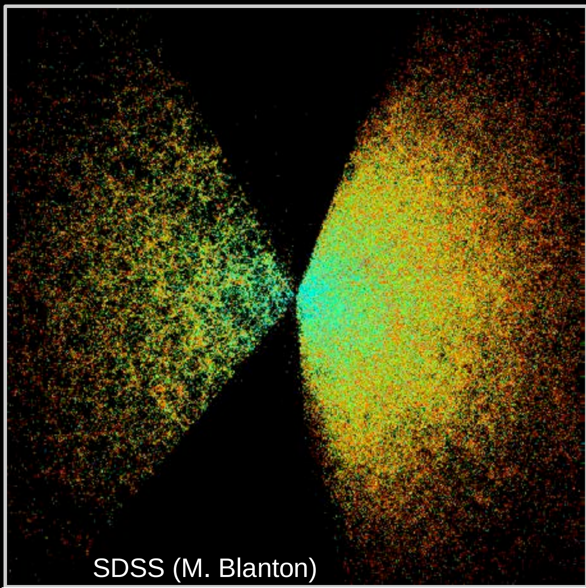
Overview of dark matter

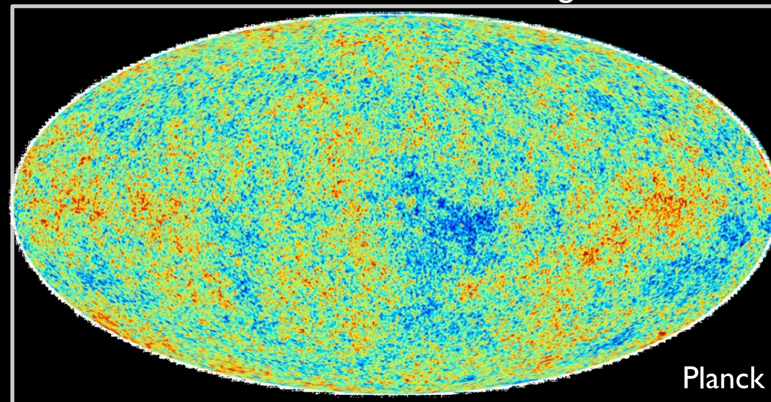
Paolo Gondolo
University of Utah

Evidence for cold dark matter

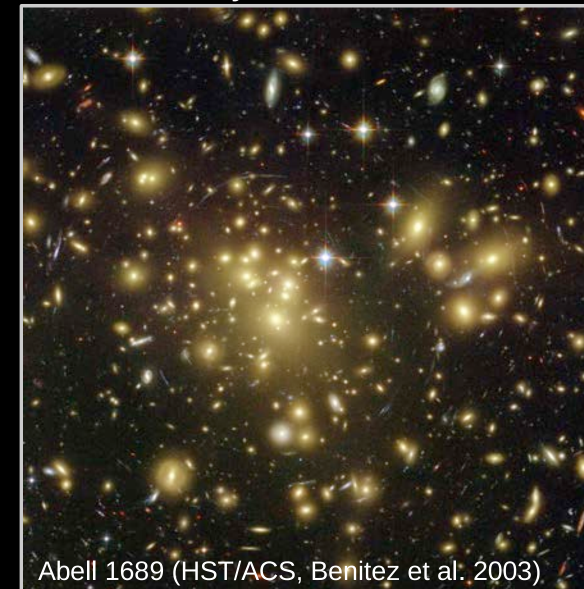
Large Scale Structure



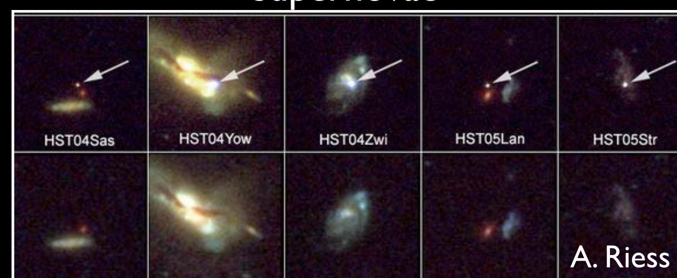
Cosmic Microwave Background

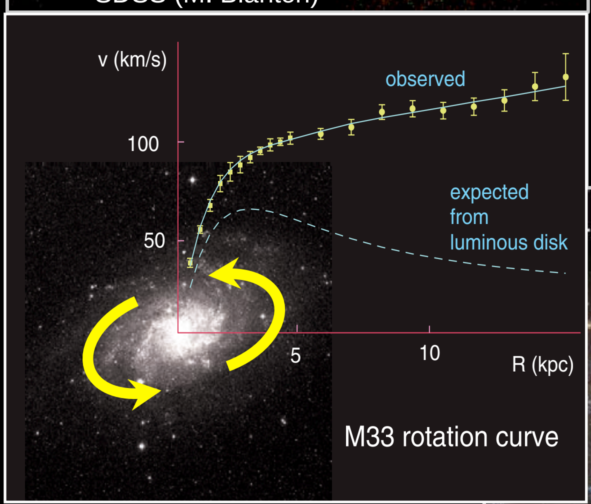


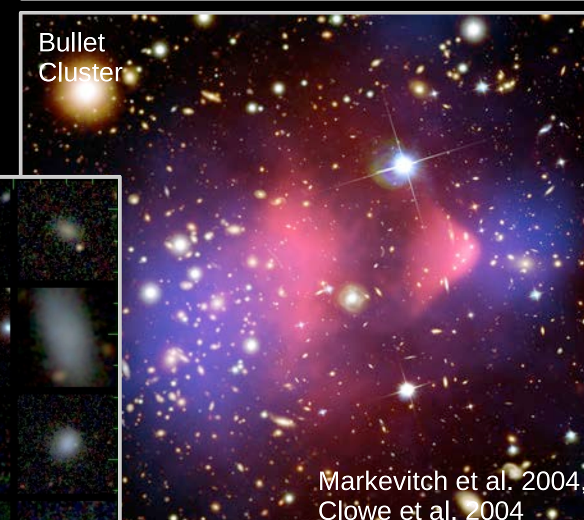
Galaxy Clusters



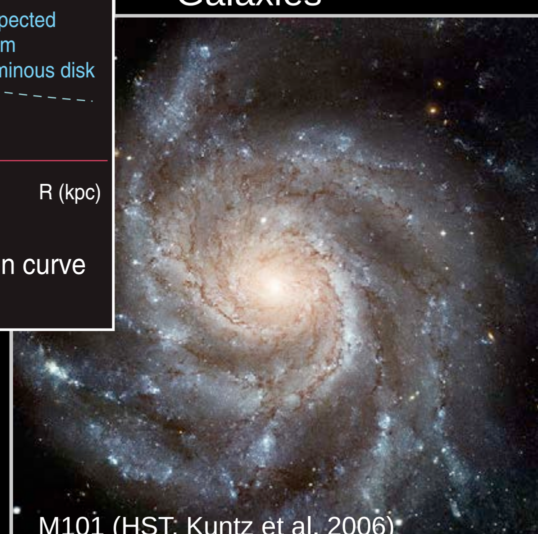
Supernovae



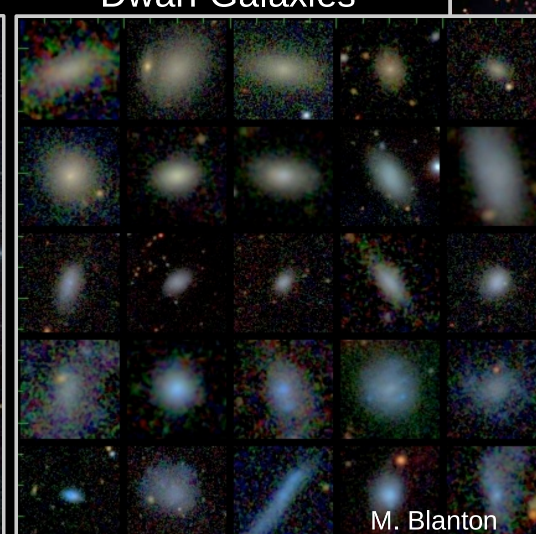




Galaxies



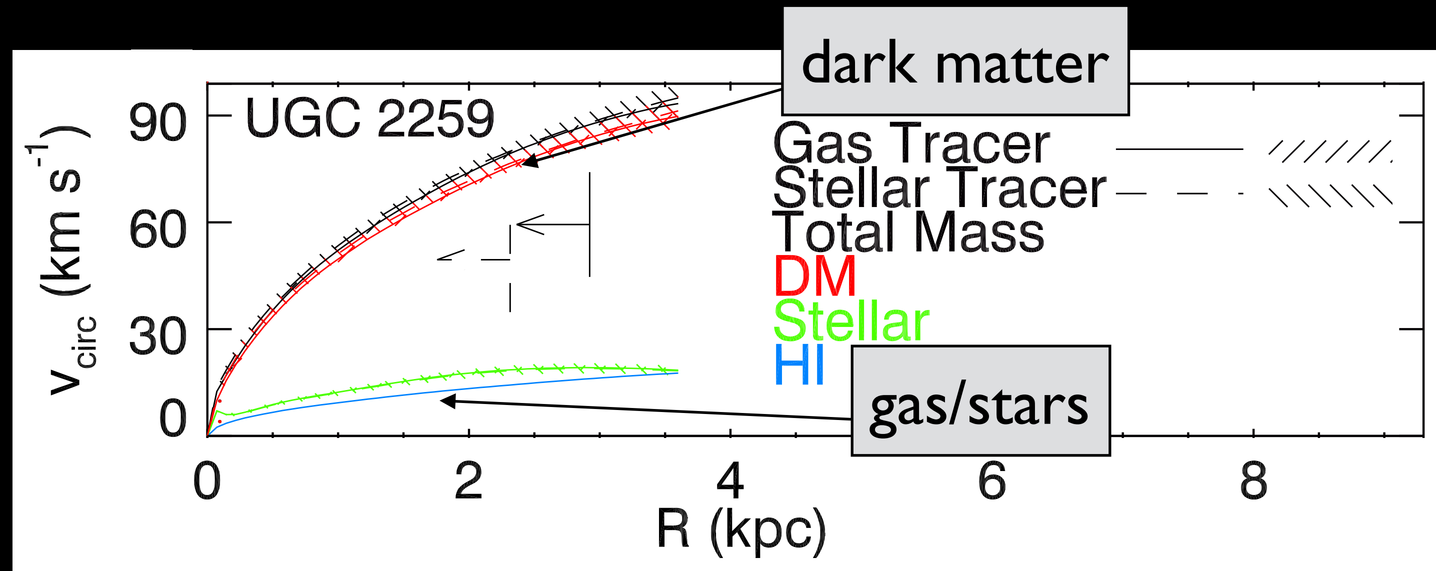
Dwarf Galaxies

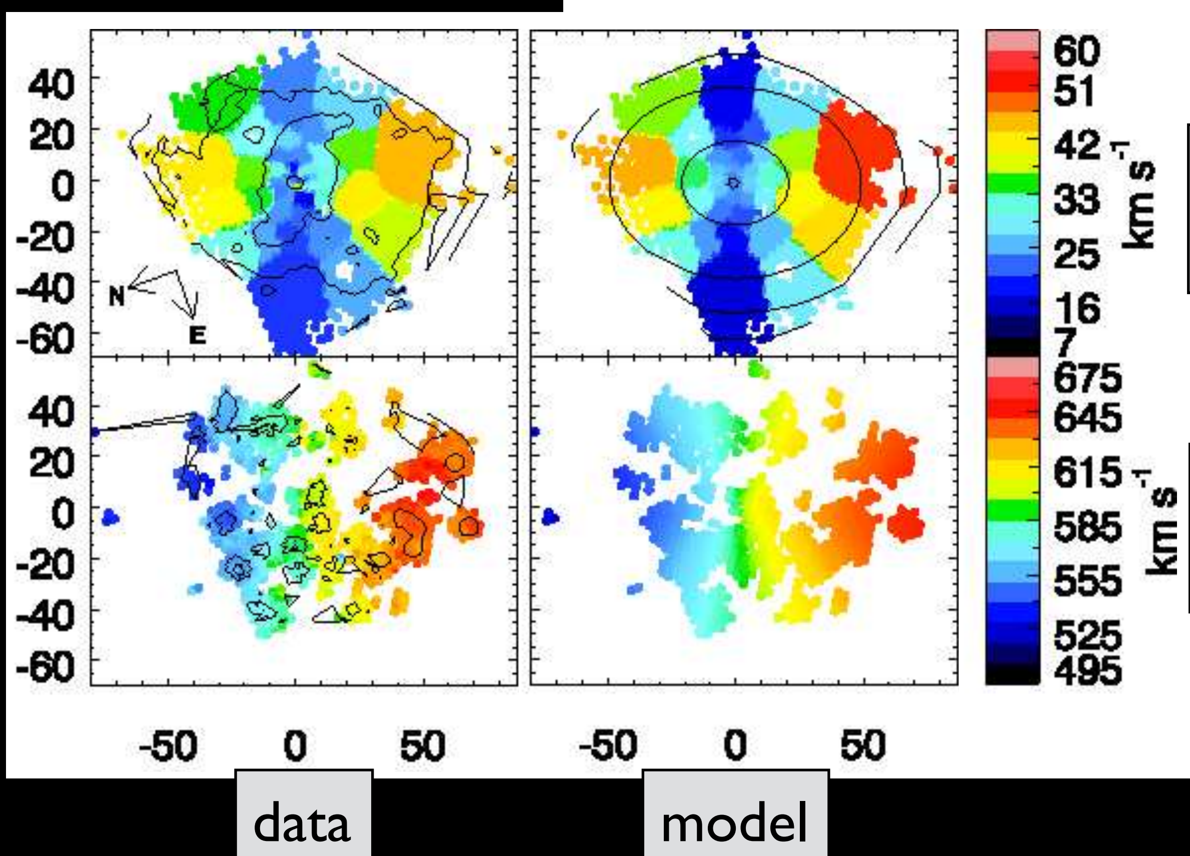


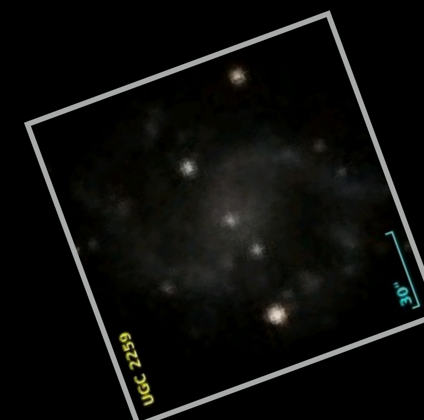
Evidence for cold dark matter

Dwarf galaxies

Dwarf galaxies are dominated by dark matter.





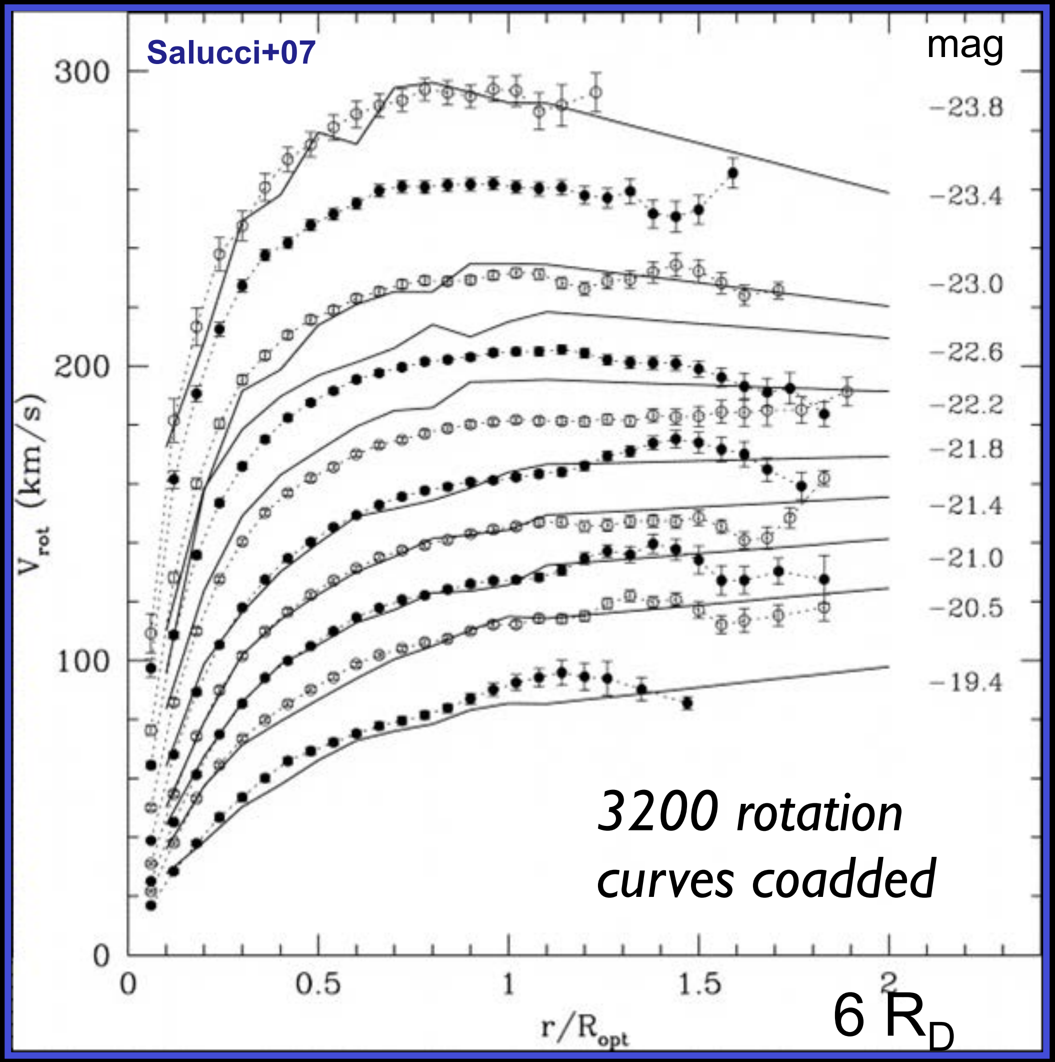


Adams et al 2014

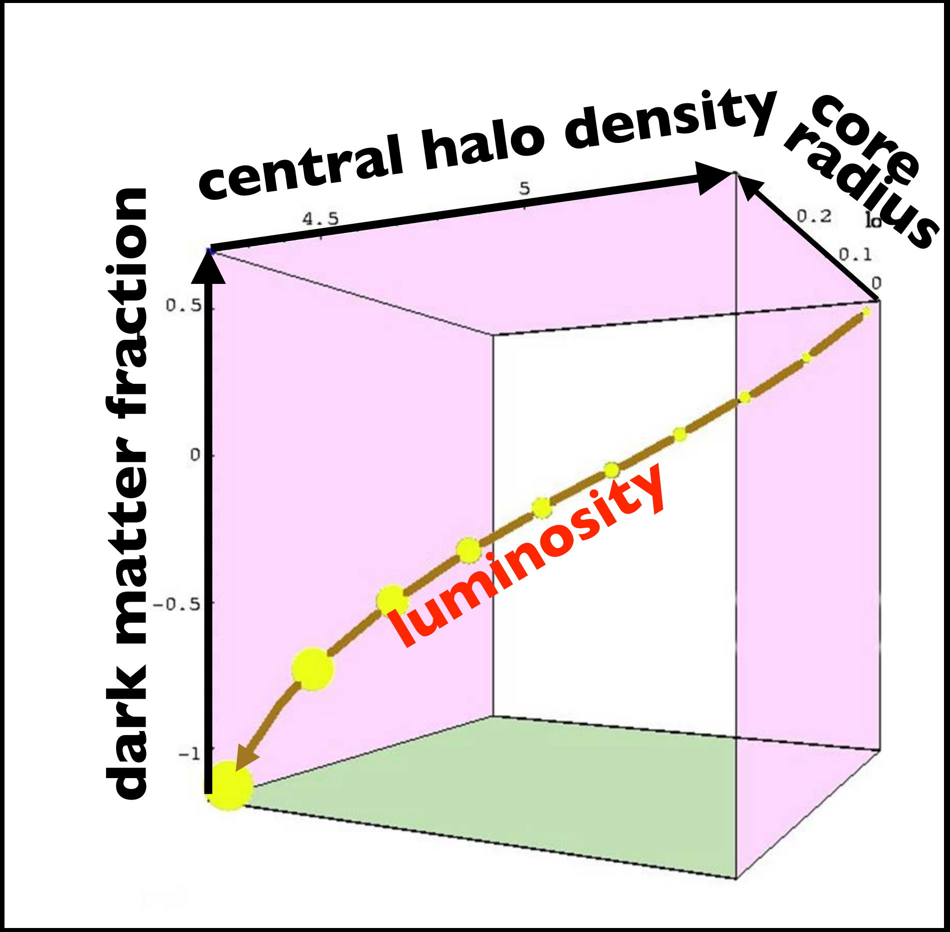
Evidence for cold dark matter

Spiral galaxies

Empirical correlations found from thousands of spiral galaxy rotation curves



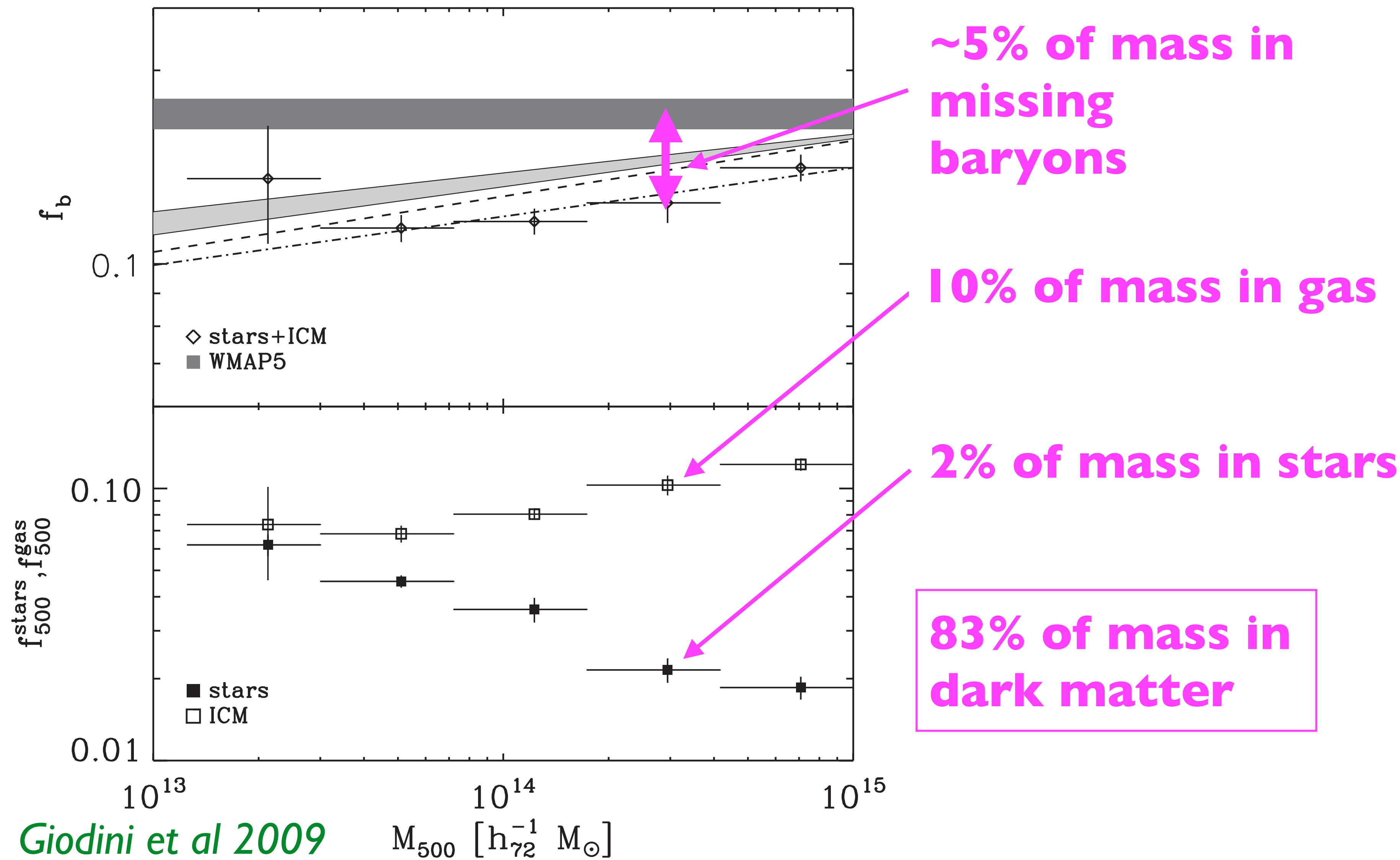
Salucci et al 2007



Evidence for cold dark matter

Galaxy clusters

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



Giodini et al 2009

Cold dark matter, *not* modified gravity

The Bullet Cluster

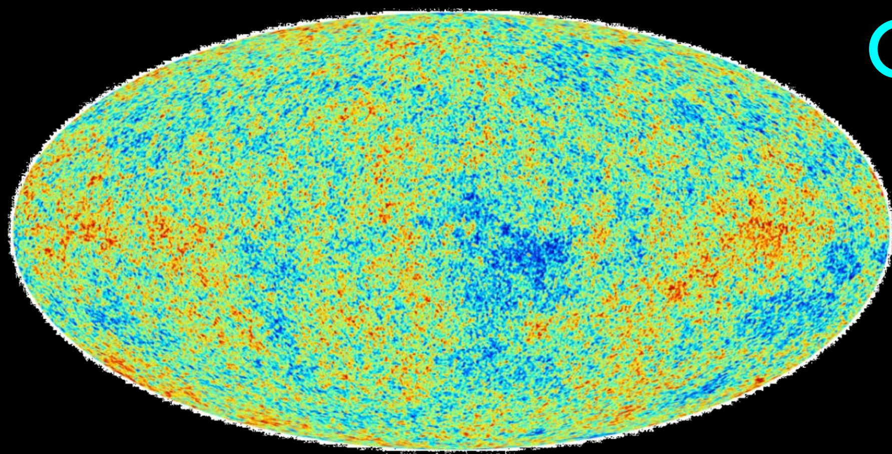
Symmetry argument: gas is at center, but potential has two wells.

Galaxies in optical (Hubble Space Telescope)

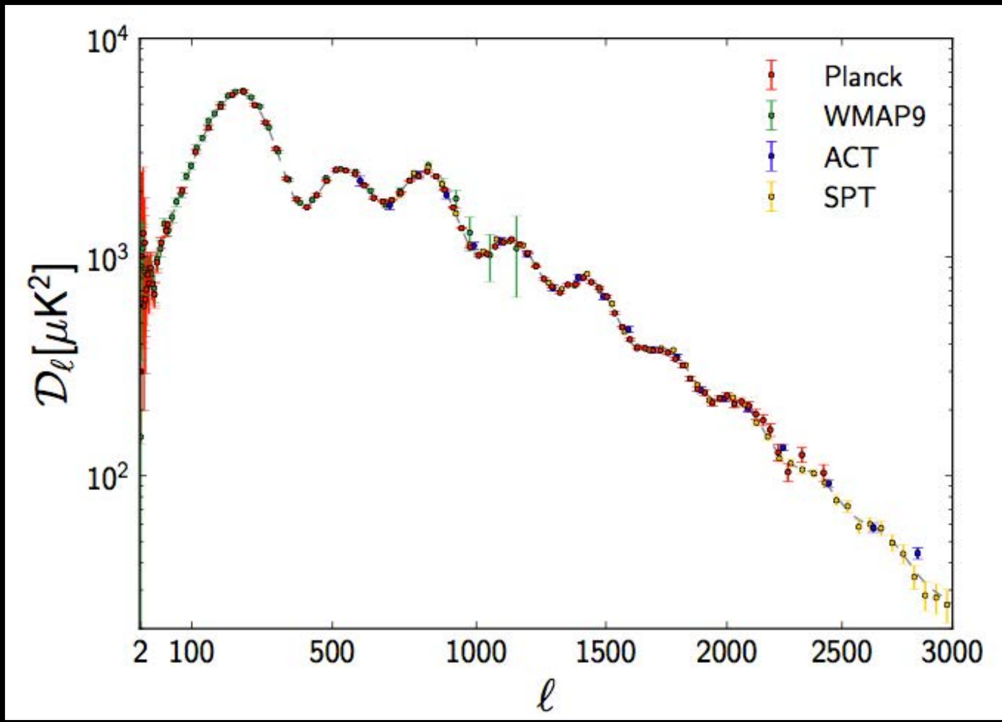
X-ray emitting hot gas (Chandra)

Gravitational potential from weak lensing

Evidence for cold dark matter



Cosmic Microwave Background fluctuations



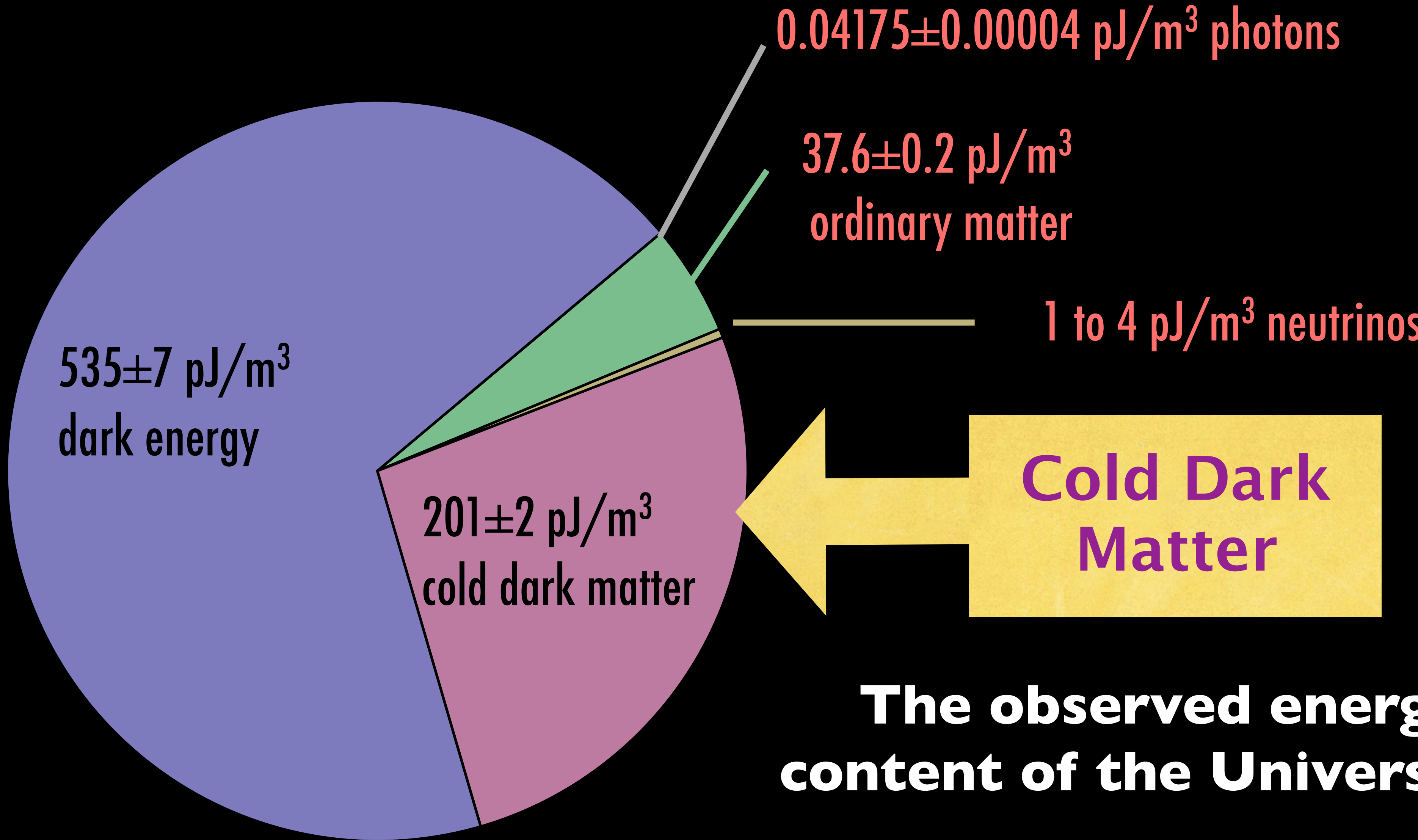
	Planck+WP+highL+BAO	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04148	1.04147 ± 0.00056
τ	0.0952	0.092 ± 0.013
n_s	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0973	3.091 ± 0.025
Ω_Λ	0.6914	0.692 ± 0.010
σ_8	0.8288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

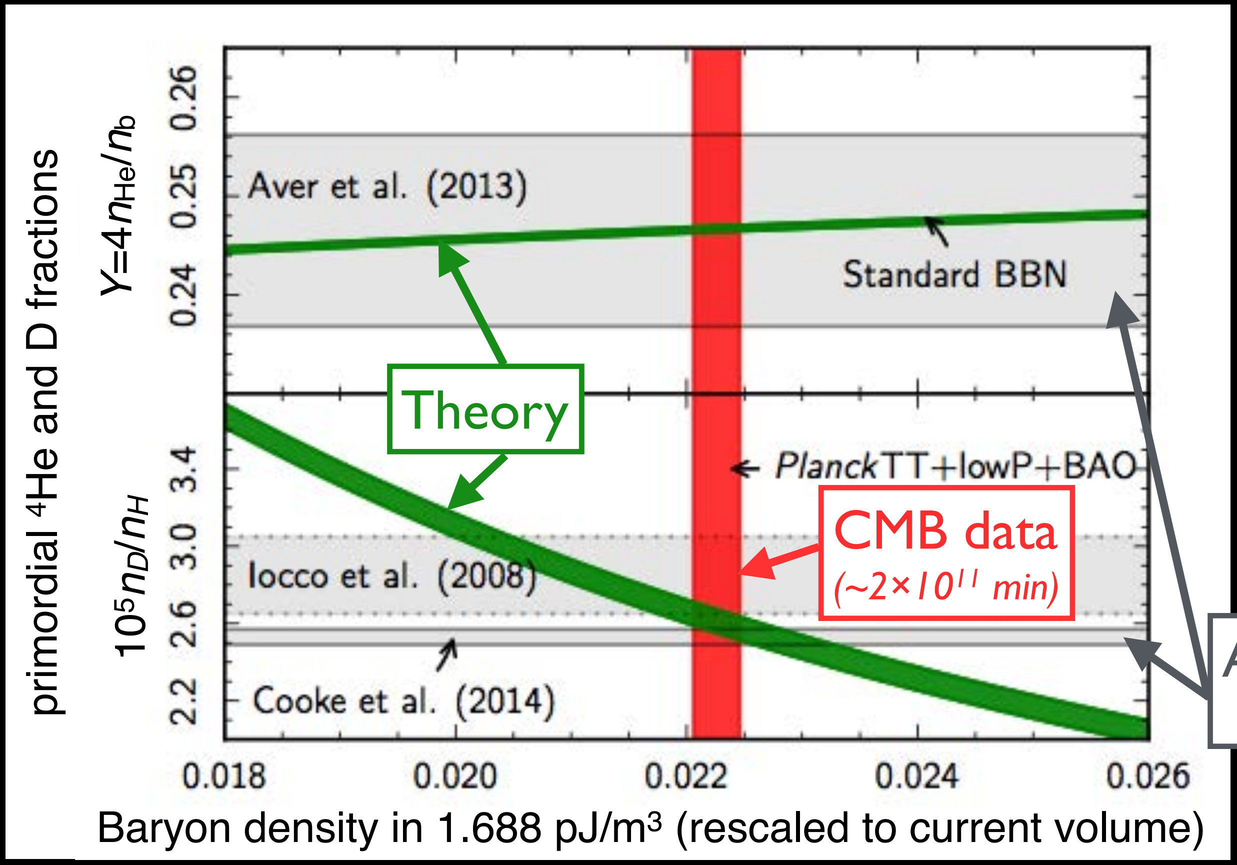
1 pJ = 10^{-12} J

$\rho_{\rm crit} = 1688.29\, h^2$ 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.



