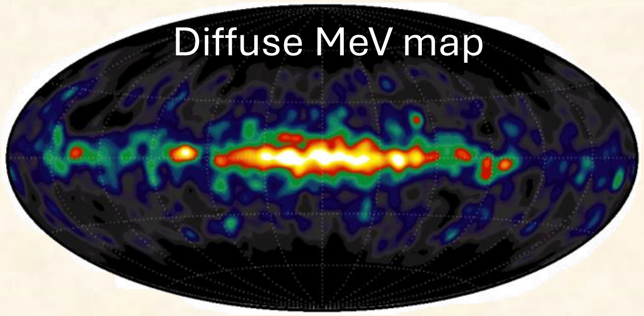
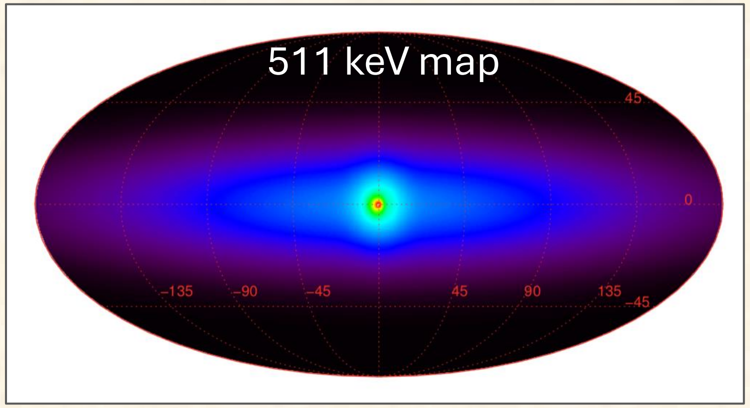
Probing new physics with diffuse γ-rays in the MeV gap





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

INTEGRAL workshop – ESA, Madrid
24/10/2024

Has DM been detected?

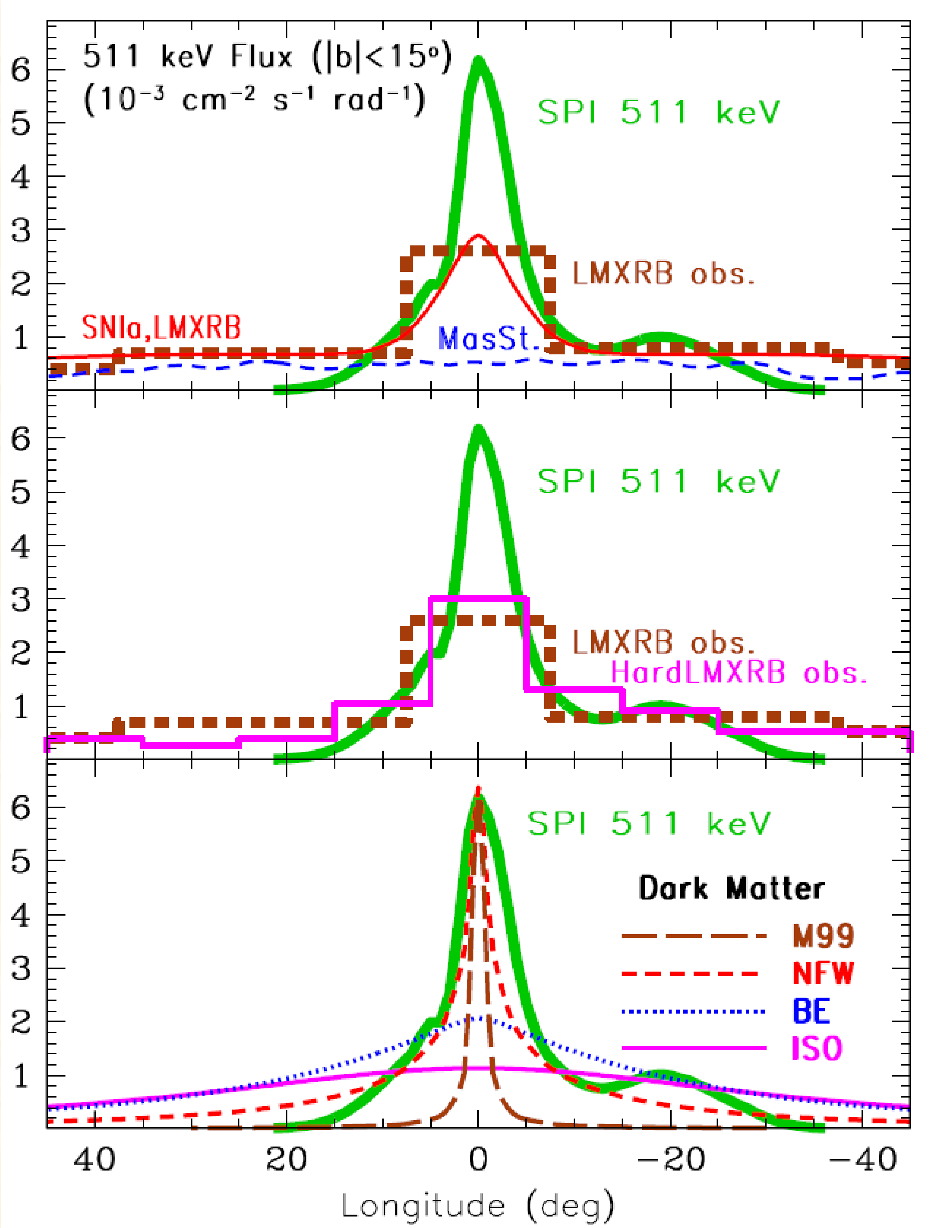
A steady injection of positrons is revealed by the observations of a bright and diffuse line at 511 keV since the 70s. However, the origin of the distribution and intensity of this line remains a mystery

Sub-GeV DM (≤hundreds MeV) was proposed as a solution by Boehm et al! (PRL92:101301,2004). **DM annihilating** with a NFW **seem to fit quire well the morphology of the signal**.

Sub-GeV DM is compatible with BBN constraints only for $m_\chi >$ a few MeV

DM particles heavier than ~10 MeV would produce e^+ that travel up to 100s of parsecs before thermalizing

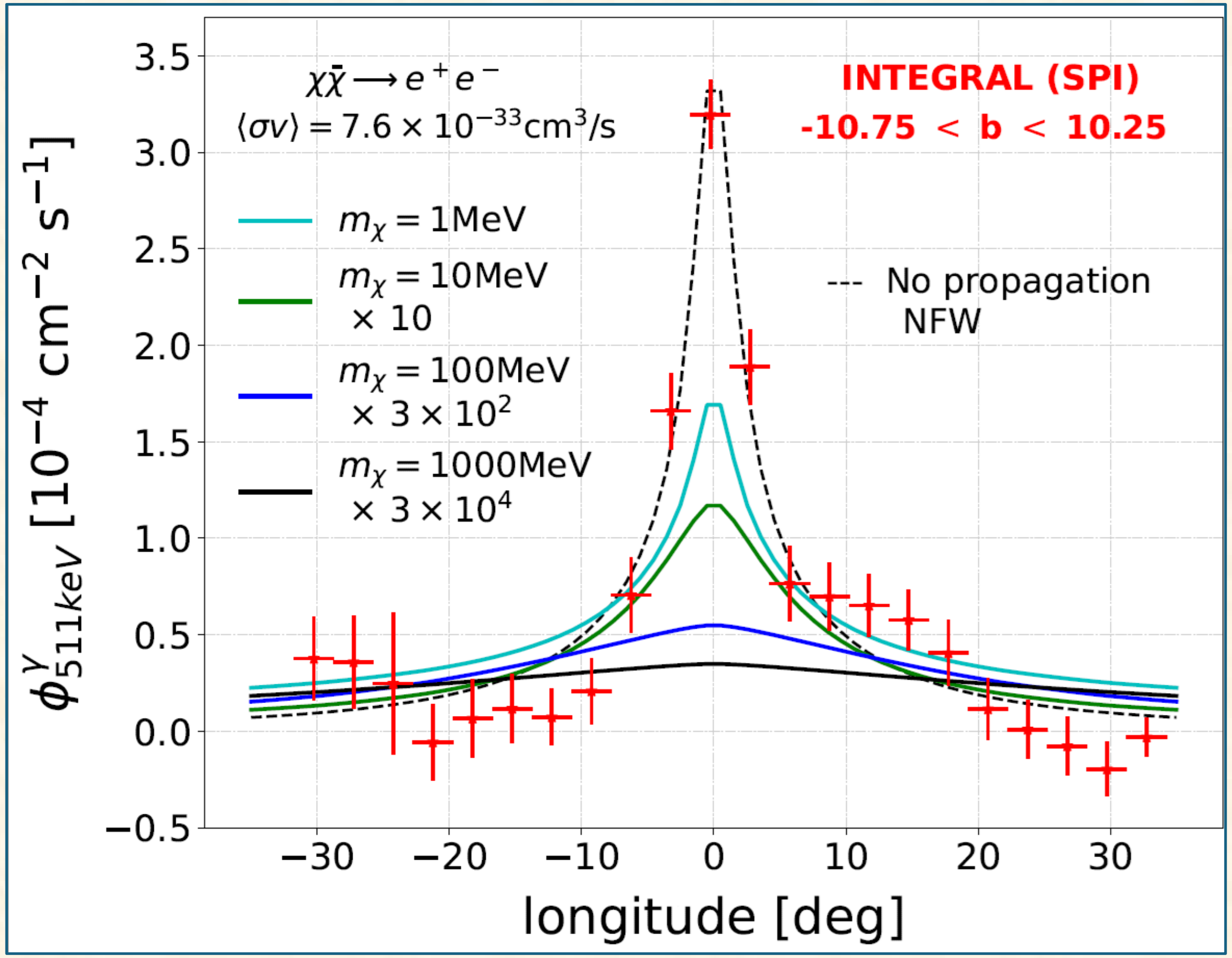
(**PDL**, S. Balaji, J. Silk ArXiv:2312.04907)



Effect of a realistic diffusion

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

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



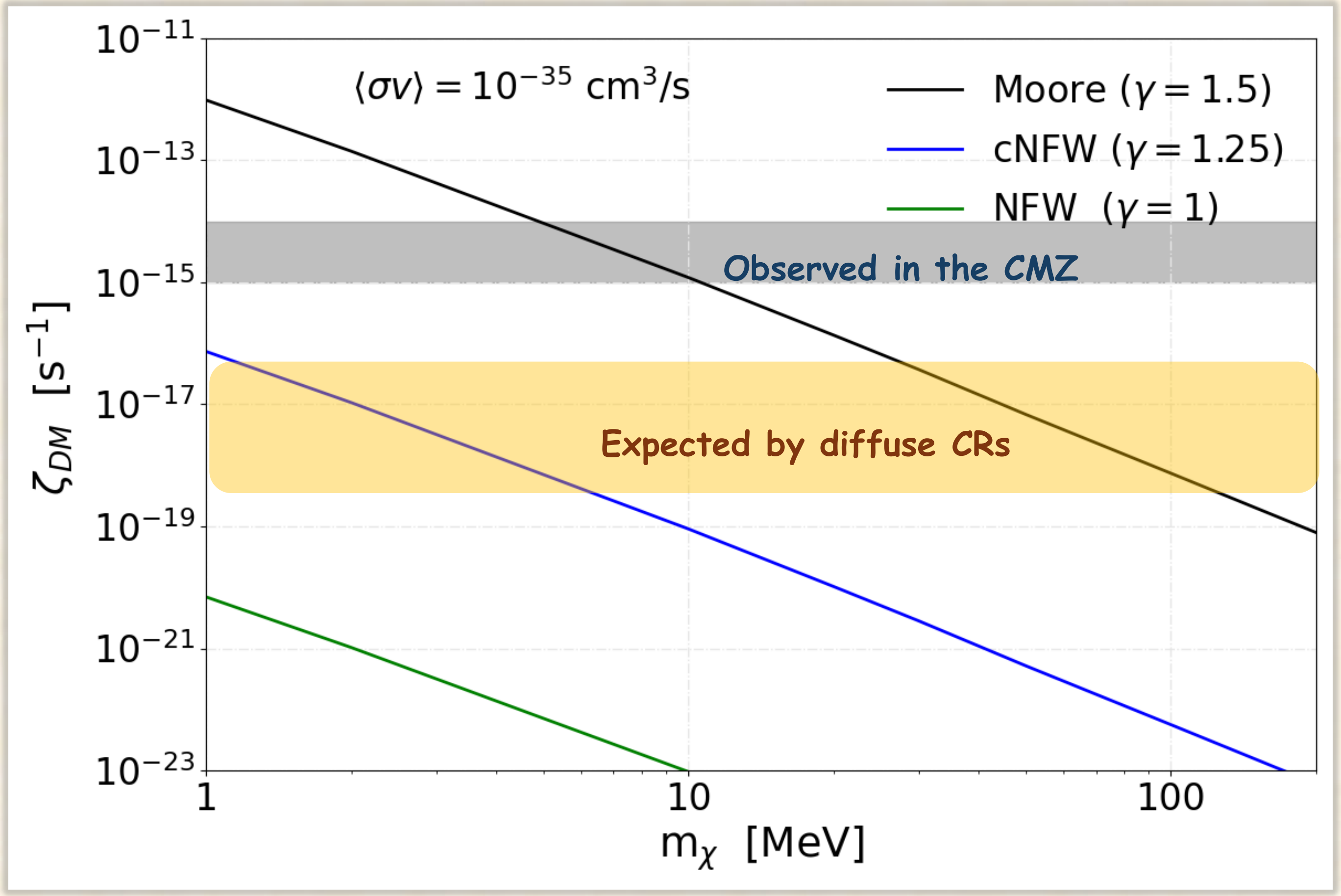
The propagation of the e+ injected by DM leads to a mass-dependent profile of the expected signal

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

Second consequence: 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



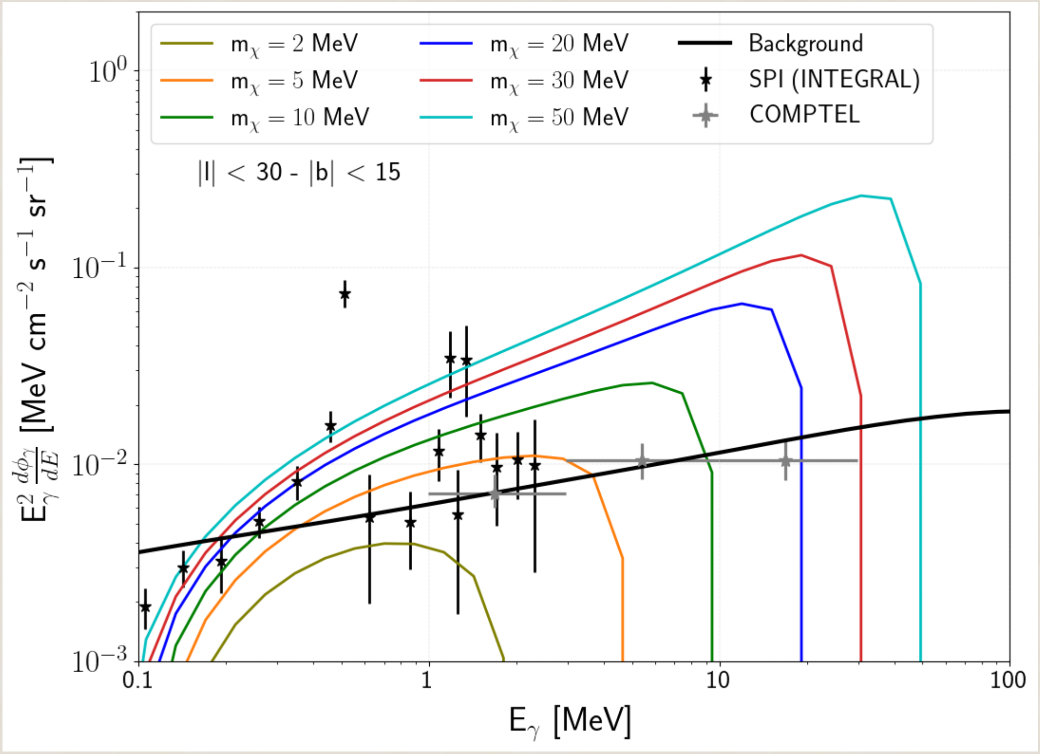
The CMZ ionization rate can be attributed to MeV dark matter annihilation for galactic dark matter profiles with slopes $\gamma > 1$

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

The associated continuum emission limits the DM hypothesis

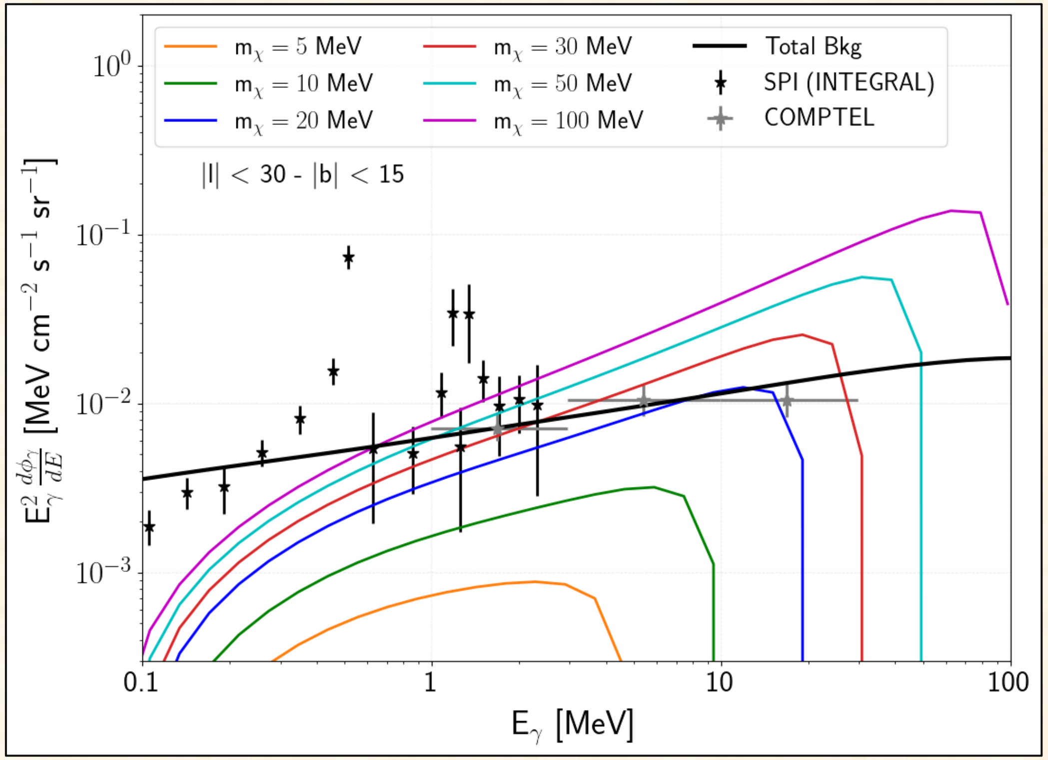
(“Stringent Constraint on Galactic Positron Production” -- Beacom, Yuksel PRL 2006)

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



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

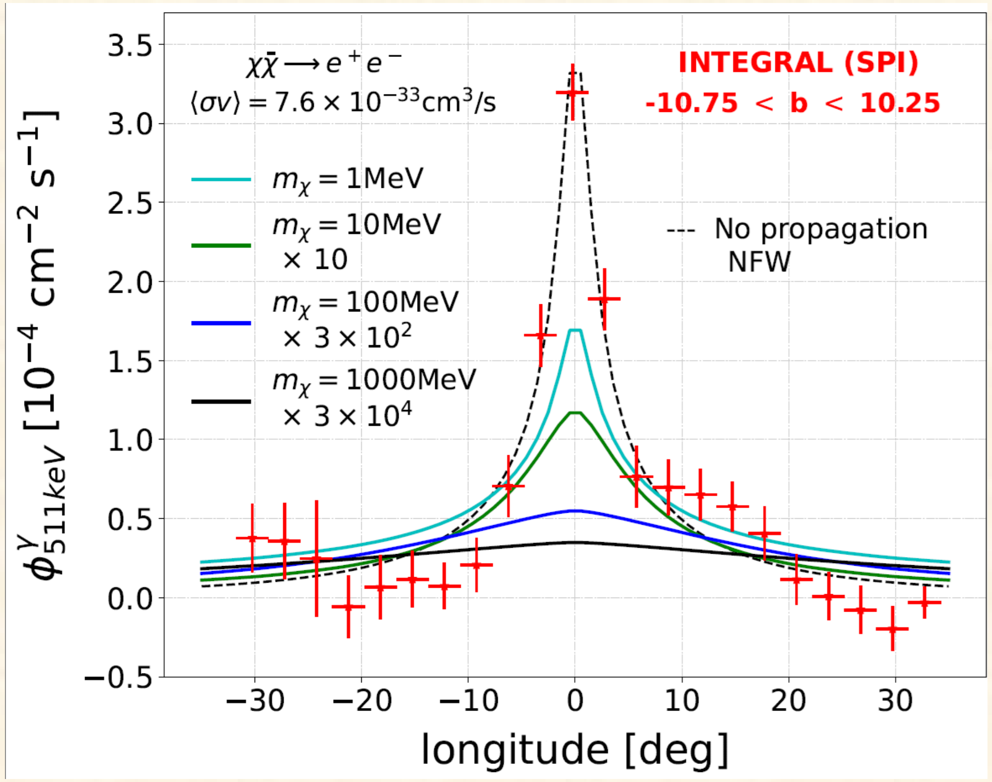
Mass limits can be mitigated!

