

DARK MATTER

STATUS AND PERSPECTIVES

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DI TORINO



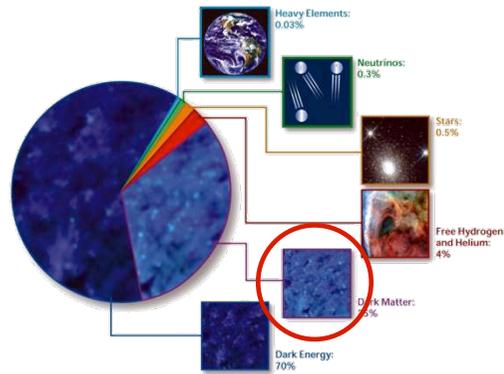
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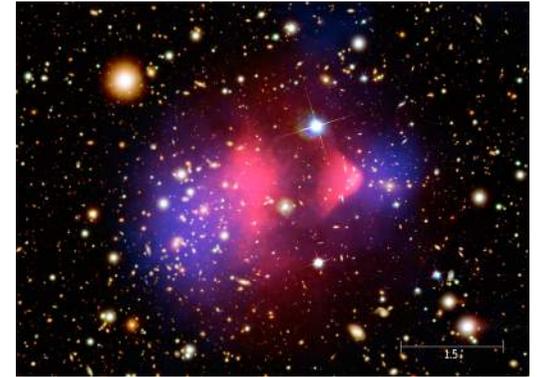
www.to.infn.it/~fornengo
www.astroparticle.to.infn.it



Giornate di studio sul Piano Triennale INFN
Centro “Le Ciminiere”, Catania – 3.12.2015



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

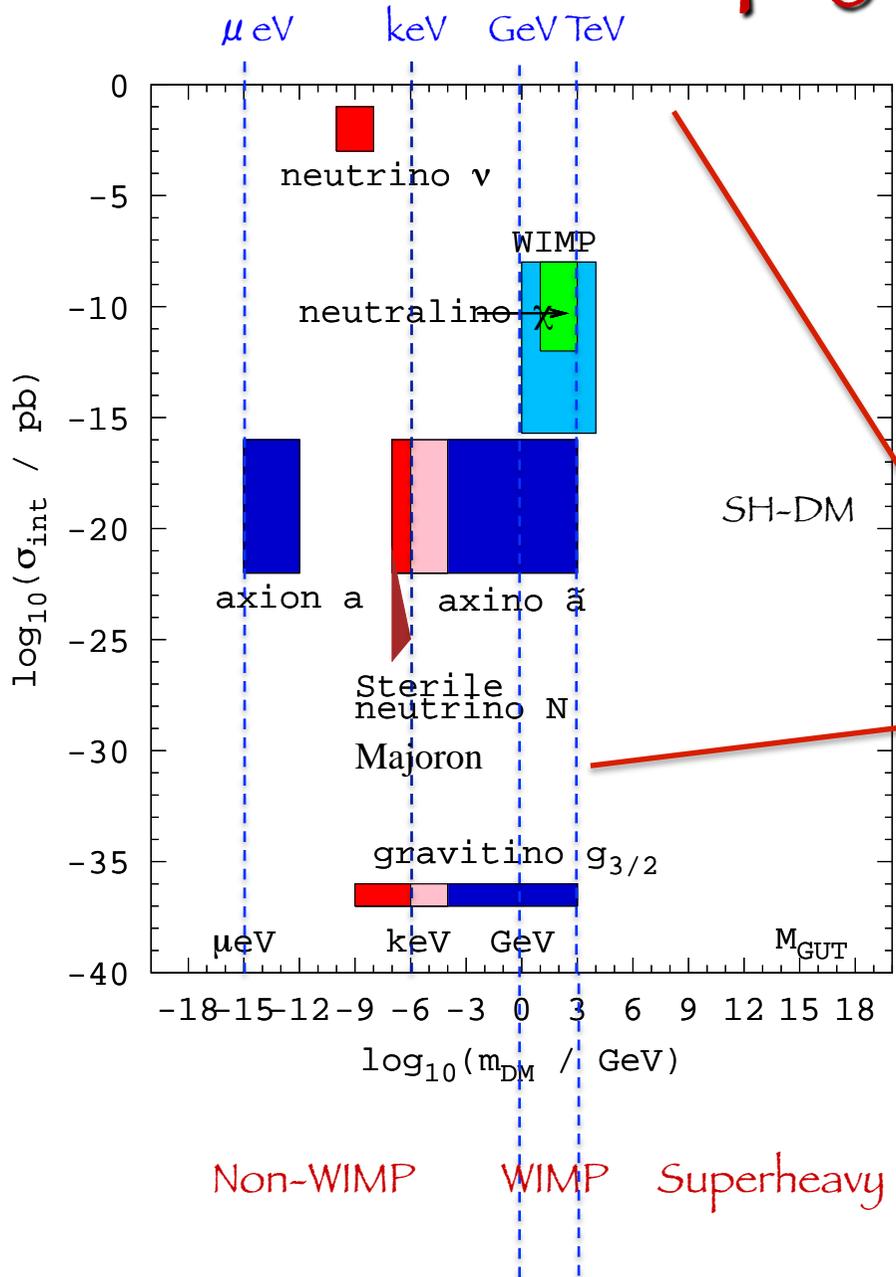
- DM evidence is purely gravitational

- 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:

- i. Modification of the theory of Gravity (attempts, but difficult to explain all observations)
- ii. 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



Non-WIMP WIMP Superheavy

“Strong (-ish)”

- Self-interacting
- Technicolor DM
- ...

“EM (-ish)”

- Millicharged DM
- Electric/magnetic dipole
- ...

Weak

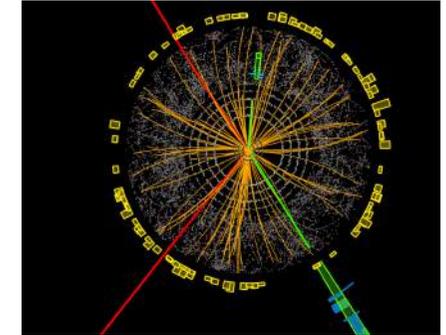
WIMP

Gravitational

- Relic from the early Universe
- Thermal
- Non thermal



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**

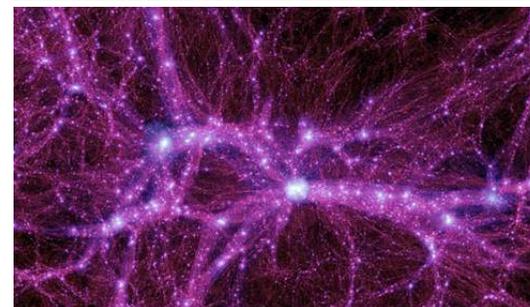
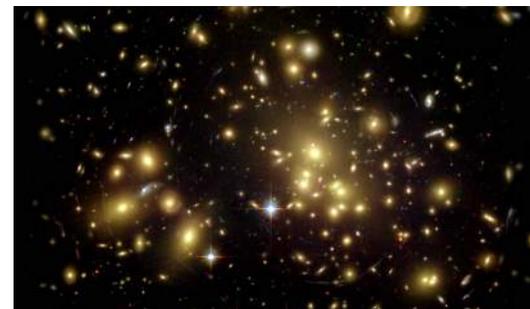
- Produce New Physics states and help in shaping the underlying model
- Allows (hopefully) to identify the physical properties of the DM sector
- Controlled environment

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

Where to look for ...

DM is present in:

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



... and what

We have a large number of messengers at disposal

$$\chi\chi \longrightarrow (\dots) \longrightarrow \gamma, \nu, e^\pm, \bar{p}, \bar{D}$$

$$\chi + \mathcal{N}(e^-) \longrightarrow \chi + \mathcal{N}(e^-)$$

Charged CR (e^\pm , antip, antiD) [G]

Neutrinos [G,E]

Photons [G,E]

- Gamma-rays

- Prompt production

- IC from e^\pm on ISRF and CMB

- X-rays

- IC from e^\pm on ISRF and CMB

- Radio

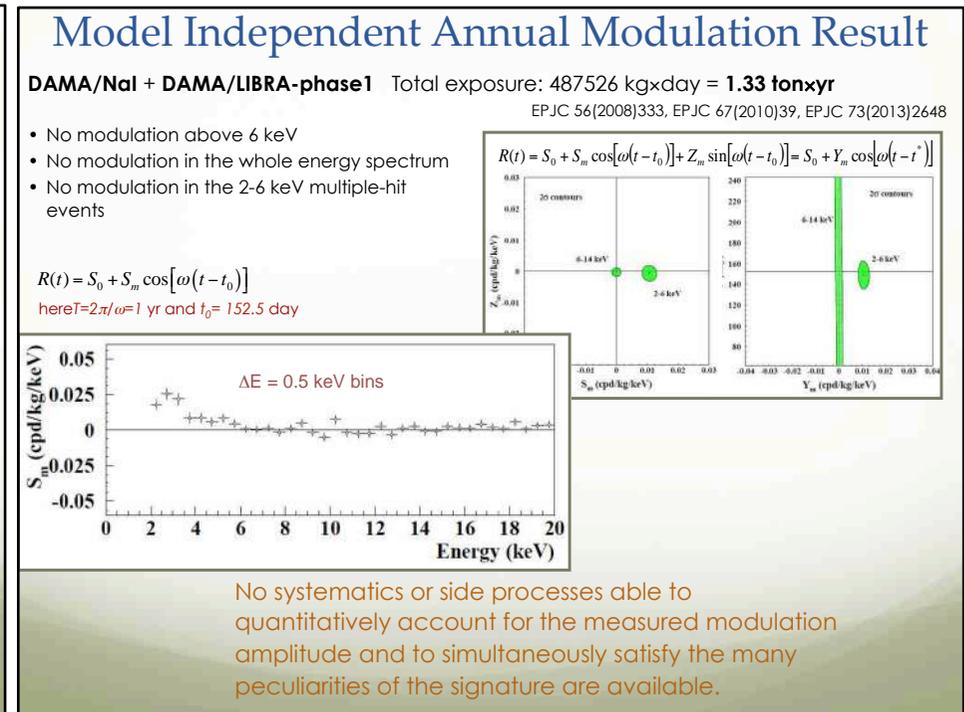
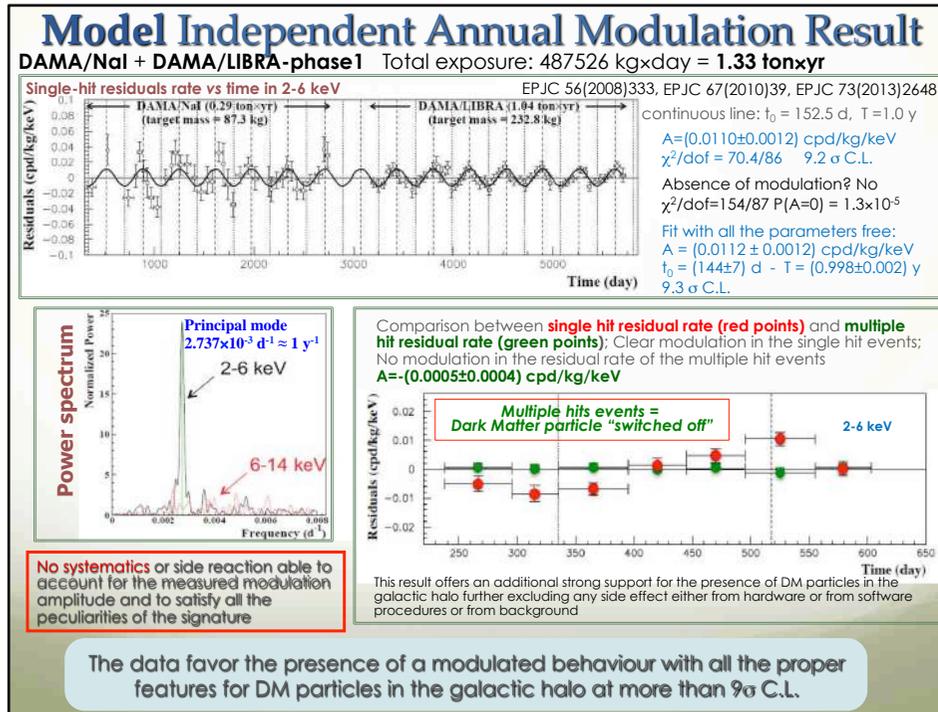
- Synchro from e^\pm on mag. field

Direct detection [L]

(Local [L] - Galactic [G] - Extragalactic [E])