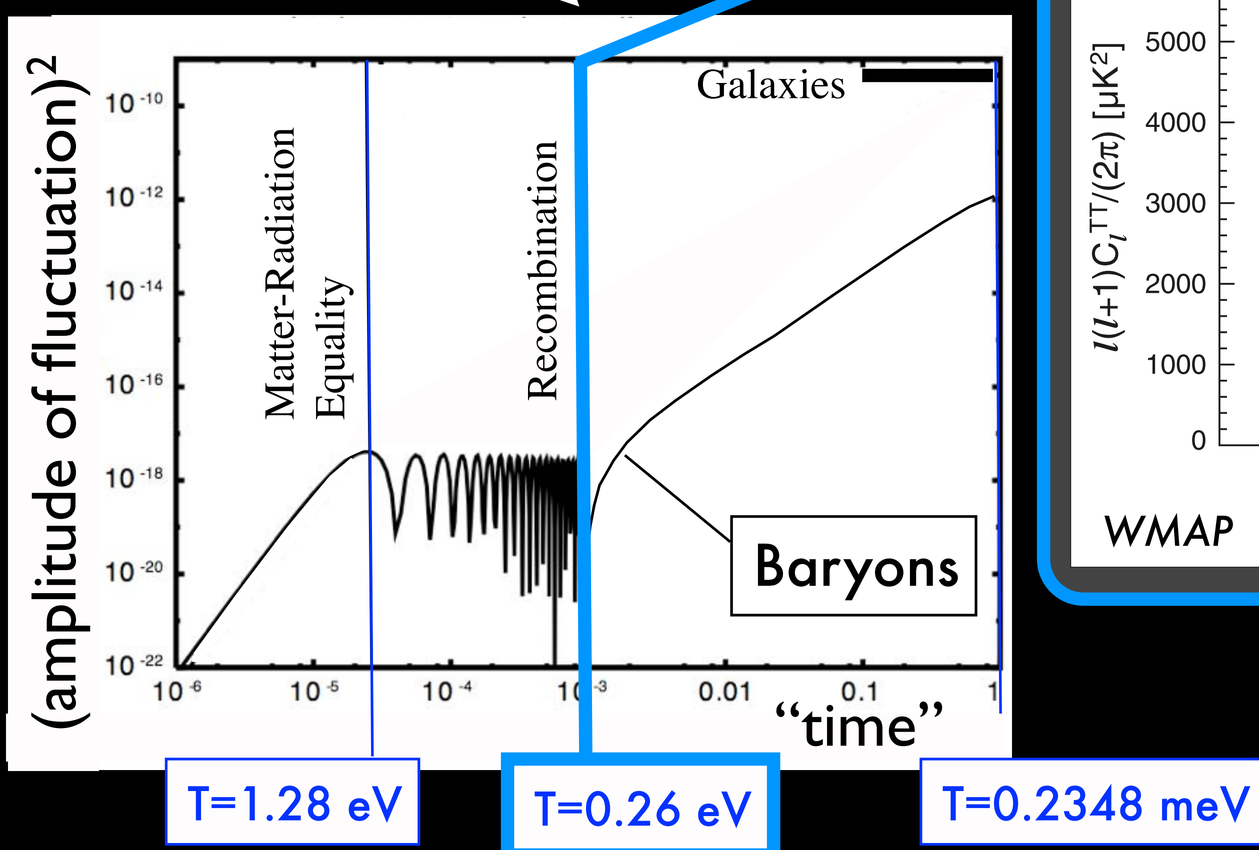
84% of matter is nonbaryonic

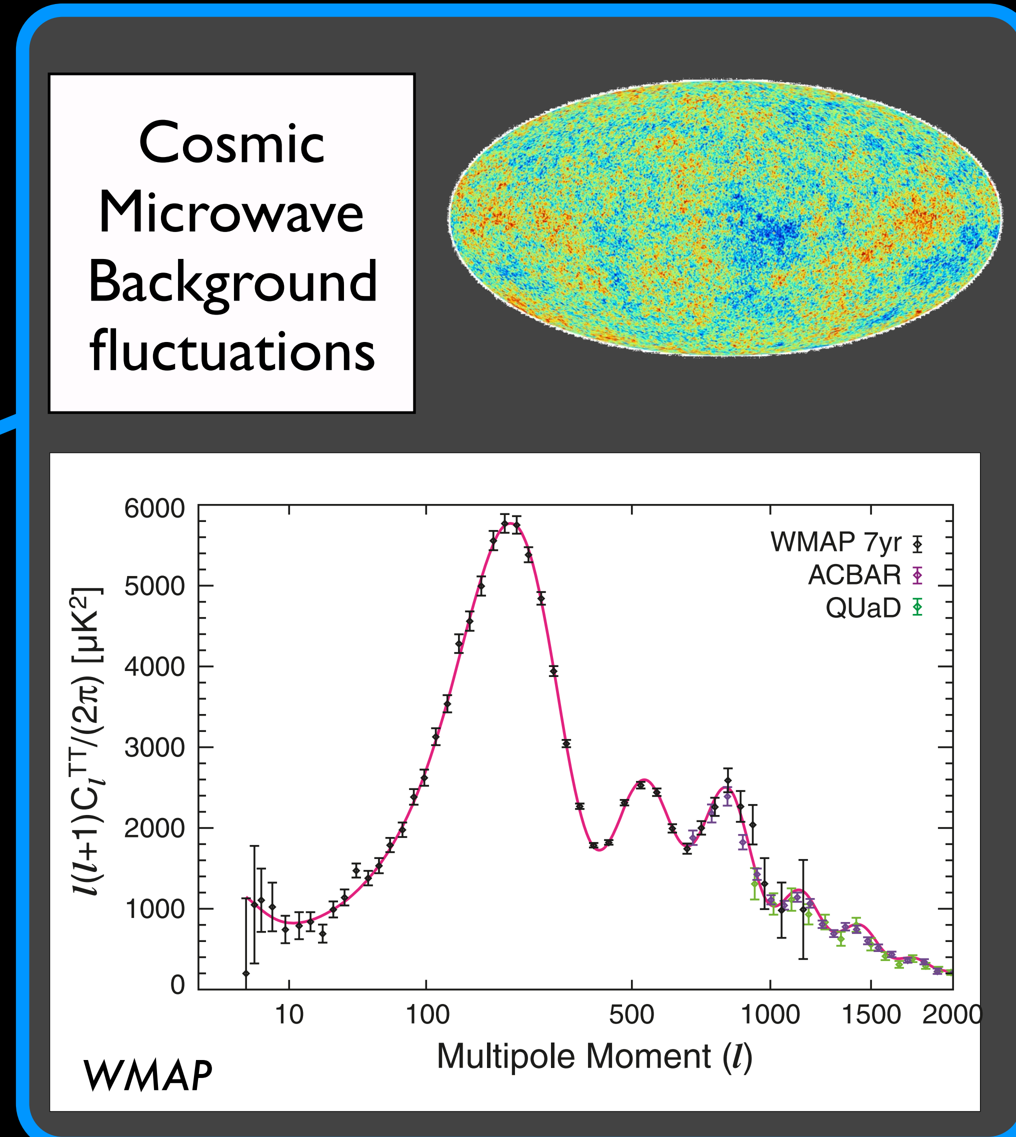
Ade et al [Planck] 2015

Evidence for *nonbaryonic* cold dark matter

GALAXY FORMATION

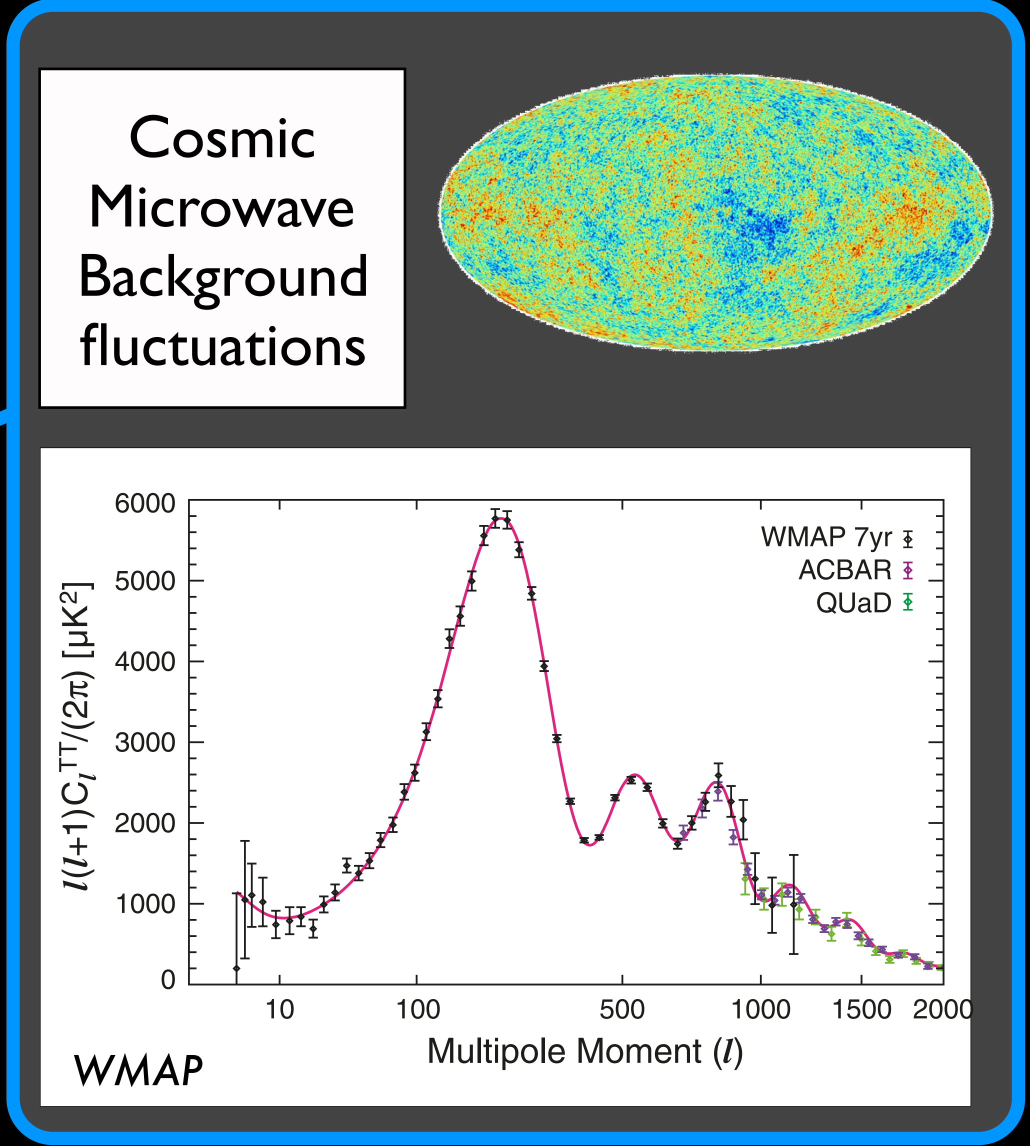
13 billion years ago

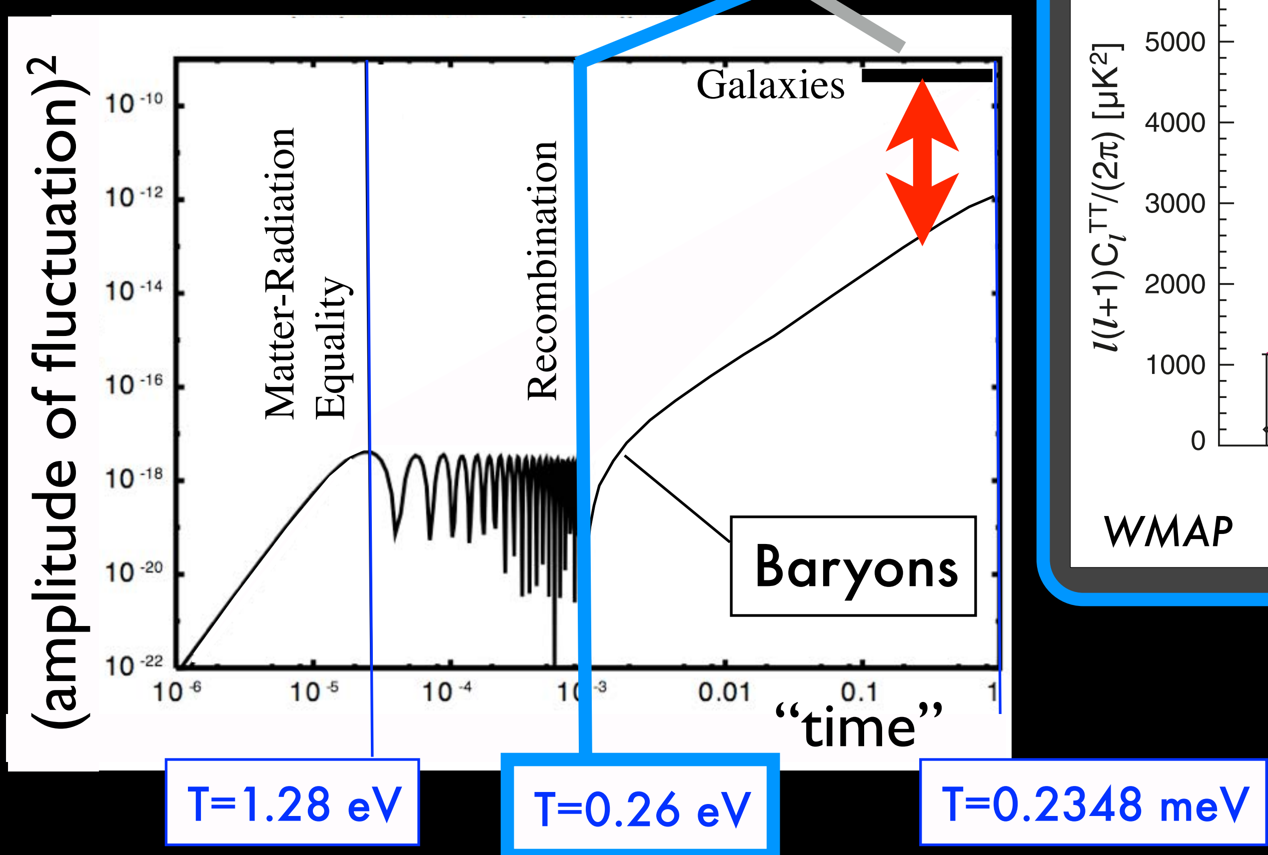




Evidence for *nonbaryonic* cold dark matter

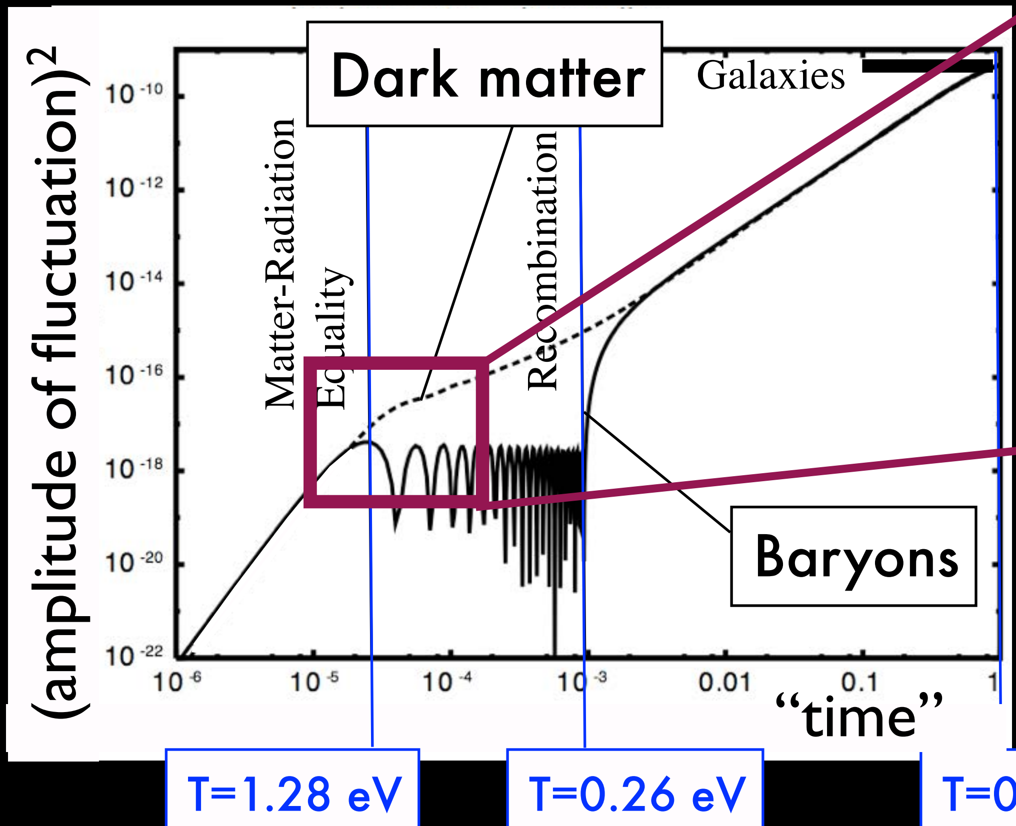
Without dark matter, fluctuations are too small to gravitationally grow into galaxies in the given 13 billion years.



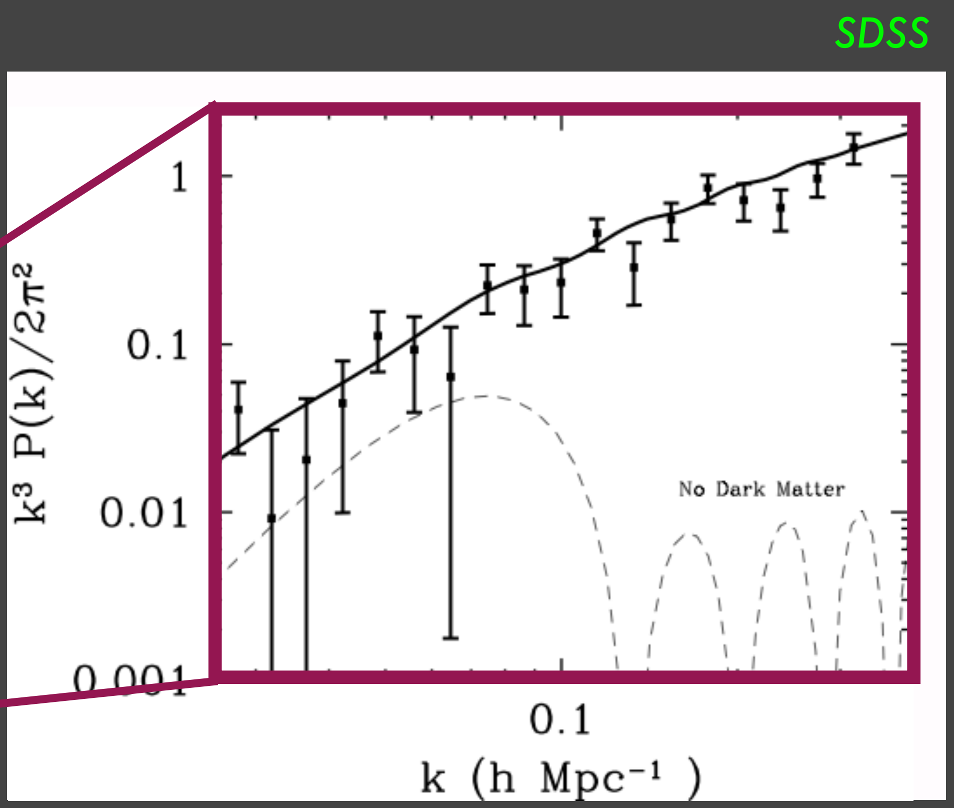


Evidence for *nonbaryonic* cold dark matter

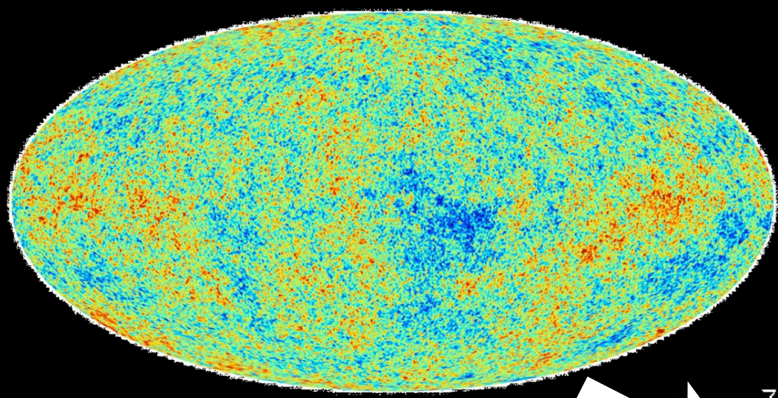
Dark matter fluctuations, uncoupled to the plasma, start growing early and have enough time to grow into galaxies

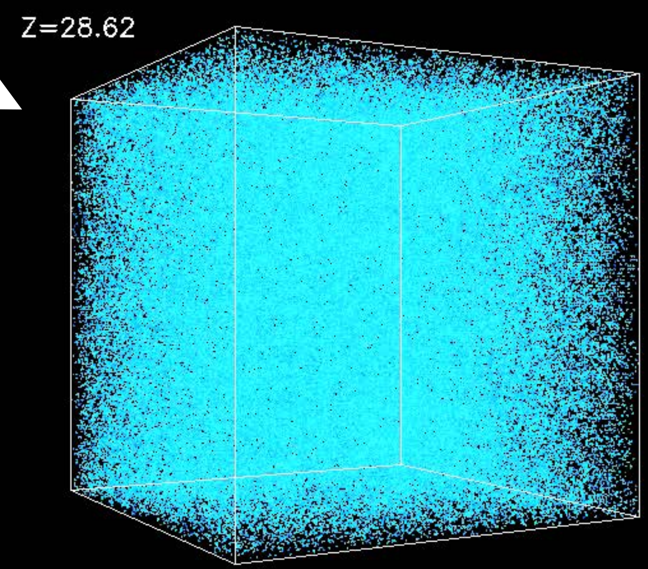


More than 80% of all matter does not couple to the primordial plasma!

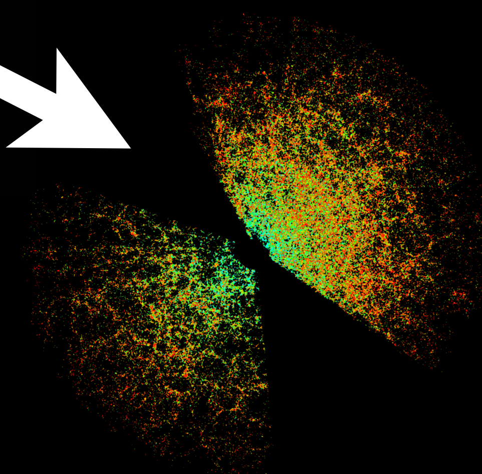


Evidence for nonbaryonic *cold* dark matter

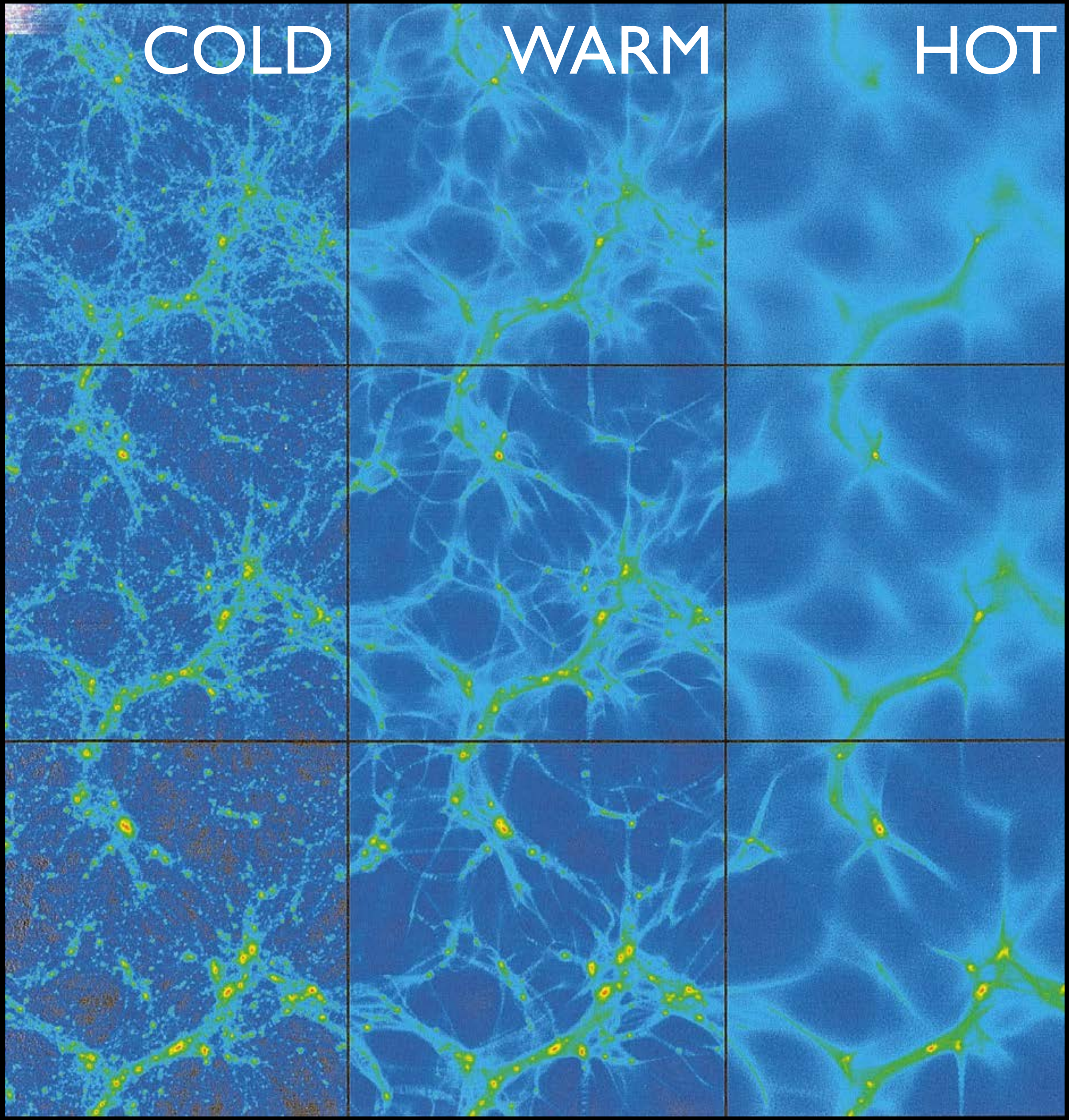




Kravtsov, Klypin

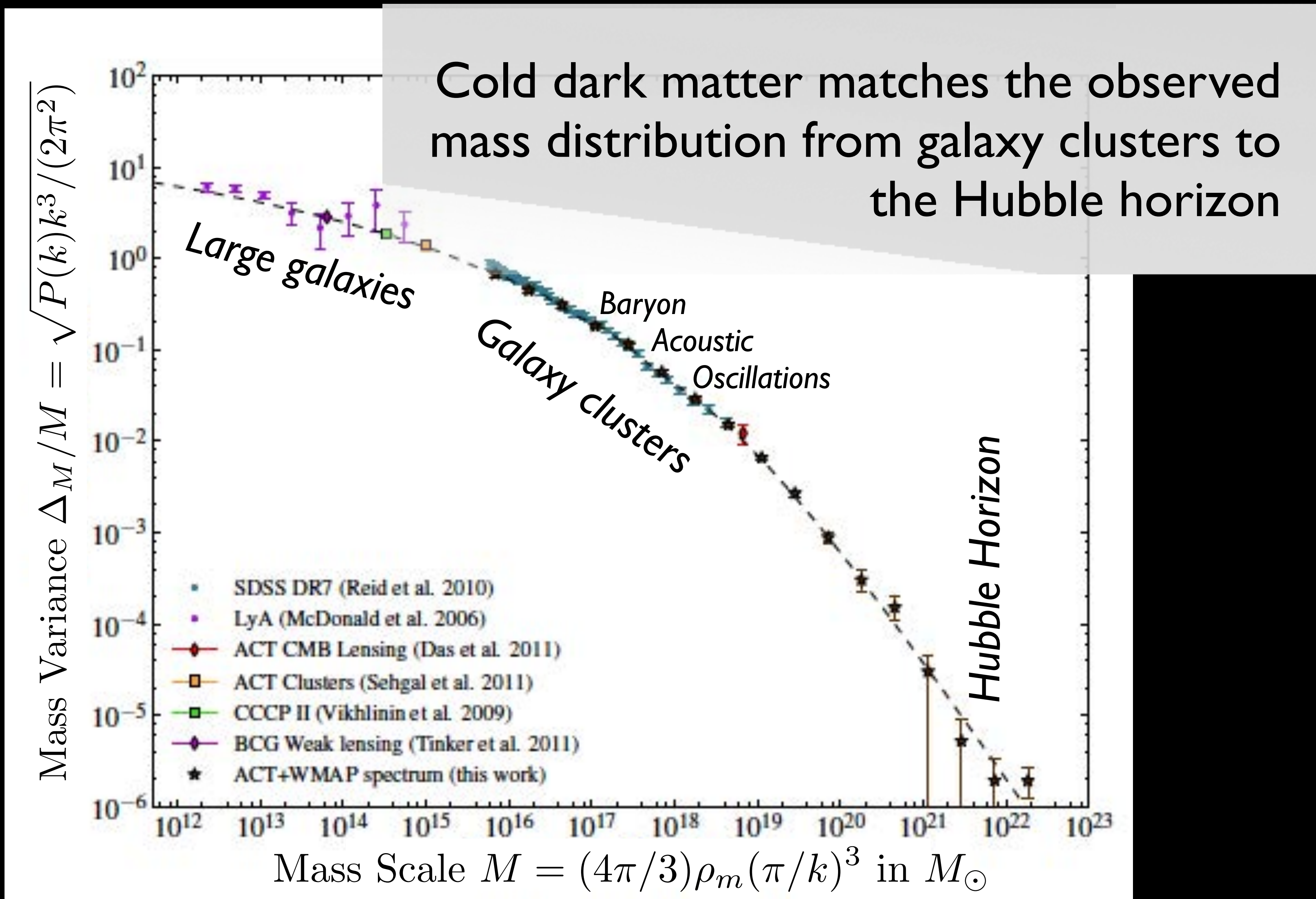


Evidence for nonbaryonic *cold* dark matter



Bode et al 2001

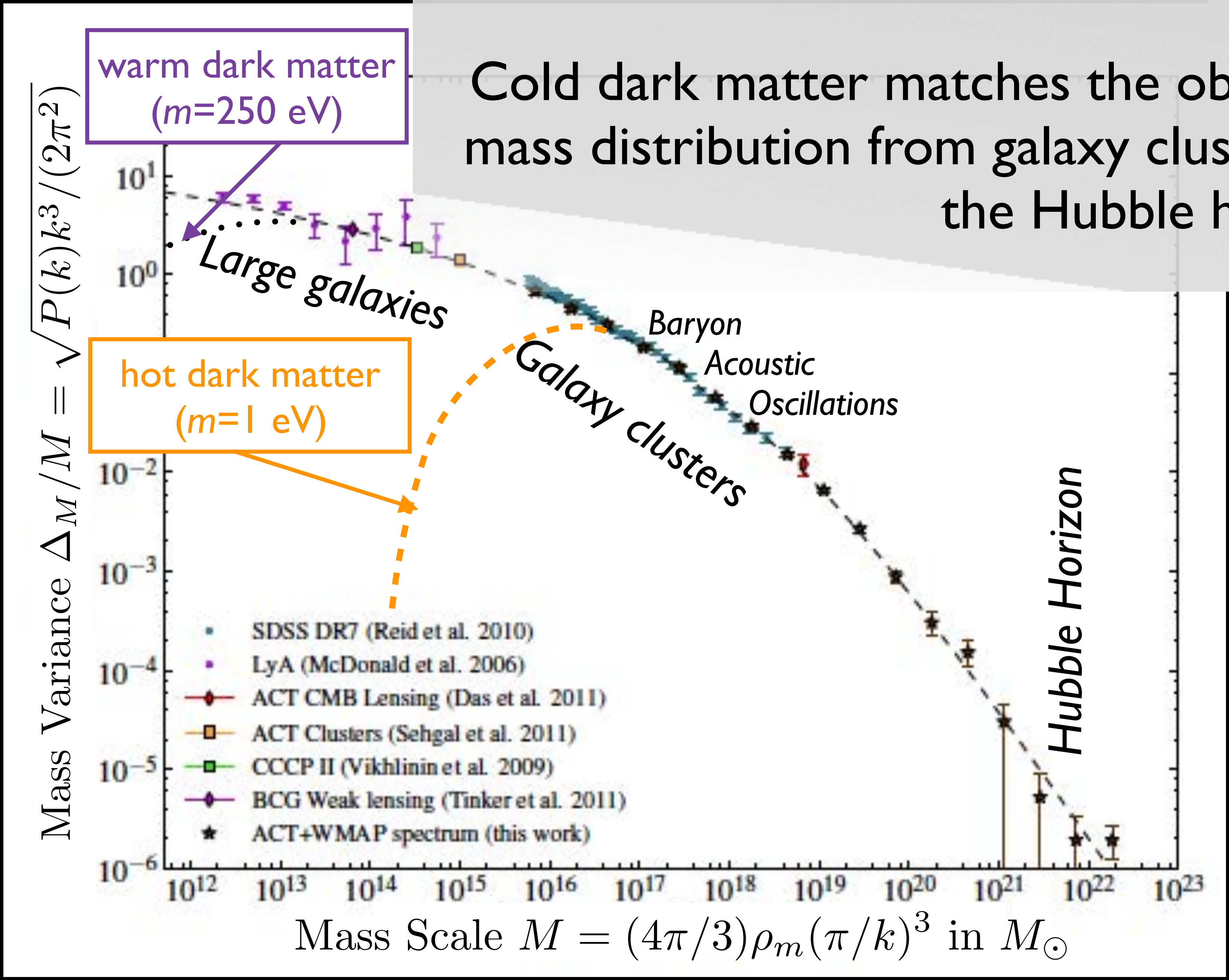
Evidence for nonbaryonic *cold* dark matter



Hlozek et al 2012

Evidence for nonbaryonic *cold* dark matter

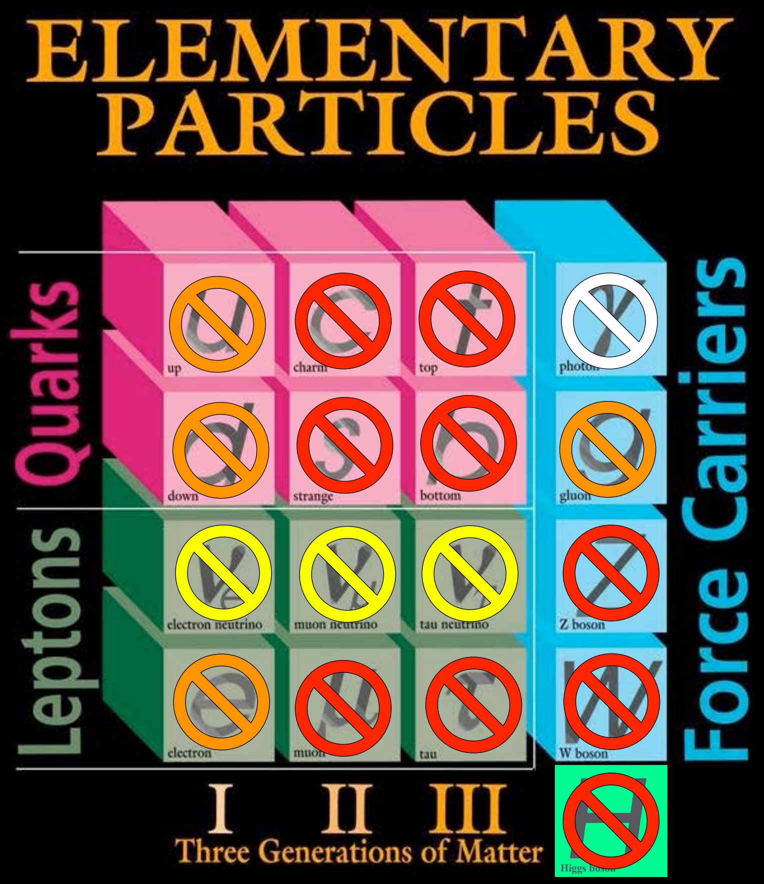
Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon



Hlozek et al 2012

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, ...

