An Excited Dark Matter Solution to the MeV Galactic Anomalies

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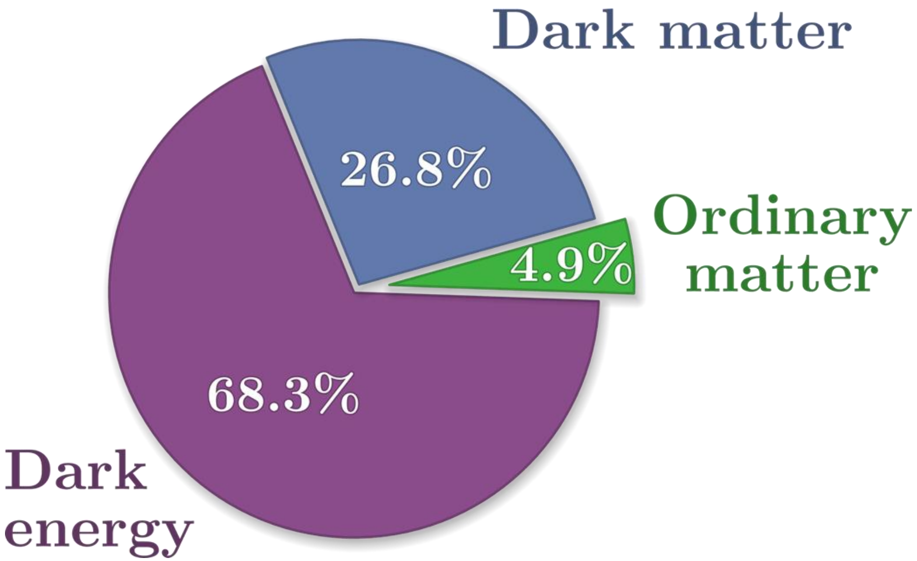
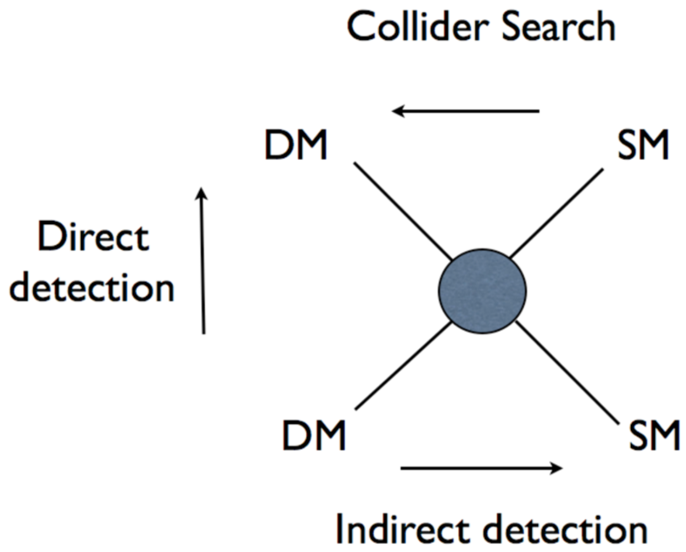
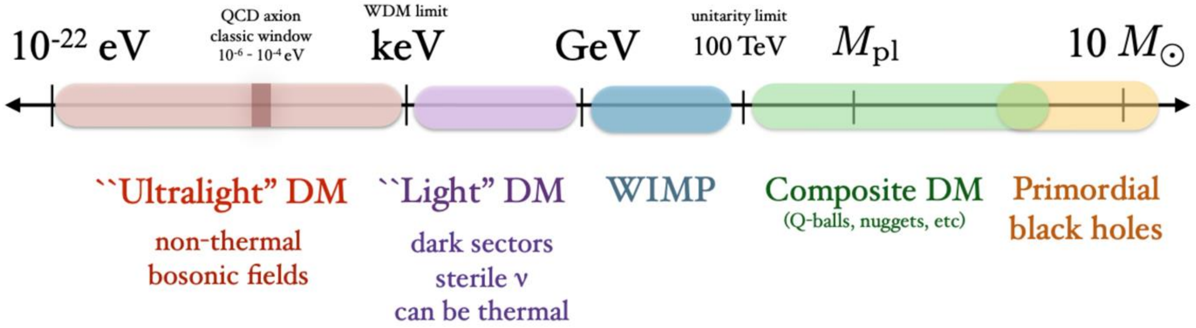
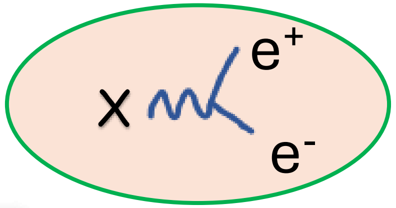
What is dark matter?

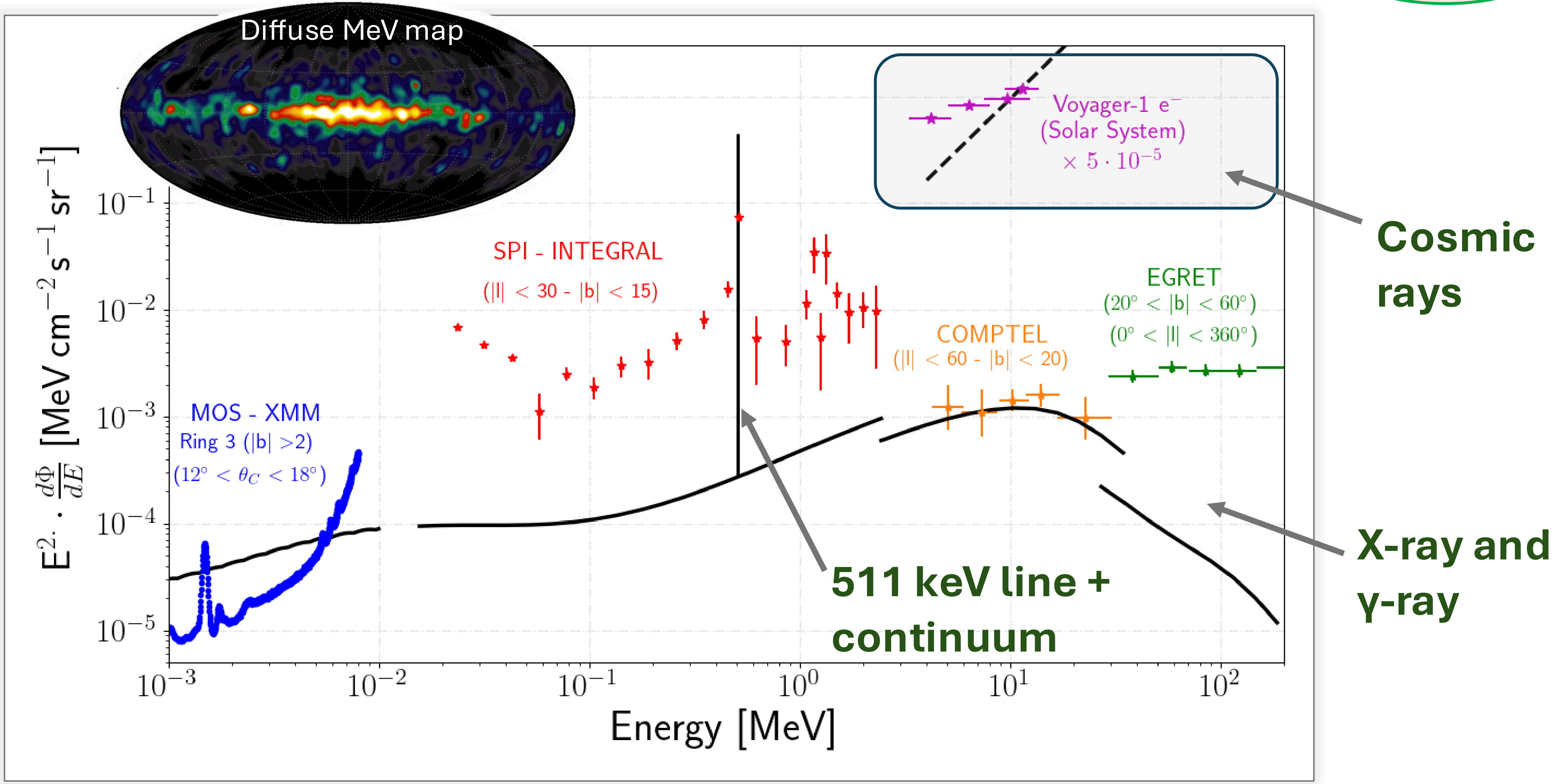






MeV diffuse emission



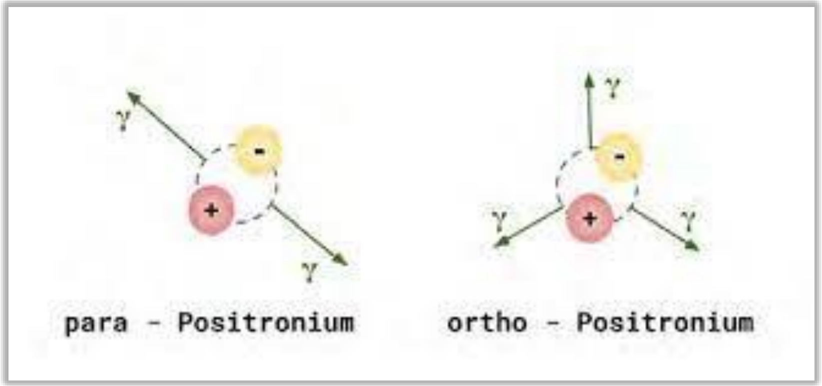


The fate of positrons in the Galaxy

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

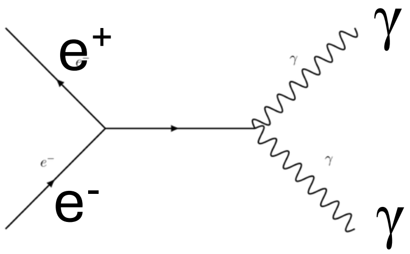


Direct annihilation cross sections:

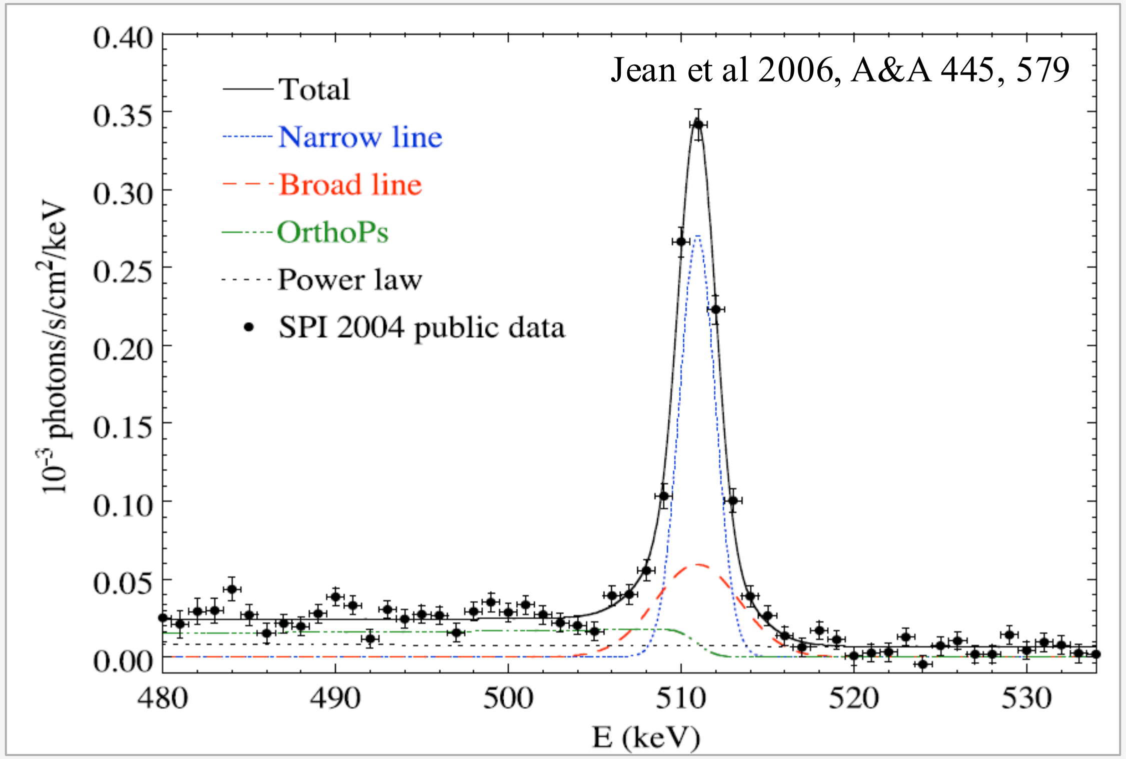
$$\sigma = \frac{\pi r_e^2}{\gamma+1}\left[\frac{\gamma^2+4\gamma+1}{\gamma^2-1}\ln\left(\gamma+\sqrt{\gamma^2-1}\right)-\frac{\gamma+3}{\sqrt{\gamma^2-1}}\right]$$