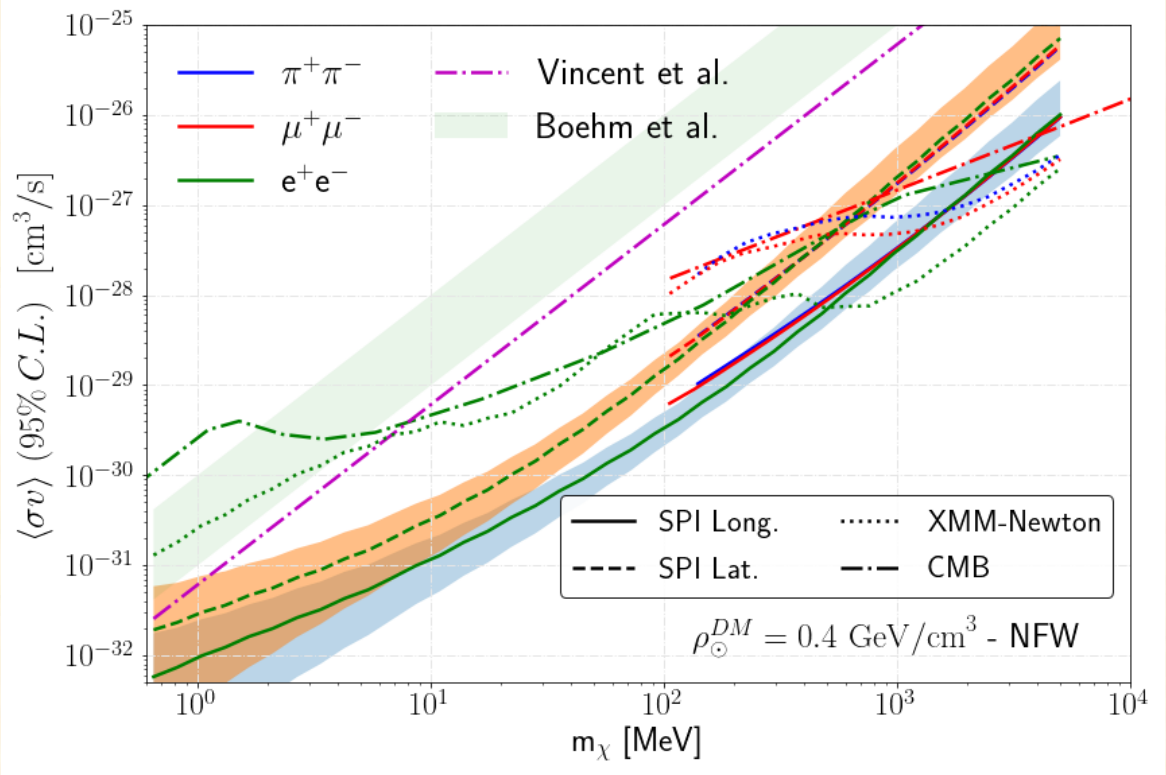


But still the line can be used to set strong constraints on light DM producing positrons

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

Annihilating DM:



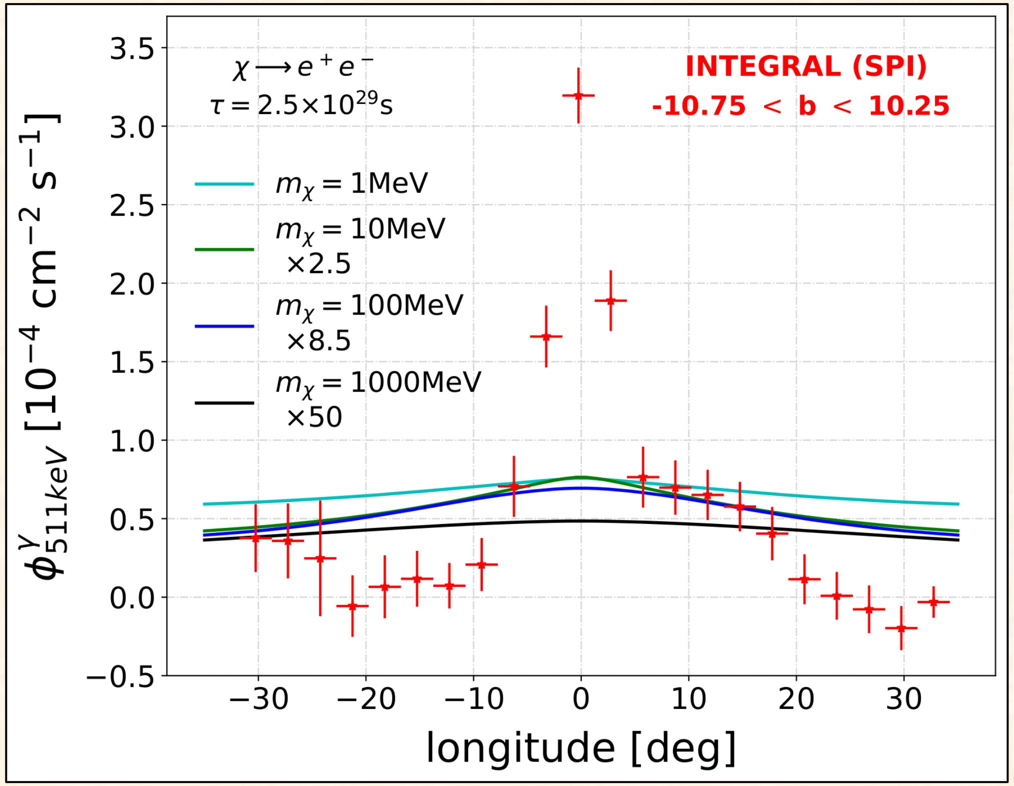


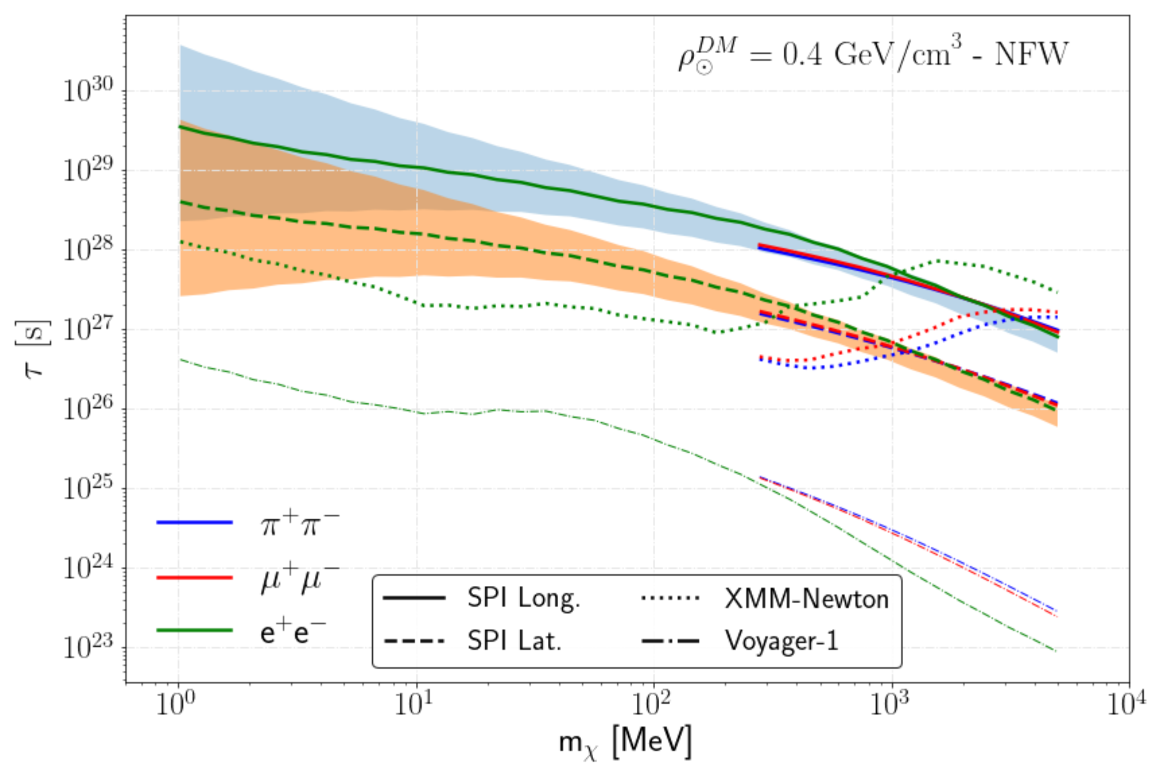
PDL, S. Balaji, J. Silk ArXiv:2312.04907

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

Decaying DM:



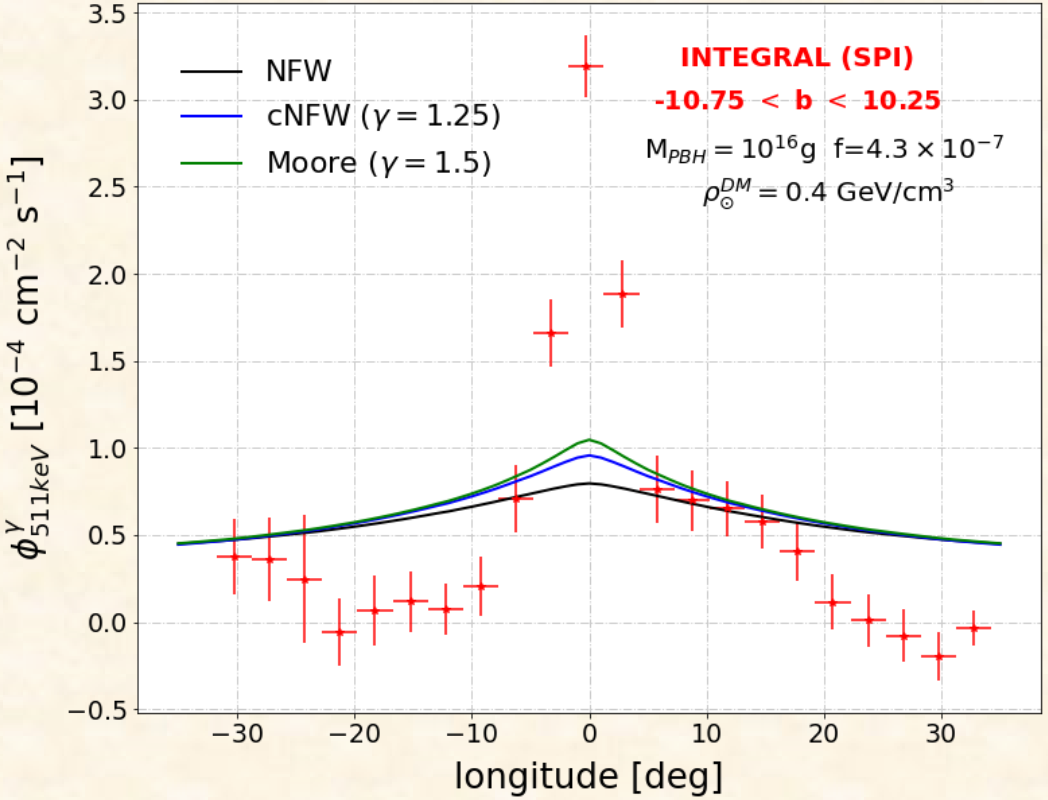


PDL, S. Balaji, J. Silk ArXiv:2312.04907

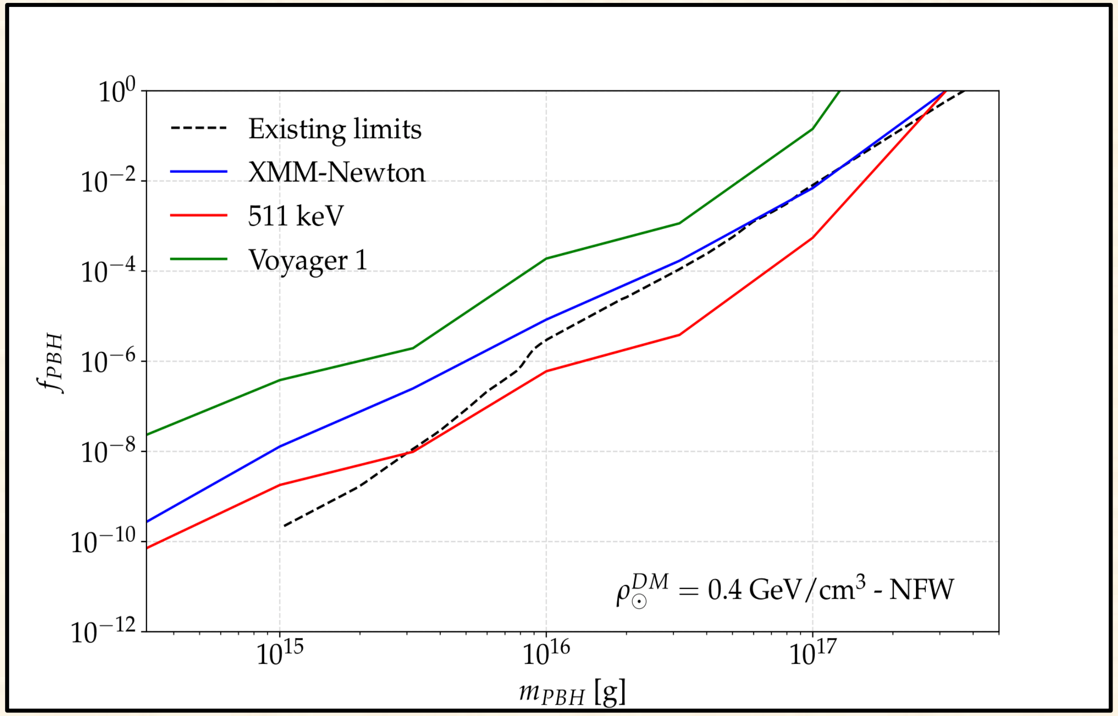
Asteroid-mass PBHs and the 511 keV line

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



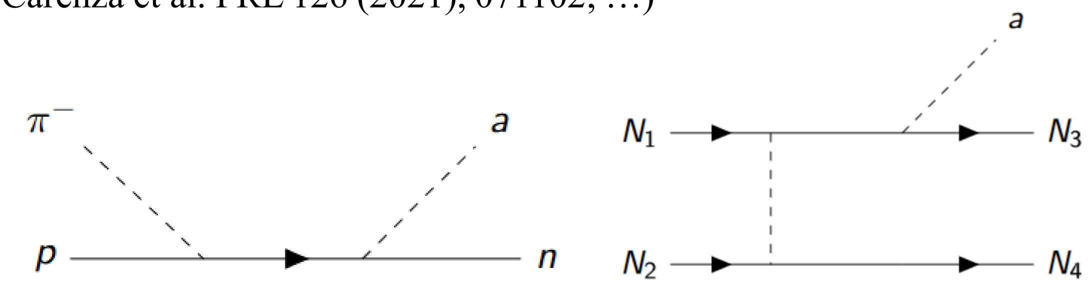
PDL, J. Koechler, S. Balaji. ArXiv:2406.11949



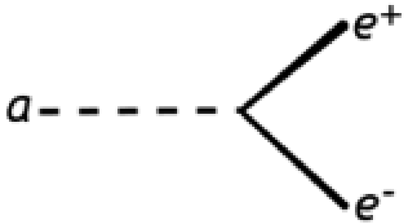
FIP production in Galactic SNe

<u>FIPs</u> → ALPs, Dark photons, sterile ν, …

SNe are expected to produce copious amounts of feebly interacting particles (Turner et al. PRL 60 (1988), 1797; Carenza et al. PRL 126 (2021), 071102; …)



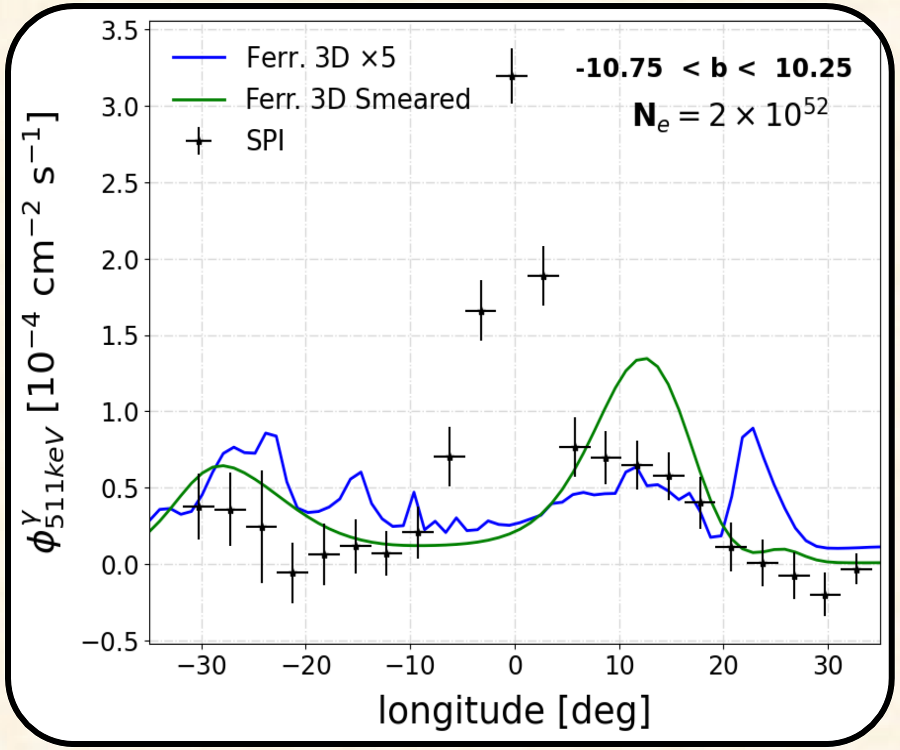
These particles can escape the SN envelope and decay into e^+e^- (and γ's – Calore et al PRD 105 (2022) 063028) in the ISM, producing a diffuse sea of particles that can be detected, either directly or via their secondary interactions

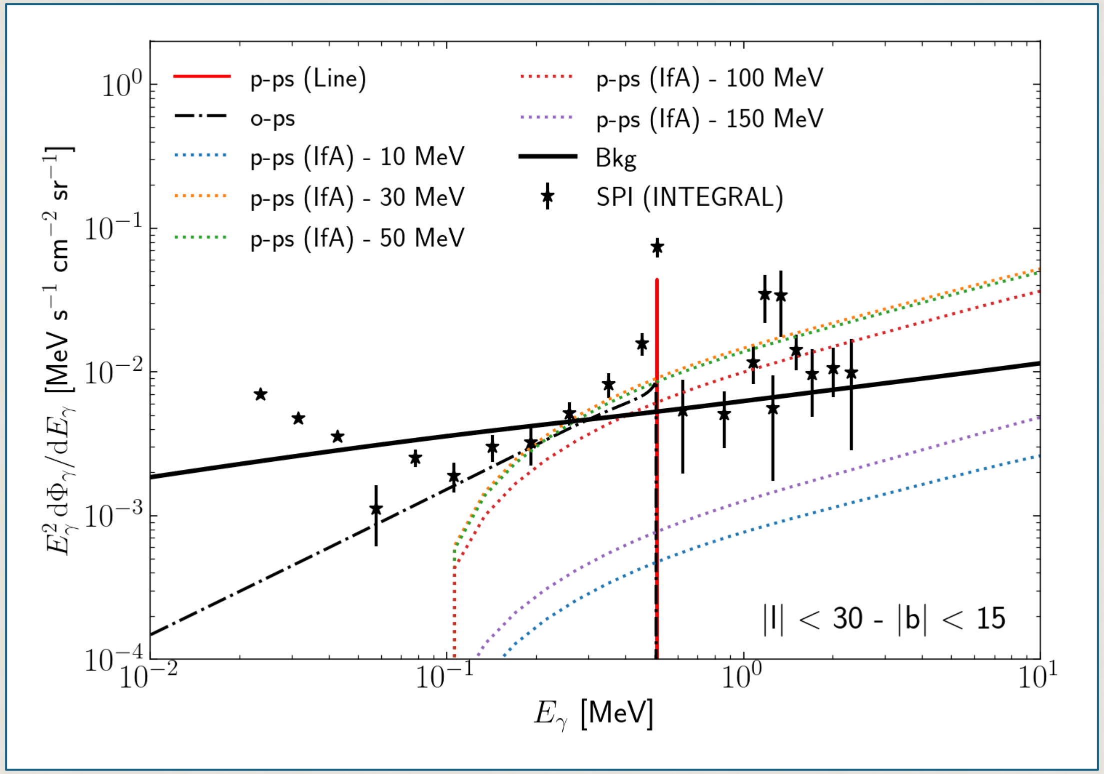


Constraints on the injected number of e+ per SNe

- This source of e+ can only constitute a fraction of the 511 keV disk emission.
- In-flight annihilation emission from these e+ beats all the other limits.

