X-ray constraints on Dark Matter

Jordan Koechler

New postdoc!

INFN Welcome Day

November 3rd , 2024

INFN TORINO

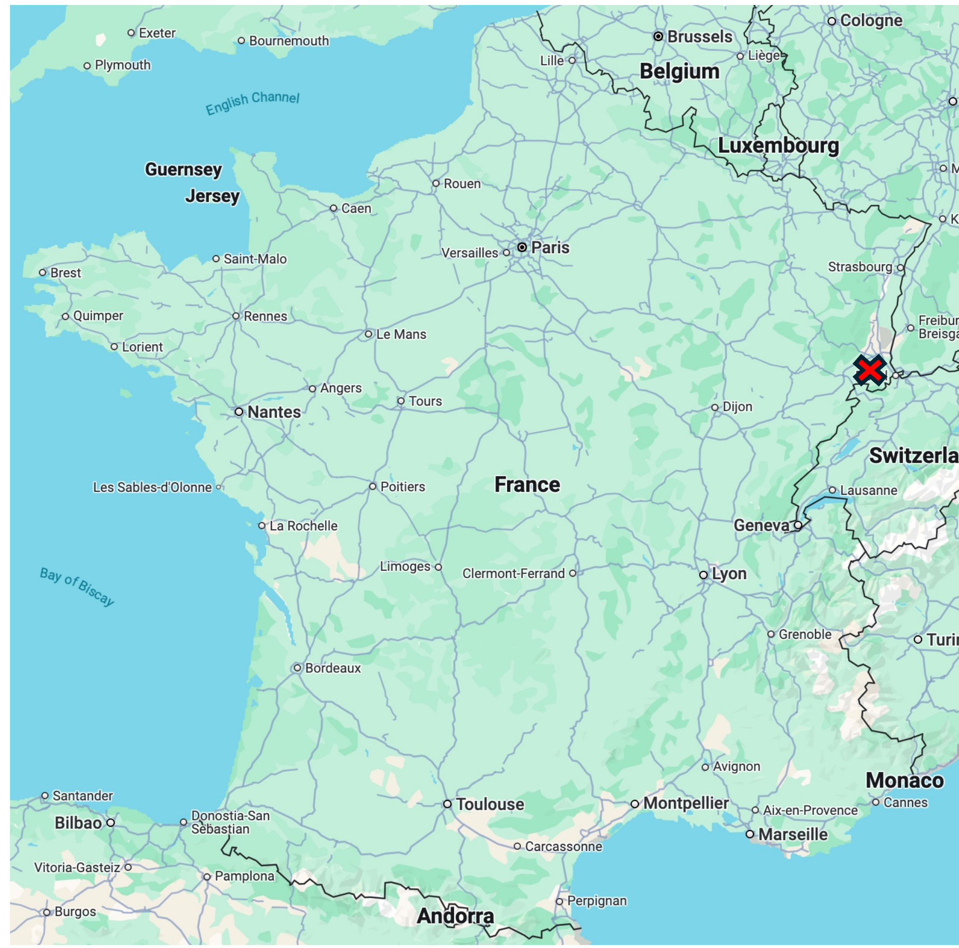
About me!


Exeter
Bournemouth
Plymouth
Cologne
Brussels
Liège
Lille
Belgium
English Channel
Luxembourg
Guernsey
Jersey
Rouen
Caen
Paris
Versailles
Saint-Malo
Brest
Strasbourg
Quimper
Rennes
Le Mans
Lorient
Freiburg i
Breisgau
Basel
Angers
Tours
Nantes
Dijon
Switzerlan
France
Les Sables-d'Olonne
Poitiers
Lausanne
La Rochelle
Geneva
Limoges
Clermont-Ferrand
Lyon
Bay of Biscay
Grenoble
Turin
Bordeaux
Avignon
Monaco
Santander
Toulouse
Montpellier
Aix-en-Provence
Cannes
Bilbao
Donostia-San
Sebastian
Marseille
Carcassonne
Vitoria-Gasteiz
Pamplona
Perpignan
Burgos
Andorra

About me!

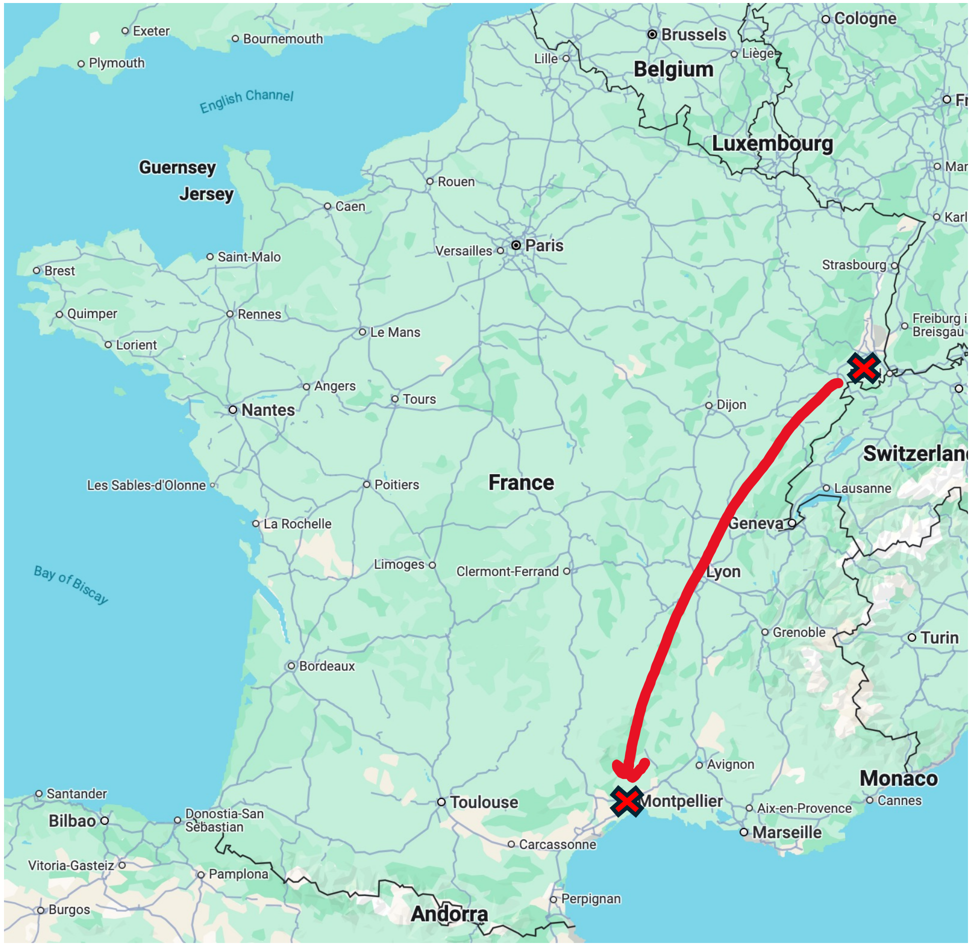
- **Step 1: Home region near the German/Switzerland border of France**

- Did my first two years of B.Sc. there



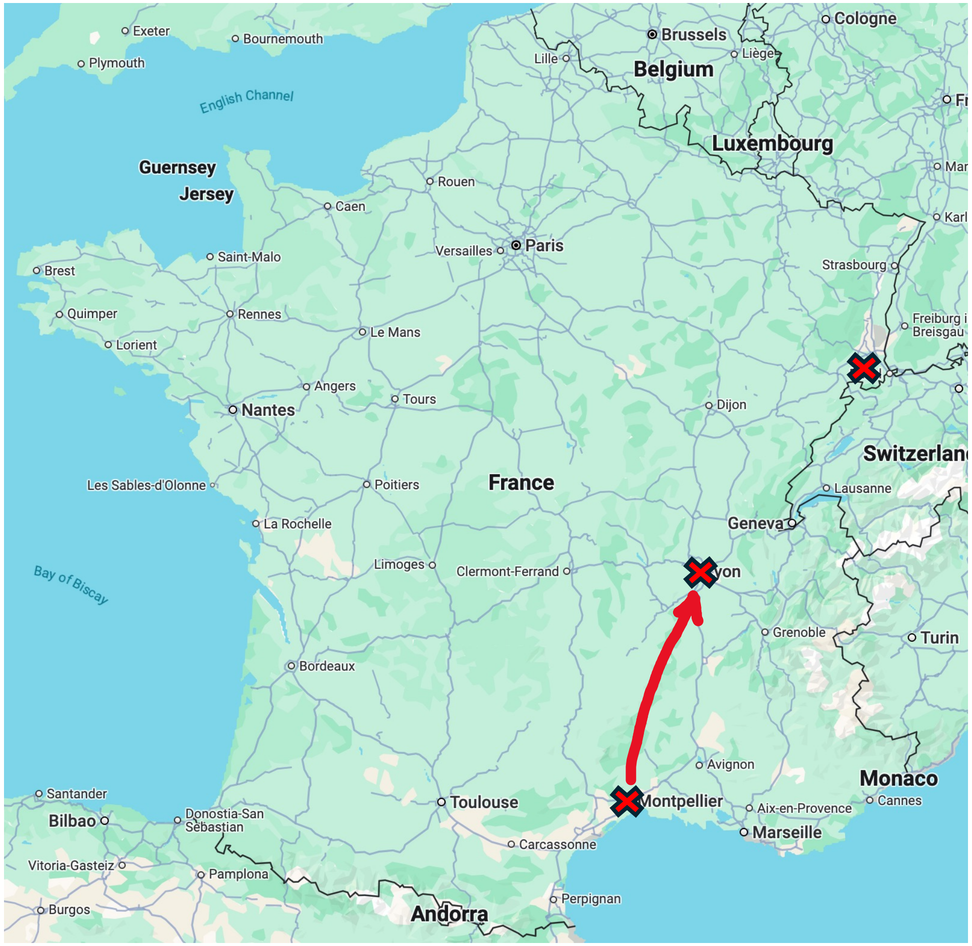
About me!

- **Step 2: Finished the B.Sc. and M.Sc. in Montpellier**



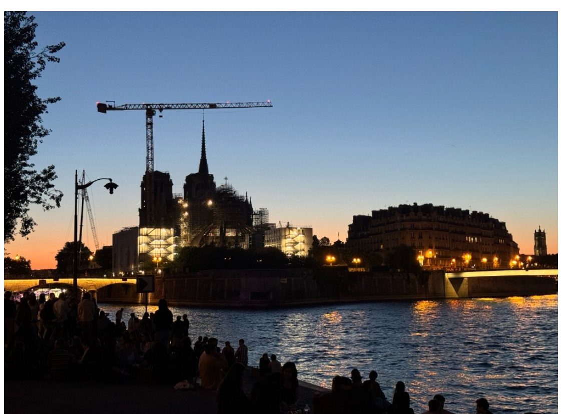
About me!

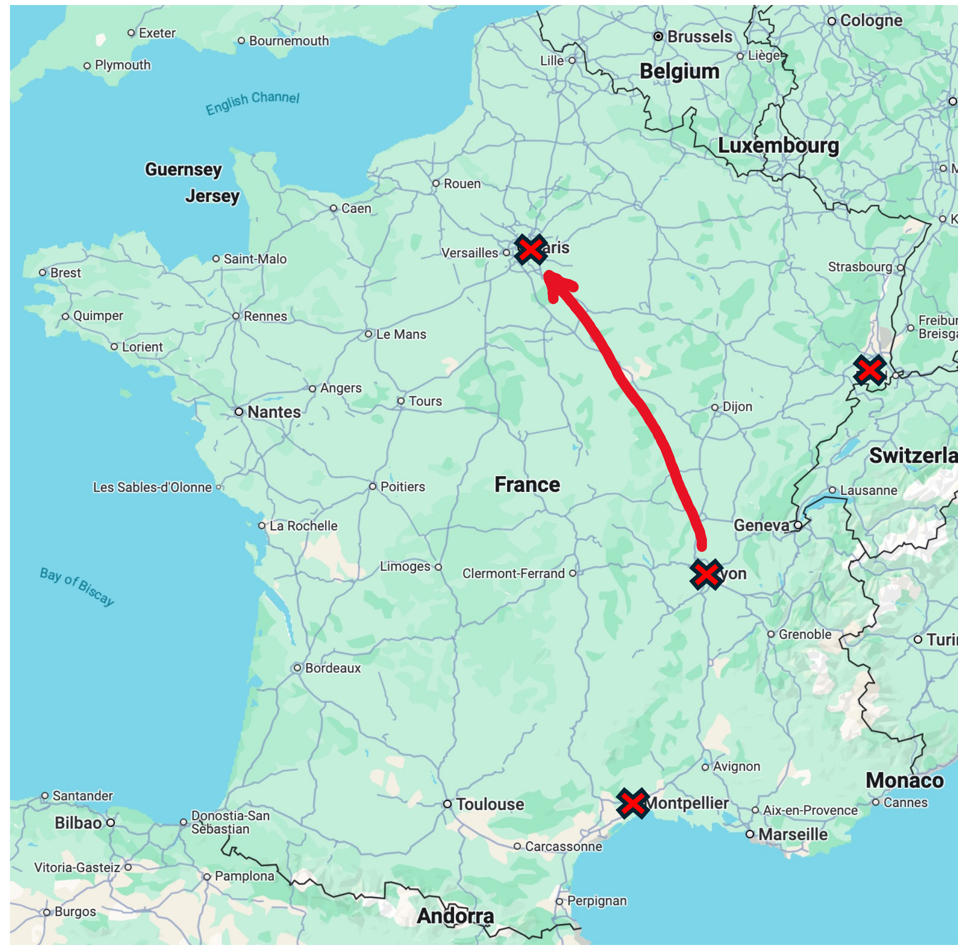
- **Step 3: M.Sc. thesis in Lyon with Giacomo Cacciapaglia @ IP2I**



About me!

