Trends in Dark Matter Physics

Paolo Gondolo
University of Utah

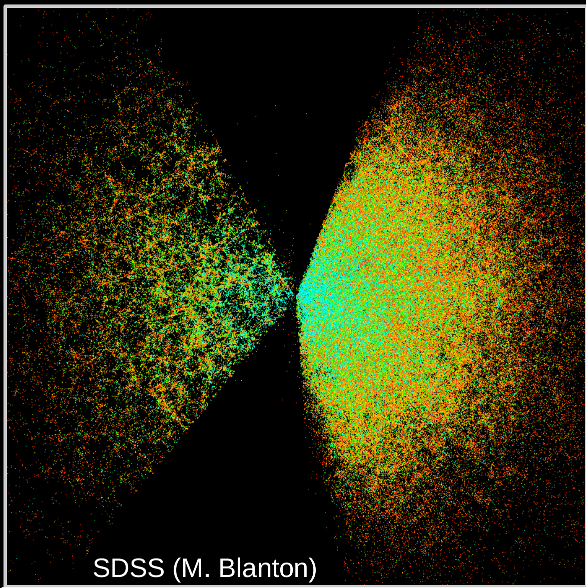
Trends in dark matter physics

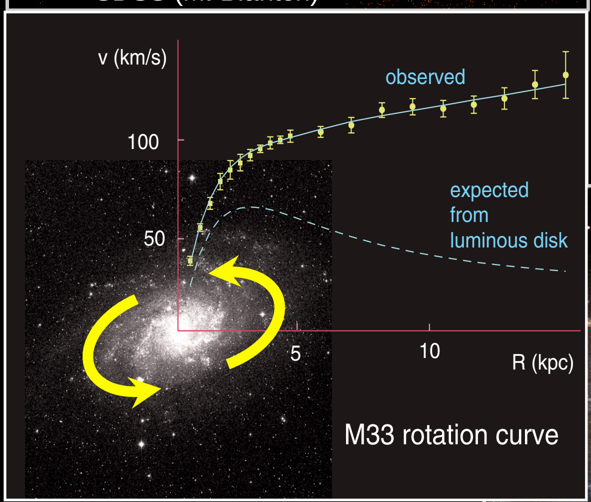
- Fifty shades of dark
- The forbidden fruit
- Confusion of the mind
- That which does not kill us makes us stronger

Fifty shades of dark

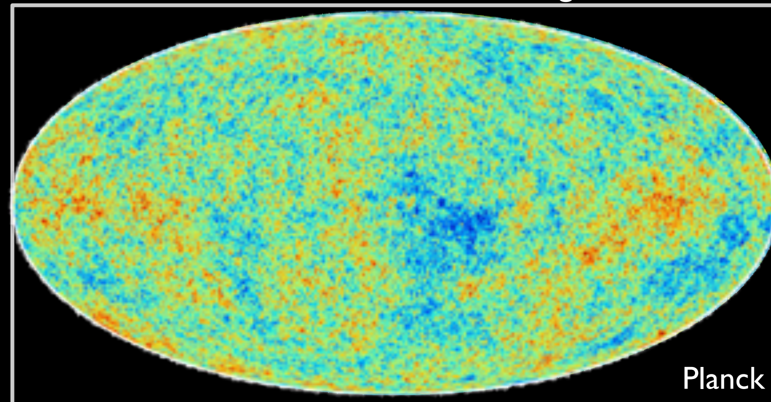
Evidence for cold dark matter

Large Scale Structure



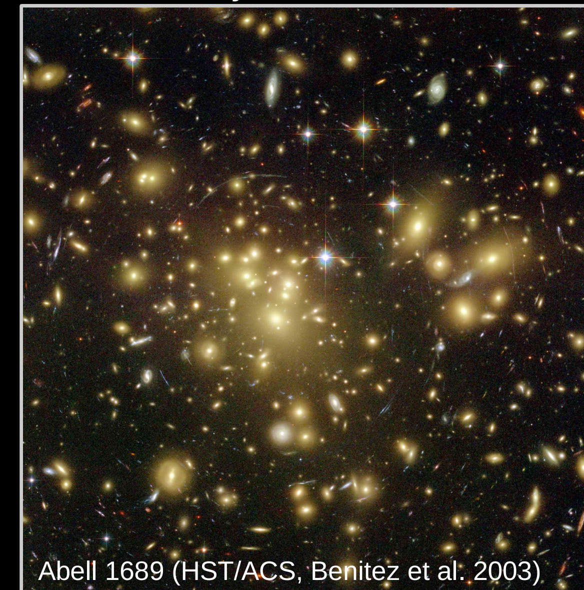


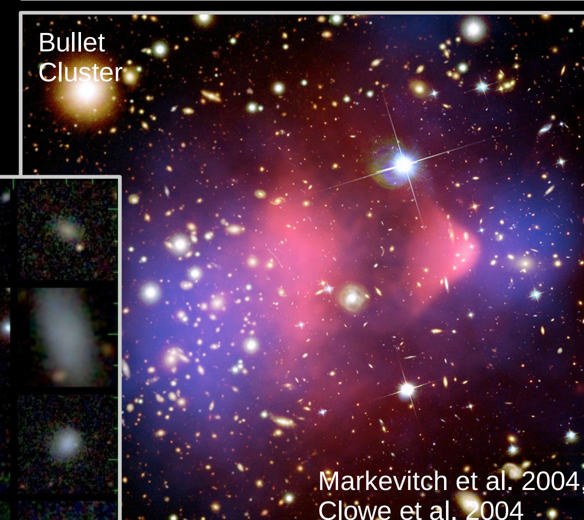
Cosmic Microwave Background



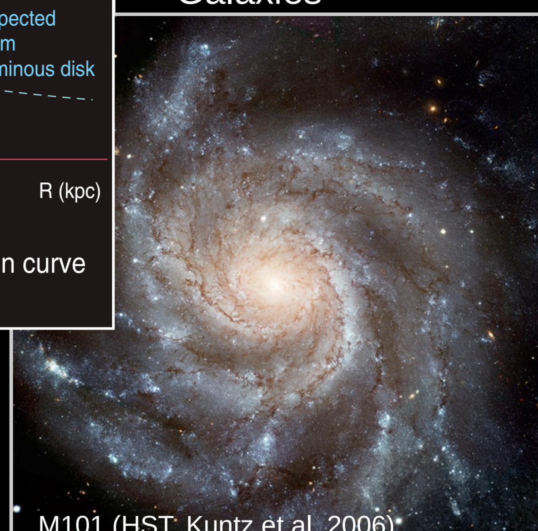
Supernovae

Galaxy Clusters

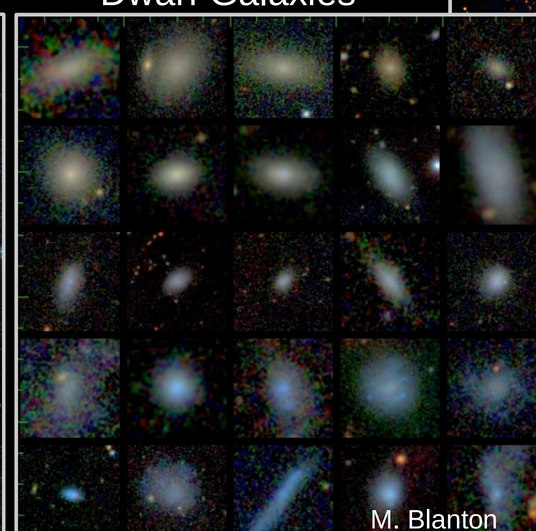




Galaxies

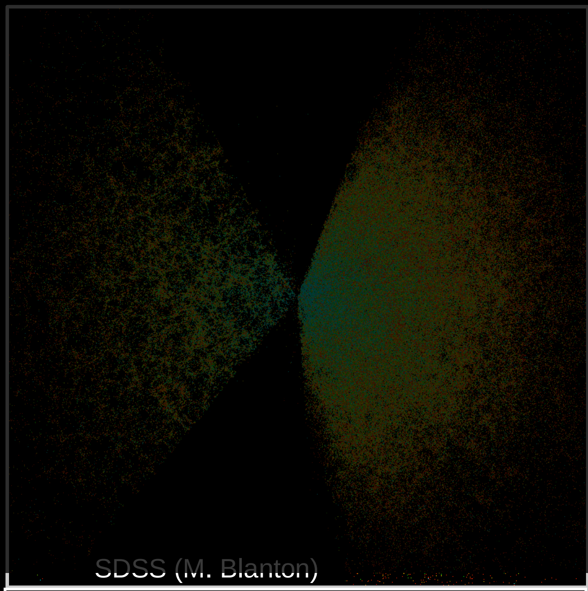


Dwarf Galaxies

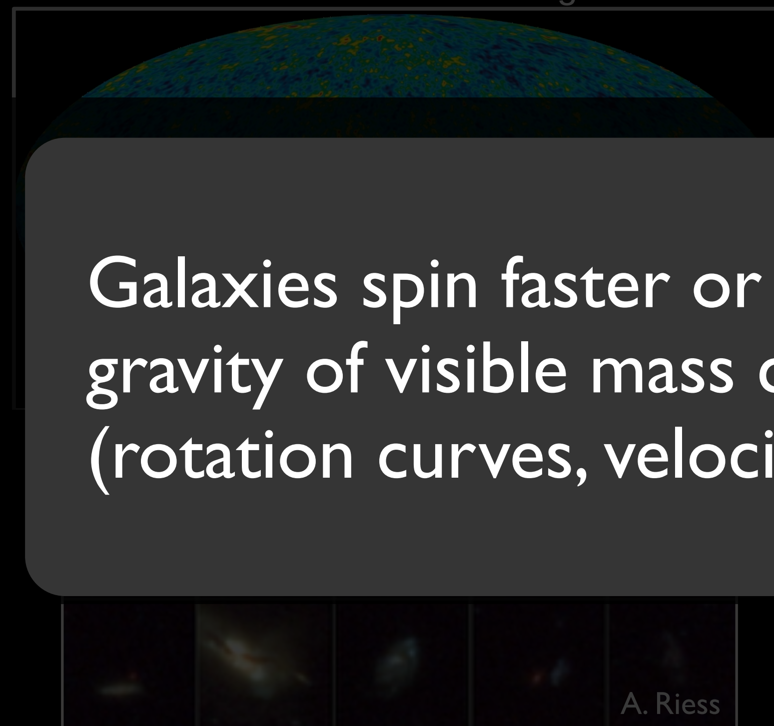


Evidence for cold dark matter

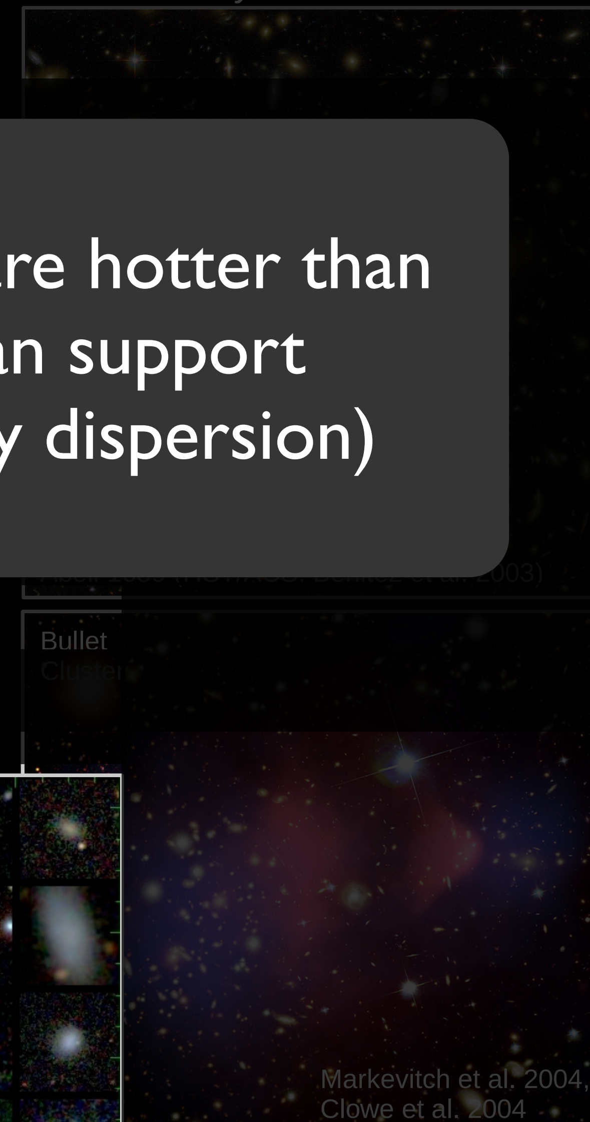
Large Scale Structure



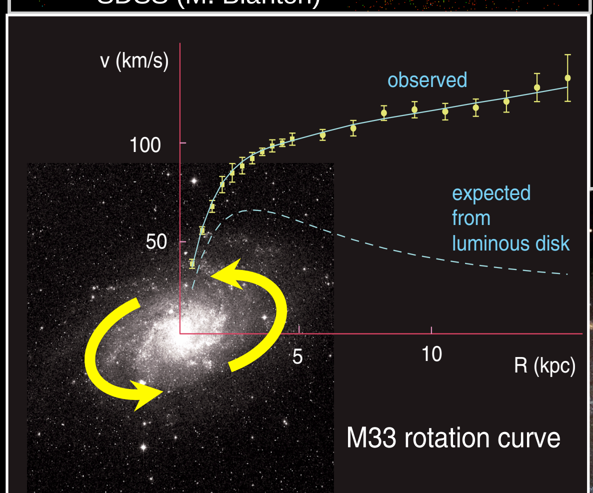
Cosmic Microwave Background



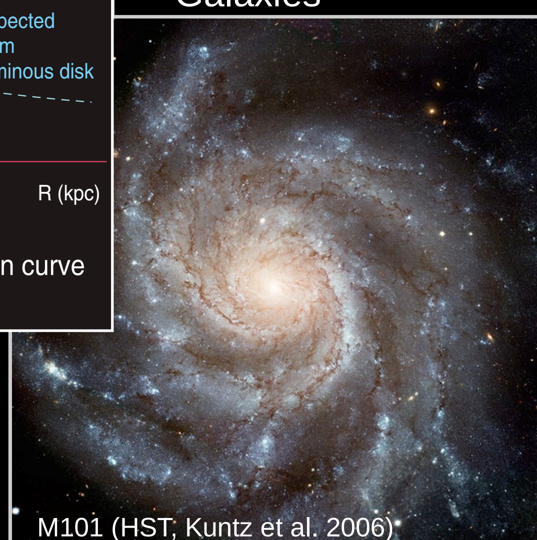
Galaxy Clusters



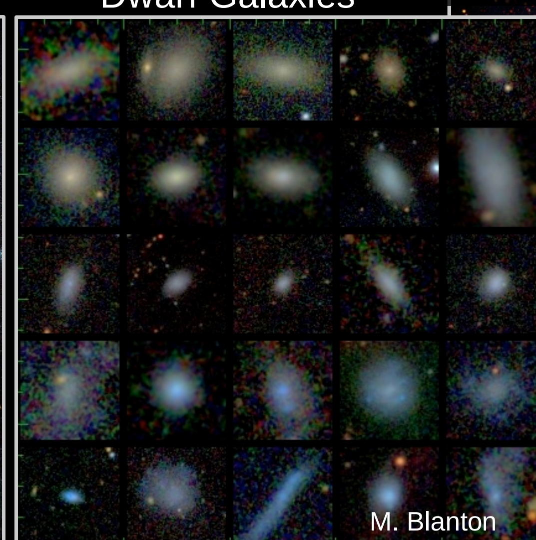
Galaxies spin faster or are hotter than gravity of visible mass can support (rotation curves, velocity dispersion)



Galaxies

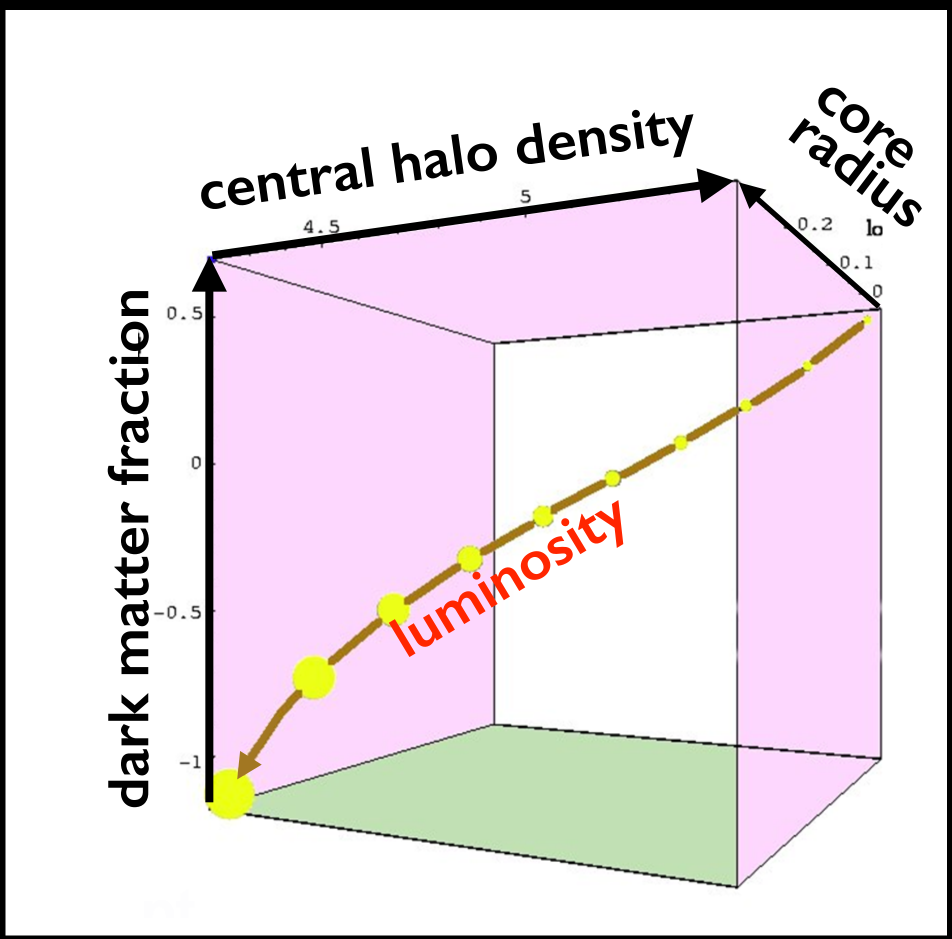


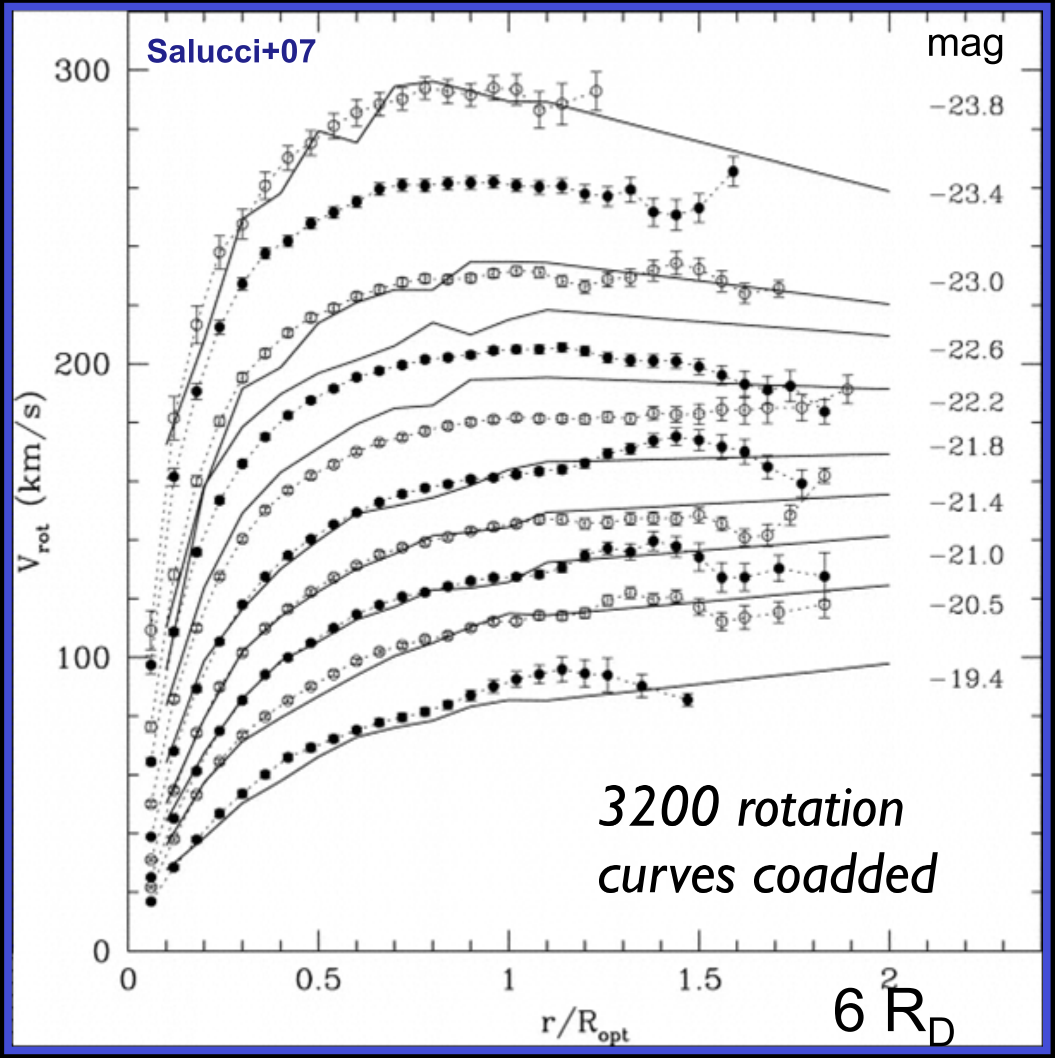
Dwarf Galaxies



Evidence for cold dark matter

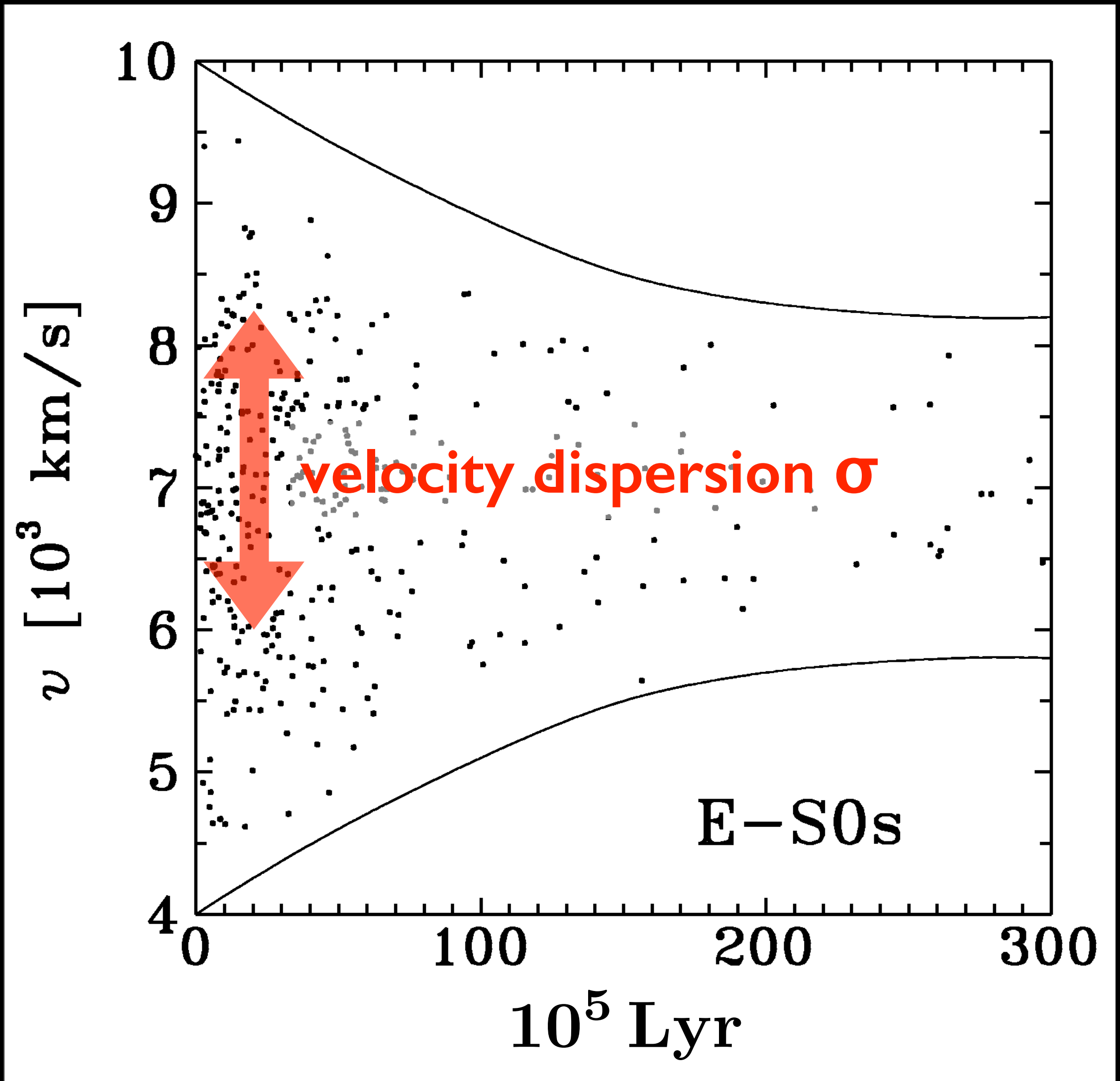
Empirical correlations found from thousands of spiral galaxy rotation curves





Salucci et al 2007

Evidence for cold dark matter



Lokas, Mamon 2003

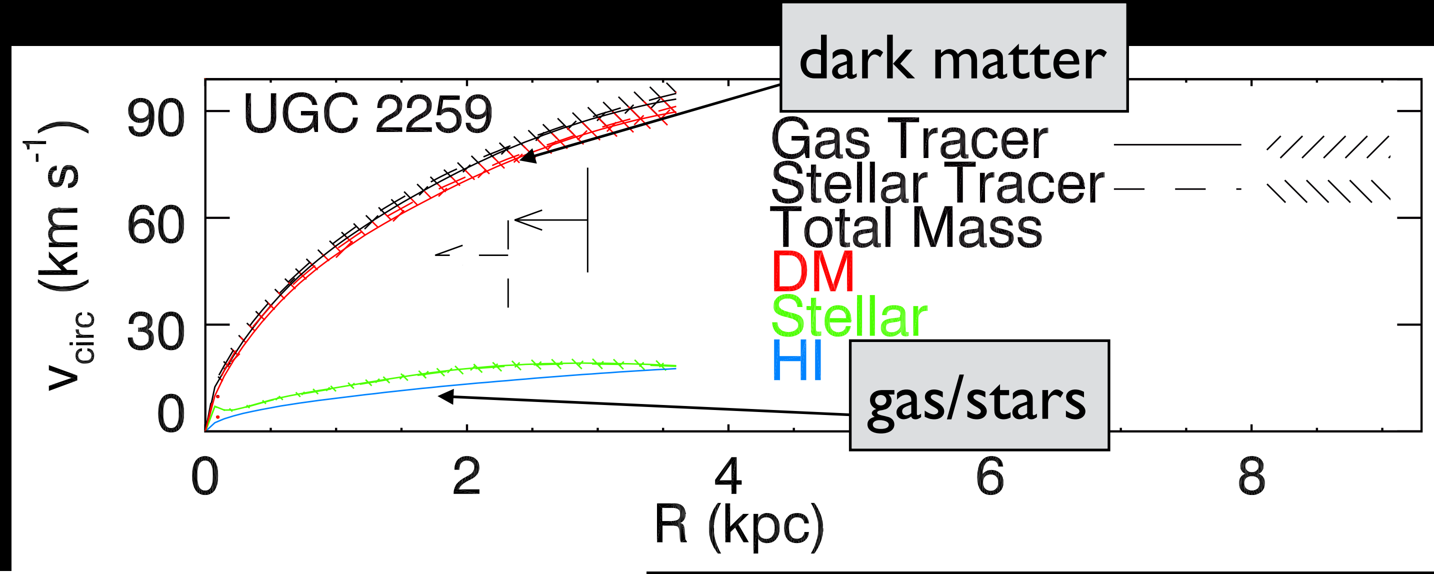
Velocity dispersion measurements reveal dark matter in elliptical galaxies

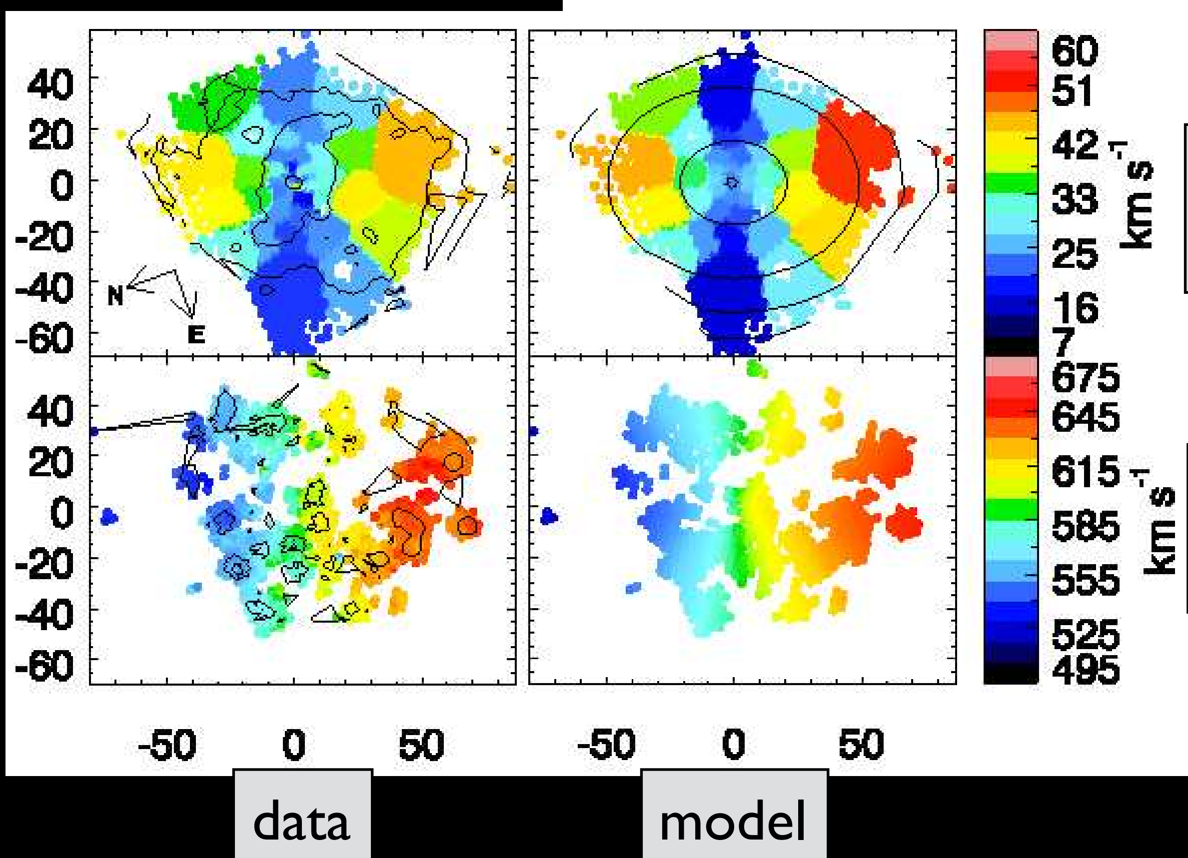
$$\sigma^2 \propto \frac{GM}{r}$$

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

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)

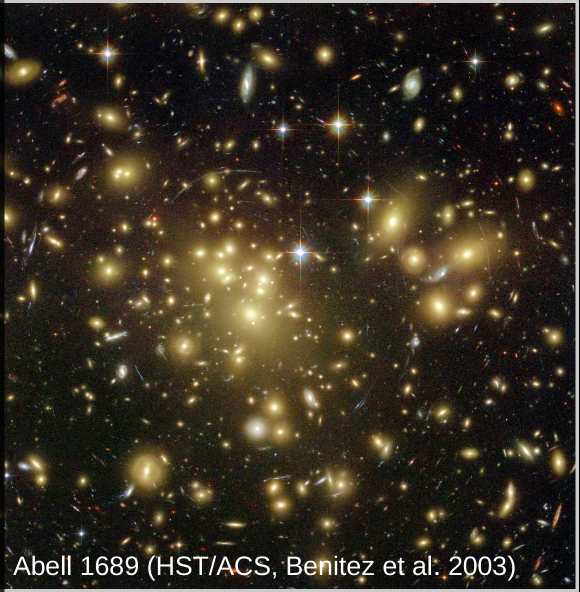
A. Riess

Dwarf Galaxies

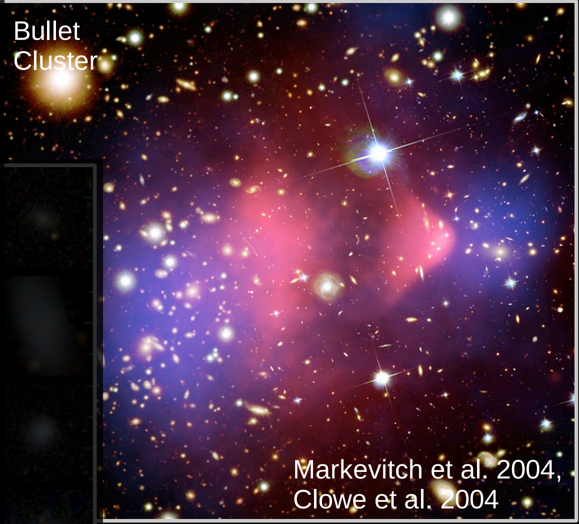
M101 (HST, Kuntz et al. 2006)

M. Blanton

Galaxy Clusters



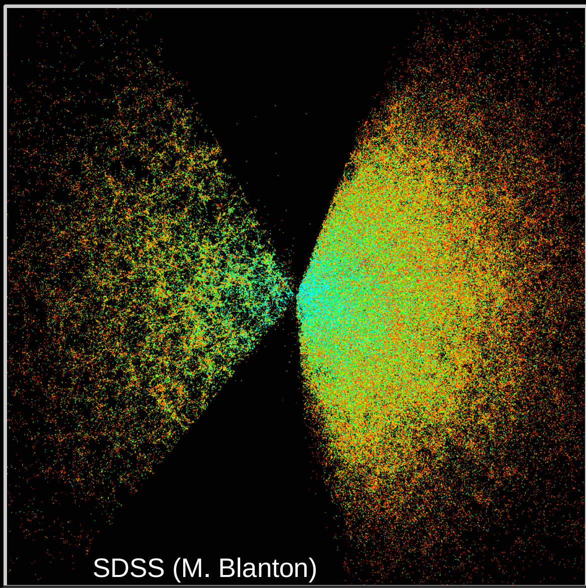
Abell 1689 (HST/ACS, Benitez et al. 2003)



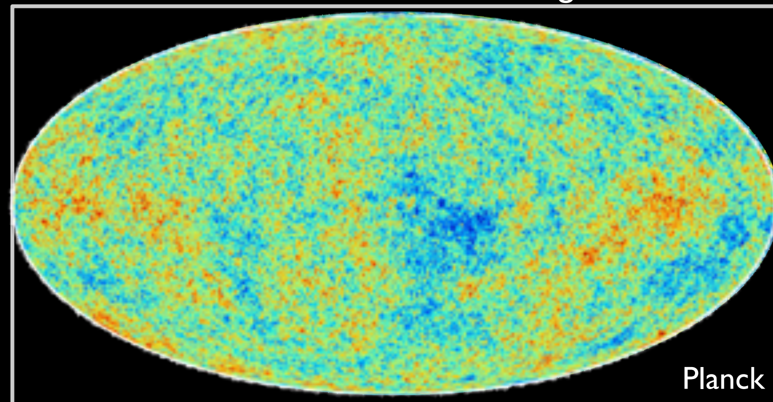
Markevitch et al. 2004, Clowe et al. 2004

