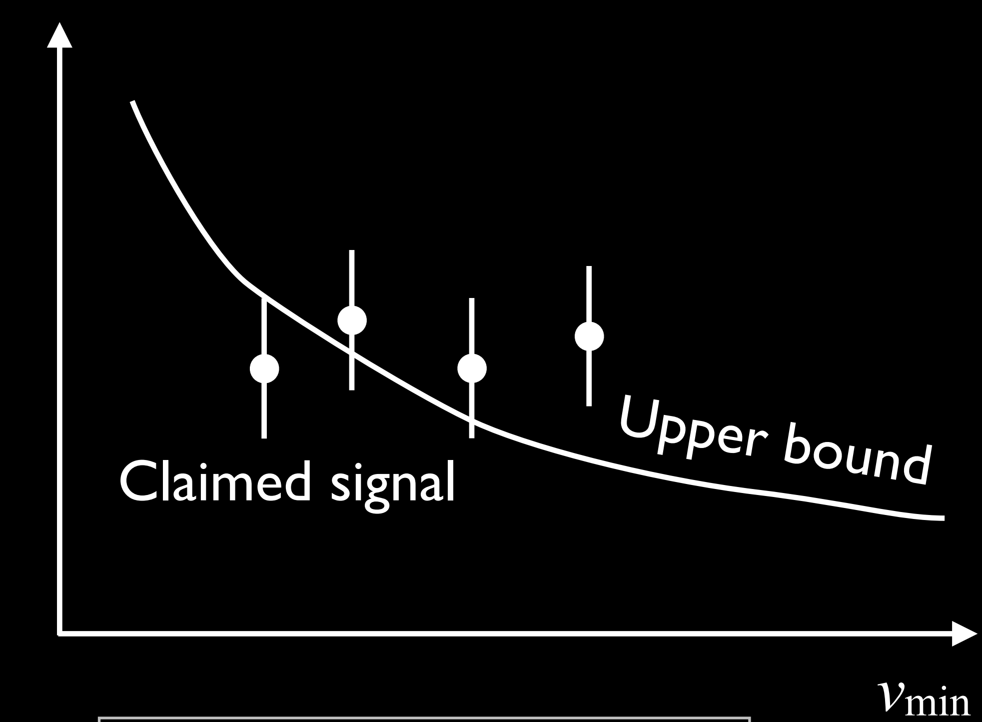
$$\begin{pmatrix}\text{event}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} \times \boxed{\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix}} \times \boxed{(\text{astrophysics})}$$

FIXED

ARBITRARY

Rescaled astrophysics factor common to all experiments

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



Minimum WIMP speed to impart recoil energy E_R

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

Astrophysics-independent approach

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

FIXED ARBITRARY

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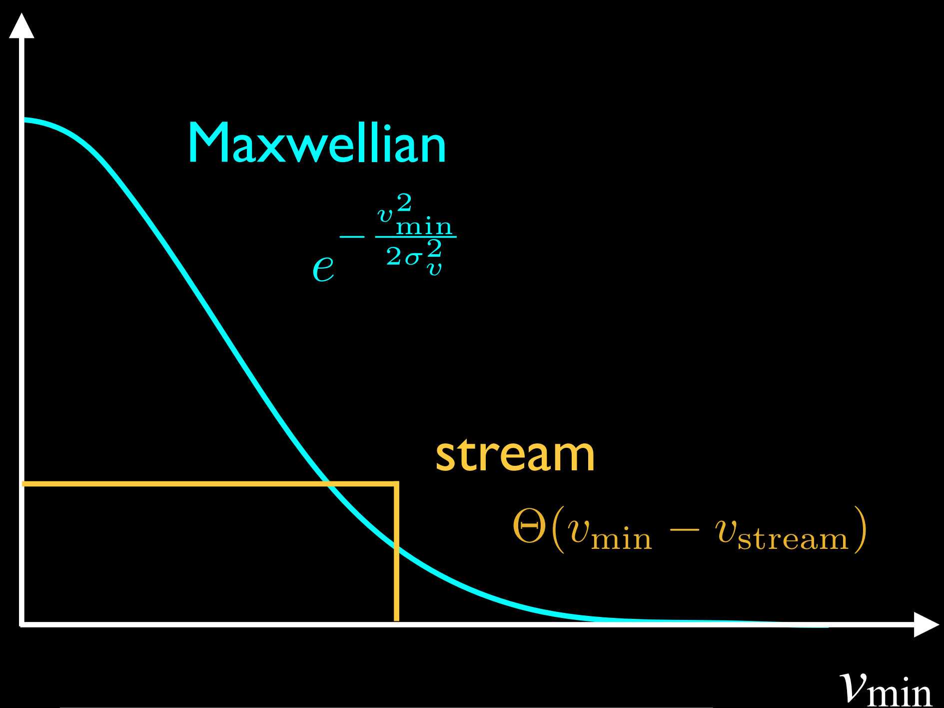


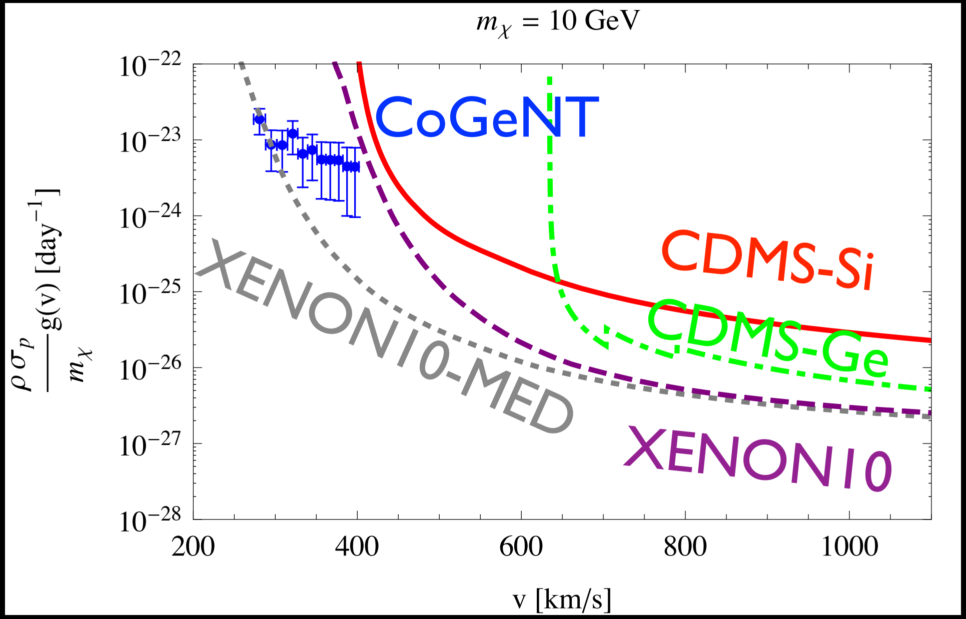
Minimum WIMP speed to impart recoil energy E_R

