

Gamma rays as leptonic portals to energetic neutrinos: a new Monte Carlo approach

Gaetano Di Marco

Rafael Alves Batista

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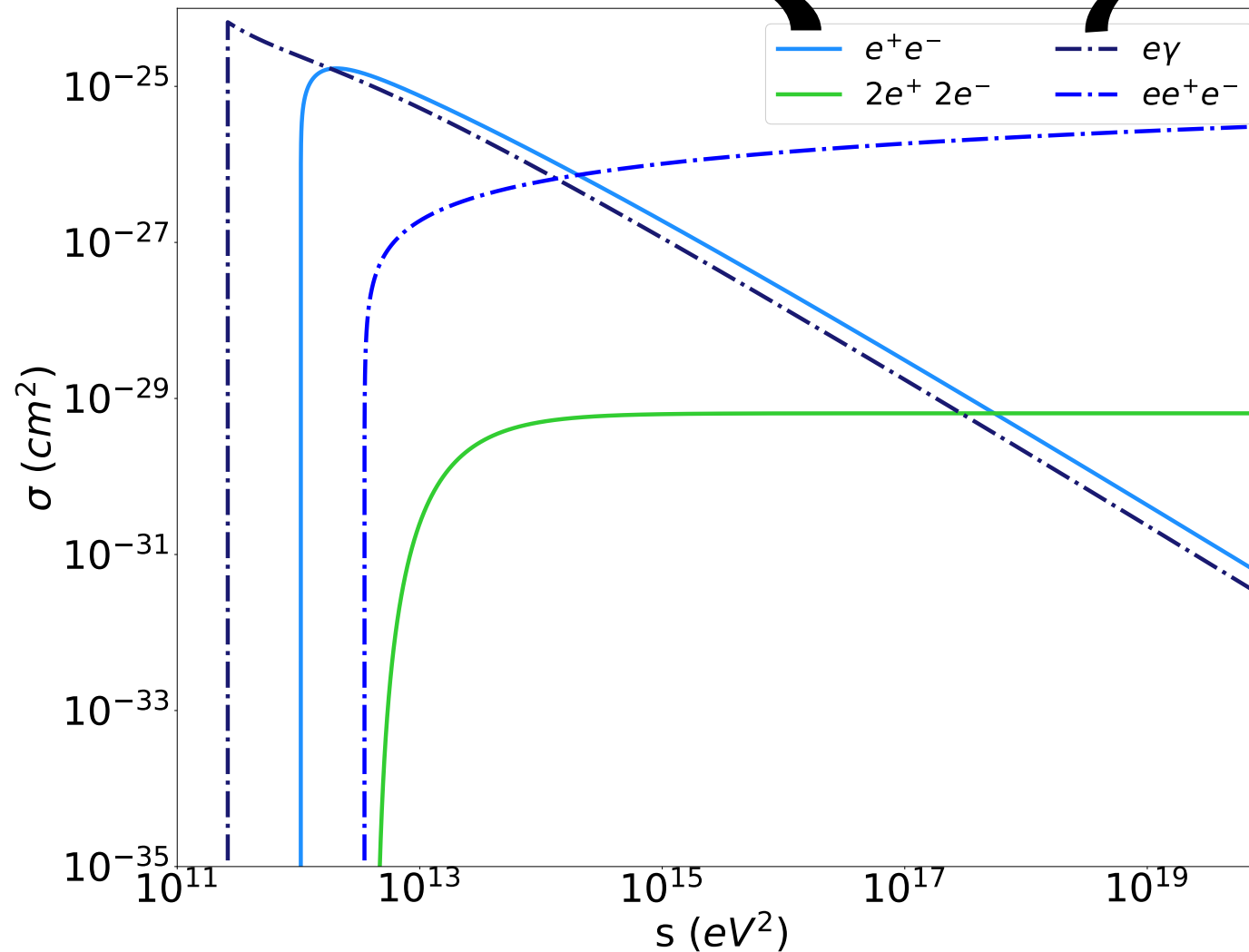
(J. Lombardi, "Processing landscape")

