Astrophysical Signals of Dark Matter

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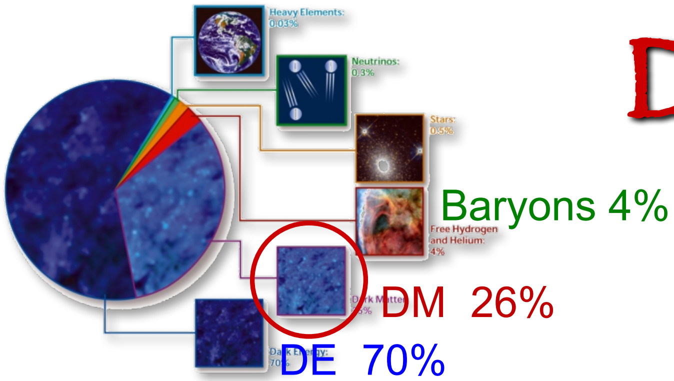
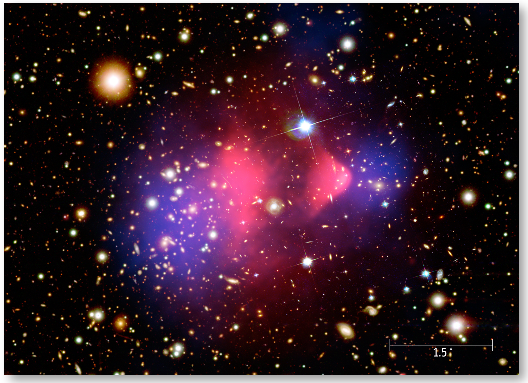
Istituto Nazionale di Fisica Nucleare

Galileo Galilei Institute Conference – Galileo's House
Collider Physics and the Cosmos – 13.10.2017



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

Solutions not involving new particles

The DM issue is not a problem of particles, but of gravity

MOND

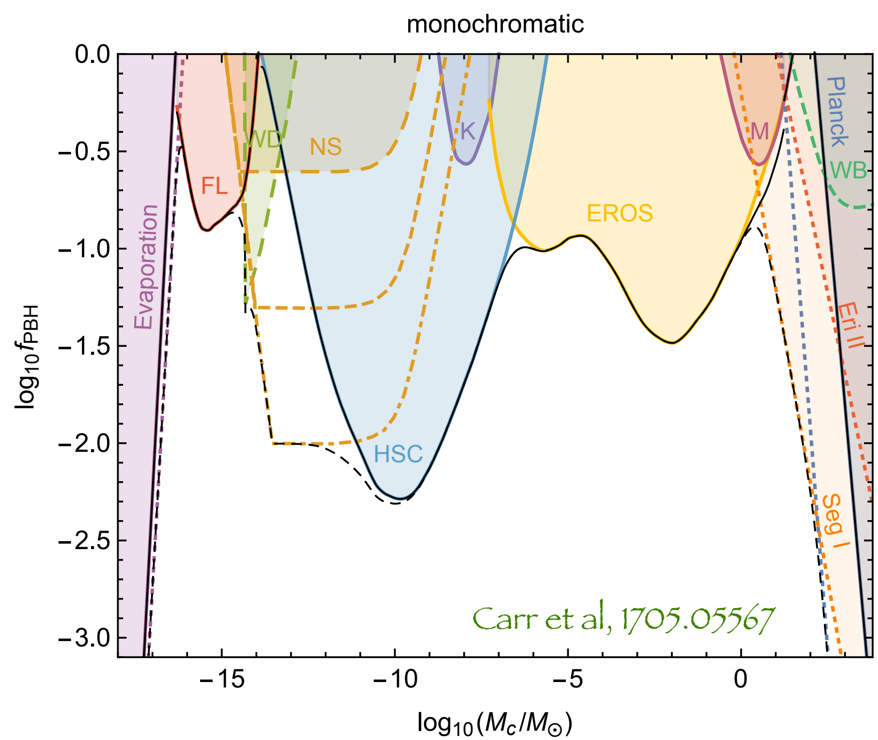
Gravity beyond General Relativity

Primordial black holes *might* solve the DM problem

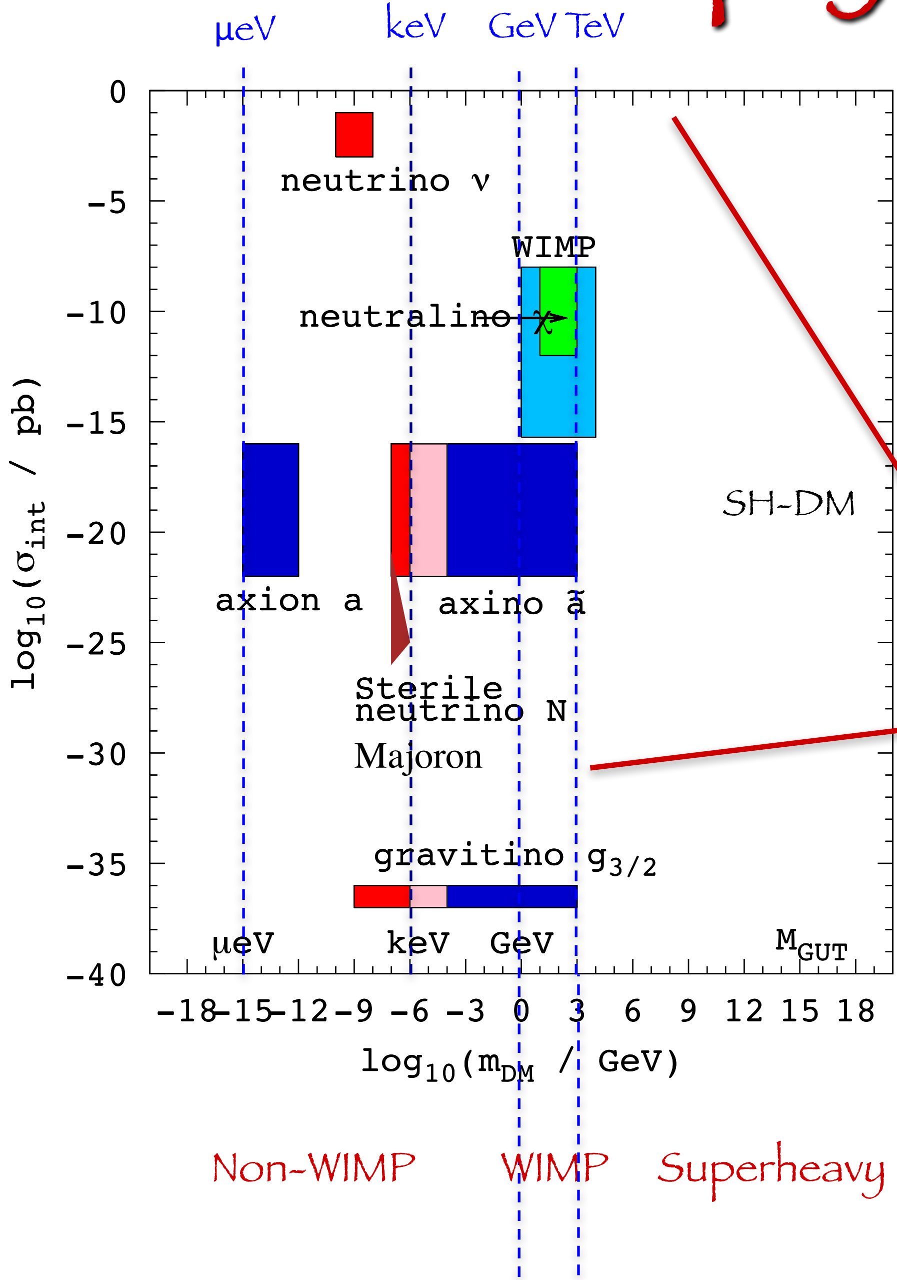
They do not count as baryonic matter

Currently under debate

FL:	femtolensing of GRB
NS:	neutron star catpure
WD:	white dwarf explosion
HSC:	microlensing from Subaru
K:	microlensing from Kepler
EROS:	microlensing from EROS
MACHO:	microlensing from MACHO



Particle physics scales



"Strong (-ish)"

Self-interacting

Technicolor DM

...

"EM (-ish)"

Millicharged DM

Electric/magnetic dipole

...

Weak

WIMP

Gravitational

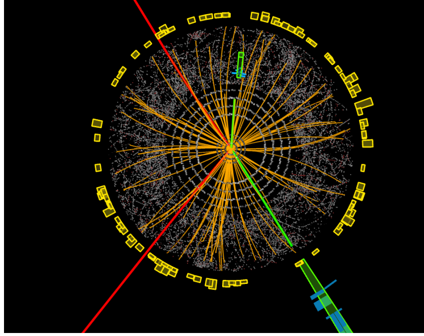
Relic from the early Universe

- Thermal
- Non thermal

Dynamically: non relativistic (cold)

collisionless

A 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 / Lab 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

DM as a particle might ...

Interact with ordinary matter — Direct detection

Produce effects in astrophysical environments, like in stars

Self annihilate or decay — Send us messengers (indirect detection)

Exotic injections that can alter properties of messengers (e.g. CMB: SZ, reionization; gamma-rays absorption)

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

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

Cosmic rays
- electrons/positrons — WIMP, non WIMP
- antiprotons, antideuterium, antinuclei — WIMP