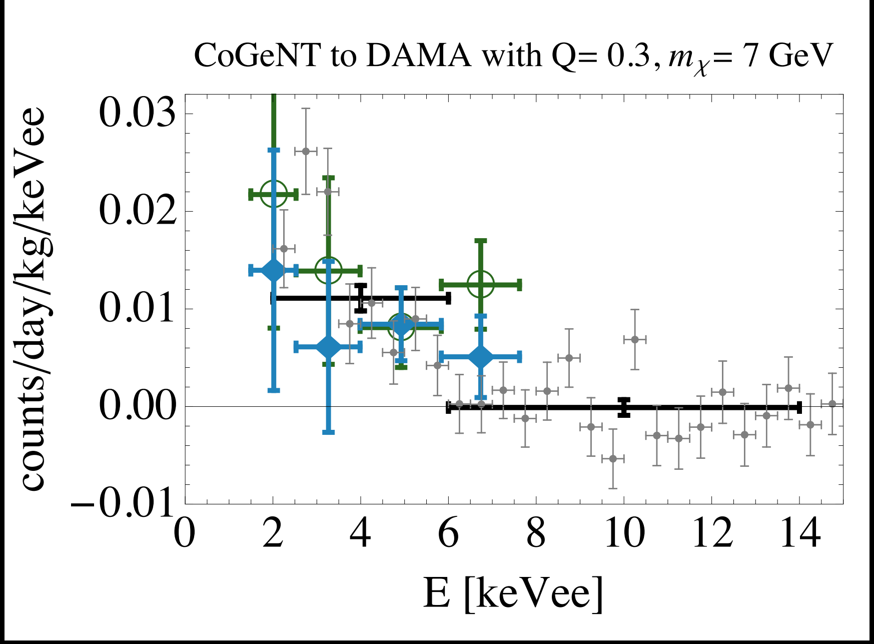
Fox, Liu, Wiener 2011; Gondolo, Gelmini 2012; Del Nobile, Gelmini, Gondolo, Huh 2013-14

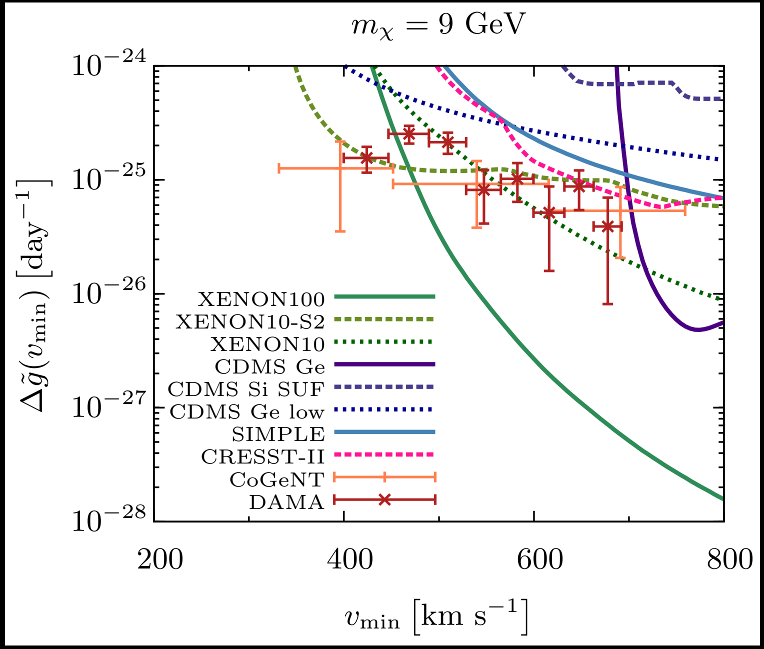
Astrophysics-independent approach

Fox, Liu, Weiner 2011

Original idea referred 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.







Fox, Kopp, Lisanti, Weiner 2011

Frandsen et al 2011

Astrophysics-independent approach

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

Gondolo Gelmini 2012

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

Measured energy

Effective energy response function

Recoil energy

Astrophysics-independent approach

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

Gondolo Gelmini 2012

Change variables:

Constant reference cross section

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

Minimum WIMP speed to impart recoil energy E_R

Astrophysics factor, same for all direct detection experiments

And integrate over measured energy intervals:

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

Astrophysics-independent approach

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

Gondolo Gelmini 2012

- 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

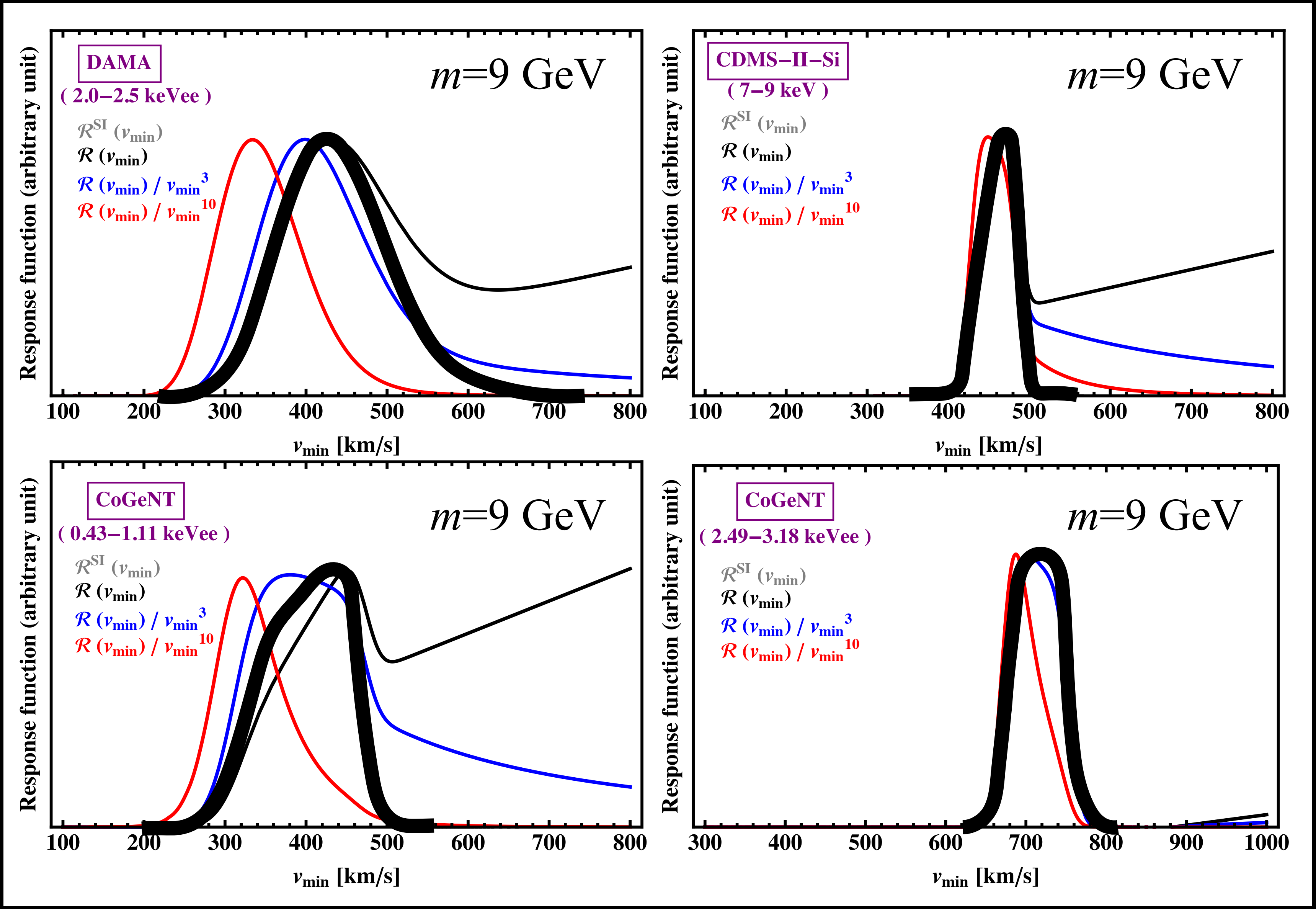
- Every experiment is sensitive to a "window in velocity space" given by the response function.