Evidence for cold dark matter

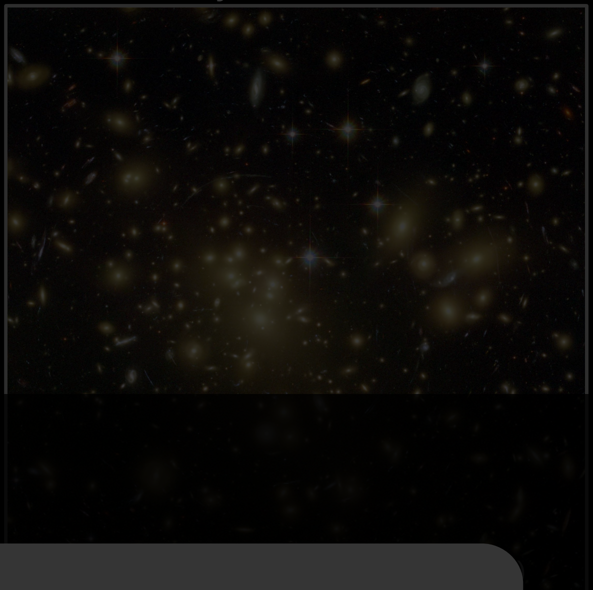
Large Scale Structure



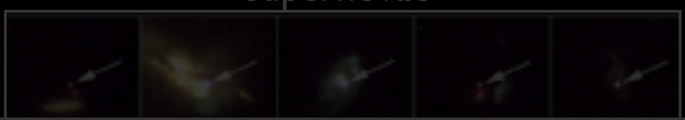
Cosmic Microwave Background

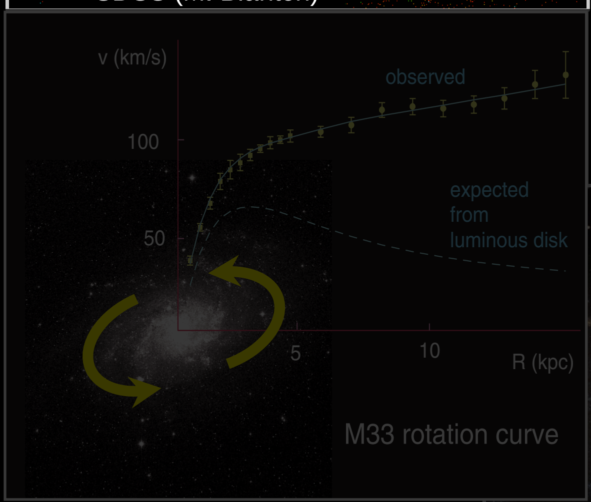


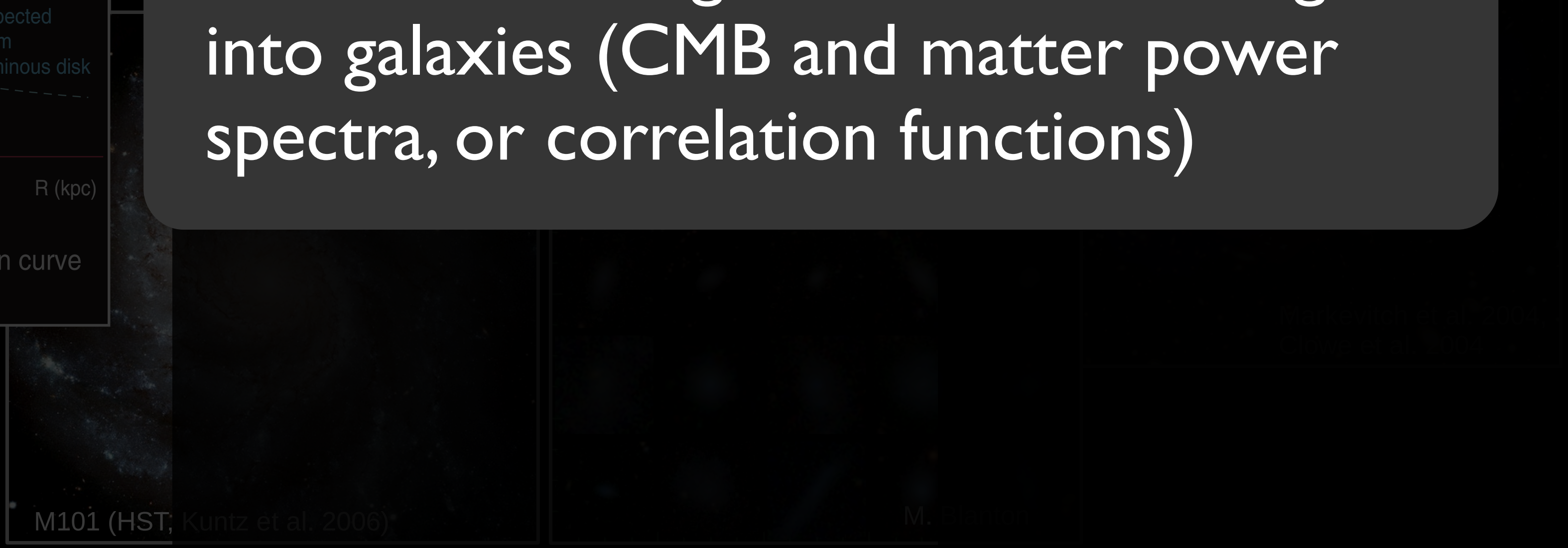
Galaxy Clusters



Supernovae



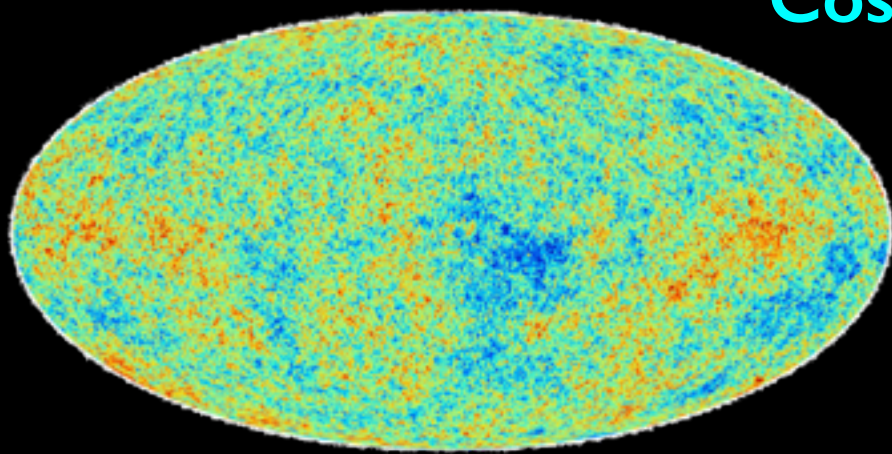


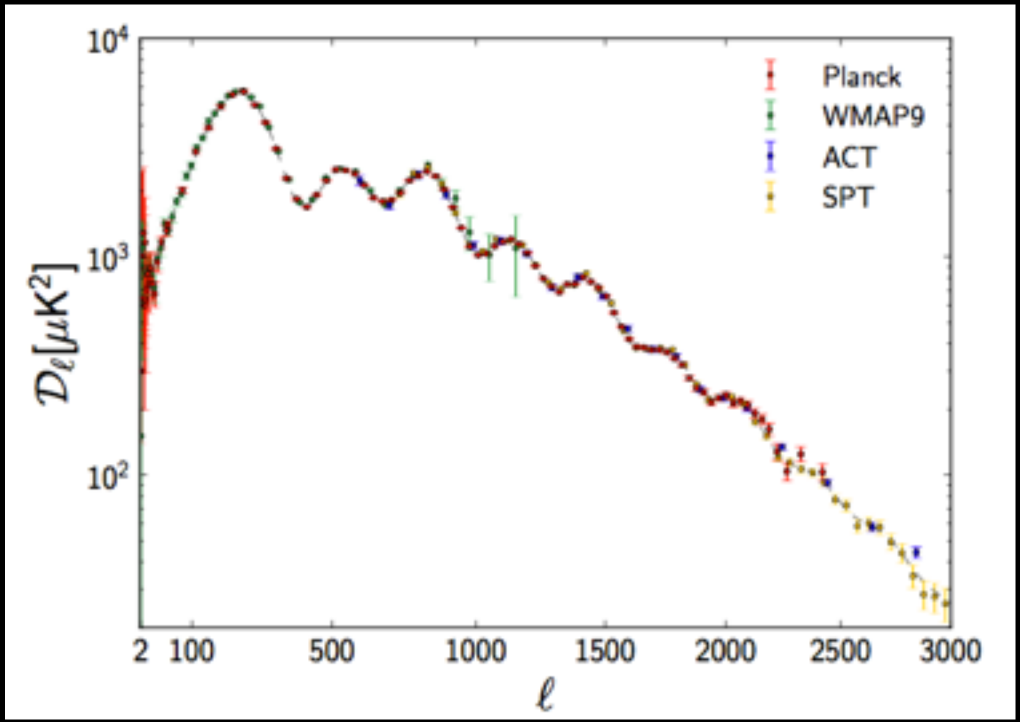


An invisible mass makes the Cosmic Microwave Background fluctuations grow into galaxies (CMB and matter power spectra, or correlation functions)

Evidence for cold dark matter

Cosmic Microwave Background fluctuations





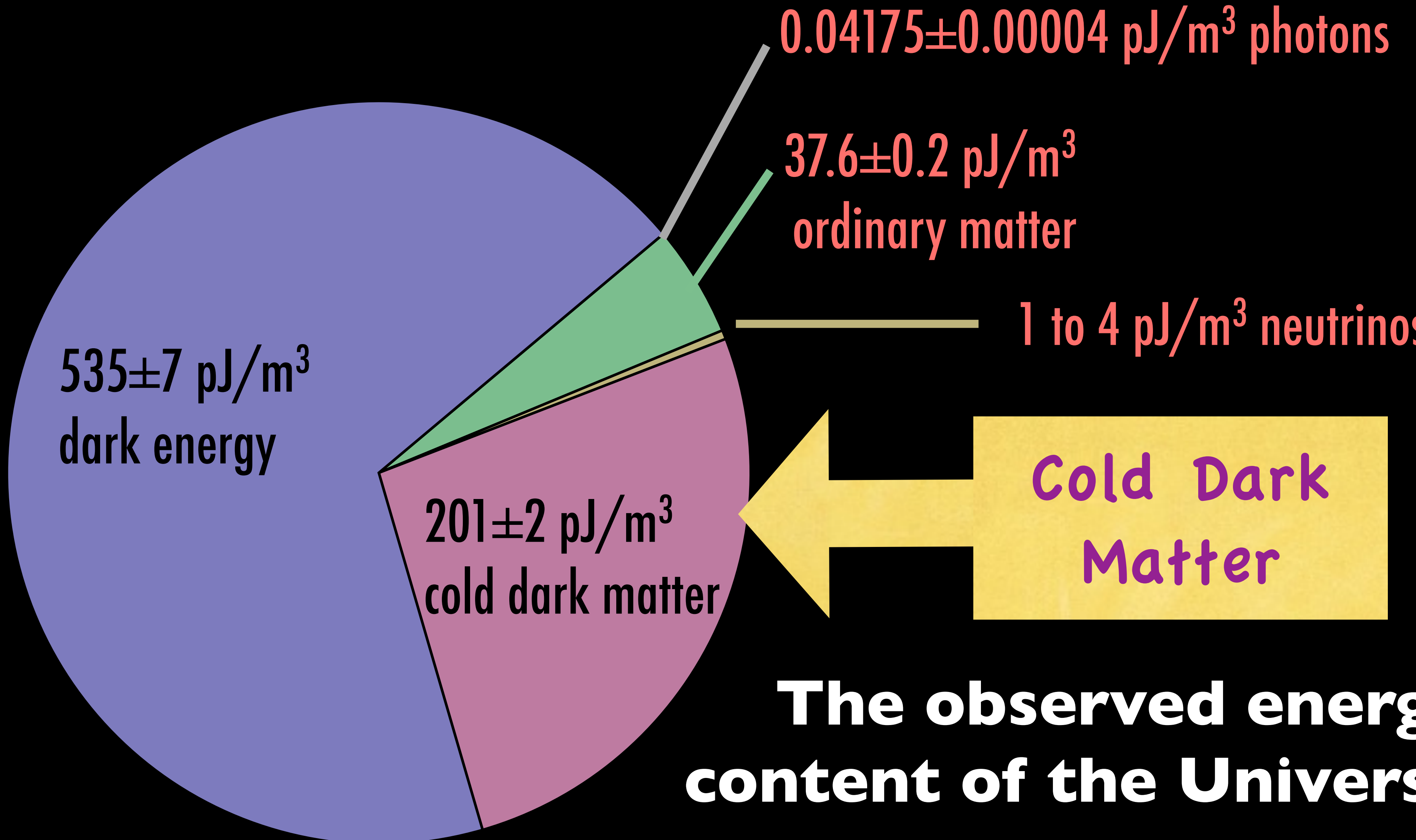
	Planck+WP+highL+BAO	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04148	1.04147 ± 0.00056
τ	0.0952	0.092 ± 0.013
n_s	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0973	3.091 ± 0.025
Ω_Λ	0.6914	0.692 ± 0.010
σ_8	0.8288	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

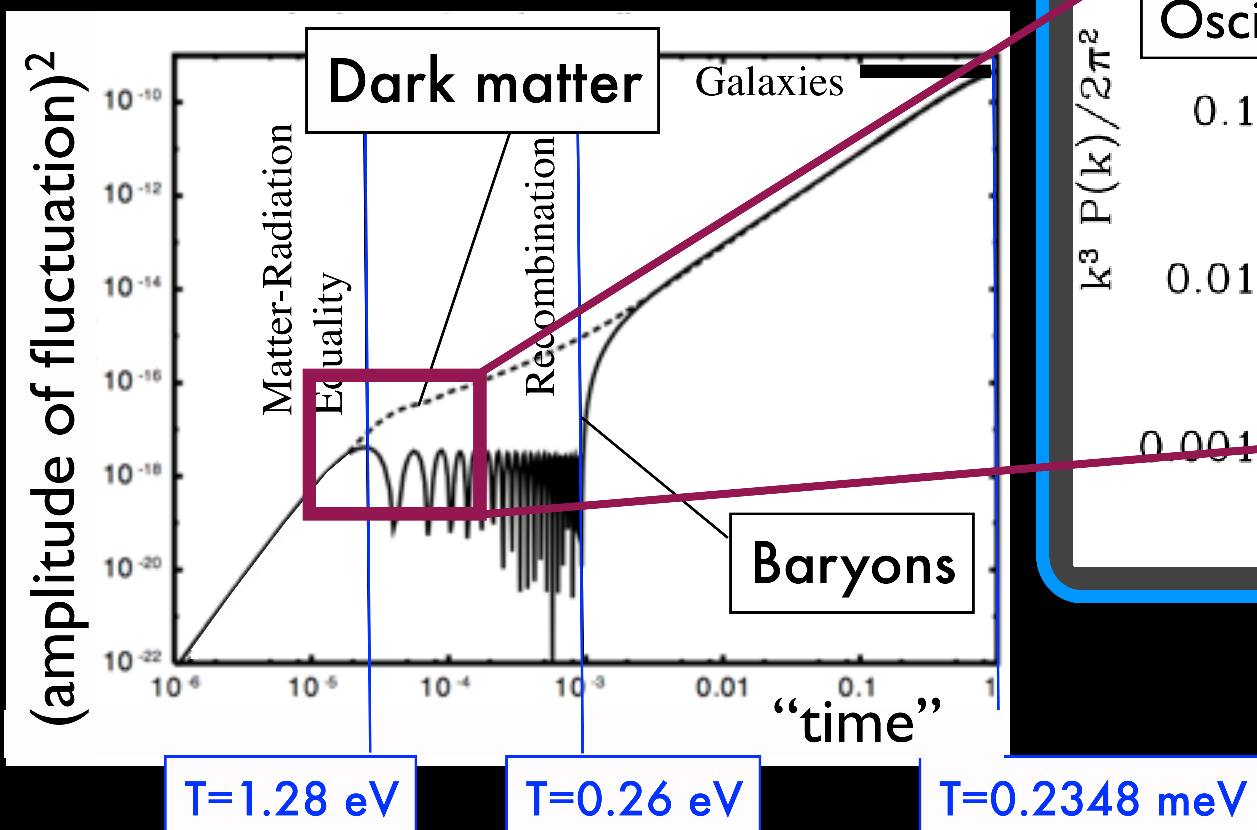
$1 \text{ pJ} = 10^{-12} \text{ J}$

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

Evidence for *nonbaryonic* cold dark matter

GALAXY FORMATION

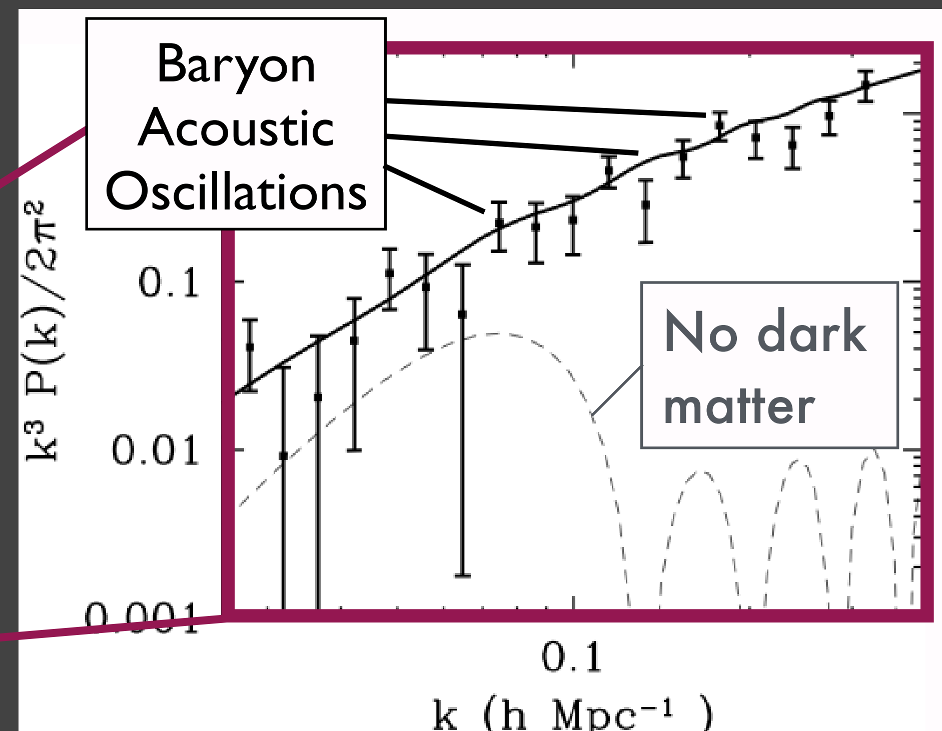
Matter fluctuations uncoupled to the plasma can gravitationally grow into galaxies in the given 13 Gyr



Dark matter is non-baryonic

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

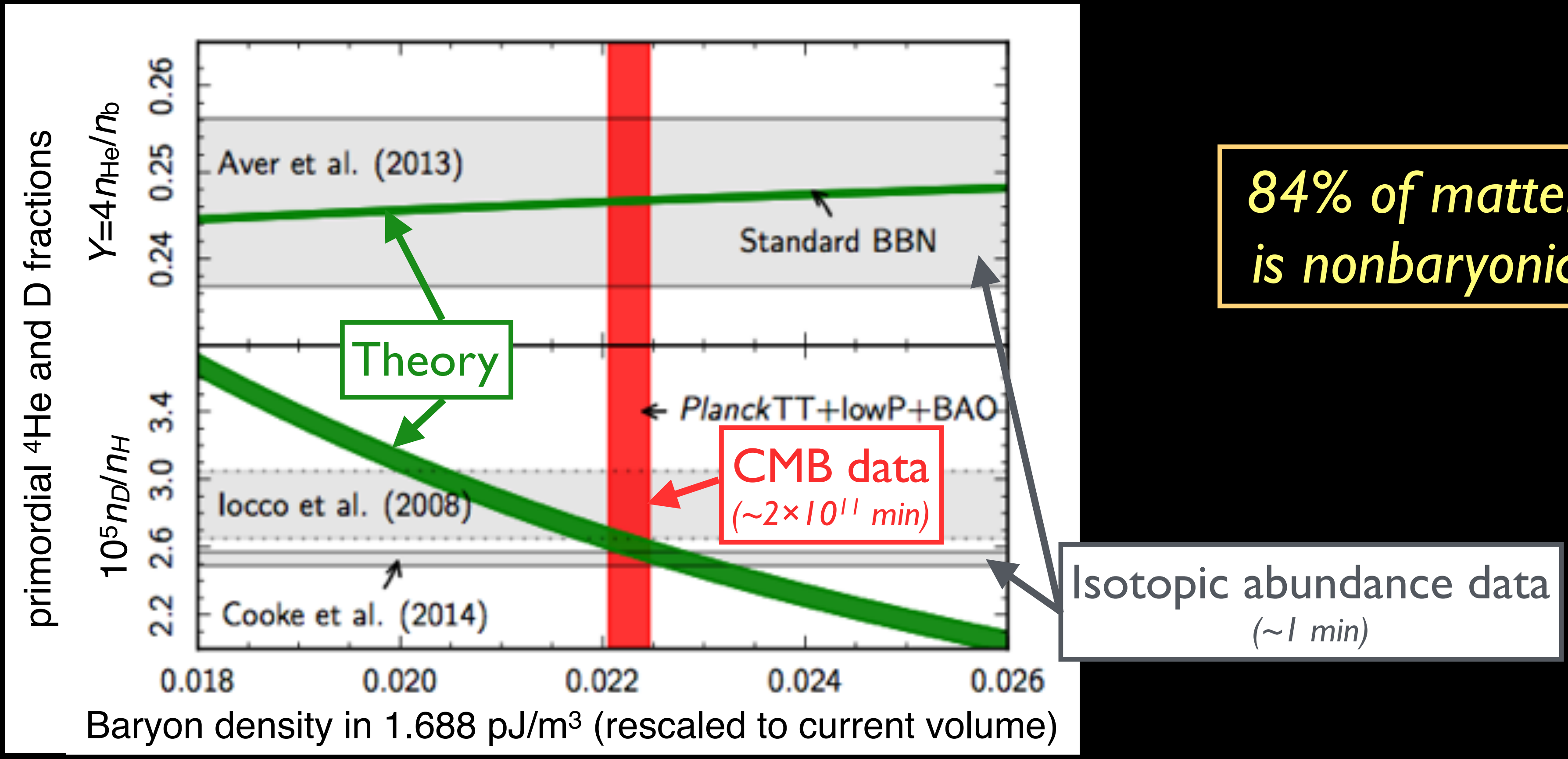
SDSS



Evidence for *nonbaryonic* cold dark matter

BIG BANG NUCLEOSYNTHESIS

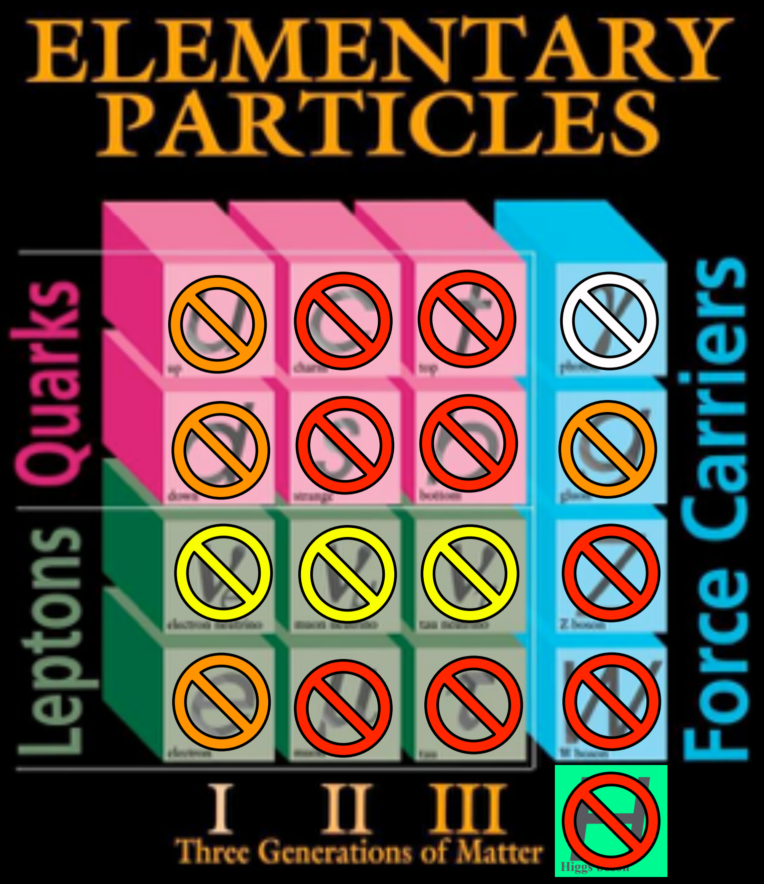
- The baryon-to-photon ratio has been the same since ~1 minute after the Big Bang.
- Baryons are ≲15.7% of the mass in matter.



84% of matter is nonbaryonic

Ade et al [Planck] 2015

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!

Particle dark matter

- SM neutrinos (hot)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

→ thermal relics

- sterile neutrinos, gravitinos (warm)
- Bose-Einstein condensates, axions, axion clusters (cold)
- solitons (Q-balls, B-balls, ...) (cold)
- supermassive wimpzillas (cold)

→ 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

neutralinos, other WIMPs, ...

Non-thermal relics

not in thermal equilibrium in the early universe

axions, WIMPZILLAs, solitons, ...

QCD Axions

QCD axions as dark matter

Hot

Produced thermally in early universe

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

Cold

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

(Vacuum realignment)

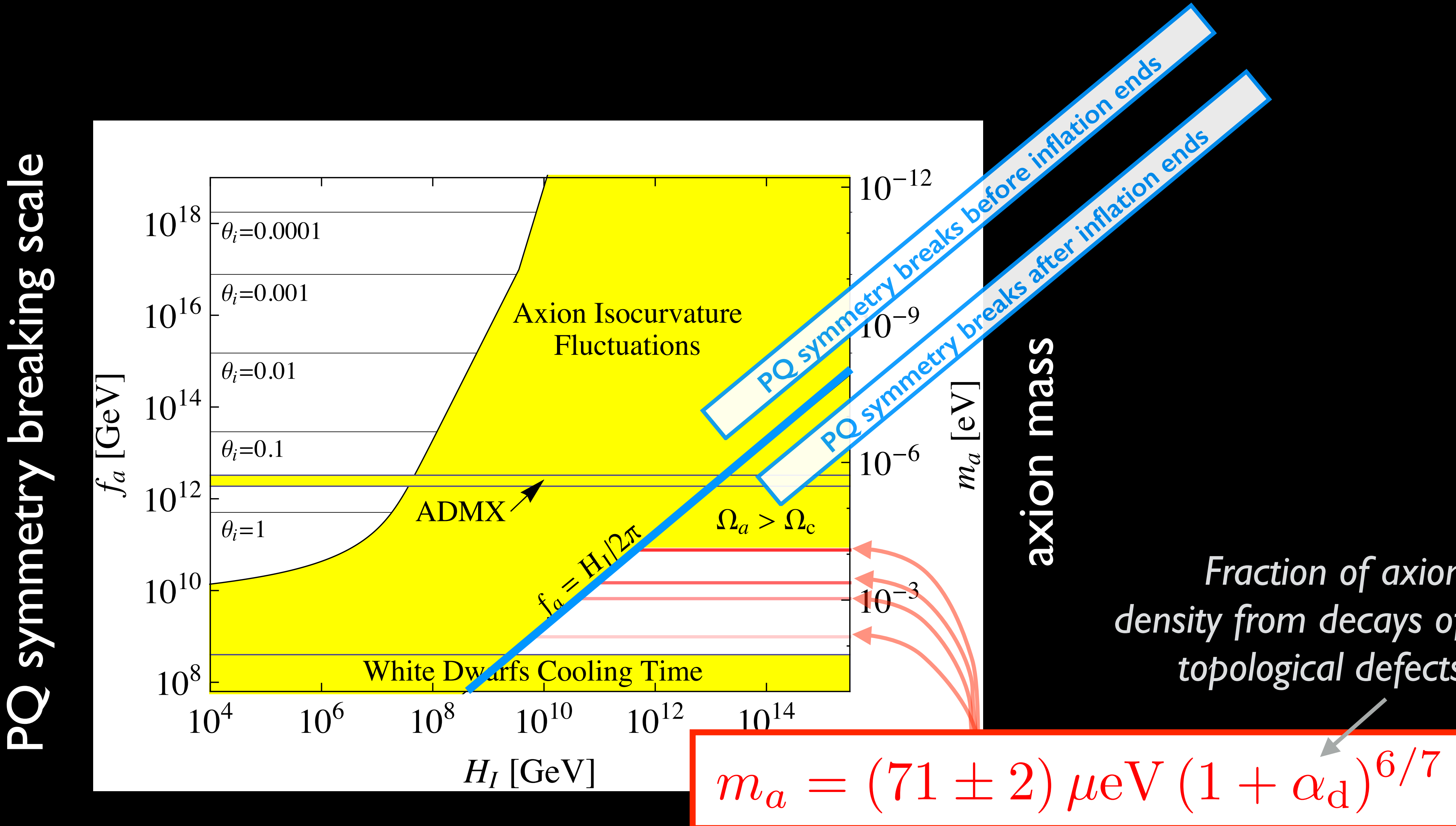
Produced by decay of topological defects

(Axionic string decays)

Still a very complicated and uncertain calculation!

e.g. Harimatsu et al 2012

QCD axions as cold dark matter



Expansion rate at end of inflation

Visinelli, Gondolo 2009, 2014

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)

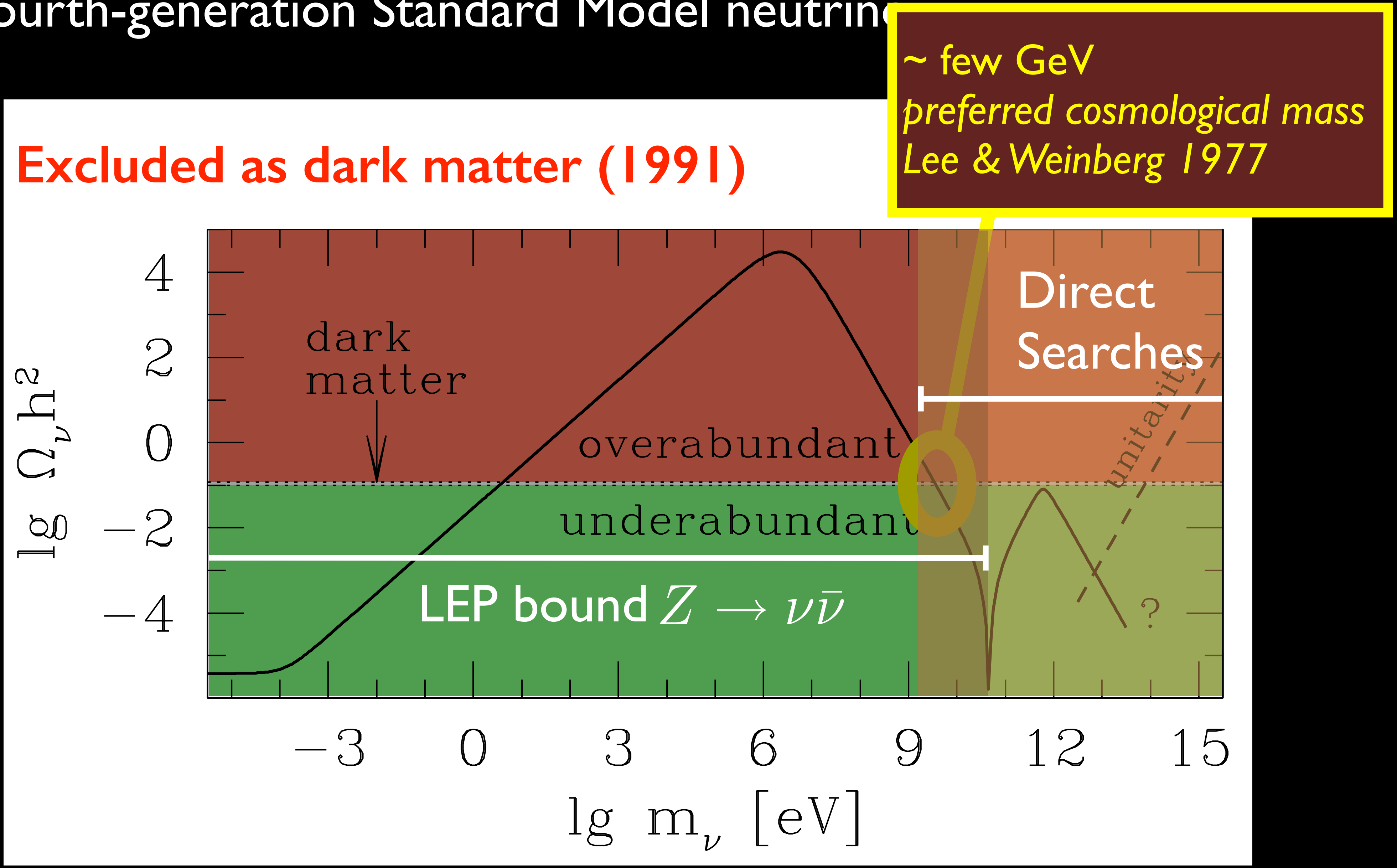
The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

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



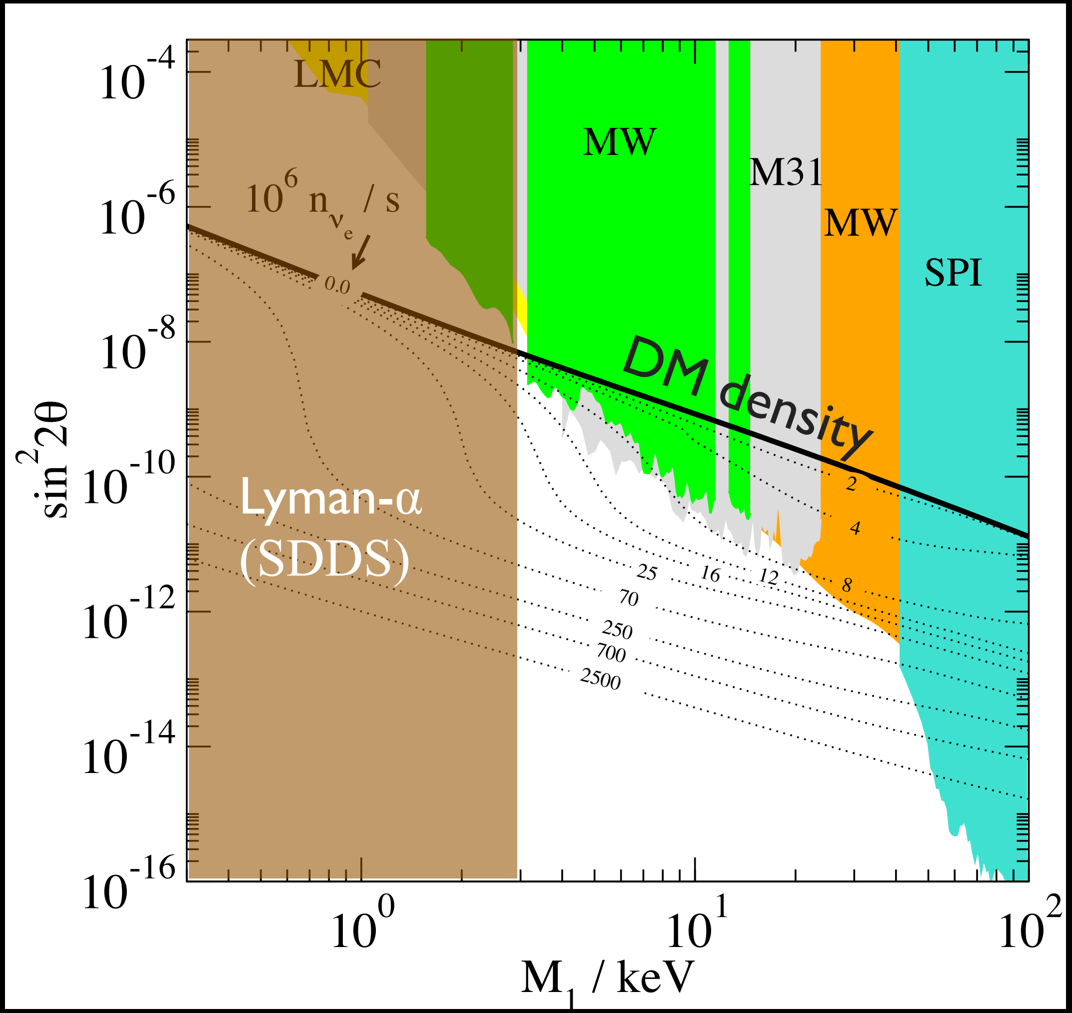
Sterile neutrino dark matter

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



*ν*MSM

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

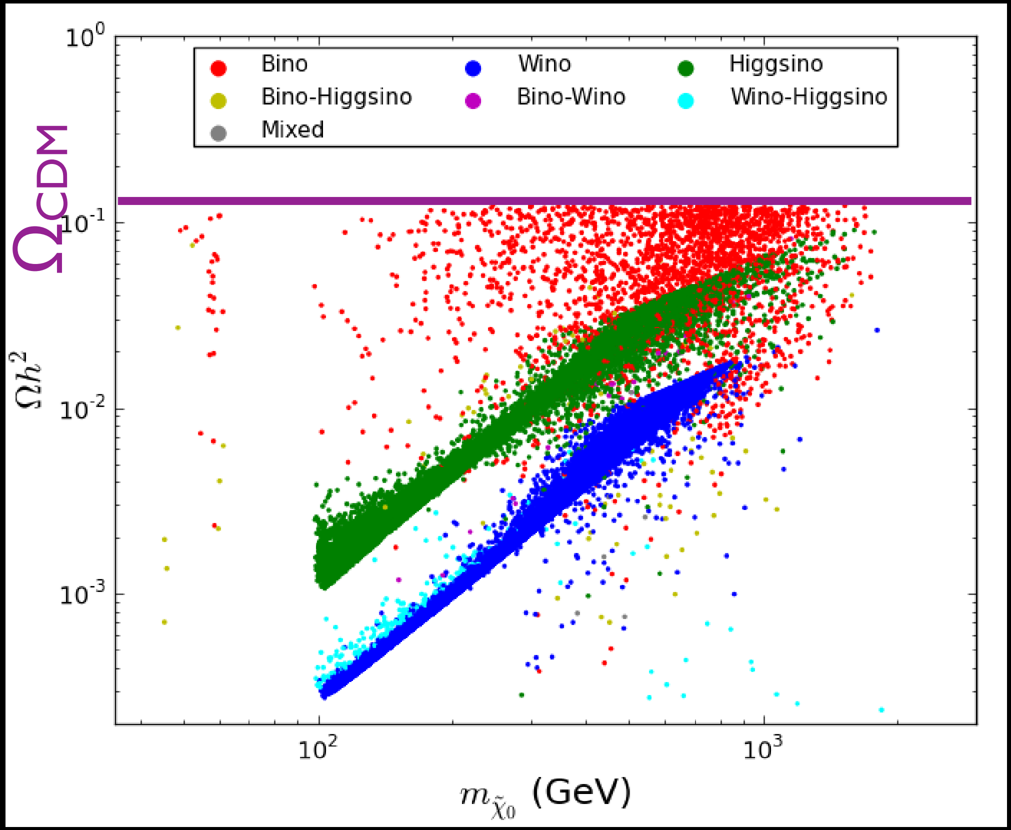
Cahill-Rowell et al 1305.6921

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

pMSSM (phenomenological MSSM)