PDL, et al ArXiv:2405.08482



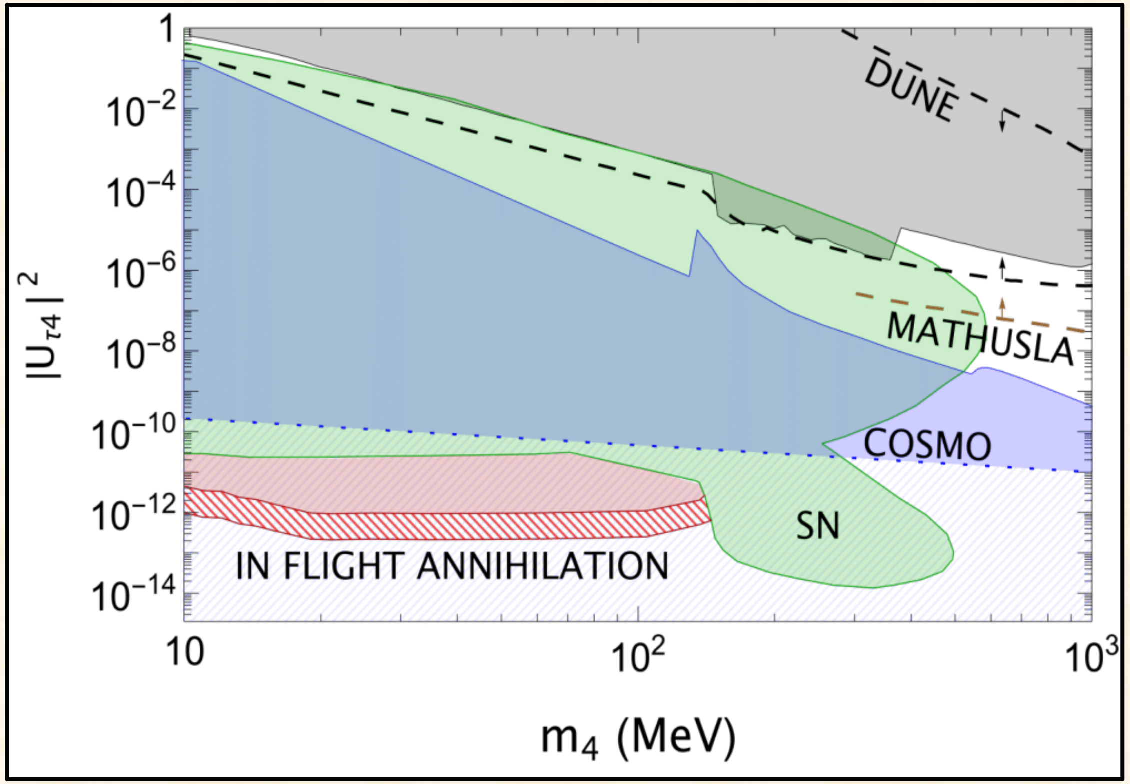


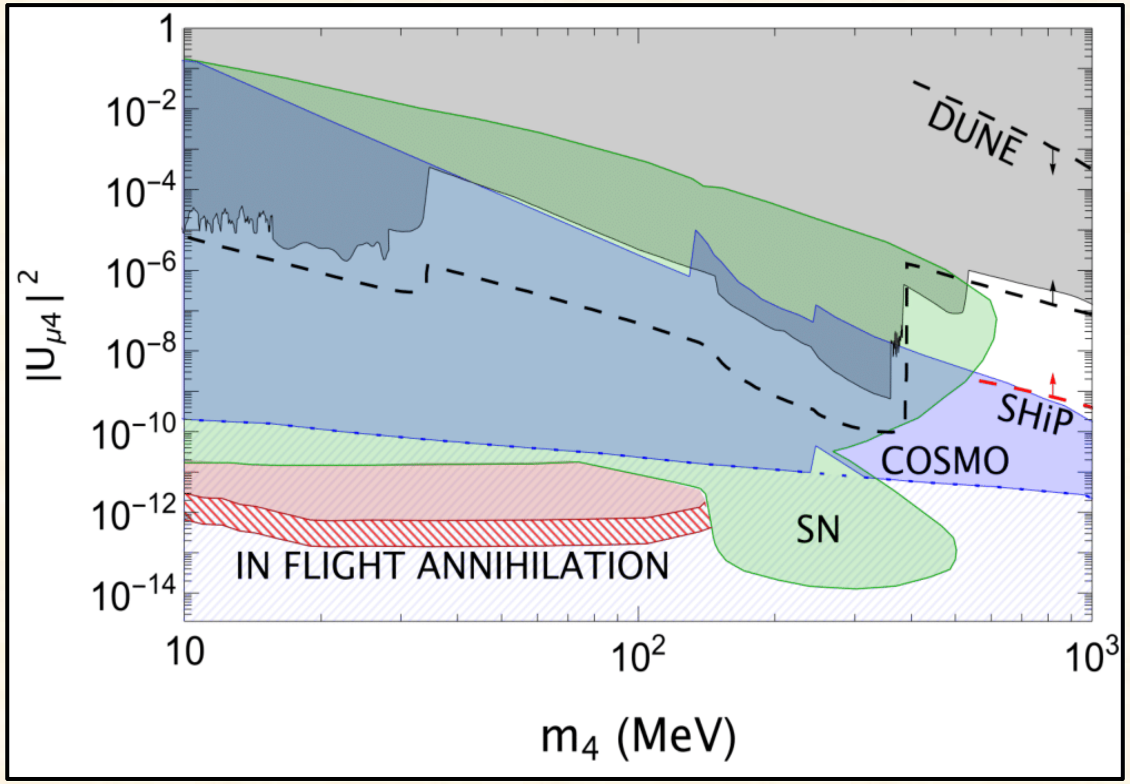
PDL, S. Balaji, P. Carenza ArXiv:2307.13728

Constraints in sterile neutrino mixing angle

It leads to an improvement on the mixing angle limits of **more than one order of magnitude!**

Previous limits are mainly based on cosmological arguments (CMB and BBN) or SN (non-detection of gamma rays from SN1987A, or diffuse gamma-ray constraints)





PDL, et al ArXiv:2405.08482

Conclusions

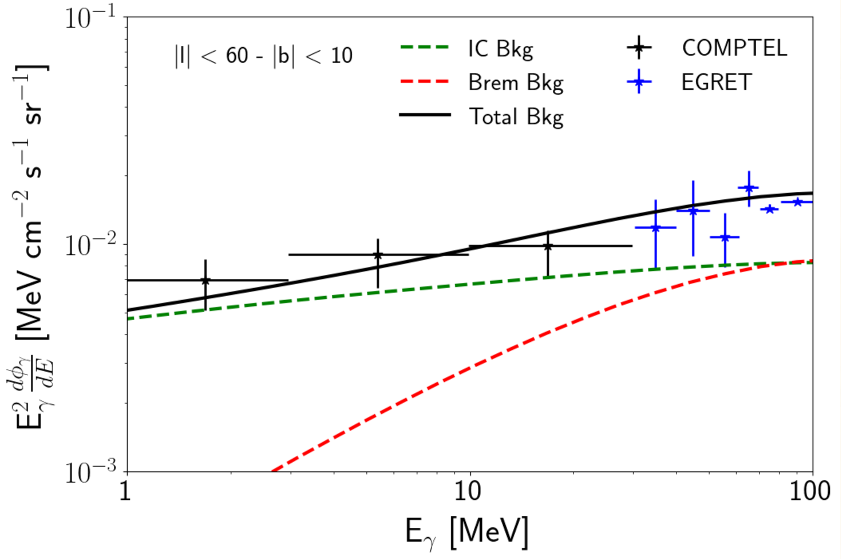
Probing new physics with Galactic diffuse γ-rays in the MeV gap

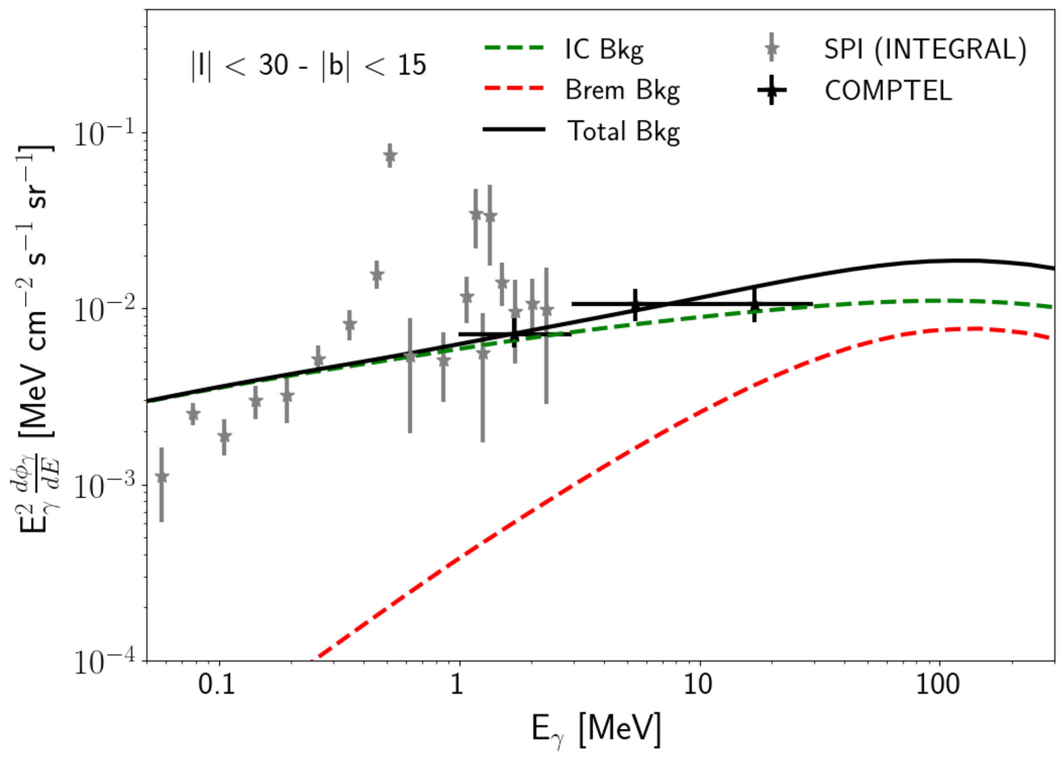
- The observations of the 511 keV line still lack a satisfactory explanation and may indicate the presence of new physics in the Galaxy
- The hard-X-ray to soft-gamma-ray band (the MeV gap) has a high potential to probe the properties of positron emitters
- The 511 keV line and the MeV continuum gamma-ray background set leading constraints for Sub-GeV DM, PBHs and FIPs (sterile neutrinos)
- Future MeV observations may solve many important open problems in the astroparticles community. However, our theoretical modelling needs to be improved to draw robust conclusions

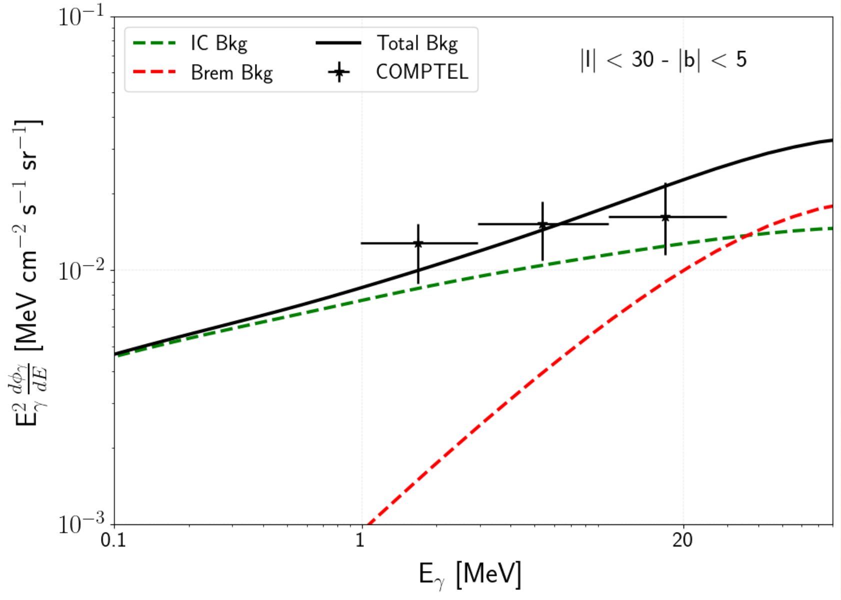
Pedro de la Torre Luque – 24/10/2024
pedro.delatorre@uam.es

Bakground model

- CR electrons dominate the γ-ray emisión below 100 MeV
- Our prediction (from **PDL** et al *JCAP* 07 (2022) 07, 008) reproduces well MeV data in several Galactic Regions
- The model is obtained from a combined fit to AMS-02 data and the local emissivity spectrum measured by Fermi-LAT

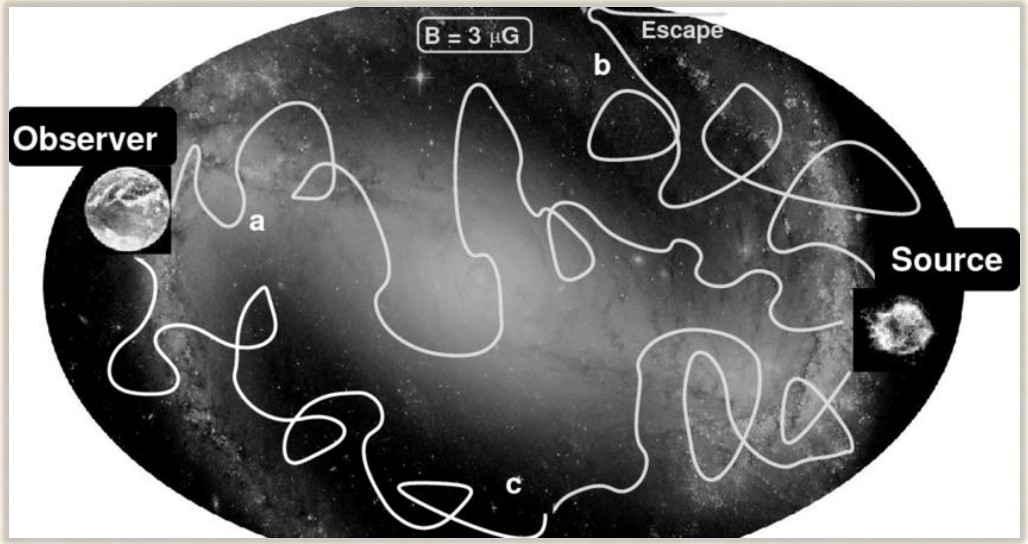






e^+e^- propagation

- Electrons and positrons interact with the Galactic magnetic field and the ISM
- DM particles heavier than ~10 MeV would produce e^+ 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 ∝ E^δ -- from CR analyses at E>MeV)

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

Injection (following DM distrib.)

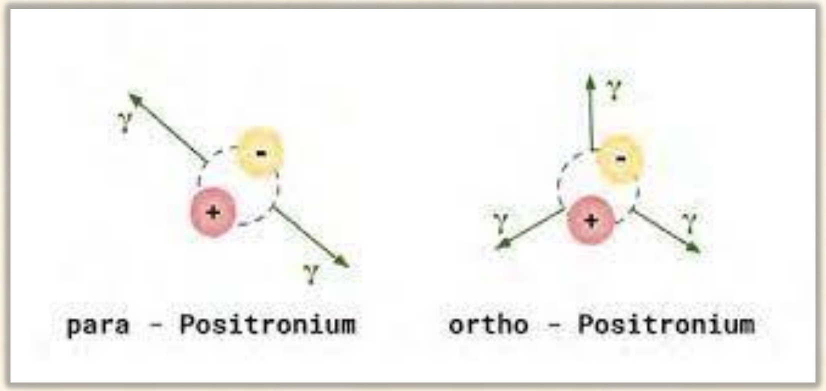
Energy losses (Coul., Ioniz., Brem., IC, Synch.)

The fate of positrons in the Galaxy

Positrons were discovered in the 30s, from CR interactions -- CRs must also produce positrons in the disk of the Milky Way

In the 40s, Dirac showed that positrons annihilate with electrons into a pair of photons – If positrons are near rest, this leads to a line at 511 keV!

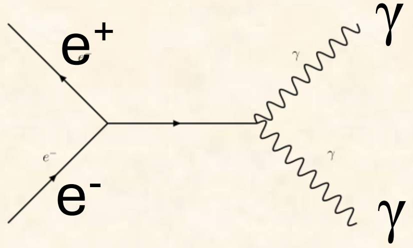
But e^+e^- pairs likely create a bound state, "positronium", which produces a line, and also a continuum emission below 511 keV



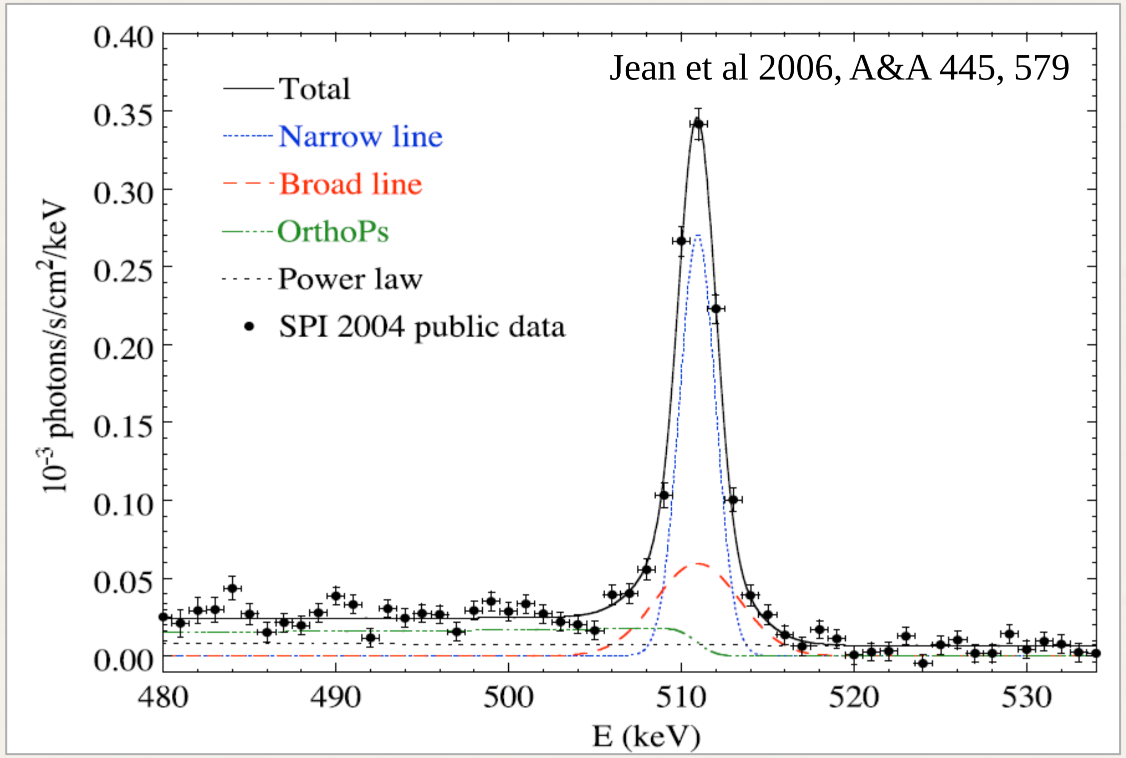
Direct annihilation cross sections:

