Trends in Dark Matter Physics

Paolo Gondolo
University of Utah

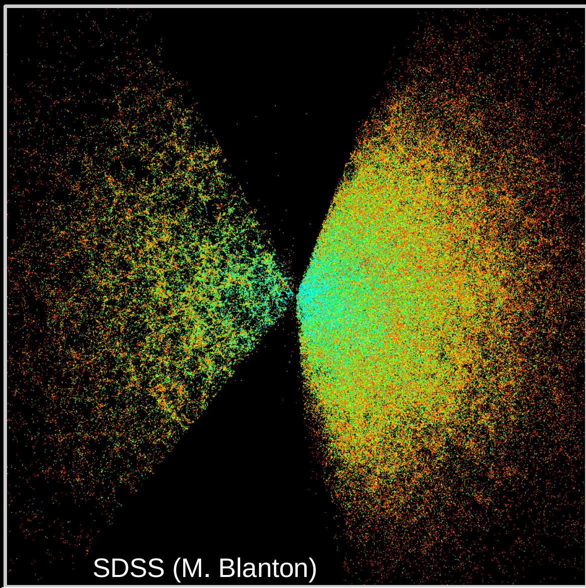
Dark matter theory

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

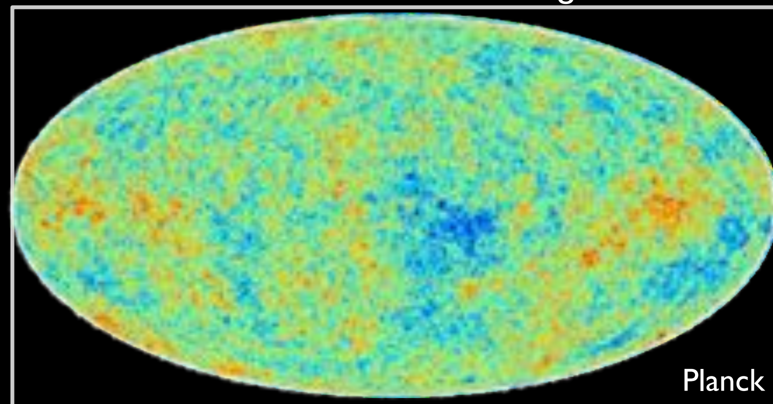
Fifty shades of dark

Evidence for cold dark matter

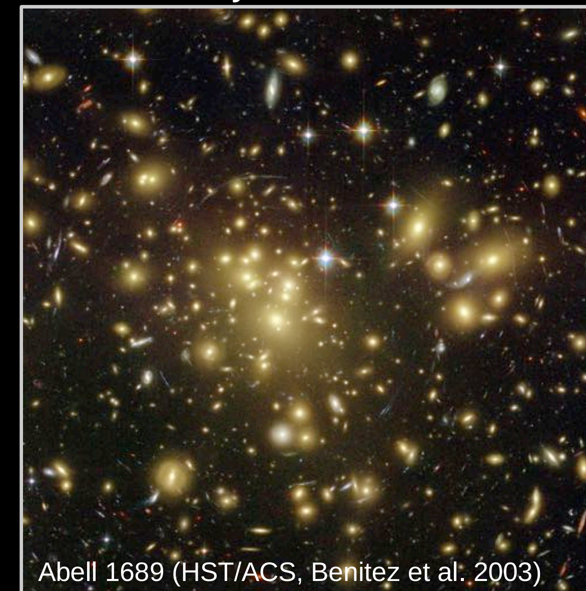
Large Scale Structure



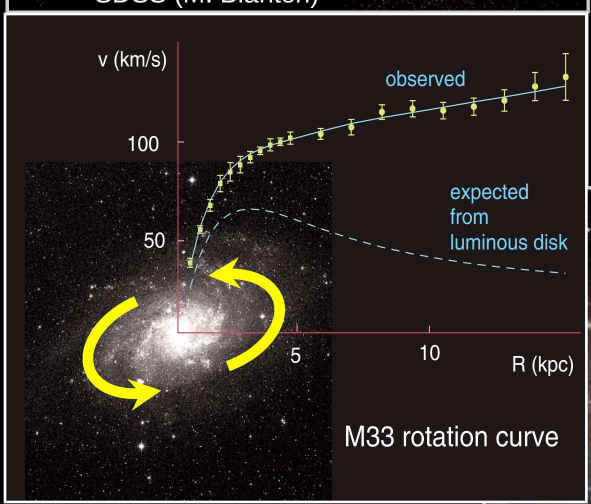
Cosmic Microwave Background

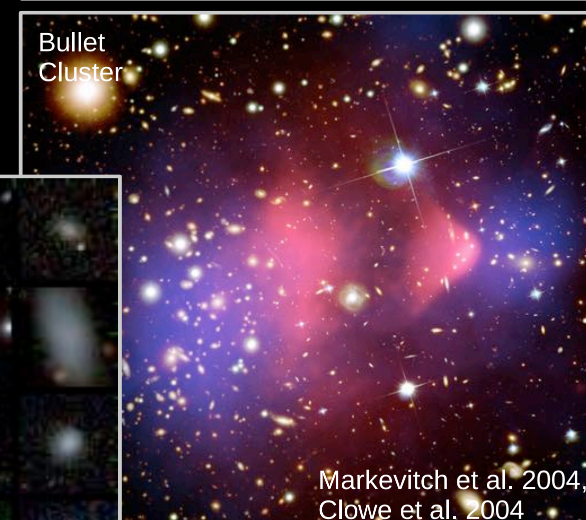


Galaxy Clusters

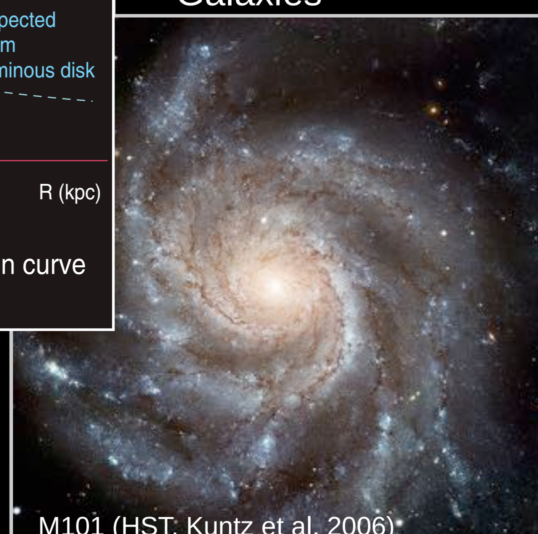


Supernovae

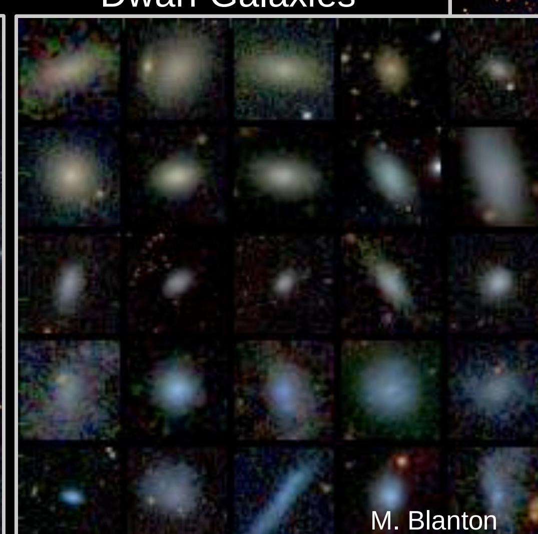




Galaxies



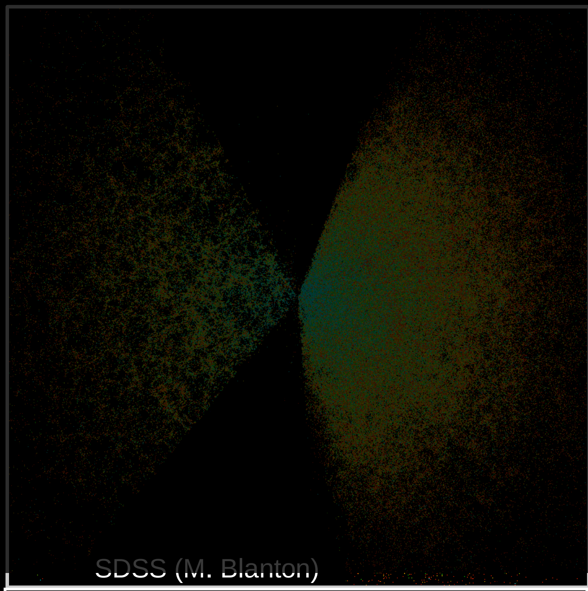
Dwarf Galaxies



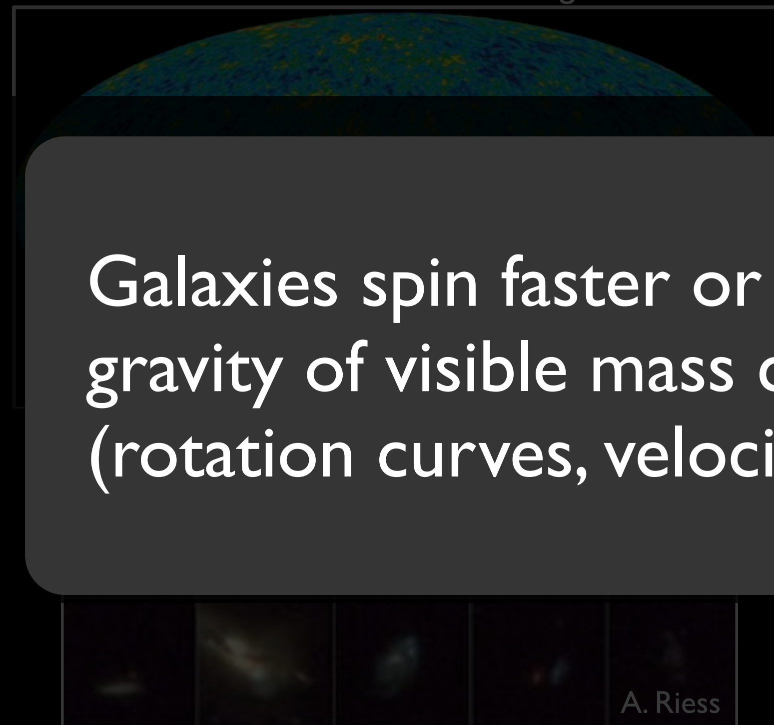
Evidence for cold dark matter

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

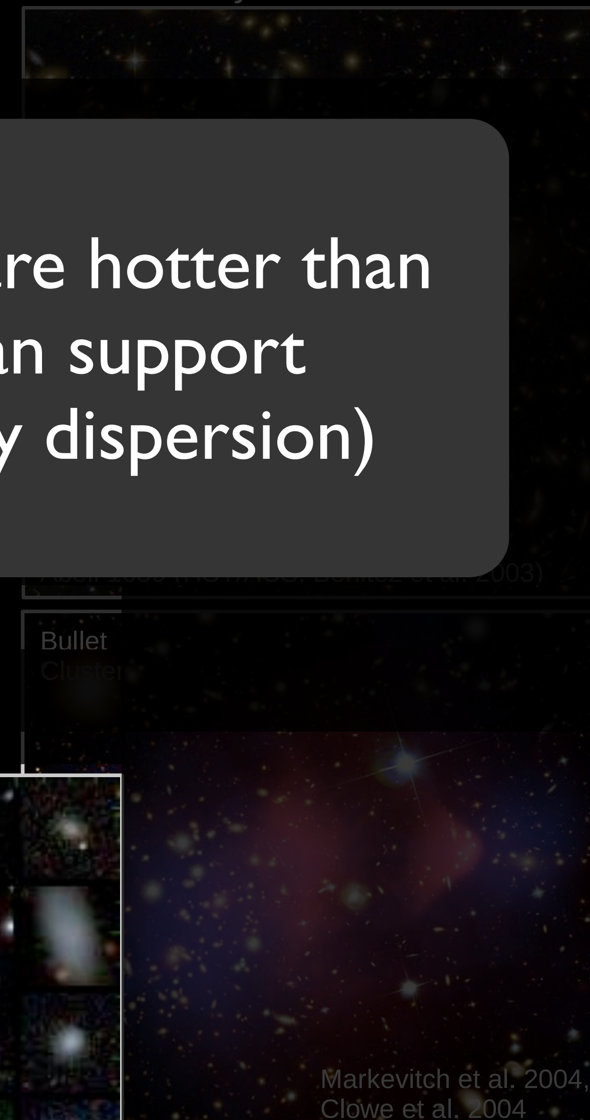
Large Scale Structure

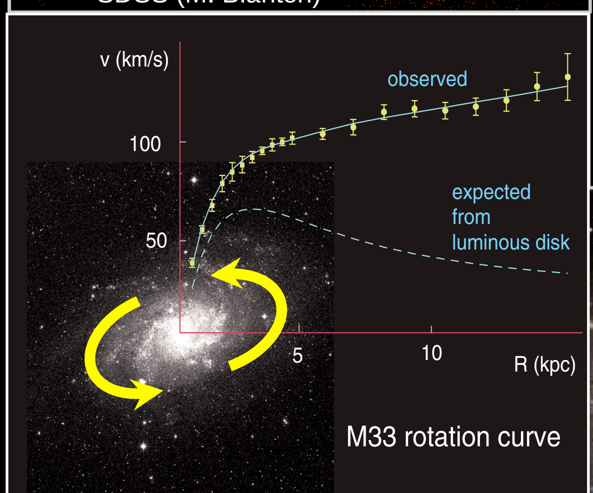


Cosmic Microwave Background

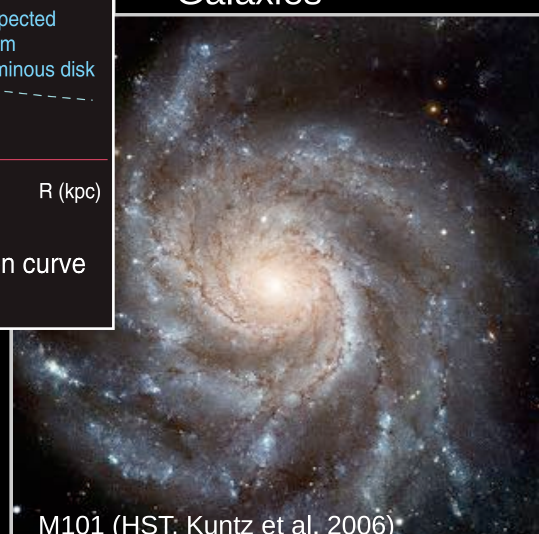


Galaxy Clusters

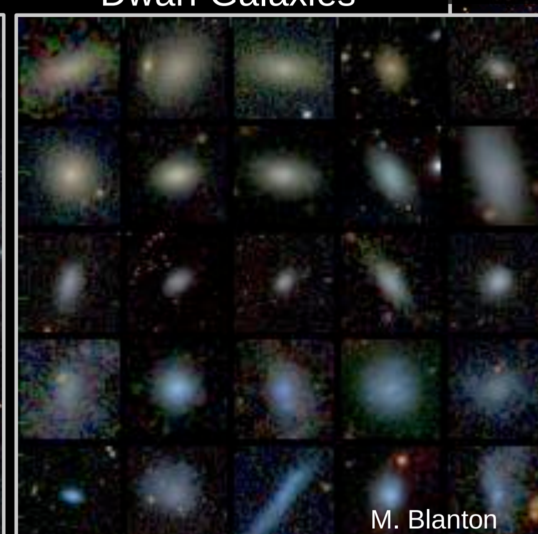




Galaxies

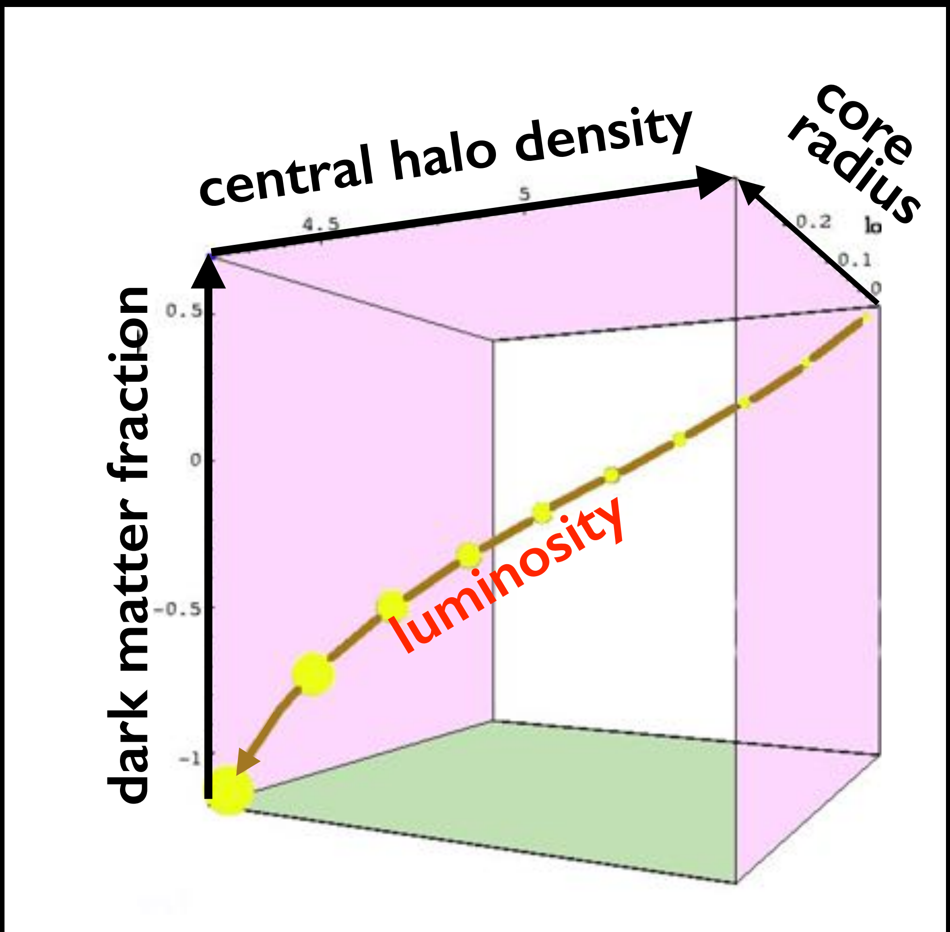


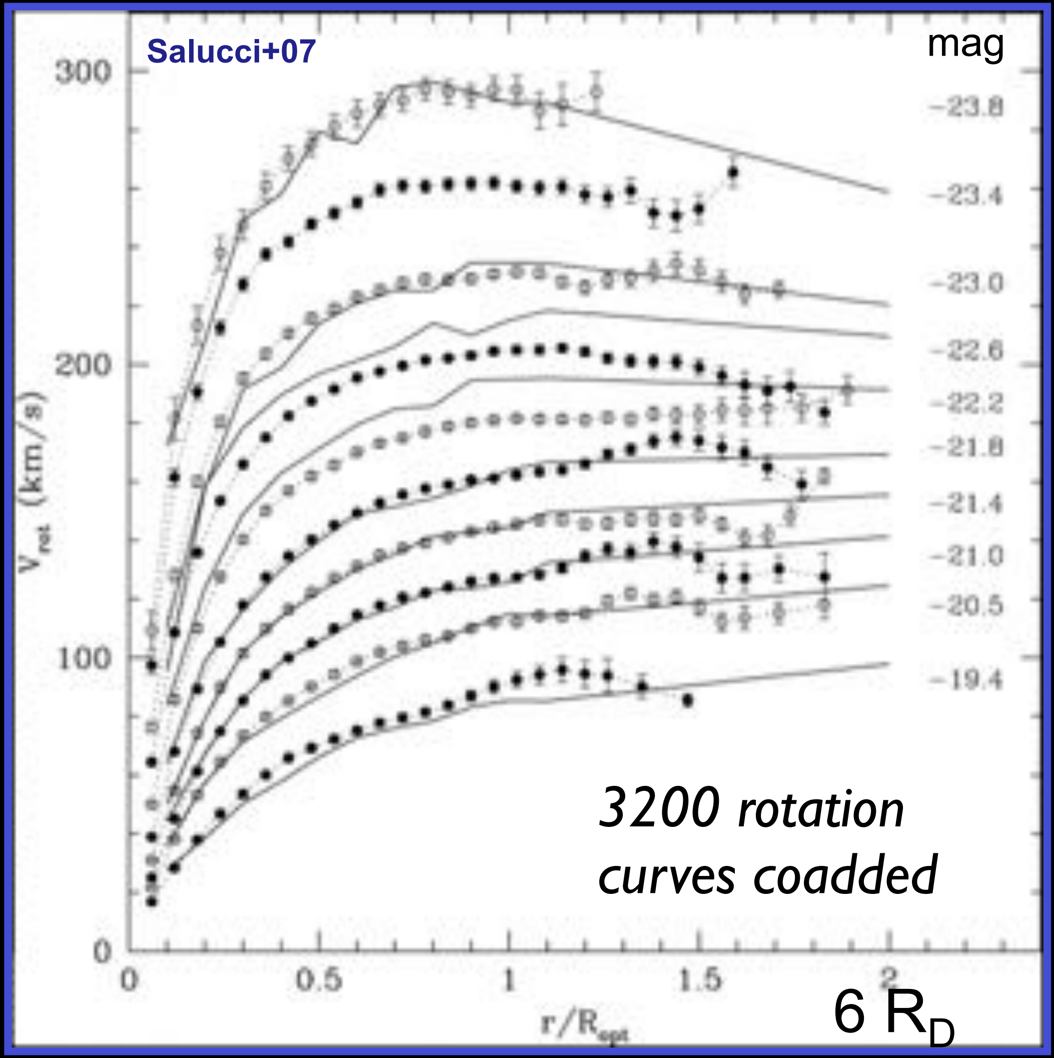
Dwarf Galaxies



Evidence for cold dark matter

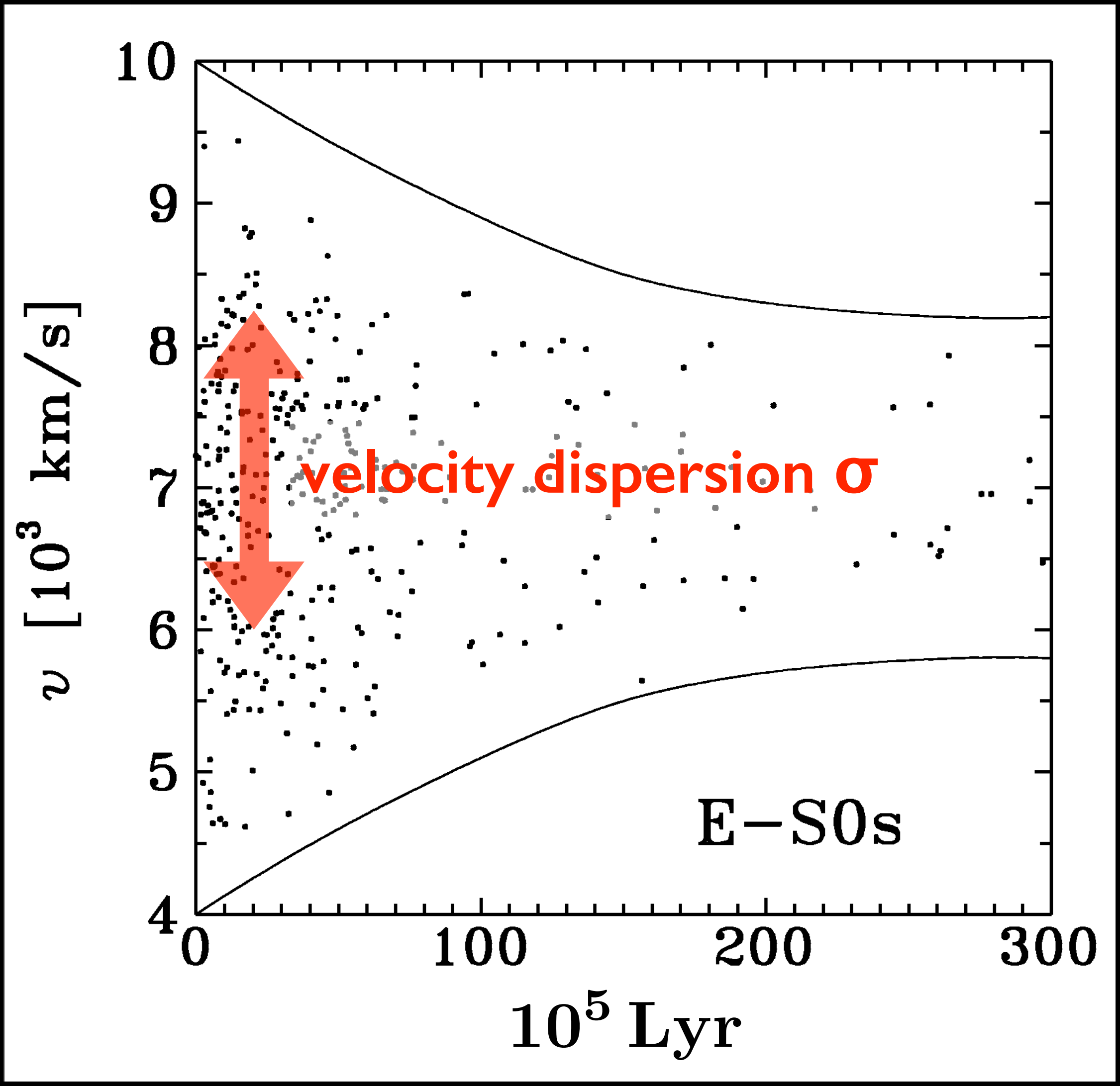
Empirical correlations found from thousands of spiral galaxy rotation curves





Salucci et al 2007

Evidence for cold dark matter



Lokas, Mamon 2003

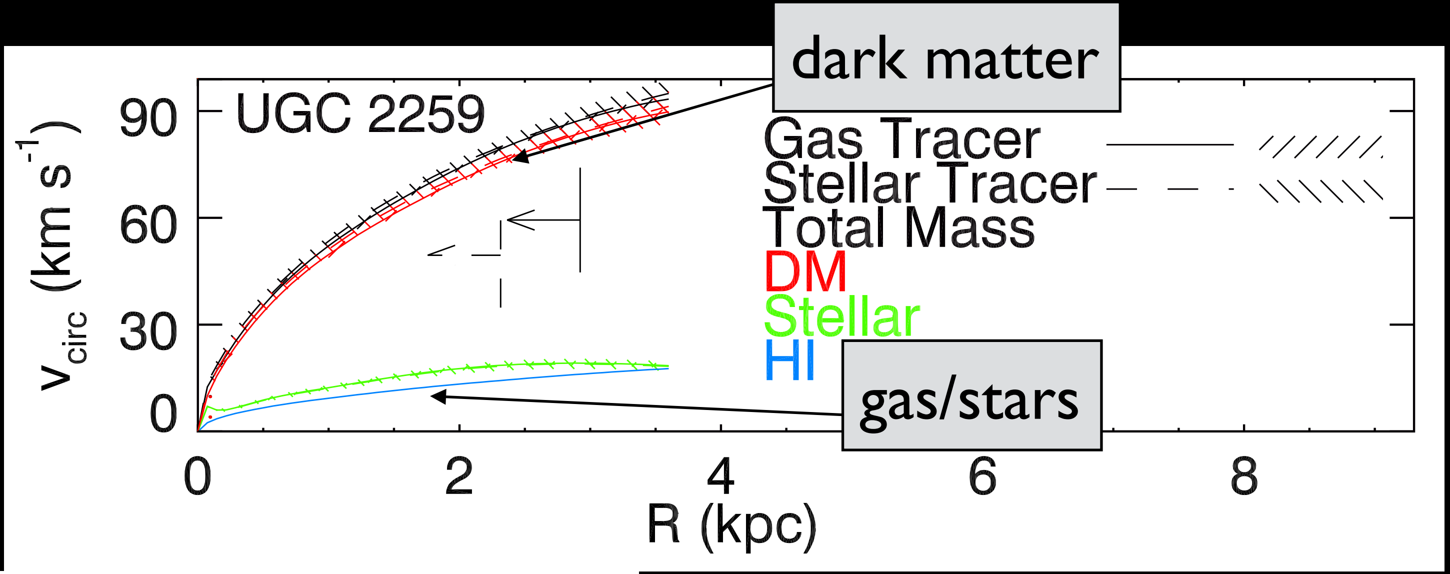
Velocity dispersion measurements reveal dark matter in elliptical galaxies

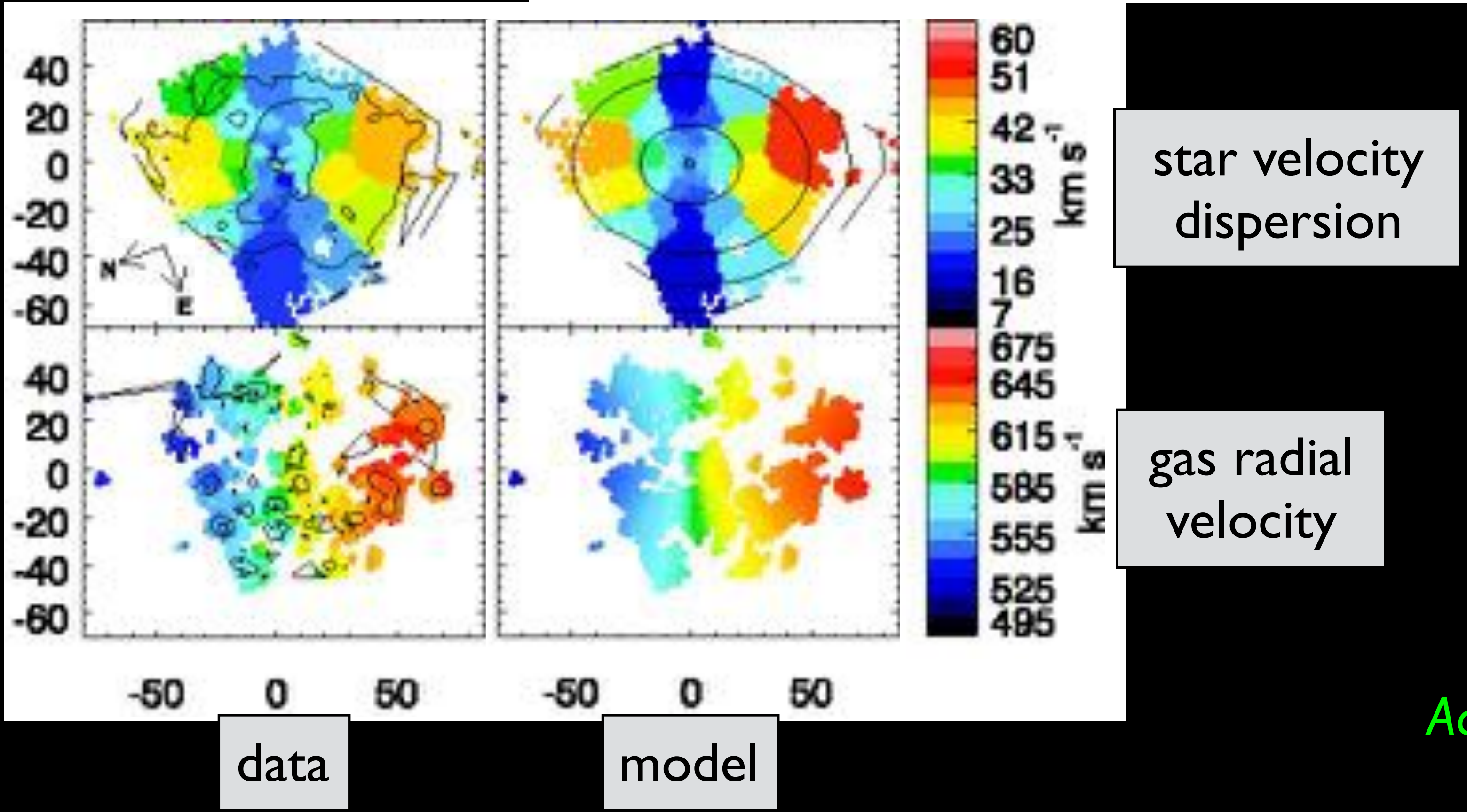
$$\sigma^2 \propto \frac{GM}{r}$$

$$M_{\rm dyn} \sim 10^{15}\, M_\odot$$

Evidence for cold dark matter

Dwarf galaxies are dominated by dark matter.