Particle dark matter

DM production	- in plasma reactions - from decays of decoupled species - emitted from extended objects	collider searches cosmic density
DM-$\overline{\text{DM}}$ annihilation $\chi+\overline{\chi}\rightarrow$anything	- self-conjugate DM - asymmetric DM	indirect detection cosmic density
DM—SM scattering χ+SM$\rightarrow\chi'$+SM	- elastic/inelastic scattering - short-/long-range interactions	hot/cold/warm halo (sub)structure direct detection
DM—DM scattering $\chi+\chi\rightarrow\chi+\chi$	- collisionless - self-interacting	dark halo structure
DM decay $\chi\rightarrow$anything	- stable - long-lived - ensemble of short-lived particles	indirect detection

Particle dark matter

Some factors affecting the particle dark matter cosmic density

— Production mechanism:

- produced in reactions of plasma (thermal) particles
  - reaching reaction equilibrium — *WIMP freeze-out, …*
  - not reaching reaction equilibrium — *FIMP freeze-in, …*
  - coannihilating with similar mass particles — *neutralinos, …*
- produced in decays of non-thermal particles — *gravitinos, …*
- emitted from extended objects — *axions, …*

— Dark matter-antimatter asymmetry:

- self-conjugate — *Majorana fermions, neutralinos, axions, gravitinos, …*
- not self-conjugate — *Dirac fermions, asymmetric dark matter, …*

— Hubble expansion rate before nucleosynthesis:

- standard vs nonstandard cosmology — *low temperature reheating, kination, …*

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)

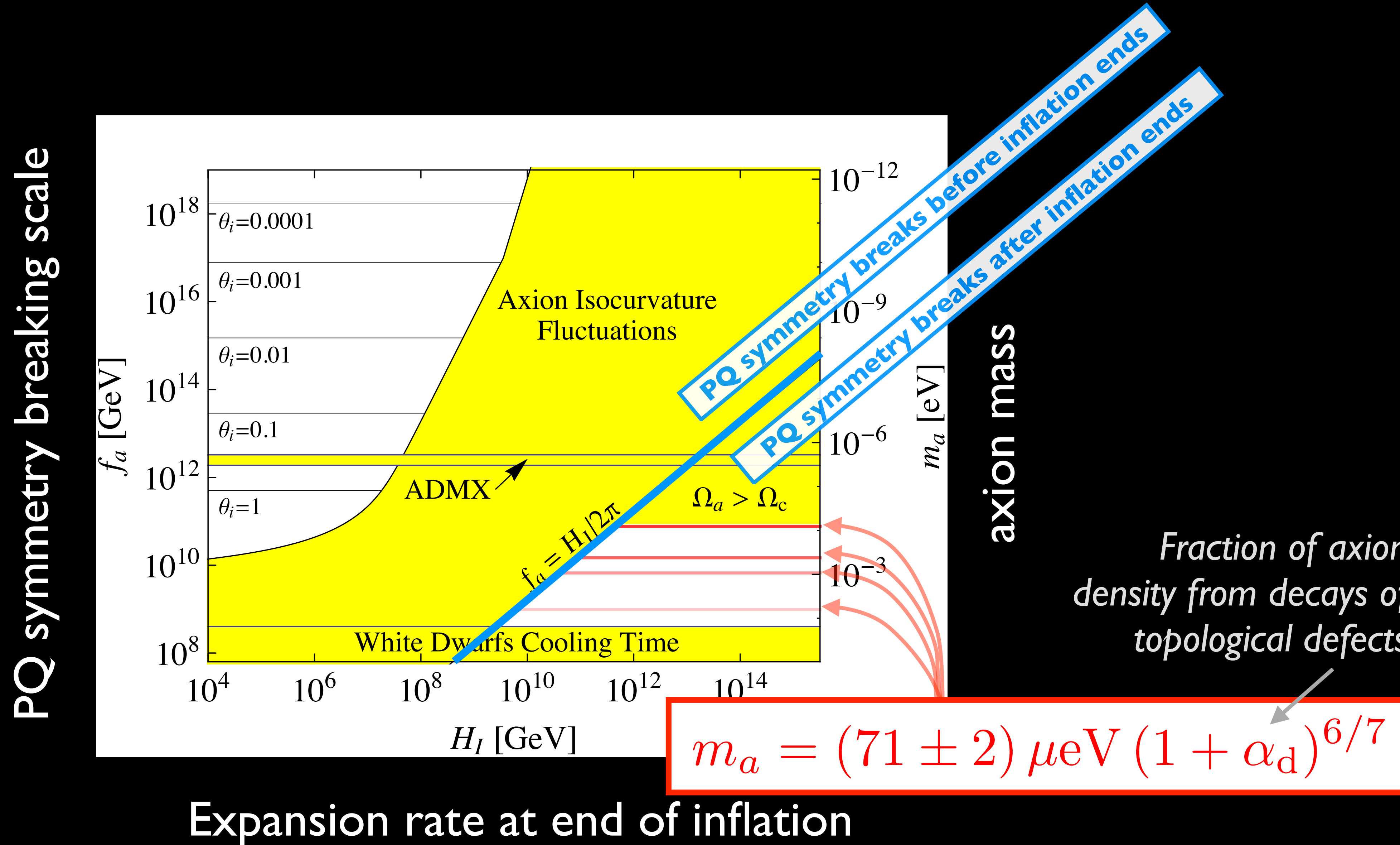
Produced by decay of topological defects

(Axionic string decays)

Still a very complicated and uncertain calculation!

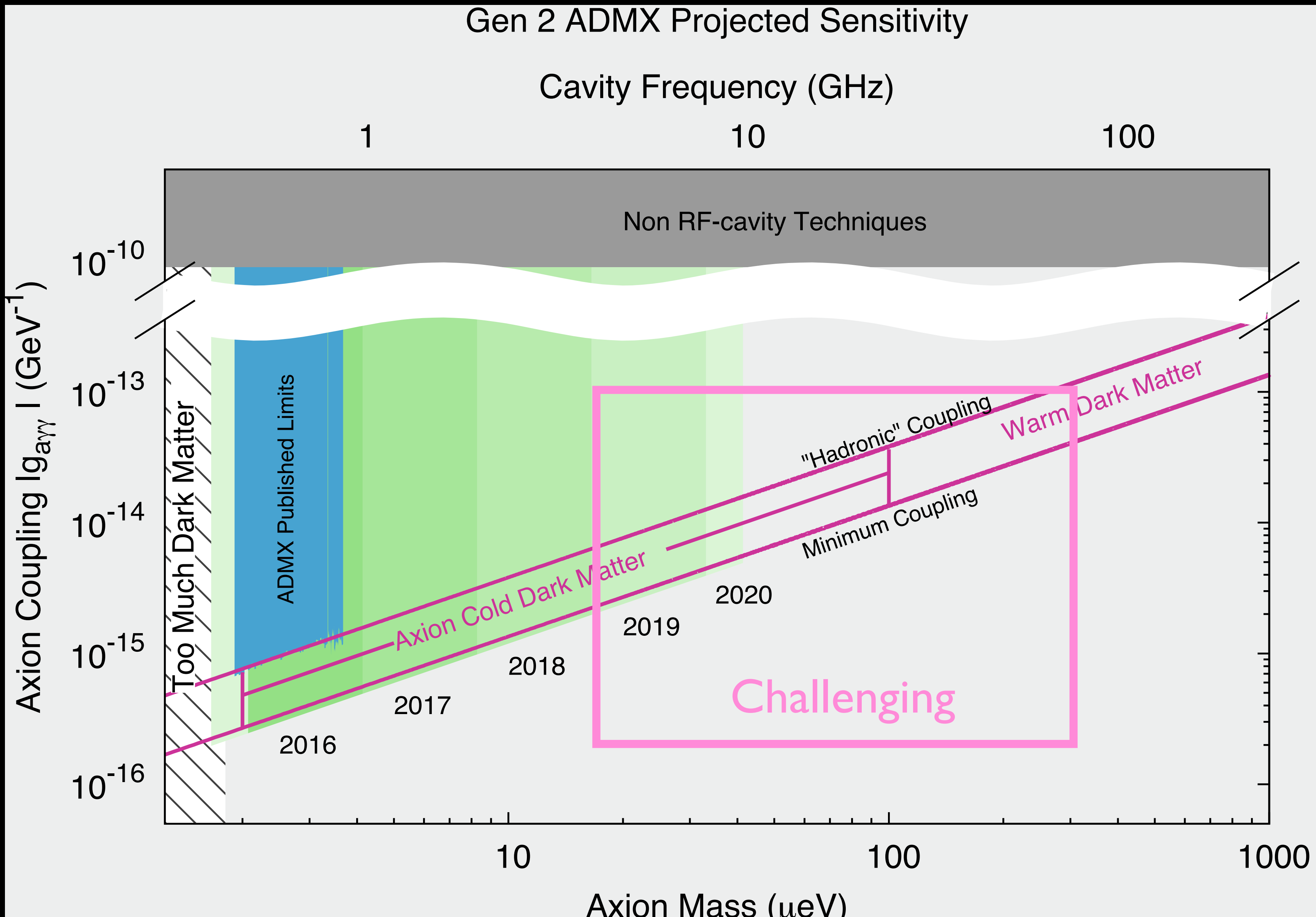
e.g. Hiramatsu et al 2012

QCD axions as cold dark matter



Visinelli, Gondolo 2009, 2014

QCD axions as cold dark matter: searches



Dielectric haloscope?

Rybka 2016

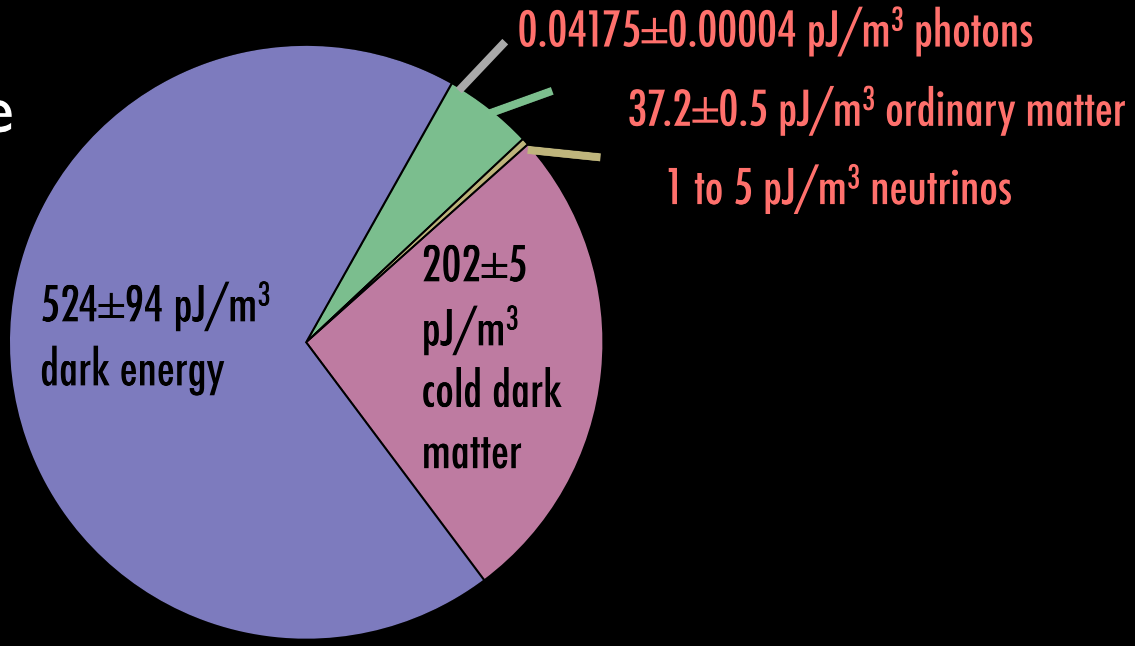
Weakly Interacting Massive Particles (WIMPs)

The magnificent WIMP

(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

  Thermal production in hot primordial plasma.



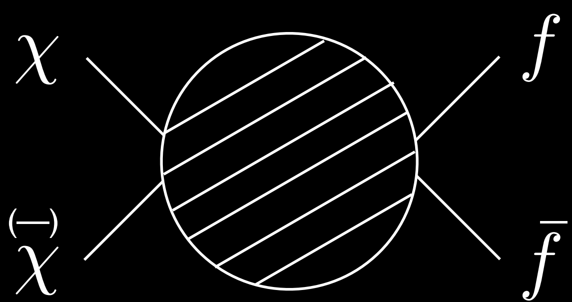
- One can experimentally test the WIMP hypothesis

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

Cosmic density of thermal WIMPs

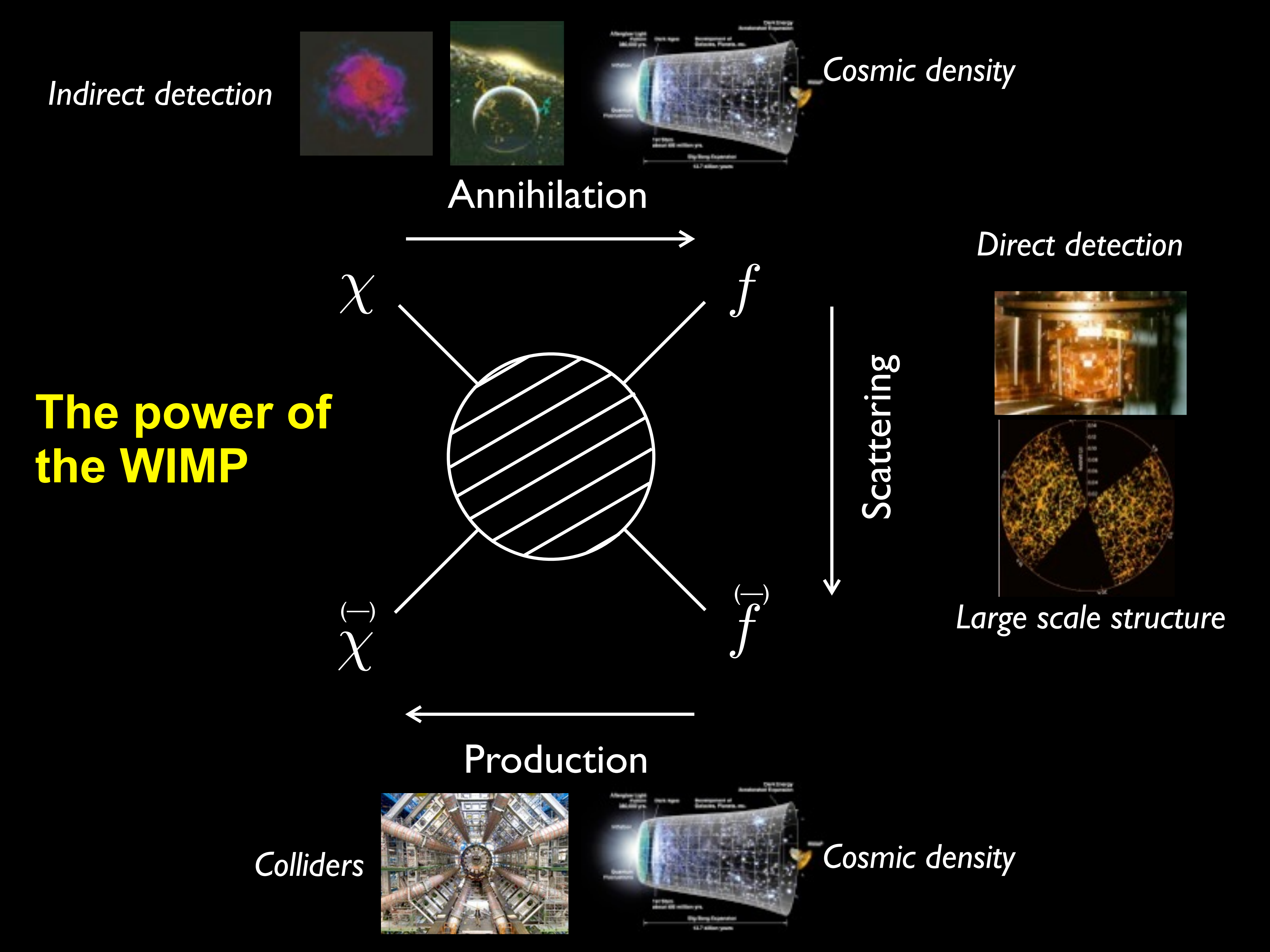
- At early times, WIMPs are produced in e^+e^-, $\mu^+\mu^-$, etc collisions in the hot primordial soup [*thermal production*].

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



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

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



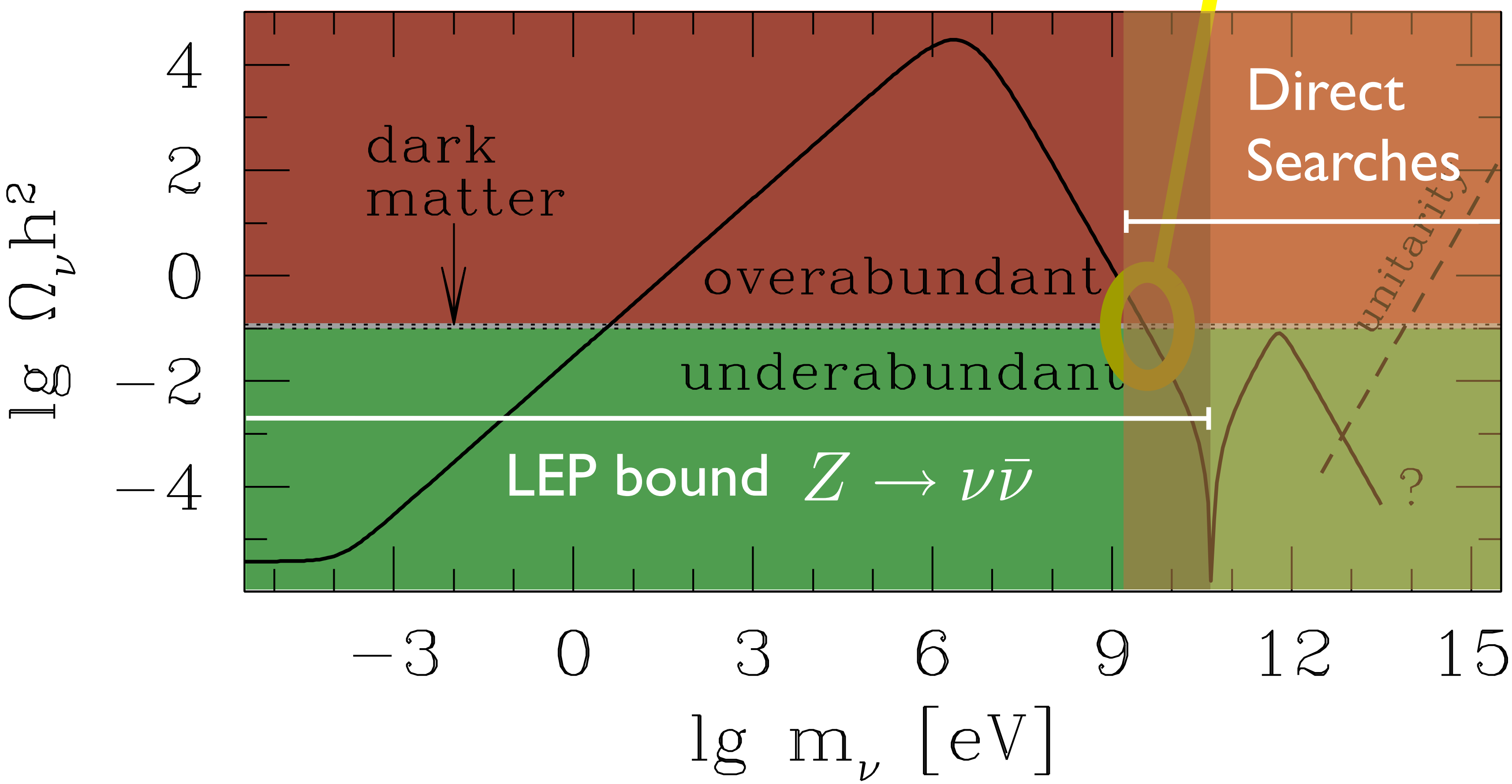
Indirect detection
Cosmic density
Annihilation
Direct detection
The power of the WIMP
Scattering
Large scale structure
Production
Colliders
Cosmic density

Massive neutrinos as dark matter

Heavy active neutrino

~ few GeV
preferred cosmological mass Lee & Weinberg 1977

Excluded as cold dark matter (1991



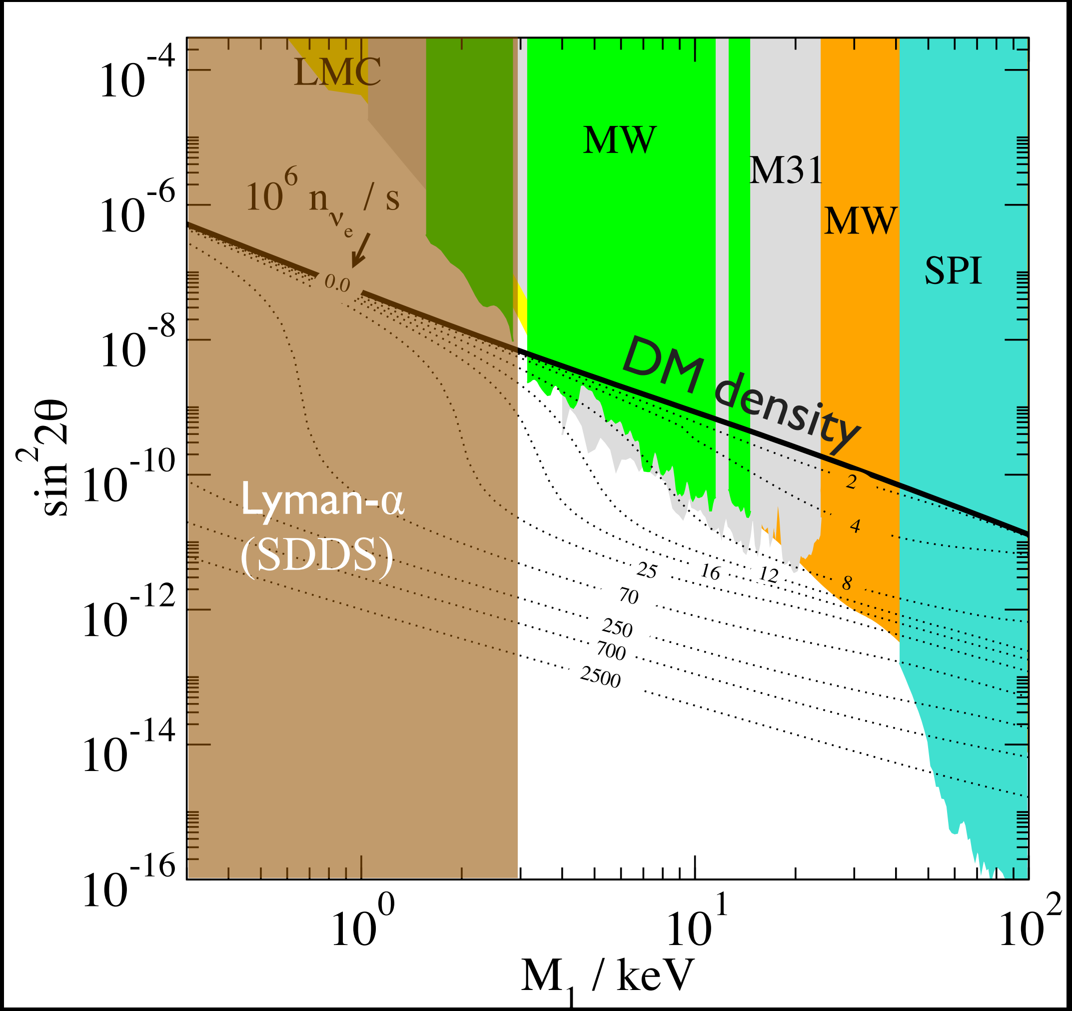
Sterile neutrino dark matter

Standard model + right-handed neutrinos

Active and sterile neutrinos oscillate into each other.

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

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



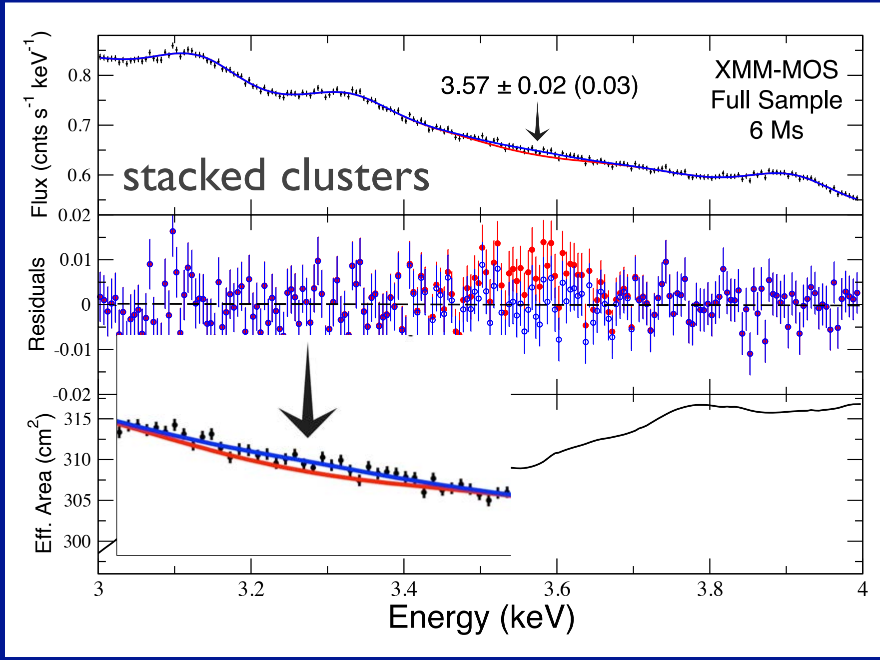
*ν*MSM

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.

