WIMP Dark Matter

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Summer Institute'26
Fujiyoshida
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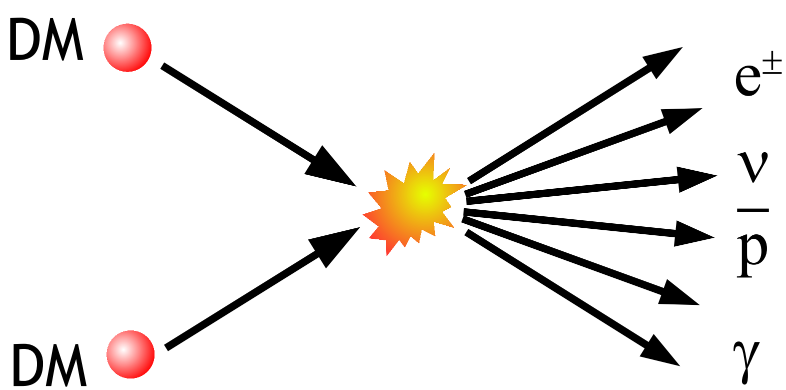
gamma-rays from DM annihilation

The gamma ray flux from dark matter annihilations/decays has two components:

- Prompt radiation of gamma rays produced in the annihilation/decay (final state radiation, pion decay...)
- May contain spectral features.

- Inverse Compton Scattering radiation of electrons/positrons produced in the annihilation/decay.
- Always smooth spectrum.



$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma^{*}$$

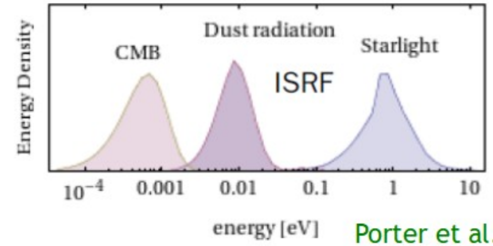
$e^{\pm}$ from dark matter annihilation/decay
$E_e \sim 1\,\mathrm{TeV}$

Interstellar radiation field (starlight, thermal radiation of dust, CMB)

Upscattered photon

$$E_{\gamma^*} \leq 4\left(\frac{E_e}{m_e}\right)^2 E_\gamma$$

This produces
$E_{\gamma^*} \lesssim 100\,\mathrm{GeV}$



Porter et al.

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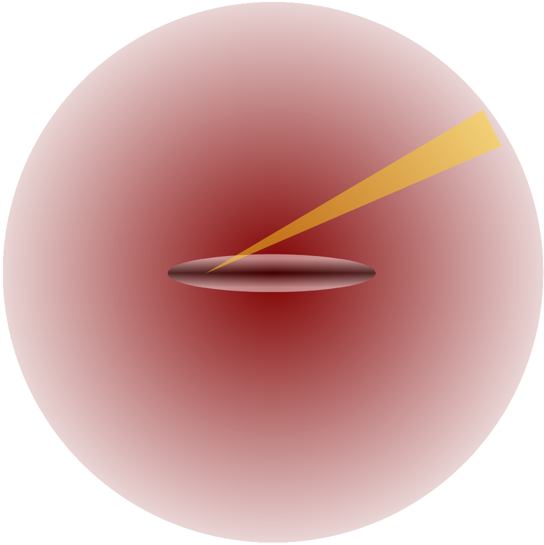
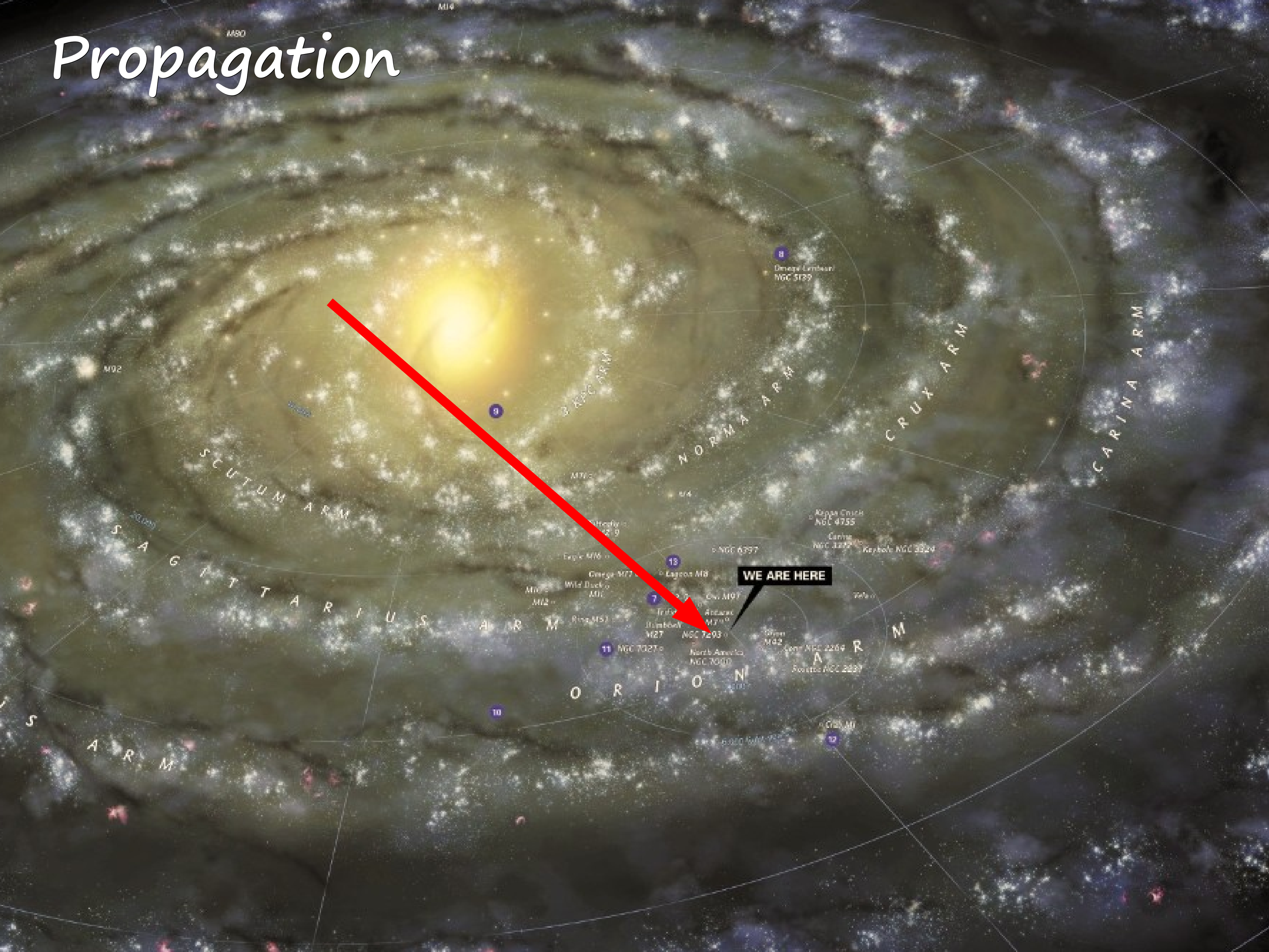


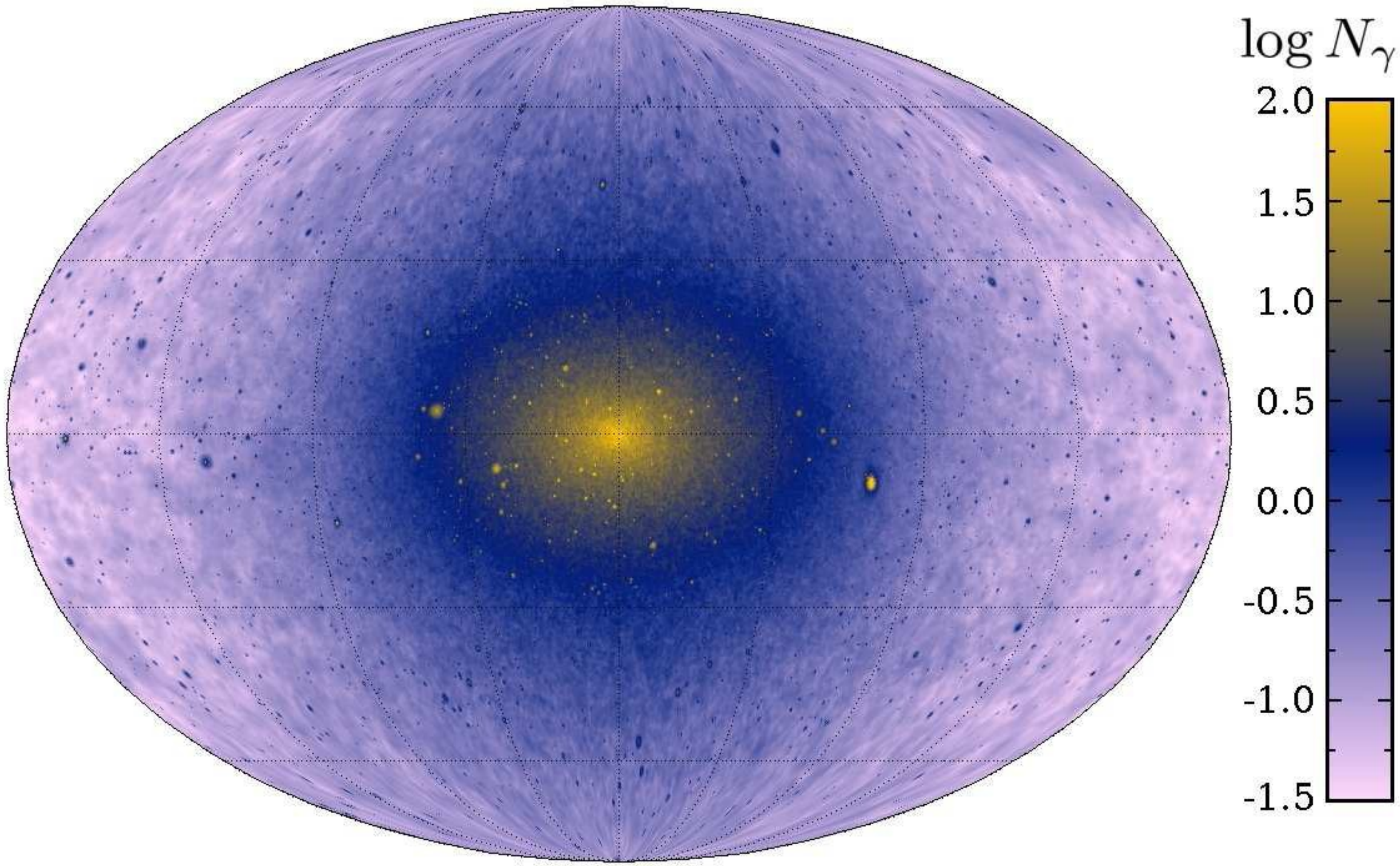
Integrate over the line of sight

Propagation



Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911



Kuhlen, Diemand, Madau

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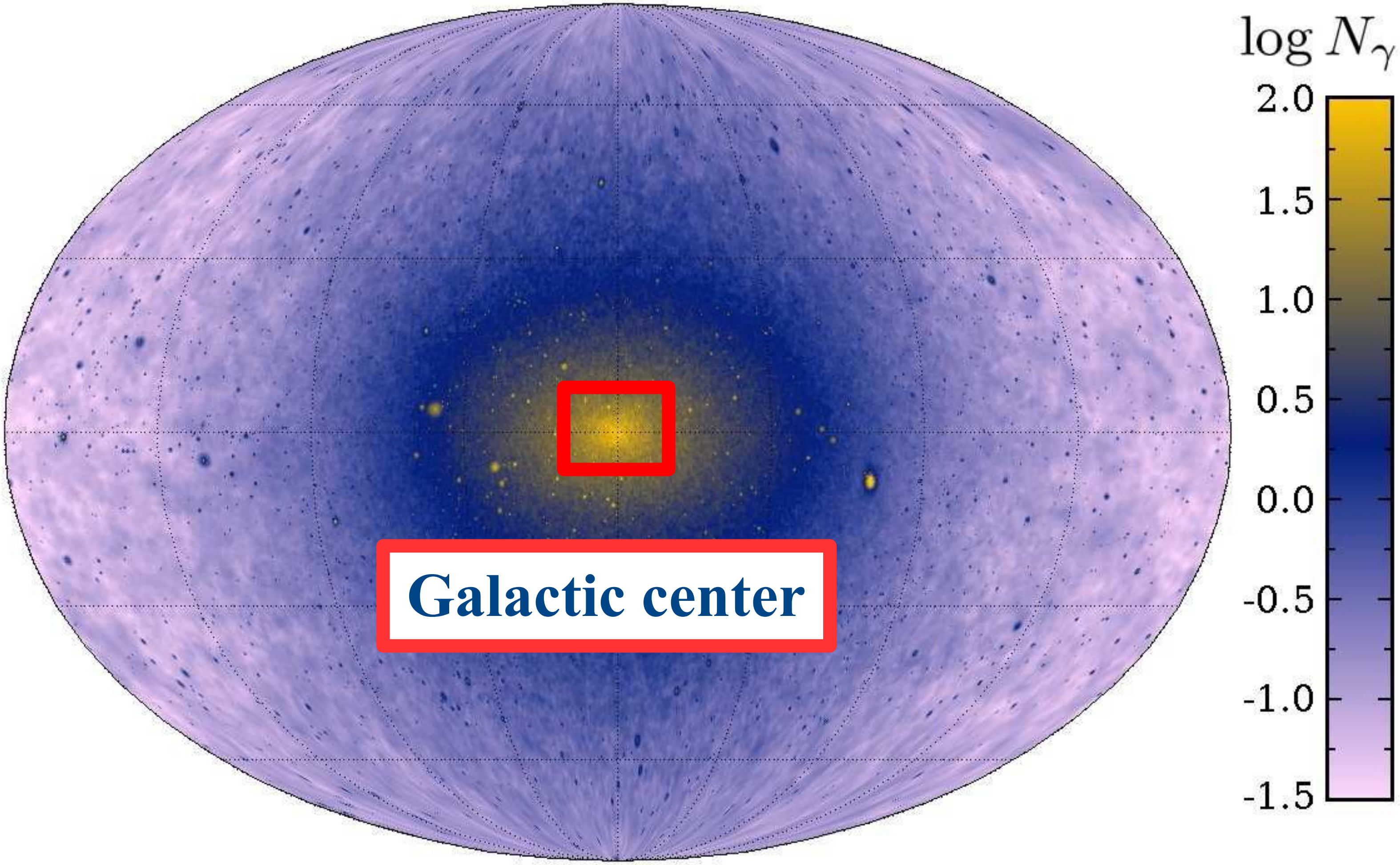

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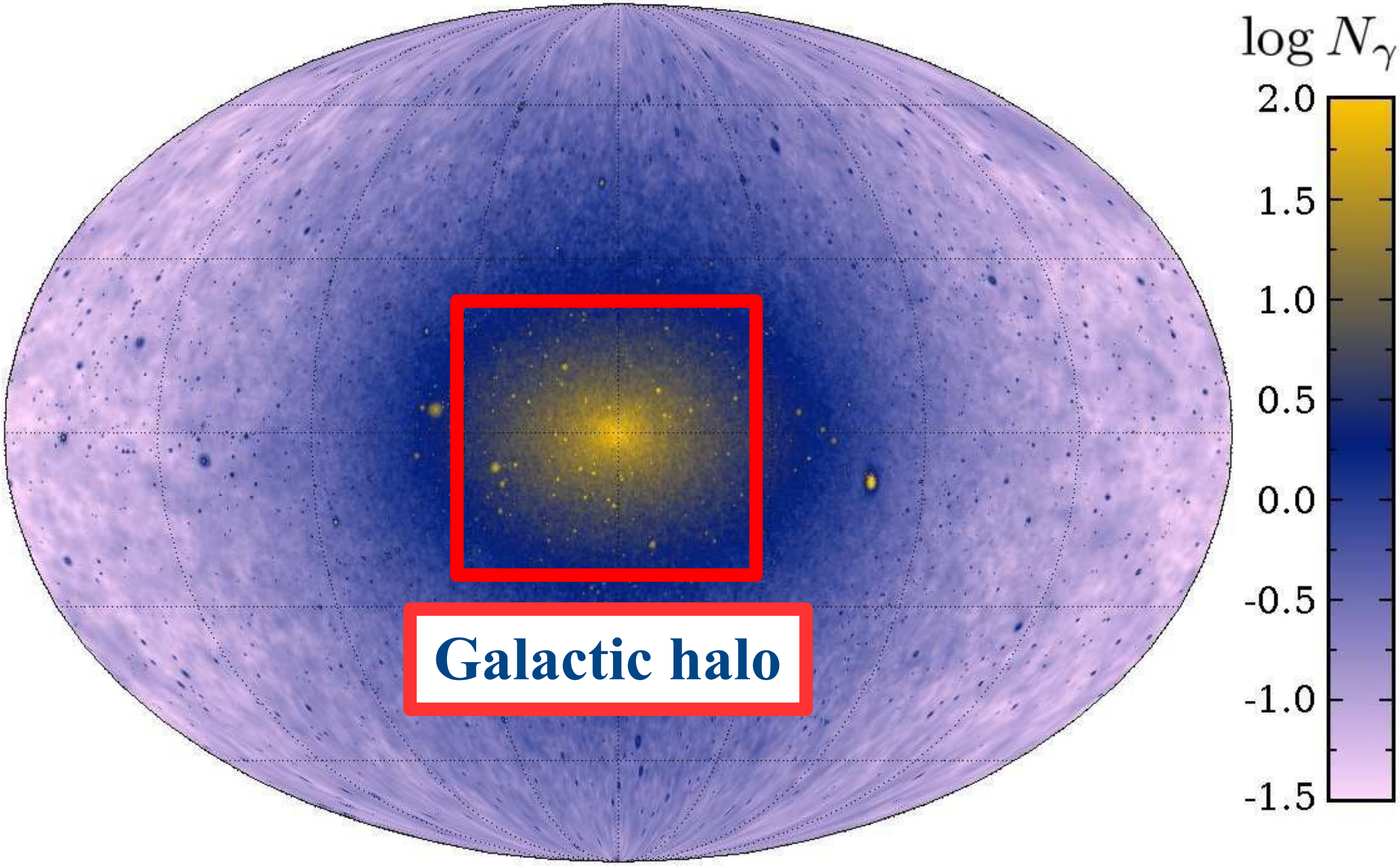

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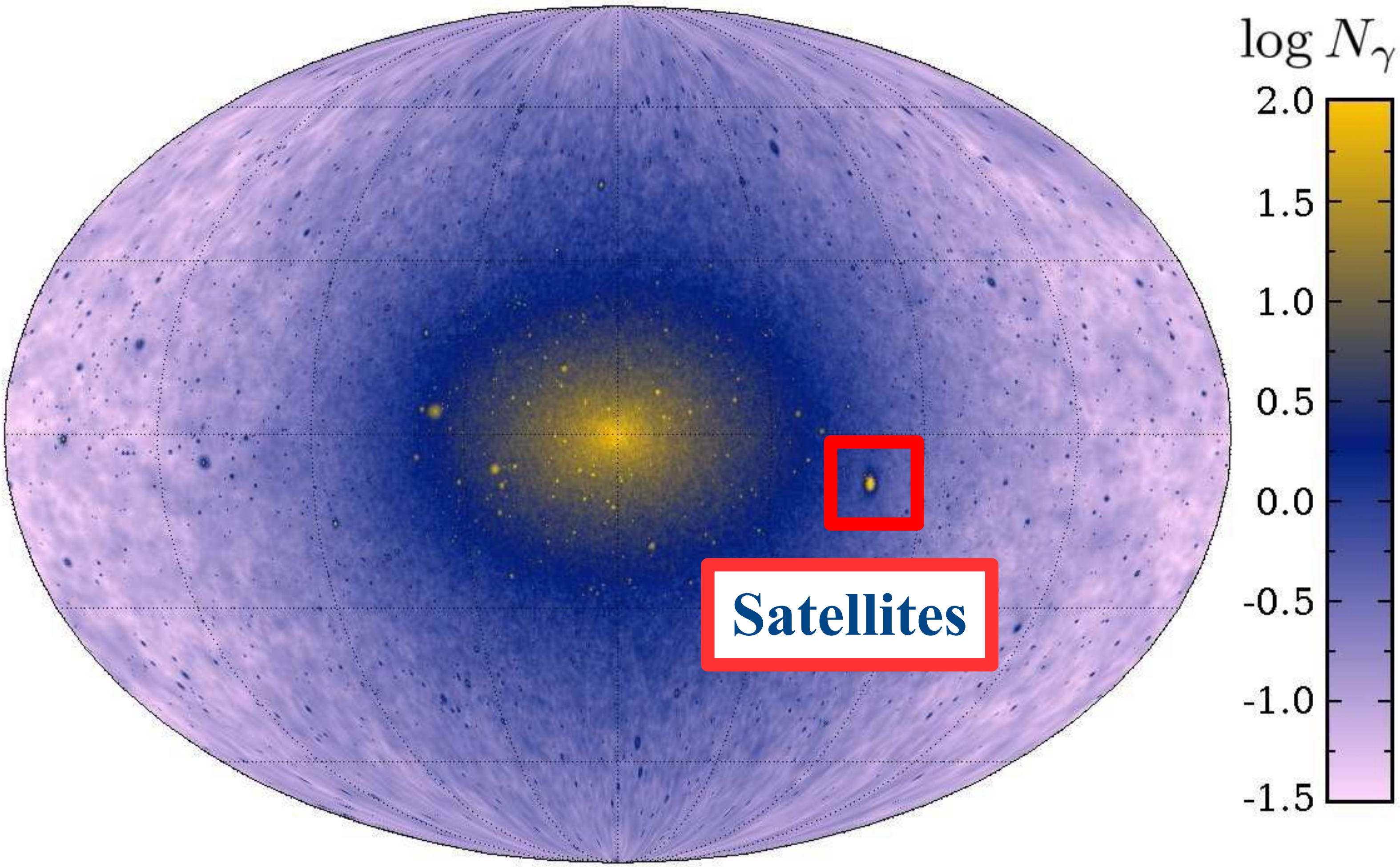

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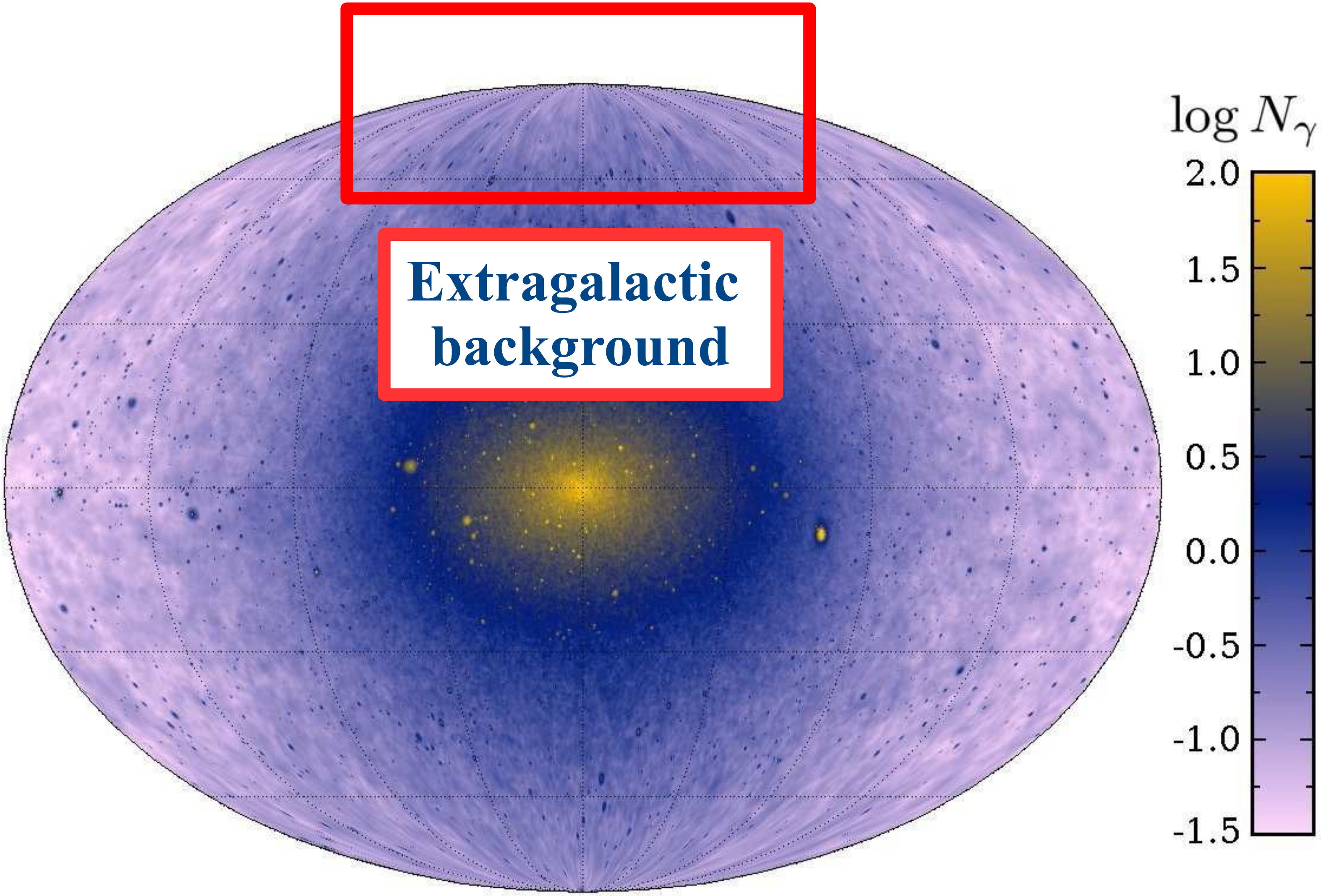

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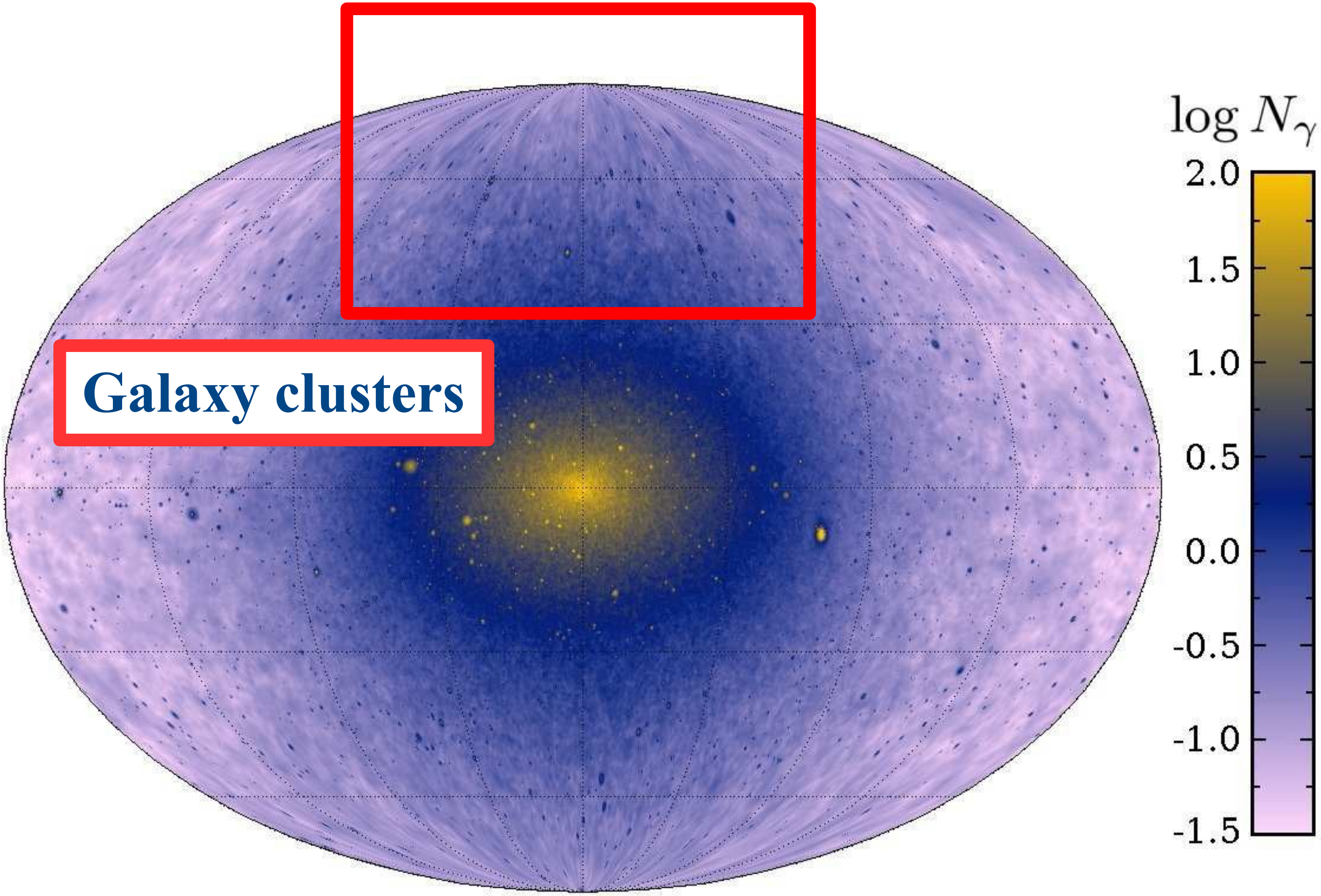

