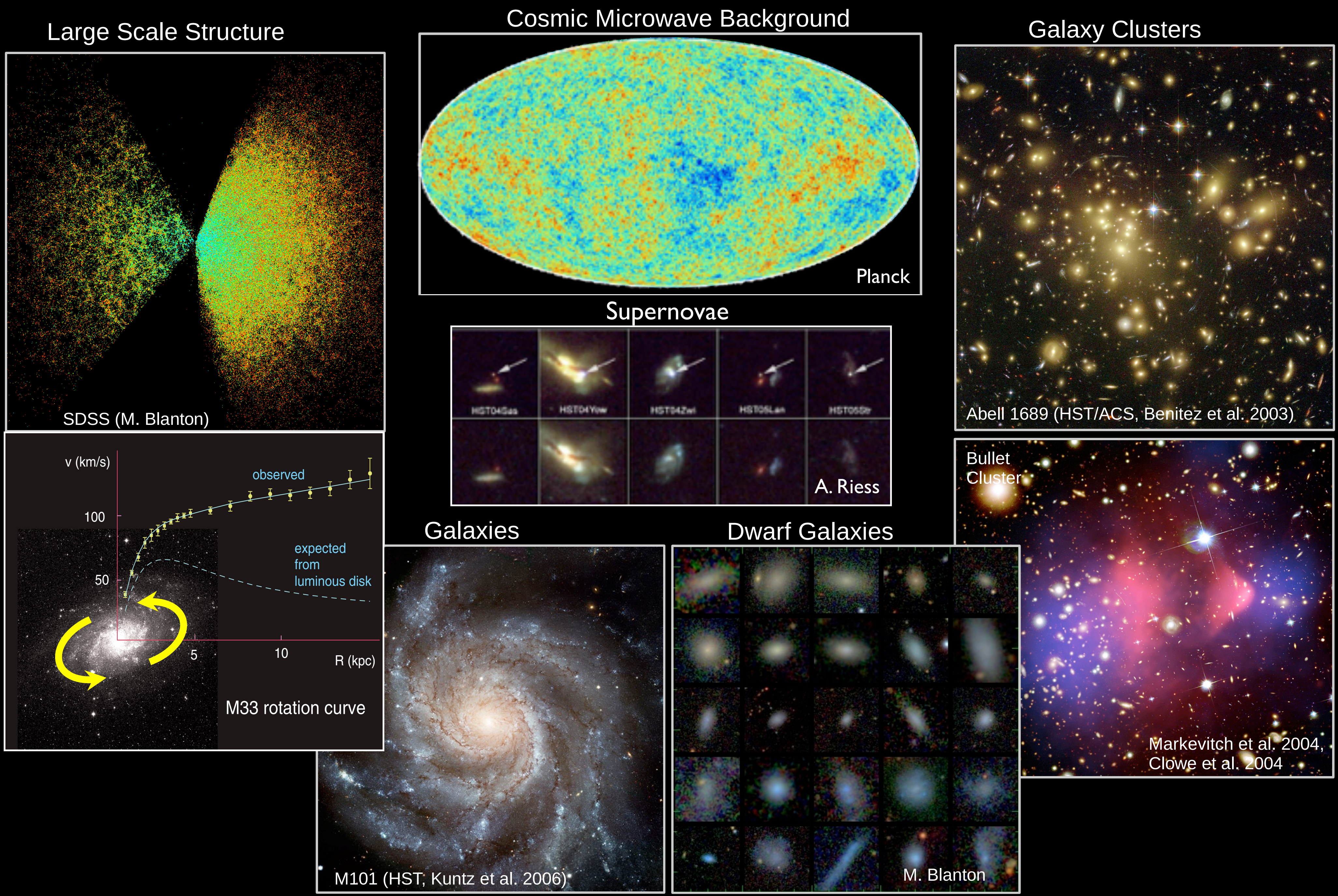
Dark matter theory

Paolo Gondolo

University of Utah

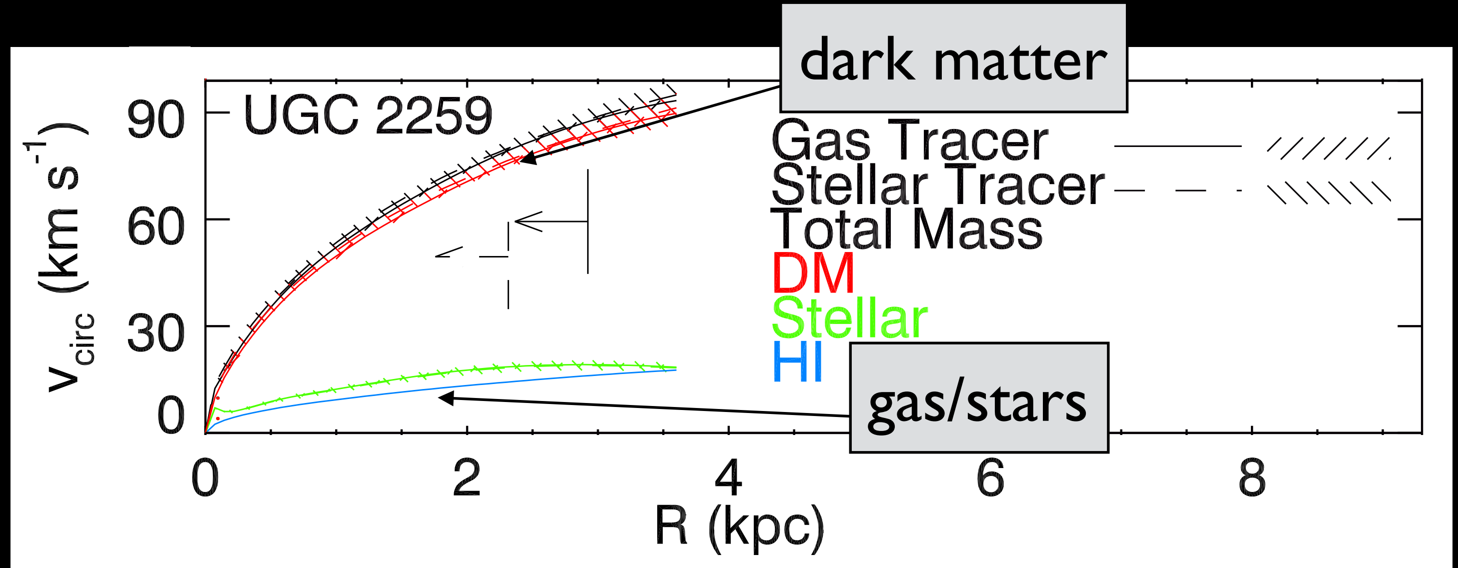
Evidence for cold dark matter

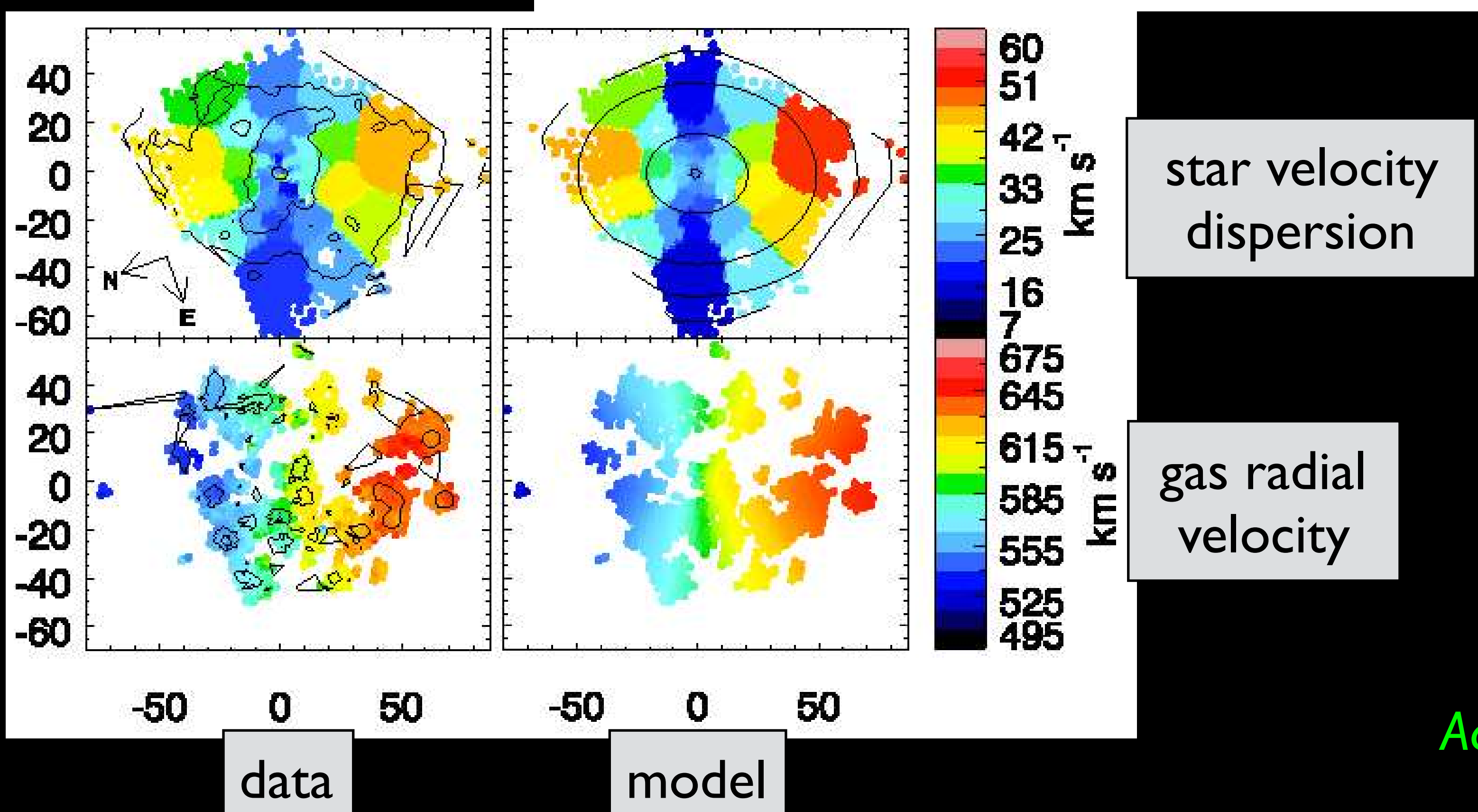


Evidence for cold dark matter

Dwarf galaxies

Dwarf galaxies are dominated by dark matter.



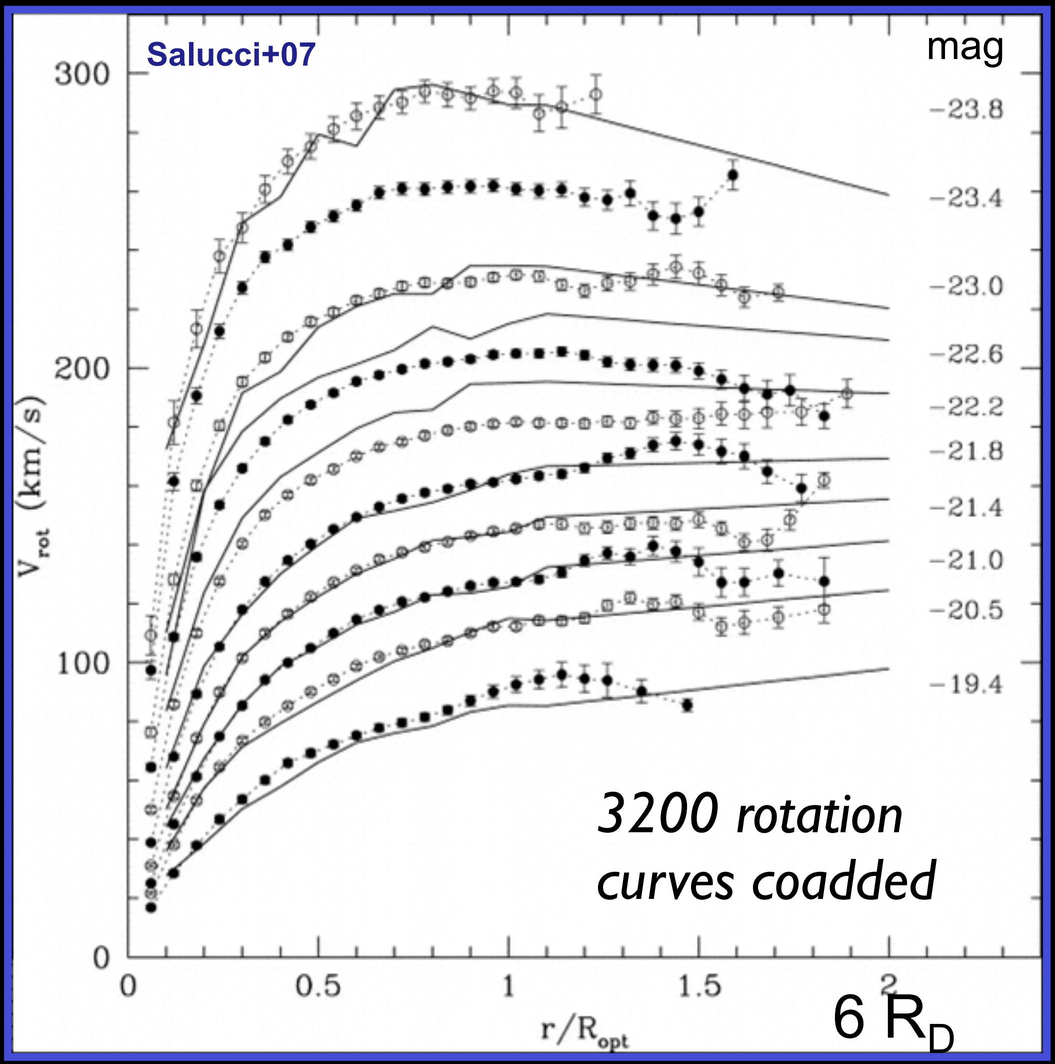


Adams et al 2014

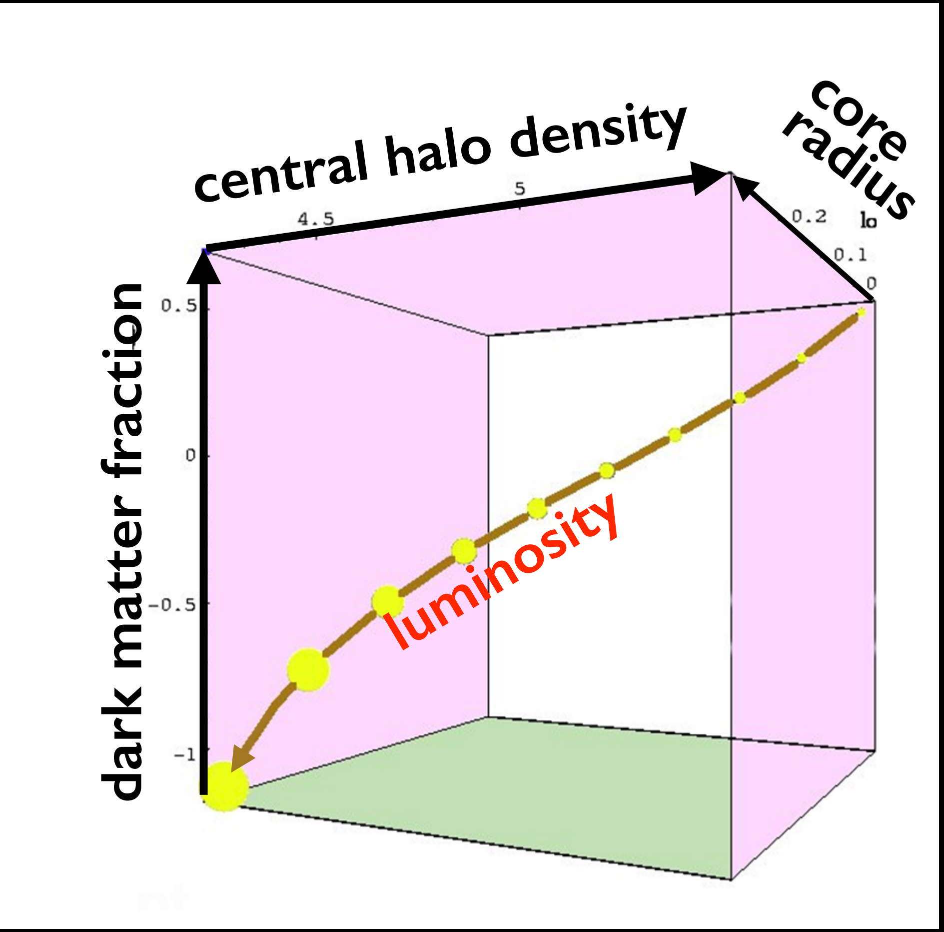
Evidence for cold dark matter

Spiral galaxies

Empirical correlations found from thousands of spiral galaxy rotation curves



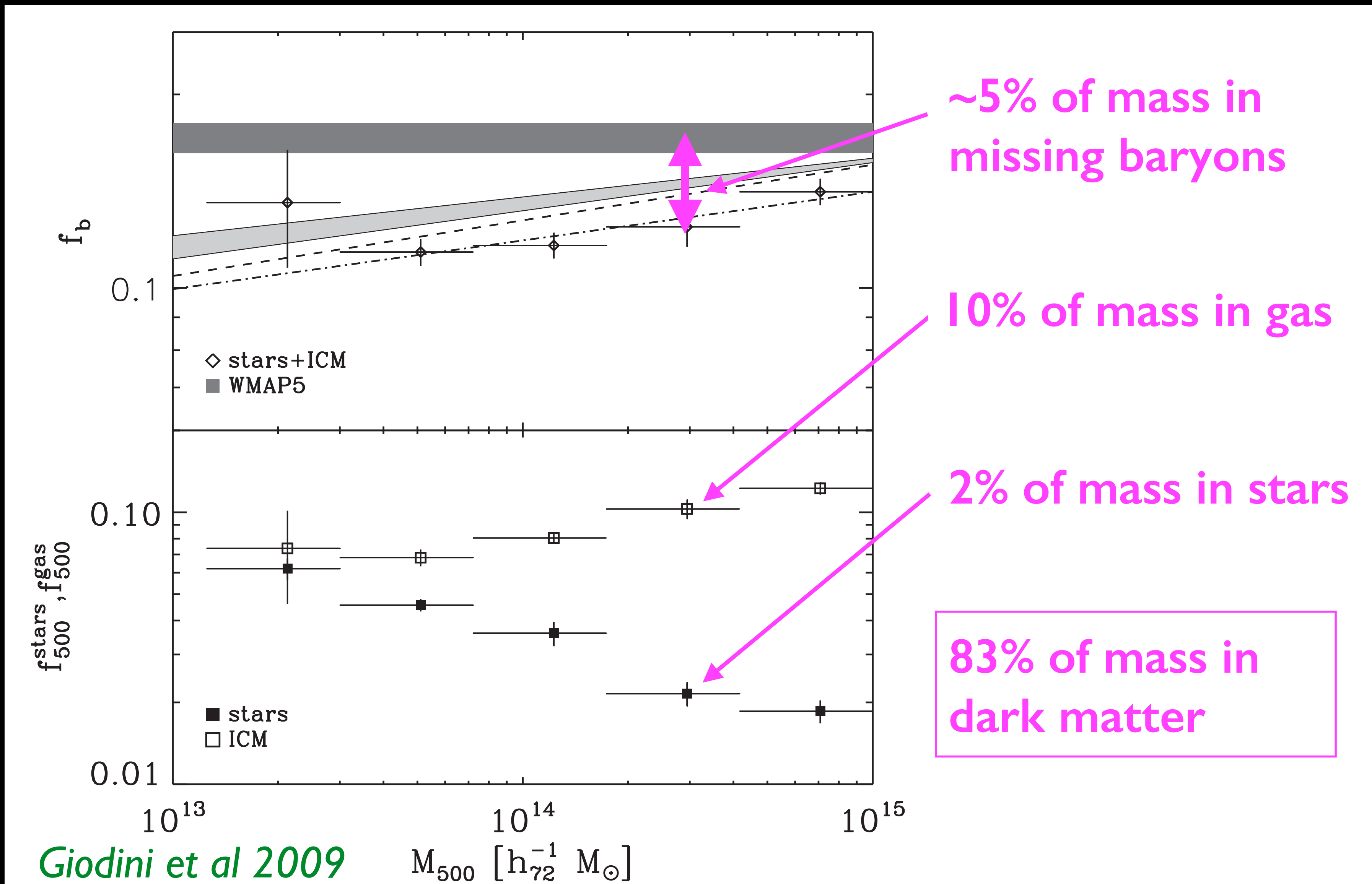
Salucci et al 2007



Evidence for cold dark matter

Galaxy clusters

Galaxy clusters are mostly dark matter with some gas and a sprinkle of galaxies



Cold dark matter, *not* modified gravity

The Bullet Cluster

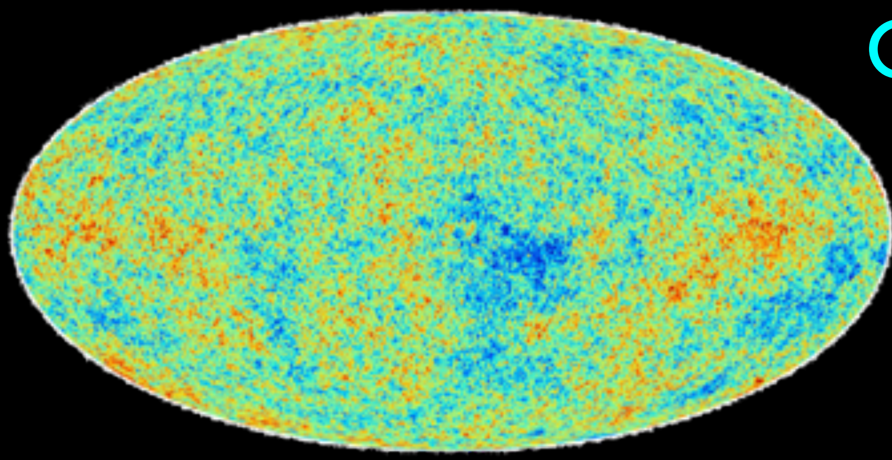
Symmetry argument: gas is at center, but potential has two wells.

Galaxies in optical (Hubble Space Telescope)

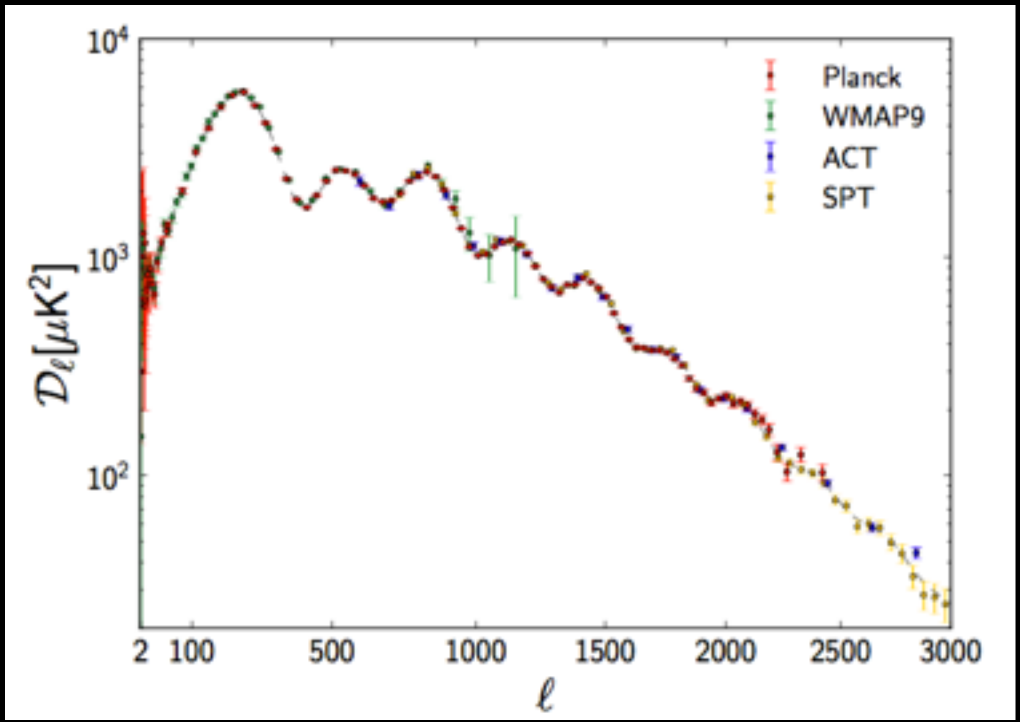
X-ray emitting hot gas (Chandra)

Gravitational potential from weak lensing

Evidence for cold dark matter



Cosmic Microwave Background fluctuations



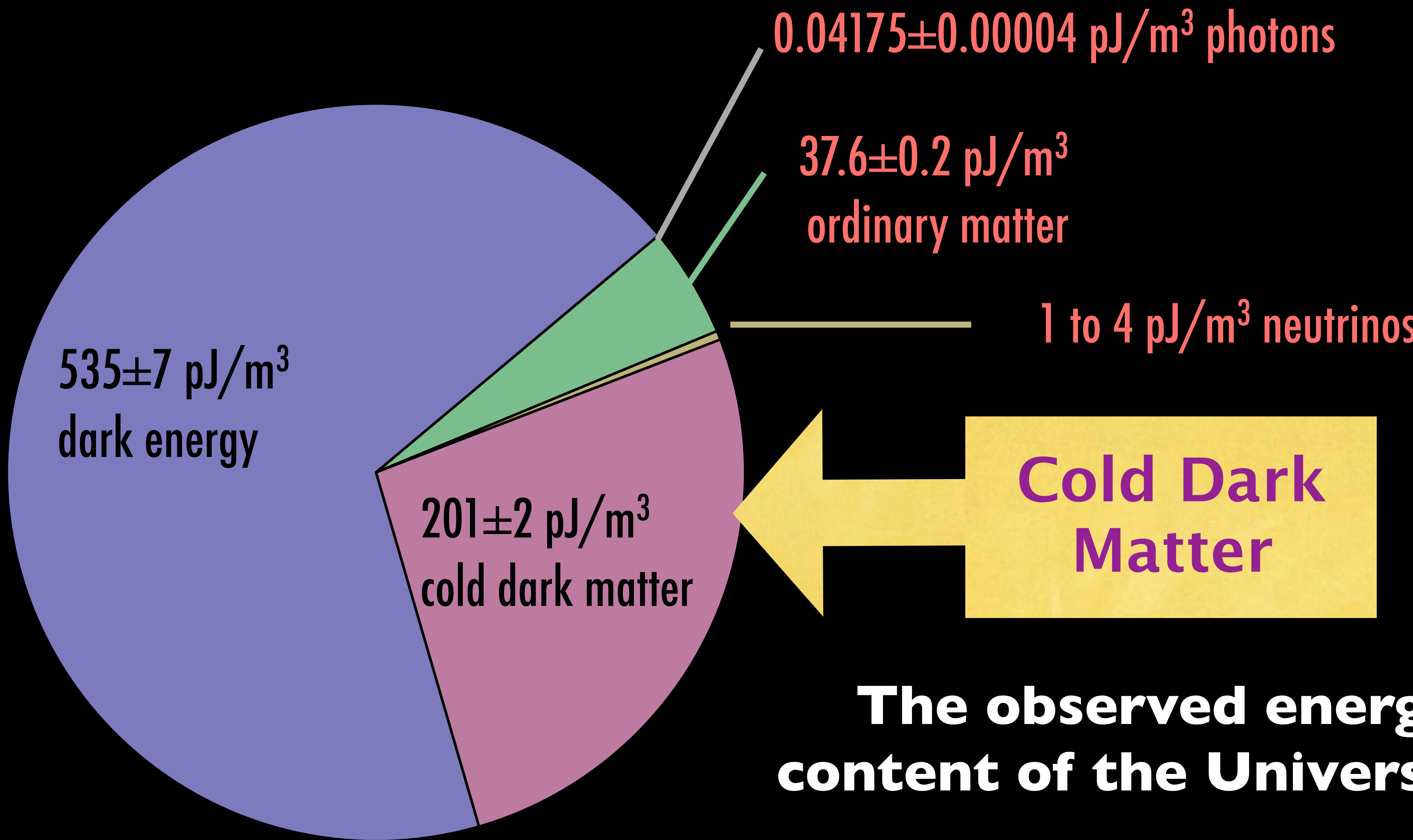
Parameter	*Planck*+WP+highL+BAO	
	Best fit	68% limits
$\Omega_b h^2$	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04148	1.04147 ± 0.00056
τ	0.0952	0.092 ± 0.013
n_s	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0973	3.091 ± 0.025
Ω_Λ	0.6914	0.692 ± 0.010
σ_8	0.8288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

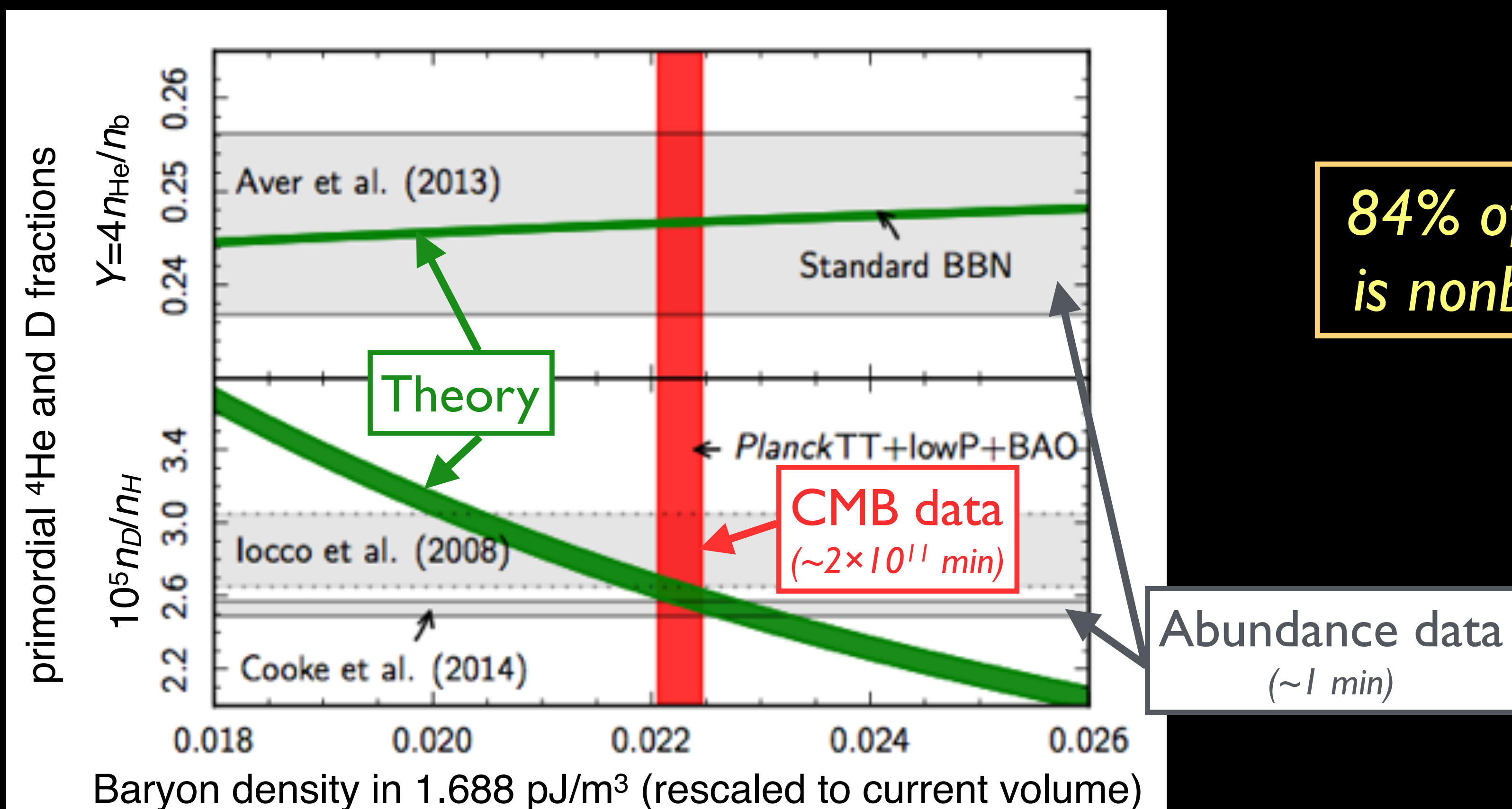
1 pJ = 10^{-12} J

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

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.