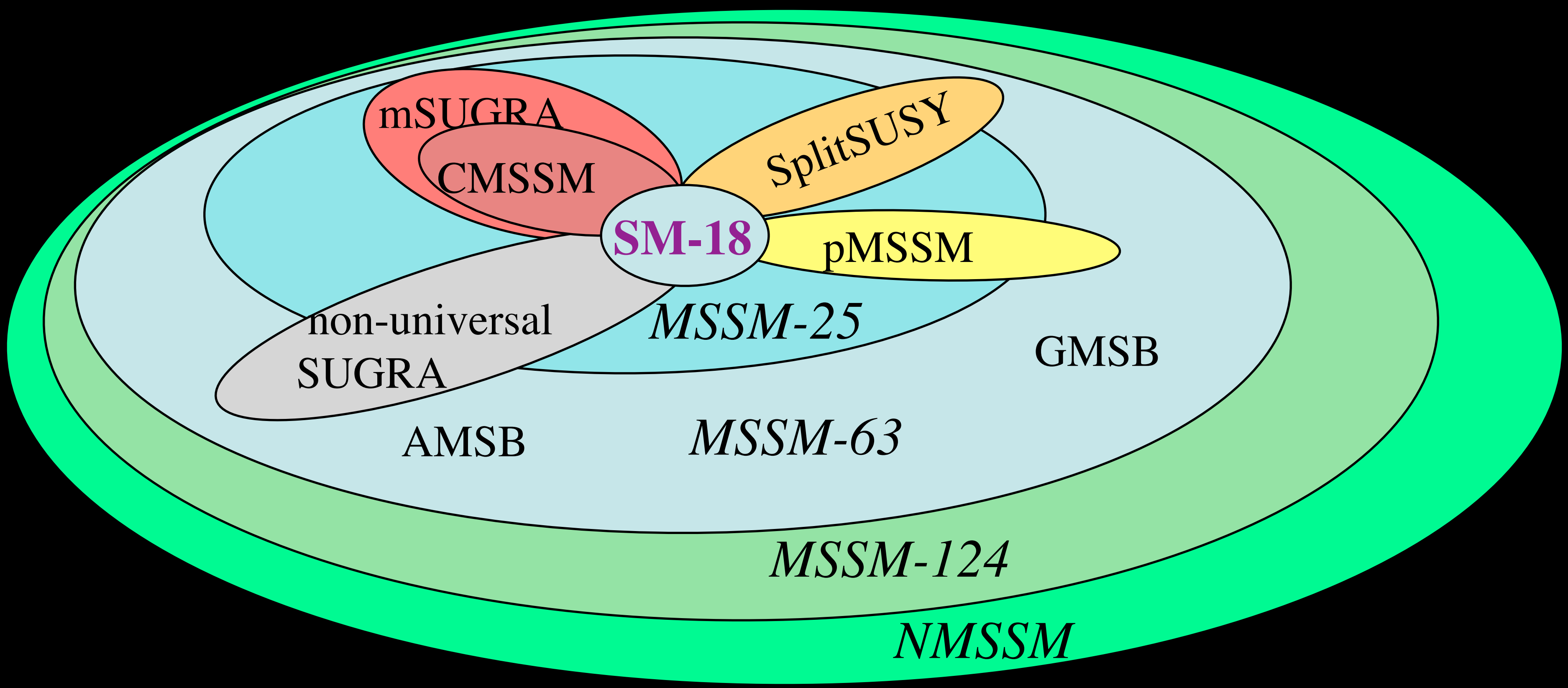
$$\mu, m_A, \tan\beta, A_b, A_t, A_\tau, M_1, M_2, M_3,$$
$$m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3},$$
$$m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}$$

(19 parameters)



Neutralino dark matter: impact of LHC

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



*Constrained Minimal Supersymmetric Standard Model

Neutralino dark matter: impact of LHC

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

"Supersymmetry cannot be experimentally ruled out"

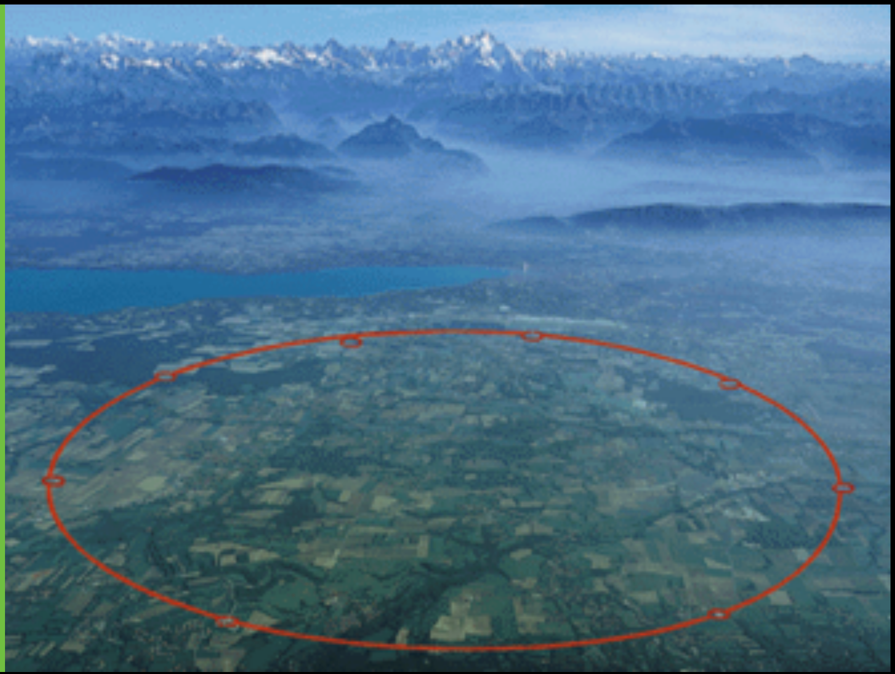
Leszek Roszkowski

**Constrained Minimal Supersymmetric Standard Model*

The forbidden fruit

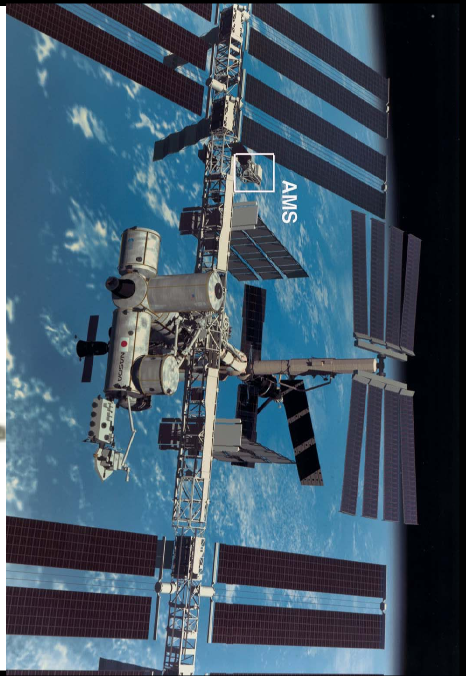
Searches for particle dark matter

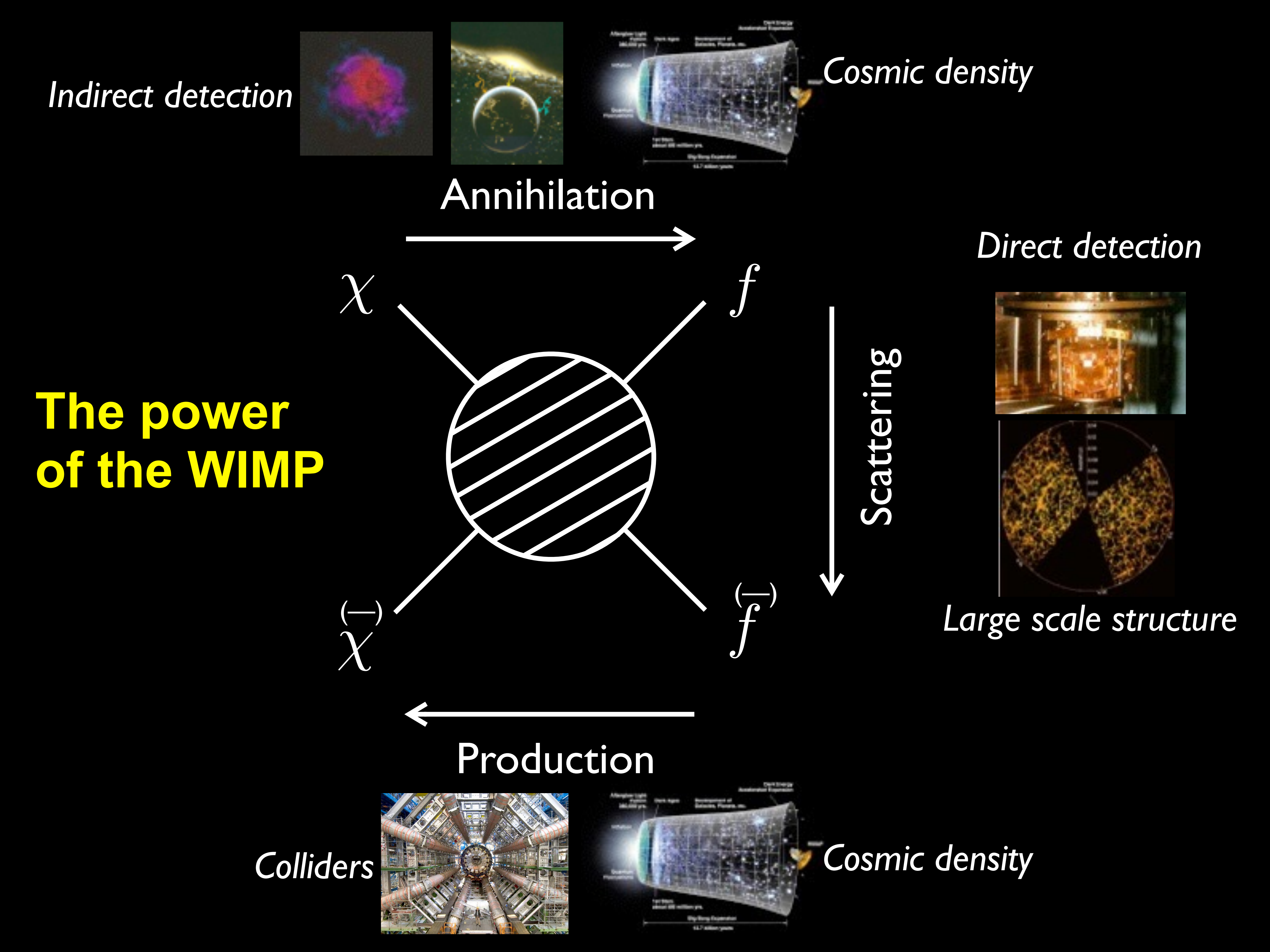
Collider



Direct

Indirect



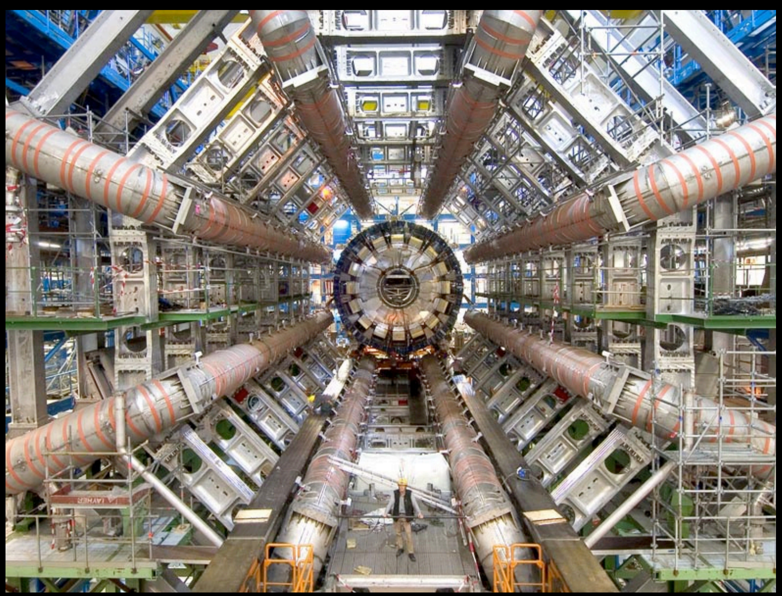


Indirect detection
Cosmic density
Annihilation
Direct detection
χ
f
Scattering
The power of the WIMP
$\overset{(-)}{\chi}$
$\overset{(-)}{f}$
Large scale structure
Production
Colliders
Cosmic density

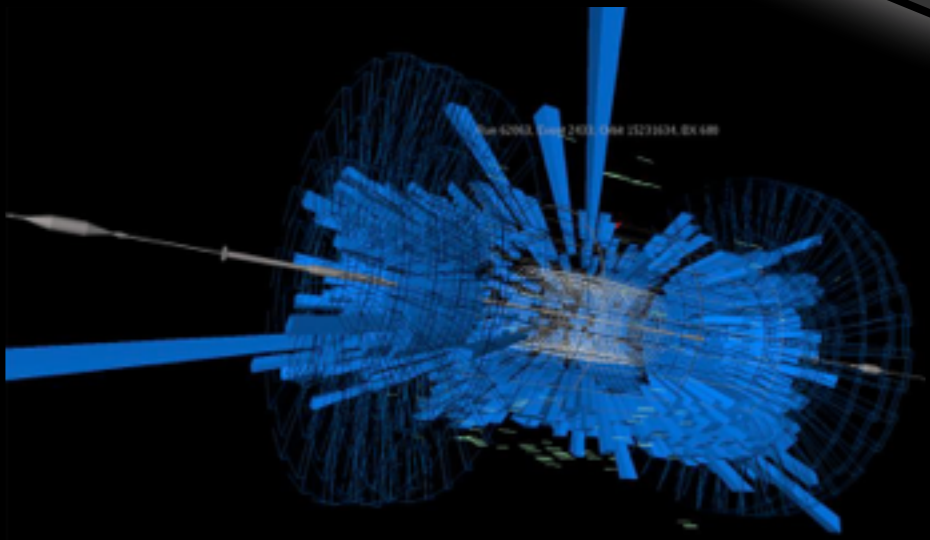
Dark matter creation with particle accelerators

Searching for the conversion
protons → energy → dark matter

$E=mc^2$ in action



The ATLAS detector

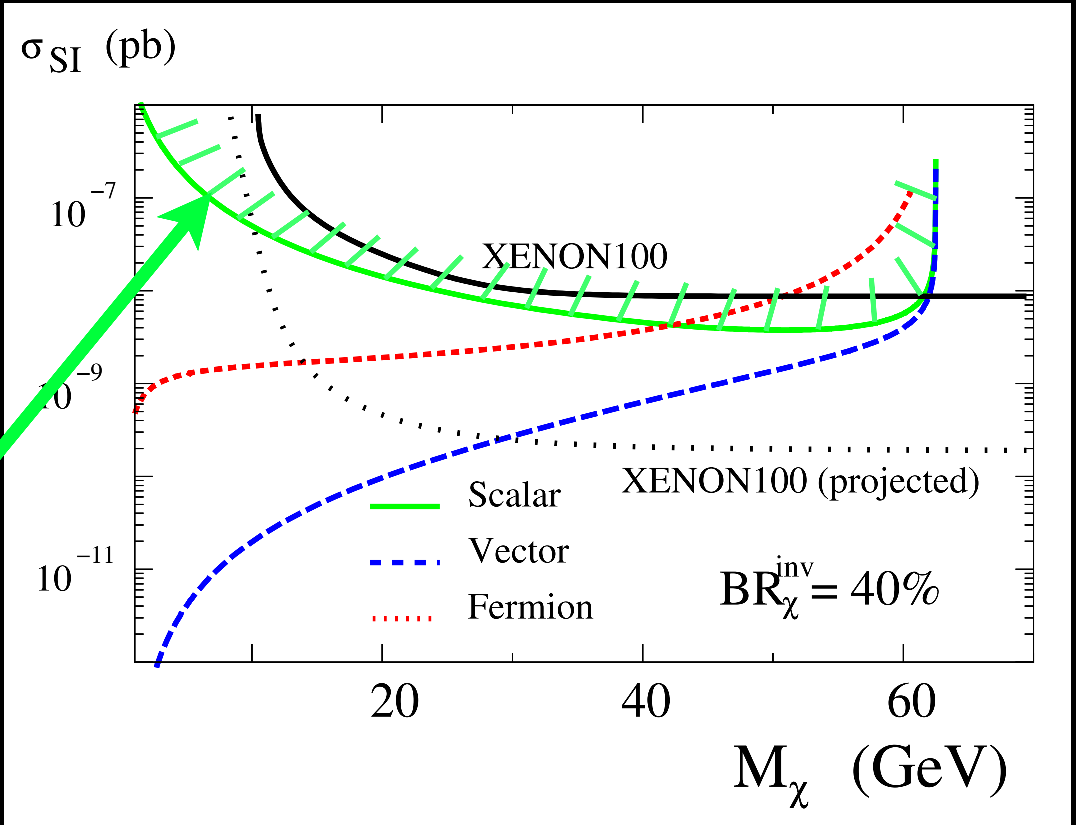


Particle production at the Large Hadron Collider

Higgs-portal dark matter: impact of LHC

Discovery of 125 GeV Higgs boson constrains models with Higgs boson mediator between dark and ordinary matter

LHC limit



Djouadi, Falkowski, Mambrini, Quevillon 2012

Indirect detection of particle dark matter

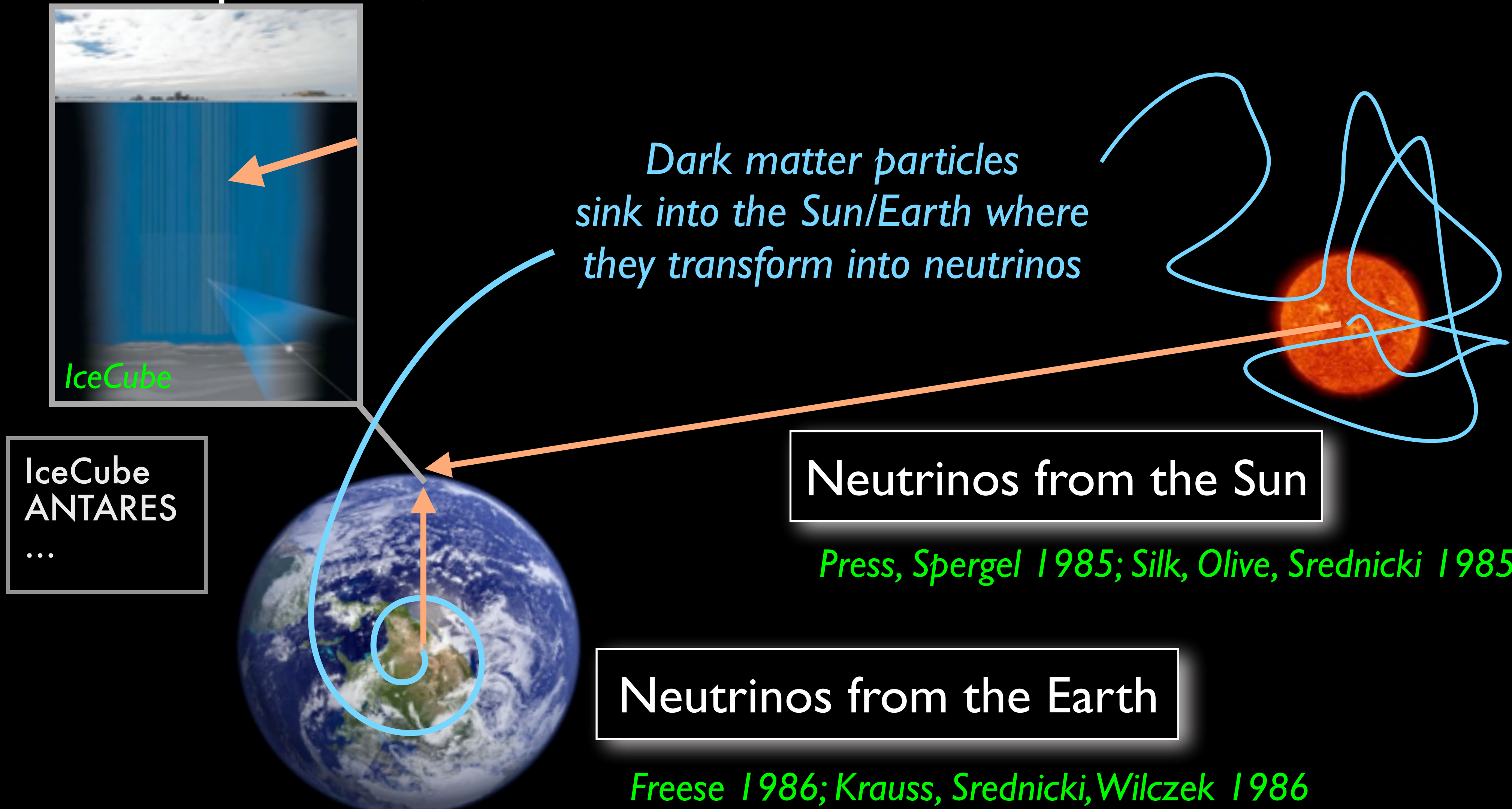
The principle

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

Indirect detection of particle dark matter

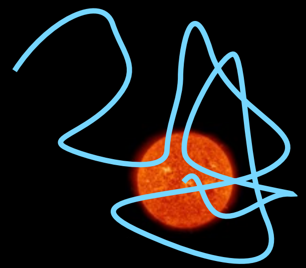
The principle

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

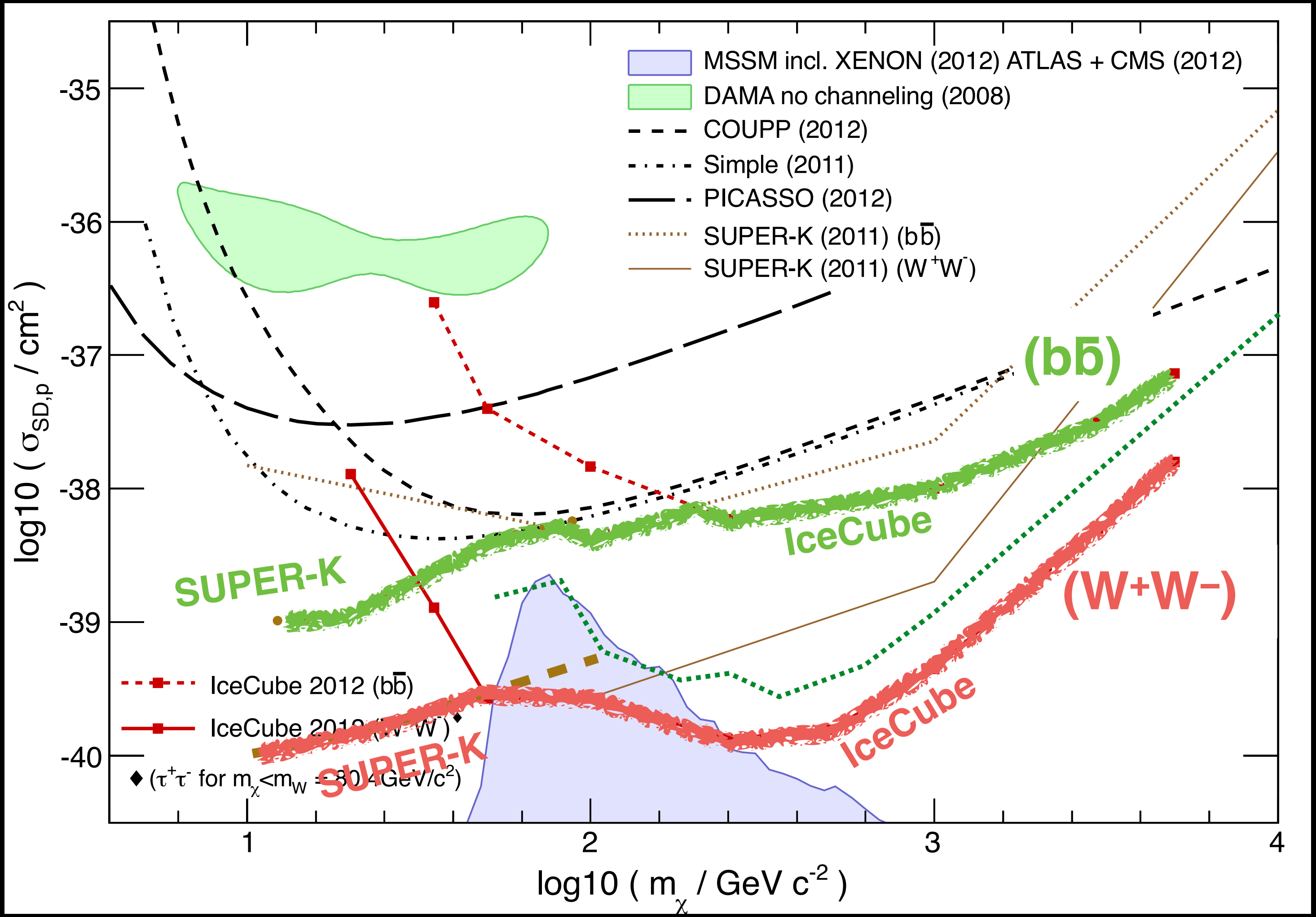


Neutrinos from WIMP annihilation in the Sun

Best limits on WIMP-proton spin-dependent scattering cross section



Capture rate equals annihilation rate



Aarsten et al (IceCube) 2012

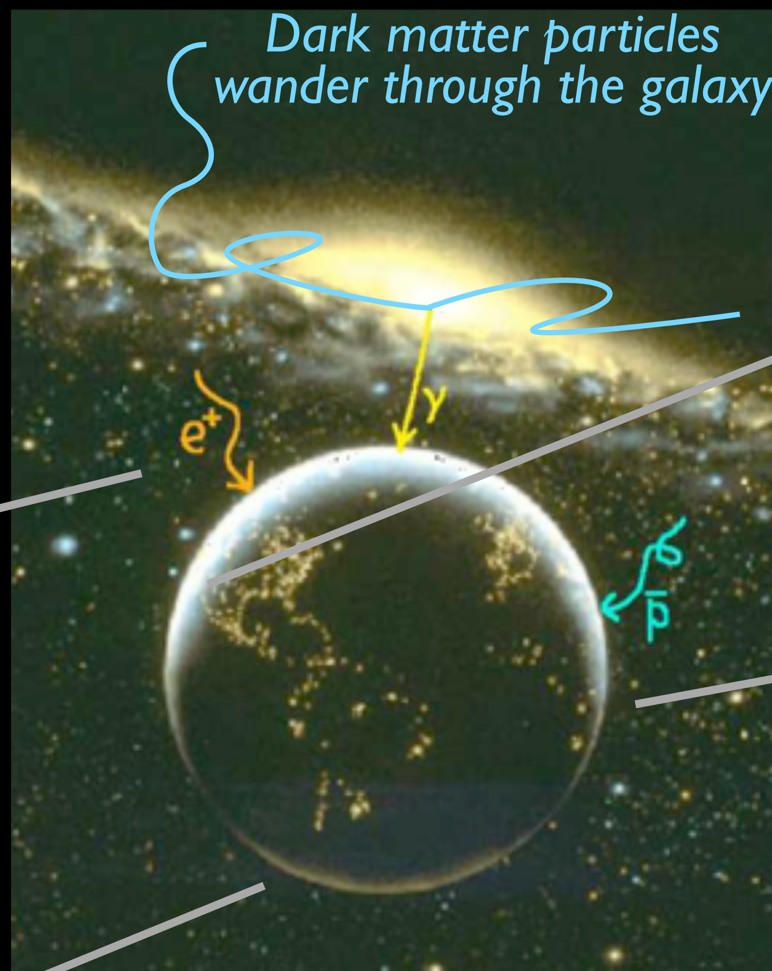
Indirect detection of particle dark matter

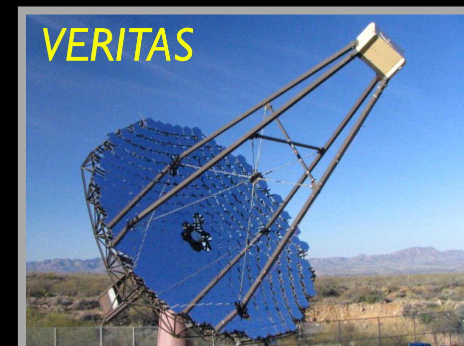
The principle

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
...

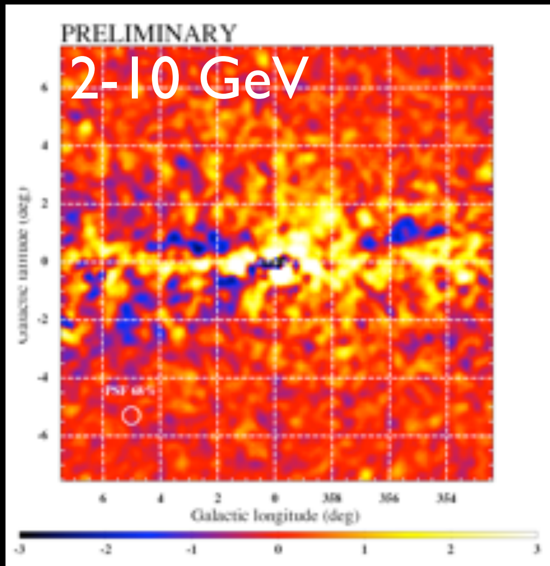
Gunn, Lee, Lerche, Schramm, Steigman 1978; Stecker 1978





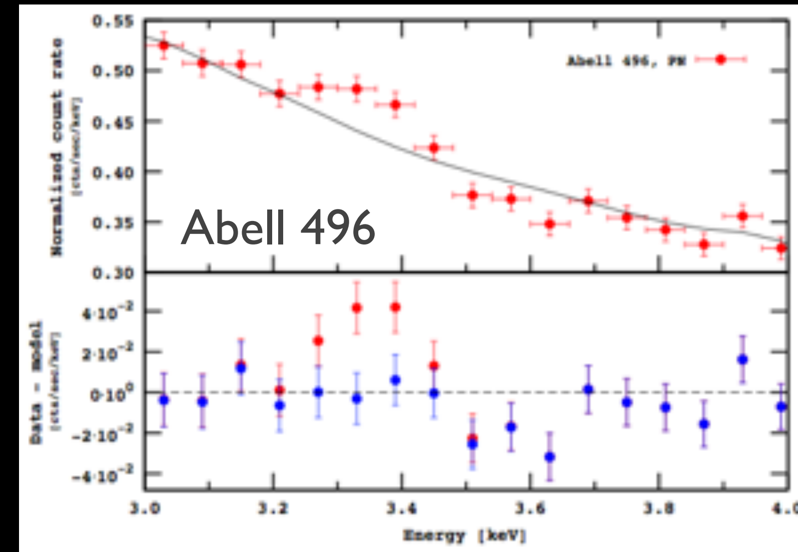
Gamma-rays, positrons, antiprotons from our galaxy and beyond

Indirect detection of particle dark matter



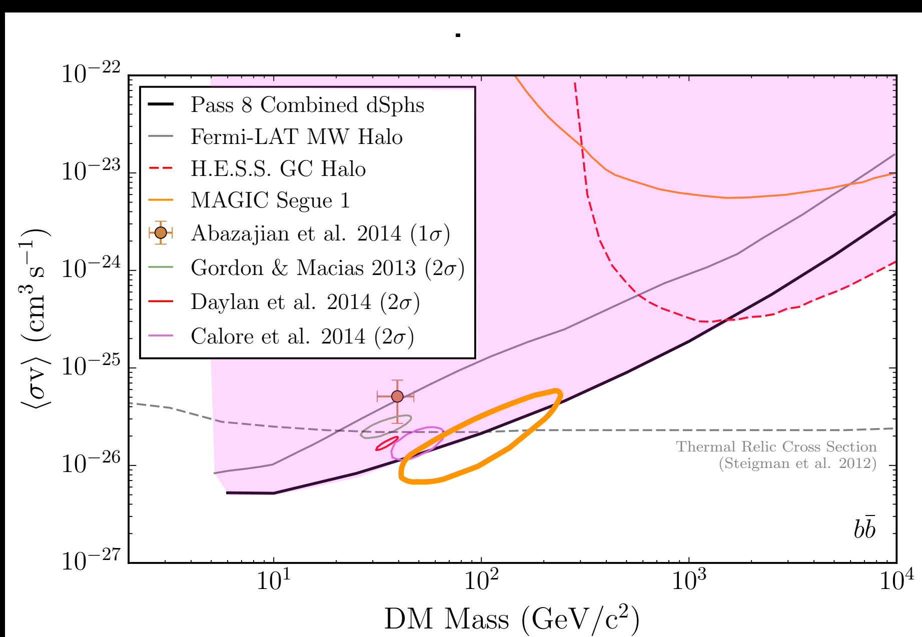
Murgia et al 2014

X-ray lines from galaxies and galaxy clusters



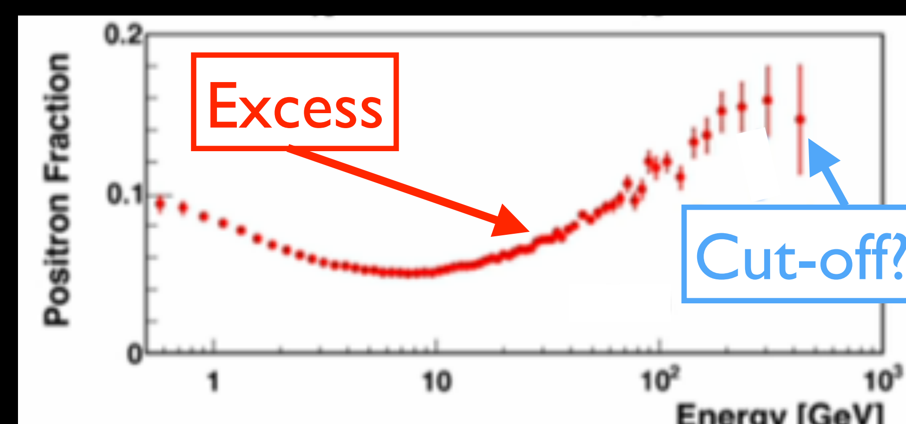
Iakubovskyi et al 2015

Gamma-rays from Galactic Center and other galaxies



Ackermann et al [FermiLAT] 2015

Cosmic ray positrons



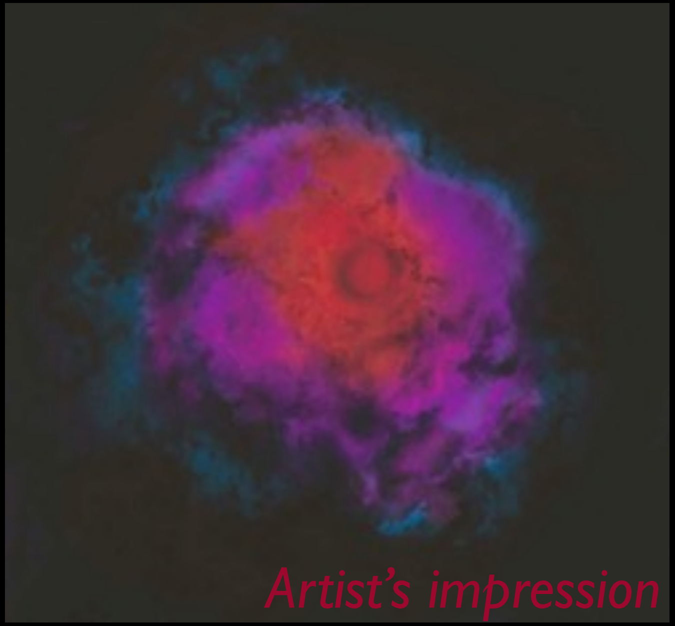
Accardo et al [AMS-02] 2014

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.



