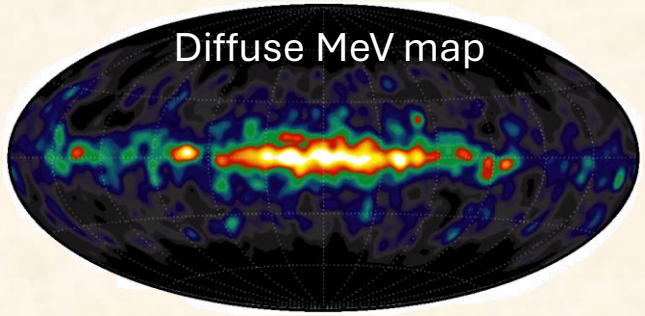
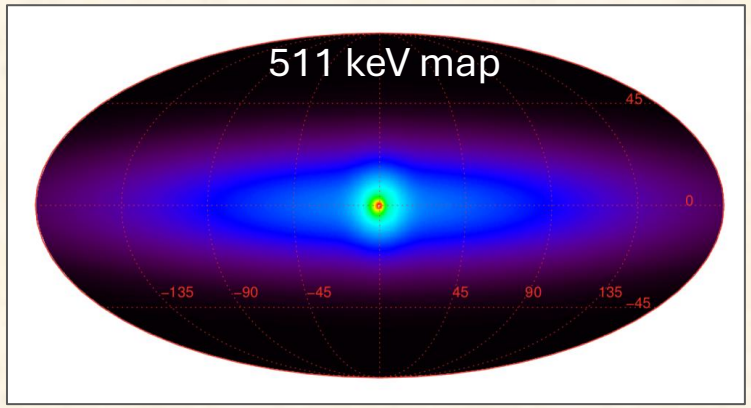
511 keV photons from dark matter in the Galactic Center

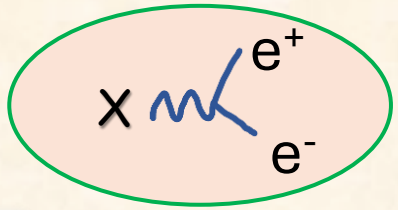


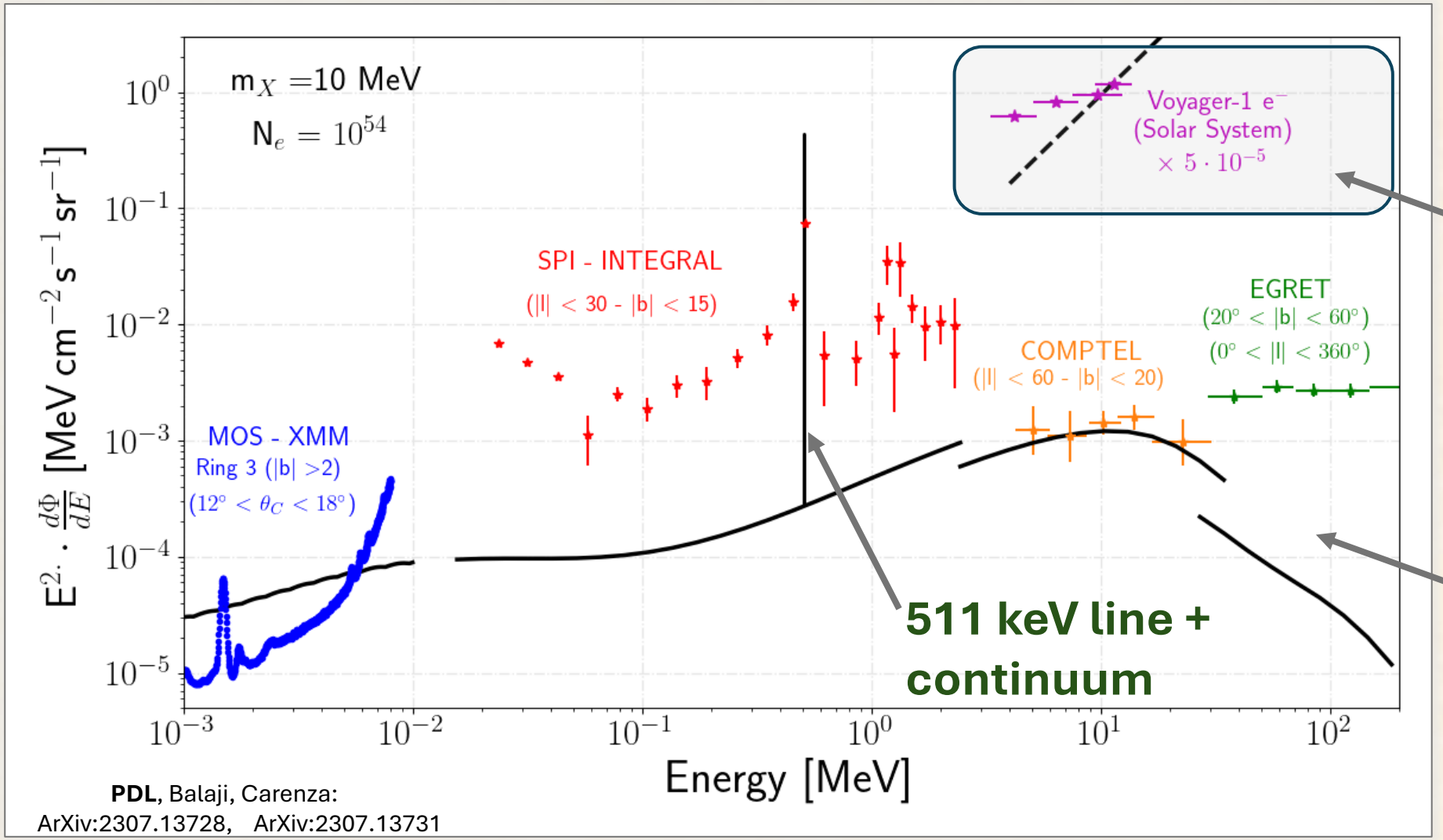


Pedro de la Torre Luque --- pedro.delatorre@uam.es
Juan de la Cierva fellowship (IFT/UAM - Madrid)

Recontres du Vietnam - TMEX
07/01/2025

Positron-induced diffuse emissions





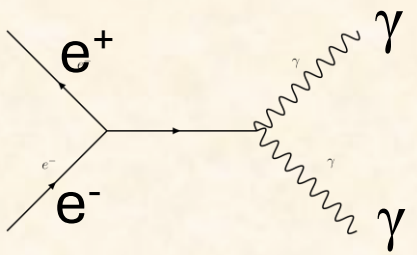
Cosmic rays

511 keV line + continuum

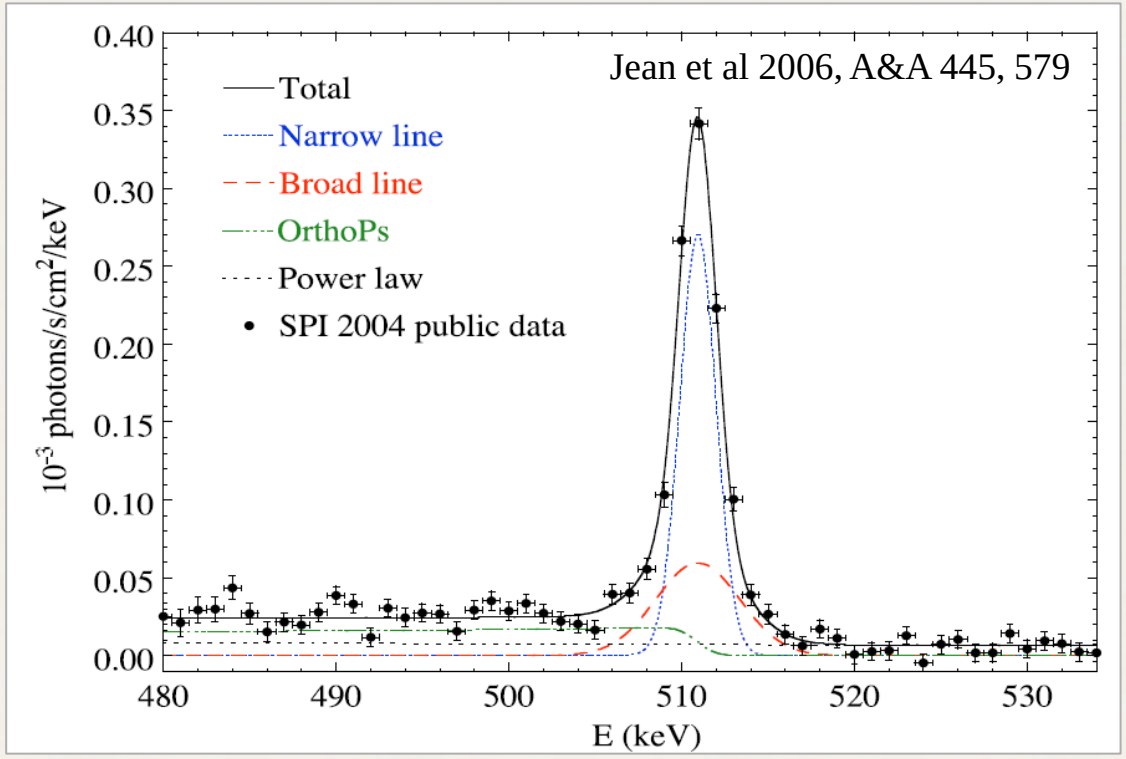
X-ray and γ-ray

PDL, Balaji, Carenza:
ArXiv:2307.13728, ArXiv:2307.13731

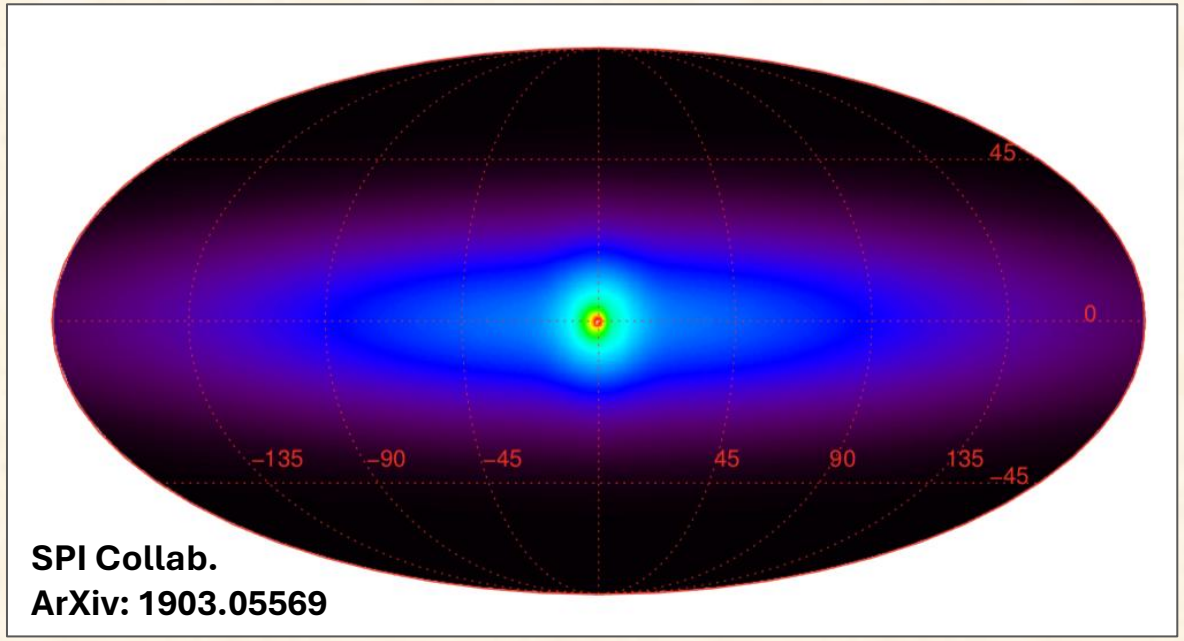
The 511 keV puzzle



A steady injection of positrons is revealed by the observations of a bright and diffuse line at 511 keV since the 70s. However, the origin of the distribution and intensity of this line remains a mystery