based on arXiv:2507.21867, sub.
to Astroparticle Physics

electromagnetic cascades – cross sections

2

*photon-photon
interactions*



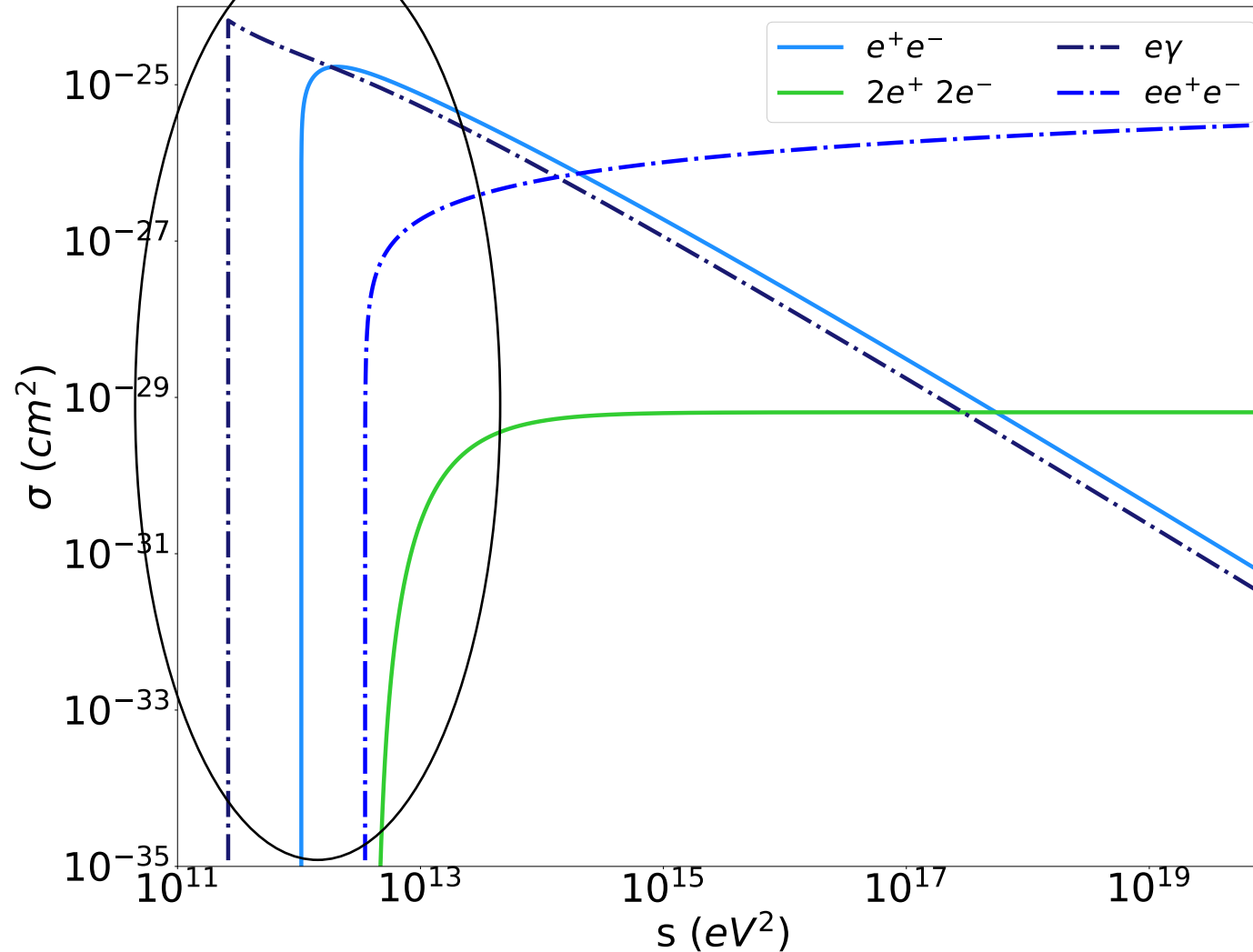
*electron-photon
interactions*