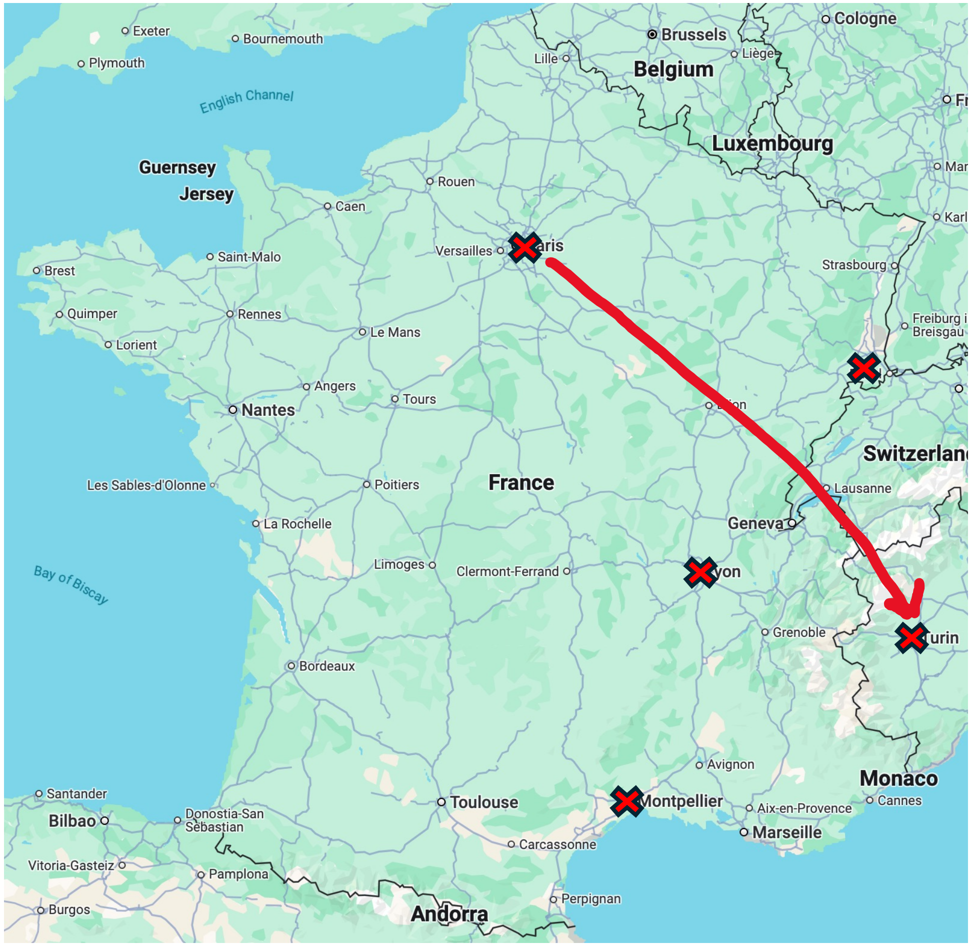
- **Step 4: Ph.D. in Paris with Marco Cirelli @ LPTHE (Sorbonne)**





About me!

- **Step 5: Here I am in Turin! Postdoc with Mattia di Mauro**



About me!

- You could probably see me running near the Po river most days of the week.
- A bit of a foodie.
- Big fan of video games. Enjoying board games too.
- Would partake in a book club if some people are into reading.
- Really into visiting museums too…

About this talk

- Dark matter 101
- Constraining dark matter candidates from diffuse X-rays
  - Sub-GeV DM
  - Primordial black holes

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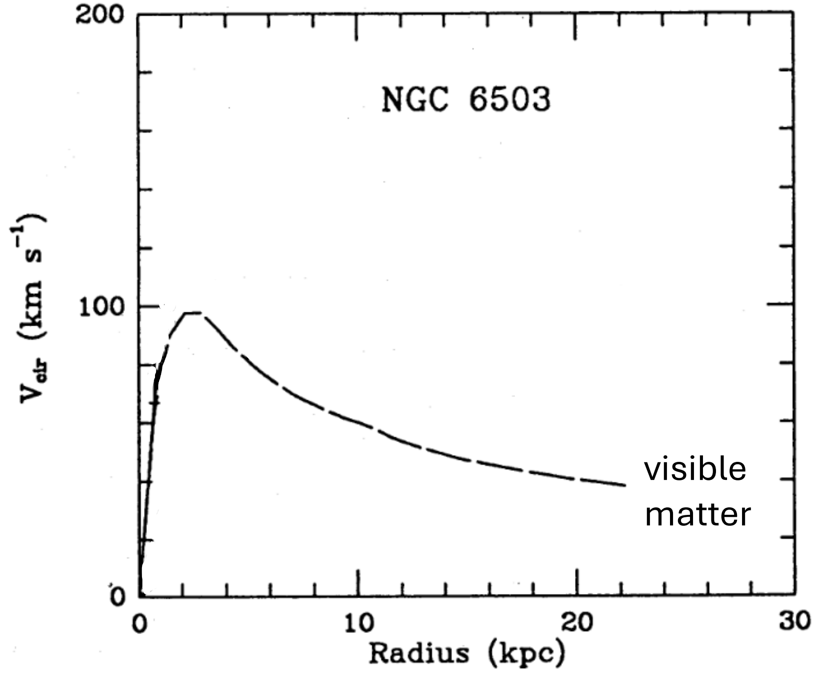
  $v_{circ}(r) \propto 1/\sqrt{r}$ for $r \to \infty$



[Begeman, Broeils & Sanders, *MNRAS* 249 (1991) 523]

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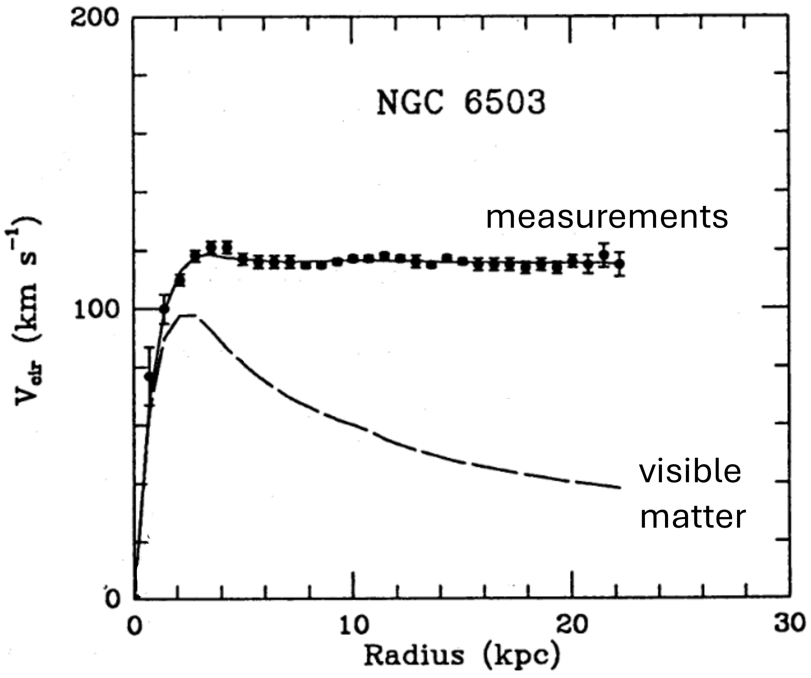
- Observed: $v_{circ}(r) = const$



[Begeman, Broeils & Sanders, *MNRAS* 249 (1991) 523]

Dark matter 101

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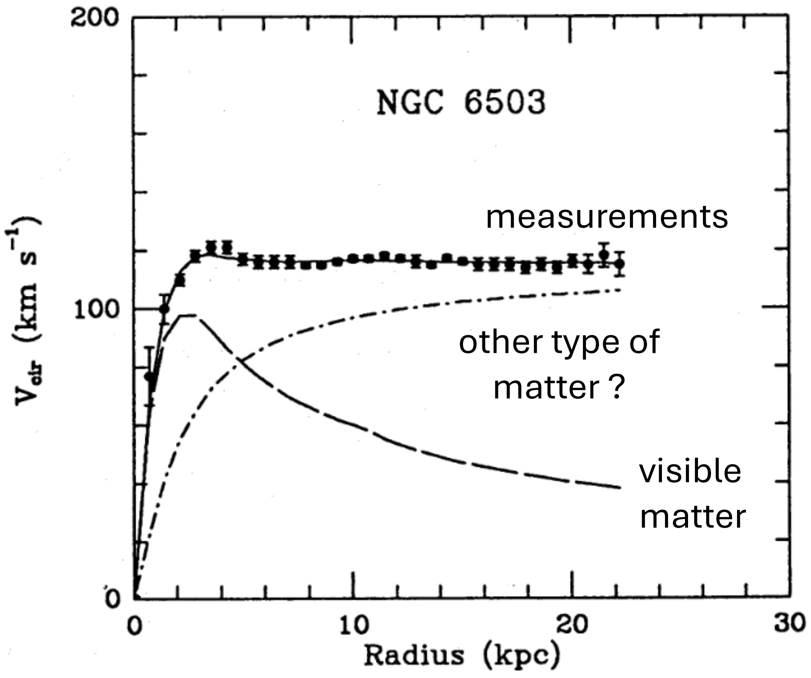
- Newton's second law: $v_{circ}(r) \propto 1/\sqrt{r}$ for $r \to \infty$
- Observed: $v_{circ}(r) = const$
- New matter type to explain the discrepancy?



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Dark matter 101

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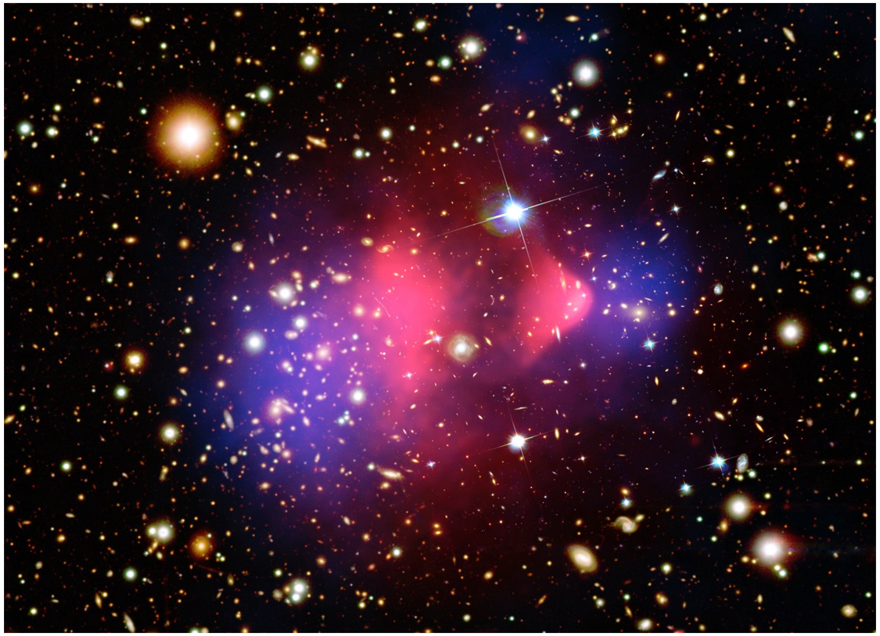

[X-ray: NASA/CXC/CfA/M.Markevitch, Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe, Lensing map: ESO WFI]

Dark matter 101

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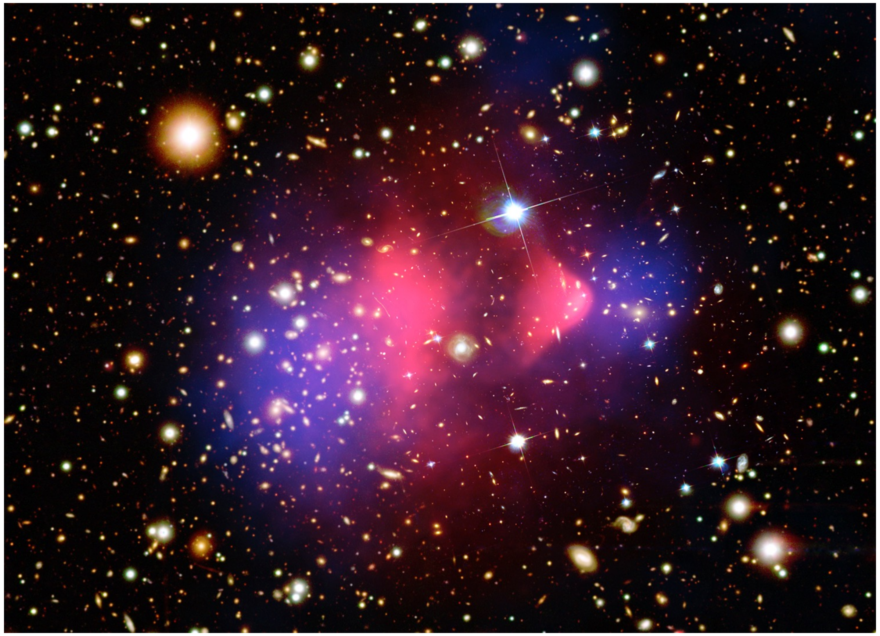

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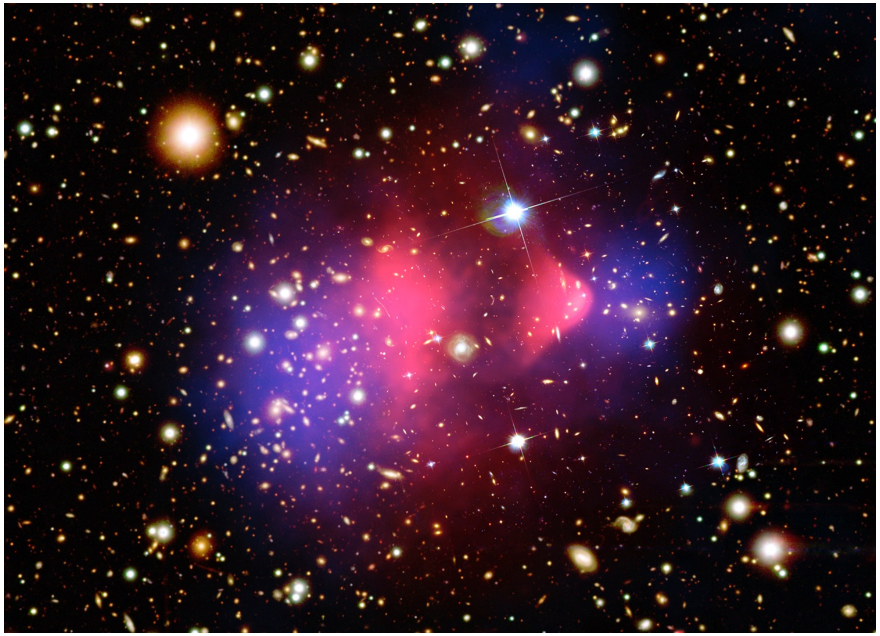

