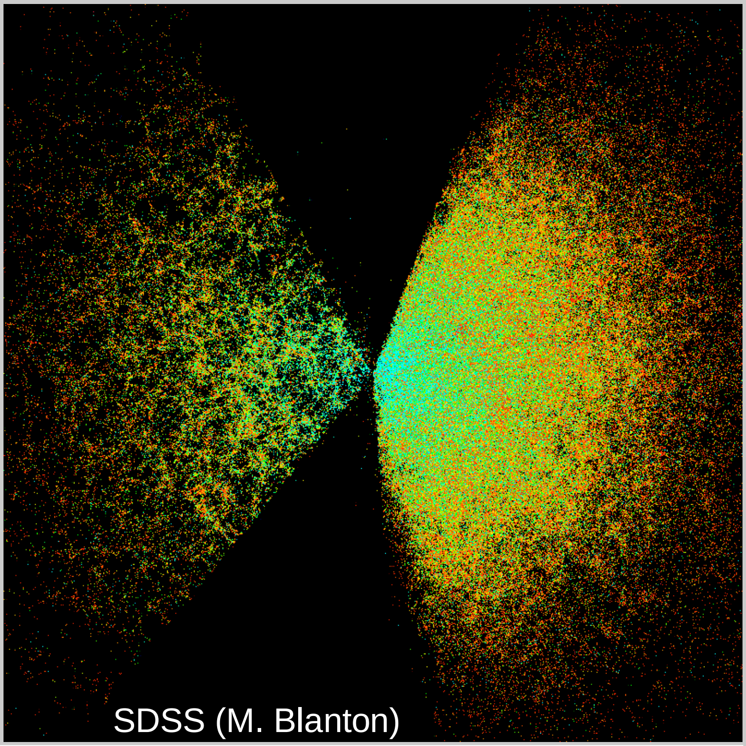
WIMP Dark Matter

Paolo Gondolo

University of Utah

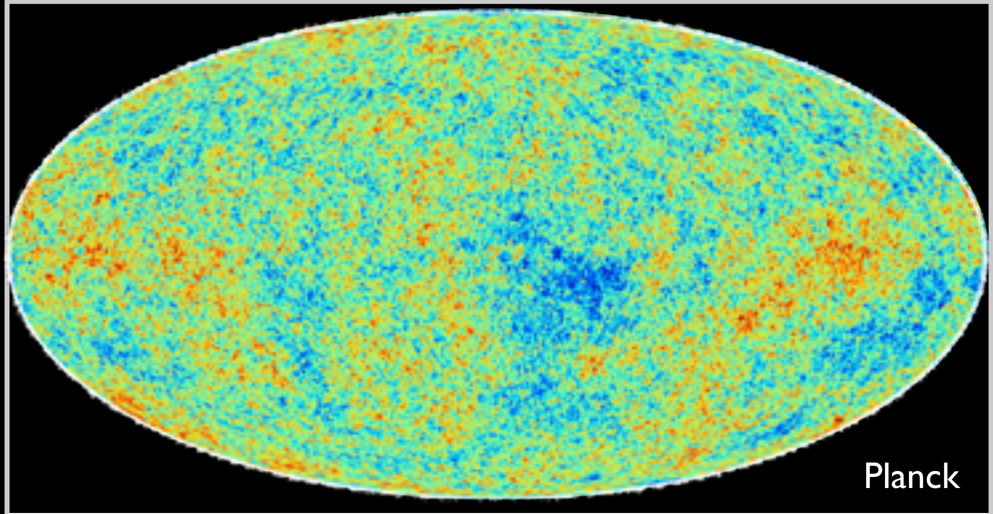
Evidence for *nonbaryonic cold* dark matter

Large Scale Structure



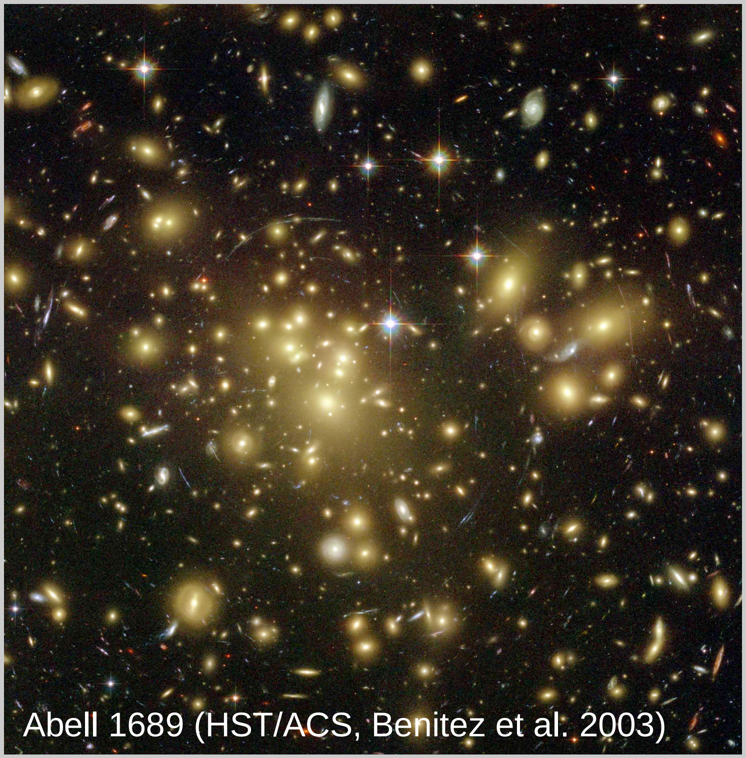
SDSS (M. Blanton)

Cosmic Microwave Background



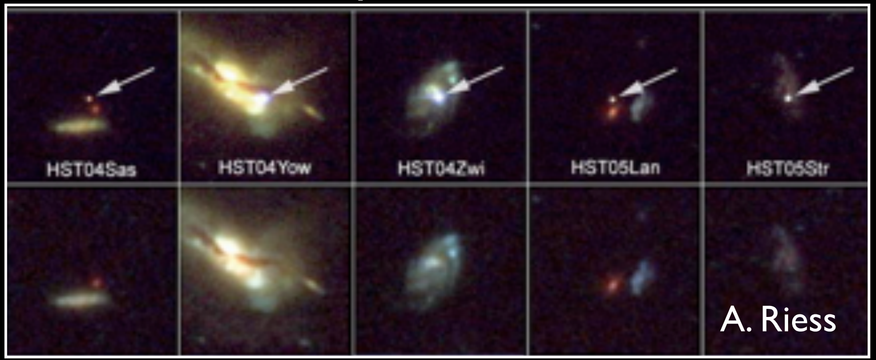
Planck

Galaxy Clusters

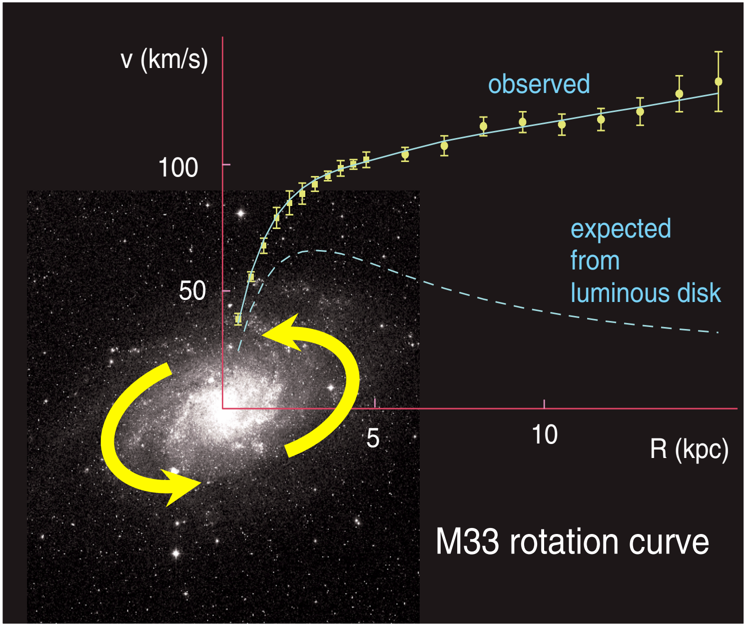


Abell 1689 (HST/ACS, Benitez et al. 2003)

Supernovae



A. Riess

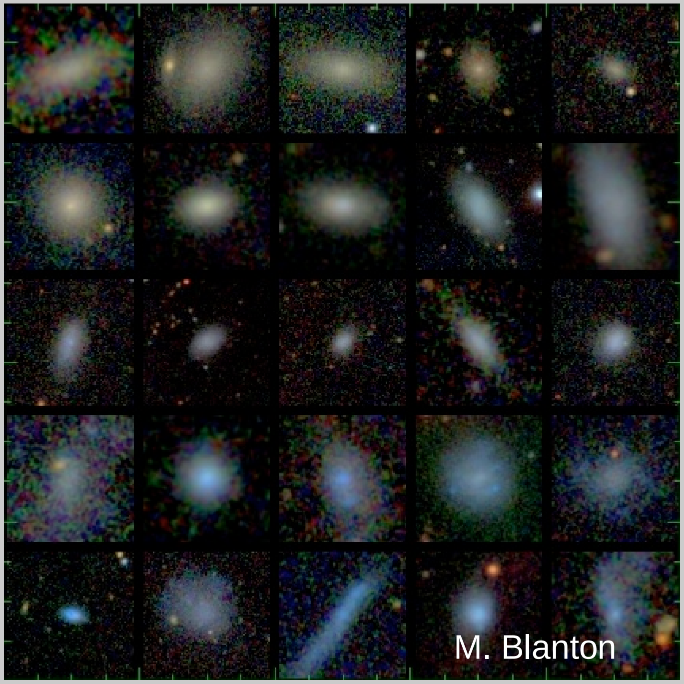


M33 rotation curve

Galaxies

M101 (HST, Kuntz et al. 2006)

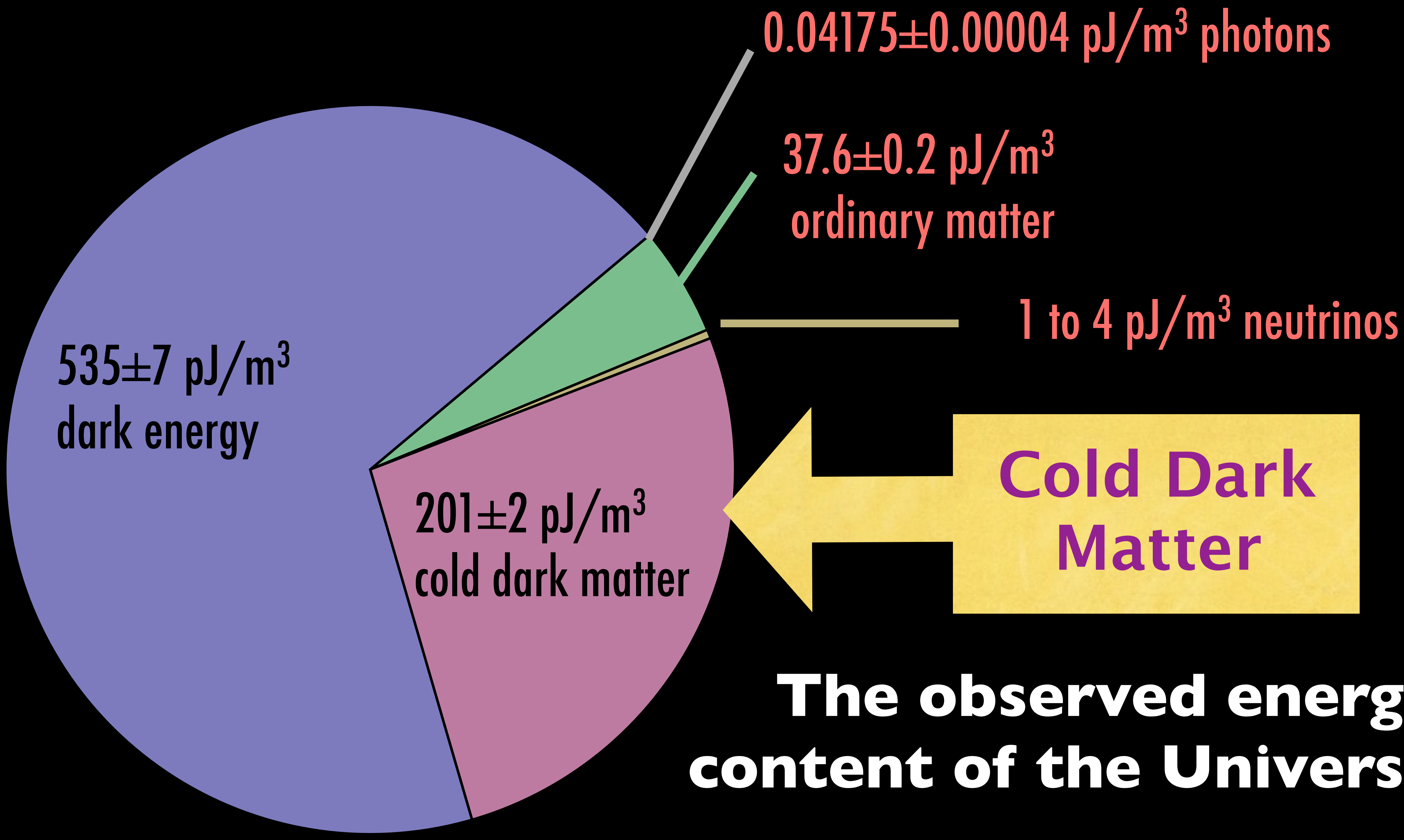
Dwarf Galaxies



M. Blanton

Markevitch et al. 2004,
Clowe et al. 2004

Evidence for *nonbaryonic cold* dark matter



Cold Dark Matter

The observed energy content of the Universe

matter $p \ll \rho$

radiation $p=\rho/3$

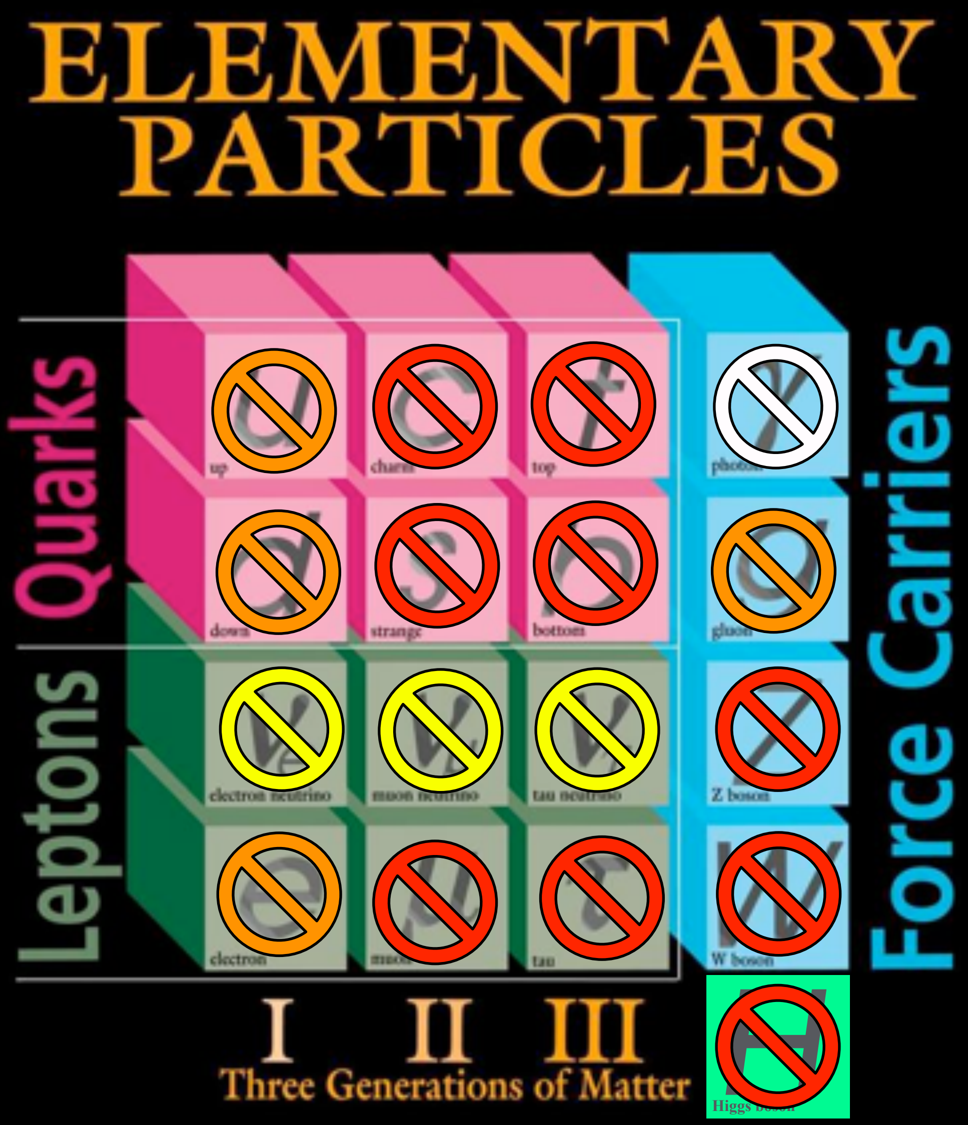
vacuum $p=-\rho$

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

1 pJ = 10^{-12} J

$\rho_{\rm crit}=1688.29\ h^2$ pJ/m^3

Is dark matter an elementary particle?



- 🚫 is the particle of light
- 🚫 couples to the plasma
- 🚫 disappears too quickly
- 🚫 is hot dark matter

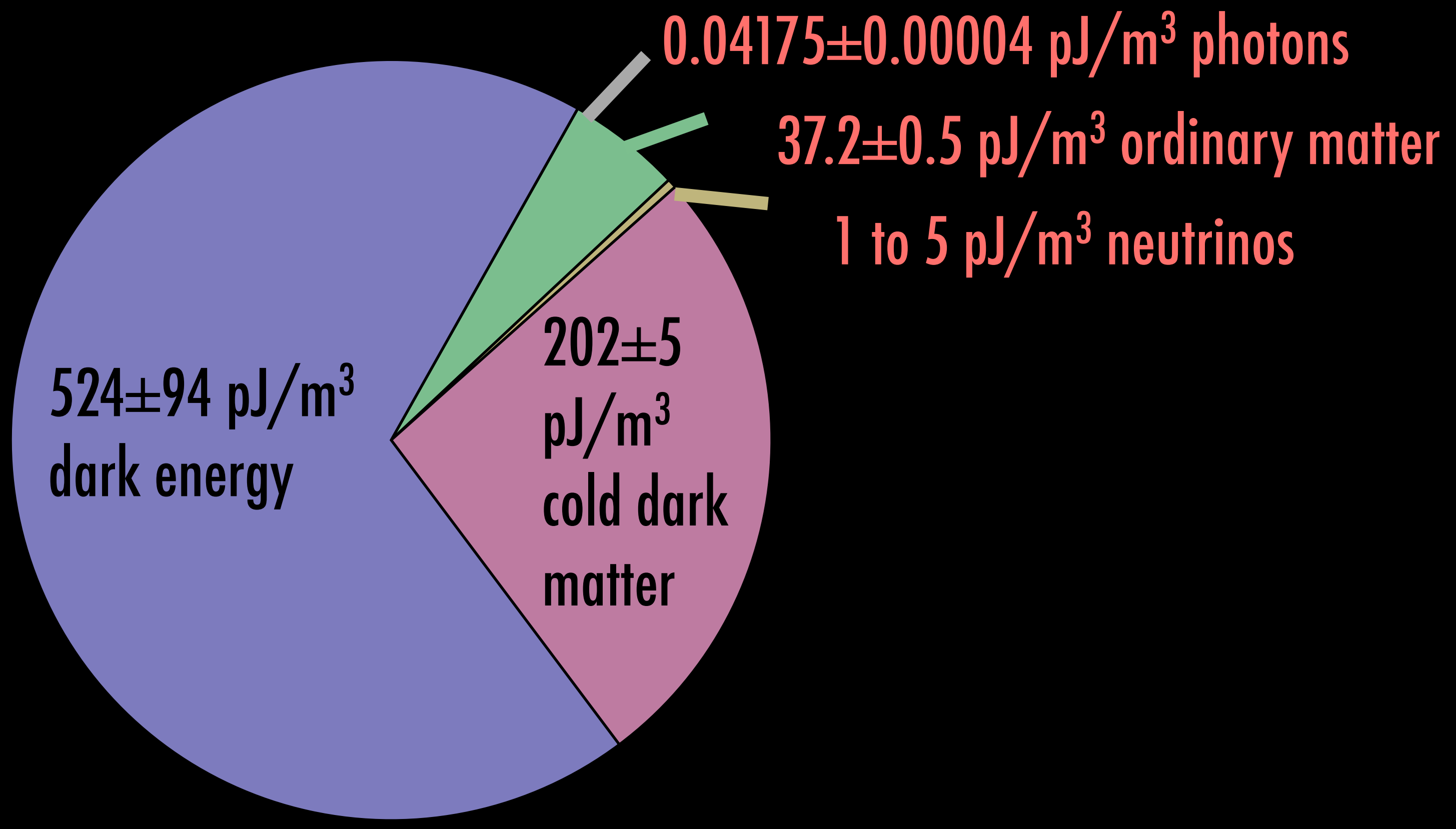
No known particle can be nonbaryonic cold dark matter!

The magnificent WIMP

(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

  Thermal production in hot primordial plasma.



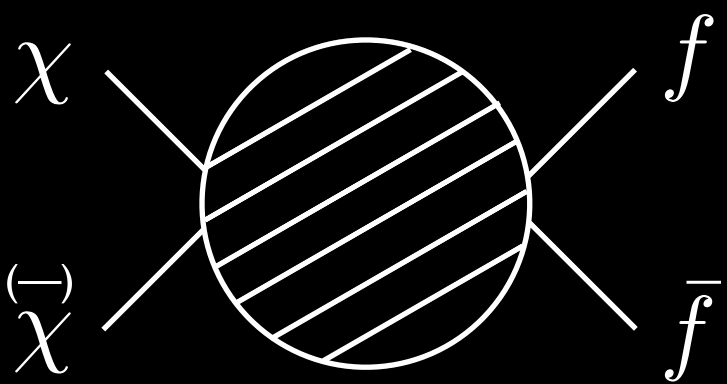
- One can experimentally test the WIMP hypothesis

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

Cosmic density of thermal WIMPs

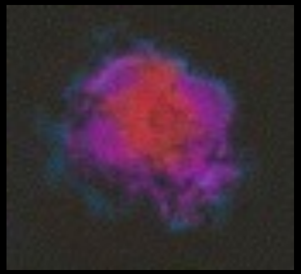
- At early times, WIMPs are produced in e^+e^-, $\mu^+\mu^-$, etc collisions in the hot primordial soup [*thermal production*].

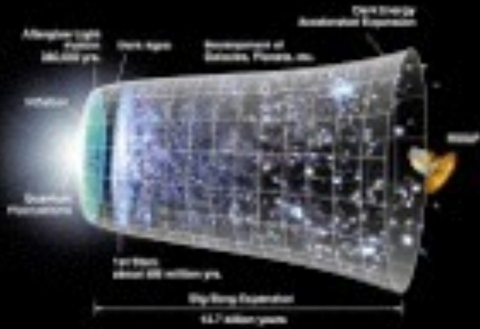
$$e^+ + e^-, \mu^+ + \mu^-, \text{etc.} \leftrightarrow \chi + \overset{(-)}{\chi}$$



- WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate [*freeze-out*].
- After freeze-out, there is a constant number of WIMPs in a volume expanding with the universe.

Indirect detection

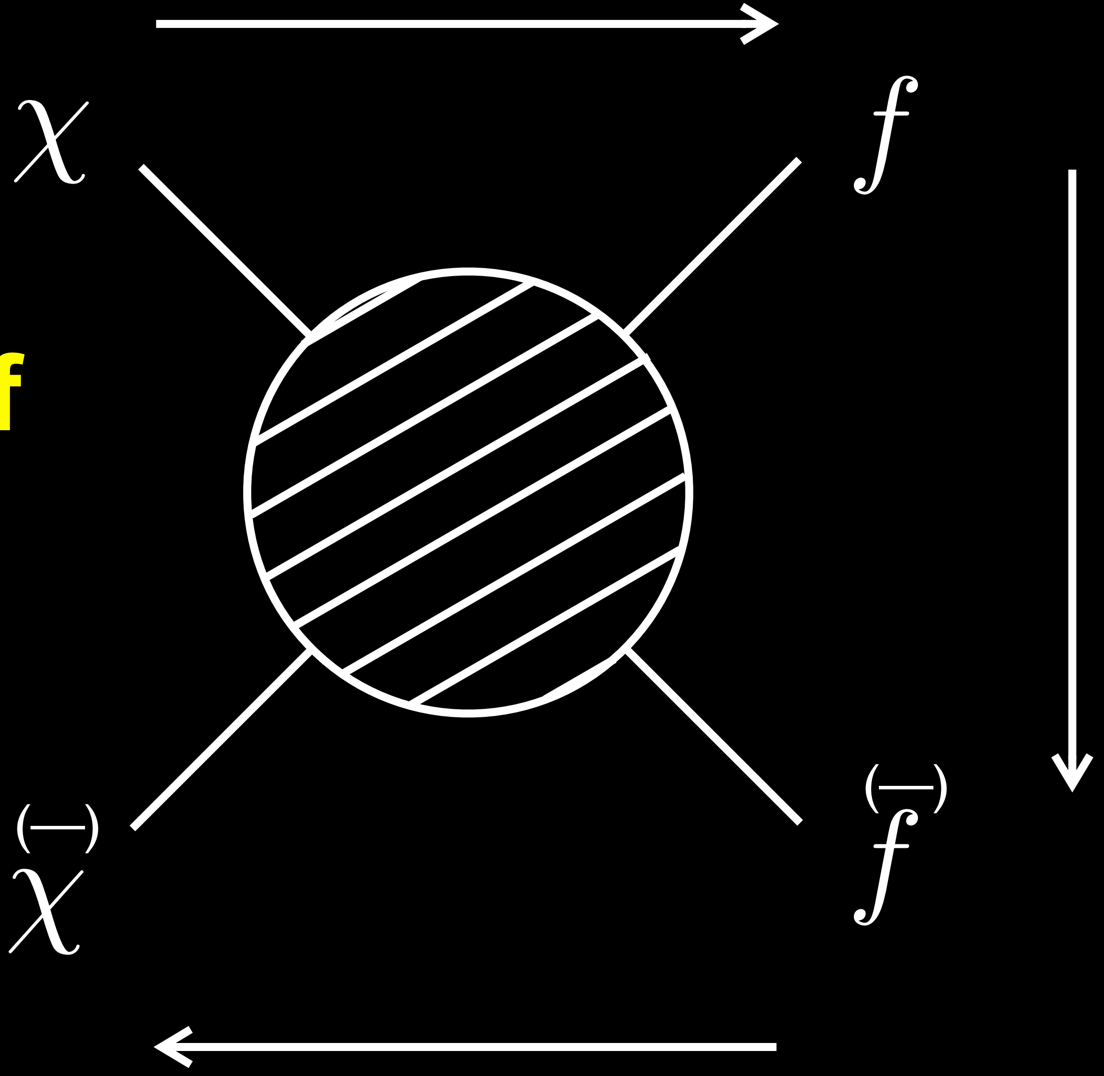




Cosmic density

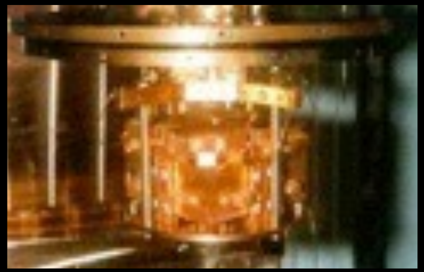
Annihilation

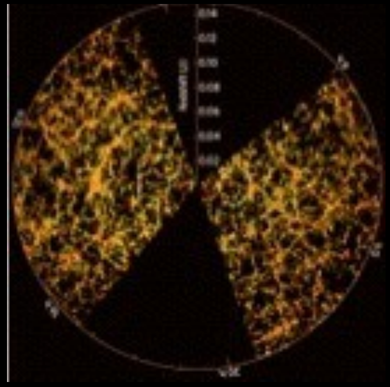
The power of the WIMP



Scattering

Direct detection

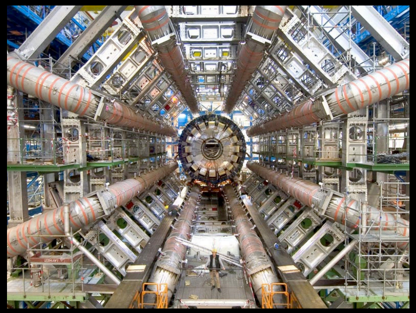


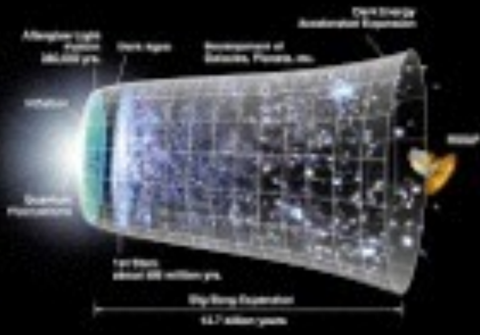


Large scale structure

Production

Colliders





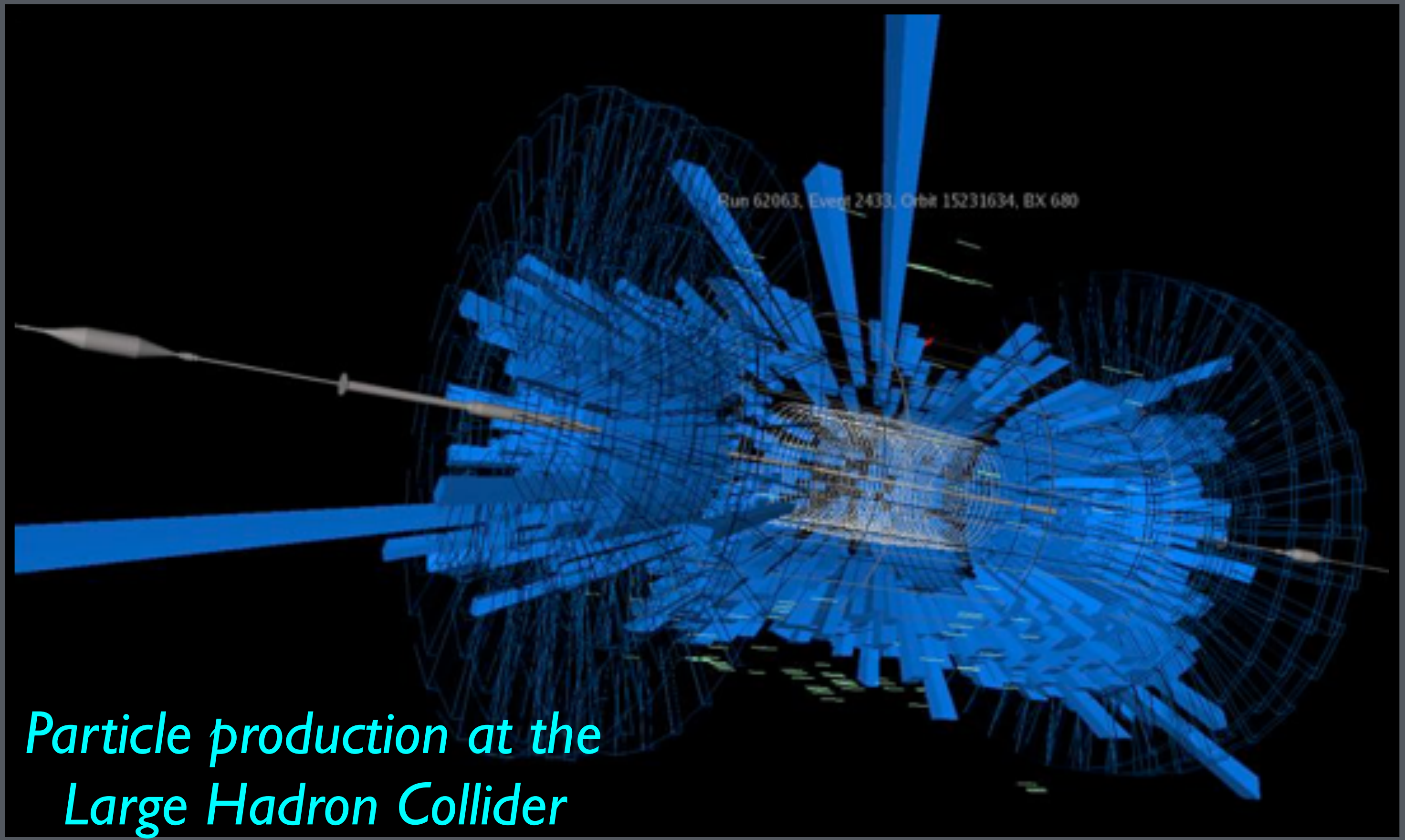
Cosmic density

Dark matter particles (or their "cousins") are produced in high-energy collisions

Dark matter particles are produced and escape detection (missing energy)

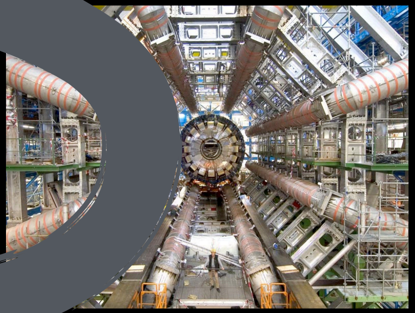
Charged/colored "cousins" of the dark matter particle are produced

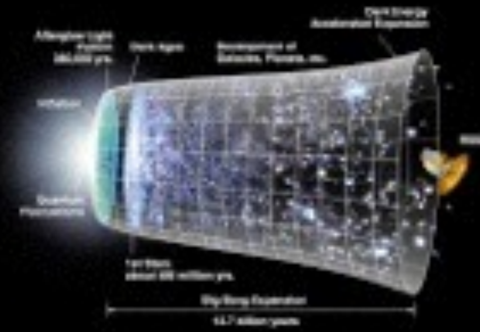
LEP ALEPH, DELPHI, OPAL, …
Tevatron CDF, D0, …
LHC ATLAS, CMS, …