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

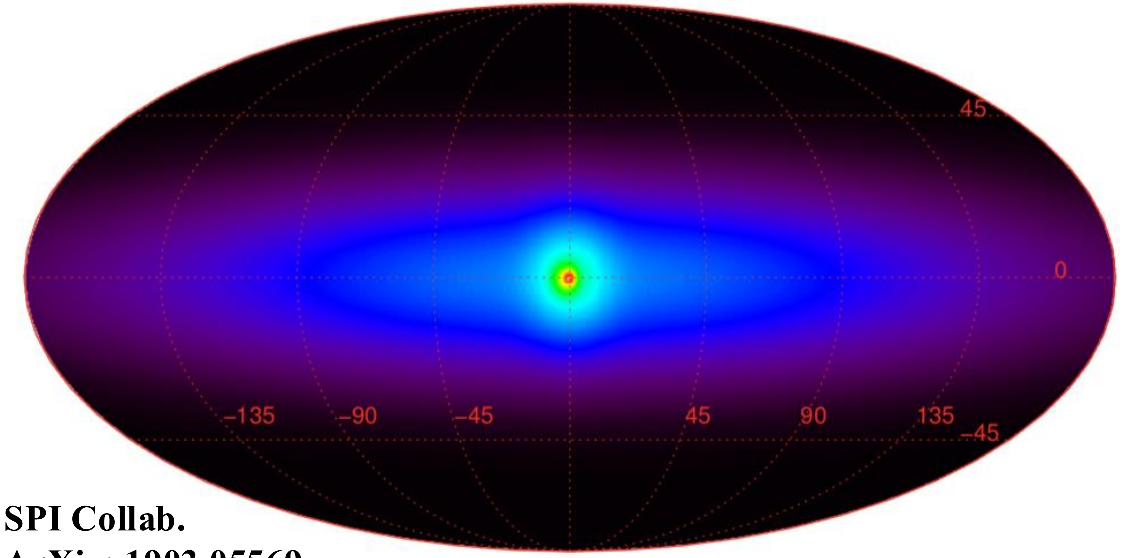
The 511 keV puzzle



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**



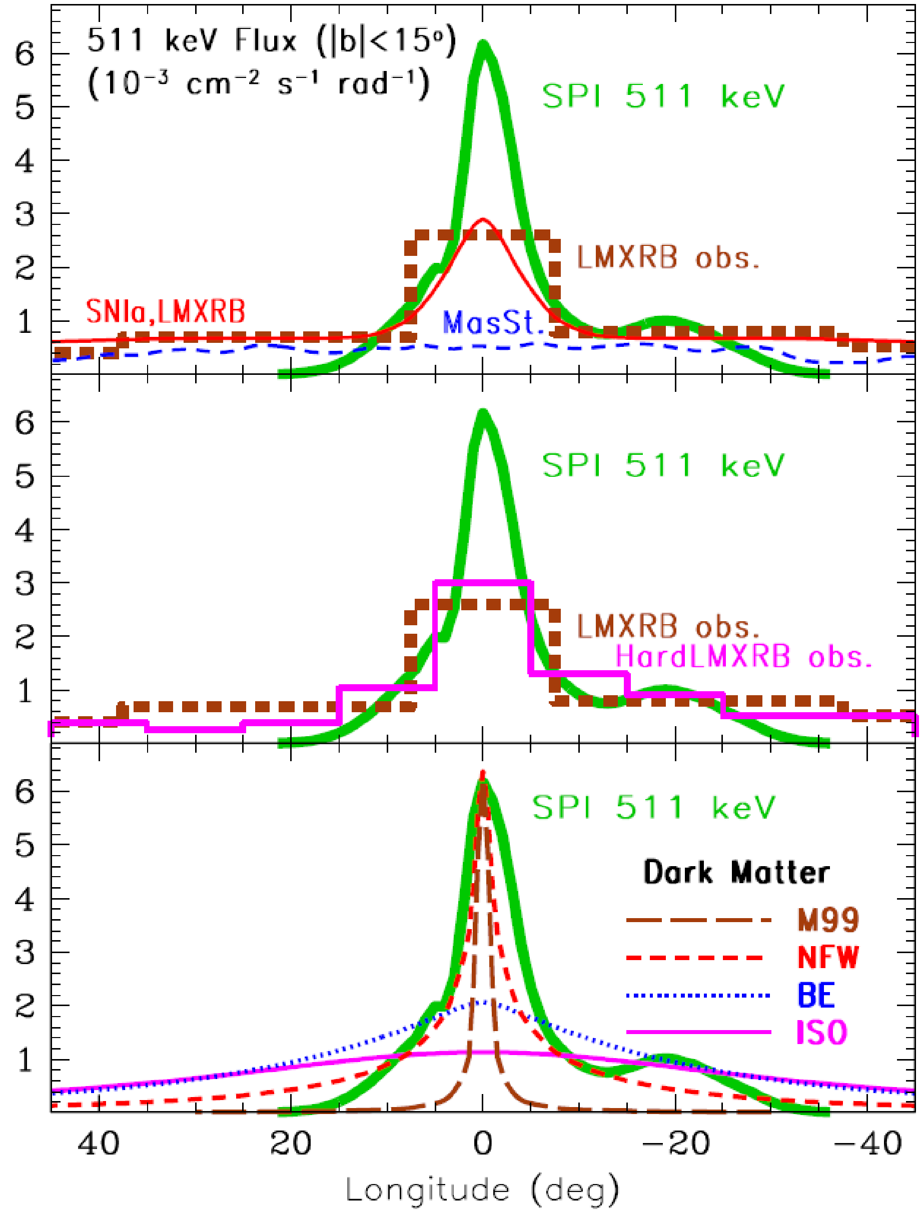
SPI Collab.
ArXiv: 1903.05569

Prantzos et al RevModPhys.83.1001

Possible positron sources

Known sources contributing to 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

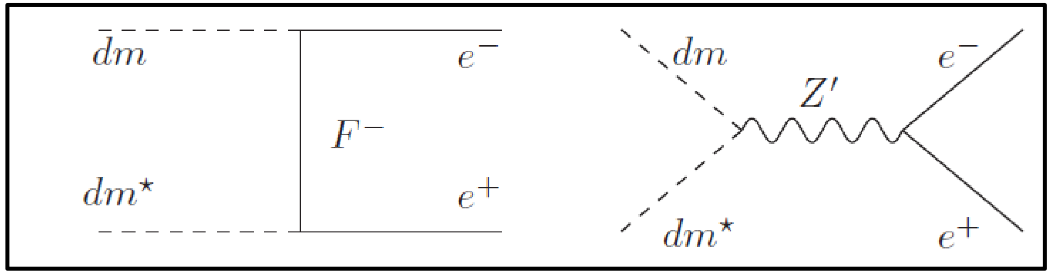


Possible positron sources

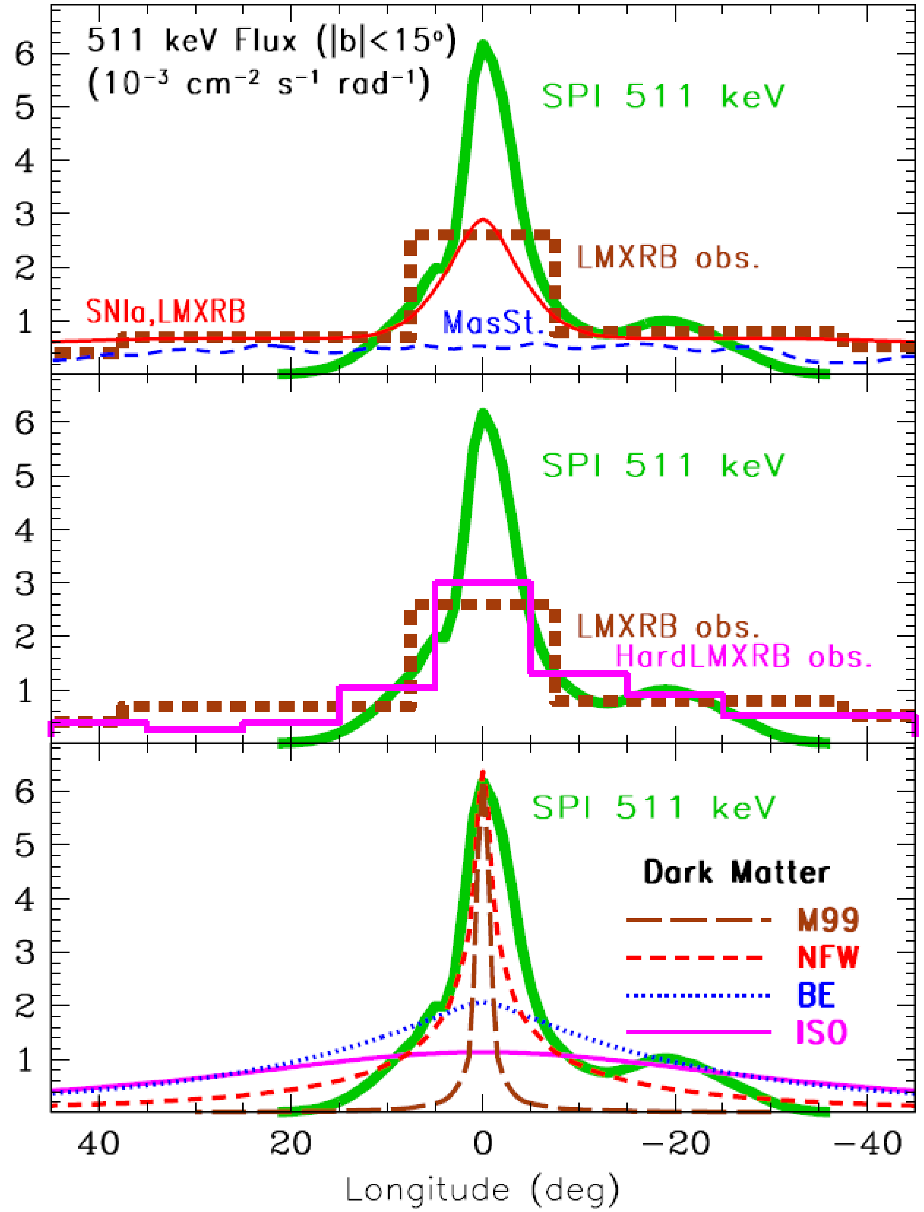
Sub-GeV DM (≤ hundreds MeV) was a possible solution considered by C. Boehm, A. Vincent and others

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

Thermal Sub-GeV DM is strongly constrained and marginal with BBN constraints for $m_\chi \gtrsim 10$ MeV (Boehm et al) or $m_\chi \gtrsim 1$ MeV (M. Escudero et al)



C. Boehm and P. Fayet



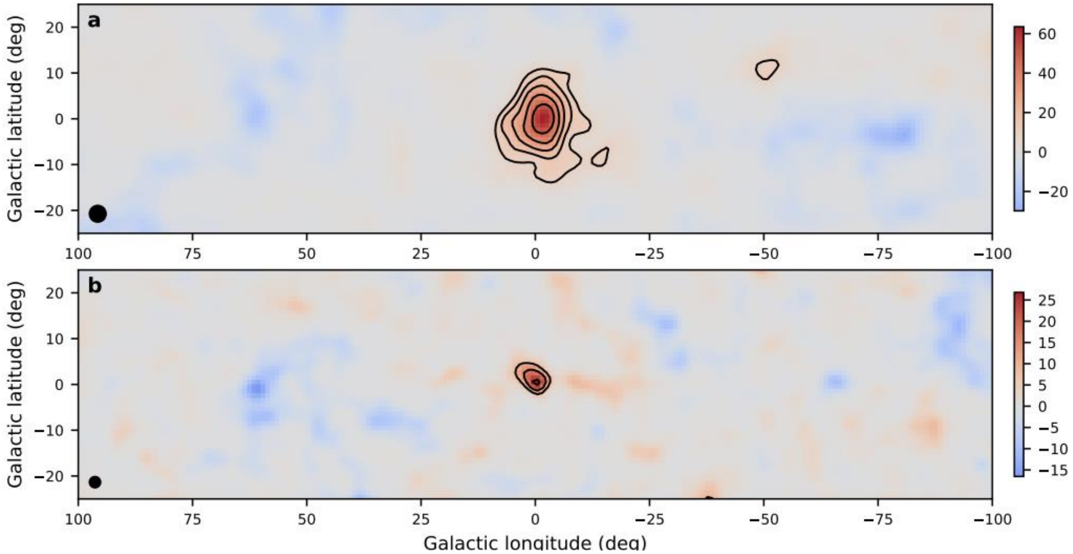
2 MeV In-flight Annihilation Excess

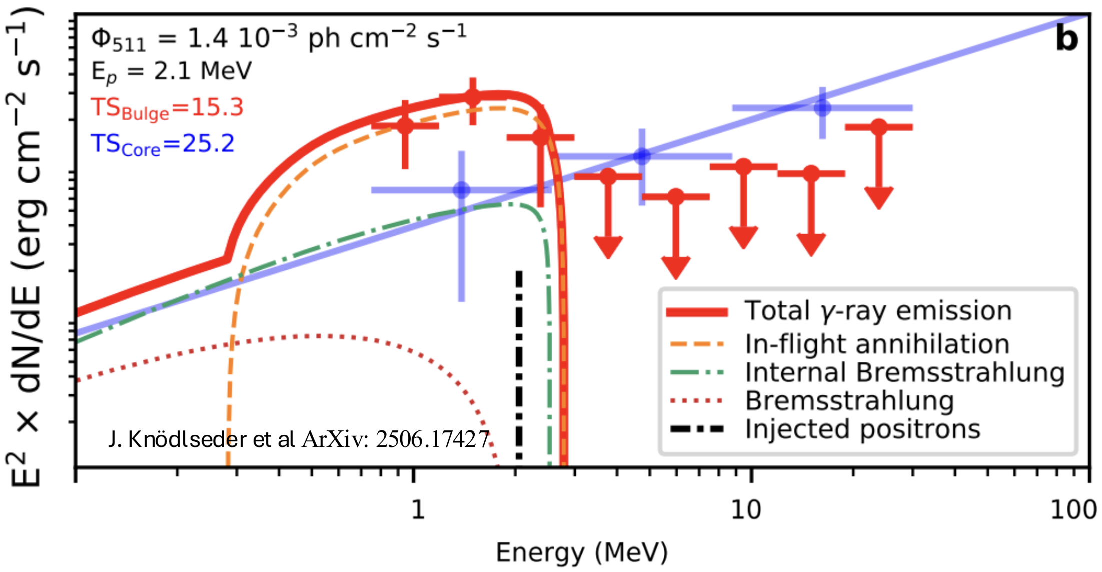
•2 MeV in-flight annihilation (IfA) bump was recently identified in COMPTEL MeV continuum data

•Top: Test statistic (TS) maps in the [0.75,3] MeV (a) and [3,30] MeV (b) energy bands. The significance, expressed in Gaussian terms, corresponds to ~√TS

• Bottom: Expected γ-ray spectra for positron emission (red lines), including contributions from IfA (dashed orange lines), and other radiative processes

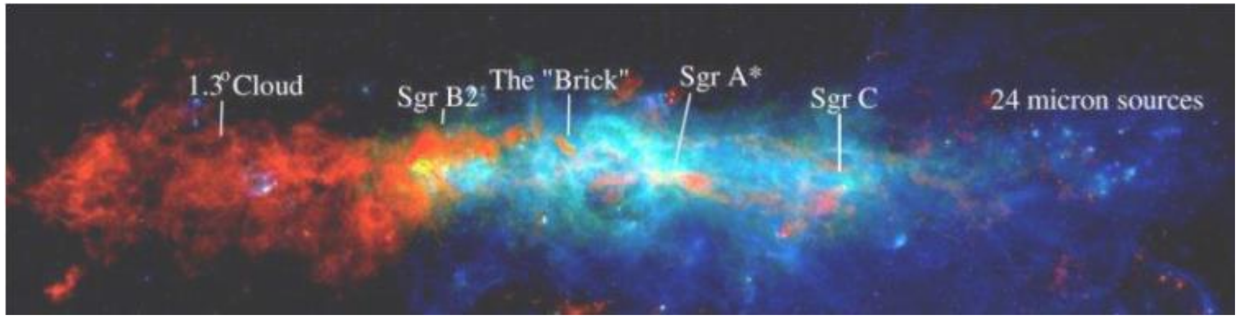
• Corresponds to a high significance excess favouring monochromatic ~2 MeV positron injection, 2 MeV thermal DM is excluded by BBN, very hard to fit a known source to this kind of injection



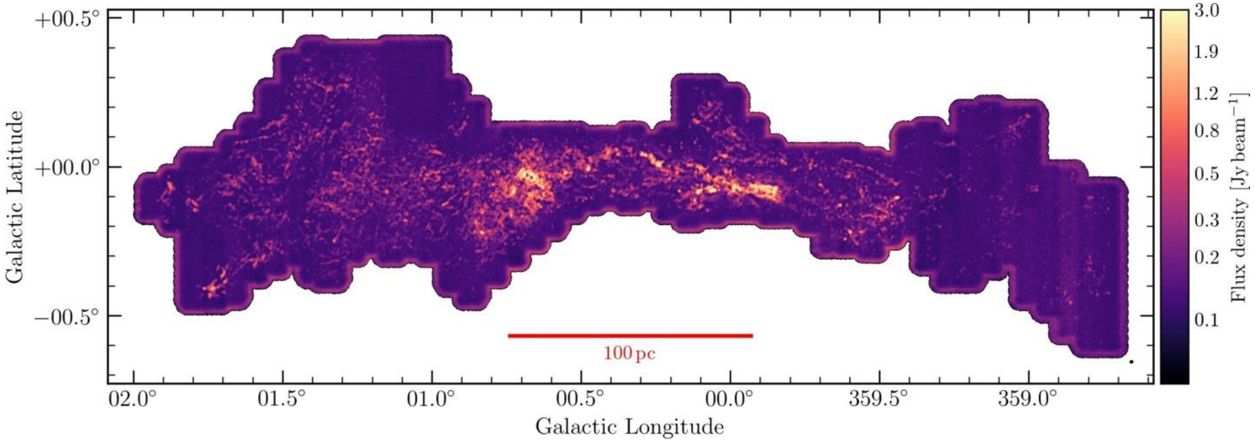


CMZ ionisation

- The CMZ is the innermost region of the Milky Way's spanning **~200–300 parsecs** around the GC
- Contains a dense concentration of molecular gas, with densities **10–100 times higher** than those in typical molecular clouds in the Galactic disk.
- Highly dynamic environment with extreme turbulence, strong magnetic fields, and intense radiation fields.
- A site of active star formation
- The CMZ provides a unique laboratory for studying astrophysical processes under extreme conditions.