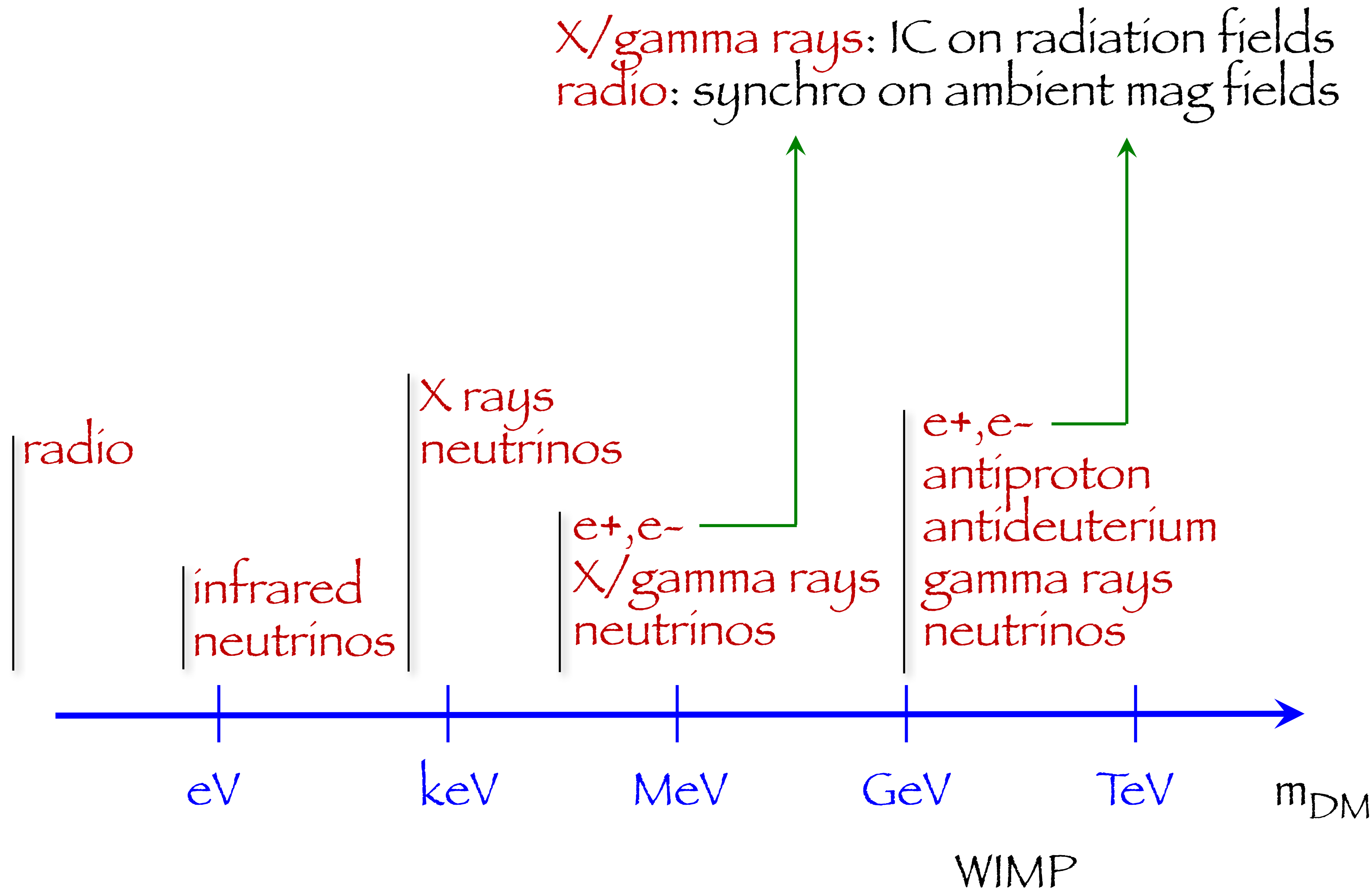
Neutrinos — WIMP, non WIMP

Gravitational waves — non WIMP (DM = primordial BH)

Direct detection — WIMP, non WIMP

Accelerator searches for New Physics — WIMP, non WIMP

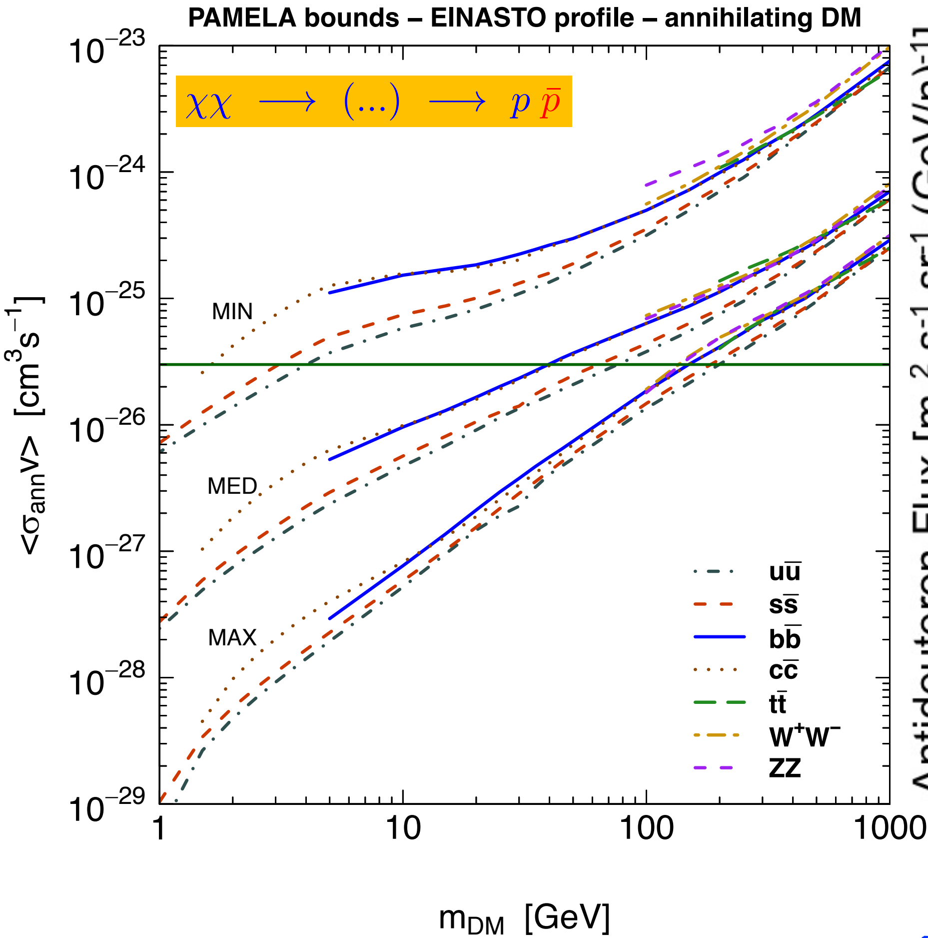
The Multimessenger Landscape



Astrophysical messengers

Antinuclei

AntiProtons

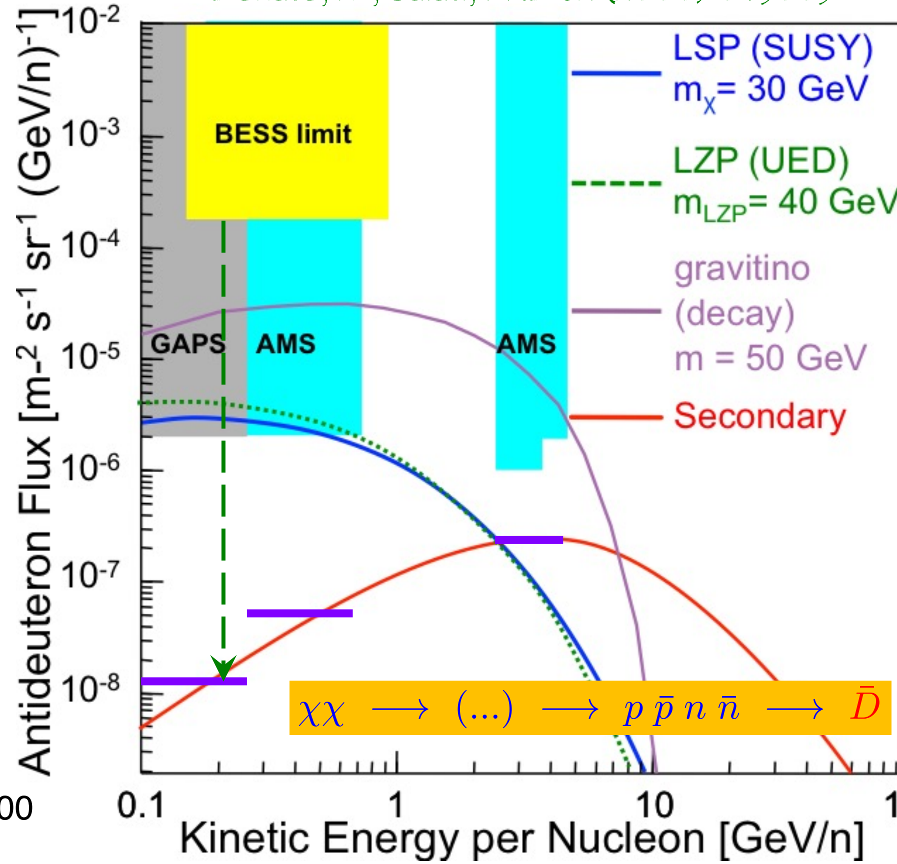


NF, Maccione, Vittino, JCAP 1404 (2014) 003

Bounds from PAMELA

AntiDeuterons

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



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

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

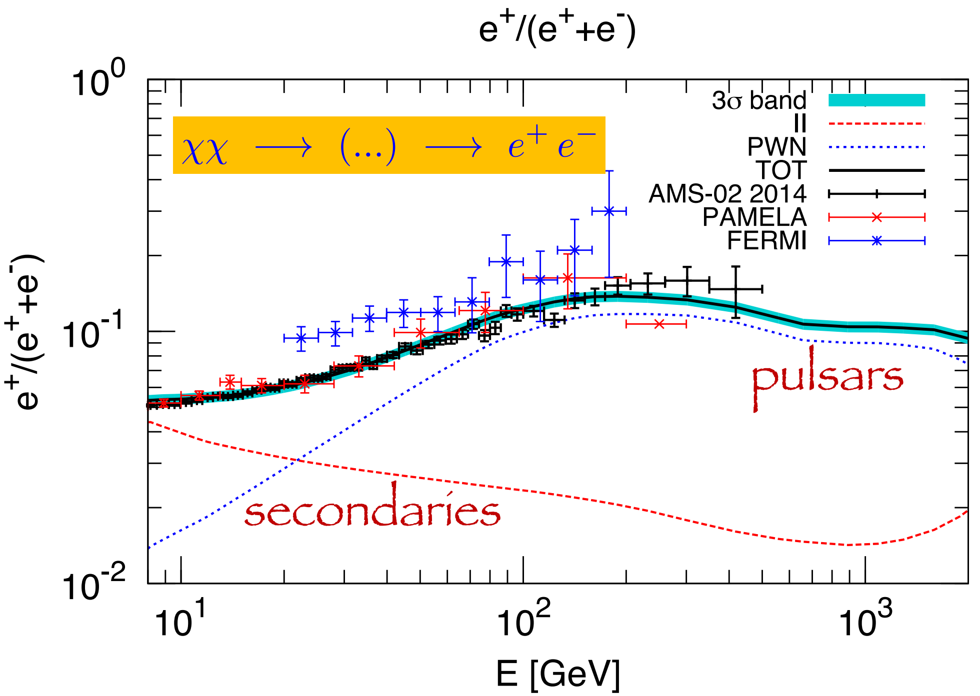
Kinematics: largely favours signal over background

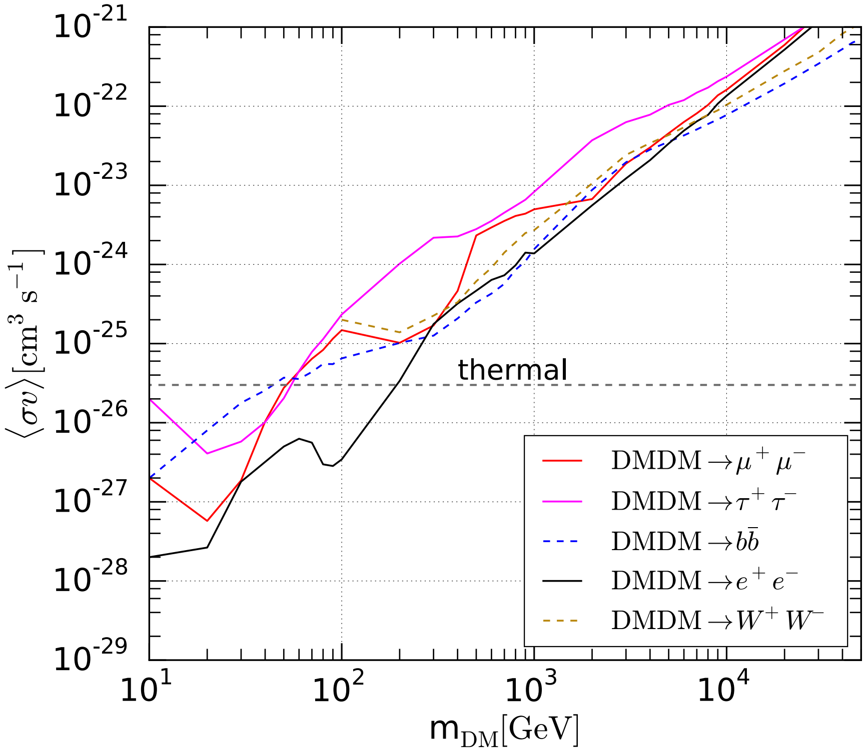
Opportunity: "0-back" over 3/4 orders of magnitude

