

High energy neutrinos from Dark Matter around blazars



Filippo Sala

U. Bologna



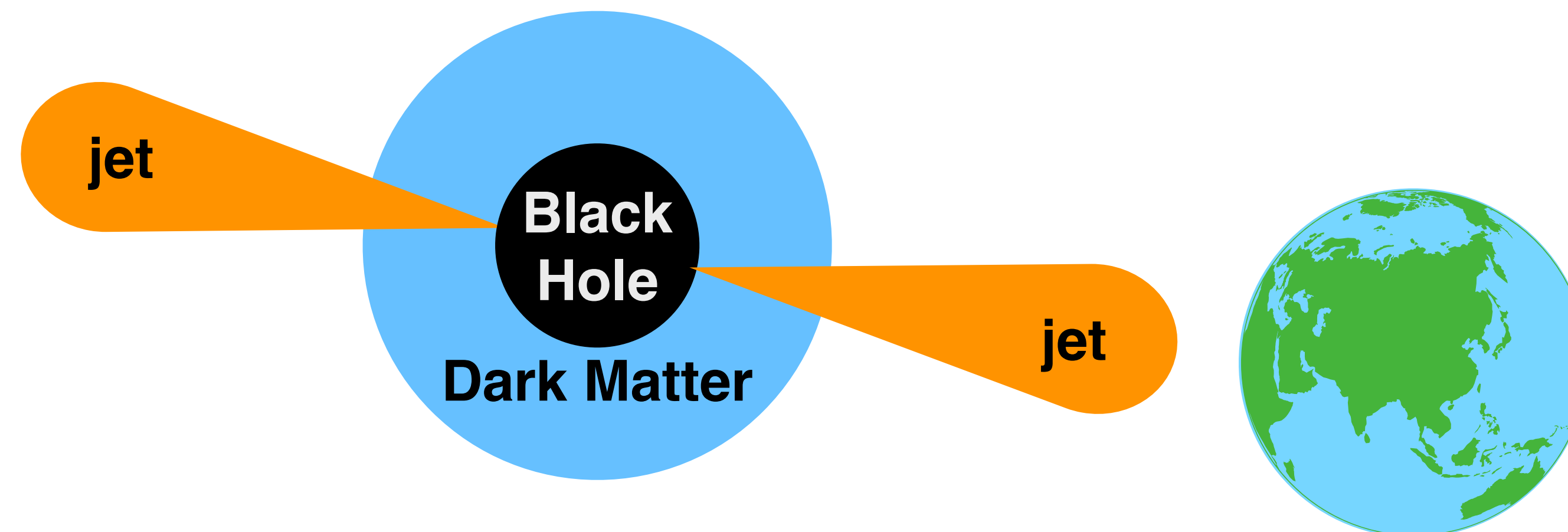
U. Oslo, 22/4/2026

Image credit: IceCube/NASA

Dark Matter ?

High energy neutrinos ?

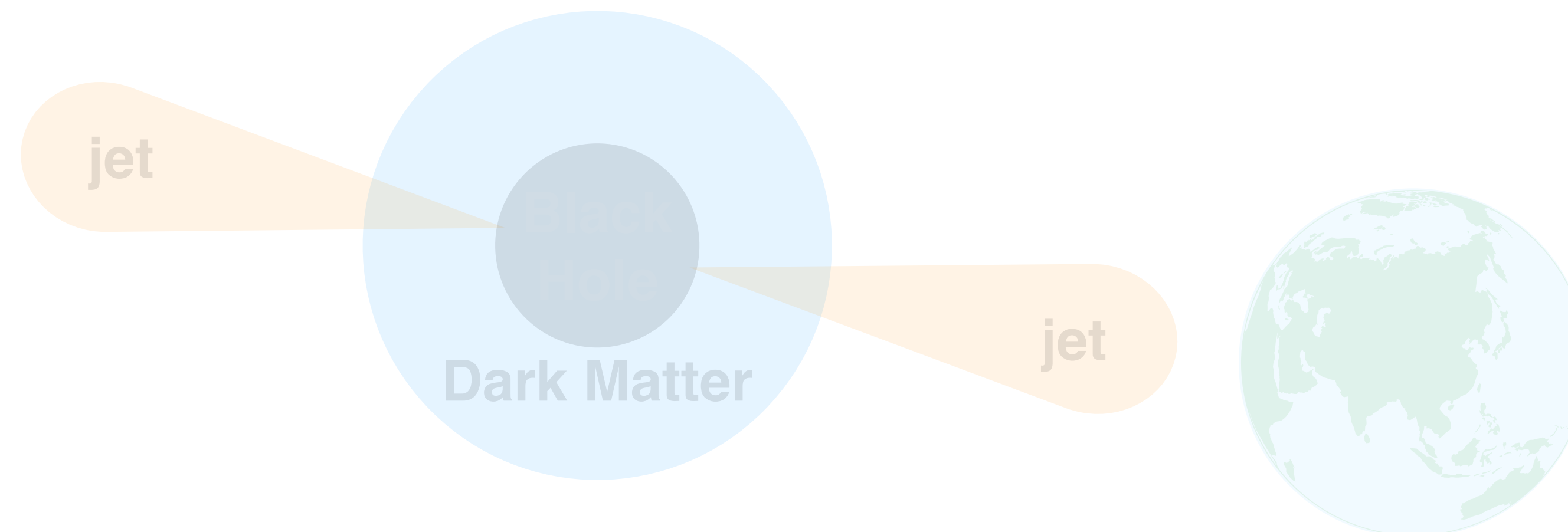
High energy neutrinos from dark matter around blazars



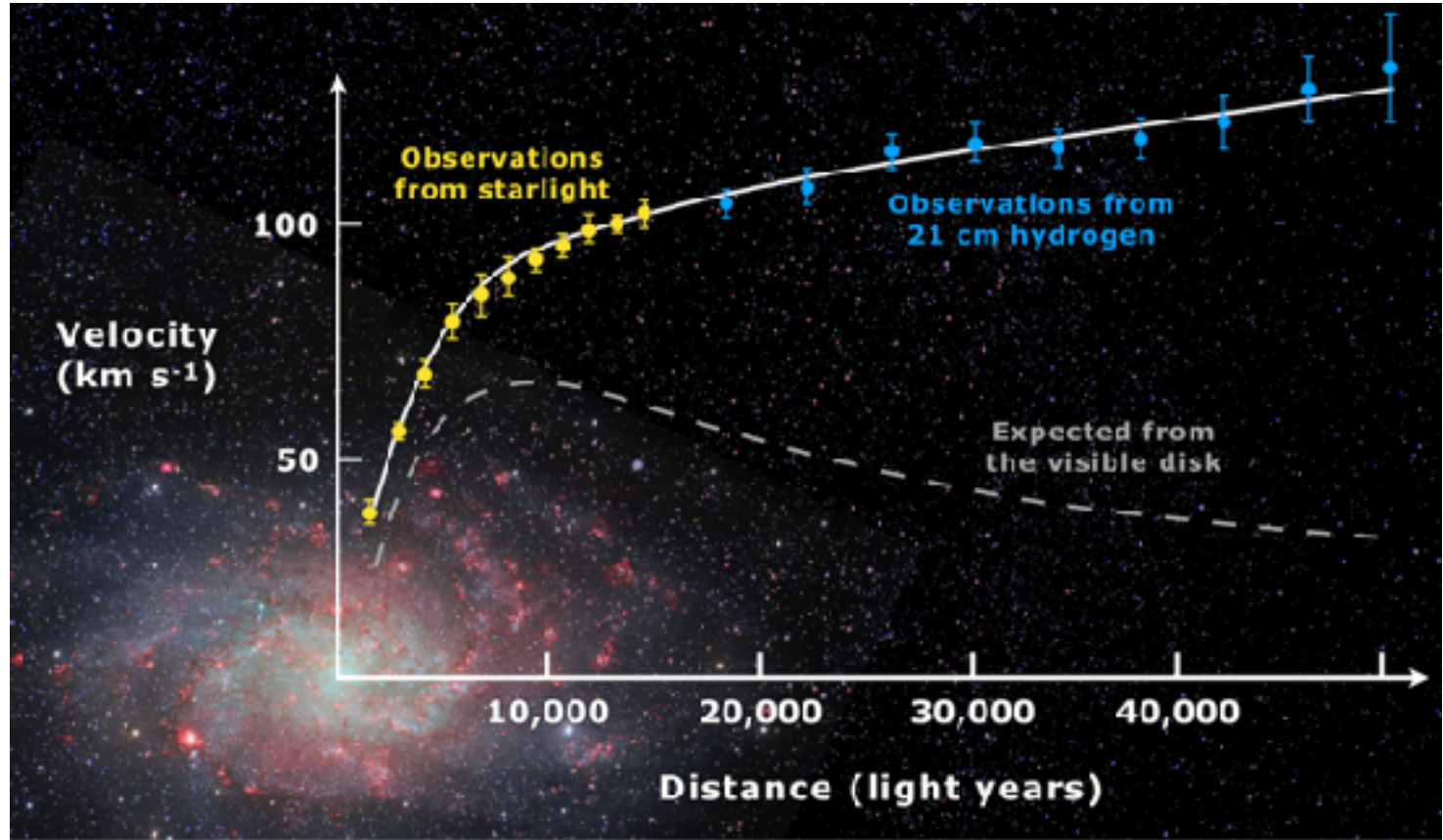
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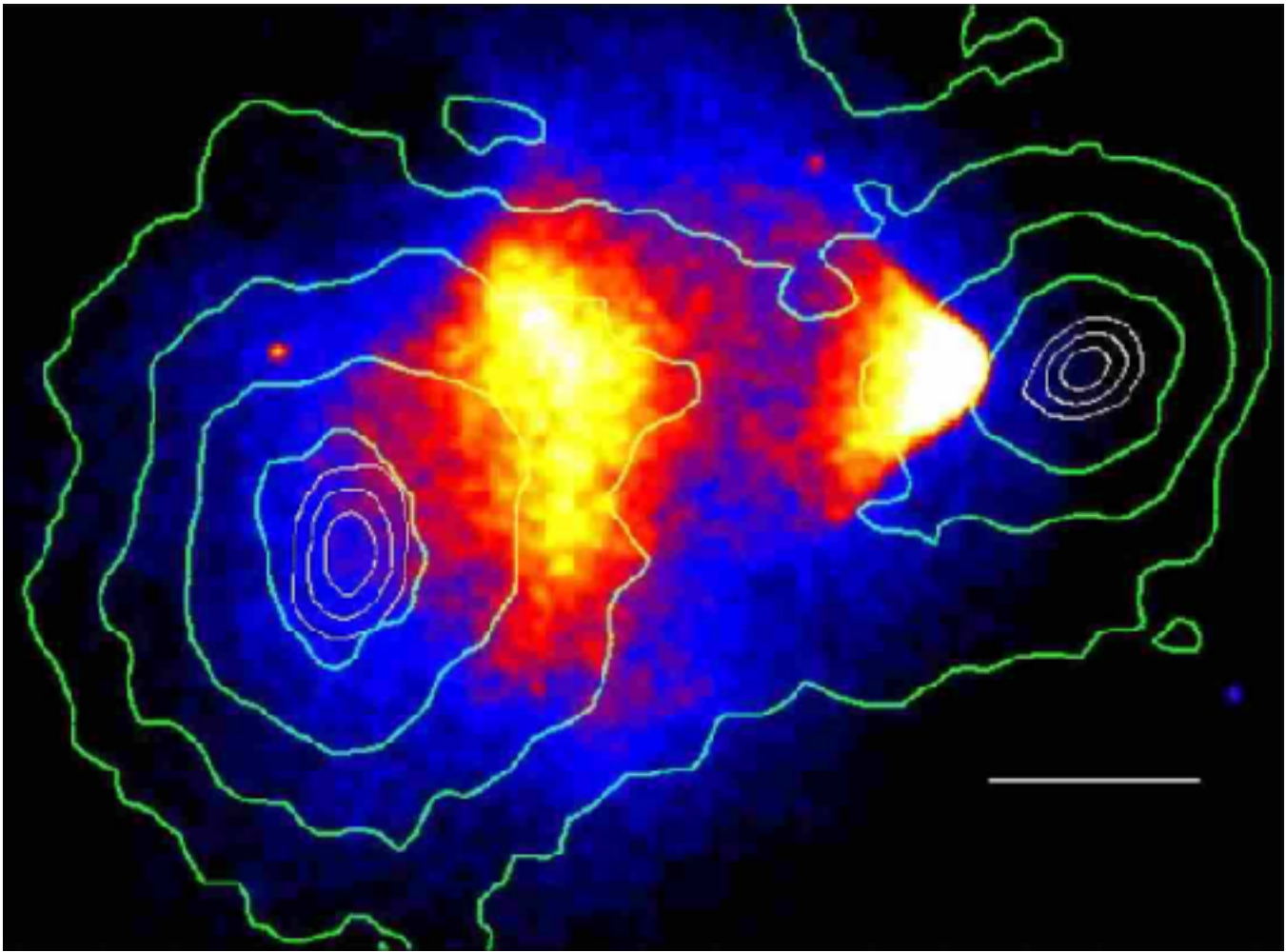
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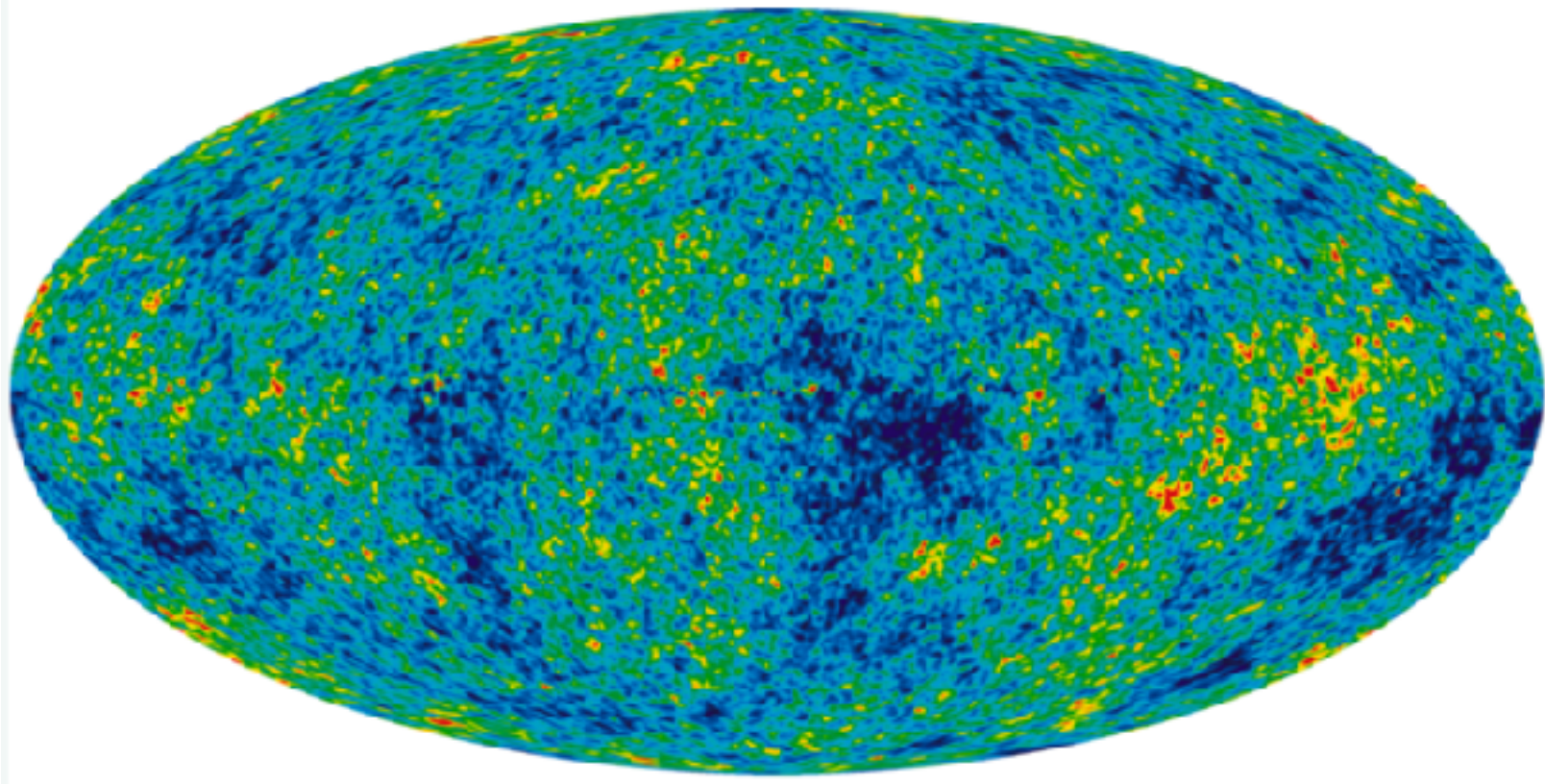
Problems with our model of the Universe



~ 10's kpc



~ Mpc



~ 10 Gpc

Very different scales!

Dark Matter

only known hypothesis that solves all of them at once

Dark Matter 2010's



Dark Matter ~~2010's~~ 2020's



Rules of the Dark Matter game

“**Particle**” properties

- feels **Gravity**
- CMB (& not spoil BBN,...) = **non-baryonic**
- Invisible now = almost **electrically neutral**
- **stable** enough

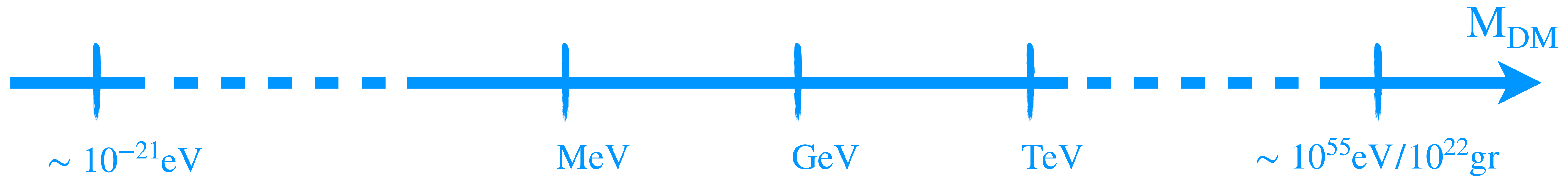
How much? $\Omega_{\text{DM}} \simeq 0.26$ $\left(\Omega_{\text{DM}} = \frac{\rho_{\text{DM}}}{\rho_{\text{crit}}} \quad \rho_{\text{crit}} = \frac{5 \text{ protons}}{\text{meter}^3} \right)$

“**Historical**” properties

Since when? enough **before CMB**

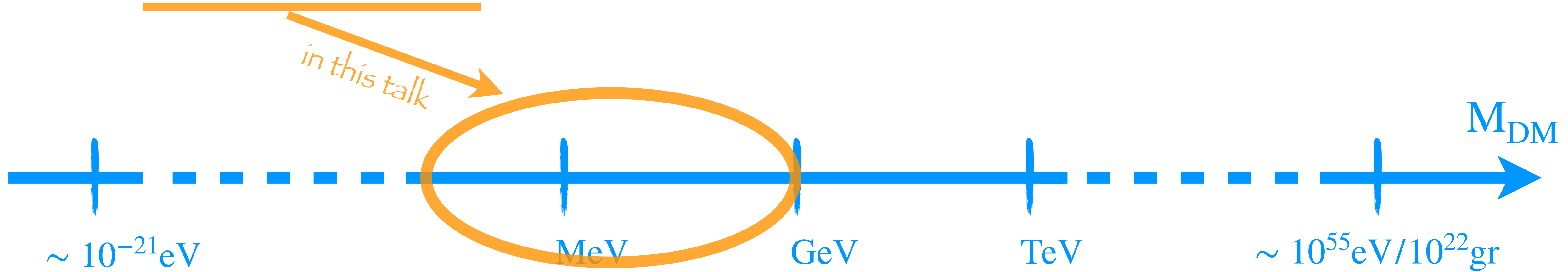
How fast? **Non-relativistic**

Status of the Dark Matter game

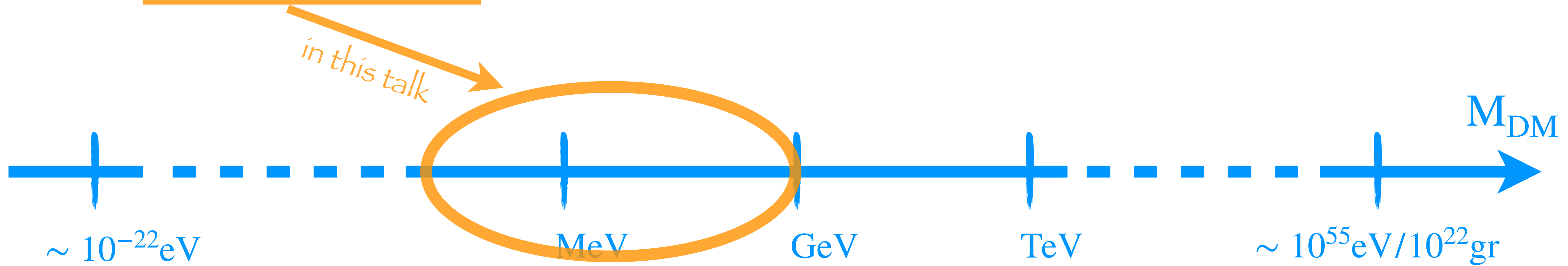


> 80 orders of magnitude in mass of viable candidates!

Sub-GeV Dark Matter



Sub-GeV Dark Matter



Cosmo histories motivate it/exist

Why?

Links with many astro questions

New experiments/analyses could “easily” find it

Sub-GeV Dark Matter

$$\langle\sigma v\rangle\approx\frac{\alpha^2}{M_{\rm DM}^2}\qquad\langle\sigma v\rangle_{\rm fo}\simeq\frac{1}{(20\text{ TeV})^2}$$

Thermal freeze-out
at small coupling

SIMP

Hochberg+ 1402.5143

...

ELDERs

Kuflik+ 1512.04545

Forbidden DM

D'Agnolo Ruderman 1505.07107

Cosmo histories motivate it/exist

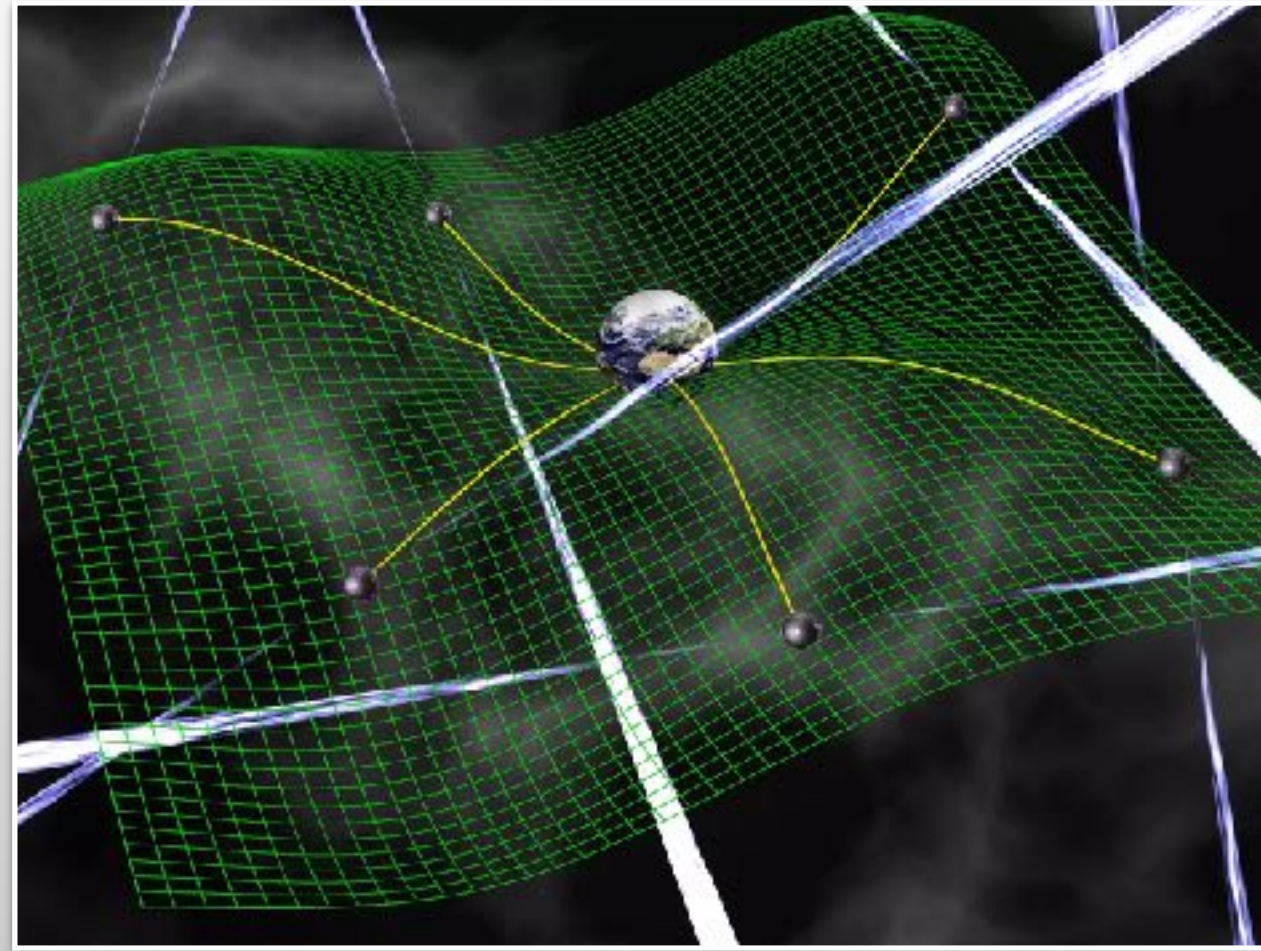
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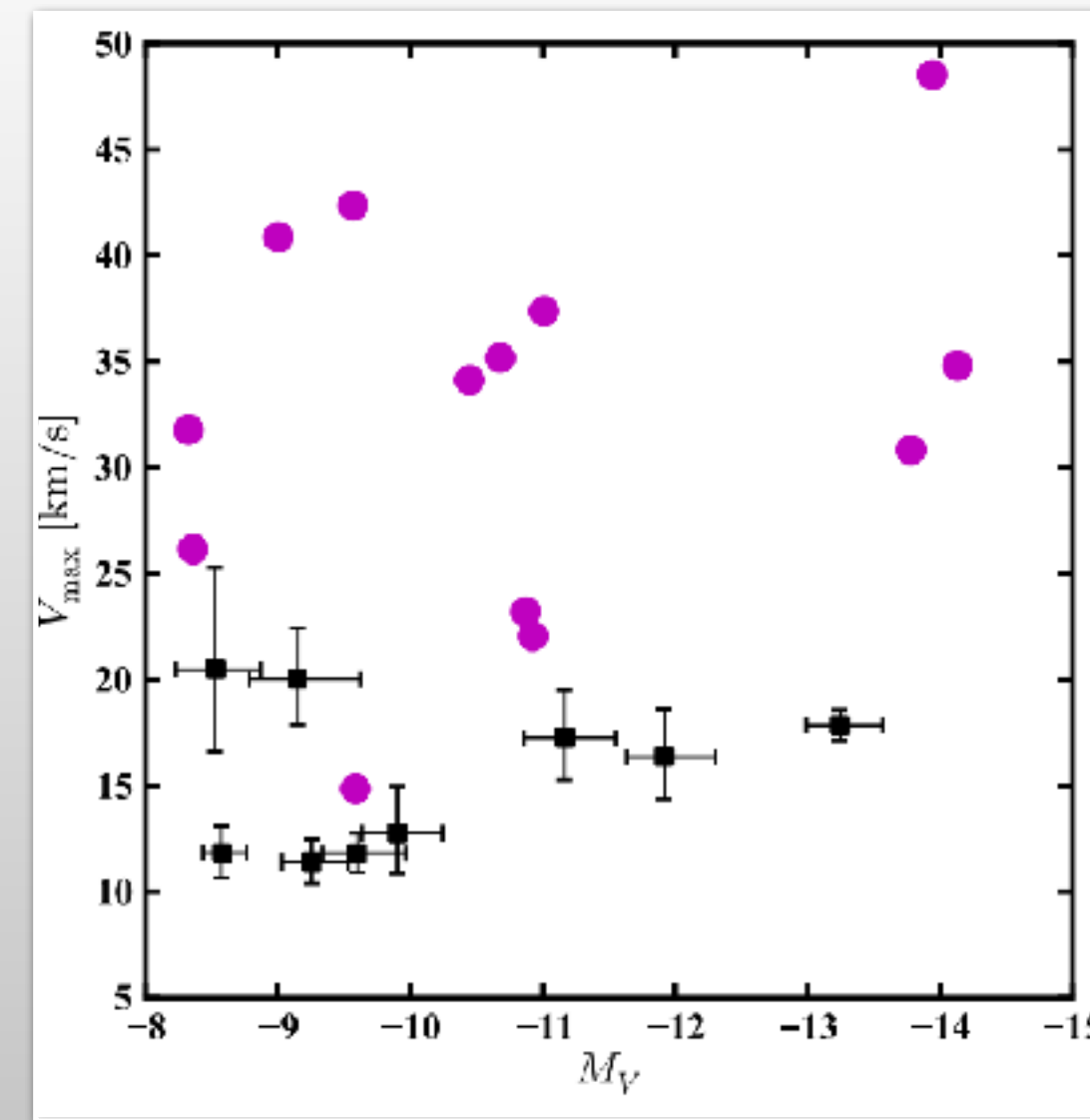
Sub-GeV Dark Matter

Gravity Waves at PTAs?



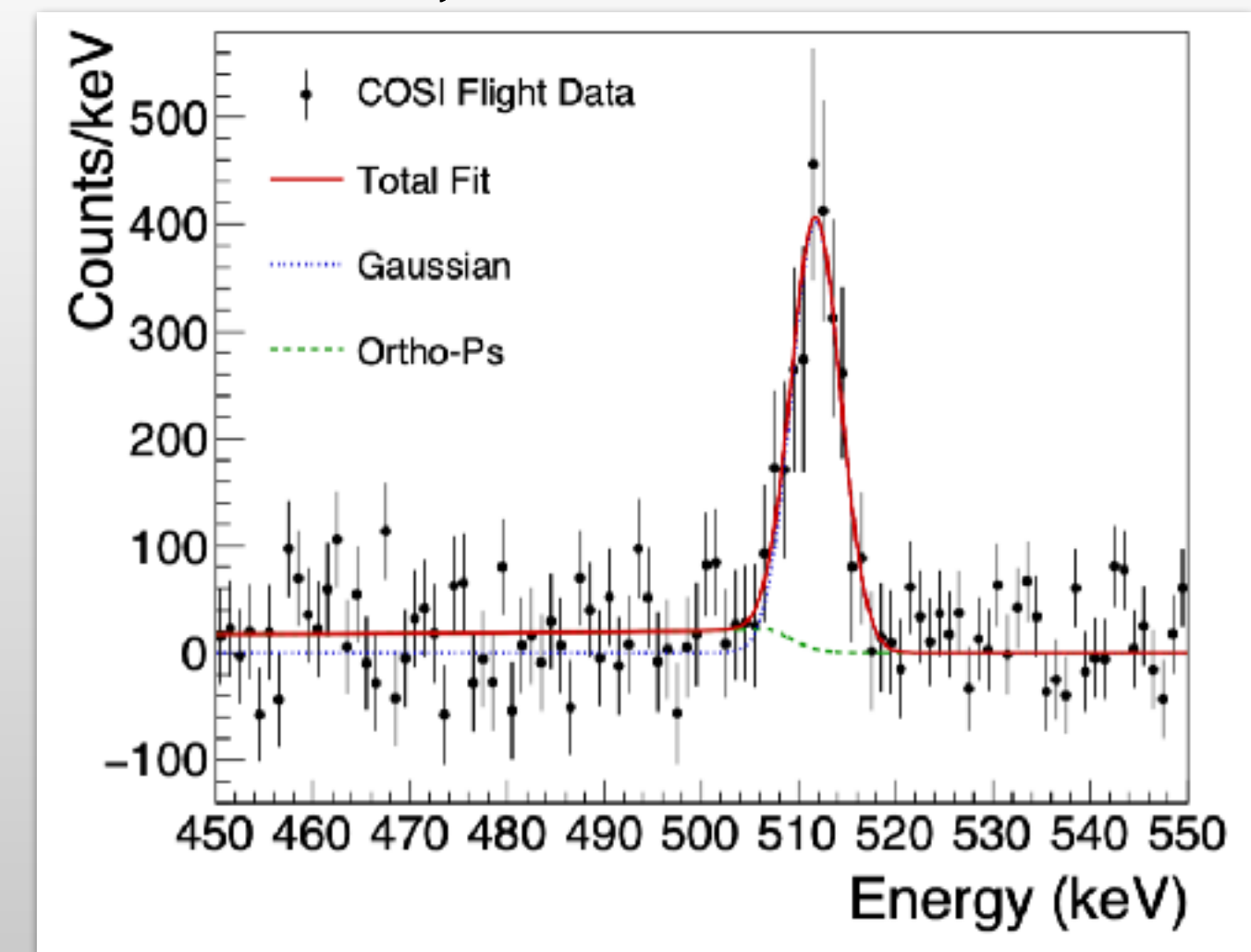
Nanograv 2104.13930, ...
Bringmann+ 2306.09411, ...

