Dark Matter Overview

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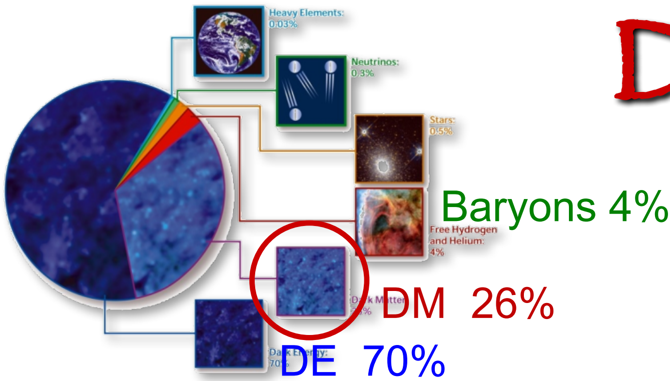
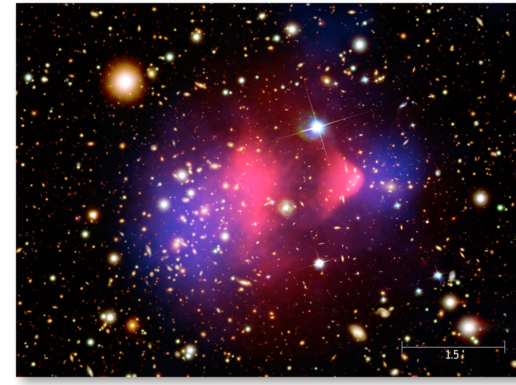
Torino, 9.09.2016

Dark Matter





- The presence of DM is supported by copious and consistent astrophysical and cosmological probes
  - Horizon-scale: average DM density about 6 times baryon density
  - Smaller scales: DM distribution is quite anisotropic and hierarchical
    clusters – galaxies – subhalos

- Observations are consistent with a theoretical understanding of cosmic structure formation through gravitational instability, based on the LCDM model

Although:

- Some issues under discussion on very small scales
- Role of baryons in galaxy formation just started to be investigated

Dark Matter

- DM evidence is purely gravitational
  - Galaxy clusters dynamics
  - Rotational curves of spiral galaxies
  - Gravitational lensing
  - Hydrodynamical equilibrium of hot gas in galaxy clusters
  - Energy budget of the Universe
  - The same theory of structure formation

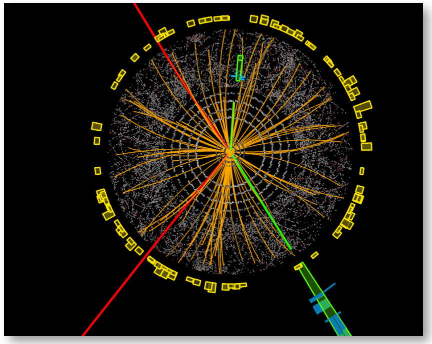
- This evidence can be ascribed either to:

  Modification of the theory of Gravity (difficult to explain all observations)

  Elementary particle, relic from the early Universe

  - No viable candidate in the SM: New Physics BSM
  - However, to demonstrate that DM is a new particle, a non-gravitational signal (due to it's particle physics nature) is needed

Multiple approach



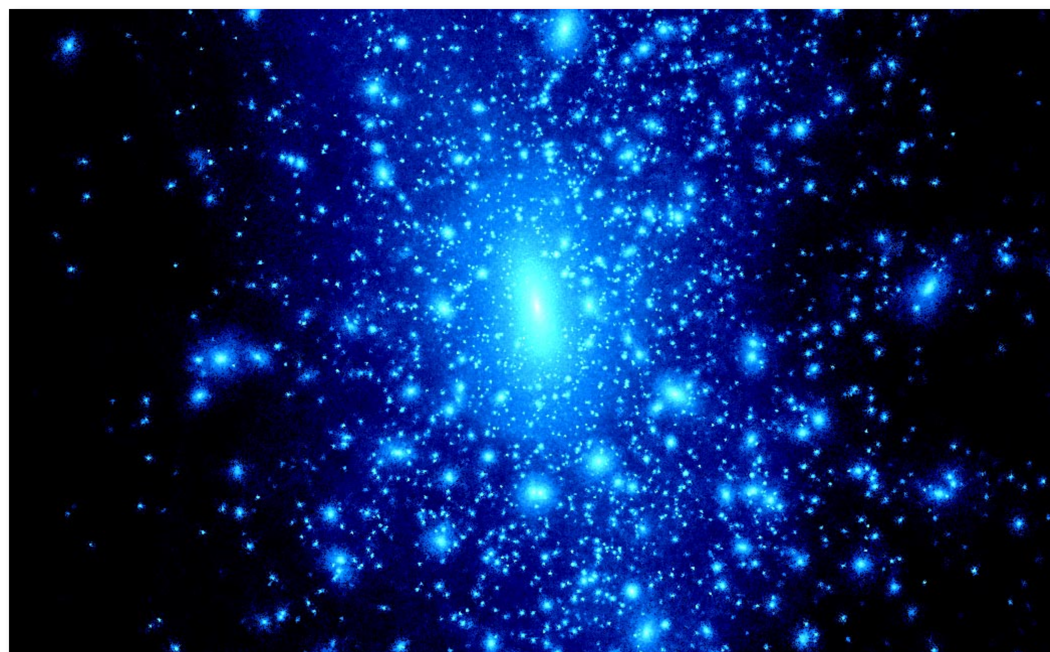
- Astrophysical signals
  - Tests DM as particle in its environment
  - Signals are not produced under our own direct control
  - Complex backgrounds
  - Multimessenger, multiwavelength, multitechnique strategy
- Accelerator signals
  - Produce New Physics states and help in shaping the underlying model
  - Allows (hopefully) to identify the physical properties of the DM sector
  - Controlled environment

One does not fit all ... profit of all opportunities

Cosmic messengers and Dark Matter

Photons — radio, IR, X, gamma

Cosmic rays — electrons/positrons; antiprotons, antideuterium, antinuclei



Neutrinos

Gravitational waves

Cosmic messengers and Dark Matter

Photons

radio	IR	X	gamma
WIMP non WIMP		WIMP non WIMP	WIMP

Cosmic rays

electrons/positrons — WIMP, non WIMP

antiprotons, antideuterium, antinuclei — WIMP

Neutrinos — WIMP, non WIMP

Gravitational waves — non WIMP (DM = primordial BH)

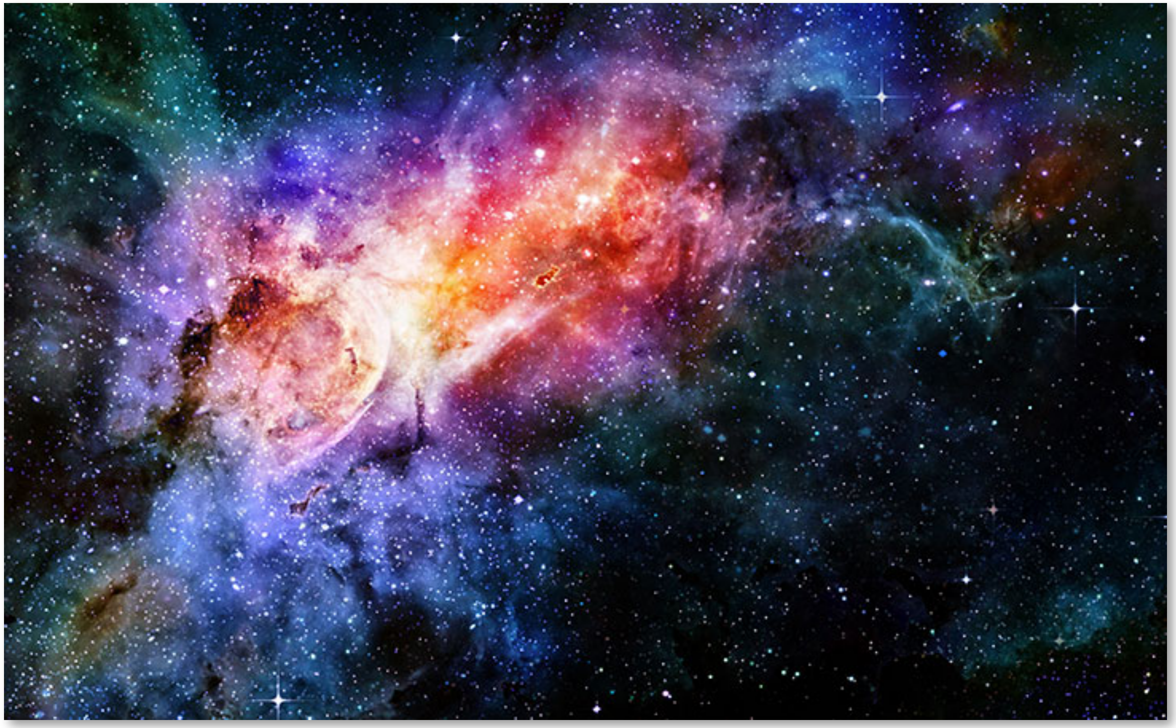
Multi: messenger/wavelength/technique

	radio	IR	X	gamma
	WIMP non WIMP		WIMP non WIMP	WIMP
Photons	radio	IR	X	gamma

Cosmic rays	electrons/positrons	WIMP, non WIMP
	antiprotons, antideuterium, antinuclei	WIMP
Neutrinos		WIMP, non WIMP

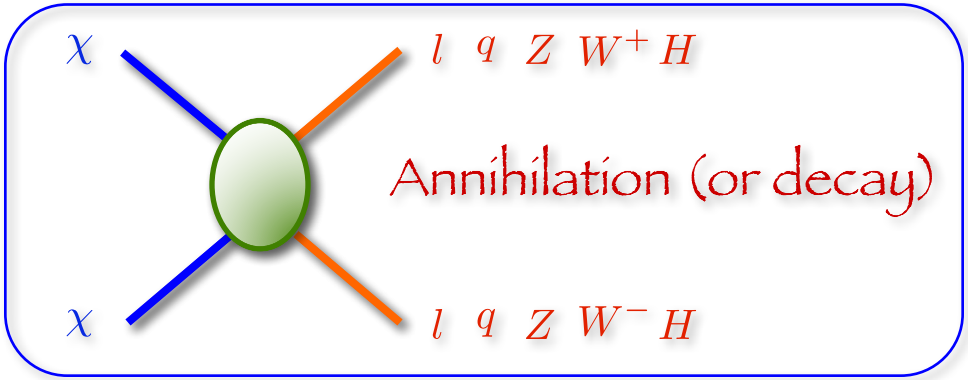
Direct detection	WIMP, non WIMP
Accelerator searches for New Physics	WIMP, non WIMP

Let's concentrate on the astrophysical messengers



Dark Matter signal

The DM signal is produced either by annihilation or decay

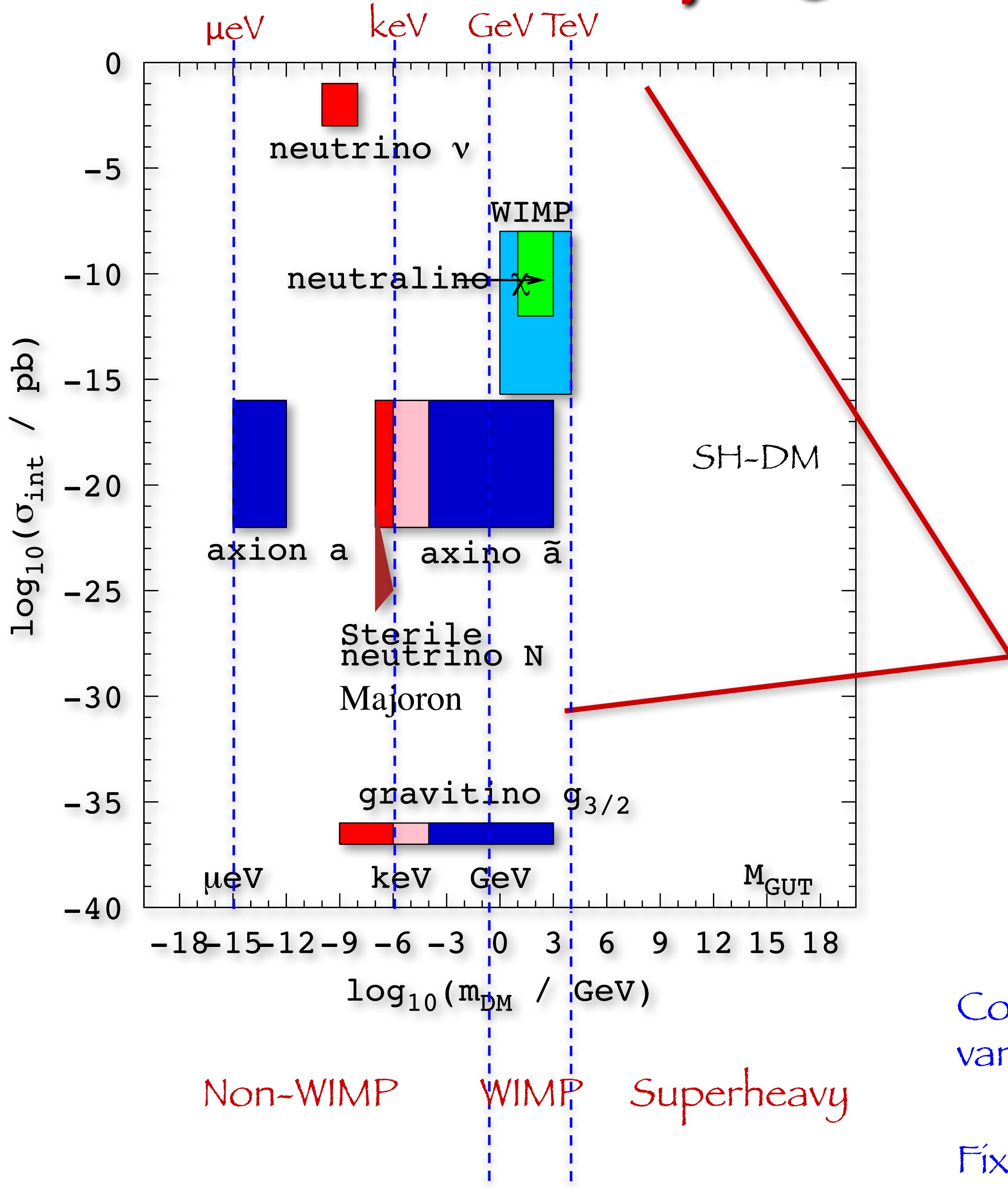


DM is cold (or "warm enough"), i.e. non-relativistic

$E_{\rm msg} \lesssim m_{\rm DM}$ annihilation

$E_{\rm msg} \lesssim m_{\rm DM}/2$ decay

Particle physics scales



"Strong (-ish)"

Self-interacting
Technicolor DM
...

"EM (-ish)"

Millicharged DM
E/M dipole
Dark photons
...

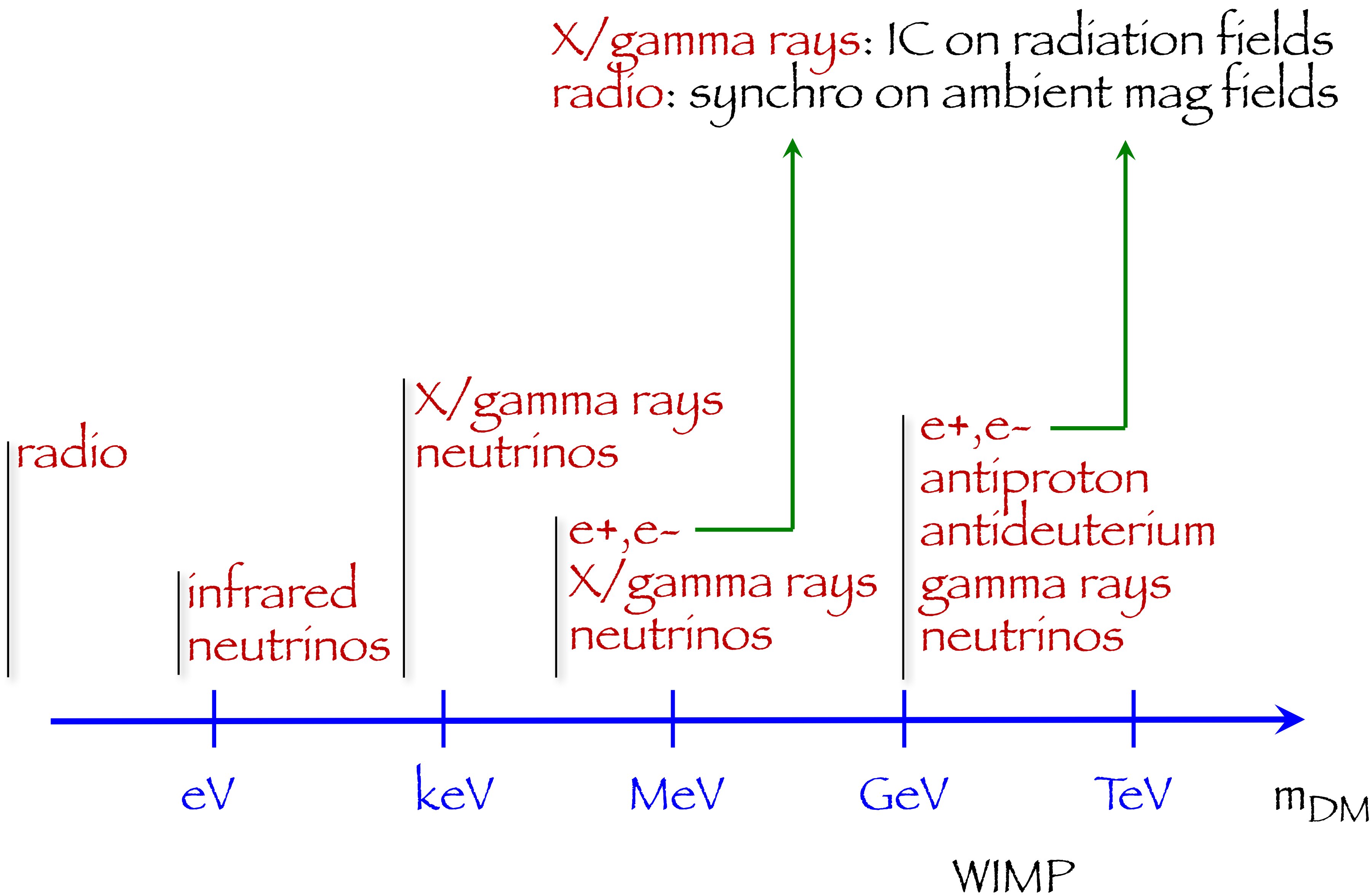
Weak

WIMP

Gravitational

Cosmological production mechanism vary for different candidates

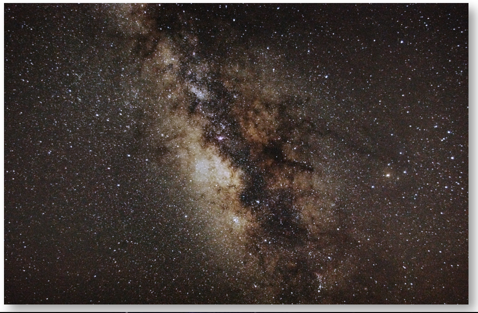
Fixed points: $\Omega_{DM} \approx 25\%$ + correct LSS

