Cosmic Radiation Signatures of Dark Matter

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Torino, Dark Tools Workshop
June 17th 2025

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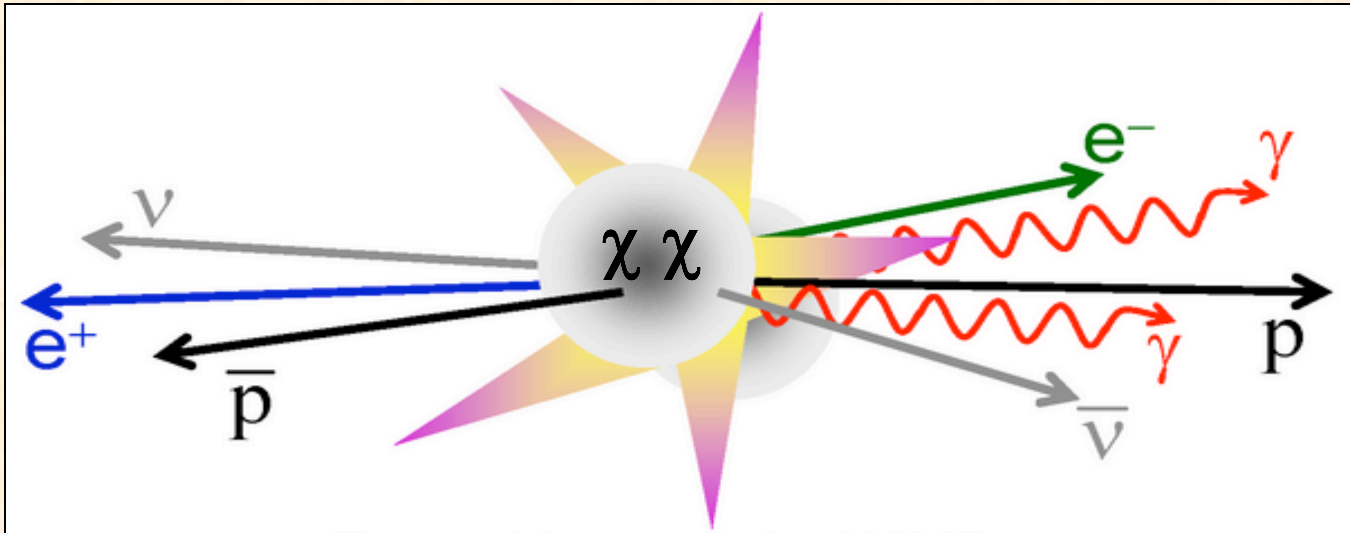
Four roads to Dark Matter

Indirect Detection of Dark Matter: the General Framework

1) **Dark Matter Annihilation** Typical final states include heavy fermions, gauge or Higgs bosons

2) **Fragmentation/Decay** Annihilation products decay and/or fragment into some combination of electrons, protons, deuterium, neutrinos and gamma rays

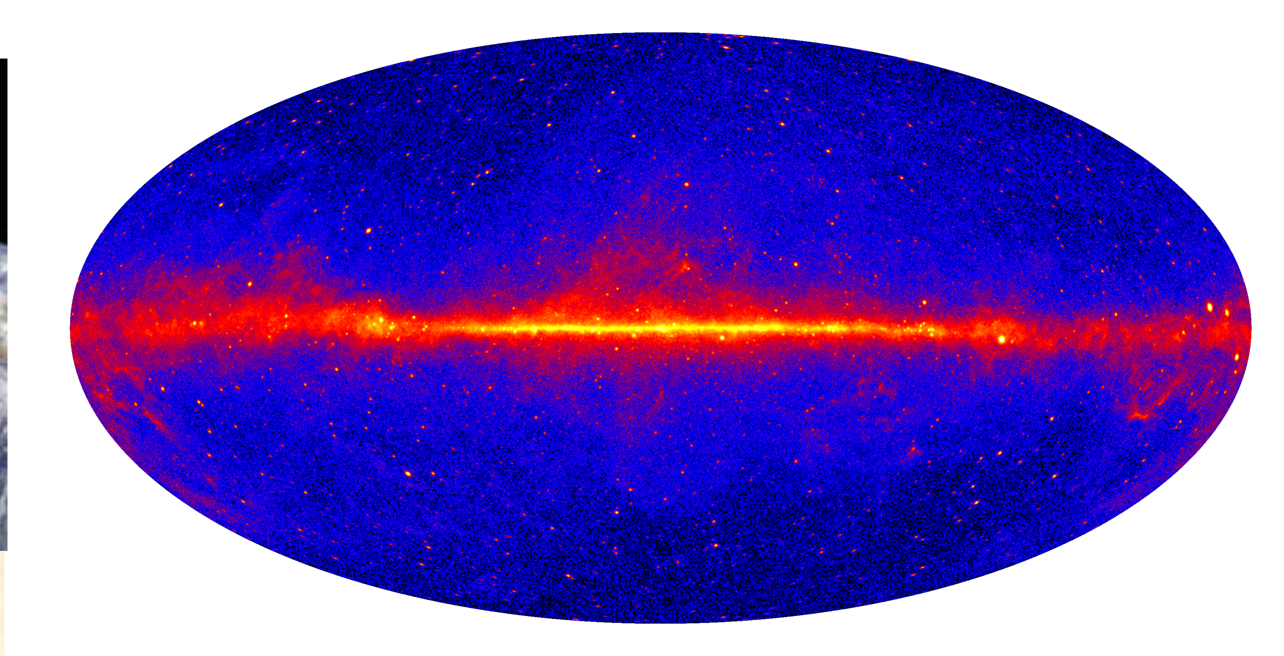


Gamma Rays

Fermi-LAT

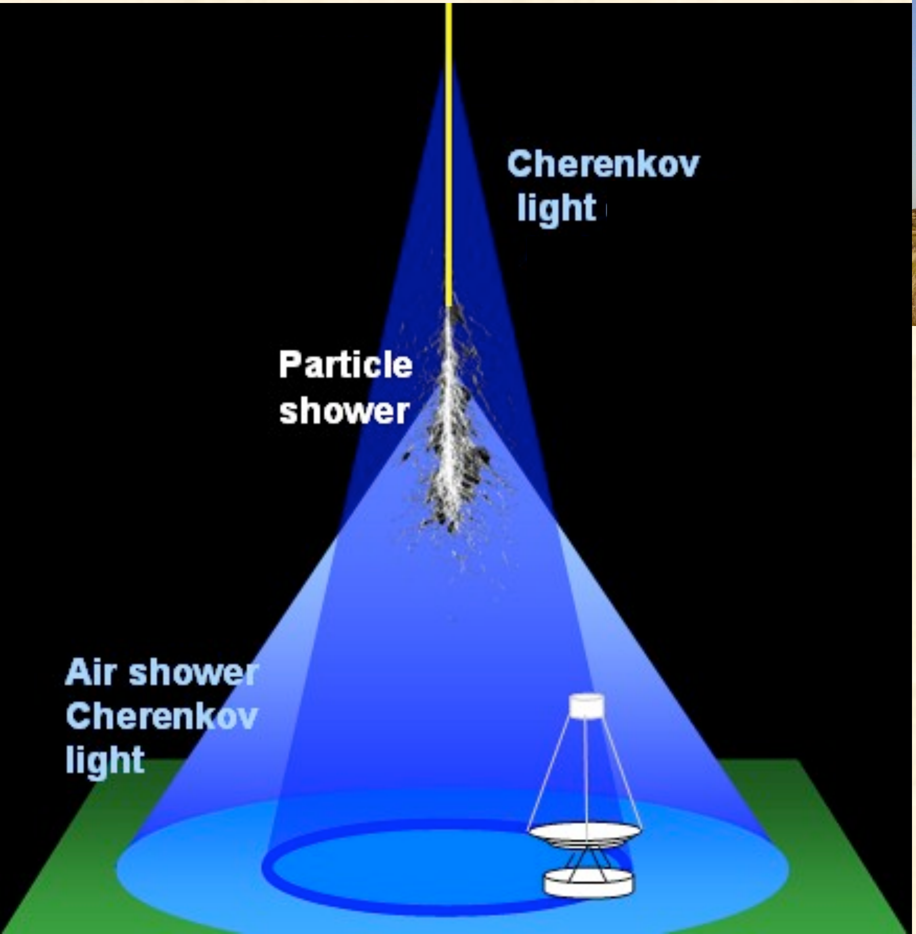
Fermi-Large Area Telescope (LAT)
Launched in 2008, 17 yrs ago!
Energy range 30 MeV- few TeV
PSF 0.1°-0.6°

Fermi Gamma-Sky, E>1 GeV



Ground based observations

Imaging Cherenkov Telescopes detect the showers produced by the gammas (and hadrons) interacting in the upper atmosphere



Advantages:

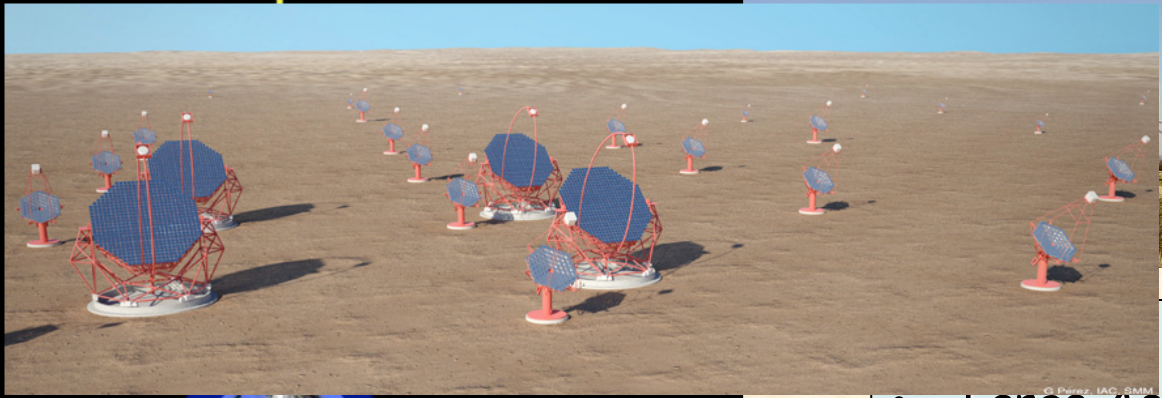
- Large Aeff: $10^{4\text{-}5}$ m2 = $10^{4\text{-}5}$ x Fermi-LAT
- Good Angular resolution: better than 0.1°

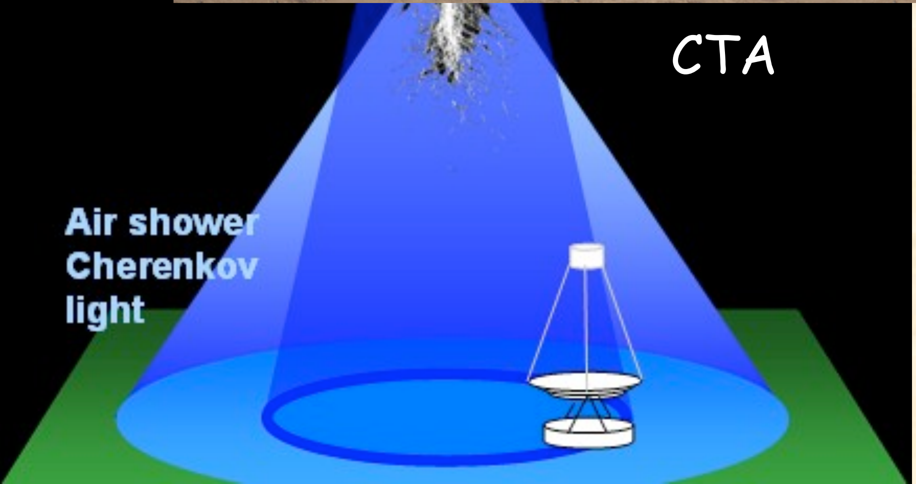
Drawbacks:

- Hadronic Background
- Narrow field of view: ~few degs
- High energy threshold: ~100 GeV

Ground based observations

Imaging Cherenkov Telescopes detect the showers produced by the gammas (and hadrons) interacting in the upper atmosphere





CTA

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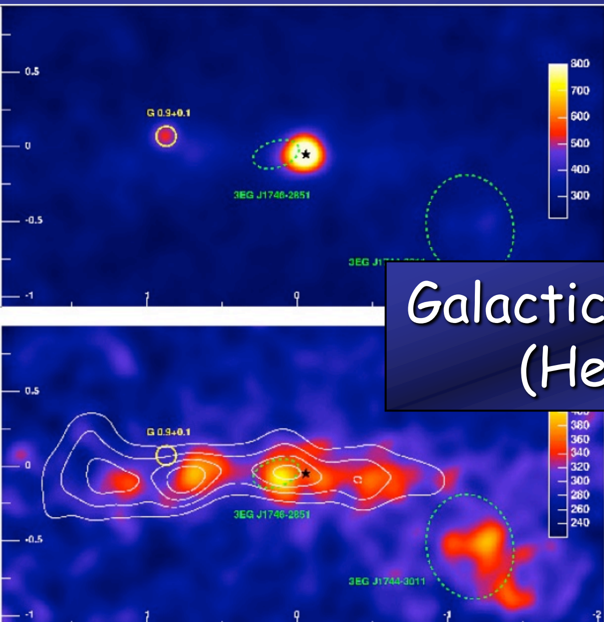
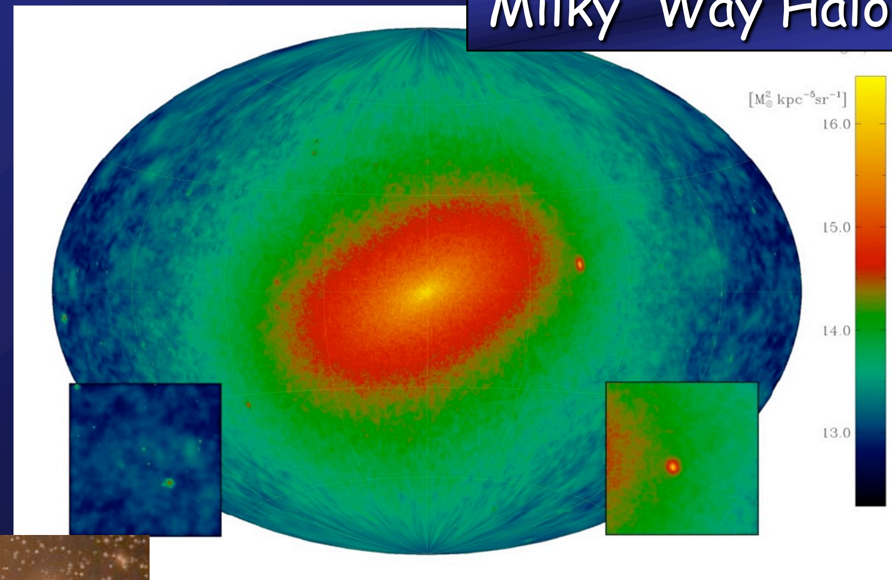
Where to look

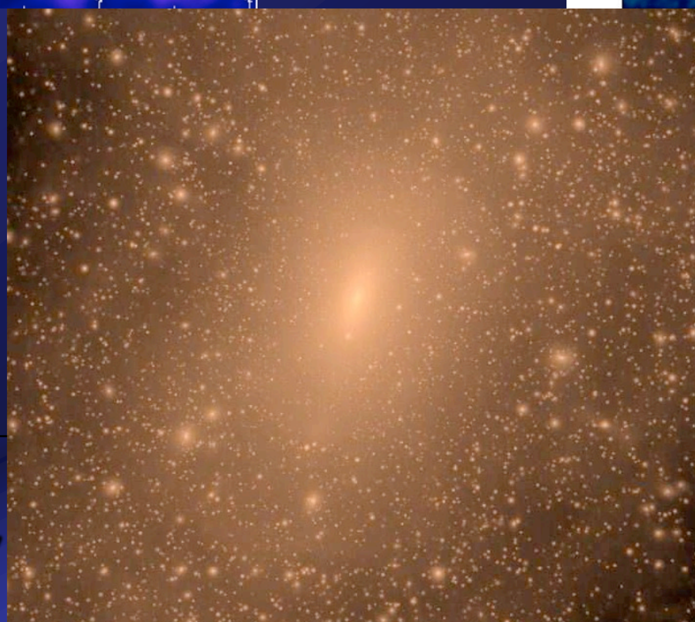


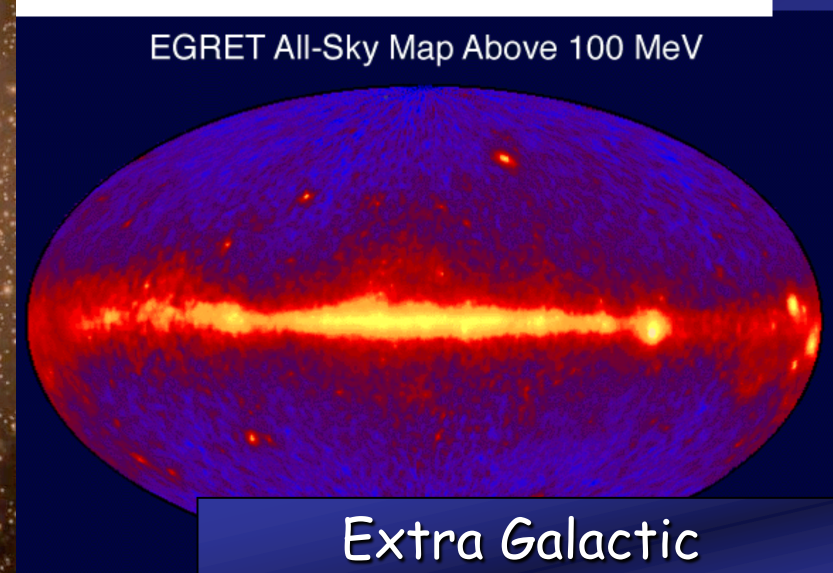
Galactic Center (Hess)

Milky Way Halo



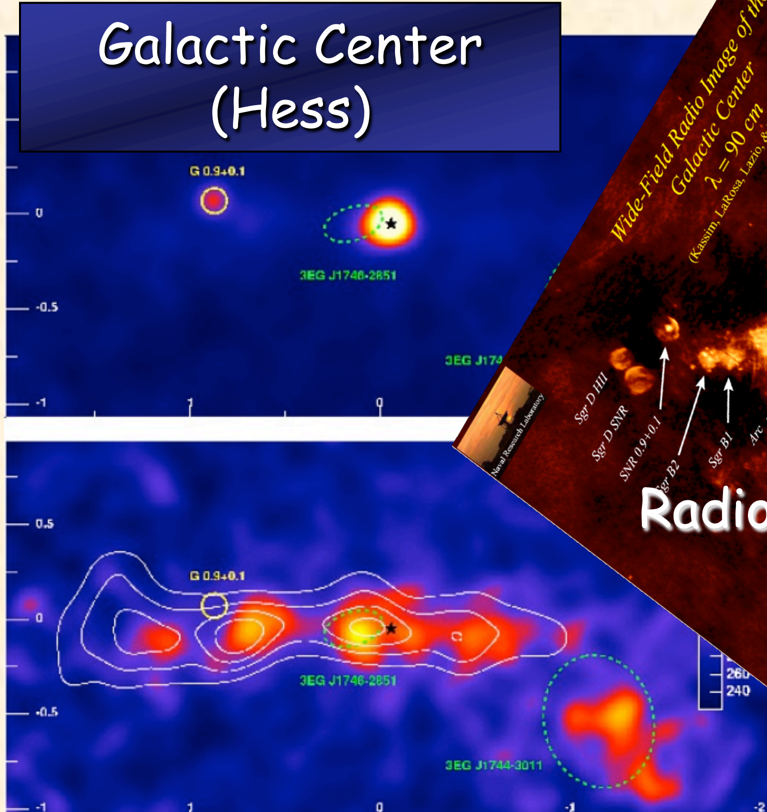
DM Clumps: From N-body simulations.

