

STATUS OF THE SEARCH OF DARK MATTER AS AN ELEMENTARY PARTICLE

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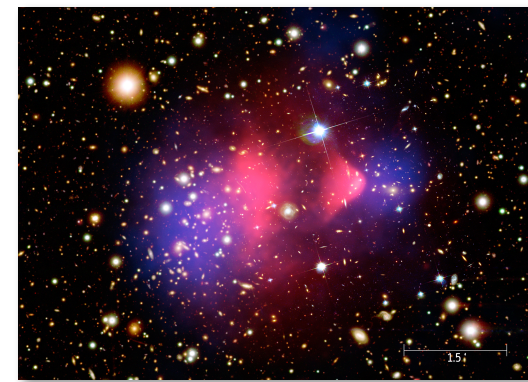
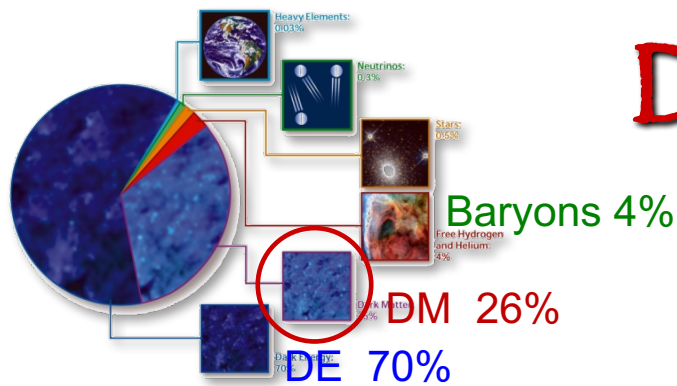
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XIX Roma 3 Topical Seminar on Subnuclear Physics
Gravitational Waves and Cosmology – 5.12.2016

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:

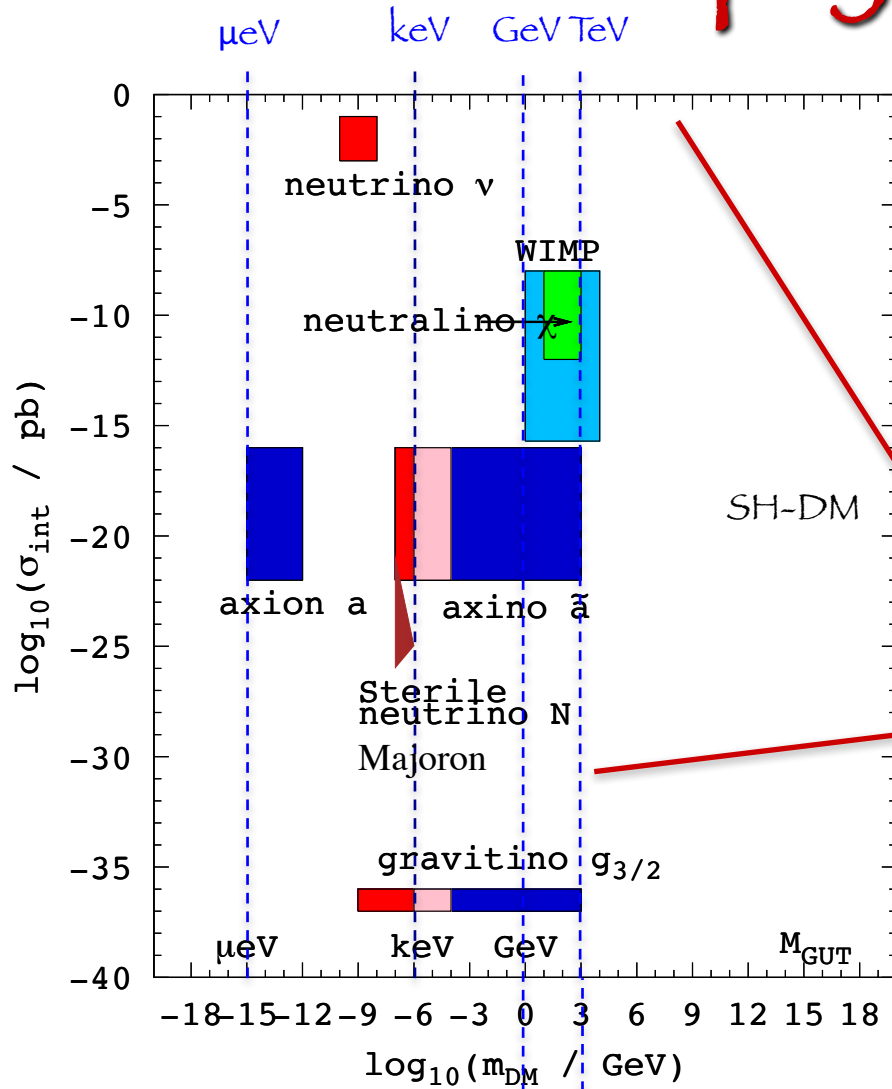
- Some issues under discussion on very small scales
- Role of baryons in galaxy formation just started to be investigated

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 its particle physics nature) is needed

Particle physics scales



“Strong (-ish)”

Self-interacting
Technicolor DM

...

“EM (-ish)”

Millicharged DM
Electric/magnetic dipole

...

Weak

WIMP

Gravitational

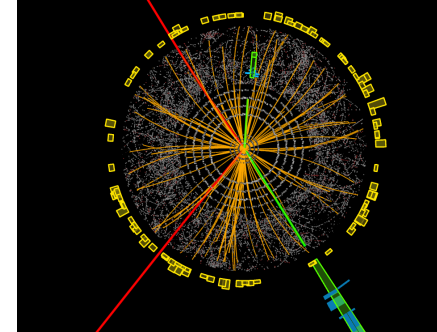
Relic from the early Universe

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

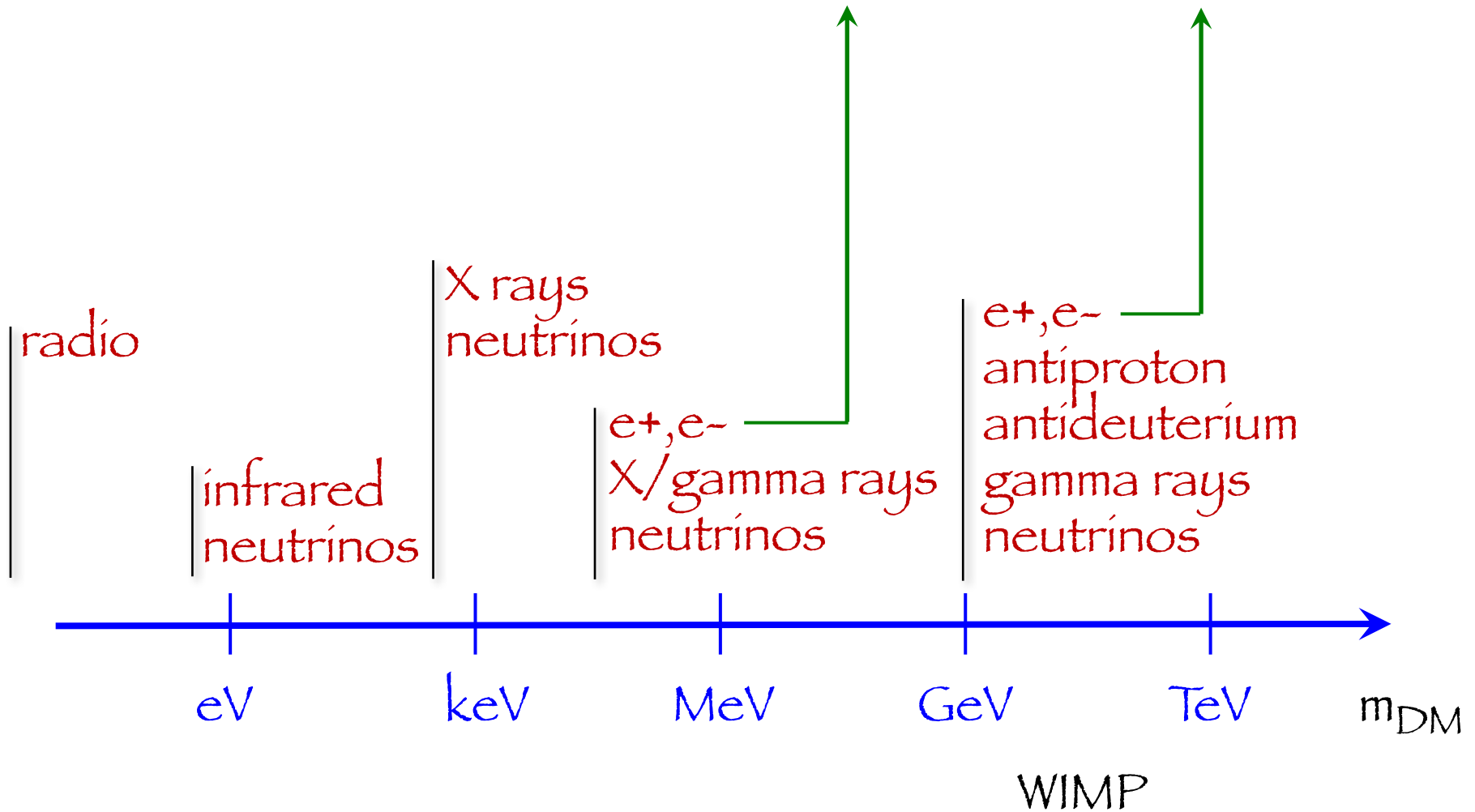
Photons	WIMP non WIMP radio	IR	WIMP non WIMP X	WIMP gamma
Cosmic rays	electrons/positrons antiprotons, antideuterium, antinuclei		WIMP, non WIMP	WIMP
Neutrinos			WIMP, non WIMP	
Gravitational waves			non WIMP (DM = primordial BH)	

Multi: messenger/wavelength/technique

	WIMP non WIMP	WIMP non WIMP	WIMP
Photons	radio	IR	X gamma
Cosmic rays	electrons/positrons antiprotons, antideuterium, antinuclei		WIMP, non WIMP 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