electromagnetic cascades – cross sections

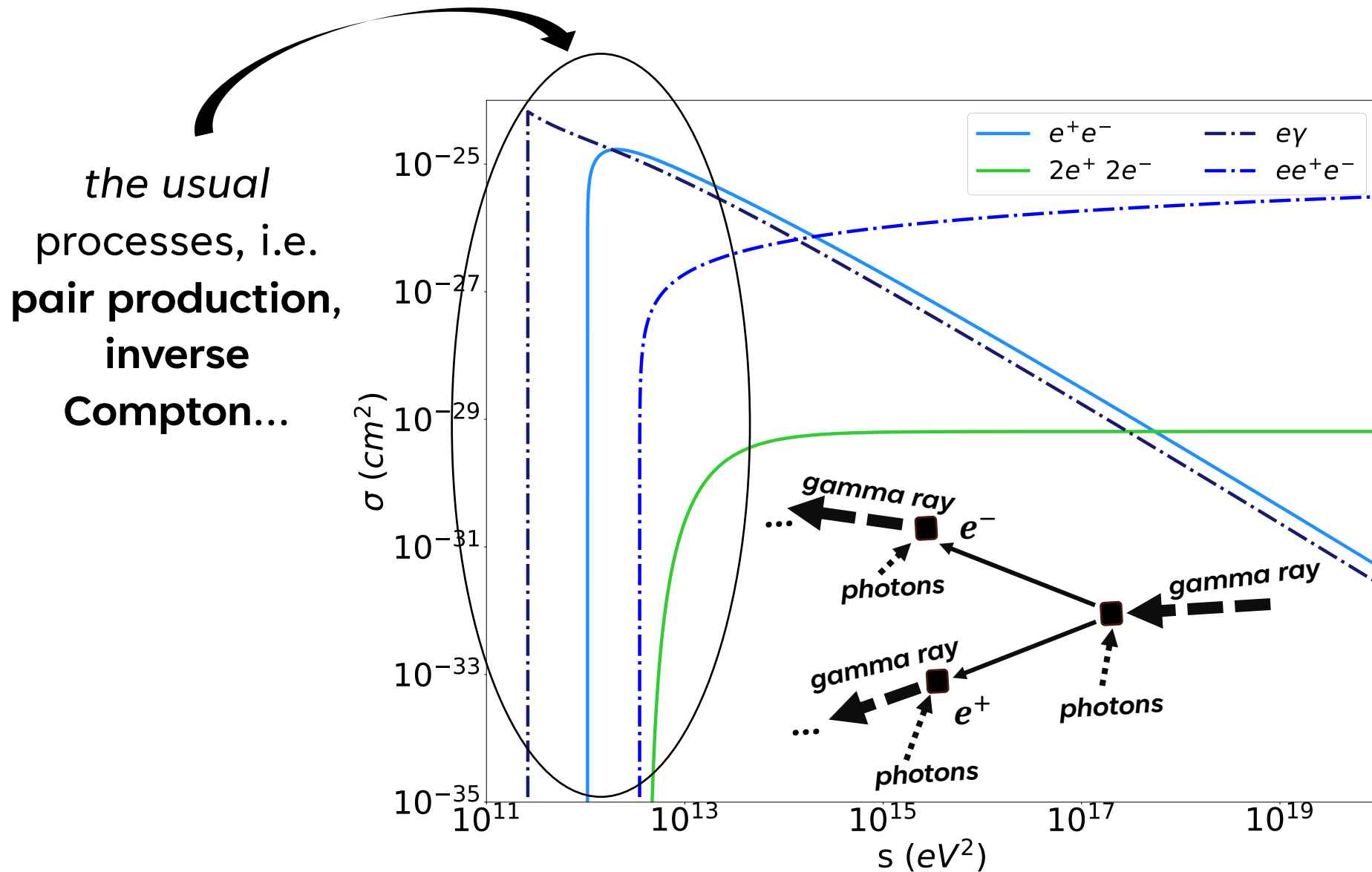
3

the usual
processes, i.e.
pair production,
inverse
Compton...



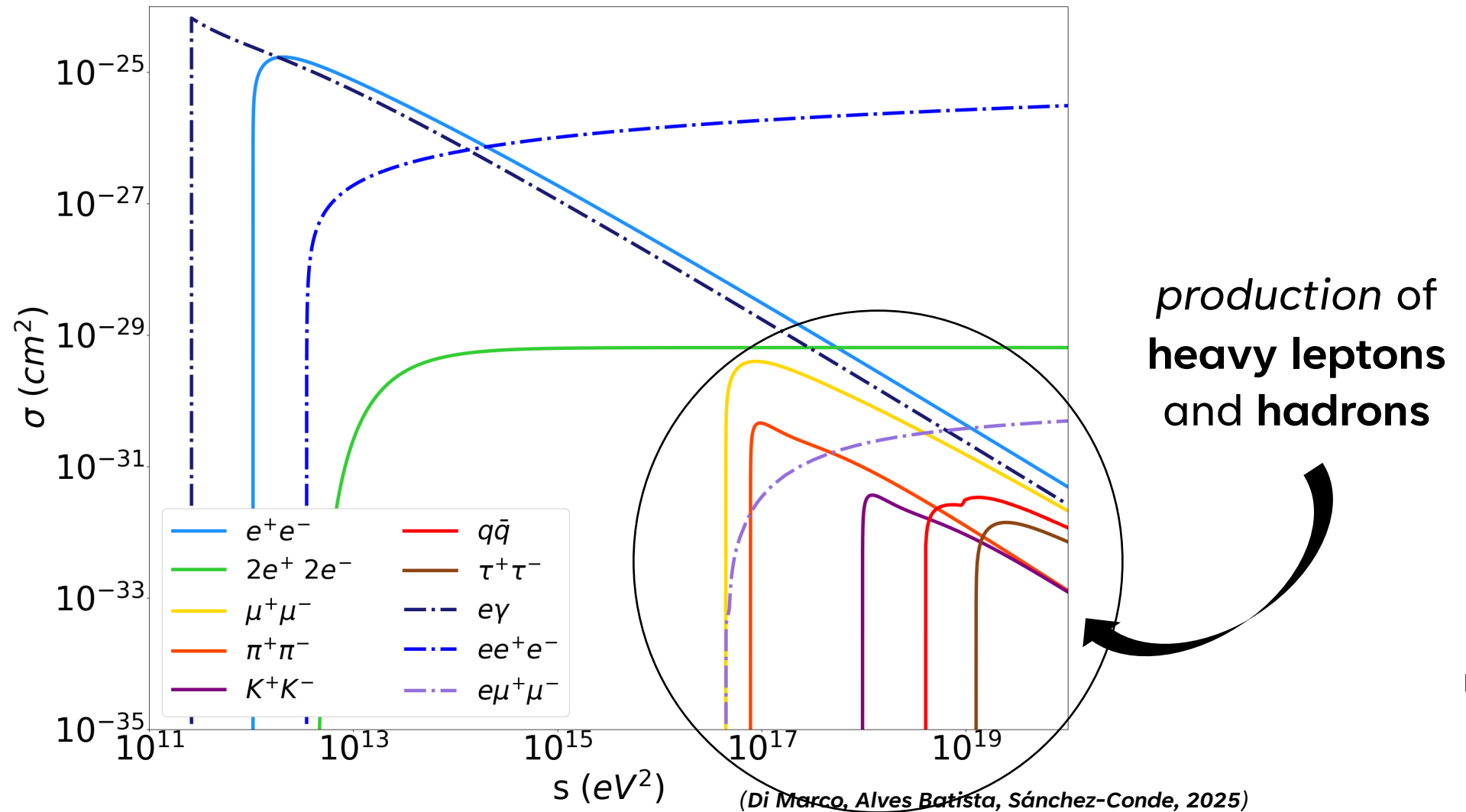
electromagnetic cascades – cross sections