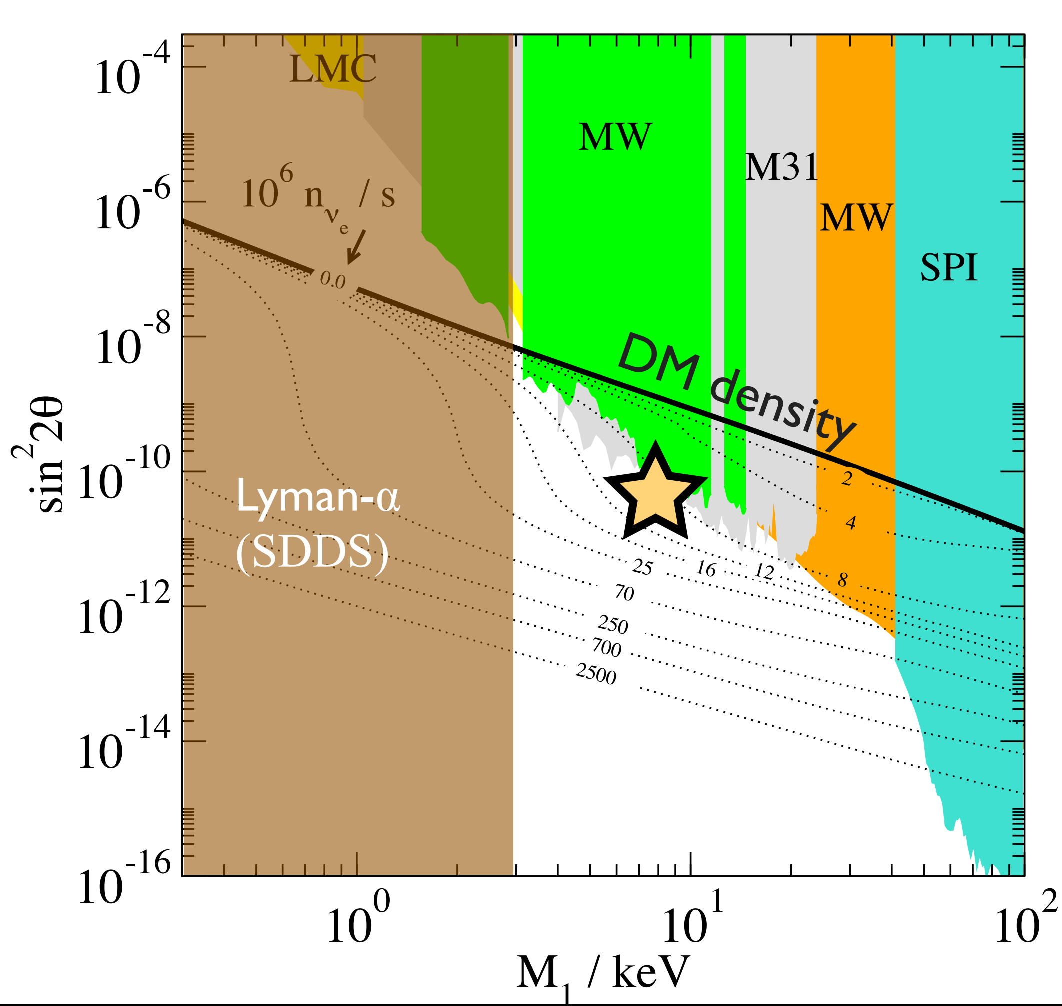
Bulbul et al 2014; Boyarski et al 2014; Iakubovskyi et al 2015



Radiative decay of sterile neutrinos

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

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



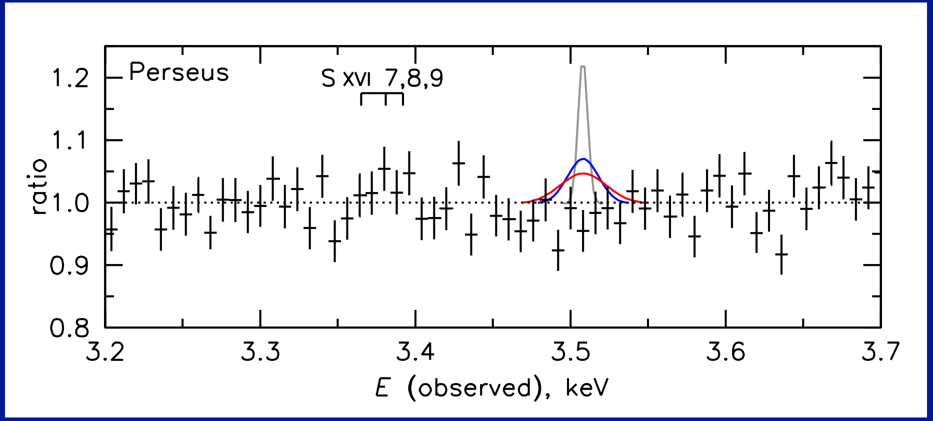
νMSM

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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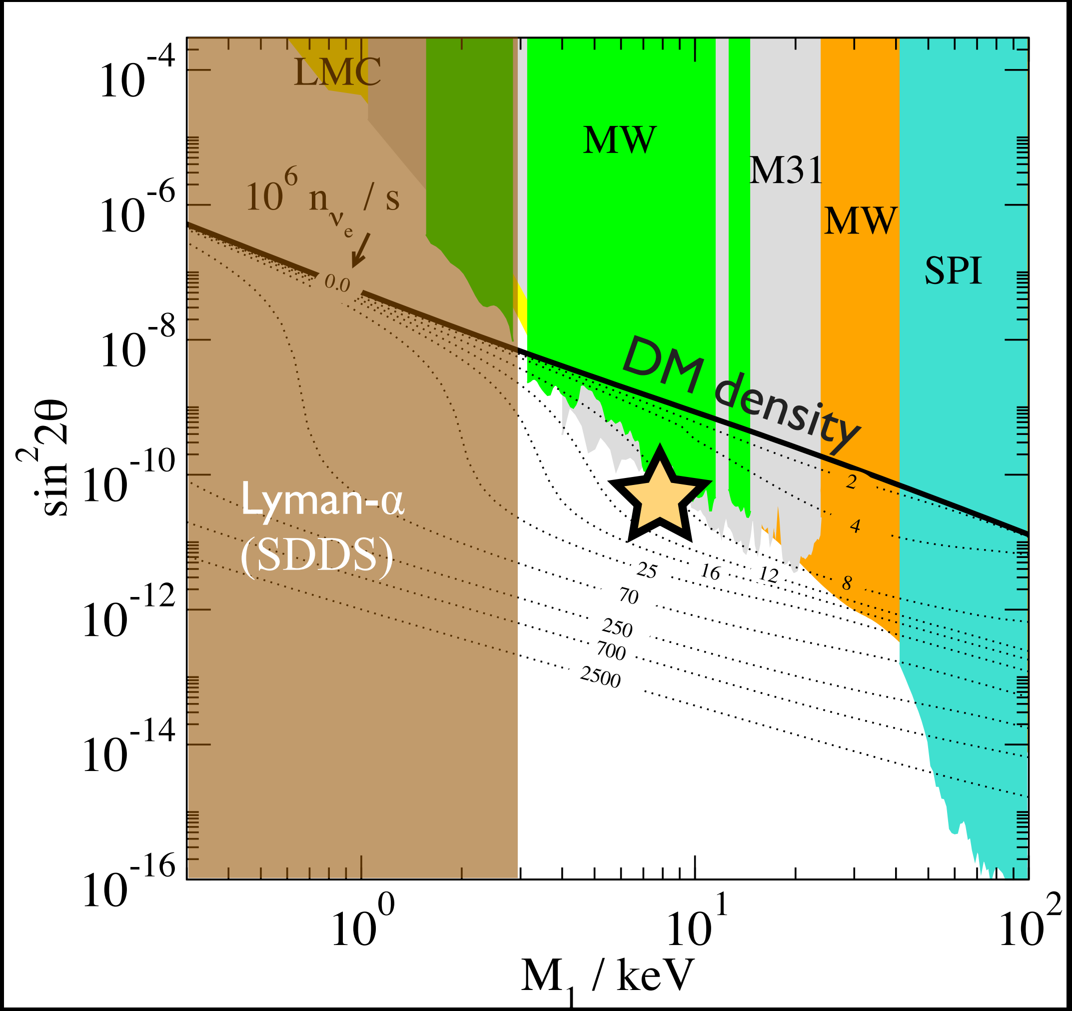


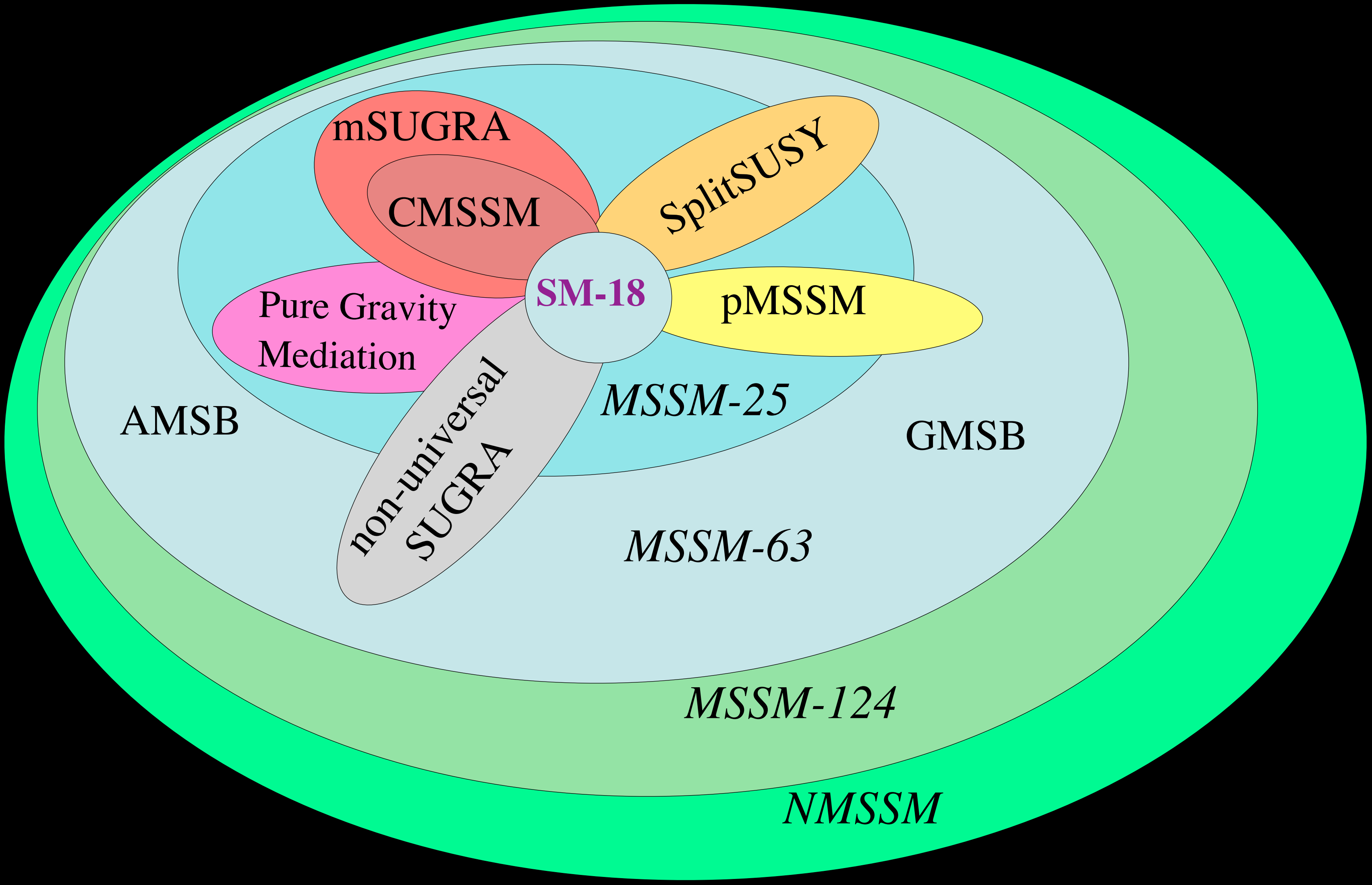
νMSM

Laine, Shaposhnikov 2008

Supersymmetric dark matter

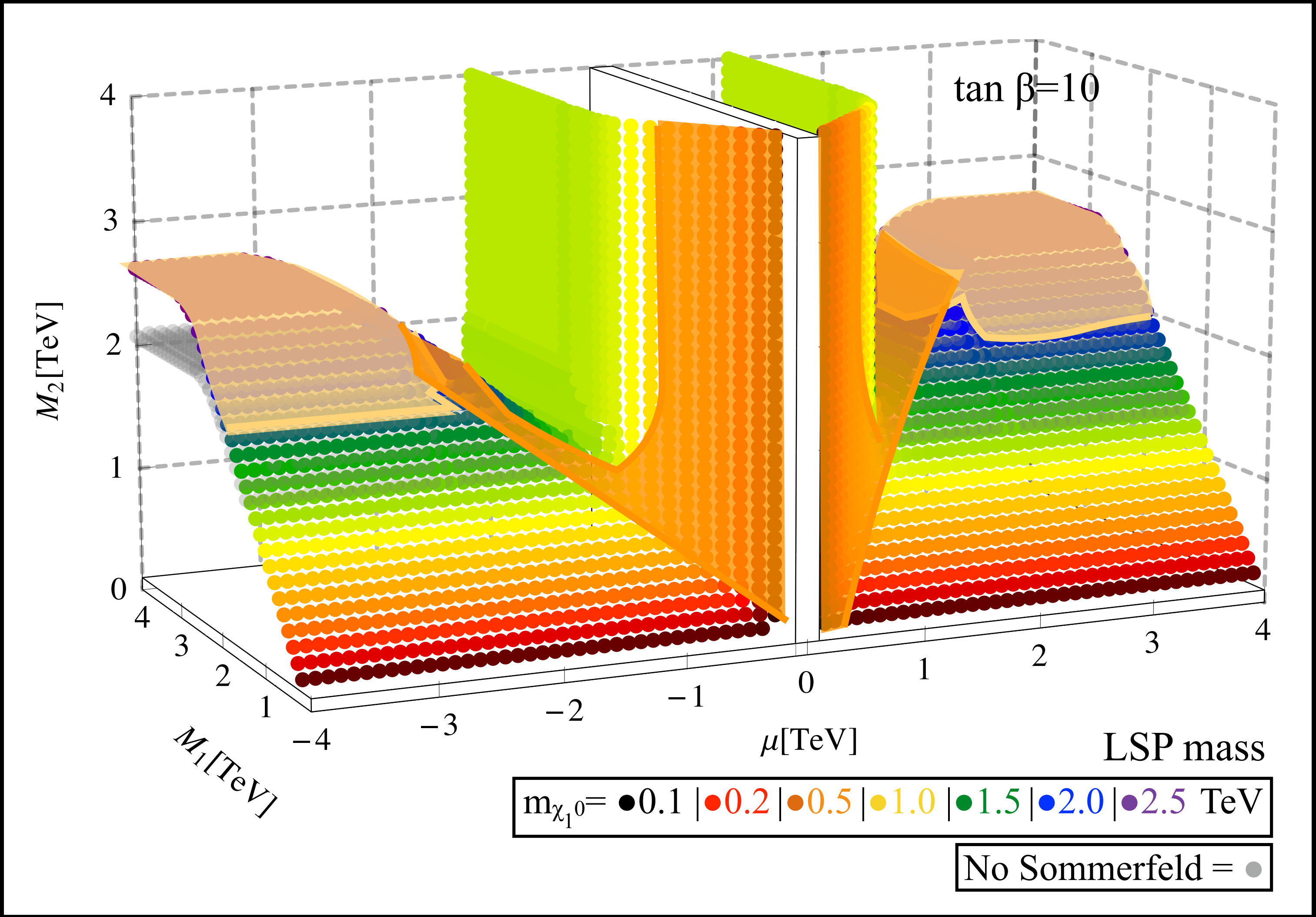
The CMSSM* is in dire straights, but there are many supersymmetric models

**Constrained Minimal Supersymmetric Standard Model*



Supersymmetric 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 ($S \to -S$)

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

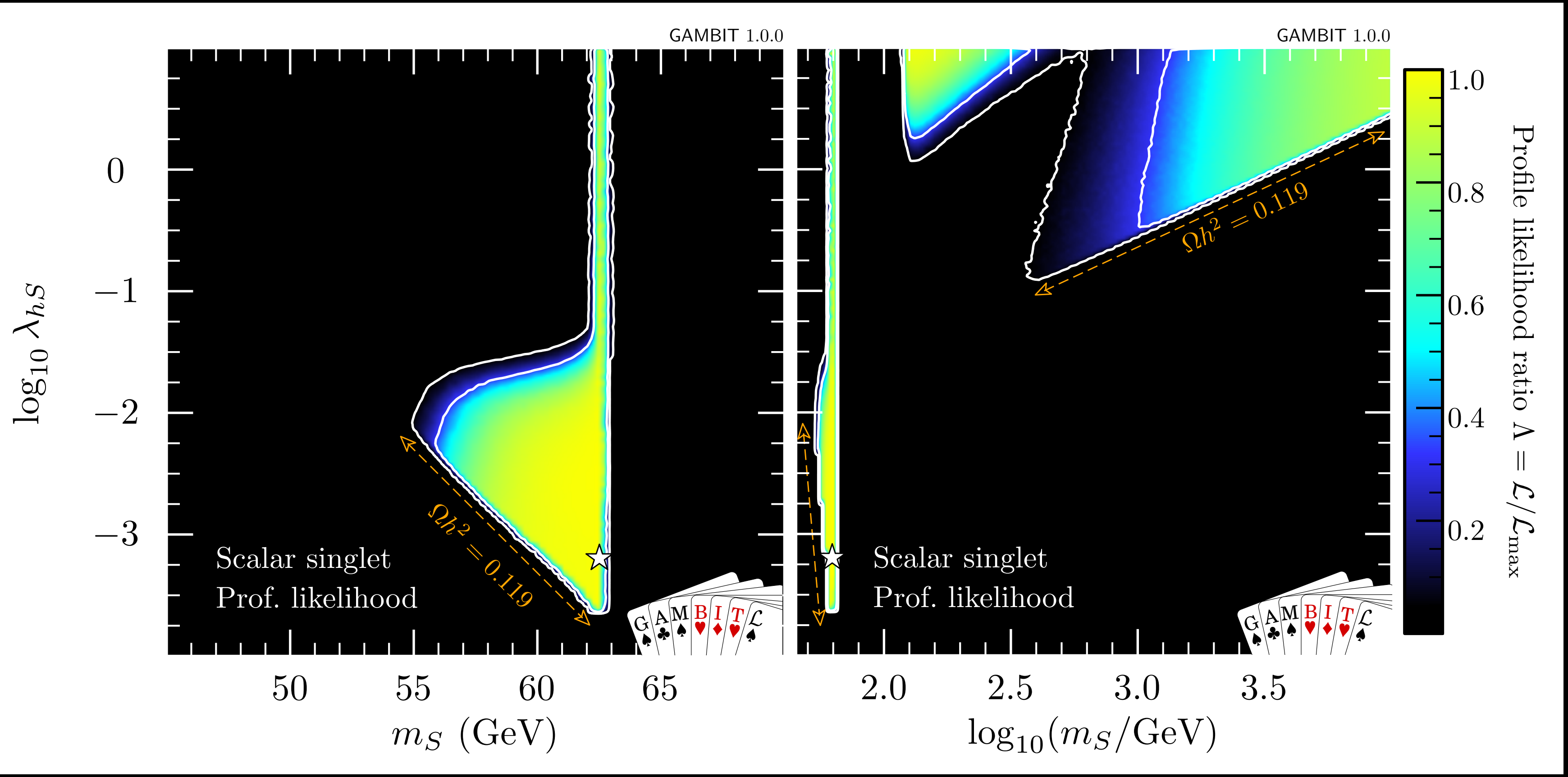
Silveira, Zee 1985; Andreas, Hambye, Tytgat 2008; Djouadi, Falkowksi, Mambrini, Quevillon 2012; Cline, Scott, Kainulainen, Weniger 2013; Hamada, Kawana 2015; Feng, Profumo, Ubaldi 2015; Athron et al 2017; etc

"Scalar phantom" is the original 1985 name

Scalar phantom dark matter

Global likelihood fits including collider, direct, indirect searches and cosmology.

The discovery of the Higgs boson at the LHC places the strongest constraints.



Athron et al 2017

Anapole dark matter

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

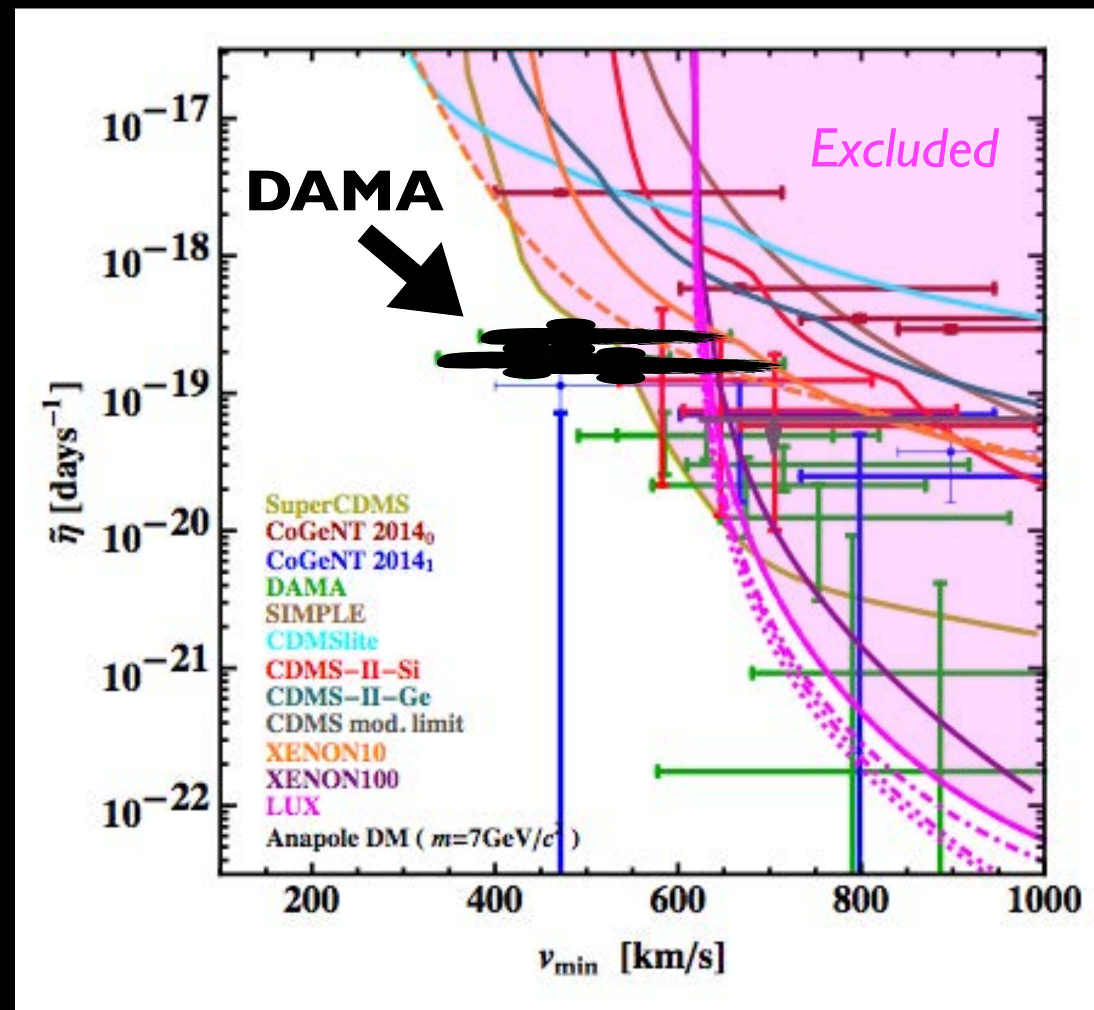
First measured experimentally in Cesium atoms *Wood et al 1997*

Anapole dark matter

spin-1/2 Majorana fermion

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

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



The DAMA modulation is compatible with other searches for some WIMP velocity distribution

Del Nobile, Gelmini, Gondolo, Huh 2014

Other candidates

Self-interacting dark matter

Proposed as solution to 'cusp vs core' and 'too big to fail' puzzles in collisionless dark matter simulations. *Spergel, Steinhardt 1999*

Tested on cluster and galaxy collisions

$\sigma/m < 0.7\ \mathrm{cm^2/g}$ mass loss in Bullet Cluster *Randall et al 2008*

$\sigma/m < 0.47\ \mathrm{cm^2/g}$ 72 cluster collisions *Harvey et al 2015*

$\sigma/m = (1.7 \pm 0.7) \times 10^{-4}\ \mathrm{cm^2/g}$ in Abell 3827 (?) *Massey et al 2015*

Several particle models exist

Light mediator *Feng, Kaplinghat, Yu; Buckley, Fox 2009; Tulin, Yu, Zurek 2013*

Hidden vector dark matter (HVDM) *Hambye 2008*

Dark matter is 3 gauge bosons of a hidden SU(2) group spontaneously broken by a hidden Higgs doublet coupled to the SM Higgs.
Allowed in some regimes *Bernal et al 2015*

$1\ \mathrm{barn/GeV} = 0.6\ \mathrm{cm^2/g}$

Asymmetric dark matter

- Dark matter in a hidden mirror sector (“dark sector”)
- Dark matter asymmetry similar to baryon asymmetry, generated by similar mechanisms

$$n_\chi \approx n_\mathrm{p}$$

- Dark matter mass is a few times the proton mass

$$\Omega_\chi \approx \frac{m_\chi}{m_p}\,\Omega_\mathrm{p} \approx (\mathrm{a\ few})\,\Omega_\mathrm{p}$$

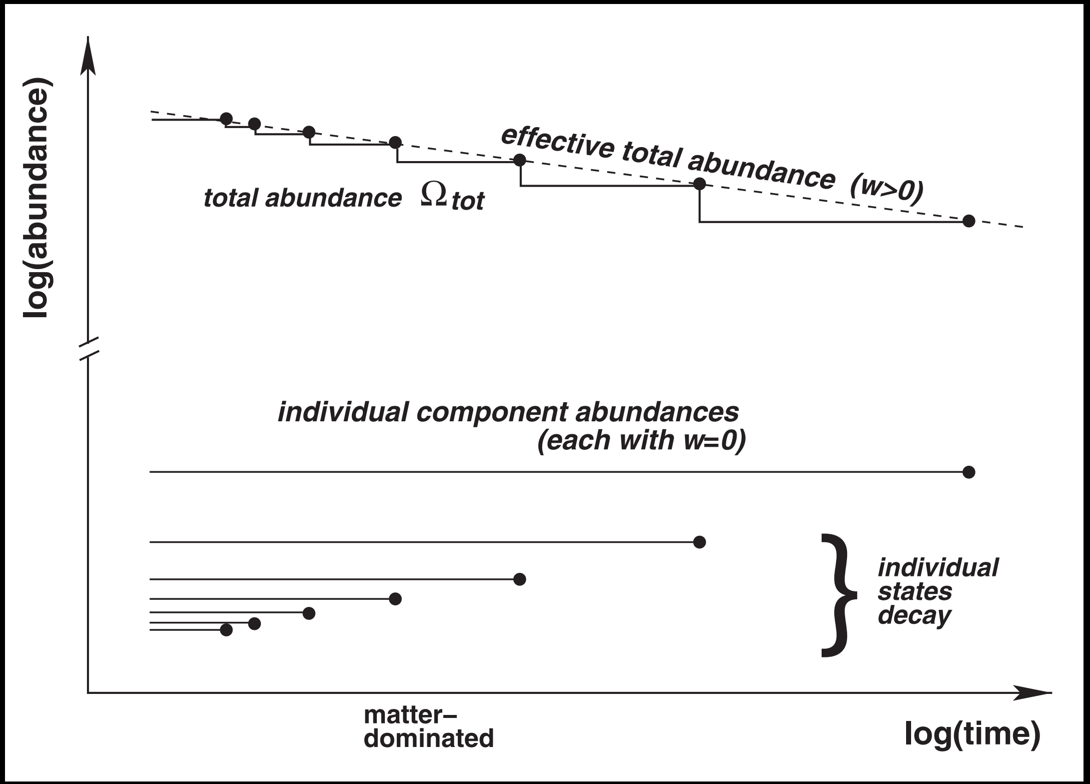
Nussinov 1985; Gelmini, Hall, Lin 1986; Hooper, March-Russell, West 2008; Kouvaris 2008; Kaplan, Luty, Zurek 2009; Hall, March-Russell, West 2010; Buckley, Randall 2010; Dutta, Kumar 2011; Cohen, Phalen, Pierce, Zurek 2010; Falkowski, Ruderman, Volansky 2011; Frandsen, Sarkar, Schmidt-Hoberg 2011; etc.

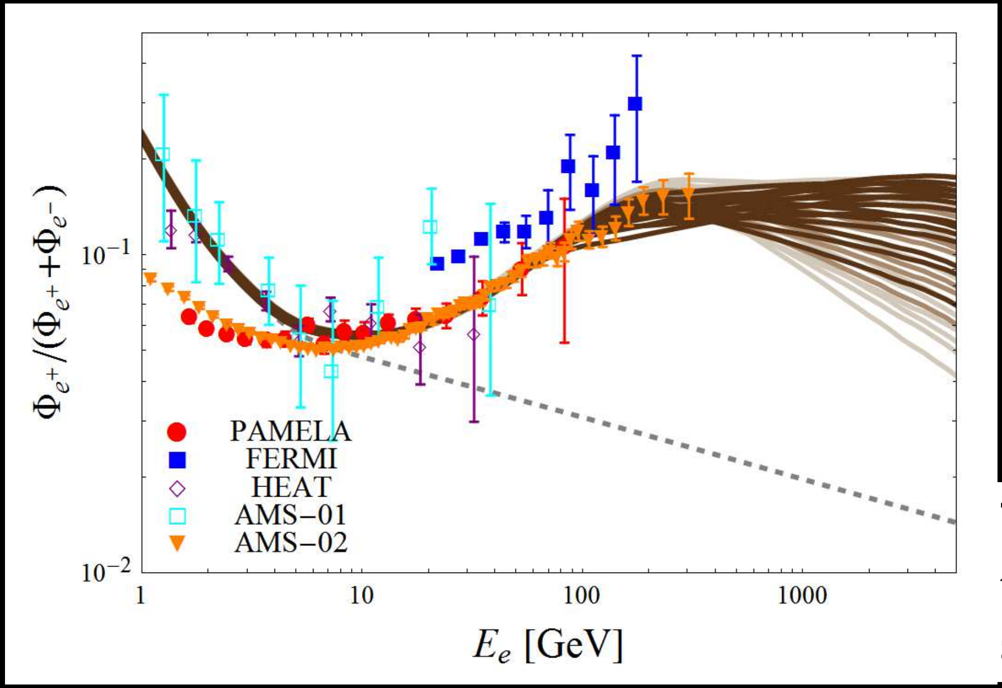
Dynamical dark matter

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

A vast ensemble of fields decaying from one to another

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





Phenomenology obtained through scaling laws

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

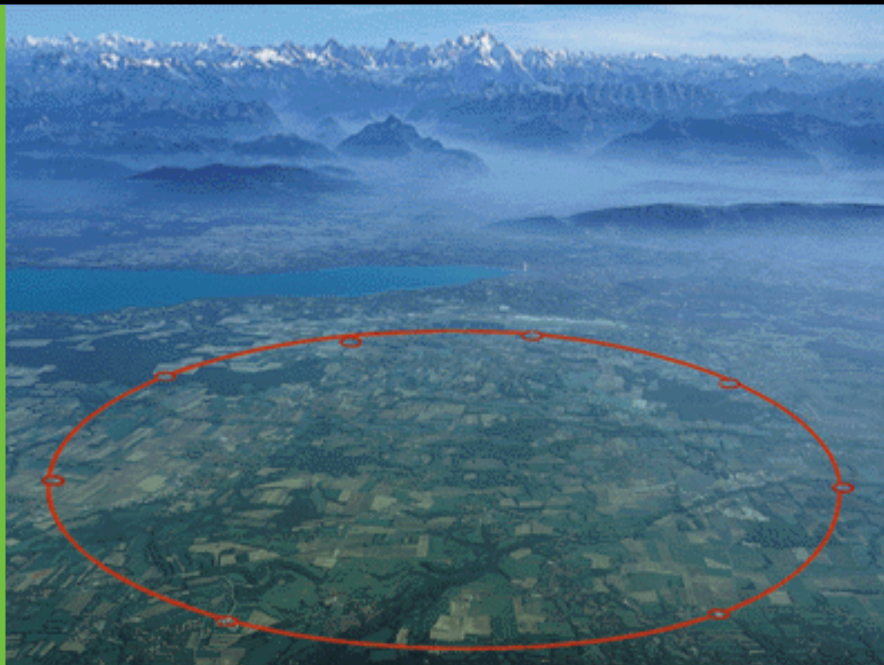
$$\rho_n \sim m_n^\alpha, \; \tau_n \sim m_n^{-\gamma}$$

This model can fit the positron excess and has no cut off.

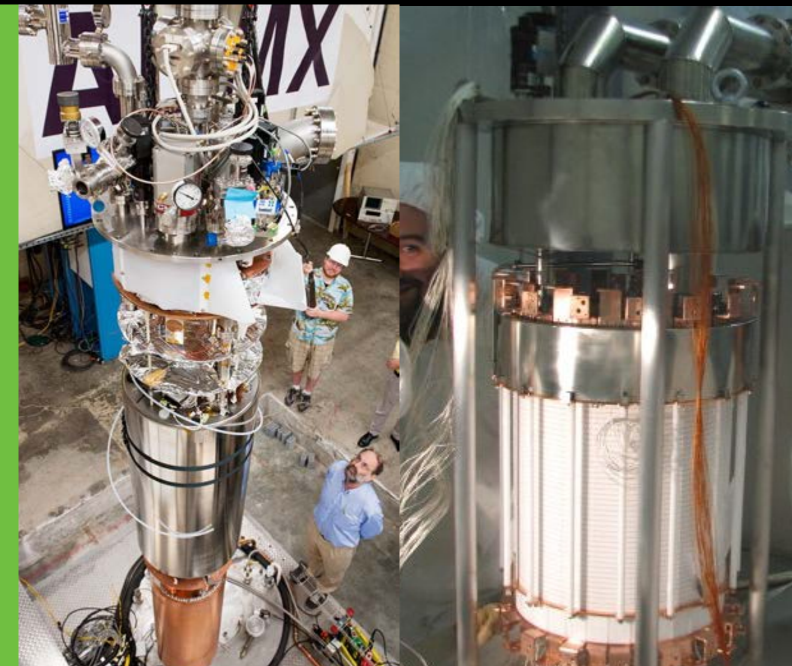
Evidence for nonbaryonic cold dark matter?

Searches for particle dark matter

Collider



Direct



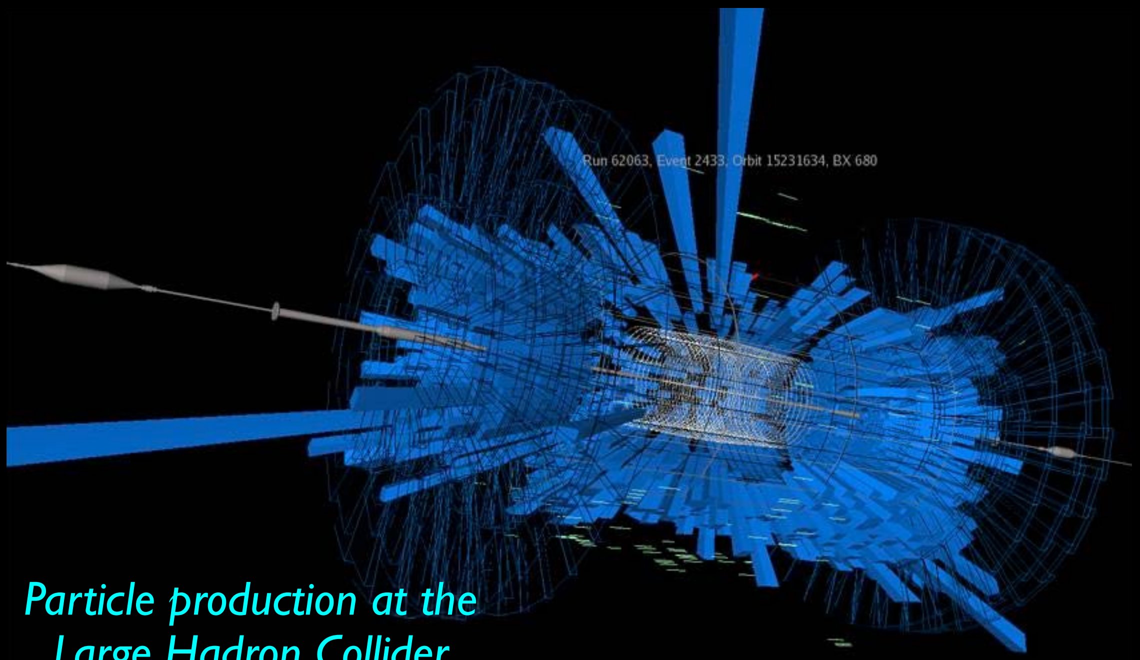
Indirect

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, ...