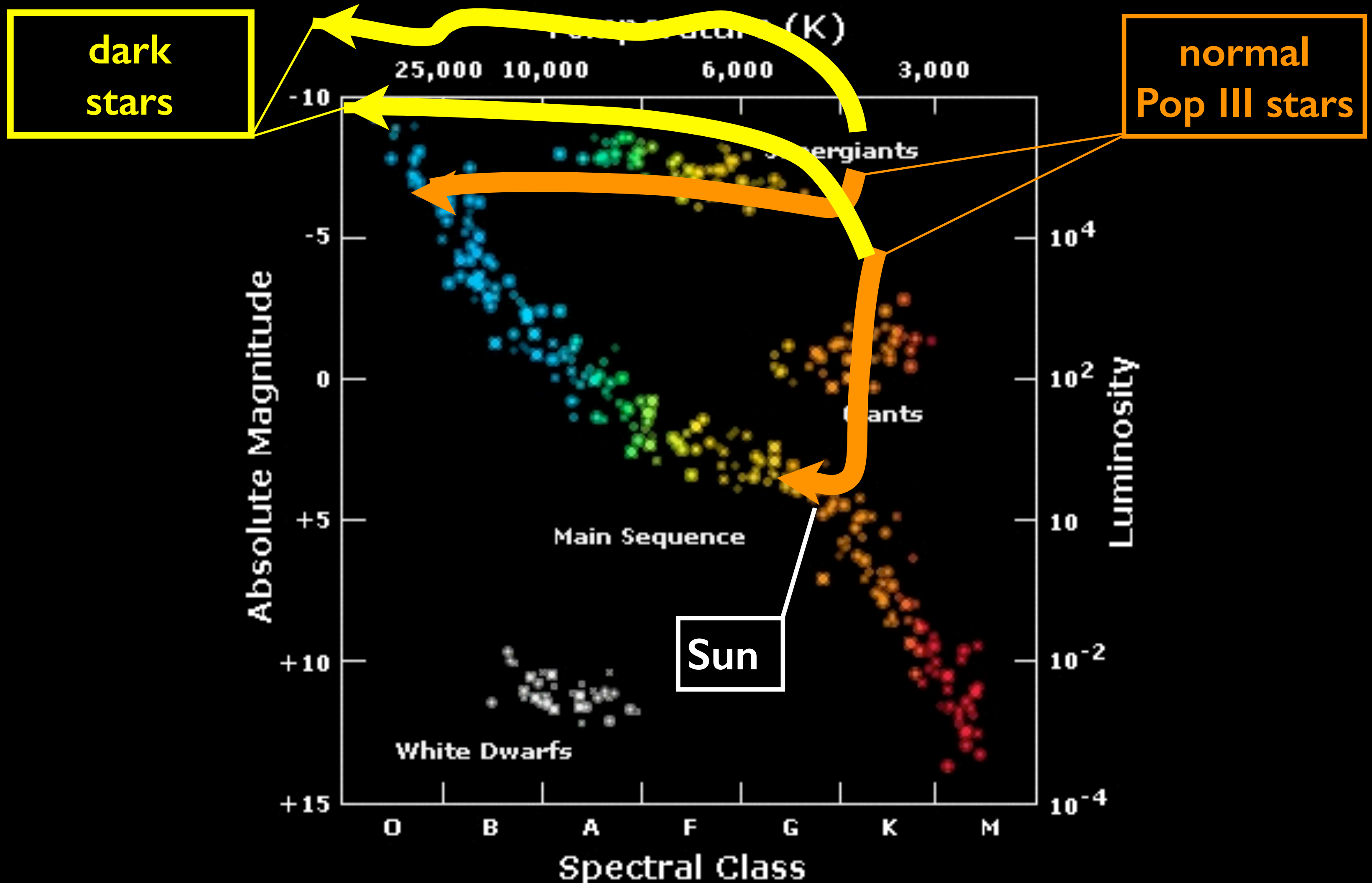
They were *dark-matter powered stars* or for short

Dark Stars

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

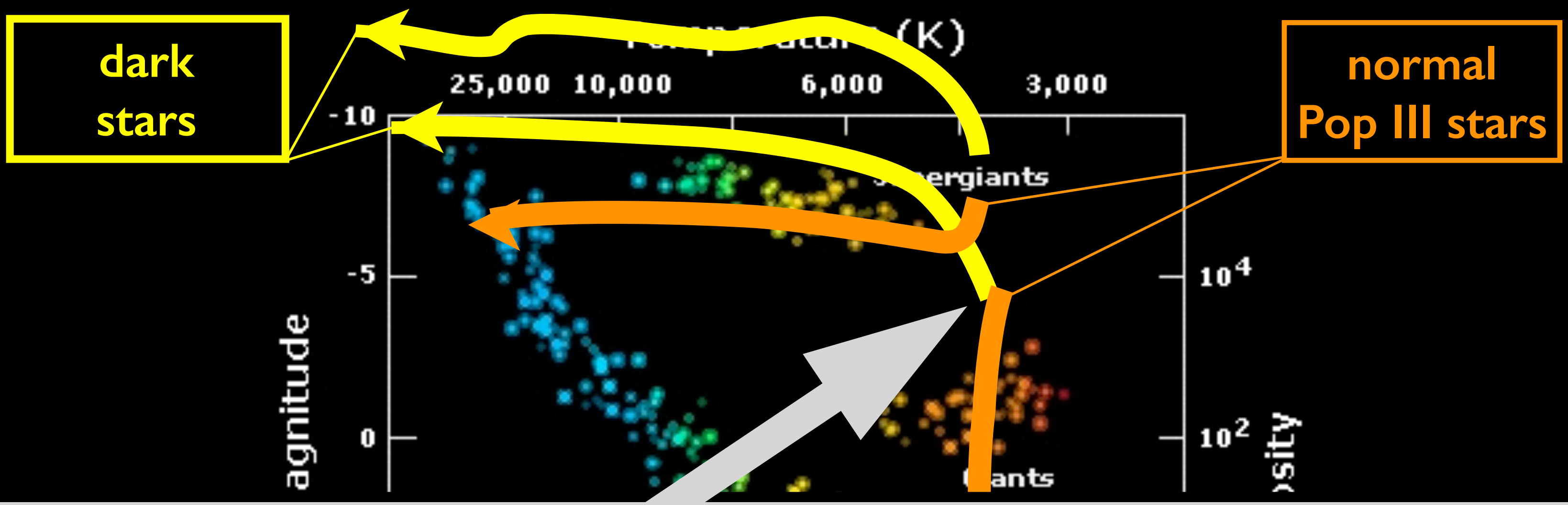
Spolyar, Freese, Gondolo 2007-2008

Life of a dark star



Spolyar, Freese, Gondolo 2007; Spolyar, Bodenheimer, Freese, Gondolo 2009

Life of a dark star



(1) Sufficiently high dark matter density to get large annihilation rate

Provided by gravity

(2) Annihilation products get stuck in star

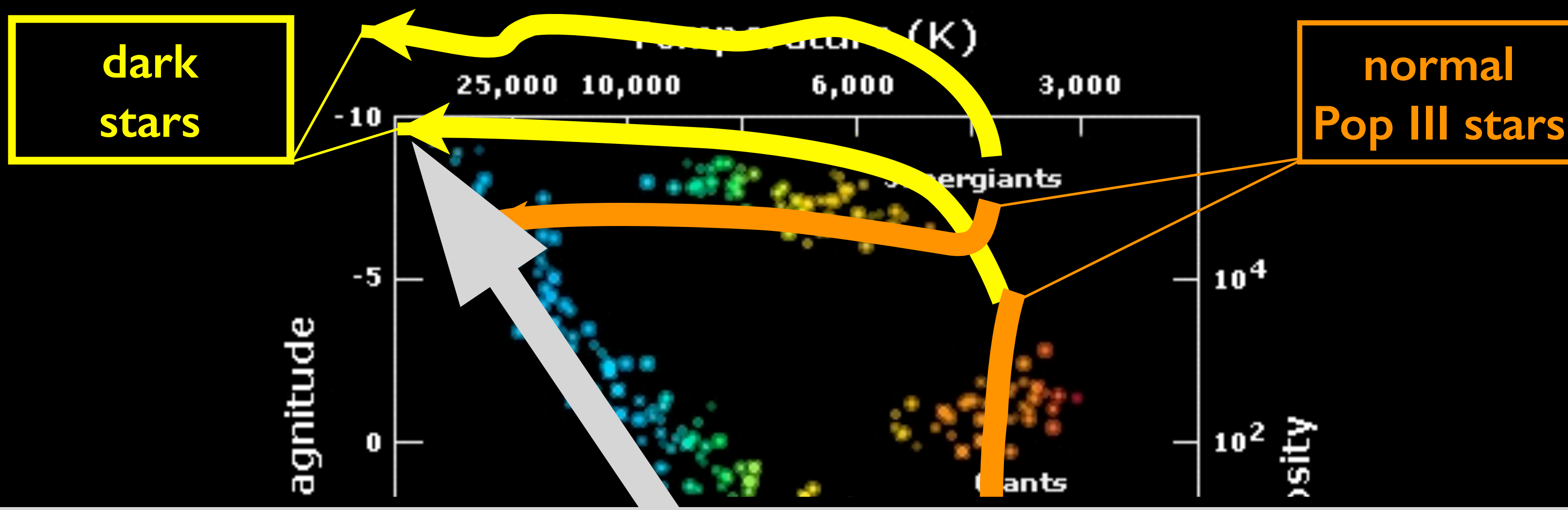
Provided by particle interactions in matter

(3) Dark matter heating beats H_2 cooling

A dark star forms (hydrogen star powered by dark matter)

Spolyar, Freese, Gondolo 2007; Spolyar, Bodenheimer, Freese, Gondolo 2009

Life of a dark star



Very bright star at high redshift

- May be searched for using gravitational lensing of galaxy clusters
- May be constrained by ionization history of early universe

May explode as hypernova and leave an early massive seed black hole

- May explain the existence of high-redshift quasars

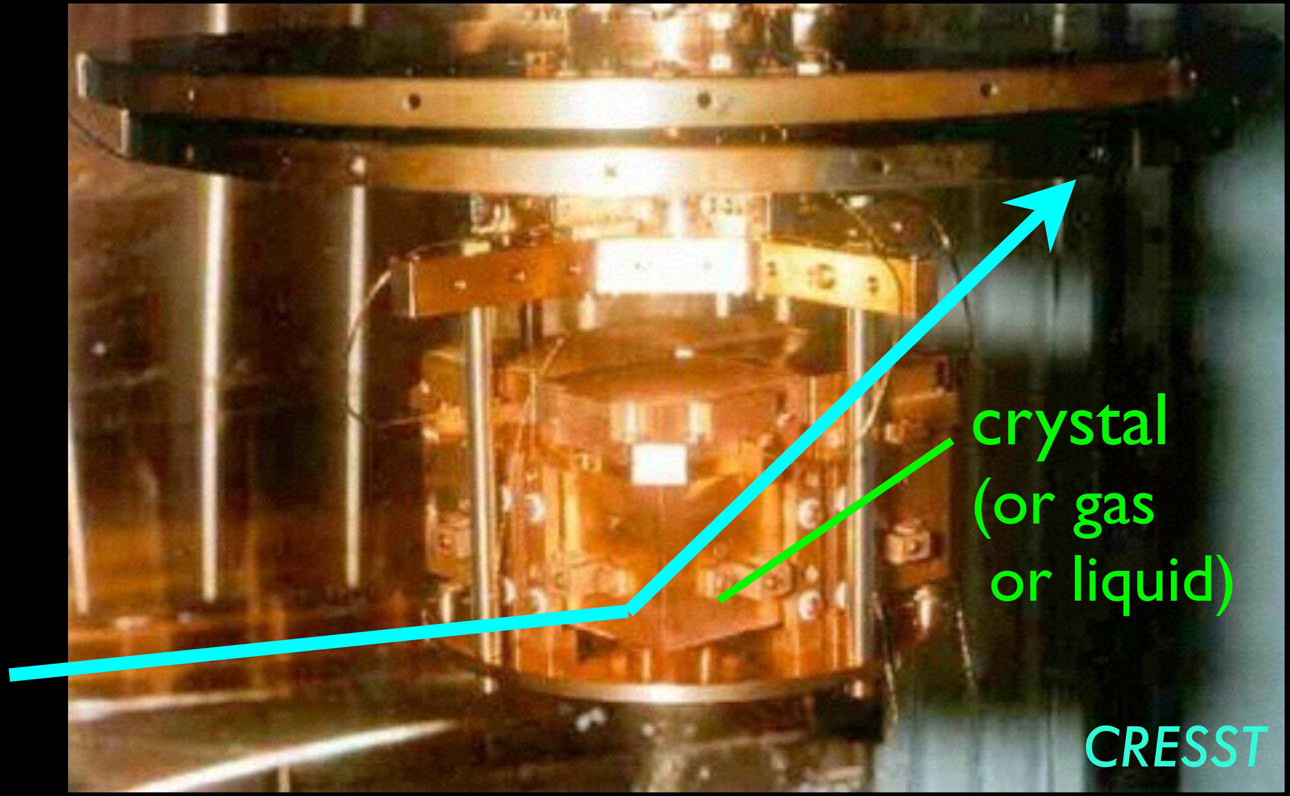
Spolyar, Freese, Gondolo 2007; Spolyar, Bodenheimer, Freese, Gondolo 2009

The principle of direct detection

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

Goodman, Witten 1985

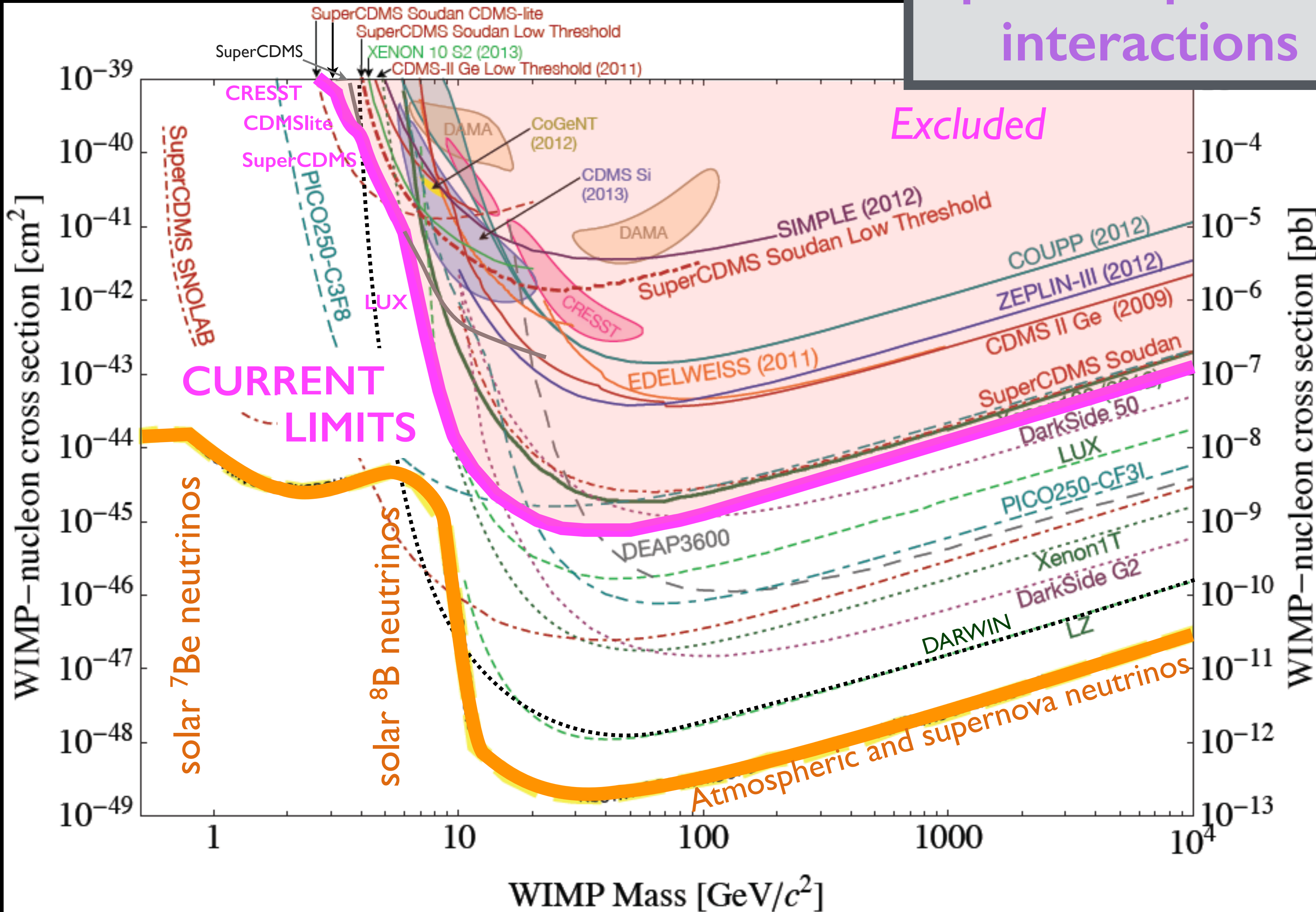
Dark matter particle



Low-background underground detector

Direct WIMP searches (2015)

Spin-independent interactions



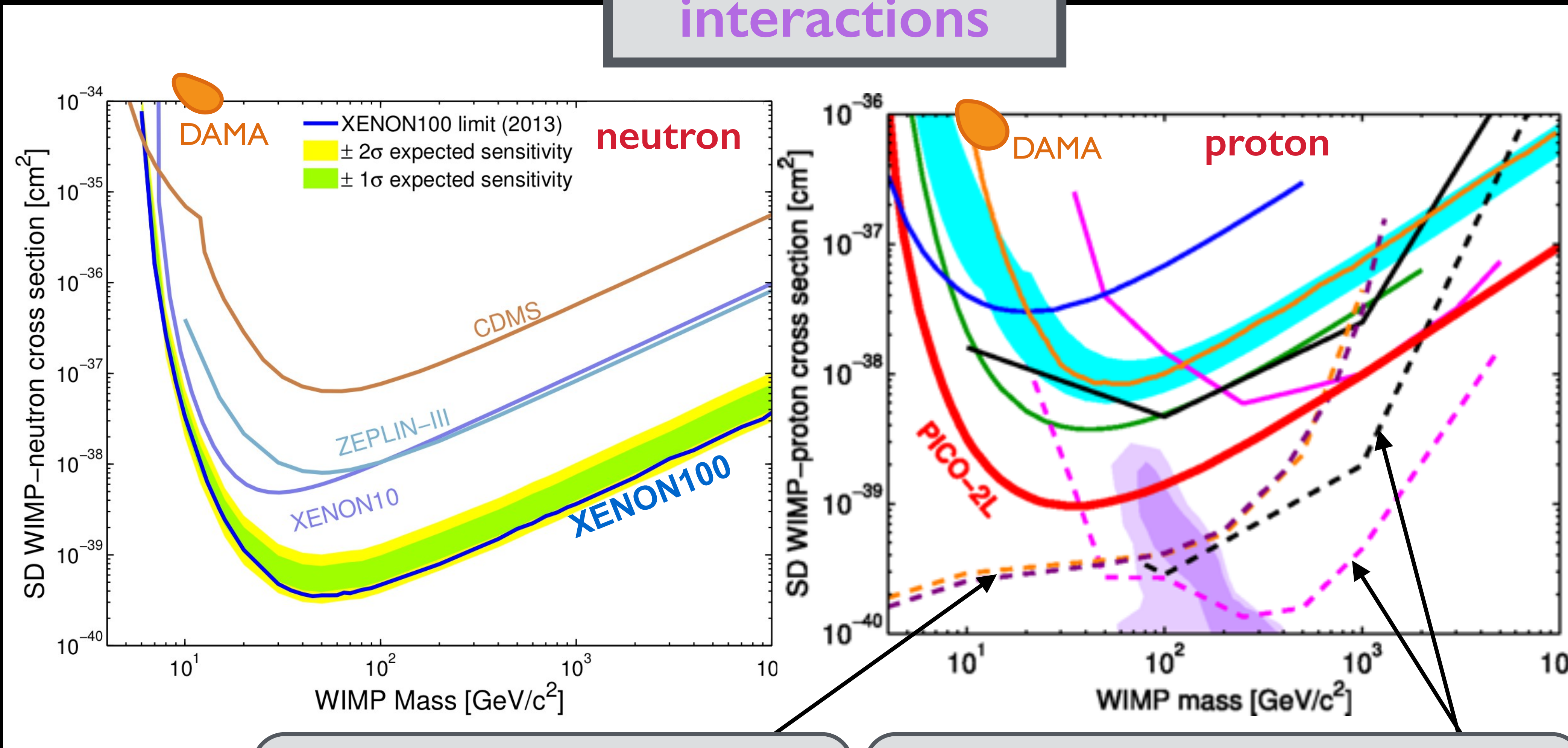
Billard et al 2013, Snowmass 2013, LUX 2013, SuperCDMS 2014

Direct WIMP searches (2015)

Aprile et al (XENON100) 2013

Spin-dependent interactions

Amole et al (PICO) 2015

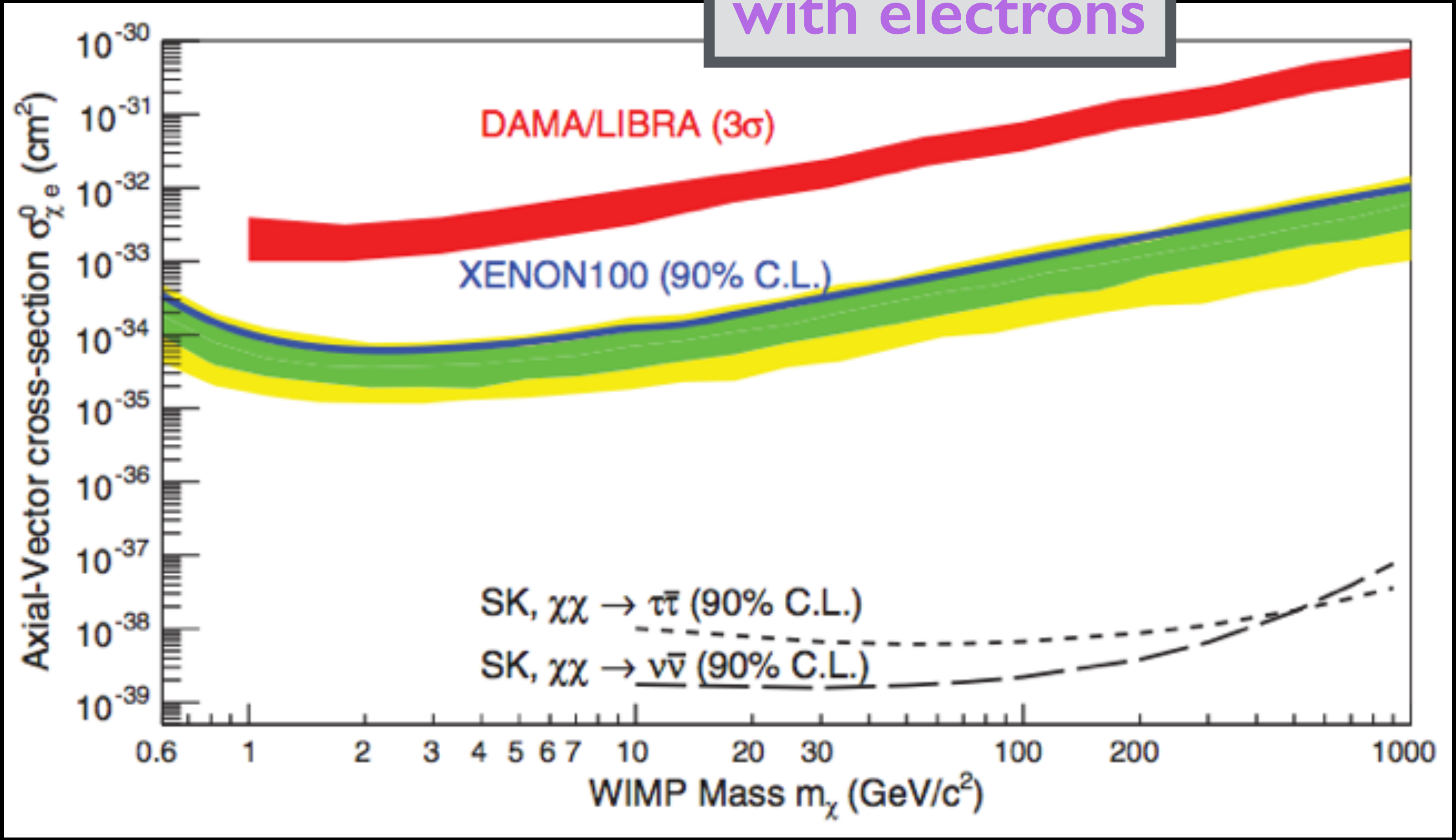


ATLAS and CMS
(WIMP production at the LHC)

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

Direct WIMP searches (2015)

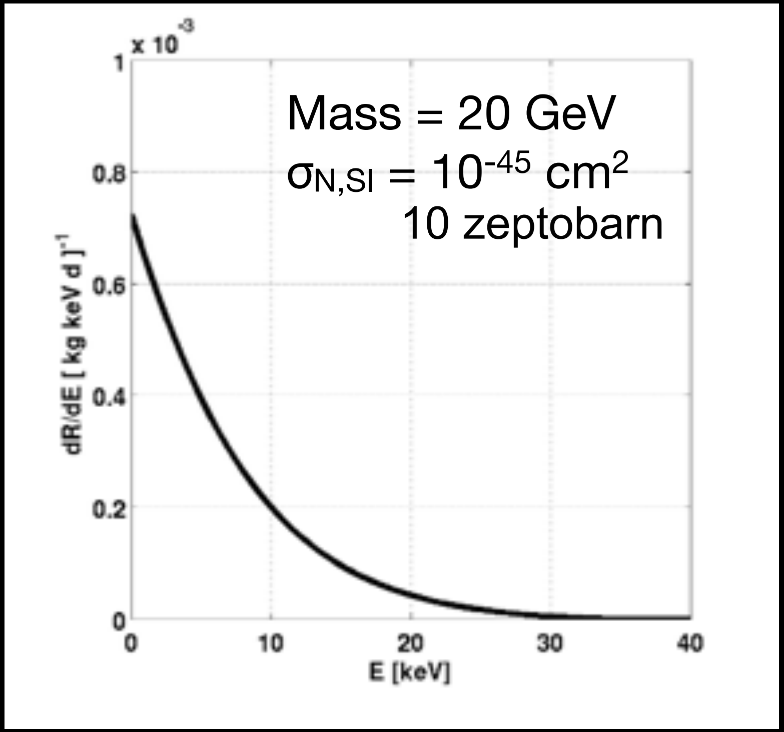
Interactions with electrons



Aprile et al (XENON100) 2015

Expected event rate is small

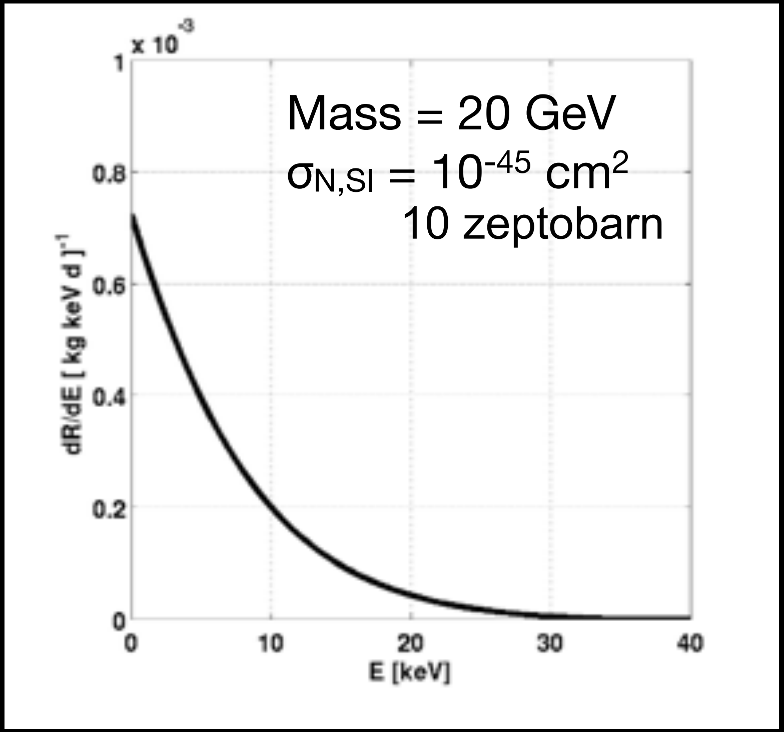
Expected
WIMP spectrum



~1 event/kg/year
(nuclear recoils)

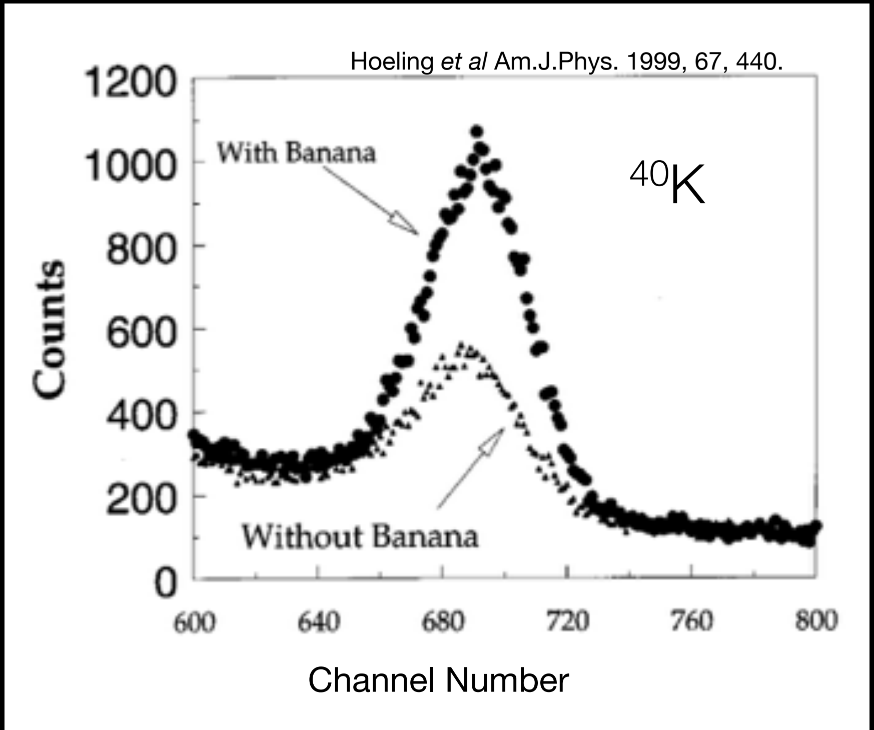
Expected event rate is small

Expected
WIMP spectrum



~1 event/kg/year
(nuclear recoils)

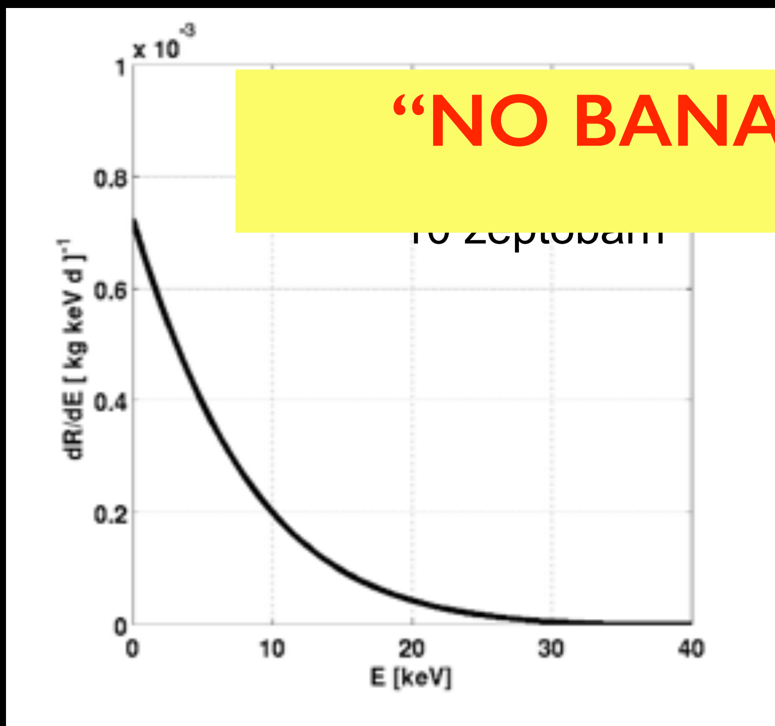
Measured
banana spectrum



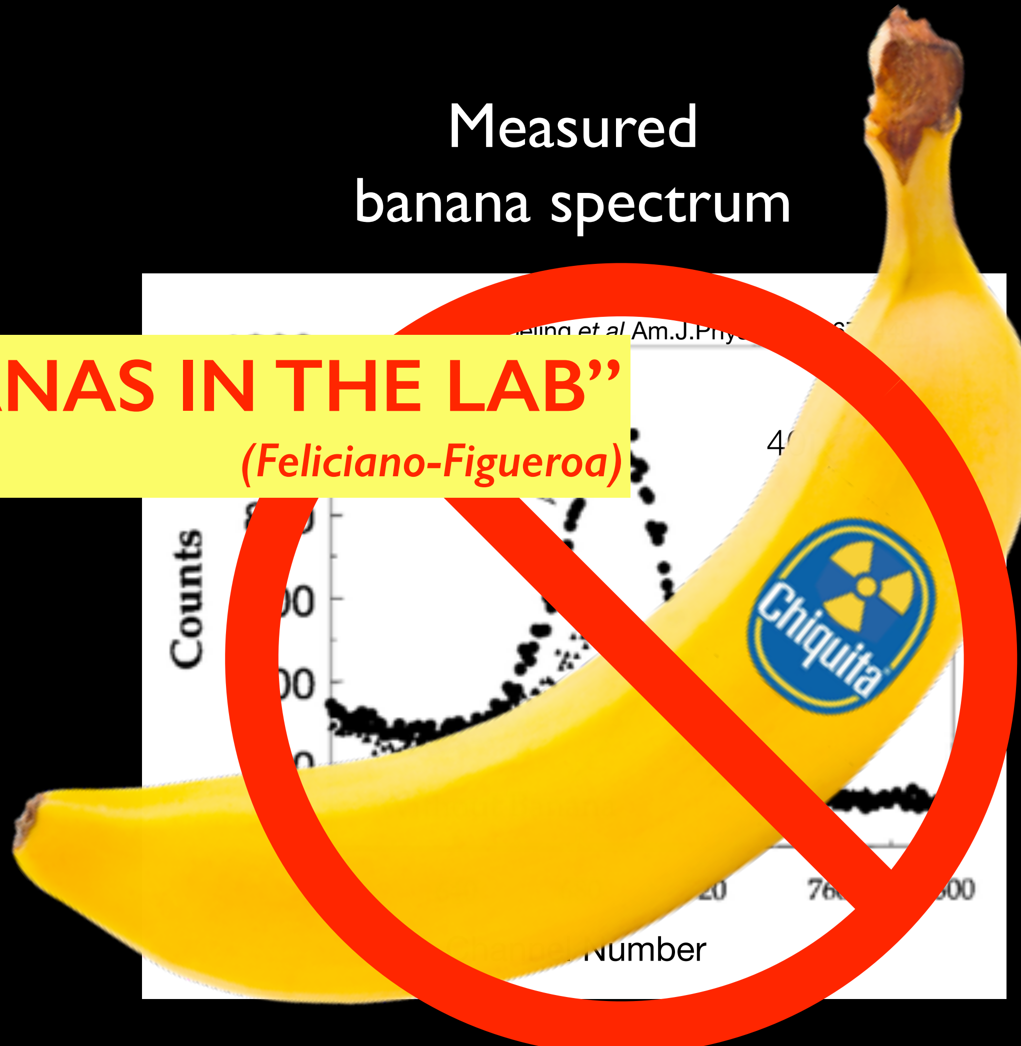
~100 events/kg/second
(electron recoils)

Expected event rate is small

Expected
WIMP spectrum



Measured
banana spectrum



"NO BANANAS IN THE LAB"

(Feliciano-Figueroa)

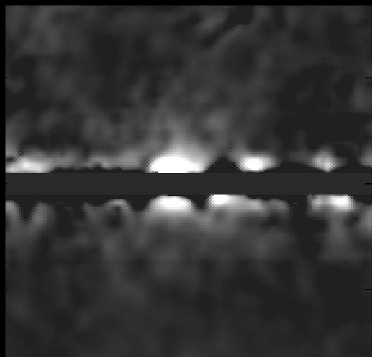
~1 event/kg/year
(nuclear recoils)

~100 events/kg/second
(electron recoils)

Confusion of the mind

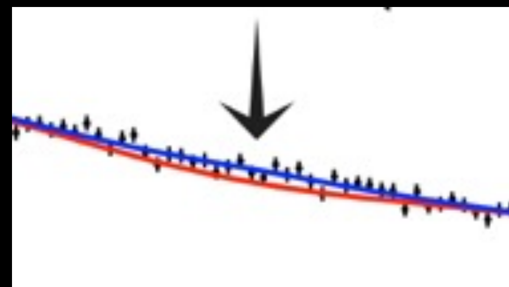
Evidence for cold dark matter particles?

GeV γ-rays



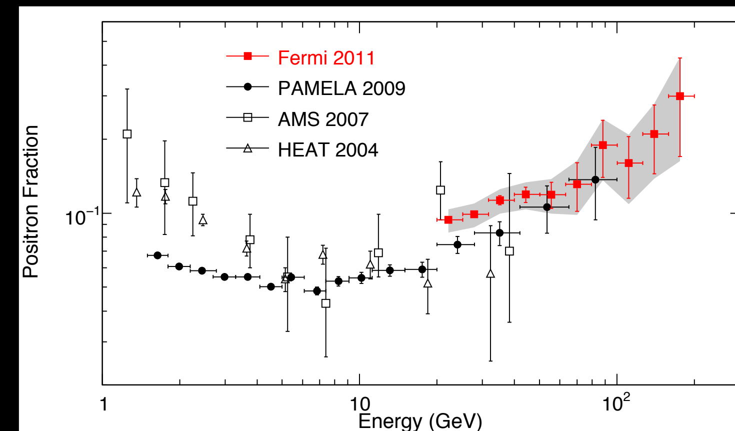
Hooper et al 2009-14

3.5 keV X-ray line



Bulbul et al 2014

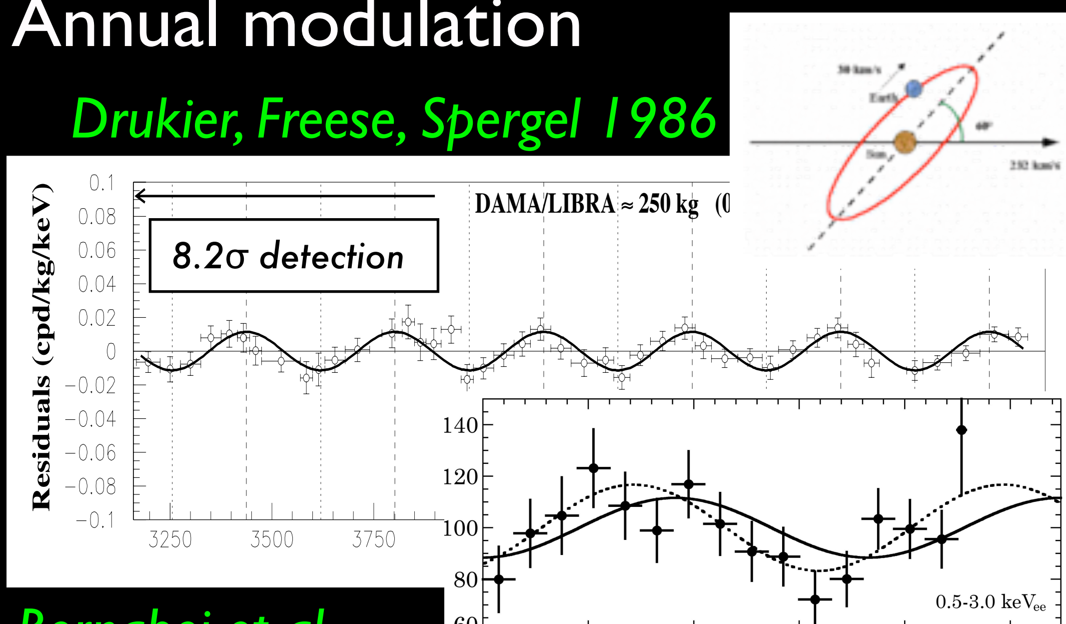
Positron excess



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?

