New 511 keV line data provides strongest sub-GeV dark matter constraints

Shyam Balaji - 11/07/2024 (based on work done in conjunction with Pedro De La Torre Luque and Joe Silk, arxiv:2312.04907)
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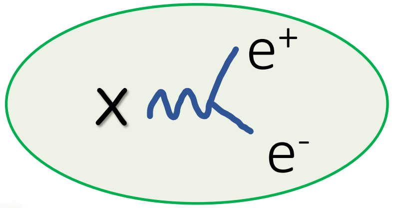
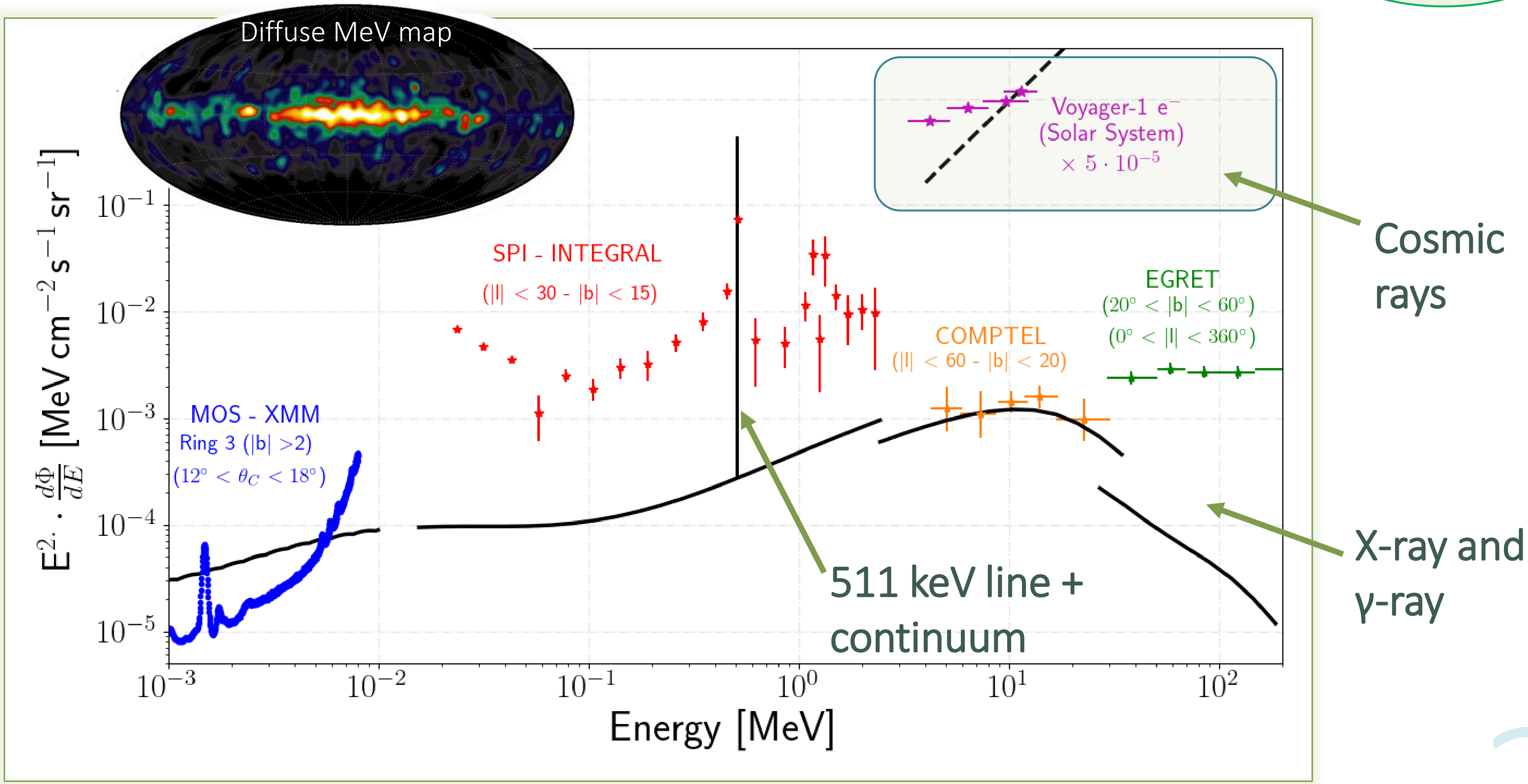
Positron-induced diffuse emissions





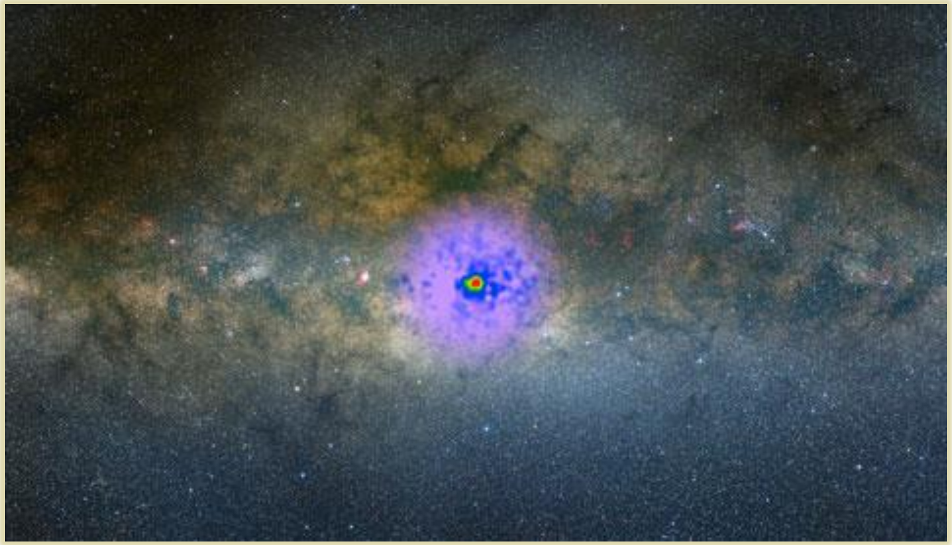
Outline

The **511 keV puzzle** and the fate of positrons in the Galaxy

Line and continuum γ-ray emission from positrons

Looking for **signatures of new physics with 511 keV and the MeV gap**

- Sub GeV DM (our focus)
- PBHs (e.g. D. Hooper and others)
- FIPs (e.g. F. Calore, A. Dekker and others)



Prospects for future MeV obs.

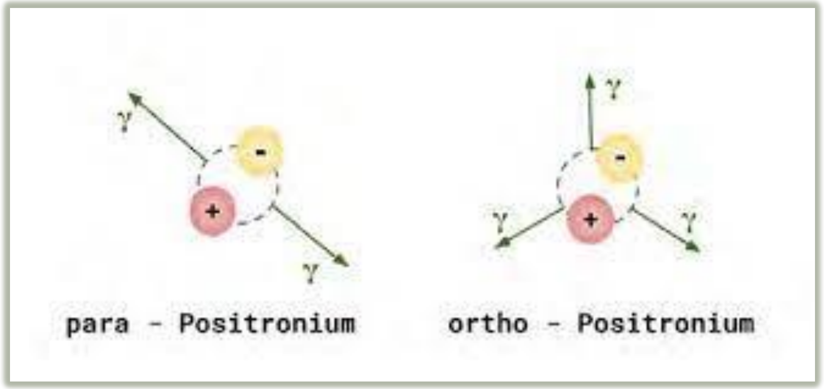
Conclusions

The fate of positrons in the Galaxy

Positrons were discovered in the 1930s, from CR interactions -- CRs must also produce positrons in the disk of the Milky Way

Later, Dirac showed that positrons annihilate with electrons into a pair of photons – If positrons are near rest, this leads to a line signal at 511 keV!

But e^+e^- pairs likely create a bound state, “positronium”, which produces a line, and also a continuum emission below 511 keV

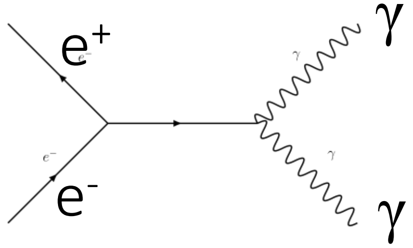


Direct annihilation cross sections:

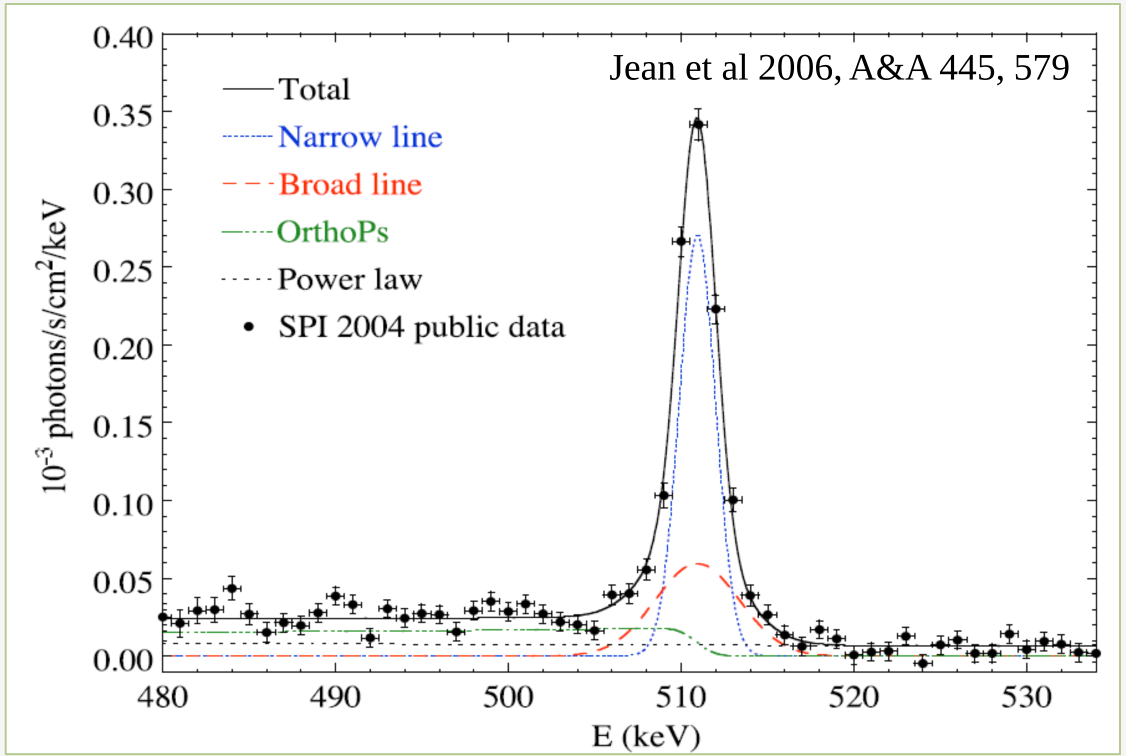
$$\sigma = \frac{\pi r_e^2}{\gamma + 1}\left[\frac{\gamma^2 + 4\gamma + 1}{\gamma^2 - 1}\ln\left(\gamma + \sqrt{\gamma^2 - 1}\right) - \frac{\gamma + 3}{\sqrt{\gamma^2 - 1}}\right]$$