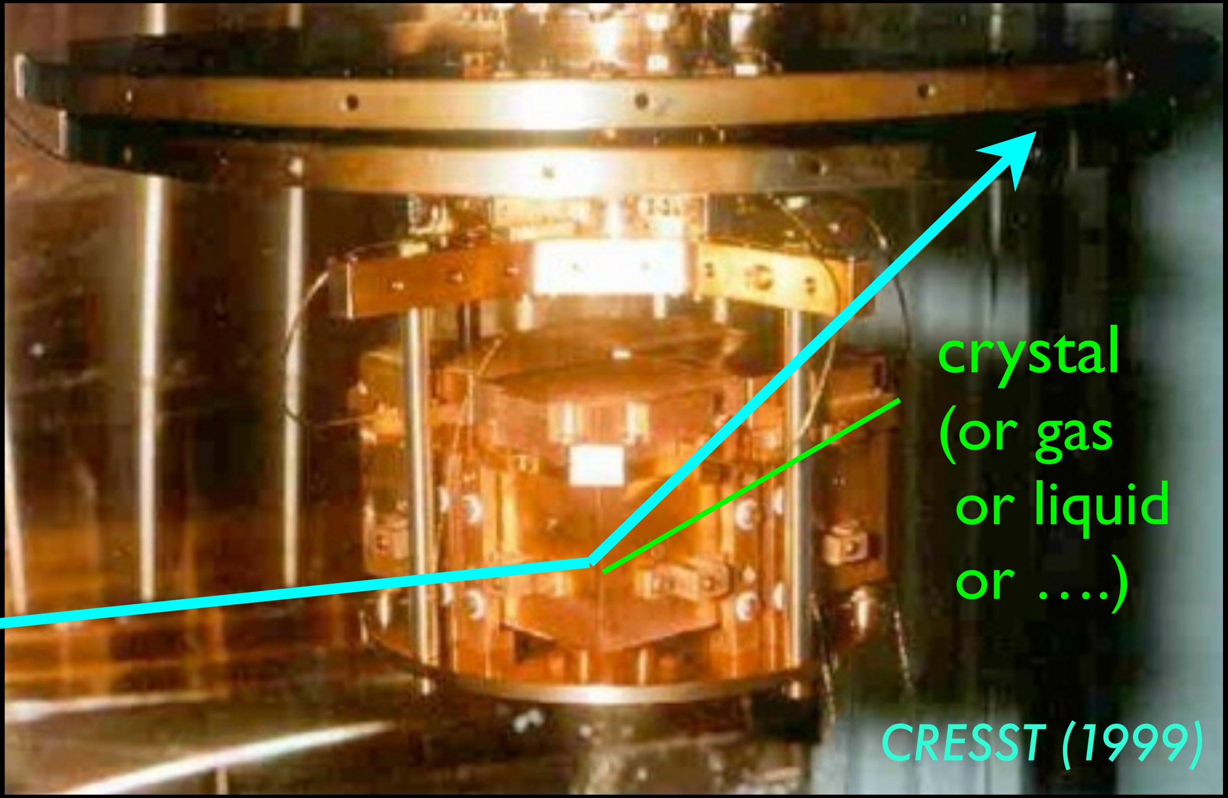
Searches for particle dark matter: direct

Dark matter particles that arrive on Earth
interact with a laboratory detector

WIMP scattering off nuclei or electrons

Goodman, Witten 1985

Dark matter particle



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

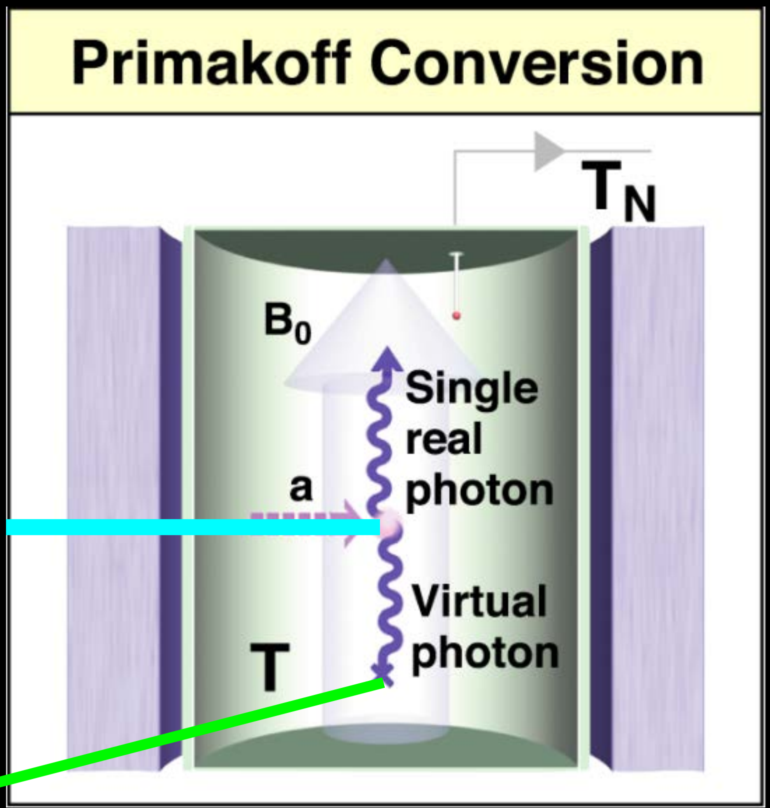
Dark matter particles that arrive on Earth
interact with a laboratory detector

Axion conversion to photons

Sikivie
1983

Dark
matter
particle

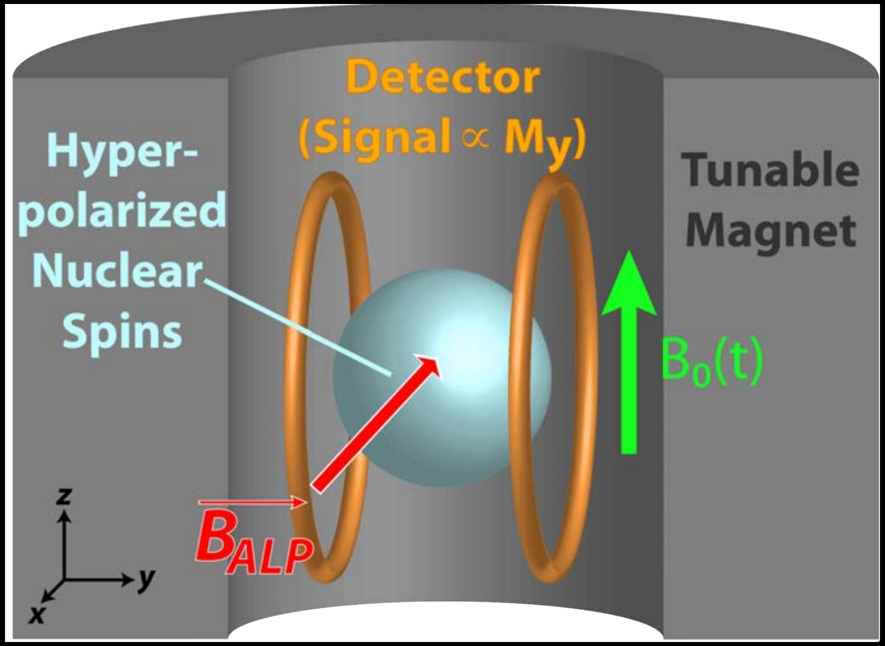
Magnetic
field



Resonating cavity *ADMX*

ADMX

Coherent axion field acts
as electromagnetic current



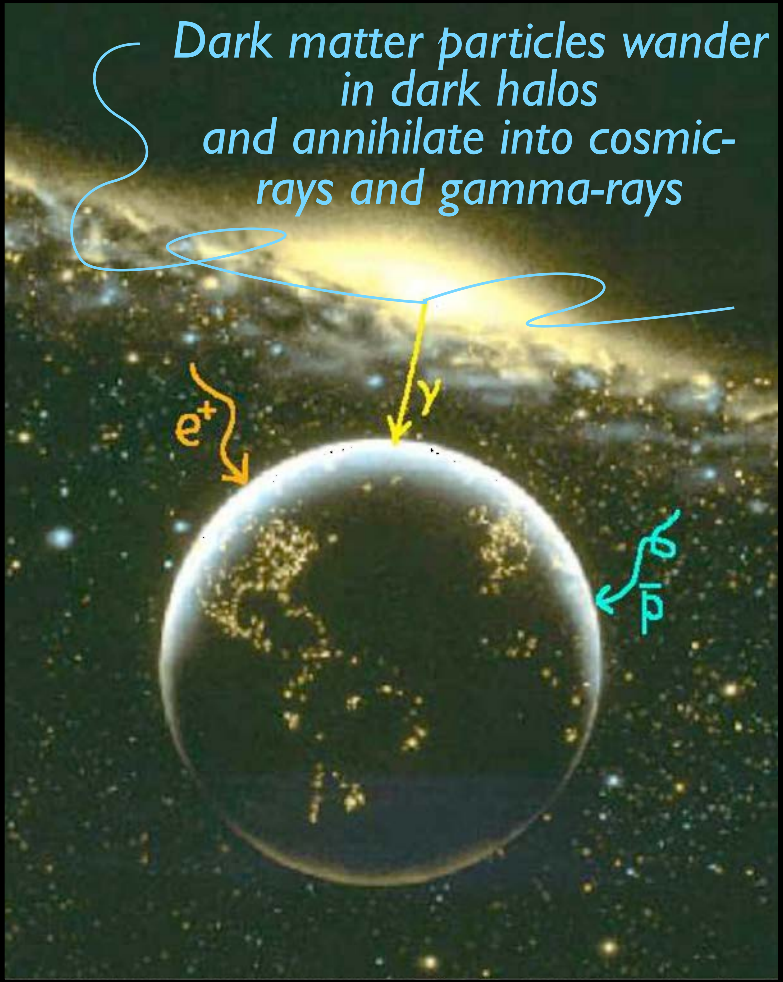
Polarized target *CASPEr*

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

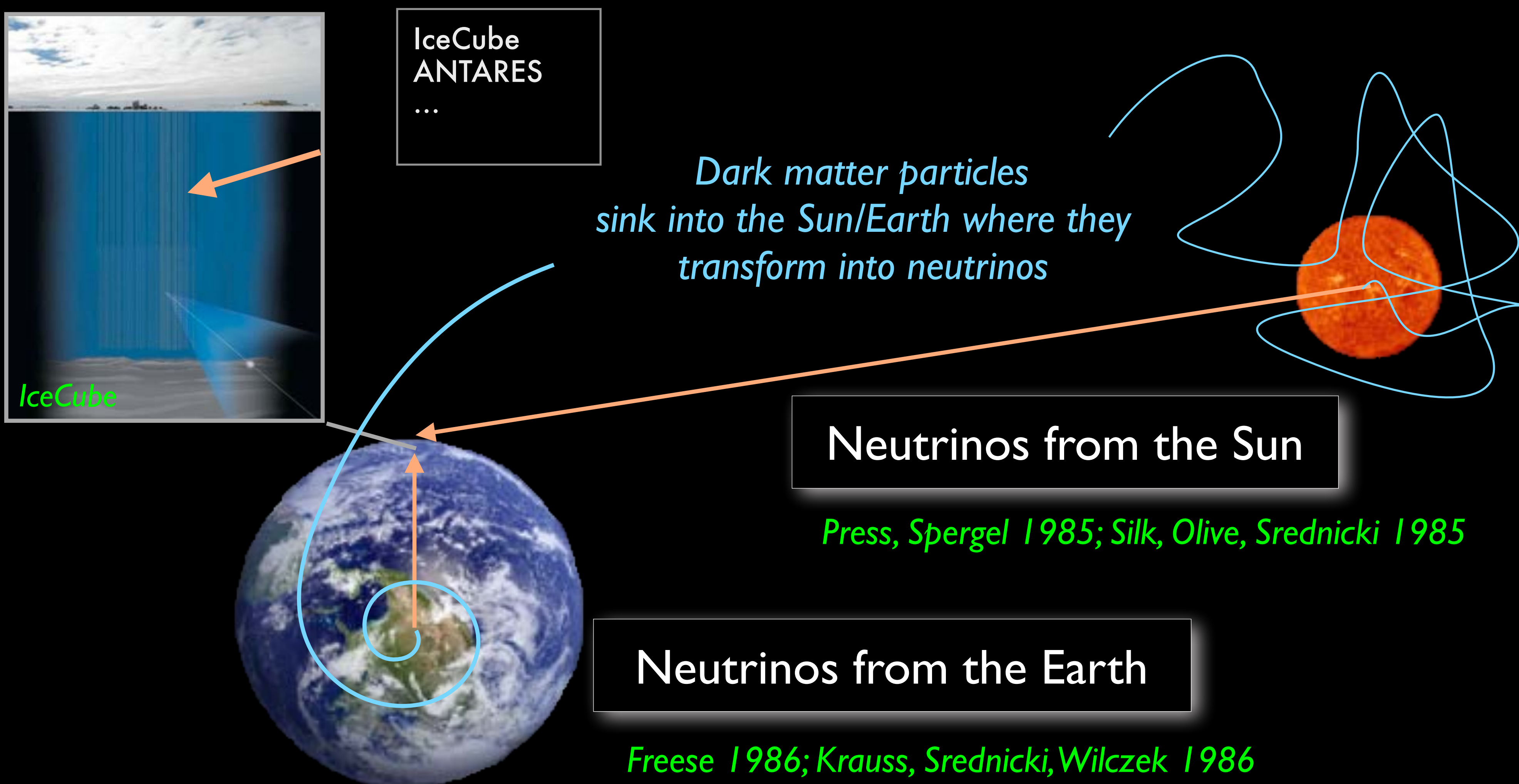


cosmic-rays
PAMELA
AMS
...

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

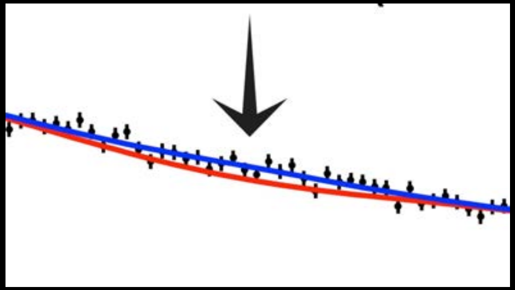


Signals from dark matter?

GeV γ-rays

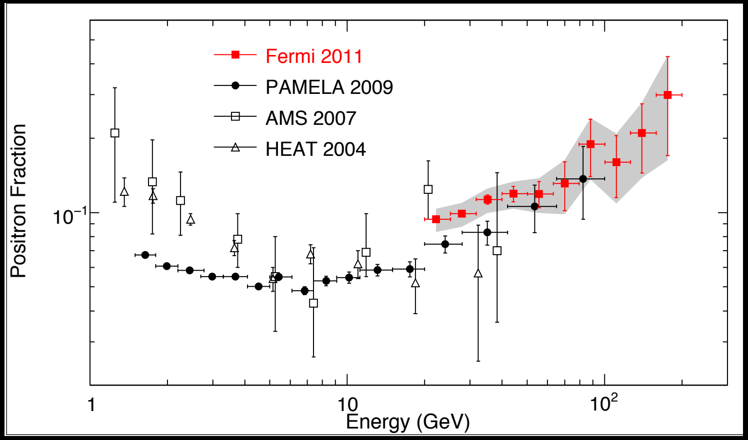
Hooper et al 2009-14

3.5 keV X-ray line



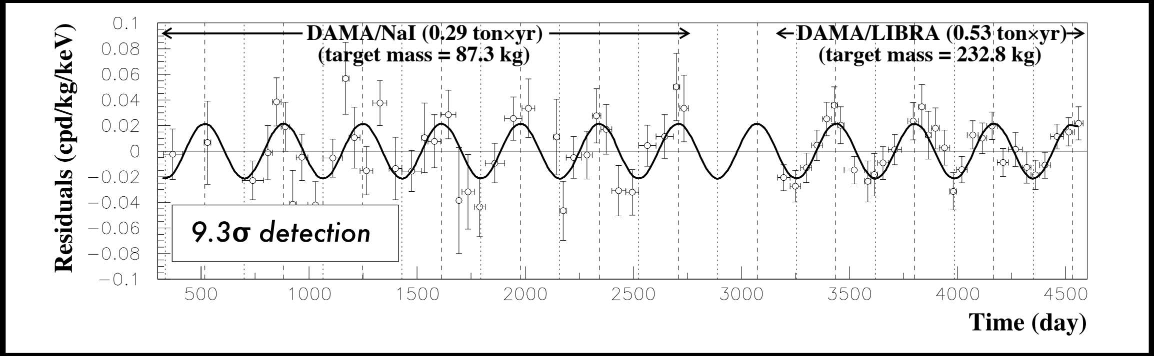
Bulbul et al 2014

Cosmic-ray positrons



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

Annual modulation in direct detection



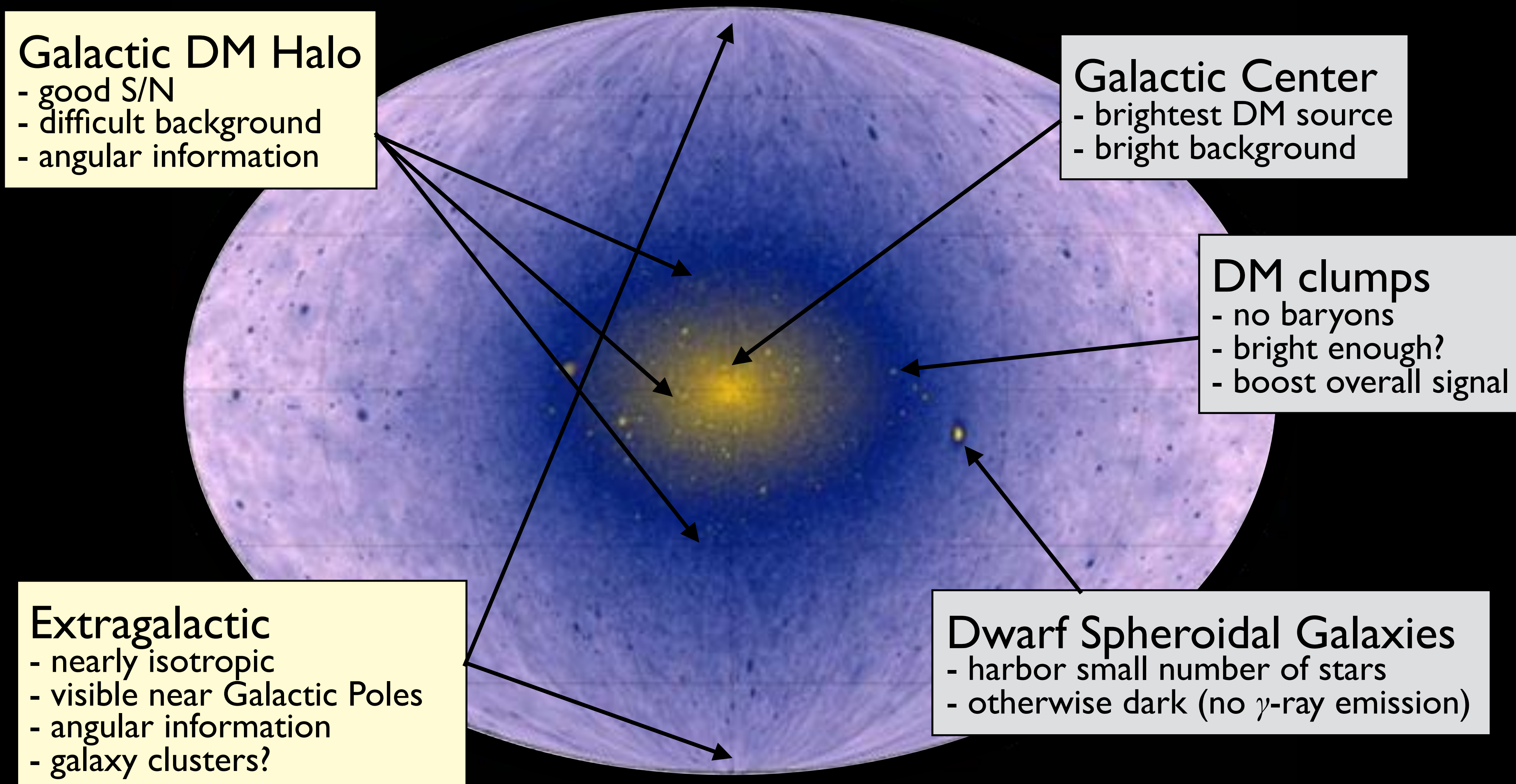
Bernabei et al 1997-now

Gamma-ray GeV excess

Gamma-rays from WIMP annihilation

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

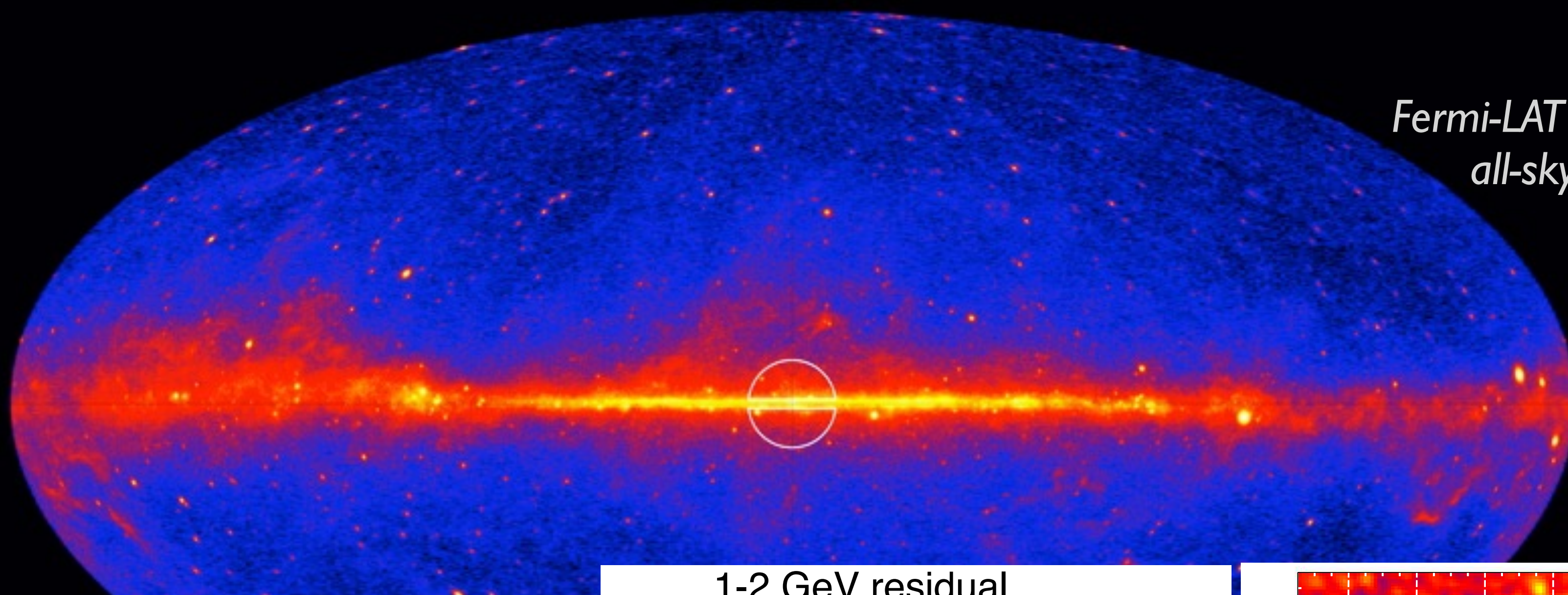
J factor



Kuhlen, Diemand, Madau 2007

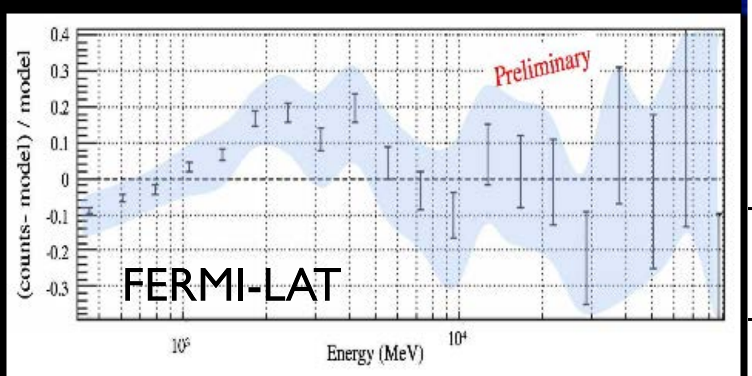
1 GeV γ-ray excess at Galactic Center

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

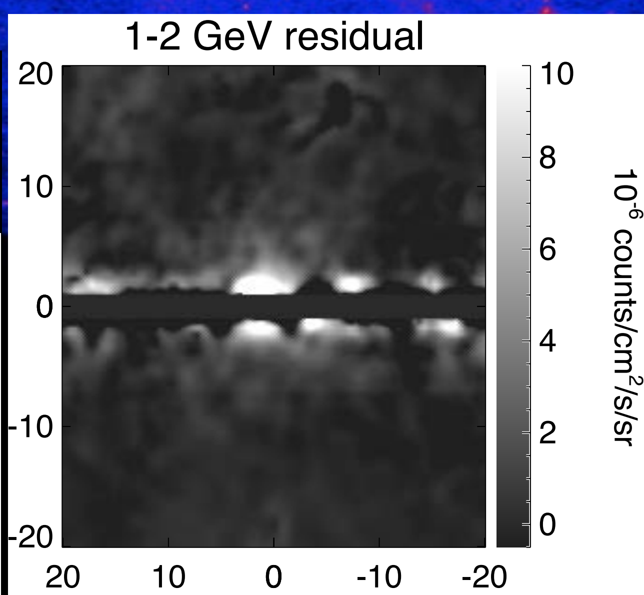


Fermi-LAT all-sky map

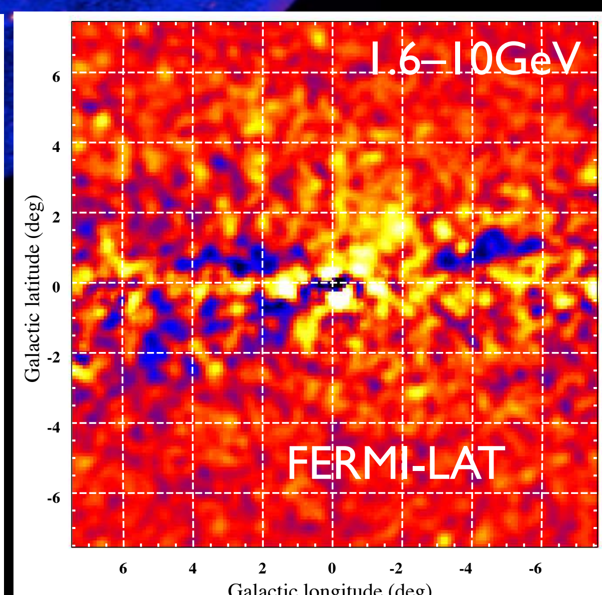
Fit model of known emission.
Find residual.



Vitale, Morselli et al 2009



Daylan et al 2014



Ajello et al 2015

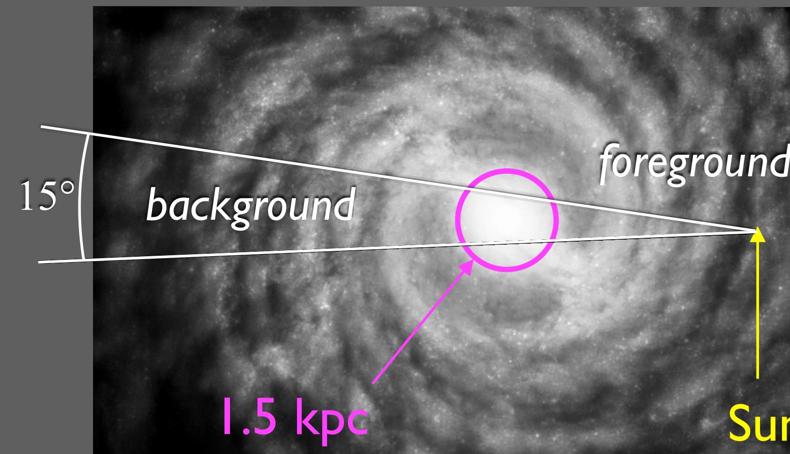
1 GeV γ-ray excess at Galactic Center

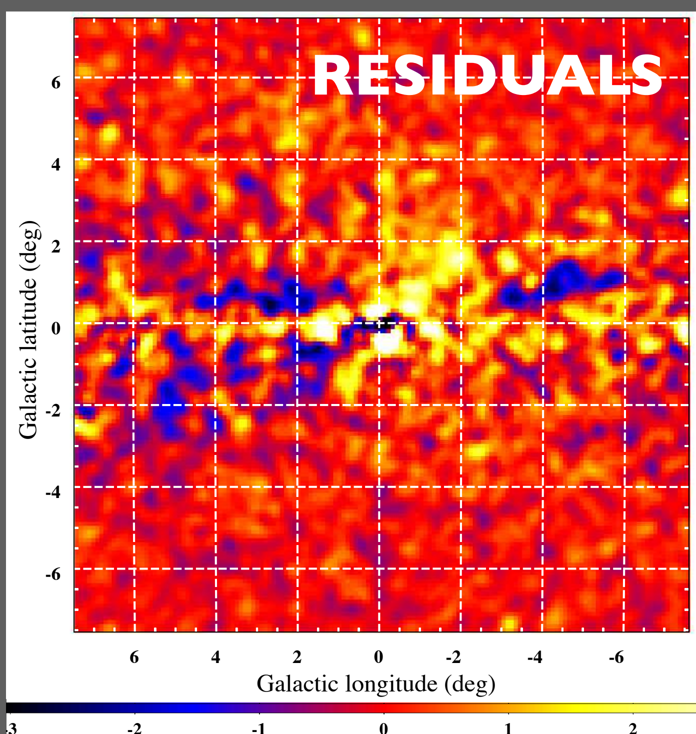
Goodenough, Hooper; Vitale, Morselli et al 2009; Hooper, Goodenough; Boyarsky, Malyshev, Ruchayskiy; Hooper, Linden 2011; Abazajian, Kaplinghat 2012; Gordon, Macias 2013; Abazajian, Canac, Horiuchi

The official Fermi-LAT analysis

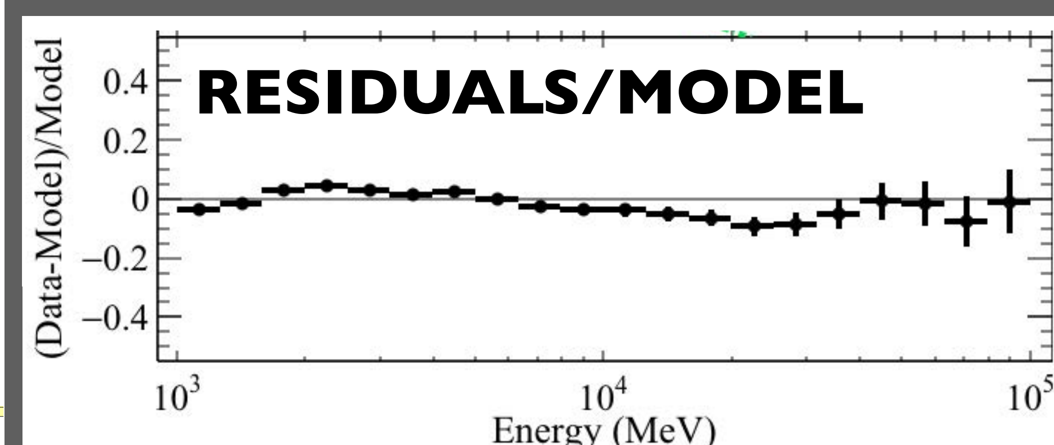
Ajello et al 2016

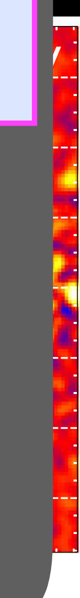
- *Four foreground+background cosmic-ray models:*
  - *Intensity-scaled or index-scaled pulsars sources*
  - *Intensity-scaled or index-scaled OB-stars sources*
- *Point sources*





An extended residual is present. A precise physical interpretation of its origin is premature.