4



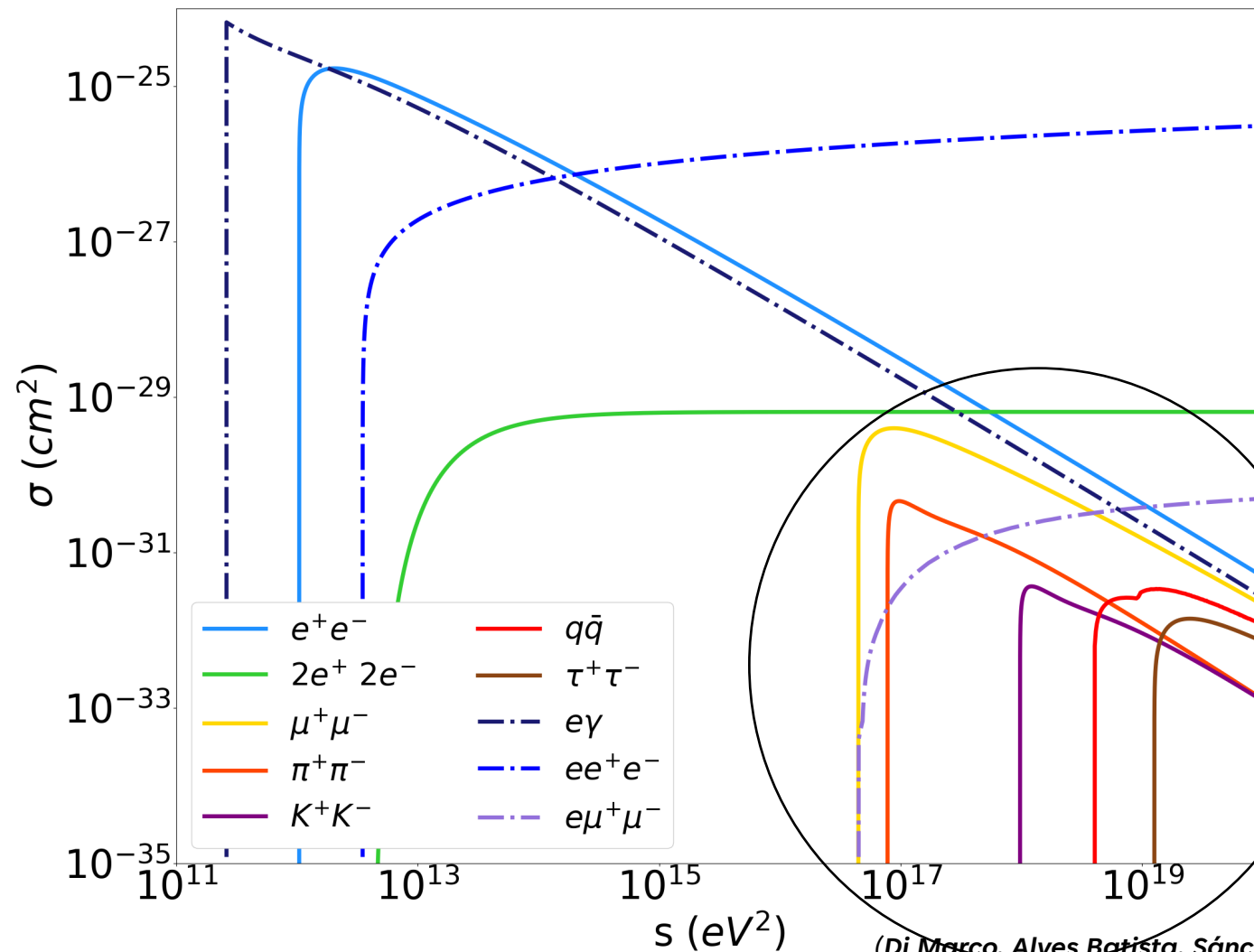
electromagnetic cascades – cross sections