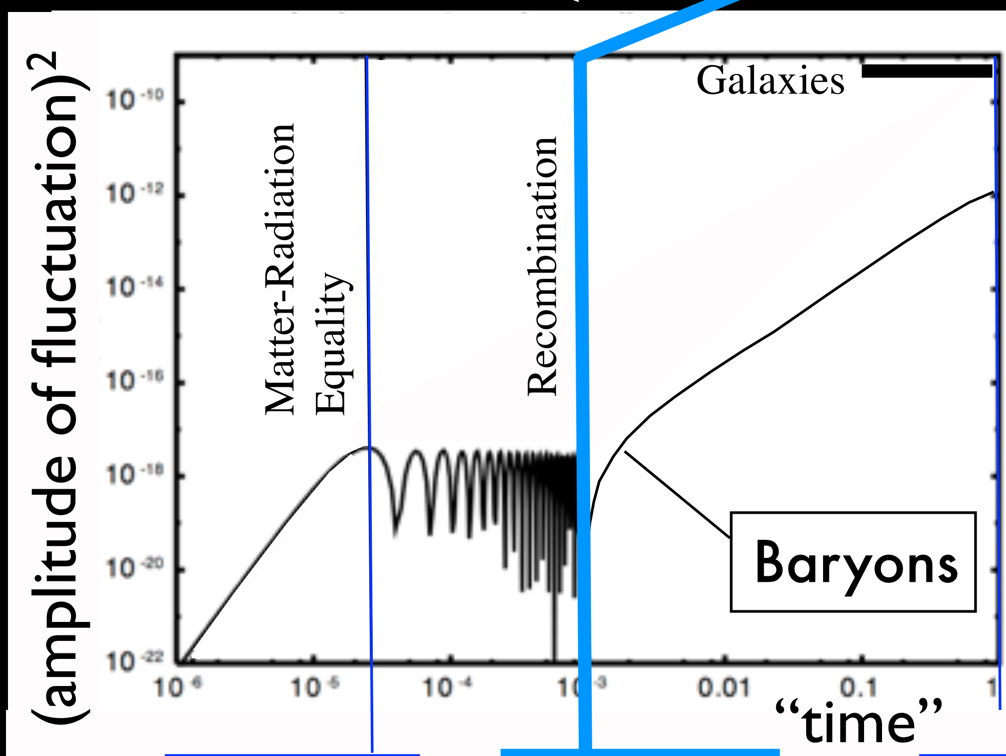
84% of matter is nonbaryonic

Ade et al [Planck] 2015

Evidence for *nonbaryonic* cold dark matter

GALAXY FORMATION

13 billion years ago

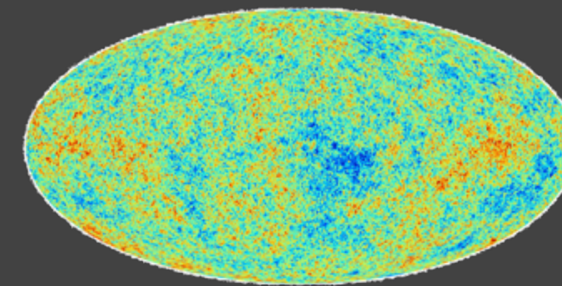


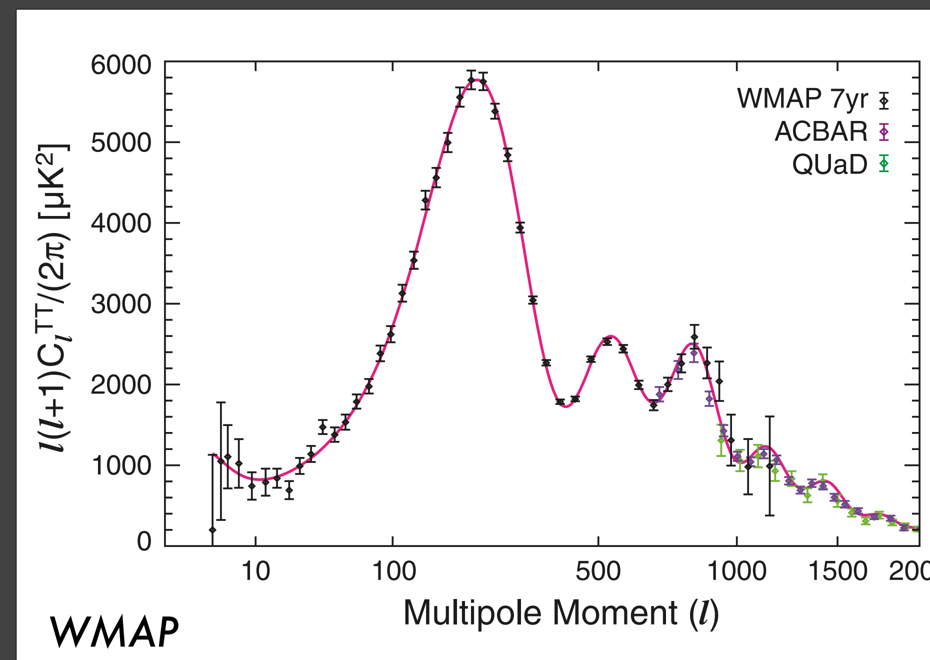
T=1.28 eV

T=0.26 eV

T=0.2348 meV

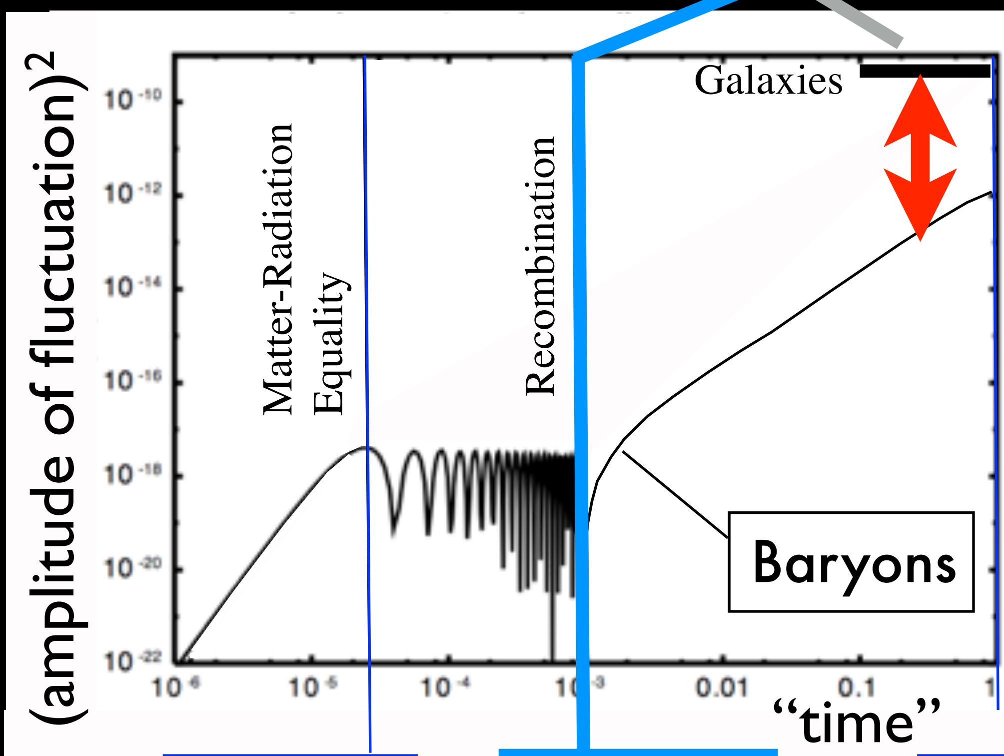
Cosmic Microwave Background fluctuations



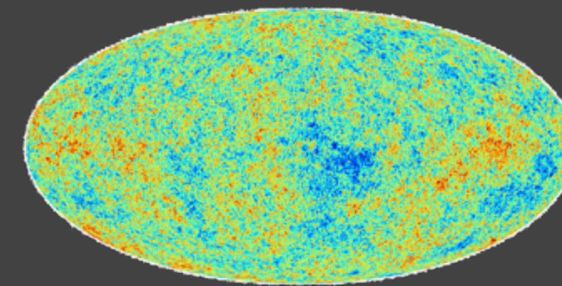


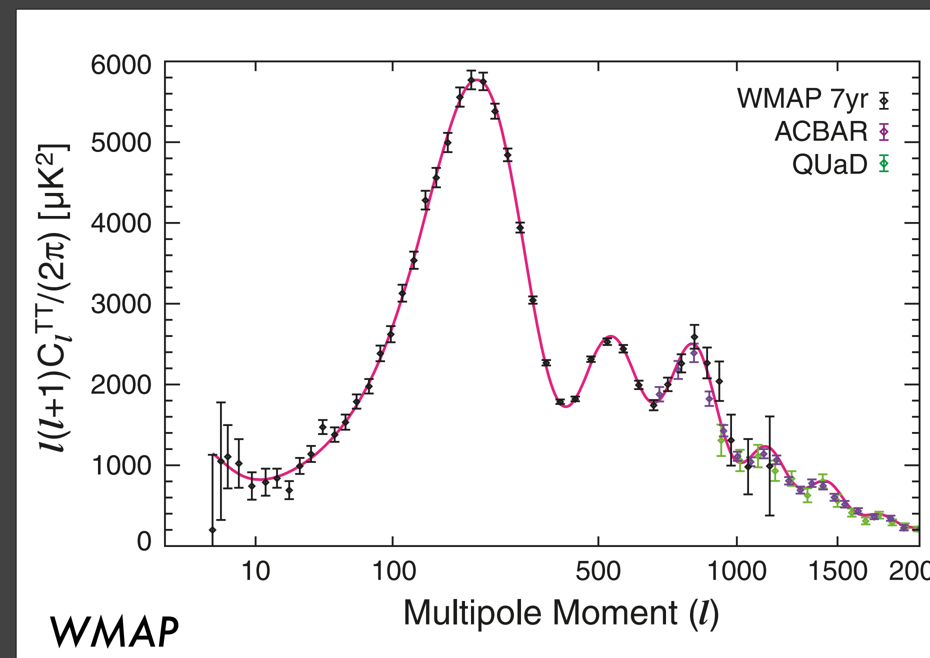
Evidence for *nonbaryonic* cold dark matter

Without dark matter, fluctuations are too small to gravitationally grow into galaxies in the given 13 billion years.



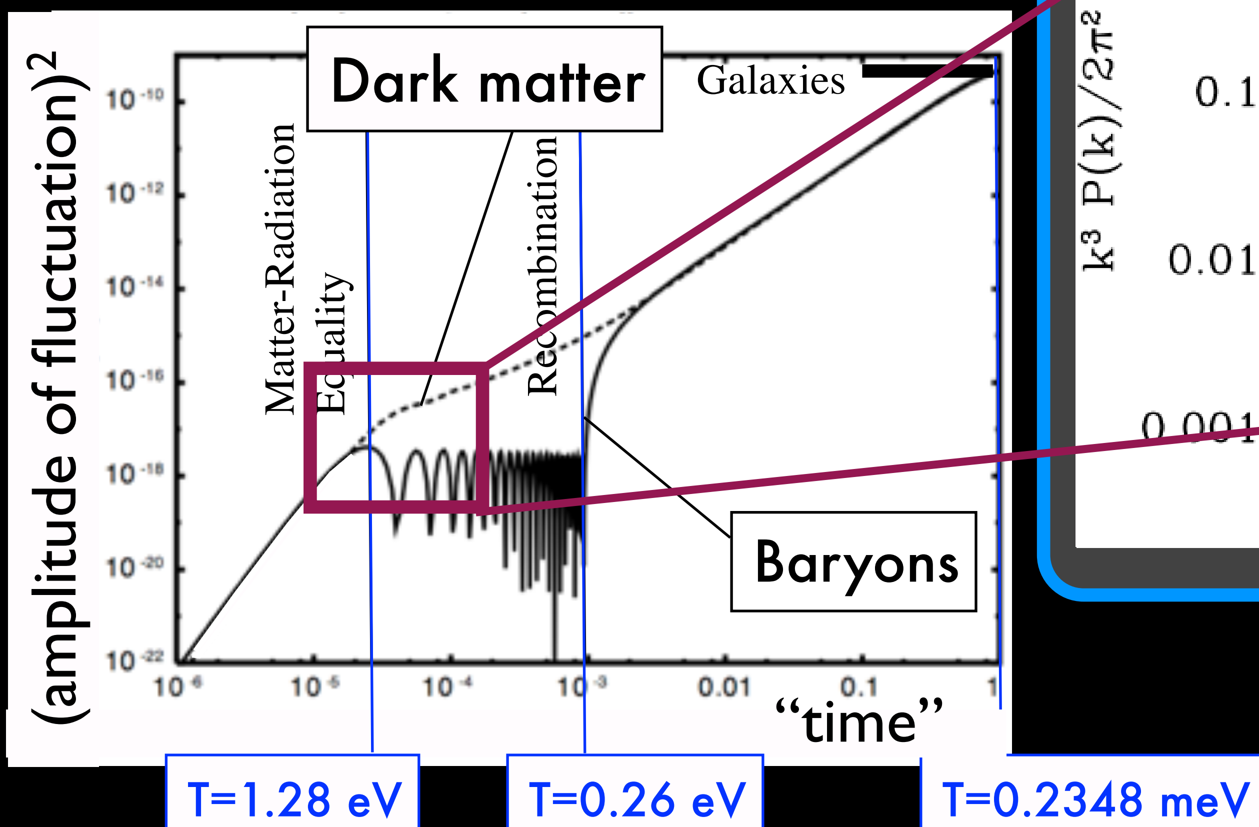
Cosmic Microwave Background fluctuations





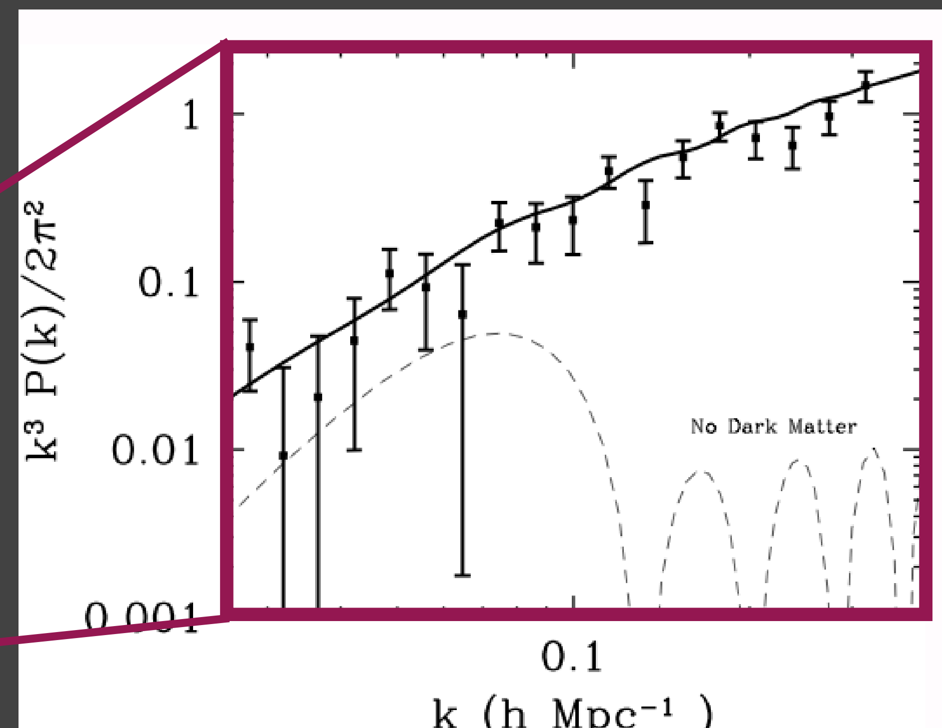
Evidence for *nonbaryonic* cold dark matter

Dark matter fluctuations, uncoupled to the plasma, start growing early and have enough time to grow into galaxies

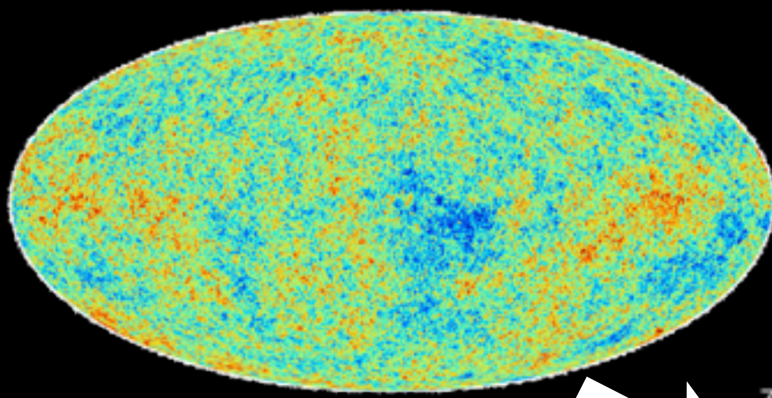


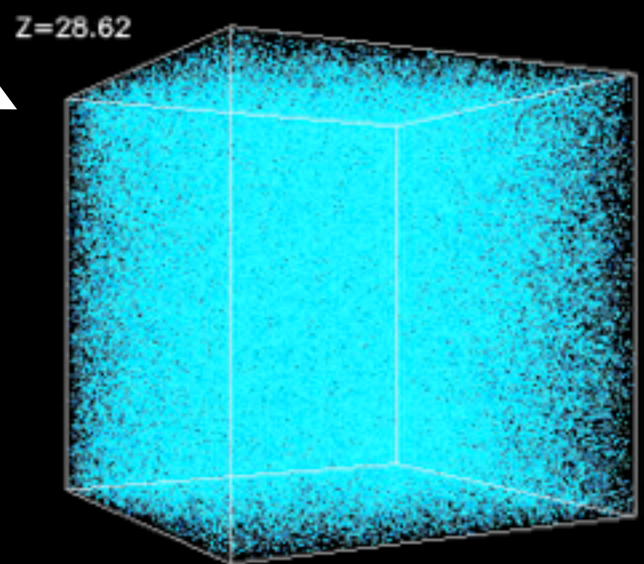
More than 80% of all matter does not couple to the primordial plasma!

SDSS

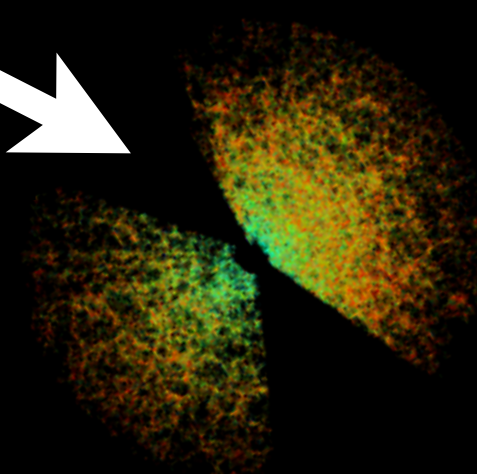


Evidence for nonbaryonic *cold* dark matter

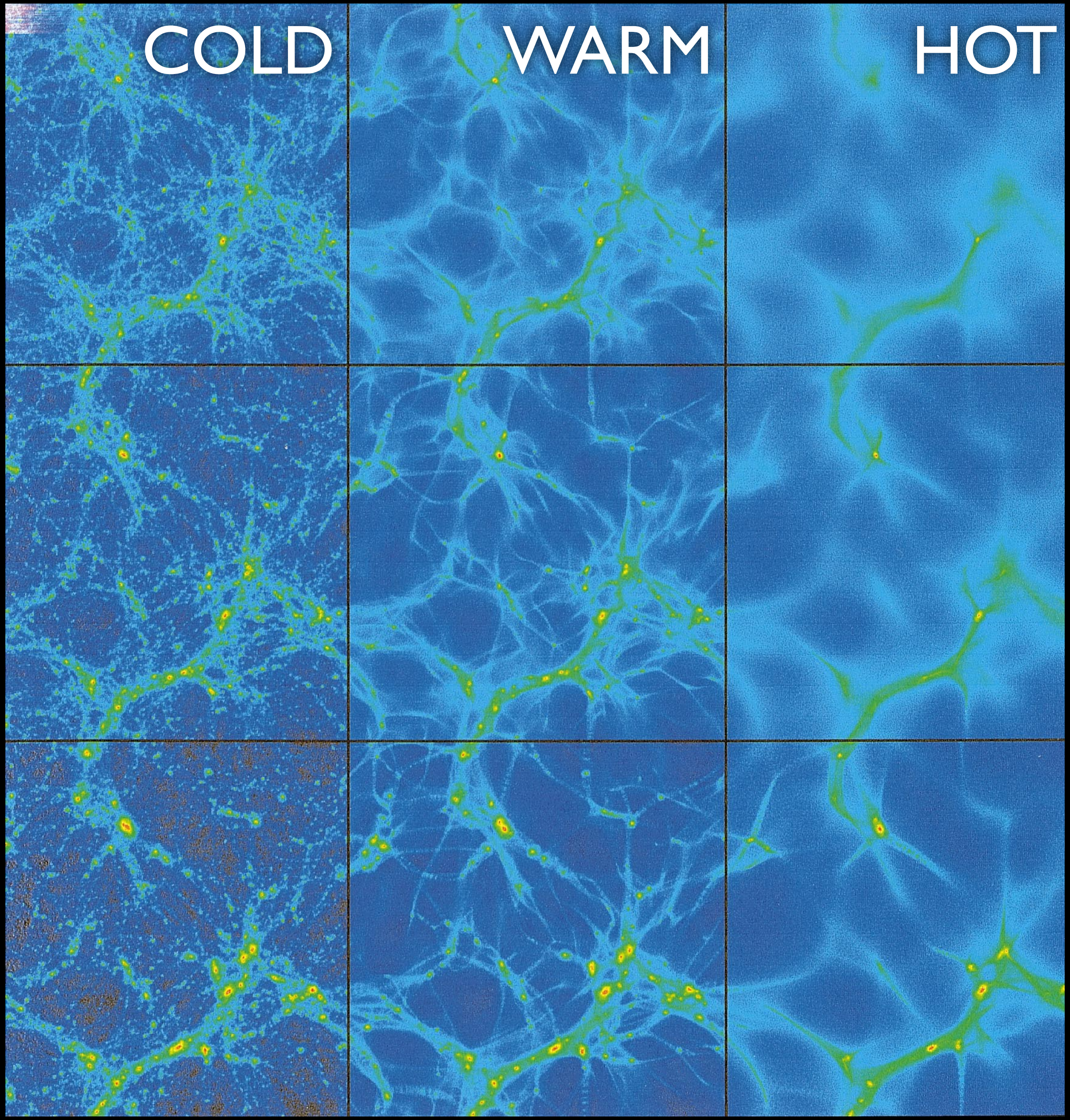




Kravtsov, Klypin



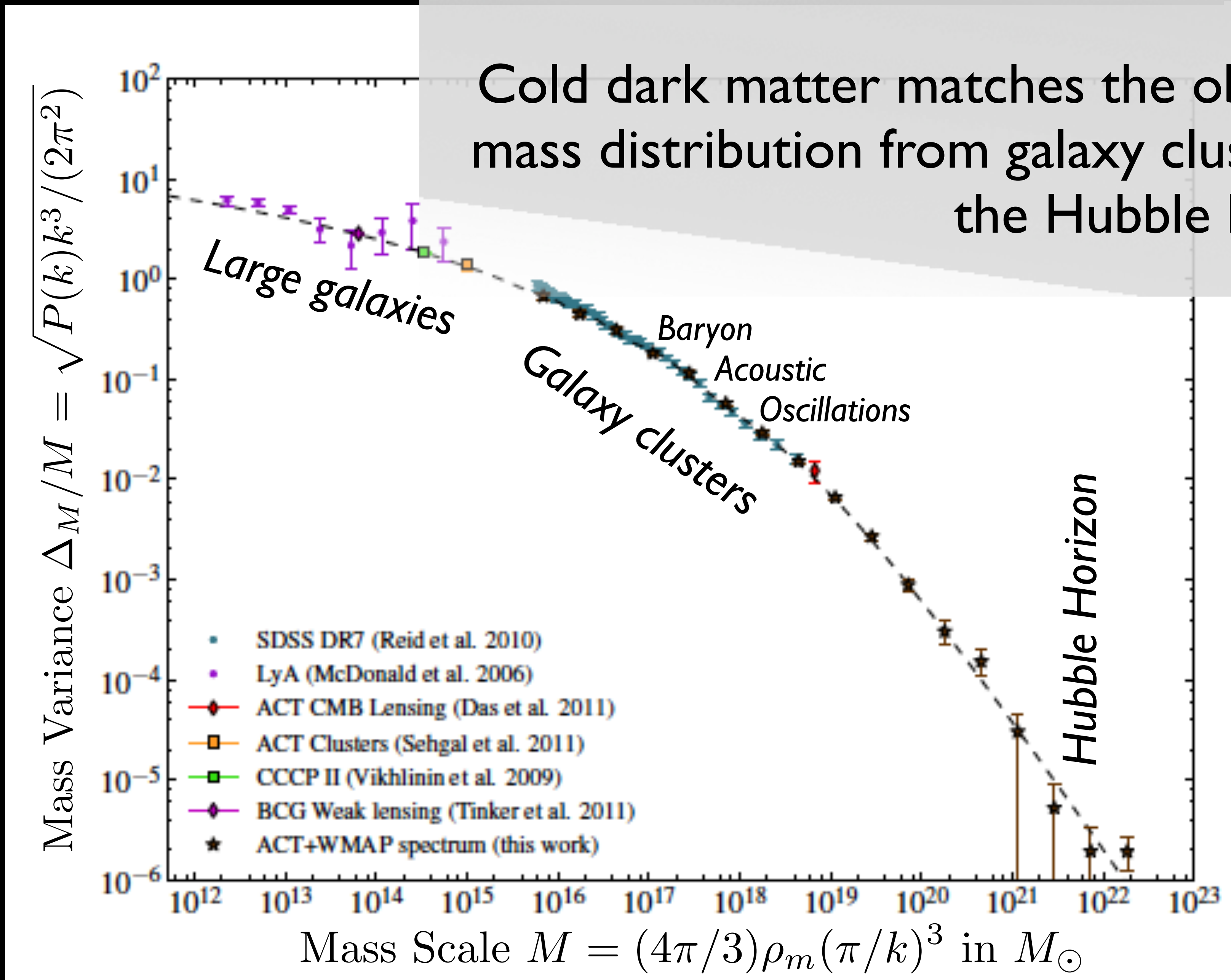
Evidence for nonbaryonic *cold* dark matter