X/gamma rays: IC on radiation fields
radio: synchro on ambient mag fields

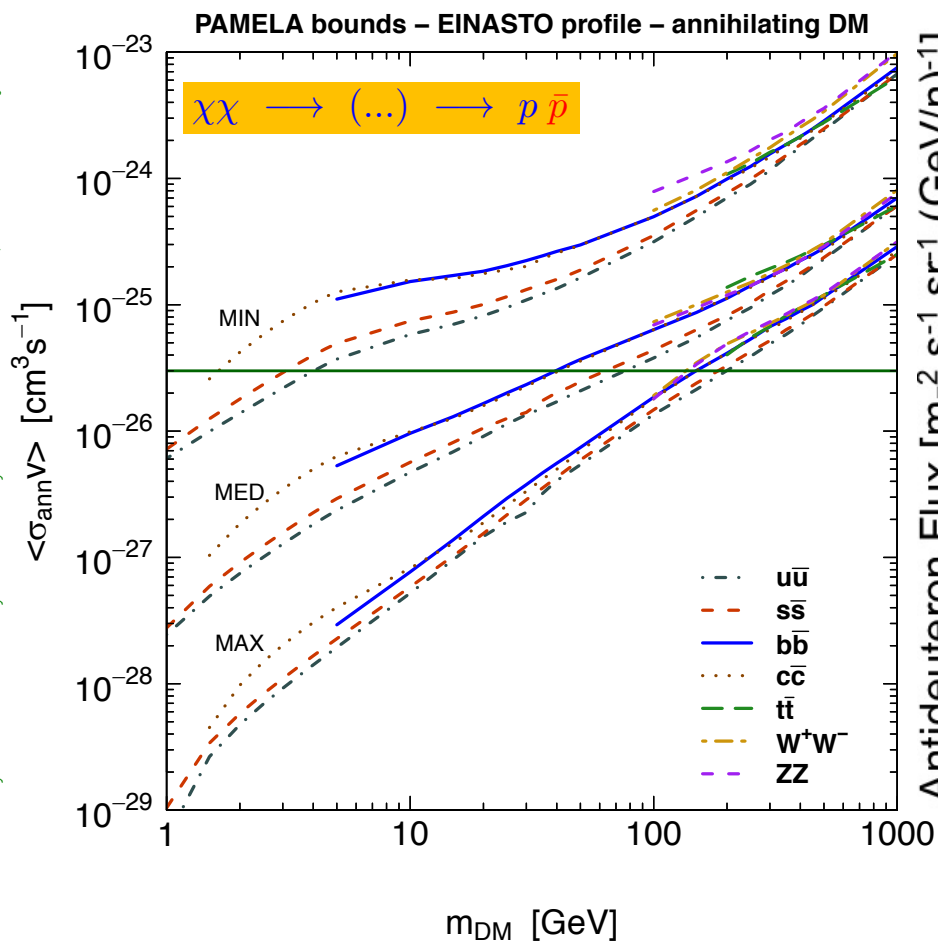




ASTROPHYSICAL MESSENGERS

Antinuclei

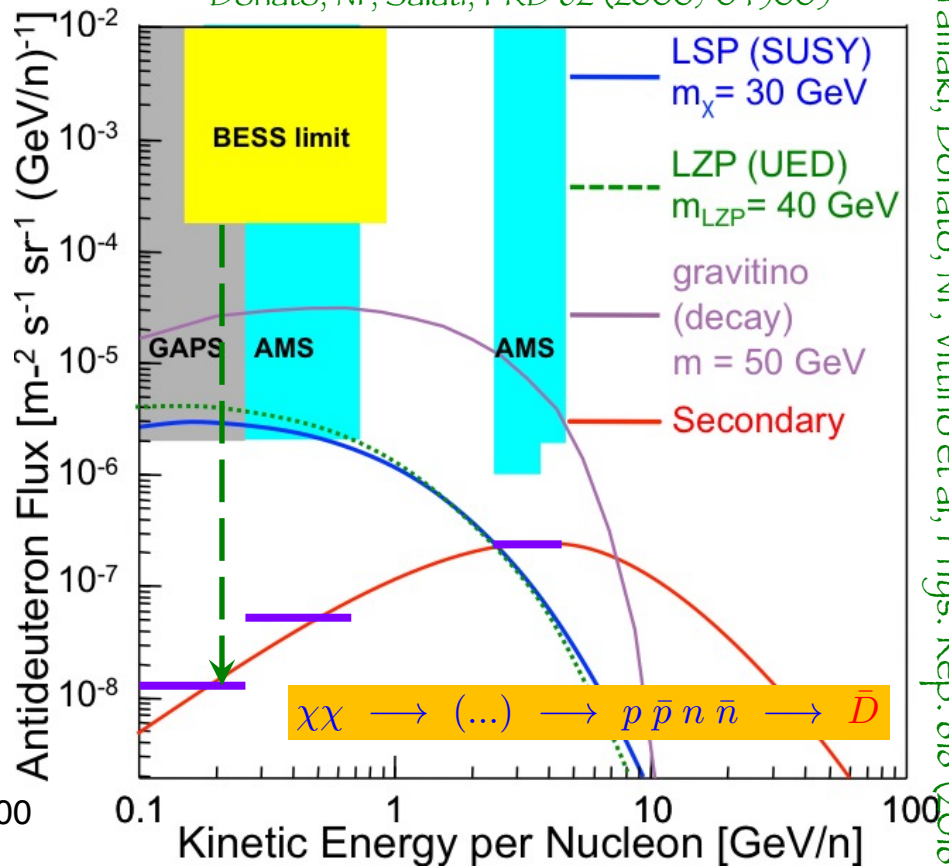
AntiProtons



Bounds from PAMELA

AntiDeuterons

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



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

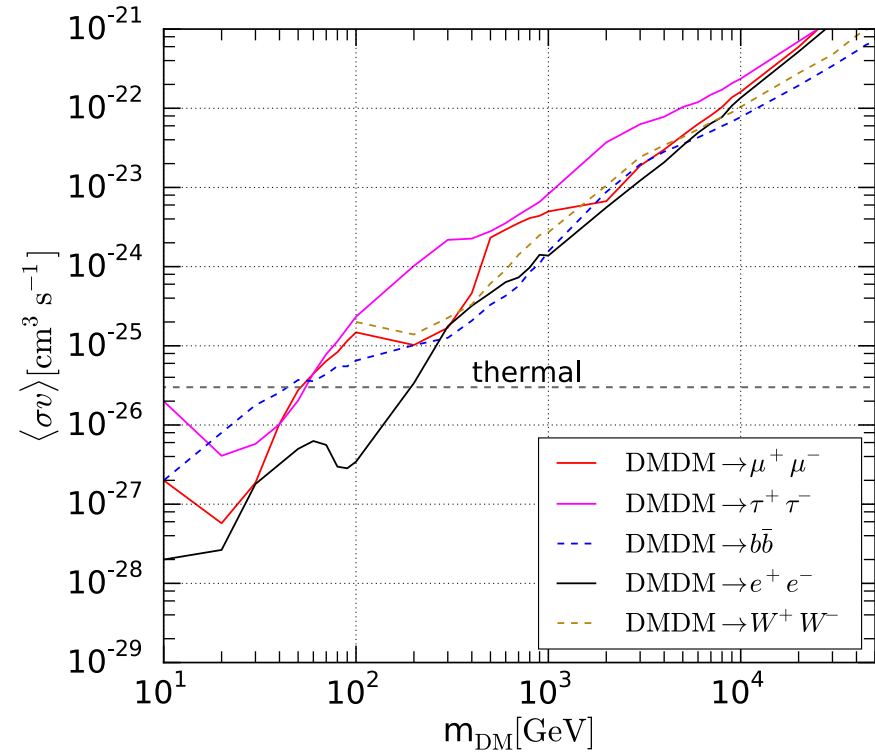
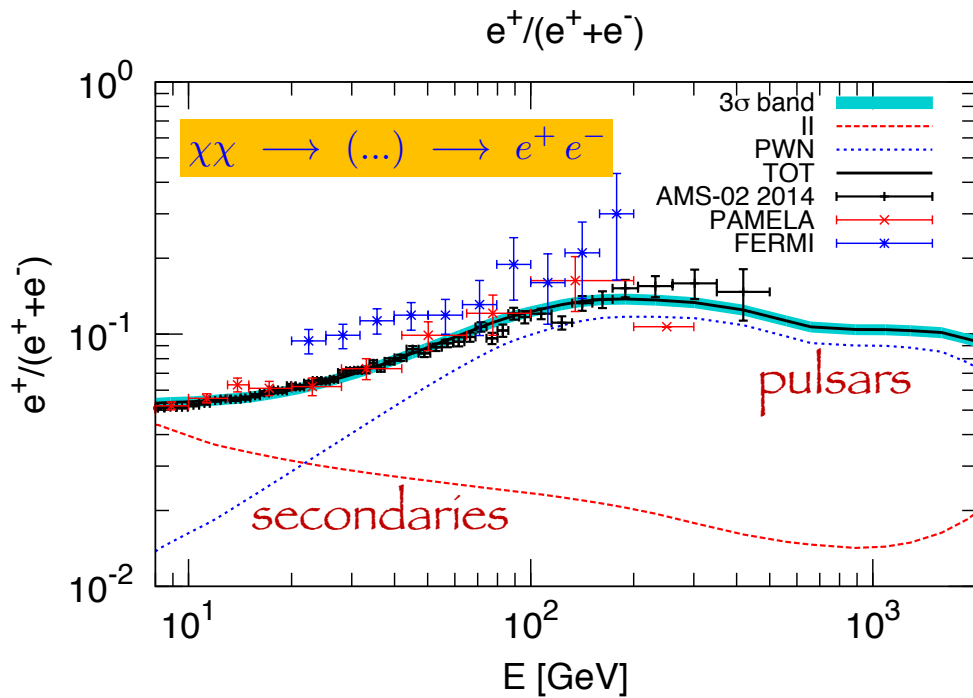
Kinematics: largely favours signal over background

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

Even a “single antiD”: smoking gun for exotics

GAPS: approved from NASA – INFN has joined

Electrons/positrons

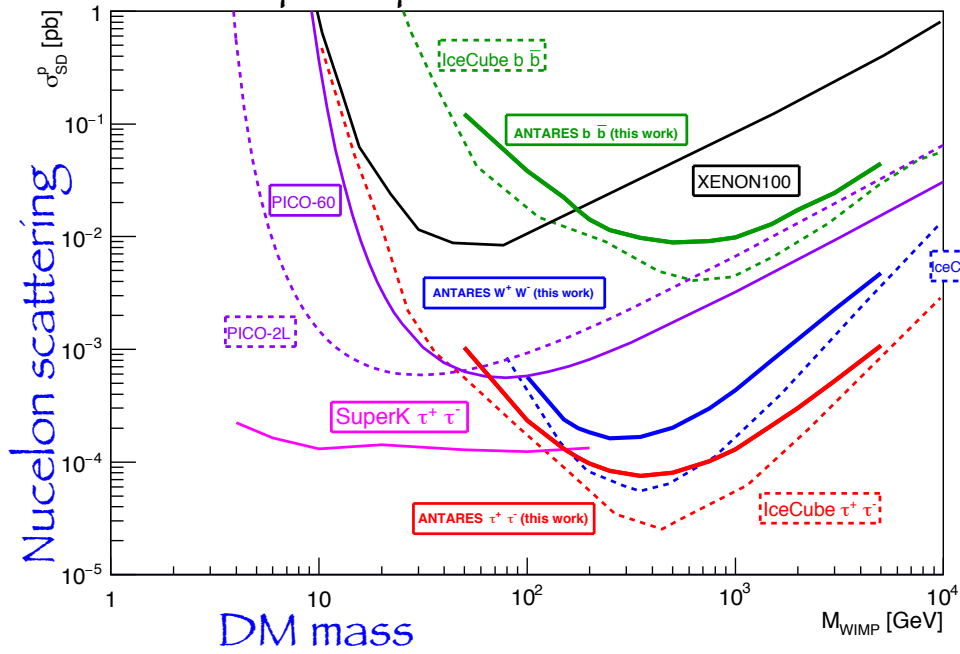


Astrophysical interpretation

Bounds on DM

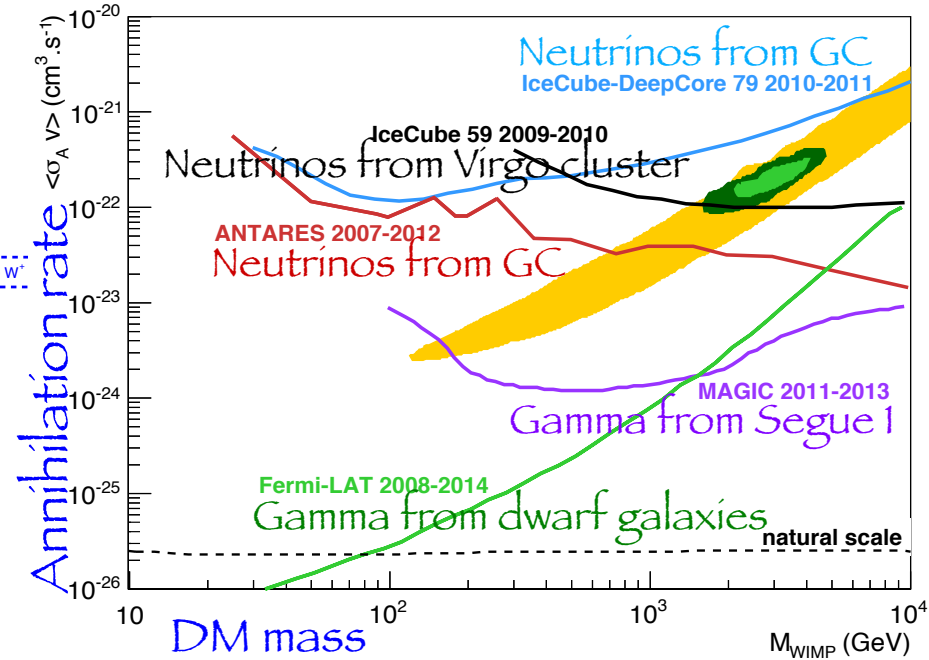
Neutrinos

From the Sun
Spin dependent interaction



ANTARES Collab, PLB 759 (2016) 69

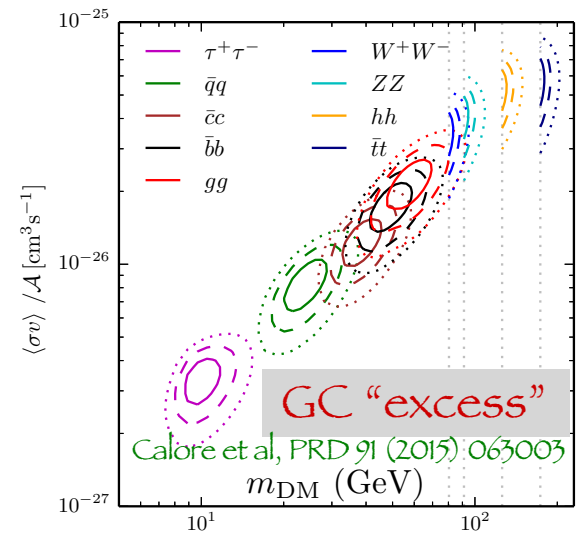
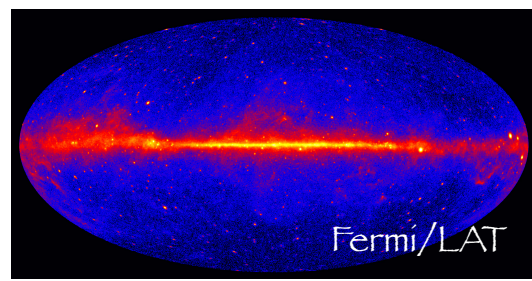
Other targets