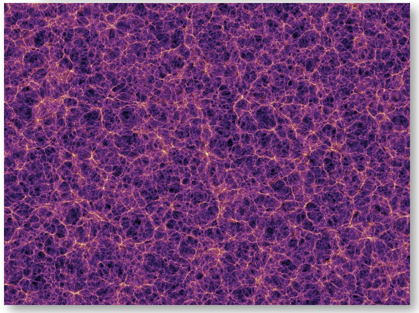

X/gamma rays: IC on radiation fields
radio: synchro on ambient mag fields
radio
infrared
neutrinos
X/gamma rays
neutrinos
e+,e-
X/gamma rays
neutrinos
e+,e-
antiproton
antideuterium
gamma rays
neutrinos
eV
keV
MeV
GeV
TeV
m_{DM}
WIMP

Where to search for a signal

DM is present in:

- Our Galaxy
  - smooth component
  - subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - smooth component
  - individual galaxies
  - galaxies subhalos
- "Cosmic web"





Targets

galactic center
galactic subhalos (clumps)
dwarf galaxies
individual galaxy clusters

Diffuse

high-lat galactic halo
extragalactic (cosmological) cumulative emission

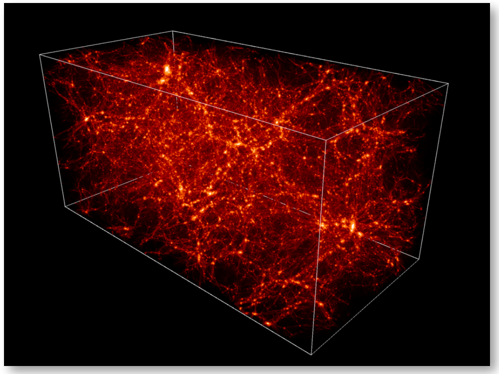
Charged messengers (antimatter)

Galactic

Neutral messengers (photons, neutrinos)

Galactic

Extragalactic (cosmological)



Charged messengers (antimatter)

Affected by transport in the galaxy + heliosphere

Diffusion	affects directionality spectral distortion
Energy losses	spectral distortion

Neutral messengers (photons, neutrinos)

Trace (more) directly the source

Energy losses only at very large energies

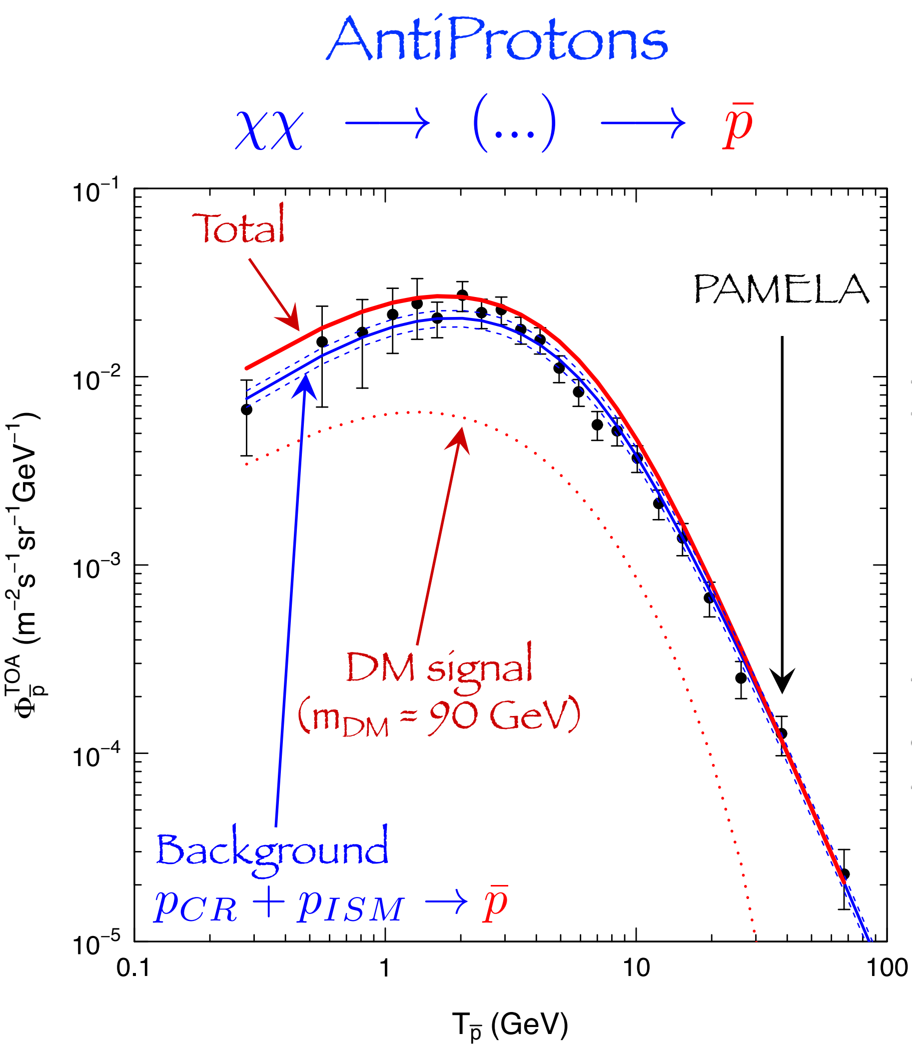
Angular and energy resolution good but not exceptional

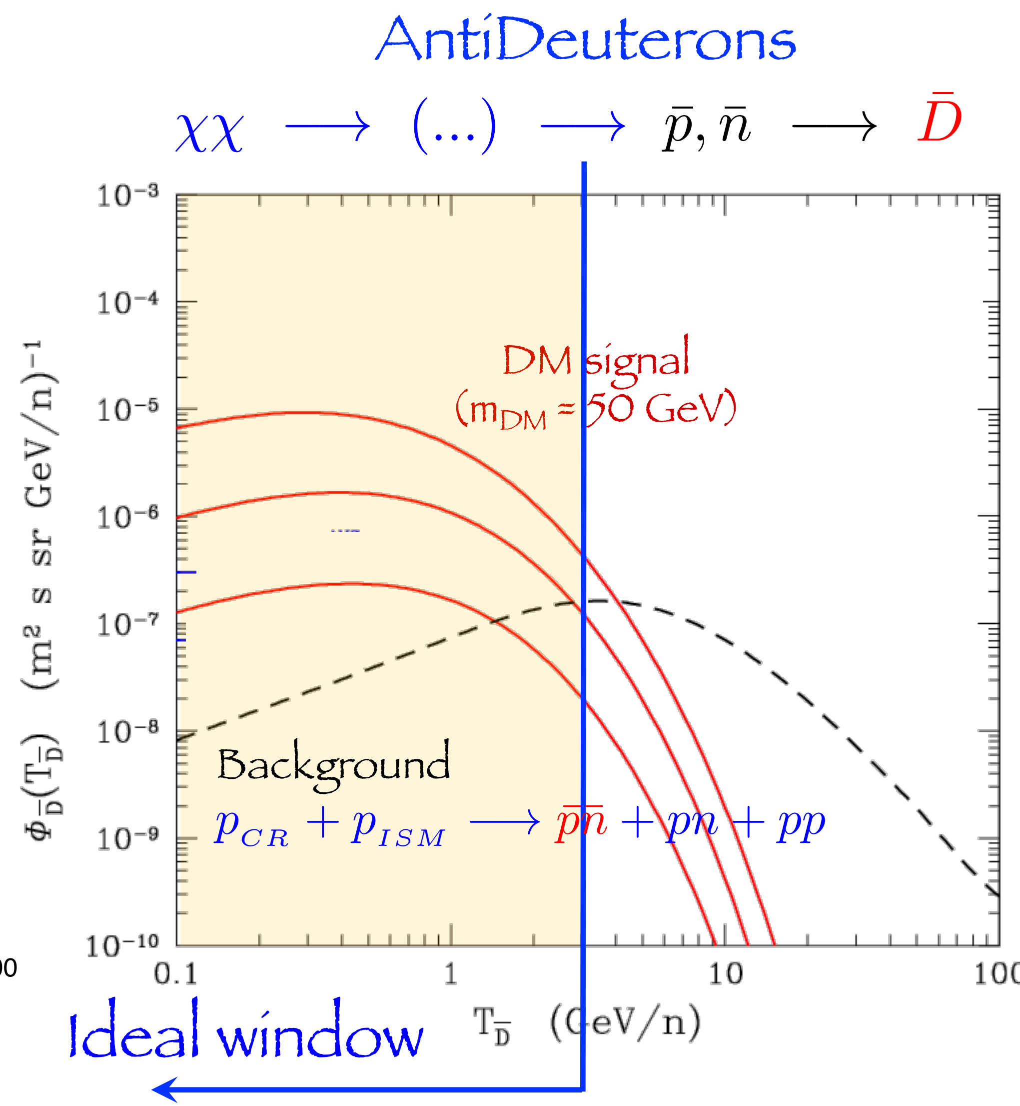
Radio

- Produced through electrons: source somehow blurred
- Depend on (highly uncertain) local magnetic fields
- Great energy and angular resolution

Antiprotons vs. Antideuterons

Donato, NF, Salati, PRD 62 (2000) 043003



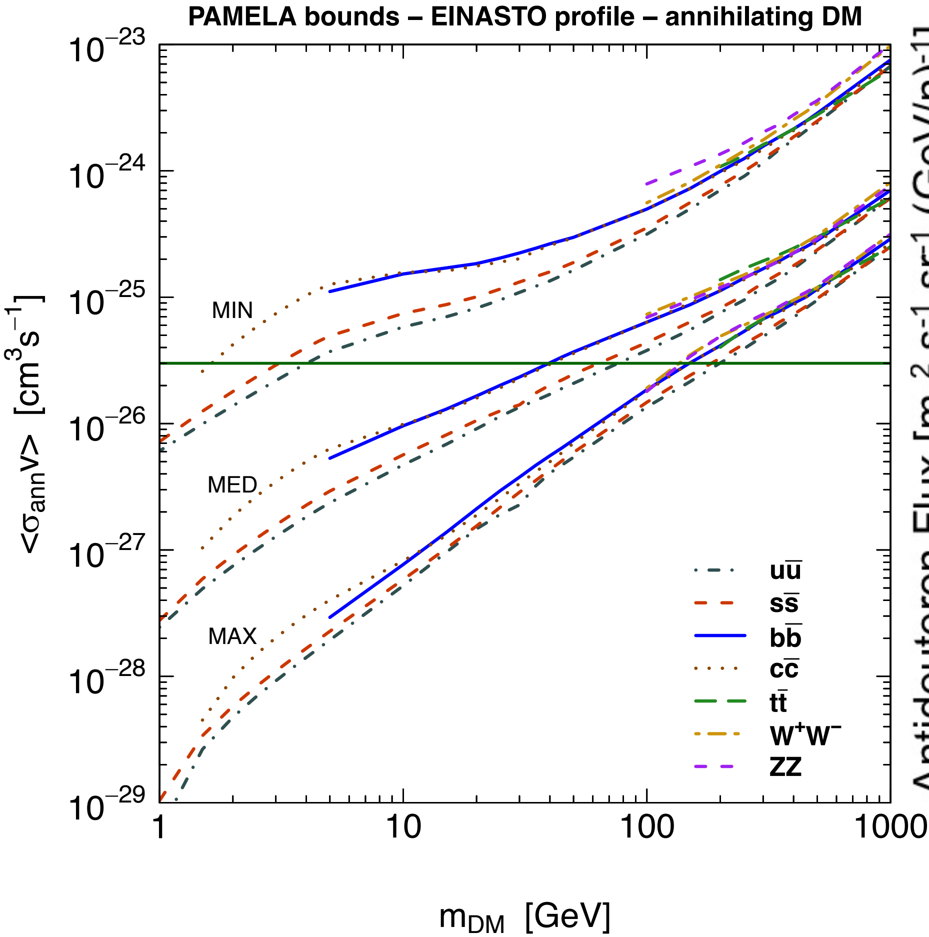


Donato, NF, Maurin, PRD 78 (2008) 0403506

Bounds and prospects

AntiProtons

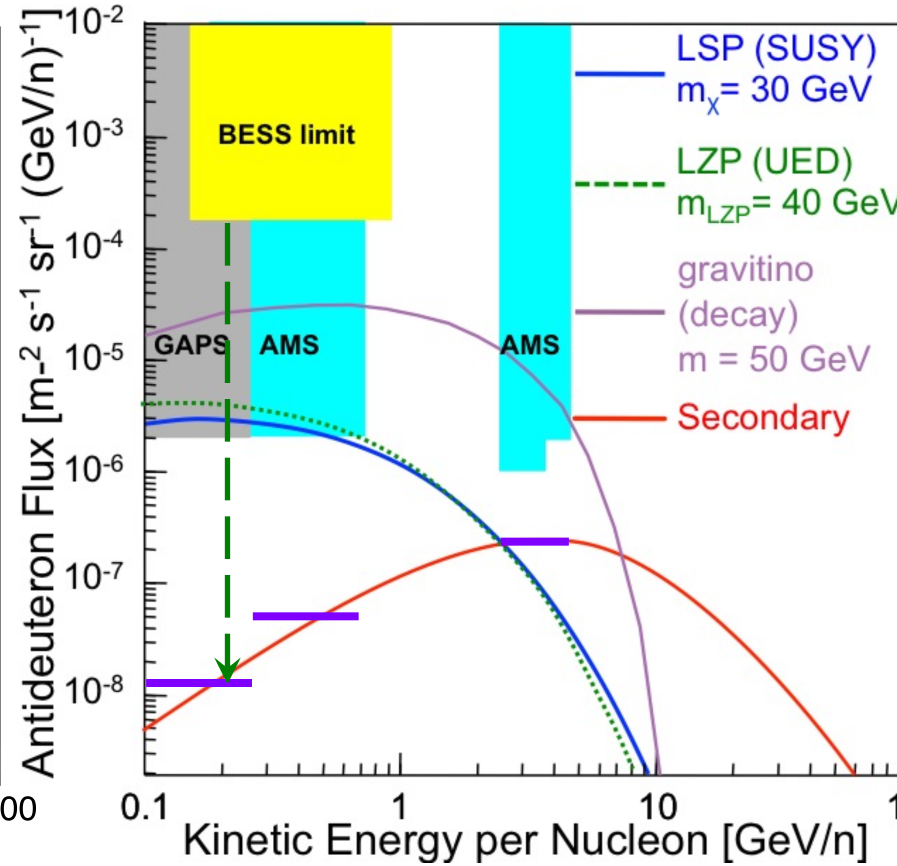
NF, Maccione, Vittino, JCAP 1404 (2014) 003



Bounds from PAMELA

AntiDeuterons

Aramaki, Donato, NF, Vittino et al, Phys. Rep. 618 (2016) 1



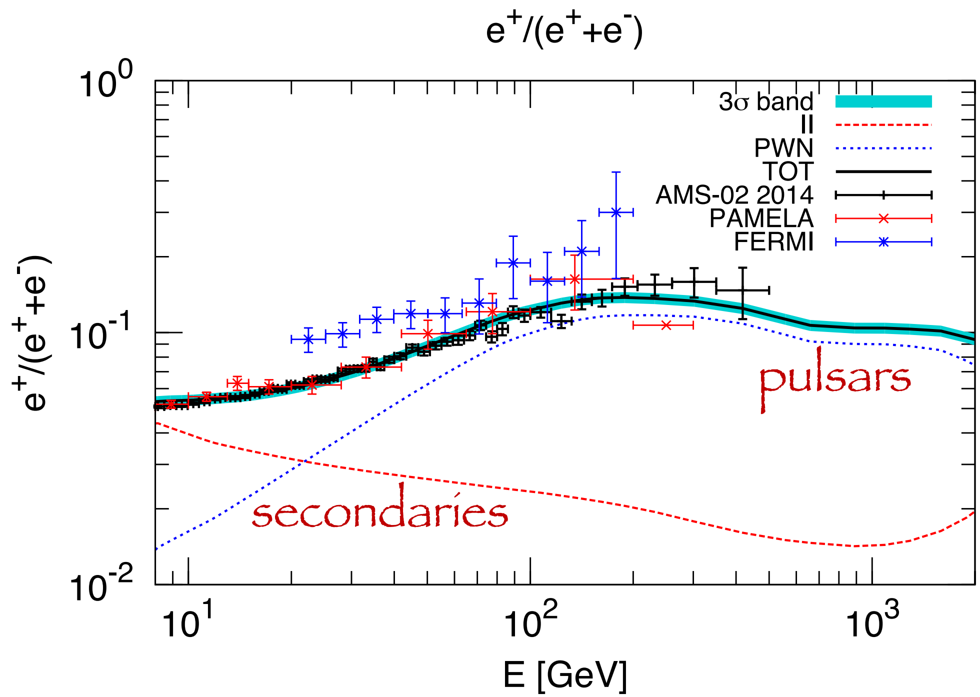
Best window: below 1 GeV/n - optimal at 100 MeV

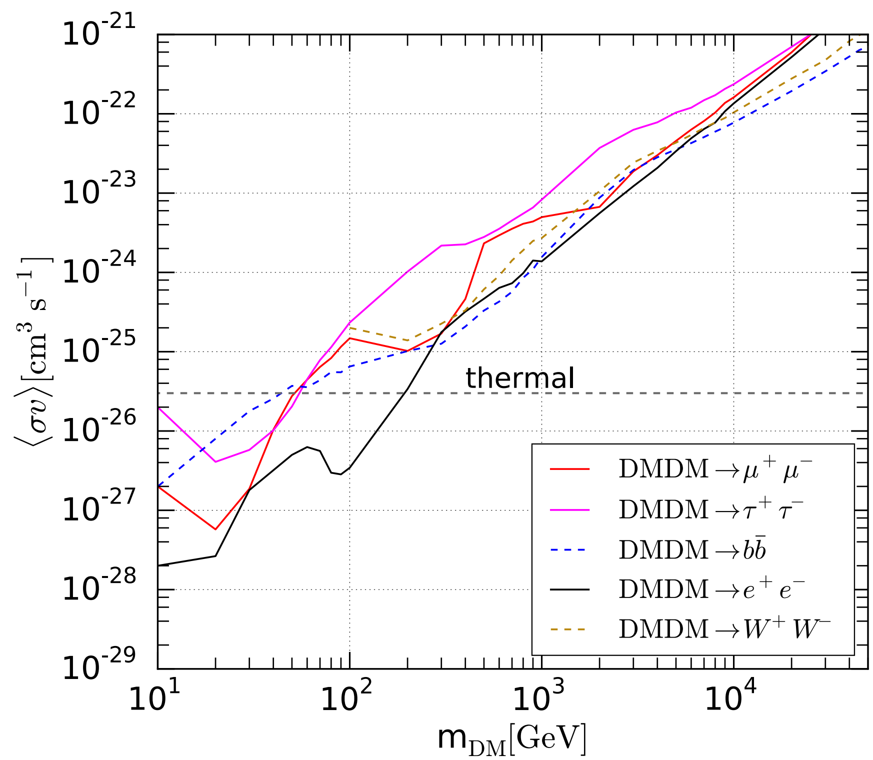
Kinematics: largely favours signal over background