Small scale troubles of DM?



Boylan-Kolchin 1103.0007, Tulin Yu 1705.02358,...

Galactic photon line @ 511 keV? ...



Boehm Hooper Silk Casse astro-ph/0309686, ...
... Das+ 2506.00847

Why?

Links with many astro questions [not true for other DM masses!]

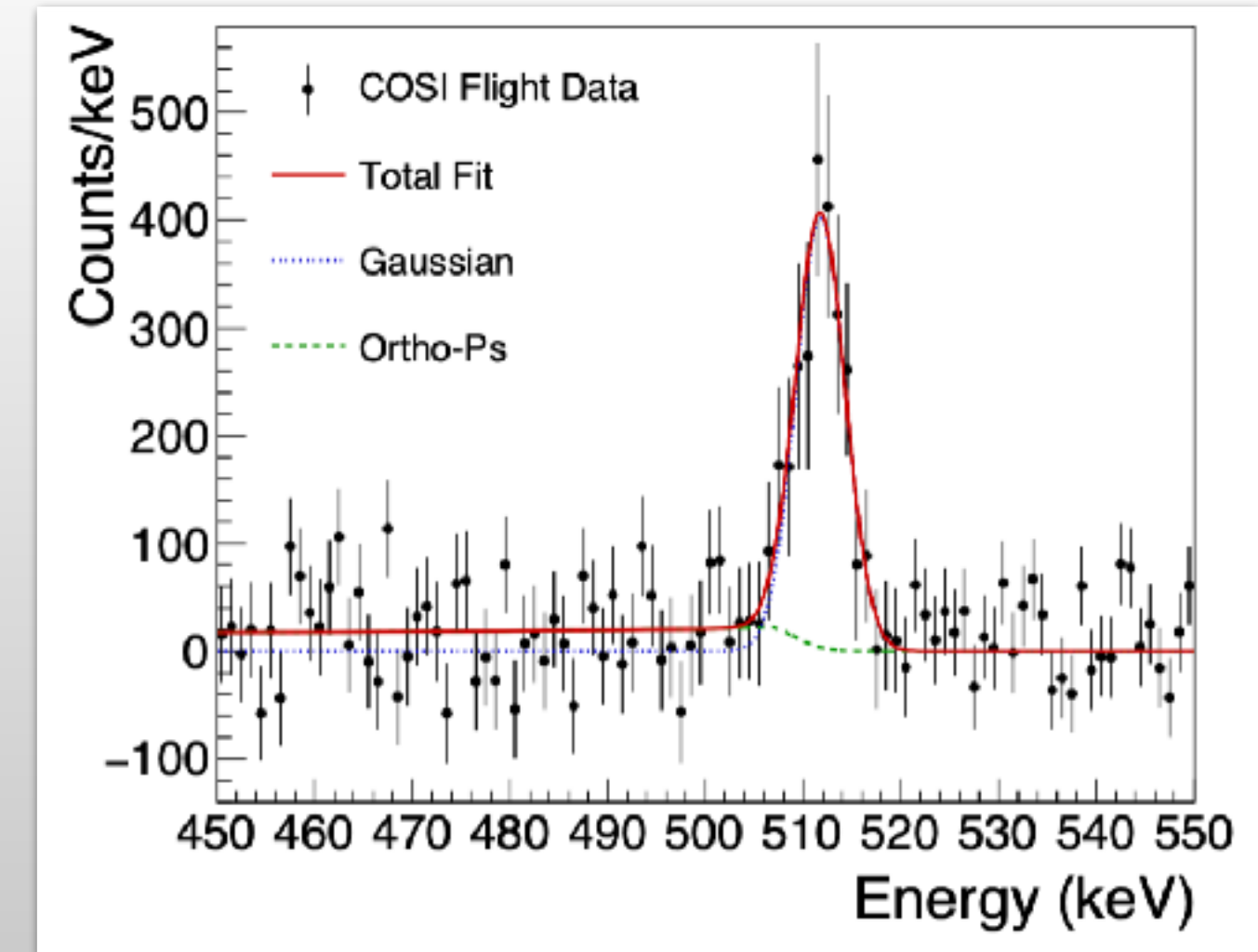
New experiments/analyses could “easily” find it

Sub-GeV Dark Matter



Can be explained with dark matter
with $M_{\text{DM}} \gtrsim 10 \text{ MeV}$
ask off-line if interested!

Galactic photon line @ 511 keV? ...



De La Torre Luque Balaji Fairbairn FS Silk 2410.16379

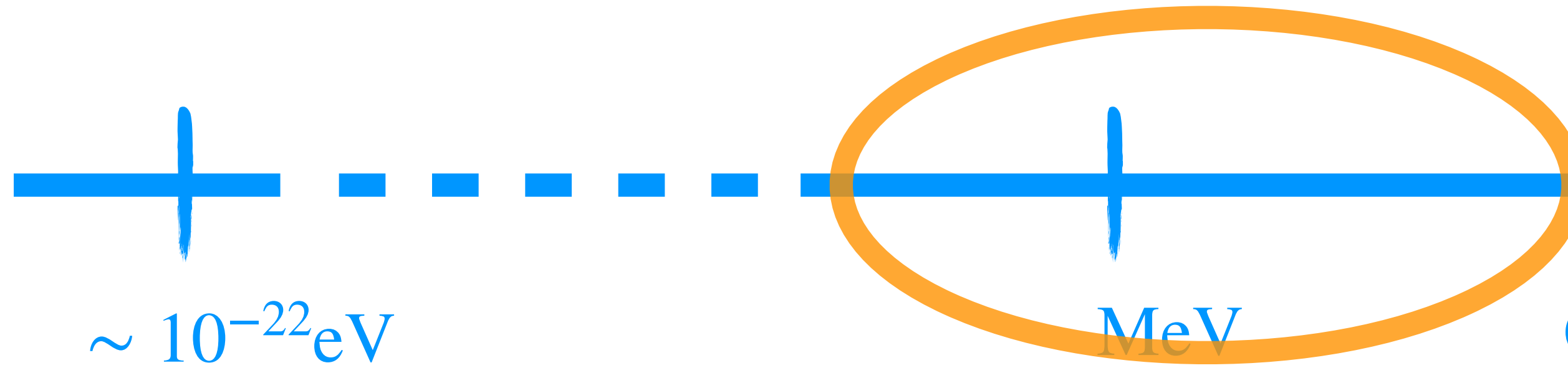
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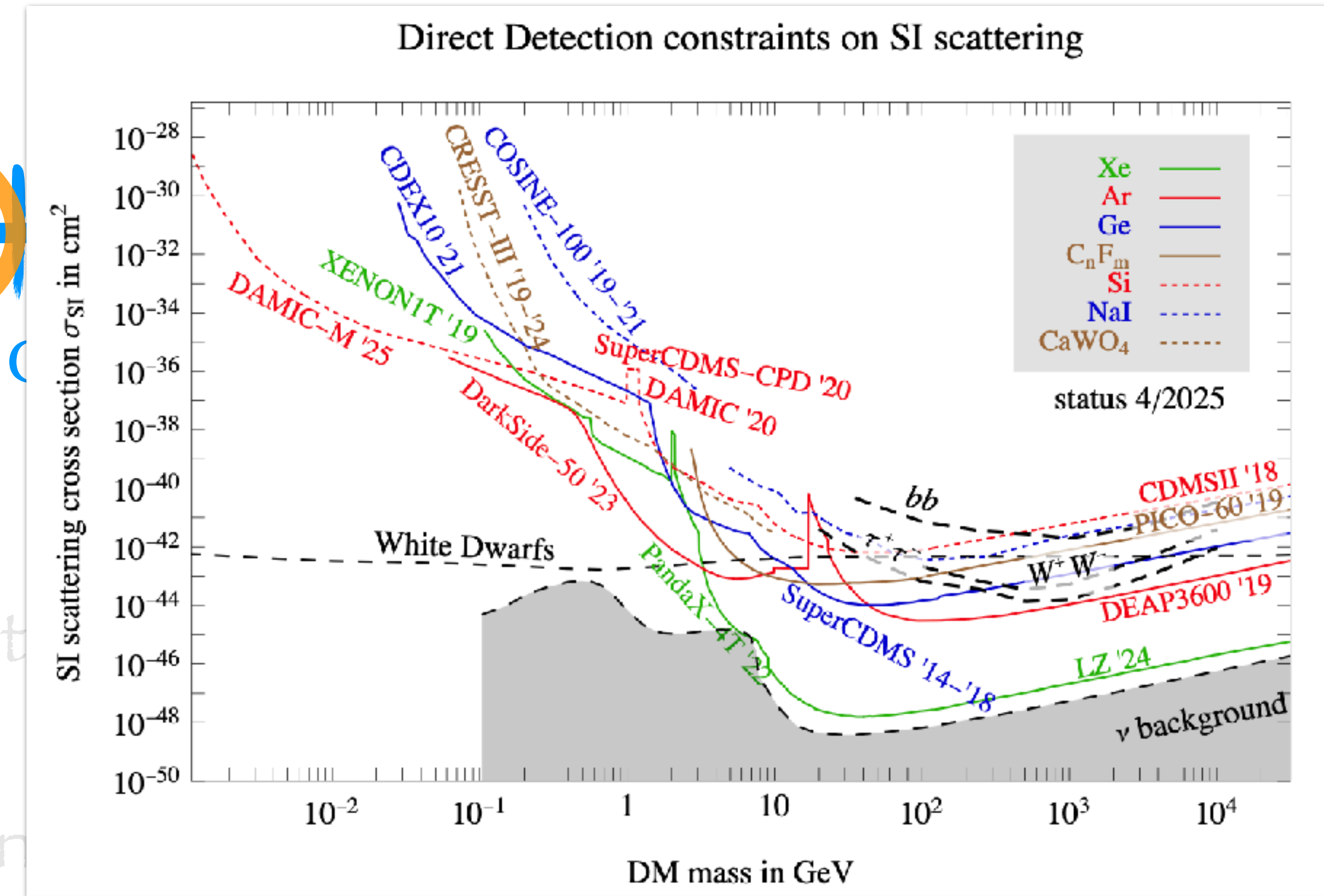
Sub-GeV Dark Matter



why?

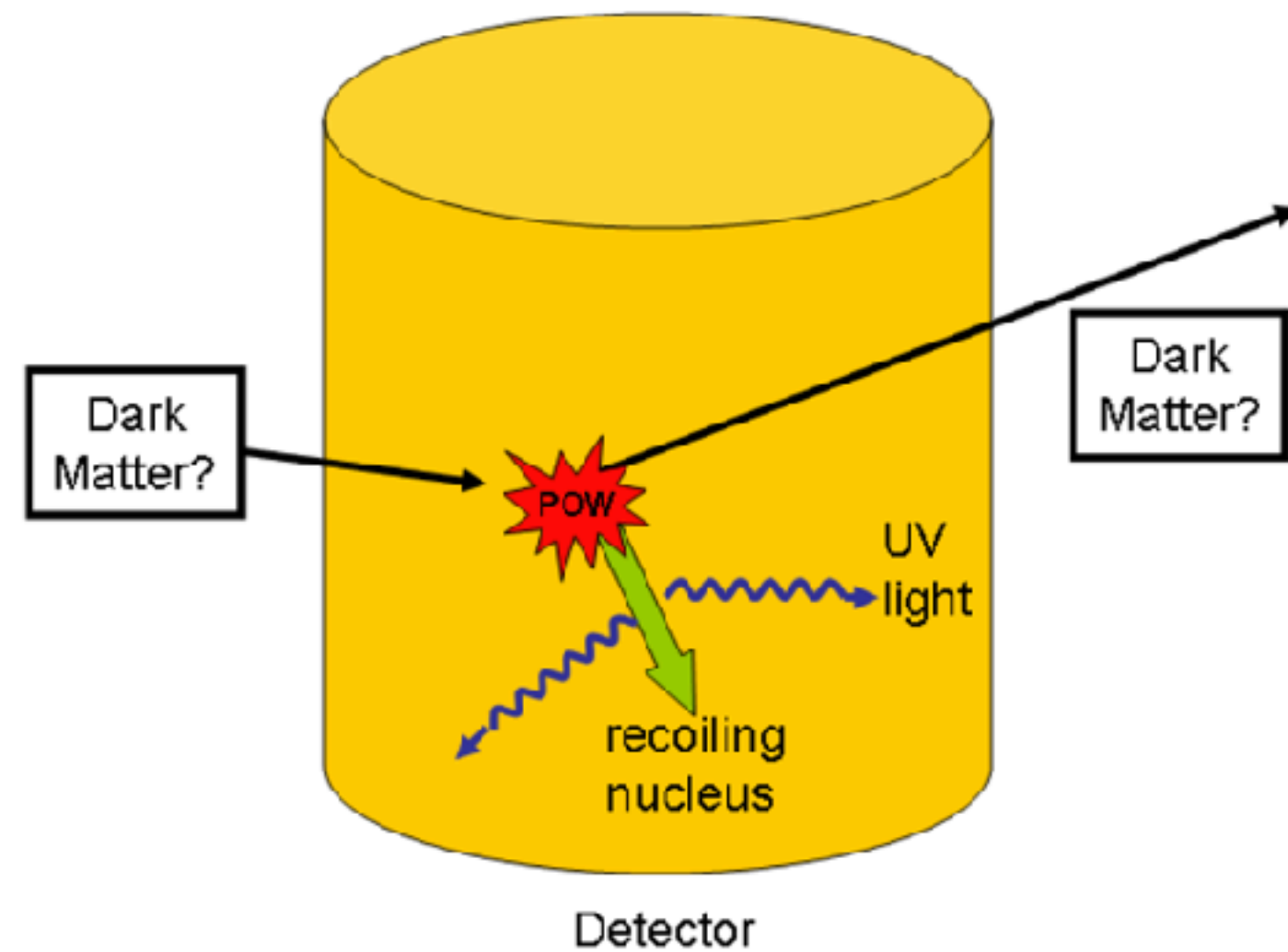
Cosmo histories motivated

Links easily with many



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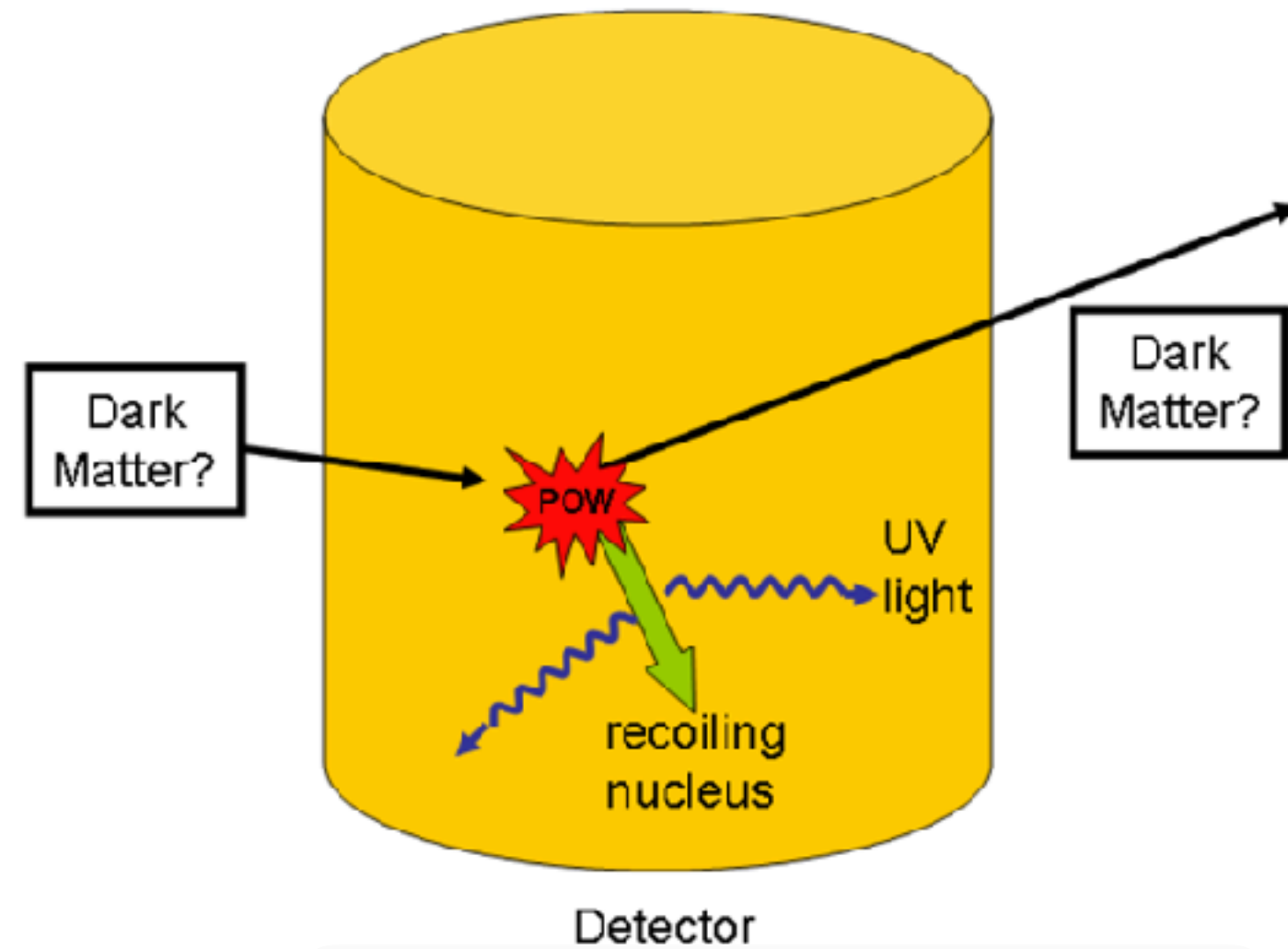
Direct detection of Sub-GeV DM?



Challenge

$$E_{\text{NR}} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim 190 \text{ eV} \times \left(\frac{m_\chi}{500 \text{ MeV}} \right)^2 \left(\frac{16 \text{ GeV}}{m_N} \right)$$

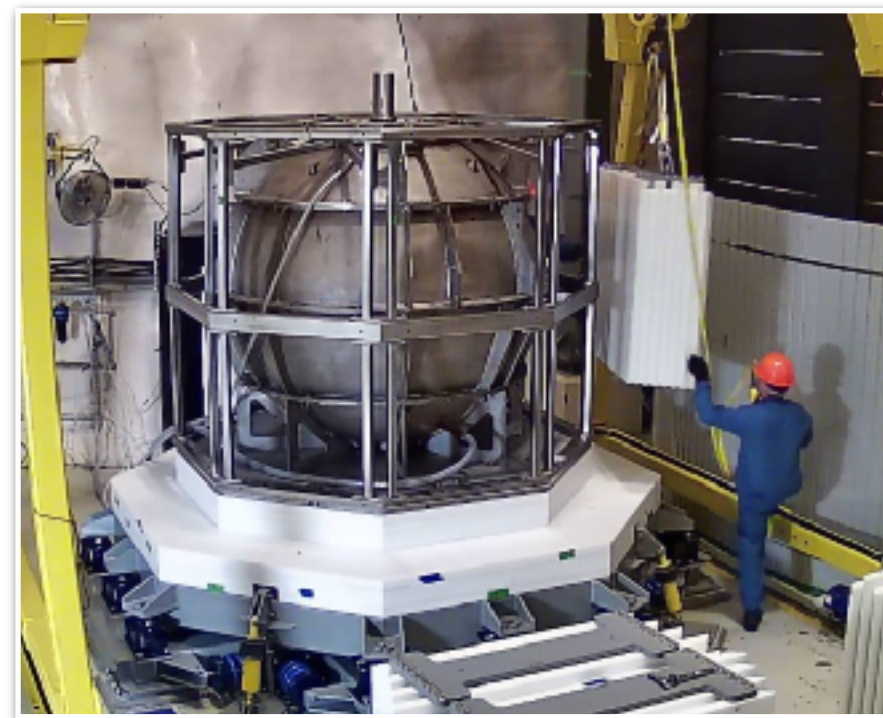
Direct detection of Sub-GeV DM?



Solutions 1: lower m_N

NEWS-G ...

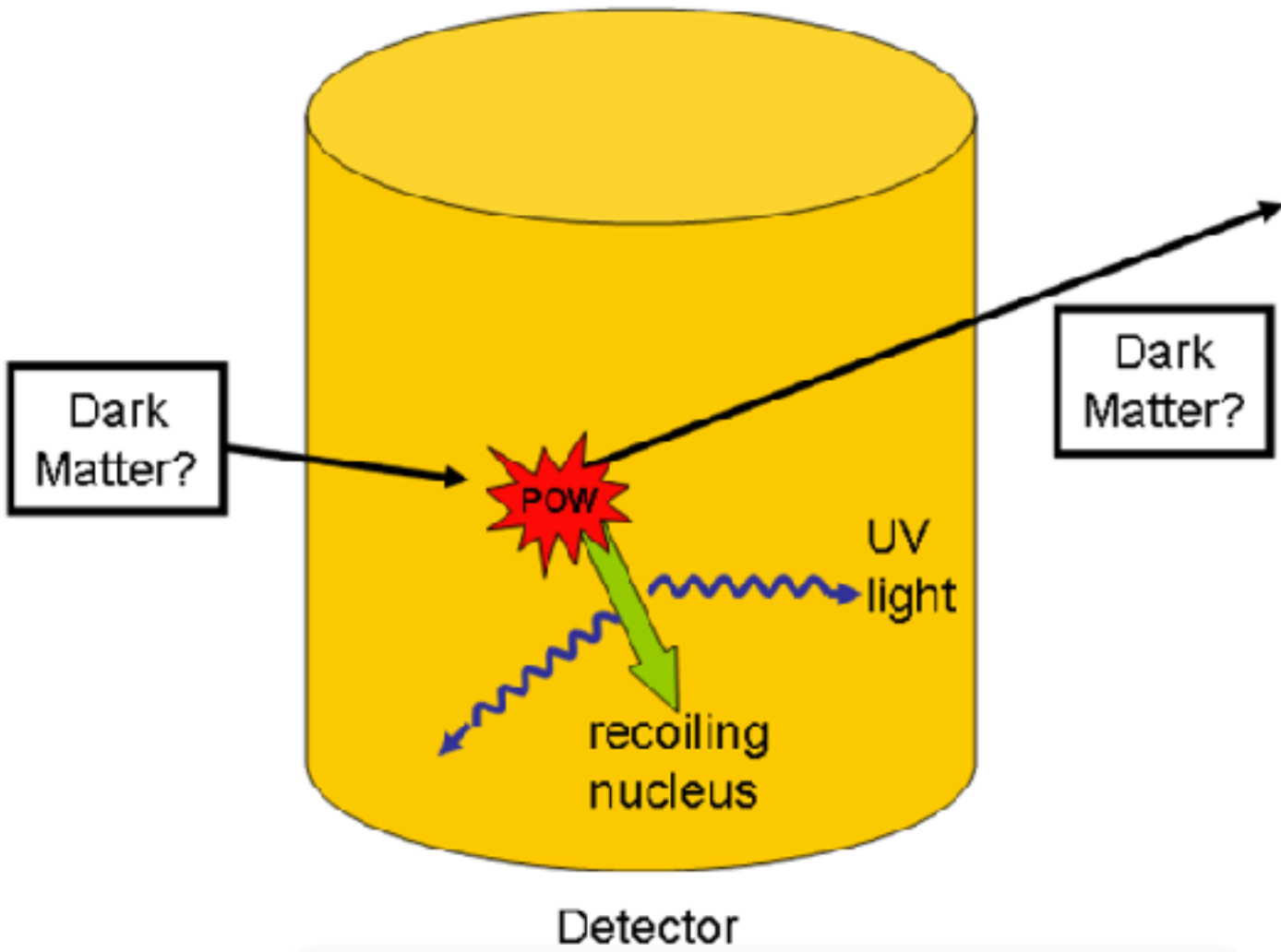
e.g. [SciPost Phys. Proc. 12 \(2023\) 024](#)



Challenge

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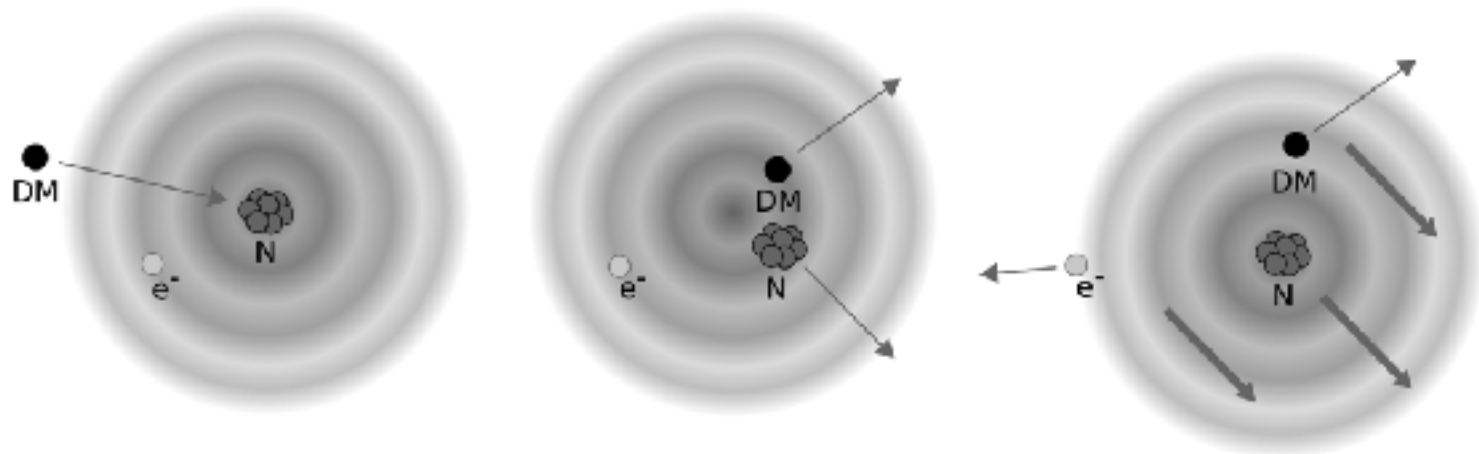
Solutions 2: lower the thresholds

PHONON(S) & similar beasts

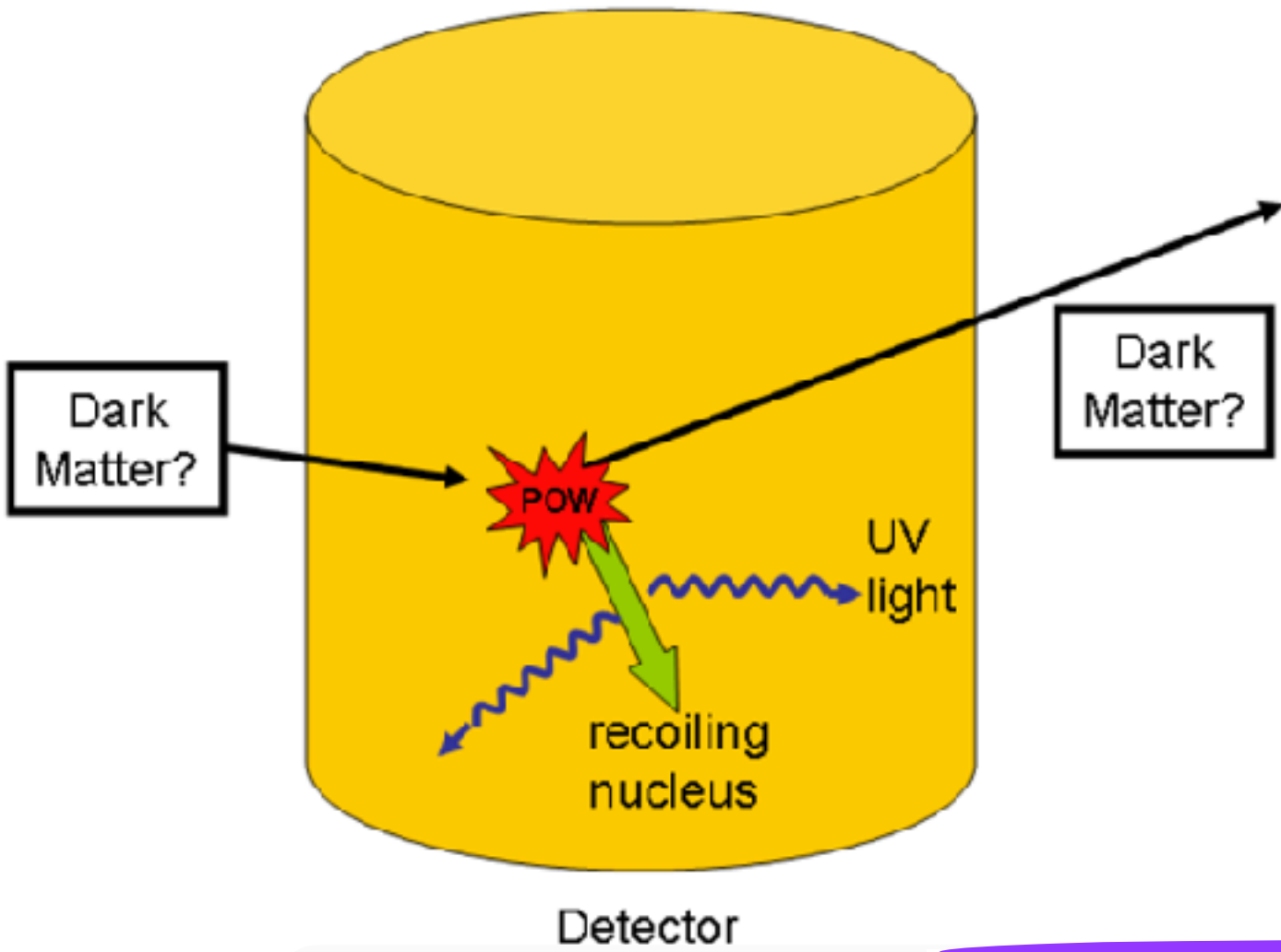
[Caputo+ 1907.10635](#)
[Campbell-Deem+ 2205.02250 ...](#)
CRESST-III ...