Bode et al 2001

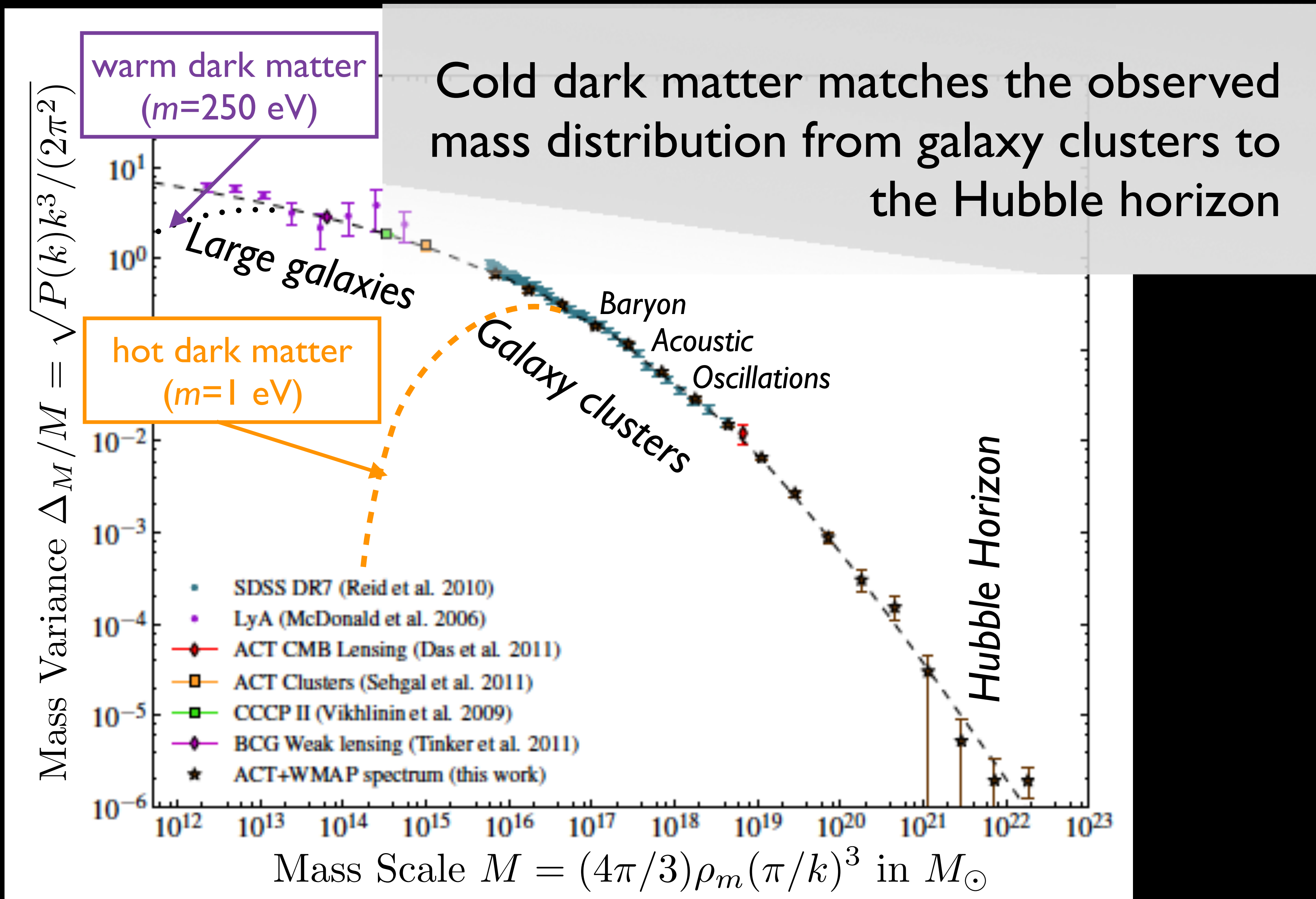
Evidence for nonbaryonic *cold* dark matter

Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon



Hlozek et al 2012

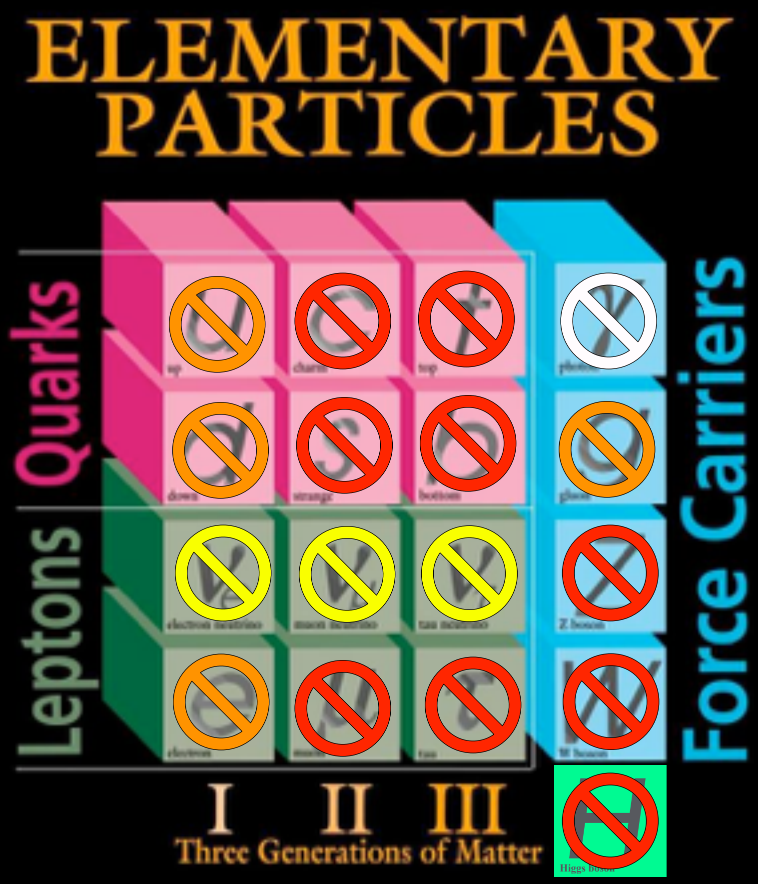
Evidence for nonbaryonic *cold* dark matter



Hlozek et al 2012

What is nonbaryonic cold dark matter?

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, ultralight scalars, axion clusters (cold)
- solitons (Q-balls, B-balls, ...) (cold)
- supermassive wimpzillas (cold)

} non-thermal relics

Mass range
10^{-22} eV (10^{-59}kg) B.E.C.s 10^{-8} $M_\odot$ (10^{+22}kg) axion clusters

Interaction strength range
Only gravitational: wimpzillas Strongly interacting: B-balls

Particle dark matter

Hot dark matter

- relativistic at kinetic decoupling (last scattering, 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 with the plasma in the early universe
- produced in collision of plasma particles
- insensitive to initial conditions

neutralinos, other WIMPs, ...

Non-thermal relics

- not in thermal equilibrium with the plasma in the early universe
- produced in decays of heavier particles or extended structures
- have a memory of initial conditions

axions, WIMPZILLAs, solitons, ...

QCD axions

QCD 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)

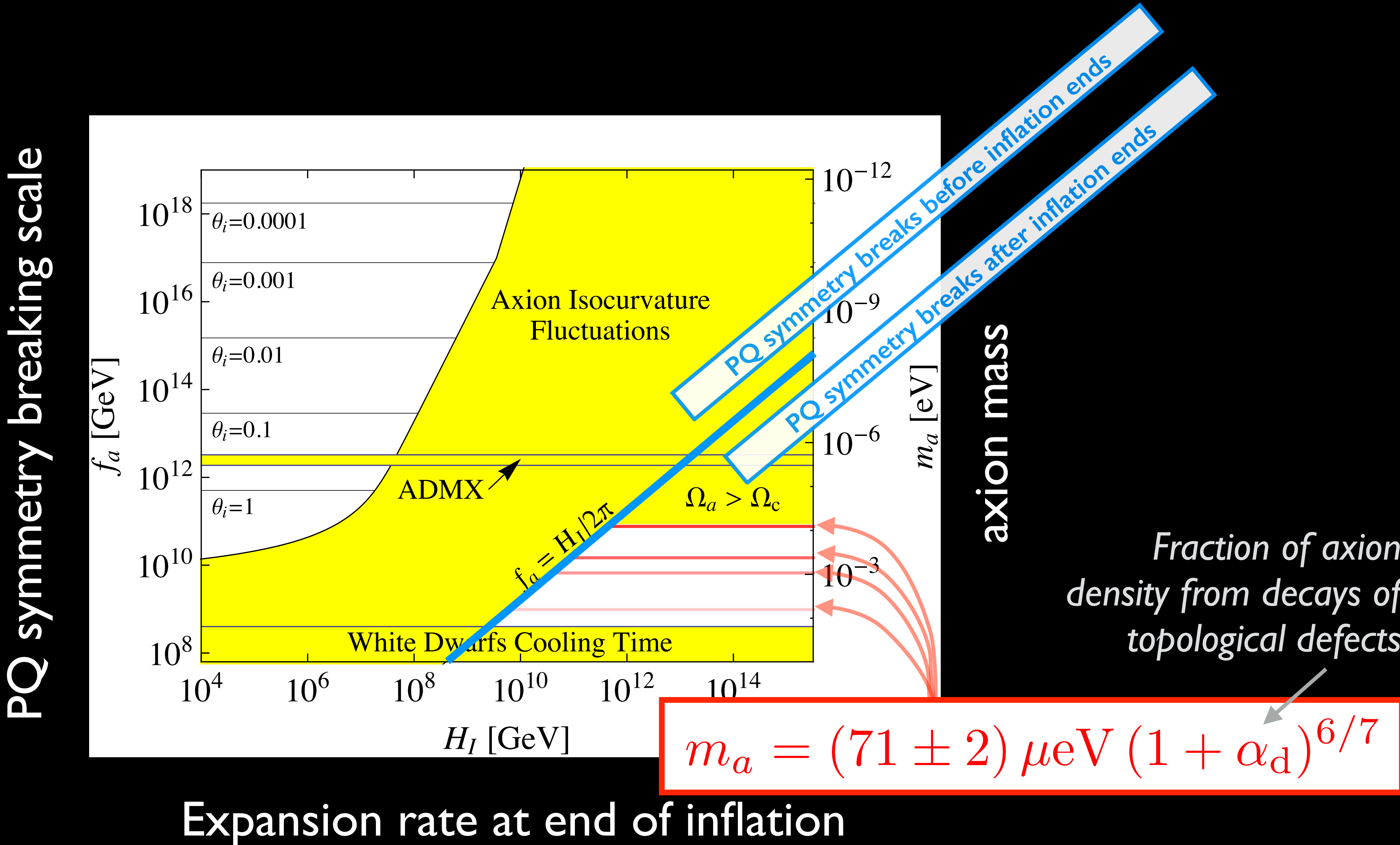
Produced by decay of topological defects

(Axionic string decays)

Still a very complicated and uncertain calculation!

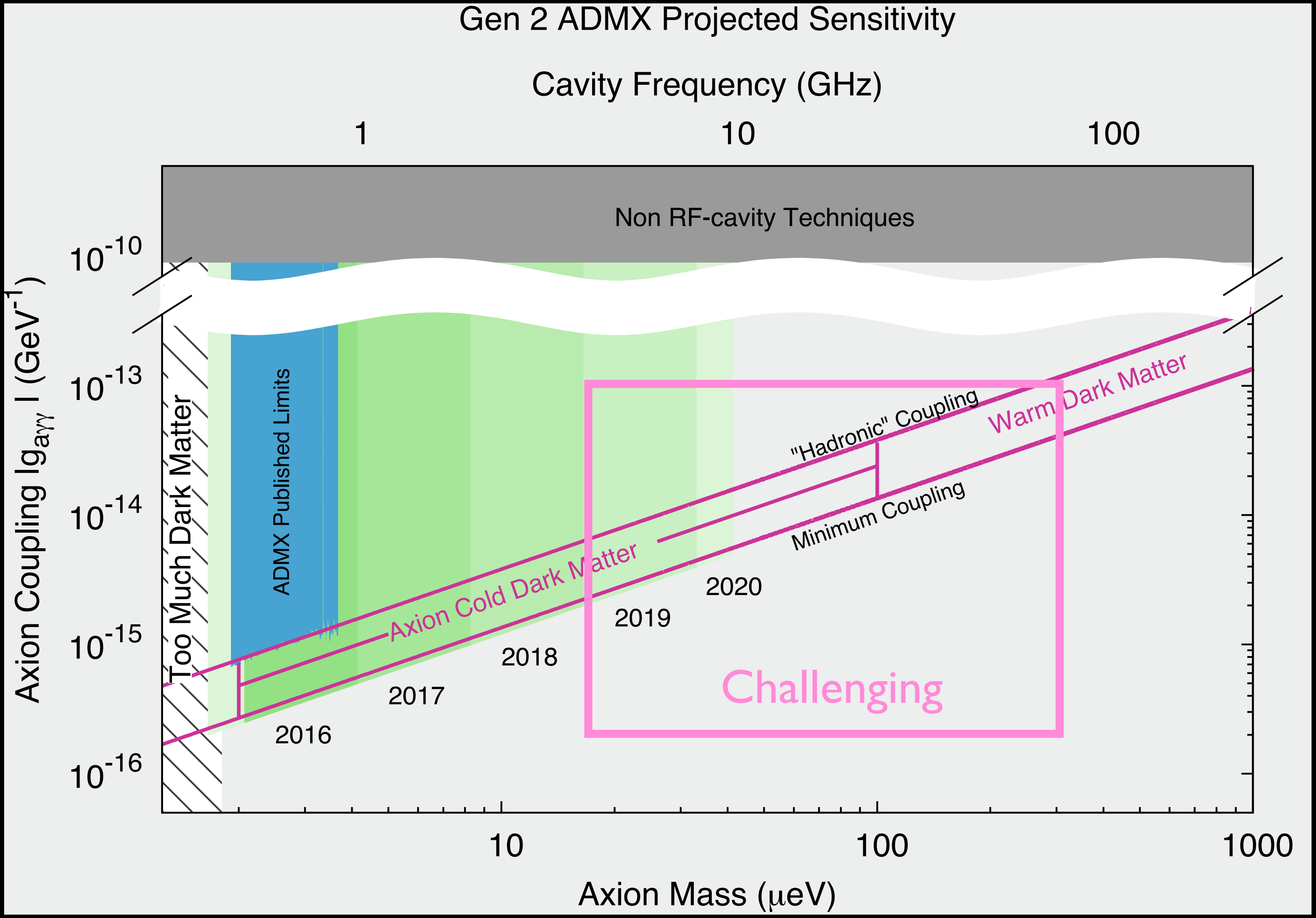
e.g. Hiramatsu et al 2012

QCD axions as cold dark matter



Visinelli, Gondolo 2009, 2014

QCD axions as cold dark matter: searches



Dielectric haloscope?

Rybka 2016

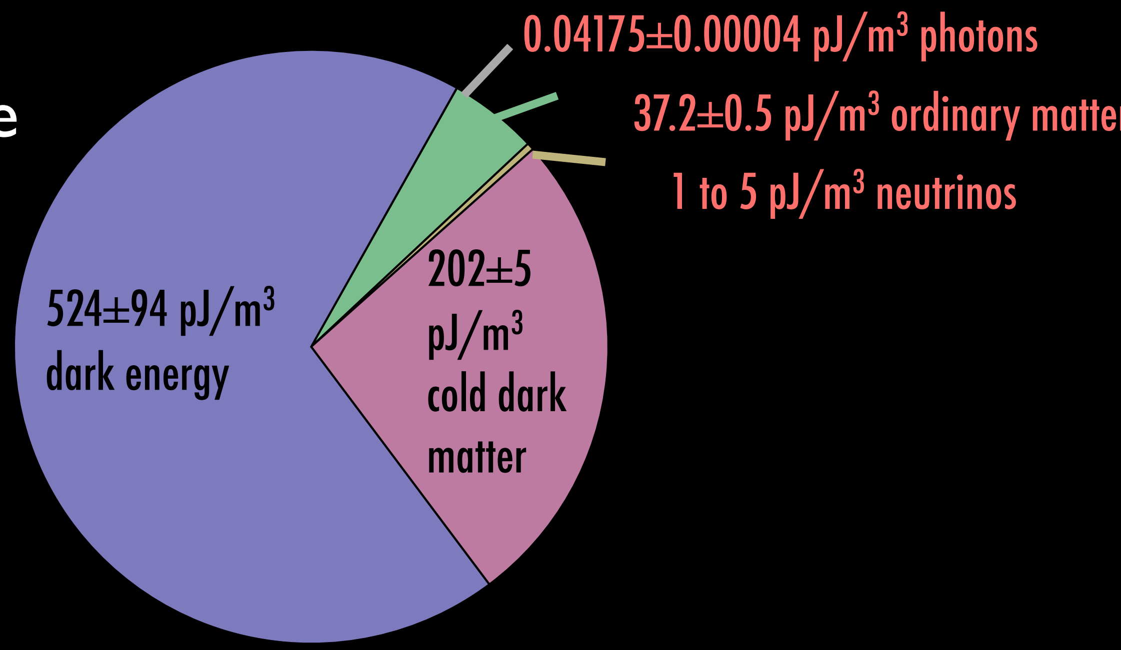
Weakly Interacting Massive Particles

The magnificent WIMP

(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

  Thermal production in hot primordial plasma.



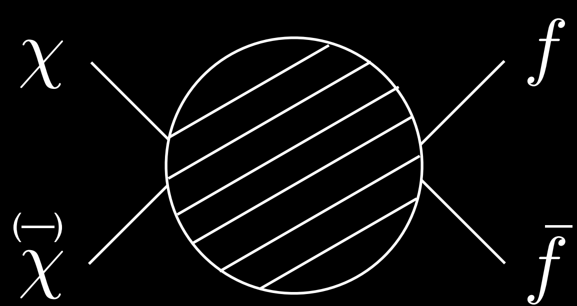
- One can experimentally test the WIMP hypothesis

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

Cosmic density of thermal WIMPs

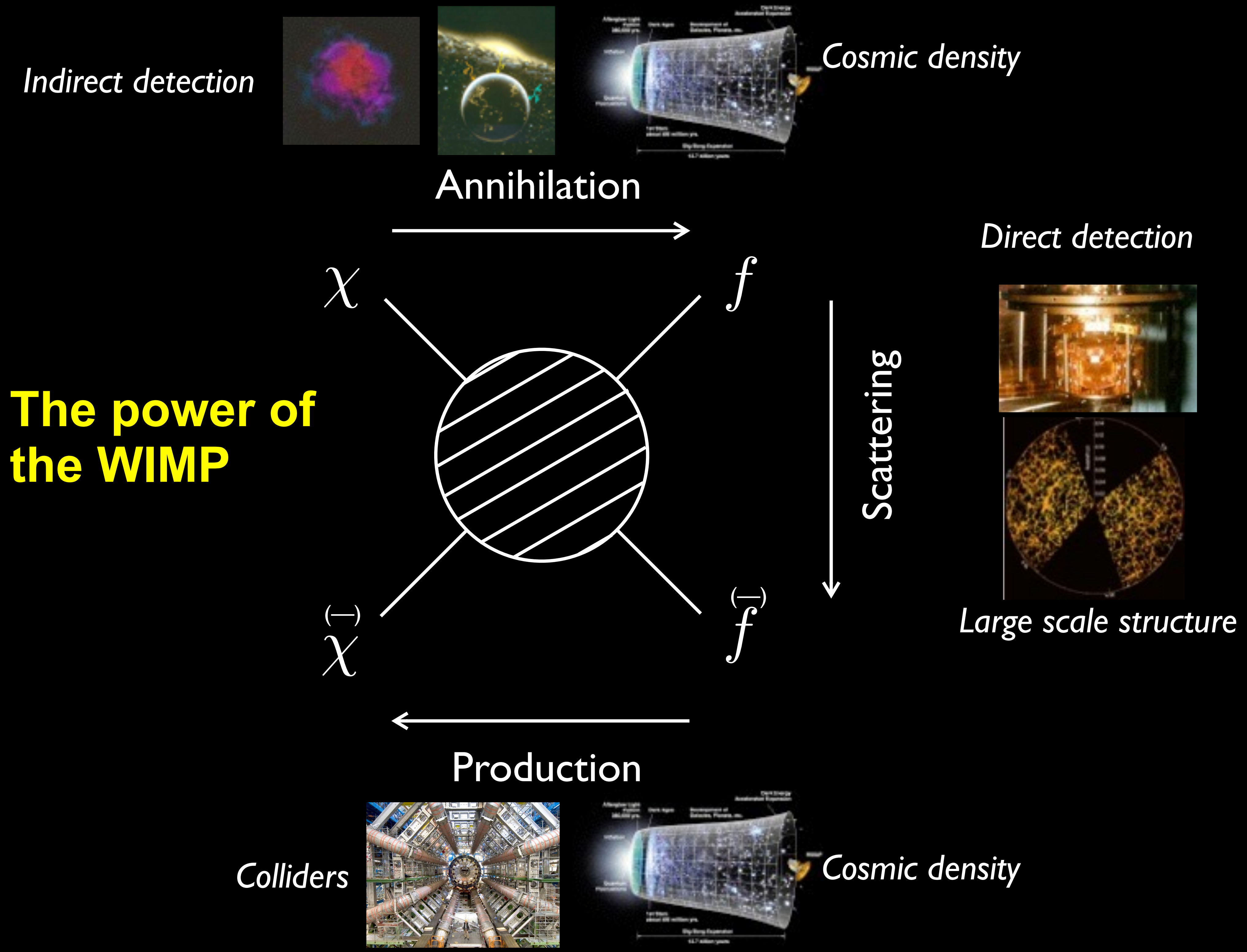
- At early times, WIMPs are produced in e^+e^-, $\mu^+\mu^-$, etc collisions in the hot primordial soup [*thermal production*].

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



- WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate [*freeze-out*].

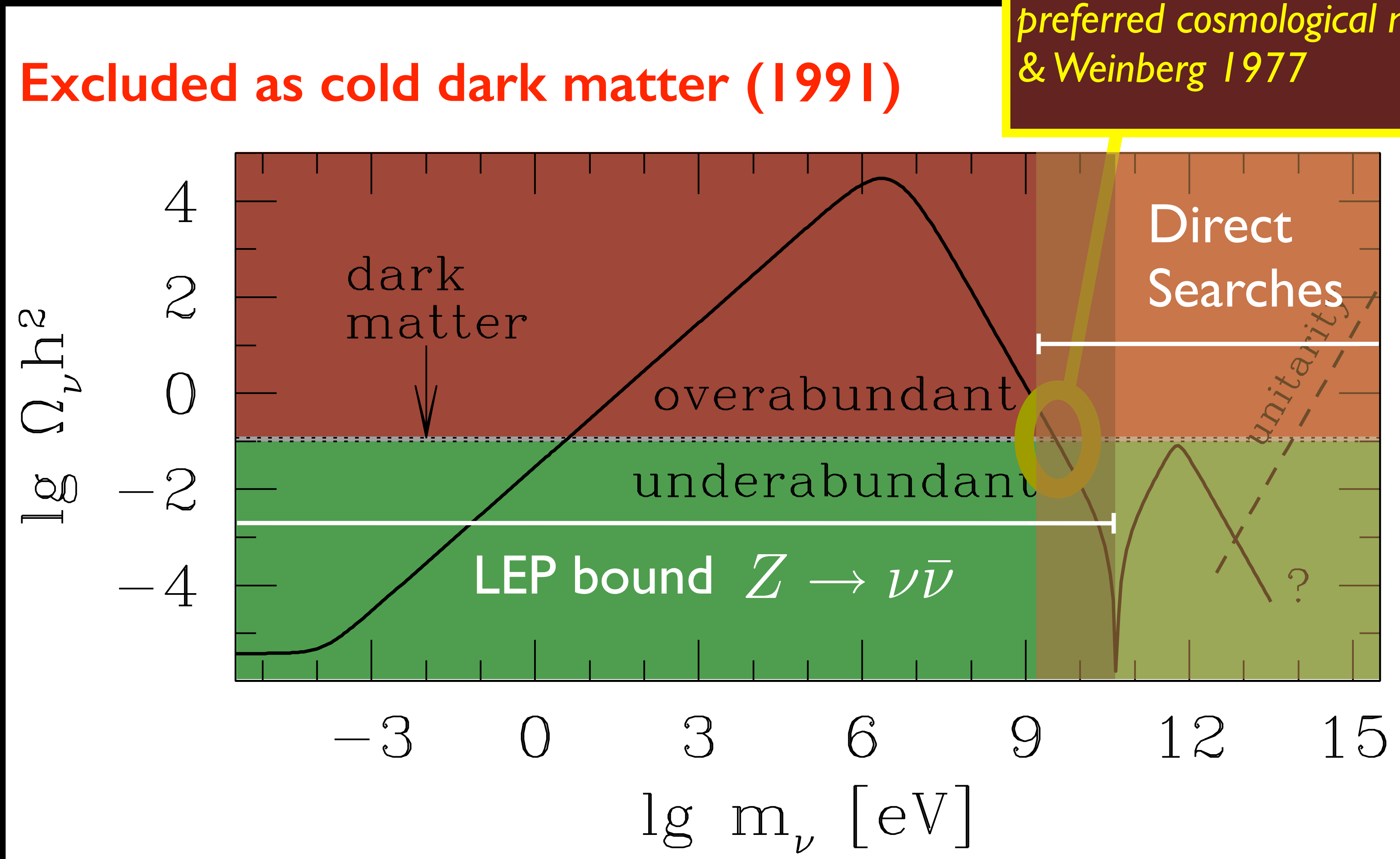
- After freeze-out, there is a constant number of WIMPs in a volume expanding with the universe.


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

Massive neutrinos as dark matter

Heavy active neutrino

~ few GeV
preferred cosmological mass Lee & Weinberg 1977



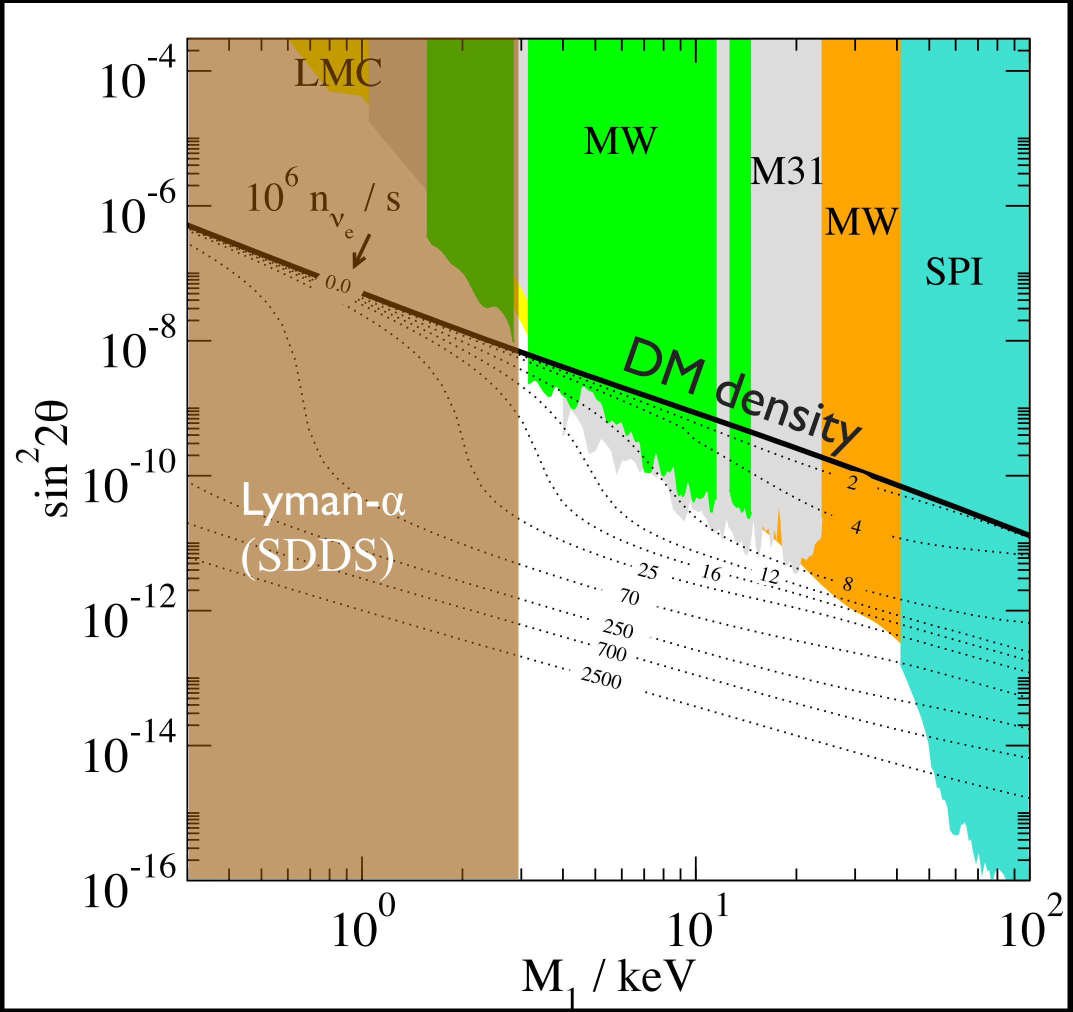
Sterile neutrino dark matter

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



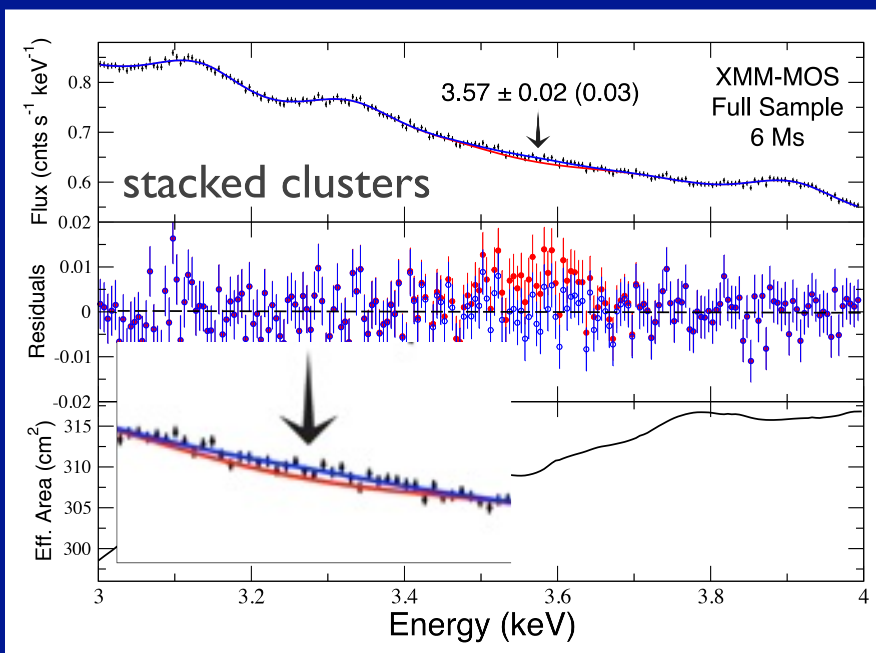
*ν*MSM

Laine, Shaposhnikov 2008

Sterile neutrino dark matter

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

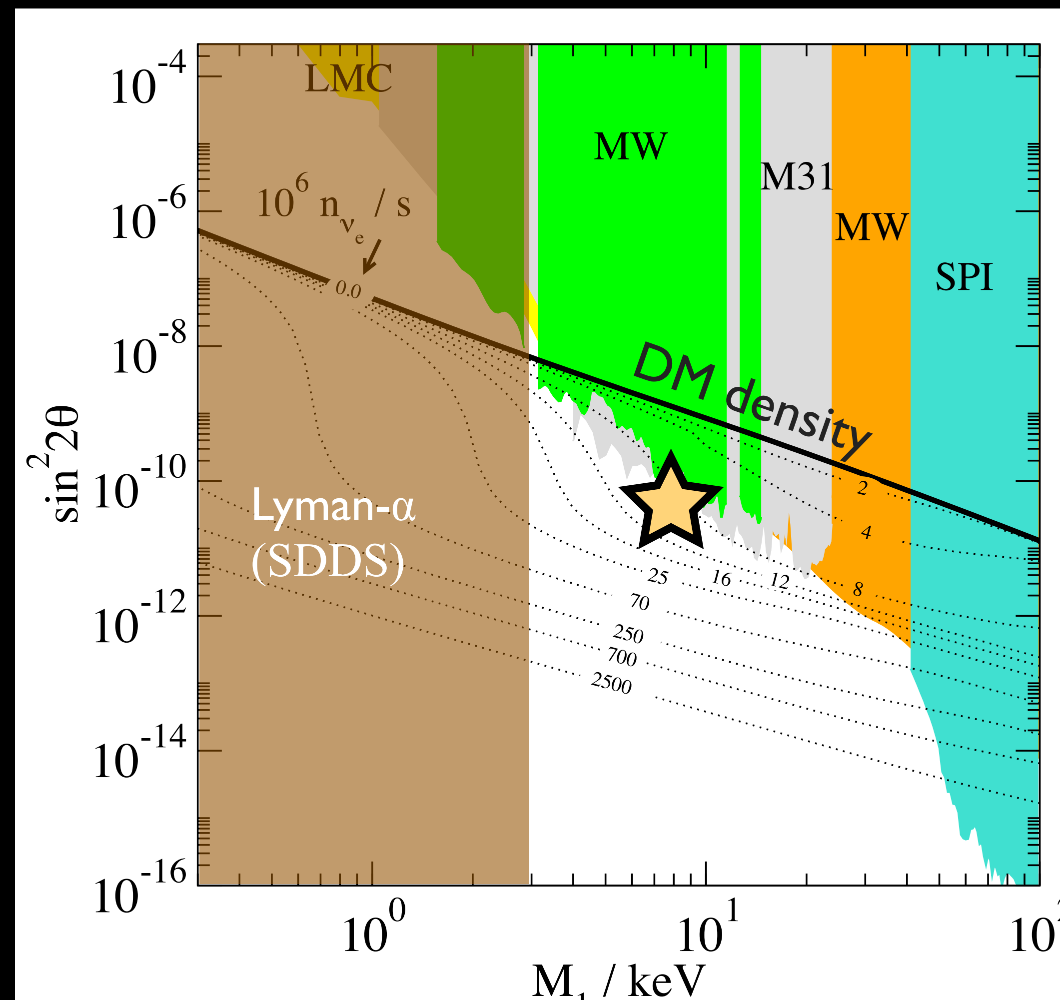
Bulbul et al 2014; Boyarski et al 2014; Iakubovskyi et al 2015



