

High energy neutrinos from Dark Matter around blazars



Filippo Sala

U. Bologna



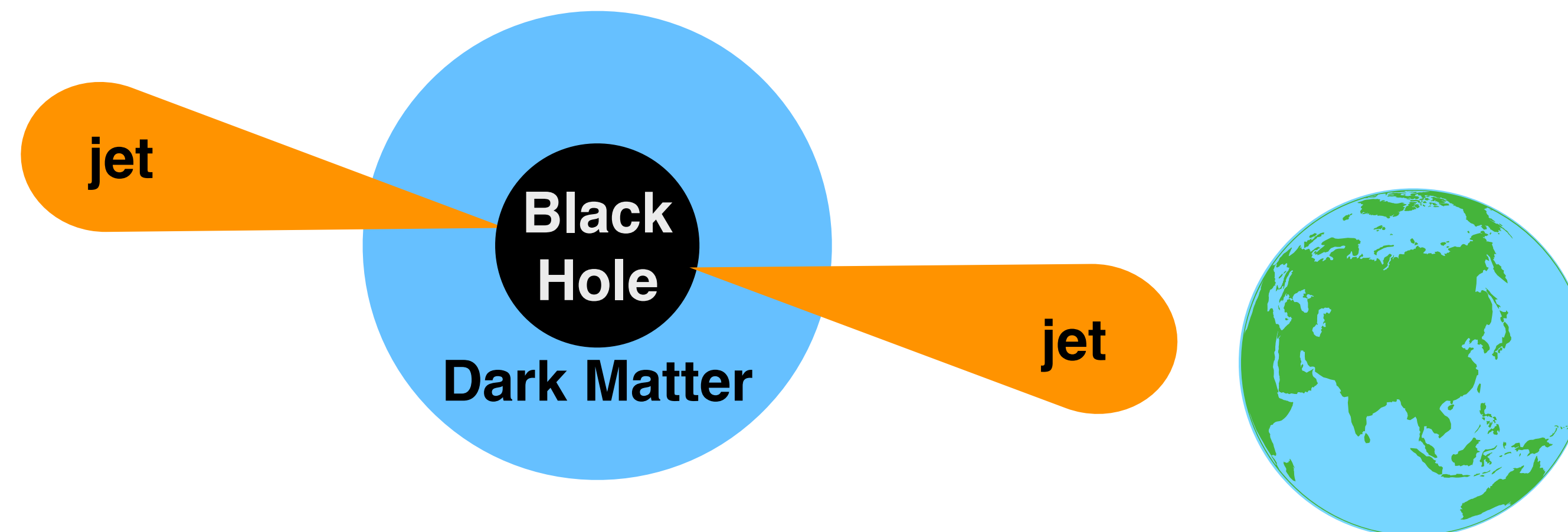
TPPC theory retreat, 18/12/2025

Image credit: IceCube/NASA

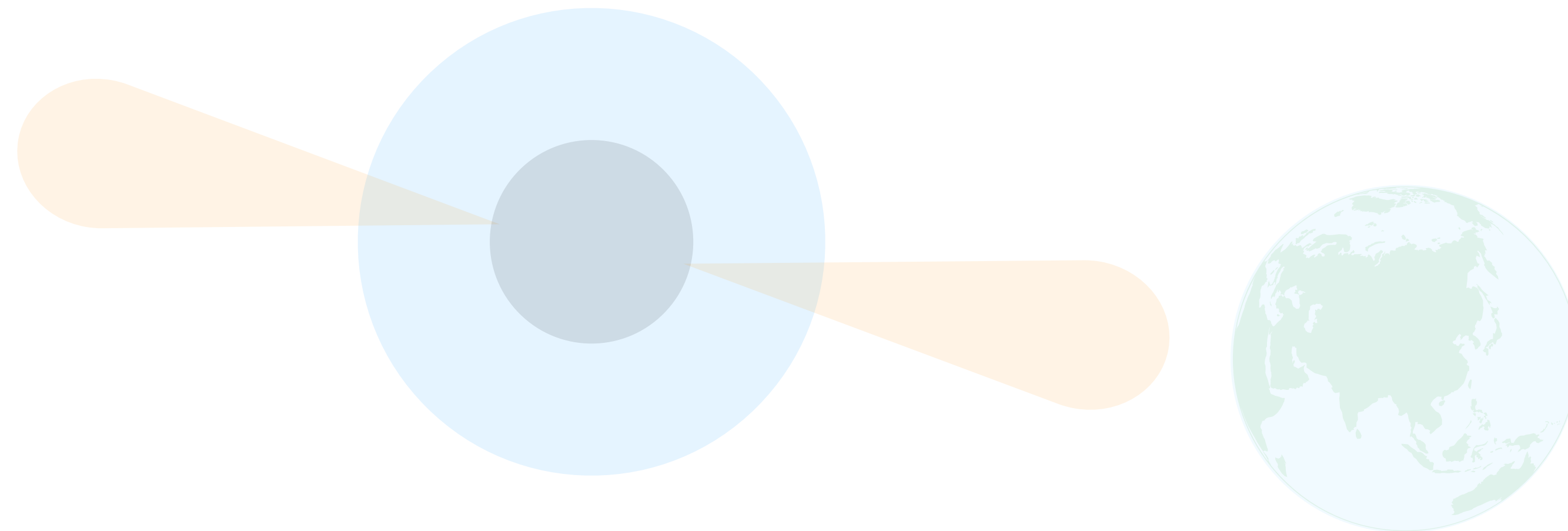
Dark Matter ?

High energy neutrinos ?

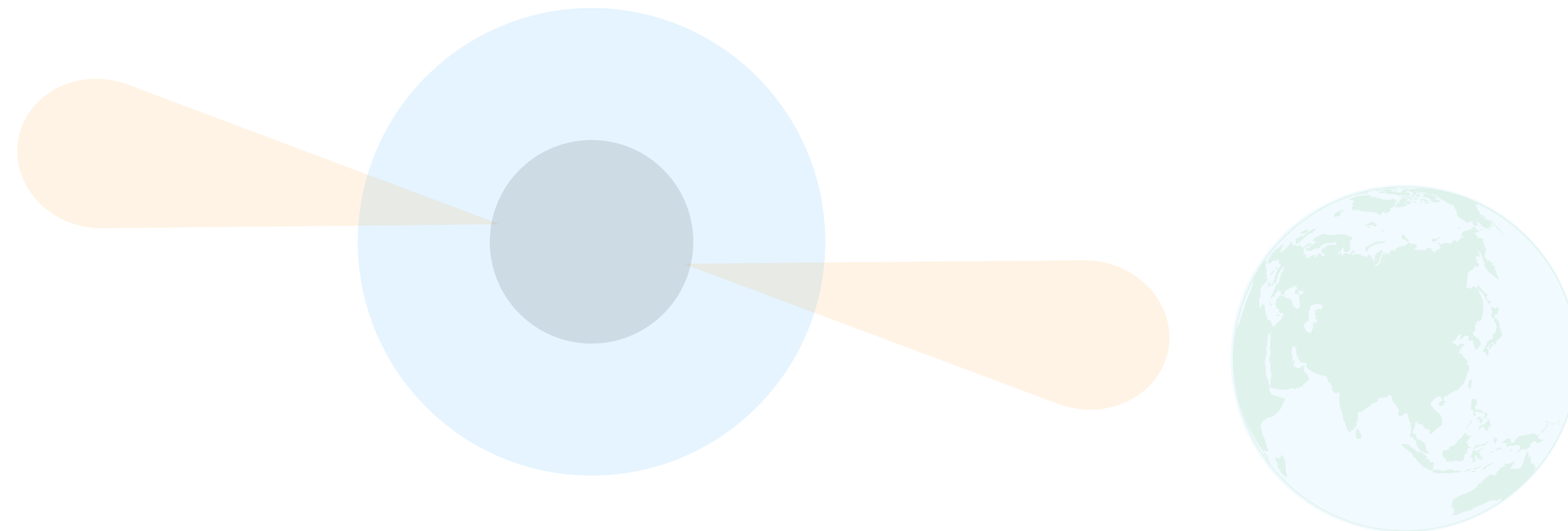
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Dark Matter ?



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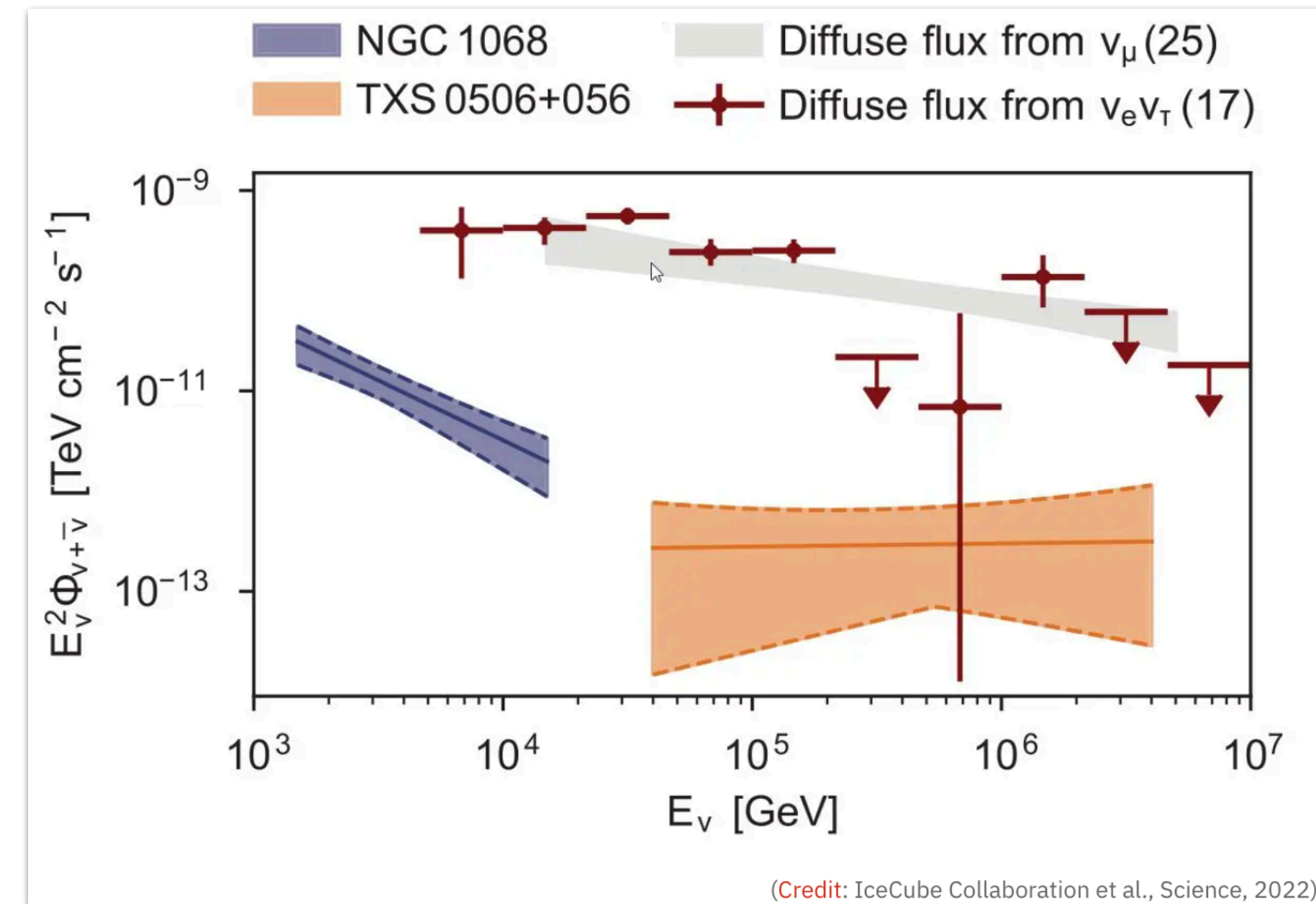


Origin of high energy neutrinos?

Of diffuse astrophysical neutrinos?

Of neutrinos seen from blazars?

Of KM3NeT ~ 200 PeV neutrino?

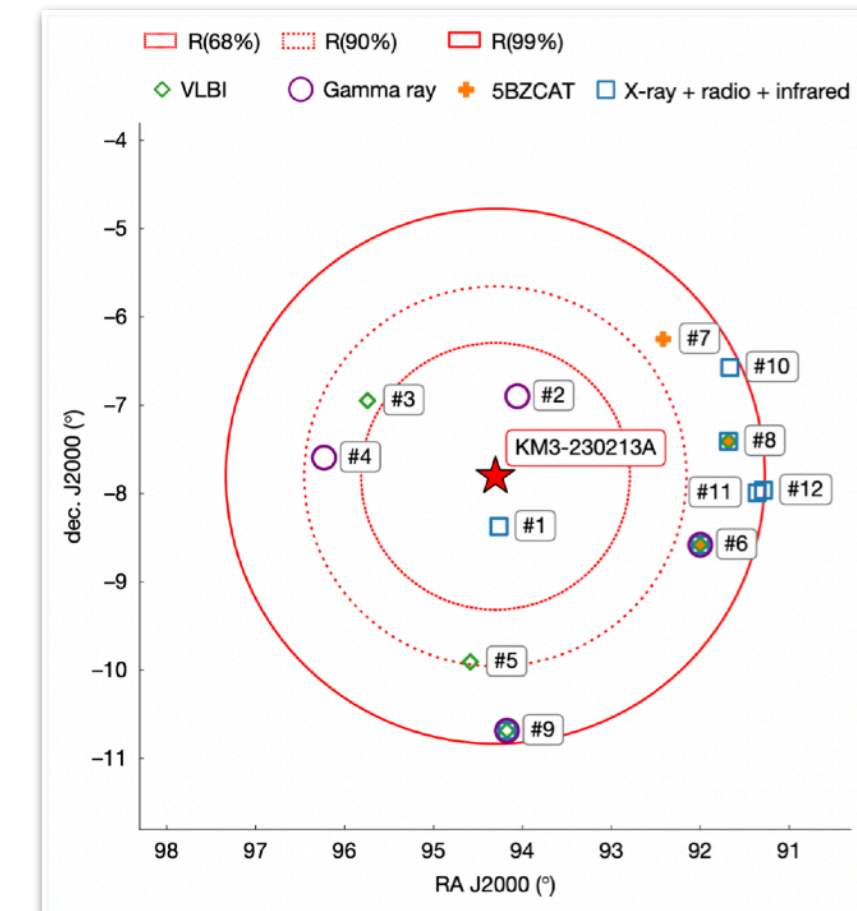
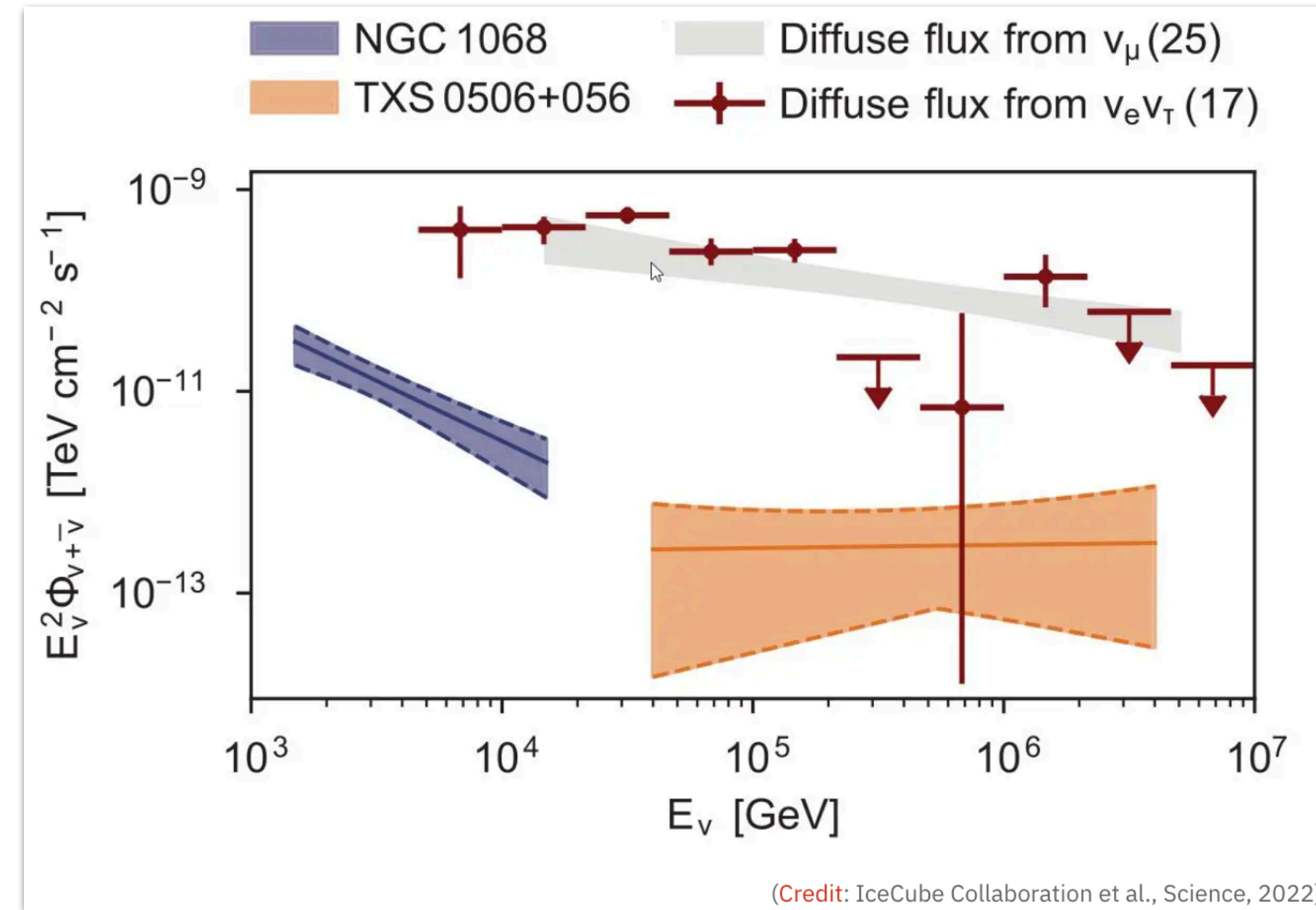


Origin of high energy neutrinos?

Of diffuse astrophysical neutrinos?

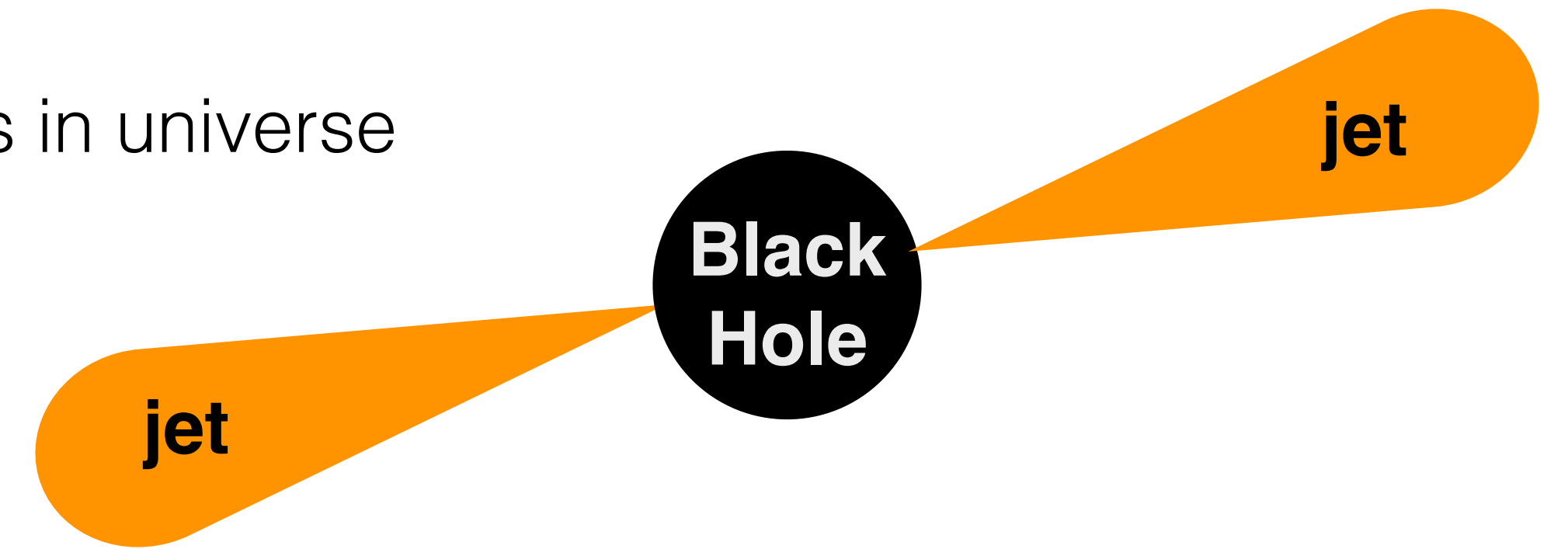
Of neutrinos seen from blazars?

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Blazars

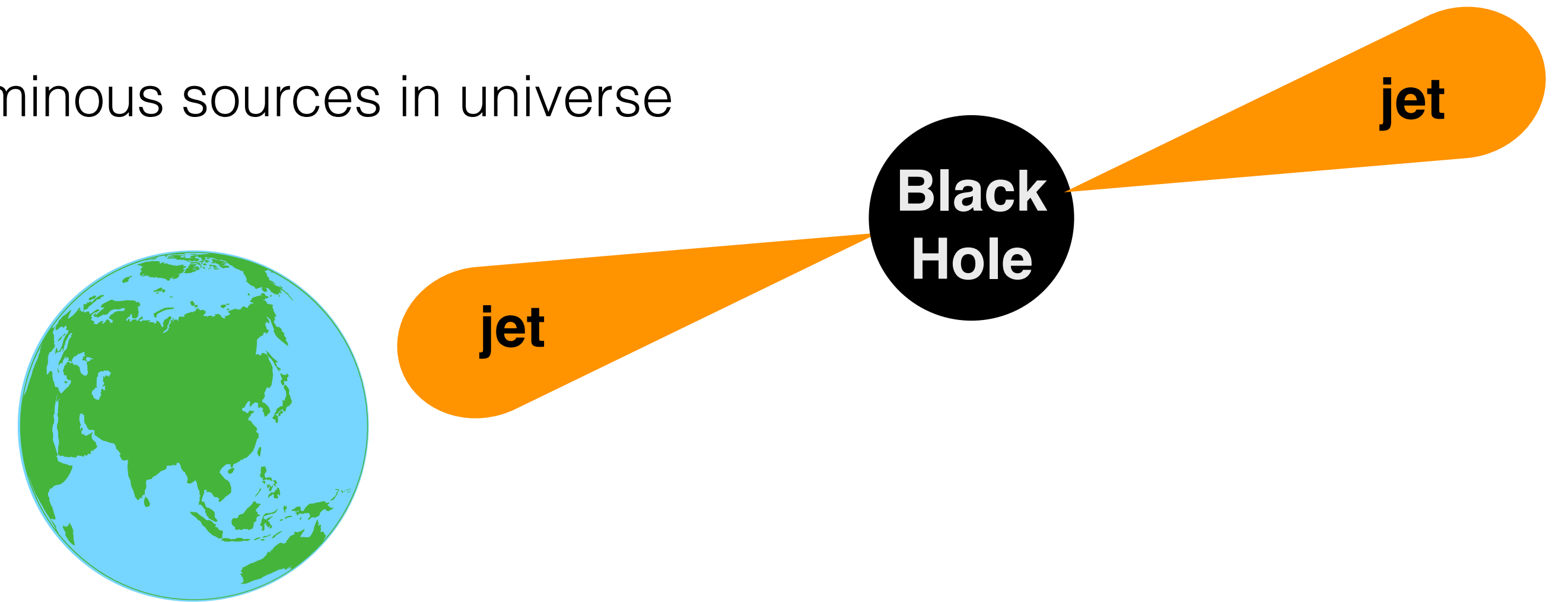
Active galactic nuclei (AGN) = most powerful luminous sources in universe



Blazars

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

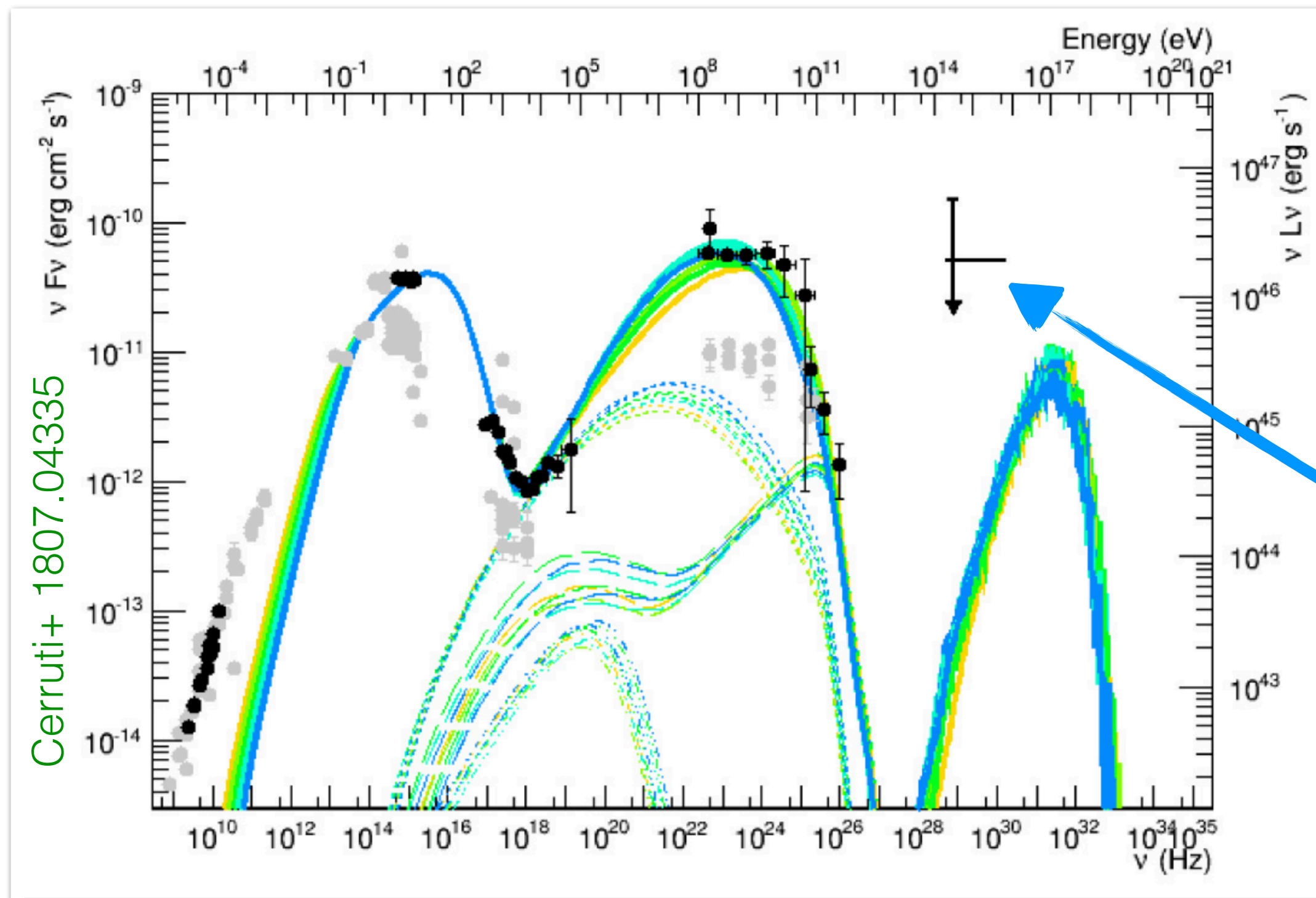
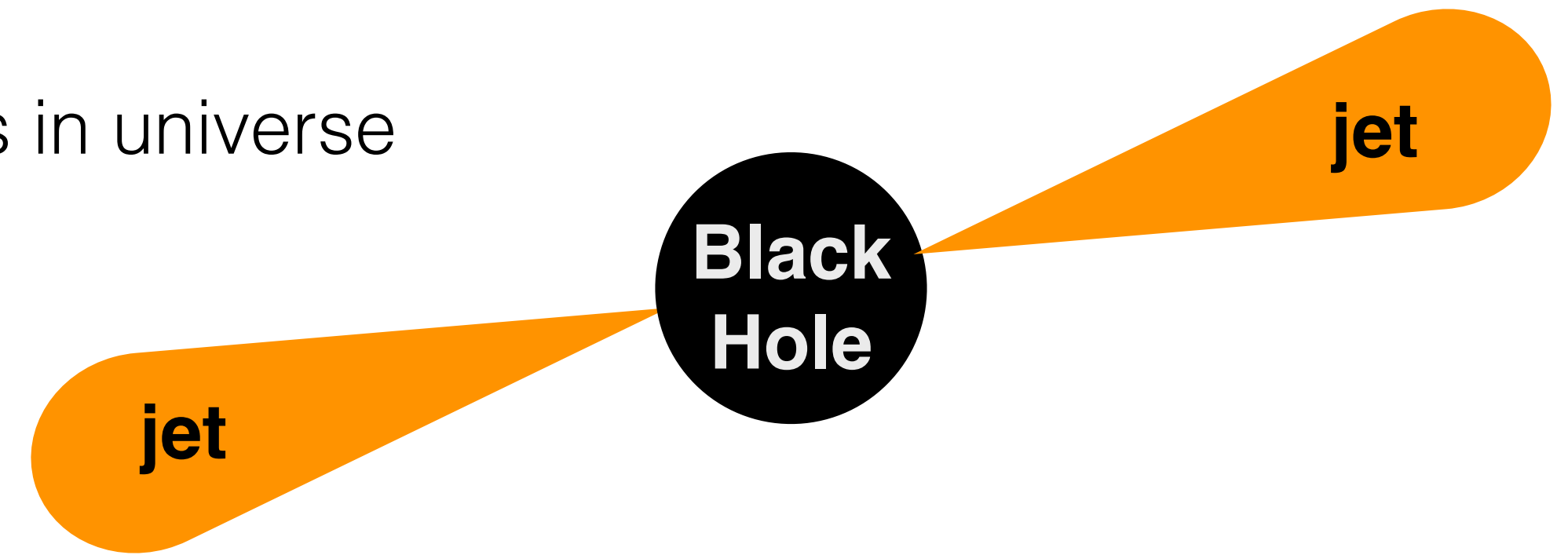
Blazar = AGN whose **jet** points to us