511 keV flux: $\frac{d\phi_\gamma^{511}}{d\Omega} = 2k_{ps}\int ds\,\frac{d\phi^{e^+}}{d\Omega}\cdot n_e \cdot \sigma^{\rm ann}(E_{\rm th})$

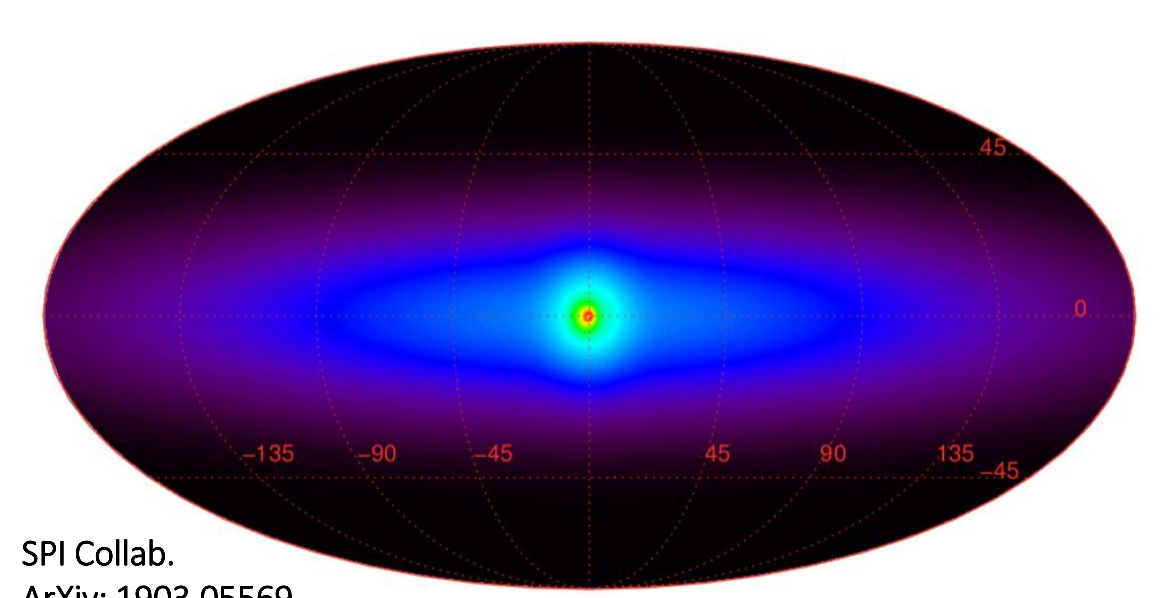
The 511 keV puzzle



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**



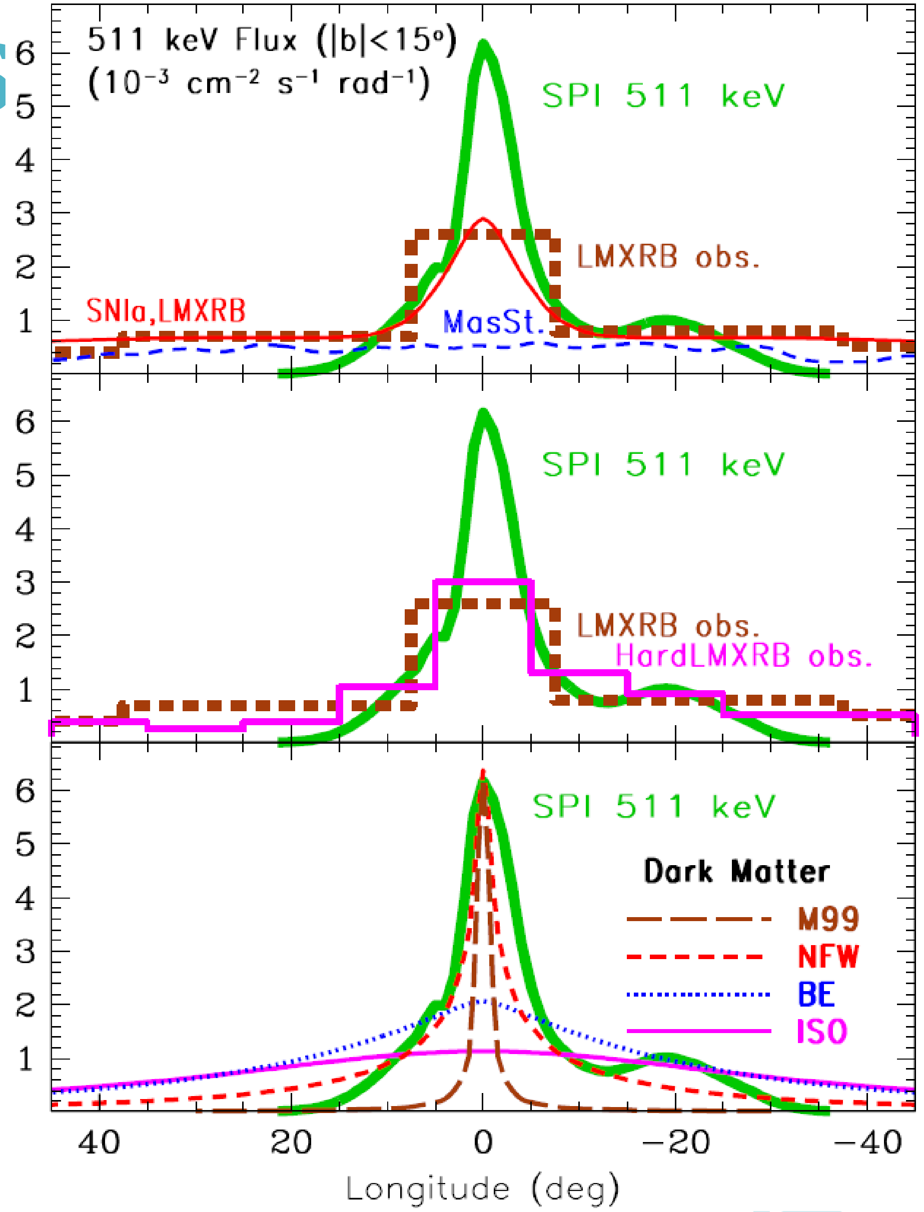
SPI Collab.
ArXiv: 1903.05569

Possible positron sources

Known sources contributing with the <u>disk emission</u> 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 <u>bulge emission</u> 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

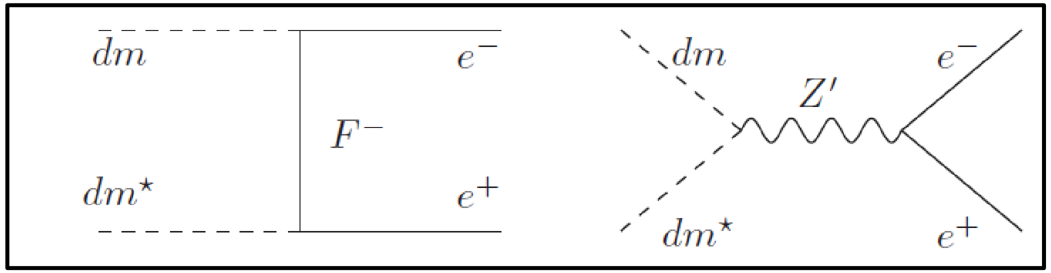


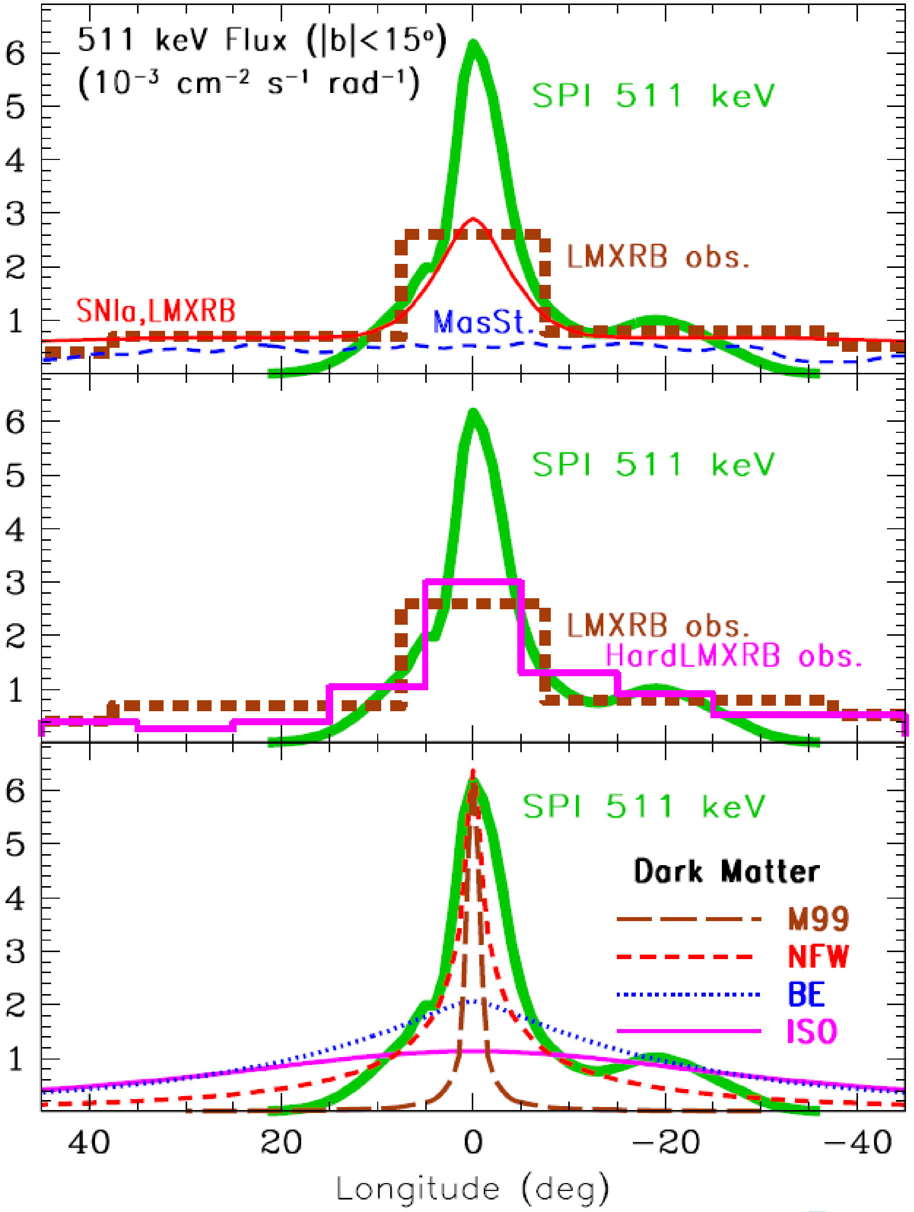
Possible positron sources

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

Cored DM profile, DM decay, p-wave DM are ruled out (Ascasibar et al 2006)

Sub-GeV DM is compatible with BBN constraints only for $m_\chi > 10 MeV$ (Boehm et a) or $m_\chi > 1\ MeV$ (M. Escudero) with extra neutrino injection