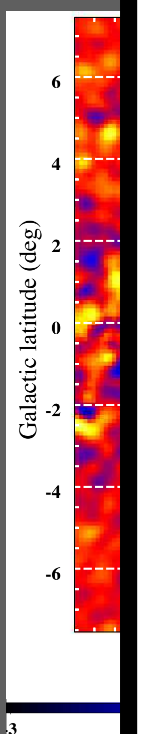


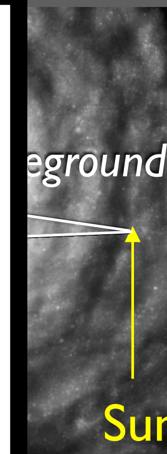


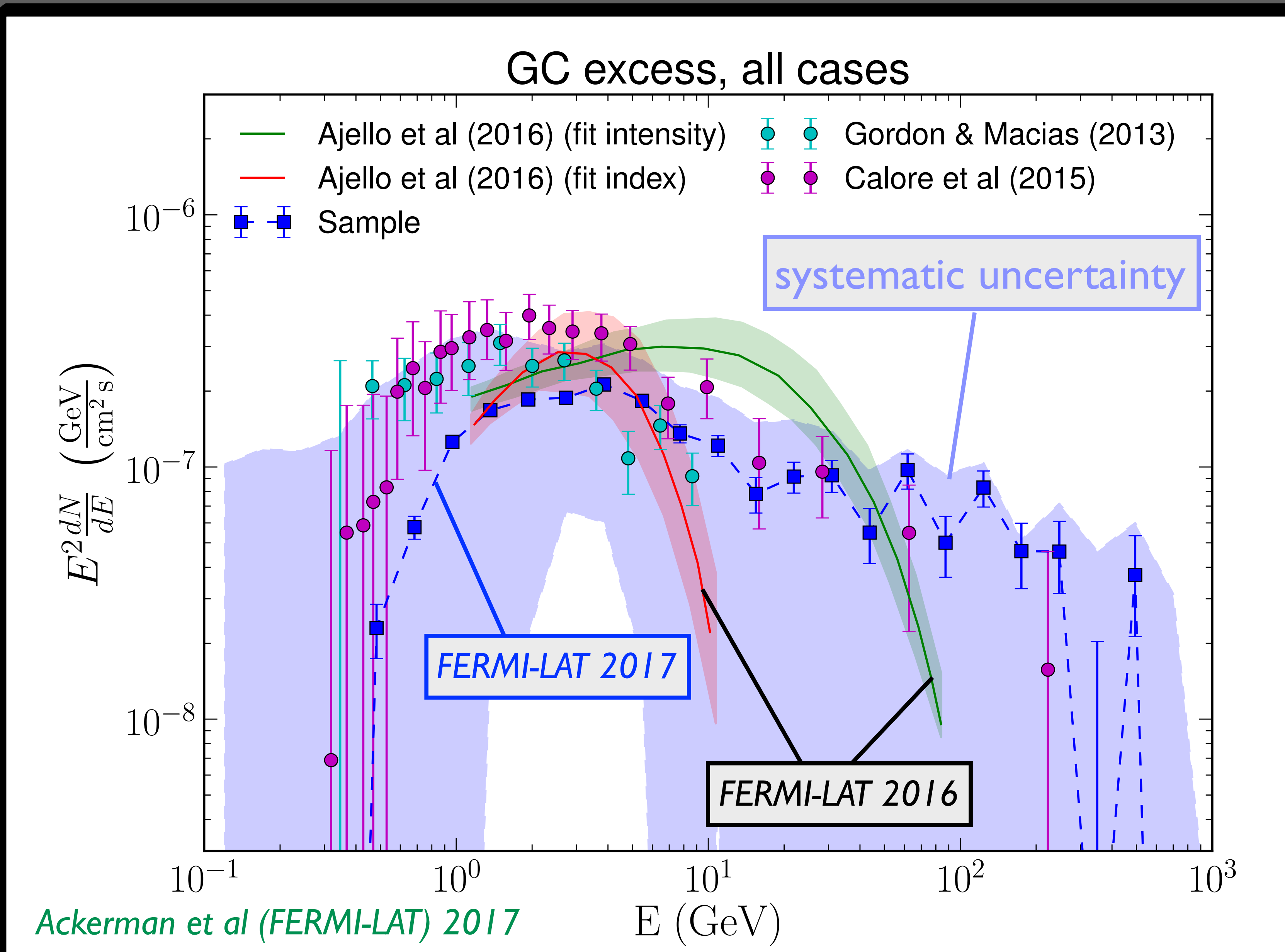
Vitale, Morselli et al 2009 *Daylan et al 2014* *Ajello et al 2015*

1 GeV γ-ray excess at Galactic Center

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







Vitale, Morselli et al 2009 — Daylan et al 2014 — Ajello et al 2015

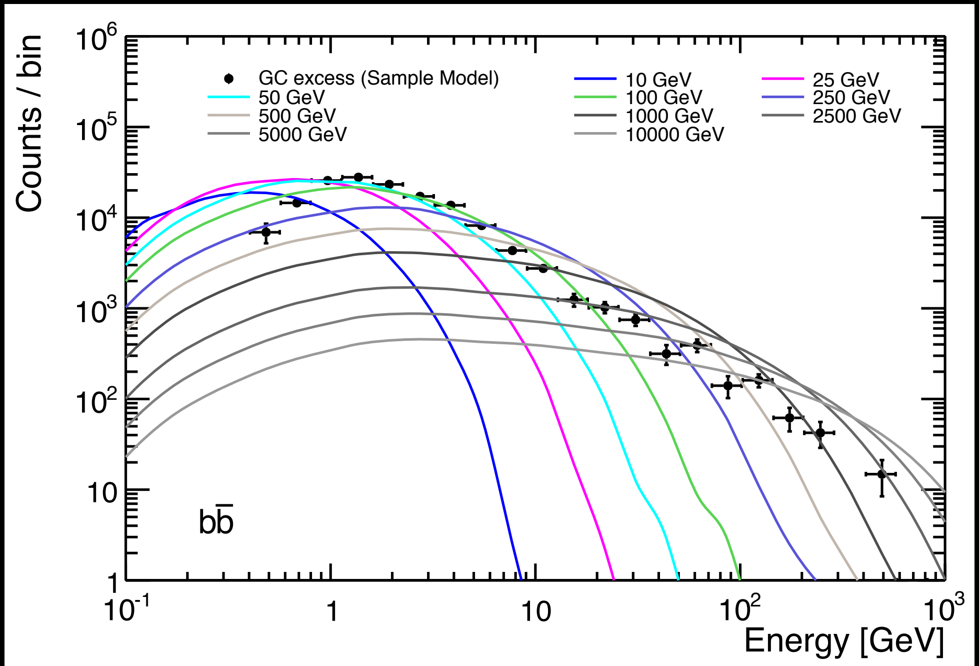
1 GeV γ-ray excess at Galactic Center

- Dark matter annihilation

Goodenough, Hooper 2009; 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

Ackerman et al (FERMI-LAT) 2017



- Millisecond pulsars

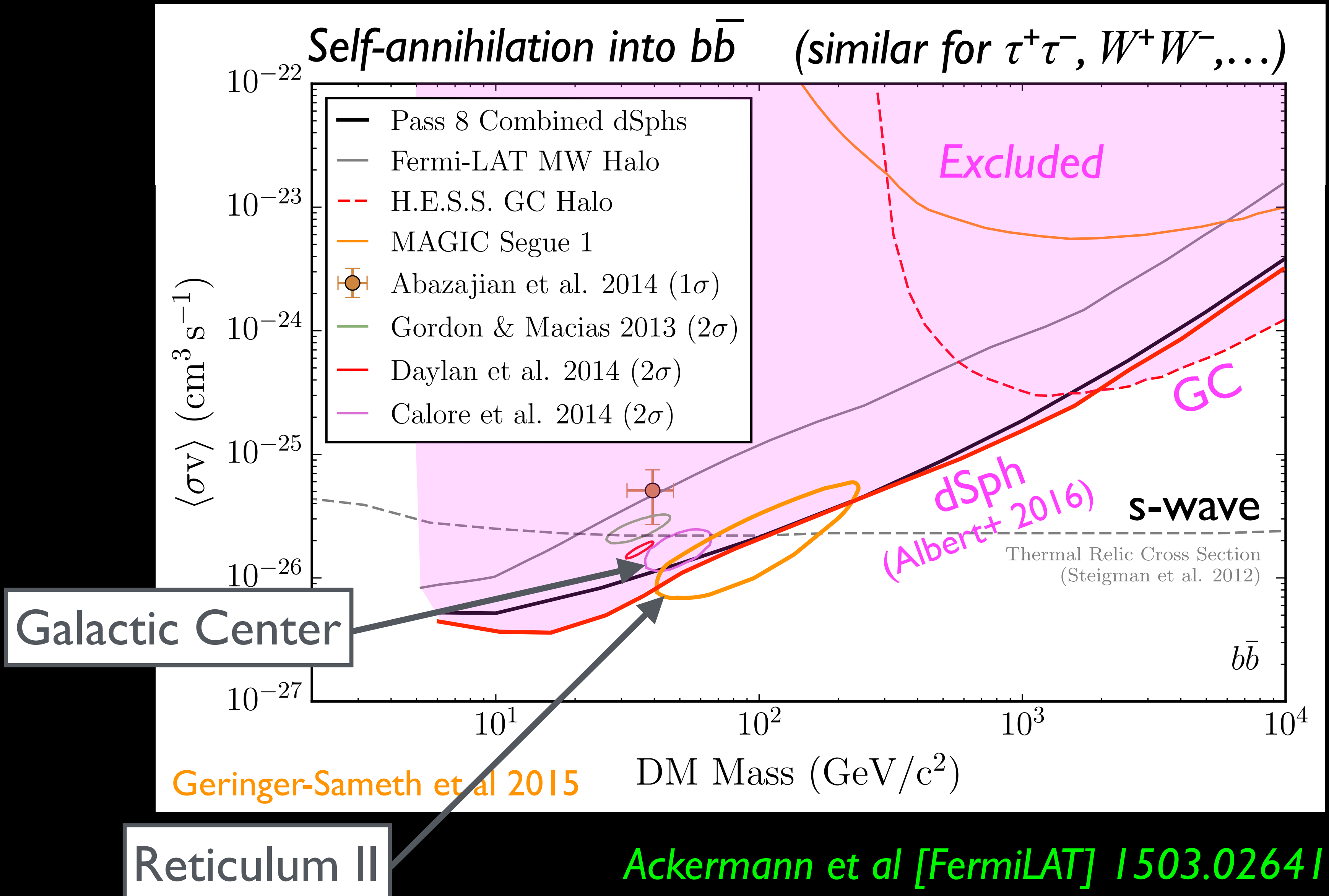
Wang et al 2005; Abazajian 2011; Gordon, Macias 2013; Hooper et al 2013; Yuan, Zhang 2014; Calore et al 2014; Cholis et al 2014; Petrovic et al 2014; Lee et al 2014; Bartels et al 2014

Favored by wavelet analysis and nonpoissonian point spread function

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

Gamma-rays from dark matter

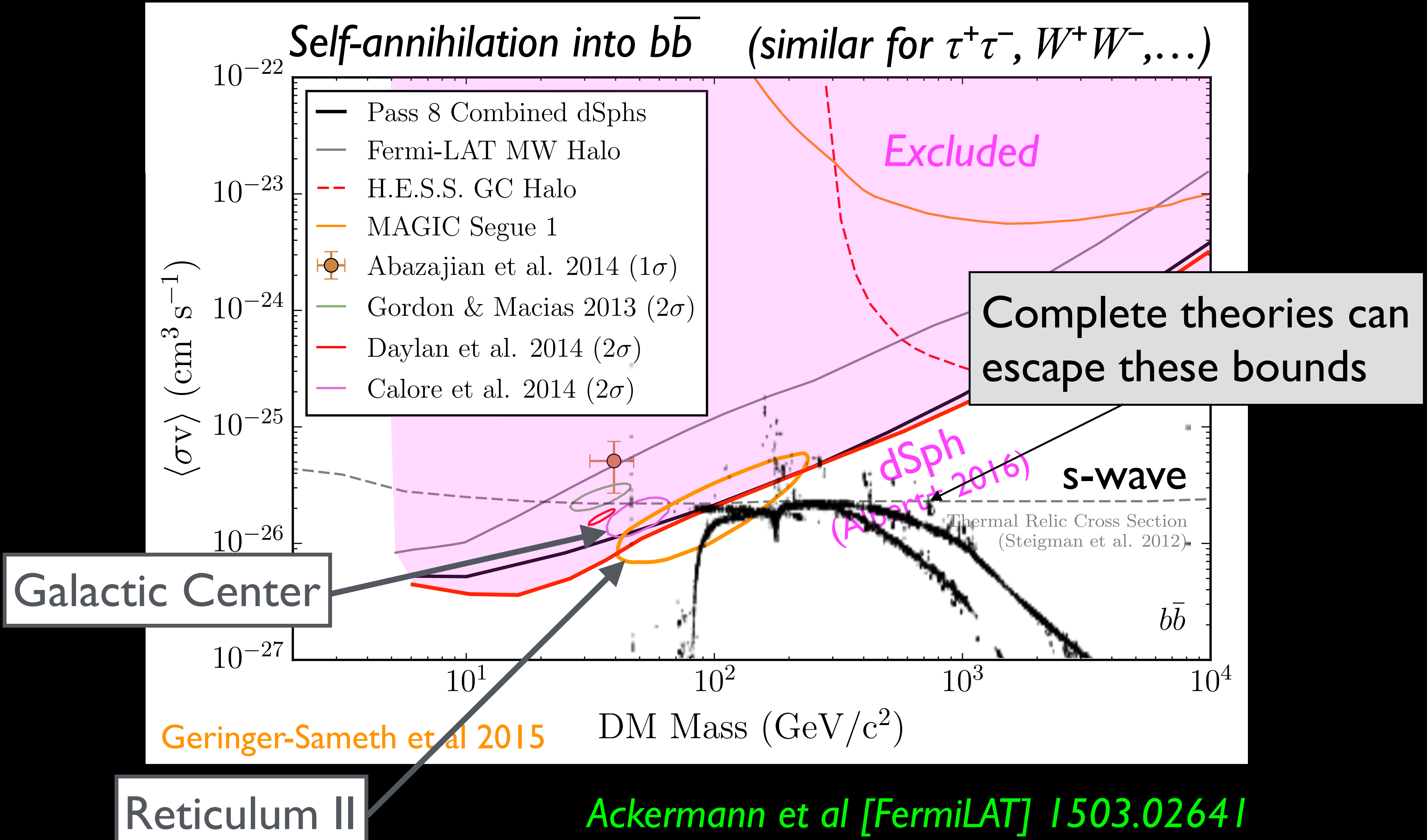
Upper limits on the WIMP annihilation cross section from dwarf spheroidal galaxies and Galactic Center



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



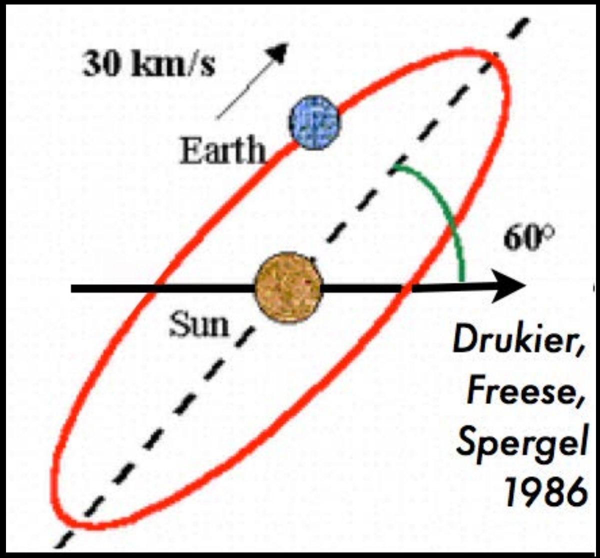
Ackermann et al [FermiLAT] 1503.02641

DAMA annual modulation

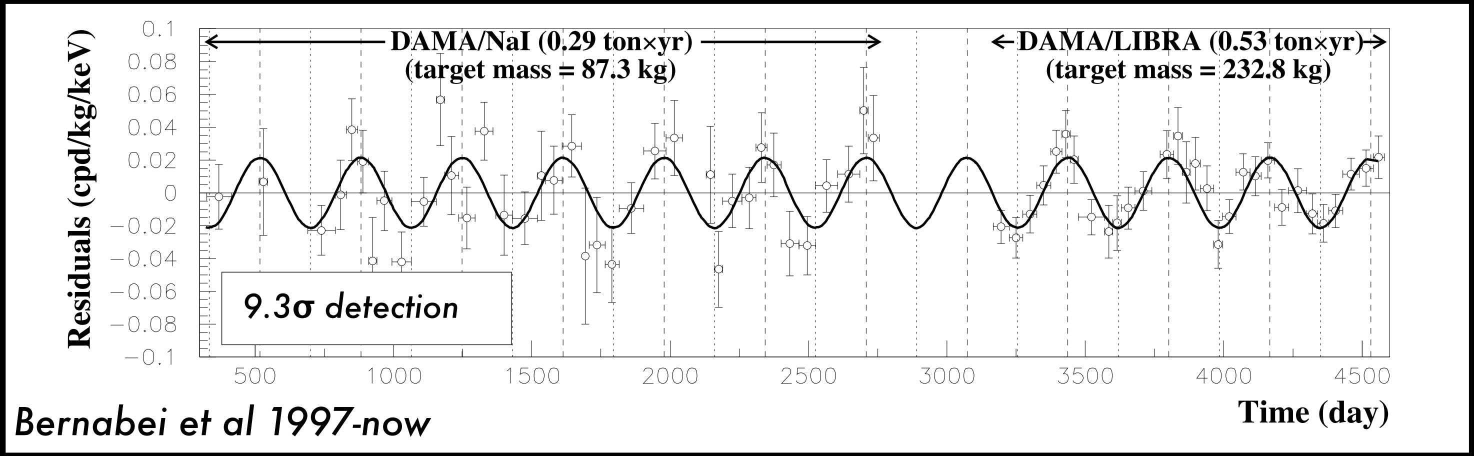
Annual modulation in direct detection

- 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

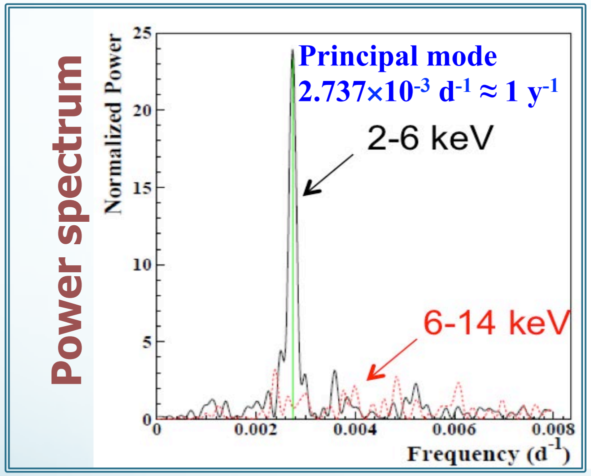
DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

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

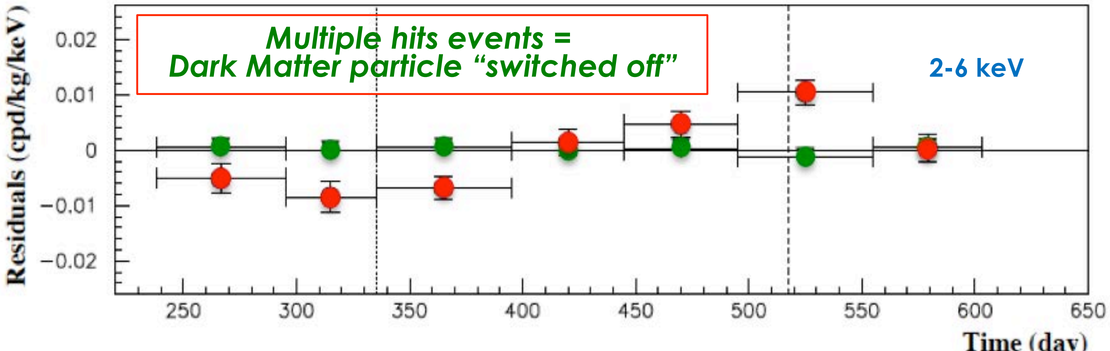
	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	0.0190 ±0.0020	0.996 ±0.0002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.0002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.0002	144 ± 7	9.3σ

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



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

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



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

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

Belli, IDM2014

DAMA annual modulation

Model Independent Annual Modulation Result

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

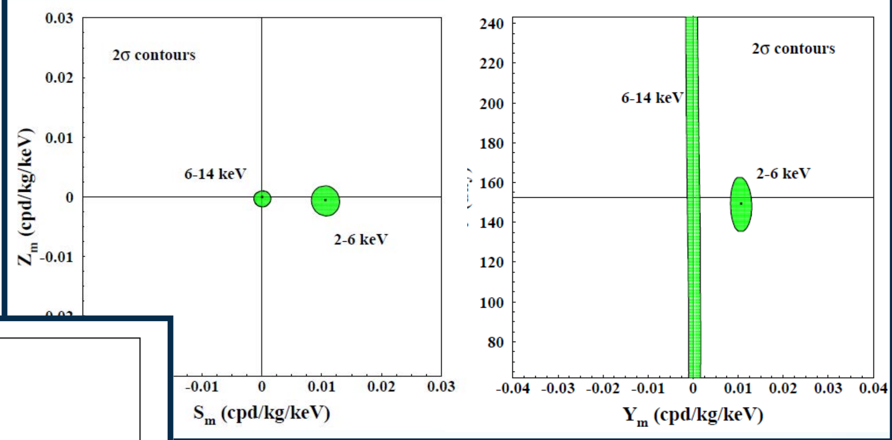
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

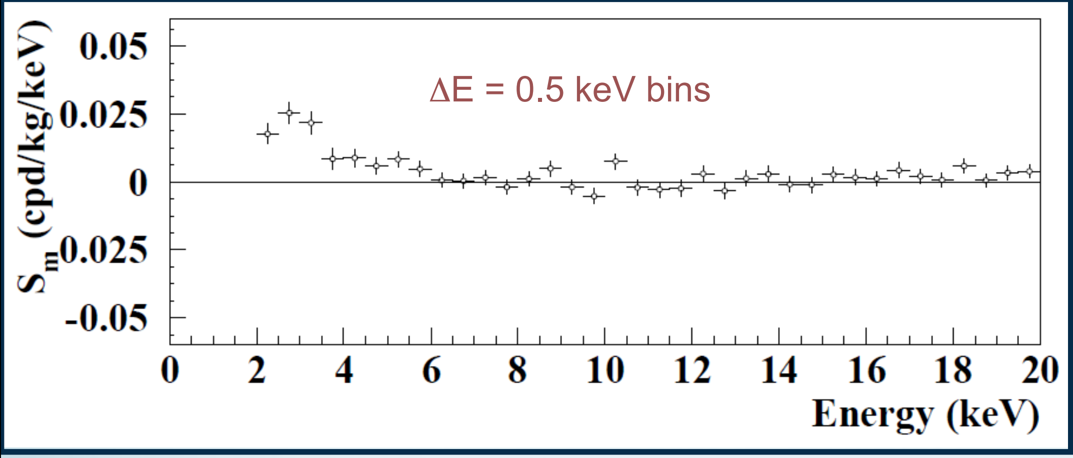
- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

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

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

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



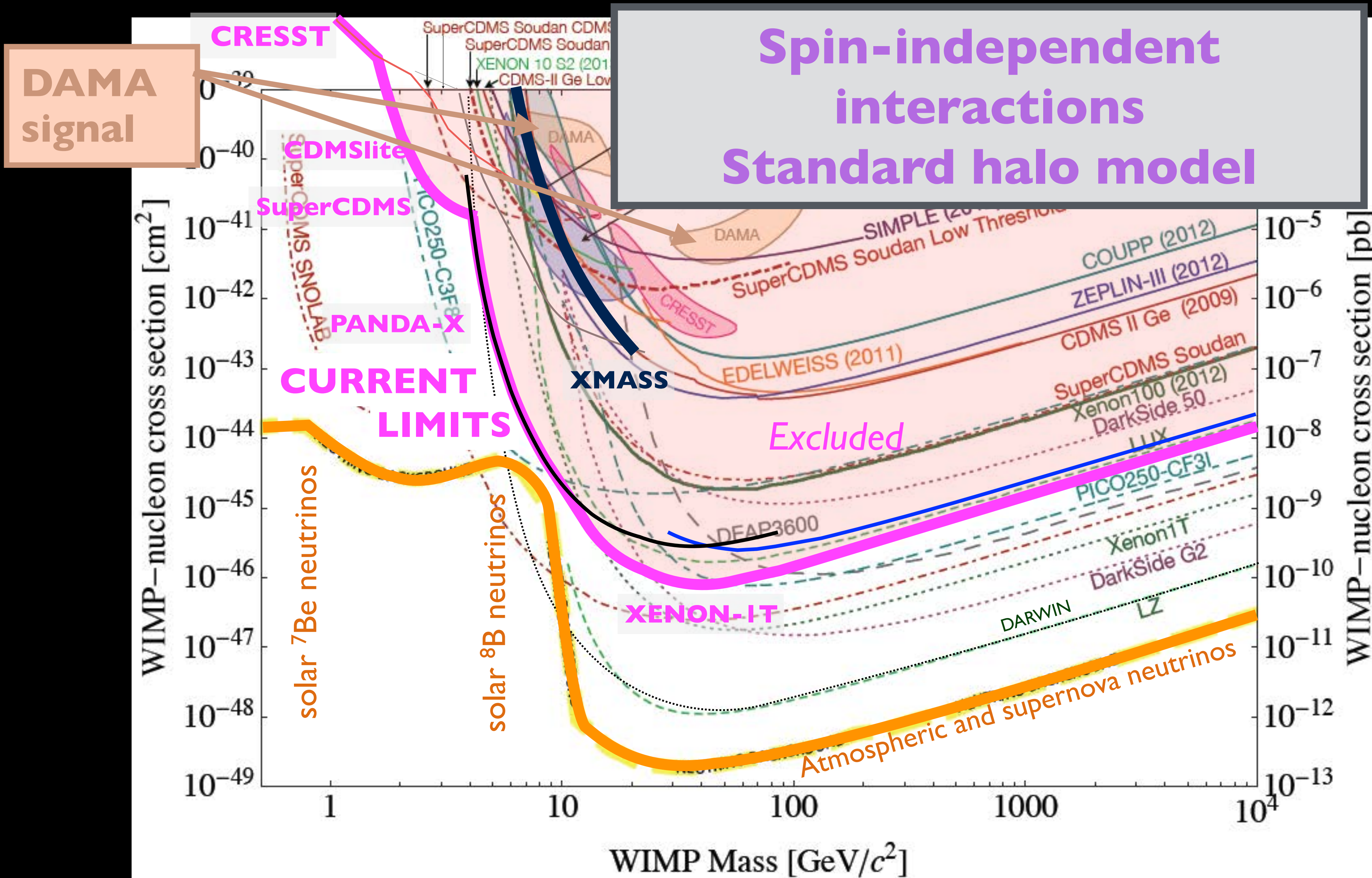


No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy the many peculiarities of the signature are available.

Belli, IDM2014

Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments



Billard+ 2013; CDMSlite, CRESST 2015; PANDA-X, XMASS 2016; XENON-1T 2017

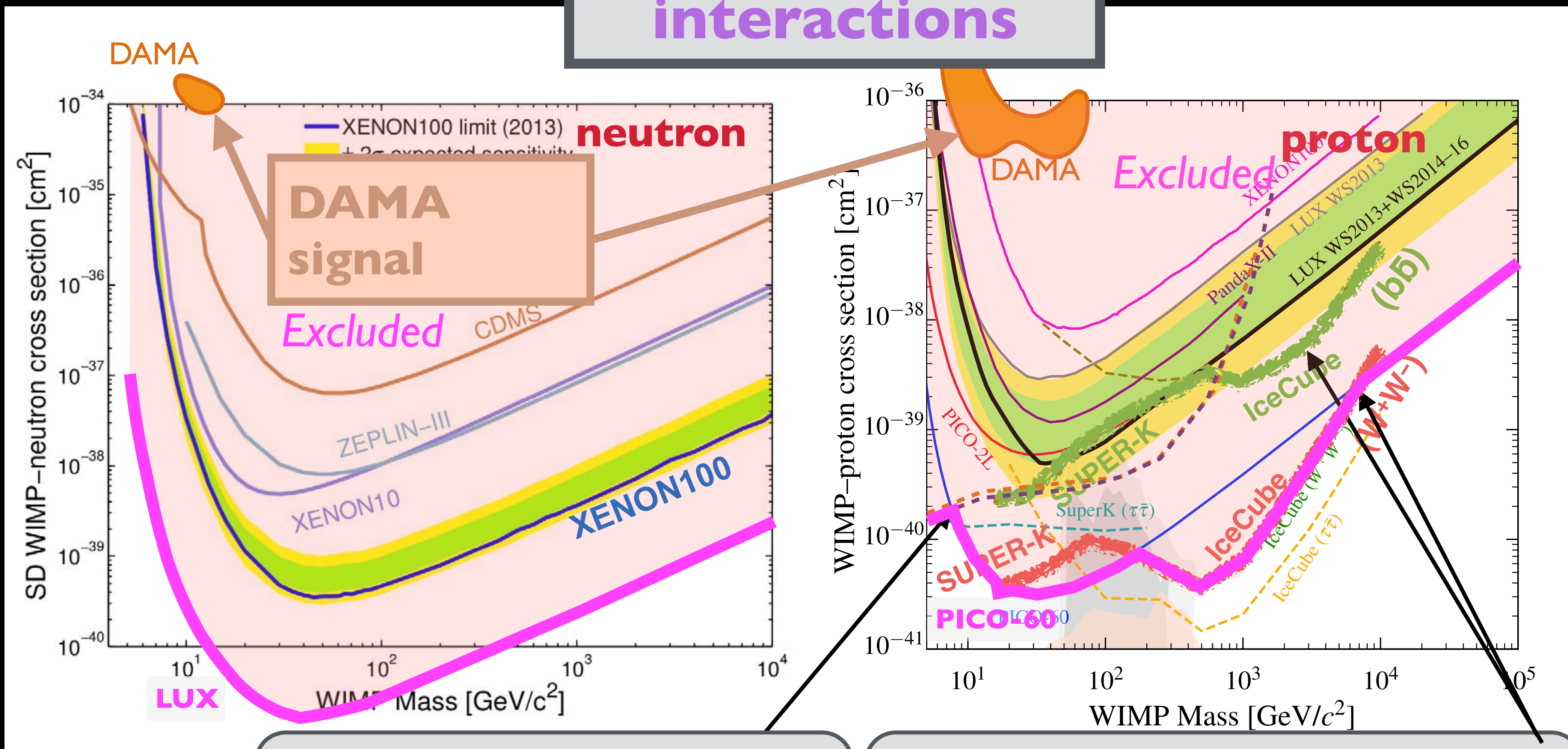
Direct evidence for dark matter particles?

The DAMA signal seems incompatible with other experiments

Spin-dependent interactions

Akerib et al (LUX) 2017

Amole et al (PICO60) 2017

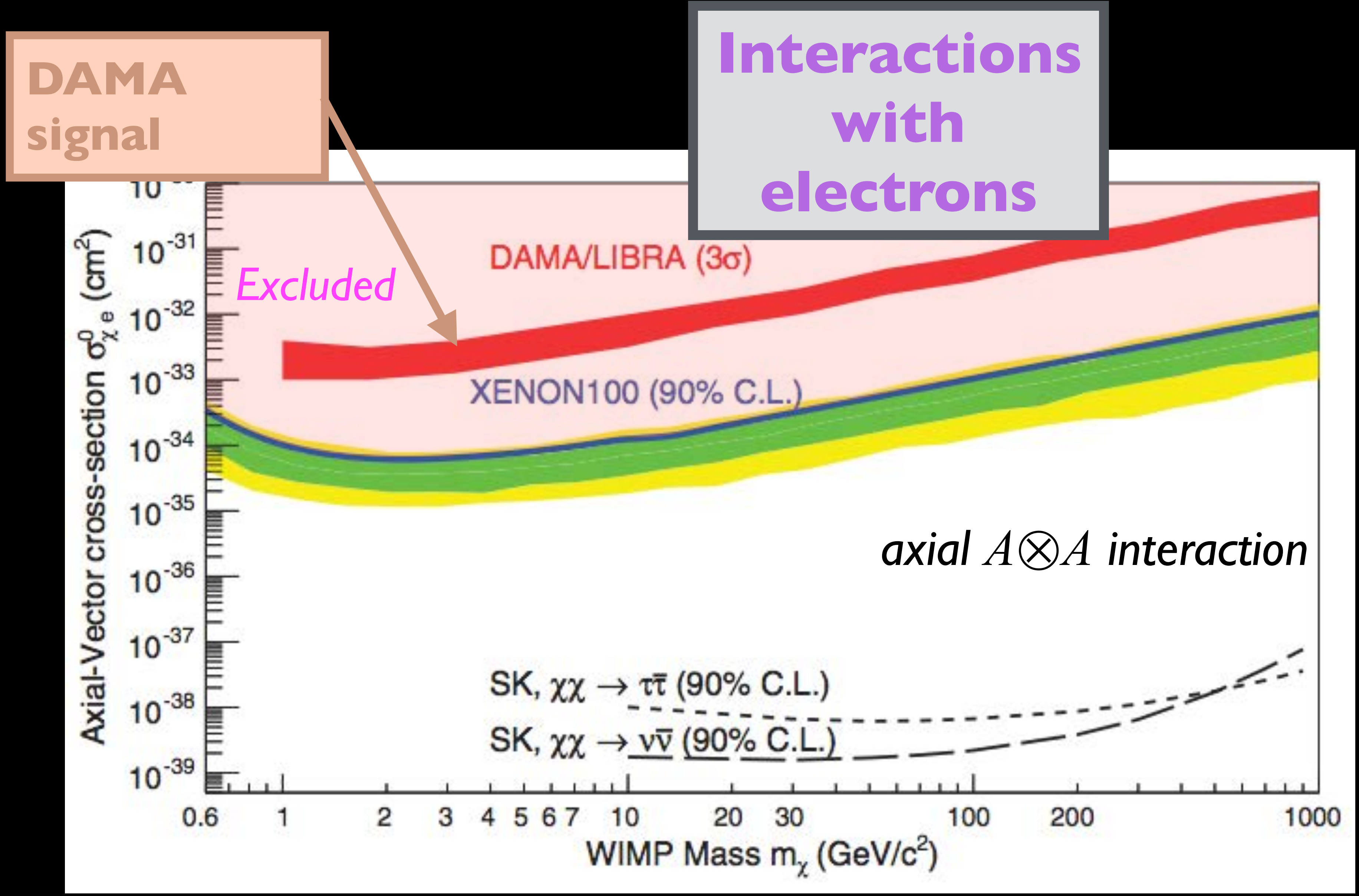


ATLAS and CMS
(WIMP production at the LHC)

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

Recent trends: “make no assumptions”

“Make no assumptions”

All particle physics models

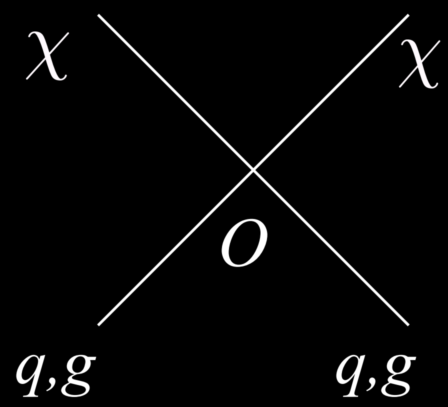
- Consider all possible interactions between dark matter and standard model particles
- This program has been carried out in some limits (e.g., non-relativistic conditions, heavy mediators)

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

Effective operators

if mediator mass ≫ exchanged energy



Four-particle effective operator

There are many possible operators.