Radiative decay of sterile neutrinos

$$\nu_s \rightarrow \gamma\nu_a \qquad E_\gamma = m_s/2$$

$m_\nu = 7.1$ keV $\quad \sin^2(2\theta) = 7\times10^{-11}$



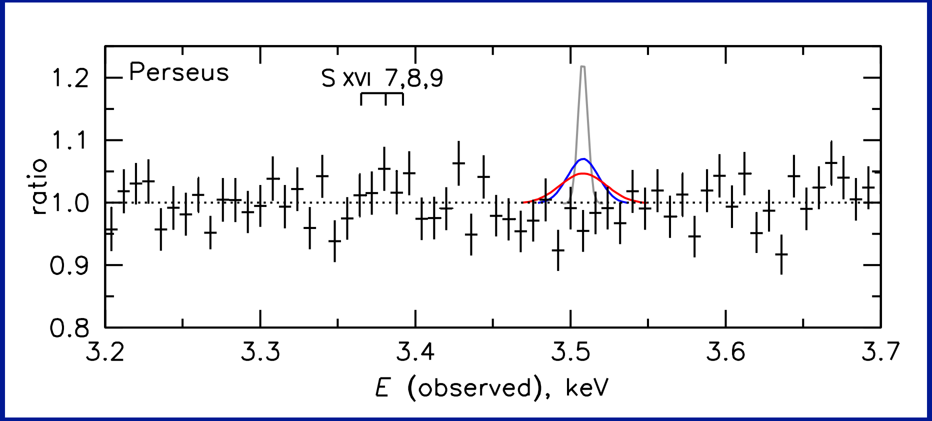
νMSM

Laine, Shaposhnikov 2008

Sterile neutrino dark matter

The HITOMI data on the Perseus galaxy cluster do not show an X-ray line with the expected strength

Aharonian et al (HITOMI Collab.) 2016



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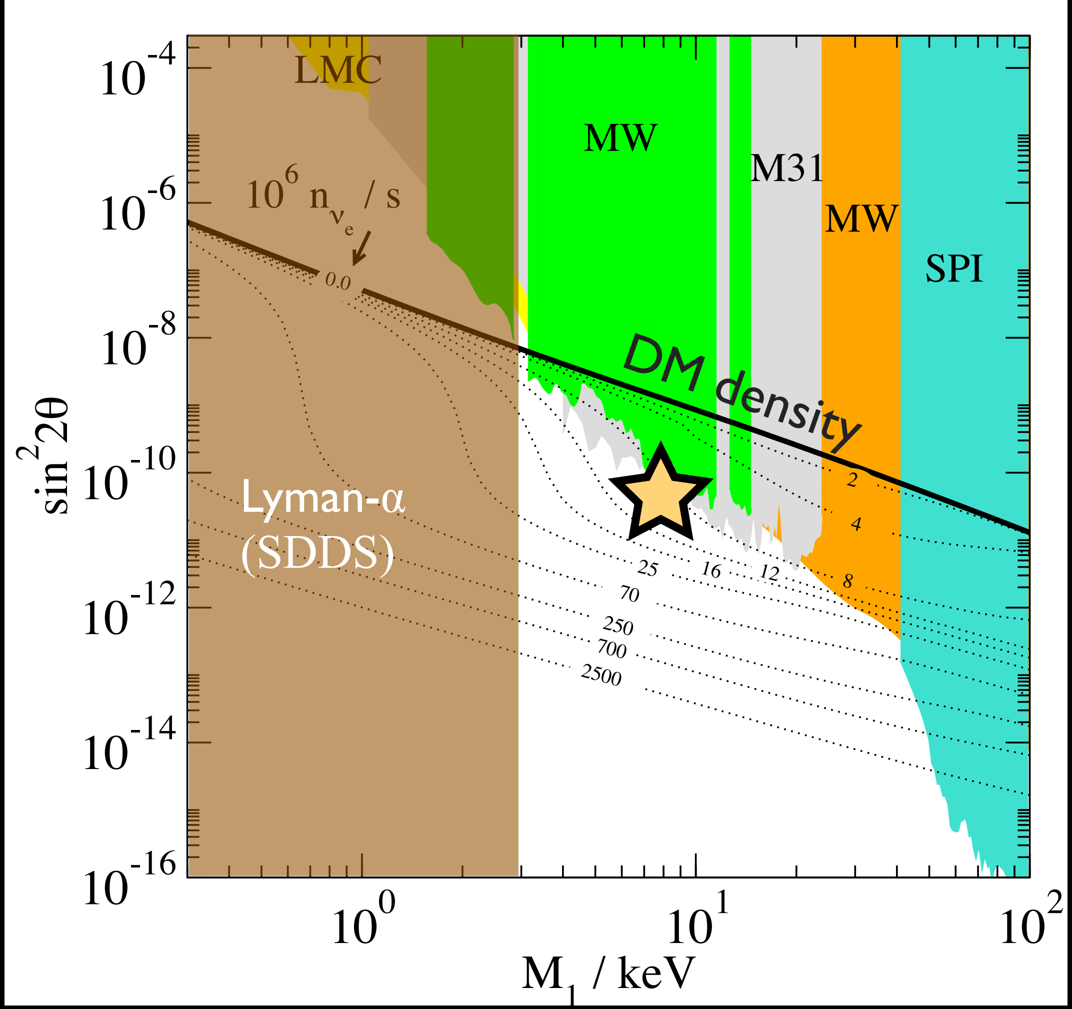


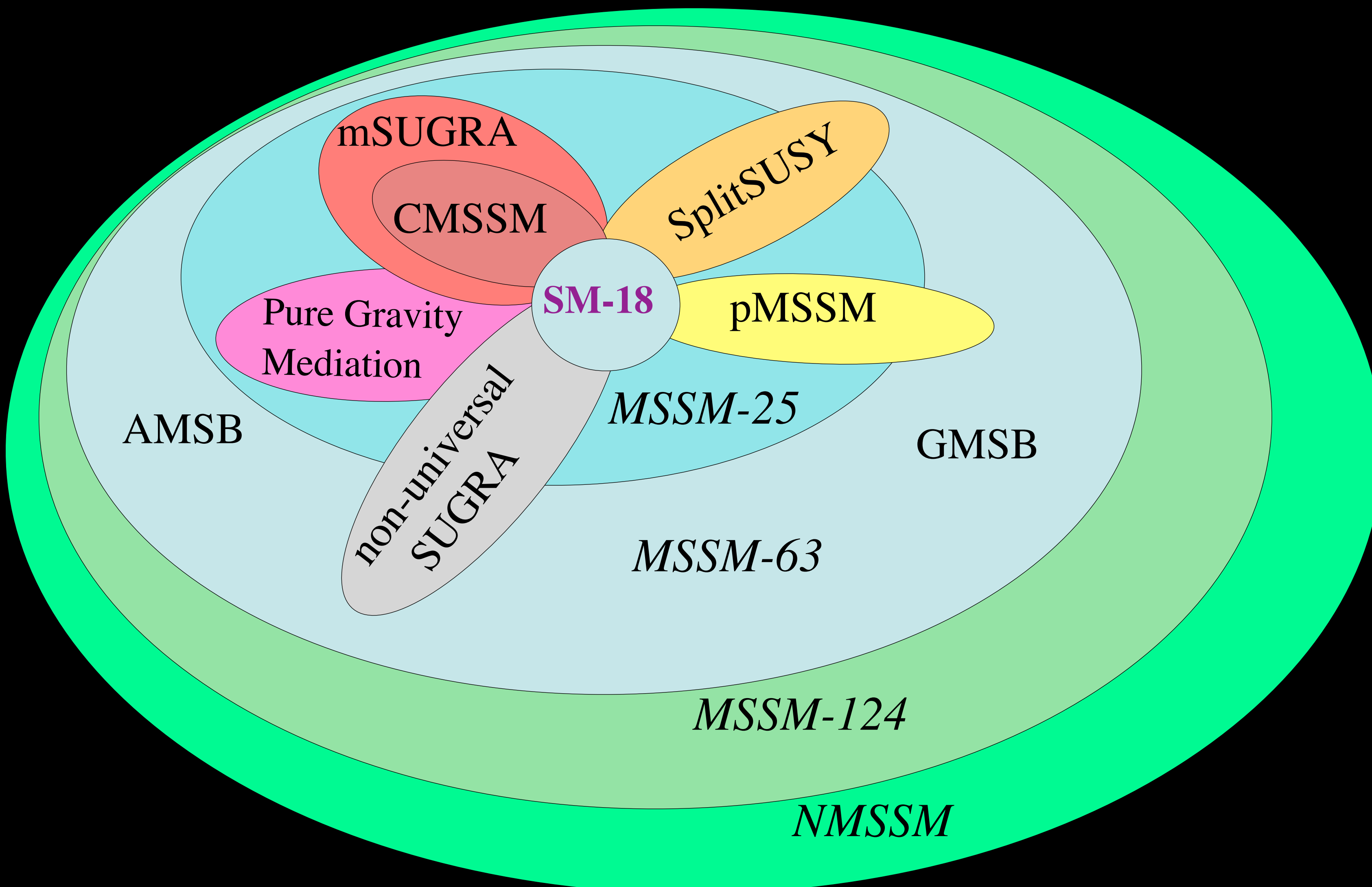
*ν*MSM

Laine, Shaposhnikov 2008

Supersymmetric dark matter

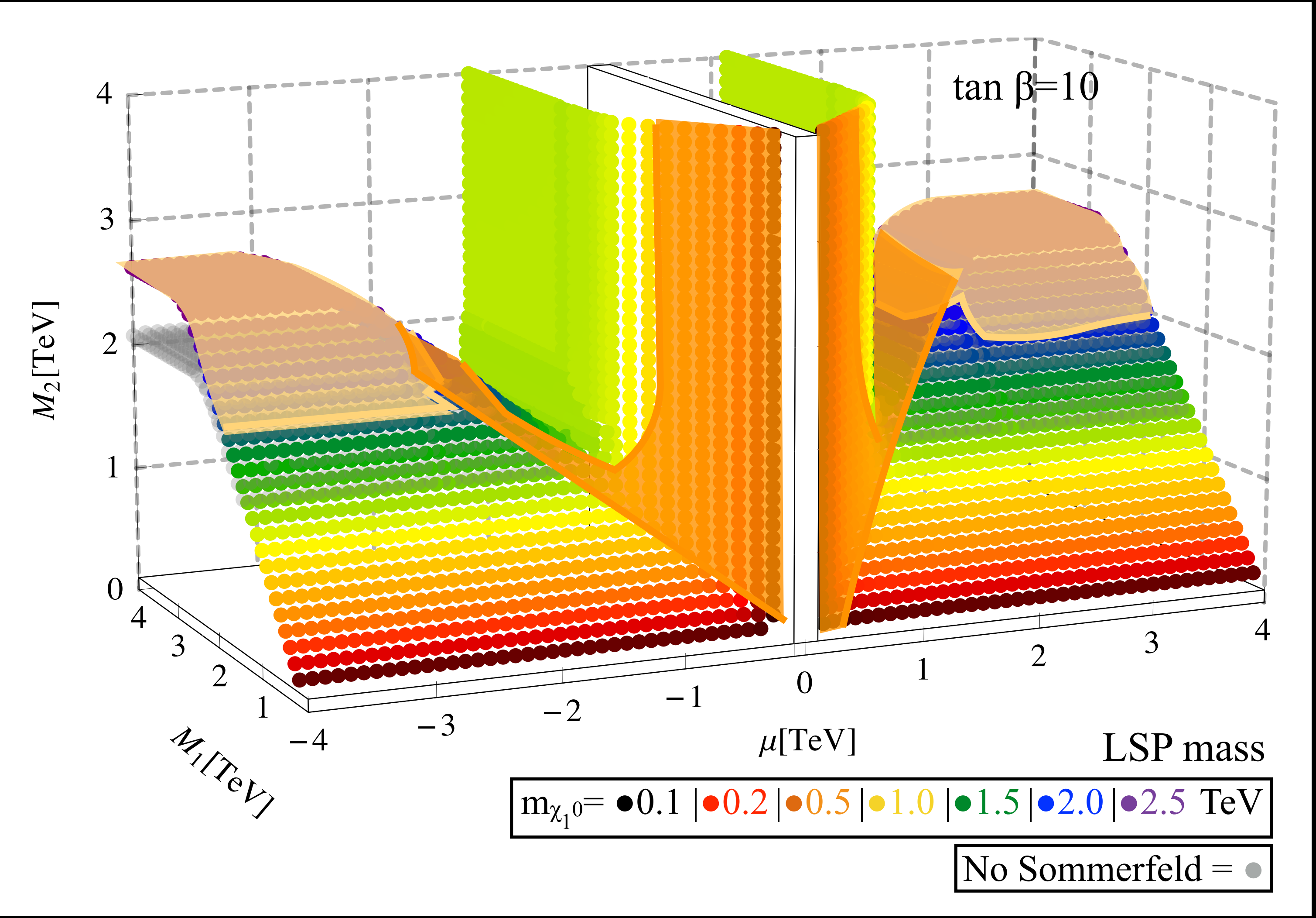
The CMSSM* is in dire straights, but there are many supersymmetric models

**Constrained Minimal Supersymmetric Standard Model*



Neutralino dark matter

Neutralino dark matter with decoupled (heavy) sfermions



Excluded by LEP, HESS, LUX

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

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

Scalar phantom dark matter

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

Minimalist dark matter

do not confuse with minimal dark matter

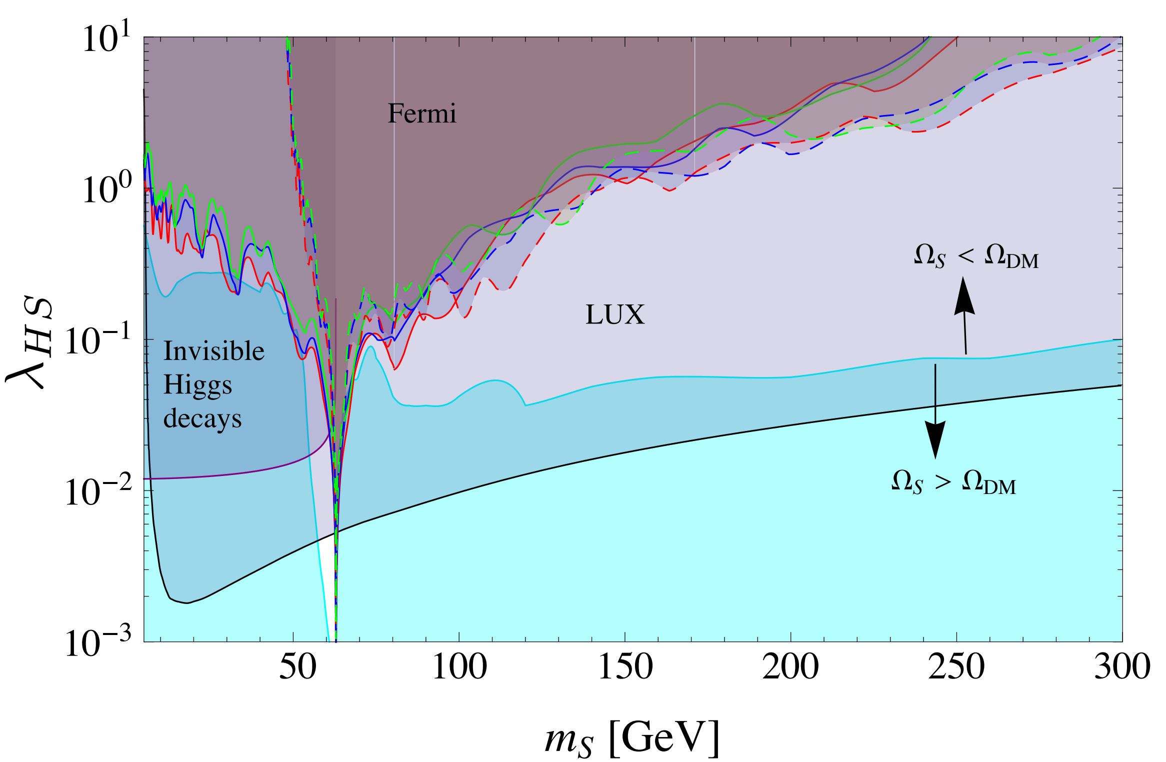
Gauge singlet scalar field S stabilized by a Z_2 symmetry ($S \to -S$)

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

Silveira, Zee 1985
Andreas, Hambye, Tytgat 2008
Djouadi, Falkowksi, Mambrini, Quevillon 2012
Cline, Scott, Kainulainen, Weniger 2013
Hamada, Kawana 2015

"Scalar phantom" is the original 1985 name

Scalar phantom dark matter



Not excluded by LUX at $m_S \approx 60$ GeV and $m_S > 1$ TeV
No density rescaling

Feng, Profumo, Ubaldi 2015

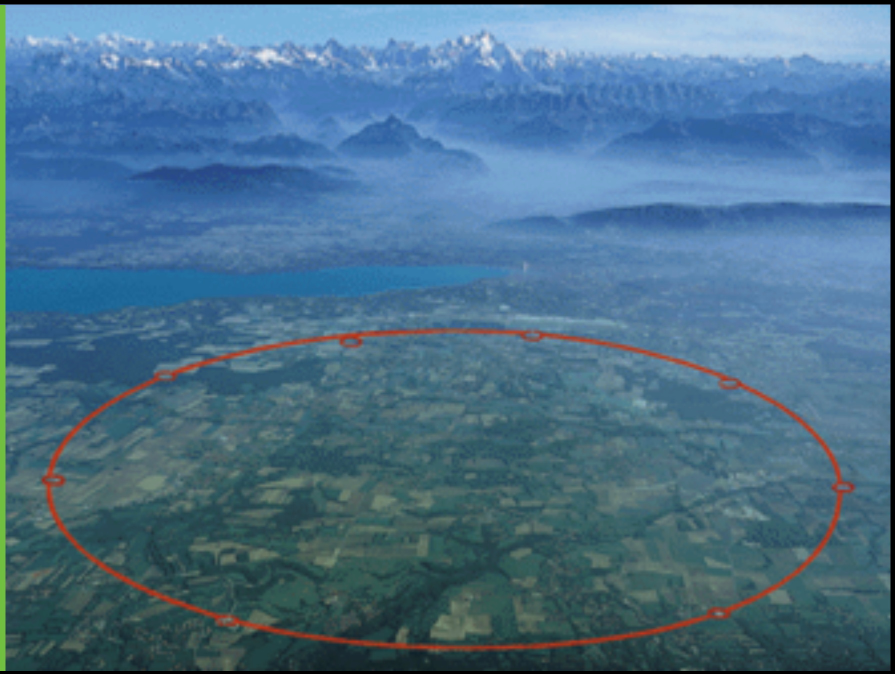
If density is rescaled according to Ω_S, LUX and FERMI exclusion regions are very different

Cline, Scott, Kainulainen, Weniger 2013

Evidence for nonbaryonic cold dark matter?

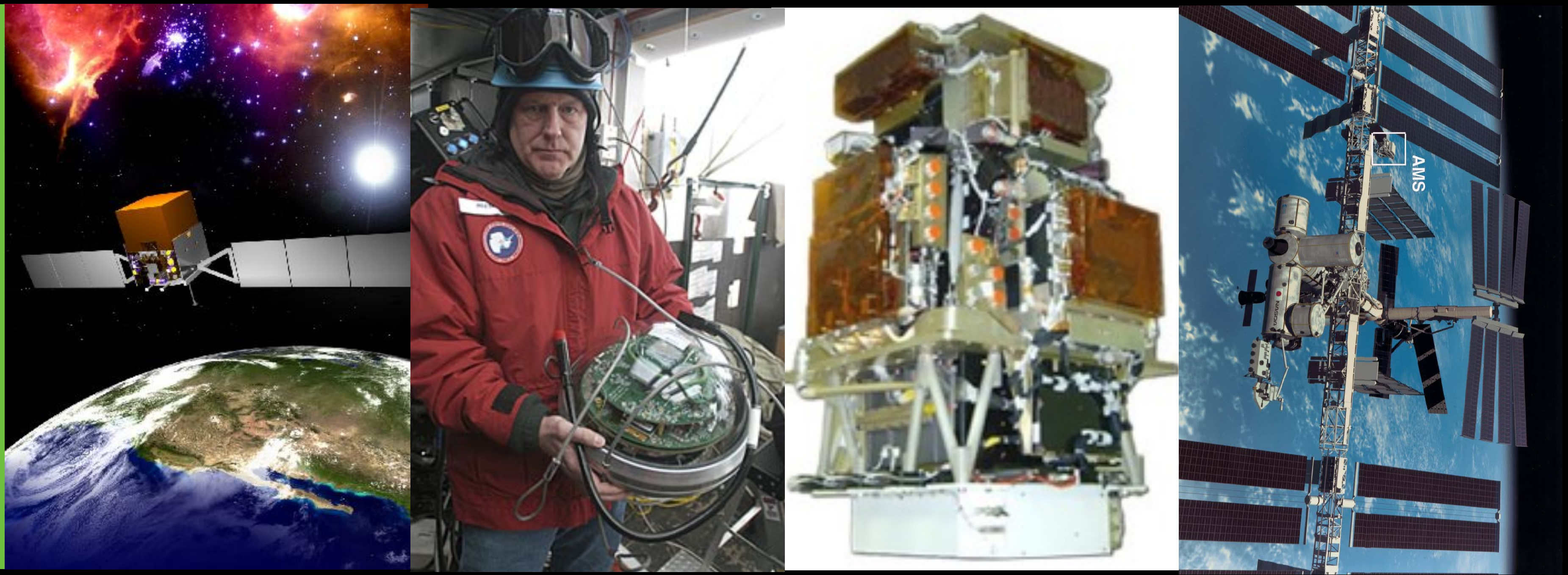
Searches for particle dark matter

Collider



Direct

Indirect

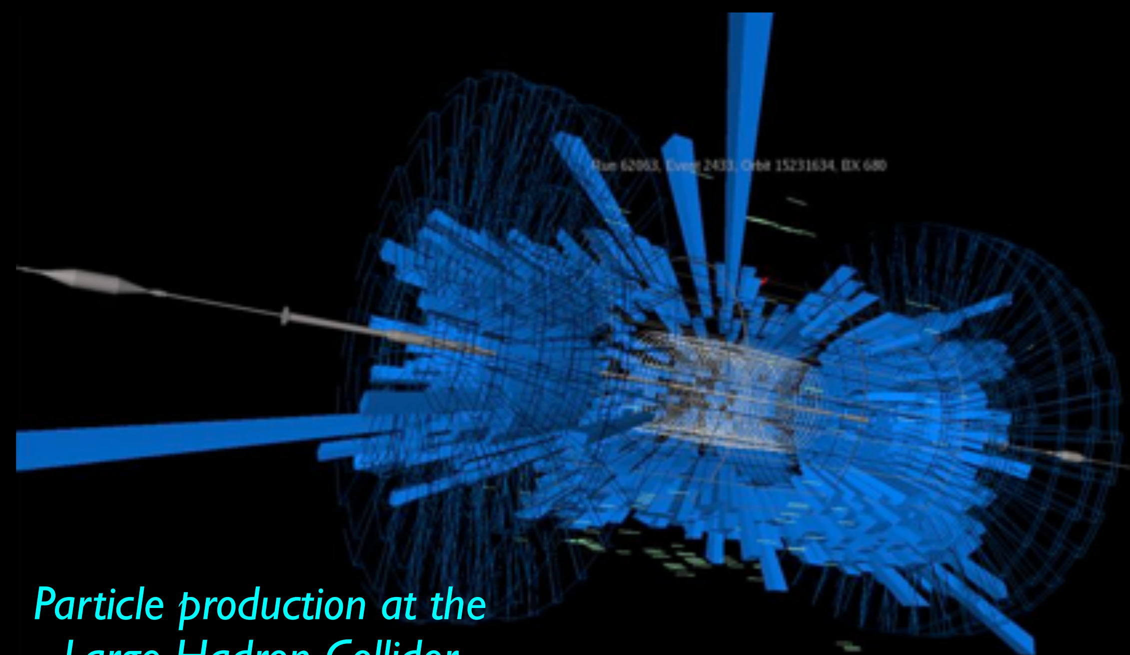


Searches for particle dark matter: colliders

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

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

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



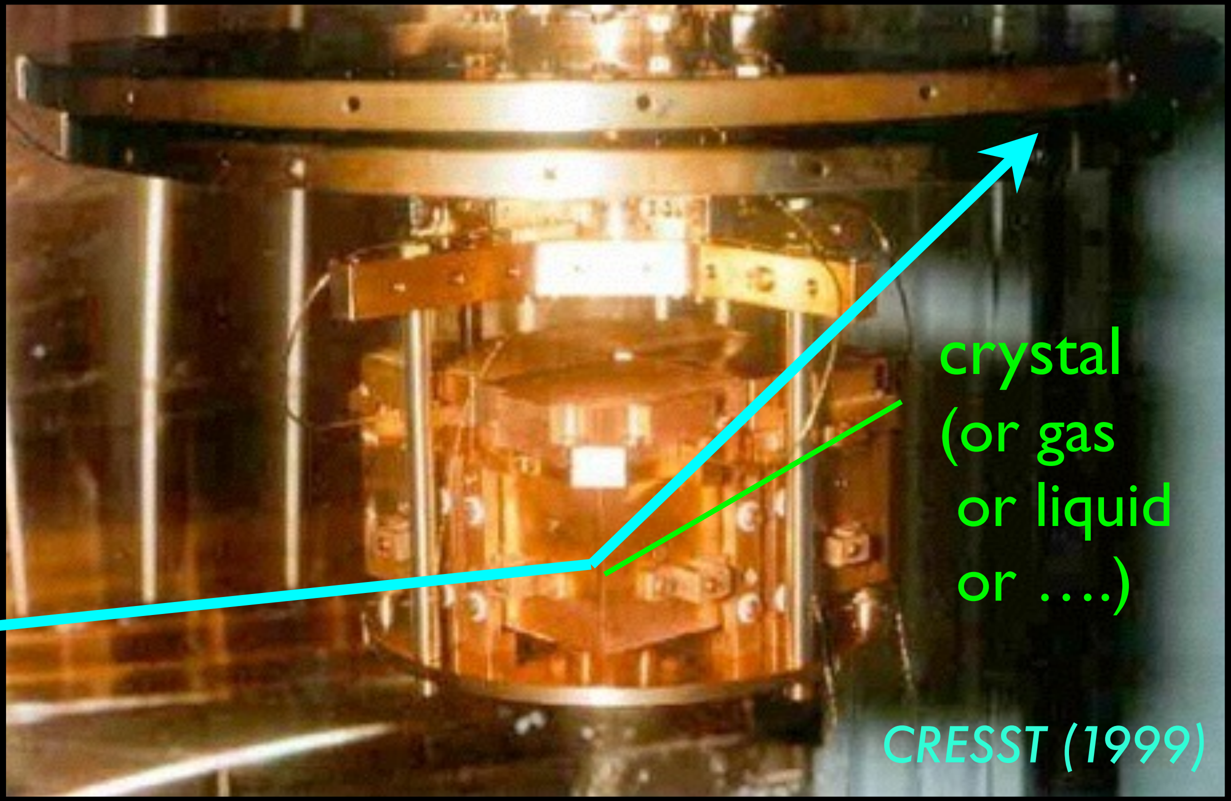
Particle production at the Large Hadron Collider