5



electromagnetic cascades – cross sections

6



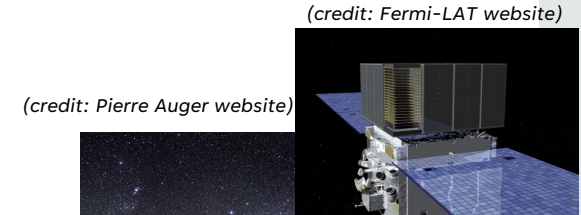
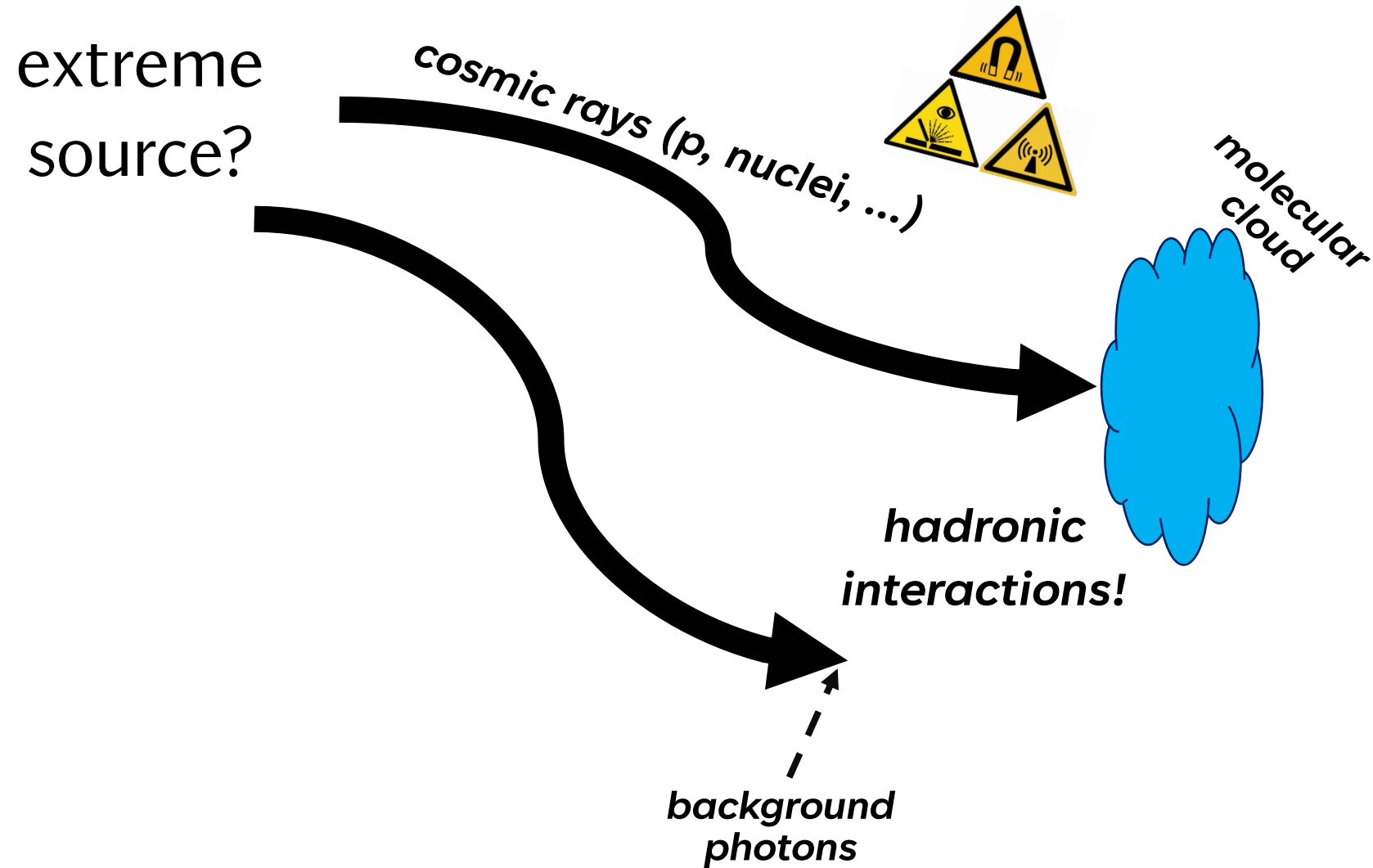
neutrinos!

*production of
heavy leptons
and hadrons*

(Di Marco, Alves Batista, Sánchez-Conde, 2025)

neutrino & γ -ray fluxes – in propagation (usually)

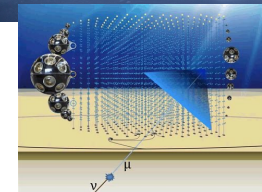
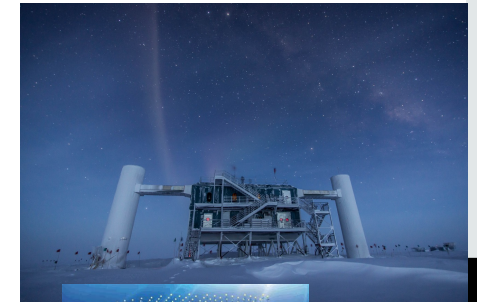
7



(credit: Pierre Auger website)



(credit: IceCube website)