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

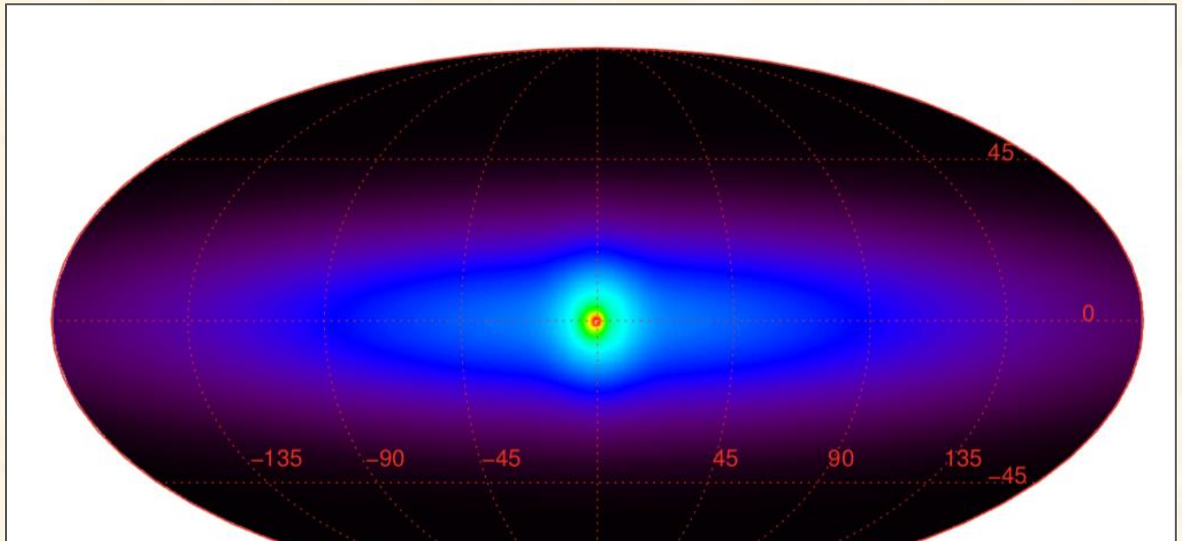
The 511 keV puzzle



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**



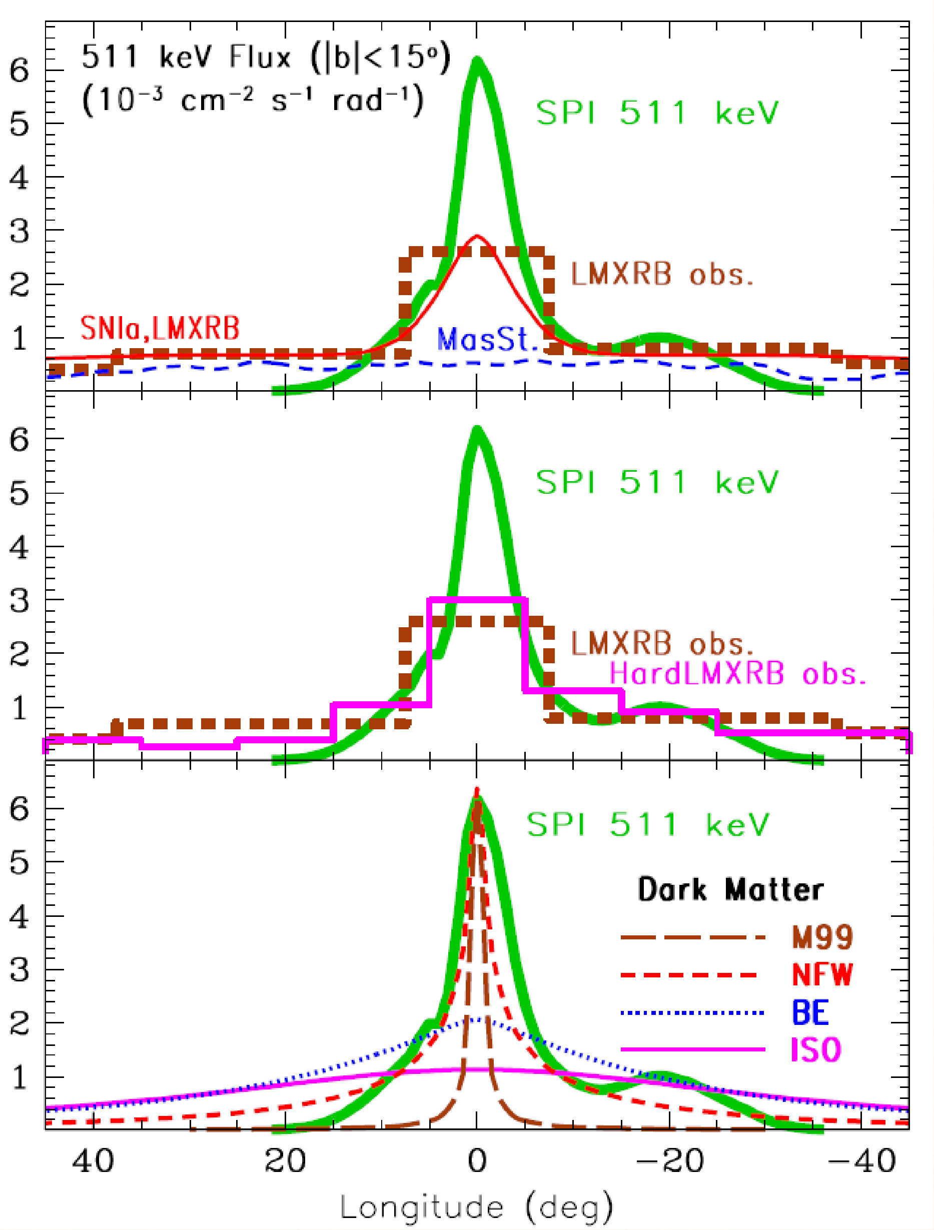
SPI Collab.
ArXiv: 1903.05569

Prantzos et al RevModPhys.83.1001

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



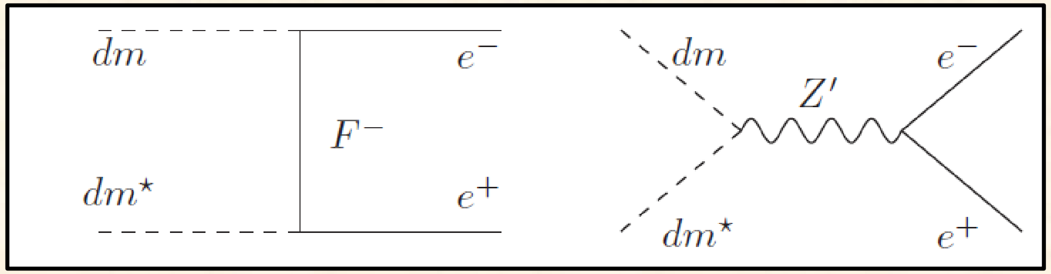
Prantzos et al RevModPhys.83.1001

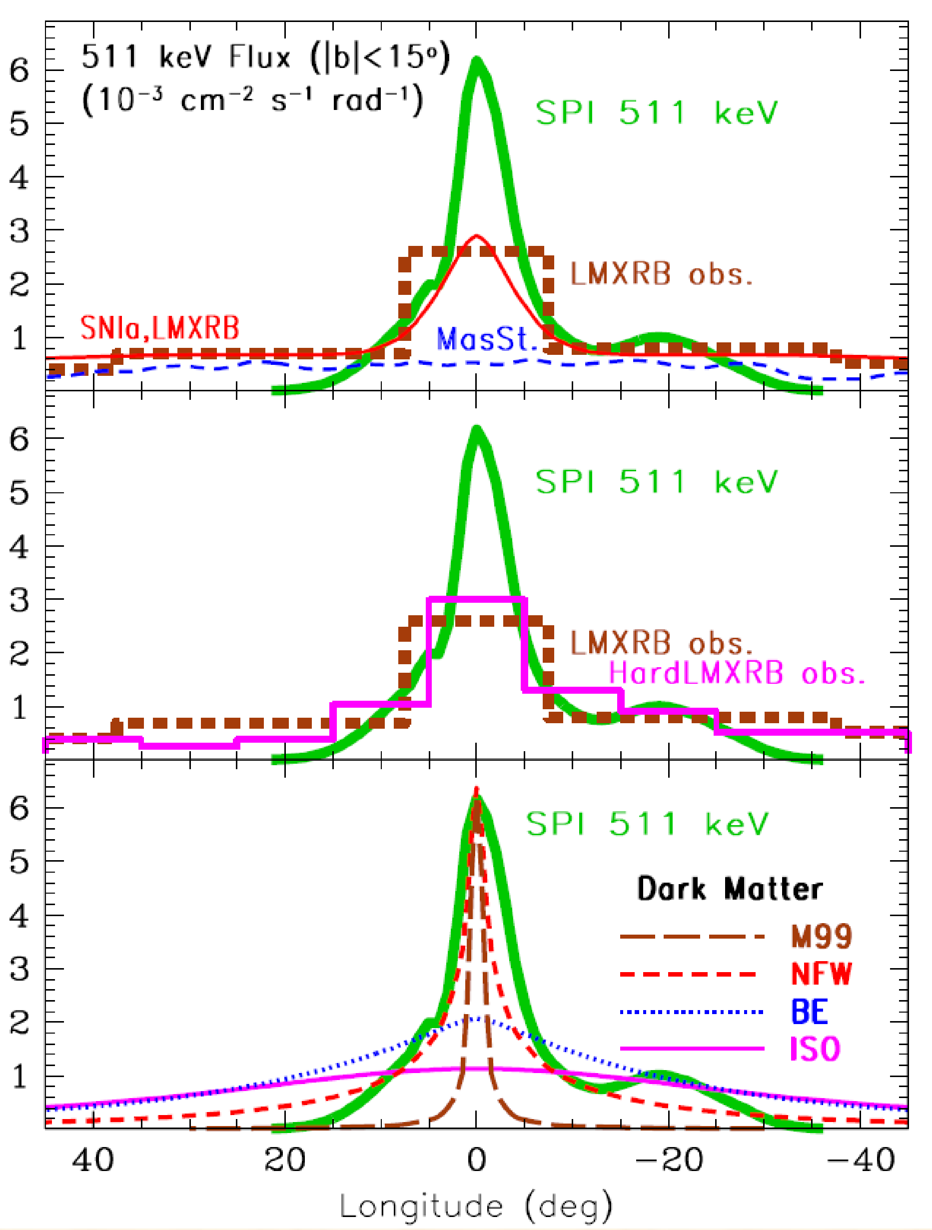
Possible positron sources

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 constraints only for $m_\chi > \sim 1\text{-}10$ MeV

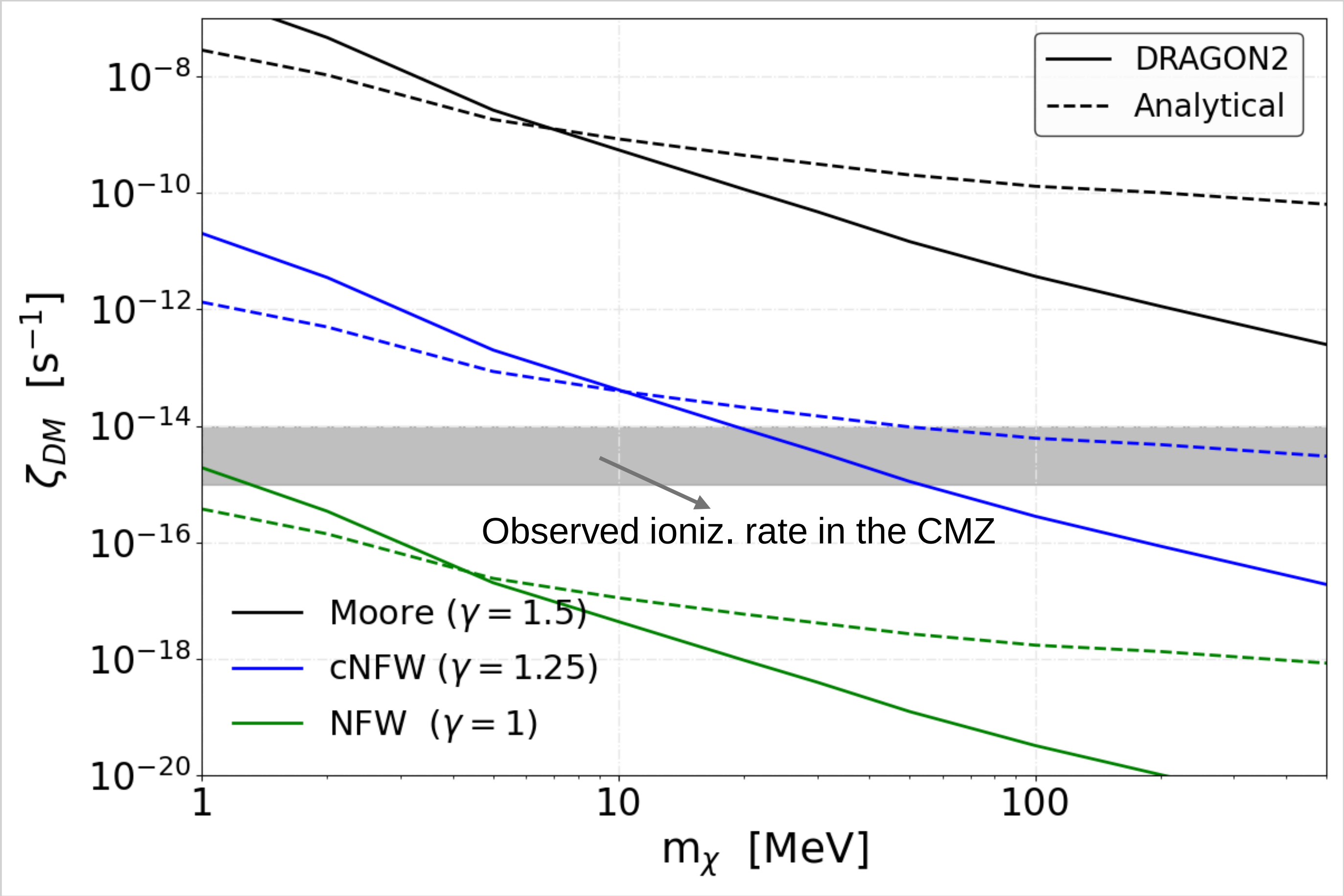




Source	Process	$E(e^+)^a$ (MeV)	e^+ rate[b] $\dot{N}_{e+}$ (10^{43} s^{-1})	Bulge/Disk[c] B/D	Comments
Massive stars: ^{26}Al	β^+-decay	~1	0.4	<0.2	$\dot{N}, B/D$: Observationally inferred
Supernovae: ^{24}Ti	β^+-decay	~1	0.3	<0.2	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+-decay	~1	*2*	<0.5	Assuming $f_{e+,esc}$=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	

Correlation with the anomalous CMZ ionization rate?

PDL, Balaji, Silk ArXiv:2409.07515



Maximum ionization rate allowed by CMB constraints

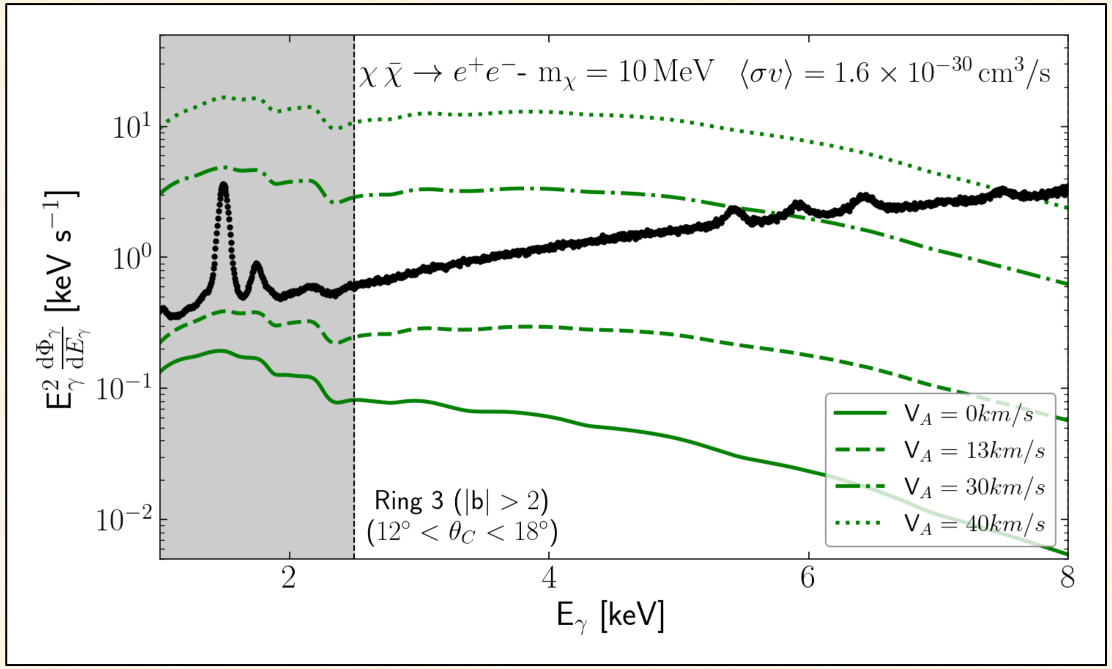
The CMZ ionization rate can be attributed to MeV dark matter annihilation for galactic dark matter profiles with slopes $\gamma > 1$

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

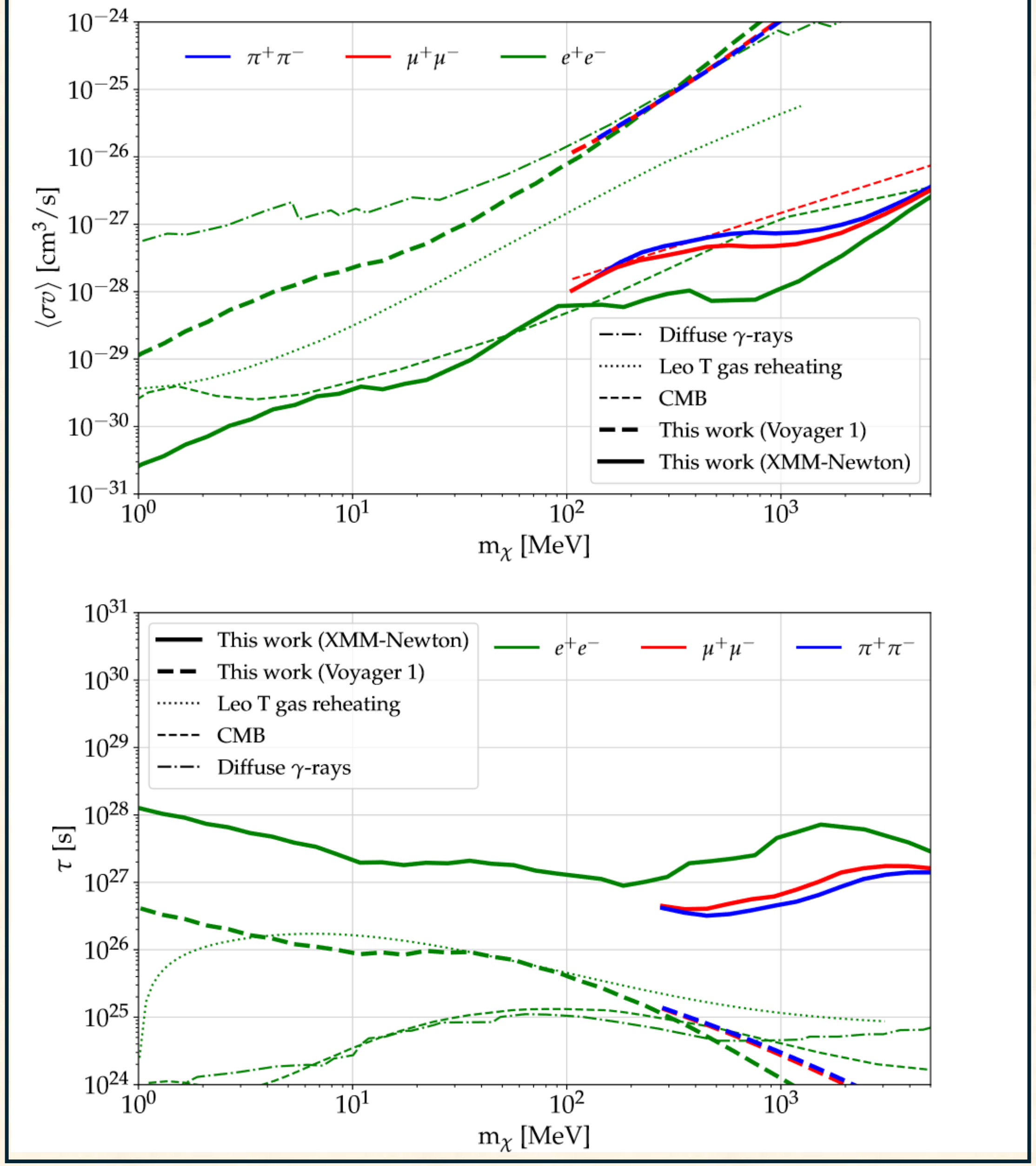
Previous constraints

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

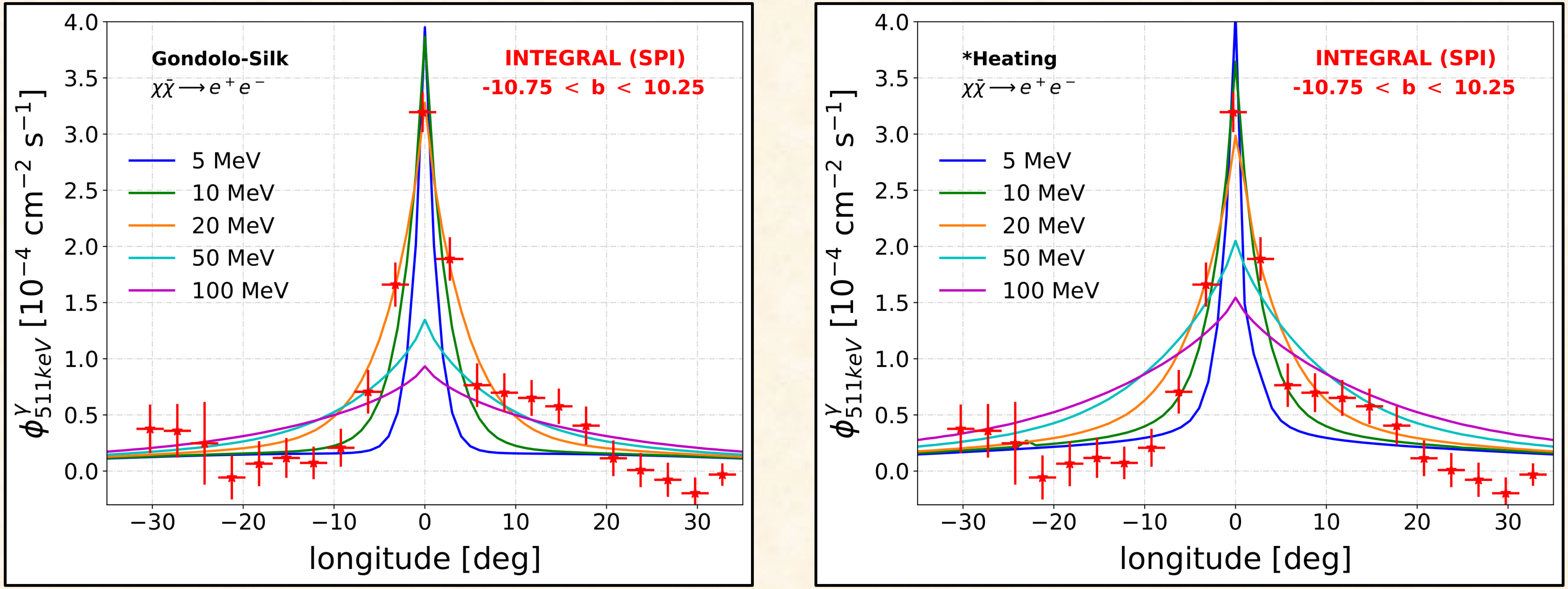
X-ray constraints suffer from uncertainties in propagation as well – Limits can be a factor of a few lower for a NFW profile