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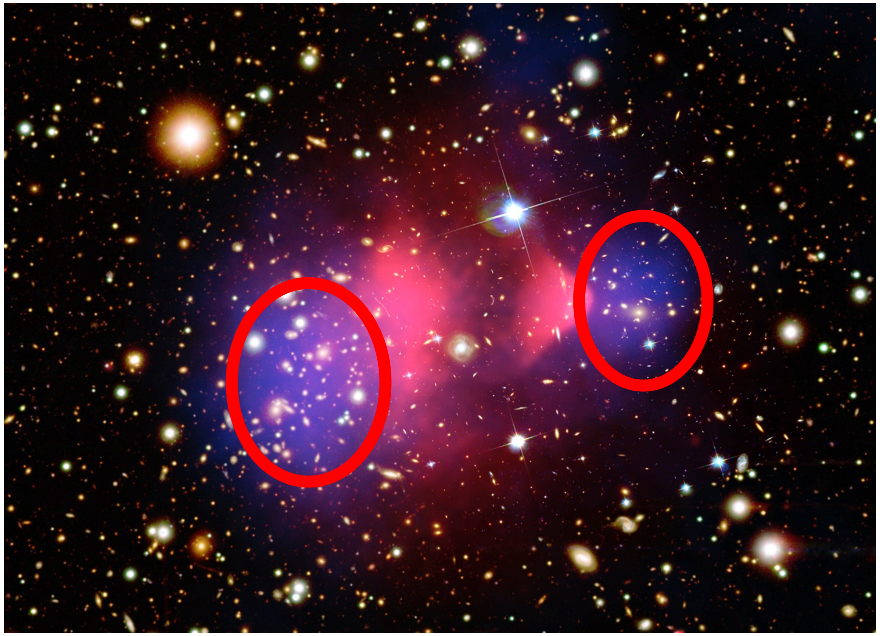
- Most of the the clusters' mass is not composed of gas



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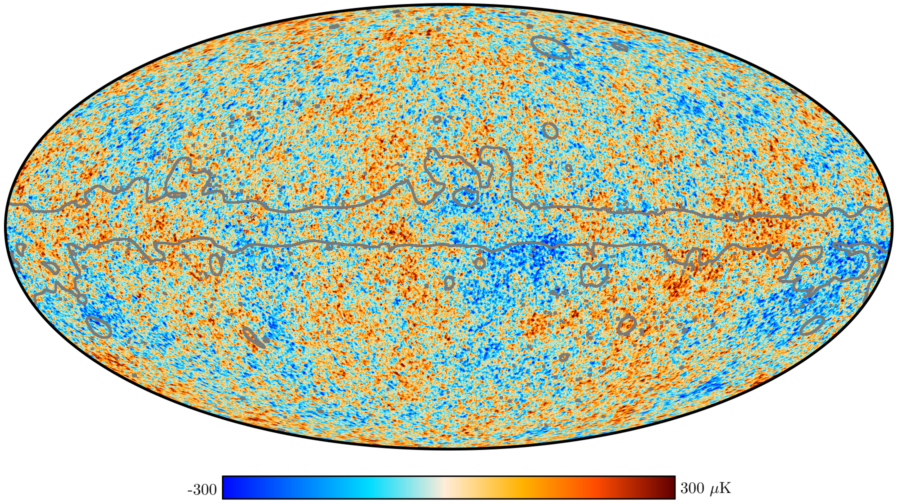

[Aghanim et al., *A&A* 641 (2020) A1]

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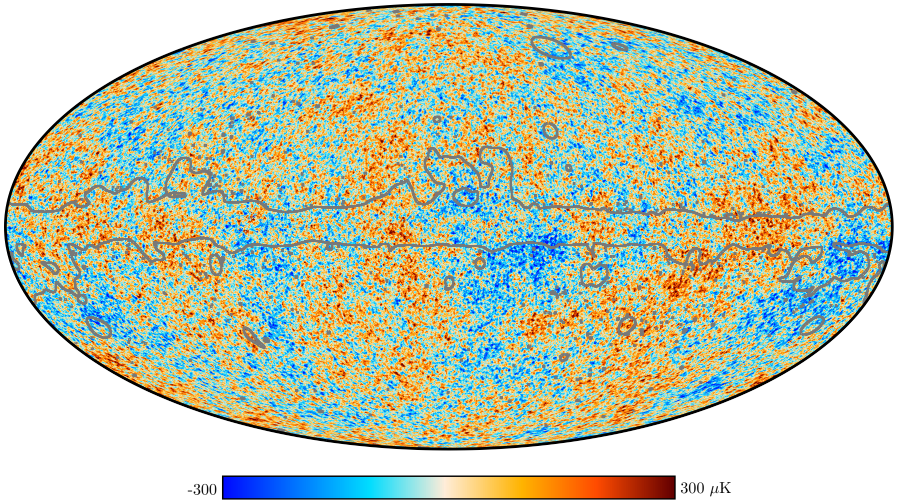

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$$T(\theta, \phi) = T_0 \sum_{l=0}^{+\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$T_0 = 2.725 \text{ K}$$

$$C_\ell = \langle a_{\ell m} a_{\ell m}^* \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

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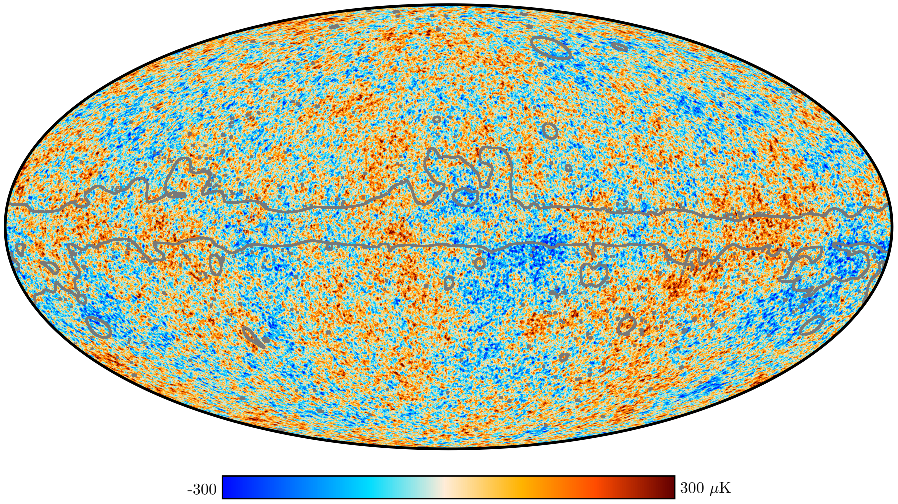

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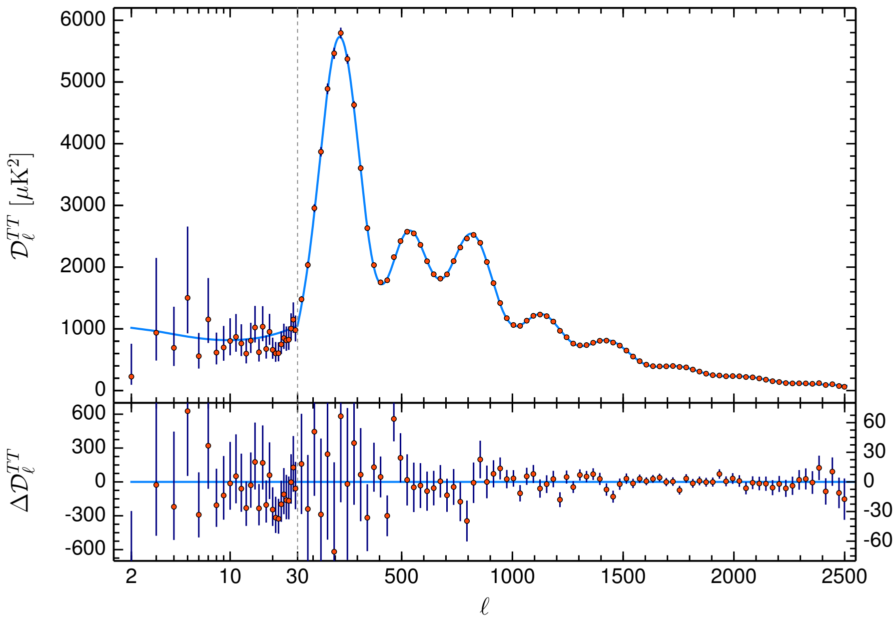

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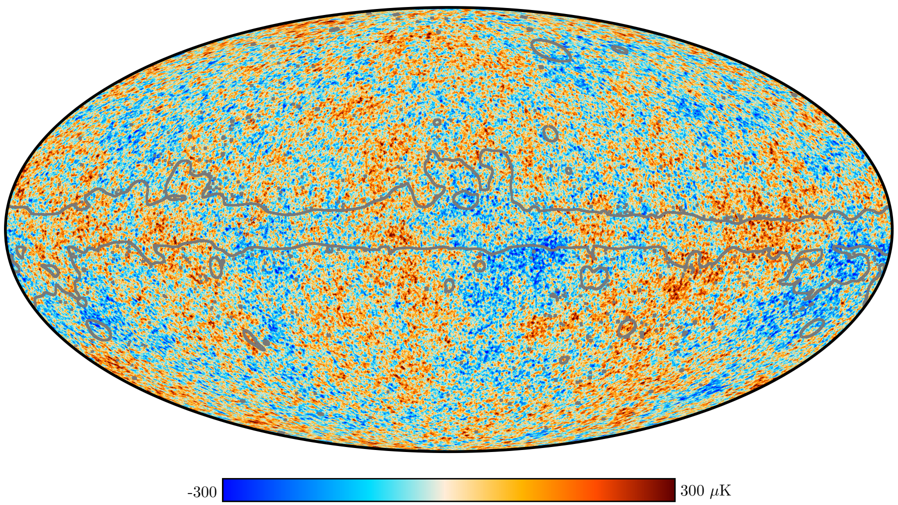

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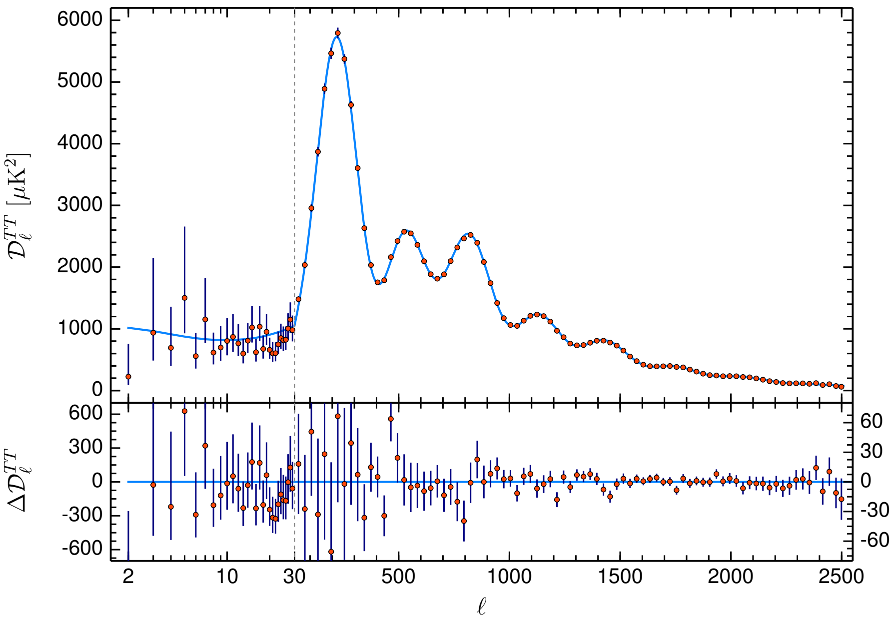
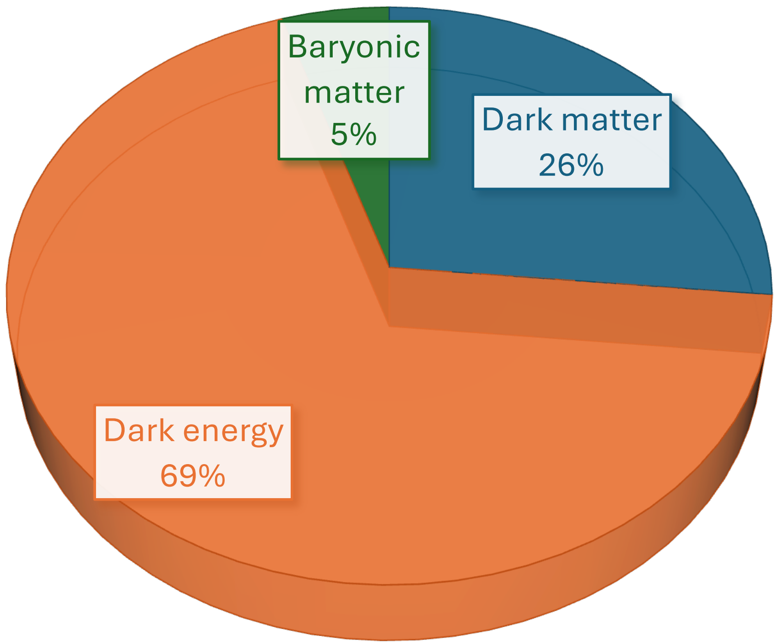


[Aghanim et al., *A&A* 641 (2020) A6]

A Universe filled with baryonic matter, dark matter, radiation and dark energy provides an excellent fit to the measurements!