MIGDAL & brem

[Kouvaris Pradler 1607.01789](#)
[Ibe+ 1707.7258 ...](#)
SuperCDMS SENSEI ...



Direct detection of Sub-GeV DM?



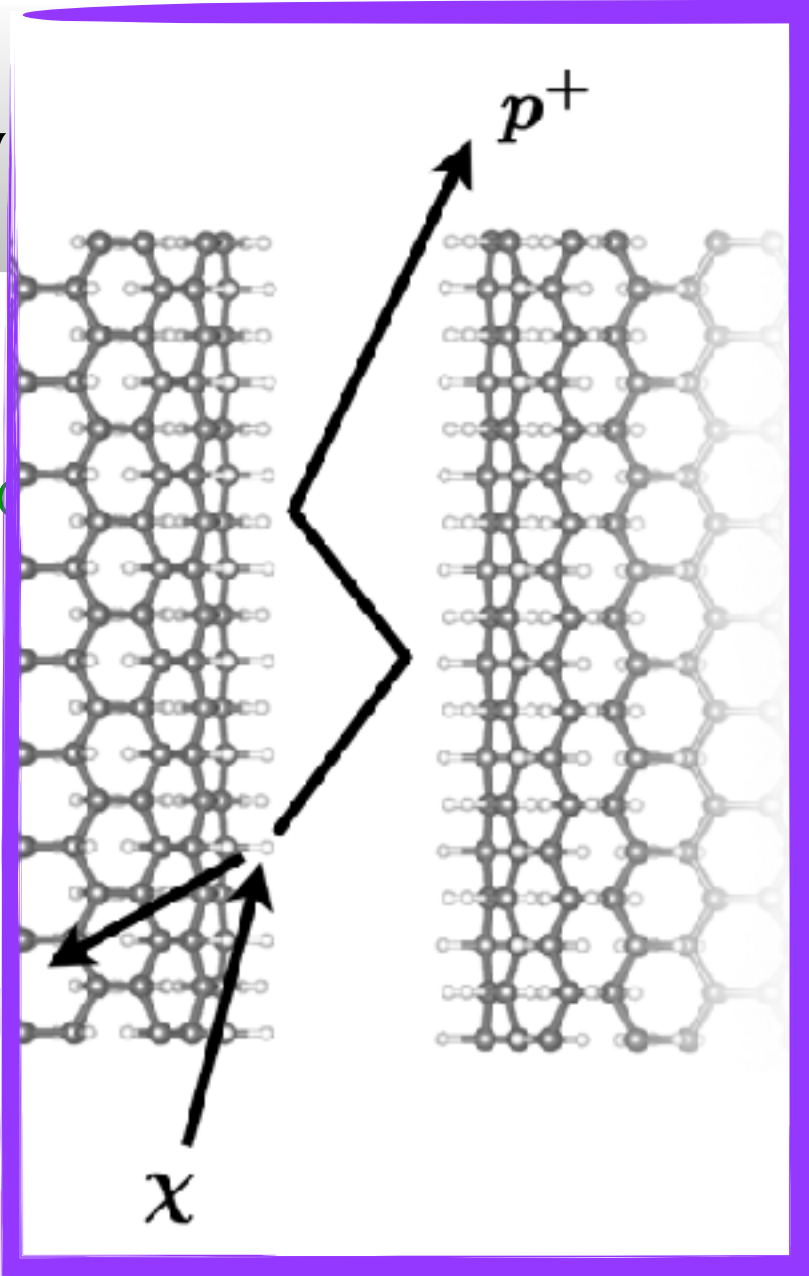
Challenge

$$E_{\text{NR}} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim \boxed{190 \text{ eV}} \times \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{16 \text{ GeV}}{m_N}\right)$$

Corresponds to 66 micro-gr, experiment in labs in Rome U!

Solutions 1: low

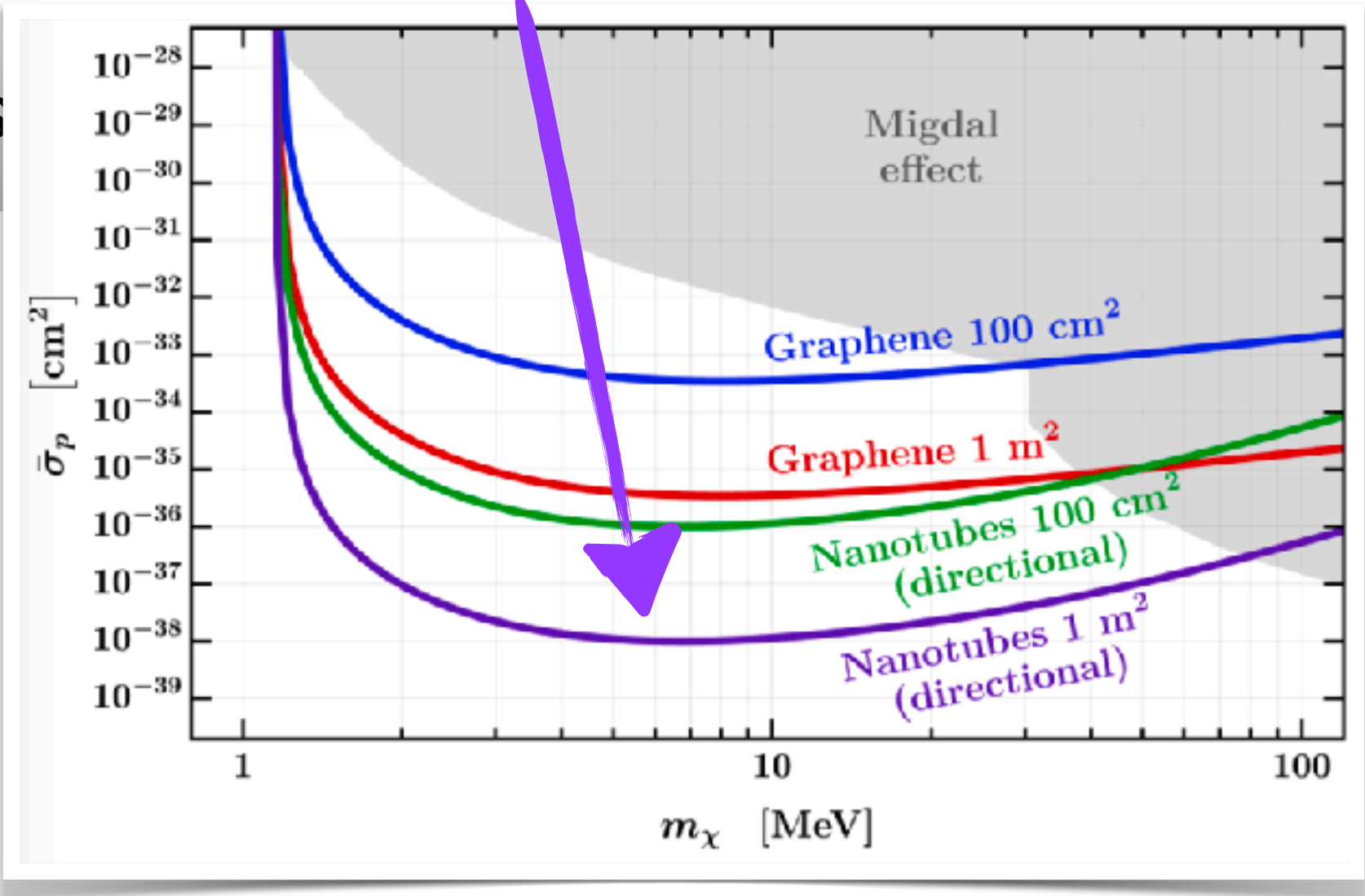
NEWS-G ...
e.g. [SciPost Phys. Proc.](#)



Solutions 2: lower the thresholds

PHONON(S) & similar beasts

MIGDAL & brem



Hydrogenated carbon nanotubes [Arias Esposito + 2602.02694](#)

High-energy fluxes of sub-GeV DM

High-velocity DM component unavoidably generated by **Cosmic-ray scatterings**



Bringmann Pospelov 1810.10543

Ema FS Sato 1811.00520

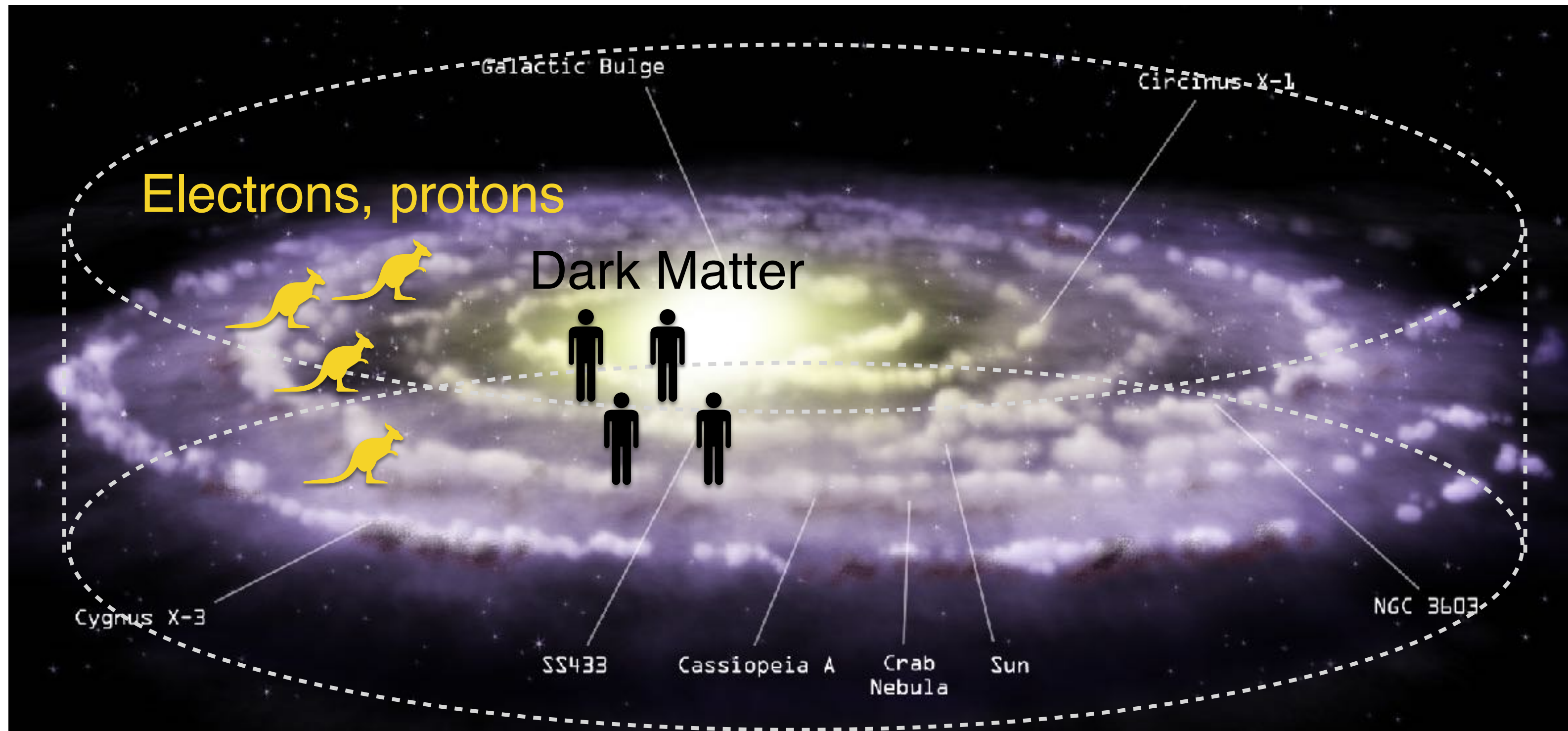
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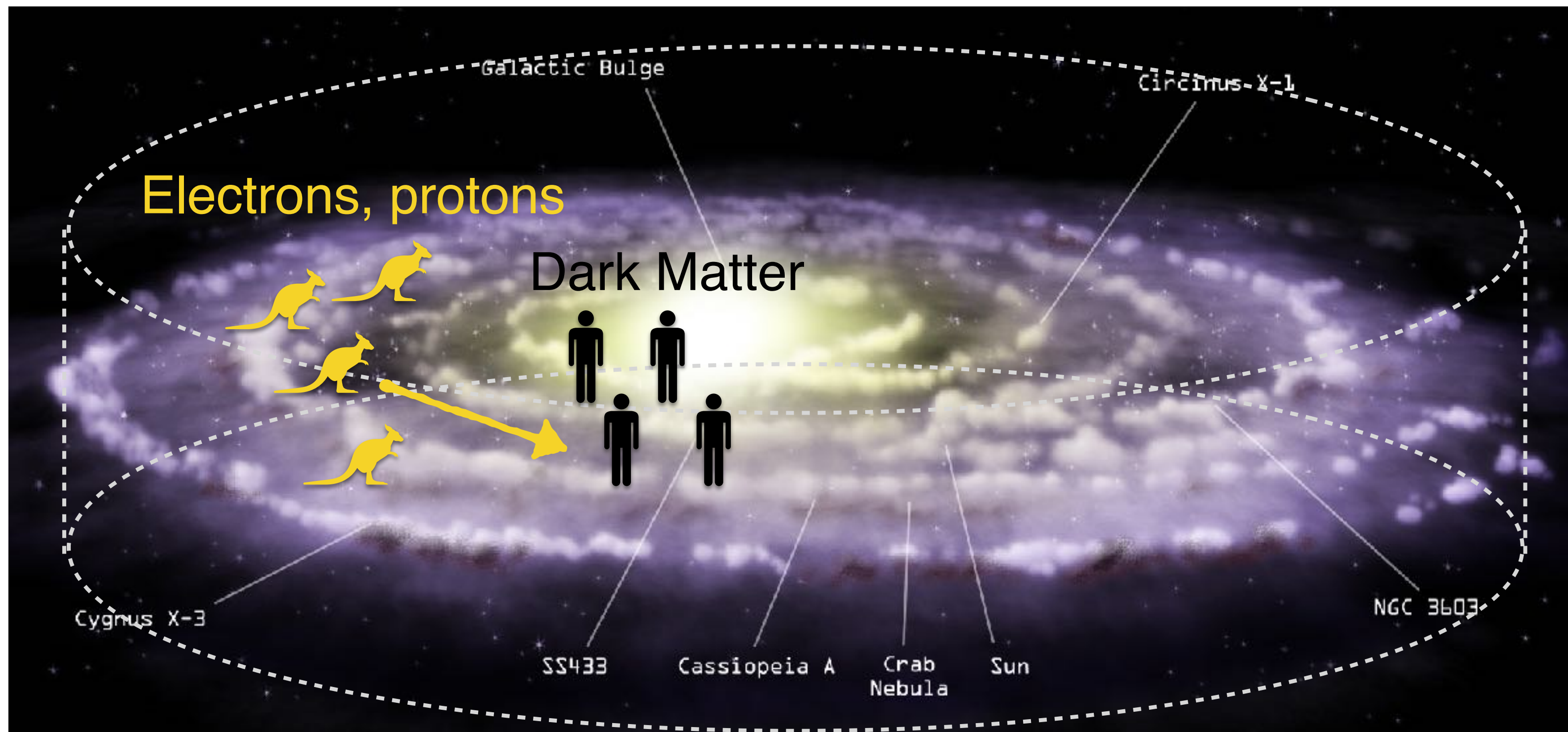
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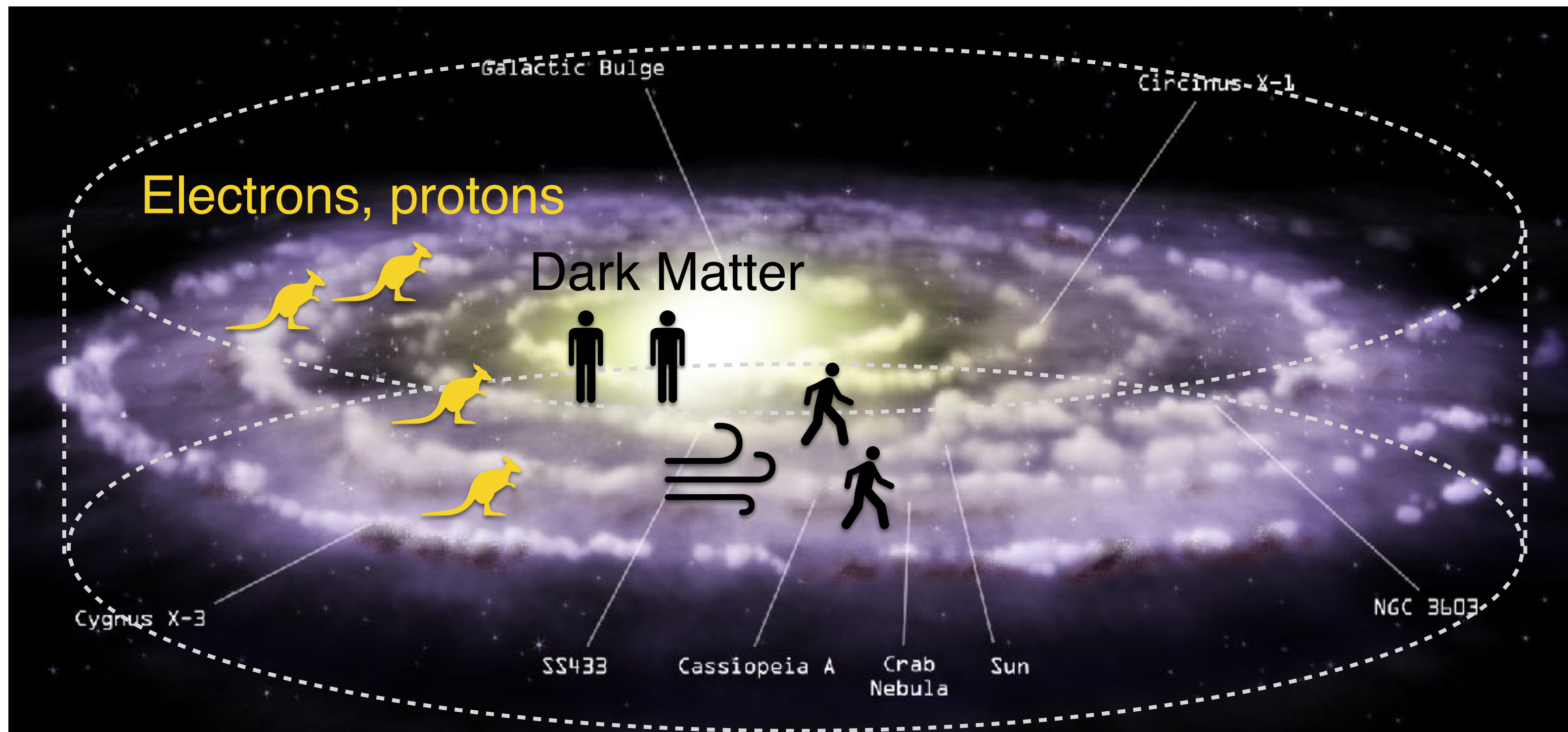
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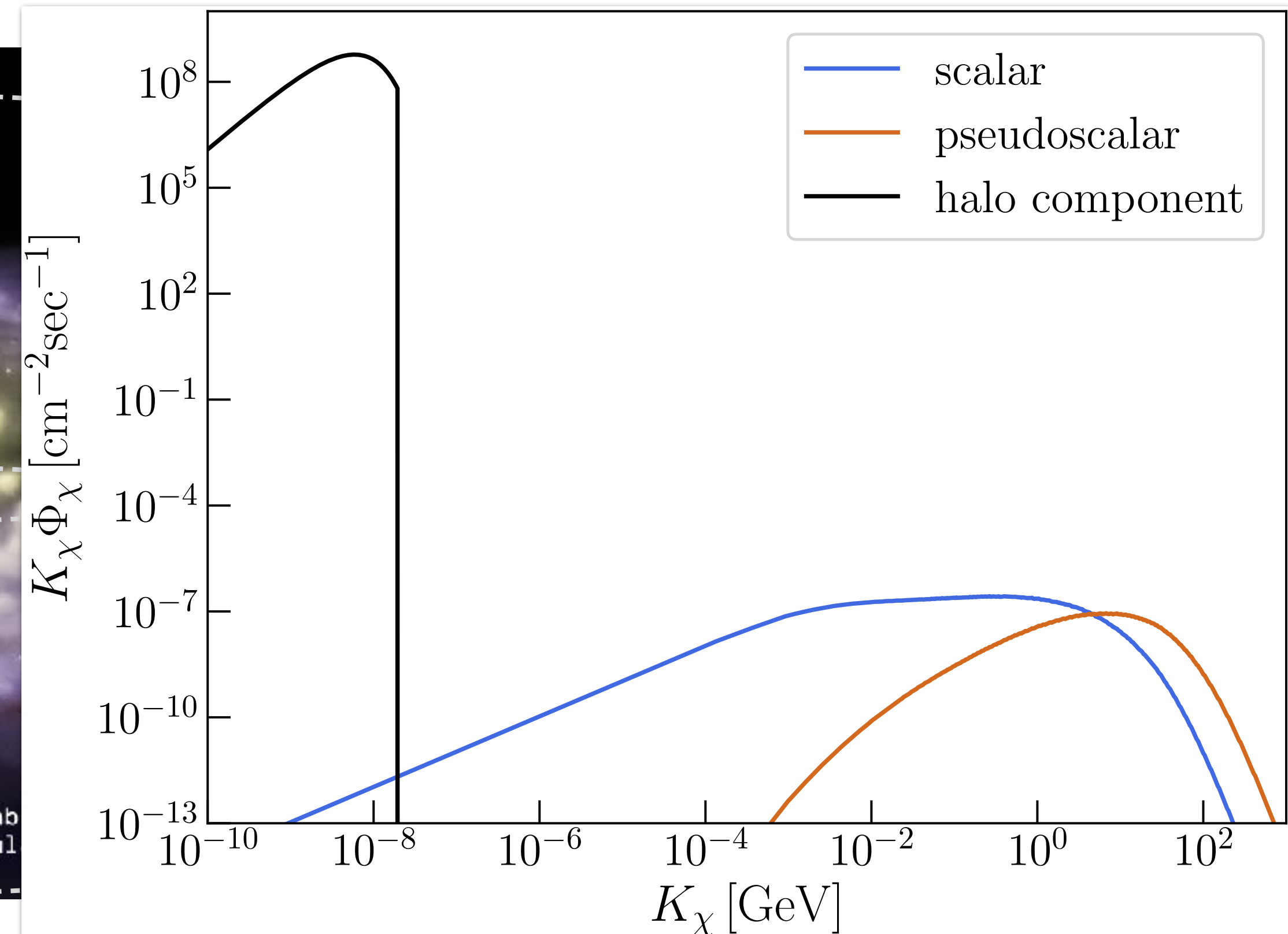
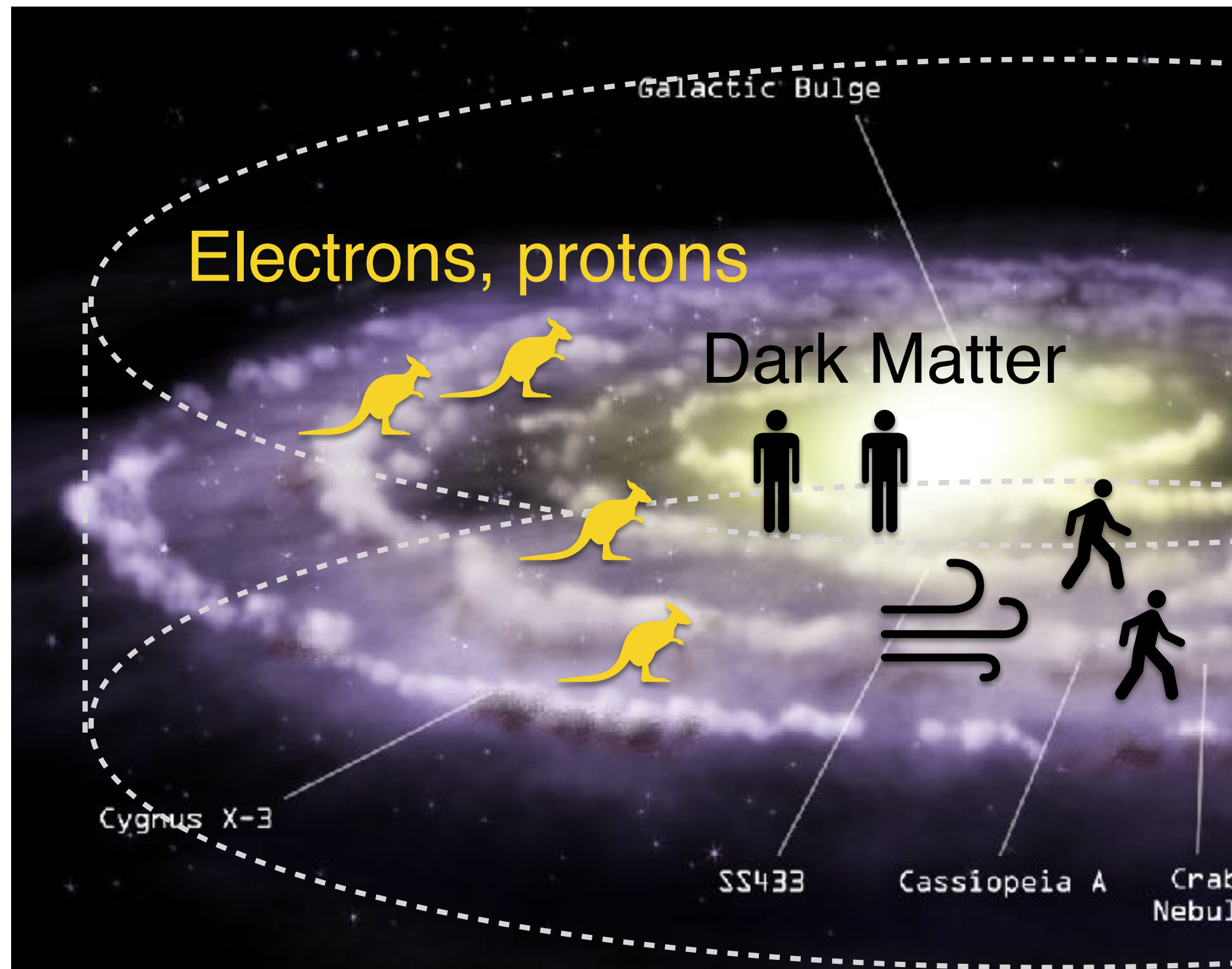
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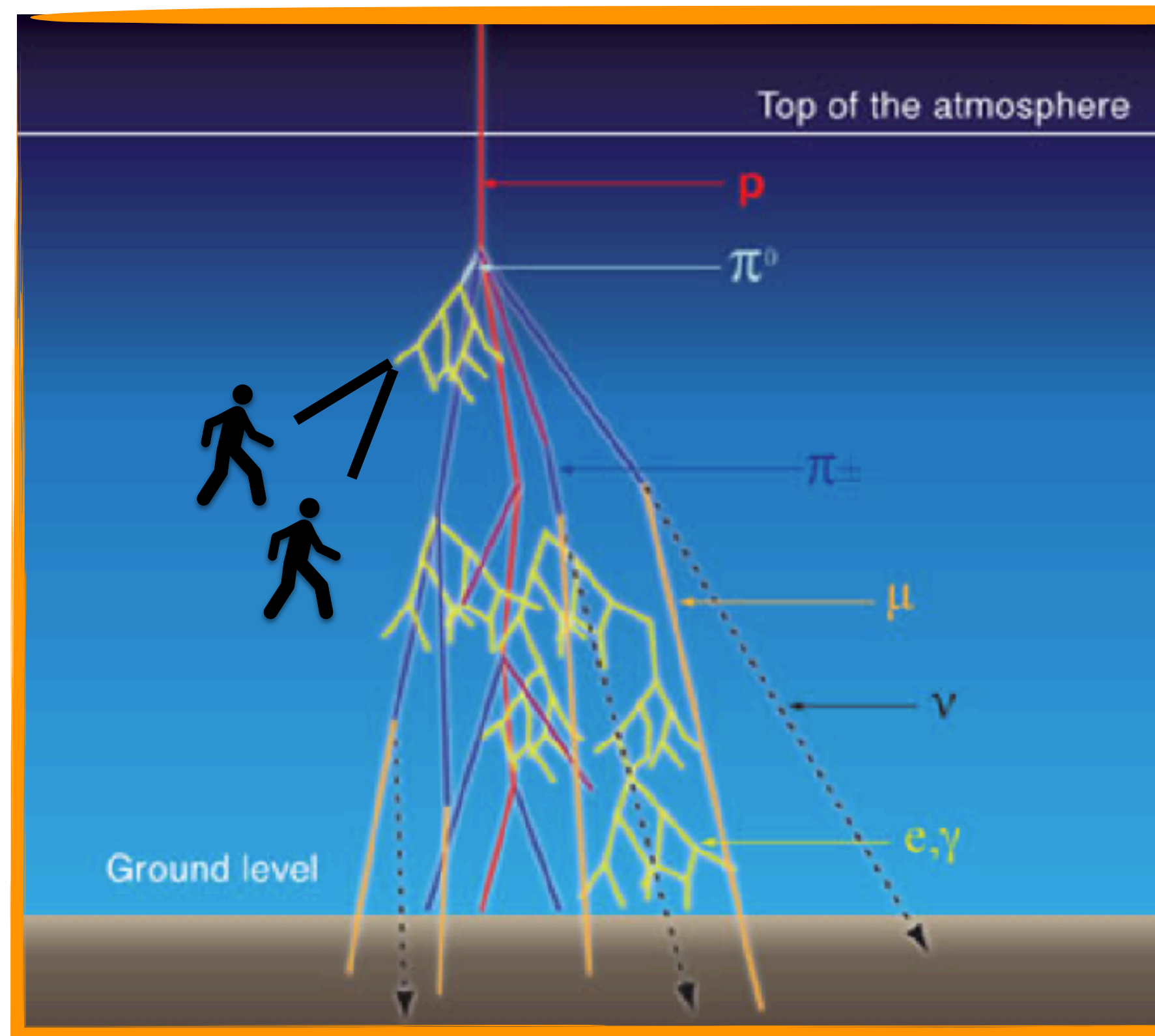
$$M_{\text{DM}} = 10 \text{ MeV}, \quad M_{\text{mediator}} = \text{GeV}, \quad g_{\chi}g_u = g_{\chi}g_d = 0.1$$

High-energy fluxes of sub-GeV DM

High-velocity DM component unavoidably generated by **Cosmic-ray scatterings**

Bringmann Pospelov 1810.10543

Ema FS Sato 1811.00520



Also by **Atmospheric Showers**

Alvey+ 1905.05776 , ...