Very peaked emission towards the center (**bulge emission**) + a very extended **disk emission**

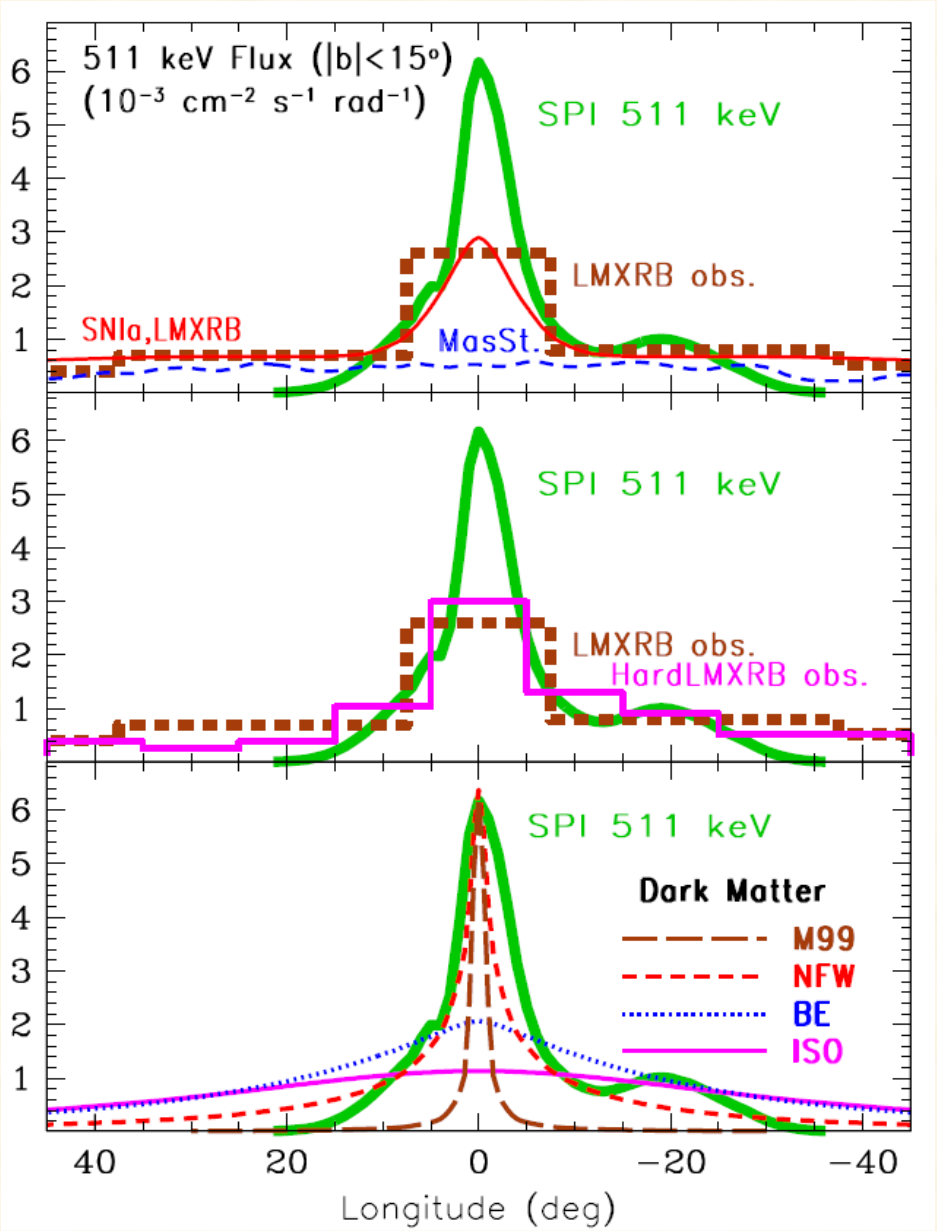


Possible positron sources

Known sources contributing with the disk emission are pulsars injecting $e^{\pm}$ or sources synthesizing β^{+} radioactive elements (e.g. ^{26}Al in massive stars, ^{24}Ti in CC-SNe or ^{56}Ni in SN 1A)

The measured bulge emission requires a spatial morphology and injection rate that does not seem to easily fit with known candidates, such as low-mass X-ray binaries, SN 1A or other sources expected to be located around the Galactic centre

Prantzos et al RevModPhys.83.1001

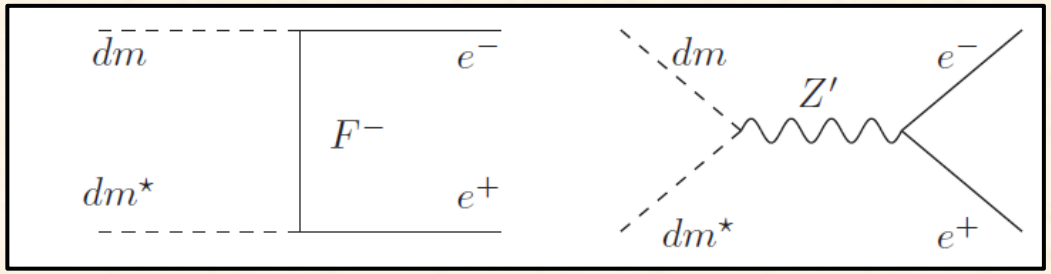


Possible positron sources

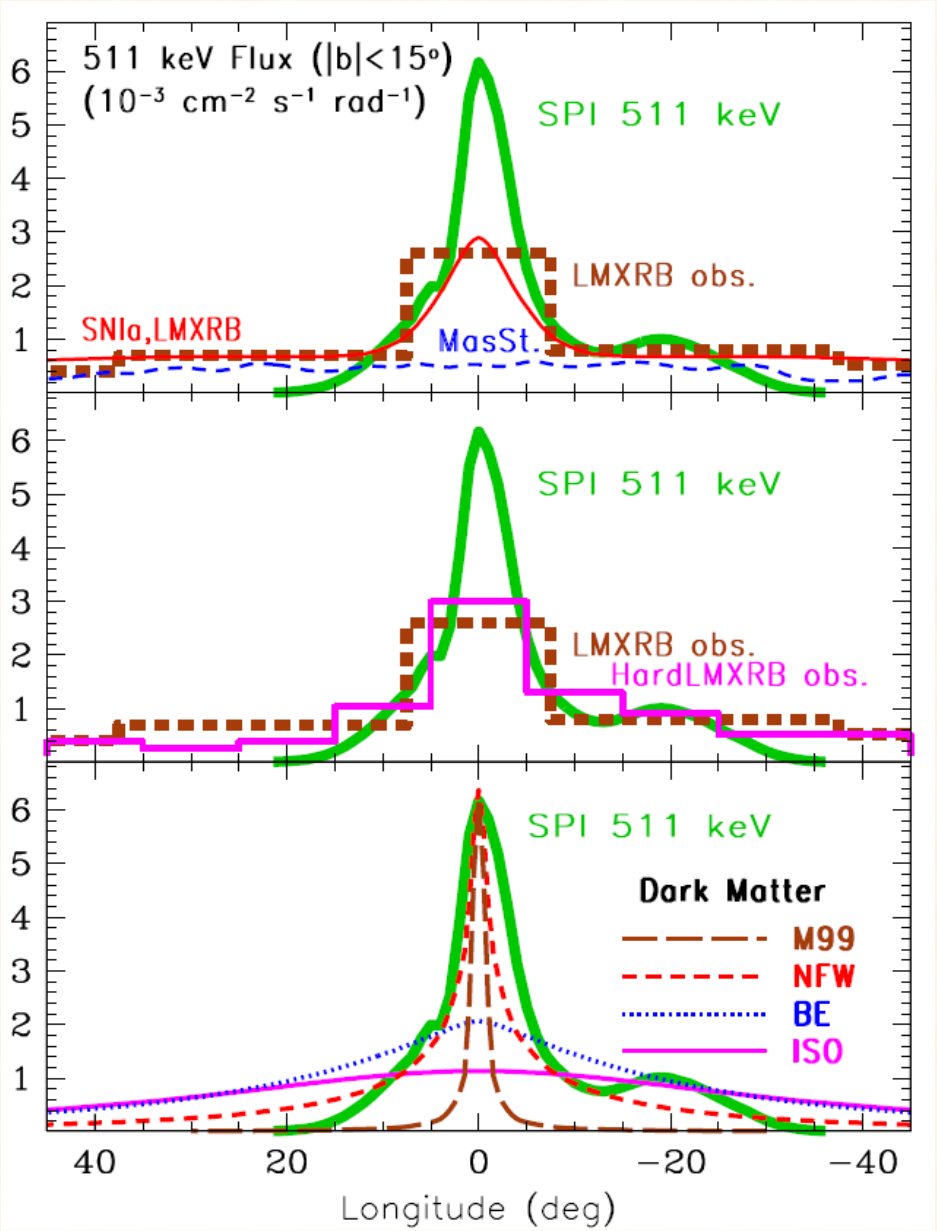
Sub-GeV DM (≤hundreds MeV) was proposed as a solution by Boehm et al! (PRL92:101301,2004)

It was soon realized that a cored DM profile cannot explain observations. Also, DM decay or velocity dependent cross section are ruled out

Sub-GeV DM is compatible with BBN and CMB constraints only for $m_\chi > \sim$1-10 MeV

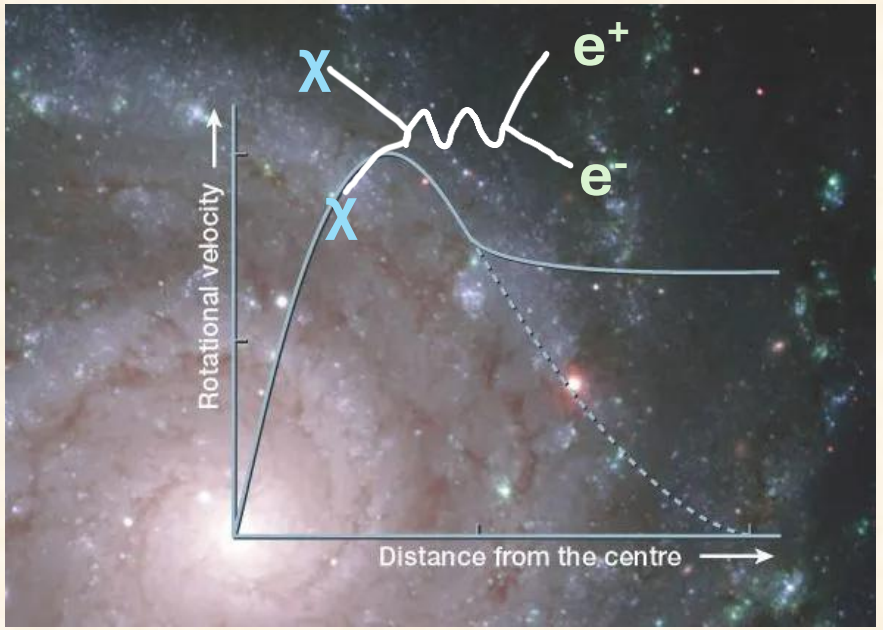


Prantzos et al RevModPhys.83.1001



e^+e^- from MeV DM

- Electrons and positrons interact with the Galactic magnetic field and the ISM
- DM particles heavier than tens of MeV would produce $e^{\pm}$ than travel up to 100s of parsecs before thermalizing (**PDL**, S. Balaji, J. Silk ArXiv:2312.04907)



The diffusion equation in this case can be approximated as:

$$\vec{\nabla}\cdot(-D\nabla N)+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N}{p^2}\right)\right]=Q_i+\frac{\partial}{\partial p}\dot{p}N$$

(Neglecting advection from winds)