Dark matter 101

- Measurements of the CMB temperature anisotropies (+ other things) provide



Dark matter 101

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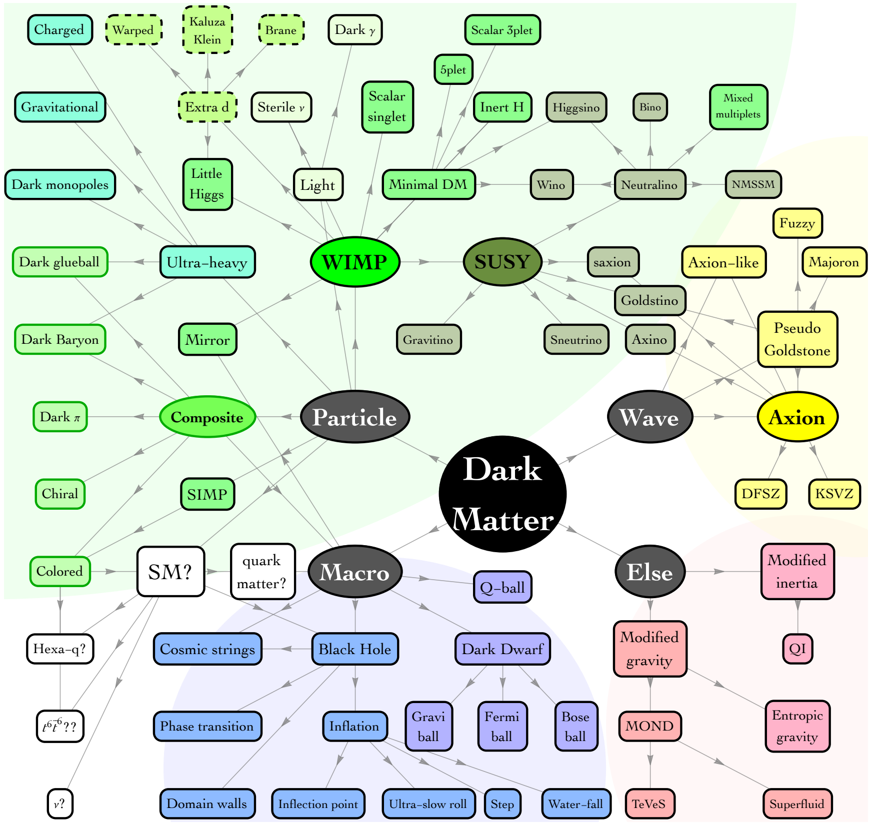

[Cirelli, Strumia & Zupan, 2024, arXiv:2406.01705]

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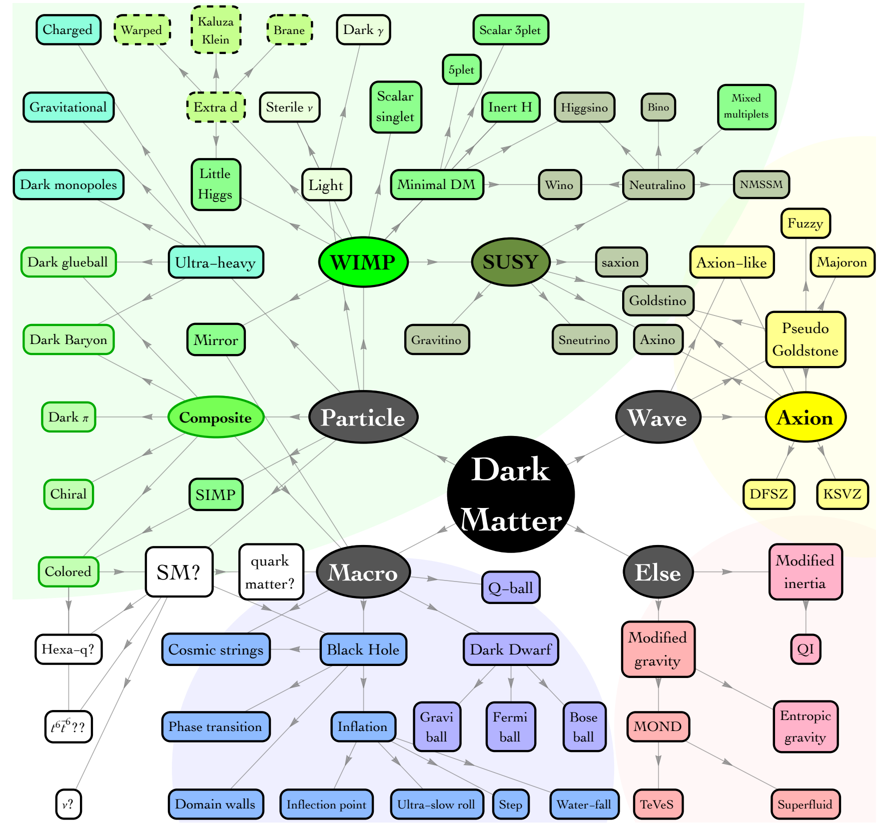

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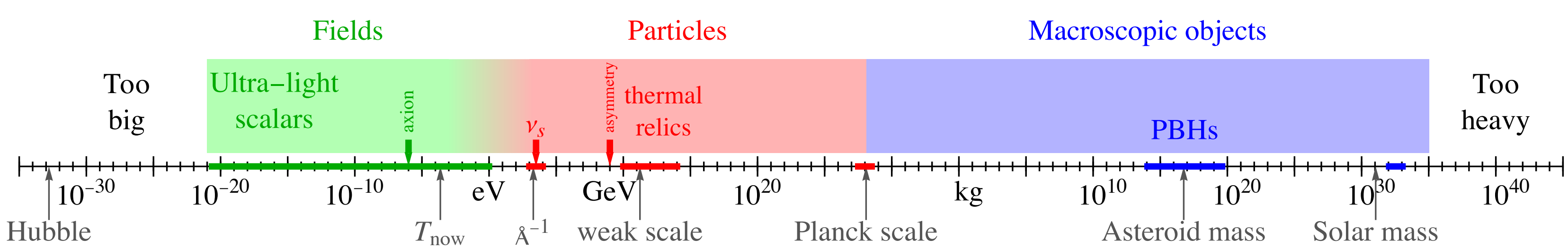

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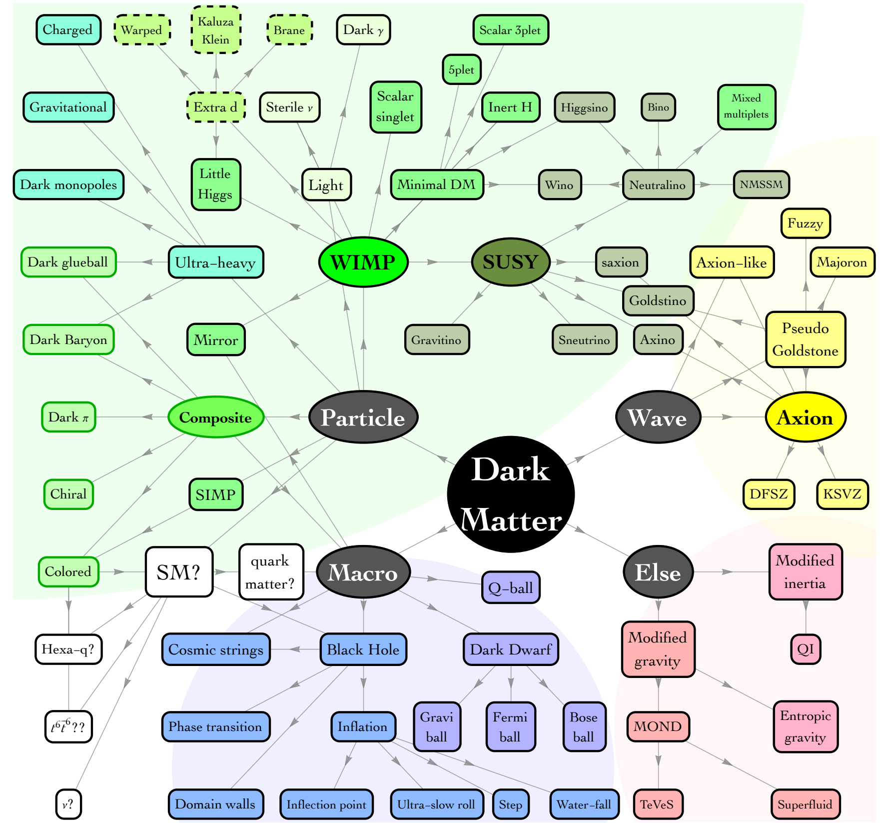

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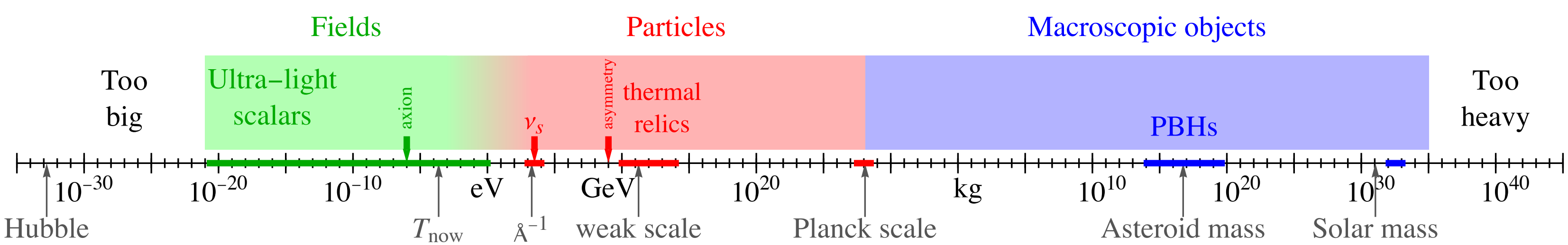
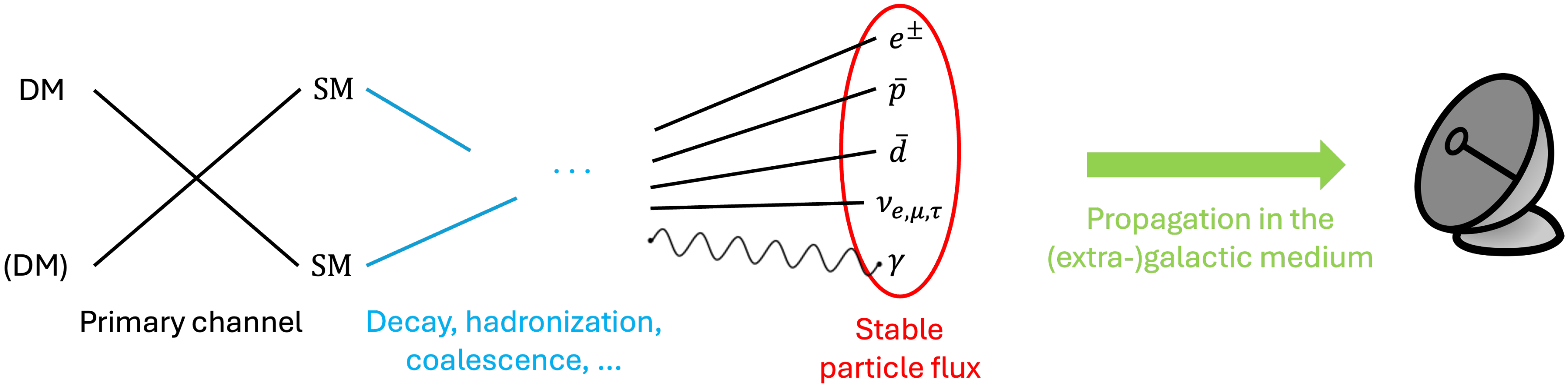
Spans over 90 orders of magnitude!

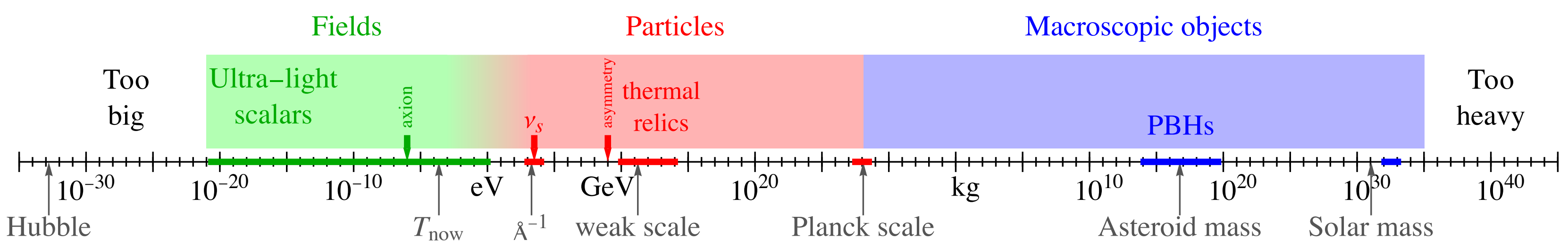


Dark matter 101

A way to potentially probe DM: indirect detection

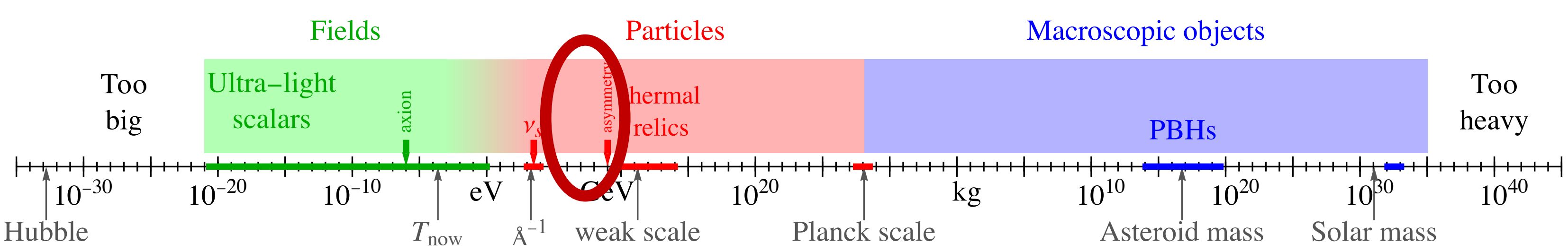


Dark matter 101



Dark matter 101

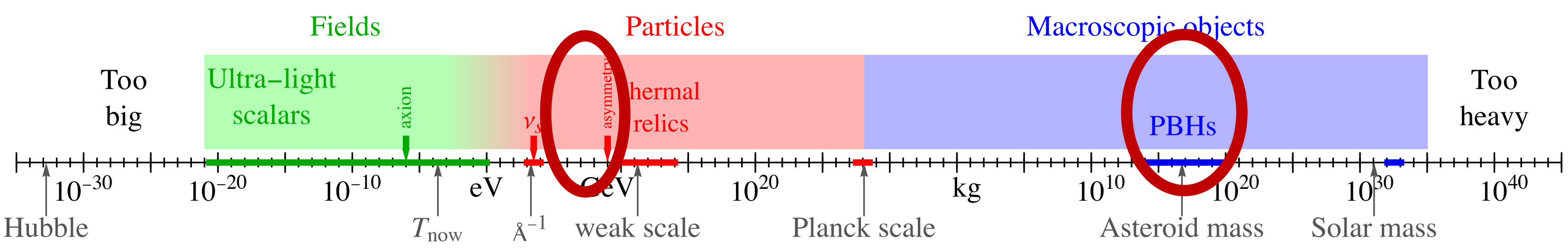
- Candidate 1: DM as sub-GeV elementary particles