Blazars

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

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



FILIPPO SALA (U. BOLOGNA)

Photons observed from many blazars over many energies

Radio, X, gamma

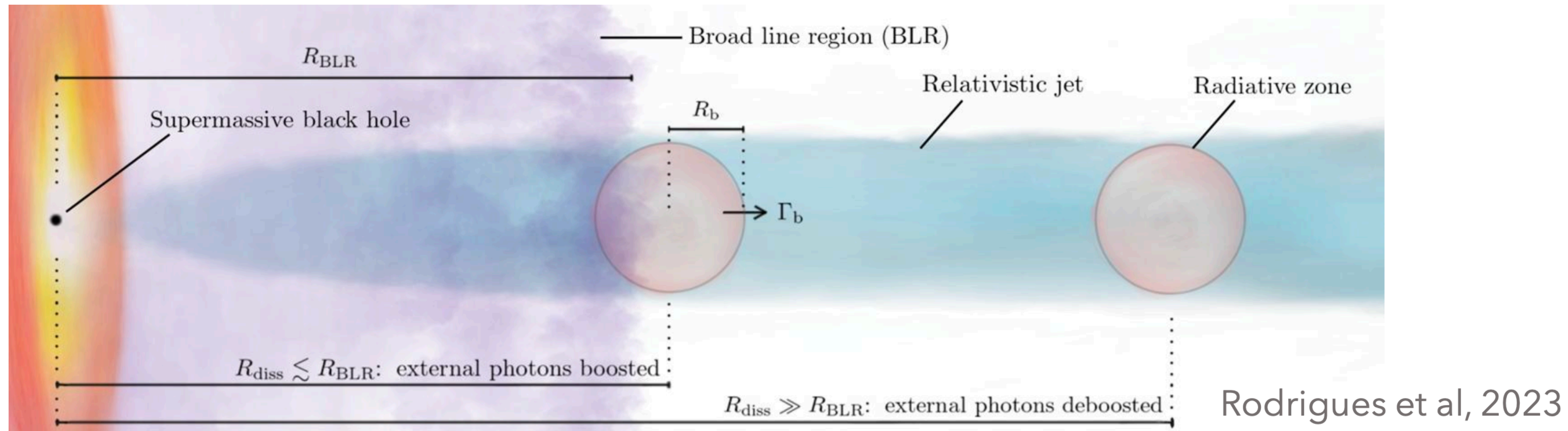
> 50% of extragalactic gammas come from blazars!

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

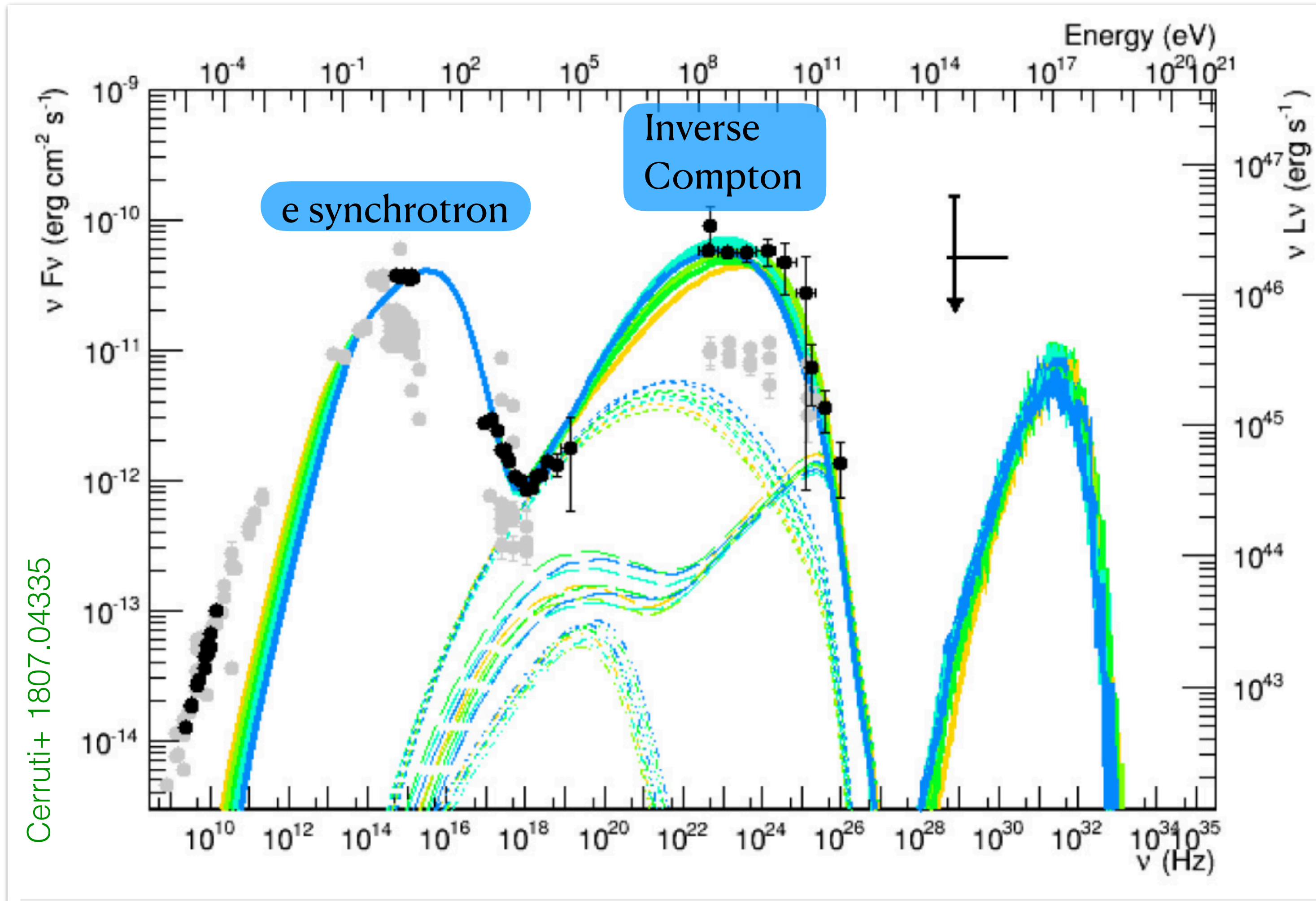
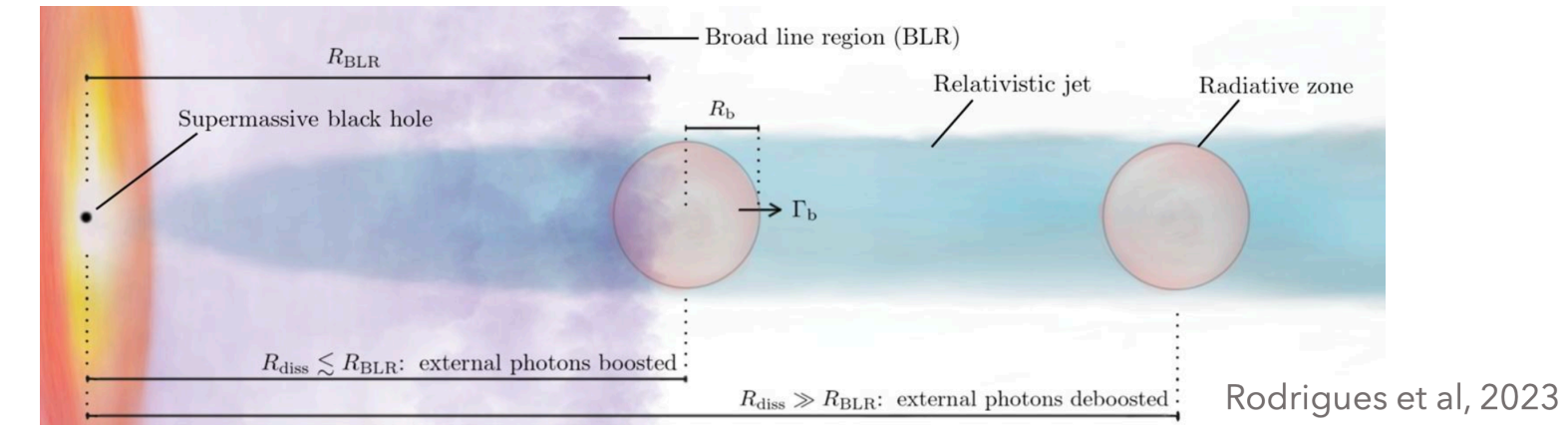


Blob of extremely energetic protons and electrons

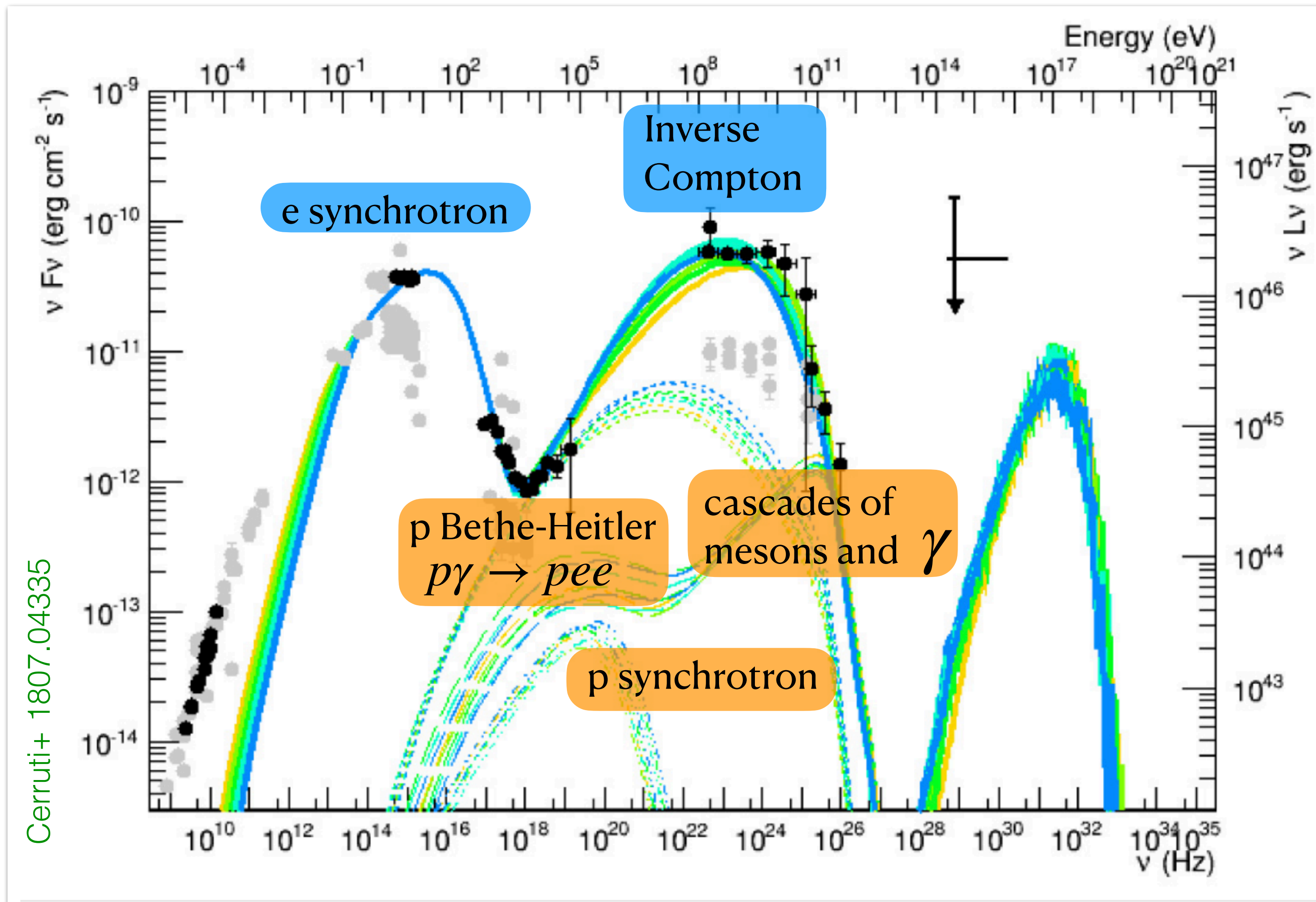
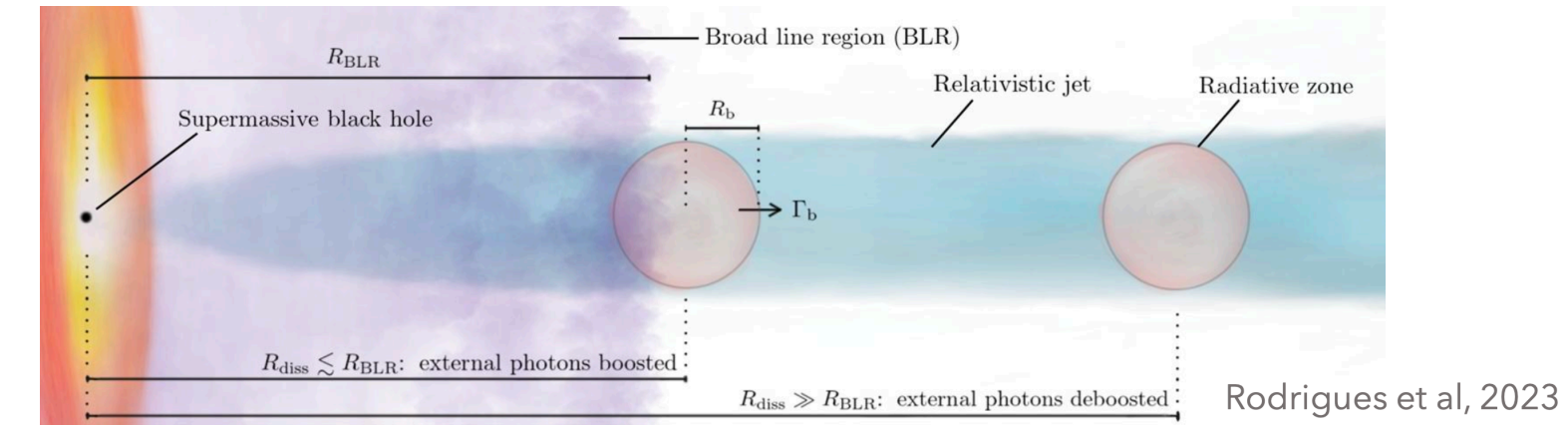
moving along the jet with Lorentz factor Γ_B

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

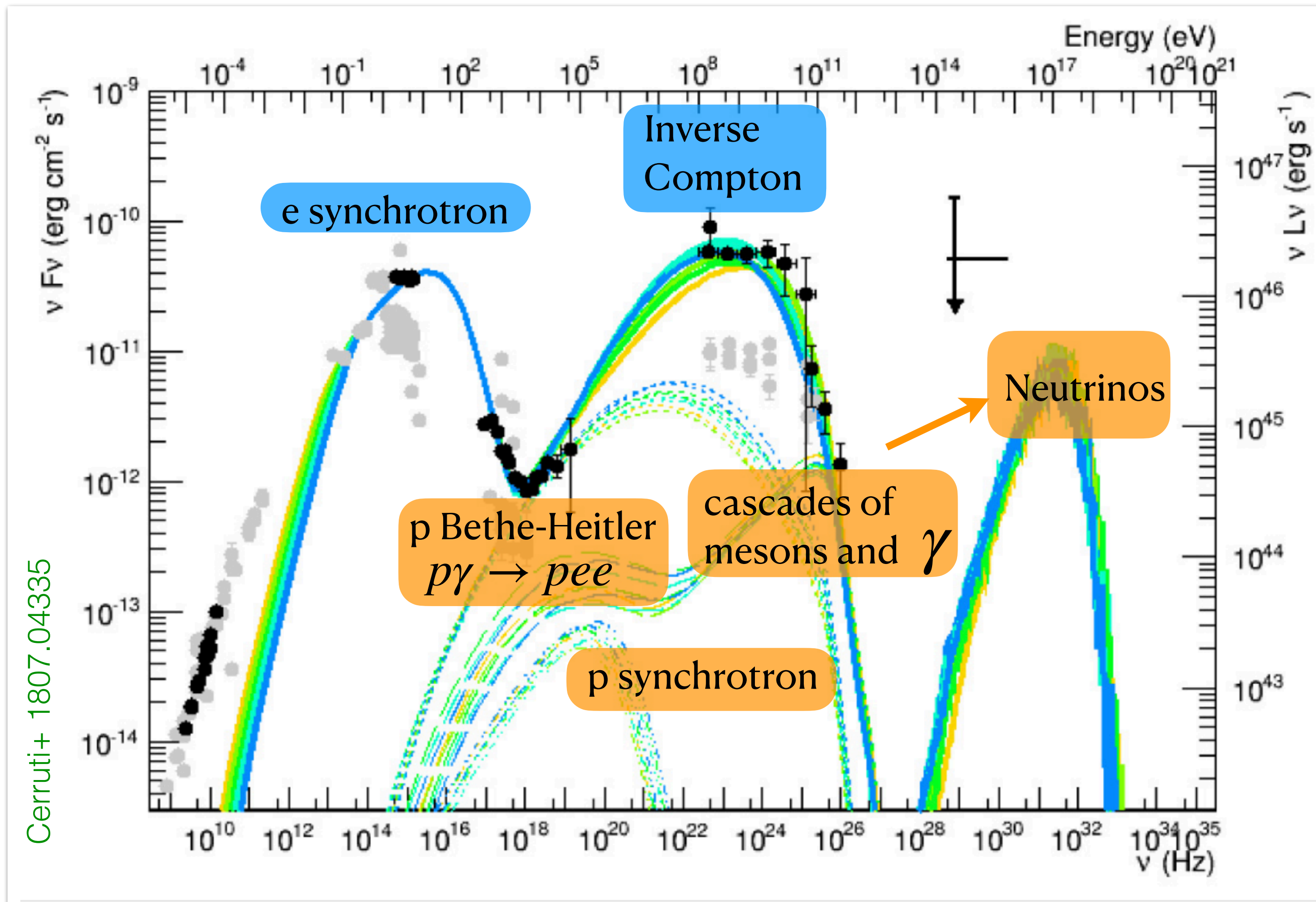
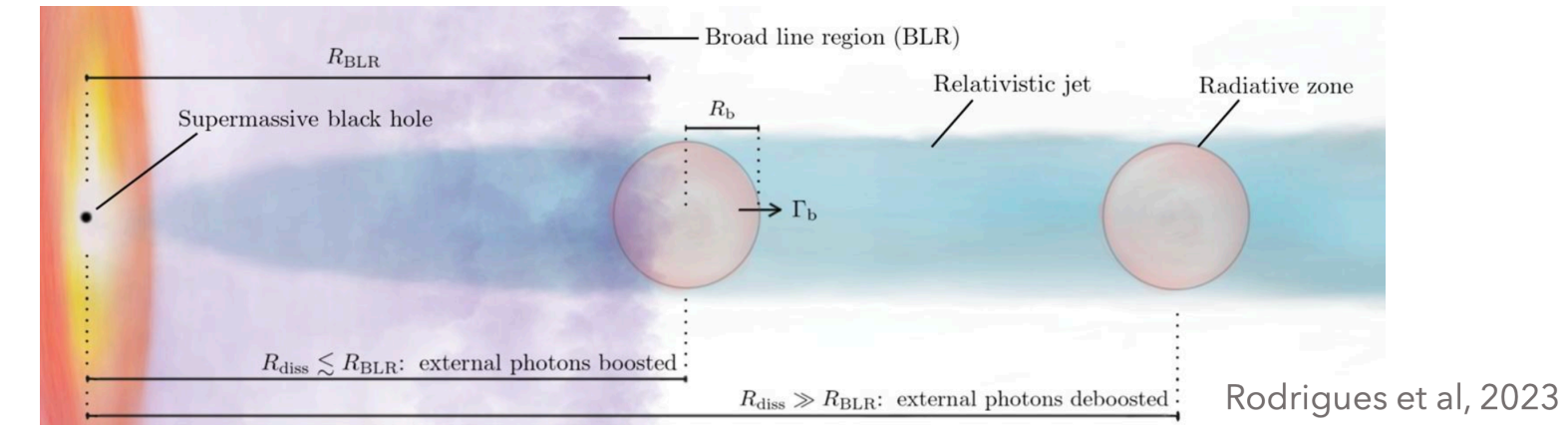
Modeling Blazars: results



Modeling Blazars: results



Modeling Blazars: results



Problem
Too few neutrinos

Different groups find same conclusion

Blazars & high energy neutrinos

Diffuse astrophysical neutrinos?

Neutrinos seen from blazars?

KM₃NeT ~ 200 PeV neutrino?

Blazars & high energy neutrinos

Diffuse astrophysical neutrinos?

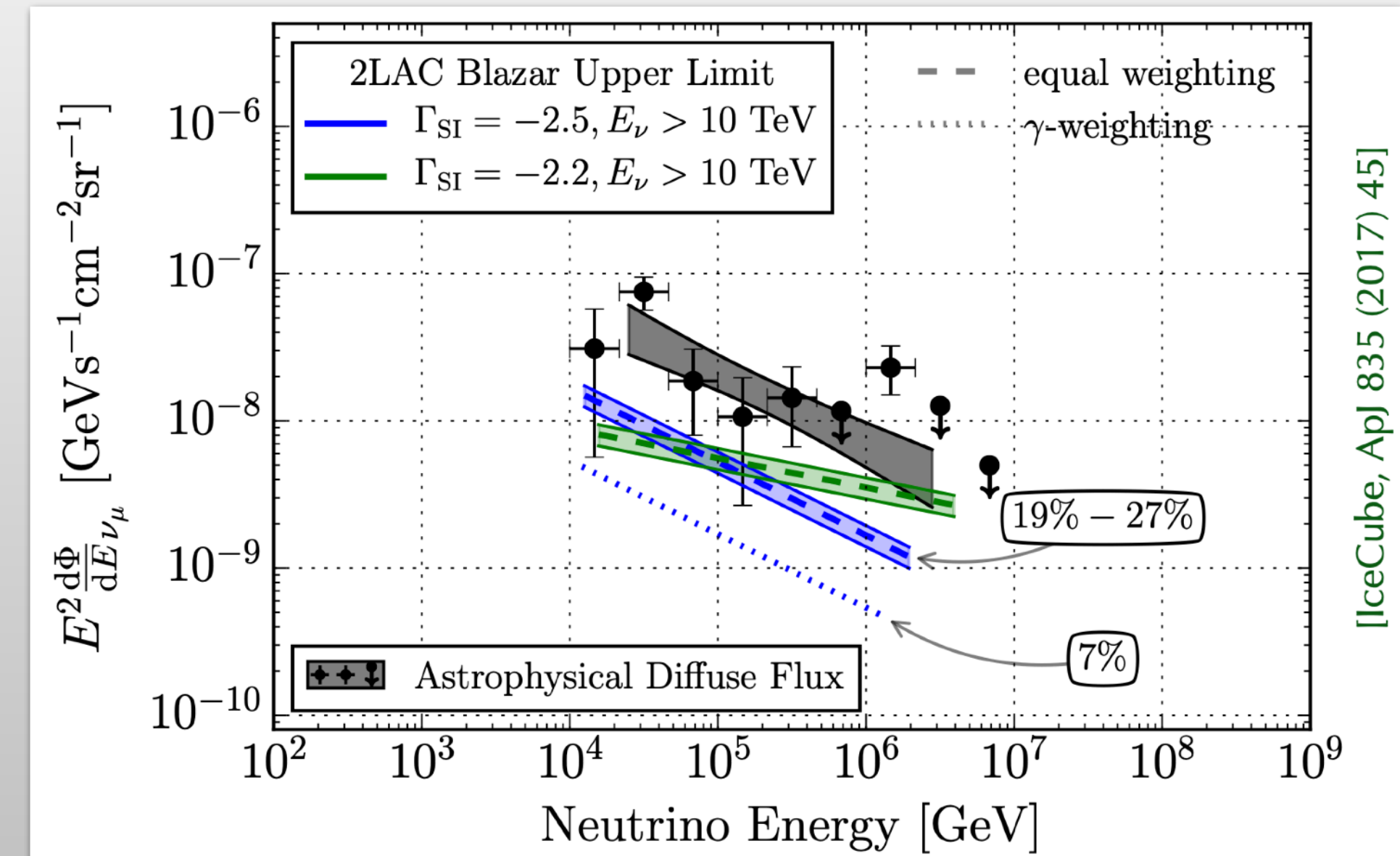
Spatial correlations

YES Buson+ 2207.06314,...

Astro priors crucial

NO Bellenghi+ 2309.03115,...

“Quantitatively”



Blazars & high energy 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

Cerruti+ 1807.04335

Keivani+ 1807.04537

...