Direct searches

Annual modulation: DAMA, 9.2σ with 1.33 ton x yr, 15 cycles



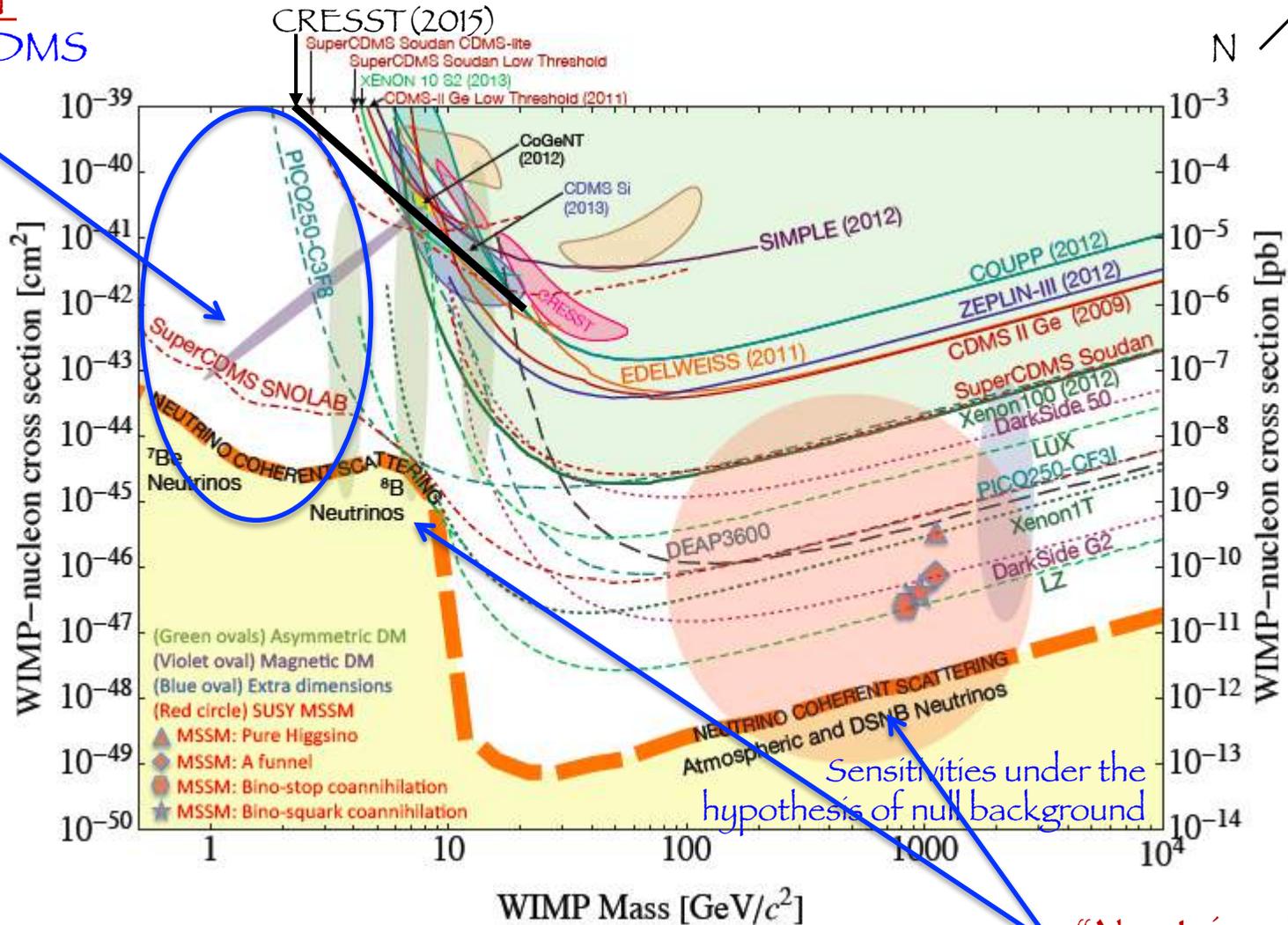
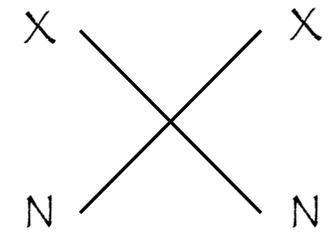
From Belli's talk at TAUP 2015, <http://taup2015.to.infn.it>

Compatible with: DM scattering on nuclei
 DM scattering on electrons

(5-100) GeV WIMPs
 (0.3-6) KeV ALPs

Light WIMPs window

CRESST
SuperCDMS
...



Bounds and expected sensitivities for DM-nucleus scattering
Under the hypothesis of contact-type interactions

WIMP

- Usually discussed in terms of contact “scalar” interactions, or spin-spin interactions, but this is just a small part of the story

- Full set of effective operators for DM – nucleus scattering

Fitzpatrick et al., JCAP 1302 (2013) 004

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}_{\chi N}^\perp$$

$$\mathcal{O}_3 = -i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_{\chi N}^\perp \right)$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_{\chi N}^\perp$$

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

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

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

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

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

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

+ interferences

The full set of operators starts now to be explored: responses from the different nuclei and detectors significantly change as compared to the “vanilla” contact-type case

See e.g.:

Arina, Del Nobile, Panci, PRL 114 (2015) 011301

Scopel, Kook-Hyun, Jong-Hyun, JCAP 1507 (2015) 041

Catena, Gondolo, JCAP 1508 (2015) 022

Catena, JCAP 1407 (2014) 055

WIMP

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Relevant for GeV-TeV DM

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

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+ interferences

- Interactions on (bound) **electrons**

Relevant for keV – MeV DM

- DM **phase space** distribution in the Galaxy (esp. the **high-v tail**)

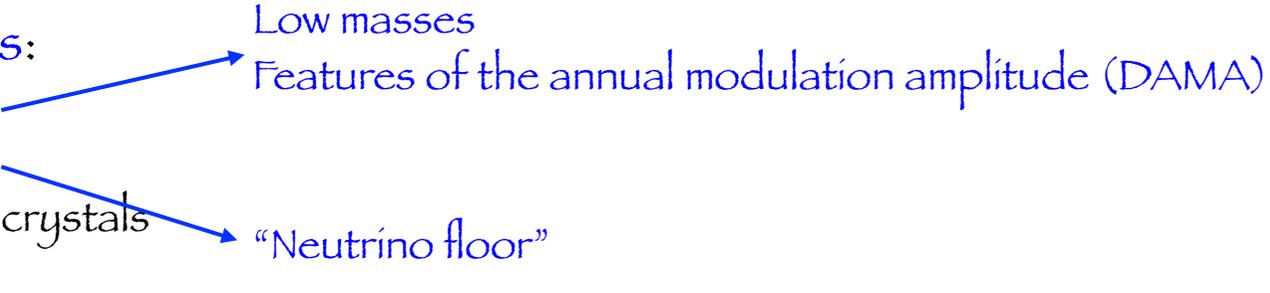
- Difficult to model, very small astrophysical scales (**simulation -> DM scale**)
- Quite some interest in theoretical modeling, recently (**analytical, numerical**)
- Prospects for observational inputs (e.g.: **GAIA**)

Prospects

- Annual modulation: ANAIS, KIMS, DM-Ice, SABRE
- Diurnal modulation: DAMA with larger mass could likely access it
- Directionality:
 - Nuclear emulsion (NEWS)
 - Anisotropic crystals (ADAMO)
 - Liquid Ar TPC
 - Negative Ion Time Expansion Chamber (NITEC)
 - Carbon nanotubes
 - *DRIFT, MIMAC, DMTPC, NEWAGE, D3, ...*
- Improved sensitivities:
 - Very low thresholds
 - “Zero background”
 - Extremely radiopure crystals
 - Light detectors

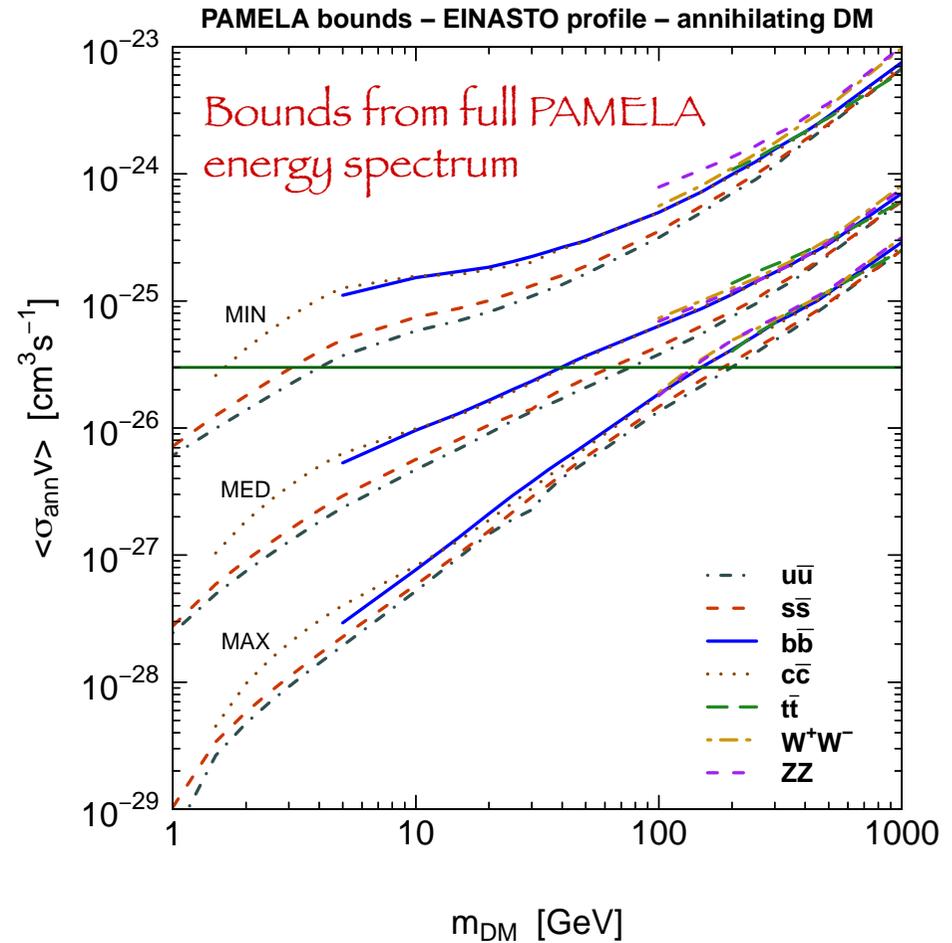
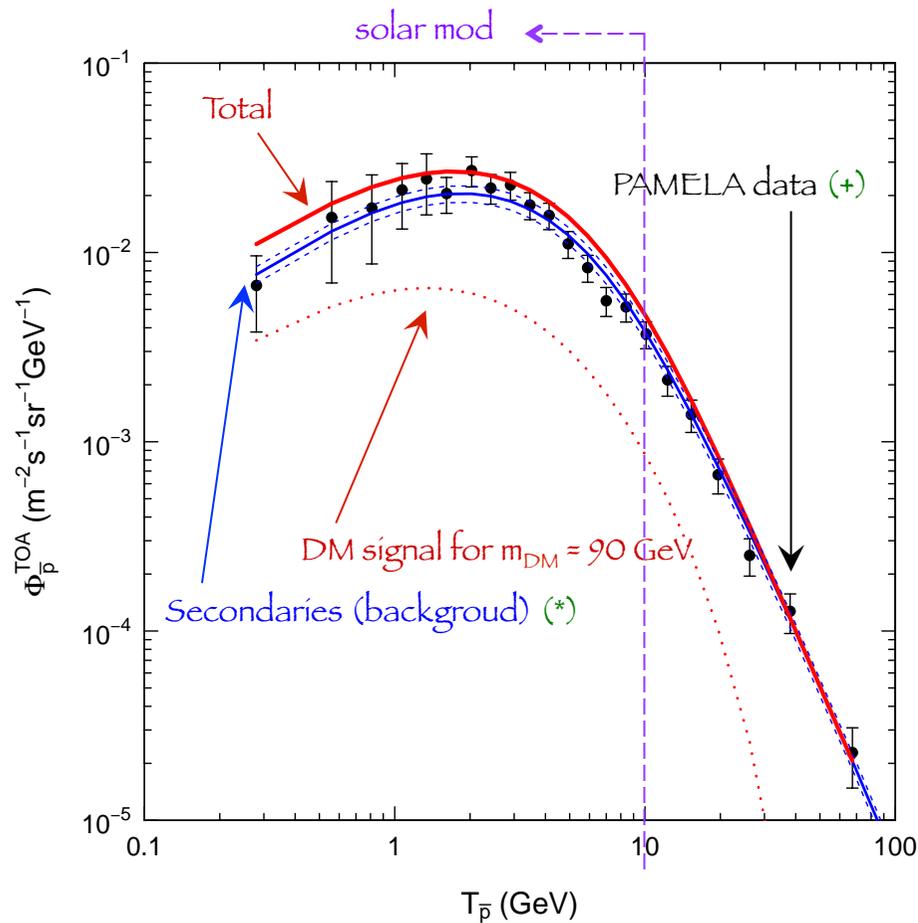
Low masses
Features of the annual modulation amplitude (DAMA)

“Neutrino floor”