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

Astrophysics-independent approach

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

Del Nobile, Gelmini, Gondolo, Huh 2013



Astrophysics-independent approach

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

Gondolo Gelmini 2012

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

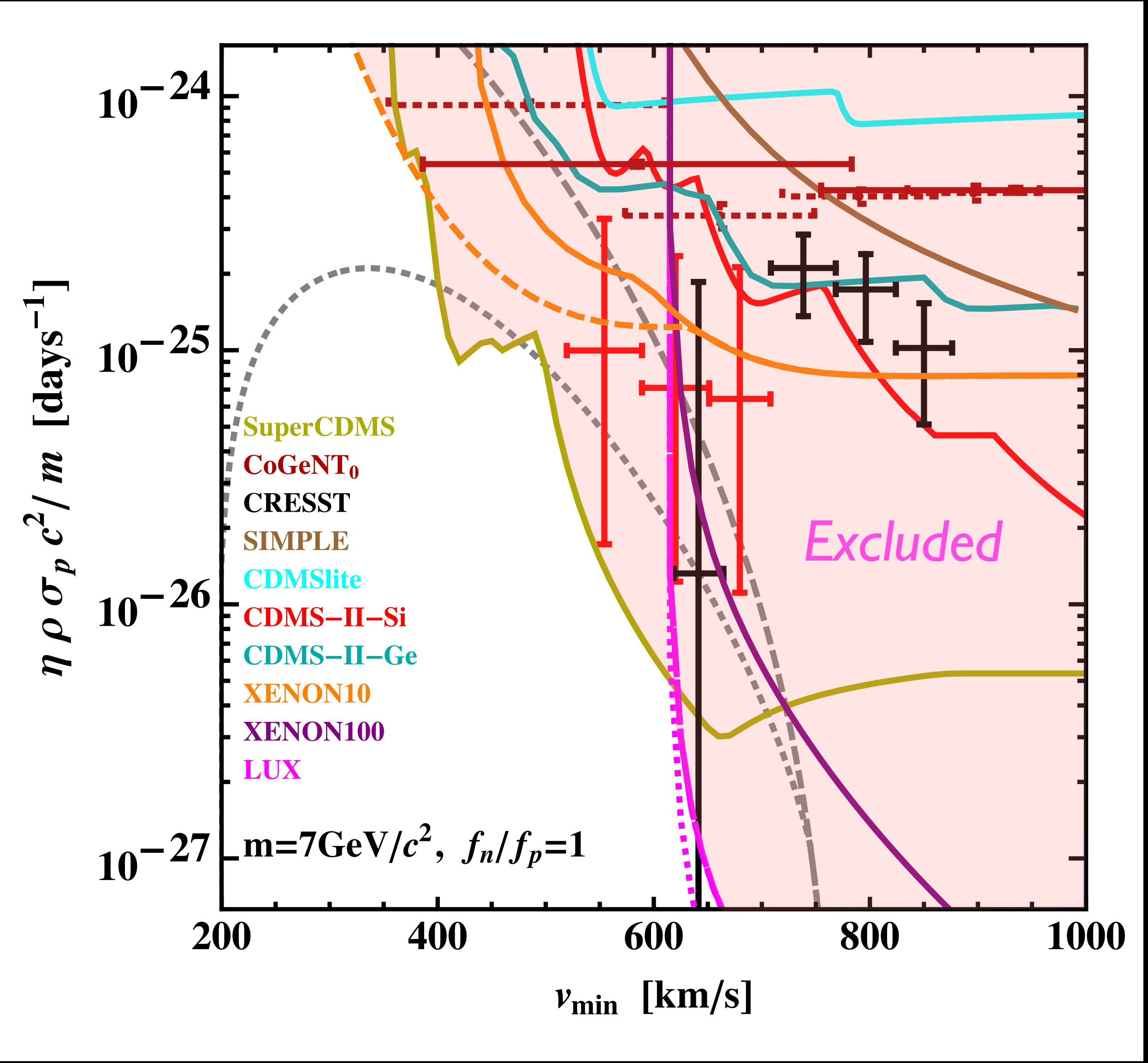
$$\bar{\tilde{\eta}}_{[v_1,v_2]} = \frac{R^{\text{measured}}_{[E_1,E_2]}}{\int_0^\infty \mathcal{R}_{[E_1,E_2]}(v_{\min})\, dv_{\min}}$$

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

Spin-independent isoscalar interactions

$$\sigma_{\chi A} = A^2 \sigma_{\chi \mathrm{p}} \mu^2_{\chi A} / \mu^2_{\chi \mathrm{p}}$$