Adams et al 2014

Evidence for cold dark matter

Large Scale Structure

Cosmic Microwave Background

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

SDSS (M. Blanton)

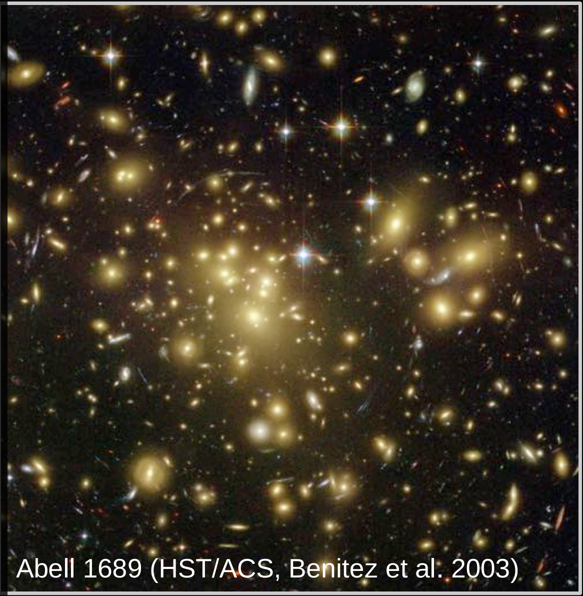
A. Riess

Dwarf Galaxies

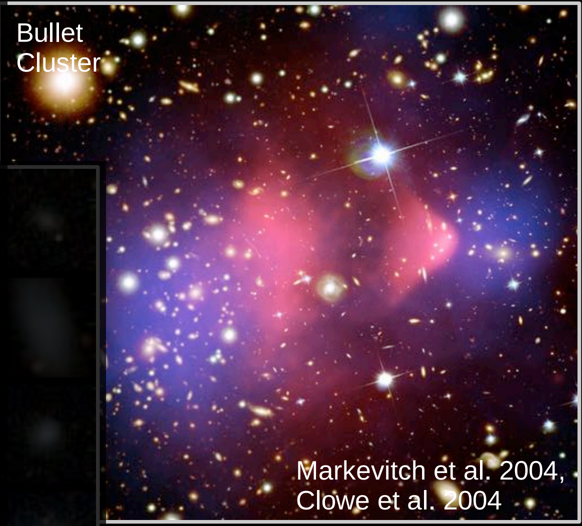
M101 (HST, Kuntz et al. 2006)

M. Blanton

Galaxy Clusters



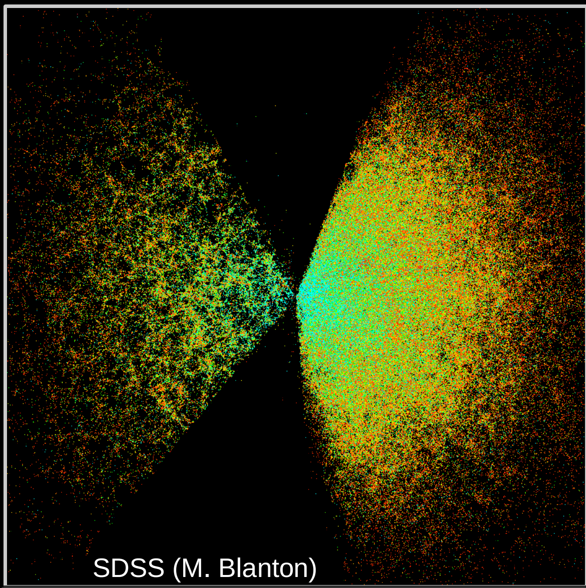
Abell 1689 (HST/ACS, Benitez et al. 2003)



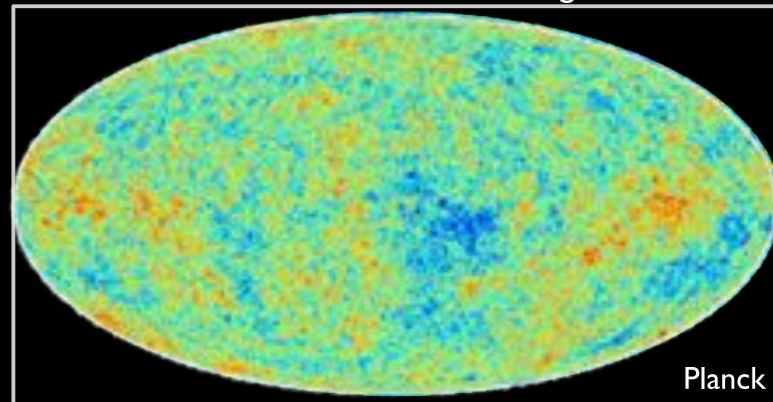
Markevitch et al. 2004, Clowe et al. 2004

Evidence for cold dark matter

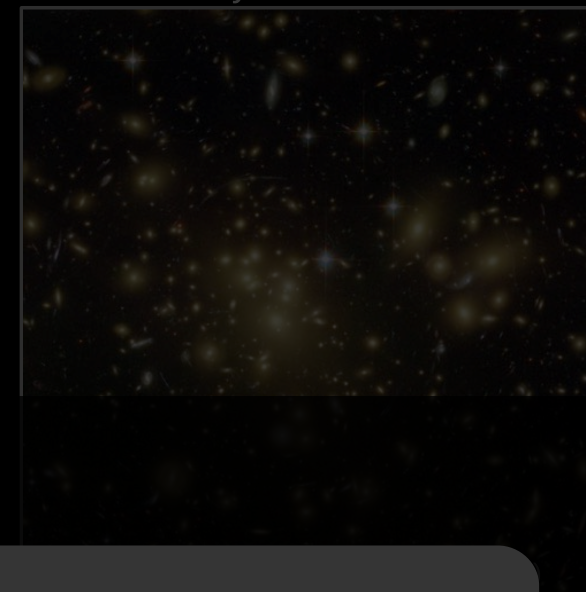
Large Scale Structure



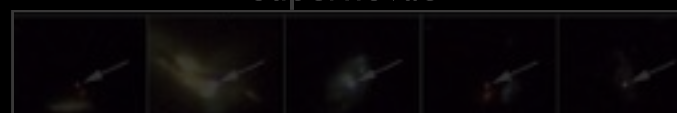
Cosmic Microwave Background

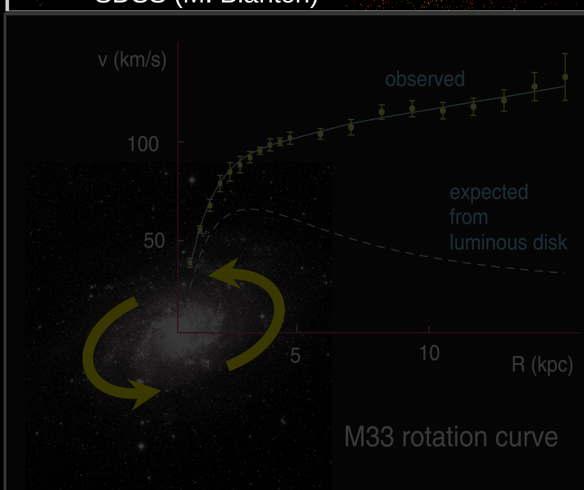


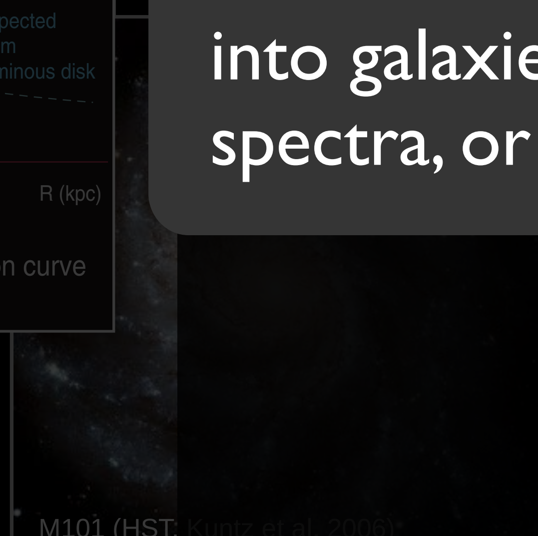
Galaxy Clusters



Supernovae



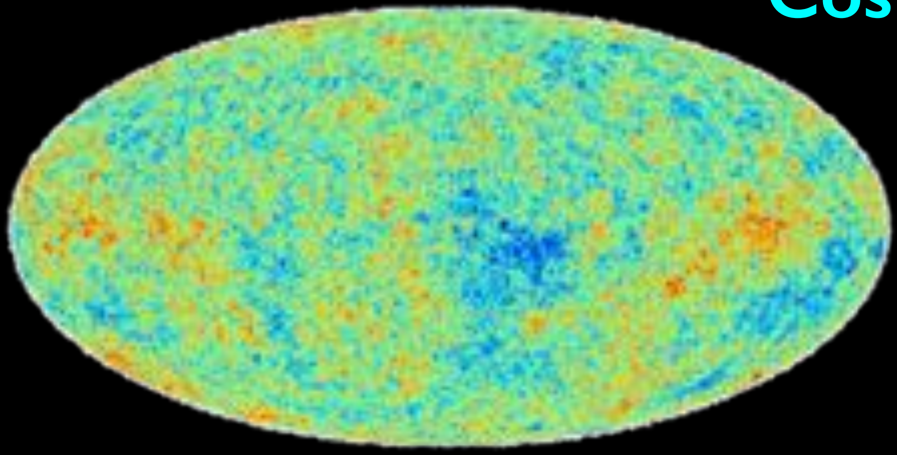


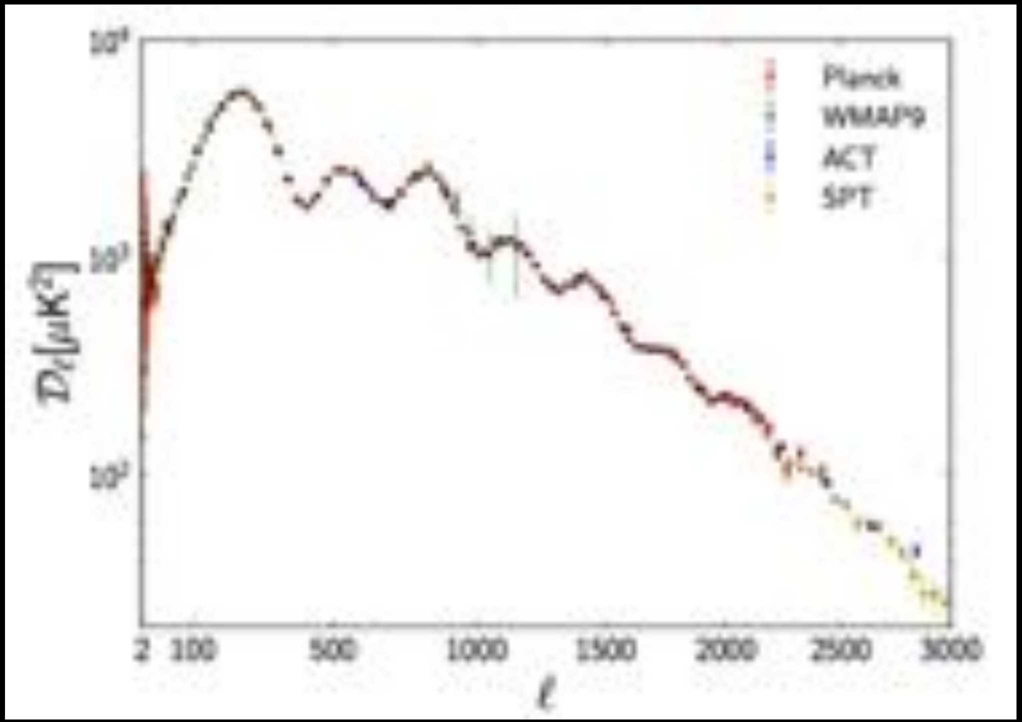


An invisible mass makes the Cosmic Microwave Background fluctuations grow into galaxies (CMB and matter power spectra, or correlation functions)

Evidence for cold dark matter

Cosmic Microwave Background fluctuations





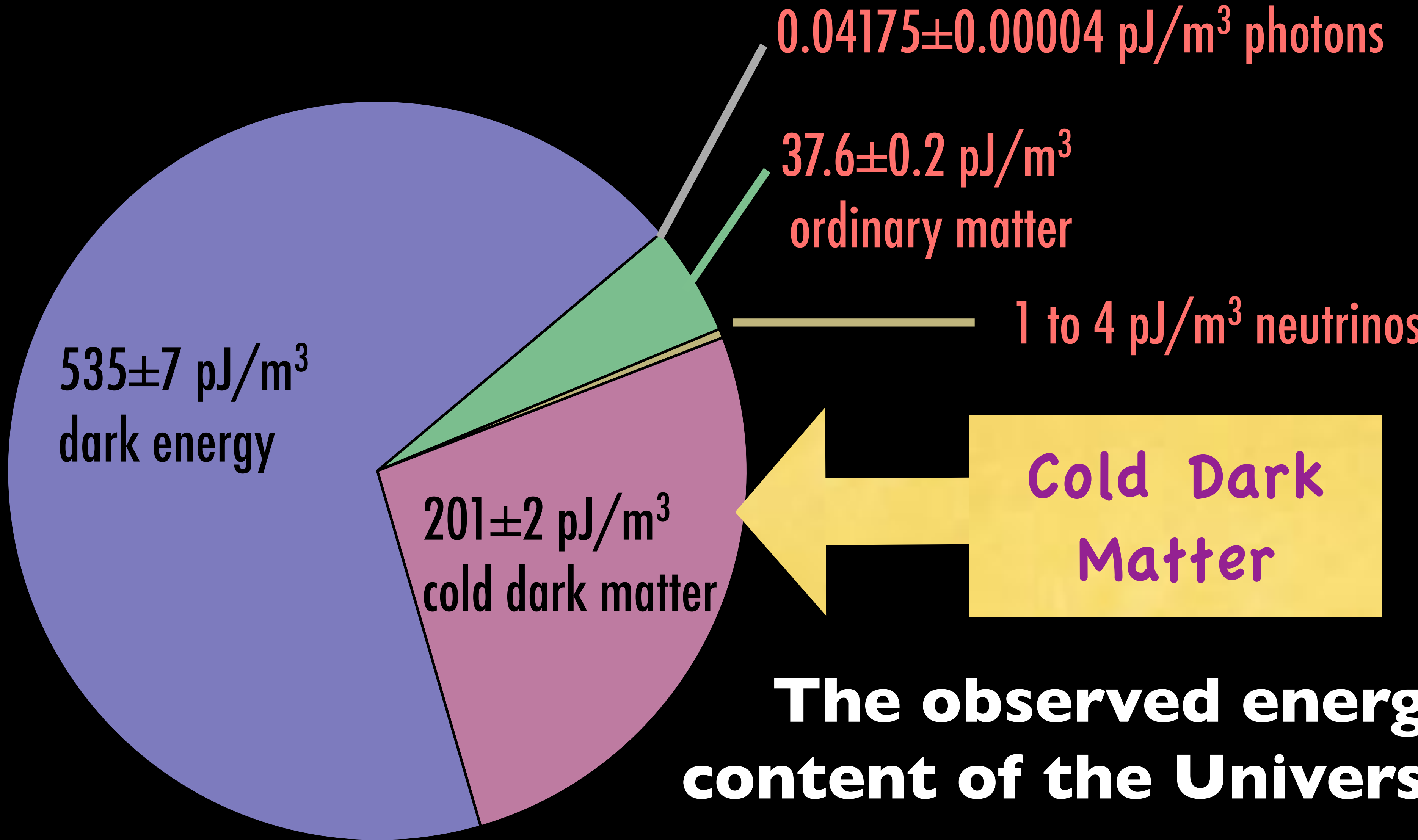
Parameter	*Planck*+WP+highL+BAO Best fit	68% limits
$\Omega_b h^2$	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04148	1.04147 ± 0.00056
τ	0.0952	0.092 ± 0.013
n_s	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0973	3.091 ± 0.025
Ω_Λ	0.6914	0.692 ± 0.010
σ_8	0.8288	0.826 ± 0.012
z_{re}	11.52	11.3 ± 1.1
H_0	67.77	67.80 ± 0.77
Age/Gyr	13.7965	13.798 ± 0.037
$100\theta_*$	1.04163	1.04162 ± 0.00056
r_{drag}	147.611	147.68 ± 0.45

Planck (2013)

linear perturbation theory

general relativity and statistical mechanics at 10^4 K ~ 1 eV/k

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

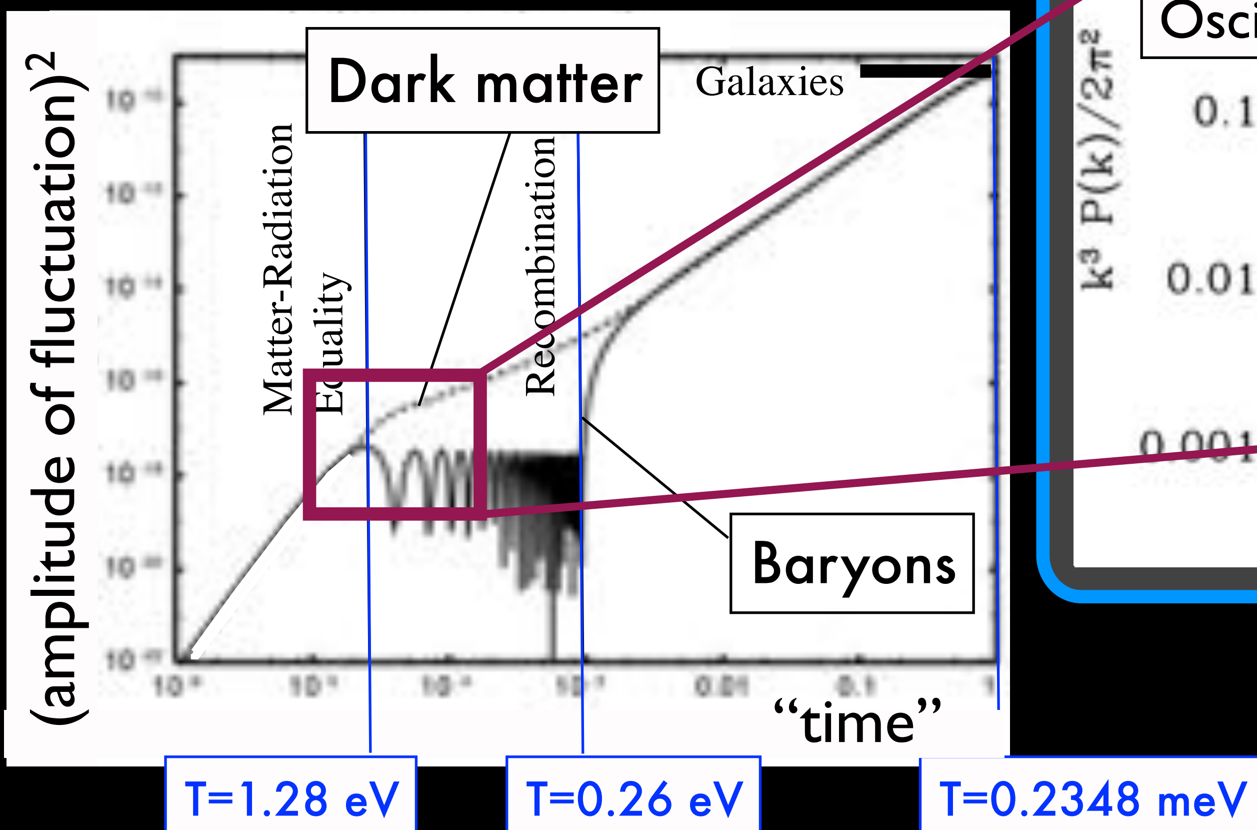
$1 \text{ pJ} = 10^{-12} \text{ J}$

$\rho_{\rm crit} = 1.68829\, h^2 \text{ pJ/m}^3$

Evidence for *nonbaryonic* cold dark matter

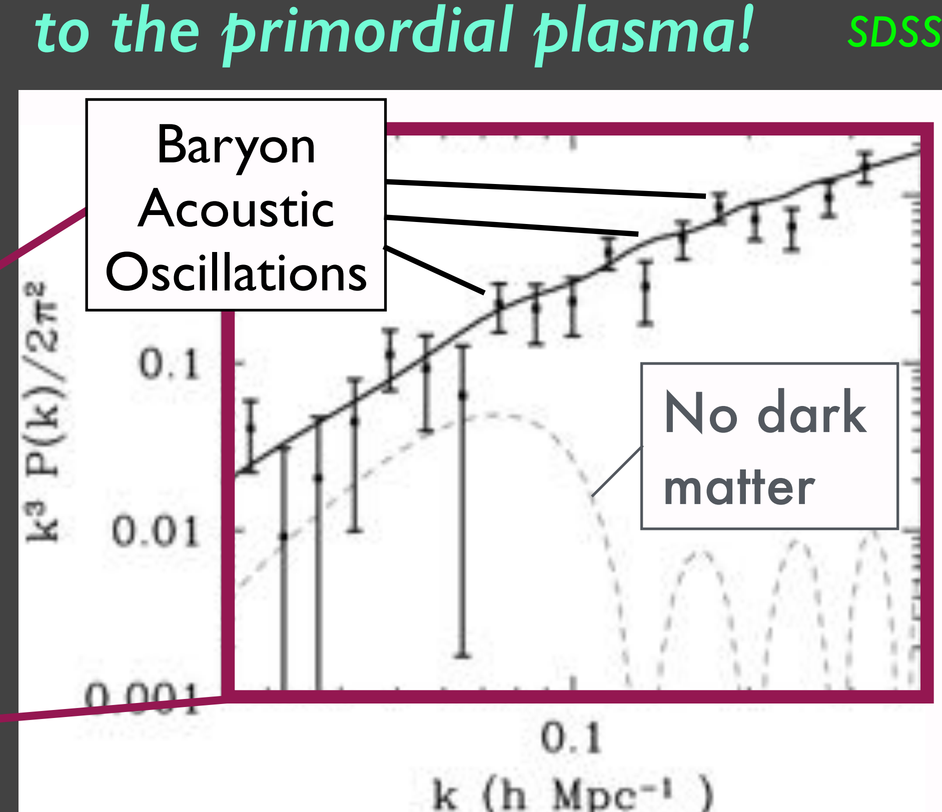
GALAXY FORMATION

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



Dark matter is non-baryonic

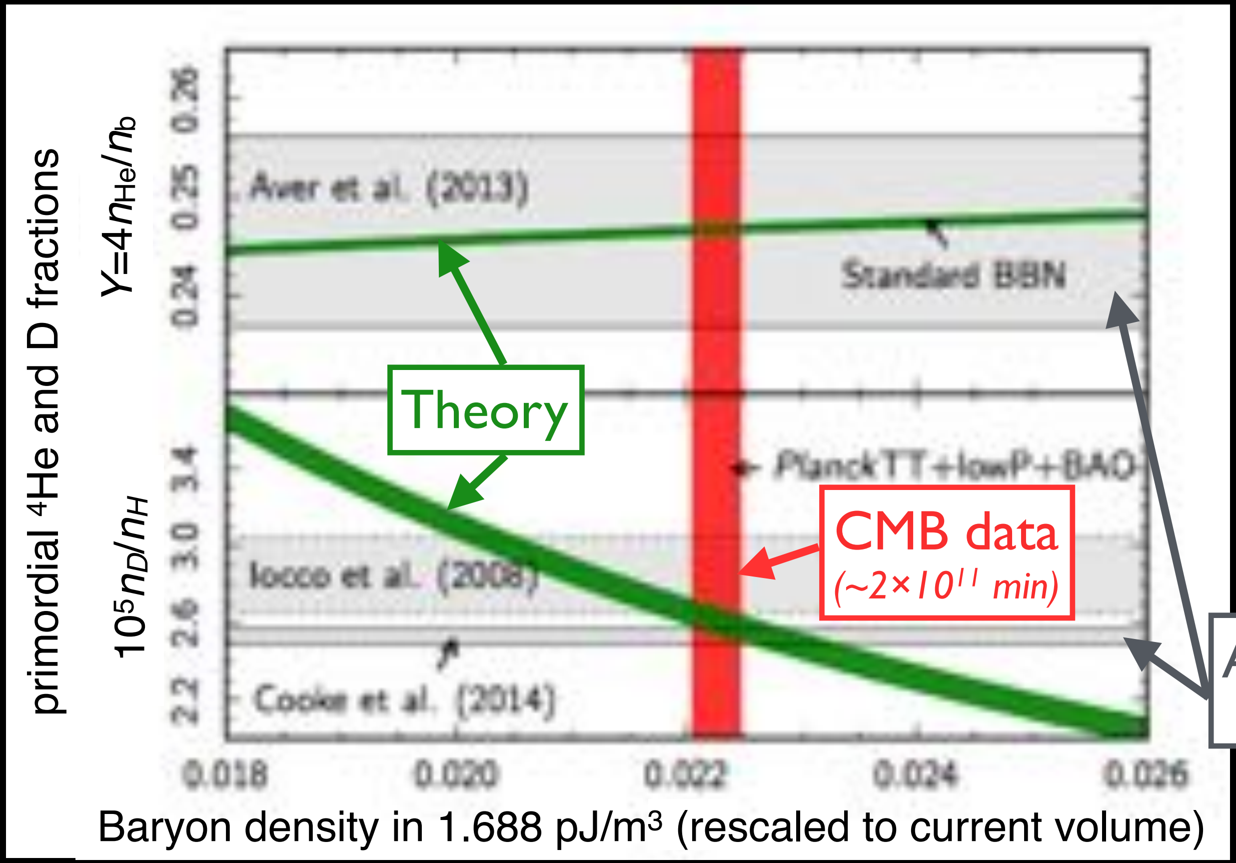
More than 80% of all matter does not couple to the primordial plasma!



Evidence for *nonbaryonic* cold dark matter

BIG BANG NUCLEOSYNTHESIS

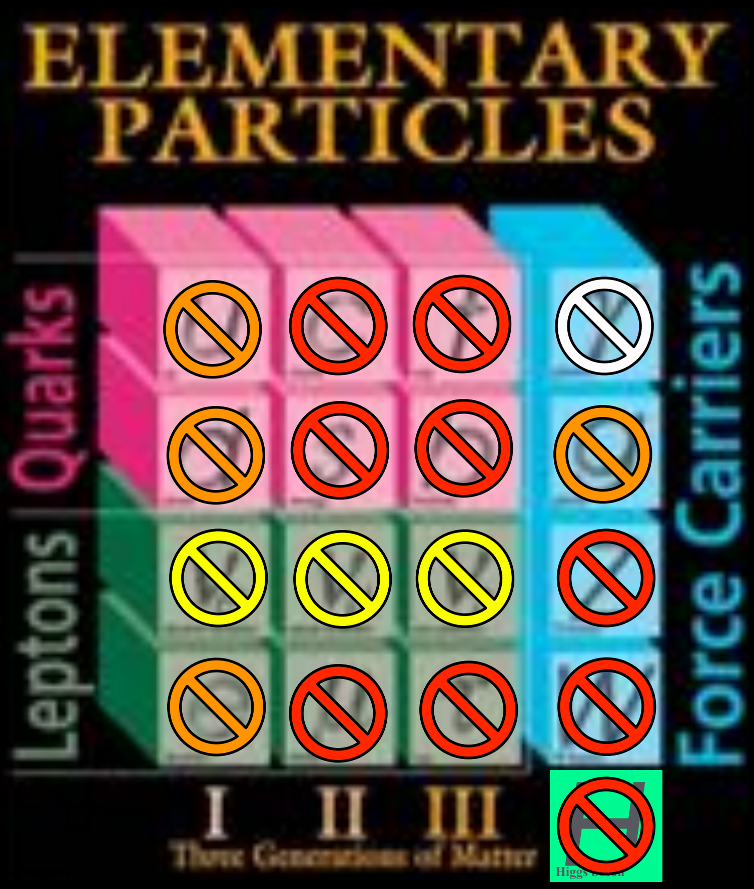
- The baryon-to-photon ratio has been the same since ~1 minute after the Big Bang.
- Baryons are ≲15.7% of the mass in matter.