Indirect searches

Antiprotons

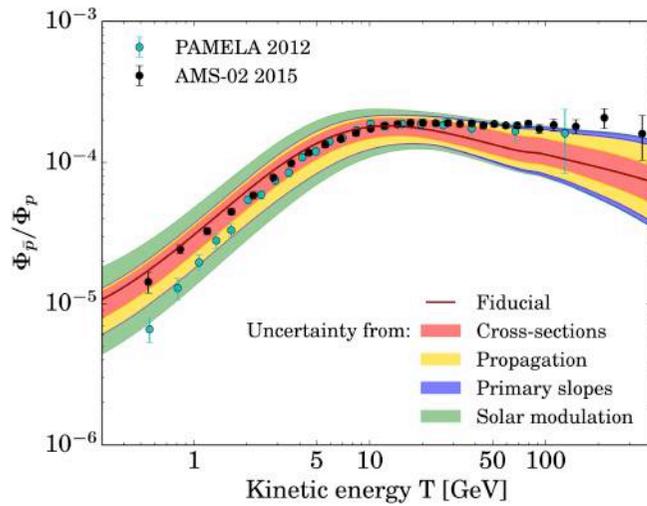


PAMELA

No evidence for deviation from astrophysical secondaries
 Set stringent bounds on DM properties
 Uncertainties from nuclear physics and galaxy transport

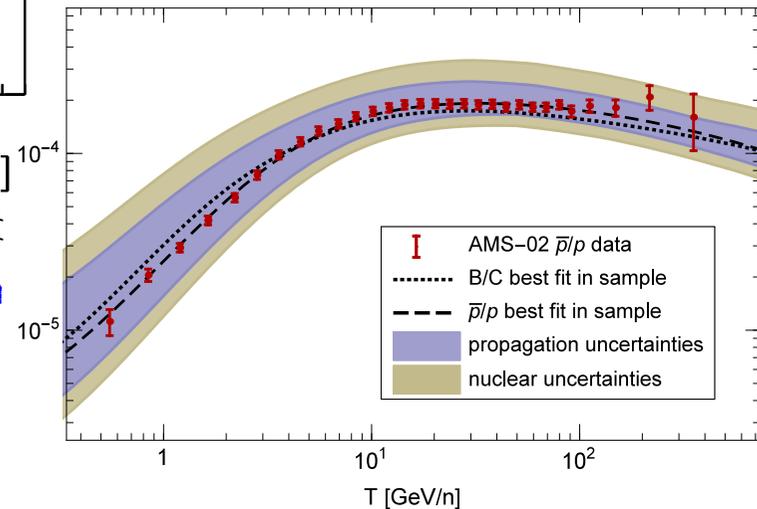
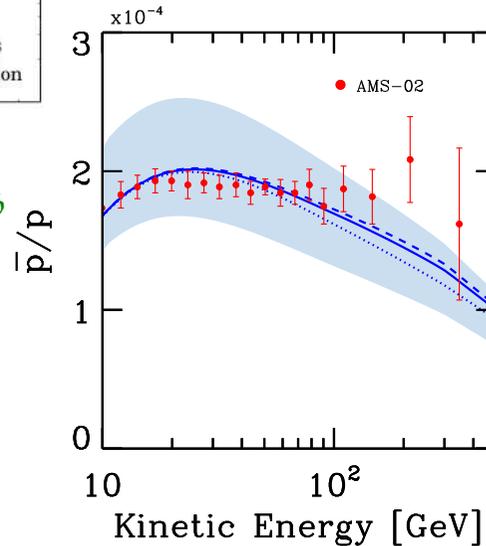
AMS-02 \bar{p}/p

Kounine, 'AMS days at CERN, April 2015



Giesen et al., JCAP 1509 (2015) 023

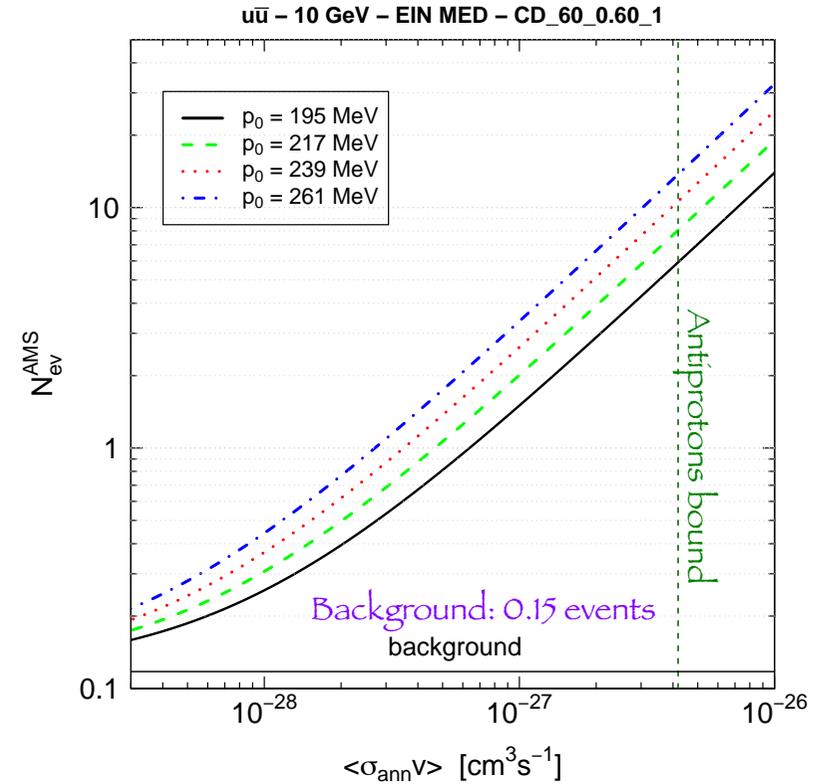
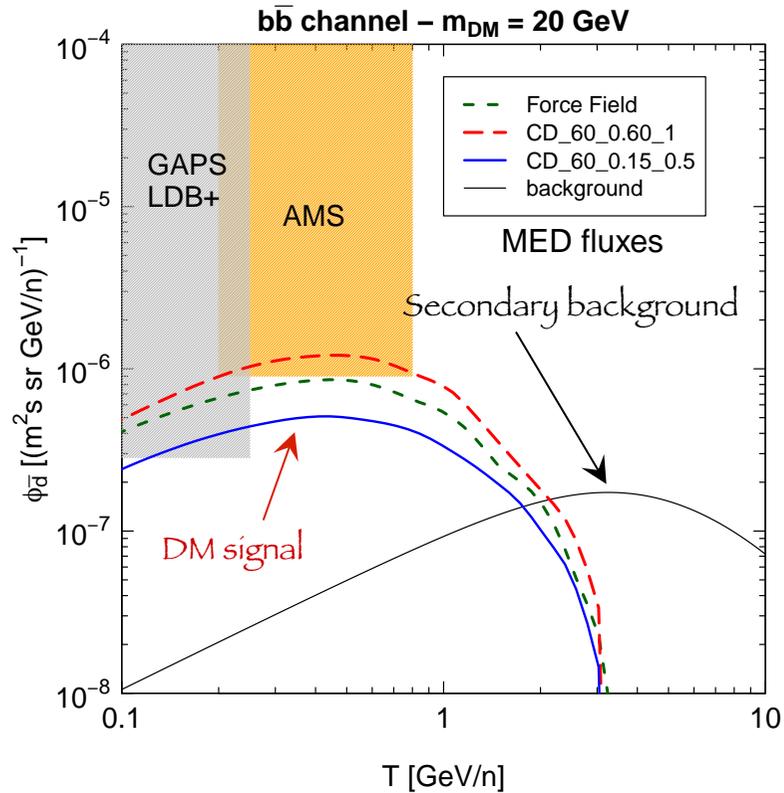
Evoli, Gaggero, Grasso, arXiv:1504.05175



Kappl, Reinert, Winkler, JCAP 1510 (2015) 034

In addition AMS is bringing very detailed information on cosmic rays nuclei (e.g. B/C) which will allow shaping the CR transport models (DRAGON, Galprop, Usine, non public codes) This is relevant for both DM signals and its backgrounds

Antideuterons



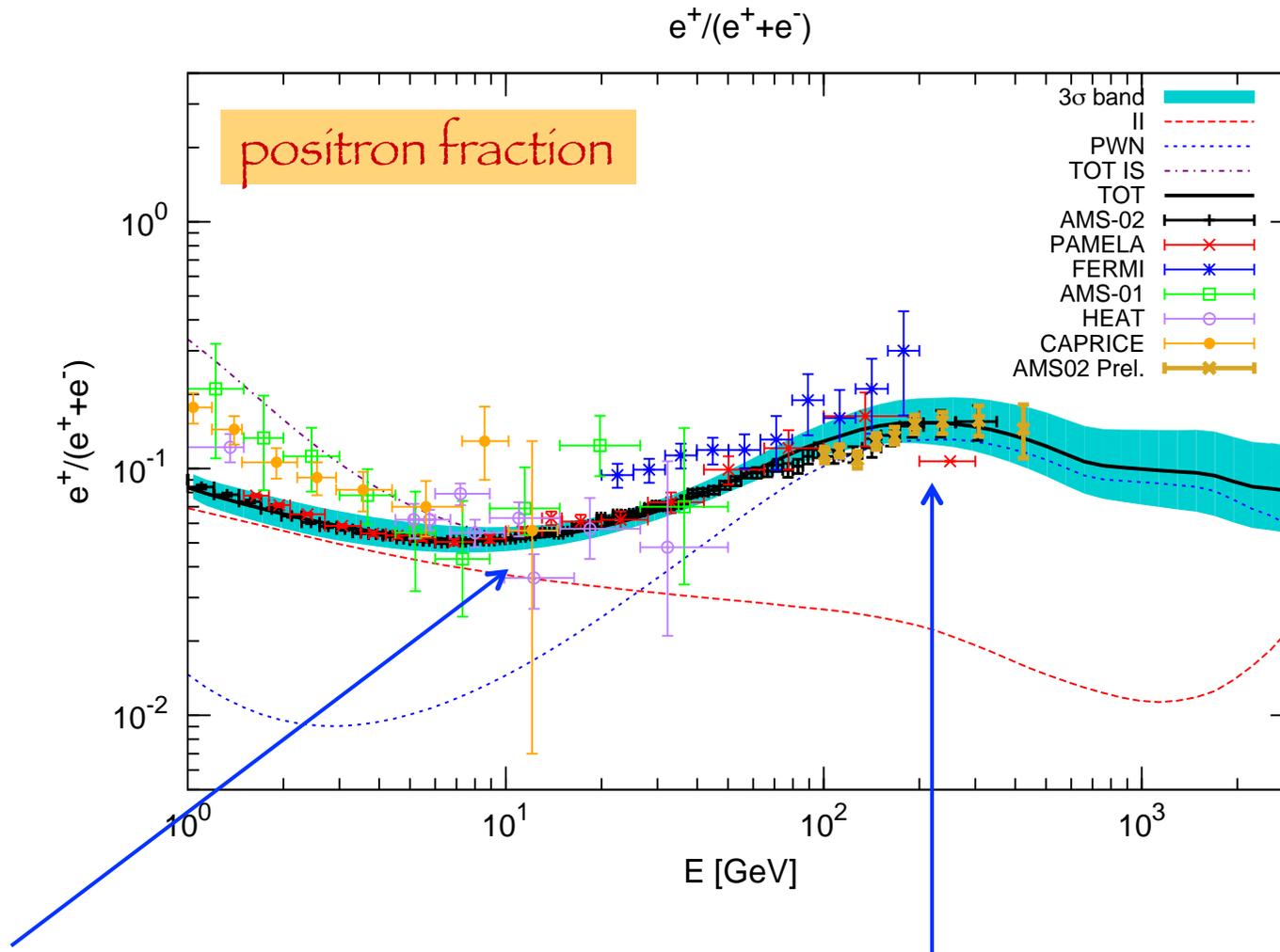
DM configurations allowed by antiproton bounds