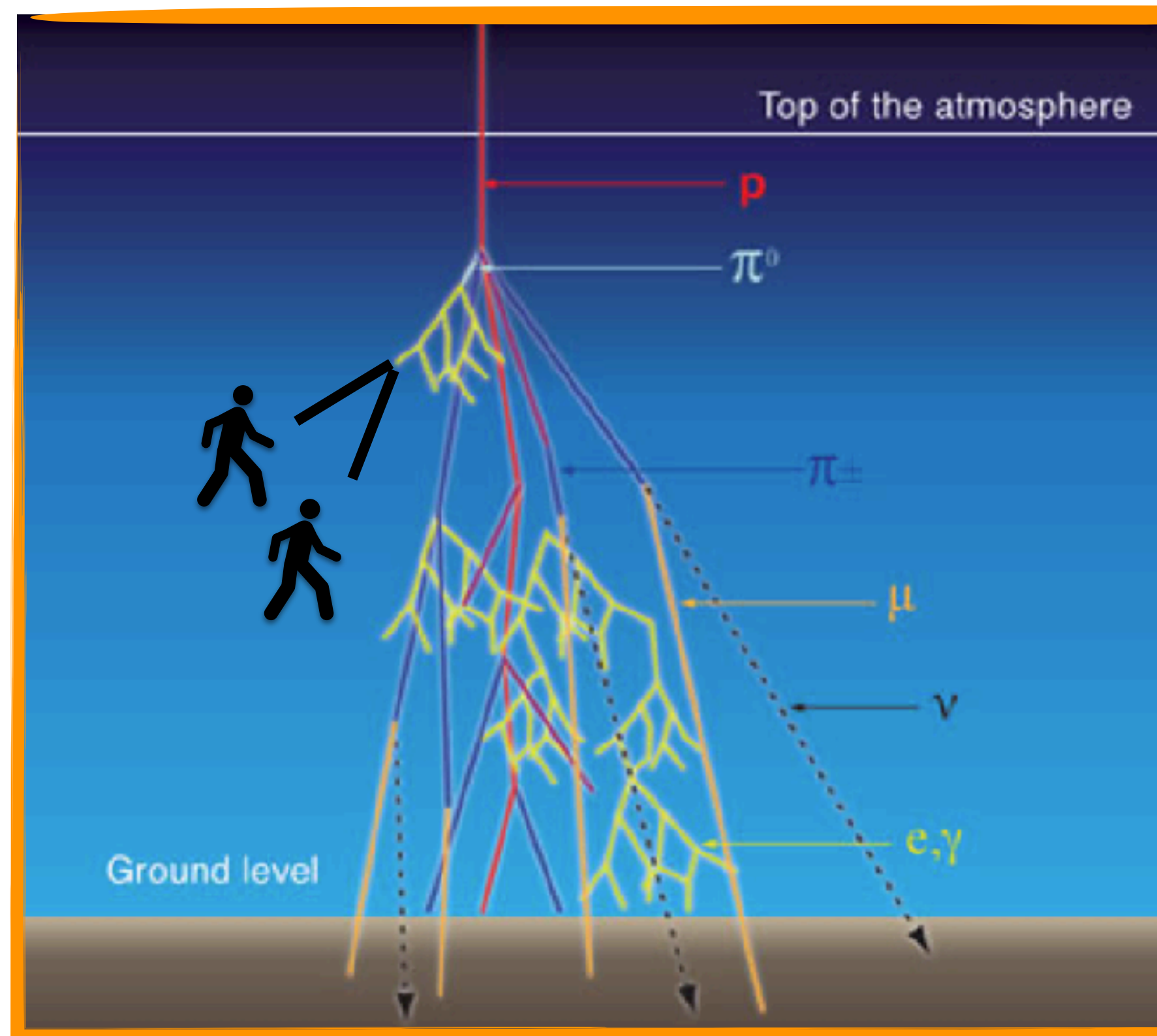
Pascoli FS Xotta in progress

High-energy fluxes of sub-GeV DM

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Also by **Atmospheric Showers**

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Pascoli FS Xotta in progress

Also by **Blazars**

Wang Granelli Ullio 2111.13644, ...

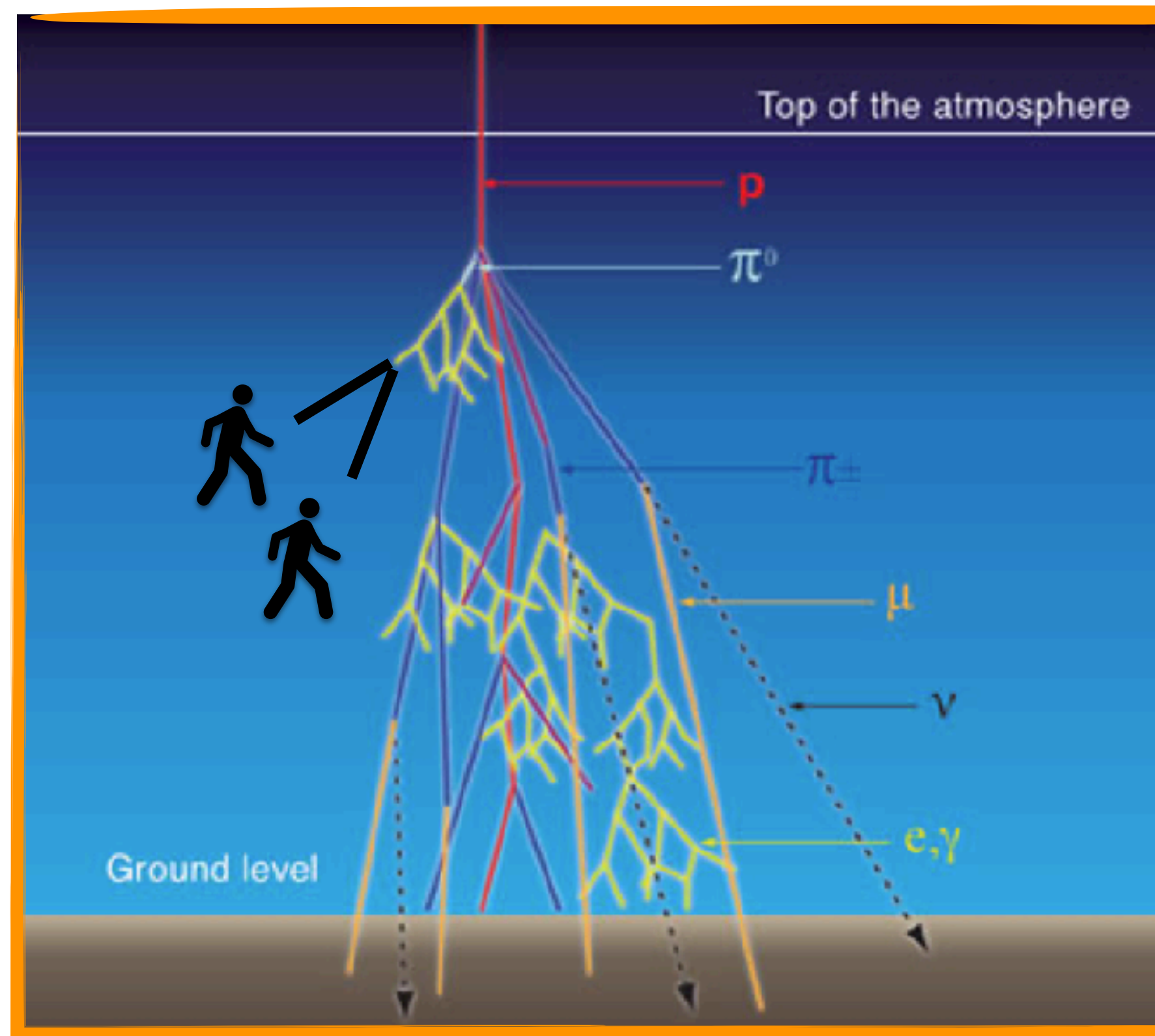
Also by ...

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Also by **Atmospheric Showers**

Alvey+ 1905.05776 , ...

Pascoli FS Xotta in progress

Also by **Blazars**

Wang Granelli Ullio 2111.13644, ...

Also by ...

Also by **Solar Upscattering** (but non-relativistic)

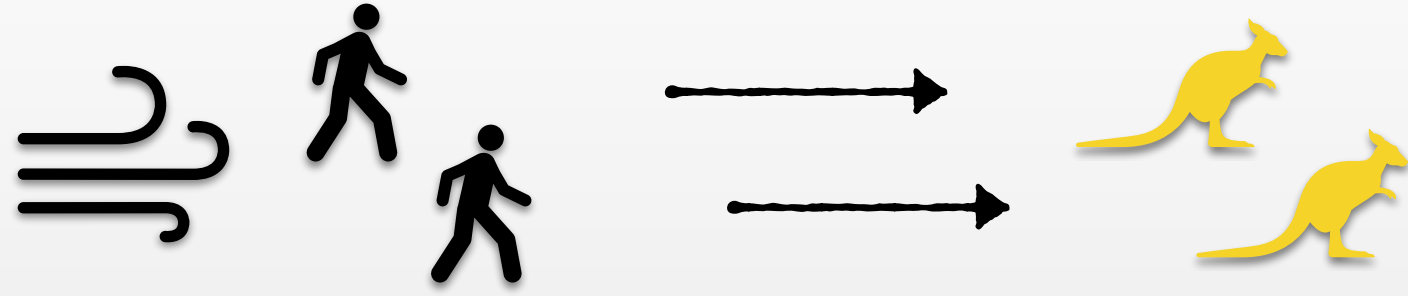
An Pospelov Pradler Ritz+ 1708.03642

Emken Kouvaris Nielsen 1709.06573

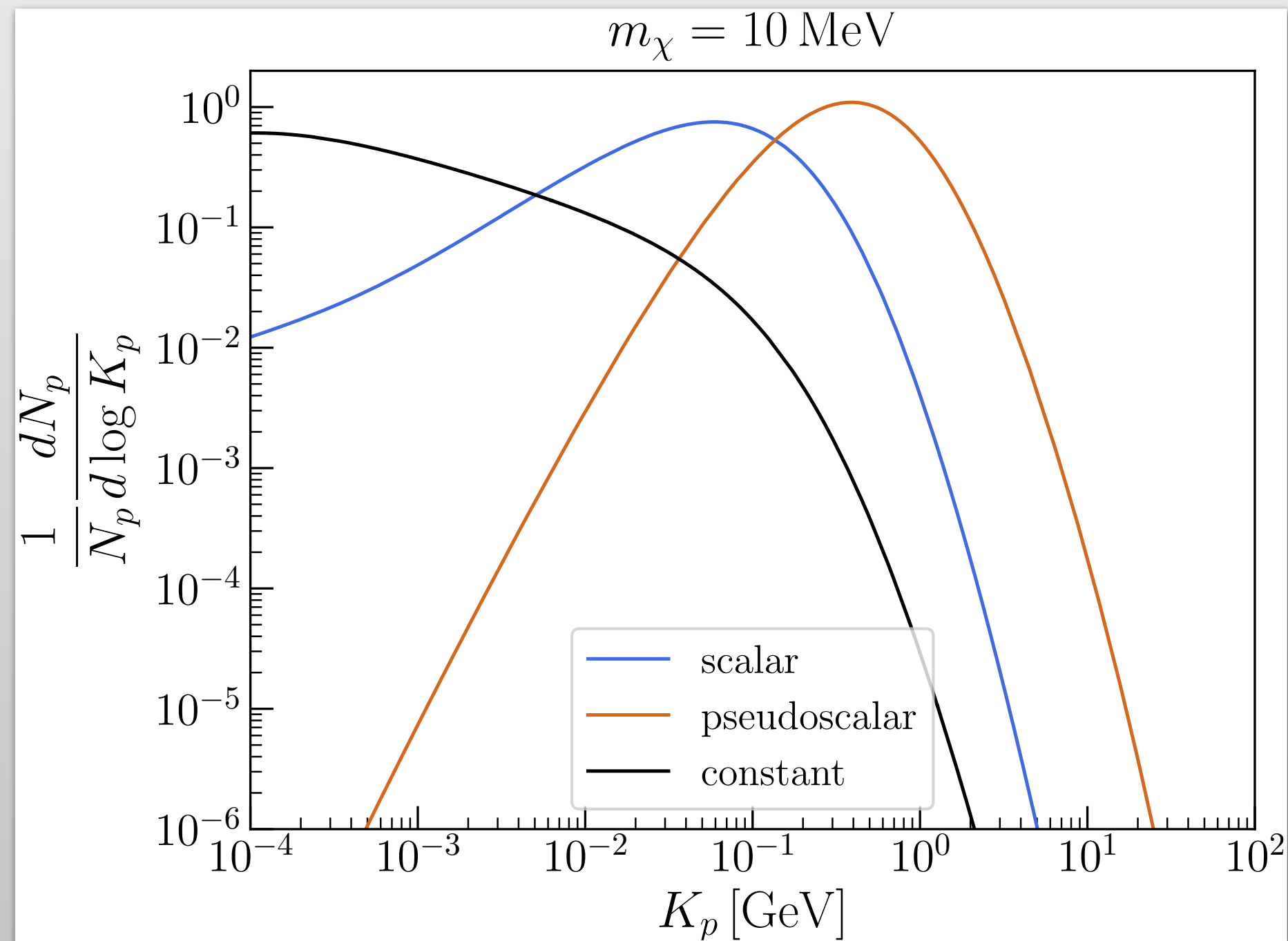
...

Detecting fast sub-GeV DM

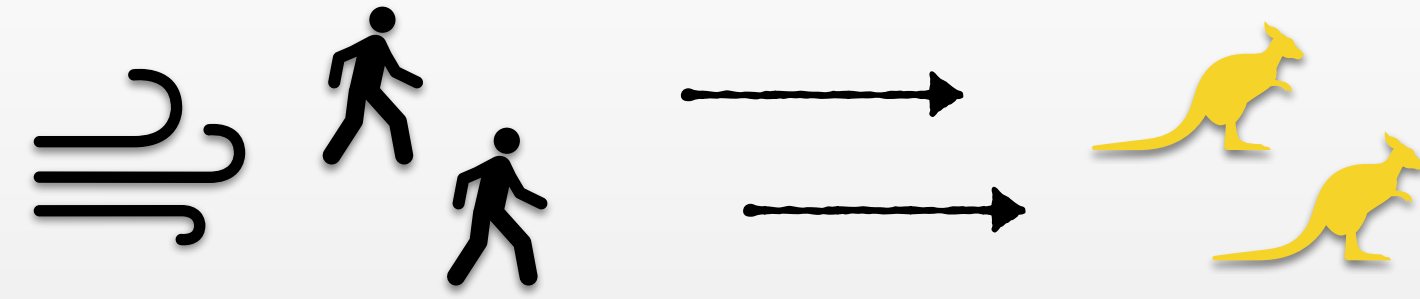
@ DM direct detection experiments PandaX 2301.03010, LZ 2503.18158,...



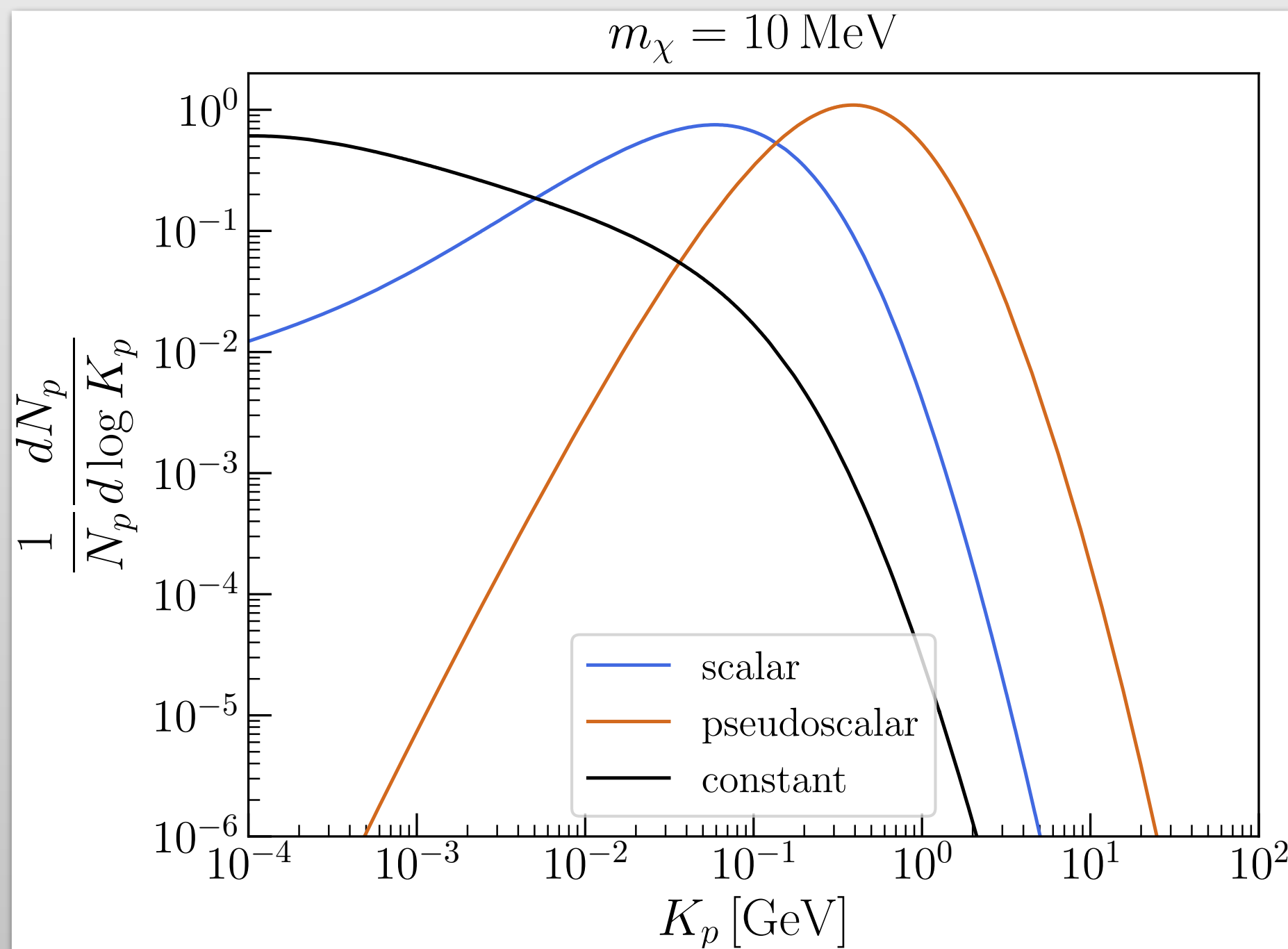
proton recoil from CR-upscattered DM



Detecting fast sub-GeV DM



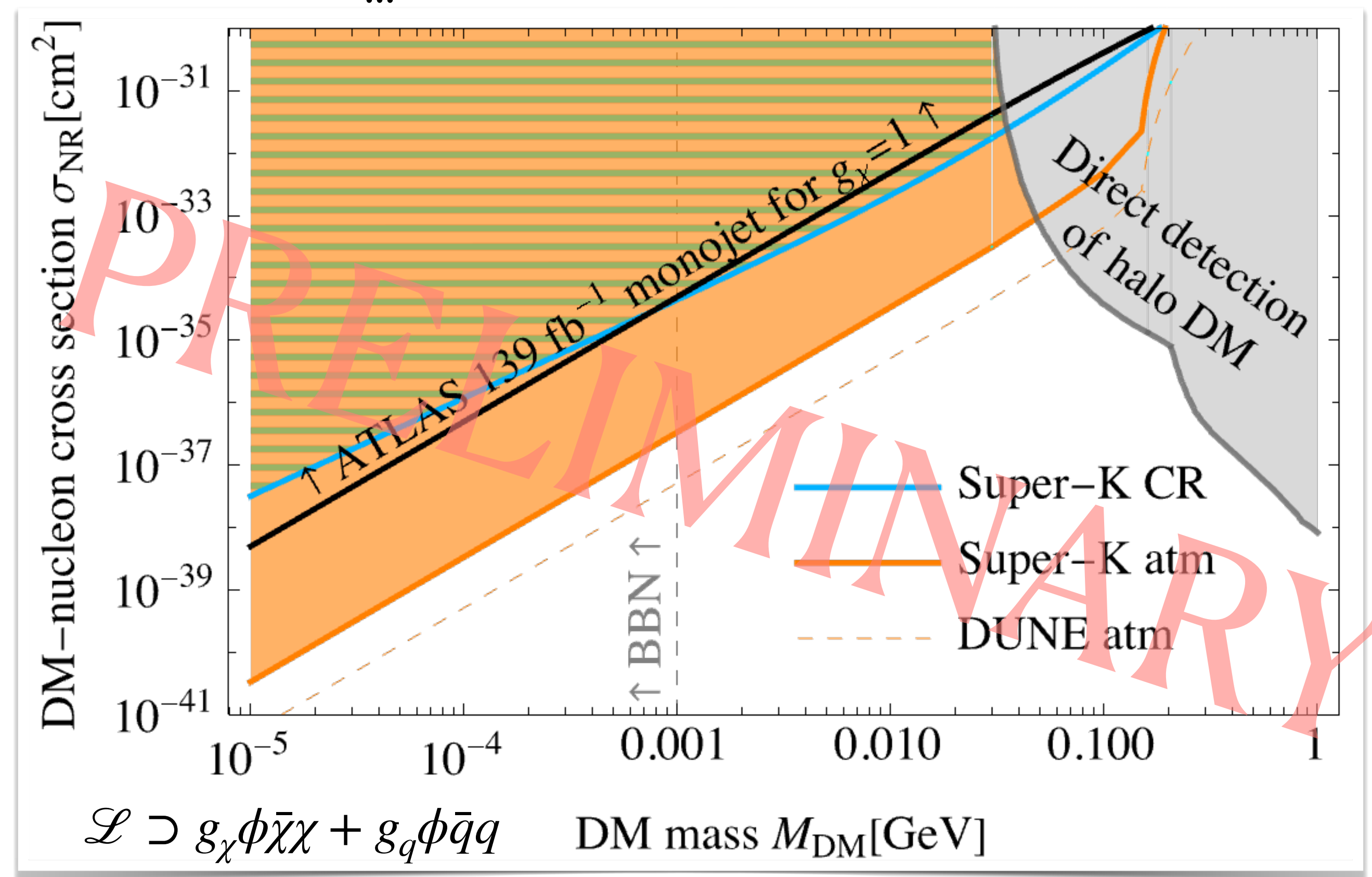
proton recoil from CR-upscattered DM



@ DM direct detection experiments [PandaX 2301.03010](#), [LZ 2503.18158](#),...

@ Neutrino detectors!

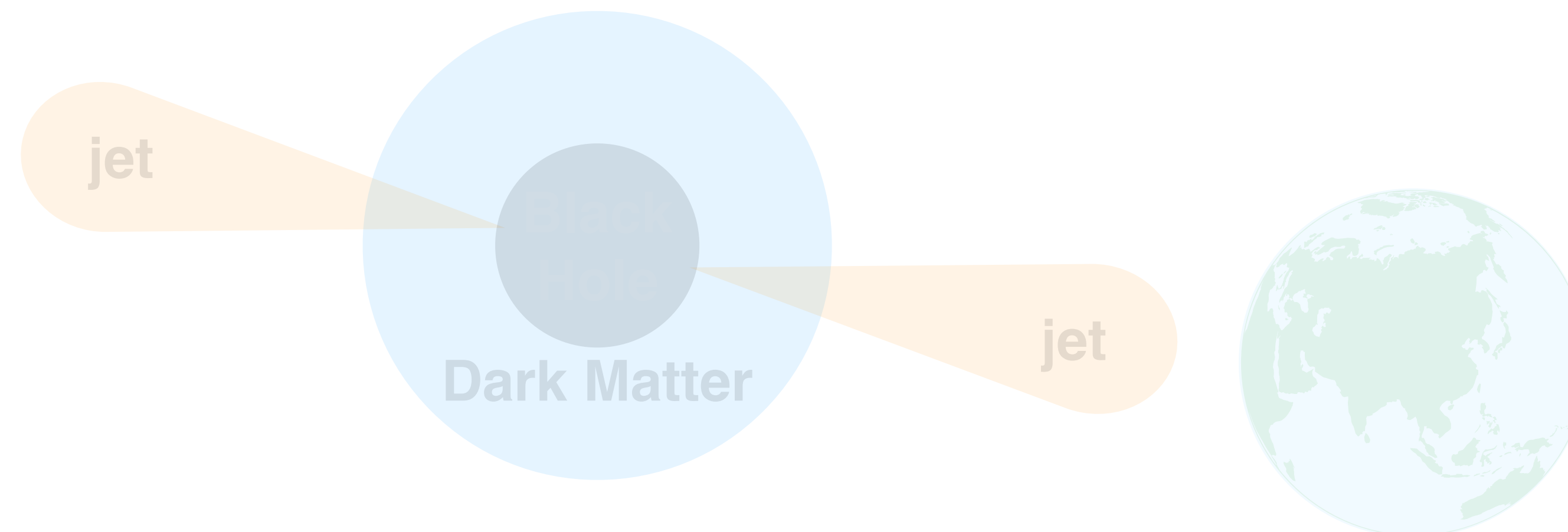
e.g. CR-upscattered @Super-K [..., Super-K 2209.14968](#)
atmospheric-DM @Super-K [Pascoli FS Xotta in progress](#)



Dark Matter ?

High energy neutrinos ?

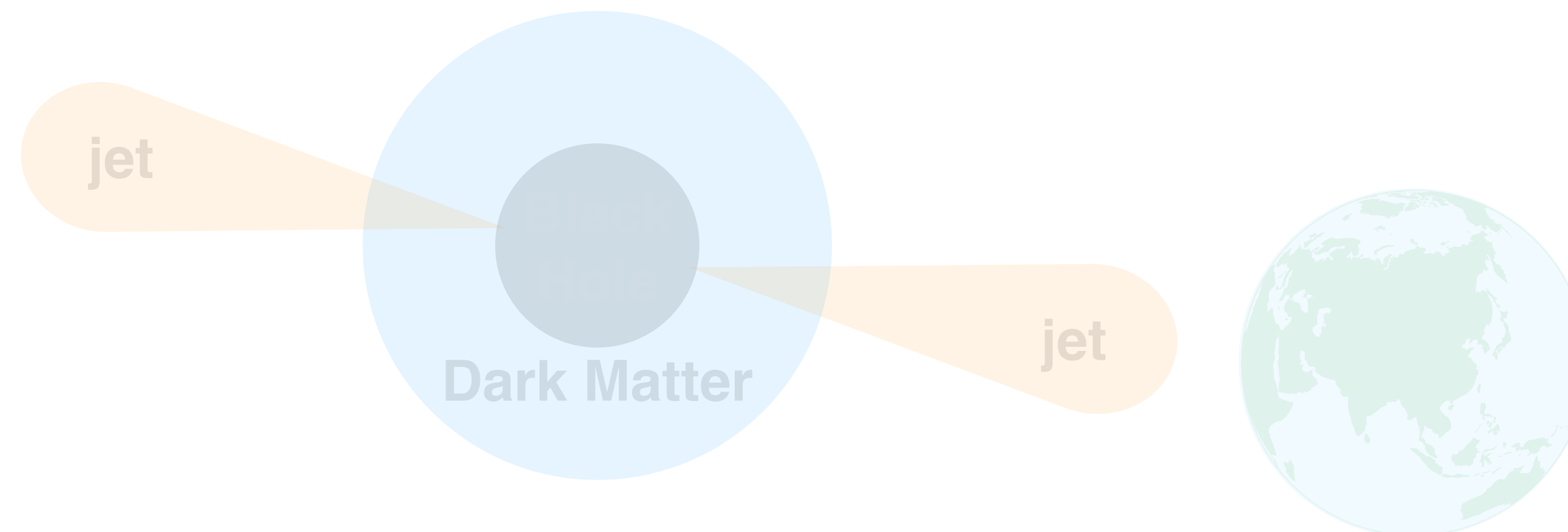
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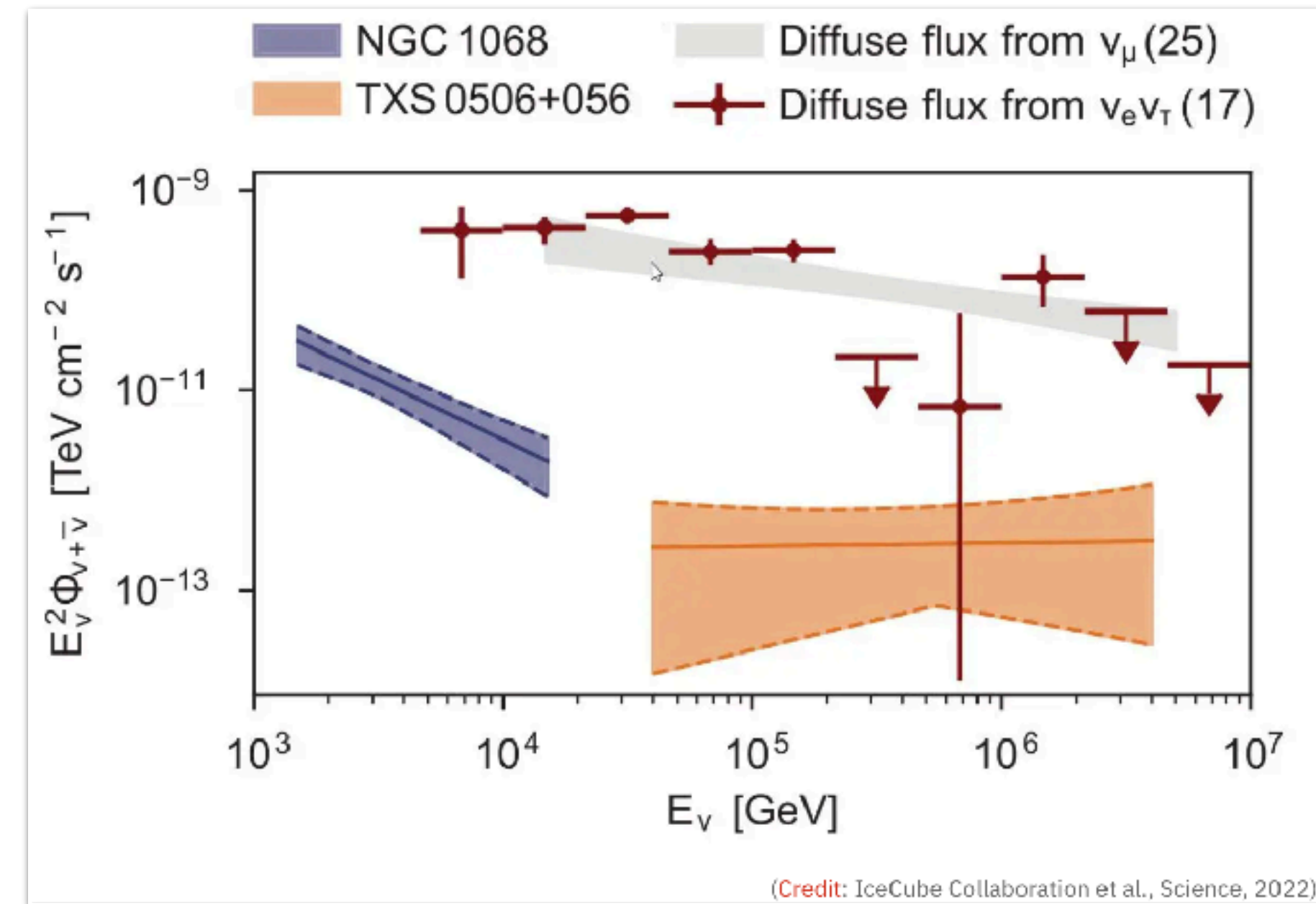


Origin of high energy neutrinos?

Of diffuse astrophysical neutrinos?

Of neutrinos seen from blazars?

Of KM3NeT ~ 200 PeV neutrino?