Diffusion
(D $\propto E^{\delta}$ -- from CR analyses at E>MeV)

Reacceleration
$D_{pp} \propto V_A^2/D$

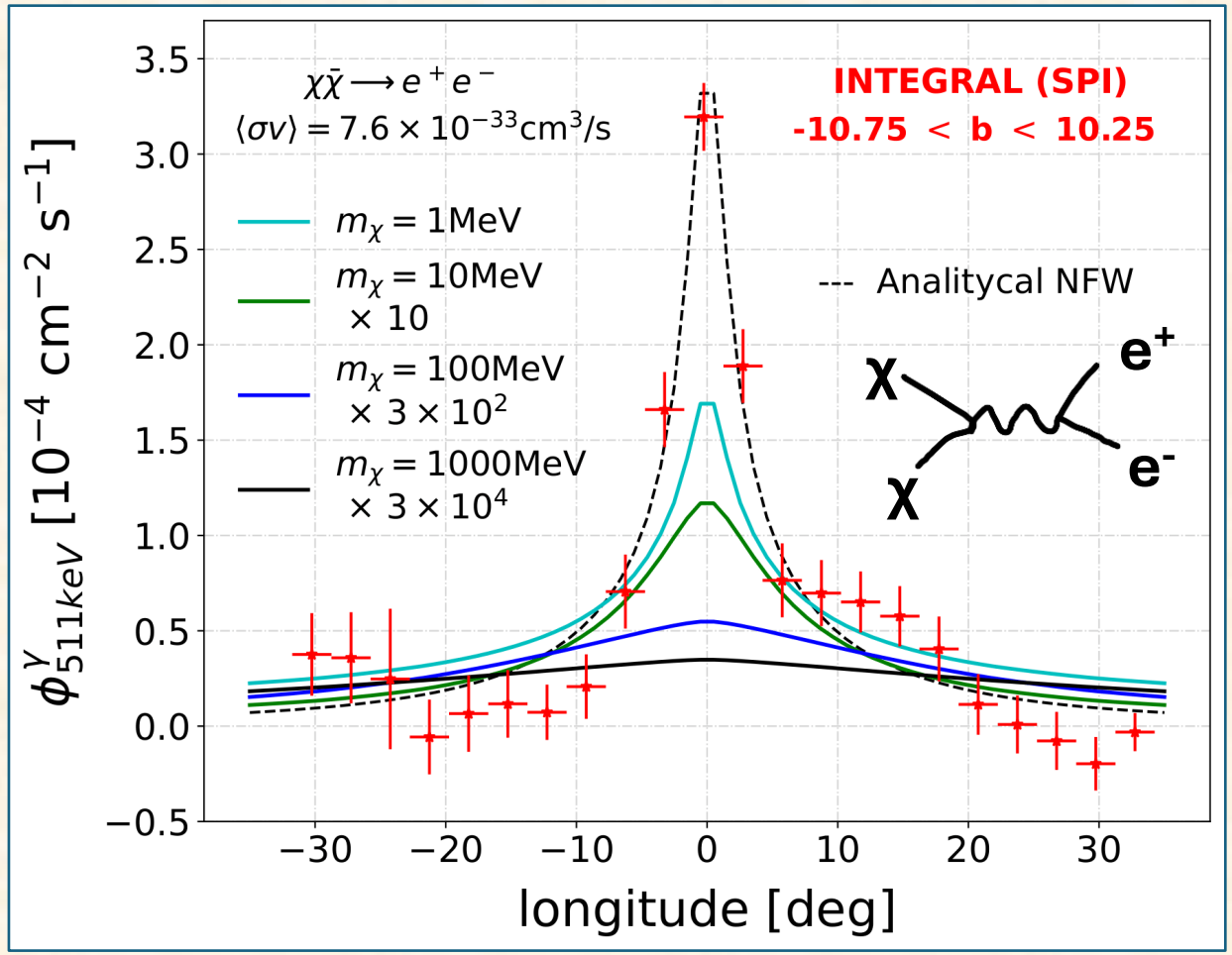
Injection
(following DM distrib.)

Energy losses
(Coul., Ioniz., Brem., IC, Synch.)

Effect of a realistic diffusion

(**PDL**, S. Balaji, J. Silk ArXiv:2312.04907)

Profile of the line follows the distribution of diffuse positron, i.e. $\phi^{511} \sim \phi_{diff}{}^{e^+}$



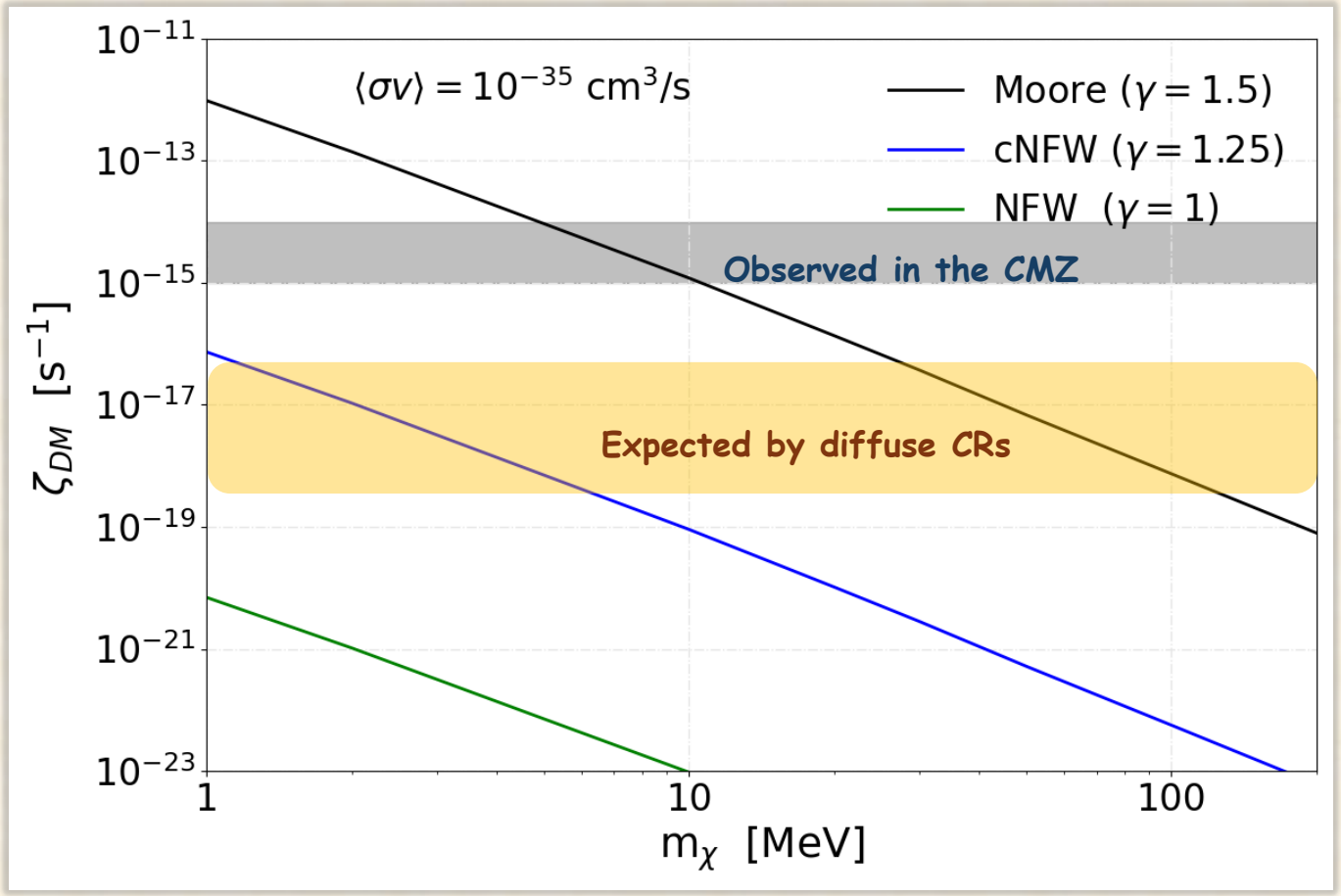
The propagation of the e^+ injected by DM leads to a mass-dependent profile of the expected signal

First consequence: Only positrons injected close to a few MeV will closely follow their source distribution

Second consequence: at higher energy, a NFW profile does not seem to match well the observations (with caveats*)

Correlation with the anomalous CMZ ionization rate?

PDL, Balaji, Silk ArXiv:2409.07515



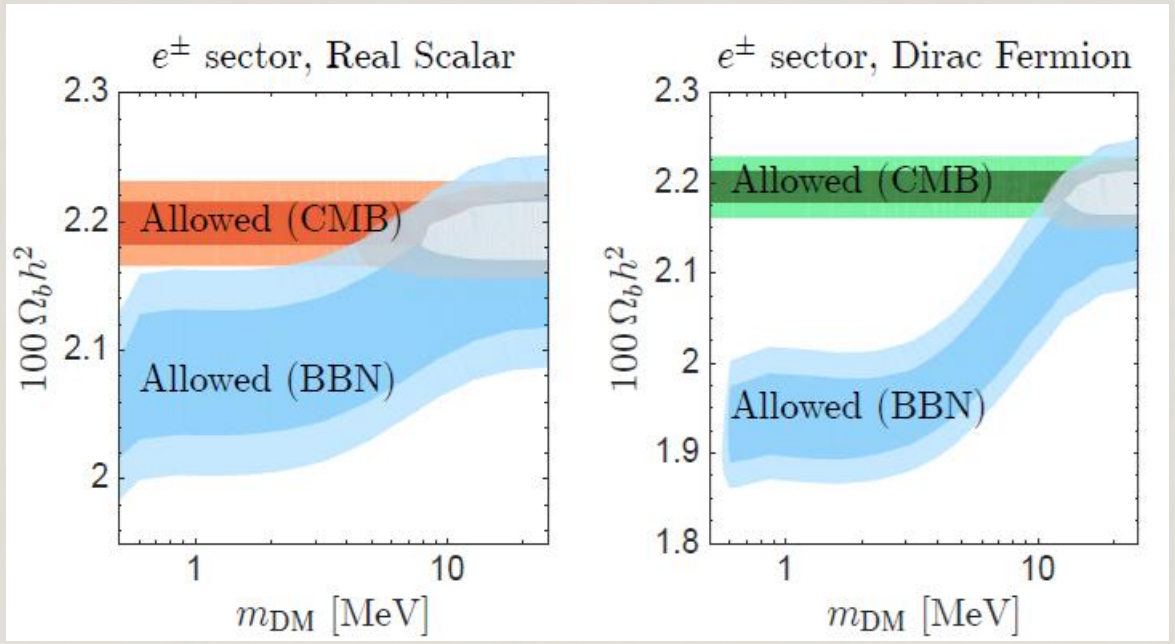
The CMZ ionization rate can be attributed to MeV dark matter annihilation for Galactic dark matter profiles with slopes $\gamma > 1$

The low $\langle\sigma v\rangle$ required avoid current cosmological constraints and imply no detectable IC, bremsstrahlung or synchrotron emissions

The associated continuum emission + cosmological observations killed the DM hypothesis for a while…

