Dark Matter Theory

Paolo Gondolo

University of Utah

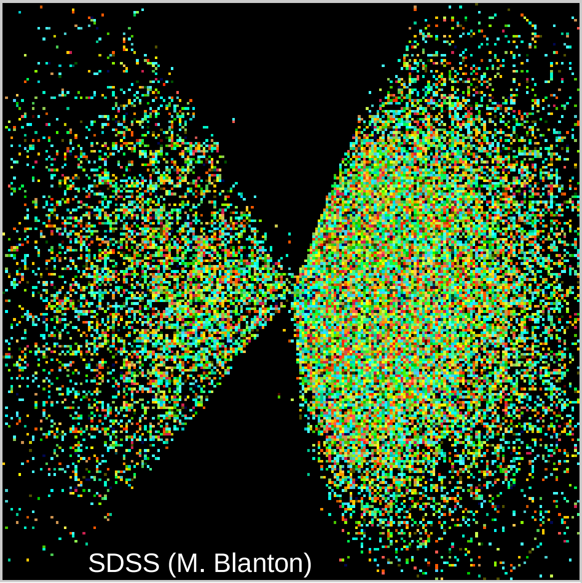
Dark matter theory

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

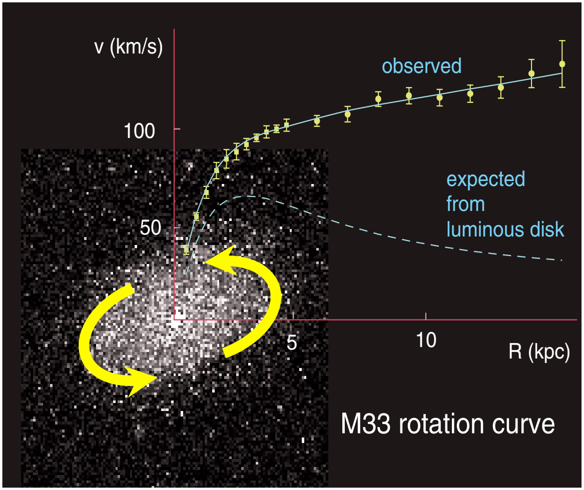
Fifty shades of dark

Evidence for cold dark matter

Large Scale Structure

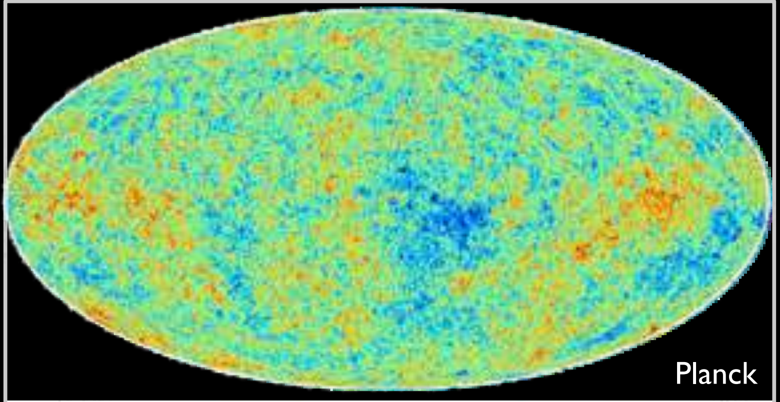


SDSS (M. Blanton)



M33 rotation curve

Cosmic Microwave Background



Planck

Supernovae

A. Riess

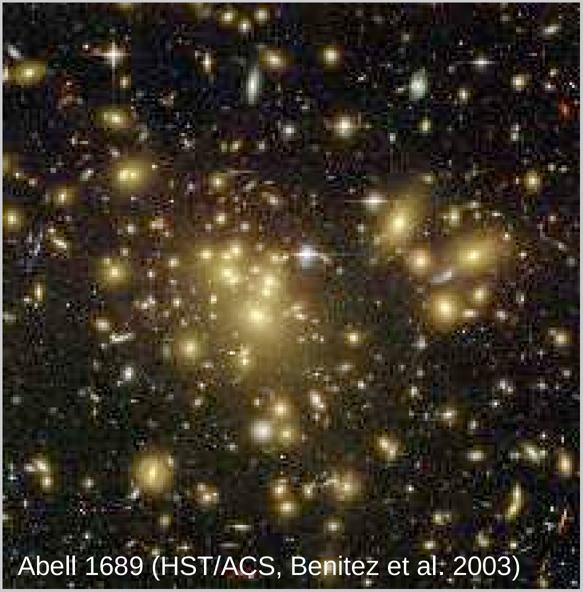
Galaxies

M101 (HST, Kuntz et al. 2006)

Dwarf Galaxies

M. Blanton

Galaxy Clusters

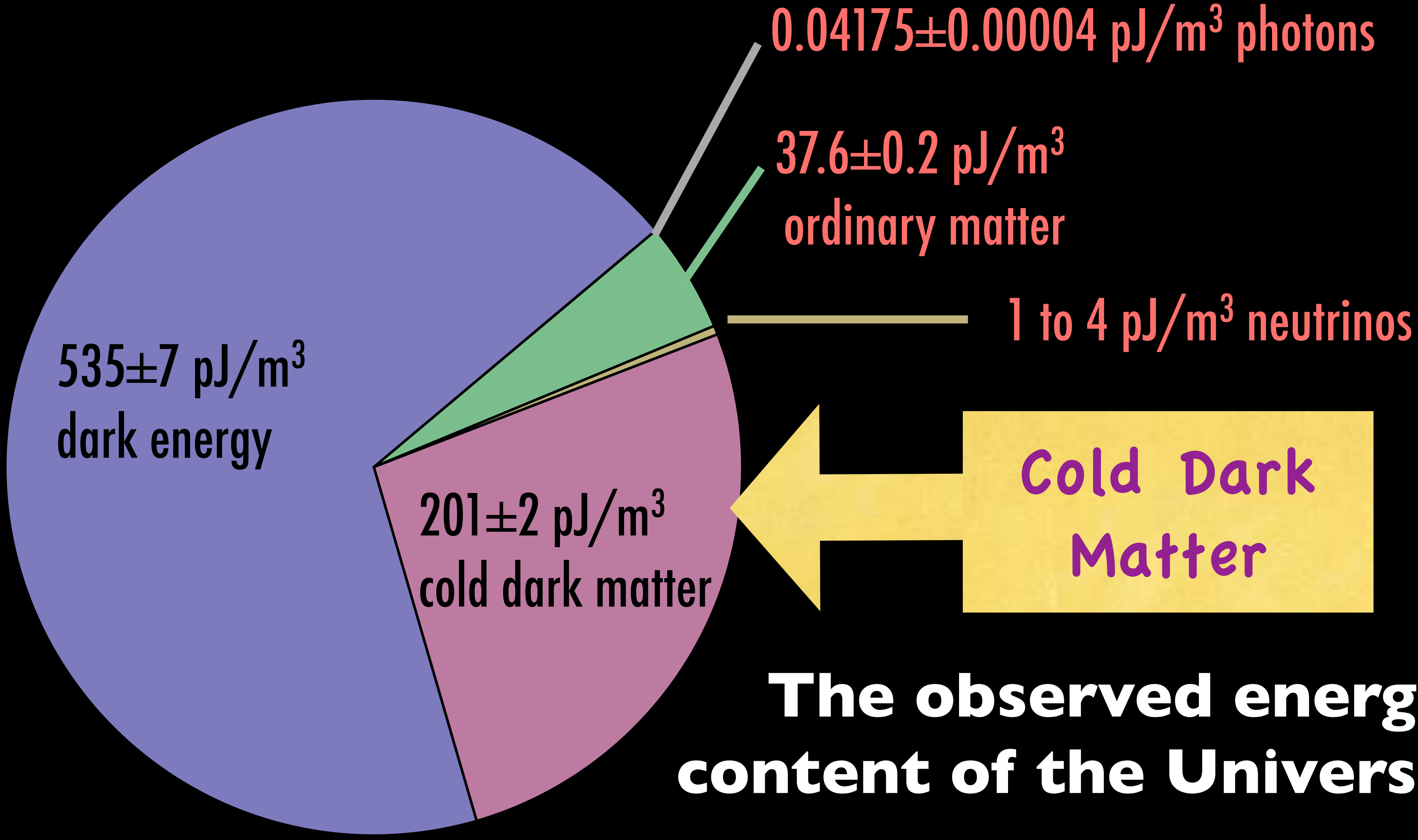


Abell 1689 (HST/ACS, Benitez et al. 2003)

Bullet Cluster

Markevitch et al. 2004,
Clowe et al. 2004

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

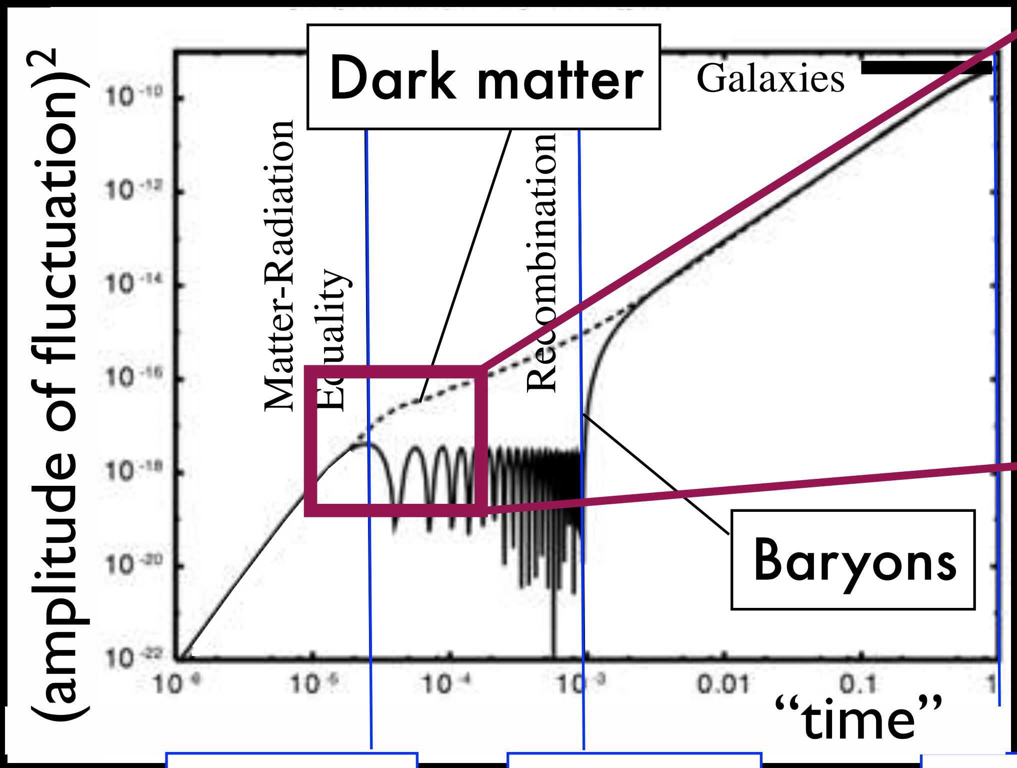
$1\ \mathrm{pJ} = 10^{-12}\ \mathrm{J}$

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

Evidence for *nonbaryonic* cold dark matter

GALAXY FORMATION

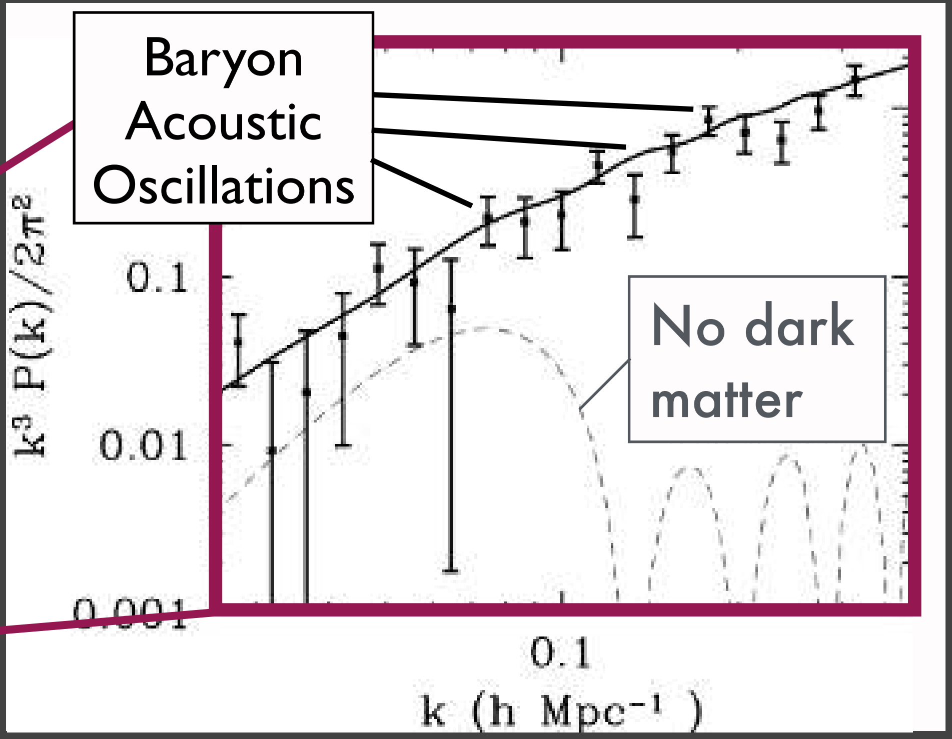
Matter fluctuations uncoupled to the plasma can gravitationally grow into galaxies in the given 13 Gyr



Dark matter is non-baryonic

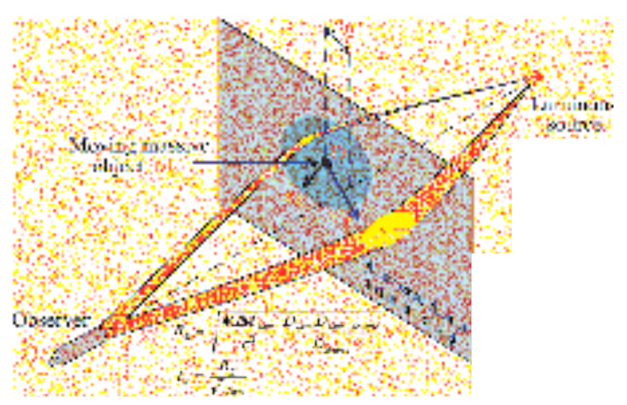
More than 80% of all matter does not couple to the primordial plasma!

SDSS



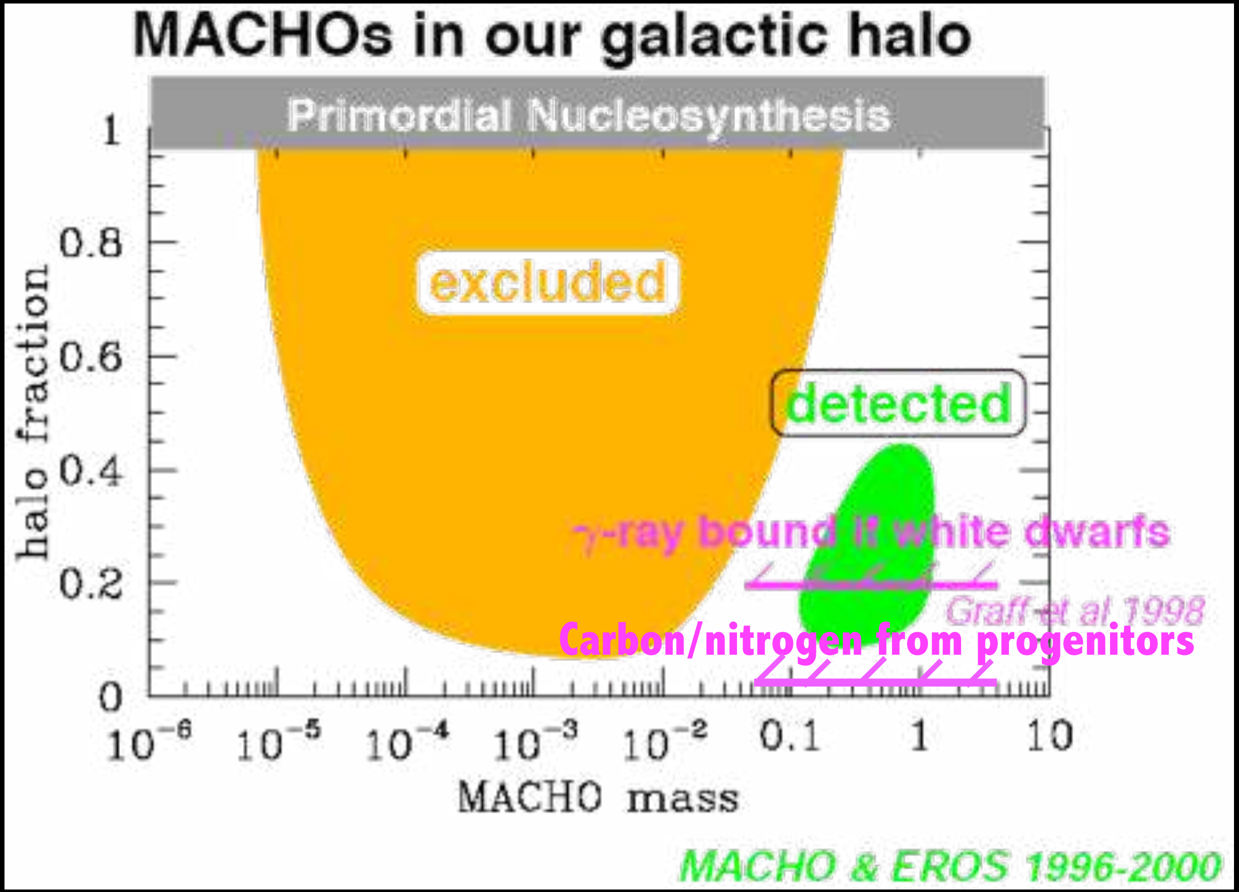
Evidence for *nonbaryonic* cold dark matter

GALACTIC DARK MATTER



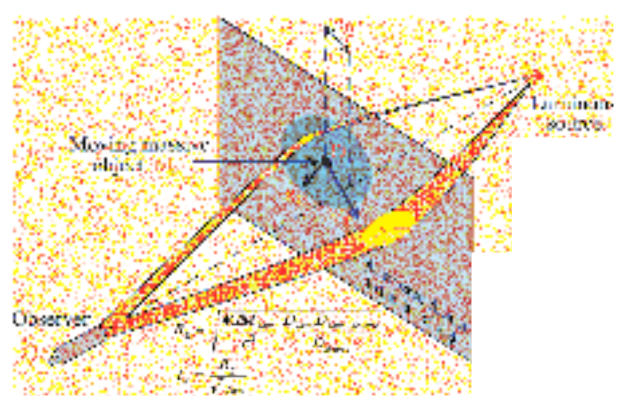
The observed microlensing events are not due to stellar remnants

Fields, Freese, Graff 1998
Graff, Freese, Walker, Pinsonneult 1999



Evidence for *nonbaryonic* cold dark matter

GALACTIC DARK MATTER



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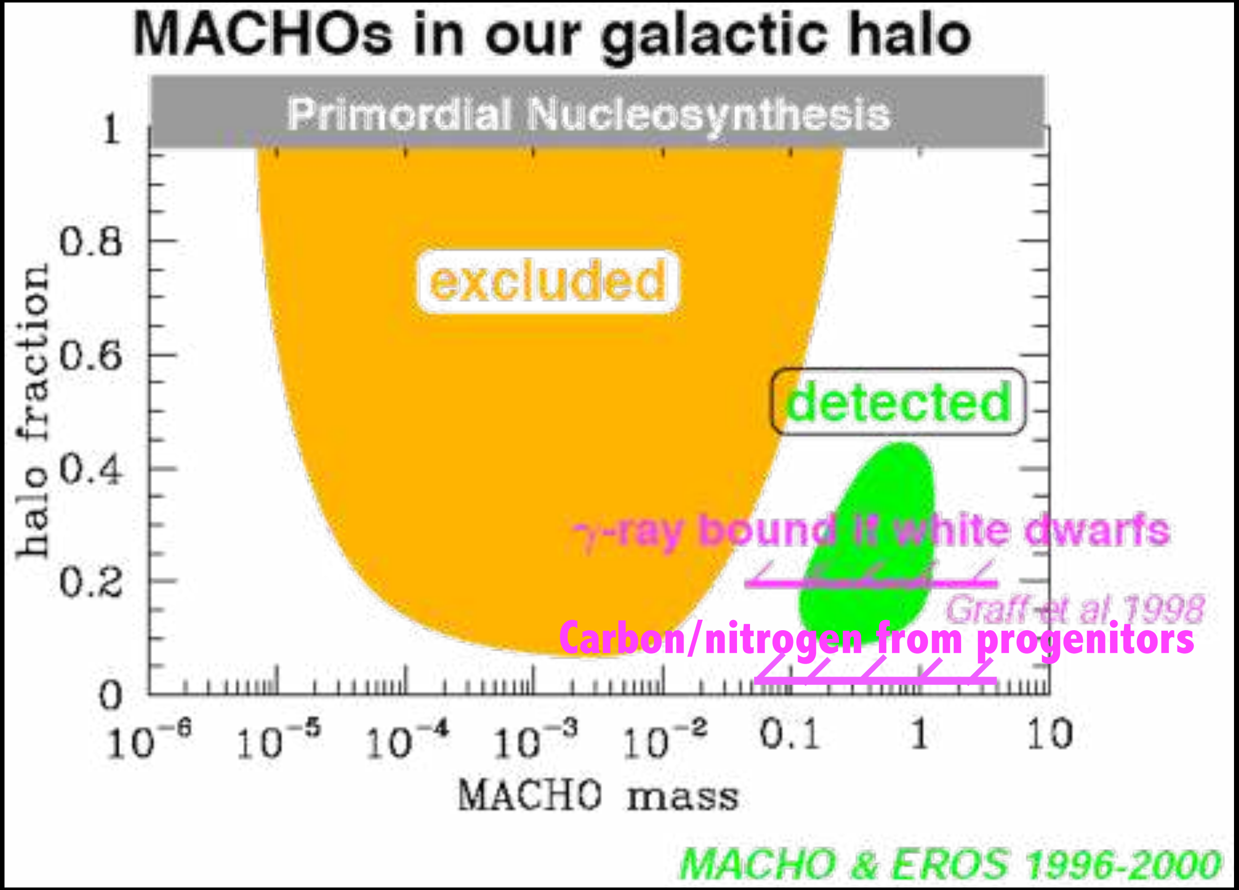
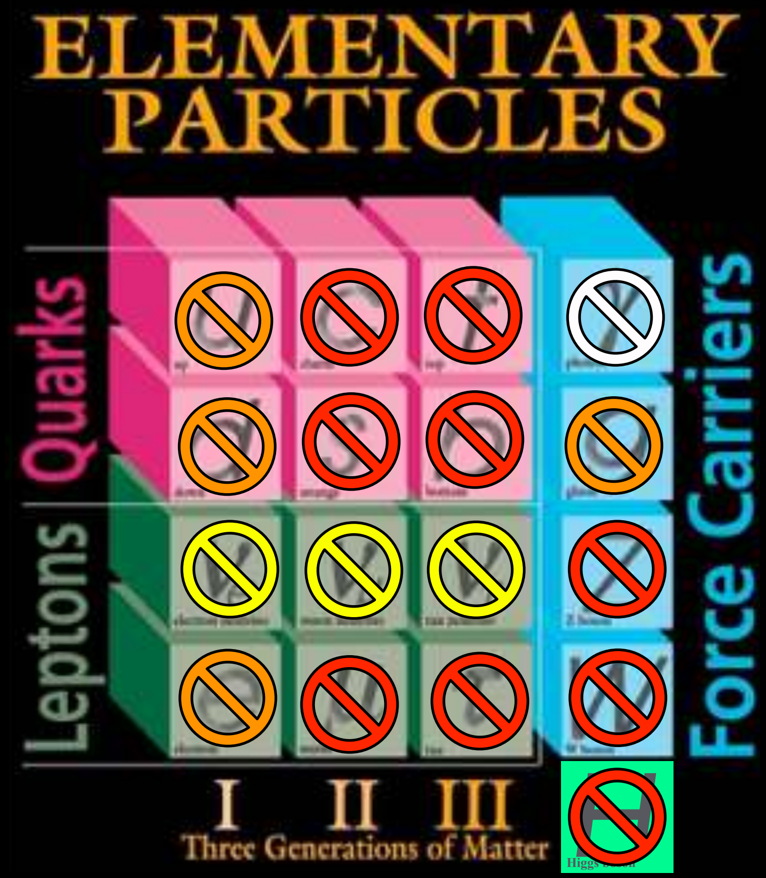


MACHO & EROS 1996-2000

I HATE MACHOS

Katherine Freese at COSMO 99, Trieste

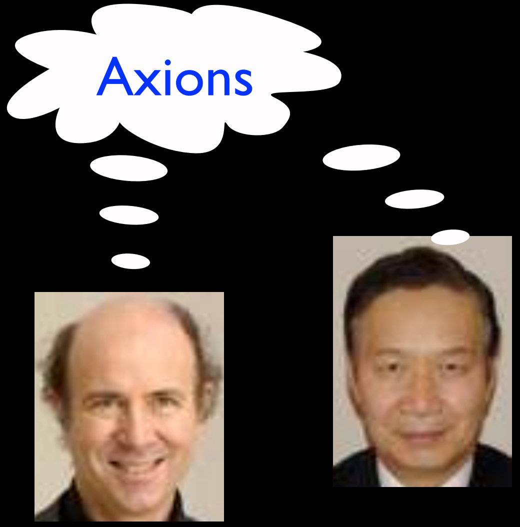
Is dark matter an elementary particle?



- 🚫 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!

Physicists have many ideas ....



Axions

Supersymmetric WIMPs

Dark matter from extra-dimensions

Excited dark matter

A new force in the dark sector

Particle dark matter

- neutrinos (hot)
- sterile neutrinos, gravitinos (warm)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

thermal relics

- Bose-Einstein condensates, axions, axion clusters
- solitons (Q-balls, B-balls, ...)
- supermassive wimpzillas

non-thermal relics

Mass range

10^{-22} eV (10^{-56}g) B.E.C.s
$10^{-8}\ M_\odot$ (10^{+25}g) axion clusters

Interaction strength range

Only gravitational: wimpzillas
Strongly interacting: B-balls

Particle dark matter

Hot dark matter

- relativistic at kinetic decoupling (start of free streaming)
- big structures form first, then fragment

light neutrinos

Cold dark matter

- non-relativistic at kinetic decoupling
- small structures form first, then merge

neutralinos, axions, WIMPZILLAs, solitons

Warm dark matter

- semi-relativistic at kinetic decoupling
- smallest structures are erased

sterile neutrinos, gravitinos

Particle dark matter

Thermal relics

in thermal equilibrium in the early universe

neutrinos, neutralinos, other WIMPs, ...