Particle production at the Large Hadron Collider

Colliders

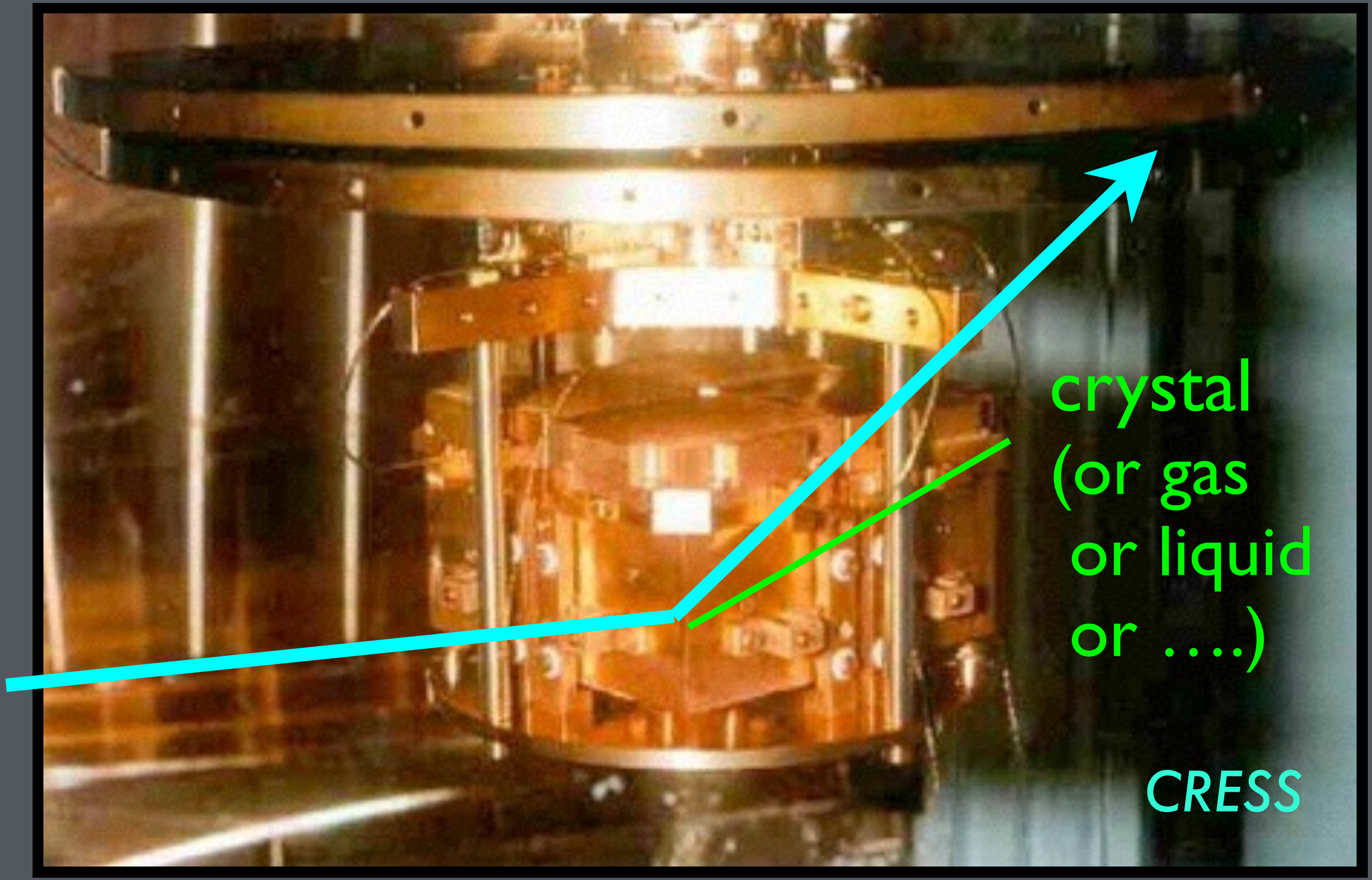




Cosmic density

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

*Goodman,
Witten
1985*

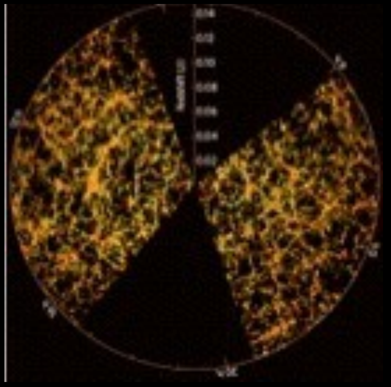


Low-background underground

DAMA, SuperCDMS, XENON, LUX, XMASS, PICO, CoGeNT, DEAP, DRIFT, ANAIS, CRESST, LZ, DARWIN, DM-ICE, …

ensity

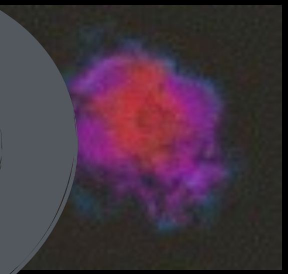
Direct detection

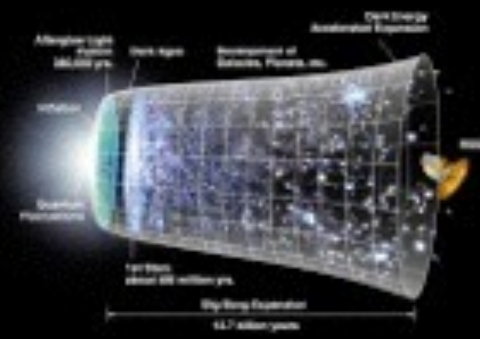


arge scale structure

ensity

Indirect detection



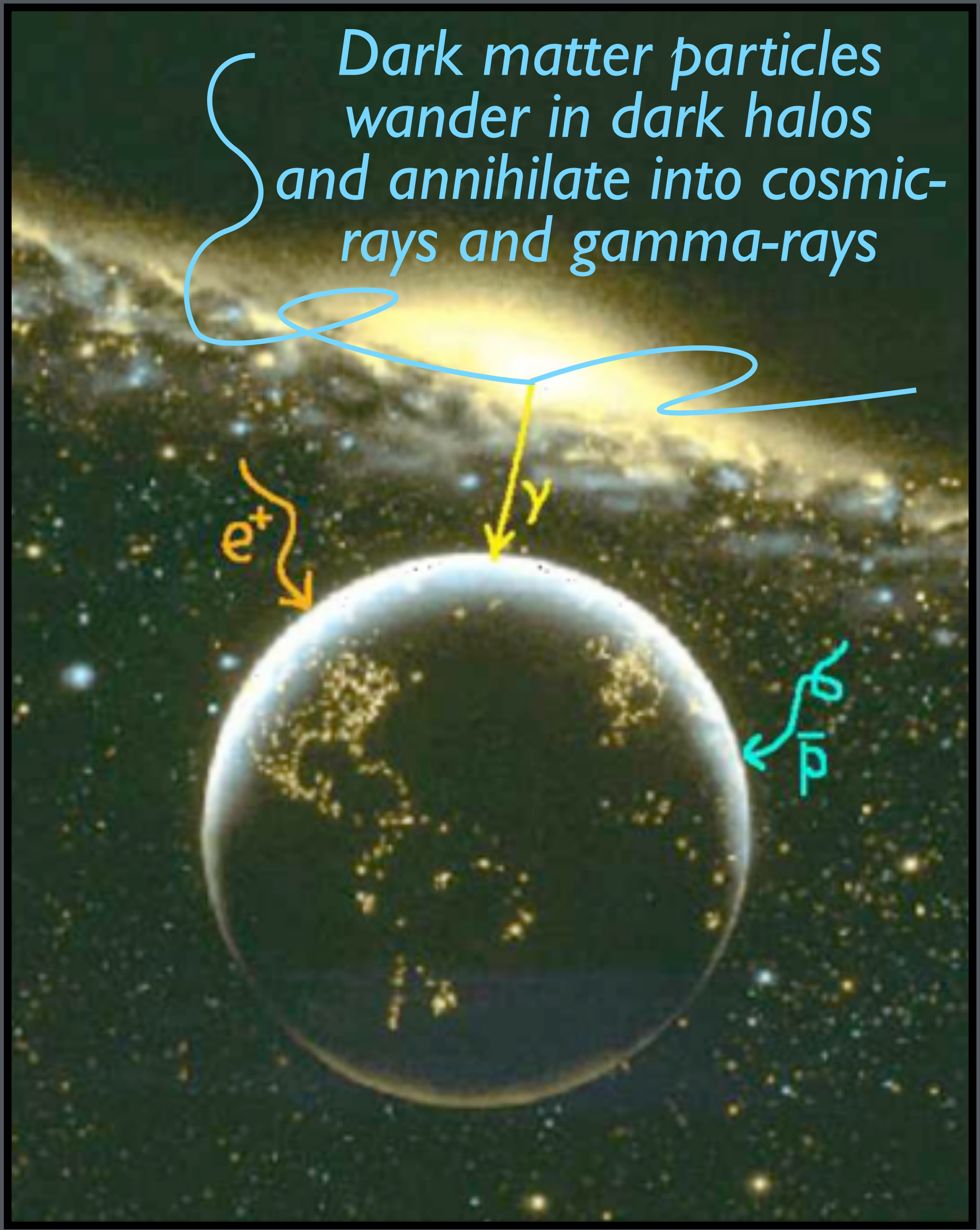


Cosmic density

Dark matter particles transform into ordinary particles, which are then detected or inferred

Gunn, Lee, Lerche, Schramm, Steigman 1978; Stecker 1978

Gamma-rays, positrons, antiprotons from our galaxy and beyond

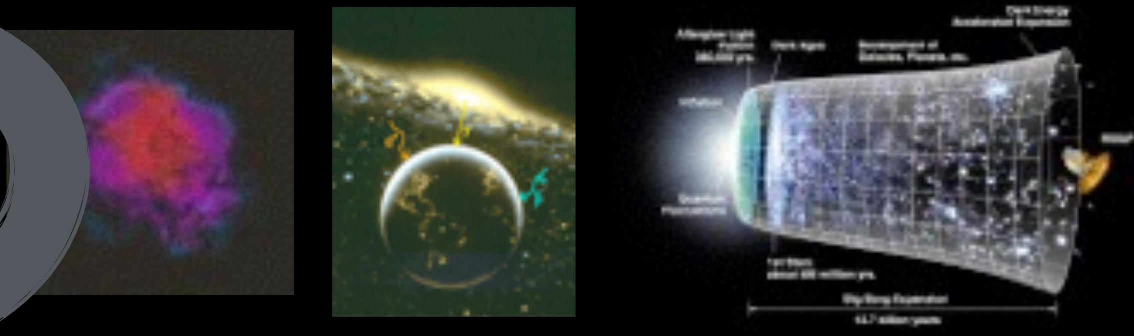


Dark matter particles wander in dark halos and annihilate into cosmic-rays and gamma-rays

cosmic-rays
PAMELA
AMS
...

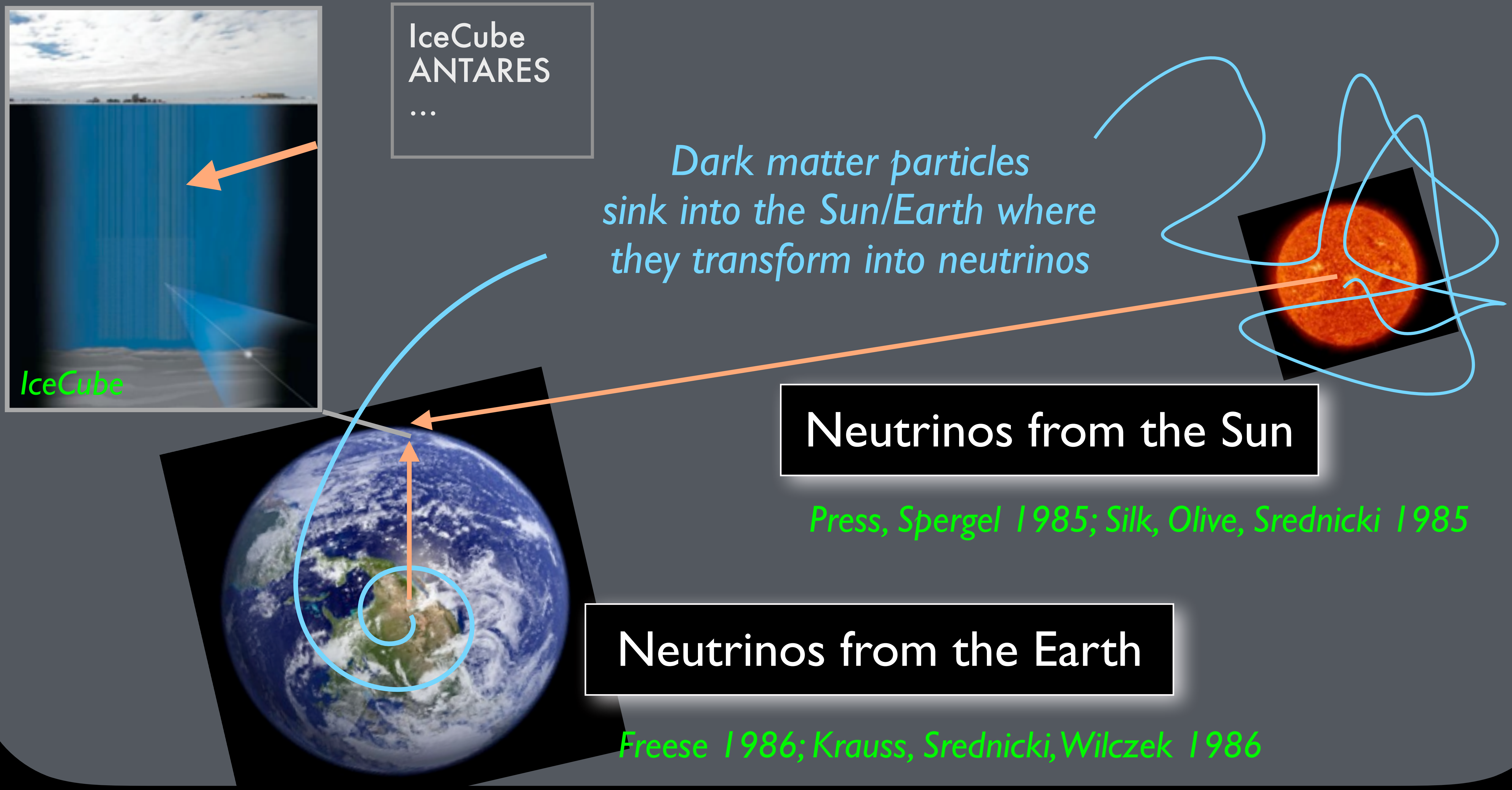
gamma-rays
MAGIC
HESS
VERITAS
Fermi-LAT
HAWK
CTA
...

Indirect detection



Cosmic density

Dark matter particles transform into ordinary particles, which are then detected or inferred



IceCube
ANTARES
…

*Dark matter particles
sink into the Sun/Earth where
they transform into neutrinos*

Neutrinos from the Sun

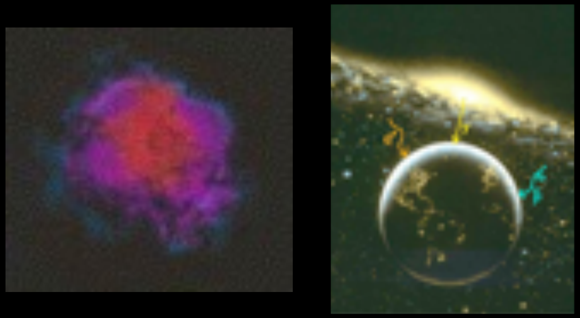
Press, Spergel 1985; Silk, Olive, Srednicki 1985

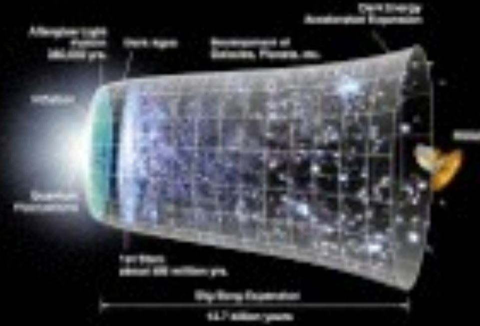
Neutrinos from the Earth

Freese 1986; Krauss, Srednicki, Wilczek 1986

The power of the WIMP

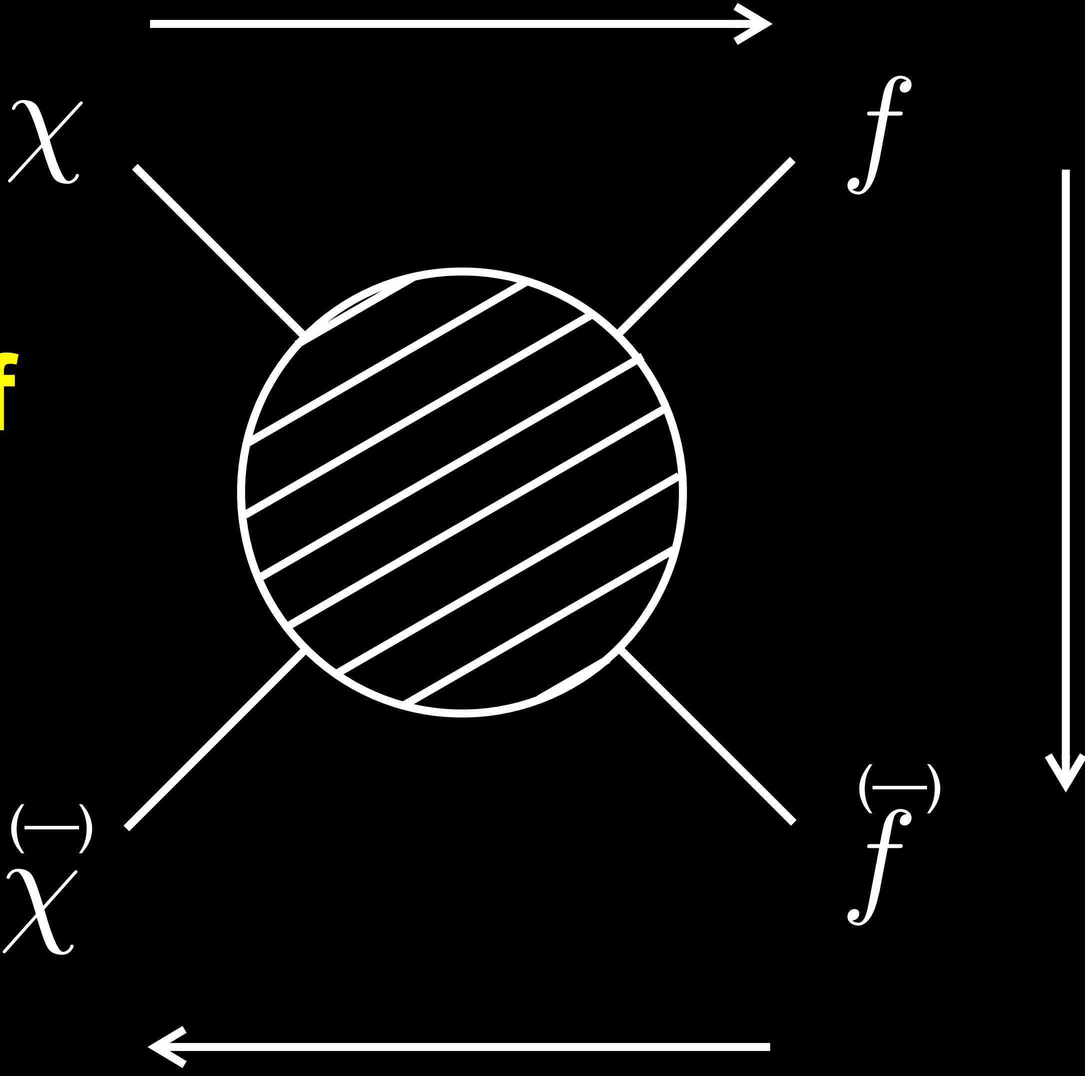
Indirect detection





Cosmic density

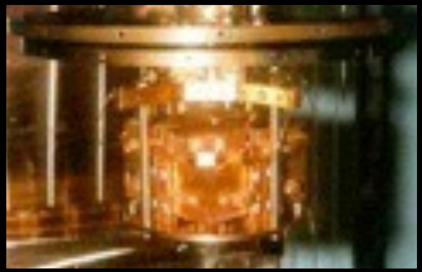
Annihilation

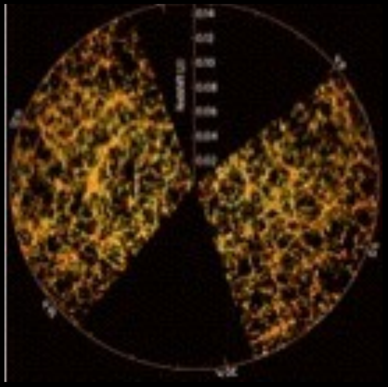


Scattering

Production

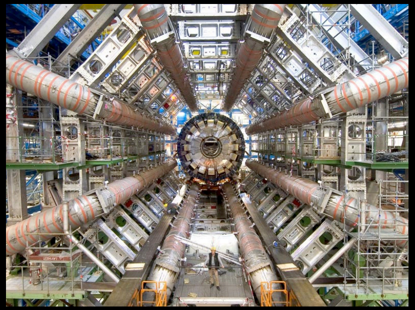
Direct detection

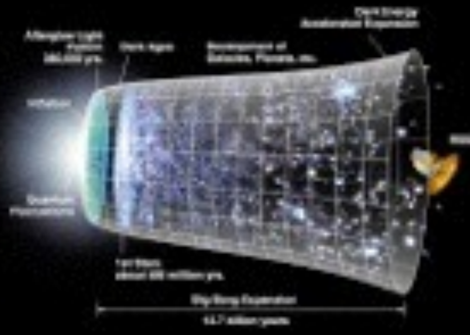




Large scale structure

Colliders

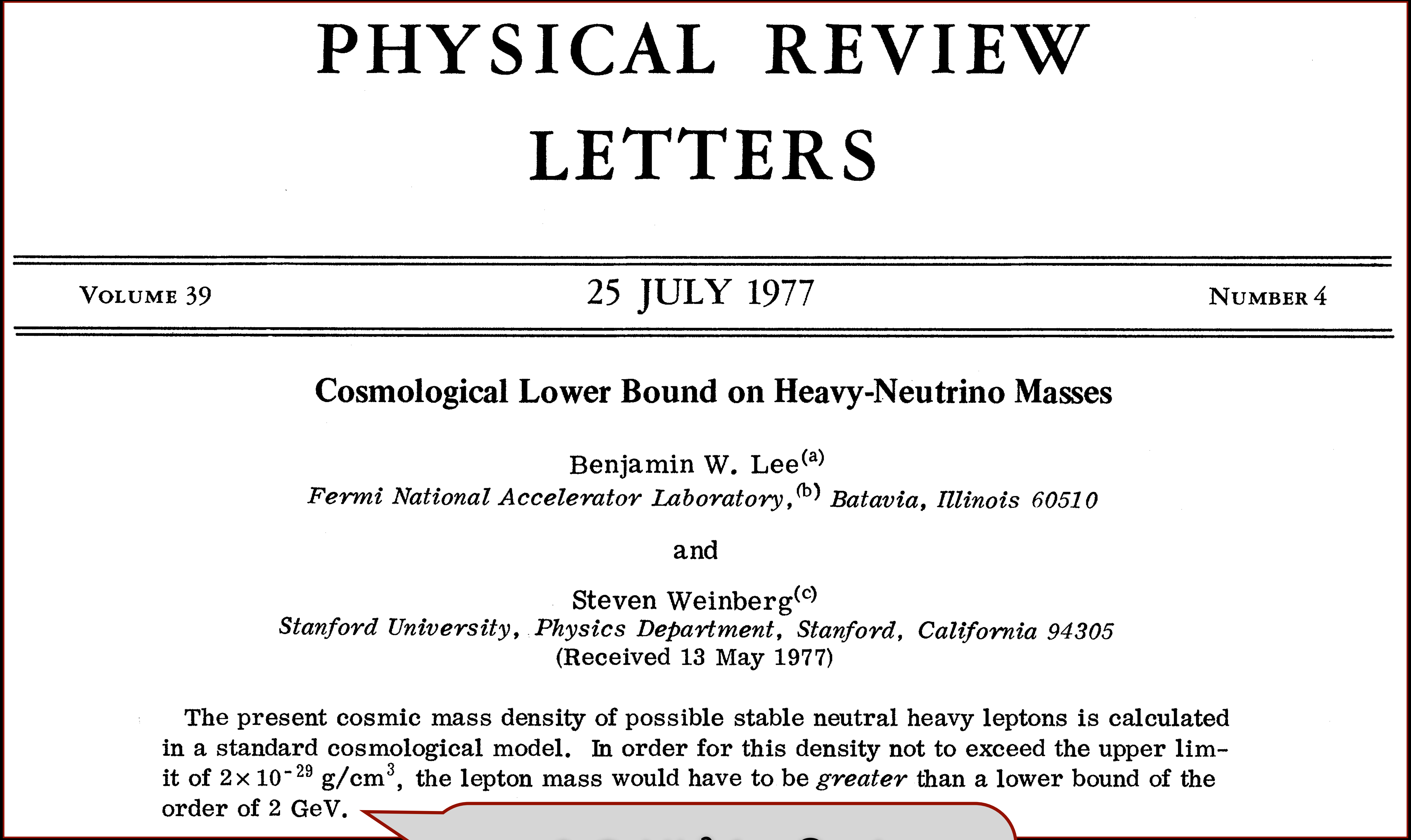




Cosmic density

Examples of WIMPs

Heavy active neutrinos



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Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee(a)
Fermi National Accelerator Laboratory,(b) *Batavia, Illinois 60510*

and

Steven Weinberg(c)
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

2 GeV/c^2 for $\Omega_c=1$

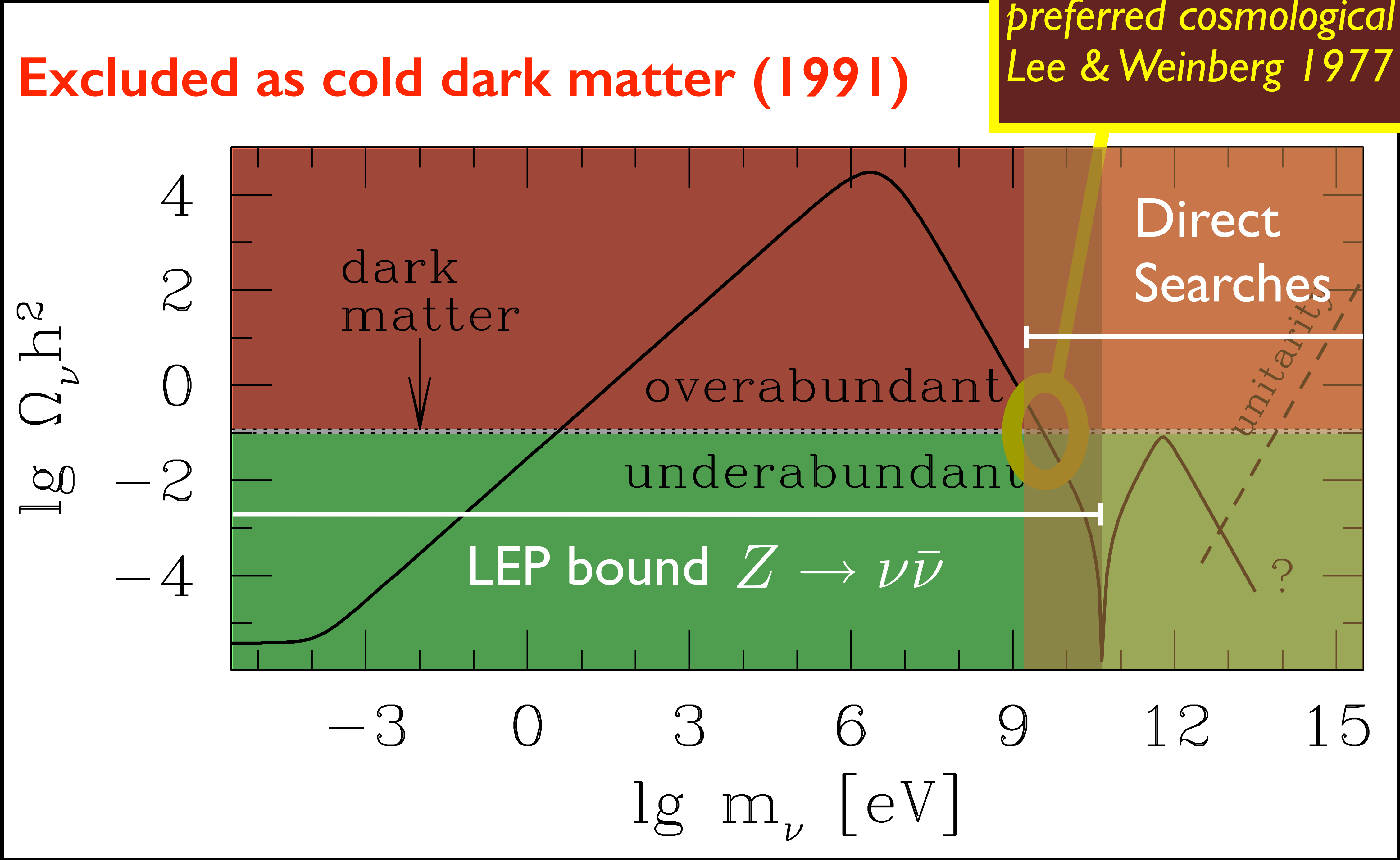
Now 4 GeV/c^2 for $\Omega_c=0.25$

Cosmic density of heavy active neutrinos

Heavy active neutrino

~ few GeV
preferred cosmological mass
Lee & Weinberg 1977

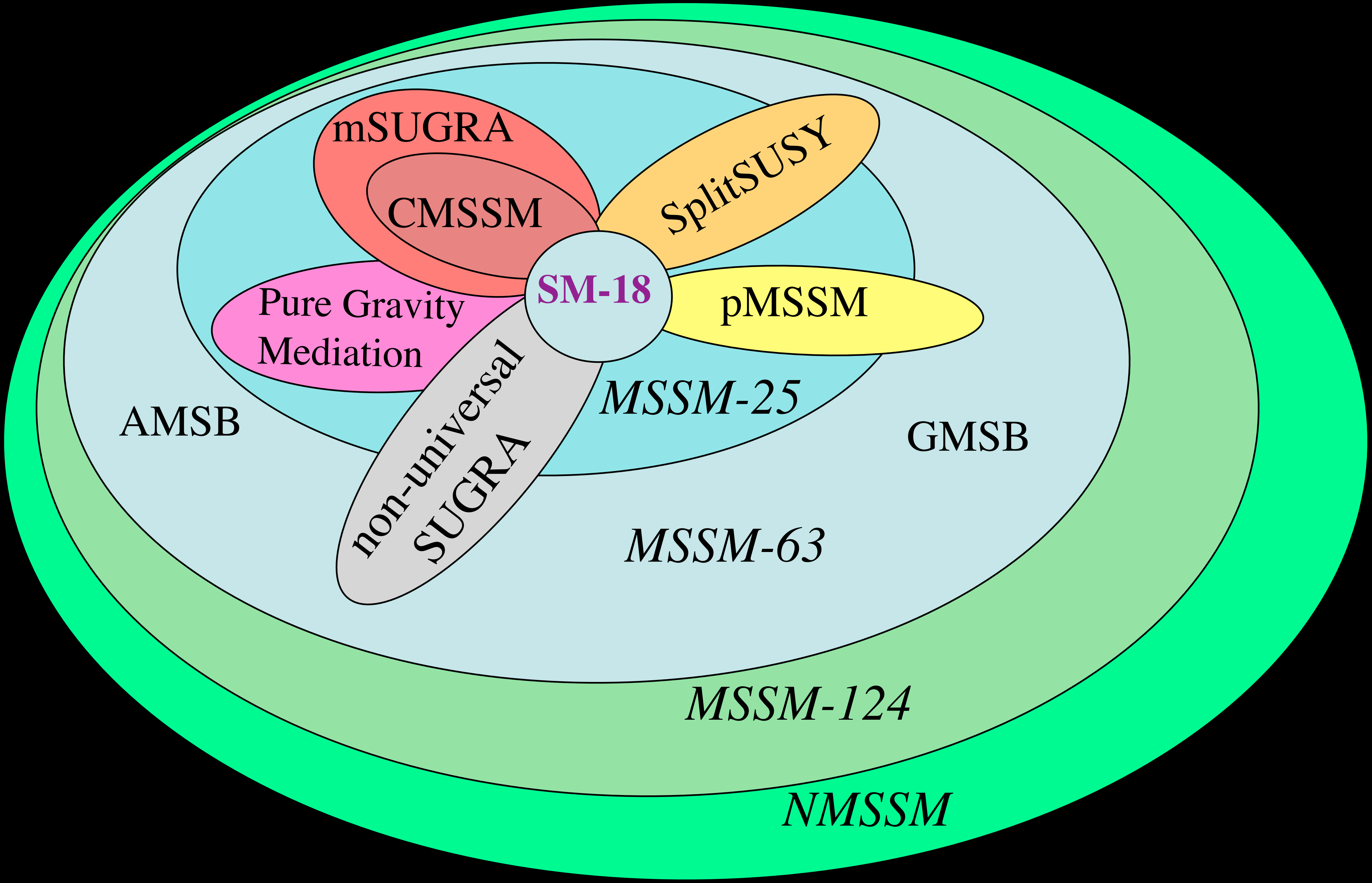
Excluded as cold dark matter (1991)