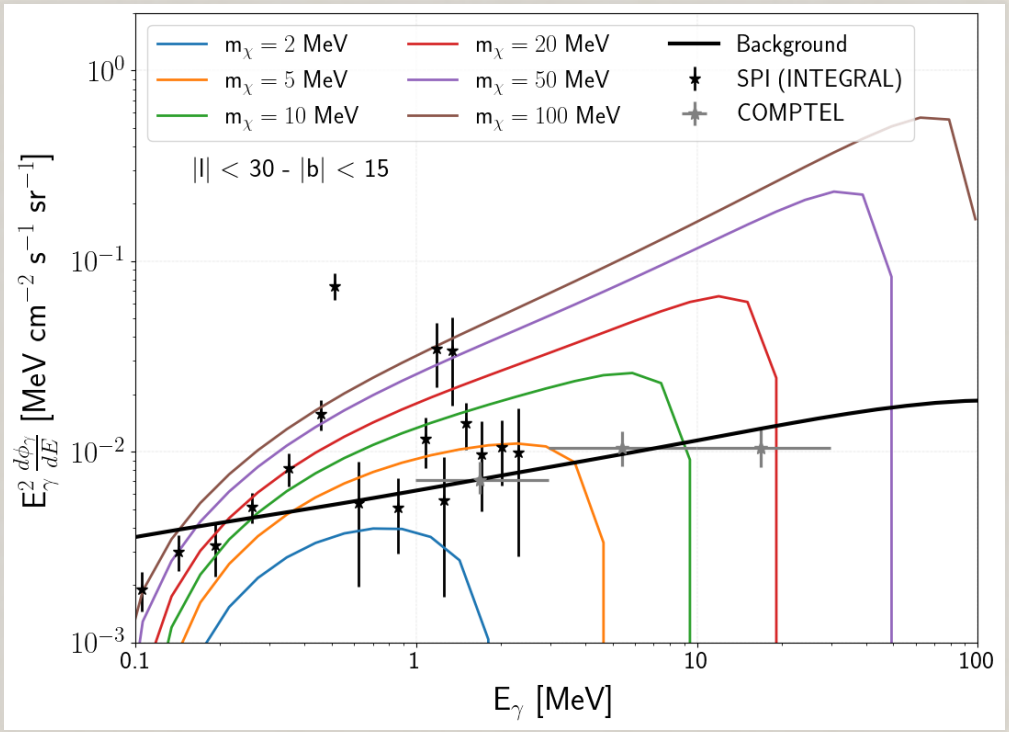
Sub-GeV DM is compatible with BBN constraints only for $m_\chi > \sim$1-10 MeV

Wilkinson et al PRD 94, 103525 (2016)



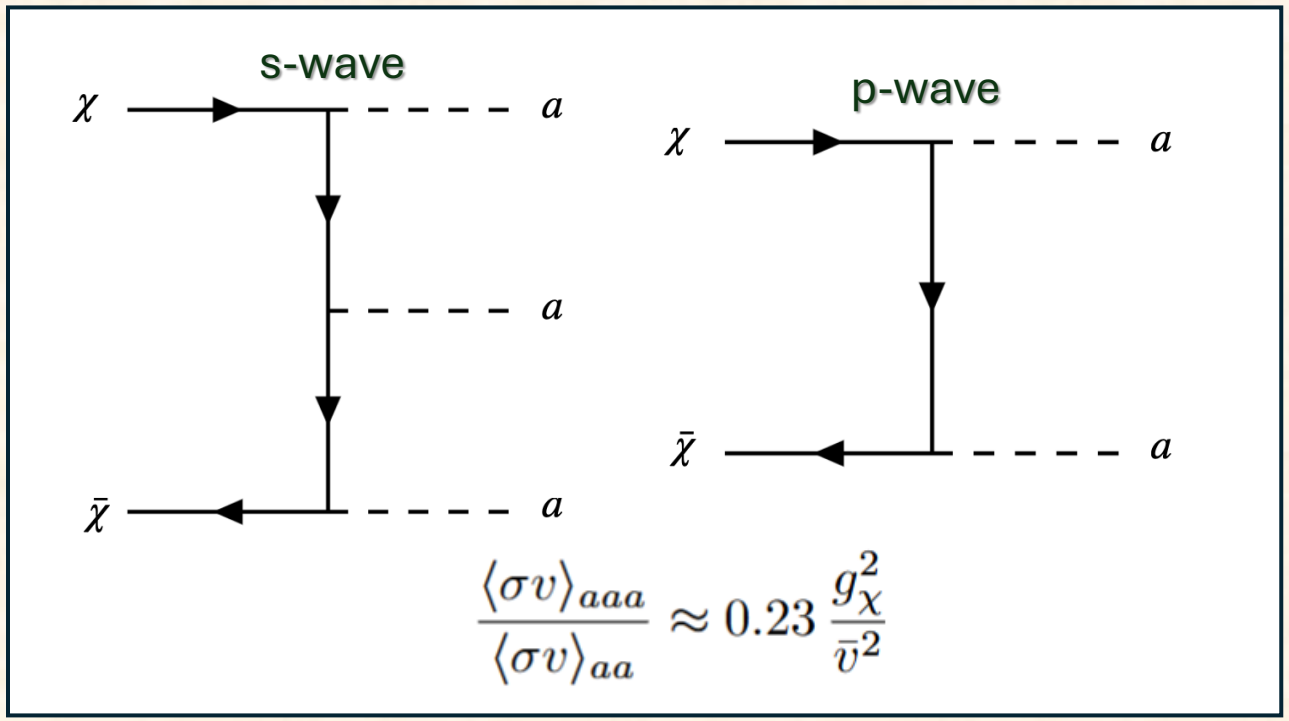
The diffuse MeV gamma-ray emission rules out masses higher than a few MeV if DM is the source of the 511 keV emission

Beacom, Yuksel PRL 2006

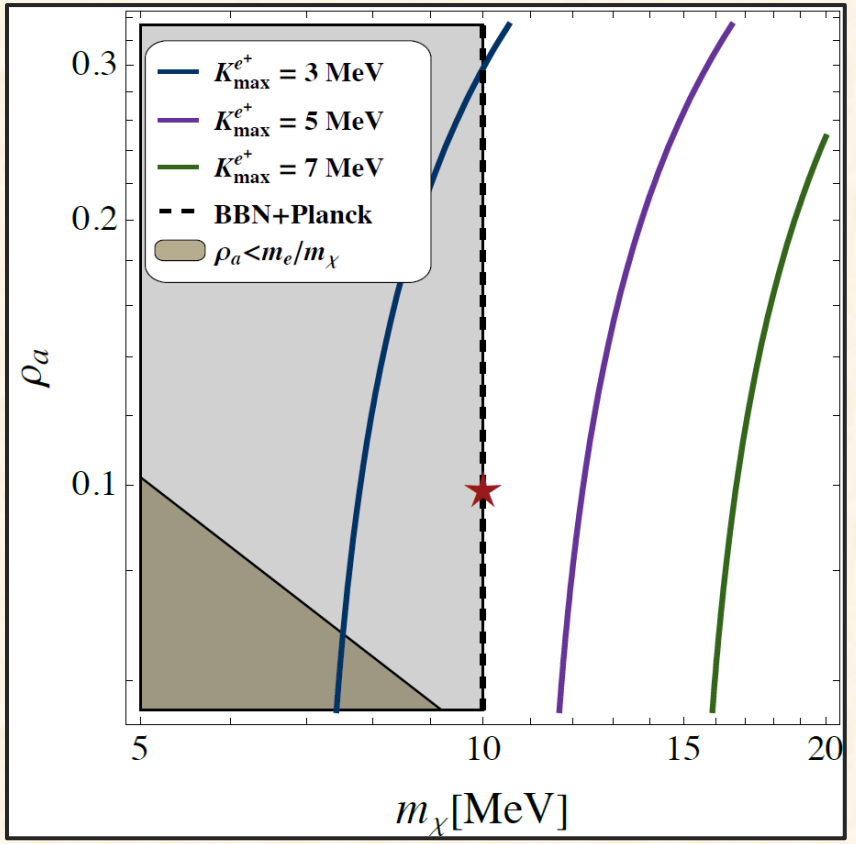


DM coupled to ALPs – a thermal candidate that matches the requisites

An MeV fermion coupling to ALPs can explain the current DM abundance and annihilate through s-wave at present. MeV ALPs will decay into $e^{\pm}$ pairs



The energy of the positrons will be very small in comparison to the DM mass and depends on $\rho_a \equiv m_a/(2m_\chi)$

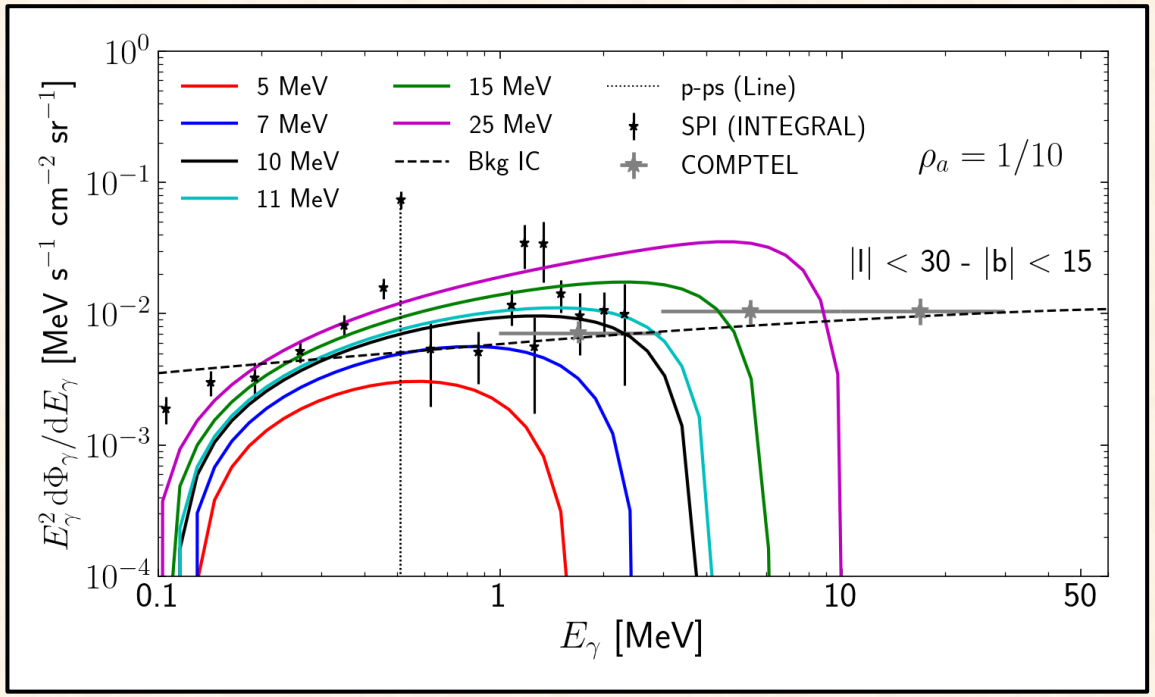


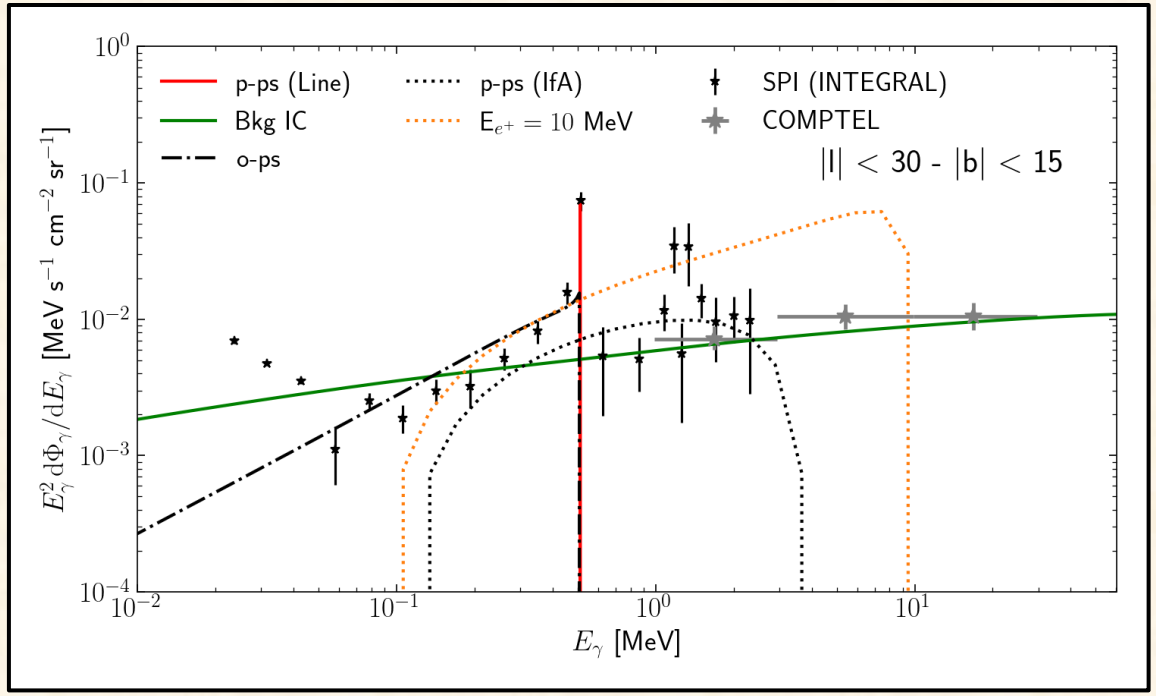
Aghaie, **PDL**, et al. To be submitted

DM coupled to ALPs – a thermal candidate that matches the requisites

The limits from in-flight positron annihilation are alleviated and **this DM candidate would be compatible with observations for masses up to ~15 MeV**