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

Long(ish) distance interactions are not included.

Effective operators: LHC & direct detection

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

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

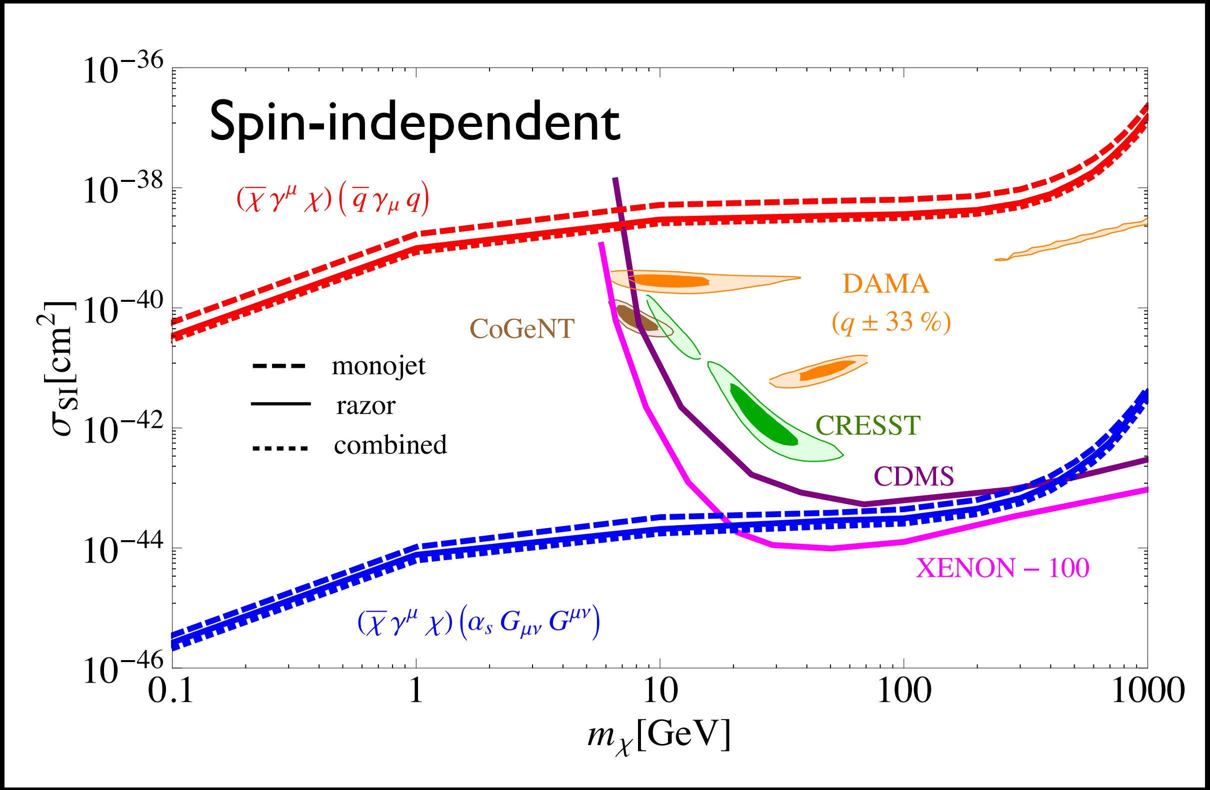
Table of effective operators relevant for the collider/direct detection connection

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

Effective operators: LHC & direct detection

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

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



Fox, Harnik, Primulando, Yu 2012

These bounds do not apply to SUSY, etc.

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

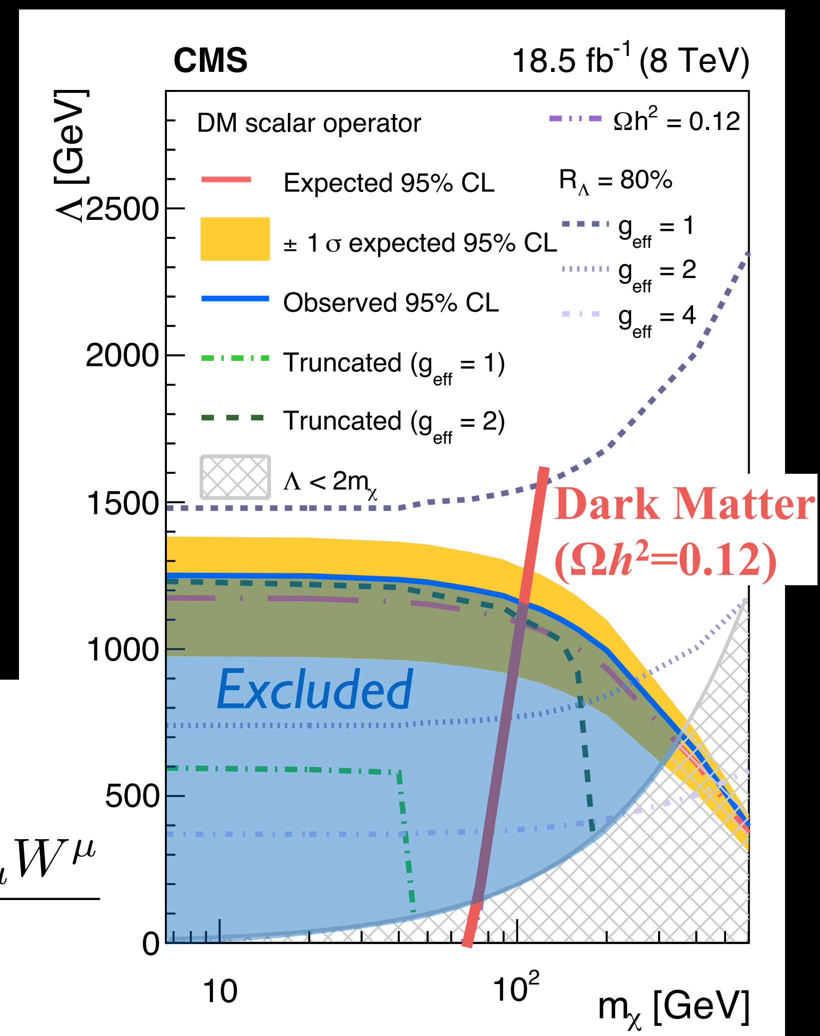
Effective operators: LHC & indirect detection

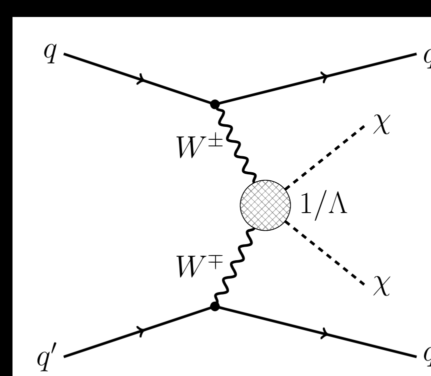
Limits on WIMP couplings to vector bosons (γ, W, g, …)

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

Cotta, Hewett, Le, Rizzo 2013

The CMS Collaboration, 2016





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

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

Effective operators: non relativistic

Nonrelativistic WIMP-nucleon contact operators classified

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

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

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

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

Effective operators: non relativistic

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

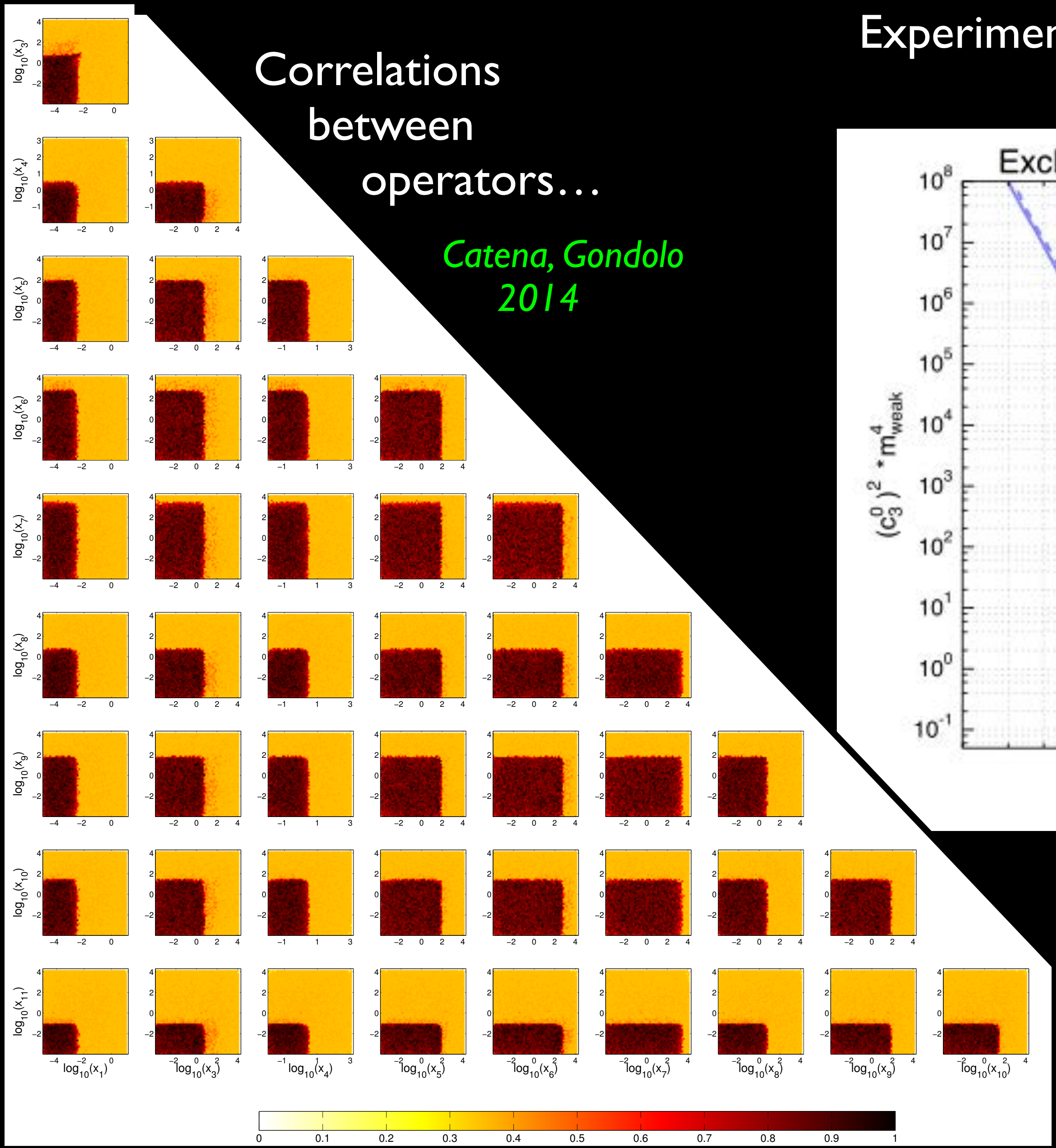
	s_χ=0 X^0	s_χ=0 X^+	s_χ=1/2 X^0	s_χ=1/2 X^+	s_χ=1 X^0	s_χ=1 X^+
S	1	1	1,11	1,11	1	1
V	—	—	1,8,9	1,8,9	4,5,6,8,9,11,17	—
T	—	—	—	4,10,11,12	—	4,11,12,18
A	10	—	4,7,9	4,7,9	4,6,9,10,14,18	—
P	10	10	6,10	6,10	10	10

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

Effective operators: non relativistic

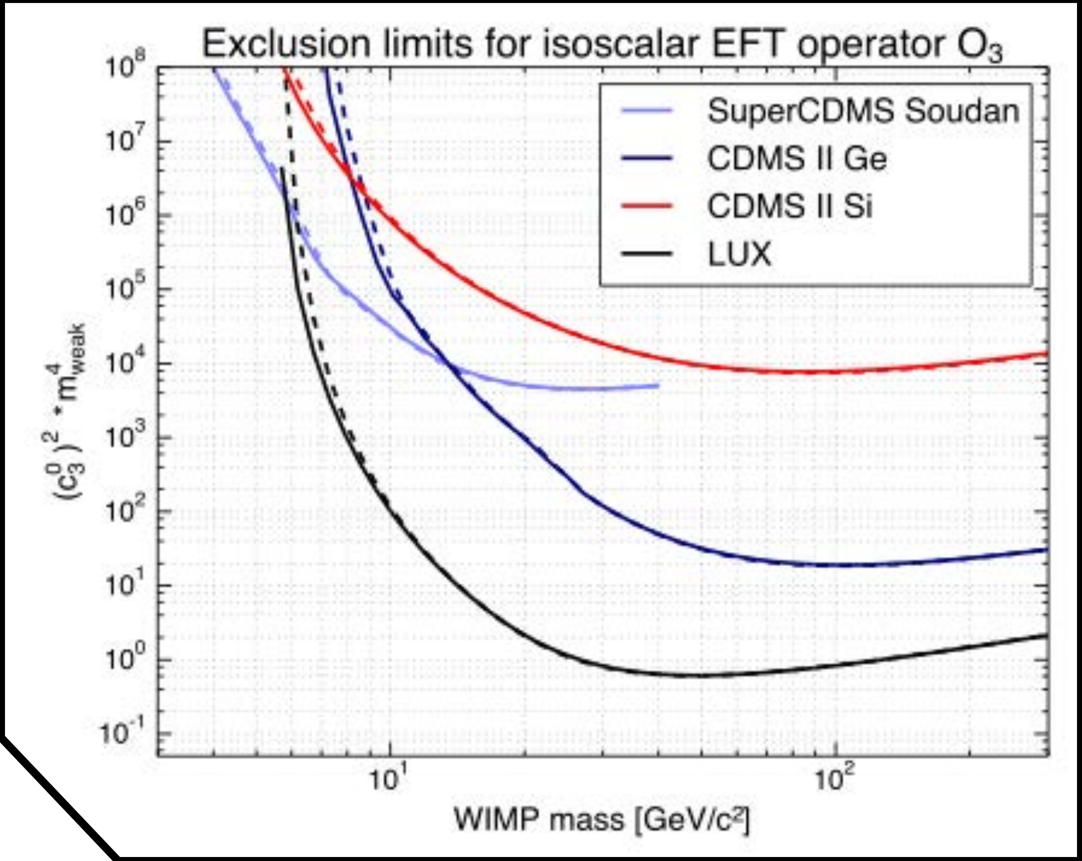
Correlations between operators…

Catena, Gondolo 2014



Experimental limits on single operators…

Schneck et al (SuperCDMS) 2015



Indirect detection…

Catena 2016

Effective operators: nucleon matrix elements

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

Nucleon matrix elements of quark and gluon currents

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

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

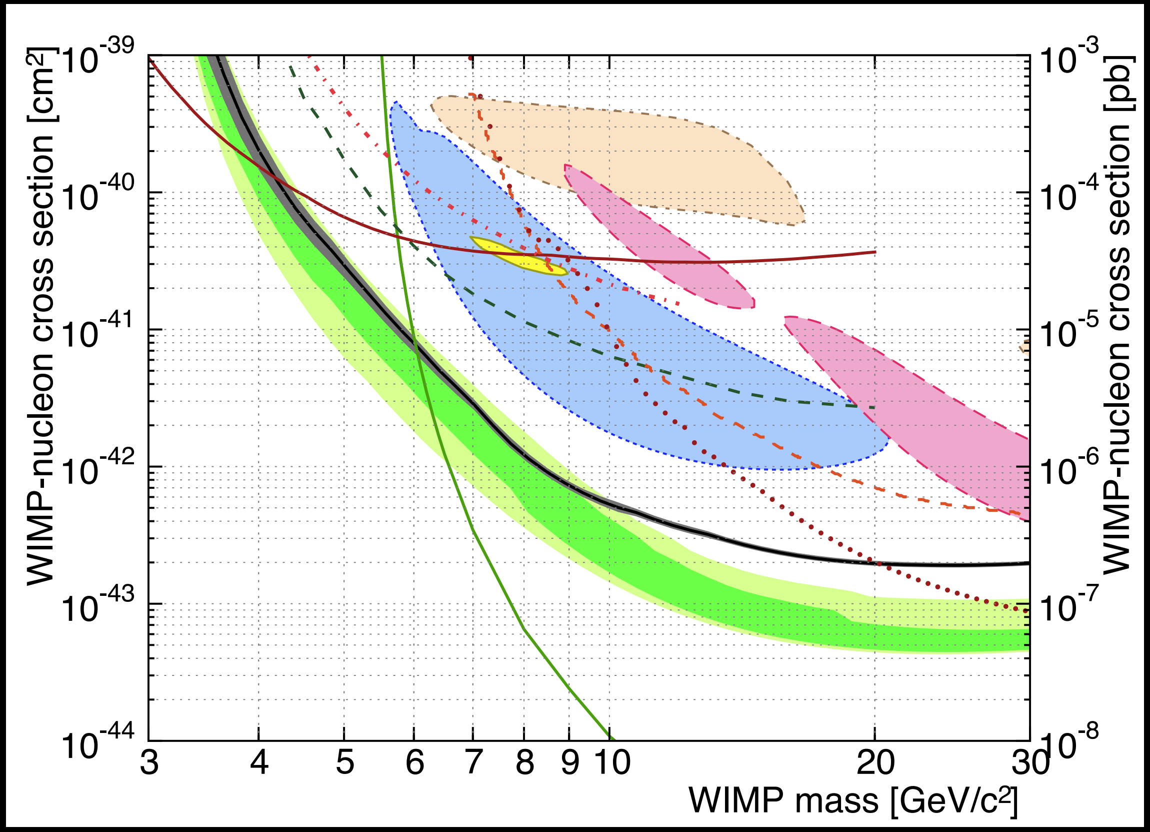
See e.g. Kaplan, Manohar 1988; Cheng 1989; Drees, Nojiri 1993; Adam+ 1995; Aoki+ 1997; Mallot 1999; Pospelov&Ritz, Leinweber+ 2004; Doi+ 2009; Alekseev+ 2010; Bacchetta+, Bali+, Hisano+ 2012; Anselmino+, Dienes+, Fuyuto+ 2013; Hill&Solon 2014; Agrawal+, Bhattacharya+, Hisano+ 2015, …

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

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

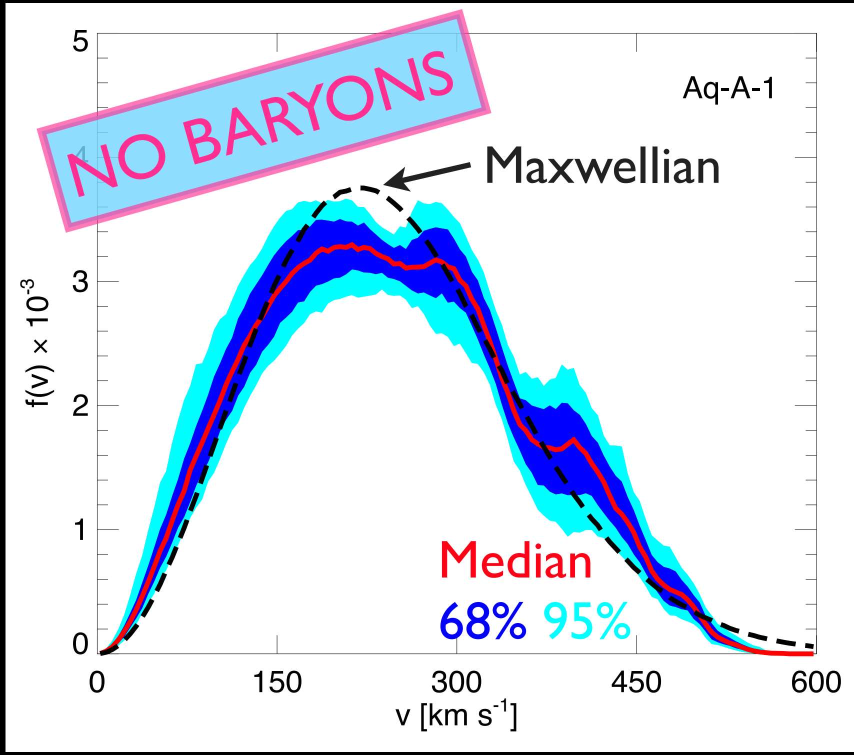
Gelmini

Astrophysics-independent approach

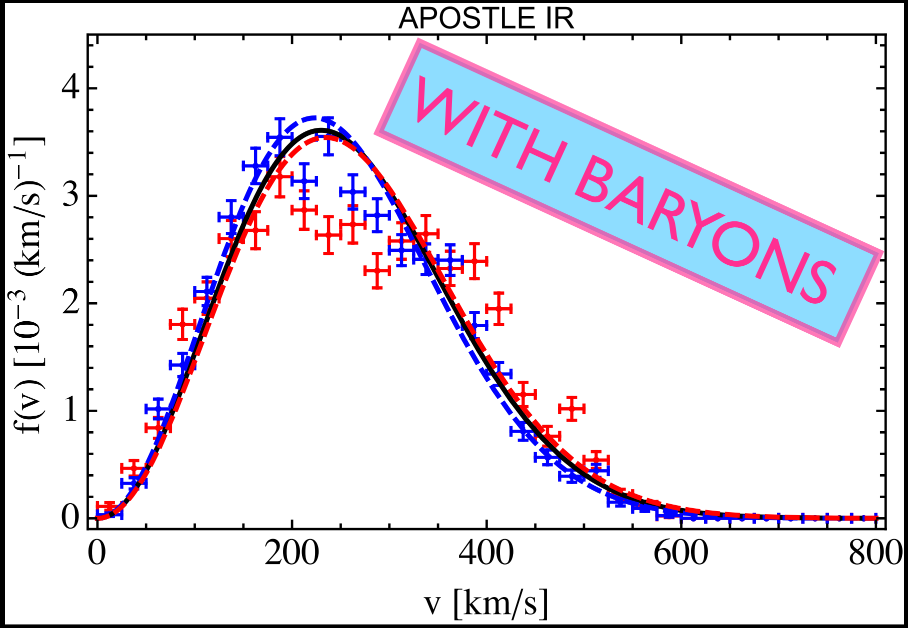
We know very little about the dark matter velocity distribution near the Sun

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 (particle physics)

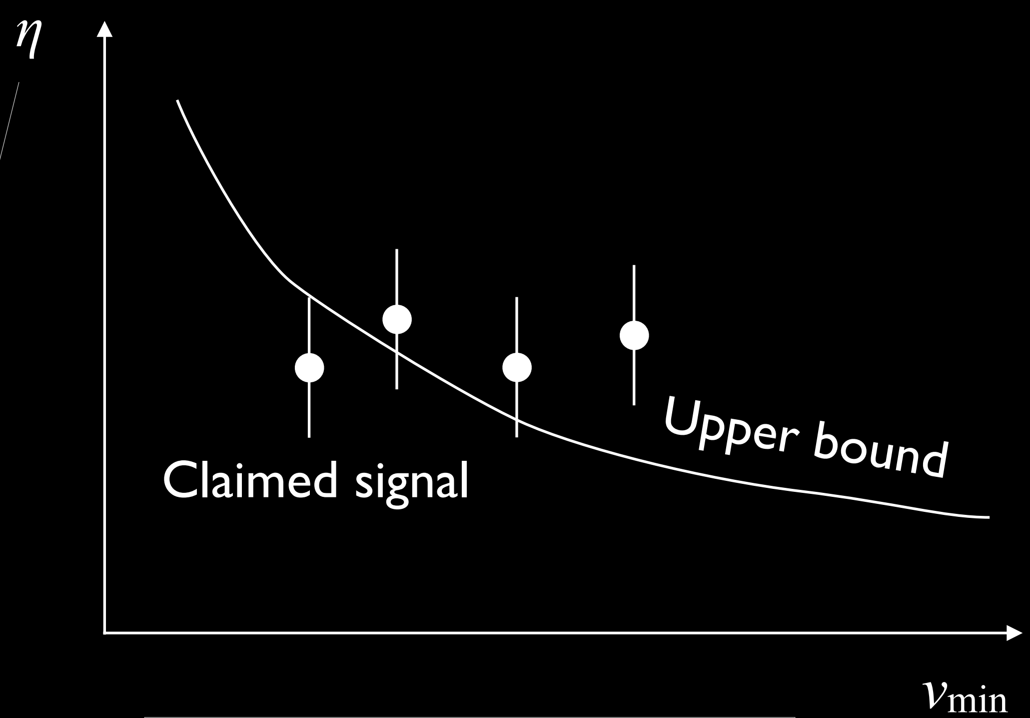
ARBITRARY (astrophysics)

Rescaled astrophysics factor common to all experiments

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

"Velocity integral"

Proxy for dark matter flux



Minimum WIMP speed to impart recoil energy E_R

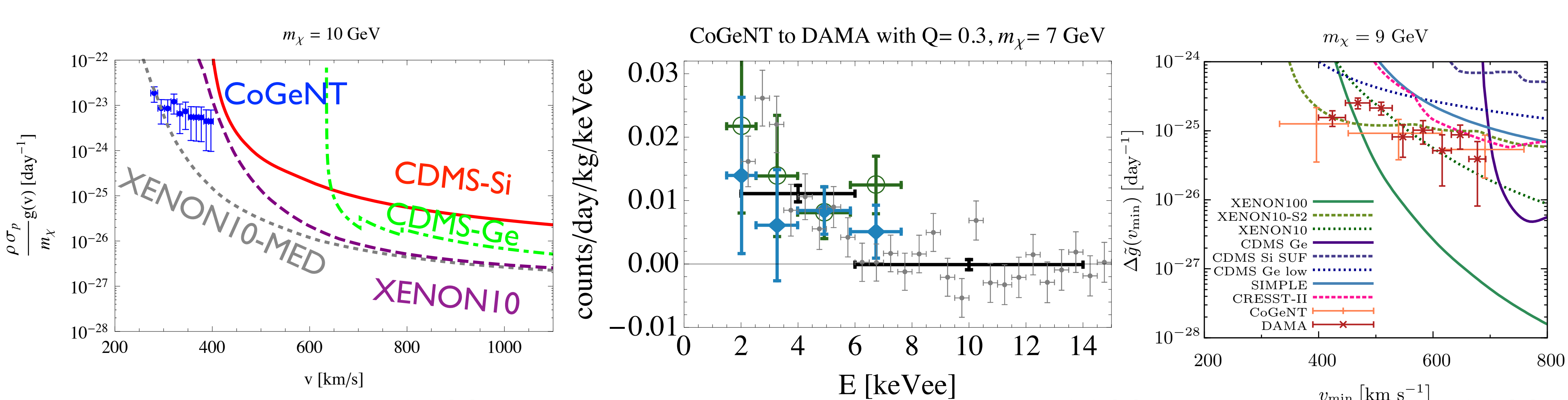
Fox, Liu, Wiener 2011; Gondolo, Gelmini 2012; Del Nobile, Gelmini, Gondolo, Huh 2013-14

Astrophysics-independent approach

Find velocity integral from one experiment and use it for another.

Fox, Liu, Weiner 2011

$$\frac{dR}{dE_R} = \frac{A^2 F^2(E_R)}{2\mu_{\chi p}^2}\,\tilde{\eta}(v_{\min}) \quad \Rightarrow \quad \tilde{\eta}(v_{\min}) = \frac{2\mu_{\chi p}^2}{A^2 F^2(E_R)}\,\frac{dR}{dE_R}$$



Fox, Liu, Weiner 2011 *Fox, Kopp, Lisanti, Weiner 2011* *Frandsen et al 2011*

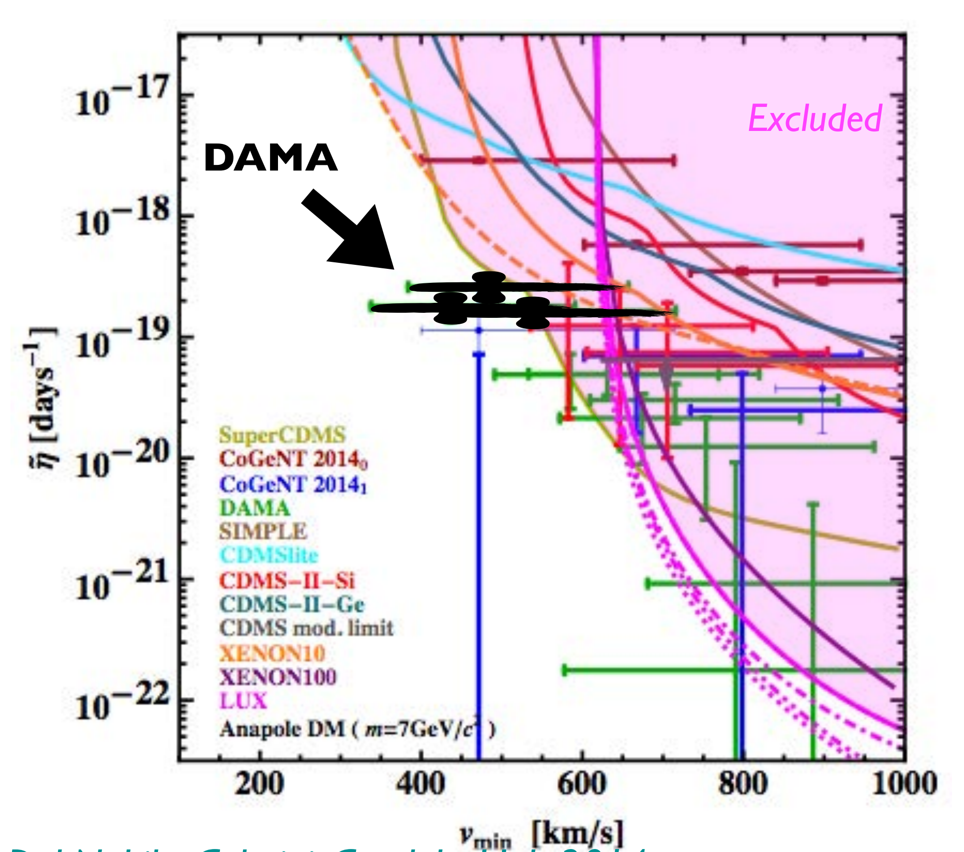
Needs unique relation between measured energy and minimum WIMP speed, available for ***single-target detectors with excellent energy resolution***.
For composite targets, lucky event pattern in CRESST allowed inversion.

Astrophysics-independent approach

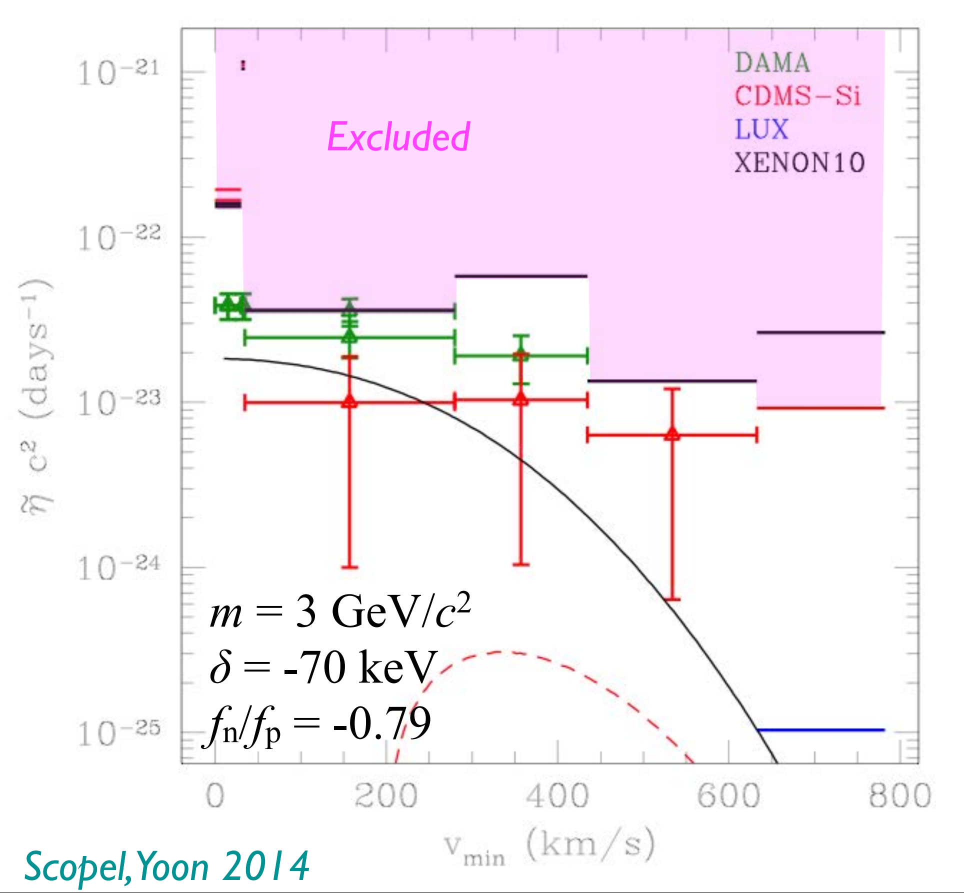
In general, for ***composite targets and finite energy resolution***, one can still find ***weighted averages of the velocity integral***.

Gondolo, Gelmini 2012

DAMA may be compatible with null searches for anapole and exothermic dark matter.