Non-thermal relics

not in thermal equilibrium in the early universe

axions, WIMPZILLAs, solitons, ...

Axions

Axions as dark matter

Hot

Produced thermally in early universe

Important for $m_a > 0.1eV$ $(f_a < 10^8)$*, mostly excluded by astrophysics*

Cold

Produced by coherent field oscillations around mimimum of $V(\theta)$

(Vacuum realignment)

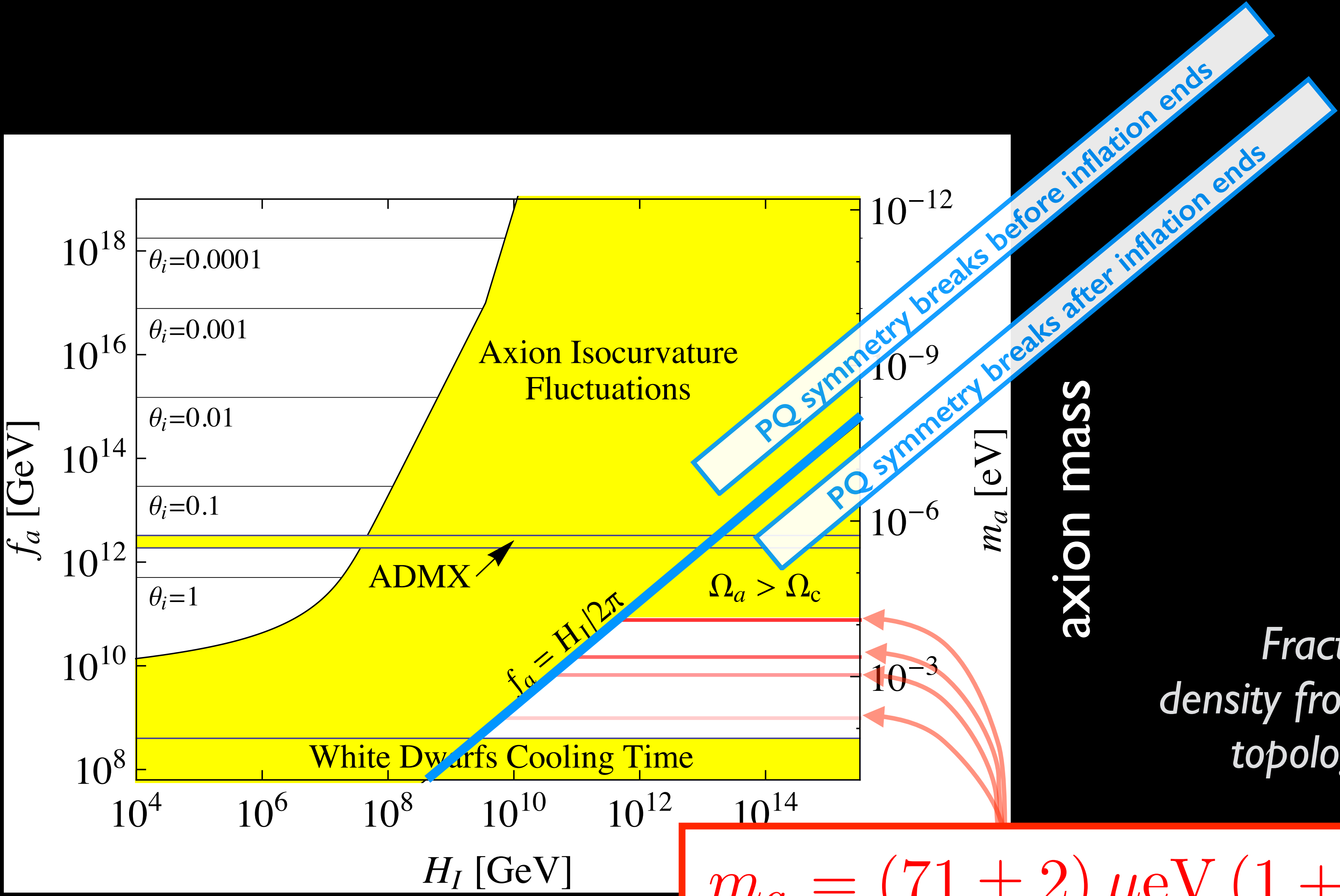
Produced by decay of topological defects

(Axionic string decays)

Still a very complicated and uncertain calculation!

e.g. Harimatsu et al 2012

Axion cold dark matter parameter space



PQ symmetry breaks before inflation ends

PQ symmetry breaks after inflation ends

PQ symmetry breaking scale

axion mass

Fraction of axion density from decays of topological defects

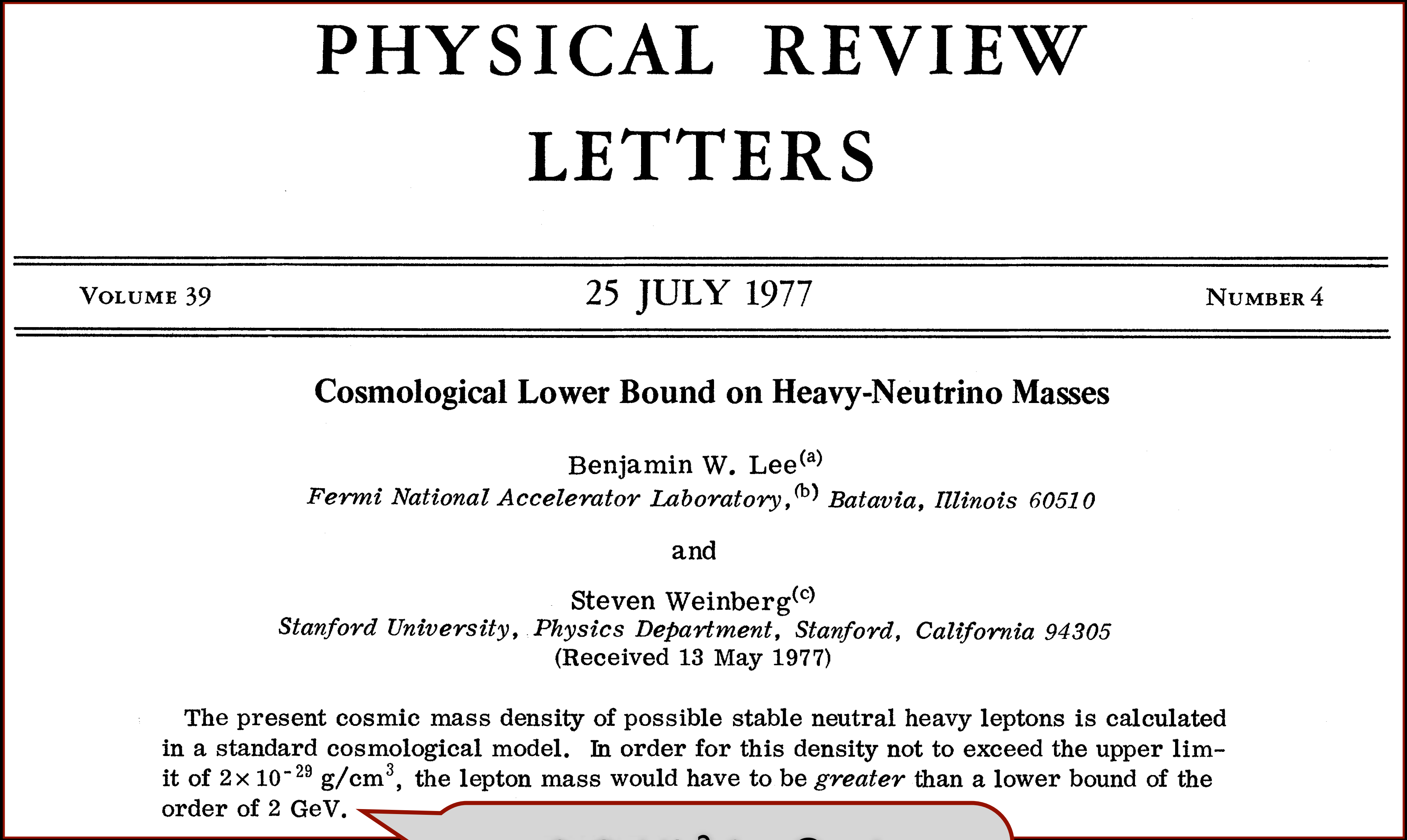
$$m_a = (71 \pm 2)\,\mu\text{eV}\,(1 + \alpha_\text{d})^{6/7}$$

Expansion rate at end of inflation

Visinelli, Gondolo 2009 + updates

Neutrinos

Heavy active neutrinos



PHYSICAL REVIEW
LETTERS

VOLUME 39 25 JULY 1977 NUMBER 4

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 Ω_c=1

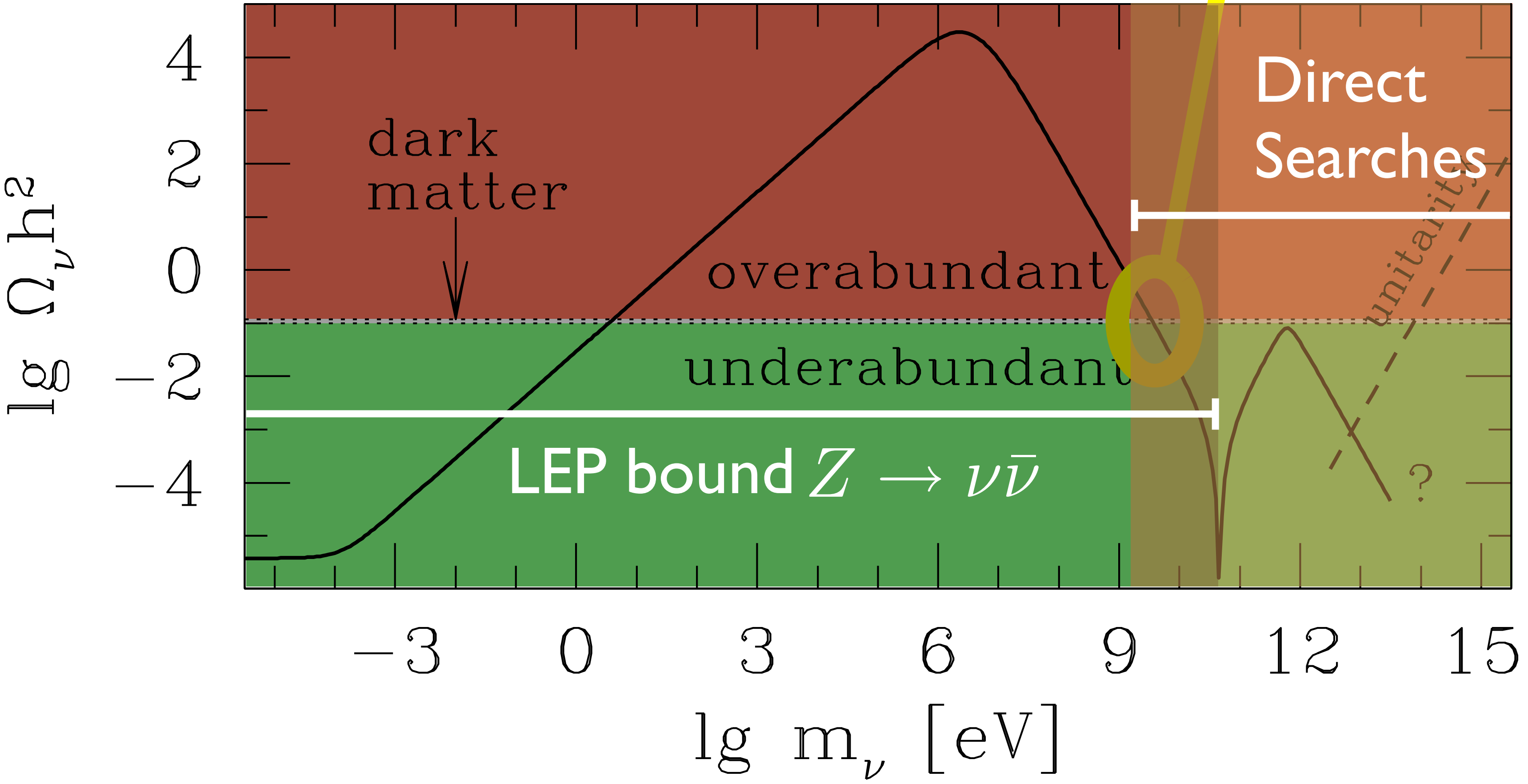
Now 4 GeV/c^2 for Ω_c=0.25

Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrin

~ few GeV
preferred cosmological mass
Lee & Weinberg 1977

Excluded as dark matter (1991)



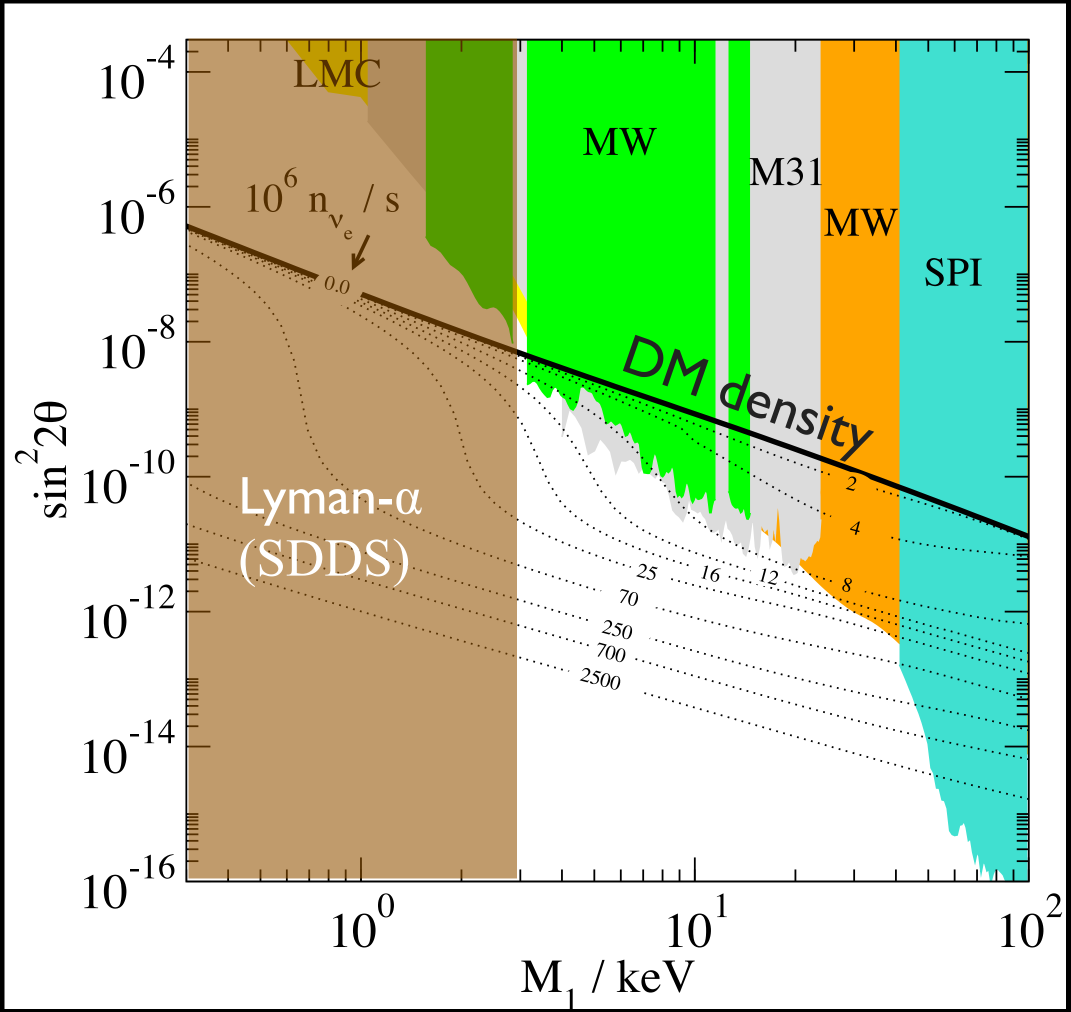
Sterile neutrino dark matter

Standard model + right-handed neutrinos

Active and sterile neutrinos oscillate into each other.

Sterile neutrinos can be warm dark matter (mass > 0.3 keV)

Dodelson, Widrow 1994; Shi, Fuller 1999; Laine, Shaposhnikov 2008



νMSM

Laine, Shaposhnikov 2008

Supersymmetric particles

Supersymmetric dark matter

Neutralinos (the most fashionable/studied WIMP)

Goldberg 1983; Ellis, Hagelin, Nanopoulos, Olive, Srednicki 1984; etc.

Sneutrinos (also WIMPs)

Falk, Olive, Srednicki 1994; Asaka, Ishiwata, Moroi 2006; McDonald 2007; Lee, Matchev, Nasri 2007; Deppisch, Pilaftsis 2008; Cerdeno, Munoz, Seto 2009; Cerdeno, Seto 2009; etc.

Gravitinos (SuperWIMPs)

Feng, Rajaraman, Takayama 2003; Ellis, Olive, Santoso, Spanos 2004; Feng, Su, Takayama, 2004; etc.

Axinos (SuperWIMPs)

Tamvakis, Wyler 1982; Nilles, Raby 1982; Goto, Yamaguchi 1992; Covi, Kim, Kim, Roszkowski 2001; Covi, Roszkowski, Ruiz de Austri, Small 2004; etc.

Neutralino dark matter: impact of LHC

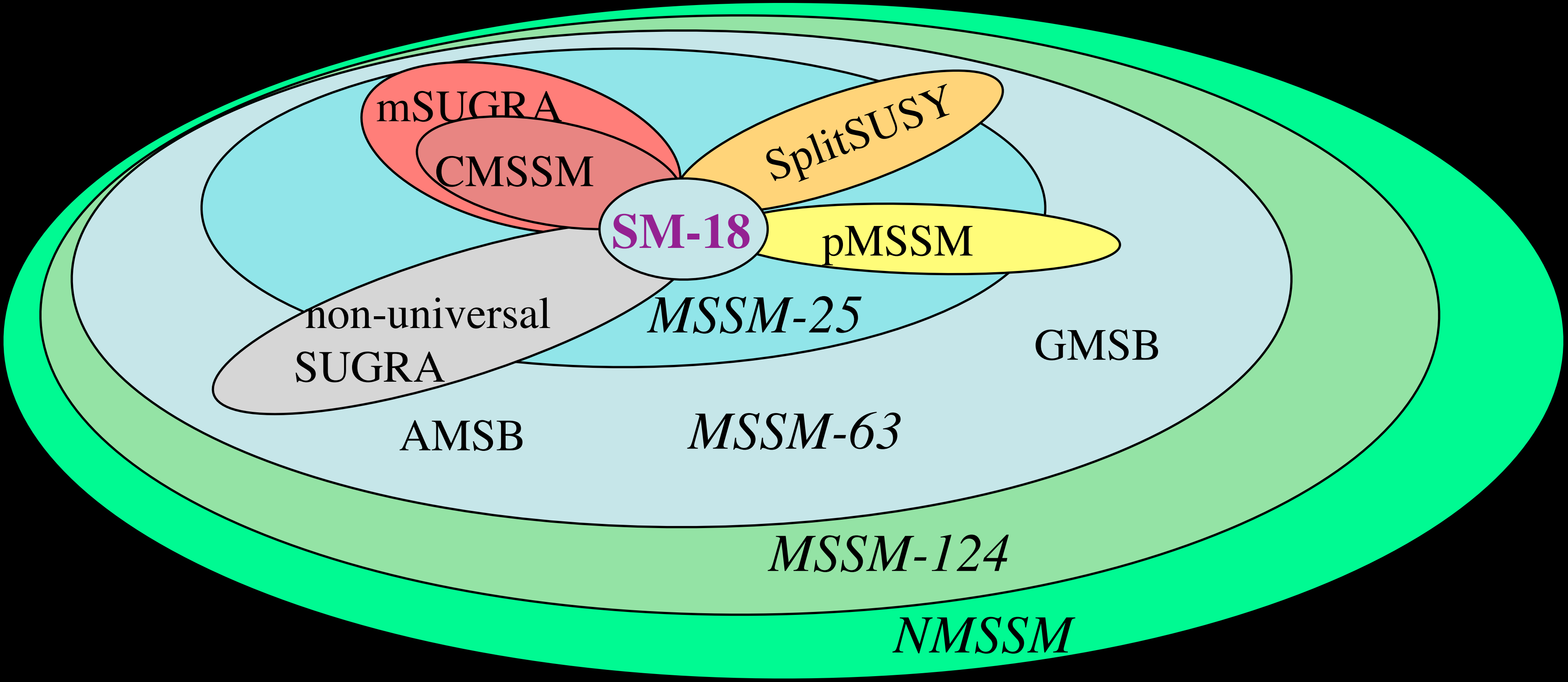
- The CMSSM is in dire straights

Constrained Minimal Superssymetric Standard Model

> "a Higgs mass of ~125 GeV excludes the least fine-tuned CMSSM points; remaining viable models may be difficult to probe with dark matter searches"

Sandick 1210.5214

- But there are many supersymmetric models



Neutralino dark matter: impact of LHC

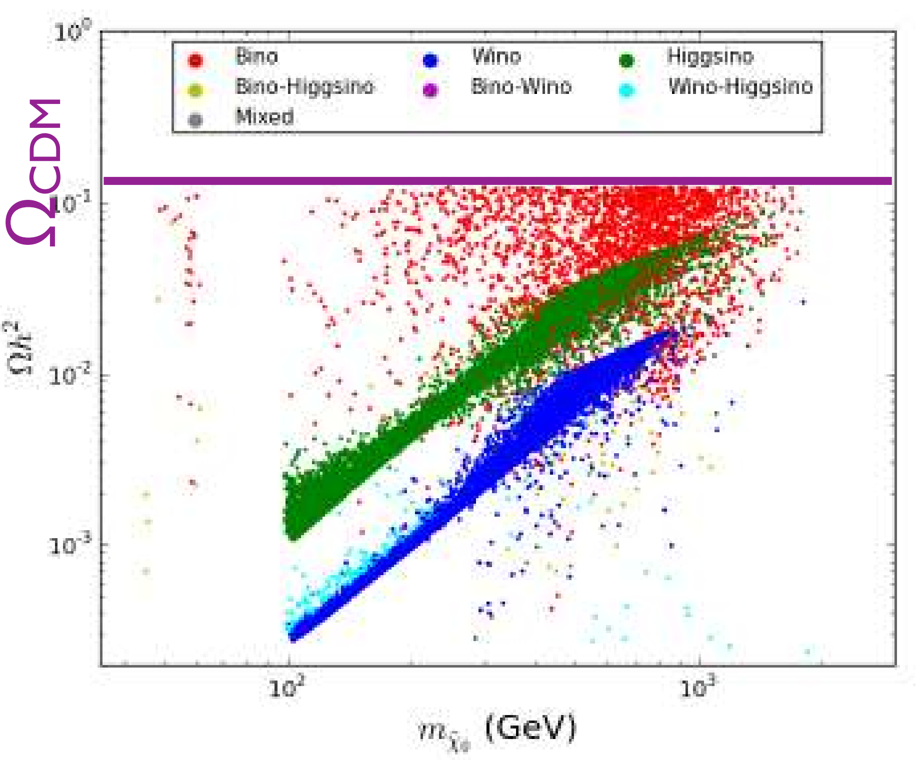
Cahill-Rowell et al 1305.6921

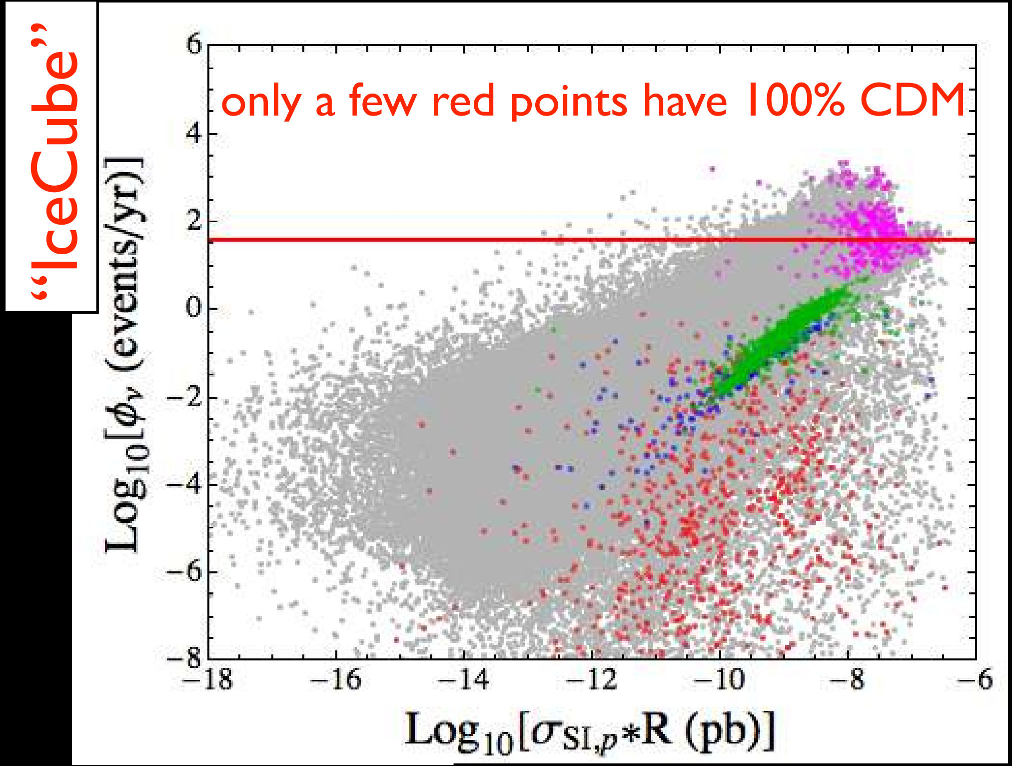
"the only pMSSM models remaining [with neutralino being 100% of CDM] are those with bino coannihilation"

pMSSM (phenomenological MSSM)

$$\mu, m_A, \tan\beta, A_b, A_t, A_\tau, M_1, M_2, M_3,$$
$$m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3},$$
$$m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}$$

(19 parameters)





only a few red points have 100% CDM

"Direct Detection"