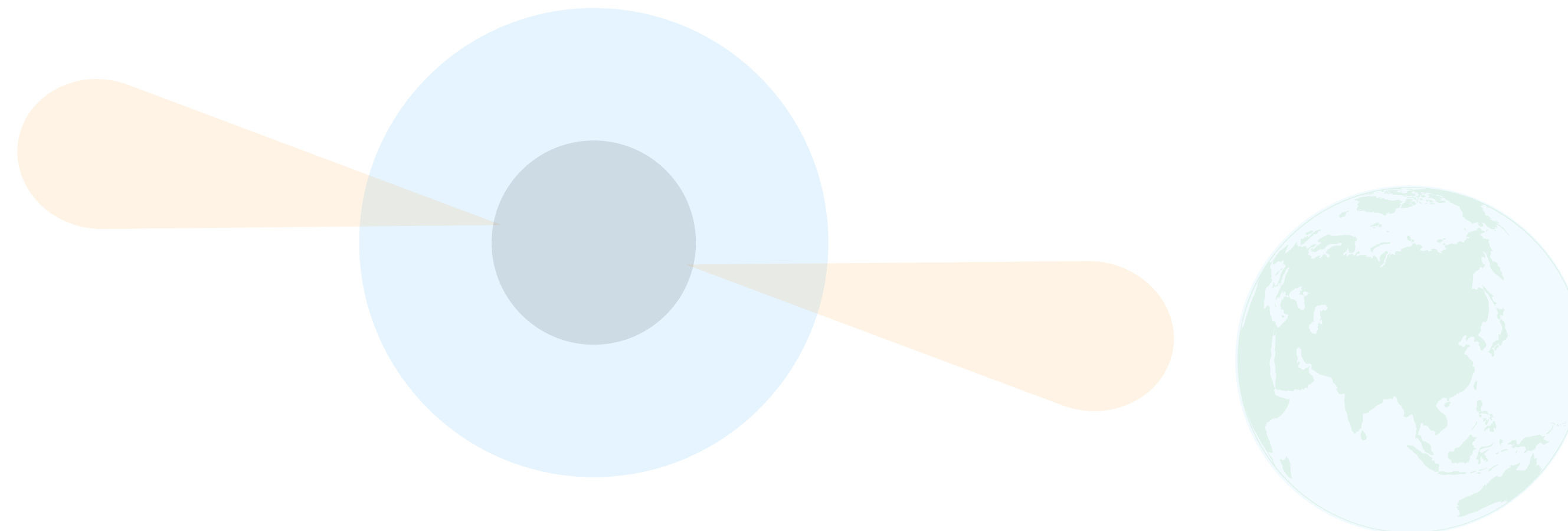
Blazars & high energy neutrinos

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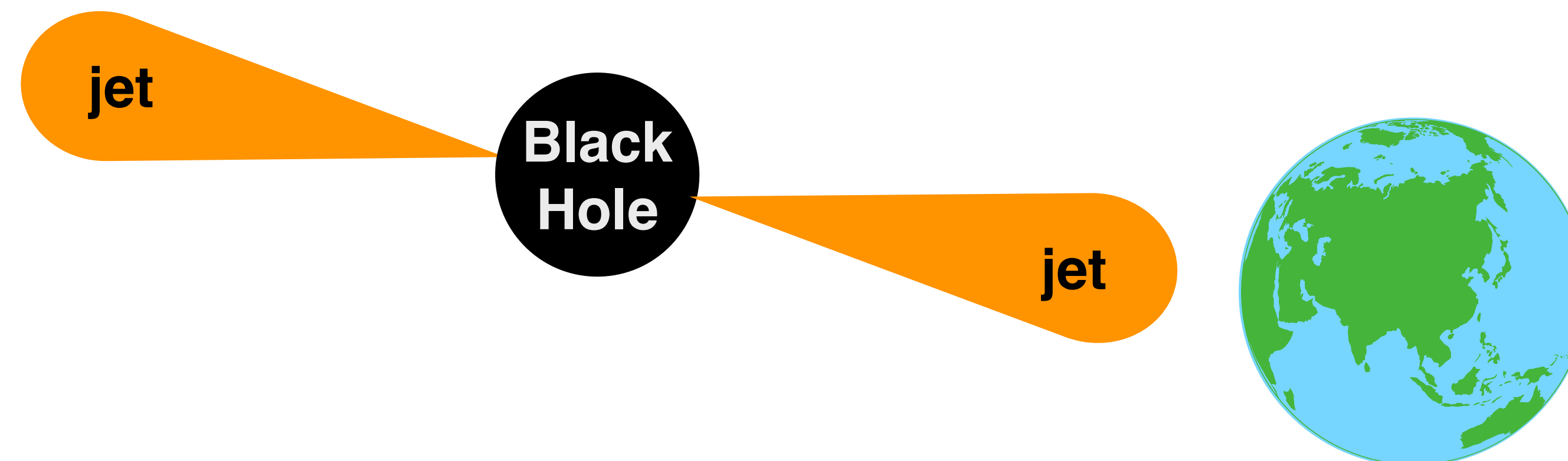
Possibly, ~ paradigm shift in jet modelling

Rodrigues Padovani + 2025

High energy neutrinos ?

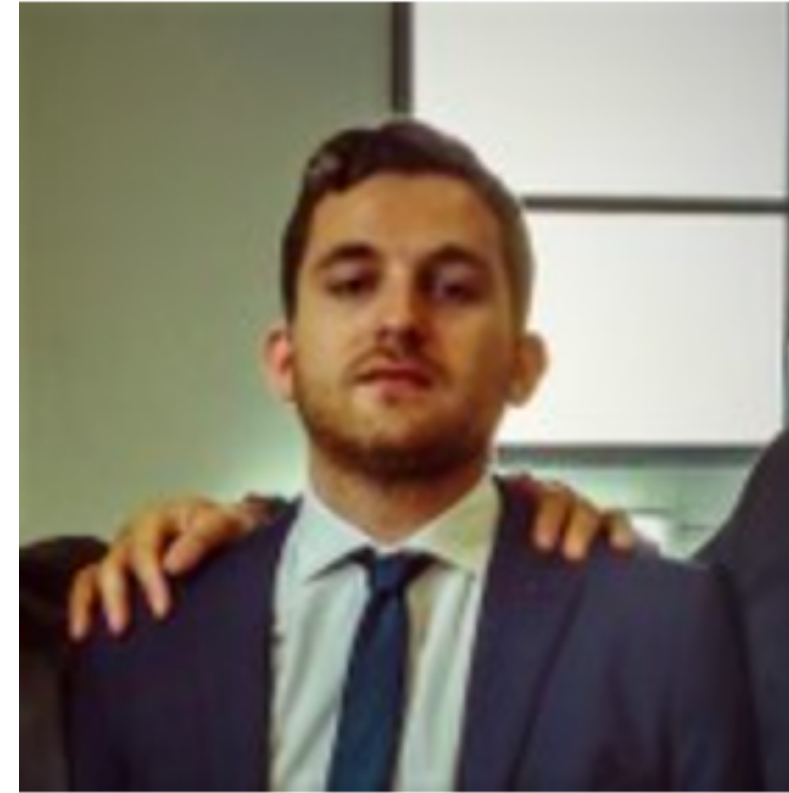


High energy neutrinos from dark matter around blazars

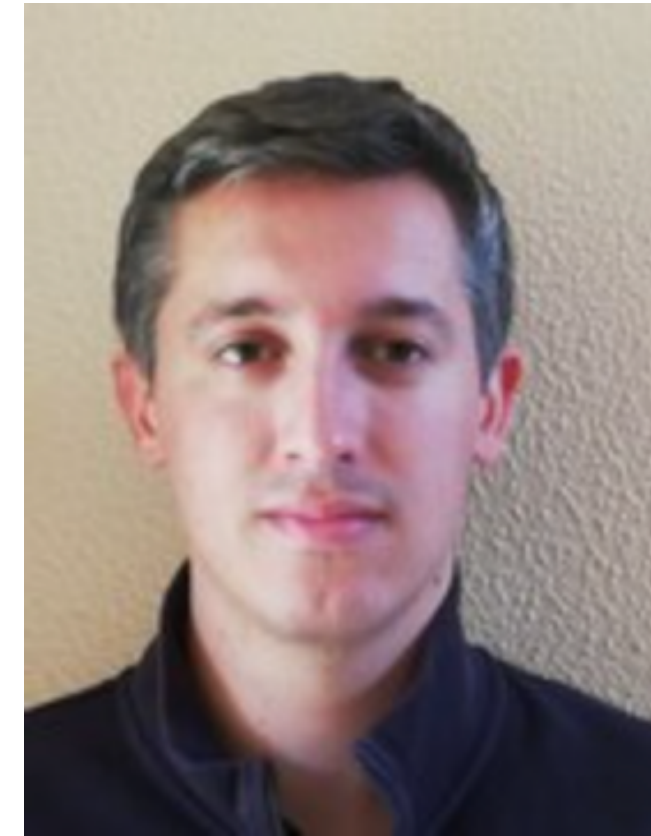




Andrea De Marchi



Alessandro Granelli



Jacopo Nava

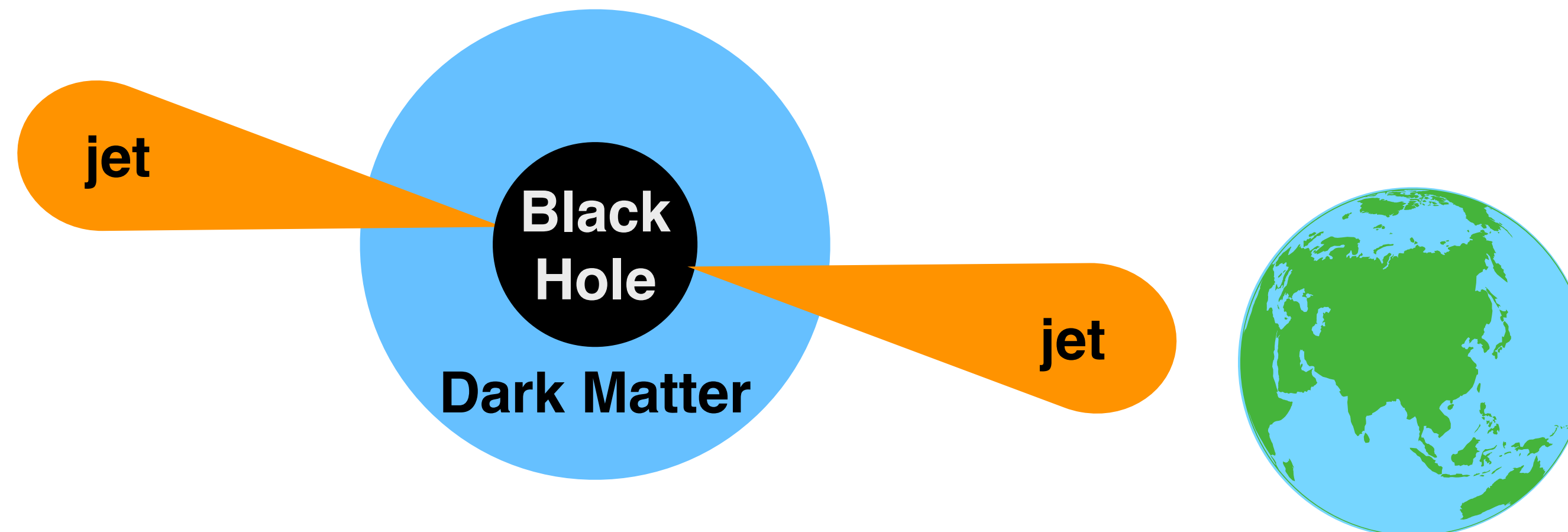
2412.07861 PRD 2025

2506.06416 JHEP 2025

2507.12278 PLB 2025

+ FS

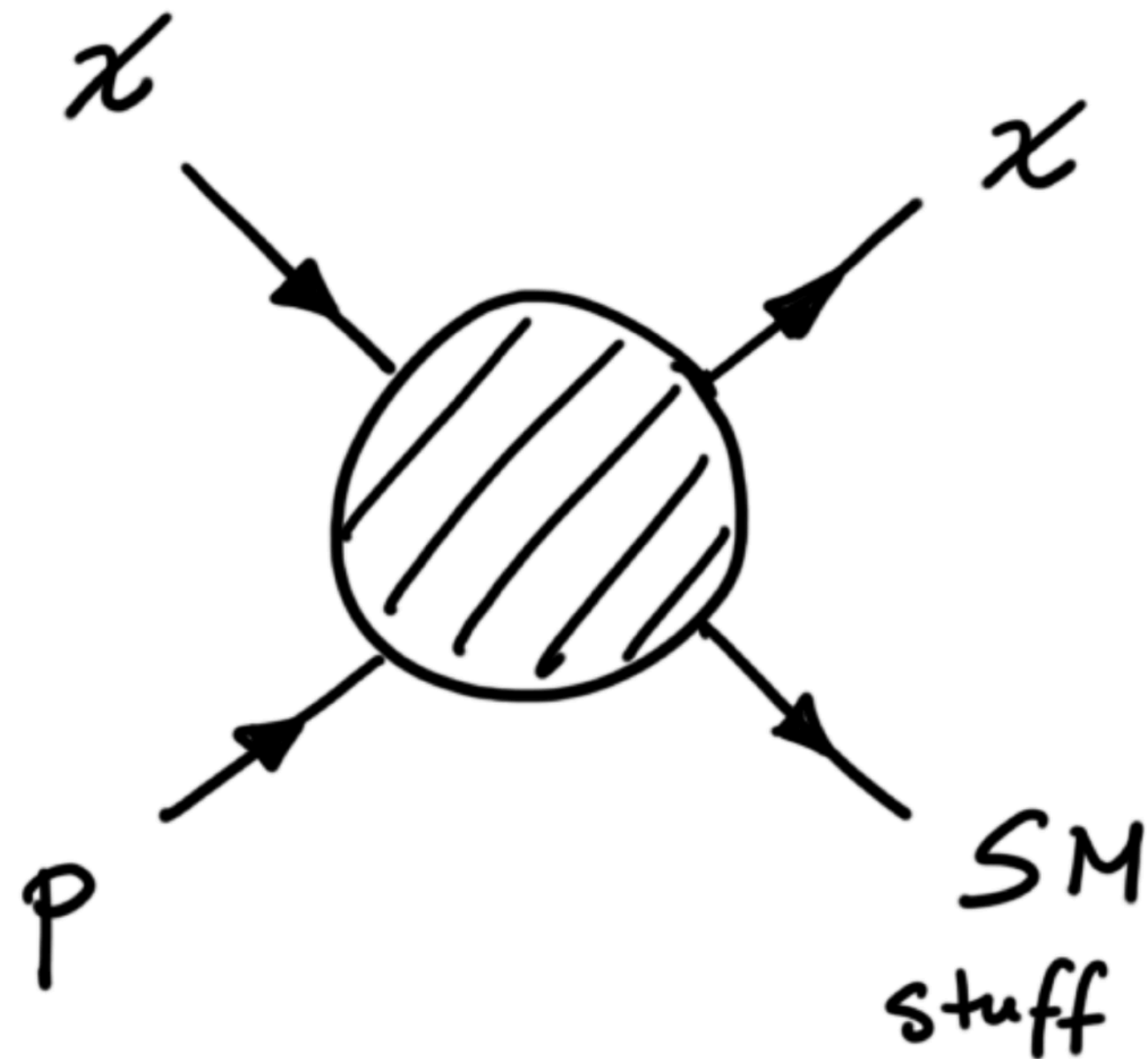
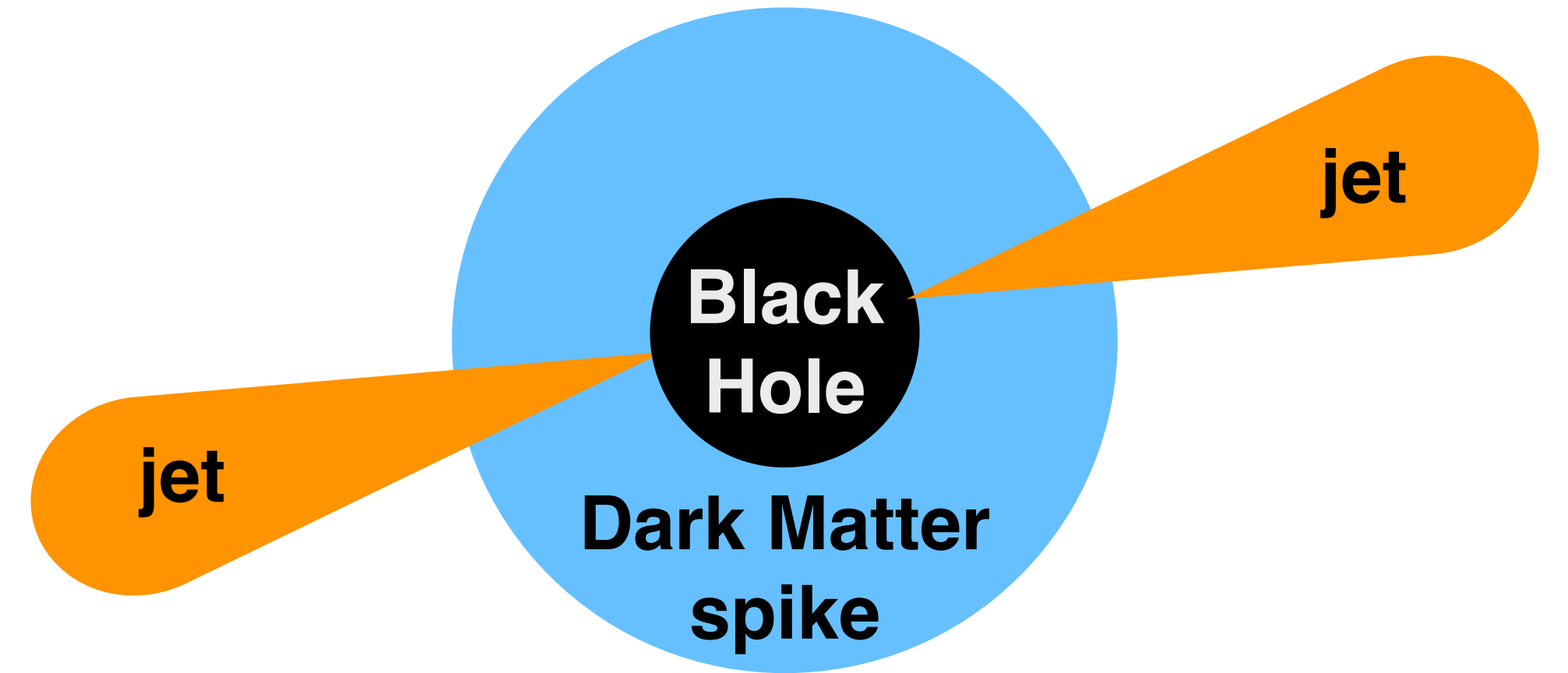
High energy neutrinos from dark matter around blazars



Neutrinos from DM around blazars?



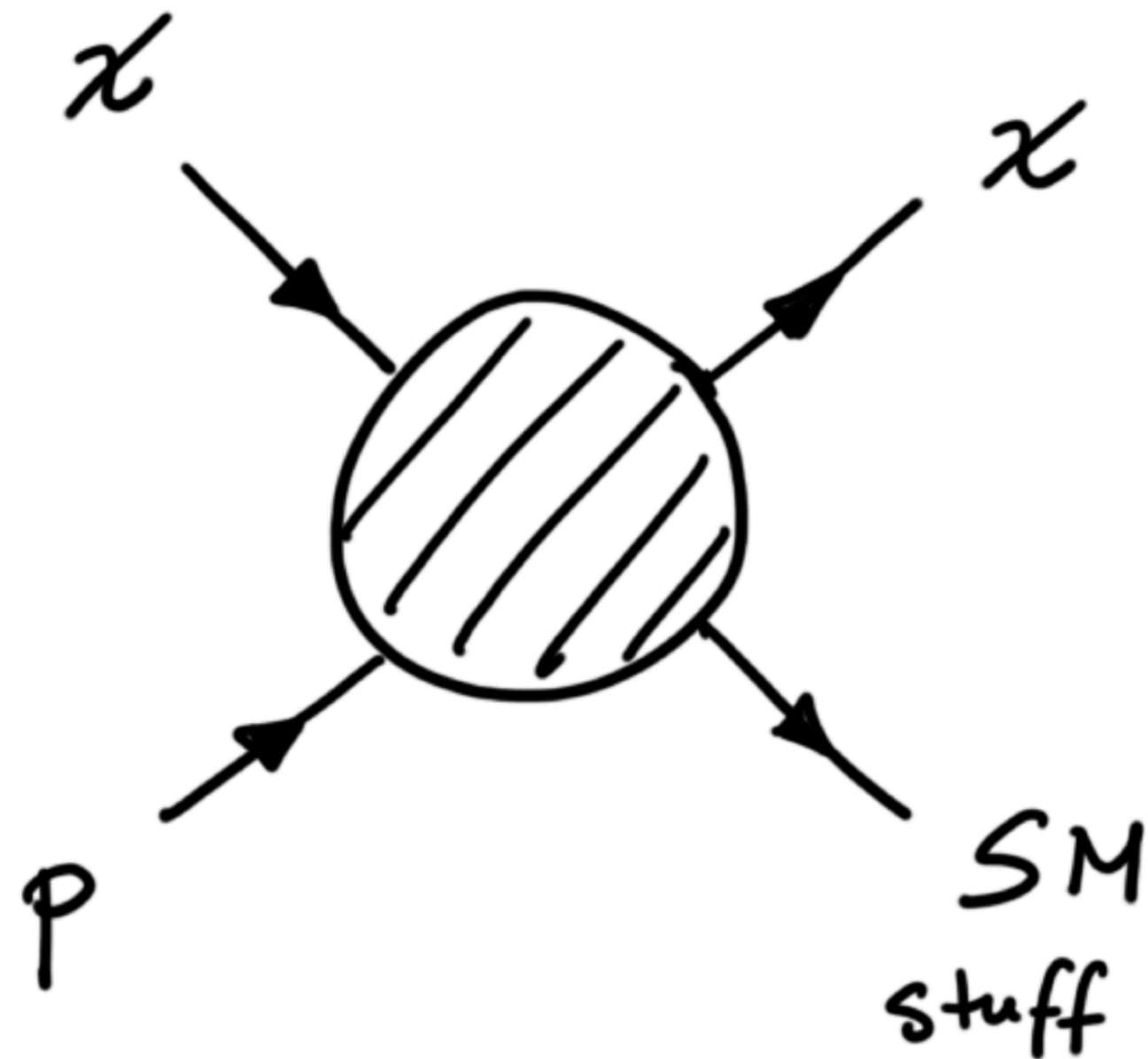
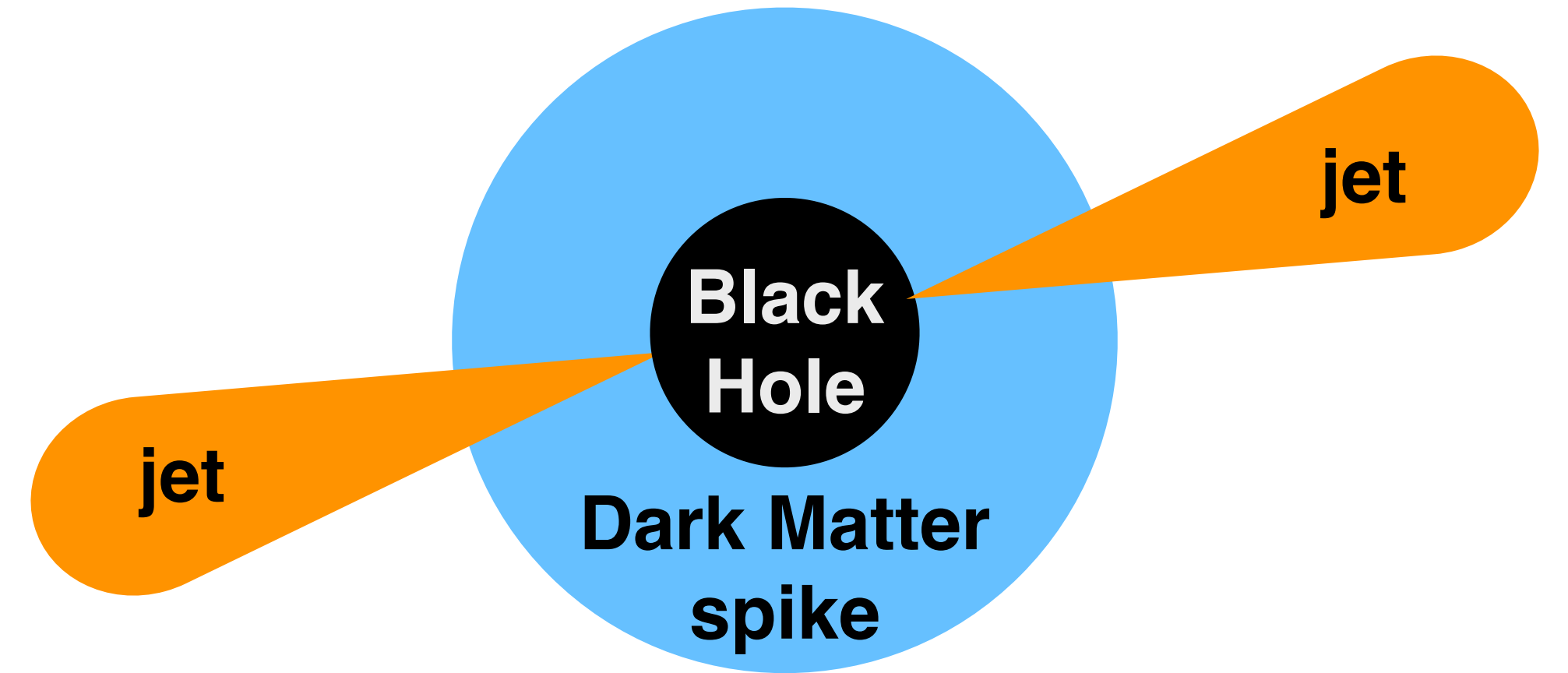
Protons break and produce ν from π^\pm
De Marchi Granelli Nava 2412.07861



Neutrinos from DM around blazars?



