The CMZ anomalous Ionization rate explained by MeV DM

Based on *De la Torre Luque, Balaji, Silk PRL 134 (2025) 10, 101001*

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LDW 2025 - IFT
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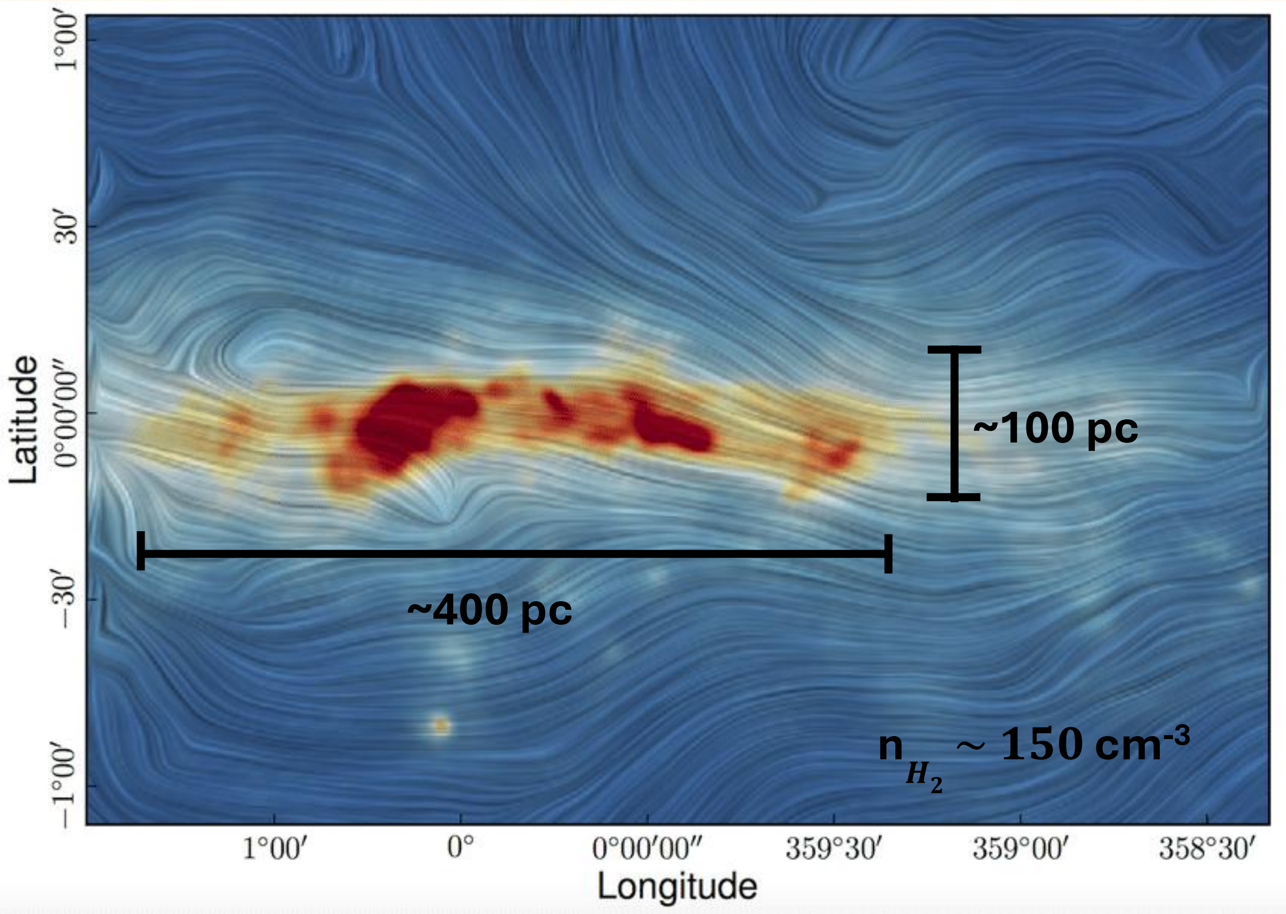
Ionized molecules indicate an anomalous ionization rate source at the CMZ

Ionized molecules emit distintictive lines (in radio) that allow us to measure their density and ionization rate (ζ) of molecules

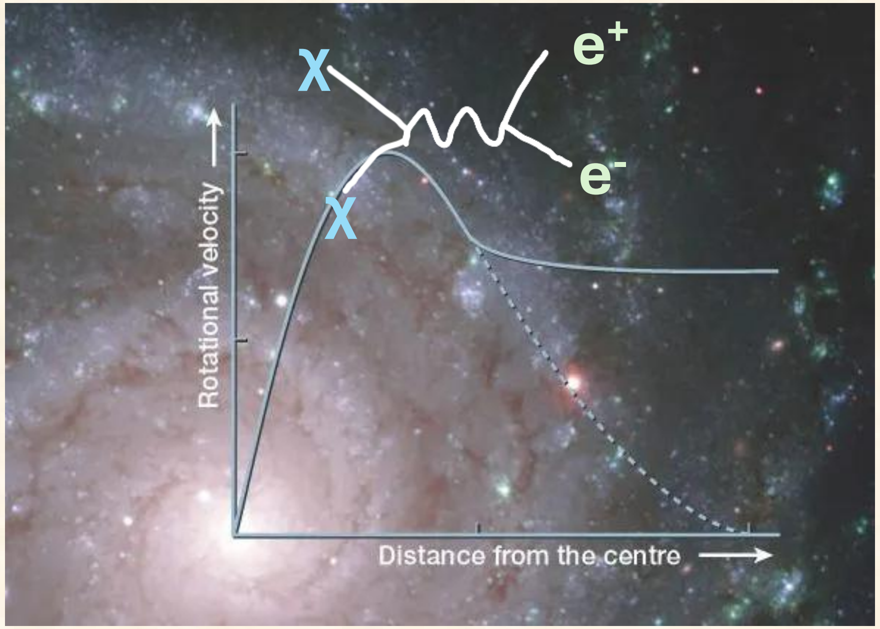
Different tracers lead to an ionization rate of $\mathbf{2 \cdot 10^{-14}\, s^{-1} < \zeta_{CMZ} < 10^{-15}\, s^{-1}}$

Known powerful sources of particles are:
- Diffuse cosmic rays
- SgrA*
- Point-like sources (HESS J1745-290)
- Dark matter?



Annihilation of MeV DM

- Low-mass DM fulfils all the conditions required and would have remained undetected
- DM particles with a few MeV mass would produce $e^{\pm}$ that travel several 10s of parsecs before thermalizing (**PDL**, S. Balaji, J. Silk ArXiv:2312.04907)



The diffusion equation in this case can be approximated as:

Solved numerically with the DRAGON2 code

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

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

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

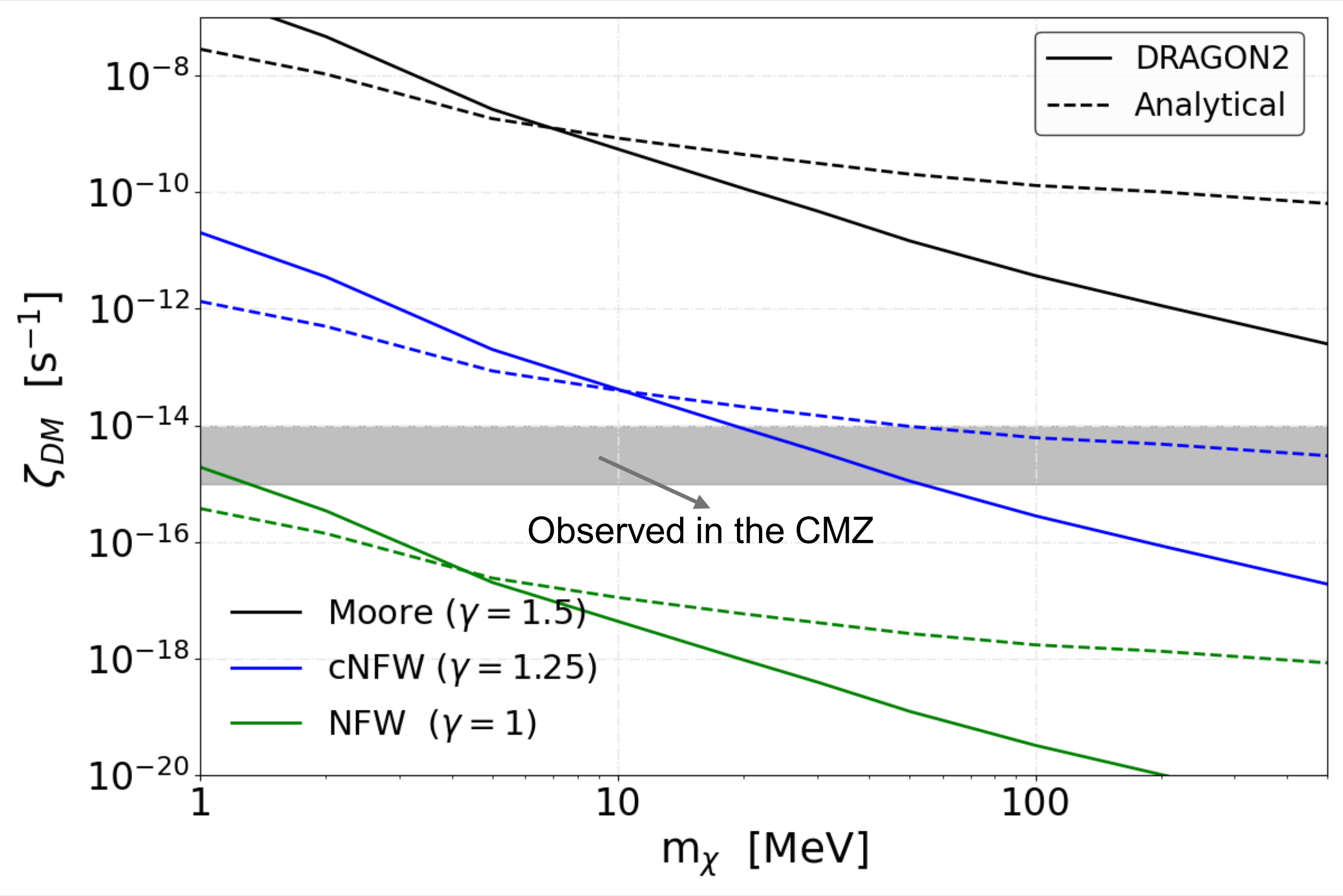
Injection
(following DM distrib.)

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

Annihilation of MeV DM

$$\zeta = 2 \cdot 4\pi \int_{E_{\min}}^{E_{\max}} J(E,\mathbf{x})\sigma(E)(1+\theta_e(E))\, dE$$

PDL, Balaji, Silk ArXiv:2409.07515



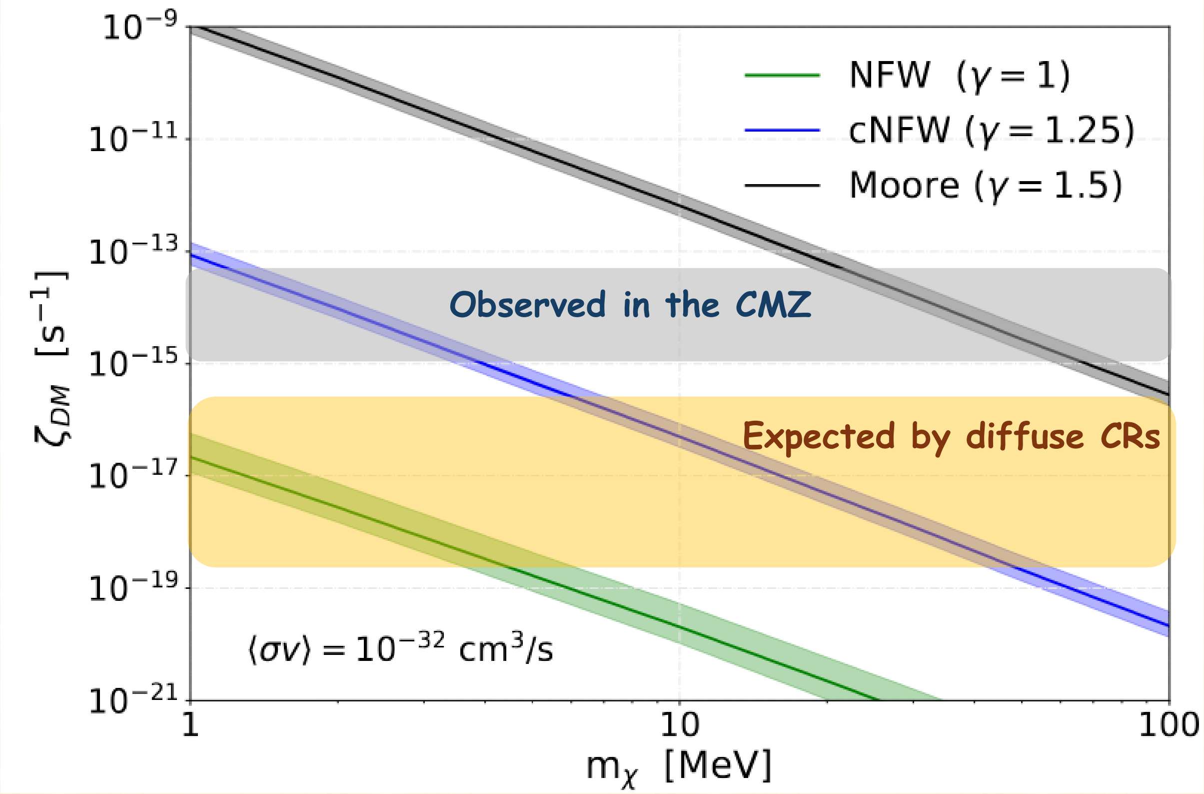
Maximum ionization rate allowed by CMB constraints

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

The $e^{\pm}$ from **MeV DM** would **deposit all their energy into the CMZ**, providing a much higher ionization rate than CRs