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

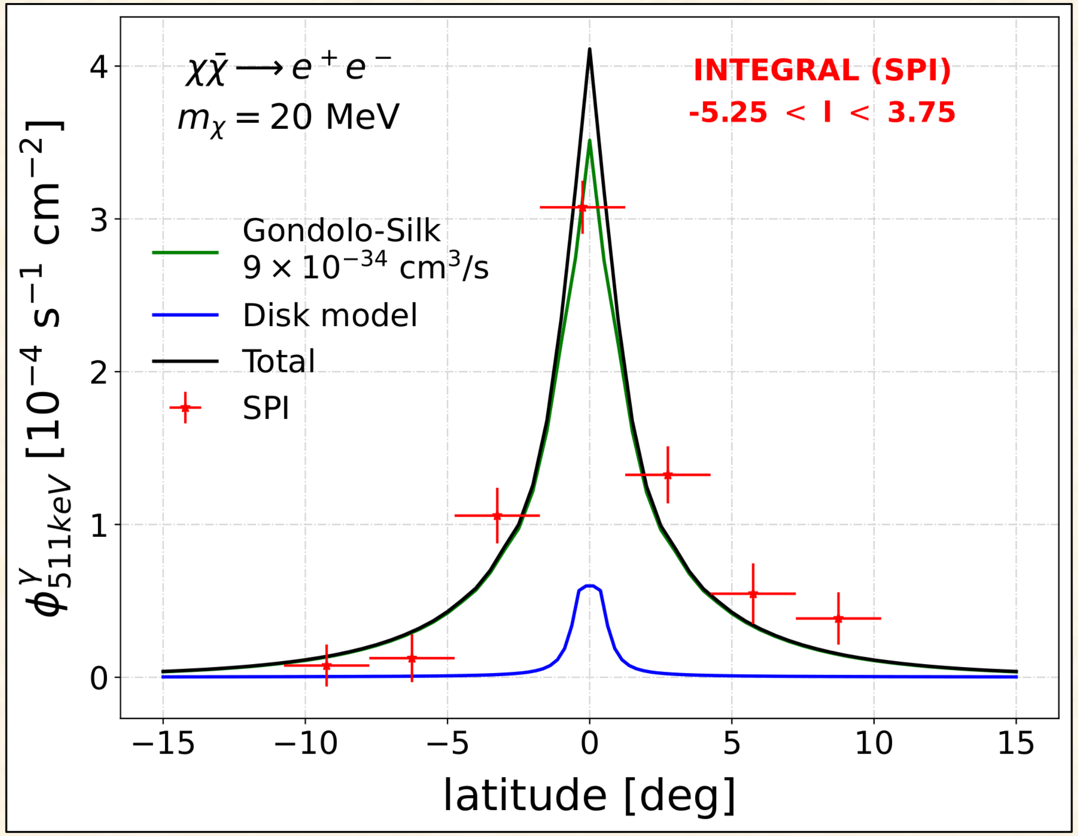


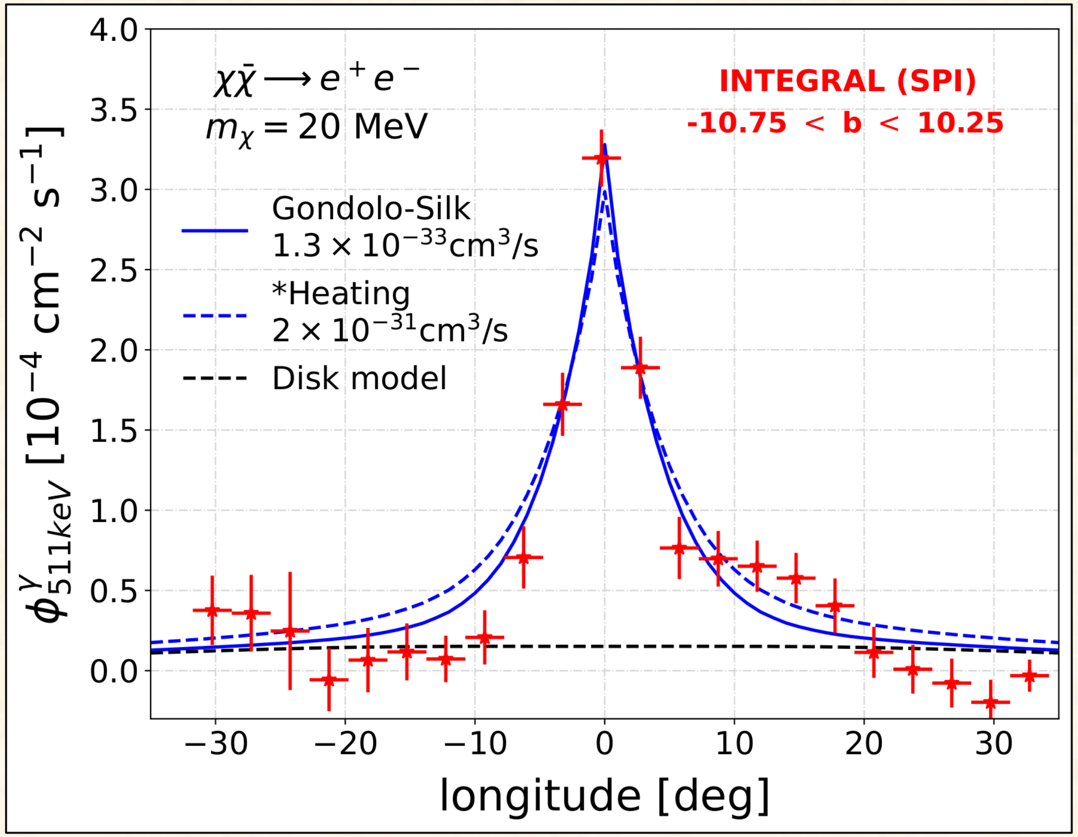
Best fit line profiles vs DM mass



The last chance for DM: spike around SgrA*

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 $<\sigma v>$

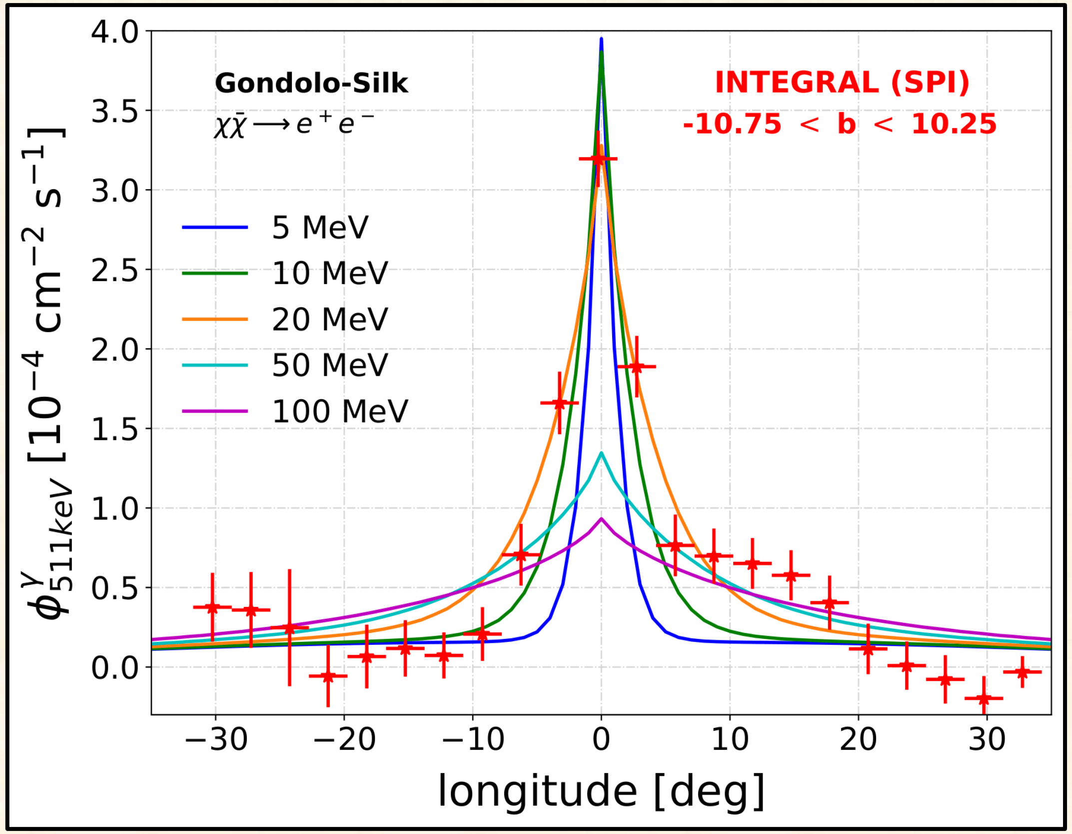


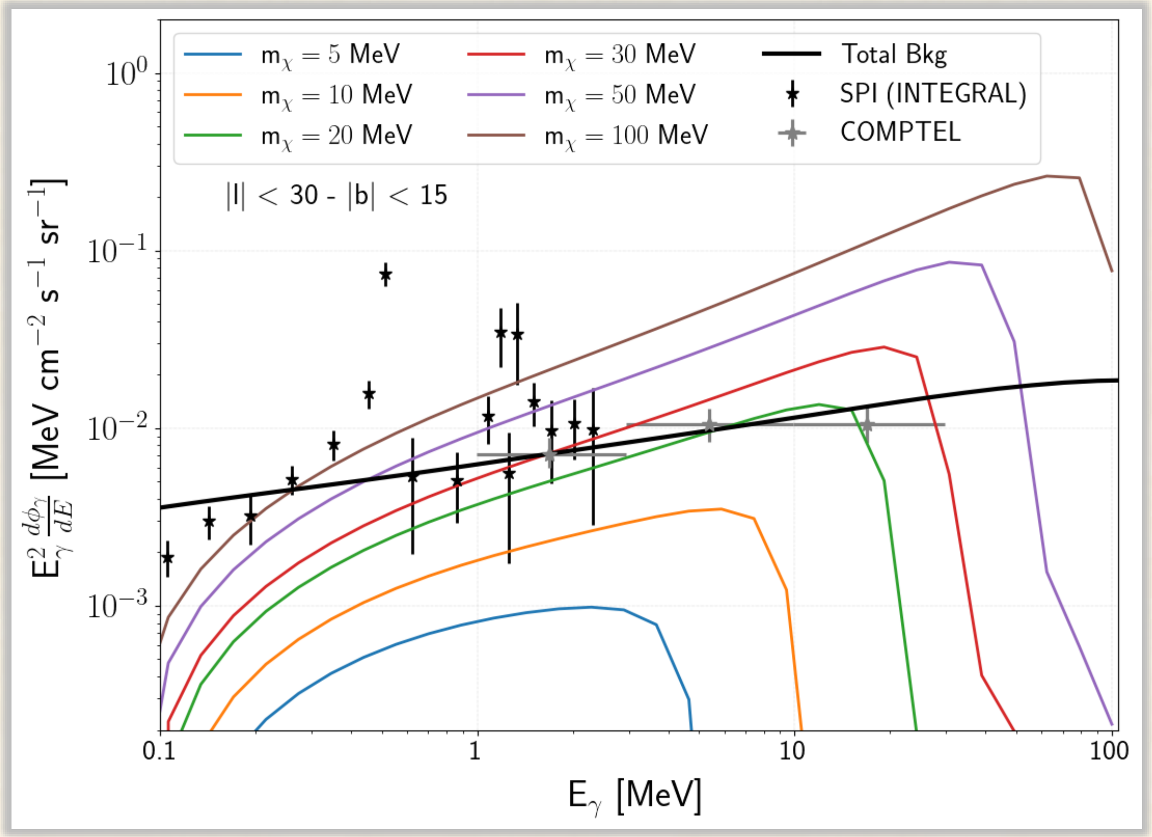


PDL, S. Balaji, F. Sala, M. Fairbarn, J. Silk. In preparation

The last chance for DM: spike around SgrA*

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





PDL, S. Balaji, F. Sala, M. Fairbarn, J. Silk. In preparation

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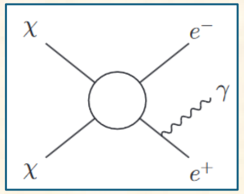
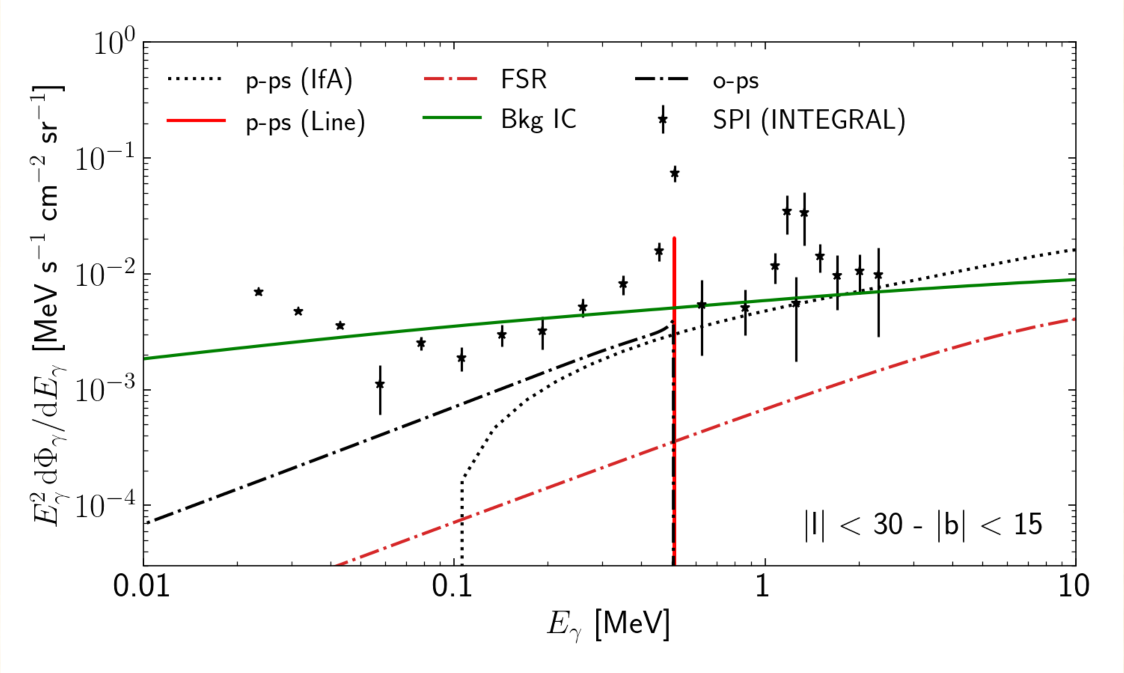


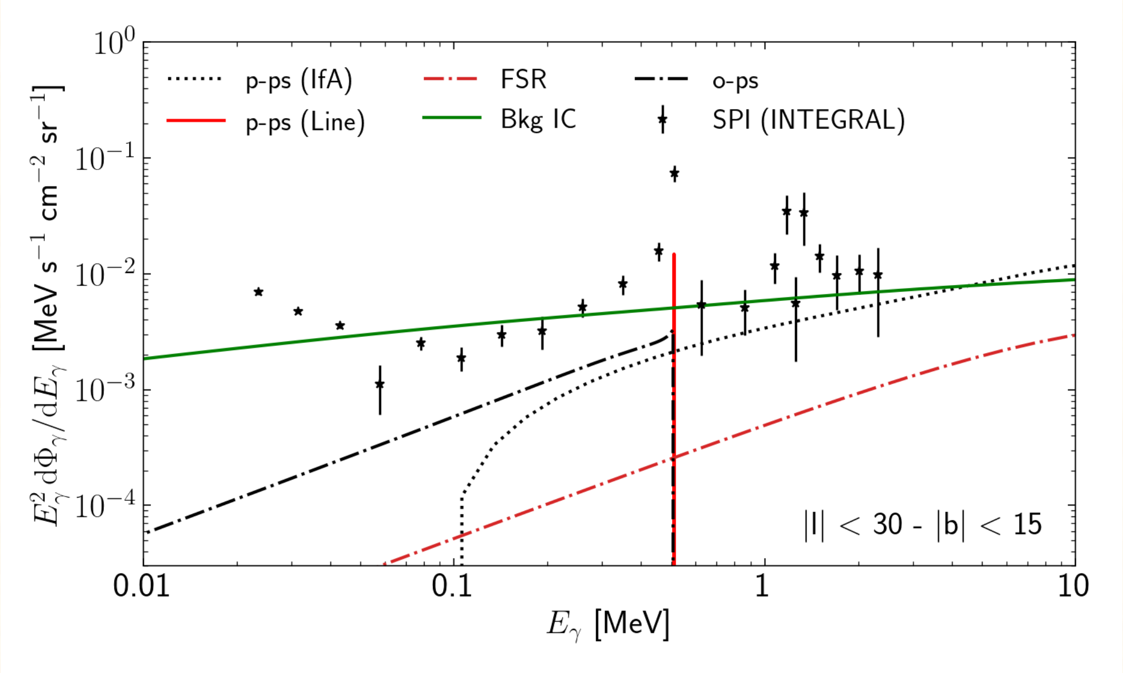
O-ps emission dominates at low energy, while IA the at high energies. Internal bremsstrahlung (FSR) is subdominant

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

Gondolo-Slik profile



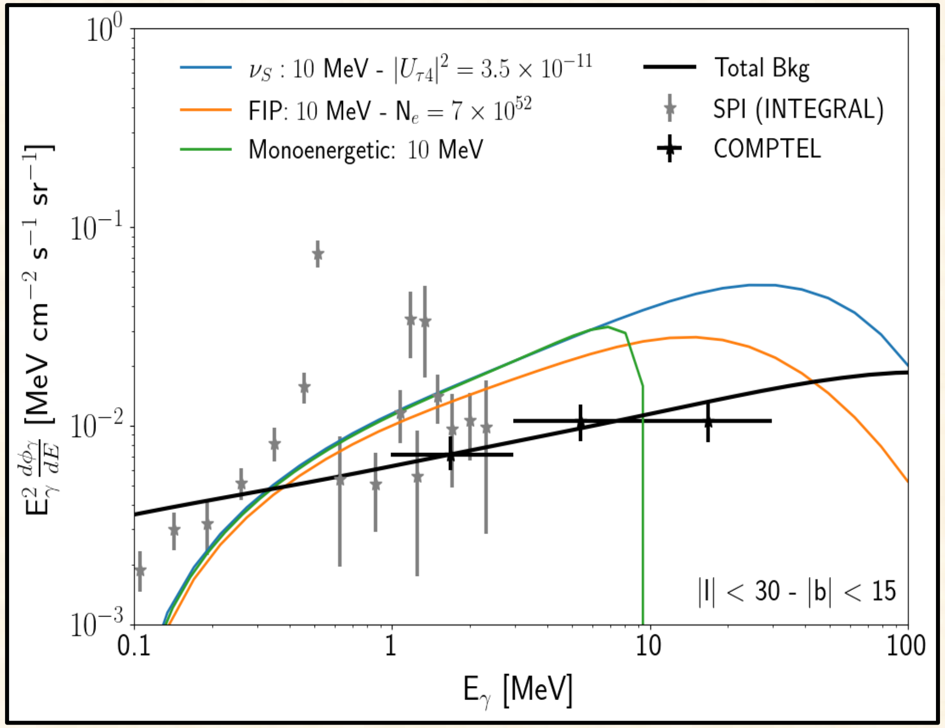
***Heating profile**



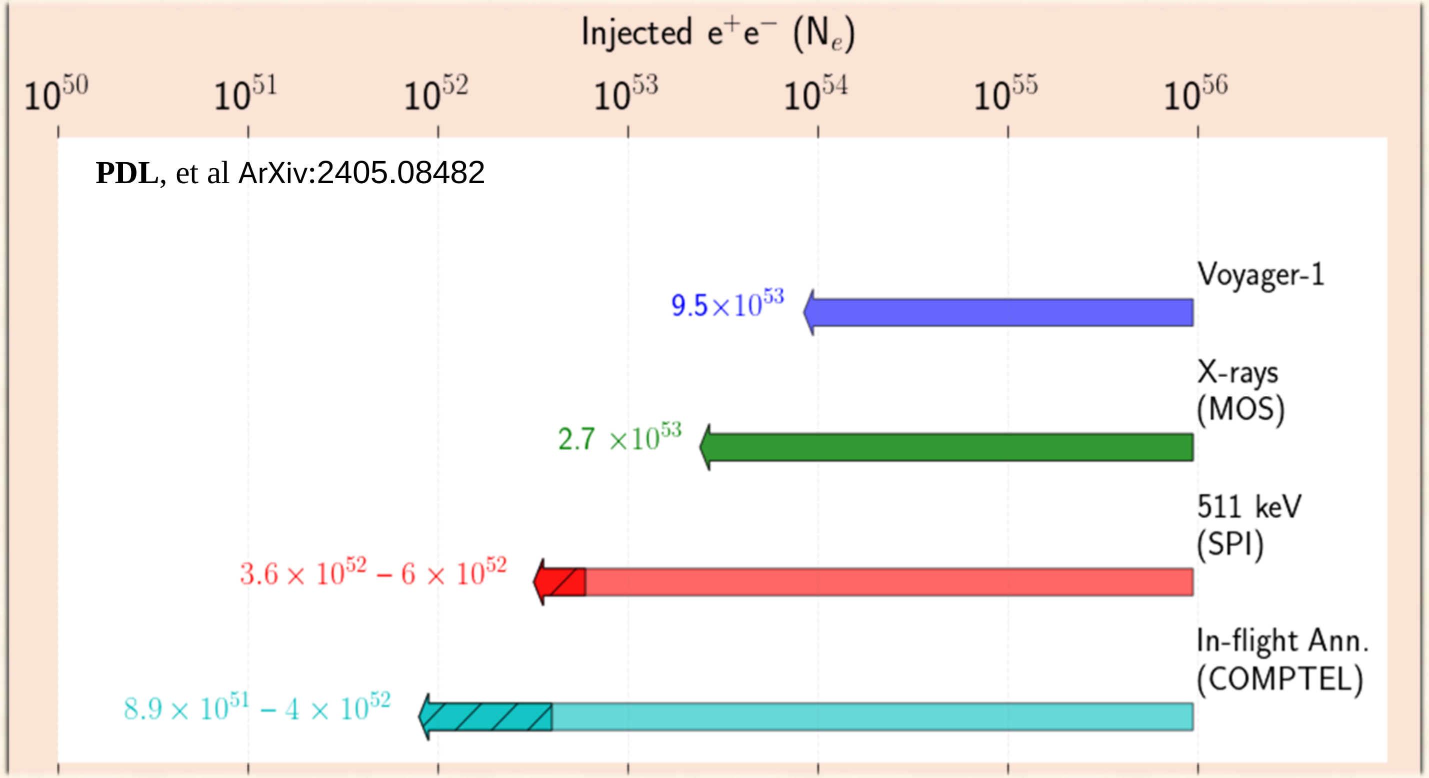
PDL, S. Balaji, F. Sala, M. Fairbarn, J. Silk. To be submitted

Constraints on the injected number of e^+ per SNe

- This source of e^+ can only constitute a fraction of the 511 keV disk emission.
- In-flight annihilation emission from these e^+ beats all the other limits.