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

Searches for particle dark matter: direct

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

Goodman, Witten 1985



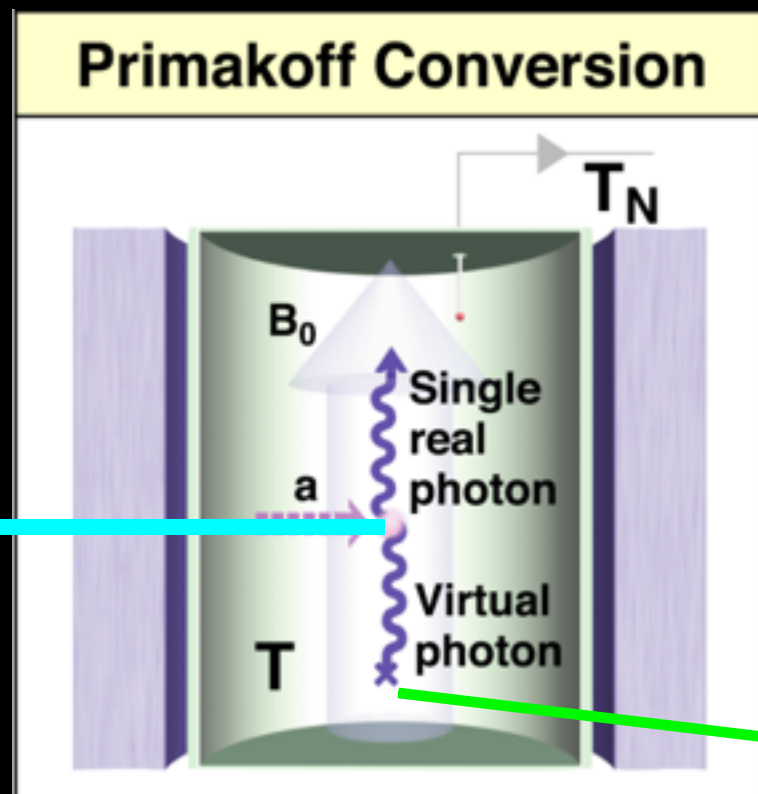
Low-background underground detector

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

Searches for particle dark matter: direct

Dark matter particles that arrive on Earth transform into photons in a detector

Sikivie 1983



ADMX

Dark matter particle

Magnetic field

Resonating cavity

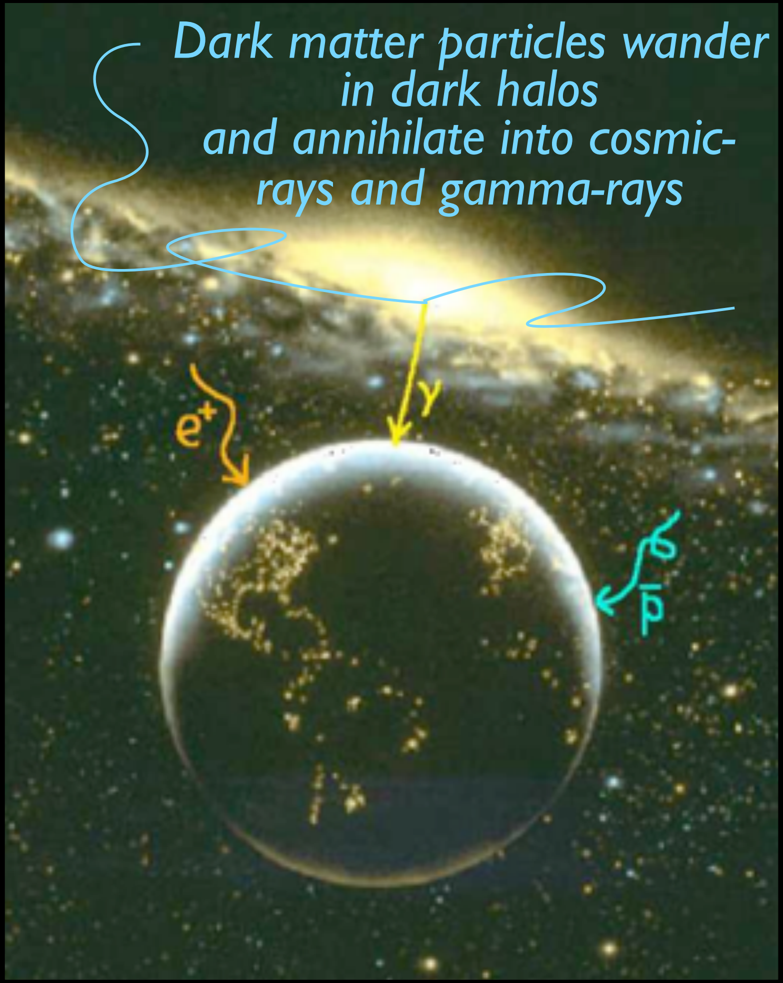
ADMX

Searches for particle dark matter: indirect

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

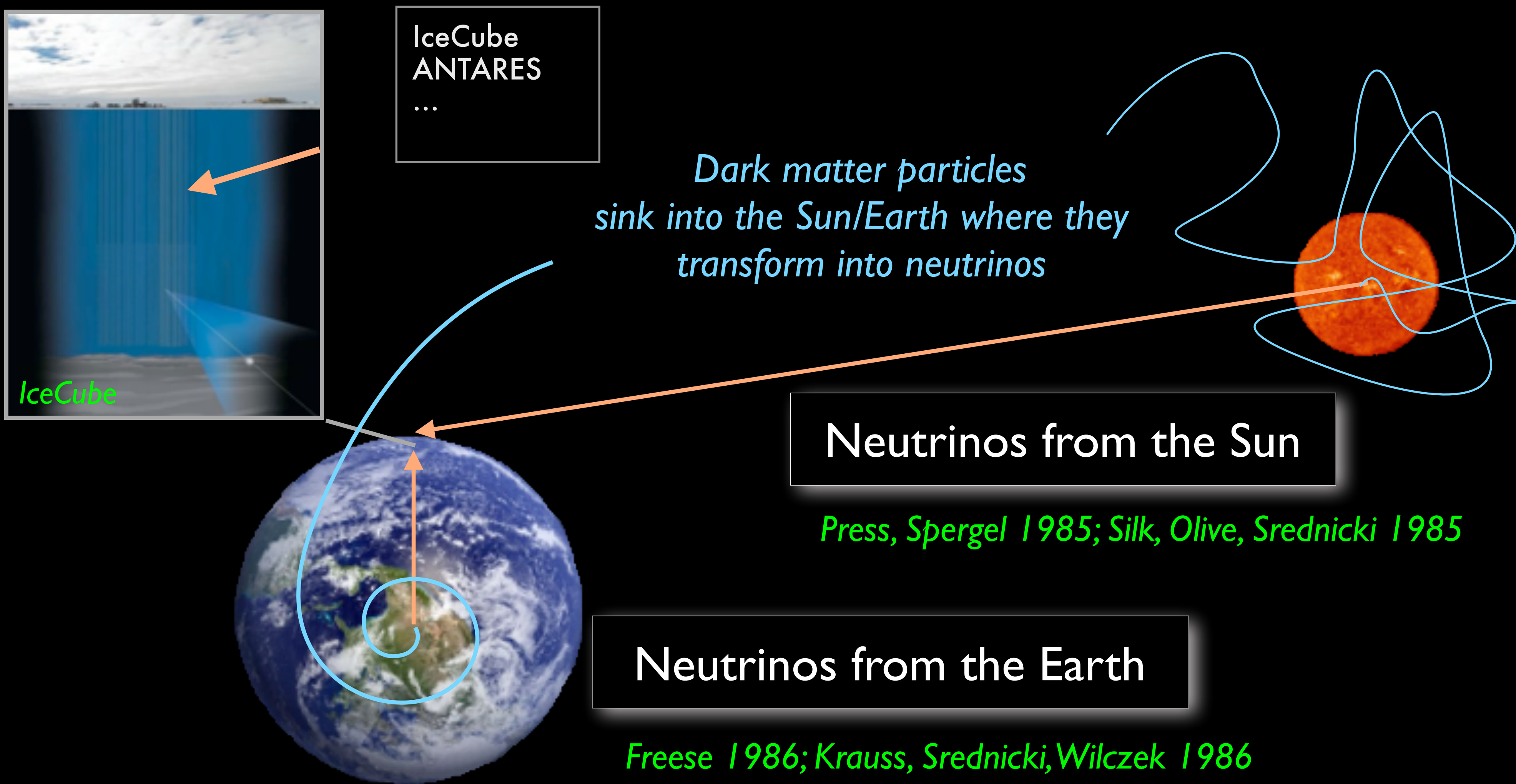


cosmic-rays
PAMELA
AMS
...

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

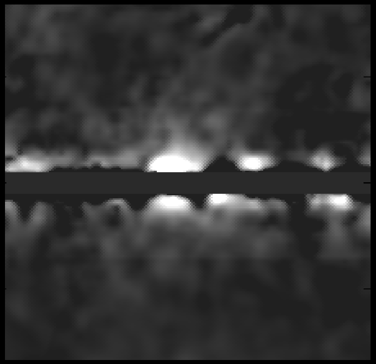
Searches for particle dark matter: indirect

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



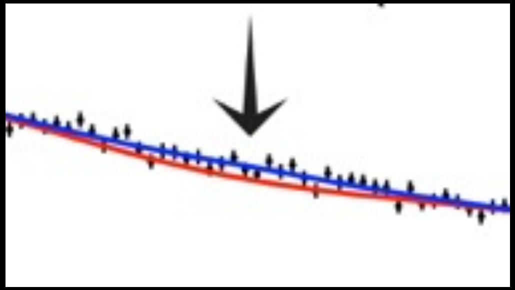
Signals from dark matter?

GeV γ-rays



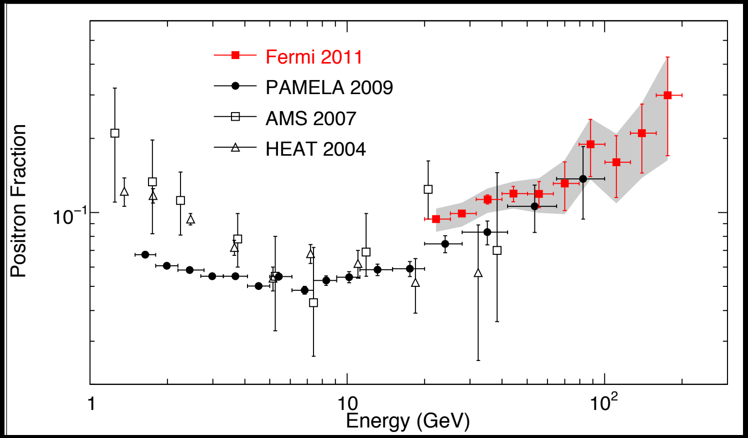
Hooper et al 2009-14

3.5 keV X-ray line



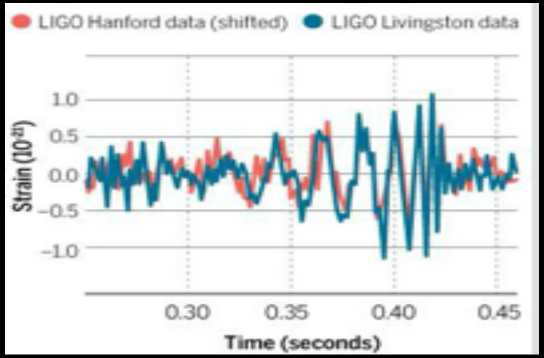
Bulbul et al 2014

Cosmic-ray positrons



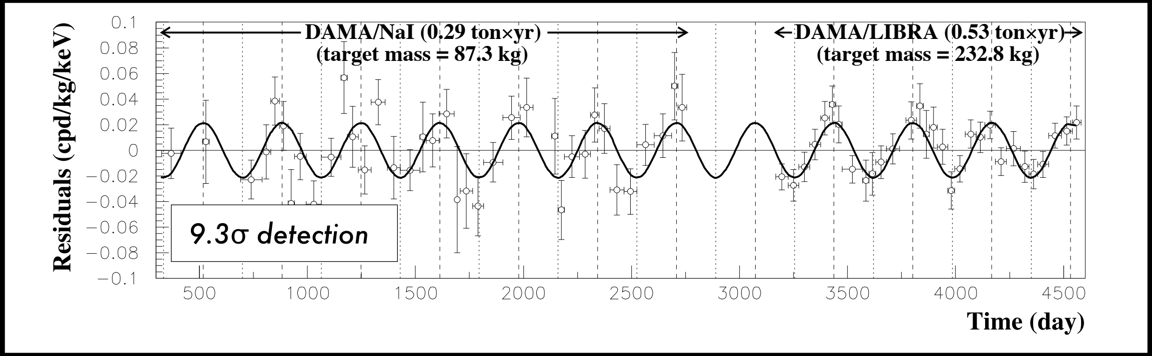
Adriani et al 2009; Ackerman et al 2011; Aguilar et al 2013

Black-hole mergers



Bird et al, Kashlinsky 2016

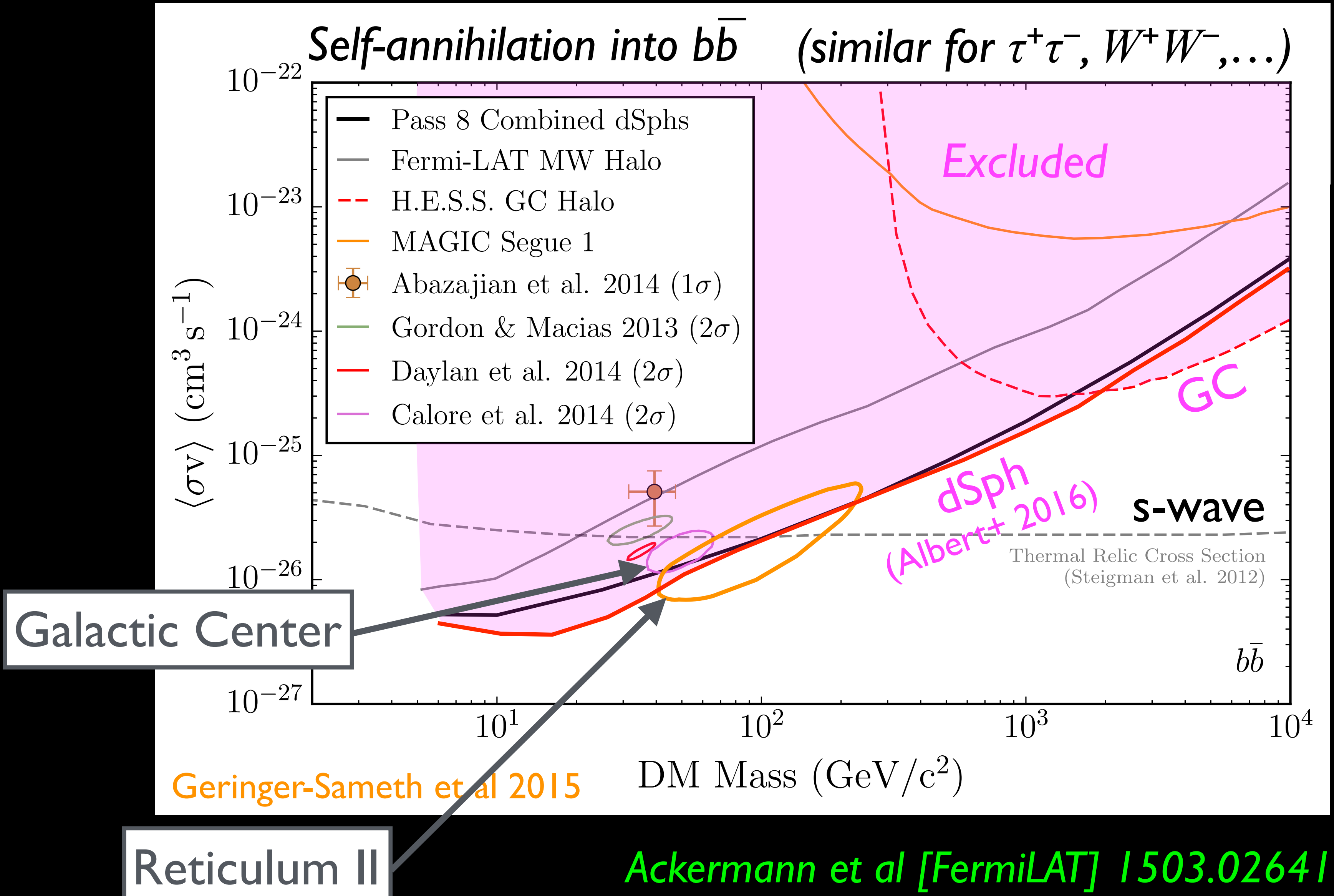
Annual modulation in direct detection



Bernabei et al 1997-now

Gamma-rays from dark matter

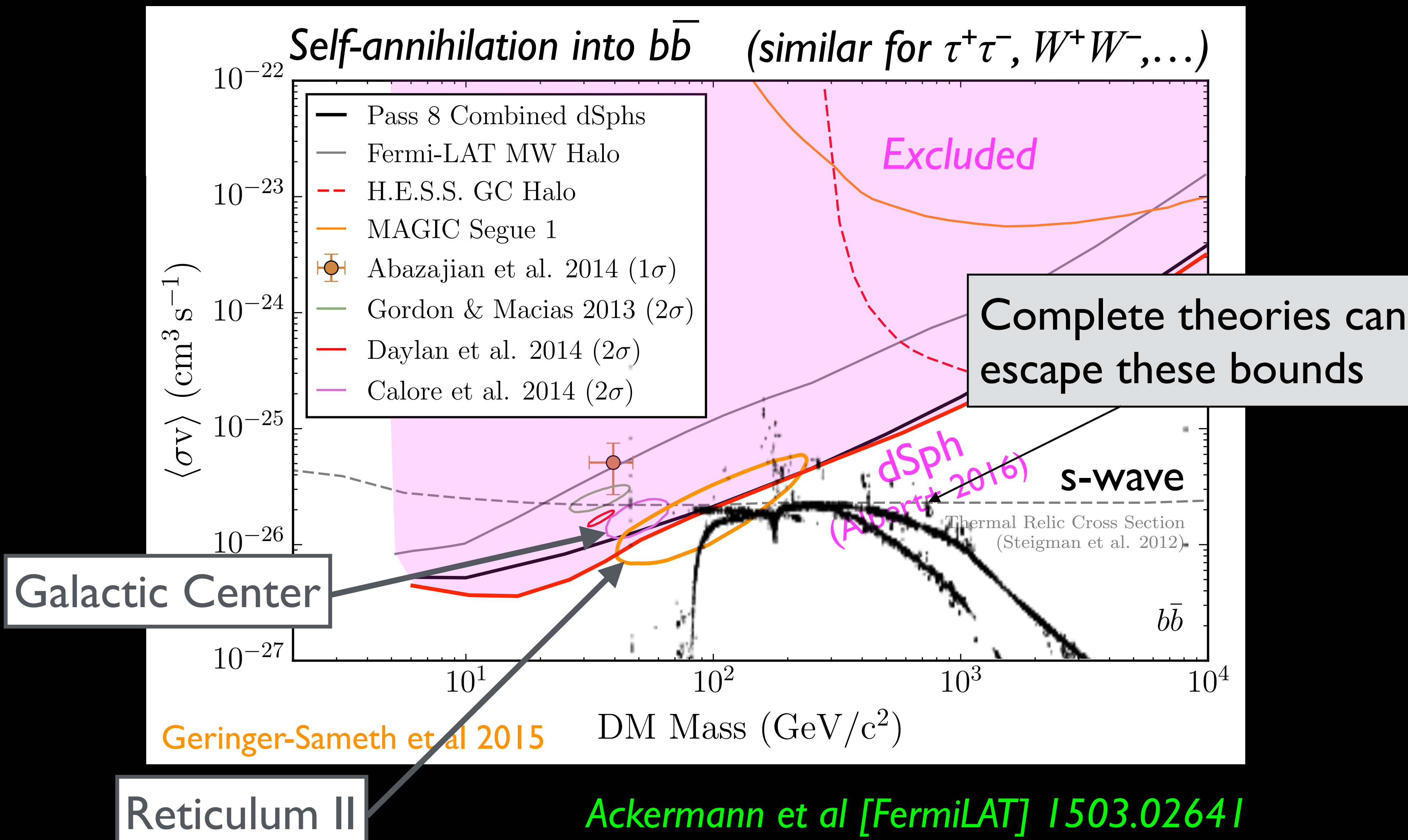
Upper limits on the WIMP annihilation cross section from dwarf spheroidal galaxies and Galactic Center



Ackermann et al [FermiLAT] 1503.02641

Gamma-rays from dark matter

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



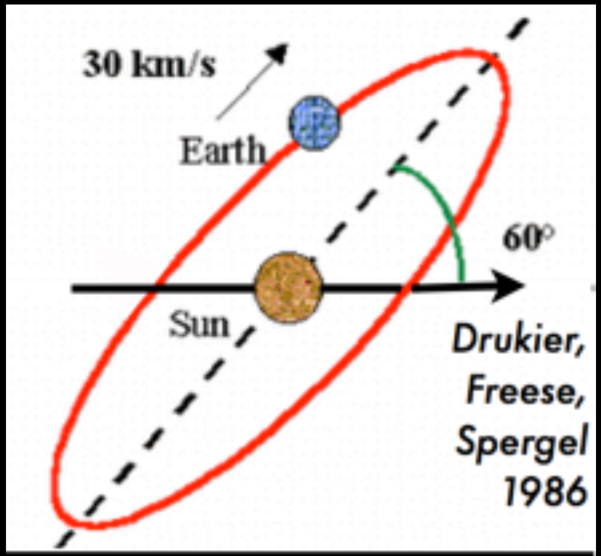
Ackermann et al [FermiLAT] 1503.02641

Recent trends: “make no assumptions”

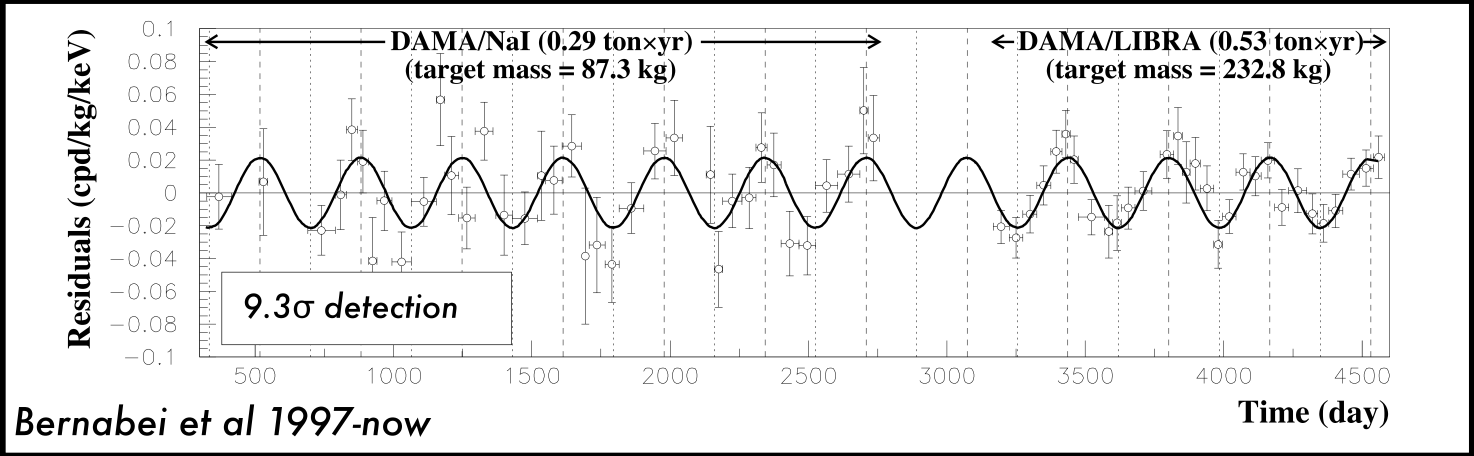
Annual modulation in direct detection

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

Drukier, Freese, Spergel 1986



- DAMA observes such kind of modulation



DAMA annual modulation

Model Independent Annual Modulation Result

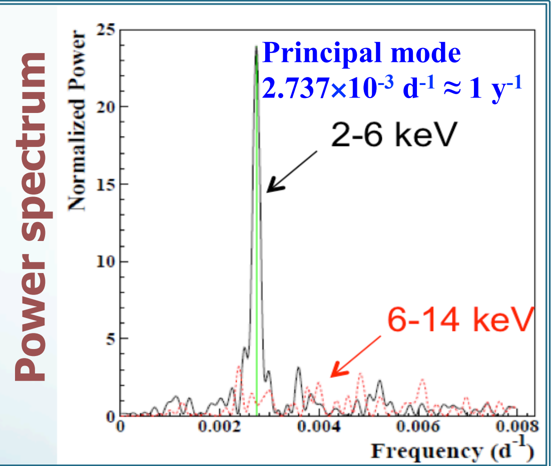
DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

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

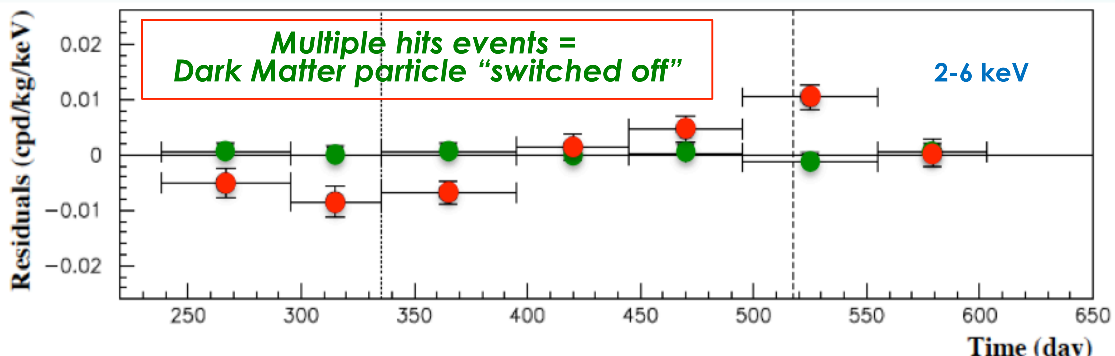
The measured modulation amplitudes (A), period (T) and phase (t_0) from the single-hit residual rate vs time

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

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



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

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

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 annual modulation

Model Independent Annual Modulation Result

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

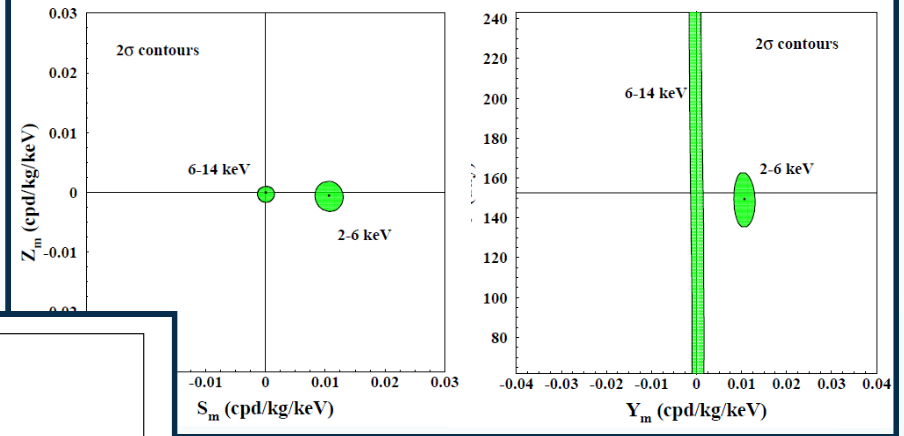
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