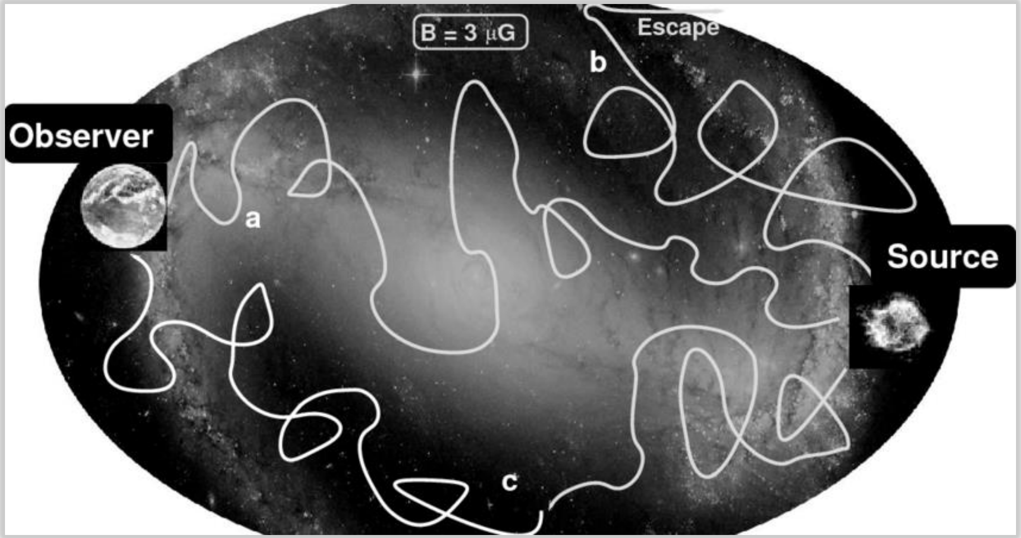




e^+e^- propagation

- Electrons and positrons interact with the Galactic magnetic field and the ISM

- DM particles heavier than ~10 MeV would produce e^+ that travel up to 100s of parsecs before thermalizing (Pedro De La Torre Luque, **SB**, 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.)

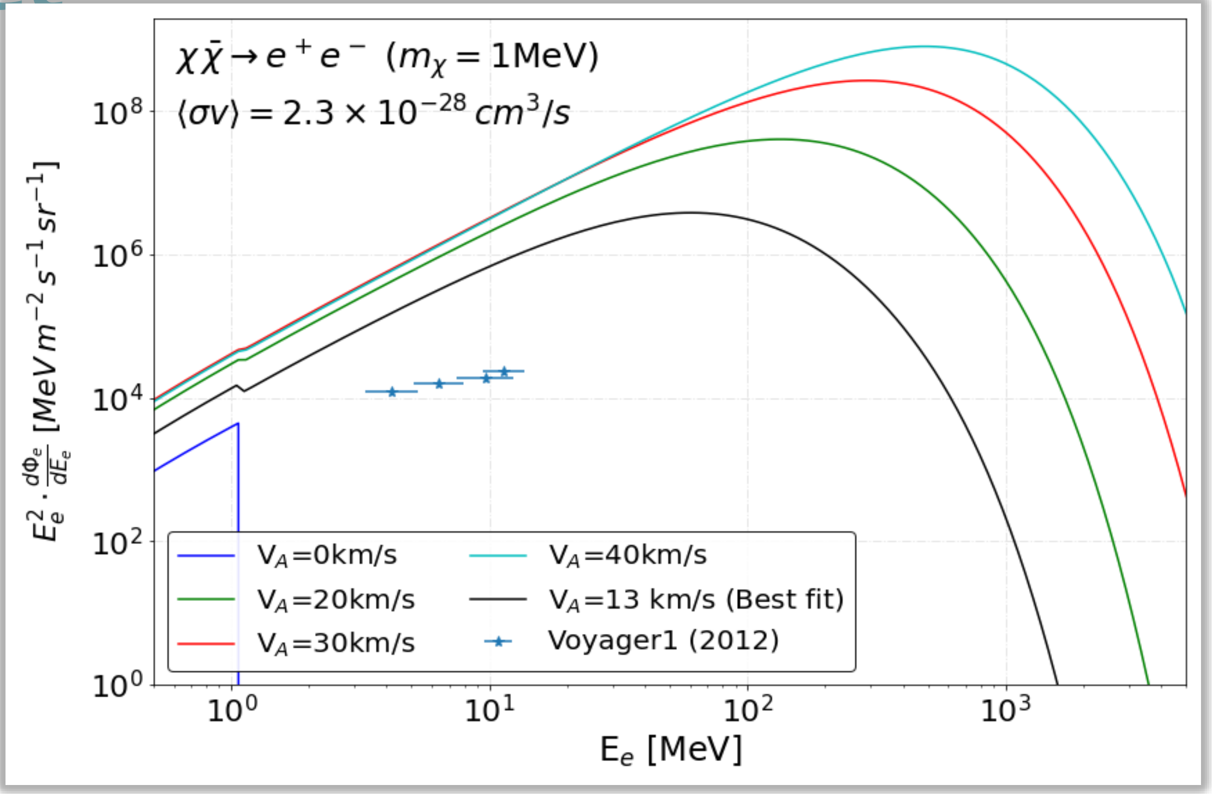
Reacceleration effect

P. De La Torre Luque, **SB**, J. Koechler ArXiv:2311.04979

The effect of reacceleration hugely impacts the expected spectra!

Exchange of energy of charged particles with plasma waves → Alfvén speed dictates speed of plasma waves

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 – key for any exotic positron emitter (including feebly interacting particles and PBHs etc.)

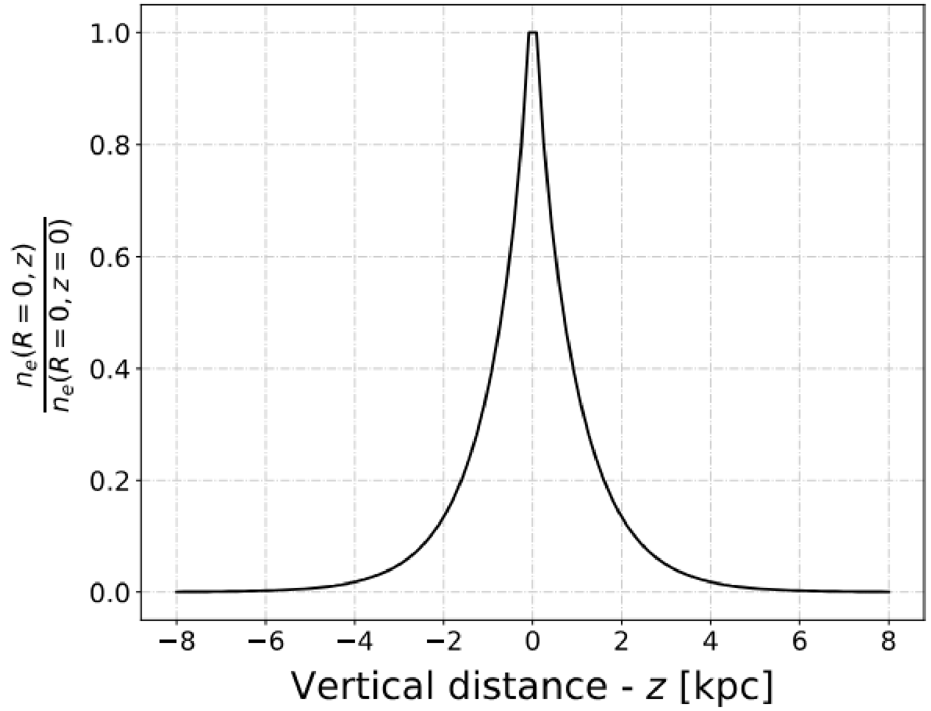
Free electron density dependence

The Latitude profile of the 511 keV can be leveraged

Different regions of the Galaxy → different rate of positronium formation

Depends strongly on the distribution of the ambient electrons

Important for **very low DM masses**, when the positrons lose energy very fast in the disk



We consider the NE2001 Model (Cordes and Lazio (2003a,b)) for the free electron density, this enables use of the 511 keV latitude profile!

Best fit parameters

Best fit propagation parameters from local CR observables and analyses

Lots to see but the important ones are H and V_A

We also consider a pessimistic setup (very slow diffusion), where the halo height is set to $H = 3$ kpc and no reacceleration (i.e. $V_A = 0$ km/s).

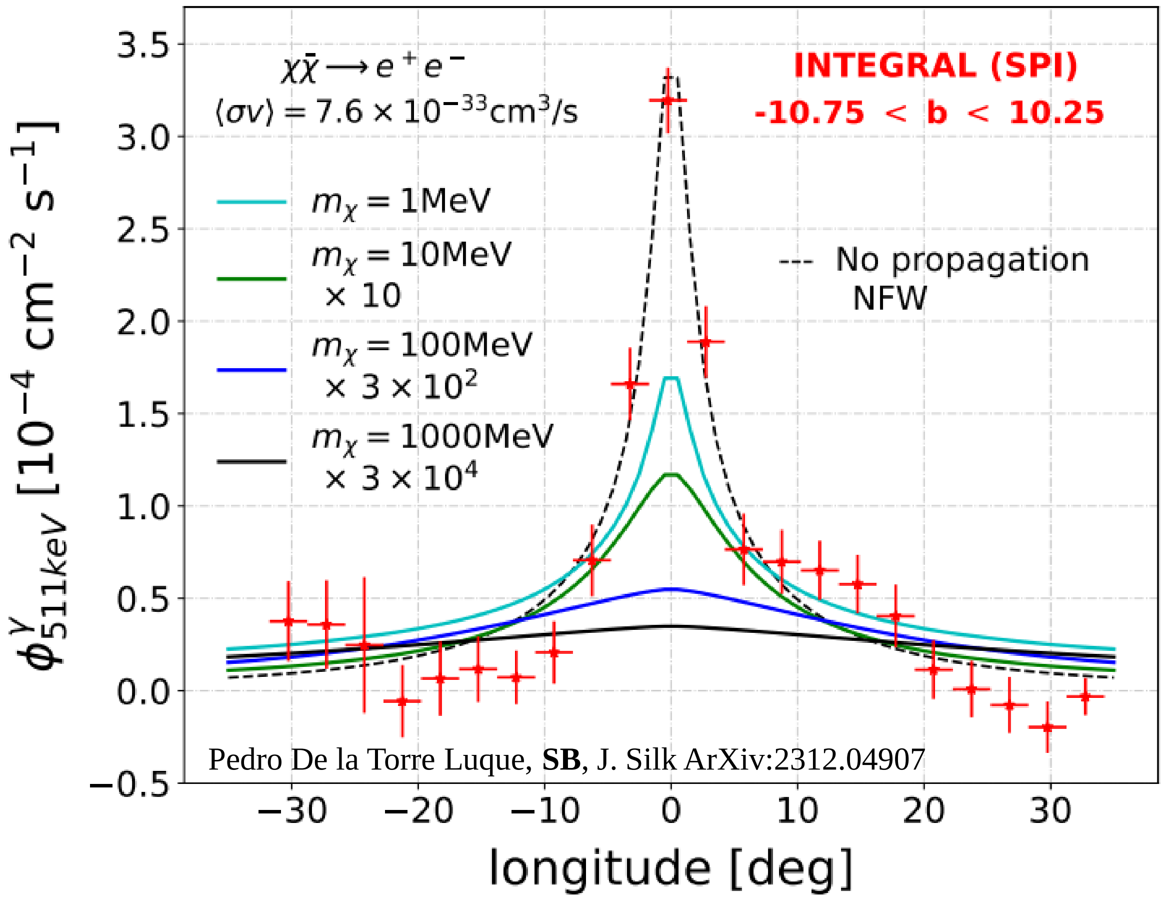
And optimistic (very fast diffusion) case, $H = 16$ kpc and $V_A = 40$ km/s.