ANTARES Collab, JCAP 1510 (2015) 068

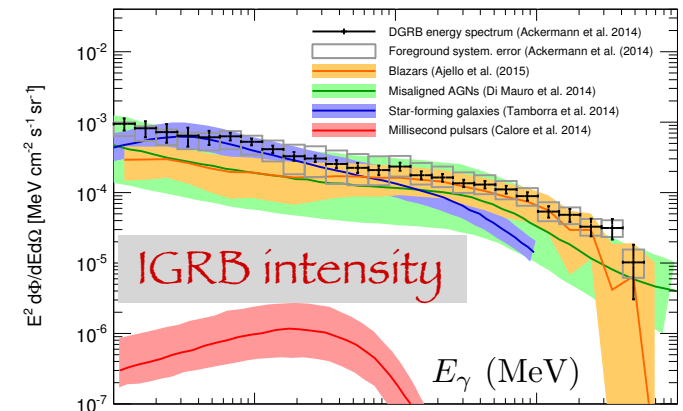
Warning: bounds are typically derived under the assumption of perfect **equilibration** between capture and annihilation (and **contact** interactions)

Gamma rays



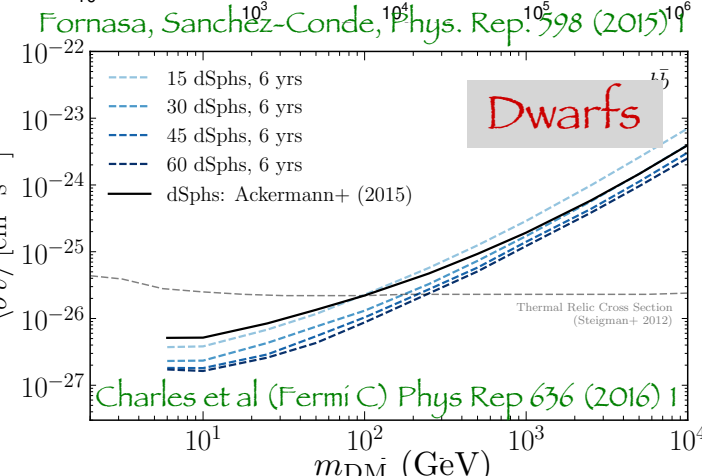
Galactic center

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 separate 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 ...

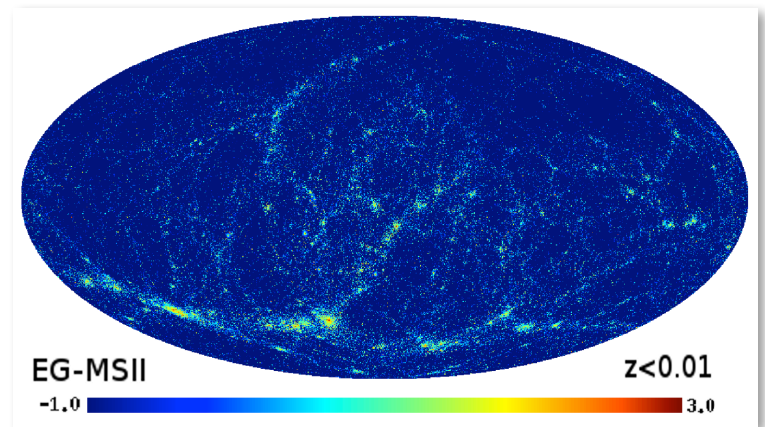
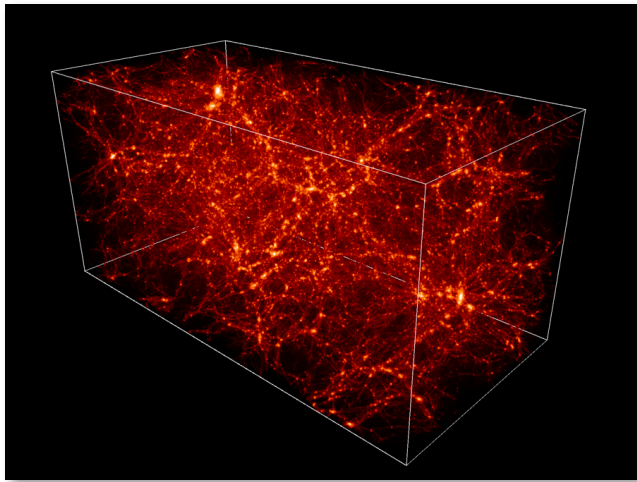
Being the cumulative sum of independent sources (astro/DM)

To first approximation:

isotropic

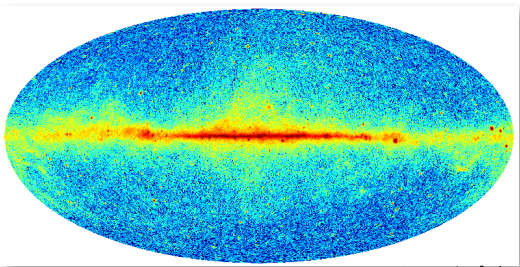
At a deeper level:

anisotropies are present

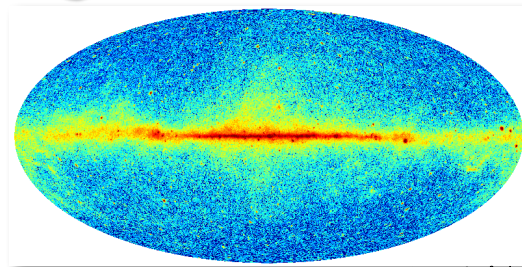


Even though sources are too dim to be individually resolved, they can affect the statistics of photons across the sky

Gamma rays auto-correlation

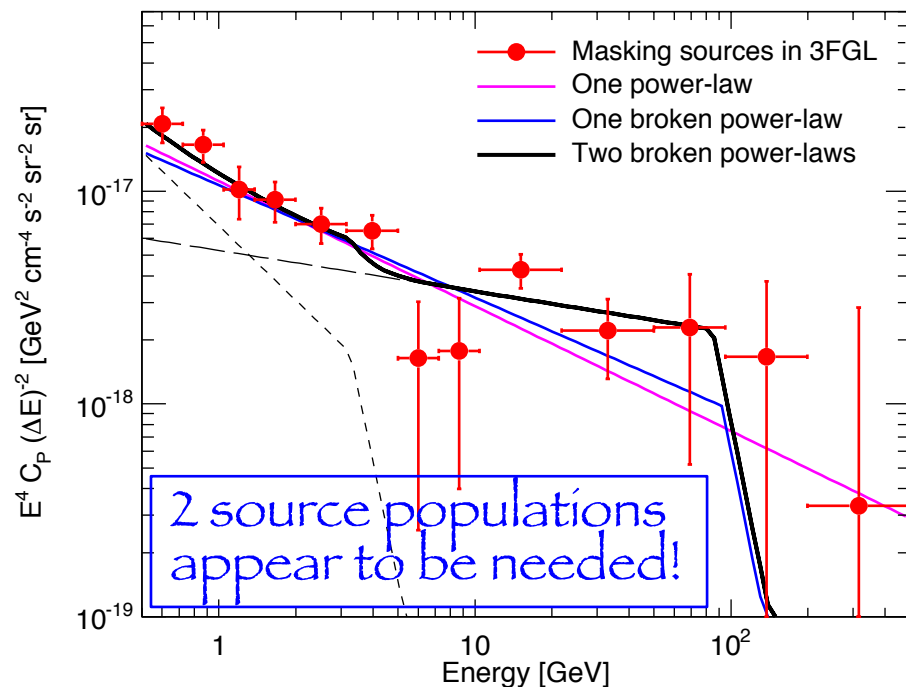
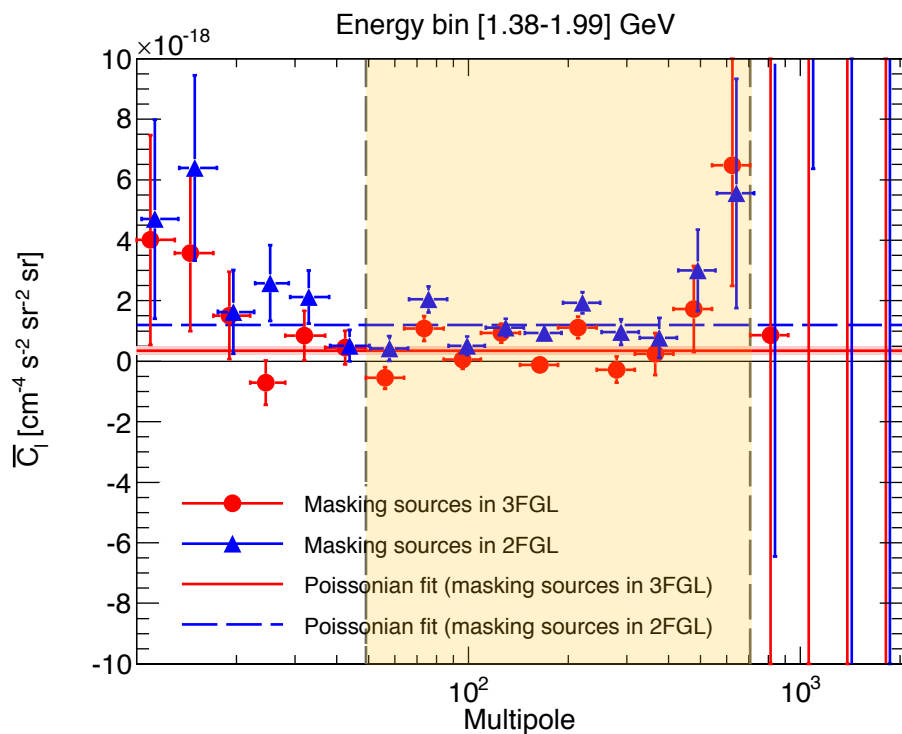


×



2 point correlator
angular power spectrum

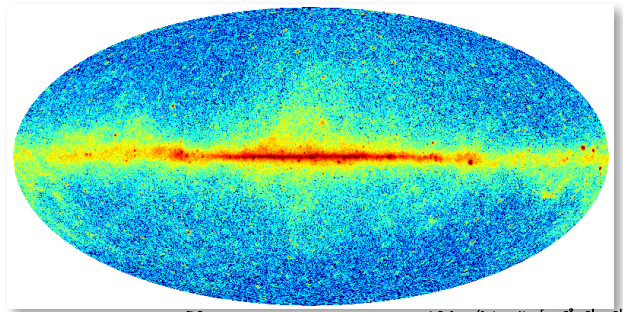
$$\langle I(\vec{n}_1)I(\vec{n}_2) \rangle \longrightarrow C(\theta) \longrightarrow C_l$$



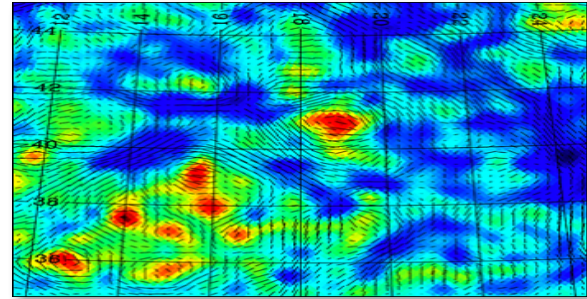
Fornasa, Cuoco et al, 1608.07289

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

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)

Xía, Cuoco, Branchini, Viel, APJS 217 (2015) 15
Regis, Xía, Cuoco, Branchini, NF, Viel, PRL 114 (2015) 241301
Cuoco, Xía, Regis, Branchini, NF, Viel, ApJS 221 (2015) 29
Shirasaki, Horiuchi, Yoshida, PRD 92 (2015) 123540

X-CORR DETECTED

Fermi x (SDSS + 2MASS + NVSS)

“

“

Fermi x SDSS LRG

Gamma rays x Cosmic shear

Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502
Shirasaki, Macias, Horiuchi, Shirai, Yoshida, 1607.02187
Troester, Camera, Fornasa, Regis, Ando, NF, Van Vaerbecke +, 1611.03554

X-CORR NOT DETECTED (YET ...)