J. D. Henshaw et al. Molecular gas kinematics within the central 250 pc of the Milky Way, *Monthly Notices of the Royal Astronomical Society* (2016)

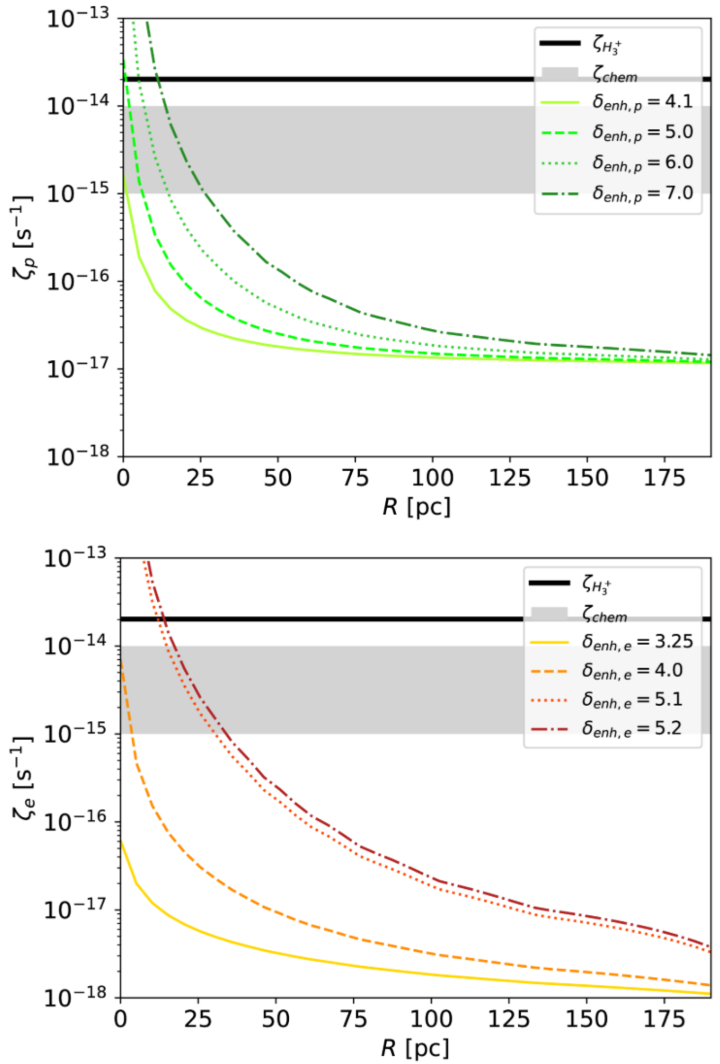


Flux intensity map of the CMZ by the Australia Telescope Compact Array observed from spectral lines in Galactic coordinates, revealing the distribution of dense molecular gas.

What could be causing it?

- This high ionisation rate is driven by several factors:
    - **CRs (default assumption)**: Supernovae and other high-energy processes near the Galactic Centre.
    - **X-rays and UV radiation**: Intense radiation from young, massive stars and accretion processes around Sgr A*.
    - **Turbulence and shocks (hard to model)**: Strong turbulence and shock waves in the CMZ

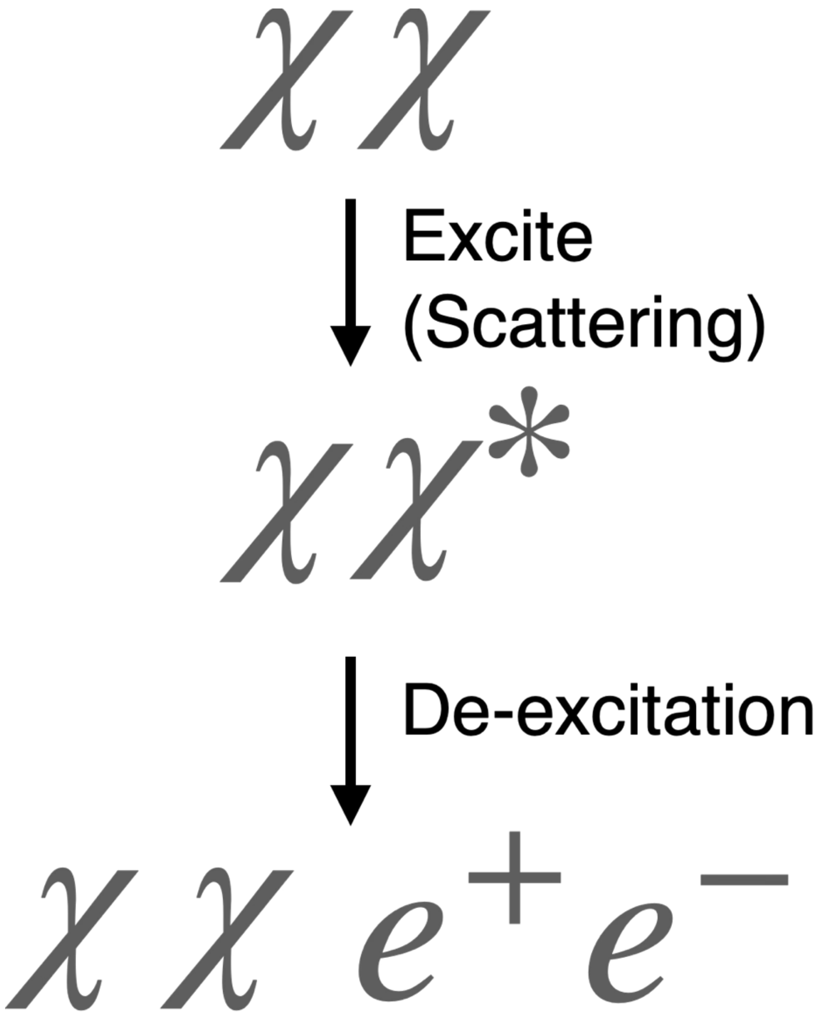
- **However recent work does NOT favour a CR explanation** (S. Ravikularaman et al. ArXiv:2406.1526)
    - The observed CR flux in the CMZ, inferred from gamma-ray data (e.g., Fermi-LAT), is **not high enough** to fully explain the extreme ionisation rates observed.
    - The distribution of CR-induced ionisation does not easily match the observed spatial variation (flat radial profile) of ionisation rates in the CMZ.
    - The energy required to sustain the observed ionisation rates exceeds what is expected from CRs alone, especially given the relatively low CR density in the CMZ compared to other regions like supernova remnants.



CR proton (top) and electron (bottom) ionisation rates averaged over lines of sight at different projected distances R from the GC. Where δ represents different spectral indices used in their analysis (taken from S. Ravikularaman et al. ArXiv:2406.1526)

Excited Dark Matter (XDM) and the GC Excesses

- Heavier state χ^* ($m_{\chi^*} = m_\chi + \delta m_\chi$) is formed via a non-perturbative transition via ground state $\chi\chi$ inelastic scattering mediated by a light boson.
- At low velocities, Sommerfeld enhancement and formation of quasi bound-state resonances become important, regime leads to simple geometric cross section scaling $\sigma_{mr} \sim 1/m_\varphi^2$.
- De-excitation injects electrons/positrons of energy $\delta m_\chi/2$ energy
- DM needs enough velocity to get excited → depends on velocity dispersion → **radially dependent!**
- Proposed by Proposed by Finkbeiner and Weiner (2007) then most recently by Vincent et al (2023) for 511 keV morphology when $\delta m_\chi = 2m_e$, here we will instead set $\delta m_\chi = 4$ MeV to get 2 MeV positron injection and include CR propagation!
- Can XDM explain the 3 excesses with the standard NFW?



XDM Velocity Dependence

- The upscattering process $\chi\chi \to \chi\chi^*$ is kinematically allowed only if the relative velocity exceeds a threshold

$$v_{\rm th} = \sqrt{\frac{4\,\Delta m}{m_\chi}}$$

- This velocity "gate" distinguishes XDM from standard annihilation models. Conventional annihilation scales as $\rho_\chi^2(r)$ the XDM positron production rate acquires an additional exponential cutoff from the velocity distribution,

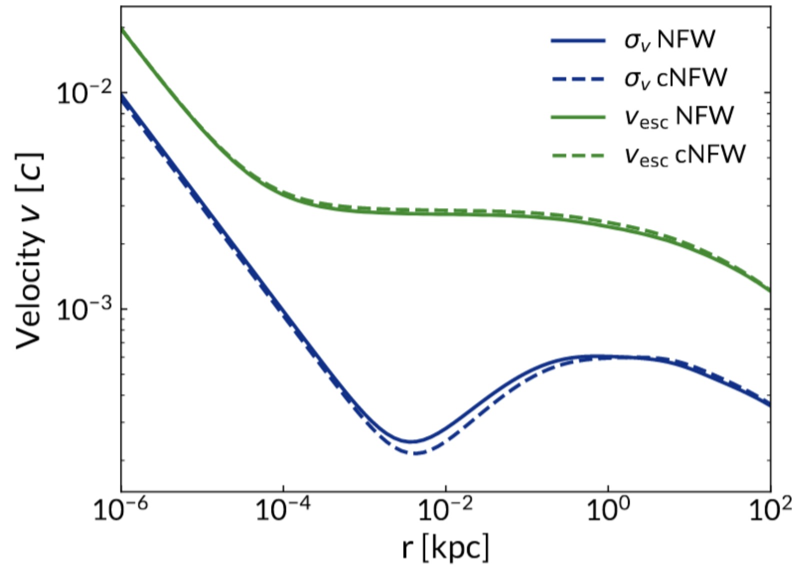
$$R_{e^+}(r) \propto \rho_\chi^2(r) \exp\left[-\frac{v_{\rm th}^2}{4\sigma_v^2(r)}\right],$$

- At the microscopic level, we parameterize the inelastic upscattering cross section as Cappiello et al 2024,where σ_{mr} sets the normalization of the inelastic scattering cross section in the moderately relativistic limit.

XDM Source Term

- Positron injection per unit volume (source terms) can be put into a Galactic CR solver like DRAGON2

$$Q_{e^+}(r, E_e) = \frac{\rho_\chi^2(r)}{2m_\chi^2} \langle \sigma v \rangle (r) \frac{dN}{dE}(E_e)\,,$$



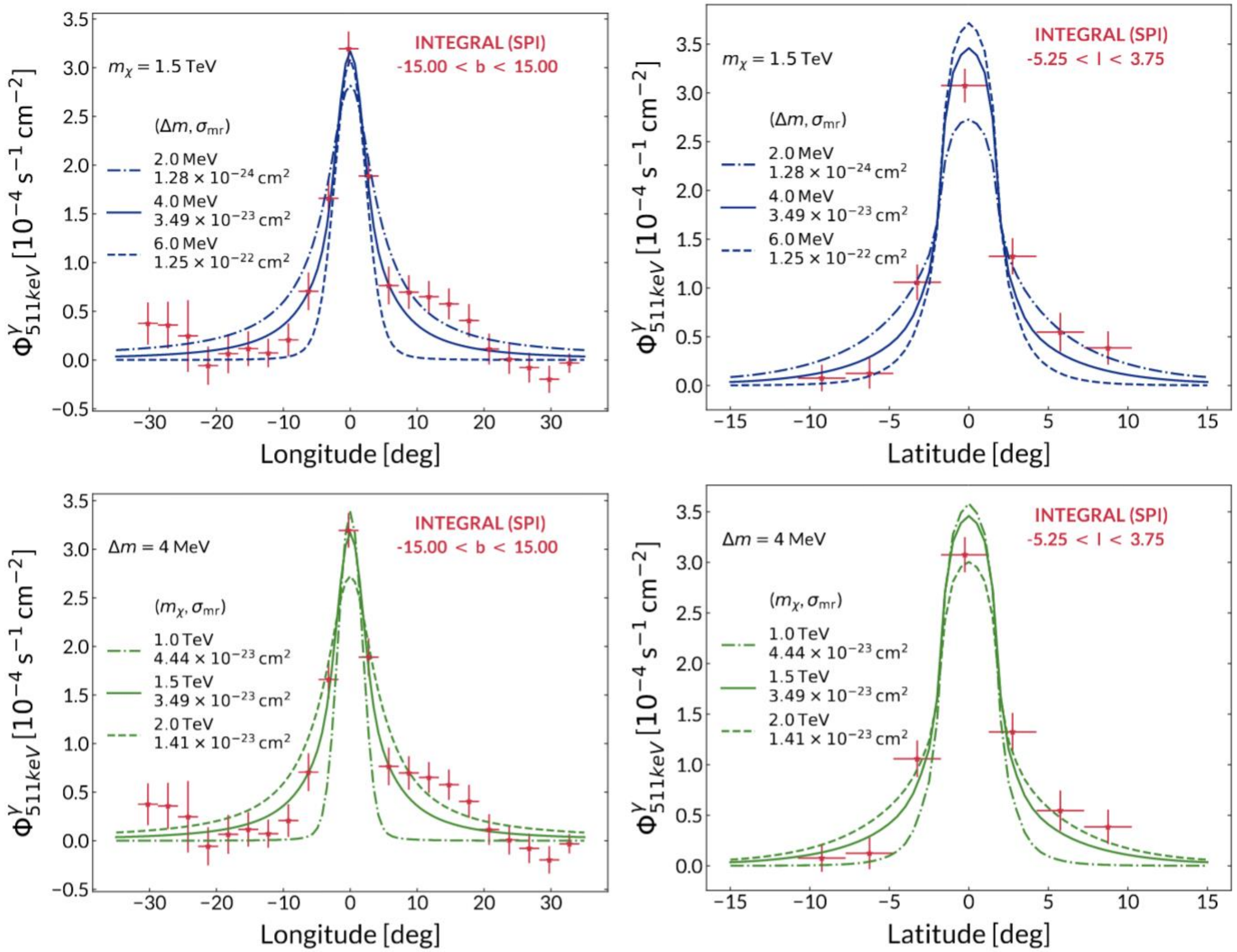
SB, Damon Cleaver, Pedro De la Torre Luque, ArXiv: 2512.13797