Astrophysics-independent approach



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

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

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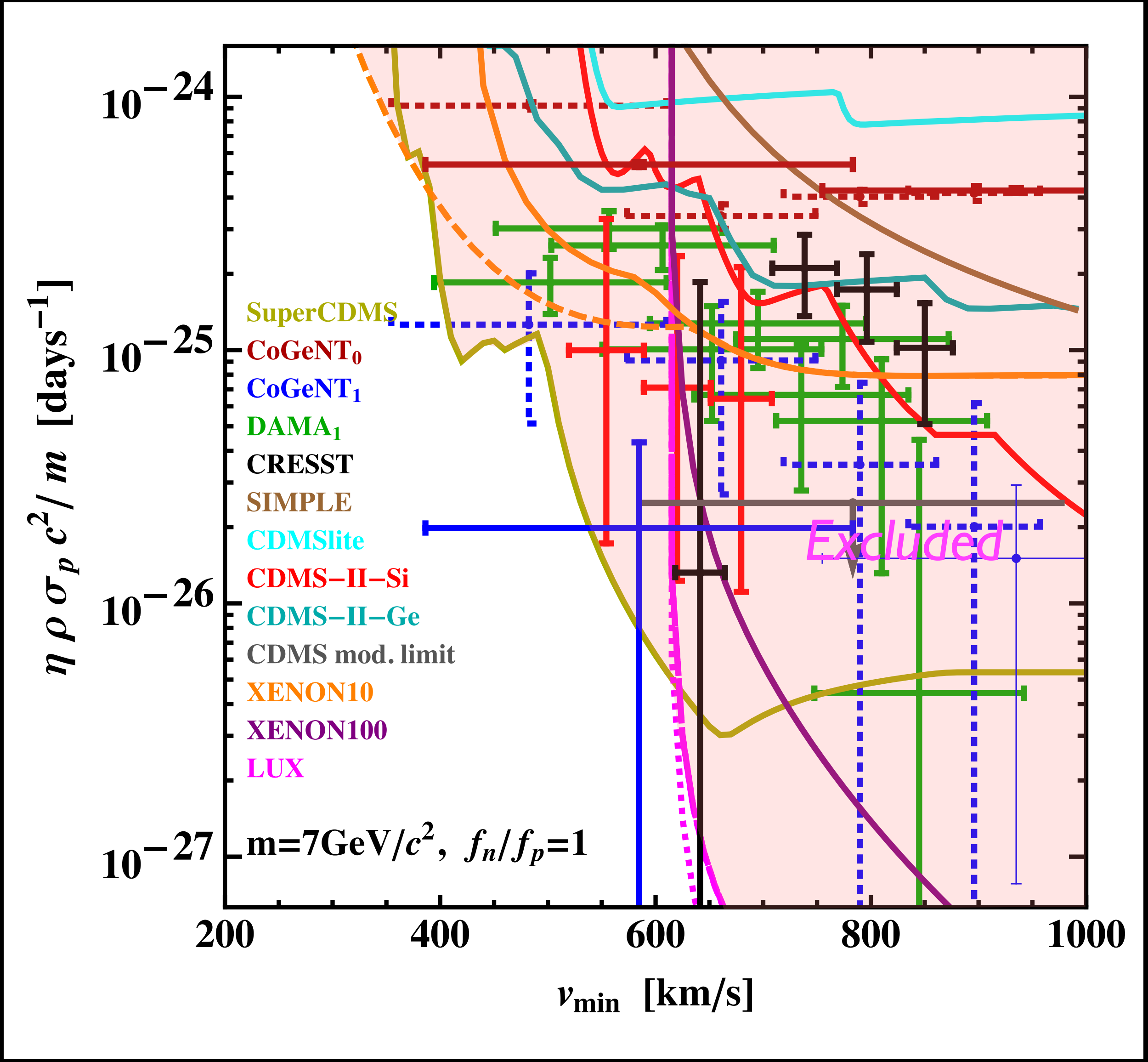


Halo modifications alone cannot save the SI signal regions from the Xe and Ge bounds

CDMS-Si event rate is similar to yearly modulated rates

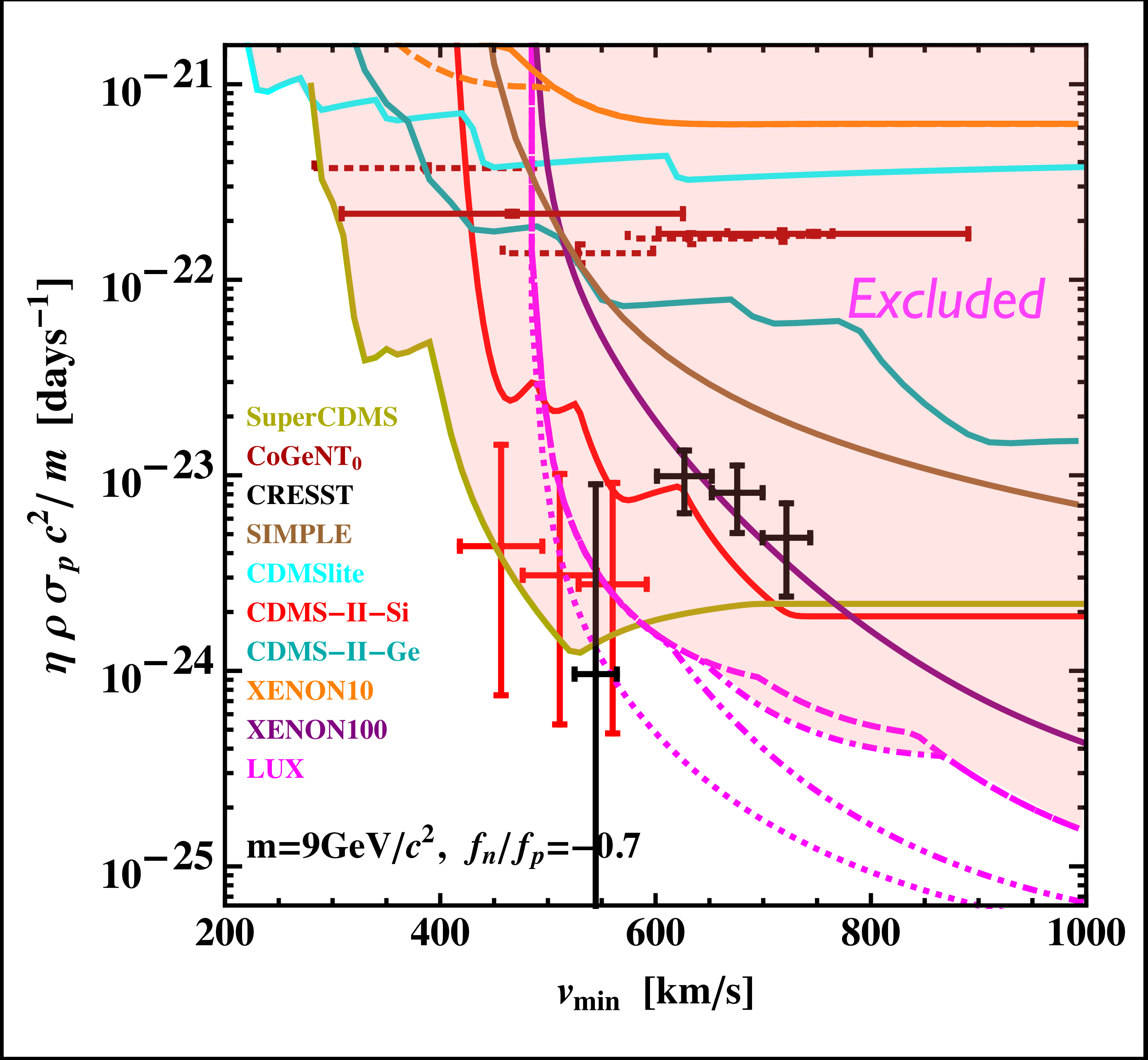
Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