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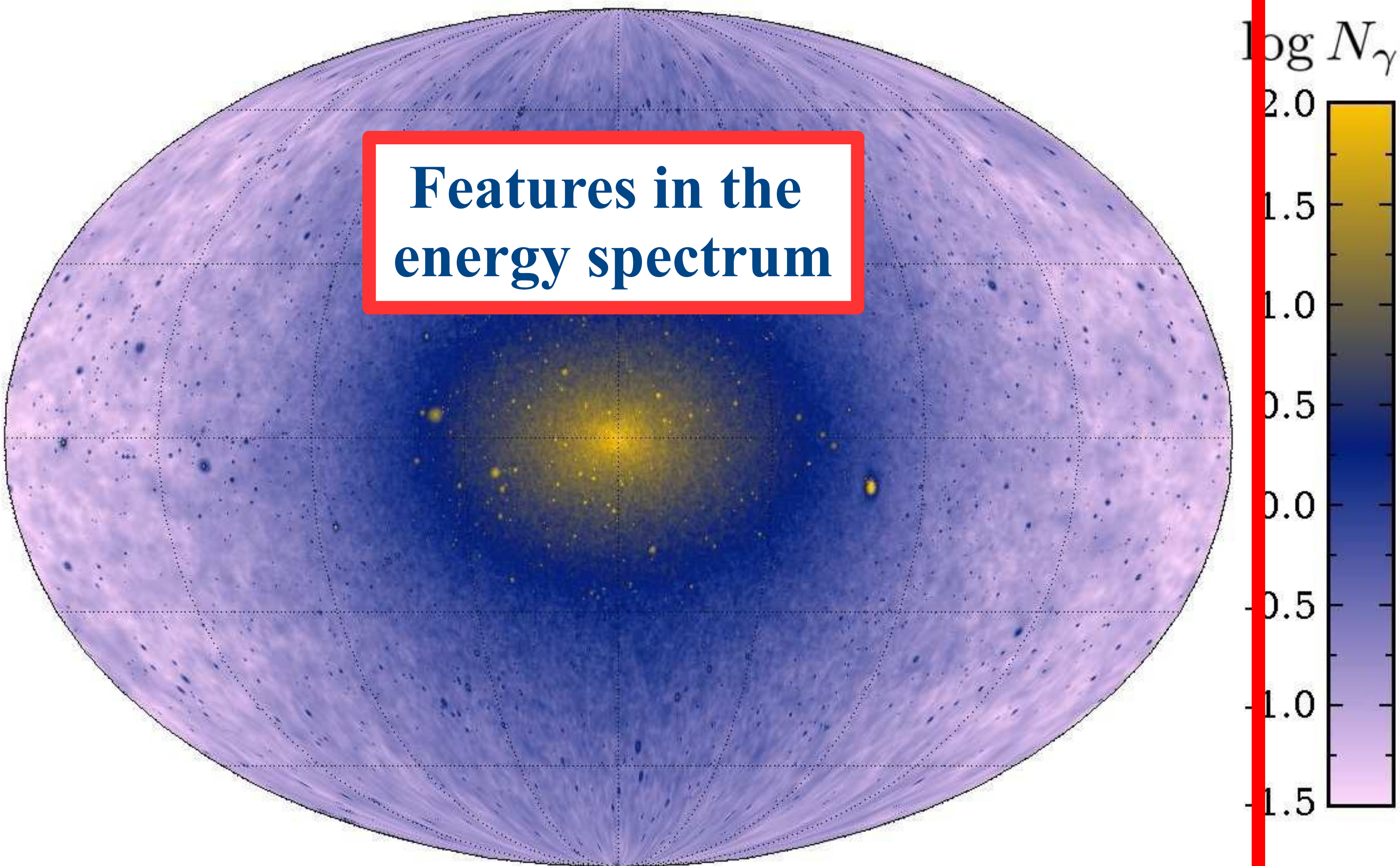
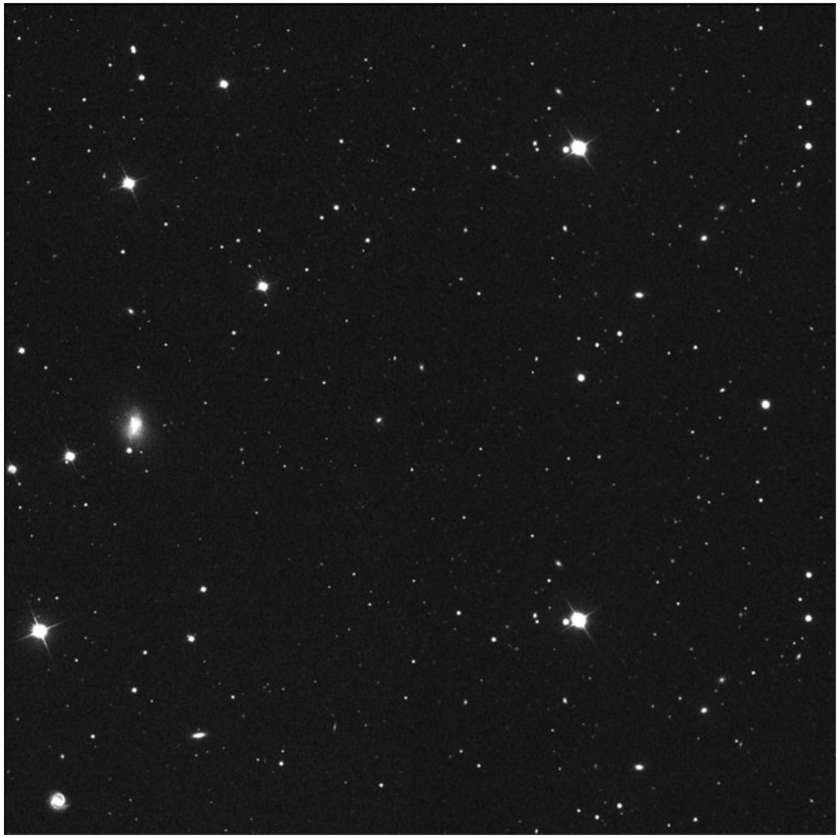


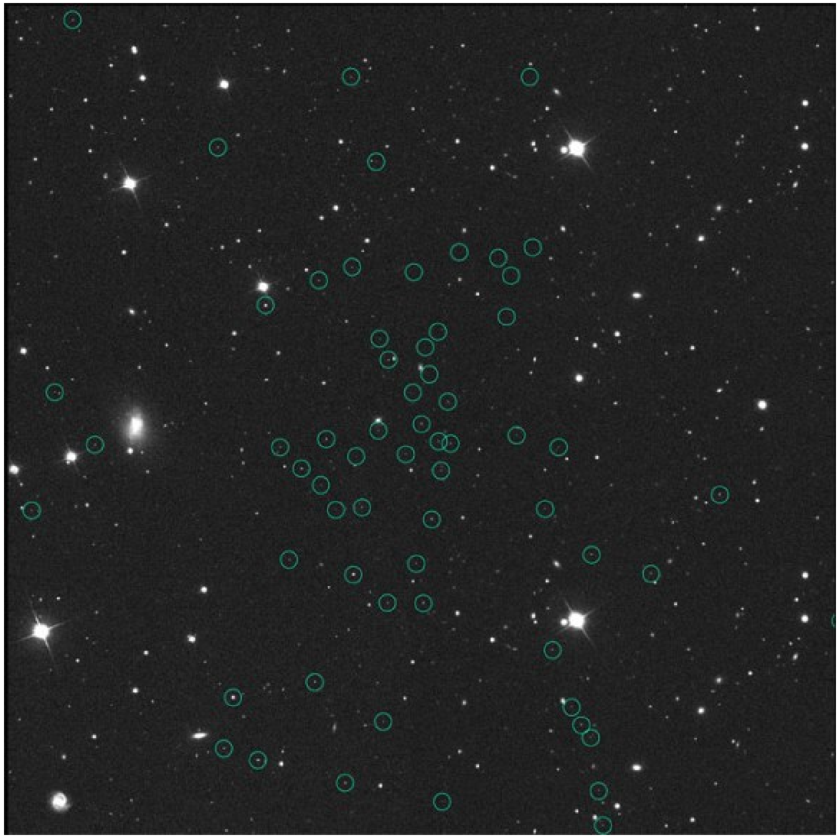
Kuhlen, Diemand, Madau

A promising target for detection: dwarf galaxies



Segue 1: Optical image

A promising target for detection: dwarf galaxies



Segue 1: Optical image

A promising target for detection: dwarf galaxies

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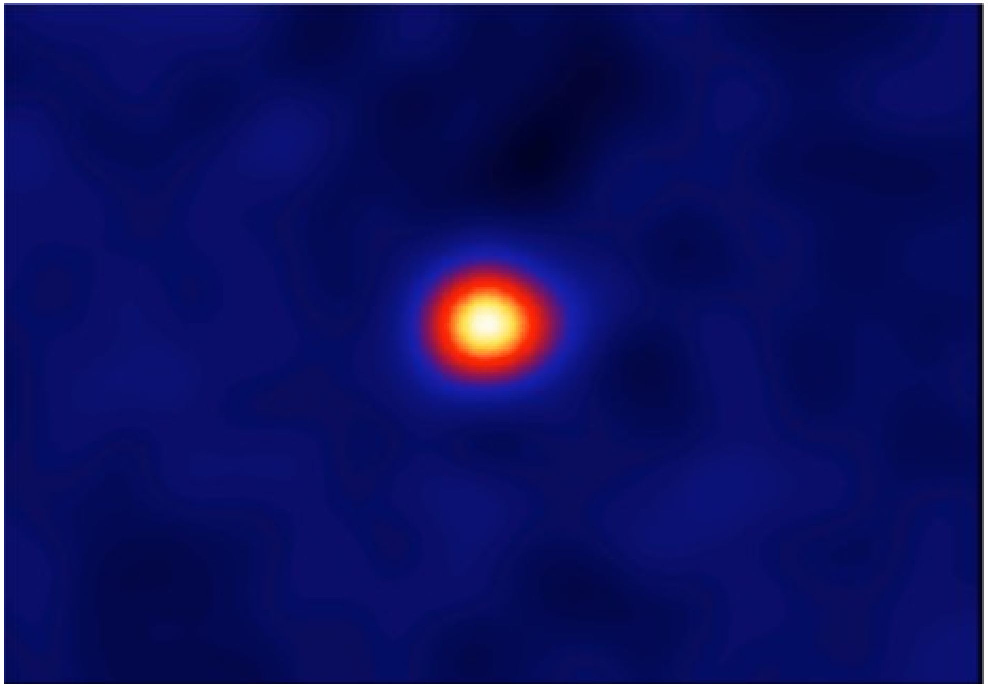
Segue 1: Optical image

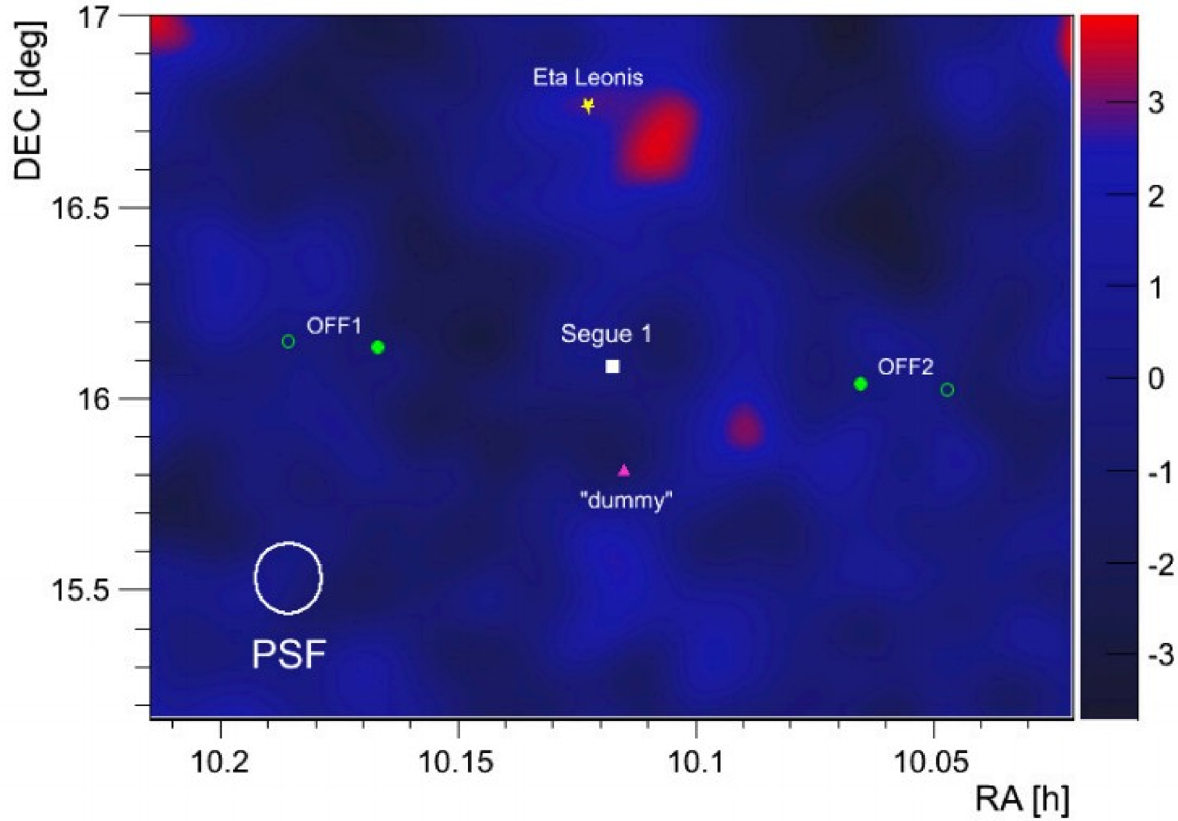
Mass-to-light ratio
~ 3400 M_{sun}/L_{sun}
Most DM-dominated object known so far!

A promising target for detection: dwarf galaxies



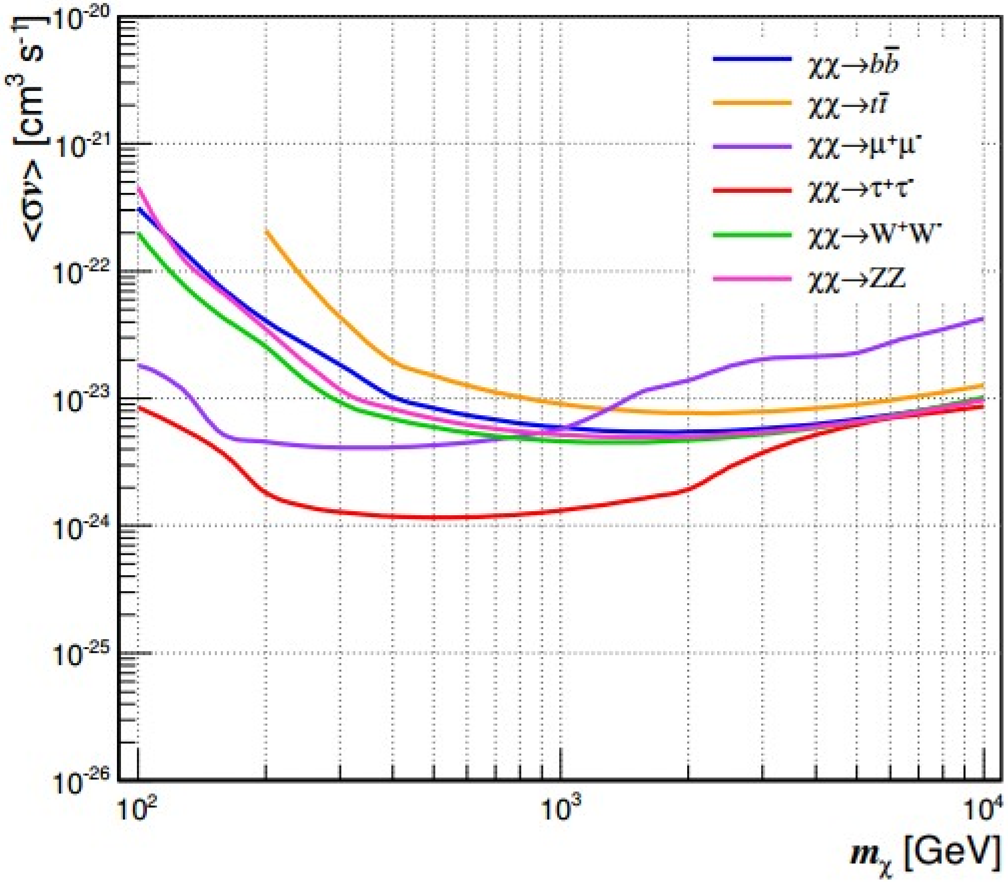
Segue 1: Gamma-ray image
(simulated!)

A promising target for detection: dwarf galaxies



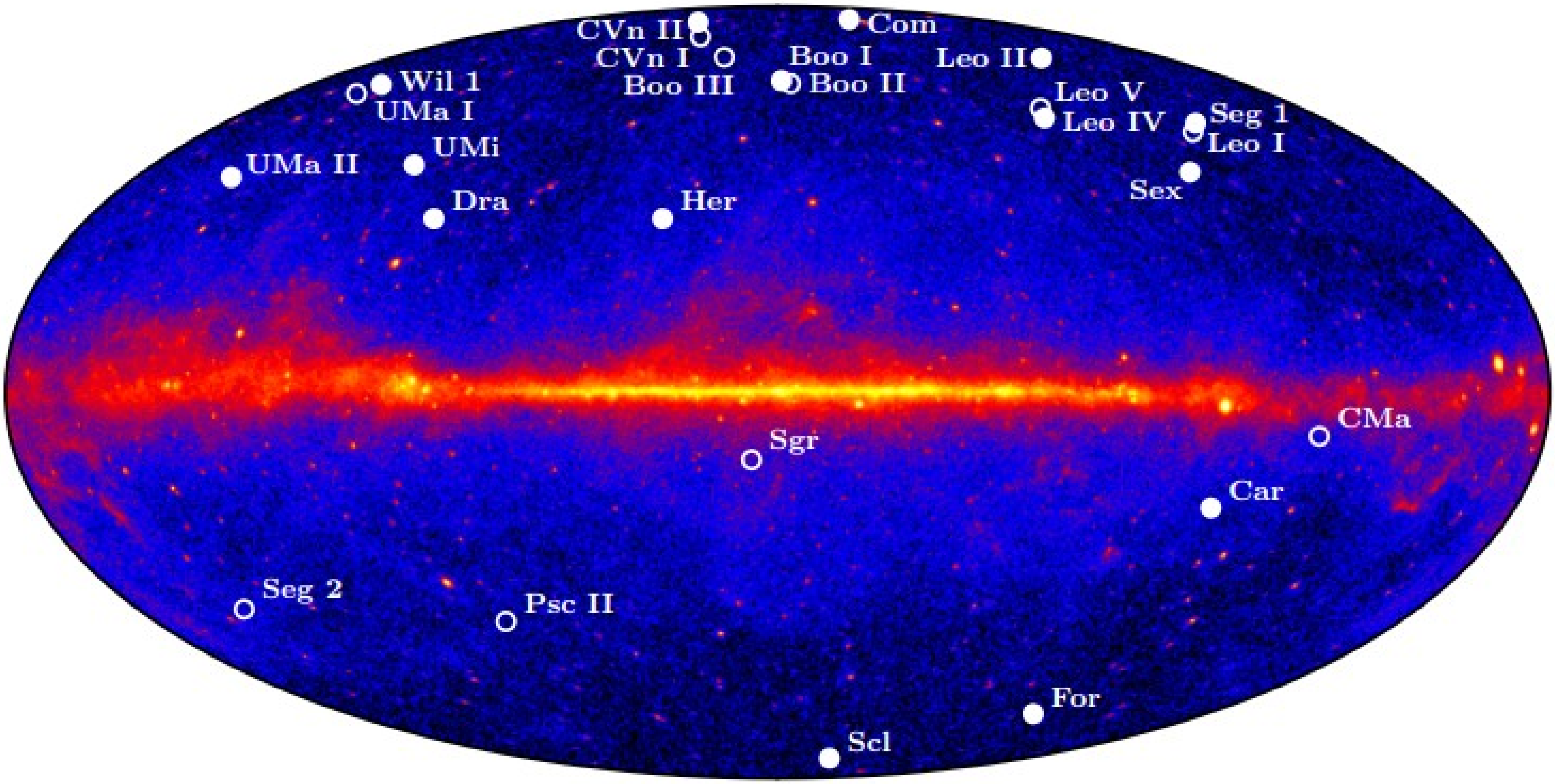
Gamma-ray image taken with the MAGIC telescopes

A promising target for detection: dwarf galaxies



MAGIC coll.
arXiv:1312.1535

A promising target for detection: dwarf galaxies



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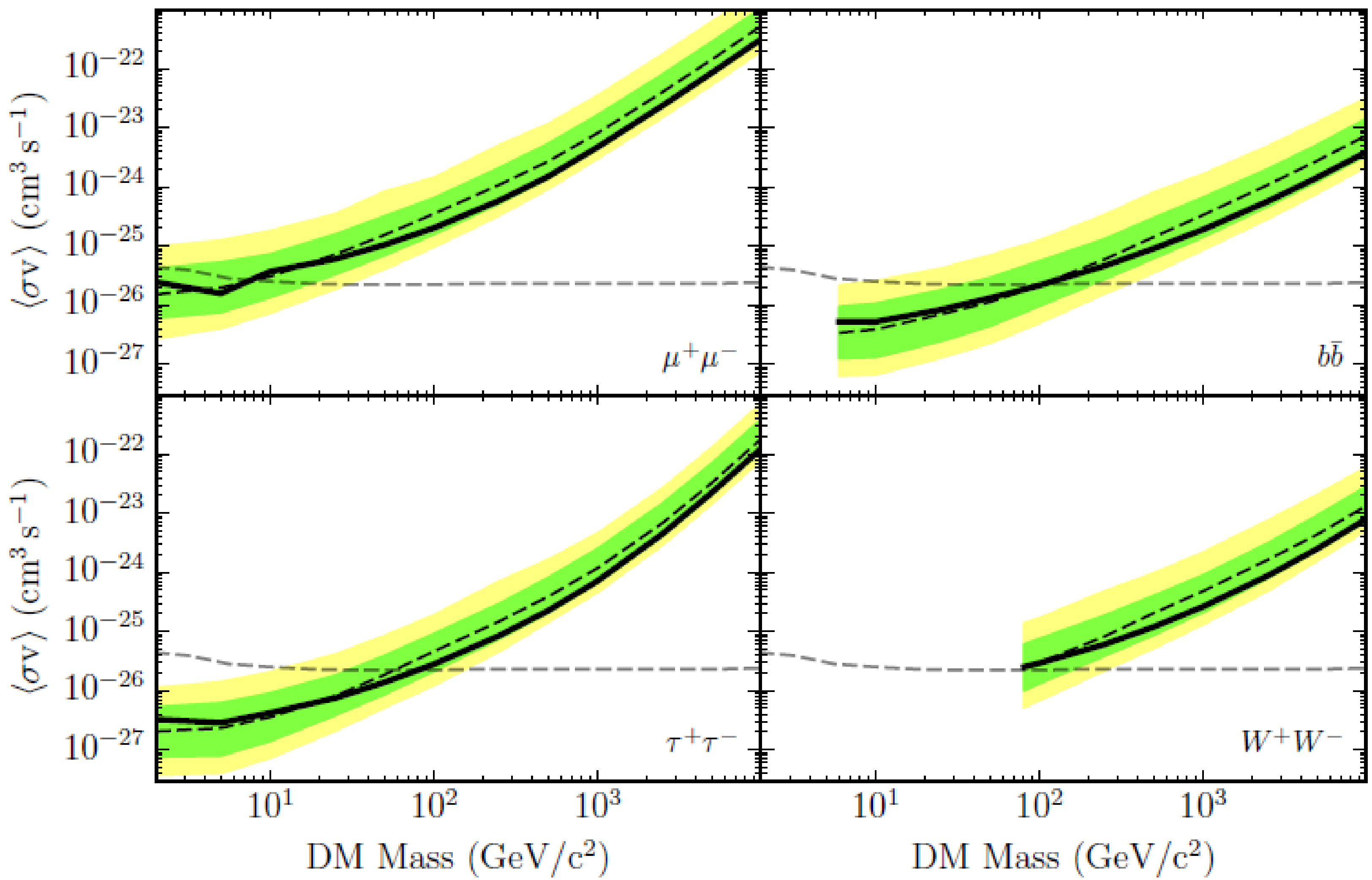
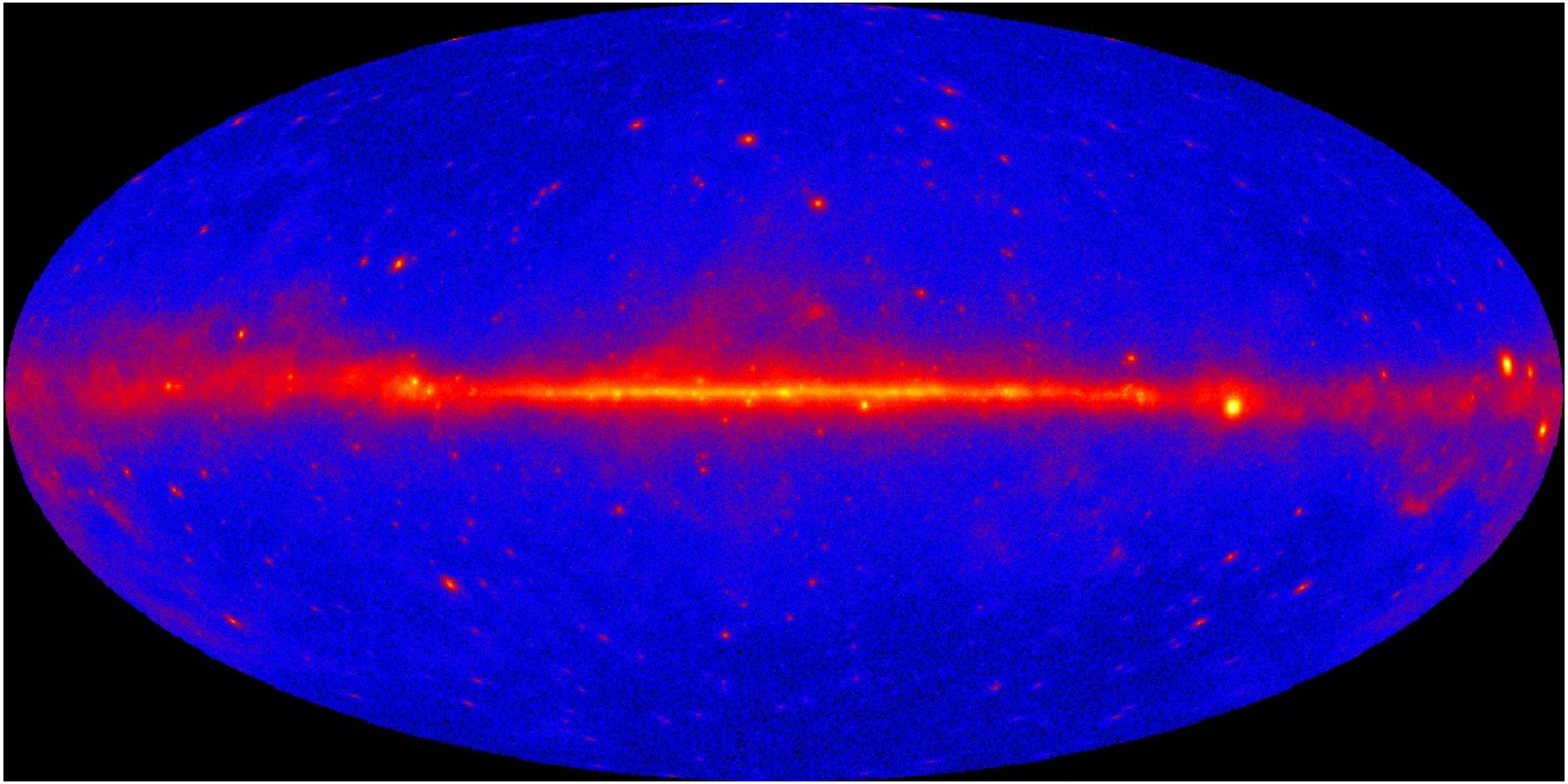
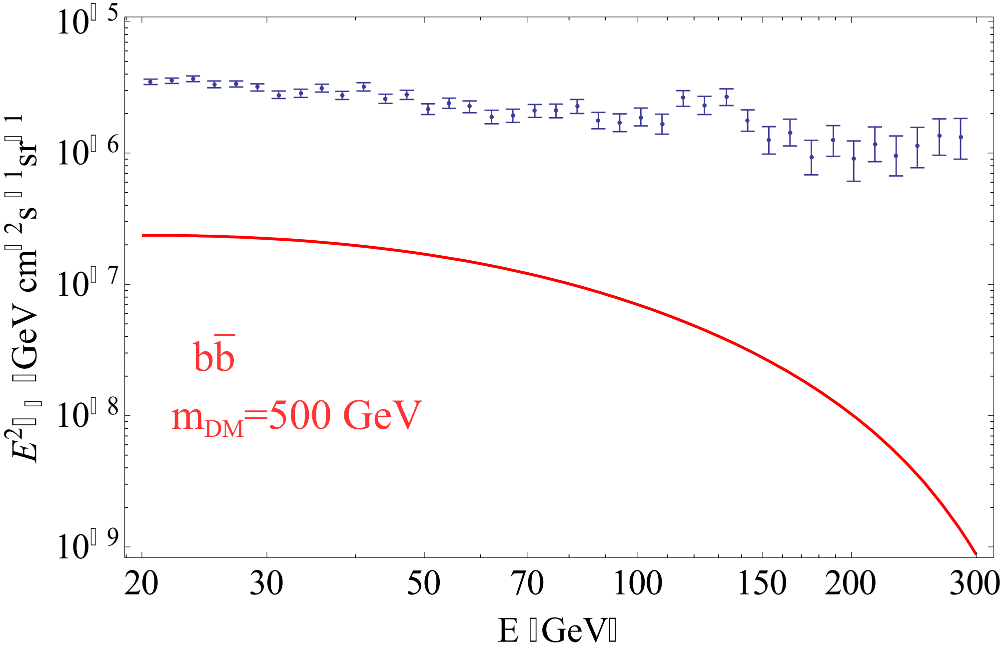