Dark matter 101

- Candidate 1: DM as sub-GeV elementary particles

- Candidate 2: DM as primordial black holes



About this talk

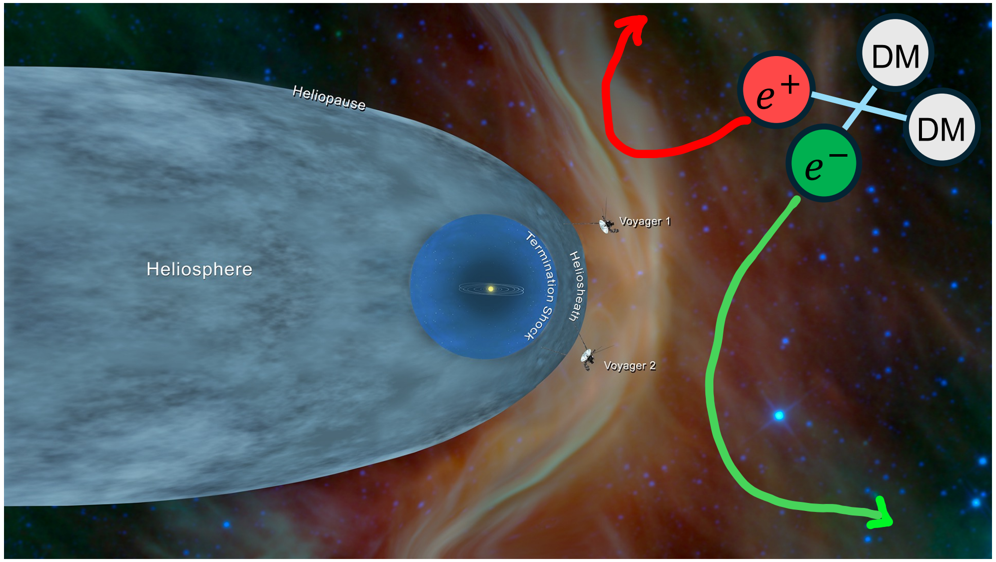
- Dark matter 101

- Constraining dark matter candidates from diffuse X-rays
  - Sub-GeV DM
  - Primordial black holes

Constraining sub-GeV dark matter from diffuse X-rays

- Issue 1: when DM produces $e^{\pm}$

  Solar screening suppresses the flux



Constraining sub-GeV dark matter from diffuse X-rays

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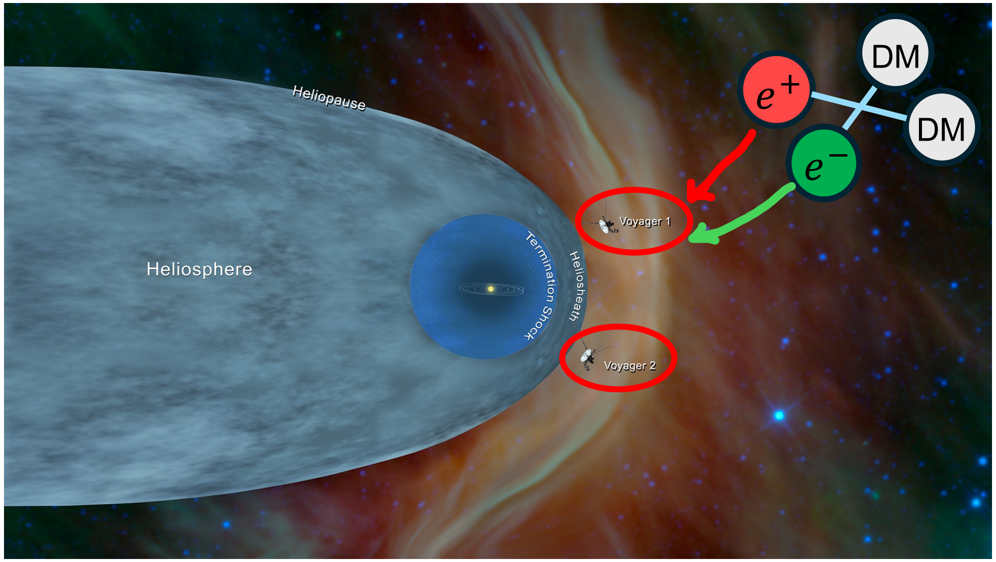
- What to do?
  - Look at Voyager 1 & 2 data!



[Boudaud, Lavalle & Salati, *Phys.Rev.Lett.* 119 (2017) 2, 021103]

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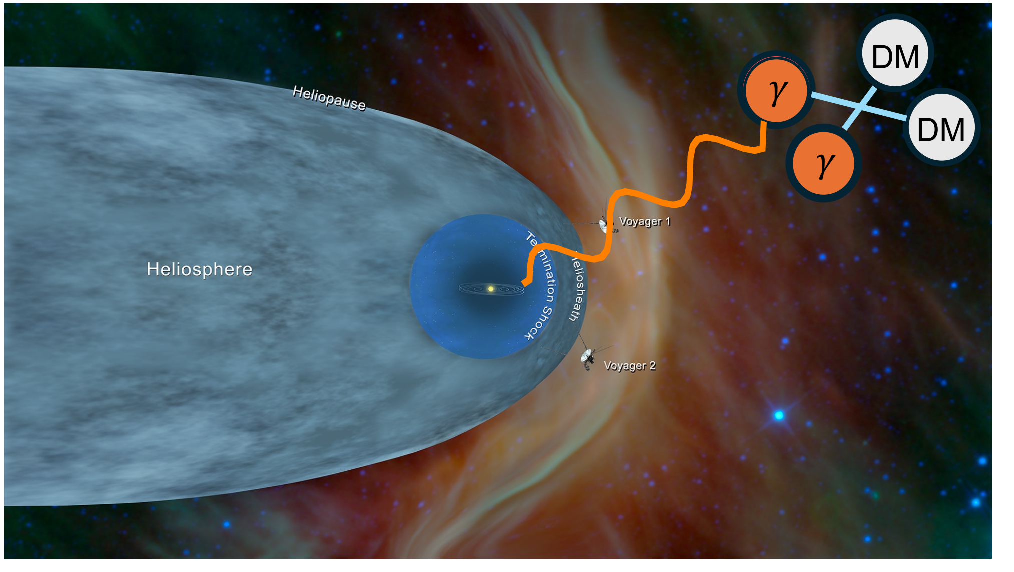


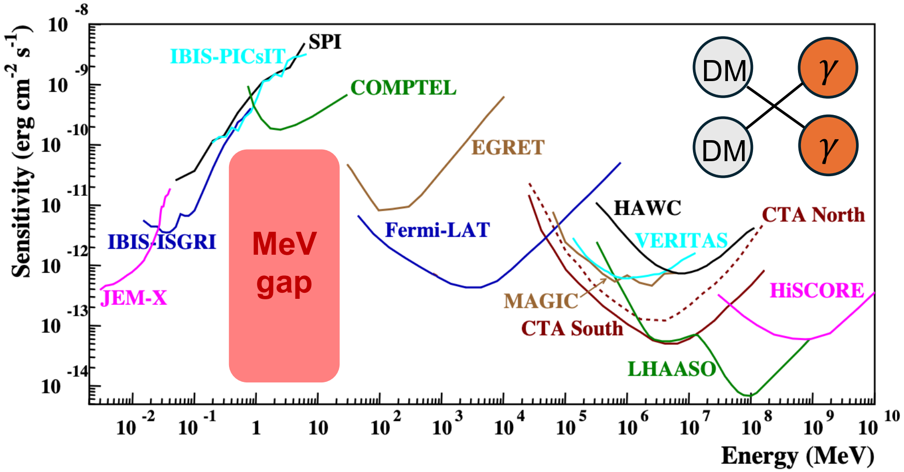
- What to do?
  - Look at Voyager 1 & 2 data!
  - Look for DM-produced γ-rays

[Boudaud, Lavalle & Salati, *Phys.Rev.Lett.* 119 (2017) 2, 021103]

Constraining sub-GeV dark matter from diffuse X-rays

- Issue 2: when DM produces γ

No sensitive enough observatories at MeV energies



Adapted from [De Angelis et al. *Exper.Astron.* 44 (2017) 1, 25]

Constraining sub-GeV dark matter from diffuse X-rays

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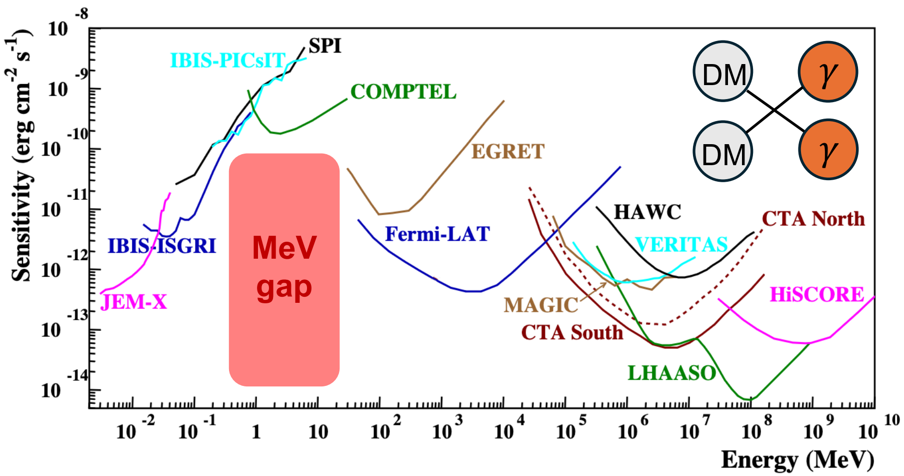
- Secondary emissions allow to circumvent the issue → study X-rays signals from light DM

[Cirelli et al., *Phys.Rev.D* 103 (2021) 6, 063022]



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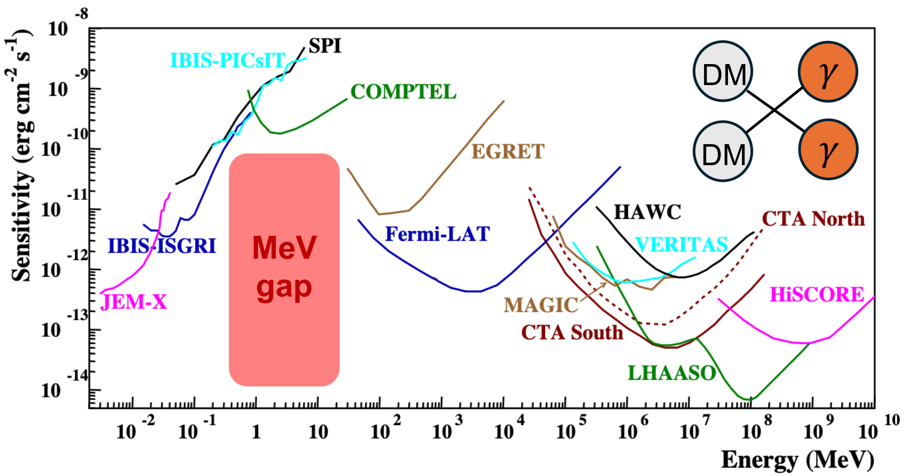
[Cirelli et al., *Phys.Rev.D* 103 (2021) 6, 063022]

Inverse-Compton scattering!



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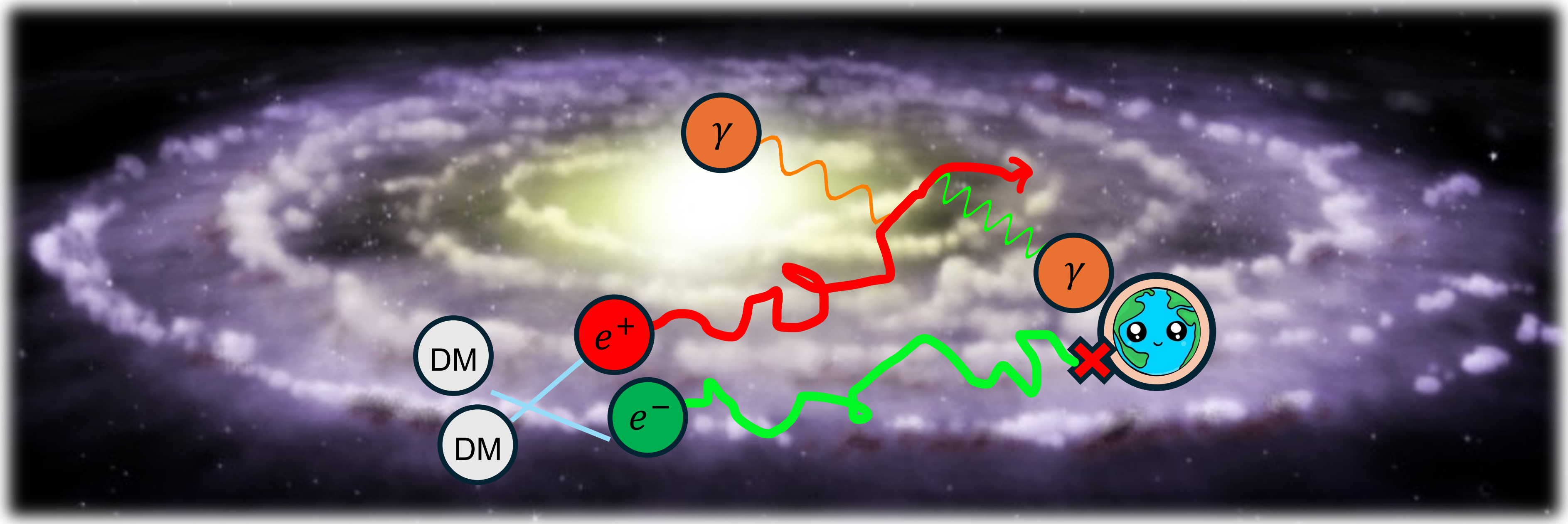
Constraining sub-GeV dark matter from diffuse X-rays