Spin-independent nonisoscalar interactions

$$\sigma_{\chi A} = \left[Z + (A - Z)\frac{f_n}{f_p} \right]^2 \frac{\sigma_{\chi \mathrm{p}} \mu_{\chi A}^2}{\mu_{\chi \mathrm{p}}^2}$$

Astrophysics-independent approach



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

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

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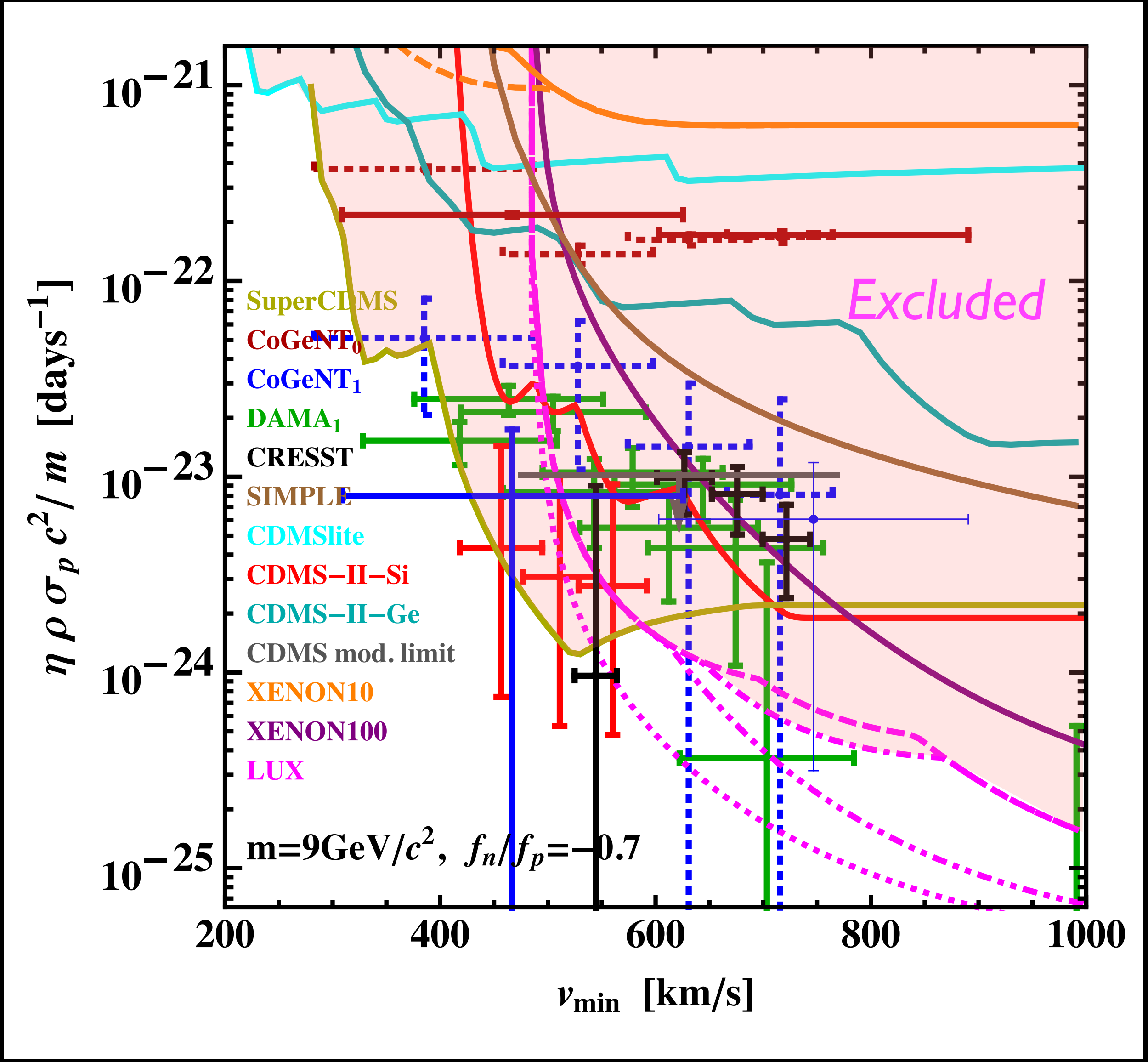