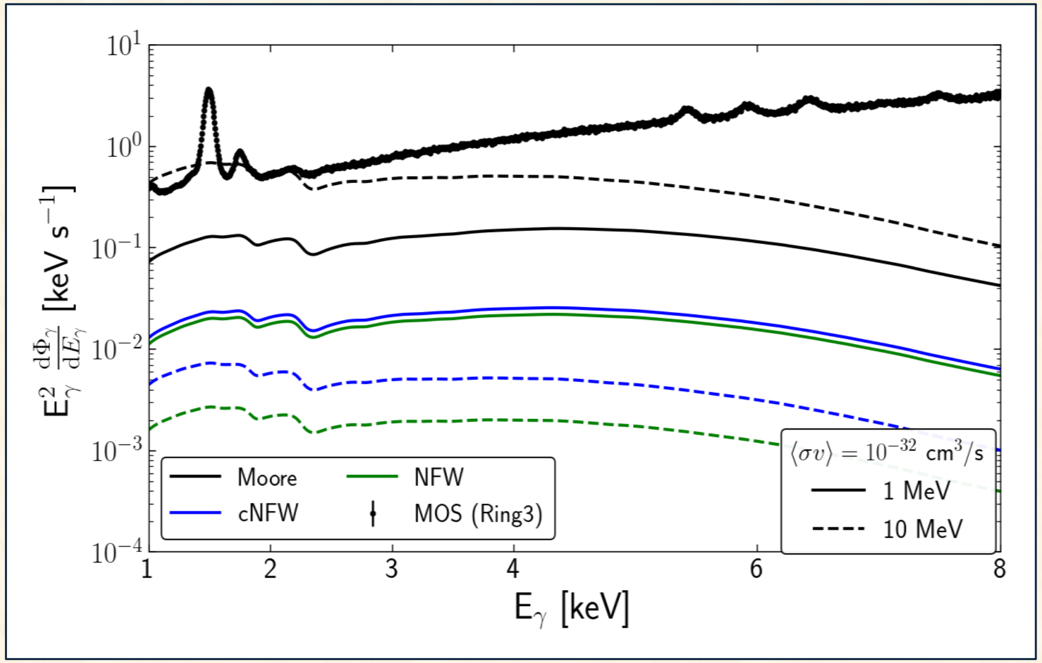
MeV DM would not leave any trace…

For 1 MeV DM, a NFW profile requires ⟨σv⟩ ~10^{-30}cm³/s, while a Moore profile would require ⟨σv⟩ ~10^{-38}cm³/s



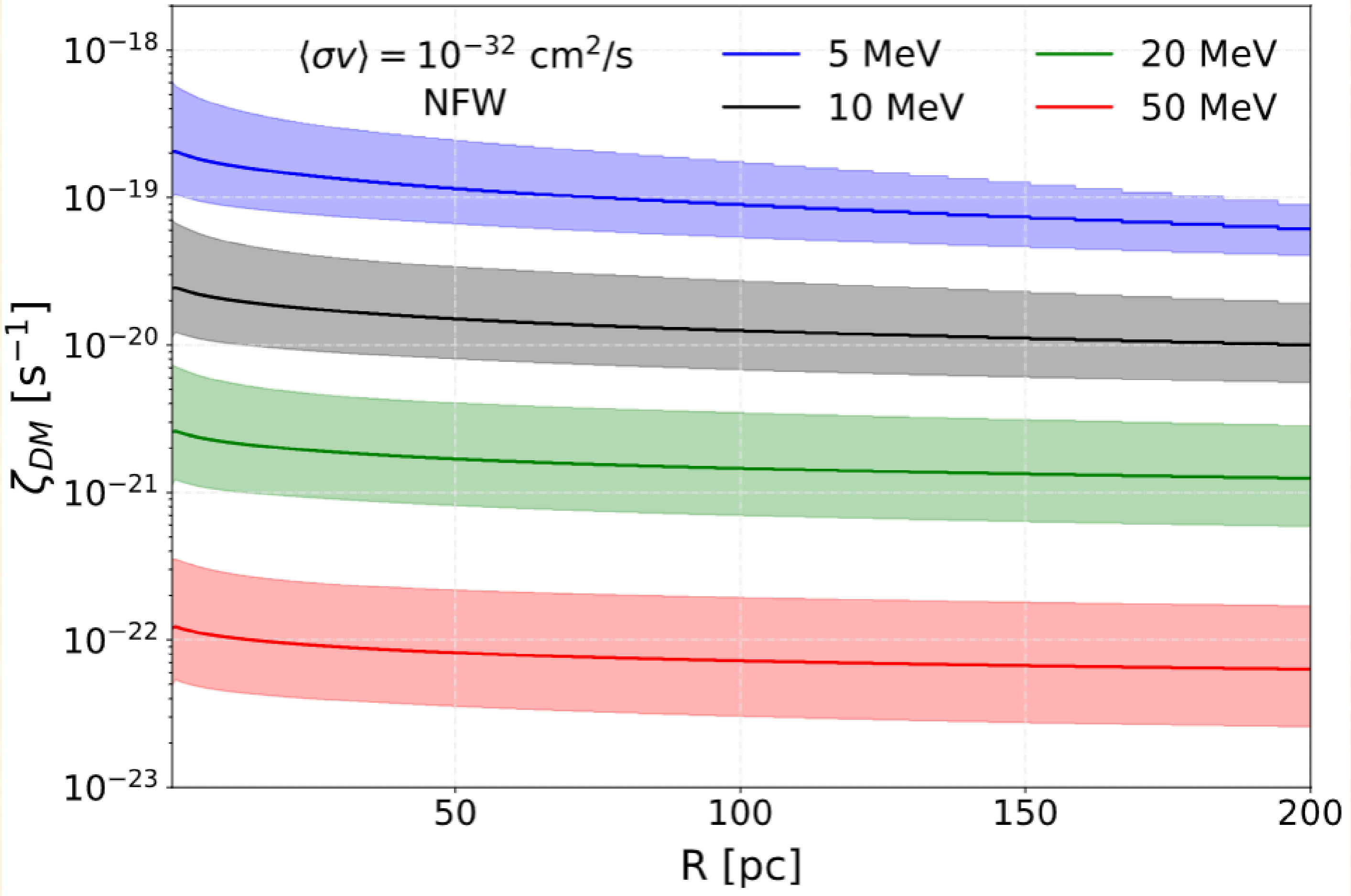
No bremsstrahlung or X-ray emission can be detected from such low annihilation rate and DM mass

X-rays from inverse-Compton emisión of $e^{\pm}$



MeV DM as the source of the CMZ ionization rate

PDL, Balaji, Silk *PRL* 134 (2025) 10, 10

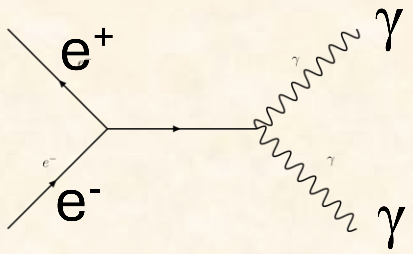


The low ⟨σv⟩ required avoid current cosmological constraints and imply no detectable IC, bremsstrahlung or synchrotron emissions

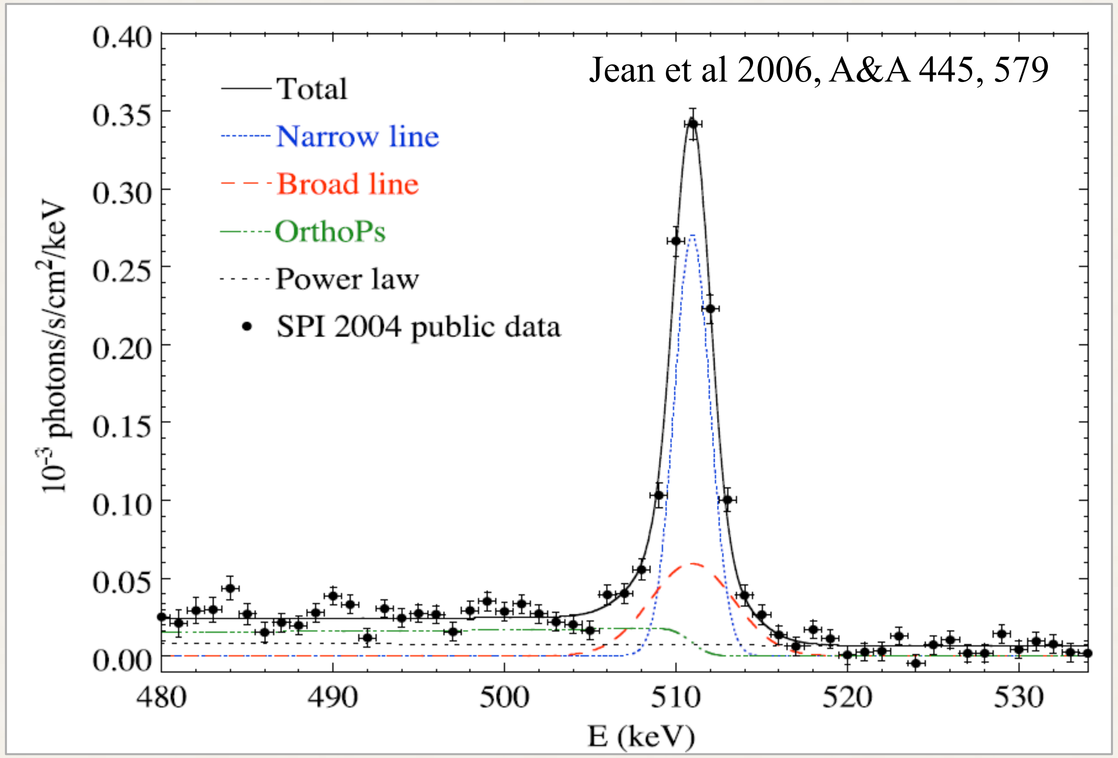
It would lead to a quite **flat ionization profile** – as observed

The **annihilation rate** needed to explain this anomaly lie **within the same order of magnitude** to those **needed to explain the 511 keV line**

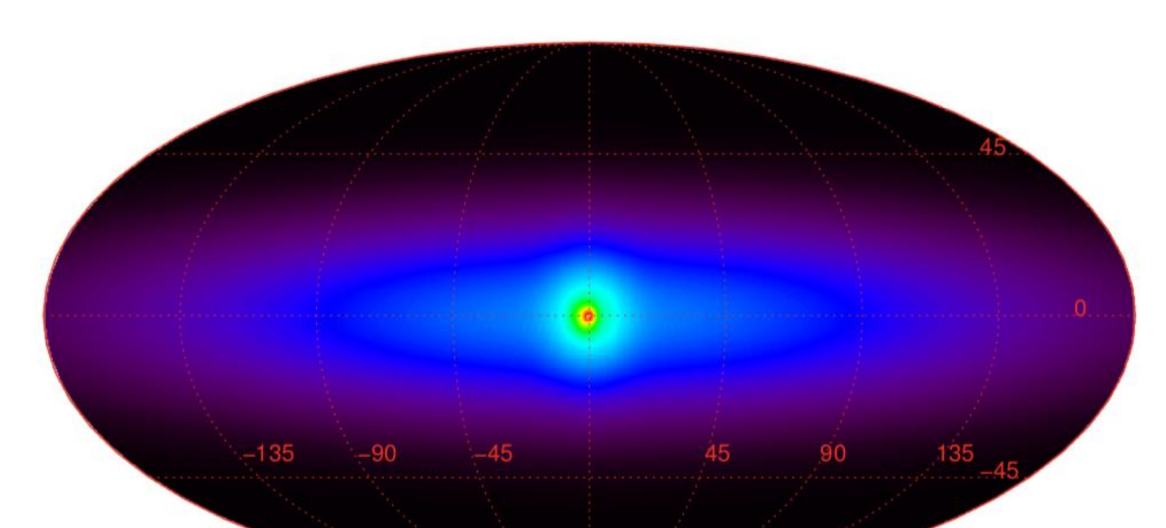
The 511 keV puzzle



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**

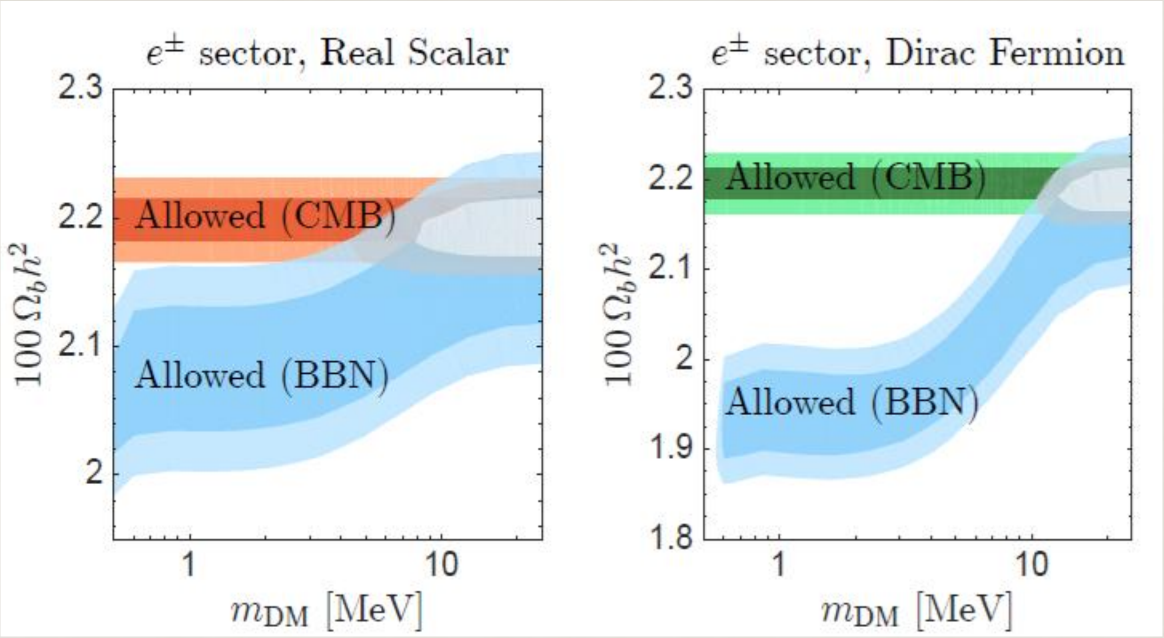


SPI Collab.
ArXiv: 1903.05569

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

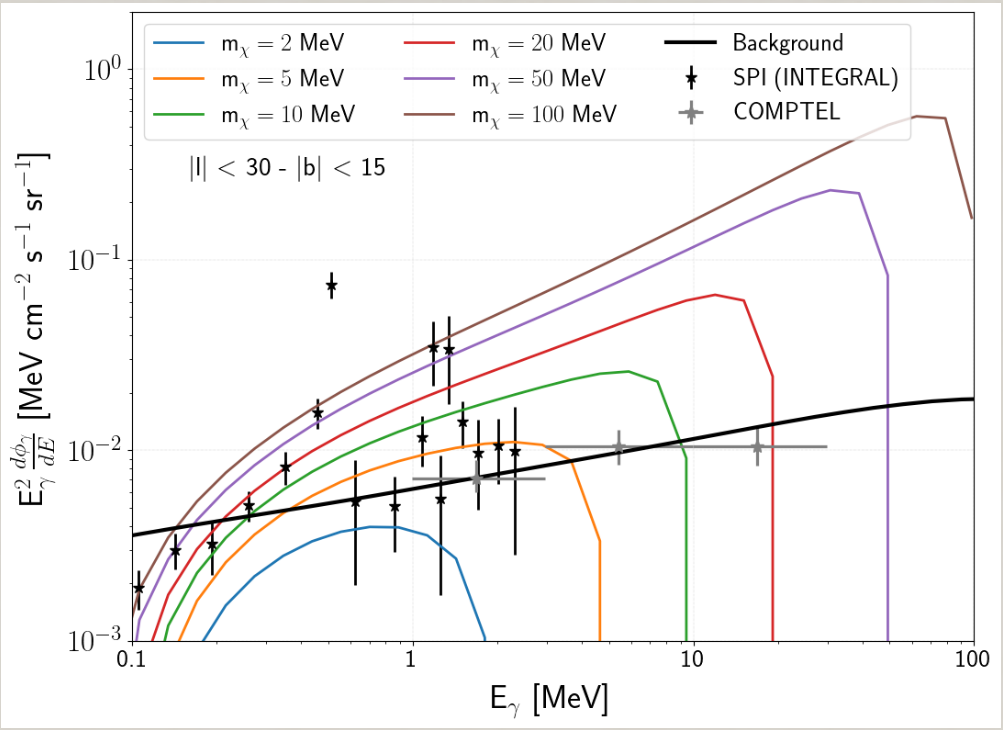
Sub-GeV DM is compatible with cosmo constraints only for $m_\chi > \sim$1-10 MeV