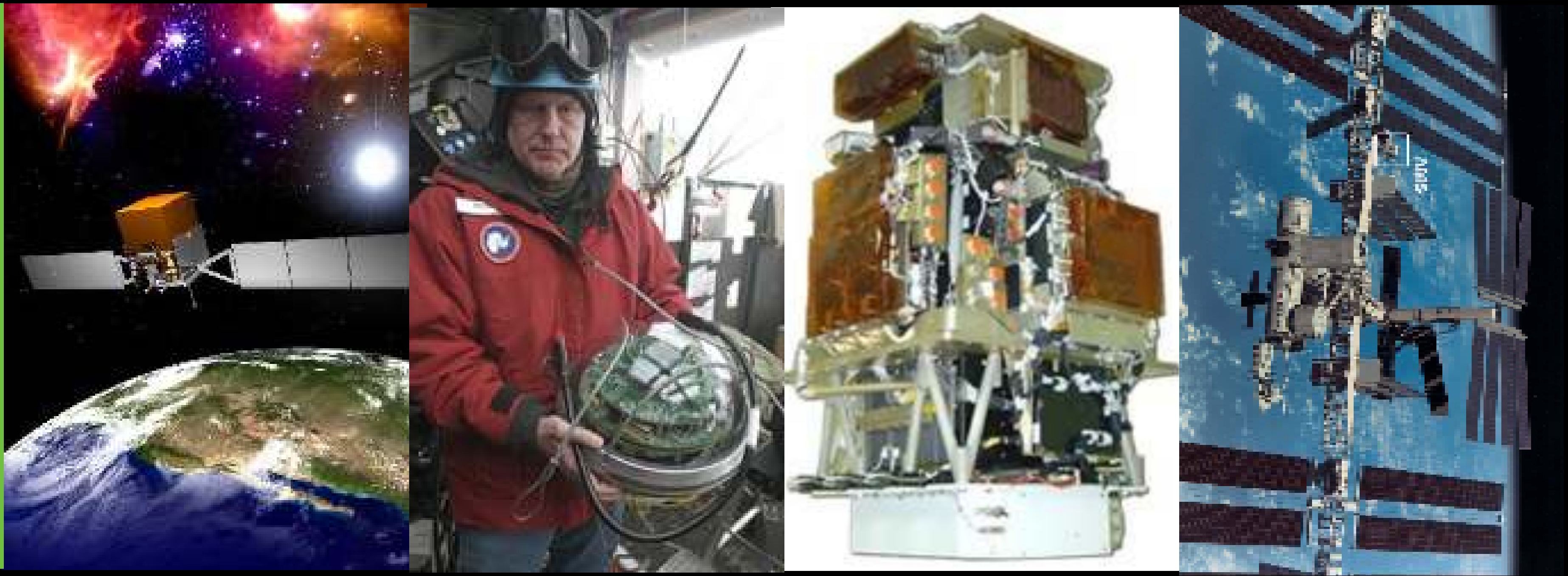
The forbidden fruit

Searches for particle dark matter

Collider

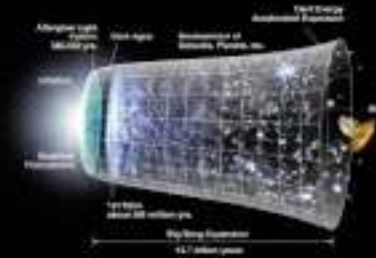
Direct

Indirect



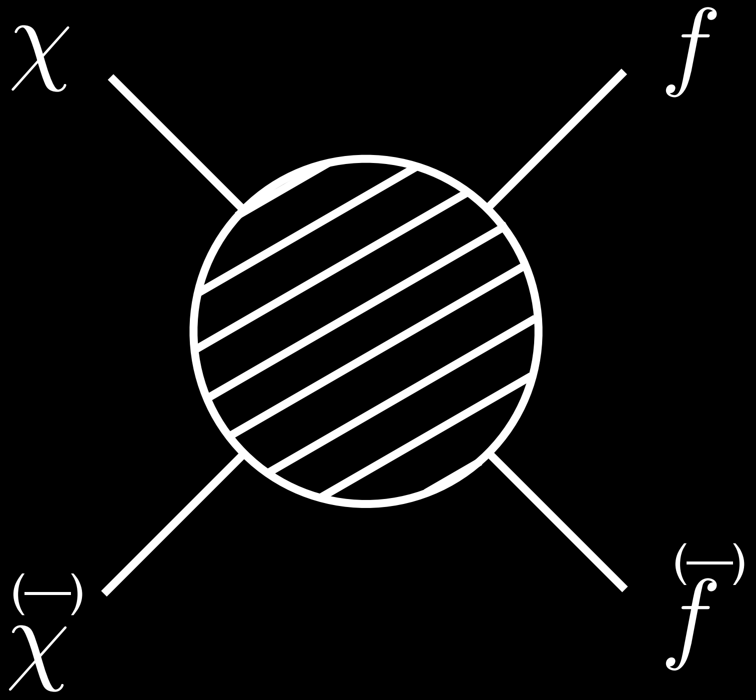
The power of the WIMP

Indirect detection



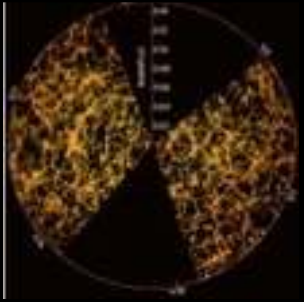
Cosmic density

Annihilation



Scattering

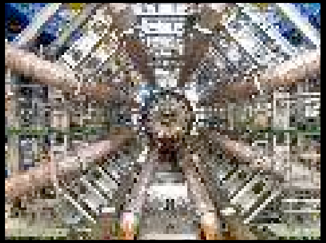
Direct detection

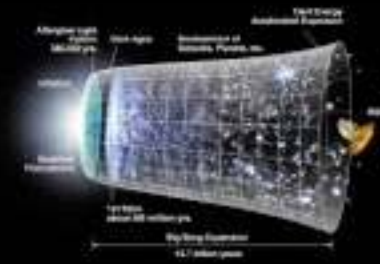


Large scale structure

Production

Colliders



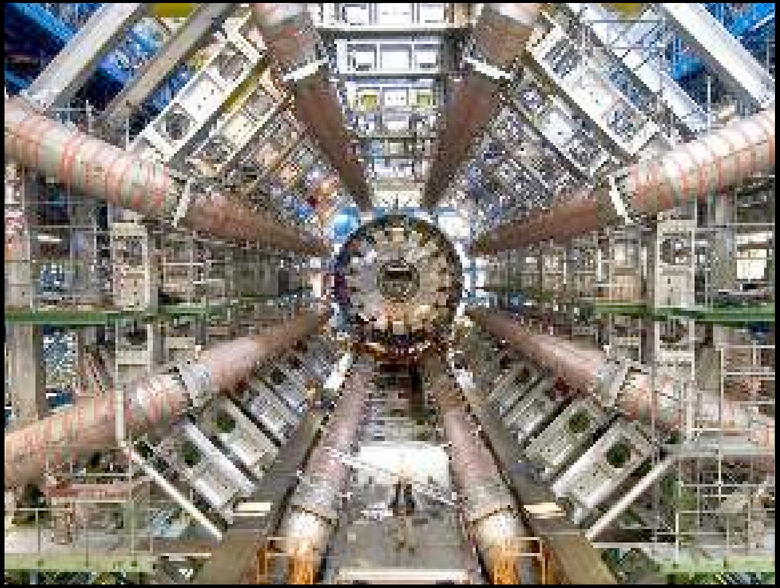


Cosmic density

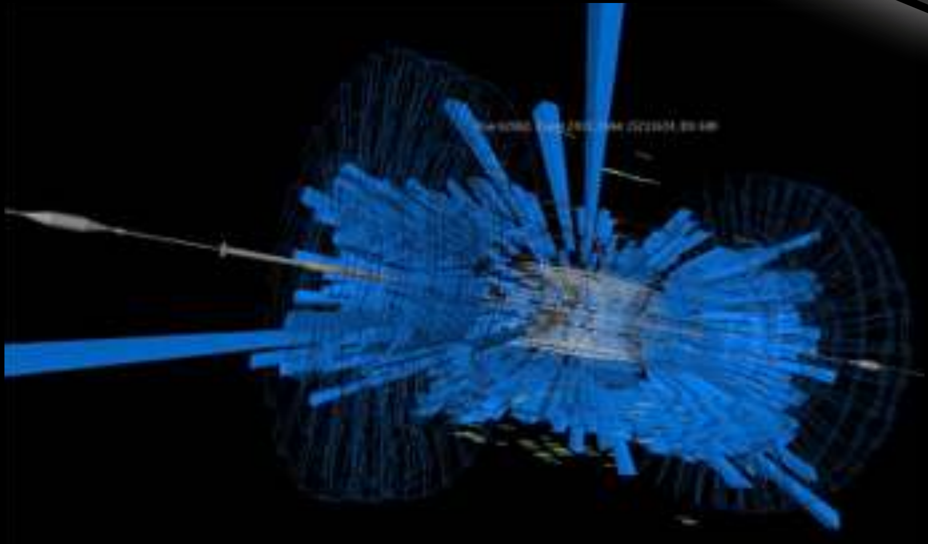
Dark matter creation with particle accelerators

Searching for the conversion
protons → energy → dark matter

$E=mc^2$ in action



The ATLAS detector



Particle production at the Large Hadron Collider

Indirect detection of particle dark matter

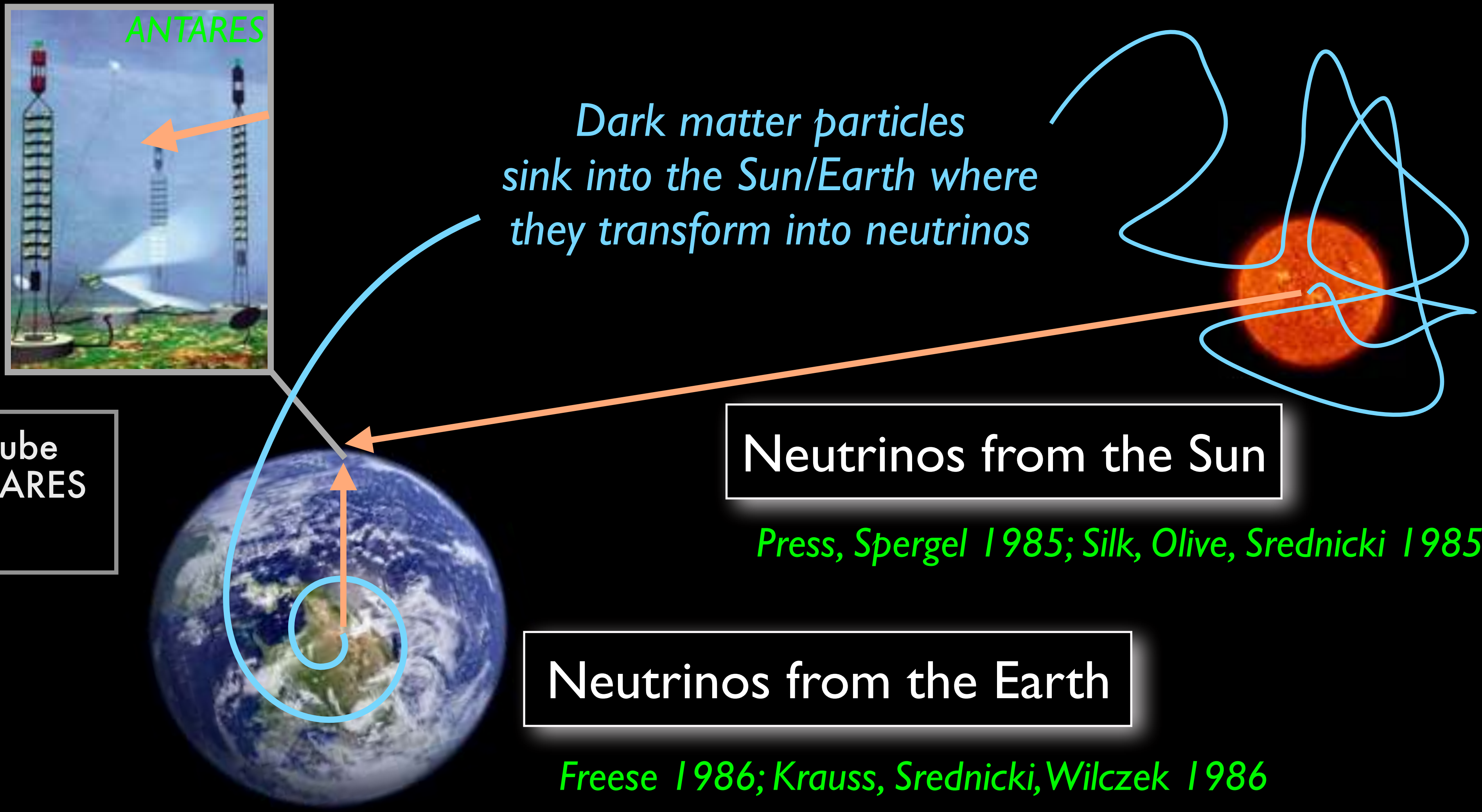
The principle

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

Indirect detection of particle dark matter

The principle

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

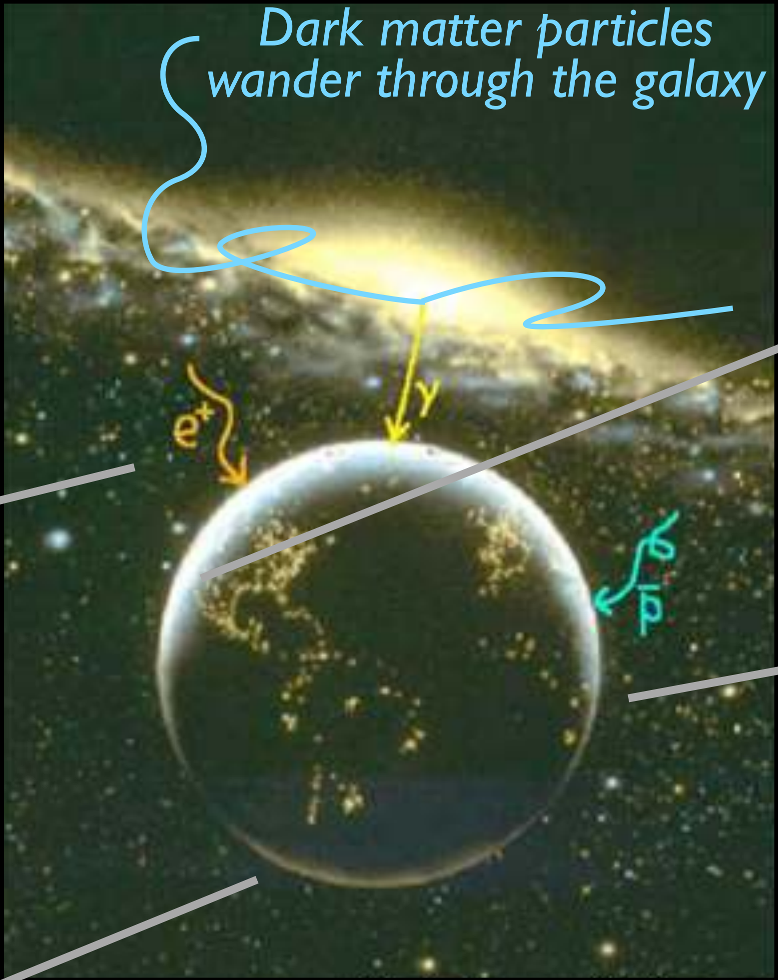
Indirect detection of particle dark matter

The principle

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

HEAT
BESS
PAMELA
AMS
GAPS
EGRET
HESS
MAGIC
VERITAS
GLAST
STACEE
CTA
...

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



Dark matter particles wander through the galaxy

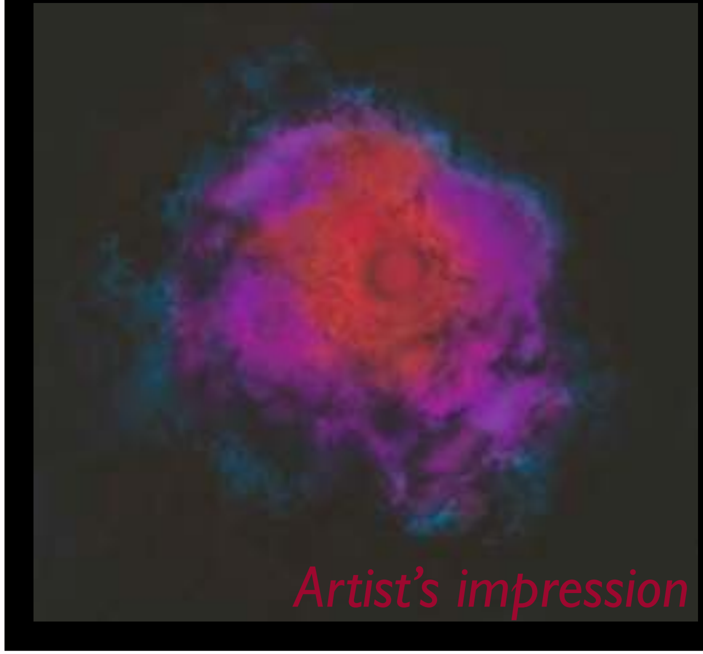
Gamma-rays, positrons, antiprotons from our galaxy and beyond

Indirect detection of particle dark matter

The principle

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

The first stars to form in the universe may have been powered by dark matter instead of nuclear fusion.



Artist's impression

They were *dark-matter powered stars* or for short

Dark Stars

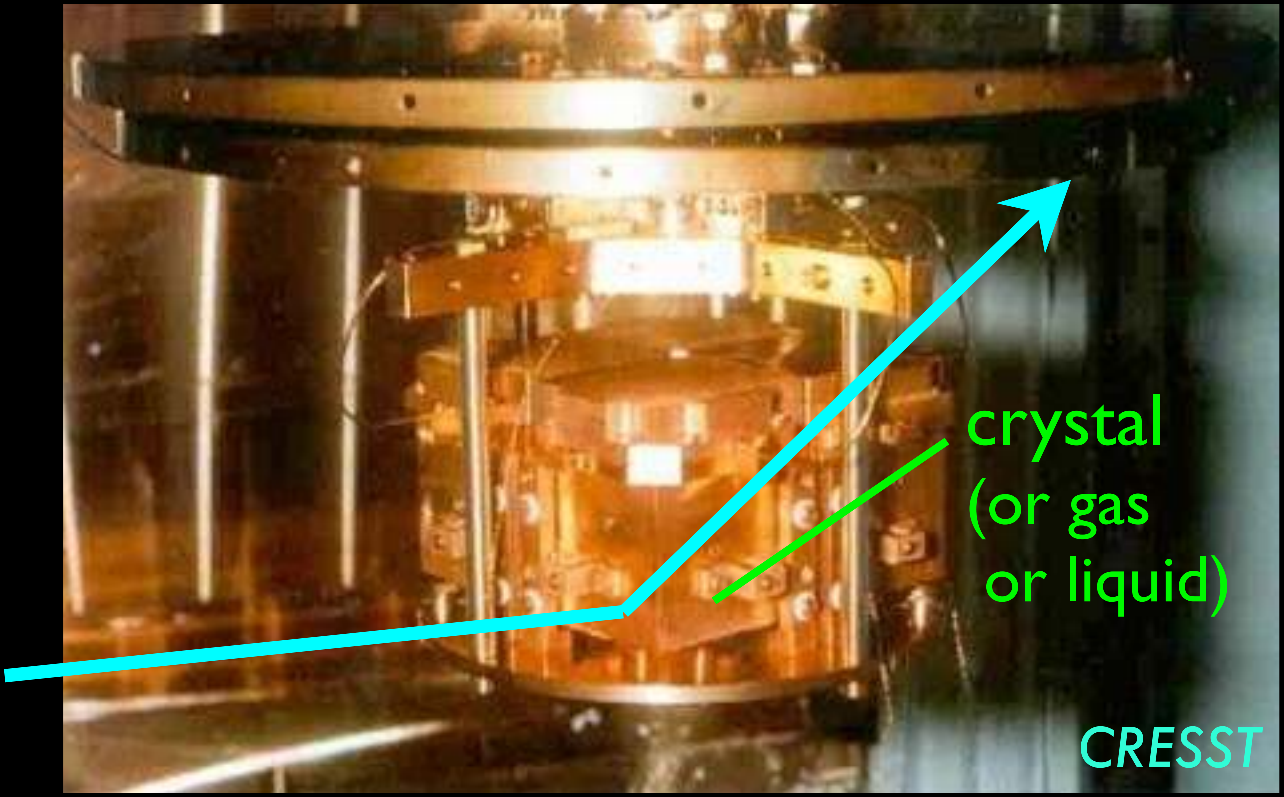
- Explain chemical elements in old halo stars
- Explain origin of supermassive black holes in early quasars

Spolyar, Freese, Gondolo 2007-2008

The principle of direct detection

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

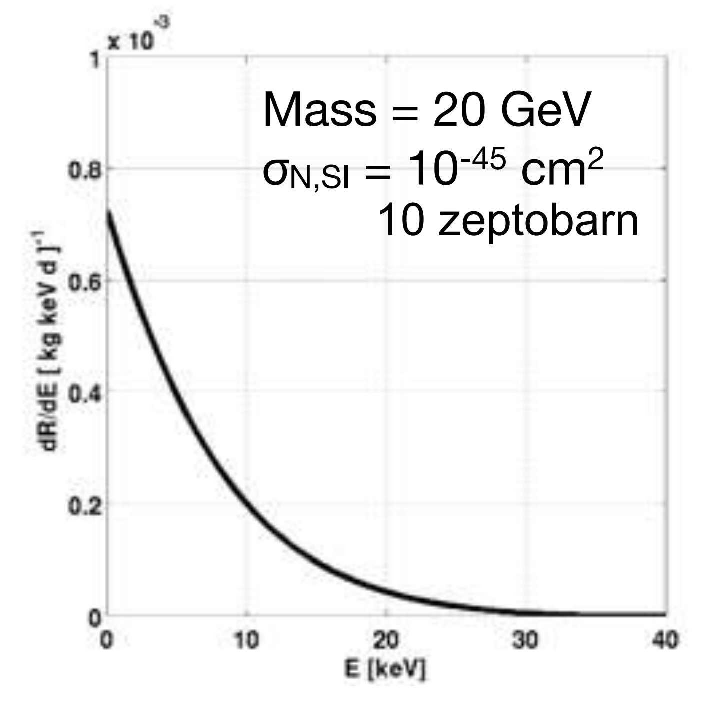
Goodman, Witten 1985



Low-background underground detector

Expected event rate is small

Expected
WIMP spectrum

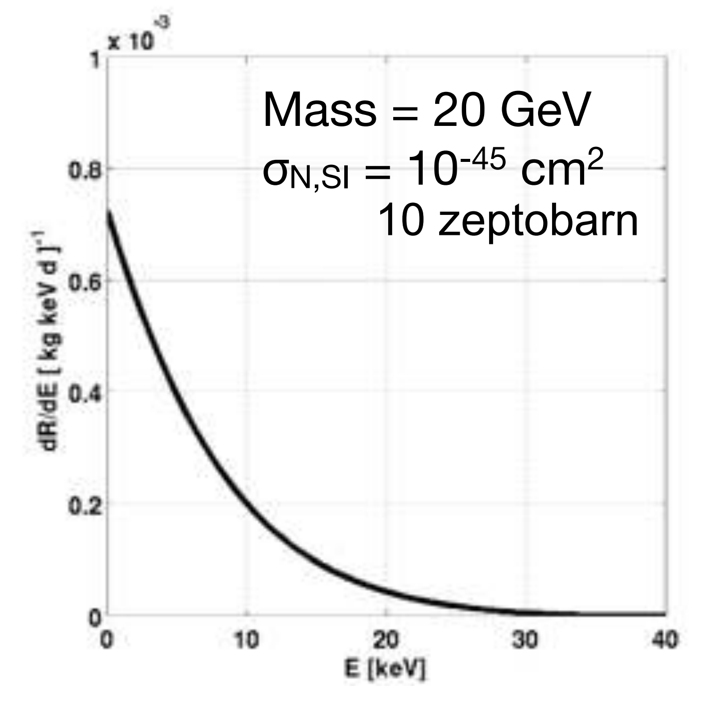


~1 event/kg/year

(nuclear recoils)

Expected event rate is small

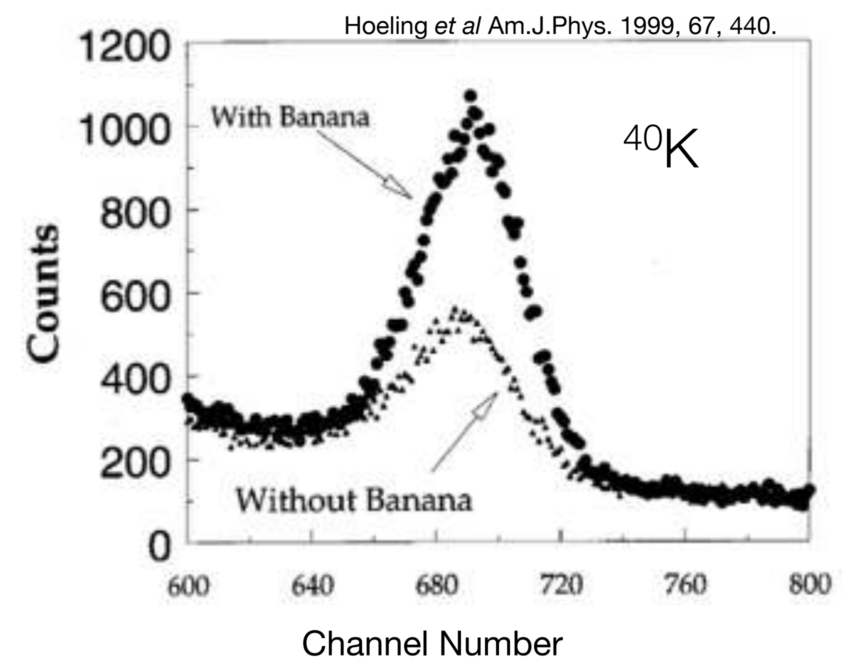
Expected
WIMP spectrum



~1 event/kg/year

(nuclear recoils)

Measured
banana spectrum


Hoeling *et al* Am.J.Phys. 1999, 67, 440.