Dark matter coupled differently to protons and neutrons may have a slim chance

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

Still depends on particle model

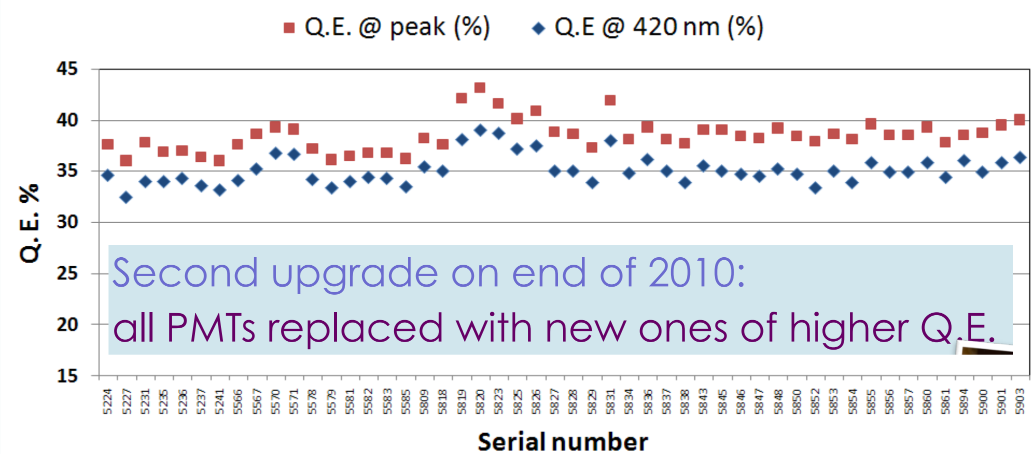
Del Nobile, Gelmini, Gondolo, Huh 2014

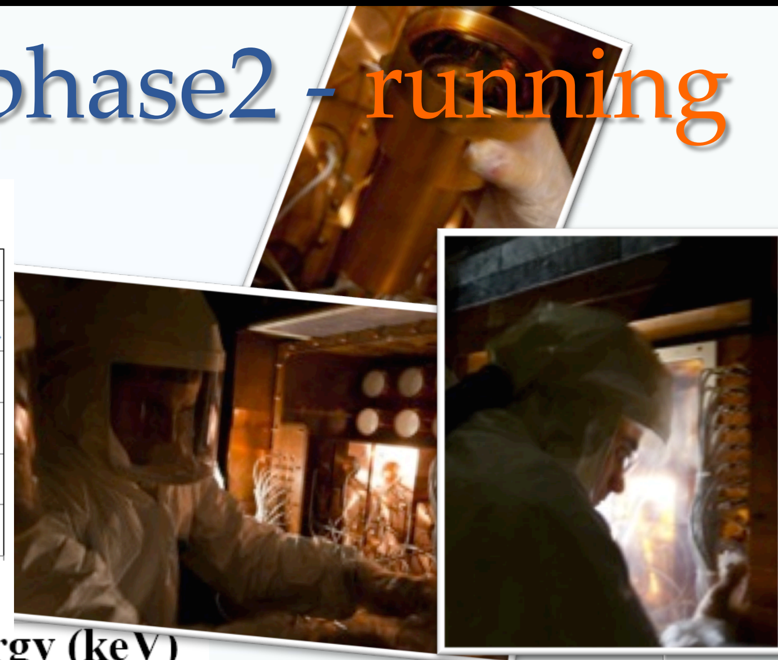
In the next episodes

In the next episodes..... Revenge

DAMA/LIBRA phase2 - running

Quantum Efficiency features



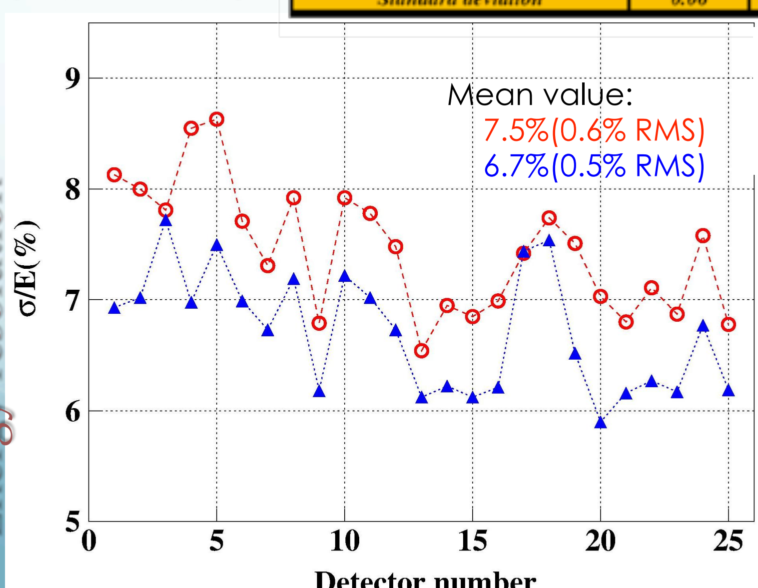


Residual Contamination

The limits are at 90% C.L.

PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
Average			*0.43*	*-*	*47*	*0.12*	*83*	*0.54*	*-*	*-*
Standard deviation			*0.06*	*-*	*10*	*0,02*	*17*	*0.16*	*-*	*-*

Energy resolution



σ/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blu points) and with previous PMT EMI-Electron Tube (red points).

The light responses

Previous PMTs:	5.5-7.5 ph.e./keV
New PMTs:	up to 10 ph.e./keV

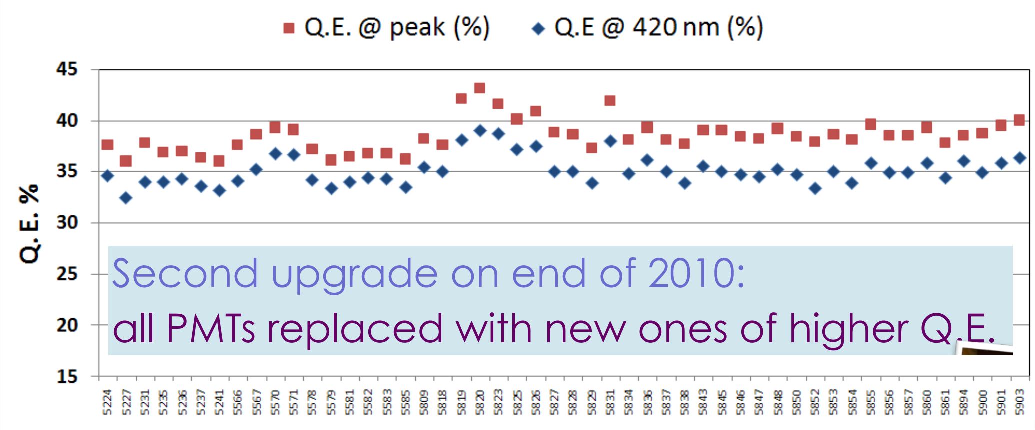
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

Belli, IDM2014

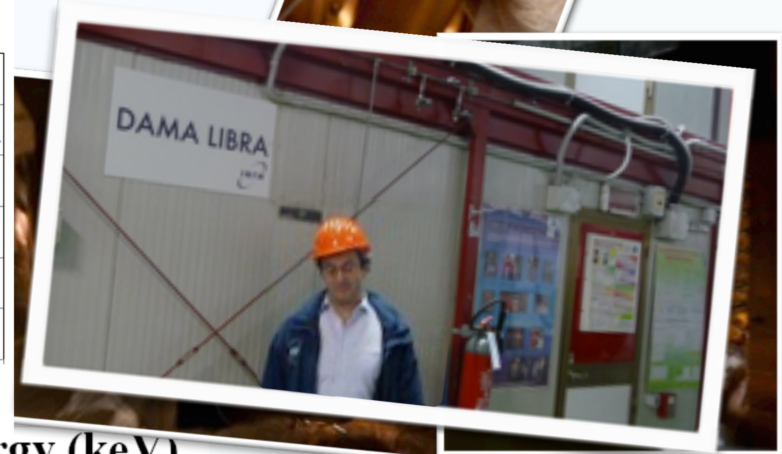
In the next episodes..... Revenge

DAMA/LIBRA phase2 - running

Quantum Efficiency features



Second upgrade on end of 2010:
all PMTs replaced with new ones of higher Q.E.