Fermi coll.
arXiv:1503.02641

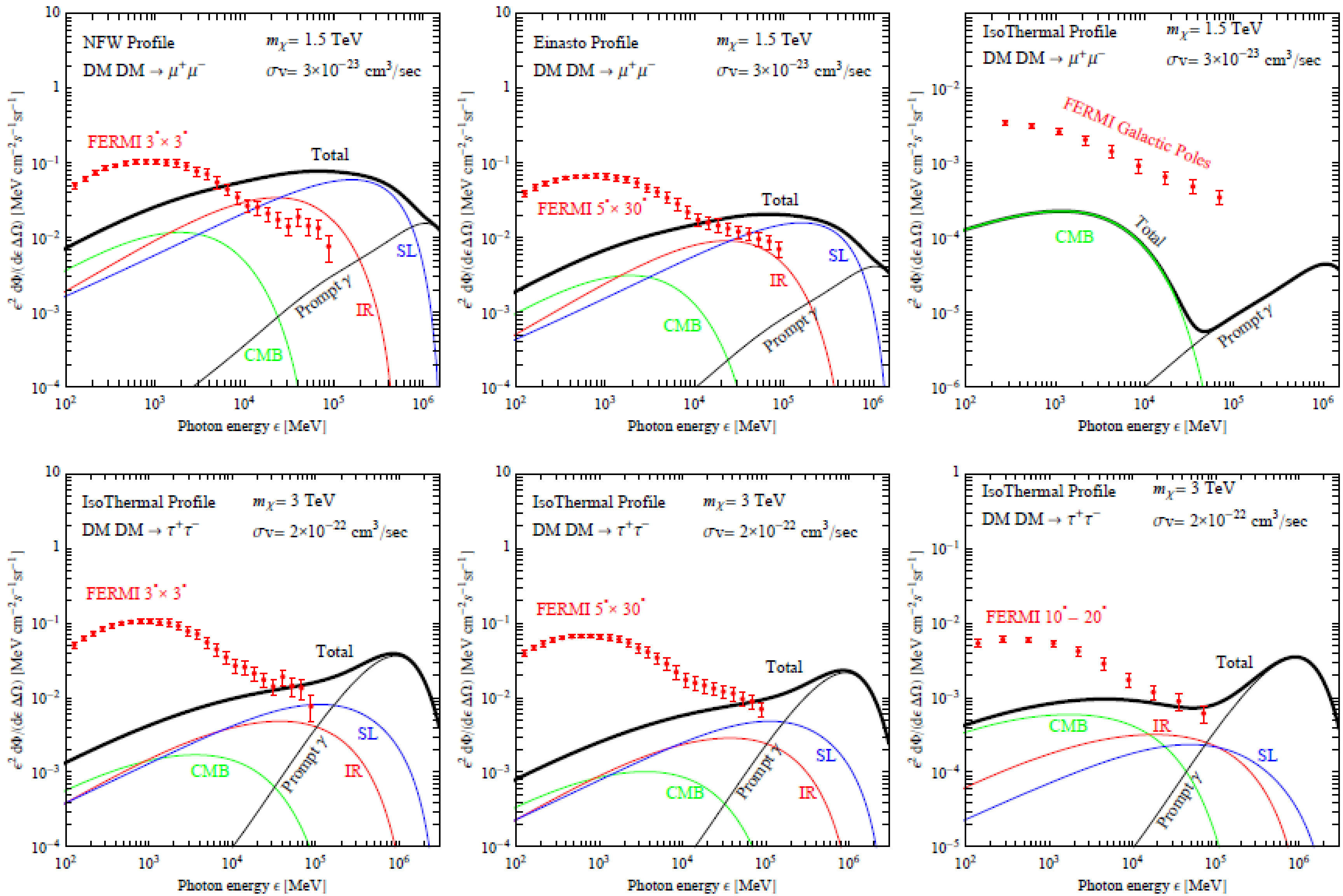
Diffuse Galactic emission



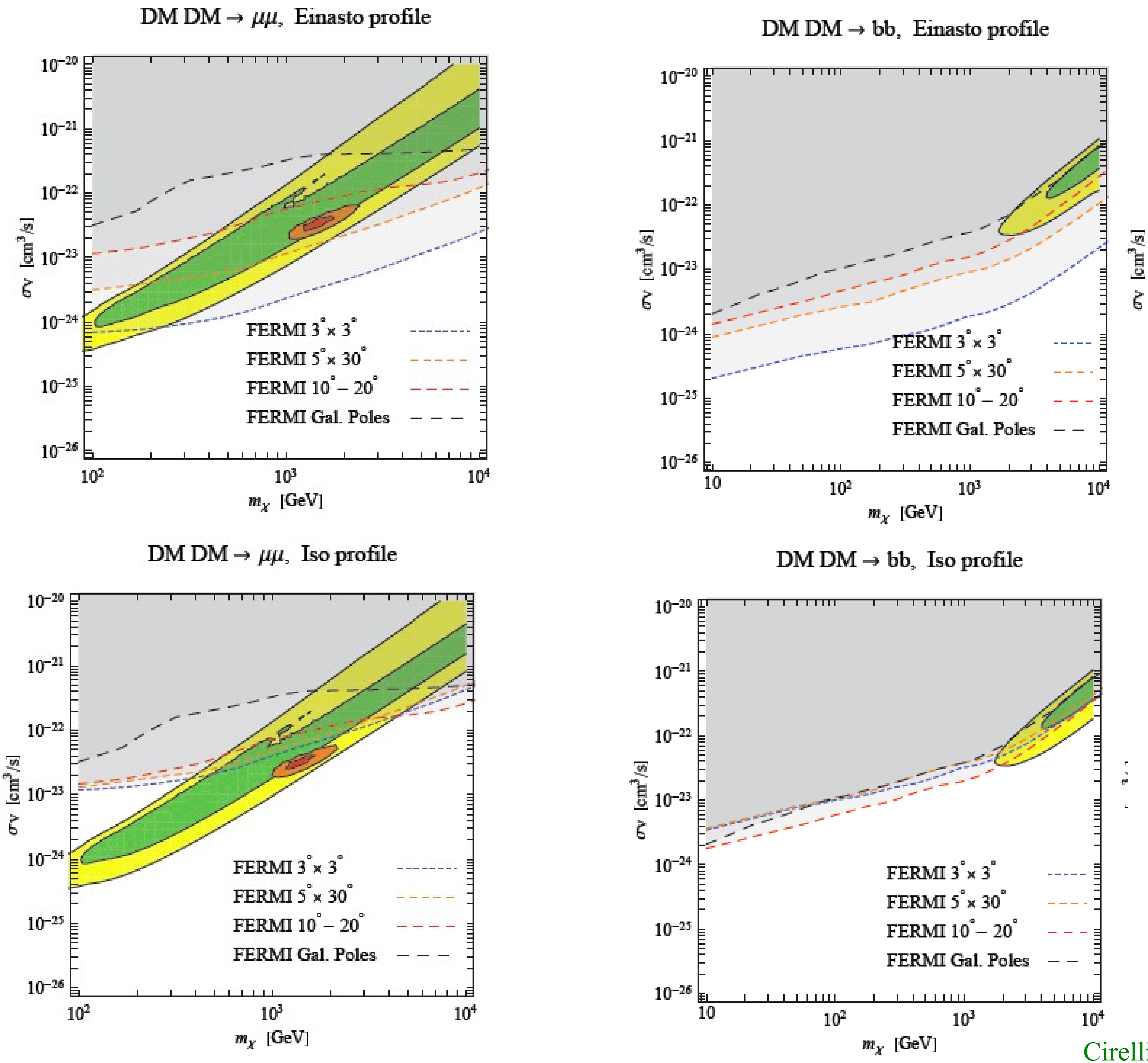
Search for DM in the galactic center region



Conservative approach: demand that the flux from dark matter annihilation does not exceed the measured flux



Cirelli et al'09

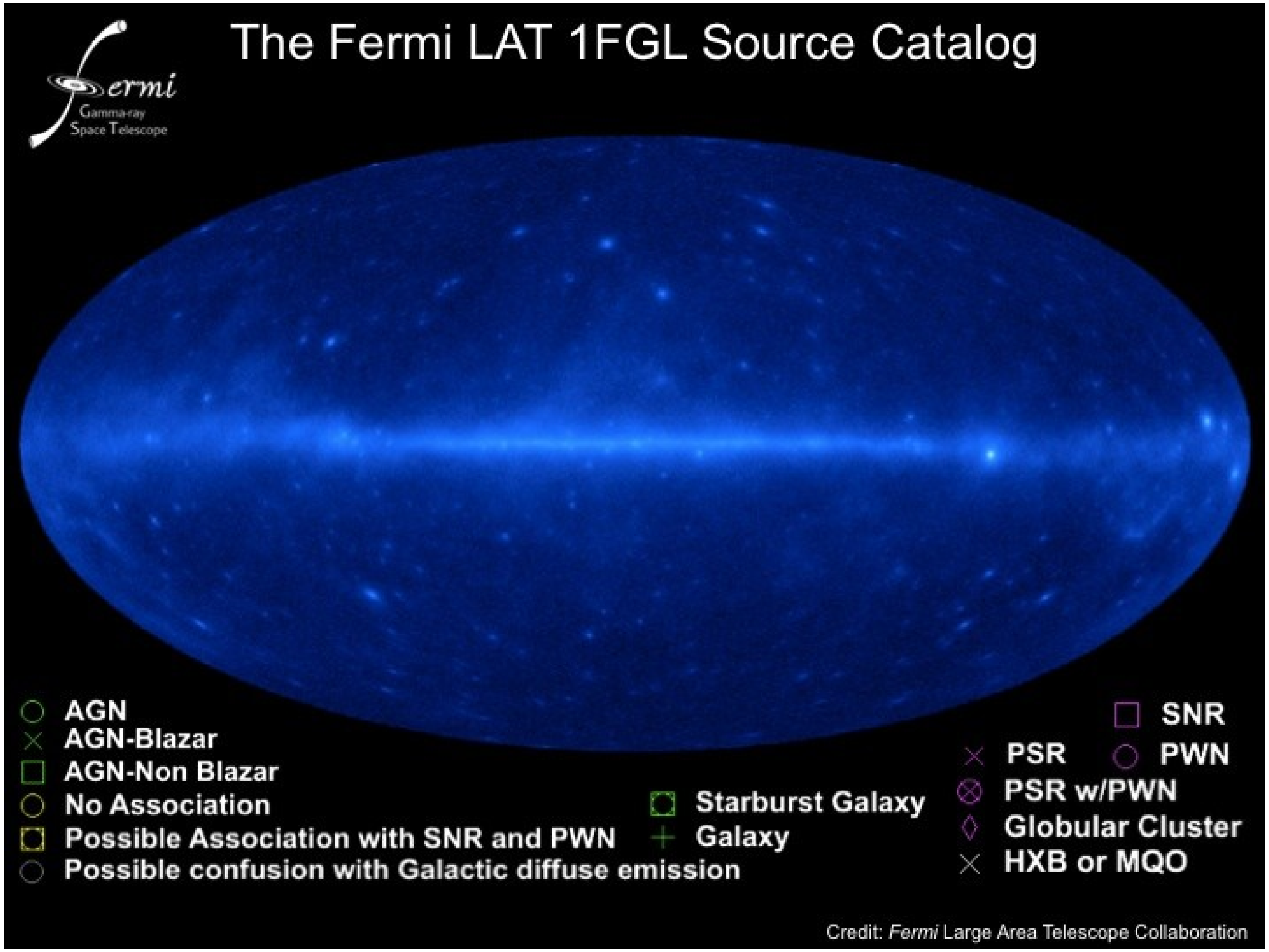


Cirelli et al'09

Galactic center

However, one could do better. Some backgrounds are well understood

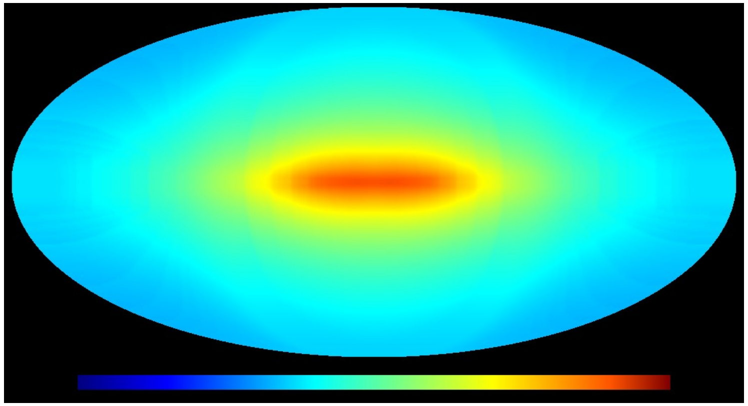
Background I: sources



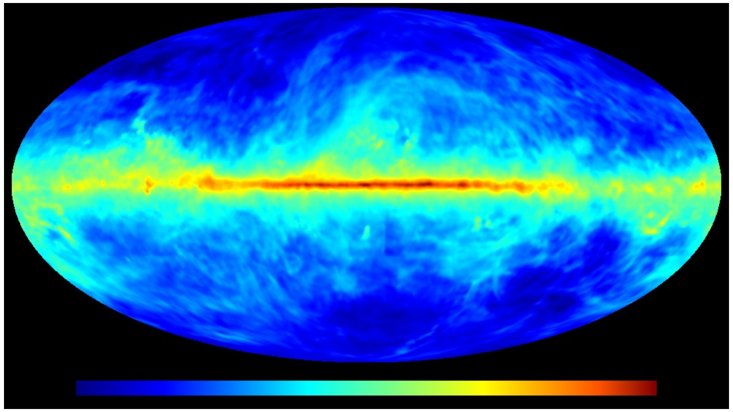
Galactic center

However, one could do better. Some backgrounds are well understood

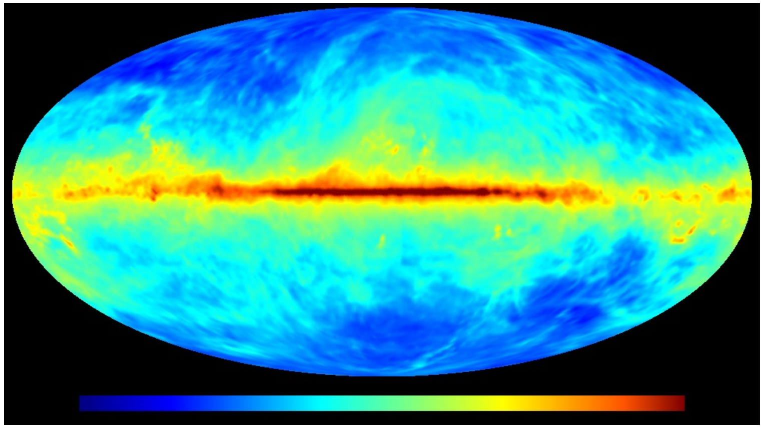
Background II: modelling of the diffuse emission



Inverse compton

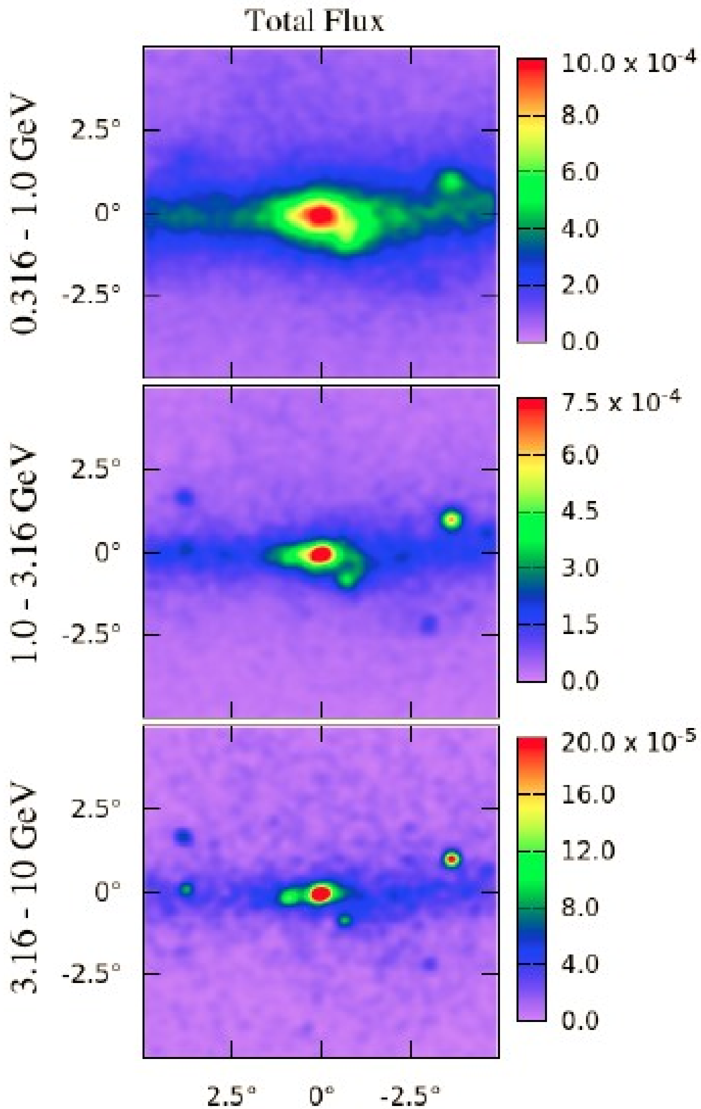


Bremmstrahlung



π^0-decay

Region |b|<5°, |l|<5°



Daylan et al. '14
Goodenough, Hooper '09, '10
Hooper, Linden '11
Huang et al '13
Abazajian et al '14
…

Region $|b|<5°$, $|l|<5°$

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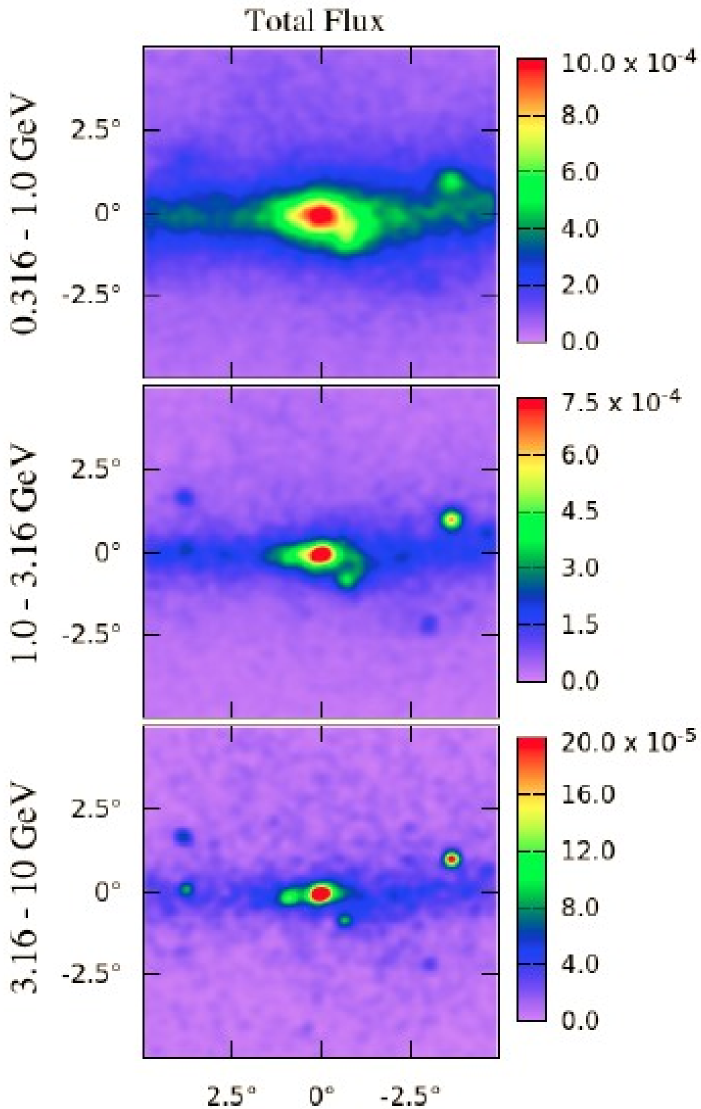

Subtract

- Sources from 2FGL

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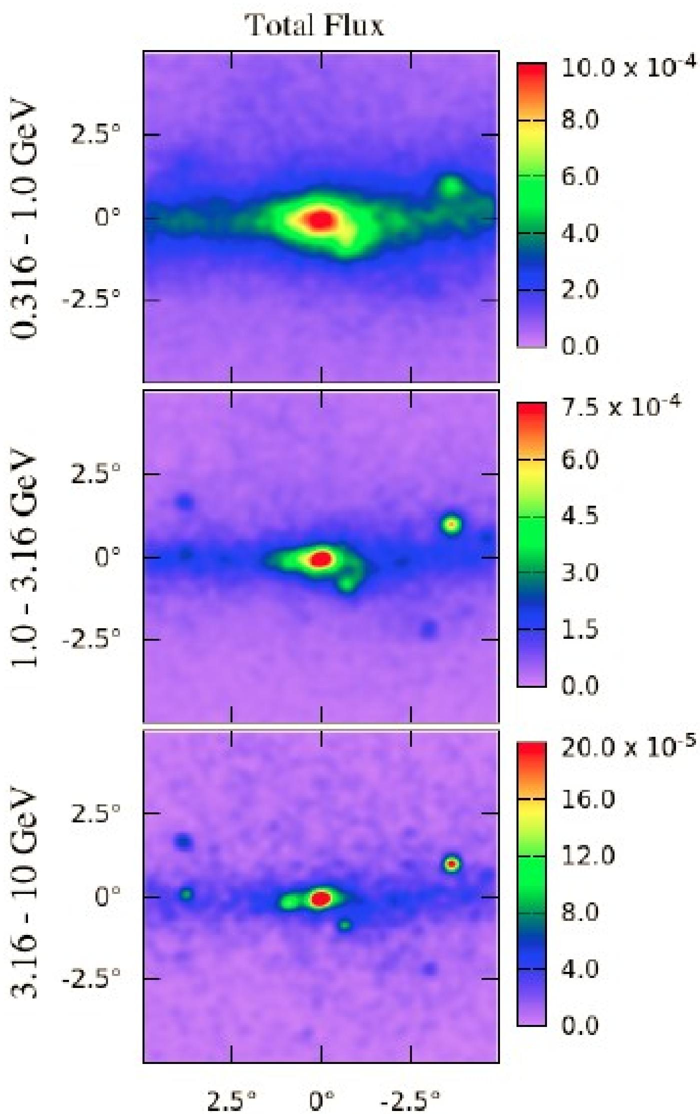
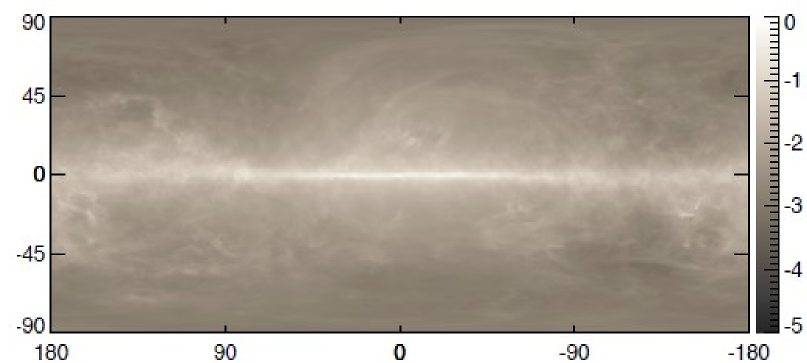


Subtract

- Sources from 2FGL
- Spatial template for diffuse galactic emission
    - π^0 component
    - Bremsstrahlung component
    - ICS component