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



Exciting DM (XDM) as an exciting solution

- Collisions between DM particles excite them into a state which then decay via e^+e^- pairs

  Finkbeiner & Weiner (2007) ArXiv:0702587

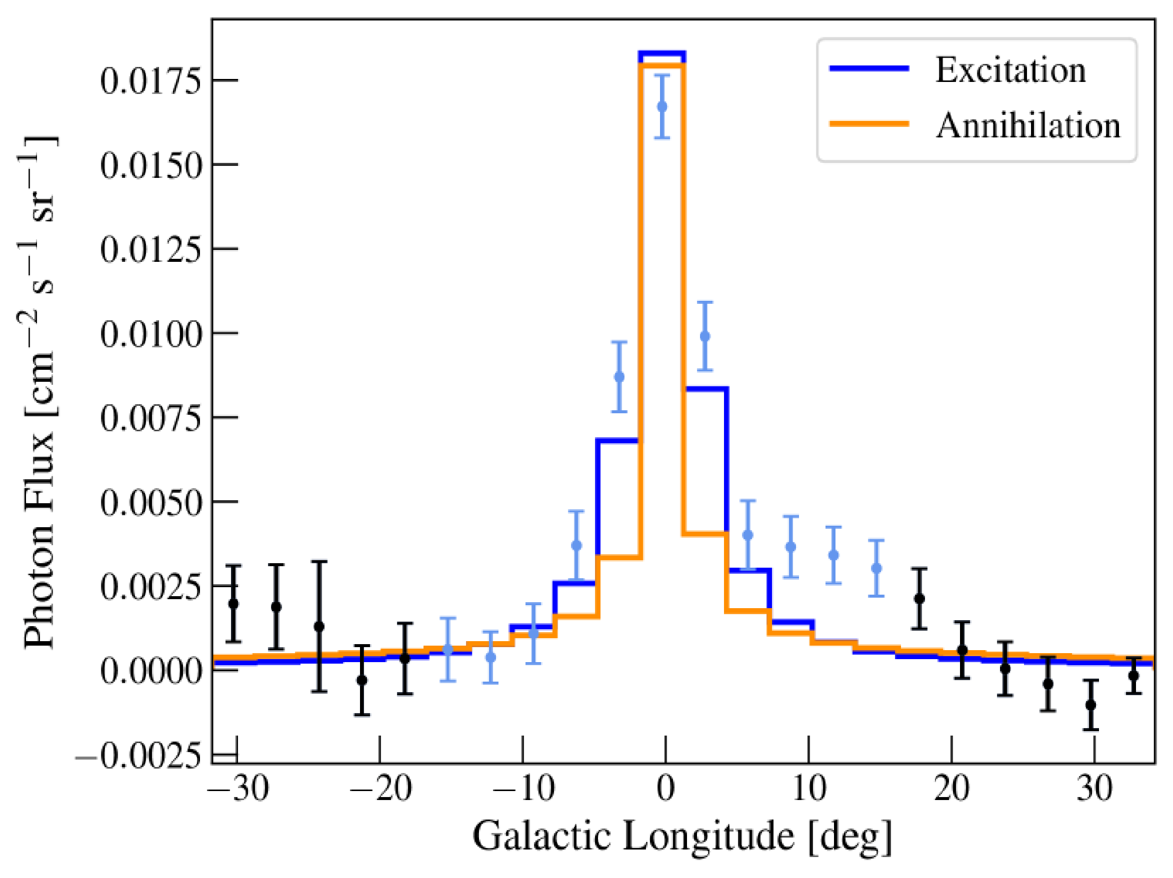
- The 511 keV signal from XDM is characterized by the interaction rate between DM particles, their mass, the energy gap between excited states and the DM density distribution

- Cappiello et al showed that the resulting distribution provides a better fit to 511 keV line

  Cappiello et al (2025) ArXiv:2307.15114

- One can understand the resulting 511 keV profile as the convolution of the DM density and a suppression factor that depends on the relative speed of DM particles in the Galaxy

Spatial profile of the 511 keV emission

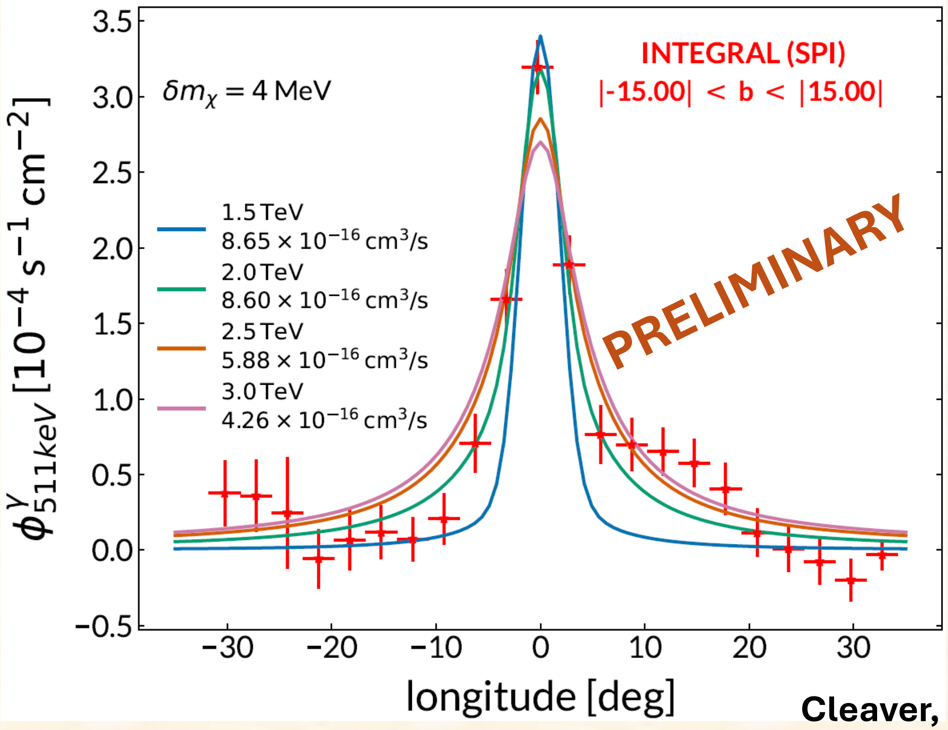


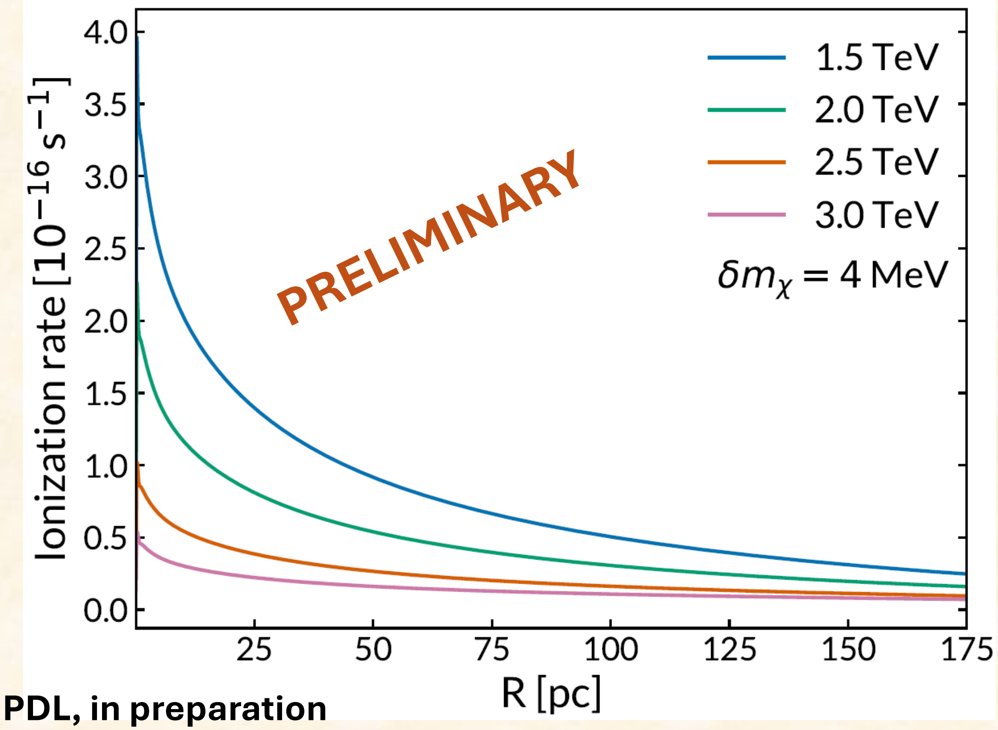
Cappiello et al (2025) ArXiv:2307.15114

Exciting DM (XDM) as an exciting solution

Recent analyses of the **511 keV line and the continuum emissions** by COMPTEL and SPI favour that **positrons are injected with energies ~2 MeV** knödlseder+ 2025 ArXiv:2506.17427

We find that setting the mass gap for **XDM** accordingly, we obtain a combined **solution for these different astrophysical problems**!





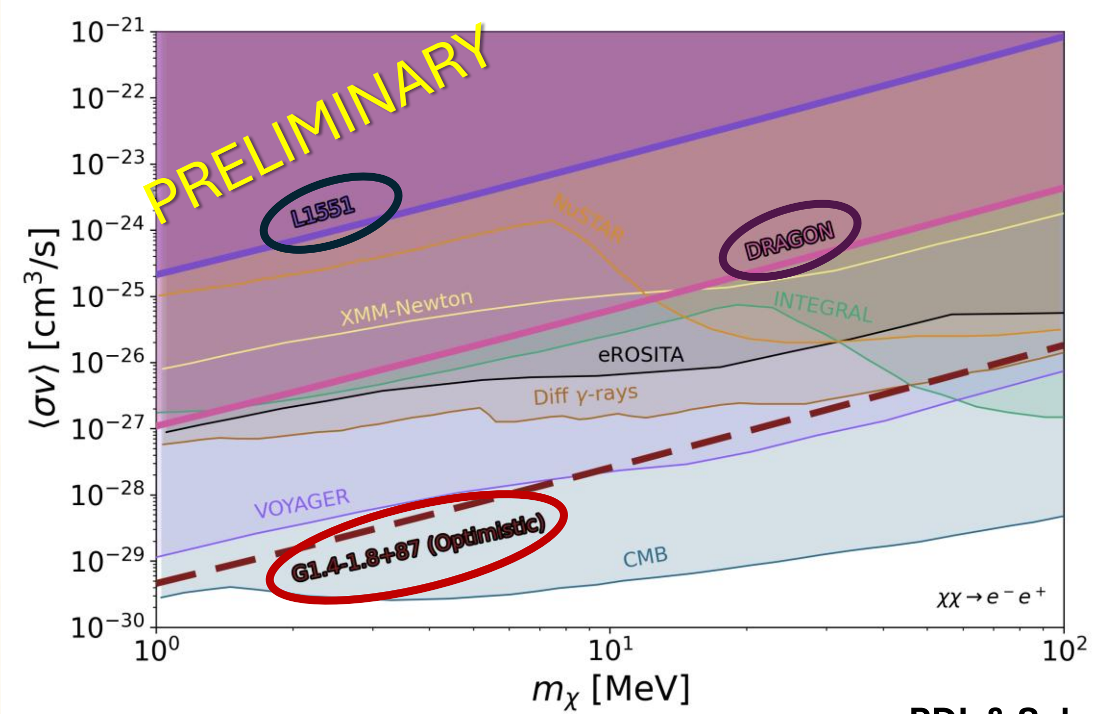
Cleaver, Balaji, PDL, in preparation

The potential of Molecular clouds

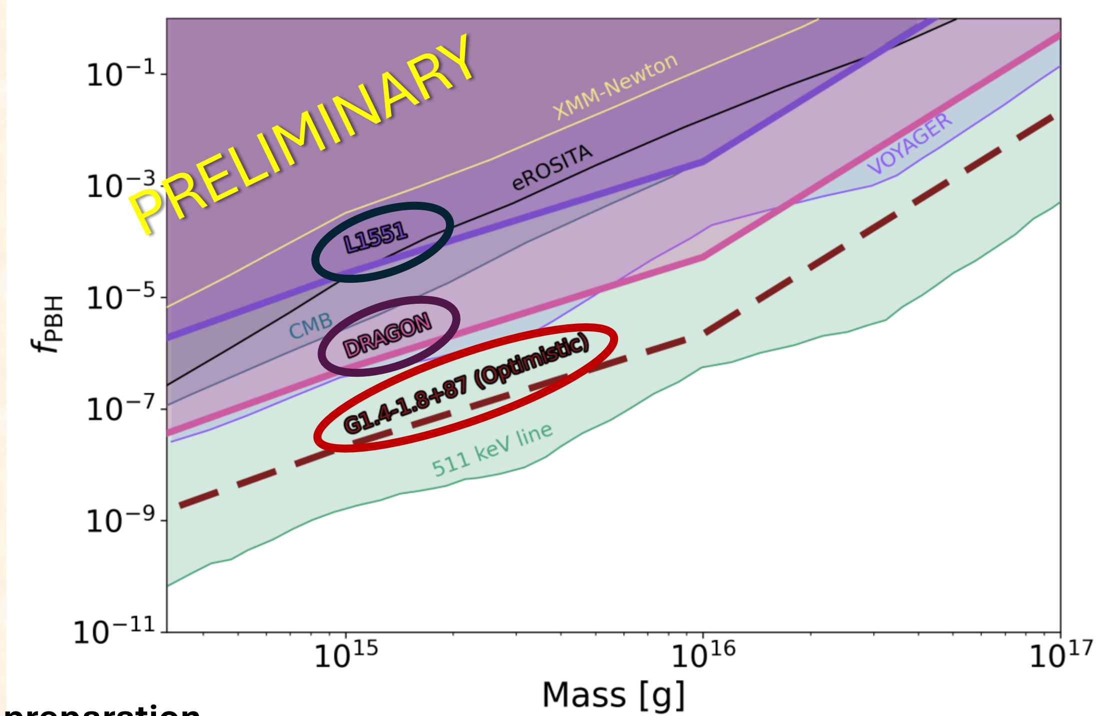
The ionization of molecular clouds can be used as a probe of light DM (see also ArXiv:2507.01962)