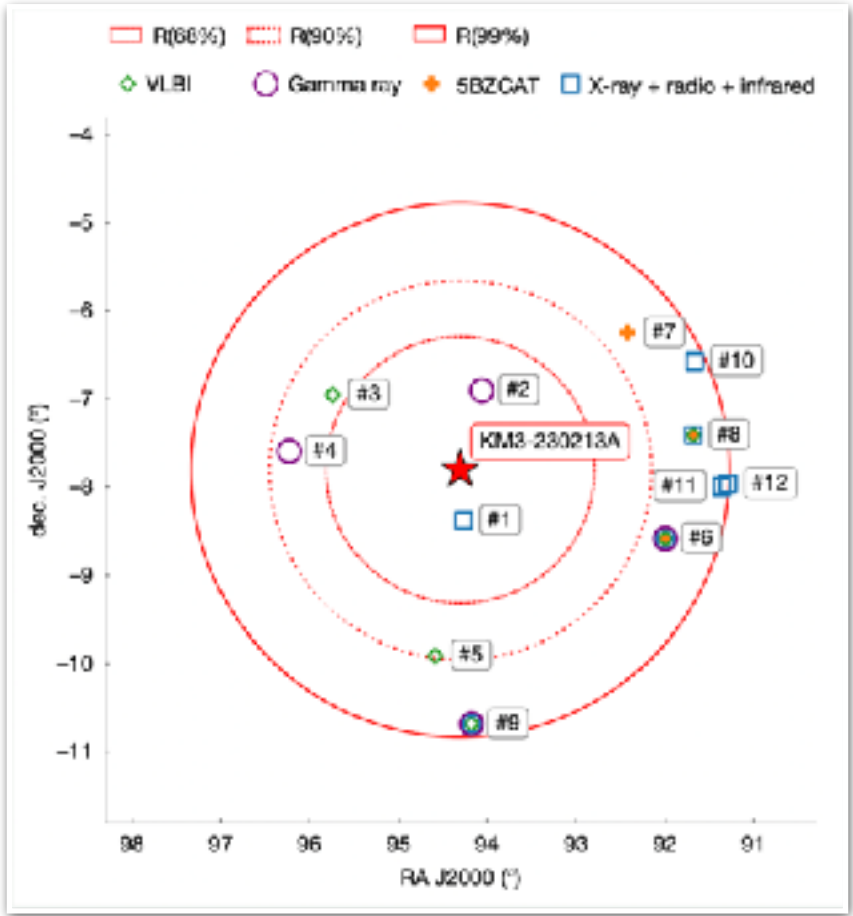
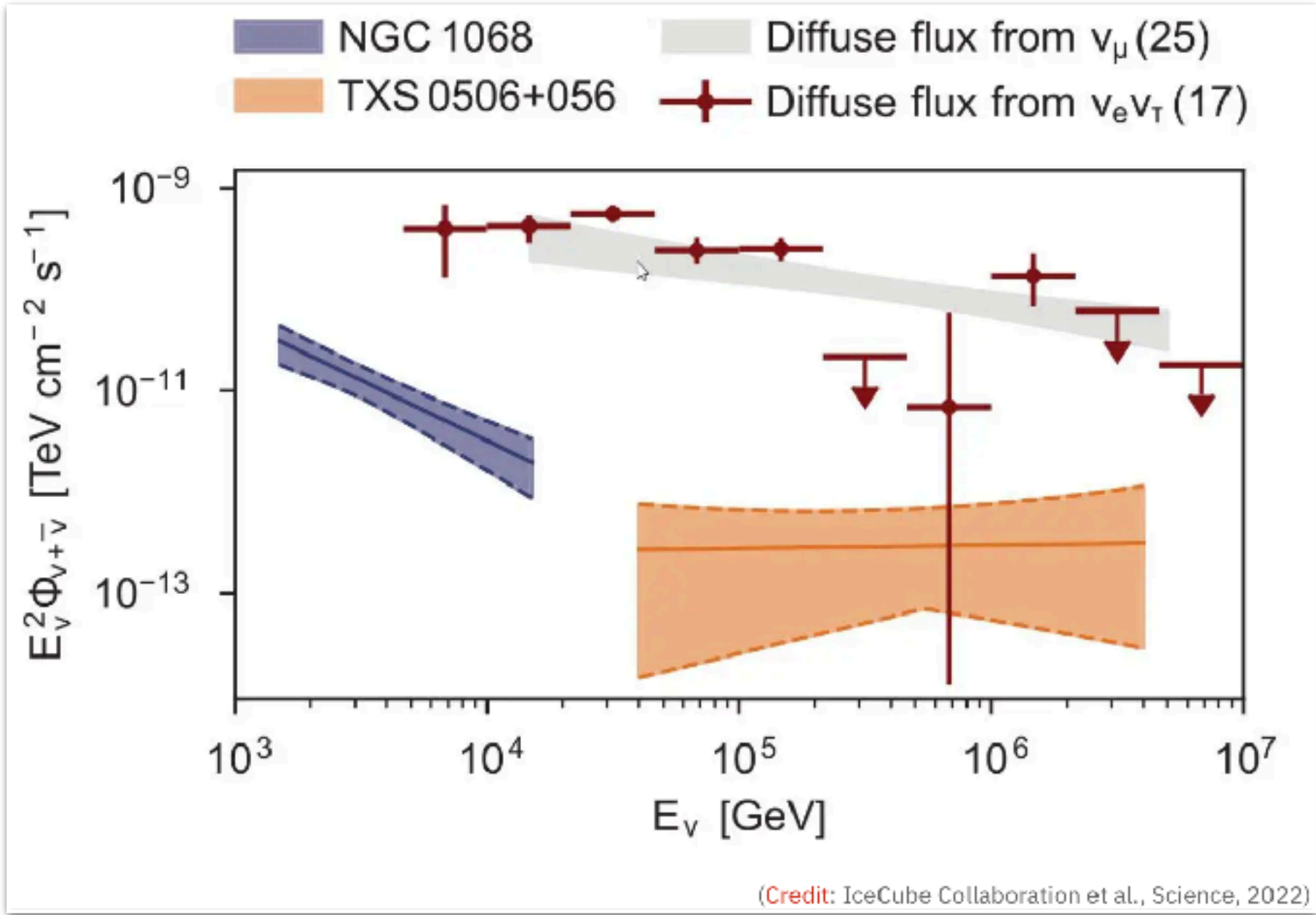


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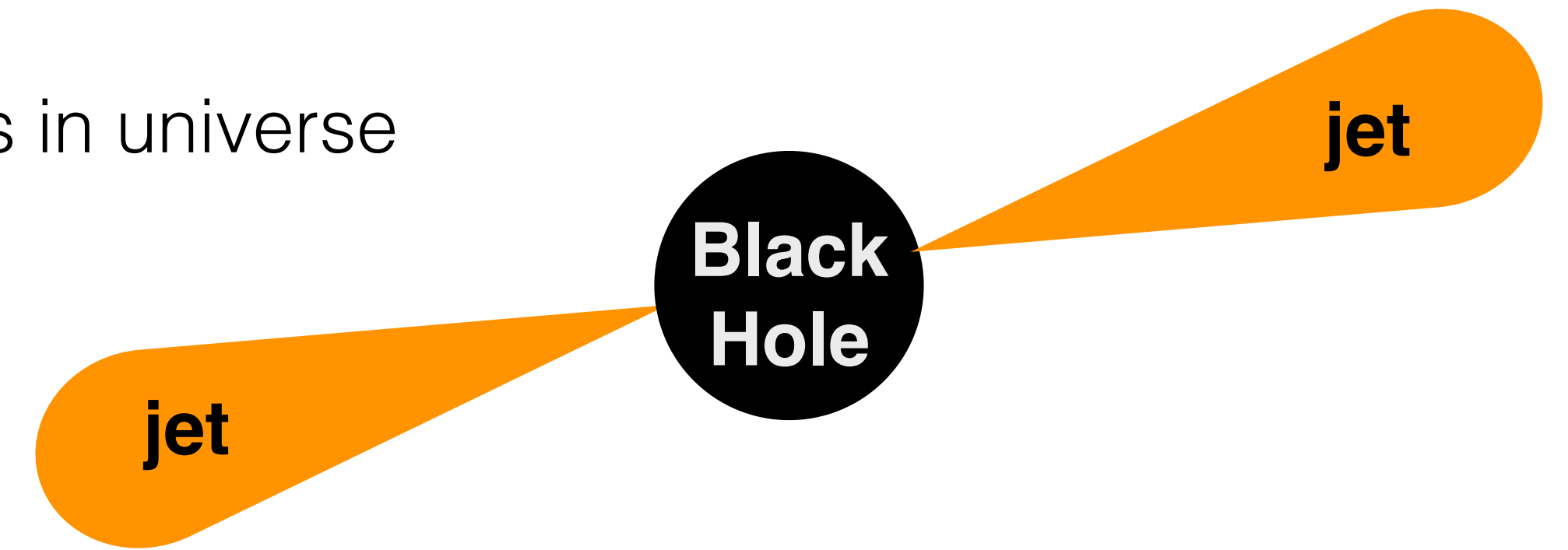
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Blazars

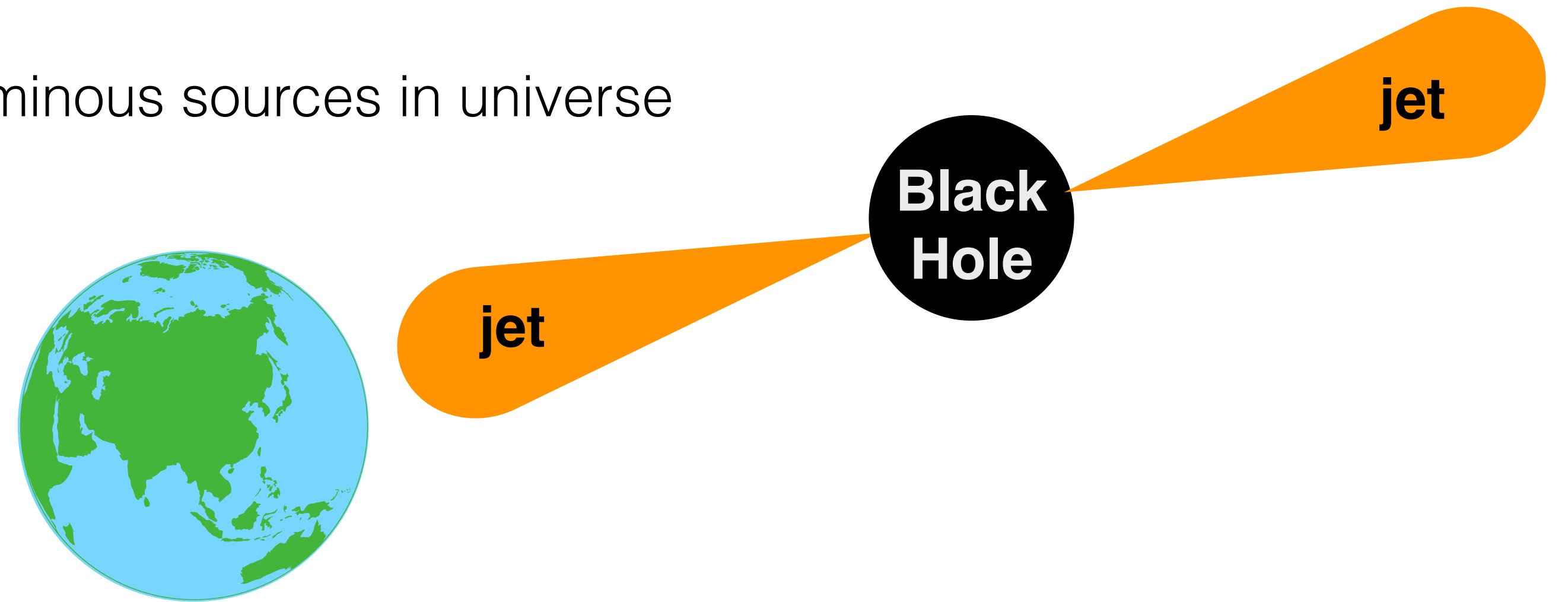
Active galactic nuclei (AGN) = most powerful luminous sources in universe



Blazars

Active galactic nuclei (AGN) = most powerful luminous sources in universe

Blazar = AGN whose **jet** points to us



Blazars

Active galactic nuclei (AGN) = most powerful luminous sources in universe

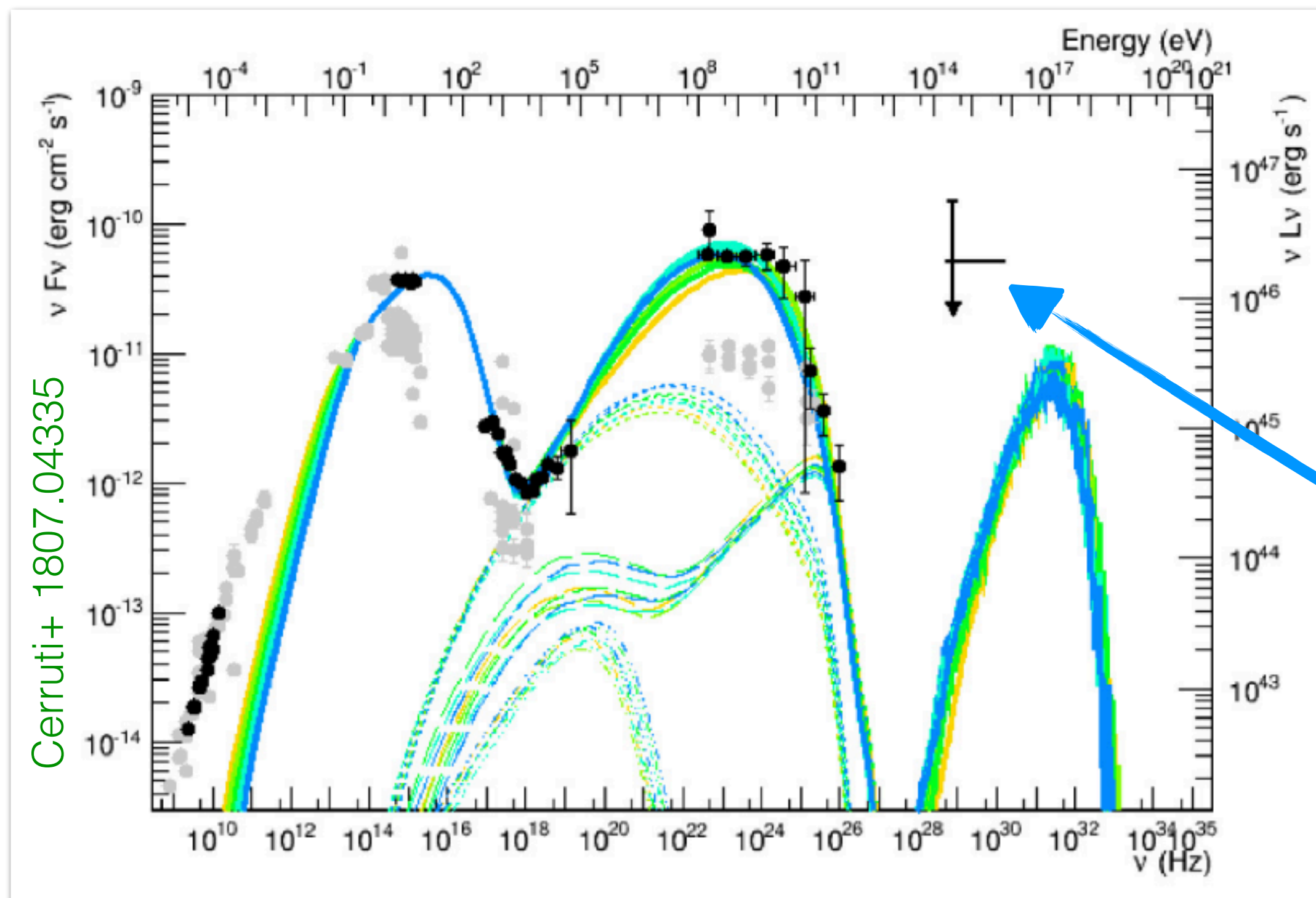
Blazar = AGN whose **jet** points to us



jet

Black Hole

jet



Photons observed from many blazars over many energies

Radio, X, gamma

> 60% of Fermi sources are blazars!

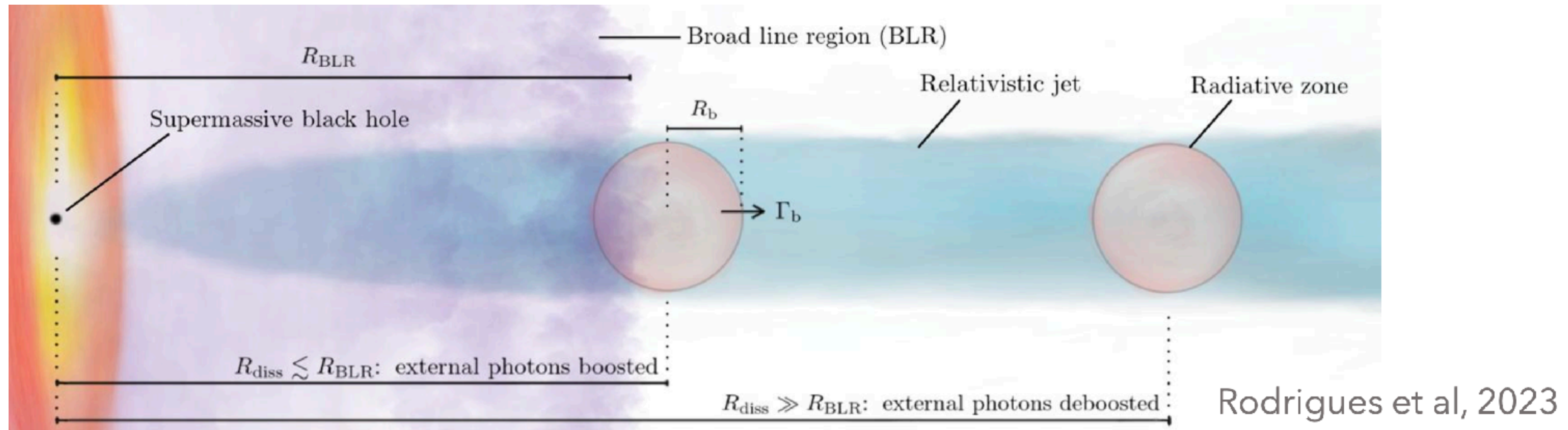
Fermi 1902.10045, Fornasa Sanchez-Conde 1502.02866

Neutrinos first detected in 2017 by IceCube from **TXS 0506+056**

Today one more source: PKS **0735+178** $\sim 3\sigma$

Also AGN (non-blazar): **NGC 1068** $> 4\sigma$

Modeling Blazars: single-zone leptohadronic

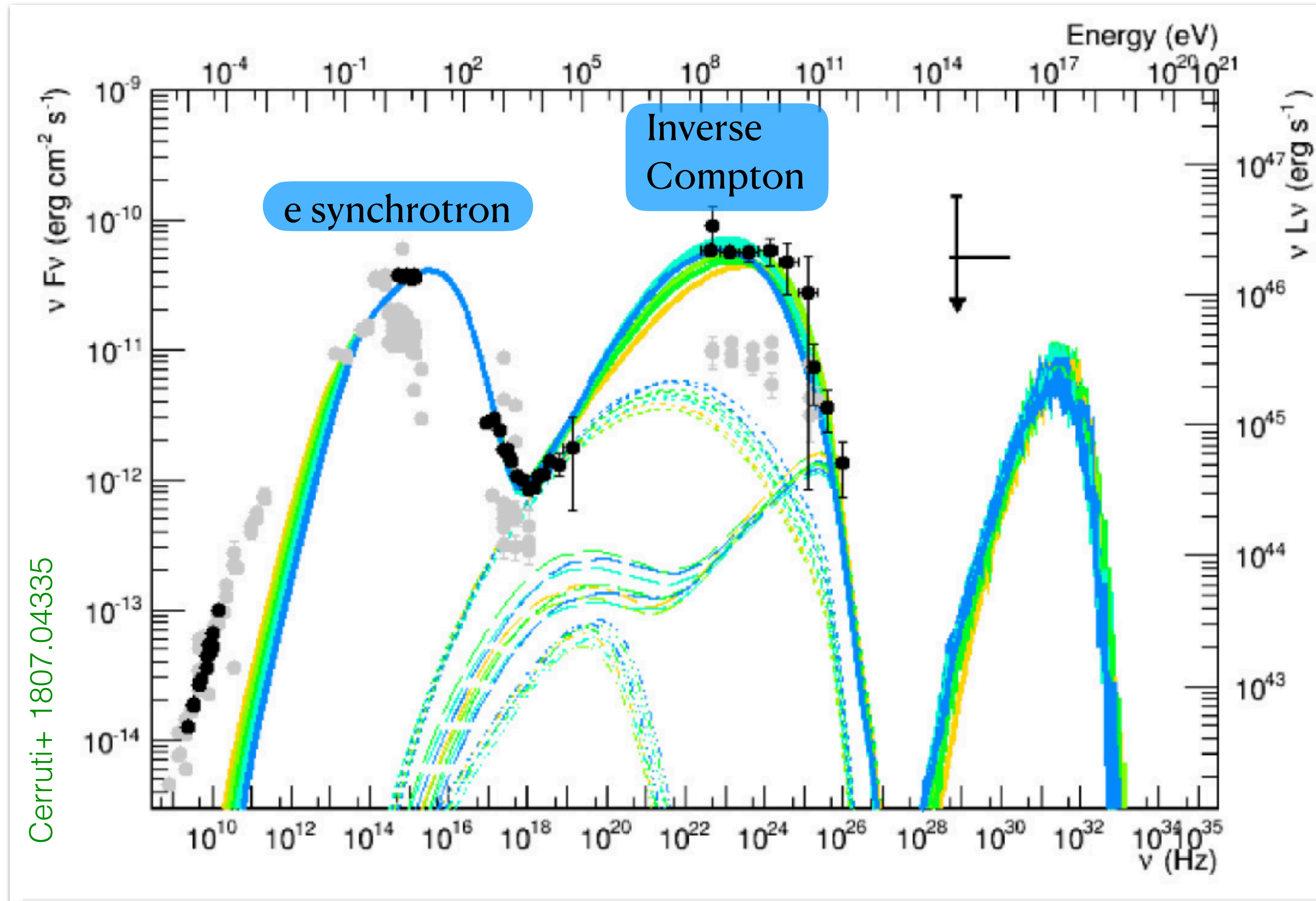
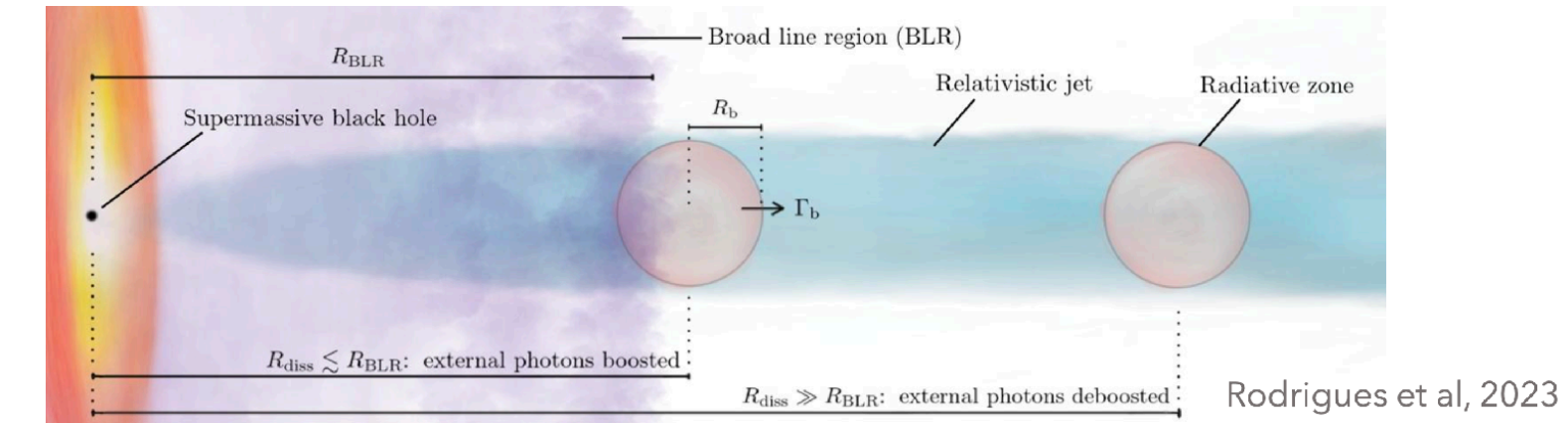


Blob of extremely energetic protons and electrons

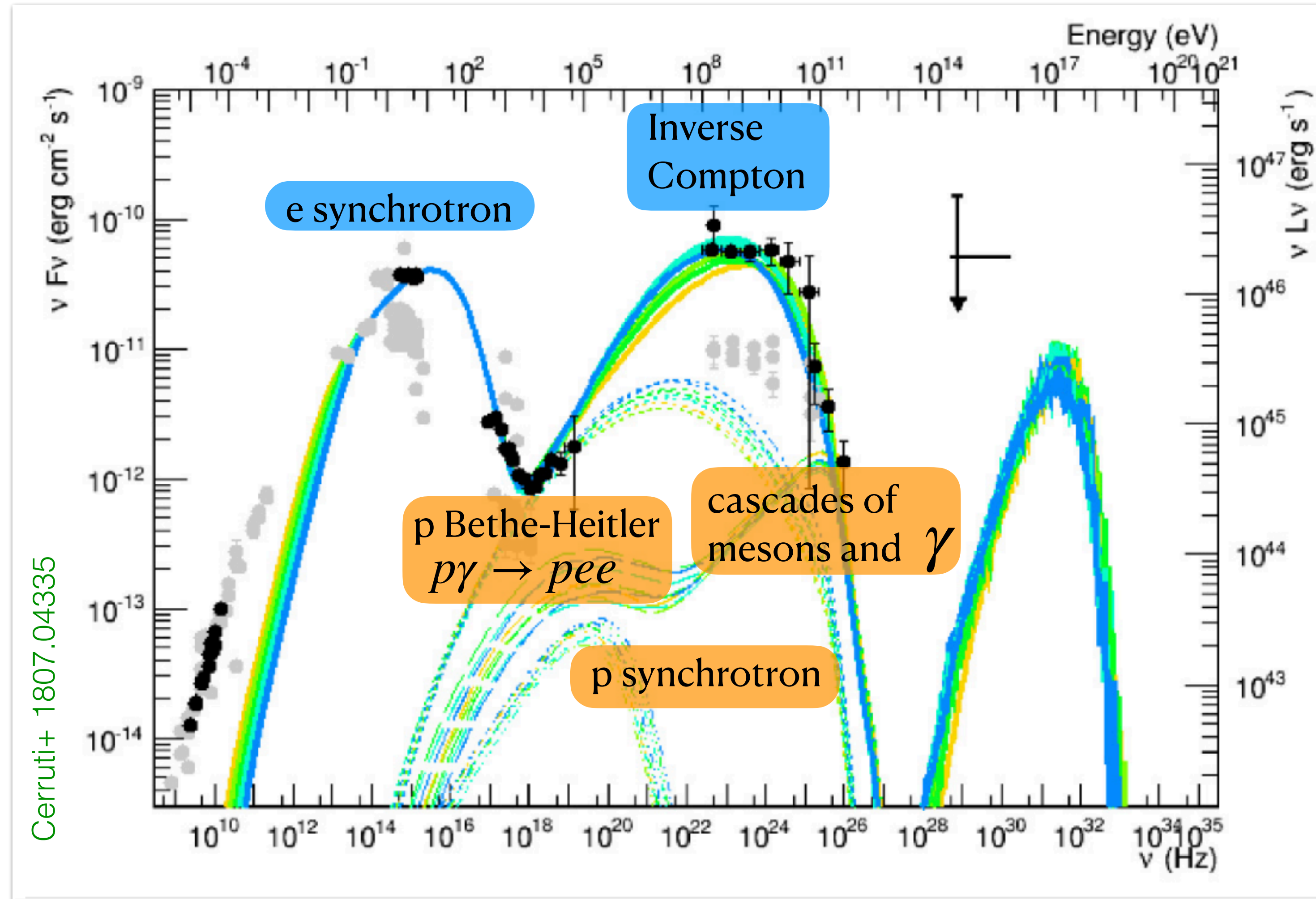
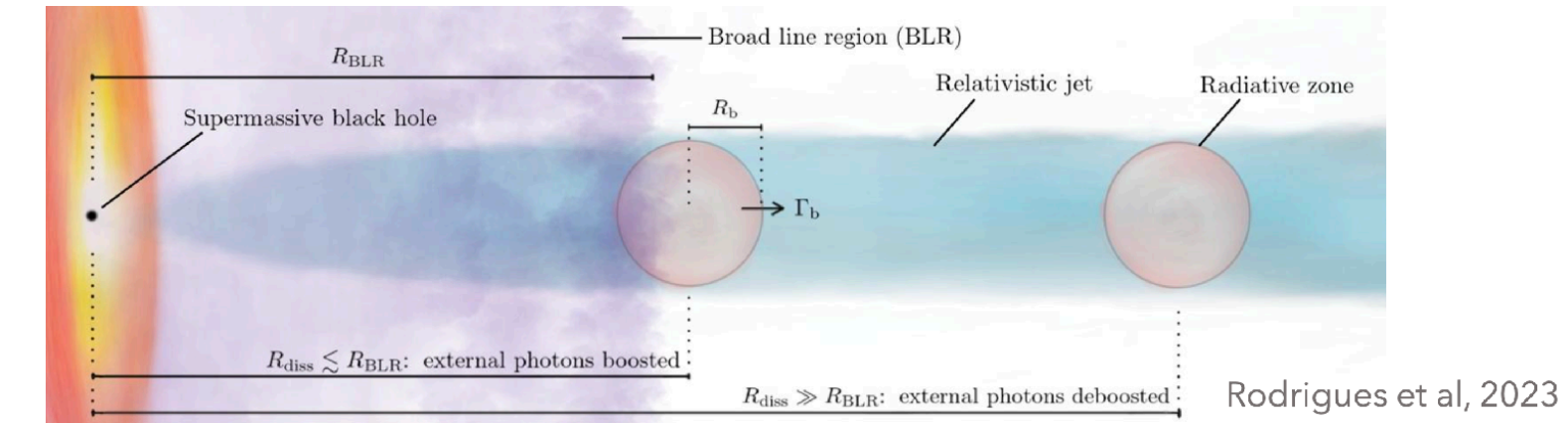
moving along the jet with Lorentz factor Γ_B

scattering within blob/jet and on accretion disk (with γ , ...)