Fermi x CFTHLenS

Fermi x (CFTHLenS + RCSLenS)

Fermi x (CFTHLenS + RCSLenS + KiDS)

Gamma rays x CMB lensing

NF, Perotto, Regis, Camera, ApJ 802 (2015) L1

X-CORR DETECTED

Fermi x Planck

Gamma rays x Galaxy clusters

Cuoco, Regis, Camera, Branchini, NF, Viel, Xía, submitted

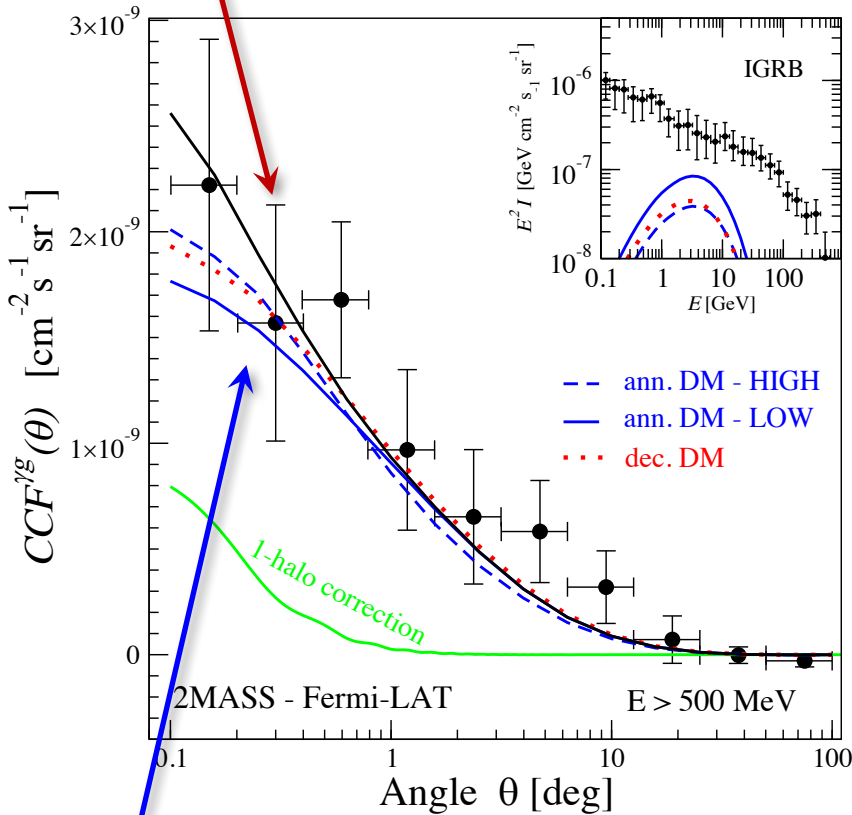
X-CORR DETECTED

Fermi x (redMaPPer + WHL12 + PlanckSZ)

Cross Correlations

measured correlation

Fermi x 2MASS

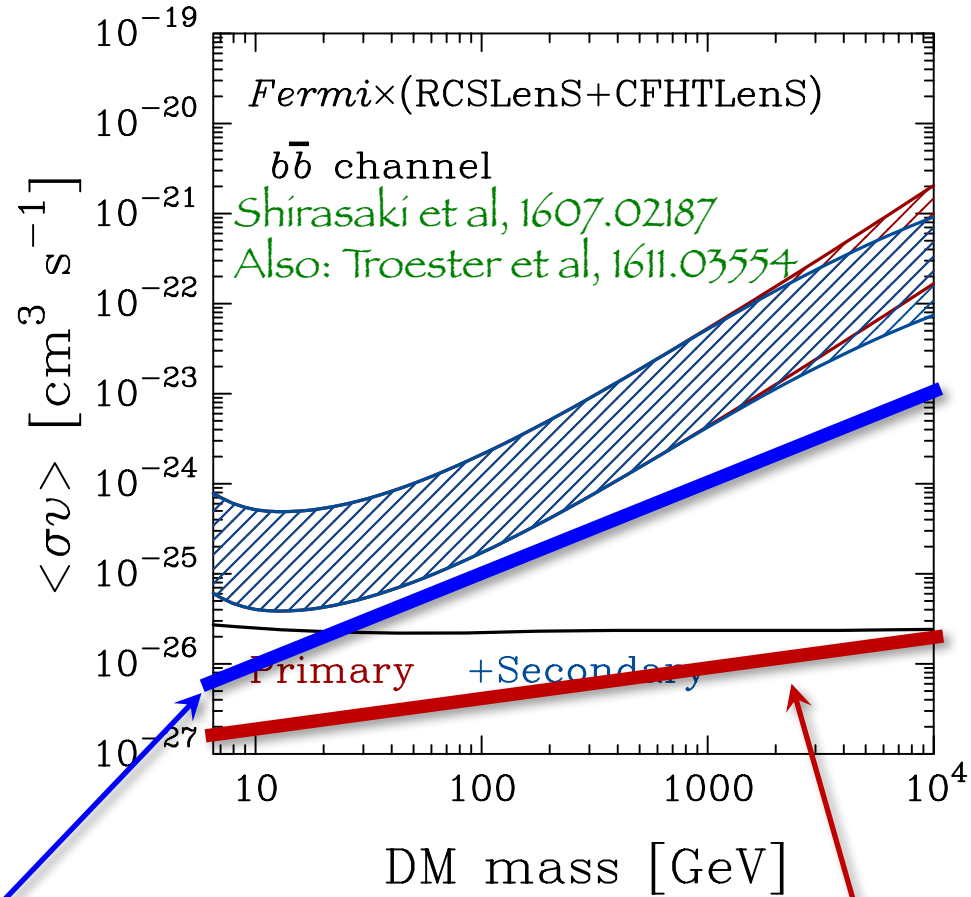


Regis et al PRL 114 (2015) 241301

DM signal

Bounds from Fermi x LSS
Cuoco et al, ApJS 221 (2015) 29

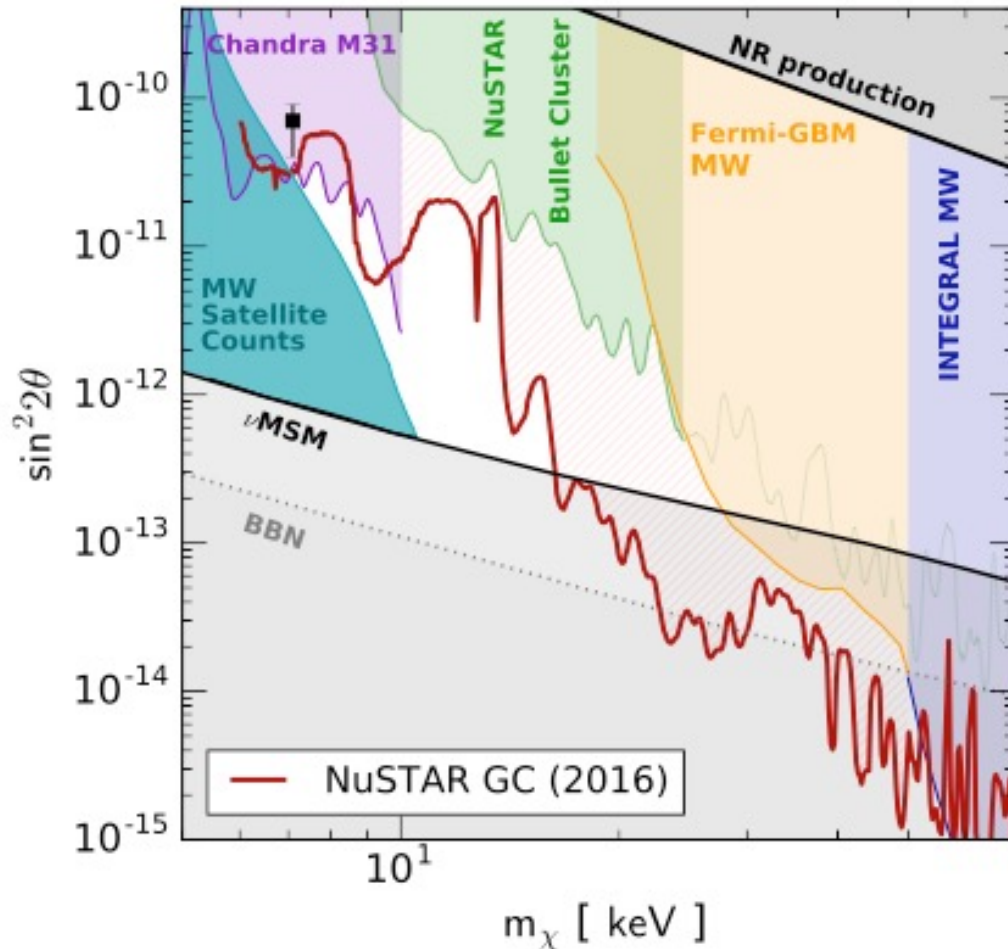
Bounds from Fermi x shear



Forecast for Fermi x Euclid
Camera et al, JCAP 06 (2015) 029

Lower frequencies and non-WIMP

X rays



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?

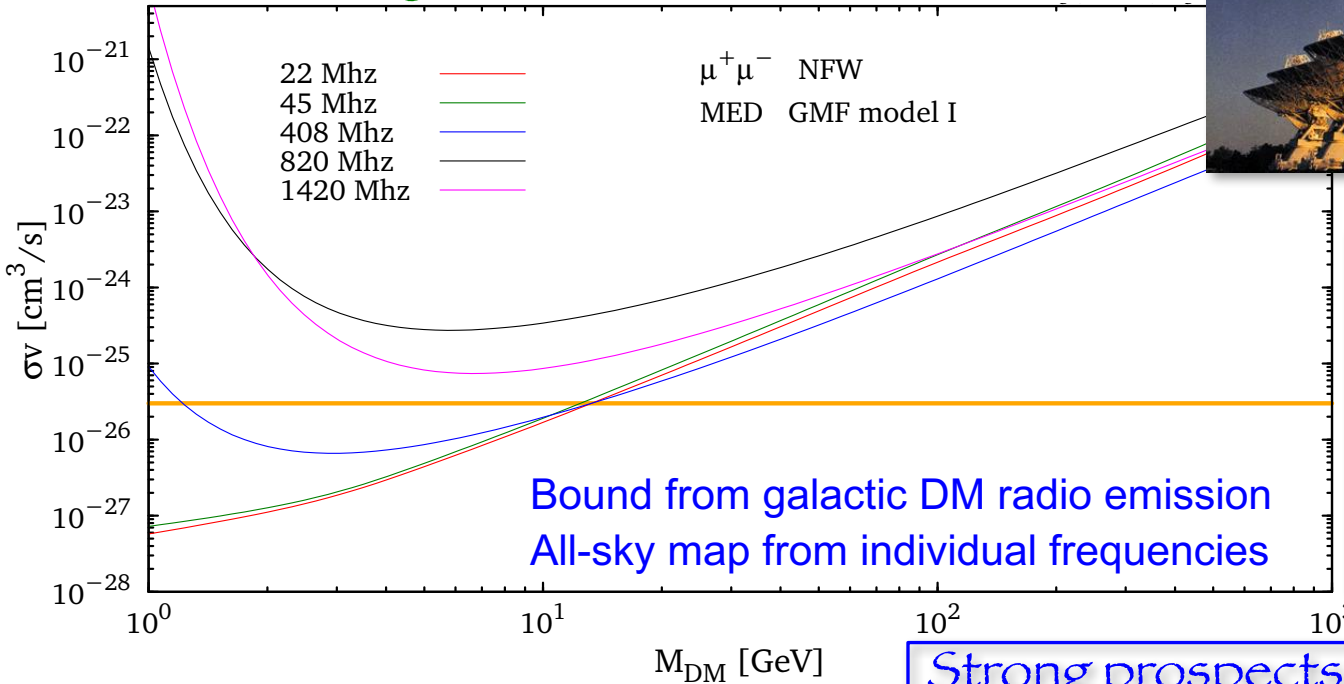
De-excitation lines?