Local molecular clouds provide very robust constraints, but clouds near the Galactic Center could be even more affected if cusp DM profiles (e.g. NFW) are considered

Annihilating DM



Asteroid-mass PBHs



PDL & Salces, in preparation

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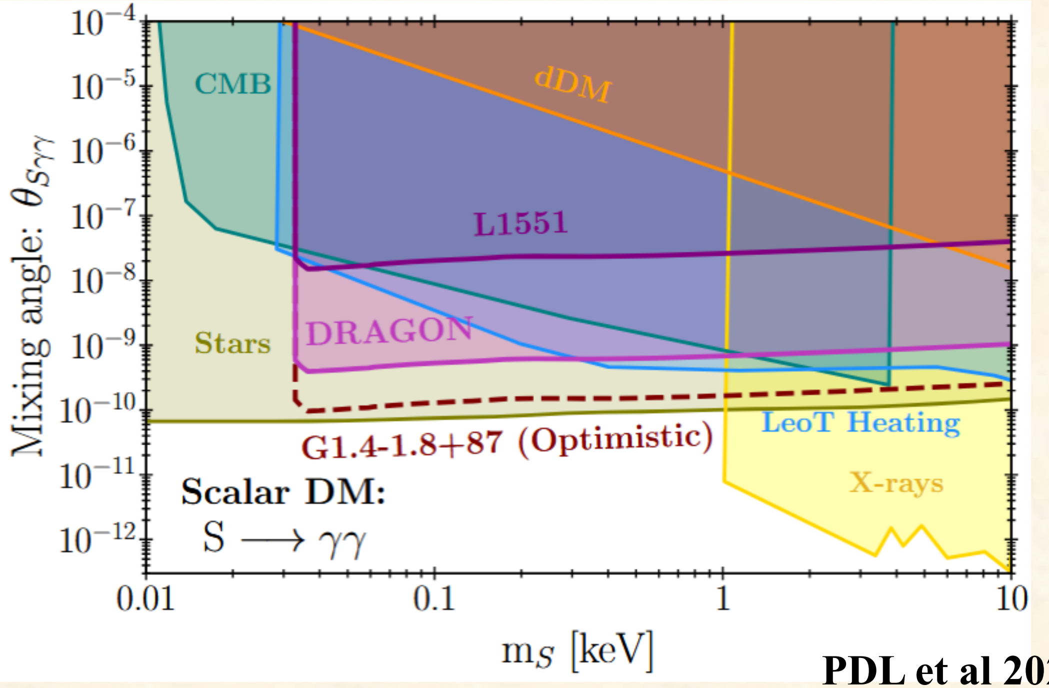
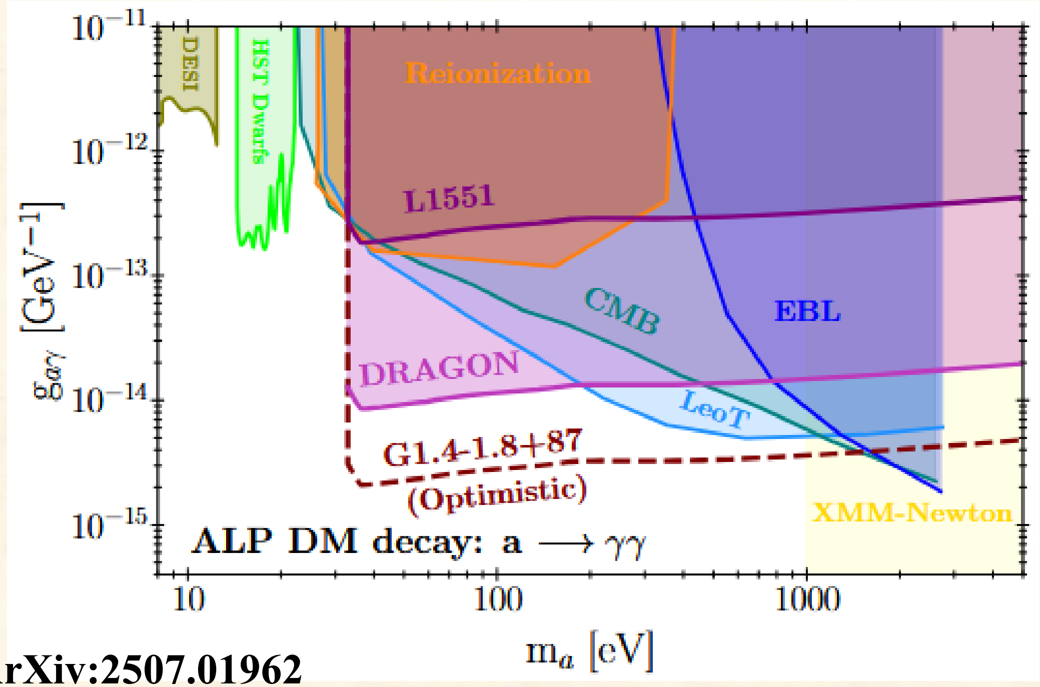
Direct production of UV/X-ray photons within such clouds could trigger substantial amounts of ionization (**PDL** et al 2025 ArXiv:2507.01962)

This allows us to impose constraints in the annihilation and decay rates of sub-keV particles that are among the strongest existing limits. These limits are specially interesting for ALPs in this mass range.

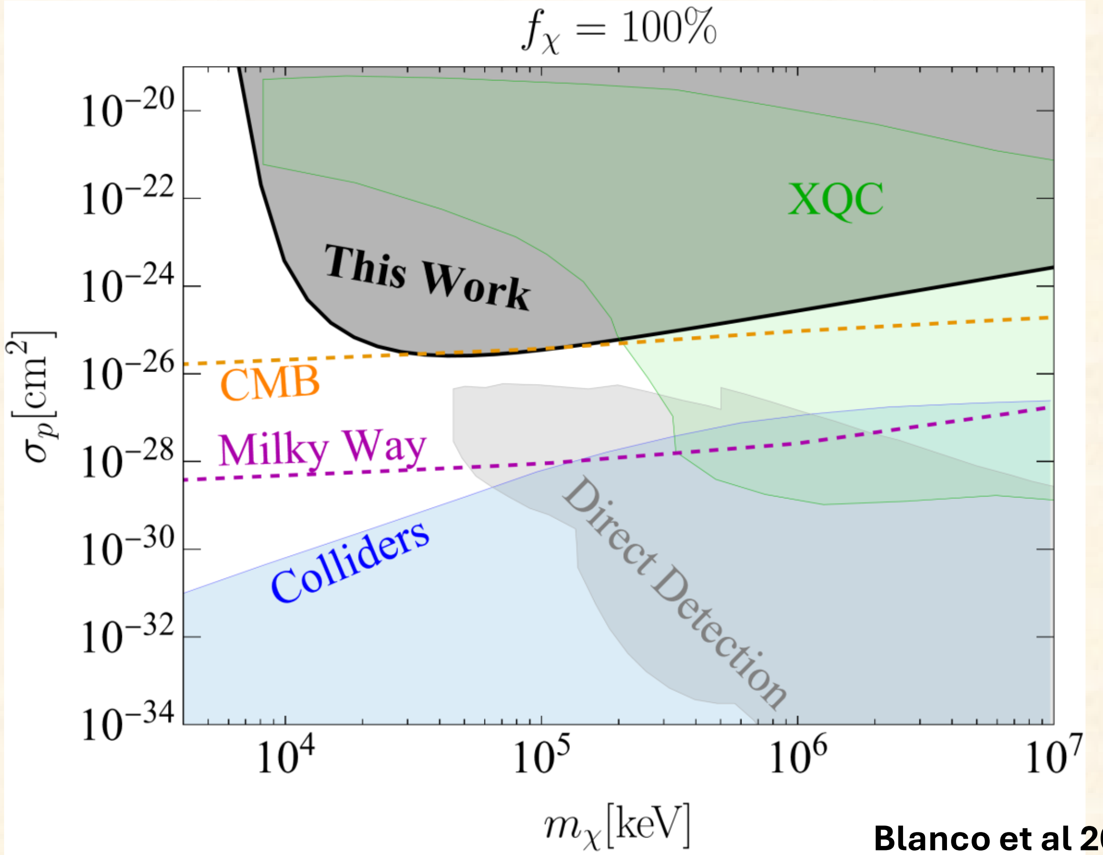


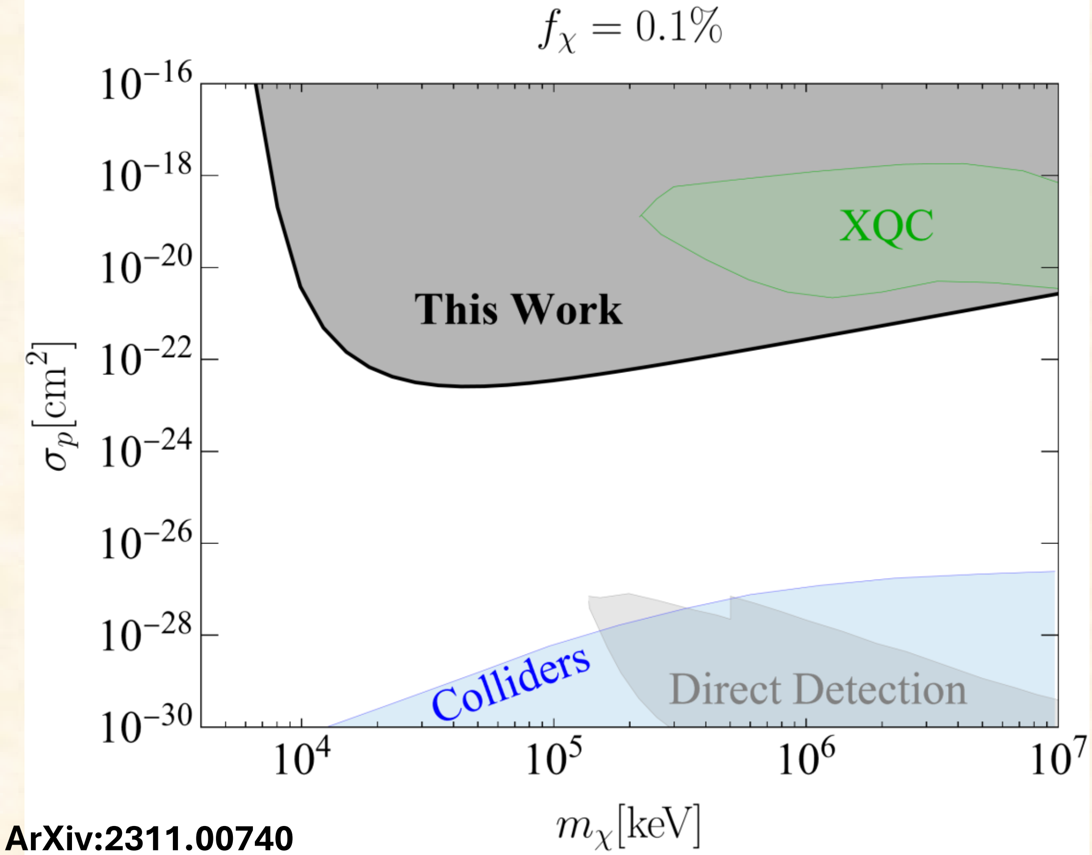


PDL et al 2025 ArXiv:2507.01962

Even beyond indirect searches...

Molecular clouds have been successfully used to set interesting constraints on the direct scattering of DM with electrons and protons → **Ongoing work on constraints from the CMZ...**





Blanco et al 2023 ArXiv:2311.00740

Conclusions

The CMZ anomalous Ionization rate explained by MeV DM

- **Anomalous ionization rate observed in the CMZ points to something exciting going on around the GC**
- **MeV DM could produce the expected ionization rate without conflicting with any constraint or leaving other traces. This also shows the potential of molecular clouds to probe MeV DM**
- **This anomaly could share a common origin with the puzzling 511 keV emission and other continuum signals recently found**
- **The ionization of gas clouds can be use as a tool to probe a plethora of different candidates of low-mass DM**