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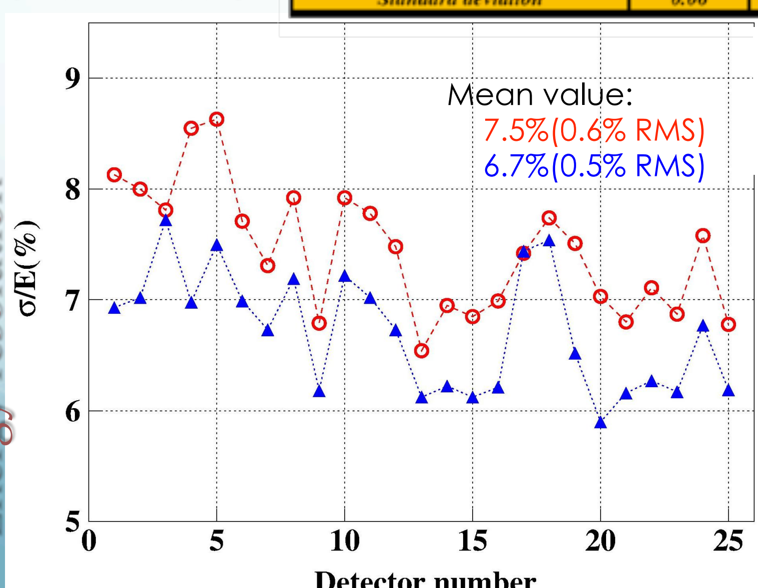

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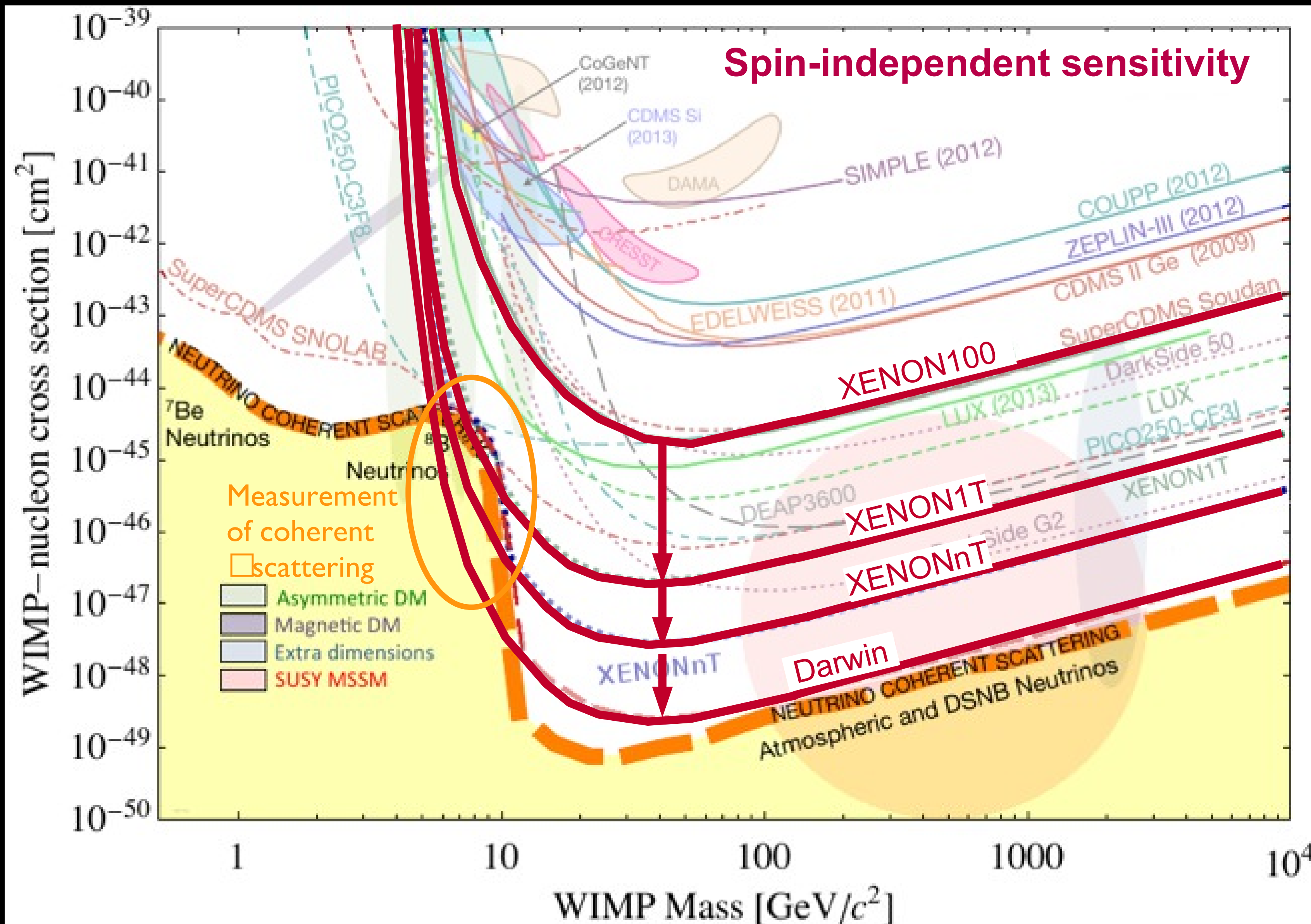
Belli, IDM2014

In the next episodes..... Giant detectors

SuperCDMS, XENON1T, XENONnT, Darwin, ...