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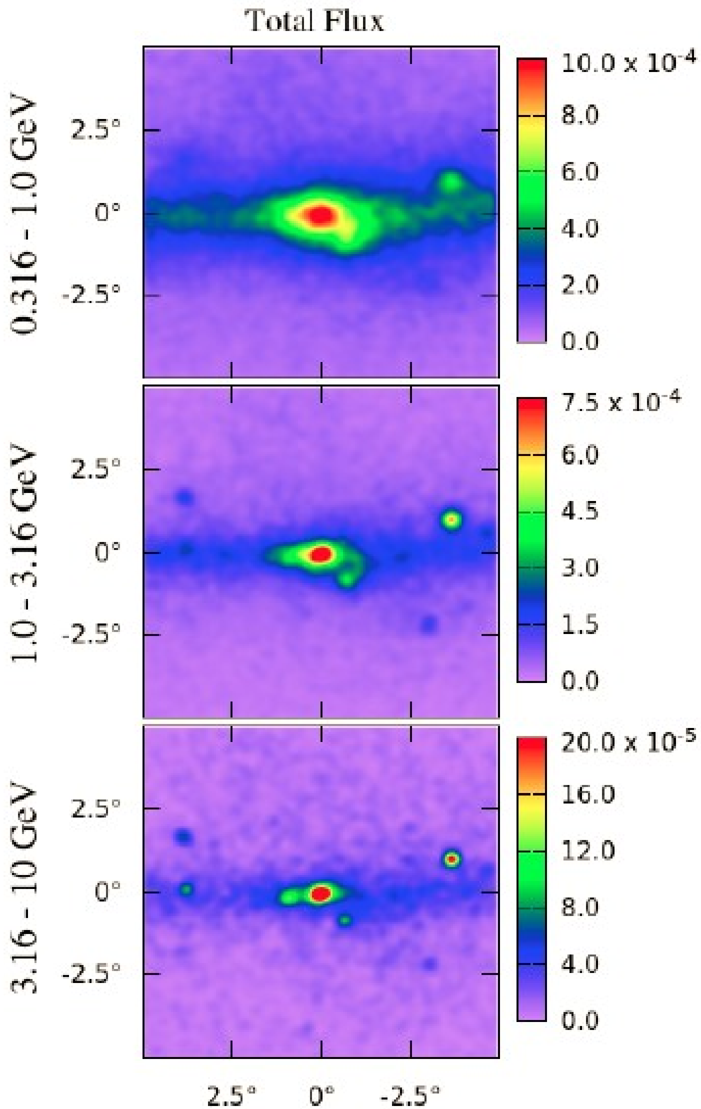

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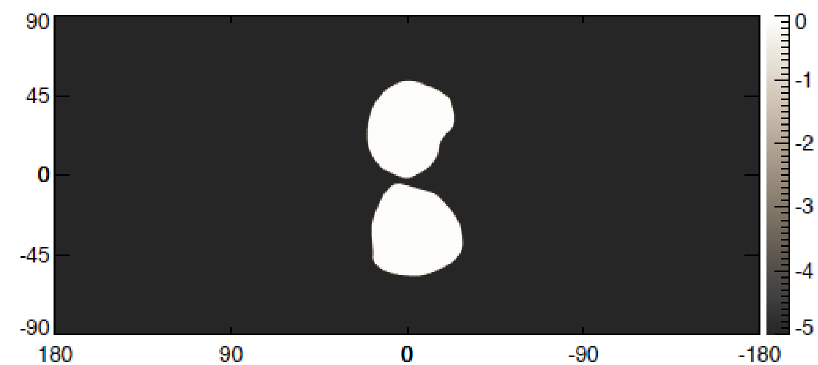
- Fermi bubbles



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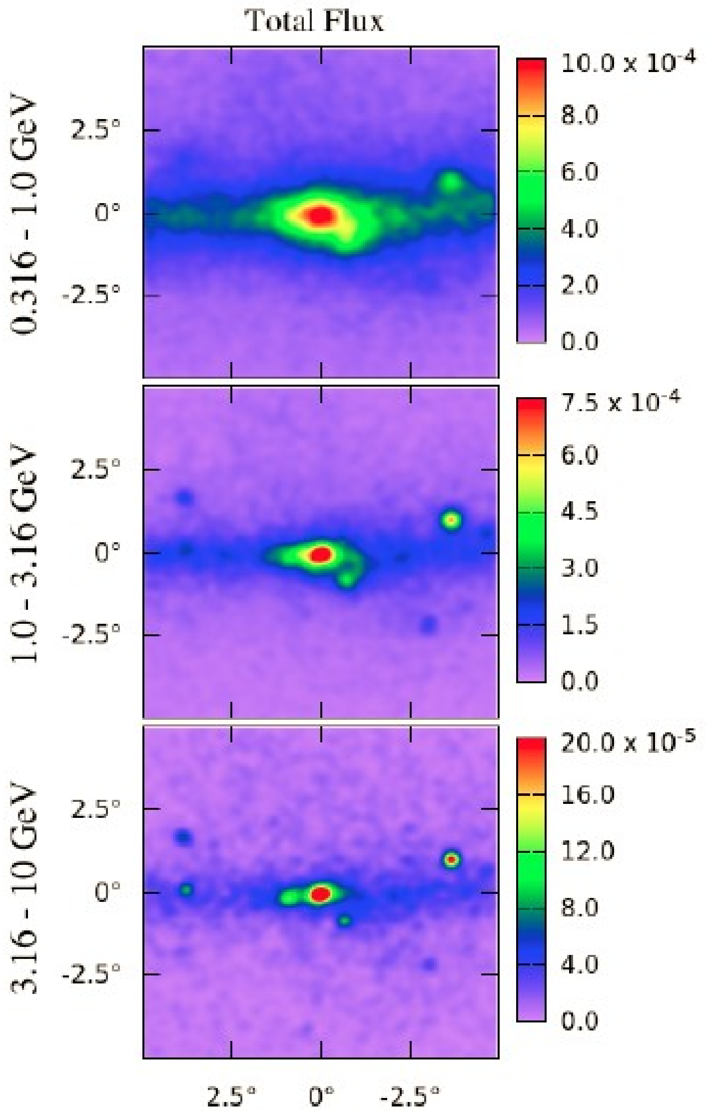

Subtract

- Sources from 2FGL
- Spatial template for diffuse galactic emission
  - π^0 component
  - Bremsstrahlung component
  - ICS component
- Fermi bubbles
- Isotropic (extragalactic) component

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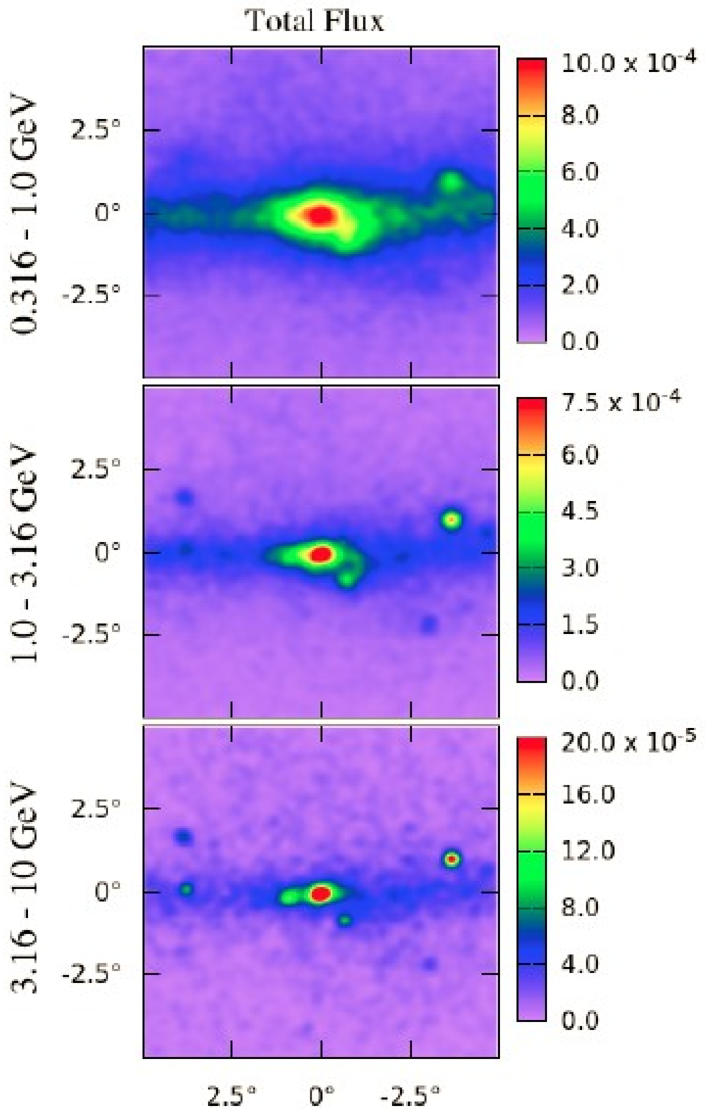

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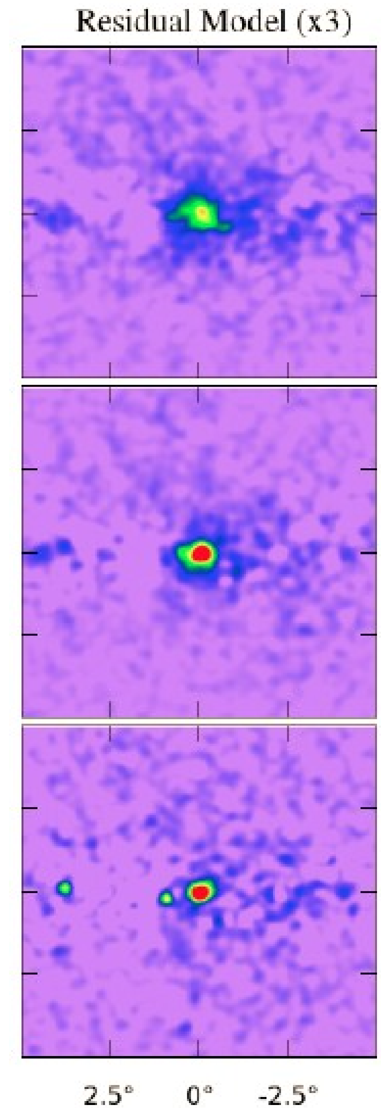

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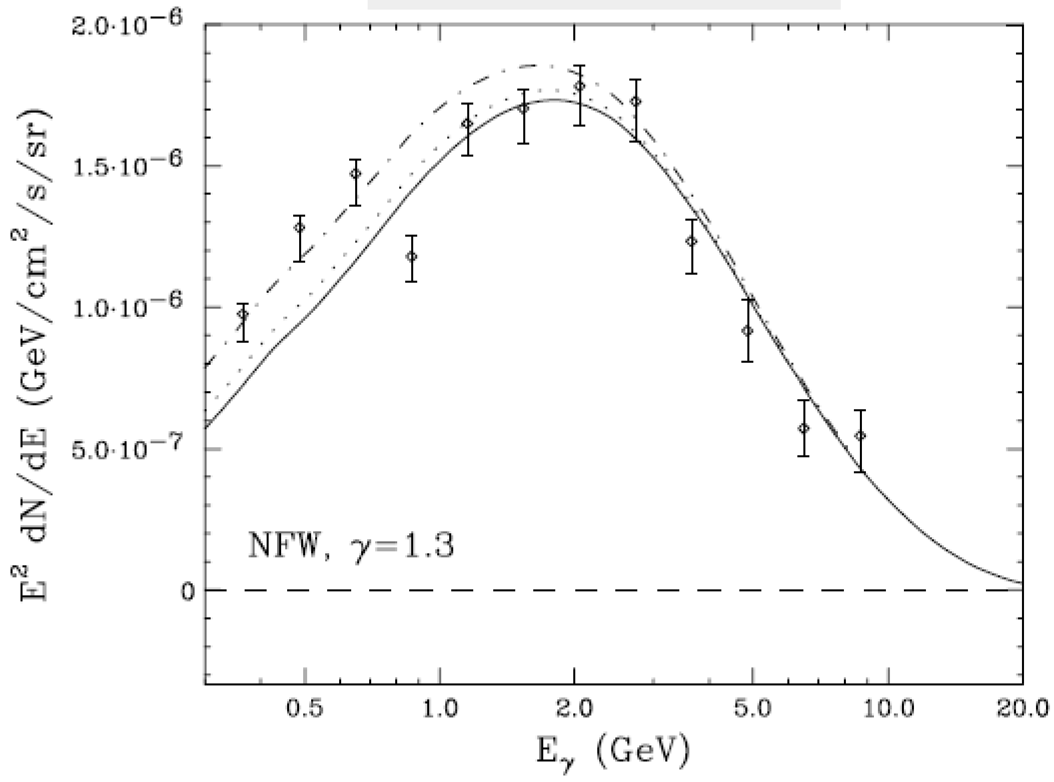
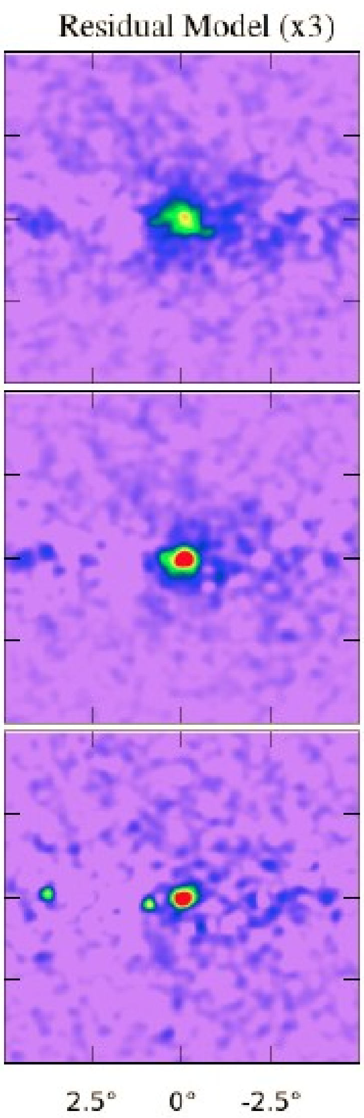
Energy spectrum





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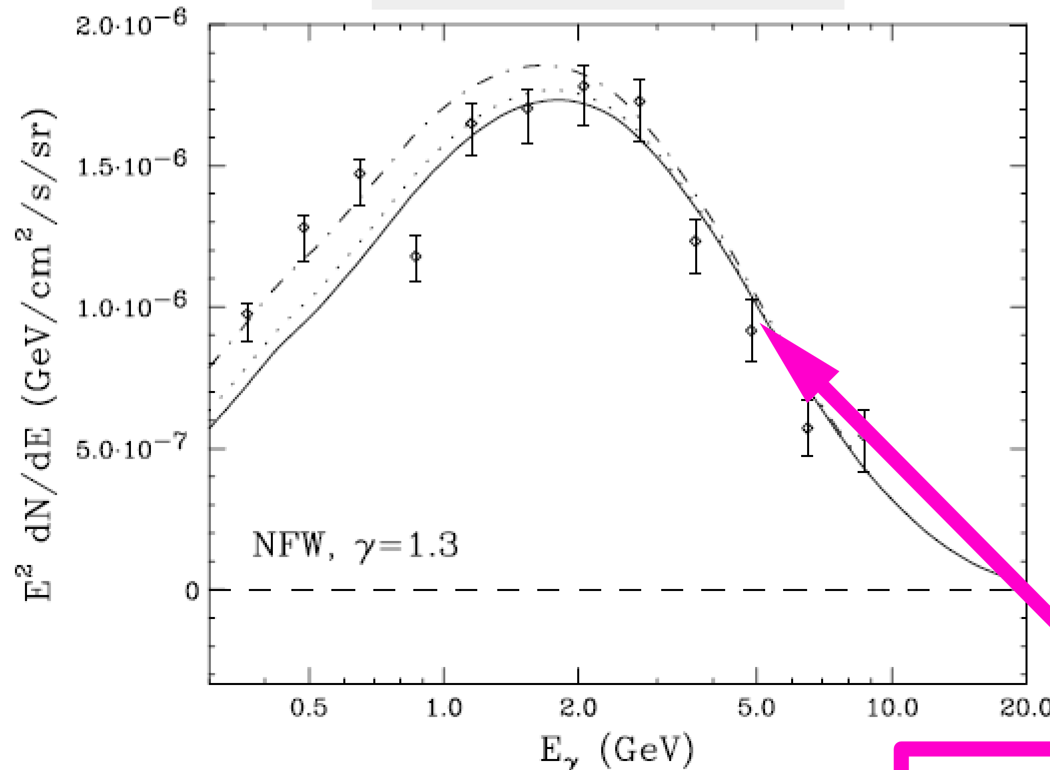

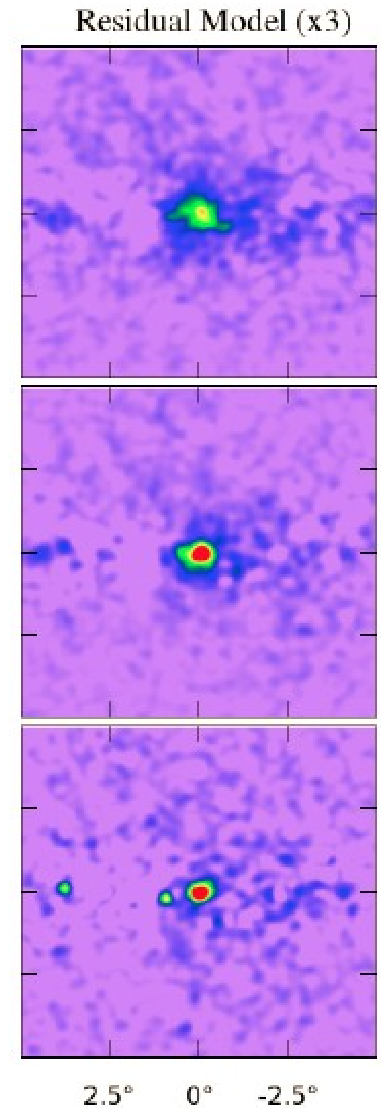

DM DM $\rightarrow b\,\bar{b}$
$m_{DM} = 35.25$ GeV
$\sigma v = 1.0\times10^{-26}\ \mathrm{cm^3/s}$

Typical WIMP parameters!

Region |b|<5°, |l|<5°

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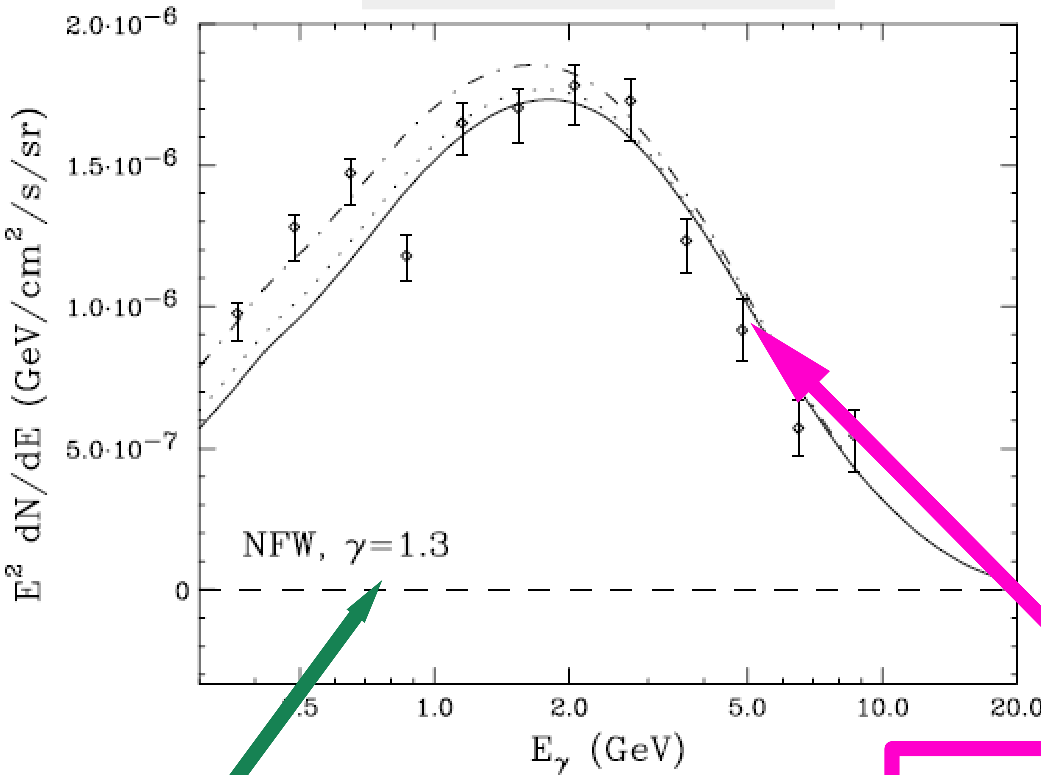

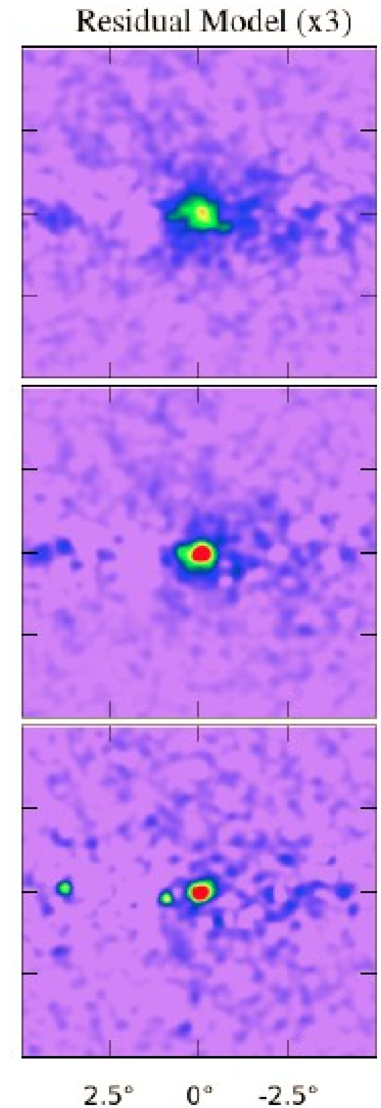

The signal is spherically symmetric and goes as $r^{-2.6}$. Requires a slightly more cuspy profile than standard NFW.

$\mathrm{DM\,DM} \rightarrow b\,\bar{b}$
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$\sigma v = 1.0\times10^{-26}\ \mathrm{cm^3/s}$

Typical WIMP parameters!

The excess does look like a WIMP signal

- The excess is extended: it is also observed in the region $1° < |b| < 20°$, $|l| < 20°$, with roughly the same spectrum.
- The excess looks spherically symmetric.
- The excess is present for any diffuse background model.
- The excess is "theoretically sound": simple models can reproduce the observations.

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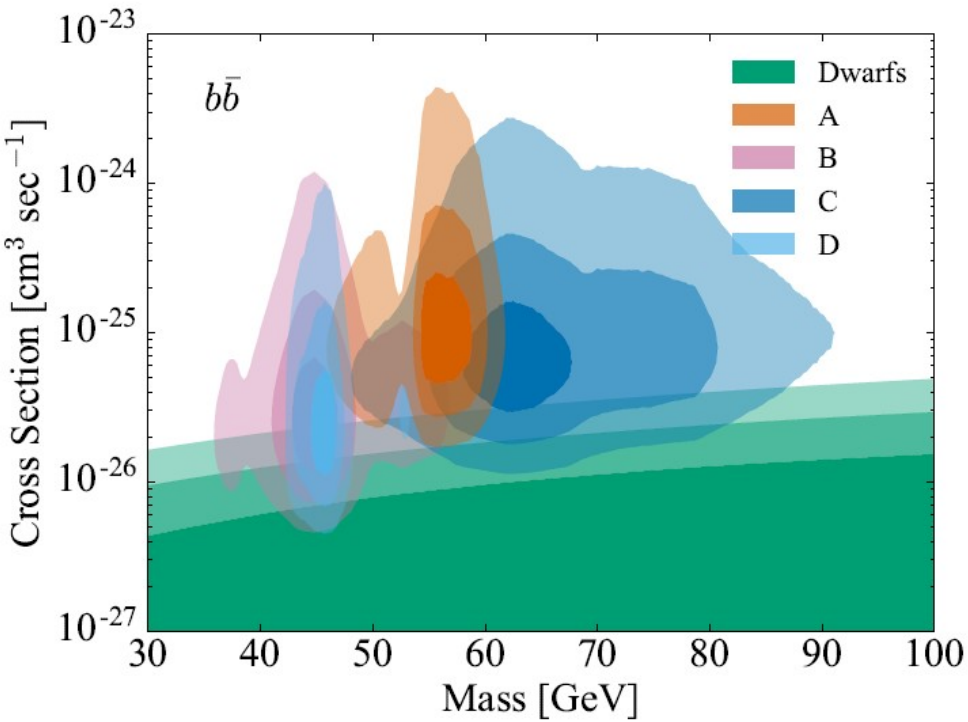
However...

- A correlated signal is expected from dwarf galaxies, but is not observed



Keeley et al. '17

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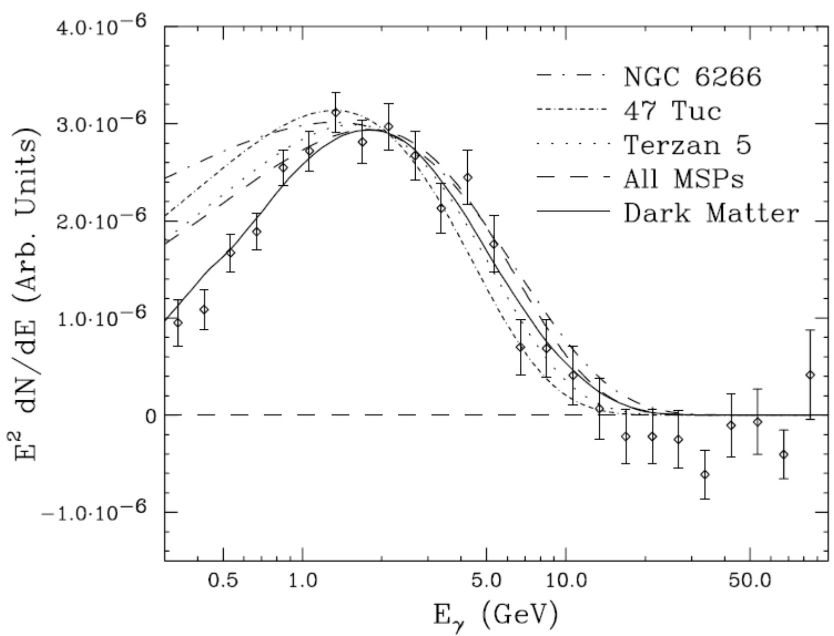
a template with a population of millisecond pulsars may account for all the excess.



Similar energy spectrum as MSPs.

Daylan et al. '14

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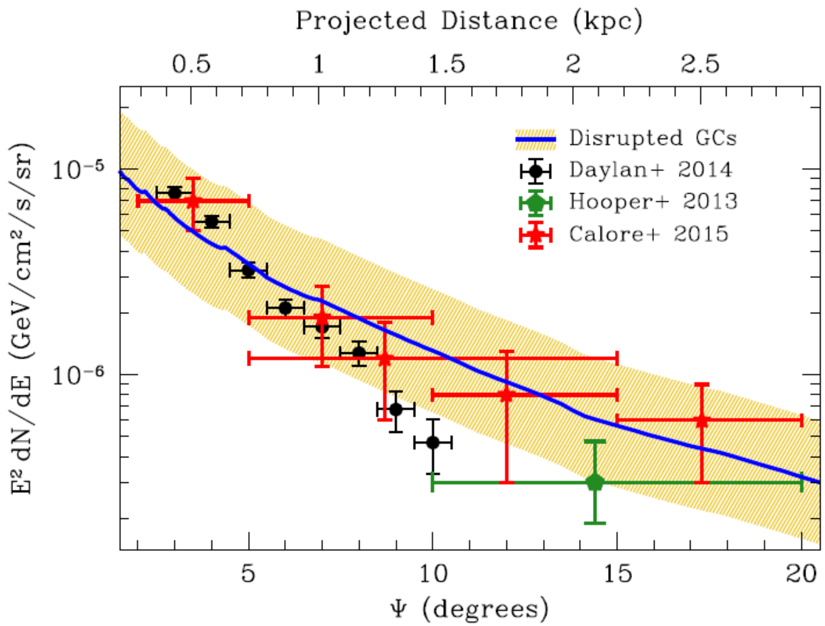

Similar morphology and intensity as the one predicted from tidally disrupted globular clusters

Brandt, Kocsis '15

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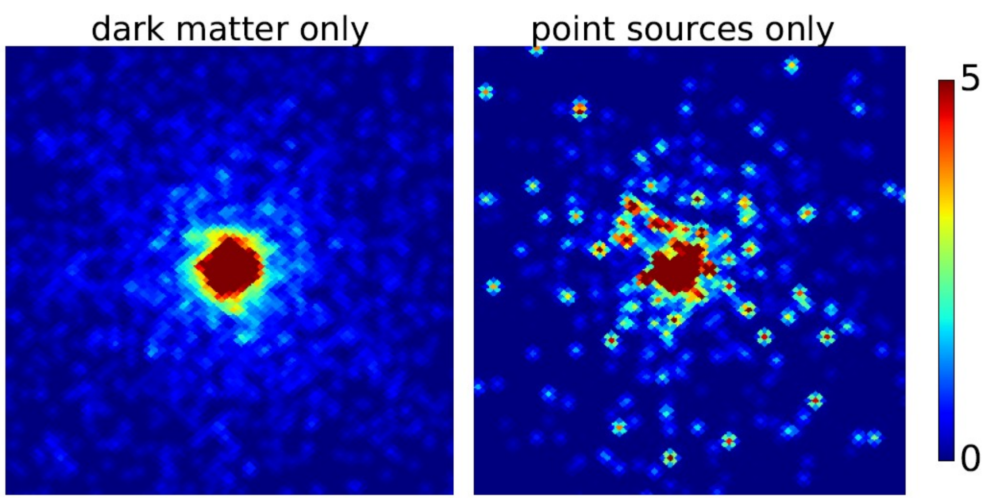

Lee et al. '14'15
Bartels et al '15

Simulated!