Aghaie, **PDL**,et al. To be submitted





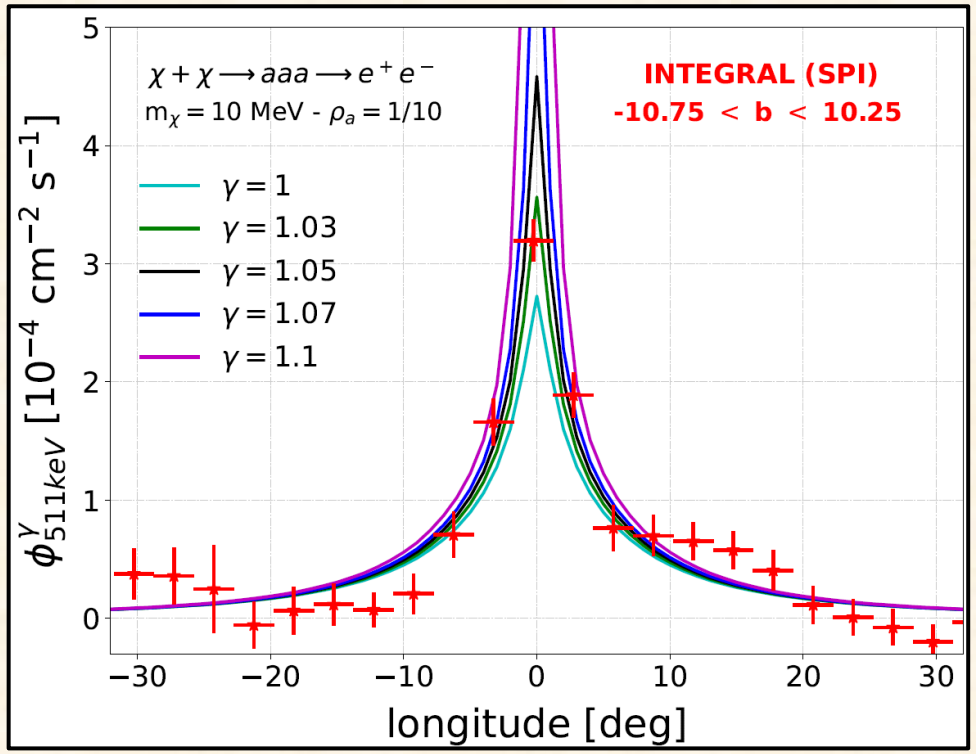
Background model from analyses of GeV CR data and Fermi-LAT emissivity - PDL et al 2202.03559, 2207.01553

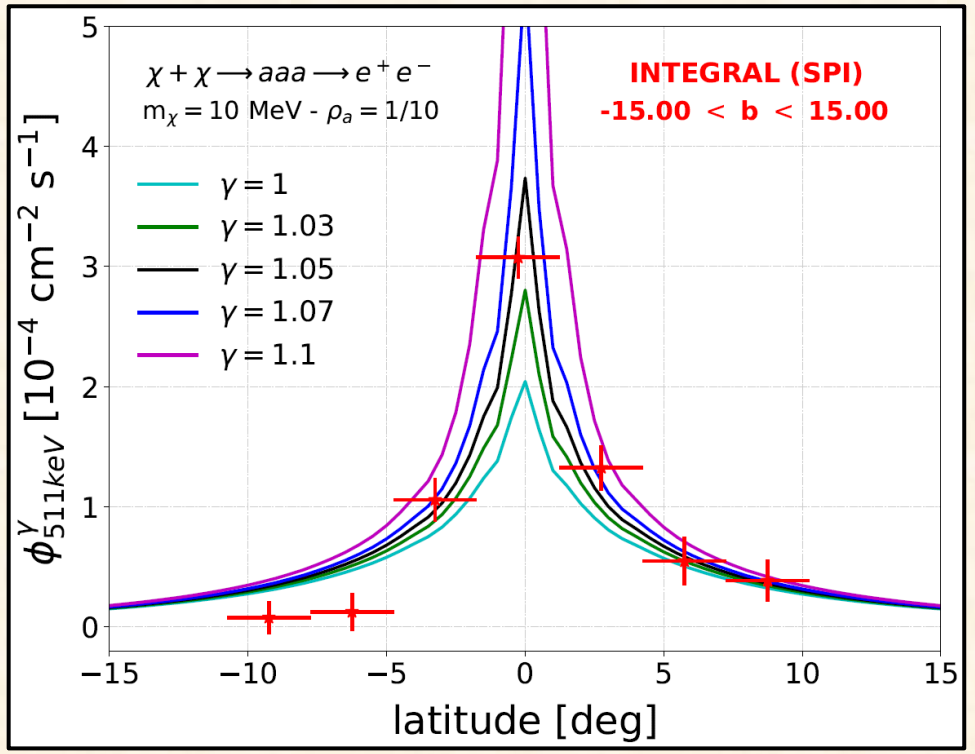
DM coupled to ALPs

Aghaie, **PDL**,et al. To be submitted

A 10 MeV DM particle coupled to ALPs reproduces the morphology of the 511 keV line emission for a DM distribution close to an NFW.

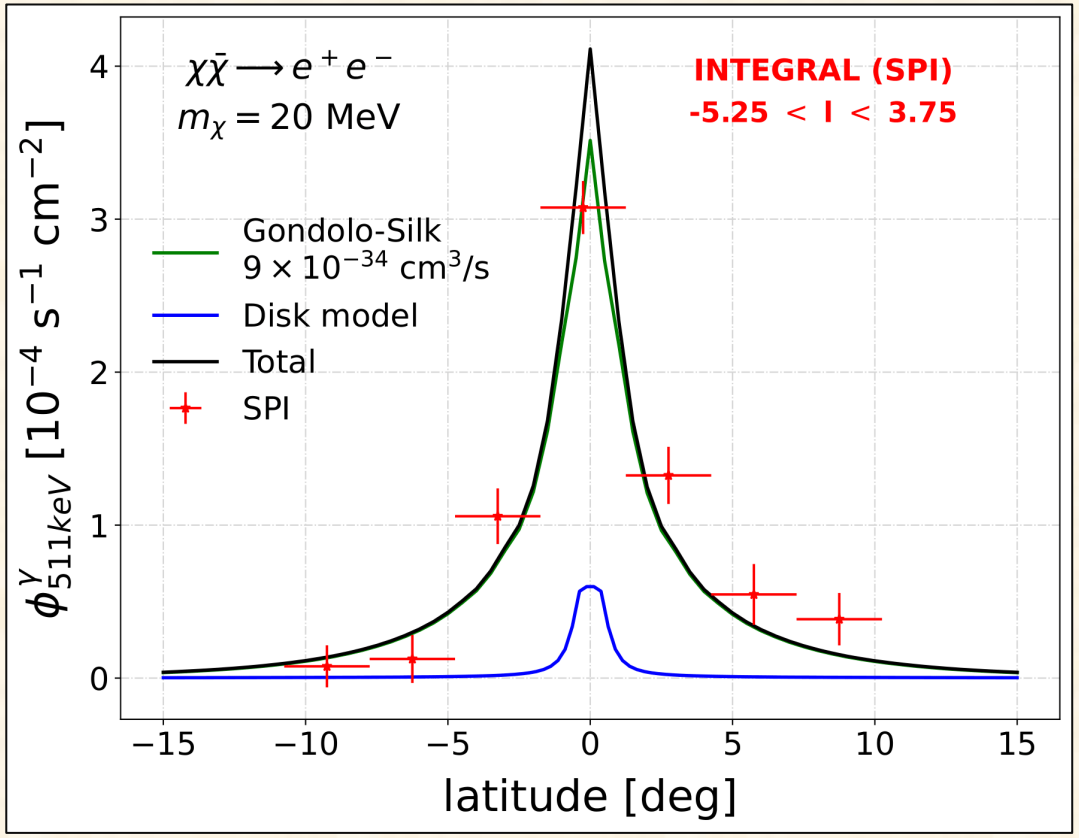
It matches both, the total normalization of the emission and the bulge-to-disk ratio, for the predicted cross sections that account for the DM abundance today

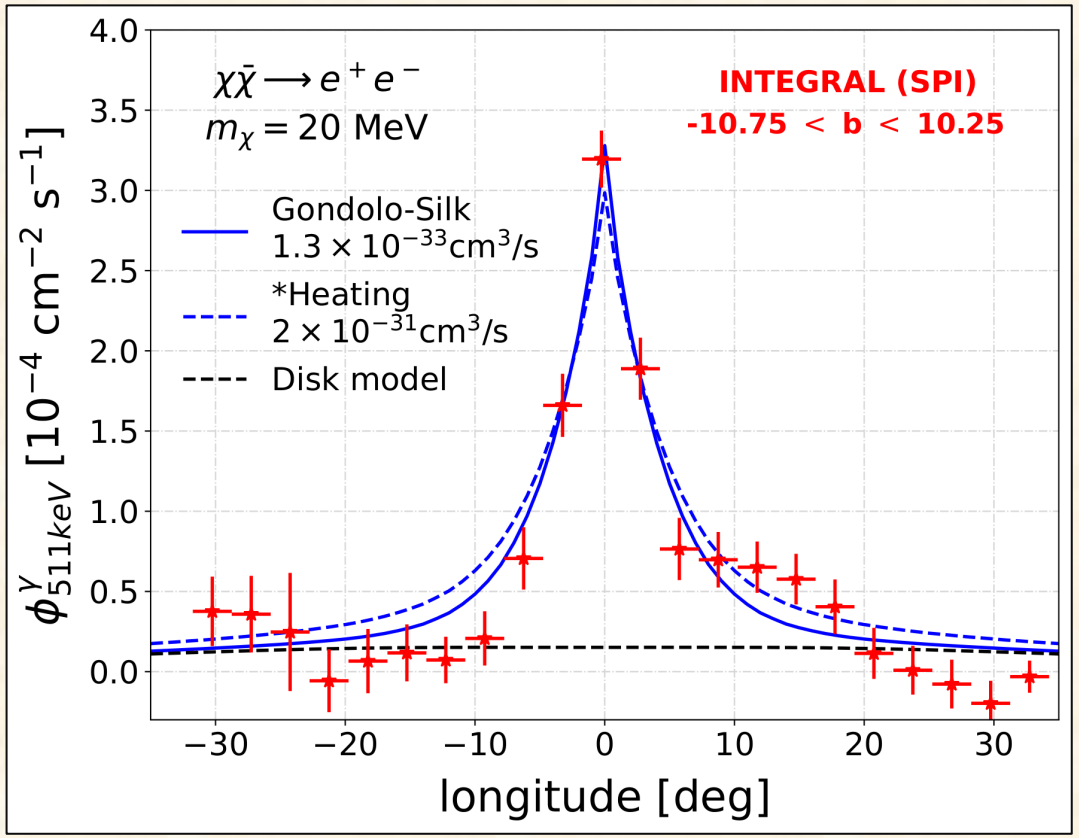




A last chance for direct annihilation: DM spikes

The high bulge emission can be still dominated by DM, while not being in conflict by the disk emission in this kind of profiles and needing very low $<\sigma v>$