Halo height	H	$8.00^{+2.35}_{-1.96}$ kpc
Norm. of Diffusion coeff.	D_0	$1.02^{+0.12}_{-0.10} \times 10^{29}$ cm^{2}s^{-1}
Norm. rigidity	R_0	4 GV
Diffusion spectral index	δ	0.49 ± 0.01
β exponent	η	$-0.75^{+0.06}_{-0.07}$
Alfvén velocity	v_A	$13.40^{+0.96}_{-1.02}$ km/s
Break rigidity	R_b	312 ± 31 GV
Index break	$\Delta\delta$	0.20 ± 0.03
Smooth. param.	s	0.04 ± 0.0015

Best fit parameters and uncertainty bands will be shown later in the limit plots

Effect of a realistic diffusion model

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

First consequence: Only positrons injected close to ~1 MeV will closely follow their source distribution

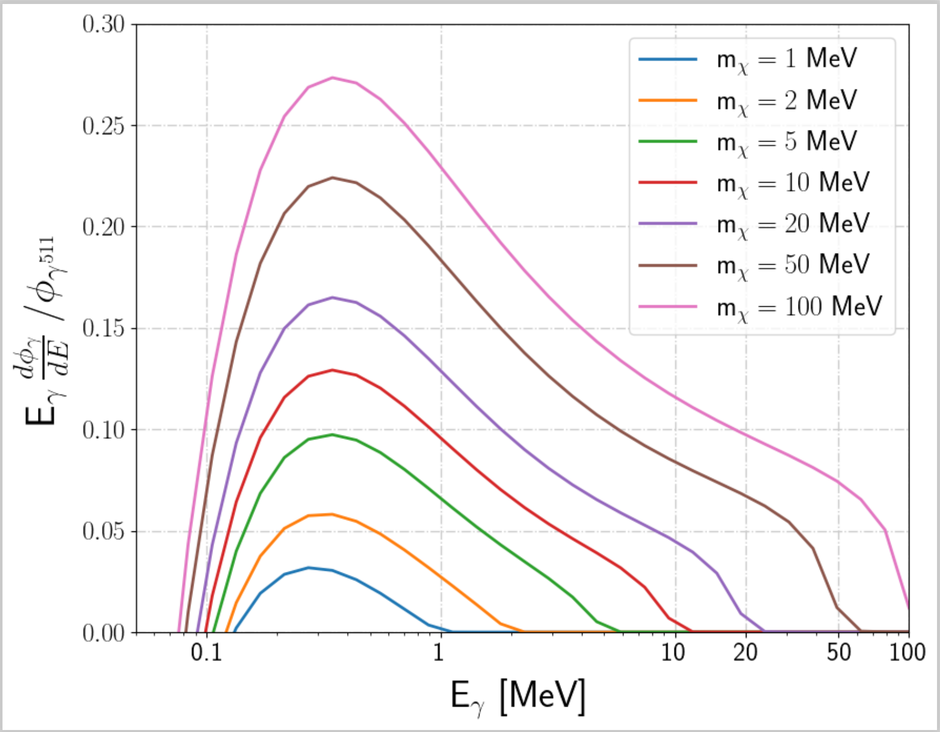
Second consequence: a NFW profile does not seem to match well the observations (with caveats*)

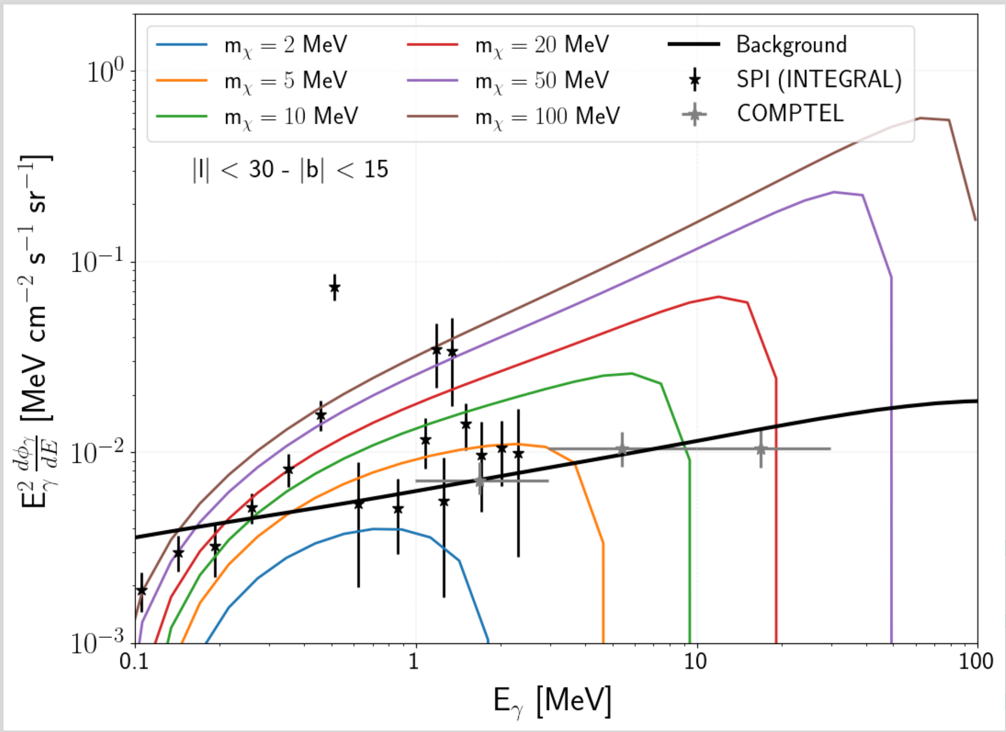
The associated continuum emission kills the DM hypothesis

("Stringent Constraint on Galactic Positron Production" (Beacom, Yuksel PRL 2006))

In-flight positron annihilation emission (IA) constitutes a fraction of the 511 keV flux, but as a continuum emission

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

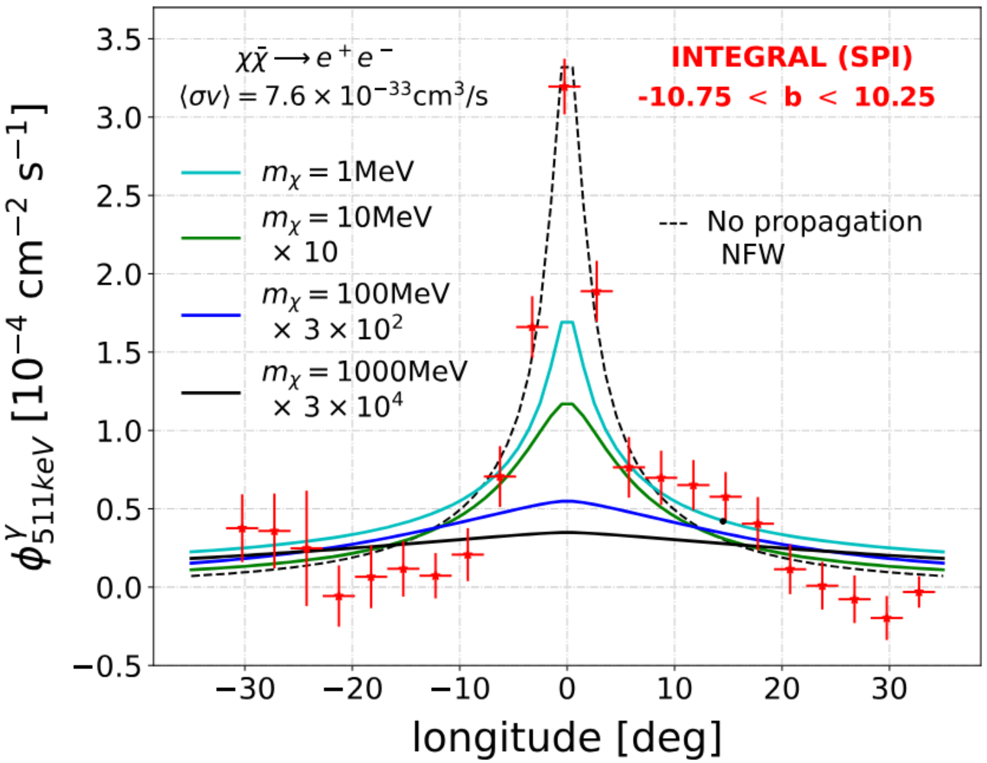


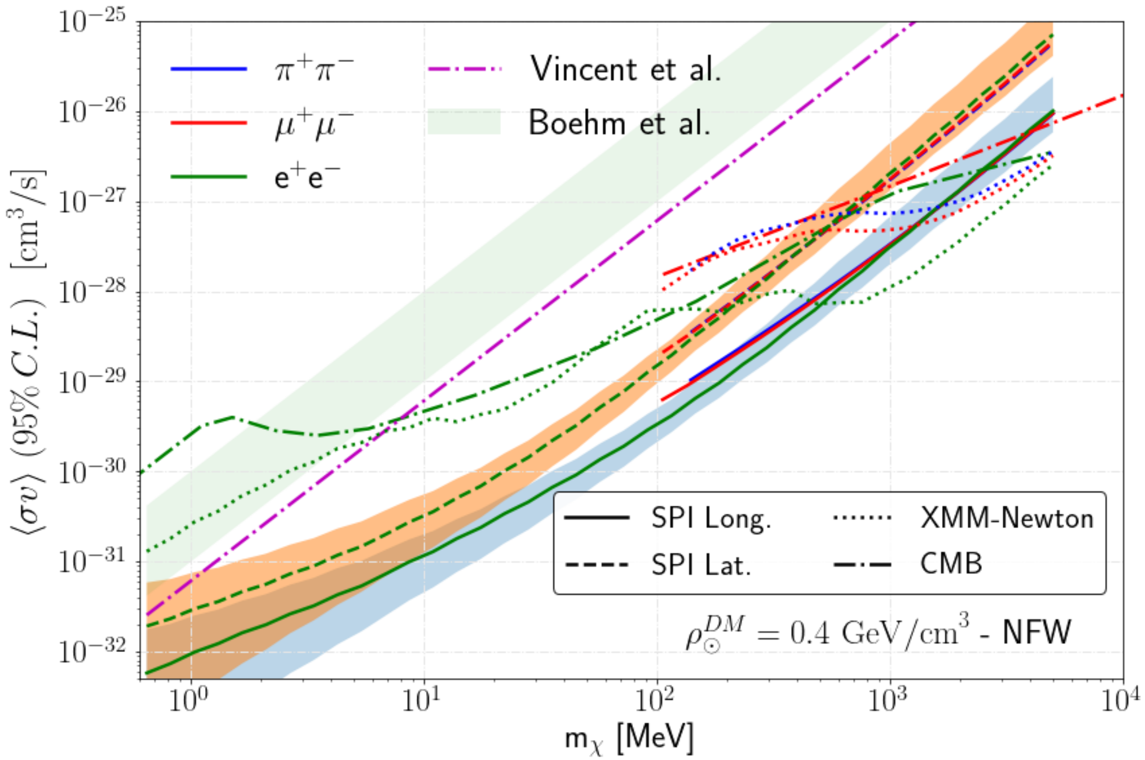


But still the line can be used to set strong constraints on light DM producing positrons