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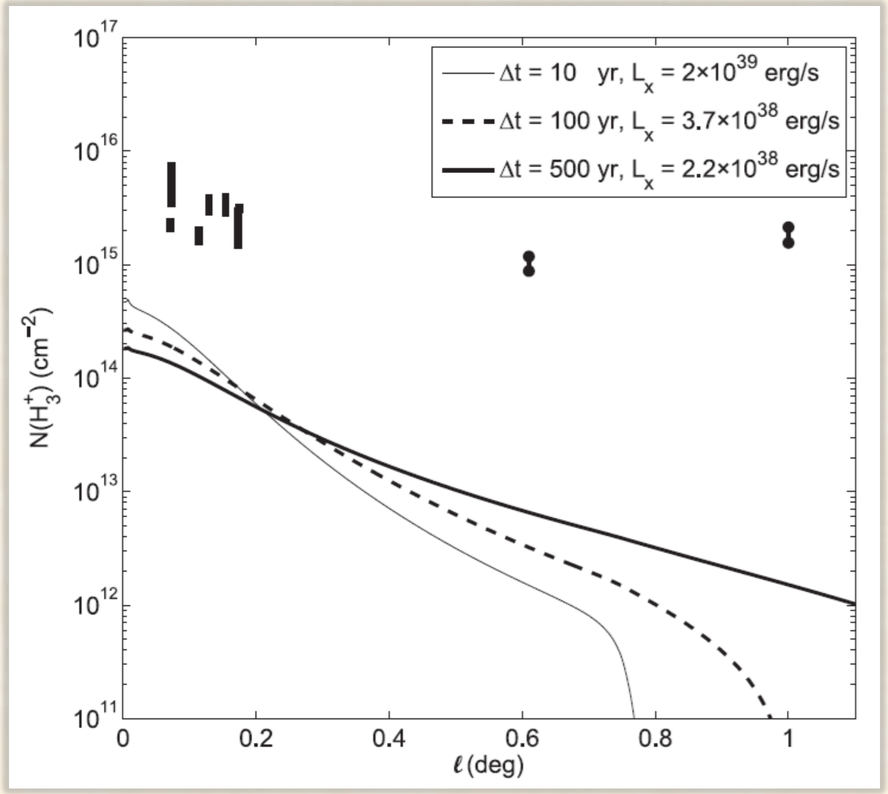
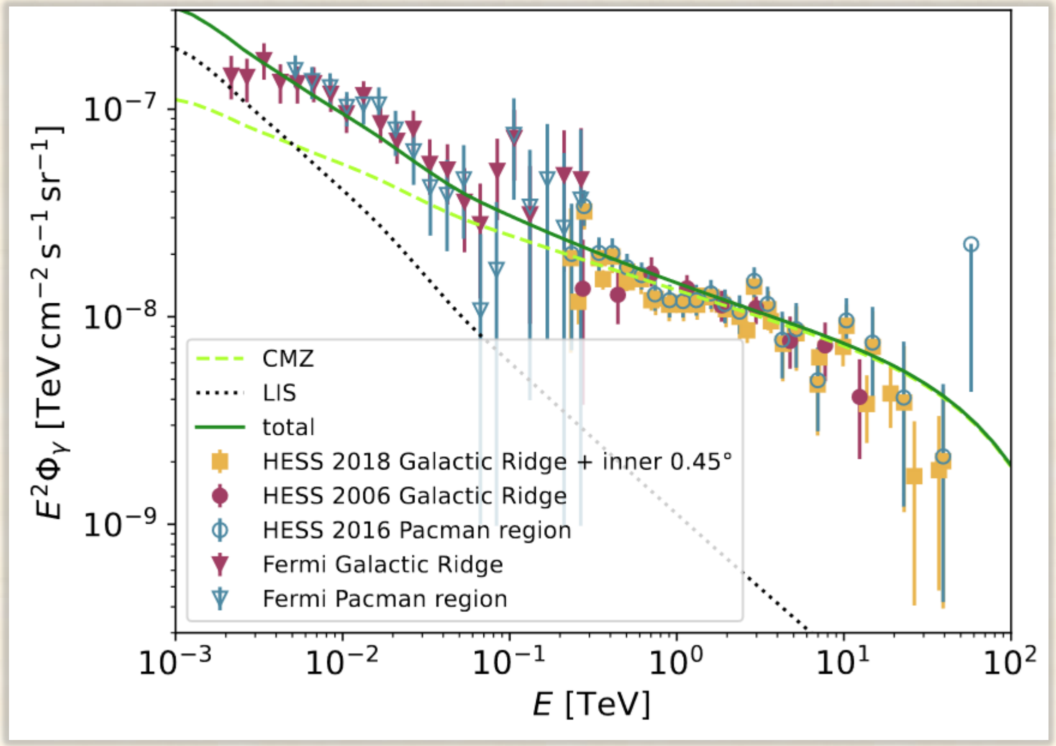
SgrA*, HESSJ1745-290 & diffuse CRs fall too short

Dogiel et al 2013 showed that the X-ray emission from SgrA* is unable to explain the observed ionization rate in the CMZ



Ravikularaman et al 2024 studied the ionization rate produced from the source of the HESS GC emission and found that it can not explain the observations at the CMZ

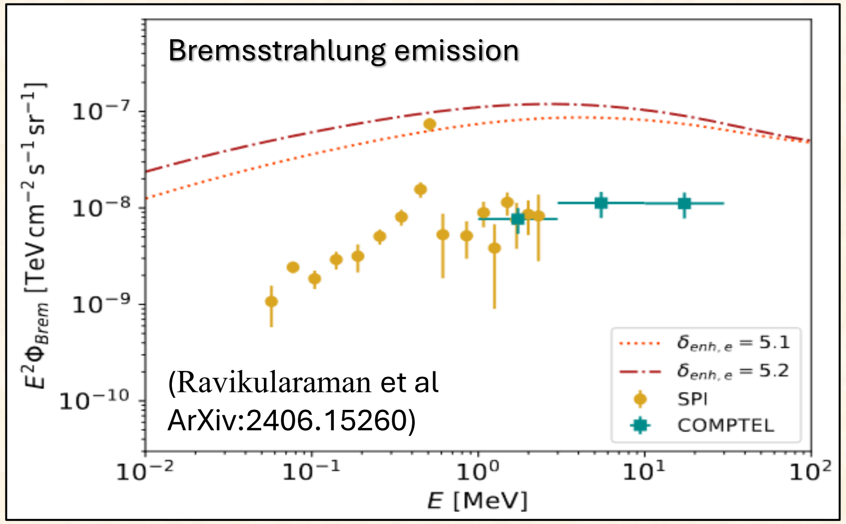


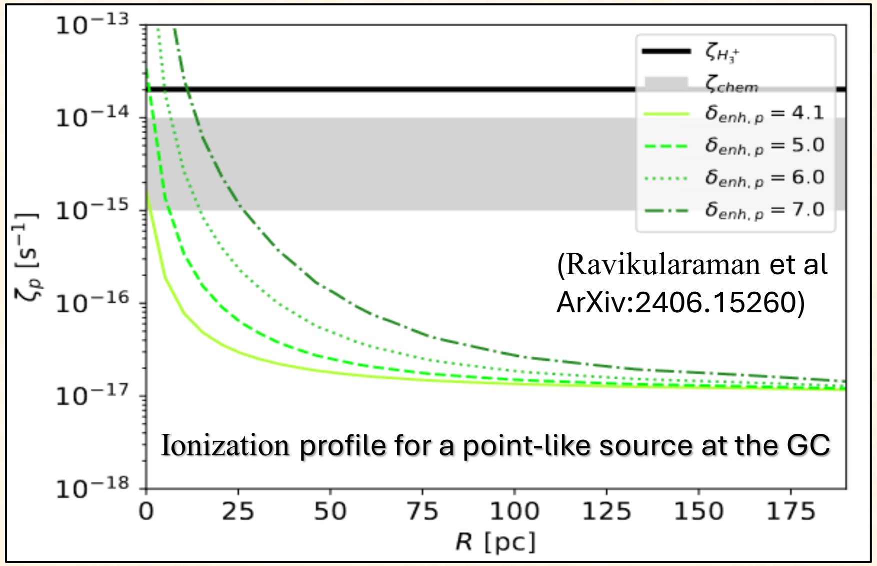
Important insights from the observations

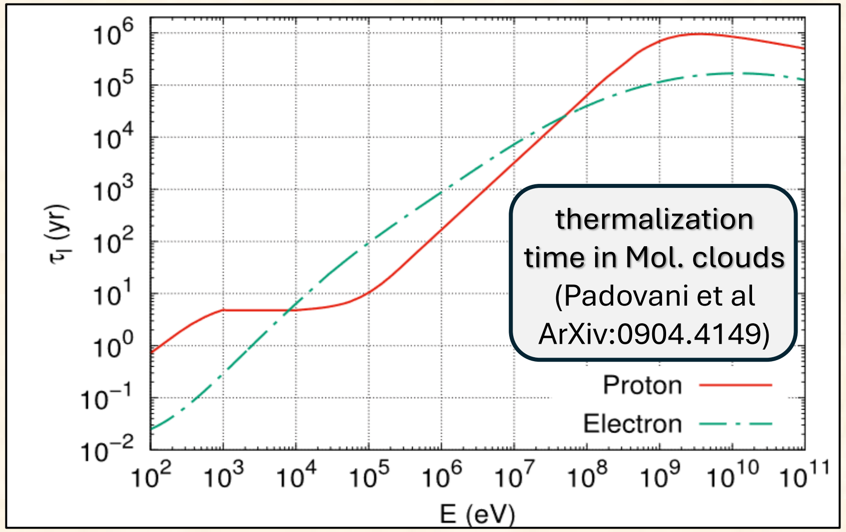
I. The source of particles must be **concentrated around the Galactic Center**

II. This source **must inject low energy** (MeV) **particles**

III. The uniformity of the ionization indicates a **diffuse emisión**, more than point-like







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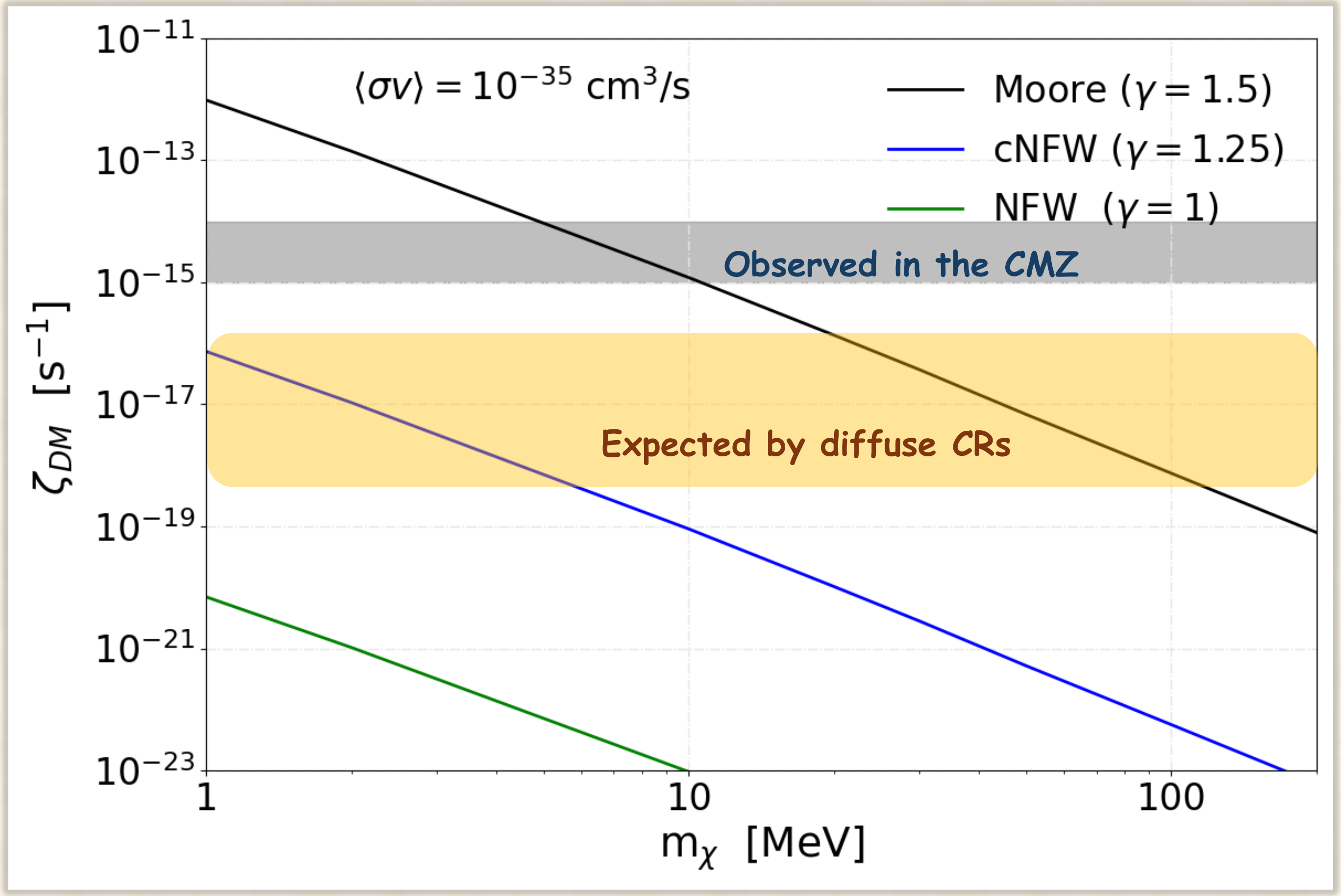


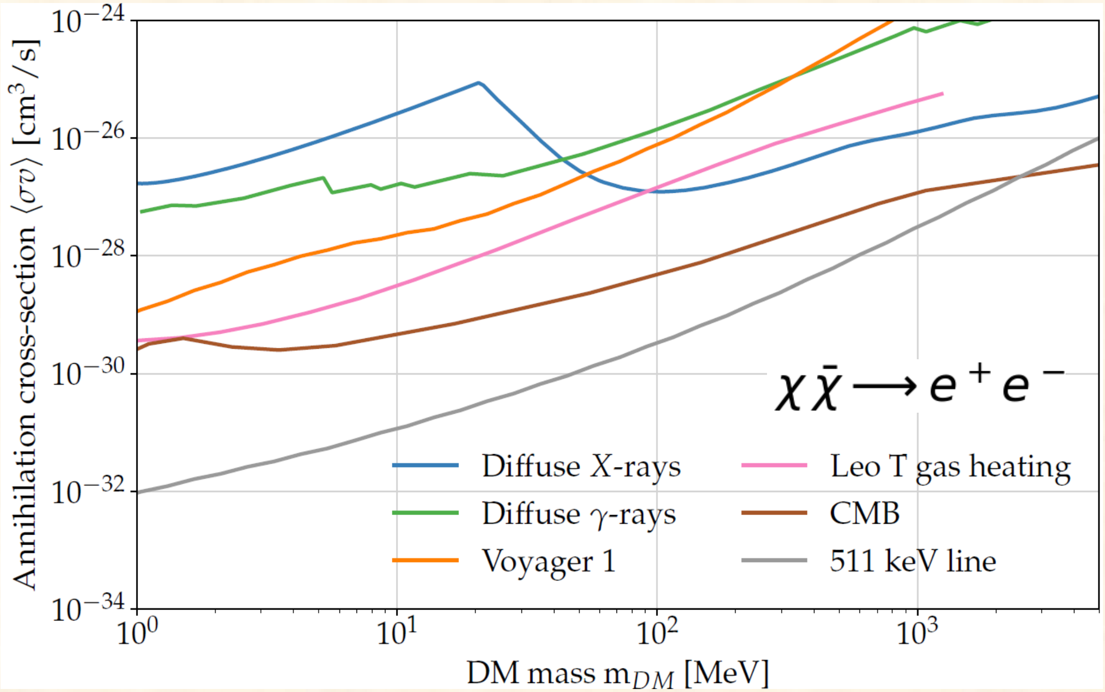
The $e^{\pm}$ from **MeV DM** would **deposit all their energy into the CMZ**, providing a much higher ionization rate than CRs