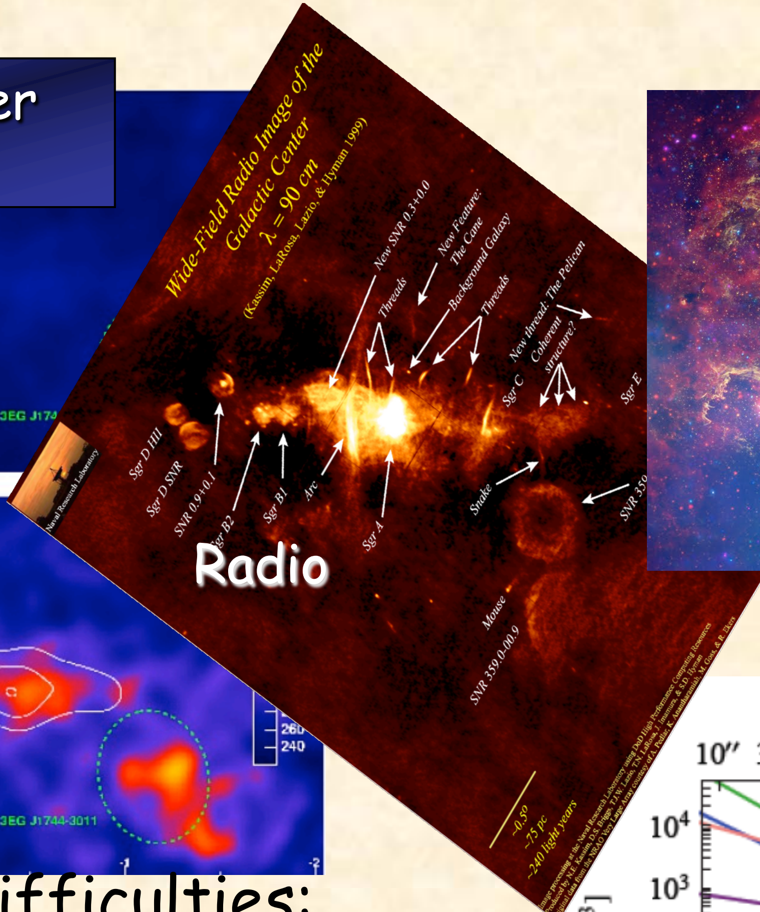


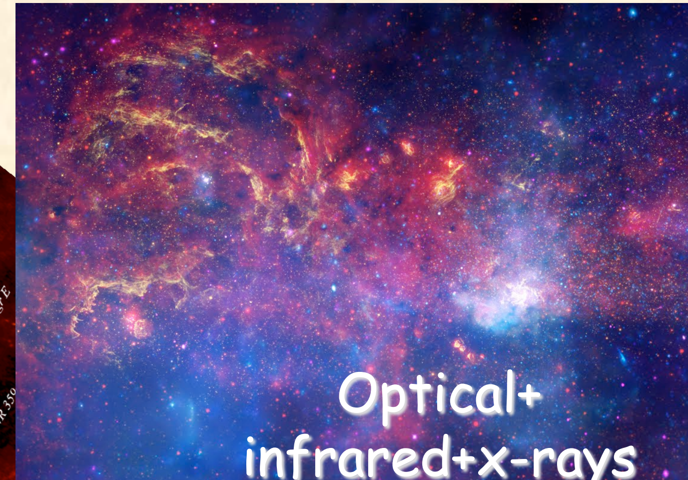


Extra Galactic Background

Galactic Center



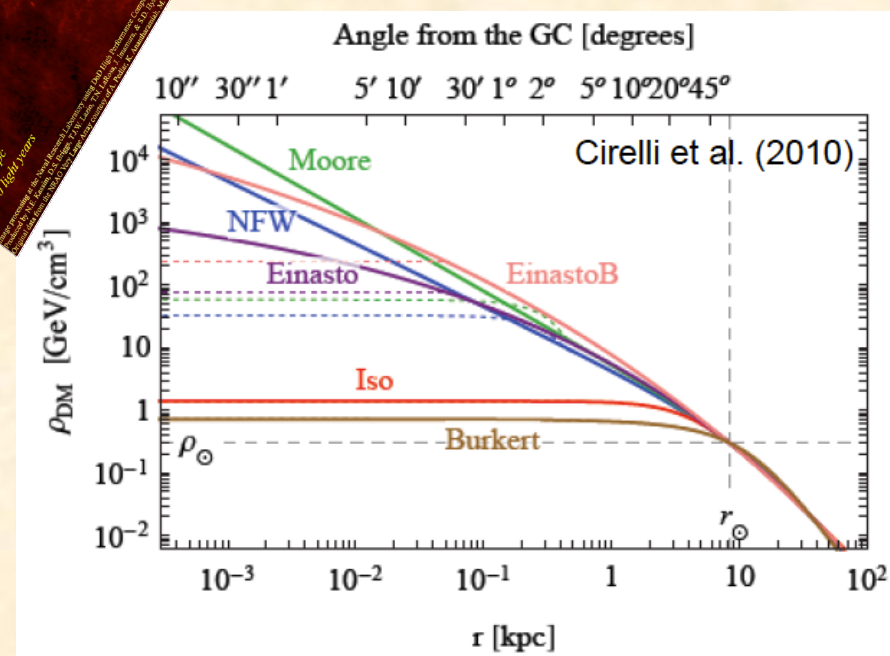




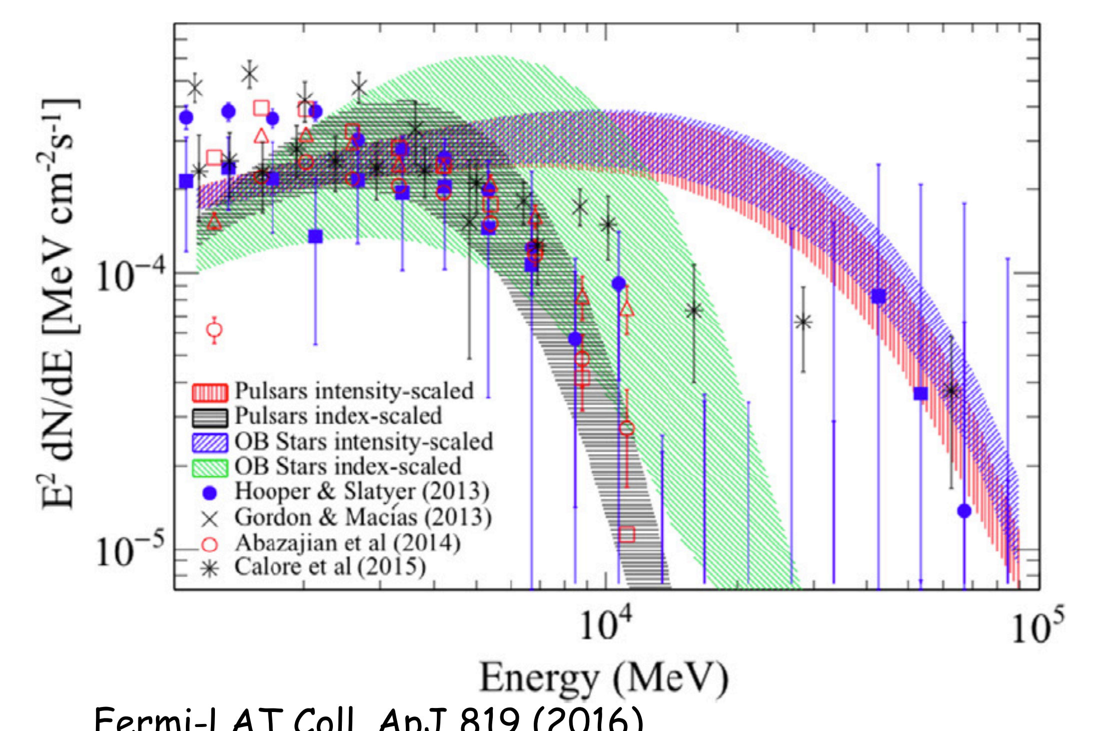
Further difficulties:

•Strong Background from the astrophysical point and diffuse sources in the GC

•Large Uncertainties in the DM profile

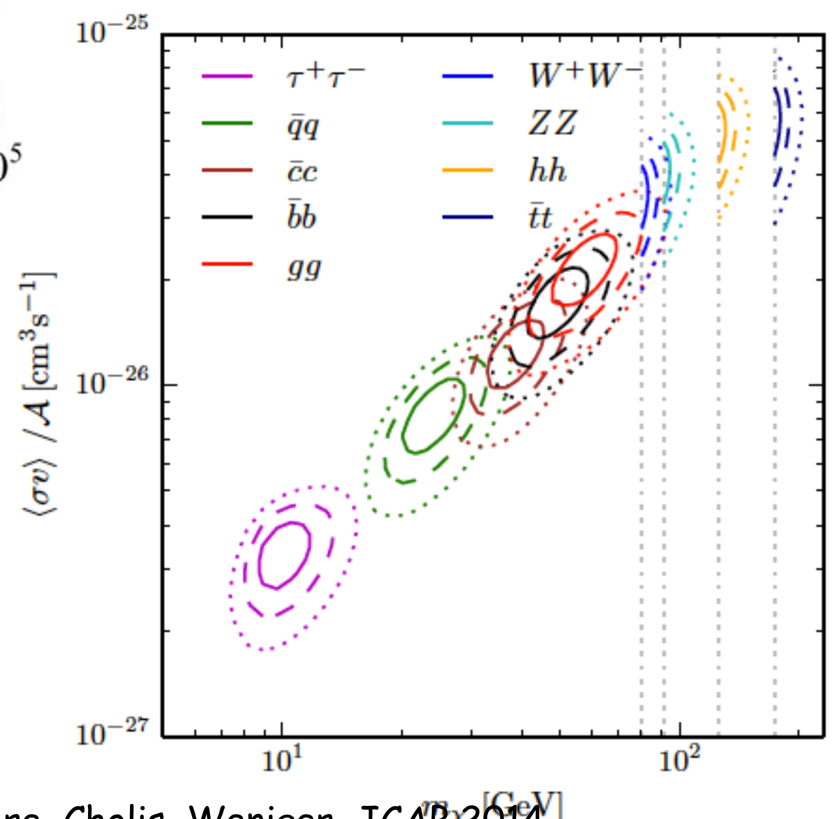


Galactic Center Excess



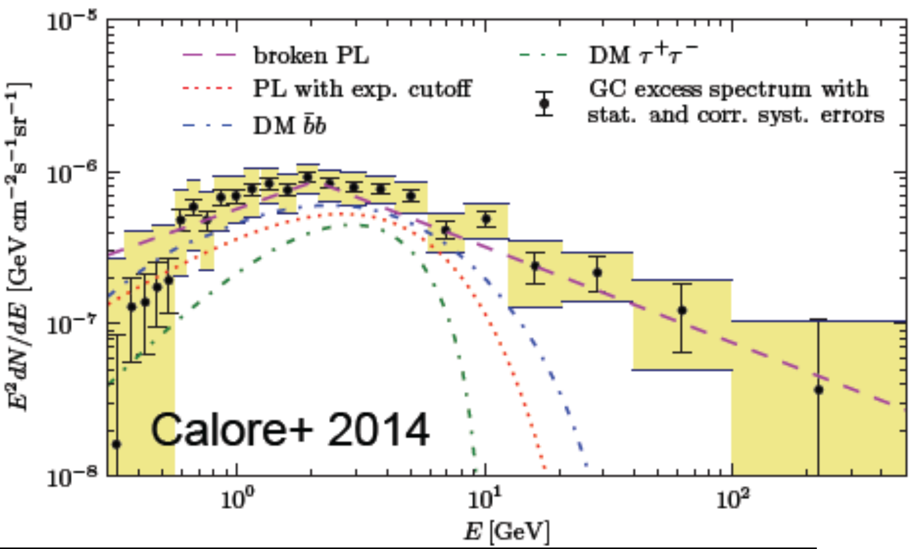
Fermi-LAT Coll. ApJ 819 (2016)

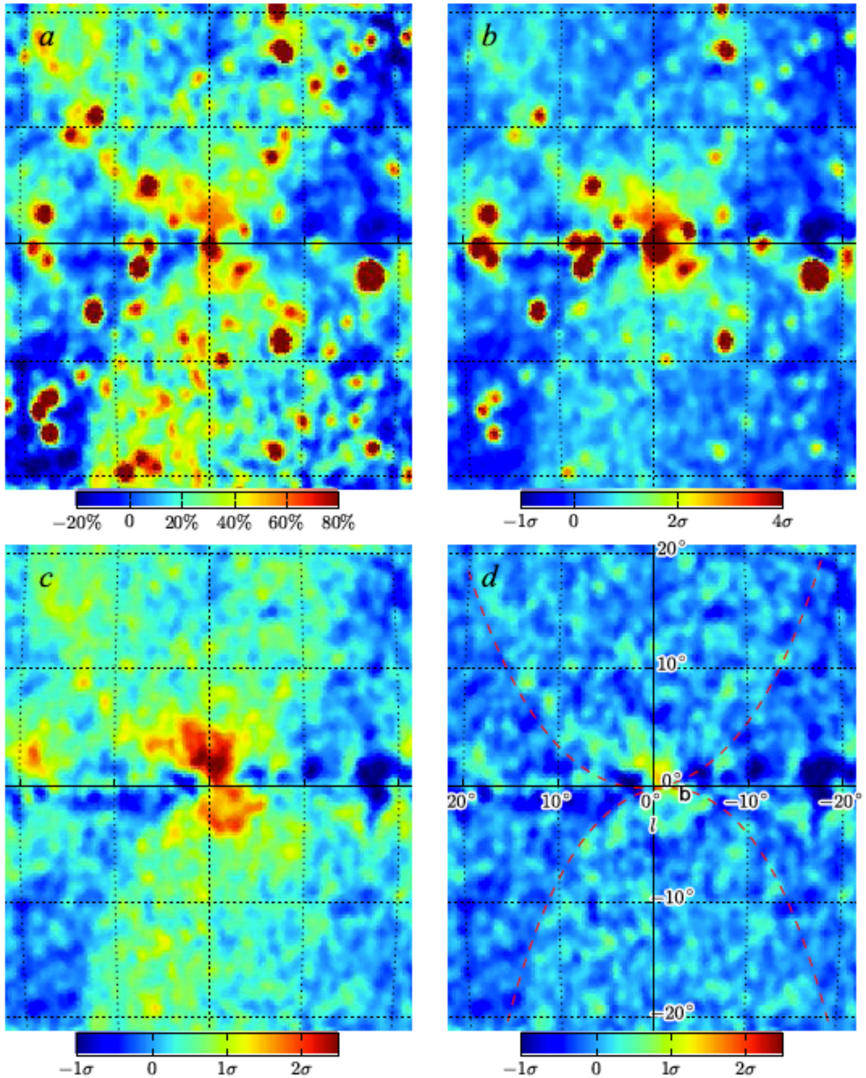
- An Excess in gamma rays toward the GC has been reported since 2010
- It's compatible with a DM interpretation with masses in the range 10-100 GeV and cross section close to thermal



Calore, Cholis, Weniger, JCAP 2014

Inner Galaxy Excess(?)