New bounds from nuSTAR @ GC

Perez et al, 1609.00667

Radio frequencies

NF, Líneros, Regís, 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, Líneros, Regís, Taoso, JCAP 03 (2012) 033

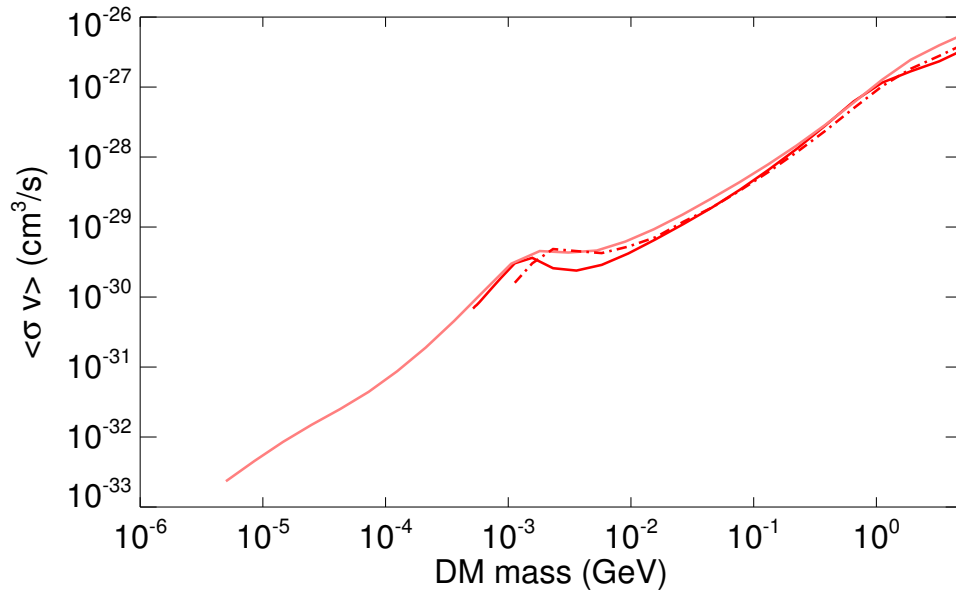
Extragalactic radio has a similar (slightly worse) constraining power (but different uncertainties in modeling)

Egorov, Pierpaoli, PRD 88 (2013) 023504

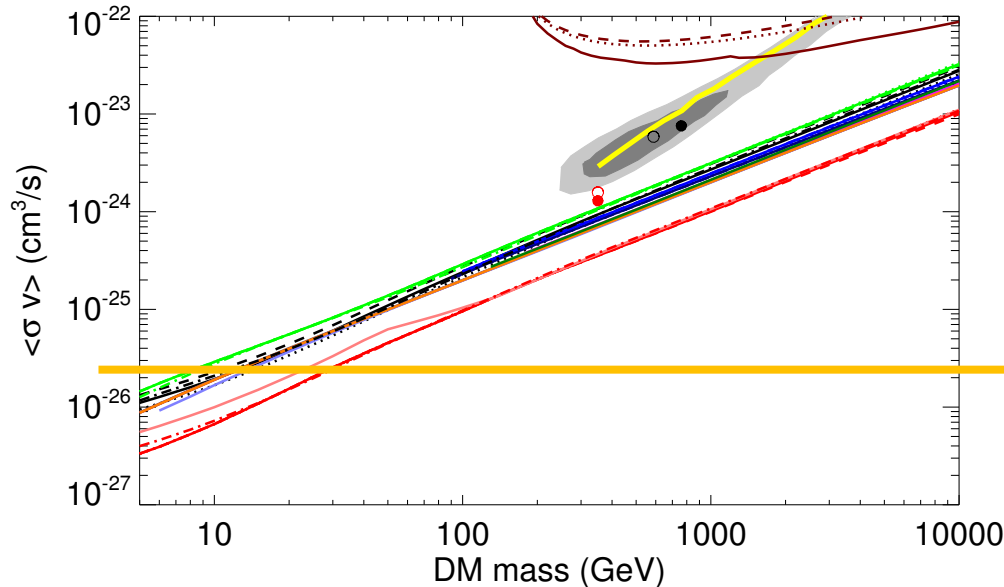
Regís et al, JCAP 1410 (2014) 016

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

Hisano 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

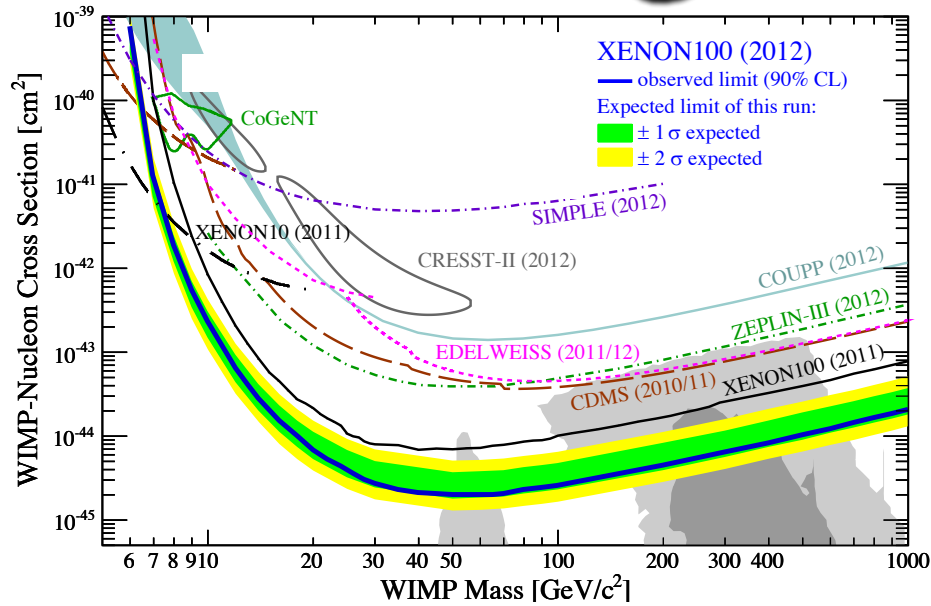
$$\hat{O}_{18} = i \left(\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N \right)$$

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
 (...)

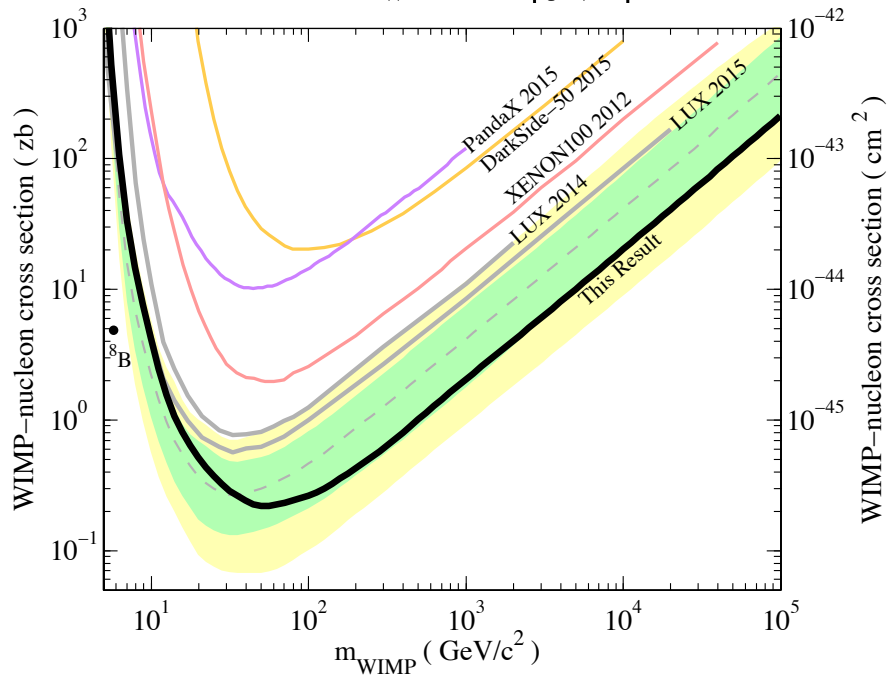
Fitzpatrick et al, JCAP 1302 (2013) 004
 Fitzpatrick et al, arXiv:1211.2818
 Anand et al, PRC 89 (2014) 065501
 Dent et al, PRD 92 (2015) 063515

High WIMP mass

Contact-type scalar interactions

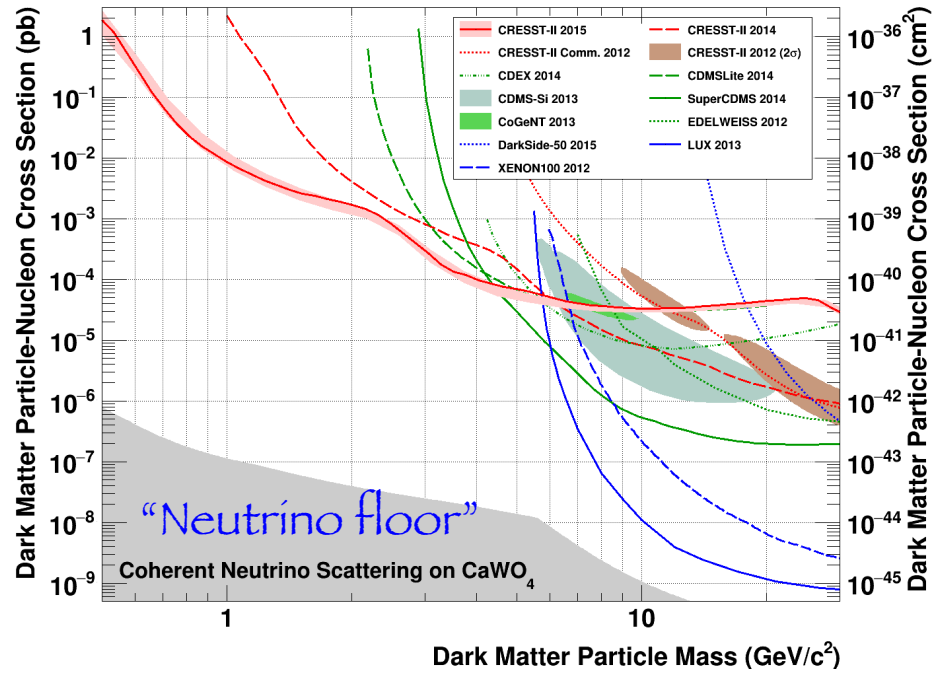


XENON 100 Collaboration, PRL 109(2012) 181301

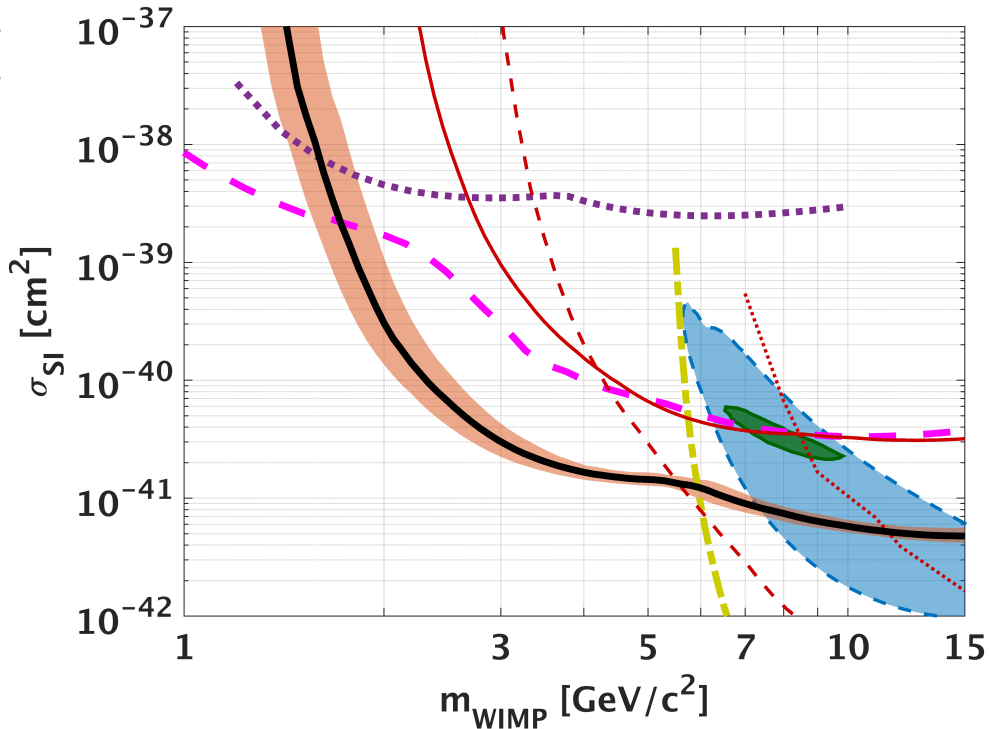


LUX Collaboration, presented at IDM 2016
332 live days

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) $3 \times 10^{-45} \text{ cm}^2$ at 1 GeV

- High WIMP mass

- Xenon IT, Xenon nT (LXe) $3 \times 10^{-47} \text{ cm}^2$ at 100 GeV
- DarkSide (Lar) 10^{-47} cm^2
- LZ (LXe) $3 \times 10^{-48} \text{ cm}^2$
- 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 $m_{\text{DM}} < 10 \text{ GeV}$ at $3 \times 10^{-45} \text{ cm}^2$ (1 GeV)
- Atmospheric neutrinos for $m_{\text{DM}} > 10 \text{ GeV}$ 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

- Possibilities:

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

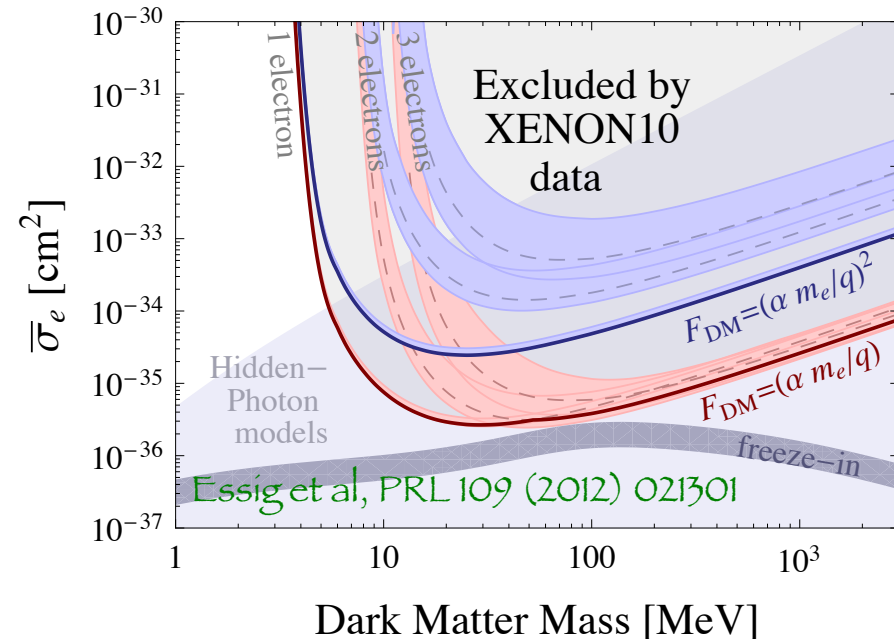
Essig et al, PRD 85 (2012) 076007

Essig et al, 1509.01598

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

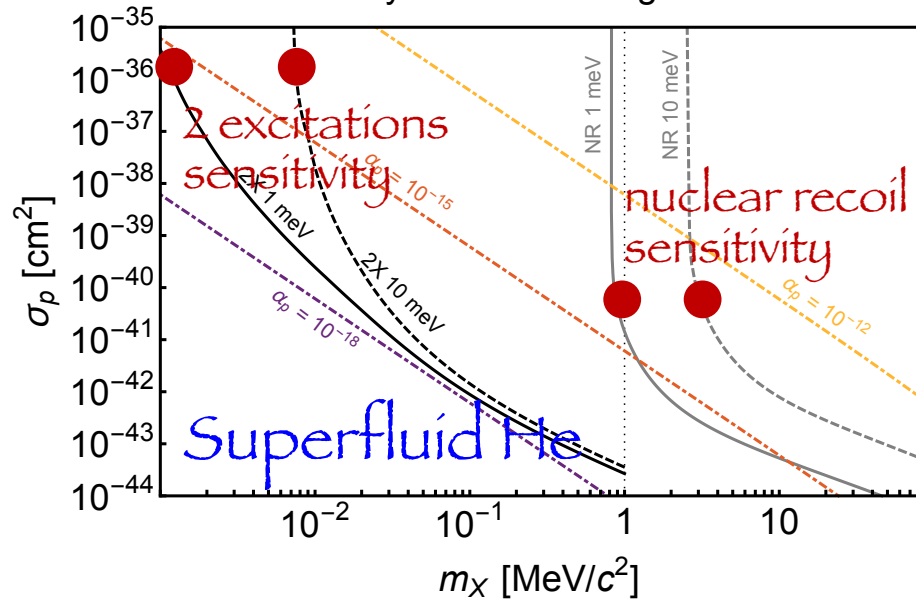
Essig et al, PRL 109 (2012) 021301

Guo, McKinsey, PRD 87 (2013) 115001

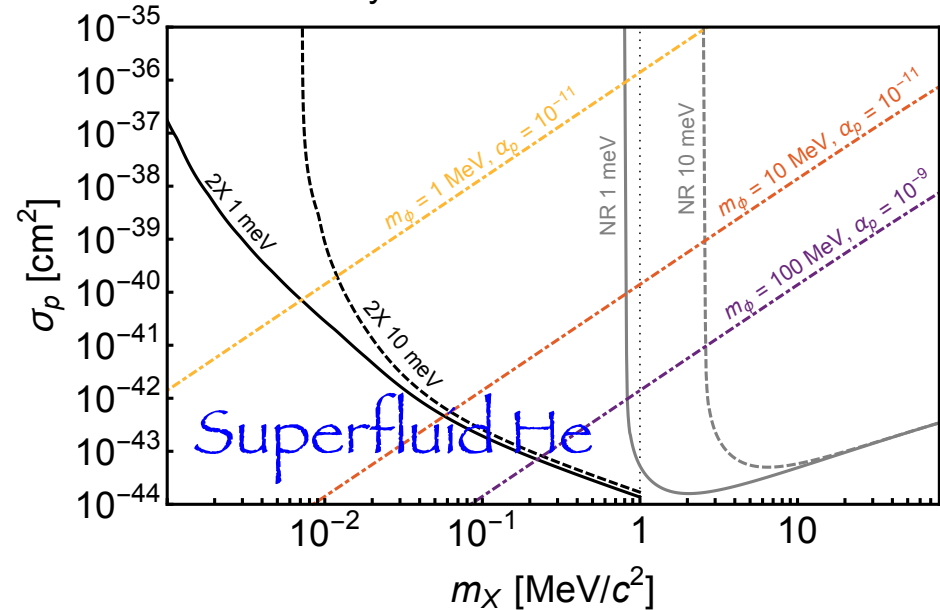


Super light DM

Sensitivity to DM via a Light Mediator



Sensitivity to DM via a Massive Mediator



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

- Superconductors

Hochberg et al, 1512.04533

Hochberg et al, PRL 116 (2016) 011301

electron interactions

- Superfluid He

Schutz, Zurek, 1604.08206

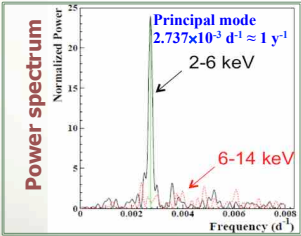
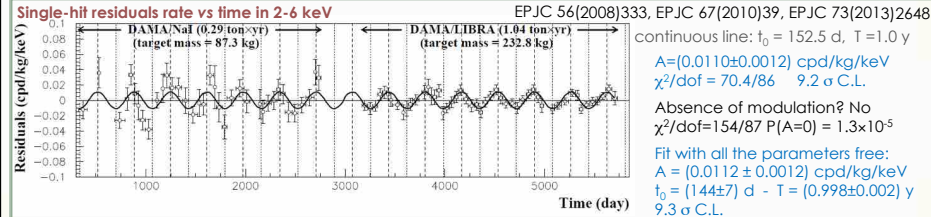
nuclear interactions

Annual modulation

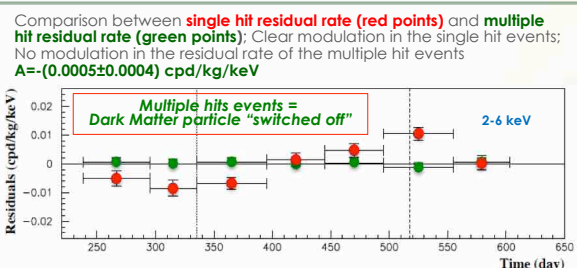
DAMA, 9.2σ with 1.33 ton x yr, 15 cycles

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kgxday = 1.33 tonxyr



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



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 more than 9σ C.L.

Model Independent Annual Modulation Result

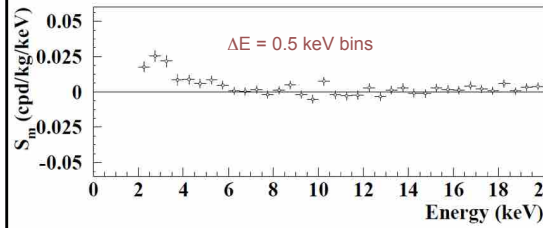
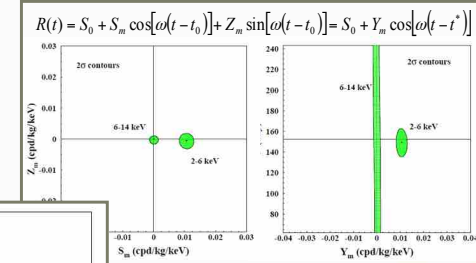
DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kgxday = 1.33 tonxyr

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

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

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

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



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.

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

DM scattering on nuclei

(1-1000) GeV WIMPs

(-43, -38) $\text{Log}(\sigma/\text{cm}^2)$

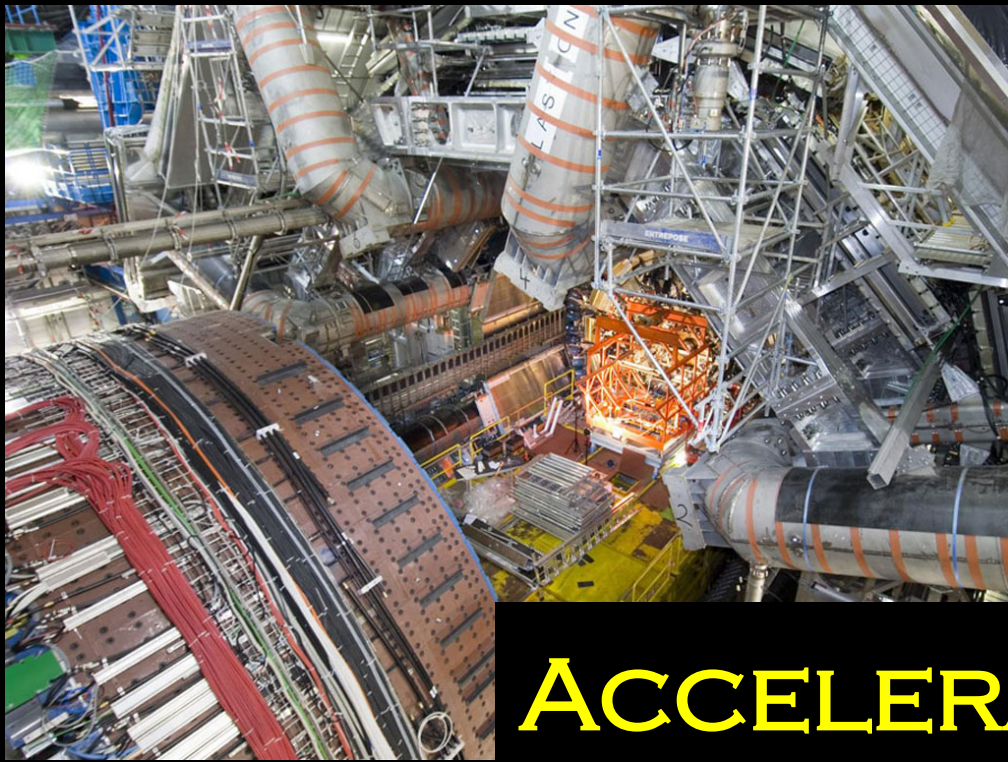
In case of "scalar" interaction

DM scattering on electrons

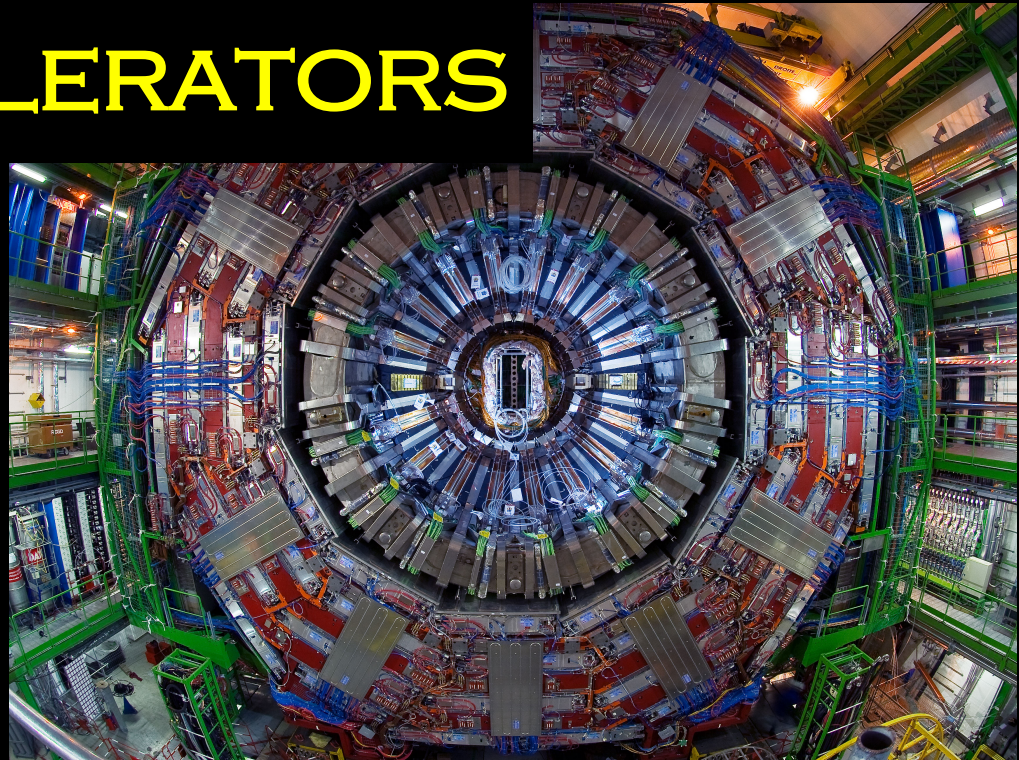
(0.1-10) KeV ALPs

Prospects

- Annual modulation: ANAIS
KIMS + DM Ice \approx COSINE 100
SABRE
CUORE
- Diurnal modulation: DAMA with larger mass might access it
- Directionality:
 - Nuclear emulsion (NEWS)
 - Anisotropic crystals (ADAMO)
 - Liquid Ar TPC
 - Negative Ion Time Expansion Chamber (NITEC)
 - Carbon nanotubes, grafene
 - DRIFT
 - MIMAC, DMTPC, NEWAGE, D3, ...