Supersymmetric models

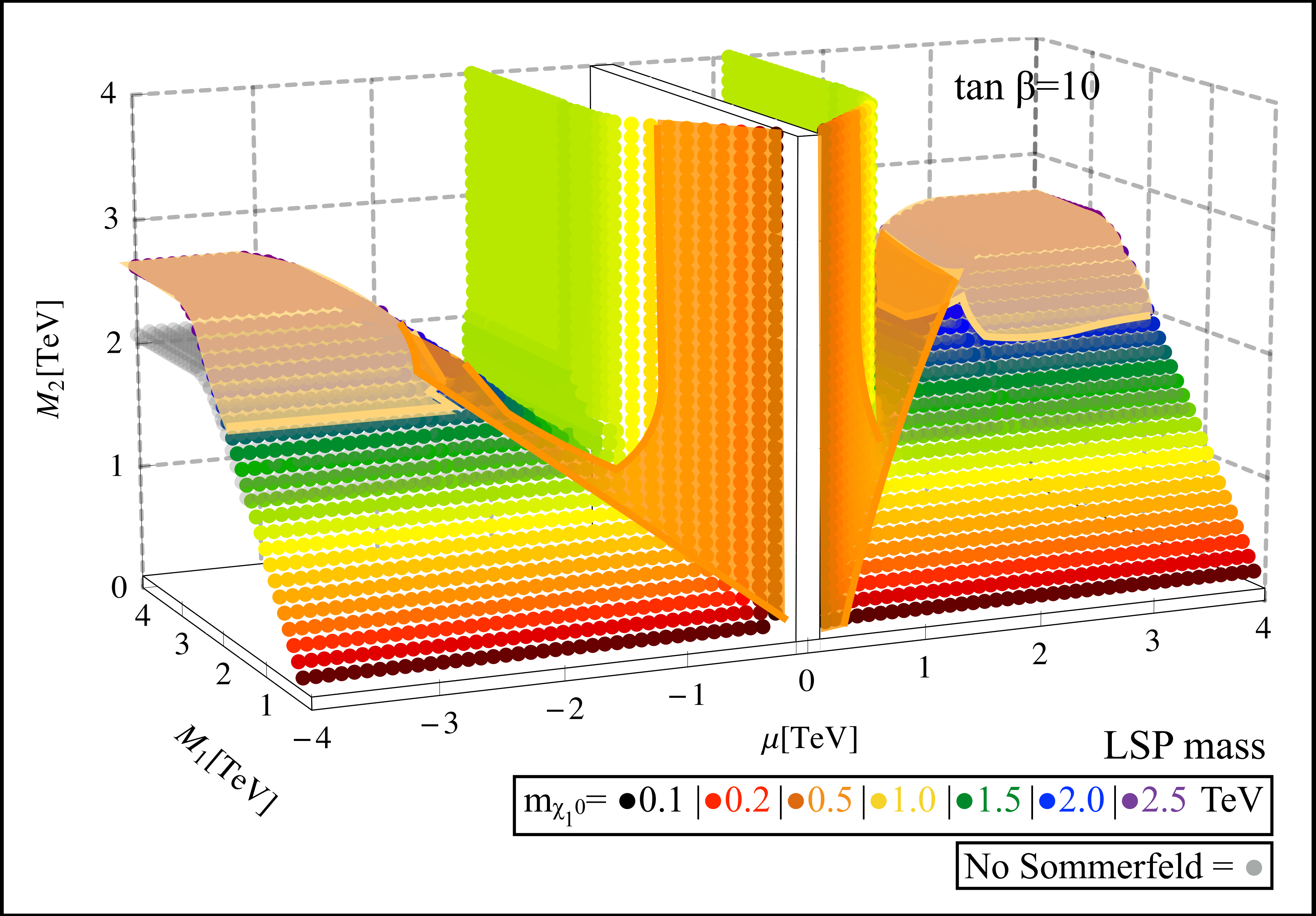
The CMSSM* is in dire straights, but there are many supersymmetric models

**Constrained Minimal Supersymmetric Standard Model*



Neutralino dark matter

Neutralino dark matter with decoupled (heavy) sfermions



Excluded by LEP, HESS, LUX

All can be tested by LZ, CTA, and a 100-TeV pp collider

Bramante, Desai, Fox, Martin, Ostdiek, Plehn 2015

Scalar phantom dark matter

"Gauge singlet scalar dark matter"
"Singlet scalar dark matter"
"Scalar singlet dark matter"
"Scalar Higgs-portal dark matter"
"The minimal model of dark matter"

Minimalist dark matter

do not confuse with minimal dark matter

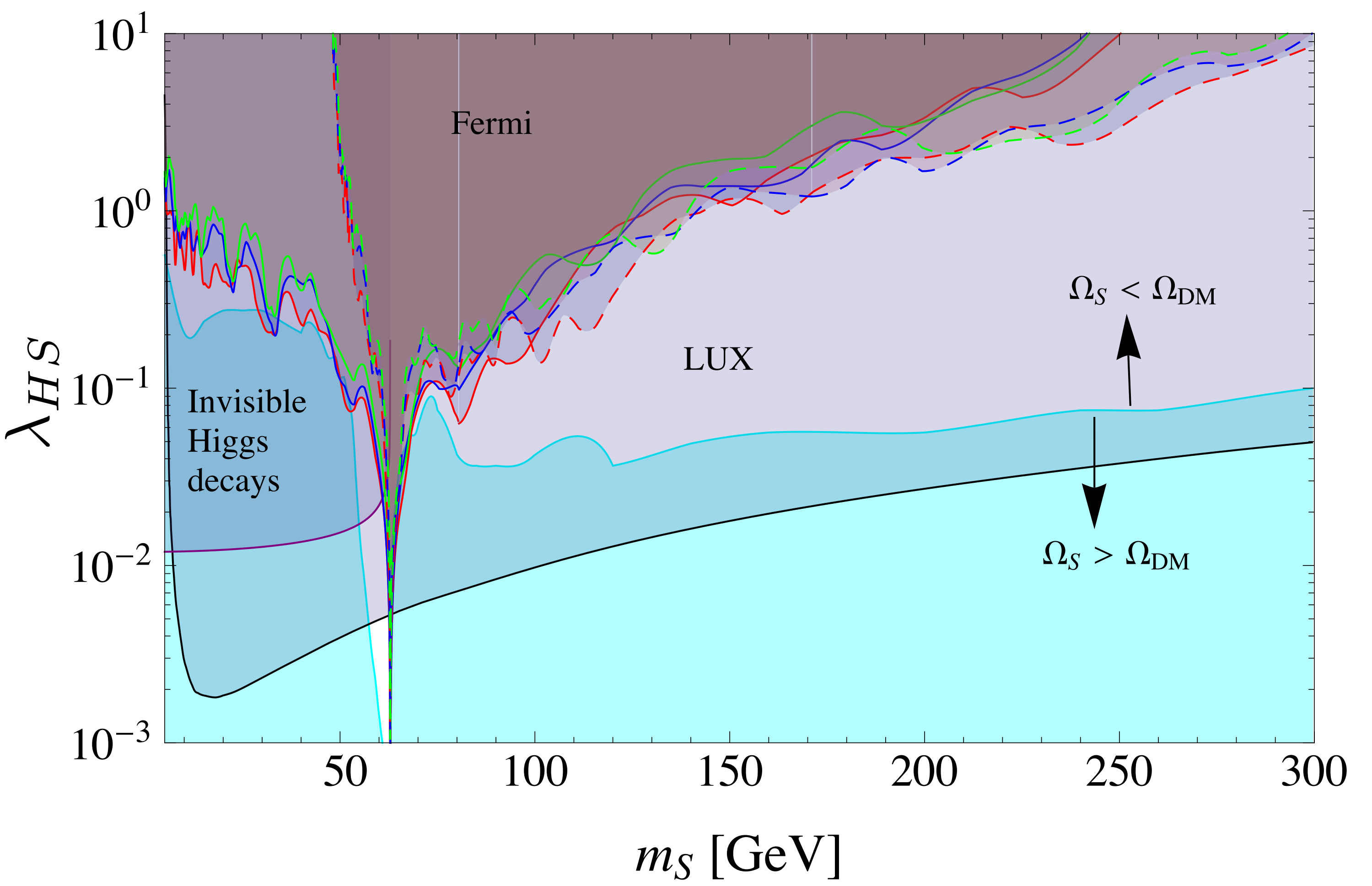
Gauge singlet scalar field S stabilized by a Z_2 symmetry ($S \rightarrow -S$)

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

Silveira, Zee 1985
Andreas, Hambye, Tytgat 2008
Djouadi, Falkowksi, Mambrini, Quevillon 2012
Cline, Scott, Kainulainen, Weniger 2013

"Scalar phantom" is the original 1985 name

Scalar phantom dark matter



Not excluded by LUX at $m_S \approx 60$ GeV and $m_S > 1$ TeV

No density rescaling

Feng, Profumo, Ubaldi 2015

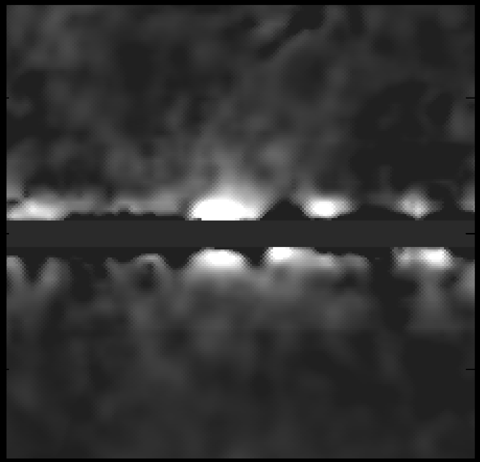
If density is rescaled according to Ω_S, LUX and FERMI exclusion regions are very different

Cline, Scott, Kainulainen, Weniger 2013

Evidence for WIMP dark matter?

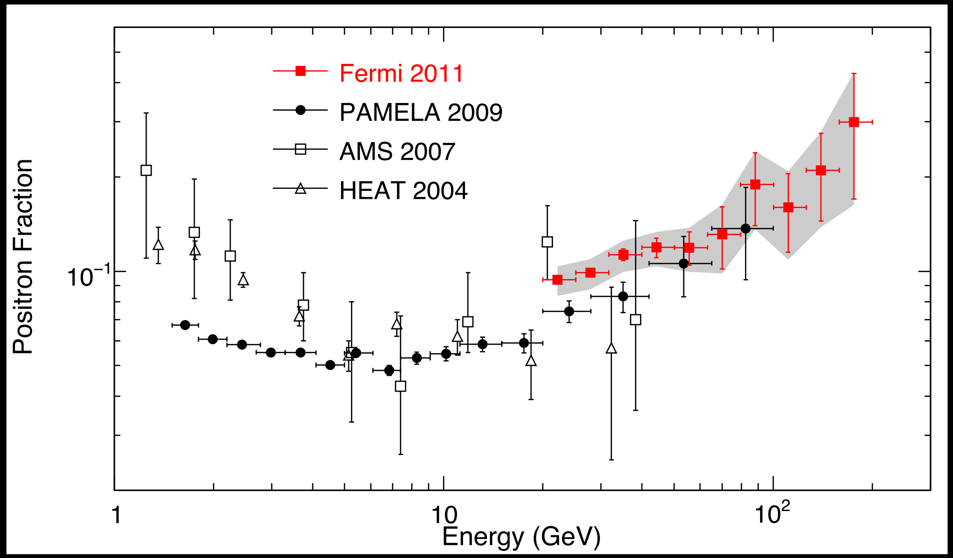
Signals from WIMP dark matter?

GeV γ-rays



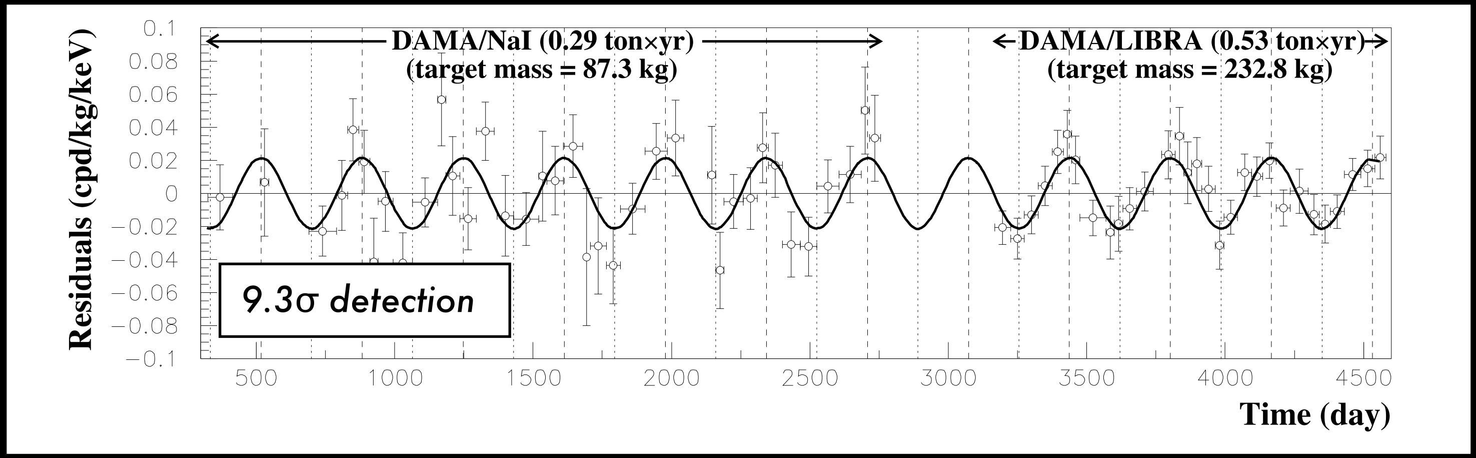
Hooper et al 2009-14

Cosmic-ray positrons



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

Annual modulation in direct detection



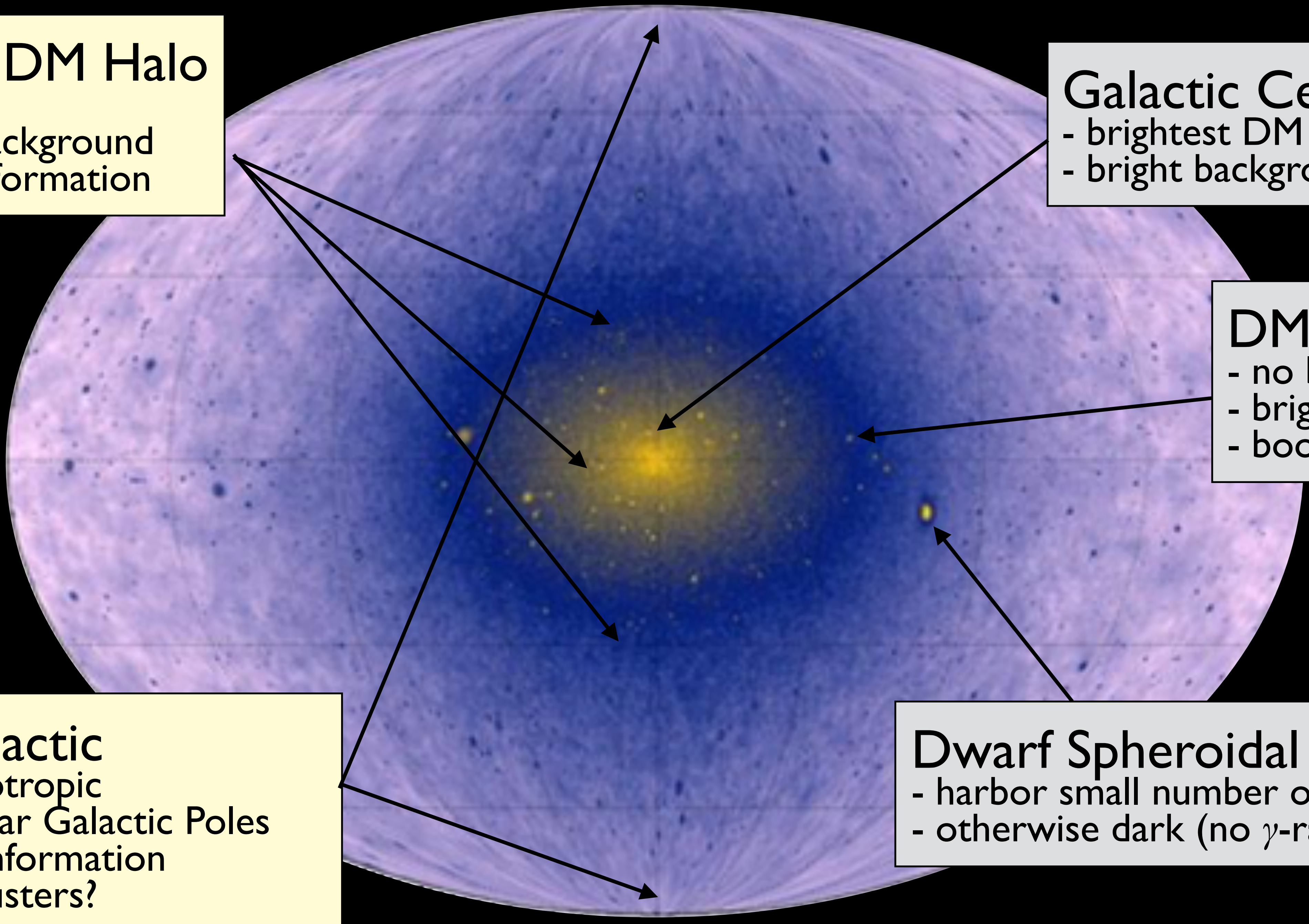
Bernabei et al 1997-now

Gamma-rays from dark matter?

Gamma-rays from WIMP annihilation

J factor

annihilation $$\frac{d^2\phi}{d\Omega\, dE} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\,\frac{dN_\gamma}{dE} \times \boxed{\int_{\mathrm{l.o.s}} \rho^2\, ds}$$



Galactic DM Halo
- good S/N
- difficult background
- angular information

Galactic Center
- brightest DM source
- bright background

DM clumps
- no baryons
- bright enough?
- boost overall signal

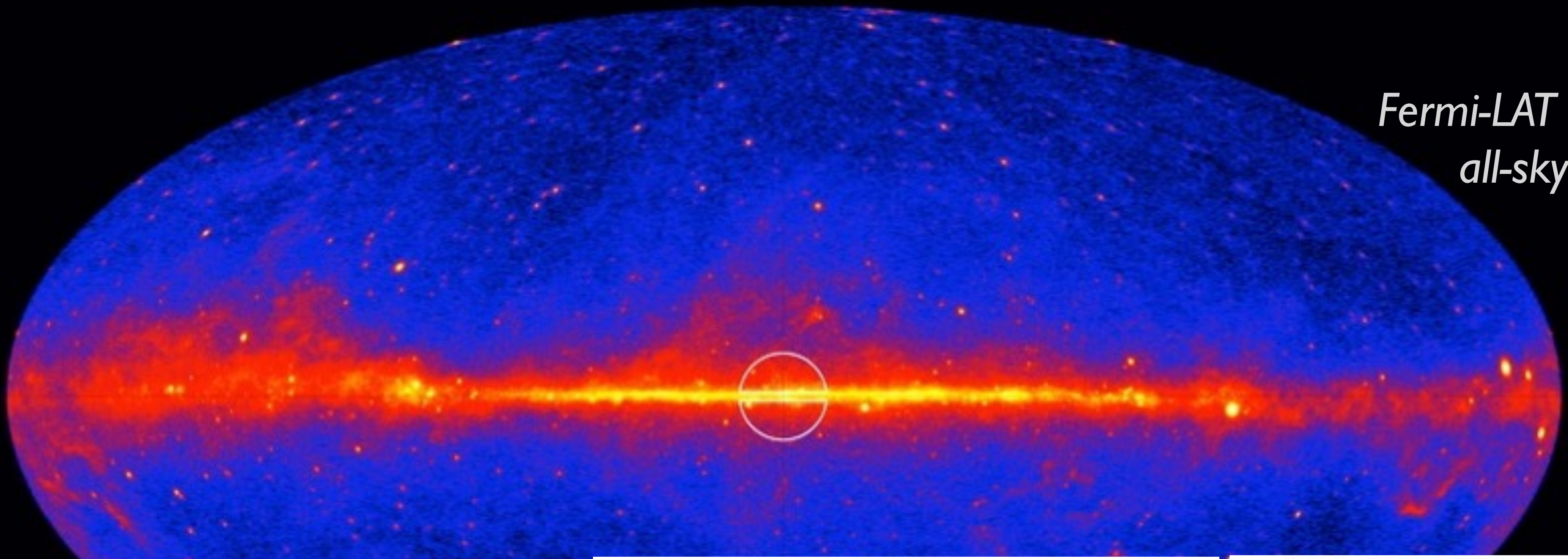
Extragalactic
- nearly isotropic
- visible near Galactic Poles
- angular information
- galaxy clusters?

Dwarf Spheroidal Galaxies
- harbor small number of stars
- otherwise dark (no γ-ray emission)

Kuhlen, Diemand, Madau 2007

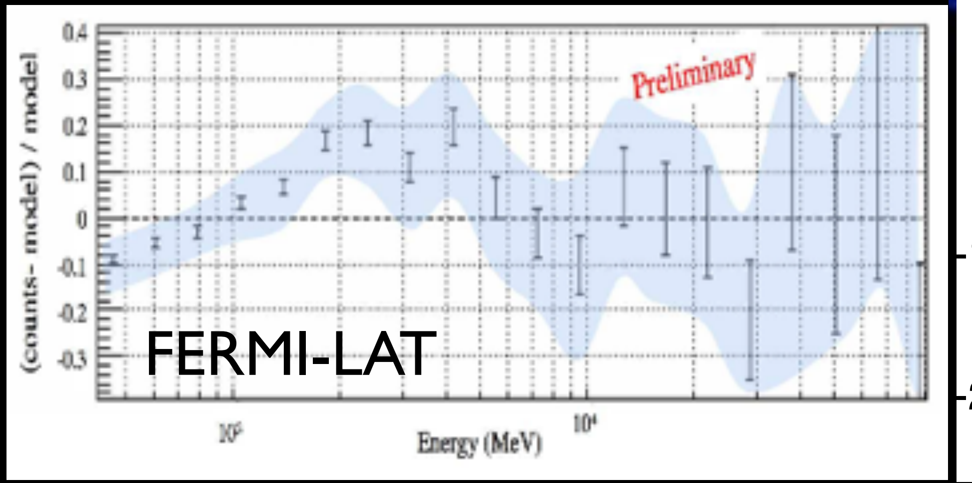
1 GeV γ-ray excess at Galactic Center?

Goodenough, Hooper; Vitale, Morselli et al 2009; Hooper, Goodenough; Boyarsky, Malyshev, Ruchayskiy; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon, Macias 2013; Abazajian, Canac, Horiuchi, Kaplinghat; Daylan et al; Calore, Cholis, Weniger 2014

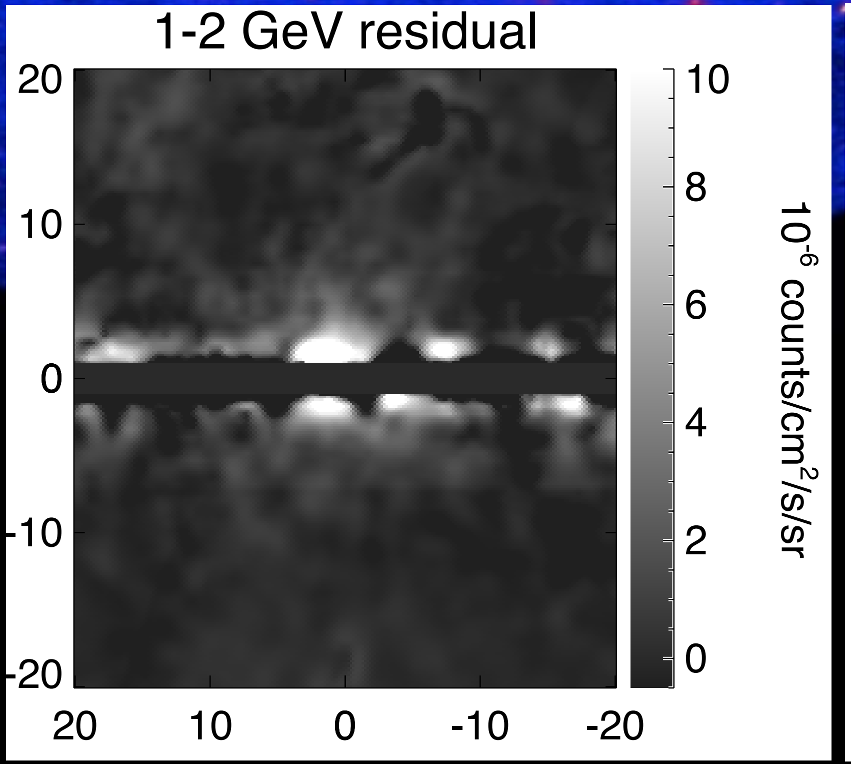


Fermi-LAT all-sky map

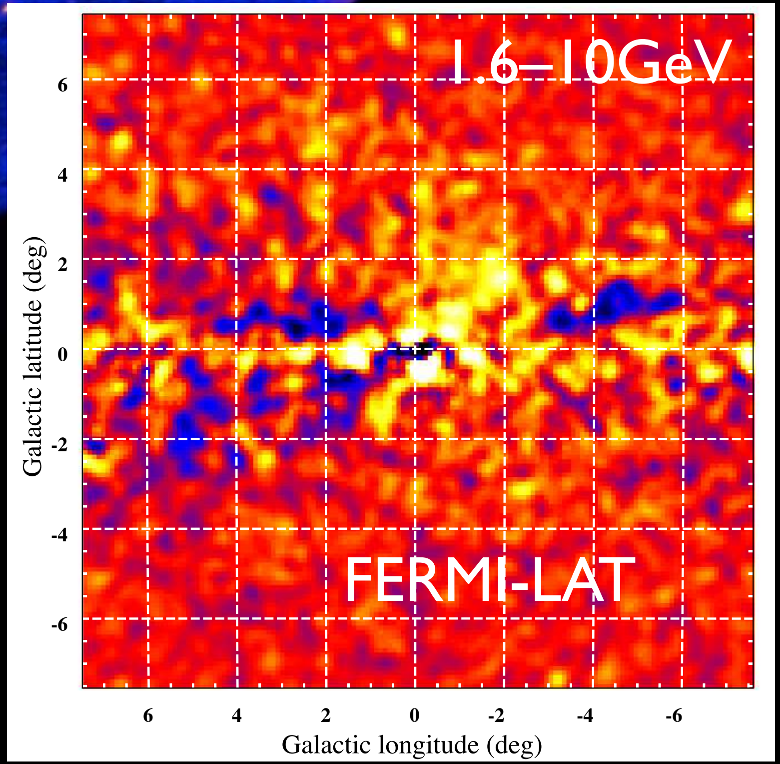
Fit model of known emission.
Find residual.



Vitale, Morselli et al 2009



Daylan et al 2014



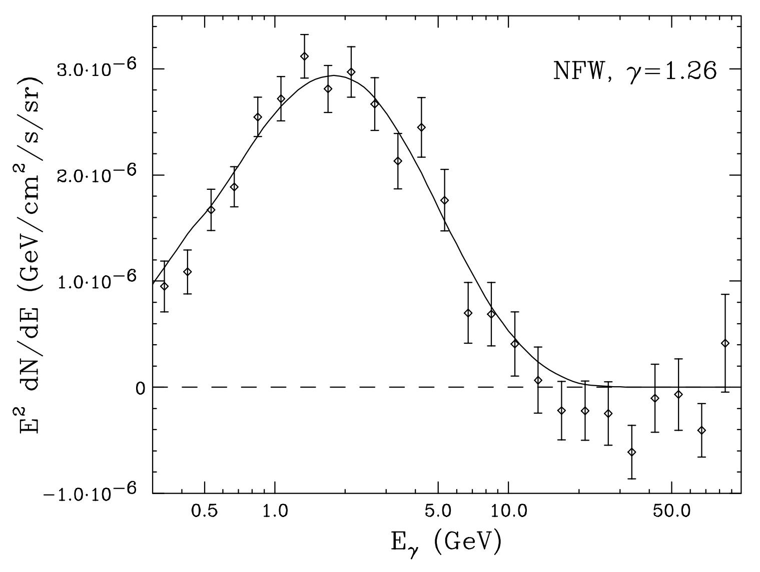
Ajello et al 2015

1 GeV γ-ray excess at Galactic Center?

- Dark matter annihilation

  Goodenough, Hooper 2014; Hooper, Goodenough; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Abazajian, Canac, Horiuchi, Kaplinghat; Daylan et al; Calore, Cholis, Weniger 2014; ....

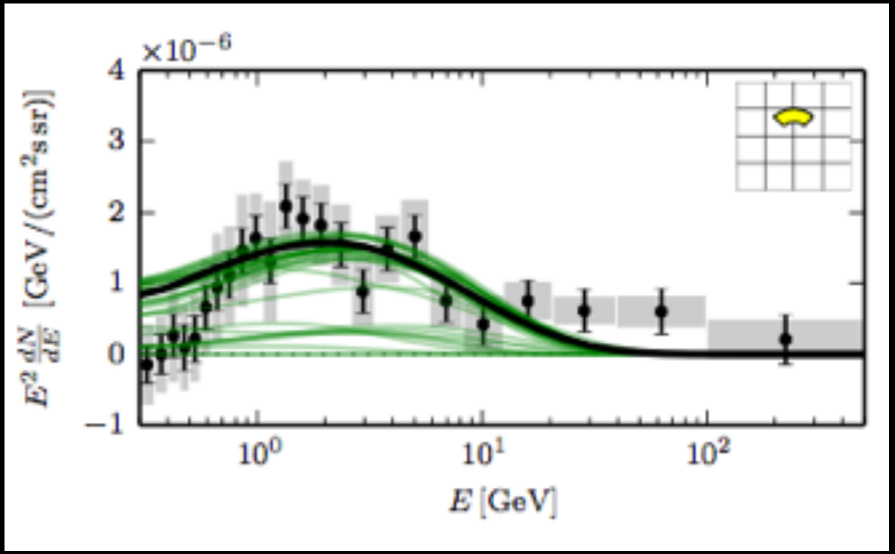
  Possible for specific WIMP and dark halo models



- Burst(s) of leptonic activity about 1 Myr ago

  Petrovic et al 2014; Cholis et al 2015; ....

  Possible with suitable diffusion parameters



- Millisecond pulsars

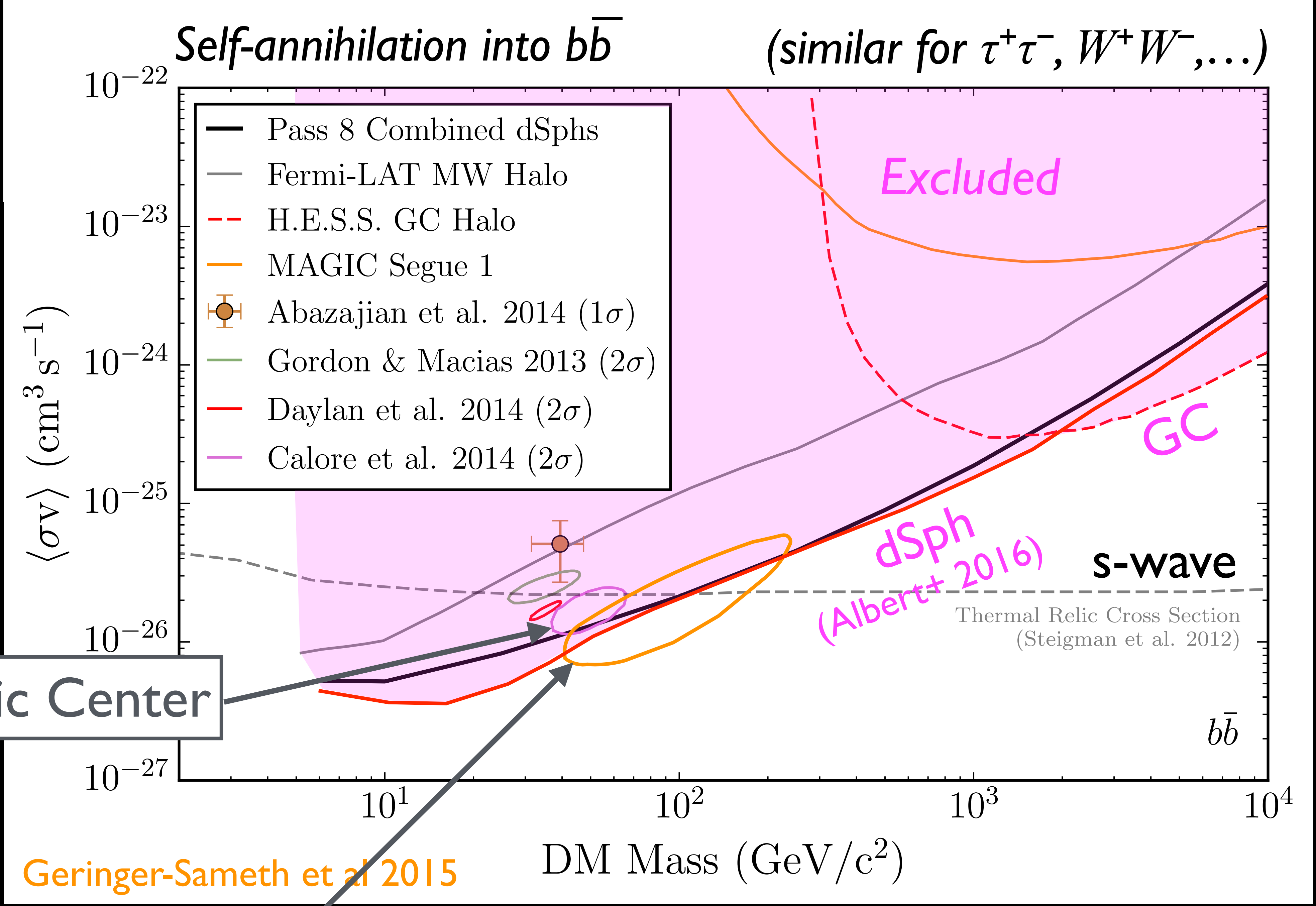
  Wang et al 2005; Abazajian 2011; Gordon, Macias 2013; Hooper et al 2013; Yuan, Zhang 2014; Calore et al 2014; Cholis et al 2014; Petrovic et al 2014; Lee et al 2014; Bartels et al 2014

  Favored by wavelet analysis and nonpoissonian point spread function

  Lee, Lisanti, Safdi 2014; Bartels, Krishnamurthy, Weniger 2015

1 GeV γ-ray excess at Galactic Center?

Upper limits on the WIMP annihilation cross section
from dwarf spheroidal galaxies and Galactic Center