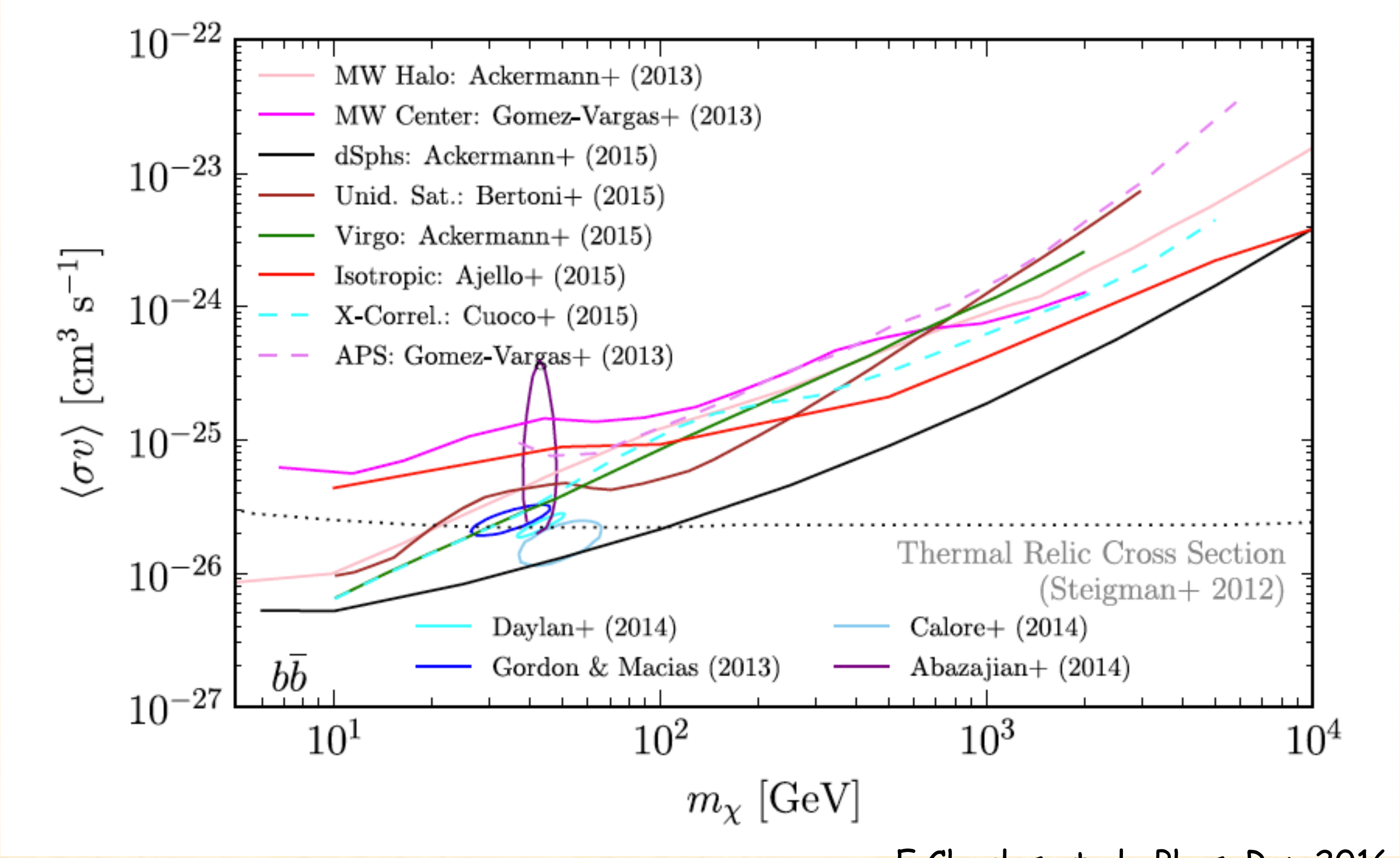
Several groups find an excess compatible with a spherical morphology.

Casandjian 2014 also finds an excess, but not spherically symmetric: related to the 'tip' of the Fermi Bubbles

Spectrally the excess is also compatible with on orgin by pulsars emission.

Overall, situation not clear yet

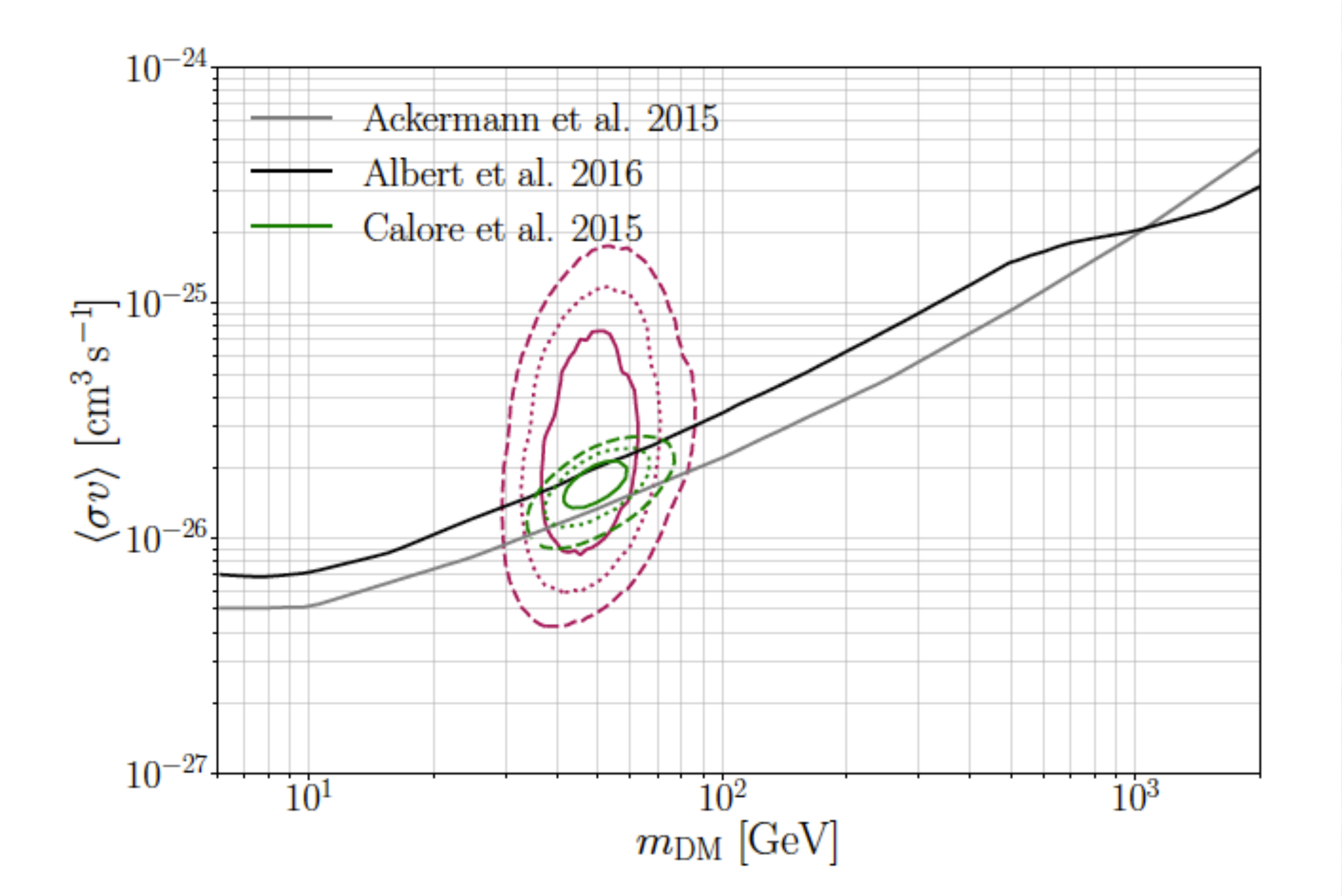
Galactic Center Excess



E.Charles at al., Phys. Rep 2016

- Some tension with dwarfs limits
- GCE Can be probed with a 4-5 improvement in dwarfs limits expected in the next ~10 yrs

Galactic Center Excess

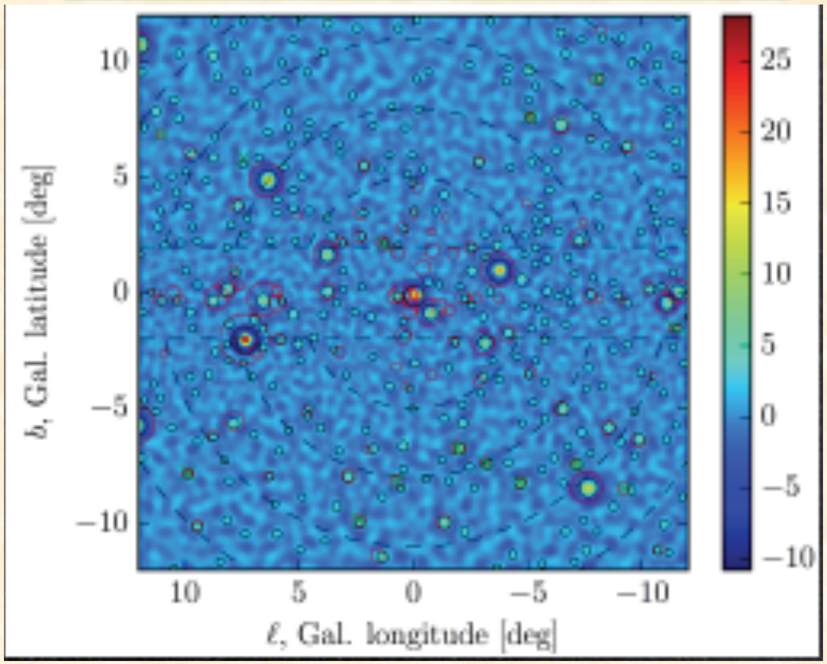


Benito, Cuoco, Iocco JCAP 2019

- However: Uncertainties in the MilkyWay DM content have been neglected!

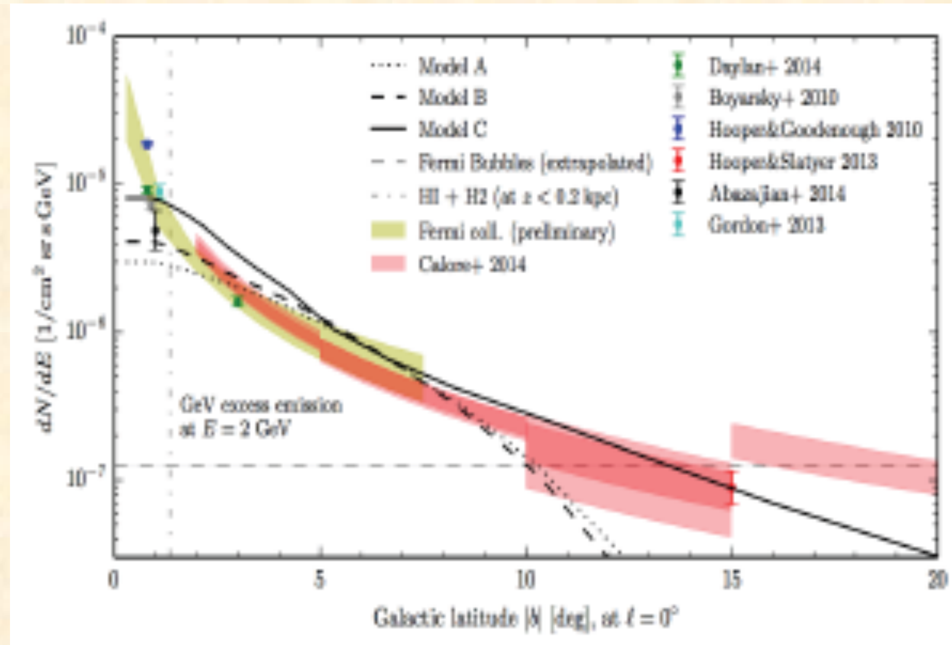
Galactic Center Excess

Unresolved Point Sources (MSP)



Bartels et al.,PRL 2016
Lee et al. PRL 2016

Series of leptonic outbursts

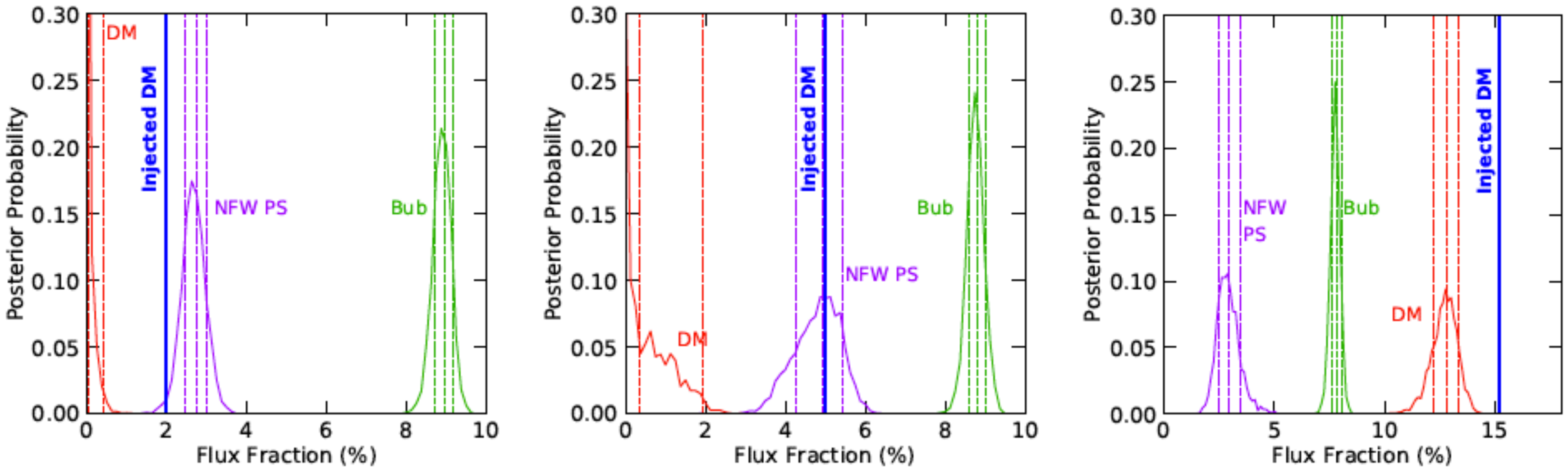


Cholis et al. JCAP 2015
Petrovic et al. JCAP 2014

Clustering analyses of the gamma-rays near the GC put the balance in favor of unresolved point sources (in particular milli-second pulsars)

See also:
Misha-Sharma & Cranmer PRD 2021
List, Rodd & Lewis PRD 2021
Song et al, MNRAS 2024
Manconi, Calore & Donato, PRD 2024

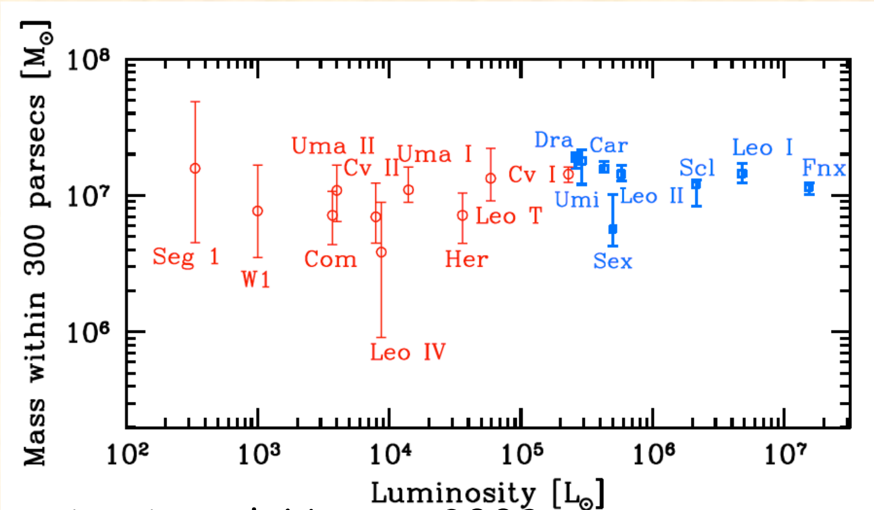
Galactic Center Excess



Leane & Slatyer,PRL 2019, PRL 2020, ArXiv: 1904.08430

However, it has been shown that the clustering analysis is very prone to systematic uncertainties in the diffuse Galactic emission. Previous studies not robust. DM back in the game!