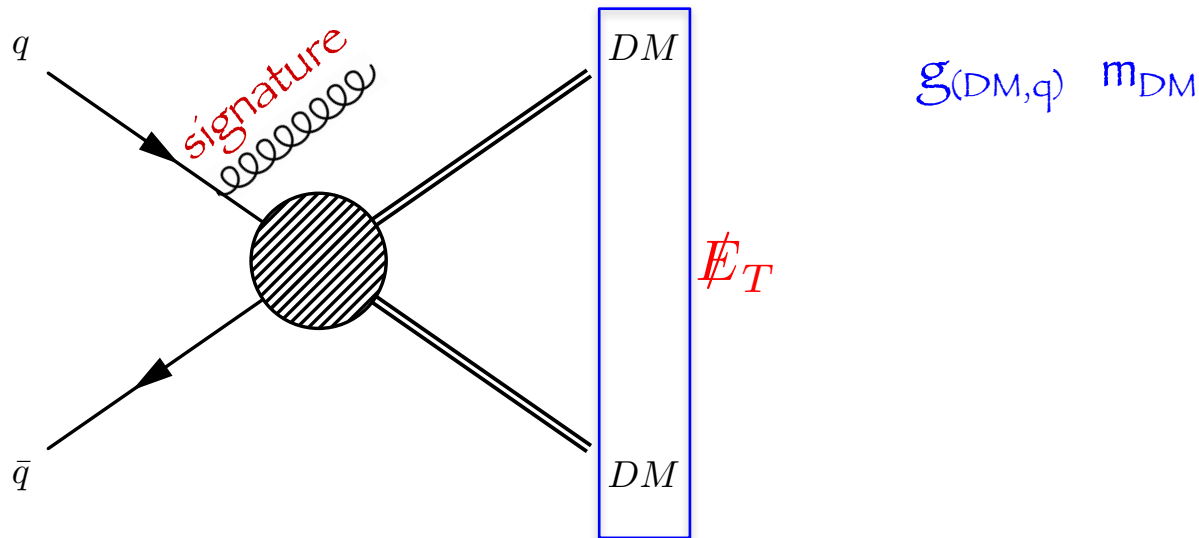


ACCELERATORS



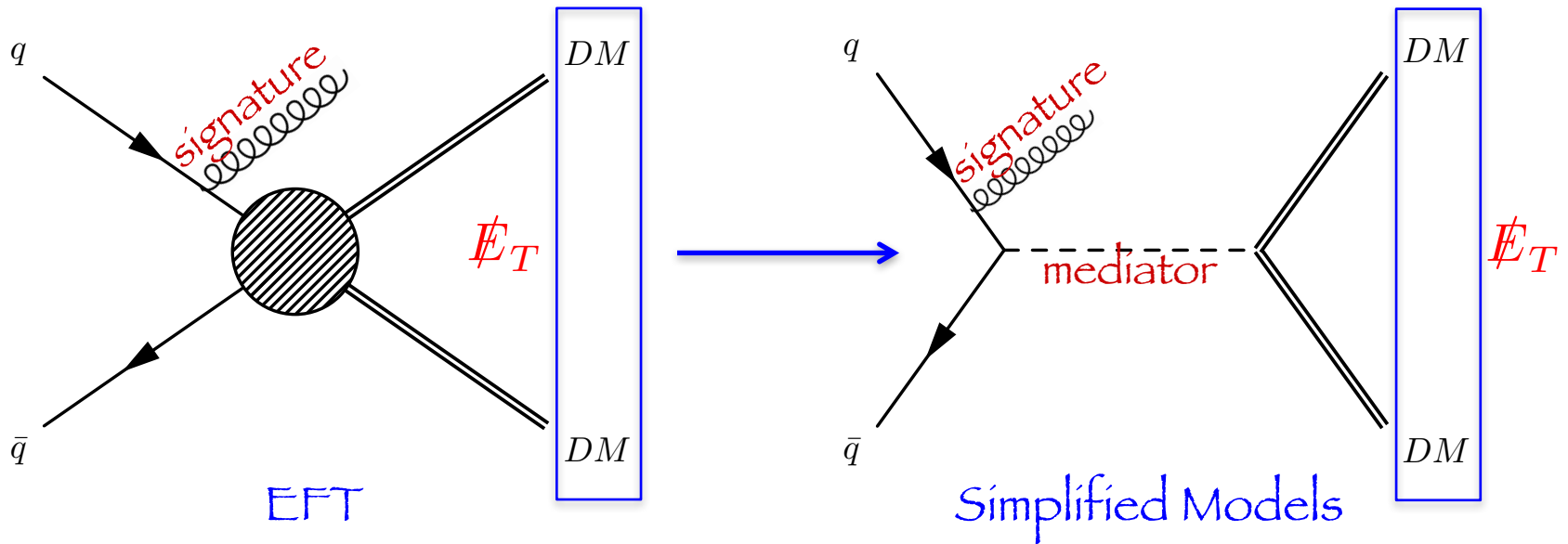
WIMPs at accelerators

- Studies at LHC Run I
- Systematic study of the Effective Field Theory approach
- Mono-X + missing ET



WIMP at accelerators

- EFT \longrightarrow Simplified Models \dashrightarrow UV Complete
- Under deep investigation at Run II



$g_{(DM,med)}$ m_{DM}

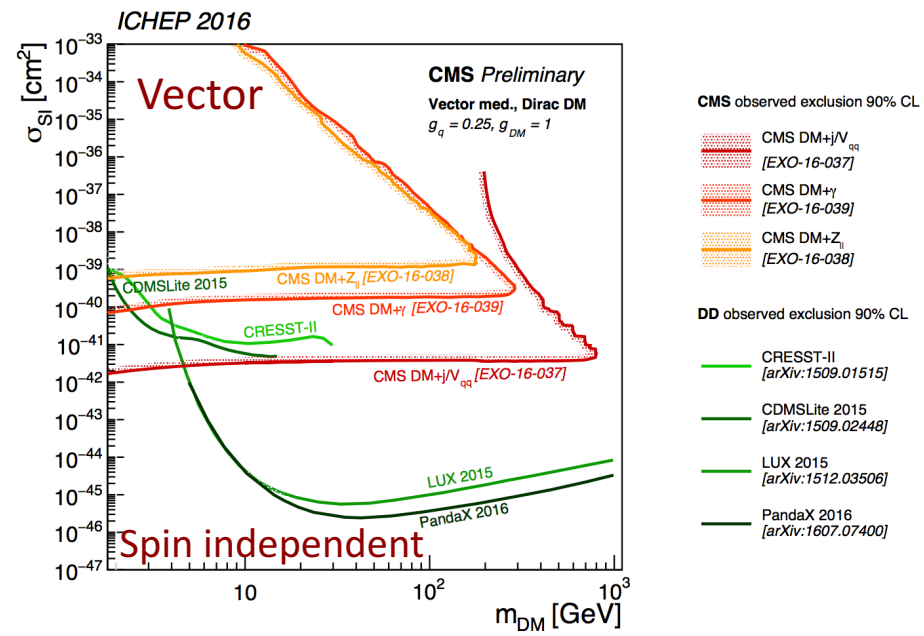
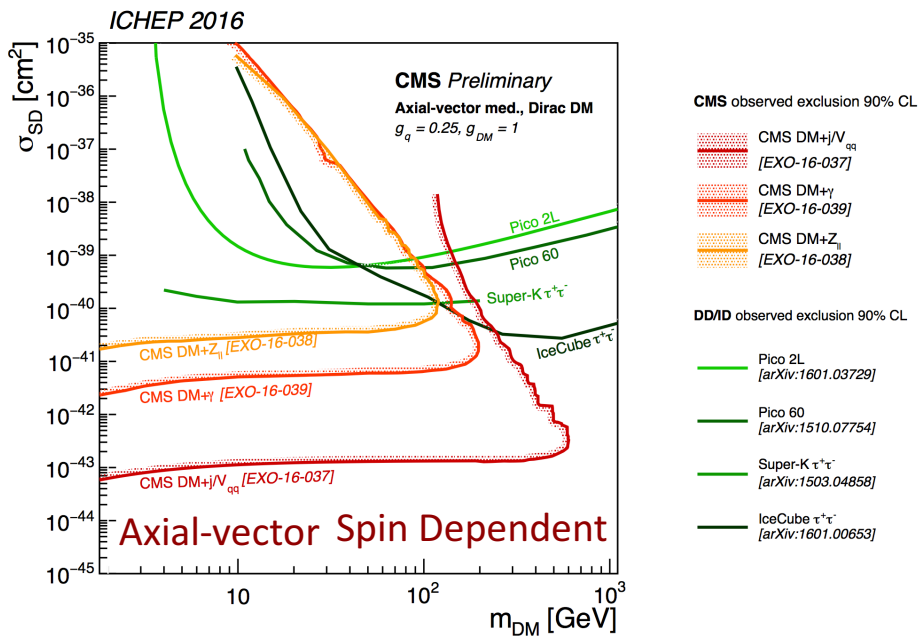
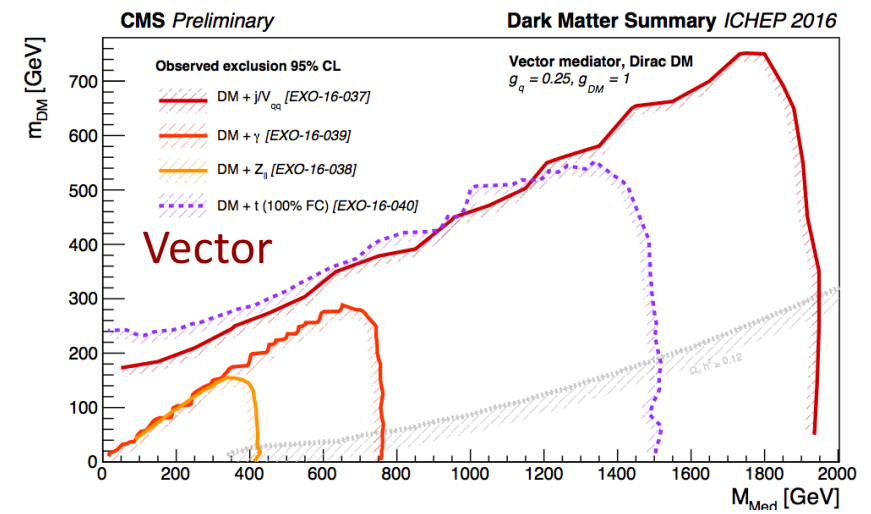
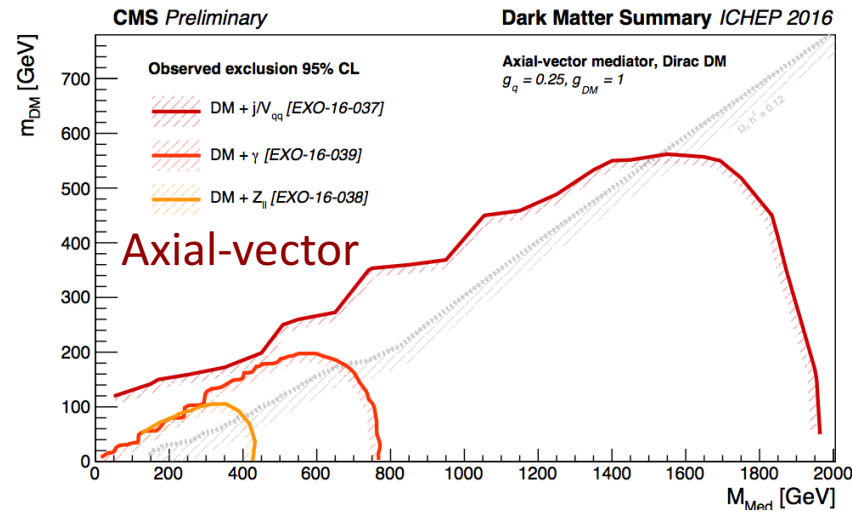
$g_{(med,q)}$ Γ_{med} m_{med} canale

coupling structure (s, v, t)

LHC DM searches at 13 TeV

Analysis	Channel	ATLAS	CMS
$E_T^{miss} + \text{jet}$	Mono-jet	3.2 fb ⁻¹ (2015)	12.9 fb ⁻¹ (2016)
	W/Z (hadronic)	3.2 fb ⁻¹ (2015)	
$E_T^{miss} + Z$	(Z → ℓℓ)	13.3 fb ⁻¹ (2015+2016)	12.9 fb ⁻¹ (2016)
$E_T^{miss} + \gamma$	Photon	3.2 fb ⁻¹ (2015)	12.9 fb ⁻¹ (2016)
$E_T^{miss} + \text{top}$	top (hadronic)	-	12.9 fb ⁻¹ (2016)
$E_T^{miss} + b\bar{b}$	b-jets	13.3 fb ⁻¹ (2015+2016)	2.2 fb ⁻¹ (2015)
$E_T^{miss} + t\bar{t}$	t \bar{t} (hadronic)	13.3 fb ⁻¹ (2015+2016)	2.2 fb ⁻¹ (2015)
	t \bar{t} (semi-leptonic)	13.2 fb ⁻¹ (2015+2016)	
	t \bar{t} (di-leptonic)	13.3 fb ⁻¹ (2015+2016)	-
$E_T^{miss} + H$	(H → bb)	3.2 fb ⁻¹ (2015)	2.3 fb ⁻¹ (2015)
	(H → γγ)	13.3 fb ⁻¹ (2015+2016)	2.3 fb ⁻¹ (2015)
	(H → ZZ → 4ℓ)	3.2 fb ⁻¹ (2015)	-

Summary of mono-X searches - CMS



Complete models

- Supersymmetry (neutralino, sneutrino)
 - High-scale inspired (SUGRA-like: CMSSM, NUHM1, NUHM2, NMSSM)
 - Low-energy (pMSSM-n)
- Technicolor
- Extra dimensions (lightest KK state, if neutral)
- ...
- Specific models (many, not all, built specifically to address DM)
 - MDM and variations
 - Inert higgs models
 - Mirror DM
 - ...
- ...