Opportunity: "0-back" over 3/4 orders of magnitude

Even a "single antiD": smoking gun for exotics

Electrons/positrons





Astrophysical interpretation

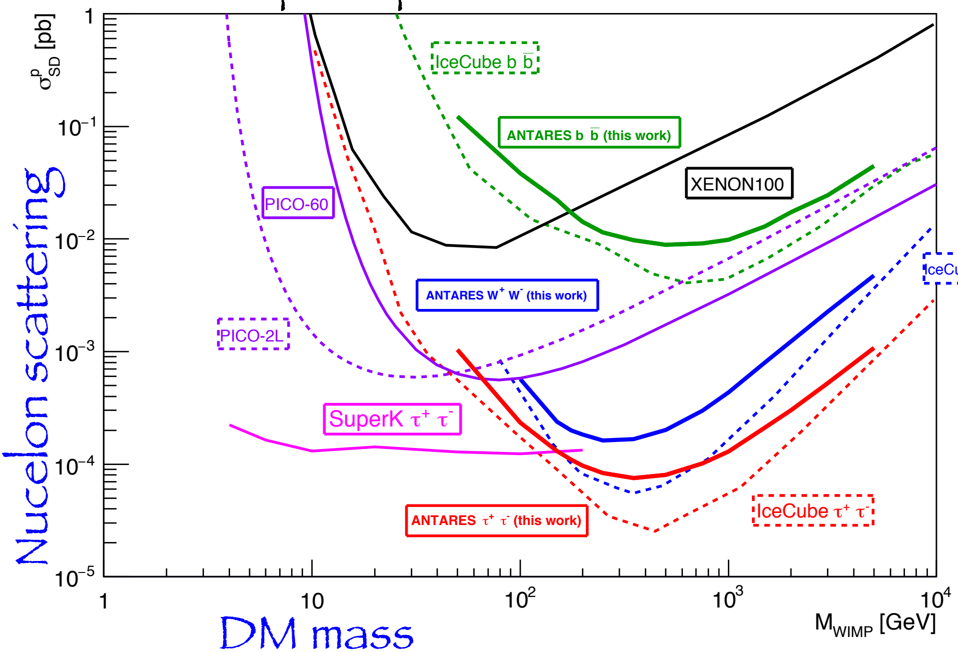
Bounds on DM

Di Mauro, Donato, NF, Vittino, JCAP 1605 (2016) 031

Neutrinos

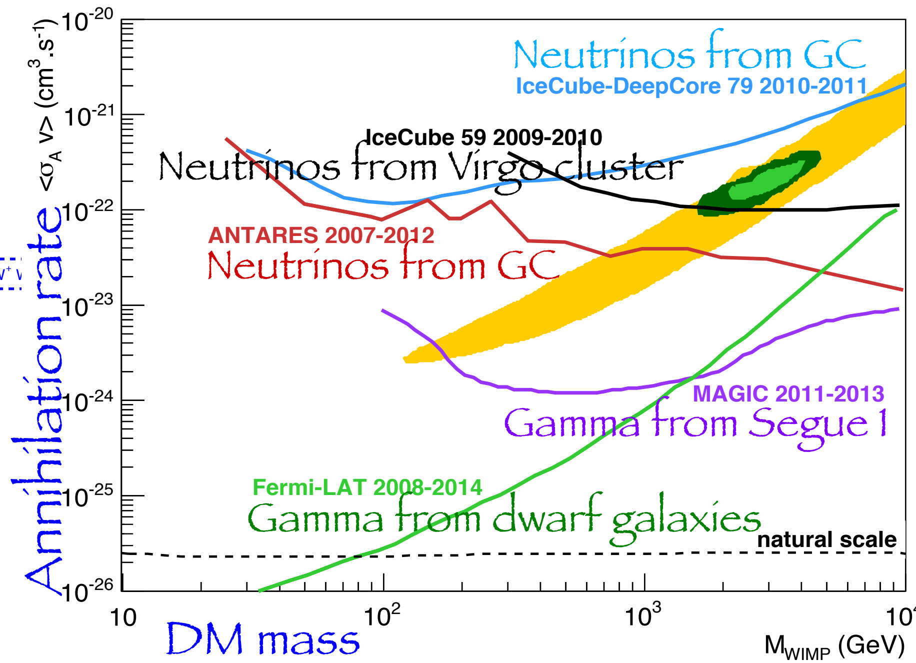
From the Sun

Spin dependent interaction



ANTARES Collab, PLB 759 (2016) 69

Other targets

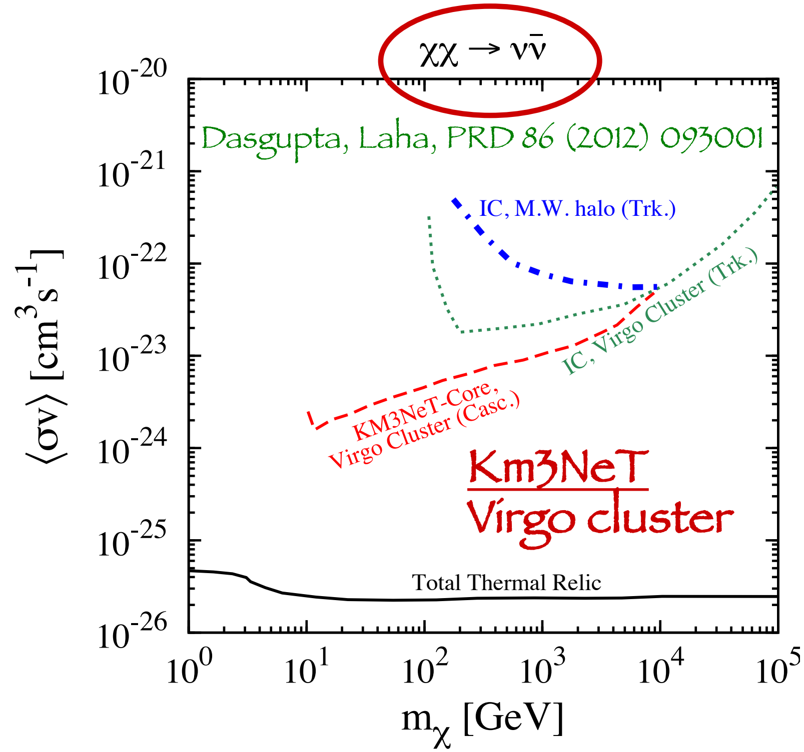


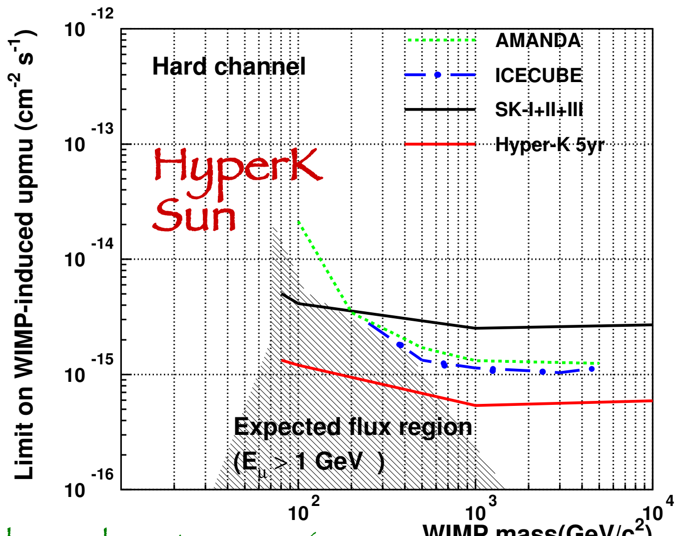
ANTARES Collab, JCAP 1510 (2015) 068

Warning: bounds are typically derived under the assumption of perfect equilibration between capture and annihilation (and contact interactions)

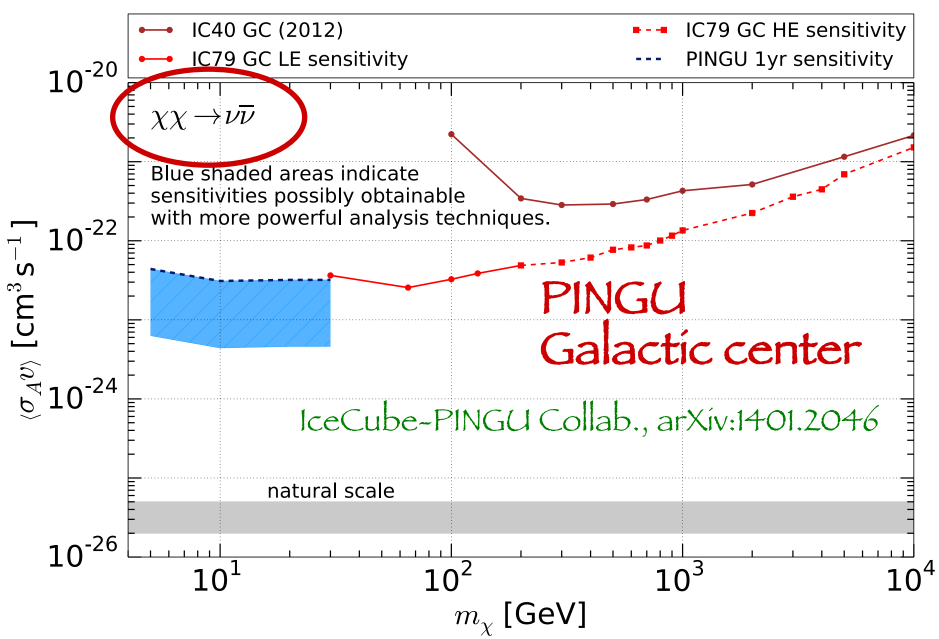
Prospects

- Relevant sensitivities for:
  - DM signal from the Sun
  - Galactic center
  - Galaxy clusters
- Km3Net
- Hyperkamiokande
- DeepCore, PINGU





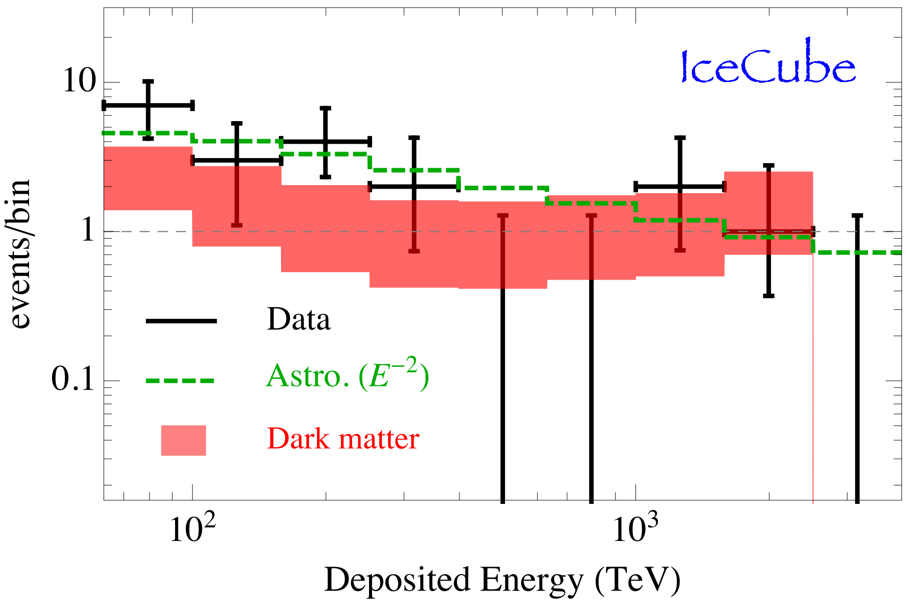
Abe et al, arXiv:1109.3262

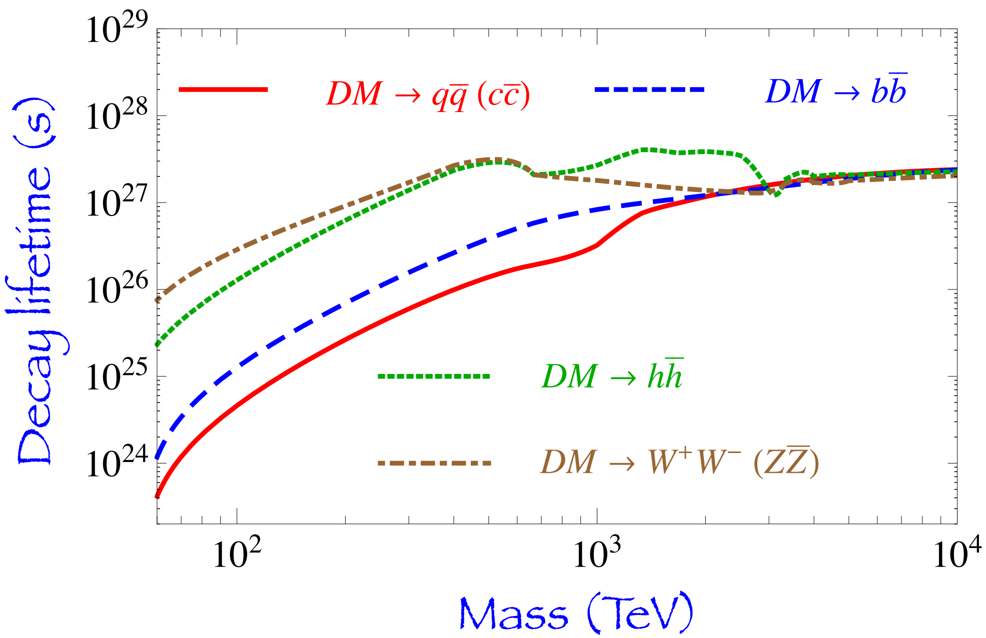


IceCube PeV neutrinos

The spectral feature of the IceCube PeV events could refer to decaying very heavy DM: PeV scale

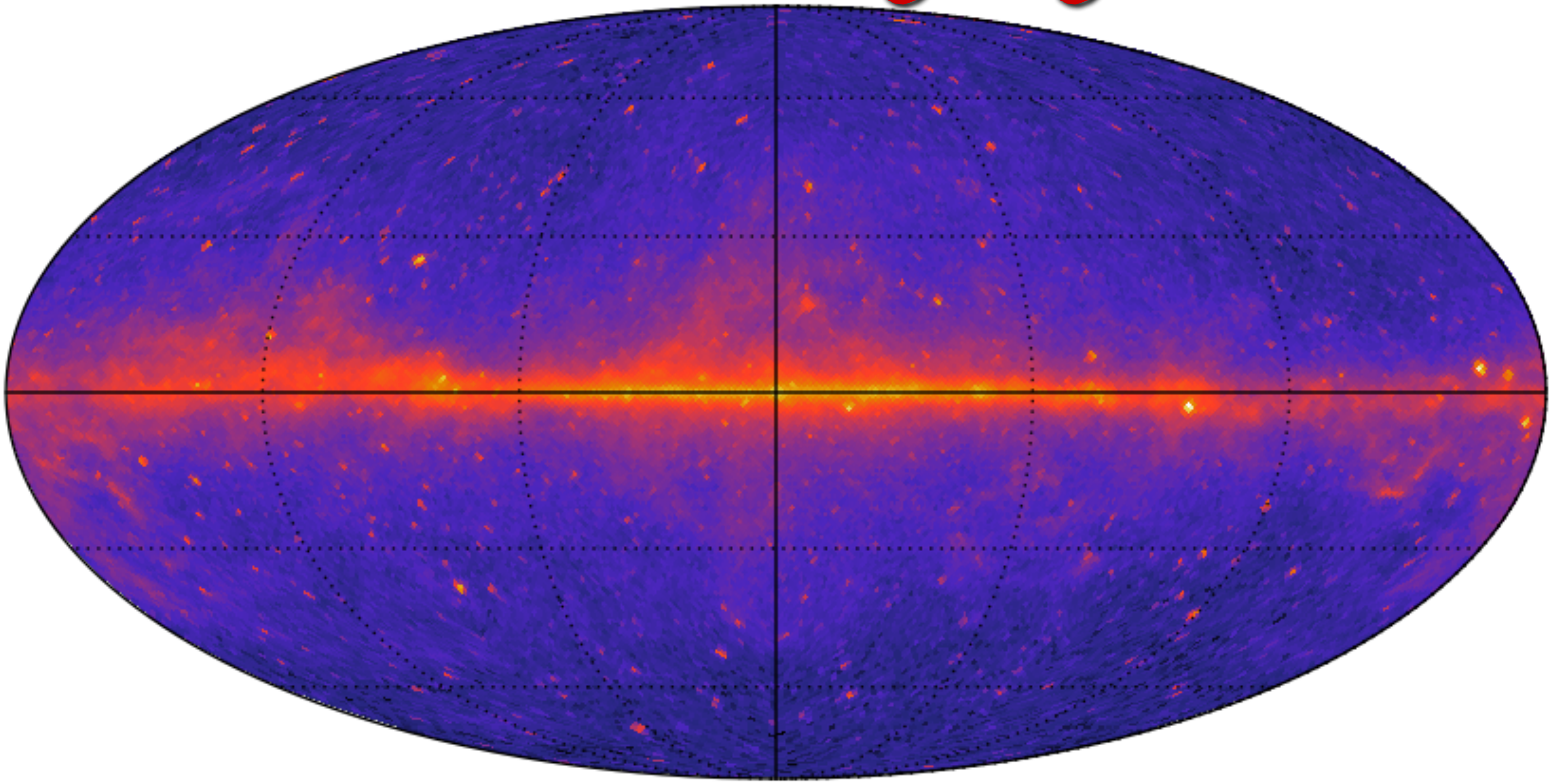
e.g. $m_{DM} \approx 4$ PeV lifetime $\approx 10^{28}$ s