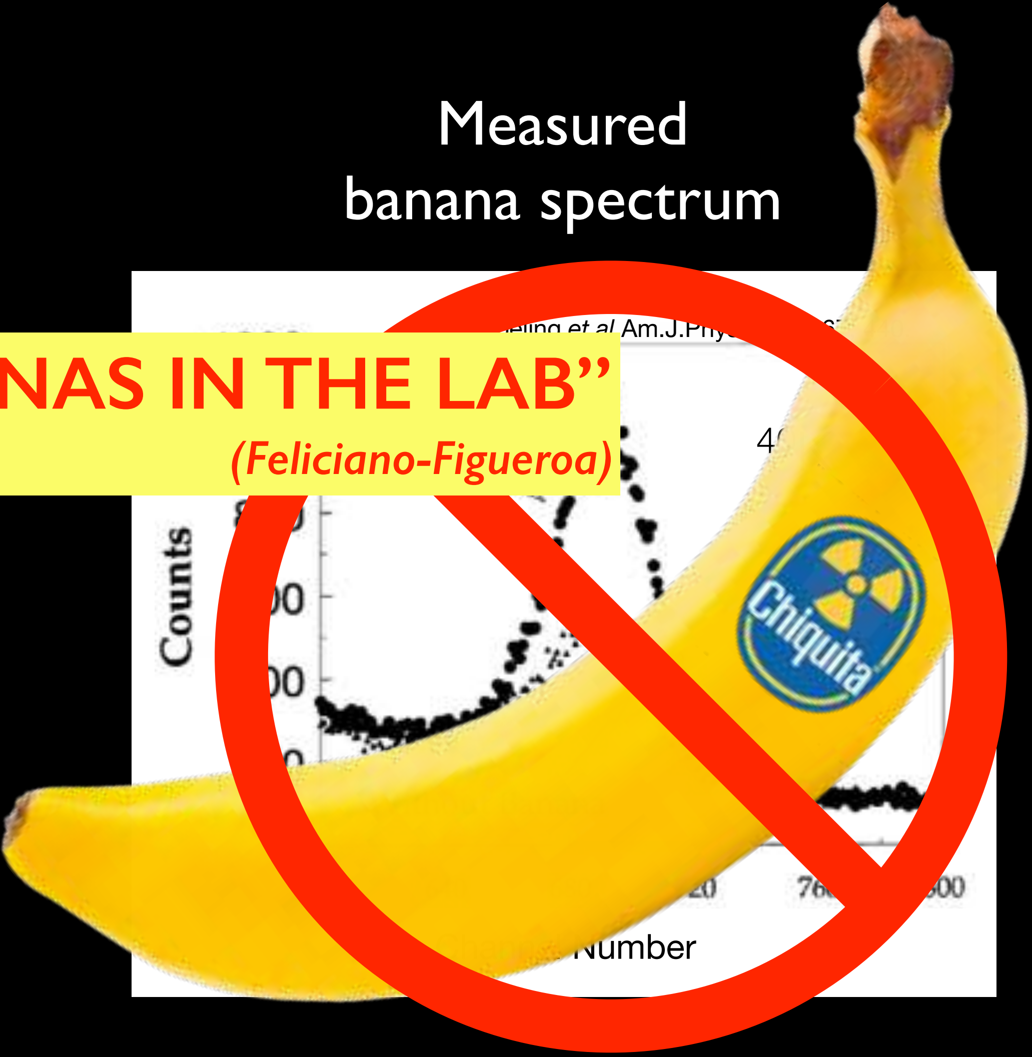
~100 events/kg/second

(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)

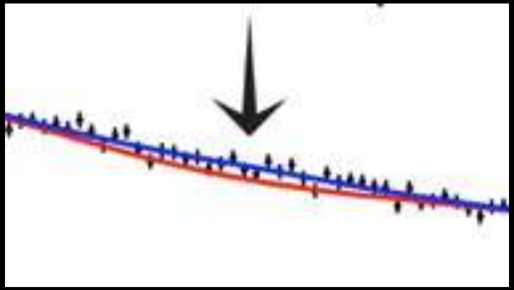
Confusion of the mind

Evidence for cold dark matter particles?

GeV γ-rays

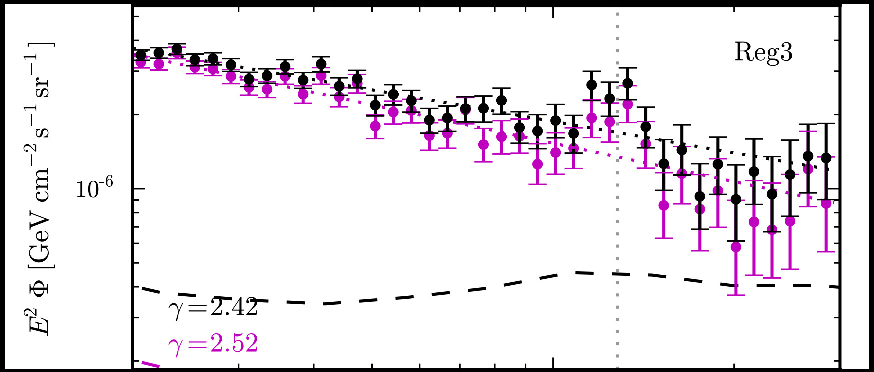
Hooper et al 2009-14

3.5 keV X-ray line



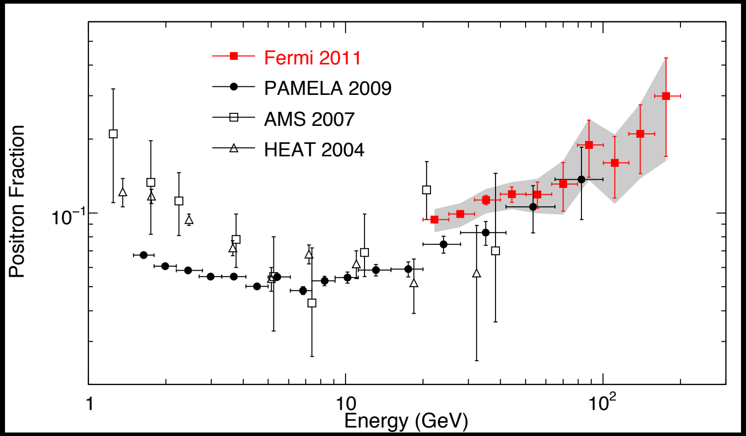
Bulbul et al 2014

135 GeV γ-ray line



Weniger 2012

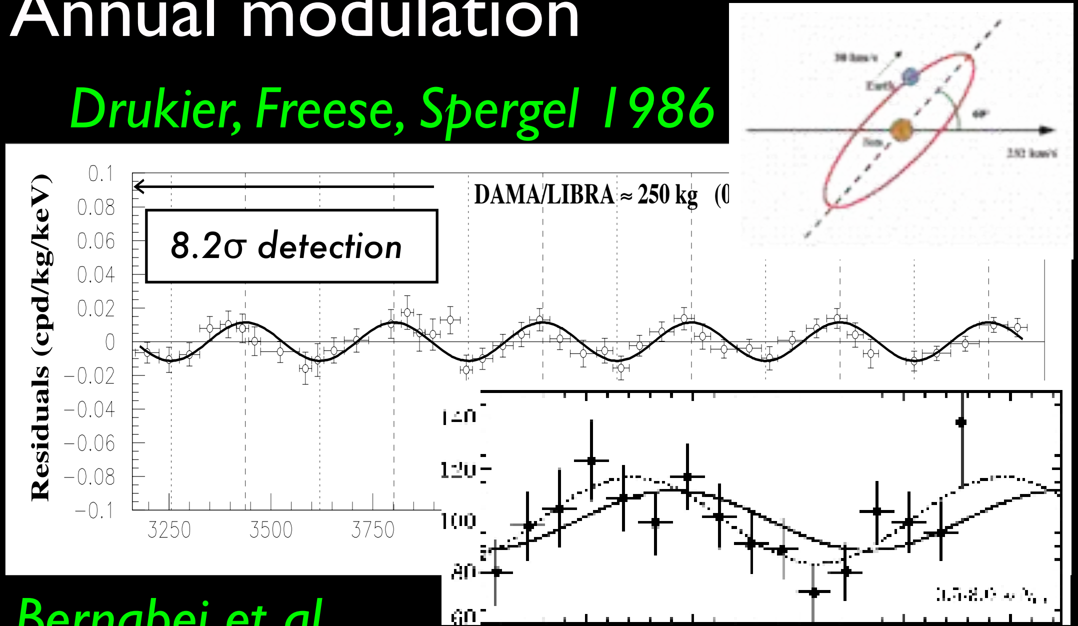
Positron excess



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

Annual modulation

Drukier, Freese, Spergel 1986



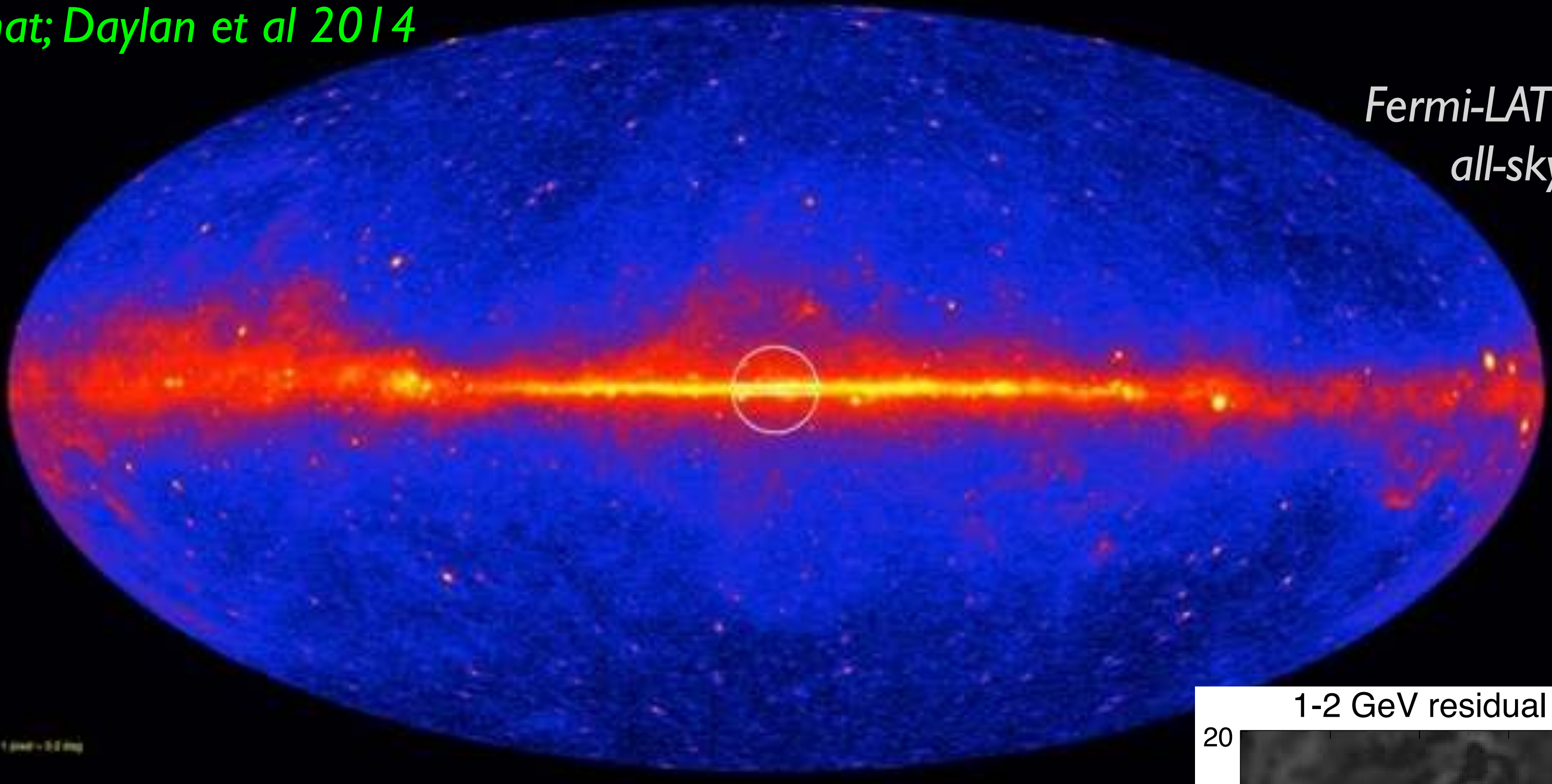
Bernabei et al 1997-2012

Aalseth et al 2011

Gamma-rays from dark matter?

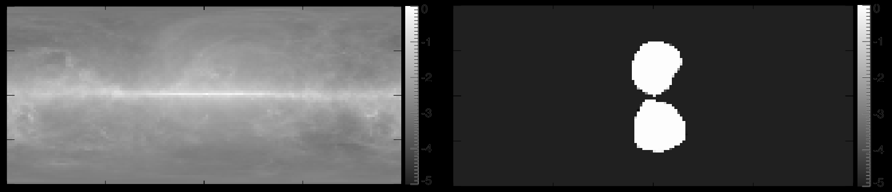
1 GeV gamma-ray excess?

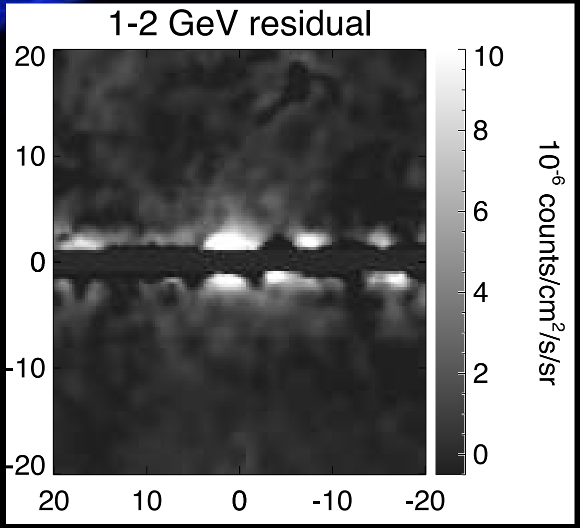
Goodenough, Hooper 2009; Hooper, Goodenough; Boyarsky, Malyshev, Ruchayskiy; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon, Macias 2013; Abazajian, Canac, Horiuchi, Kaplinghat; Daylan et al 2014



Fermi-LAT all-sky map

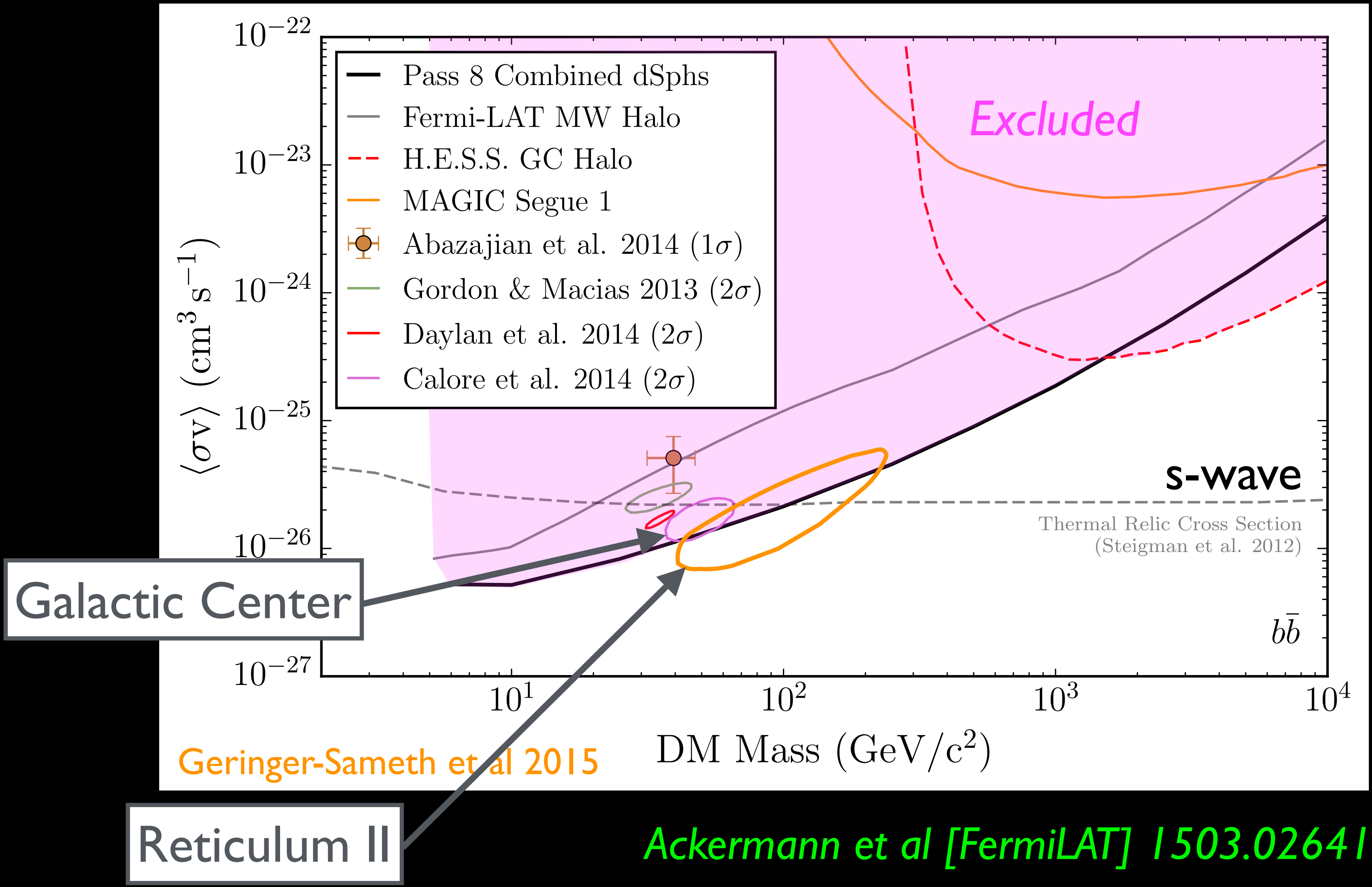
Fit diffuse + Fermi-bubble, find residual





Gamma-rays from dark matter (2015)

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



Geringer-Sameth et al 2015

Ackermann et al [FermiLAT] 1503.02641

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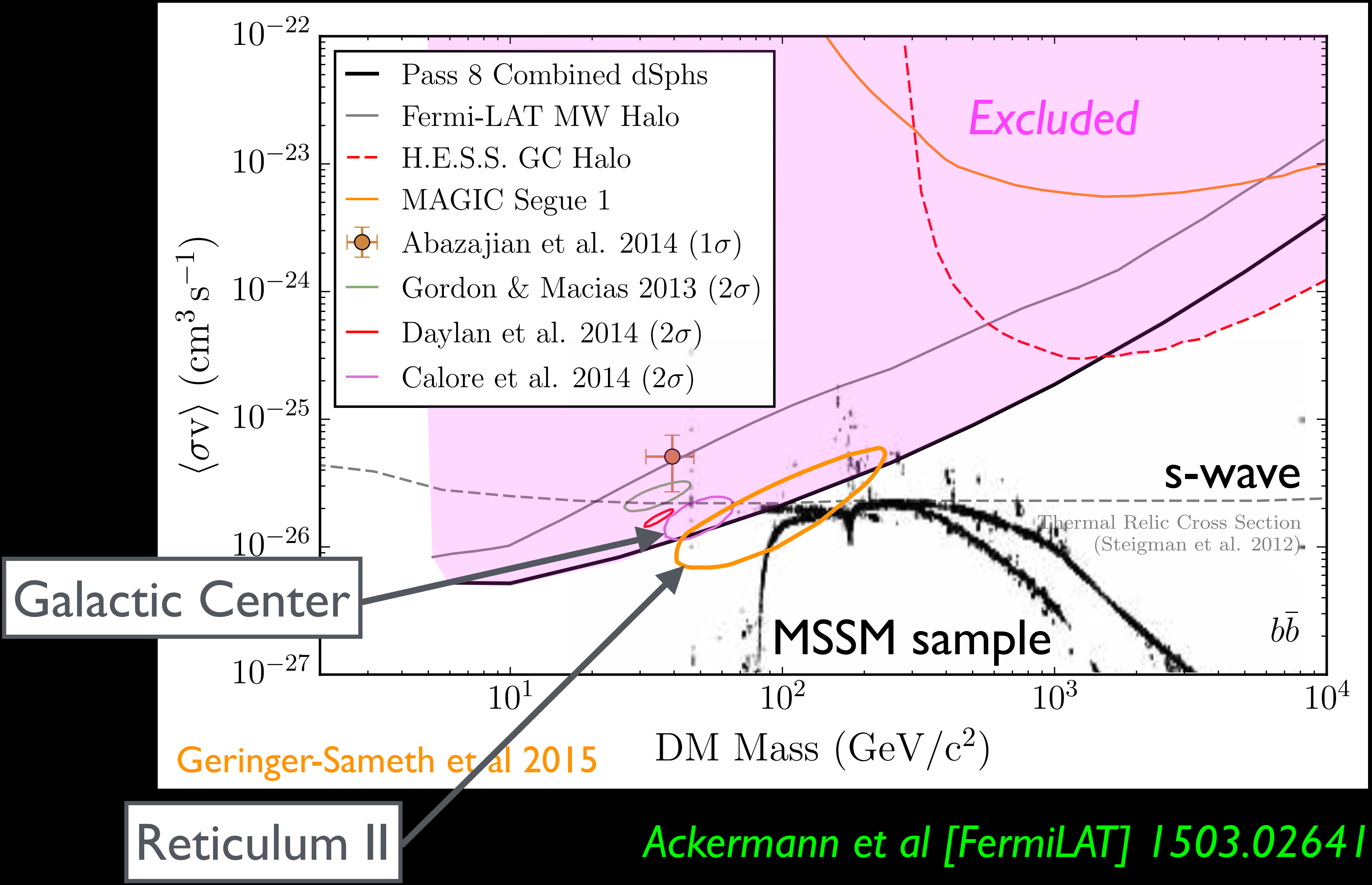
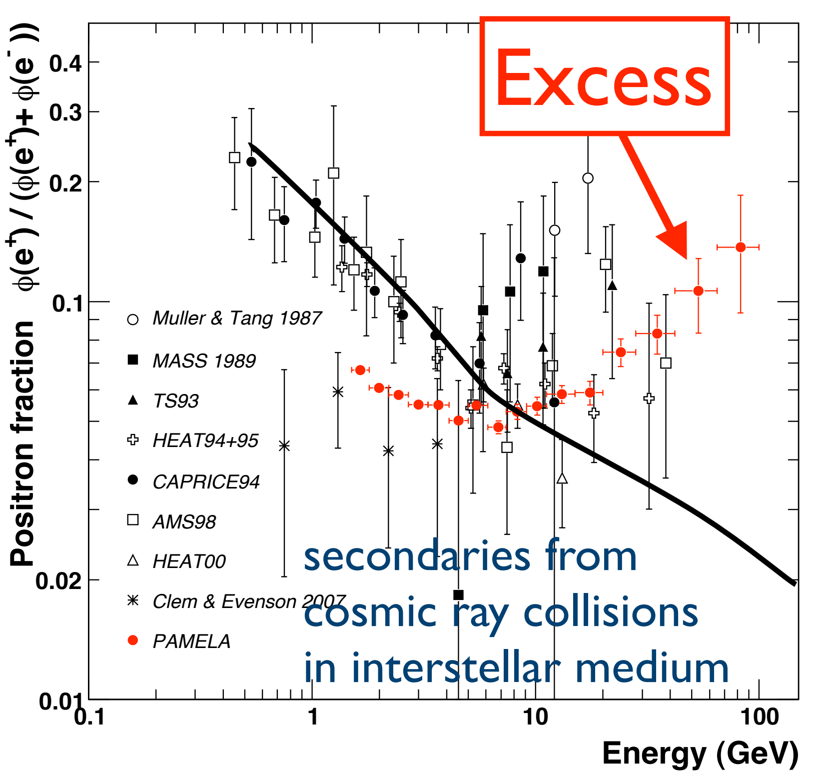


Ackermann et al [FermiLAT] 1503.02641

Positrons from dark matter?

Excess in cosmic ray positrons

High energy cosmic ray positrons are more than expected

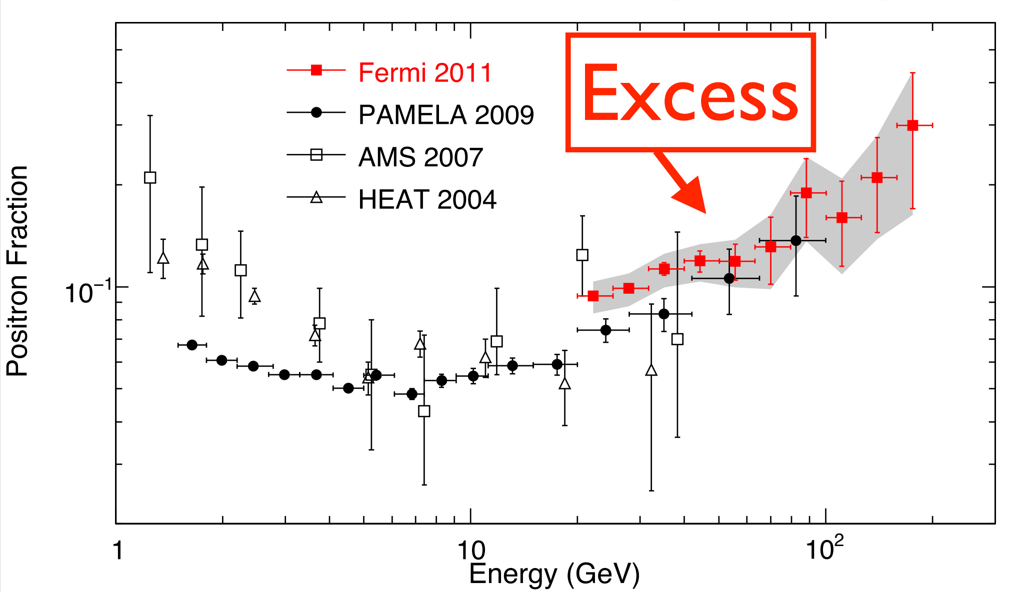


Excess

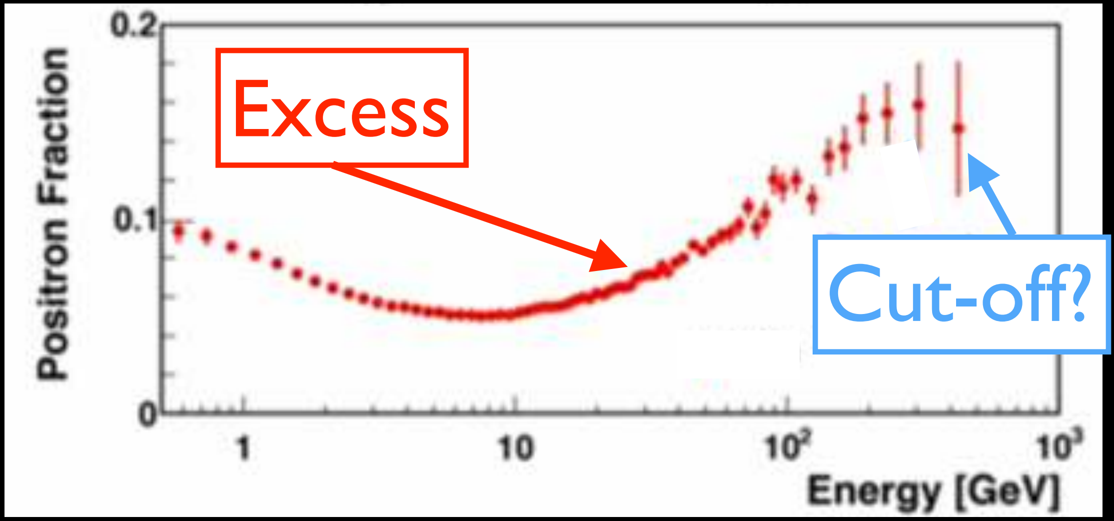
secondaries from cosmic ray collisions in interstellar medium

Adriani et al. [PAMELA ,2008

Ackernmann et al [Fermi-LAT] 2011



Excess



Excess

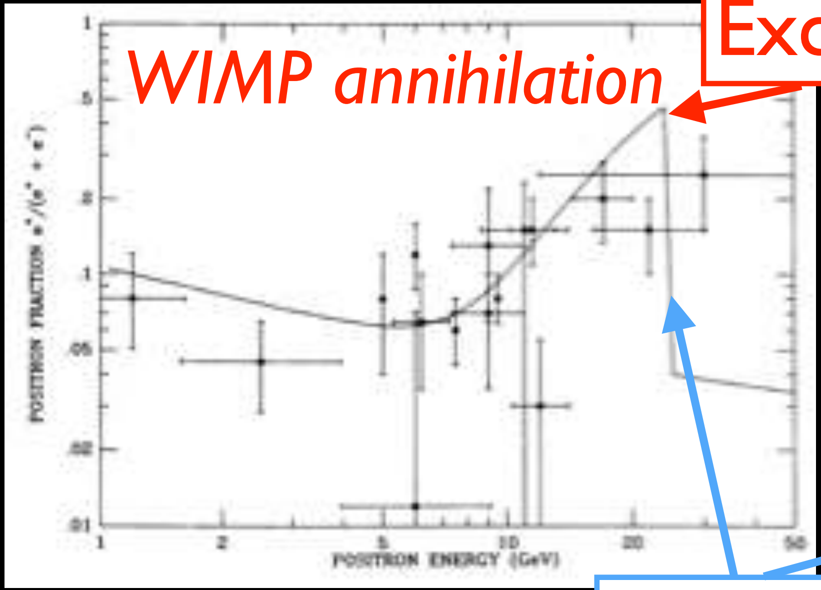
Cut-off?