Even a "single antiD": smoking gun for exotics

GAPS: approved from NASA

Electrons/positrons





Astrophysical interpretation

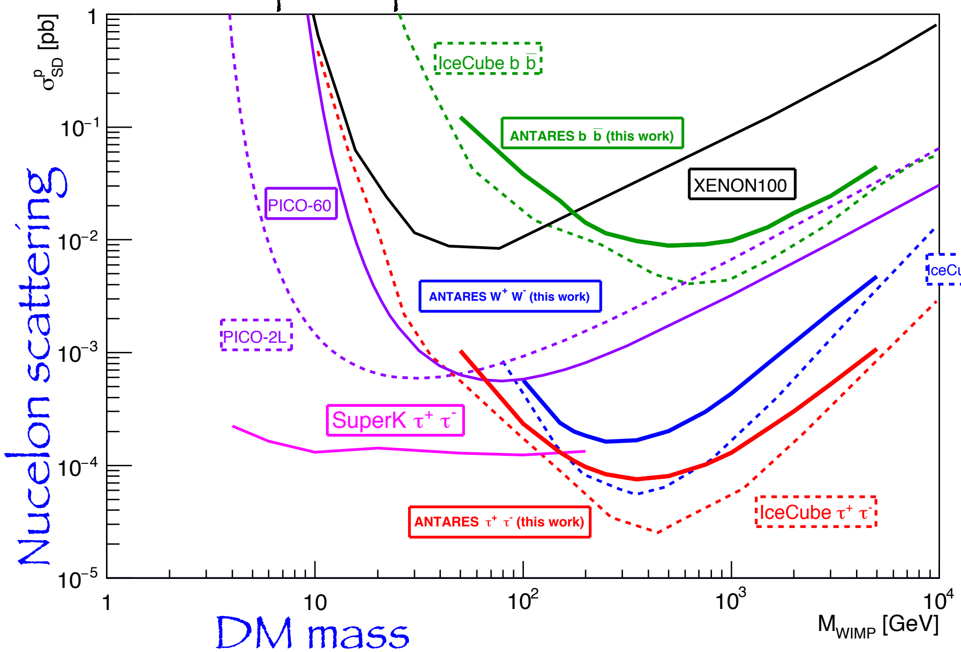
Bounds on DM

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

Neutrinos

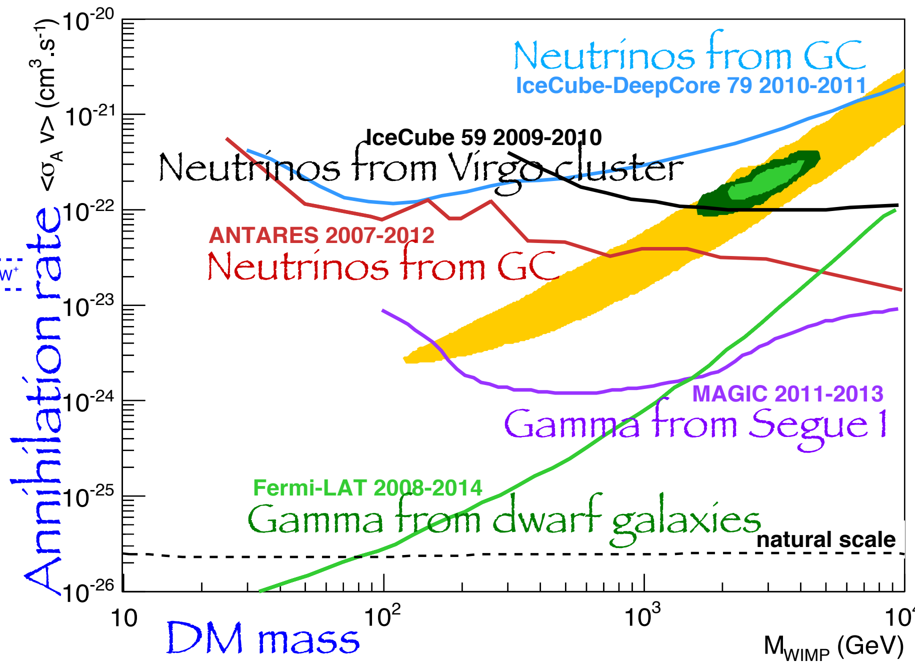
From the Sun

Spin dependent interaction



ANTARES Collab, PLB 759 (2016) 69

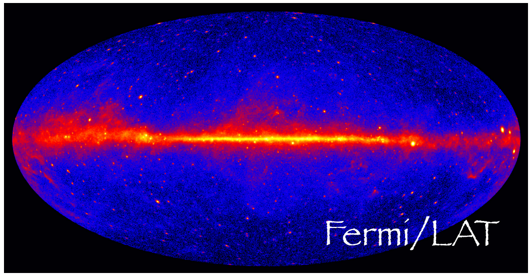
Other targets



ANTARES Collab, JCAP 1510 (2015) 068

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

Gamma rays



Galactic center

Very interesting target, but difficult

Potential hints, under hot discussion

The "excess" can be: DM, PSR, bursts

Diffuse gamma ray background

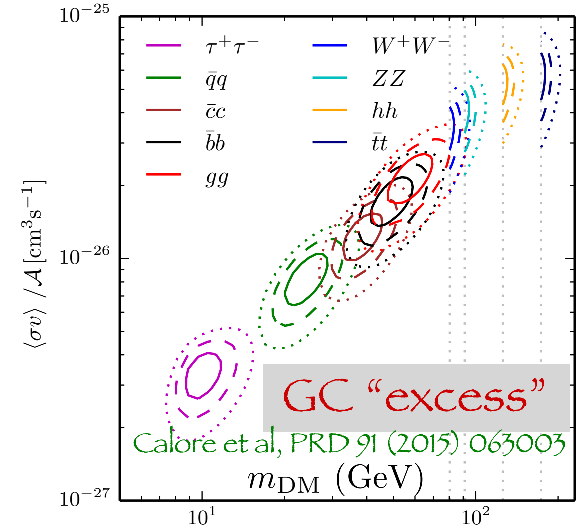
Relevant for extragalactic DM

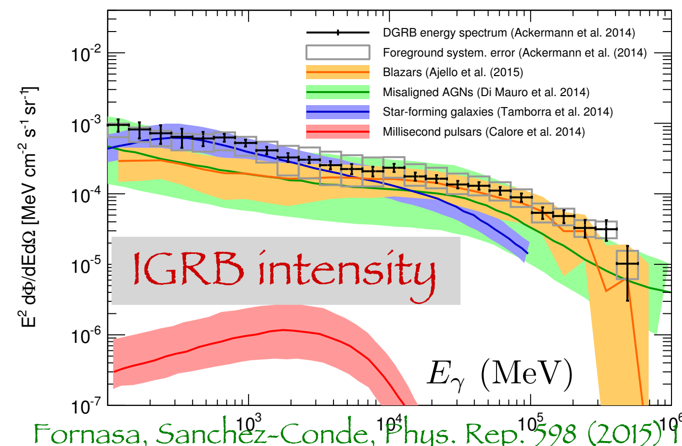
Complex to seperate a DM signal from astrophysical sources

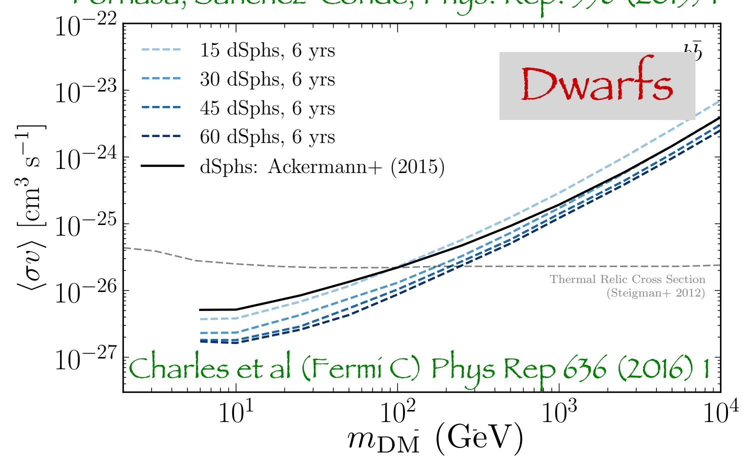
Dwarf galaxies

One of the best targets (DM dominated)

Recently, new dwarfs have been discovered (DES): great potentiality





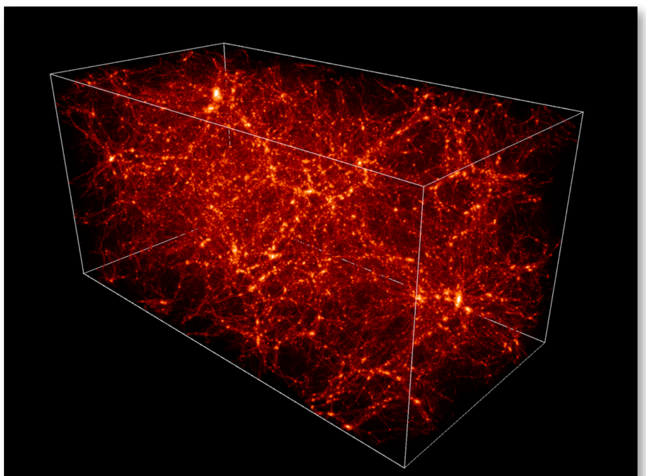


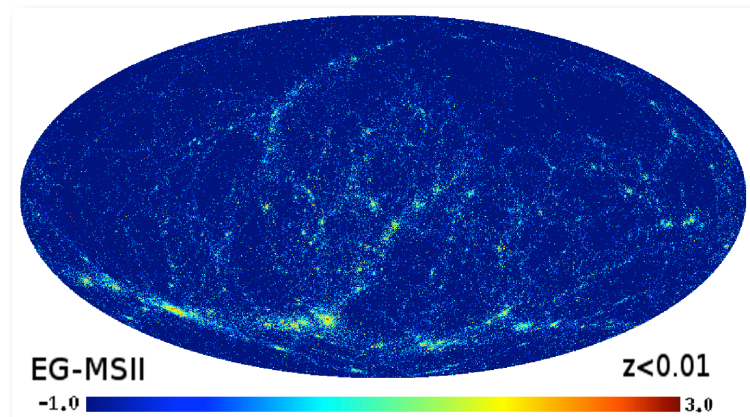
Diffuse signals: faint & not isotropic ...