Clean targets: Nearby Dwarfs Galaxies



Strigari et al. Nature 2009

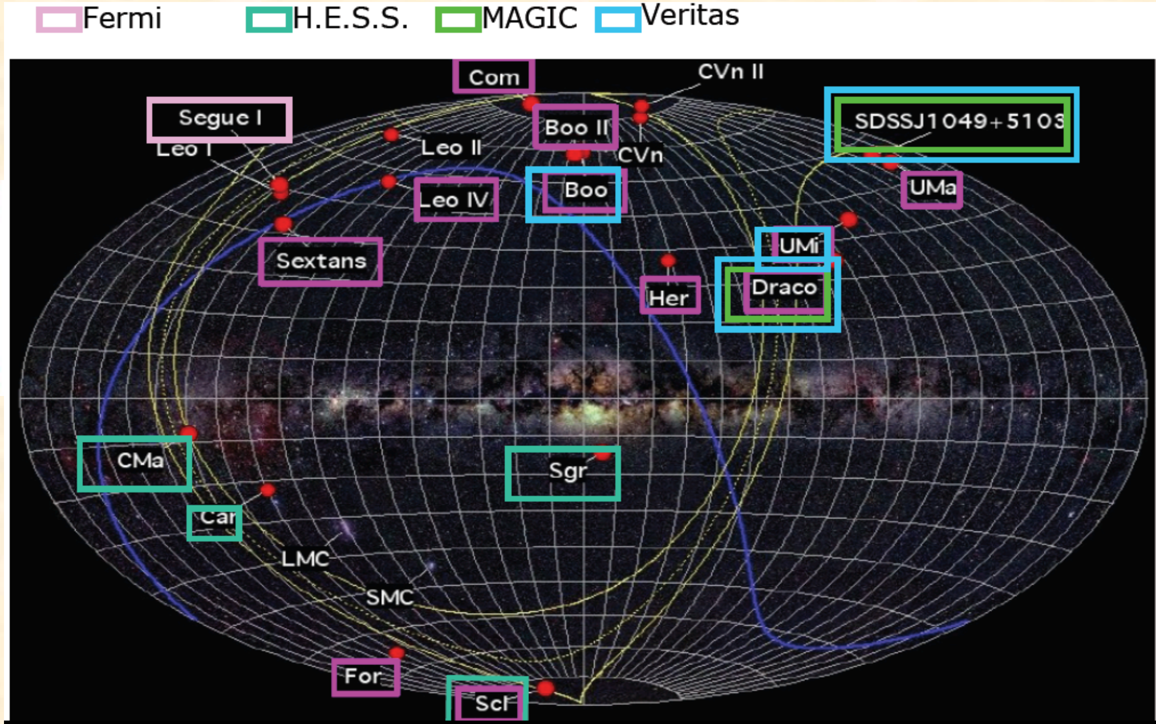
The faintest dwarfs detected have a mass to light ratio of more than 10^4: they are DM dominated system with very little astrophysical signal expected

J-factor

$$J(\psi) = \int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\, \rho_\chi^2(l)$$

J-factors (DM signal) and their uncertainties can be calculated from stellar kinematical data of the dwarfs

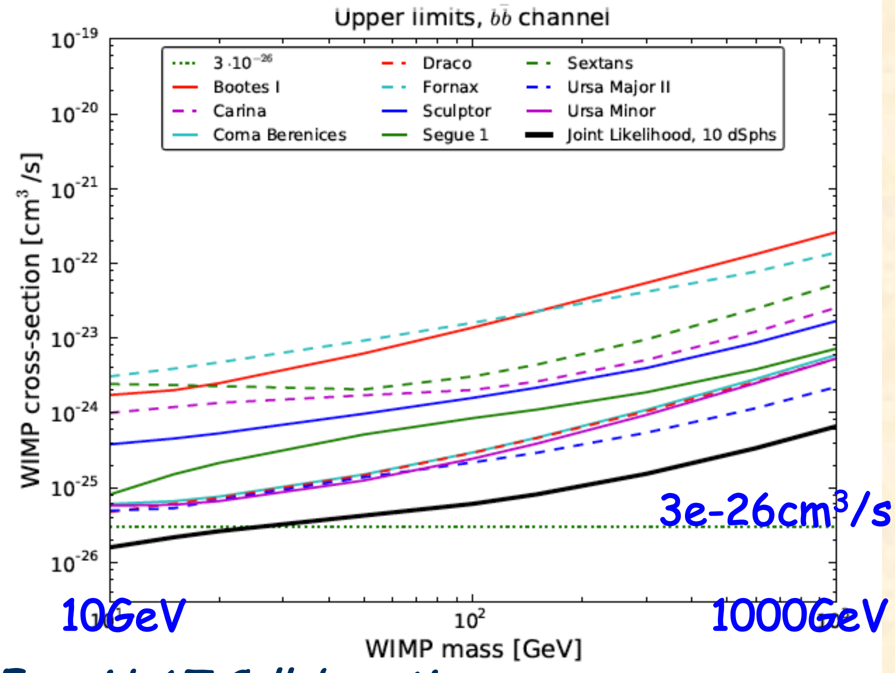
Dwarfs probed in gamma-rays



Novel constraints using a combined likelihood and including J-factor uncertainties

$$L(<\sigma_{ann}v>, m_{WIMP}; \vec{\Theta}) =$$
$$\prod_i^N L_i(<\sigma_{ann}v>, m_{WIMP}, J_i^m, C, b_i; \vec{\Theta}_i) \frac{1}{J_i^m \sigma_{J,i}\sqrt{2\pi}} e^{\frac{-(\ln(J_i^m)-J_i^{true})^2}{2\sigma_{J,i}^2}}$$

- J-factor uncertainties included

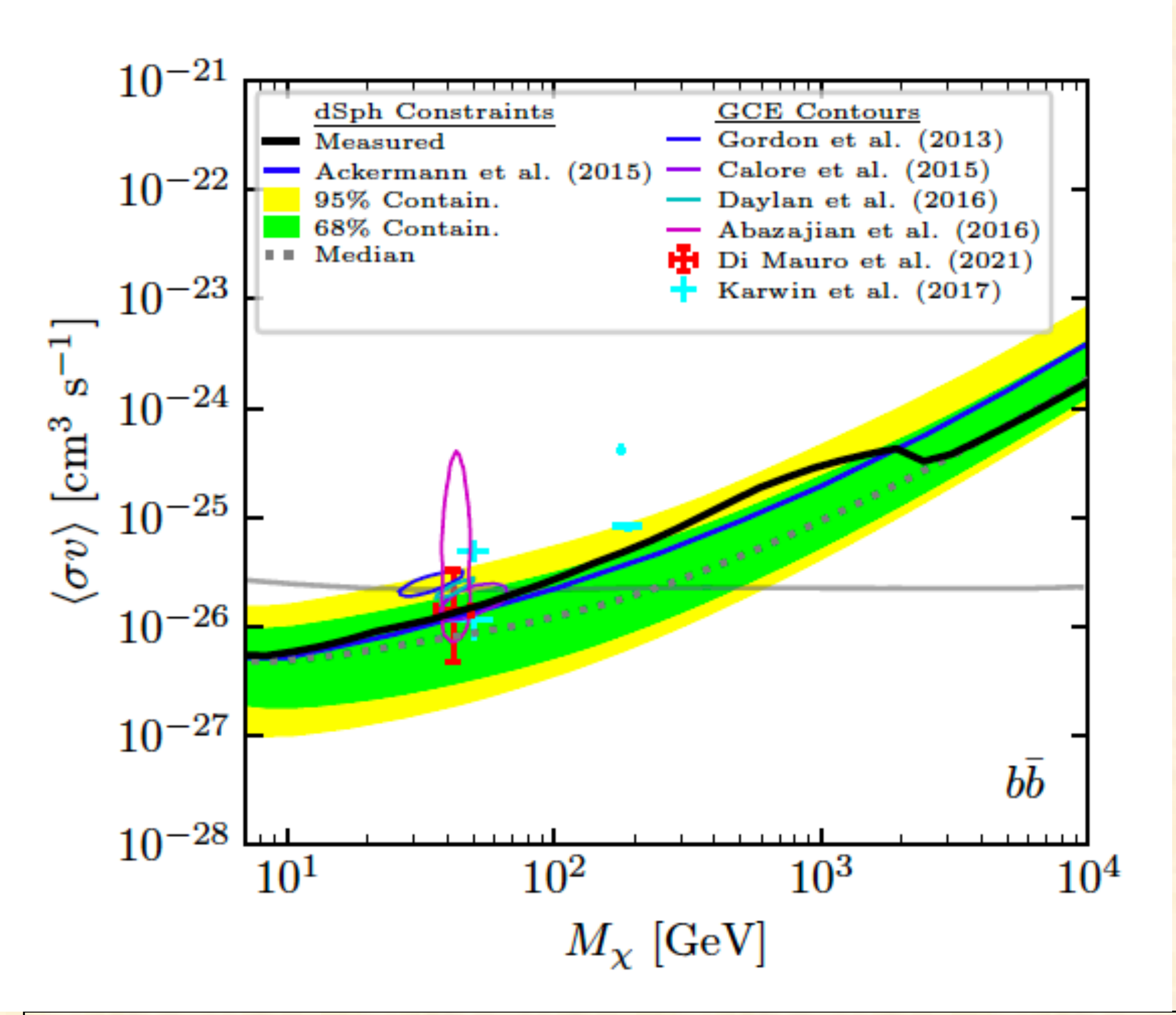


The method implements a product of likelihoods from the single dwarfs, instead of the usual multiple source stacking. The formalism also allows to take into account easily the J-factor uncertainties.

Including the J-factor uncertainties changes the constraint by roughly 40 %.

Fermi LAT Collaboration, arXiv:1108.3546, PRL 2012

Constraints with 14 yrs p8 data

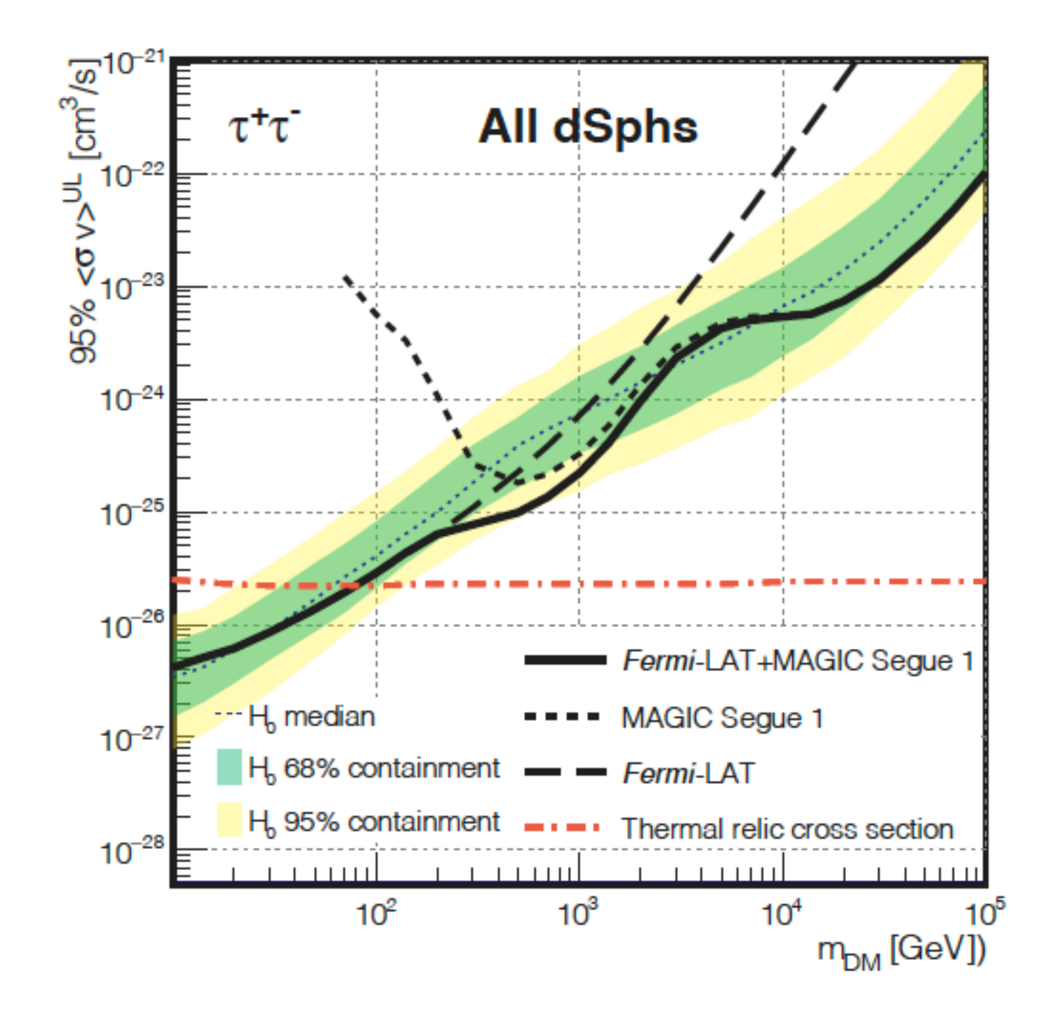


Excludes thermal relic WIMPs with masses smaller than ~100 GeV

Mc Daniel et al. PRD 2024, Arxiv: 2311.04982

Fermi LAT Collaboration, 2015 PRL. arXiv:1503.02641

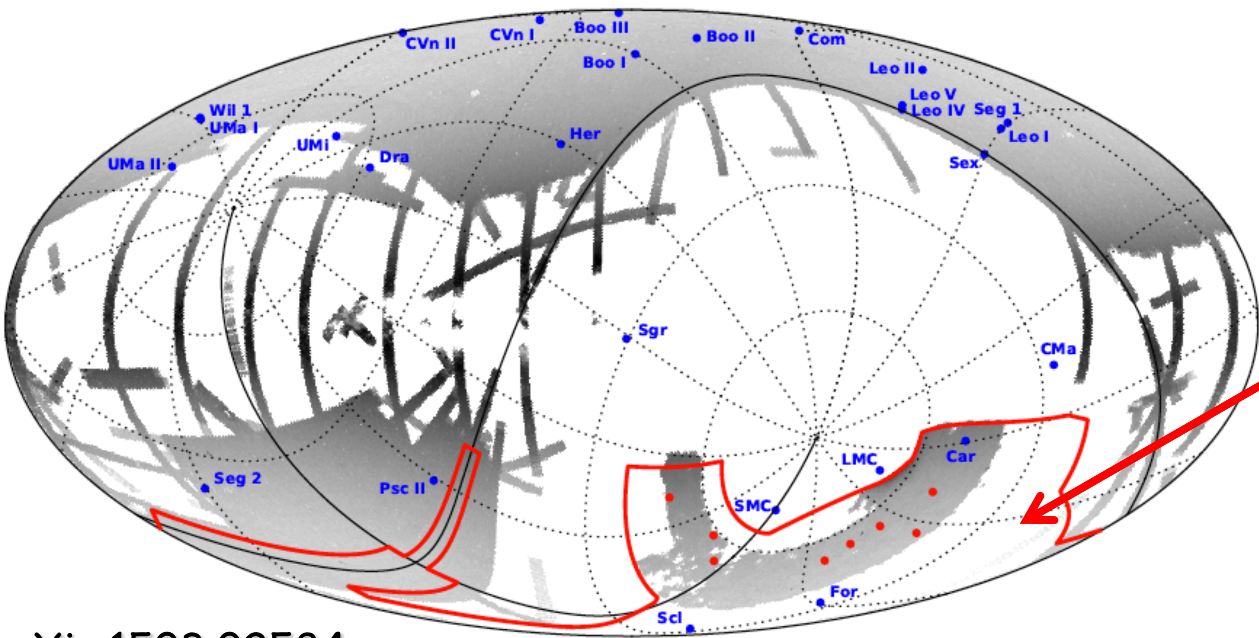
In combination with Cherenkov telescopes



Fermi and Magic Collaborations, JCAP 2016. arXiv: 1601.06590

Observation from Cherenkov telescopes further extends the constraints up to 100 TeV DM mass