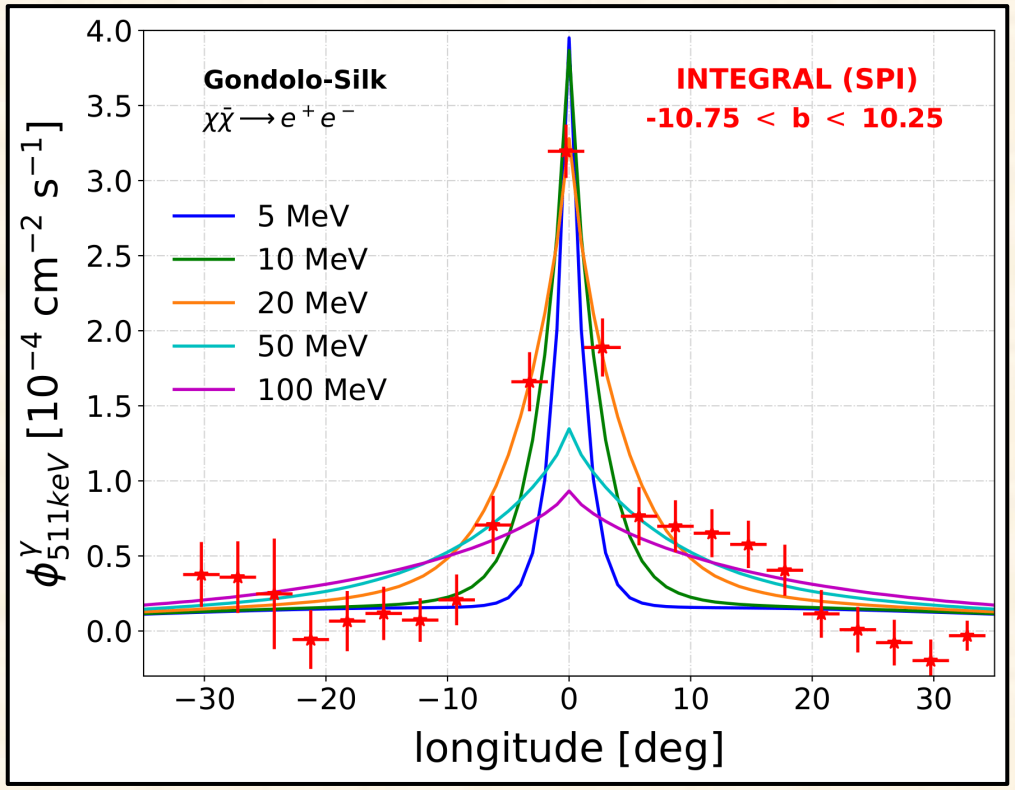




PDL, S. Balaji, F. Sala, M. Fairbarn, J. Silk. ArXiv:2410.16379

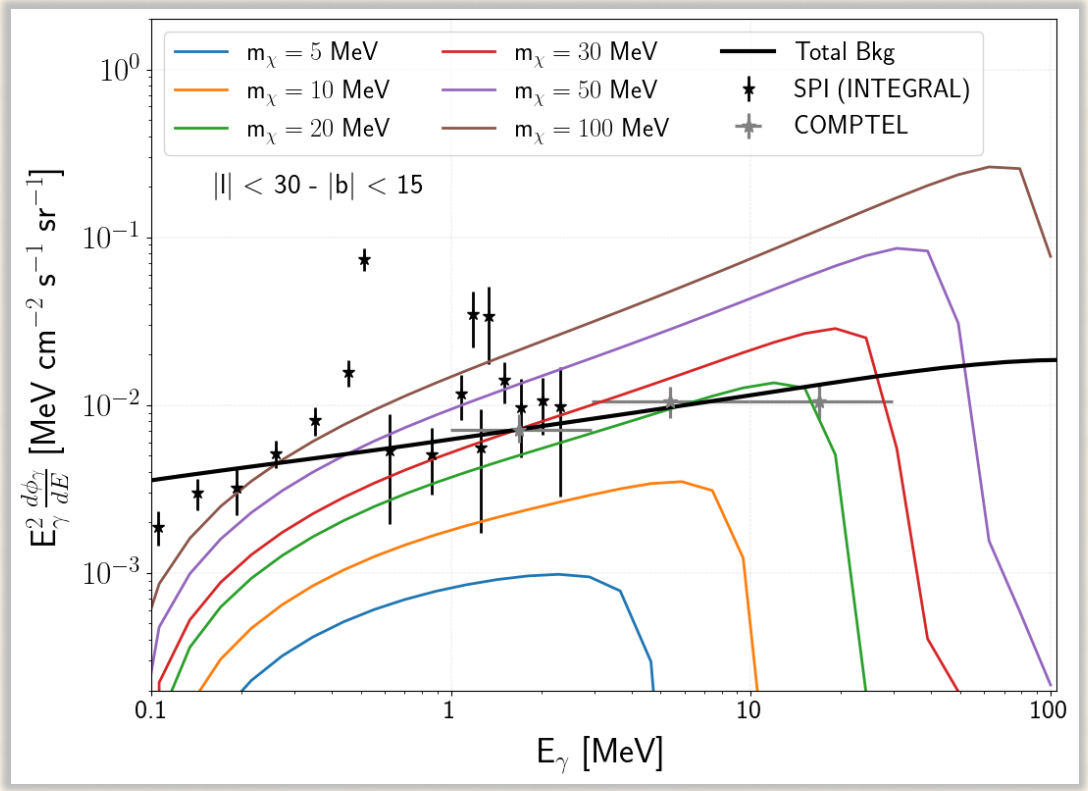
A last chance for direct annihilation: DM spikes

The associated in-flight annihilation emission is compatible with MeV diffuse gamma-ray observations up to DM masses around 10-20 MeV



In DM spike models the bulge emission is still DM-dominated, but it does not contribute significantly to the disk emission:

Mass limits can be mitigated!



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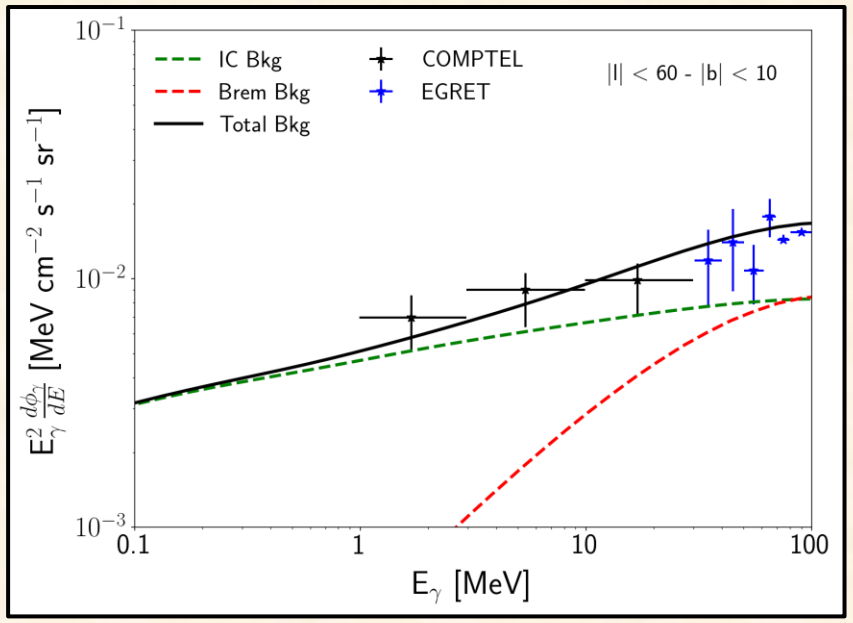
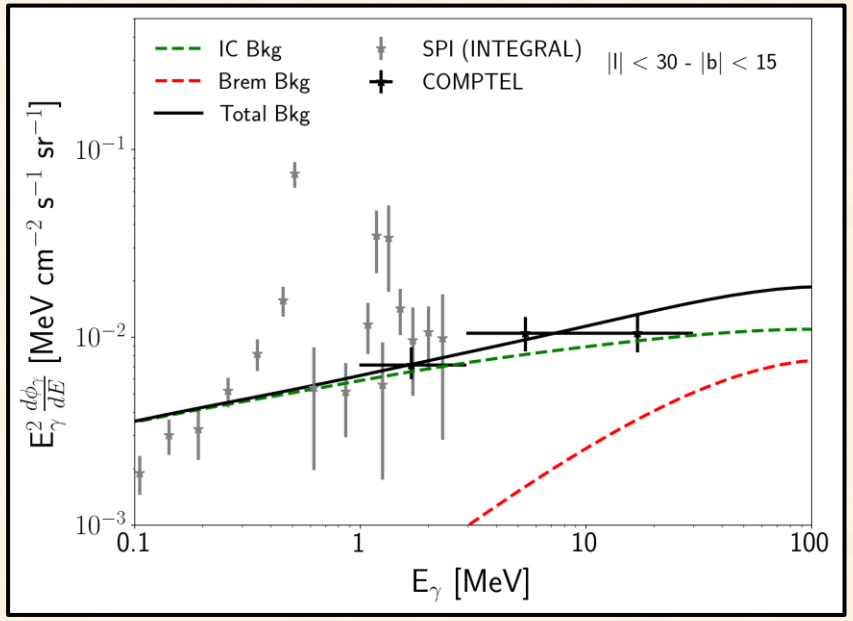
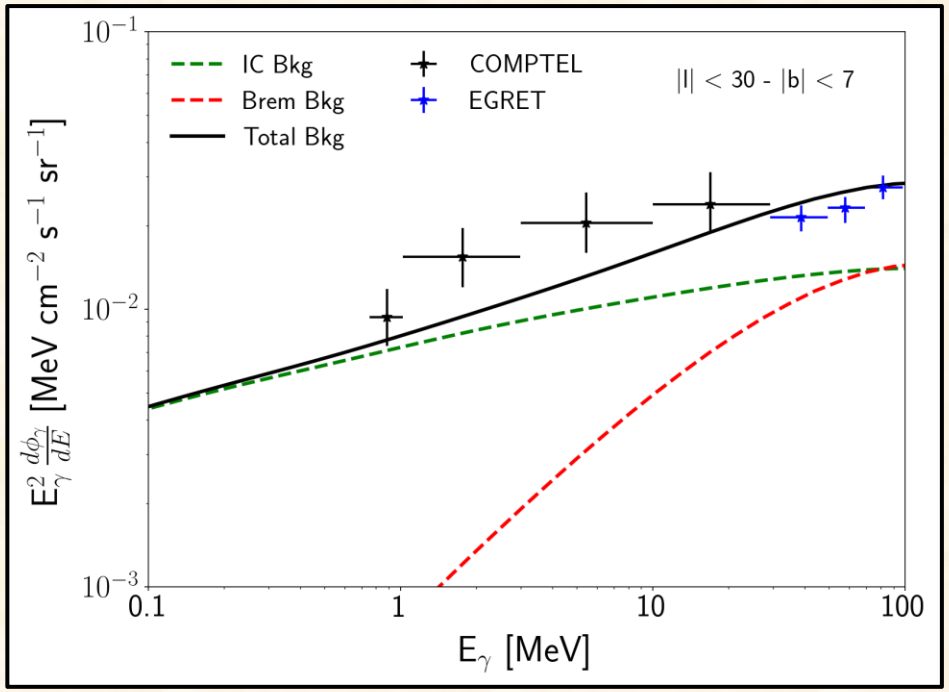
Issues with the diffuse MeV emission





Some studies point to a diffuse MeV emission that is a factor of ~2 higher than expected (still under debate)

A spectral excess is clear when we go closer to the GC!