Accardo et al [AMS-02] 2014

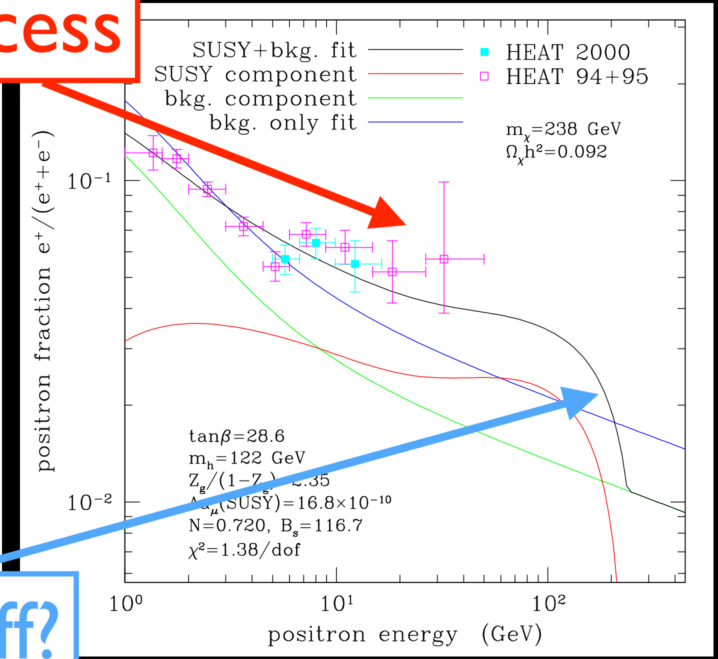
Excess in cosmic ray positrons

Positron excess as "smoking gun" for dark matter

Turner, Wilczek 1990

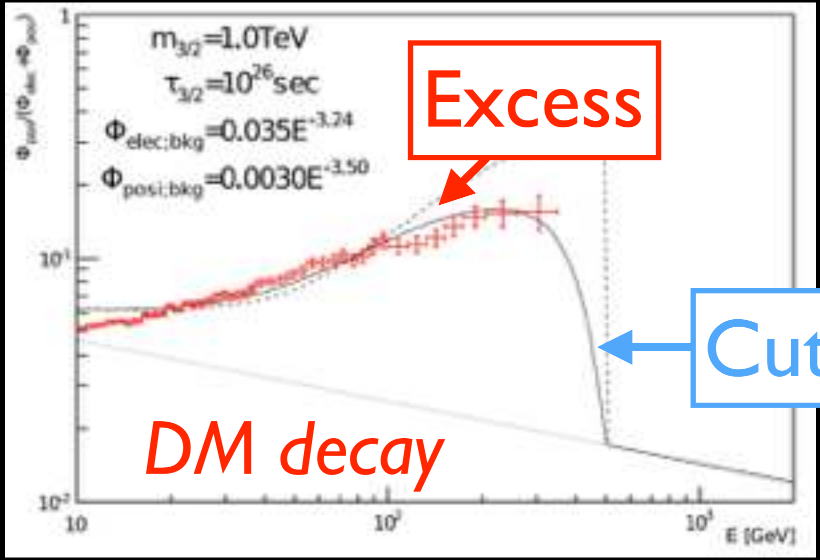


Excess



Cut-off?

Baltz, Esjo, Freese, Gondolo 2001



Excess

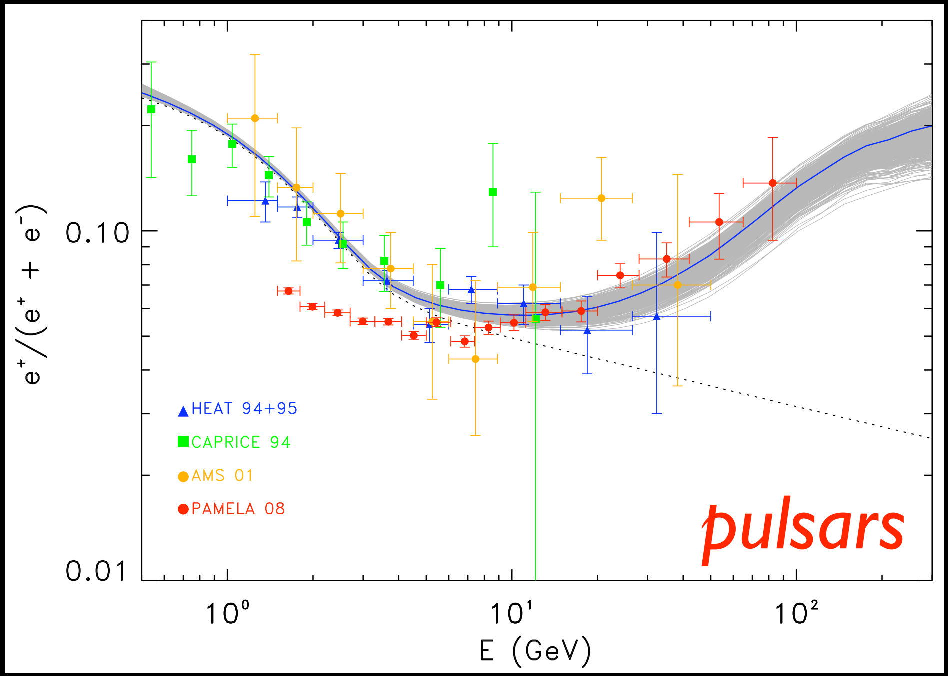
Cut-off?

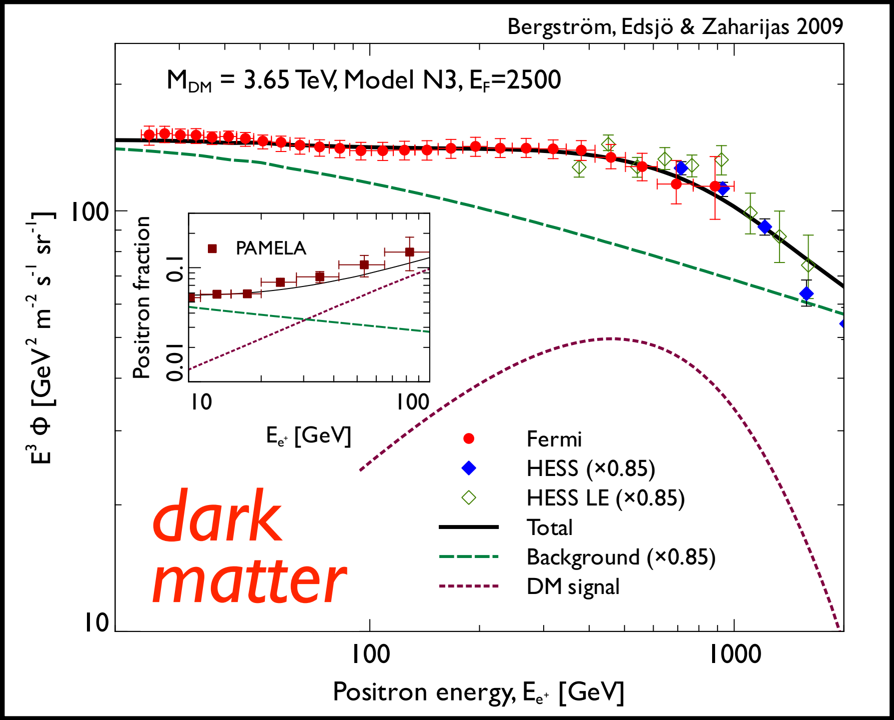
Ibe et al 2013

Excess in cosmic ray positrons

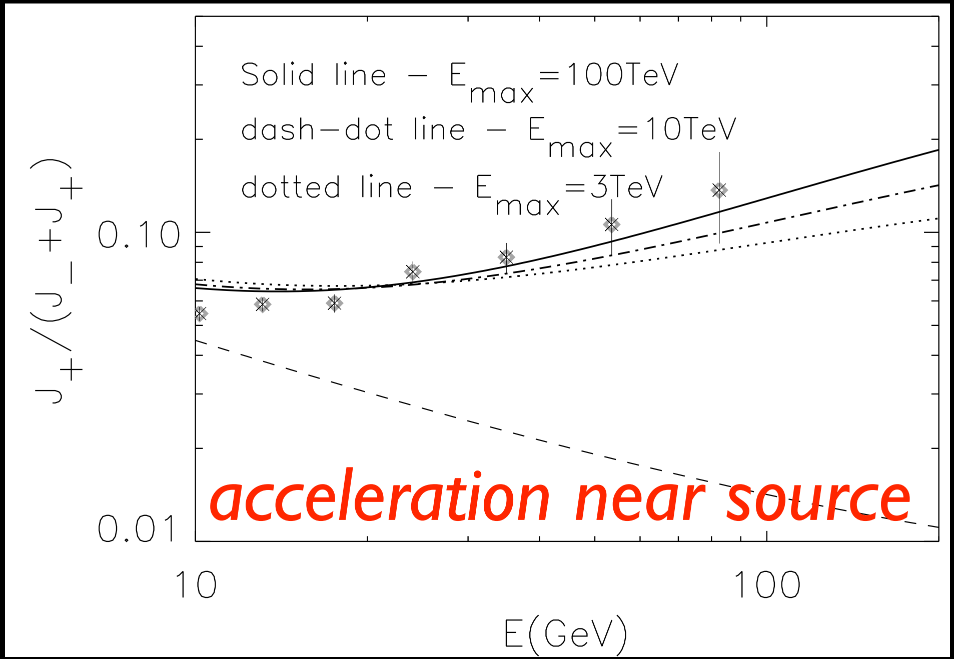
Dark matter?
Pulsars?
Secondaries from extra primaries?

Grasso et al [Fermi-LAT] 2009





Bergstrom, Edsjo, Zaharijas 2009



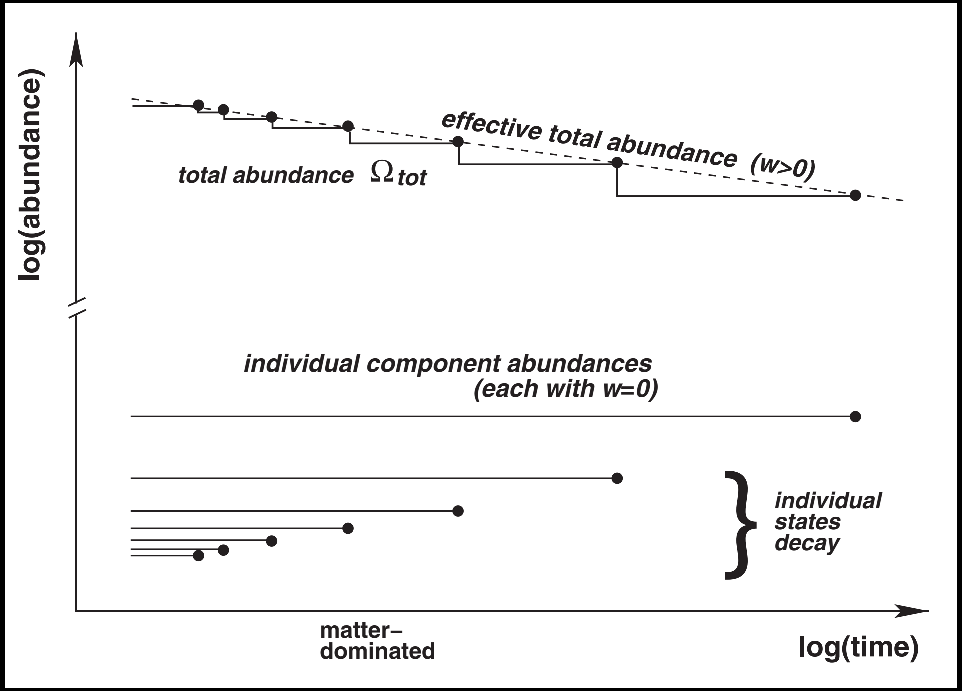
Blasi 2009

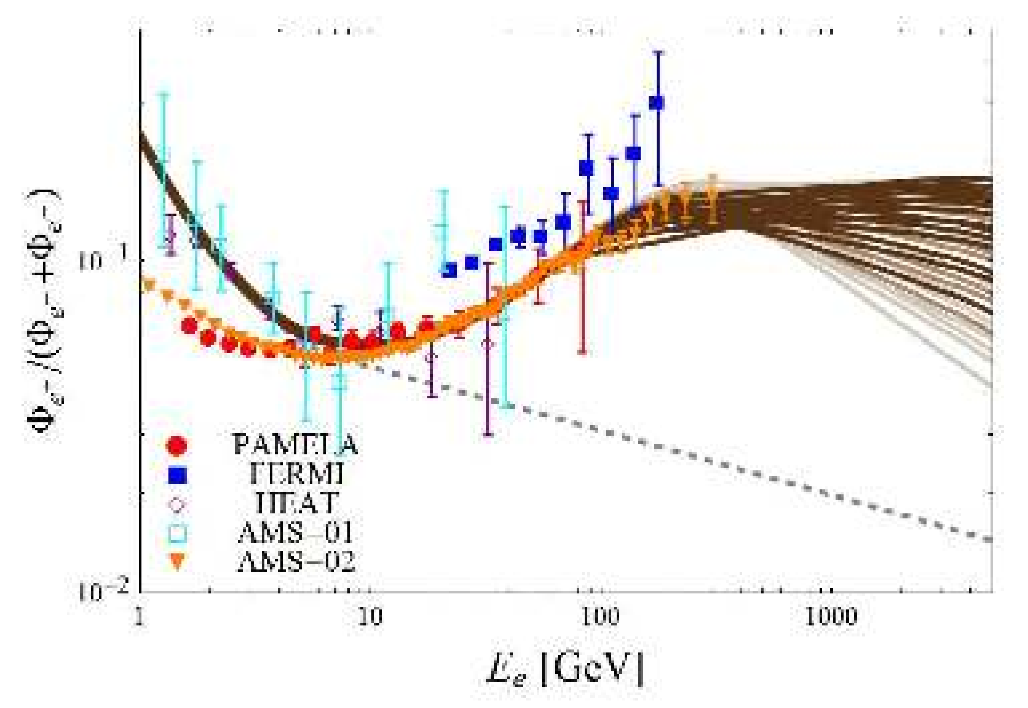
Dynamical dark matter

Dienes, Thomas 2011, 2012
Dienes, Kumar, Thomas 2012, 2013

A vast ensemble of fields decaying one into another

Example: Kaluza-Klein tower of axions in extra-dimensions





Phenomenology obtained through scaling laws

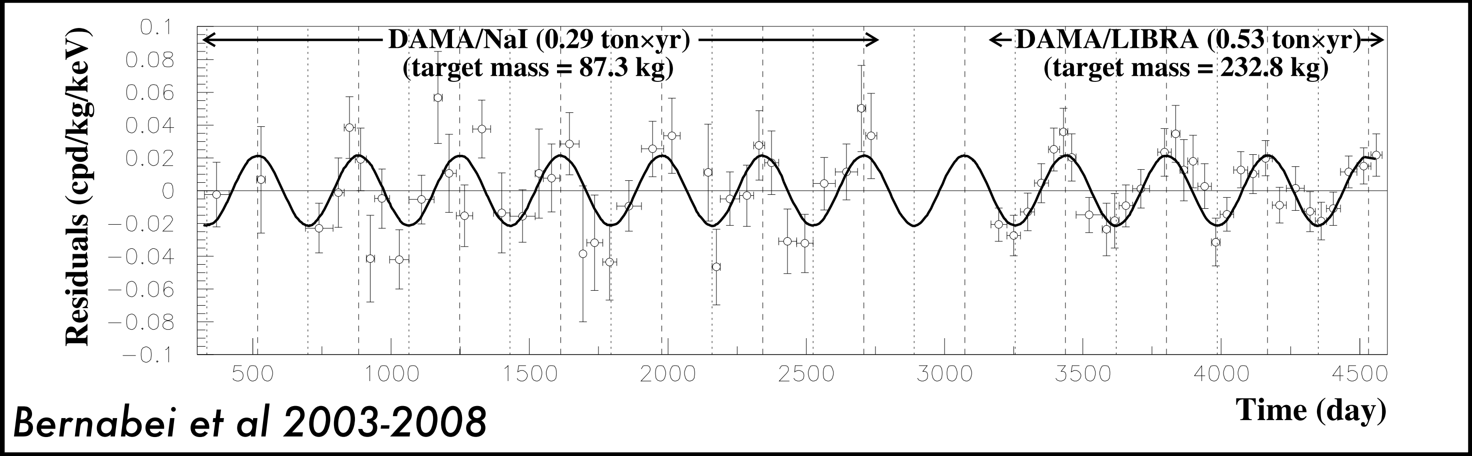
$$m_n = m_0 + n^\delta \Delta m,$$

$$\rho_n \sim m_n^\alpha, \ \tau_n \sim m_n^{-\gamma}$$

Direct detection of dark matter?

Annual modulation in direct detection

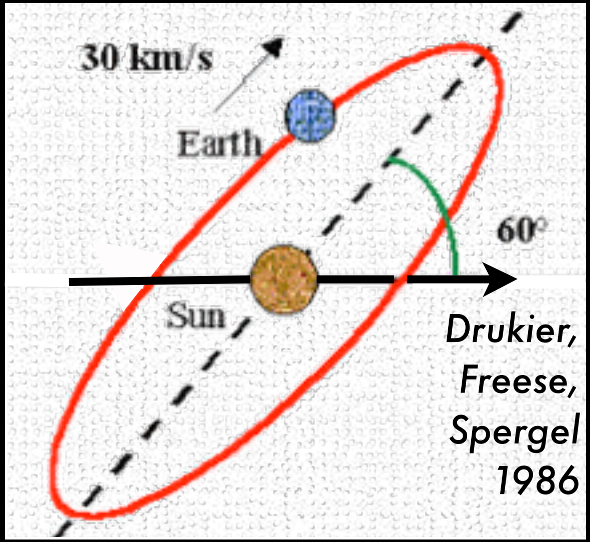
- DAMA observes more nuclei are “hit” in Summer, fewer in Winter



Bernabei et al 2003-2008

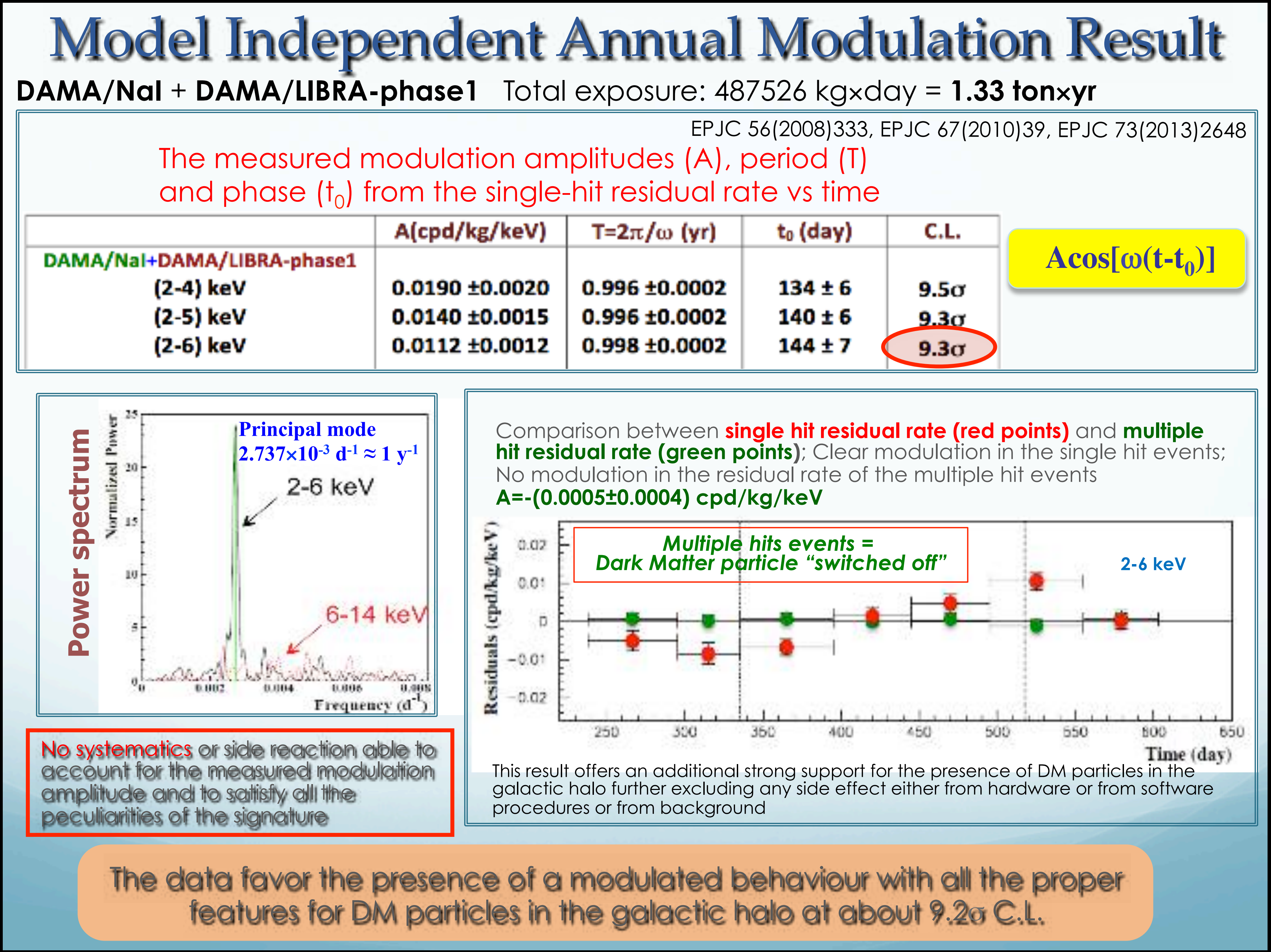
- This is exactly what is expected of dark matter WIMPs

Drukier, Freese, Spergel 1986



Drukier, Freese, Spergel 1986

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

Principal mode 2.737×10^{-3} $d^{-1} \approx 1$ y^{-1}

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**

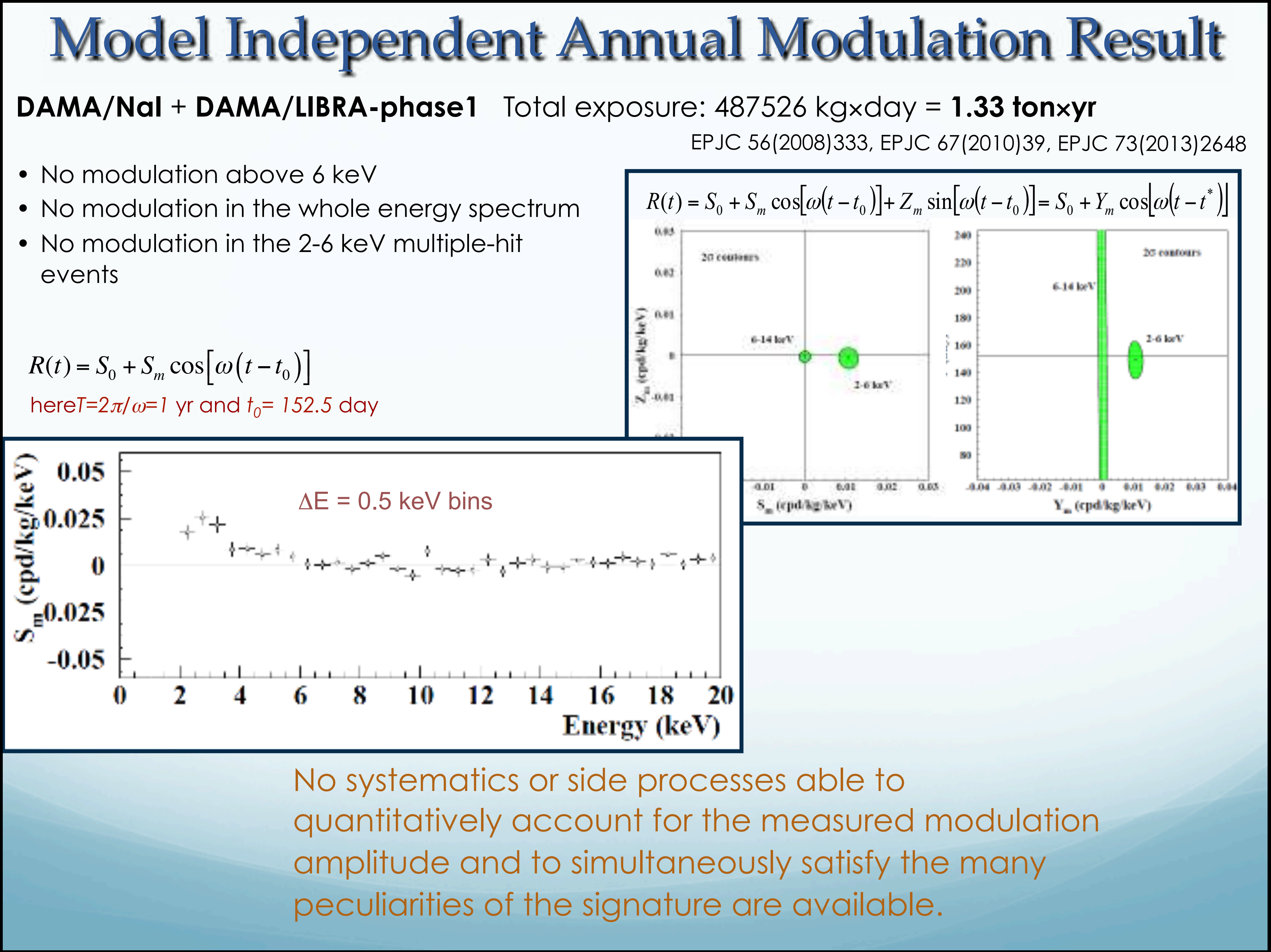
Multiple hits events = Dark Matter particle "switched off"