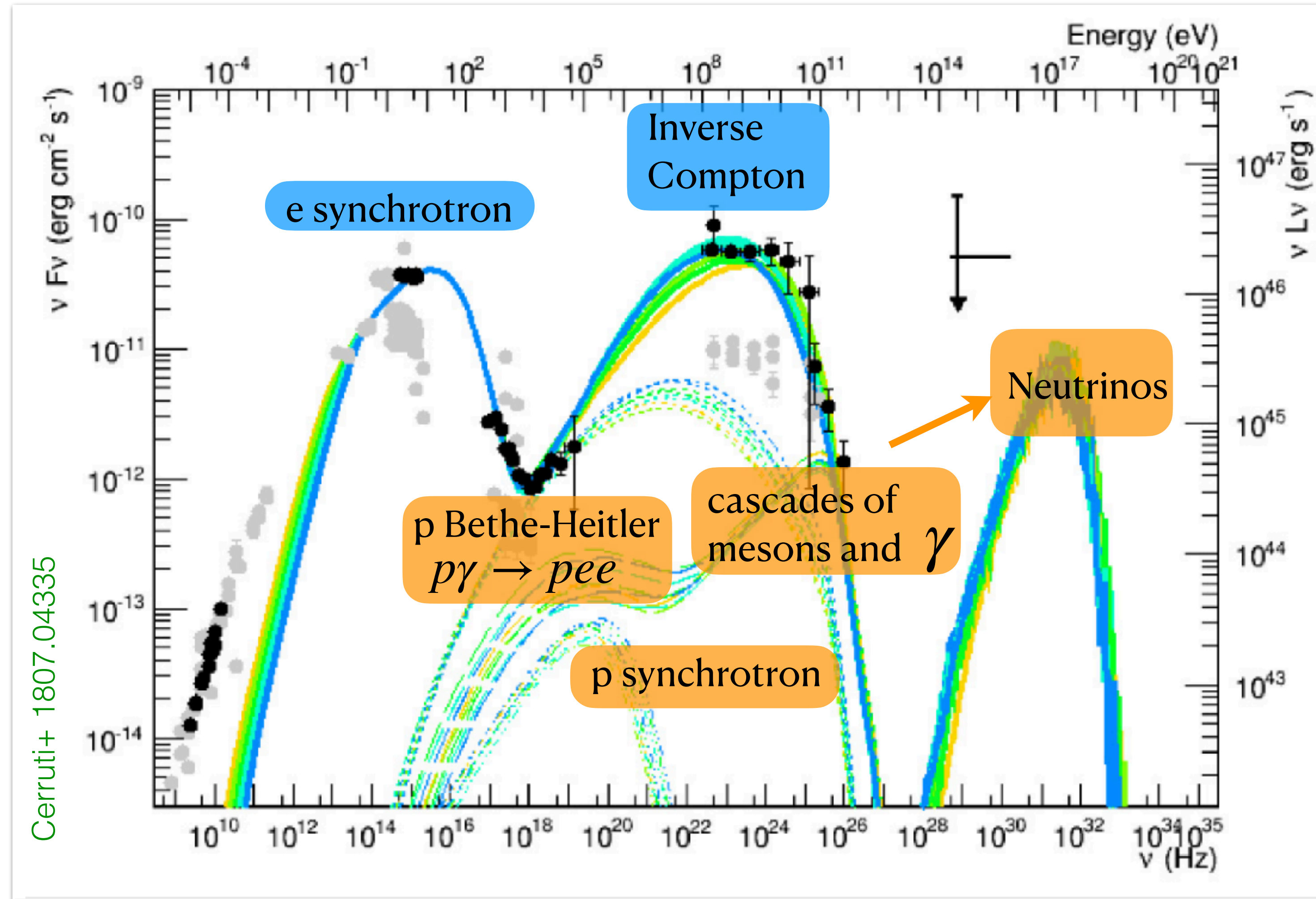
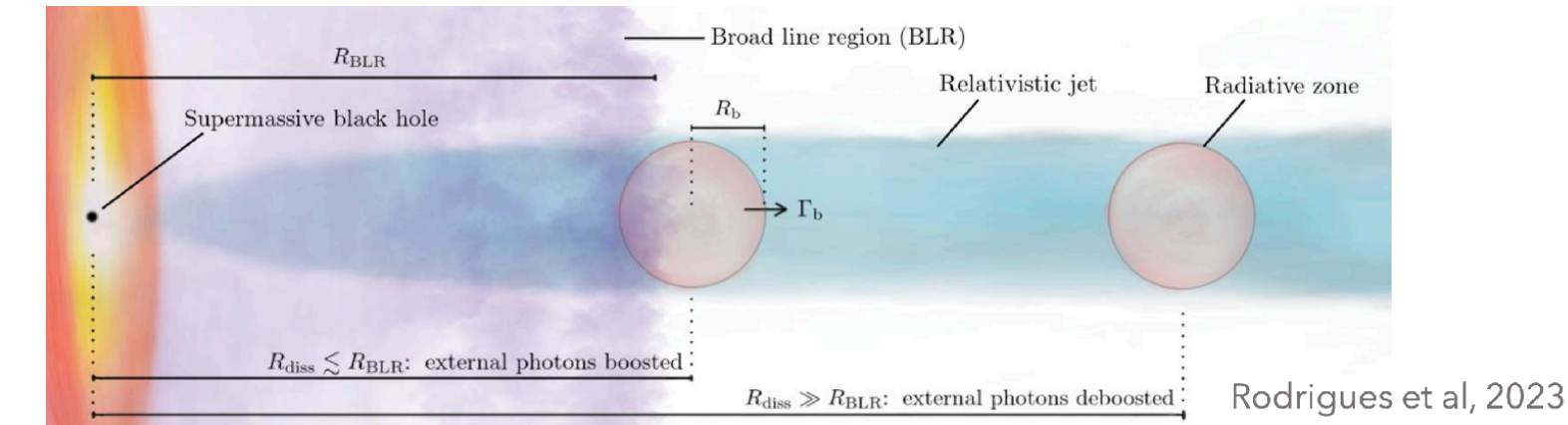
Modeling Blazars: results



Modeling Blazars: results



Modeling Blazars: results



Problem

Too few neutrinos

Different groups find same conclusion

TXS: Cerruti+ 1807.04335
Gao+ 1807.04275
Keivani+ 1807.04537 ...

Diffuse: Rodrigues+ 2307.13024
IceCube APJ 835 (2017) ...

Blazars & high energy neutrinos

Diffuse astrophysical neutrinos?

Neutrinos seen from blazars?

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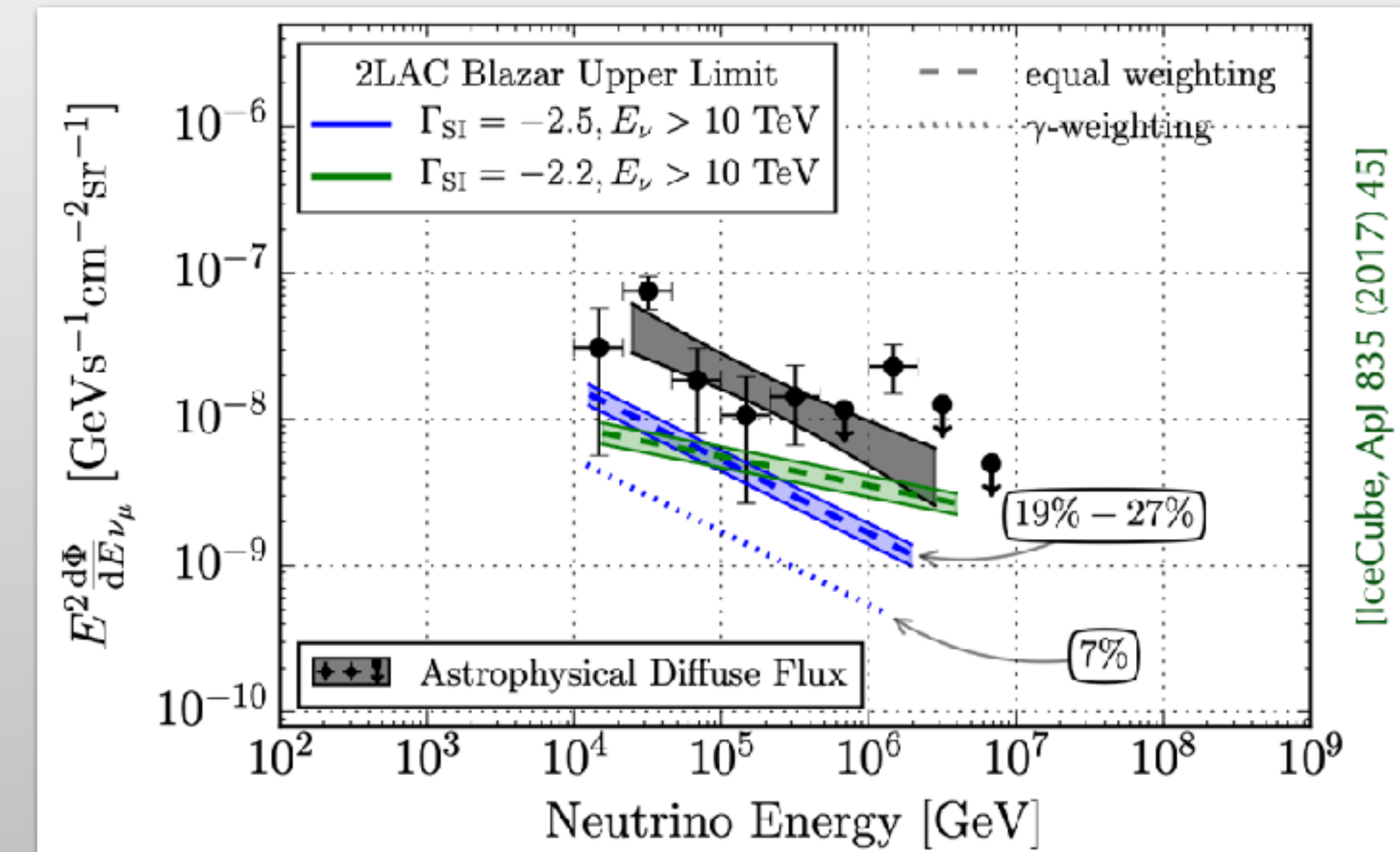
Spatial correlations

“Quantitatively”

YES Buson+ 2207.06314,...

NO Bellenghi+ 2309.03115,...

Astro priors crucial



Blazars & high energy neutrinos

Diffuse astrophysical neutrinos?

Neutrinos seen from blazars?

Open problem: find jet model that explain all observations

`Leptohadronic single-zone' models:

None explains ν from TXS or PKS

Gao+ 1807.04275

Cerruti+ 1807.04335

Keivani+ 1807.04537

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Neutrinos seen from blazars?

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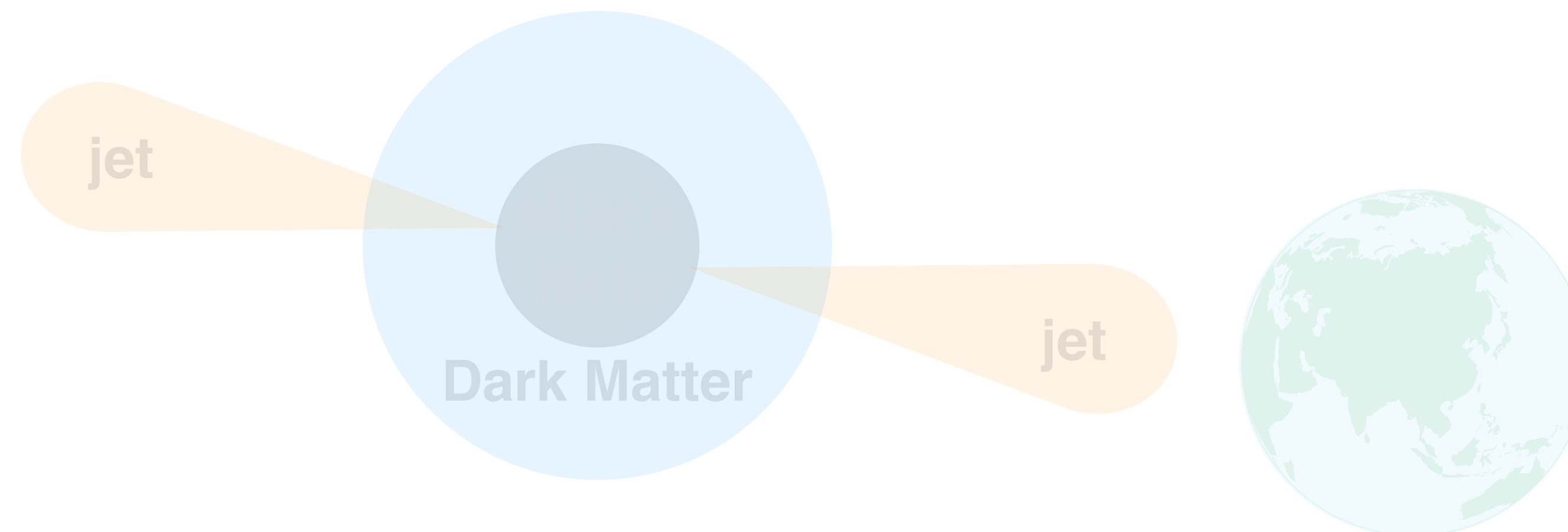
Possibly, ~ paradigm shift in jet modelling

Rodrigues Padovani + 2025

Dark Matter ?

High energy neutrinos ?

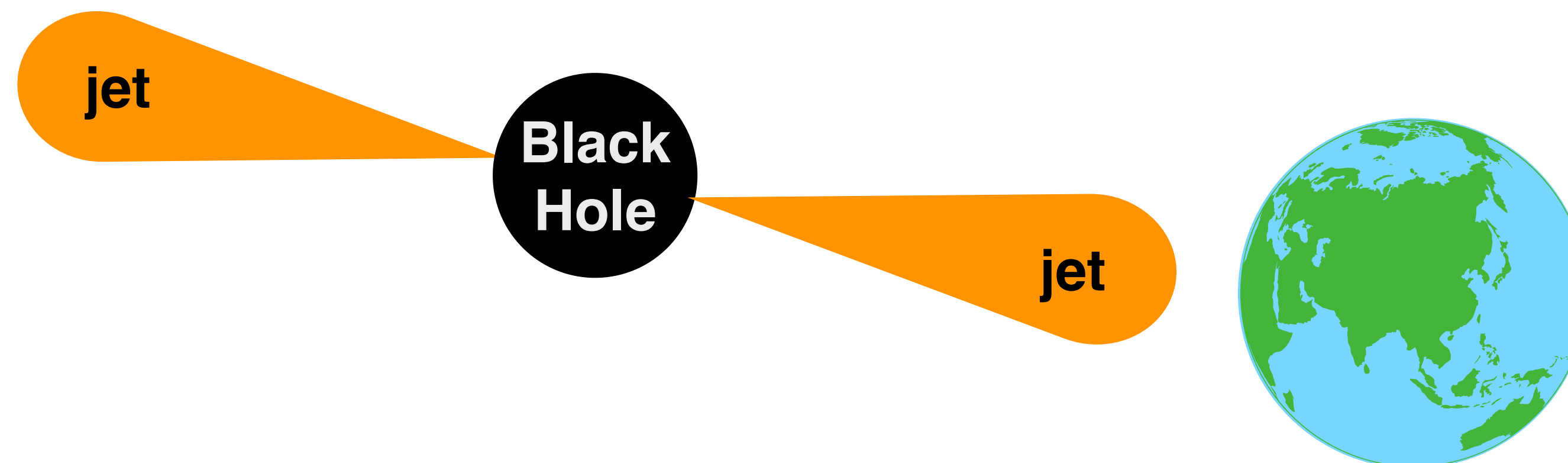
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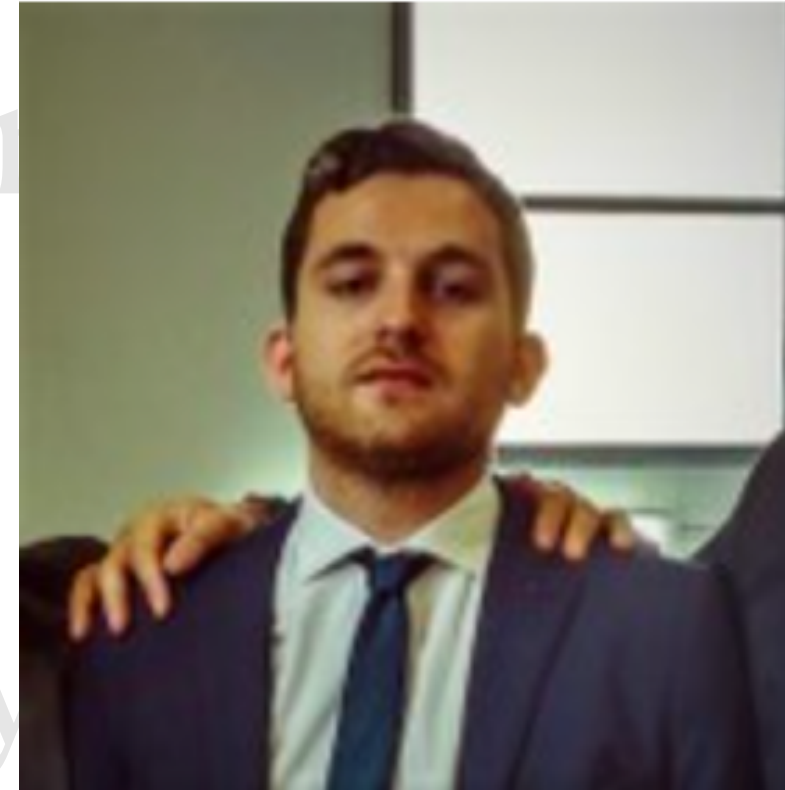
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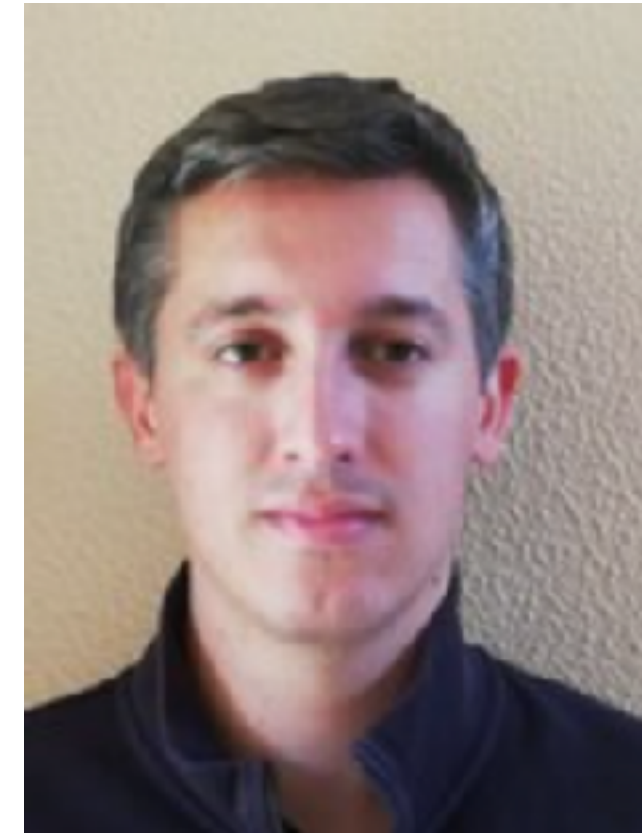




Andrea De Marchi



Alessandro Granelli



Jacopo Nava

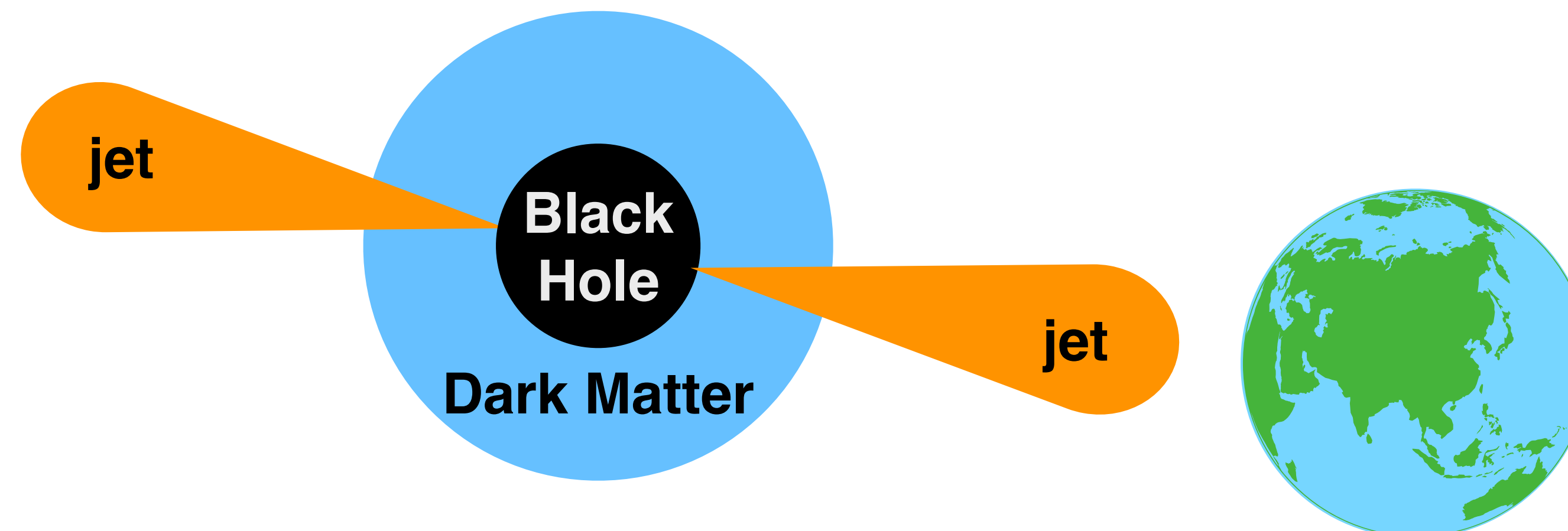
+ FS

2412.07861 PRD 2025

2506.06416 PLB 2025

2507.12278 JHEP 2025

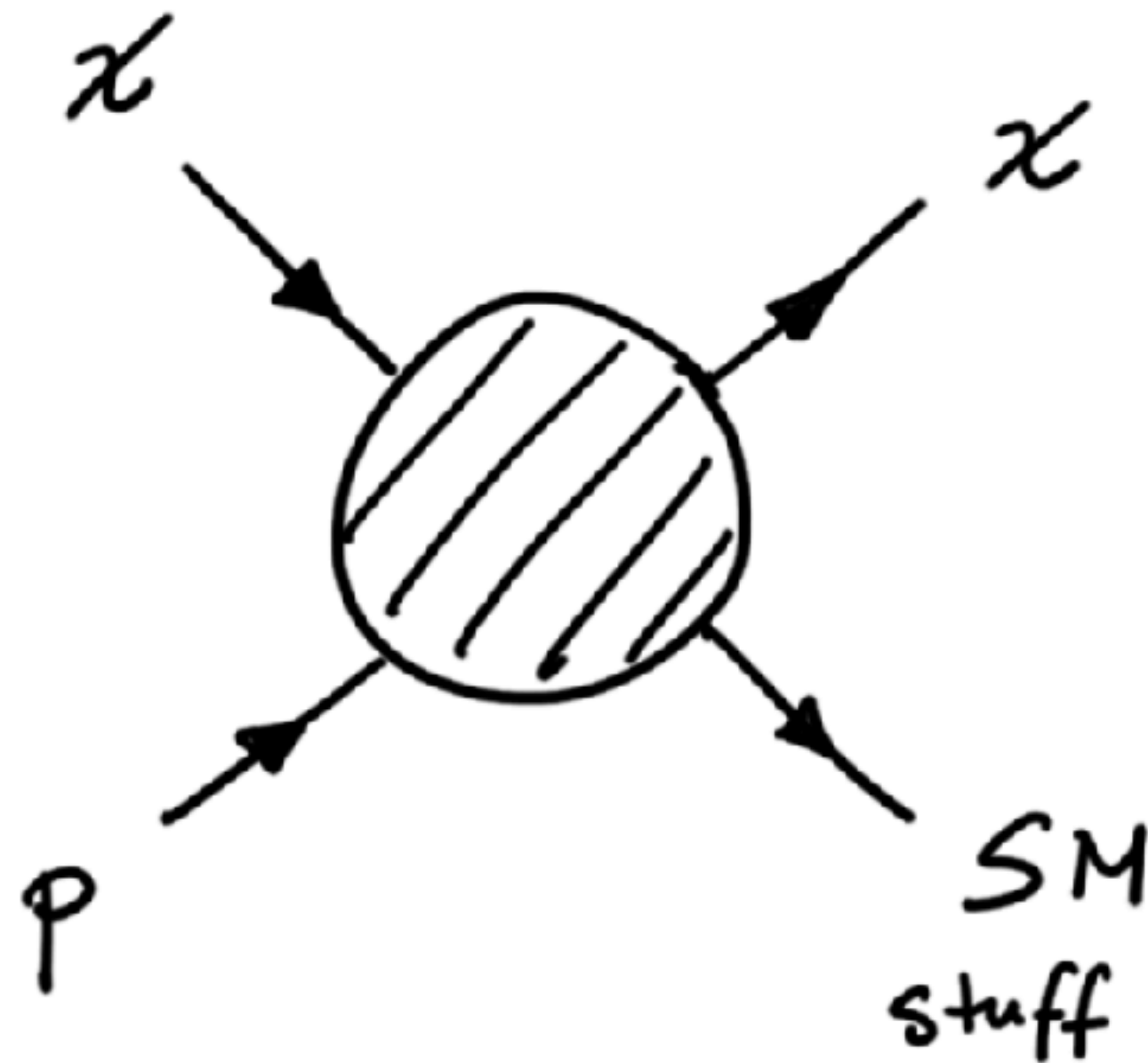
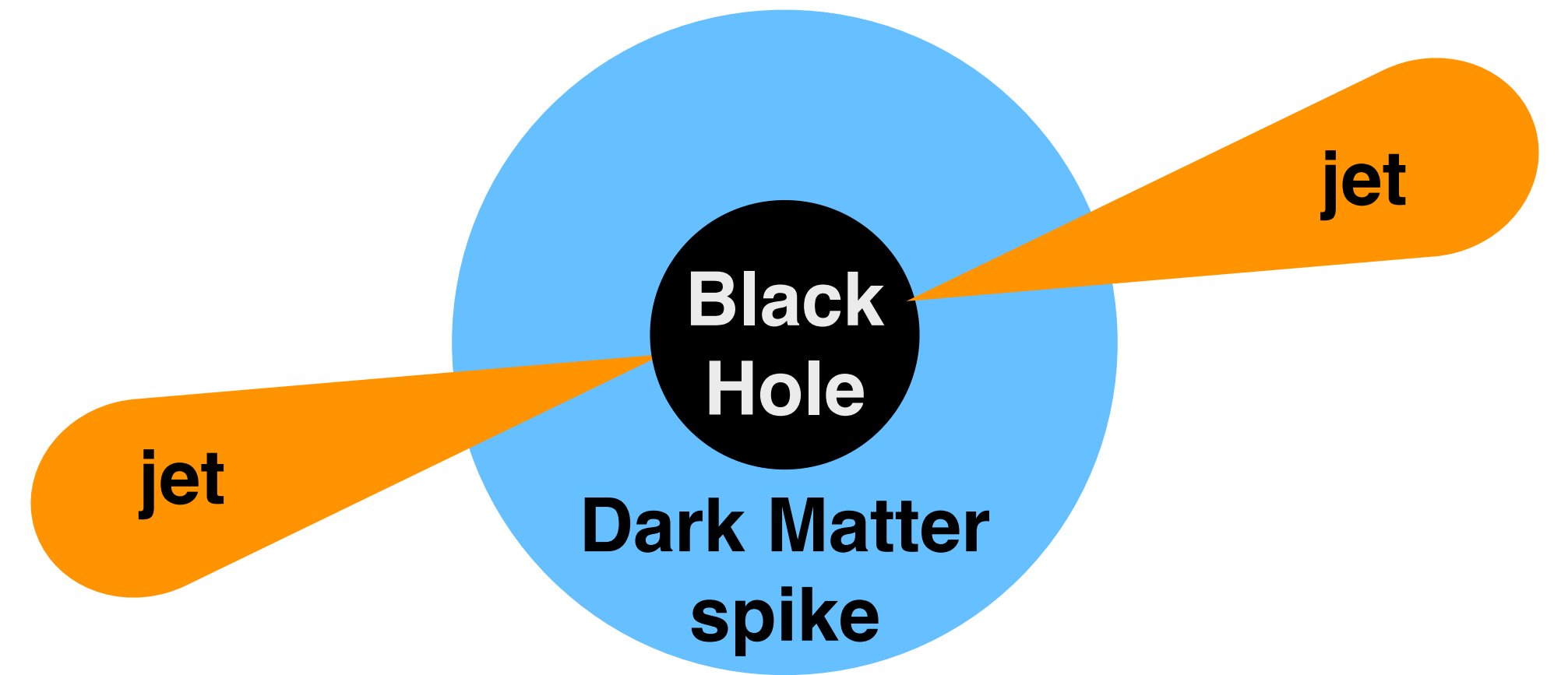
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Neutrinos from DM around blazars?