Esmaili, Serpico, JCAP 1412 (2014) 054

Gamma-ray sky



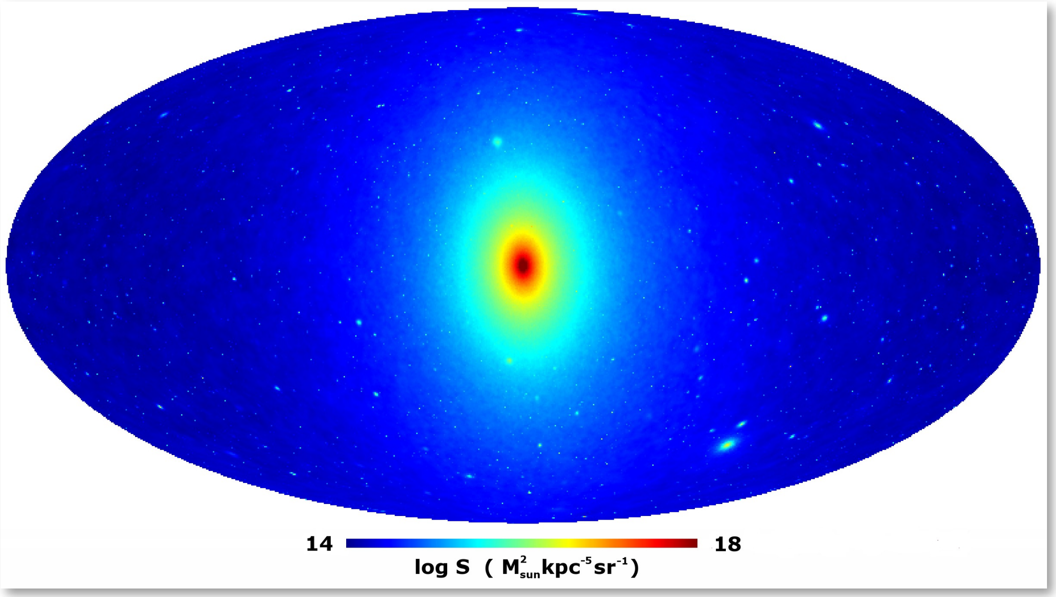
Fermi/LAT map

Galactic foreground emission

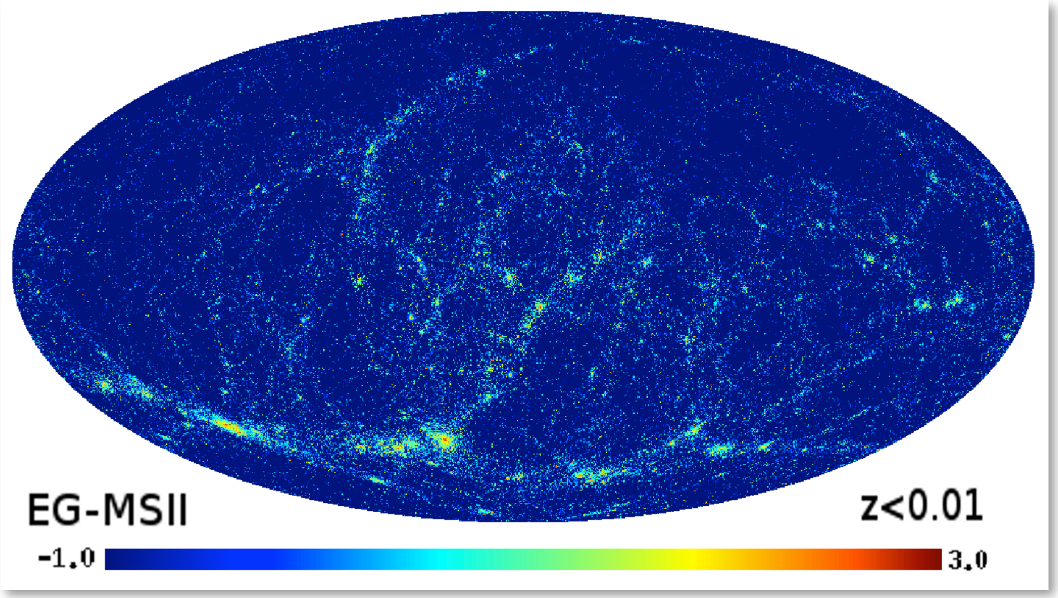
Resolved sources

Diffuse Gamma-Ray Backgound (DGRB)

Gamma-ray sky and DM



Galactic emission



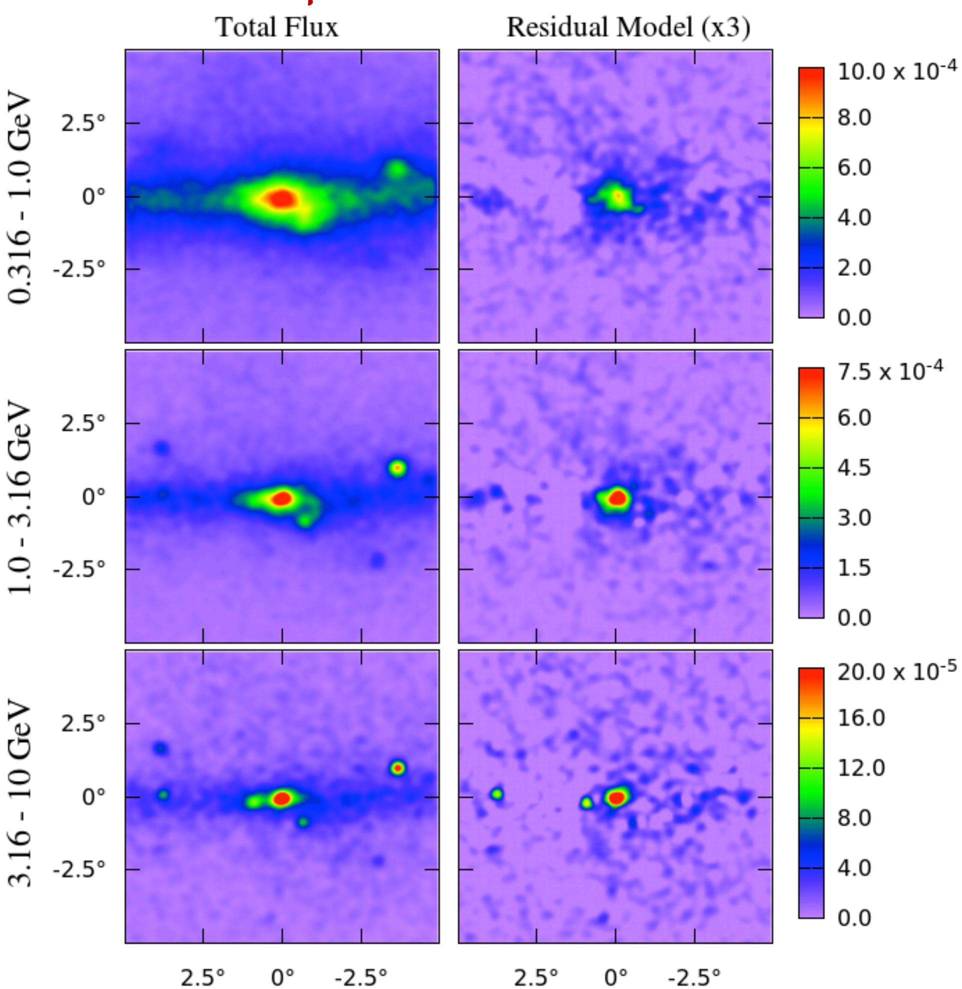
Extra galactic emission

Galactic center: an "excess" ?

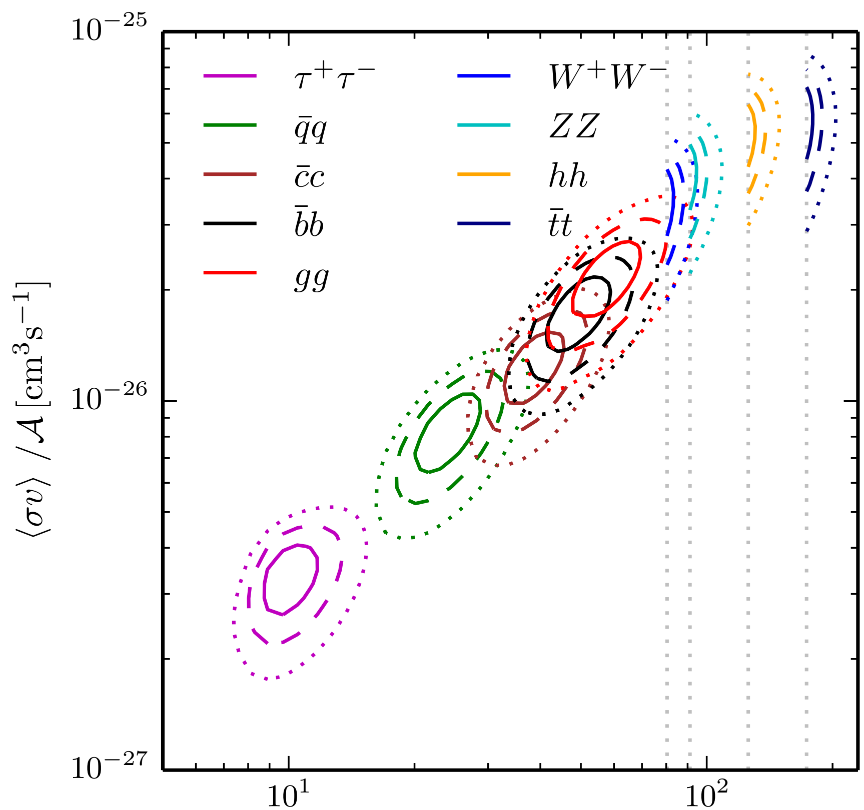
Hooper, Goodenough, PLB (2011) 697 (2011)
Hooper, Linden, PRD 84 (2011) 123005
Boyarsky et al., PLB (2011) 705
Daylan et al., Phy Dark Univ 12 (2016) 1
Abazajian et al, PRD 90 (2014) 023526
Lacroix, Boehm, Silk, PRD 90 (2014) 043508

Fermi/LAT excess(es) at the galactic center

DM or pulsars or bursts?

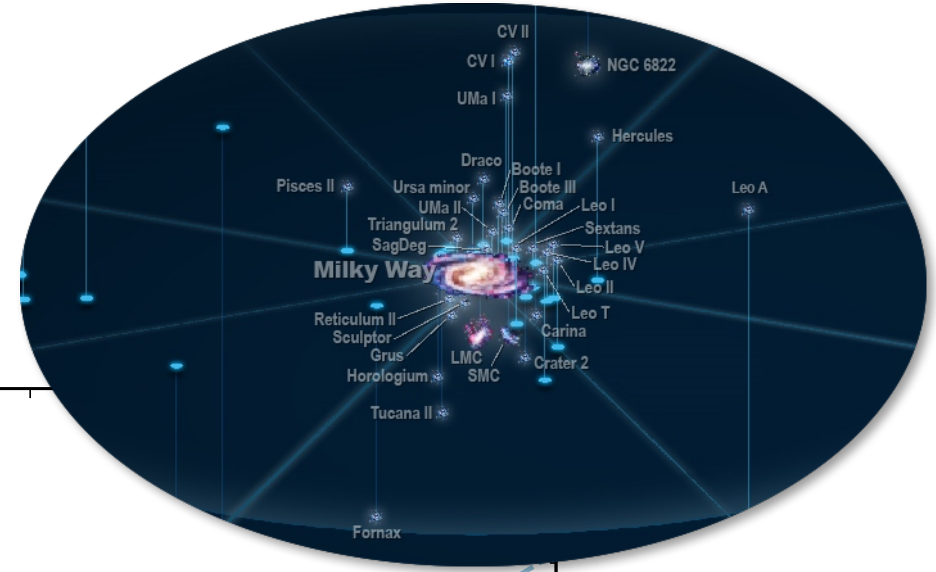


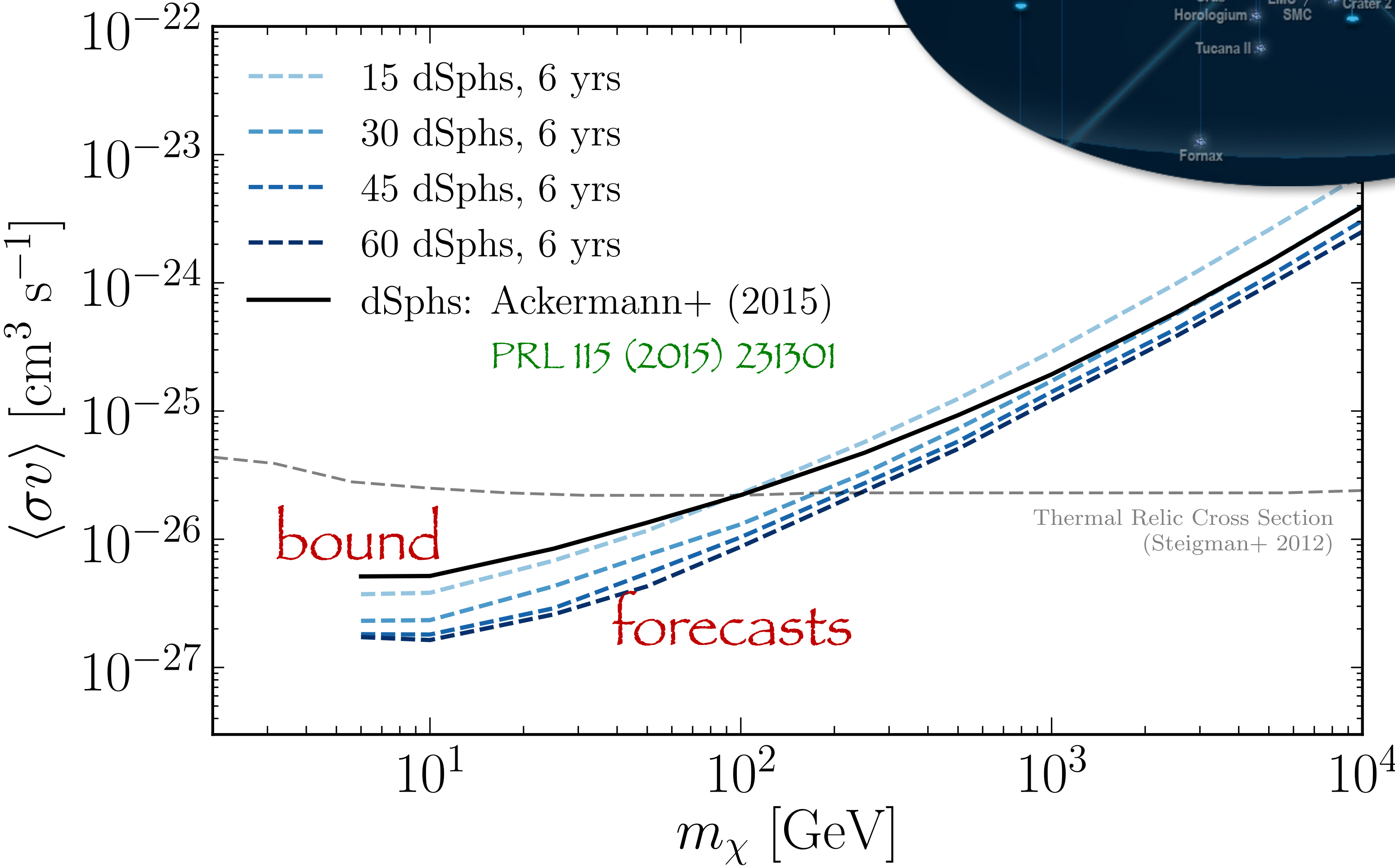
Daylan et al, Phys Dark Univ 12 (2016) 1



Calore et al, PRD 91 (2015) 063003

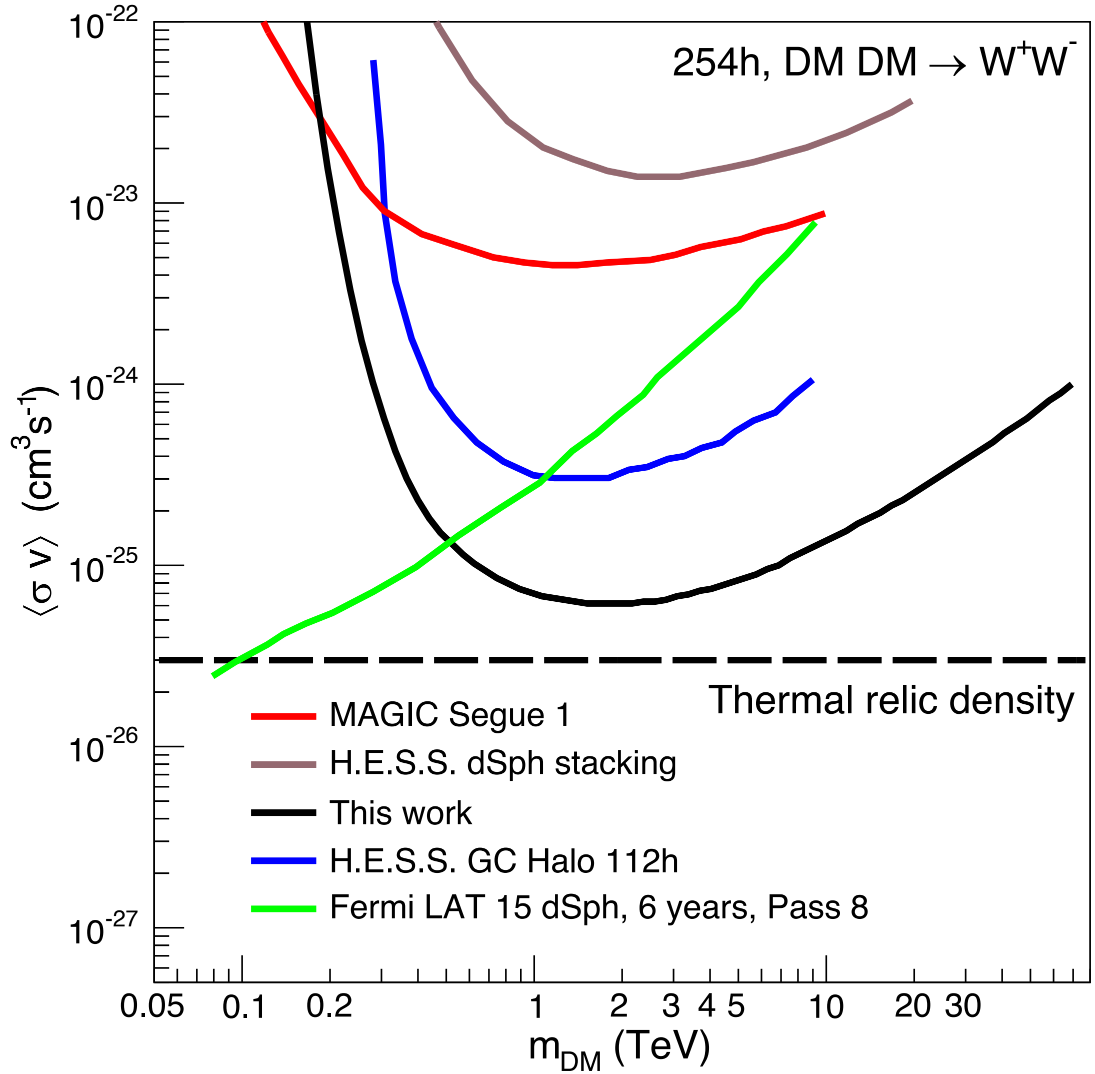
Dwarf galaxies





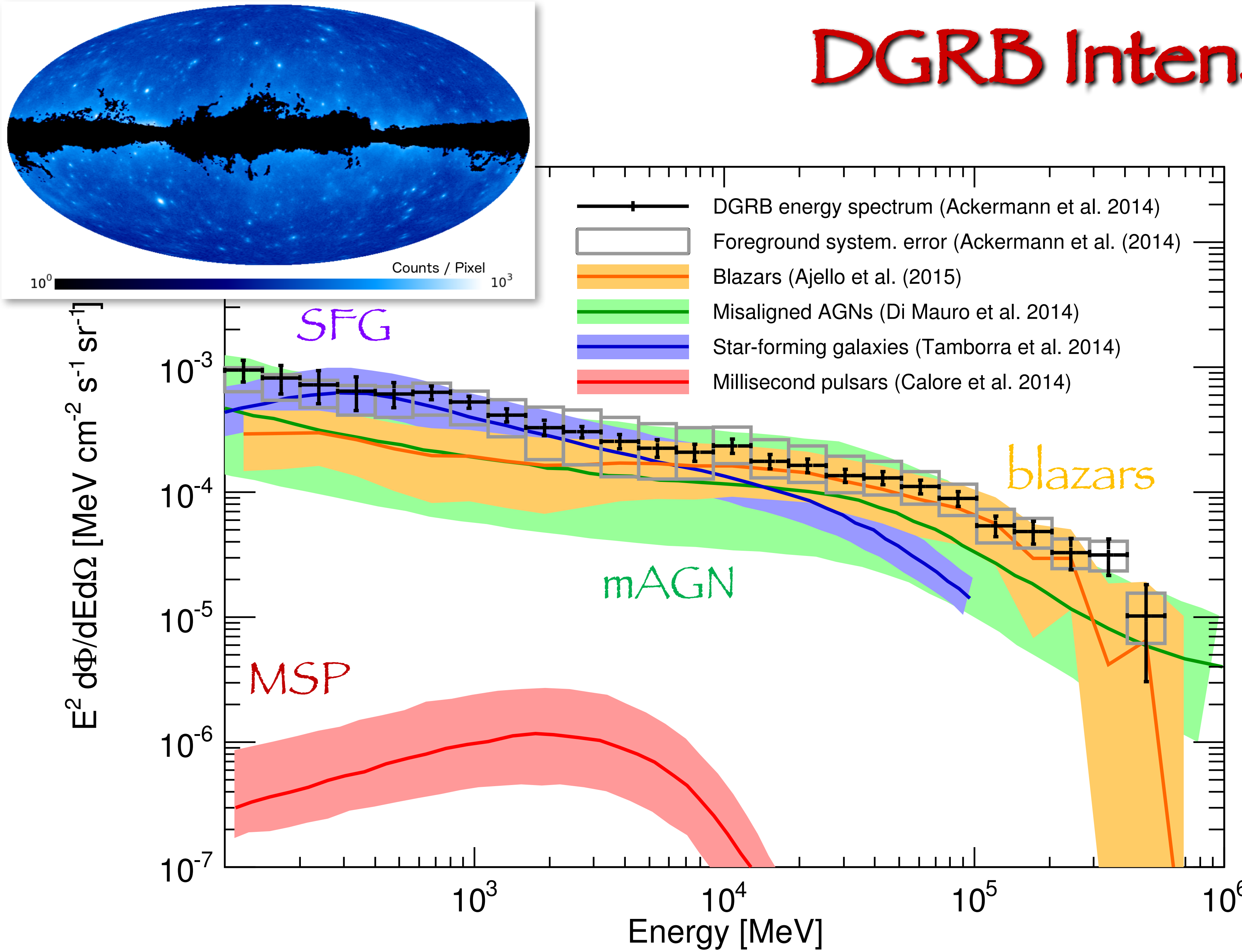
Charles et al (Fermi Collab) Phys Rep 636 (2016) 1