Ade et al [Planck] 2015

84% of matter is nonbaryonic

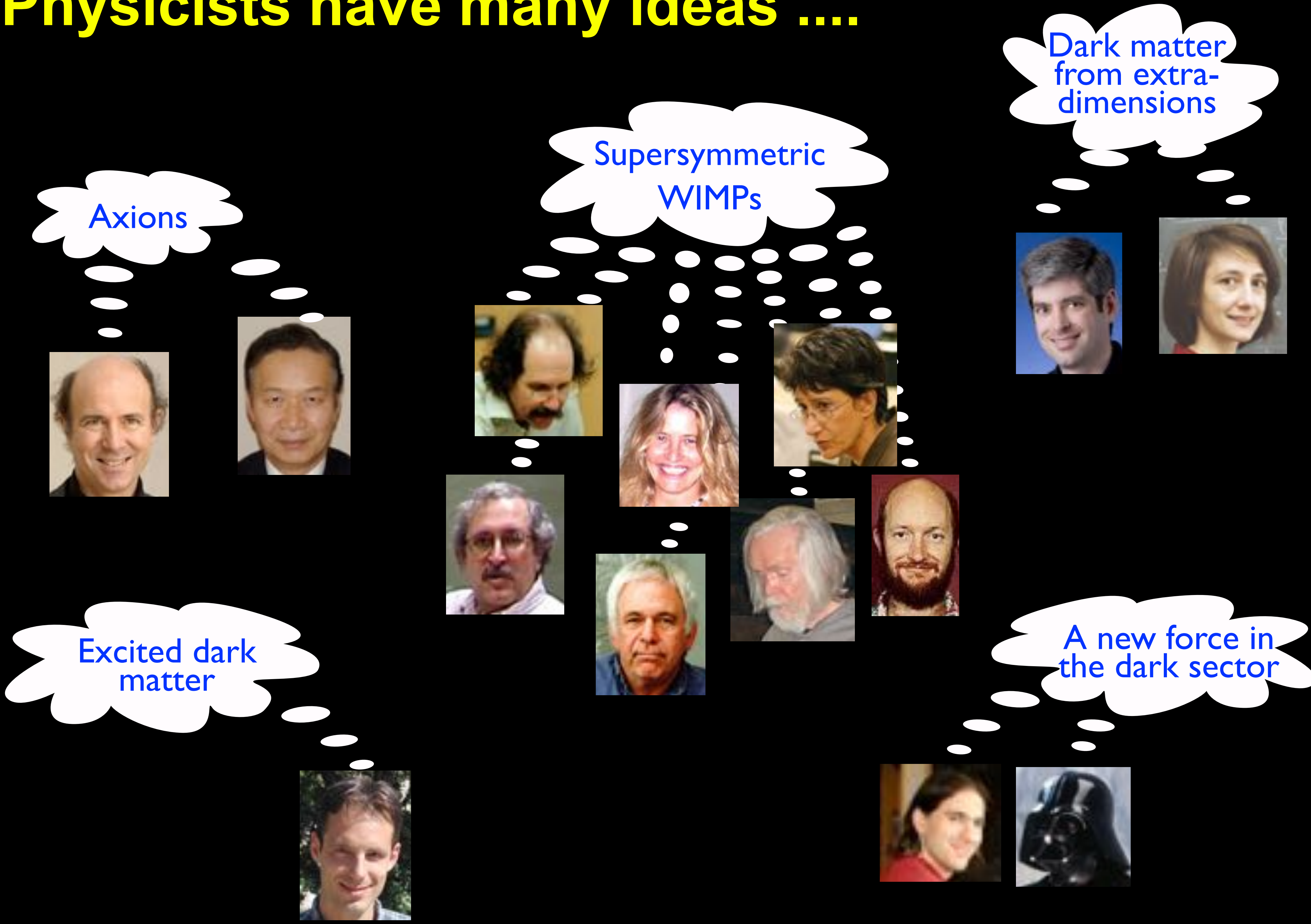
Is dark matter an elementary particle?



- 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 ....



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)

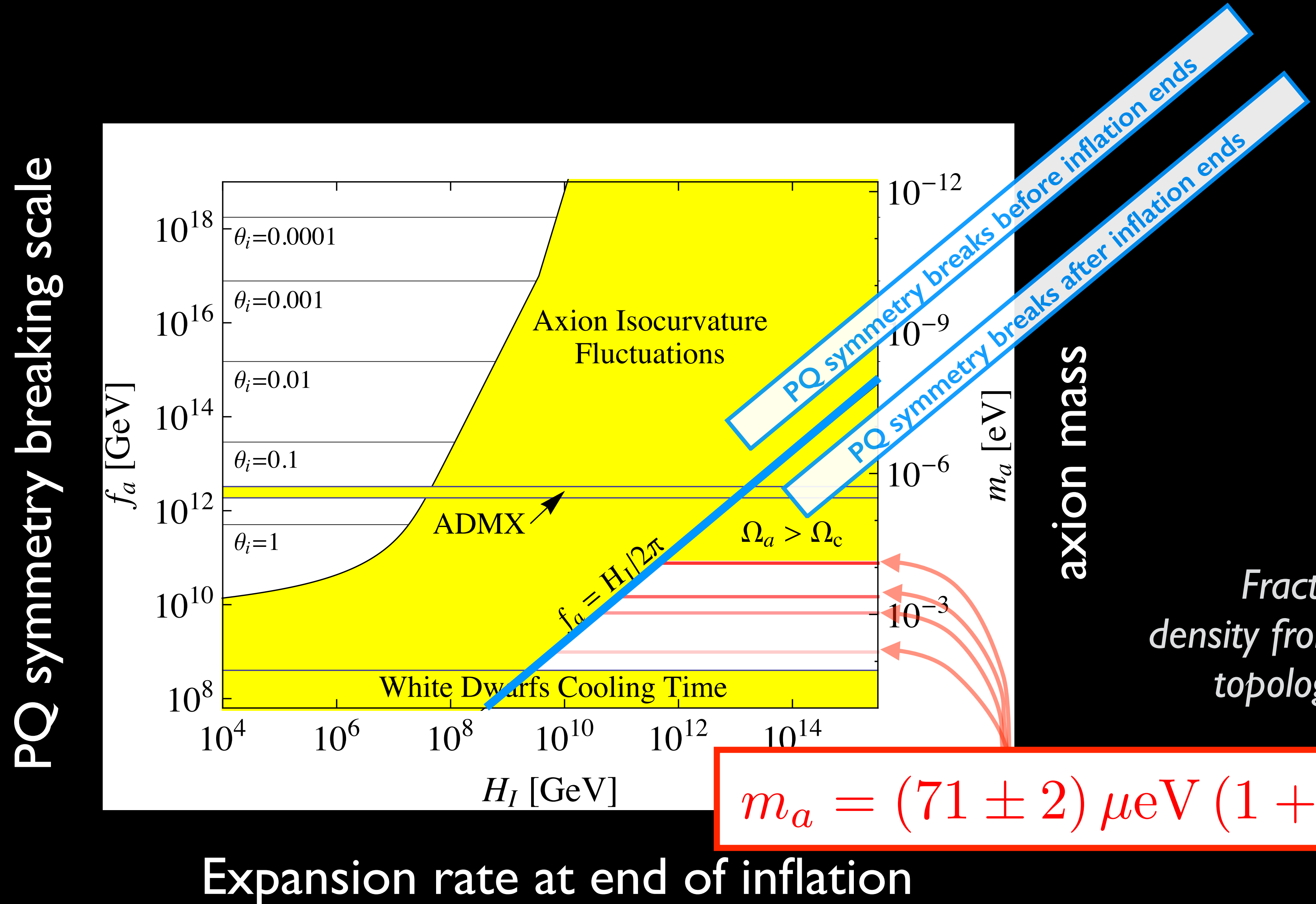
Produced by decay of topological defects

(Axionic string decays)

Still a very complicated and uncertain calculation!

e.g. Harimatsu et al 2012

Axion cold dark matter parameter space



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

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.

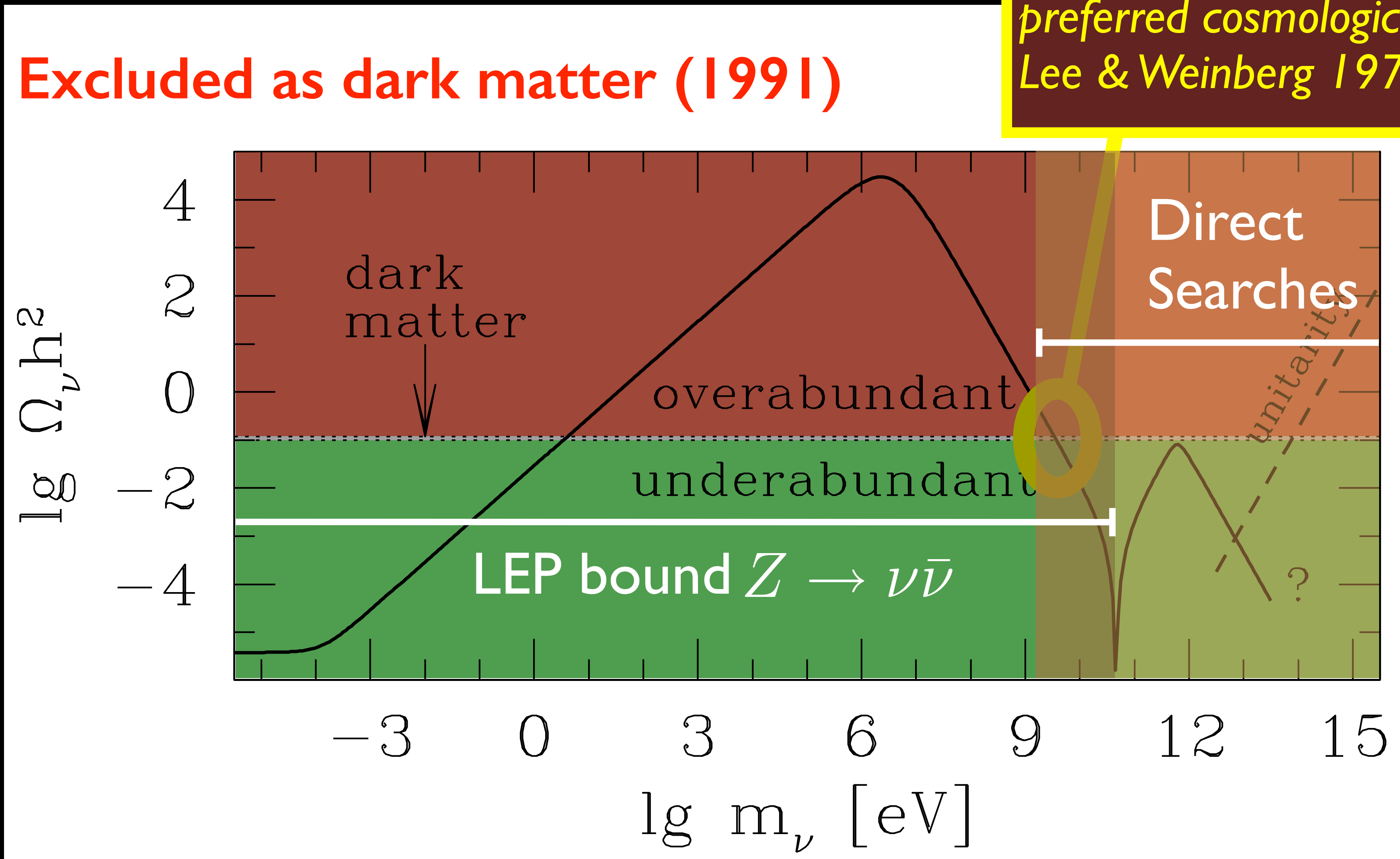
2 GeV/c^2 for Ω_c=1

Now 4 GeV/c^2 for Ω_c=0.25

Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino

~ few GeV
preferred cosmological mass
Lee & Weinberg 1977



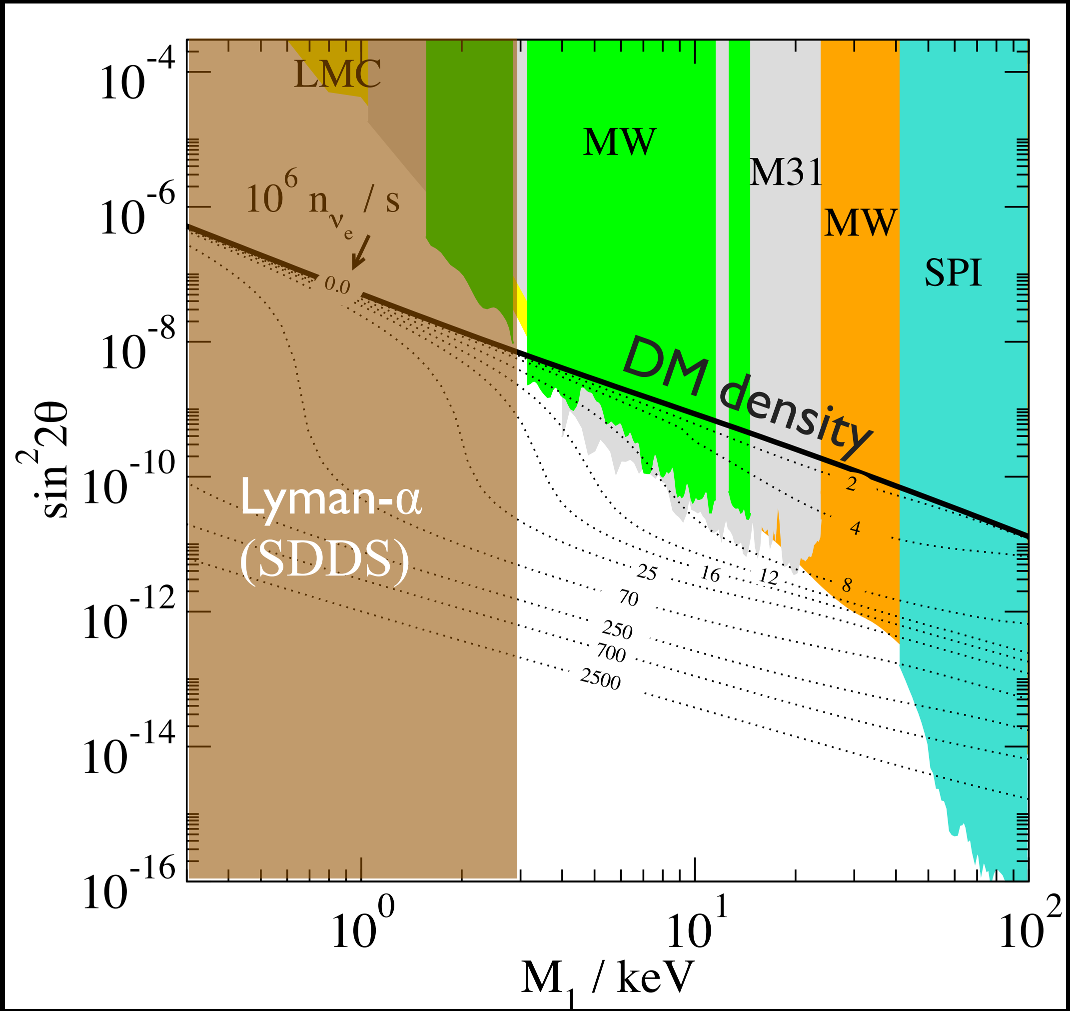
Sterile neutrino dark matter

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.

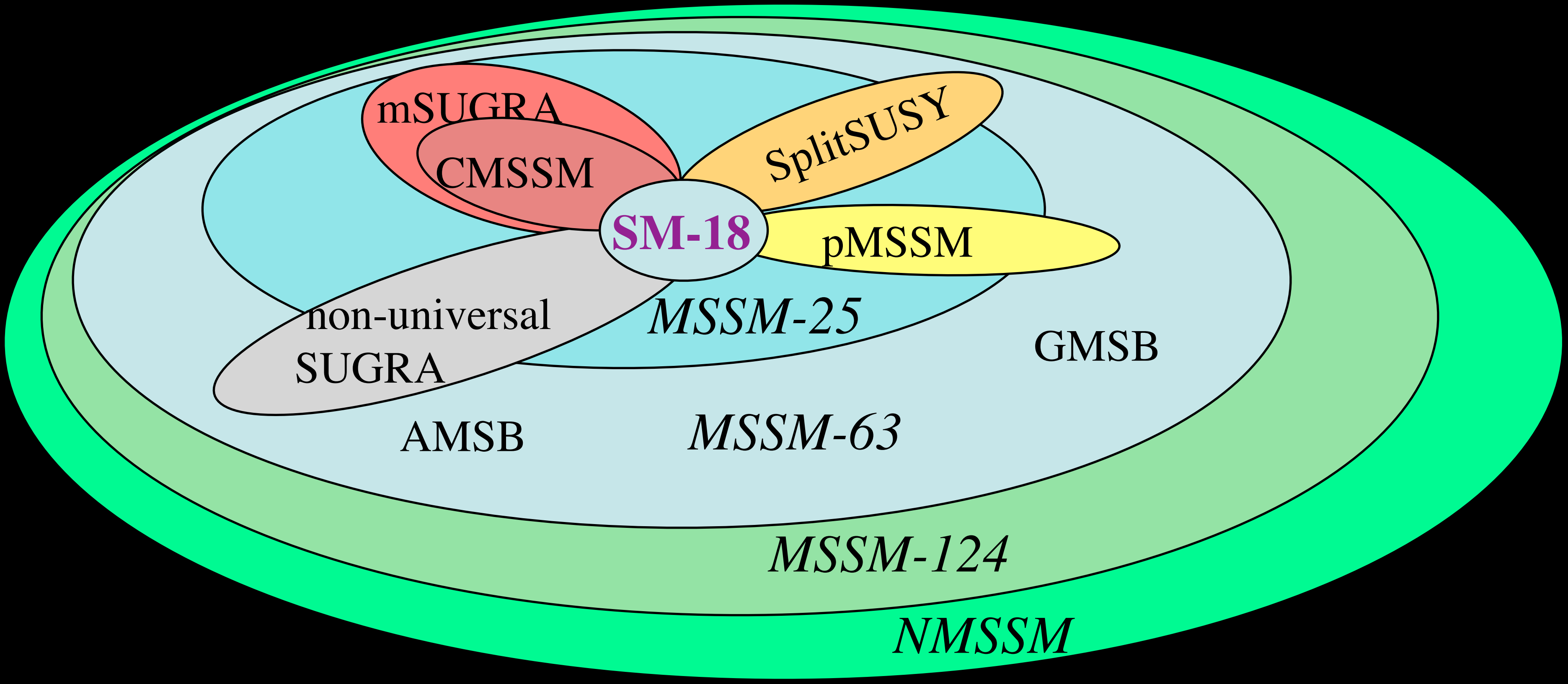
Neutralino dark matter: impact of LHC

- 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

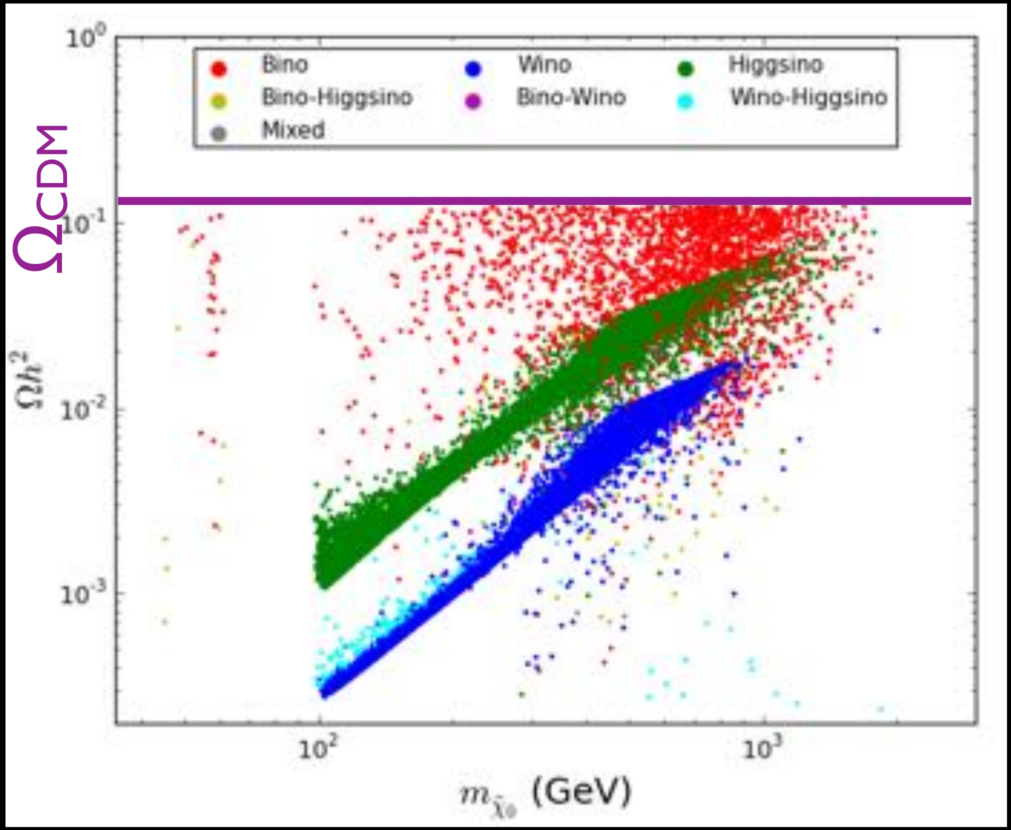
Cahill-Rowell et al 1305.6921

"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)



Neutralino dark matter: impact of LHC

"Supersymmetry cannot be experimentally ruled out: it can either be discovered or abandoned."

Leszek Roszkowski

The forbidden fruit

Searches for particle dark matter

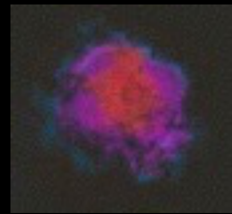
Collider

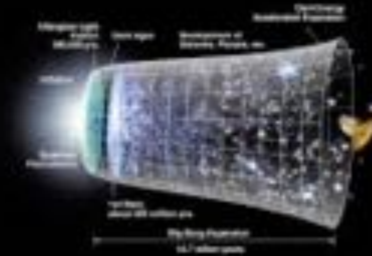
Direct

Indirect

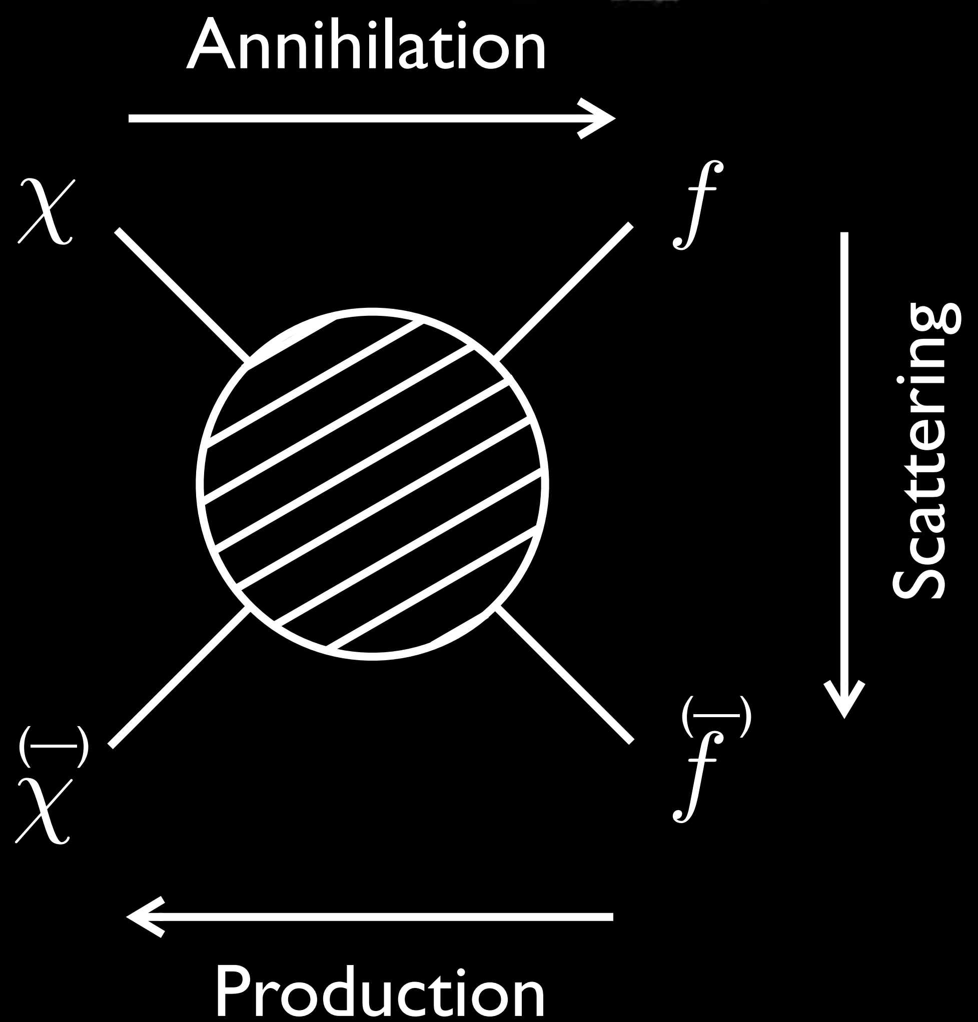
The power of the WIMP

Indirect detection

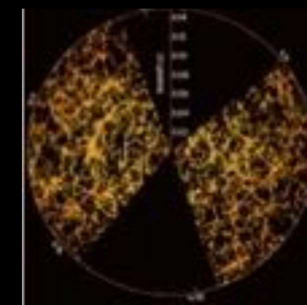




Cosmic density

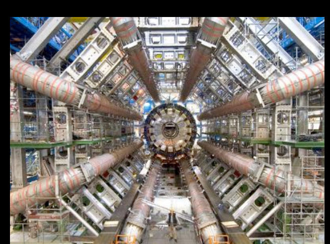


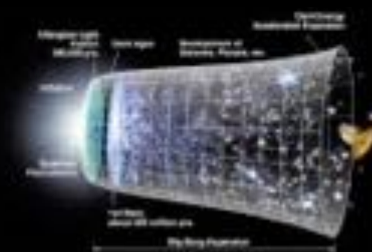
Direct detection



Large scale structure

Colliders



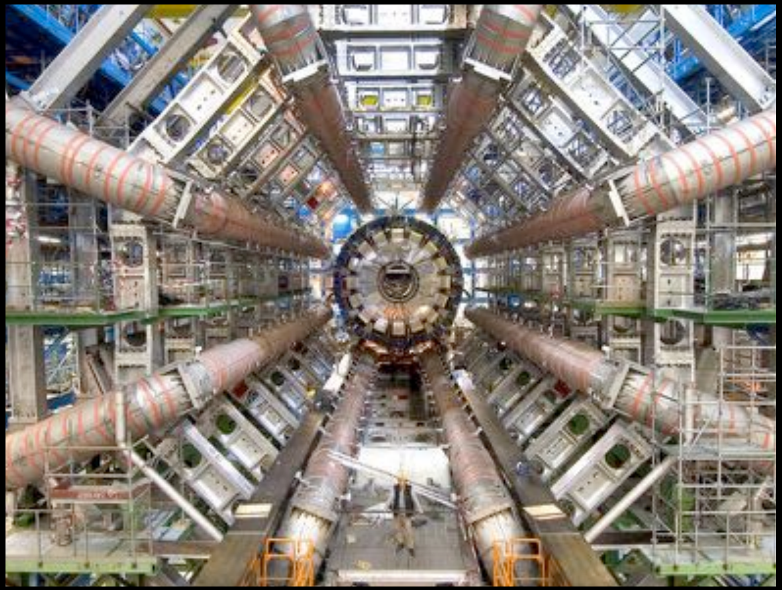


Cosmic density

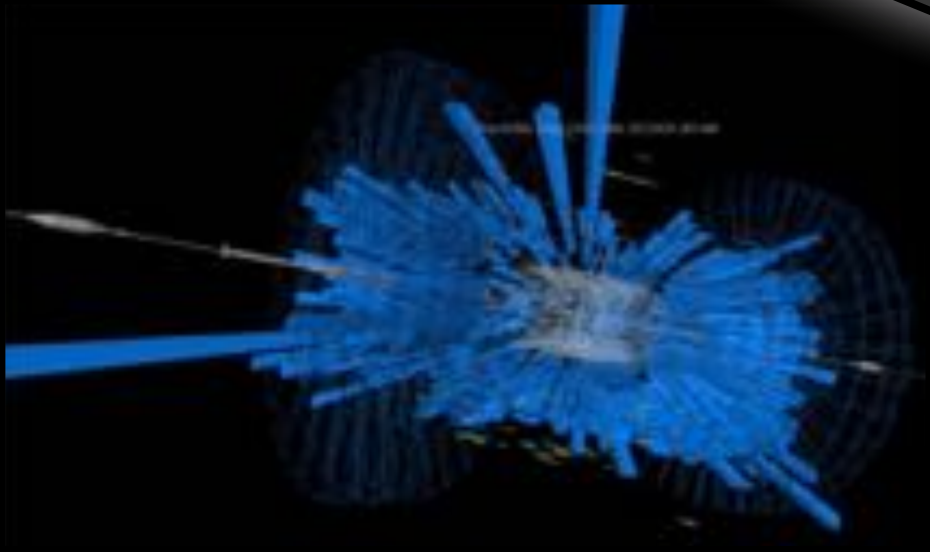
Dark matter creation with particle accelerators