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

To first approximation: isotropic

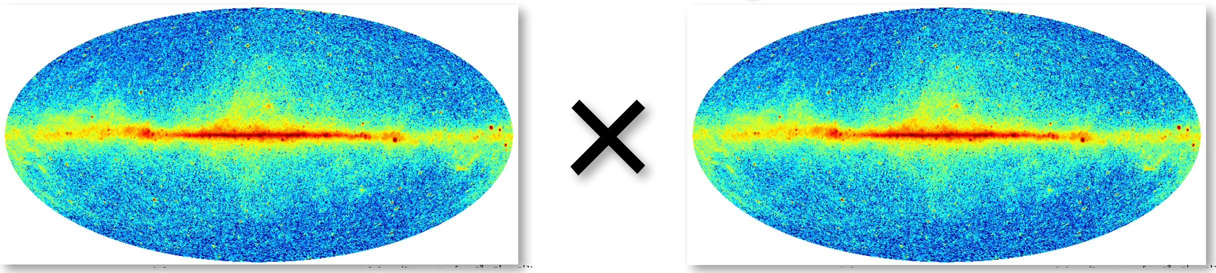
At a deeper level: anisotropies are present





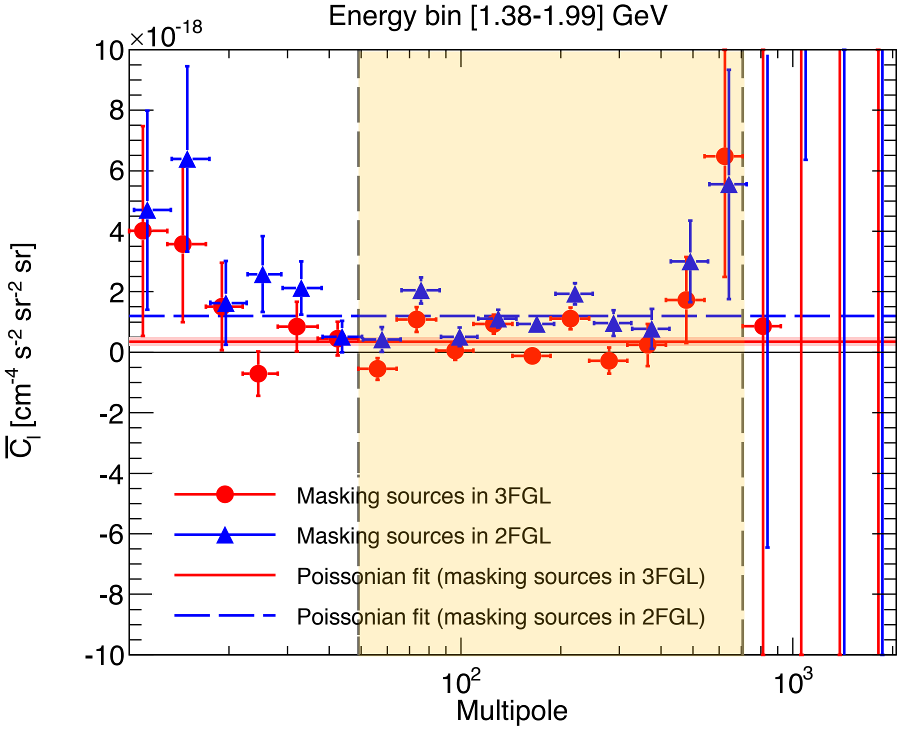
Even though sources are too dim to be individually resolved, they can affect the statistics of photons across the sky

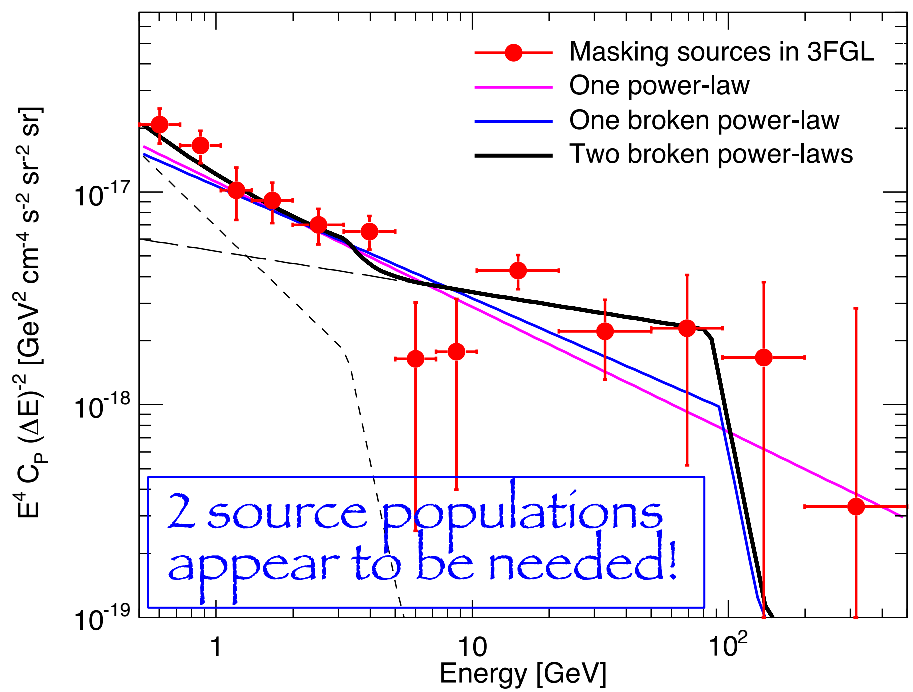
Gamma rays auto-correlation



2 point correlator
angular power spectrum

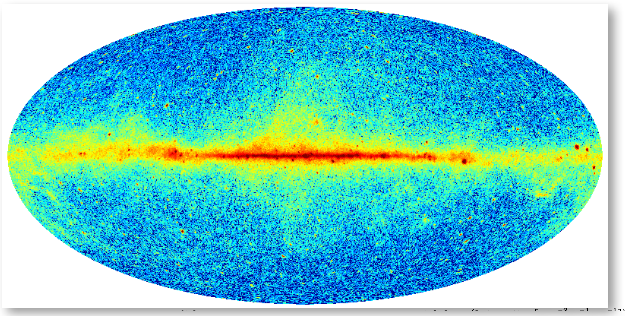
$$\langle\, I(\vec{n}_1) I(\vec{n}_2) \,\rangle \;\longrightarrow\; C(\theta) \;\longrightarrow\; C_l$$



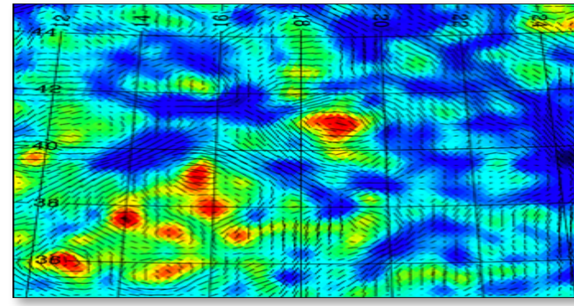


Fornasa, Cuoco et al, 1608.07289
See also: Ackerman et al (Fermi Collab) PRD 85 (2012) 083007

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)

X–CORR 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

X–CORR 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 et al, MNRAS 467 (2017) 2706 — Fermi x (CFTHLenS + RCSLenS + KiDS)

Gamma rays x CMB lensing

X–CORR DETECTED

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

Gamma rays x Galaxy clusters

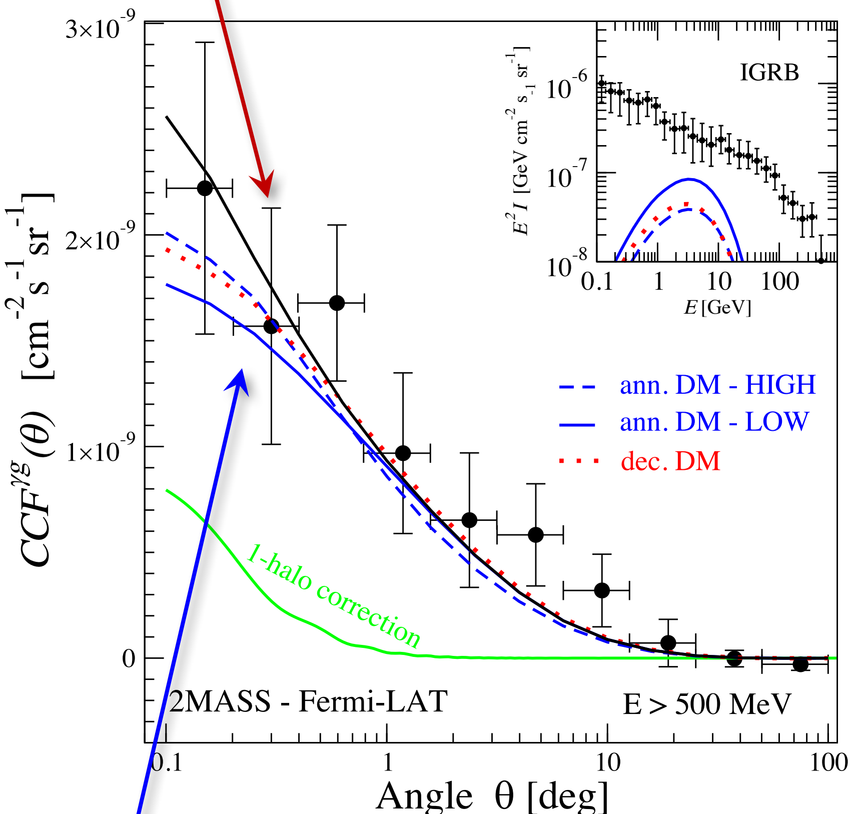
X–CORR DETECTED

Cuoco et al, ApJS 228 (2017) 8 — Fermi x (redMaPPer + WHL12 + PlanckSZ)