Inner galactic halo: HESS 10 yrs



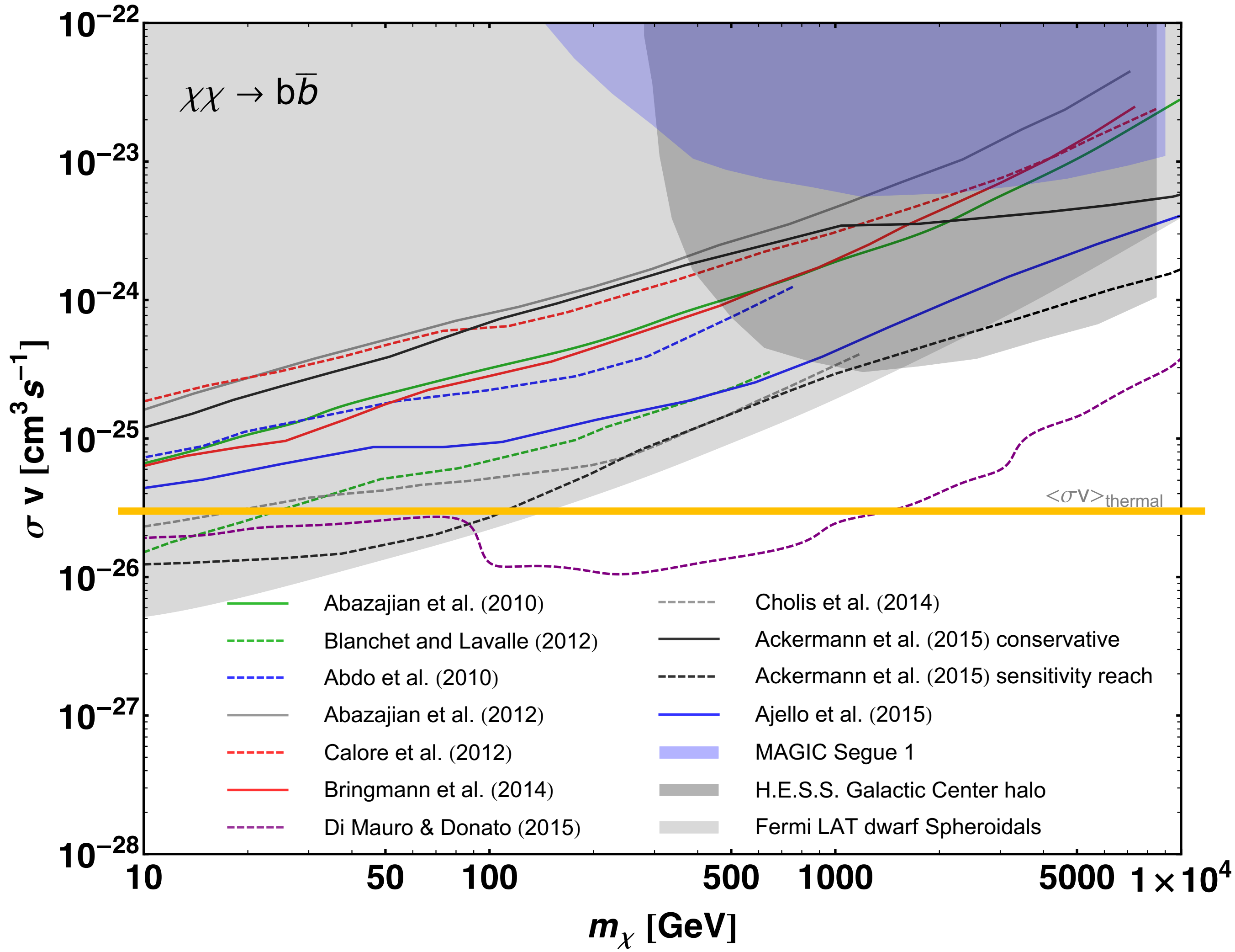
HESS Collaboration, 1607.08142

DGRB Intensity



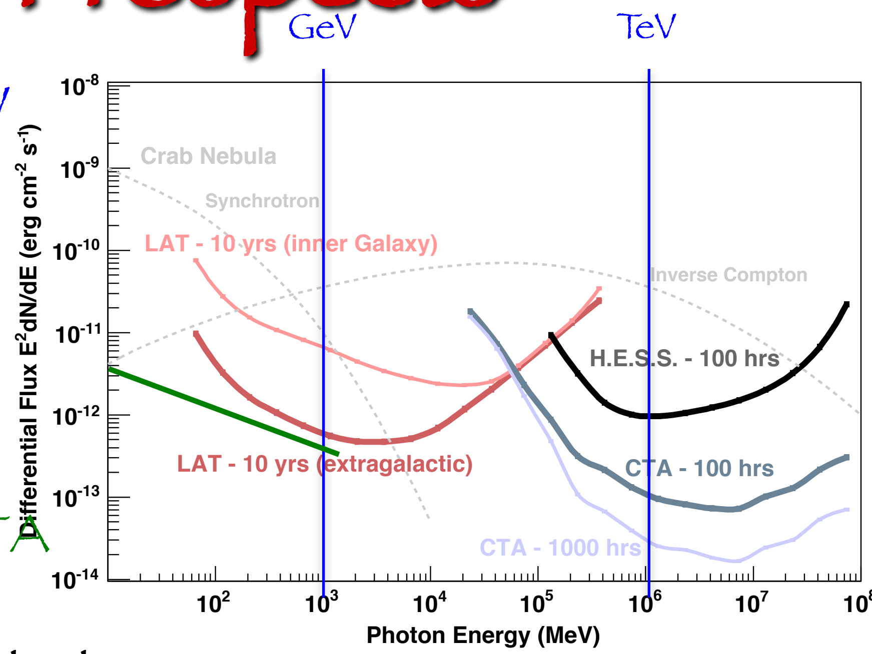
Fornasa, Sanchez-Conde, Phys. Rep. 598 (2015) 1

DGRB intensity bounds on DM



Fornasa, Sanchez-Conde, Phys. Rep. 598 (2015) 1

Gamma rays - Prospects



- Higher energies (ground): >300 GeV

  Probe TeV+ DM

  Targets

  Galactic center
  DM clumps
  dSphs galaxies
  Galaxy clusters

  Magic, HESS, Hawc, LHAASO, CTA

- GeV – TeV energies (space) or even higher

  Probe GeV-TEV DM

  Improved energy and angular resolution

  DAMPE (2 GeV – 10 TeV), HERD (up to PeV), ...

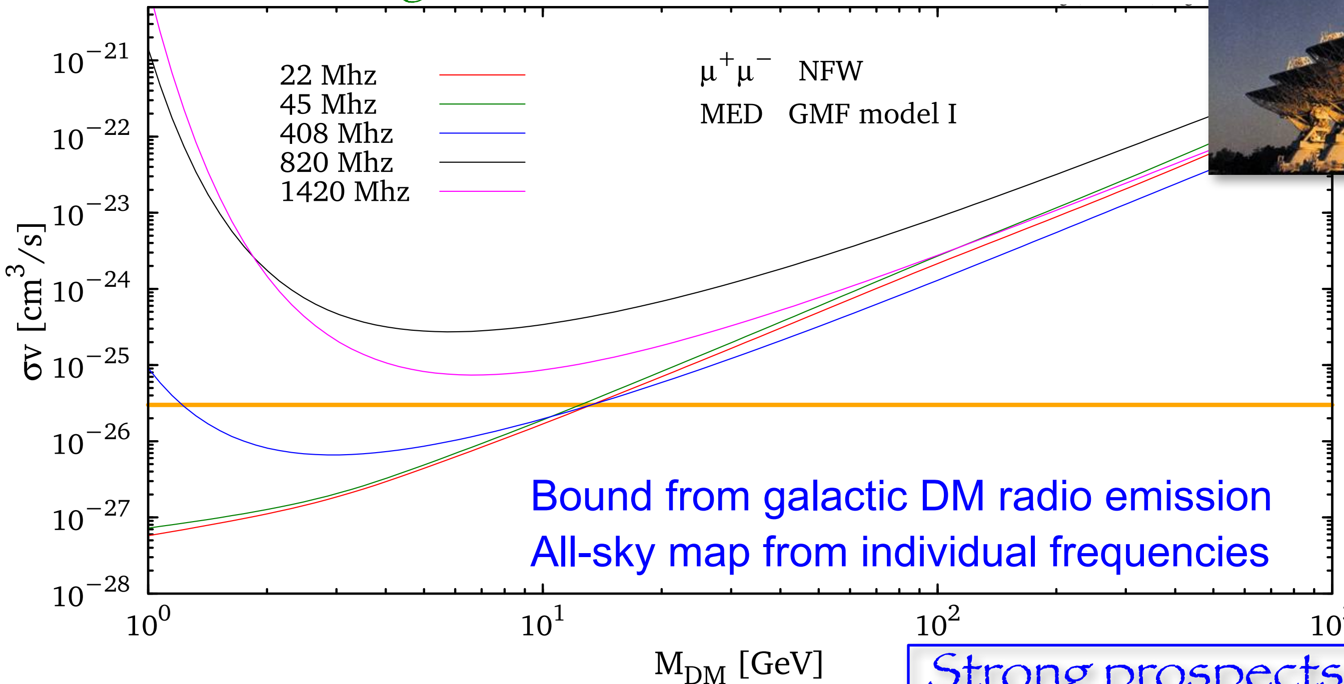
- Lower energies (space): MeV – GeV

  Probe subGeV DM or the low-energy tail of WIMP DM

  AstroGam, PANGU, ...

Radio frequencies

NF, Lineros, Regis, Taoso, JCAP 01 (2012) 005



For:
e+,e- GeV-TeV
B microG

synchro: MHz - GHz

Strong prospects: SKA and precursors, Lofar, ...

Lower frequencies better for lighter DM

Constraining power also depends on sky-coverage and sensitivity of the survey

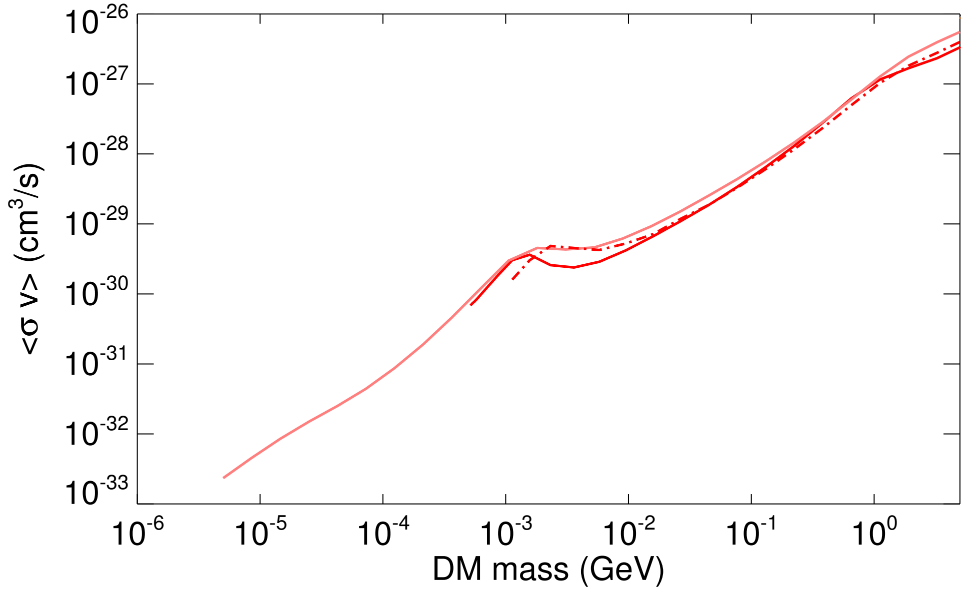
NF, Lineros, Regis, Taoso, JCAP 03 (2012) 033

Extragalactic radio has a similar (slightly worse) constraining power (but different uncertainties in modeling)

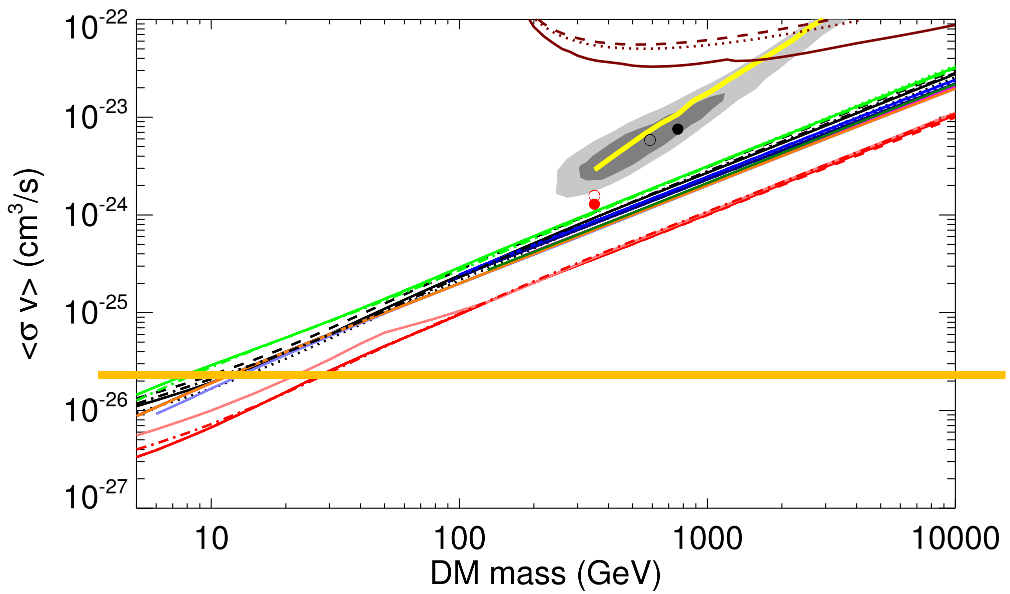
Egorov, Pierpaoli, PRD 88 (2013) 023504
Regis et al, JCAP 1410 (2014) 016

Bounds from specific target start to be competitive (dwarf galaxies; Andromeda)

CMB



Slatyer, PRD 93 (2016) 023527



Injection of ionizing particles during the cosmic dark ages

Increase in the residual ionization fraction and affect CMB

See also:

- Zhang et al, PRD 76 (2007) 061301
- Galli et al, PRD 80 (2009) 023505
- Slatyer et al, PRD 80 (2009) 043526
- Kanzakiet et al, Prog. Theor. Phys. 123 (2010) 853
- Hisanoet et al, PRD 83 (2011) 123511
- Hutsi et al., A&A 535 (2011) A26
- Galli et al, PRD 84 (2011) 027302
- Finkbeiner et al, PRD 85 (2012) 043522
- Slatyer et al, PRD 87 (2013) 123513 (2013)
- Galli et al, PRD 88 (2012) 063502
- Lopez-Honorez et al, JCAP 1307 (2013) 046
- Madhavacheril et al, PRD 89 (2014) 103508

Low frequencies and non-WIMP

X rays

Impossibile trovare nel file la parte immagine con ID relazione rId2.

3.5 KeV line

73 galaxy clusters

Perseus cluster + Andromeda

Bulbul et al, ApJ 789 (2014) 13

Boyarski et al, PRL 113 (2014) 251301

Sterile neutrino DM decay?

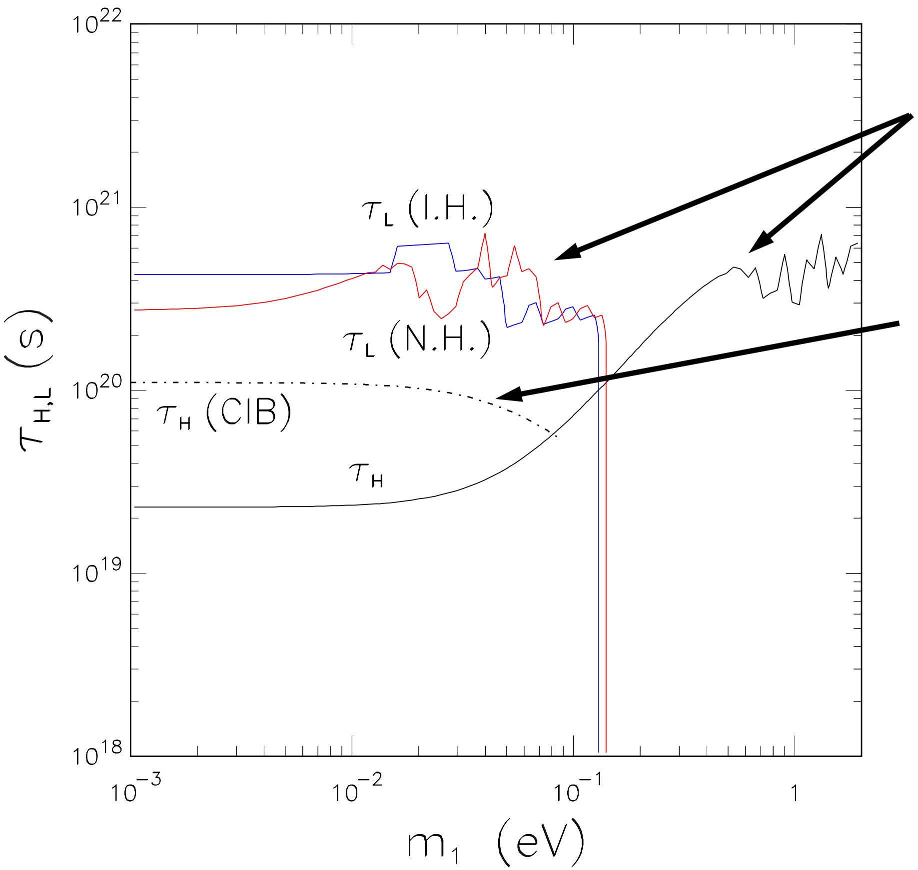
De-excitation lines?