- The velocity averaged excitation rate coefficient is given by

$$\langle \sigma v \rangle = \sigma_{\rm mr} 2\pi \left(\frac{1}{N_{esc}} \frac{1}{(2\pi\sigma_v^2)^{3/2}} \right)^2$$

$$\times \int_{v_{\rm th}}^{2v_{\rm esc}} {\rm d}v_{\rm rel}\, v_{\rm rel} \sqrt{v_{\rm rel}^2 - v_{\rm th}^2}\, e^{-\frac{2v_{\rm esc}^2 + v_{\rm rel}^2}{2\sigma_v^2}} \sigma_v^3 \left[2\sigma_v \left(e^{\frac{v_{\rm rel}^2}{2\sigma_v^2}} - e^{\frac{v_{\rm esc} v_{\rm rel}}{2\sigma_v^2}}\right) + \sqrt{\pi} v_{\rm rel} e^{\frac{4v_{\rm esc}^2 + v_{\rm rel}^2}{4\sigma_v^2}} {\rm erf}\left(\frac{2v_{\rm esc} - v_{\rm rel}}{2\sigma_v} \right) \right],$$

XDM Results (from a χ^2-fit to 511 keV line)



SB, Damon Cleaver, Pedro De la Torre Luque, ArXiv: 2512.13797

511 keV longitude profiles (left panels) and latitude profiles (right panels) for XDM models compared to INTEGRAL/SPI data (red points). Top: fixed $m_\chi = 1.5$ TeV and varying mass splitting δm. Bottom: fixed δm and varying m_χ

XDM in-flight annihilation

•We have the source term so we have all the machinery to compute the 511 keV line and CMZ ionization as before, we also need to compute the IfA signal as the final piece given from the seminal result by Beacom, Bell & Bertone 2005 and Beacom & Yuksel 2006

$$\frac{d\Phi^{\mathrm{IfA}}}{d\Omega\, dE_\gamma} = \frac{d\Phi^{511}}{d\Omega} \frac{n_H}{P(1-\frac{3}{4}f_{\mathrm{Ps}})} \times \int_{E_\gamma=m_e/2}^{E_{\mathrm{max}}} dE' \frac{1}{N_{\mathrm{pos}}} \frac{dN_{\mathrm{pos}}}{dE'} \times \int_{m_e}^{E'} P_{E'\to E} \frac{d\sigma}{dE_\gamma} \frac{dE}{|dE/dx|},$$

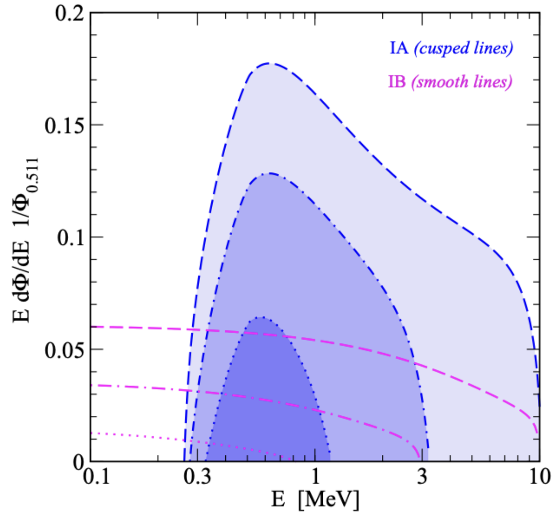
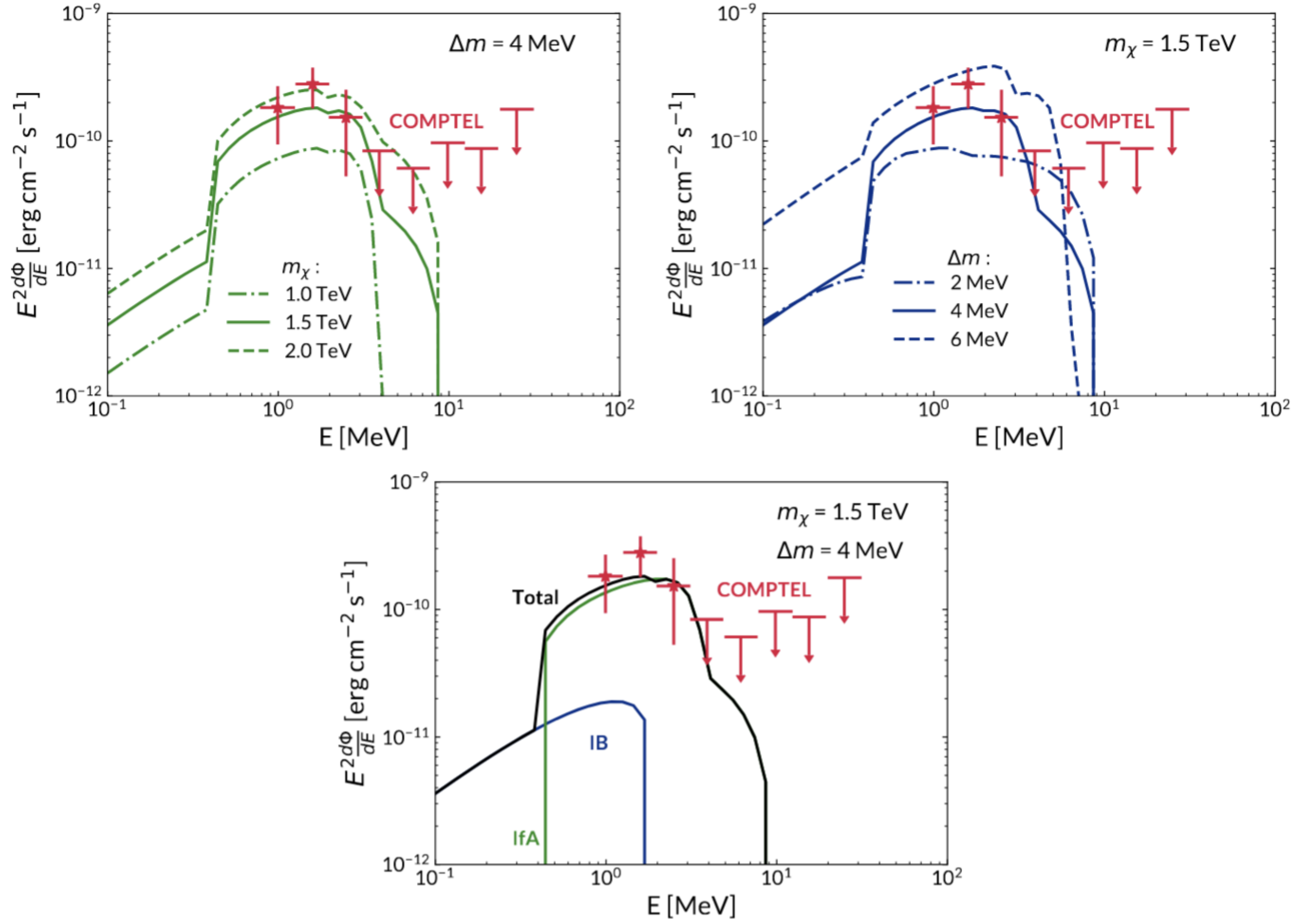


FIG. 1: Gamma-ray spectra (cusped lines, inflight annihilation; smooth lines, internal bremsstrahlung) from relativistic positrons, normalized to the 0.511 MeV flux; the injection energies are 1, 3, and 10 MeV (dotted, dot-dashed and dashed).

•where the first integral over E' accounts for the propagated positron energy distribution, bounded between E_{max} (the maximum steady-state energy) and $m_e/2$. The hydrogen density n_H sets the number of target electrons, $P_{E'\to E}$ is the probability for a positron to produce a photon before cooling from E' to E and $P = P_{E'\to m_e}$ is the total probability to emit a photon before reaching thermal energies.

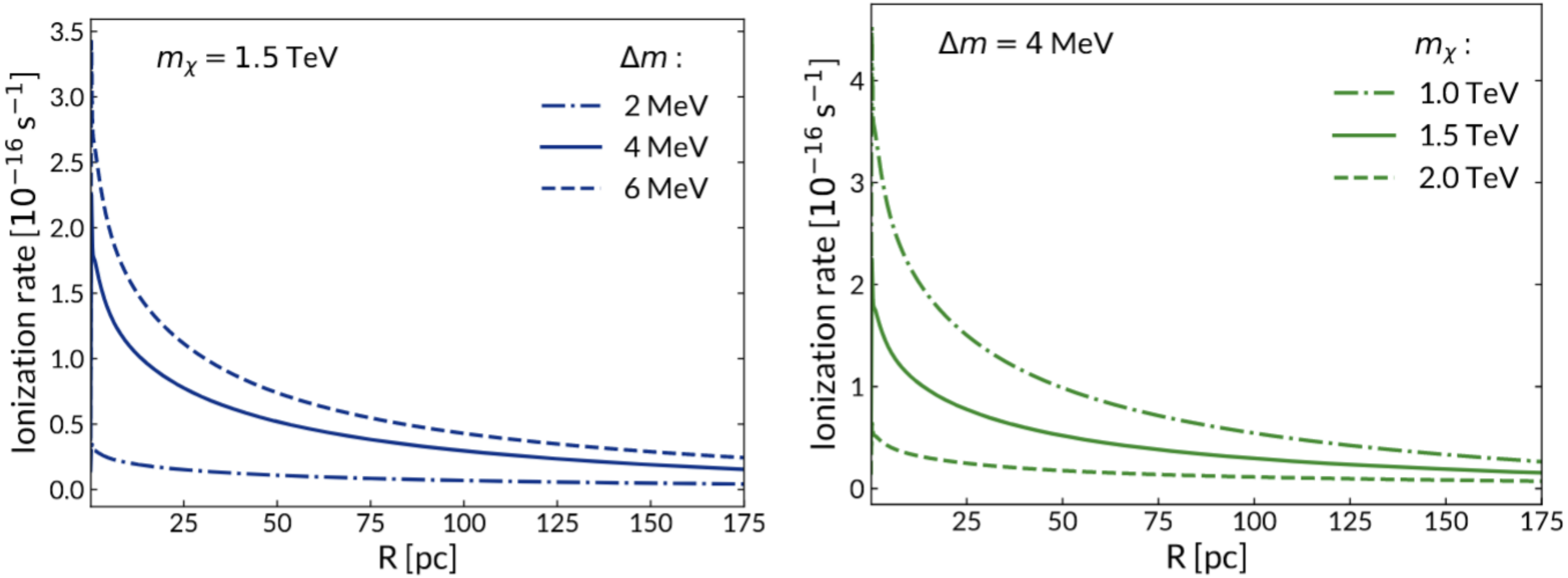
XDM Results (IfA flux)



SB, Damon Cleaver, Pedro De la Torre Luque, ArXiv: 2512.13797

Top Left: COMPTEL IfA spectrum in the bulge region (red points) compared to XDM fits from previous page. Bottom: Decomposition of the XDM signal for $m_\chi = 1.5$ TeV and $\delta m = 4$ MeV into internal bremsstrahlung (IB, blue) and in-flight annihilation (IfA, green). The sum (black) is compared to COMPTEL data.

XDM Results (CMZ Ionization)



SB, Damon Cleaver, Pedro De la Torre Luque, ArXiv: 2512.13797

•Radial profile of the H_2 ionization rate in the CMZ for XDM models as a function of cylindrical distance R from the GC. For the same best fits show previously and an NFW profile

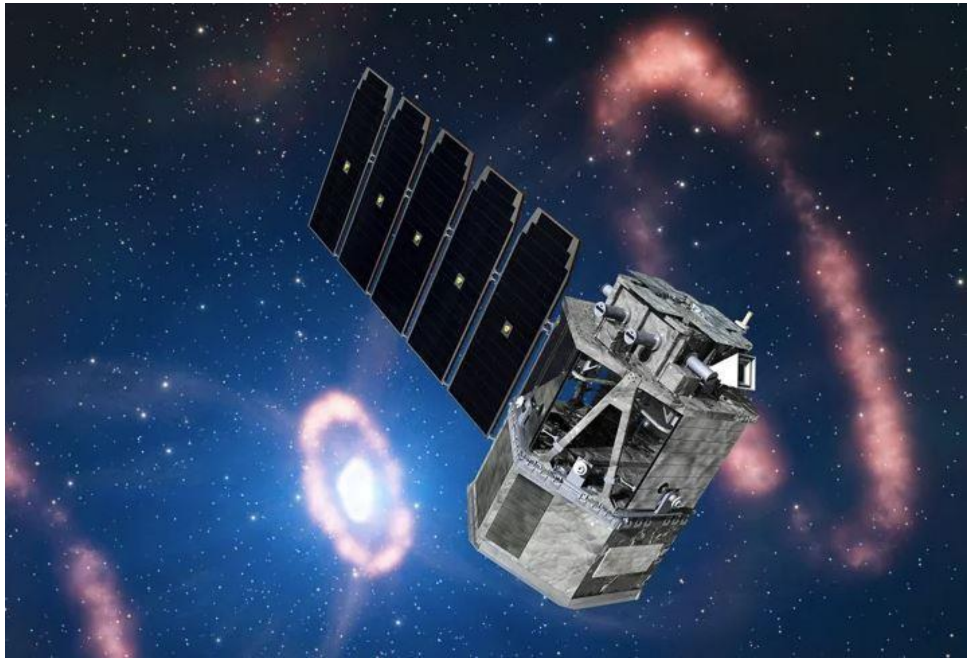
What next?

•**More precise ionisation maps** of the CMZ could reveal or exclude patterns matching DM density.

•**Low-energy CR constraints** could rule out alternative explanations.

•**Upcoming telescopes** could detect faint secondary gamma-ray signals.