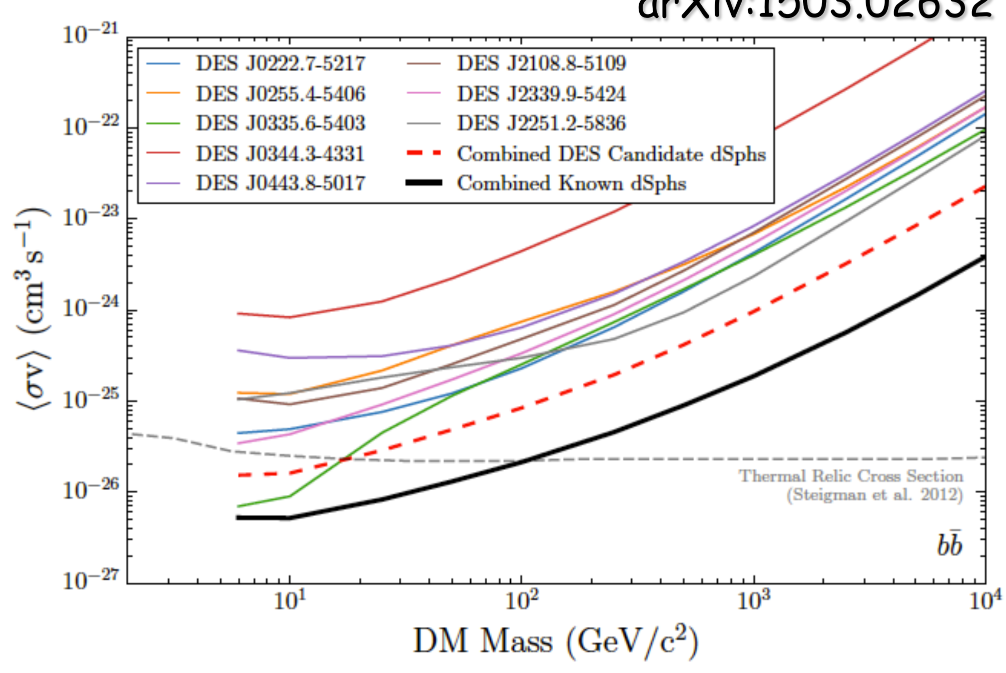
More dwarfs in new galaxy surveys



DES Survey Region

arXiv:1503.02584

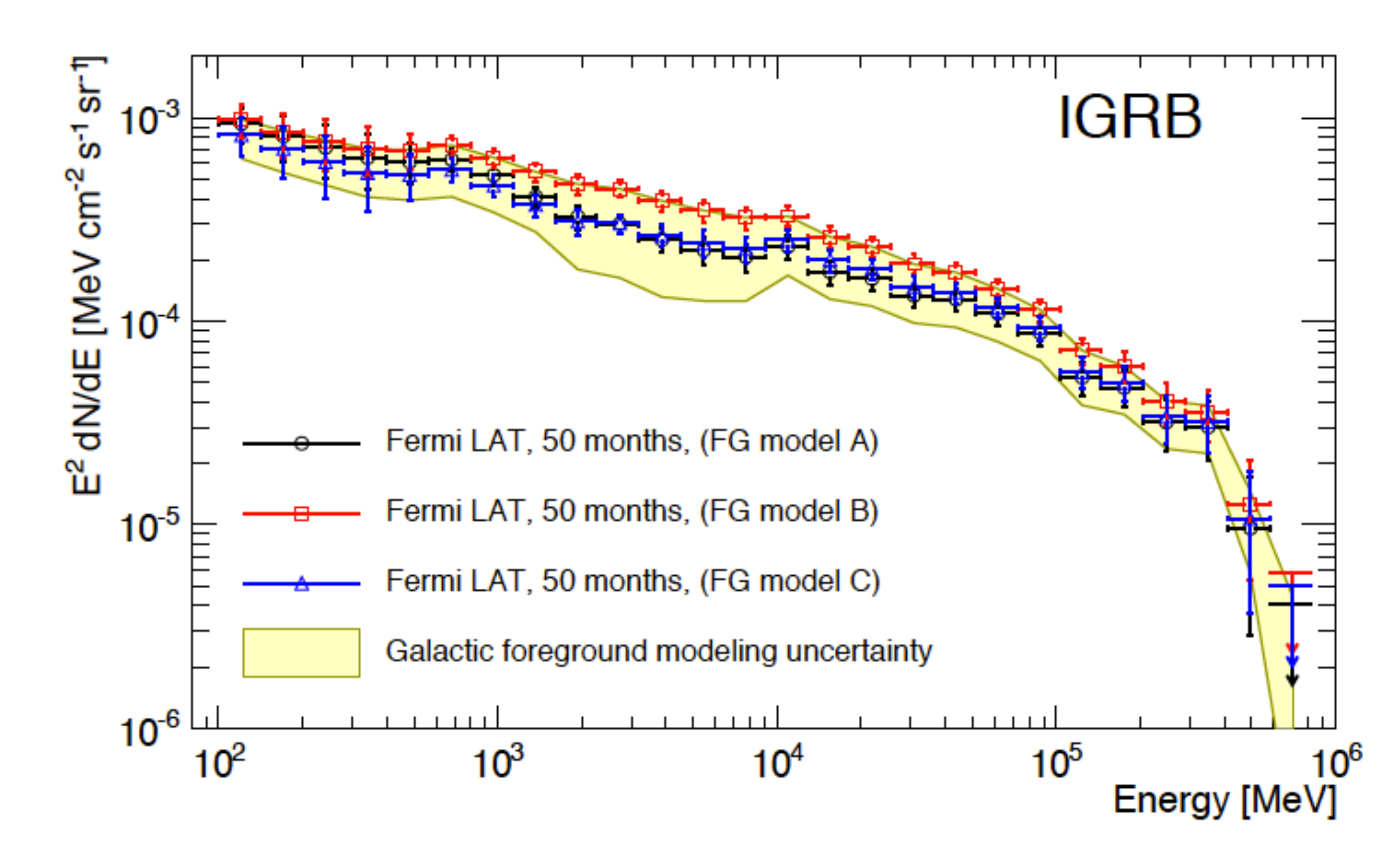
arXiv:1503.02632



More dwarfs will be likely discovered in the next years with larger J-factors:

- More data from DES,DESI
- Other surveys: LSST, Euclid

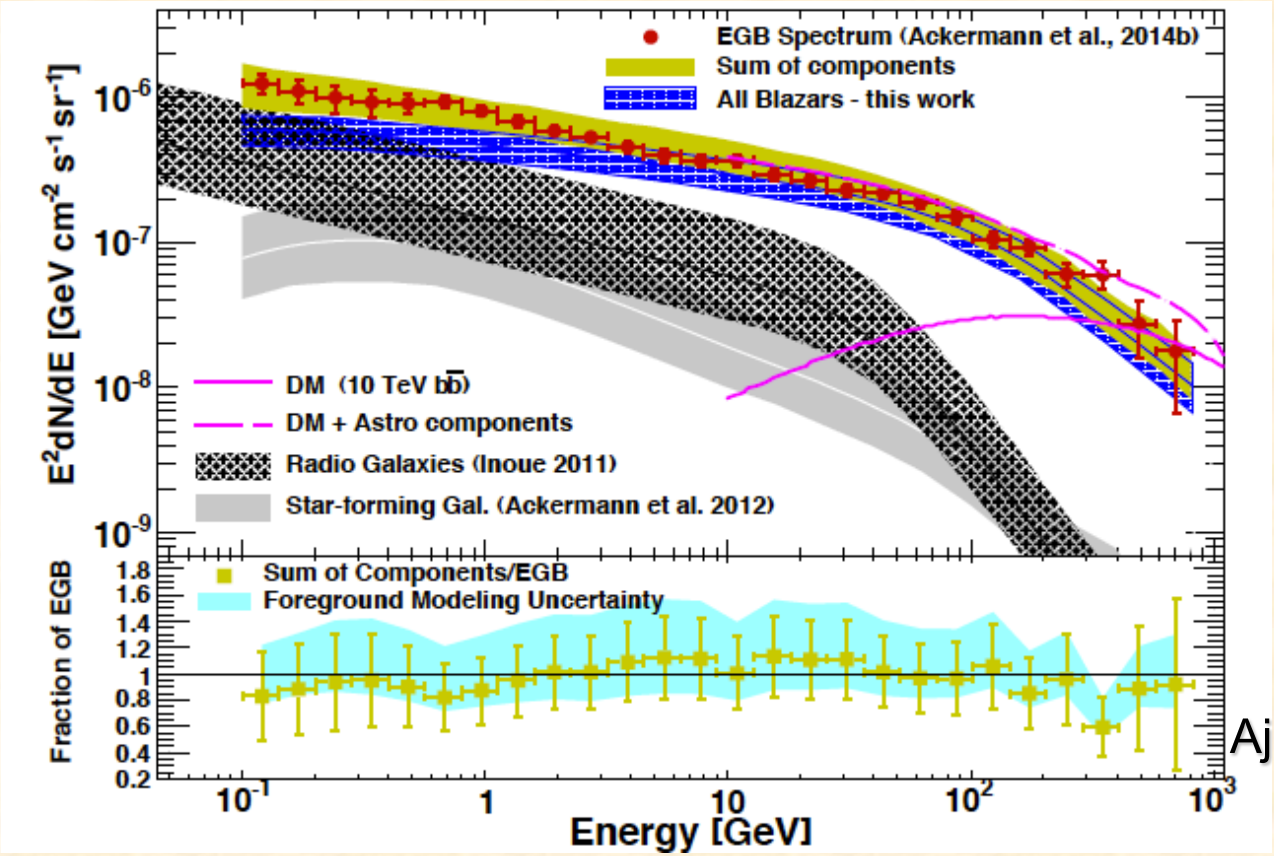
The Extra-Galactic Gamma-ray Background (EGB)



Fermi LAT collaboration, Astrophys.J. 799 (2015) 1, 86

- Power Law for E < 100 GeV
- Spectral softening at high energies

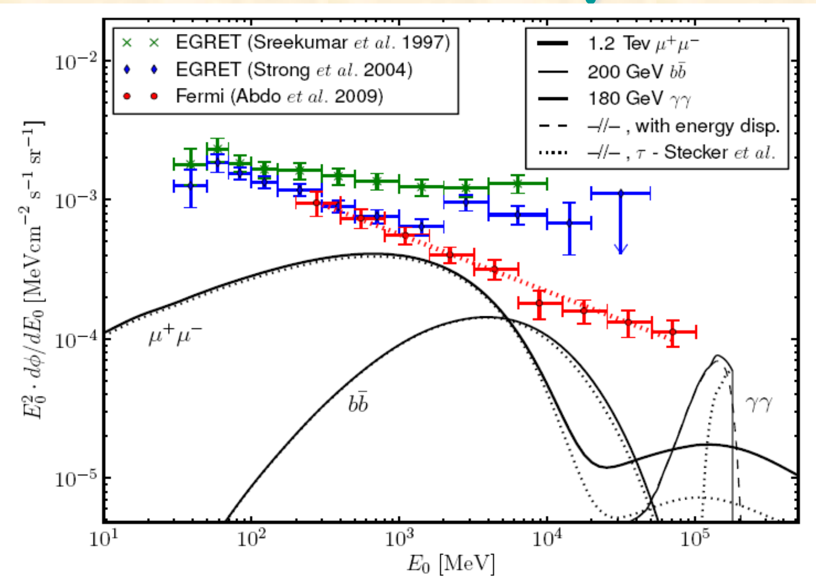
IGRB Energy Sprectrum



Ajello et al. ApjL 2015

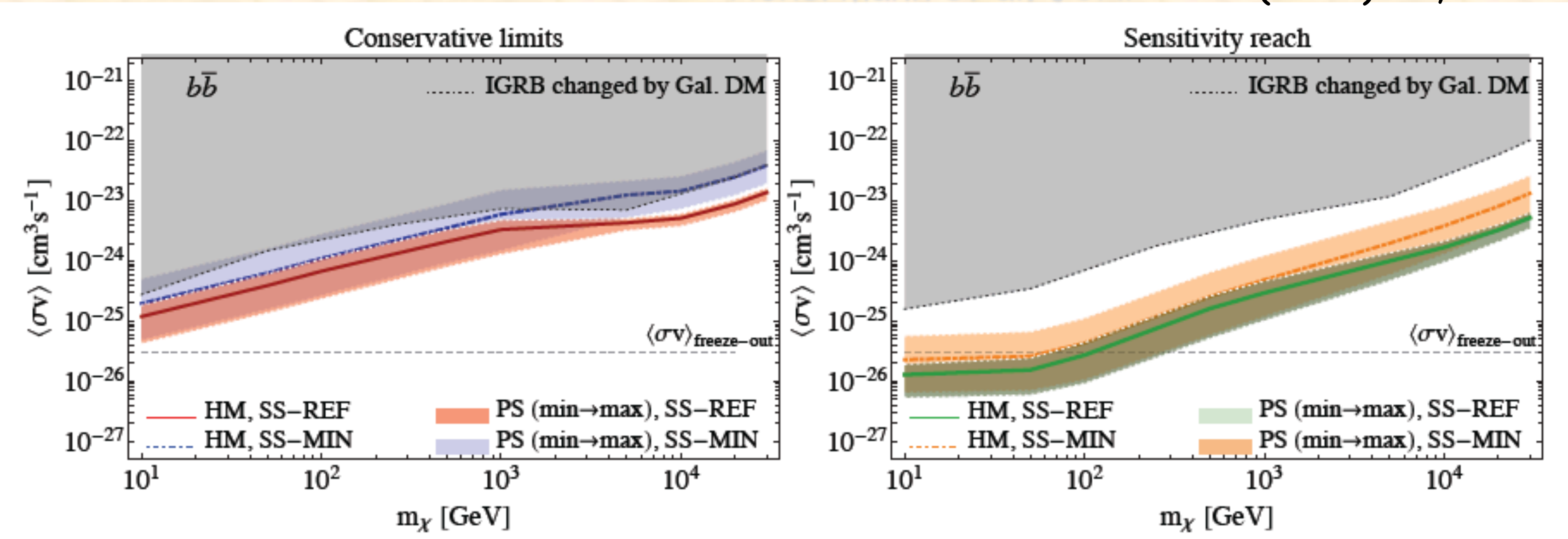
- The IGRB energy spectrum can be well fitted by a sum of different astro-physical components.
- No obvious need of Dark Matter

Constraints from the Extra-Galactic Gamma-ray Background



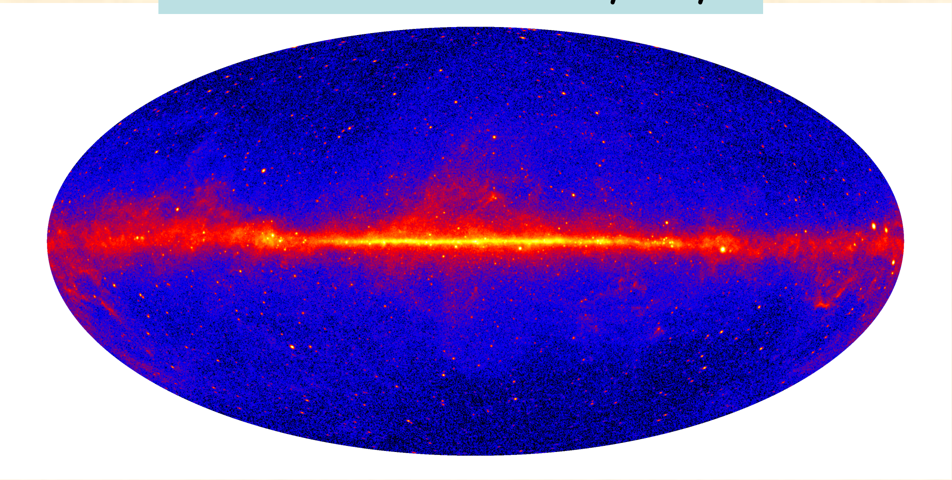
- Potentially very constraining, but gives very model dependent limits due to large uncertainties in the predicted DM signal
- Better understanding of the DM clustering at small scales can help tight the uncertainties.

Abdo et al. (Fermi-LAT) JCAP 1004 (2010) 014,
Ackermann et al. JCAP 1509 (2015) 09, 008

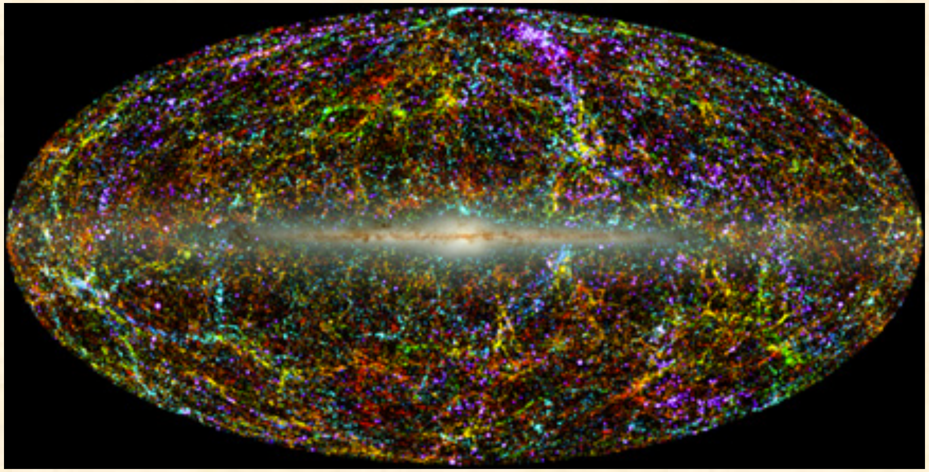


Exploring different techniques to search for DM in gamma rays

Fermi-LAT Gamma-ray Sky



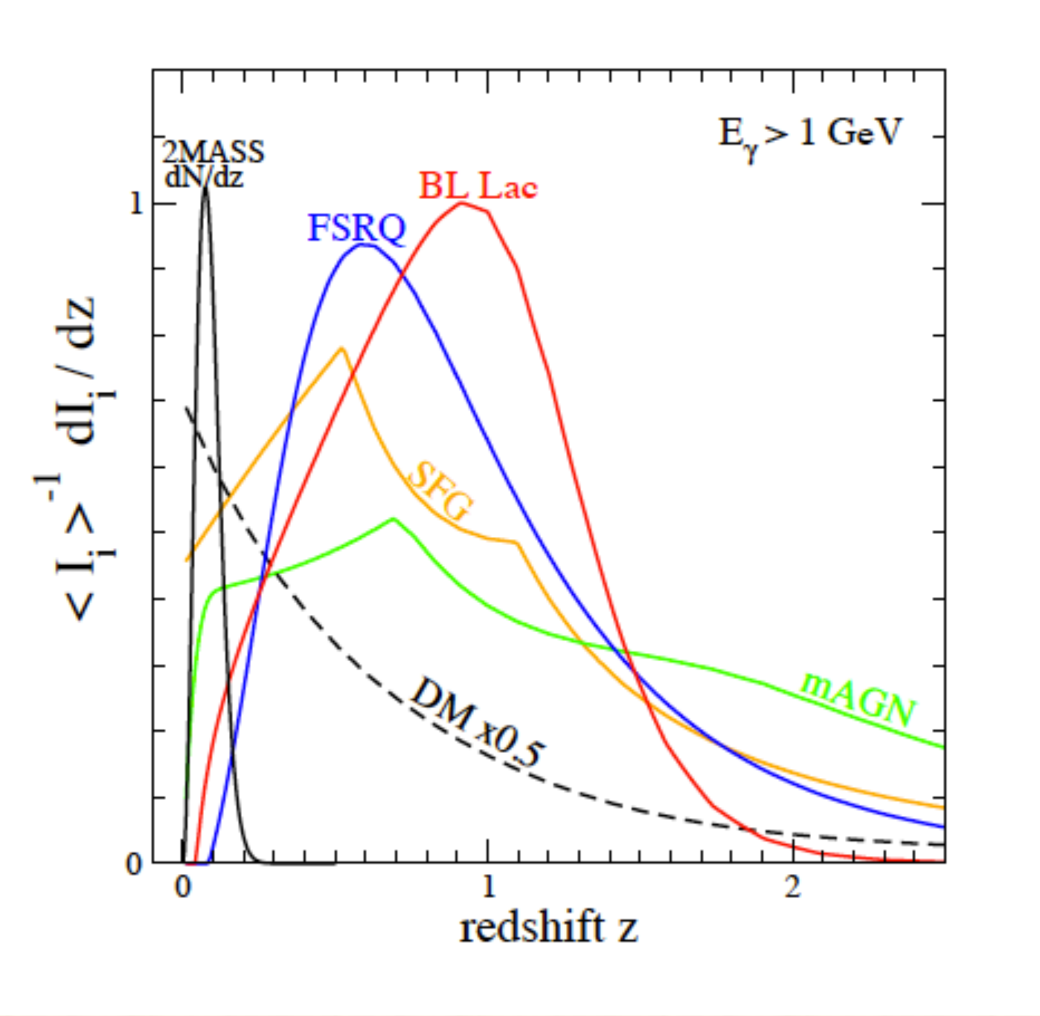
2MASS Galaxy catalog



- Anisotropies: Fornasa, Cuoco et al. PRD 2016, Cuoco, Komatsu, Gaskins, PRD 2012, Ando et al. PRD 2017
- Cross-correlations: Xia, Cuoco et al. ApjS 2015, Cuoco et al. APJS 2015, Regis, Xia, Cuoco et al. PRL 2015, Ando, JCAP 2014, Ando, Benoit-Levy, Komatsu PRD 2014, Troster et al. MNRAS 2017, Shirasaki et al. PRD 2018, Ammazzalorso et al. PRL 2020, Thakore et al. JCAP 2025