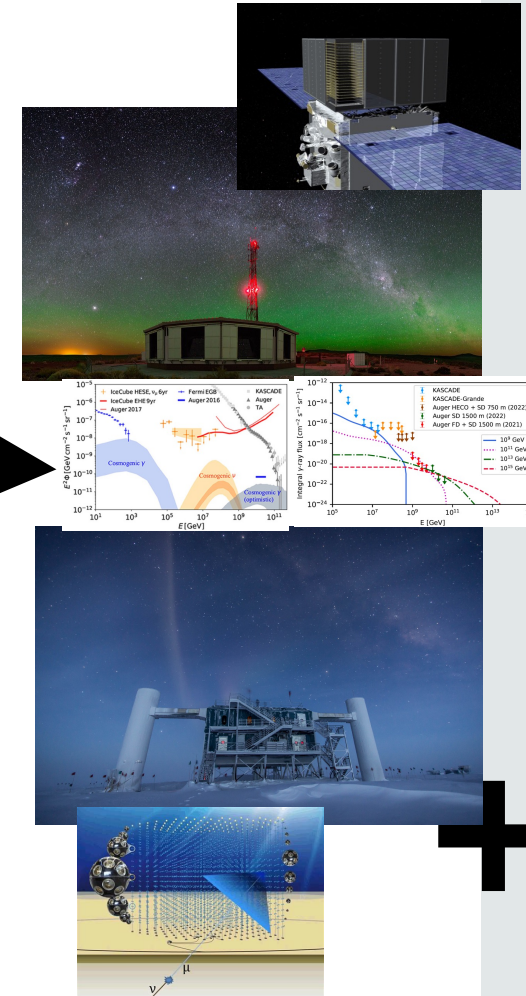
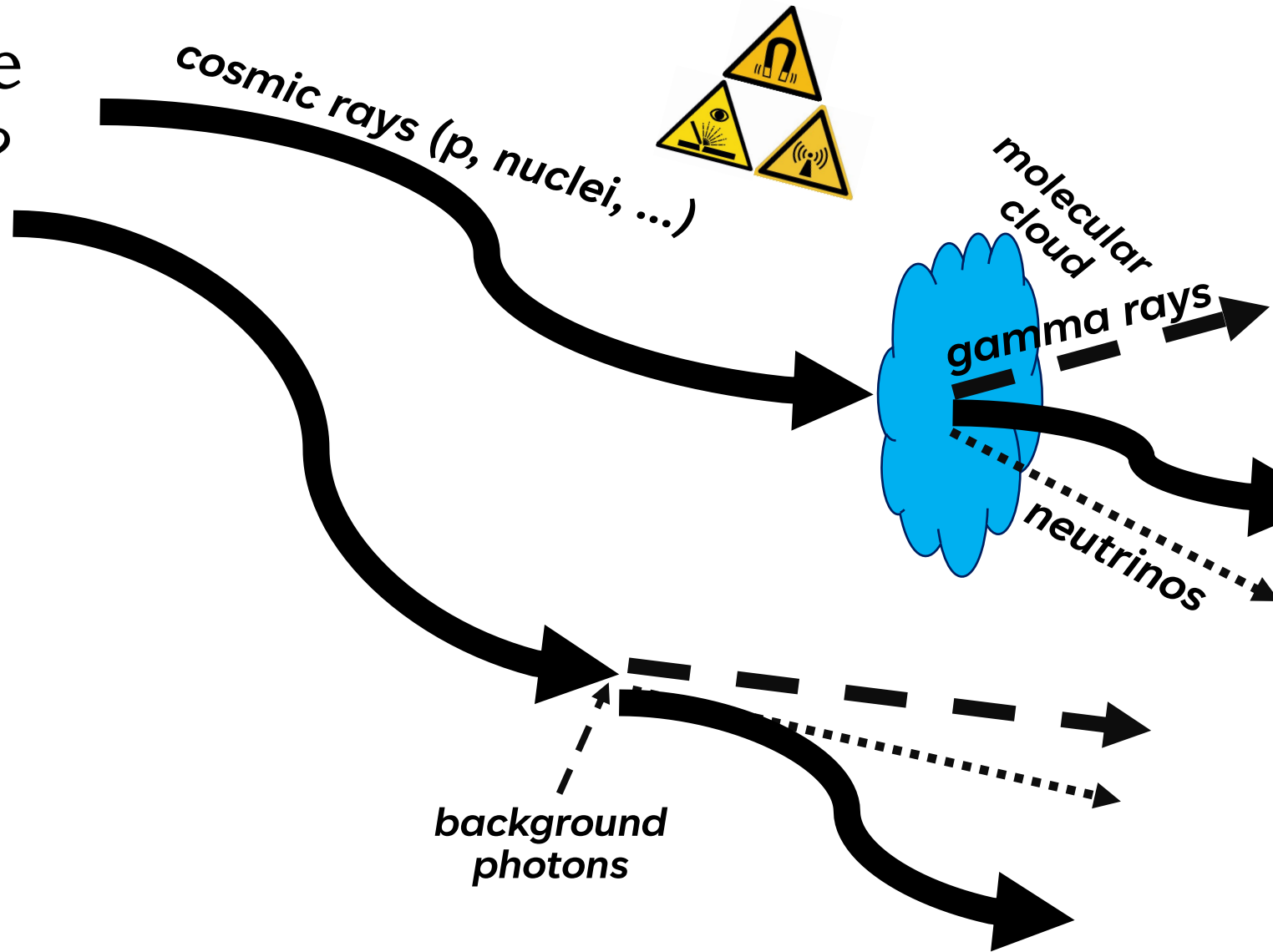