PDL, et al ArXiv:2405.08482

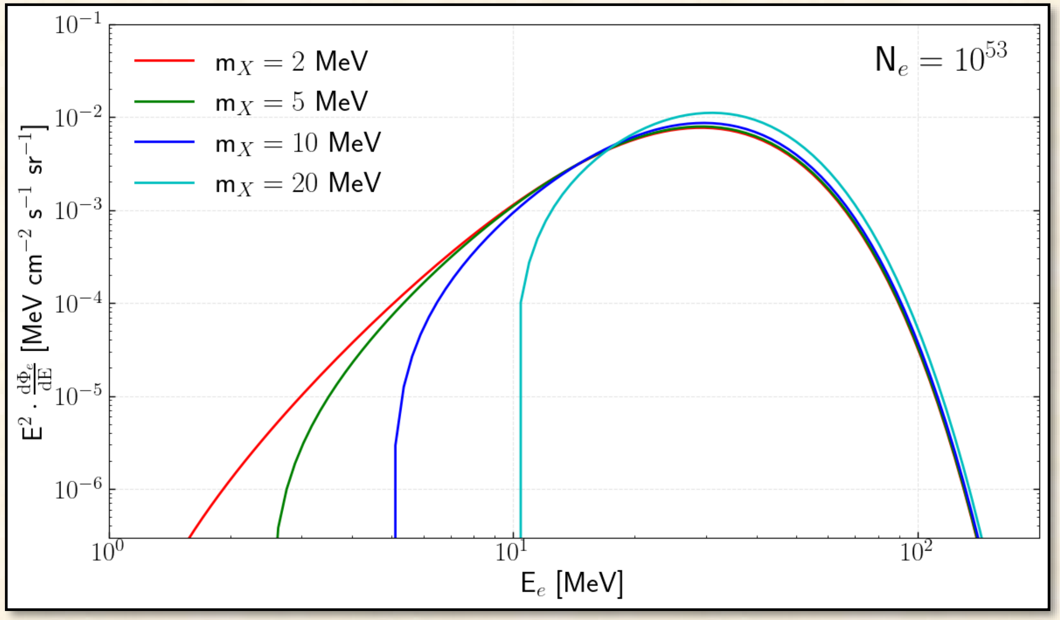


FIP production in Galactic SNe

<u>FIPs</u> → ALPs, Dark photons, sterile ν, …

The production for these particles can be described as a thermal Boltzmann emission. Therefore, **the injection of positrons and electrons** produced in their decay **can be parameterized as**:

$$\frac{dN_e}{dE_e} = N_e C_0 \left(\frac{4E_e^2 - m_X^2}{E_0^2} \right)^{\beta/2} e^{-(1+\beta)\frac{2E_e}{E_0}}$$



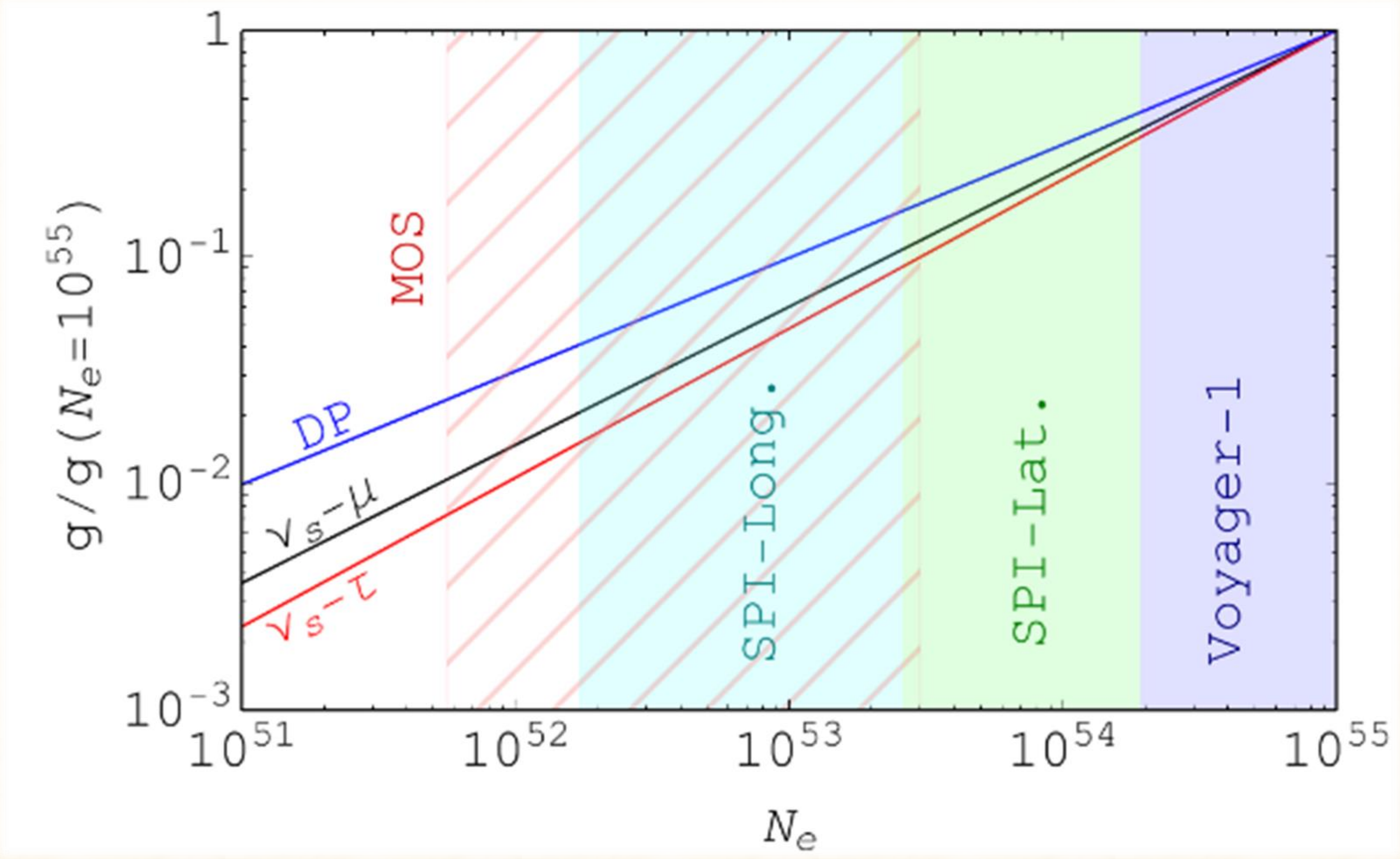
FIP constraints on FIP parameters

(ArXiv:2307.13728, ArXiv:2307.13731)

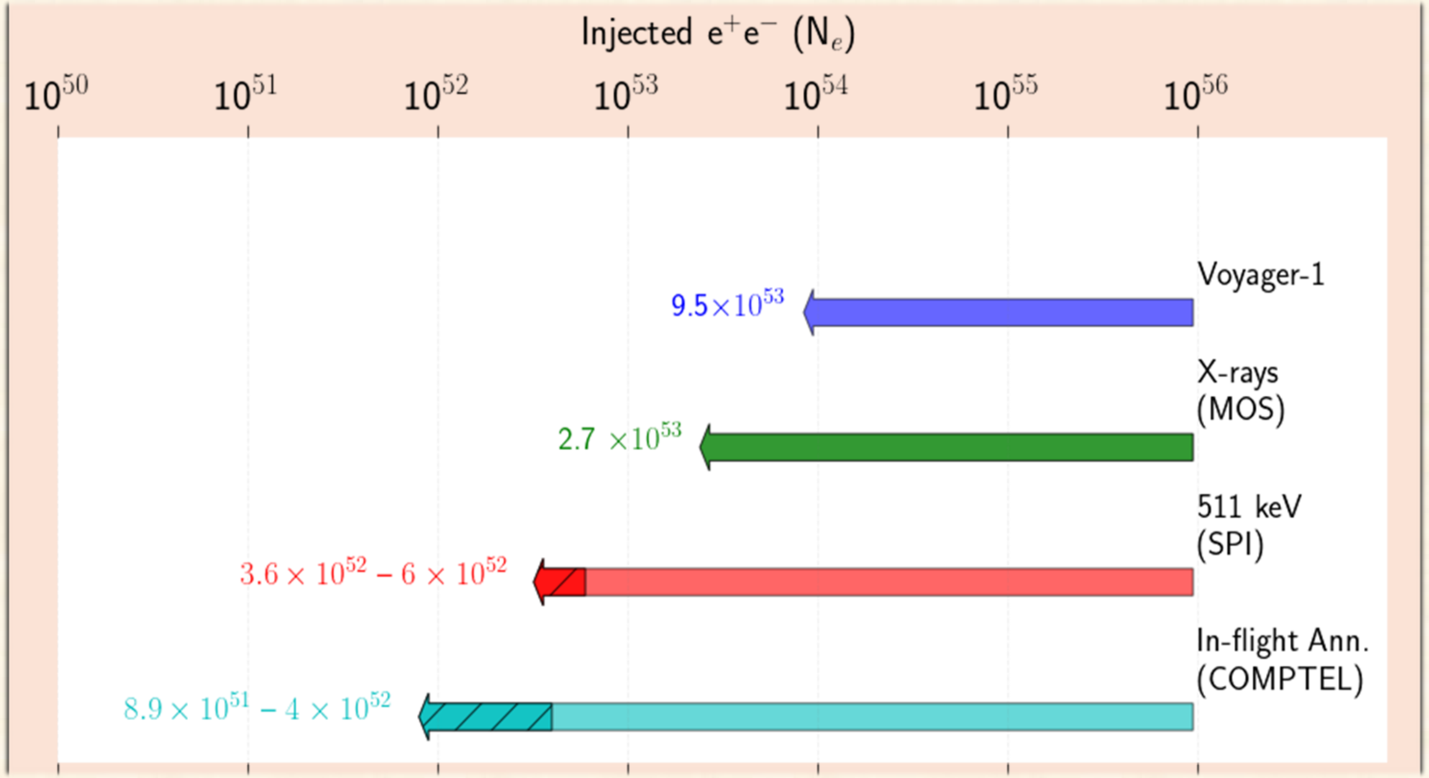
The upper limits on the e^+e^- injection can be applied to several FIP models

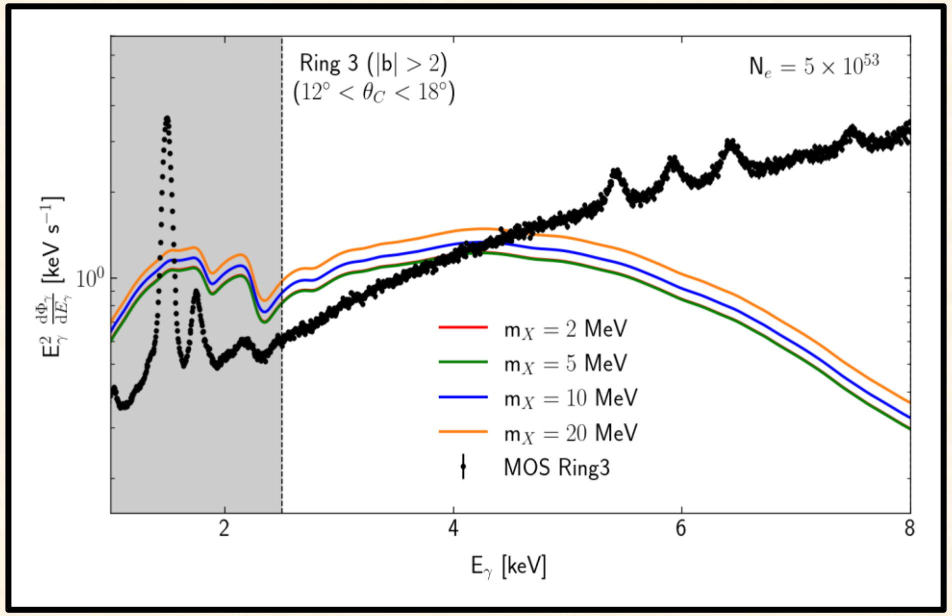
Here, we assume a simple dependency of the coupling, as $\boldsymbol{g \sim N_e^{-\alpha}}$, with g being the coupling to electrons for ALPs, $|U_{\nu_s}|^2$ for sterile ν, or ε for dark photons.

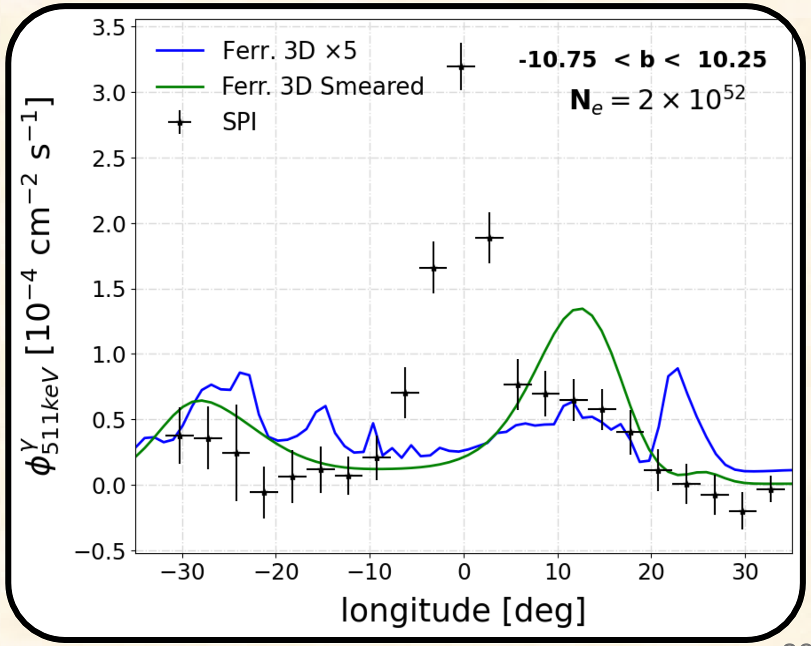
For example, for ALPs in the low-coupling regime, the positron production rate per SN grows as g^2



Limits on the injected number of positrons emitted by FIPs produced in SNe

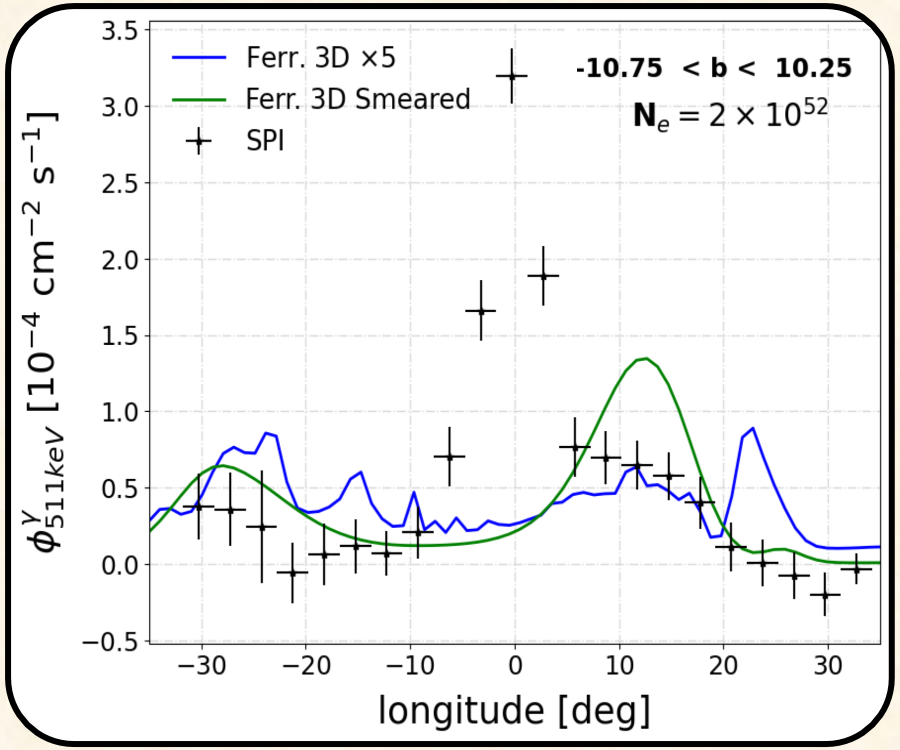




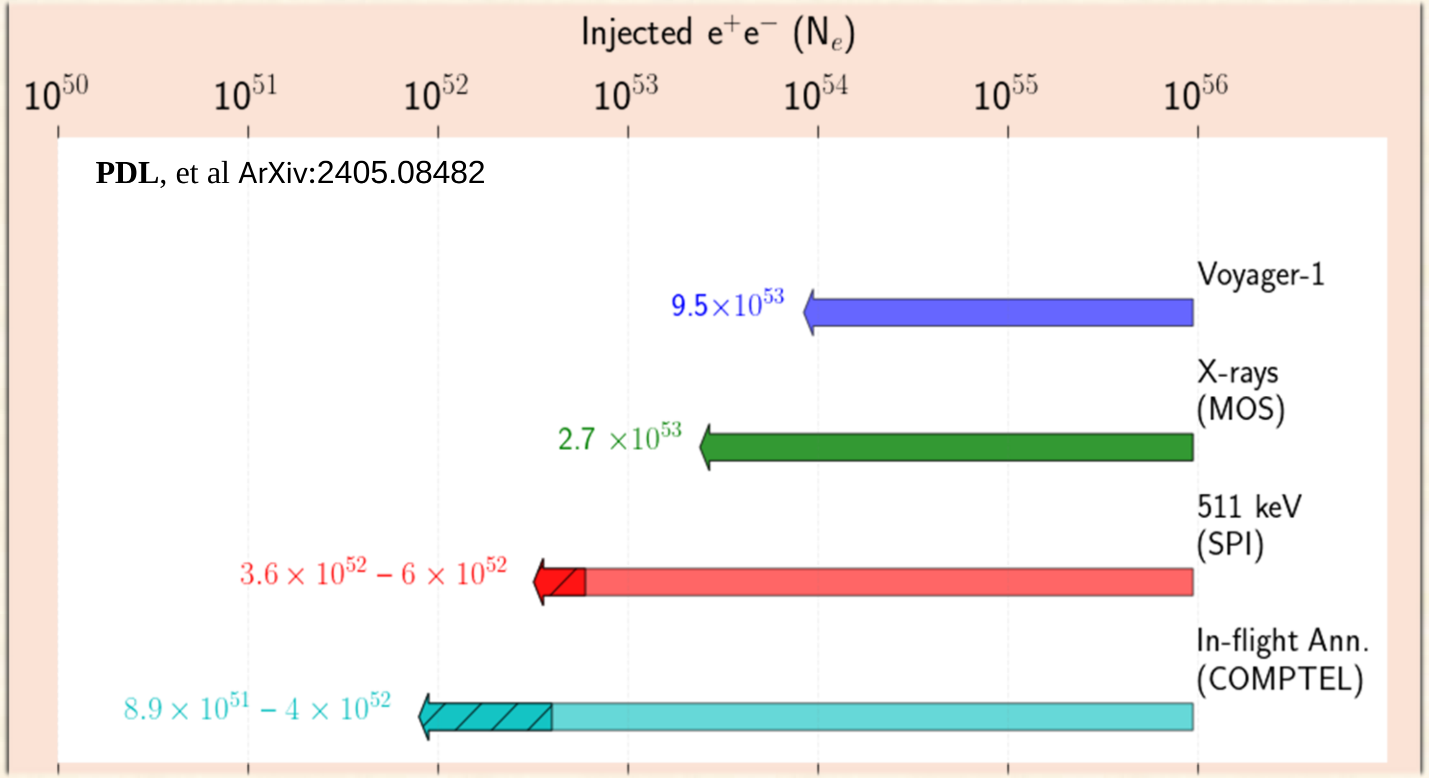


Constraints on the injected number of e^+ per SNe

- ➢ This source of e^+ can only constitute a fraction of the 511 keV disk emission.
- ➢ In-flight annihilation emission from these e^+ beats all the other limits.



PDL, S. Balaji, P. Carenza ArXiv:2307.13728



PDL, et al ArXiv:2405.08482

The specific case of sterile neutrinos

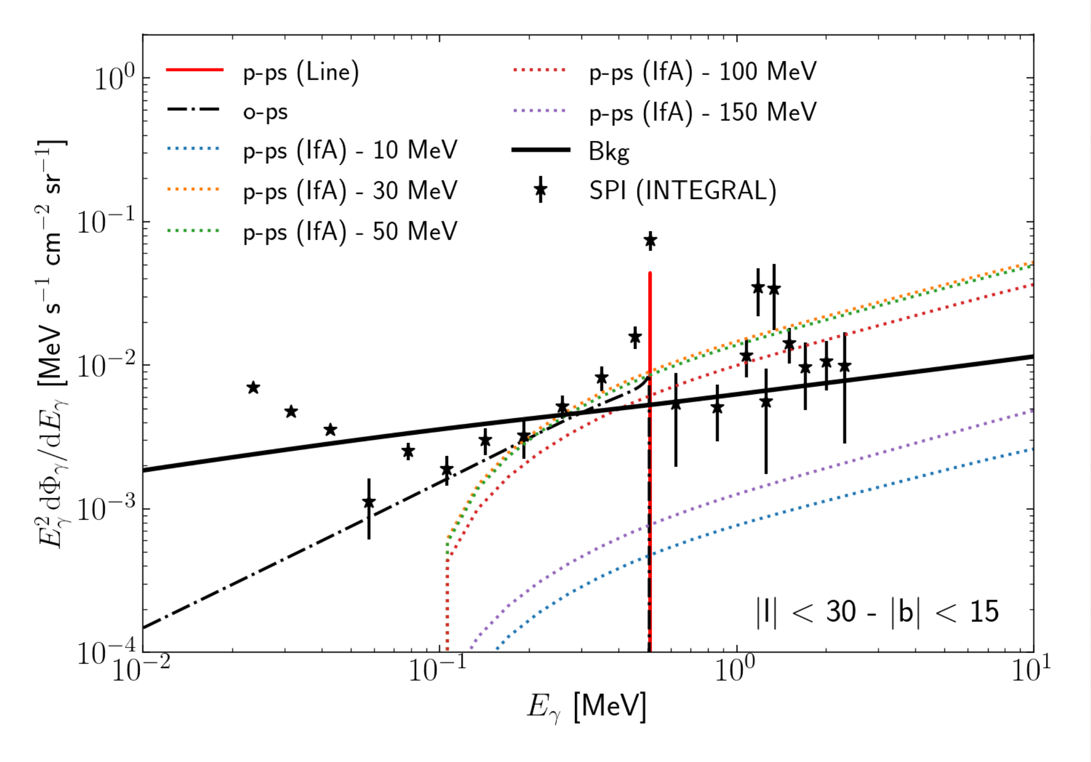
$$\nu_\alpha = U_{\alpha 1}\,\nu_\ell + U_{\alpha 4}\,\nu_4$$
$$\nu_s = -U_{\alpha 4}\,\nu_\ell + U_{s4}\,\nu_4$$