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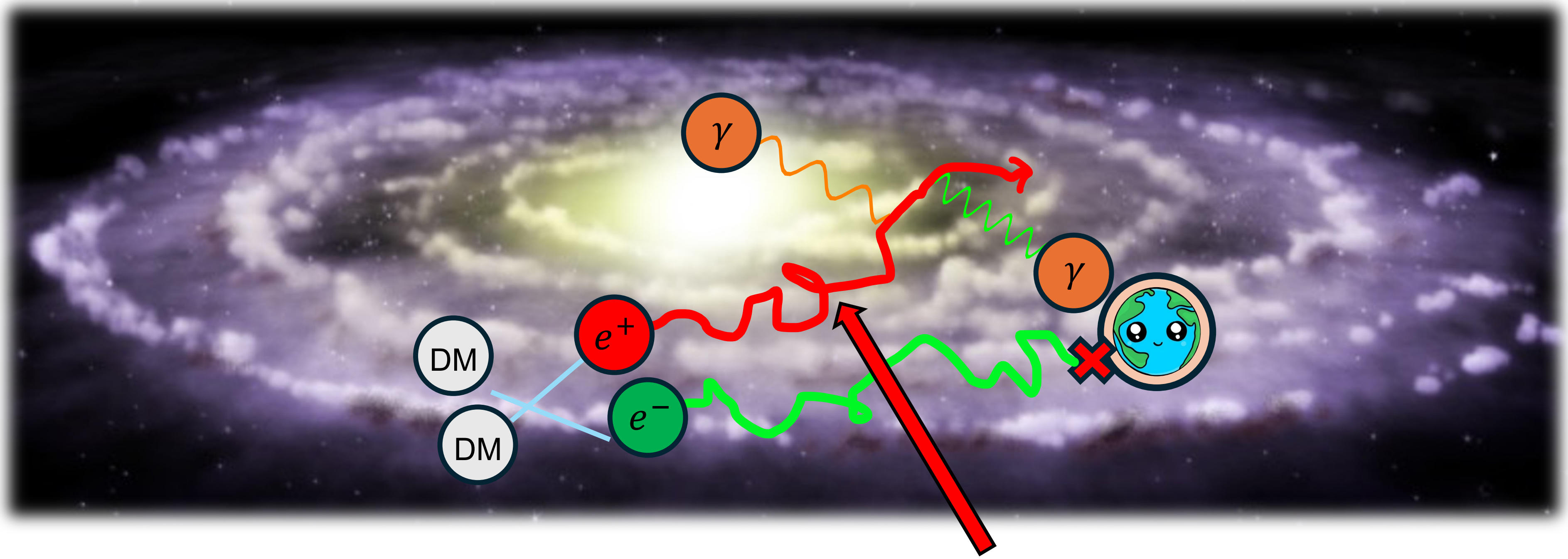
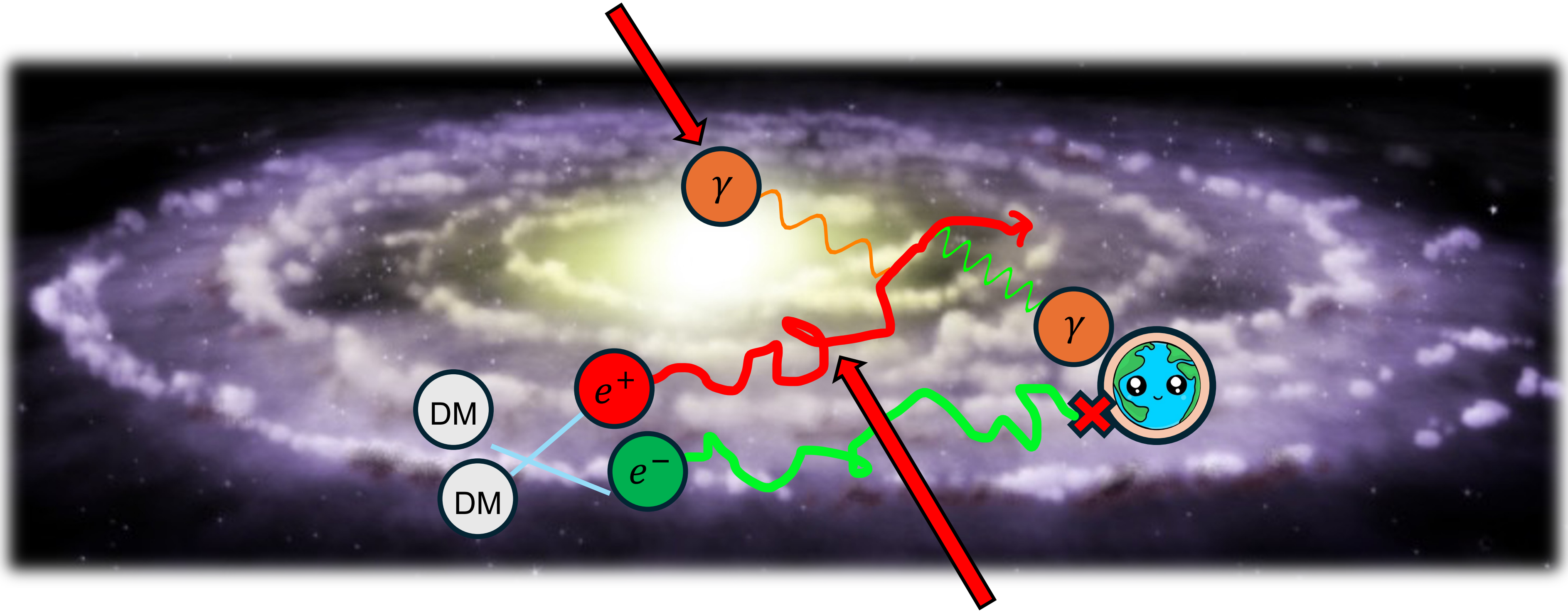


Local number density of DM-produced $e^{\pm}$

Constraining sub-GeV dark matter from diffuse X-rays

Local number density of ambient photons



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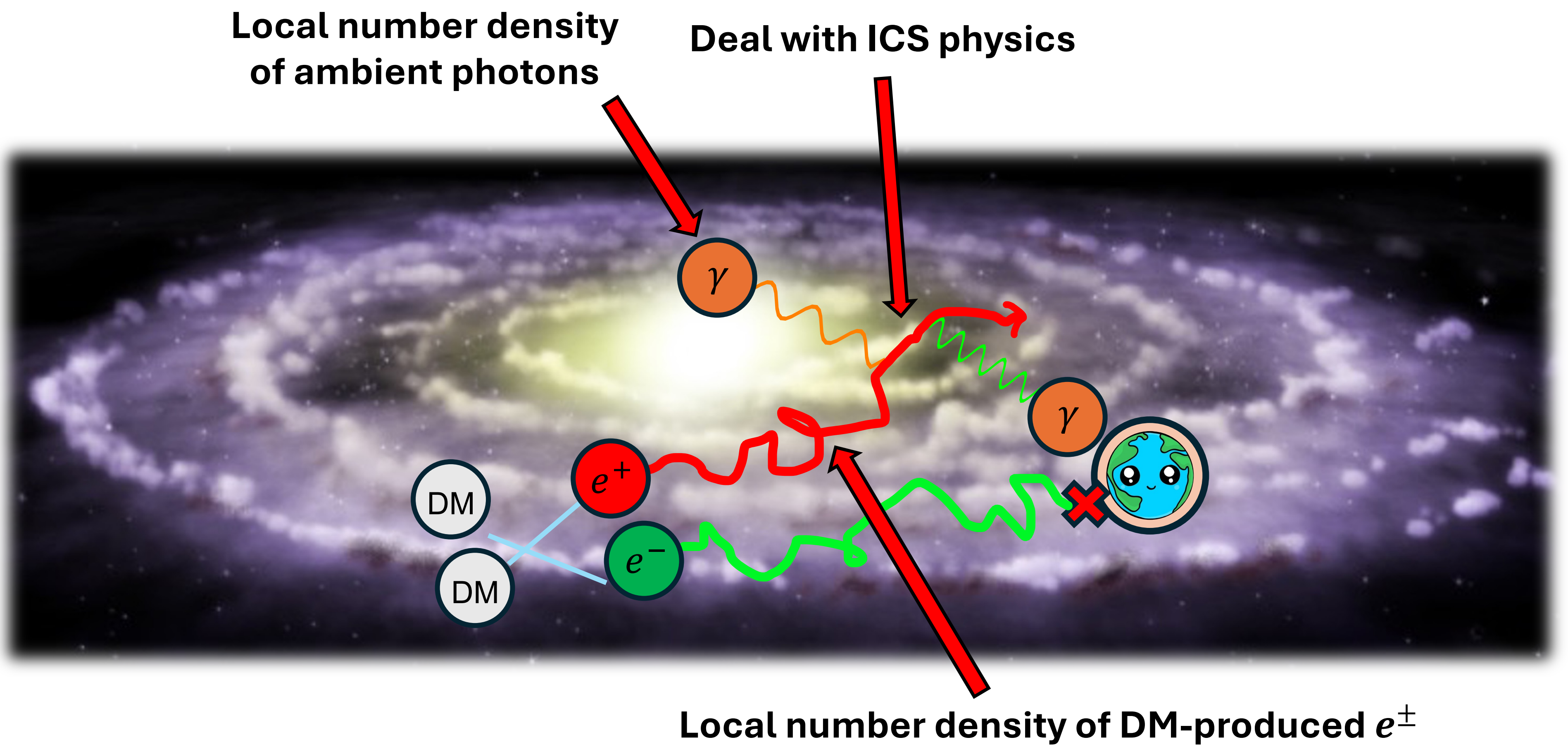
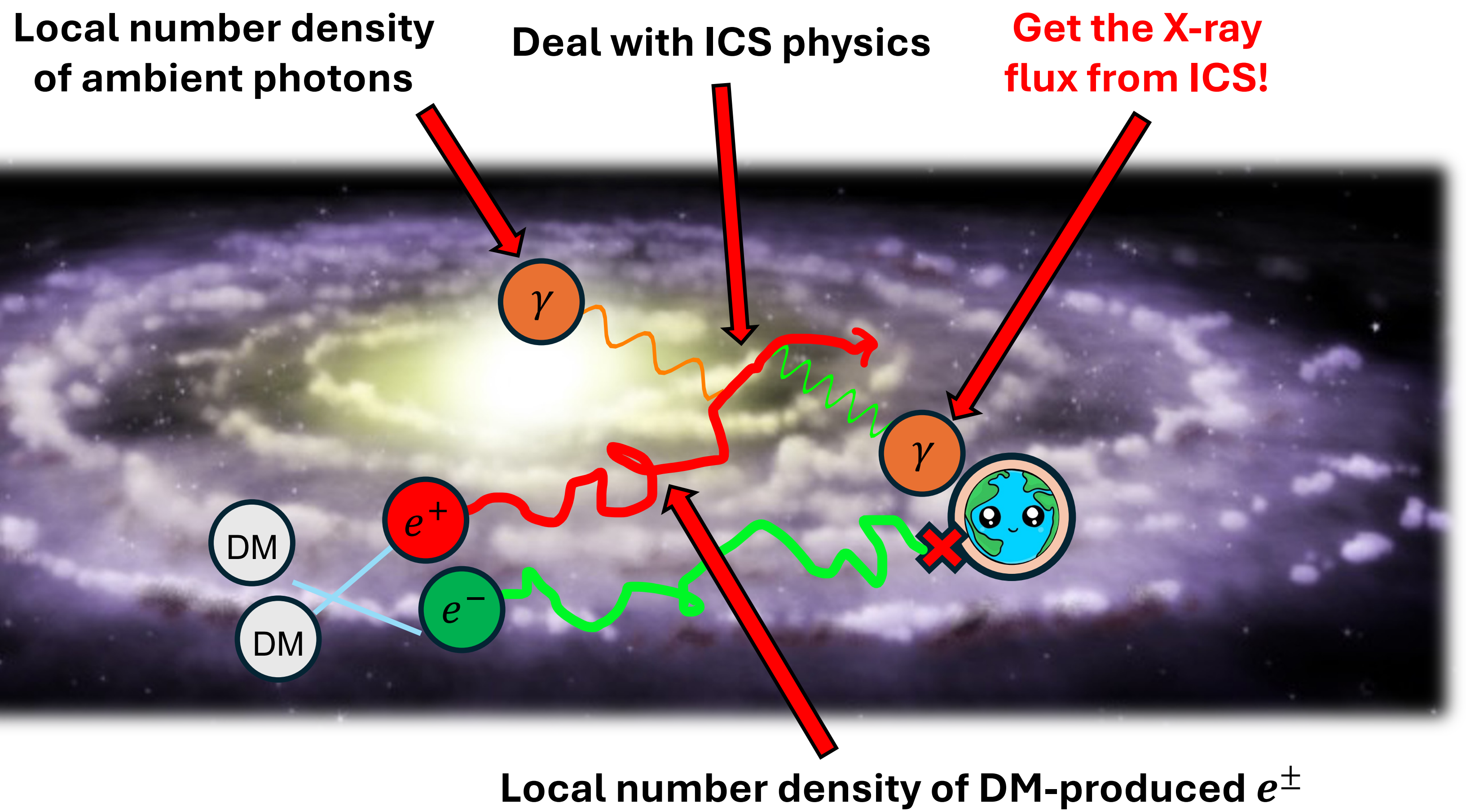


Constraining sub-GeV dark matter from diffuse X-rays



Constraining sub-GeV dark matter from diffuse X-rays

Local number density of DM-produced $e^{\pm}$

$$\vec{\nabla}\left(D\,\vec{\nabla}f_{e^{\pm}} - \vec{v}_c f_{e^{\pm}}\right) + \frac{\partial}{\partial K_e}\left(b_{loss} f_{e^{\pm}} + \beta^2 D_{pp}\frac{\partial f_{e^{\pm}}}{\partial K_e}\right) + Q_{e^{\pm}}^{DM} = 0$$

spatial diffusion — convection — energy loss — momentum space diffusion — source

Constraining sub-GeV dark matter from diffuse X-rays

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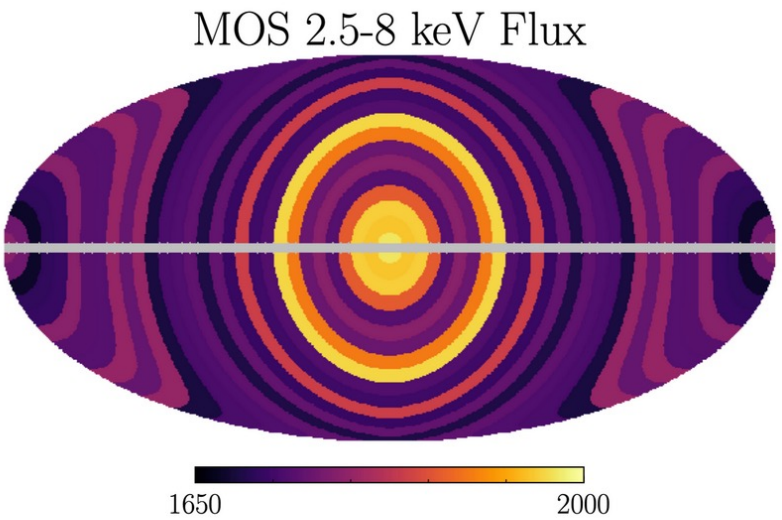
$$D = D_0\beta^{\eta}\frac{(R/R_0)^{\delta}}{[1+(R/R_0)^{\Delta\delta/s}]^{s}} \qquad D_{pp} = \frac{4}{3}\frac{1}{\delta(4-\delta^2)(4-\delta)}\frac{v_A^2 p^2}{D}$$

Transport parameters $(D_0, \eta, R_0, \delta, \Delta\delta, s, v_c, v_A, L)$ are set using CR fits