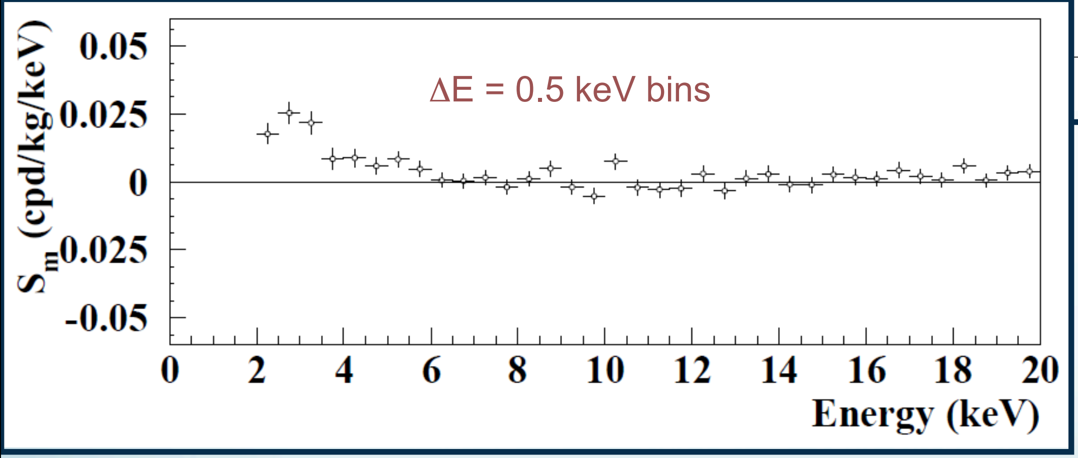
- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

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

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

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



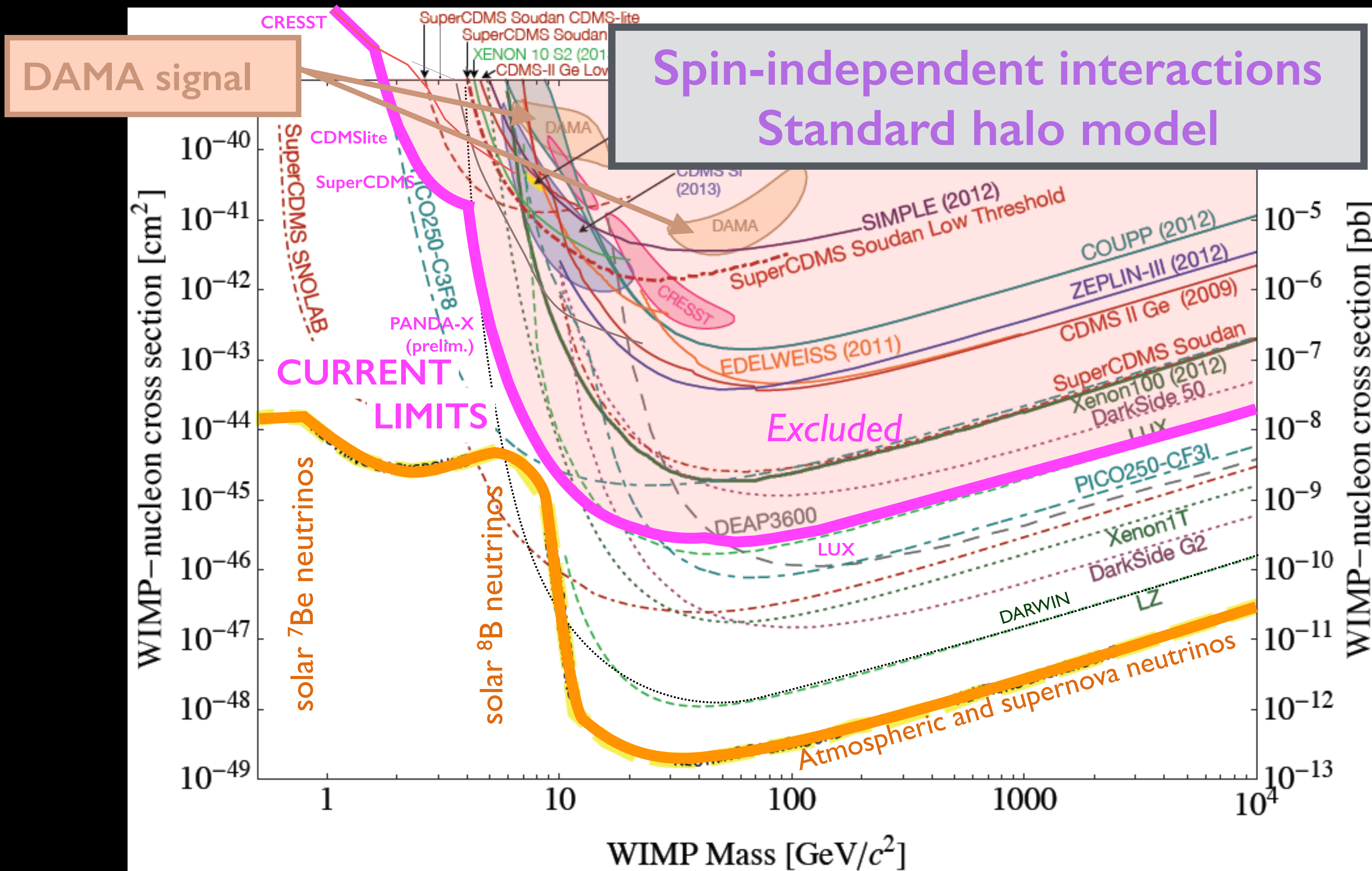


No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy the many peculiarities of the signature are available.

Belli, IDM2014

Direct evidence for dark matter particles?

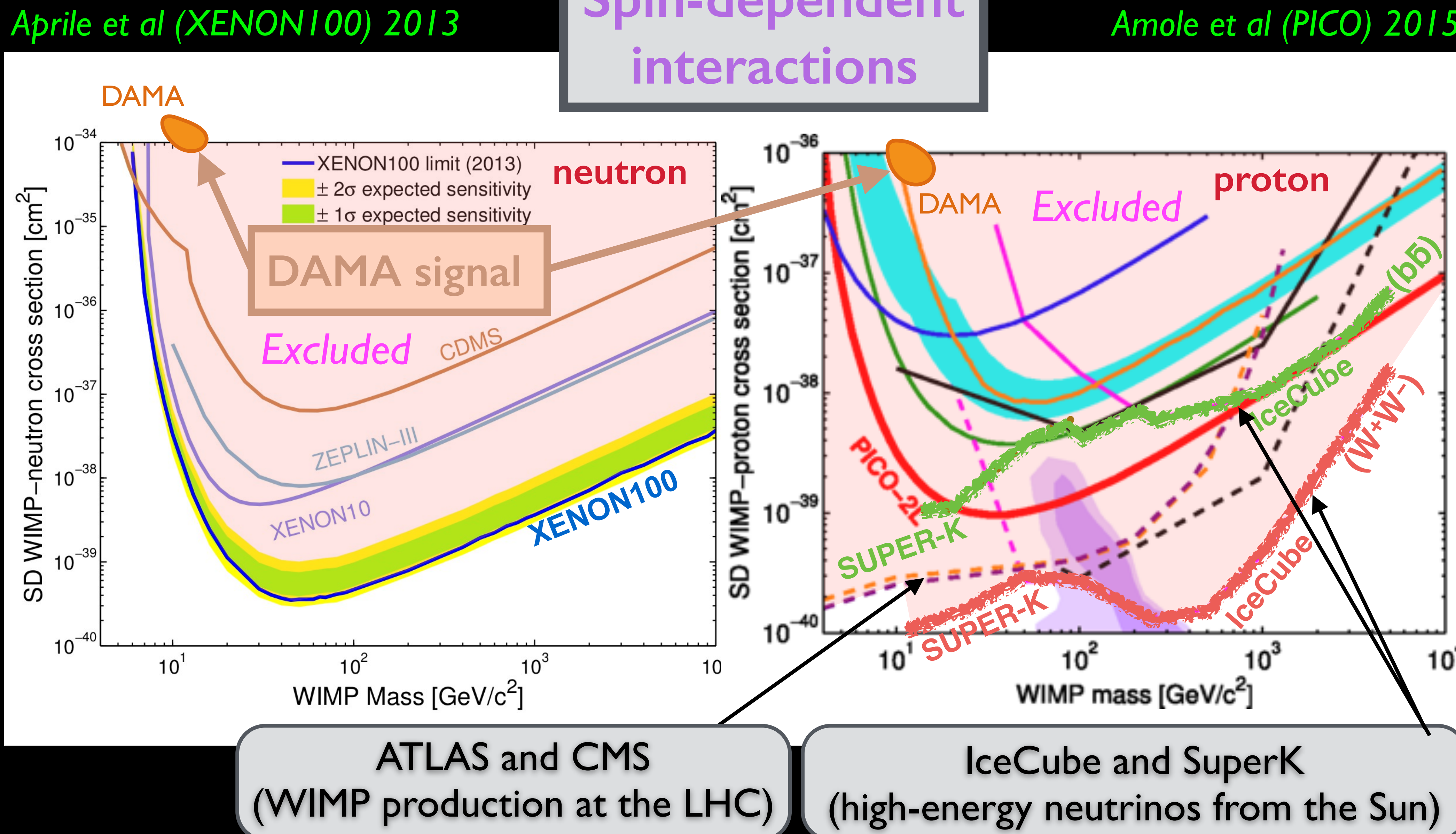
The DAMA signal seems incompatible with other experiments



Billard et al, Snowmass 2013; CDMSlite, CREST 2015; LUX, PANDA-X 2016

Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments



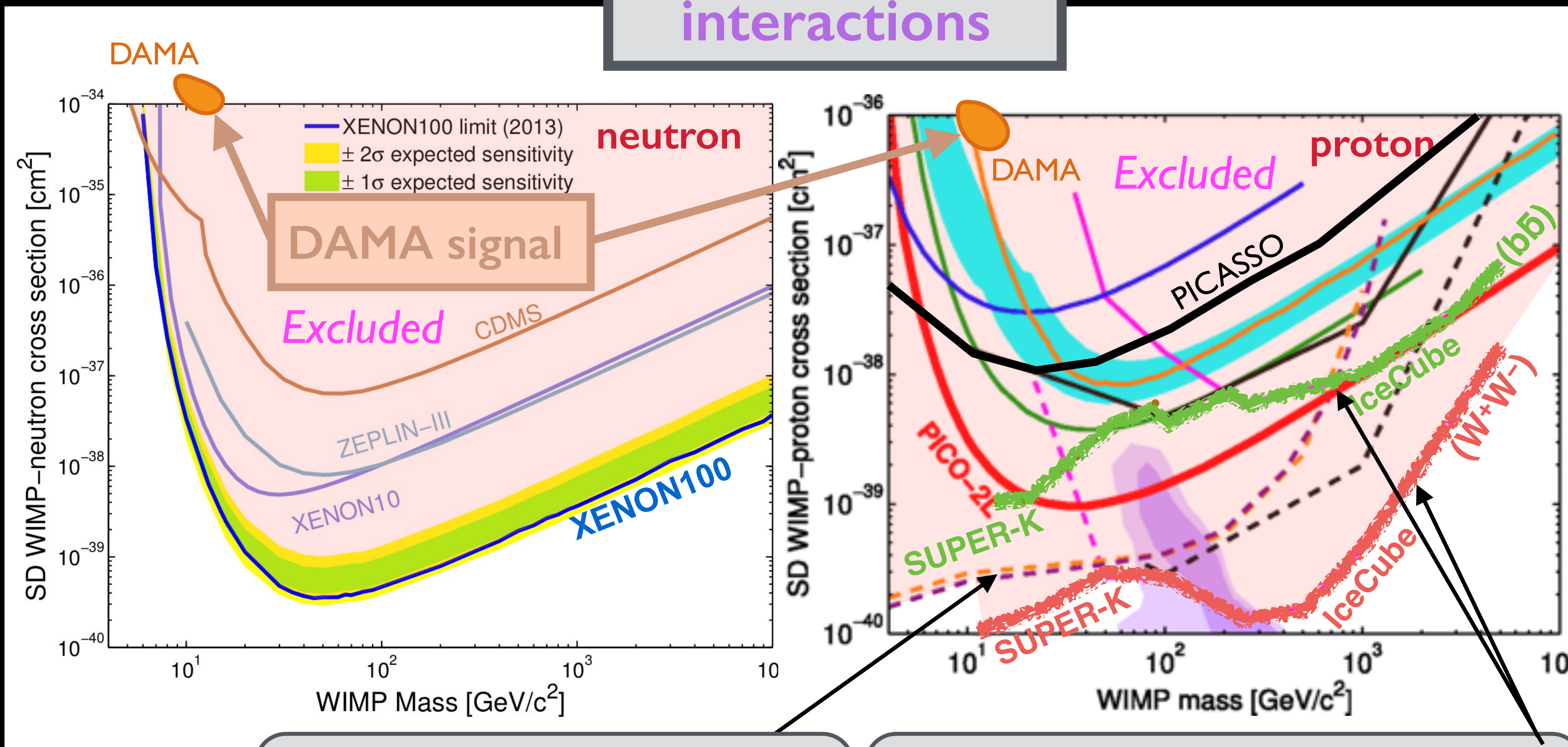
Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments

Aprile et al (XENON100) 2013

Spin-dependent interactions

Amole et al (PICO) 2015

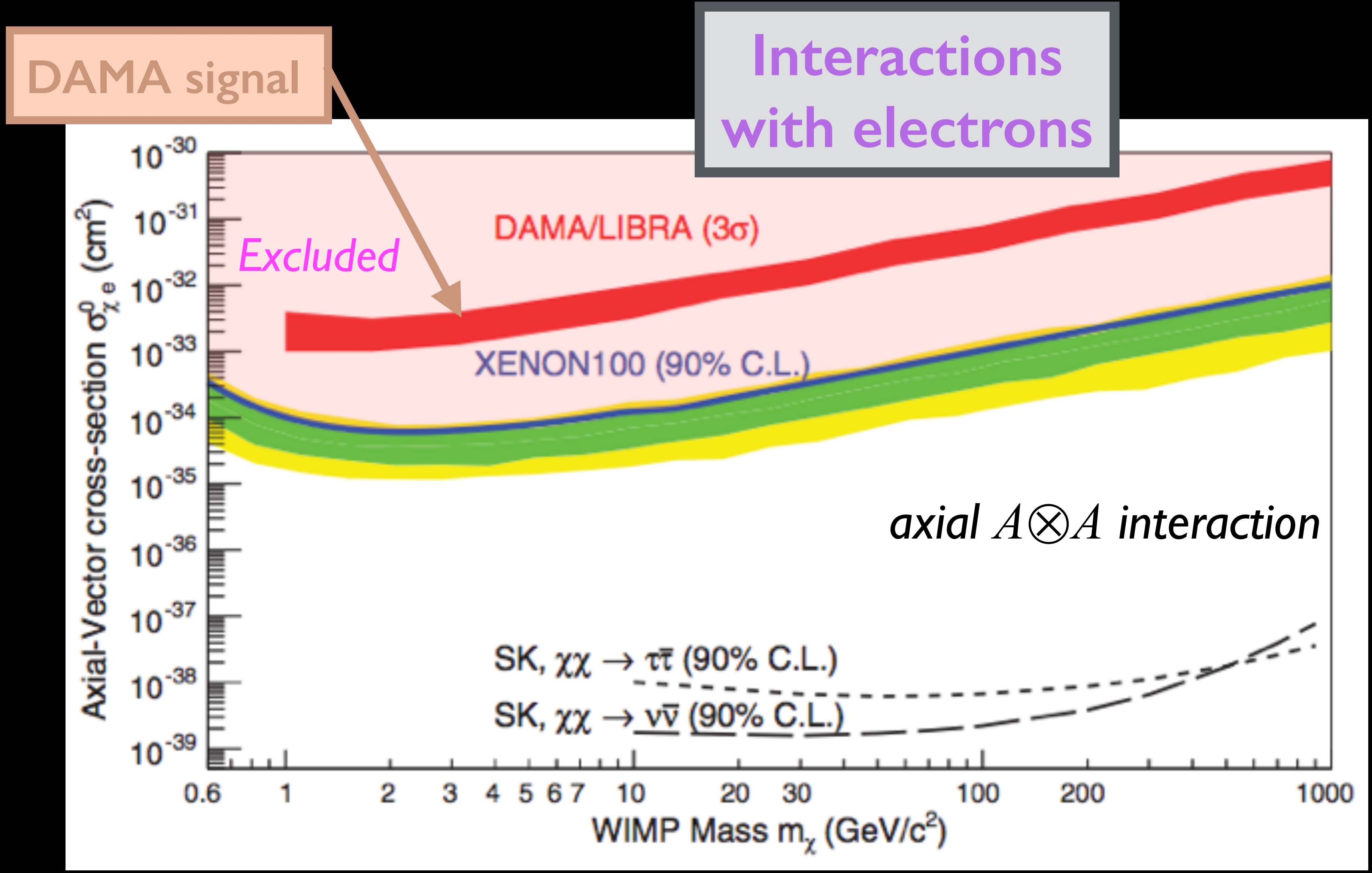


ATLAS and CMS
(WIMP production at the LHC)

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

Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments



Aprile et al (XENON100) 2015

Recoil spectrum

The recoil spectrum (scattering rate per unit target mass)

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

Traditionally, $v^2 \, d\sigma/dE_R = \text{const} \times (\text{nuclear form factor})$

In trying to explain the data, modify the cross section

– set different couplings to neutrons and protons ("isospin-violating")

– put additional velocity or energy dependence in $v^2 \, d\sigma/dE_R$

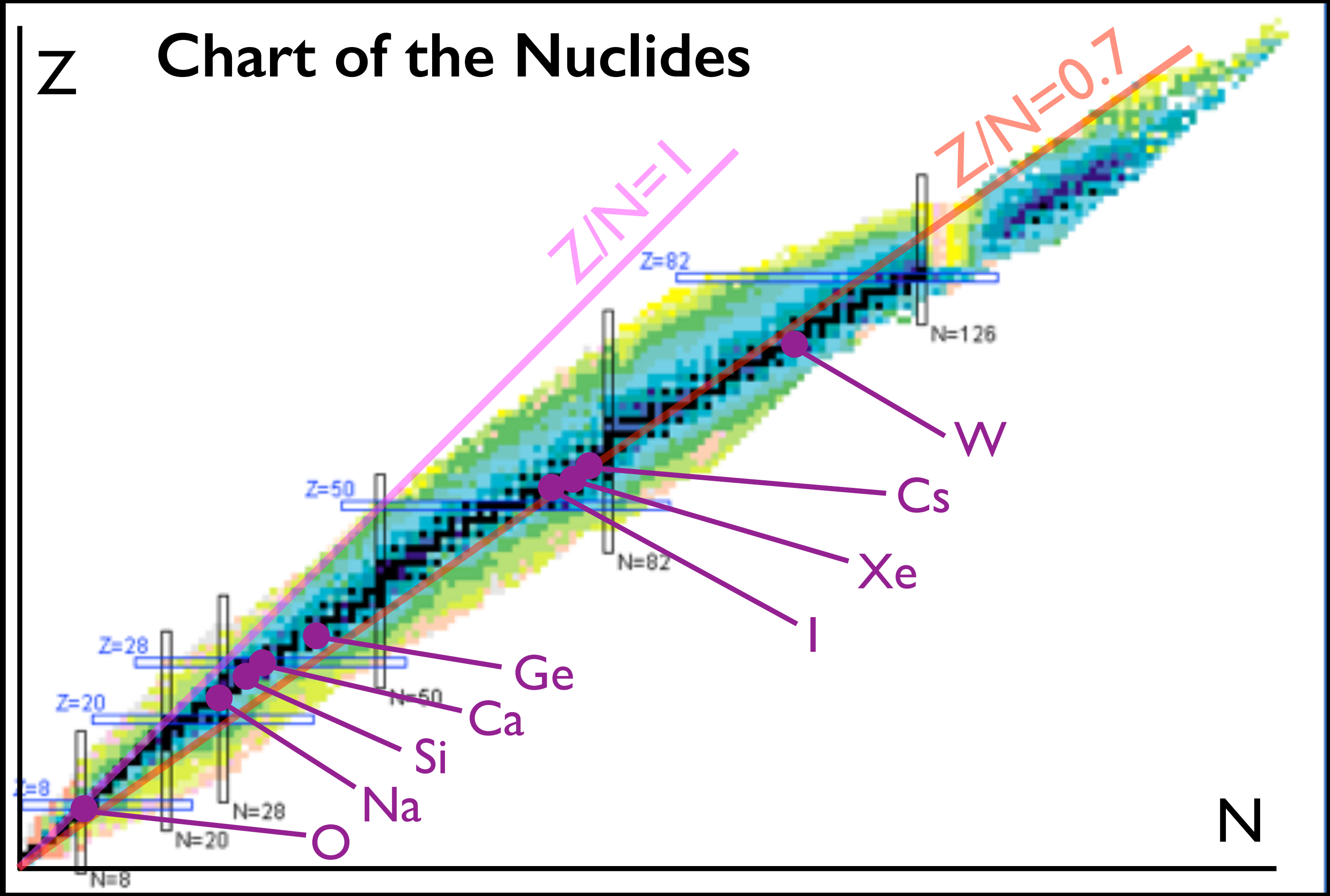
Isospin-violating (nonisoscalar) dark matter

Spin-independent couplings to protons stronger than to neutrons may allow modulation signals compatible with other null searches

Kurylov, Kamionkowski 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010; Feng et al 2011; Del Nobile et al 2011; .....

coupling $N f_n + Z f_p \approx 0$ for $f_n/f_p \approx -Z/N$

Why f_n/f_p=-0.7 suppresses the coupling to Xe



Velocity and energy-dependent scattering

Energy and/or velocity dependent scattering cross sections

nucleus	DM	$v^2\, d\sigma/dE_R$	
		light mediator	heavy mediator
“charge”	*“charge”*	$1/E_R$	$1/M^4$
“charge”	*dipole*	$1/E_R$	E_R/M^4
dipole	*dipole*	$\mathrm{const} + E_R/v^2$	E_R^2/M^4

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

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

“Make no assumptions”

All particle physics models

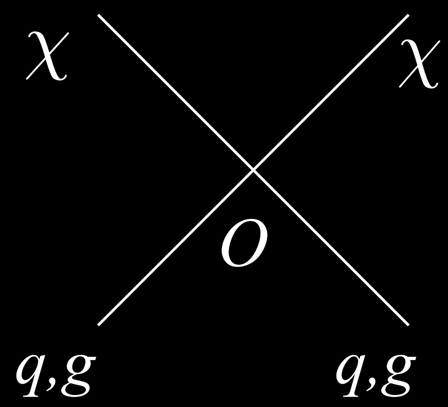
- Consider all possible interactions between dark matter and standard model particles
- This program has been carried out in some limits (e.g., non-relativistic conditions, heavy mediators)

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

Contact operators

if mediator mass ≫ exchanged energy



Four-particle contact operator

There are many possible operators.

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

Long(ish) distance interactions are not included.

Nonrelativistic contact operators

Nonrelativistic WIMP-nucleon contact operators classified

Fitzpatrick et al 2012, Dent et al 2015

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

and more in Dent et al 2015

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

Nonrelativistic contact operators

Operators appearing in "simplified" WIMP models *Dent et al 2015*

	$s_\chi=0$ X^0	$s_\chi=0$ X^+	$s_\chi=1/2$ X^0	$s_\chi=1/2$ X^+	$s_\chi=1$ X^0	$s_\chi=1$ X^+
S	1	1	1,11	1,11	1	1
V	—	—	1,8,9	1,8,9	4,5,6,8,9,11,17	—
T	—	—	—	4,10,11,12	—	4,11,12,18
A	10	—	4,7,9	4,7,9	4,6,9,10,14,18	—
P	10	10	6,10	6,10	10	10

Entries denote operator index.
X^0 (X^+) is neutral (charged) mediator.

Contact operators: direct detection

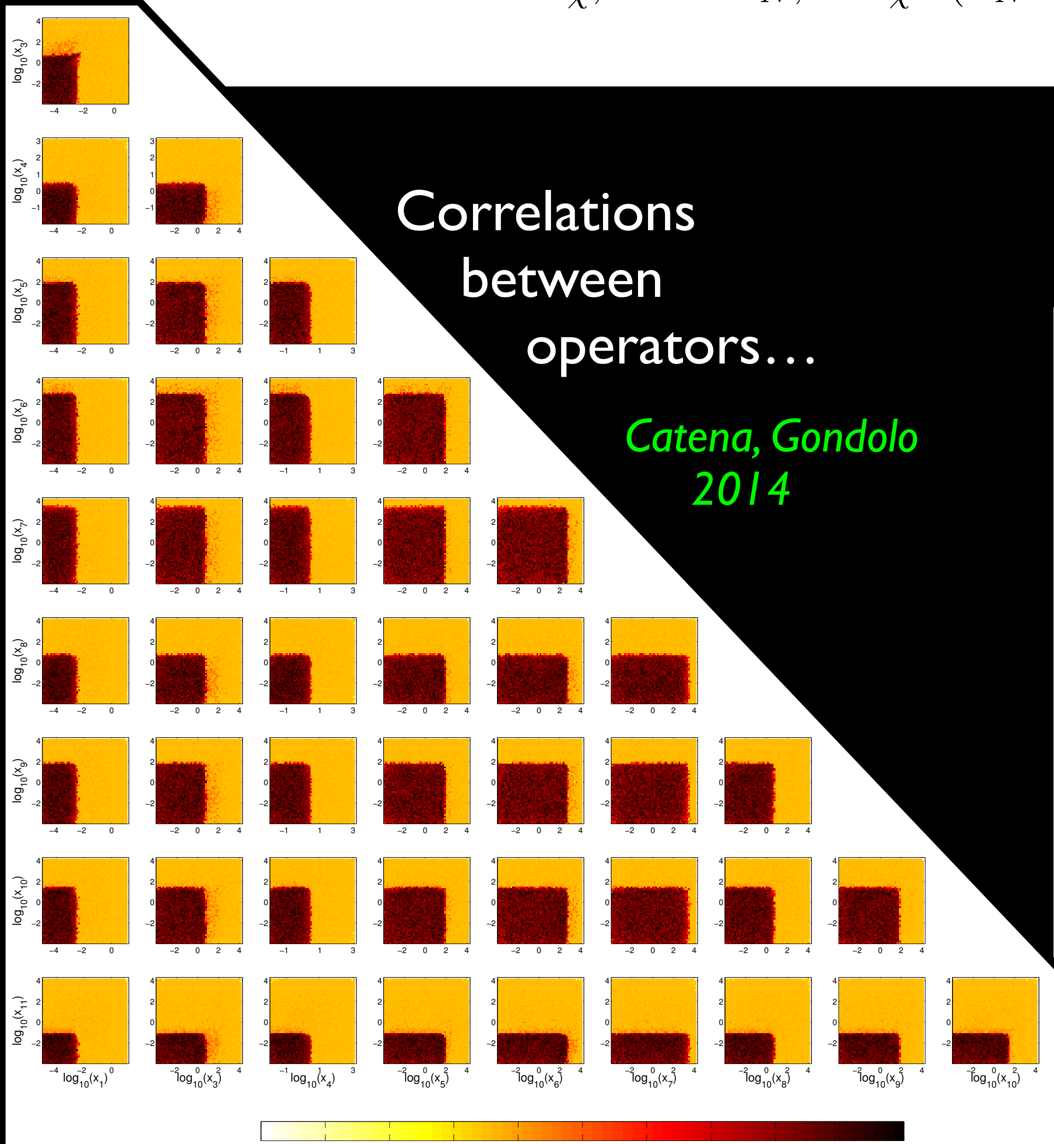
Short-distance WIMP-nucleon operators classified