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

Annihilating DM:





Pedro De La Torre Luque, **SB**, J. Silk ArXiv:2312.04907

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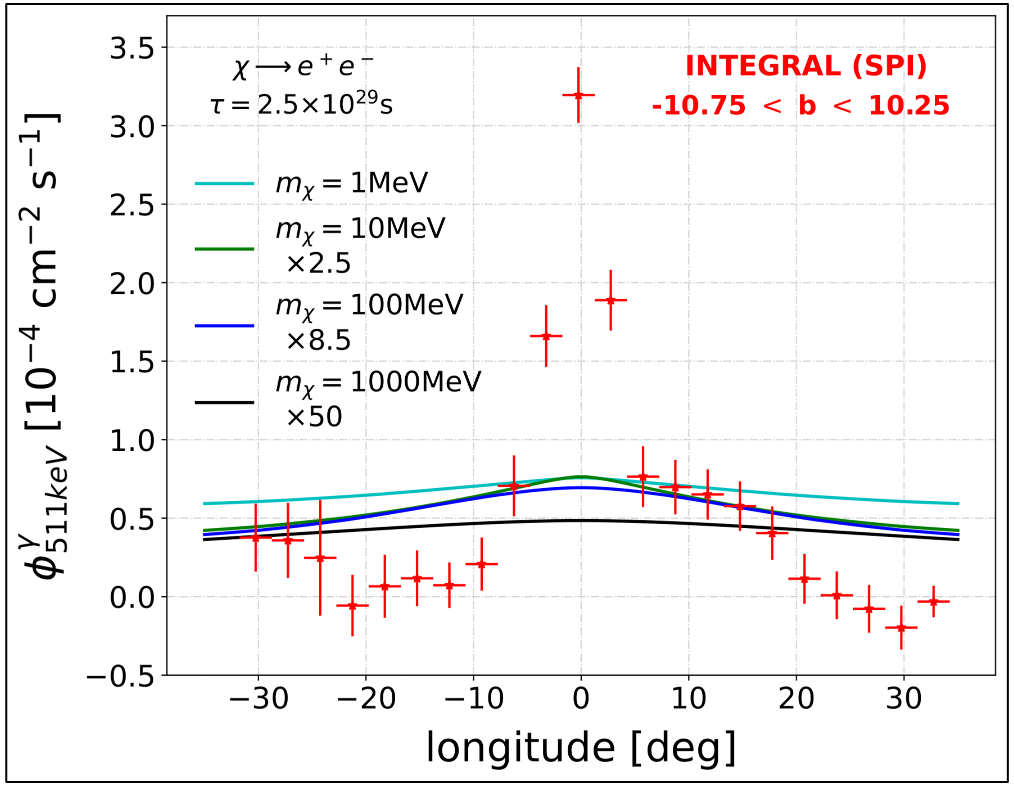
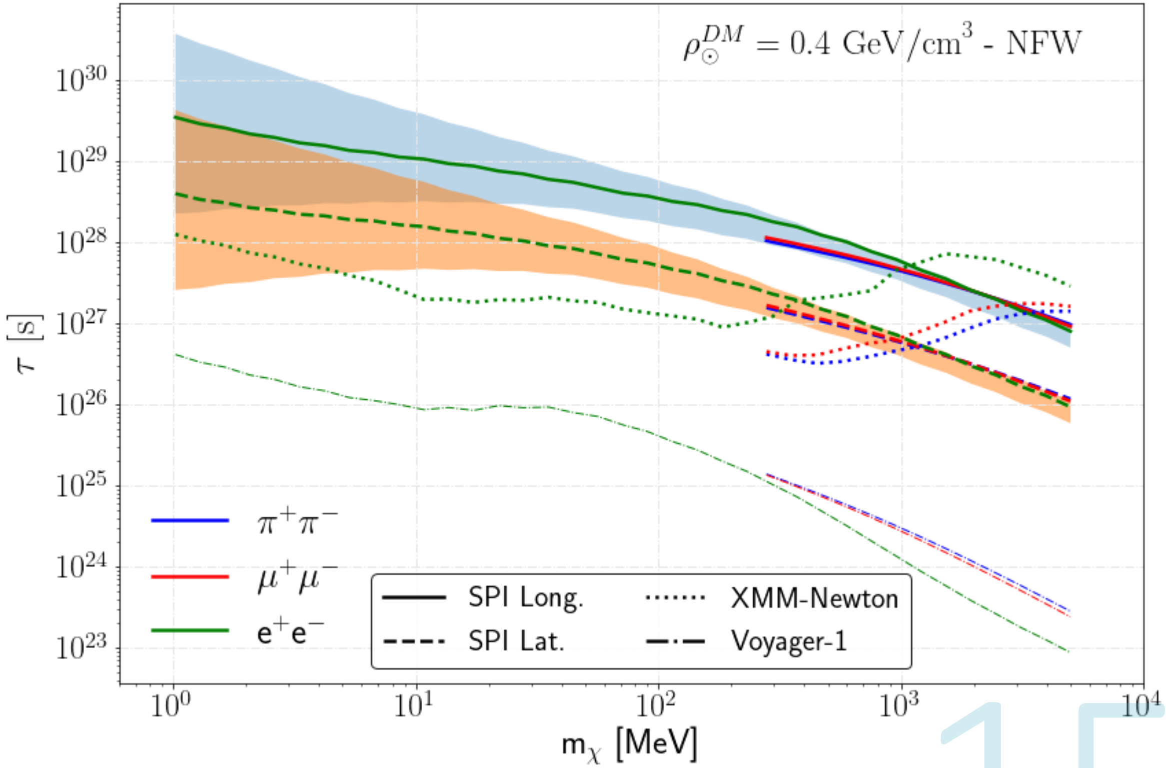
Decaying DM:

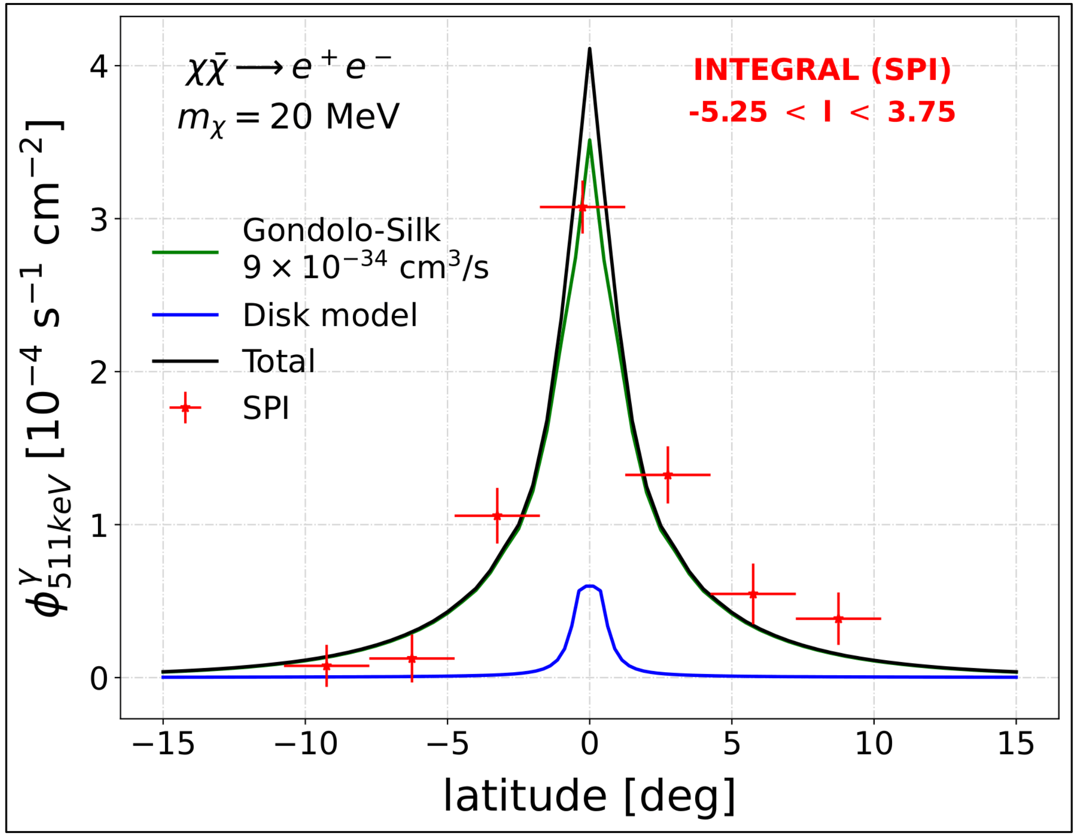


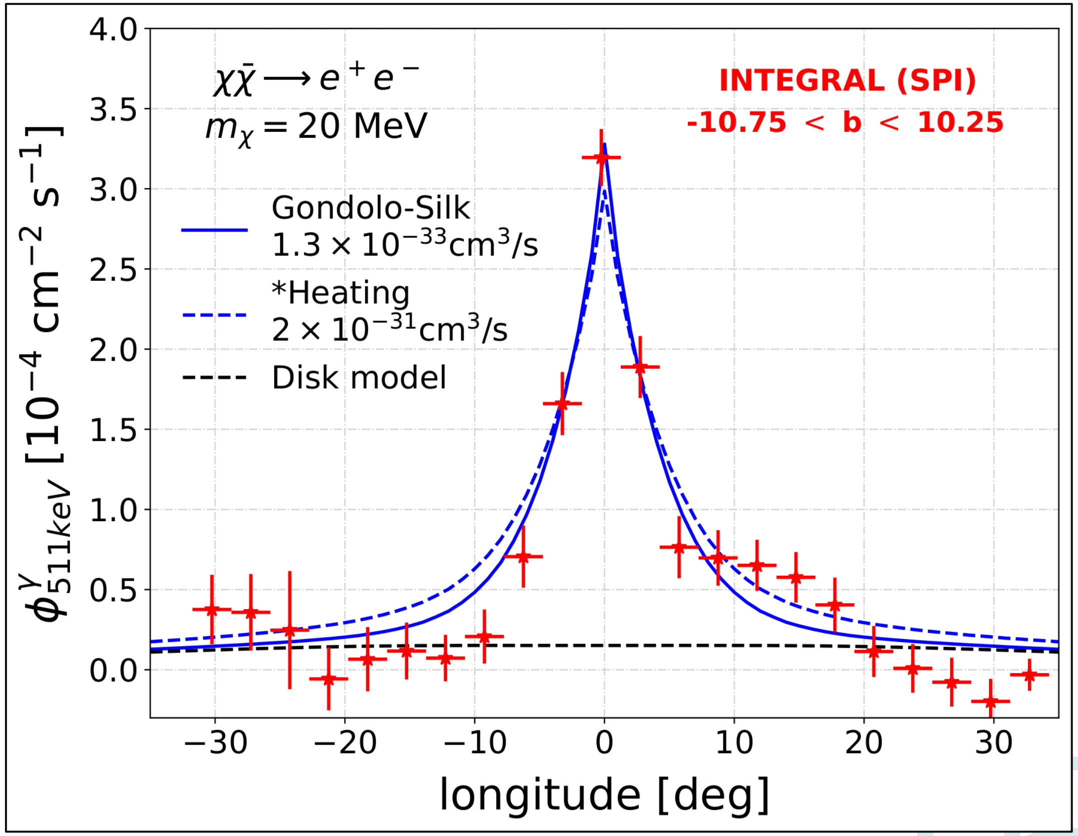


Pedro De La Torre Luque, **SB**, J. Silk arXiv:2312.04907

Limits are great, but what about a DM explanation?