•Looking for **similar effects in other dense galactic environments** could provide additional evidence.

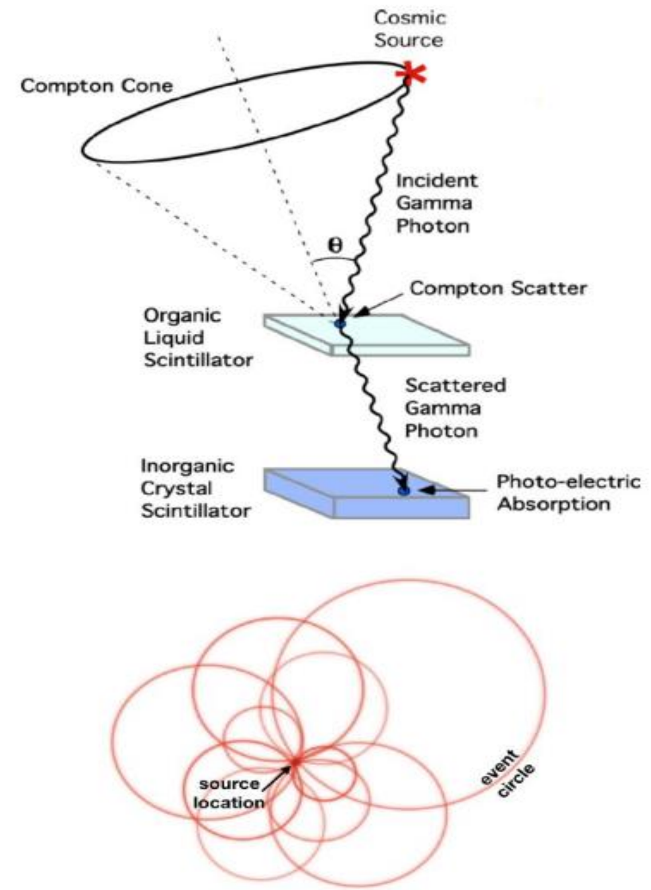


COSI image from NASA

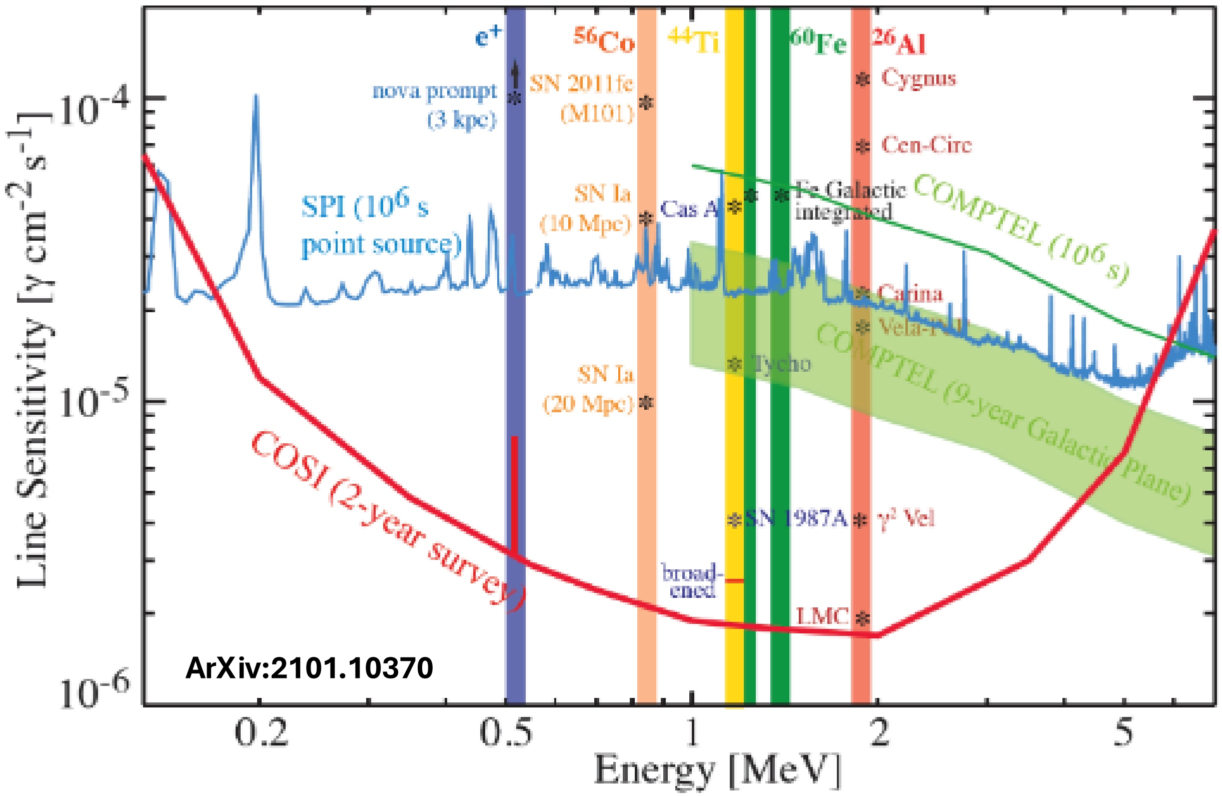
A look into the future

The sensitivity at ~0.1-30 MeV very low compared to adjacent energies (**MeV gap**) due to high instrumental noise and the nature of Compton scattering process

Credit: Nicola Mazziotta (ASAPP talk)



The Compton Spectrometer and Imager (COSI)

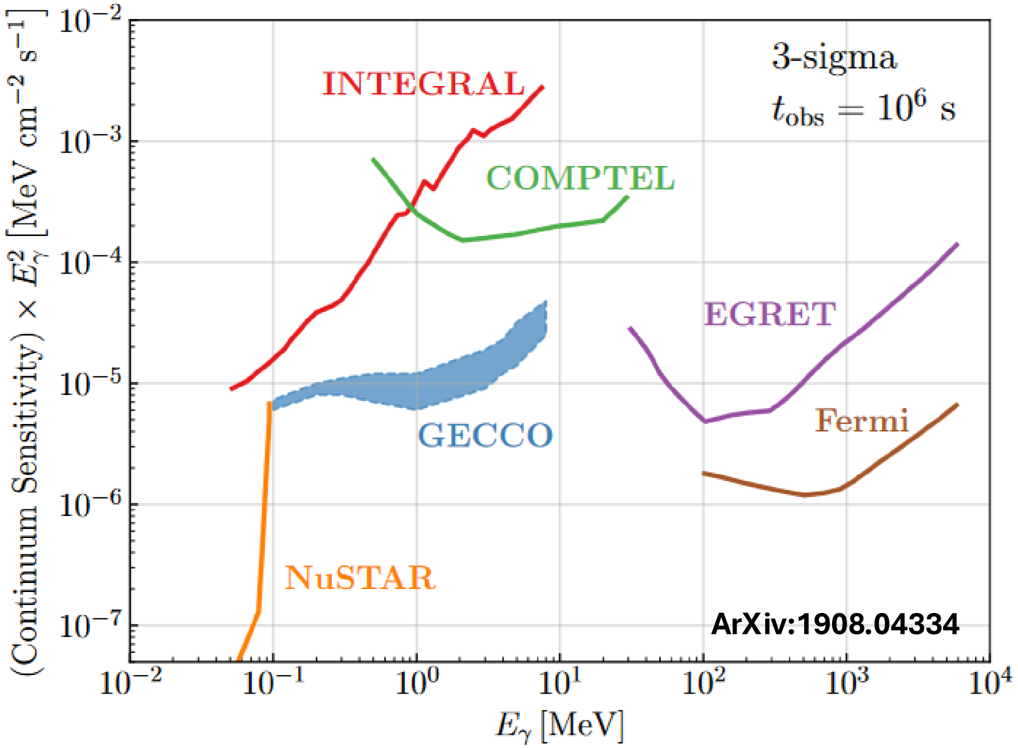


A look into the future

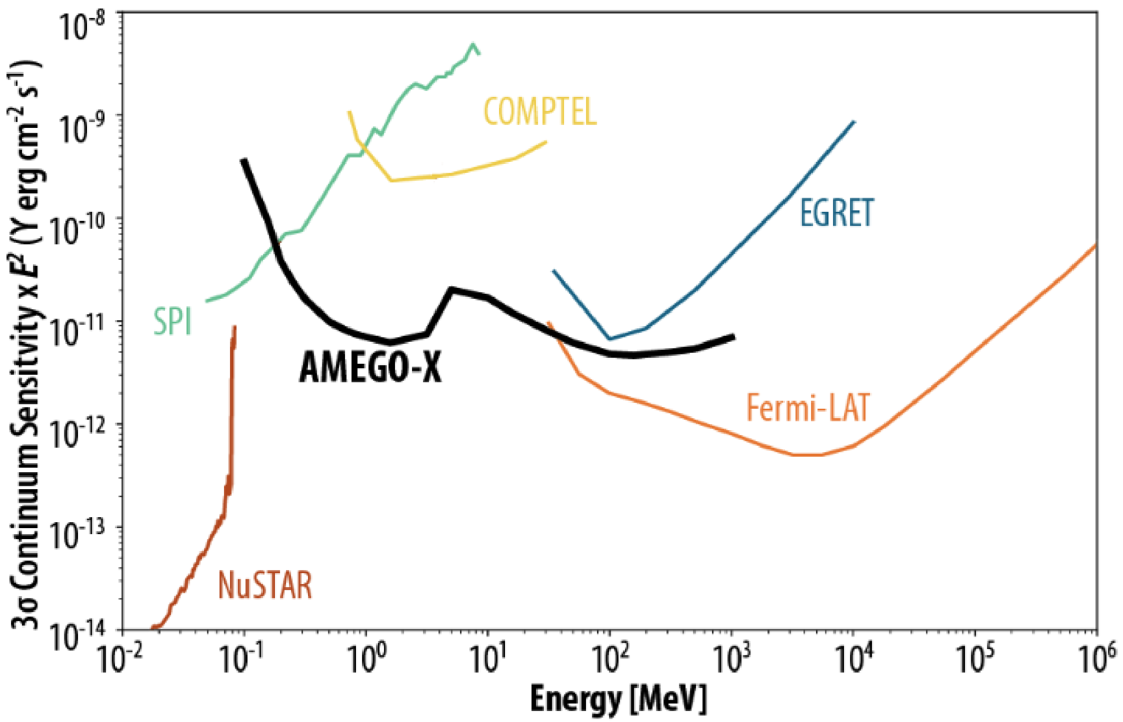
The sensitivity at ~0.1-30 MeV very low compared to adjacent energies (MeV gap) due to high instrumental noise and the nature of Compton scattering process

The need of better measurements at the MeV is manifested by the amount of mission proposals for MeV astronomy. Not only for lines, also for continuum, sources and transients

GECCO



AMEGO



Conclusions

- The hard-X-ray to soft-gamma-ray band (the MeV gap) has a high potential to probe the properties of exotic positron emitters
- XDM provides a remarkably consistent with the 511 keV line even with NFW because of its velocity dependence for a 1.5 TeV DM particle with a mass splitting of 4 MeV
- For the same parameter space that fits the 511 keV line well, we can also explain the ~2 MeV IfA bump consistently
- A good alternative to thermal sub-GeV DM that is very strongly cosmologically constrained
- Recovers a ~flat ionization profile but undershoots observed rate
- Future MeV gap experiments such as COSI will help us target this interesting energy scale

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	

Fits to local CR spectrum

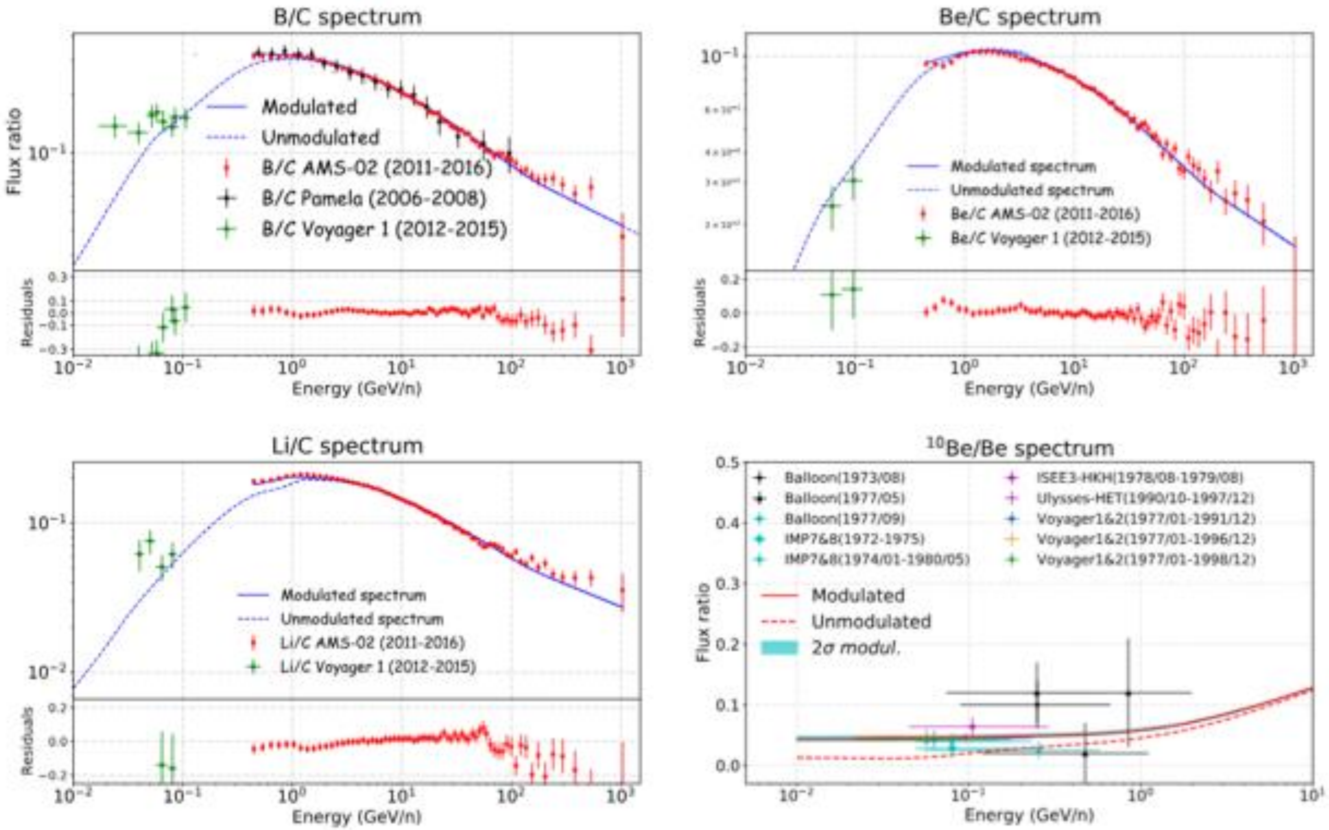


Figure 7. Main CR observables used to determine the propagation parameters employed in this work. AMS-02 data are shown as red markers and Voyager-1 data as green markers.