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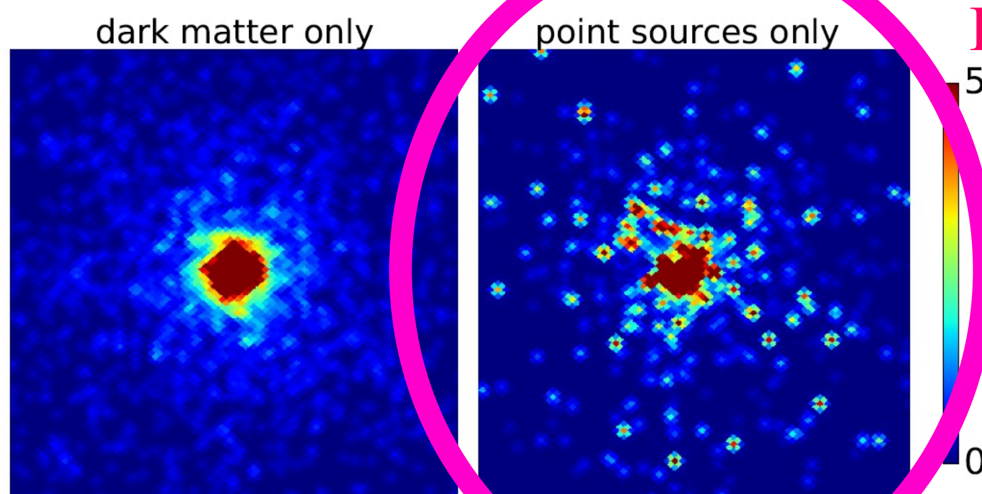
Favored by data



Lee et al. '14'15
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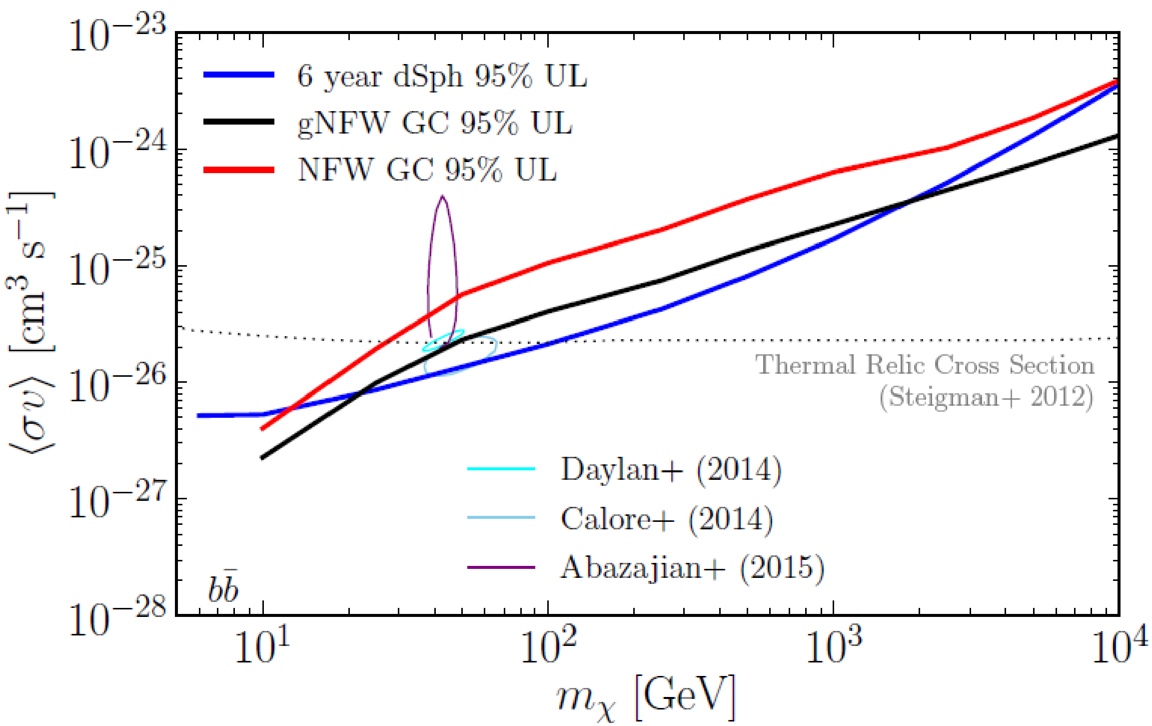
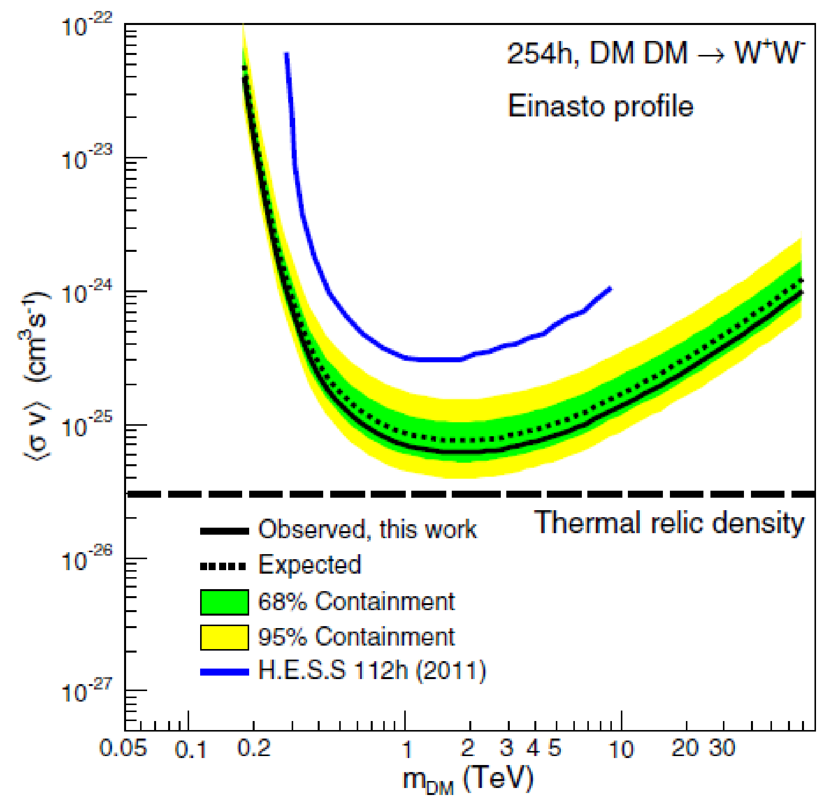
Simulated!

Constraints on WIMP parameters

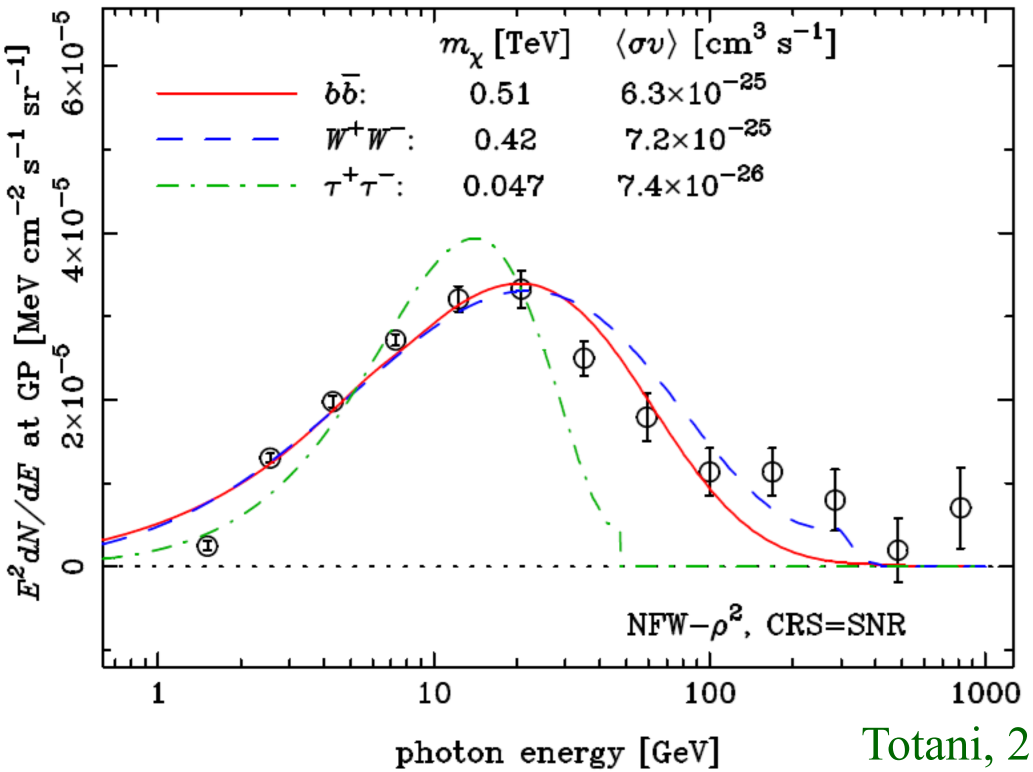


Fermi-LAT collaboration
arXiv:1704.03910



H.E.S.S. Collaboration
arXiv:1607.08142

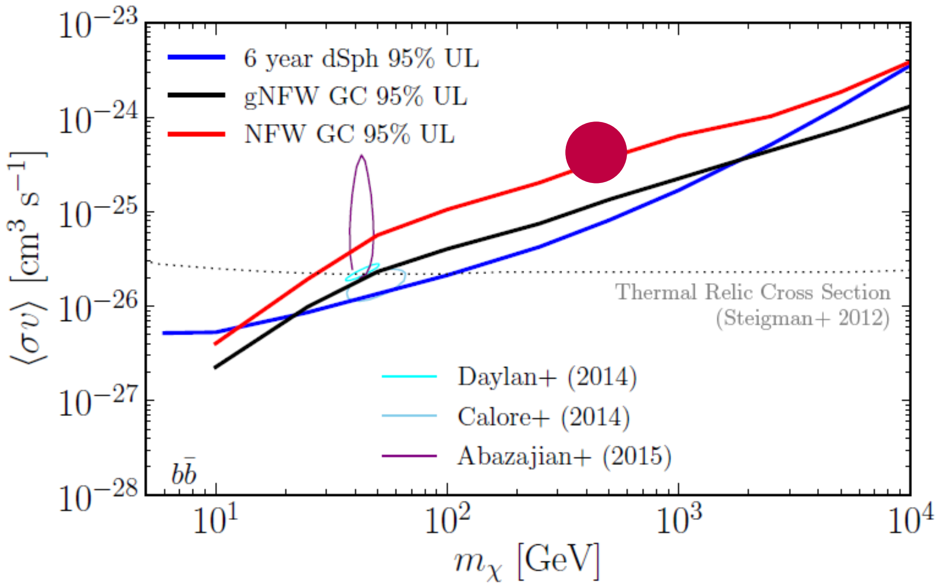
A new gamma-ray excess?

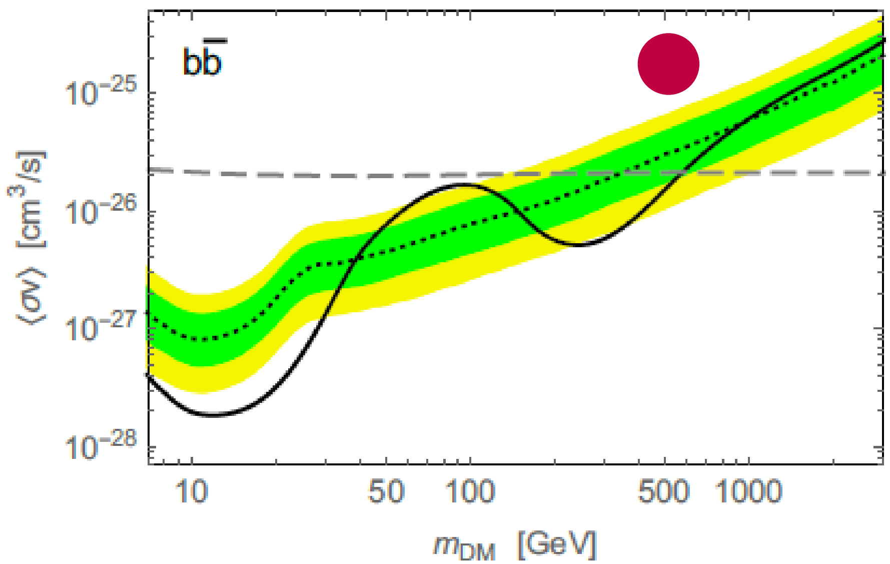


Totani, 2507.07209

- Spatially very extended: |l|<60°,10°<|b|<60°
- Peaks at ~ 20 GeV
- Points to a DM mass of 400-500 GeV
- Requires a fairly large cross-section

A new gamma-ray excess?

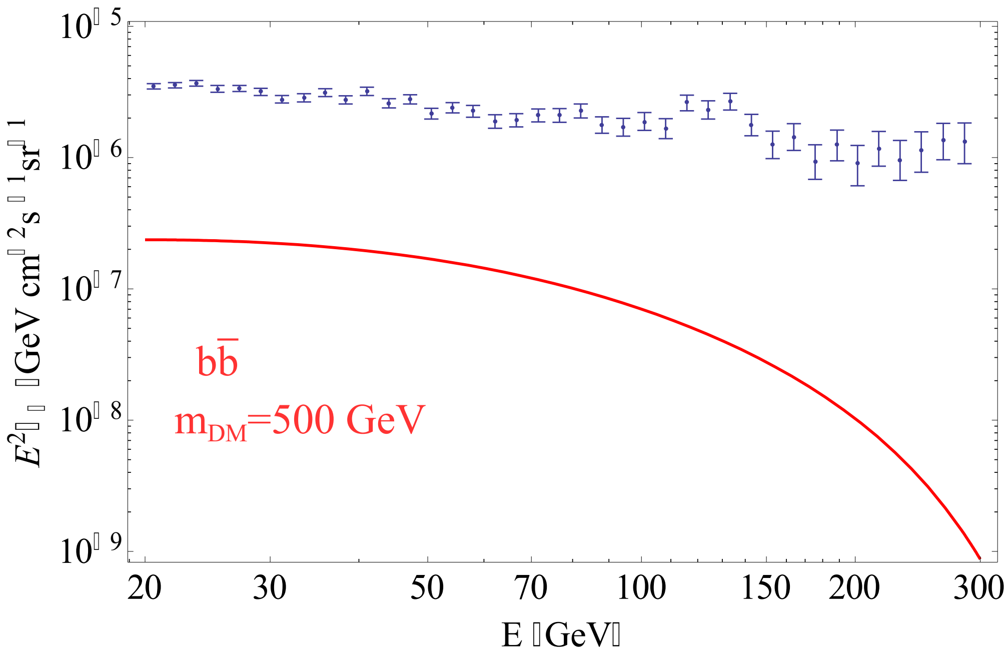




- Spatially very extended: |l|<60°,10°<|b|<60°
- Peaks at ~ 20 GeV
- Points to a DM mass of 400-500 GeV
- Requires a fairly large cross-section
- In tension with dwarf galaxy constraints and antiproton constraints
- Modelling of backgrounds extremely difficult

Gamma-ray features

Idea: Search for a gamma-ray excess with an energy spectrum qualitatively different from the background.



"Smoking gun" for dark matter: no (known) astrophysical process can produce a sharp feature in the gamma-ray energy spectrum

Gamma-ray features

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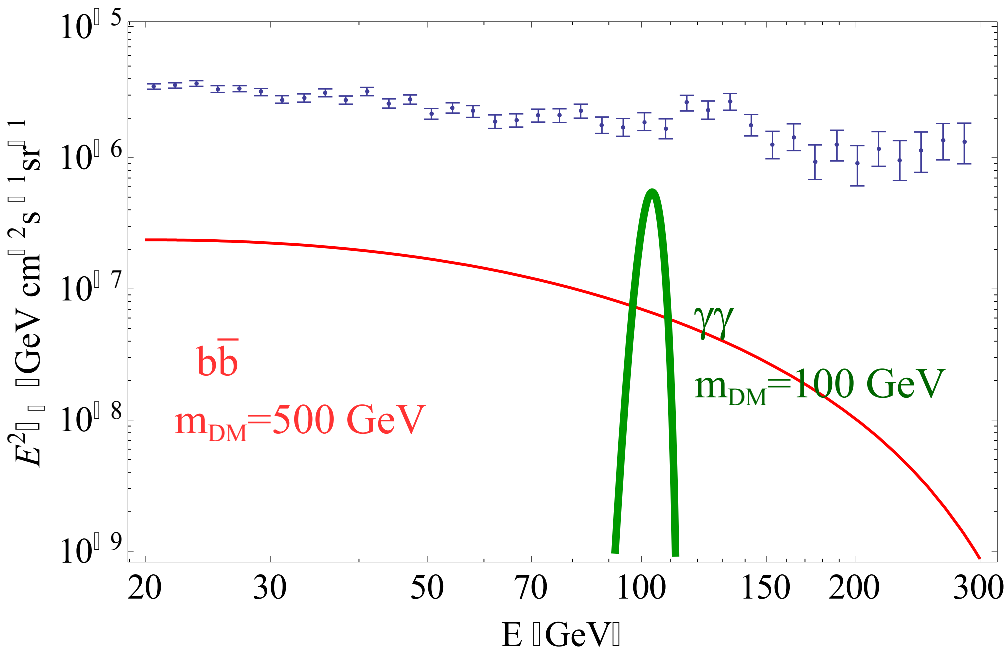
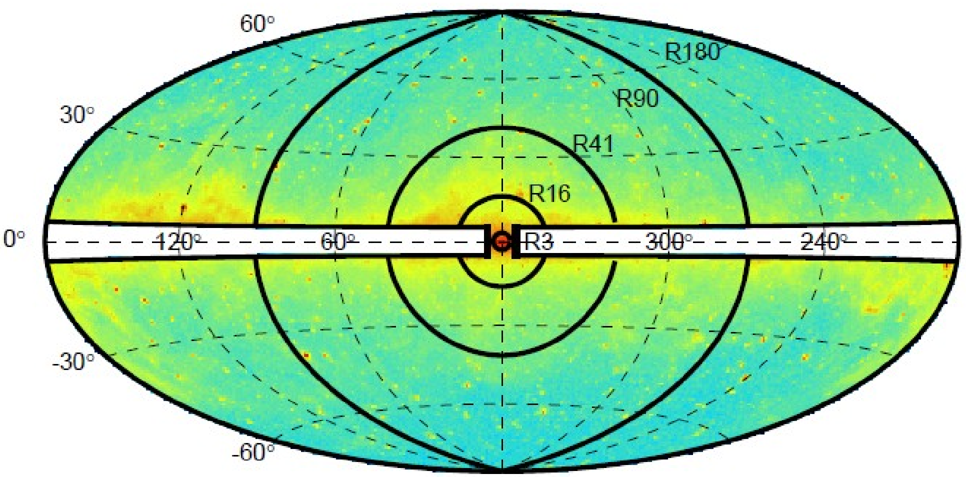
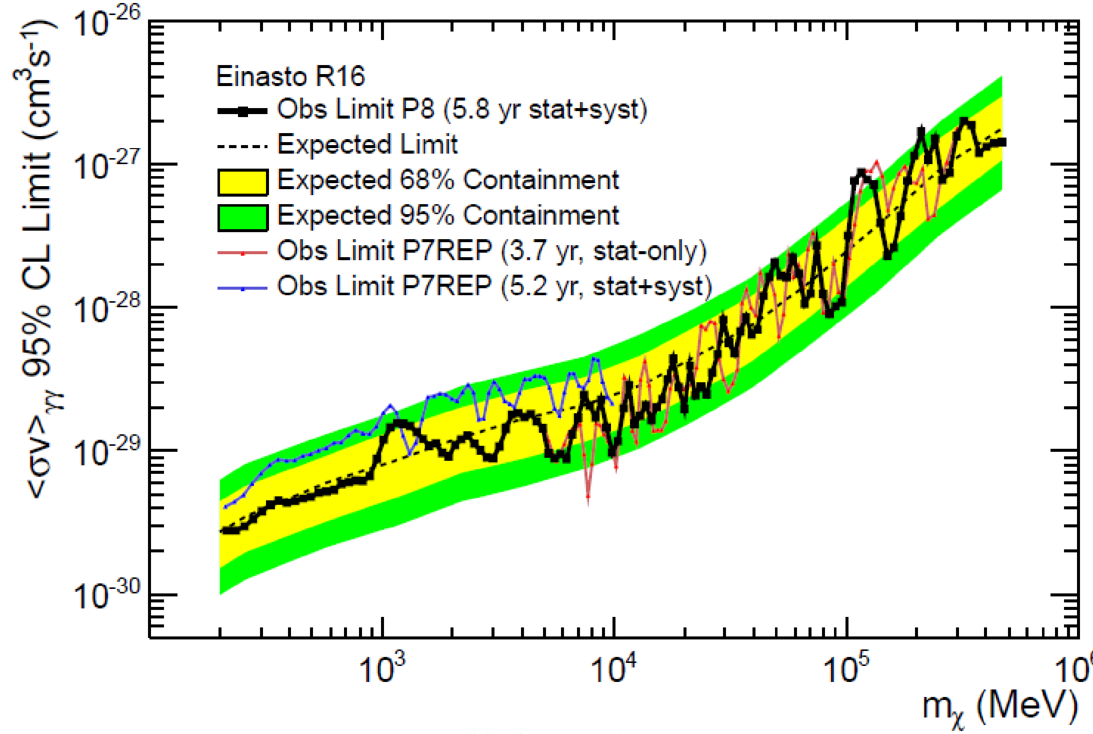


"Smoking gun" for dark matter: no (known) astrophysical process can produce a sharp feature in the gamma-ray energy spectrum