Fitzpatrick et al 2012

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

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

plus two more in Dent et al 2015

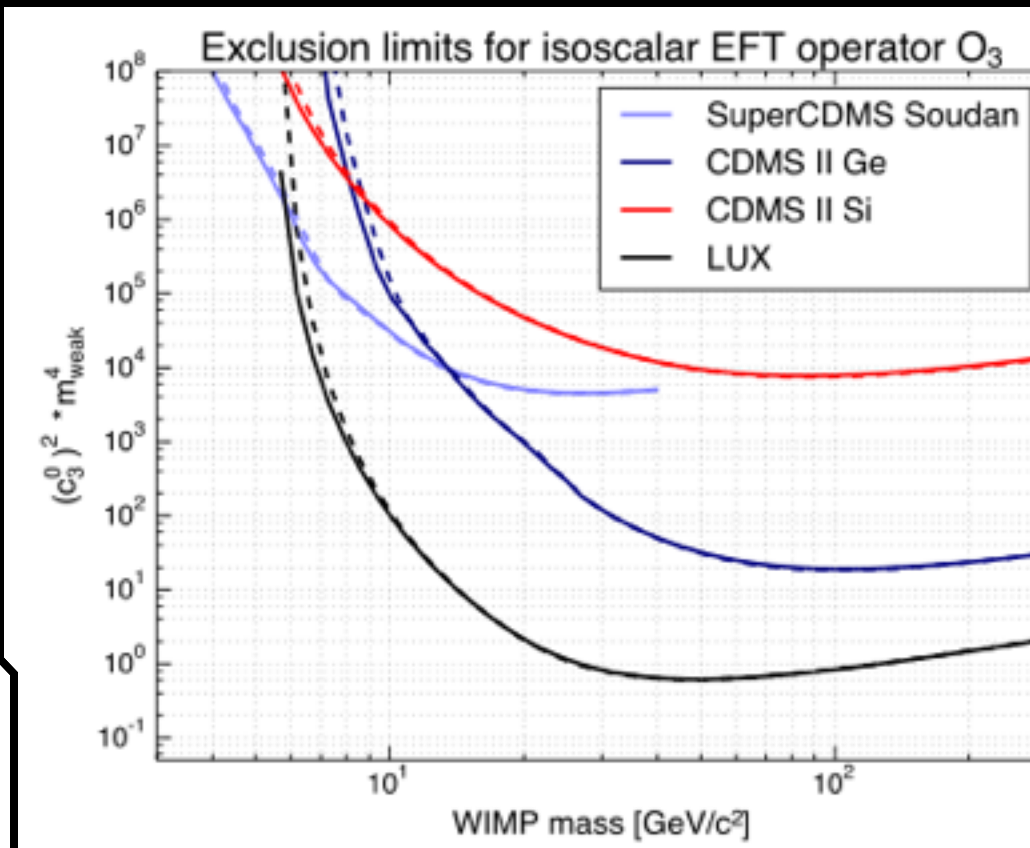


Correlations between operators…

Catena, Gondolo 2014

Experimental limits on single operators…

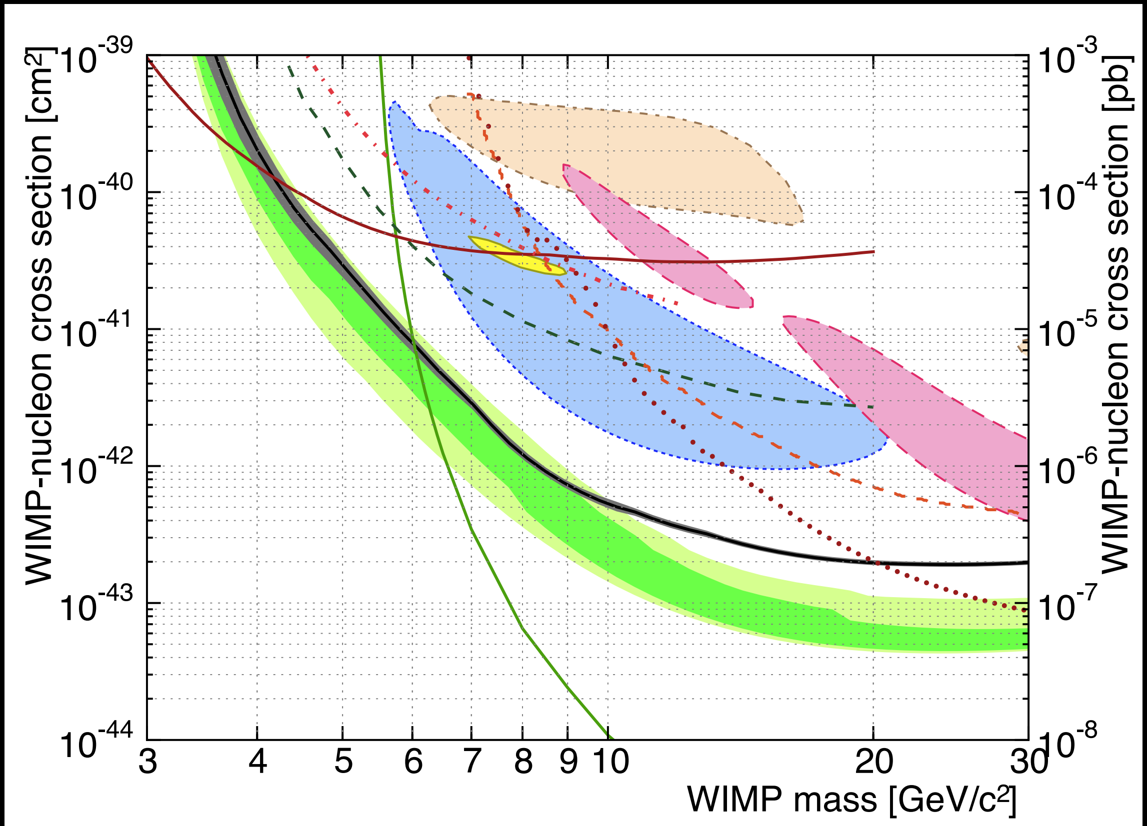
Schneck et al (SuperCDMS) 2015



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 FIXED



Agnese et al (SuperCDMS) 2014

Standard Halo Model

truncated Maxwellian

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

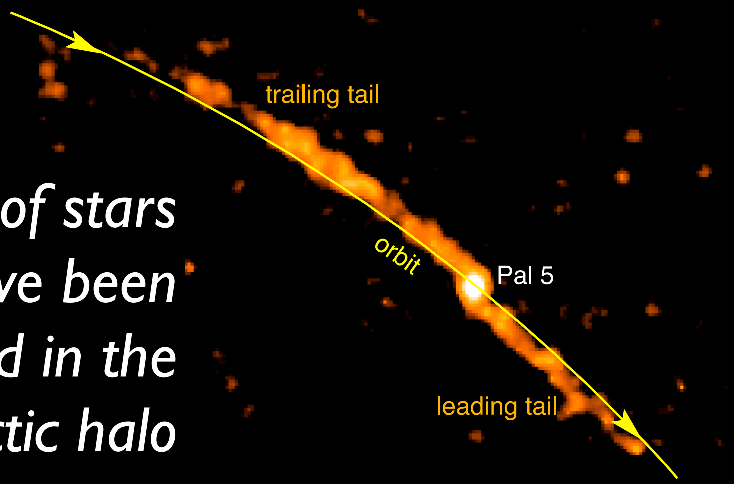
The spherical cow of direct WIMP searches

Gelmini

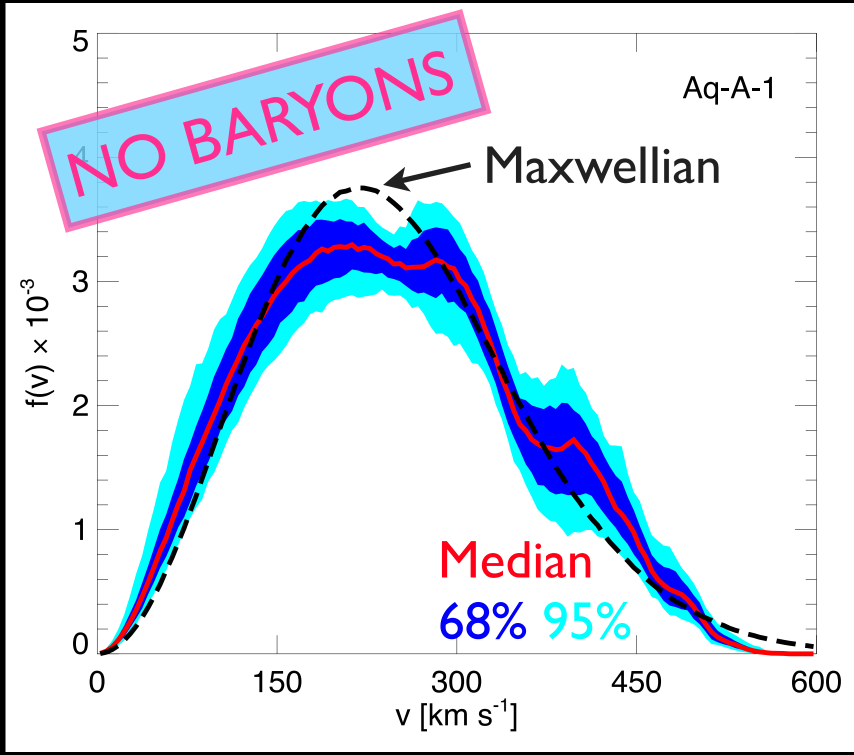
Astrophysics-independent approach

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

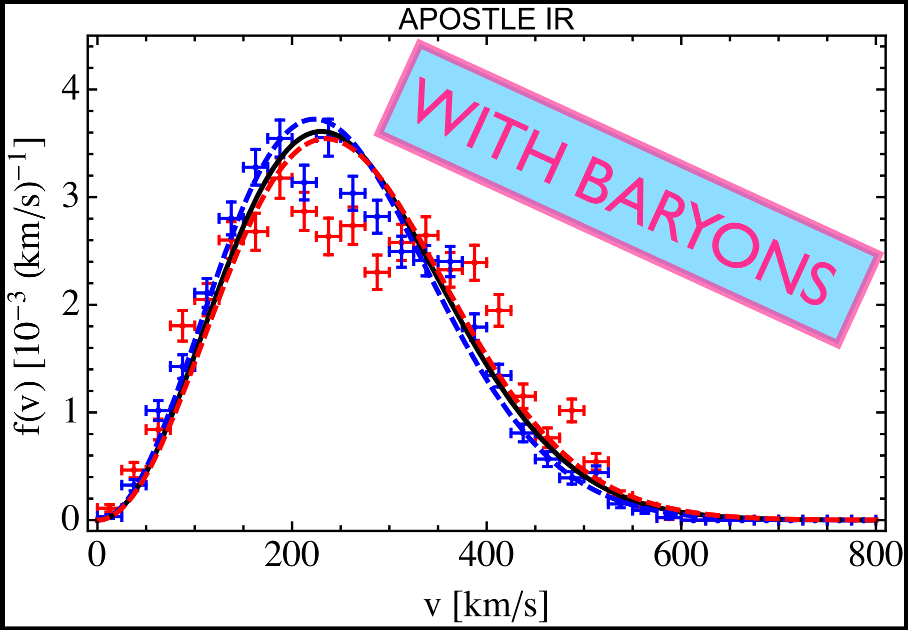
Streams of stars have been observed in the galactic halo



Odenkirchen et al 2002 (SDSS)



Vogelsberger et al 2009



Bozorgnia et al 2016

Cosmological N-Body simulations including baryons are challenging but underway

Astrophysics-independent approach

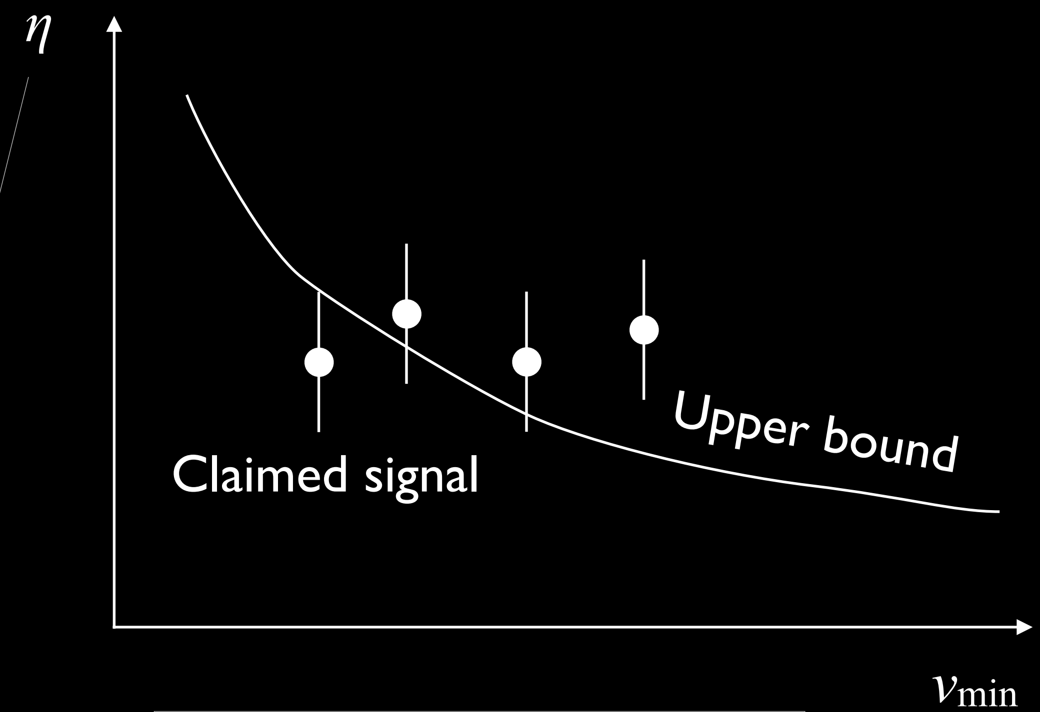
$$\begin{pmatrix}\text{event}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} \times \begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} \times (\text{astrophysics})$$

FIXED ARBITRARY

Rescaled astrophysics factor common to all experiments

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

Proxy for dark matter flux

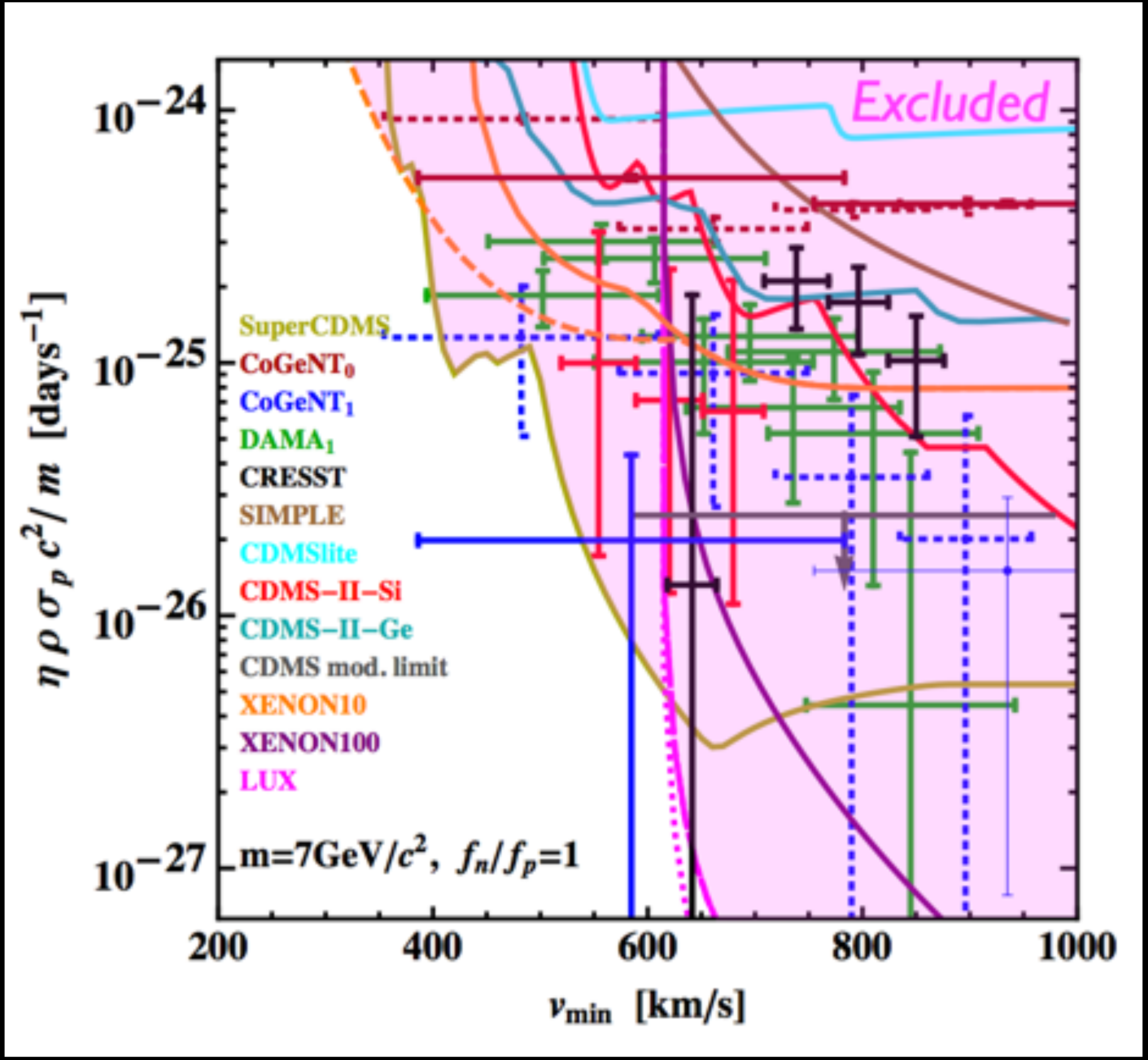


Minimum WIMP speed to impart recoil energy E_R

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

Spin-independent isoscalar interactions

$$\frac{d\sigma}{dE_R} = \frac{2m}{\pi v^2} A^2 f_p^2 F^2(E_R)$$



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

CDMS-Si event rate is similar to yearly modulated rates

Still depends on particle model

Del Nobile, Gelmini, Gondolo, Huh 2014

Anapole dark matter

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

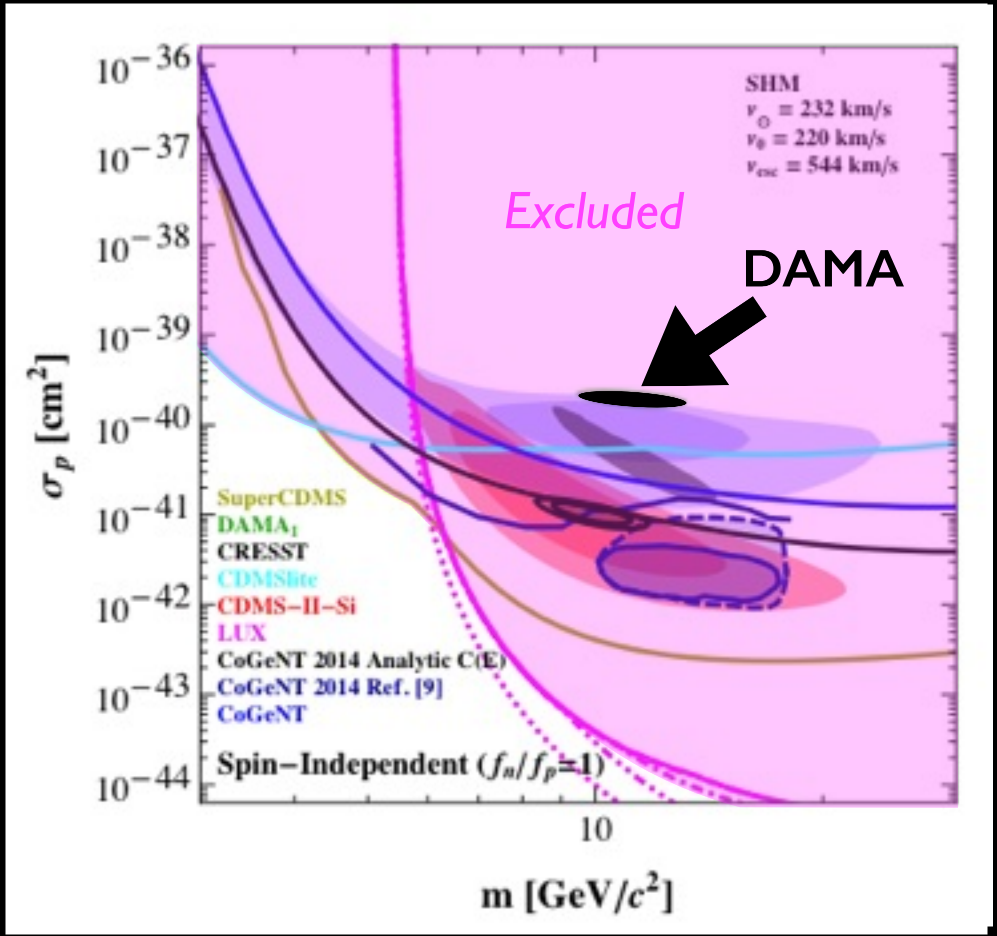
First measured experimentally in Cesium atoms *Wood et al 1997*

Anapole dark matter

spin-1/2 Majorana fermion

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

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

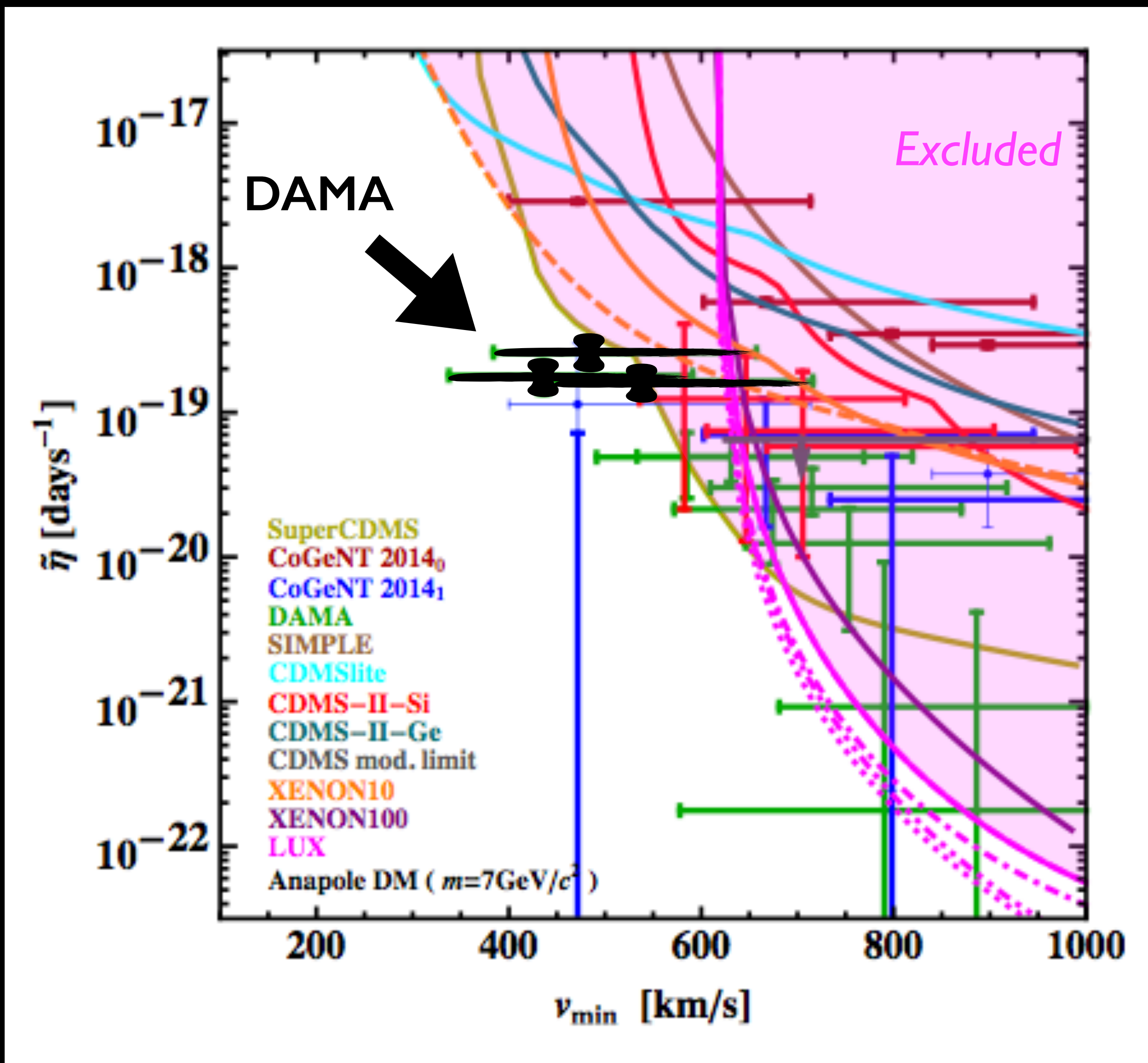


Direct detection limits with standard dark halo

Del Nobile, Gelmini, Gondolo, Huh 2014

Anapole dark matter

$$\frac{d\sigma}{dE_R} = \frac{2m}{\pi v^2}\frac{e^2 g^2}{\Lambda^2}\left[\left(v^2 - v_{\rm min}^2\right)F_L^2(E_R) + F_T^2(E_R)\right]$$



spin-1/2 Majorana fermion

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

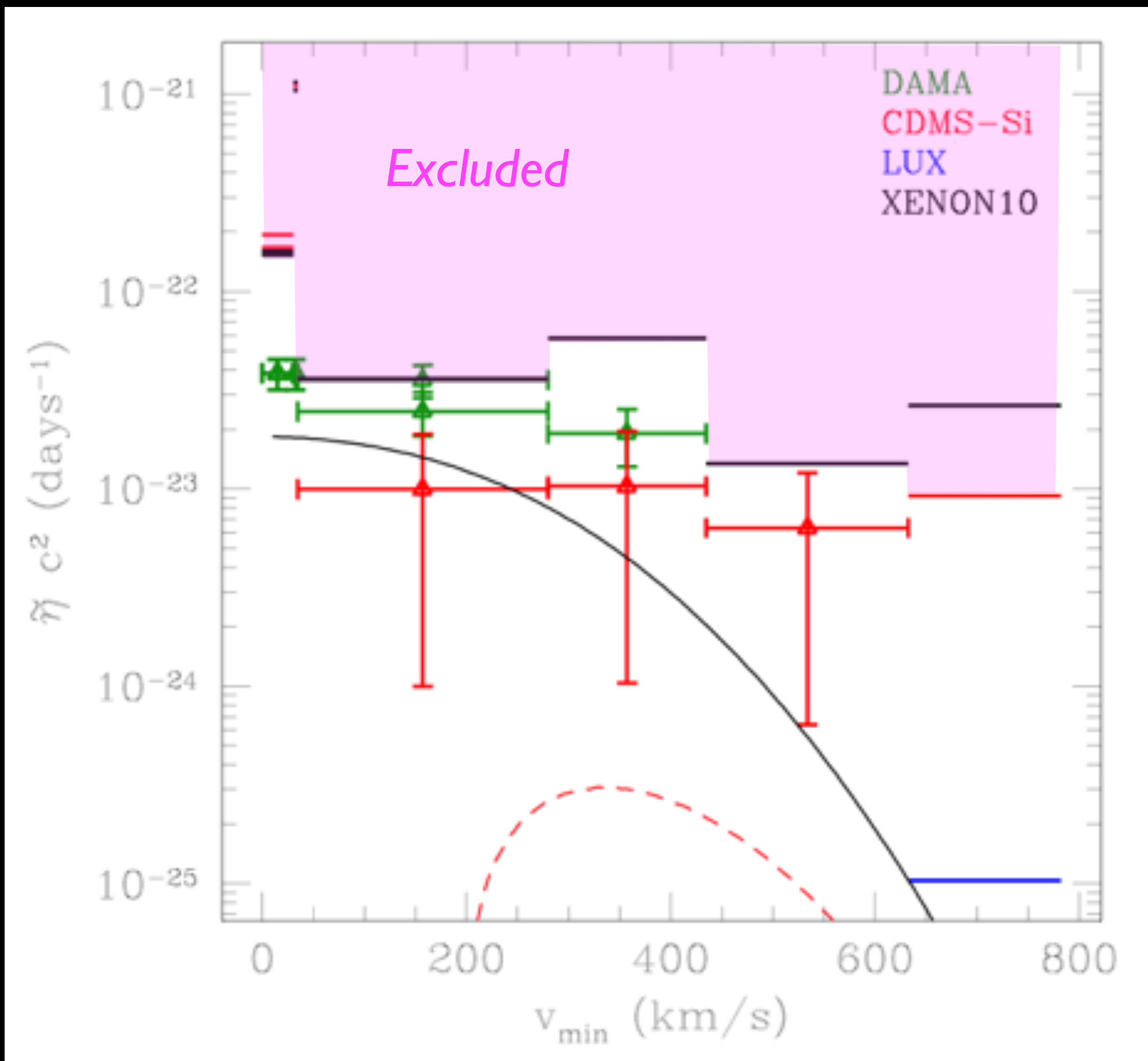
$$H = -\frac{g}{\Lambda^2}\vec{\sigma}\cdot\vec{\nabla}\times\vec{B}$$

For anapole dark matter, the lowest DAMA bins may be compatible with null searches

Del Nobile, Gelmini, Gondolo, Huh 2014

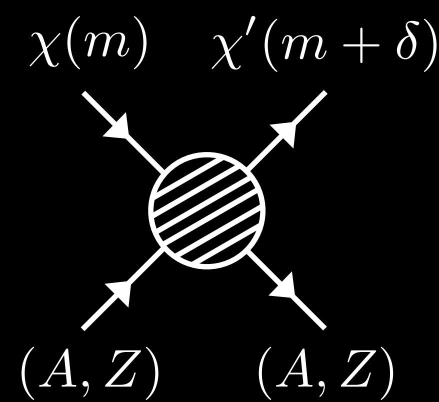
Exothermic nonisoscalar scattering

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



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

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



Still depends on particle model

Scopel, Yoon 2014

Astrophysics-independent approach

The statistics of the halo-independent approach is being understood.