New bounds from nuSTAR

Perez et al, 1609.00667

Low frequencies and non-WIMP

CMB, Infrared (CIB)



CMB: FIRAS spectral information

CIB: Spitzer: peak 100 μm (10^{-2} eV)
flux ≈ 24 nW m^{-2} sr^{-1}

NIRB (eV)

See e.g.: Gong et al, ApJ 825 (2016) 104
Evoli, NF, Regis, Vittino, to appear

Mirizzi, Montanino, Serpico, PRD 76 (2007) 053007

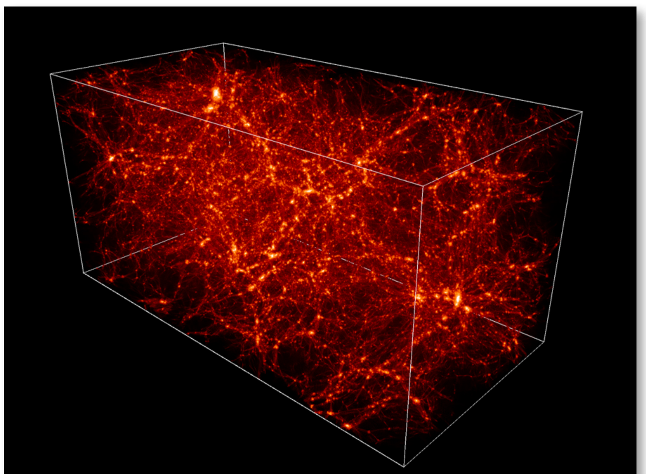
See also: Mirizzi, Raffelt, Serpico PRD (2005) 023501
Melchiorri et al, PLB 650 (2007) 417

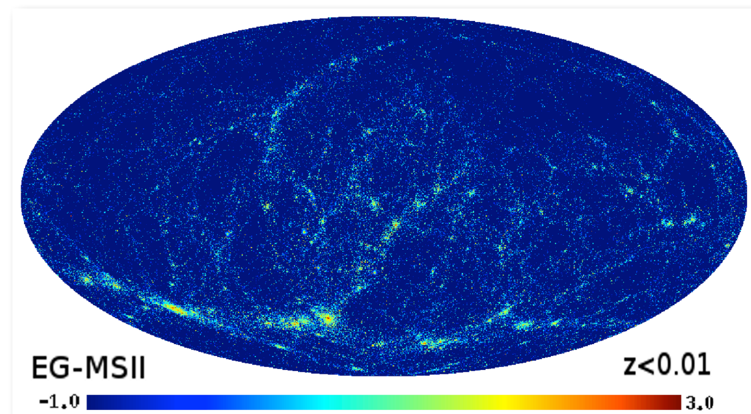

Going
beyond

Diffuse signals: faint & not isotropic ...

Being the cumulative sum of independent sources (astro/DM)

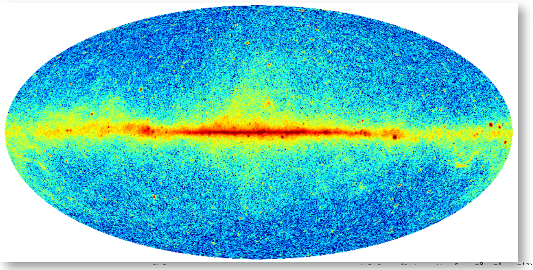
To first approximation: isotropic
At a deeper level: anisotropies are present





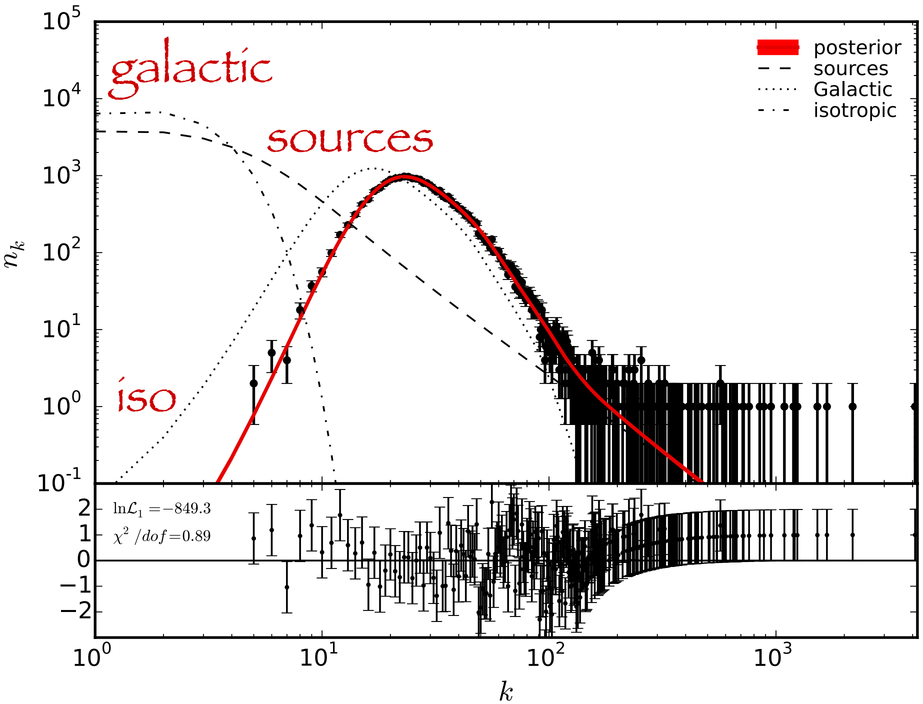
Even though sources are too dim to be individually resolved, they can affect the statistics of photons across the sky

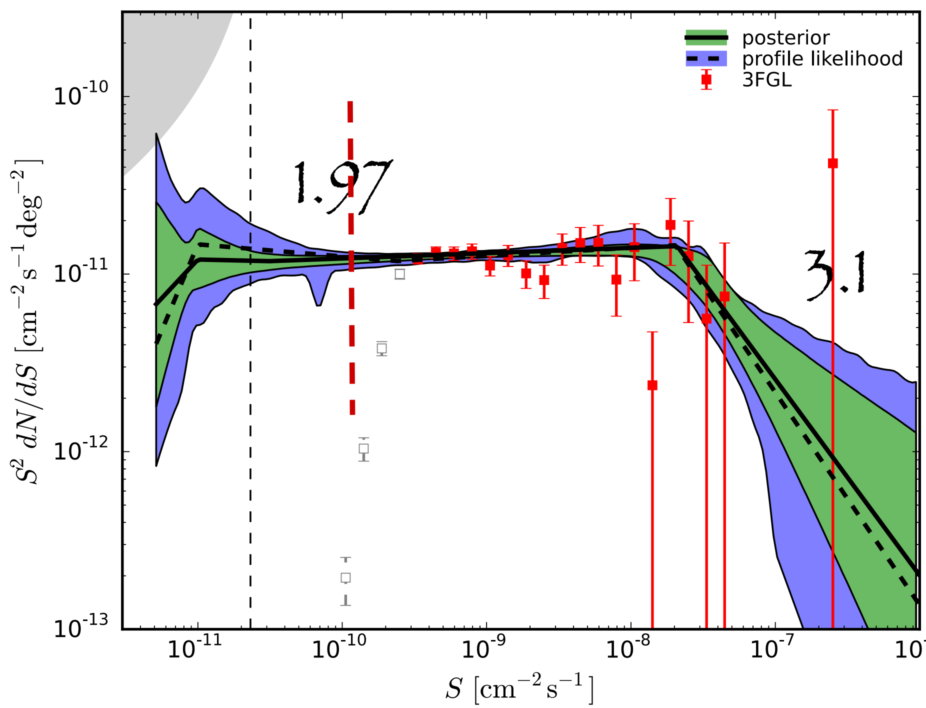
Photon statistics



Photon pixel counts (1 point PDF)

Source count number dN/dS below detection threshold

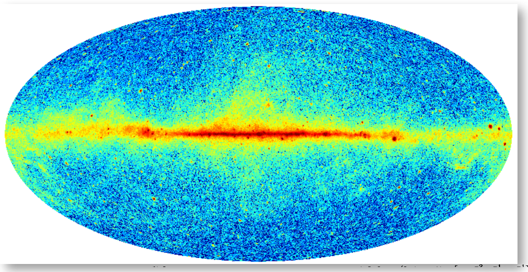




Zechlin, Cuoco, Donato, NF, Vittino, ApJS 225 (2015) 039
Zechlin, Cuoco, Donato, NF, Regis, ApJL 826 (2016) 831

See also: Malyshev, Hogg, Astrophys. J. 738 (2011) 181
Lisanti et al, 1606.0401

Photon statistics



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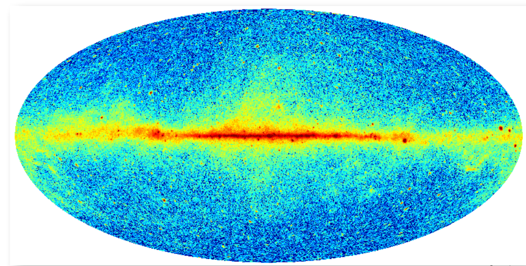
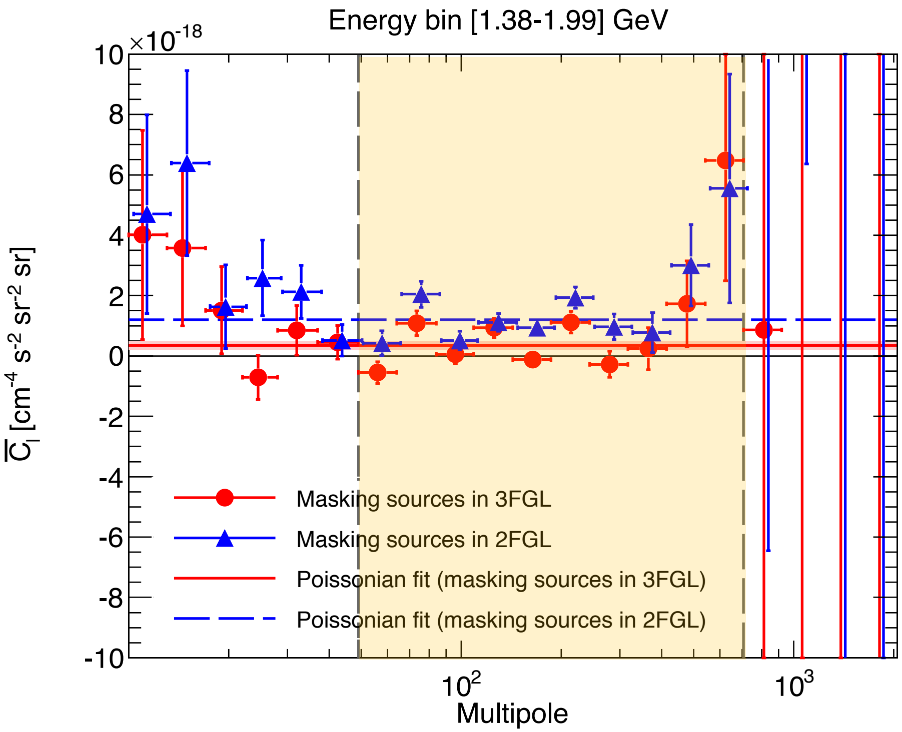
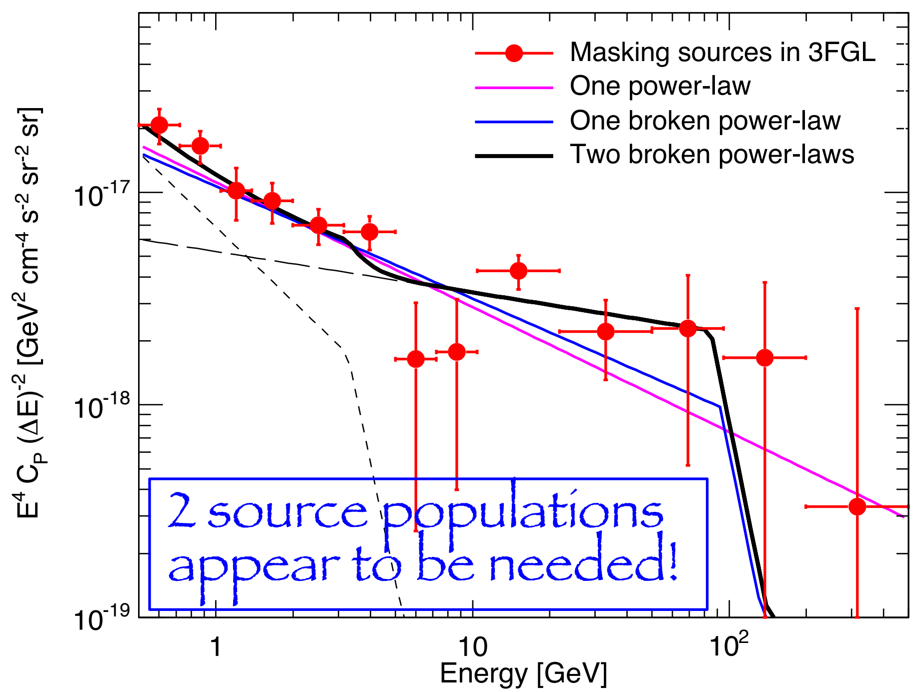


2 point correlator
angular power spectrum

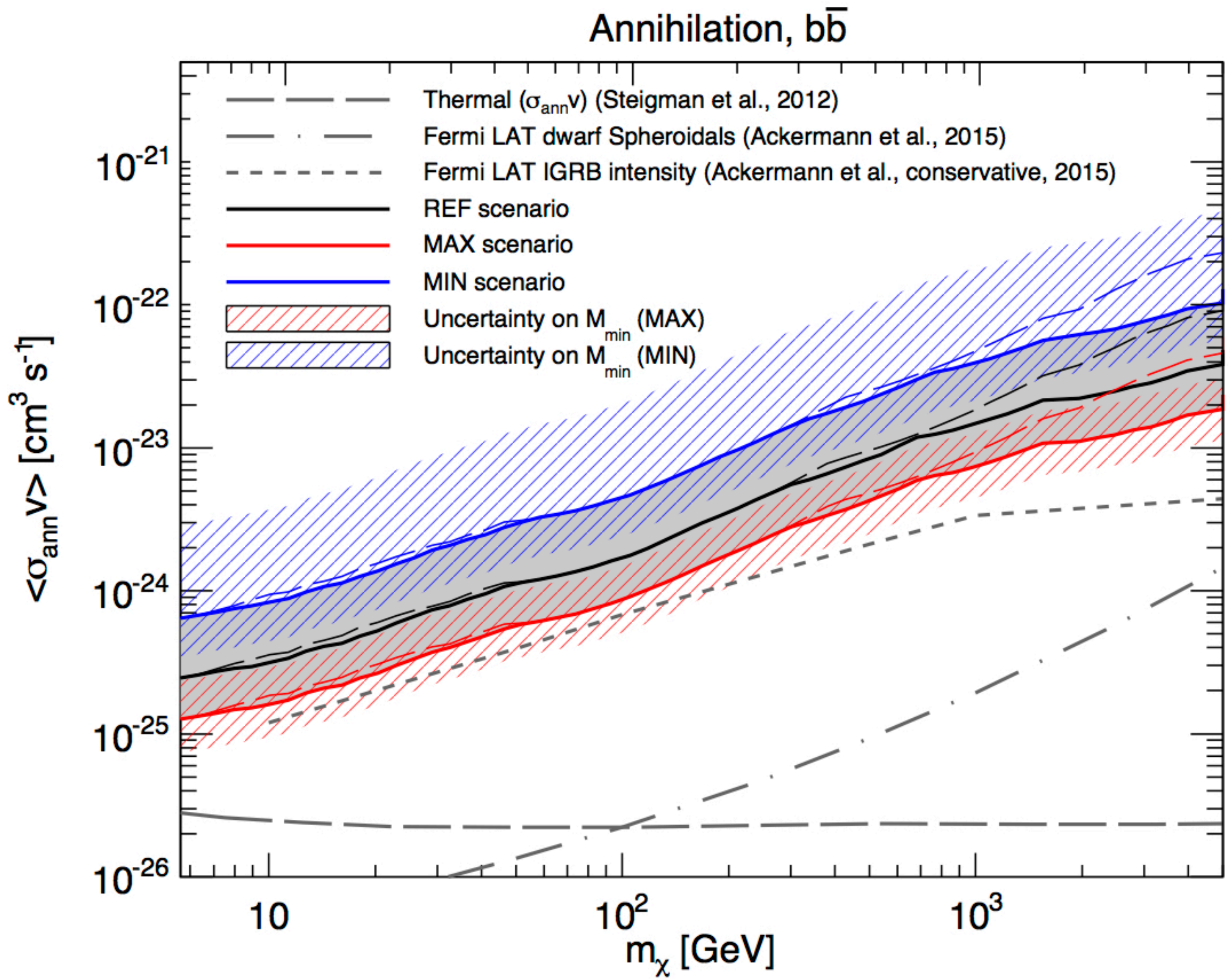
$$\langle\, I(\vec{n}_1) I(\vec{n}_2) \,\rangle \;\longrightarrow\; C(\theta) \;\longrightarrow\; C_l$$





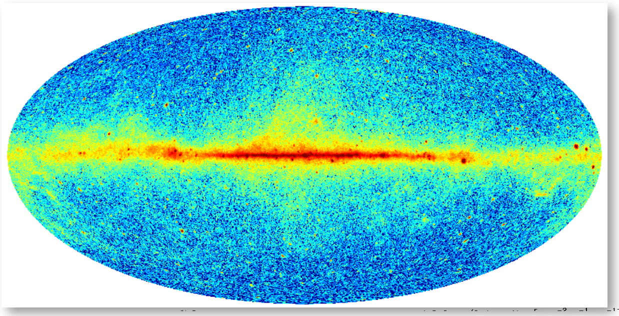
Fornasa et al, 1608.07289
See also: Ackerman et al (Fermi Collab) PRD 85 (2012) 083007

DM bounds from auto - correlation

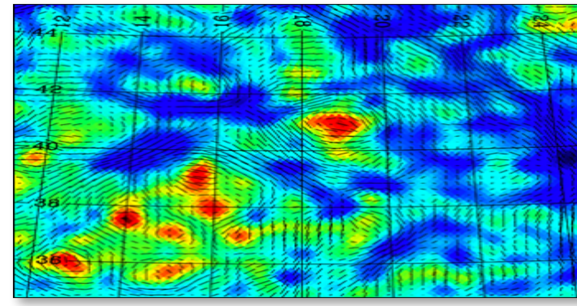


Fornasa et al, 1608.07289

Fold two pieces of information



×



Cross-correlation of EM signal with gravitational tracer of DM

It exploits two distinctive features of particle DM:

- Electromagnetic signal: manifestation of the particle nature of DM
- Gravitational tracer: probe of the existence of DM

It can offer a direct evidence that what is measured by means of gravity is indeed due to DM as a particle

Camera, Fornasa, NF, Regis, Ap. J. 771 (2013) L5 + JCAP 1506 (2015) 029
NF, Regis, Front. Physics 2 (2014) 6

Cross - Correlations

Lensing observables

- Cosmic shear: directly traces the whole DM distribution
  Camera, Fornasa, NF, Regis, Ap. J. Lett. 771 (2013) L5
  Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029
- CMB lensing: traces DM imprints on CMB anisotropies
  NF, Perotto, Regis, Camera, Ap. J. Lett. 802 (2015) 1 L1
  NF, Regis, Frontiers in Physics, 2 (2014) 6

Large scale structure:

- Galaxy catalogs: trace DM by tracing light
  Cuoco, Brandbyge, Hannestad, Haugbolle, Miele, PRD 77 (2008)123518
  Ando, Benoit-Levy, Komatsu, PRD 90 (2014) 023514
  NF, Regis, Front. Physics 2 (2014) 6
  Ando, JCAP 1410 (2014) 061

Cross - Correlations

Gamma rays x Galaxy catalogs (LSS) — SIGNAL DETECTED

Xia, Cuoco, Branchini, Viel, APJS 217 (2015) 15 — Fermi x (SDSS + 2MASS + NVSS)
Regis, Xia, Cuoco, Branchini, NF, Viel, PRL 114 (2015) 241301 — "
Cuoco, Xia, Regis, Branchini, NF, Viel, ApJS 221 (2015) 29 — "
Shirasaki, Horiuchi, Yoshida, PRD 92 (2015) 123540 — Fermi x SDSS LRG

Gamma rays x Cosmic shear — SIGNAL NOT DETECTED (YET ...)

Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502 — Fermi x CFTHLenS
Shirasaki, Macias, Horiuchi, Shirai, Yoshida, 1607.02187 — Fermi x (CFTHLenS + RCSLenS)
Troester, Camera, Fornasa, Regis, Ando, NF, Van Vaerbecke +, to apper — Fermi x (CFTHLenS + RCSLenS + KiDS)

Gamma rays x CMB lensing — SIGNAL DETECTED

NF, Perotto, Regis, Camera, ApJ 802 (2015) L1 — Fermi x Planck

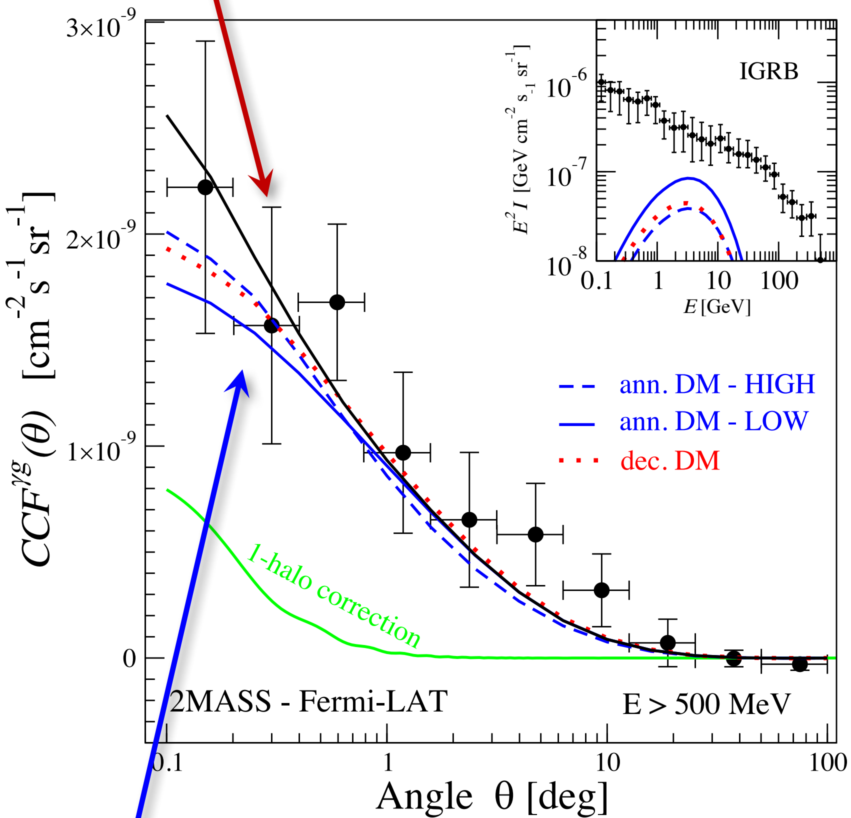
Gamma rays x Galaxy clusters — SIGNAL DETECTED

Cuoco, Regis, Camera, Branchini, NF, Viel, Xia, to appear — Fermi x (redMaPPer + WHL12 + PlanckSZ)

Cross - Correlations

measured correlation

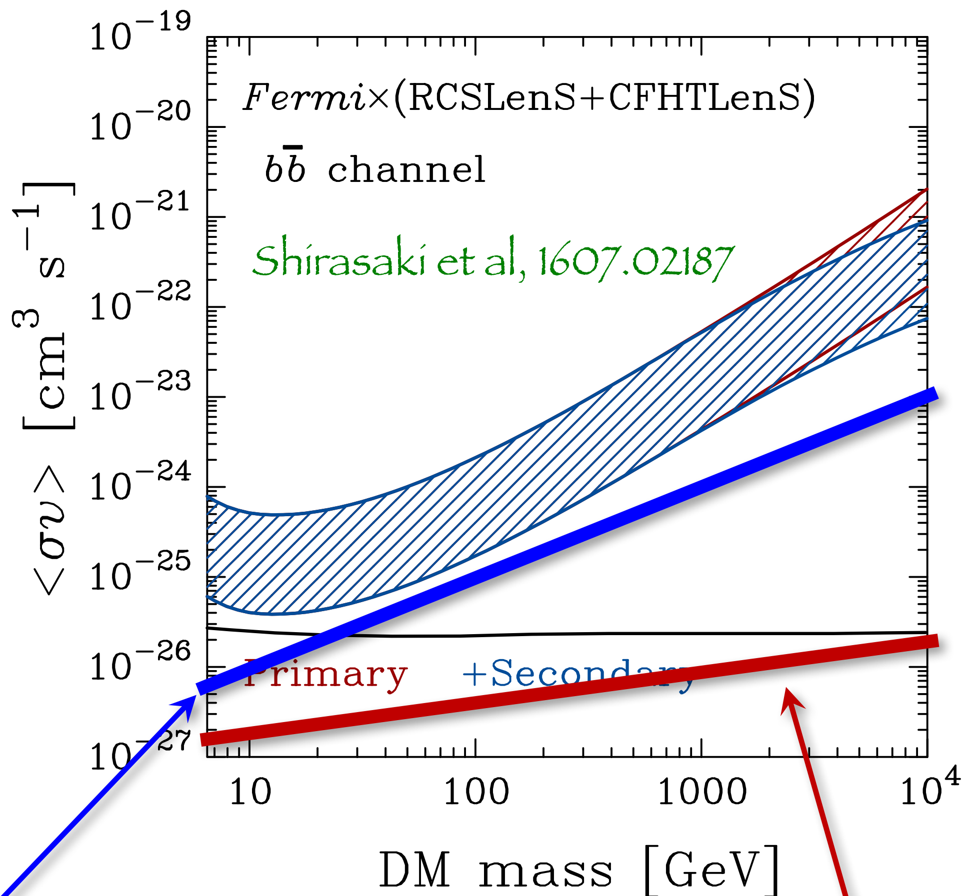
Fermi x 2MASS



Regis et al PRL 114 (2015) 241301

DM signal

Bounds from Fermi x shear



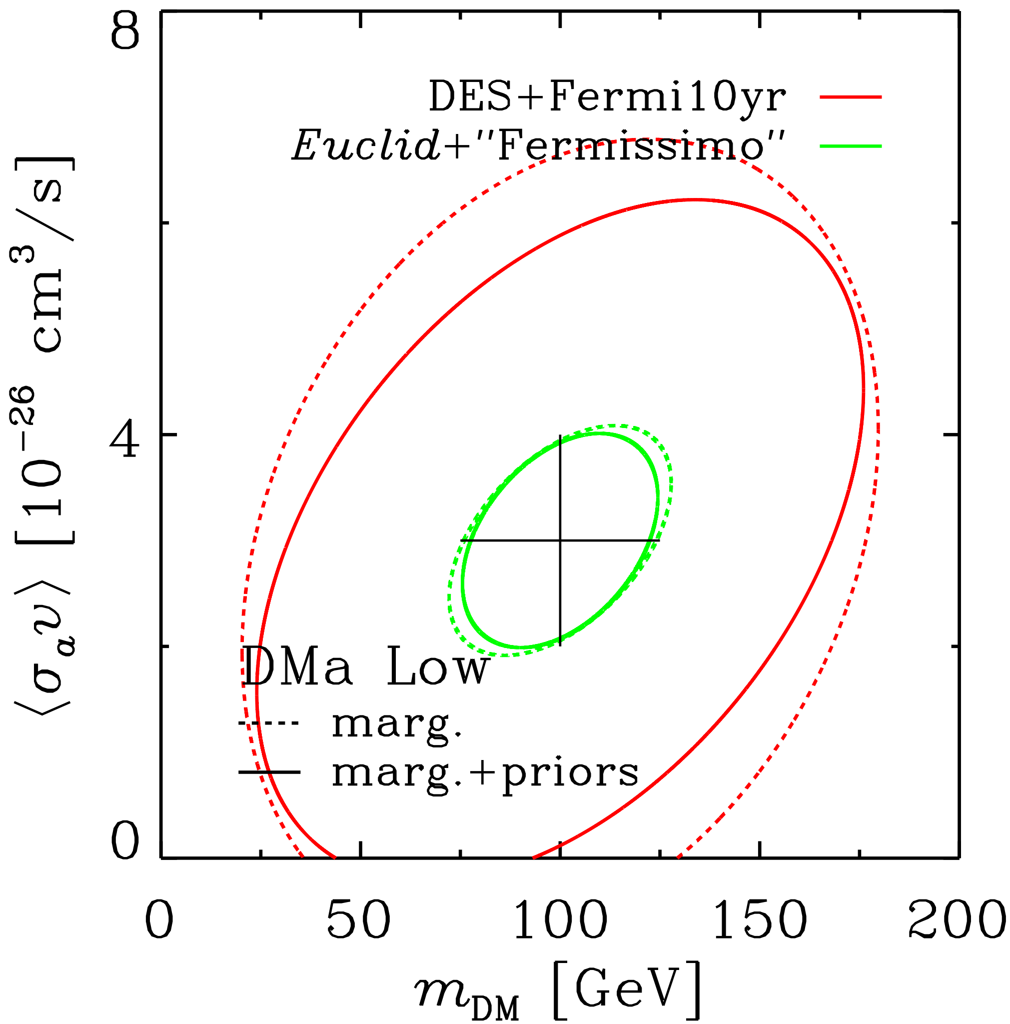
Bounds from Fermi x LSS

Cuoco et al, ApJS 221 (2015) 29

Forecast for Fermi x Euclid

Camera et al, JCAP 06 (2015) 029

Forecast for Fermi x (DES , Euclid)



Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029

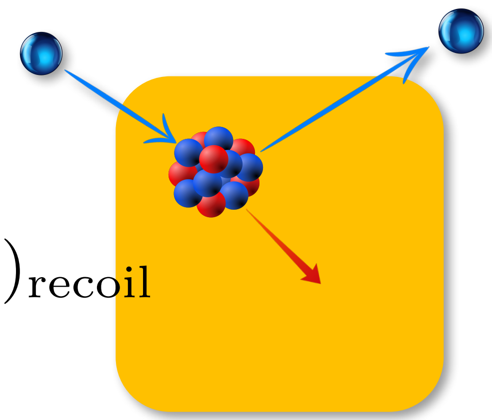
Conclusions

- Multimessenger astrophysics offers a wide range of opportunities to study dark matter in its full mass range
- Astrophysical fore/back-grounds are very complex and typically dominant over the sought-after DM signals
- Clever identification of potential targets/signatures/features is necessary
- The DM searches will progress together with a better understanding and modeling of the astrophysical contributors
- Some hints, but no established signal: however, the field is progressing rapidly, with new ideas, proposed techniques and will profit from a large wealth of data expected in the next 5-10 years

Backup Slides

Direct Detection

Direct detection signal



Typical process for WIMP DM

$$\chi + \mathcal{N}(A_\mathcal{N}, Z_\mathcal{N})_{\rm at\ rest} \to \chi + \mathcal{N}(A_\mathcal{N}, Z_\mathcal{N})_{\rm recoil}$$

Recoil rate

$$\frac{dR}{dE_R} = \frac{\xi_\mathcal{N}}{m_\mathcal{N}} \frac{\rho_\odot}{m_\chi} \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} d^3v\, v\, f_E(\vec{v}) \frac{d\sigma_\mathcal{N}}{dE_R}(v, E_R)$$

For non-WIMP (kev, MeV) DM: interaction on electrons

Set of operators

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$

$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

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

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

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

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$

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

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

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

$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

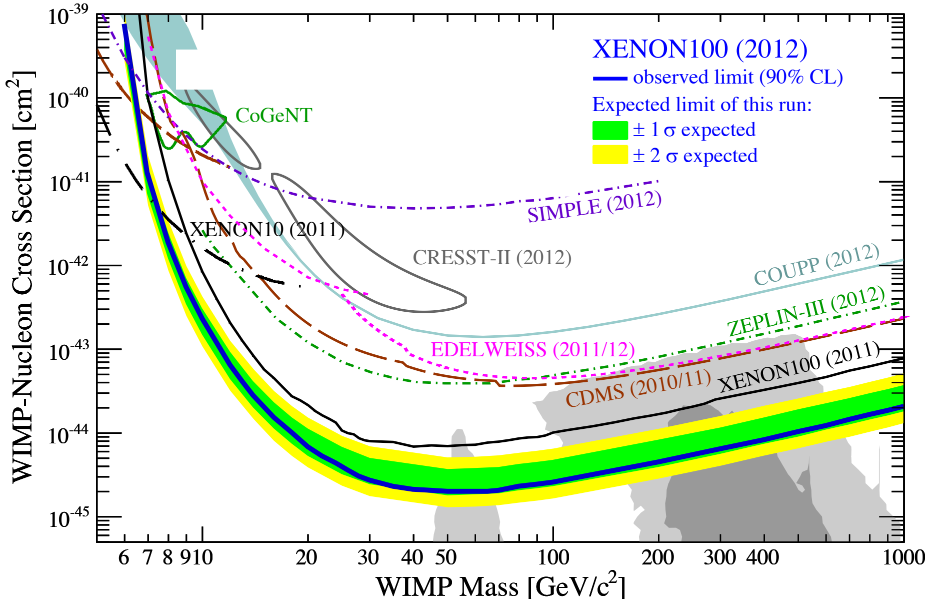
$$\hat{\mathcal{O}}_{17} = i\left(\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp\right)$$

$$\hat{\mathcal{O}}_{18} = i\left(\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N\right)$$

Catena, JCAP 1407 (2014) 055
Arina, Del Nobile, Panci, PRL 114 (2015) 011301
Scopel, Yoon, JCAP 1507 (2015) 041
Catena, Gondolo, JCAP 08 (2015) 022
Gluscevic et al, JCAP 12 (2015) 057
Catena, Ibarra, Wild JCAP 05 (2016) 039
Kalhofer, Wild, arXiv:1607.04418
(...)

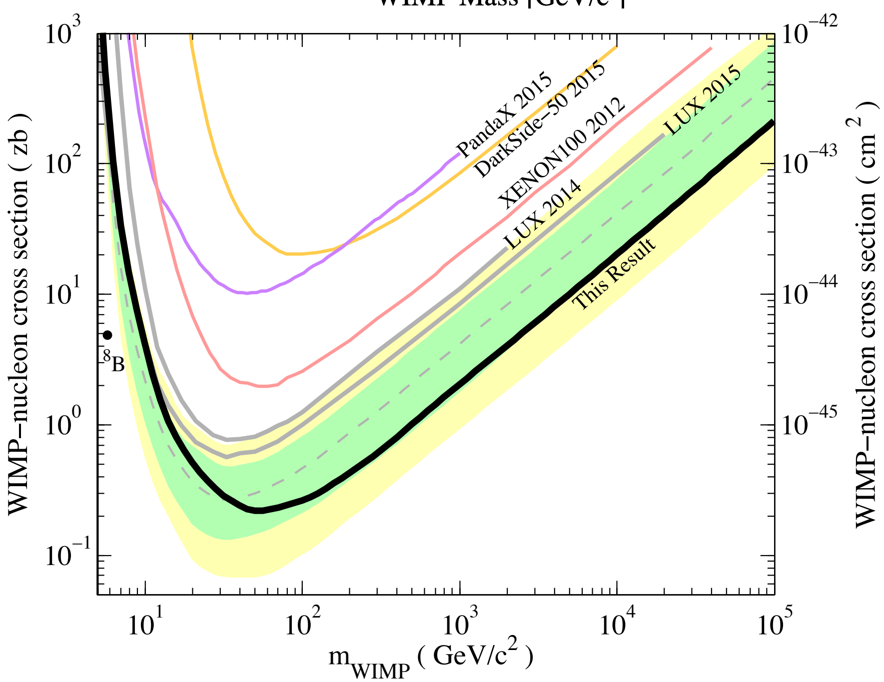
Fitzpatrick et al, JCAP 1302 (2013) 004
Fitzpatrick et al, arXiv:1211.2818
Anand et al, PRC 89 (2014) 065501
Dent et al, PRD 92 (2015) 063515

High WIMP mass



Contact-type scalar interactions

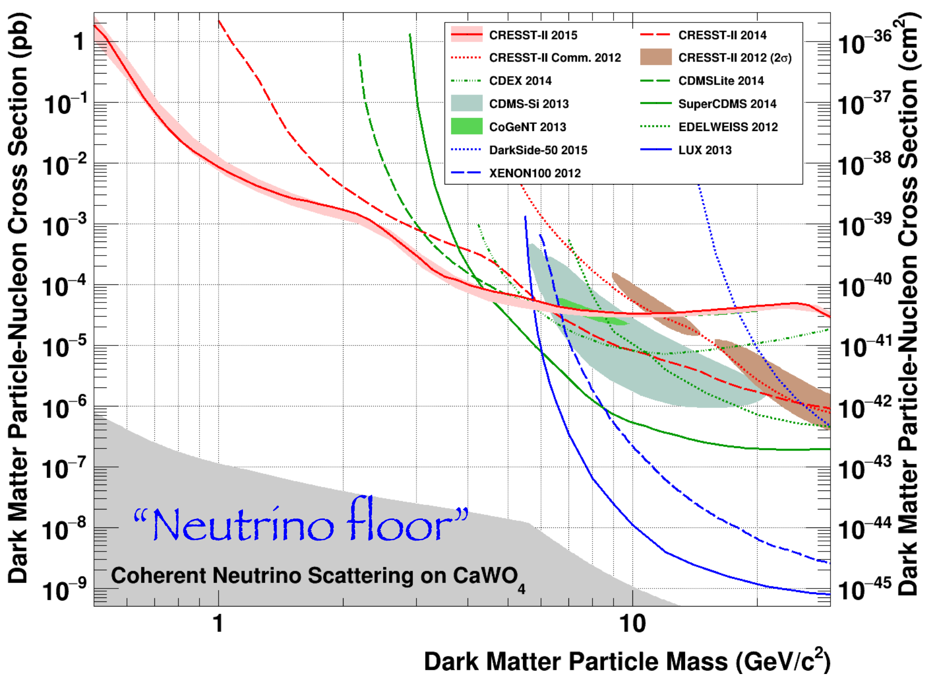
XENON 100 Collaboration, PRL 109 (2012) 181301