Relevant detection prospects for energies below few GeV/n

Potentially: a detection channel

Expected number of events for AMS nominal sensitivity

Positrons



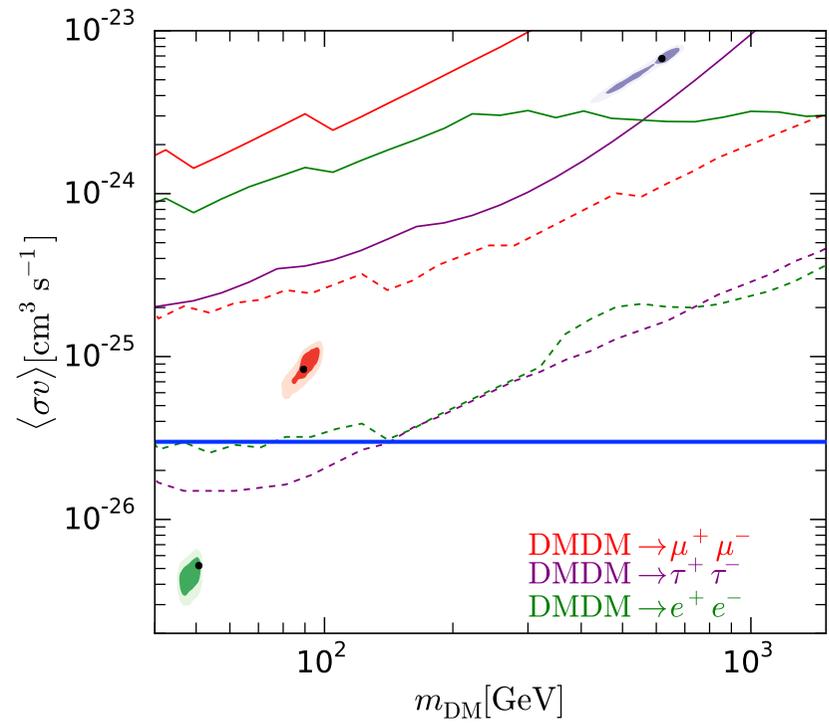
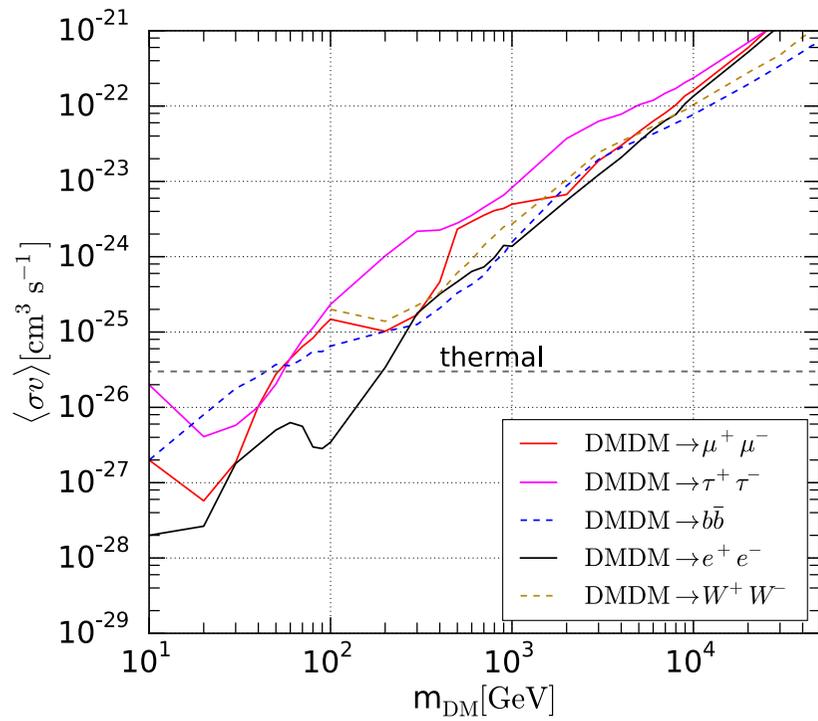
Low energies: reproduced by secondary production

High-energy: (local) sources needed

Positrons

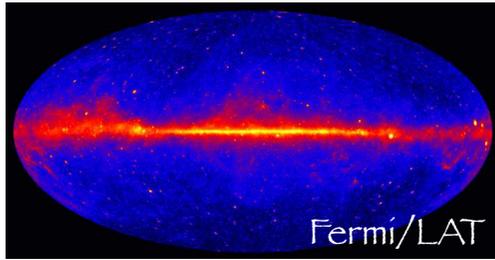
- The high energy tails requires a local production
 - Pulsars
 - Dark matter
- The spectral feature might not be conclusive (unless a very clear sharp cut-off is seen, peculiar of direct e^+e^- production)
- AMS will further extend the energy range
- Fermi/LAT has just reported a new analysis on the sum (power law up to 2 TeV)

Positrons



bounds

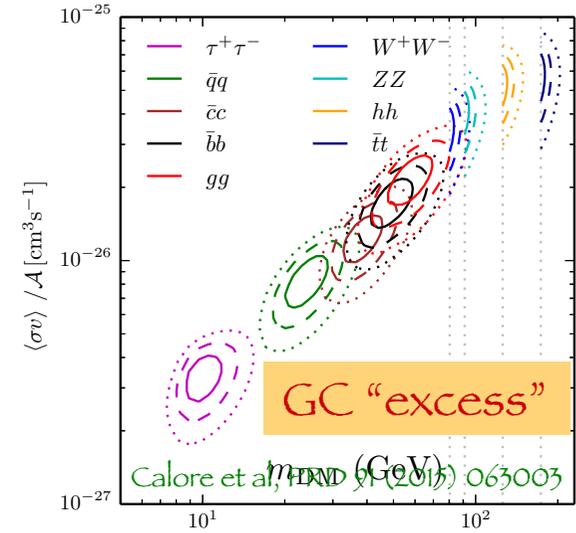
Analysis including astro modeling



Gamma rays

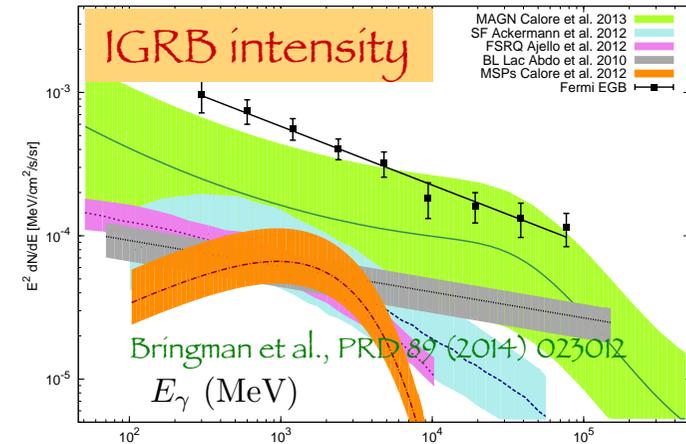
Galactic center

Very interesting target, but difficult
Potential hints, under hot discussion



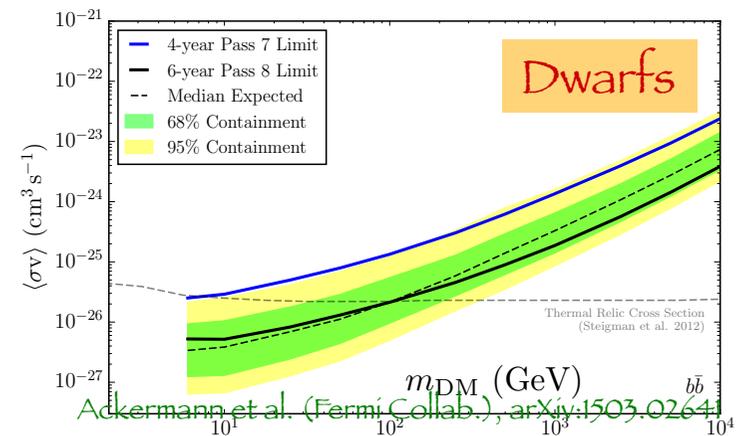
Isotropic gamma ray background

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



Gamma rays

- Higher energies (ground): >300 GeV

Probe **TeV+** DM

Targets

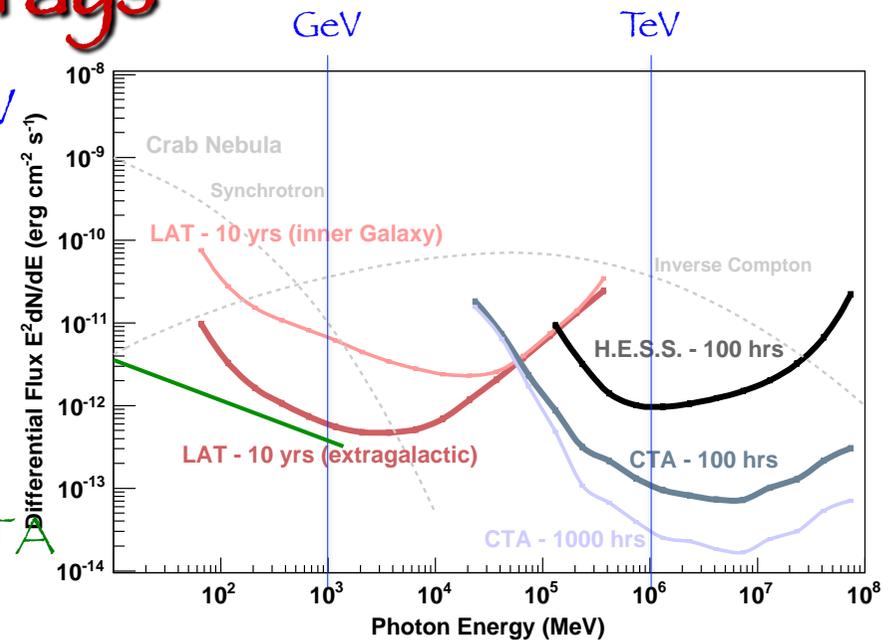
Galactic center

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), GAMMA400, HERD (up to PeV), ...

- Lower energies (space): MeV – GeV

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

AstroGam, PANGU, ...

Lower frequencies

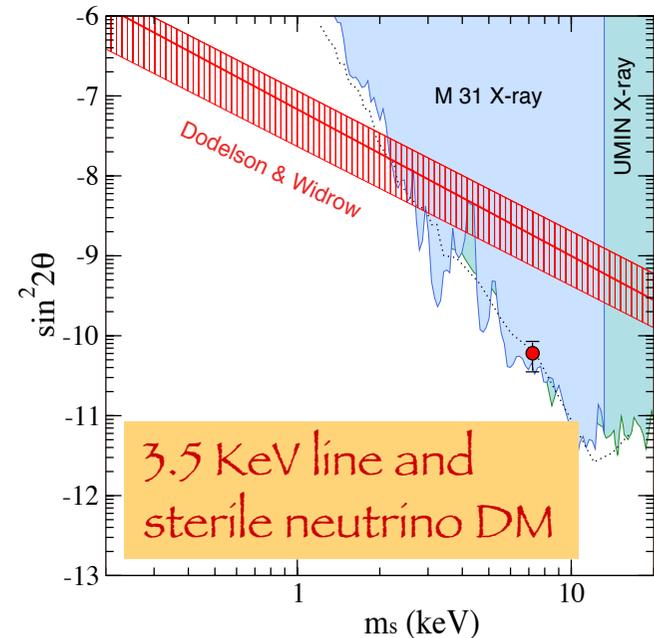
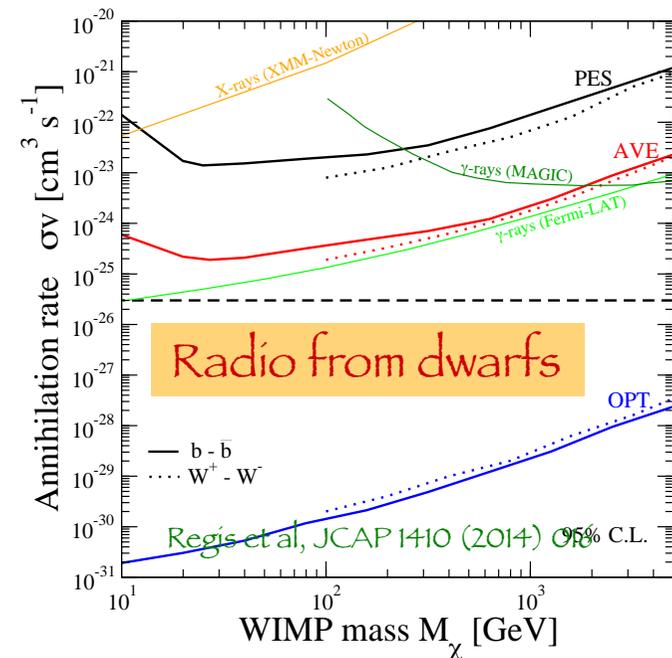
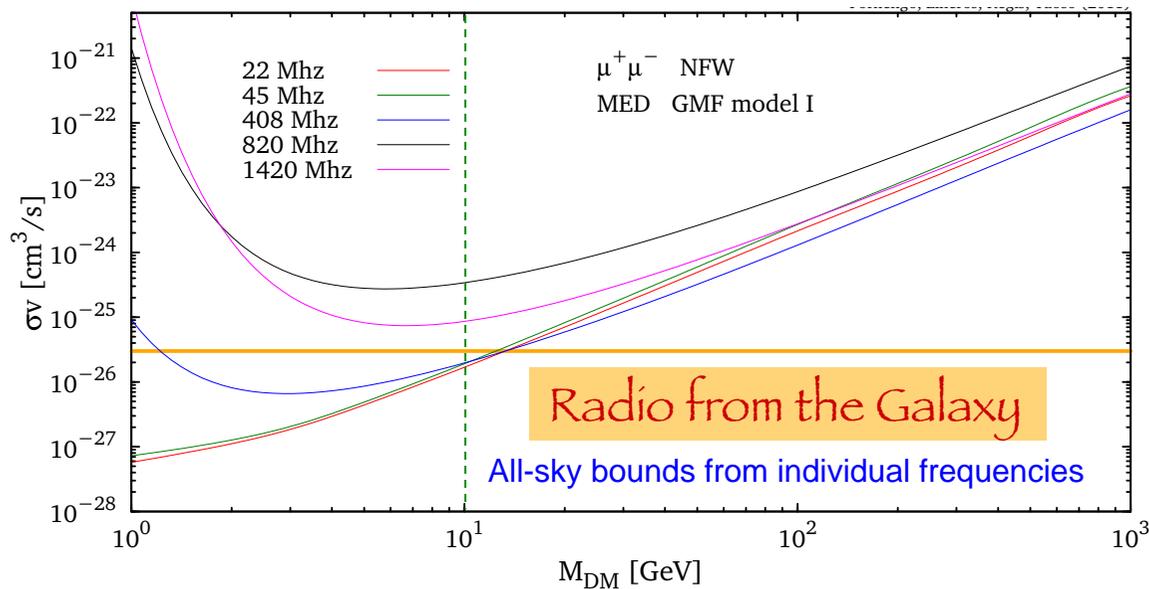
Radio emission

$$E \sim 15 \sqrt{\nu_{\text{GHz}} / B_{\mu\text{G}}} \text{ GeV}$$

- Galactic center
- Galactic diffuse emission
- Extragalactic diffuse emission
- Dwarf galaxies
- Larger uncertainties, but promising for discovery