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Propagation lengths

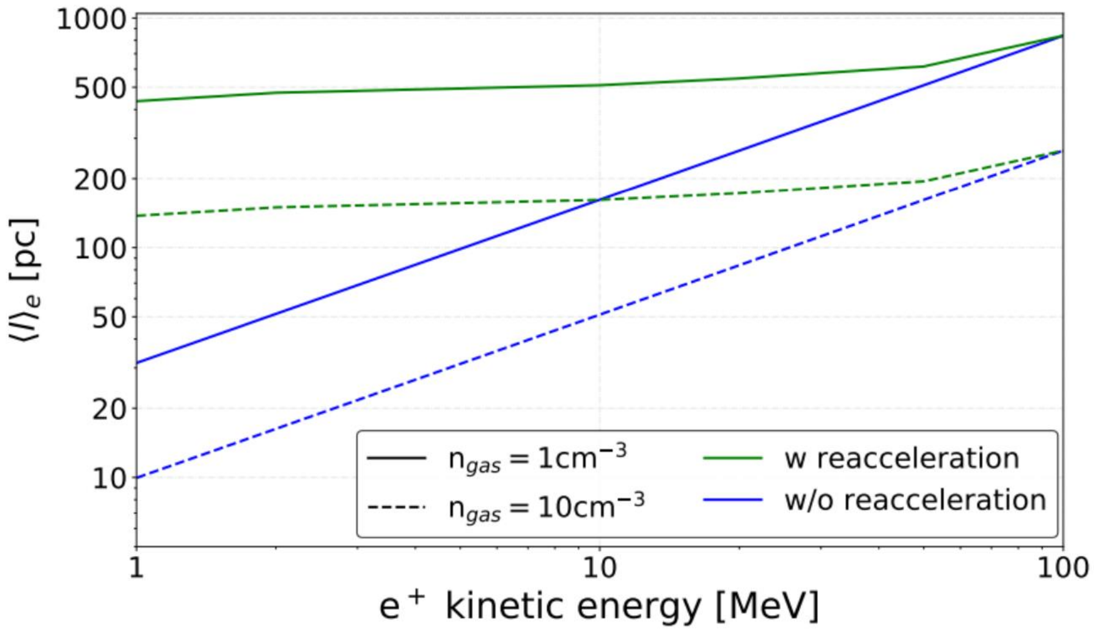


Figure 9. Average distance travelled by positrons in a medium with total density of 1 cm^{-3} (solid lines) and 10 cm^{-3} (dashed lines), assuming 10% of He. The blue lines denote the average distance travelled by positrons without including the effect of reacceleration and the green lines represent a rough estimation of the mean distance travelled by positrons when including the effect of reacceleration.

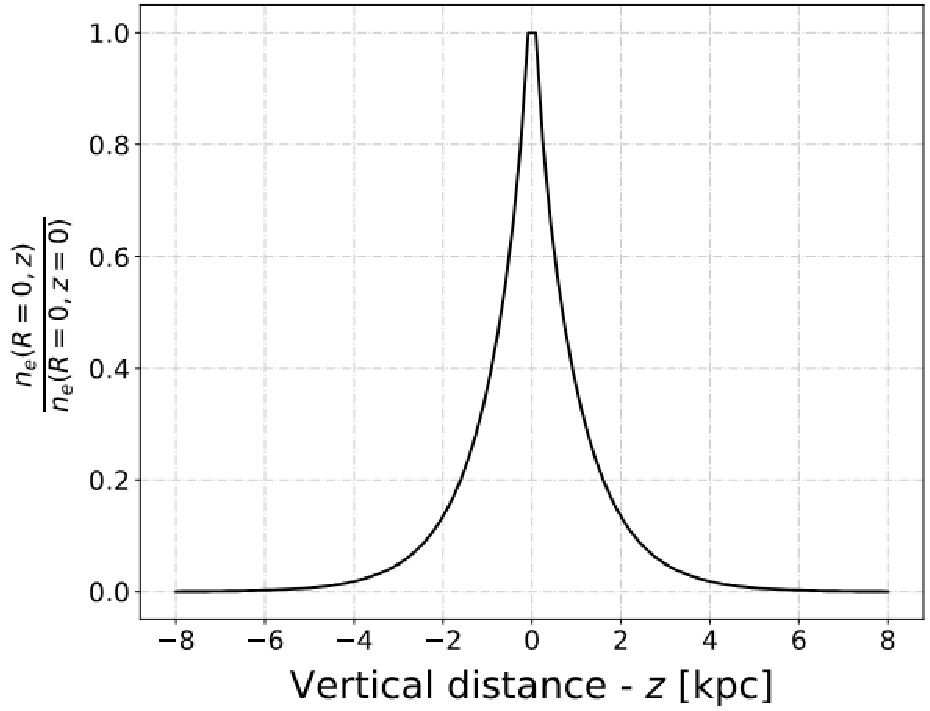
Free electron density dependence

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

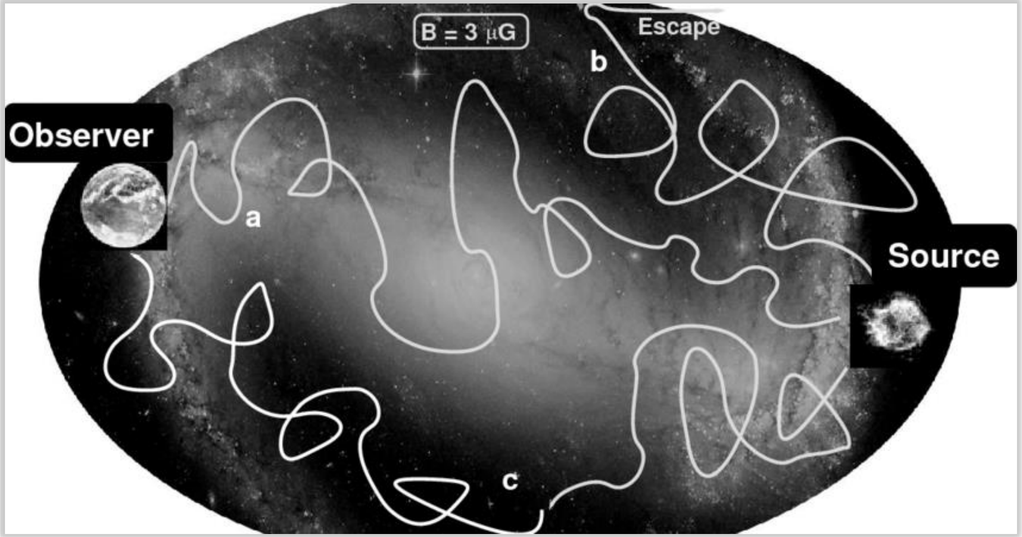
Important for very low DM masses, when the positrons lose energy very fast in the disk



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

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 (with DRAGON2):

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

(Neglecting advection from winds)

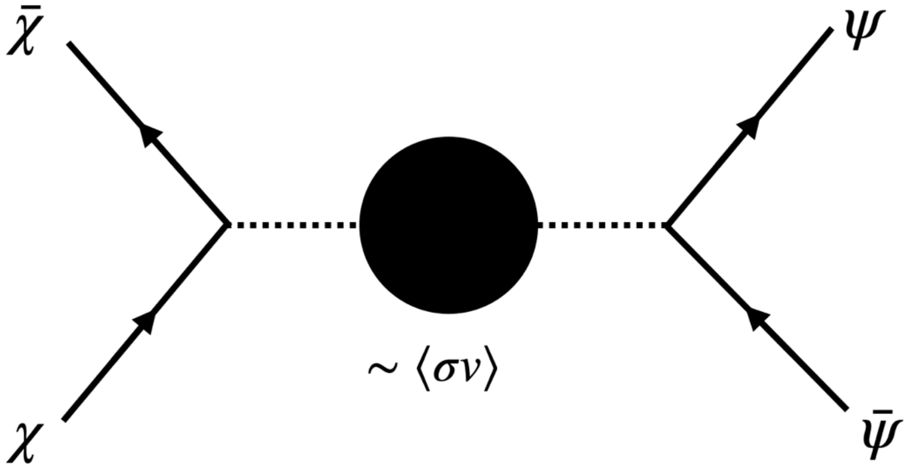
Diffusion ($D \propto E^{\delta}$ -- from CR analyses at E>MeV)

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

Injection (following DM distrib.)

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

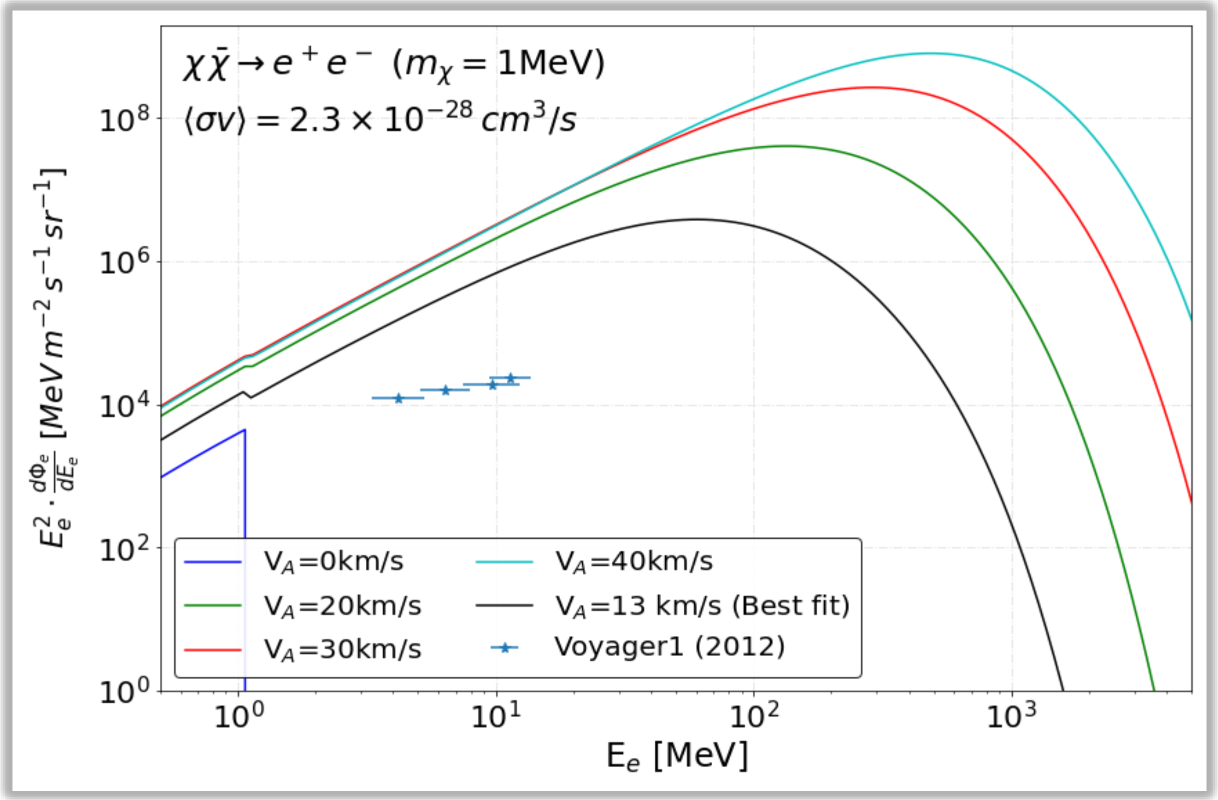
DM source term in the Galaxy



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

Reacceleration effect

Pedro De La Torre Luque, **SB**, 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 sub-GeV e^+e^- signal to higher energies

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

And a fast diffusion setup 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

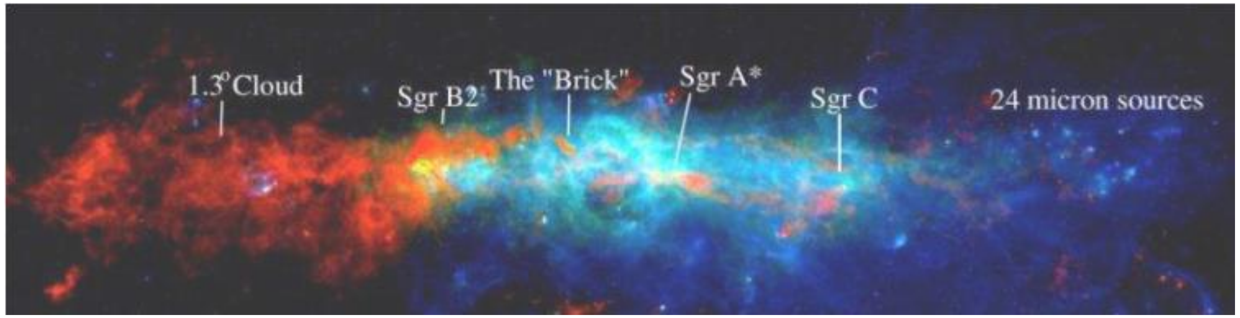
Best fit parameters and uncertainty bands will be shown later in the limit plots

How is it measured?

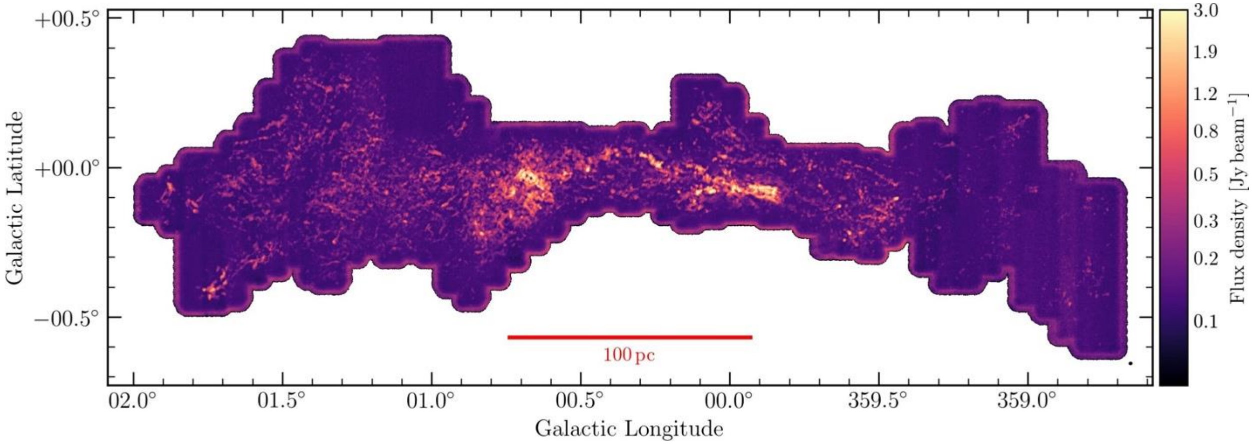
- The ionisation rate in the CMZ is **order(s) of magnitude higher ($\zeta > 10^{-15}s^{-1}$)** → one of the most ionised regions in the Milky Way.