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

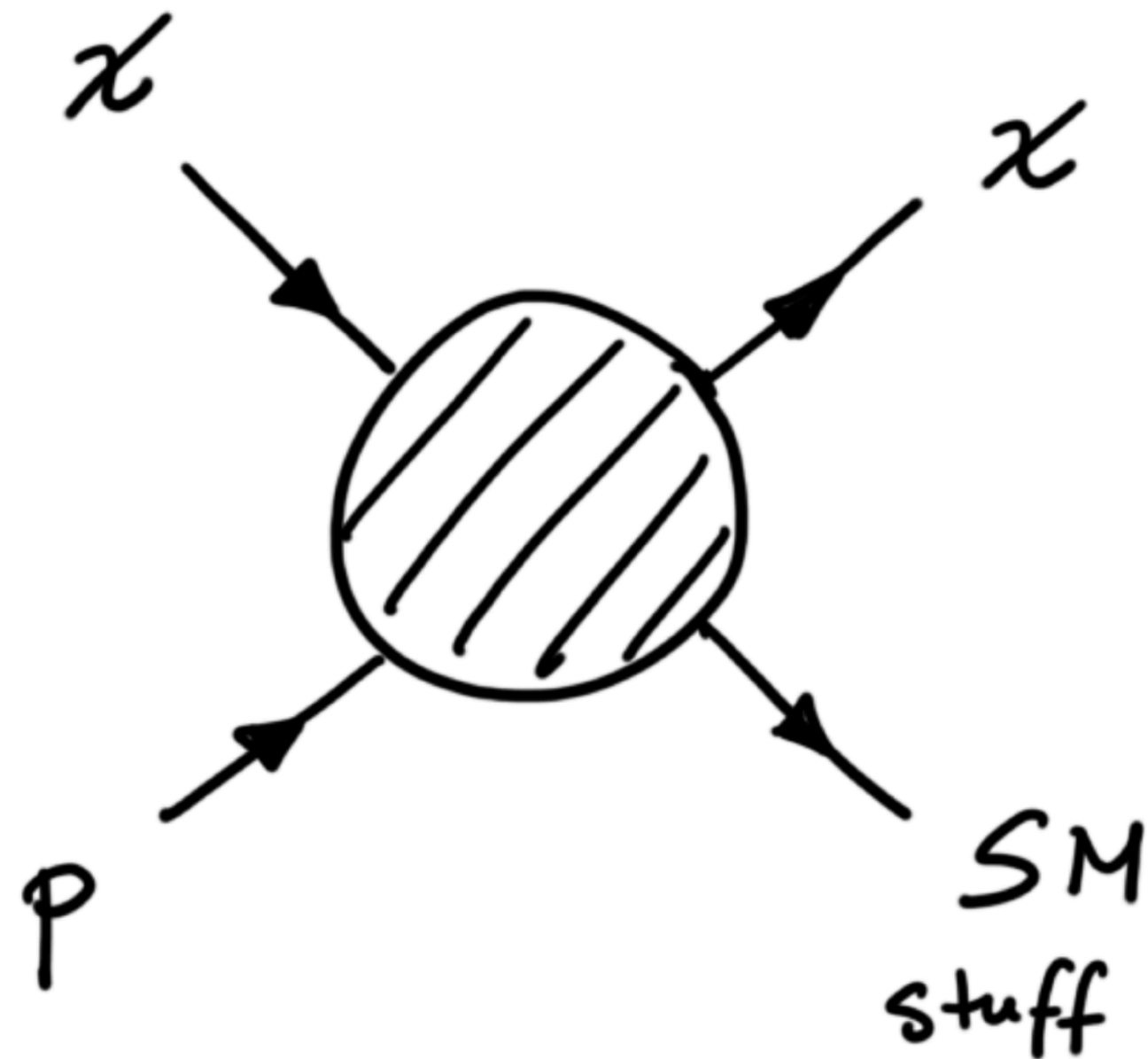
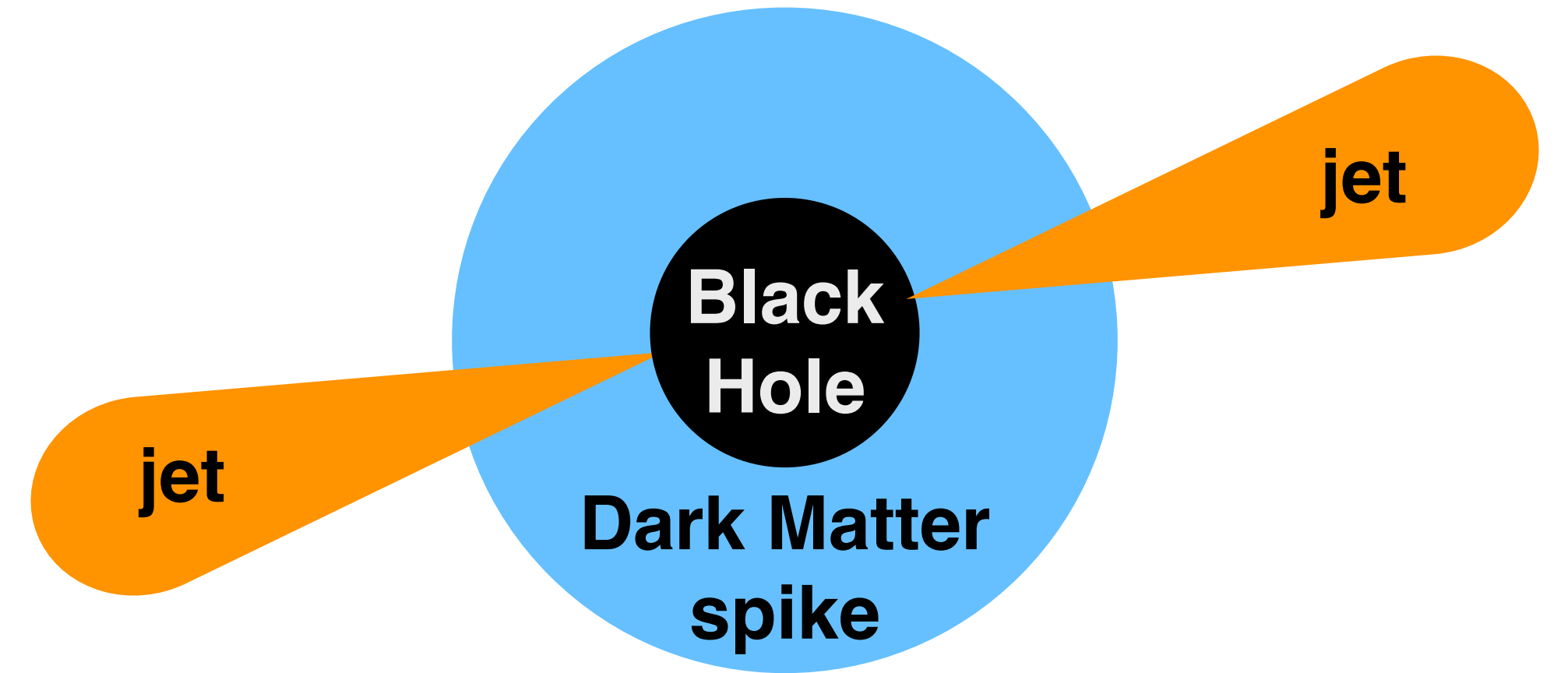


$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Sigma_{\text{los}}}{m_\chi d_L^2} \int dE_p \frac{d\Gamma_p}{dE_p d\Omega} \Big|_{\text{los}} \sigma_{\text{DIS}} \left\langle \frac{dN_\nu}{dE_\nu} \right\rangle$$

Neutrinos from DM around blazars?



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



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

DM spike around BH

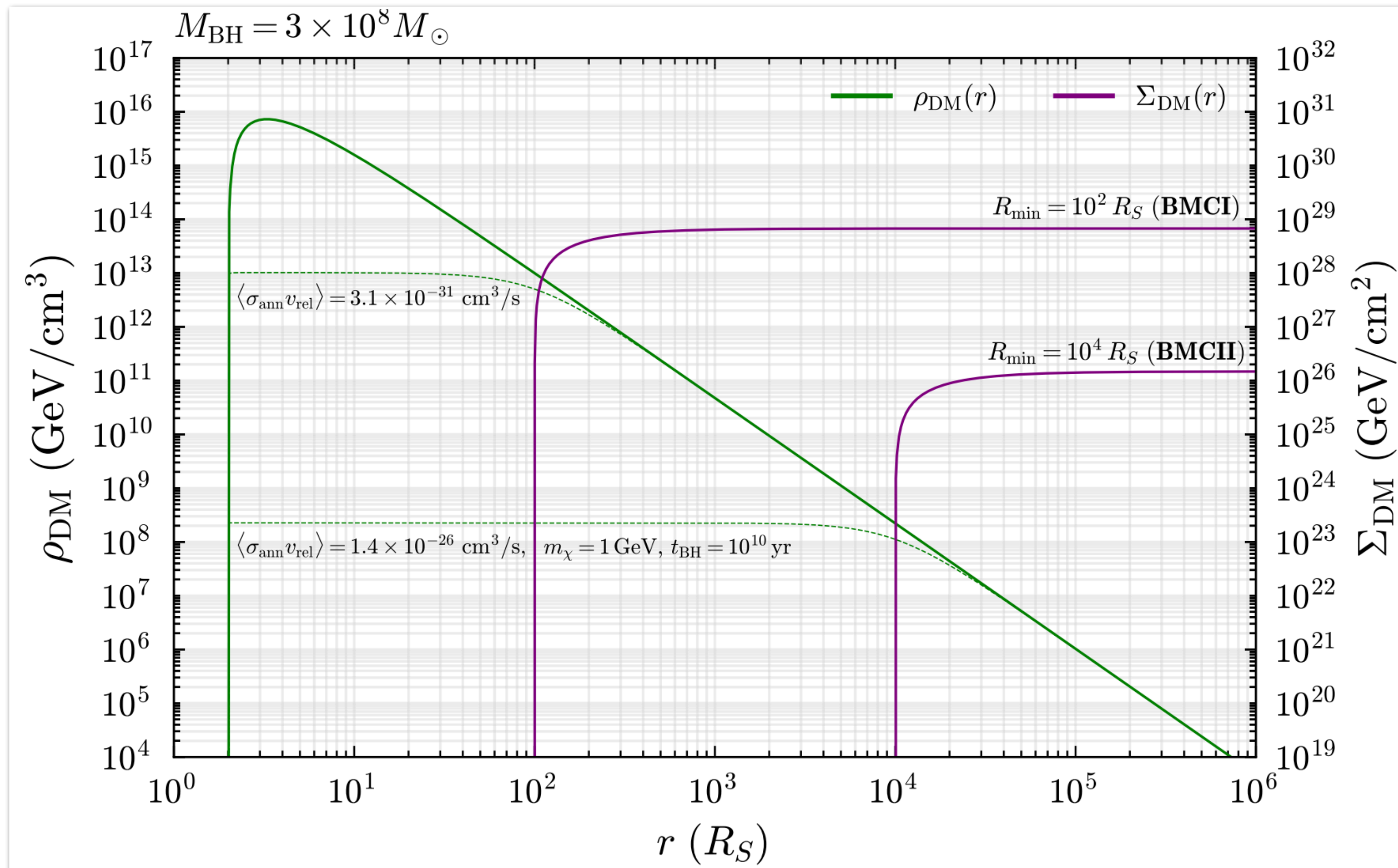
Model of blazar jet

Particle DM model

DM density around SuperMassive BH

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

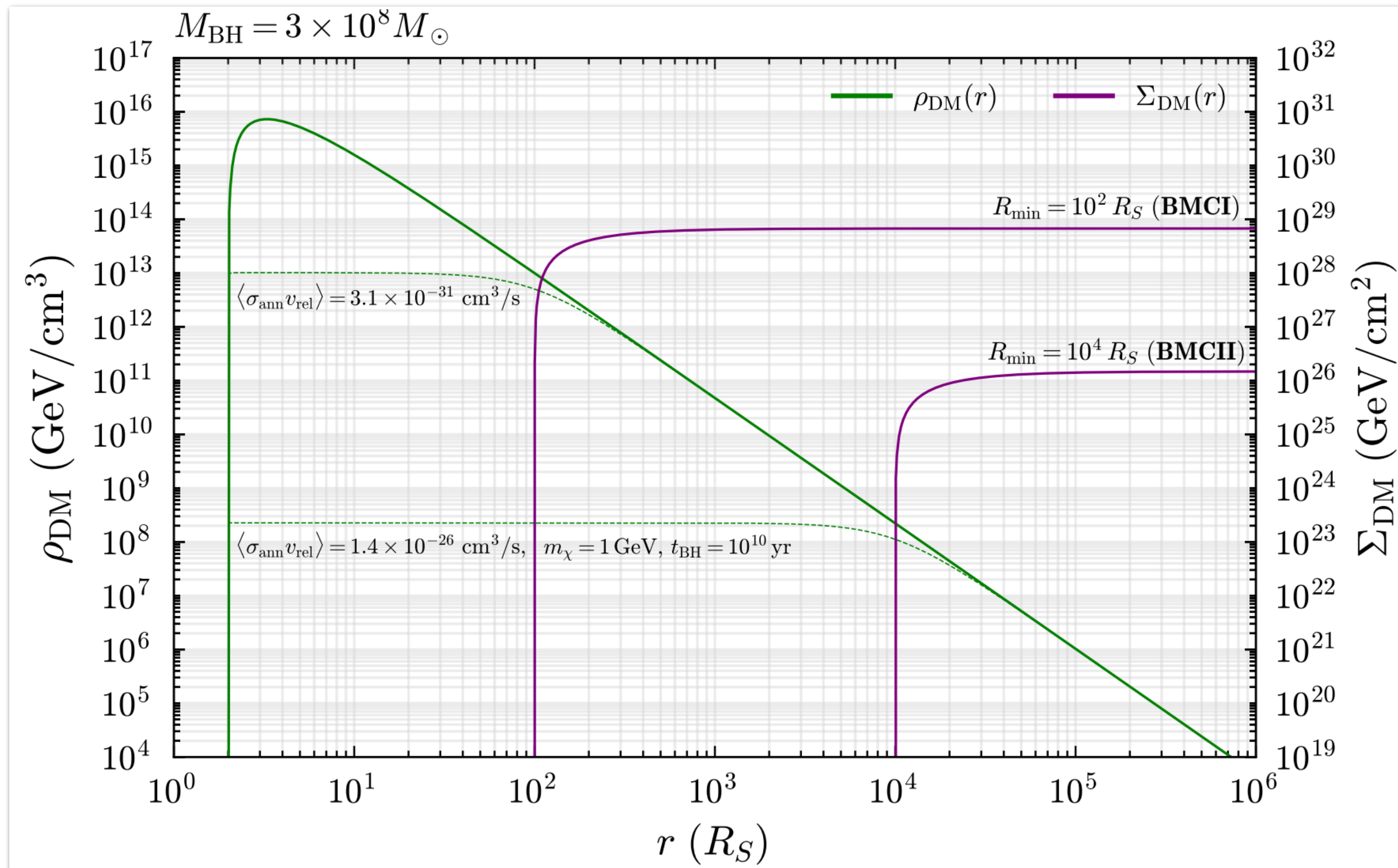
$$\Sigma_{\text{los}} = \int_{r_{\text{min}}}^{r_{\text{max}}} dr \rho(r)$$



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: 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](https://arxiv.org/abs/2506.10122)

Reverberation mapping:

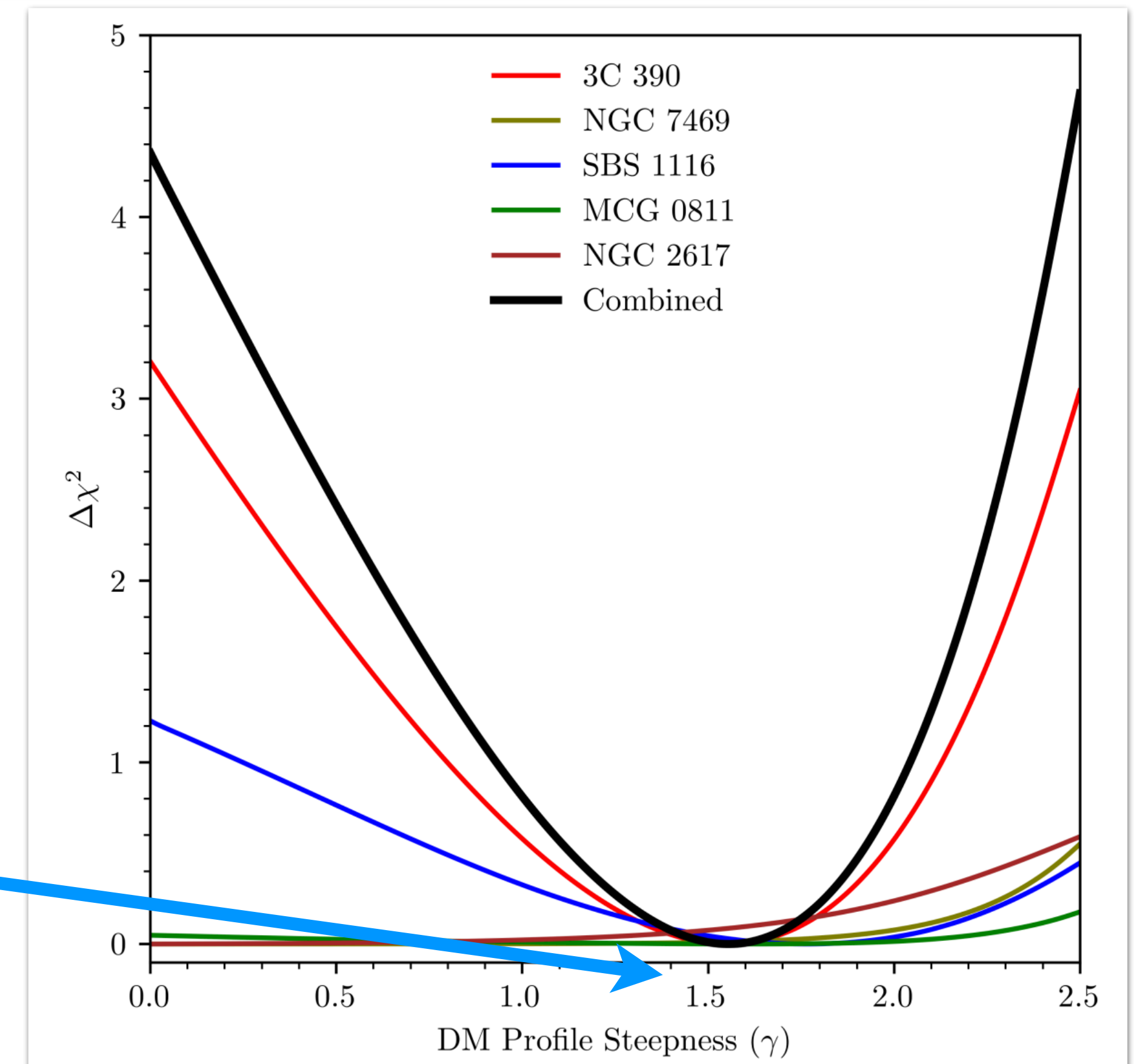
broad emission lines in AGN spectra



gas velocity dispersion → mass of SMBH and DM spike

We checked that $\gamma \simeq 1.6$

corresponds to our conservative benchmark



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

$$\mathcal{L}_{\text{DM}} = g_q \bar{q} \gamma_\mu q V^\mu + g_\chi \bar{\chi} \gamma_\mu \chi V^\mu + \frac{1}{2} m_V^2 V^\mu V_\mu \quad + \text{axial-vector, scalar, pseudoscalar}$$

Calculation:



Implement model in FeynRules



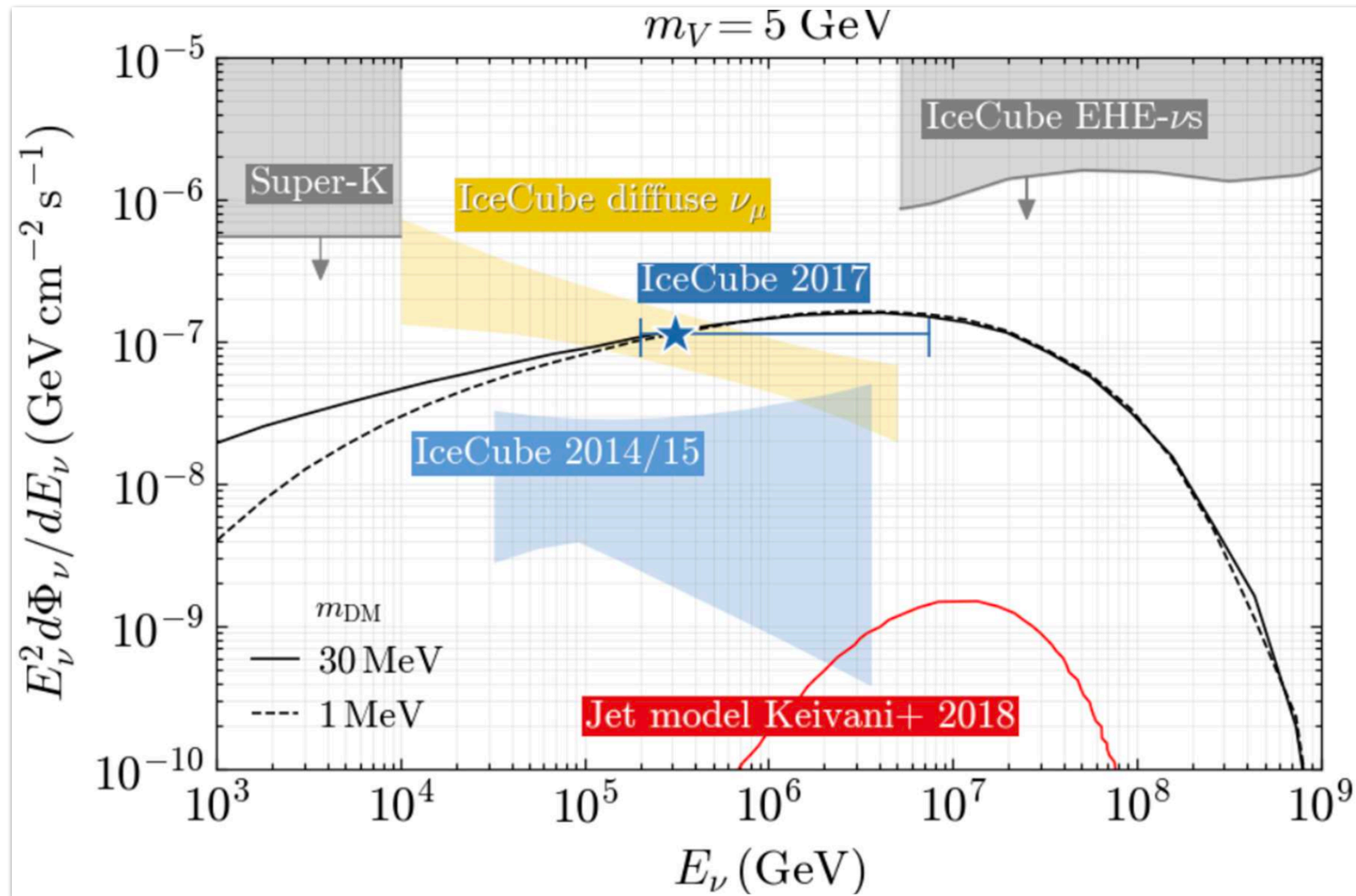
Parton-level scattering in MADGRAPH5 (in COM frame)



Hadronization and decay with PYTHIA8

Neutrino flux from TXS 0506

De Marchi Granelli Nava FS 2412.07861

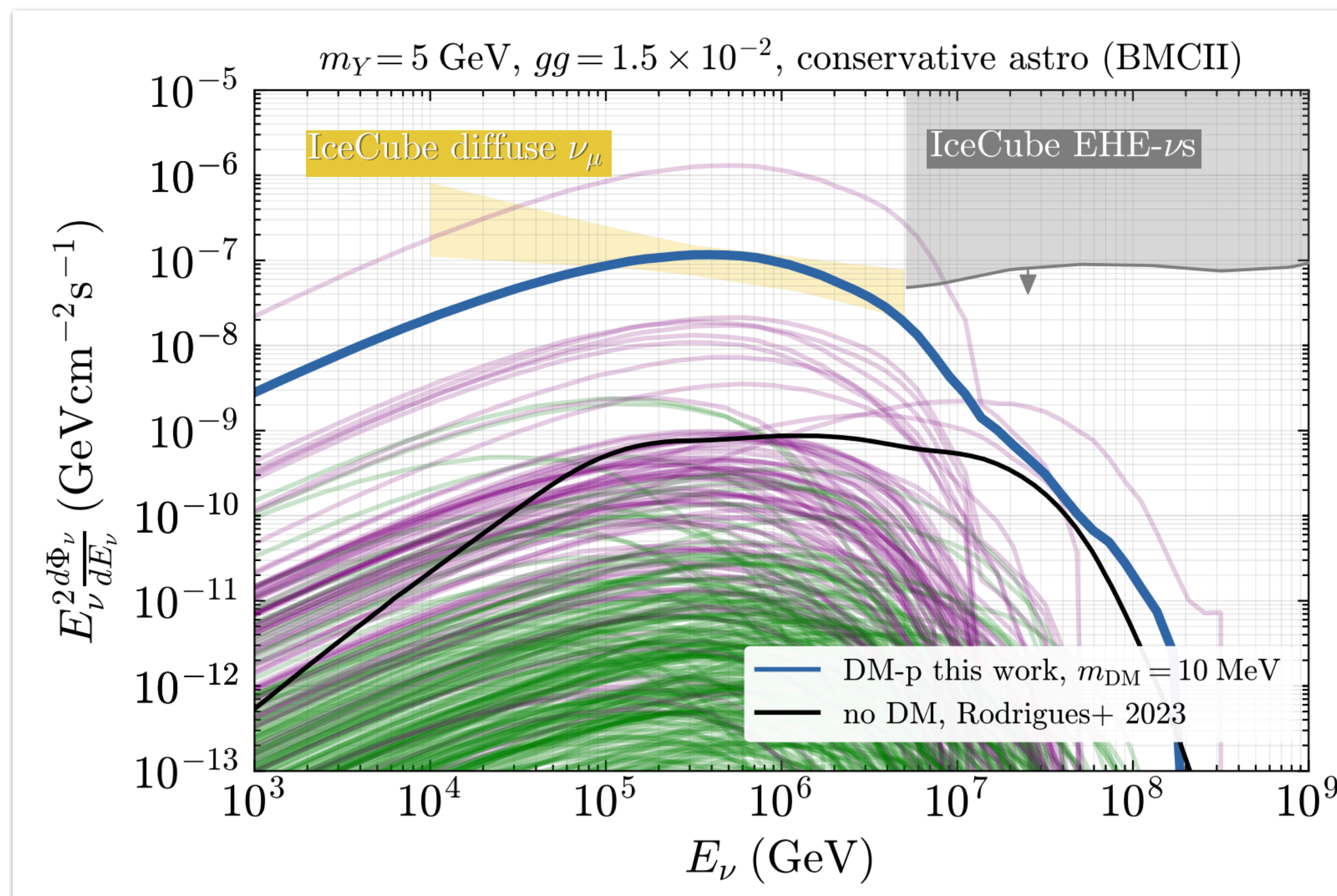


We make it!

Neutrino flux from stacked blazars

De Marchi Granelli Nava FS 2506.06416

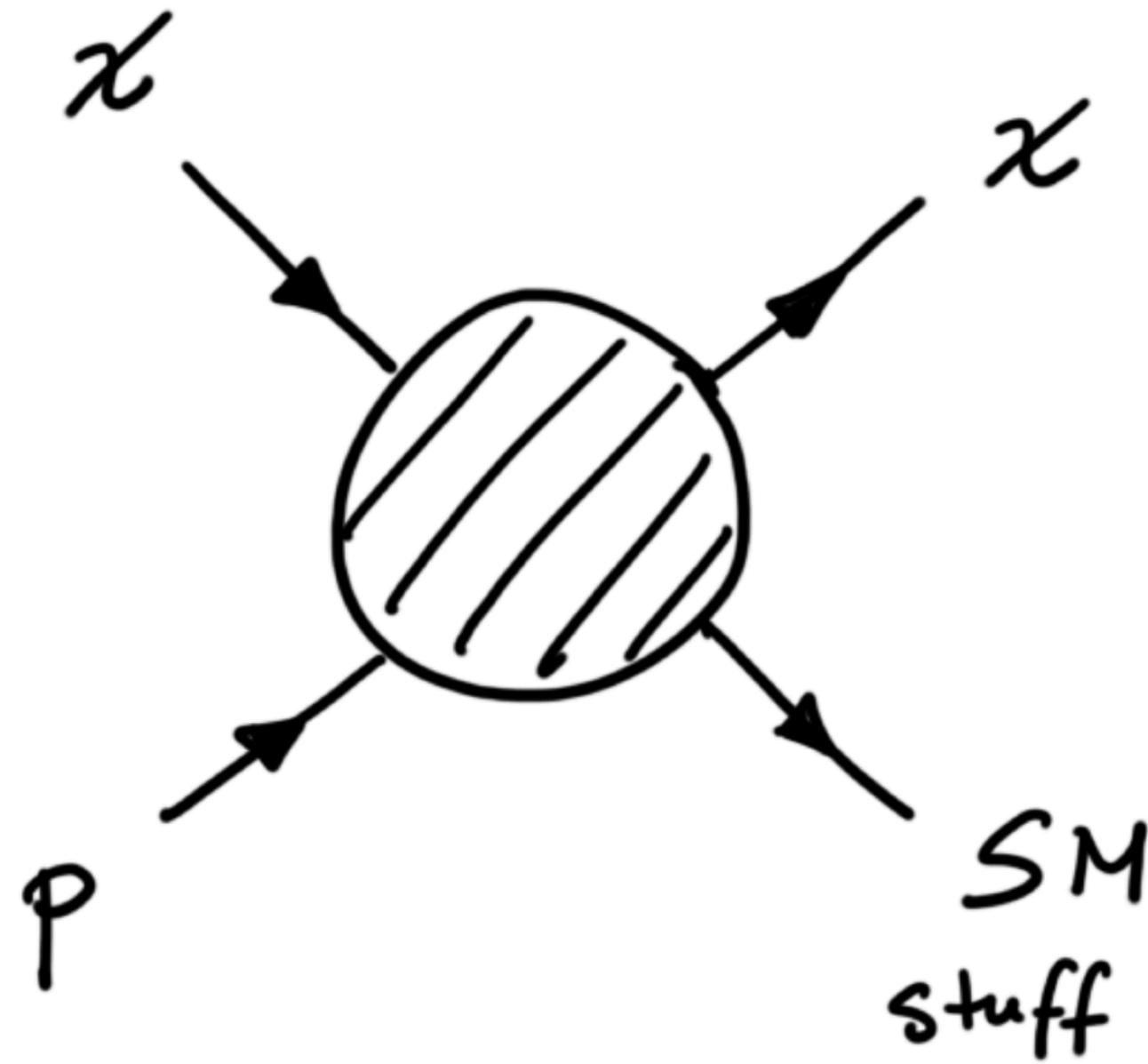
We saturate IceCube's observations!