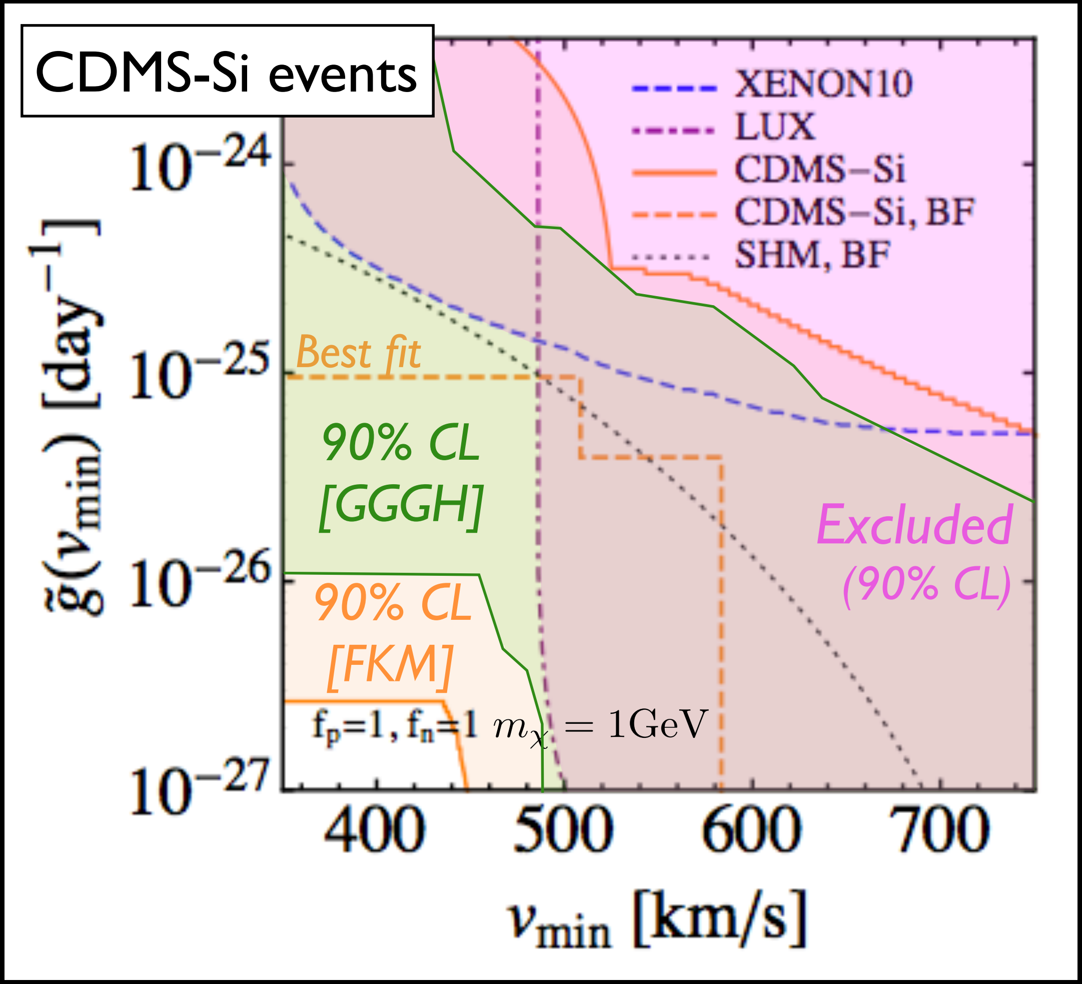
Unbinned likelihood analysis

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

The extent of the 90% CL region is still unclear

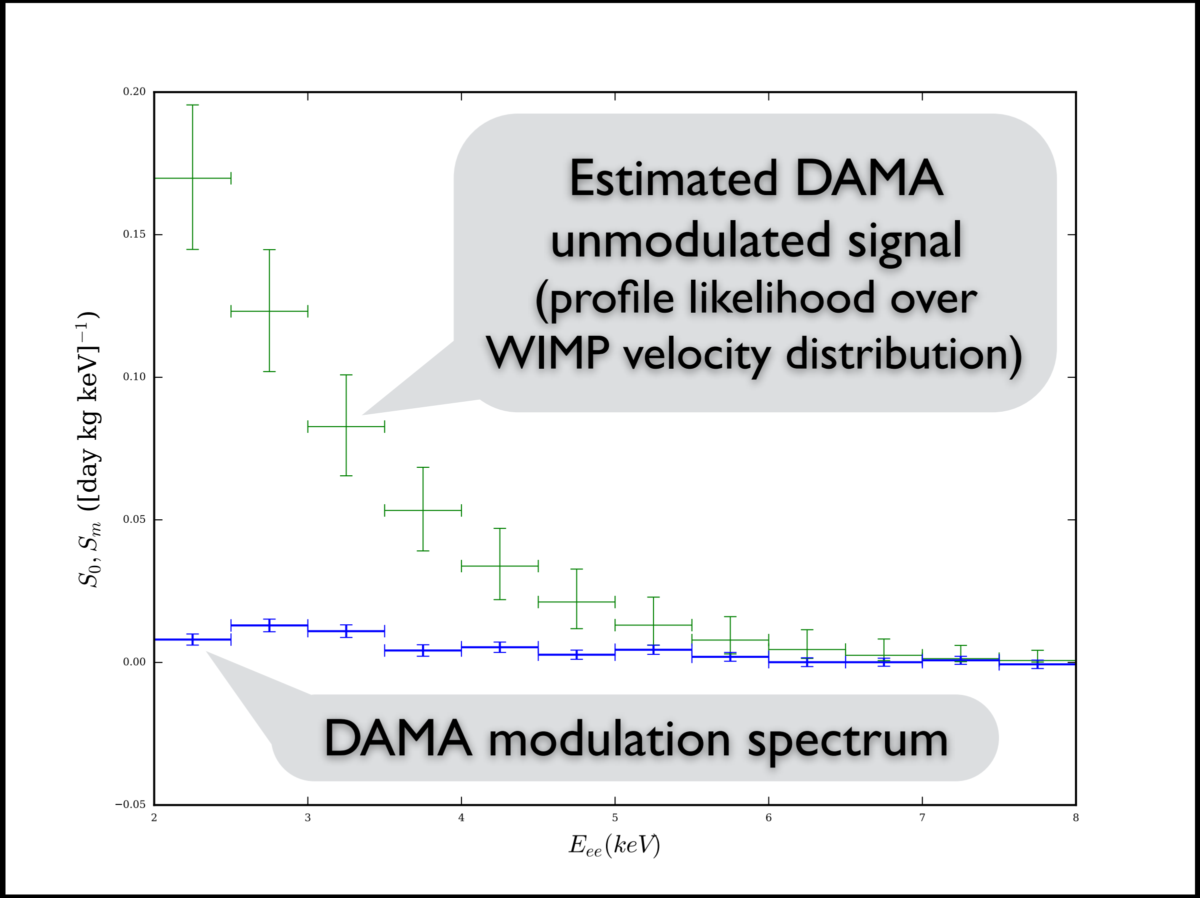
Fox, Kahn, McCullough 2015

Gelmini, Georgescu, Gondolo, Huh 2015



Astrophysics-independent approach

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



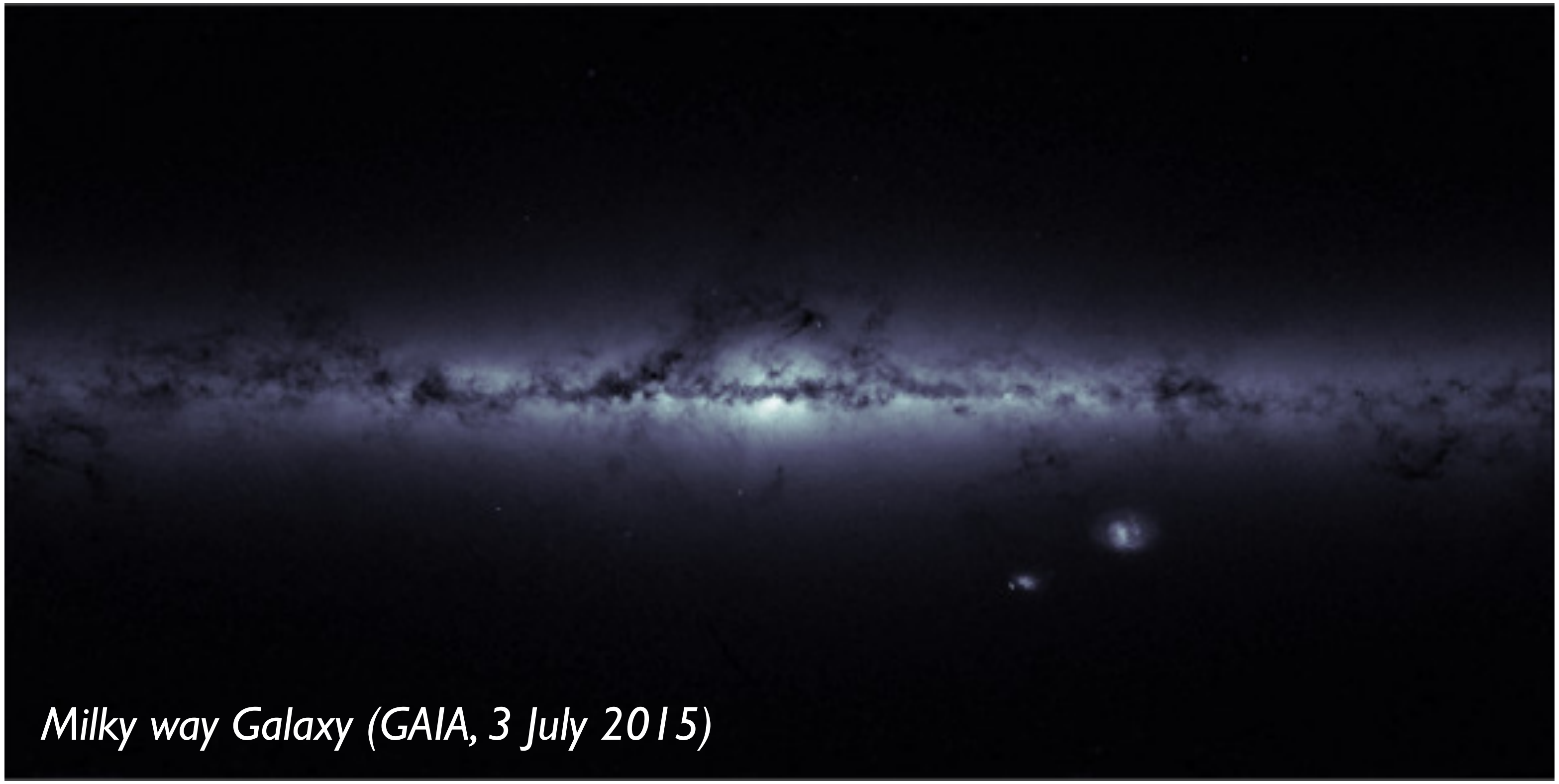
Astrophysics-independent estimate of the DAMA unmodulated signal

Gondolo, Scopel 2016 (in preparation)

In the next future

In the next future..... Small-scale structure

GAIA is measuring the 3D position of about one billion stars.



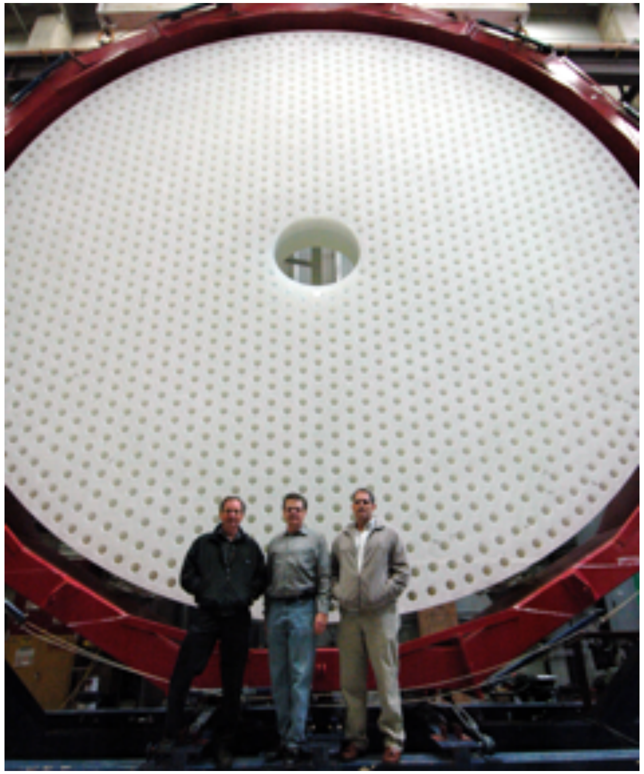
GAIA may detect dark matter substructures in the galactic halo.

Feldmann, Spolyar 2014

In the next future..... Large-scale structure

The Dark Energy Survey (DES) and the Large Synoptic Survey Telescope (LSST) will map the large-scale distribution of dark matter and its growth with time.

DES

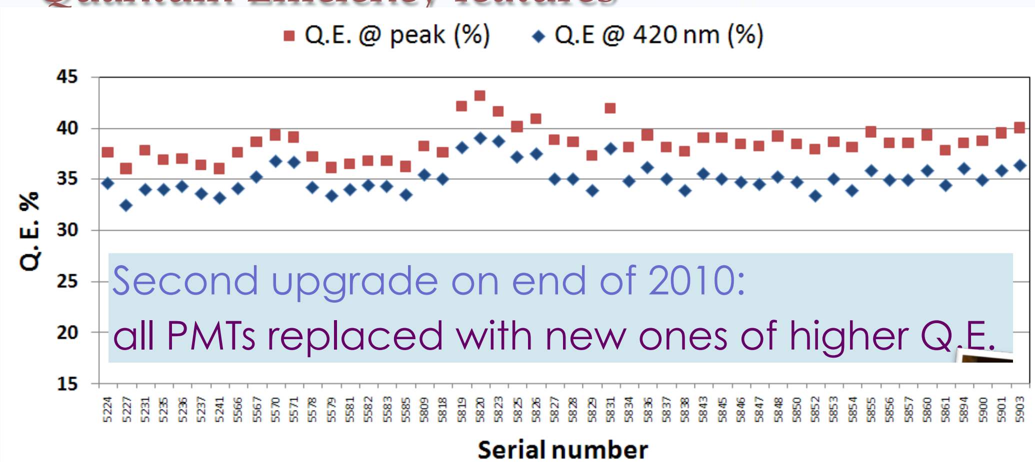


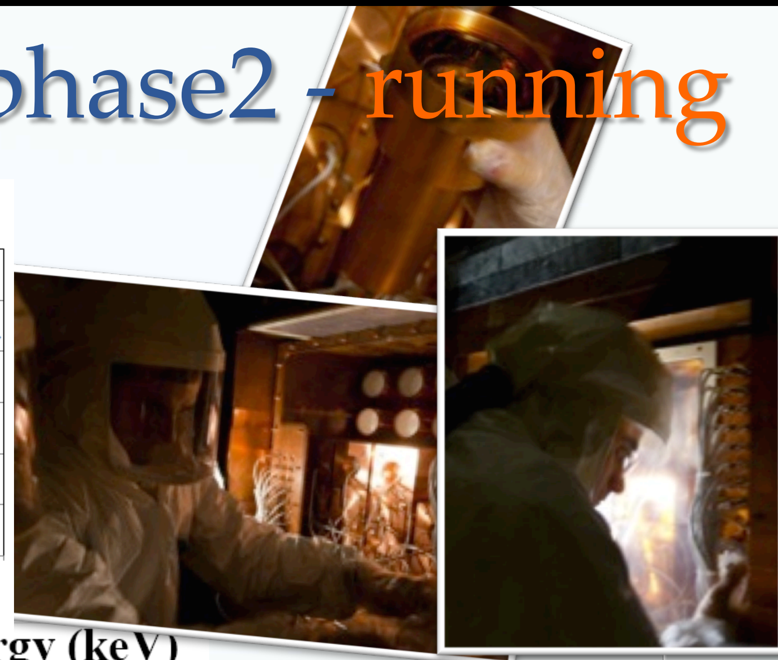
LSST

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

DAMA/LIBRA phase2 - running

Quantum Efficiency features





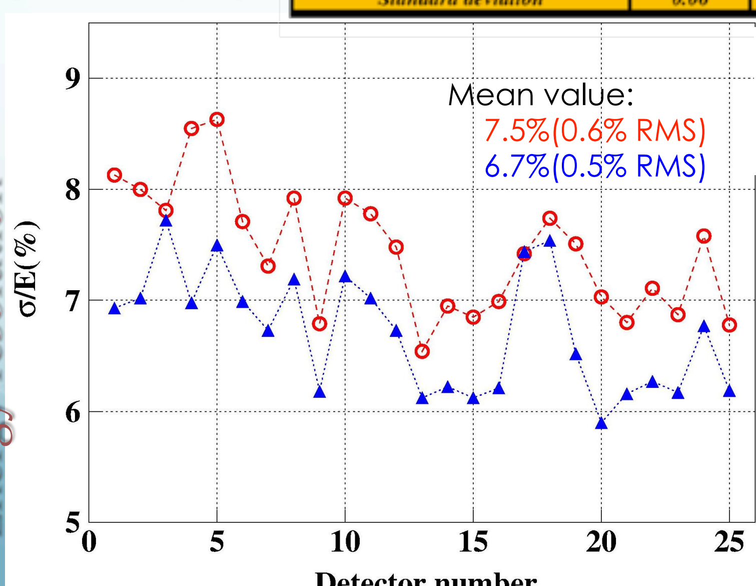
Residual Contamination

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

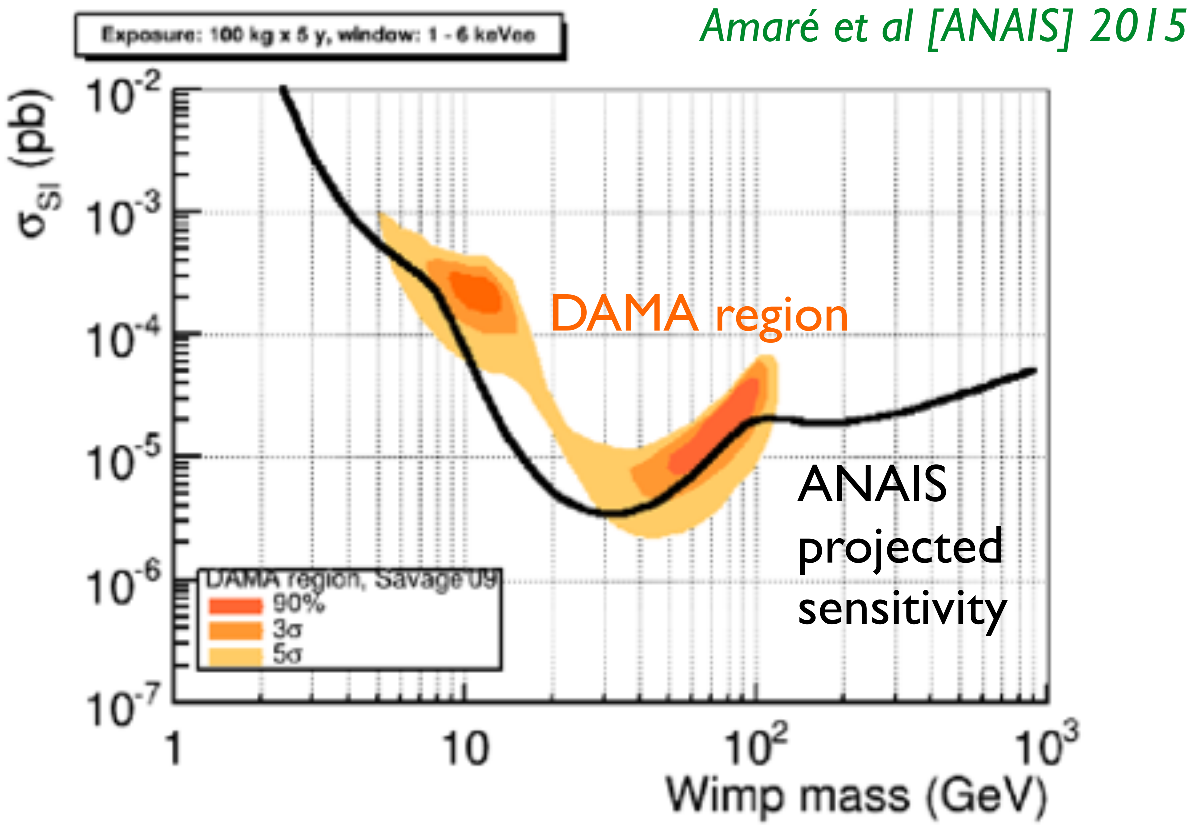
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

Belli, IDM2014

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

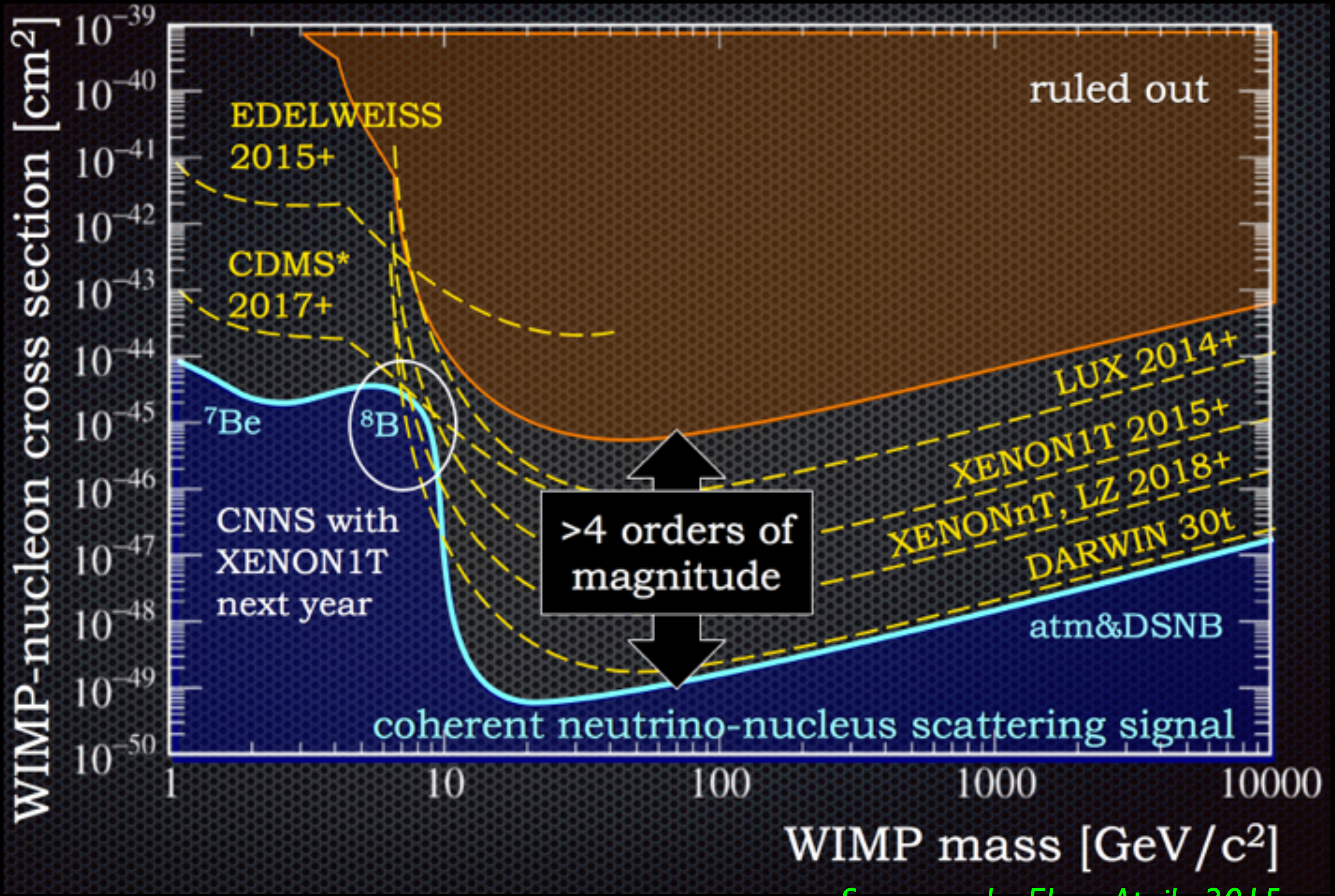
Experiments have been proposed that can directly check the DAMA modulation using the same target material

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



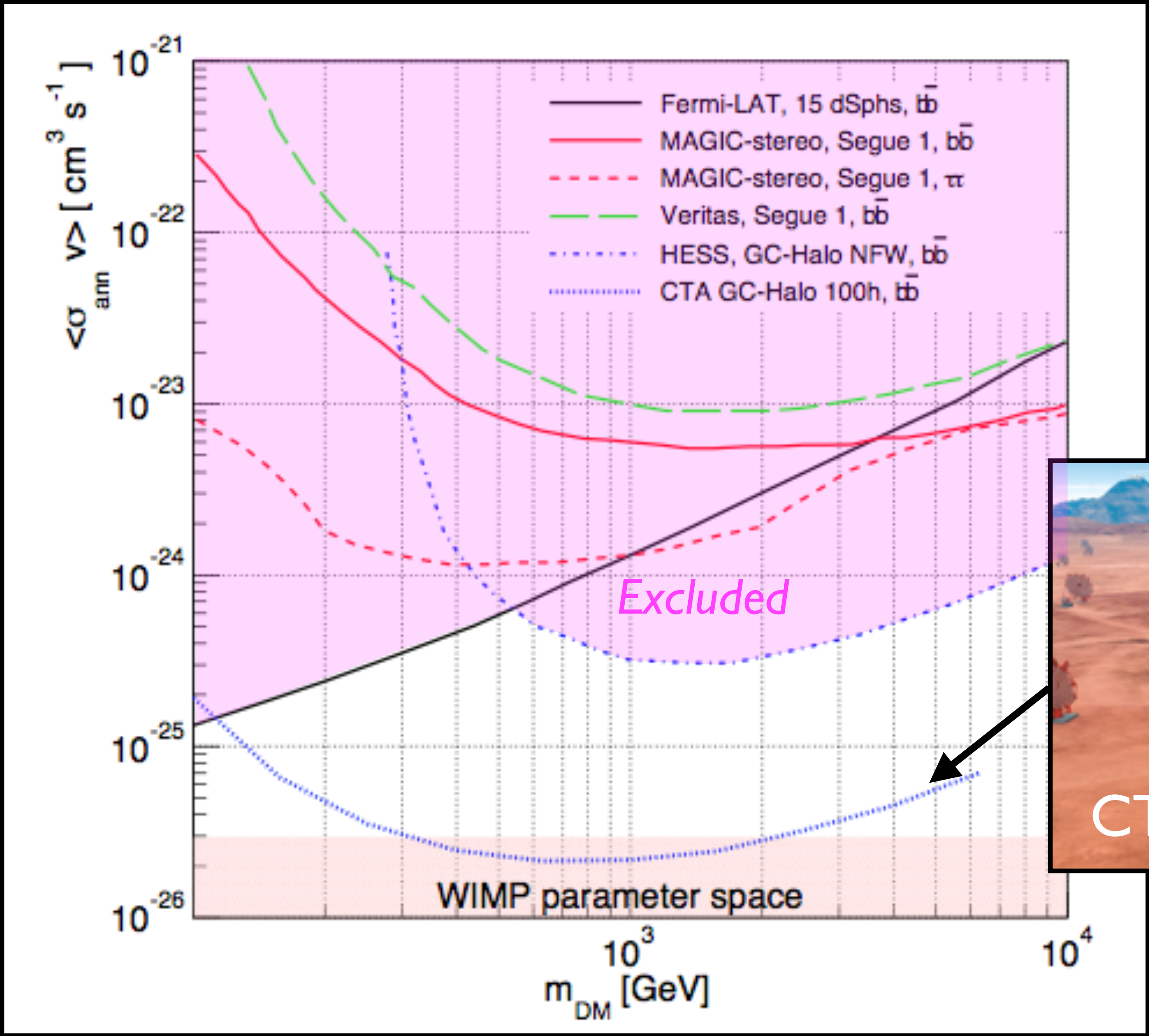
In the next future….. Giant direct detectors

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



Summary by Elena Aprile 2015

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



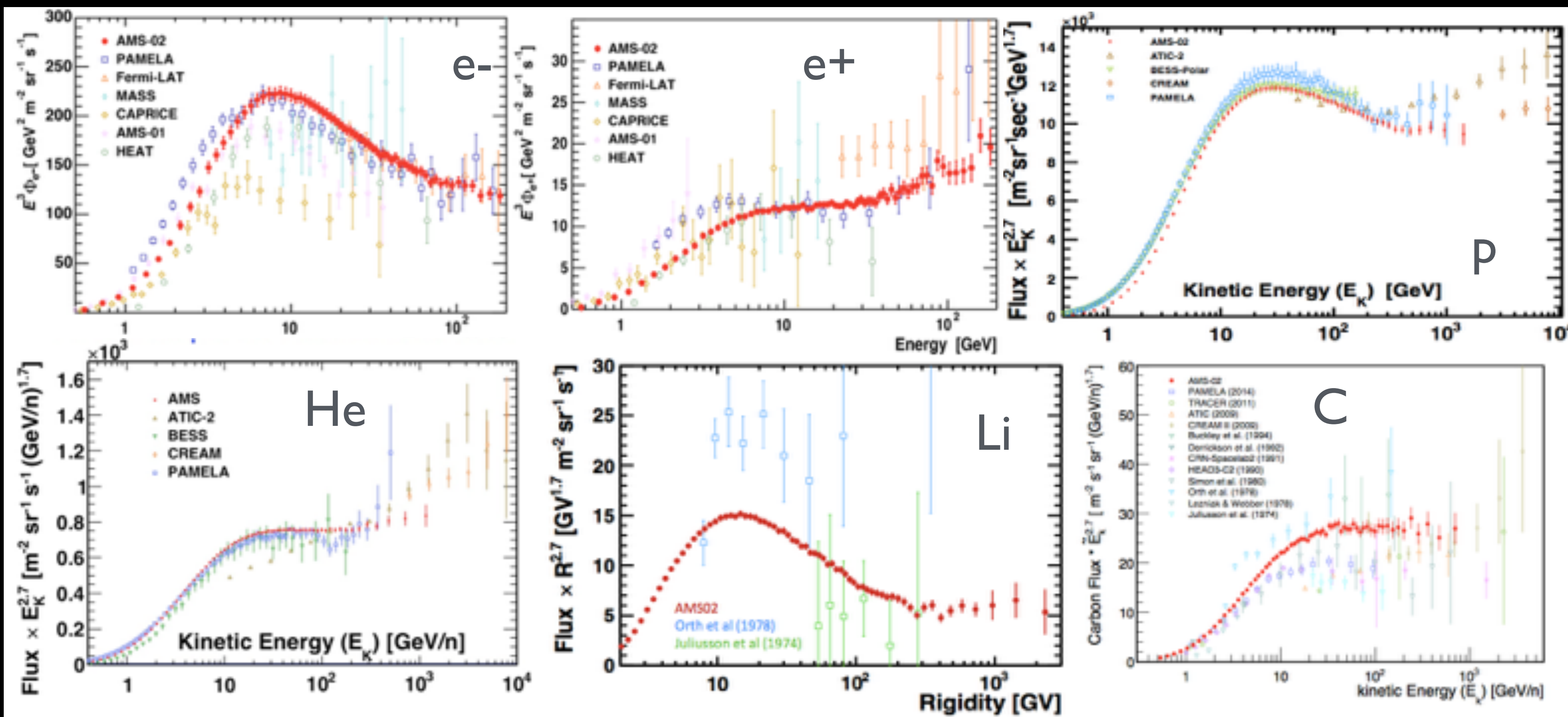
The Cherenkov Telescope Array (CTA) promises a lower energy threshold and a higher sensitivity.

Doro, 2014

In the next future….. Precision cosmic rays

AMS (Alpha Magnetic Spectrometer)

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



Summary

- There is overwhelming astrophysical evidence for non-baryonic cold dark matter
- The nature of cold dark matter is still unknown, and many candidates have been proposed
- There is some controversial detection of dark matter signals
- The next future will see measurements of the small- and large-scale structure of dark matter, as well as larger and more precise searches for dark matter signals