(credit: KM3Net website)

neutrino & γ -ray fluxes – in propagation (usually)

8

extreme
source?



neutrino & γ -ray fluxes – in propagation (usually)

9

extreme
source?

cosmic rays (p, nuclei, ...)

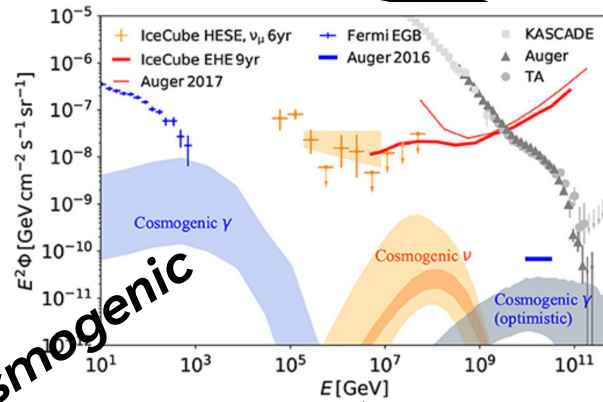


molecular
cloud

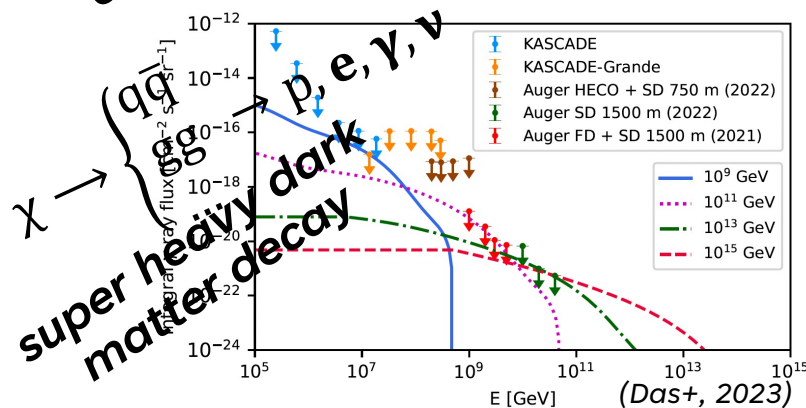
gamma rays

neutrinos

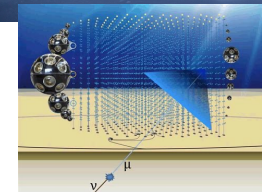
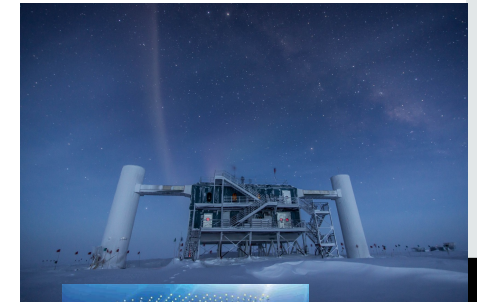
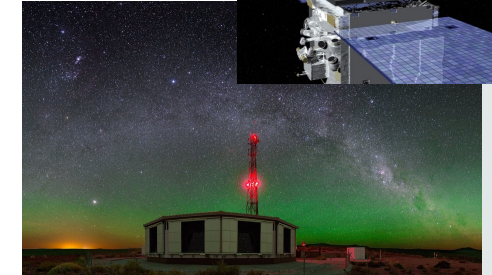
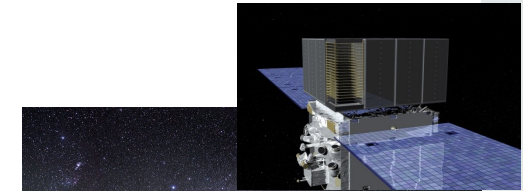
background
photons



(Alves Batista+, 2019)