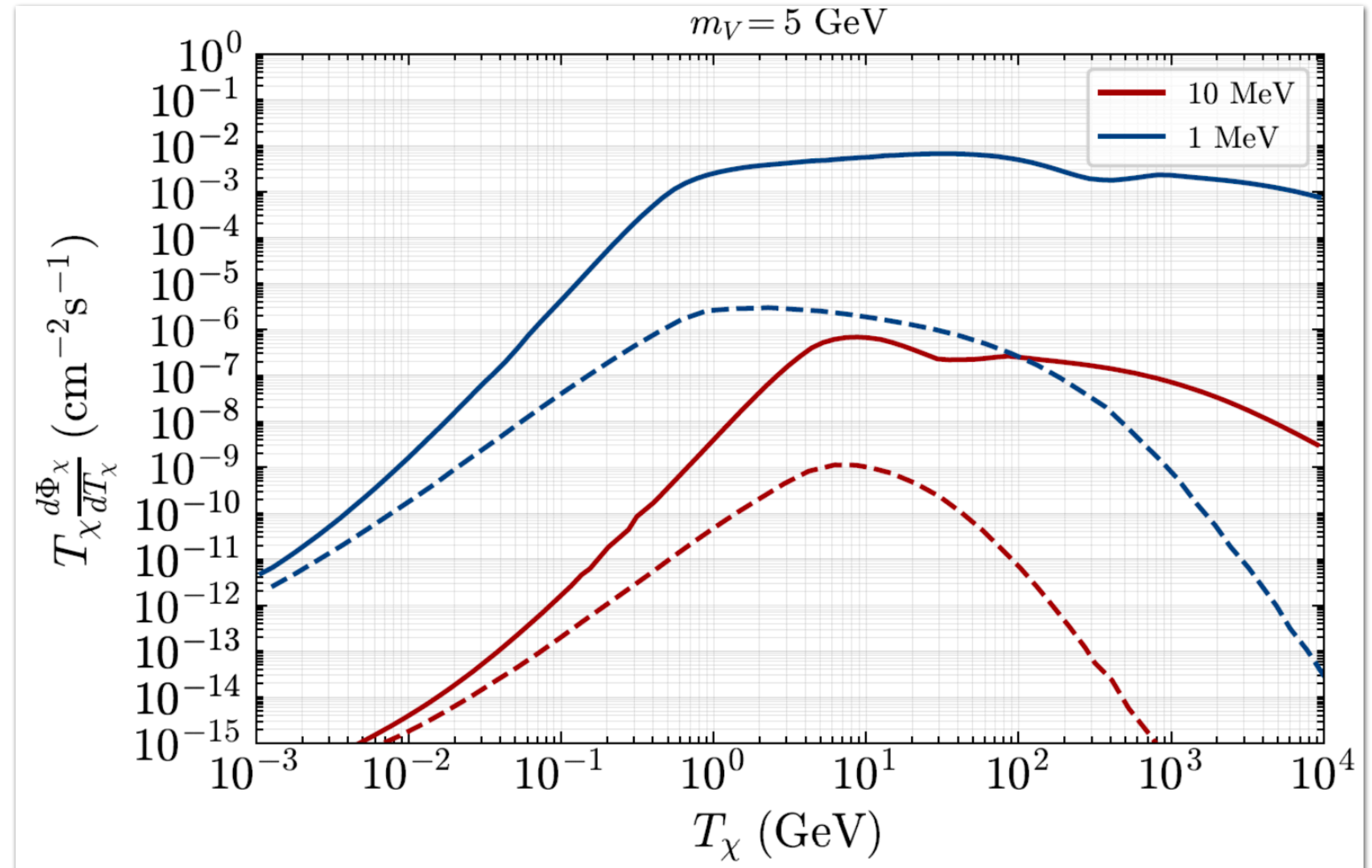
Using catalogue of 324 blazar modelled in [Rodrigues+ 2307.13024](#)

Associated DM fluxes

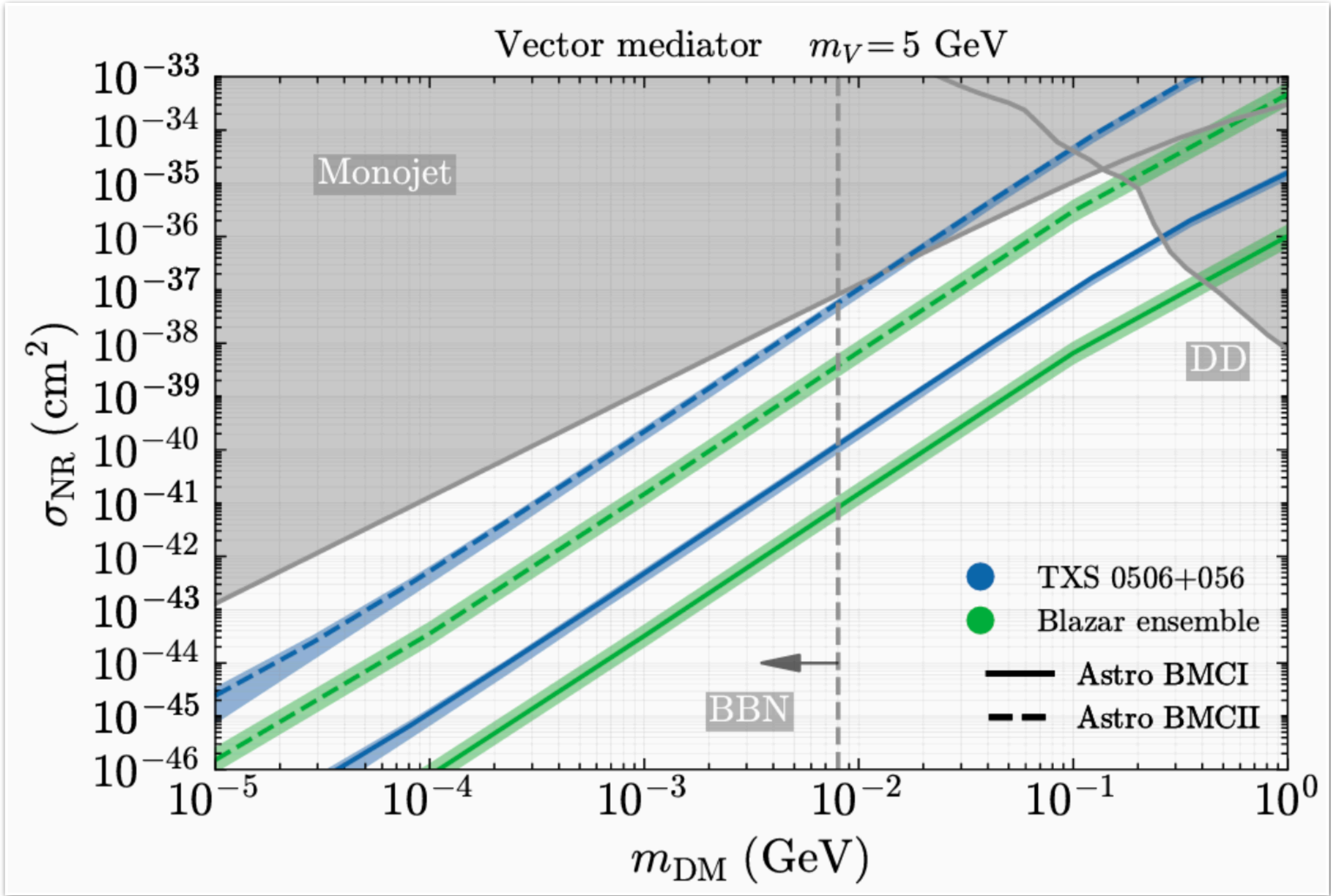
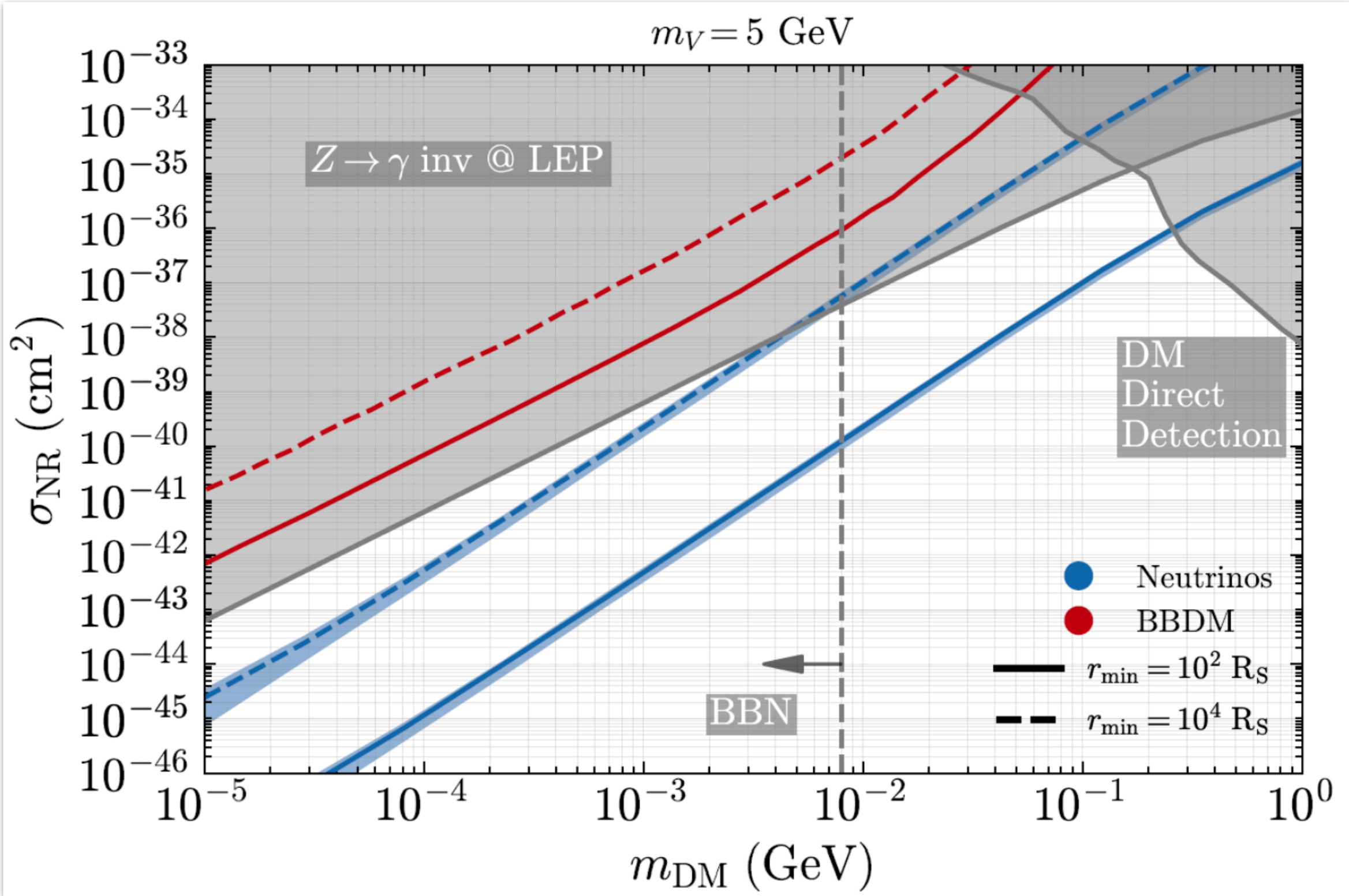
De Marchi Granelli Nava FS 2507.12278



Now we look for this



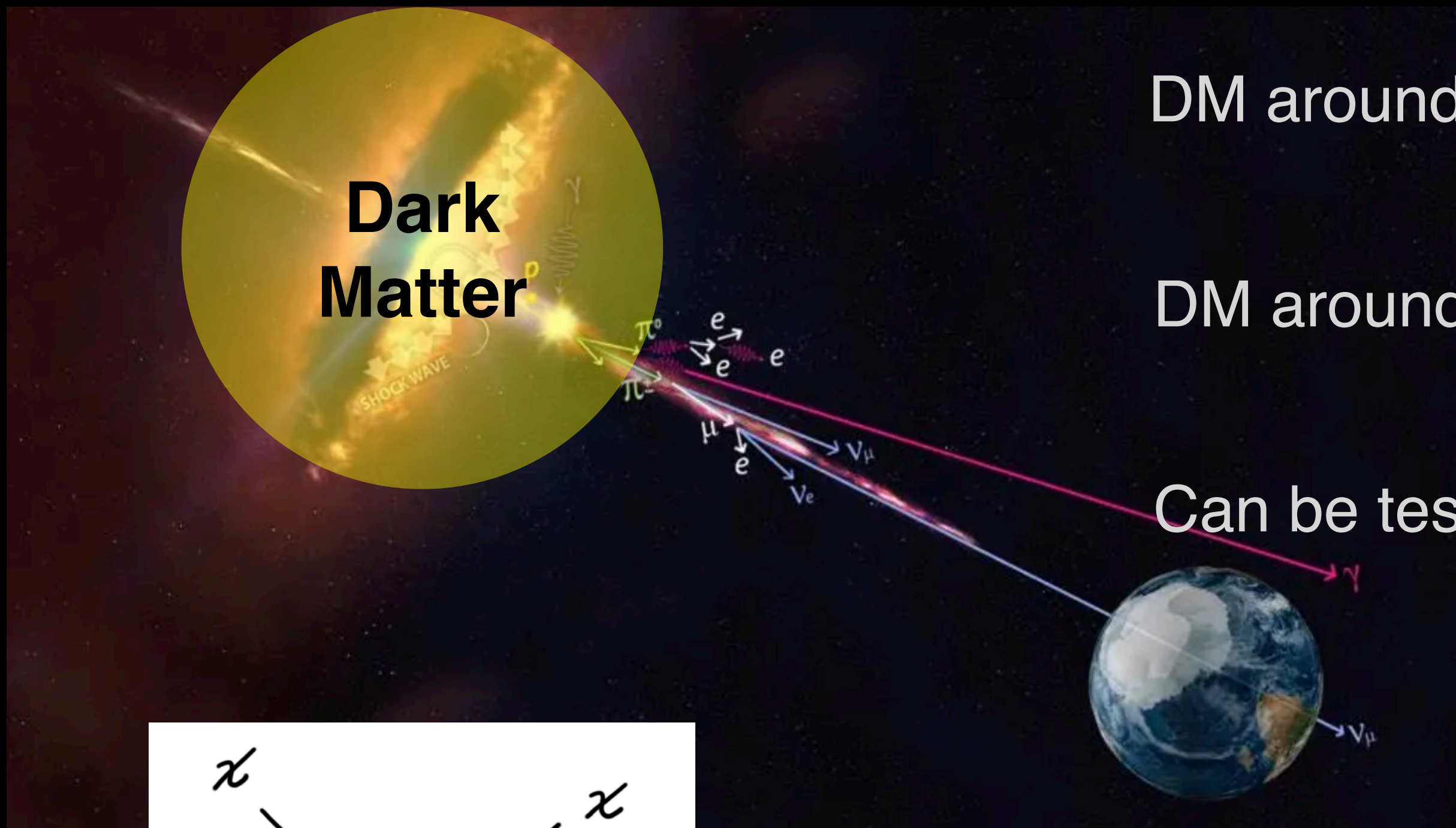
DM neutrino explanation is OK with other limits



Can be tested in the lab!

De Marchi Granelli Nava FS 2024-2025

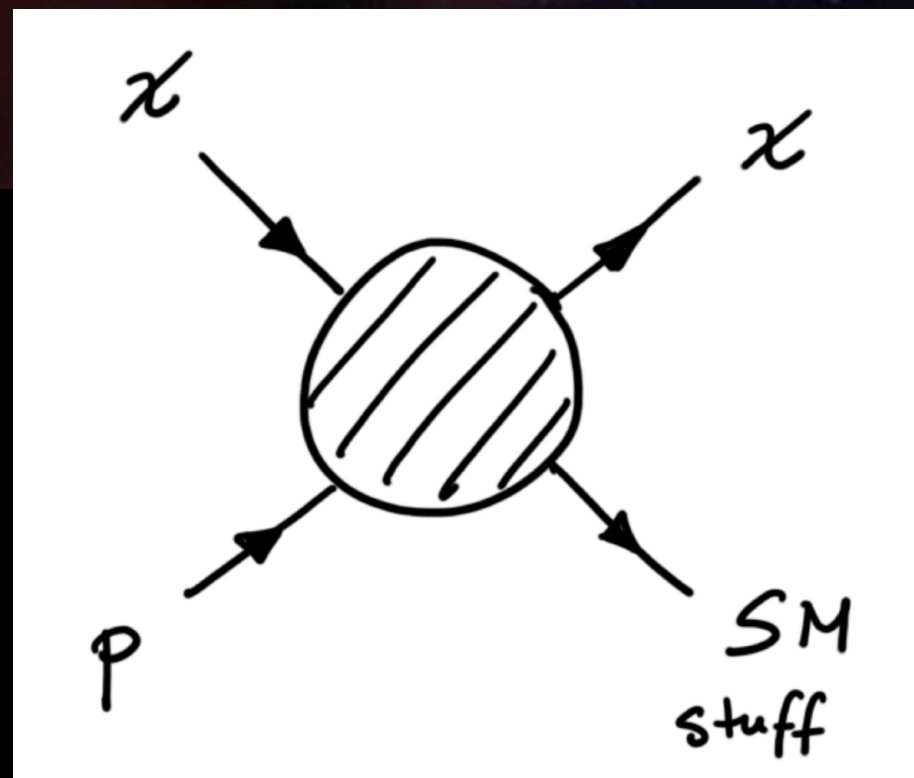
Summary and Outlook



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?

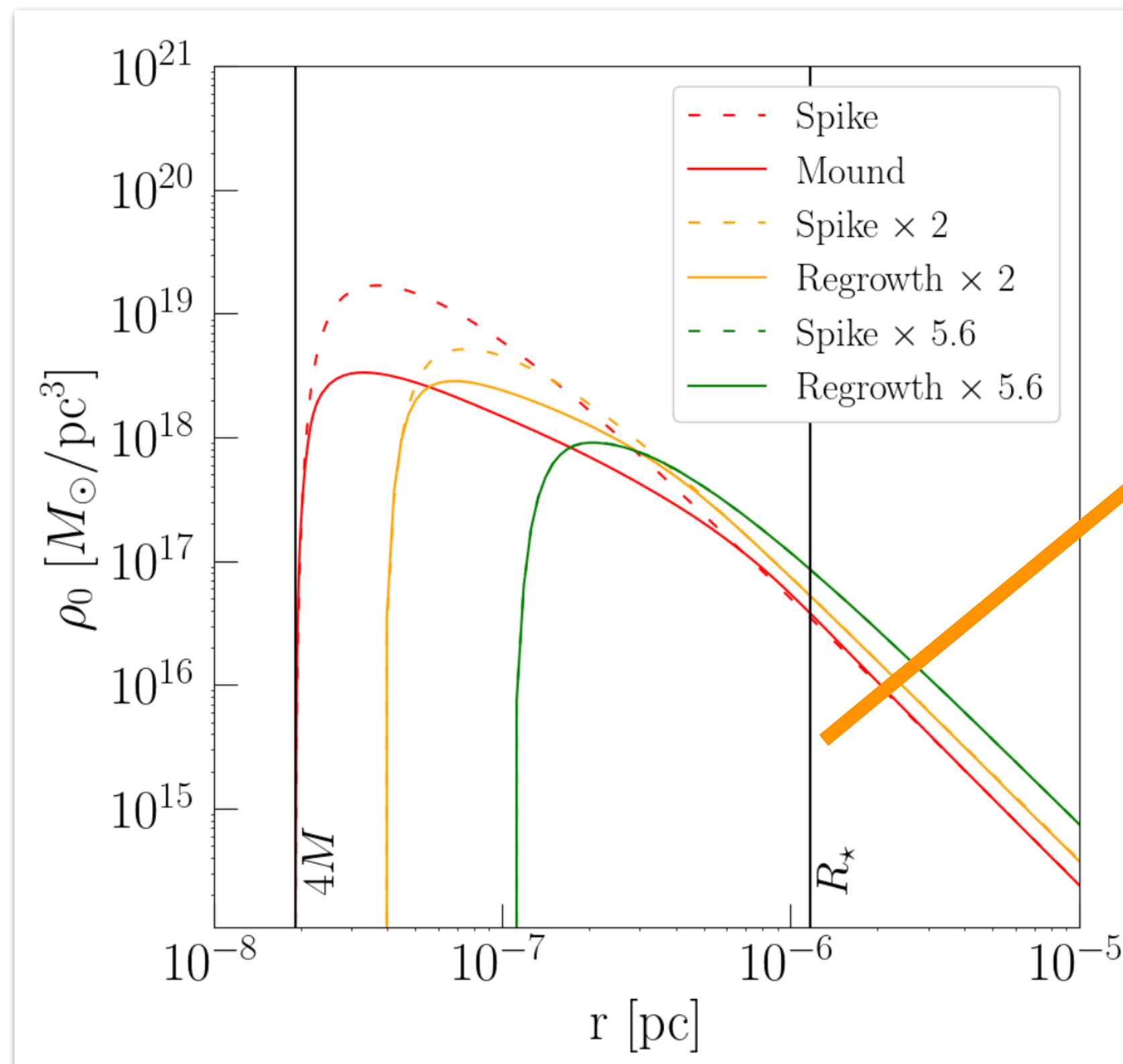
What about the photons? work in progress

Back up

DM spike around AGN: predictions

Dark matter mounds from the collapse of supermassive stars:
a general-relativistic analysis 2512.09985

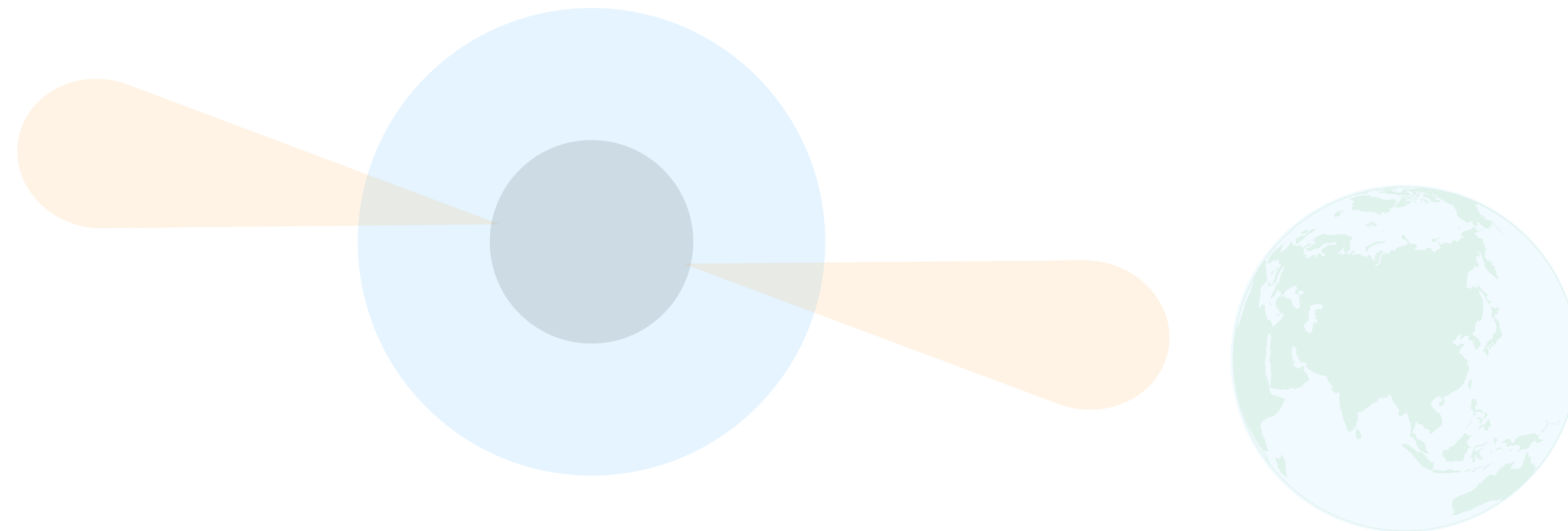
Roberto Caiozzo,^{1,*} Gianfranco Bertone,² Piero Ullio,^{1,3,4}
Rodrigo Vicente,² Bradley J. Kavanagh,⁵ and Daniele Gaggero⁶



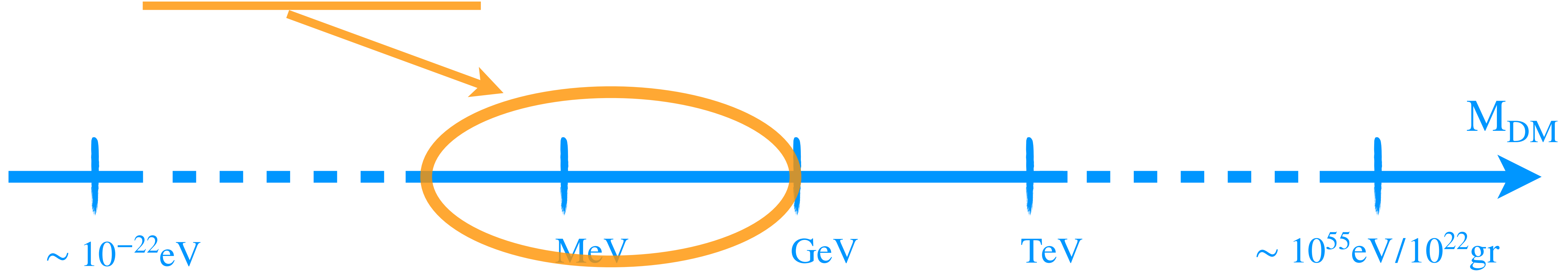
Our aggressive benchmark starts from here

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

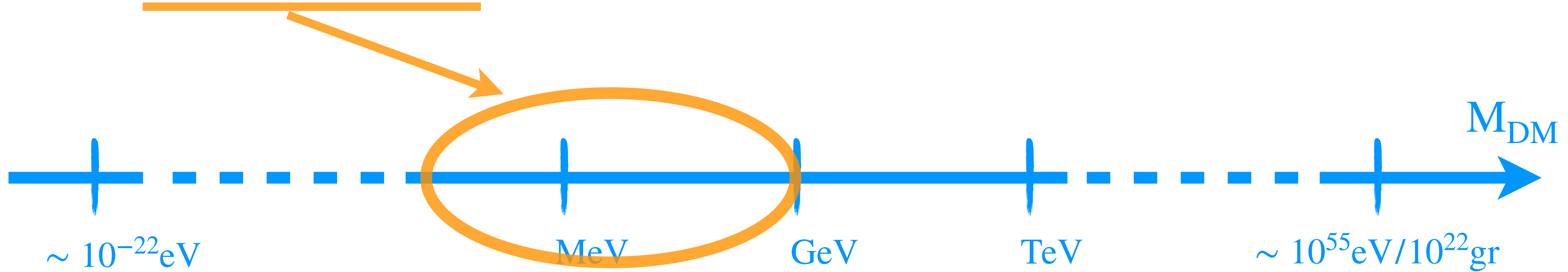
Dark Matter ?