Cross Correlations

measured correlation

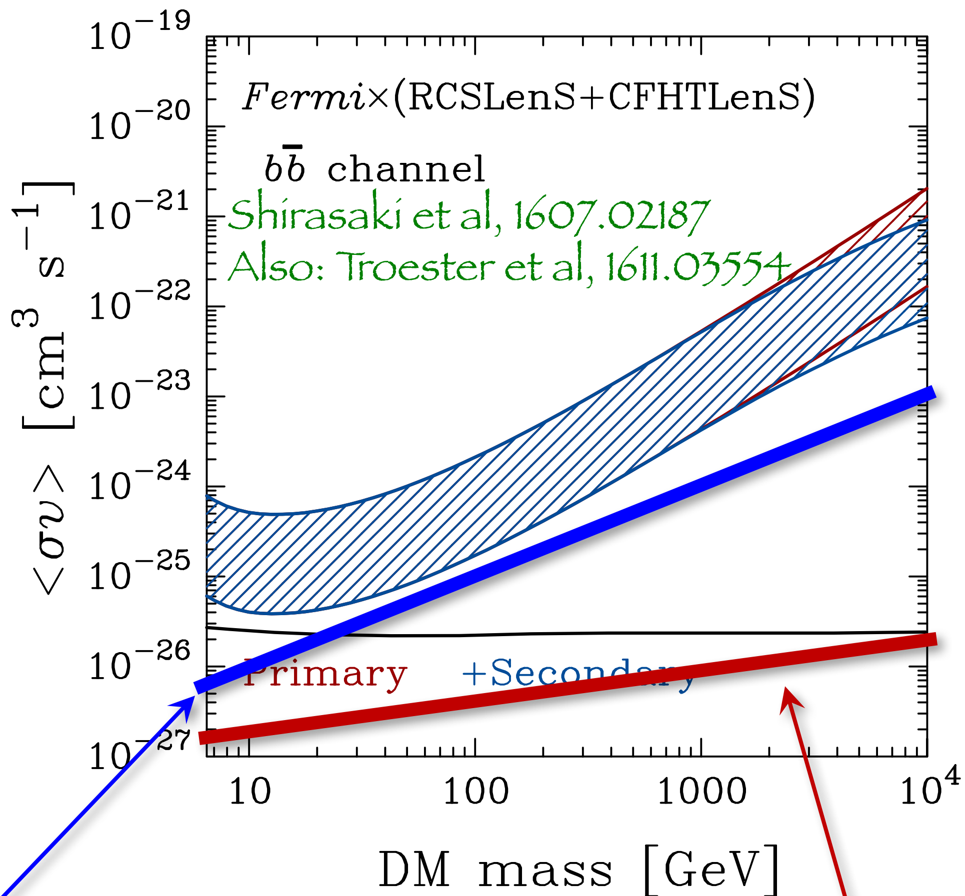
Fermi x 2MASS



Regis et al PRL 114 (2015) 241301

DM signal

Bounds from Fermi x shear



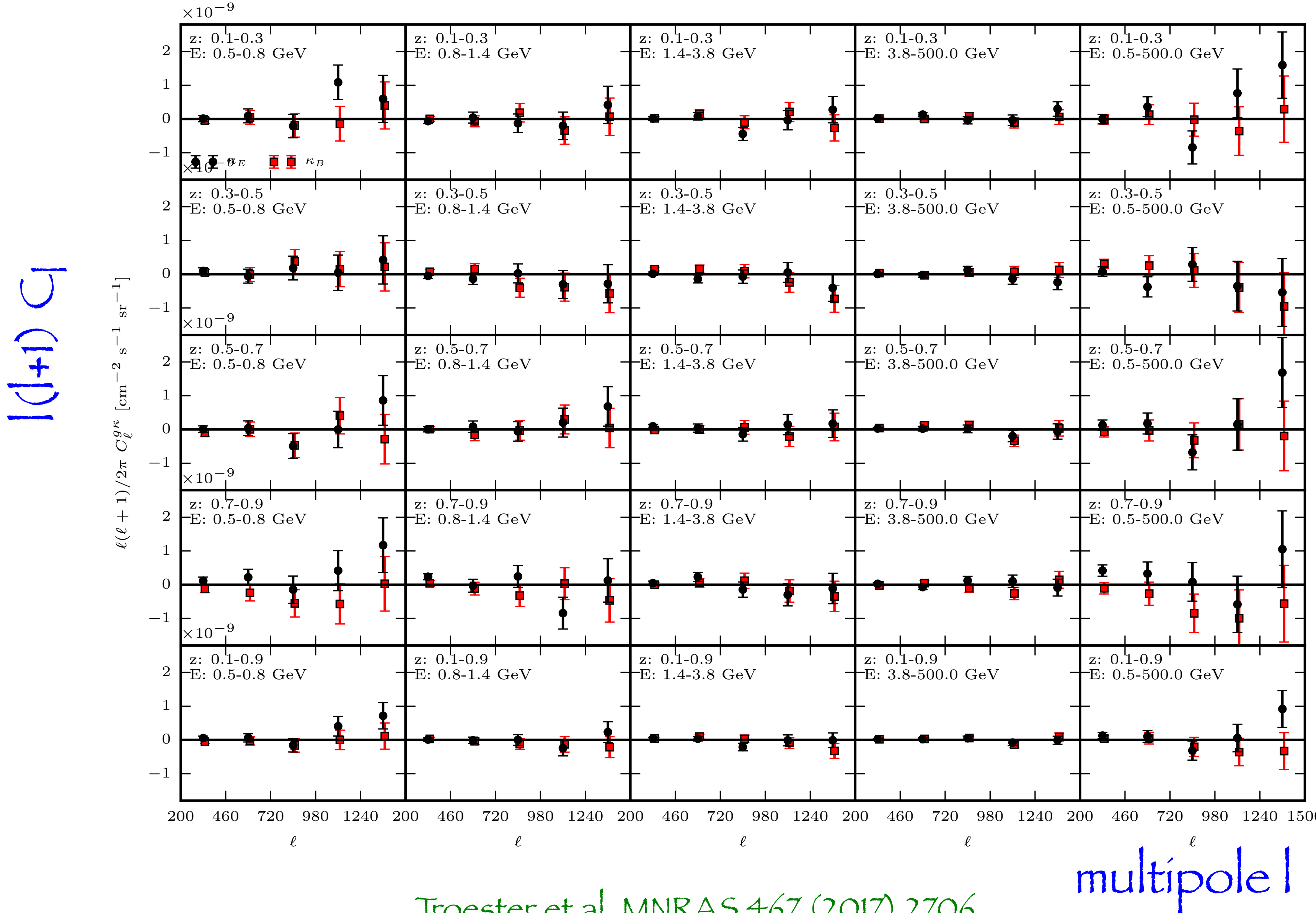
Bounds from Fermi x LSS

Cuoco et al, ApJS 221 (2015) 29

Forecast for Fermi x Euclid

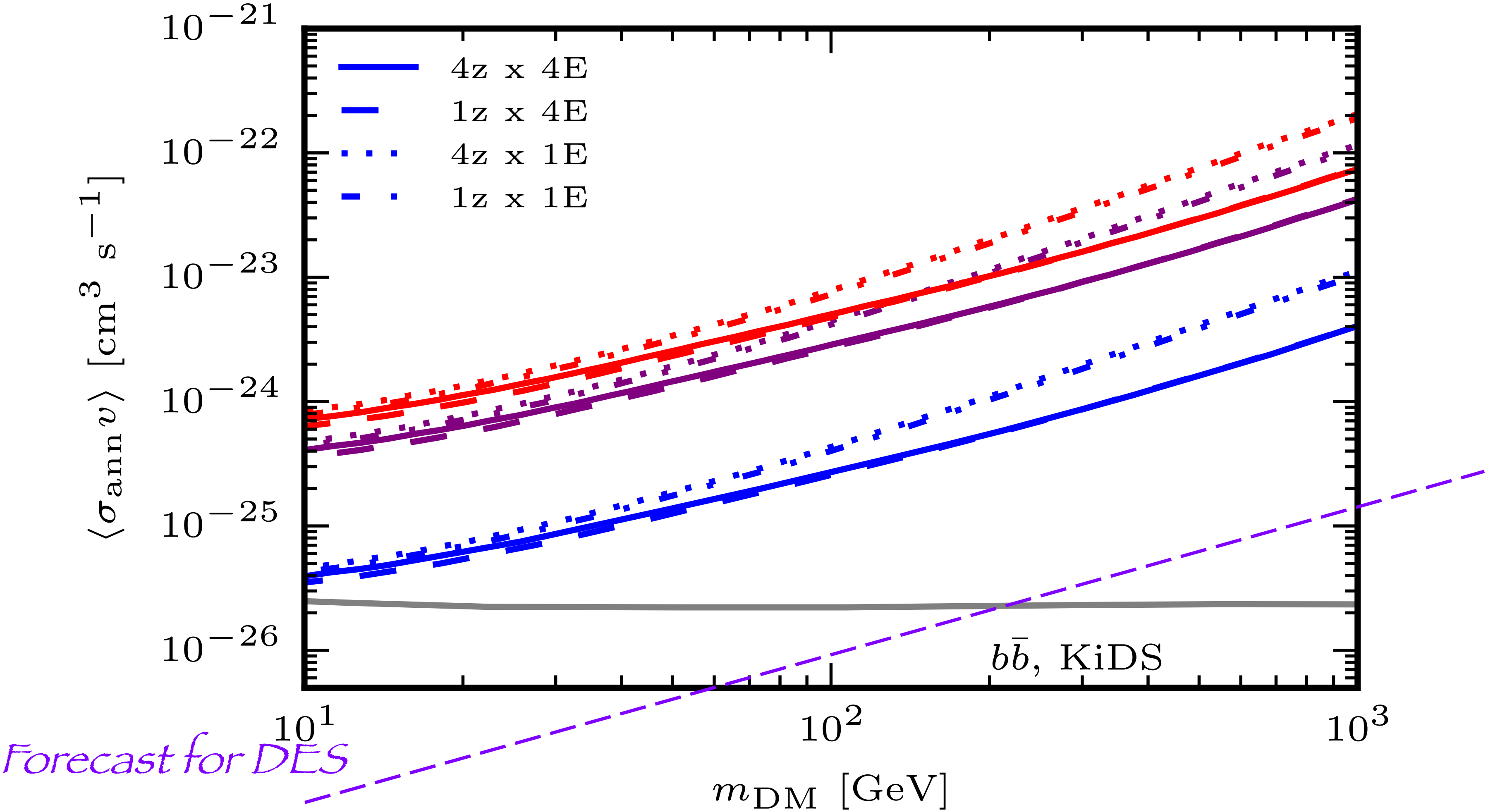
Camera et al, JCAP 06 (2015) 029

Fermi x KiDS+RCSLens+CFTHLens



Troester et al, MNRAS 467 (2017) 2706

Fermi x KiDS+RCSLens+CFTHLens

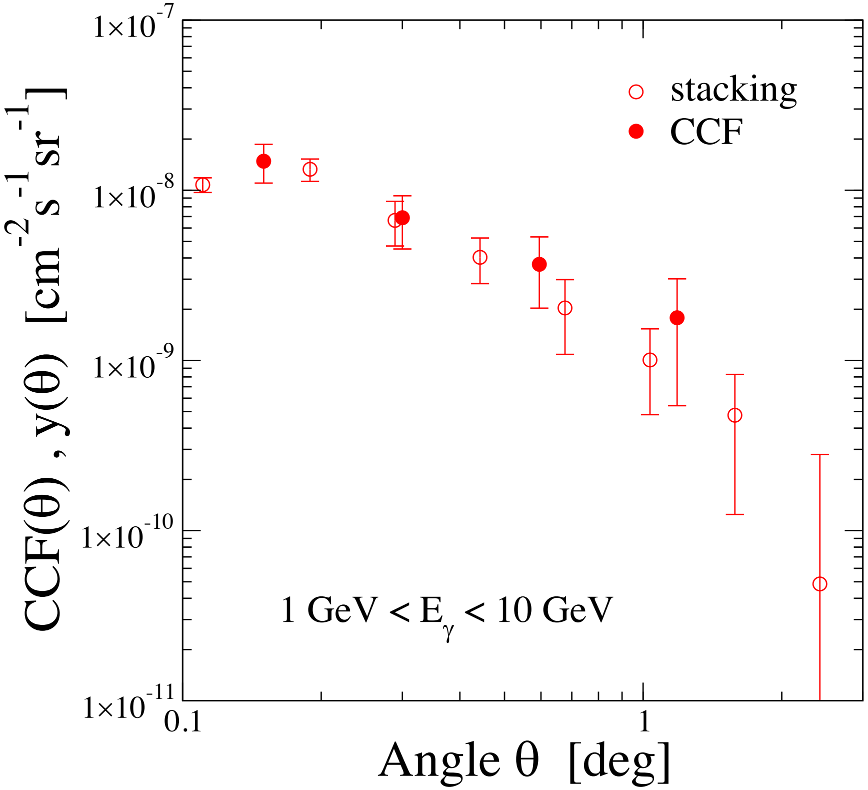


Troester et al, MNRAS 467 (2017) 2706

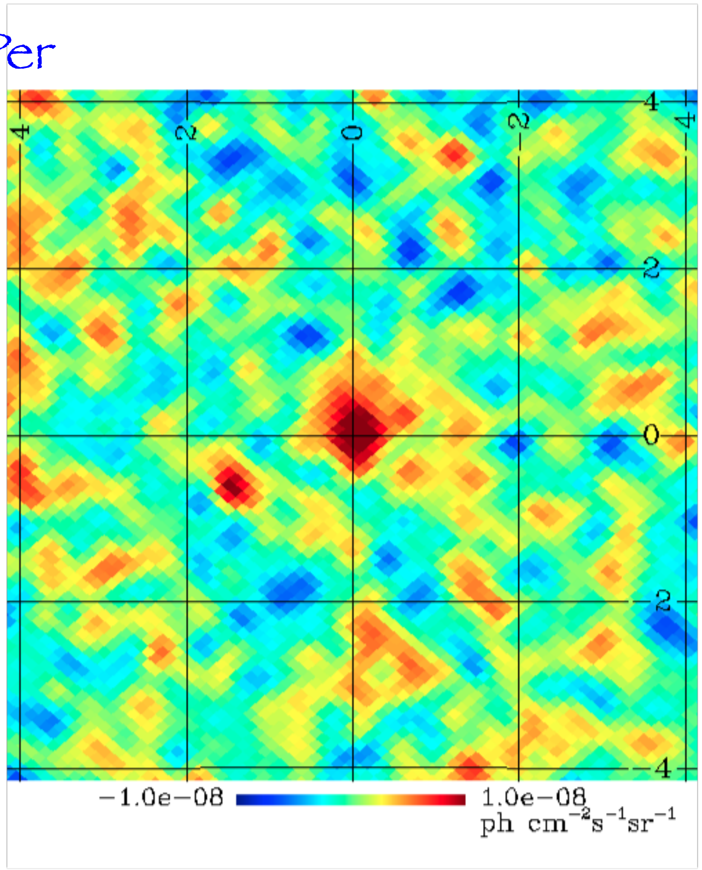
See also: Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502
Shirasaki, Marcias, Horiuchi, Shirai, Yoshida, PRD 94(2016) 063522