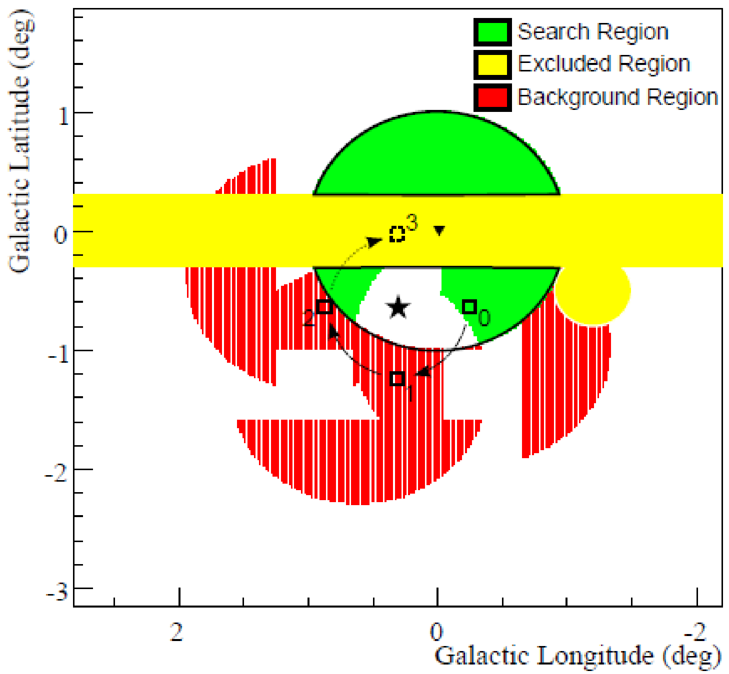
Gamma-ray features

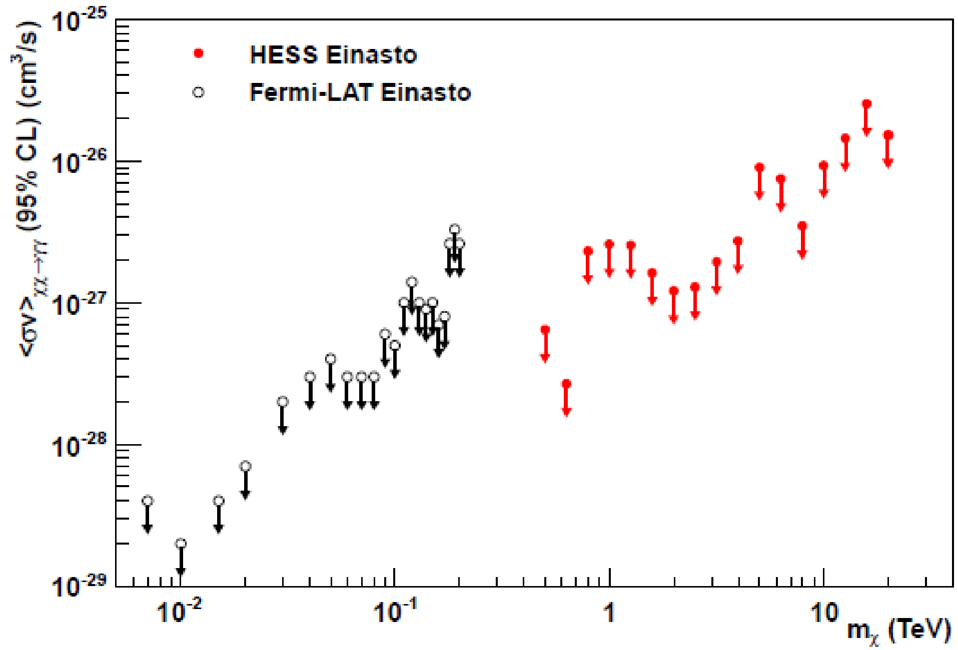




Fermi collaboration
arXiv:1503.02641

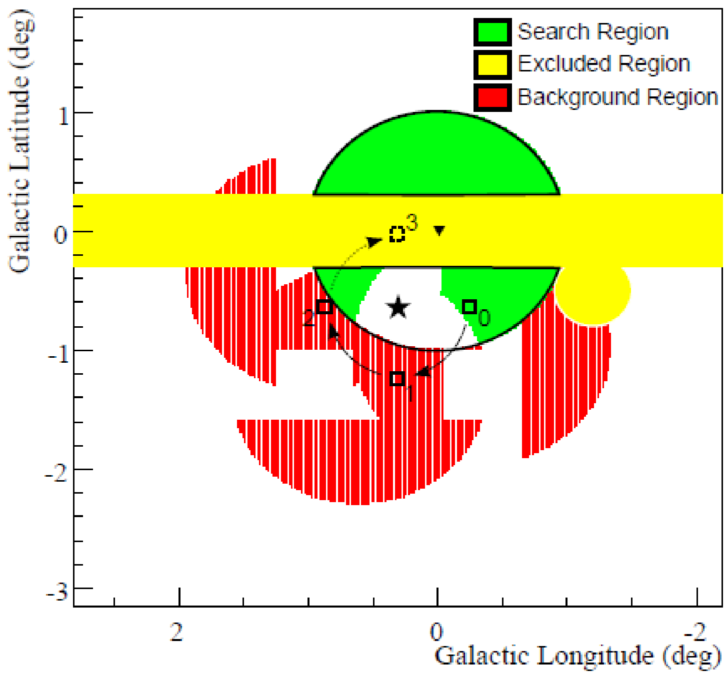
Gamma-ray features

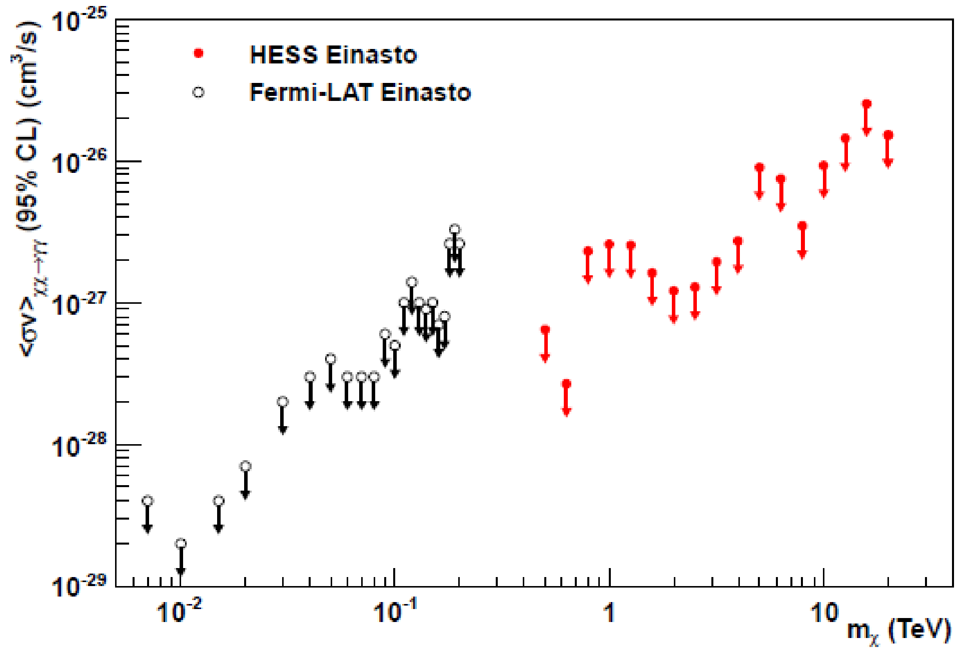




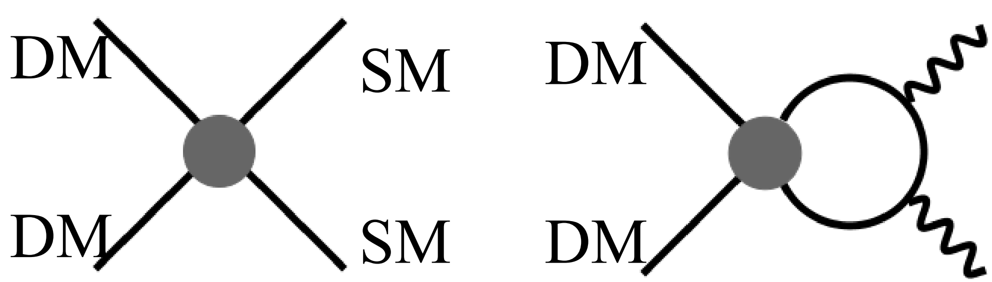
H.E.S.S. collaboration
arXiv:1301.1173

Gamma-ray features



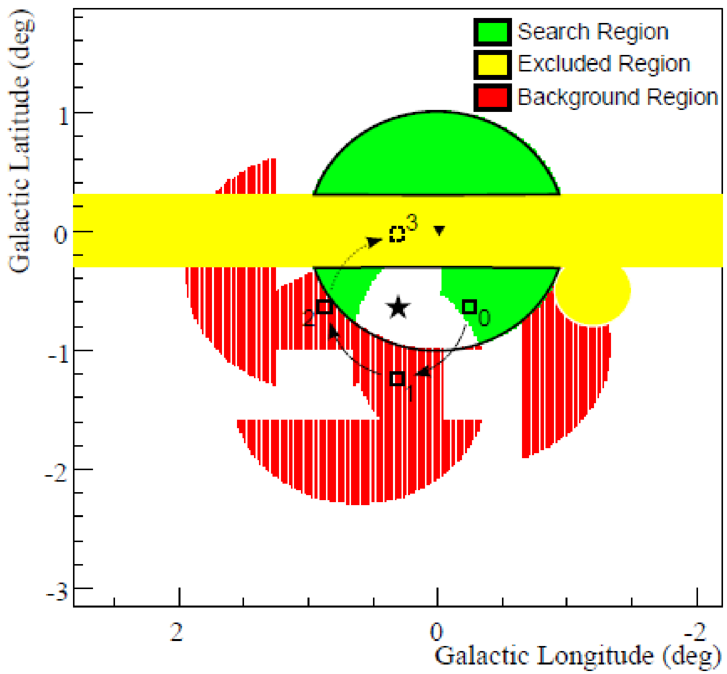


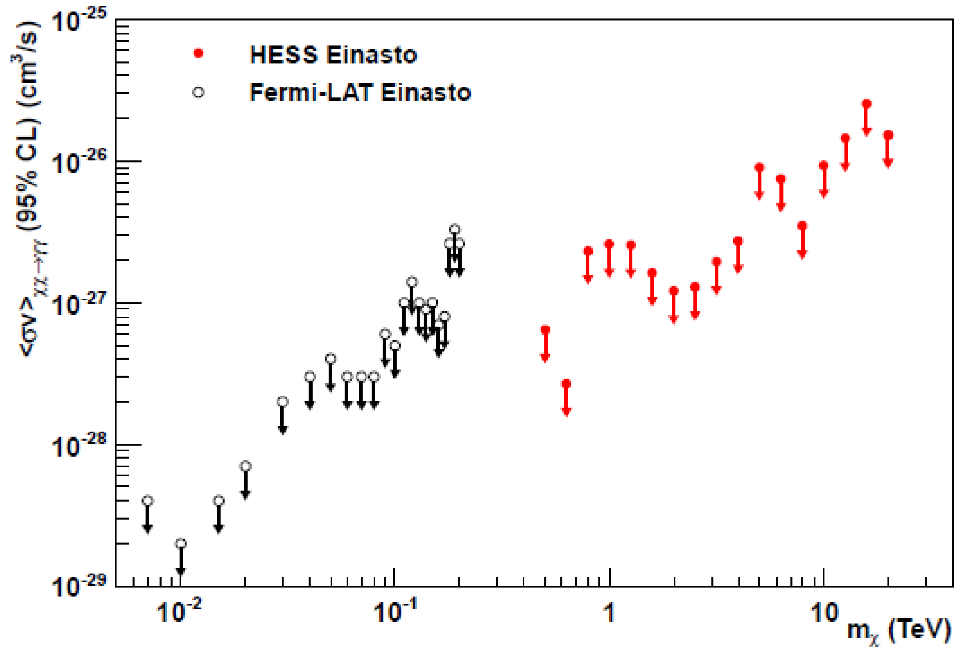
The annihilation DM DM → γ γ typically arises at the one loop level



$$\boxed{(\sigma v)_{\gamma\gamma} \sim \mathcal{O}(\alpha^2)(\sigma v)_{\rm thermal} \sim 10^{-30}{\rm cm}^3{\rm s}^{-1}}$$

Gamma-ray features





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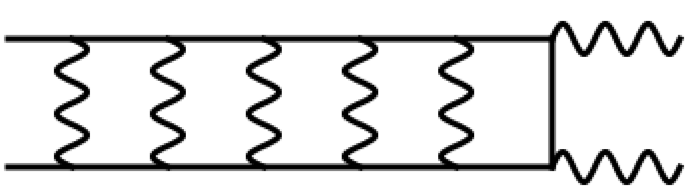
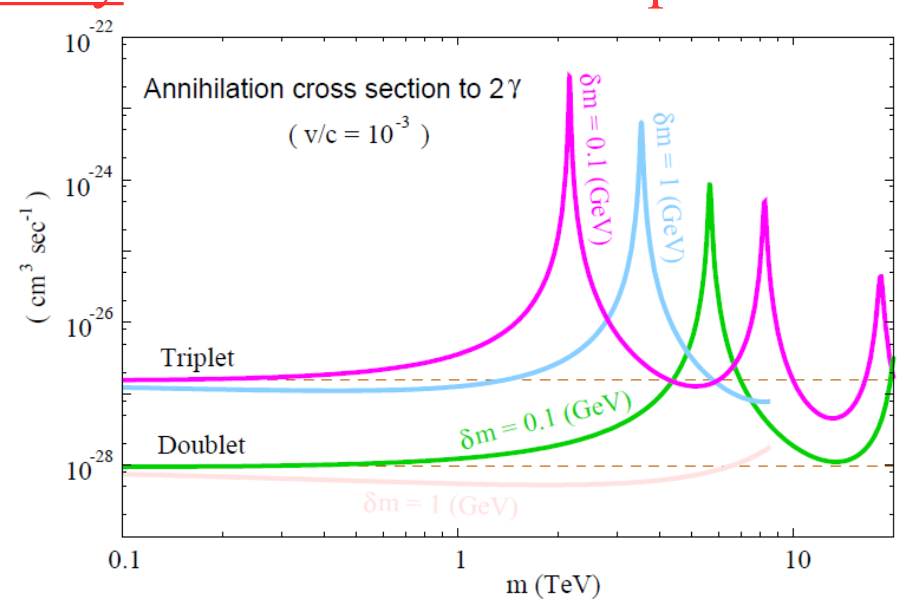


Hisano, Matsumoto, Nojiri



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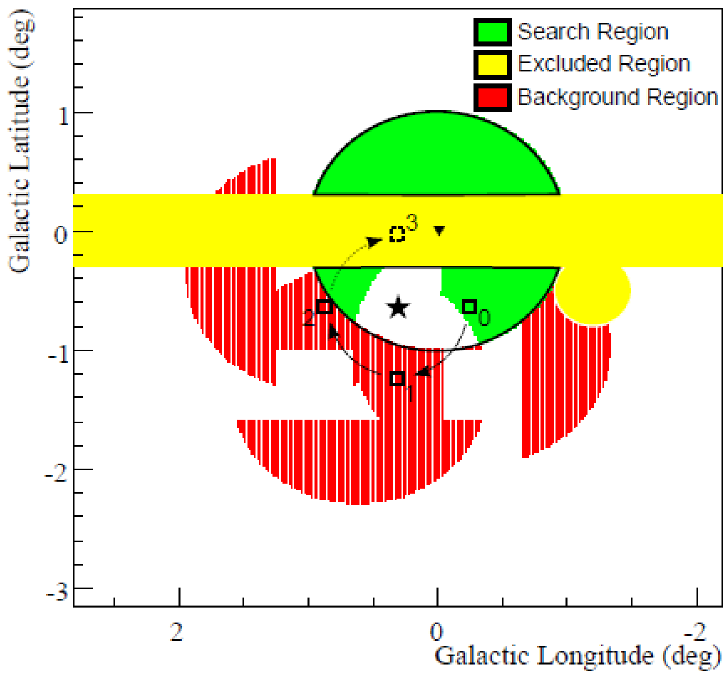

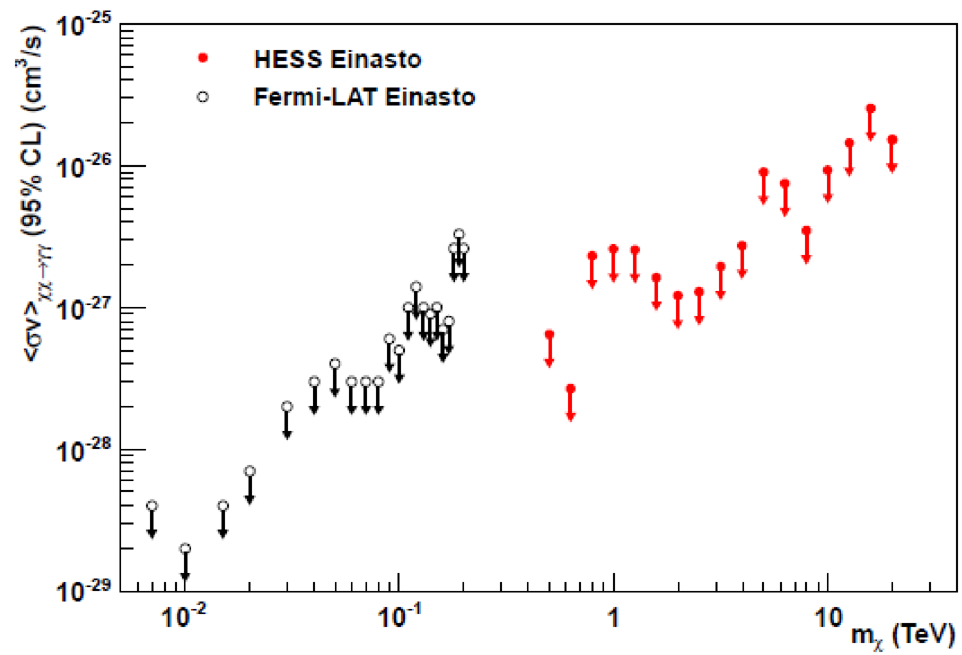

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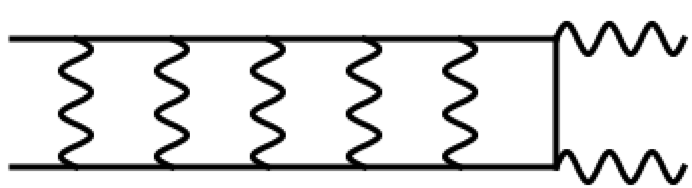
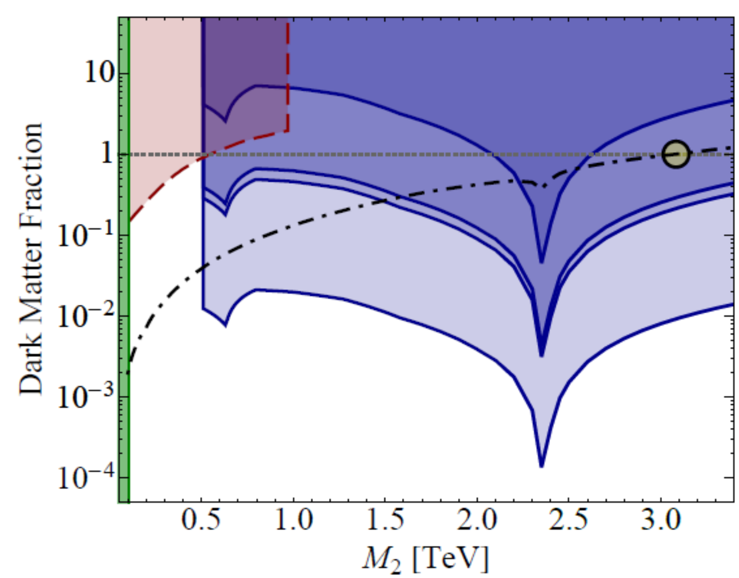
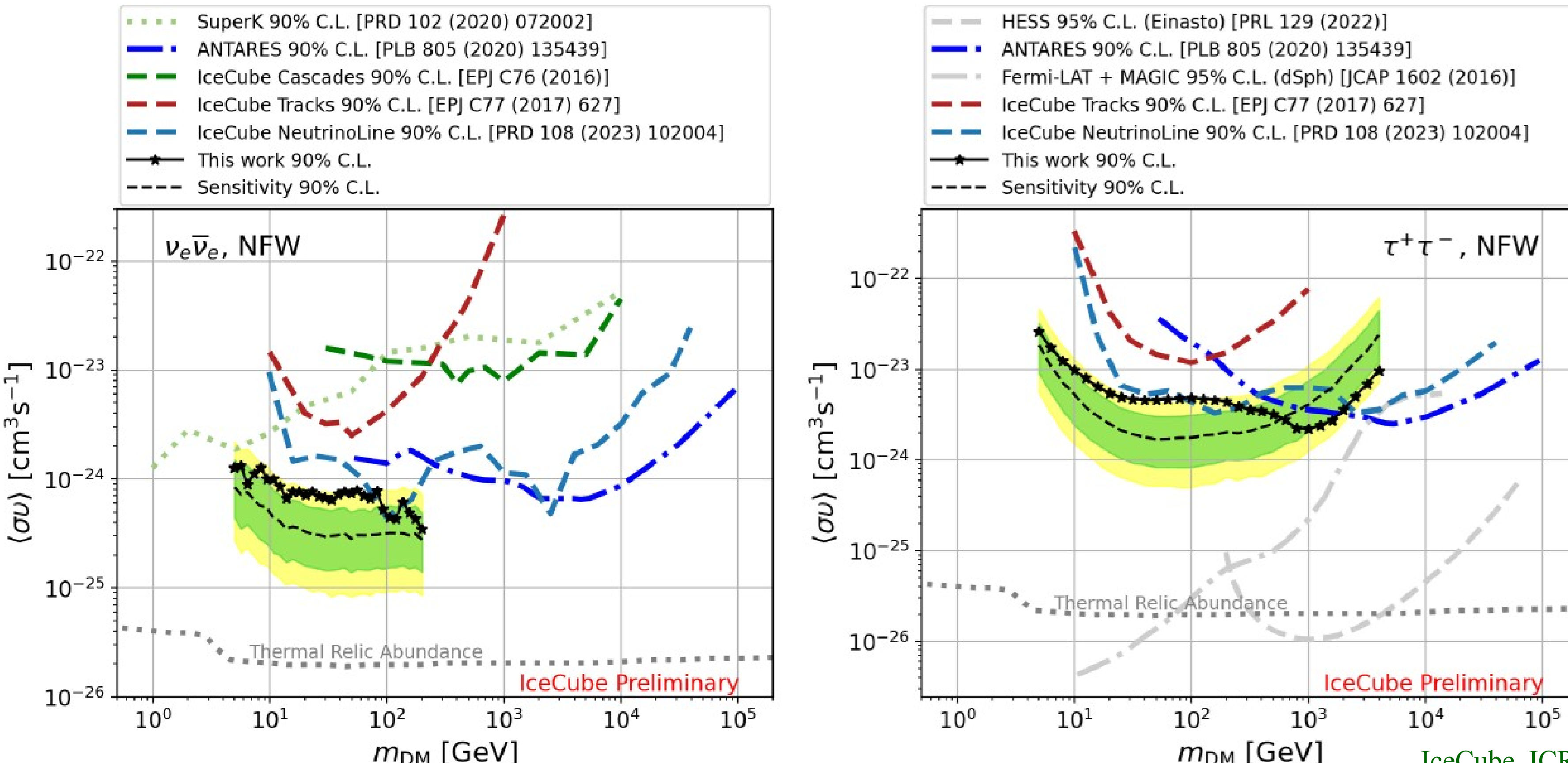


Hisano, Matsumoto, Nojiri



Cohen et al

Neutrinos from dark matter annihilation



IceCube, ICRC'15

Need better instruments, or new targets

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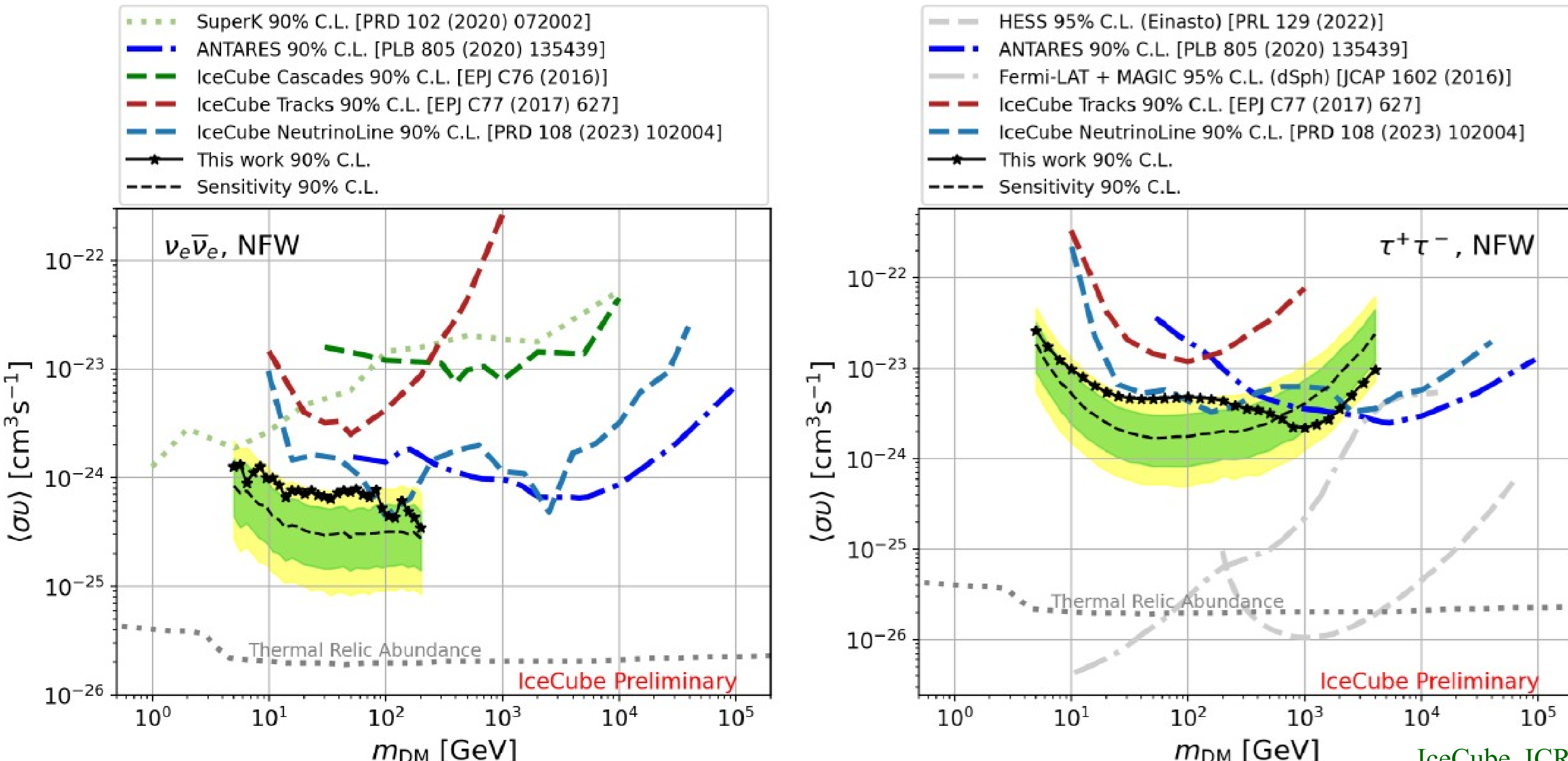


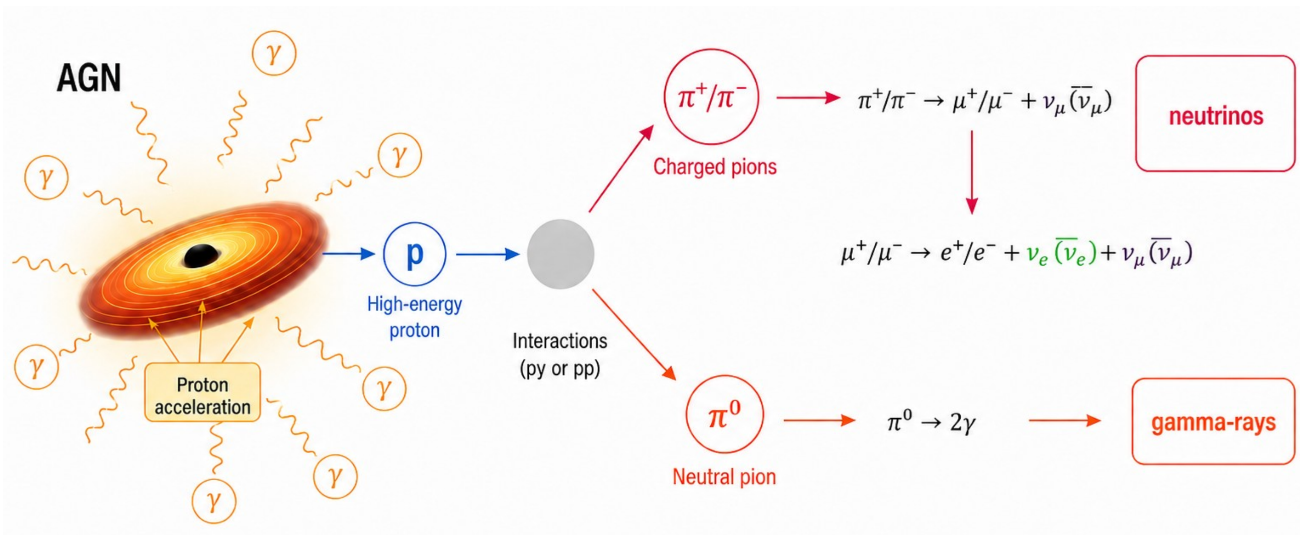
IceCube, ICRC'15

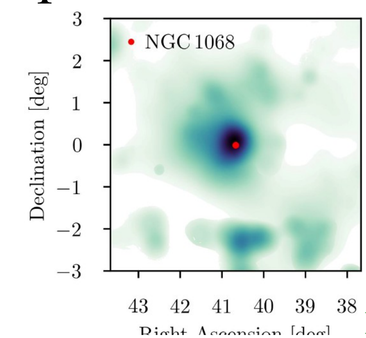
Need better instruments, or new targets

Active Galactic Nuclei as probes of new physics?

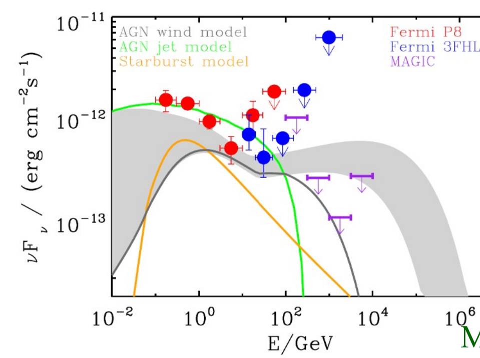
A dark matter signal from NGC 1068?

- IceCube has detected a 4.2σ neutrino excess in the range 1.5-15 TeV in the direction of the Seyfert galaxy NGC 1068, located at 14.4 Mpc from the Earth.