Self-annihilation into $b\bar{b}$ *(similar for $\tau^+\tau^-$, W^+W^-,…)*

Geringer-Sameth et al 2015

Galactic Center

Reticulum II

Ackermann et al [FermiLAT] 1503.02641

1 GeV γ-ray excess at Galactic Center?

Upper limits on the WIMP annihilation cross section
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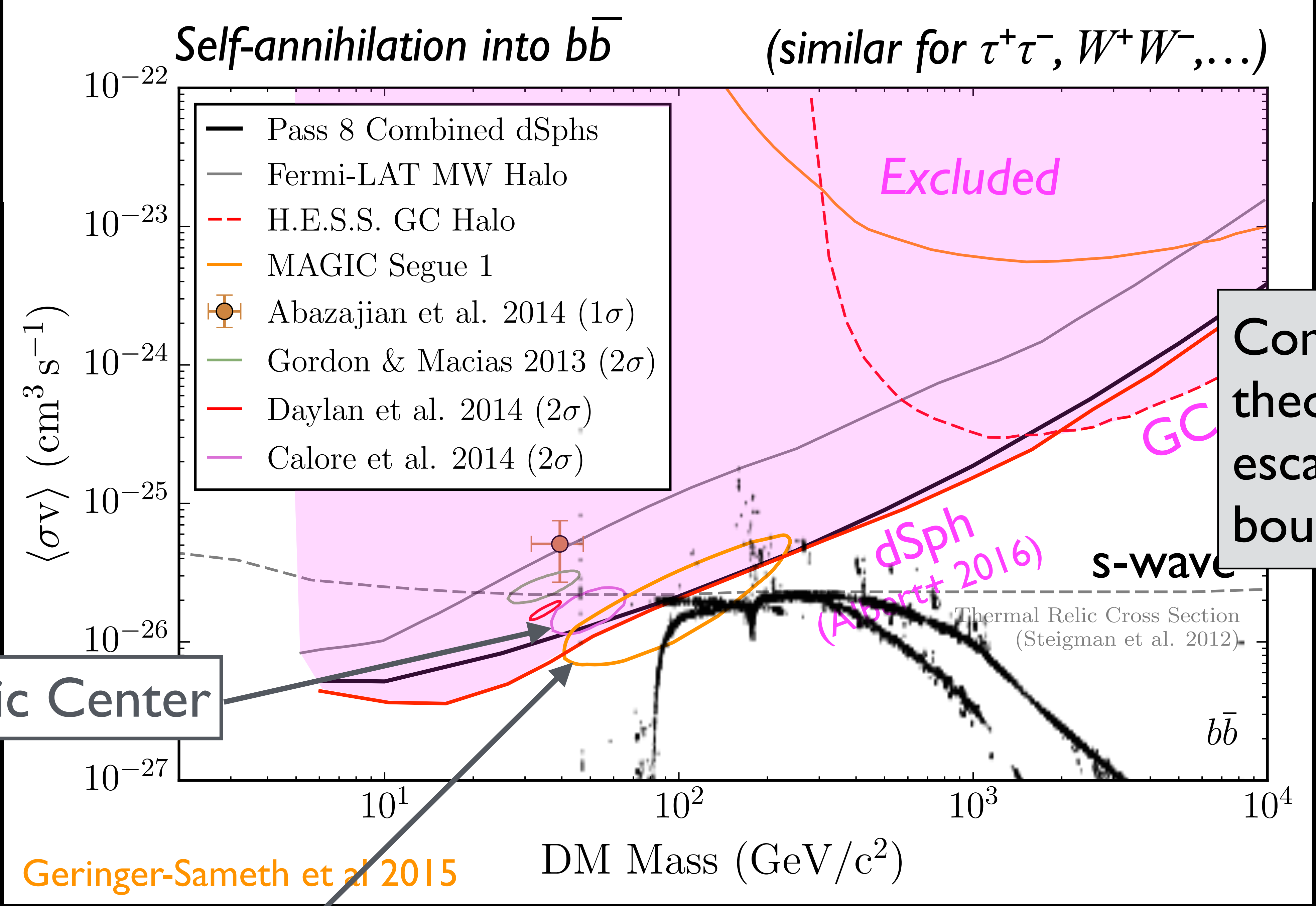


Complete theories can escape these bounds

Galactic Center

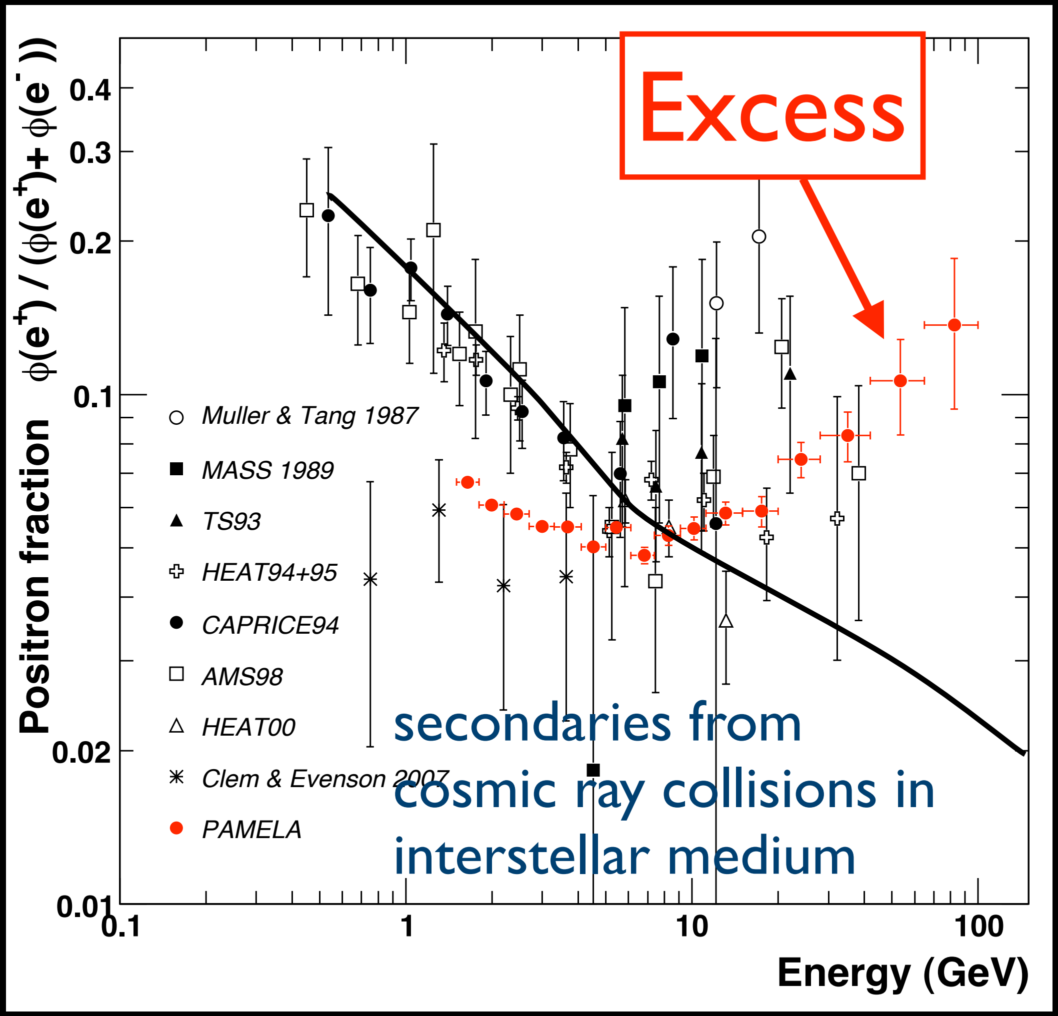
Reticulum II

Ackermann et al [FermiLAT] 1503.02641

Positrons from dark matter?

Excess in cosmic ray positrons

High-energy cosmic-ray positrons are more than expected

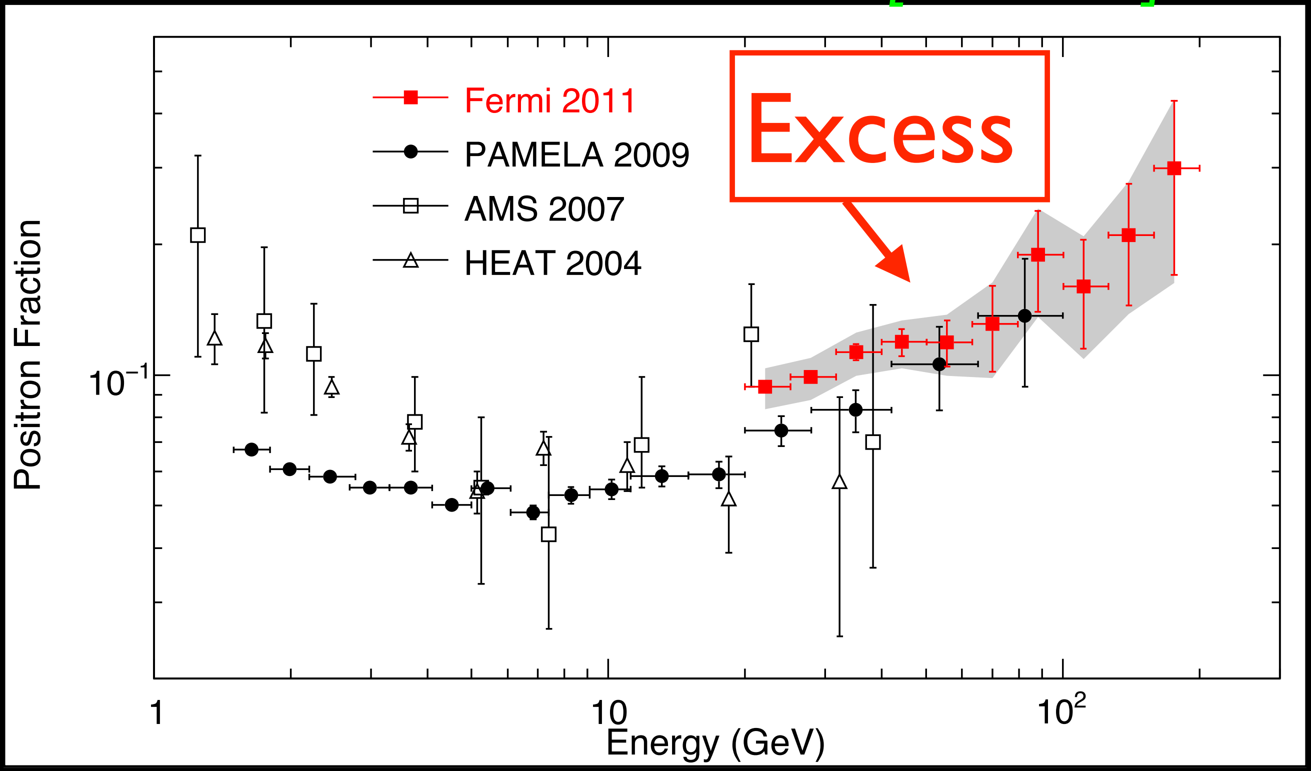


Excess

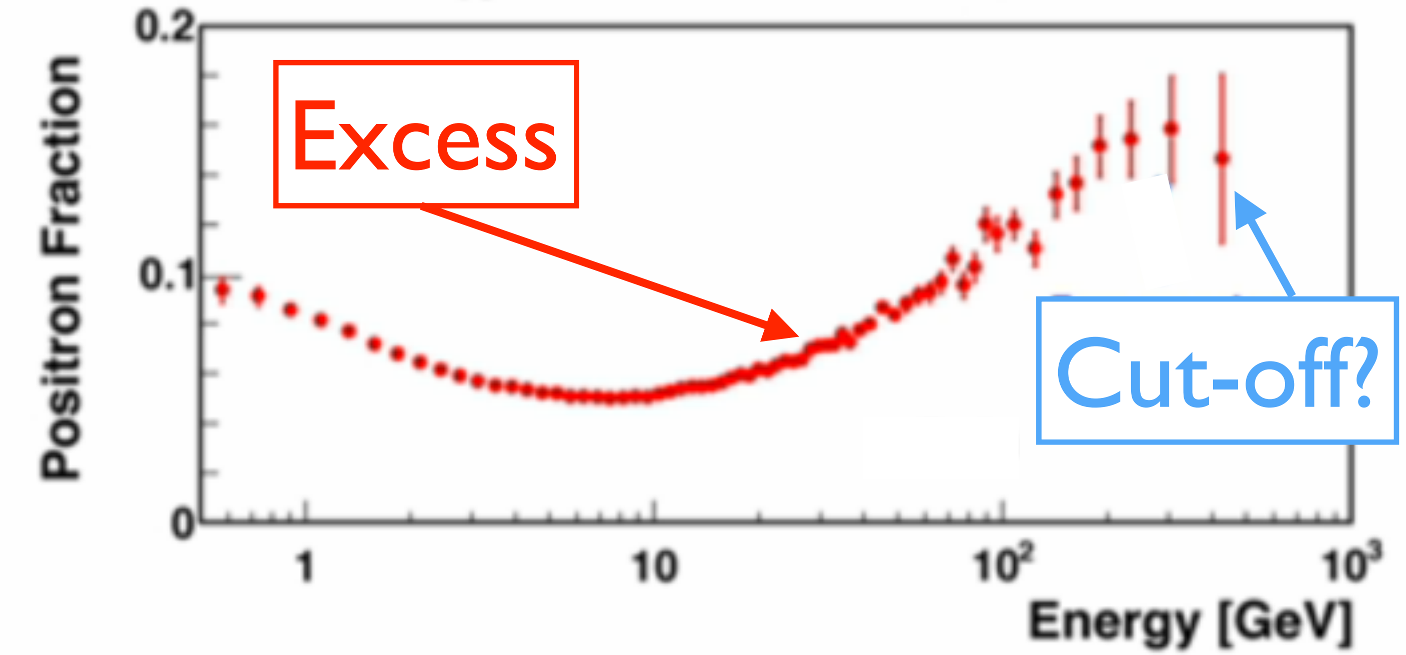
secondaries from cosmic ray collisions in interstellar medium

Adriani et al. [PAMELA] 2008

Ackermann et al [Fermi-LAT] 2011



Excess

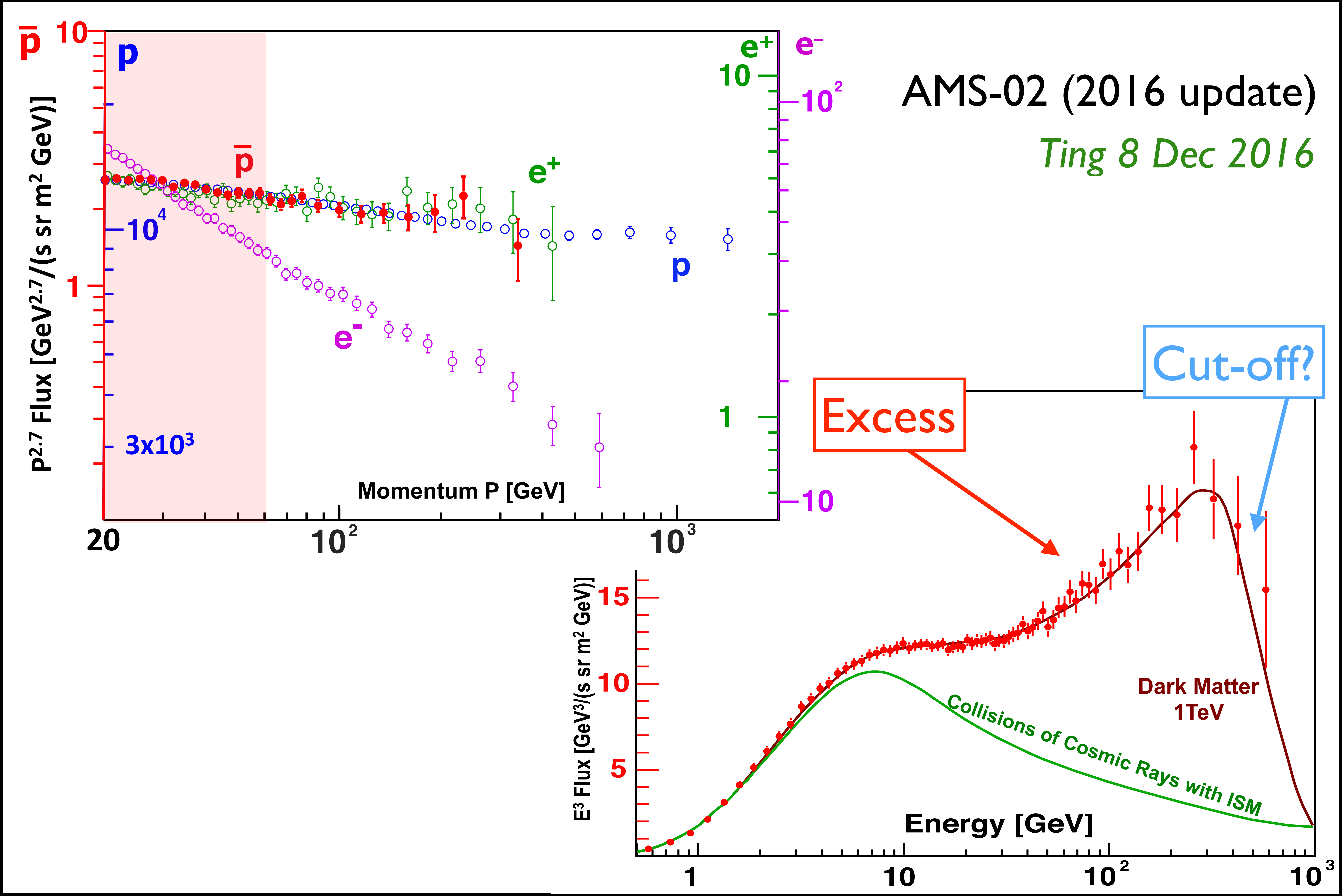


Excess

Cut-off?

Accardo et al [AMS-02] 2014

Excess in cosmic ray positrons



AMS-02 (2016 update)

Ting 8 Dec 2016

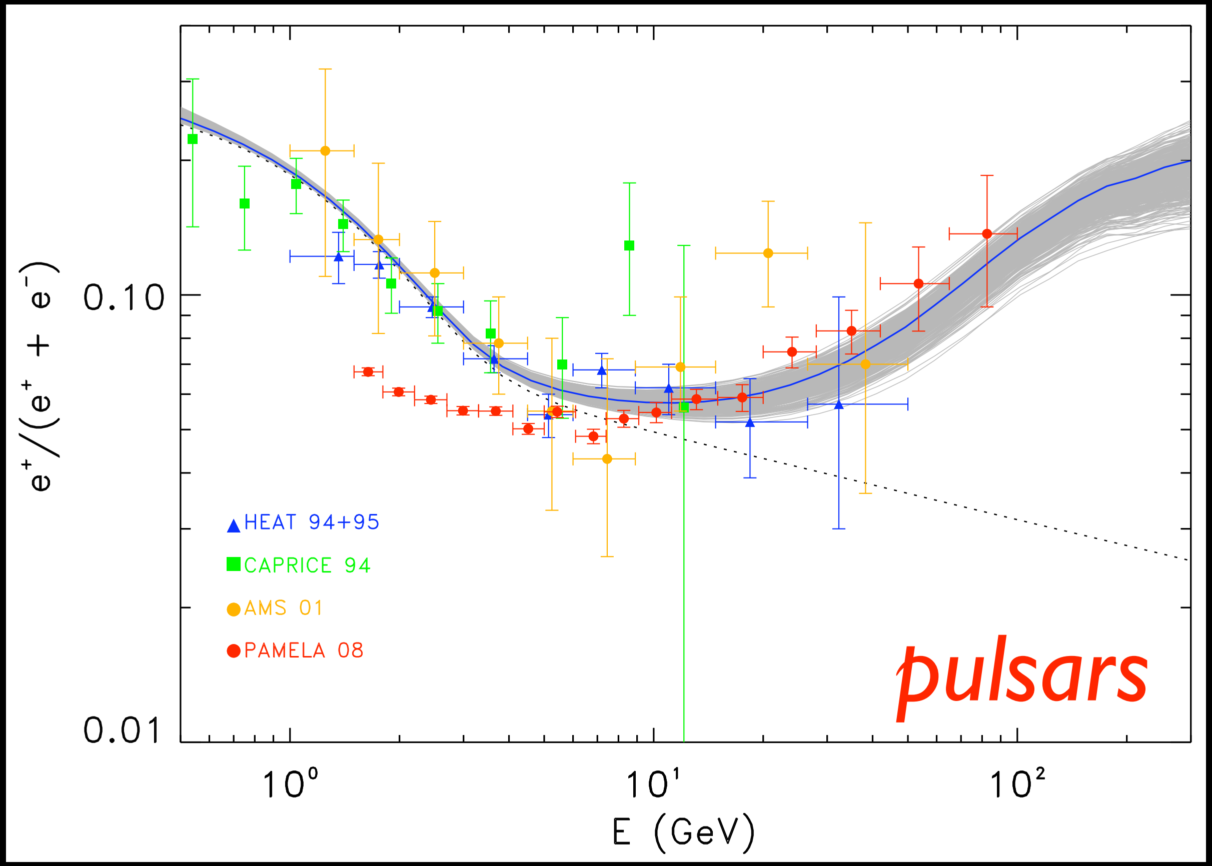
Excess

Cut-off?

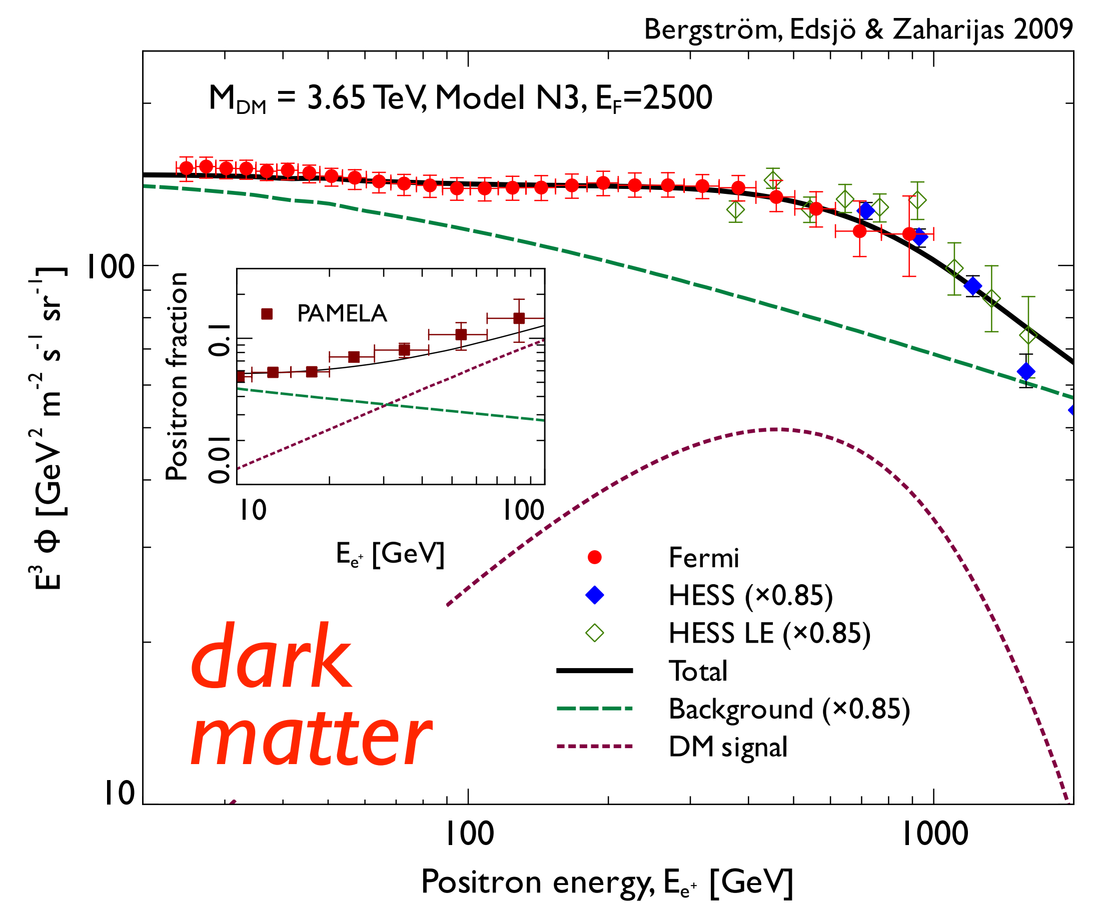
Excess in cosmic ray positrons

Dark matter?
Pulsars?
Secondaries from extra primaries?

Grasso et al [Fermi-LAT] 2009

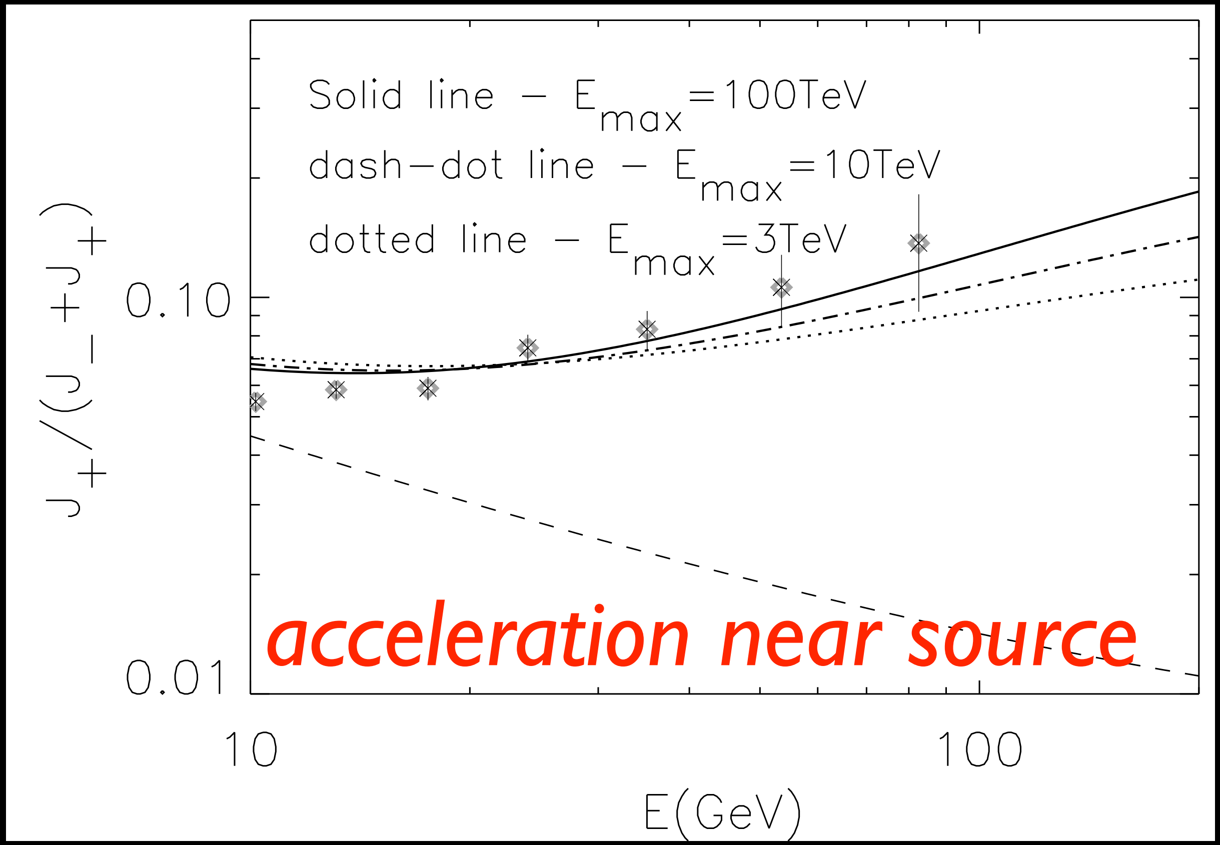


pulsars



dark matter

Bergstrom, Edsjo, Zaharijas 2009



acceleration near source

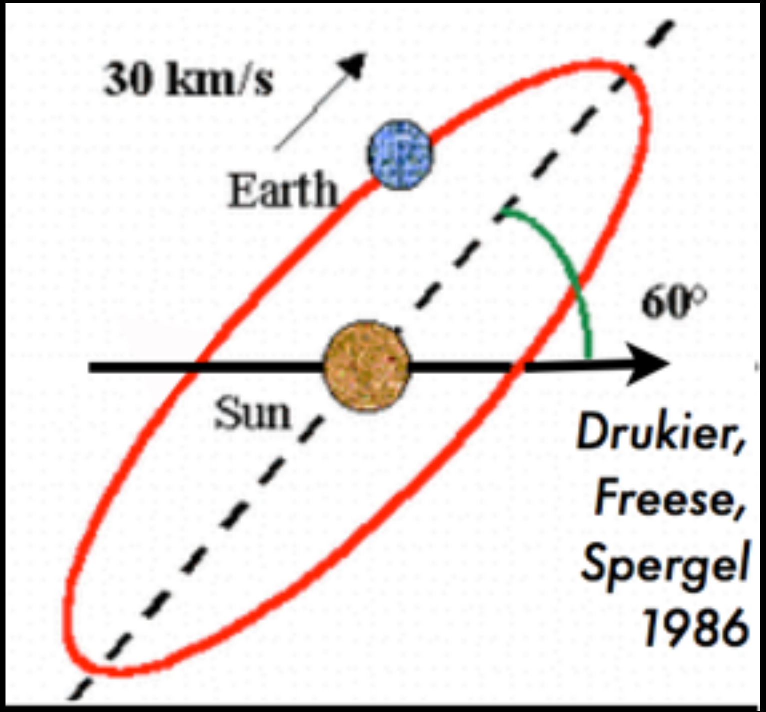
Blasi 2009

Direct detection of dark matter?

Annual modulation in direct detection

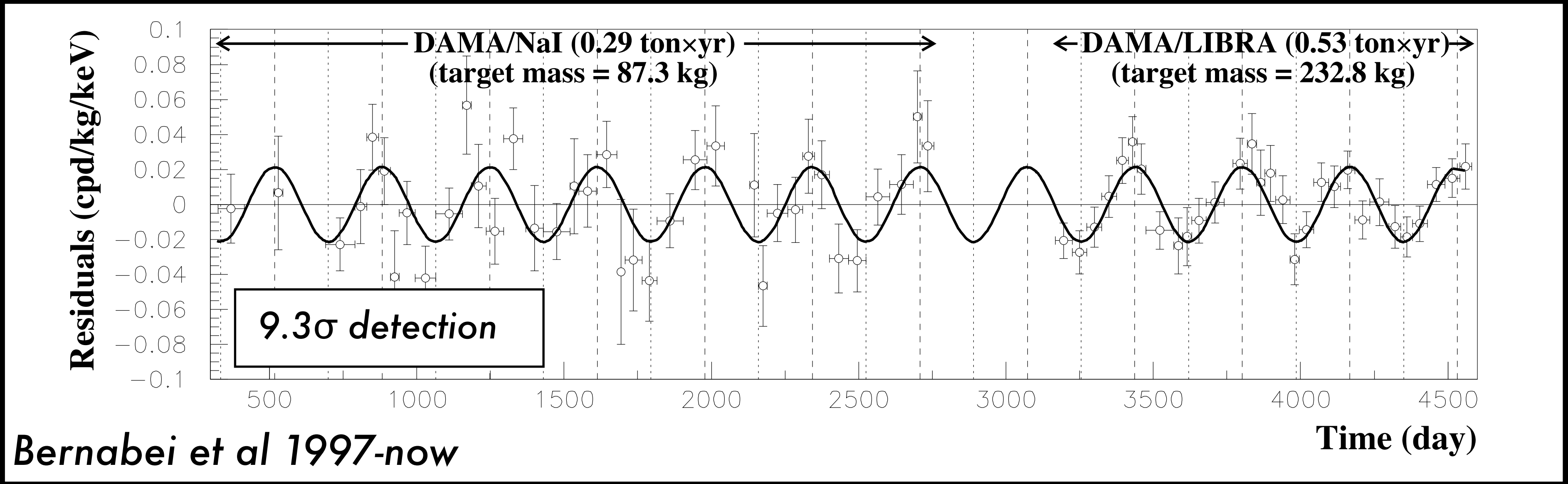
- The revolution of the Earth around the Sun modulates the WIMP event rate