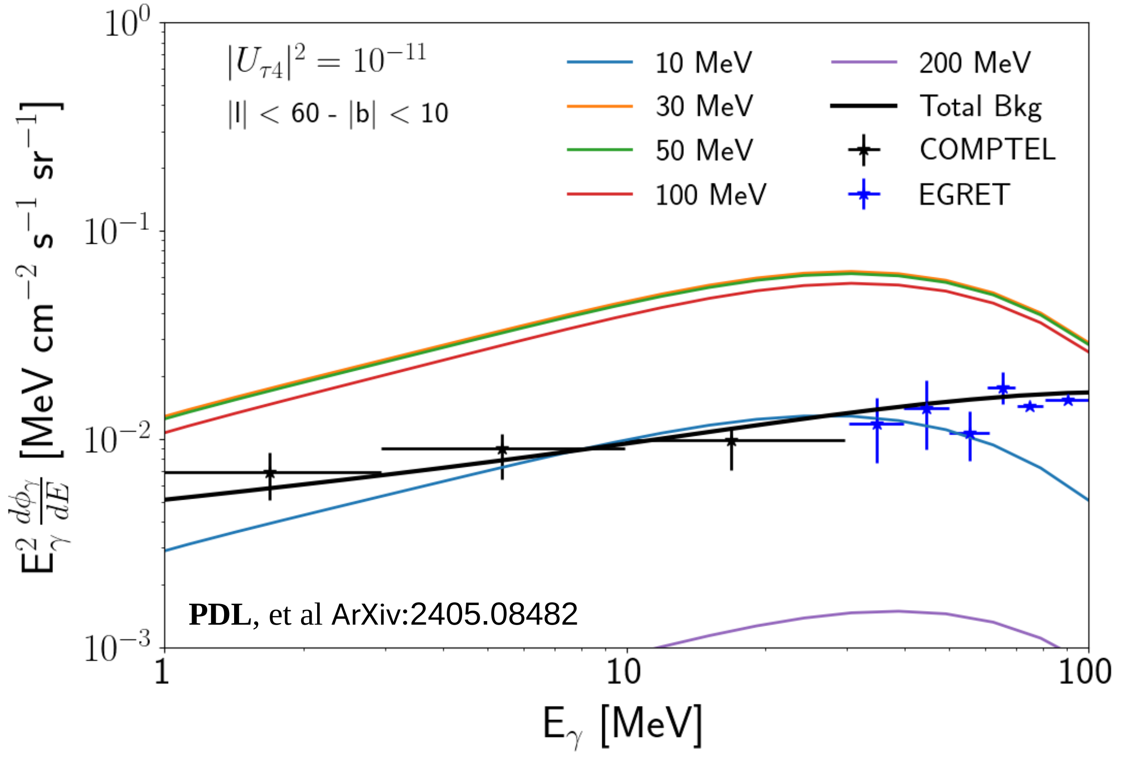
We compute the sterile neutrino production using as a benchmark an 18 $M_\odot$ progenitor mass, based on the *AGILE BOLTZTRAN* code

Most important decays are $\upsilon_4 \rightarrow \upsilon_\alpha\, l_\alpha^{\,+}\, l_\alpha^{\,-}$

See Carenza et al 2023 (ArXiv:2311.00033) for details

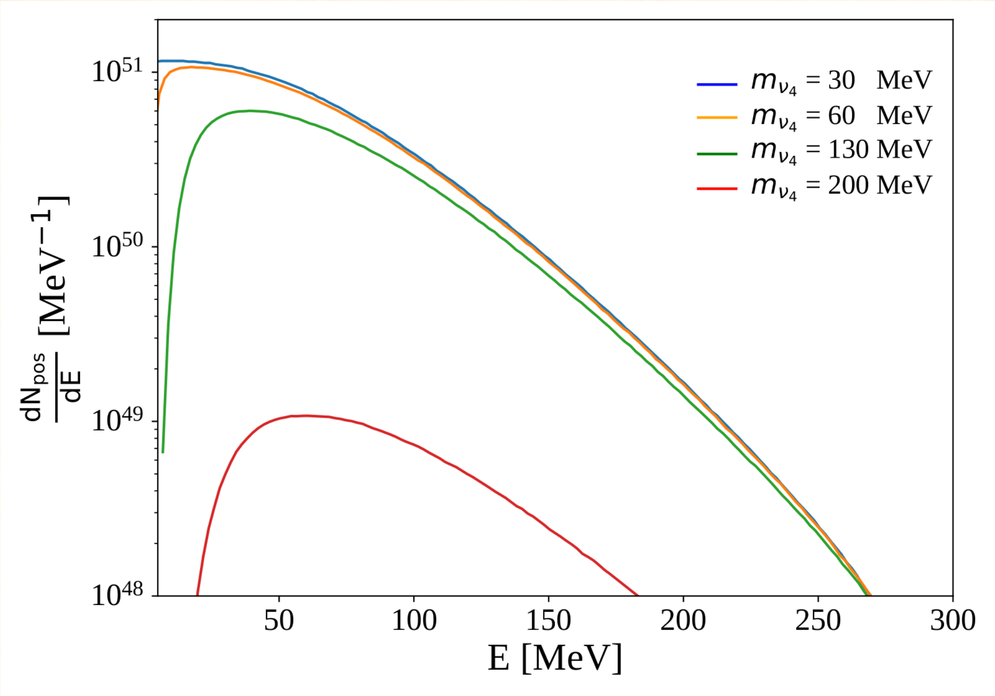
$$\frac{dN_{\rm pos}}{dE} = n_{\rm pos}\frac{dN_4}{dE_4}\left(\epsilon_{II}e^{-r_{II}/\lambda_{\rm dec}} + \epsilon_I\, e^{-r_I/\lambda_{\rm dec}}\right)$$



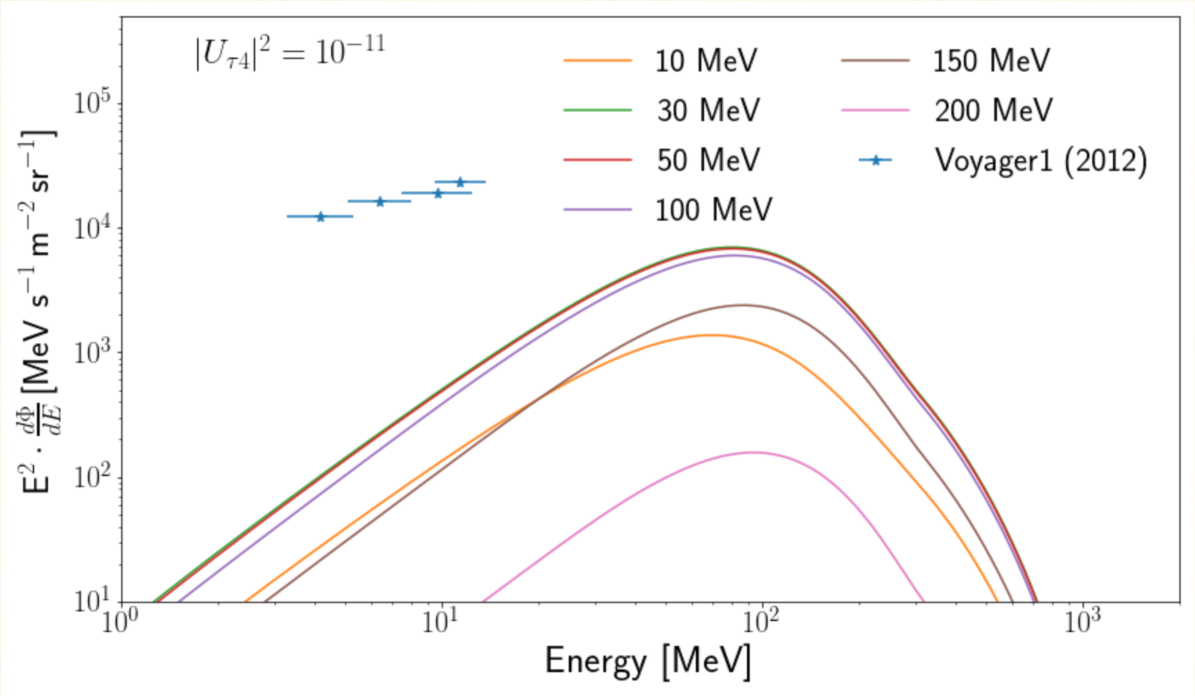


Constraints on sterile neutrinos produced in SNe

Injected distribution of positrons

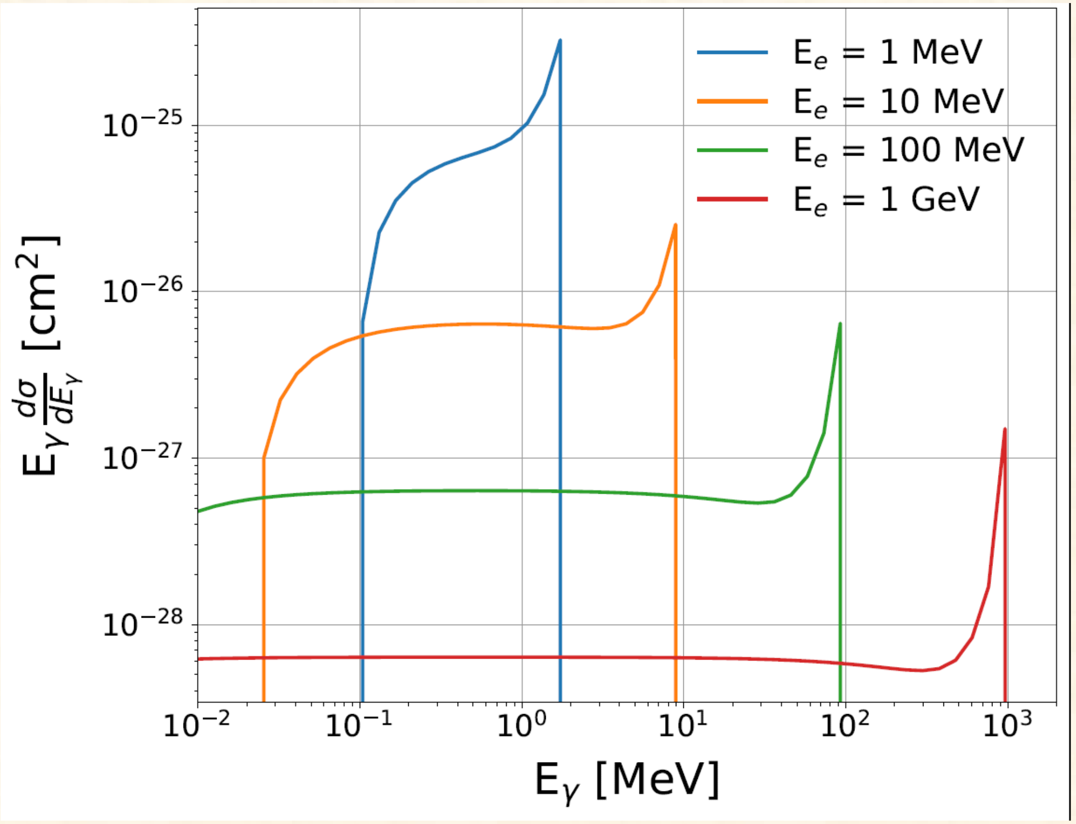


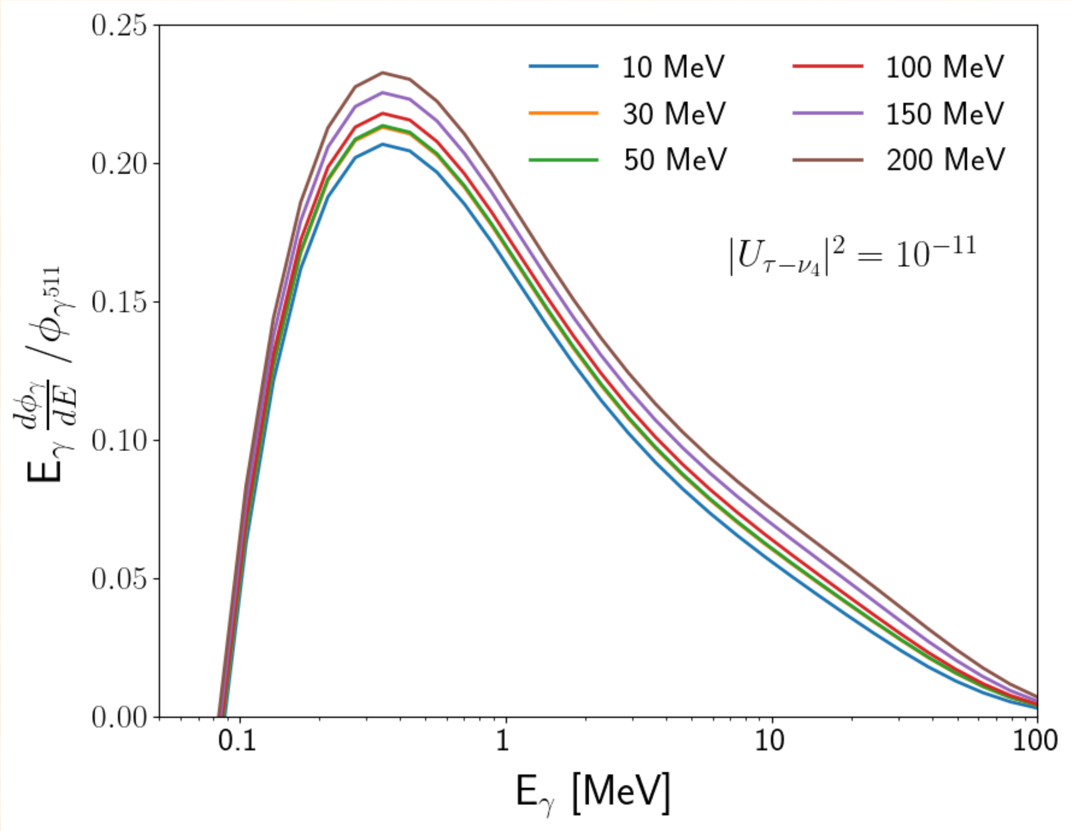
Propagated positrons: Local spectra vs mass



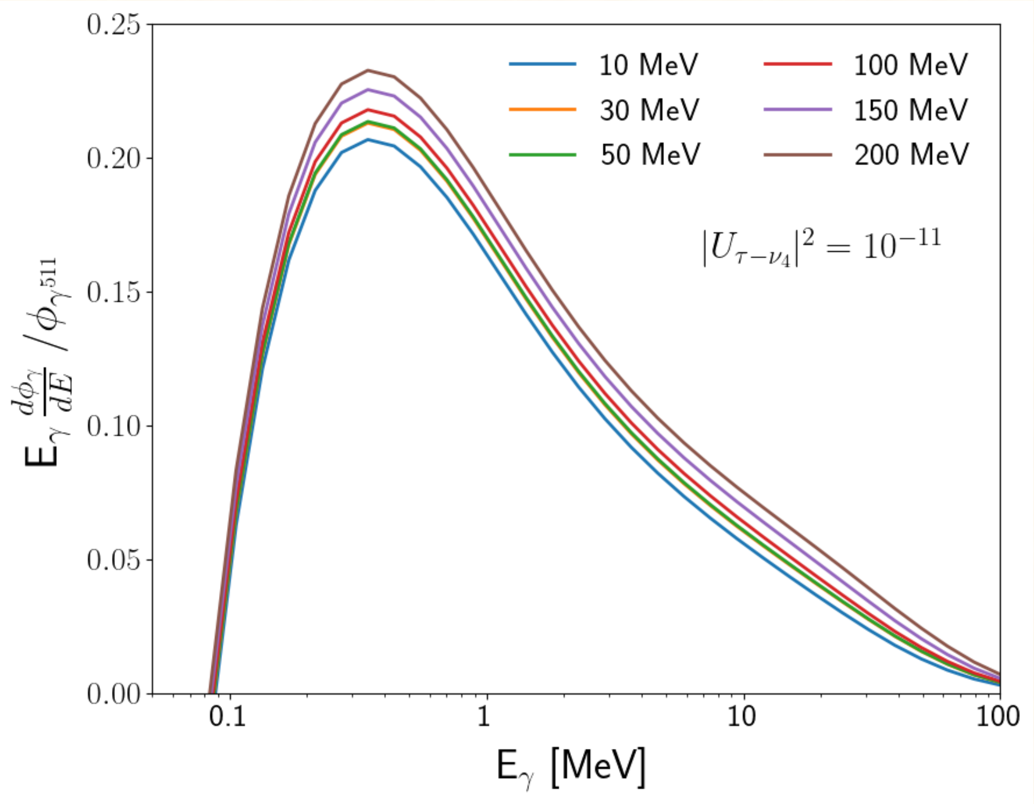
in-flight positron annihilation

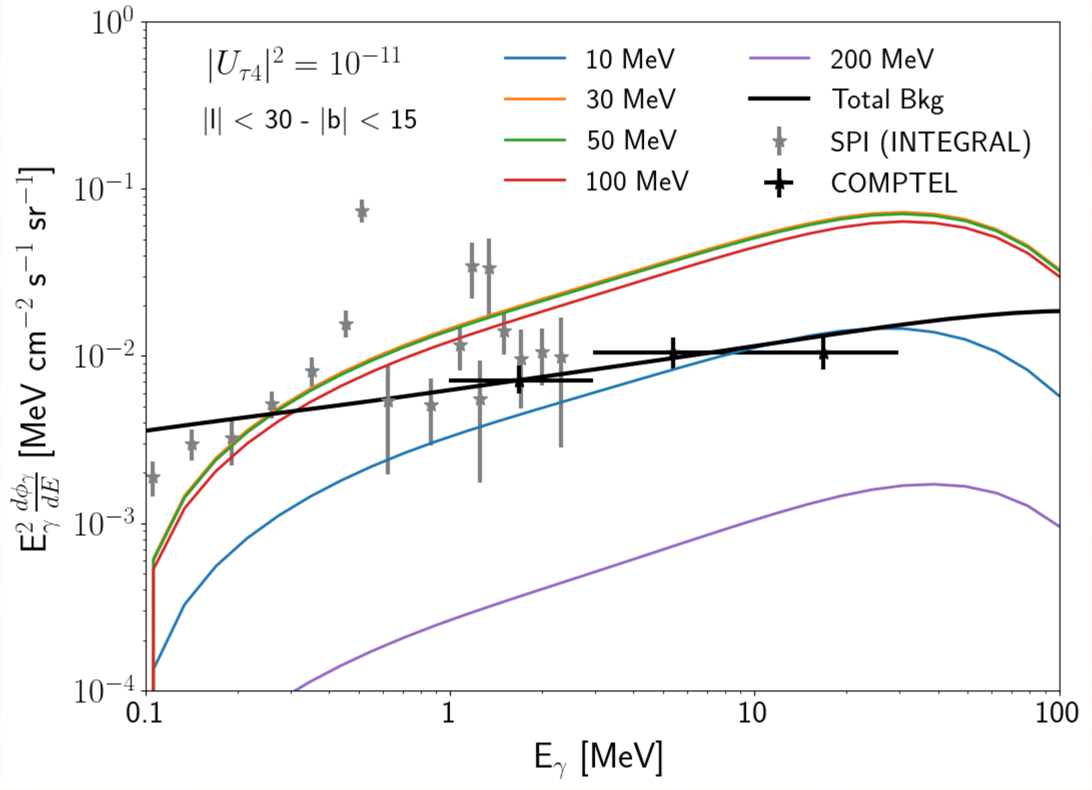
$$\frac{d\phi^{\mathrm{IA}}}{d\Omega\, dE_\gamma} = \frac{d\phi^{511}}{d\Omega} \frac{n_H}{P(1-\frac{3}{4}f)} \times \int_{E_\gamma}^{E_{\max}} dE' \frac{1}{N_{\mathrm{pos}}} \frac{dN_{\mathrm{pos}}}{dE'} \int_{m_e}^{E'} P_{E'\to E} \frac{d\sigma}{dE_\gamma} \frac{dE}{|dE/dx|}$$





Constraints on sterile neutrinos





Evaporating primordial black holes

Using BlackHawk

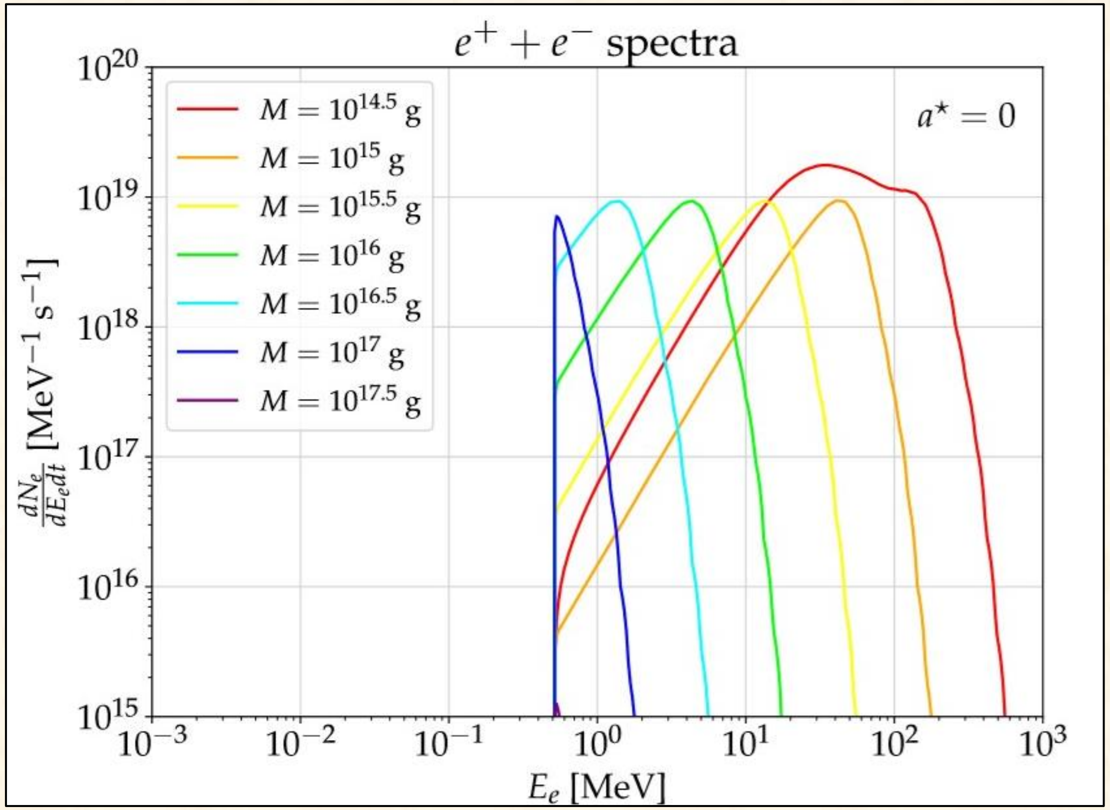
$$\frac{d^2 N_i}{dt dE_i} = \frac{1}{2\pi} \sum_{\text{d.o.f.}} \frac{\Gamma_i(E_i, M, a^\star)}{e^{E'_i/T} \pm 1}$$