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

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

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

DAM

3)2648

- No
- No
- No ev

R(t)

here

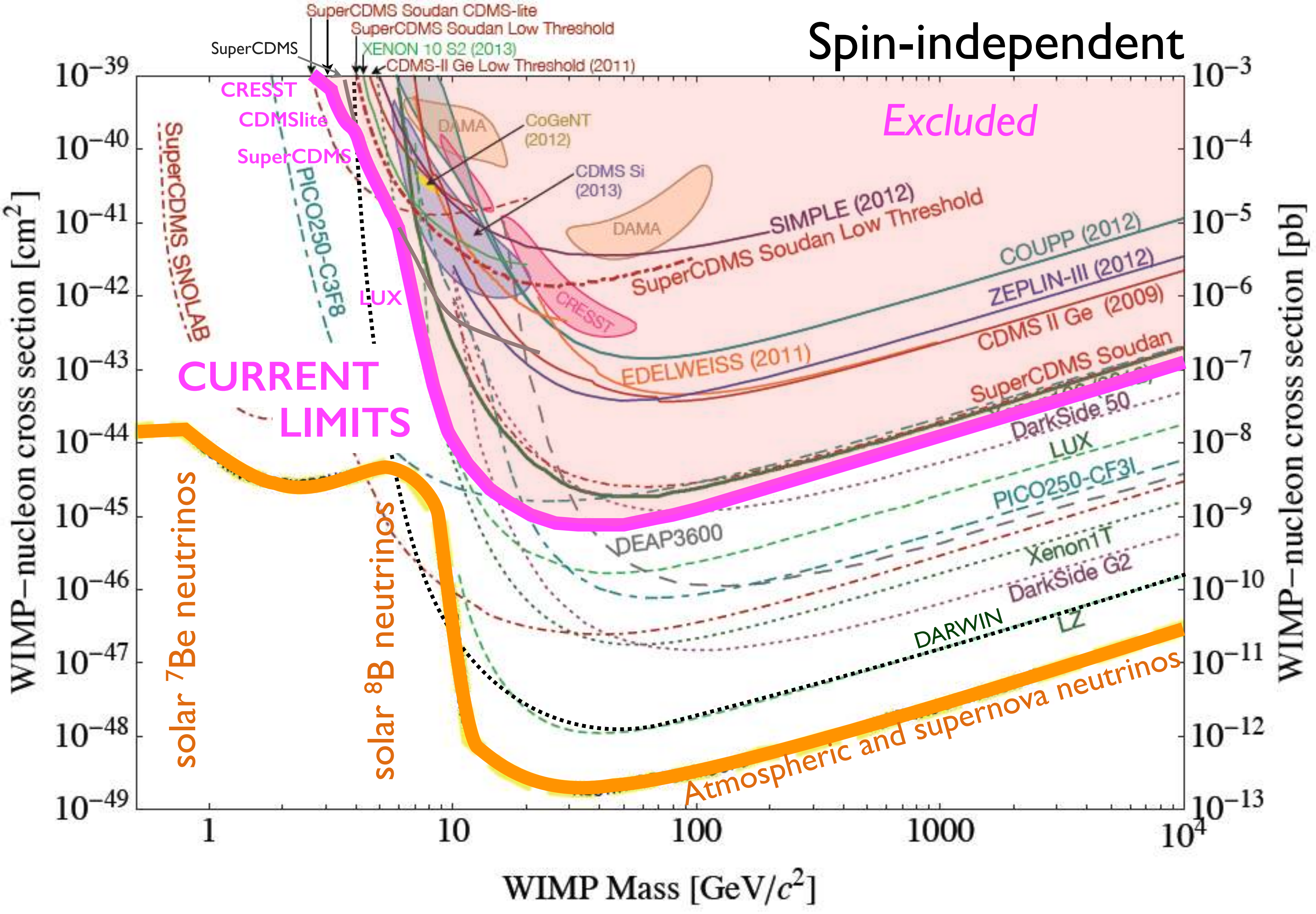
“Public?
What does it mean?”

Pierluigi Belli at IDM2014

amplitude and to simultaneously satisfy the many peculiarities of the signature are available.

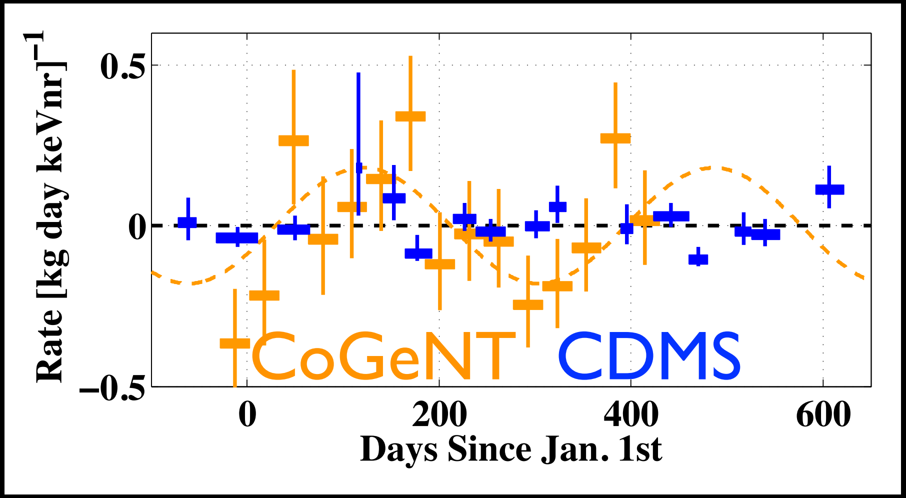
Belli, IDM2014

Direct dark matter searches (2015)



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

Evidence for light dark matter particles?



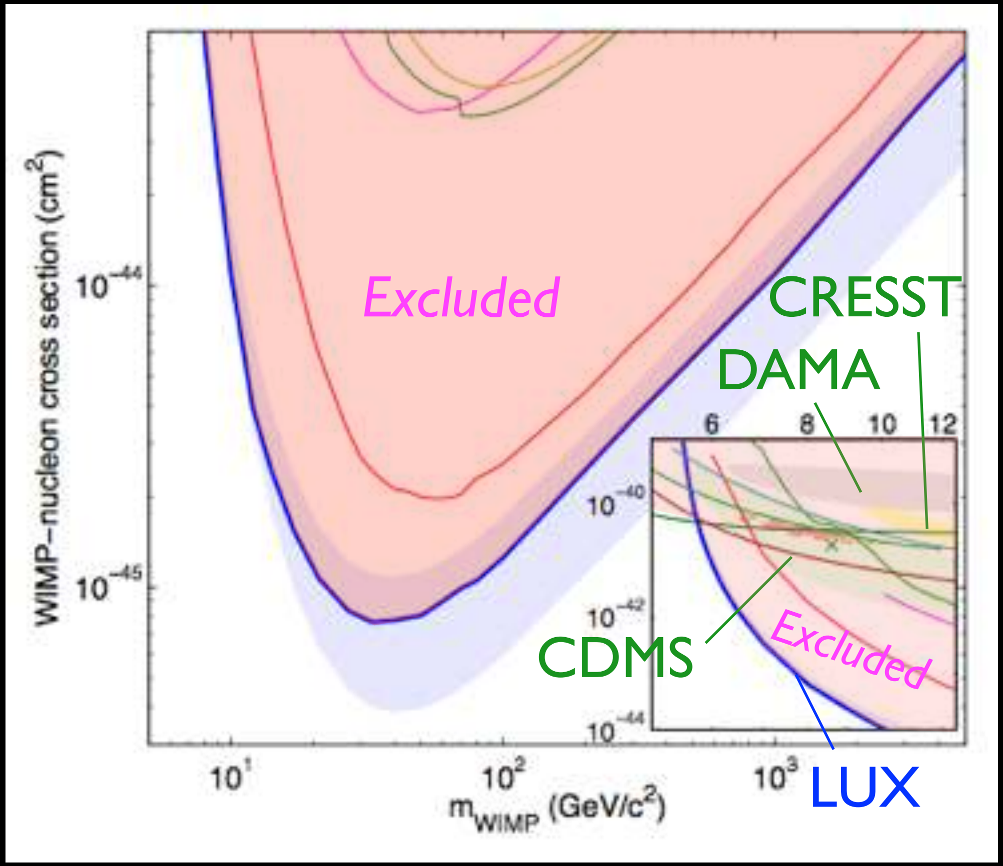
No significant modulation

Same target material

Ahmed et al (CDMS)
1203.1309

Not so many events

Akerib et al (LUX) 2013



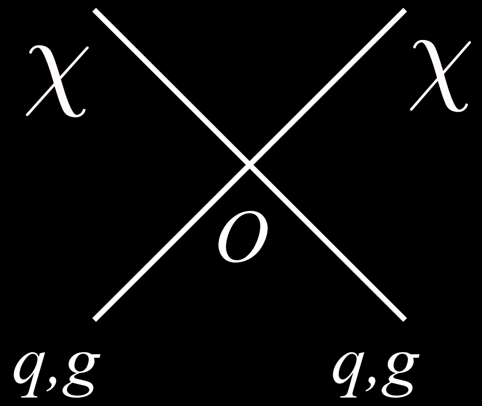
That which does not kill us
makes us stronger

All particle physics models

Write down and analyze all possible WIMP interactions with ordinary matter

Effective operators

if mediator mass ≫ exchanged energy



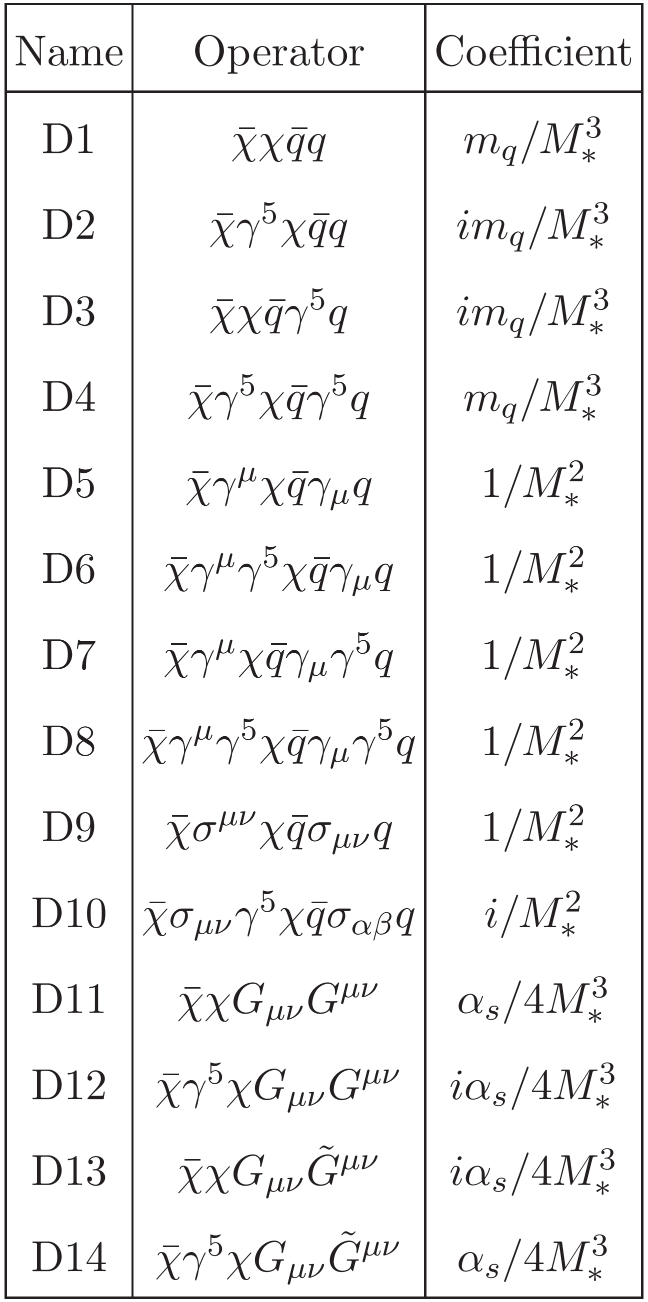
Four-particle effective operator

There are many possible operators.

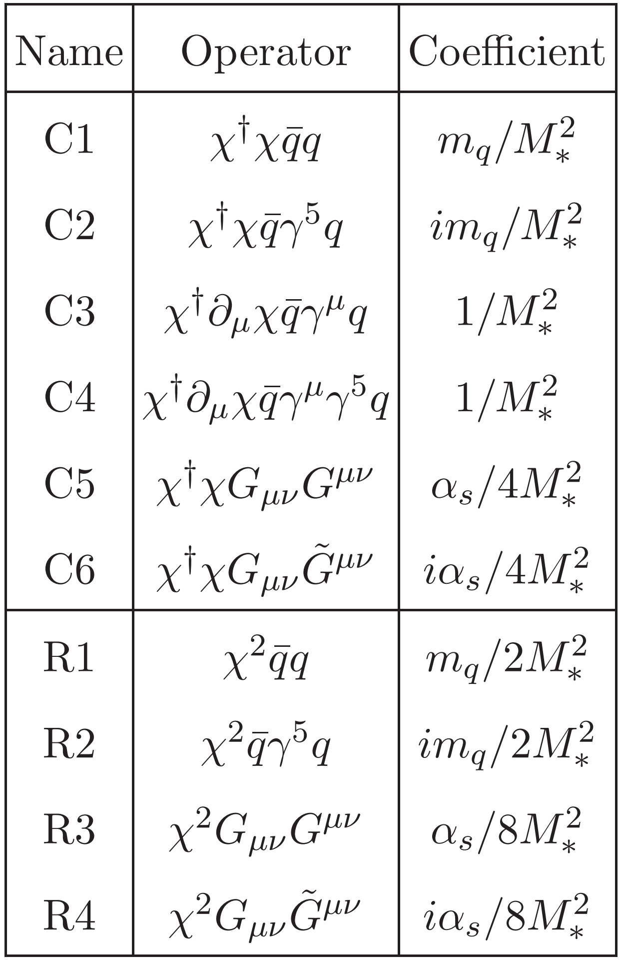
Interference is important although often neglected.

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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

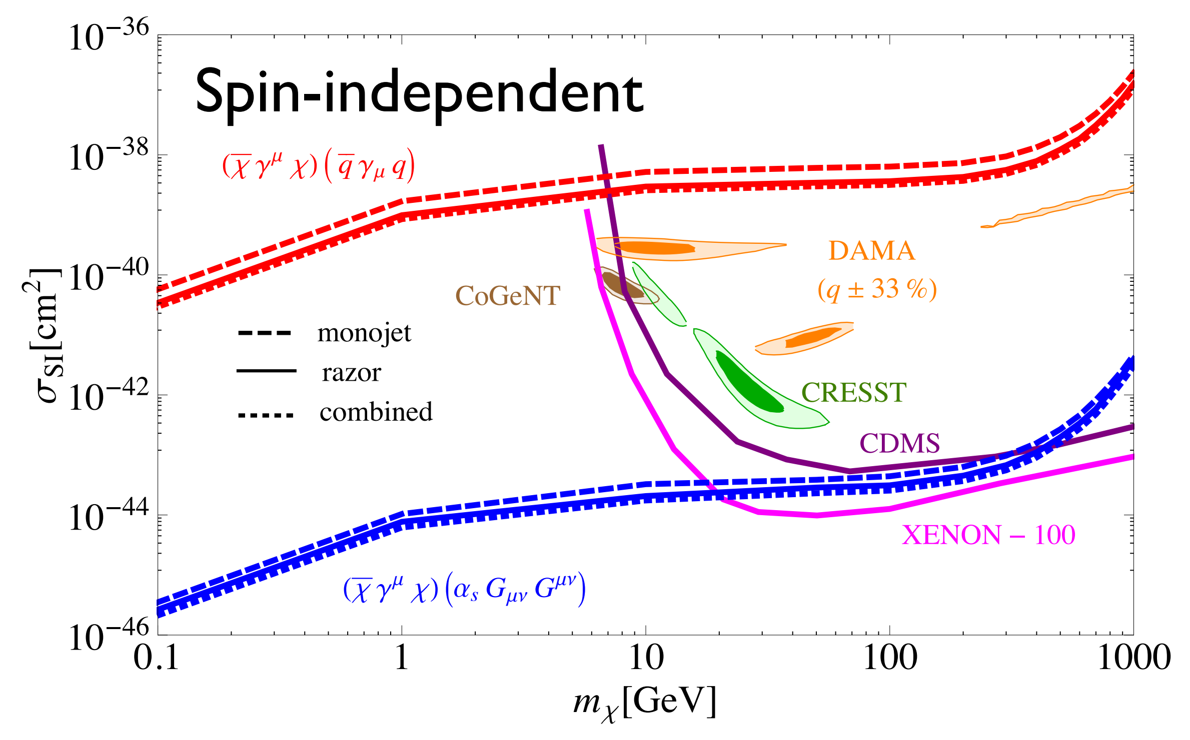
Table of effective operators relevant for the collider/direct detection connection

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

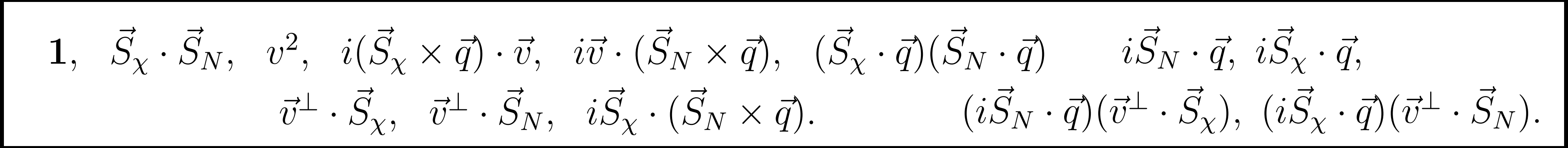
These bounds do not apply to SUSY, etc.

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

Effective operators: direct detection

All short-distance operators classified

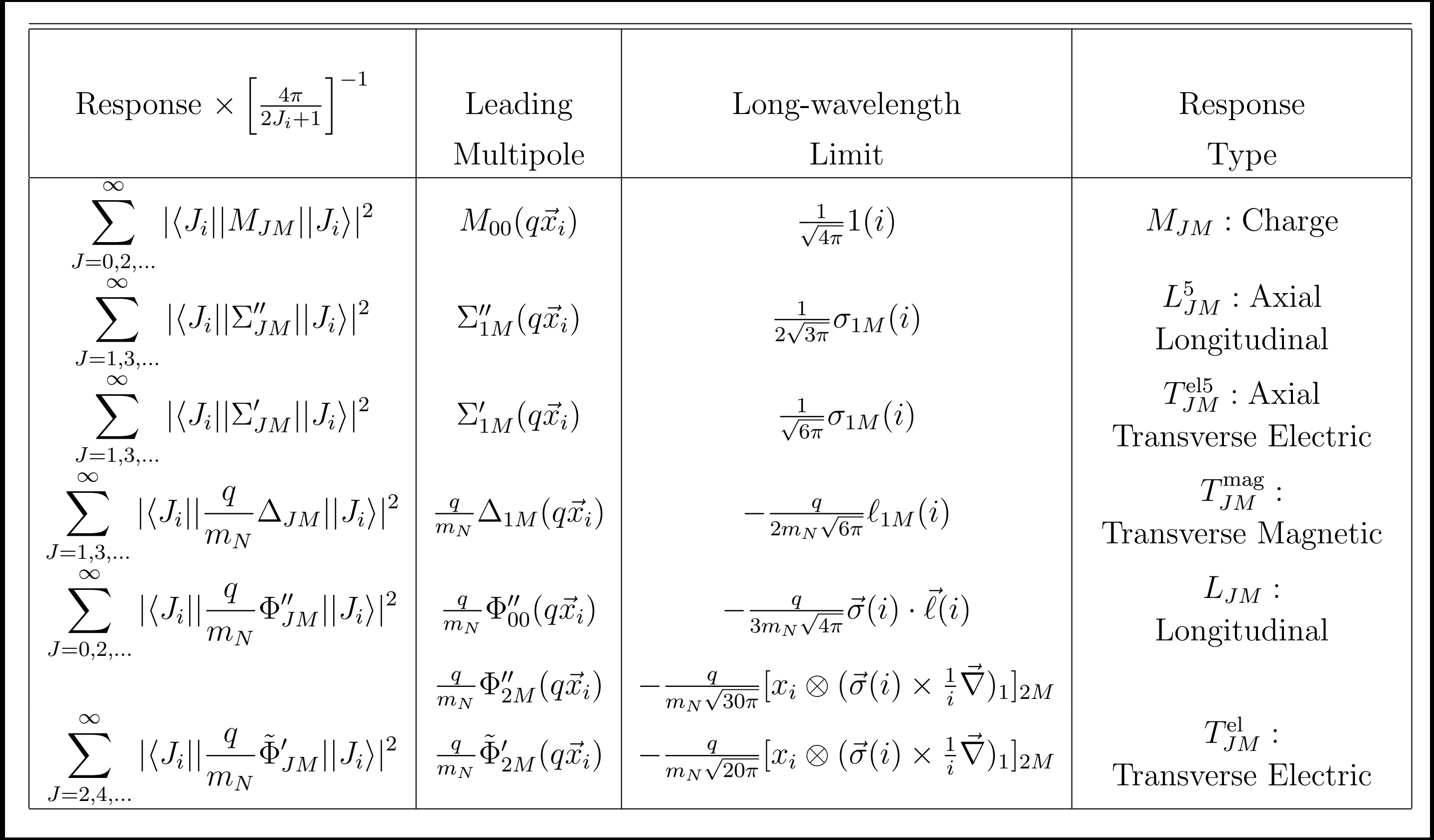
Fitzpatrick et al 2012



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

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

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^{el5}_{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