X-rays

Opportunity for non-WIMP DM



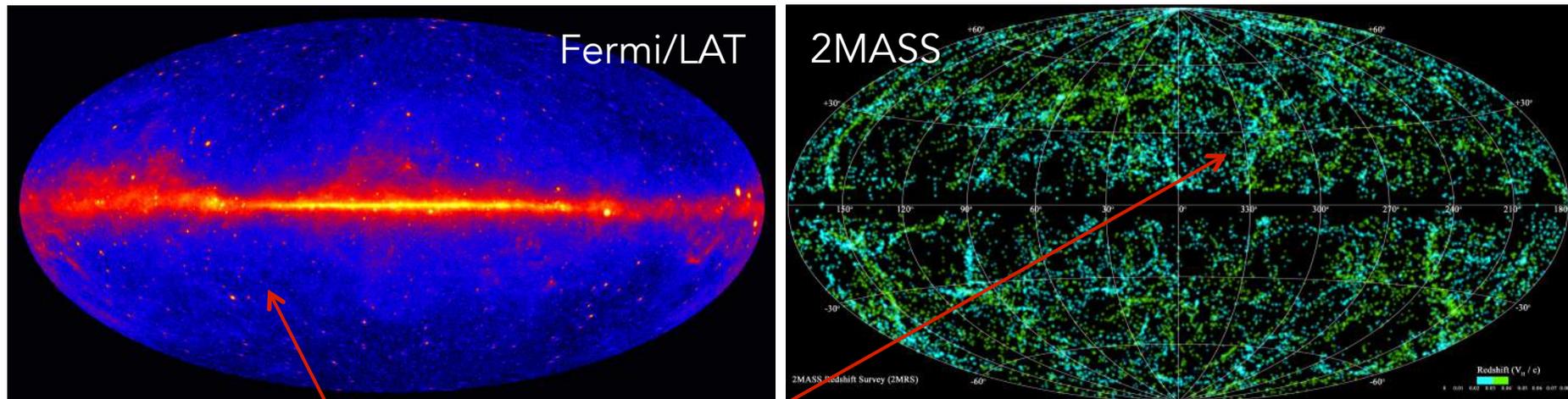
Some additional features

- 511 KeV line from the galactic center
 - Requires a large number of positrons at the GC
 - Still unexplained
- “Hazes” in the central regions of the Galaxy
 - Microwaves (WMAP haze)
 - Gamma-rays (Fermi bubbles) unrelated to DM
- Arcade excess
 - Radio excess, not accounted for by astrophysical sources
 - Requires a large number of very faint sources (and DM is just so)

Cross-correlations

Cross-correlations between the **unresolved gamma-ray** component and the large scale DM distribution, measured through **gravitational tracers**:

- Cosmic shear (weak lensing)
- Galaxy catalog (large scale structure)



$$\langle I_i(\vec{n}_1) I_j(\vec{n}_2) \rangle \longrightarrow C^{ij}(\theta) \longrightarrow C_l^{ij}$$

Cross-correlations

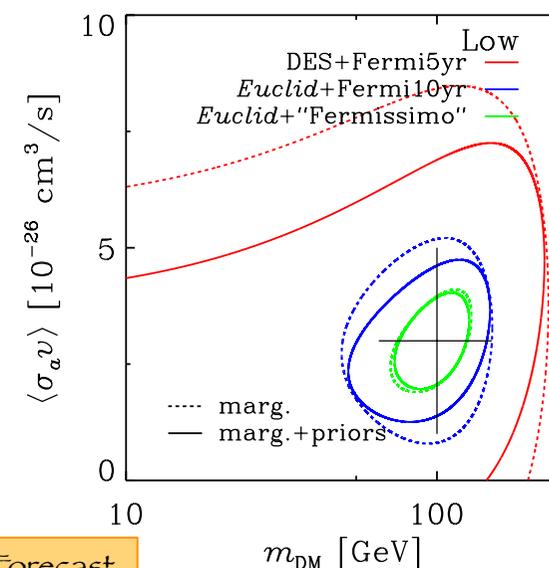
Cross-correlations with DM gravitational tracers

CMB lensing (Planck) measured!

LSS (2MASS, SDSS, ...) measured!

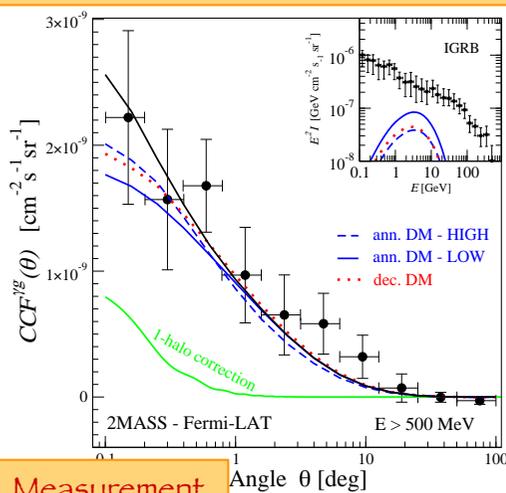
Cosmic shear (DES, Euclid)

DES/Euclid [shear] x Fermi (like) [gamma]

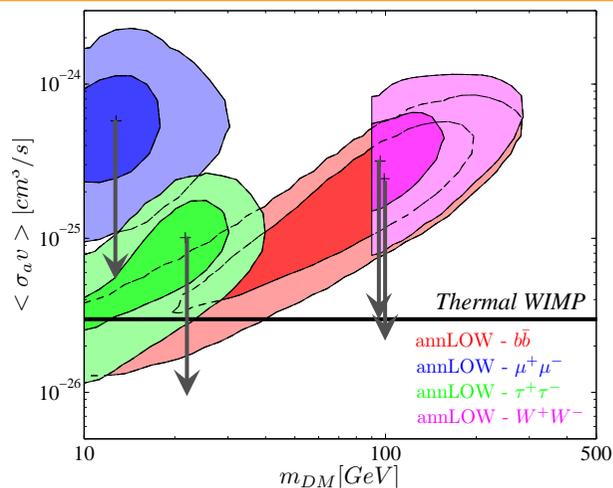


Forecast

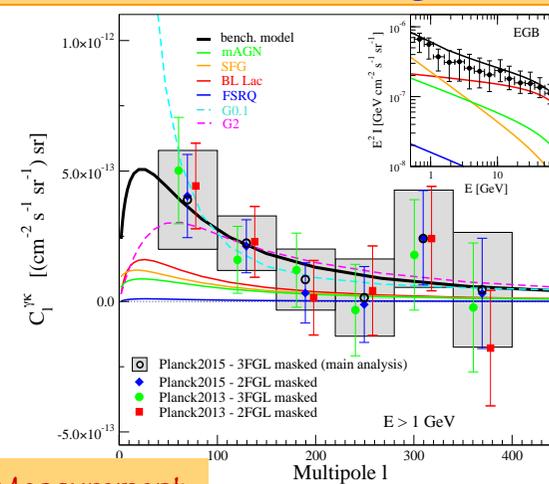
2MASS (LSS) x Fermi (gamma)



Measurement

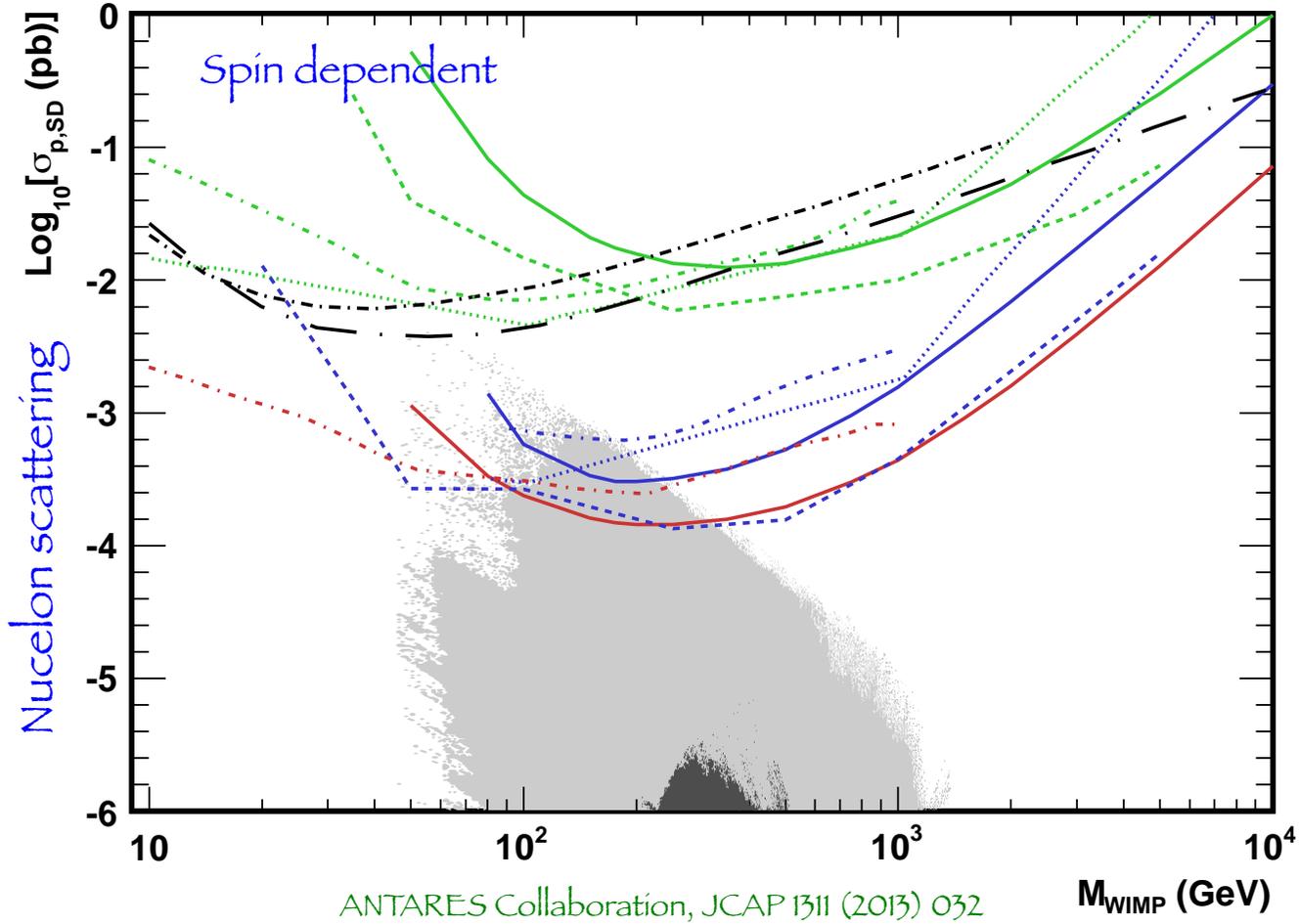


Planck (CMB) x Fermi (gamma)