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

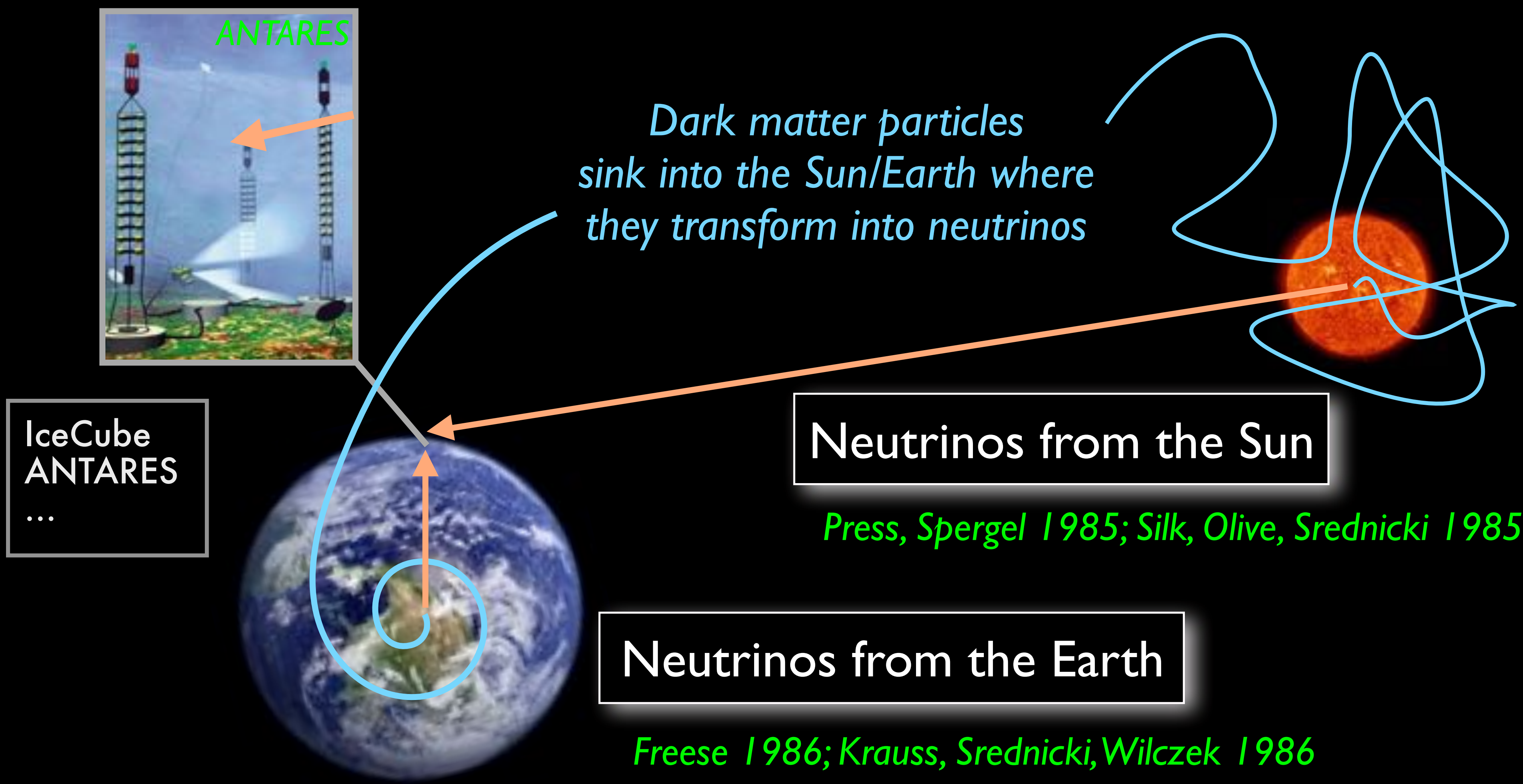
The principle

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

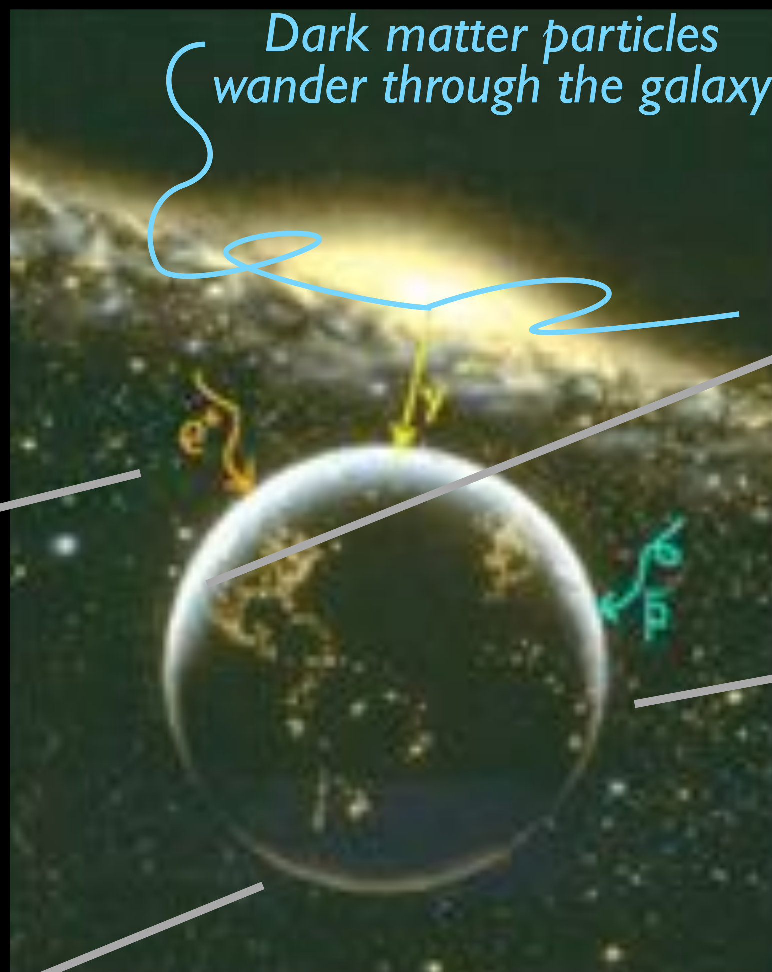


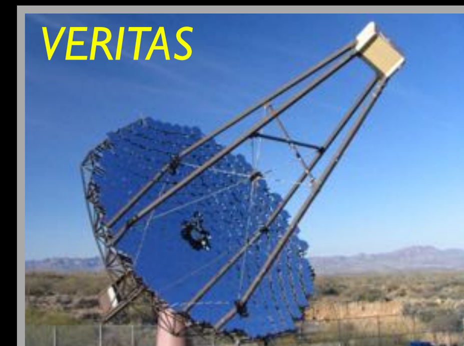
Indirect detection of particle dark matter

The principle

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

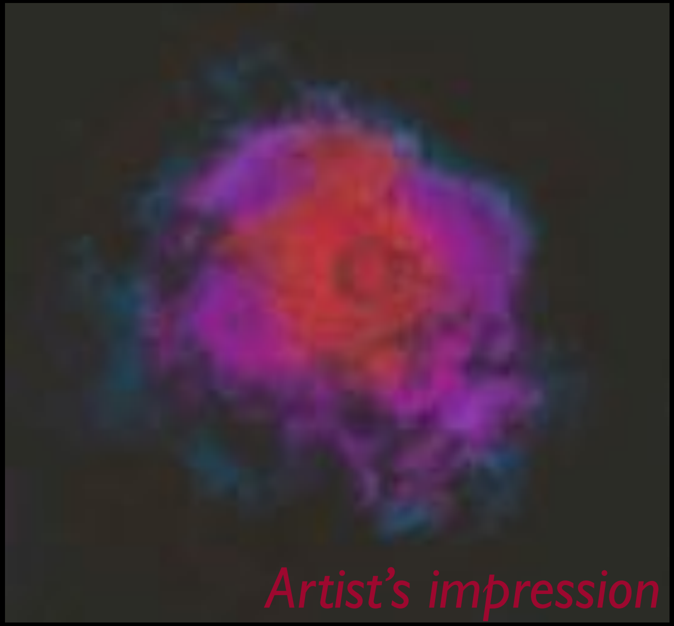
HEAT
BESS
PAMELA
AMS
GAPS
EGRET
HESS
MAGIC
VERITAS
GLAST
STACEE
CTA
...

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.



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

Dark Stars

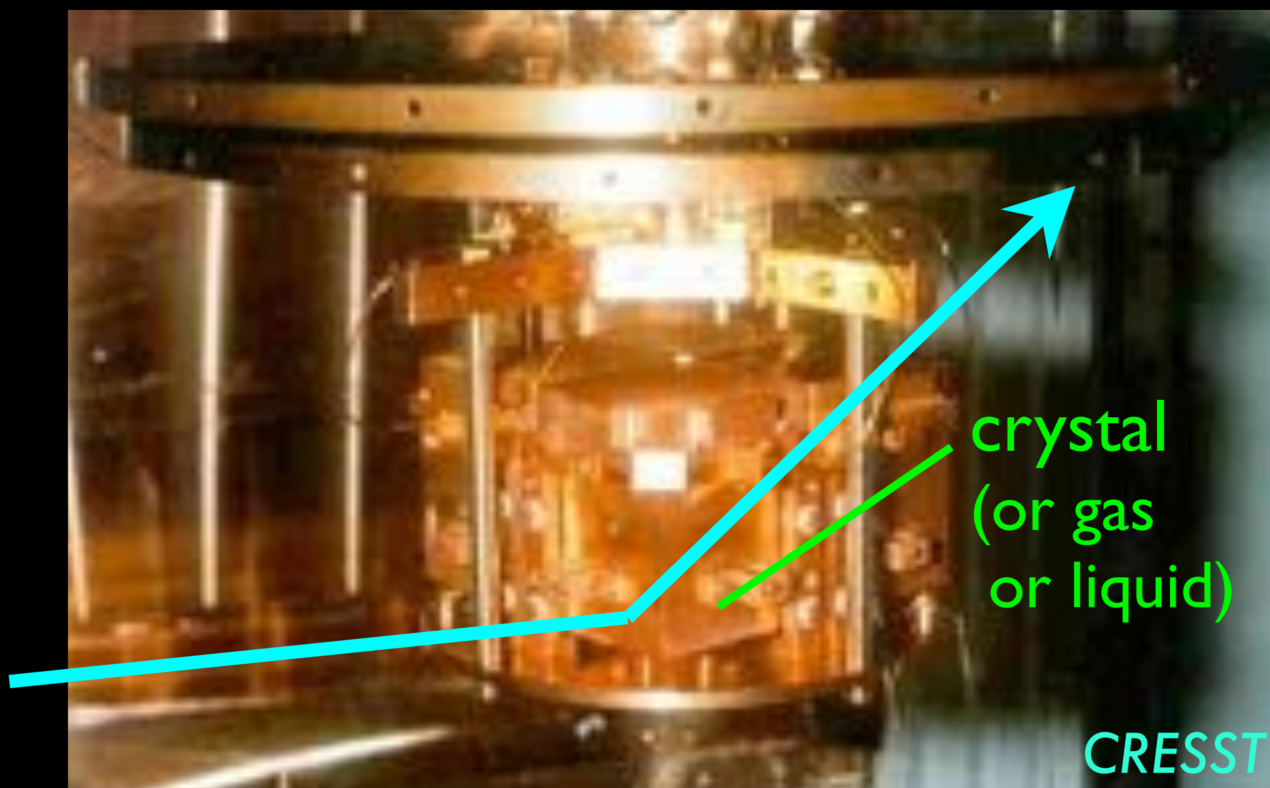
- Explain chemical elements in old halo stars
- Explain origin of supermassive black holes in early quasars

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

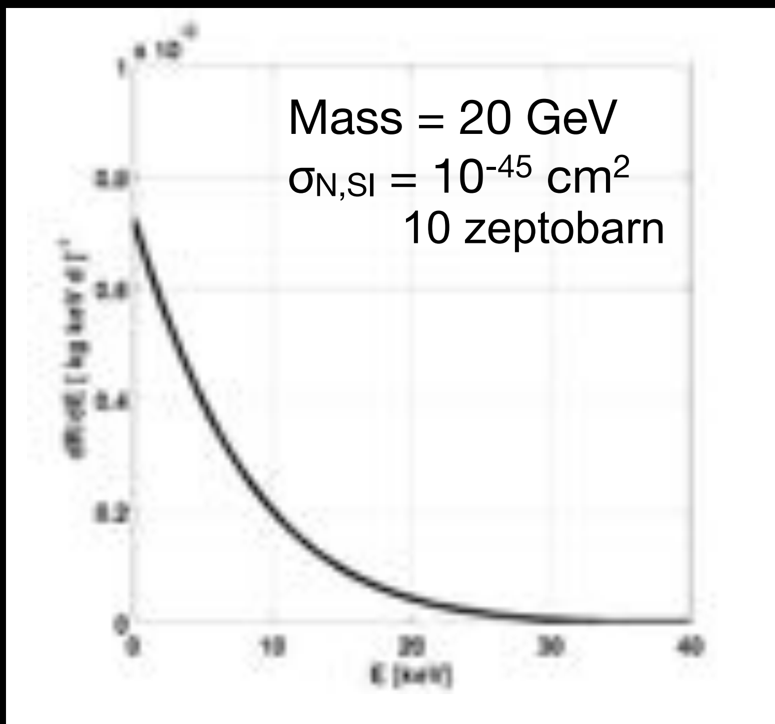


Dark matter particle

Low-background underground detector

Expected event rate is small

Expected
WIMP spectrum

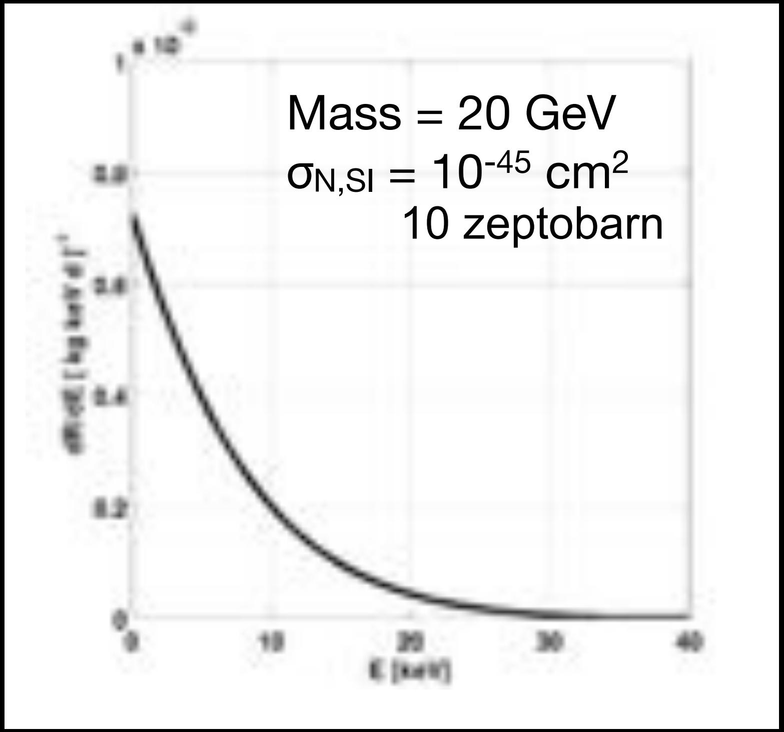


~1 event/kg/year

(nuclear recoils)

Expected event rate is small

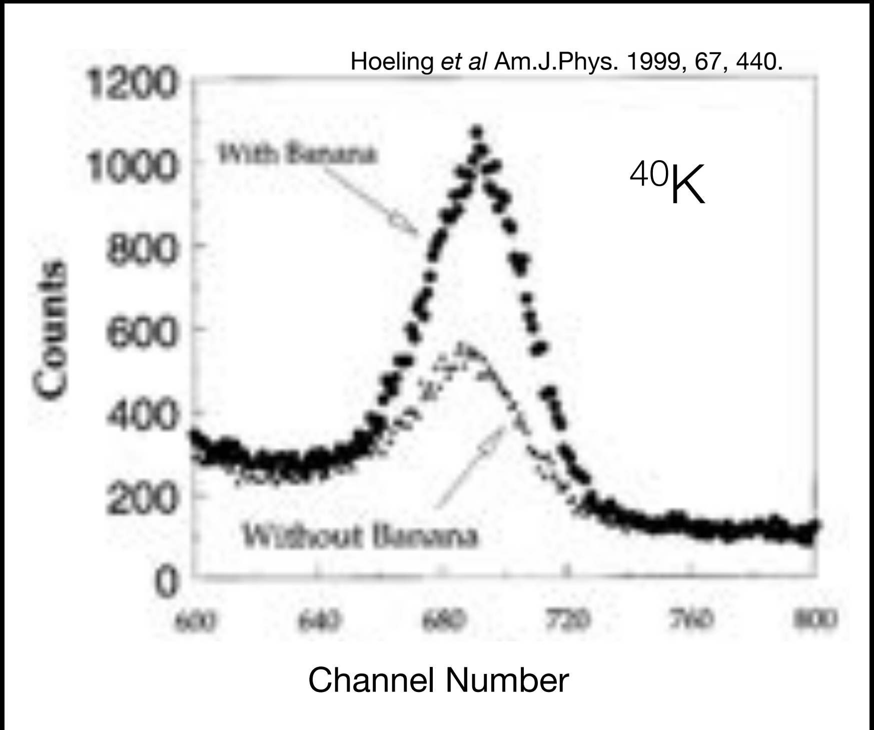
Expected
WIMP spectrum



~1 event/kg/year

(nuclear recoils)

Measured
banana spectrum



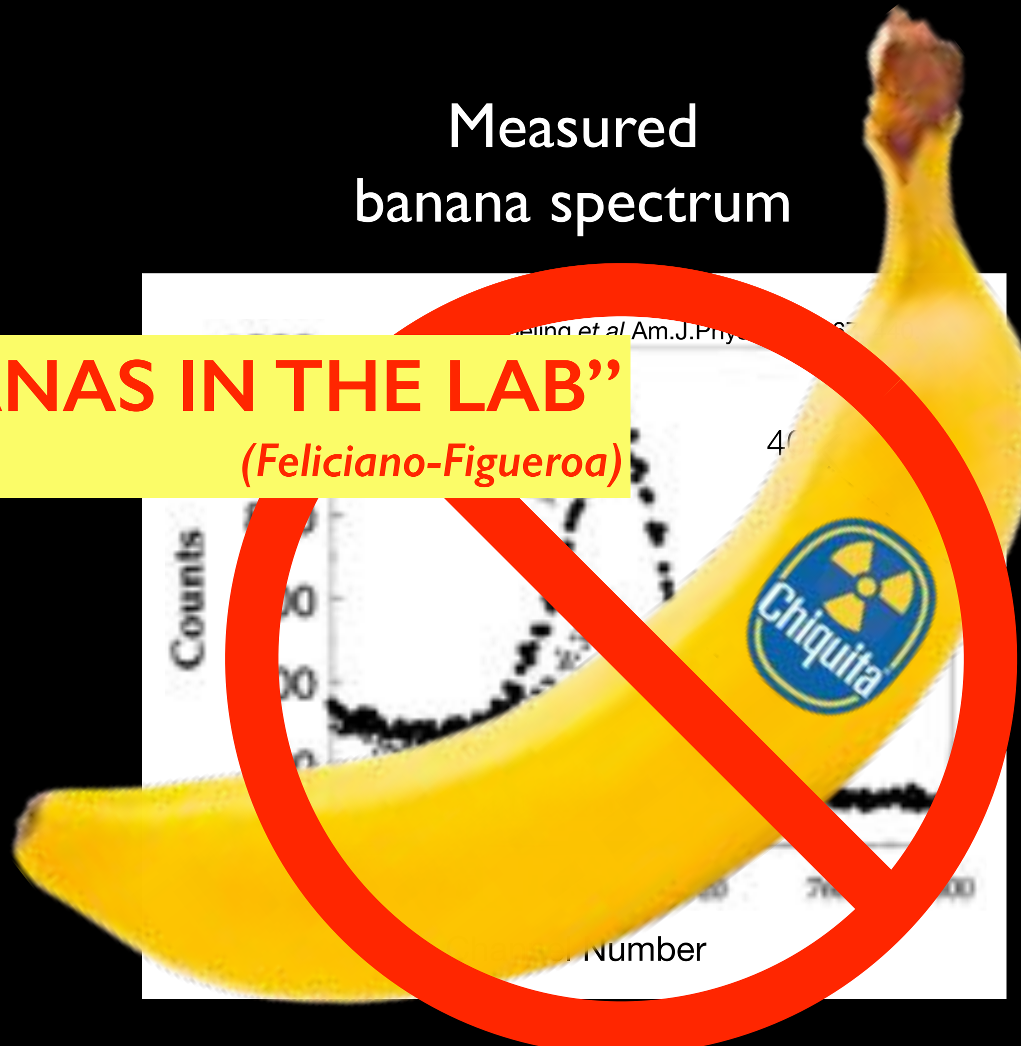
~100 events/kg/second

(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)

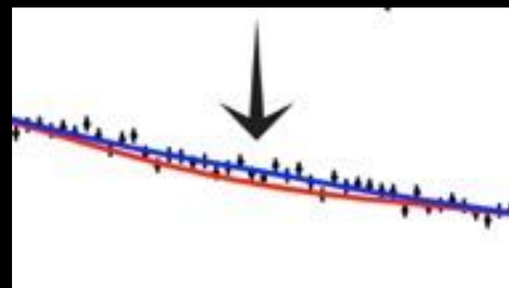
Confusion of the mind

Evidence for cold dark matter particles?

GeV γ-rays

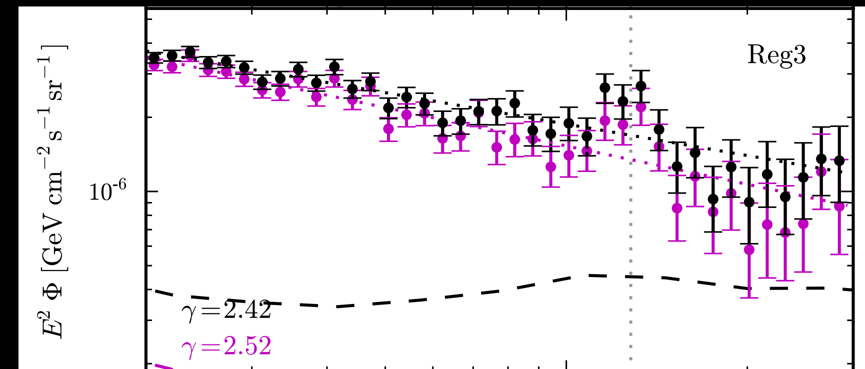
Hooper et al 2009-14

3.5 keV X-ray line



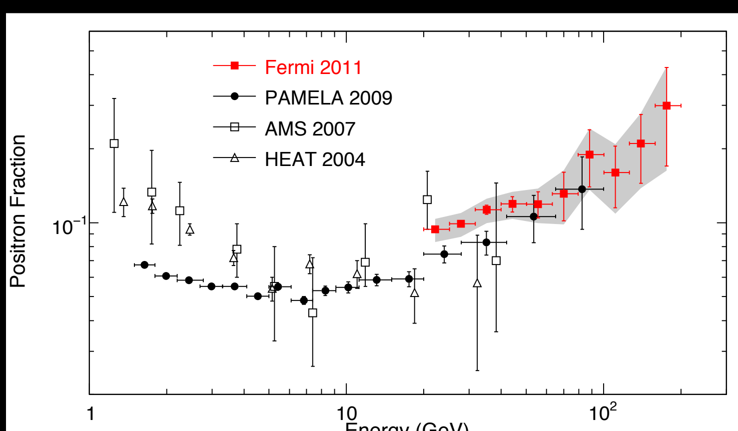
Bulbul et al 2014

135 GeV γ-ray line



Weniger 2012

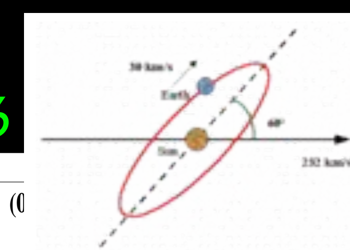
Positron excess

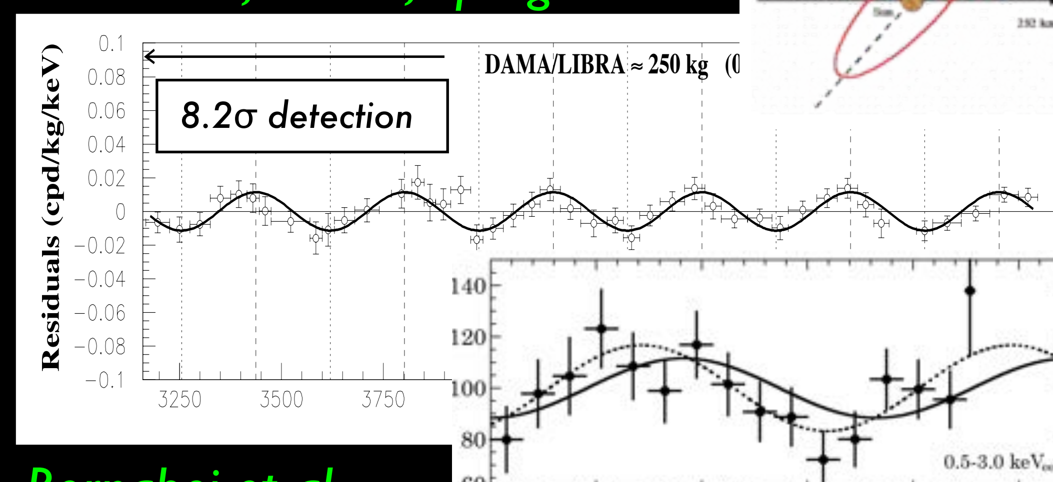


Adriani et al 2009; Ackerman et al 2011; Aguilar et al 2013

Annual modulation

Drukier, Freese, Spergel 1986





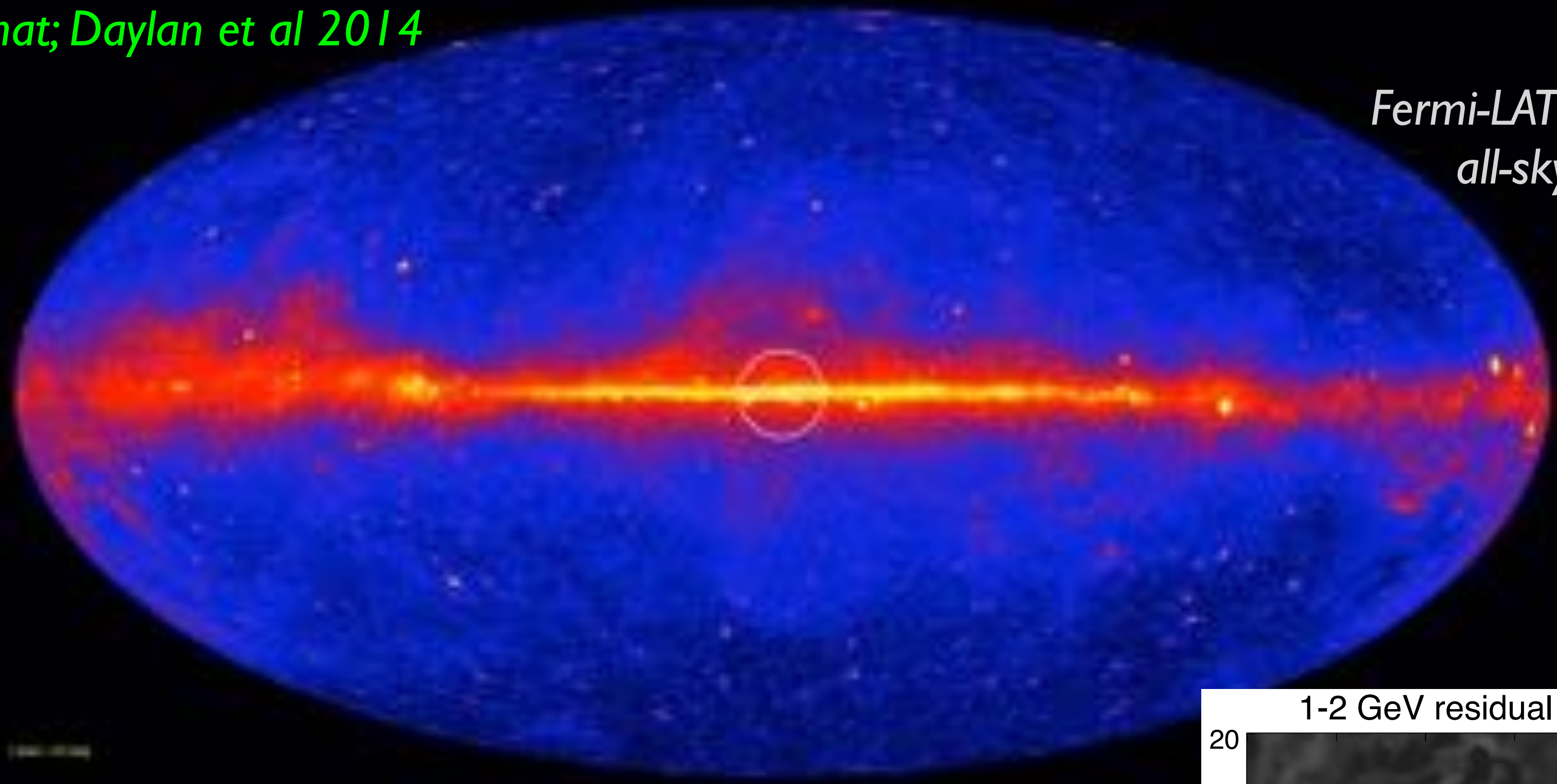
Bernabei et al 1997-2012

Aalseth et al 2011

Gamma-rays from dark matter?

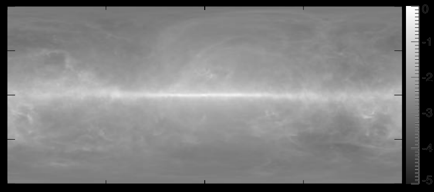
1 GeV gamma-ray excess?