WIMPs and SUSY

Channels for SUSY searches at the LHC

Squarks, Gluinos

Sleptons

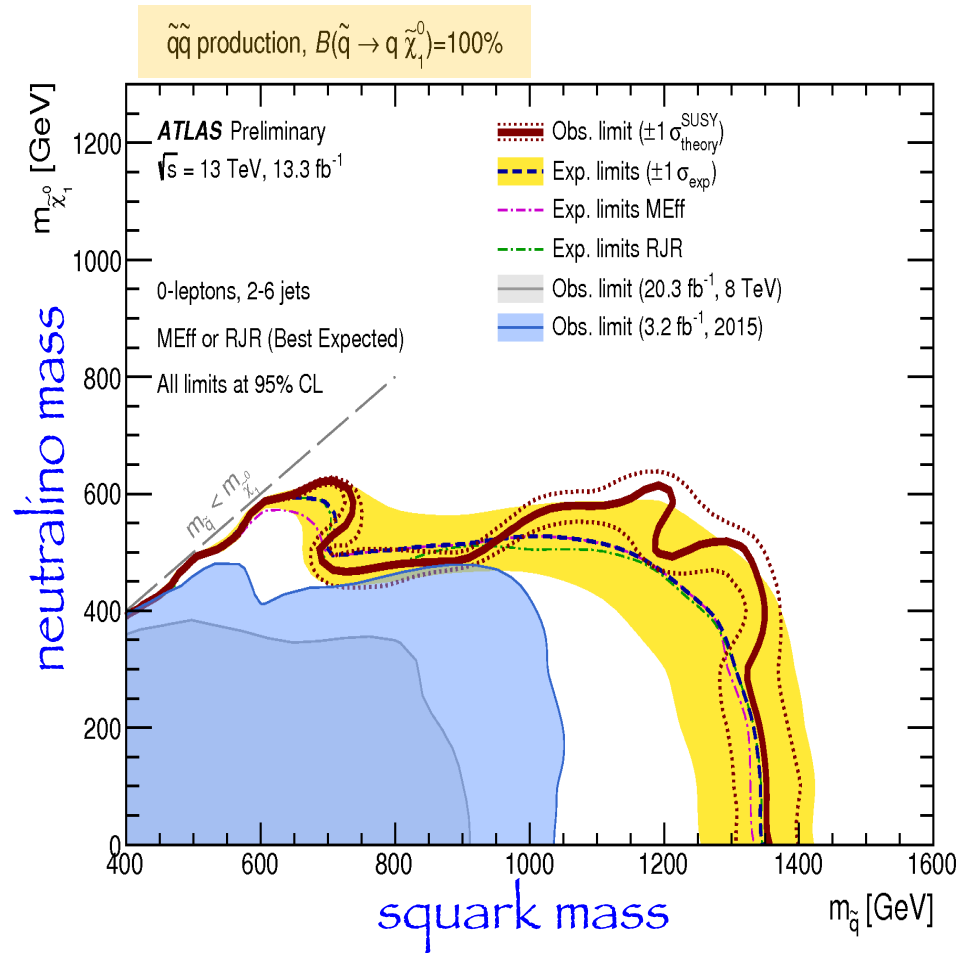
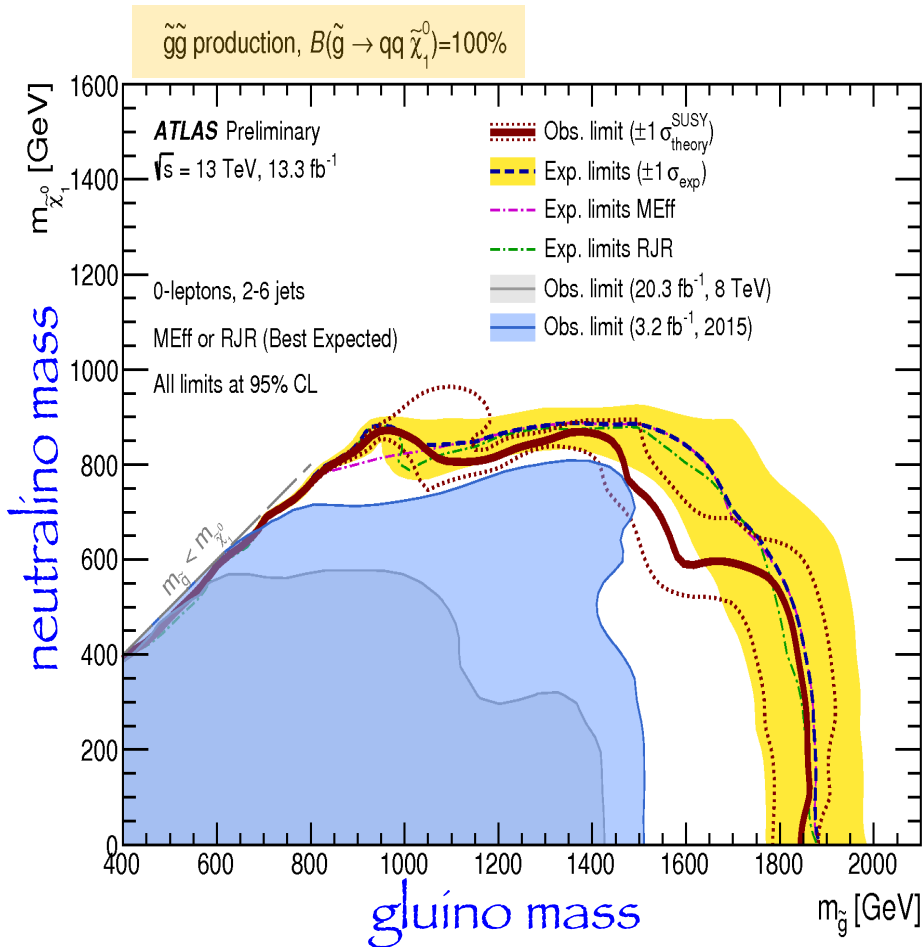
Charginos

Followed by their decays in Neutralinos (MET)

Also sneutrinos can be the DM

Searches and ensuing results (currently: bounds)
largely dependent on the specific SUSY framework

Some bounds - ATLAS



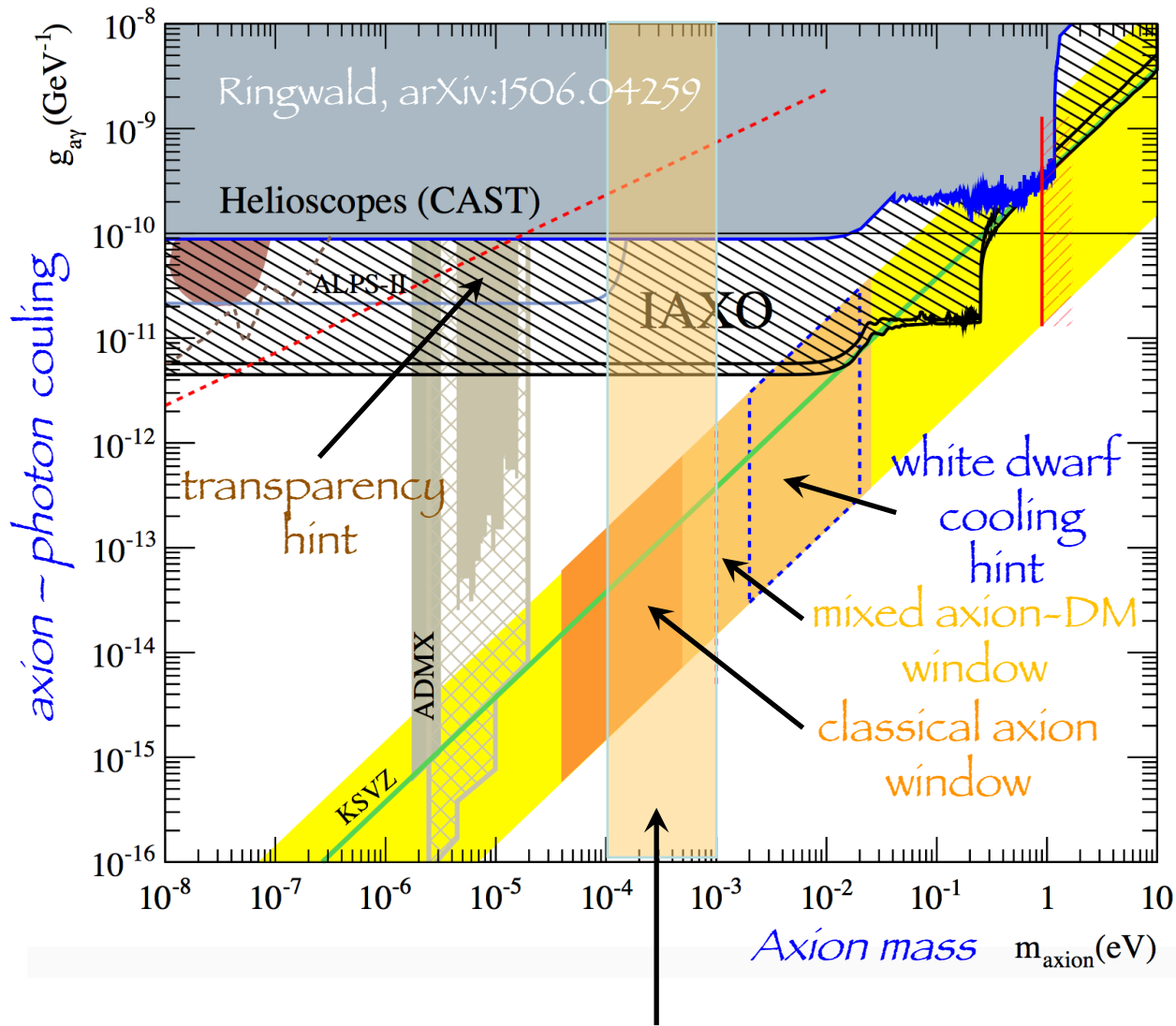
Non-WIMPs at accelerators

- Light DM at the MeV-GeV scale:
 - Dirac or Majorana fermions
 - Scalars or pseudoscalars
 - Asymmetric LDM
 - Dark photons
- Mediators:
 - Vector portal
 - Higgs portal
 - Neutrino portal
 - Axion portal
- Impact both on multimessenger/multiwavelength searches and on cosmological probes (CMB, dark ages)
- Search of visible decays (e^+e^- and studies for invisible decays)
- Rich experimental program:
 - Hadronic beams: SHIP e NA62 at CERN
 - Electron beams
 - Meson decays

Electron beams

- LNF: PADME + BDX (Beam Dump eXperiment)
 - Linac upgrade at 1-1.2 GeV, up to 10^{20} EOT/year
- JLab: BDX (HPS, APEX, DarkLight)
 - Beam: 12 GeV, 10^{22} EOT/year
- MAINZ (MESA): BDX
 - Beam: 150 MeV, 10^{22} EOT/year
- Cornell: PADME-like
 - Beam: 5 GeV, reach x2 as compared to LNF
- Belle:
 - Trigger mono-jet to search for “heavy photons”

Axions and ALPs



QUAX: high-frequency magnetometer
axion-electron coupling

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 complementary to WIMPs
- A signal of DM is clearly faint, but the opportunities are rich:
multimessenger, multiwavelength, multitechnique