Cross correlation with gamma rays

redMaPPer



Correlation function and stacking profile

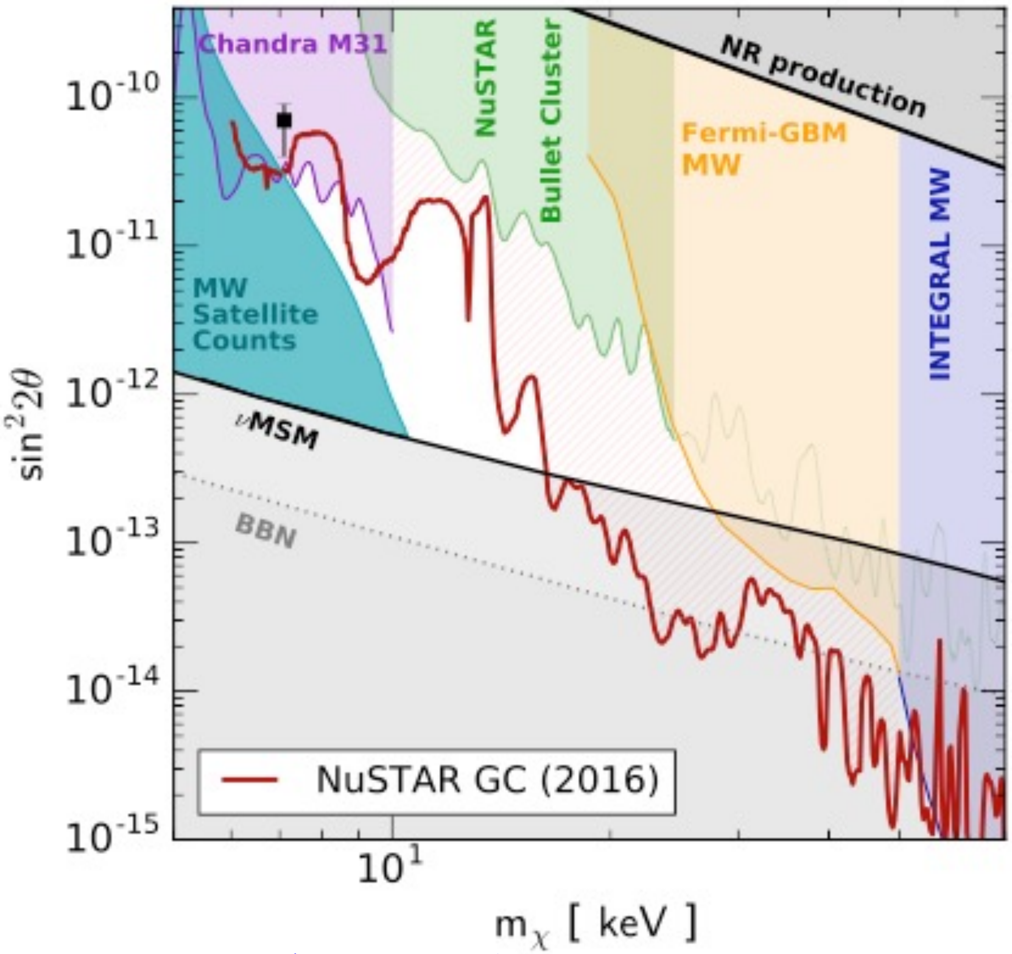


Gamma ray stacking

Branchini, Camera, Cuoco, NF, Regis, Viel, Xia, ApJS 228 (2017) 8

Lower frequencies and non-WIMP

X rays



New bounds from nuSTAR @ GC

Perez et al, 1609.00667

3.5 KeV line

73 galaxy clusters

Perseus cluster + Andromeda

Bulbul et al, ApJ 789 (2014) 13

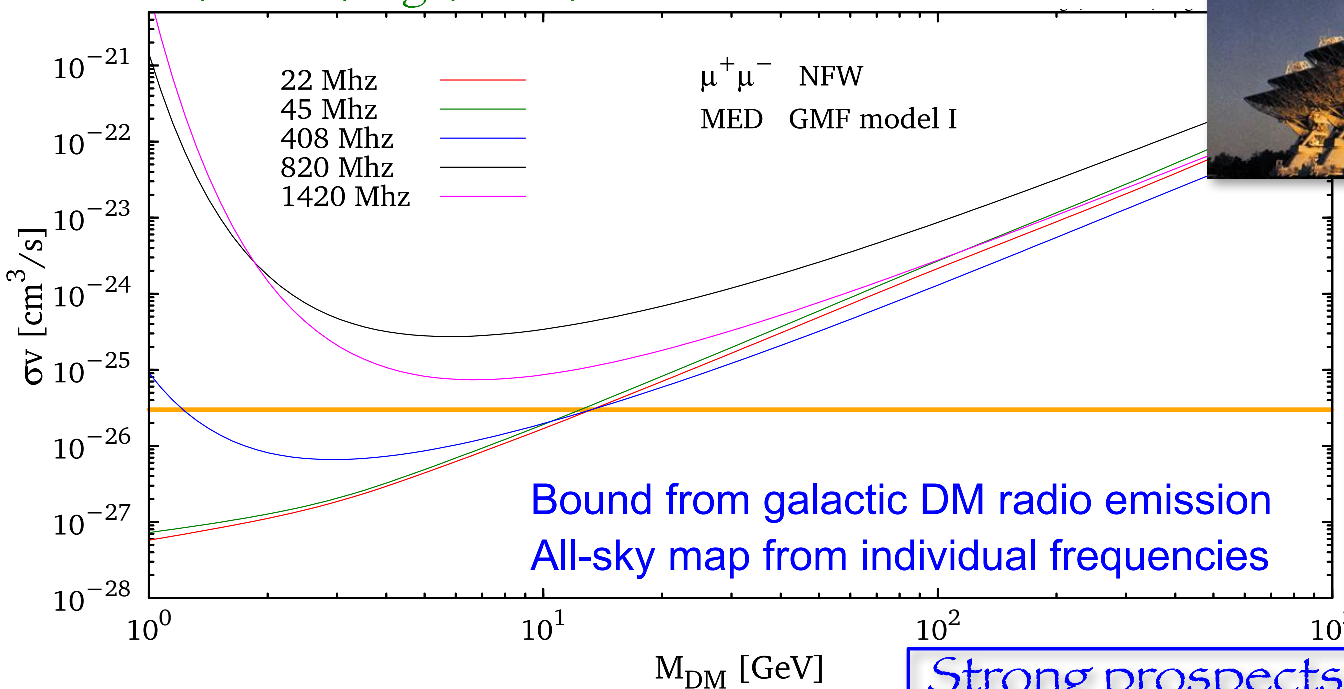
Boyarski et al, PRL 113 (2014) 251301

KeV DM decay?

De-excitation lines?

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

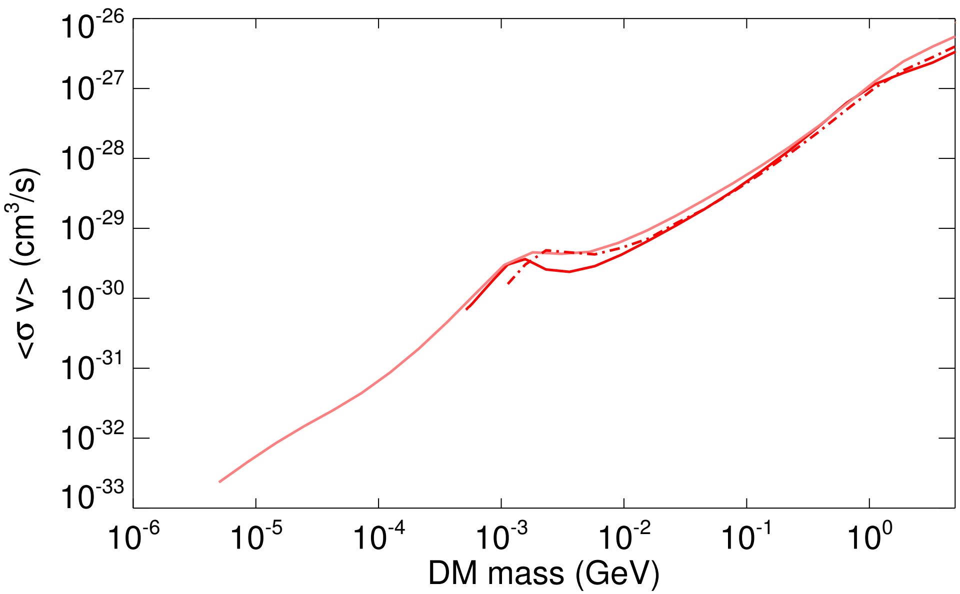
Extragalactic radio has a similar (slightly worse) constraining power (but different uncertainties in modeling)