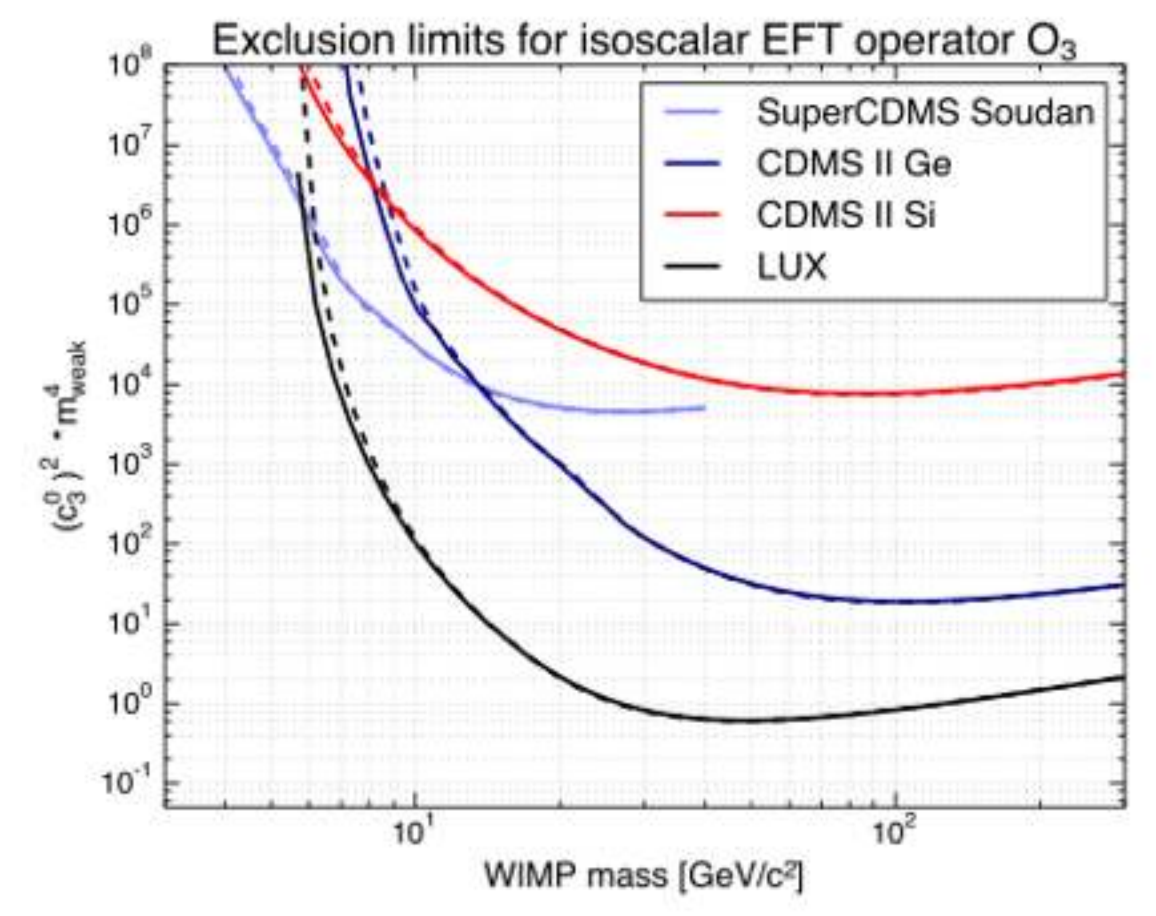
nuclear oscillator model

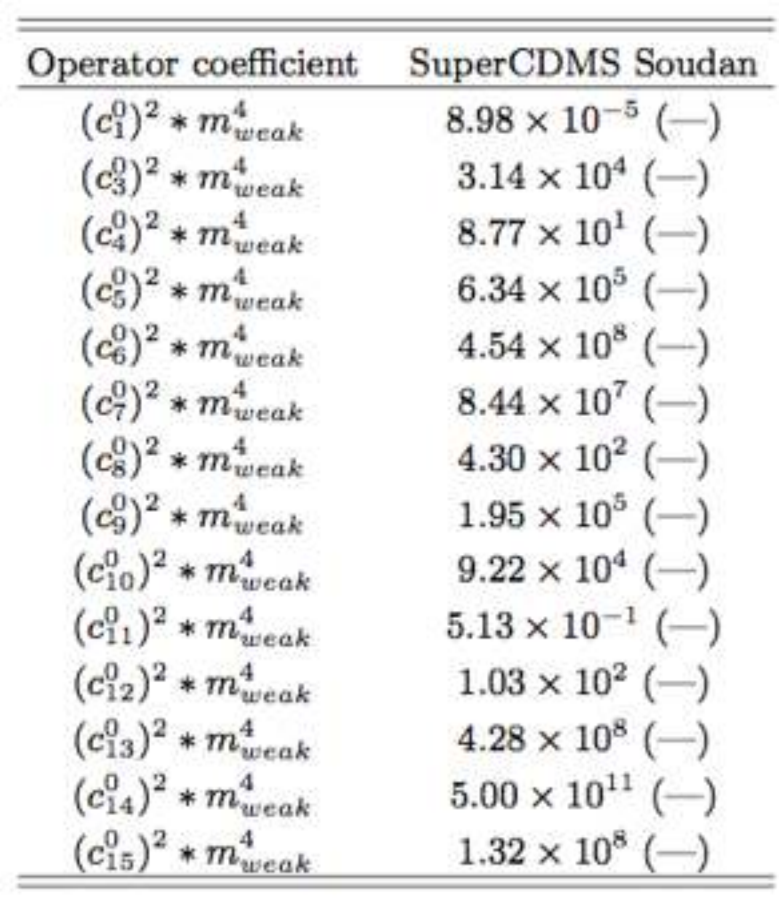
Fitzpatrick et al 2012

Effective operators: direct detection

Experimental limits on single operators…

Schneck et al (SuperCDMS) 2015





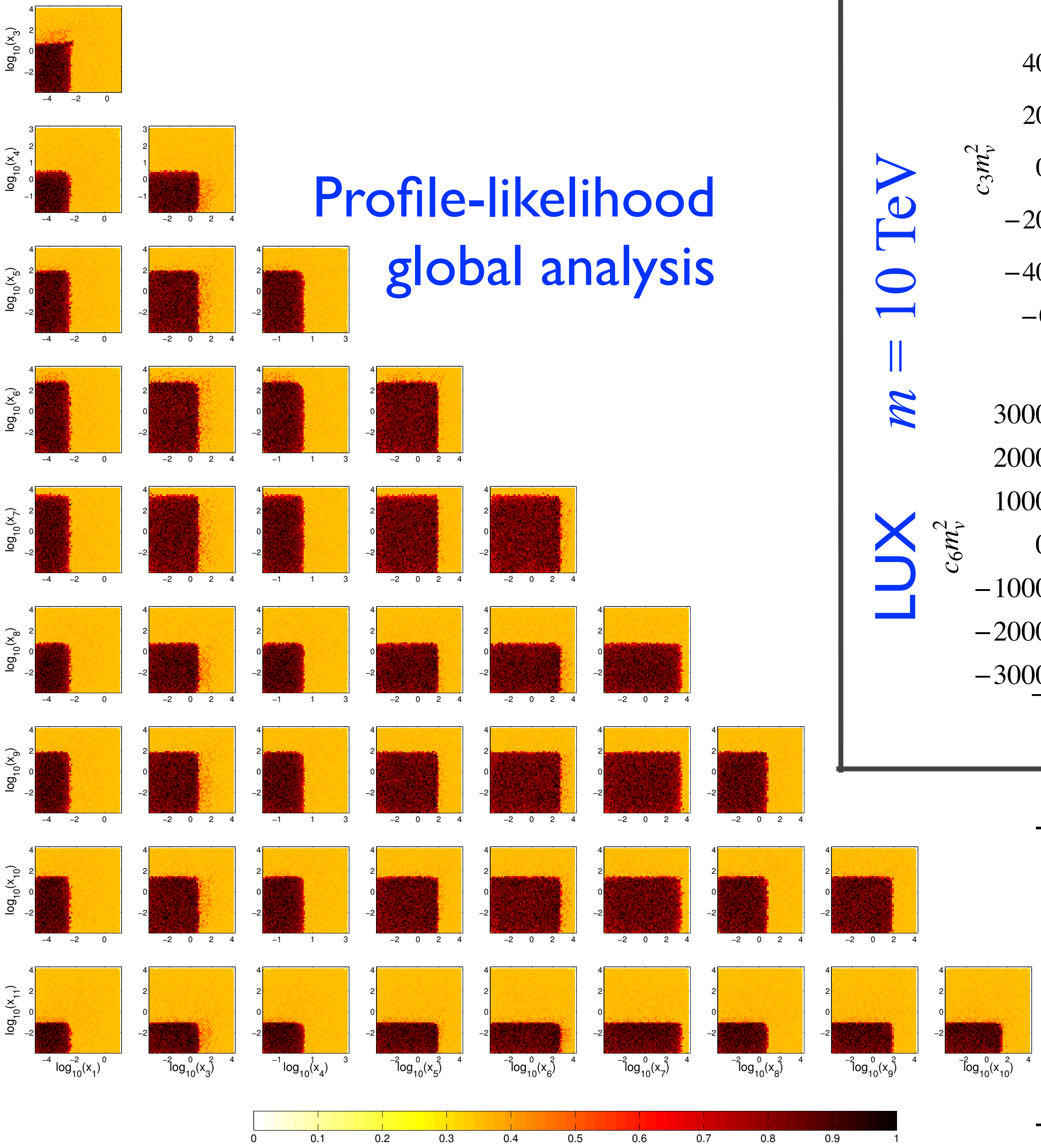
Operator coefficient	SuperCDMS Soudan
$(c_1^0)^2 * m_{weak}^4$	8.98×10^{-5} (—)
$(c_3^0)^2 * m_{weak}^4$	3.14×10^{4} (—)
$(c_4^0)^2 * m_{weak}^4$	8.77×10^{1} (—)
$(c_5^0)^2 * m_{weak}^4$	6.34×10^{5} (—)
$(c_6^0)^2 * m_{weak}^4$	4.54×10^{8} (—)
$(c_7^0)^2 * m_{weak}^4$	8.44×10^{7} (—)
$(c_8^0)^2 * m_{weak}^4$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

Effective operators: direct detection

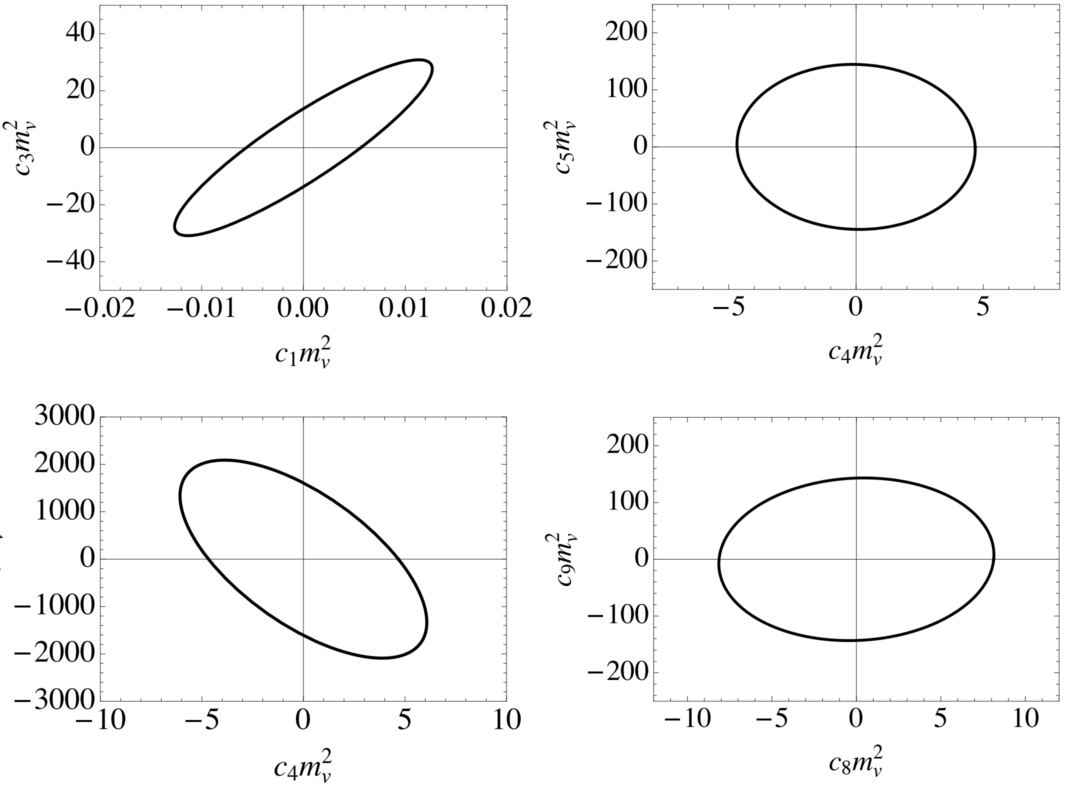
Combined analysis of short-distance operators

Catena, Gondolo 2014

Profile-likelihood global analysis



LUX $m = 10$ TeV



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

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

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

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

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

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

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

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

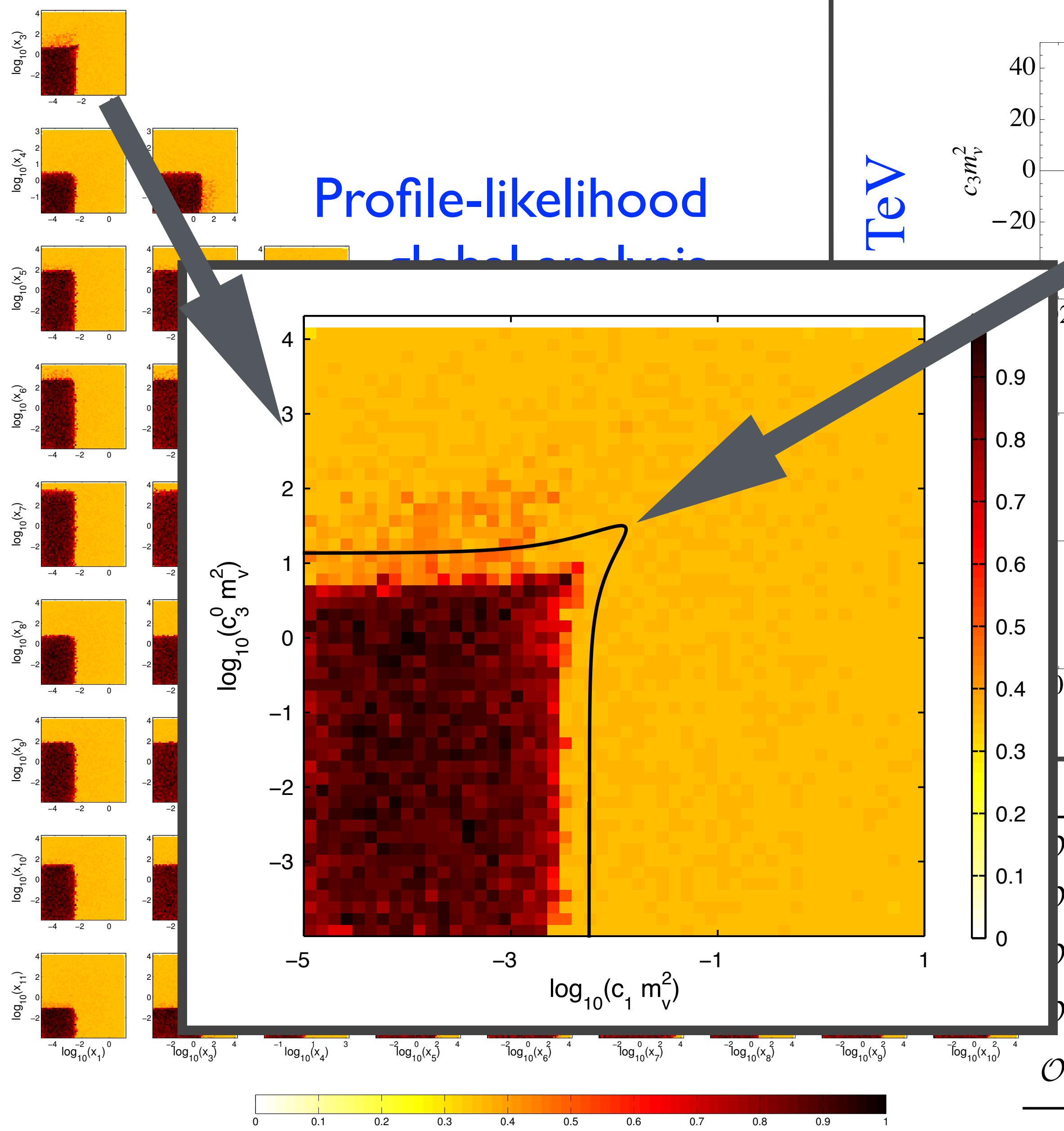
$$\mathcal{O}_{10} = -i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

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

Effective operators: direct detection

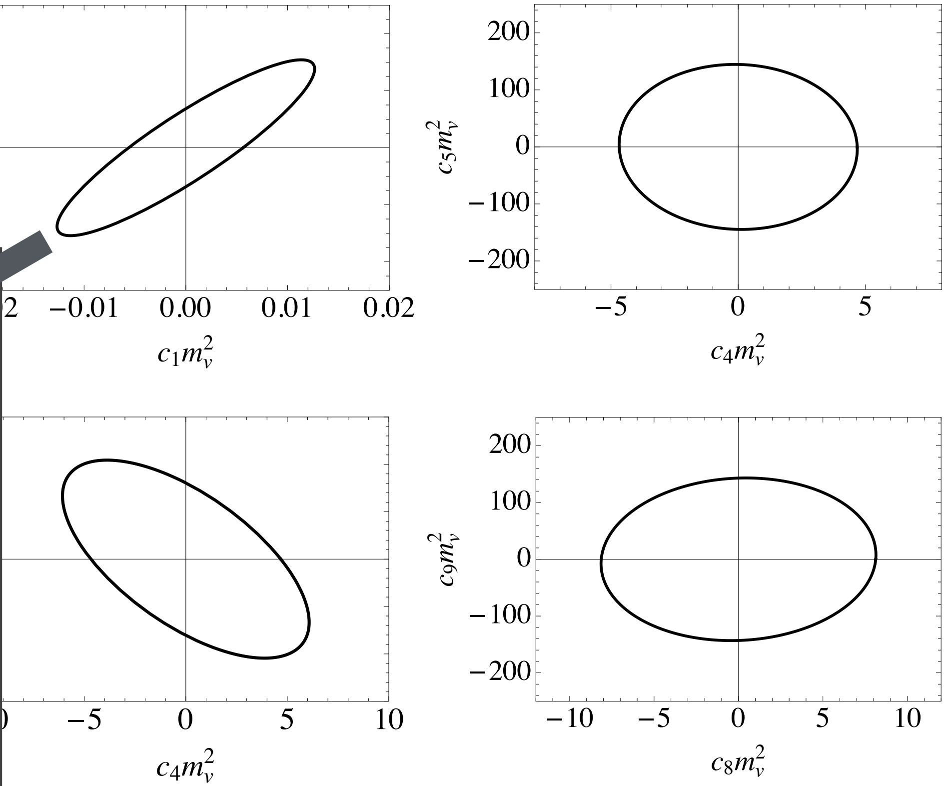
Combined analysis of short-distance operators

Catena, Gondolo 2014



Profile-likelihood
global analysis

TeV



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

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

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

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

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

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

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

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

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

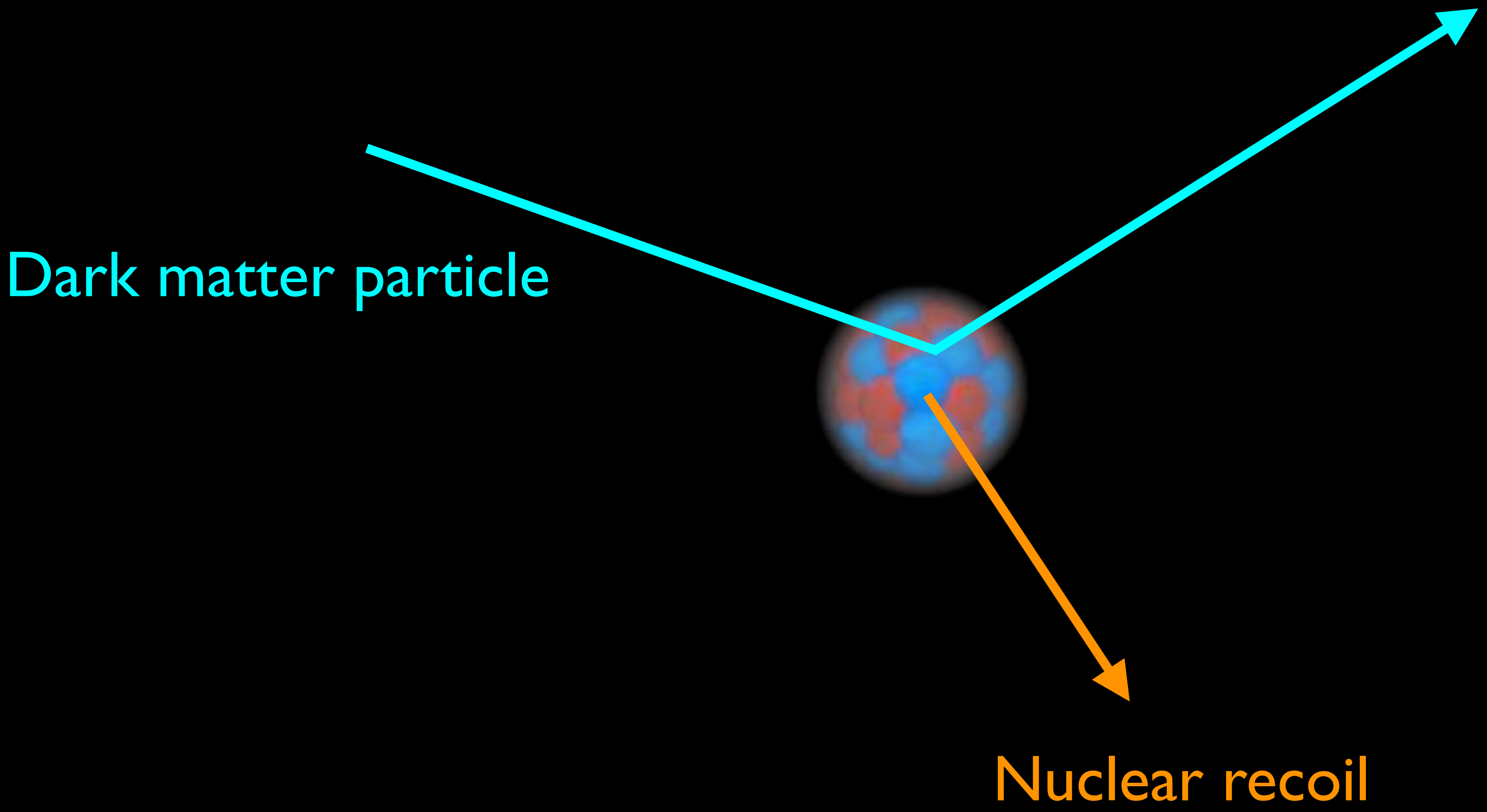
$\mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

All astrophysics models

Do not assume any particular
WIMP density or velocity distribution

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.

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

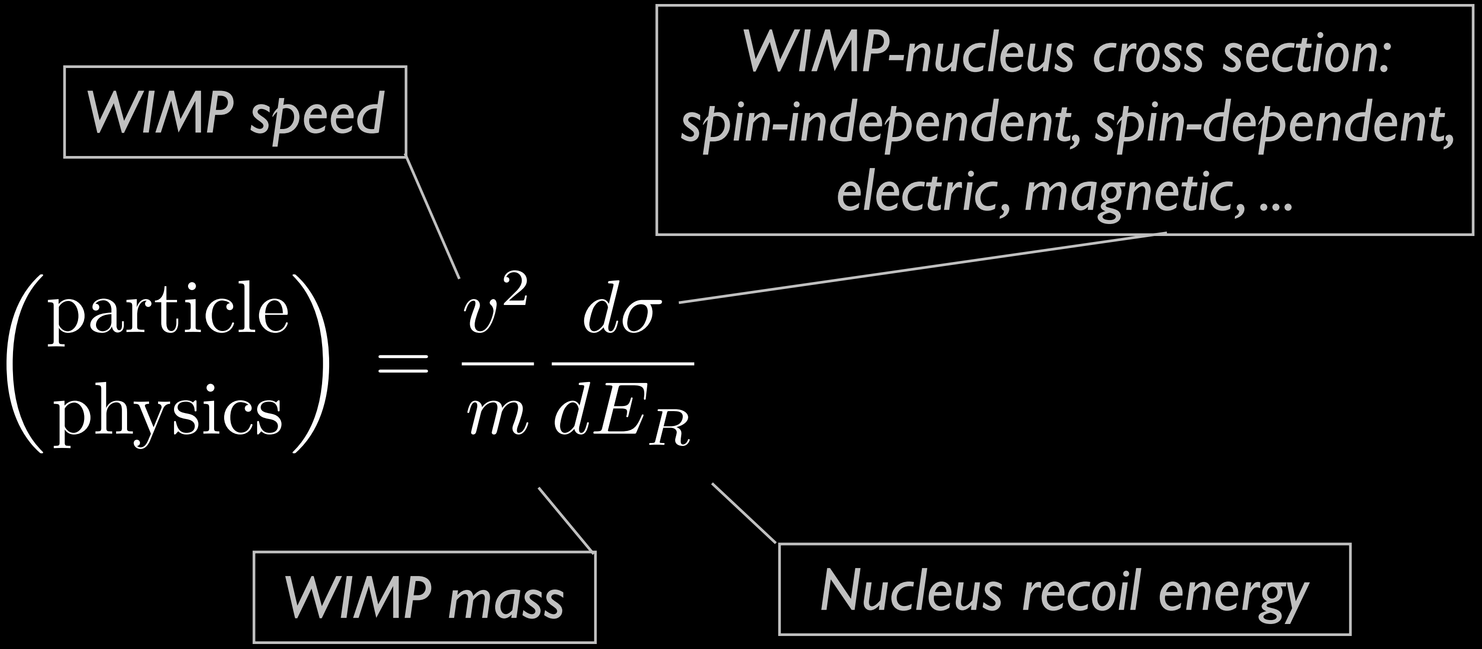
Probability of detecting an event with energy (or number of photoelectrons) E, given an event occurred with recoil energy E_R.

Particle physics model

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

What force couples dark matter to nuclei?

Coupling to nucleon number density, nucleon spin density, ...



WIMP speed

WIMP-nucleus cross section: spin-independent, spin-dependent, electric, magnetic, ...

$$\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} = \frac{v^2}{m}\frac{d\sigma}{dE_R}$$

WIMP mass

Nucleus recoil energy

Astrophysics model

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

How much dark matter comes to Earth?

Velocity distribution

Local halo density

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

Minimum WIMP speed to impart recoil energy E_R

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

Astrophysics model: velocity distribution

Standard Halo Model

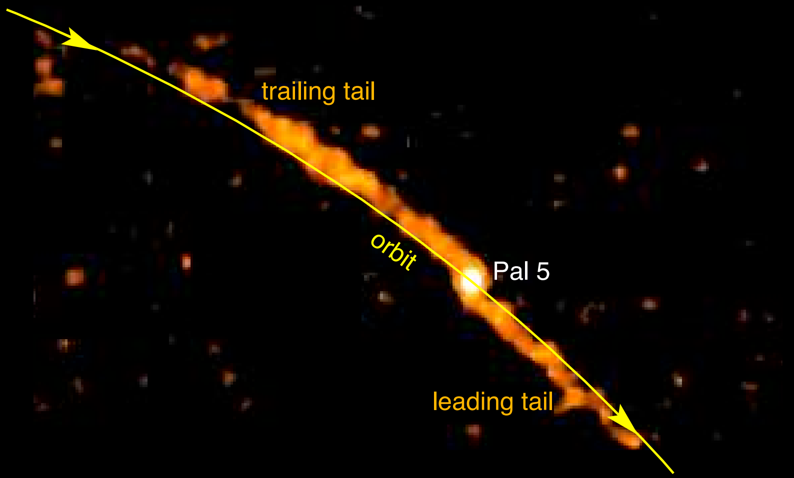
truncated Maxwellian

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

The spherical cow of direct WIMP searches

Astrophysics model: velocity distribution

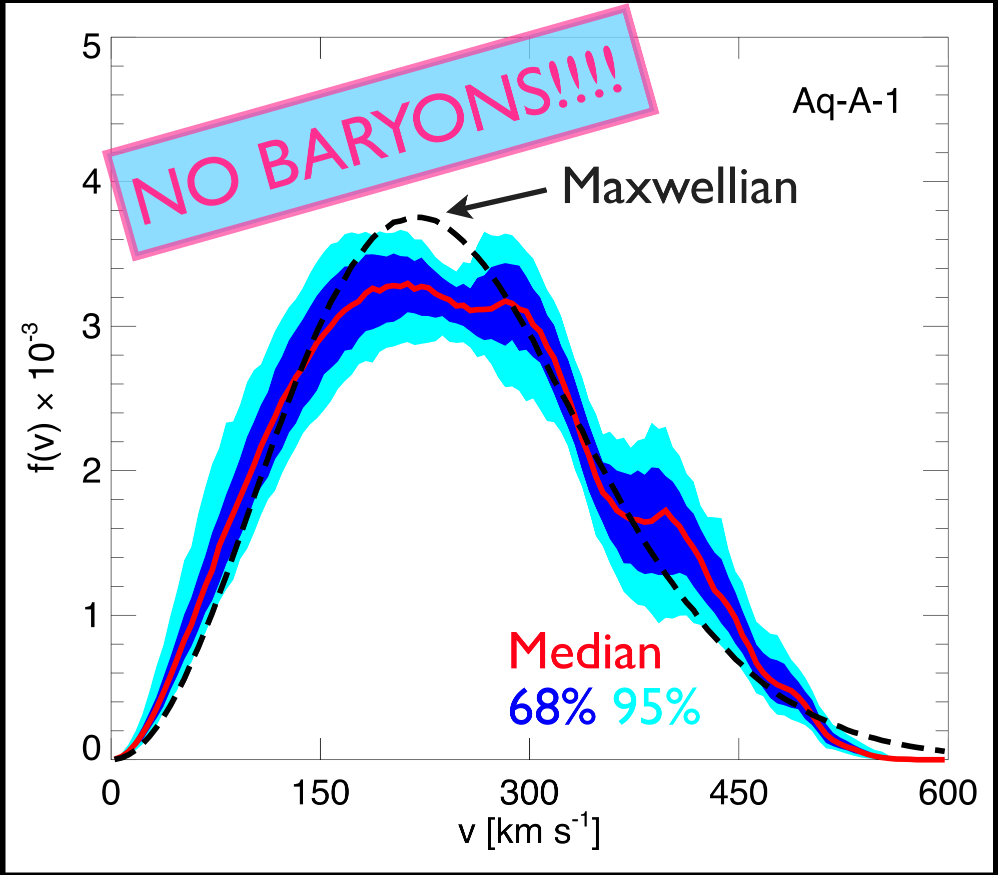
We know very little about the dark matter velocity distribution near the Sun



Odenkirchen et al 2002 (SDSS)

Streams of stars have been observed in the galactic halo

SDSS, 2MASS, SEGUE,…….