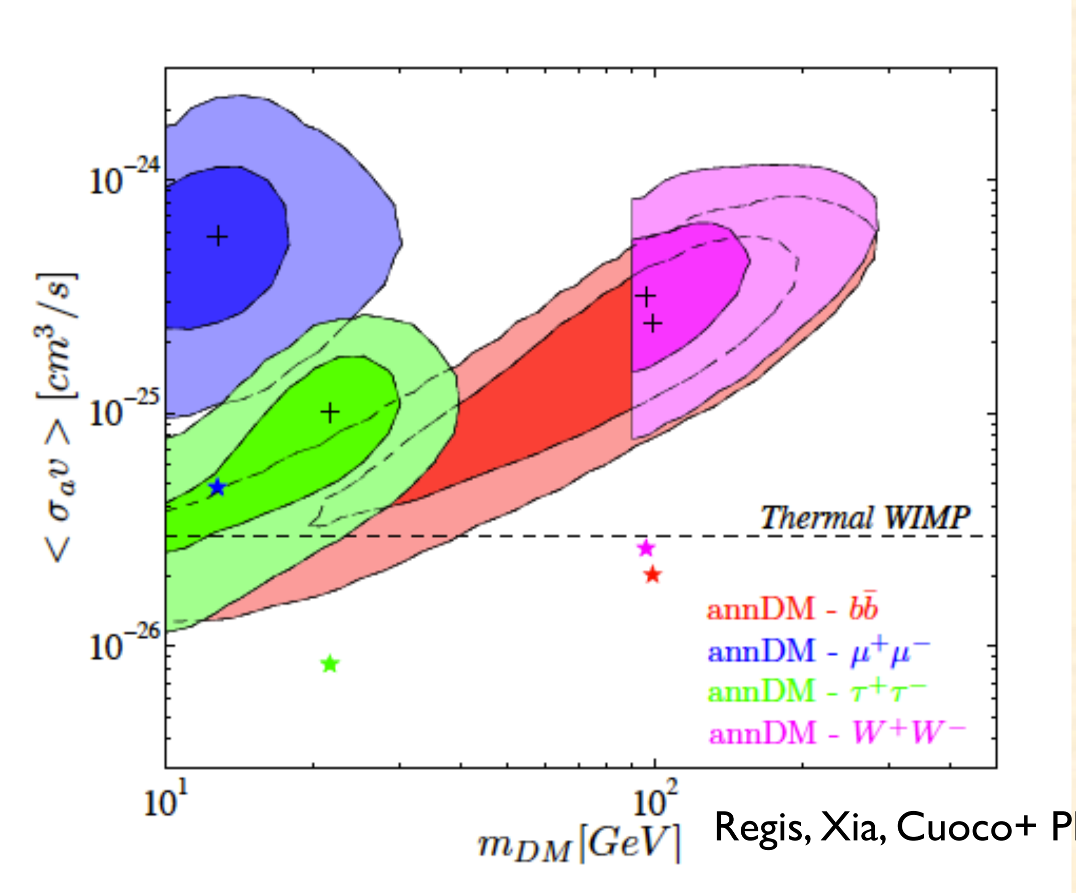
See also Bhashin Thakore's talk

IGRB redshift distribution



- Besides the energy spectrum, the various components differ also by their distribution in z. In particular DM is expected to peak at low redshift.
- Need to isolate the IGRB emission coming from different redshifts!

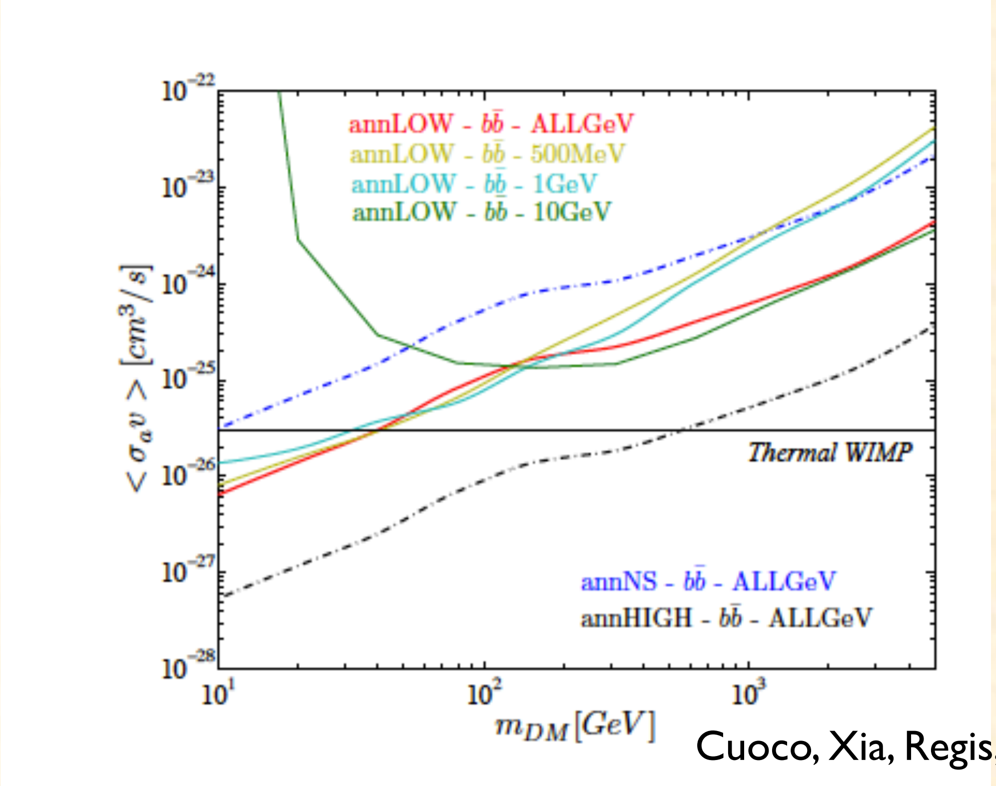
Dark Matter Interpretation



Regis, Xia, Cuoco+ PRL 2015

- A large DM contribution to the 2MASS correlation cannot be excluded, since, due to the peaking at low z, an high 2MASS correlation does not affect the correlations at higher z.
- A recent update, Ammazzalorso + 2018, finds that the 2MASS signal comes more likely from MAGNs, although a large DM component is still possible.

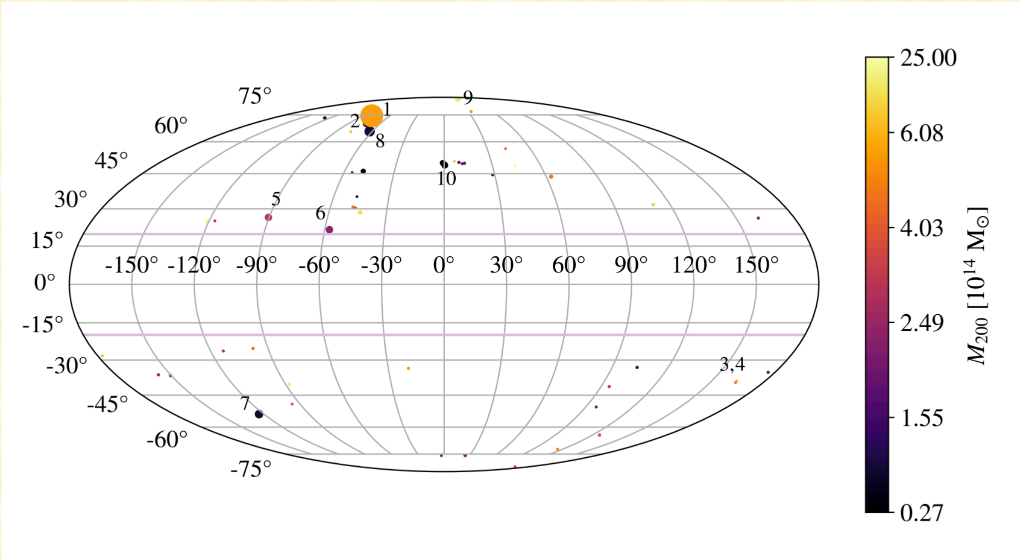
Dark Matter Constraints

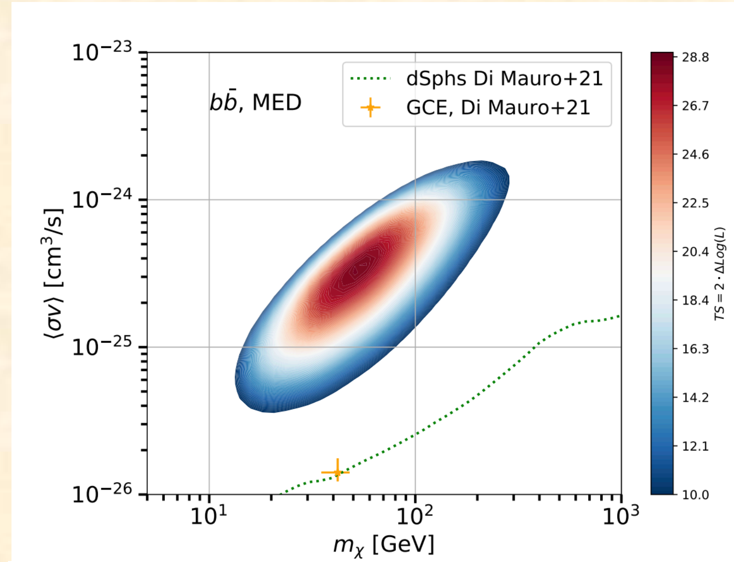


Cuoco, Xia, Regis,+ ApJS, 2015

- Limits on the DM contribution can be placed, although they depend on the DM Halo substructure modeling.
- They are, however, competitive even in the most conservative substructure boost scenario (i.e. no boost)

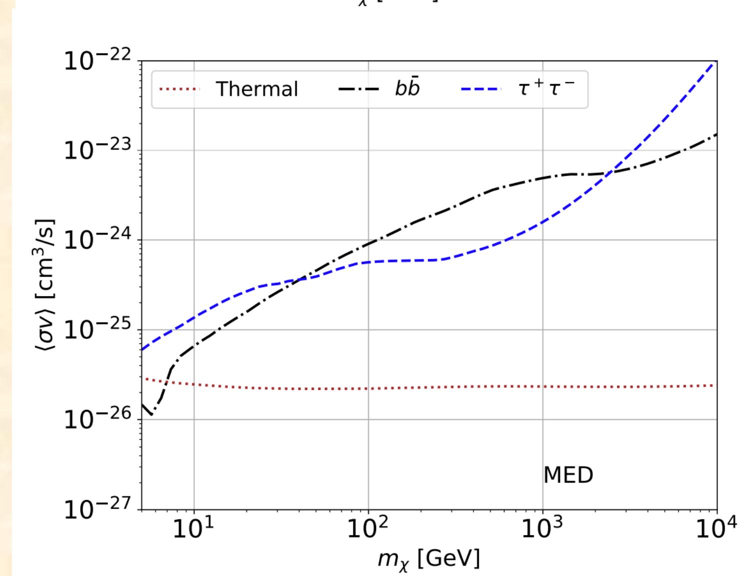
Galaxy Clusters





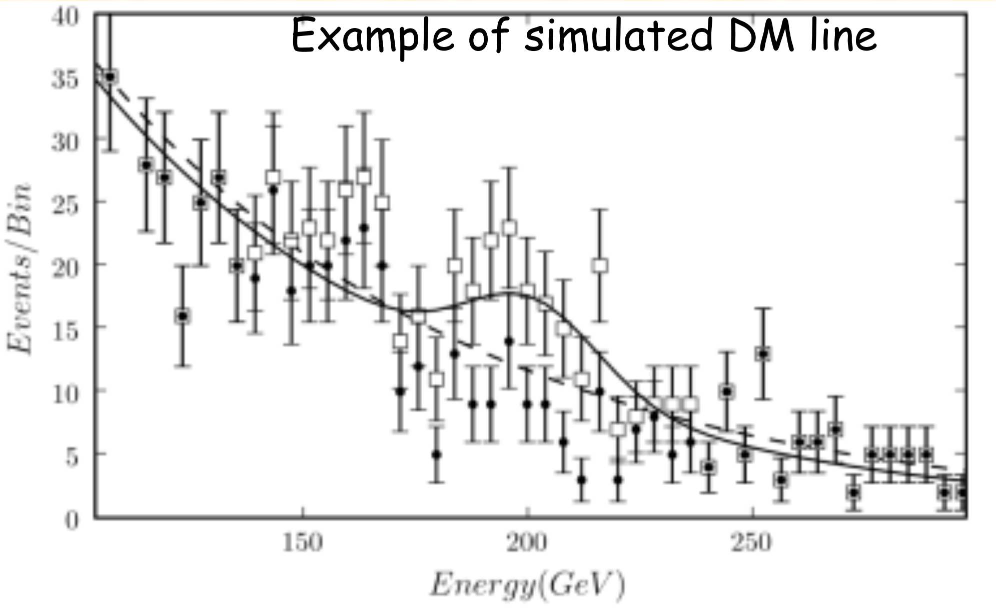
3 sigma evidence for a signal. DM or astro?

Stacking analysis of 49 clusters

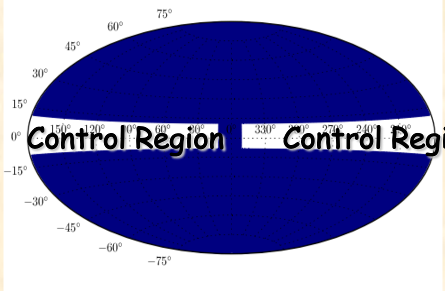


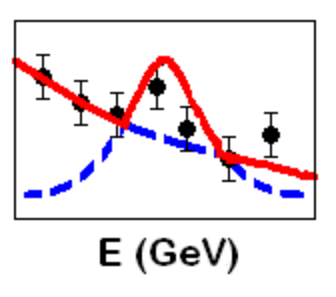
Di Mauro et al: PRD2023, Arxiv: 2303.16930

The Smoking Gun: a DM line



Limits from GC+high latitude sky
Control region along the GP



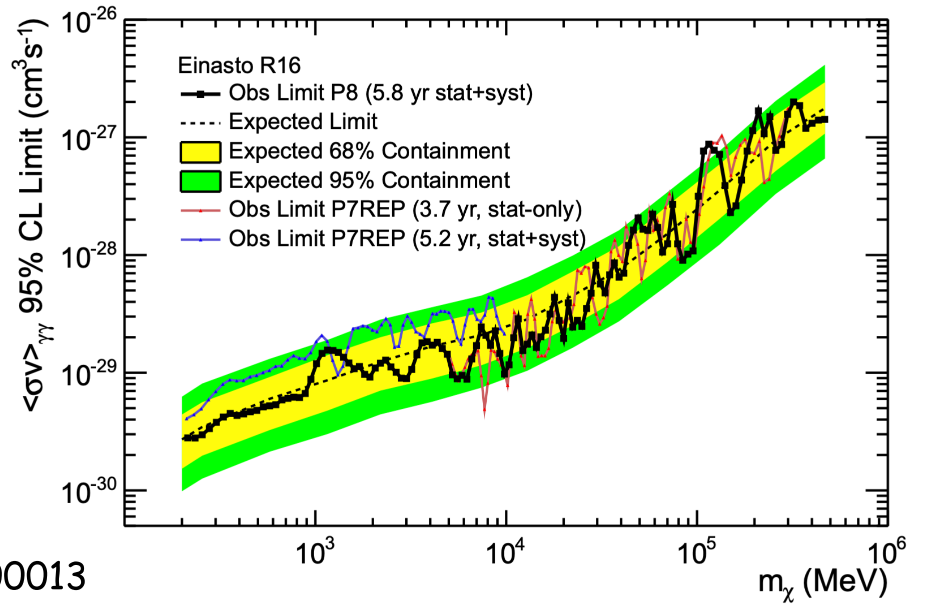


Advantages:

- No astrophysical source confusion
- Background determined from data.