Egorov, Pierpaoli, PRD 88 (2013) 023504

Regis et al, JCAP 1410 (2014) 016

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

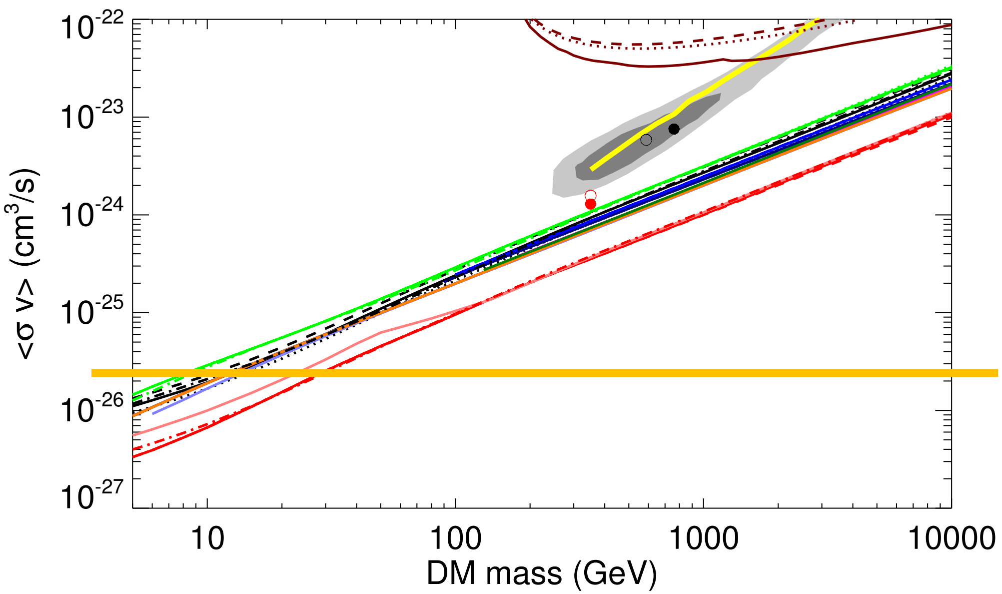
CMB



Injection of ionizing particles during the cosmic dark ages

Increase in the residual ionization fraction and affect CMB

Slatyer, PRD 93 (2016) 023527



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

Underground direct detection

Set of operators

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

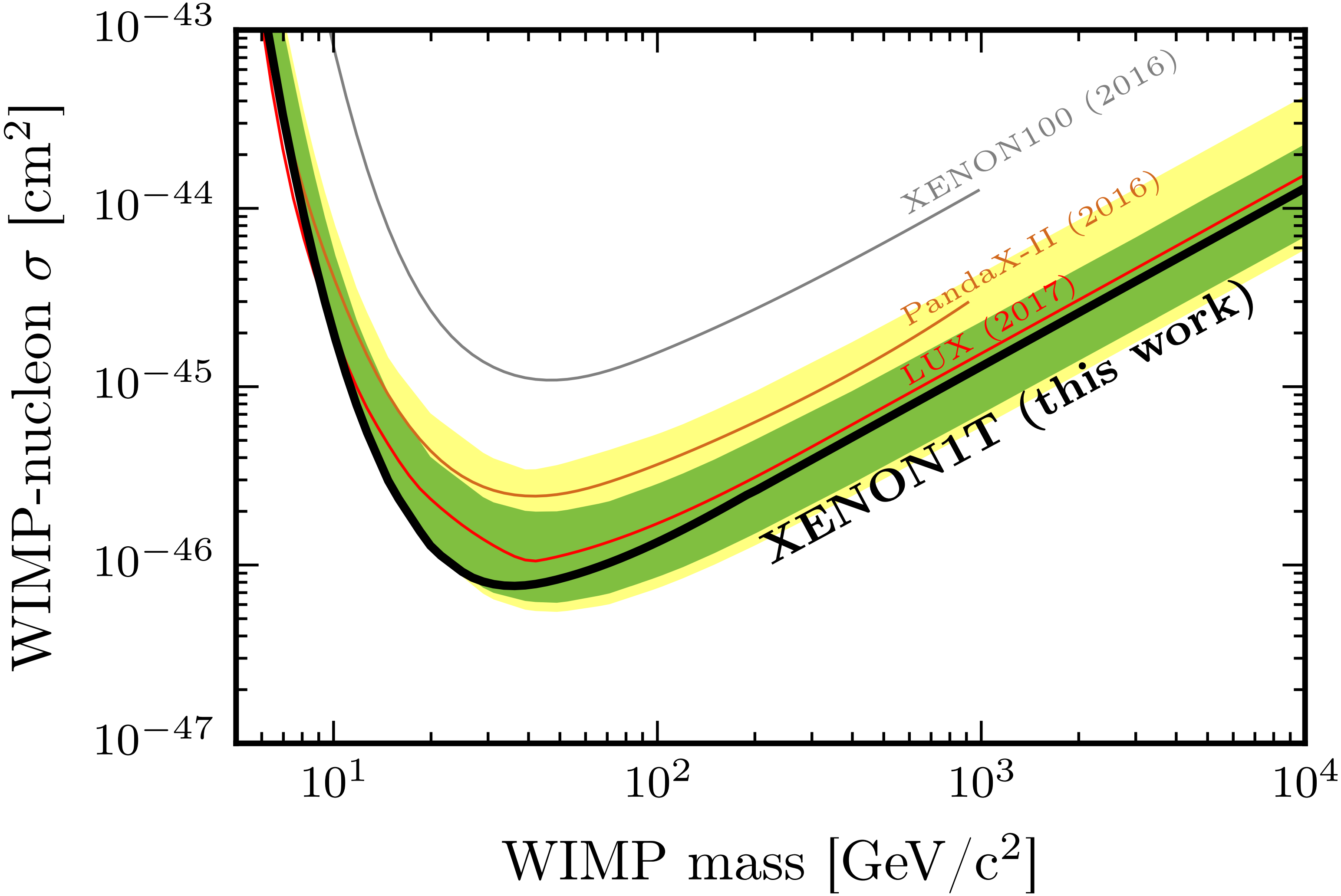
$$\hat{\mathcal{O}}_{18} = i\left(\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N\right)$$

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

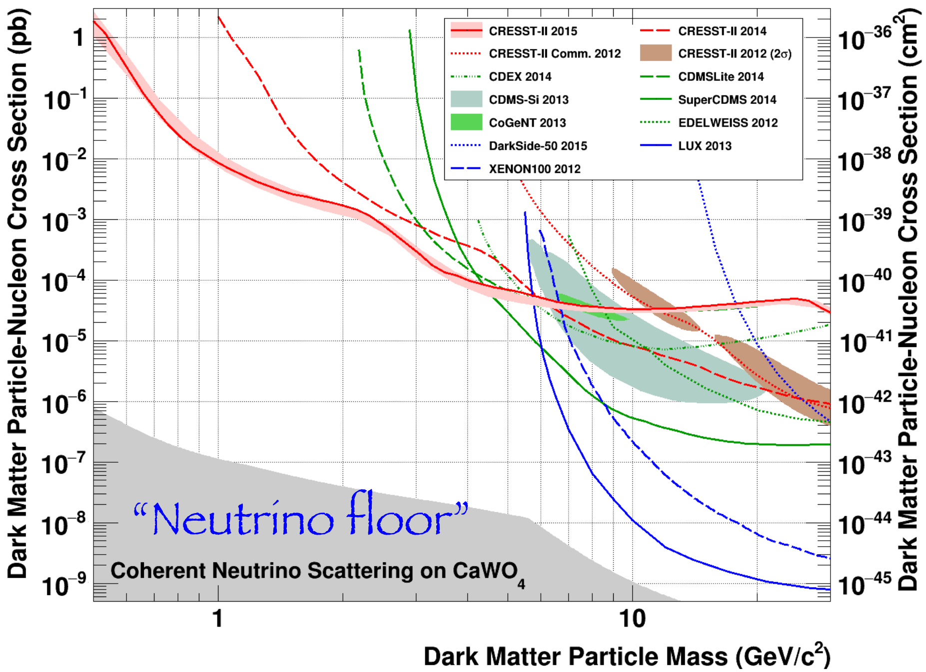
High WIMP mass

Contact-type scalar interactions (O_1)

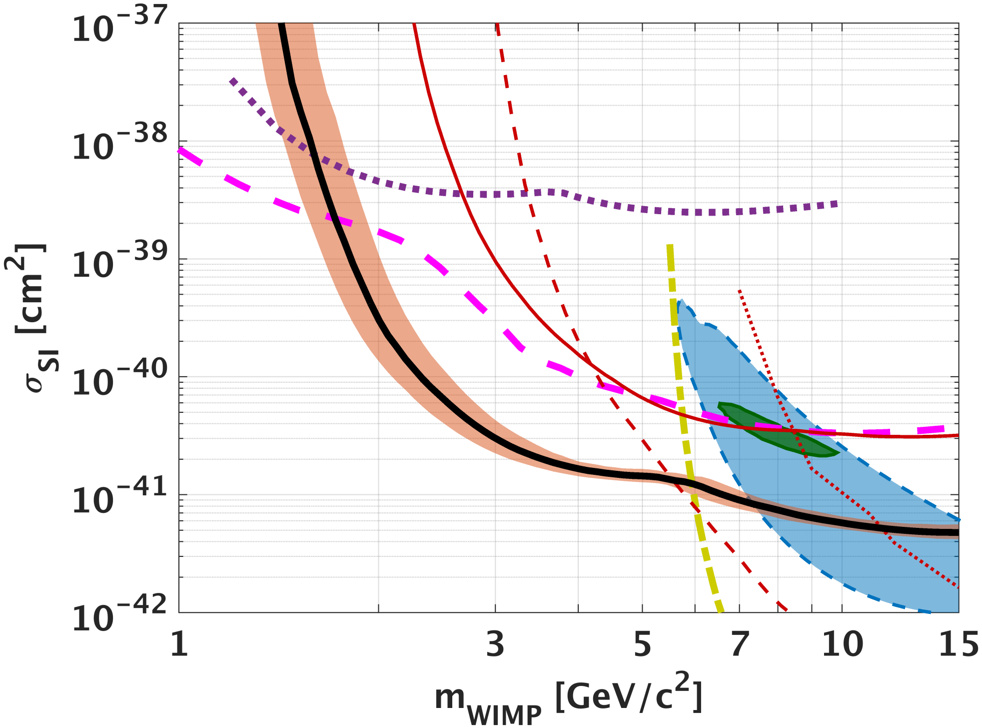


Aprile et al (XENON 1T Collab), 1705.06655

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) 10^{-47} cm^2
  - LZ (LXe) 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:

Guo, McKinsey, PRD 87 (2013) 115001

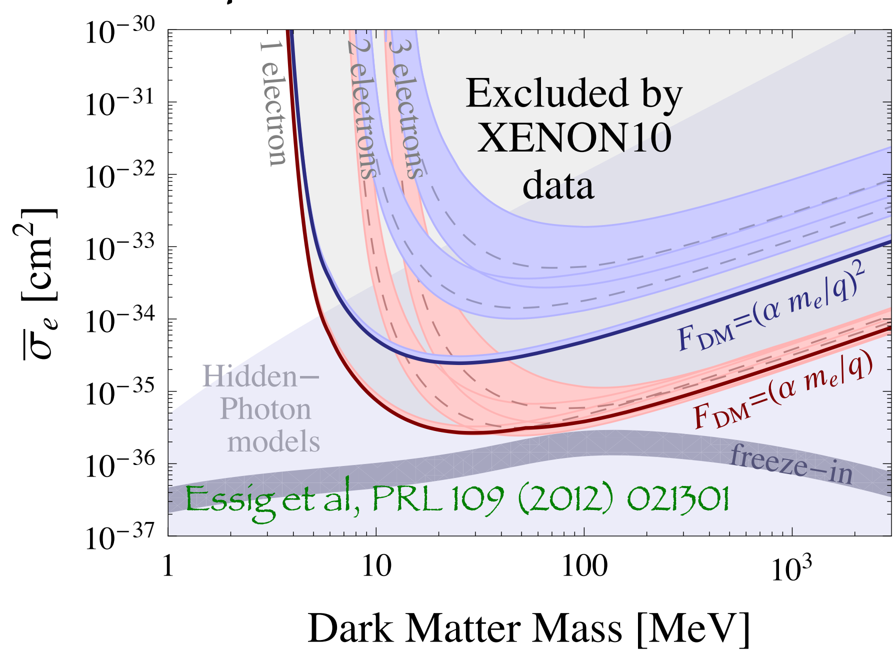
  - Nuclear interactions on light targets, e.g. liquid He
  - Electron recoils