Hawking radiation is expected to produce all kind of particles with a thermal spectrum

The lower the mass of the PBH, the higher is the PBH temperature and, hence, the higher is the mass of the particles that it produces

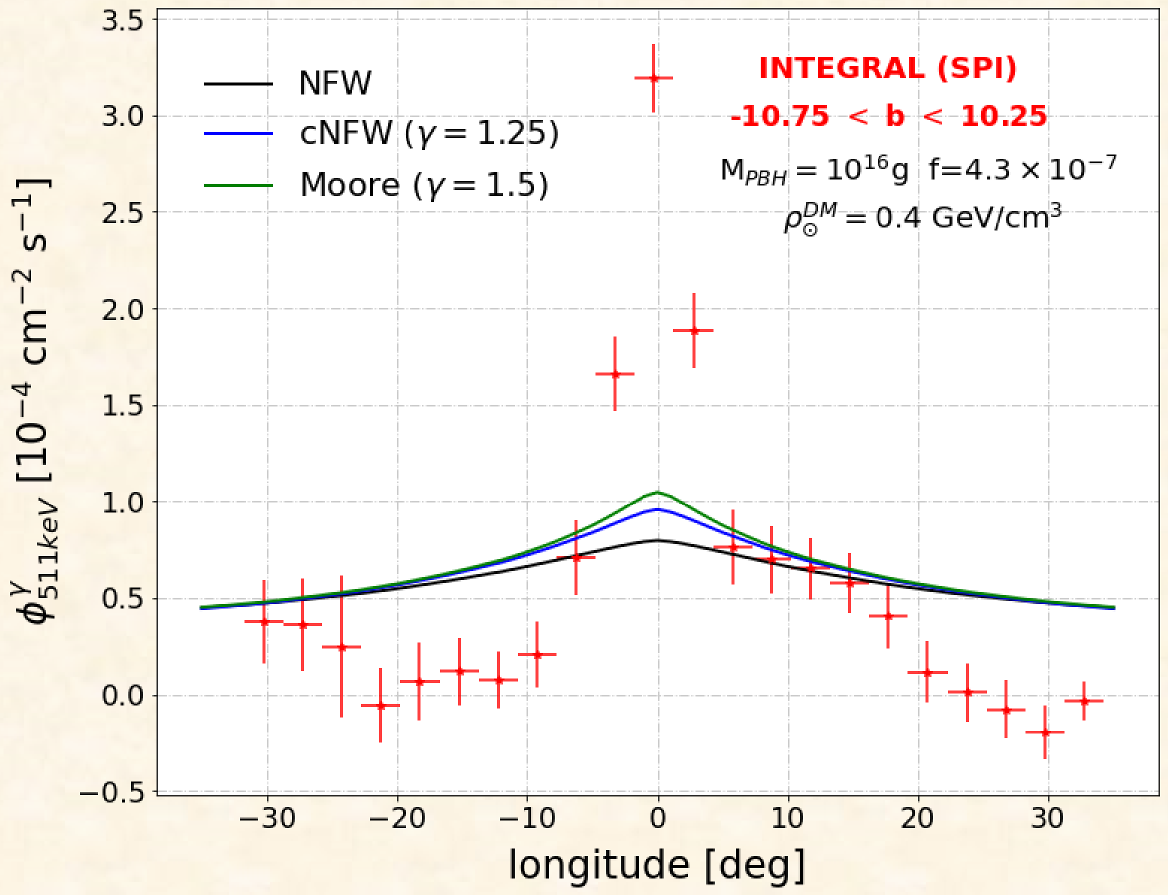
Satellite-mass PBHs would produce detectable emission of e^+e^- and secondary radiations. Constraints are placed on the fraction of DM that is in the form of PBHs

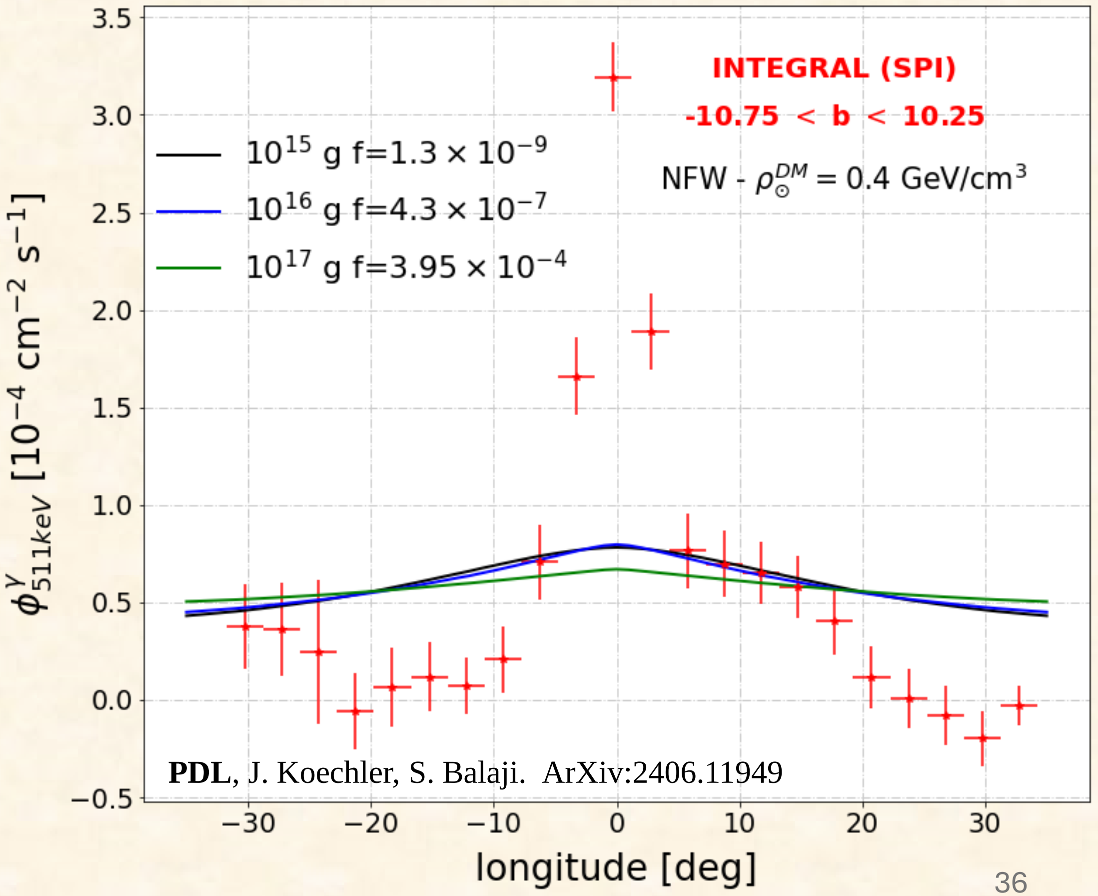
Strongest previous constraints were based on Voyager-1 data, direct decay to gamma rays and the isotropic X-ray background.



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. At 10^{18} g their production is very low, and *f* cannot be constrained





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

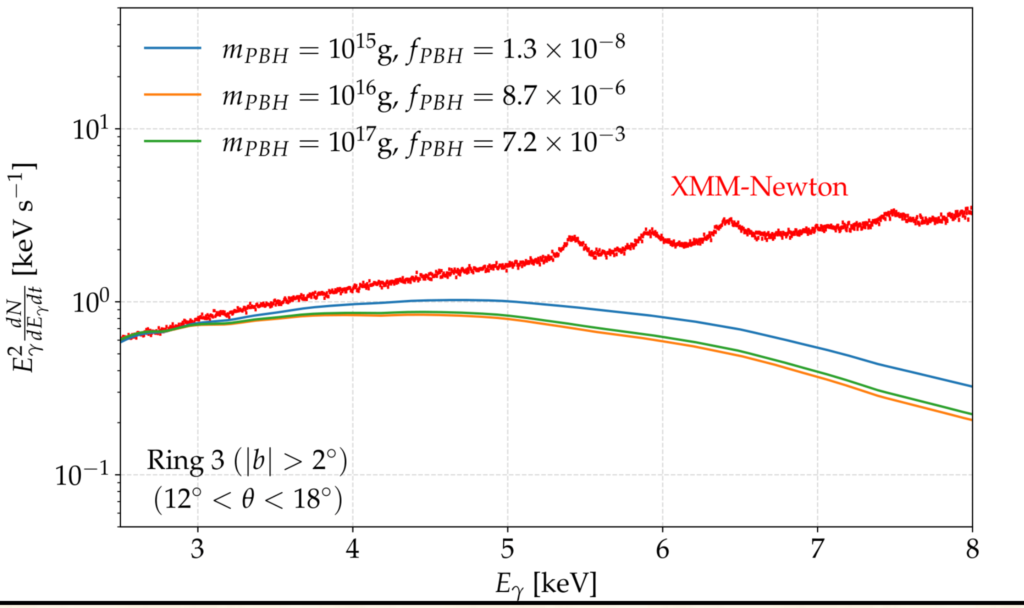
PBHs and the 511 keV line: constraints

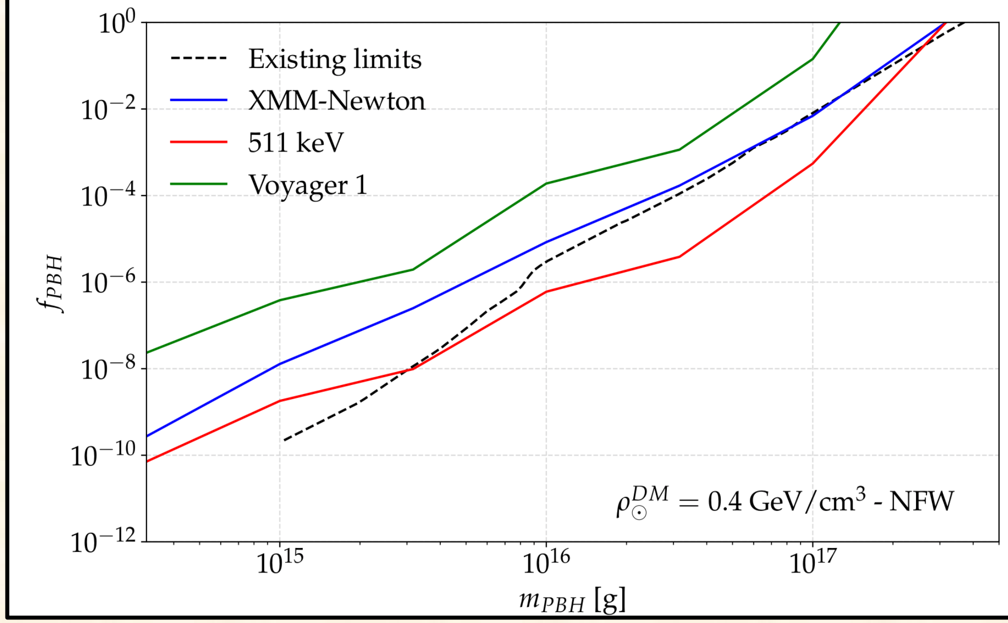
XMM-Newton limits are obtained from the inverse-Compton emission of the injected e^+e^-

For the high masses, these limits improve, by far, the existing ones.

Monochromatic and non-rotating PBHs

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





PBHs and the 511 keV line: constraints

Kerr BHs (a ≡ Spin)

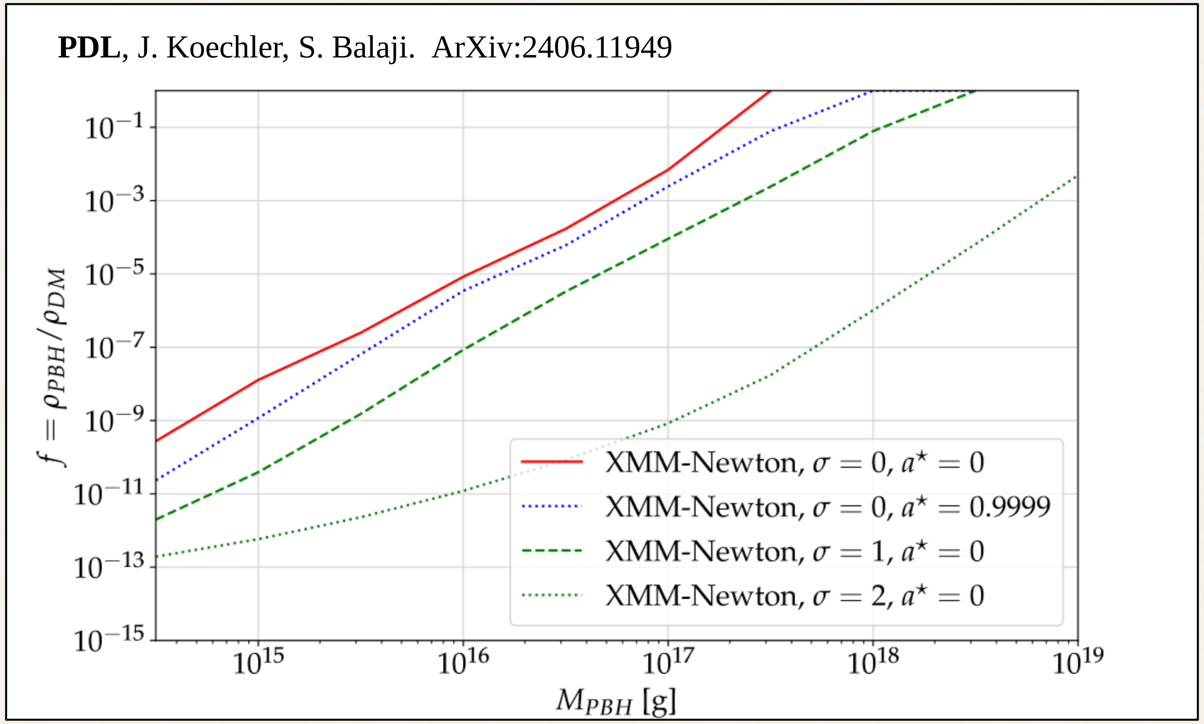
$$T = \frac{1}{2\pi}\left(\frac{r_+ - M}{r_+^2 + a^2}\right)$$

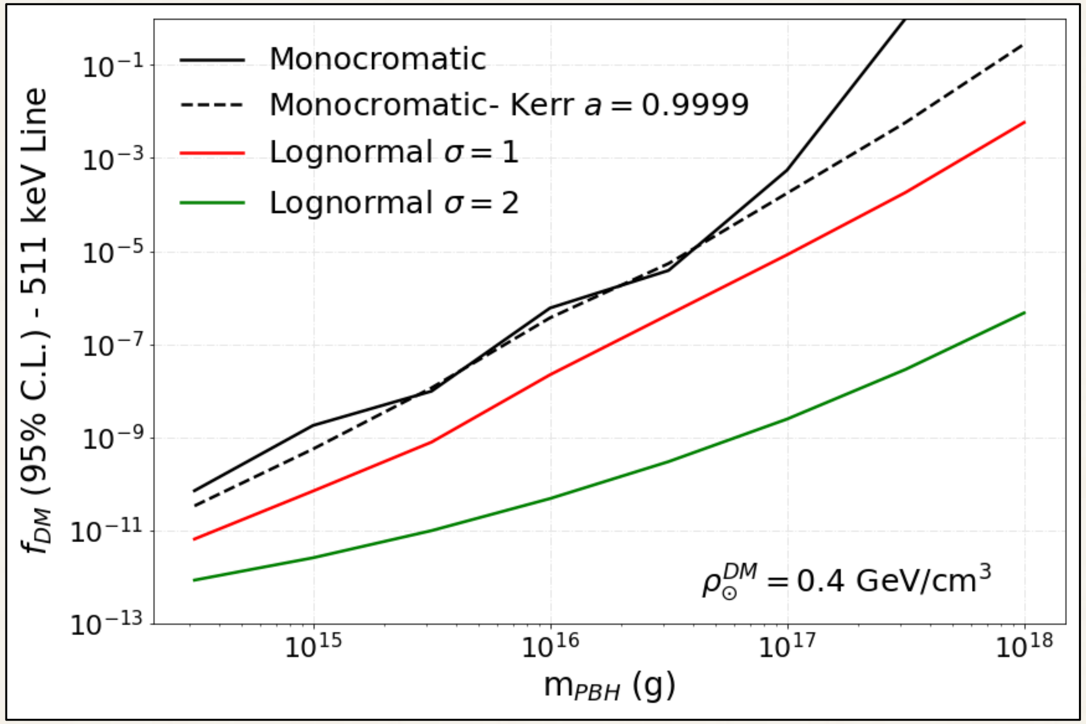
Non-rotating BHs

$$T = 1/(8\pi M)$$

Mass distribution of PBHs

$$Q_e(E_e, \vec{x}) = f\rho_{\rm DM}(\vec{x}) \int_{M_{\rm min}}^{\infty} \frac{dM}{M} \frac{dN_{\rm PBH}}{dM} \frac{d^2 N_e}{dt dE_e}$$





PBHs and the 511 keV line: constraints

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$$T = \frac{1}{2\pi}\left(\frac{r_+ - M}{r_+^2 + a^2}\right)$$

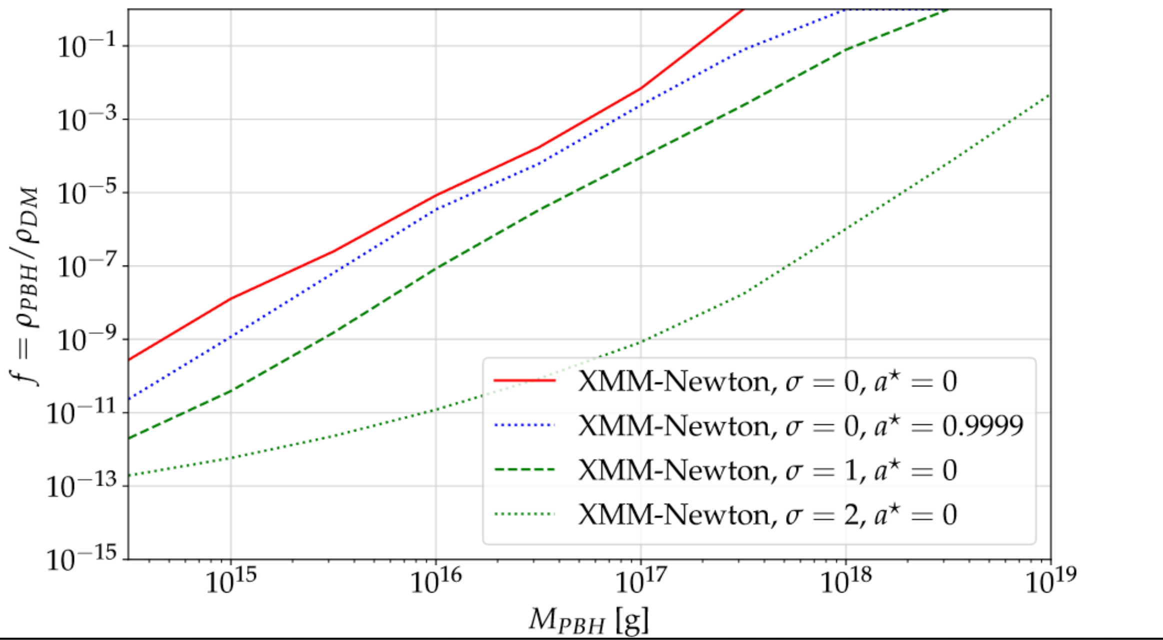
Non-rotating BHs

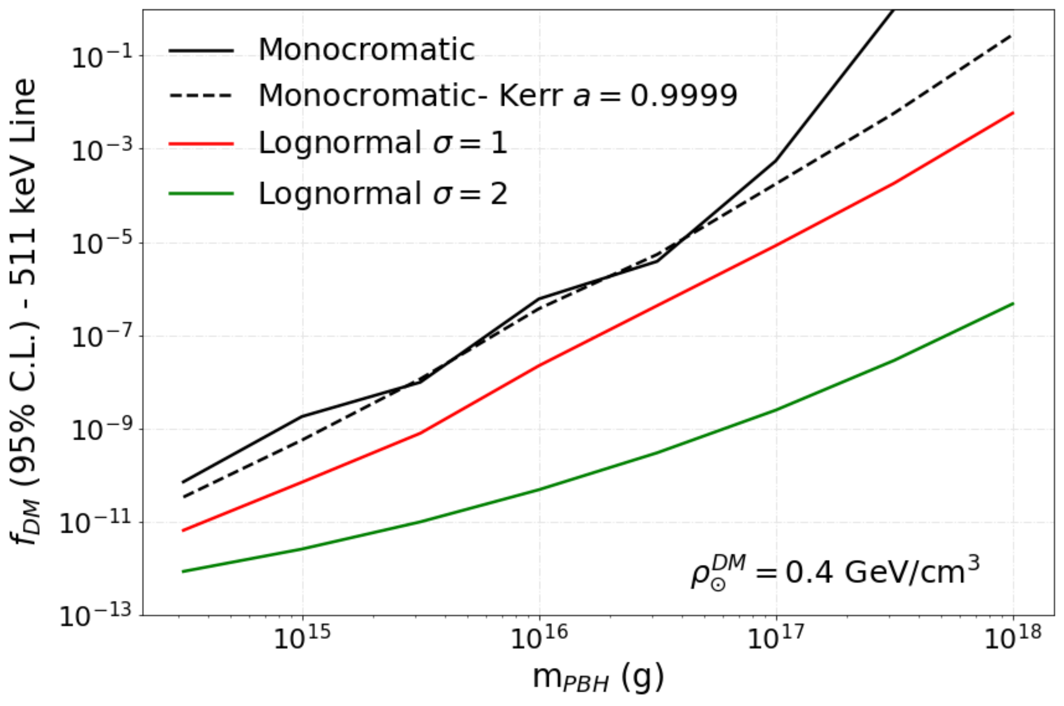
$$T = 1/(8\pi M)$$

Mass distribution of PBHs

$$\frac{dN_{\rm PBH}}{dM} = \frac{1}{\sqrt{2\pi}\sigma M}\exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

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





In-flight positron annihilation emission from PBHs

Our first calculations suggest that the limits obtain for low PBH masses would improve those from the 511 keV line when including the gamma-ray background