Constraining sub-GeV dark matter from diffuse X-rays



https://github.com/bsafdi/XMM_BSO_DATA

Datasets + Instrument response functions

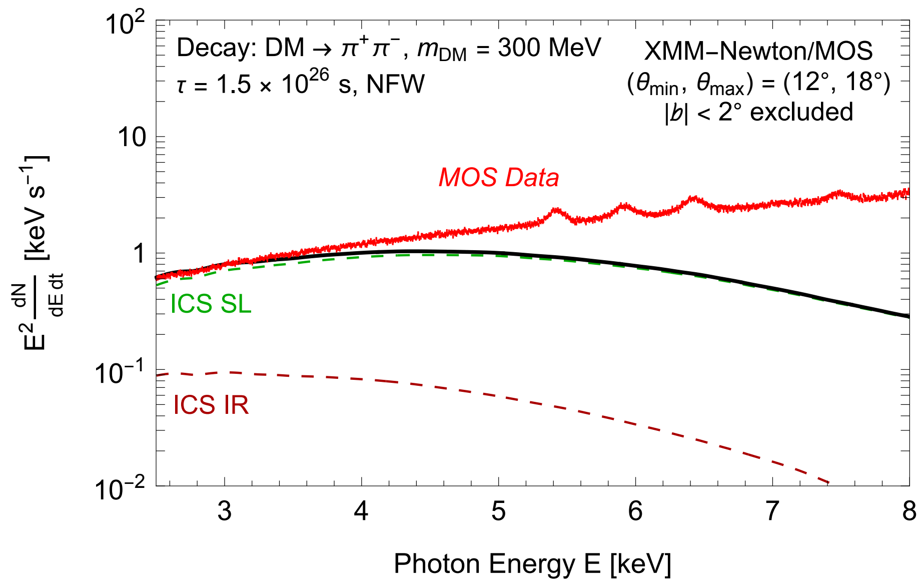
Constraining sub-GeV dark matter from diffuse X-rays

- Conservative approach

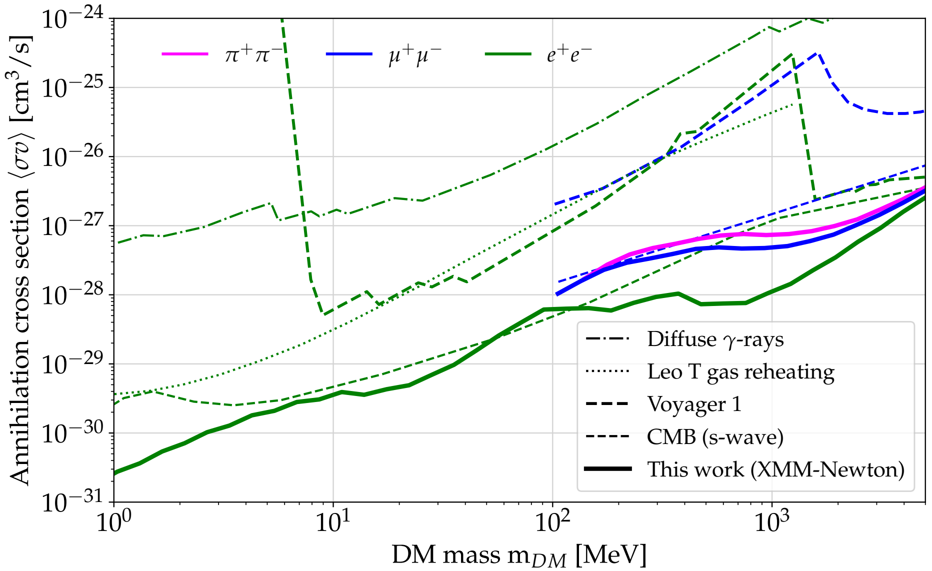
$$\chi^2_{>}(p, m_{DM}) = \sum_{i \in \text{bins}} \frac{\text{Max}\left(\Phi_{DM\gamma,i}(p, m_{DM}) - \Phi_i, 0\right)^2}{\sigma_i^2}$$

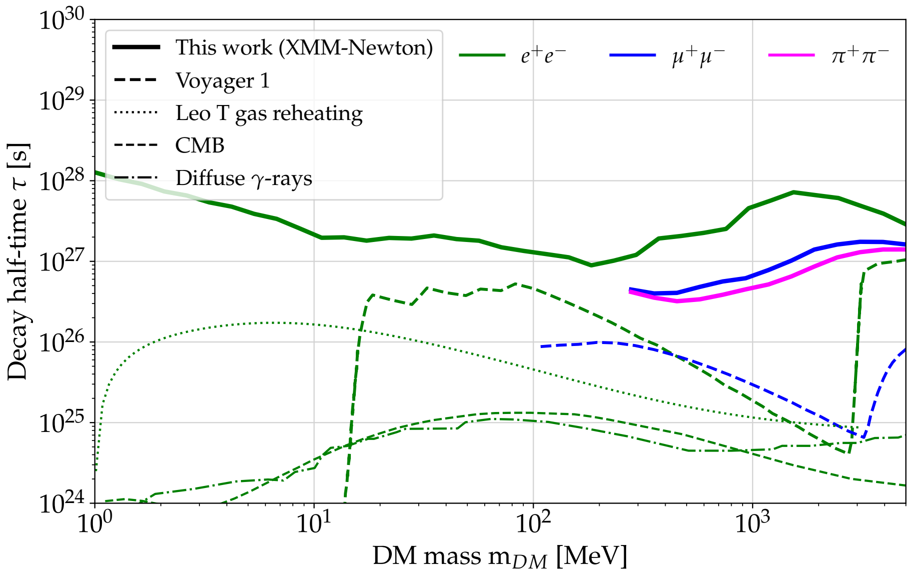
$$p = \langle \sigma v \rangle, \Gamma$$

- Impose a 2σ bound whenever $\chi^2_{>}(p, m_{DM}) \geq 4$



Constraining sub-GeV dark matter from diffuse X-rays





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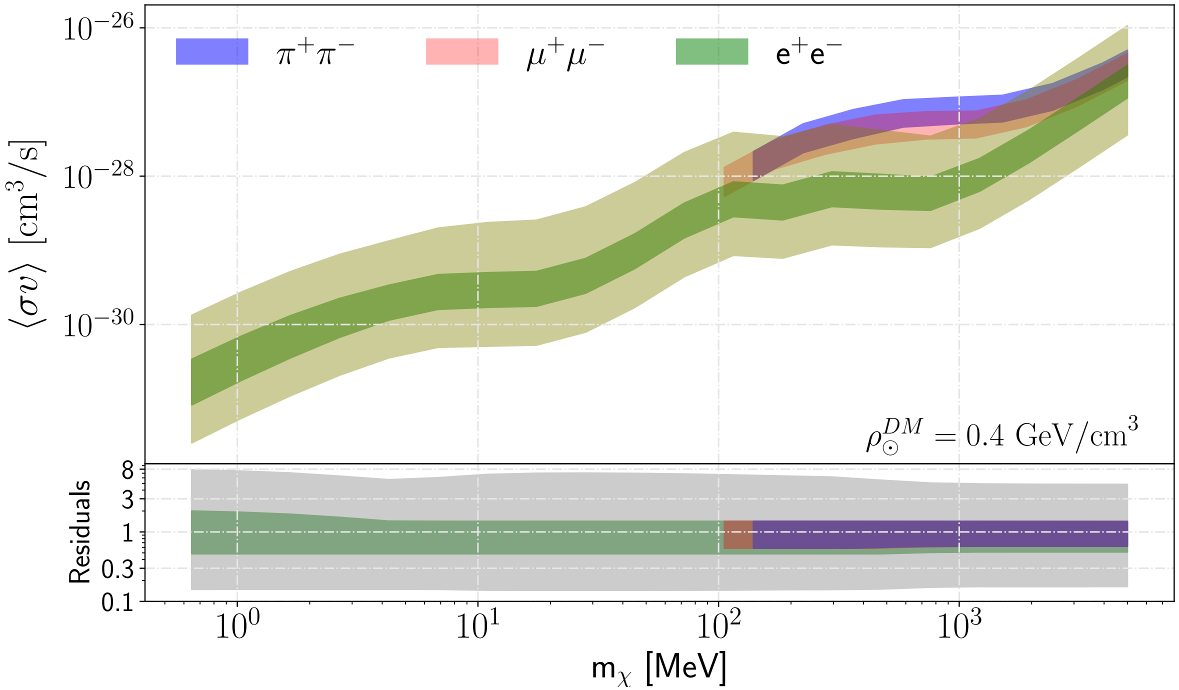


Halo height	H	$8.00^{+2.35}_{-1.96}$ kpc
Norm. of Diffusion coeff.	D_0	$1.02^{+0.12}_{-0.10} \times 10^{29}$ cm^{2}s^{-1}
Norm. rigidity	R_0	4 GV
Diffusion spectral index	δ	0.49 ± 0.01
β exponent	η	$-0.75^{+0.06}_{-0.07}$
Alfvén velocity	v_A	$13.40^{+0.96}_{-1.02}$ km/s
Break rigidity	R_b	312 ± 31 GV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

DM profiles:

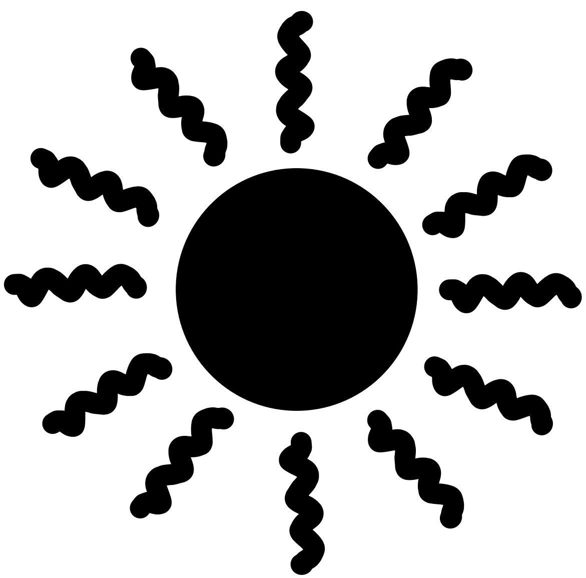
- NFW
- Burkert
- cNFW with $\gamma = 1.26$

About this talk

- Dark matter 101
- Constraining dark matter candidates from diffuse X-rays
  - Sub-GeV DM
  - Primordial black holes

Constraining PBHs from diffuse X-rays

[Hawking, *Commun.Math.Phys.* 43 (1975) 199]

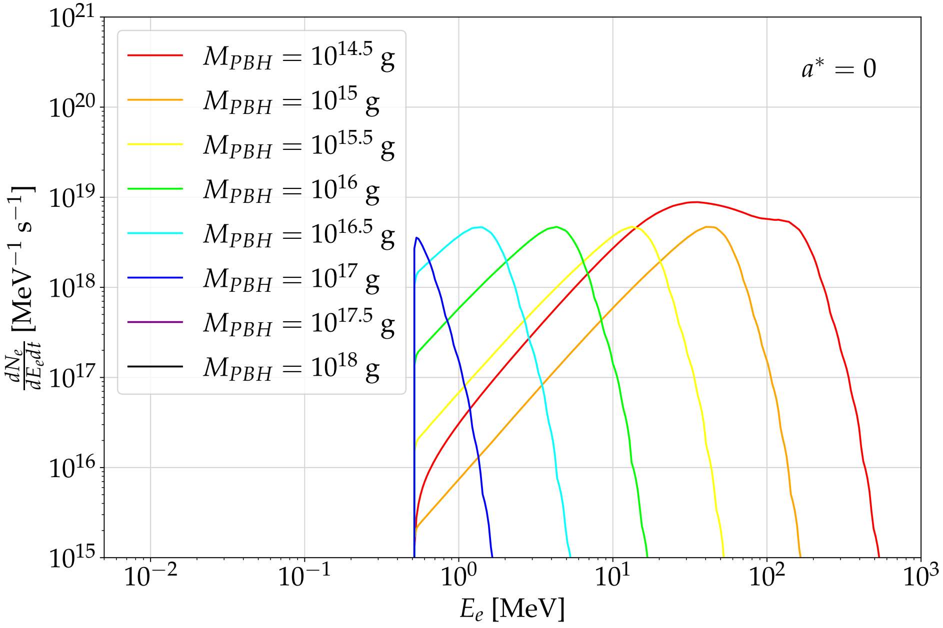


$$T = \frac{1}{4\pi G M} \frac{\sqrt{1-a^{\star 2}}}{1+\sqrt{1-a^{\star 2}}} \qquad a^\star = J/(GM)^2$$

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

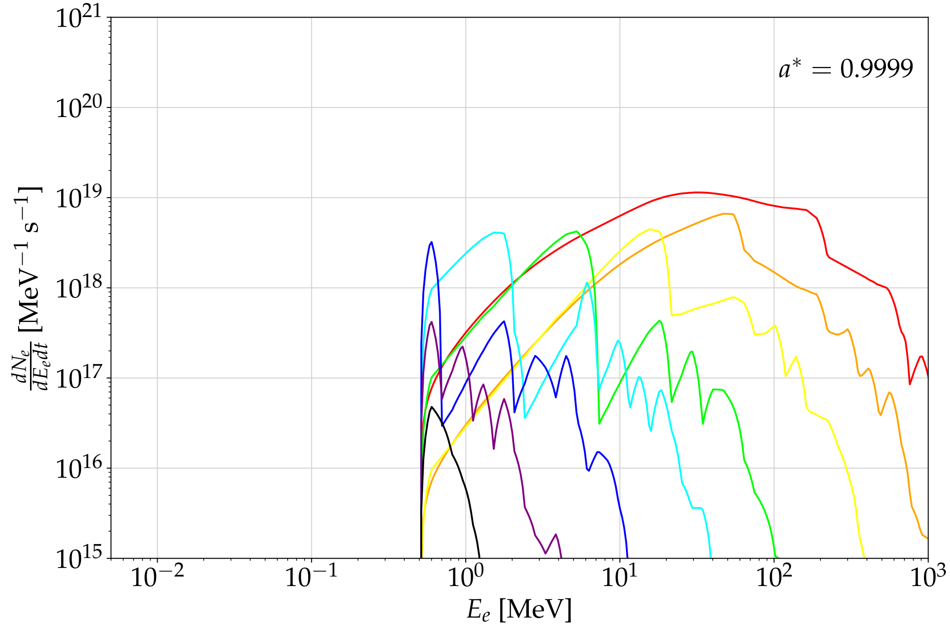
$$E_i' = E_i - m\Omega \qquad \Omega = \frac{a^\star}{2GM\left(1+\sqrt{1-a^{\star 2}}\right)}$$