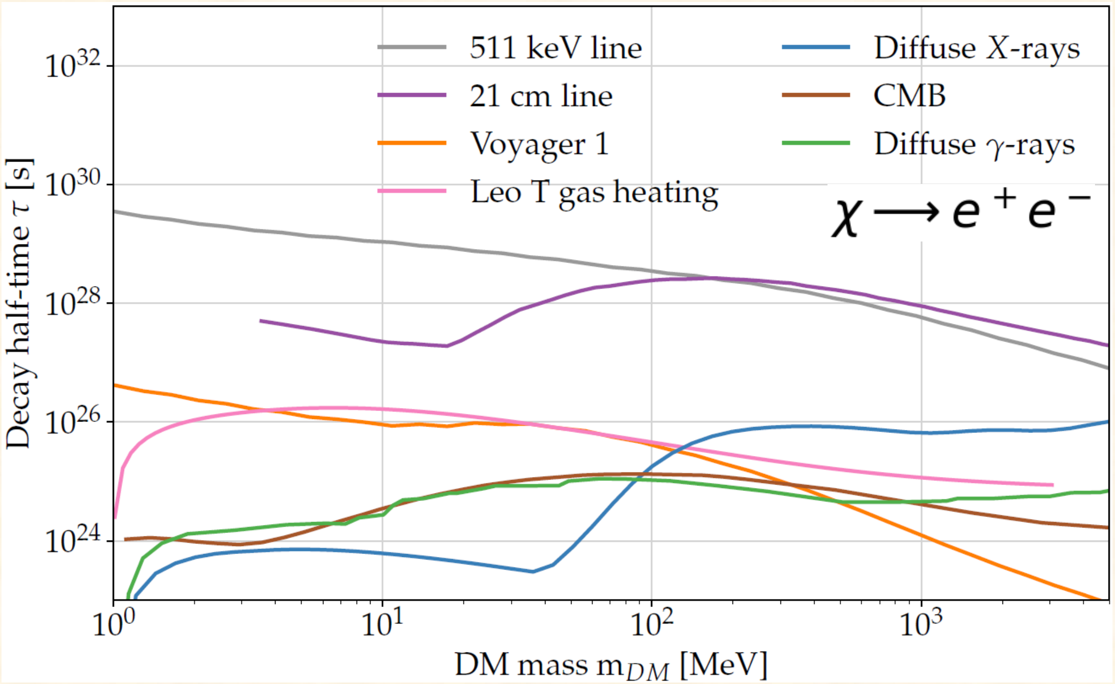
The CMZ ionization rate can be attributed to MeV dark matter annihilation for Galactic dark matter profiles with slopes $\gamma > 1$

Sub-GeV DM constraints: Current status

Main probes: Direct observations of e^+e^- (**Voyager-1**), **X-ray** and soft gamma-ray measurements (via FSR and inverse Compton), **gas heating** in dwarf galaxies (e.g. Leo T), **ionization** of molecular clouds, the **511 keV** emission from e+ annihilation, **CMB** power spectrum and the **21 cm line**

De la Torre+ 2311.04979, 2312.04907 Slatyer+ 1506.03811, 2411.00087
Cirelli+ 2303.08854 Sun+ 2312.11608 Lopez-Honorez+ 1303.5094



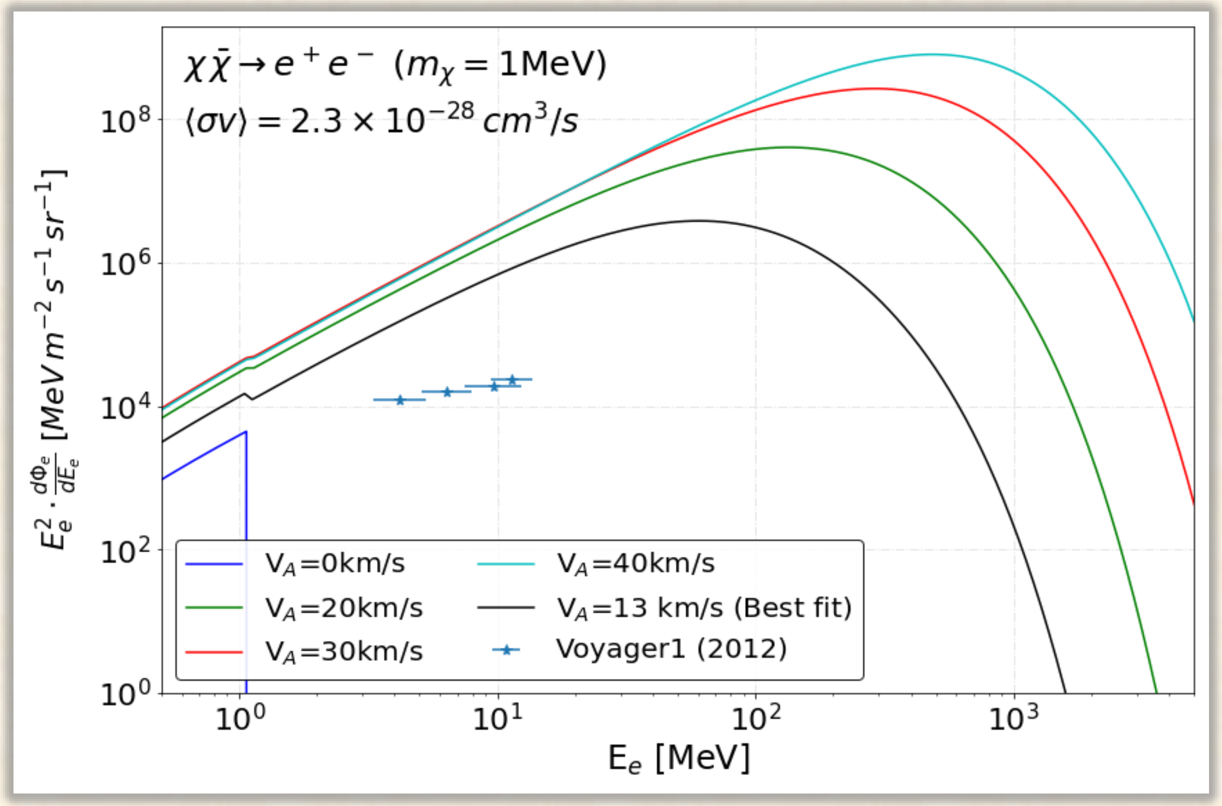


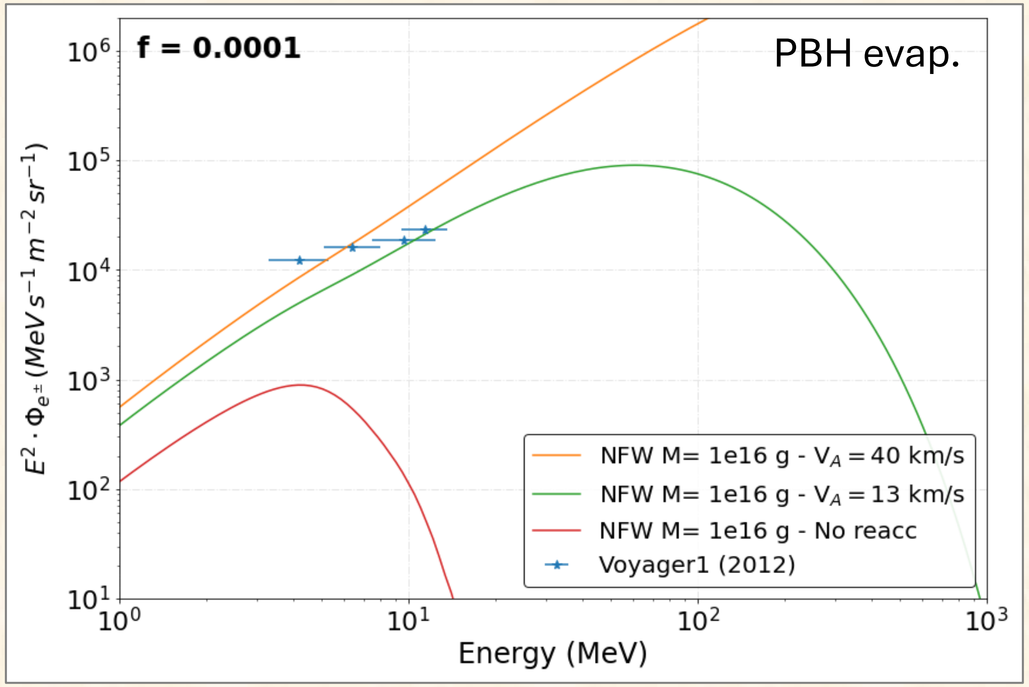
Reacceleration effect

PDL, S. Balaji, J. Koechler ArXiv:2311.04979

The effect of reacceleration hugely impacts the expected spectra!

The predicted Alfvén speed (V_A) changes from analysis to analysis due to systematic uncertainties in CR analyses



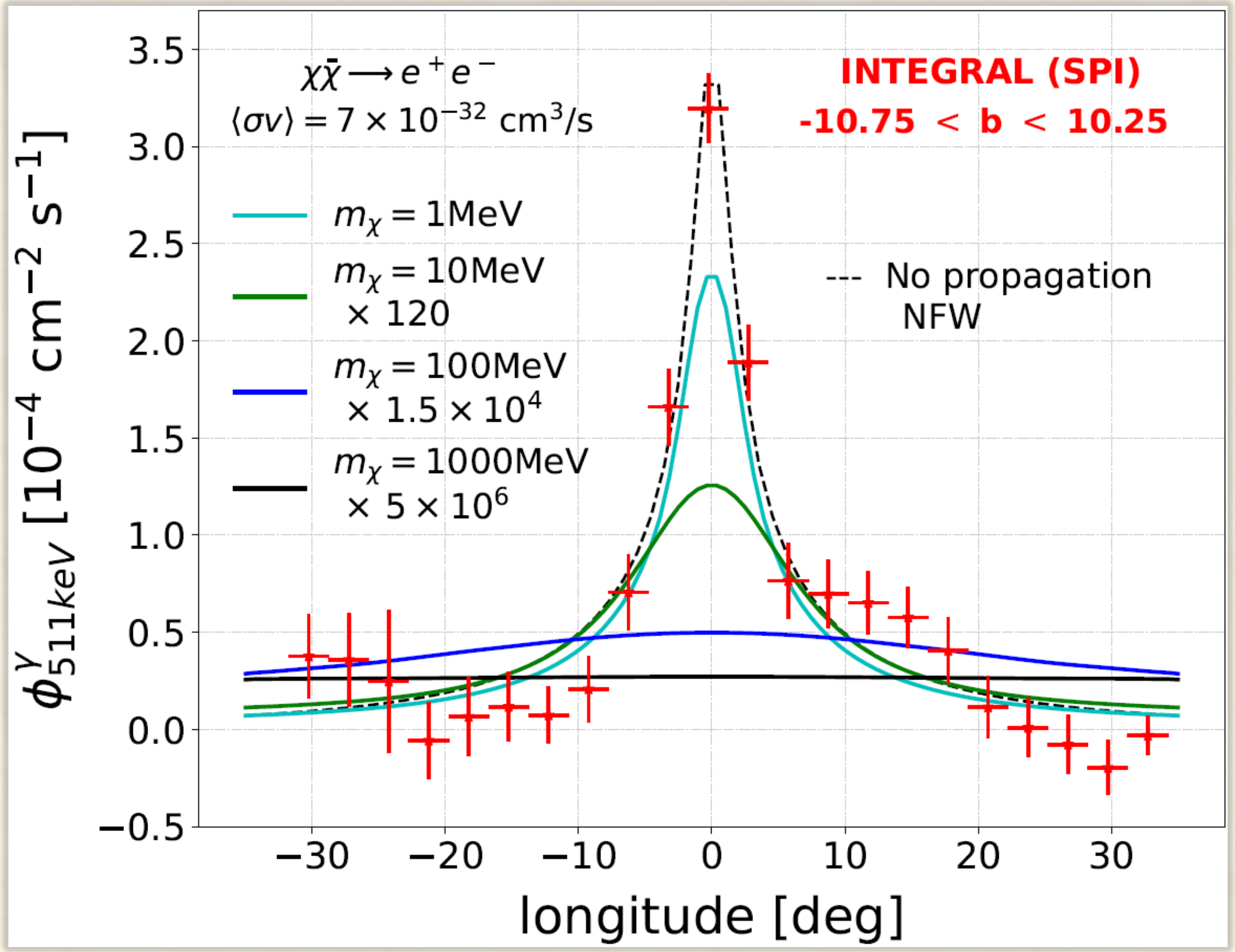


Reacceleration boosts any sub-GeV e^+e^- signal to high energies – Also key for FIPs or PBH emission

511 keV line from MeV DM

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

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



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

Only e+ injected close to ~1 MeV will closely follow their source distribution

An NFW profile does not seem to match well the observations (with caveats*)

Possibly connected with the origin on the anomalous CMZ ionization rate!