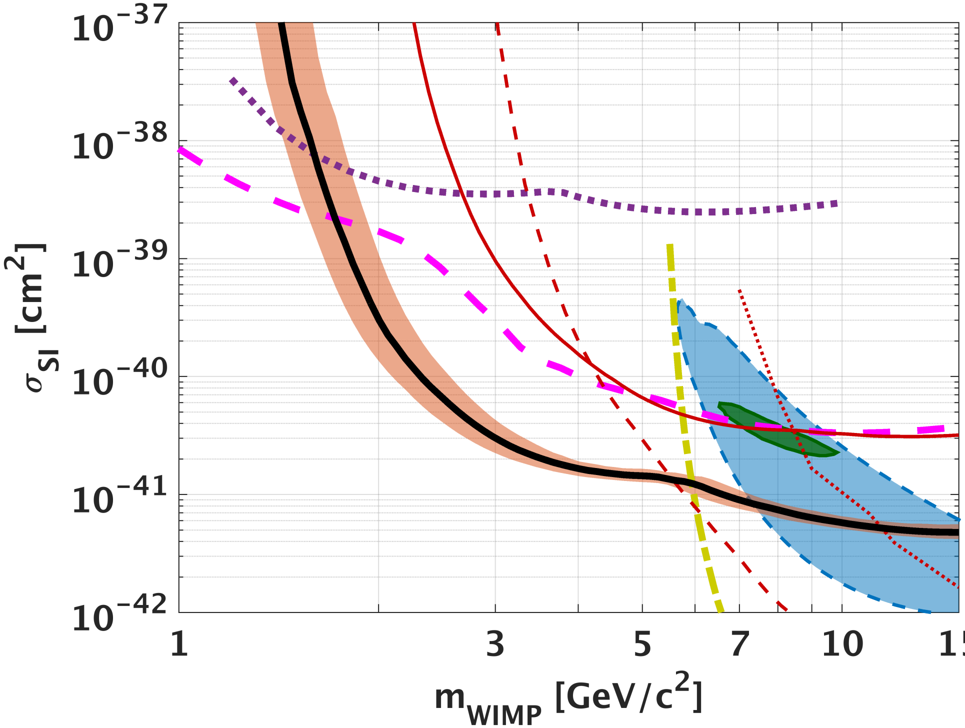
LUX Collaboration, presented at IDM 2016

332 live days

Low WIMP mass



Angloher et al (CRESST), EPJC 76 (2016) 25



Agnese et al (SuperCDMS) PRL 116 (2016) 071301

Contact-type scalar interactions (O_1)

Prospects

- Low WIMP mass
  - SuperCDMS (Ge) 10^{-44} cm^2 at 1 GeV
  - CRESST III ($CAWO_4$) 3×10^{-45} cm^2 at 1 GeV
- High WIMP mass
  - Xenon 1T, Xenon nT (LXe) 3×10^{-47} cm^2 at 100 GeV
  - DarkSide (LAr) [See Paganis's talk] 10^{-47} cm^2
  - LZ (LXe) [see Woodward's talk] 3×10^{-48} cm^2
  - DEAP 10^{-46} cm^2
  - Pico 10^{-46} cm^2
  - DARWIN (LXe)
- In both cases, approach the "neutrino floor" (due to neutrino coherent interactions
  - Solar neutrinos for $m_{DM} < 10$ GeV at 3×10^{-45} cm^2 (1 GeV)
  - Atmospheric neutrinos for $m_{DM} > 10$ GeV at 10^{-49} cm^2 (100 GeV)

Very light DM

- Very light DM (down to the warm regime):
  - Available kinetic energy can be as low as meV (for KeV DM)
  - Too low deposited energy on nuclear target

- Possibilites:
  - Nuclear interactions on light targets, e.g. liquid He
  - Electron recoils

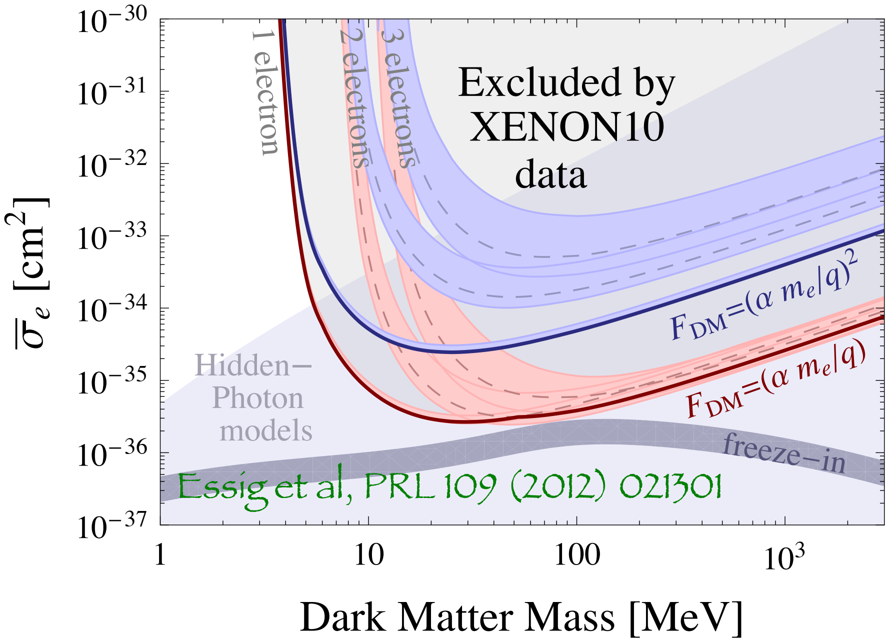
Guo, McKinsey, PRD 87 (2013) 115001

Essig et al, PRD 85 (2012) 076007

Essig et al, 1509.01598

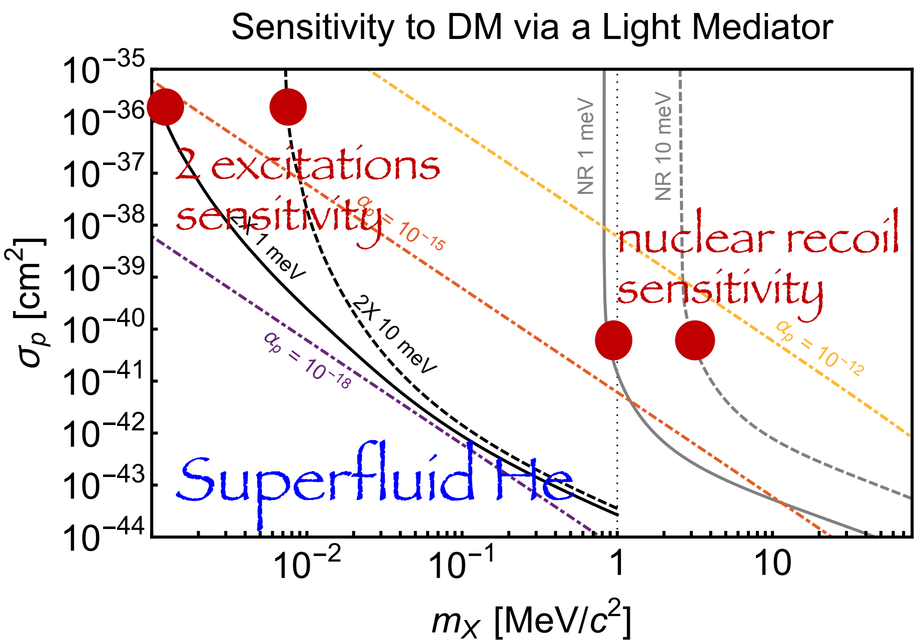
Agnese et al (SuperCDMS) PRL 112 (2014) 041302

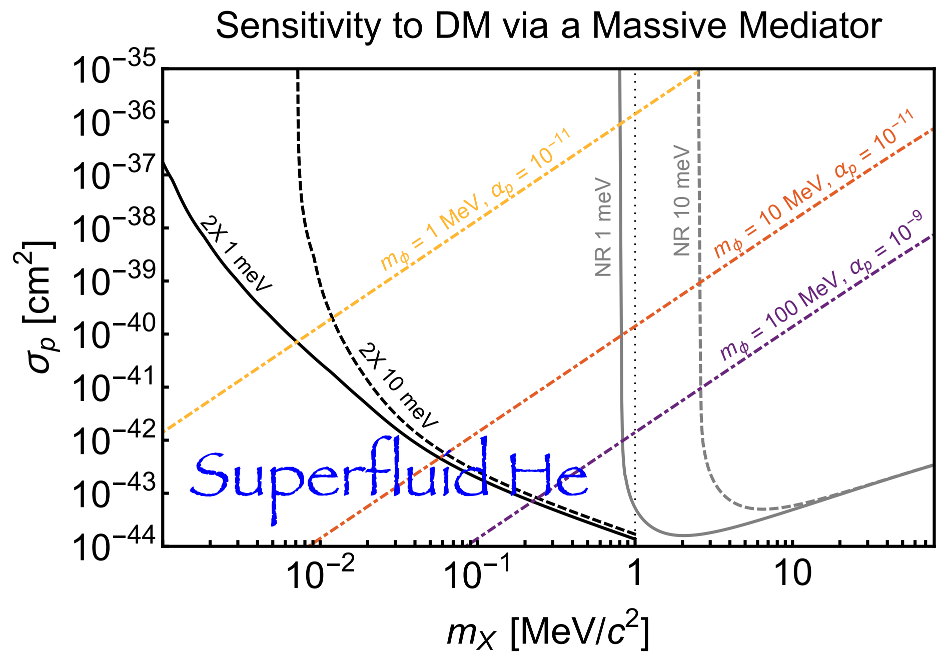
Essig et al, PRL 109 (2012) 021301



Essig et al, PRL 109 (2012) 021301

Super light DM



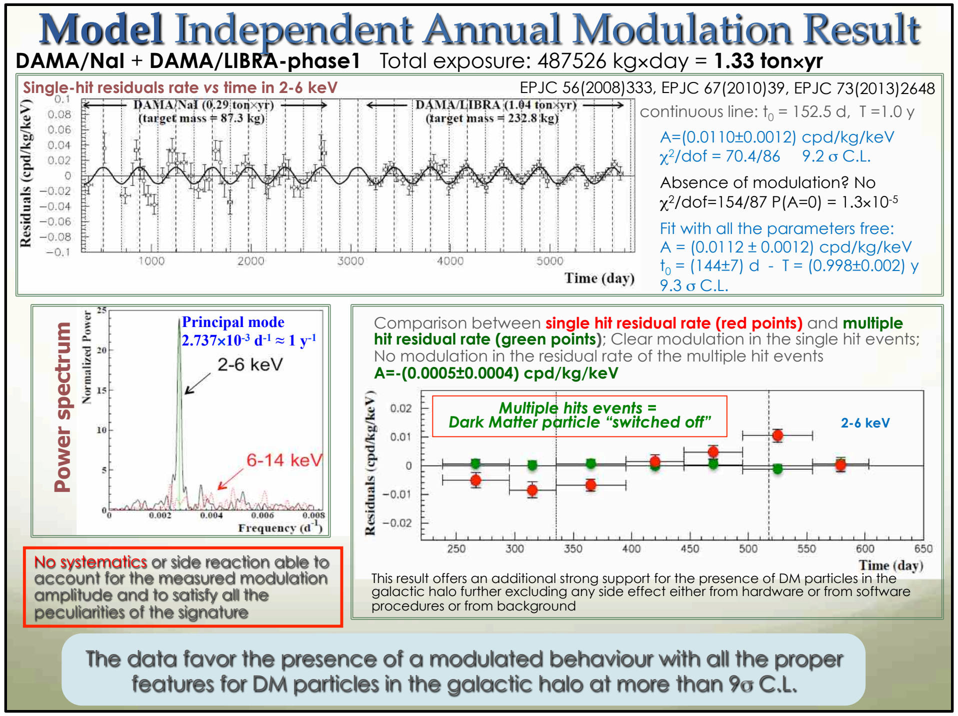


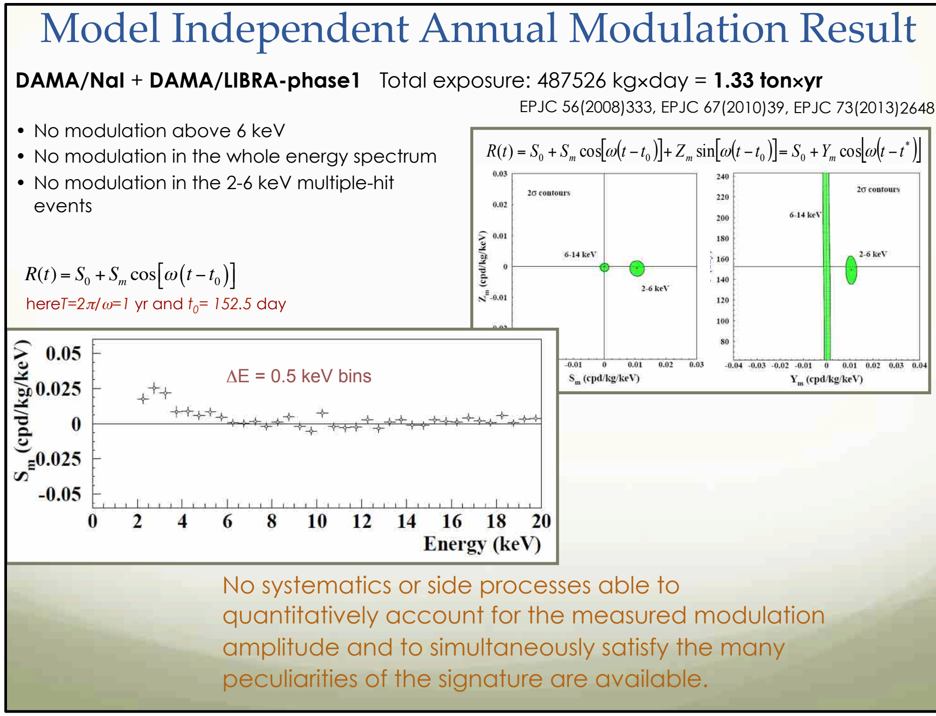
To go below 10 MeV DM: conversion of the full tiny energy needed

- Superconductors — electron interactions
  Hochberg et al, 1512.04533
  Hochberg et al, PRL 116 (2016) 011301
- Superfluid He — nuclear interactions
  Schutz, Zurek, 1604.08206

Annual modulation

DAMA, 9.2σ with 1.33 ton x yr, 15 cycles





From Belli's talk at TAUP 2015, http://taup2015.to.infn.it

DM scattering on nuclei	(1-1000) GeV WIMPs
	(-43,-38) Log(σ/cm²)
	In case of "scalar" interaction
DM scattering on electrons	(0.1-10) KeV ALPs

Prospects

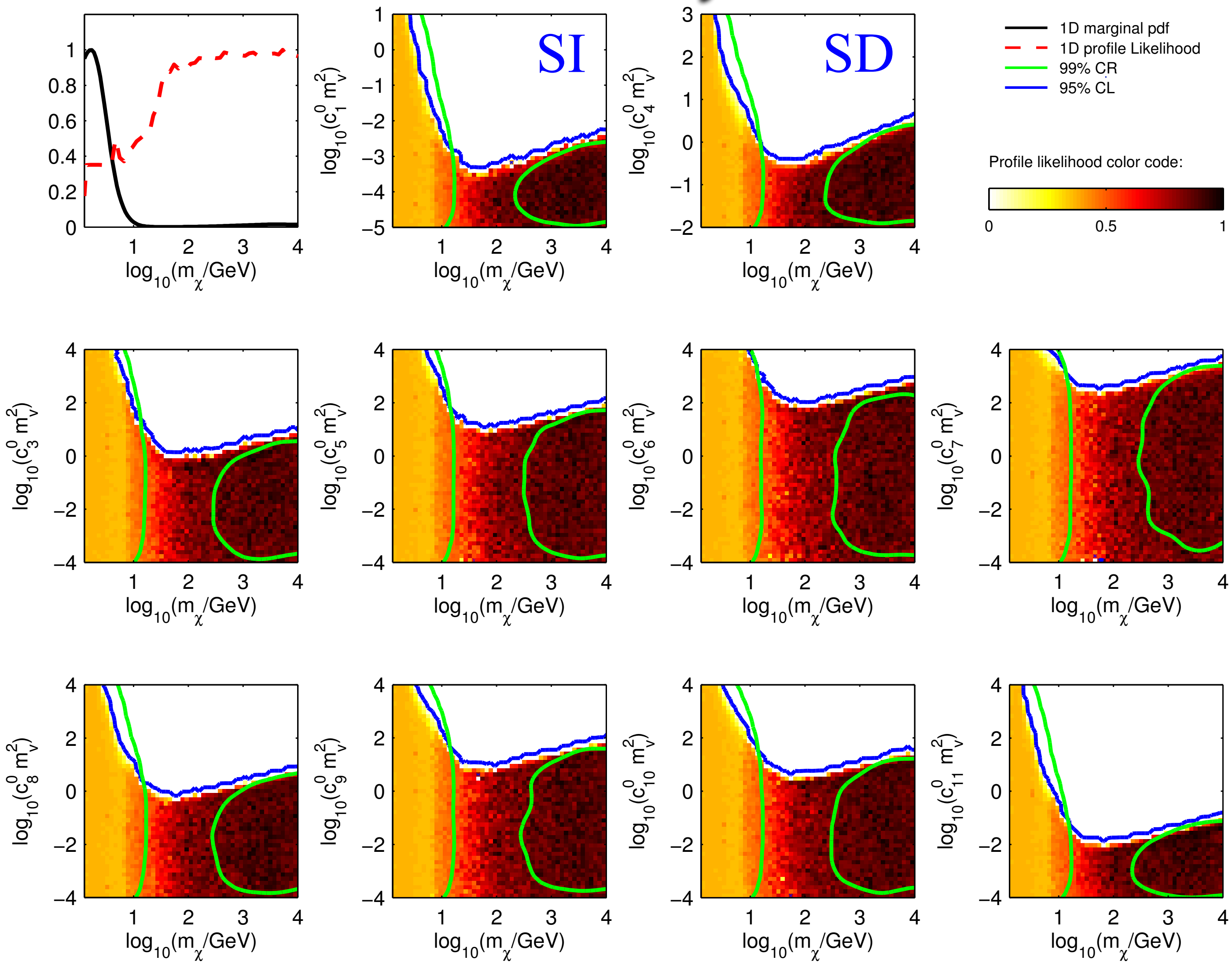
- Annual modulation: ANAIS
  KIMS + DM Ice = COSINE 100
  SABRE
  CUORE

- Diurnal modulation: DAMA with larger mass could likely access it

- Directionality:
  - Nuclear emulsion (NEWS)
  - Anysotropic crystals (ADAMO)
  - Liquid Ar TPC
  - Negative Ion Time Expansion Chamber (NITEC)
  - Carbon nanotubes, grafene
  - DRIFT
  - MIMAC, DMTPC, NEWAGE, D3, …

Full set of operators

Catena, Gondolo, JCAP 09 (2014) 045
See also: Scheck et al (SuperCDMS), PRD 91 (2015) 092004



Combined analysis of
CDMS, XENON, LUX, COUPP, PICASSO, SIMPLE