Gamma-rays from dark matter

$$\begin{pmatrix}\gamma\text{-ray}\\ \text{flux}\end{pmatrix} = \begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} \times (\text{astrophysics})$$

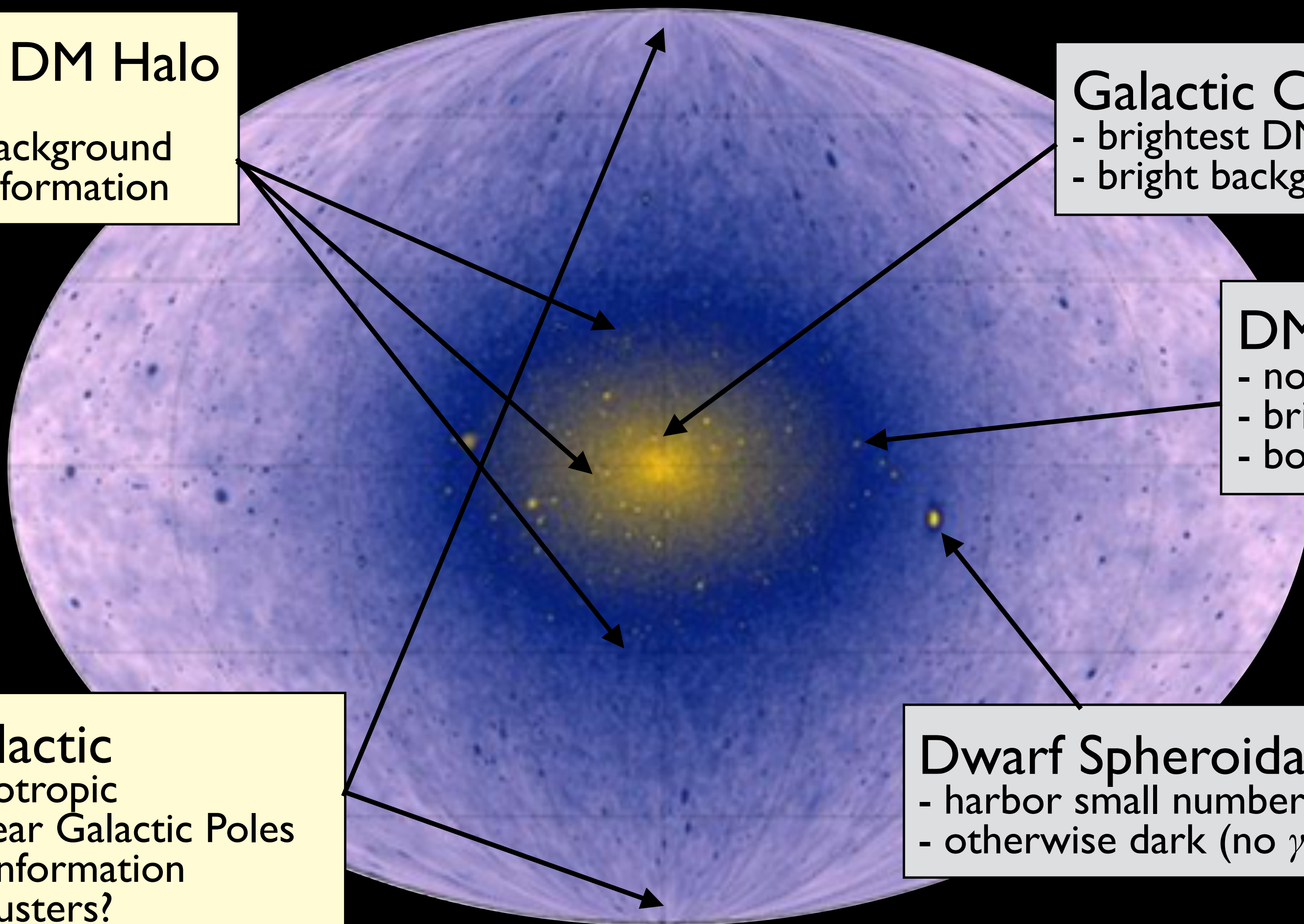
annihilation $$\frac{d^2\phi}{d\Omega\, dE} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN_\gamma}{dE} \times \int_{\text{l.o.s}} \rho^2\, ds$$

decay $$\frac{d^2\phi}{d\Omega\, dE} = \frac{1}{4\pi\tau_\chi m_\chi}\frac{dN_\gamma}{dE} \times \int_{\text{l.o.s}} \rho\, ds$$

Gamma-rays from WIMP annihilation

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

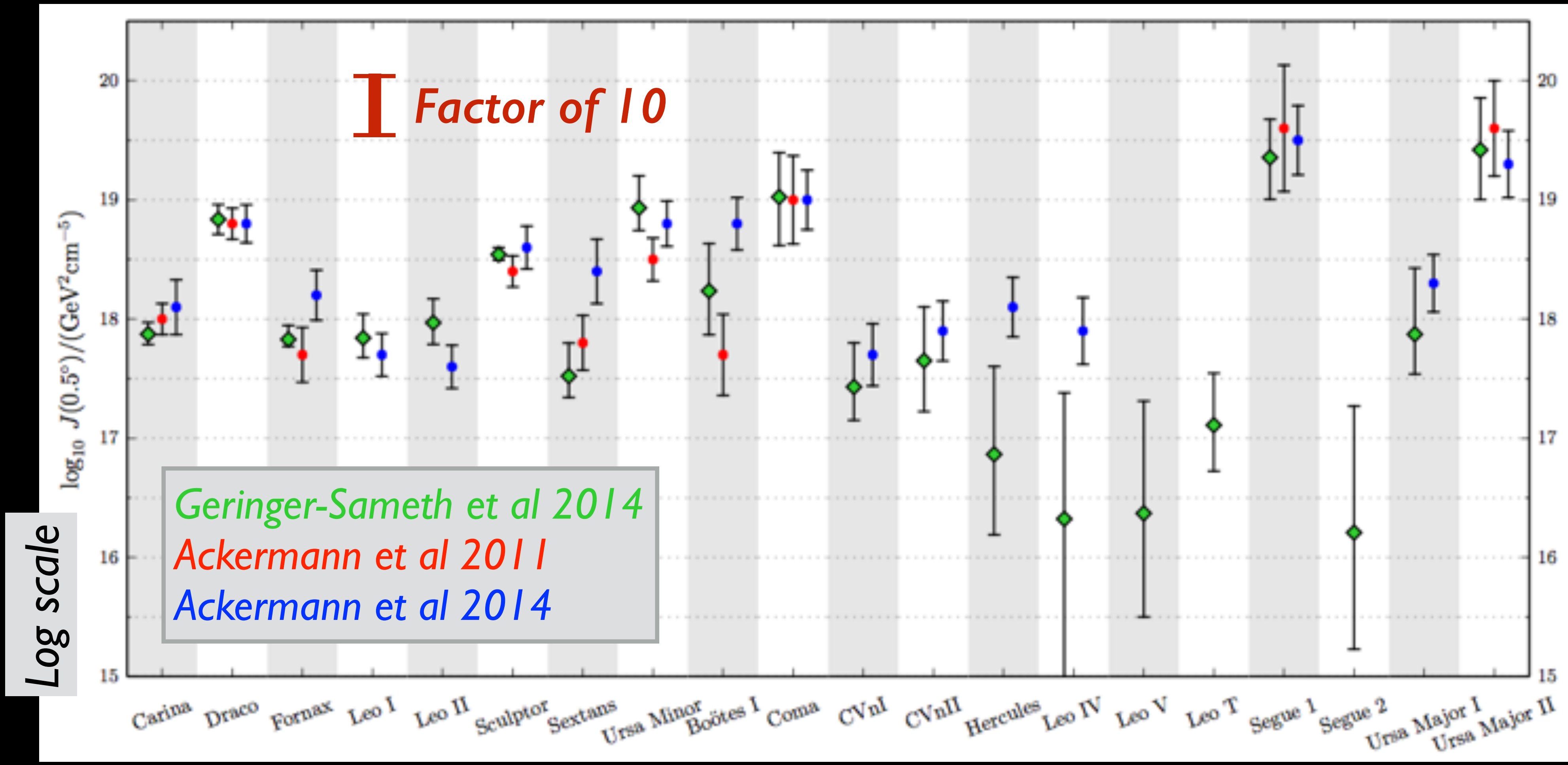
J factor



Kuhlen, Diemand, Madau 2007

Gamma-rays from dark matter

Astrophysical uncertainty in the J factors of dwarf spheroidals

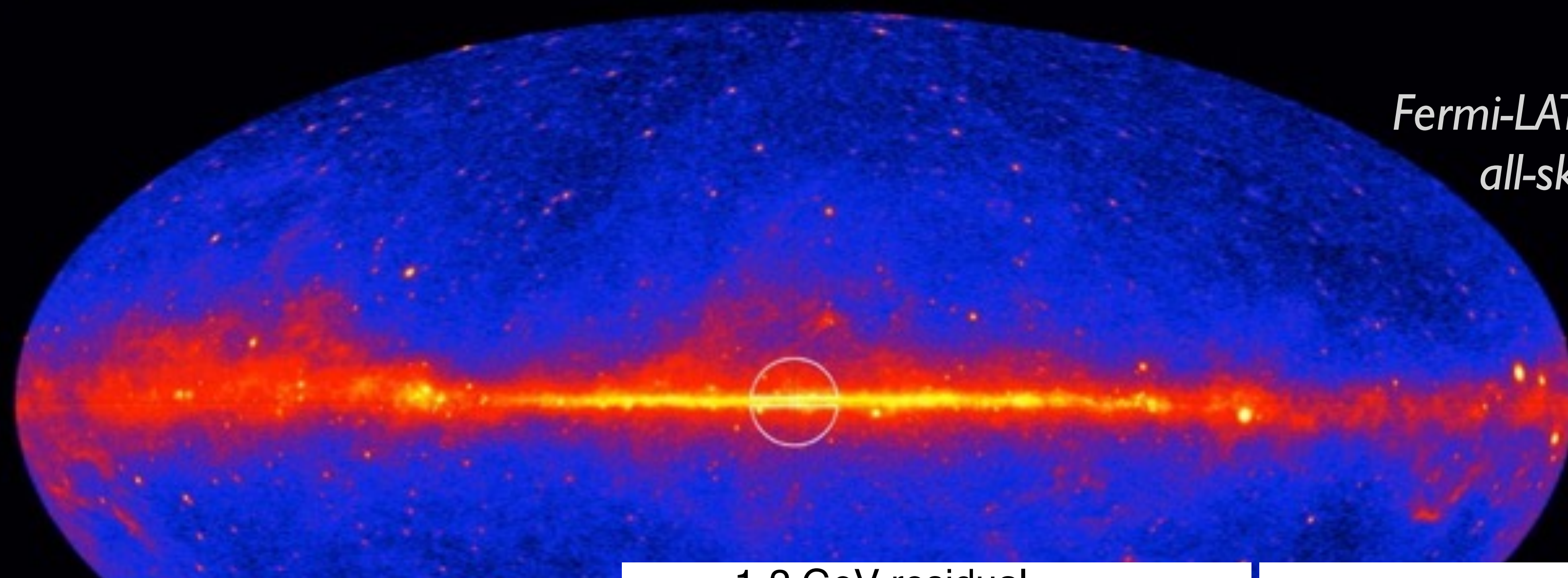


Geringer-Sameth, Koushiappas, Walker 1408.0002

Large statistical and systematic uncertainties

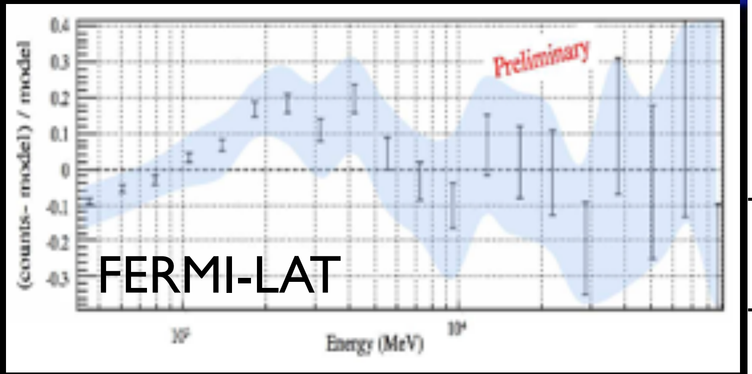
1 GeV gamma-ray excess?

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

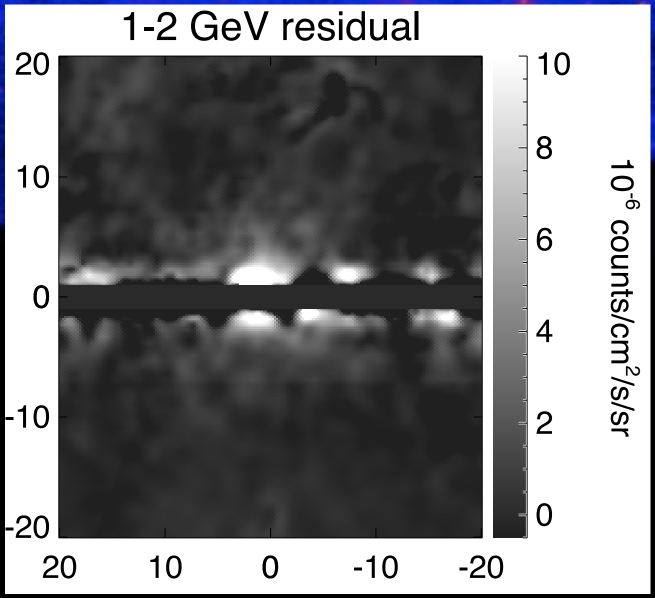


Fermi-LAT all-sky map

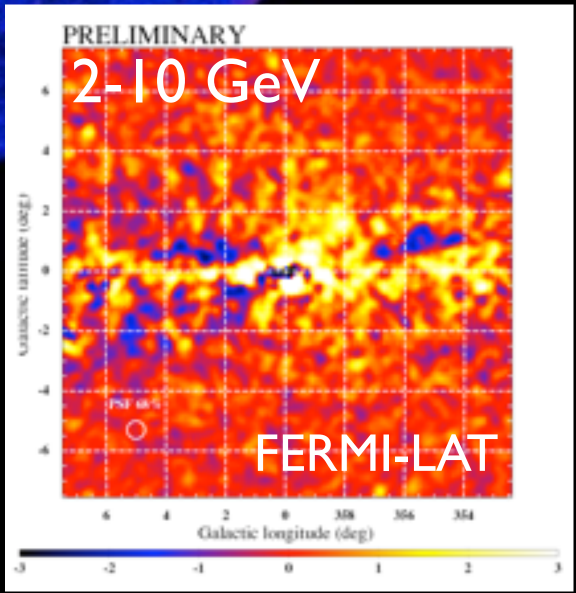
Fit model of known emission.
Find residual.



Vitale, Morselli et al 2009



Daylan et al 2014



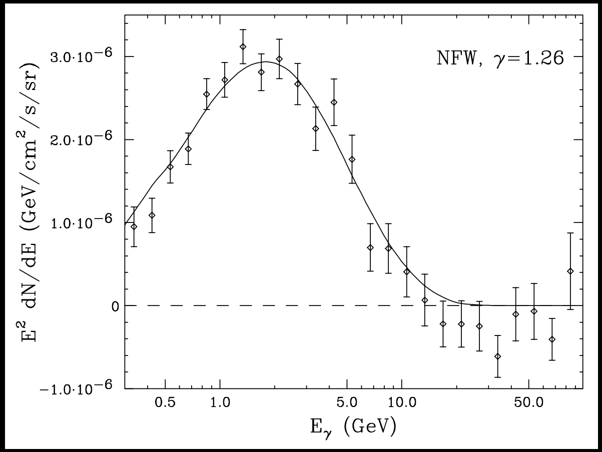
Murgia et al 2014

1 GeV gamma-ray excess?

- Dark matter annihilation

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

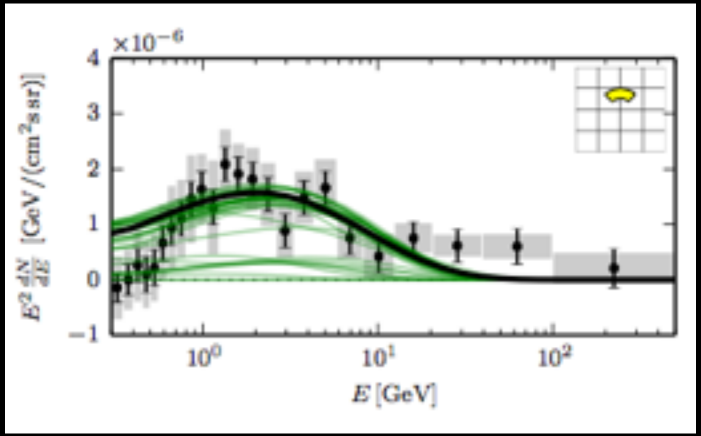
  Possible for specific WIMP and dark halo models



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

  Petrovic et al 2014; Cholis et al 2015; ………

  Possible with suitable diffusion parameters



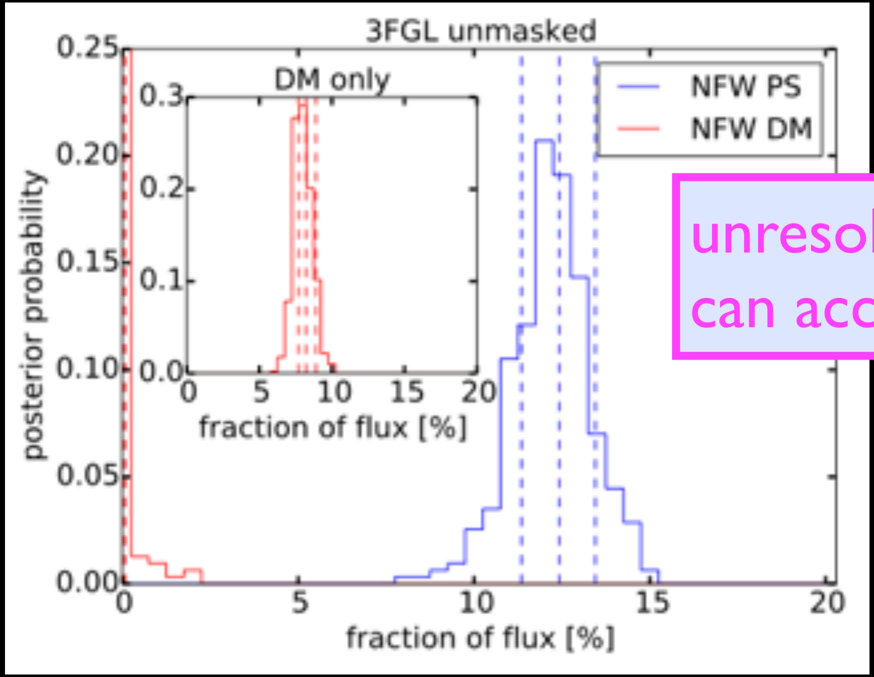
- Millisecond pulsars

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

  Can be tested by one-point statistics or wavelet analysis

1 GeV gamma-ray excess?

Dark matter or point sources?



Lee, Lisanti, Safdi 2014

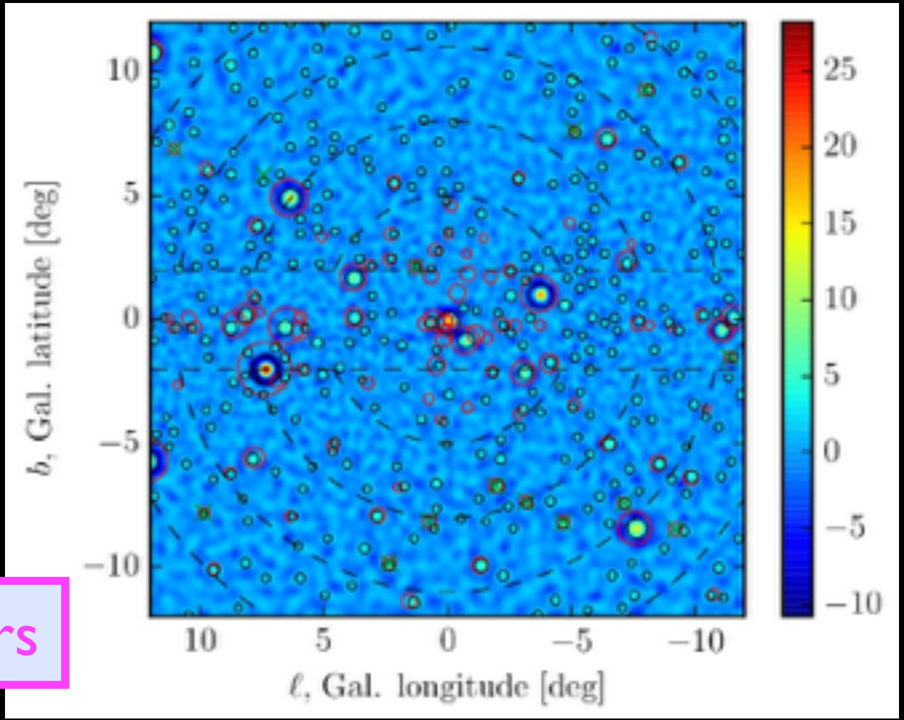
Non-Poissonian point-source templates

unresolved point sources can account for the excess

Wavelet analysis favors millisecond pulsars

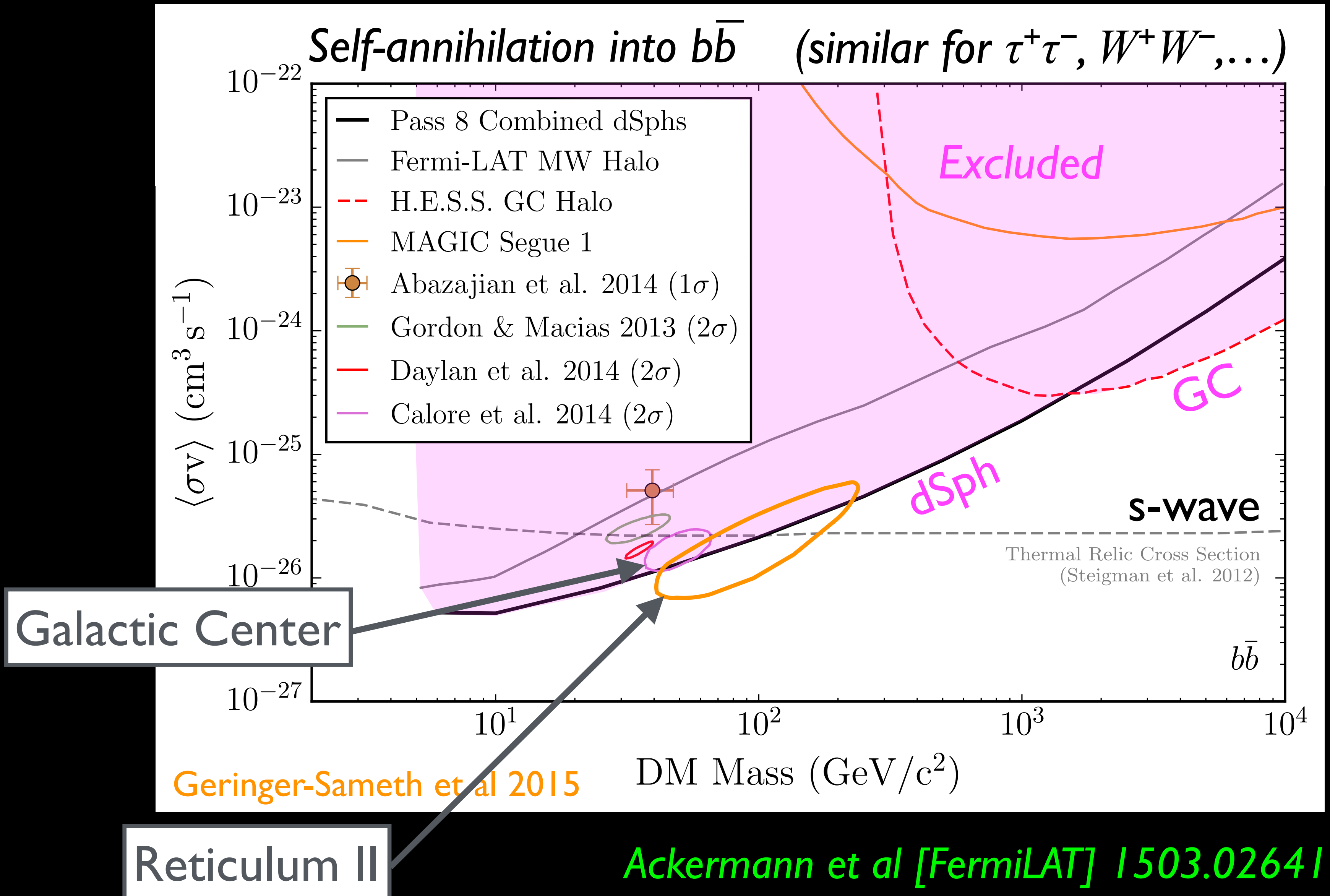
Bartels, Krishnamurthy, Weniger 2015

looks like pulsars



Gamma-rays from dark matter

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



Ackermann et al [FermiLAT] 1503.02641

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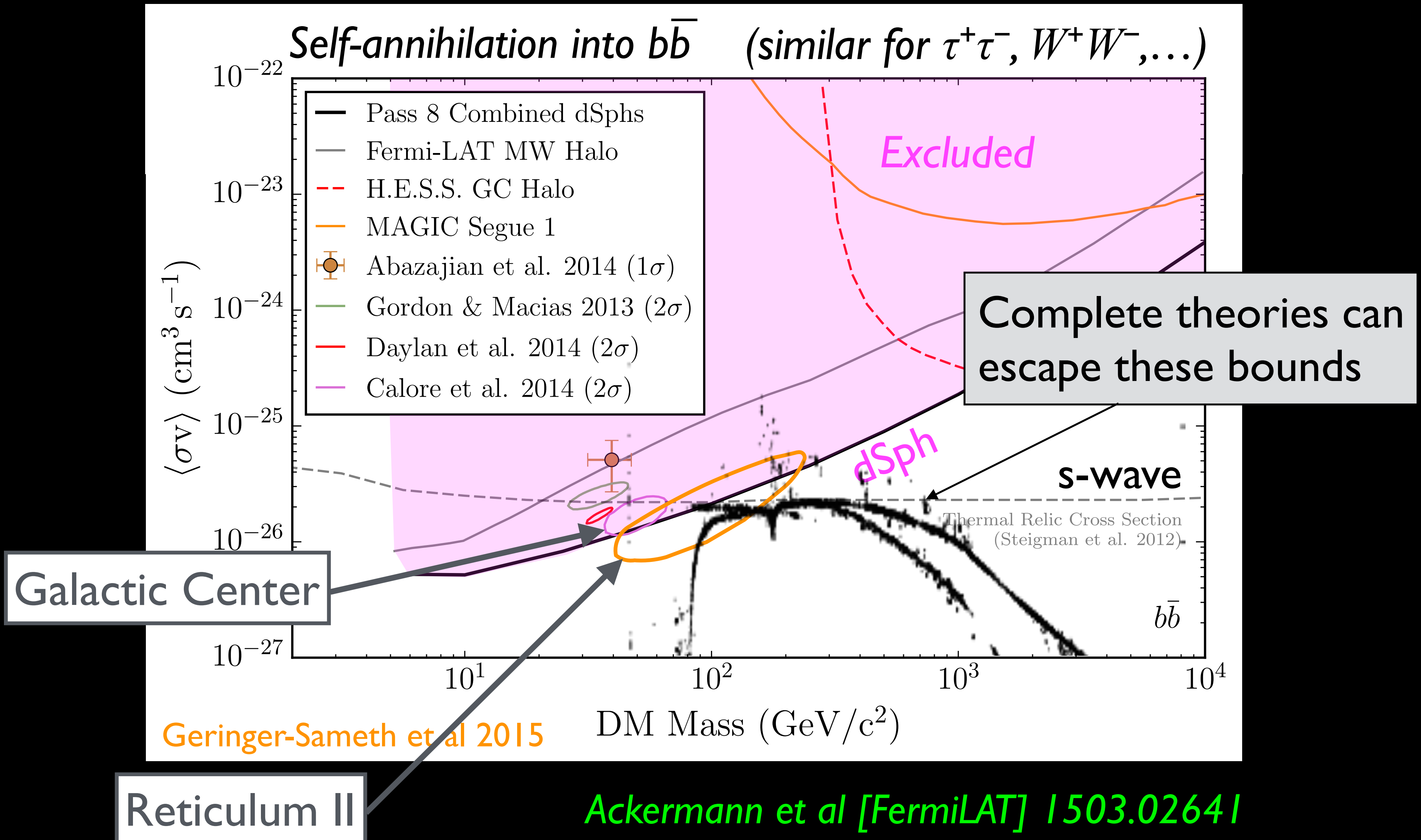
Upper limits on the WIMP annihilation cross section
from dwarf spheroidal galaxies and Galactic Center



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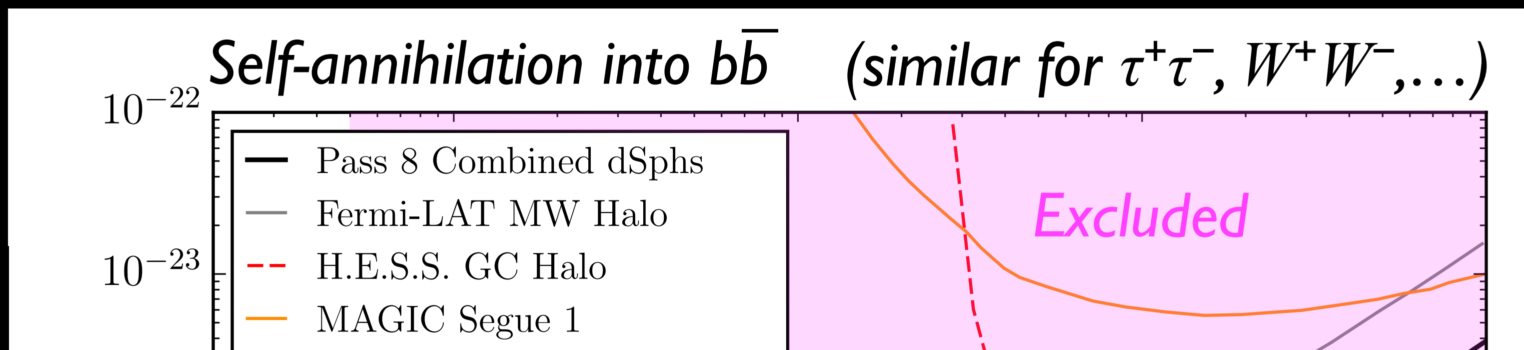
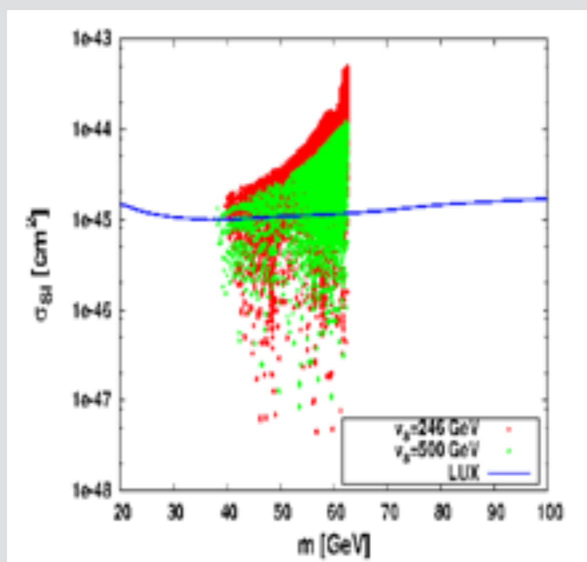


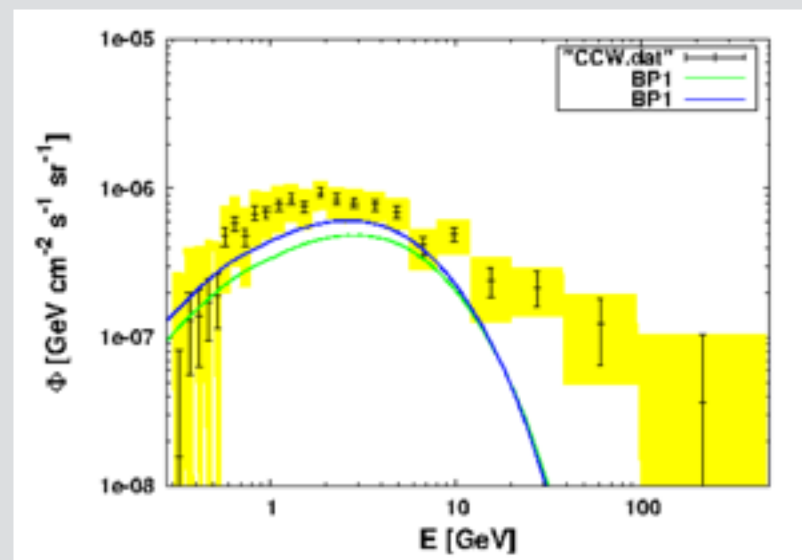
Galactic Center

Reticulum II

Ackermann et al [FermiLAT] 1503.02641

Complete theories can be compatible with all constraints





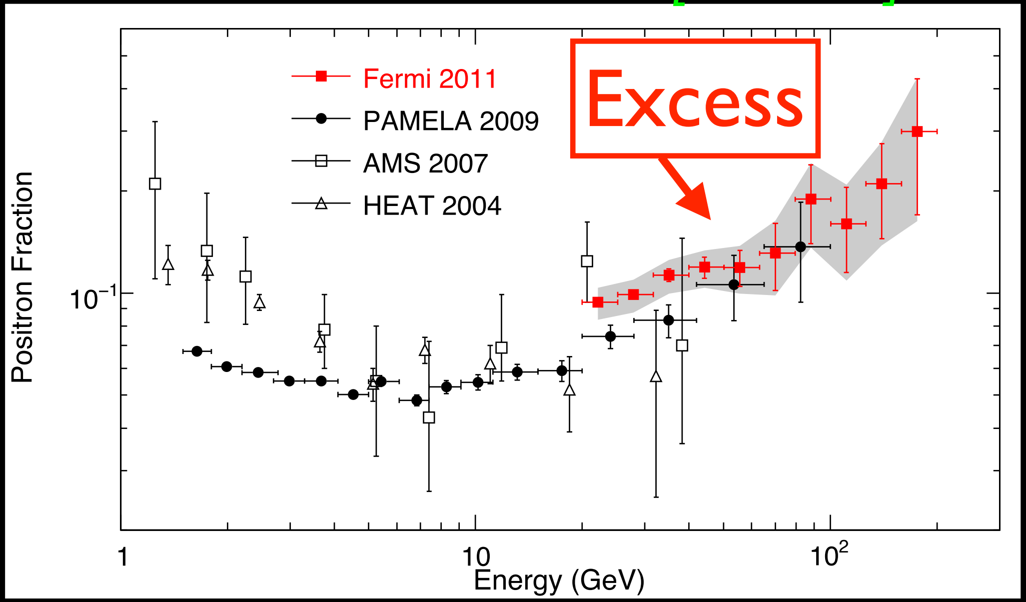
Banik, Majumdar, Biswas 2015

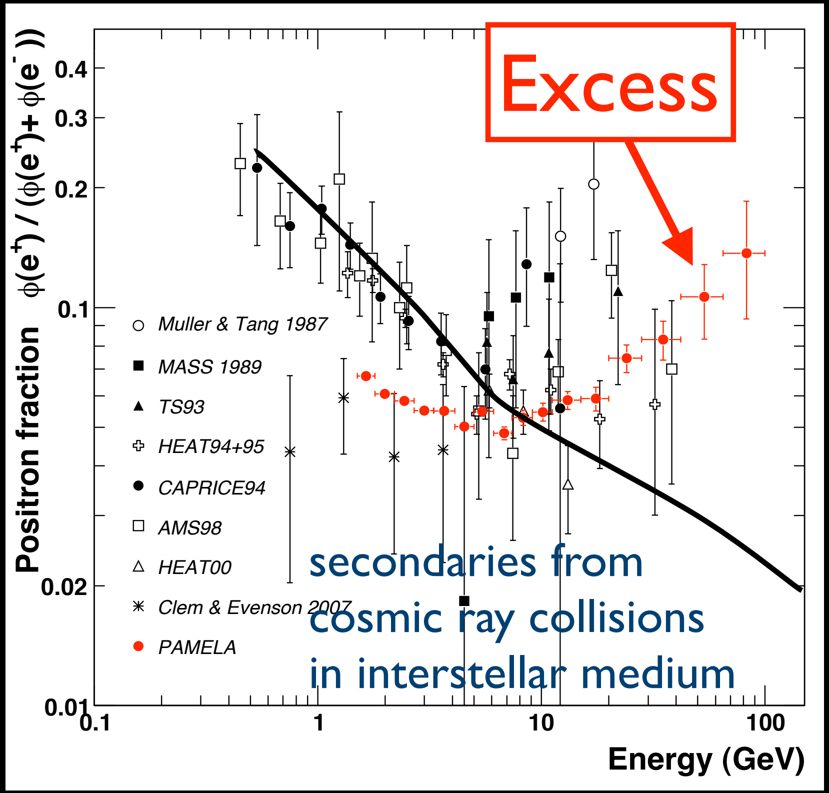
Positrons from dark matter?