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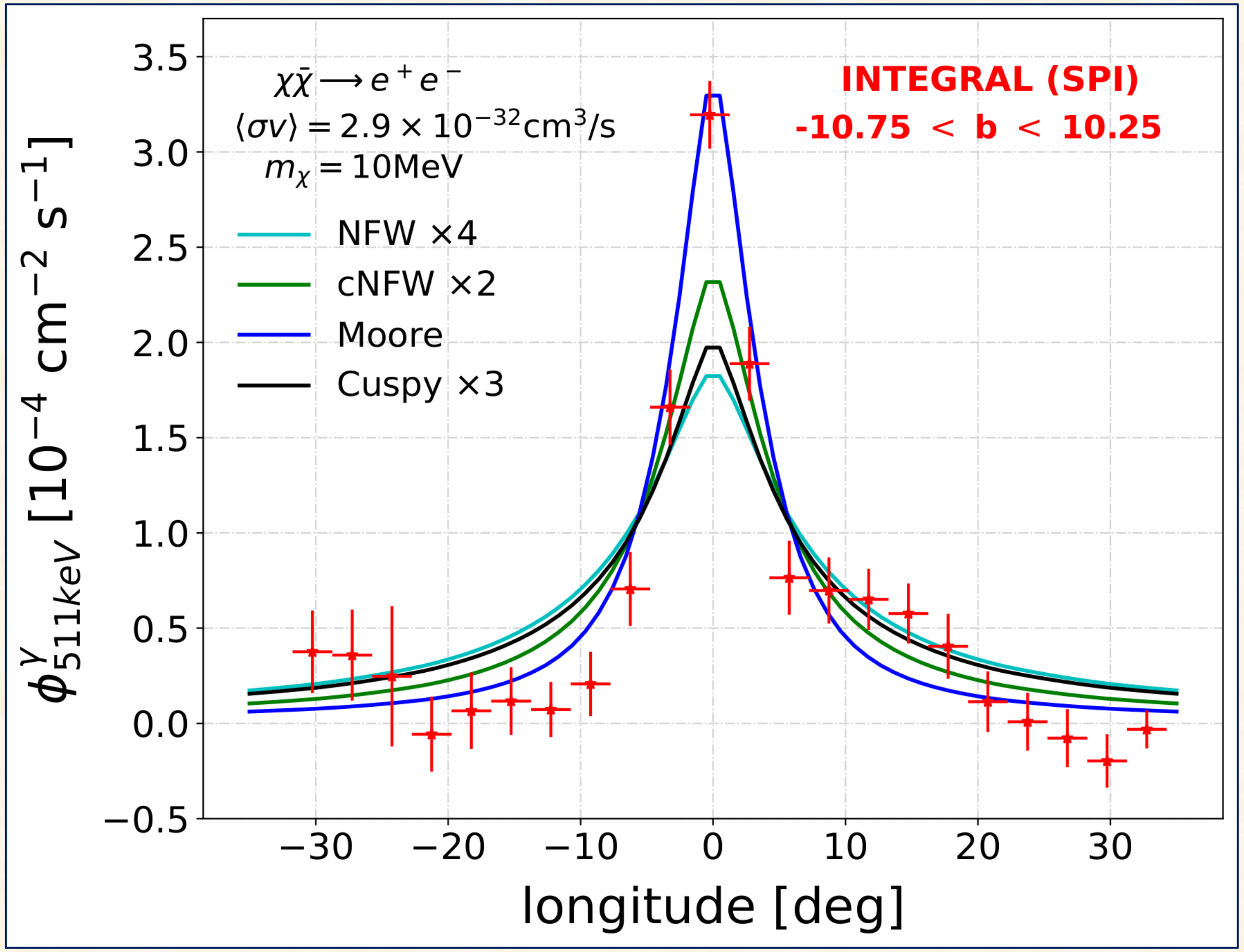

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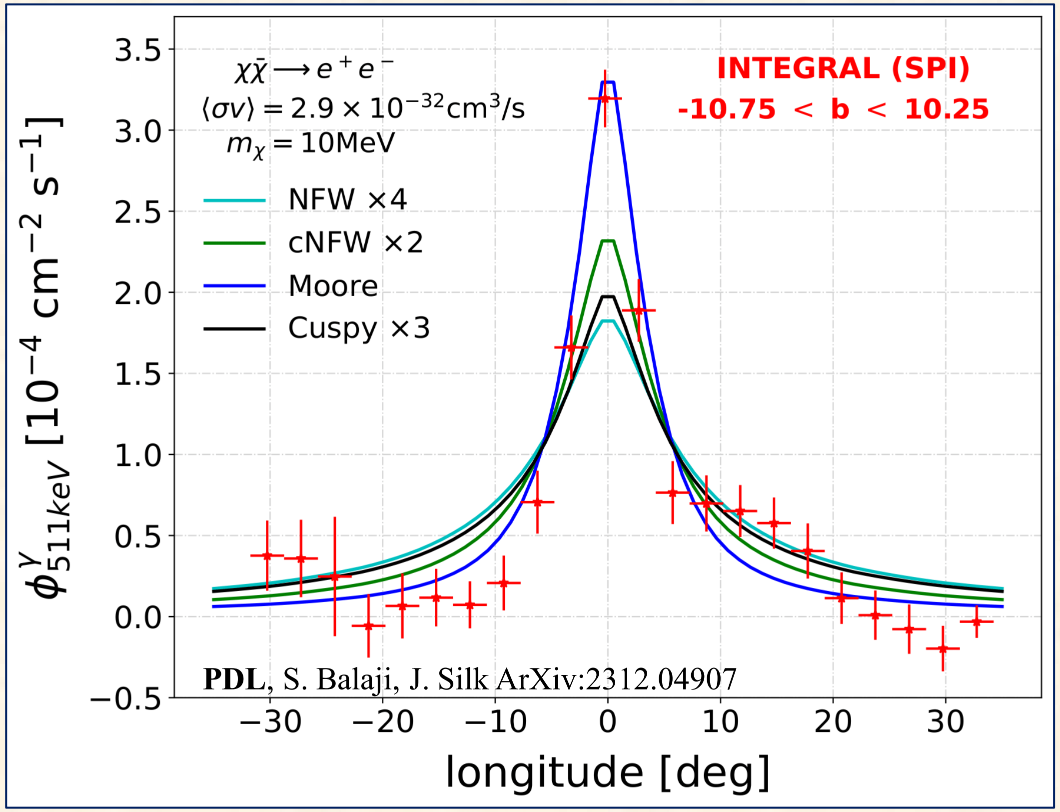
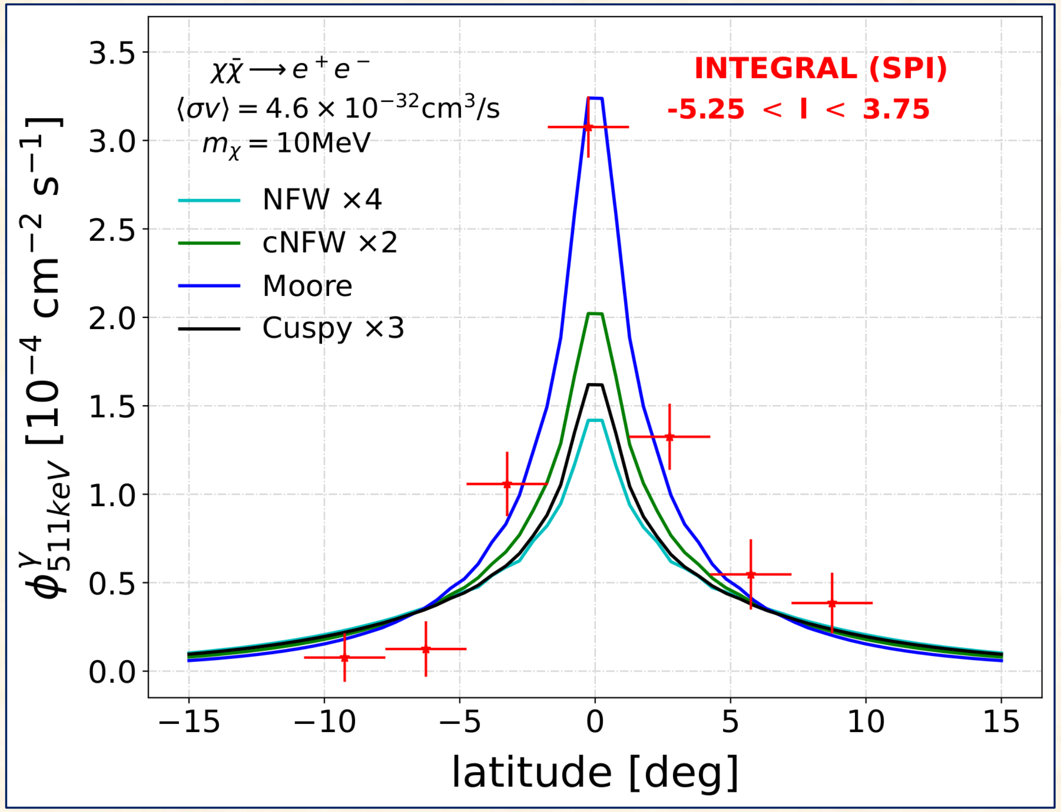
Even steeper than an NFW

A cuspier DM distribution (a contracted NFW profile) could reproduce well the latitude and longitude profiles of the emission without being in conflict with previous constrains – For masses up to a few tens MeV

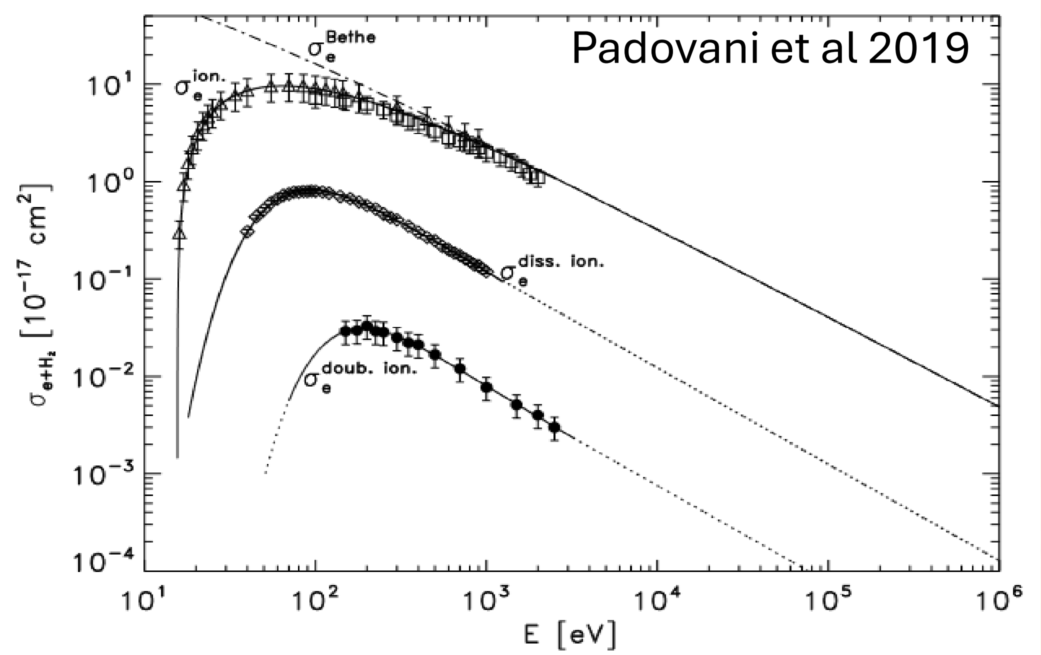




Source	Process	$E(e^+)^a$ (MeV)	e^+ rate[b] $\dot{N}_{e+}$ (10^{43} s^{-1})	Bulge/Disk[c] B/D	Comments
Massive stars: ^{26}Al	β^+-decay	~1	0.4	<0.2	$\dot{N}, B/D$: Observationally inferred
Supernovae: ^{24}Ti	β^+-decay	~1	0.3	<0.2	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+-decay	~1	*2*	<0.5	Assuming $f_{e+,esc}$=0.04
Novae	β^+-decay	~1	*0.02*	<0.5	Insufficent e^+ production
Hypernovae/GRB: ^{56}Ni	β^+-decay	~1	?	<0.2	Improbable in inner MW
Cosmic rays	p-p	~30	0.1	<0.2	Too high e^+ energy
LMXRBs	$\gamma-\gamma$	~1	*2*	<0.5	Assuming L_{e+} ~0.01 $L_{obs,X}$
Microquasars (μQs)	$\gamma-\gamma$	~ 1	*1*	<0.5	e^+ load of jets uncertain
Pulsars	$\gamma-\gamma$ / $\gamma-\gamma_B$	>30	*0.5*	<0.2	Too high e^+ energy
ms pulsars	$\gamma-\gamma$ / $\gamma-\gamma_B$	>30	*0.15*	<0.5	Too high e^+ energy
Magnetars	$\gamma-\gamma$ / $\gamma-\gamma_B$	>30	*0.16*	<0.2	Too high e^+ energy
Central black hole	p-p	High	?		Too high e^+ energy, unless B >0.4 mG
	$\gamma-\gamma$	1	?		Requires e^+ diffusion to ~1 kpc
Dark matter	Annihilation	1 (?)	?		Requires light scalar particle, cuspy DM profile
	Deexcitation	1	?		Only cuspy DM profiles allowed
	Decay	1	?		Ruled out for all DM profiles
Observational constraints		<7	2	>1.4	

Dogiel et al. 2013, arXiv:1306.1654: “We conclude that a source of ionisation of molecular hydrogen in the CMZ other than CRs is very likely to exist. The most obvious candidate is a radiation field made of UV and/or X-ray photons. As it is known that X-ray photons emitted by Sgr A∗ during outbursts do not suffice to explain the observed ionisation rates, the sources of ionising photons Will have to be distributed across the entire CMZ”

reaction
$p_{CR} + H_2 \rightarrow p_{CR} + H_2^+ + e$
$p_{CR} + H_2 \rightarrow H + H_2^+$
$p_{CR} + H_2 \rightarrow p_{CR} + H + H^+ + e$
$p_{CR} + H_2 \rightarrow p_{CR} + 2H^+ + 2e$
$e_{CR} + H_2 \rightarrow e_{CR} + H_2^+ + e$
$e_{CR} + H_2 \rightarrow e_{CR} + H + H^+ + e$
$e_{CR} + H_2 \rightarrow e_{CR} + 2H^+ + 2e$
$p_{CR} + He \rightarrow p_{CR} + He^+ + e$
$p_{CR} + He \rightarrow H + He+$
$e_{CR} + He \rightarrow e_{CR} + He^+ + e$