Yes, a DM spike is required, simultaneous fit of latitude and longitude profiles possible with very low $<\sigma v>$





Pedro De la Torre Luque, **SB**, F. Sala, M. Fairbarn, J. Silk. To be submitted

Conclusions

The 511 keV puzzle still remains a mystery – annihilation of sub-GeV DM is a tantalizing possibility. Systematic uncertainties still persist.

Fully leveraged the SPI Integral data, including the latitude profile and included cosmic ray propagation

NFW DM doesn't match observation, enables us to set strongest limits to date

DM Spike profiles could match the observations well of the bulge emission evading current constraints

This work reinforces the power of the 511 keV line and in-flight annihilation emission for exotic sources of e^+, including PBHs and feebly interacting particles

Fits to local CR spectrum

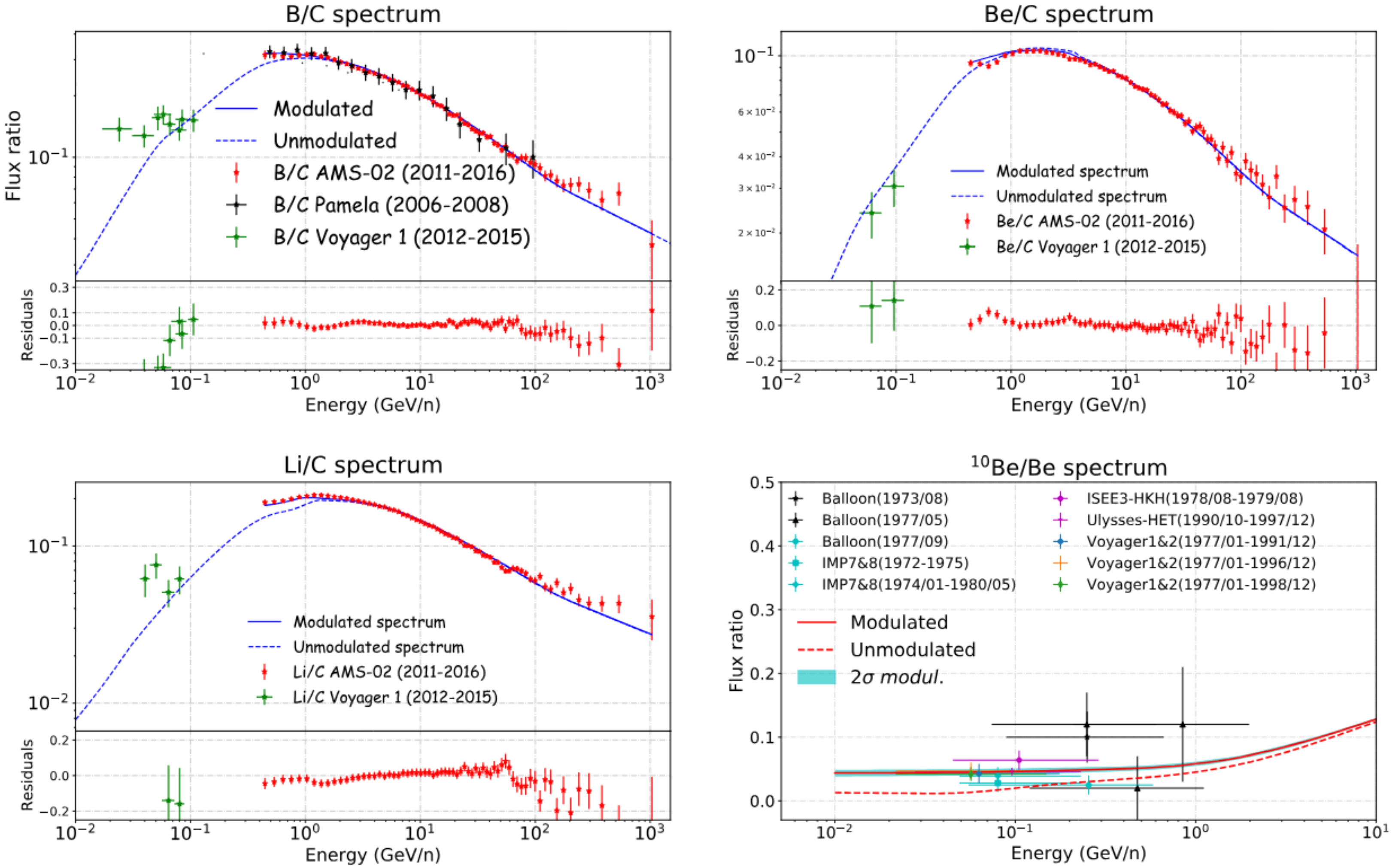


Figure 7. Main CR observables used to determine the propagation parameters employed in this work. AMS-02 data are shown as red markers and Voyager-1 data as green markers.

Useful formulae

Given the propagated and integrated flux of diffuse positrons in the Galaxy as a function of 3D position (x, y, z), $\phi_e(x, y, z)$, we calculate the emission of 511 keV X-rays from a given direction by integrating over the line of sight, as

$$\frac{d\phi_\gamma^{511}}{d\Omega} = 2k_{ps} \int ds\, s^2 \frac{\phi_e(x_{s,b,l}, y_{s,b,l}, z_{s,b,l})}{4\pi s^2}, \quad (2)$$

where $k_{ps} = 1/4$ is the fraction of positronium decays corresponding to (singlet) para-positronium states) contributing to the 511 keV line signal, $\phi_e = \int \frac{d\phi_e}{dE} dE$ is the energy-integrated emissivity of positrons, $d\Omega = dl db \cos b$ is the solid angle element with l, b and s denoting the Galactic longitude, latitude and distance s (along the line of sight) from the Earth.

$$\frac{d\phi_\gamma^{511}}{d\Omega} = 2k_{ps} \int ds\, \frac{d\phi^{e^+}}{d\Omega} \cdot n_e \cdot \sigma^{\rm ann}(E_{\rm th}),$$

$$D_{pp} = \frac{4}{3} \frac{1}{\delta(4-\delta^2)(4-\delta)} \frac{v_A^2 p^2}{D}.$$

$$Q_e(\vec{x}, E_i) = \begin{cases} \frac{\langle\sigma v\rangle}{2} \left(\frac{\rho_\chi(\vec{x})}{m_\chi}\right)^2 \frac{dN_e^{\rm ann}}{dE_e} & \text{(annihilation)} \\ \Gamma \left(\frac{\rho_\chi(\vec{x})}{m_\chi}\right) \frac{dN_e^{\rm dec}}{dE_e} & \text{(decay)} \end{cases}, \quad (2)$$

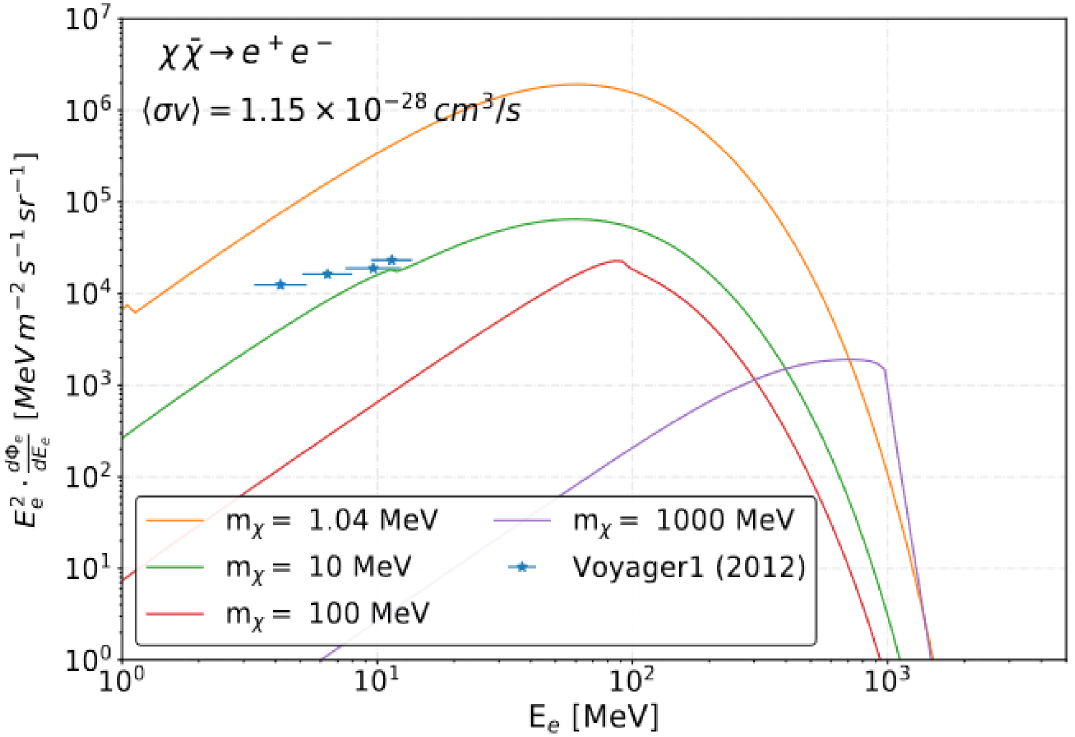
where $\langle\sigma v\rangle$ and Γ are the DM thermally averaged annihilation cross section and the DM decay rate, respectively. $\rho_\chi(\vec{x})$ is the DM energy density at the position $\vec{x}$ and dN_e/dE_e the injection spectrum of DM-produced electrons. The three following DM annihilation/decay channels are relevant for the sub-GeV DM case that we study here