Excess in cosmic ray positrons

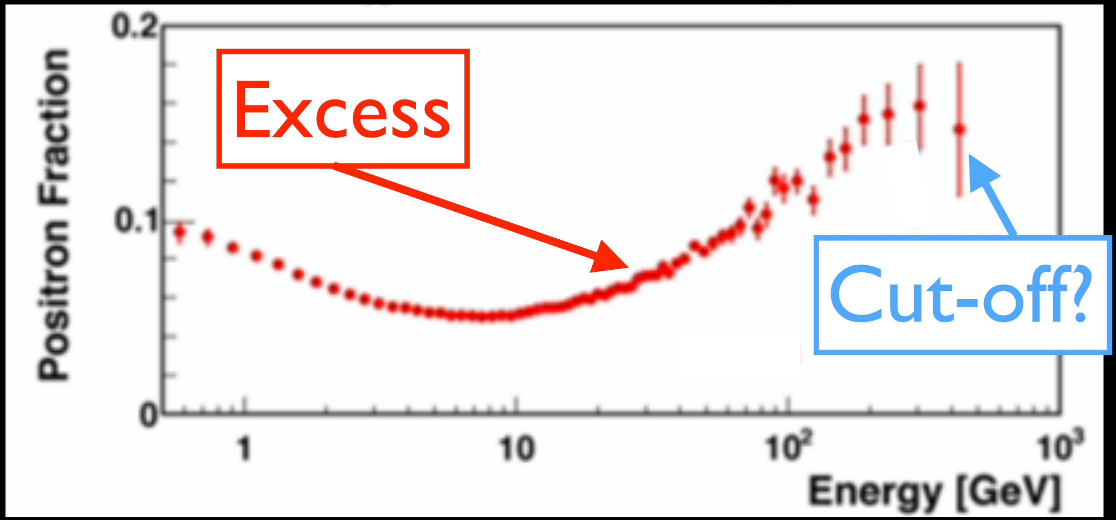
High energy cosmic ray positrons are more than expected

Ackernmann et al [Fermi-LAT] 2011





Adriani et al. [PAMELA ,2008

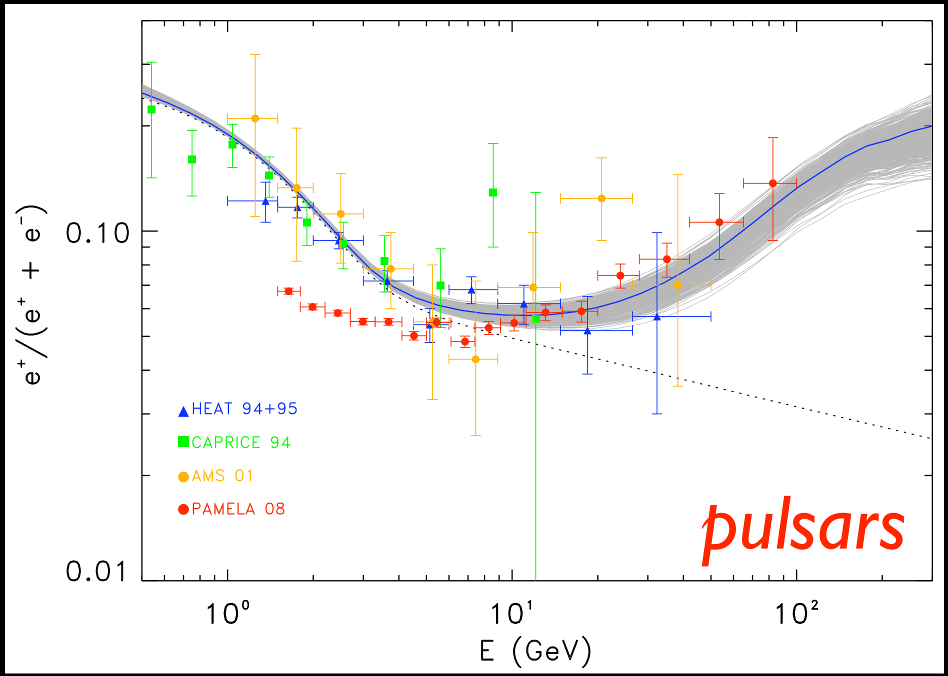


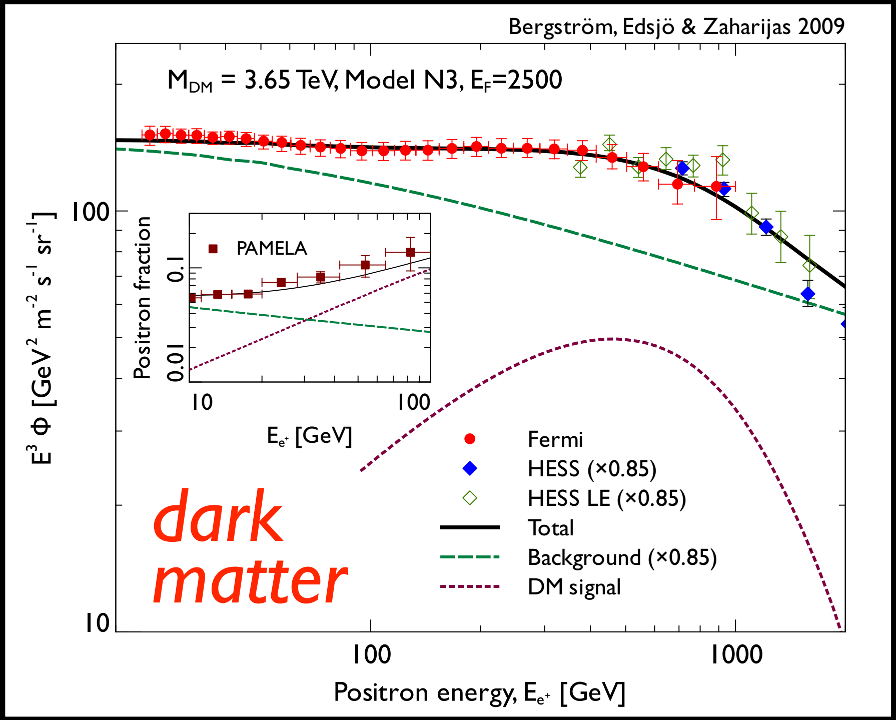
Accardo et al [AMS-02] 2014

Excess in cosmic ray positrons

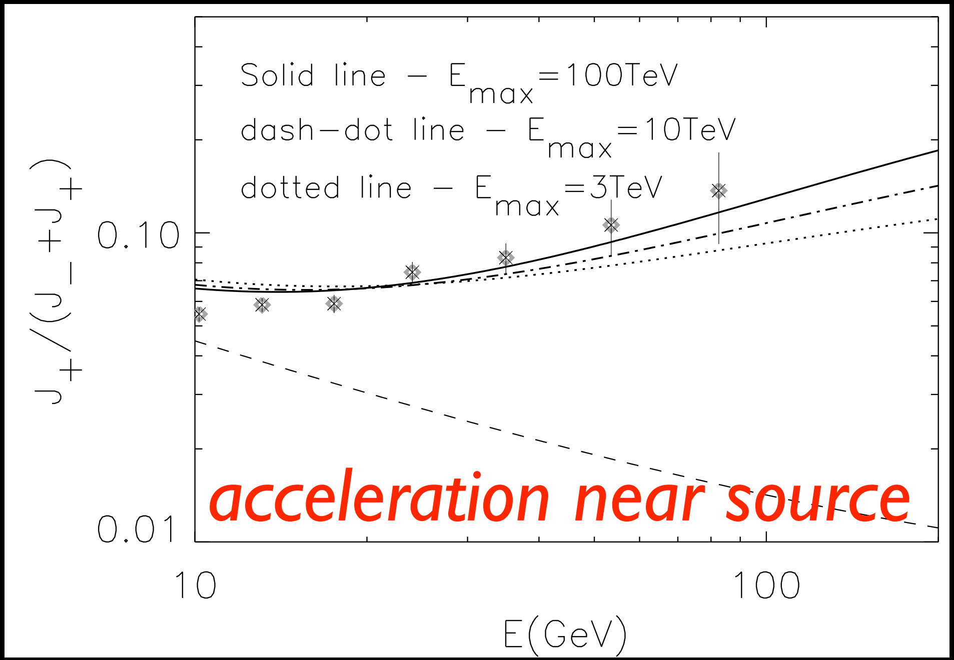
Dark matter?
Pulsars?
Secondaries from extra primaries?

Grasso et al [Fermi-LAT] 2009





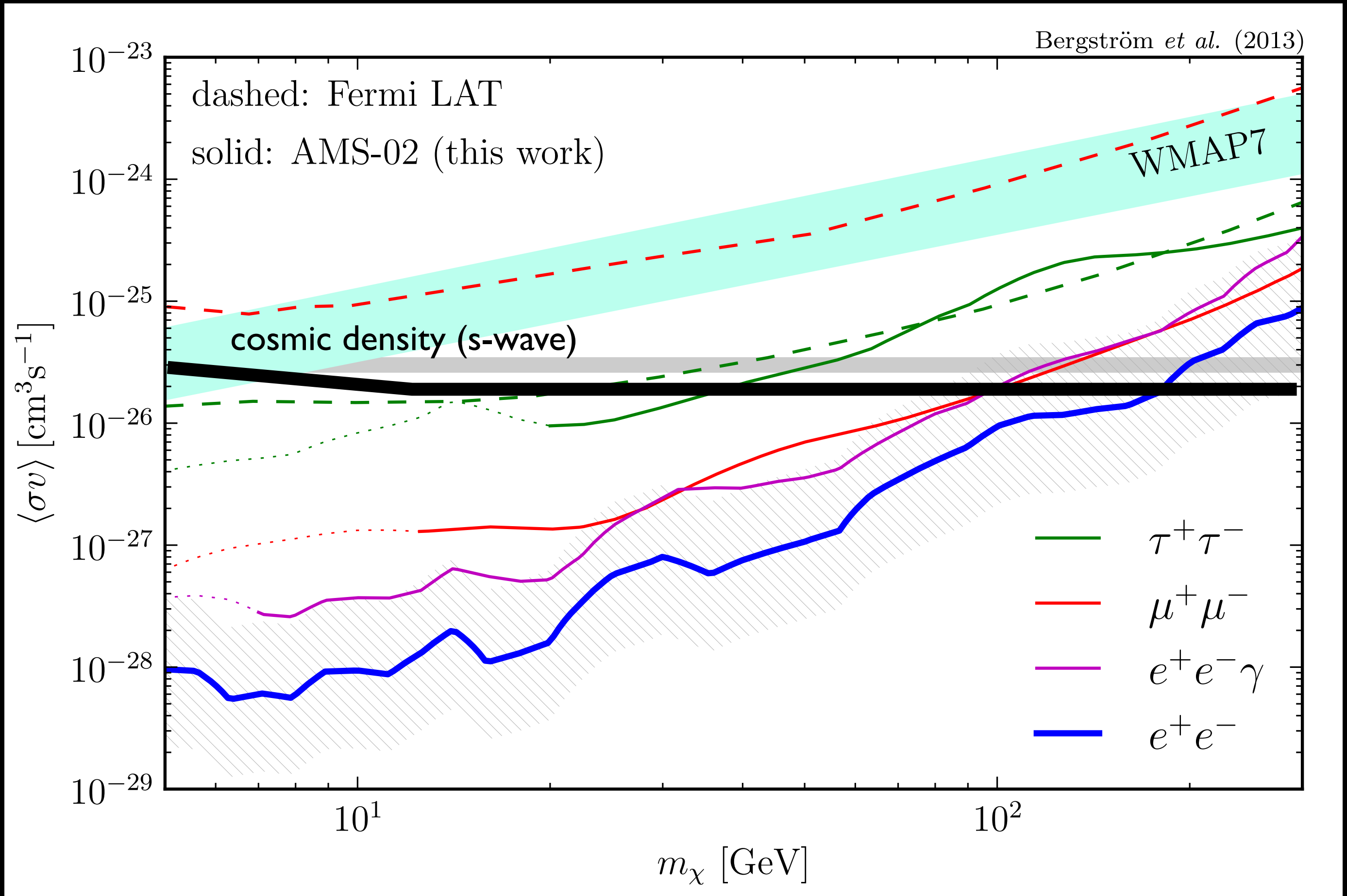
Bergstrom, Edsjo, Zaharijas 2009



Blasi 2009

Excess in cosmic ray positrons

The safe way: use the AMS spectrum purely as upper limit on positrons from WIMP dark matter.



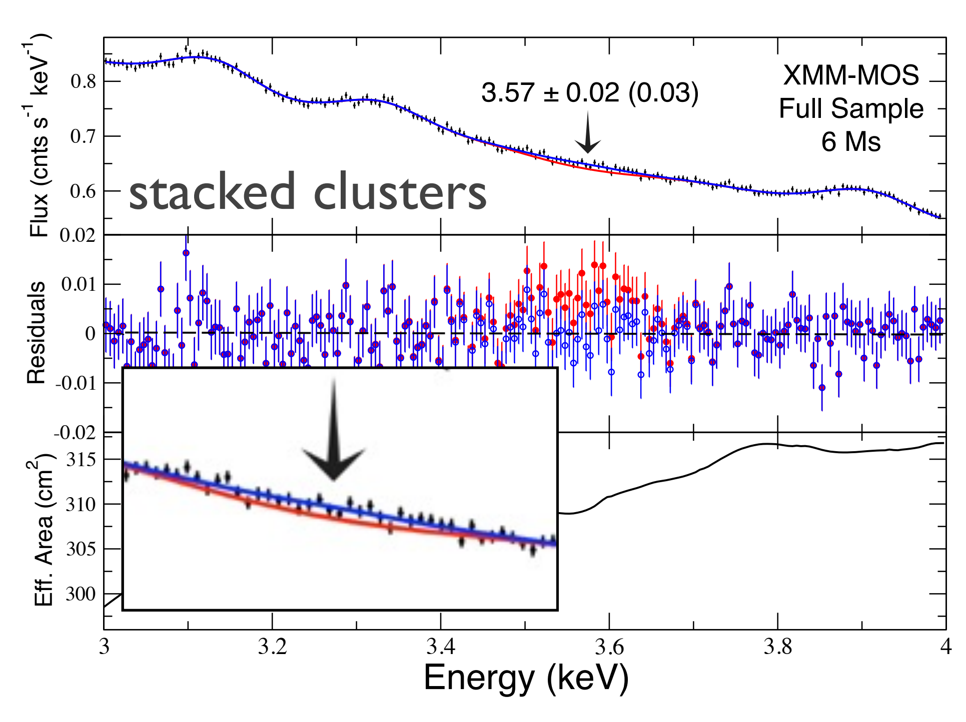
Bergstrom et al 2013

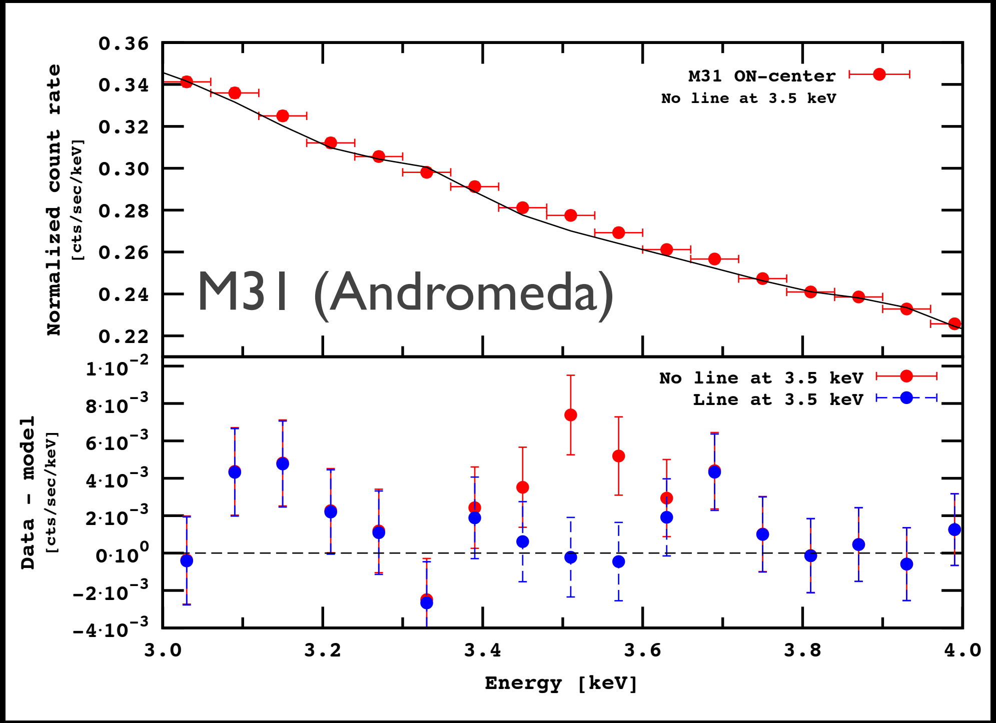
X-rays from dark matter?

X-rays from dark matter?

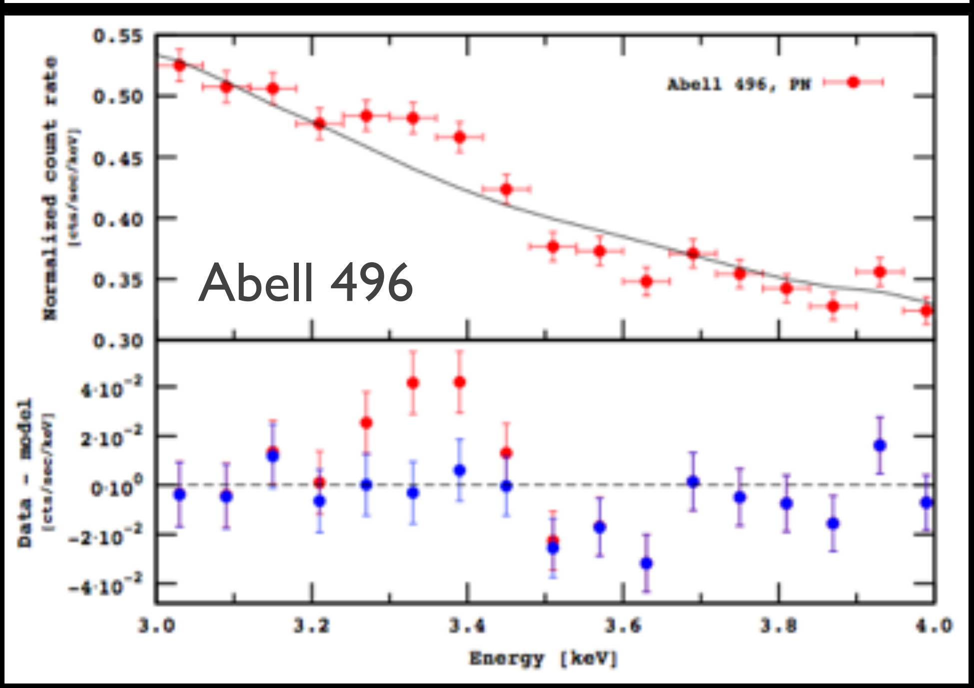
Bulbul et al 2014

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





Boyarsky et al 2014



Iakubovskyi et al 2015

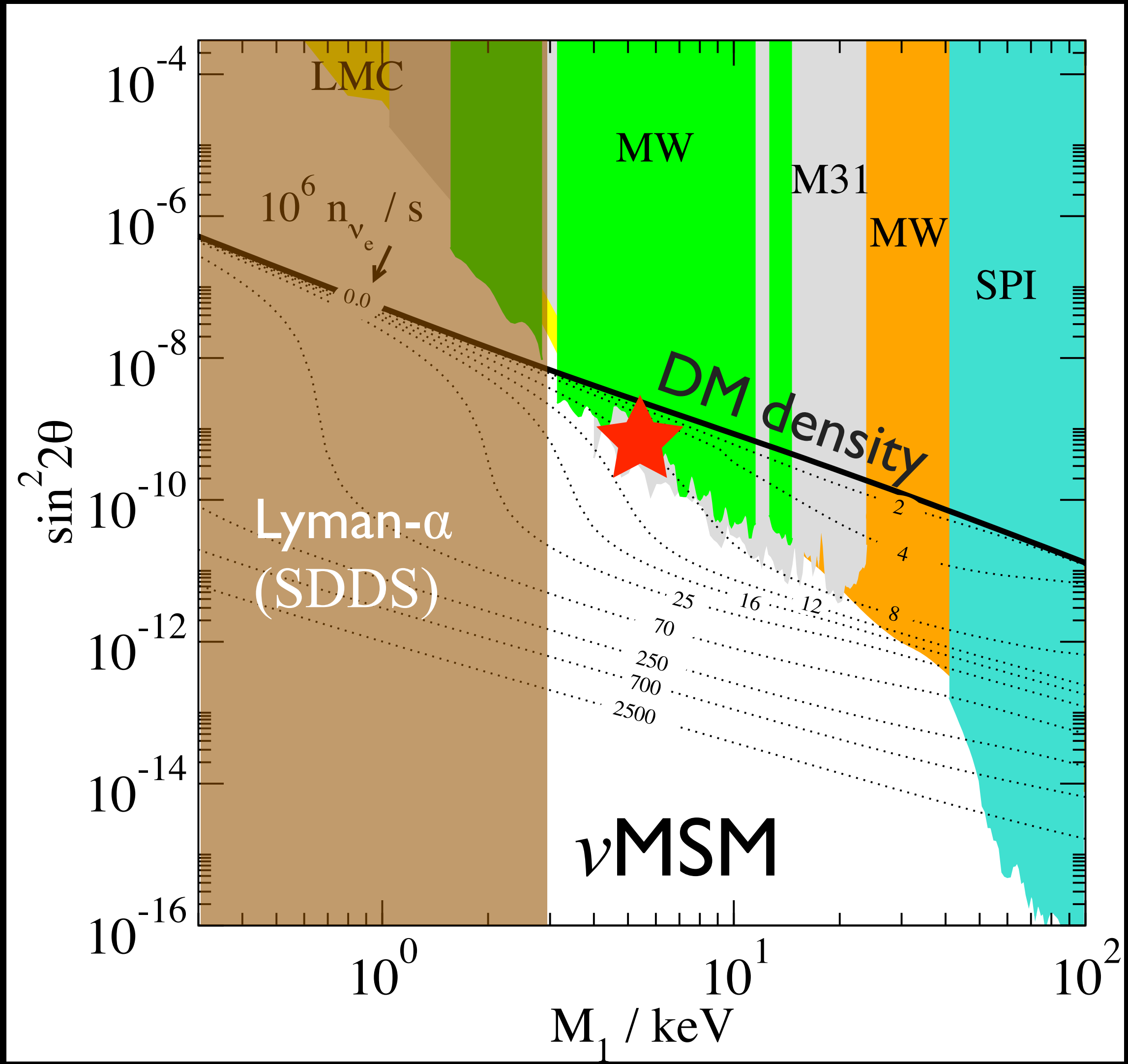
X-rays from dark matter?

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

X-ray line $E_\gamma = \frac{1}{2}m_s$

m_ν = 7.1 keV

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



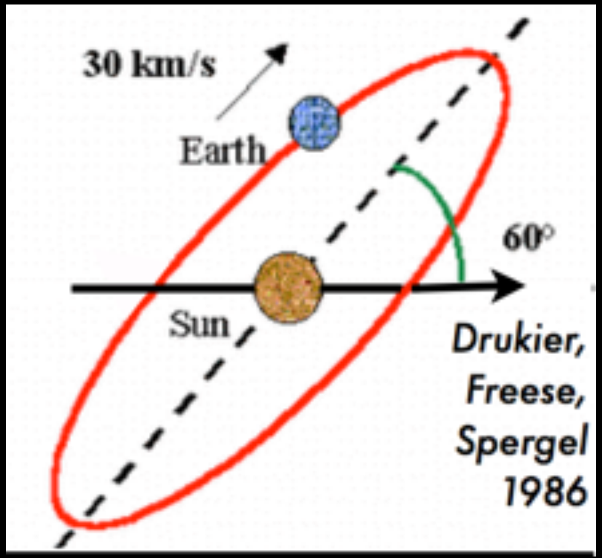
Laine, Shaposhnikov 2008

Direct detection of dark matter?

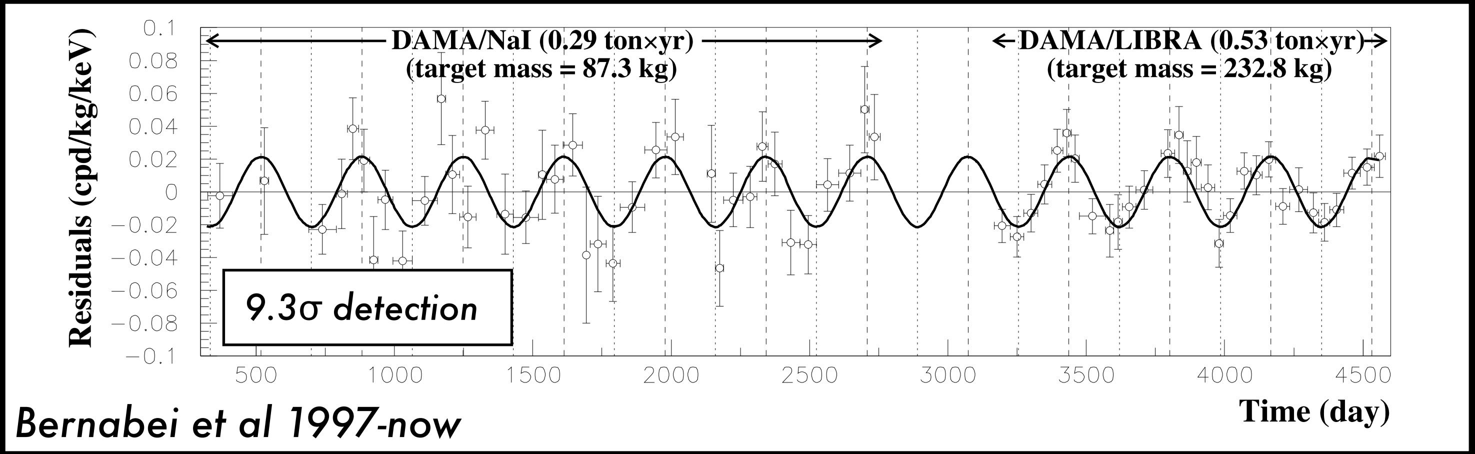
Annual modulation in direct detection

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

Drukier, Freese, Spergel 1986

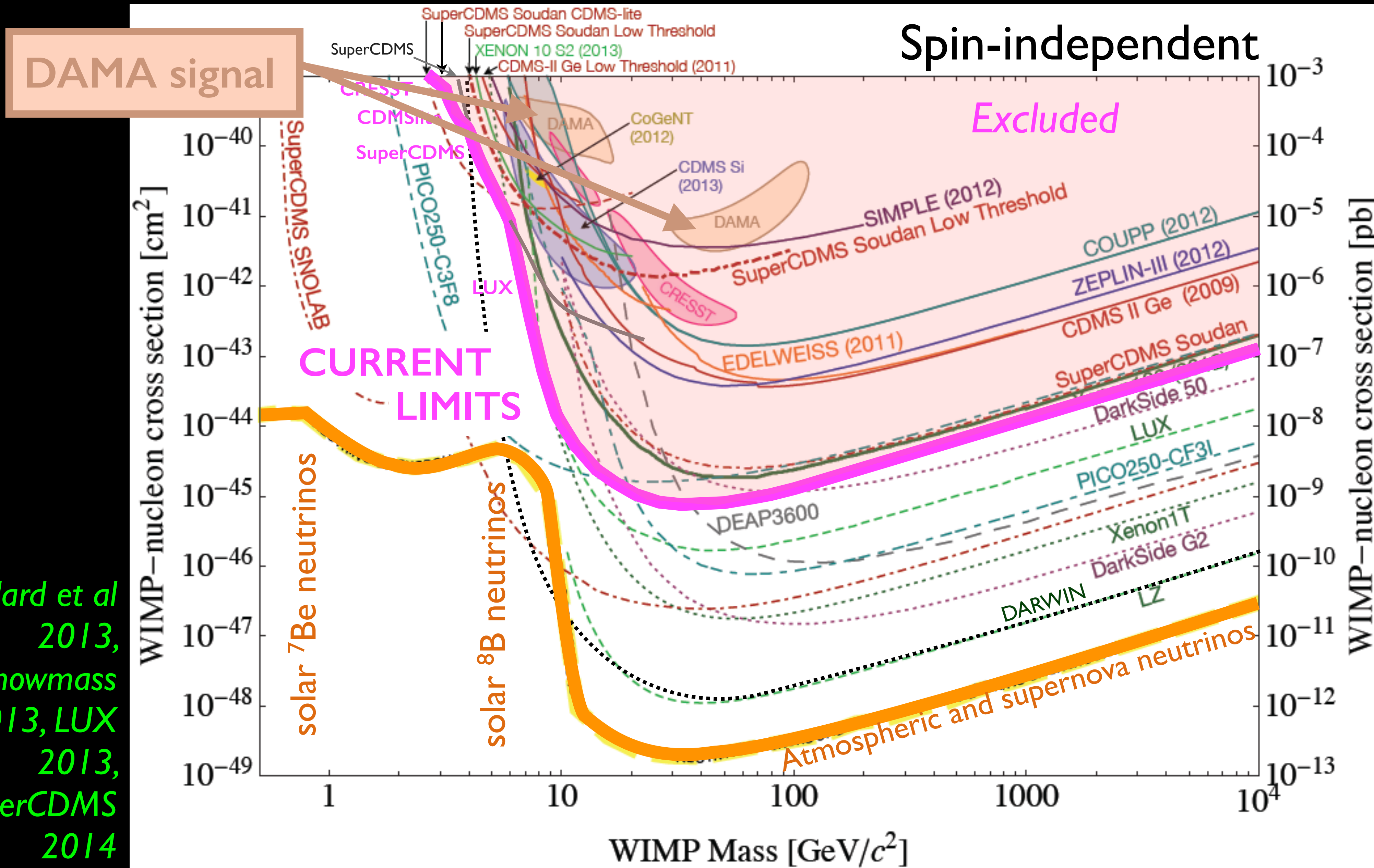


- DAMA observes such kind of modulation



Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments



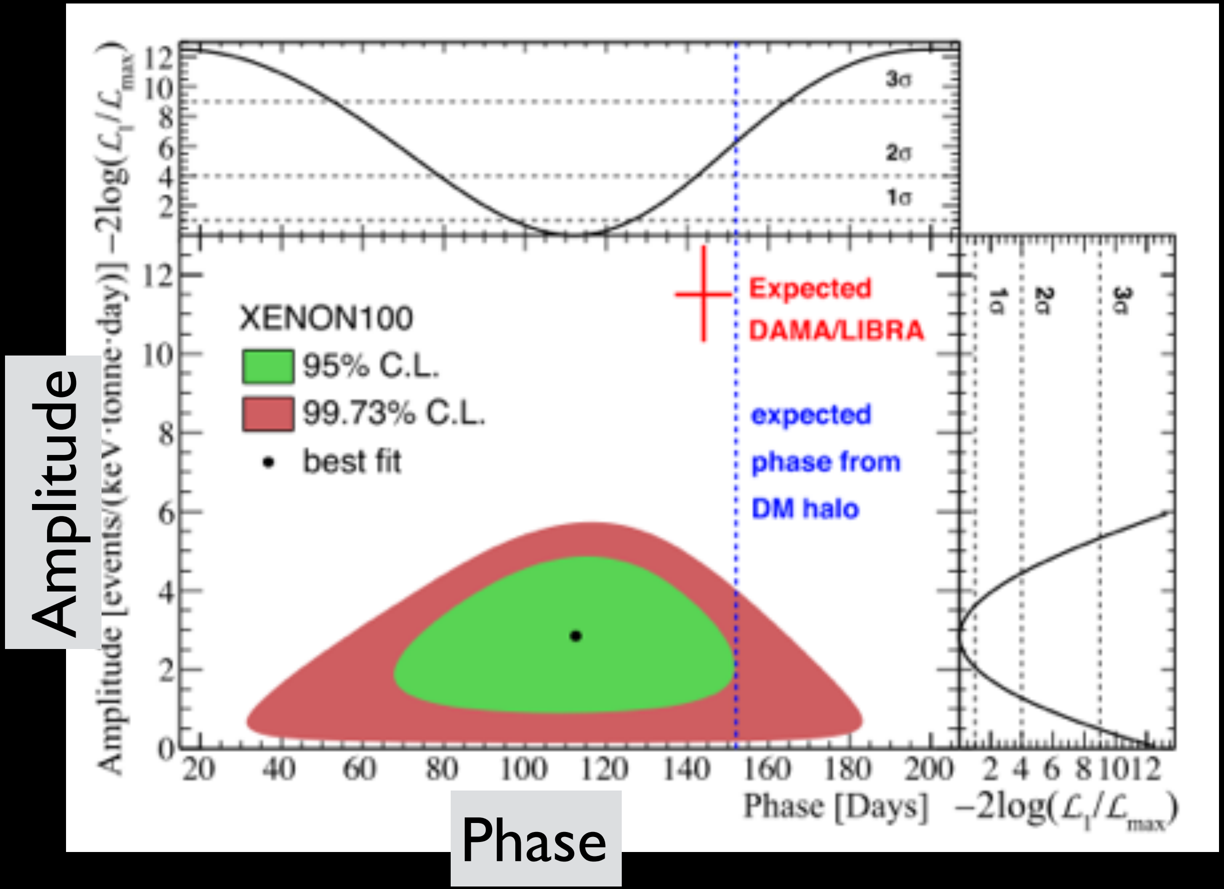
Billard et al 2013, Snowmass 2013, LUX 2013, SuperCDMS 2014

Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments

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

NOT due to dark matter
NOT compatible with DAMA's



Aprile et al (XENON) 2015

DAMA modulation

Model Independent Annual Modulation Result

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

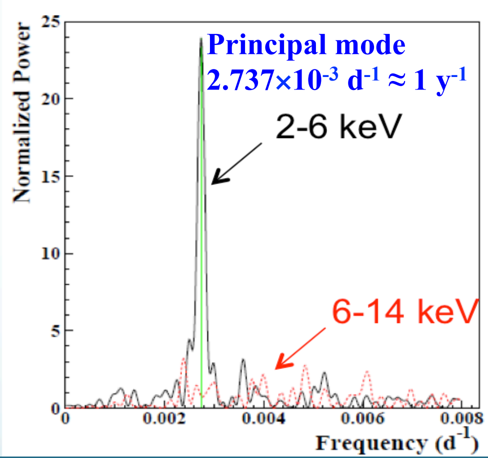
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

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

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

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

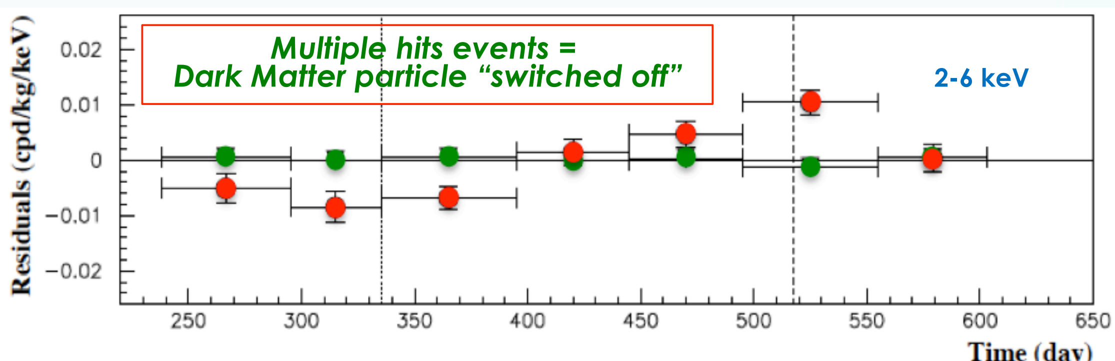
Power spectrum



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

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events

A=-(0.0005±0.0004) cpd/kg/keV



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

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

Belli, IDM2014

DAMA modulation

Model Independent Annual Modulation Result

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

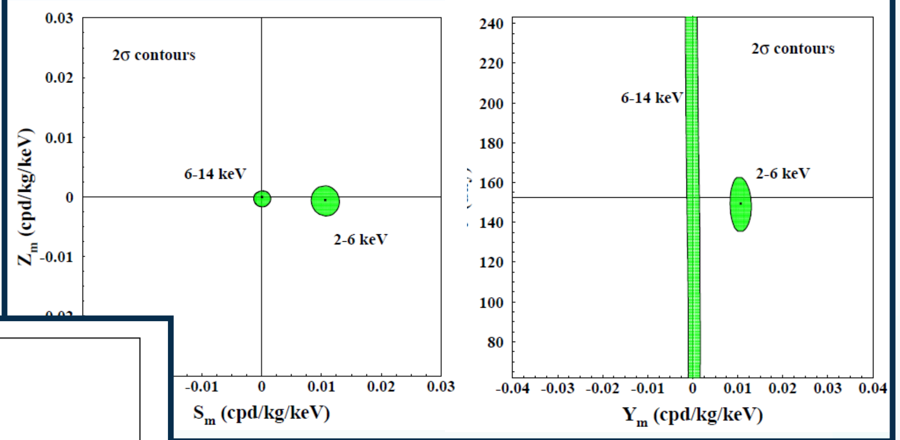
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

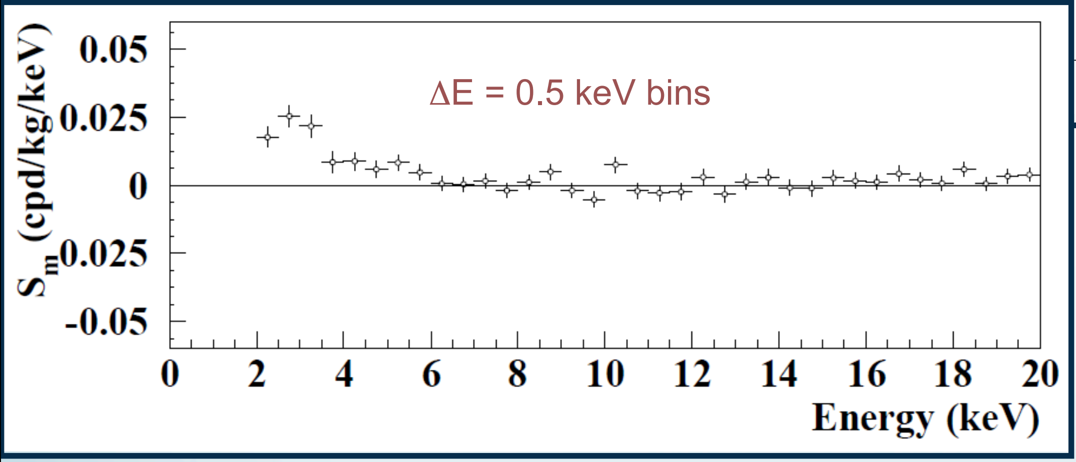
- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

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

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

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

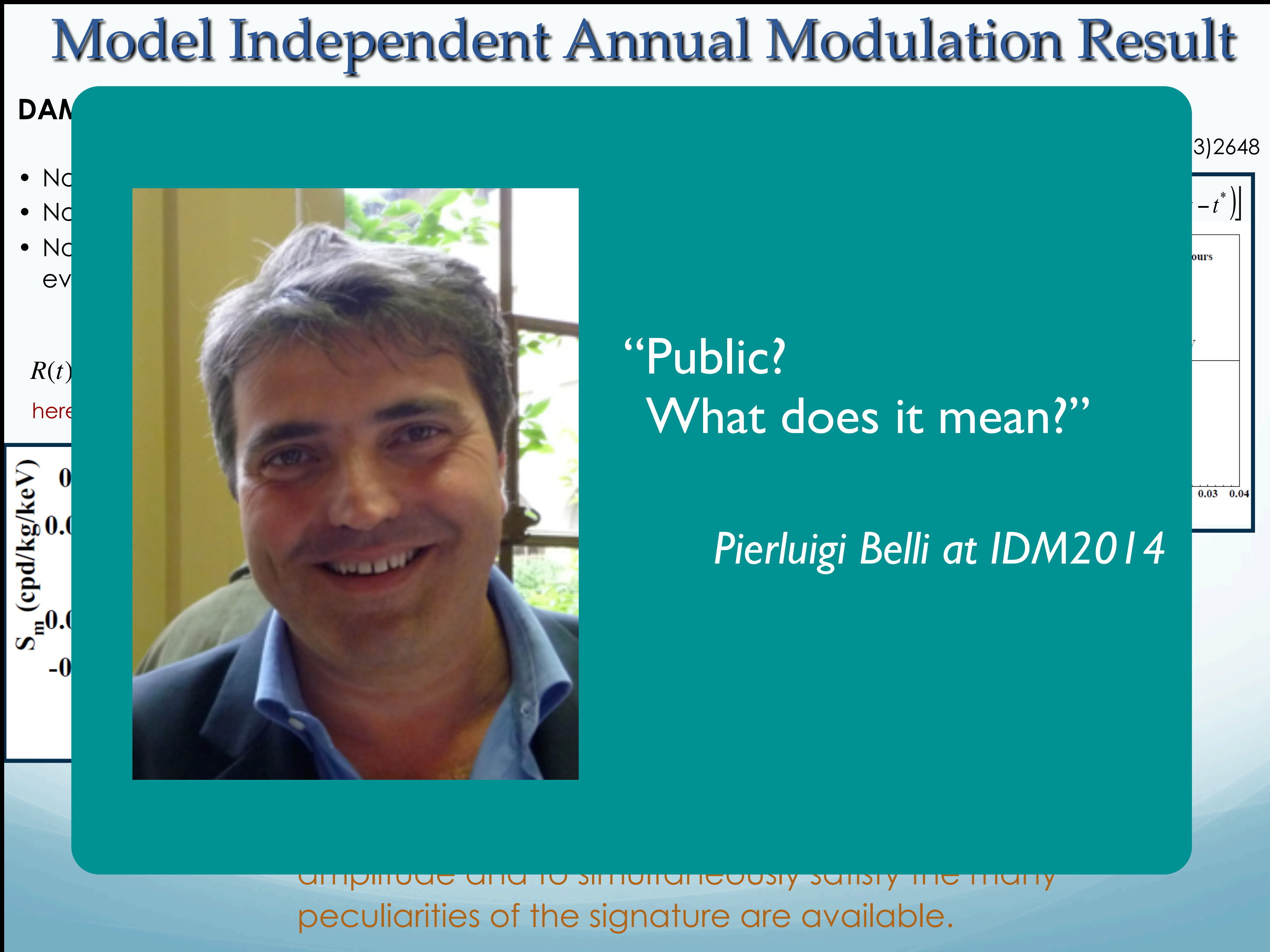




No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy the many peculiarities of the signature are available.