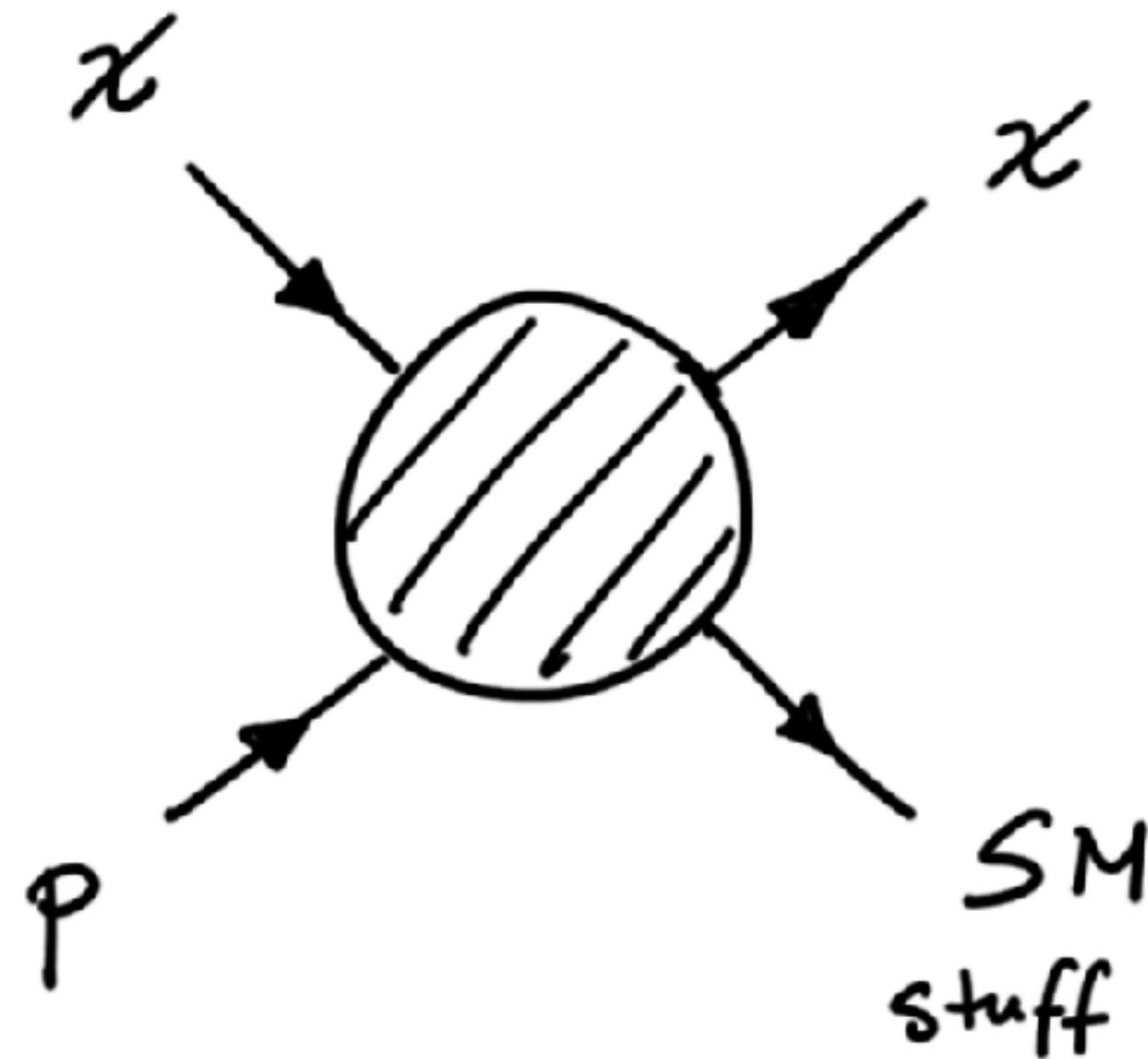
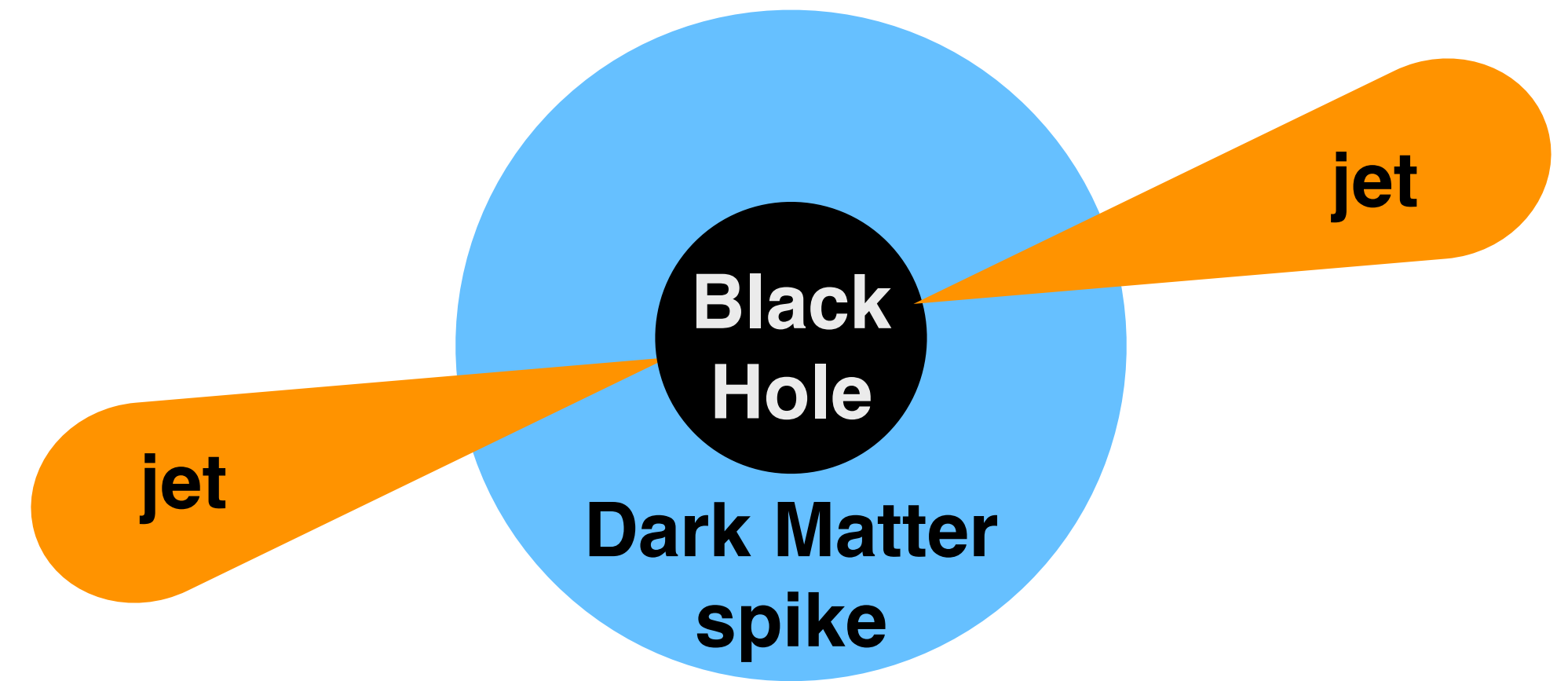
Protons break and produce ν from $\pi^\pm$
De Marchi Granelli Nava 2412.07861



Neutrinos from DM around blazars?



Protons break and produce ν from $\pi^\pm$
De Marchi Granelli Nava 2412.07861

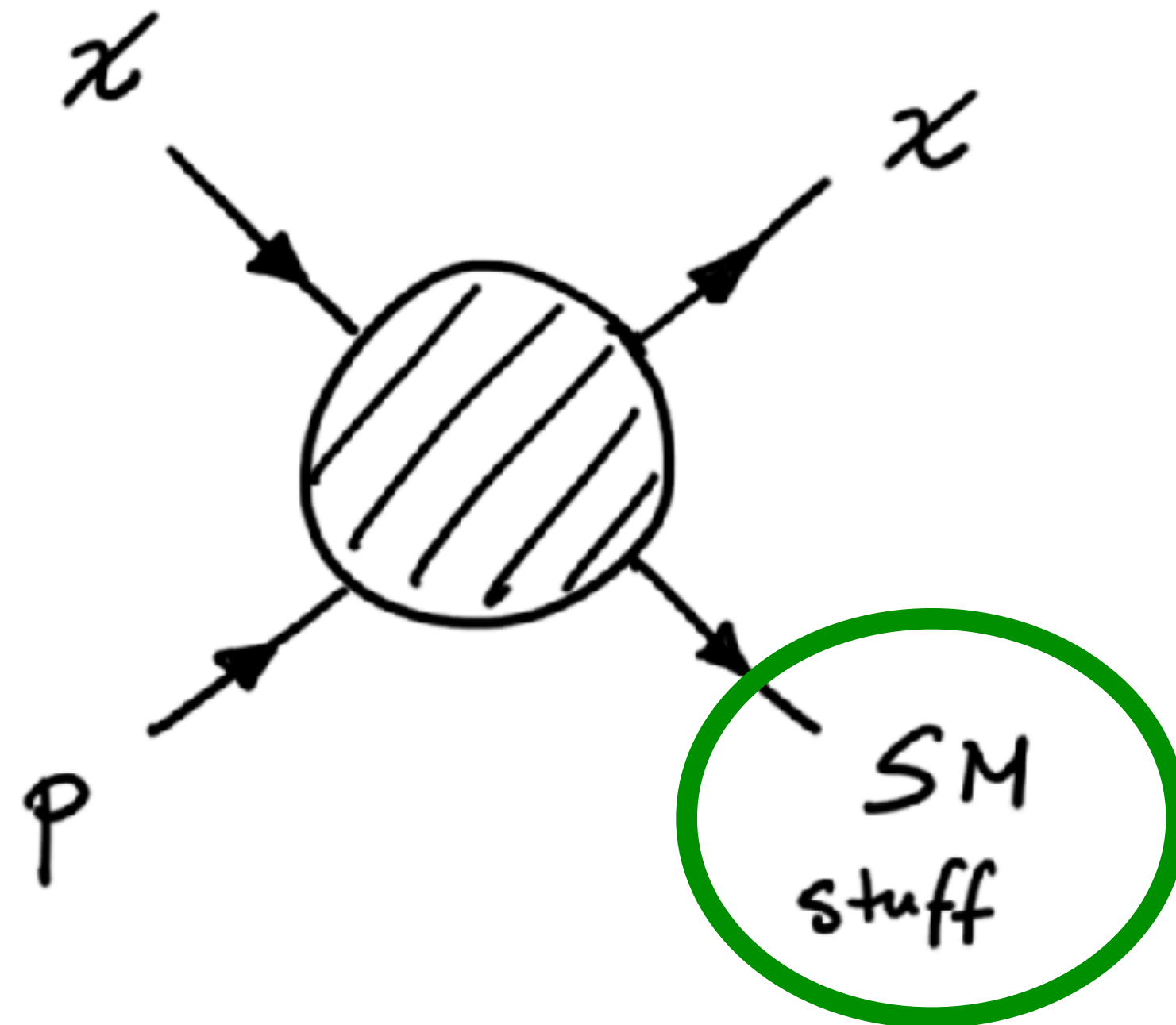
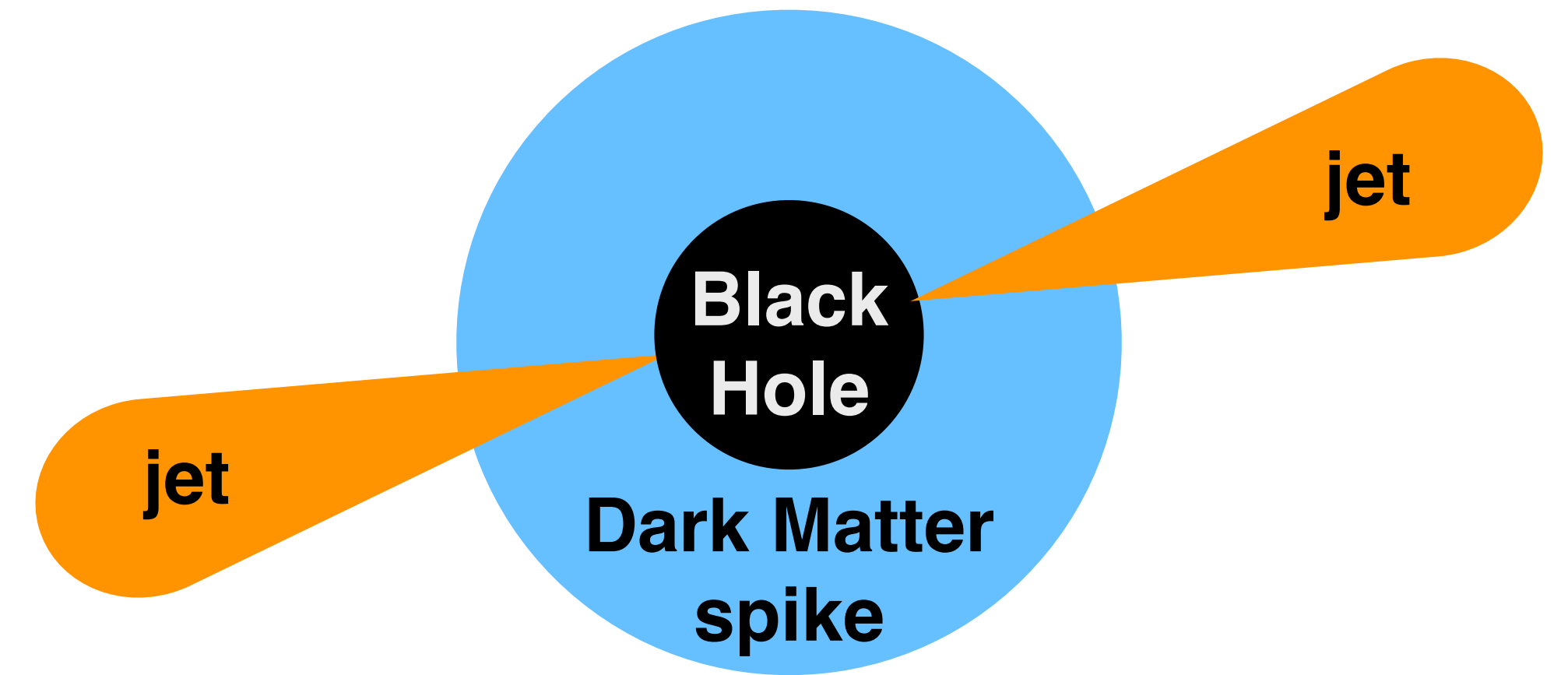


$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Sigma_{\text{los}}}{m_\chi d_L^2} \int dE_p \frac{d\Gamma_p}{dE_p d\Omega} \Big|_{\text{los}} \sigma_{\text{DIS}} \left\langle \frac{dN_\nu}{dE_\nu} \right\rangle$$

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$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Sigma_{\text{los}}}{m_\chi d_L^2} \int dE_p \frac{d\Gamma_p}{dE_p d\Omega} \Big|_{\text{los}} \sigma_{\text{DIS}} \left\langle \frac{dN_\nu}{dE_\nu} \right\rangle$$

DM spike around BH

Model of blazar jet

Particle DM model

DM density around SuperMassive BH

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Sigma_{\text{los}}}{m_\chi d_L^2} \int dE_p \frac{d\Gamma_p}{dE_p d\Omega} \Big|_{\text{los}} \sigma_{\text{DIS}} \left\langle \frac{dN_\nu}{dE_\nu} \right\rangle$$

Particle DM model

$$\mathcal{L}_{\text{DM}} = g_q \bar{q} \gamma_\mu q V^\mu + g_\chi \bar{\chi} \gamma_\mu \chi V^\mu + \frac{1}{2} m_V^2 V^\mu V_\mu$$

+ axial-vector, scalar, pseudoscalar

Calculation:



Implement model in FeynRules



Parton-level scattering in
MADGRAPH5 (in COM frame)



Hadronization and
decay with PYTHIA8

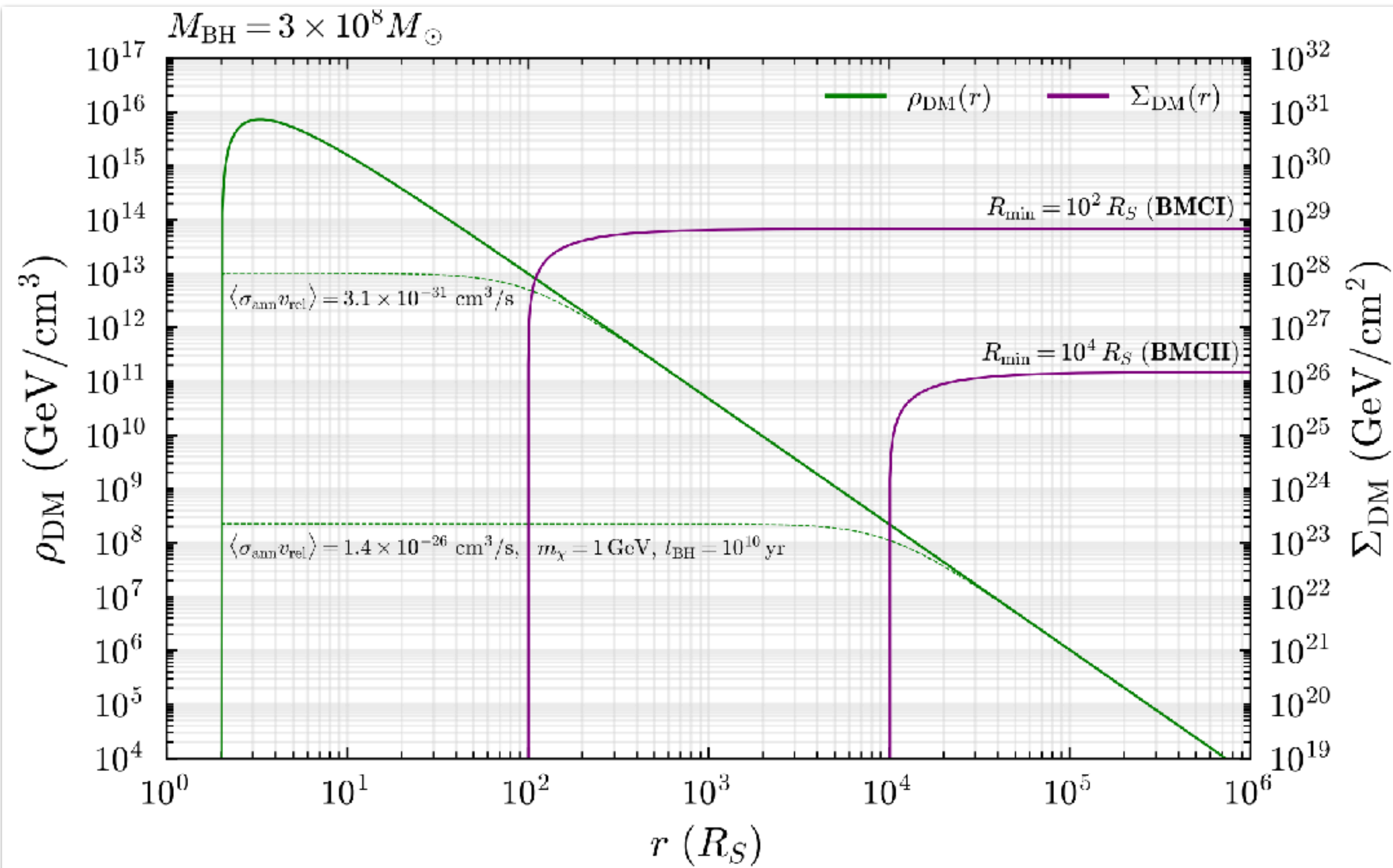
DM density around SuperMassive BH

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Sigma_{\text{los}}}{m_\chi d_L^2} \int dE_p \frac{d\Gamma_p}{dE_p d\Omega} \Big|_{\text{los}} \sigma_{\text{DIS}} \left\langle \frac{dN_\nu}{dE_\nu} \right\rangle$$

$$\Sigma_{\text{los}} = \int_{r_{\text{min}}}^{r_{\text{max}}} dr \rho(r)$$

**Black
Hole**

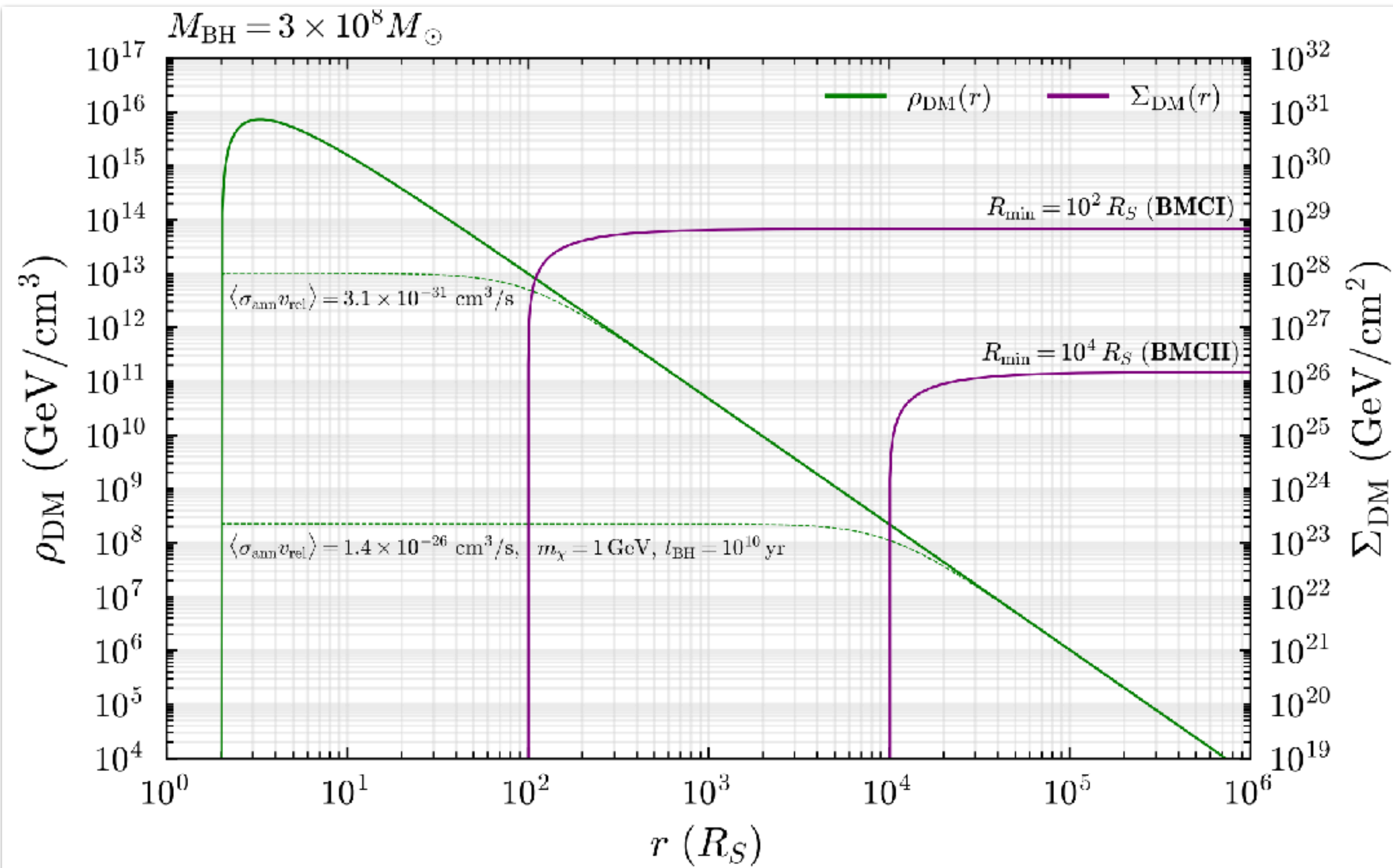
**Dark Matter
spike**



DM density around SuperMassive BH

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Sigma_{\text{los}}}{m_\chi d_L^2} \int dE_p \frac{d\Gamma_p}{dE_p d\Omega} \Big|_{\text{los}} \sigma_{\text{DIS}} \left\langle \frac{dN_\nu}{dE_\nu} \right\rangle$$

$$\Sigma_{\text{los}} = \int_{r_{\text{min}}}^{r_{\text{max}}} dr \rho(r)$$



Benchmark 1 (BMCI)

Gondolo-Silk profile down to $r = 10^2 R_{\text{Sch}}$

Benchmark 2 (BMCII)

Gondolo-Silk profile down to $r = 10^4 R_{\text{Sch}}$

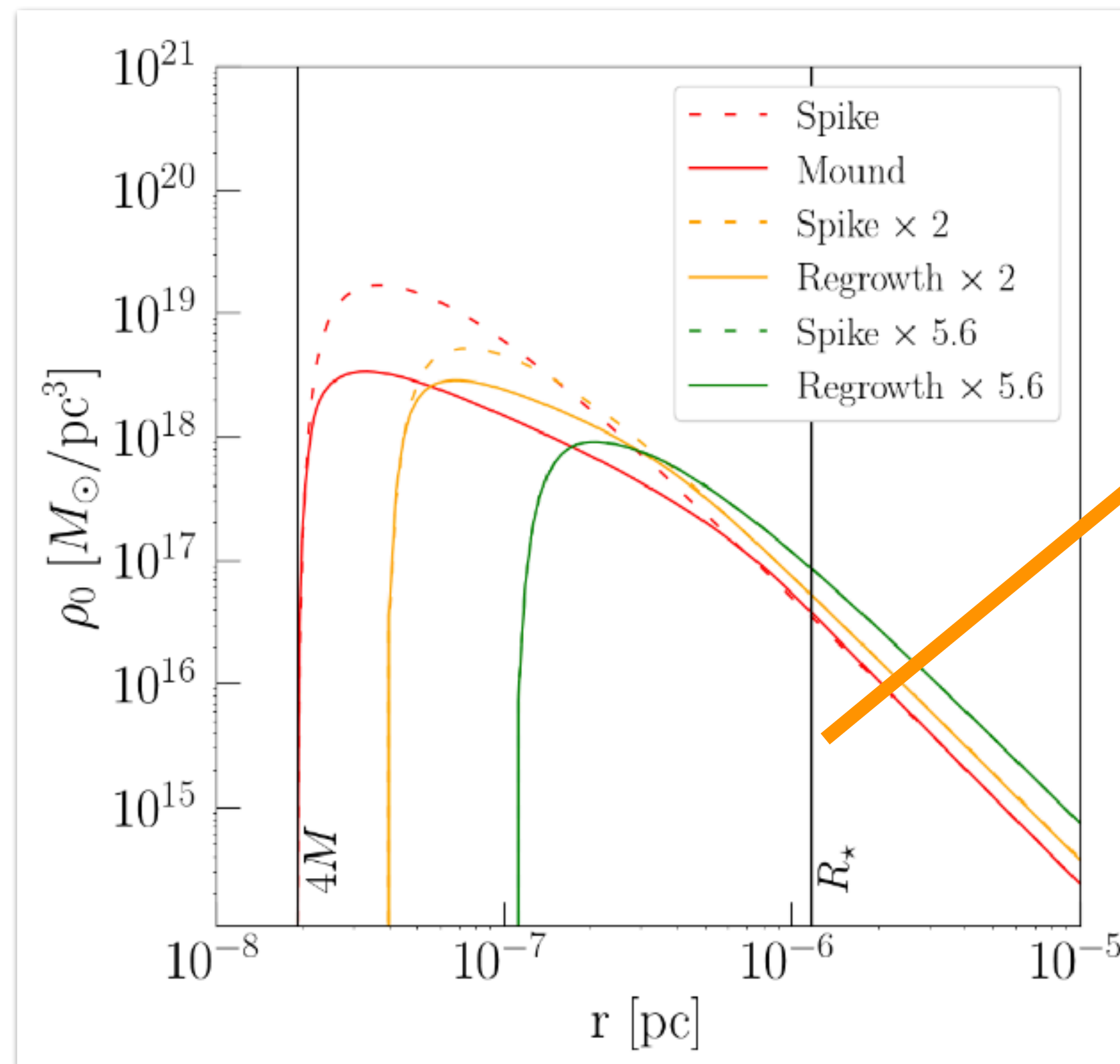
Both more conservative than
in literature on the subject

DM spike around AGN: predictions

Dark matter mounds from the collapse of supermassive stars: a general-relativistic analysis

2512.09985

Roberto Caiozzo,^{1,*} Gianfranco Bertone,² Piero Ullio,^{1,3,4}
Rodrigo Vicente,² Bradley J. Kavanagh,⁵ and Daniele Gaggero⁶



Our aggressive benchmark starts from here



Our studies seem robust with respect to
effects of formation effects of SMBHs

DM spike around AGN: observations!

A novel method to trace the dark matter density profile around supermassive black holes with AGN reverberation mapping

Mayank Sharma^{1,★}, Gonzalo Herrera^{2,★}, Nahum Arav¹, and Shunsaku Horiuchi^{3,2,4} [2506.10122](#)

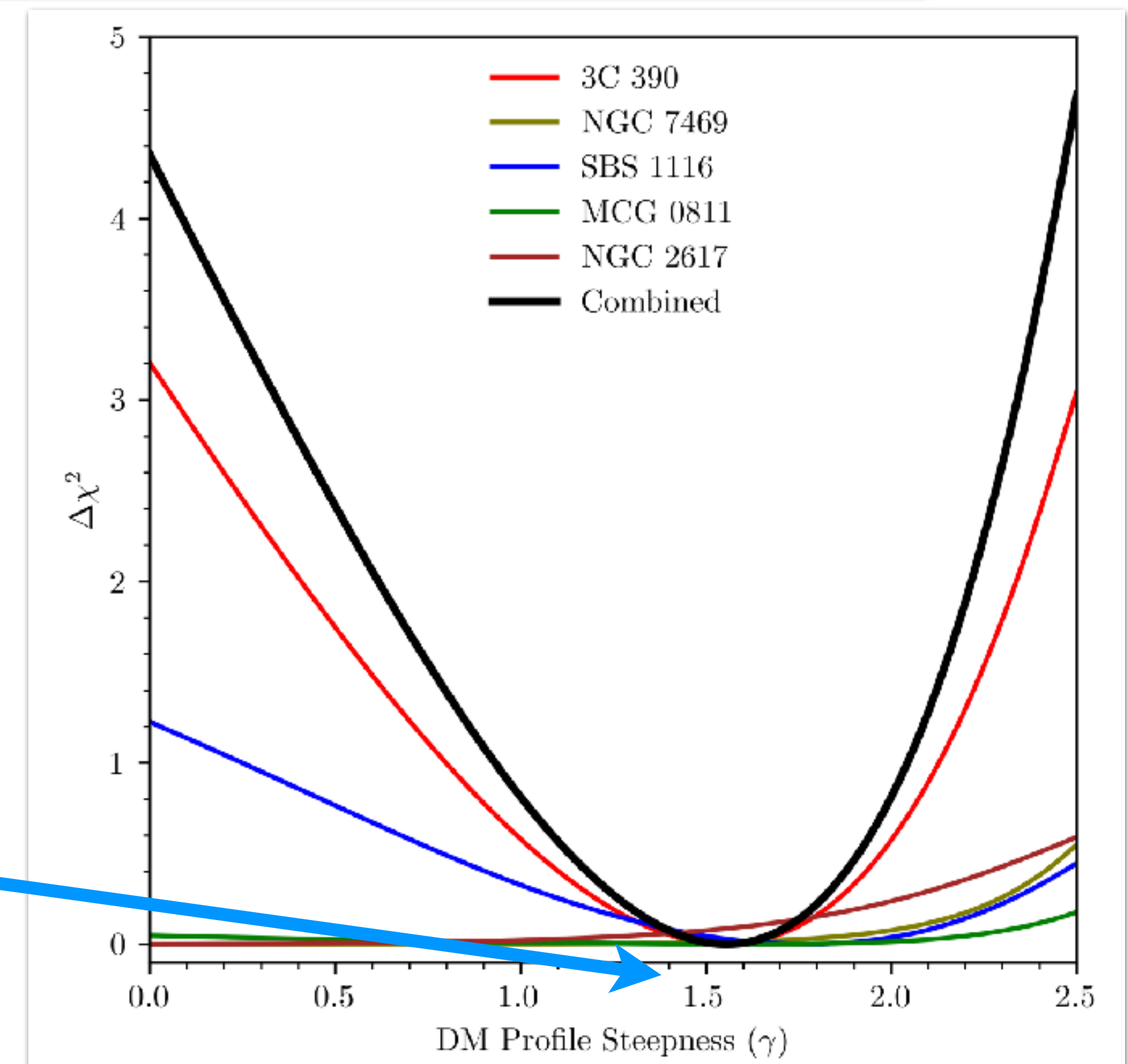
Reverberation mapping:

broad emission lines in AGN spectra



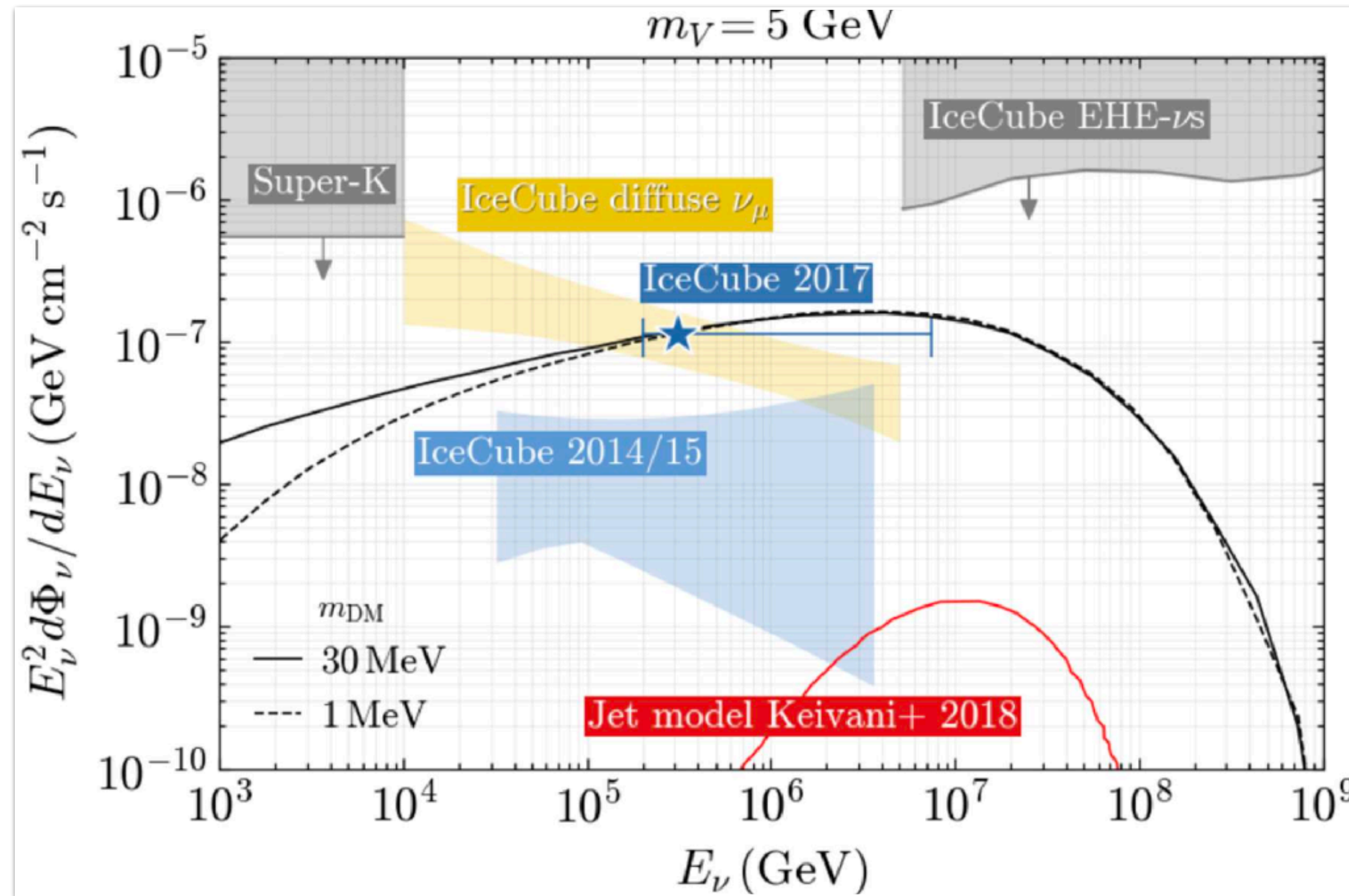
gas velocity dispersion → mass of SMBH and DM spike