Constraining PBHs from diffuse X-rays



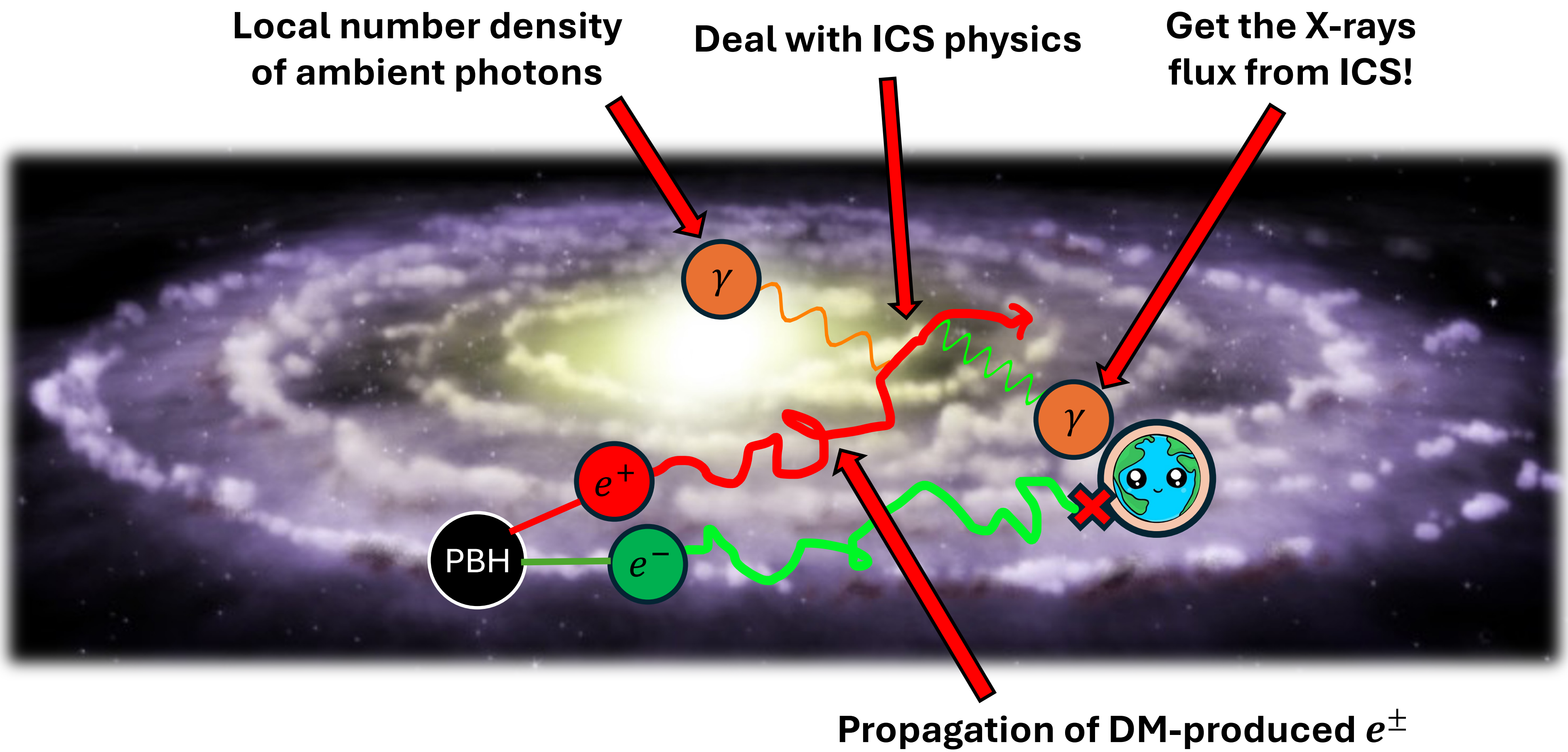
BlackHawk

[Arbey, Auffinger, *Eur.Phys.J.C* 79 (2019) 8, 693],
[Arbey, Auffinger, *Eur.Phys.J.C* 81 (2021) 10]



[De la Torre Luque, **JK** & Balaji, arXiv:2406.11949 (accepted in *Phys.Rev.D*)]

Constraining PBHs from diffuse X-rays



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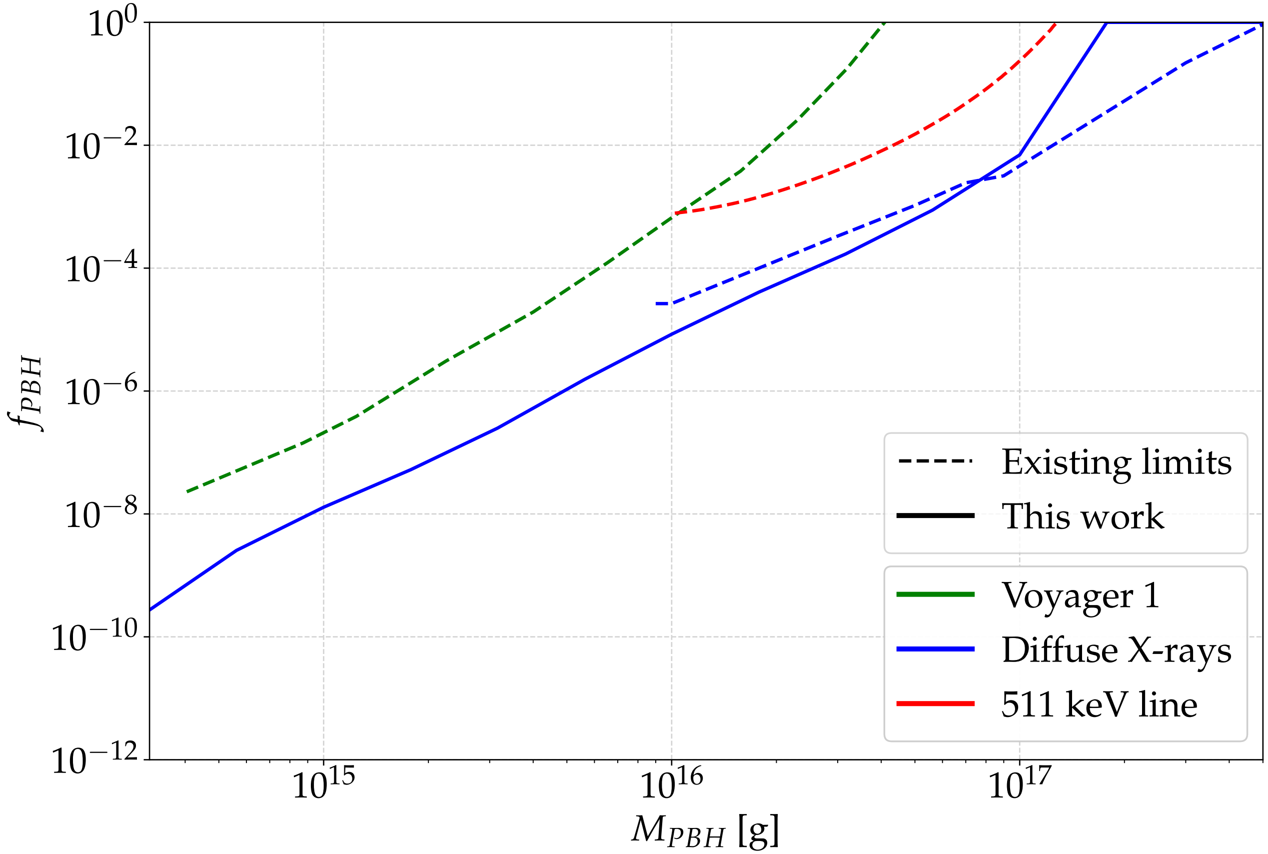

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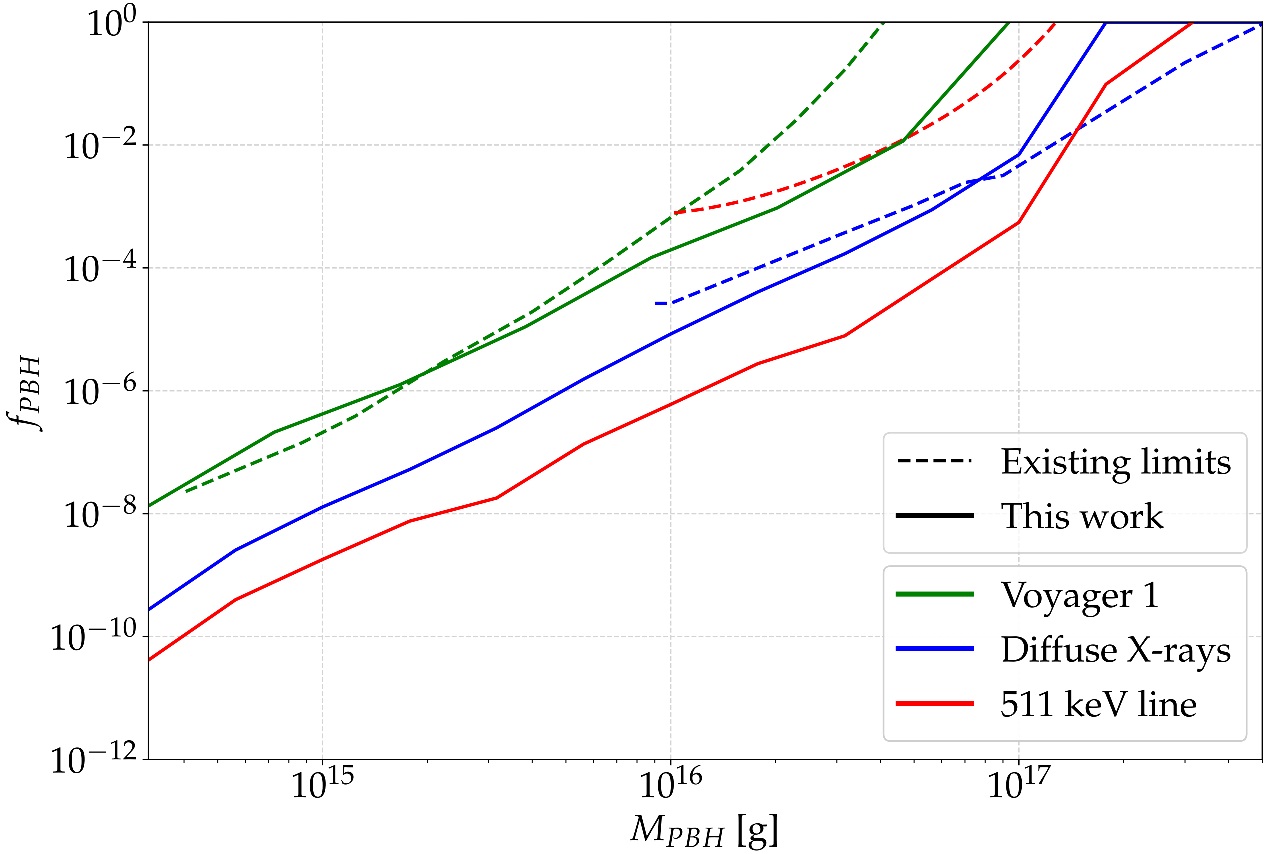

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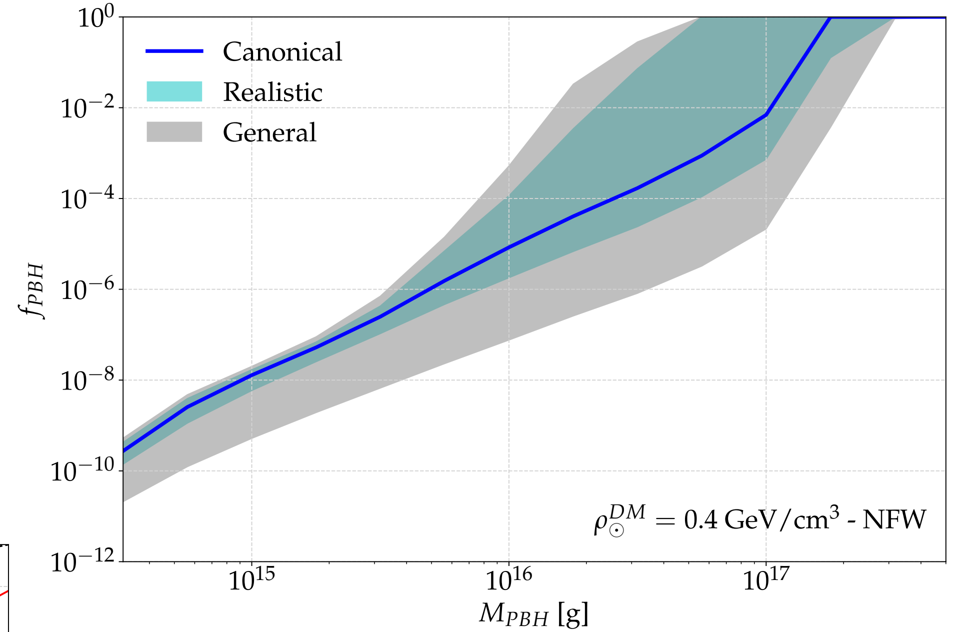

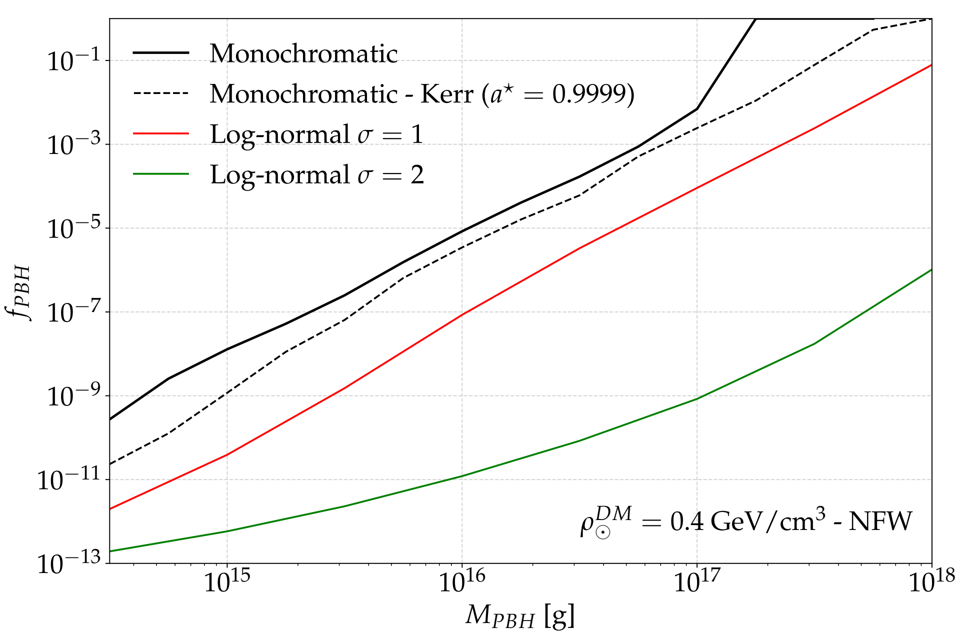

Realistic: $v_A \in [7, 20]$ km/s
$L \in [4, 12]$ kpc

General: $v_A \in [0, 40]$ km/s
$L \in [3, 16]$ kpc

Conclusion

- Considering secondary emissions can help us circumventing the MeV gap in γ-ray observatories
- As a bonus: it has a great constraining power
- Robustness is debatable, due to numerous astro uncertainties
- Possible improvement: Astrophysical background modeling

Thank you for your attention!