Essig et al, PRD 85 (2012) 076007

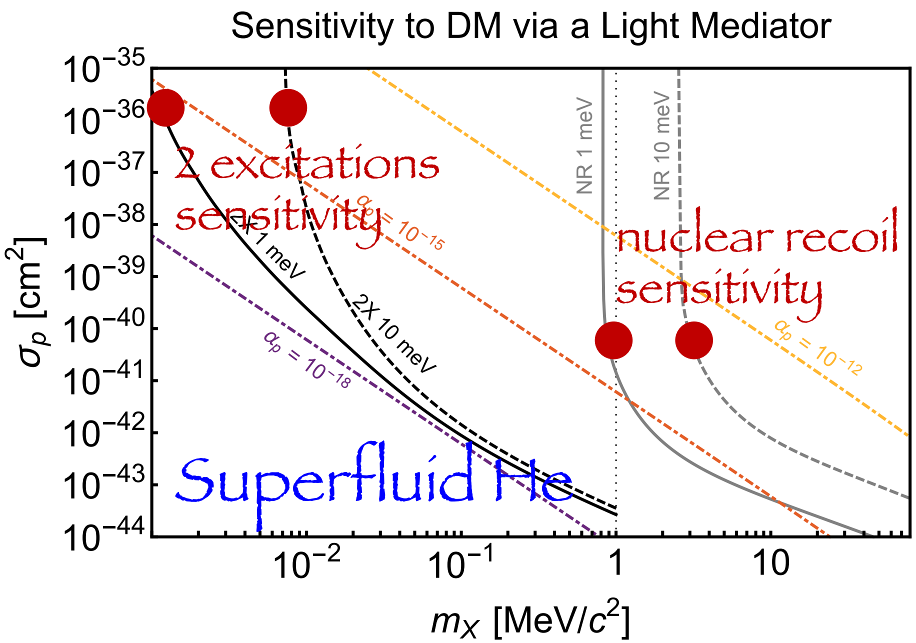
Essig et al, 1509.01598

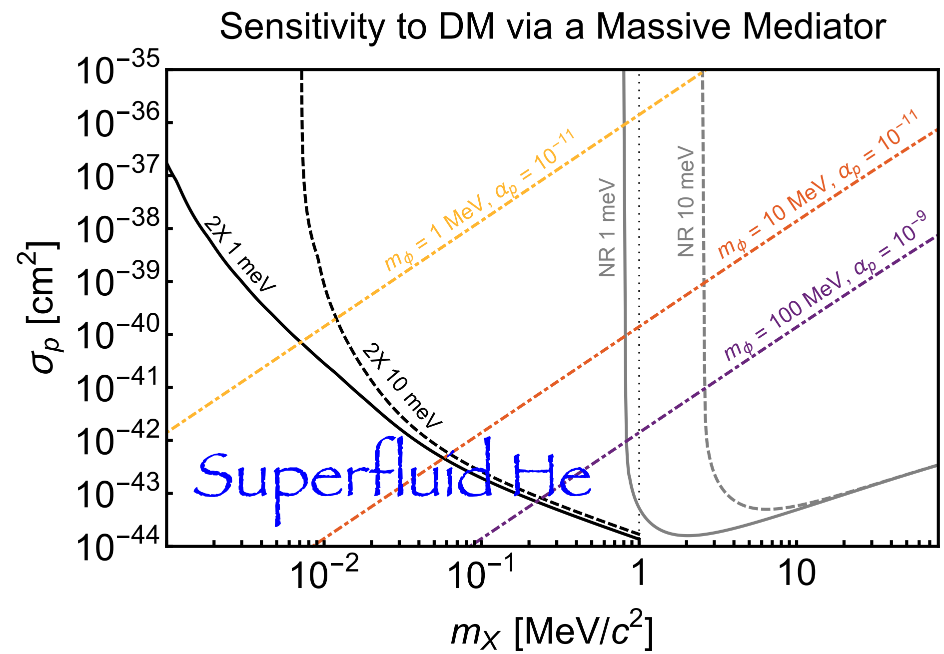
Agnese et al (SuperCDMS) PRL 112 (2014) 041302

Essig et al, PRL 109 (2012) 021301



Super light DM



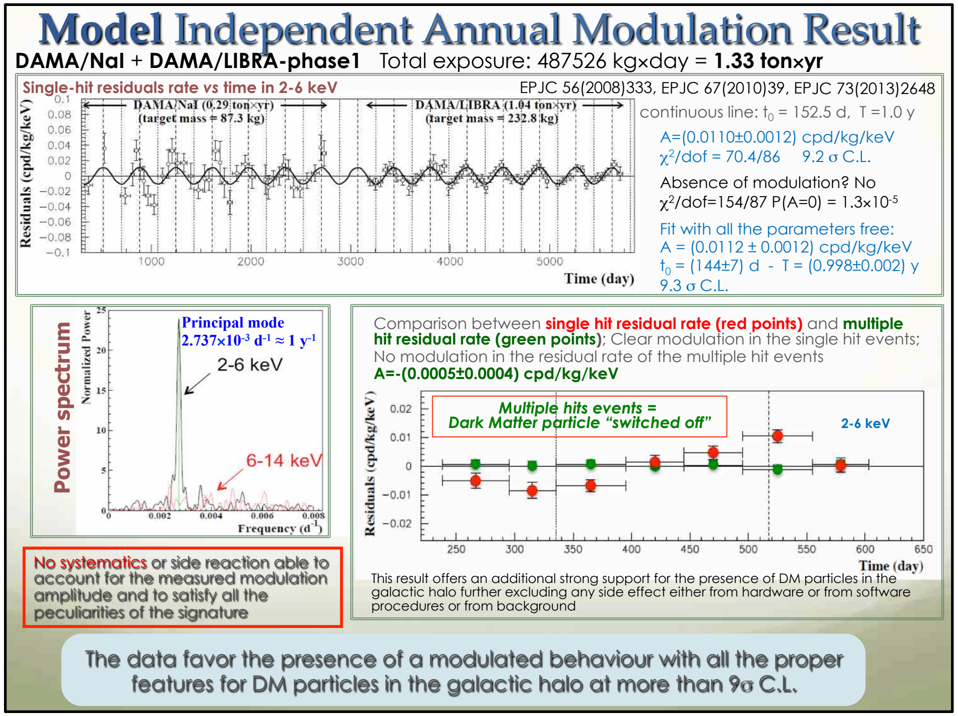


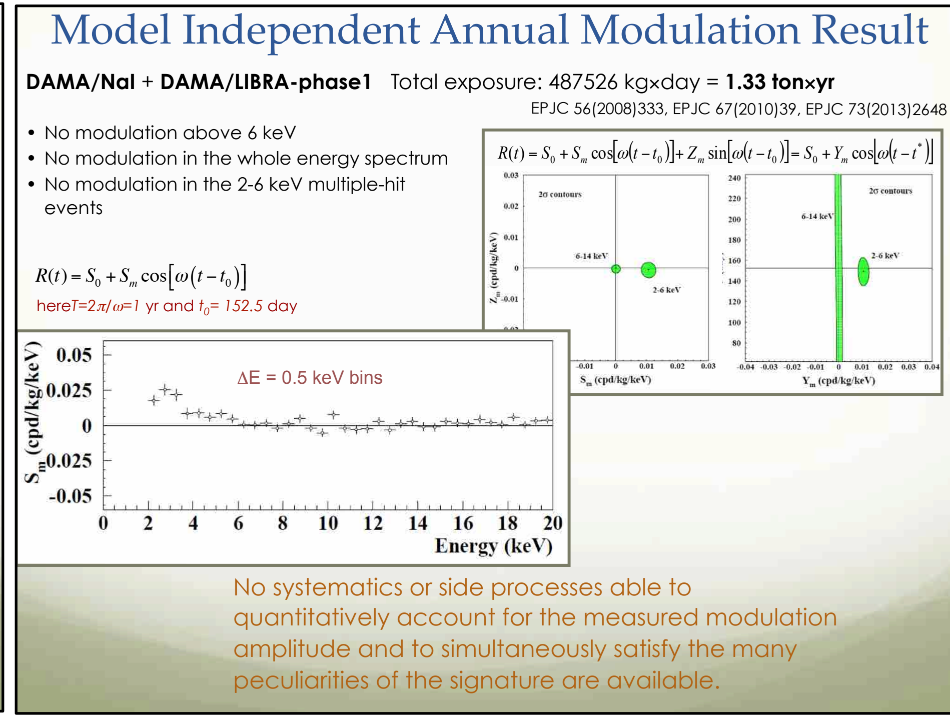
To go below 10 MeV DM: conversion of the full tiny energy needed

- 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/cm^2)

In case of "scalar" interaction

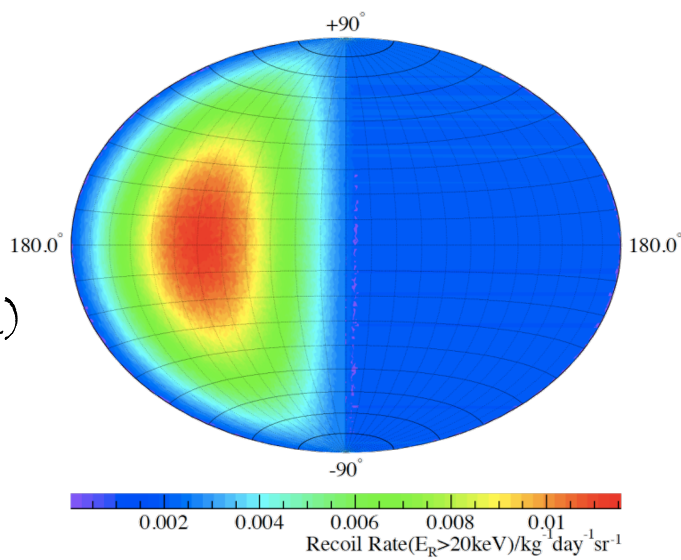
DM scattering on electrons — (0.1-10) KeV ALPs

Prospects

- Annual modulation: SABRE
  COSINE
  ANAIS

- Diurnal modulation: DAMA with larger mass might 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, …



Conclusions

- The solution to the DM problem requires to identify (or disprove) its particle physics nature: either way, New Physics is there
- This can be done only through a coordinated and multifaceted effort which gets input both from:
  - Accelerator physics
  - Astrophysical and cosmological probes
- WIMP Current techniques have started probing the region of interest
  It is the right moment to push forward
- Non WIMP The interest has been recently strongly revived, new ideas
  Window of opportunity complemetary to WIMPs
- A signal of DM is clearly faint, but the opportunities are rich: multimessenger, multiwavelength, multitechnique