We checked that $\gamma \simeq 1.6$
corresponds to our conservative benchmark



Neutrino flux from TXS 0506

De Marchi Granelli Nava FS 2412.07861

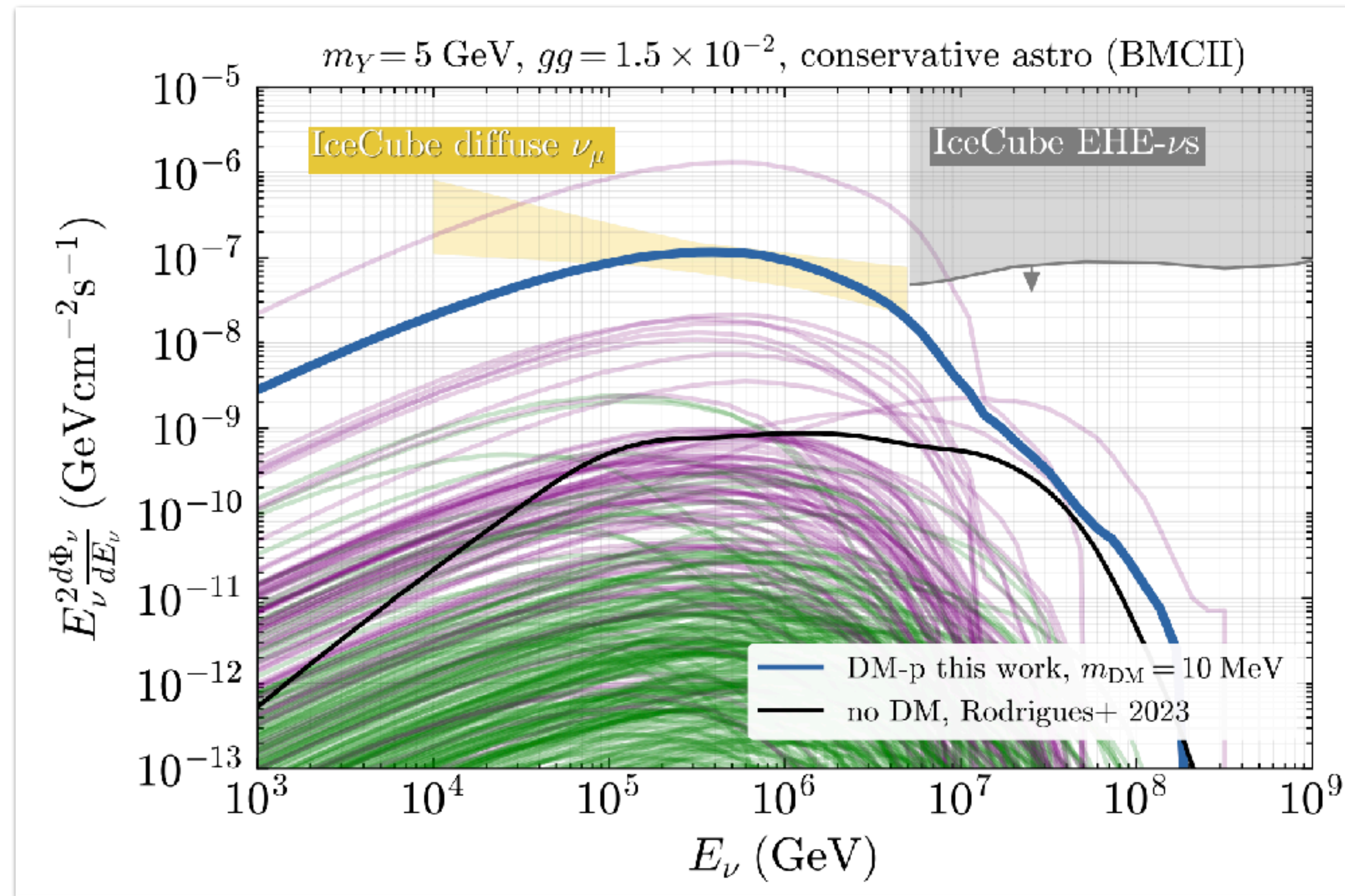


We make it!

Neutrino flux from stacked blazars

De Marchi Granelli Nava FS 2506.06416

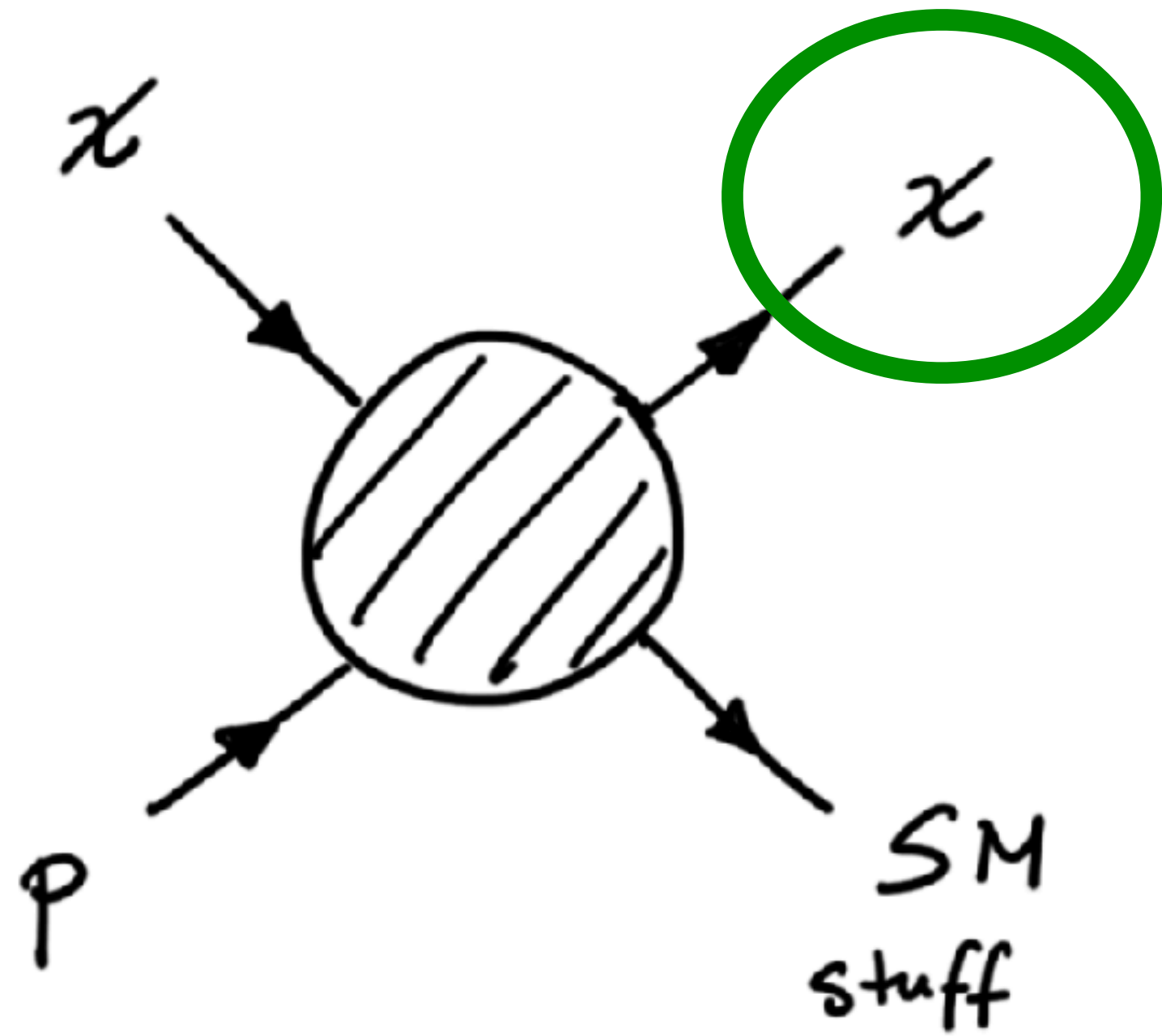
We saturate IceCube's observations!



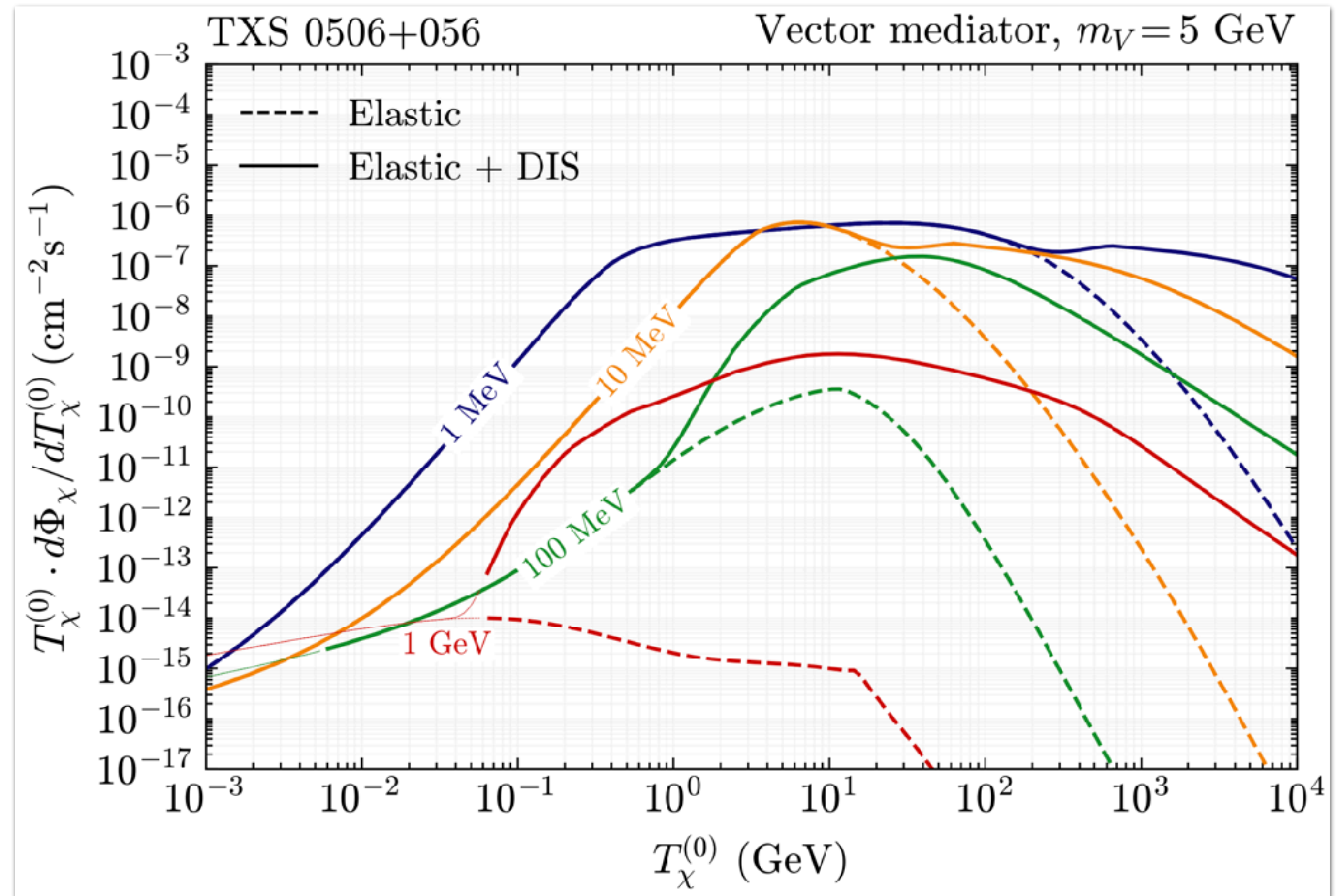
Using catalogue of 324 blazar modelled in [Rodrigues+ 2307.13024](#)

Associated DM fluxes

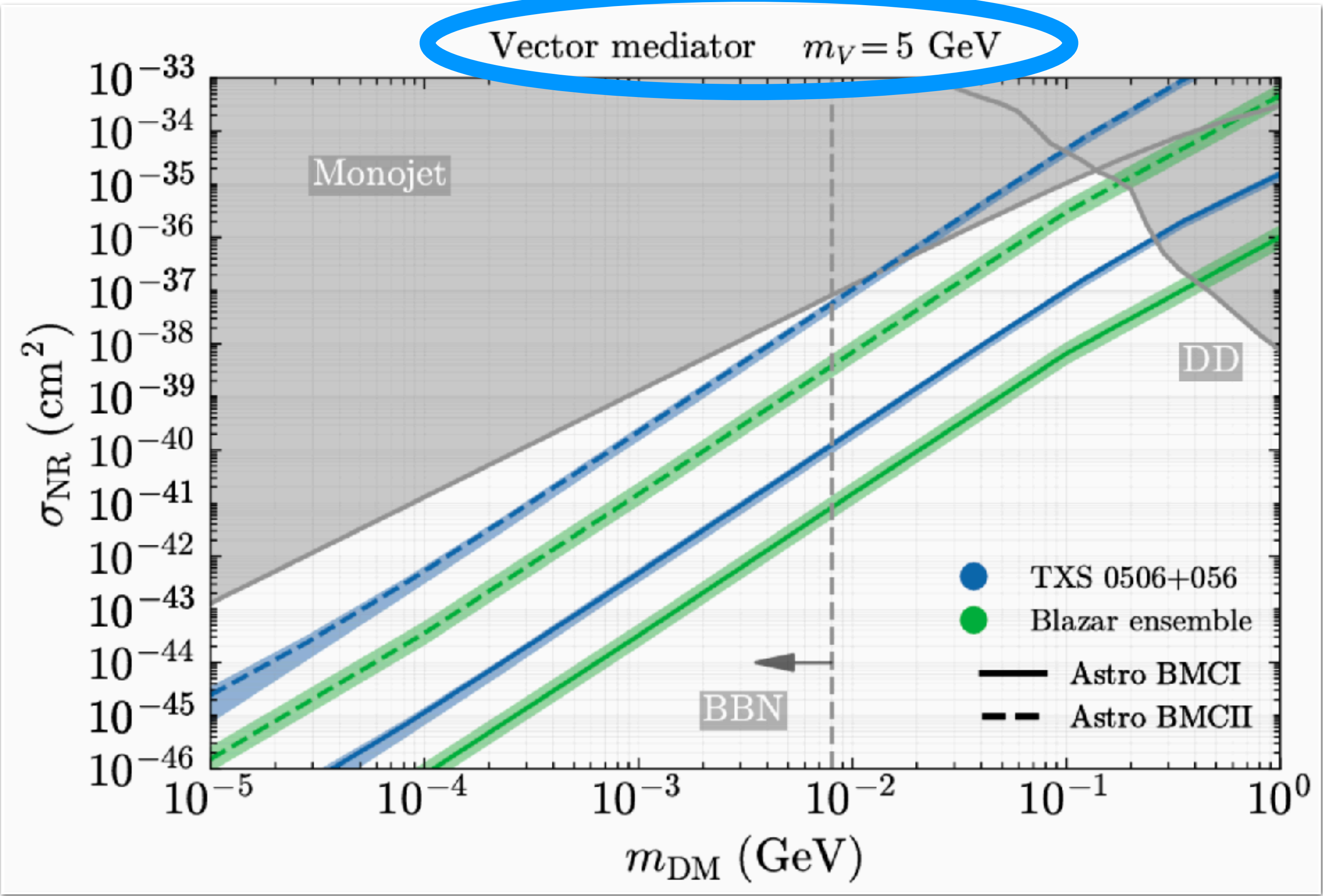
De Marchi Granelli Nava FS 2507.12278



Now we look for this



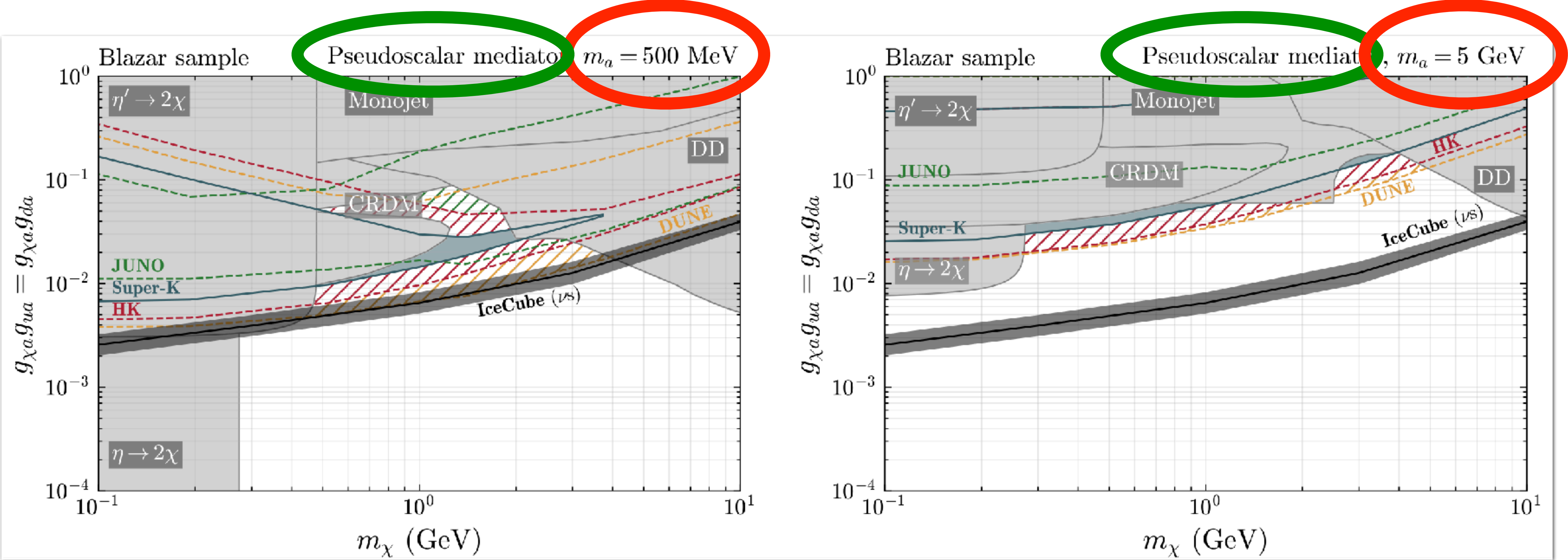
DM neutrino explanation is OK with other limits



Can be tested in the lab!

De Marchi Granelli Nava FS 2024-2025

DM neutrino explanation is OK with other limits



Different mediators and masses lead to different signals

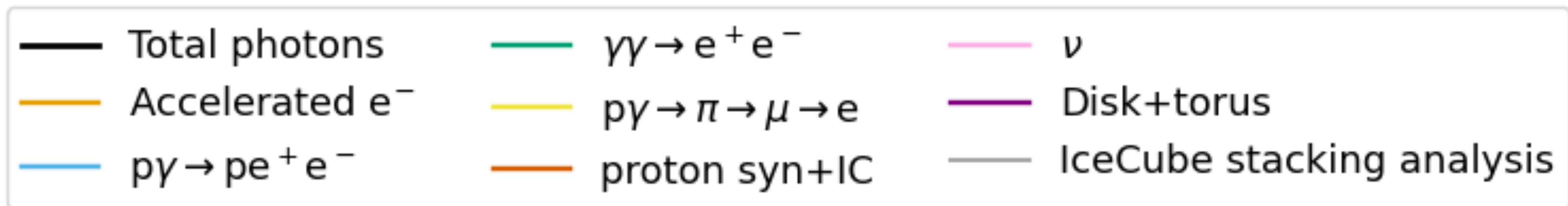
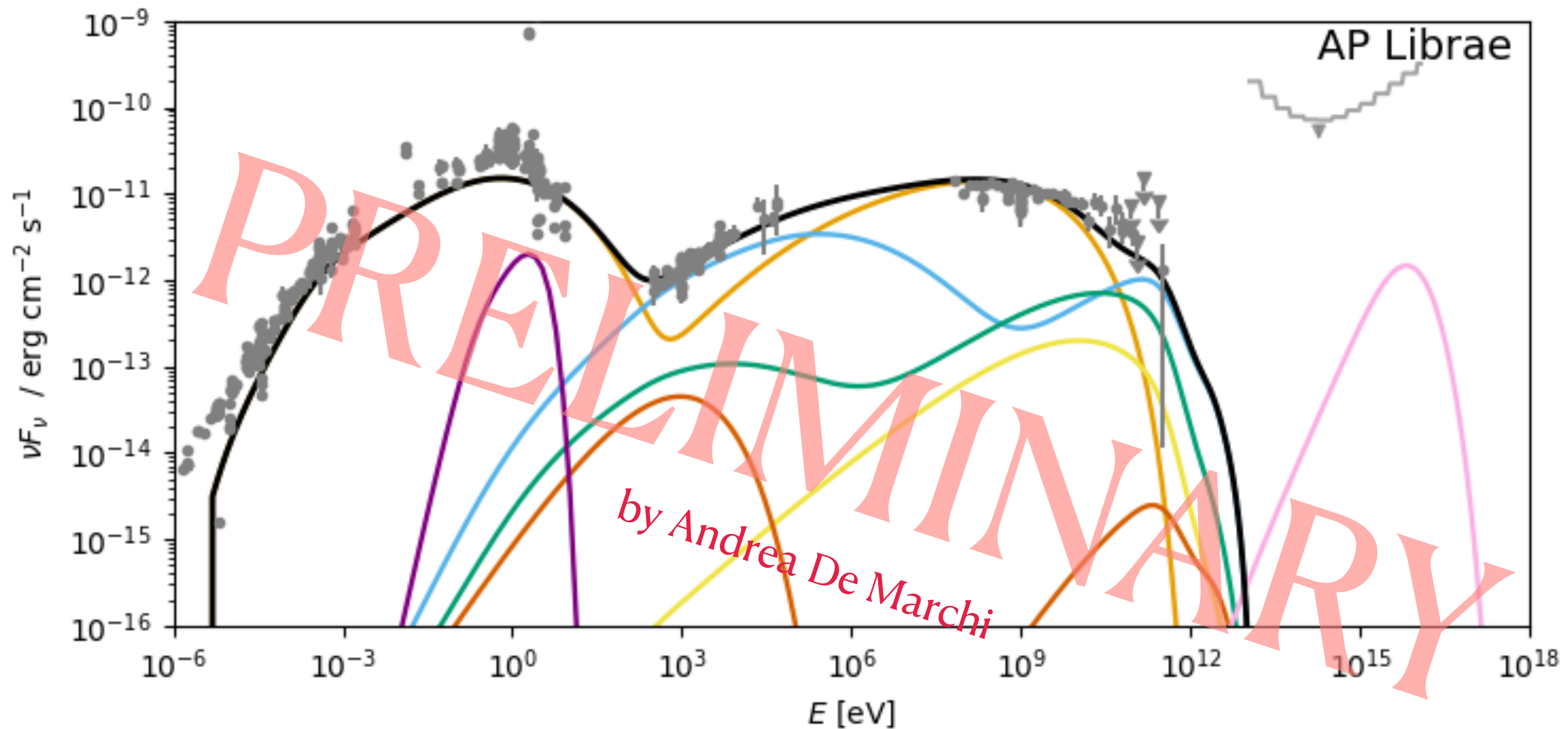
De Marchi Granelli Nava FS 2024-2025

(Too many?) gamma rays from DM around blazars

De Marchi Granelli Nava FS + Cerruti Rodrigues Padovani, in progress



Using blazar code AM3, we reproduce data (+ spectrum of Rodrigues+ 2307.13024) for blazar AP Librae

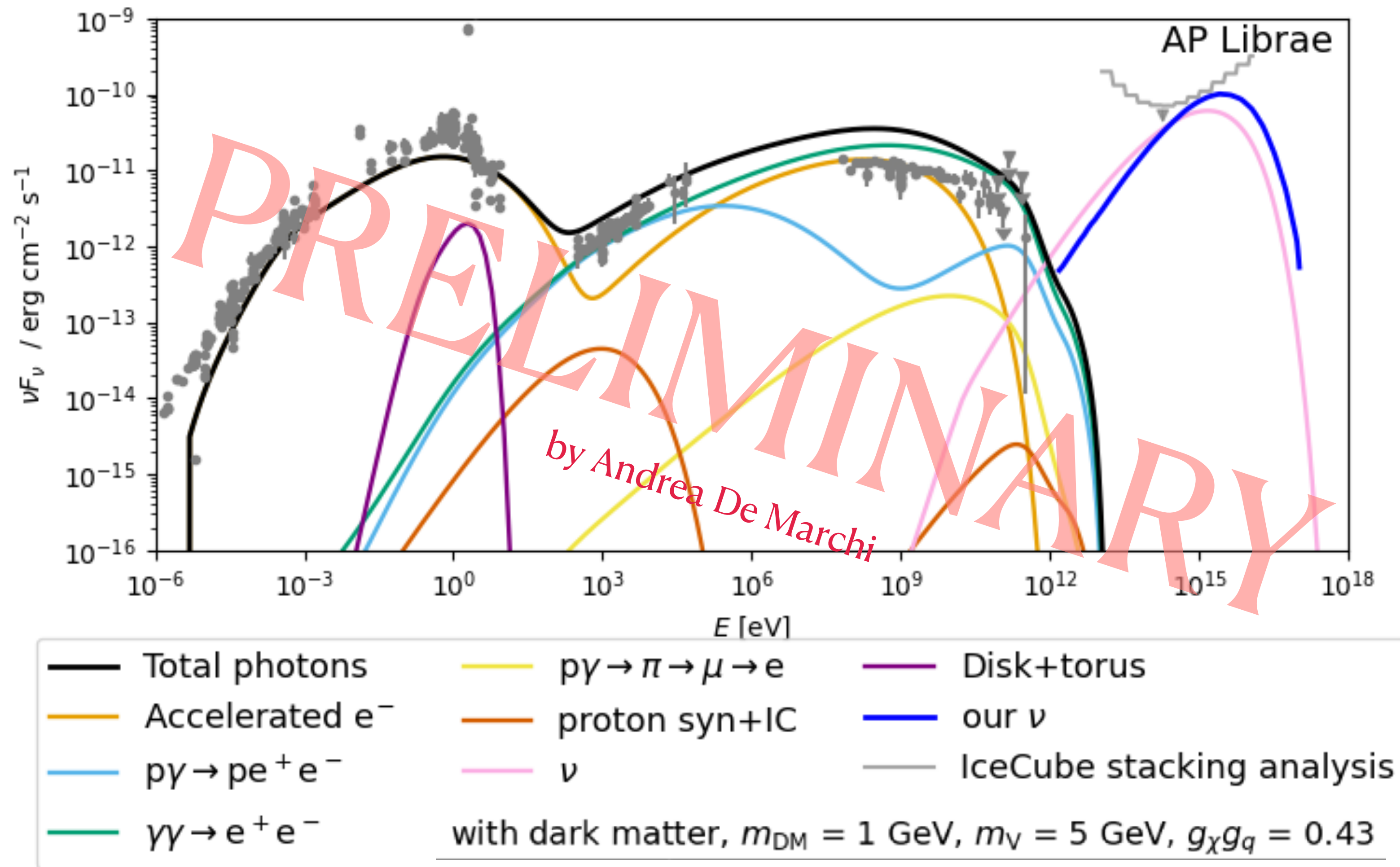


(Too many?) gamma rays from DM around blazars

De Marchi Granelli Nava FS + Cerruti Rodrigues Padovani, in progress



AP librae + Rodrigues fit: 2 order of magnitude more neutrino -> factor of 2 more photons.



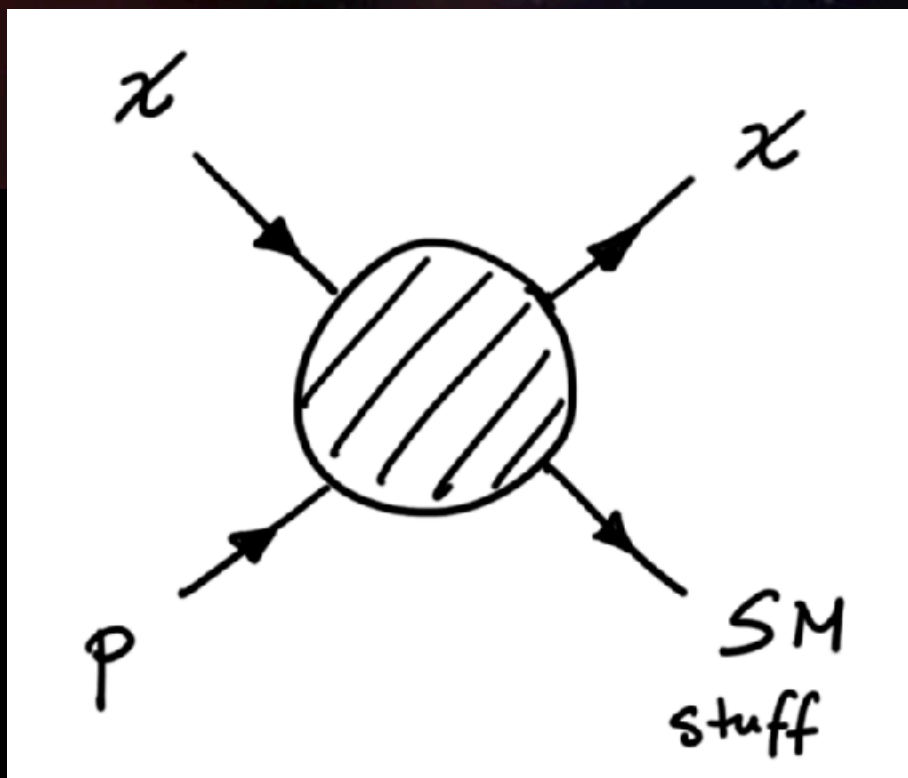
Summary and Outlook

Dark Matter

DM around blazar can explain neutrinos from TXS 05056

DM around blazar can saturate diffuse neutrinos above 100 TeV

Can be tested in lab searches for DM



How can one know more about the DM around the blazar?

What about the photons? work in progress