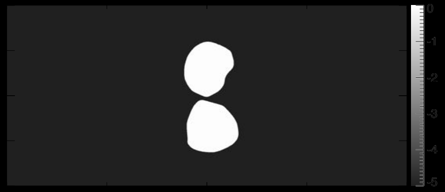
Goodenough, Hooper 2009; Hooper, Goodenough; Boyarsky, Malyshev, Ruchayskiy; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon, Macias 2013; Abazajian, Canac, Horiuchi, Kaplinghat; Daylan et al 2014

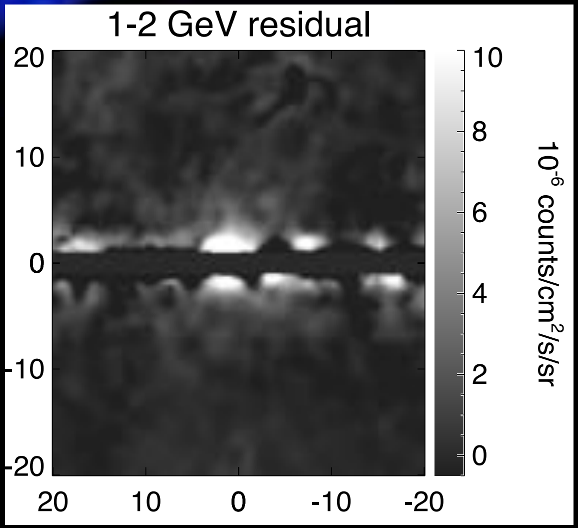


Fermi-LAT all-sky map

Fit diffuse + Fermi-bubble, find residual

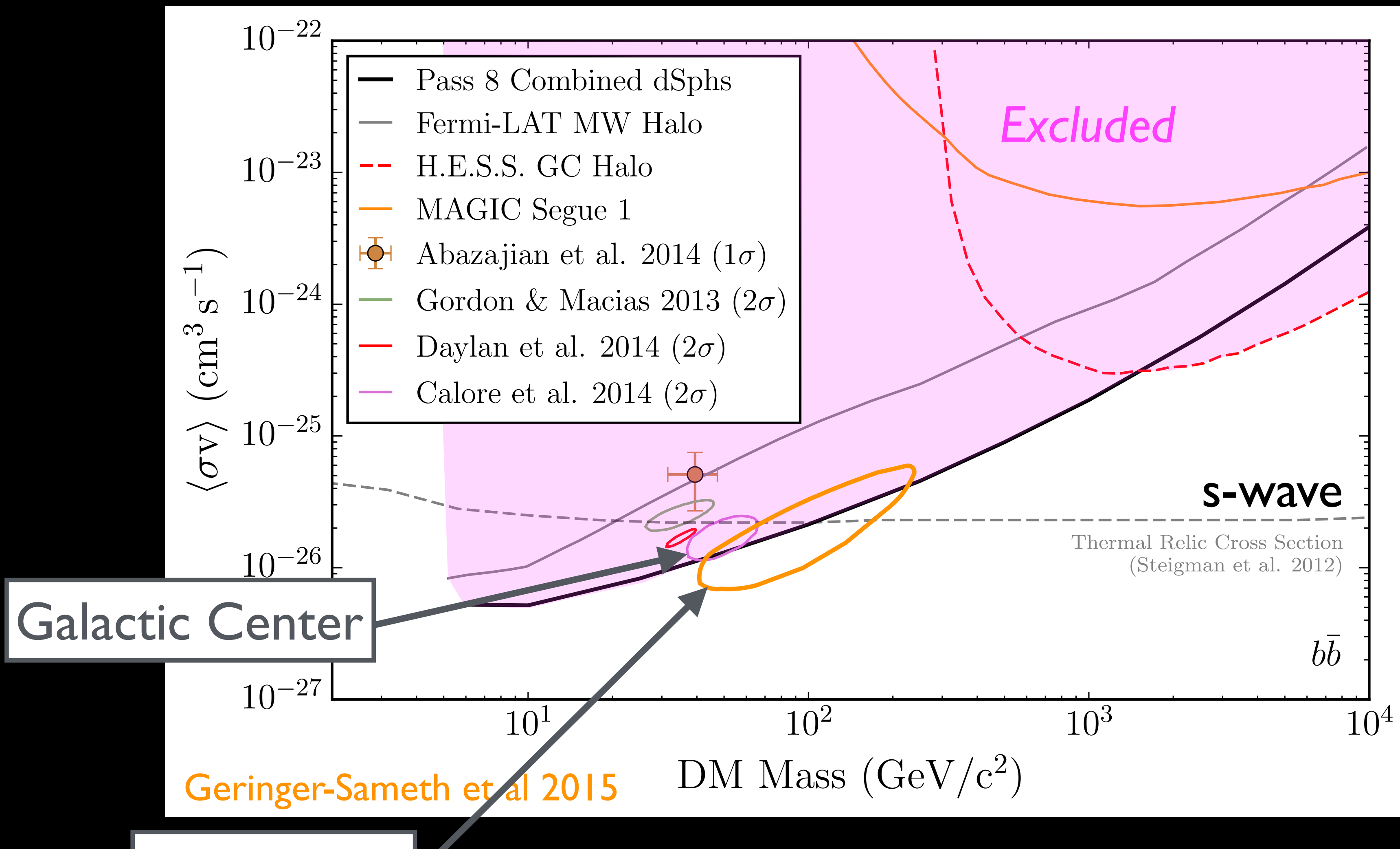






Gamma-rays from dark matter (2015)

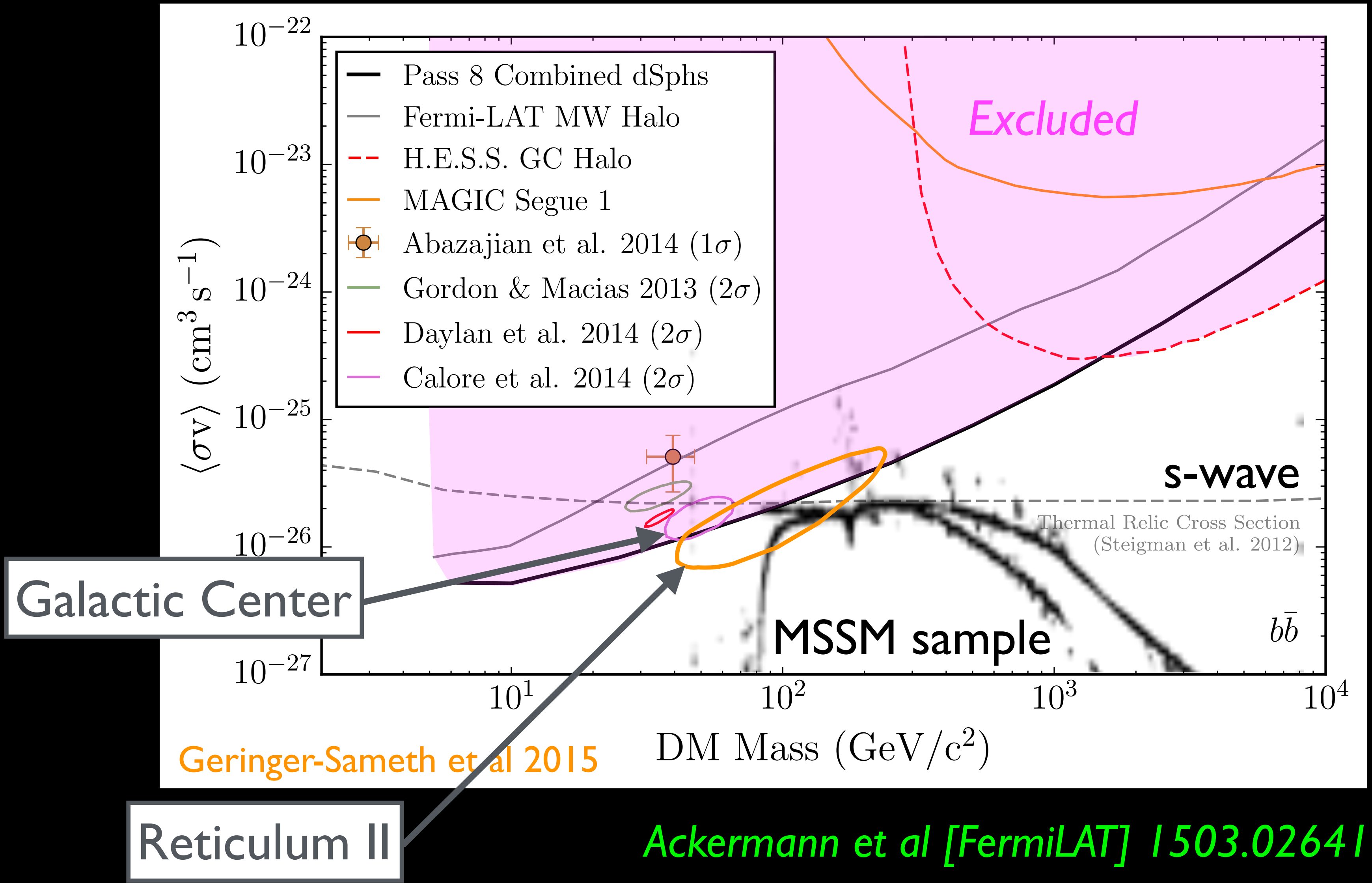
Self-annihilation into $b\bar{b}$ *(similar for $\tau^+\tau^-$, W^+W^-,…)*



Ackermann et al [FermiLAT] 1503.02641

Gamma-rays from dark matter (2015)

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



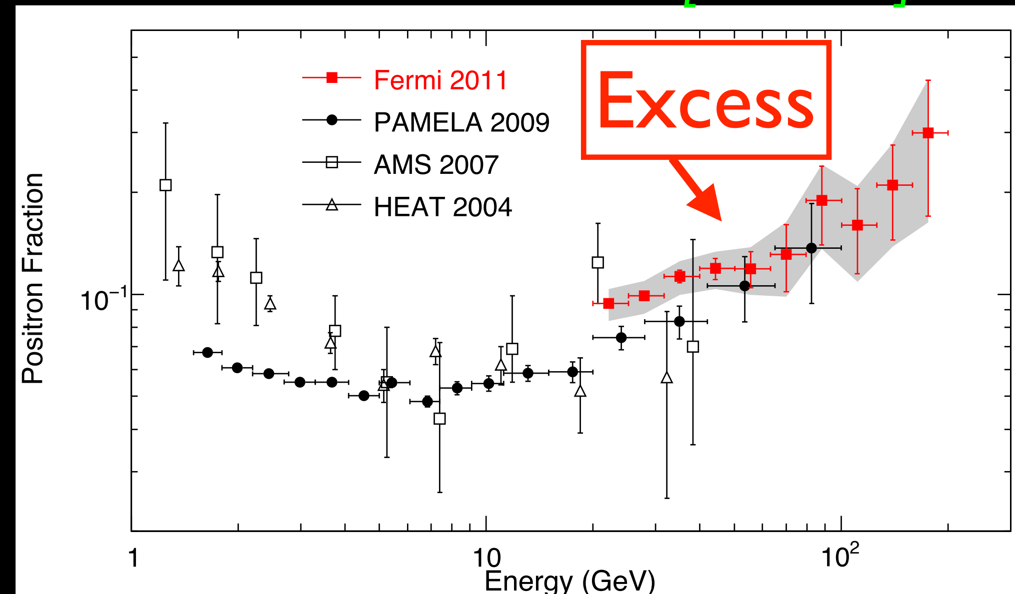
Ackermann et al [FermiLAT] 1503.02641

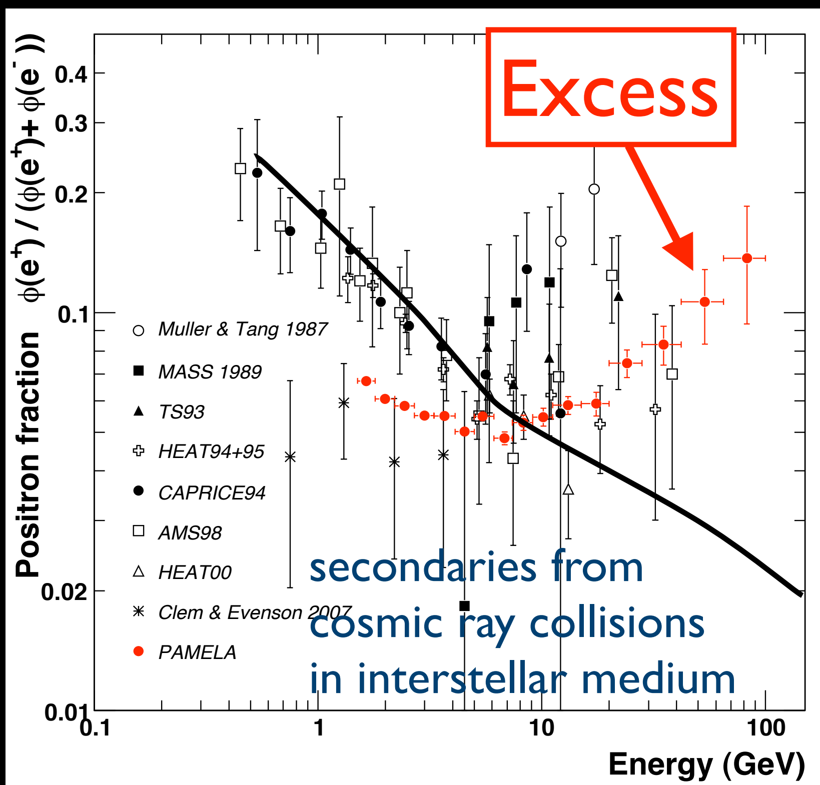
Positrons from dark matter?

Excess in cosmic ray positrons

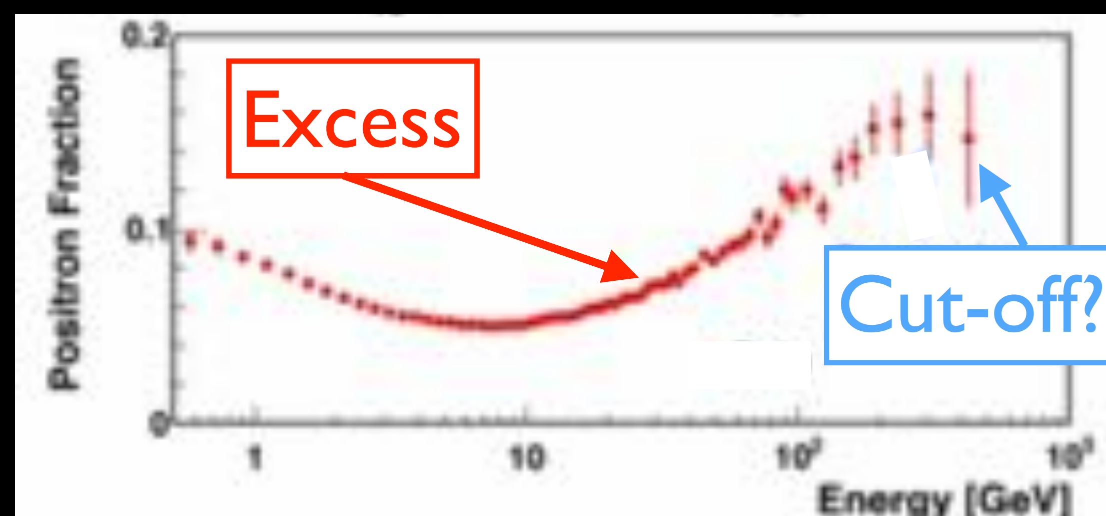
High energy cosmic ray positrons are more than expected

Ackernmann et al [Fermi-LAT] 2011





Adriani et al. [PAMELA ,2008

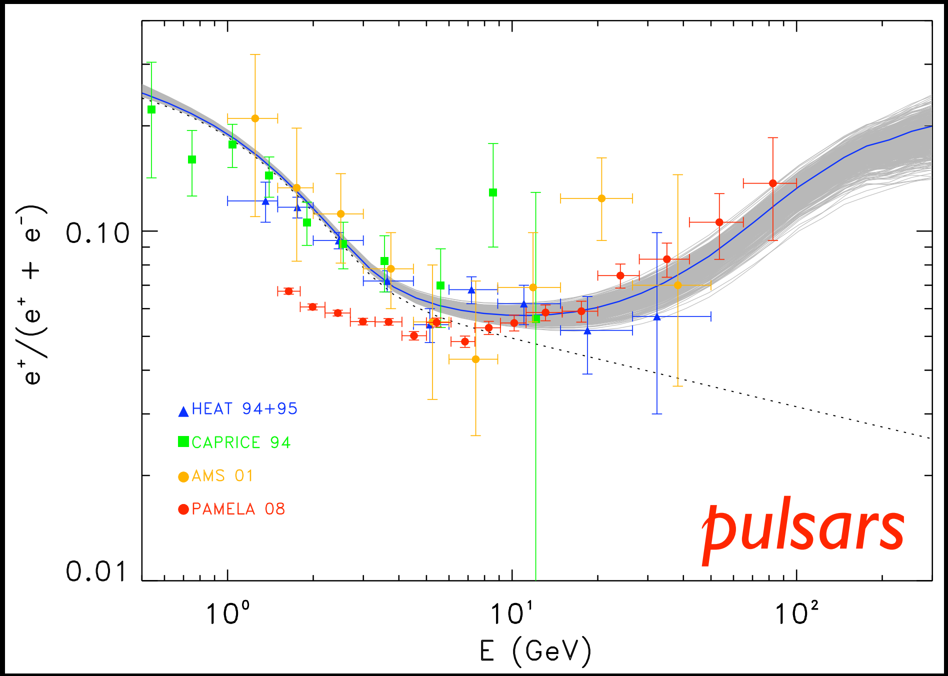


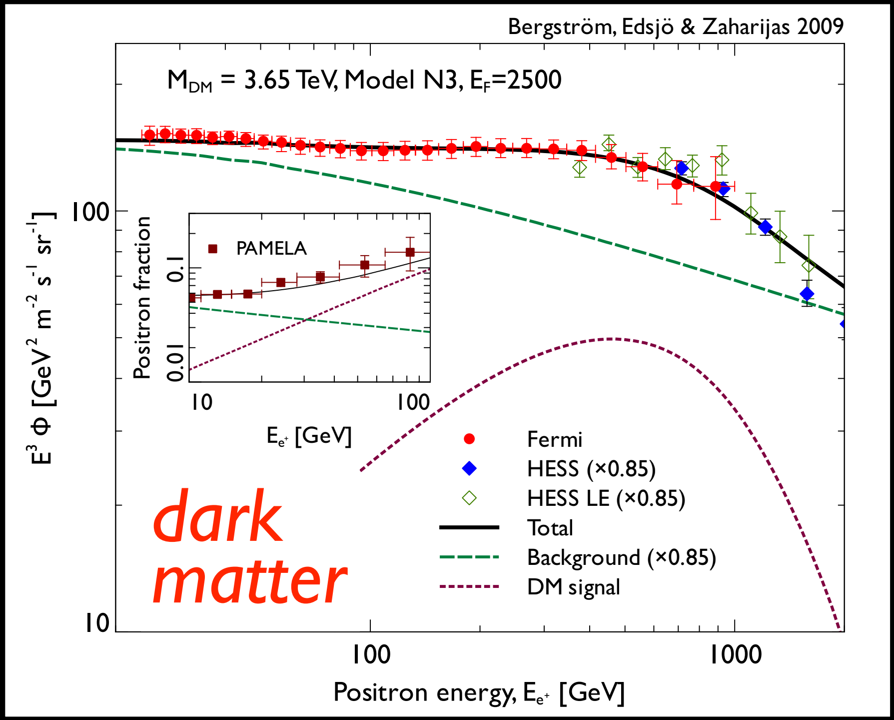
Accardo et al [AMS-02] 2014

Excess in cosmic ray positrons

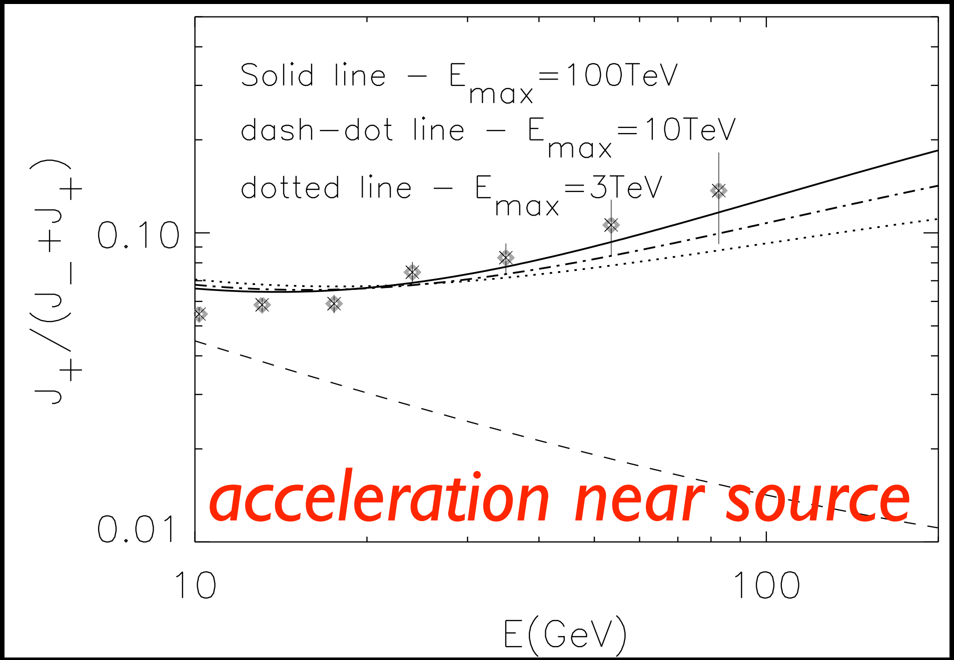
Grasso et al [Fermi-LAT] 2009

Dark matter?
Pulsars?
Secondaries from extra primaries?





Bergstrom, Edsjo, Zaharijas 2009



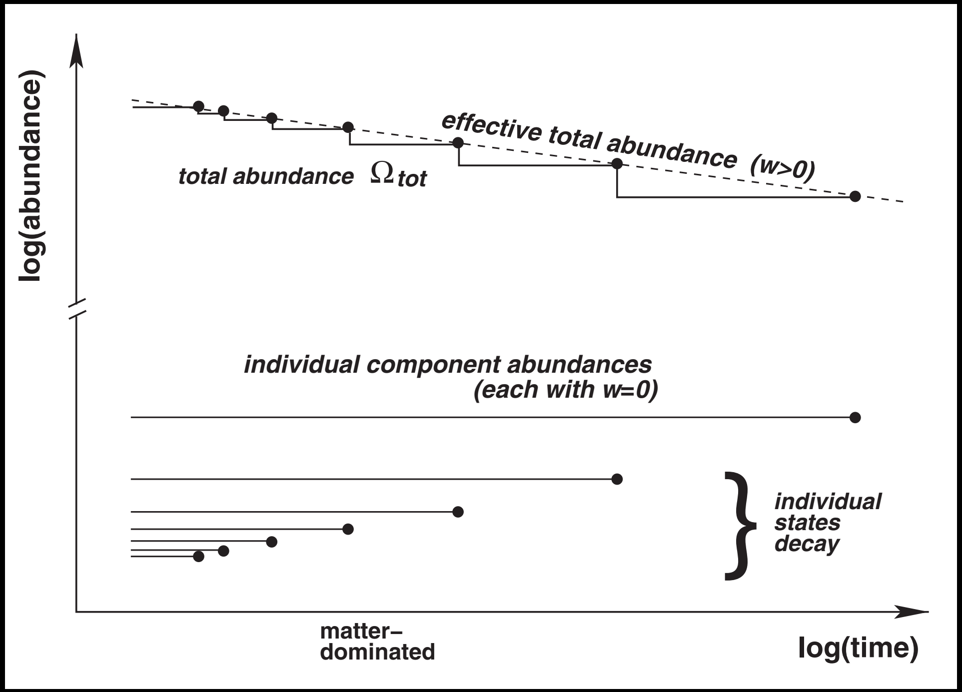
Blasi 2009

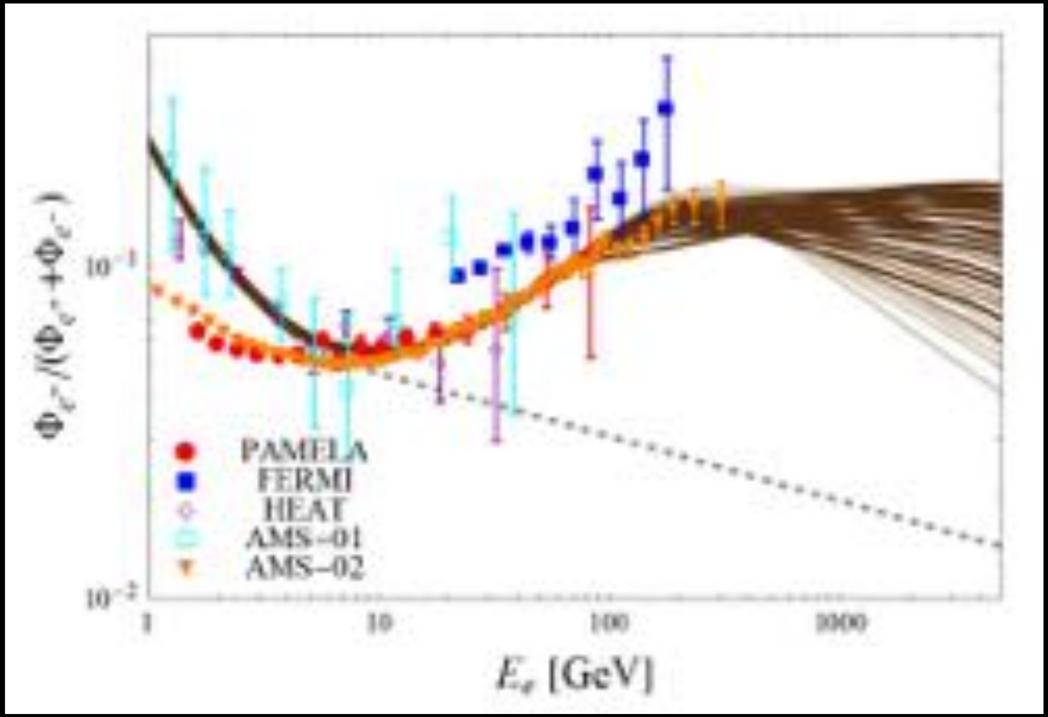
Dynamical dark matter

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

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

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

X-rays from dark matter?

Sterile neutrino dark matter

The main decay mode of keV sterile neutrinos ($\nu_s \rightarrow 3\nu$) is undetectable

Radiative decay of sterile neutrinos $\nu_s \rightarrow \gamma \nu_a$

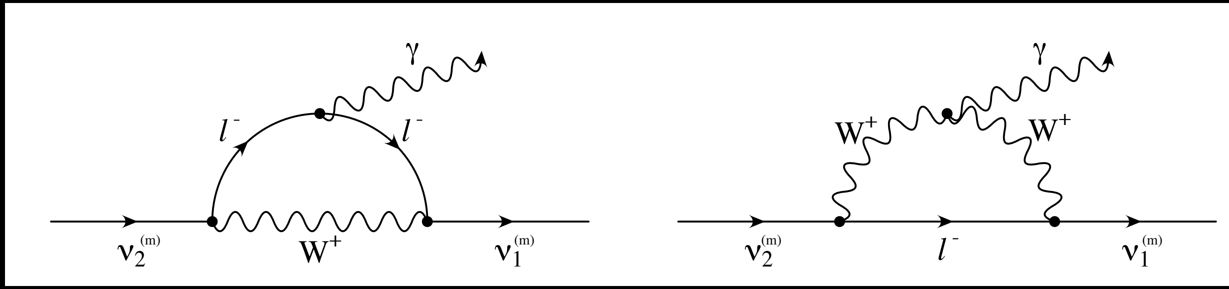


Figure from Kusenko 0906.2968

X-ray line

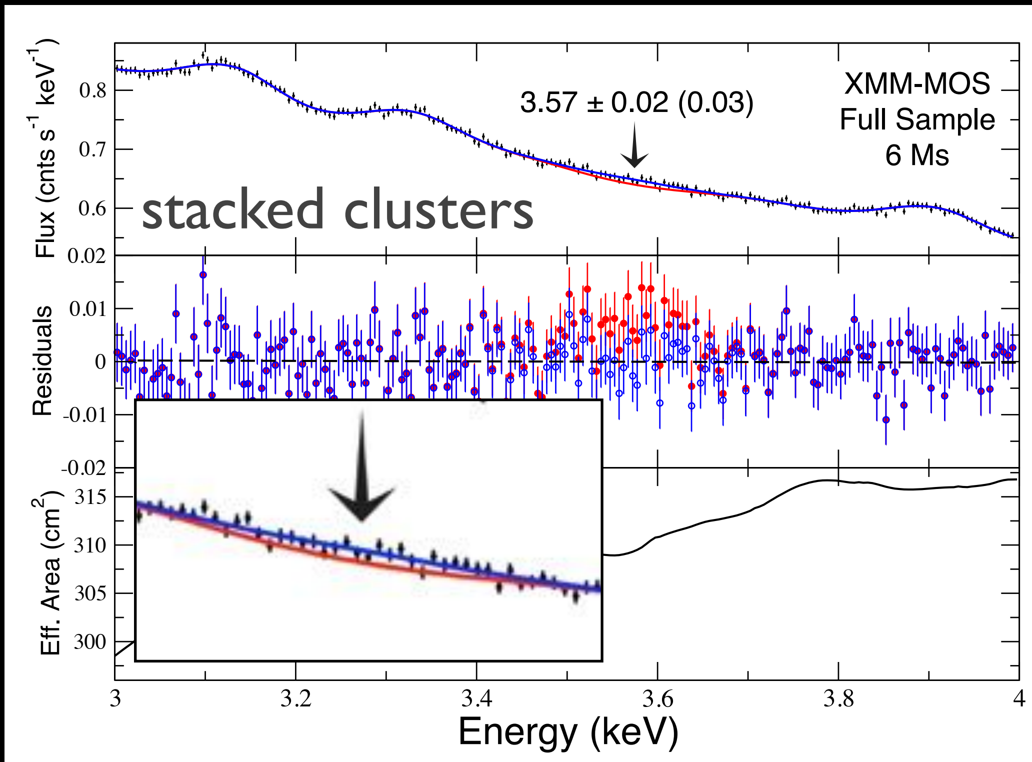
$$E_\gamma = \frac{1}{2} m_s$$

$$\Gamma_{\nu_s \to \gamma \nu_a} = \frac{9}{256\pi^4} \alpha_{\rm EM} \, {\rm G_F^2} \, \sin^2\theta \, m_{\rm s}^5 = \frac{1}{1.8 \times 10^{21} {\rm s}} \sin^2\theta \left(\frac{m_{\rm s}}{\rm keV}\right)^5$$