Belli, IDM2014

DAMA modulation



“Public?
What does it mean?”

Pierluigi Belli at IDM2014

Belli, IDM2014

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

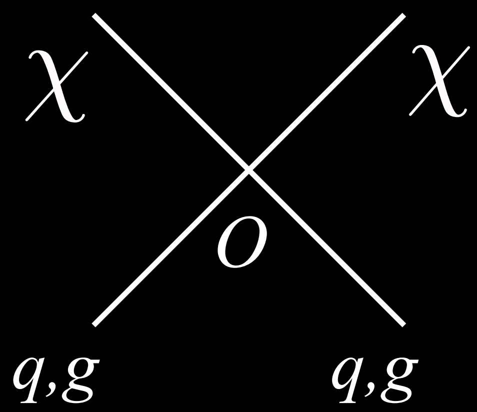
- Halo-independent methods of analysis have been developed
- Ideally they require no assumption on the astrophysical density and velocity distributions of dark matter particles

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

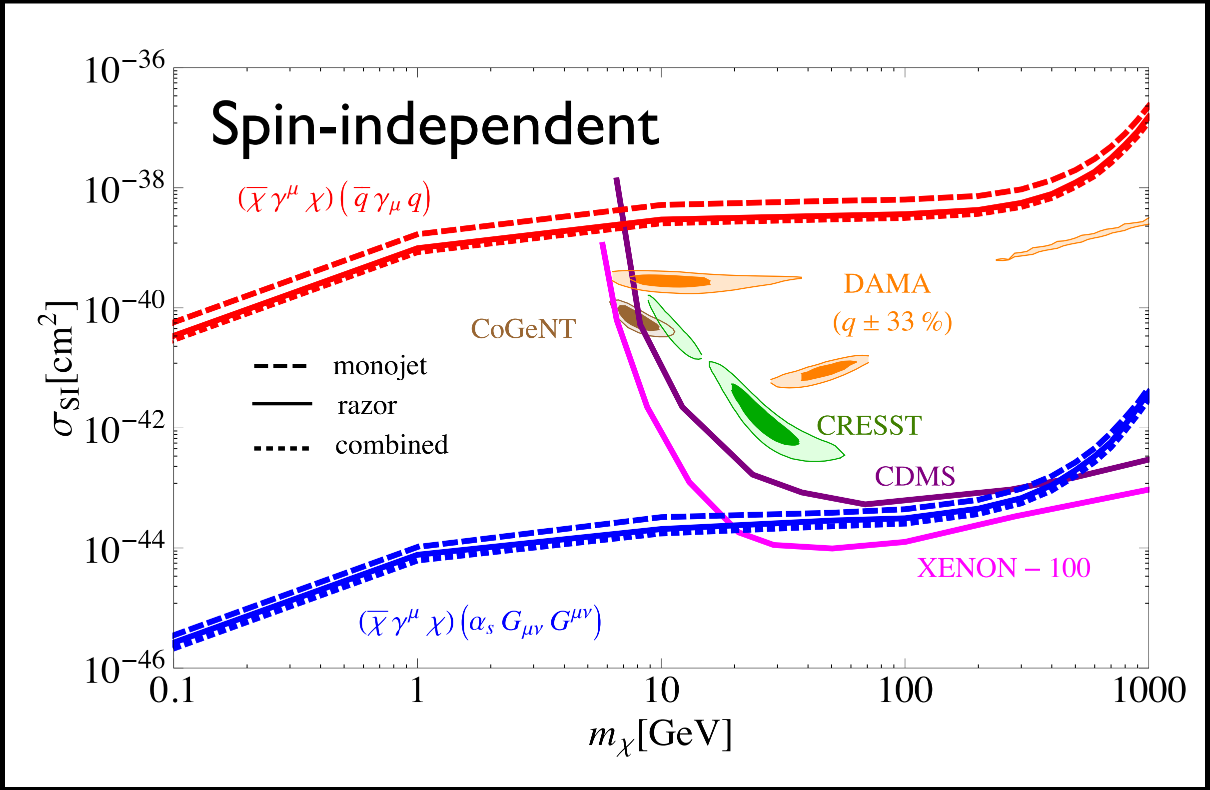
Table of effective operators relevant for the collider/direct detection connection

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......



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

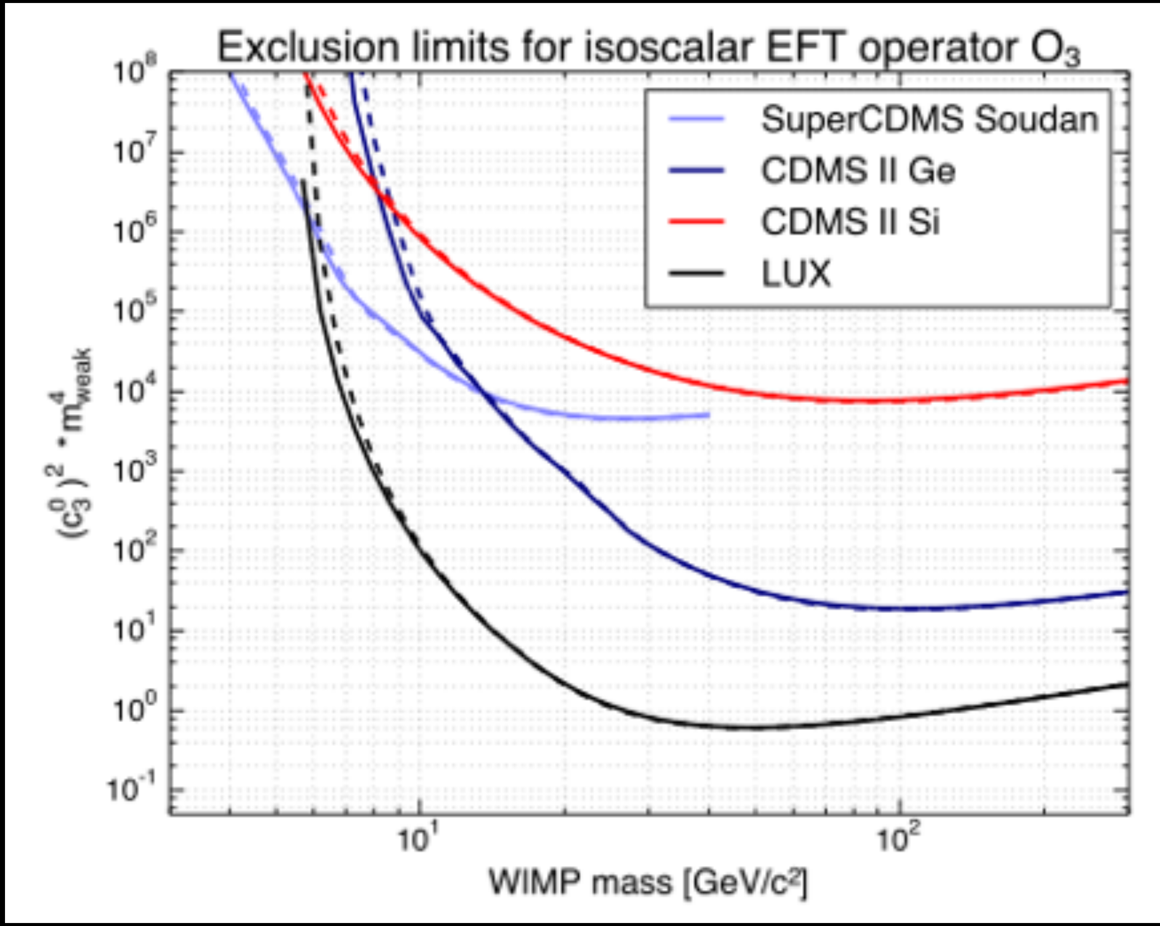
Response $\times \left[\frac{4\pi}{2J_i+1}\right]^{-1}$	Leading Multipole	Long-wavelength Limit	Response Type
$\sum_{J=0,2,\ldots}^{\infty} \lvert\langle J_i \vert\vert M_{JM} \vert\vert J_i\rangle\rvert^2$	$M_{00}(q\vec{x}_i)$	$\frac{1}{\sqrt{4\pi}} 1(i)$	M_{JM} : Charge
$\sum_{J=1,3,\ldots}^{\infty}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

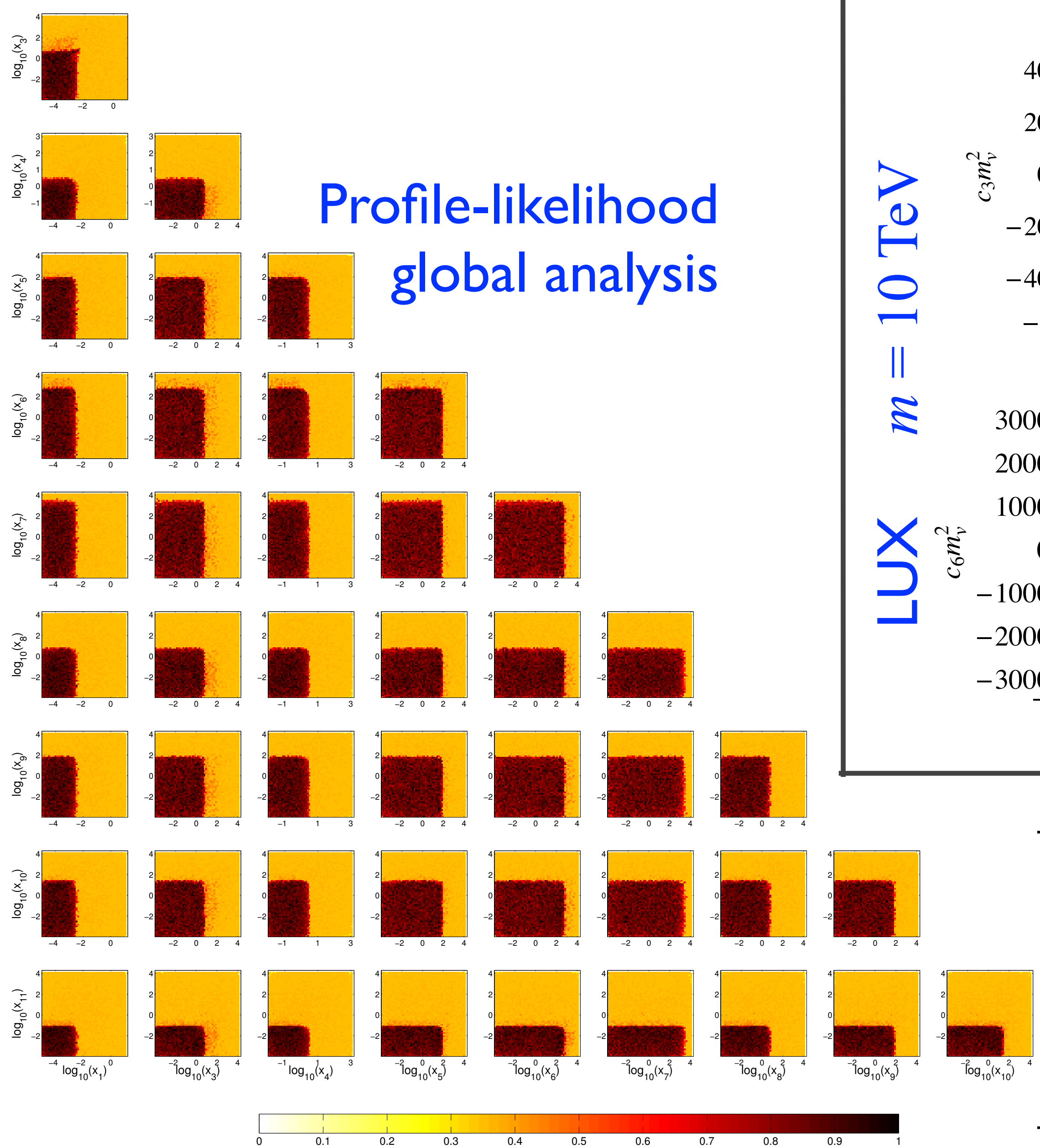


Operator coefficient	SuperCDMS Soudan
$(c_1^0)^2 * m_{weak}^4$	8.98×10^{-5} (—)
$(c_3^0)^2 * m_{weak}^4$	3.14×10^{4} (—)
$(c_4^0)^2 * m_{weak}^4$	8.77×10^{1} (—)
$(c_5^0)^2 * m_{weak}^4$	6.34×10^{5} (—)
$(c_6^0)^2 * m_{weak}^4$	4.54×10^{8} (—)
$(c_7^0)^2 * m_{weak}^4$	8.44×10^{7} (—)
$(c_8^0)^2 * m_{weak}^4$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

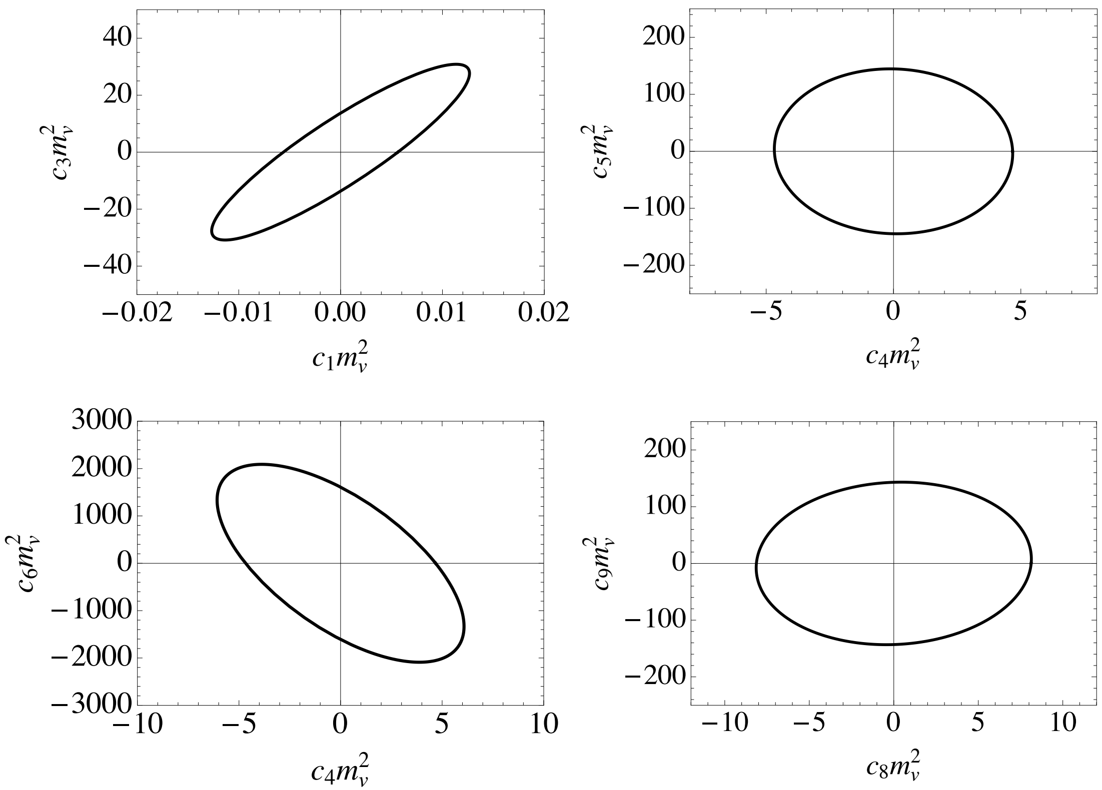
Combined analysis of short-distance operators

Catena, Gondolo 2014



Profile-likelihood global analysis

LUX $m = 10$ TeV



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

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

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

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

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

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

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

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

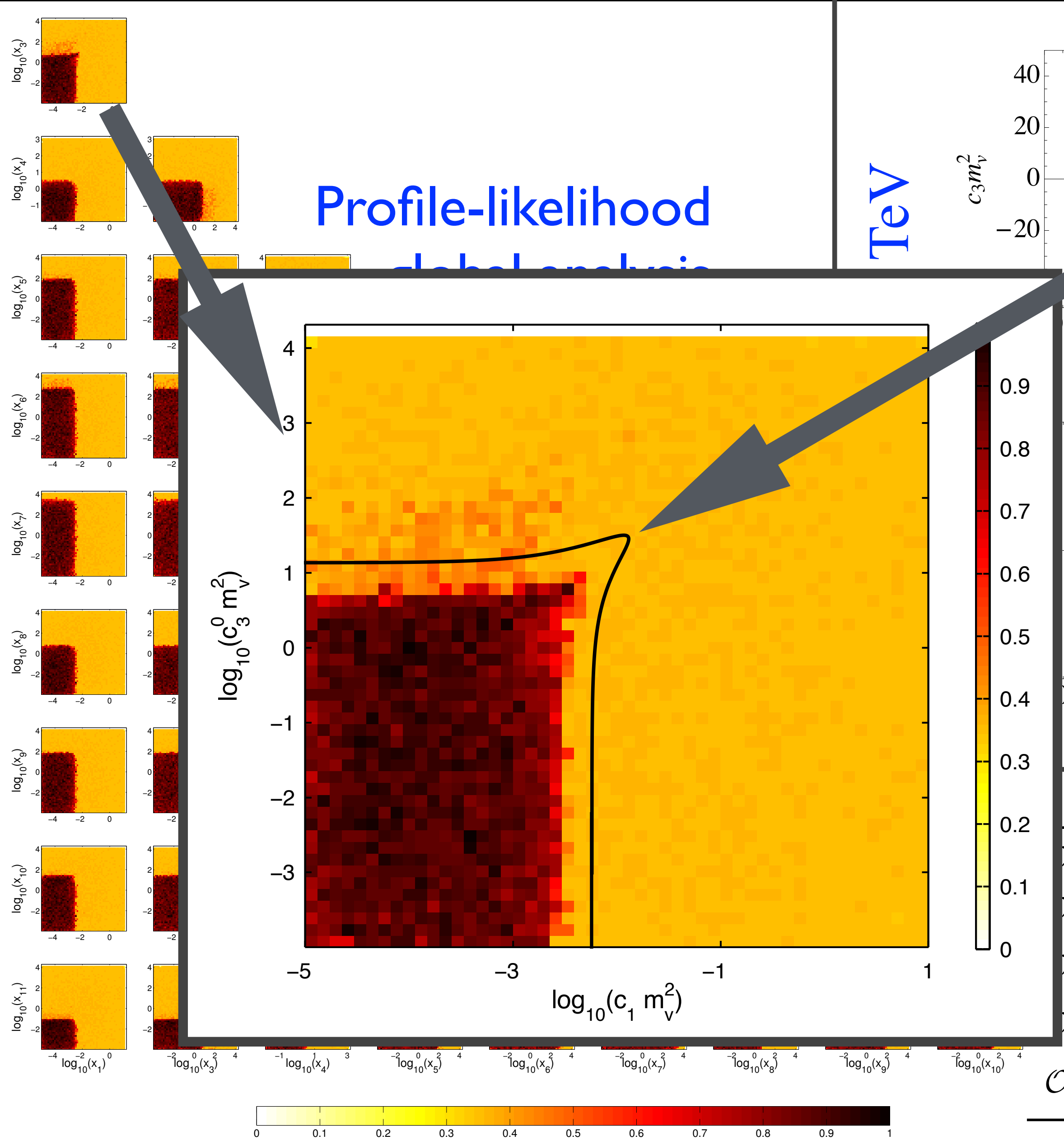
$$\mathcal{O}_{10} = -i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

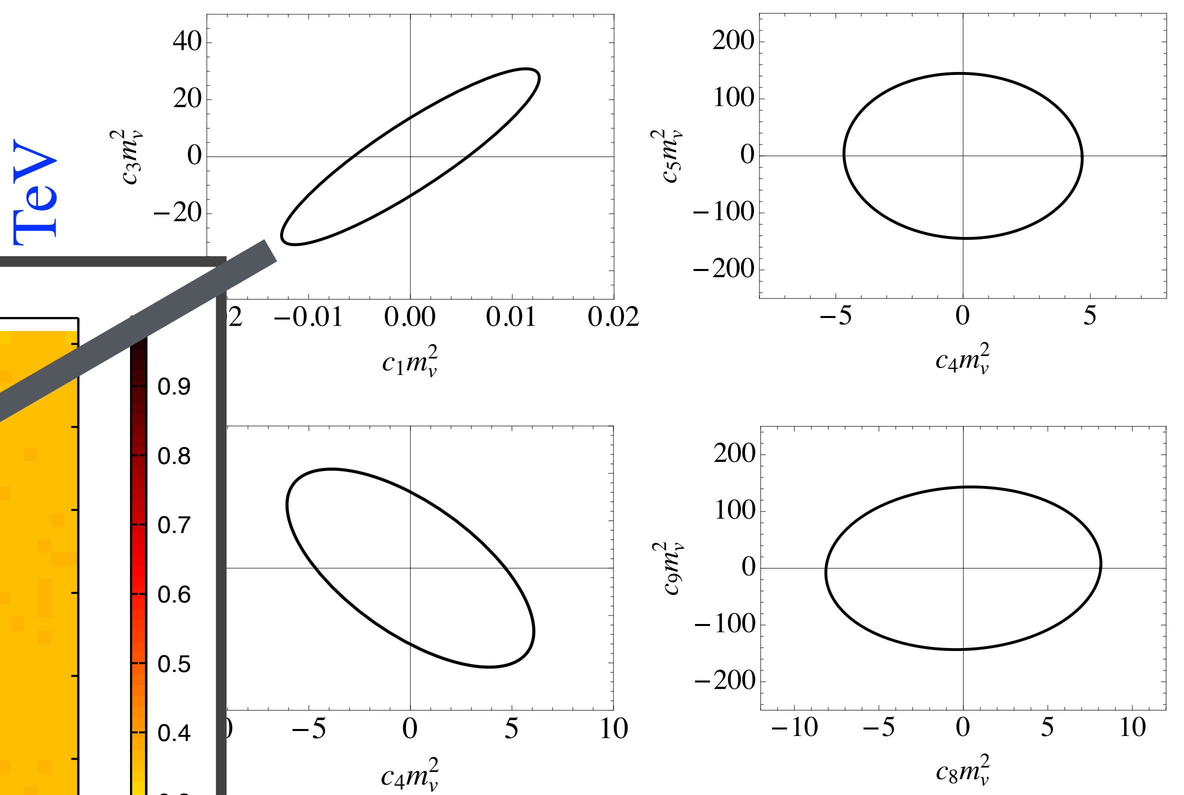
$$\mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

Effective operators: direct detection

Combined analysis of short-distance operators

Catena, Gondolo 2014





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

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

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

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

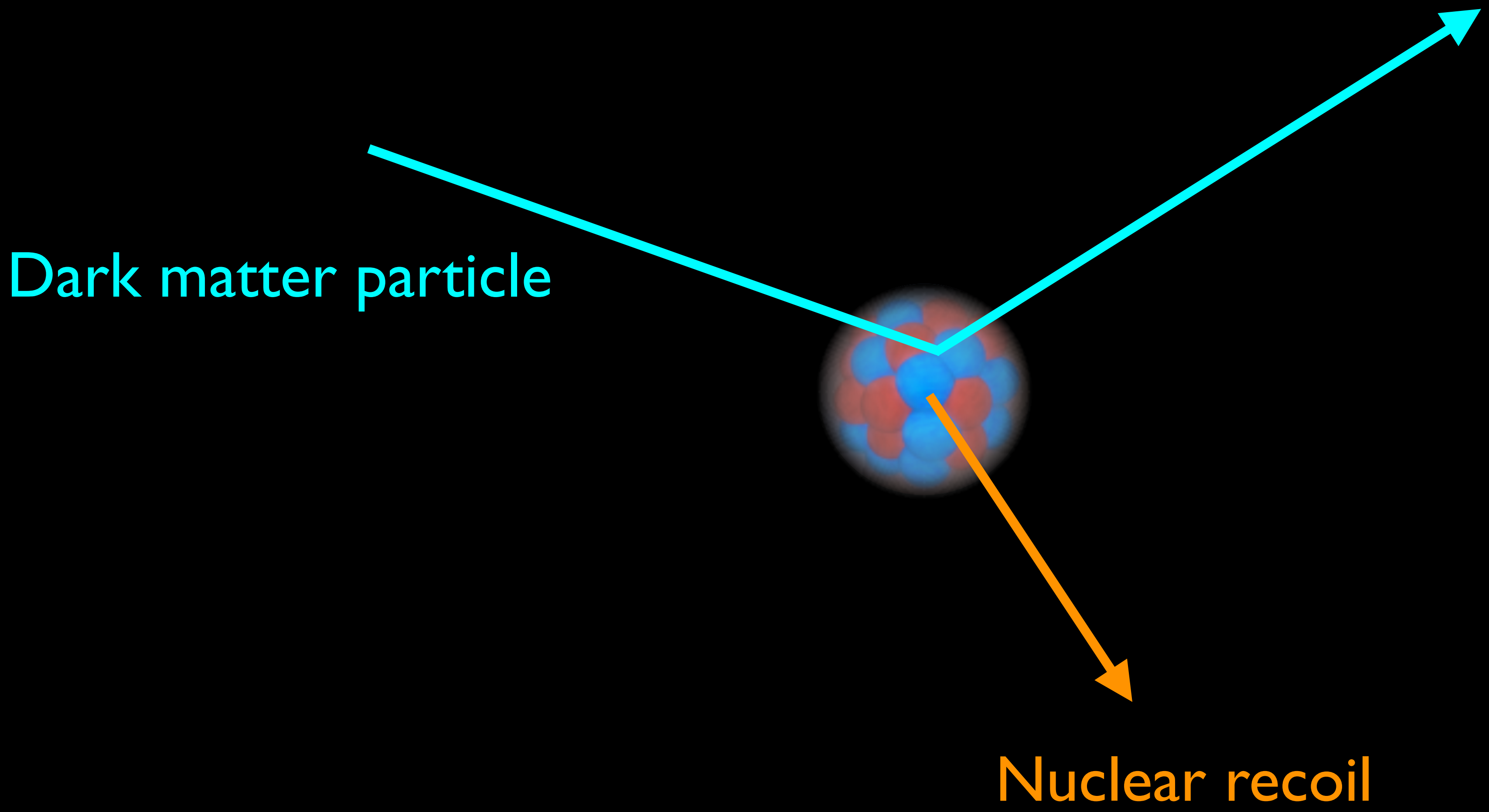
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right) \qquad \mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

All astrophysics models

Do not assume any particular
WIMP density or velocity distribution

DM-nucleus elastic scattering

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



Astrophysics model

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

Dark matter flux on Earth

Local halo density

Velocity distribution

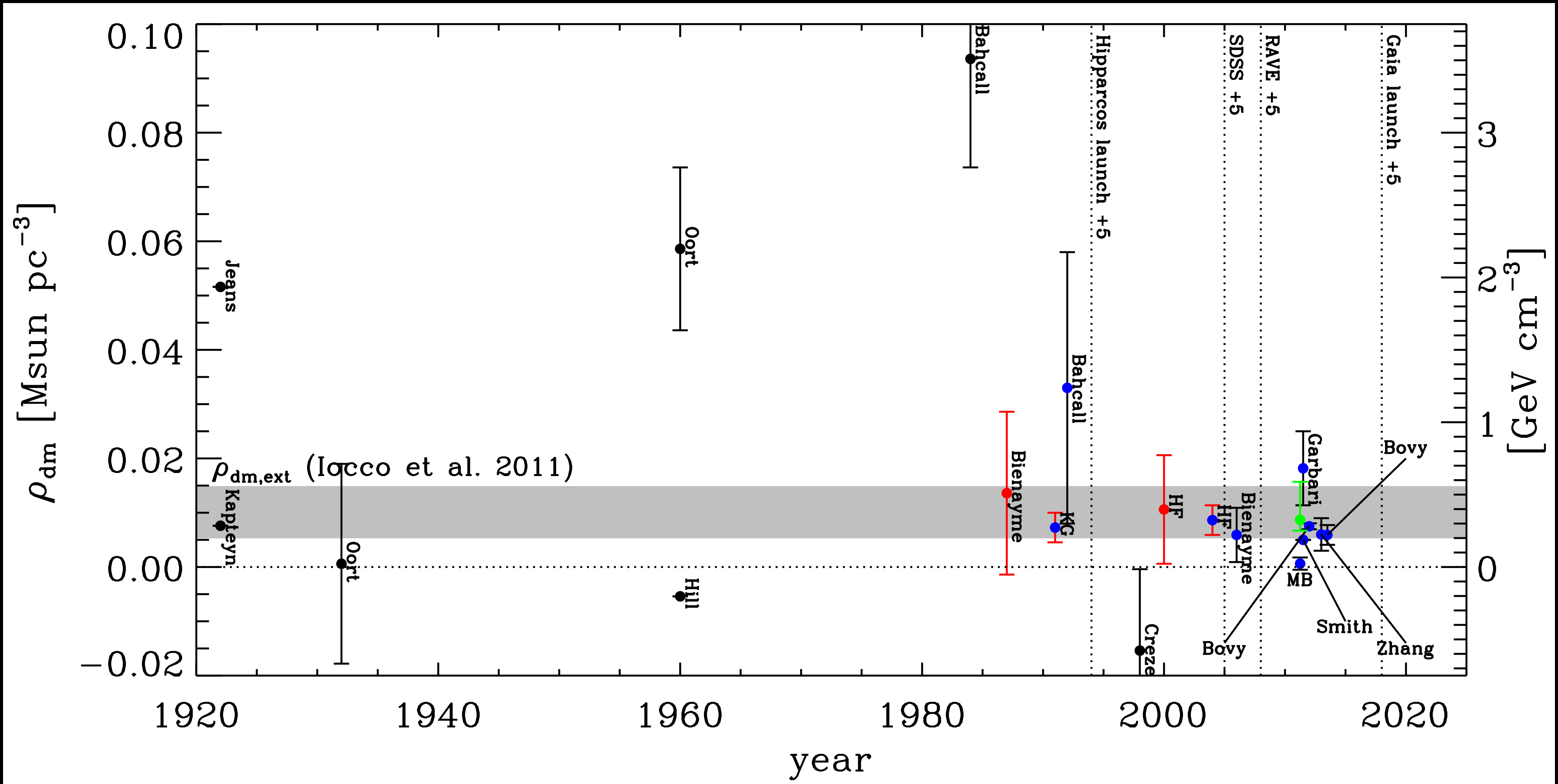
$$(\text{astrophysics}) = \eta(v_{\min}, t) \equiv \rho_\chi \int_{v>v_{\min}} \frac{f(\mathbf{v}, t)}{v}\, \mathrm{d}^3 v$$

Minimum WIMP speed to impart recoil energy E_R

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

Astrophysics model: 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]

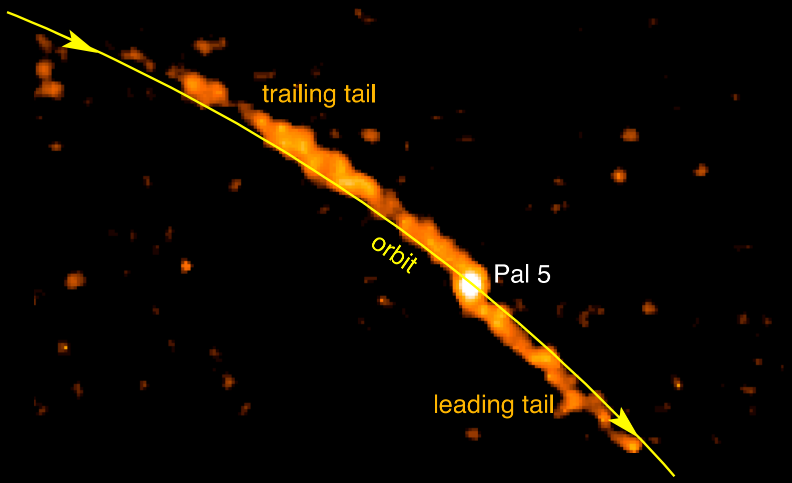
$$\rho_{\rm dm} = 0.25 \pm 0.09\,{\rm GeV\,cm^{-3}}$$

[SDSS; Z13]

Read at IDM 2014

Astrophysics model: velocity distribution

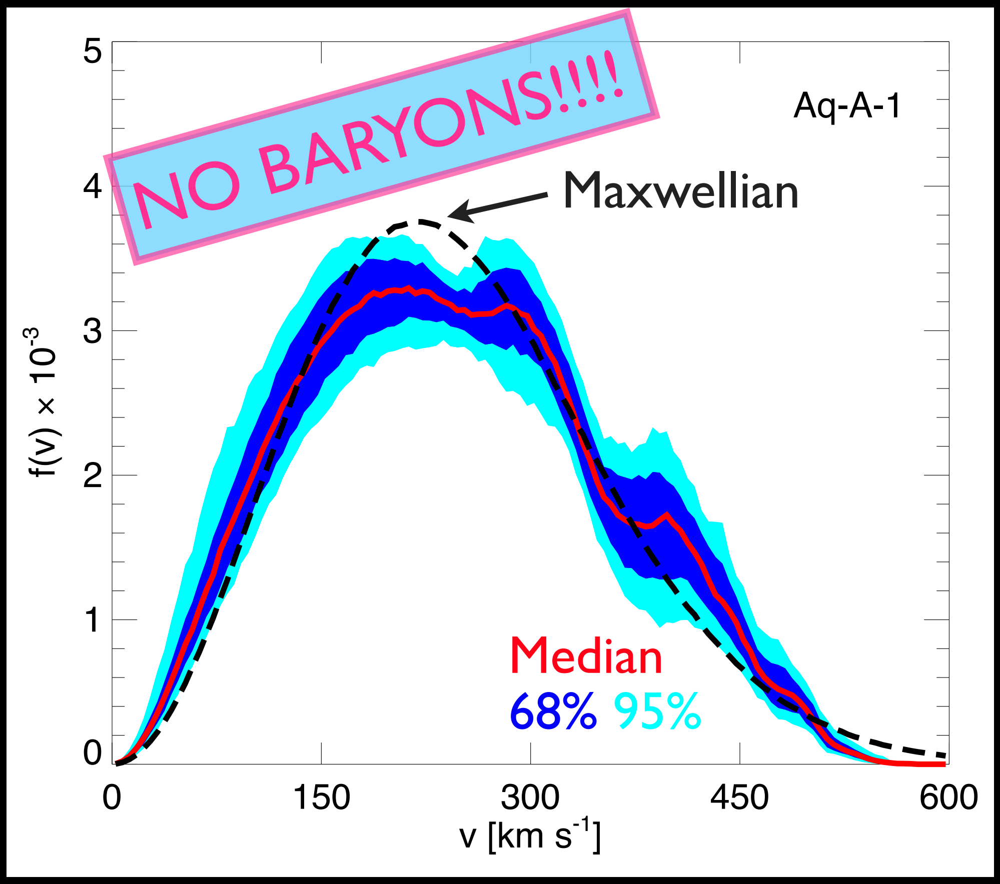
We know very little about the dark matter velocity distribution near the Sun



Odenkirchen et al 2002 (SDSS)

Streams of stars have been observed in the galactic halo

SDSS, 2MASS, SEGUE,…….



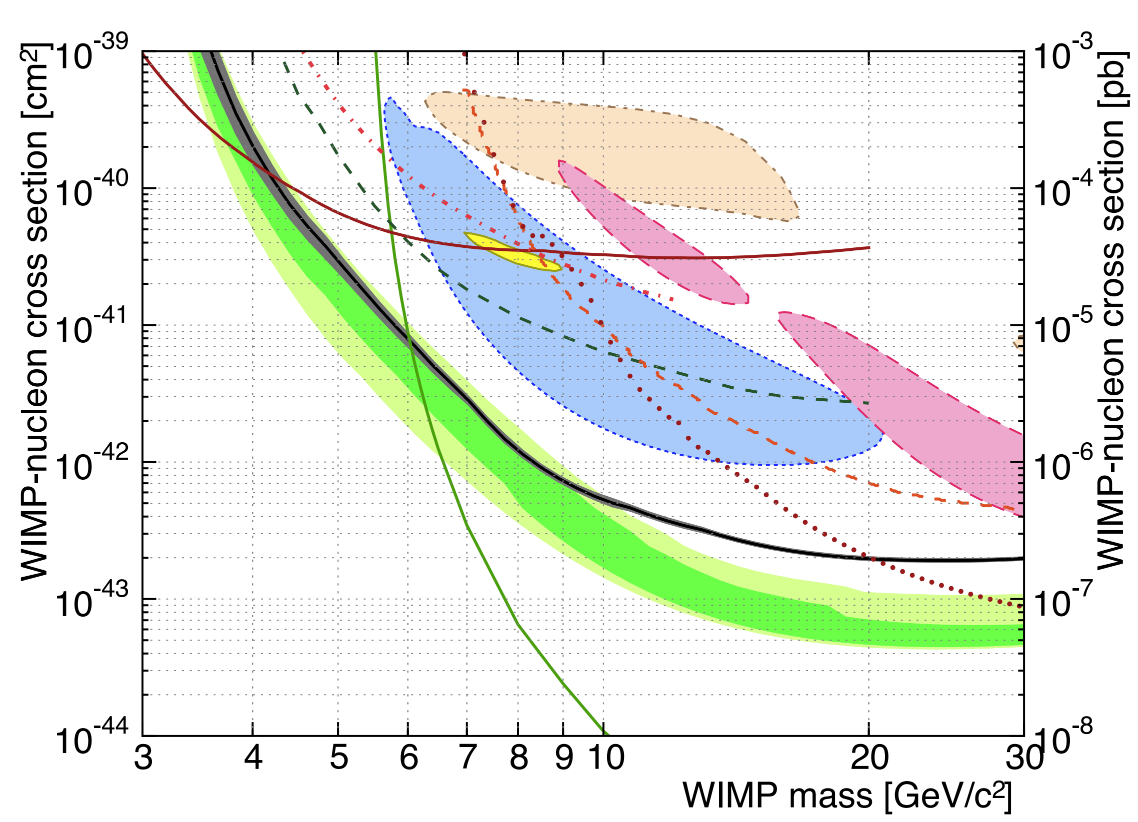
Vogelsberger et al 2009

Cosmological N-Body simulations including baryons are challenging but underway

Astrophysics model: velocity distribution

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

FIXED FIXED



Agnese et al (SuperCDMS) 2014

Standard Halo Model

truncated Maxwellian

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

The spherical cow of direct WIMP searches

Gelmini

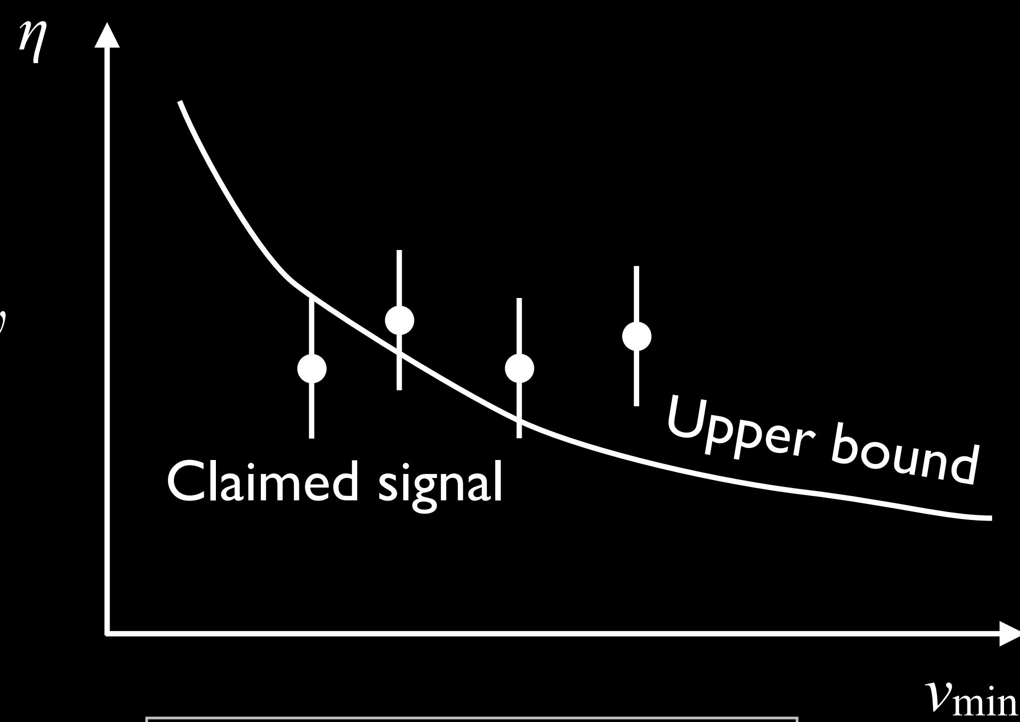
Astrophysics-independent approach

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

FIXED (particle physics)   ARBITRARY (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.