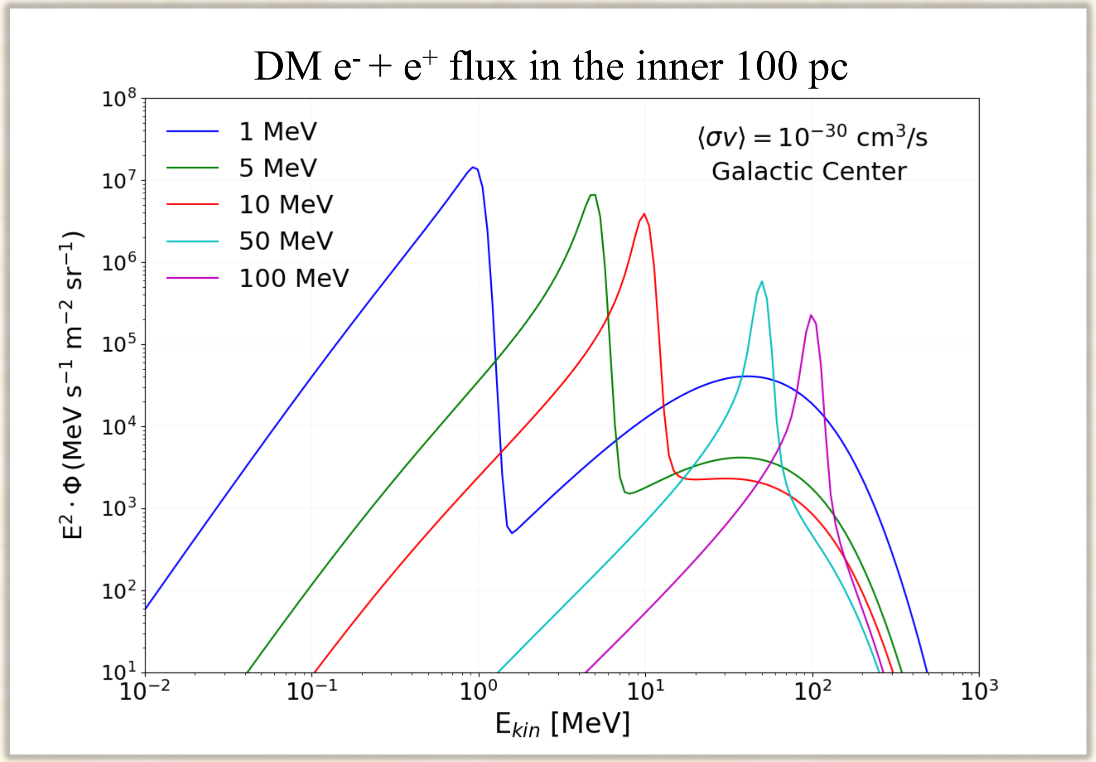


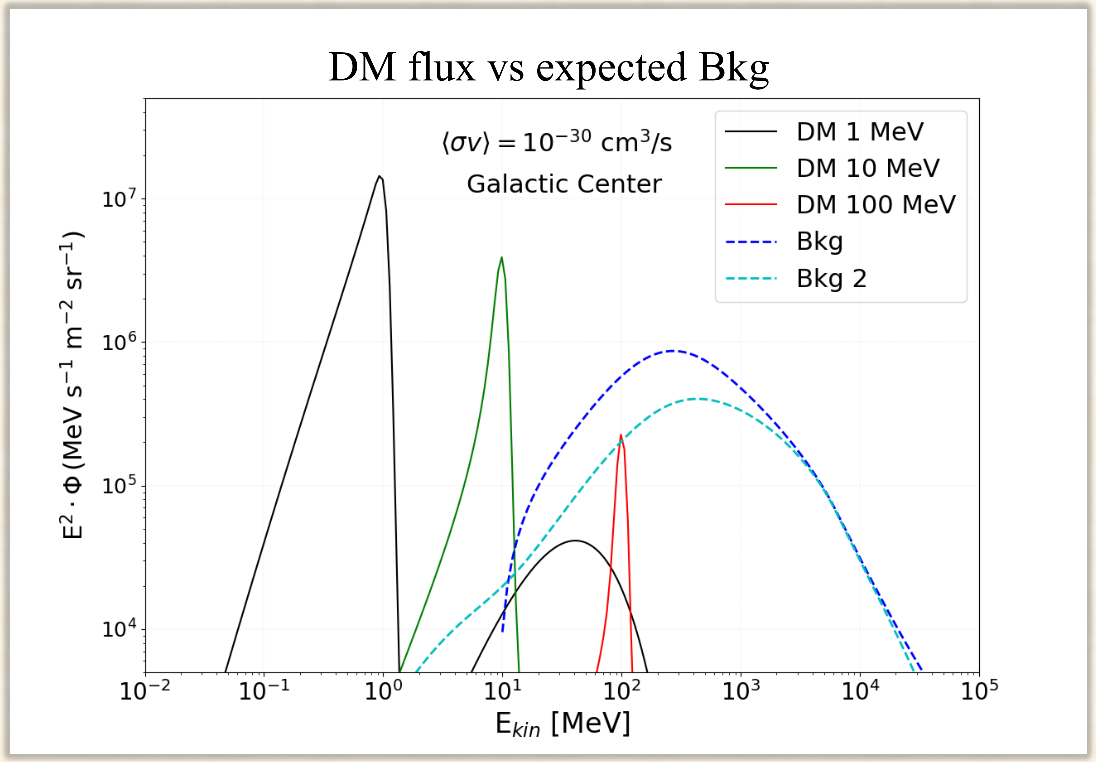
MeV DM in the center of the Galaxy

The $e^{\pm}$ emission from DM annihilation can be higher than that expected from cosmic rays!
Current constraints are unable to rule out DM as the dominant $e^{\pm}$ source in the Gal. Center

Impact of DM in the star formation rate at the CMZ?

Could DM affect the chemistry of the GC?





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Direct production of UV/X-ray photons within such clouds could trigger substantial amounts of ionization (**PDL** et al 2025 ArXiv:2507.01962)

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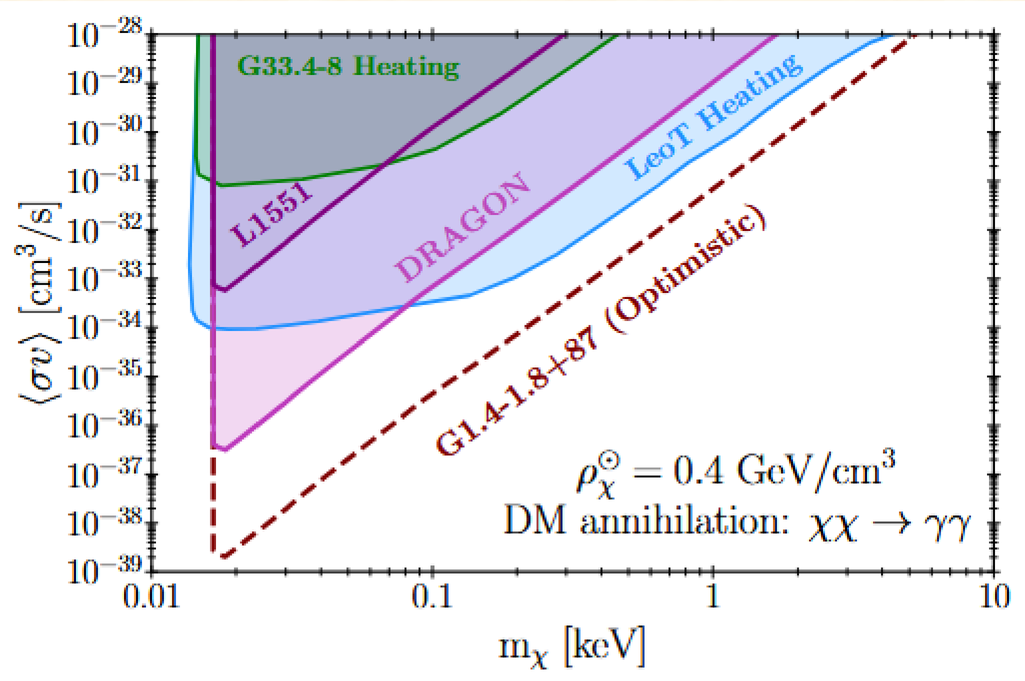
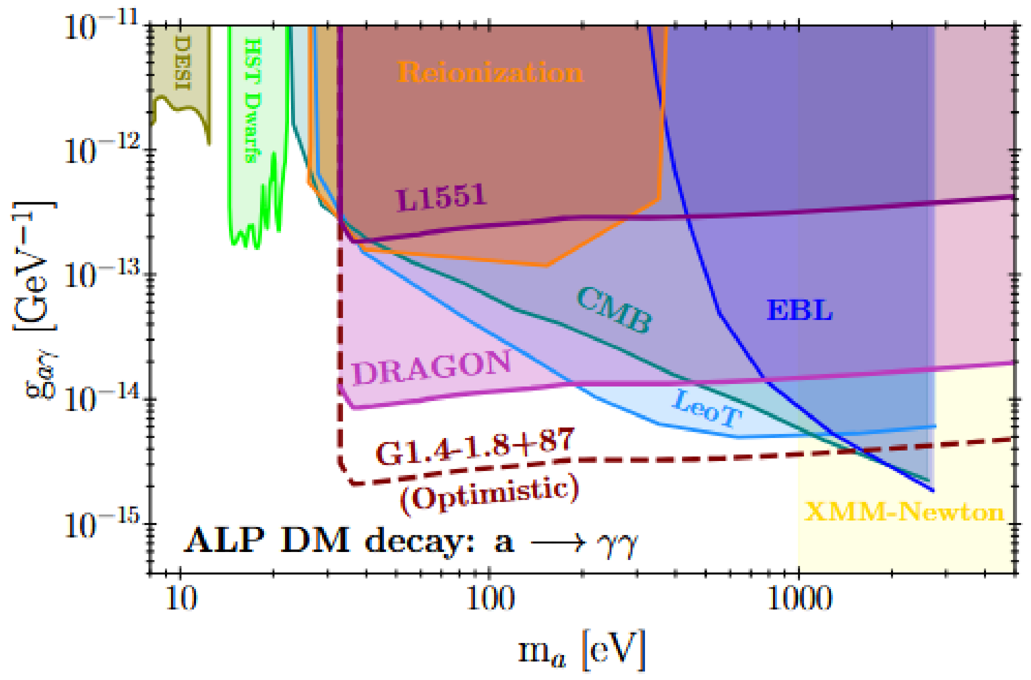
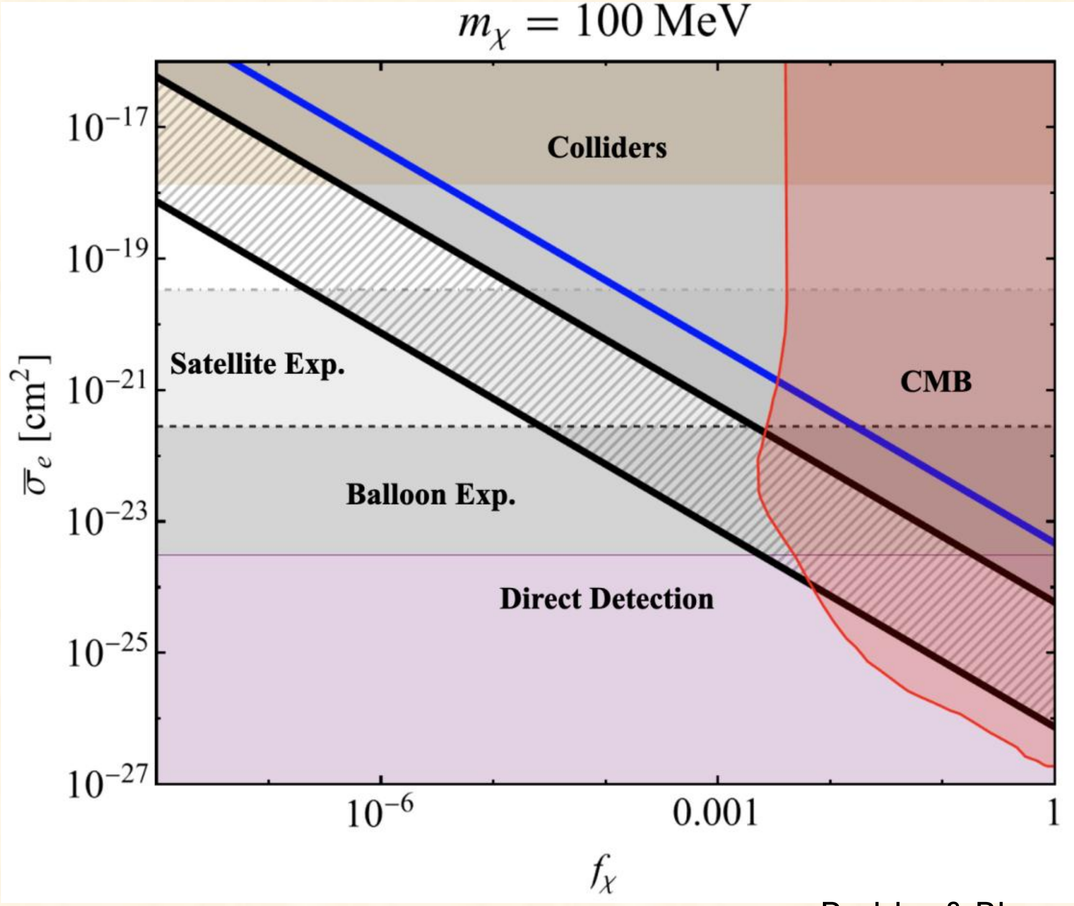
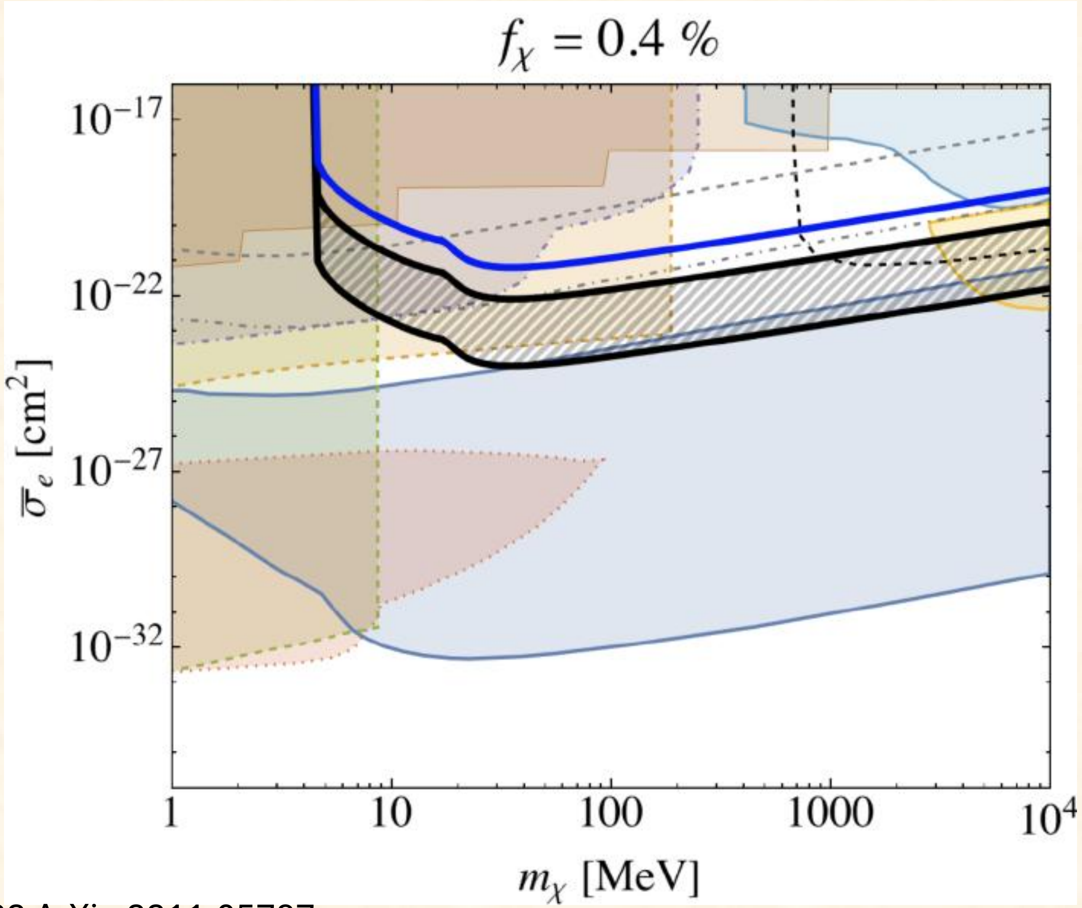




Even beyond indirect searches...





Prabhu & Blanco 2022 ArXiv:2211.05787