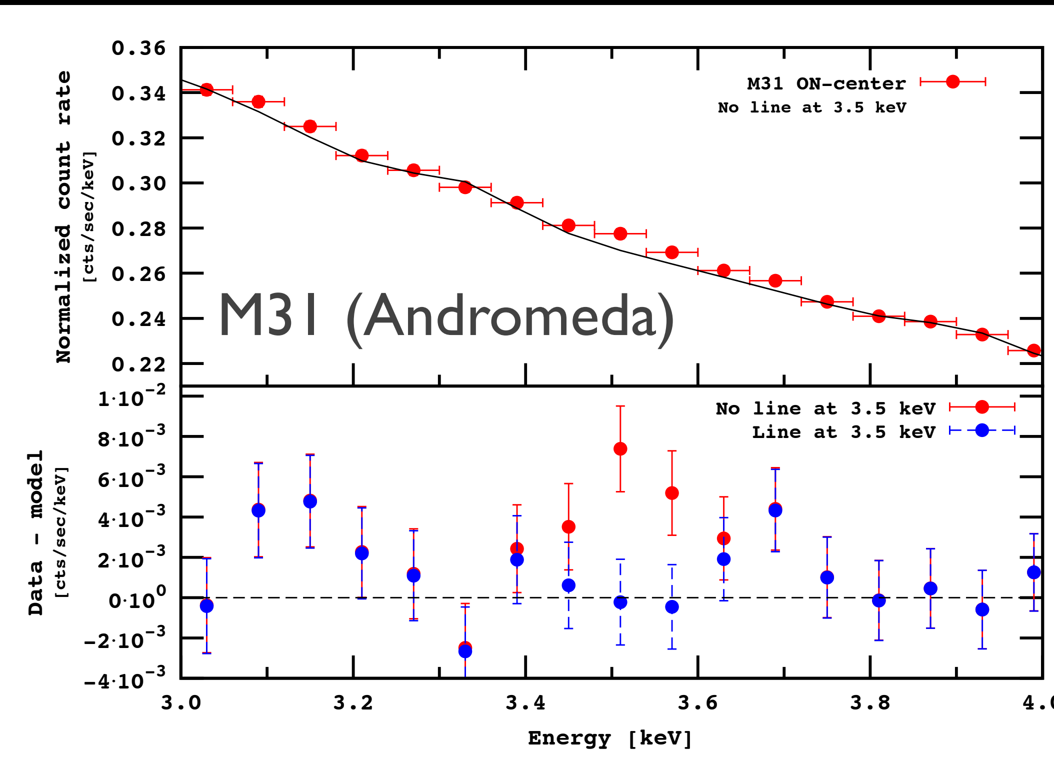
Sterile neutrino dark matter

An unidentified 3.5 keV X-ray line has been reported in stacked images of 73 galaxy clusters and in the Andromeda galaxy

Bulbul et al 2014



Boyarsky et al 2014

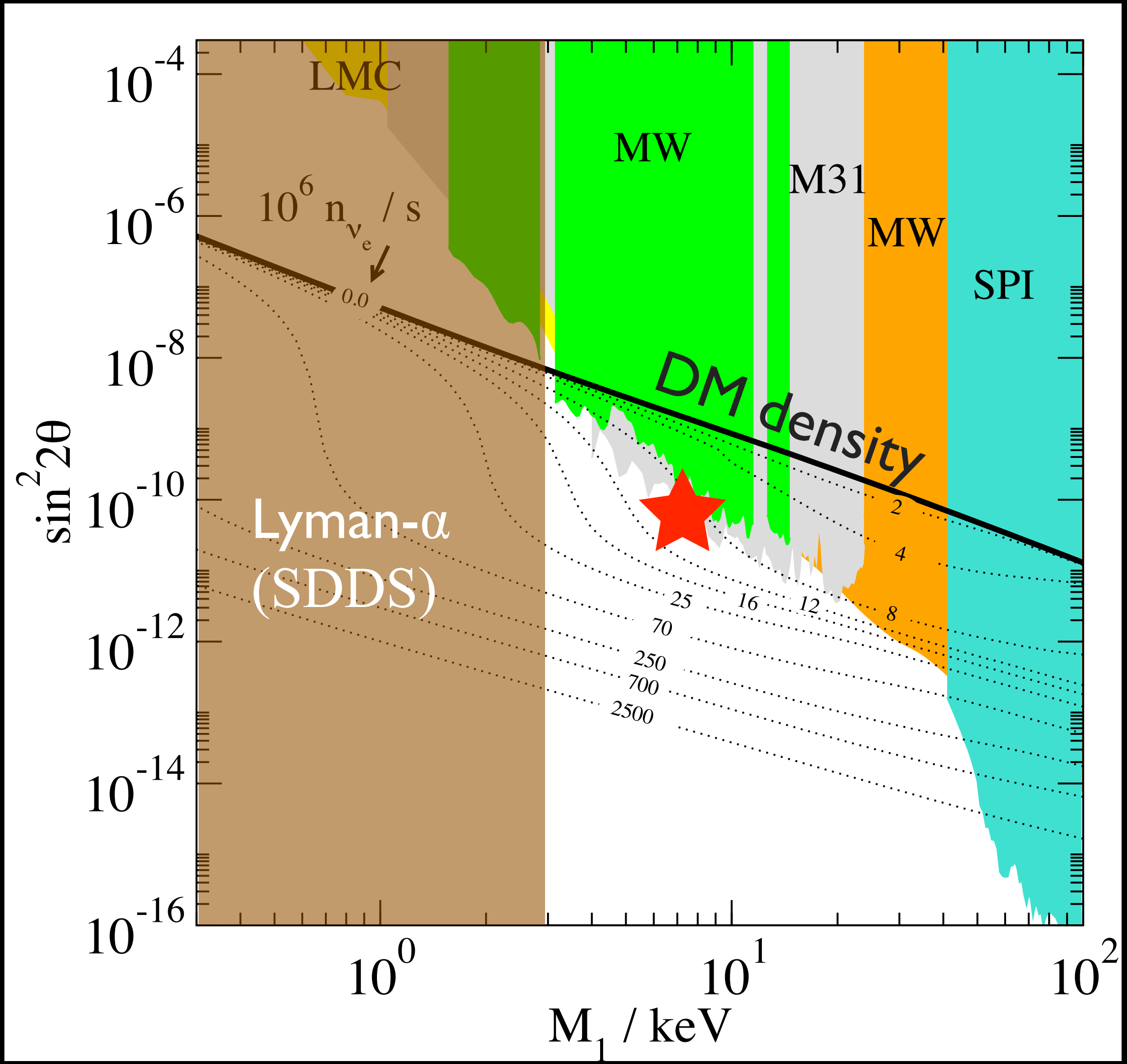


Sterile neutrino dark matter

*ν*MSM

m_ν = 7.1 keV

$\sin^2(2\theta) = 7\times10^{-11}$

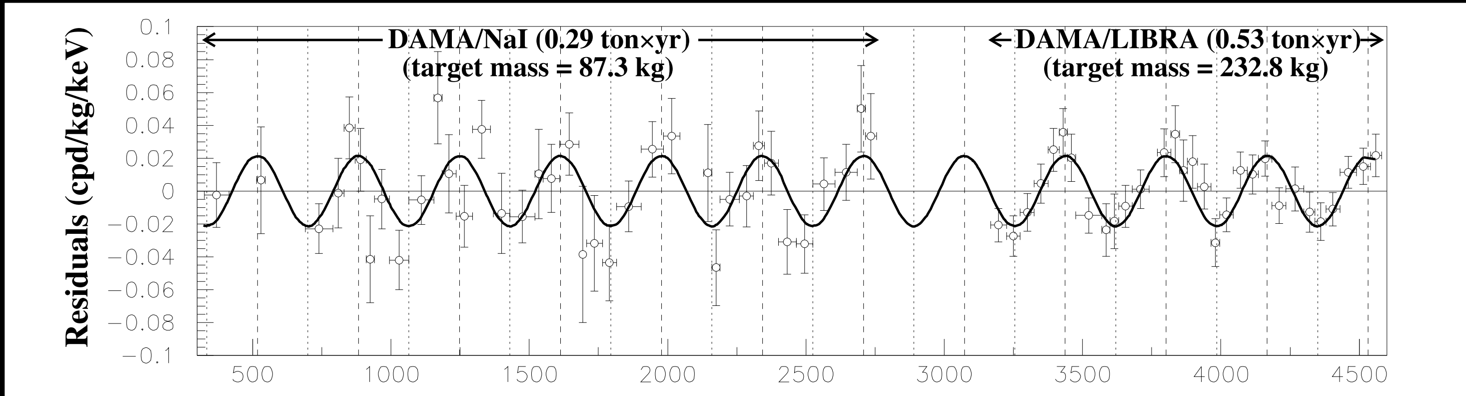


Laine, Shaposhnikov 2008

Direct detection of dark matter?

Annual modulation in direct detection

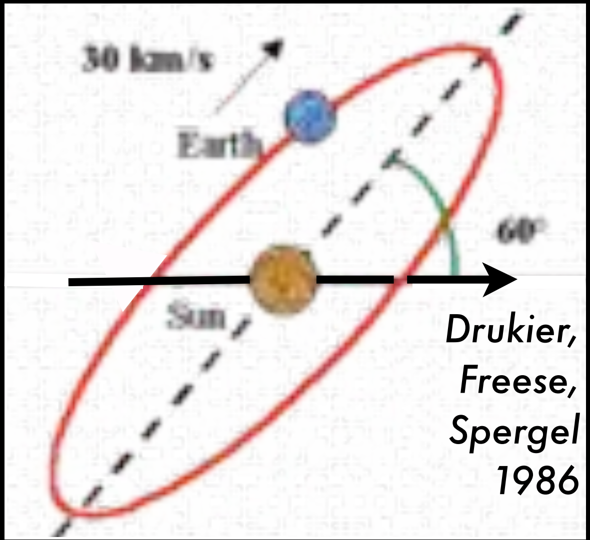
- DAMA observes more nuclei are "hit" in Summer, fewer in Winter



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

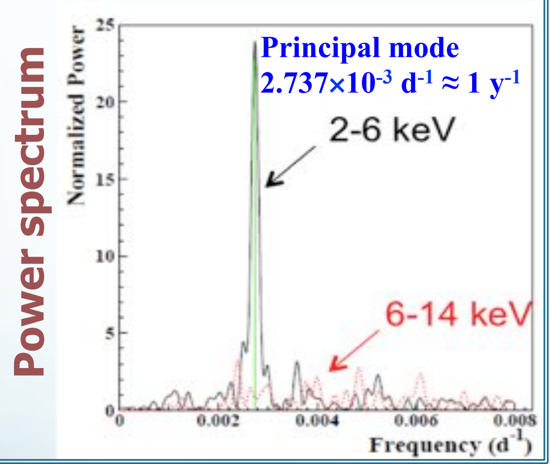
DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

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

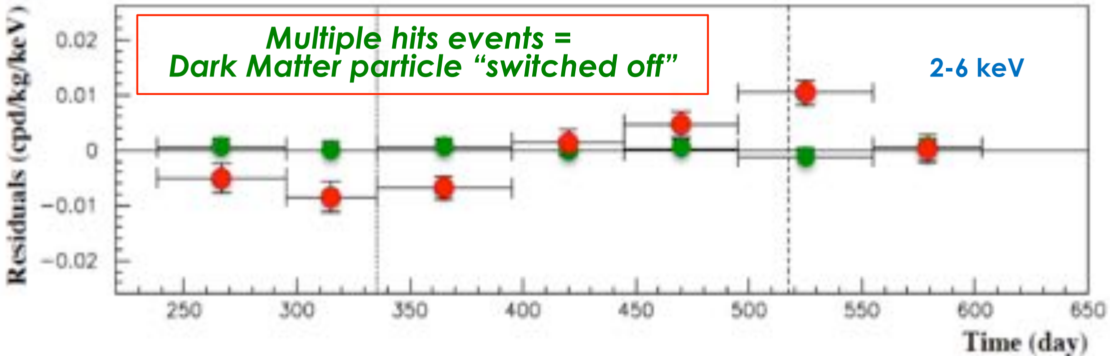
	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	0.0190 ±0.0020	0.996 ±0.0002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.0002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.0002	144 ± 7	9.3σ

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



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

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



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

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

Belli, IDM2014

DAMA modulation

Model Independent Annual Modulation Result

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

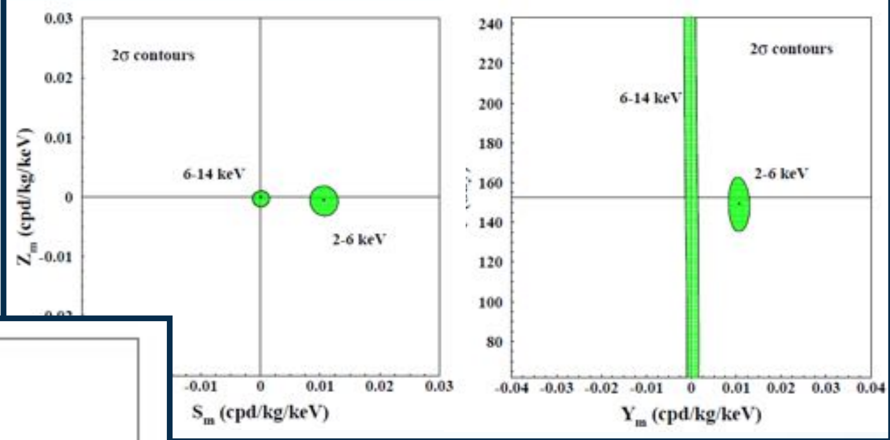
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

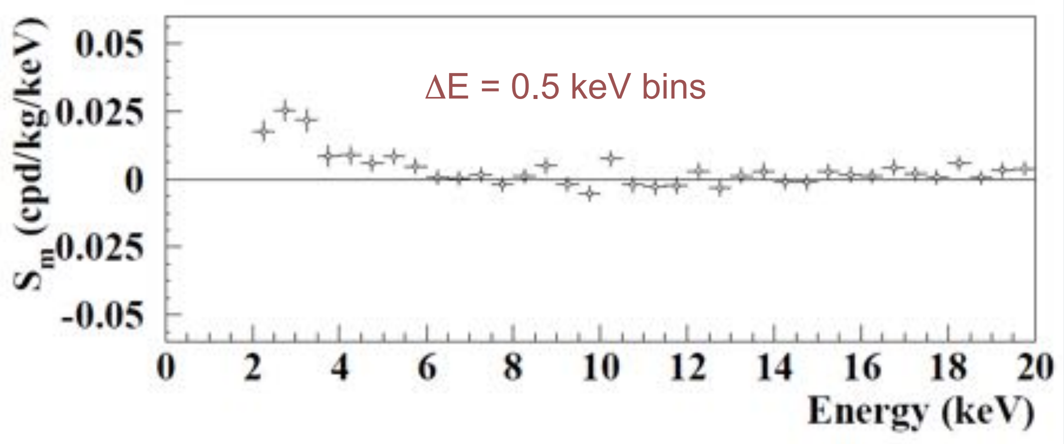
- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

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

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

• No
• No
• No ev

3)2648

$R(t)$

here

S_m (cpd/kg/keV)

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

"Public?
What does it mean?"

Pierluigi Belli at IDM2014

Belli, IDM2014

CoGeNT made their data public

CoGeNT decided to publish energy and time of their events

Independent groups reanalyzed the CoGeNT data

Pulse-shape discrimination of surface/bulk events

No significant annual modulation found

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

Davis, McCabe, Boehm 1405.0495

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

Bellis, Collar, Field, Kelso at IDM2014

CoGeNT made their data public

CoGeNT decided to publish energy and time of their events

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

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

arXiv:1401.6234v1 24 Jan 2014

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arXiv:1401.6234v2 27 Jan 2014

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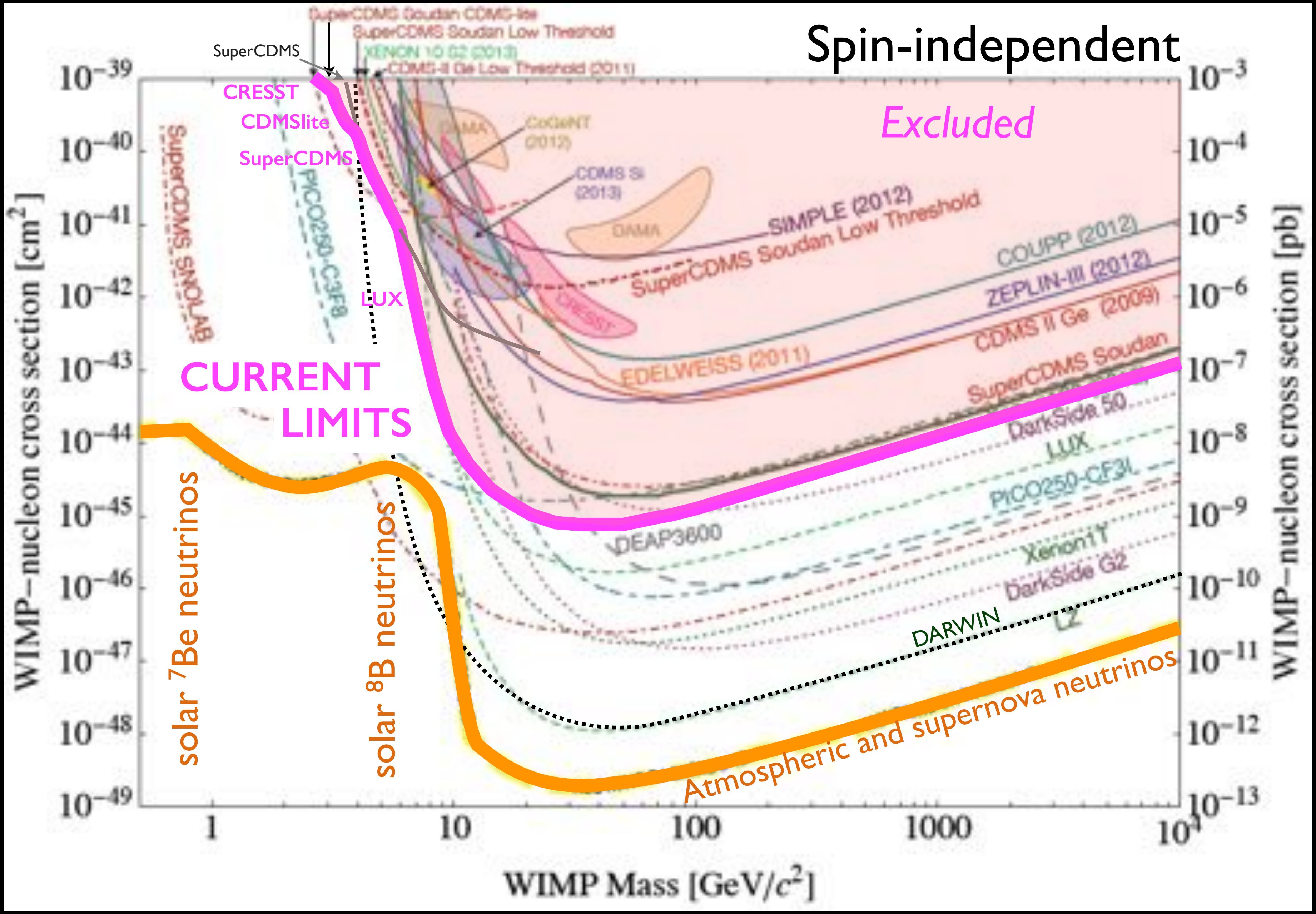
Bellis, Collar, Field, Kelso at IDM2014

CoGeNT leader

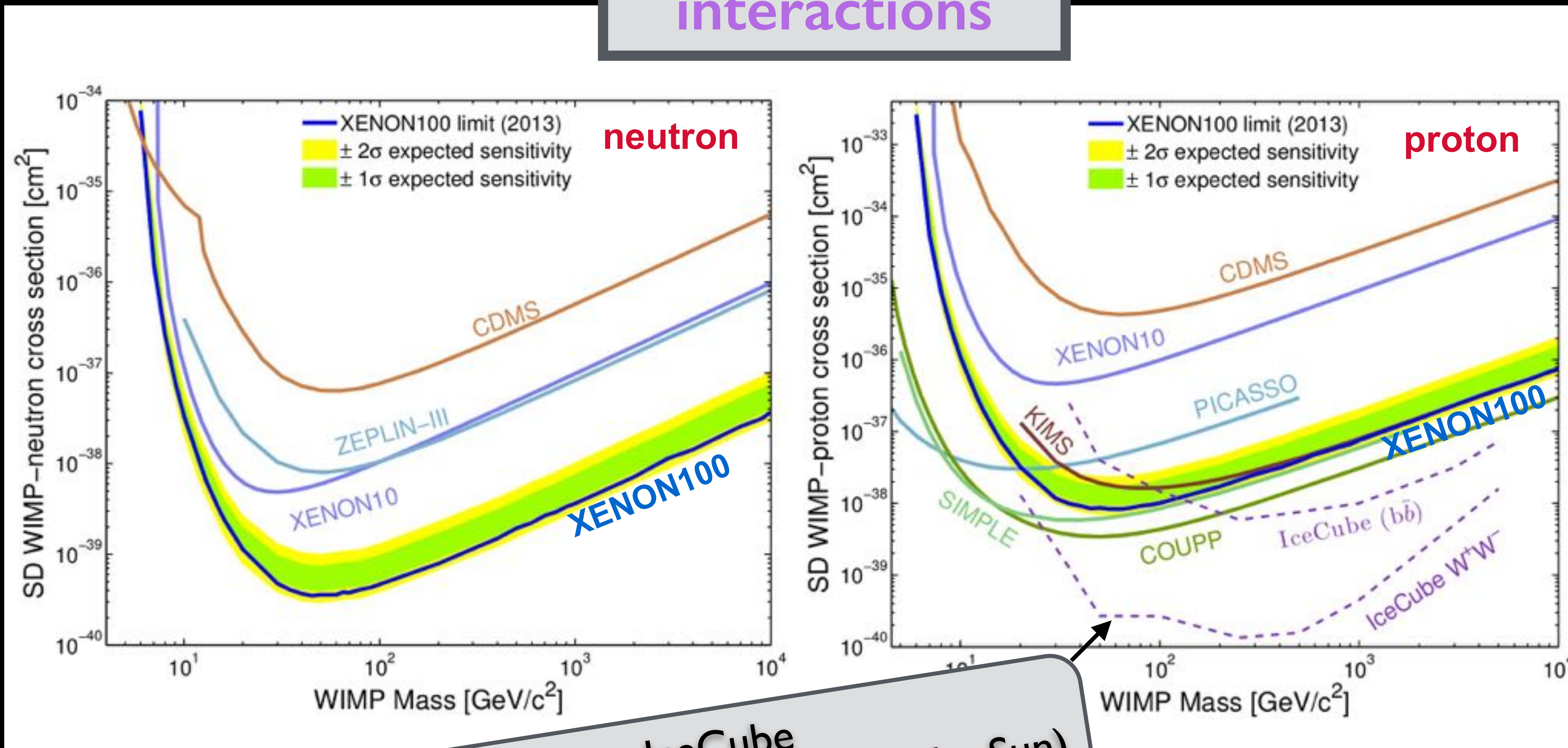
Direct WIMP searches (2015)



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

Direct WIMP searches (2015)

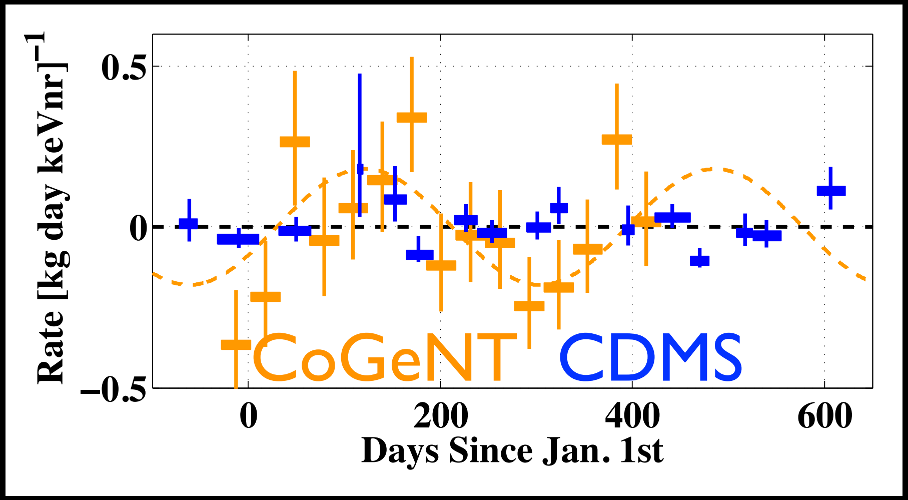
Spin-dependent interactions



Best limits are from IceCube
(indirect detection of high-energy neutrinos from the Sun)

(XENON100) 2013, Oberlack at IDM2014

Evidence for light dark matter particles?



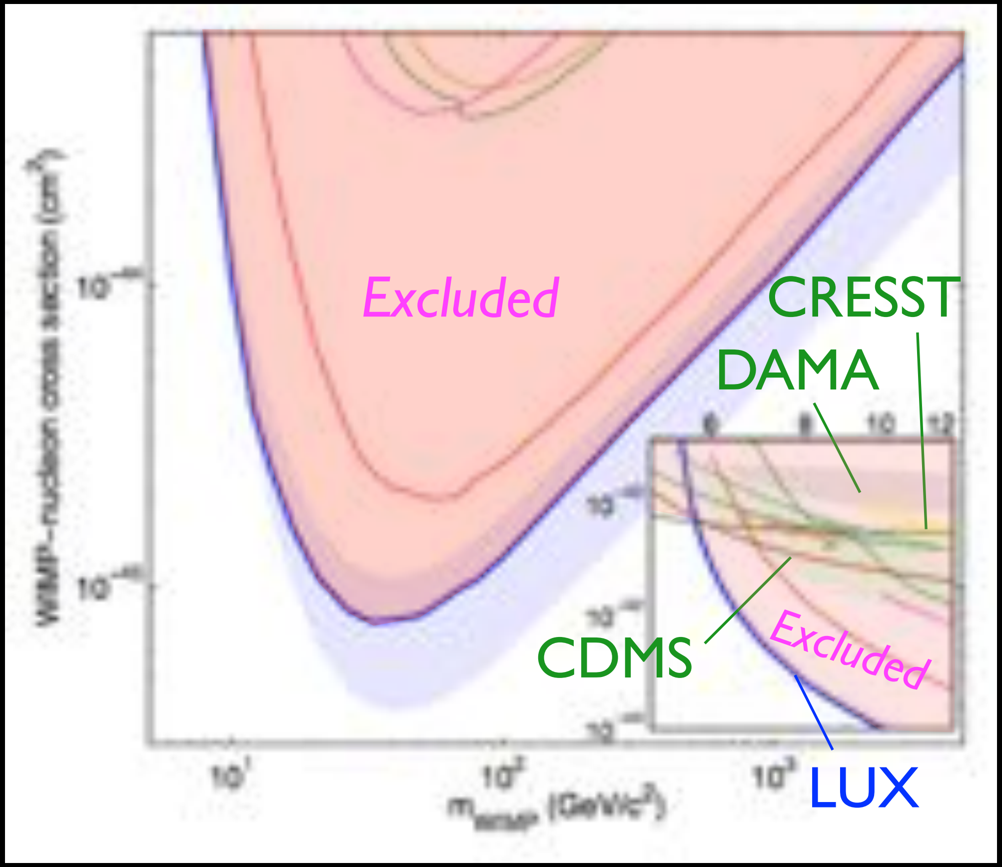
No significant modulation

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

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

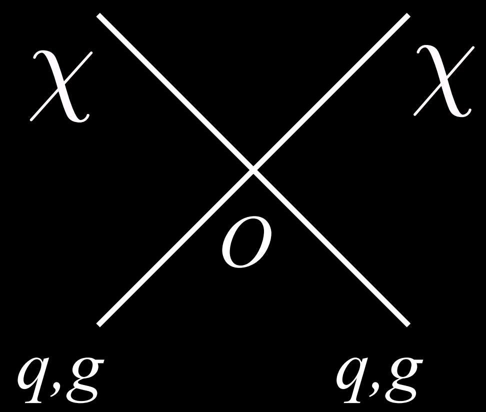
- Halo-independent methods of analysis have been developed
- Ideally they require no assumption on the astrophysical density and velocity distributions of dark matter particles

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

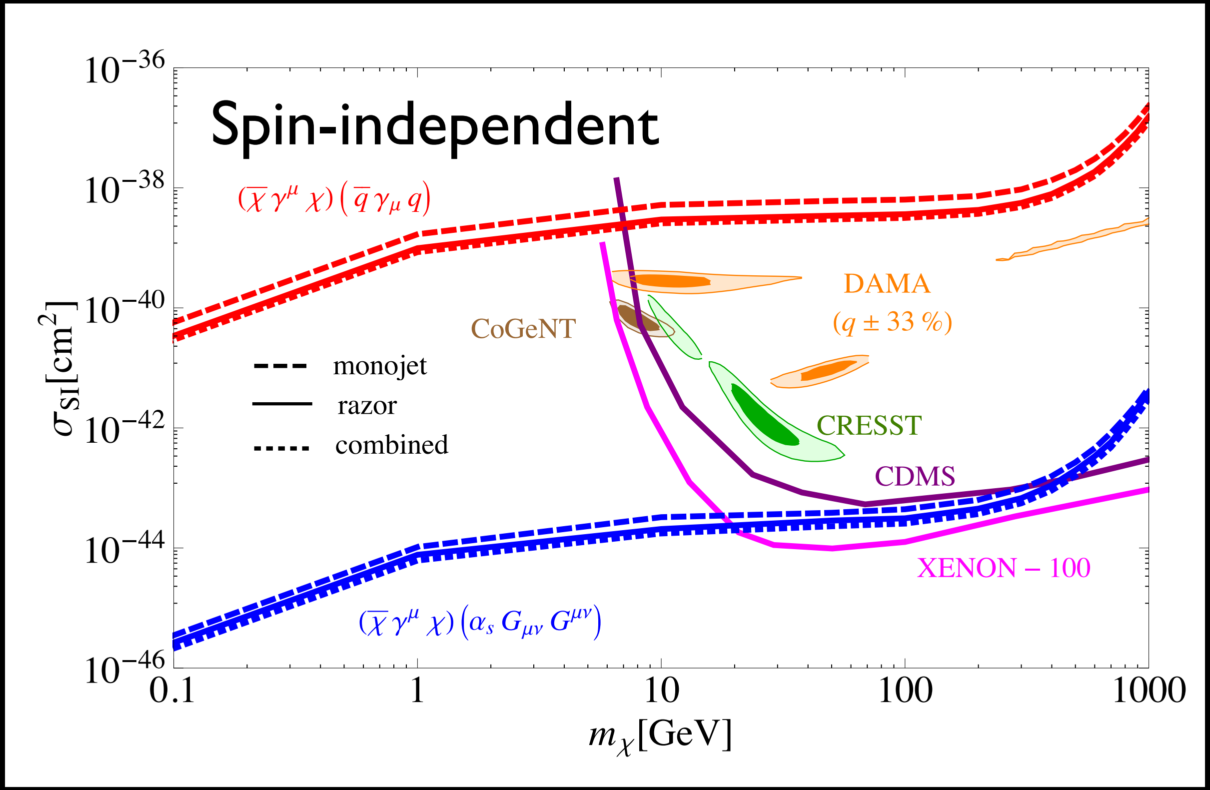
Table of effective operators relevant for the collider/direct detection connection

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......