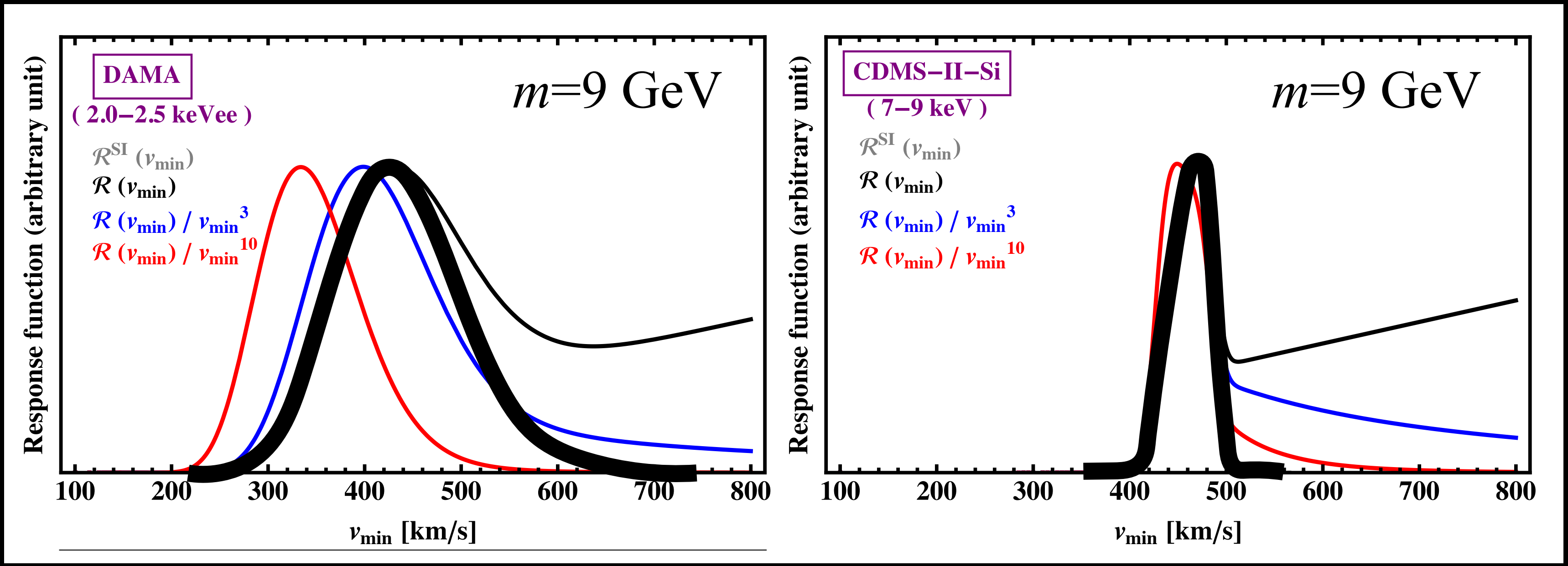
Measured rate

Rescaled astrophysics factor

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

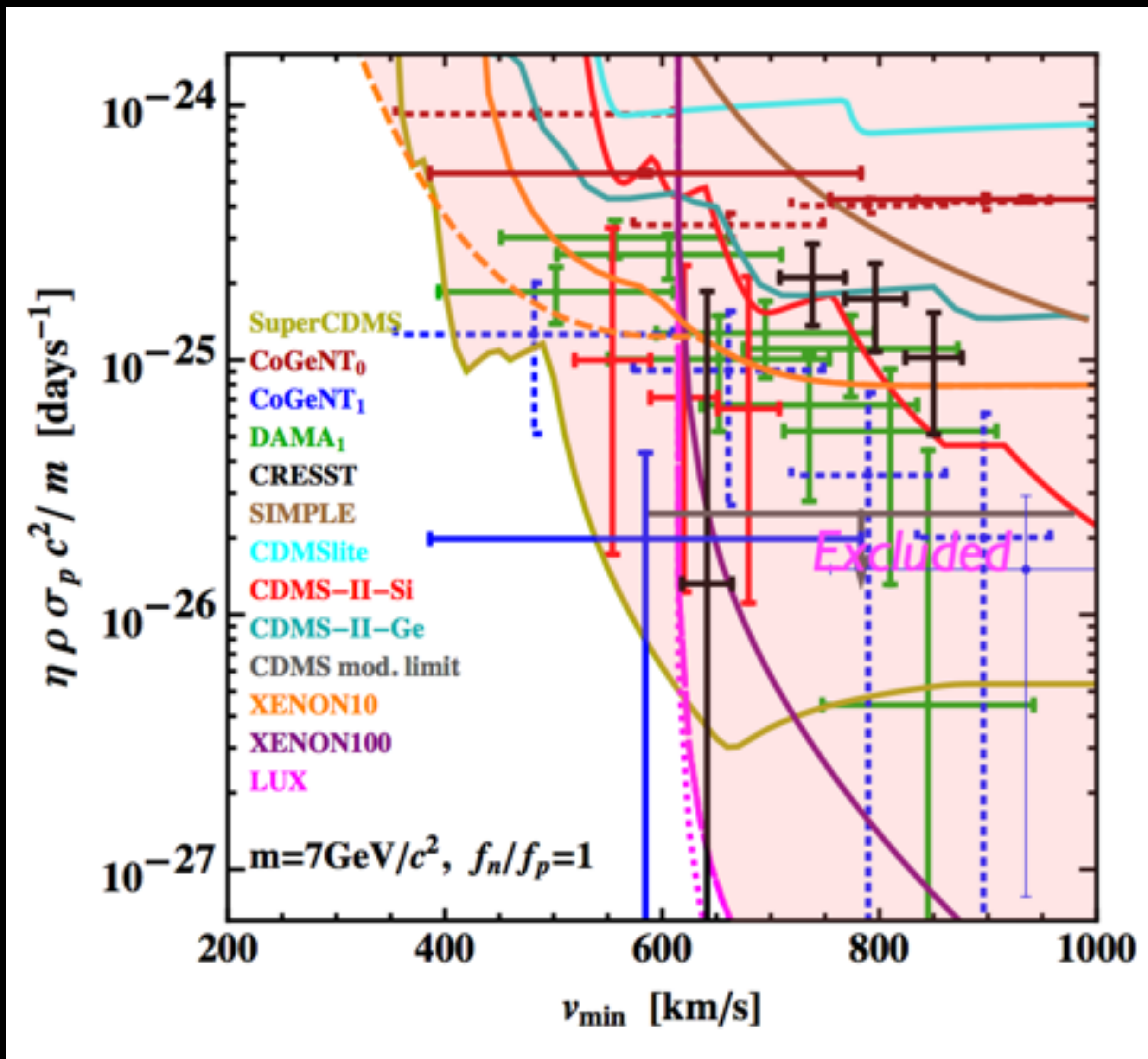
Response function

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



Spin-independent isoscalar interactions

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



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

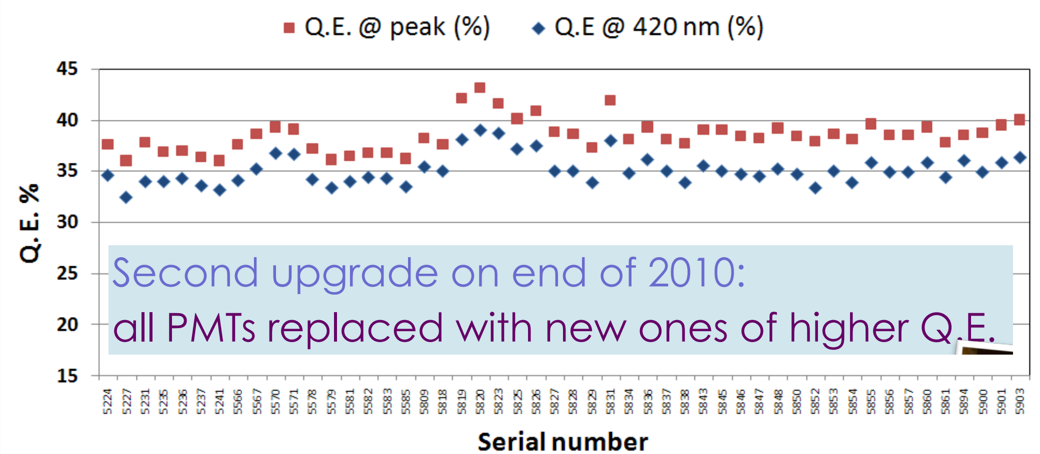
Del Nobile, Gelmini, Gondolo, Huh 2014

In the next episodes

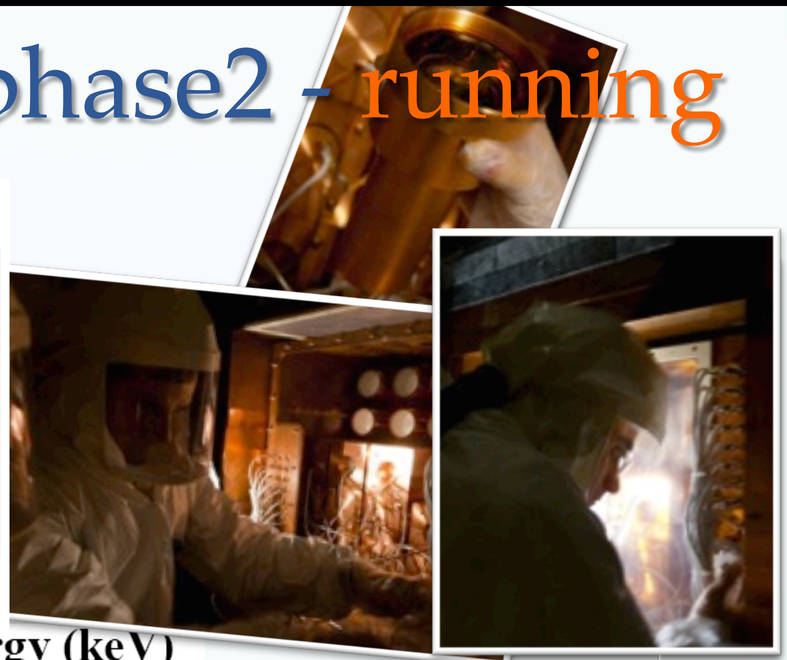
In the next episodes..... DAMA's revenge?

DAMA/LIBRA phase2 - running

Quantum Efficiency features



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



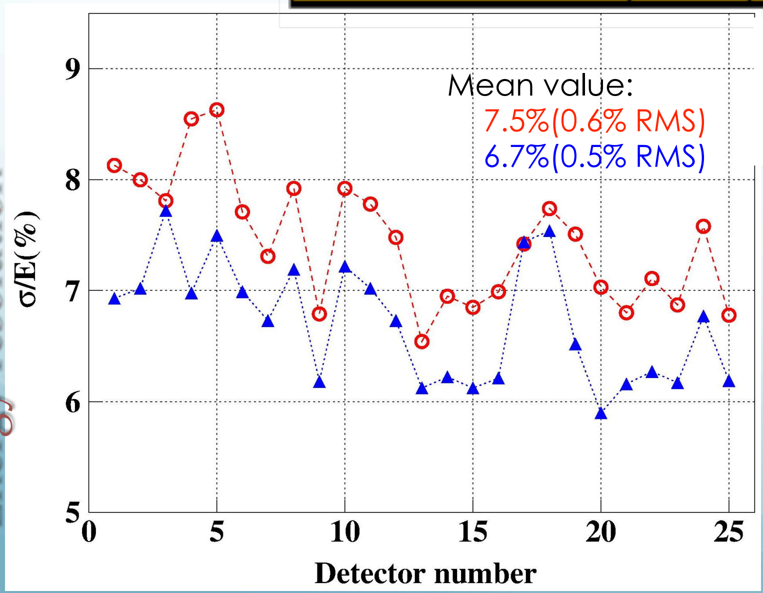
Residual Contamination

The limits are at 90% C.L.

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*

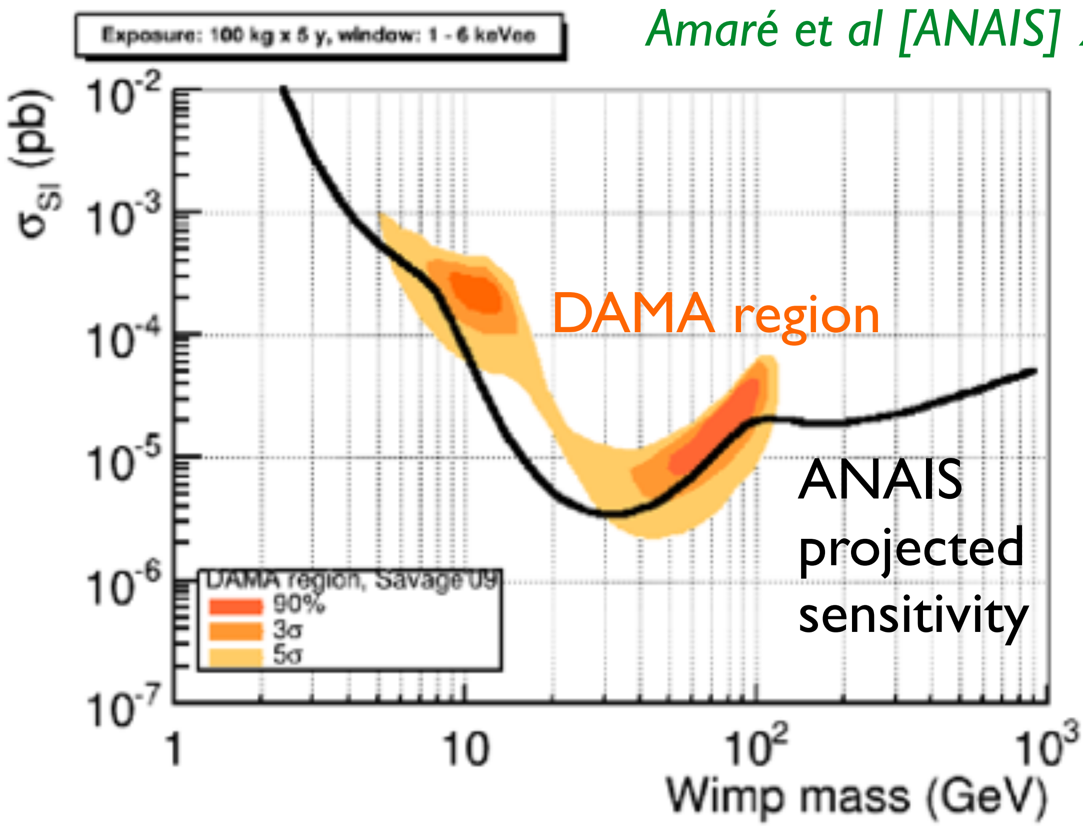
Belli, IDM2014

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

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

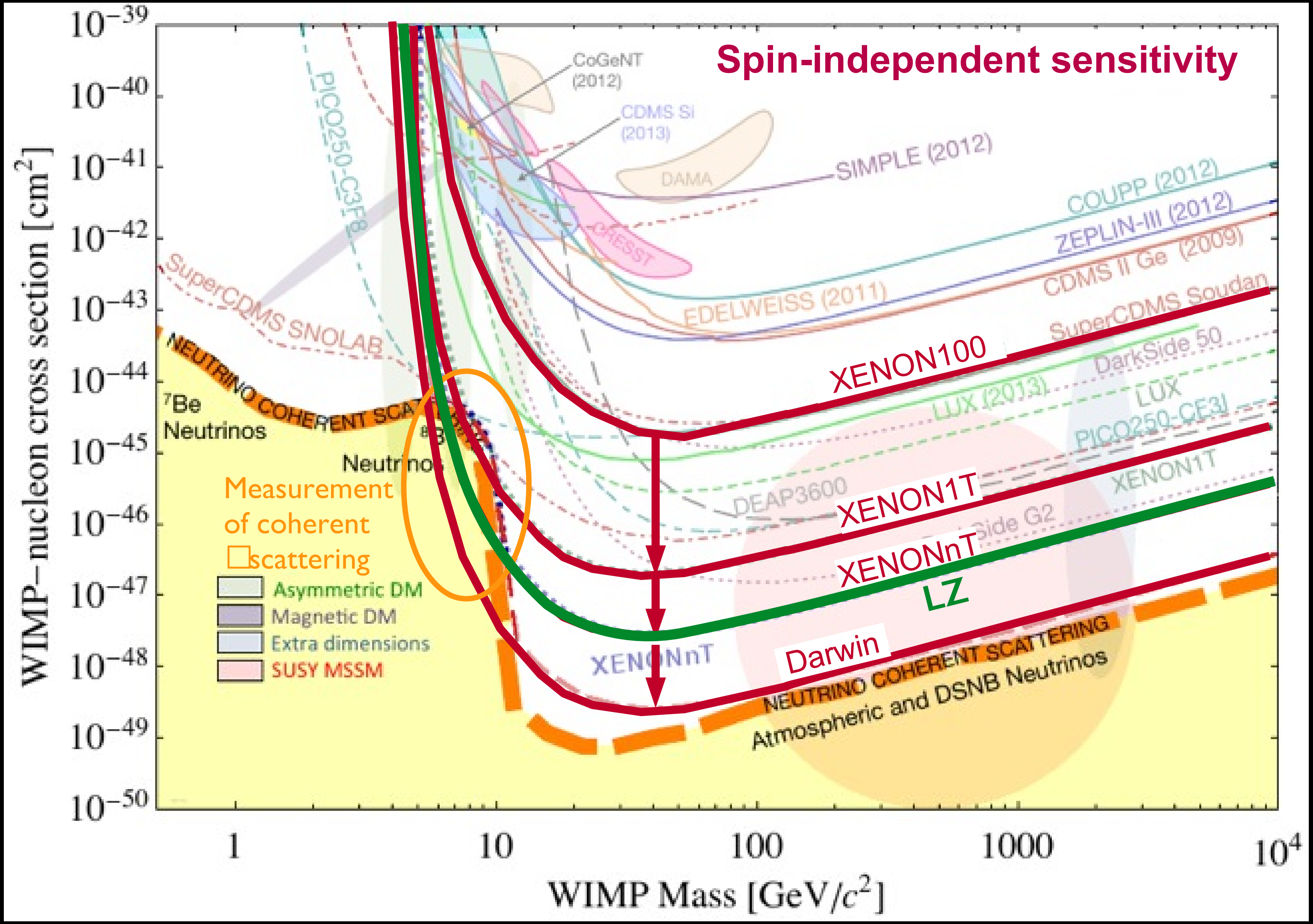
DM-ICE, ANAIS, KIMS-NaI,…

Amaré et al [ANAIS] 2015



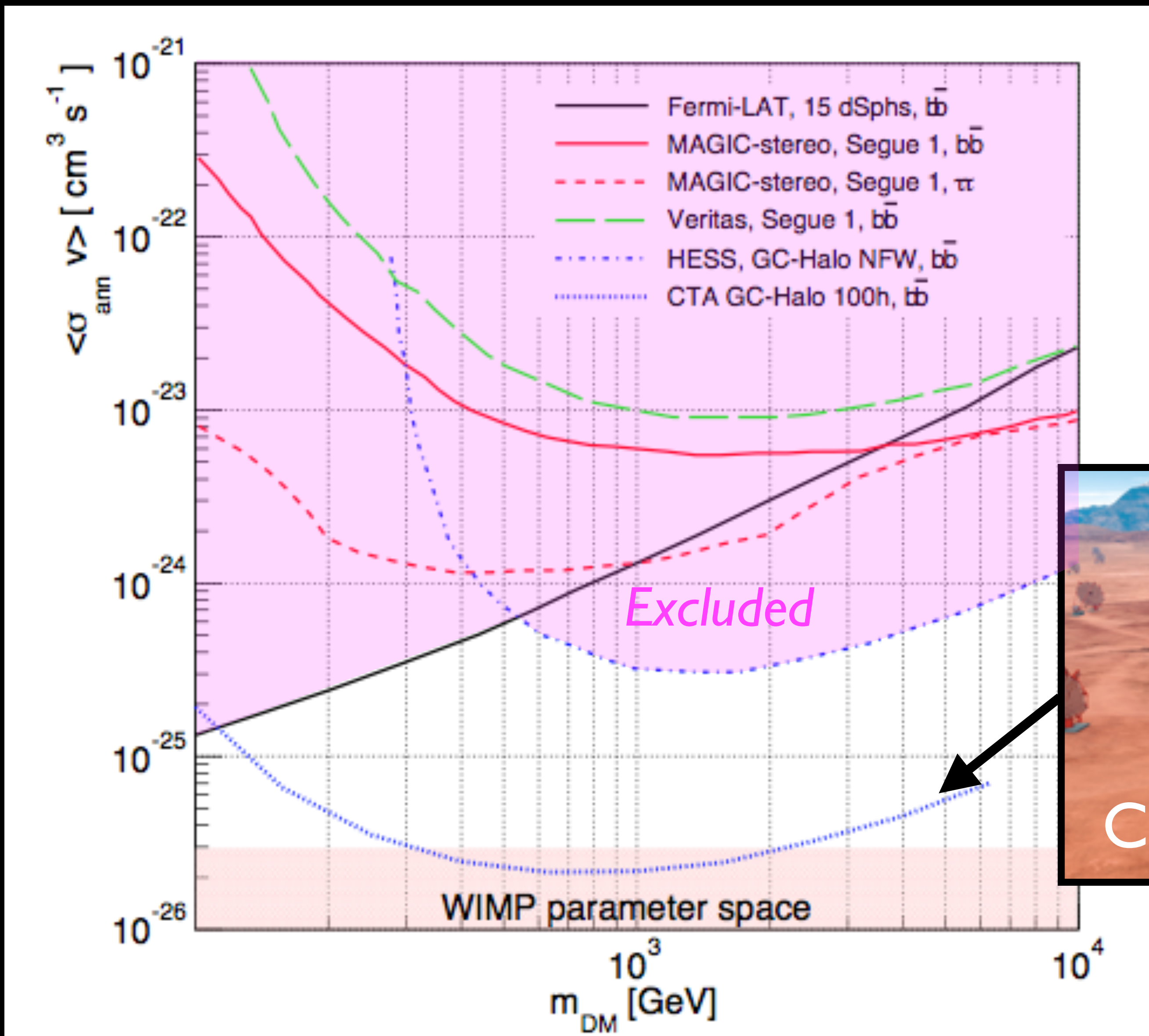
In the next episodes..... Giant direct detectors

SuperCDMS, LZ, XENON1T, XENONnT, Darwin, ...



Oberlack, IDM2014

In the next episodes..... High-energy γ-rays



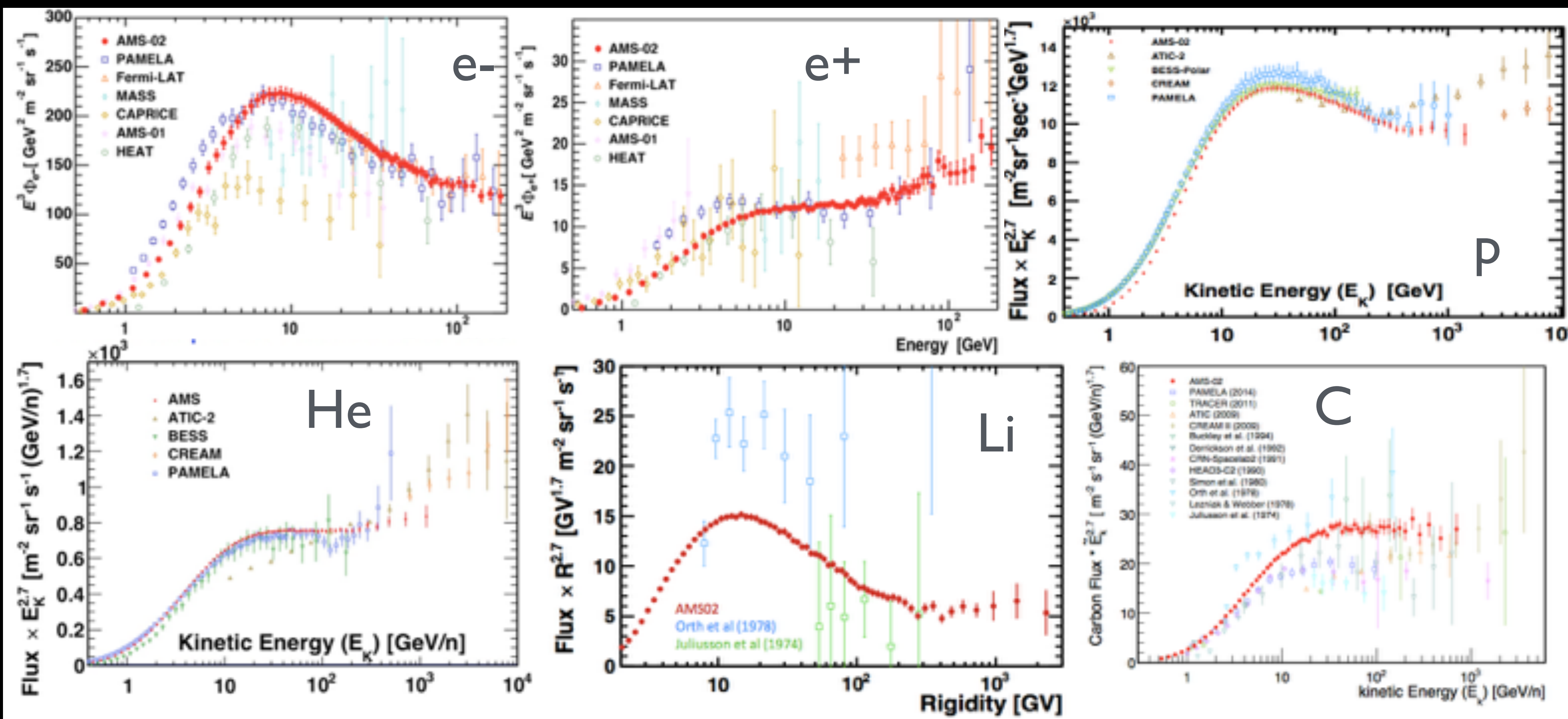
The Cherenkov Telescope Array (CTA) promises a lower energy threshold and a higher sensitivity.

Doro, 2014

In the next episodes….. Precision cosmic rays

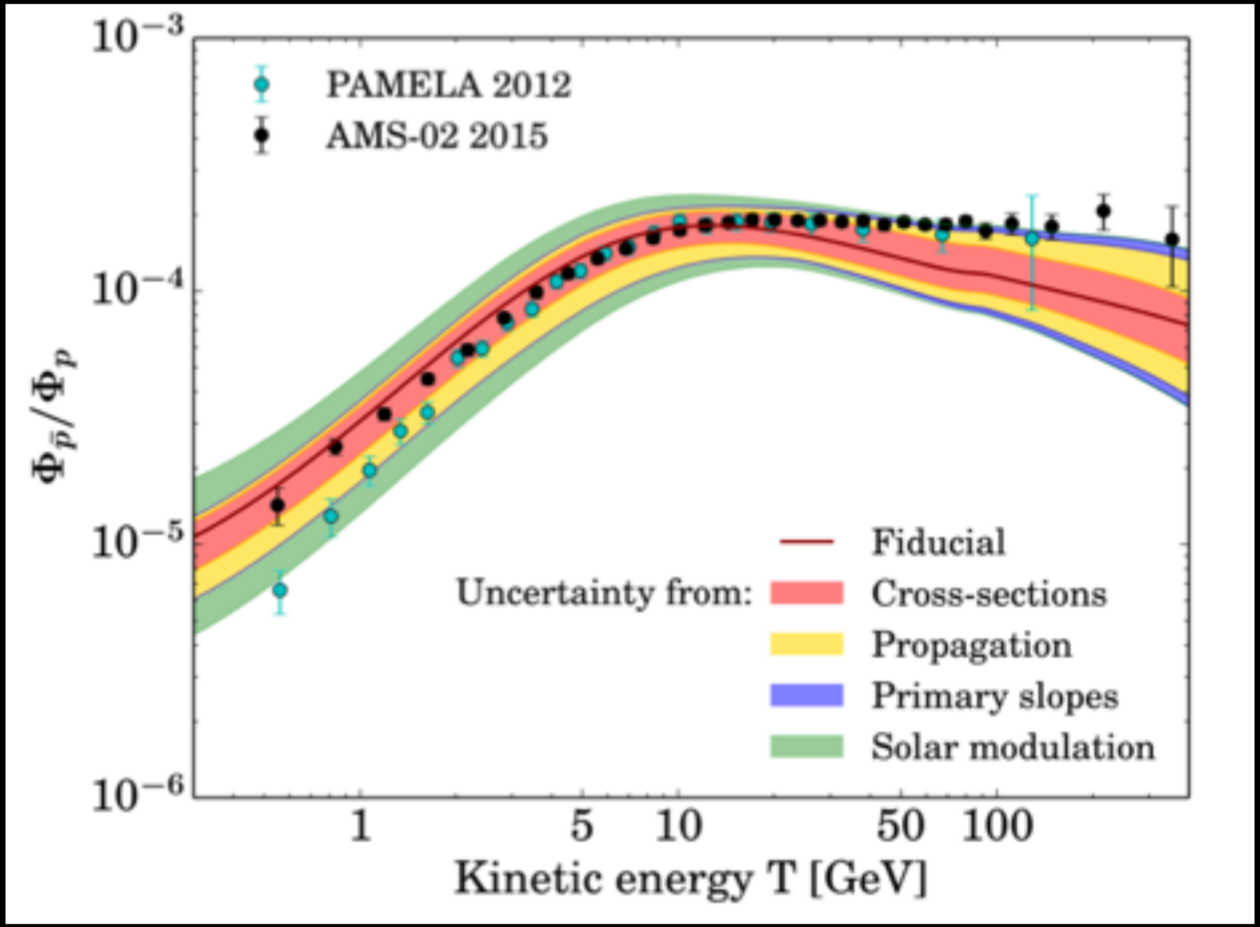
AMS (Alpha Magnetic Spectrometer)

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



In the next episodes..... Precision cosmic rays

For example, use of the new precise AMS-02 proton and helium spectra shows no unambiguous evidence for a significant antiproton excess over the expectation for secondary antiprotons.

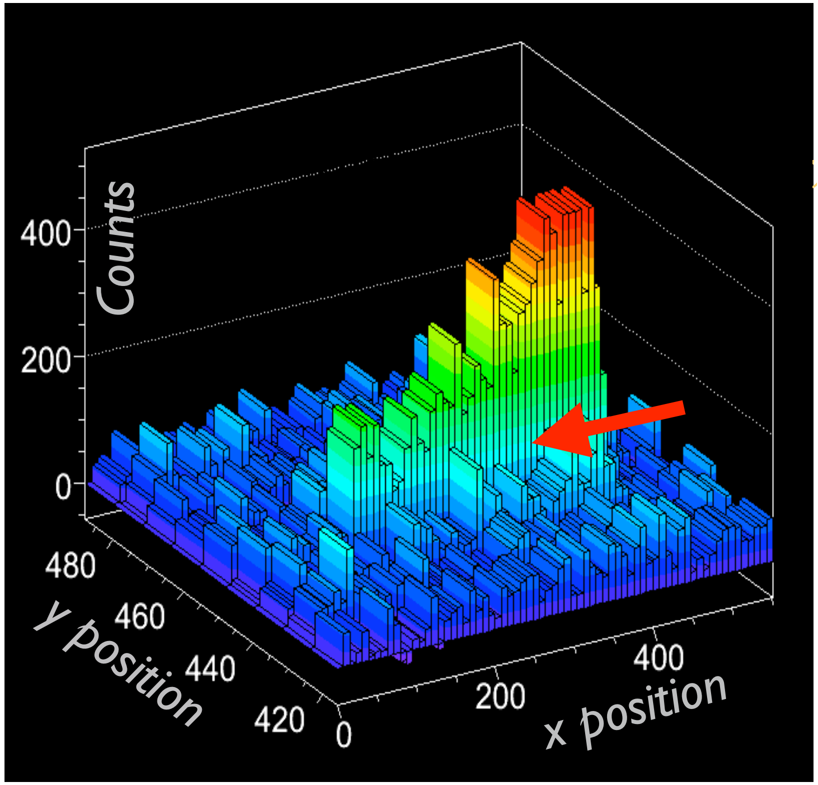


Giesen et al 2015

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

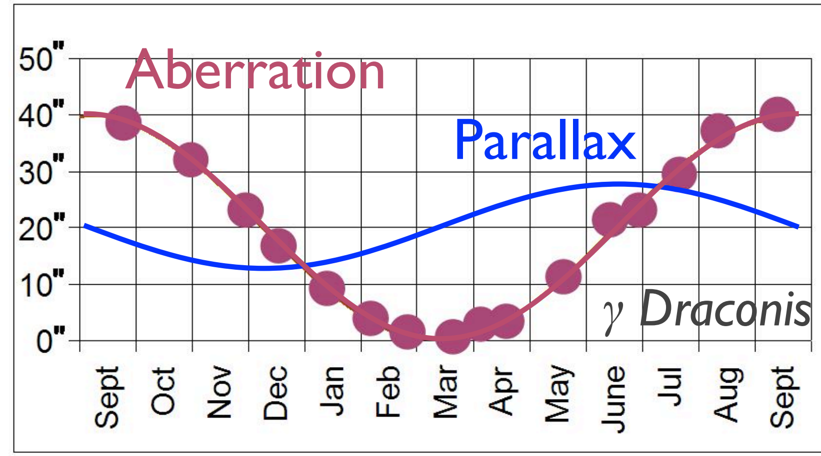
Only ~10 events needed to confirm extraterrestrial signal

In the next episodes..... WIMP astronomy

Aberration of WIMPs

Photon arrival direction

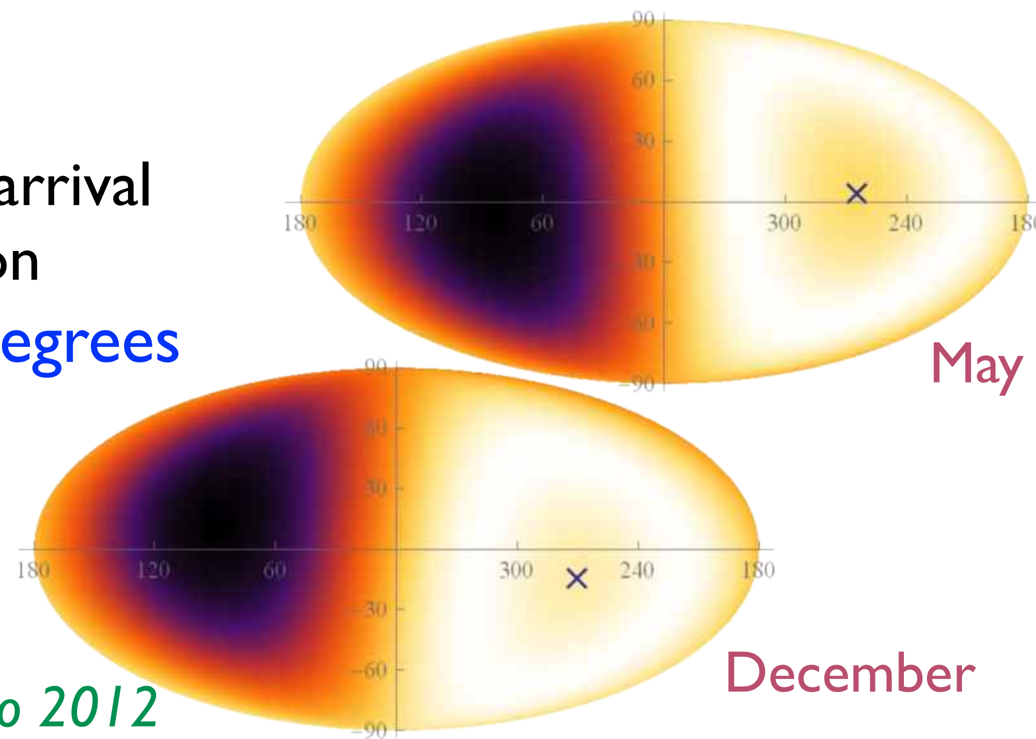
20 arcsec



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
  - *Search DM particles through production, scattering, and annihilation/decay.*
  - *Interaction rates 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.*
- In the next episodes
  - *DAMA vs giant direct detectors, γ-rays, precision cosmic rays, WIMP astronomy, etc.*