Drawbacks:

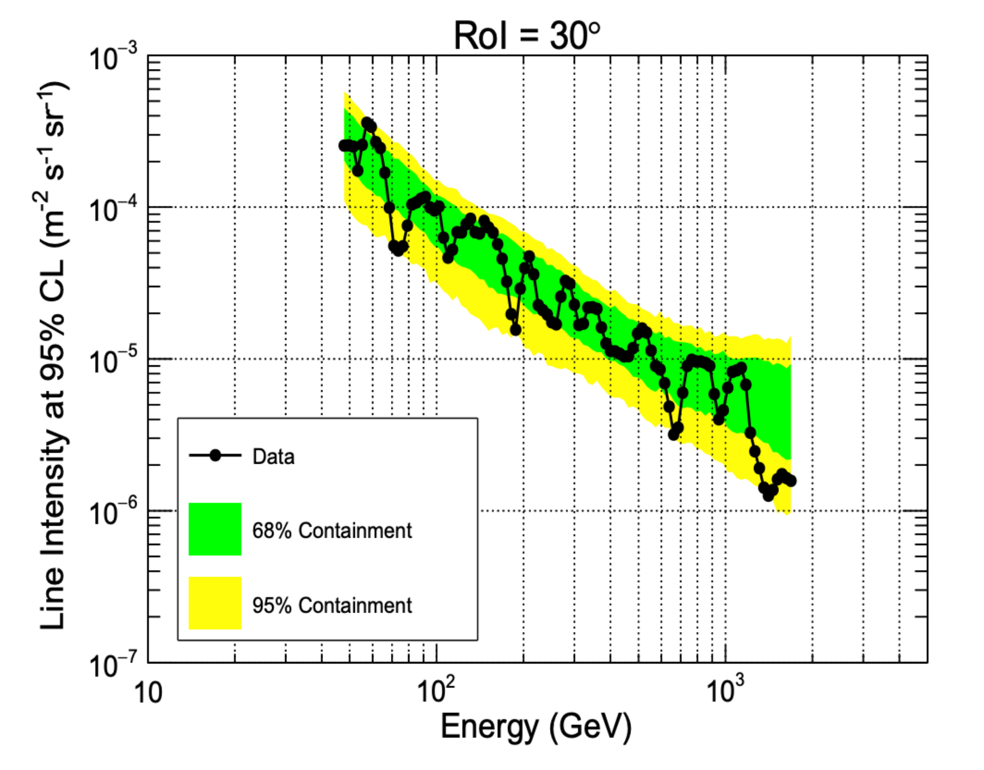
- Care required with the Instrument response
- Low branching ratios(?)



Fermi-LAT: PRD2015 Arxiv:1506.00013

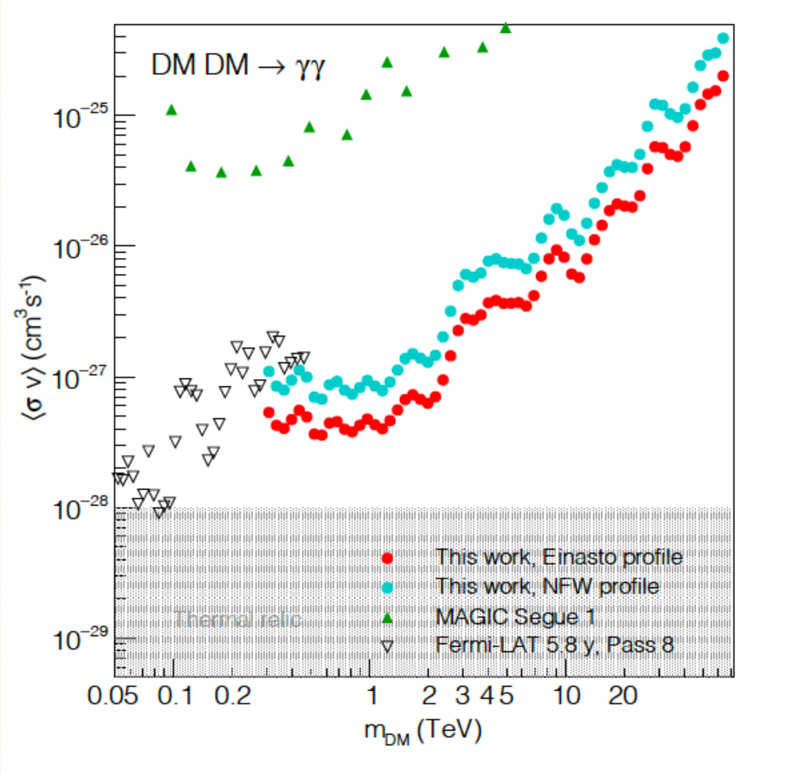
The Smoking Gun: a DM line

DM line from e+e- annihilation in the Sun



Cuoco et al: PRD2020, Arxiv:1912.09373

Combined gamma-ray line from Fermi-LAT and HESS

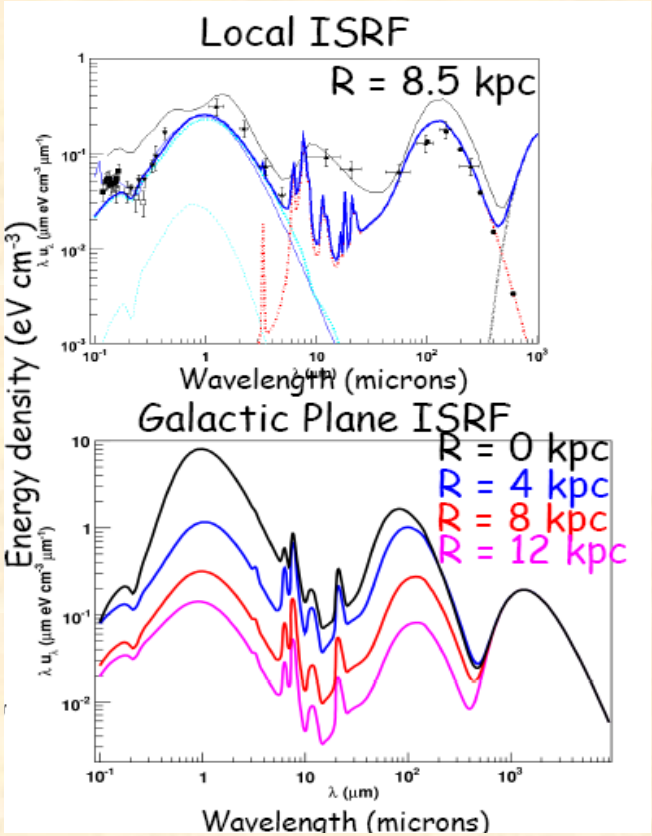


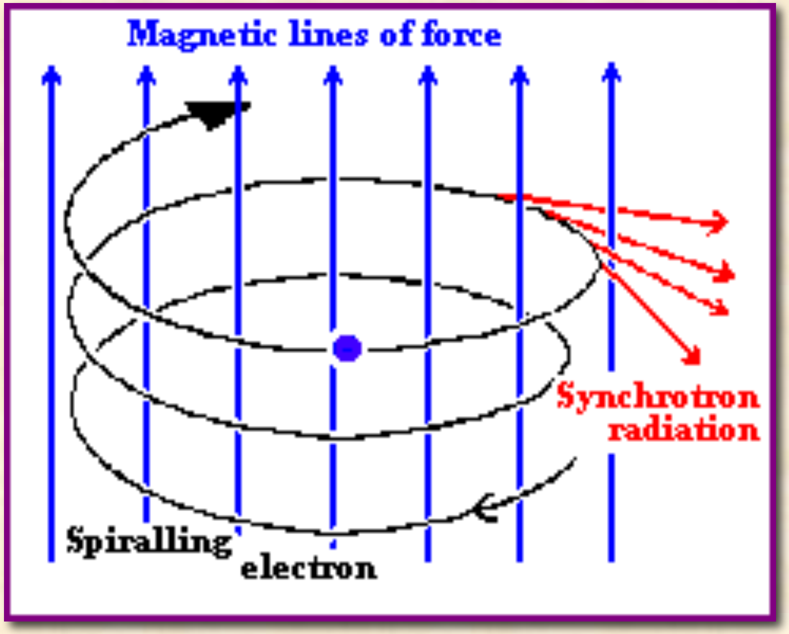
HESS Collaboration, PRL2018, arXiv:1805.05741

Indirect Detection With Synchrotron and Inverse Compton Radiation

ICS on the Galactic ISRF

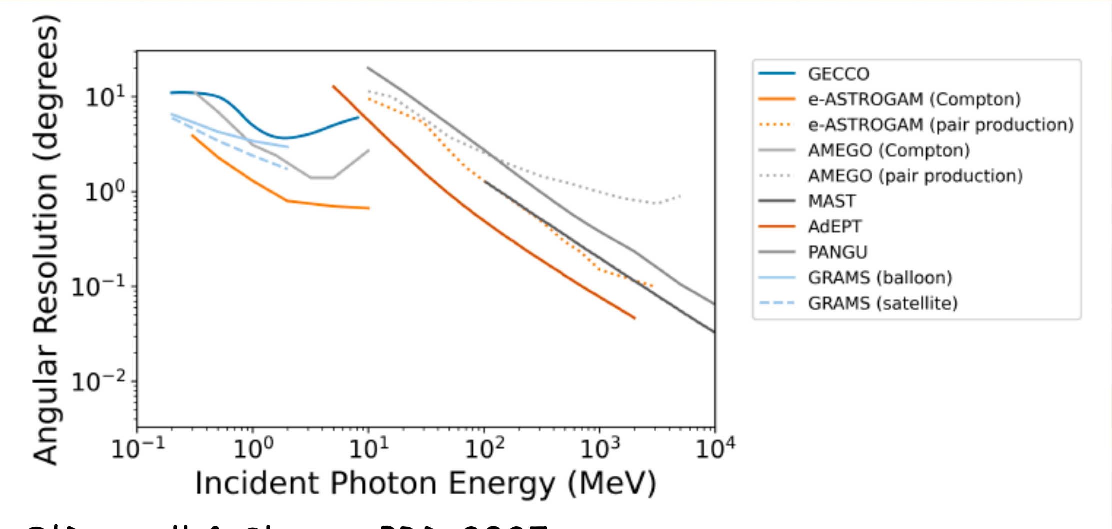
Synchrotron on the GMF



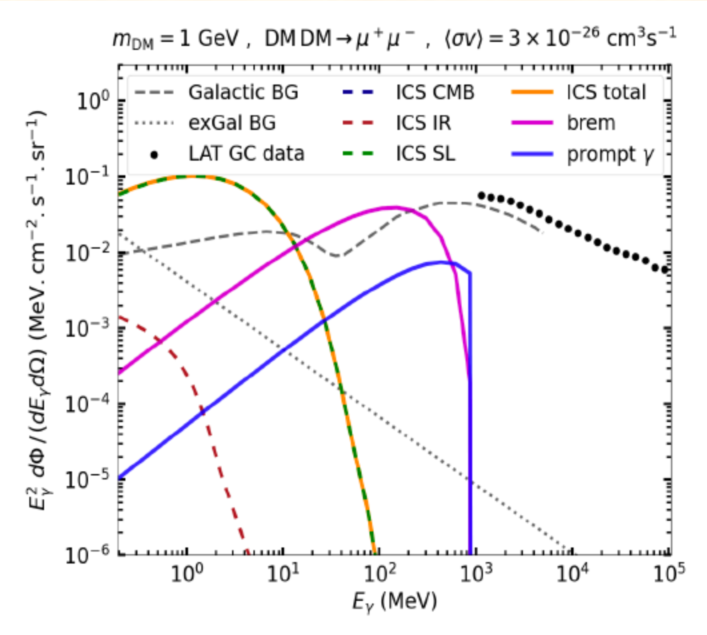


- Charged leptons and nuclei strongly interact with gas, Interstellar Radiation and Galactic Magnetic Field.
- During the process of thermalization HE e+e− release secondary low energy radiation, in particular in the radio and X-ray/soft Gamma band.

The MeV Gap



O'Donnell & Slatyer PRD 2025



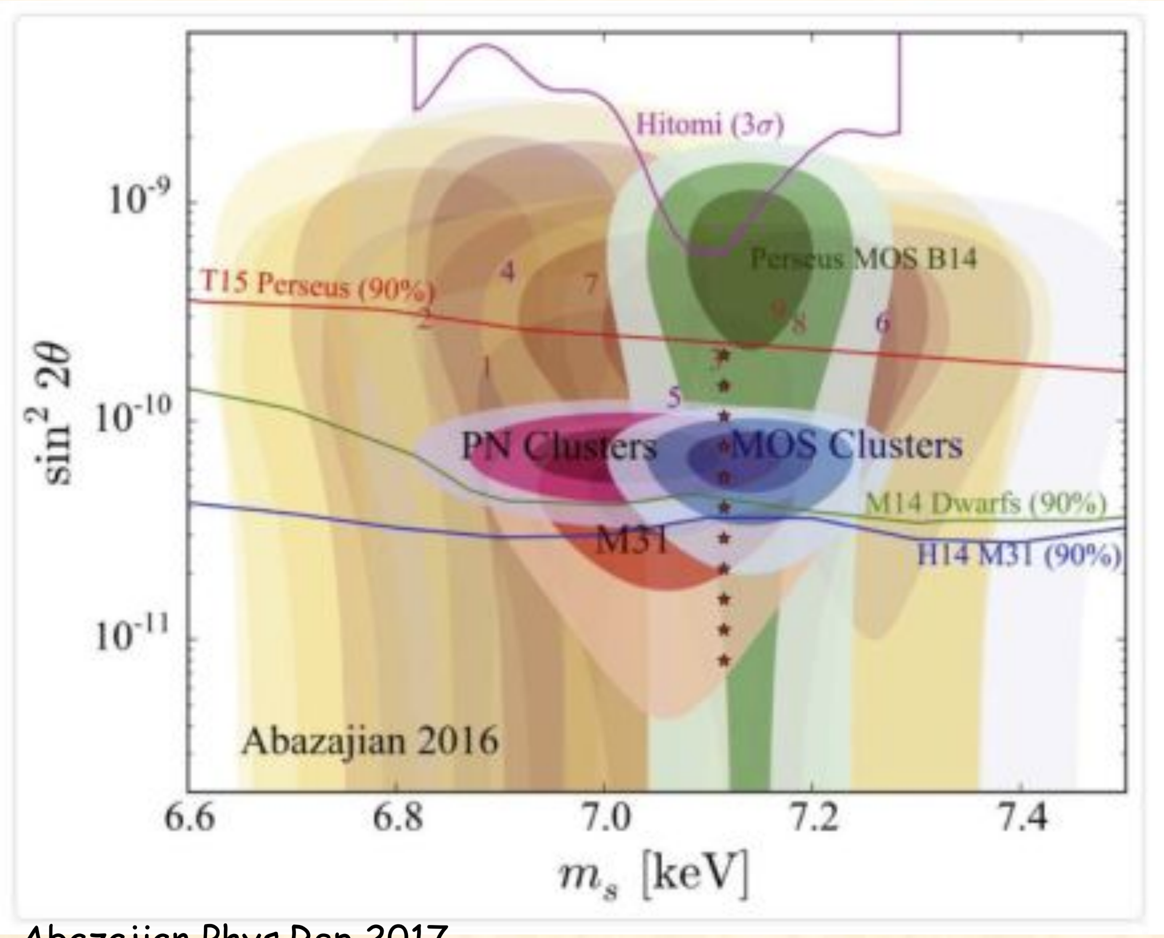
Cirelli & Arpan ArXiv:2503.04907

The MeV region is challenging for detection techniques and not well explored.

To fill the gap several MeV missions are foreseen in the next few years

DM emission in the MeV is expected from ICS and Synchrotron emission or from prompt emission from light (< 1 GeV) DM.