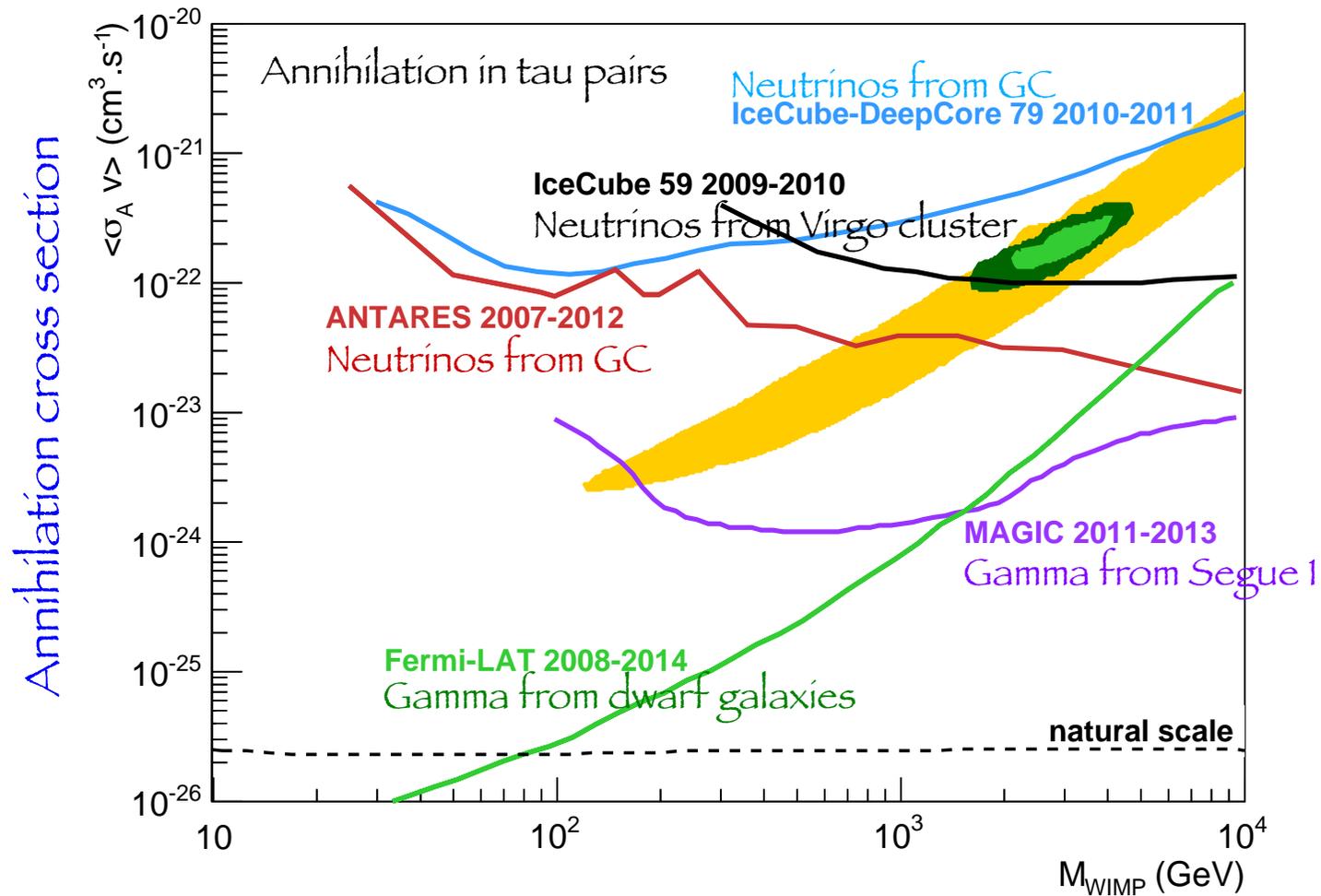
Measurement

Neutrinos from the Sun



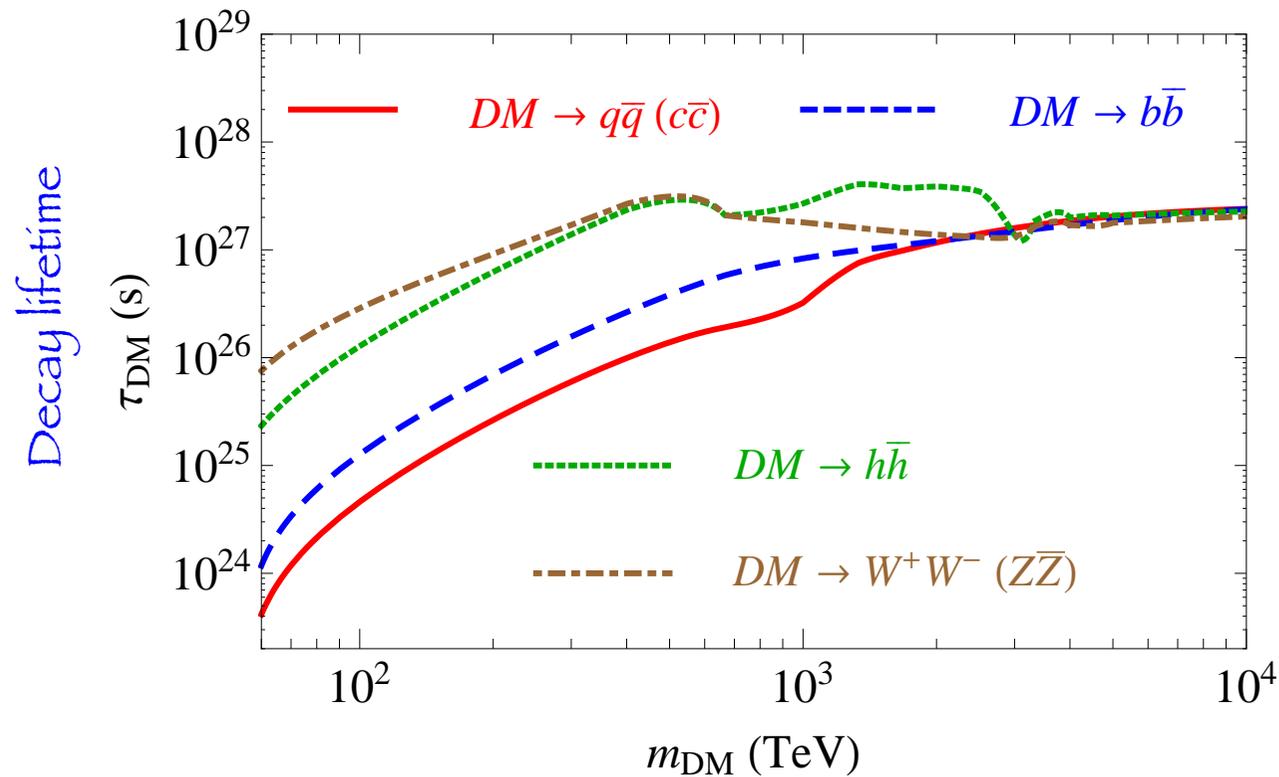
Warning: bounds are derived under the assumption of perfect equilibration between capture and annihilation (and contact interactions)

Neutrinos from targeted sources



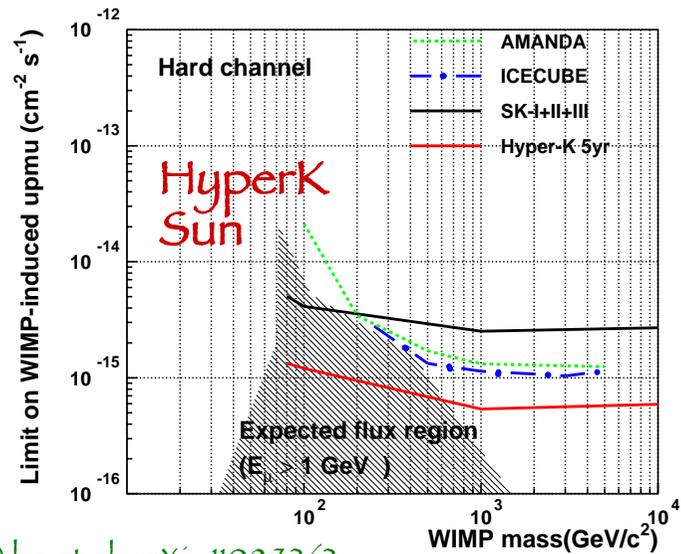
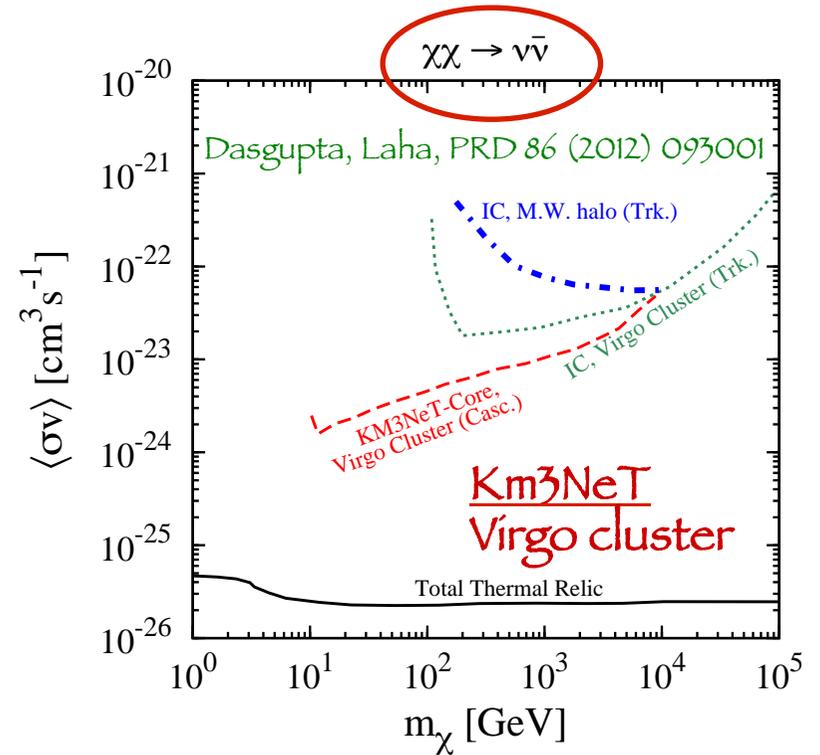
IceCube PeV neutrinos

The spectral feature of the IceCube PeV events could refer to **decaying** (not annihilating) **very heavy DM**