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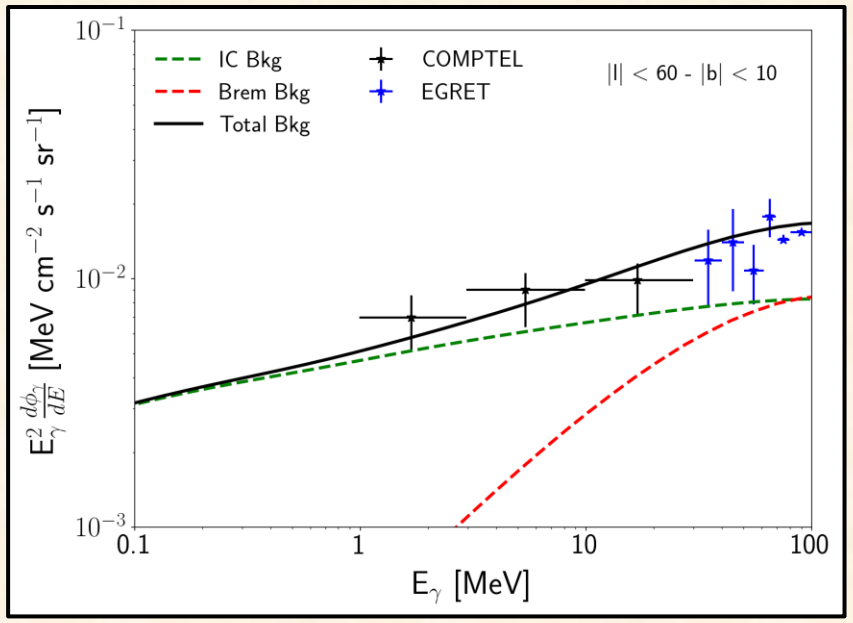

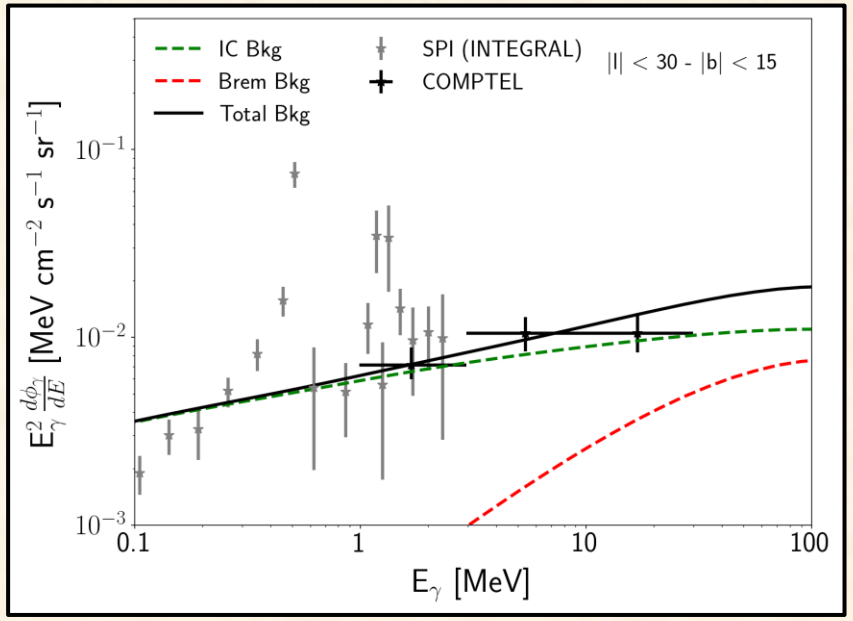

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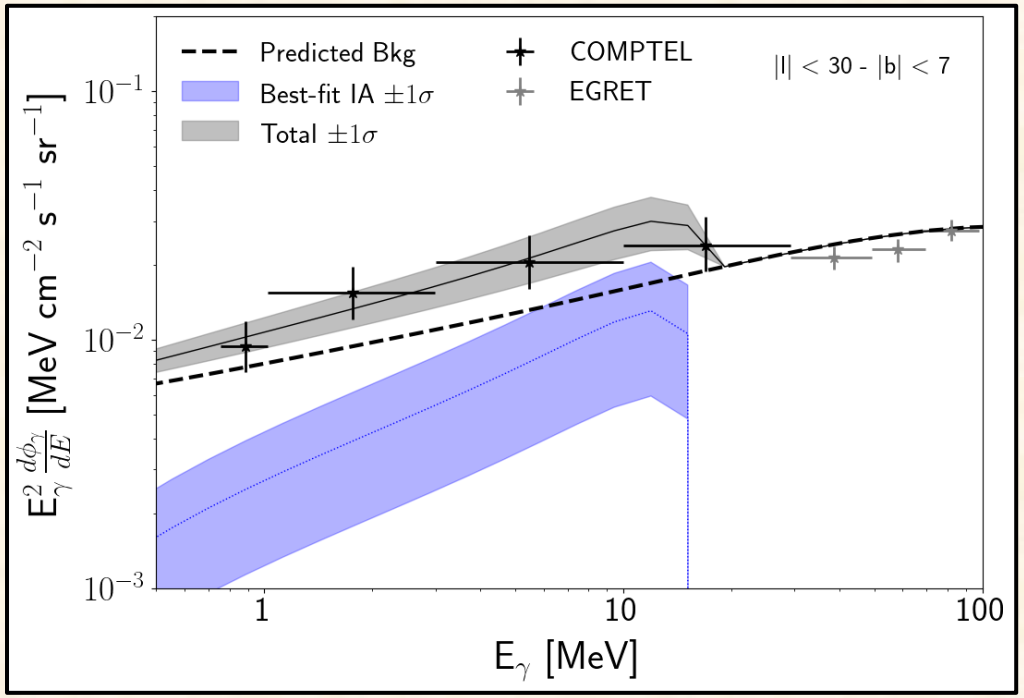
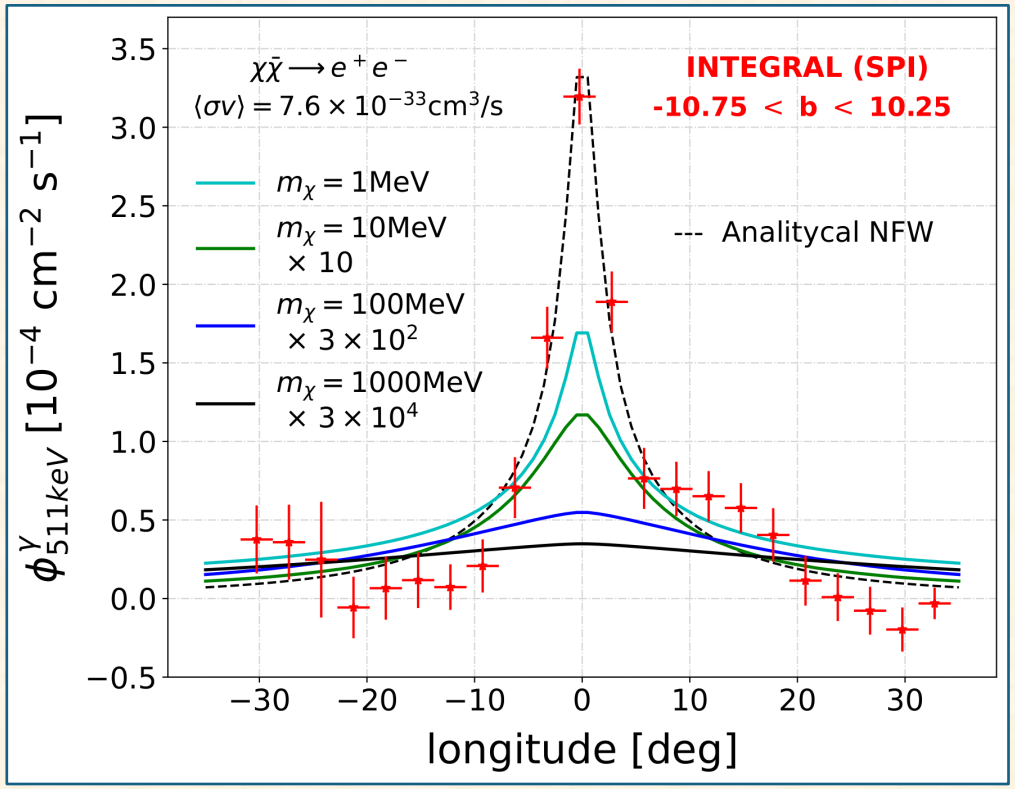


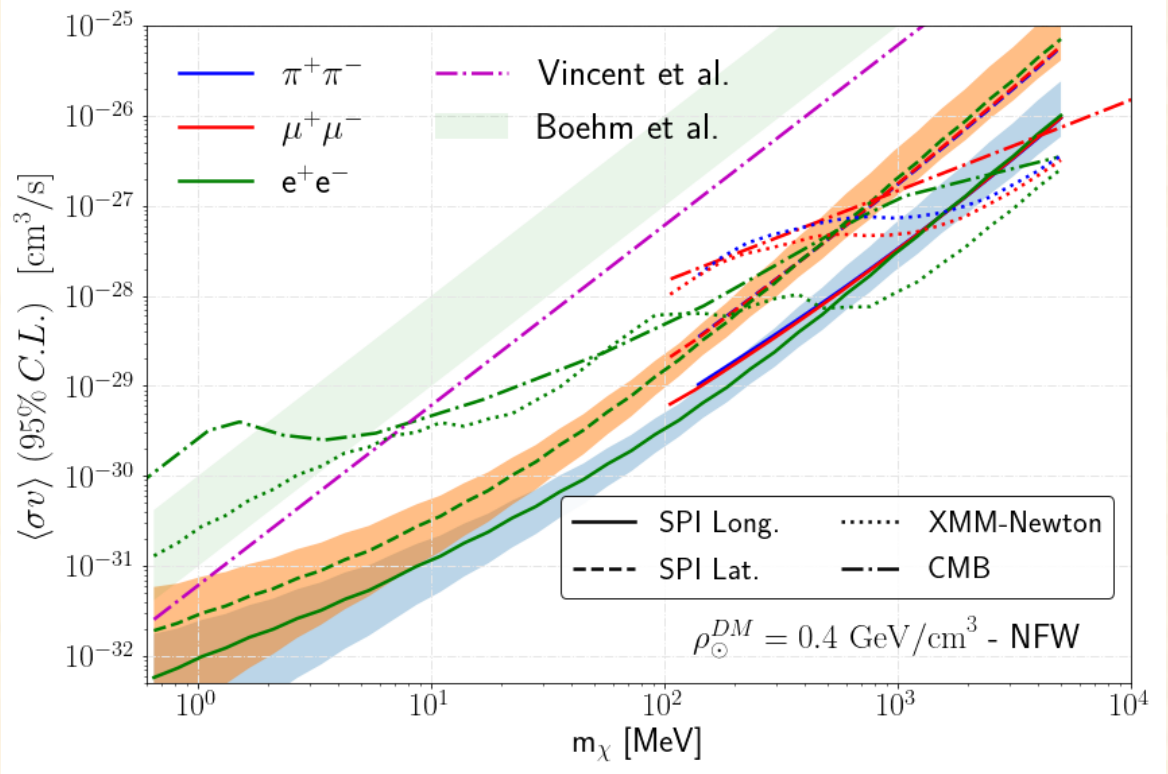
PDL, S. Balaji, F. Sala, M. Fairbarn, J. Silk. ArXiv:2410.16379

But still the line can be used to set strong constraints on light DM producing positrons

The longitude profile leads to strongest constraints up to a few hundreds of MeV

Annihilating DM:





PDL, S. Balaji, J. Silk ArXiv:2312.04907

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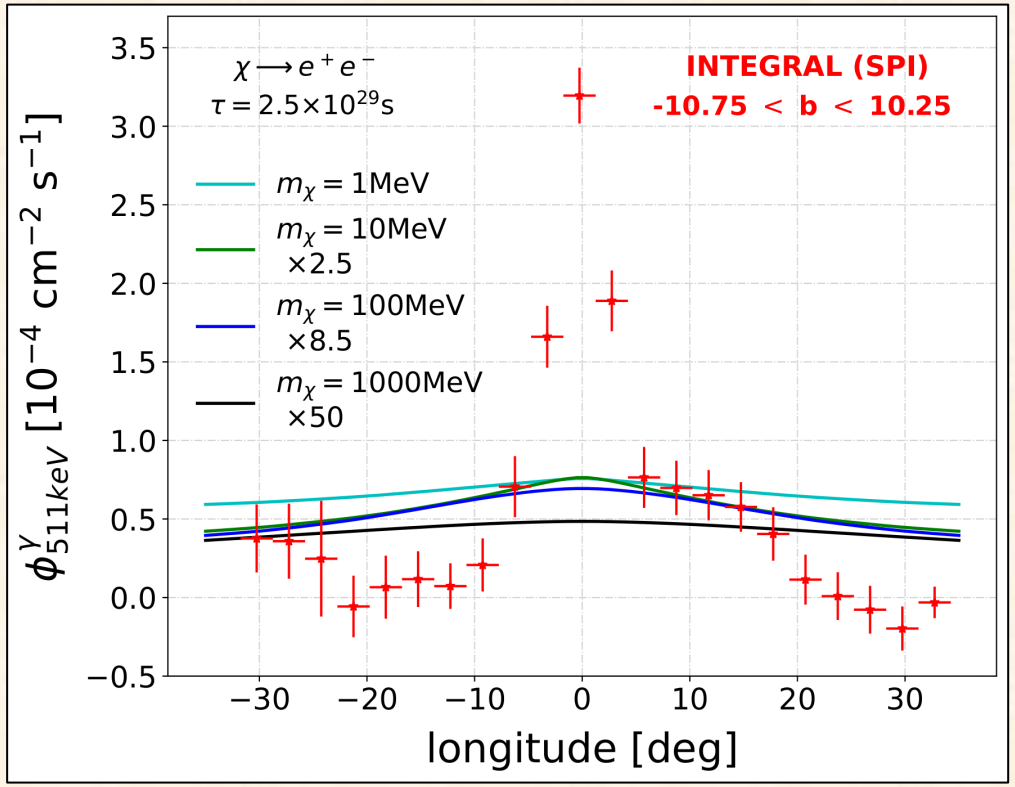
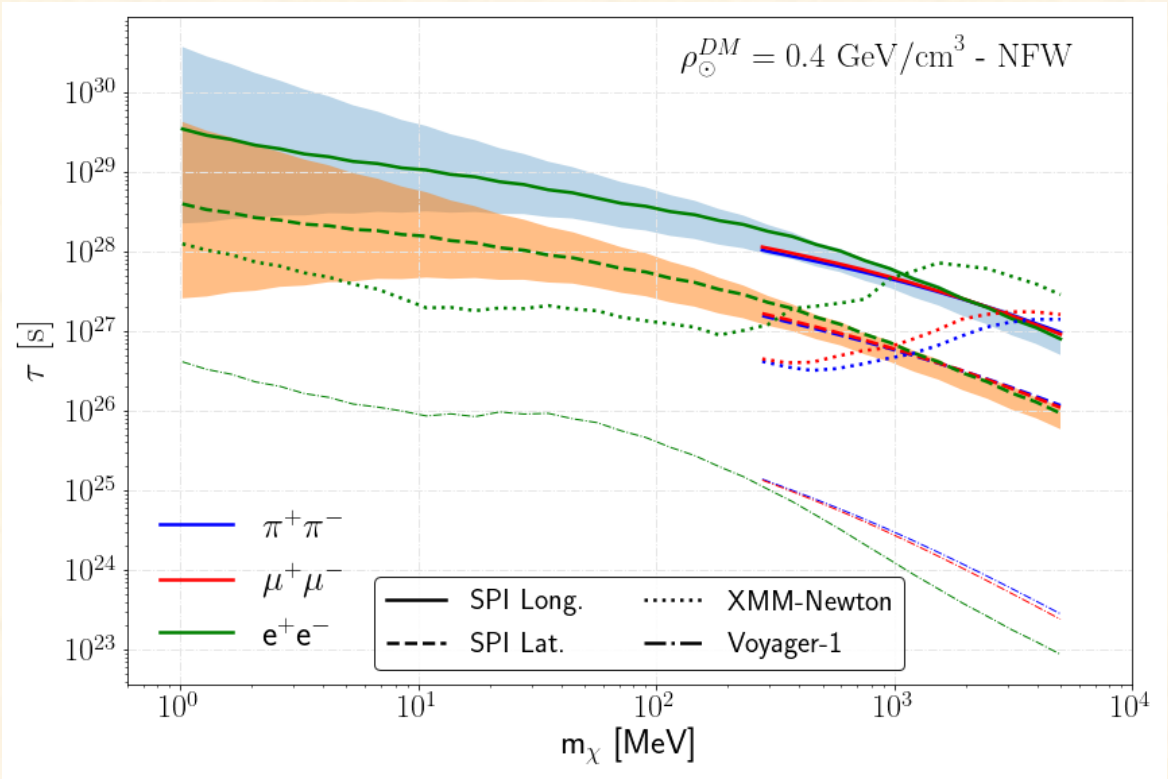
Decaying DM:



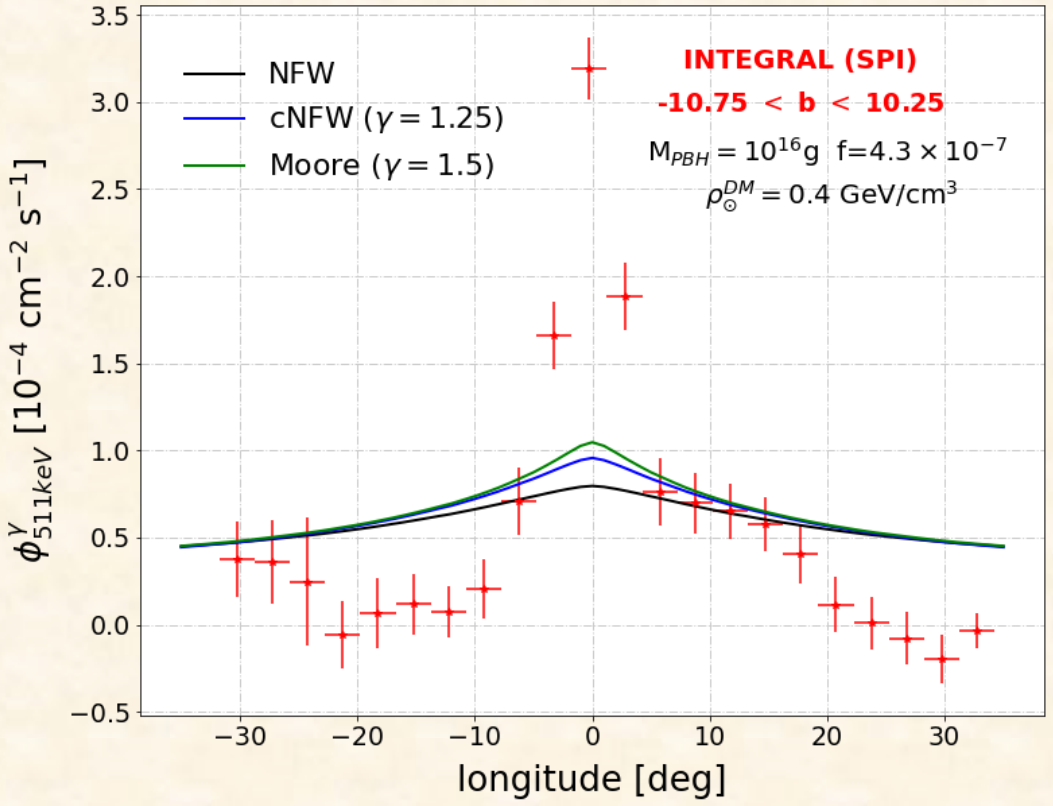


PDL, S. Balaji, J. Silk ArXiv:2312.04907

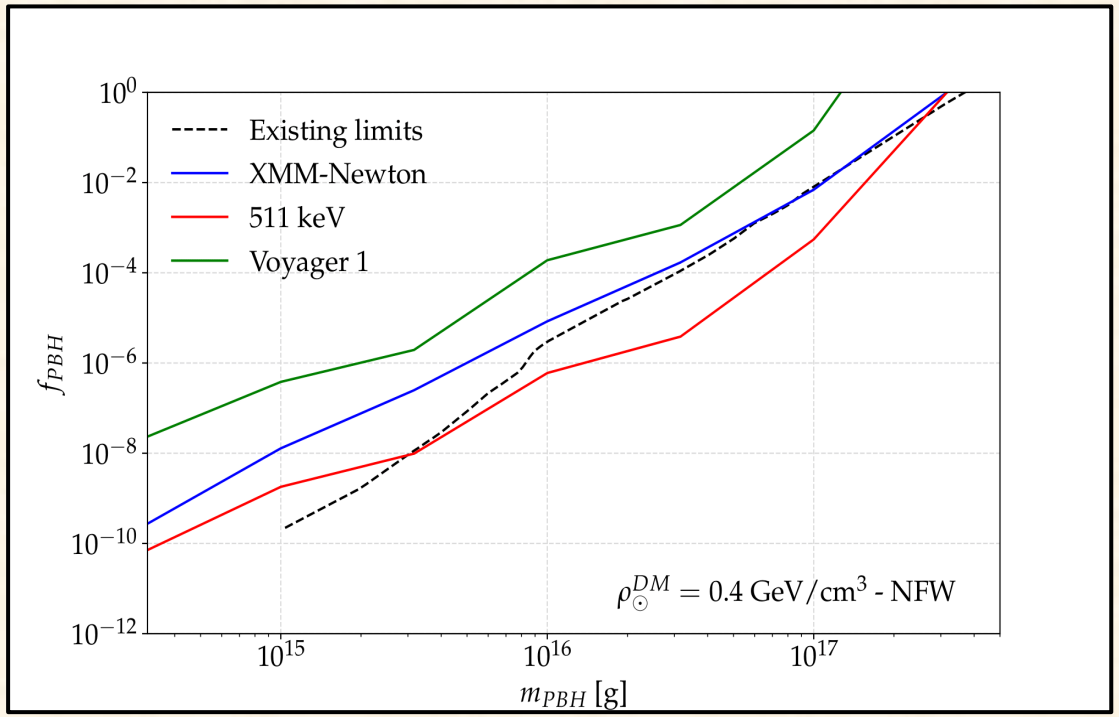
Asteroid-mass PBHs and the 511 keV line

PBHs follow the same spatial morphology as decaying DM → they can be a fraction of the disk emission but not the dominant source of the bulge (at least in a NFW DM distribution)

The 511 keV line allows to set the strongest constraints on asteroid-mass PBHs



PDL, J. Koechler, S. Balaji. ArXiv:2406.11949



Conclusions

511 keV photons from dark matter in the Galactic Center

- The observations of the 511 keV line still lack a satisfactory explanation and may indicate the presence of new physics in the Galaxy
- Different dark matter models may explain this anomaly: DM coupled to ALPs, DM in a DM-spike distribution, inelastic DM, …
  It seems to require a very low energy positron emitter which may also lead to β^+ radionuclides from stars
- The hard-X-ray to soft-gamma-ray band (the MeV gap) has a high potential to probe the properties of positron emitters and set leading constraints for Sub-GeV DM, PBHs and feebly interactive particles
- Future MeV observations may solve many important open problems in the astroparticles community.

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