- Ionisation is measured through tracer ions such as H_3^+ (trihydrogen cation) and OH^+.

- H_3^+ is produced by CR ionisation of H_2. Its abundance is directly linked to the ionisation rate.
  - **Infrared spectroscopy** (e.g., H_3^+),
  - **Radio/submillimeter observations** (e.g., HCO^+, N_2H^+),
  - **Gamma-ray and X-ray data** (CRs and high-energy radiation),
  - **Theoretical models** (chemical and cosmic ray propagation).

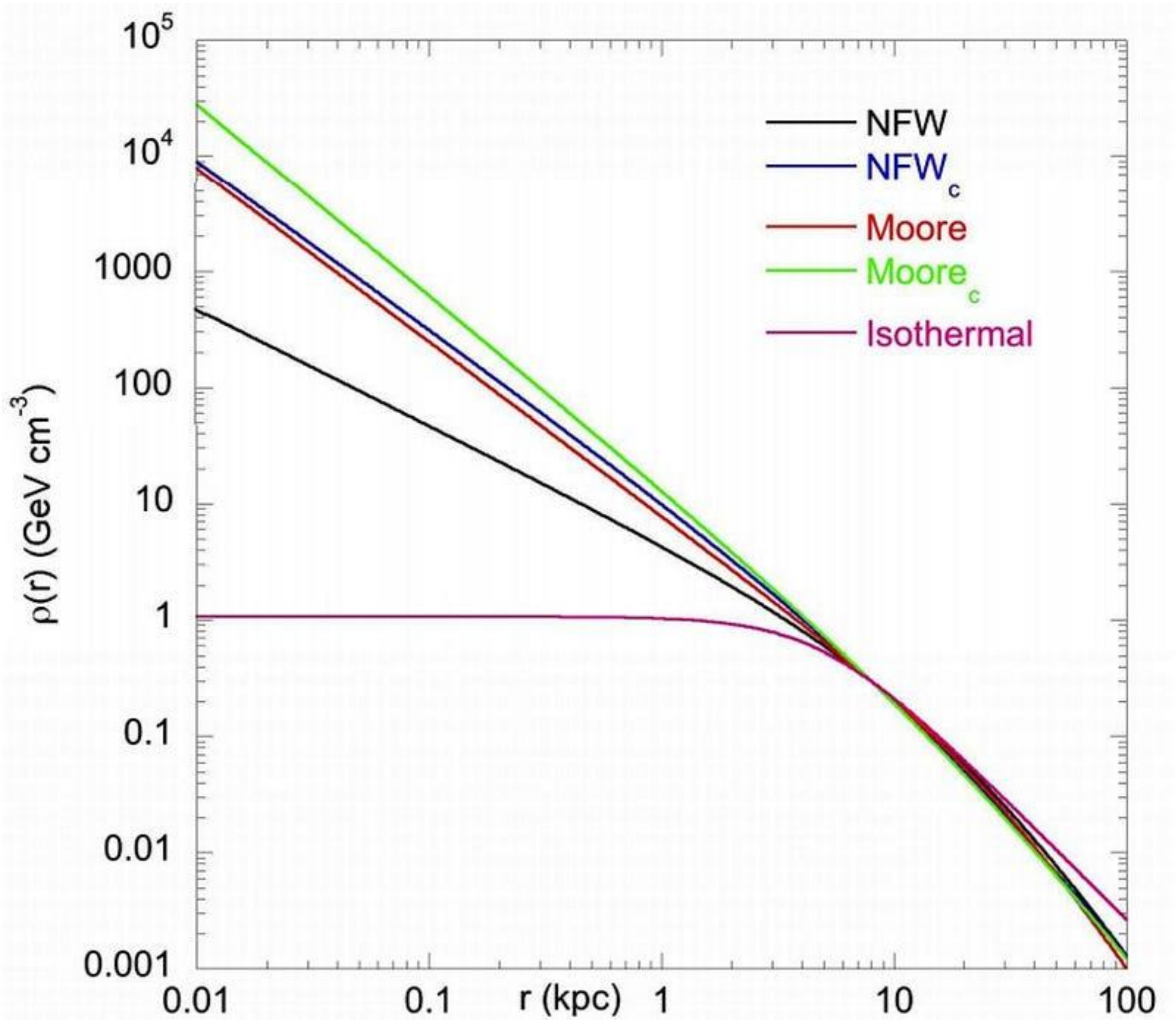


J. D. Henshaw et al. Molecular gas kinematics within the central 250 pc of the Milky Way, *Monthly Notices of the Royal Astronomical Society* (2016)



Flux intensity map of the CMZ by the Australia Telescope Compact Array observed from spectral lines in Galactic coordinates, revealing the distribution of dense molecular gas.

DM profiles



NFW
NFW$_c$
Moore
Moore$_c$
Isothermal
$\rho(r)$ (GeV cm^{-3})
10^5
10^4
1000
100
10
1
0.1
0.01
0.001
0.01
0.1
r (kpc)
1
10
100

XDM (uncertainties)

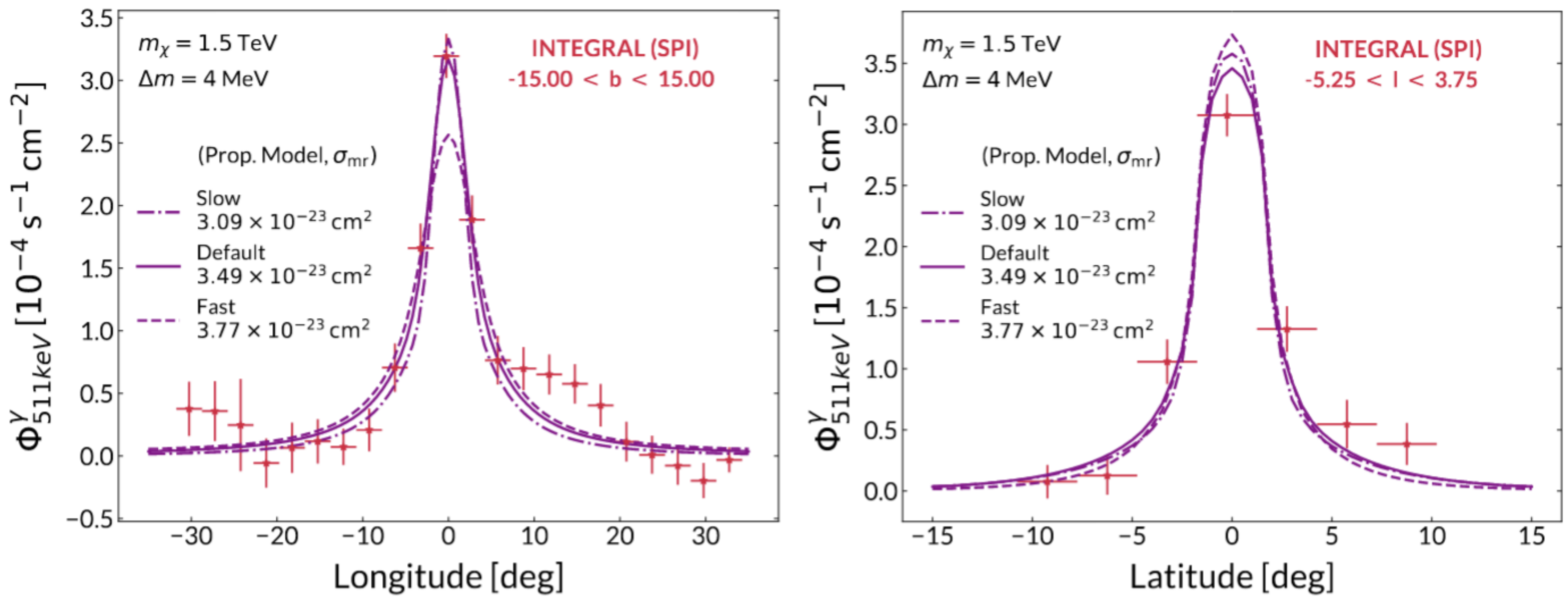


Figure 3. 511 keV longitude (left) and latitude (right) profiles for XDM with $m_\chi = 1.5$ TeV and $\Delta m = 4$ MeV, compared to INTEGRAL/SPI data (red points), for three propagation setups: "Default" (solid), "Fast" (dashed) and "Slow" (dash-dotted), following De la Torre Luque *et al.* (2024).

XDM (profile dependence)

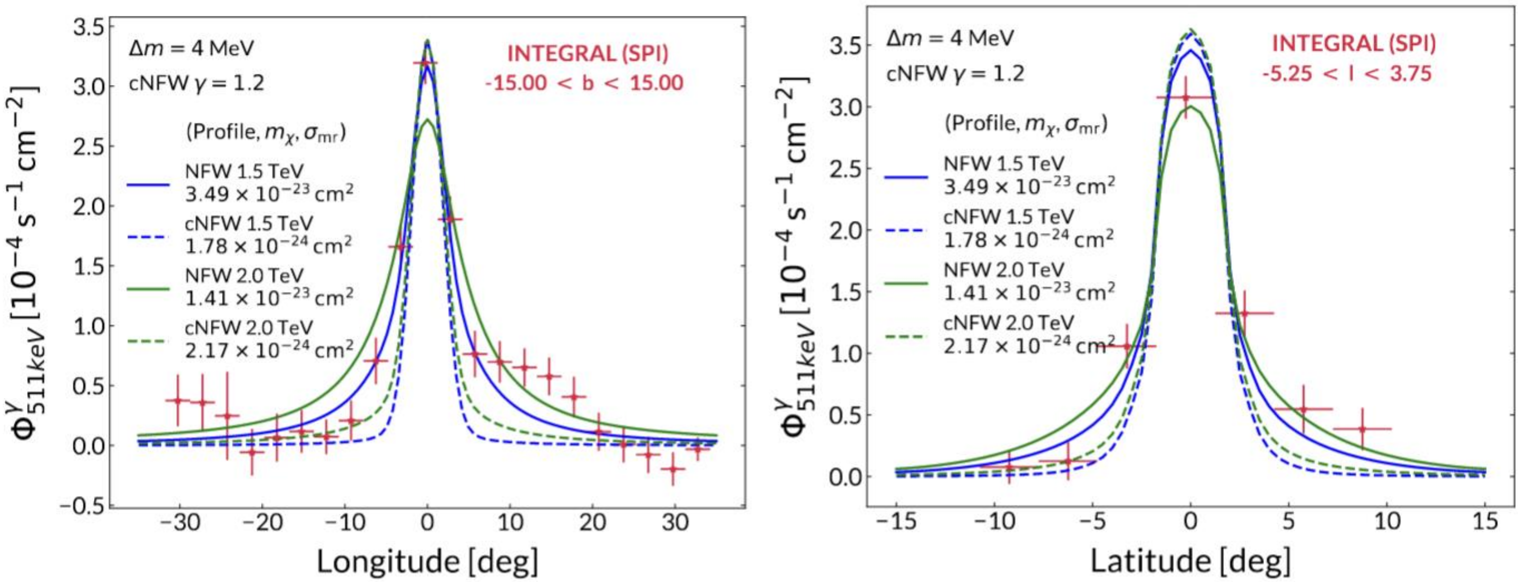


Figure 6. 511 keV longitude (left) and latitude (right) profiles for XDM models with $m_\chi = 1.5$ TeV (blue) and $m_\chi = 2$ TeV (green), and fixed mass splitting $\Delta m = 4$ MeV, compared to INTEGRAL/SPI data (red points). Solid lines correspond to an NFW profile, dashed lines to a cNFW profile. The best-fit values of $\sigma_{\rm mr}$ for each case are indicated in the legend.

XDM (profile dependence)

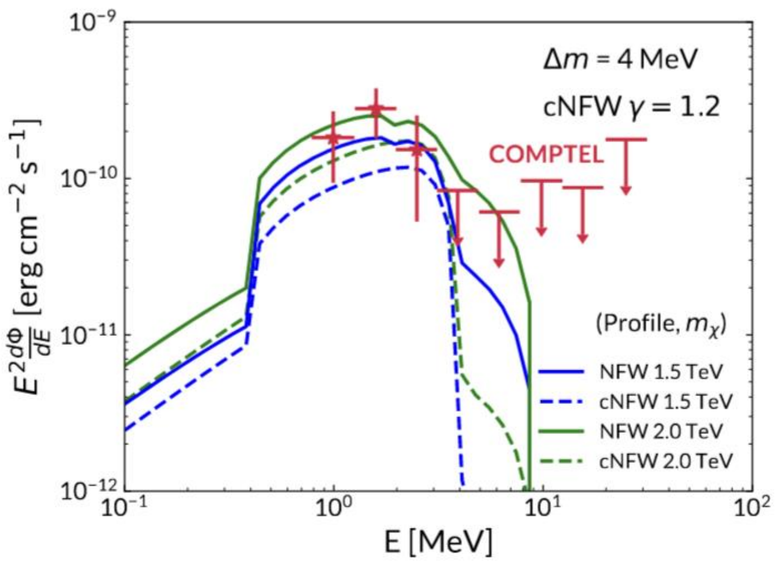


Figure 7. IfA flux measurements from COMPTEL (red points) compared to the XDM predictions for the same NFW and cNFW scenarios as in Fig. 6. The normalization in each case is set by the corresponding best-fit cross section $\sigma_{\rm mr}$ obtained from the 511 keV morphology.