DM in X-rays

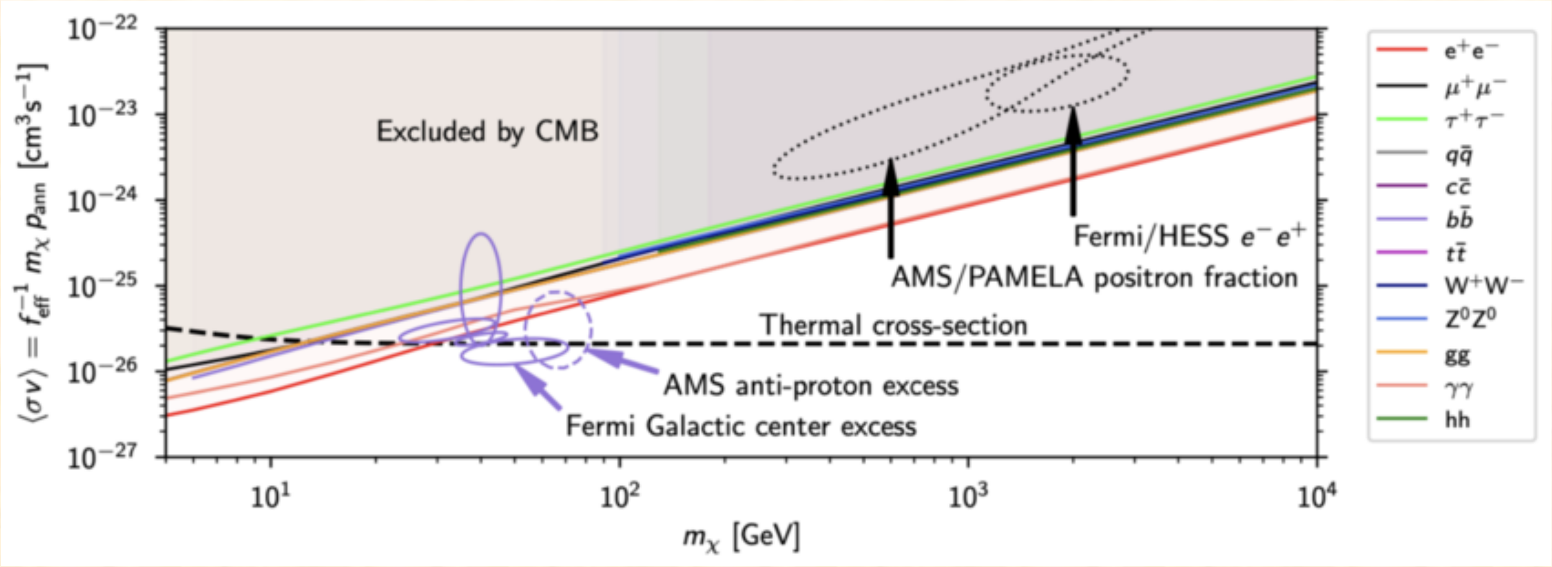


Abazajian Phys.Rep 2017

A line in x-rays at 3.5 KeV is observed in various clusters pointing at Sterile neutrino DM explanation of 7 KeV.

Bulbul et al. ApJ 2014
Boyarsky et al. PRL 2014

CMB Constraints

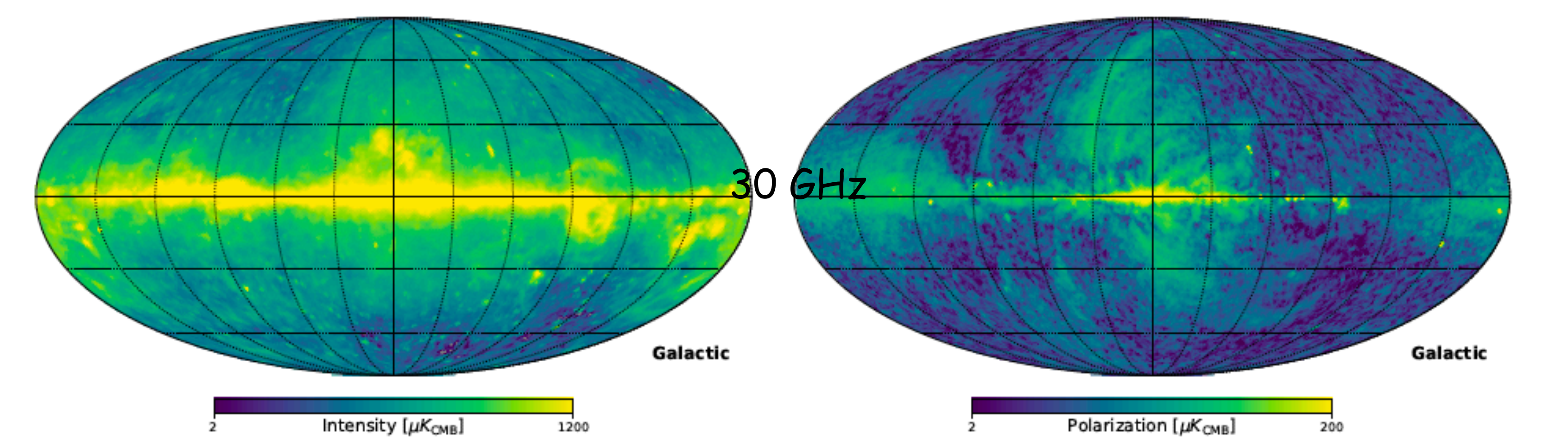


Planck Collaboration A&A2020,641,A6,
Arxiv: 1807.06209

DM annihilation during the recombination (CMB formation) era (z ~1100) causes distortions in CMB power spectrum, which provide constrains comparable to gamma-ray observations

See Tracy Slatyer's Talk

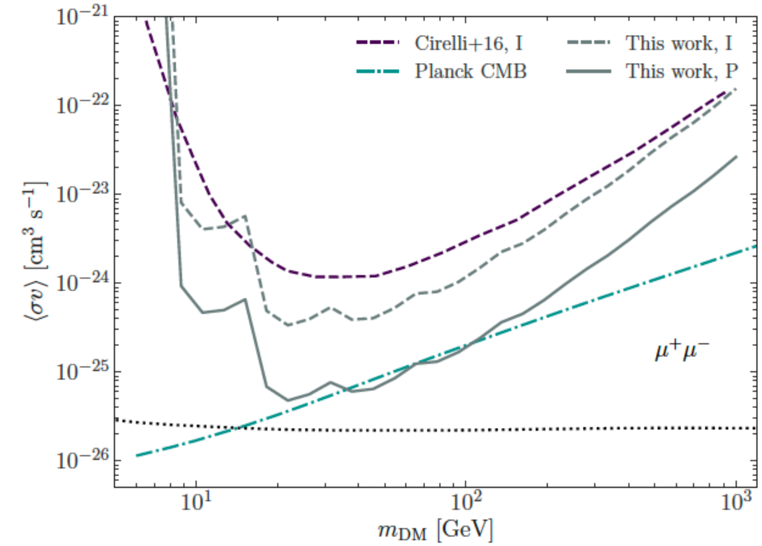
DM constraints from Planck Polarized Synchrotron emission



Manconi, Cuoco, Lesgourgues, PRL 2022,
Arxiv: 2204.04232

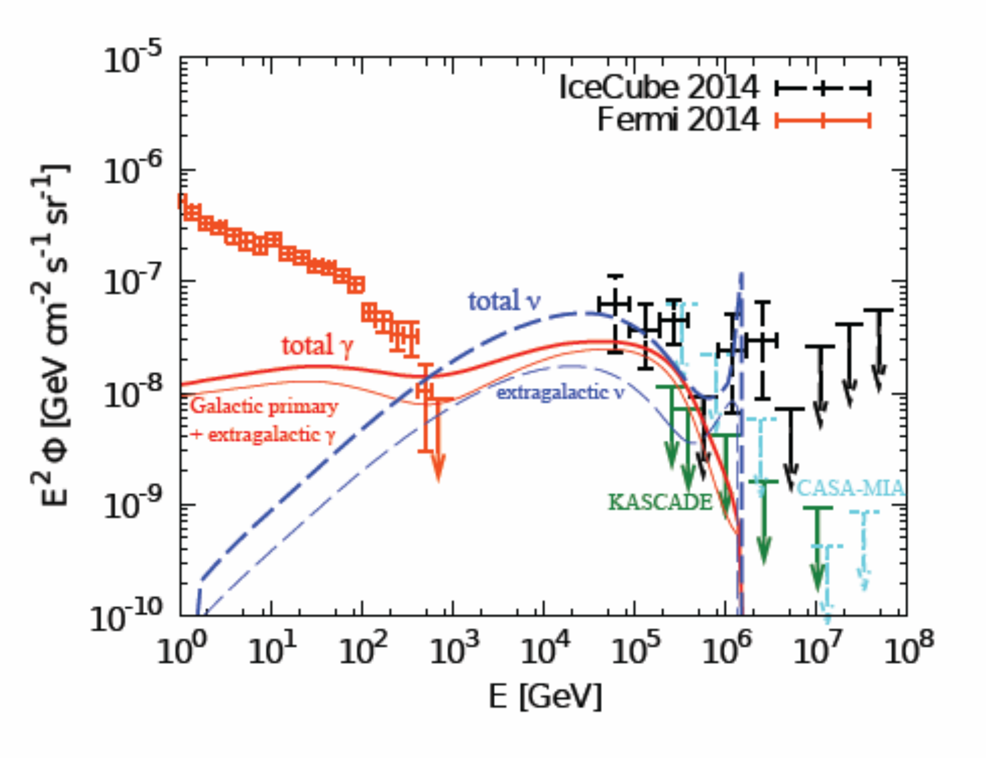
Updated all-sky radio polarization data are available from Planck measuremnets.

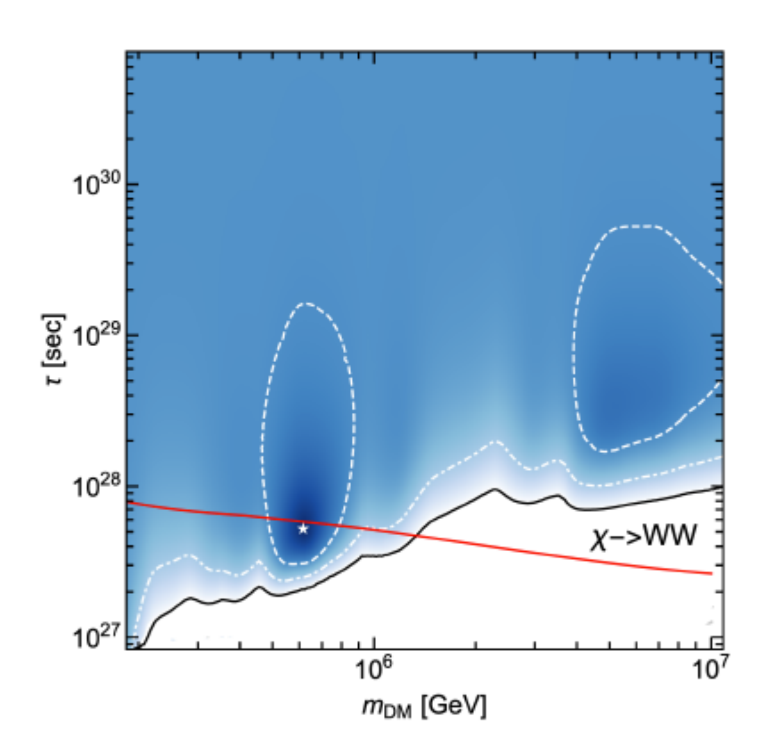
We use these measurements to derive conservative DM constraints requiring that the DM signal does not exceed the observed emission



Neutrinos

Icecube Diffuse and DM





Feldstein et al. PRD 2013, Esmaili & Serpico JCAP 2013,
Zavala PRD 2014, Murase et al. PRL 2015
IceCube Collab Eur.Phys.J. 2018.
Bhattacharya et al. JCAP 2019

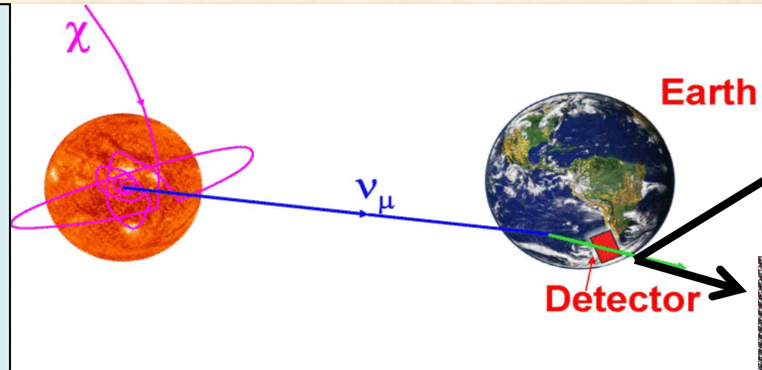
Chianese et al. 2019 arXiv:1907.11222
Cohen et al. PRL 2017
Ishiwata et al. ArXiv:1907.11671

- An interesting possibility is that part of the PeV diffuse neutrino emission observed by ICECube is due to PeV DM
- The result is constrained by the accompanying gamma ray emission

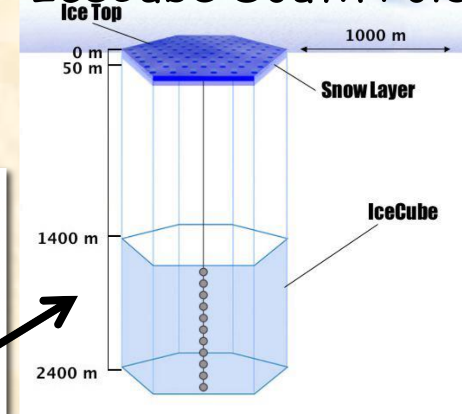
Neutrinos from annihilation in the core of the Sun

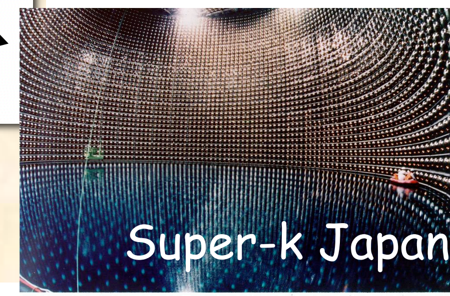
•Limits on the Spin-Dependent Cross Section from IceCube and Super-K are complementary to direct detection experiments on Earth.

•Neutrinos from the Sun might be soon detected. In this case be aware of Solar Corona Neutrinos!

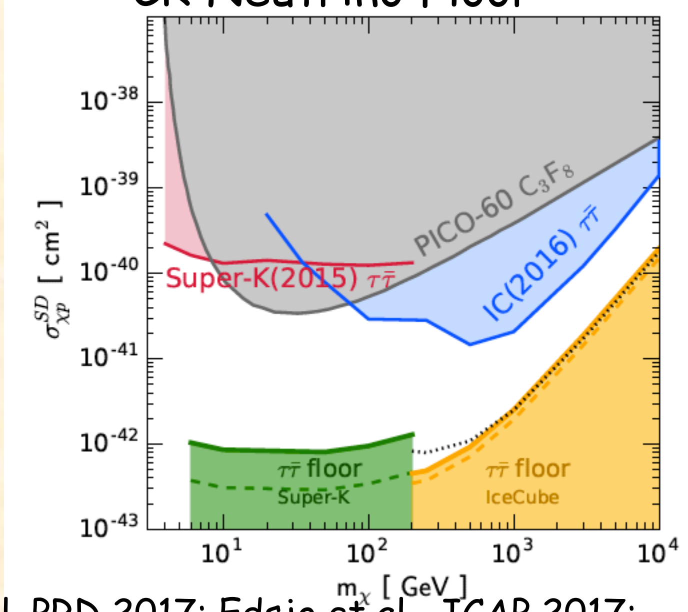


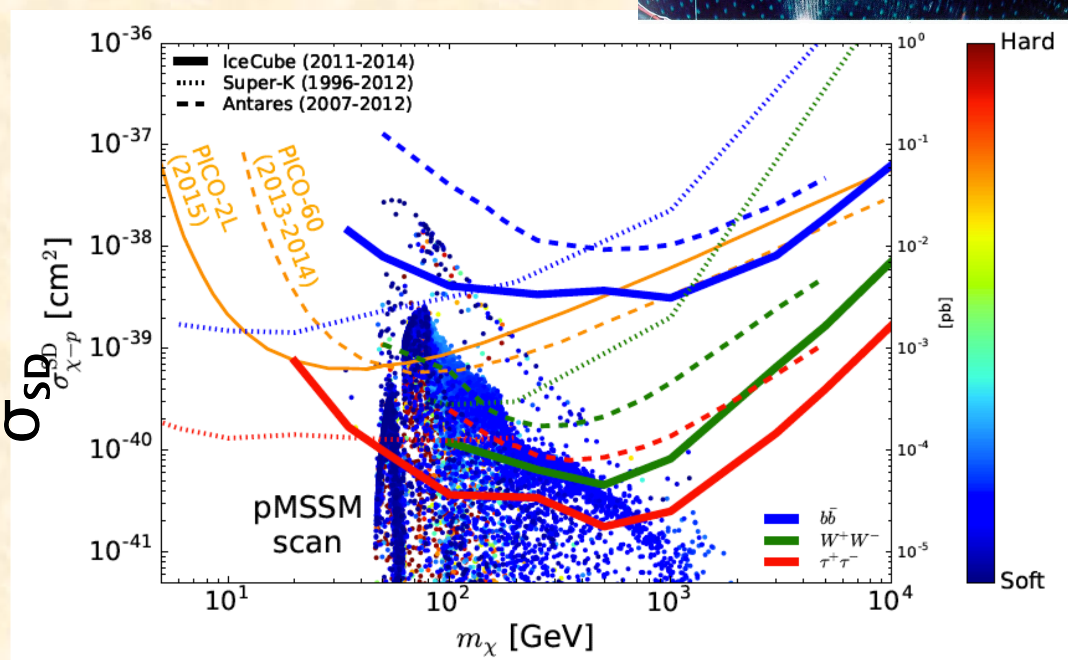
IceCube South Pole





CR Neutrino Floor





r al. PRD 2017; Edsjo et al., JCAP 2017;
elles et al. JCAP 2017

AArtsenet al., ICECube Collaboration EPJC 2017

Thanks!