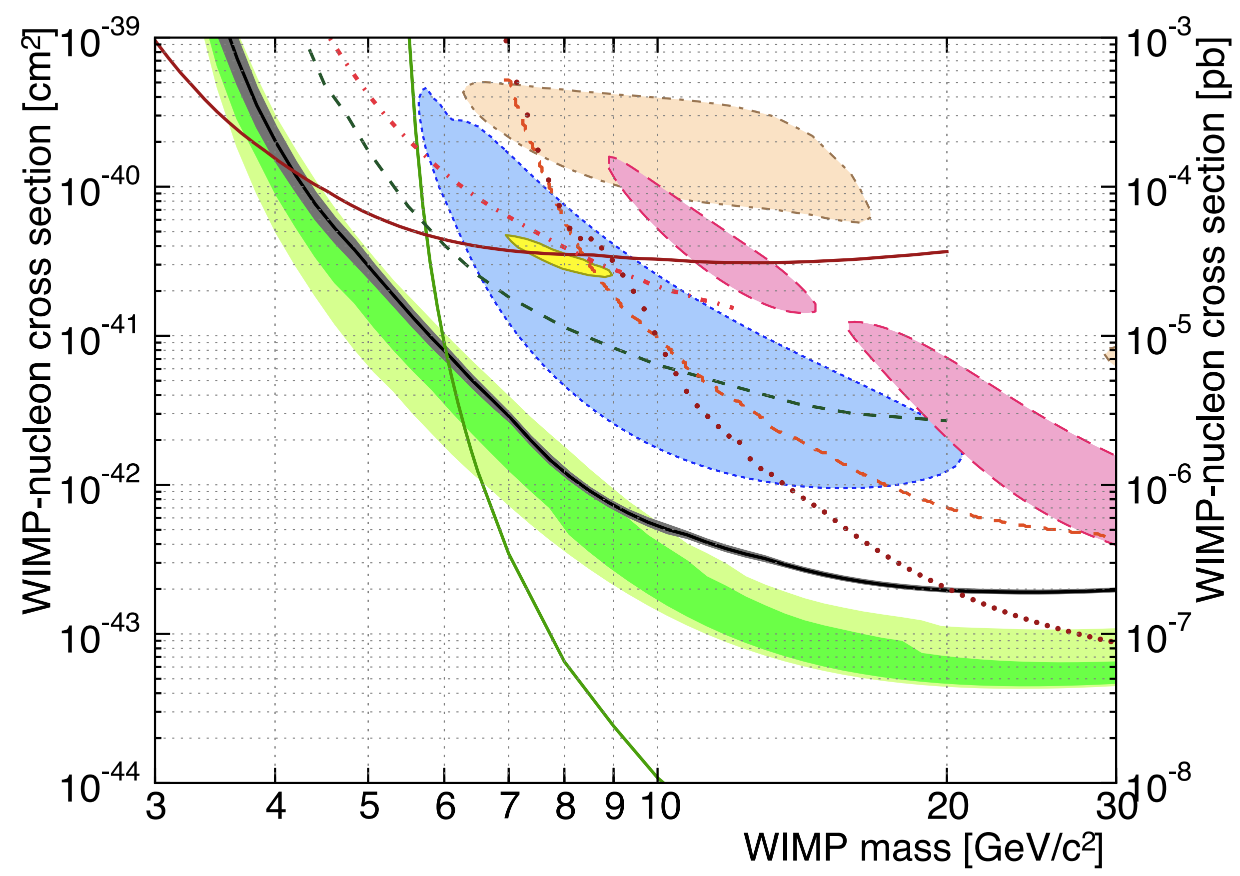
Vogelsberger et al 2009

Cosmological N-Body simulations including baryons are challenging but underway

Astrophysics model: velocity distribution

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

FIXED FIXED



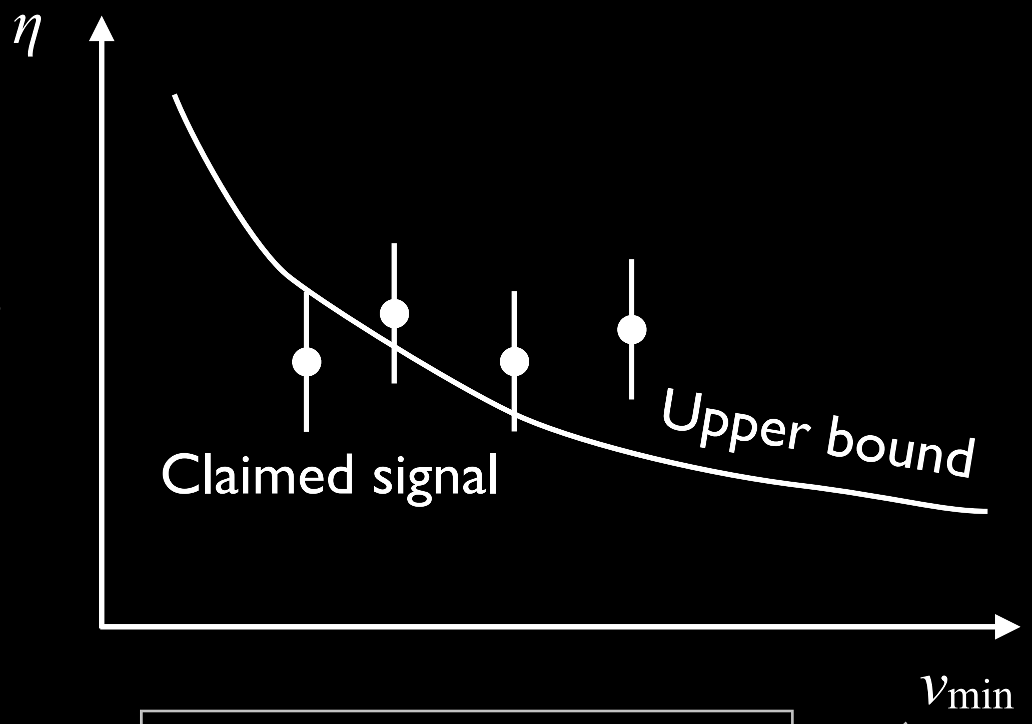
Agnese et al (SuperCDMS) 2014

Astrophysics-independent approach

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

Rescaled astrophysics factor common to all experiments

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



Minimum WIMP speed to impart recoil energy E_R

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.

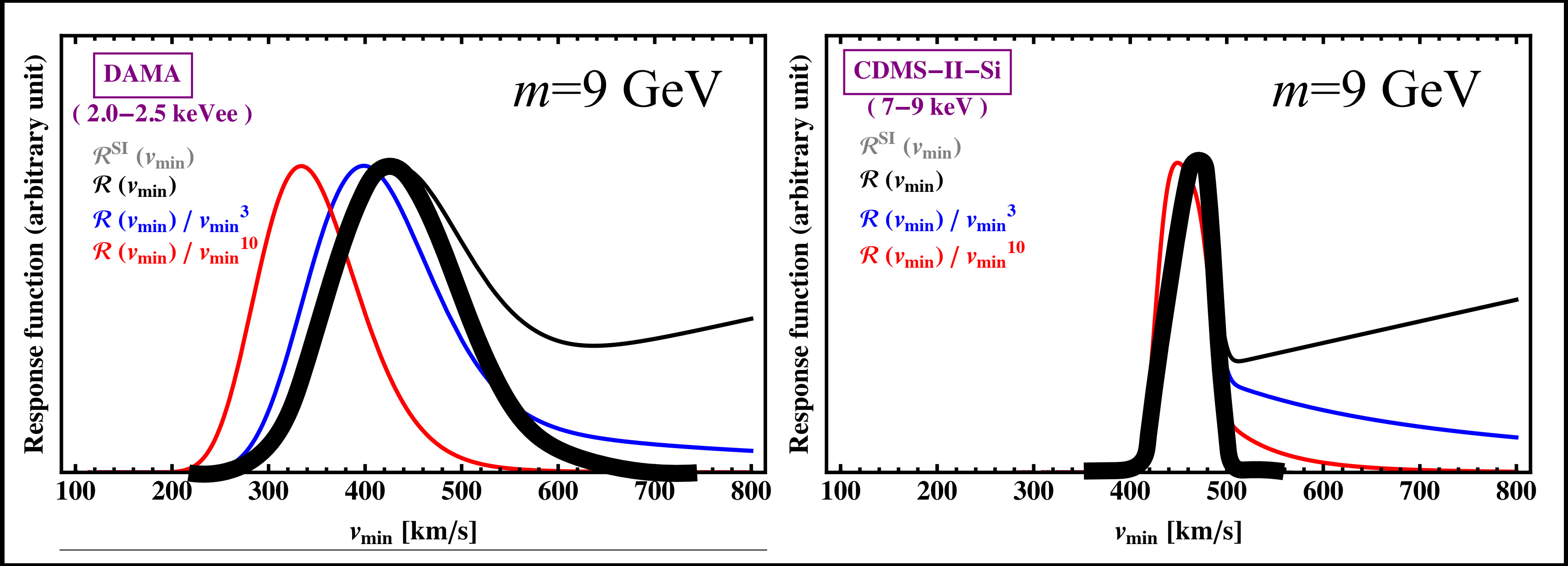
Measured rate

Rescaled astrophysics factor

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

Response function

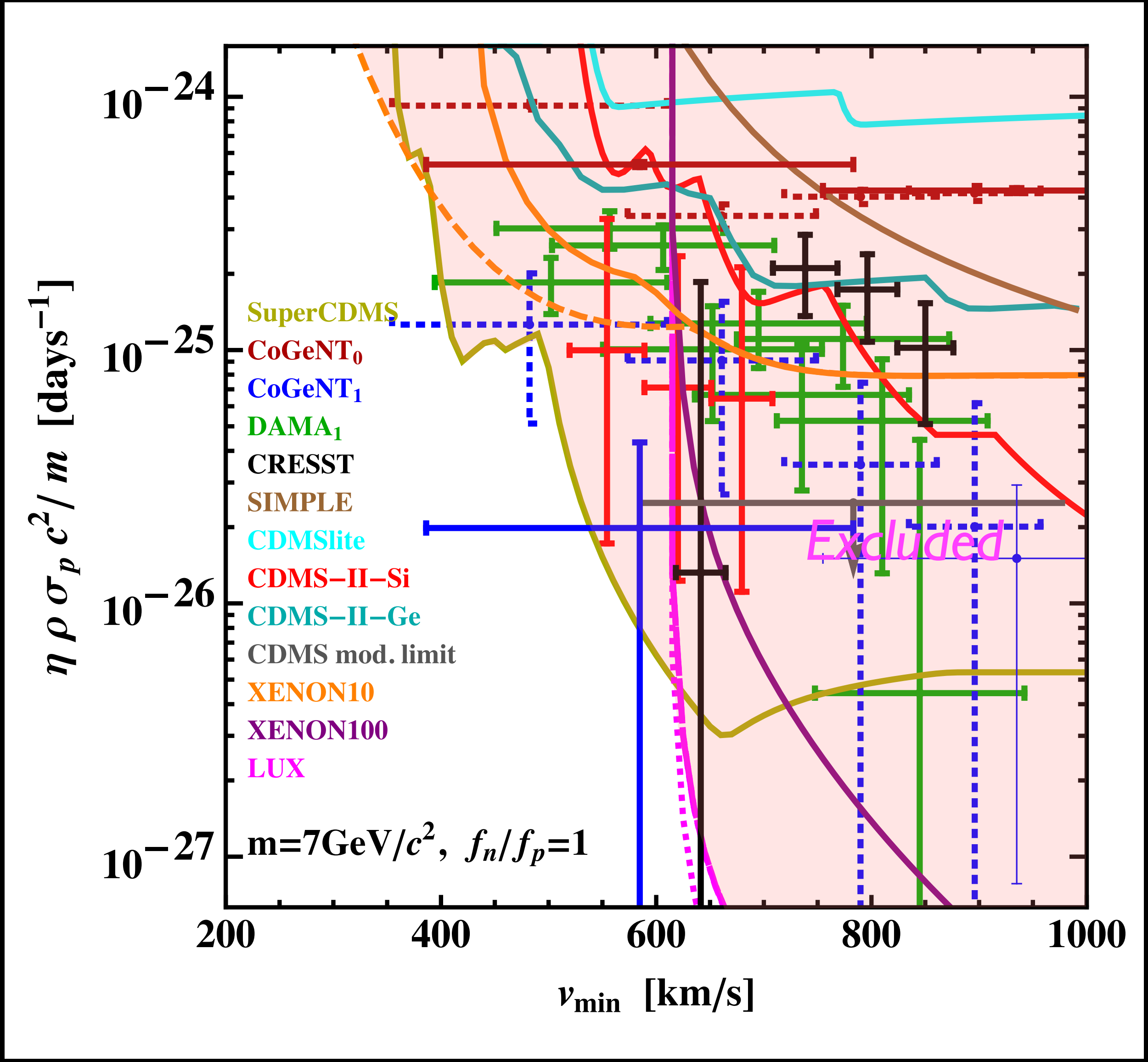
- Every experiment is sensitive to a "window in velocity space."



Spin-independent isoscalar interactions

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

Astrophysics-independent approach



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

CDMS-Si event rate is similar to yearly modulated rates

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

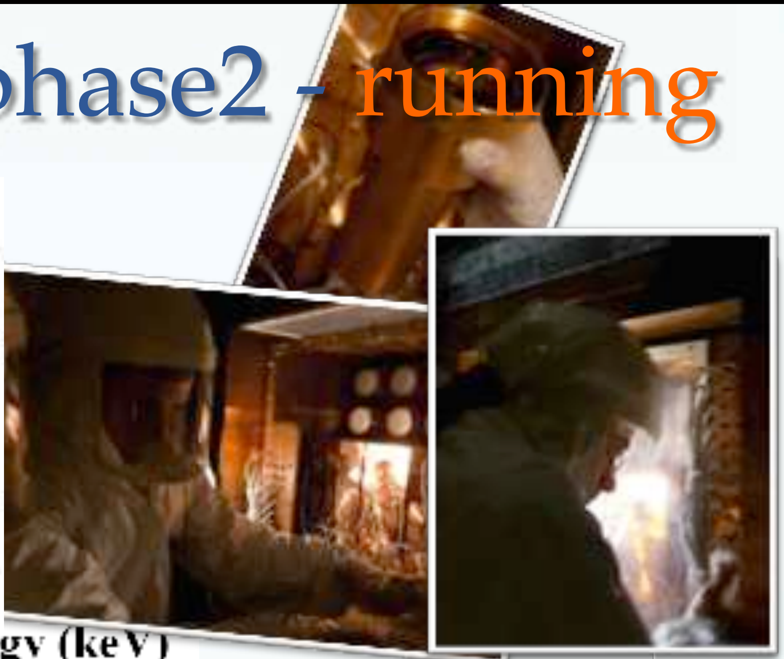
In the next episodes

In the next episodes..... Revenge

DAMA/LIBRA phase2 - running

Quantum Efficiency features

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



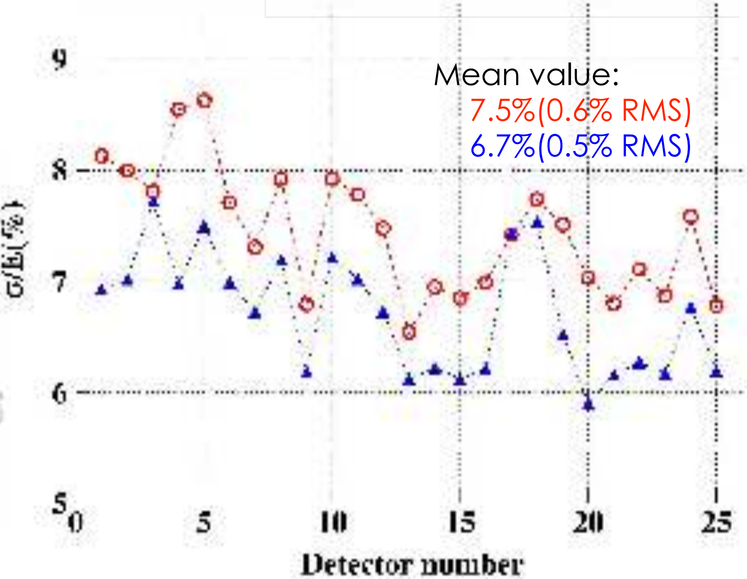
Residual Contamination

The limits are at 90% C.L.

Energy (keV)

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



Mean value:
7.5%(0.6% RMS)
6.7%(0.5% RMS)

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

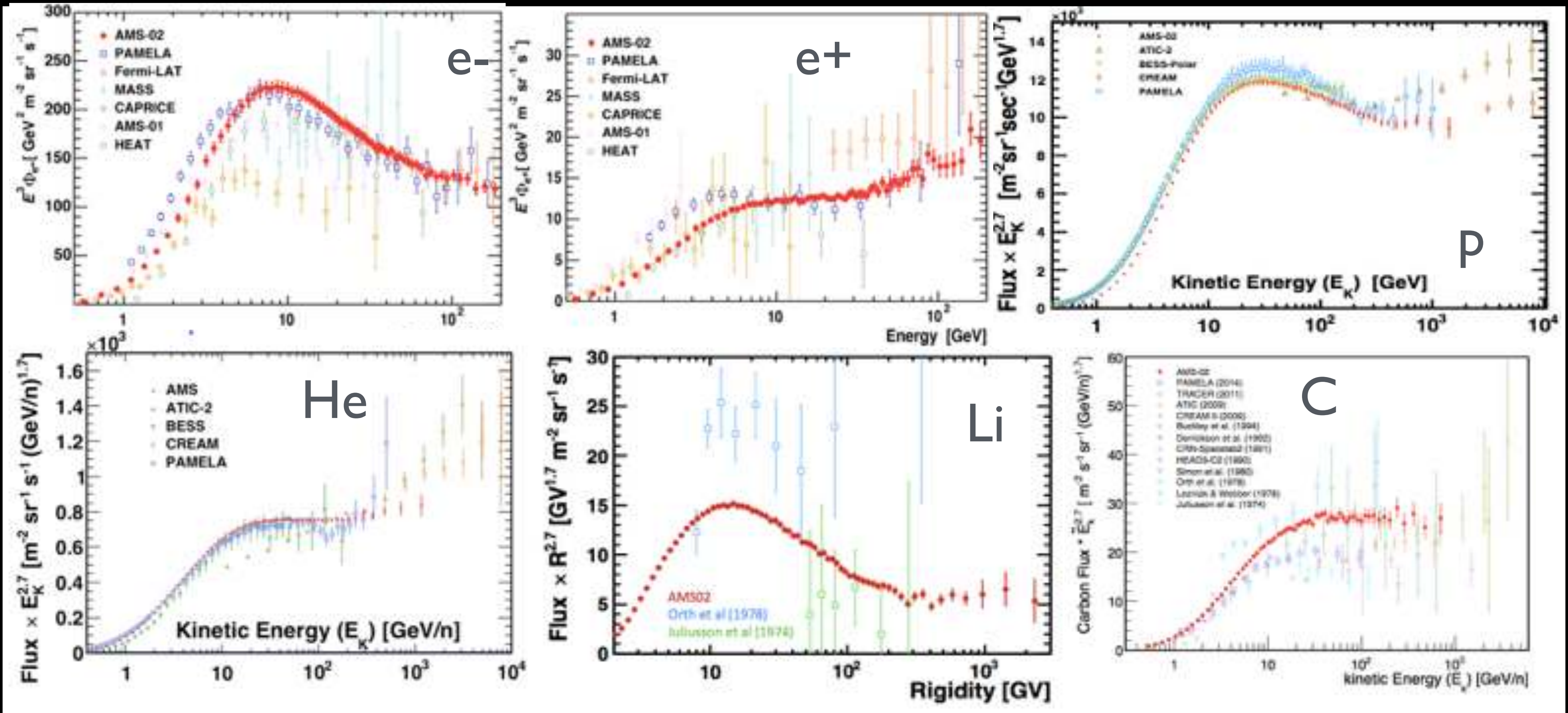
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

Belli, IDM2014

In the next episodes….. Precision cosmic rays

AMS (Alpha Magnetic Spectrometer)

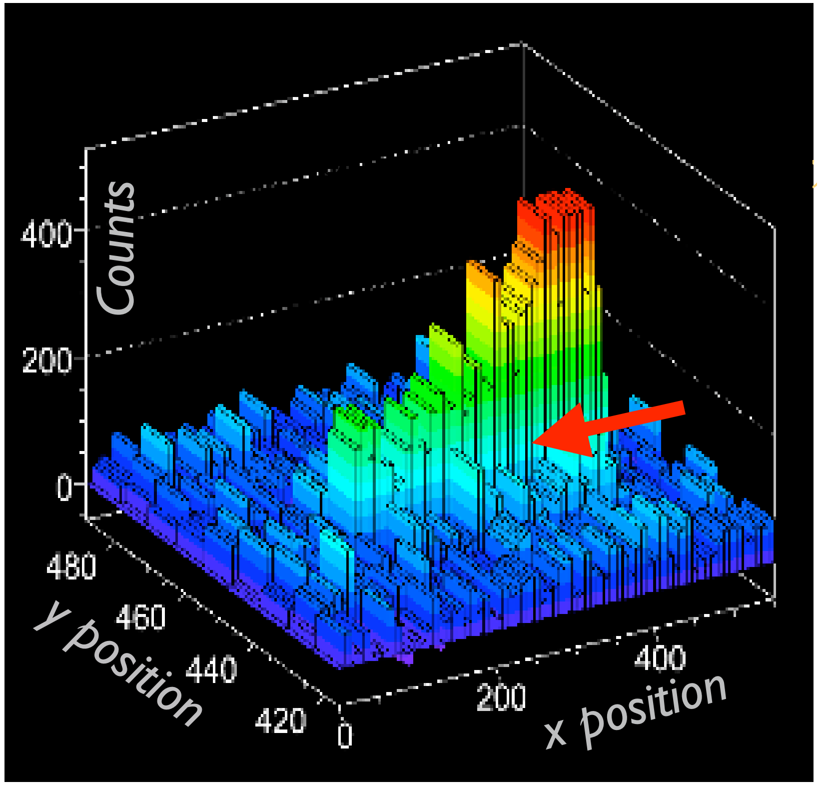
AMS-02 can measure isotopic ratios to ~1% precision up to Fe and ~100 GeV/nucleon, and much better at lower energies.



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

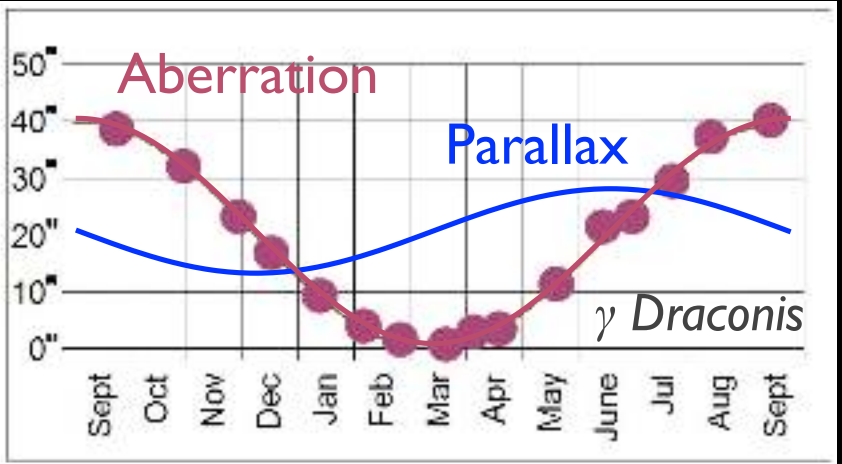
Only ~10 events needed to confirm extraterrestrial signal

In the next episodes..... WIMP astronomy

Aberration of WIMPs

Photon arrival direction

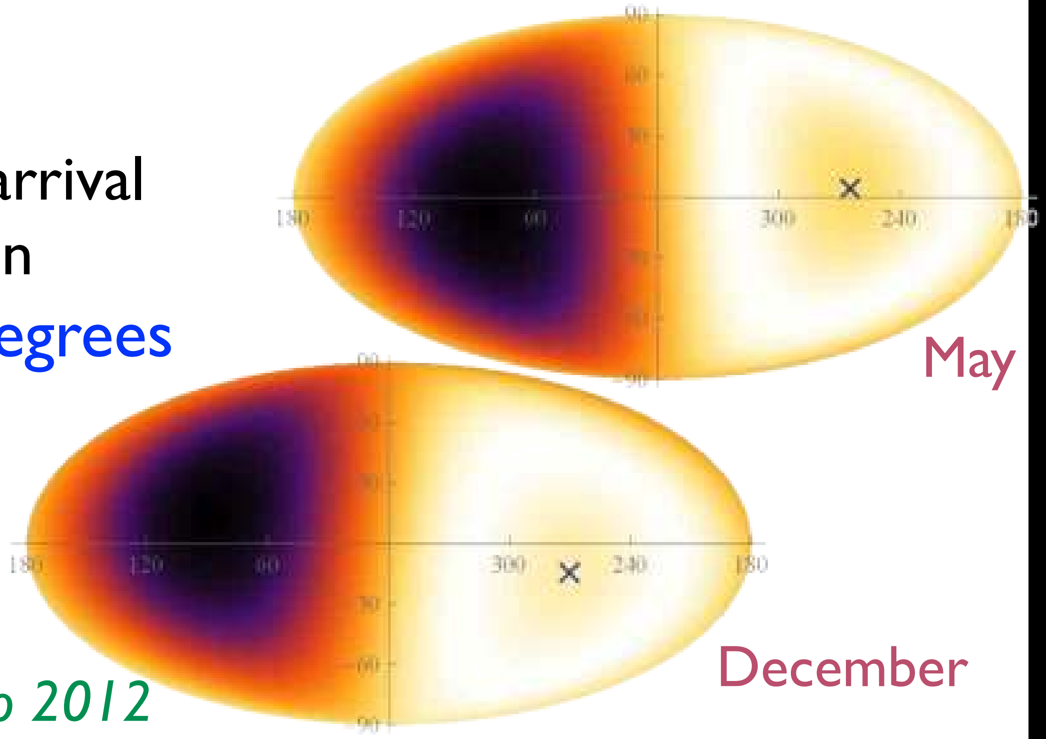
20 arcsec



Bradley 1725

WIMP arrival direction

10 degrees



Bozorgnia, Gelmini, Gondolo 2012

Synopsis

- Fifty shades of dark
  - *There is evidence for nonbaryonic cold dark matter.*
  - *There are many candidates for nonbaryonic dark matter particles.*
- The forbidden fruit
  - *WIMP interaction rates in direct searches are very small.*
  - *No bananas in the lab.*
- Confusion of the mind
  - *Some experiments claim dark matter detection while others exclude it.*
- That which does not kill us makes us stronger
  - *Move to consider all possible WIMP-SM currents.*
  - *Do not assume any specific dark halo model.*