Oberlack, IDM2014

In the next episodes..... All interactions

WIMP-nucleus effective theory

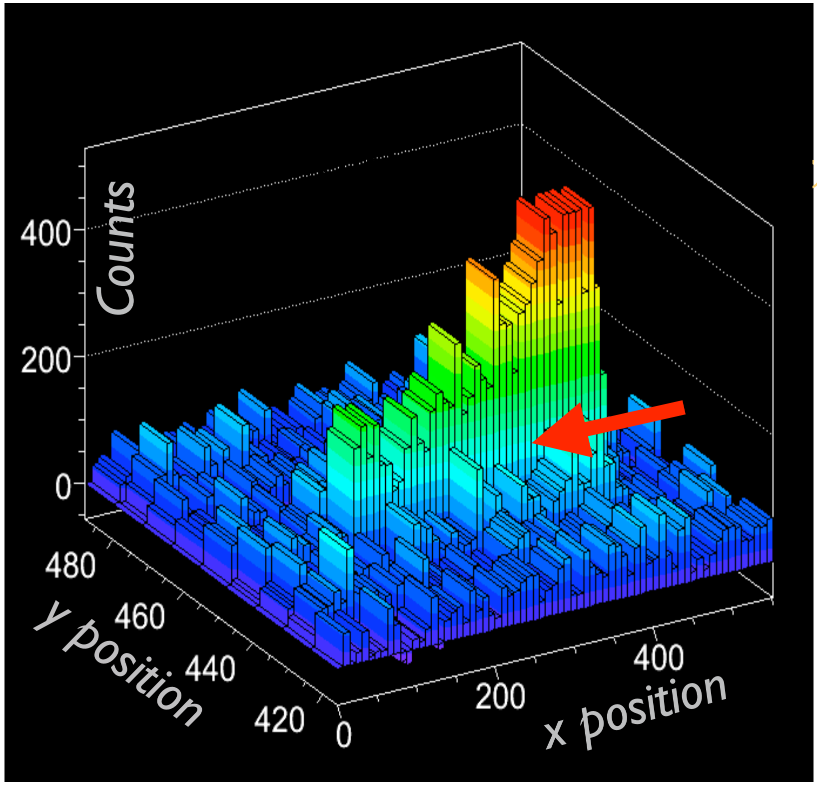
- Analyze all WIMP-nucleus currents in the spirit of the 1960's analysis of weak currents (Haxton)

- Velocity- and momentum-dependent operators

- Expected developments
  - long-distance operators
  - improved nuclear physics
  - improved comparison to data
  - astrophysics-independent analysis

In the next episodes..... WIMP astronomy

- Directional direct detection
  - measure direction of nuclear recoil
- Several R&D efforts
  - DRIFT
  - Dark Matter TPC
  - NEWAGE
  - MIMAC
  - D3
  - Emulsion Dark Matter Search
  - Columnar recombination



DMTPC

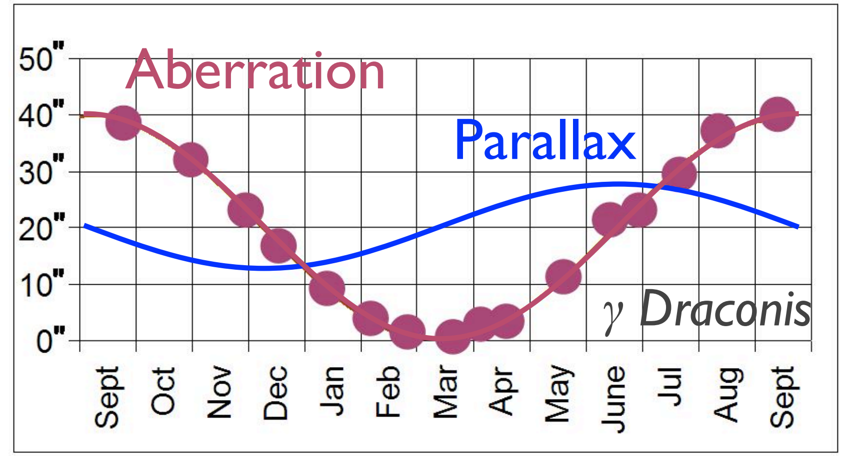
Only ~10 events needed to confirm extraterrestrial signal

In the next episodes..... WIMP astronomy

Aberration of WIMPs

Photon arrival direction

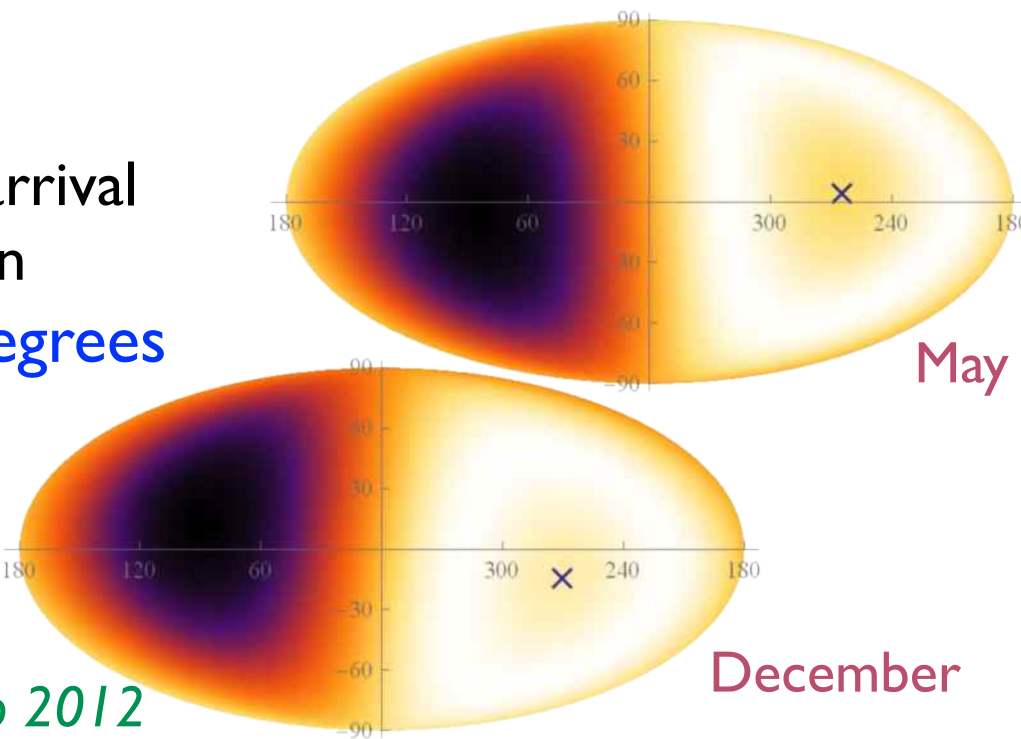
20 arcsec



Bradley 1725

WIMP arrival direction

10 degrees



Bozorgnia, Gelmini, Gondolo 2012

Synopsis

- Fifty shades of dark
  - *WIMPs are testable candidates for cold dark matter*
- The forbidden fruit
  - *WIMP interaction rates in direct searches are very small.*
  - *No bananas in the lab.*
- Confusion of the mind
  - *Some experiments claim WIMP detection while others exclude it.*
- Treason and murder
  - *Analysis of CoGeNT's public data disagrees with official result.*
  - *Improved CRESST-II data reject previous CRESST excess.*
- That which does not kill us makes us stronger
  - *Move to consider all possible WIMP-nucleus currents.*
  - *Do not assume any specific dark halo model.*