XDM (profile dependence)

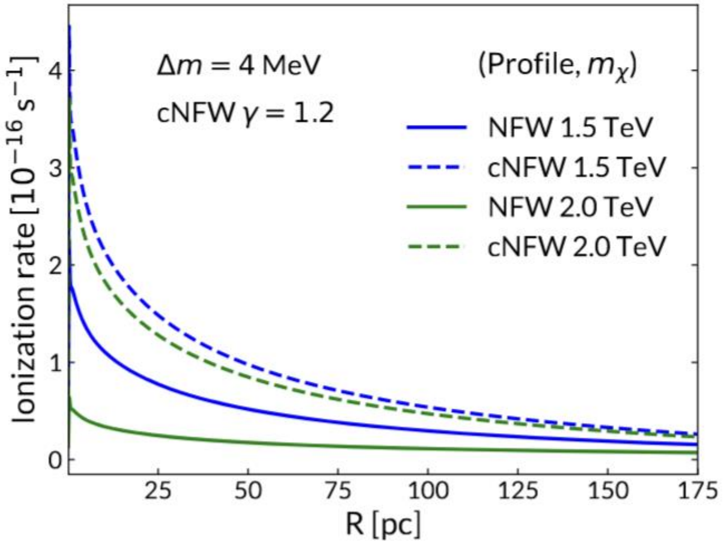
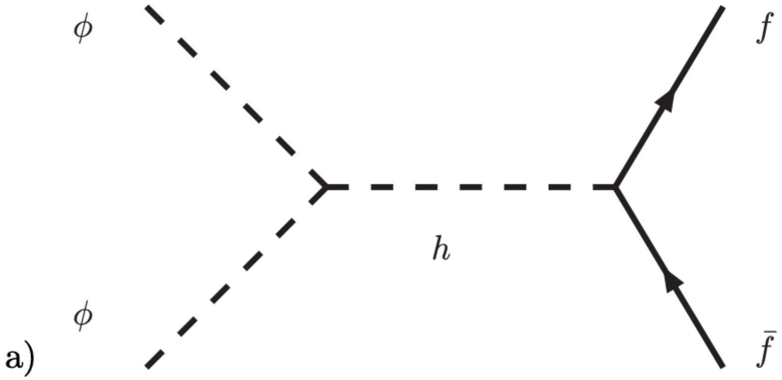
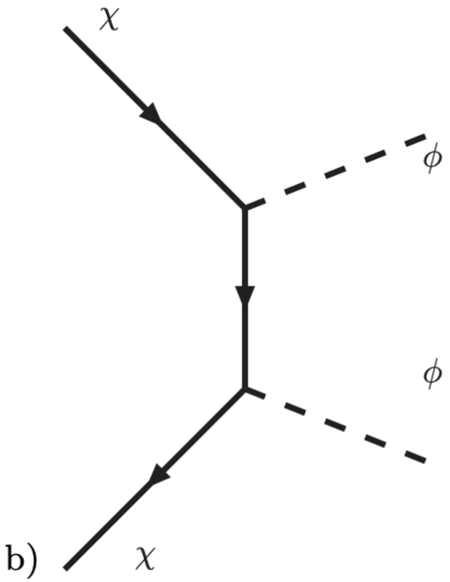
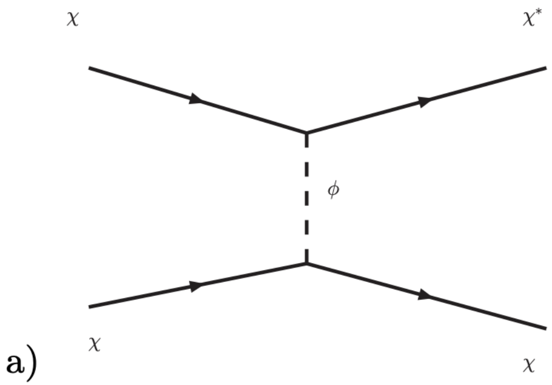


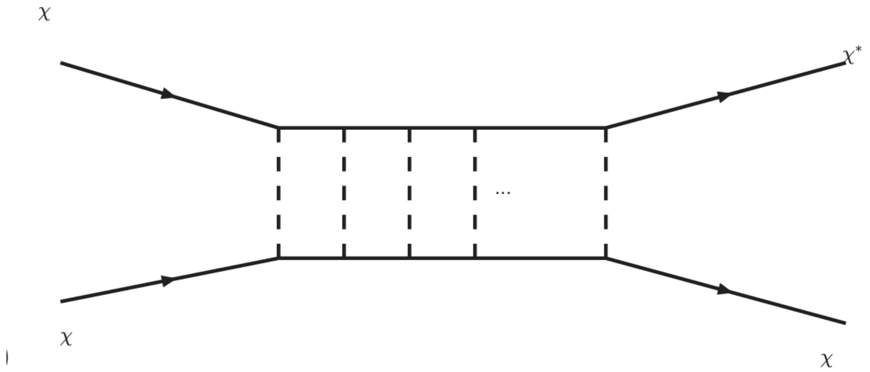
Figure 8. Radial profile of the H_2 ionization rate in the CMZ for the NFW and cNFW scenarios of Fig. 6. The normalization is again fixed by the best-fit $\sigma_{\rm mr}$ from the 511 keV fit.

XDM Feynman Diagrams









XDM (relic abundance)

The process of excitation arises from a sum of all ladder diagrams in addition to the tree level diagrams. We sum these using the spectator approach, where we take the intermediate fermion lines to be on-shell. Neglecting logarithmic dependencies on the momenta and scalar mass, one then finds the n^{th} diagram to be proportional to $q^{-2}(\lambda^2/v)^n$, where $\lambda^2 = \lambda^2_{-,+}, \lambda_-\lambda_+$ depending on the diagram considered. Here v is the velocity of *one* of the initial states χ in the center of mass frame. This allows us to sum the diagrams by solving

$$M_{i,j\to k,l} = i\frac{\lambda_{i,k}\lambda_{j,l}}{q^2} + i\frac{L_{i,j,\alpha,\beta}\lambda_{i,\alpha}\lambda_{j,\beta}M_{\alpha,\beta,k,l}}{v} \tag{A1}$$

and equivalently for the u-channel (crossed) diagrams. Here L is a loop factor which can depend on the states considered, and will be evaluated numerically.

Because we are taking the intermediate fermion lines to be on-shell, we neglect diagrams where both fermions are excited, which are suppressed due to phase space.

$$\sigma v_{rel} = \frac{2v\beta\left(v^2+\beta^2\right) - \left(v^2-\beta^2\right)^2 \tanh^{-1}\left(\frac{2v\beta}{v^2+\beta^2}\right)}{4m^2\pi v\left(v^2-\beta^2\right)^2\left(v^2+\beta^2\right)} M^2 \tag{A2}$$

where M^2 arises from summing the internal single excitation ladder diagrams, excluding the external leg contributions to the amplitudes, which is

$$\begin{aligned} M^2 \;=\; & \left(v^2\lambda_-^2\lambda_+^2\left(\left(L_0-L_1\right)^2\lambda_-^4 - 2\lambda_+^2\left(L_0-L_1\right)^2\lambda_-^2 + v^2 + \lambda_+^4\left(L_0-L_1\right)^2\right)\right) / \\ & \left[L_0^2L_1^2\lambda_+^8 + 2\lambda_-^2L_0^2L_1^2\lambda_+^6 + \left(\left(L_1^2\lambda_-^4+v^2\right)L_0^2 + v^2L_1^2\right)\lambda_+^4 \right. \\ & \left. +2v^2\lambda_-^2\left(2L_0-L_1\right)L_1\lambda_+^2 + v^4 + v^2\lambda_-^4L_1^2\right] \end{aligned} \tag{A3}$$

where here, $L_{0,1}$ are the loop factors for diagrams involving zero or one excited internal fermions. β is the final state velocity of one of the dark matter particles. To a reasonable approximation, L_1 is just suppressed relative to L_0 by phase space, that is, $L_1 \approx L_0\beta^2/v^2$. With this simplification

$$\begin{aligned} M^2 = & \, v^2\lambda_-^2\lambda_+^2\left(v^6 + \left(v^2-\beta^2\right)^2\lambda_-^4L_0^2 + \left(v^2-\beta^2\right)^2\lambda_+^4L_0^2 - 2\left(v^2-\beta^2\right)^2\lambda_-^2\lambda_+^2L_0^2\right) / \\ & \left(\beta^4L_0^2\left(L_0^2\lambda_+^4+v^2\right)\lambda_-^4 + 2\beta^2\lambda_+^2L_0^2\left(2v^4-\beta^2v^2+\beta^2\lambda_+^4L_0^2\right)\lambda_-^2 + \left(L_0^2\lambda_+^4+v^2\right)\left(v^6+\beta^4\lambda_+^4L_0^2\right)\right) \end{aligned} \tag{A4}$$

DM/PBH -> e+e- in the Milky Way

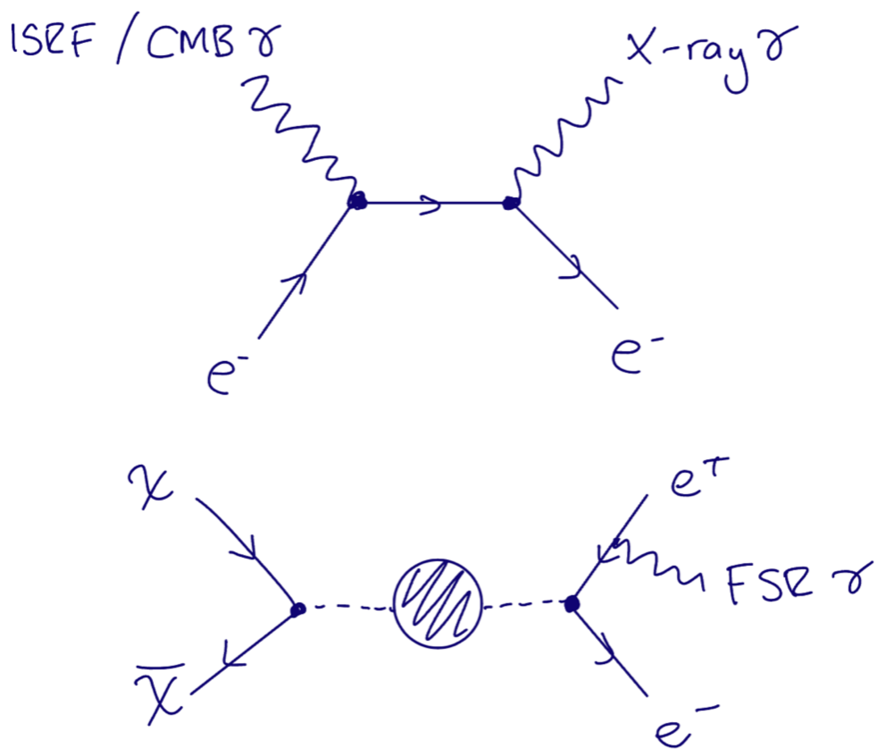
- Look for ***secondary particles*** *(not directly produced by the DM/PBH).*

- Main signals:

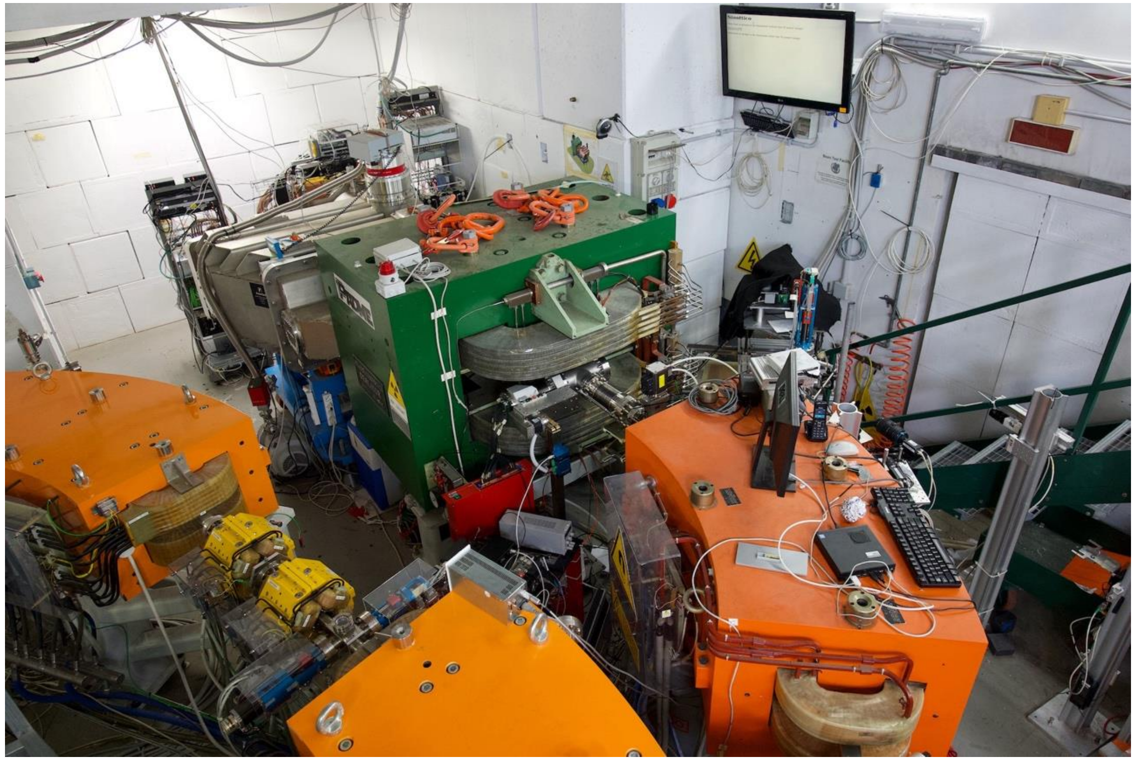
  - Inverse Compton (IC) scattering on interstellar radiation fields (ISRFs) and CMB

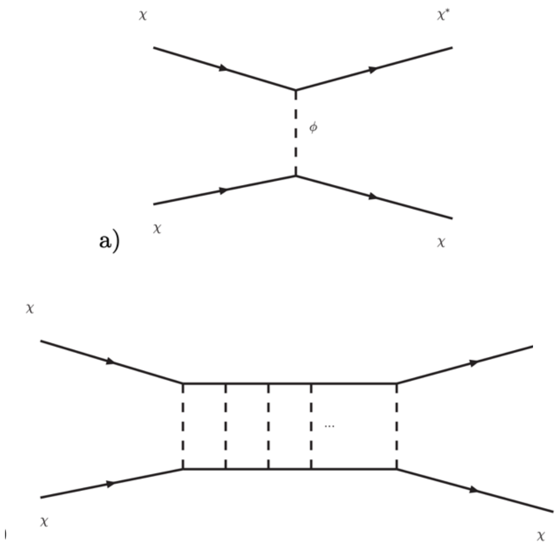
  - Final State Radiation (FSR) (sub 10 MeV mass only, no propagation)

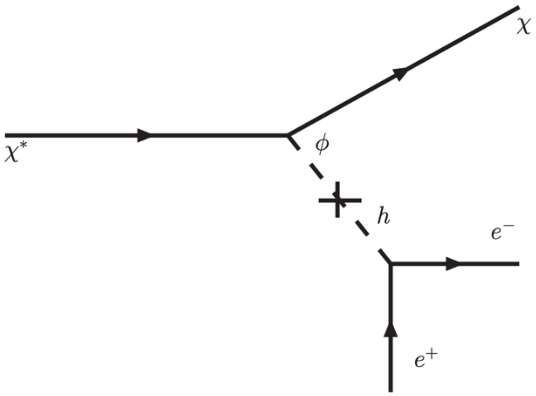
  - Produces **keV-MeV X-rays -> use X-ray telescopes!**



Interesting Hint of Light New Physics (PADME)







•PADME, a fixed target experiment has found evidence of an electrophilic boson at 17 MeV mass (around ~2σ) coupling to $e^{\pm}$, this could play the role of the light mediator for the XDM model! This could be an interesting link between lab-Galactic scales. Very speculative at this stage, but still intriguing.