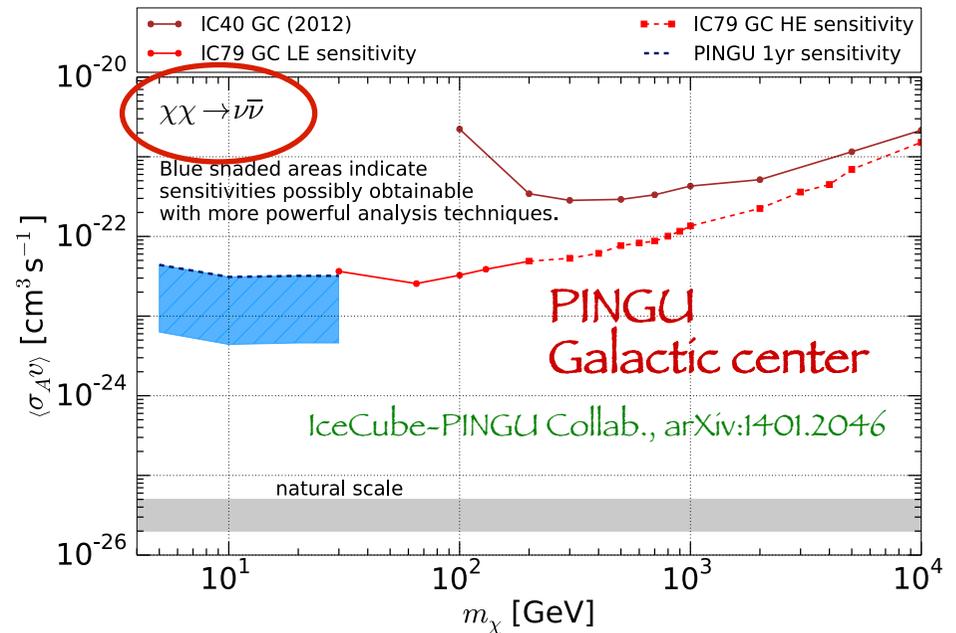


Large detectors

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

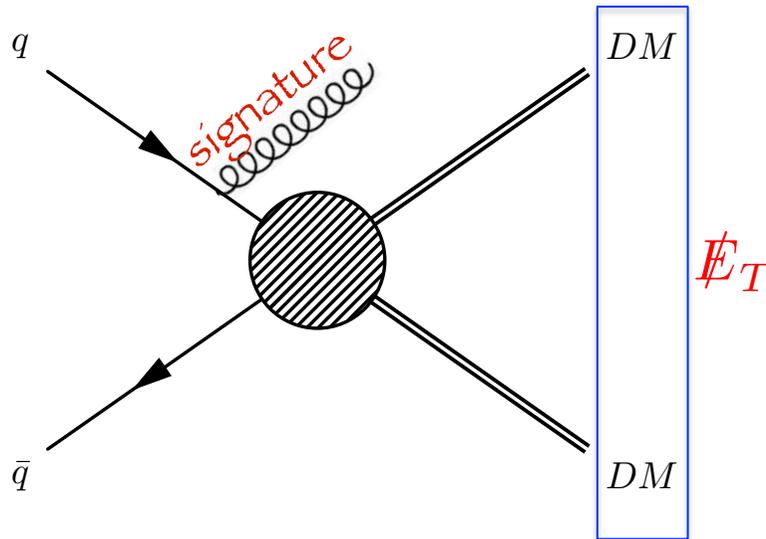


Abe et al, arXiv:1109.3262



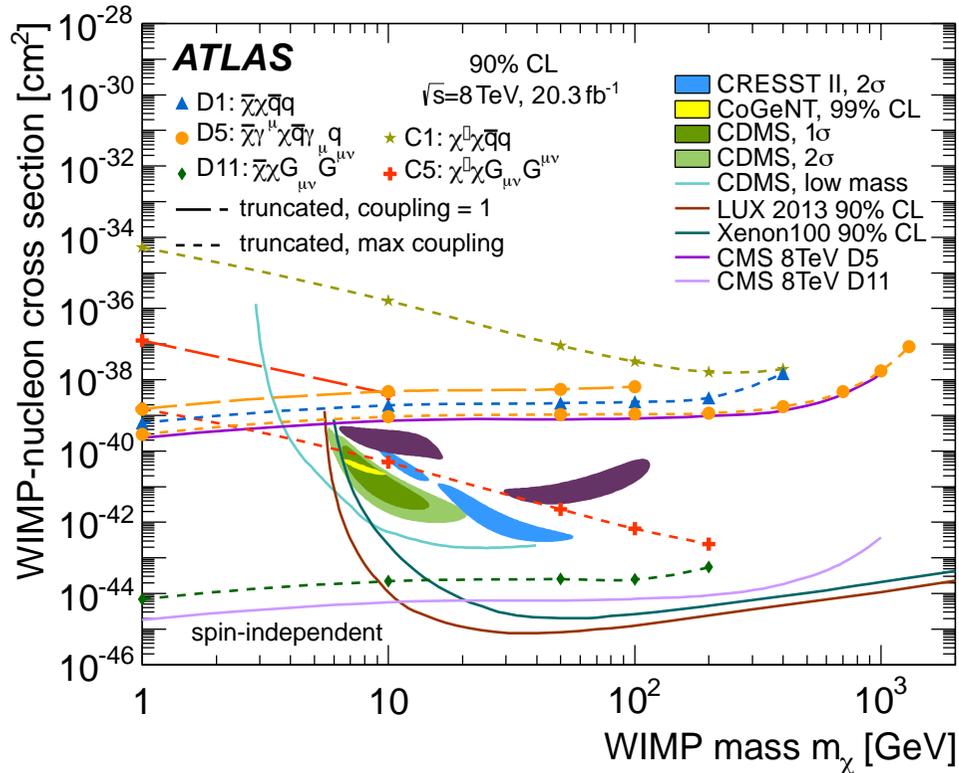
WIMPs at accelerators

- Focus now is on the Run II of LHC
- Systematic study of the Effective Field Theory approach
- Mono-X + missing ET

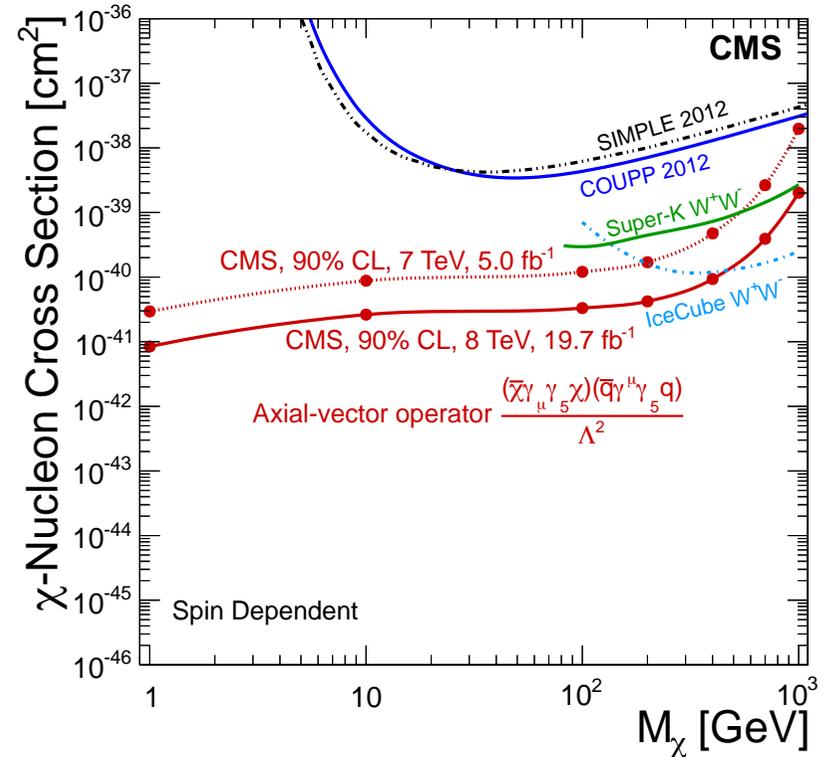


$g_{(DM,q)}$ m_{DM}
coupling structure (s, v, t)

Mono-X searches



spin independent

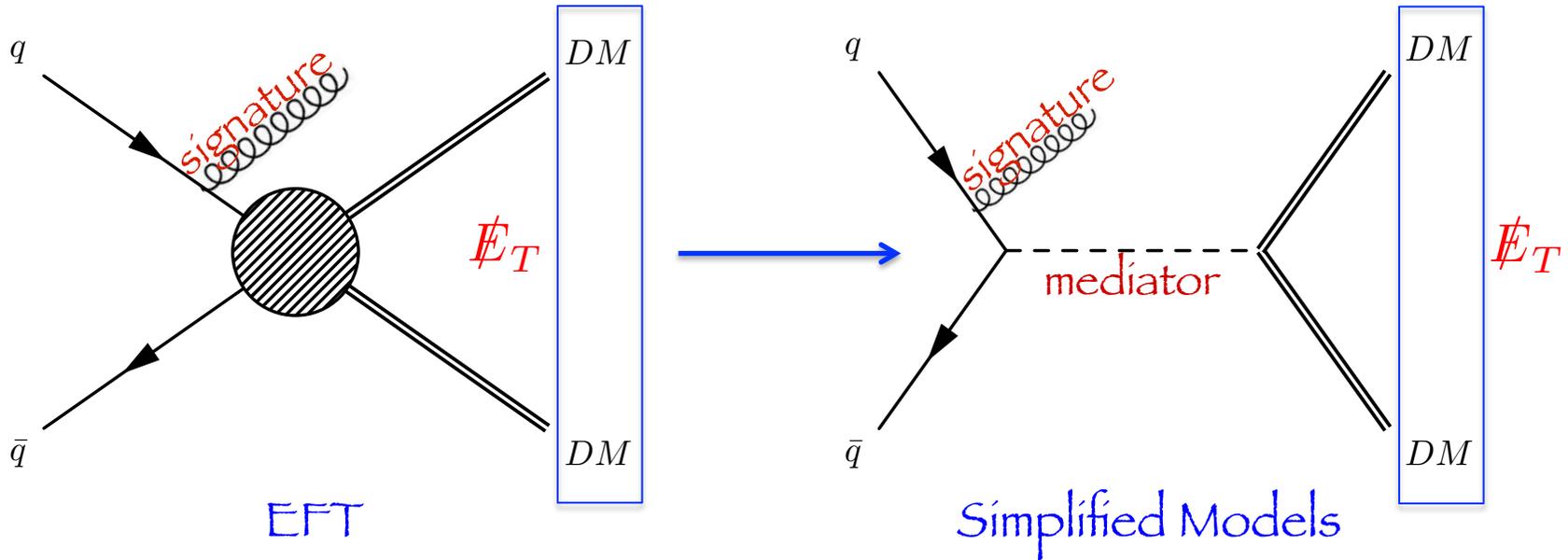


spin dependent

Inferred bounds on the direct detection scattering cross section, valid under a specific EFT modeling

WIMP at accelerators

- EFT \longrightarrow Simplified Models \dashrightarrow UV Complete



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

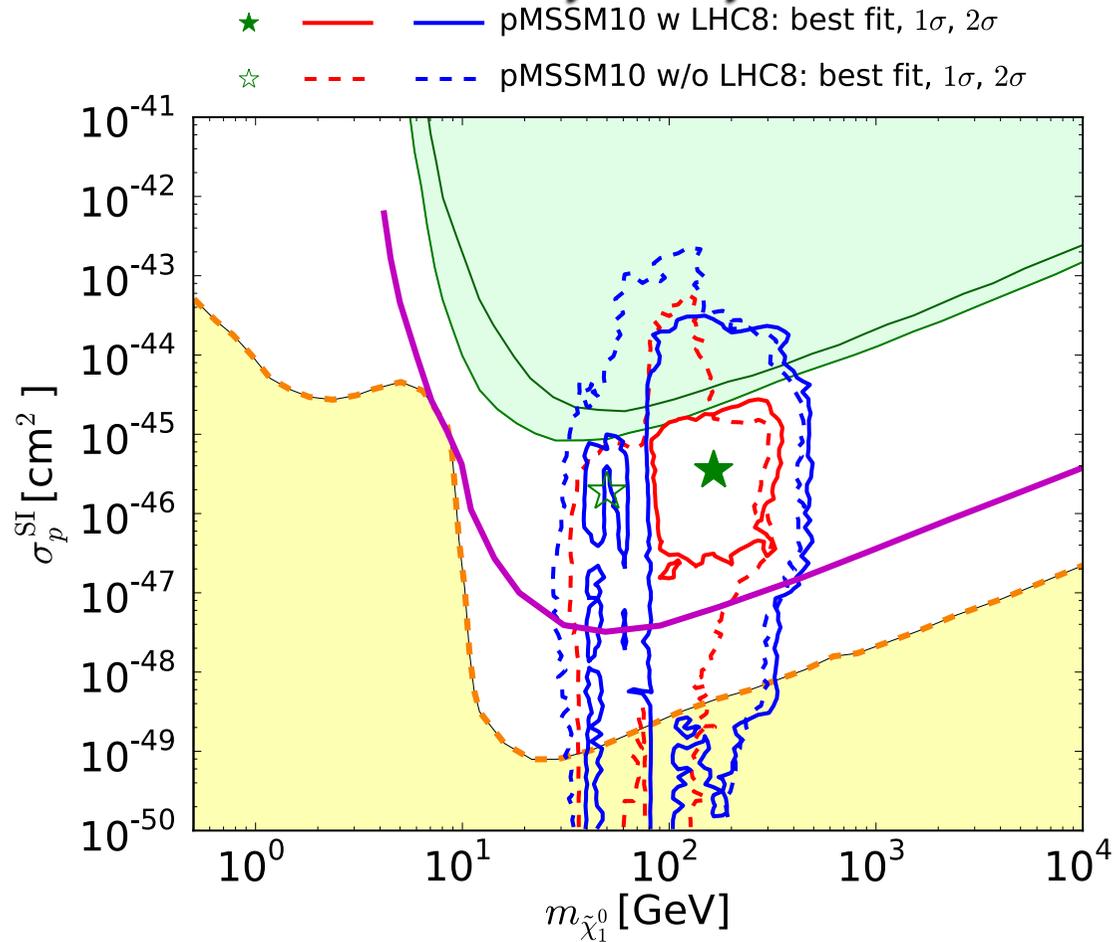
$$g_{(med, q)} \quad \Gamma_{med} \quad m_{med} \quad \text{canale}$$

coupling structure (s, v, t)

WIMPs at accelerators

- Complete NP 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
 - ...
 - ...

Example: pMSSM-10 after Run 1



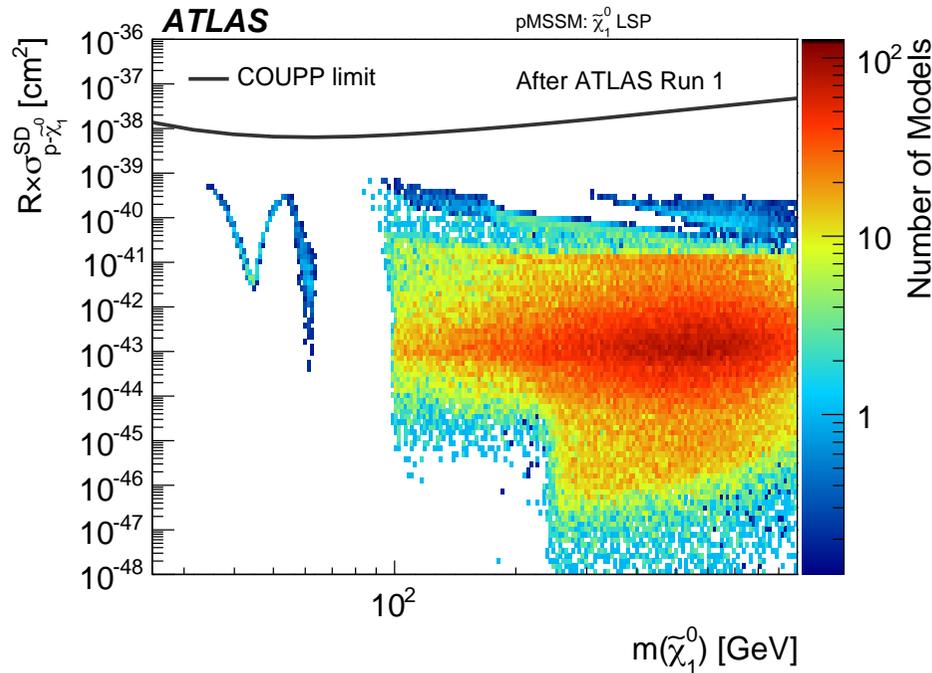
Bounds from:

- CMS, ATLAS
- Higgs searches
- Flavour physics
- Precision physics
- Cosmology

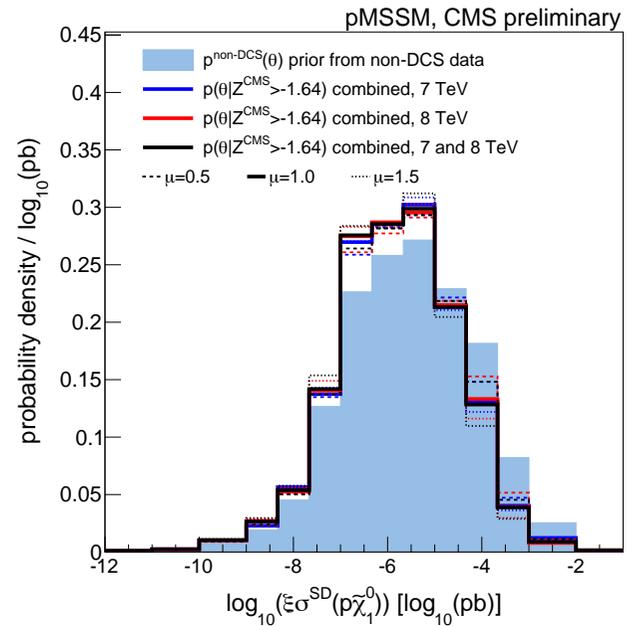
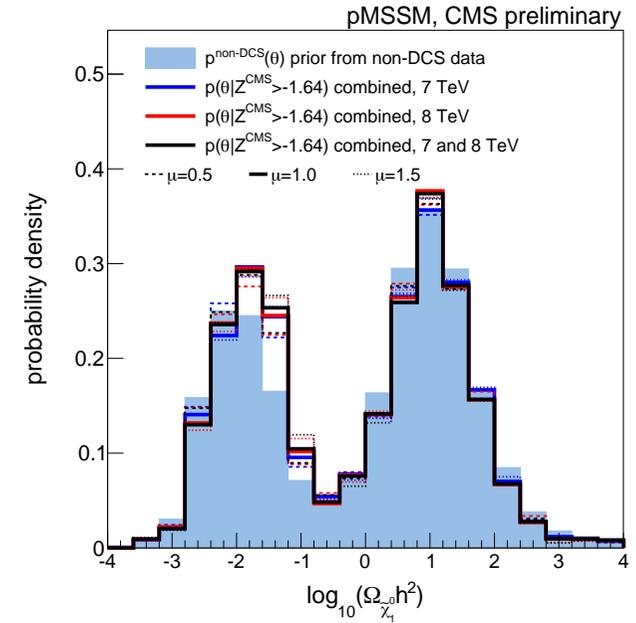
3 gaugino masses : $M_{1,2,3}$,
 2 squark masses : $m_{\tilde{q}_1} = m_{\tilde{q}_2} \neq m_{\tilde{q}_3}$
 1 slepton mass : $m_{\tilde{\ell}}$,
 1 trilinear coupling : A ,
 Higgs mixing parameter : μ ,
 Pseudoscalar Higgs mass : M_A ,
 Ratio of vevs : $\tan \beta$.

Example: pMSSM-19

Parameter
$m_{\tilde{L}_1} (= m_{\tilde{L}_2})$
$m_{\tilde{e}_1} (= m_{\tilde{e}_2})$
$m_{\tilde{L}_3}$
$m_{\tilde{e}_3}$
$m_{\tilde{Q}_1} (= m_{\tilde{Q}_2})$
$m_{\tilde{u}_1} (= m_{\tilde{u}_2})$
$m_{\tilde{d}_1} (= m_{\tilde{d}_2})$
$m_{\tilde{Q}_3}$
$m_{\tilde{u}_3}$
$m_{\tilde{d}_3}$
$ M_1 $
$ M_2 $
$ \mu $
M_3
$ A_t $
$ A_b $
$ A_\tau $
M_A
$\tan\beta$



ATLAS Collab, JHEP (2015) 134

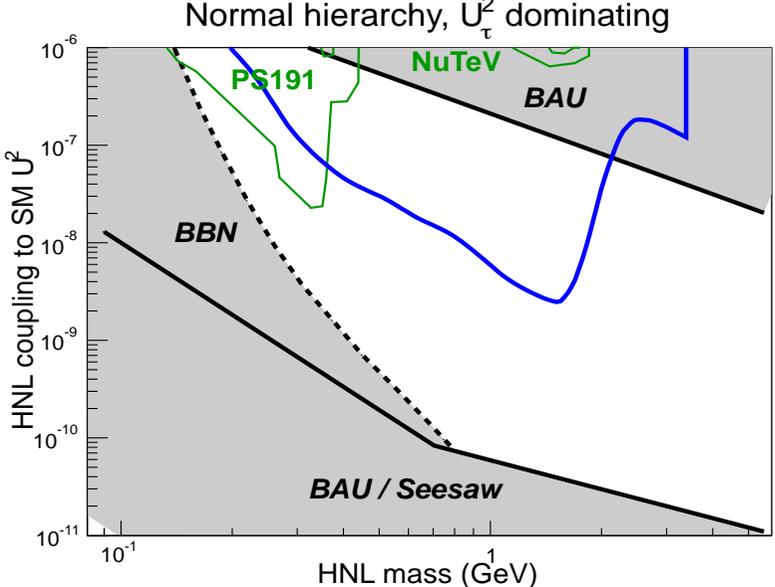
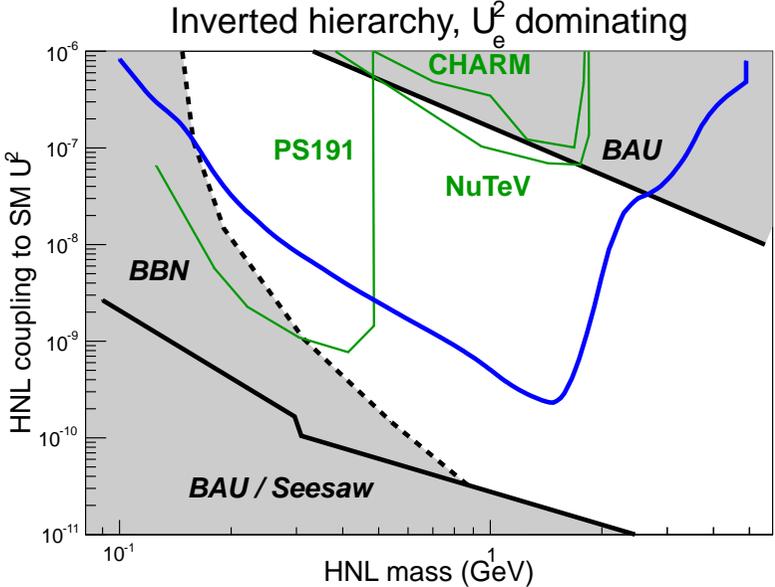


CMS Collab, CMS PAS SUS-13-020

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^-) under way, and studies for accessing invisible decays
- Rich experimental program:
 - Hadronic beams: SHIP e NA62 at CERN
 - Electron beams
 - Meson decays

Example: SHIP for neutrino portal



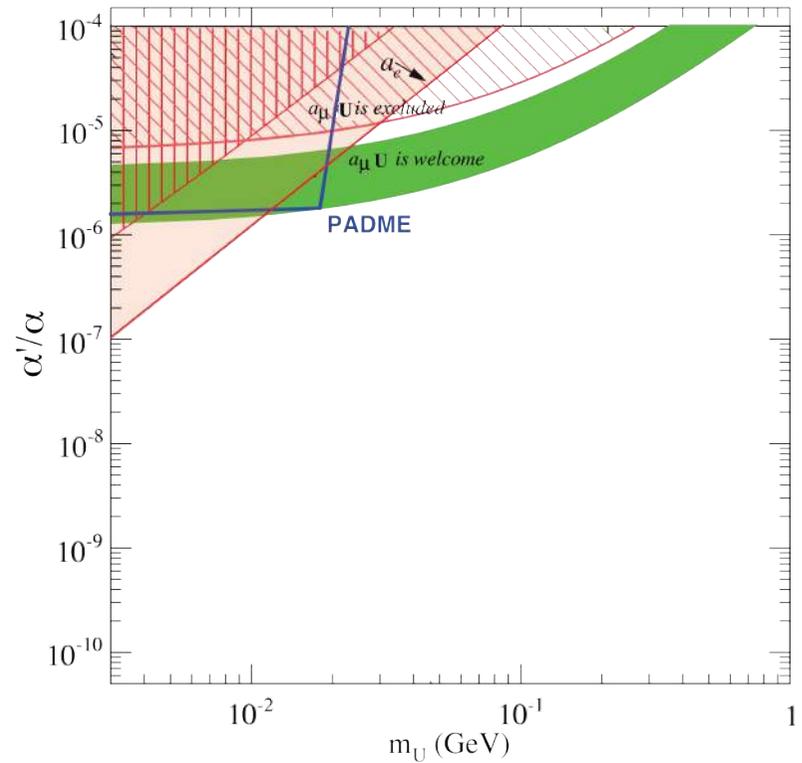
Proposals for electron beams

- 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”

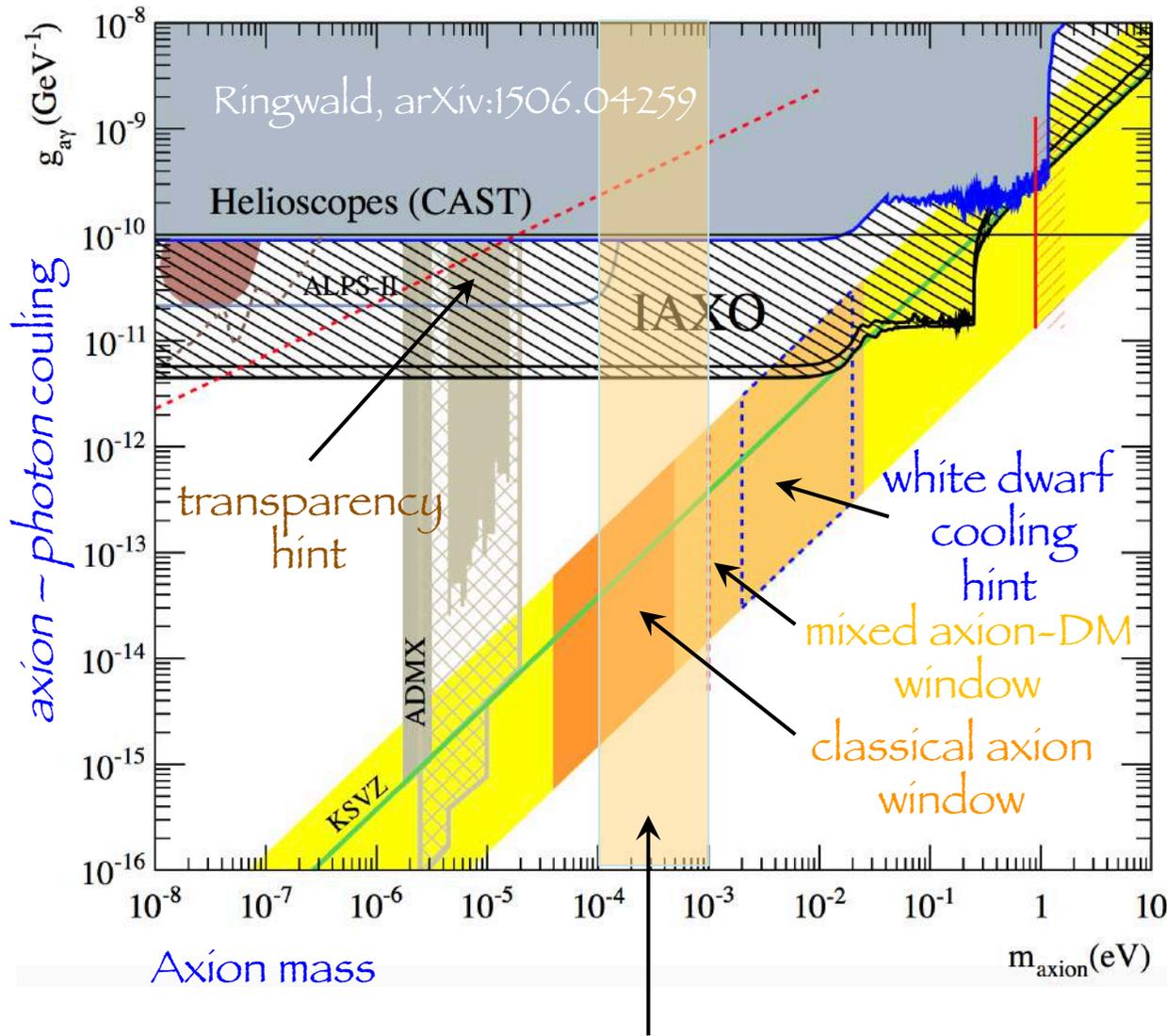
PADME at LNF

Dark photon search in e^+e^- to gamma + missing energy

In one year, sensitivity in the relative interaction strength down to 10^{-6} in the mass region (2.5, 22.5) MeV



Axions and ALPs



- Techniques:
- Shine through wall (ALPS, OSQAR)
 - Helioscopes (CAST, IAXO)
 - Haloscopes (ADMX)
 - Magnetic resonance (CASPEr)

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