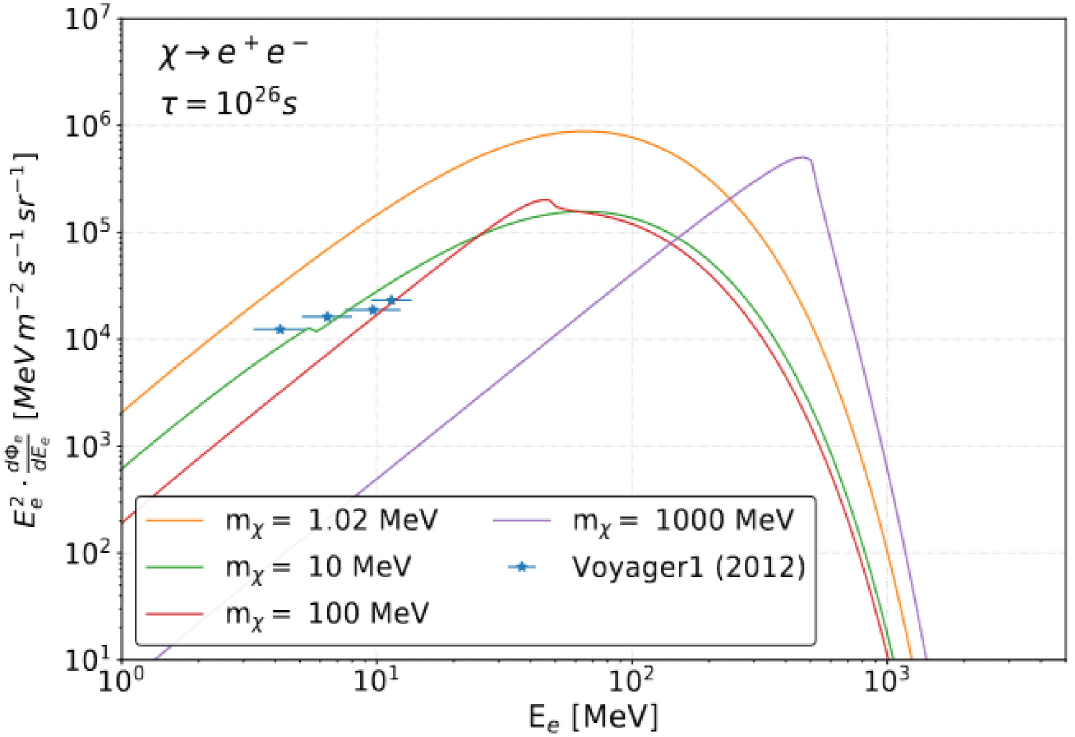
$$\chi\overline{\chi} \to e^+e^-, \qquad \chi\overline{\chi} \to \mu^+\mu^-, \qquad \chi\overline{\chi} \to \pi^+\pi^-, \quad (3)$$

Positron sources

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	

Also important for sub-GeV DM

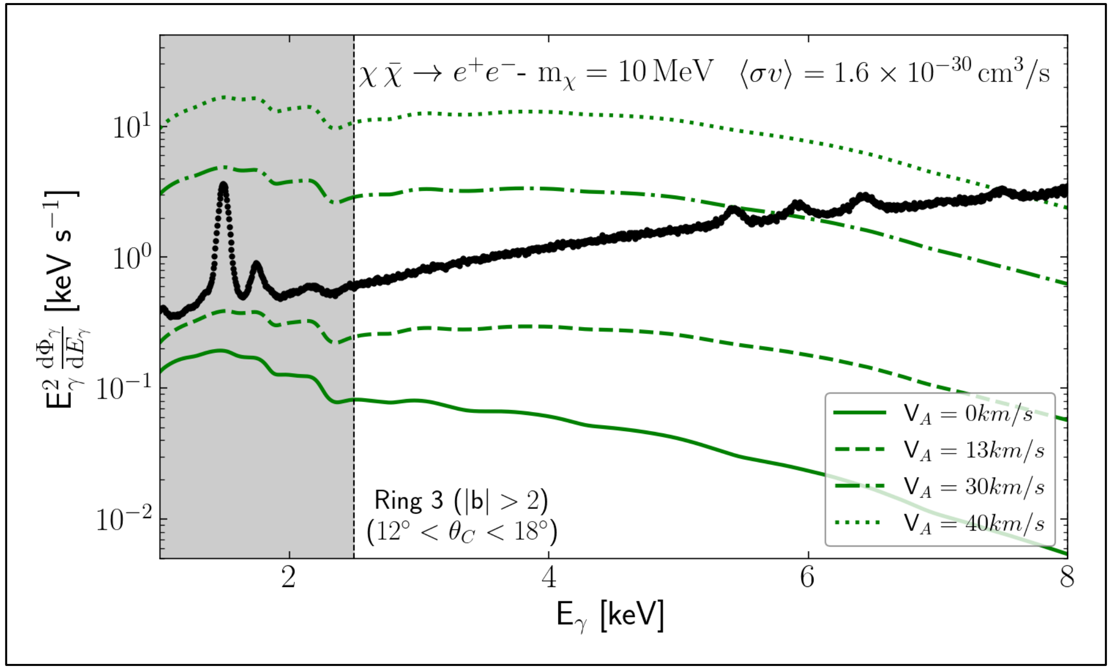




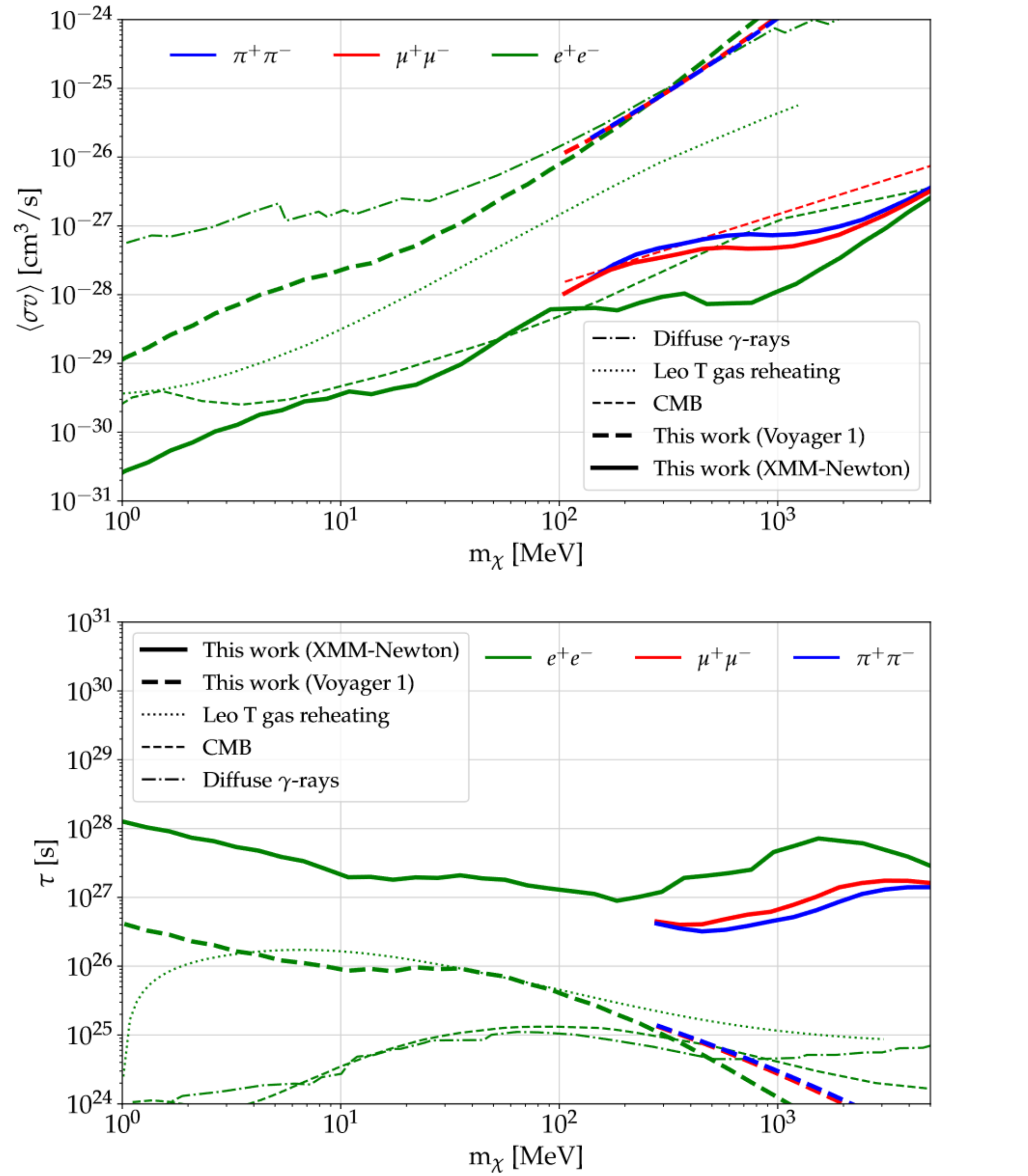
Previous constraints

Strongest previous constraints come from the **X-ray Galactic diffuse emission and CMB**

X-ray constraints suffer from uncertainties in propagation as well – Limits can be a factor of a few lower for a NFW profile