Drukier, Freese, Spergel 1986



Drukier, Freese, Spergel 1986

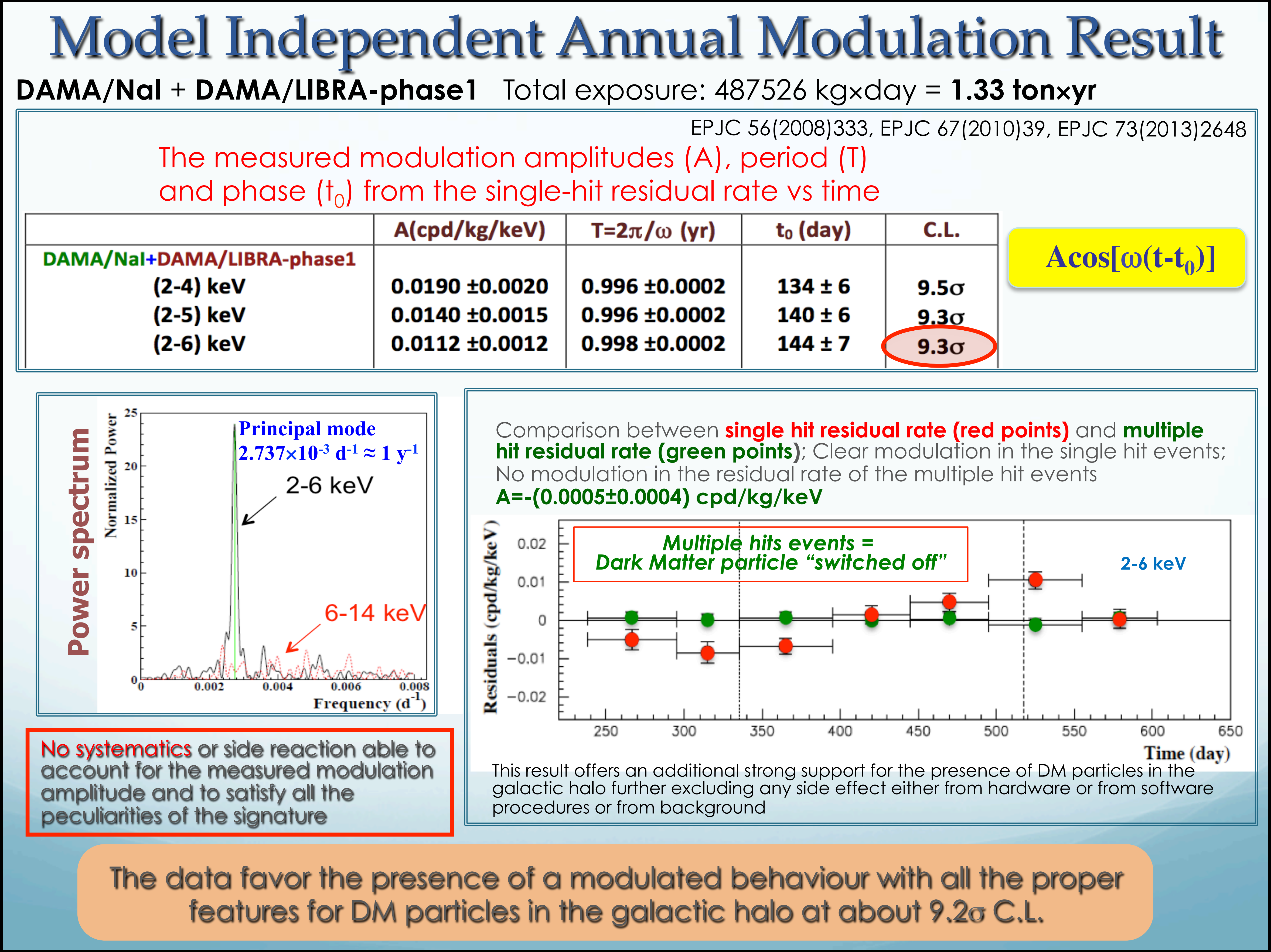
- DAMA observes such kind of modulation



9.3σ detection

Bernabei et al 1997-now

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**

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

Power spectrum

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

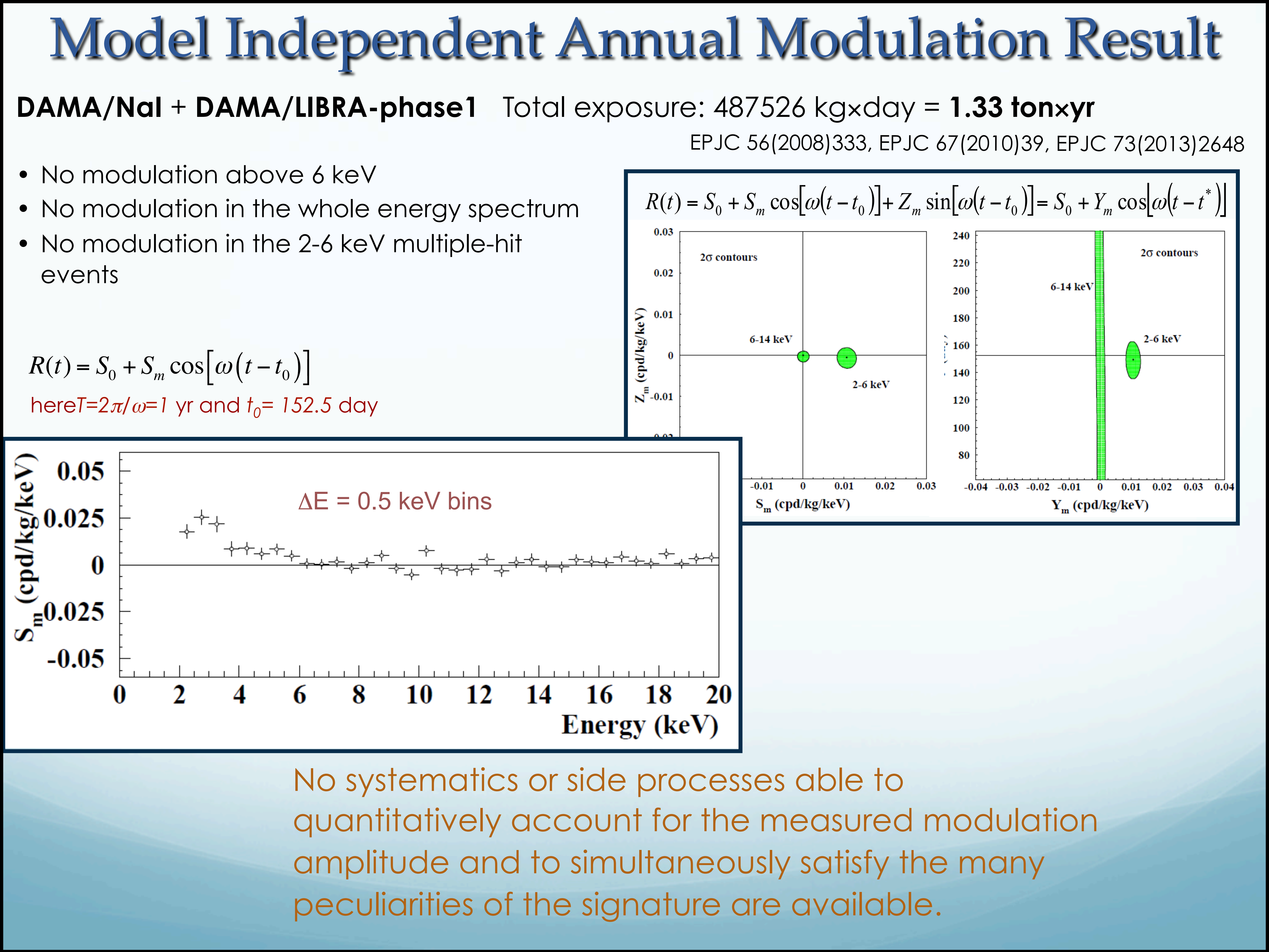
A=-(0.0005±0.0004) cpd/kg/keV

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

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

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

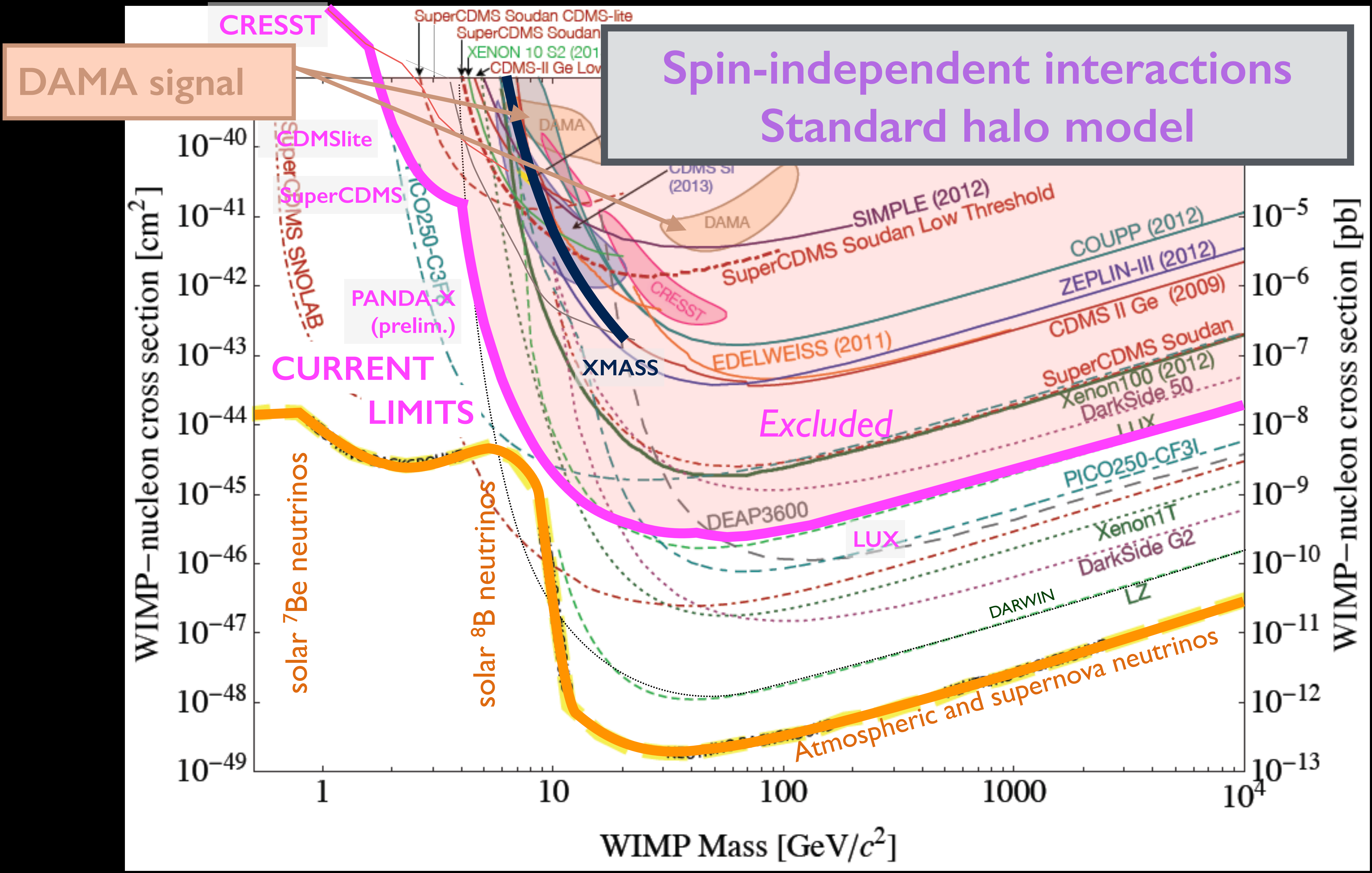
$$R(t) = S_0 + S_m \cos\left[\omega(t - t_0)\right] + Z_m \sin\left[\omega(t - t_0)\right] = S_0 + Y_m \cos\left[\omega(t - t^*)\right]$$

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



DAMA signal

Spin-independent interactions
Standard halo model

Billard+ 2013; CDMSlite, CRESST 2015; LUX, PANDA-X, XMASS 2016

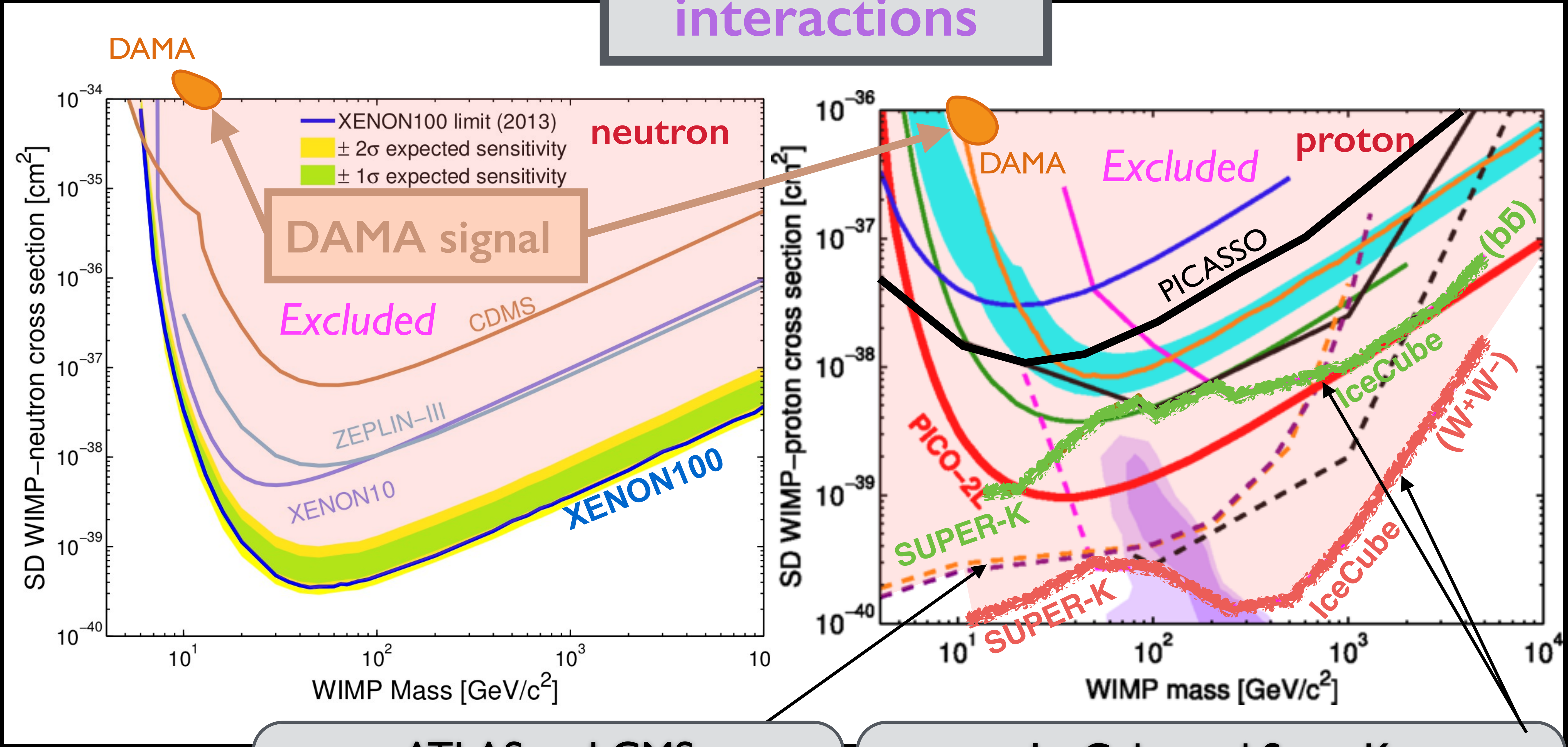
Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments

Spin-dependent interactions

Aprile et al (XENON100) 2013

Amole et al (PICO) 2015



ATLAS and CMS
(WIMP production at the LHC)

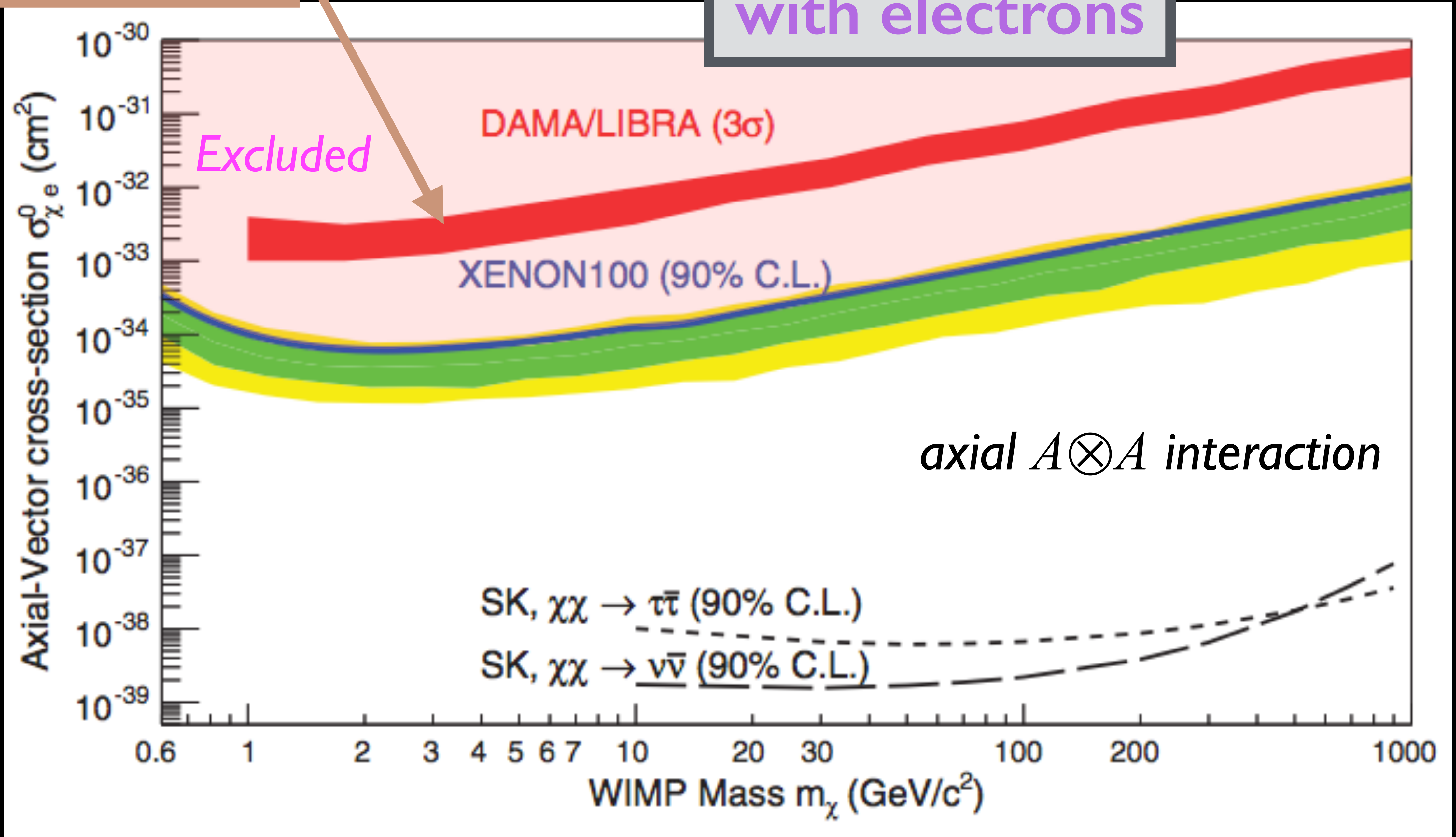
IceCube and SuperK
(high-energy neutrinos from the Sun)

Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments

DAMA signal

Interactions with electrons



Excluded

axial $A \otimes A$ interaction

Aprile et al (XENON100) 2015

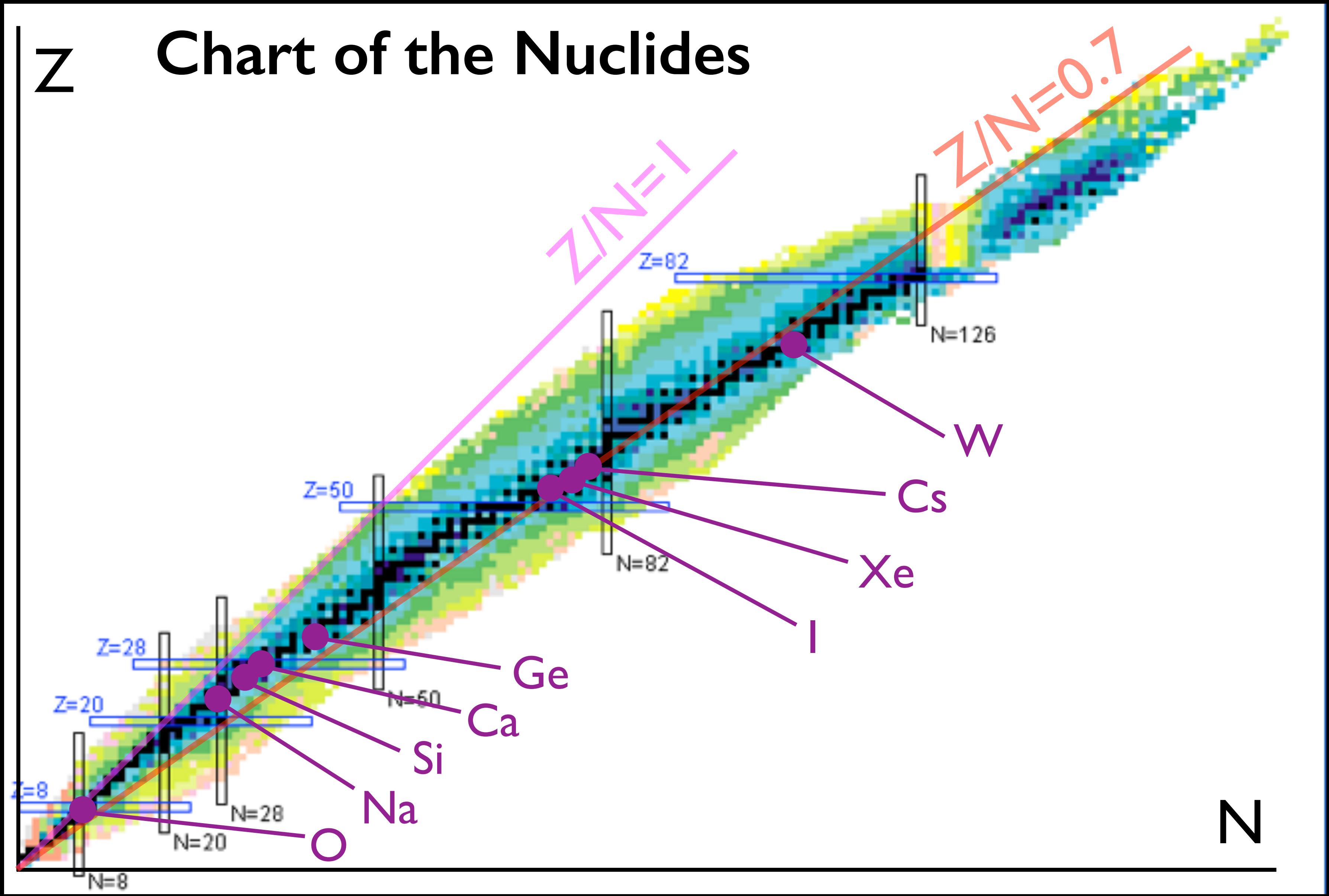
Isospin-violating (nonisoscalar) dark matter

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

Theoretical attempts to make DAMA compatible with other experiments have introduced velocity and/or energy-transfer dependences in the scattering cross section

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

Current trends

Make no assumptions

All particle physics models

- Consider all possible interactions between dark matter and standard model particles
- This program has been carried out in some limits (e.g., non-relativistic conditions, heavy mediators)

All astrophysical models

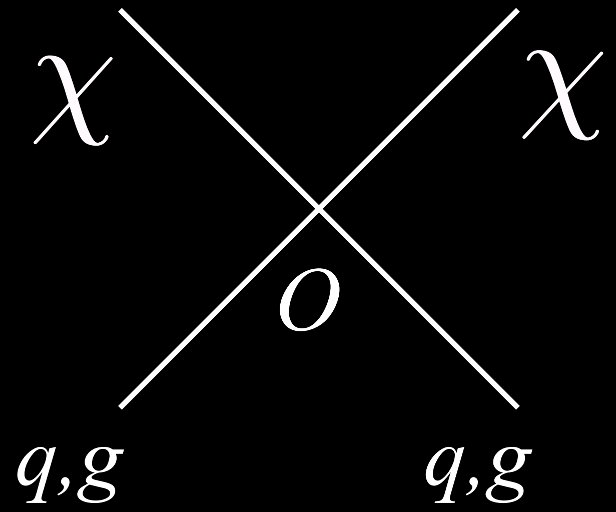
- Halo-independent methods of analysis have been developed
- Ideally they require no assumption on the astrophysical density and velocity distributions of dark matter particles

All particle physics models

Write down and analyze all possible WIMP interactions
with ordinary matter

Effective operators

if mediator mass ≫ exchanged energy



Four-particle effective operator

There are many possible operators.

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

Long(ish) distance interactions are not included.

Effective operators: LHC & direct detection

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

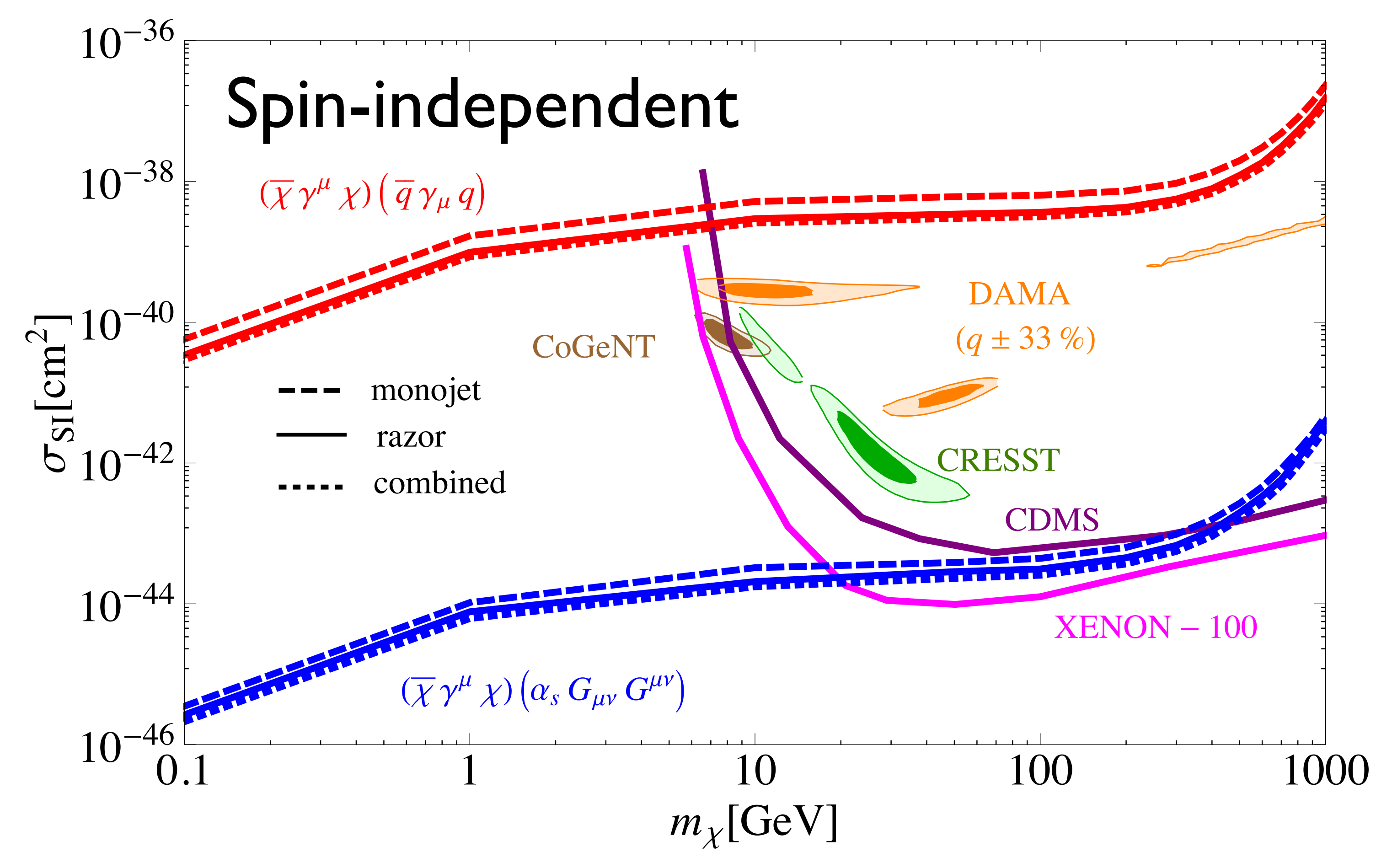
Table of effective operators relevant for the collider/direct detection connection

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2010

Effective operators: LHC & direct detection

LHC limits on WIMP-quark and WIMP-gluon interactions are competitive with direct searches

Beltran et al, Agrawal et al., Goodman et al., Bai et al., 2010; Goodman et al., Rajaraman et al. Fox et al., 2011; Cheung et al., Fitzptrick et al., March-Russel et al., Fox et al., 2012.......



Fox, Harnik, Primulando, Yu 2012

These bounds do not apply to SUSY, etc.

Complete theories contain sums of operators (interference) and not-so-heavy mediators (Higgs)

Effective operators: LHC & direct detection

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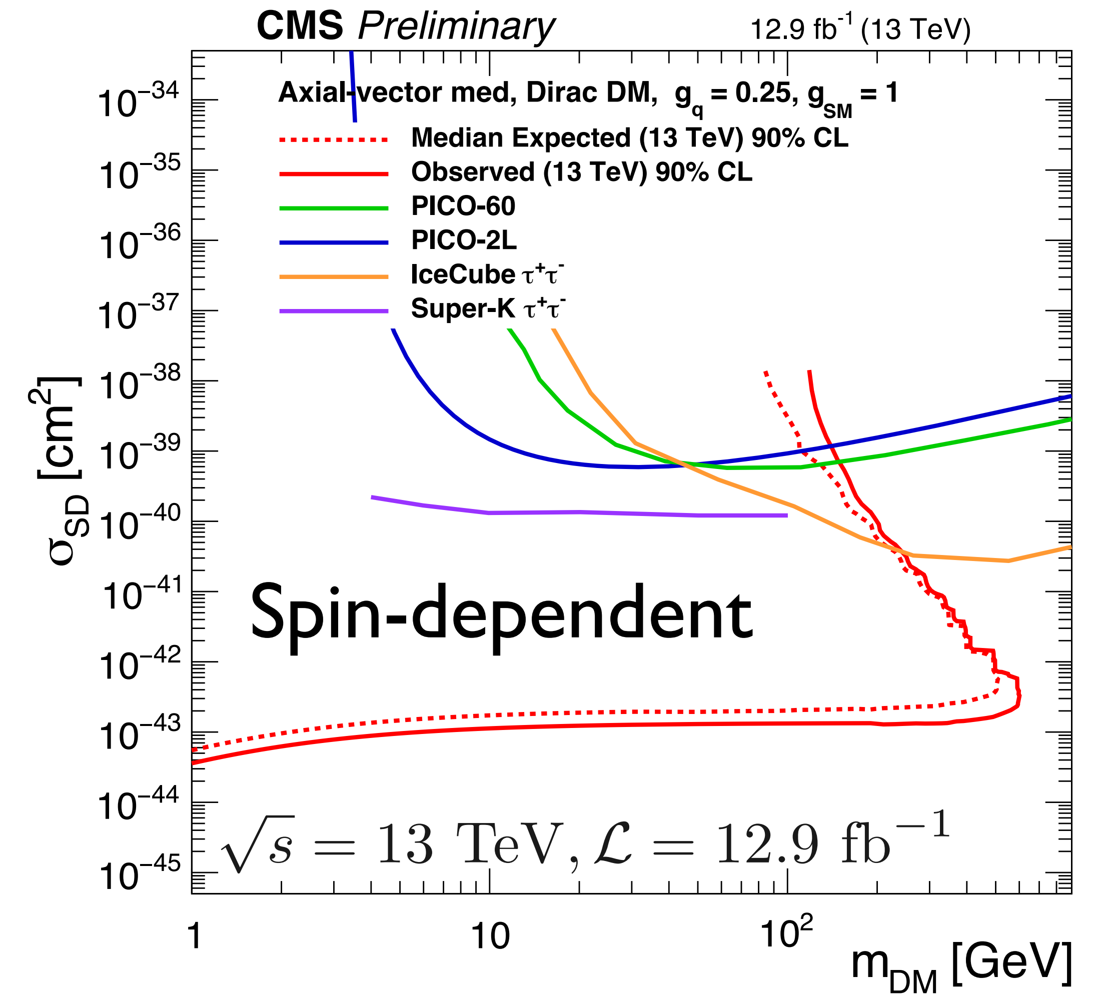


CMS Collaboration (EXO-16-037) 2016

These bounds do not apply to SUSY, etc.

Complete theories contain sums of operators (interference) and not-so-heavy mediators (Higgs)

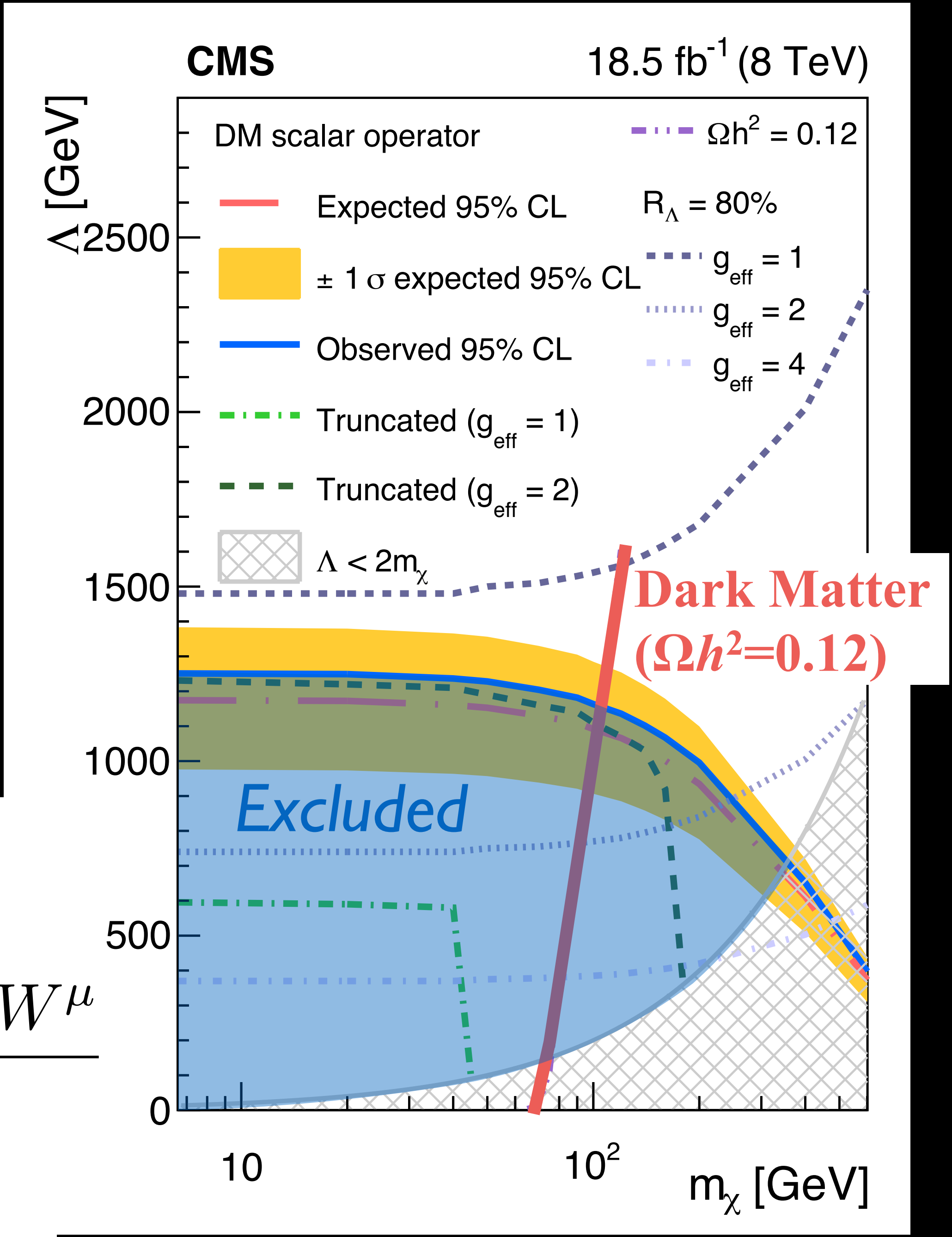
Effective operators: LHC & indirect detection

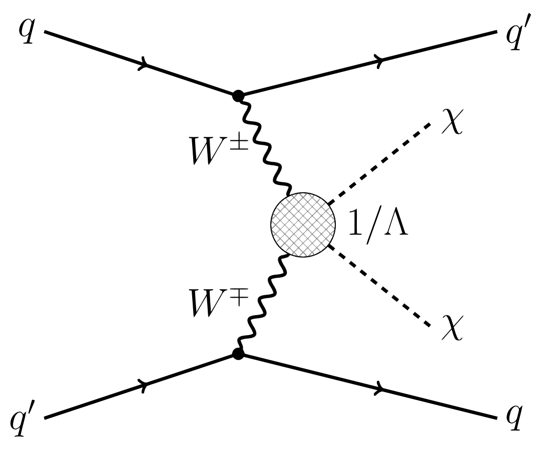
Limits on WIMP couplings to vector bosons (γ, W, g, …)