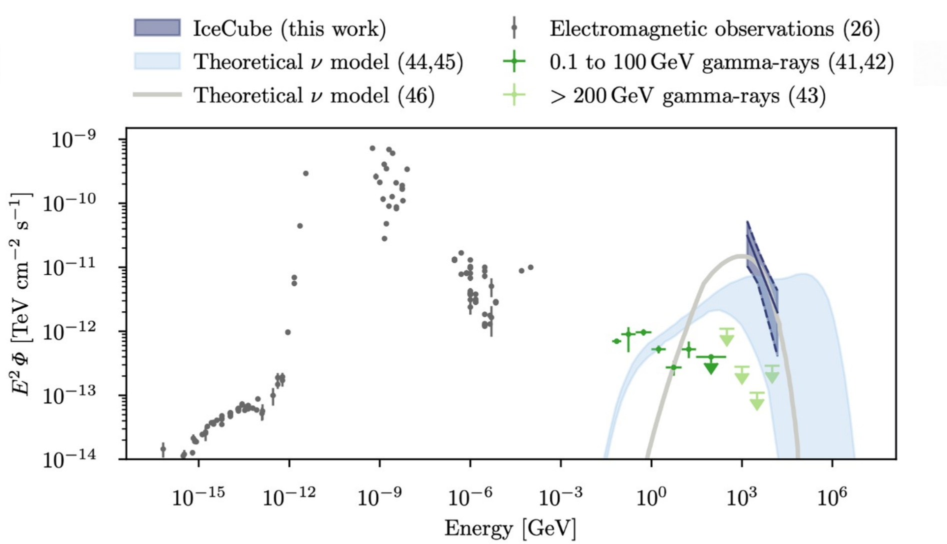


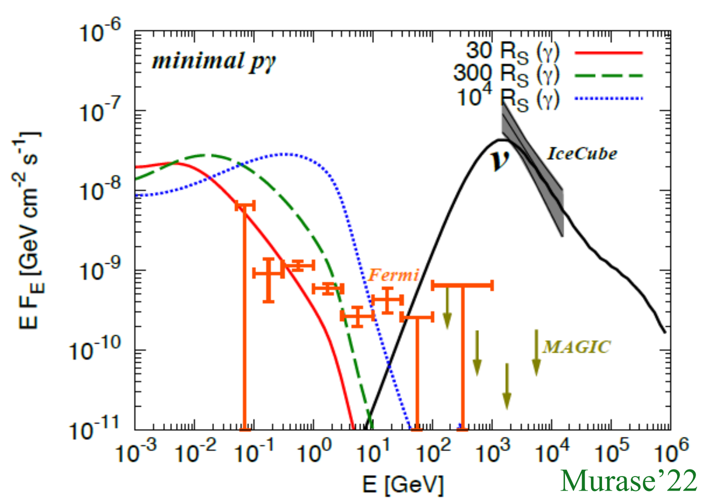


IceCube’22



MAGIC’19





Murase’22

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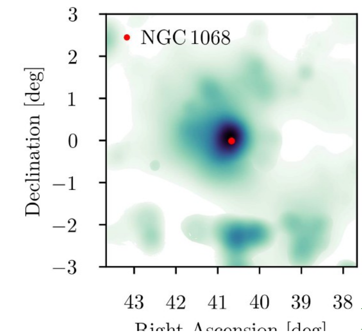
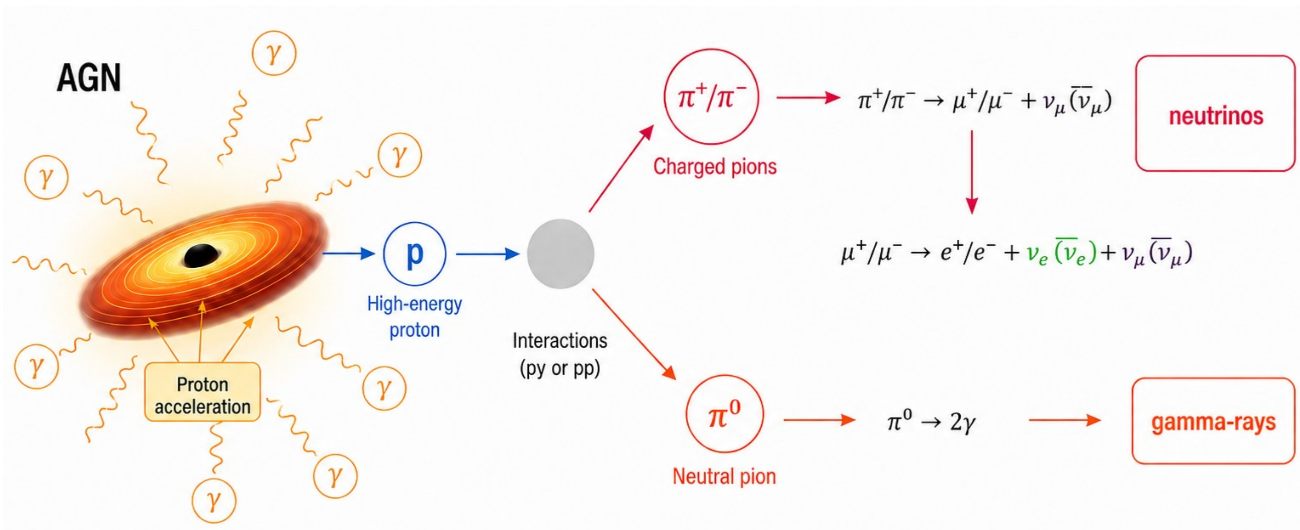
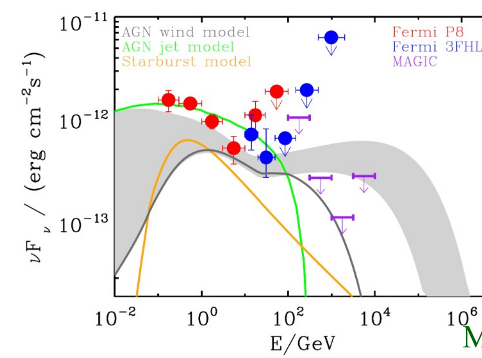


IceCube'22





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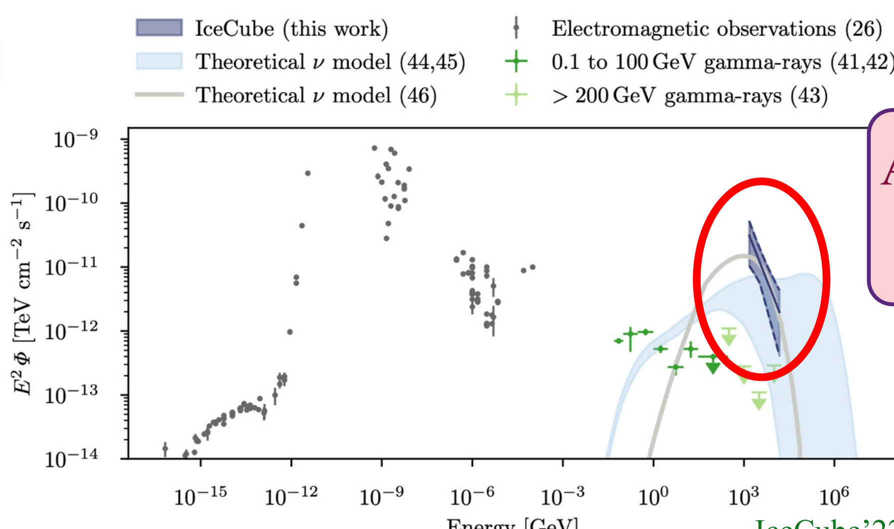

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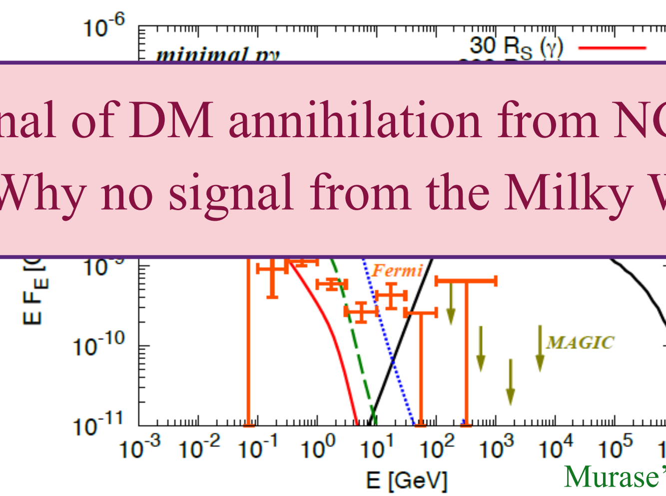


Murase'22

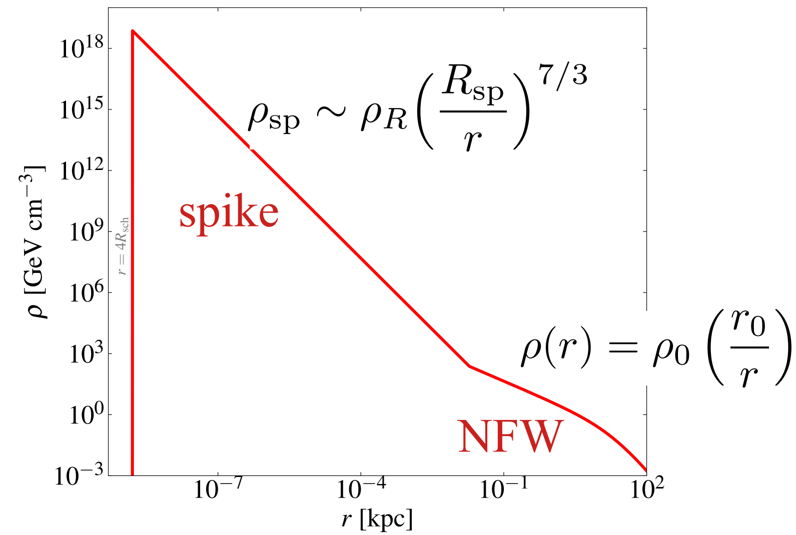
A signal of DM annihilation from NGC 1068?

Why no signal from the Milky Way?

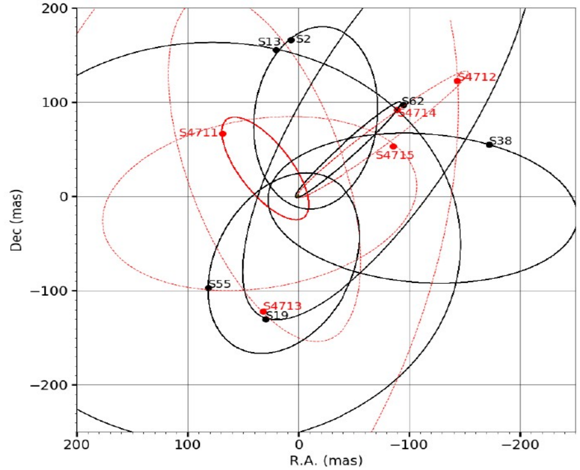
Dark matter spikes in the MW and NGC 1068

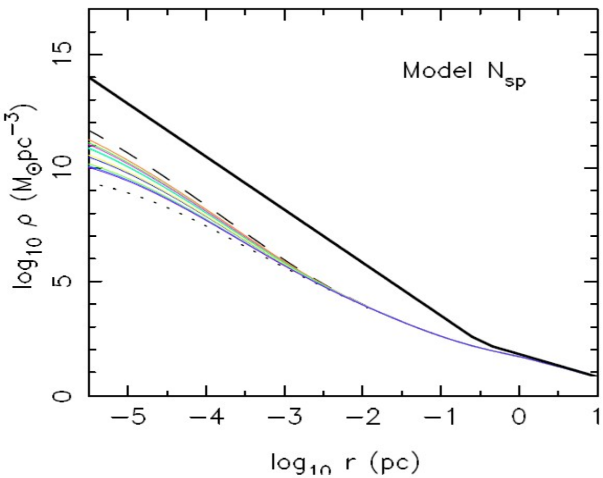
- Most galaxies contain a supermassive black hole at its center.
- The growth of the black hole produces a "spike" in the dark matter distribution

Gondolo, Silk'99,
Peebles '72,
Quinlan, Hernquist, Sigurdsson '95



- However, the Milky Way is known to contain stars orbiting very close to the supermassive black hole. Stellar heating significantly softens the spike.





Merritt'03
Bertone, Merritt'05

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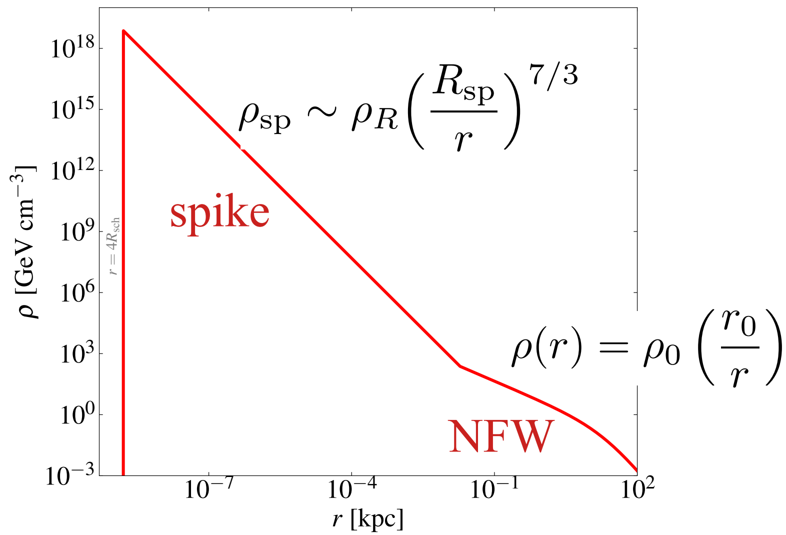
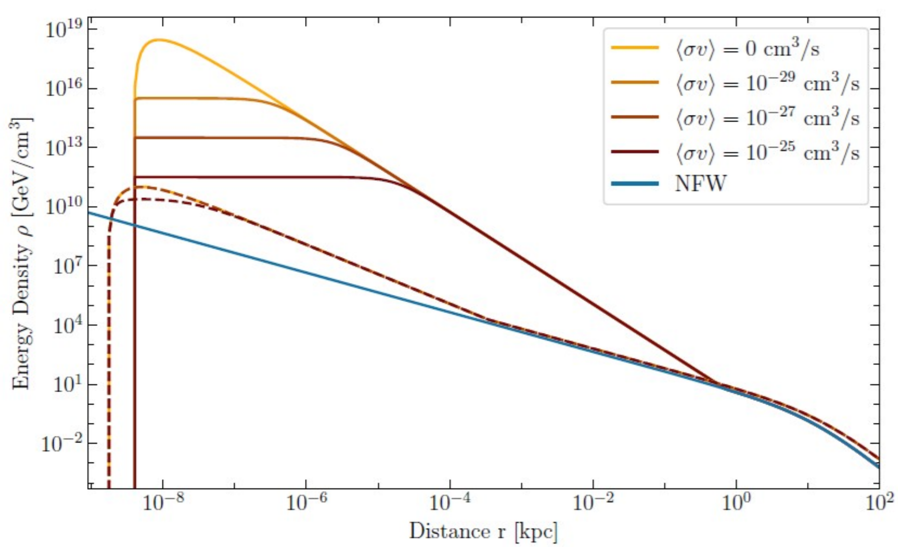
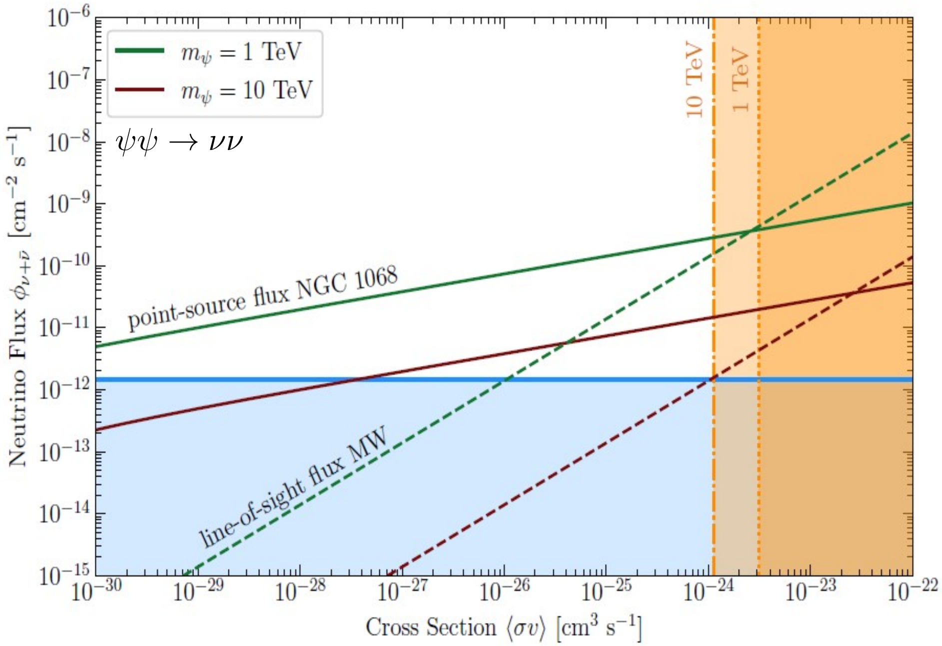


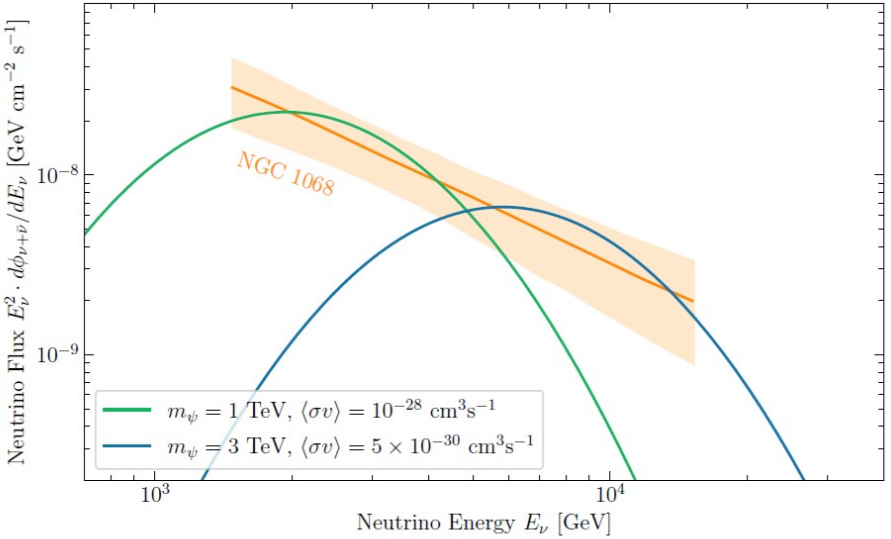
- Stellar heating might not occur in other galaxies, and in particular in AGNs. The DM spike might remain intact.



ÂI, Akita, Zimmermann'25,

A dark matter signal from NGC 1068?



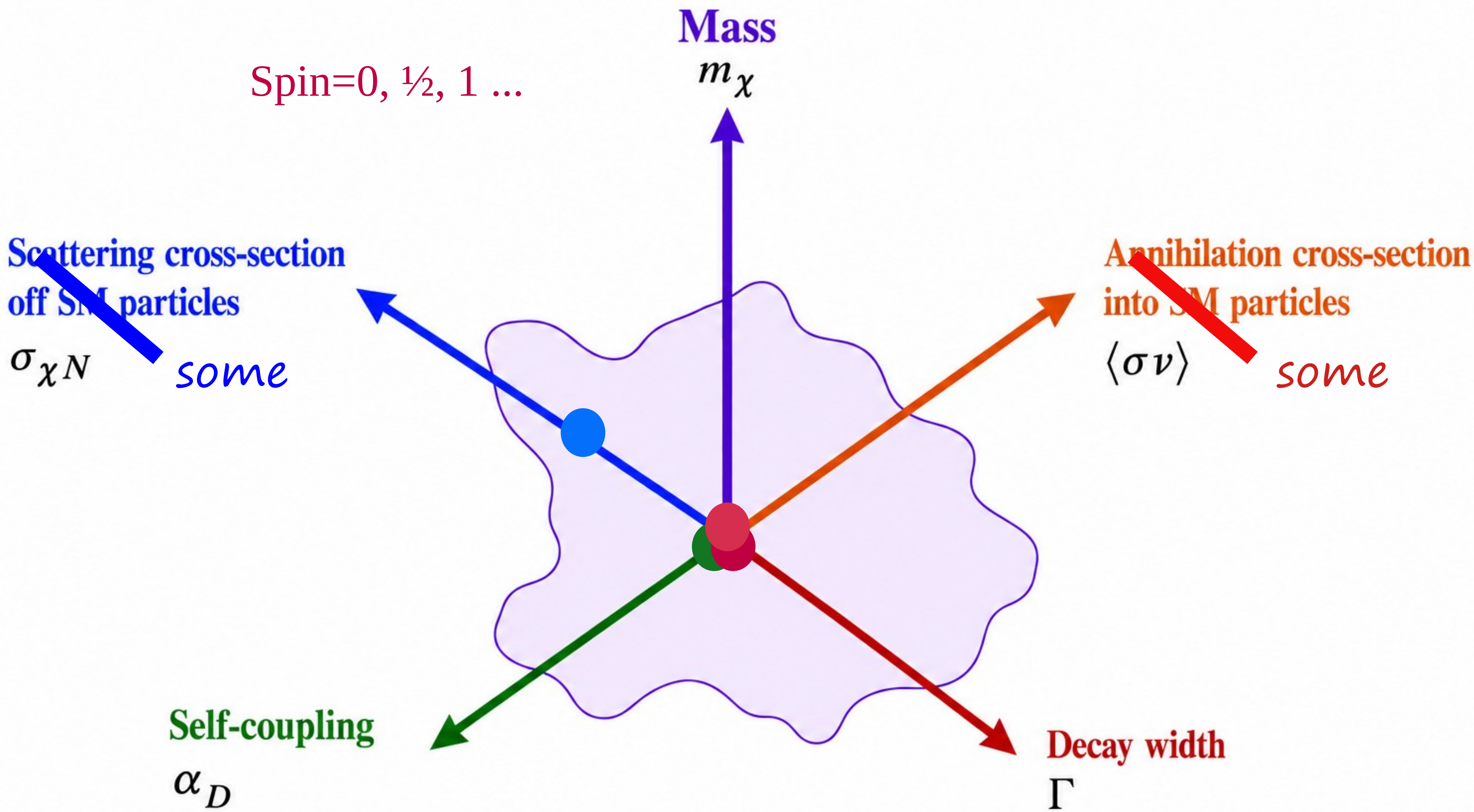


Akita, AI, Zimmermann'25

- Dark matter annihilations in the spike of NGC 1068 could produce a neutrino flux detectable at Earth as a point source (for reasonable values of the cross-section).
- The neutrino flux produced in the Milky Way center is below the sensitivity of current experiments, due to the effect of the stellar heating on the spike.

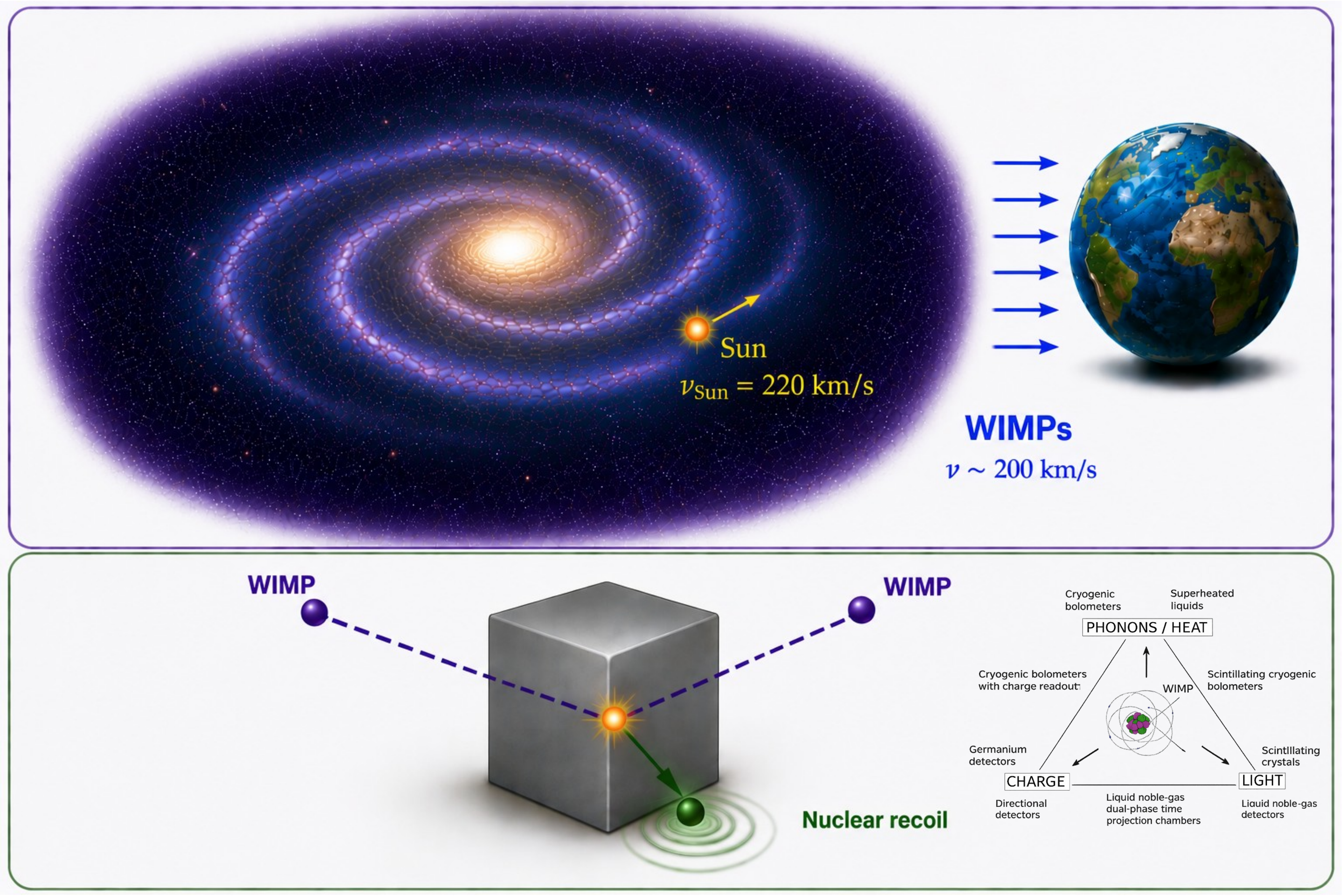
NGC 1068 an other nearby active galaxies are potentially interesting targets for dark matter annihilation.