Sub-GeV Dark Matter



Sub-GeV Dark Matter



Cosmo histories motivate it/exist

Why?

Links easily with many astro questions

We can look for it “easily”

Sub-GeV Dark Matter

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

Thermal freeze-out
at small coupling

SIMP

Hochberg+ 1402.5143

...

ELDERs

Kuflik+ 1512.04545

Forbidden DM

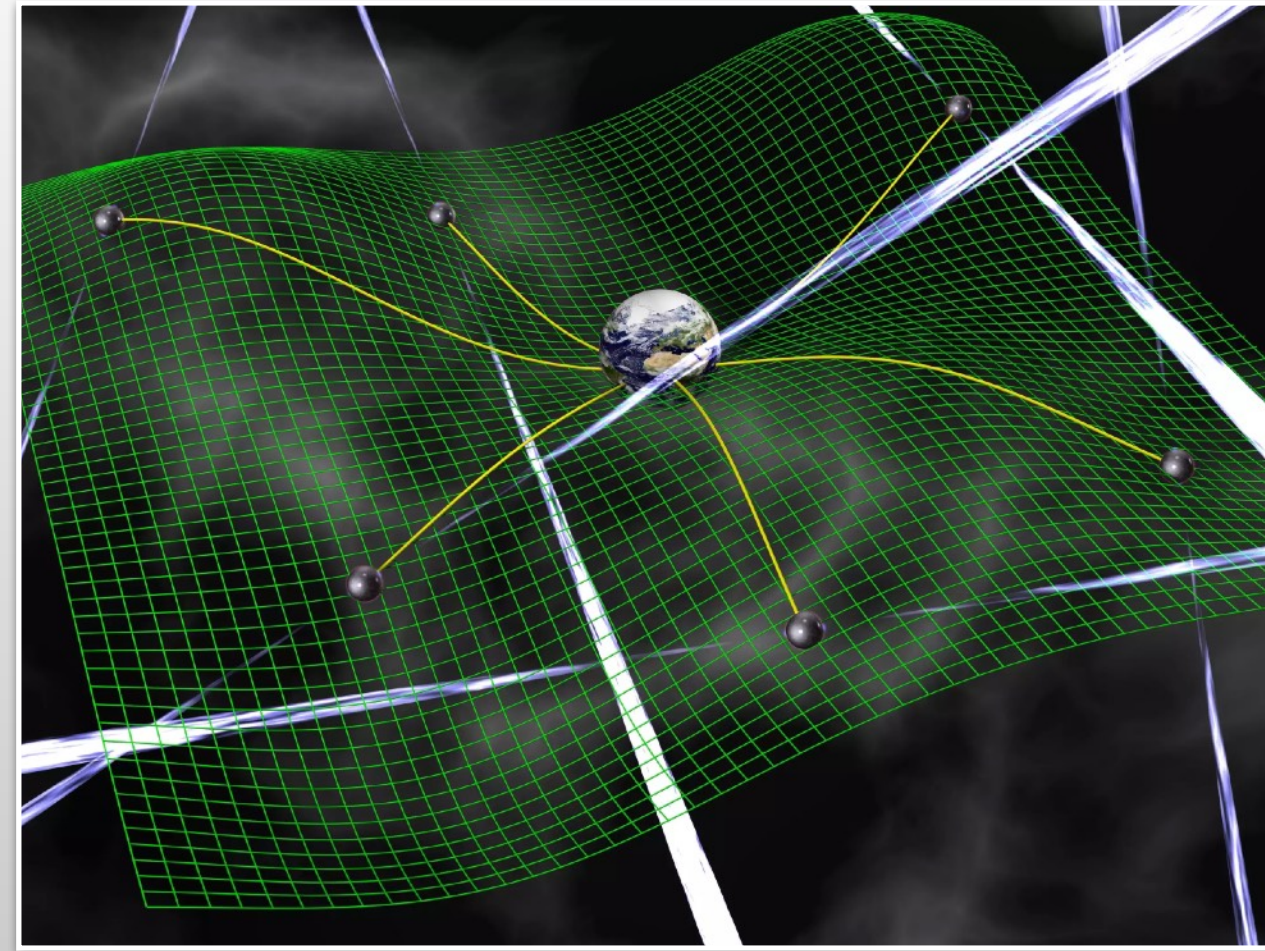
D'Agnolo Ruderman 1505.07107

Cosmo histories motivate it/exist

Why?

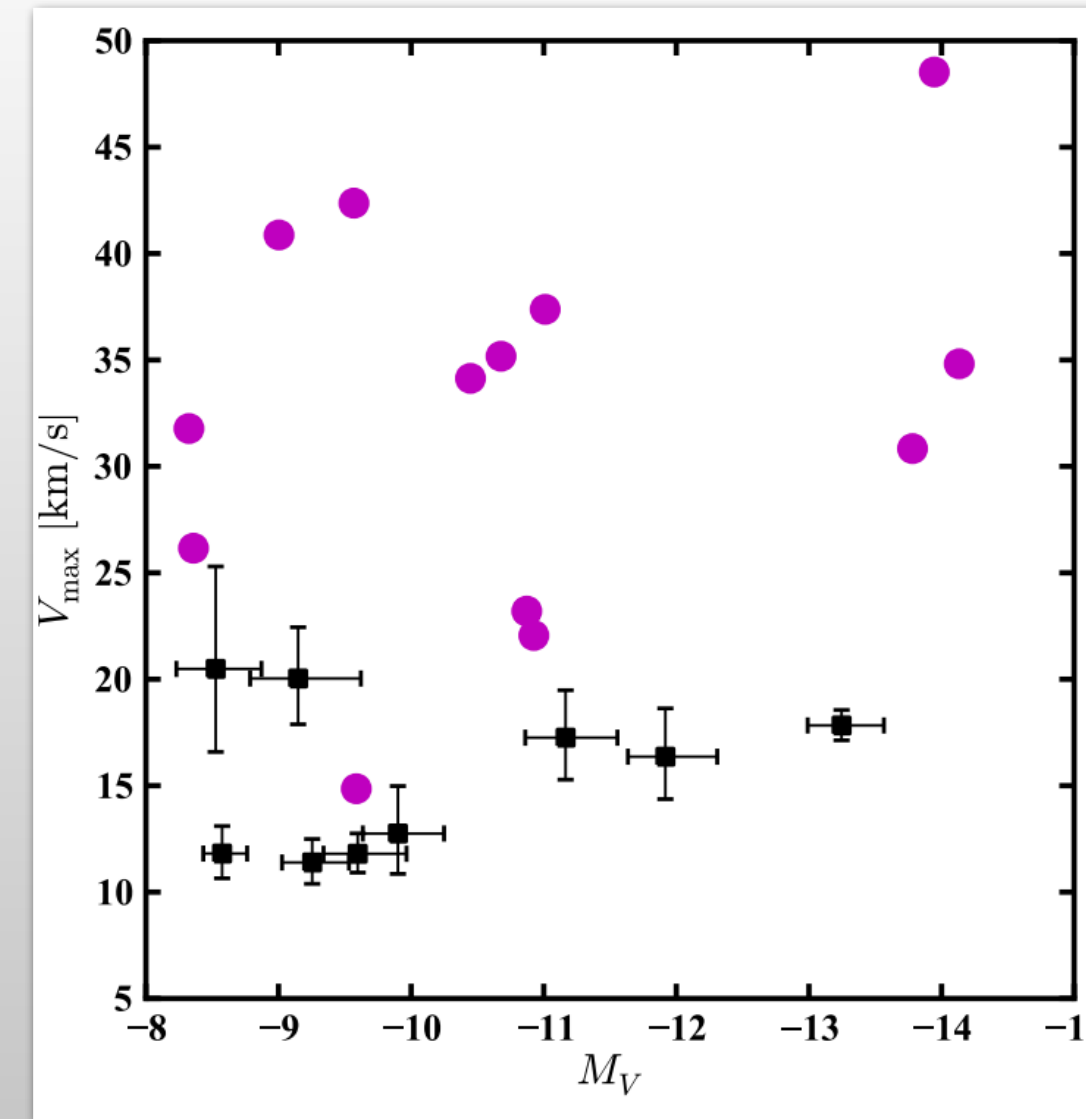
Sub-GeV Dark Matter

Gravity Waves at PTAs?



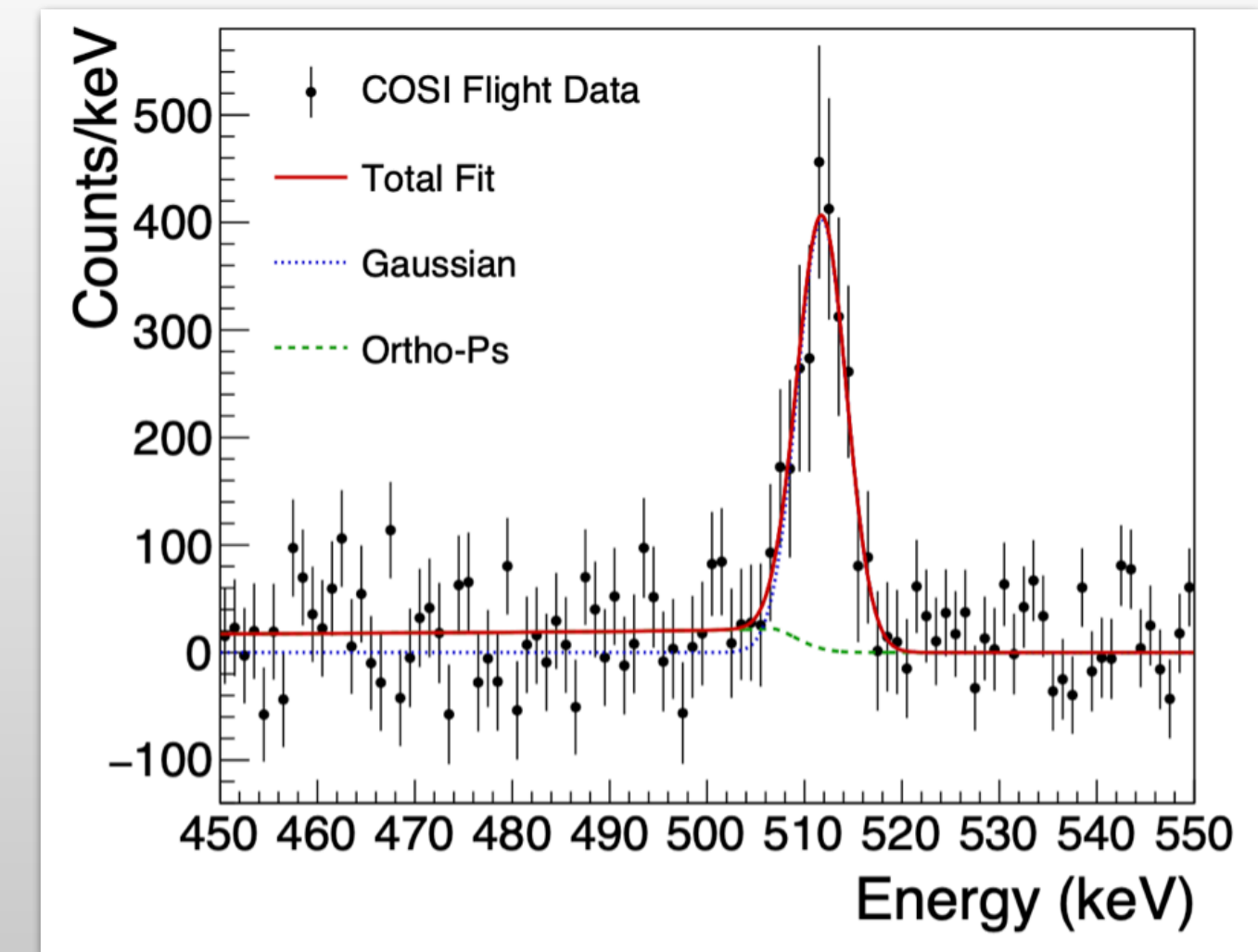
Nanograv 2104.13930, ...
Bringmann+ 2306.09411, ...

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 easily with many astro questions

[not true for other DM masses!]

Sub-GeV Dark Matter

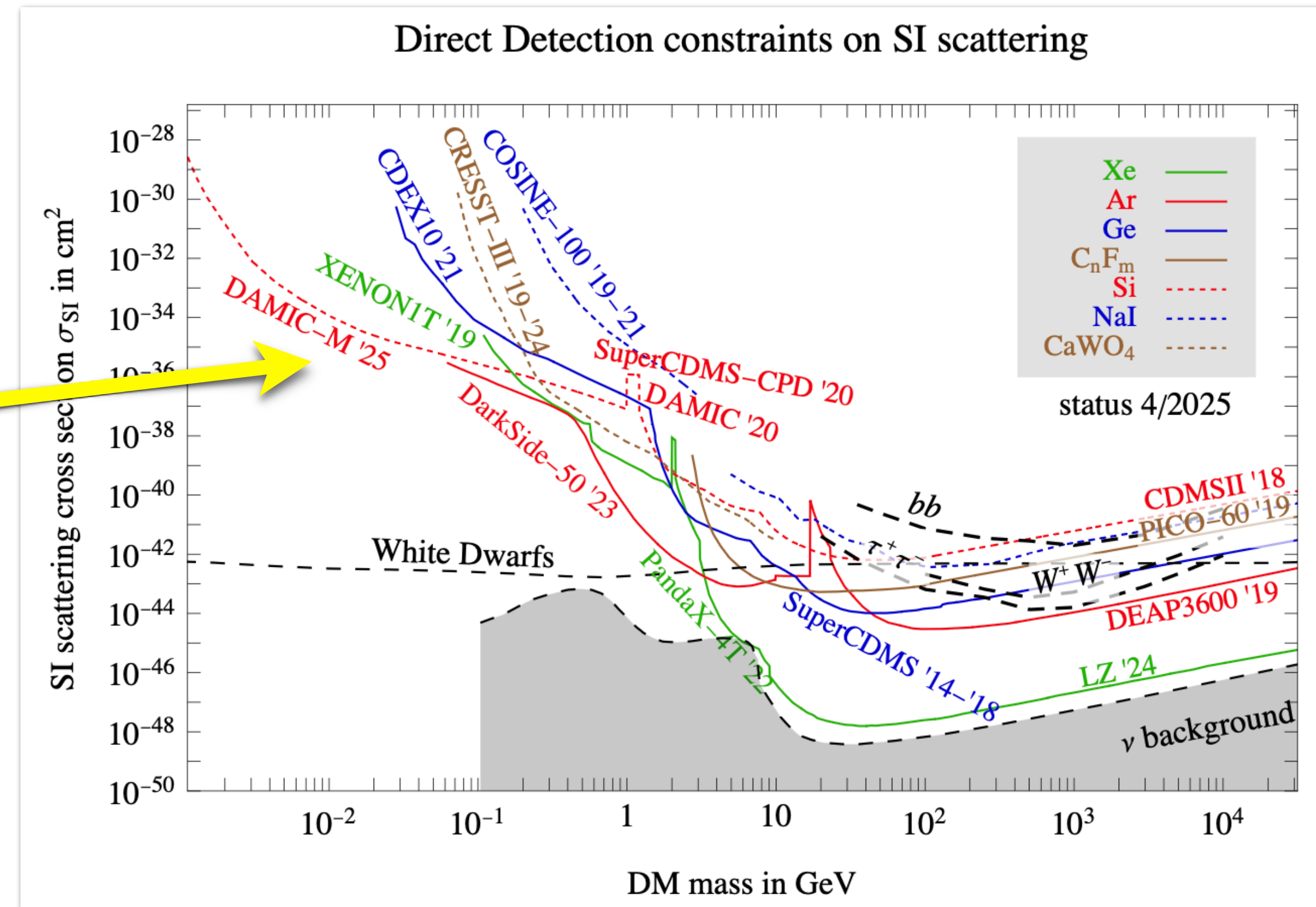
@ $M_{\text{DM}} \lesssim \text{GeV}$:

PHONON(S)

MIGDAL & brem

...

Why?

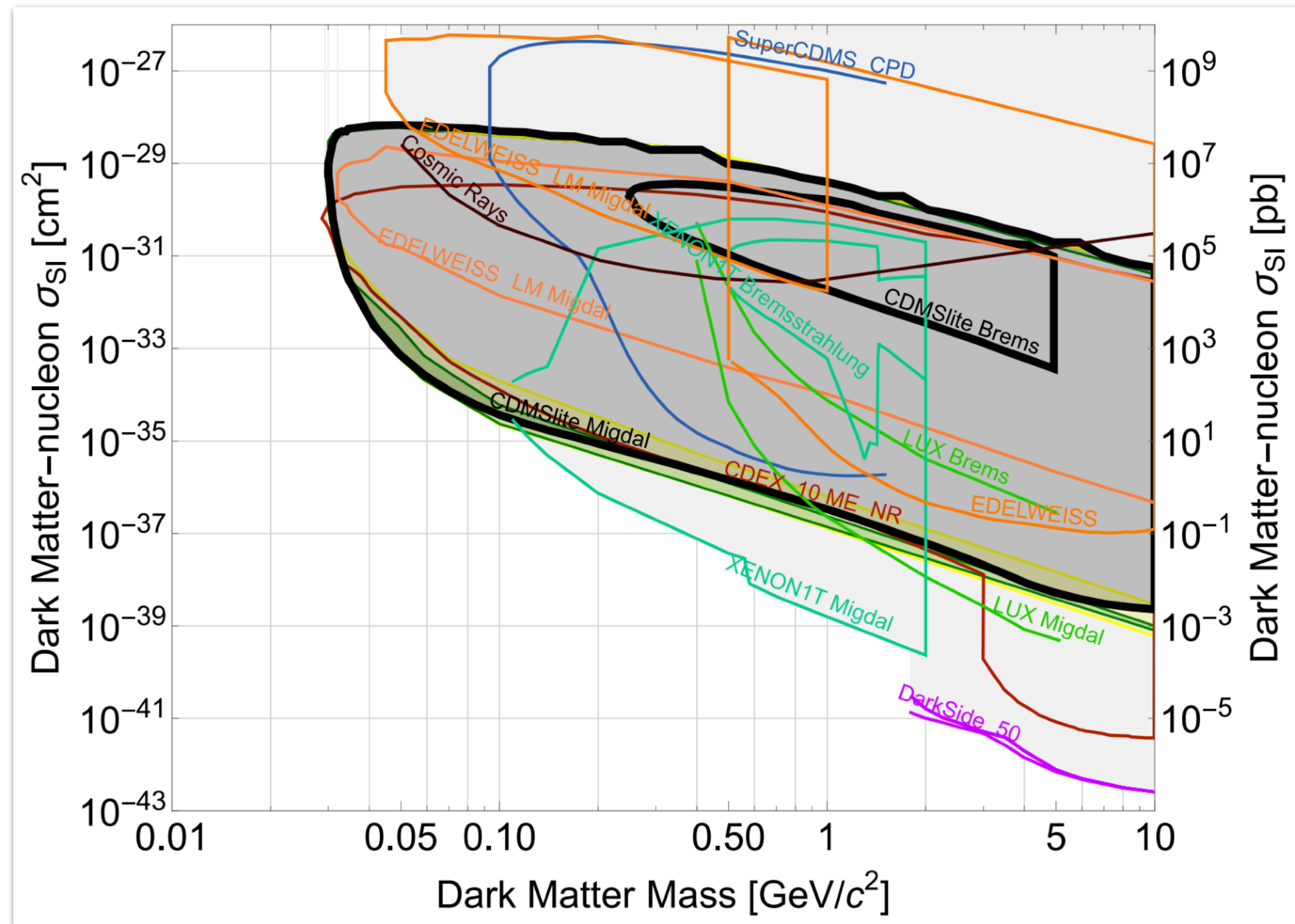


Cirelli Strumia Zupan review 2025

We can look for it “easily”

Direct detection of Sub-GeV DM: status

Promising, not cutting deep yet

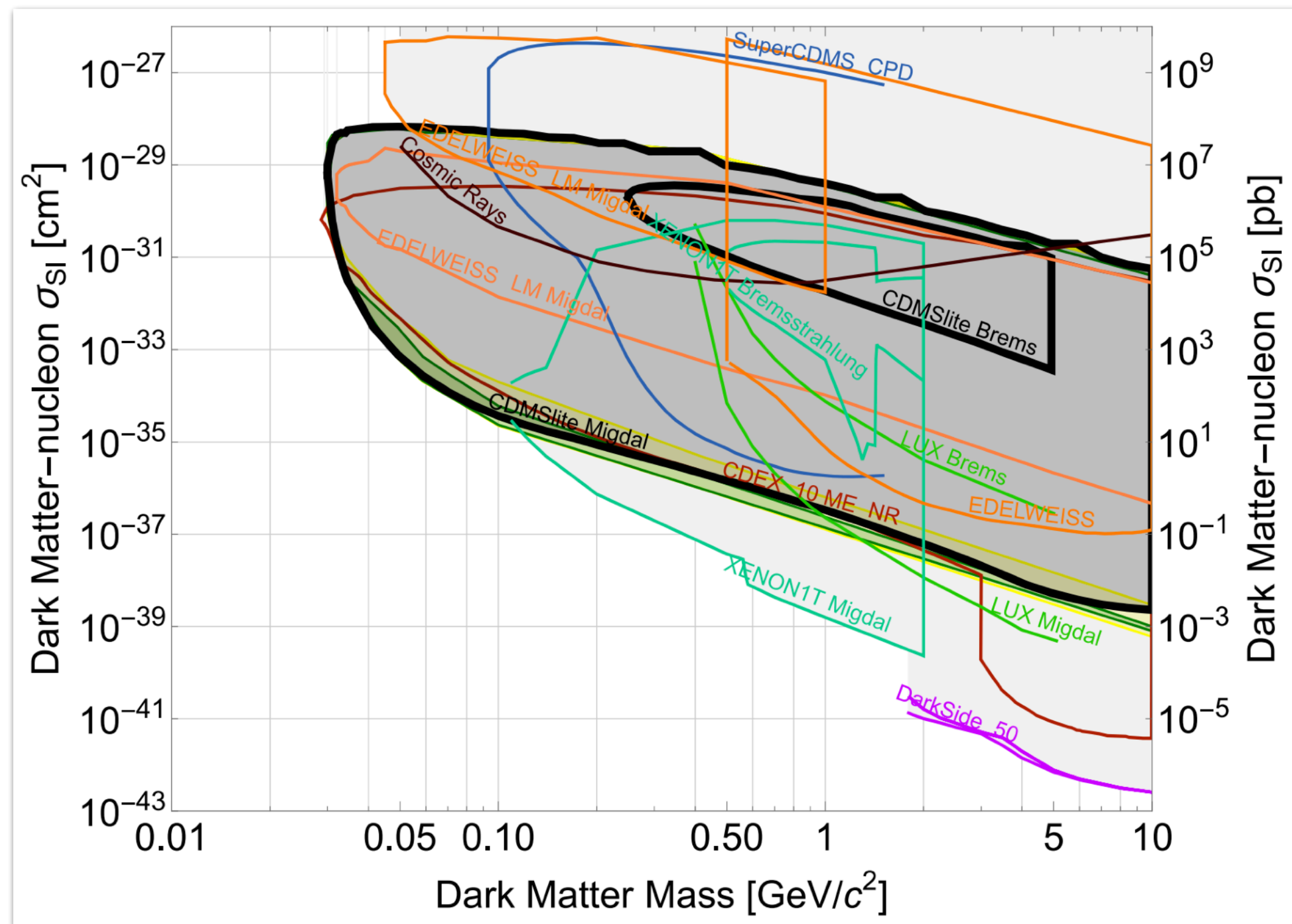


SuperCDMS 2302.09115

Direct detection of Sub-GeV DM: status

Promising, not cutting deep yet

New exp. techniques: better understanding needed



SuperCDMS 2302.09115

MIGDAL effect widely used

DarkSide, XENON, PandaX
SuperCDMS, SENSEI ...

BUT: was never observed in the Standard Model

When tried with neutrons in liquid Xenon

SM signal not found despite ~100 events predicted!