Name	Expression	Norm.	Vertices	Sub-Procs.	Ann.
$dim = 5$:					
D5a	$\bar{\chi}\chi V^{a\mu}V^a_\mu$	Λ^{-1}	4pt	ZZ,WW	v^2
D5b	$\bar{\chi}i\gamma_5\chi V^{a\mu}V^a_\mu$	Λ^{-1}	4pt	ZZ,WW	1
D5c	$\bar{\chi}\sigma_{\mu\nu}t^a\chi V^{a\mu\nu}$	Λ^{-1}	3/4pt	A,Z,WW	1
D5d	$\bar{\chi}\sigma_{\mu\nu}t^a\chi \widetilde{V}^{a\mu\nu}$	Λ^{-1}	3/4pt	A,Z,WW	1 (VV), v^2 ($f\bar{f}$)
$dim = 6$:					
D6a	$\bar{\chi}\gamma_\mu t^a D_\nu\chi V^{a\mu\nu}$	Λ^{-2}	3/4pt	A,Z,WW	1
D6b	$\bar{\chi}\gamma_\mu\gamma_5 t^a D_\nu\chi V^{a\mu\nu}$	Λ^{-2}	3/4pt	A,Z,WW	1 (VV), v^2 ($f\bar{f}$)
$dim = 7$:					
D7a	$\bar{\chi}\chi V^{\mu\nu}V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	v^2
D7b	$\bar{\chi}i\gamma_5\chi V^{\mu\nu}V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	1
D7c	$\bar{\chi}\chi V^{\mu\nu}\widetilde{V}_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	v^2
D7d	$\bar{\chi}i\gamma_5\chi V^{\mu\nu}\widetilde{V}_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	1

Cotta, Hewett, Le, Rizzo 2013

The CMS Collaboration, 2016





$$\frac{\bar{\chi}\chi W_\mu W^\mu}{\Lambda}$$

Limits on non-standard-model dijets with vector boson fusion topology

Beyond effective operators: Simplified Models

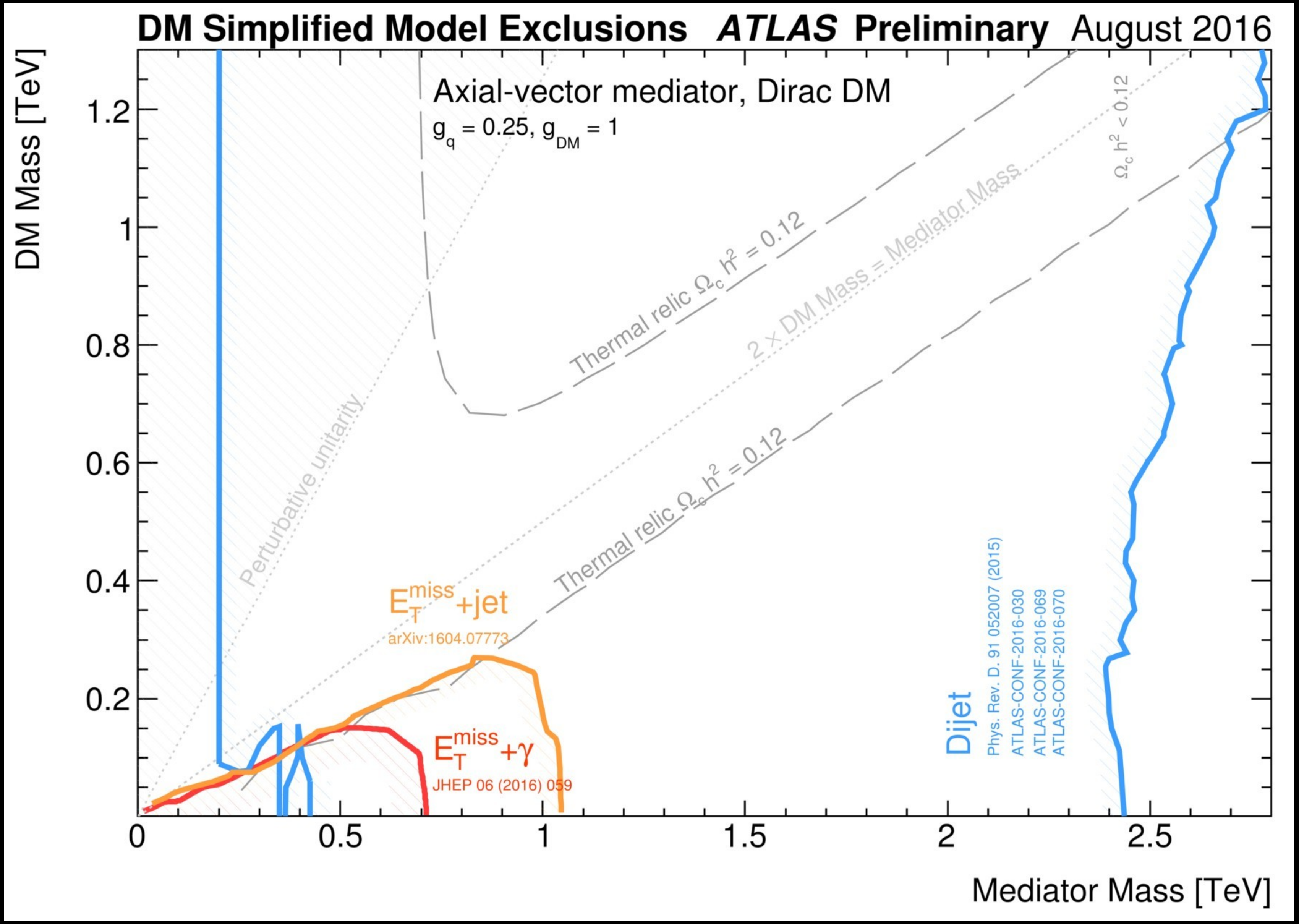
Assume new particles and interactions, without forcing a complete theory

Alwall, Schuster, Toro 2009

Example: axial-vector mediator

$$\mathcal{L} = -g_q\,\phi\,\bar{q}\,\gamma_5\,q - g_{\rm DM}\,\phi\,\bar{\chi}\,\gamma_5\,\chi$$

ATLAS Collaboration, 2016
(from Petersen, this conference)

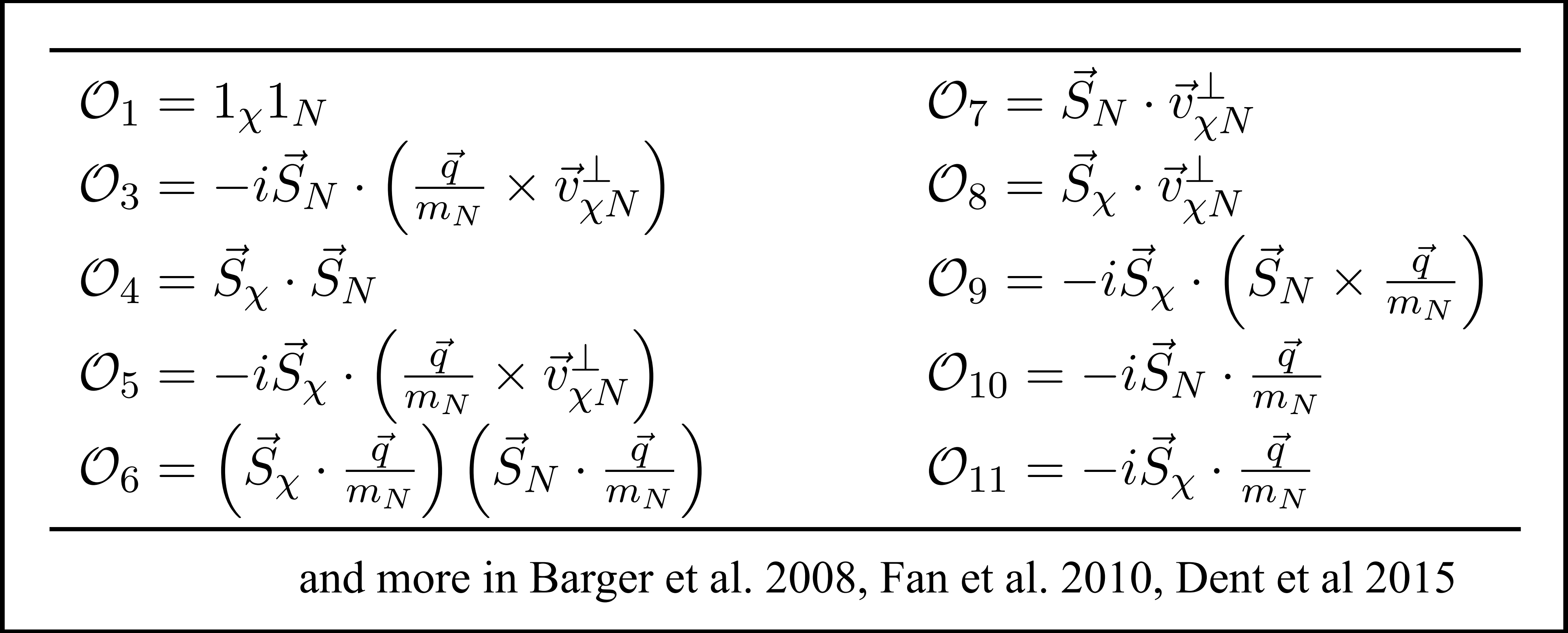


Exclusion regions depend strongly on model and coupling strengths

Nonrelativistic contact operators

Nonrelativistic WIMP-nucleon contact operators classified

Barger et al 2008, Fan et al 2010, Fitzpatrick et al 2012, Dent et al 2015



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

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

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

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

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

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

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

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

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

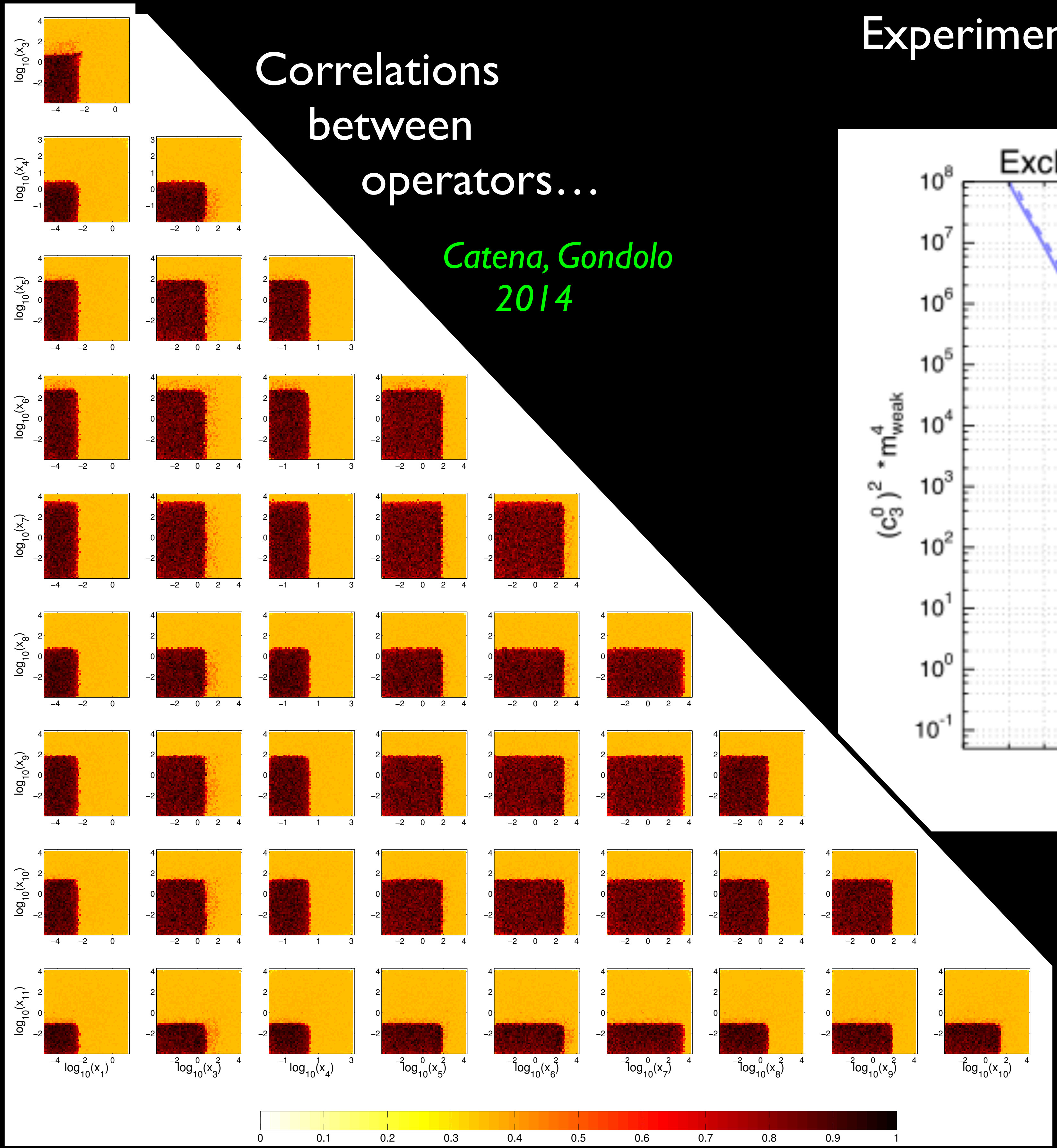
$$\mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

and more in Barger et al. 2008, Fan et al. 2010, Dent et al 2015

At leading order in q and v, only O_1 and O_4 appear, which are the spin-independent and spin-dependent terms, respectively.

Nuclear form factors available from measurements or computations (shell model, harmonic oscillator model, …)

Nonrelativistic contact operators

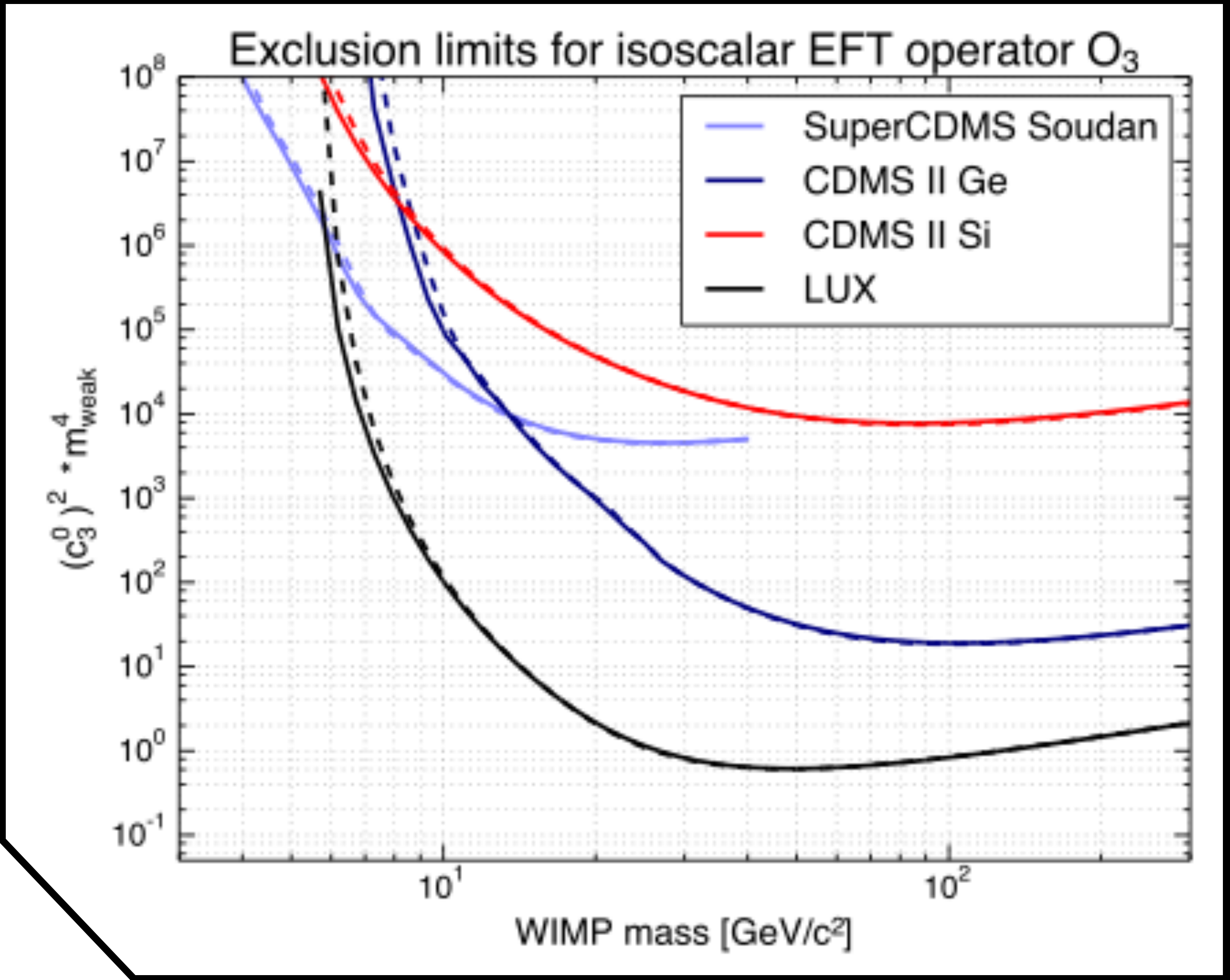


Correlations between operators…

Catena, Gondolo 2014

Experimental limits on single operators…

Schneck et al (SuperCDMS) 2015



Indirect detection…

Catena 2016

Nucleon matrix elements

To connect high-energy theories to the nonrelativistic contact operators one must obtain WIMP-nucleon interactions from WIMP-quark and WIMP-gluon interactions.

Nucleon matrix elements of quark and gluon currents

$$\langle N|\bar{q}\Gamma_i q|N\rangle = \sum_j f_{ij}^{(q,N)}\,\overline{N}\Gamma_j N \qquad (q = u, d, s)$$

$$\langle N|G^a_{\mu\nu}G^a_{\lambda\rho}h_i^{\mu\nu\lambda\rho}|N\rangle = \sum_j f_{ij}^{(g,N)}\,\overline{N}\Gamma_j N$$

See e.g. Kaplan, Manohar 1988; Cheng 1989; Drees, Nojiri 1993; Adam+ 1995; Aoki+ 1997; Mallot 1999; Pospelov&Ritz, Leinweber+ 2004; Doi+ 2009; Alekseev+ 2010; Bacchetta+, Bali+, Hisano+ 2012; Anselmino+, Dienes+, Fuyuto+ 2013; Hill&Solon 2014; Agrawal+, Bhattacharya +, Hisano+ 2015, …

Systematic analysis under way: some large uncertainties, some unknown matrix elements, ……

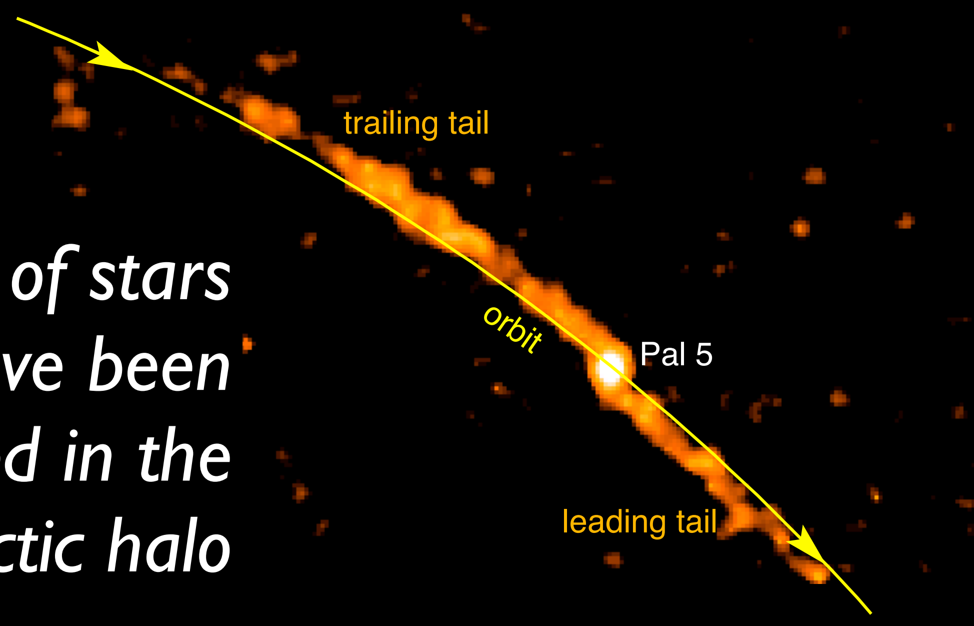
All astrophysics models

Do not assume any particular
WIMP density or velocity distribution

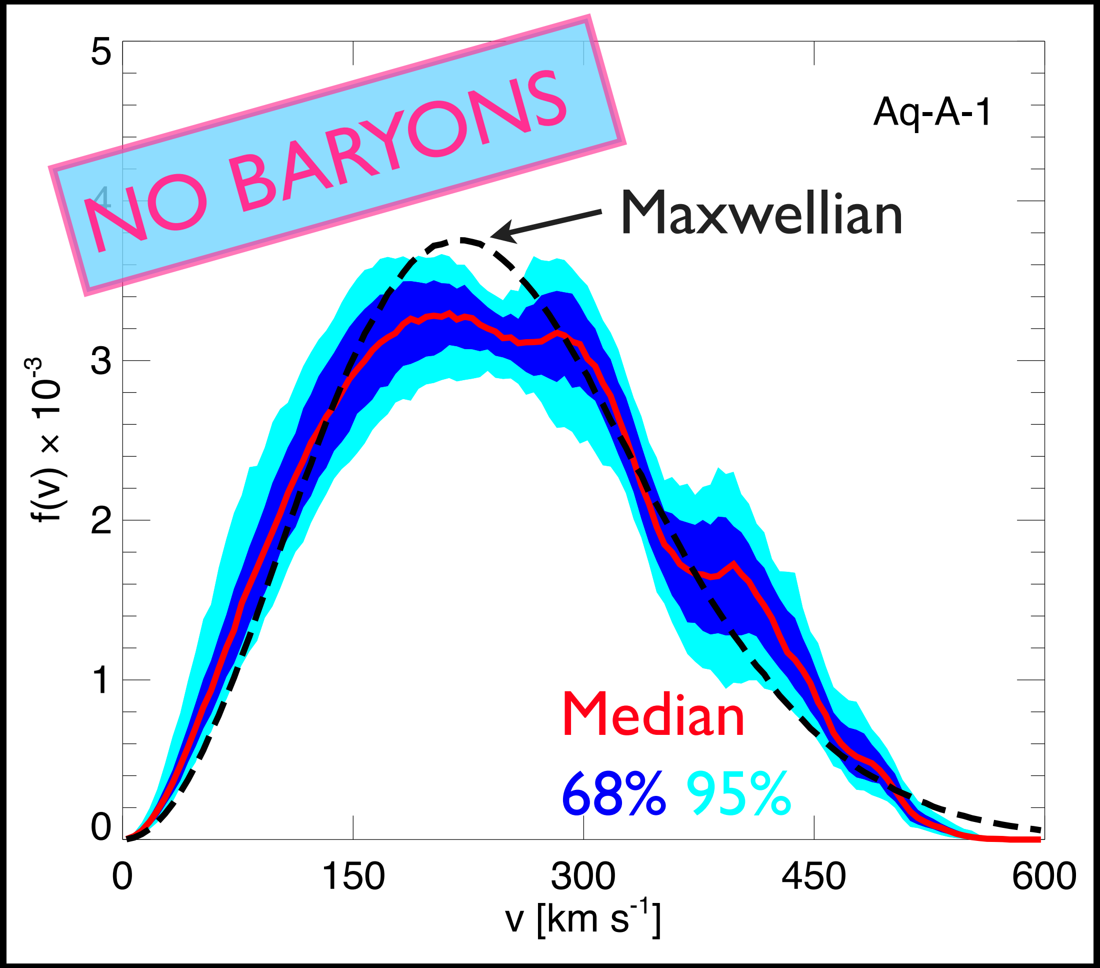
Astrophysics-independent approach

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

Streams of stars have been observed in the galactic halo

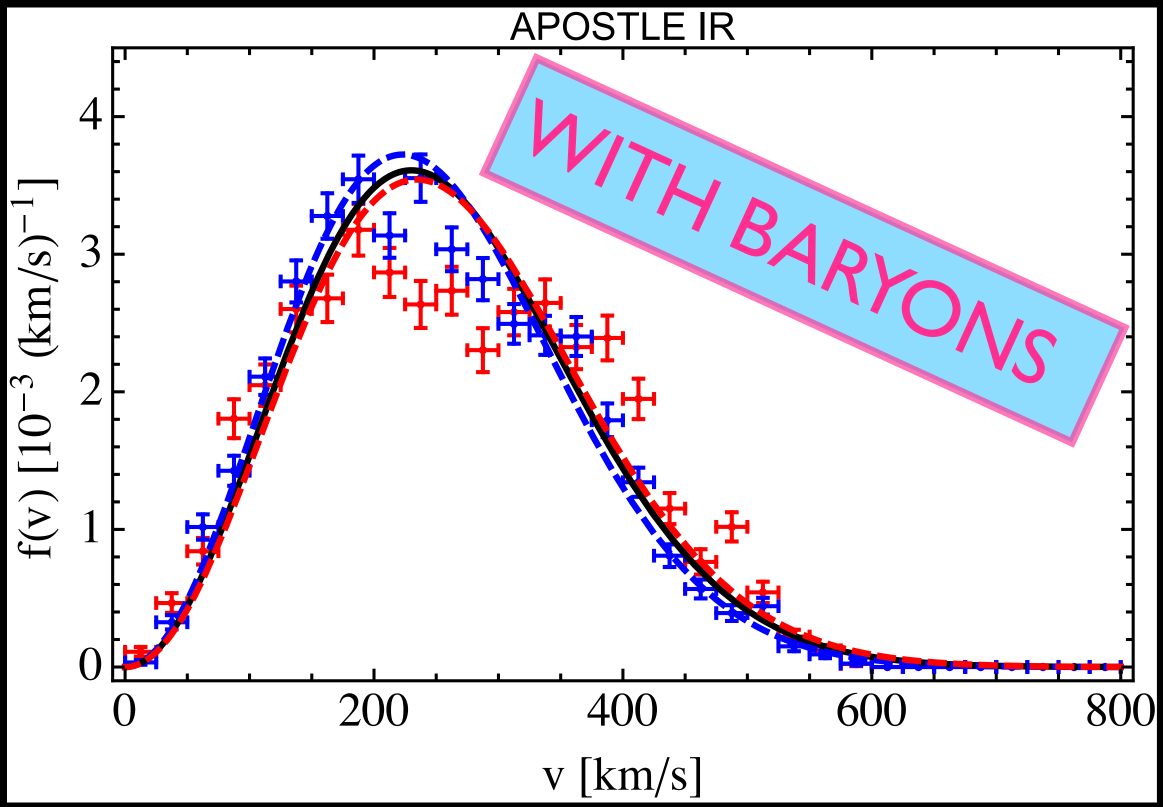


Odenkirchen et al 2002 (SDSS)



Vogelsberger et al 2009

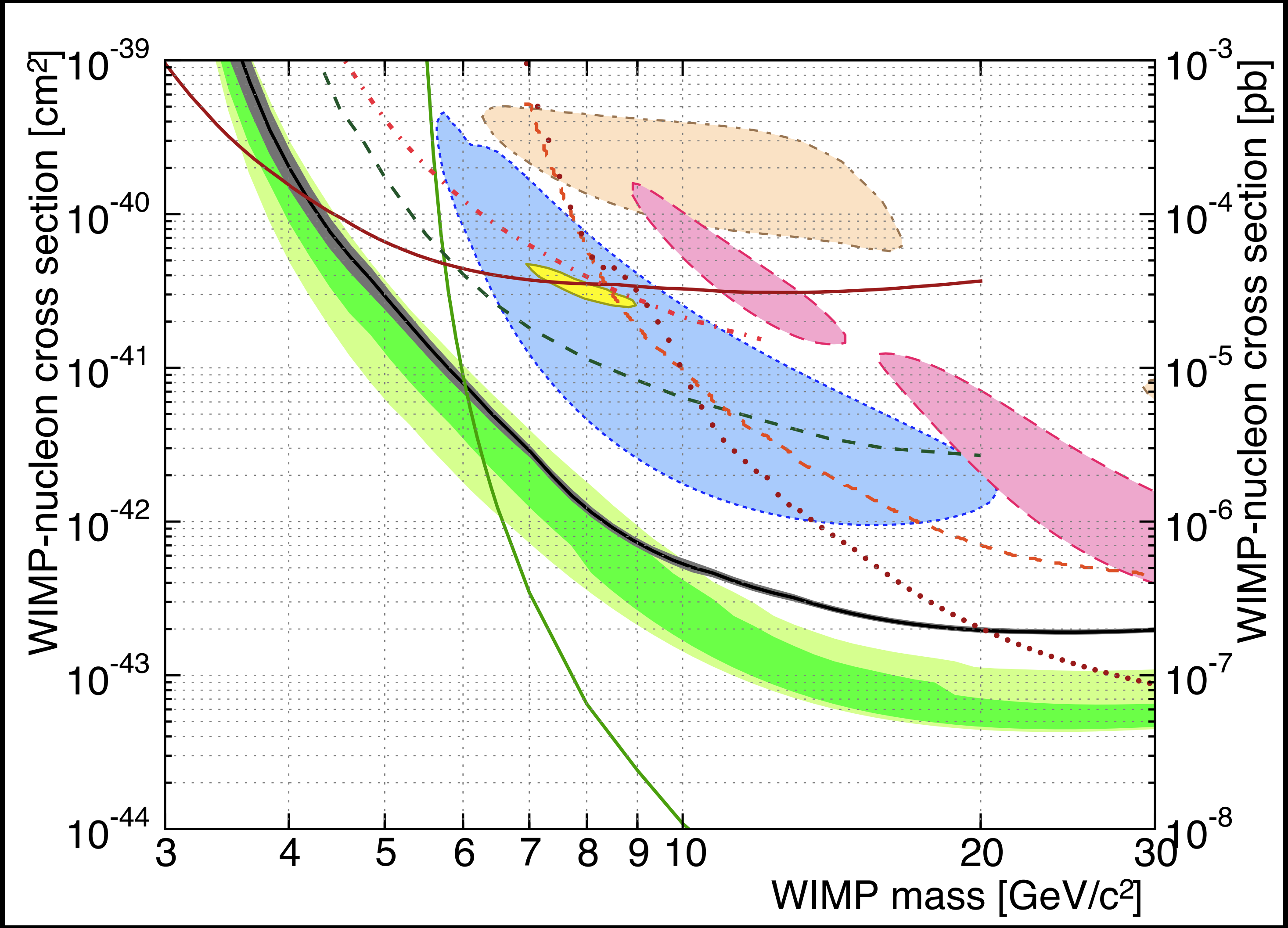
Cosmological N-Body simulations including baryons are challenging but underway



Bozorgnia et al 2016

Astrophysics model: velocity distribution

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



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

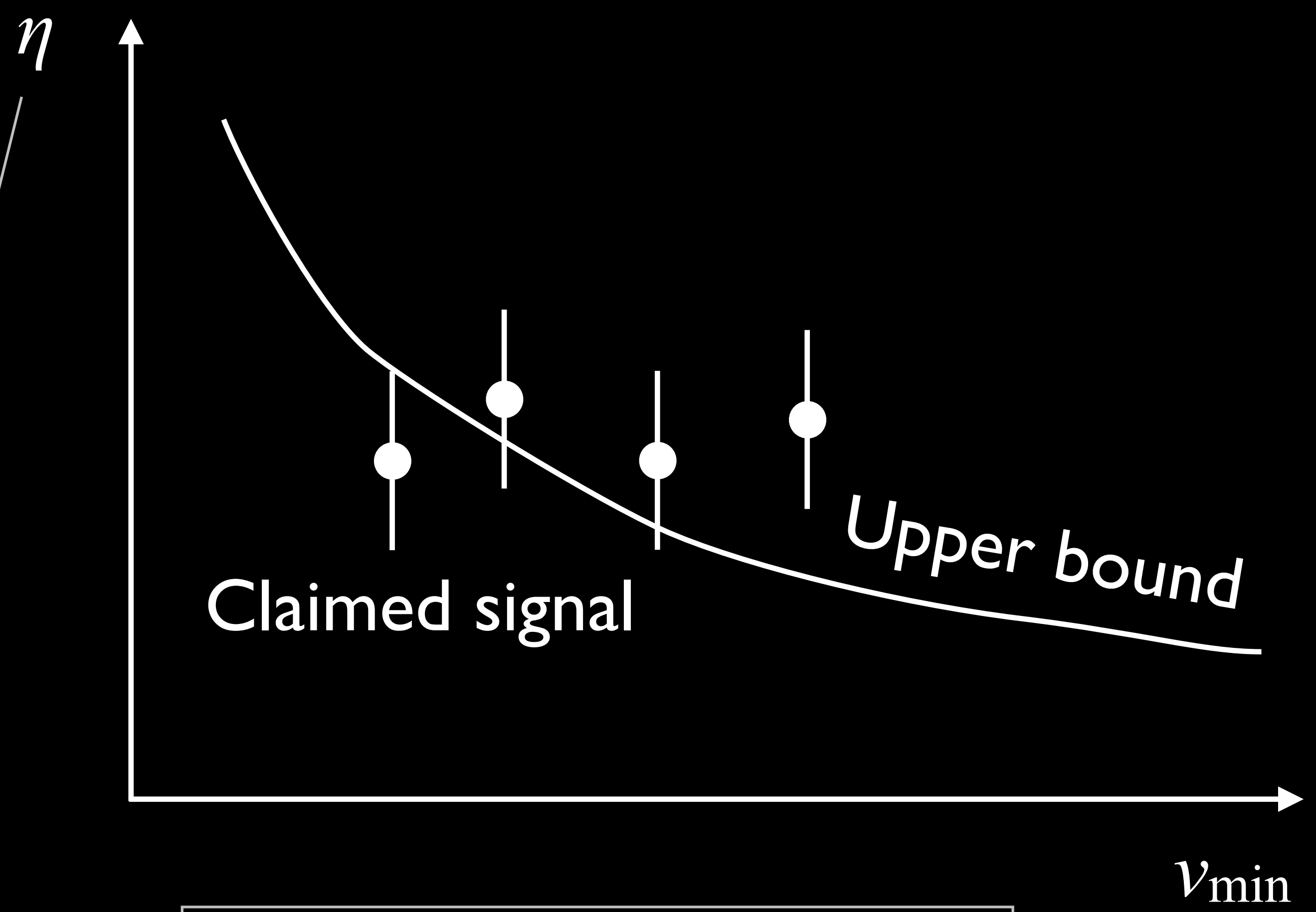
Astrophysics-independent approach

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

Rescaled astrophysics factor common to all experiments

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

Proxy for dark matter flux



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

Gondolo Gelmini 2012

- The measured rate is a "weighted average" of the astrophysical factor.