Particle Dark Matter Parameter Space

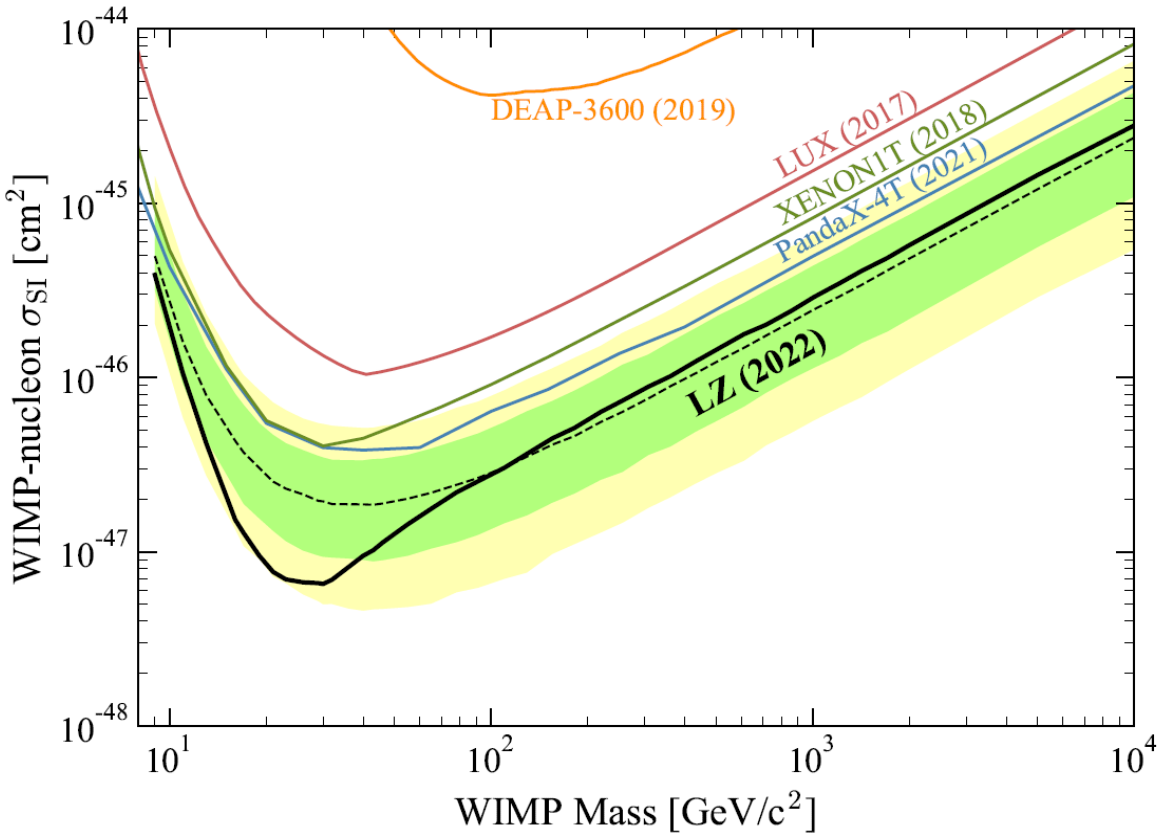


Dark matter searches

Probing DM scattering with nucleons

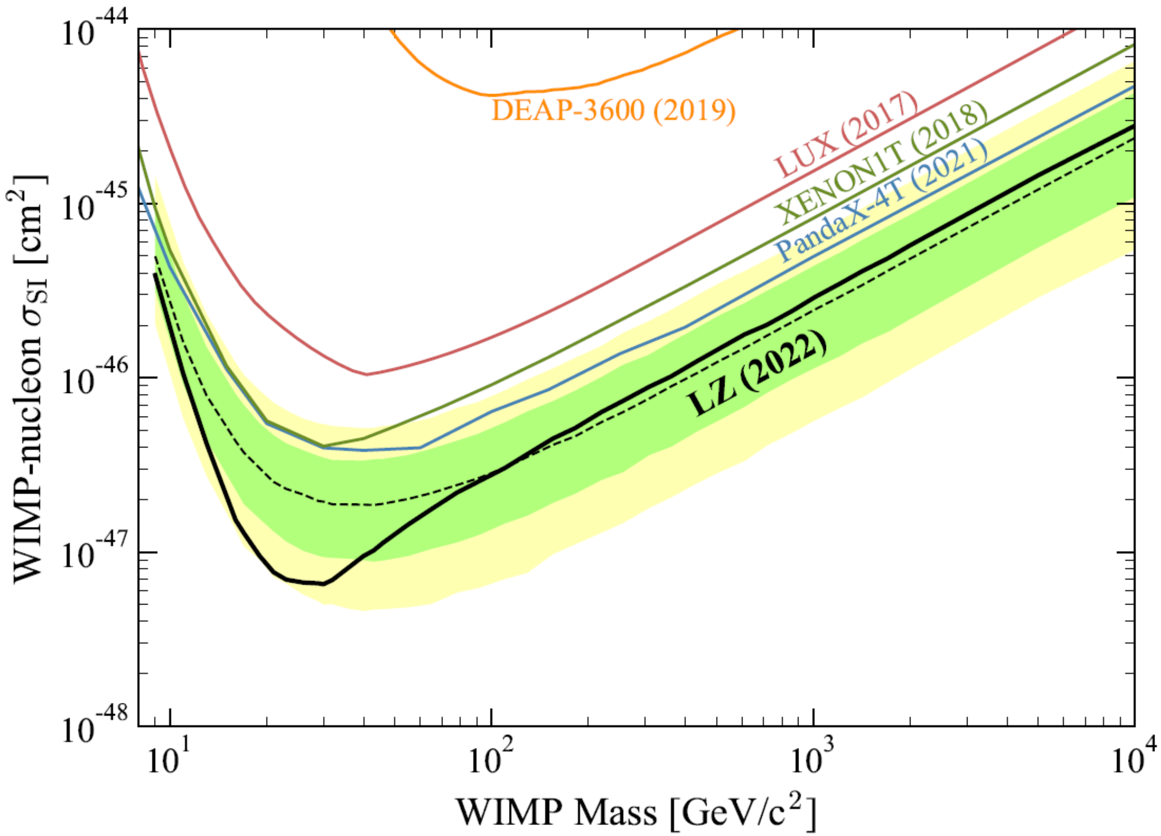


Probing the scattering with nucleons



$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \, \frac{{\rm d}\sigma}{{\rm d}E_R}$$

Probing the scattering with nucleons



Beware of the smallprint:

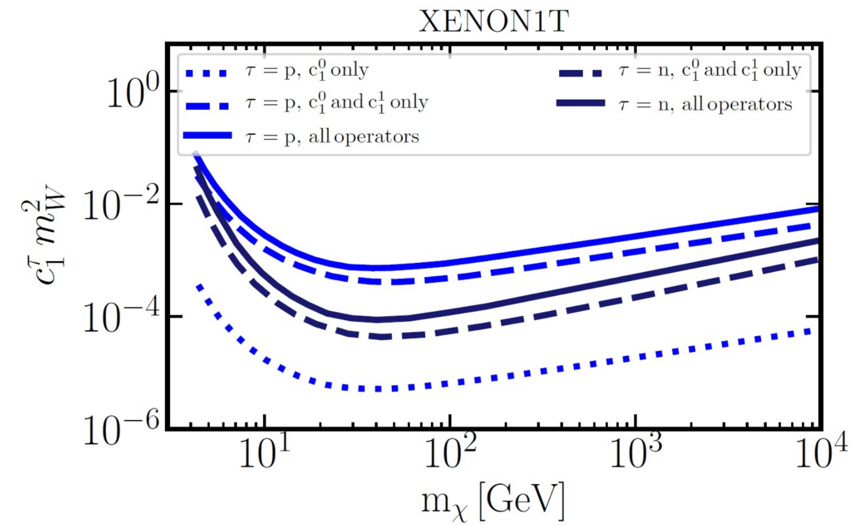
- DM interacts only through the spin-independent interaction
- DM couples with equal strength to protons and neutrons (isoscalar)
- Local DM density ρ=0.3 GeV/cm3.
- DM velocity distribution given by a Maxwell-Boltzmann, truncated at the escape velocity.

Probing the scattering with nucleons

Several efforts to investigate more general scenarios.

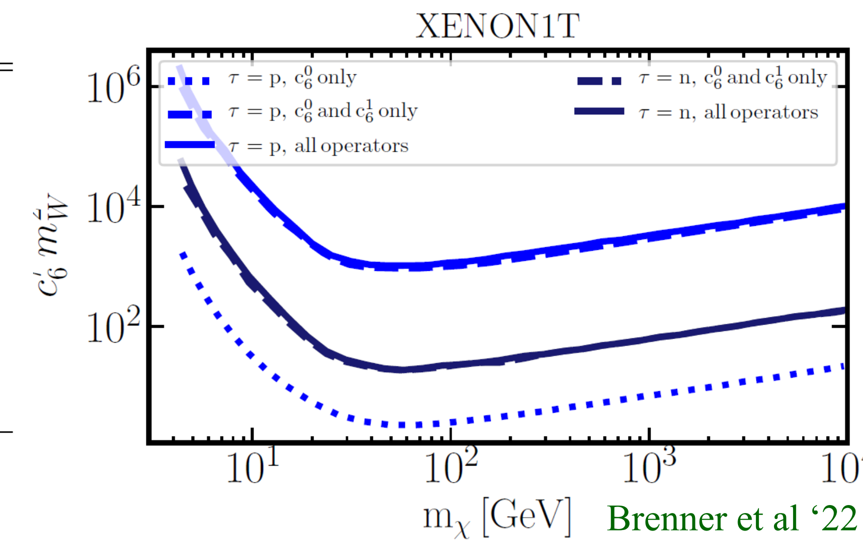
- Scenarios without isospin invariance

$$\mathcal{H} = c_p(\overline{\chi}p)(\overline{p}\chi) + c_n(\overline{\chi}n)(\overline{n}\chi)$$



- Non-relativistic theory of DM-nucleon interactions

$\mathcal{O}_1 = 1_\chi 1_N$	$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$
$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$
$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$	$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})$



Brenner et al '22

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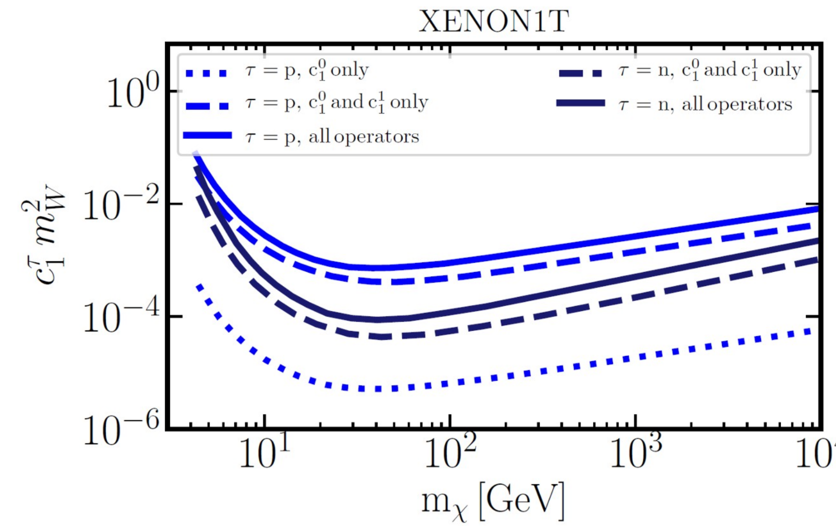

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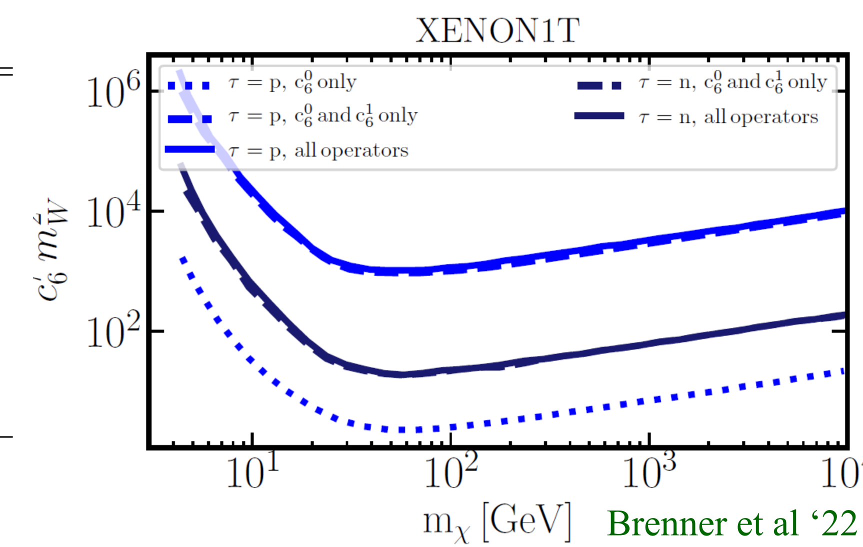
Pseudoscalar mediator



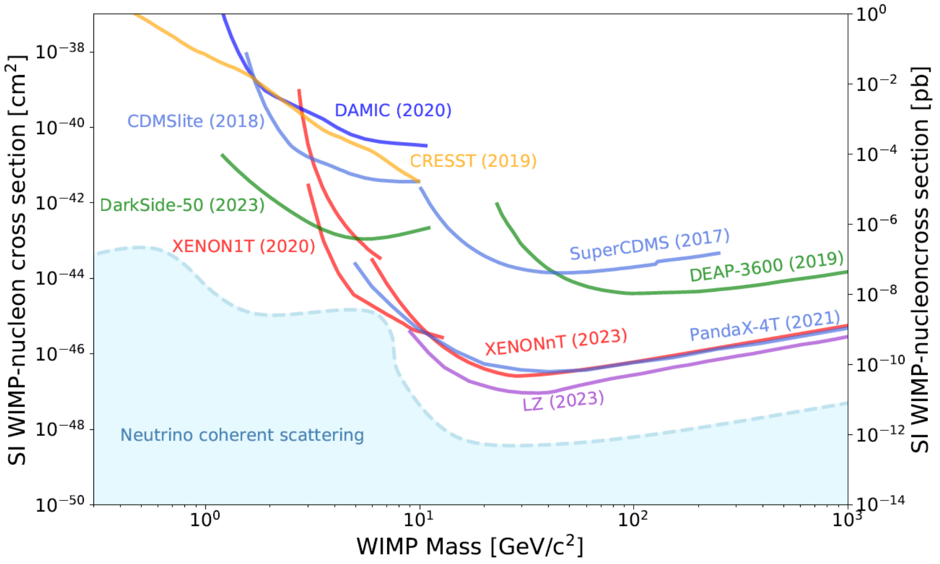
Brenner et al '22

Current experiments very sensitive to the O_1 and O_4 operators ("standard" SI and SD)
Still poorly sensitive to other scenarios, some of them well motivated theoretically.

Probing light dark matter

The region of light dark matter is still largely uncharted in direct detection experiments.

Several new ideas proposed to detect light DM



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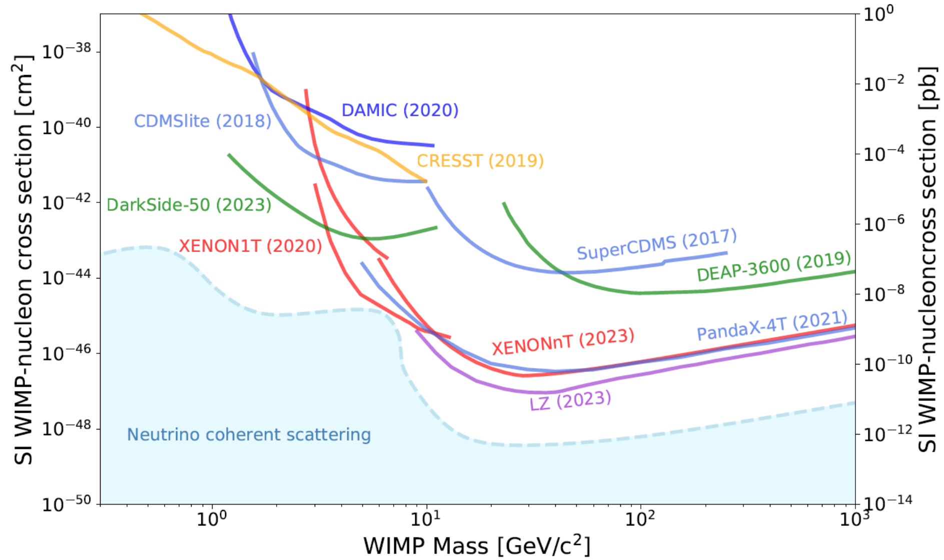
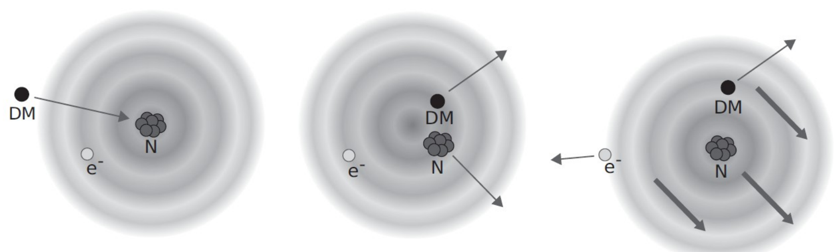
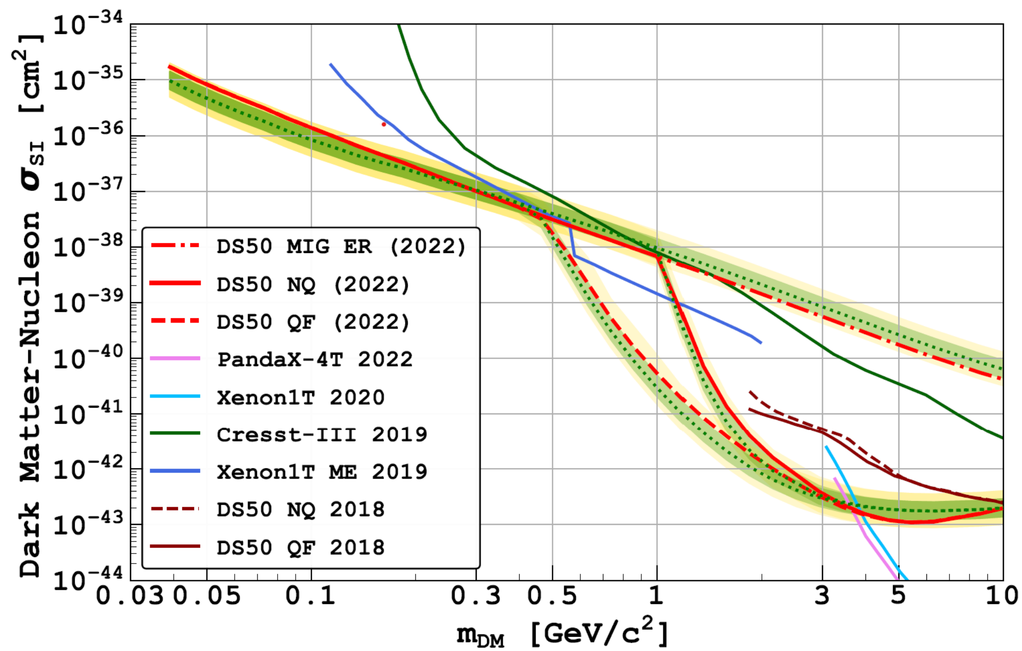


- The Migdal effect

- Proposed in 1931 as a possibility to ionize atoms with neutron projectiles.

- The electrons from the ionization can be used to detect light dark matter when the nuclear recoil is undetectable





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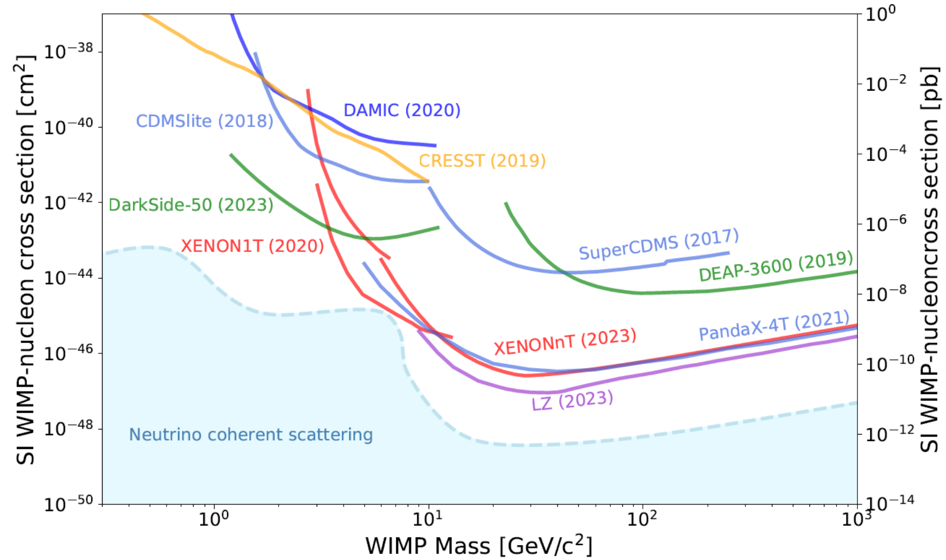

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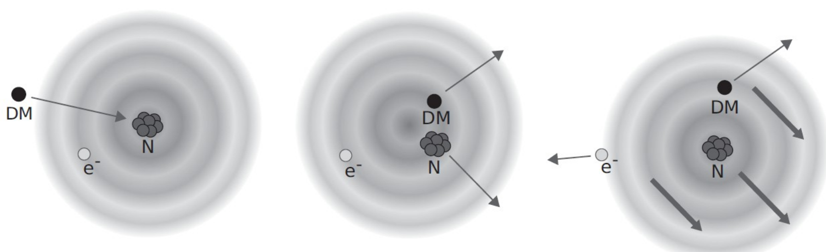

Article

Direct observation of the Migdal effect induced by neutron bombardment

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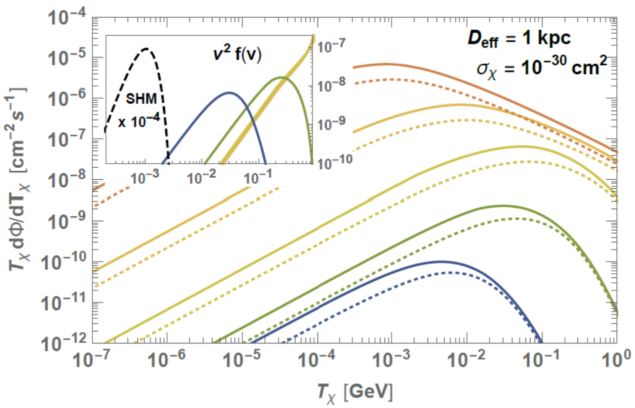
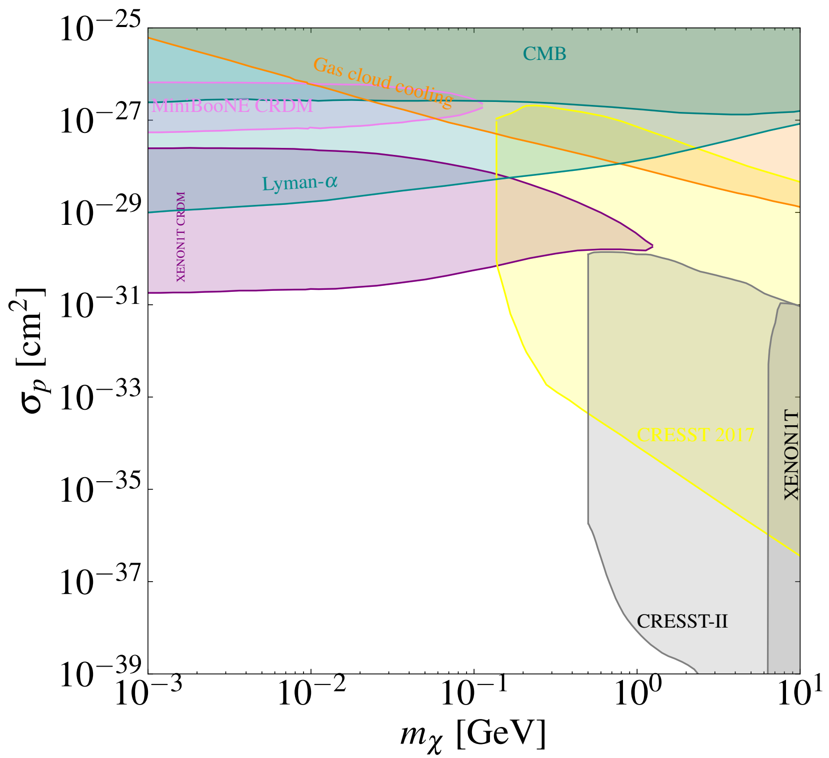
The search for dark matter focuses now on hypothetical light particles with masses ranging from MeV to GeV (refs. 1–12). These particles would leave very faint signals experimentally. A potential avenue for enhancing experimental sensitivity to light matter relies on the Migdal effect[13–15], which involves the detectable ejection of

Probing light dark matter

- Boosted dark matter

- A dark matter particle at rest in the galaxy can recoil due to collisions with energetic cosmic rays Bringmann, Pospelov '18





Probing light dark matter

- Boosted dark matter

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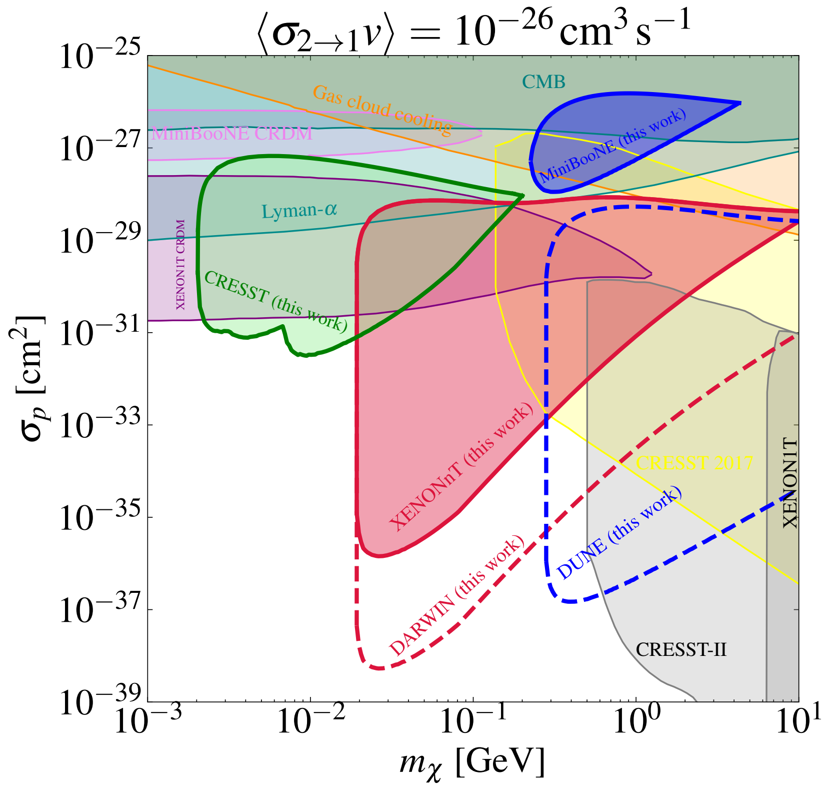
- There are other sources of boosted DM, for example, semi-annihilations in the Milky Way center:

$$\chi\chi \to \chi^c \phi$$

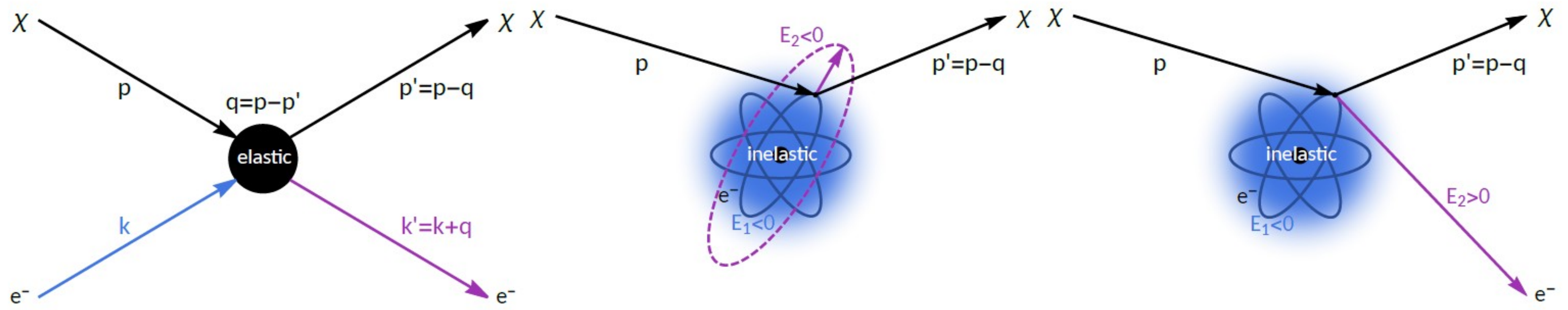
(SU(2) symmetry, Z3 symmetry ...)

- Fixed dark matter energy $T_\chi = m_\chi/4$
- Large improvement in sensitivity.
- Neutrino detectors (MiniBooNE, DUNE) are sensitive to boosted dark matter from semiannihilations.

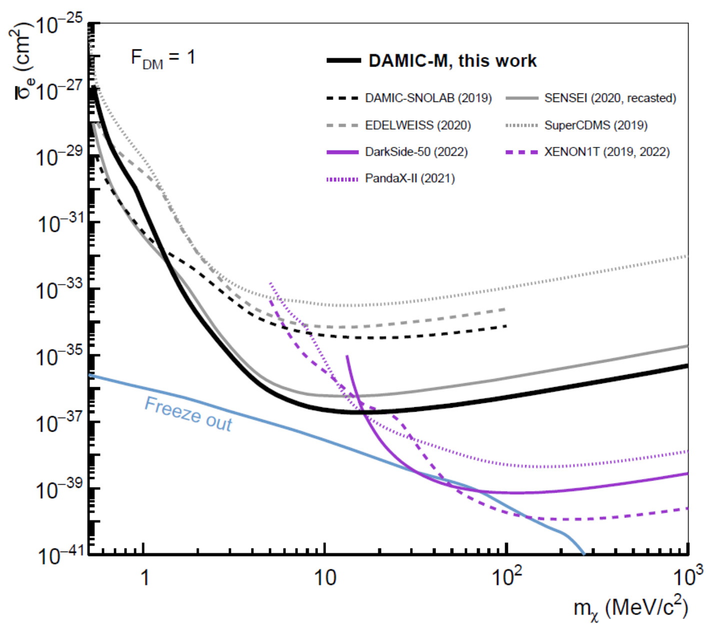


Betacourt et al '26

Probing DM scattering with electrons



From Catena et al'20



Conclusions

- After 40+ years of search, there is still no concluding evidence that dark matter is made of elementary particles.

- "Traditional" searches put some tension on some WIMP scenarios. Many other scenarios still poorly constrained by data.

- Better experiments are needed, and also new ideas for dark matter detection.

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