Xu+ 2307.12952, PRD 2024

Same prediction goes into DM searches...

wait for other measurements e.g. Kahn Perez-Rios 2403.08866

High-energy fluxes of sub-GeV DM

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



Bringmann Pospelov 1810.10543

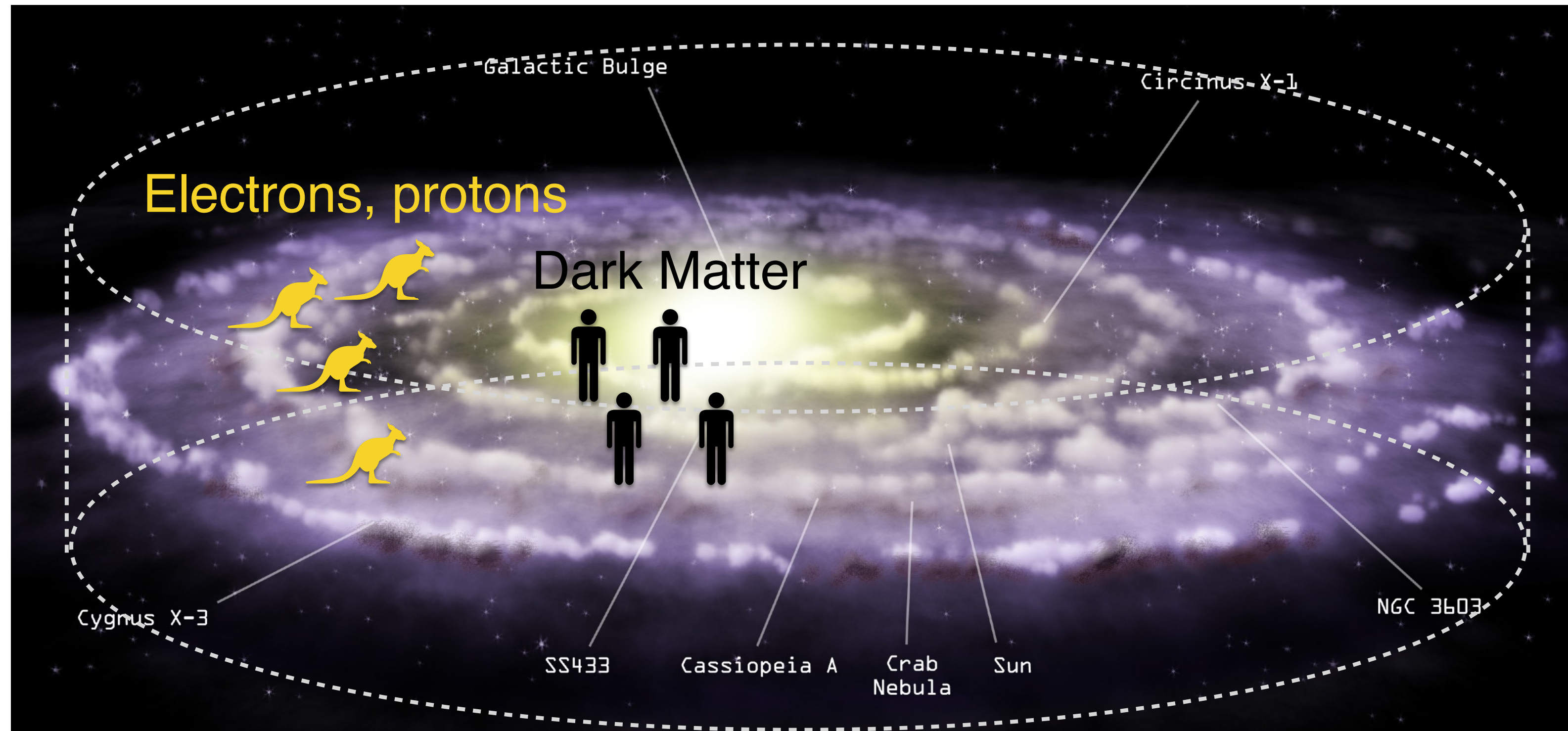
Ema FS Sato 1811.00520

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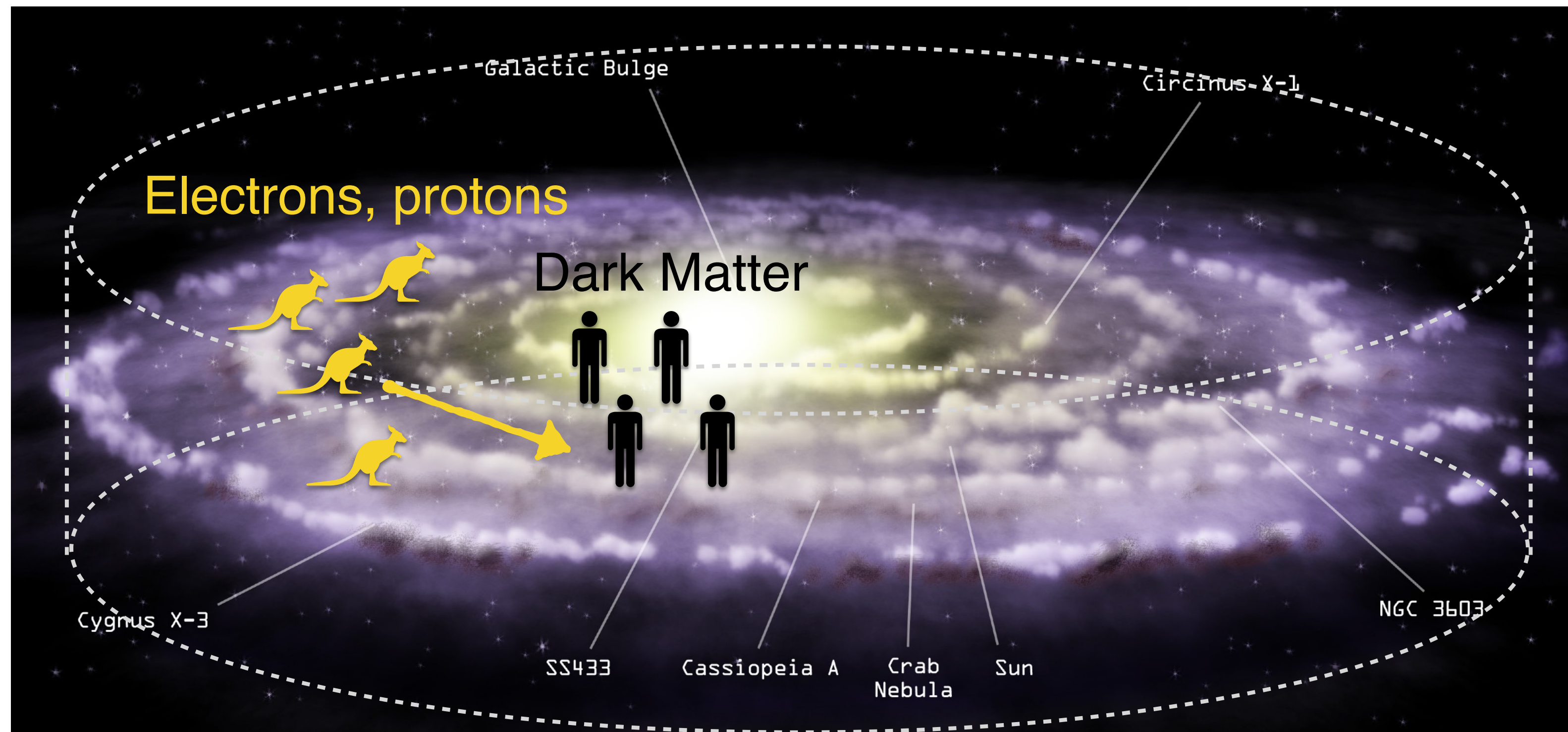


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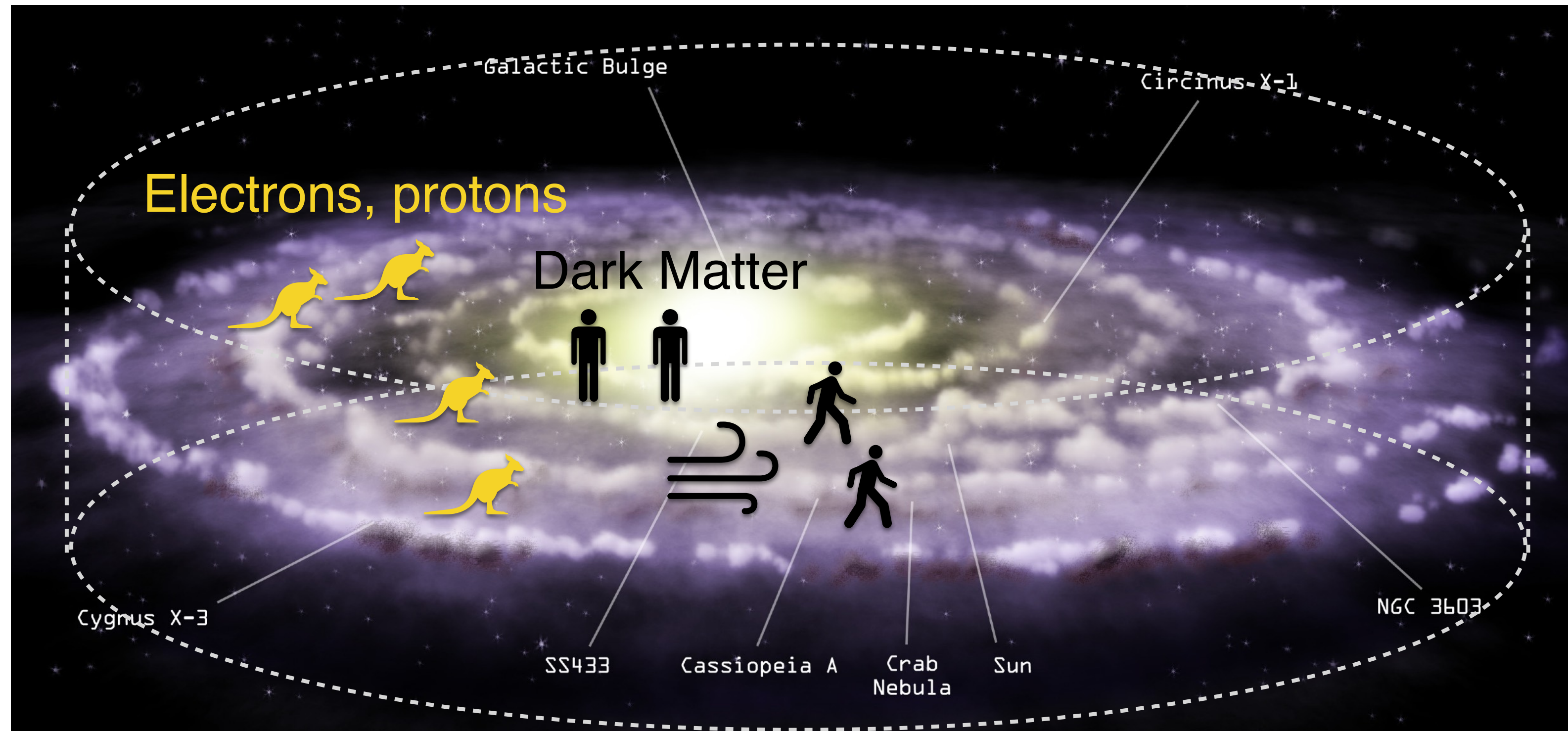


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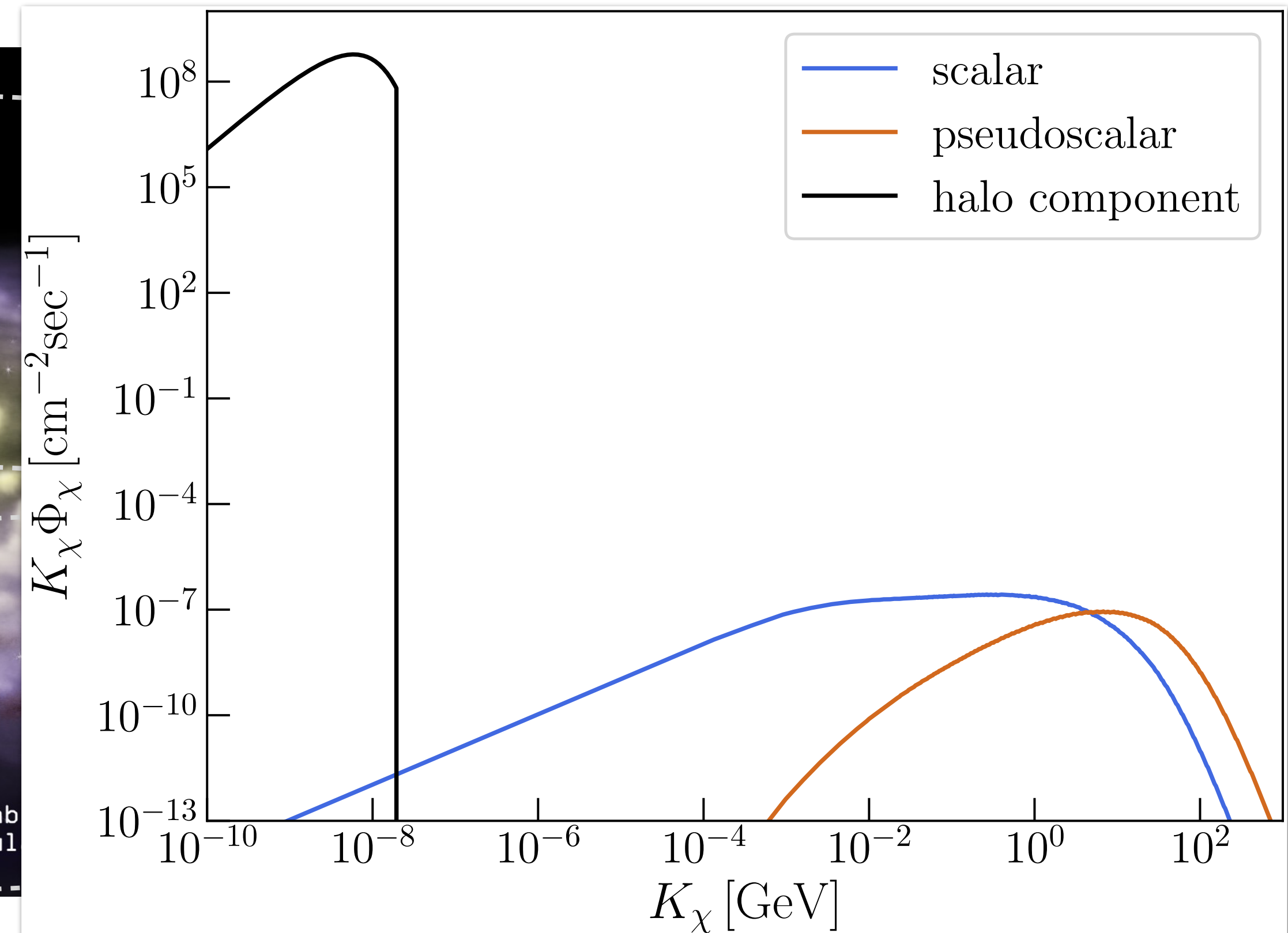
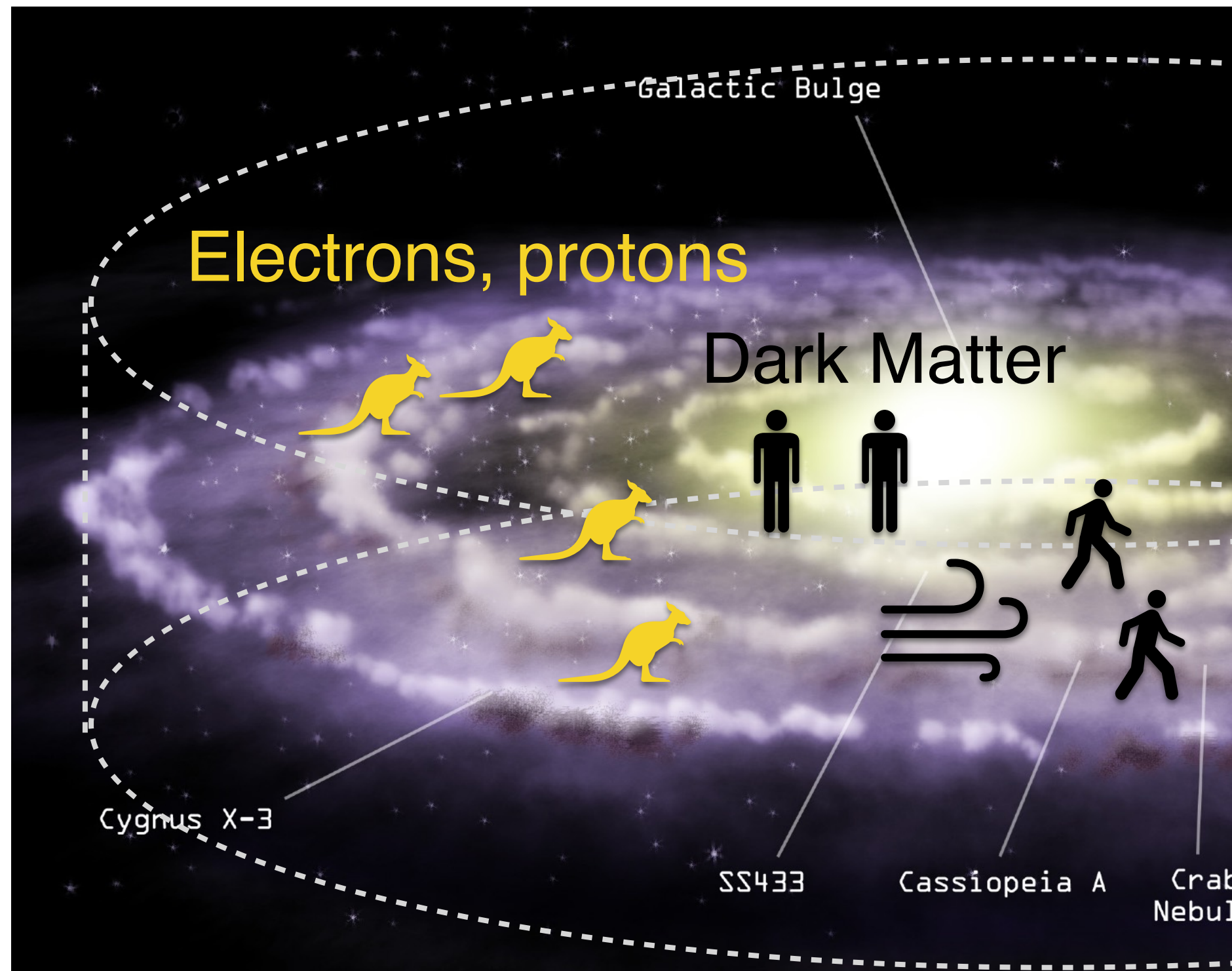


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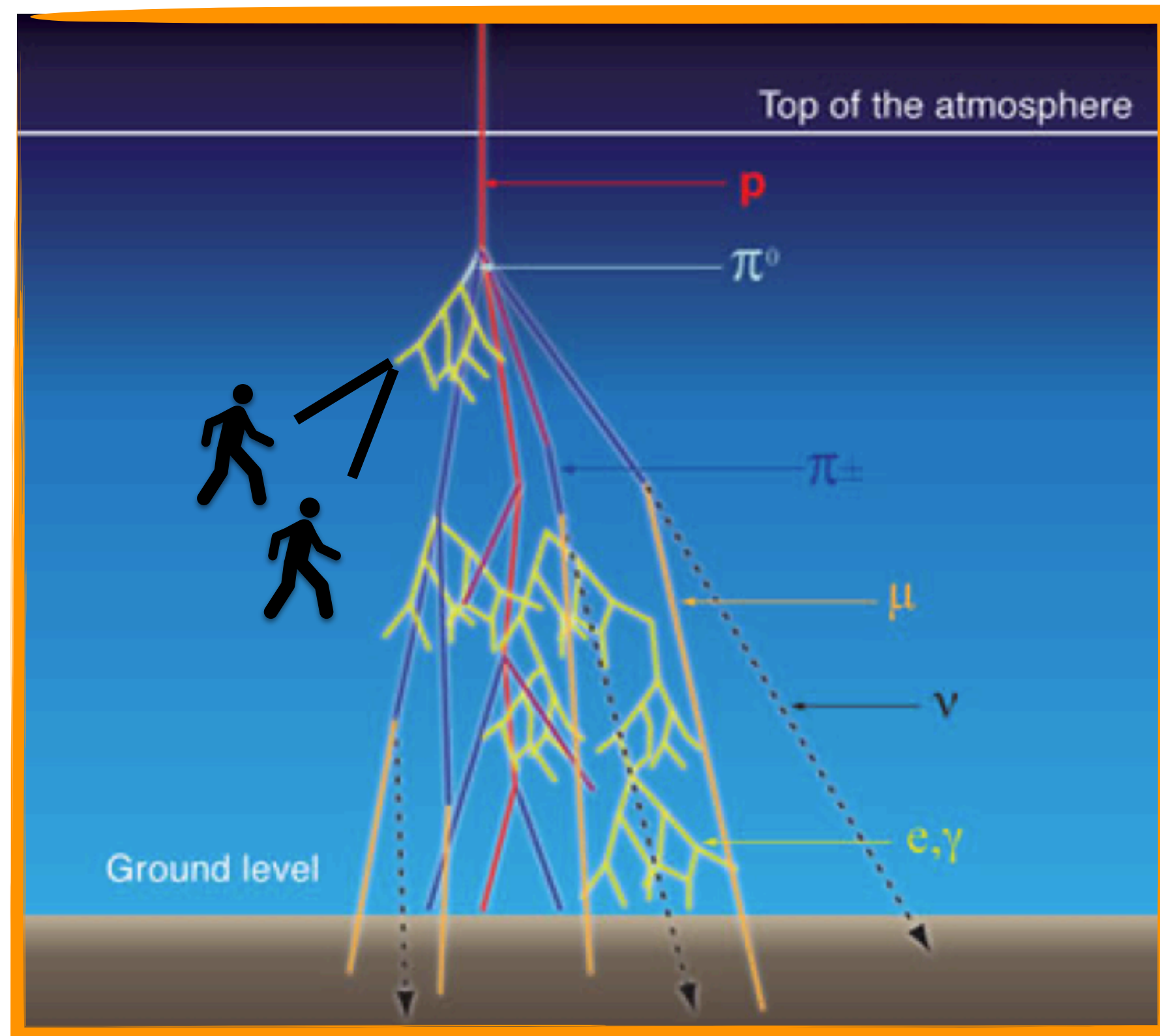
$$M_{\text{DM}} = 10 \text{ MeV}, \quad M_{\text{mediator}} = \text{GeV}, \quad g_{\chi}g_u = g_{\chi}g_d = 0.1$$

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

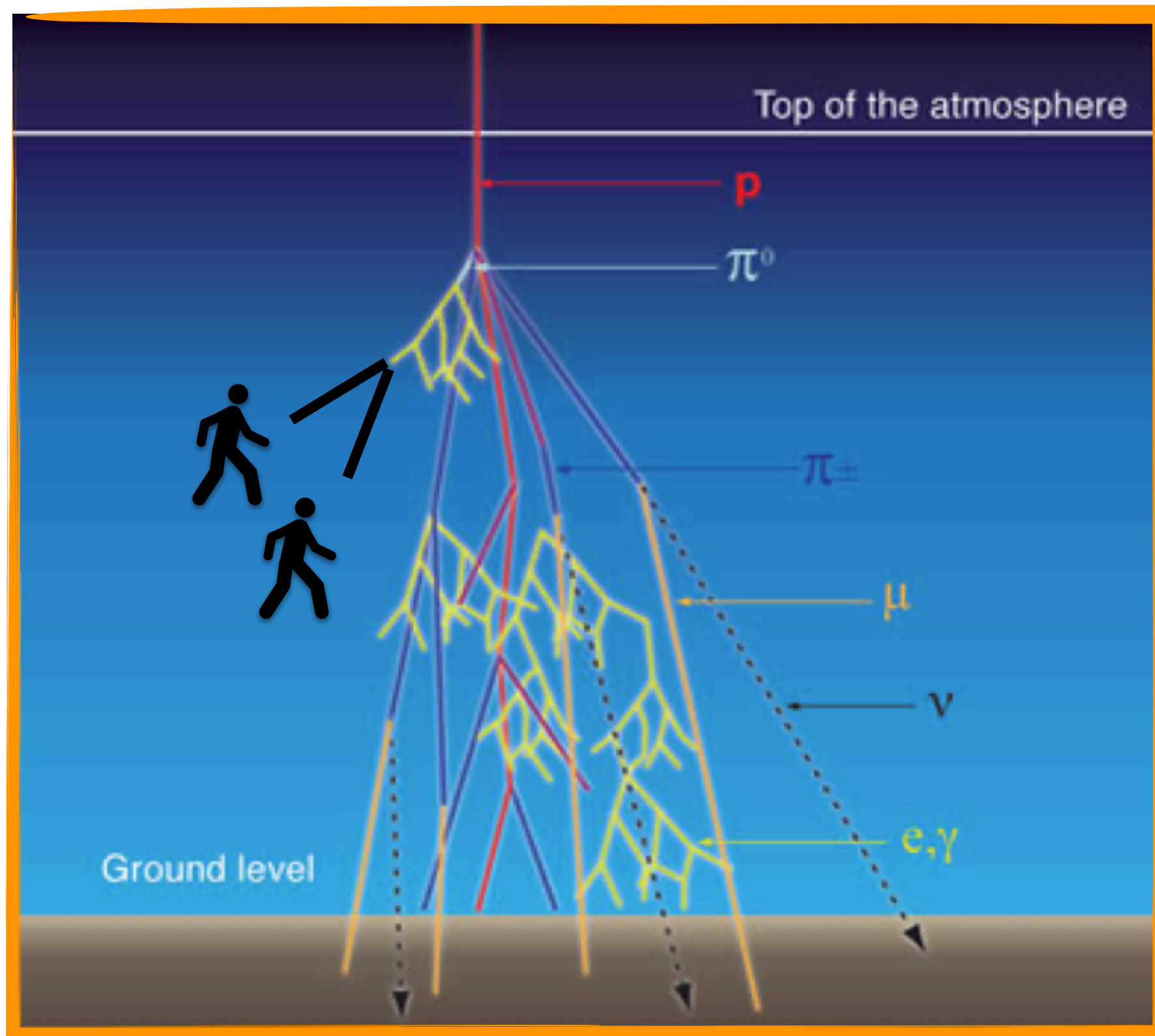


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Ema FS Sato 1811.00520



← Also by **Atmospheric Showers**

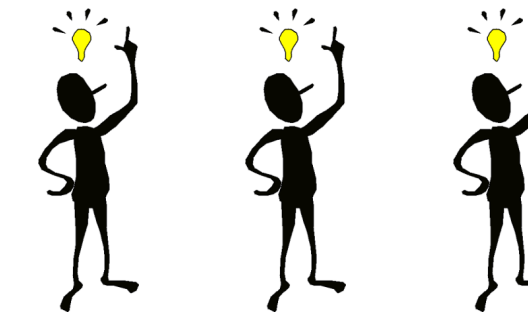
Alvey+ 1905.05776 , ...

Pascoli FS Xotta in progress

Also by **Blazars**

Wang Granelli Ullio 2111.13644, ...

Also by ...

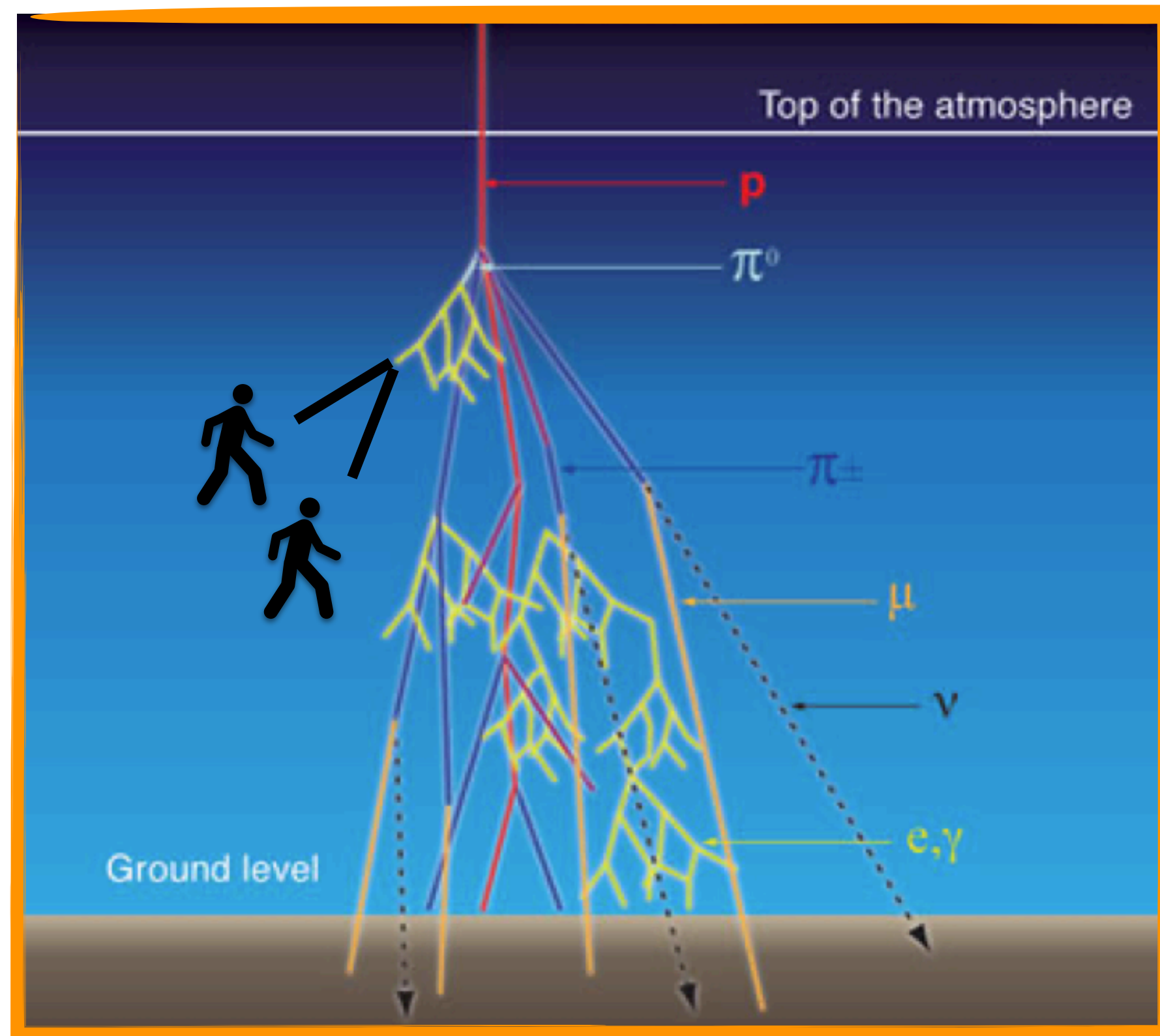


High-energy fluxes of sub-GeV DM

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

Also by **Blazars**

Wang Granelli Ullio 2111.13644, ...