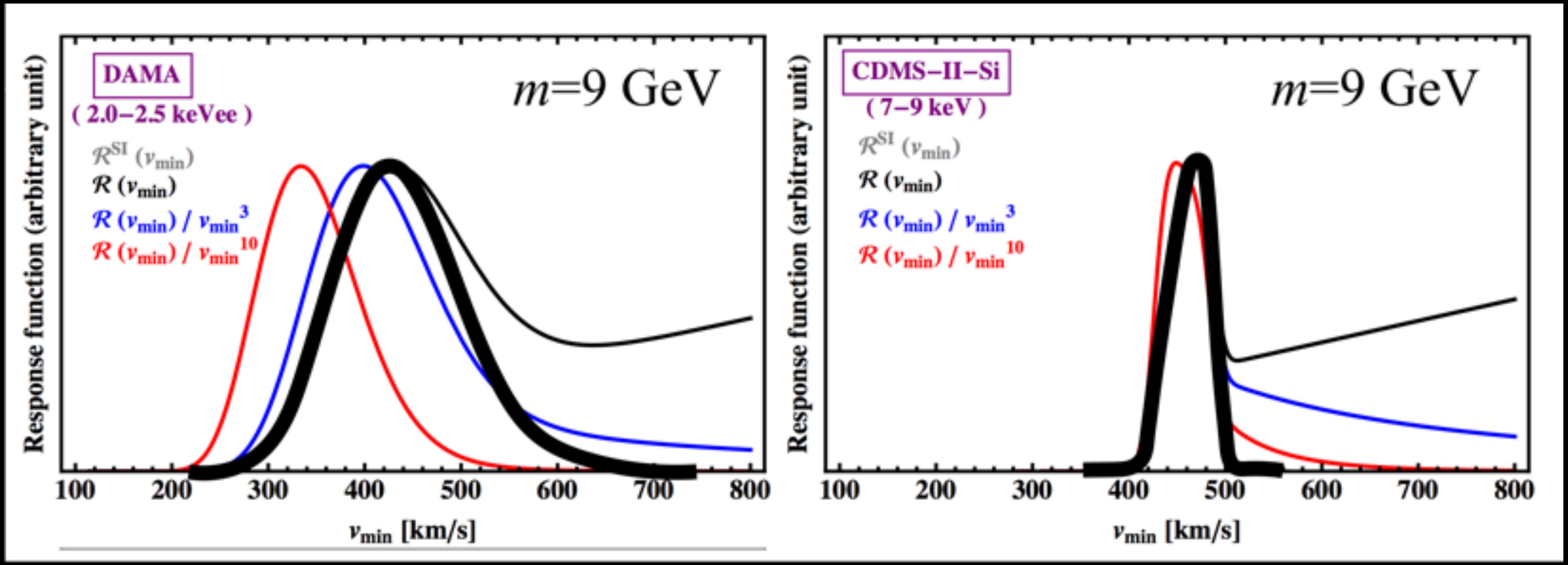
Measured rate

Rescaled astrophysics factor

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

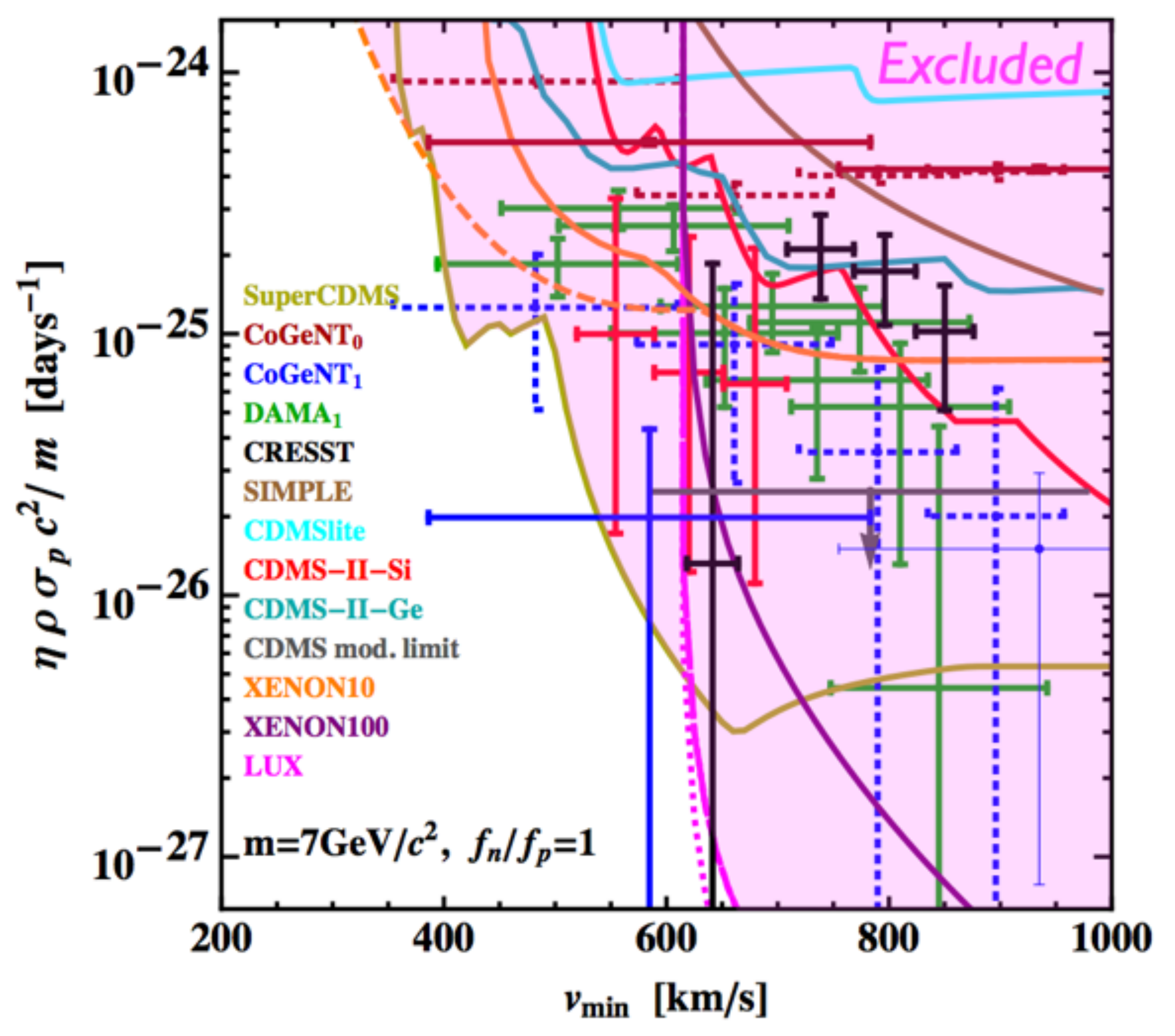
Response function

- Every experiment is sensitive to a "window in velocity space."



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

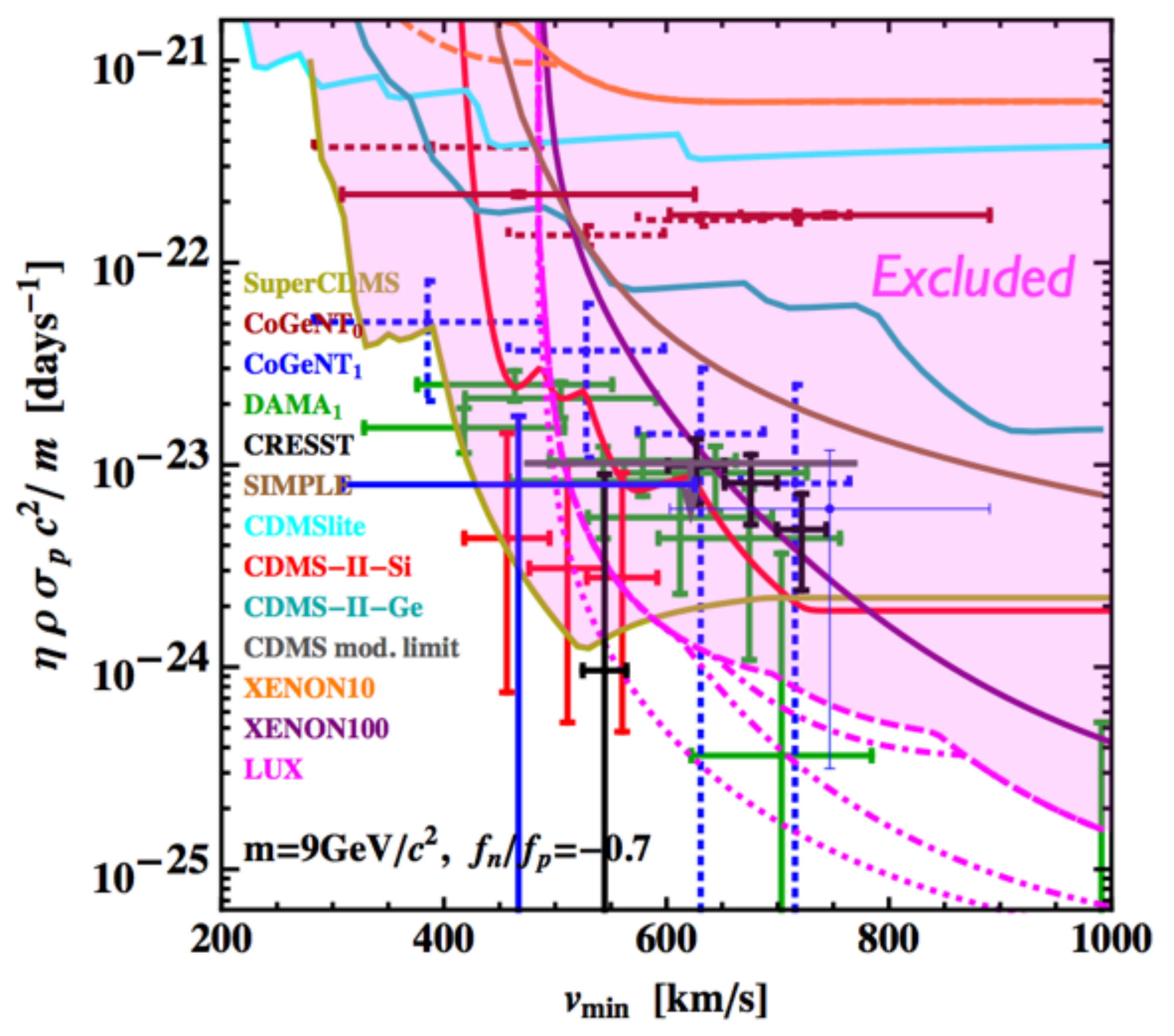
CDMS-Si event rate is similar to yearly modulated rates

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

Spin-independent nonisoscalar interactions

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



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

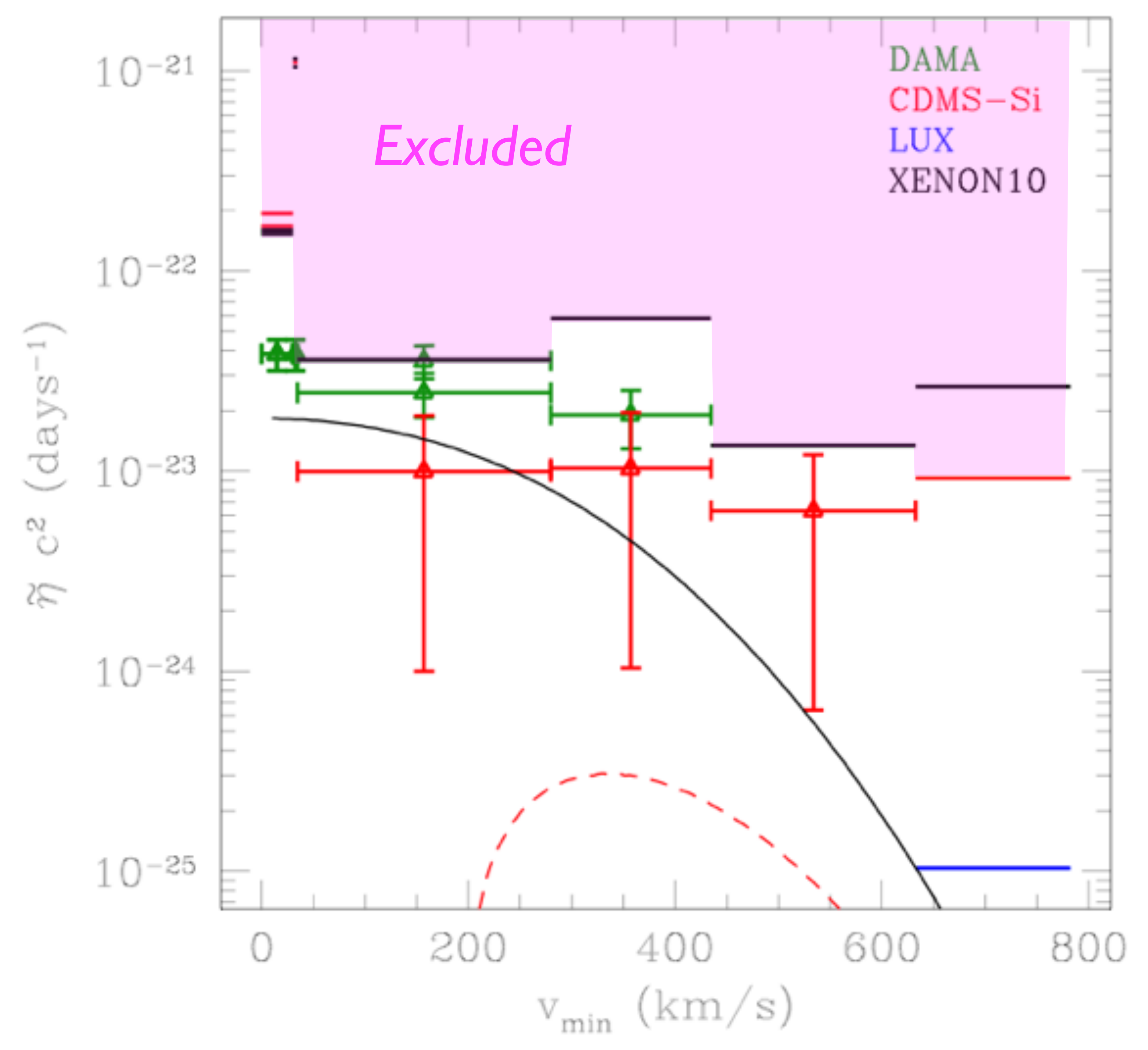
The CDMS-Si events lie "below" the CoGeNT/DAMA modulation amplitudes

Still depends on
particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

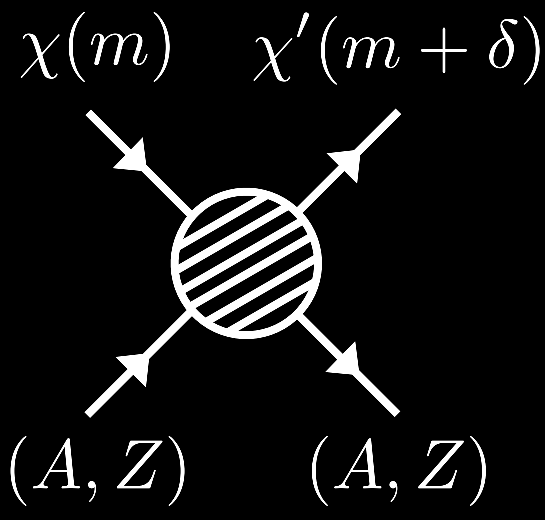
Exothermic nonisoscalar scattering

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



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

m = 3 GeV/c^2
δ = -70 keV
f_n/f_p = -0.79



Still depends on particle model

Scopel, Yoon 2014

Anapole dark matter

The anapole moment is a C and P violating, but CP-conserving, electromagnetic moment *Zeldovich 1957*

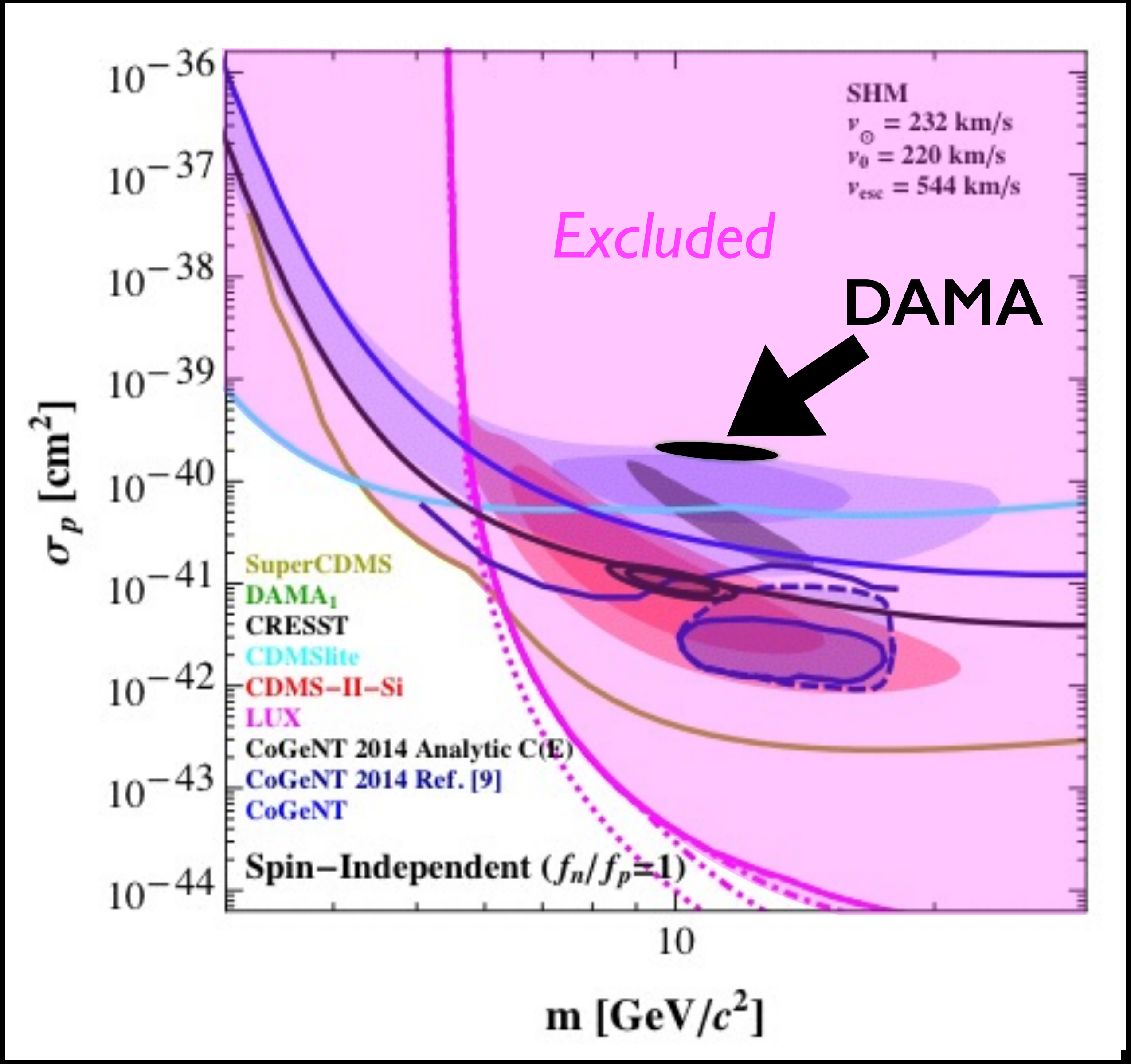
First measured experimentally in Cesium atoms *Wood et al 1997*

Anapole dark matter

spin-1/2 Majorana fermion

$$\mathcal{L} = \frac{g}{2\Lambda^2} \bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$

$$H = -\frac{g}{\Lambda^2}\,\vec{\sigma}\cdot\vec{\nabla}\times\vec{B}$$

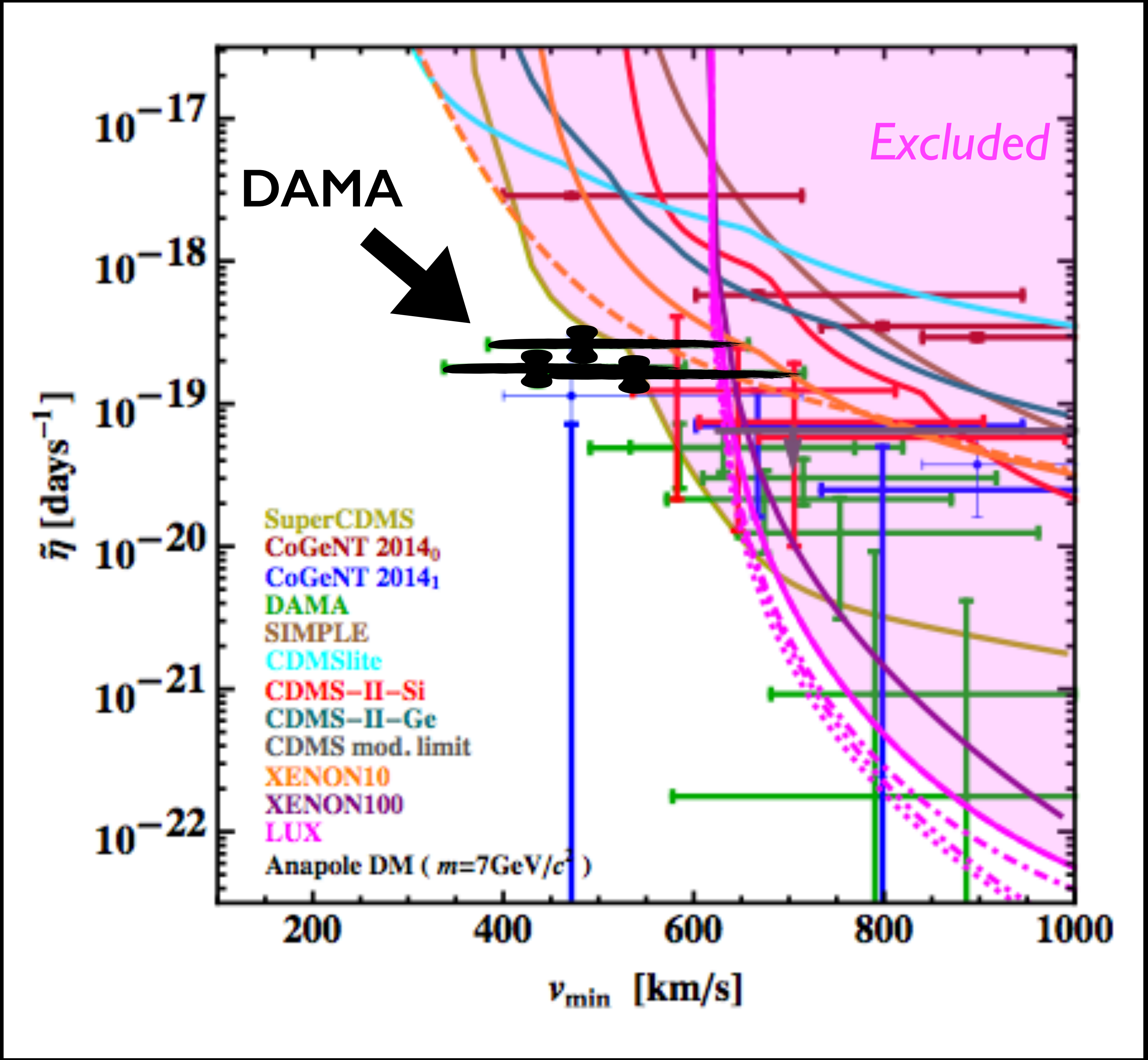


Direct detection limits
with standard dark halo

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

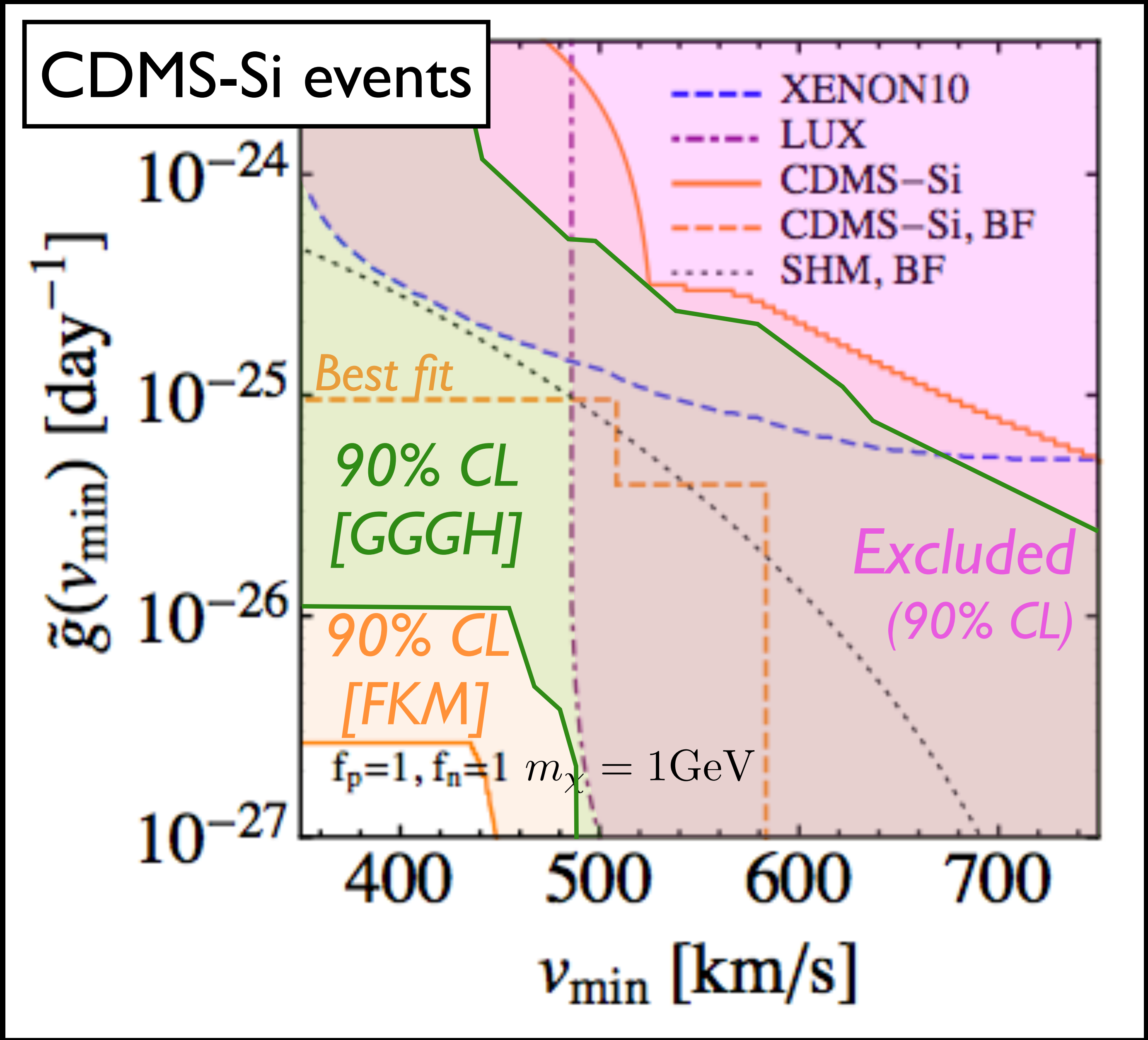
Astrophysics-independent approach

The statistics of the halo-independent approach is beginning to be understood.

Unbinned likelihood analysis

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

The extent of the 90% CL region is still unclear

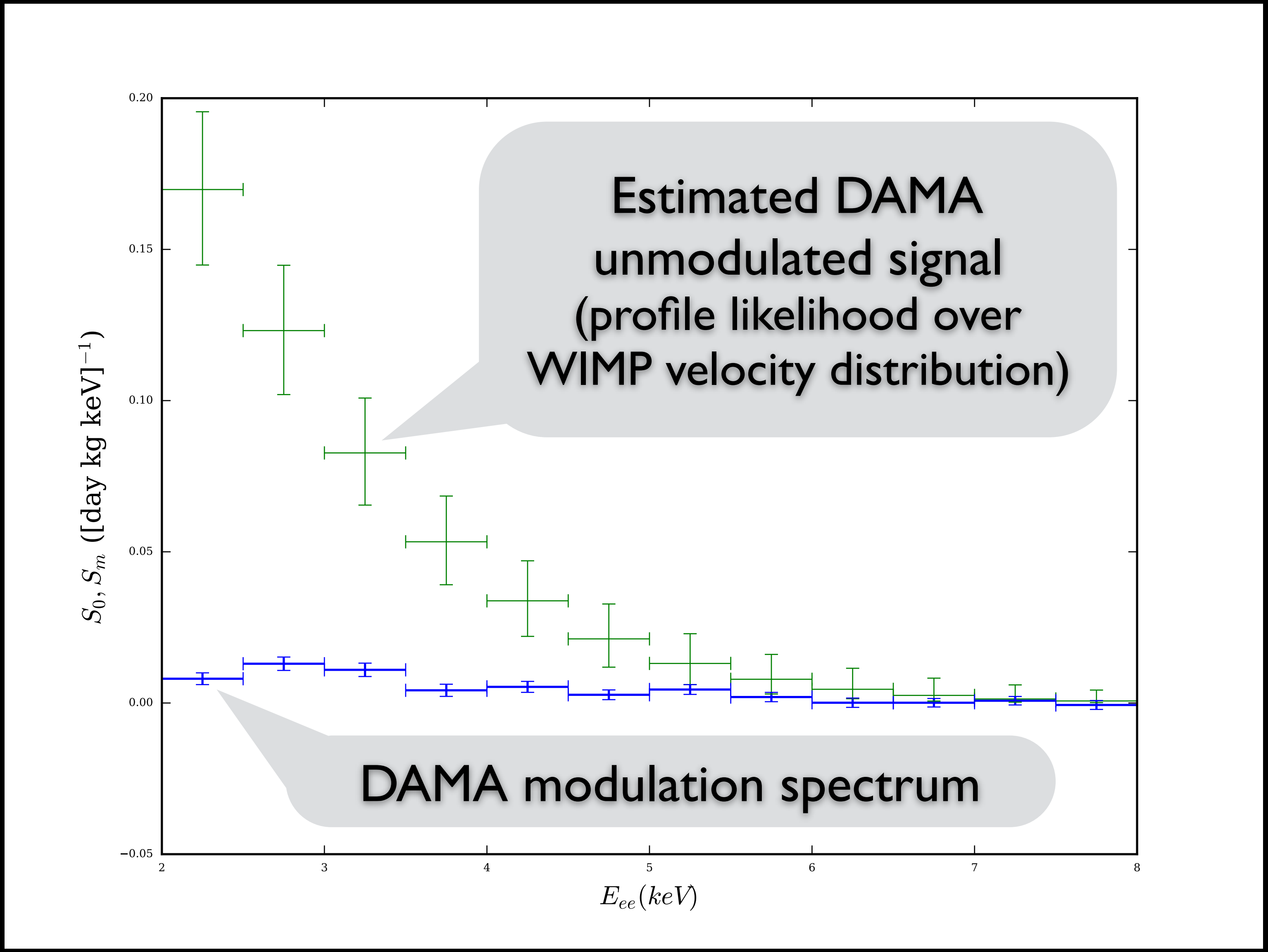


Fox, Kahn, McCullough 2015

Gelmini, Georgescu, Gondolo, Huh 2015

Astrophysics-independent approach

New techniques and proper statistical treatment let the astrophysics-independent approach address questions beyond the comparison of experiments.



Estimated DAMA unmodulated signal (profile likelihood over WIMP velocity distribution)

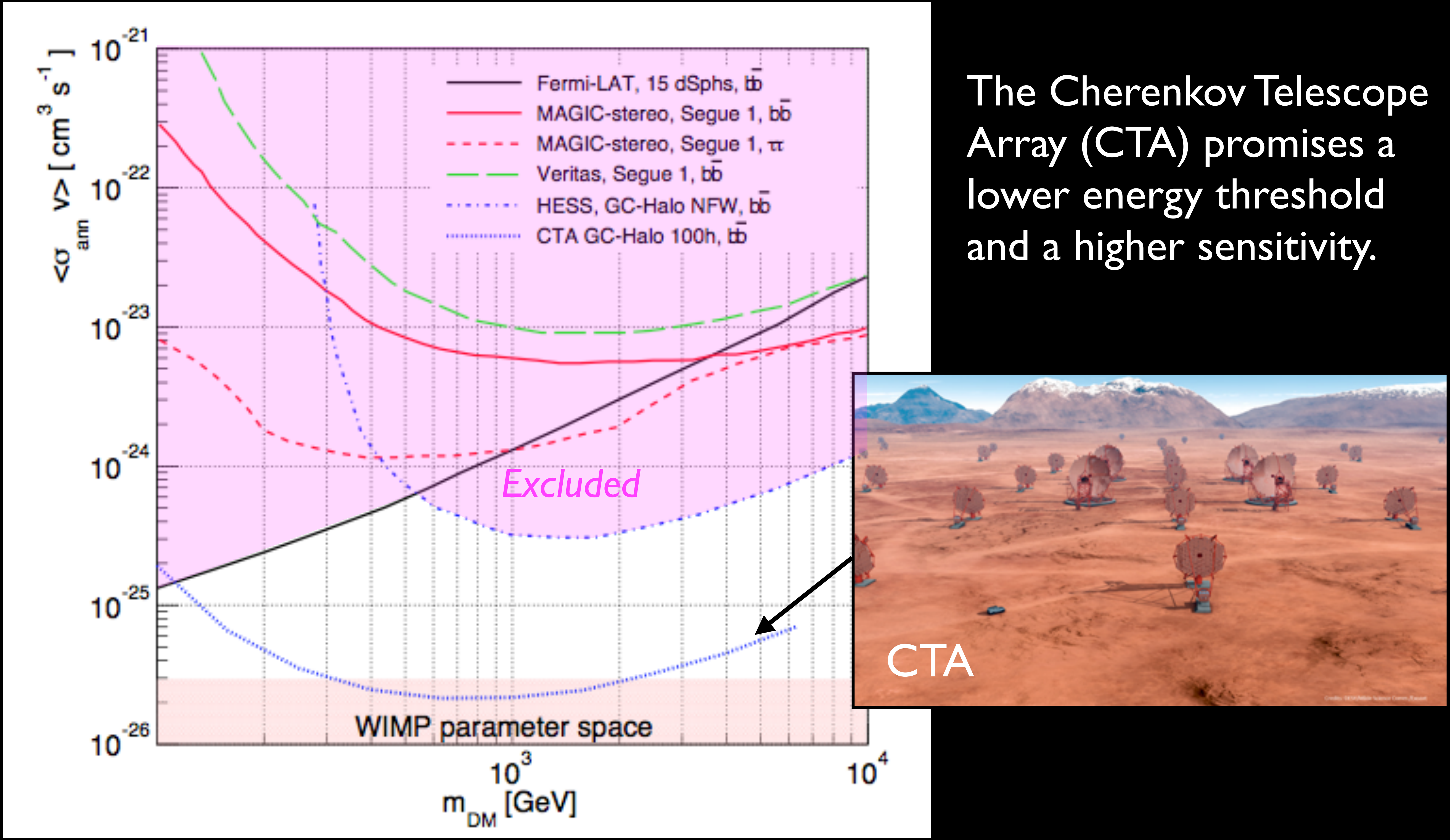
DAMA modulation spectrum

Astrophysics-independent estimate of the DAMA unmodulated signal

Gondolo, Scopel 2016
(in preparation)

In the next future

In the next future….. High-energy γ-rays



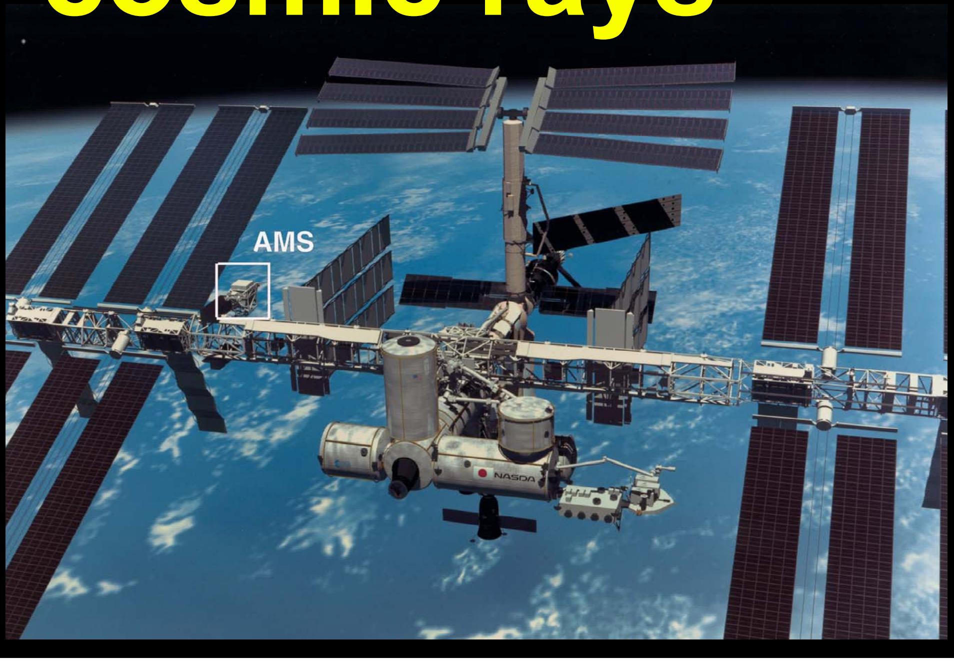
The Cherenkov Telescope Array (CTA) promises a lower energy threshold and a higher sensitivity.