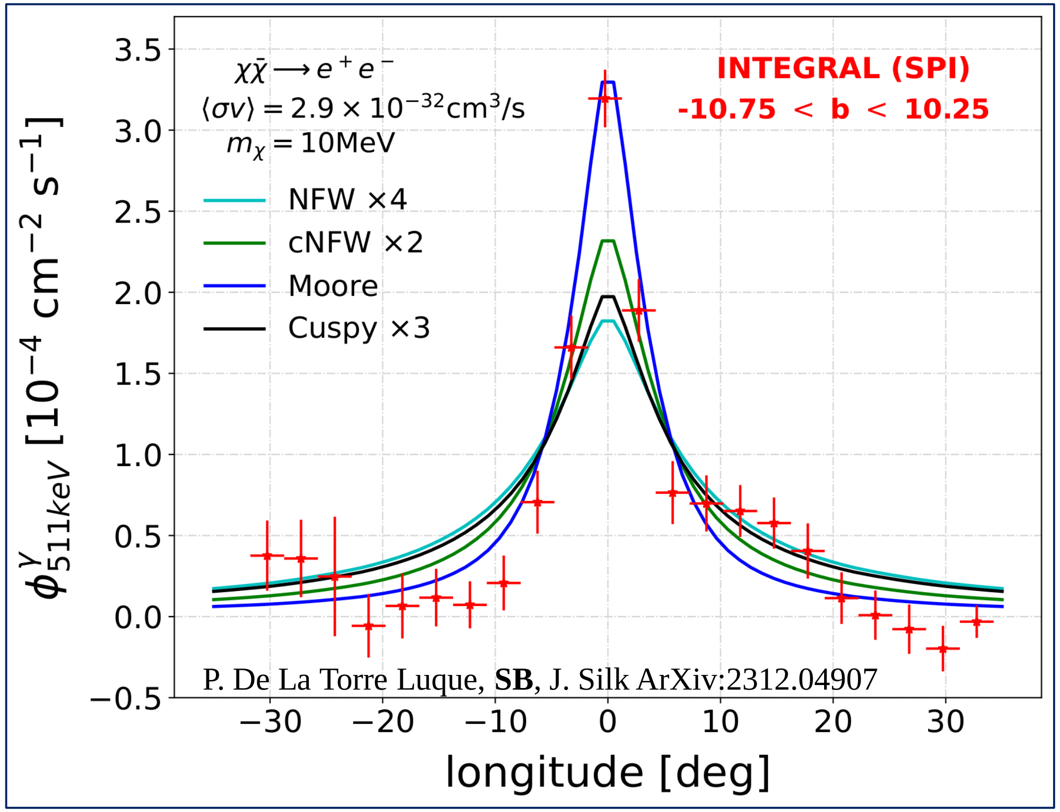


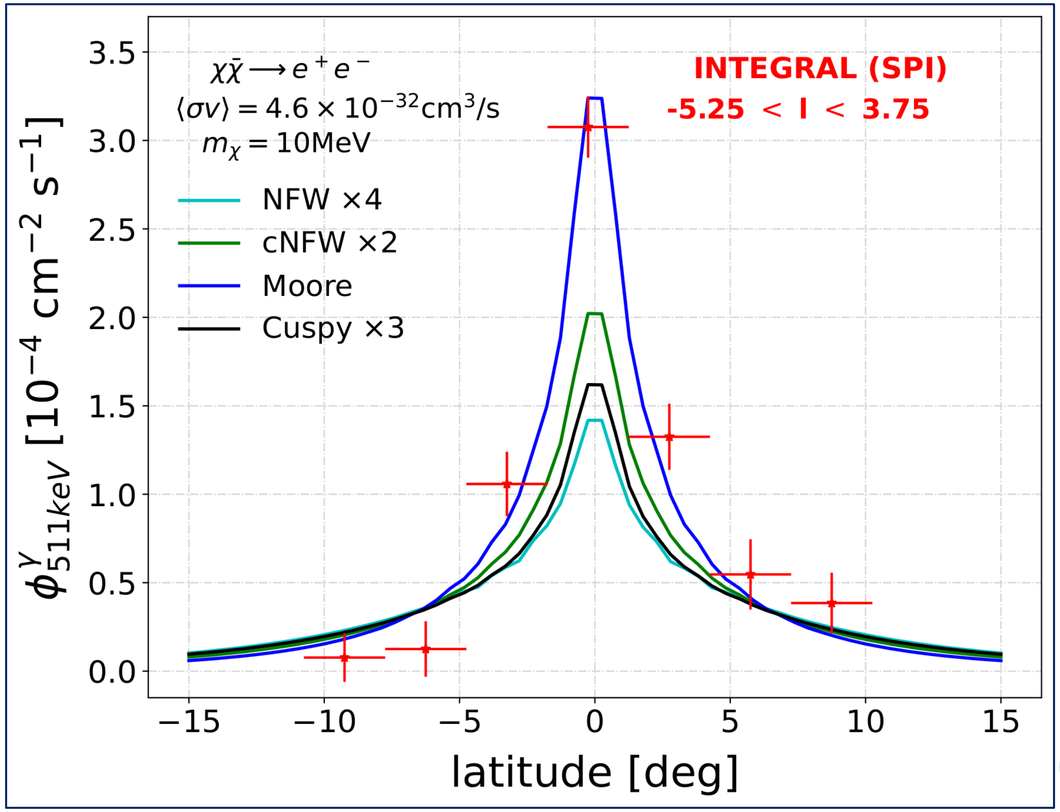
PDL, S. Balaji, J. Koechler ArXiv:2311.04979



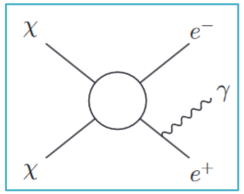
Even steeper than a NFW

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





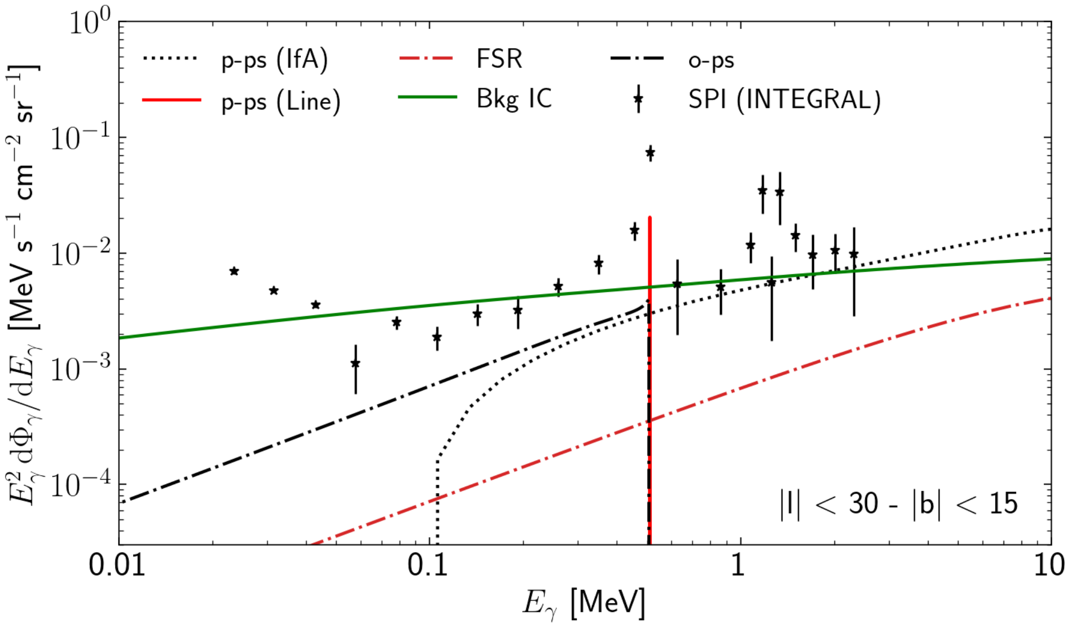
The last chance for DM: spike around SgrA*



O-ps emission dominates at low energy, while IA the at high energies. Internal bremsstrahlung (FSR) is subdominant

DM spike distributions open a window of m_χ compatible the 511 keV bulge emission

Gondolo-Silk profile



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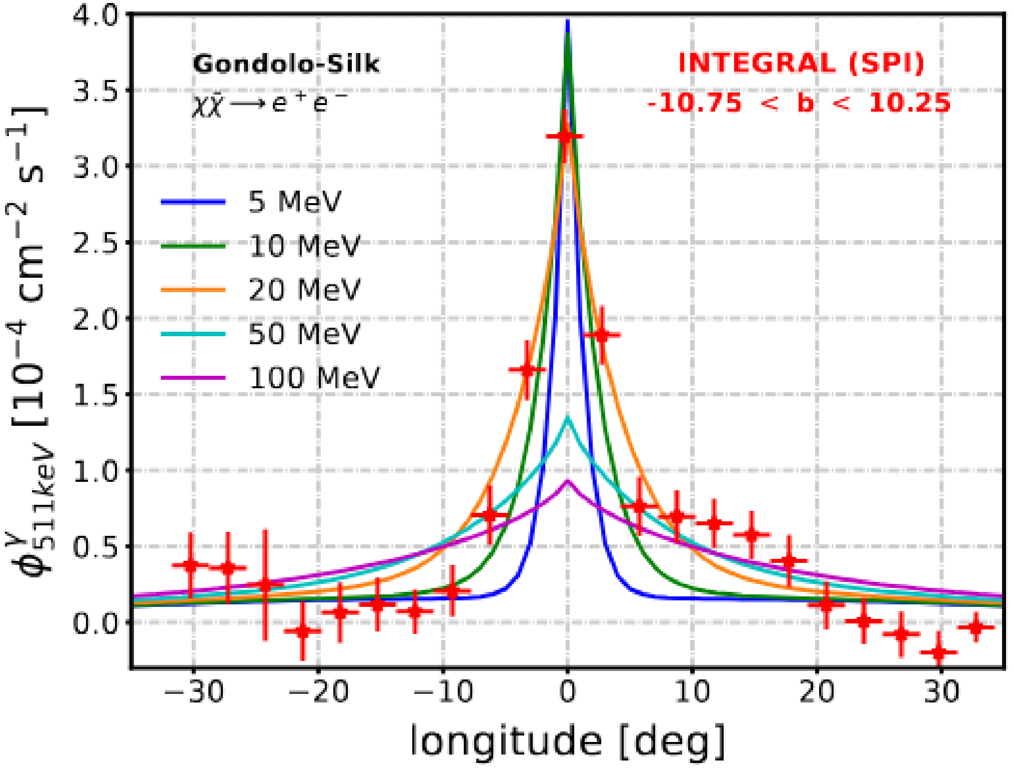
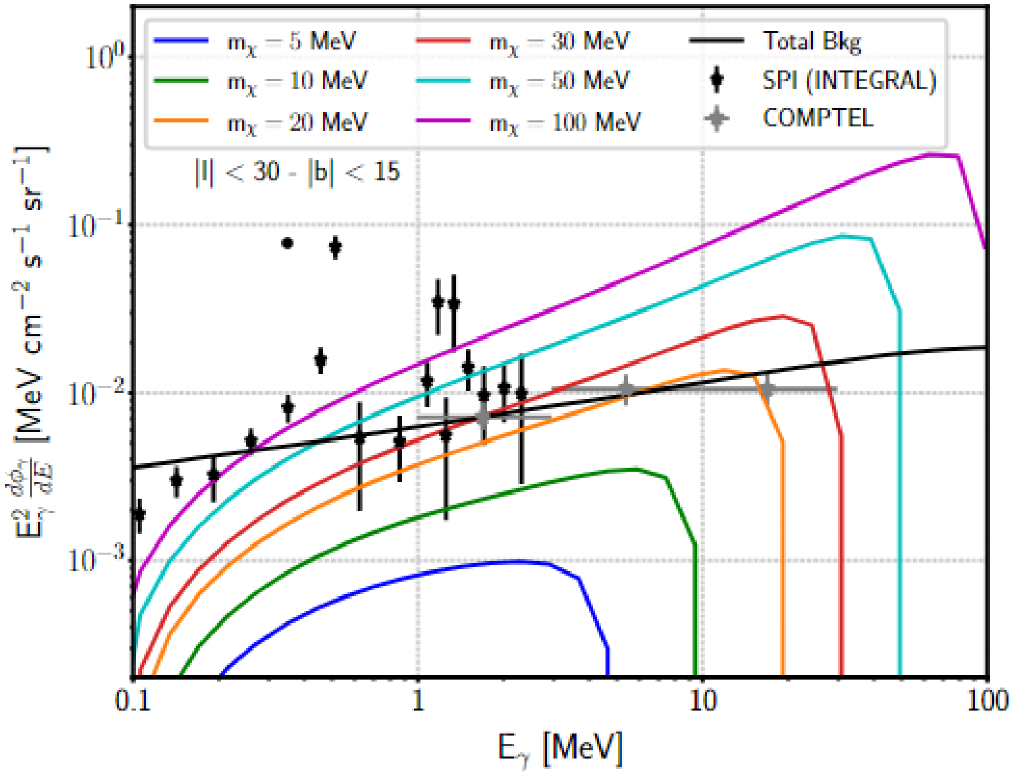
DM spike around SgrA* explanation

The associated in-flight annihilation emission is compatible with MeV diffuse gamma-ray observations up to DM masses around 20-30 MeV





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Future detectors at the MeV