These bounds do not apply to SUSY, etc.

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

Fox, Harnik, Primulando, Yu 2012

Effective operators: direct detection

All short-distance operators classified

Fitzpatrick et al 2012

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

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

All nuclear form factors classified

Response $\times \left[\frac{4\pi}{2J_i+1}\right]^{-1}$	Leading Multipole	Long-wavelength Limit	Response Type
$\sum_{J=0,2,\ldots}^{\infty} \lvert\langle J_i \lVert M_{JM} \rVert J_i\rangle\rvert^2$	$M_{00}(q\vec{x}_i)$	$\frac{1}{\sqrt{4\pi}}1(i)$	M_{JM} : Charge
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \lVert \Sigma''_{JM} \rVert J_i\rangle\rvert^2$	$\Sigma''_{1M}(q\vec{x}_i)$	$\frac{1}{2\sqrt{3\pi}}\sigma_{1M}(i)$	L^5_{JM} : Axial Longitudinal
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \lVert \Sigma'_{JM} \rVert J_i\rangle\rvert^2$	$\Sigma'_{1M}(q\vec{x}_i)$	$\frac{1}{\sqrt{6\pi}}\sigma_{1M}(i)$	T^{el5}_{JM} : Axial Transverse Electric
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N}\Delta_{JM} \rVert J_i\rangle\rvert^2$	$\frac{q}{m_N}\Delta_{1M}(q\vec{x}_i)$	$-\frac{q}{2m_N\sqrt{6\pi}}\ell_{1M}(i)$	T^{mag}_{JM} : Transverse Magnetic
$\sum_{J=0,2,\ldots}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N}\Phi''_{JM} \rVert J_i\rangle\rvert^2$	$\frac{q}{m_N}\Phi''_{00}(q\vec{x}_i)$	$-\frac{q}{3m_N\sqrt{4\pi}}\vec{\sigma}(i)\cdot\vec{\ell}(i)$	L_{JM} : Longitudinal
	$\frac{q}{m_N}\Phi''_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{30\pi}}[x_i\otimes(\vec{\sigma}(i)\times\frac{1}{i}\vec{\nabla})_1]_{2M}$	
$\sum_{J=2,4,\ldots}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N}\tilde{\Phi}'_{JM} \rVert J_i\rangle\rvert^2$	$\frac{q}{m_N}\tilde{\Phi}'_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{20\pi}}[x_i\otimes(\vec{\sigma}(i)\times\frac{1}{i}\vec{\nabla})_1]_{2M}$	T^{el}_{JM} : Transverse Electric

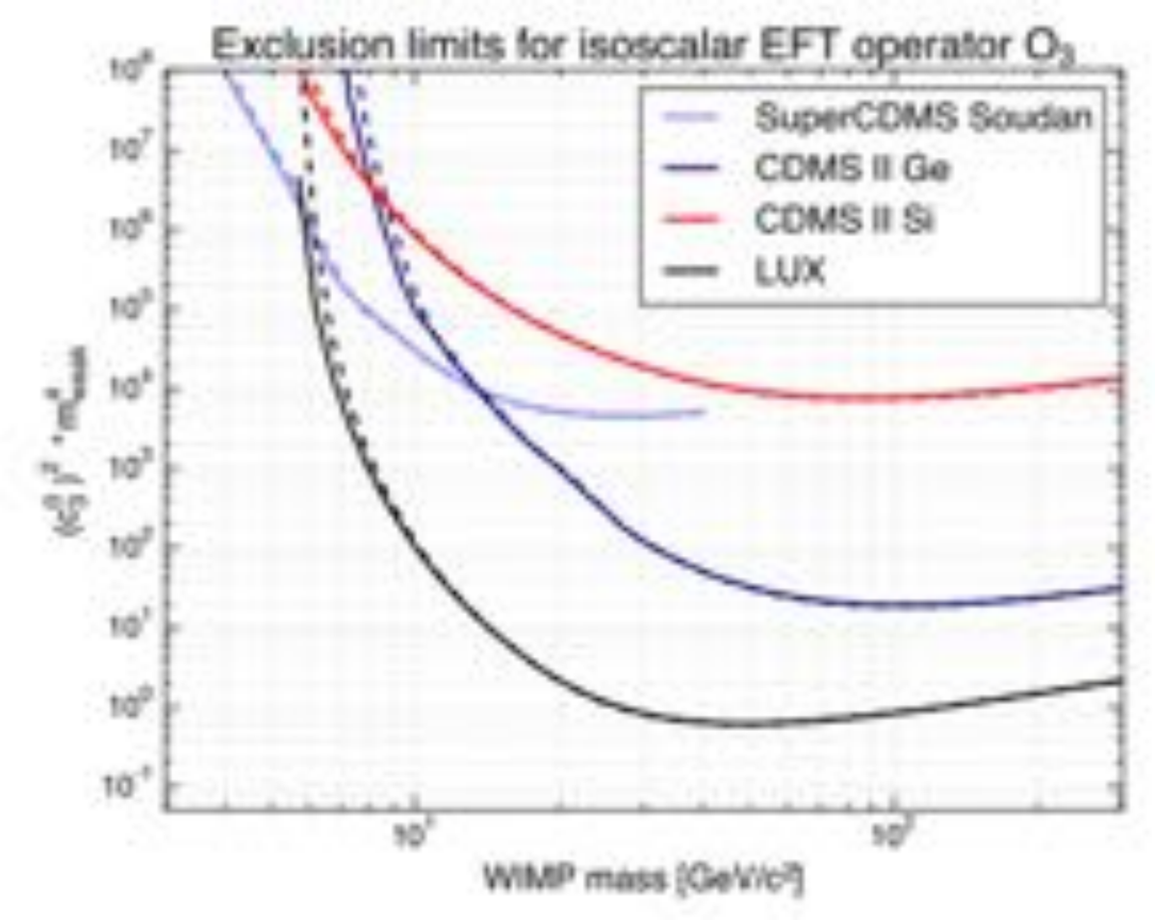
nuclear oscillator model

Fitzpatrick et al 2012

Effective operators: direct detection

Experimental limits on single operators…

Schneck et al (SuperCDMS) 2015



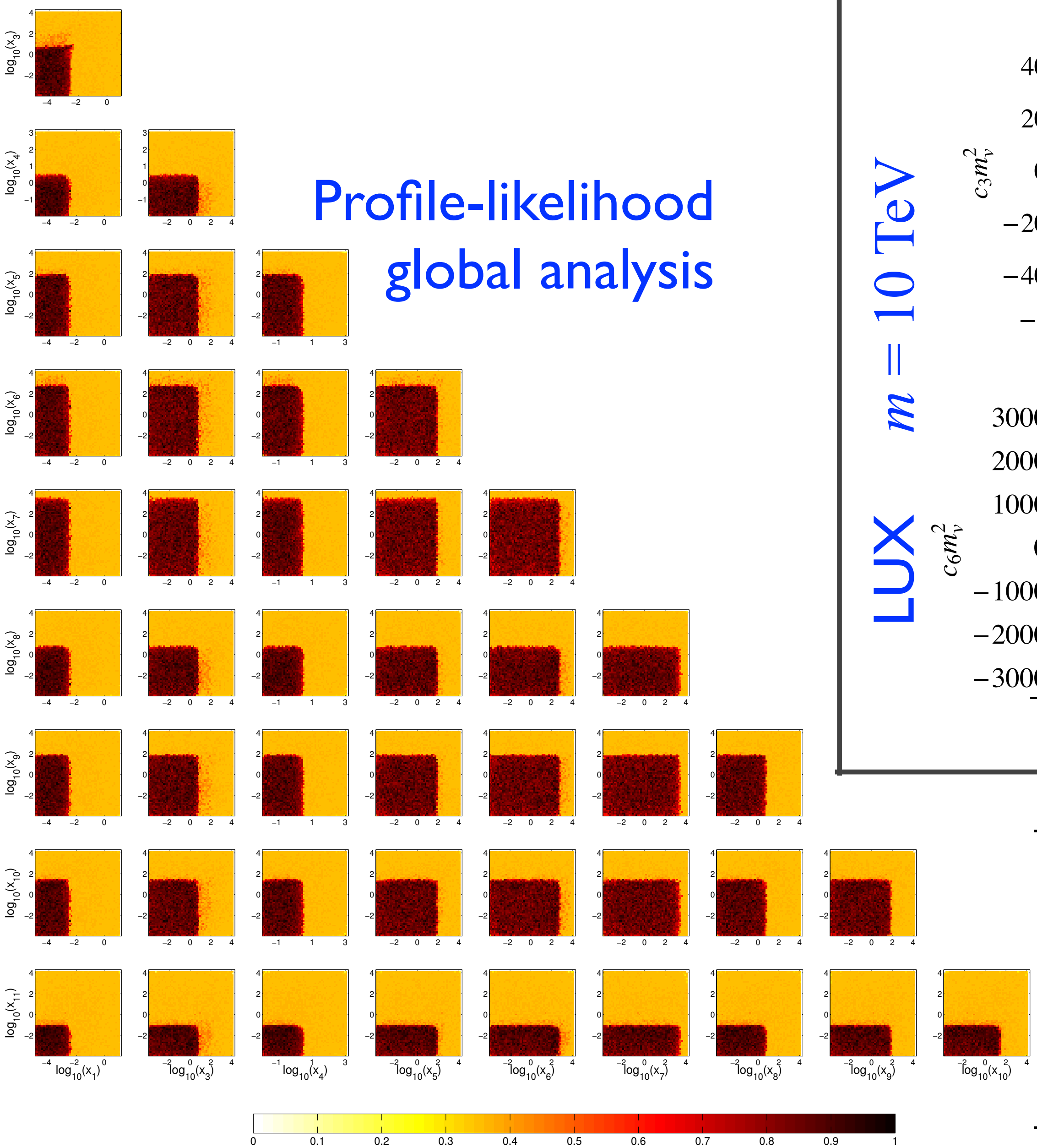
Operator coefficient	SuperCDMS Soudan
$(c_1^0)^2 * m_{weak}^4$	8.98×10^{-3} (—)
$(c_3^0)^2 * m_{weak}^4$	3.14×10^{4} (—)
$(c_4^0)^2 * m_{weak}^4$	8.77×10^{3} (—)
$(c_5^0)^2 * m_{weak}^4$	6.34×10^{5} (—)
$(c_6^0)^2 * m_{weak}^4$	4.54×10^{8} (—)
$(c_7^0)^2 * m_{weak}^4$	8.44×10^{7} (—)
$(c_8^0)^2 * m_{weak}^4$	4.30×10^{2} (—)
$(c_9^0)^2 * m_{weak}^4$	1.95×10^{3} (—)
$(c_{10}^0)^2 * m_{weak}^4$	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} (—)

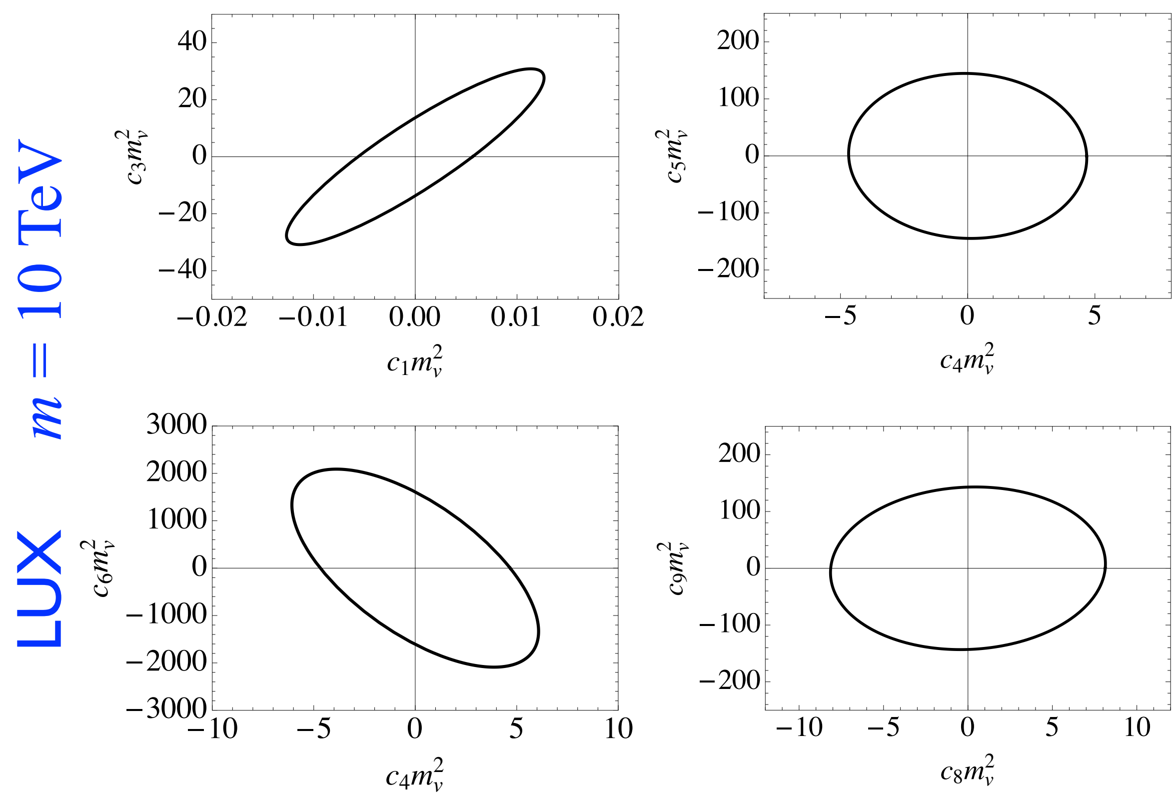
Effective operators: direct detection

Combined analysis of short-distance operators

Catena, Gondolo 2014

Profile-likelihood global analysis



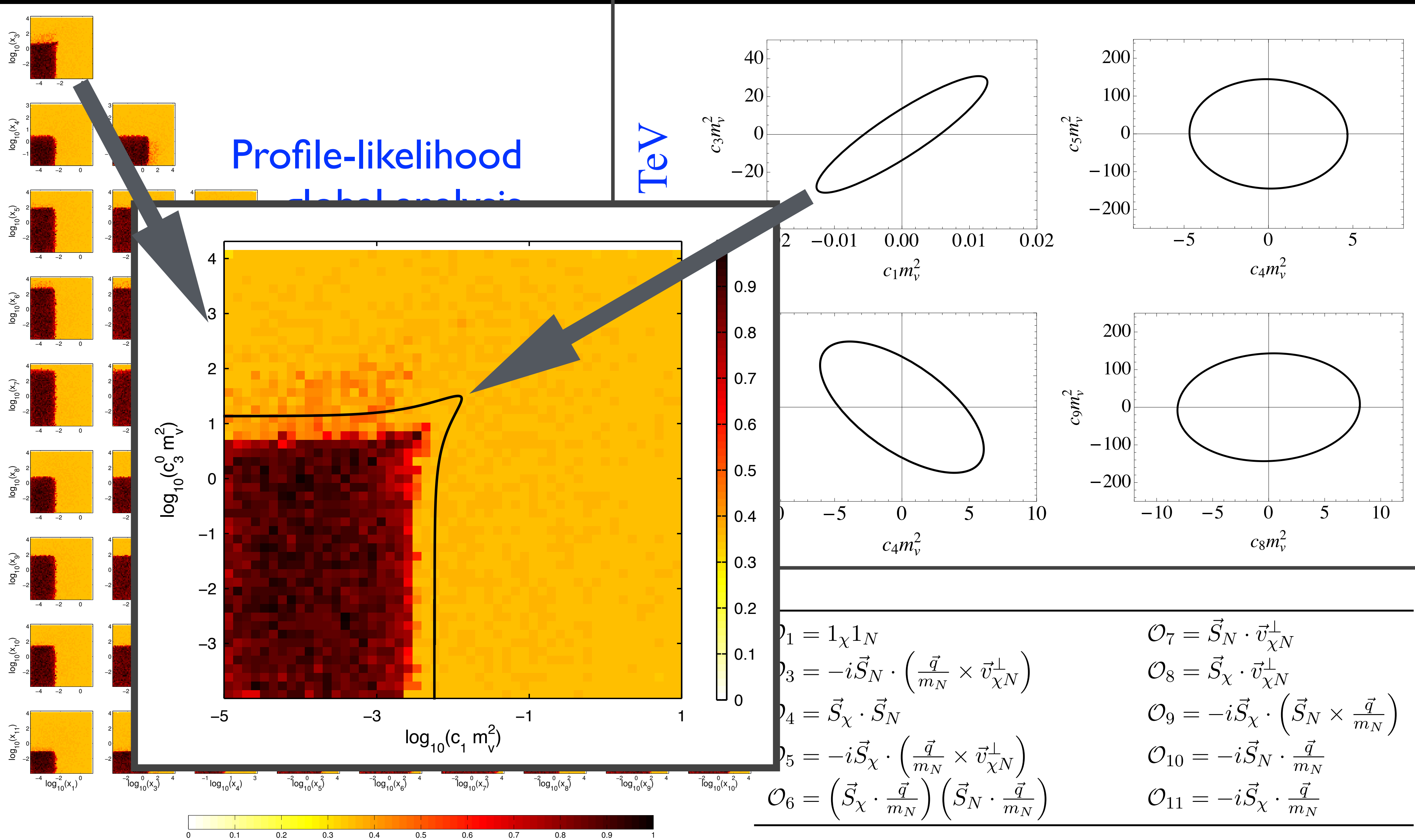


$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = -i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = -i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$$
$$\mathcal{O}_6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

Effective operators: direct detection

Combined analysis of short-distance operators

Catena, Gondolo 2014

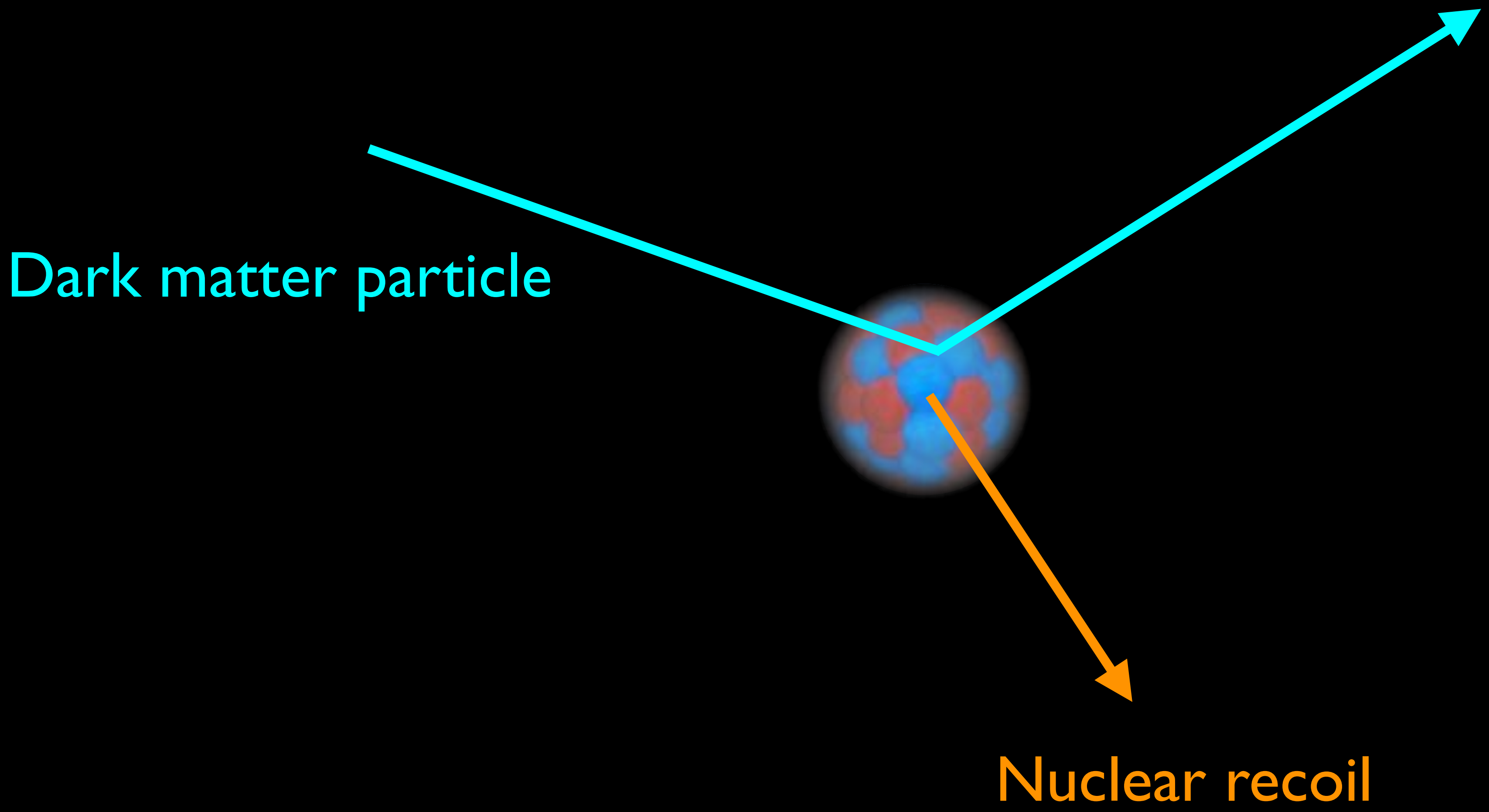


All astrophysics models

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

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

What force couples dark matter to nuclei?

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

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

WIMP speed

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

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

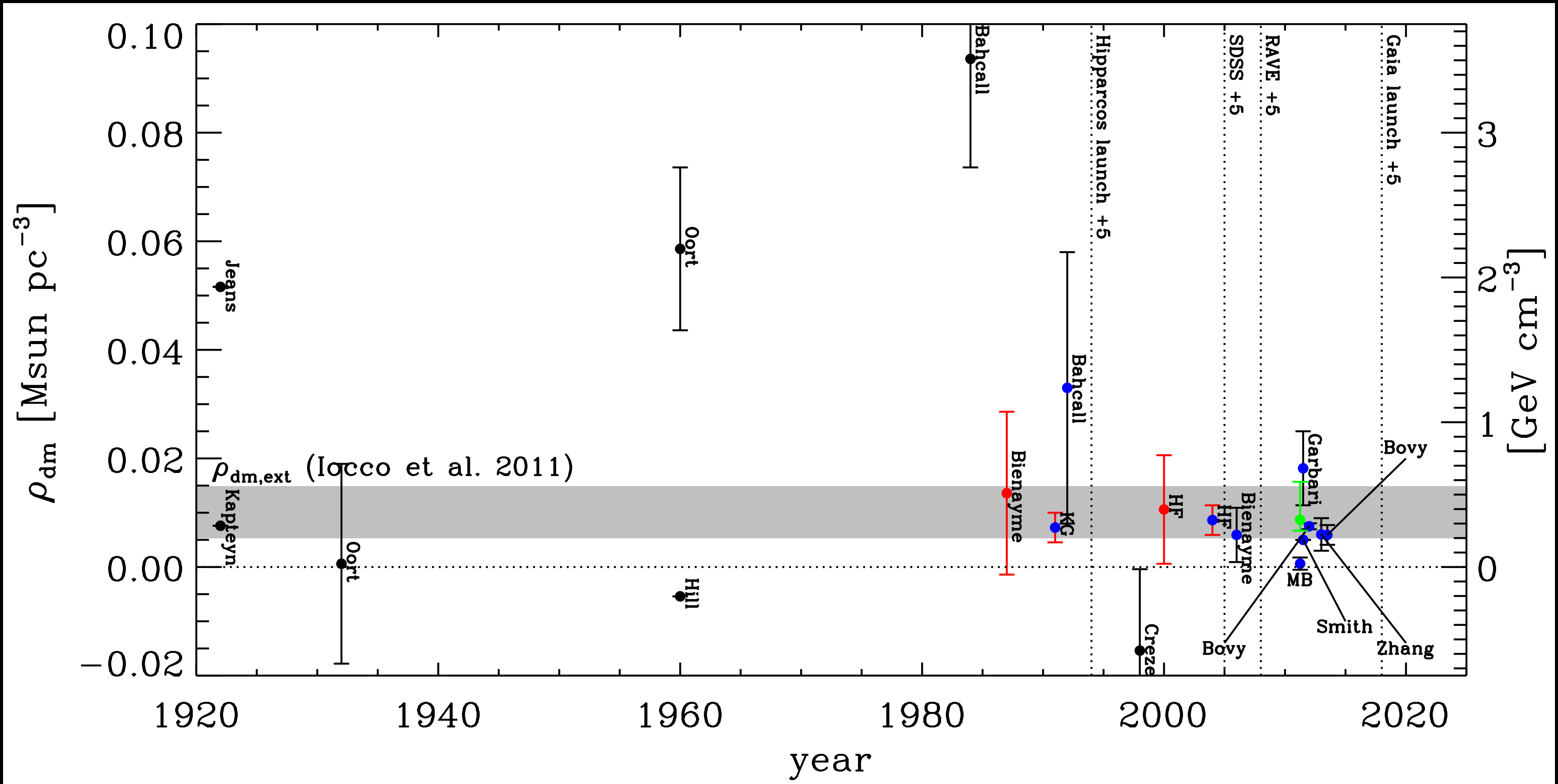
truncated Maxwellian

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

The spherical cow of direct WIMP searches

Astrophysics model: local density

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



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

[volume complete; G12*;R14]

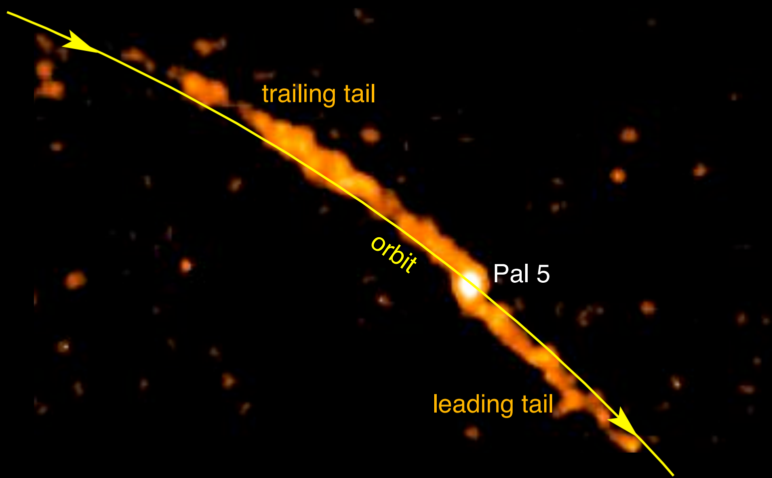
$$\rho_{\rm dm} = 0.25 \pm 0.09\,{\rm GeV\,cm^{-3}}$$

[SDSS; Z13]

Read at IDM 2014

Astrophysics model: velocity distribution

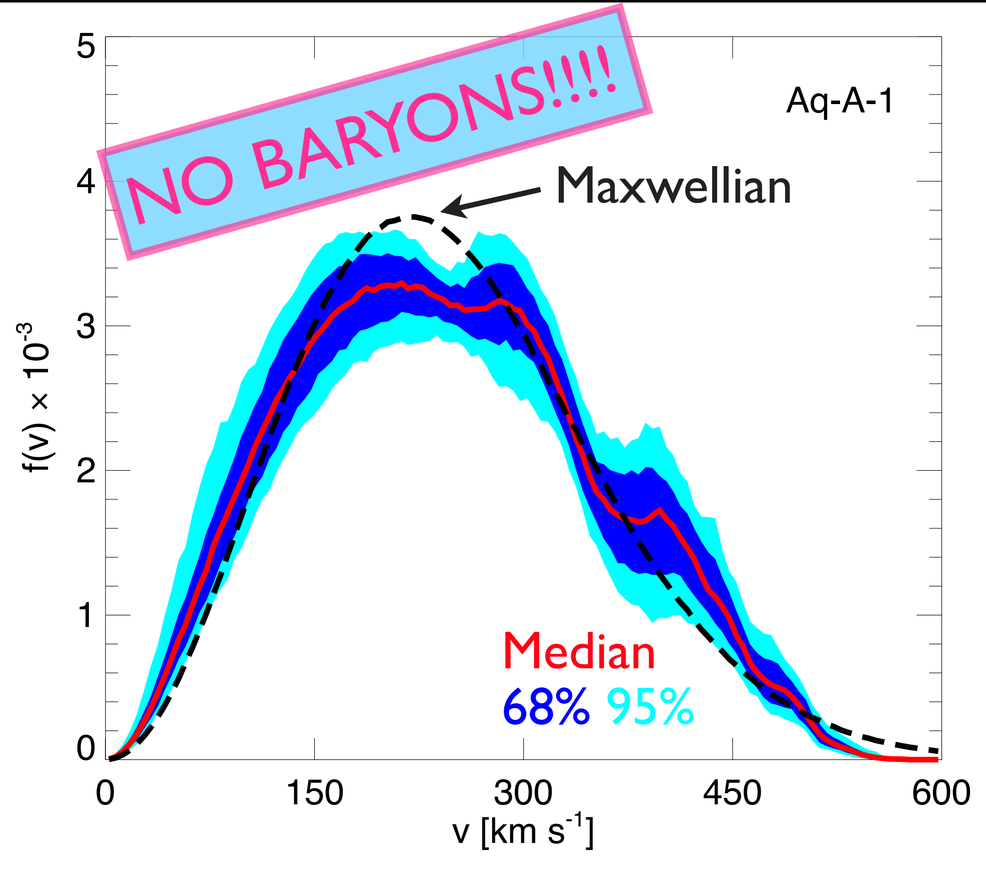
We know very little about the dark matter velocity distribution near the Sun



Odenkirchen et al 2002 (SDSS)

Streams of stars have been observed in the galactic halo

SDSS, 2MASS, SEGUE,…….