Del Nobile, Gelmini, Gondolo, Huh 2014



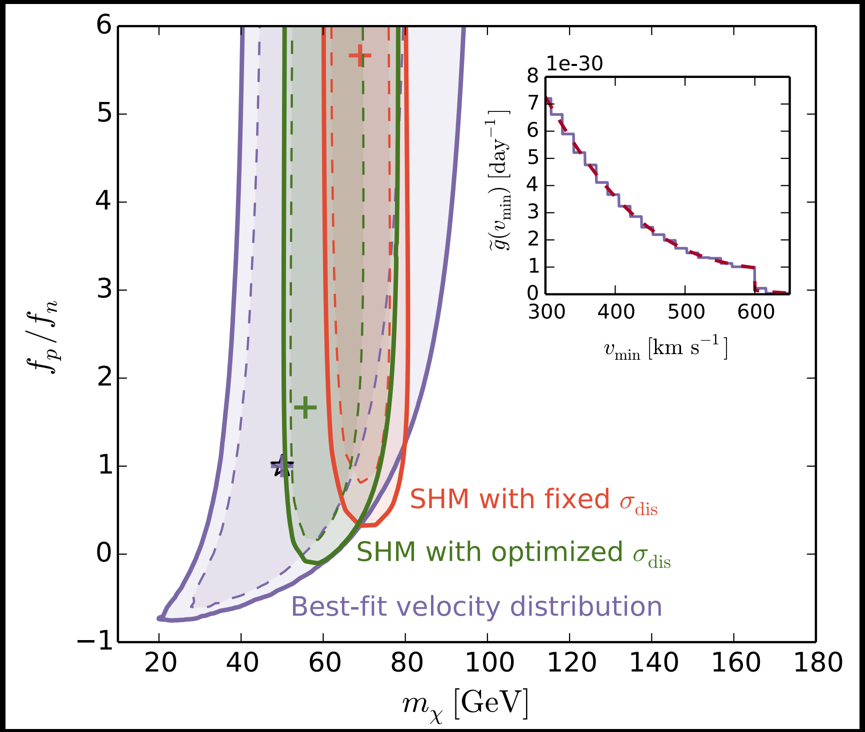
Scopel, Yoon 2014

Allows for ***any velocity and energy dependent cross section***, and indirect searches through ***neutrinos from the Sun/Earth***.

Astrophysics-independent approach

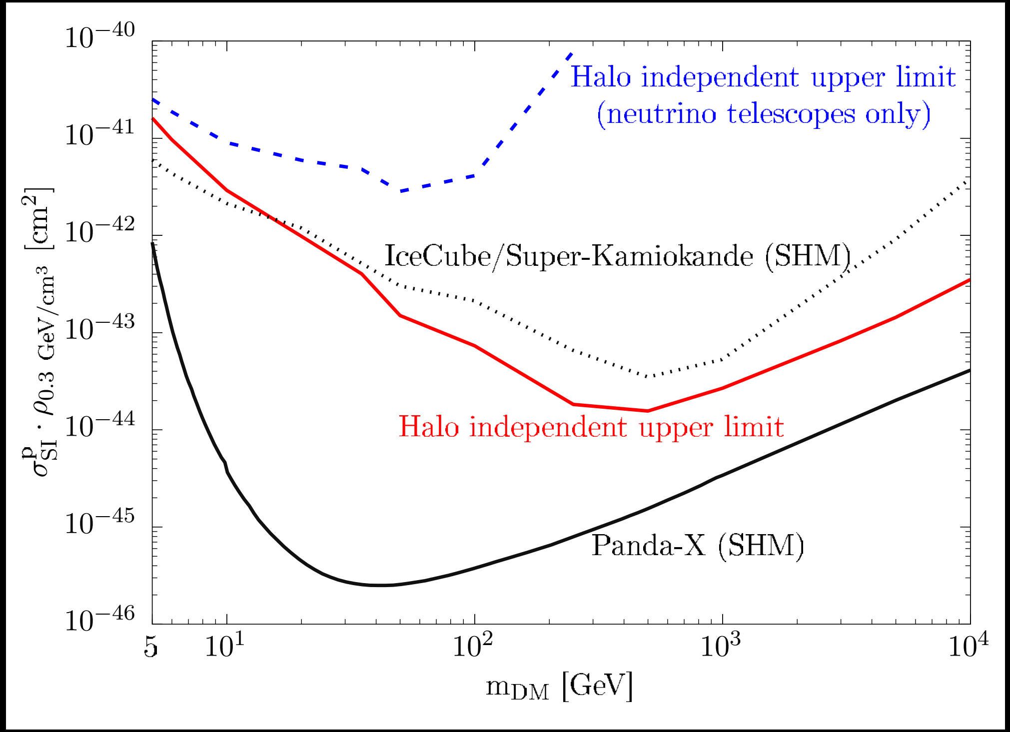
Alternatively, one has sampled ***discretized velocity distributions*** to find bounds from direct and indirect experiments (neutrinos from the Sun).

Likelihood for particle-physics parameters (mock data)



Feldstein, Kahlhoefer 2014

Bounds on cross section from direct detection and neutrinos from the Sun



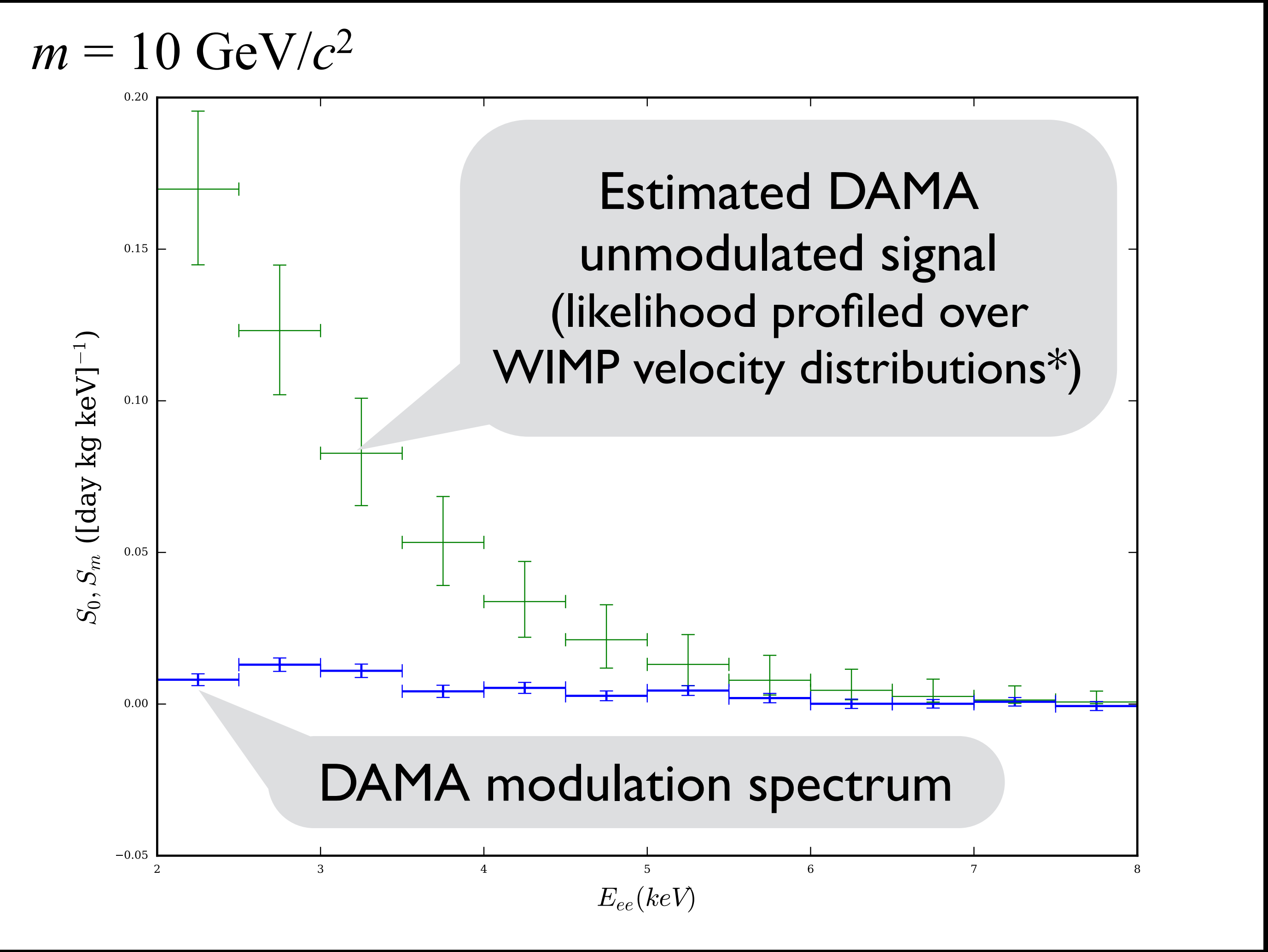
Ibarra, Rappelt 2017

Astrophysics-independent approach

New powerful techniques inspired by probability theory (problem of moments and Chebyshev inequalities) have just been introduced.

Gondolo, Scopel 2017

First application: halo-independent DAMA unmodulated signal



(*isotropic in galactic rest frame)

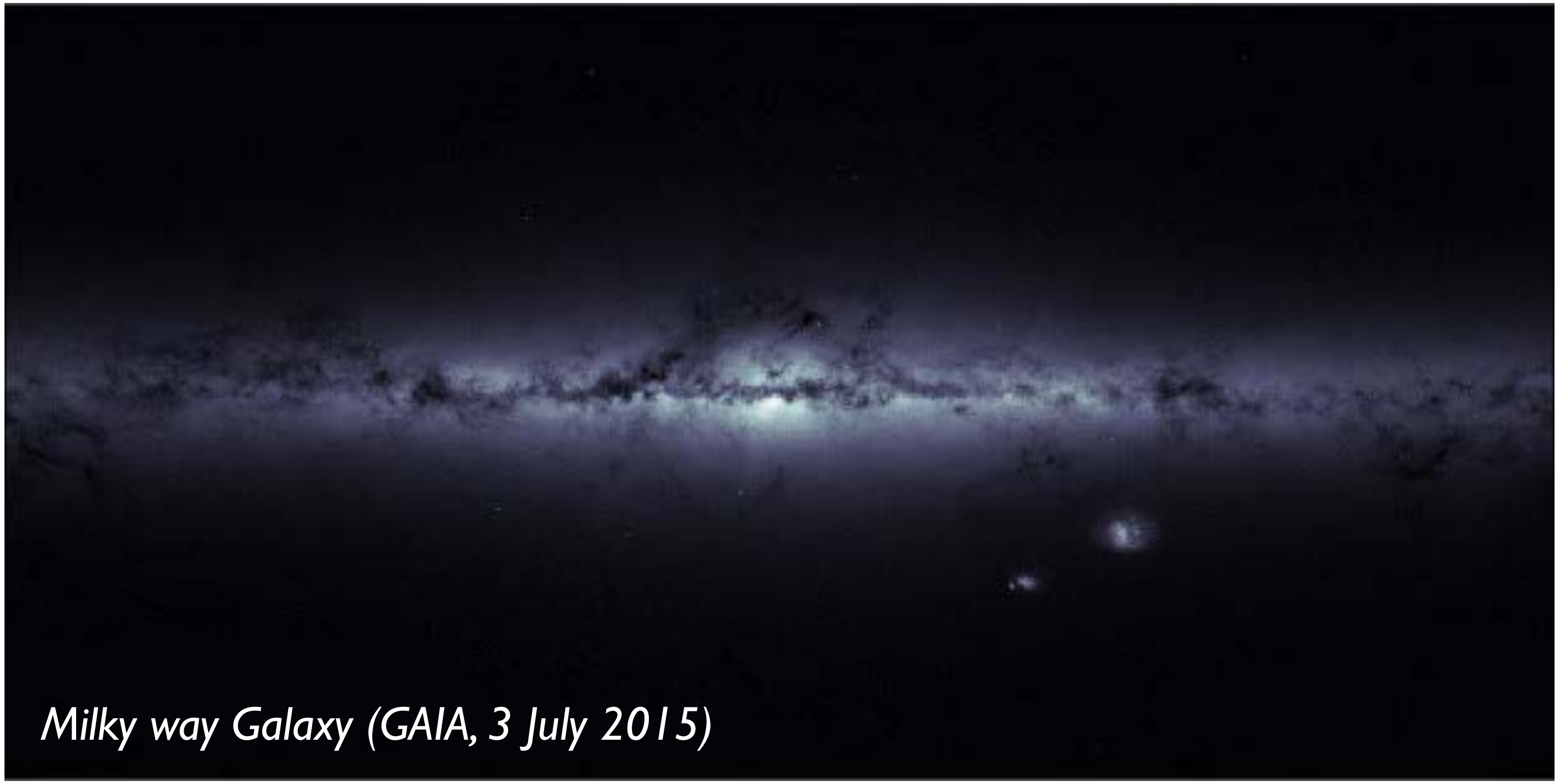
$S_{0,i}$	$S_{0,i} + B_i$
$0.17^{+0.026}_{-0.025}$	1.029
$0.12^{+0.022}_{-0.021}$	1.228
$0.083^{+0.018}_{-0.017}$	1.294
$0.053^{+0.015}_{-0.014}$	1.140
$0.034^{+0.013}_{-0.012}$	0.956

The unmodulated signal is compatible with the background

In the next future

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

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



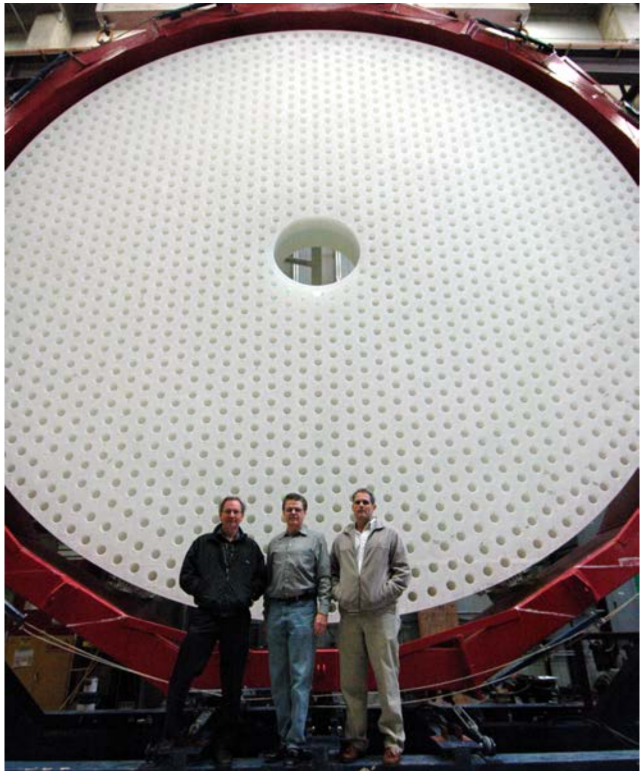
GAIA may detect dark matter substructures in the galactic halo.

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

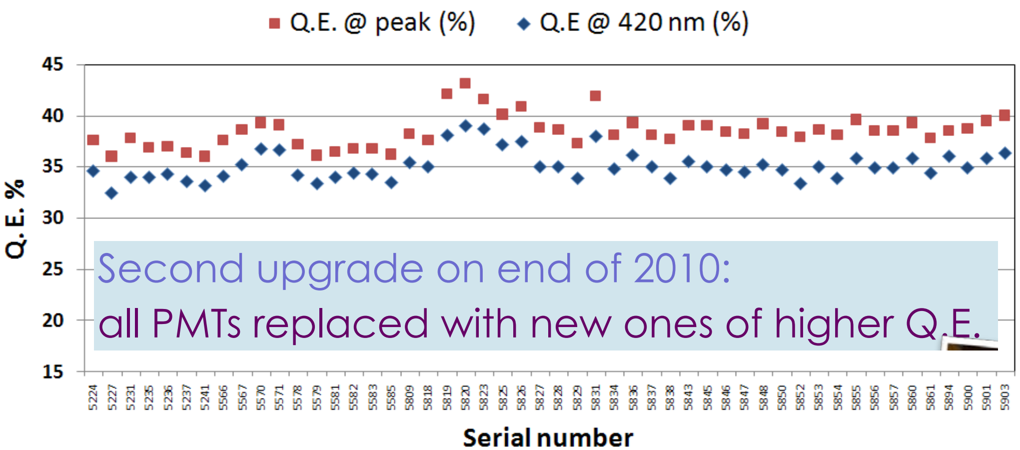


LSST

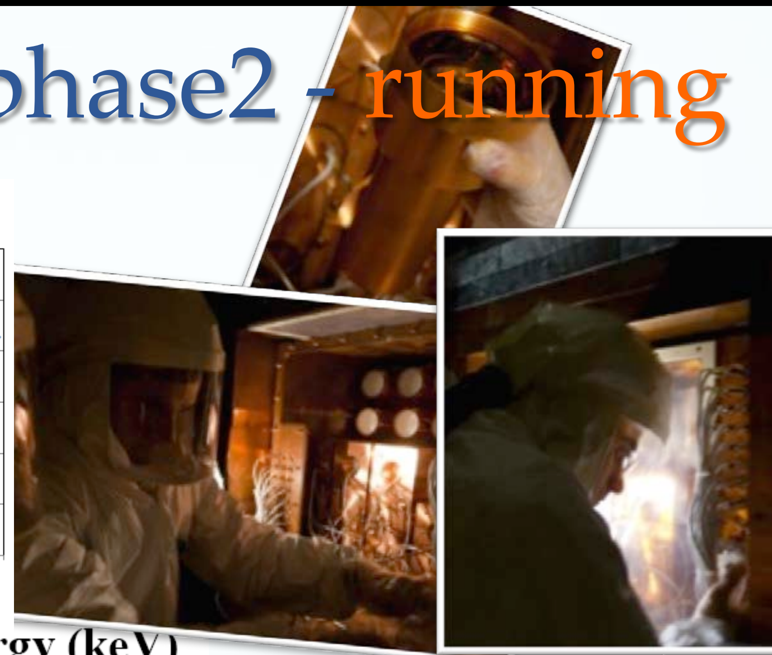
In the next future..... DAMA's revenge?

DAMA/LIBRA phase2 - running

Quantum Efficiency features



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

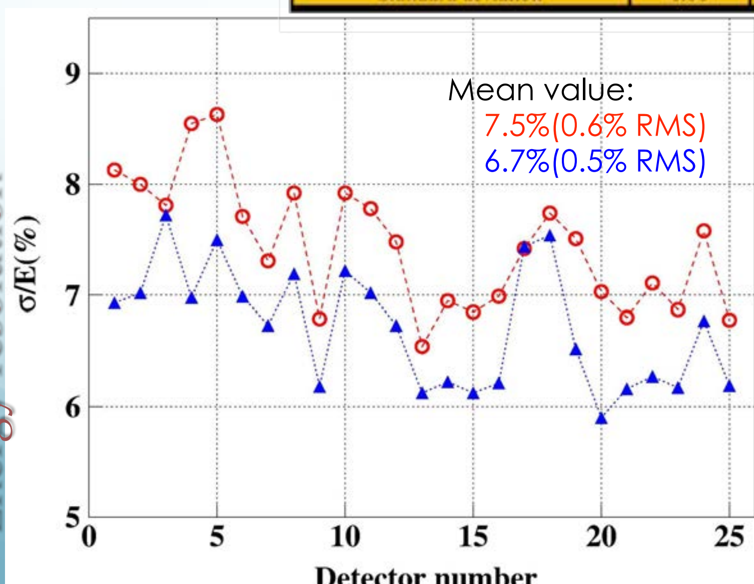


Residual Contamination

The limits are at 90% C.L.

PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
Average			*0.43*	-	*47*	*0.12*	*83*	*0.54*	-	-
Standard deviation			*0.06*	-	*10*	*0,02*	*17*	*0.16*	-	-

Energy resolution



σ/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blu points) and with previous PMT EMI-Electron Tube (red points).

The light responses

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

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

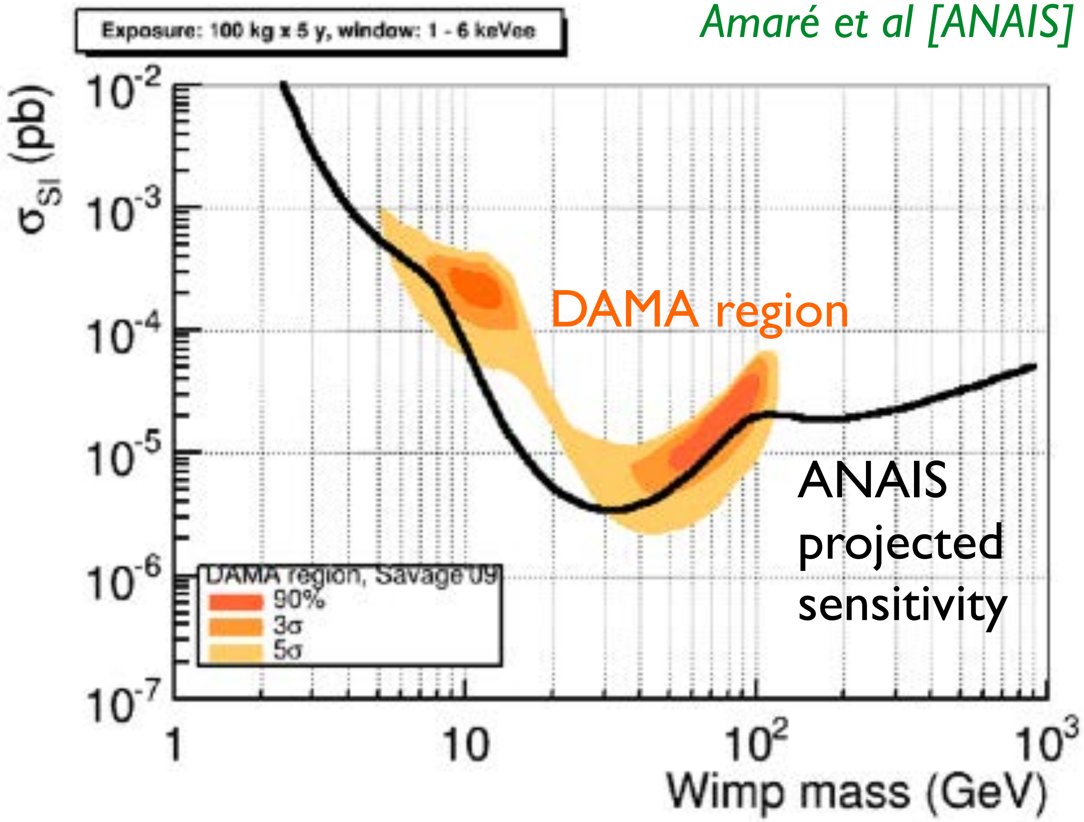
Belli, IDM2014

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

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

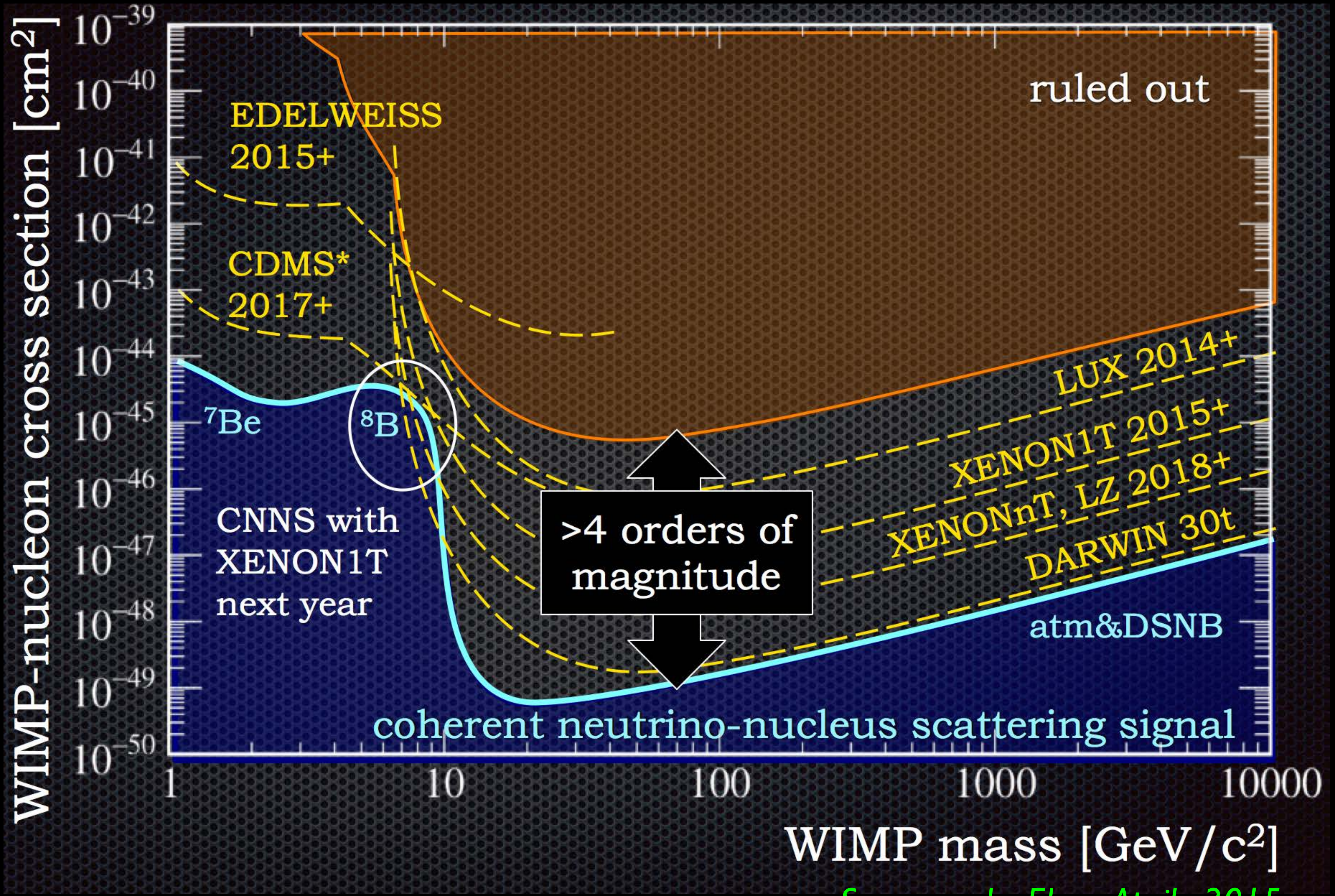
COSINE-100 (DM-ICE+KIMS-NaI)
ANAIS, SABRE, …

Amaré et al [ANAIS] 2015



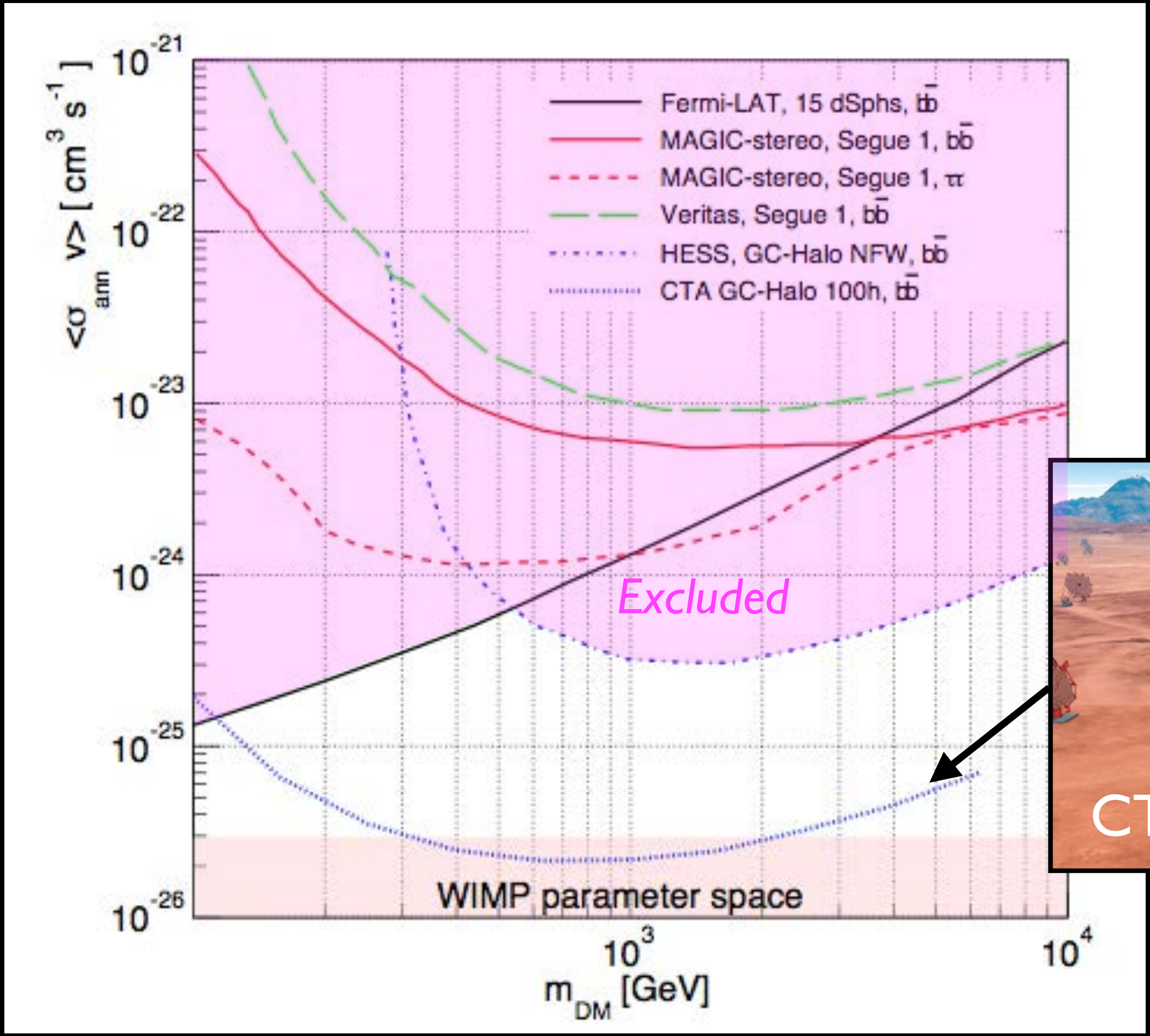
In the next future….. Giant direct detectors

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



Summary by Elena Aprile 2015

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



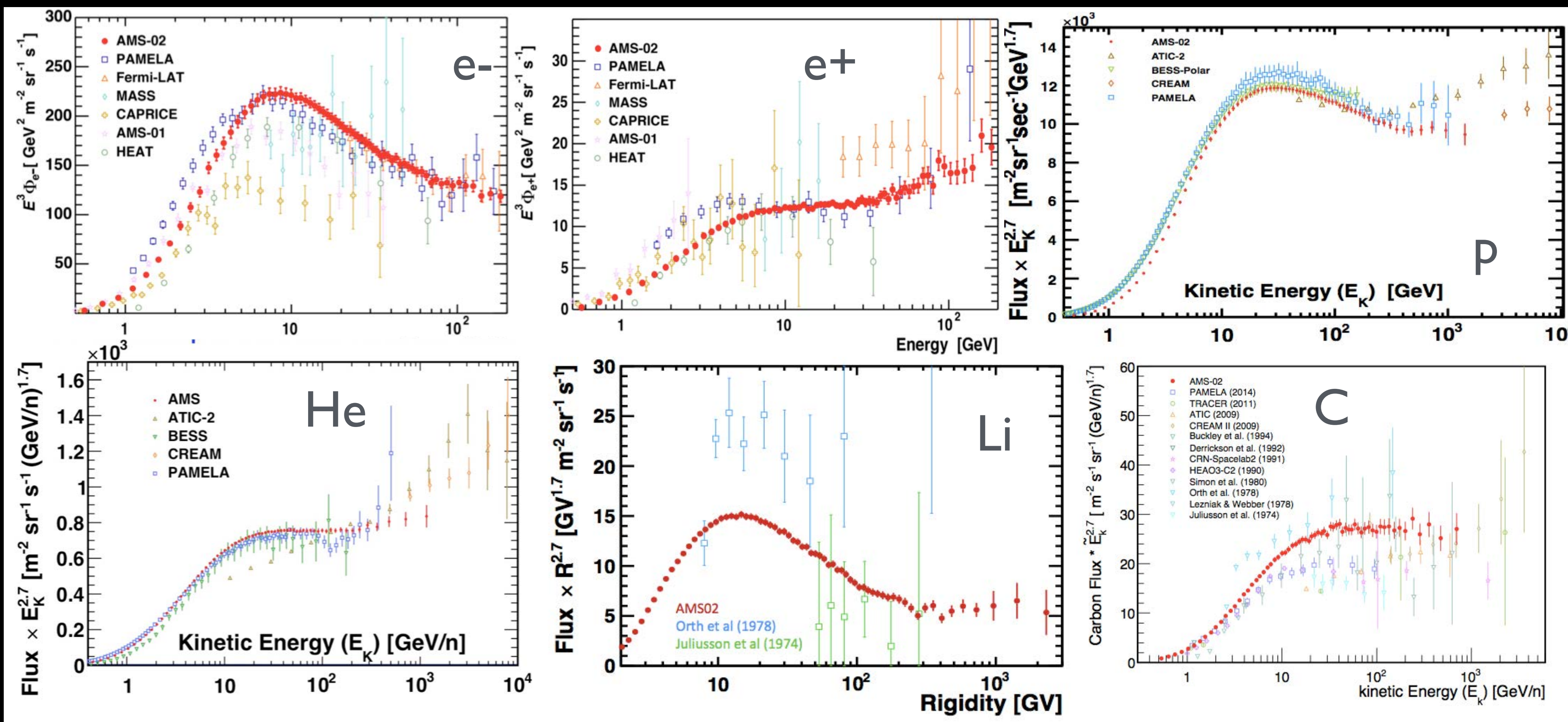
The Cherenkov Telescope Array (CTA) promises a lower energy threshold and a higher sensitivity.

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 are some controversial claims of having detected signals from particle dark matter
- 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