Also by ...

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

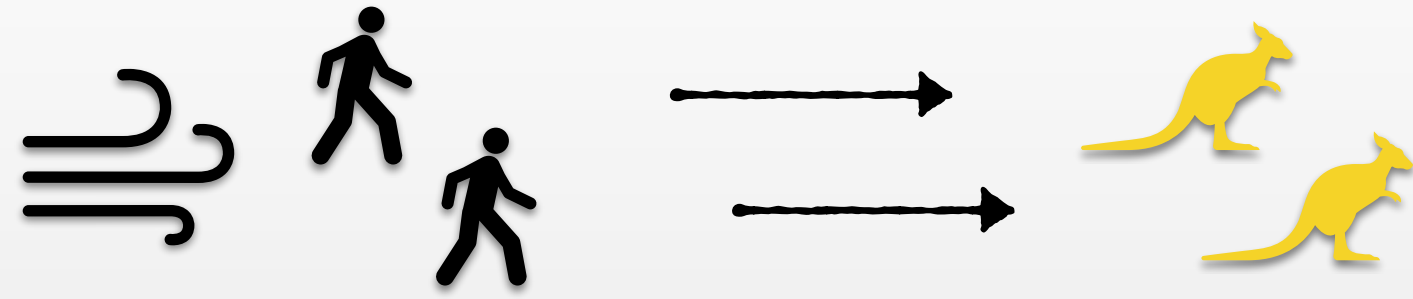
An Pospelov Pradler Ritz+ 1708.03642

Emken Kouvaris Nielsen 1709.06573

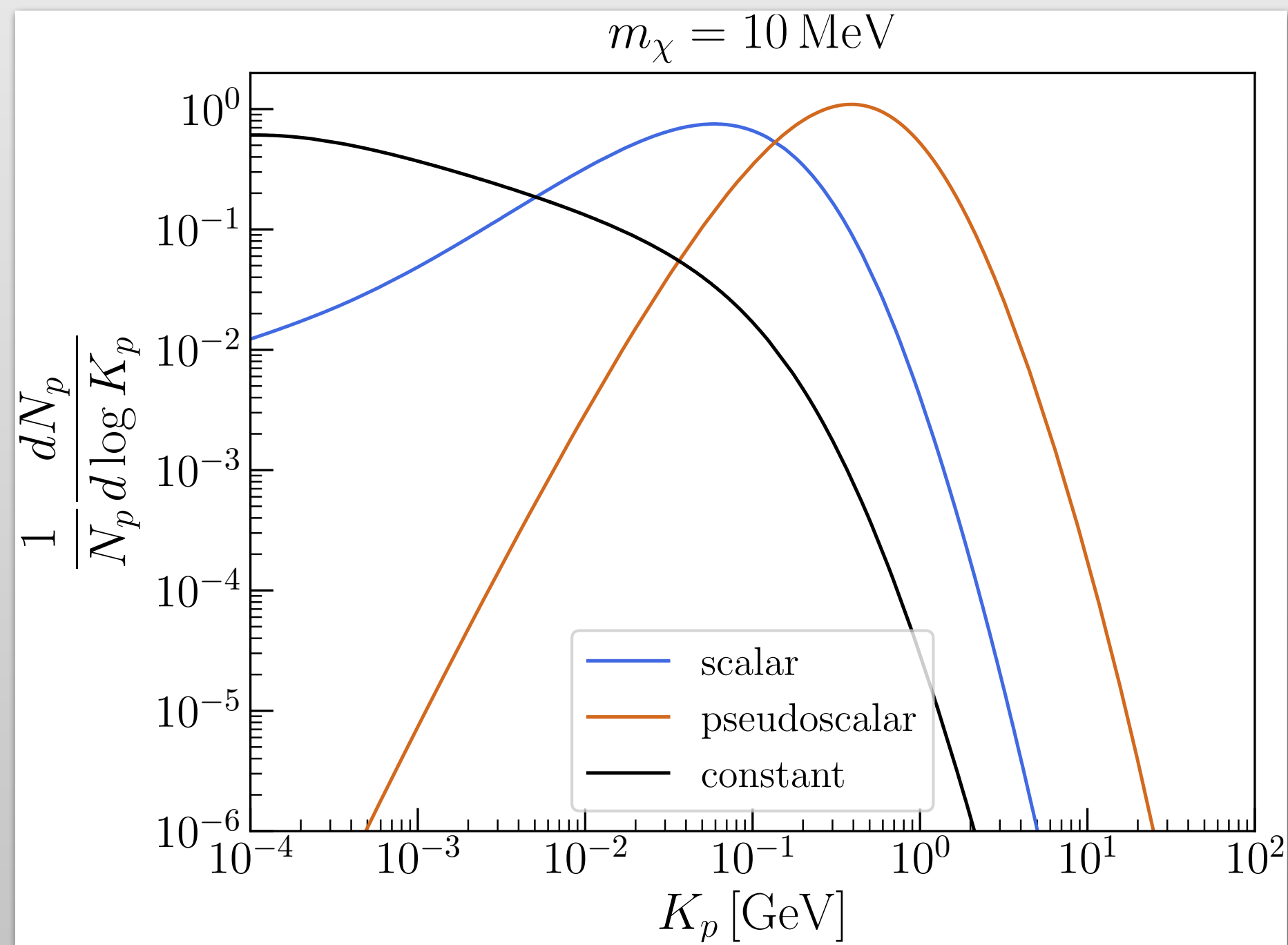
...

Detecting fast sub-GeV DM

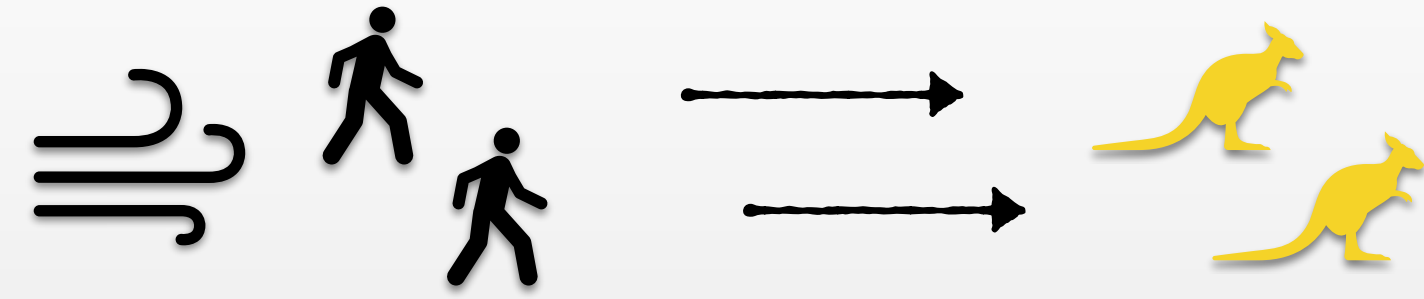
@ DM direct detection experiments [PandaX 2301.03010](#), [LZ 2503.18158](#),...



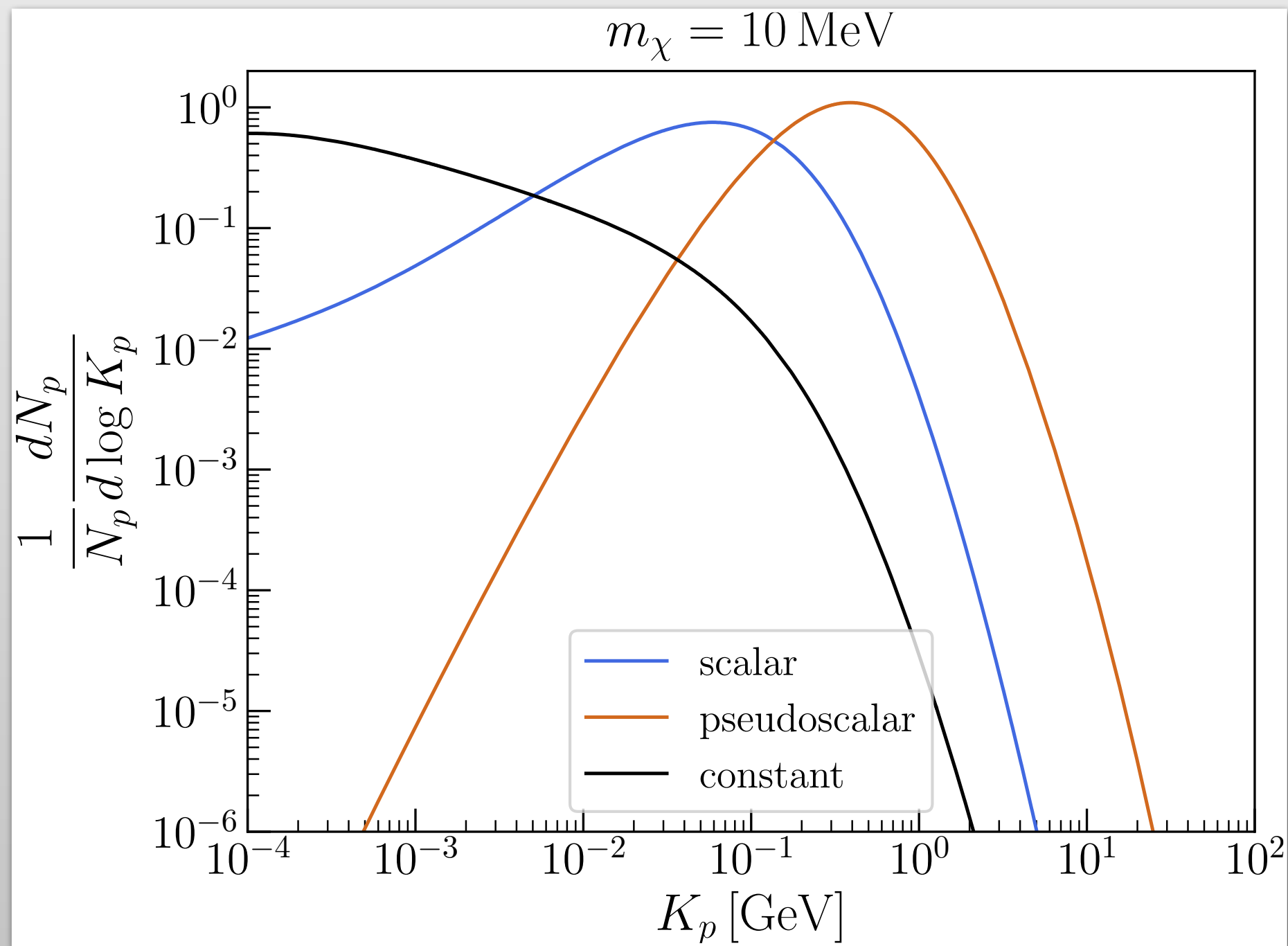
proton recoil from CR-upscattered DM



Detecting fast sub-GeV DM



proton recoil from CR-upscattered DM



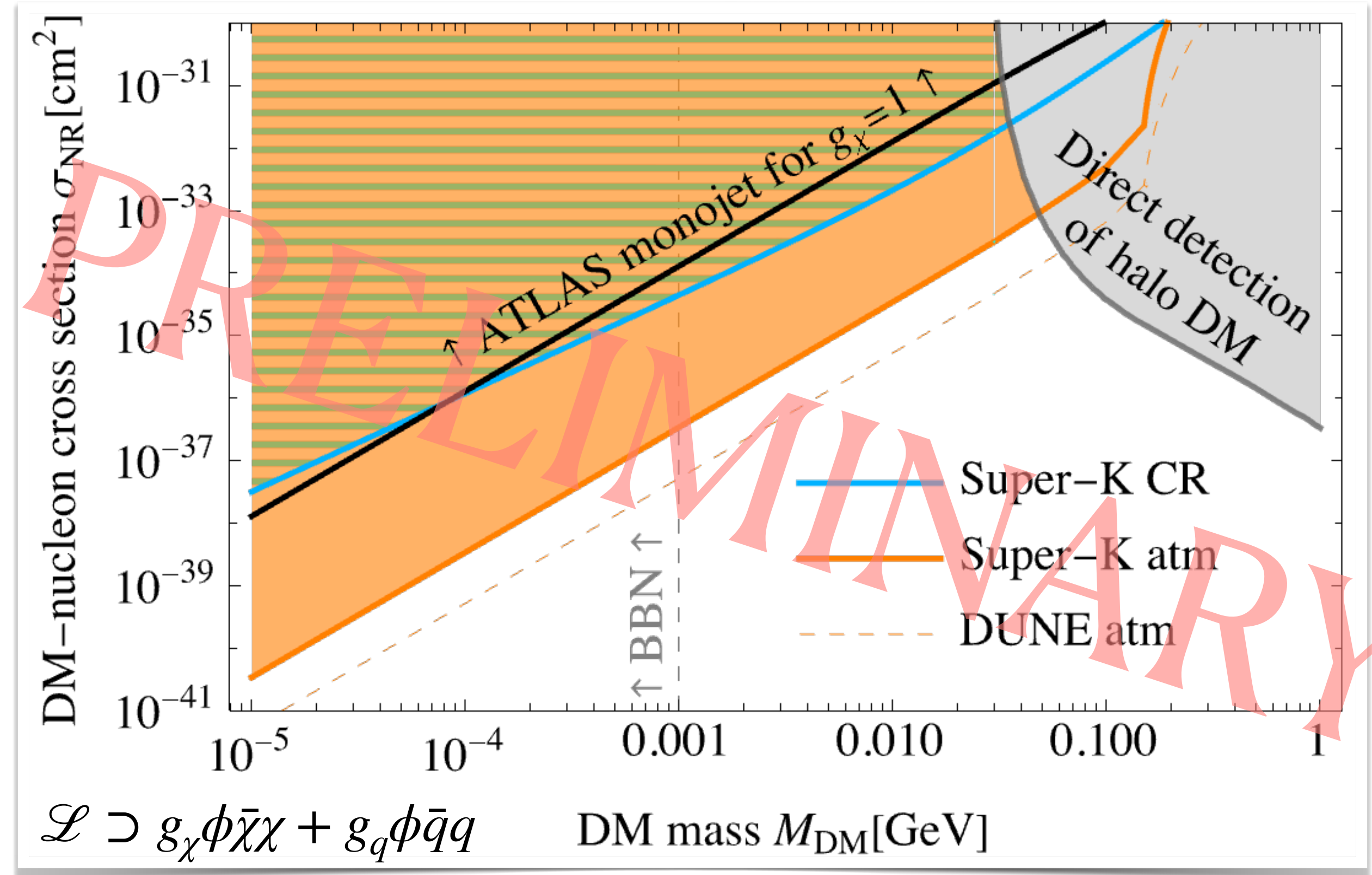
@ DM direct detection experiments PandaX 2301.03010, LZ 2503.18158, ...

@ Neutrino detectors!

e.g. CR-upscattered @Super-K ..., Super-K 2209.14968

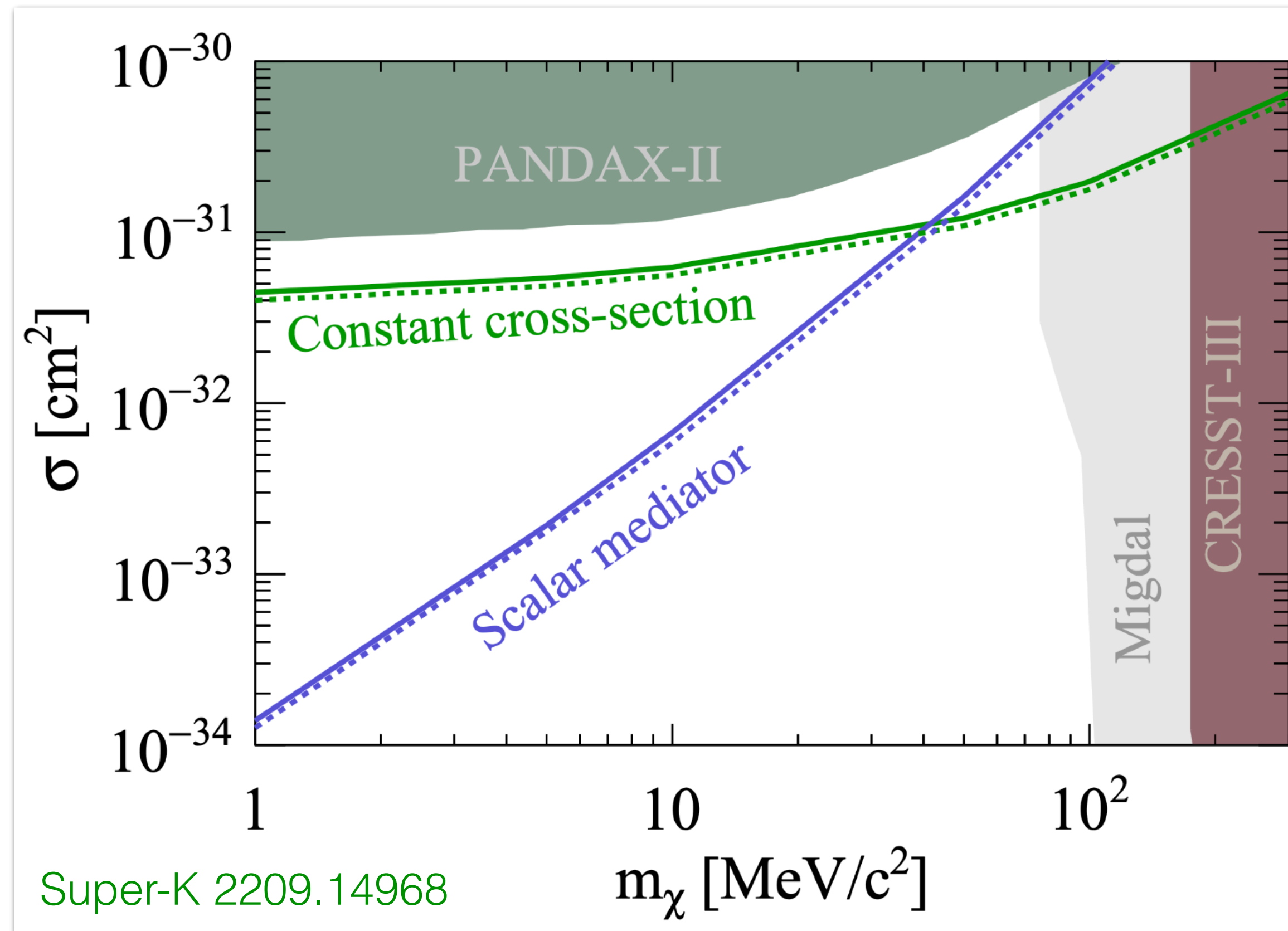
atmospheric-DM @Super-K Pascoli FS Xotta in progress

...



Using DM models is necessary

Ema Sala Sato 2011.01939,...



Scalar mediator

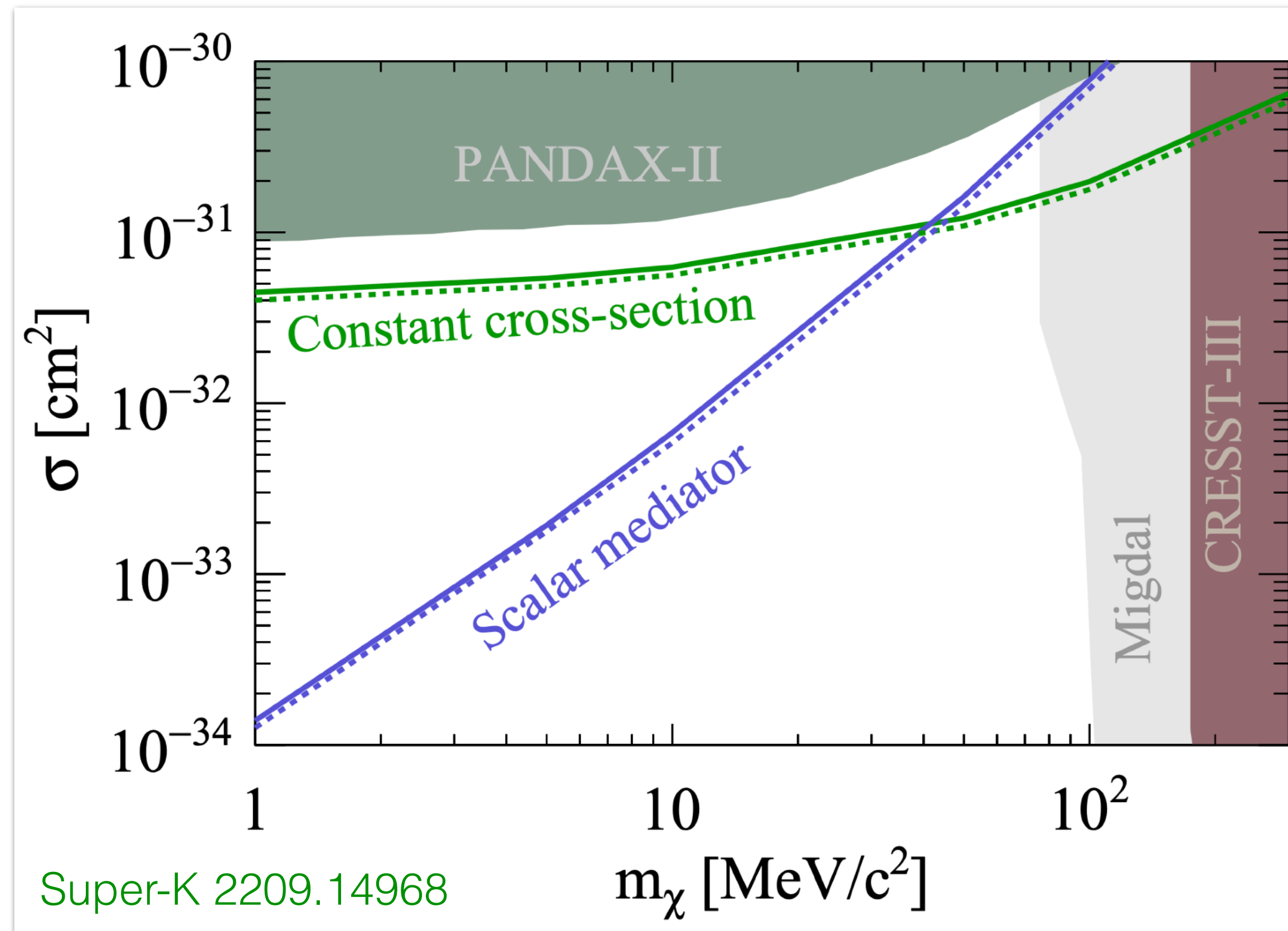
$$\mathcal{L} \supset g_\chi \phi \bar{\chi} \chi + g_q \phi \bar{q} q$$

$$\sigma_{\text{NR}} = C \frac{g_{\chi\phi}^2 g_{u\phi}^2 \mu_{\chi p}^2}{\pi m_\phi^4}$$

$$m_\phi = 1 \text{ GeV}$$

Using DM models is necessary

Ema Sala Sato 2011.01939,...



To avoid being inconsistent!

No model exists (?) that gives high constant cross sections of fast DM

Scalar mediator

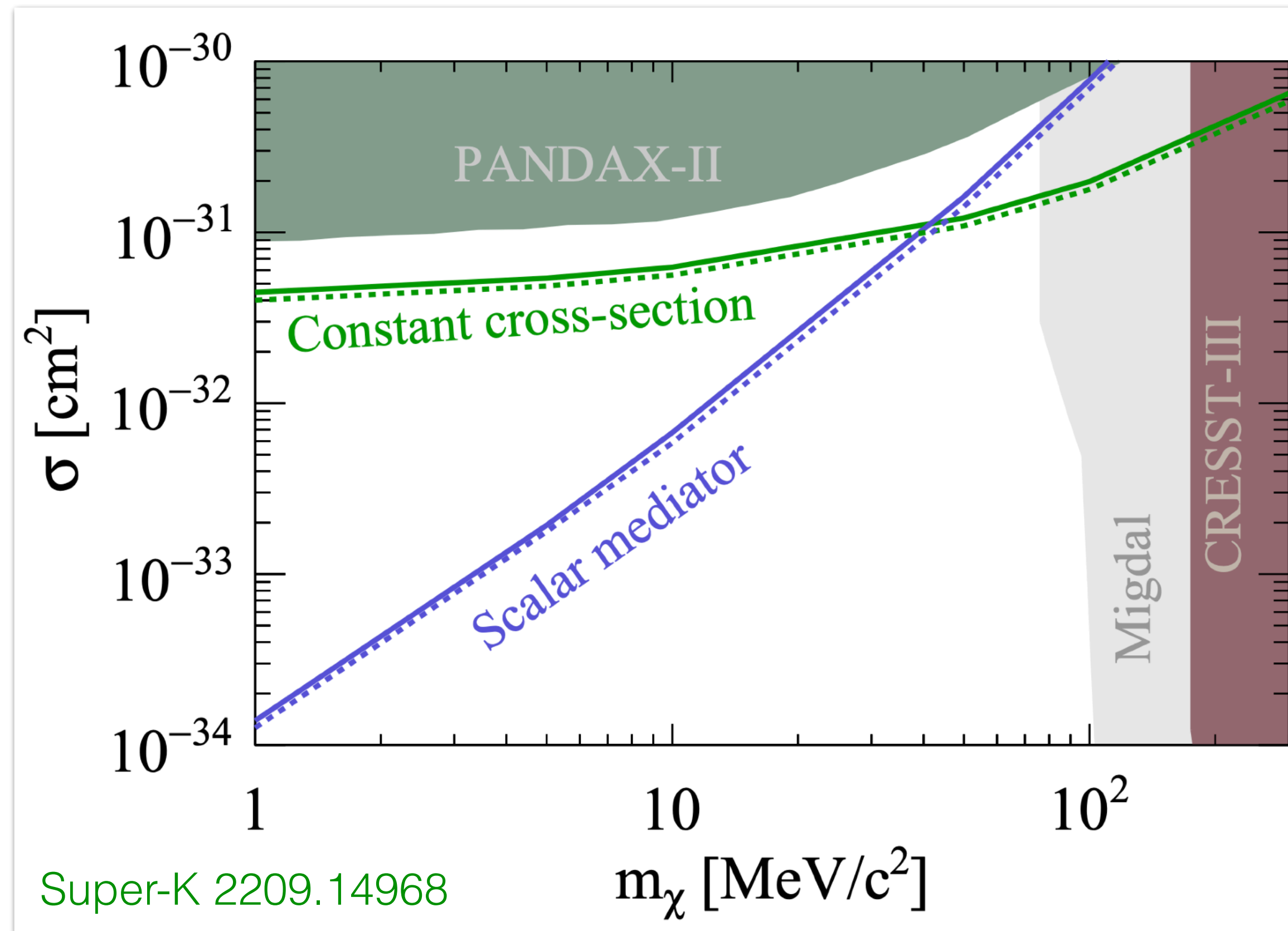
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Using DM models is necessary

Ema Sala Sato 2011.01939,...



To avoid being inconsistent!

No model exists (?) that gives high constant cross sections of fast DM

To compare with results from DM direct detection

Energy in standard DD is very different

To compare with results from non-DM experiments

colliders, telescopes, ...

Scalar mediator

$$\mathcal{L} \supset g_\chi \phi \bar{\chi} \chi + g_q \phi \bar{q} q$$

$$\sigma_{\text{NR}} = C \frac{g_{\chi\phi}^2 g_{u\phi}^2 \mu_{\chi p}^2}{\pi m_\phi^4}$$

$$m_\phi = 1 \text{ GeV}$$

To look for EW invariant completion