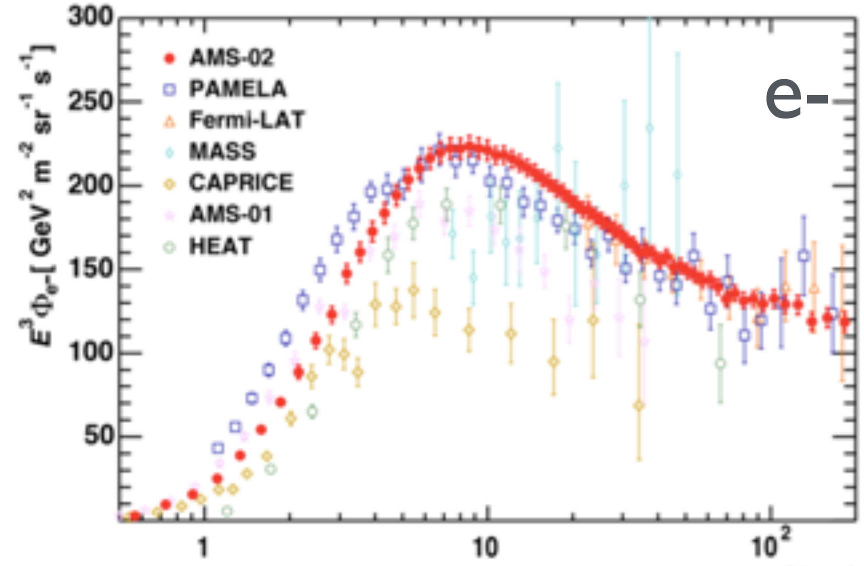
Doro, 2014

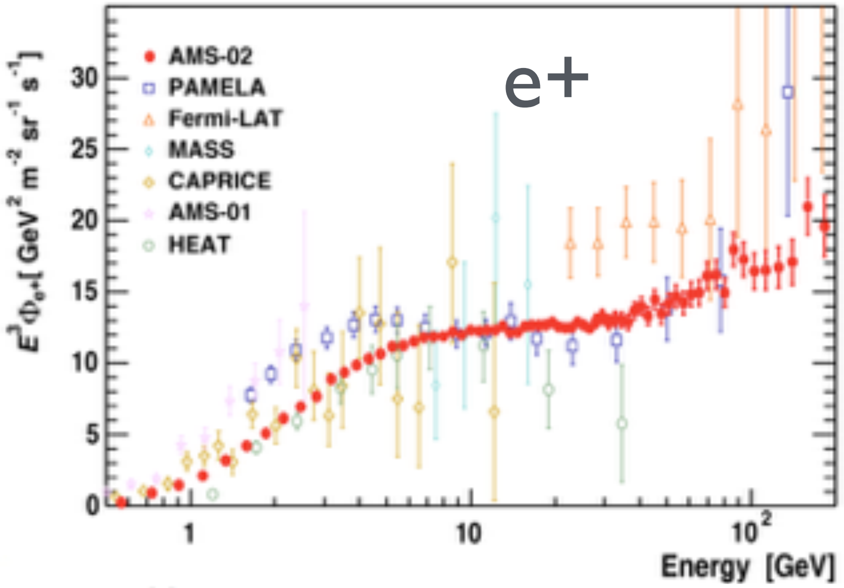
In the next future….. Precision cosmic rays

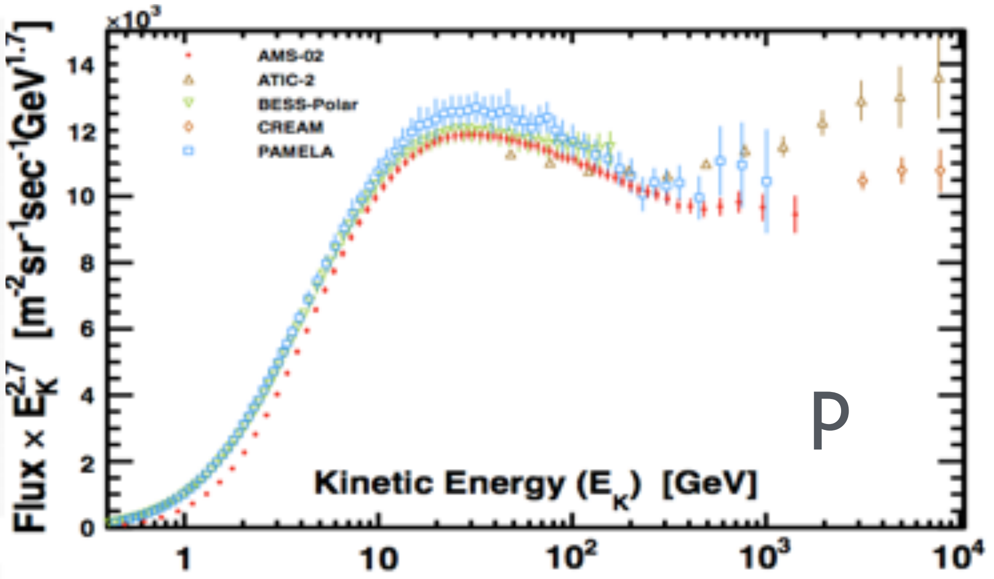
AMS (Alpha Magnetic Spectrometer)

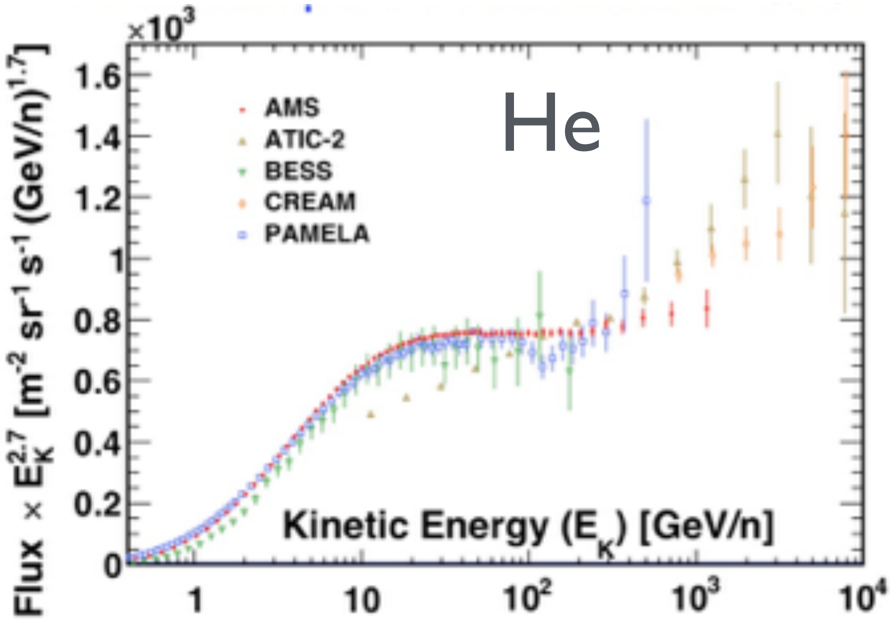
Isotopic ratios measured to better than 1% precision up to Fe and ~100 GeV/nucleon allow for better Galactic cosmic ray models

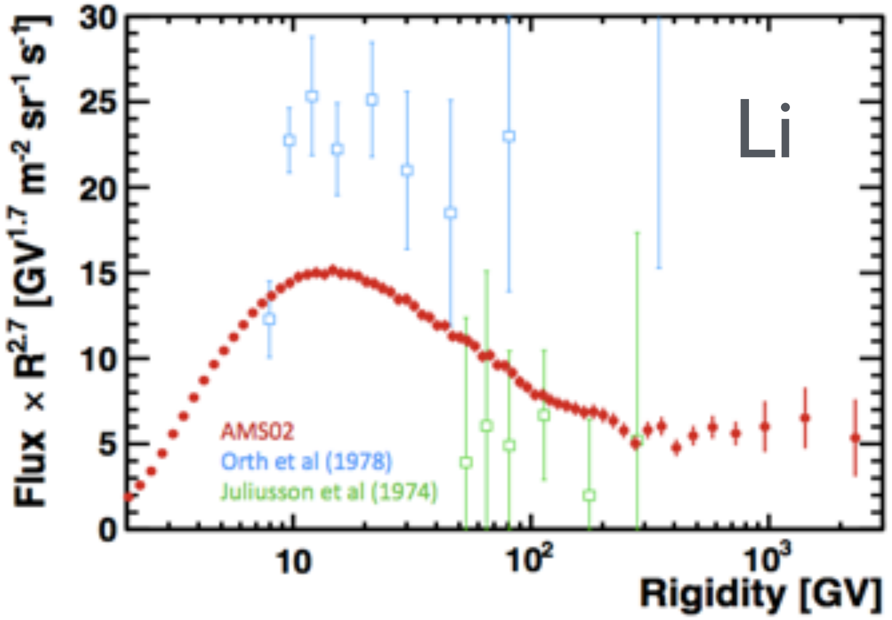


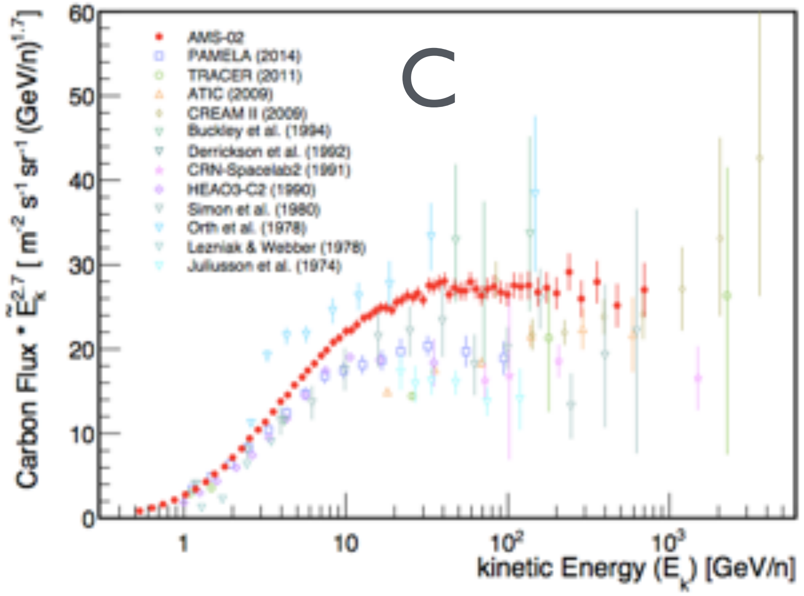








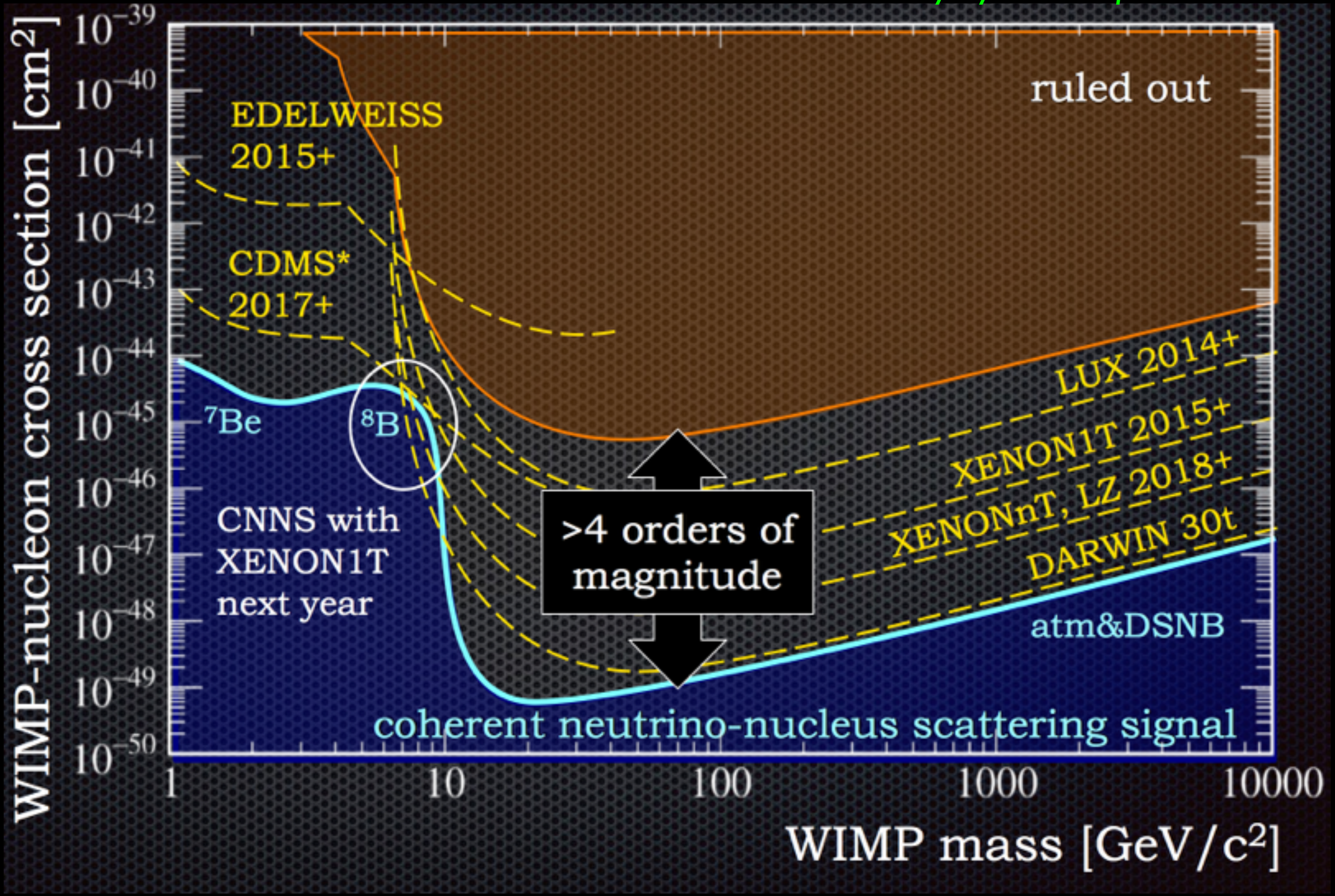




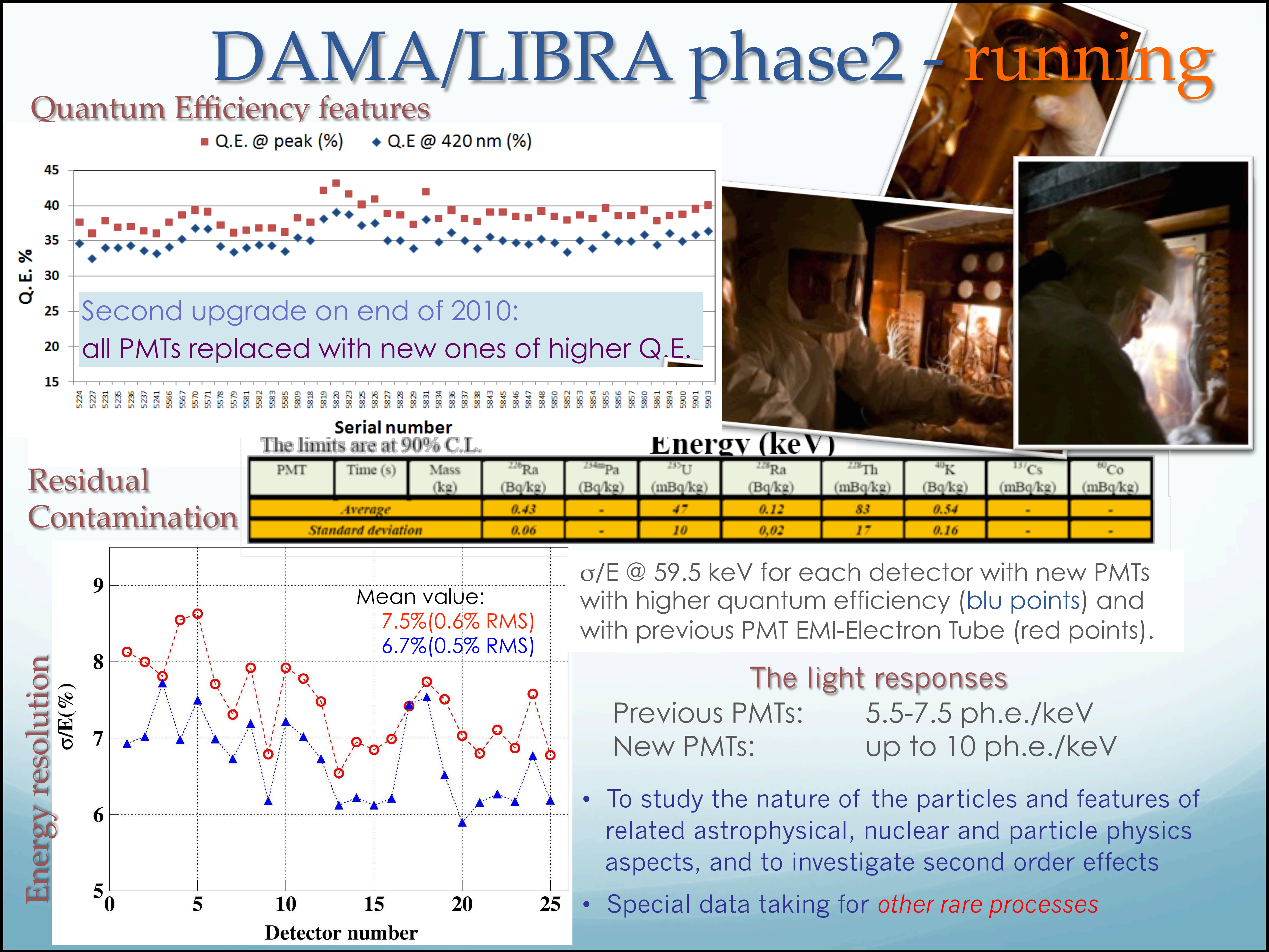
In the next future….. Giant direct detectors

SuperCDMS, LZ, XENON1T, XENONnT, XMASS, Darwin, ……..

Summary by Elena Aprile 2015



In the next future..... DAMA's revenge?



DAMA/LIBRA phase2 - running

Quantum Efficiency features

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

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

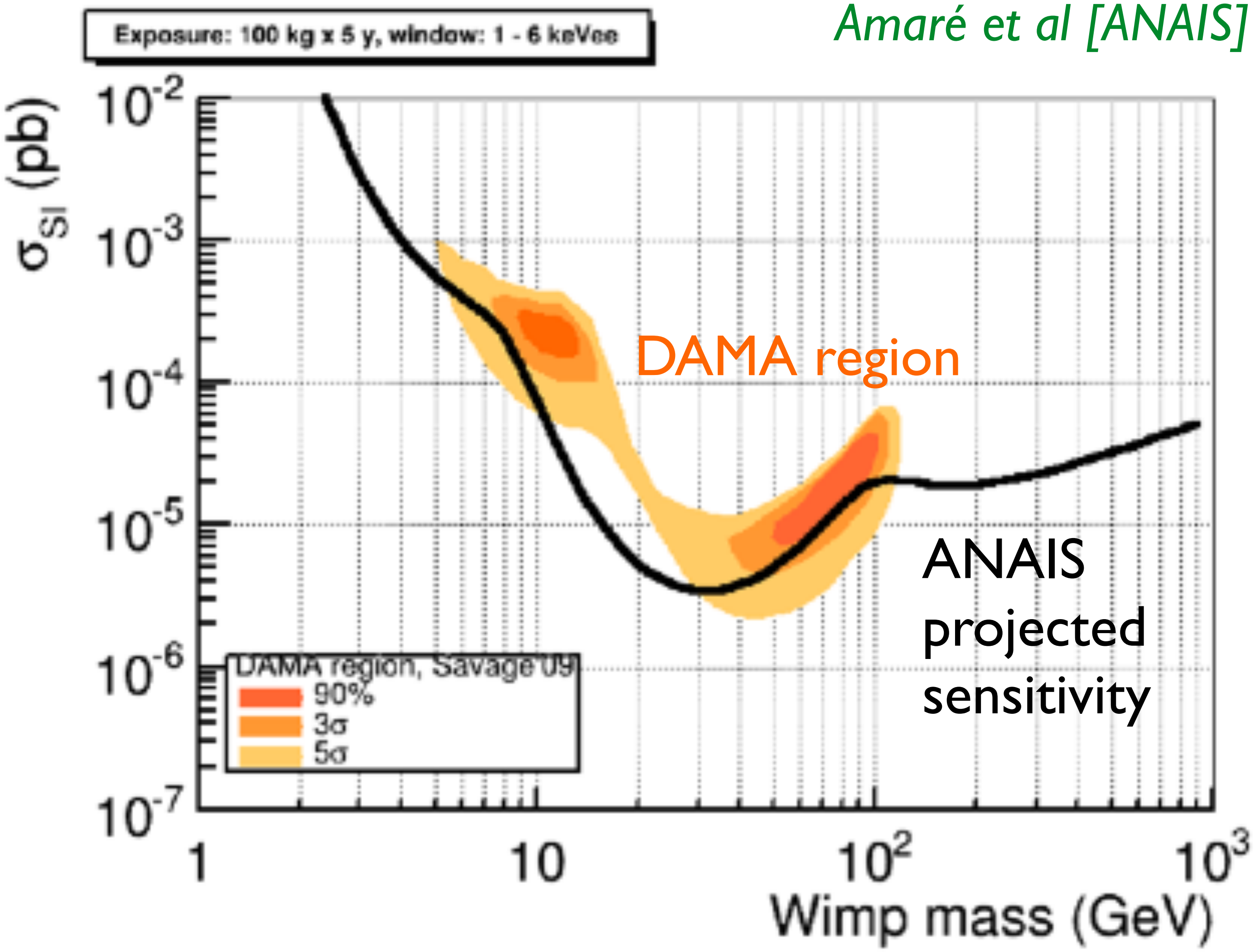
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

Belli, IDM2014

In the next future..... Direct check on DAMA

Experiments have been proposed that can directly check the DAMA modulation using the same target material

COSINE-100 (DM-ICE+KIMS-NaI)
ANAIS, SABRE,
XMASS, …

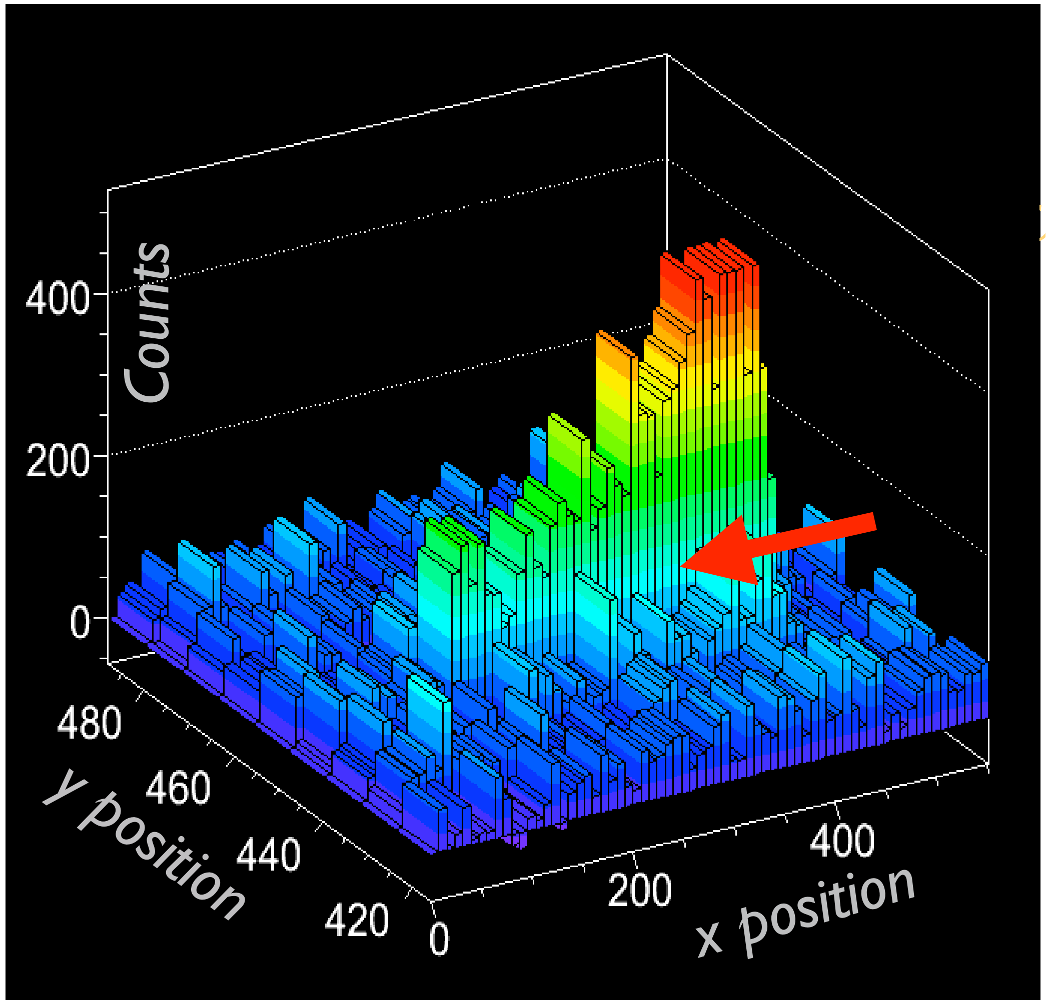


Amaré et al [ANAIS] 2015

In the next future..... 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

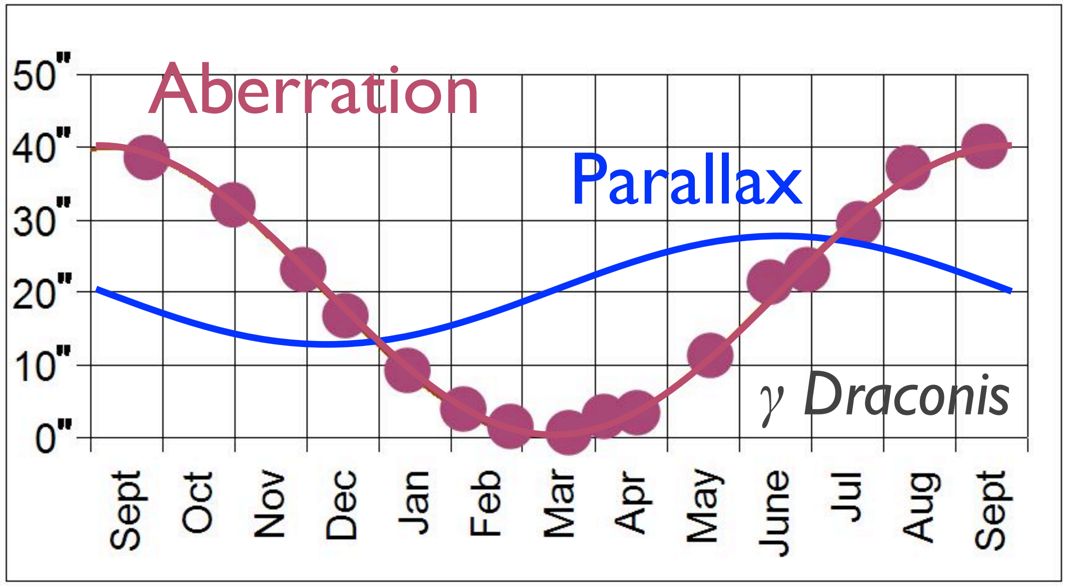
Only ~10 events needed to confirm extraterrestrial signal

In the next future..... WIMP astronomy

Aberration of WIMPs

Photon arrival direction

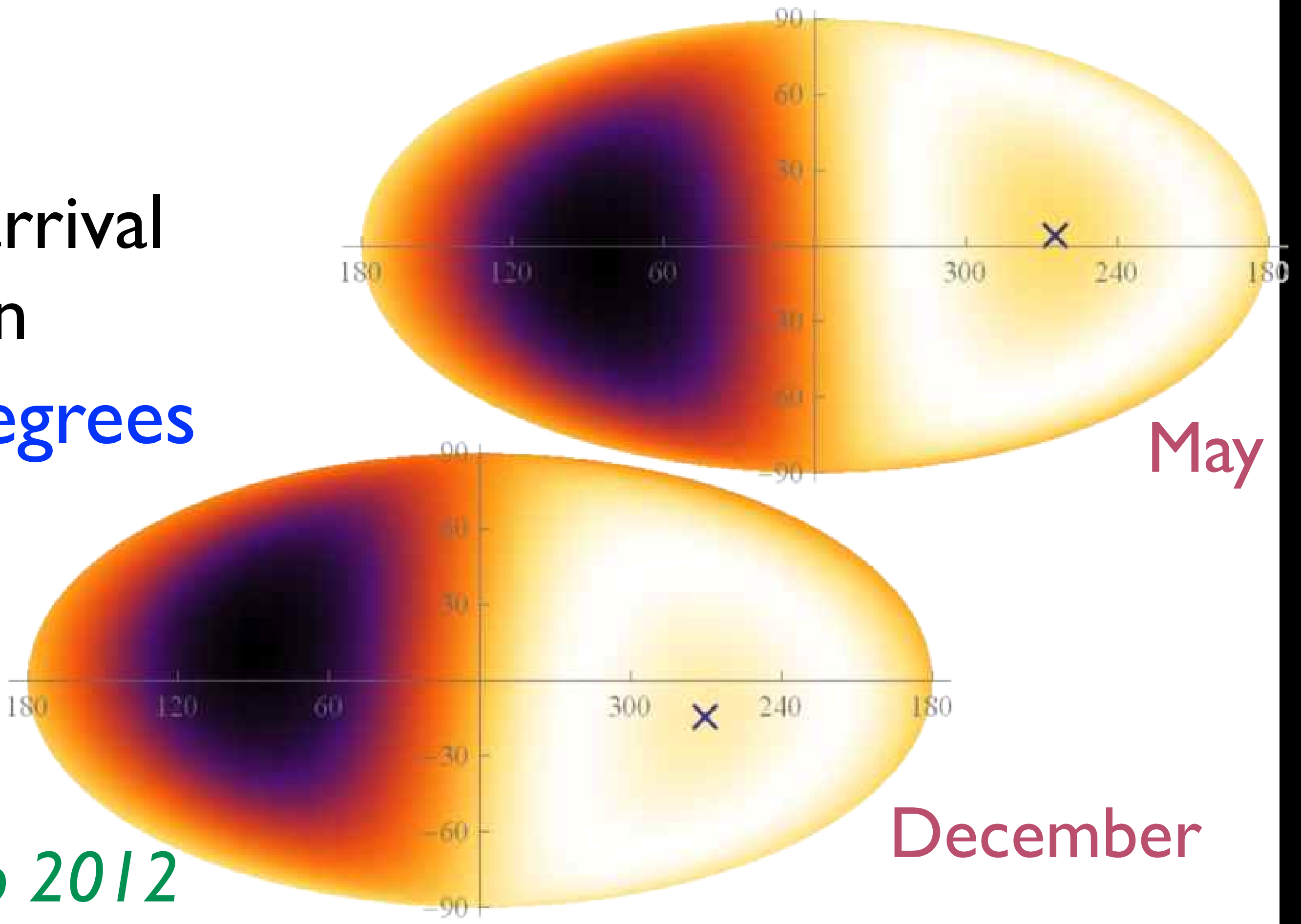
20 arcsec



Bradley 1725

WIMP arrival direction

10 degrees



Bozorgnia, Gelmini, Gondolo 2012

Summary

- Weakly Interacting Massive Particles are well-studied candidates for nonbaryonic cold dark matter.

- There are many searches for WIMP dark matter, through production, scattering and annihilation/decay.

- Some experiments claim detection while others exclude it.

- Recent trends are to consider all possible dark matter interactions and all possible dark halo models.

- The next future will see improved and bigger direct detectors, new γ-ray observatories, and precision cosmic ray data.