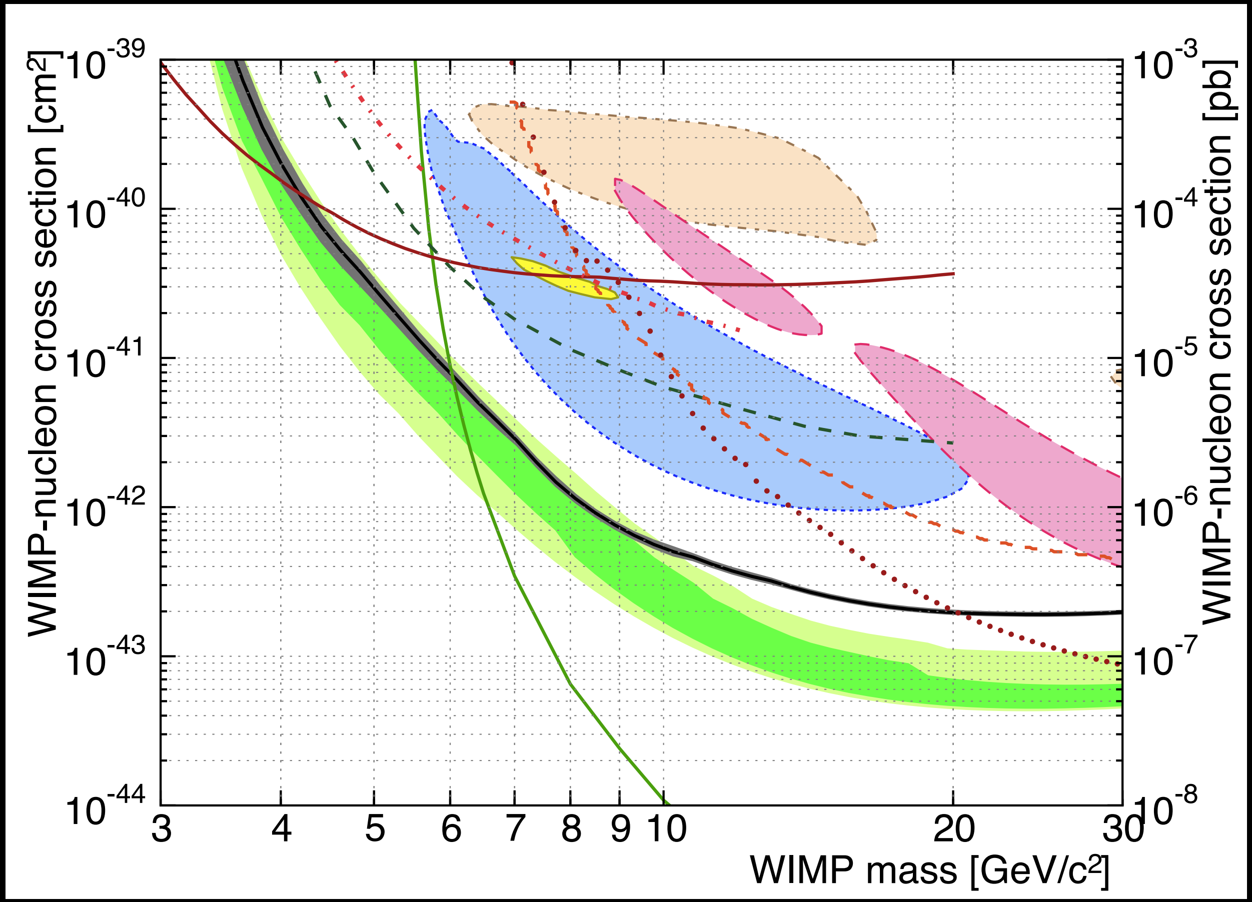
Vogelsberger et al 2009

Cosmological N-Body simulations including baryons are challenging but underway

Astrophysics model: velocity distribution

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

FIXED FIXED



Agnese et al (SuperCDMS) 2014

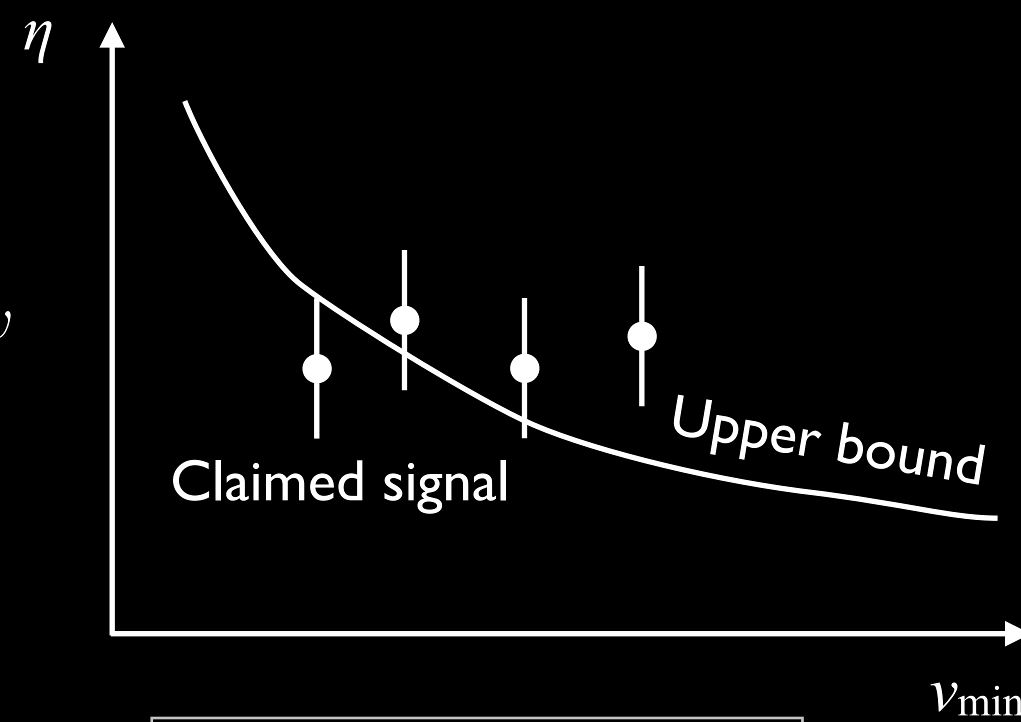
Astrophysics-independent approach

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

FIXED ARBITRARY

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

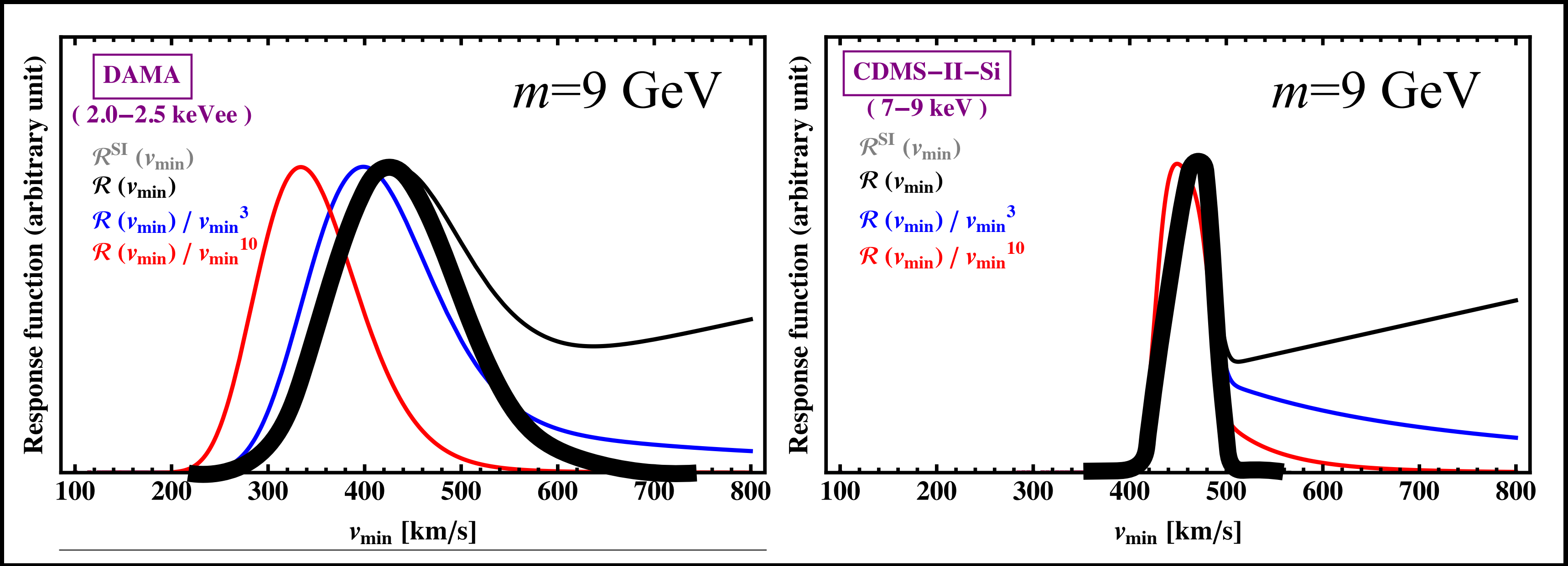
Gondolo Gelmini 2012

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

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

Measured rate — R; *Response function* — $\mathcal{R}(v)$; *Rescaled astrophysics factor* — $\tilde{\eta}(v)$

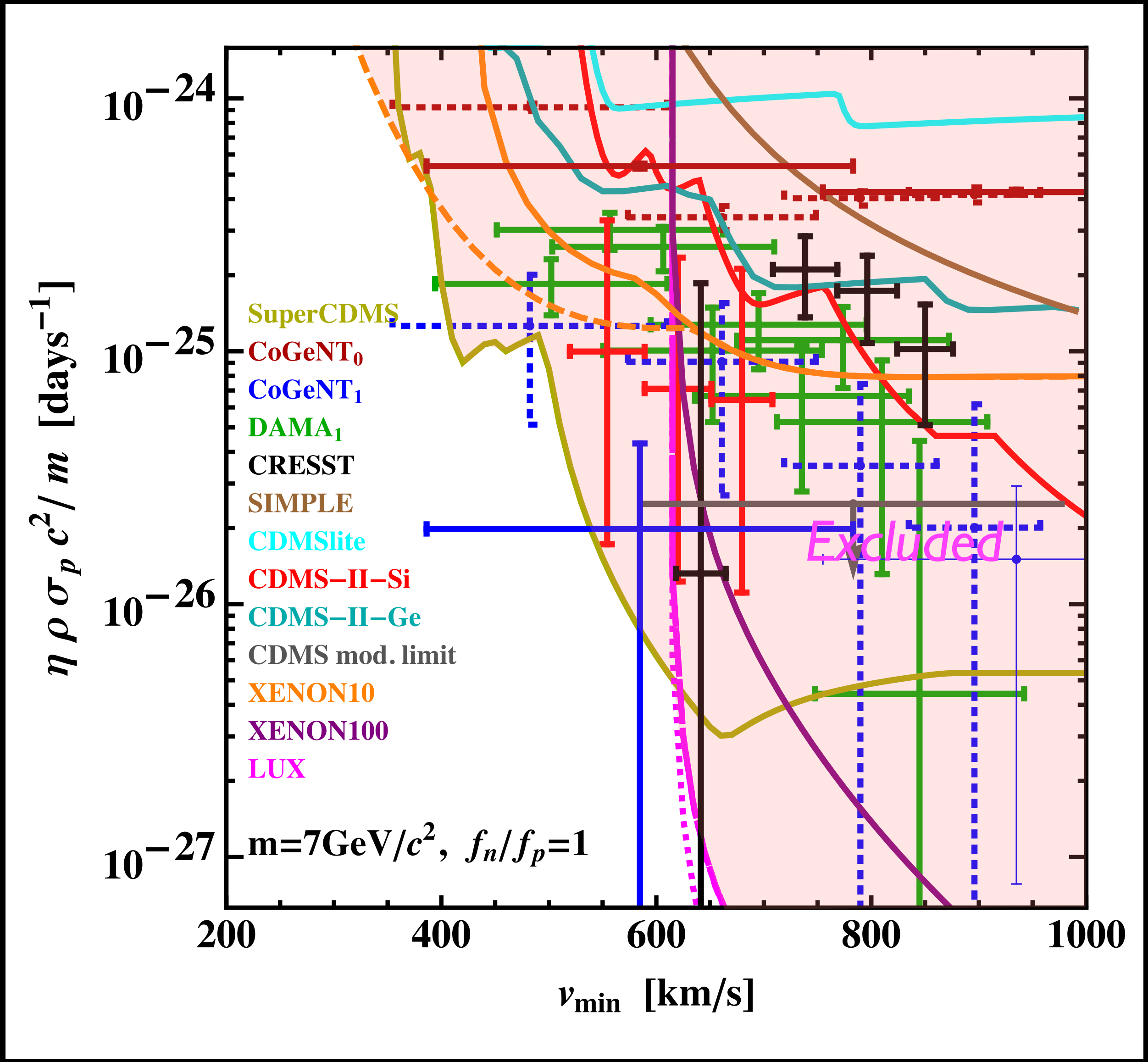
- Every experiment is sensitive to a "window in velocity space."



Spin-independent isoscalar interactions

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

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

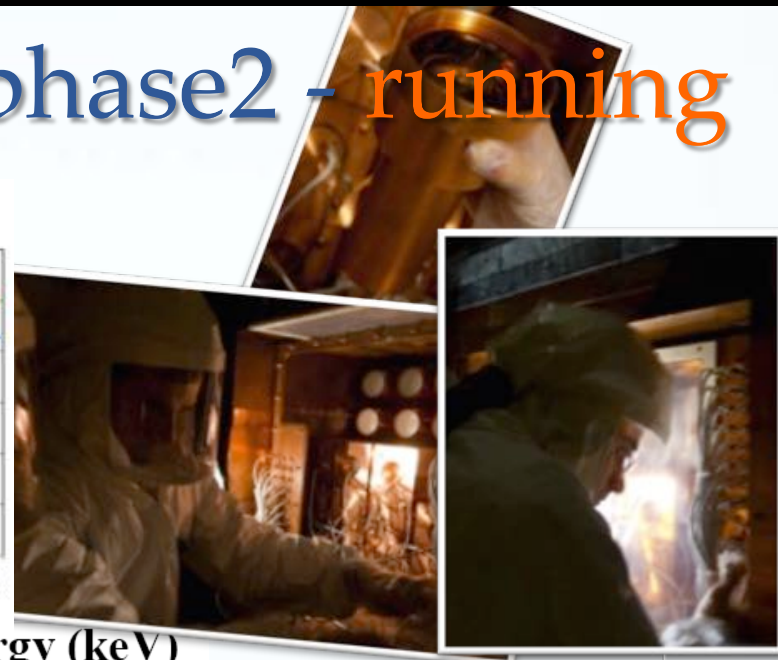
Still depends on particle model

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.

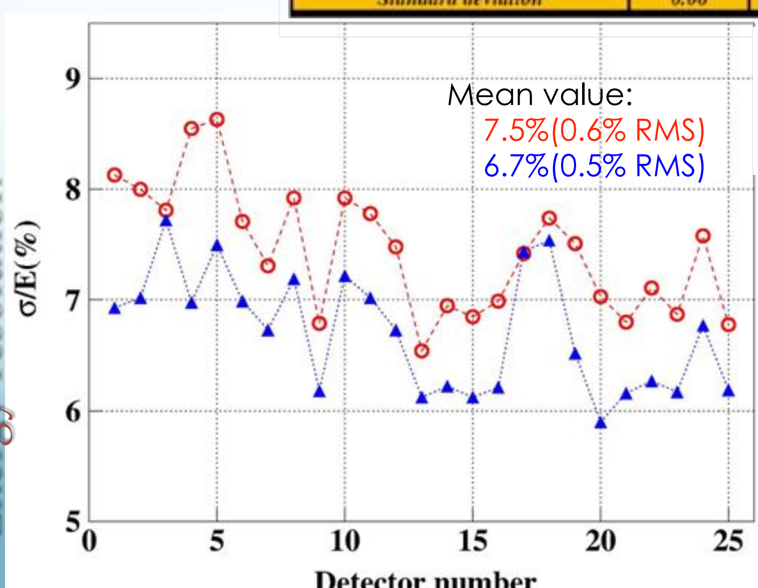
Residual Contamination

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



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

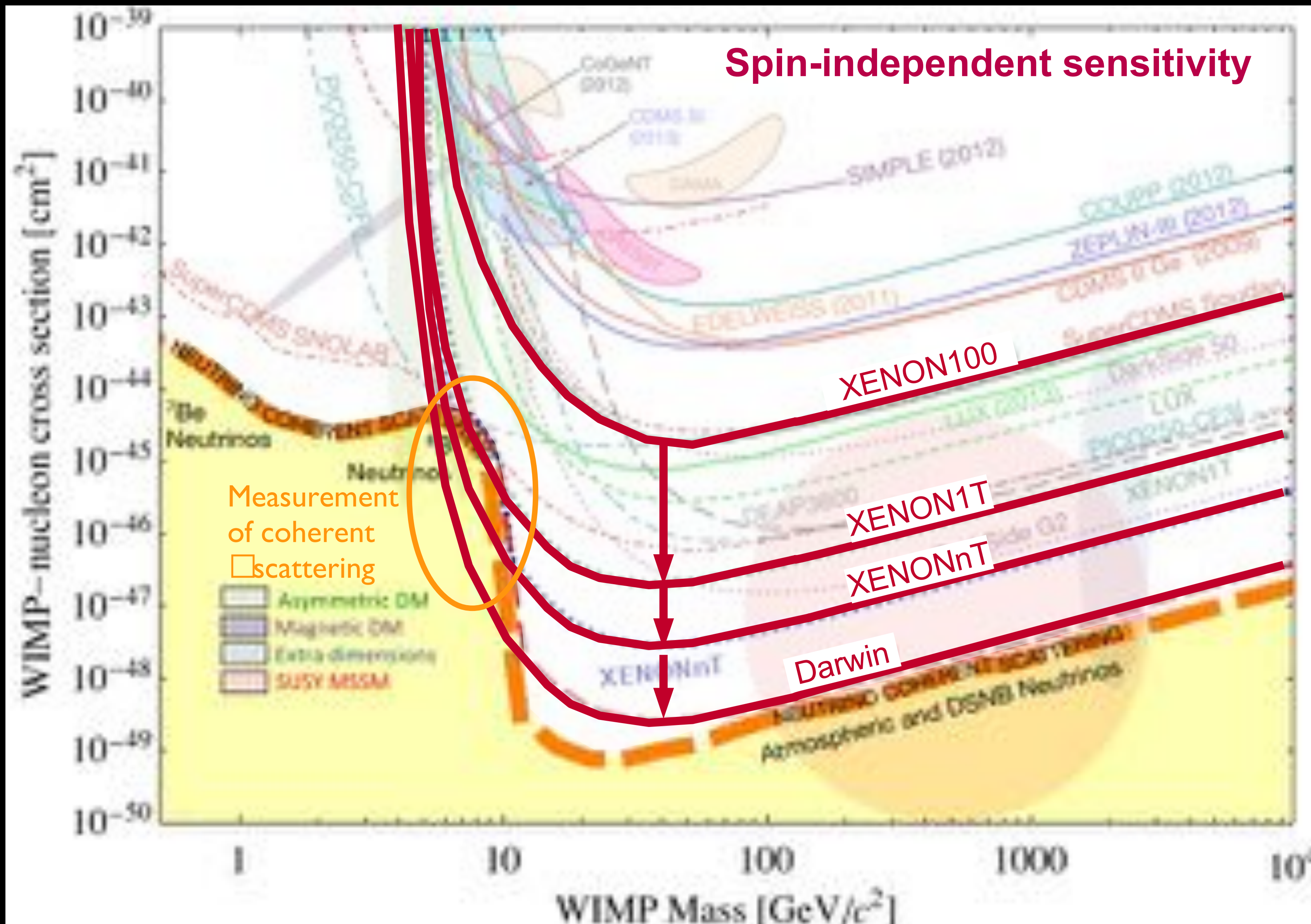
Previous PMTs:	5.5-7.5 ph.e./keV
New PMTs:	up to 10 ph.e./keV

- 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..... Giant detectors

SuperCDMS, XENON1T, XENONnT, Darwin, ...

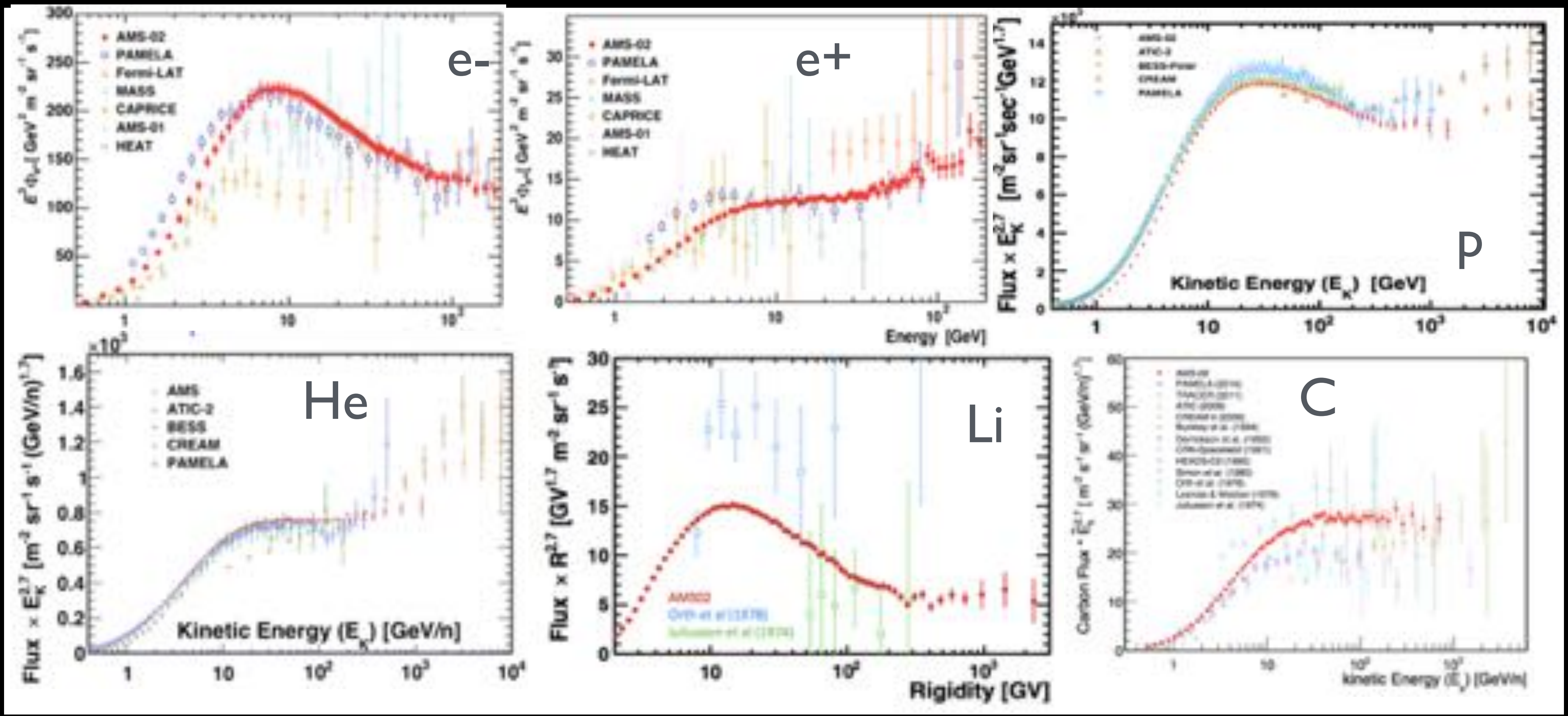


Oberlack, IDM2014

In the next episodes….. Precision cosmic rays

AMS (Alpha Magnetic Spectrometer)

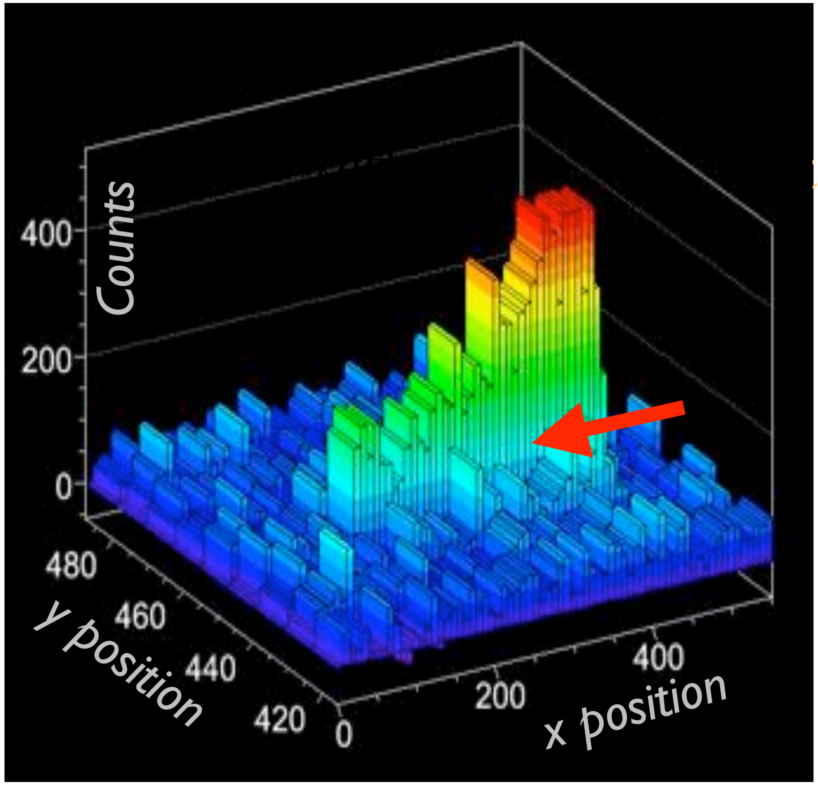
AMS-02 can measure isotopic ratios to ~1% precision up to Fe and ~100 GeV/nucleon, and much better at lower energies.



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

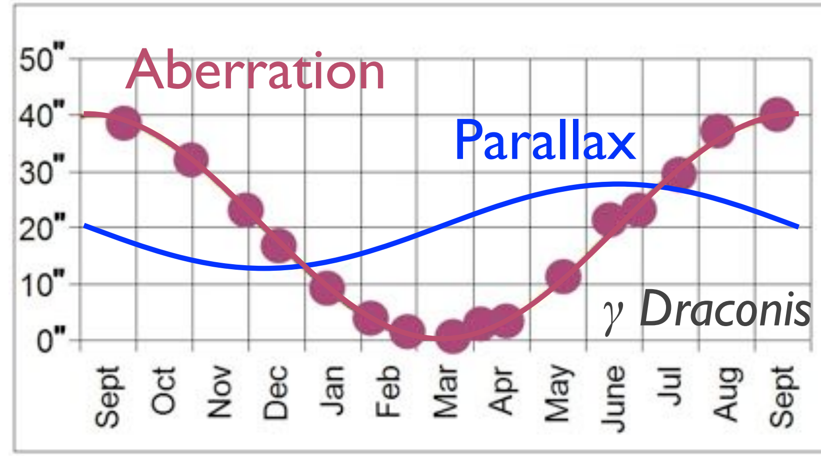
Only ~10 events needed to confirm extraterrestrial signal

In the next episodes..... WIMP astronomy

Aberration of WIMPs

Photon arrival direction

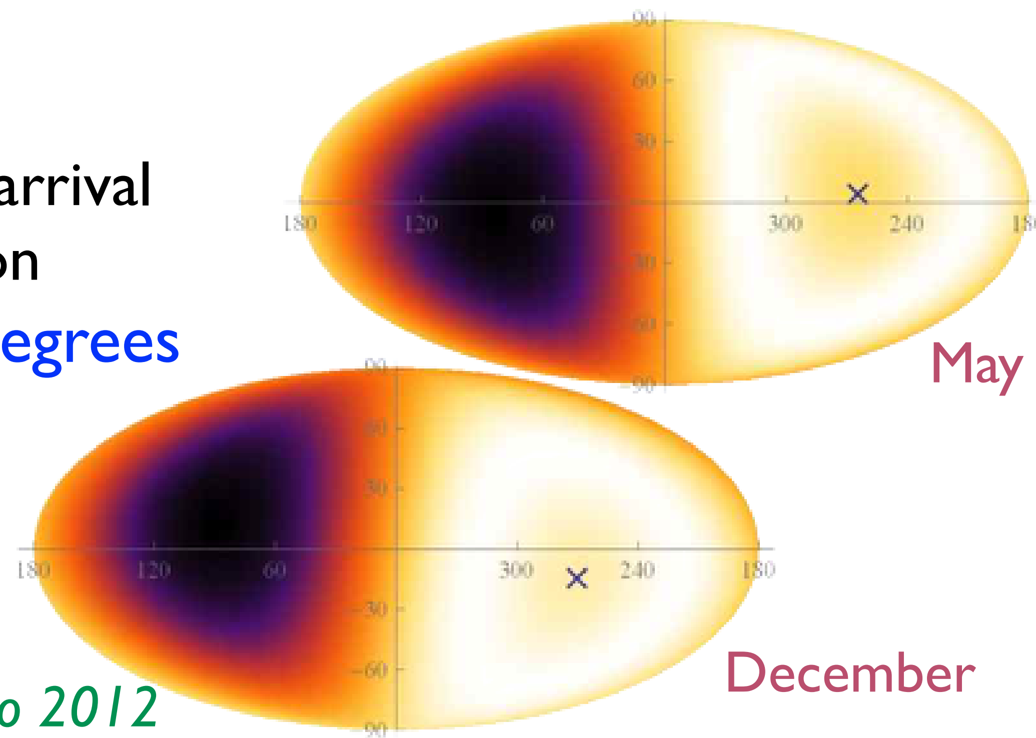
20 arcsec



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.*