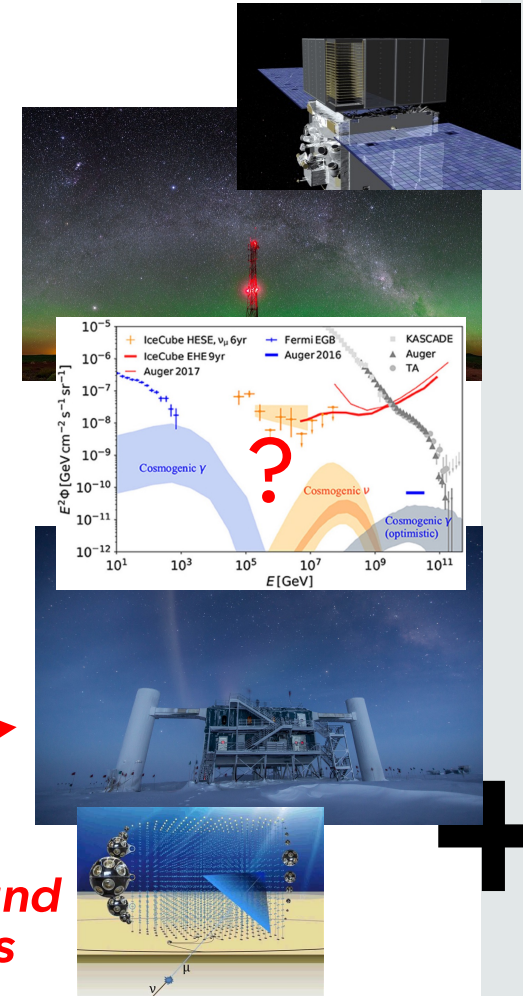
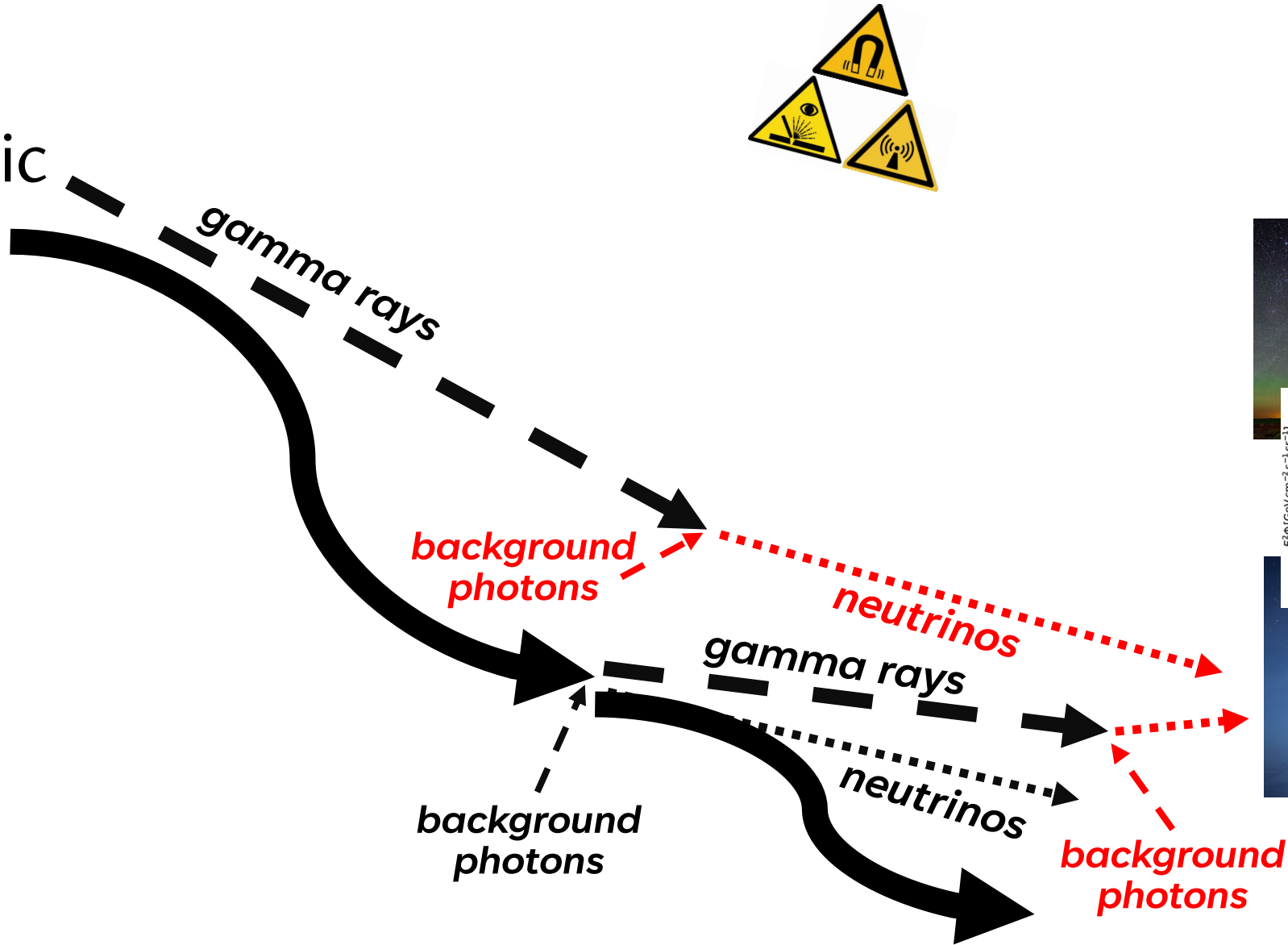
(Das+, 2023)



neutrino & γ -ray fluxes – in propagation?

10

extreme
and/or exotic
source?



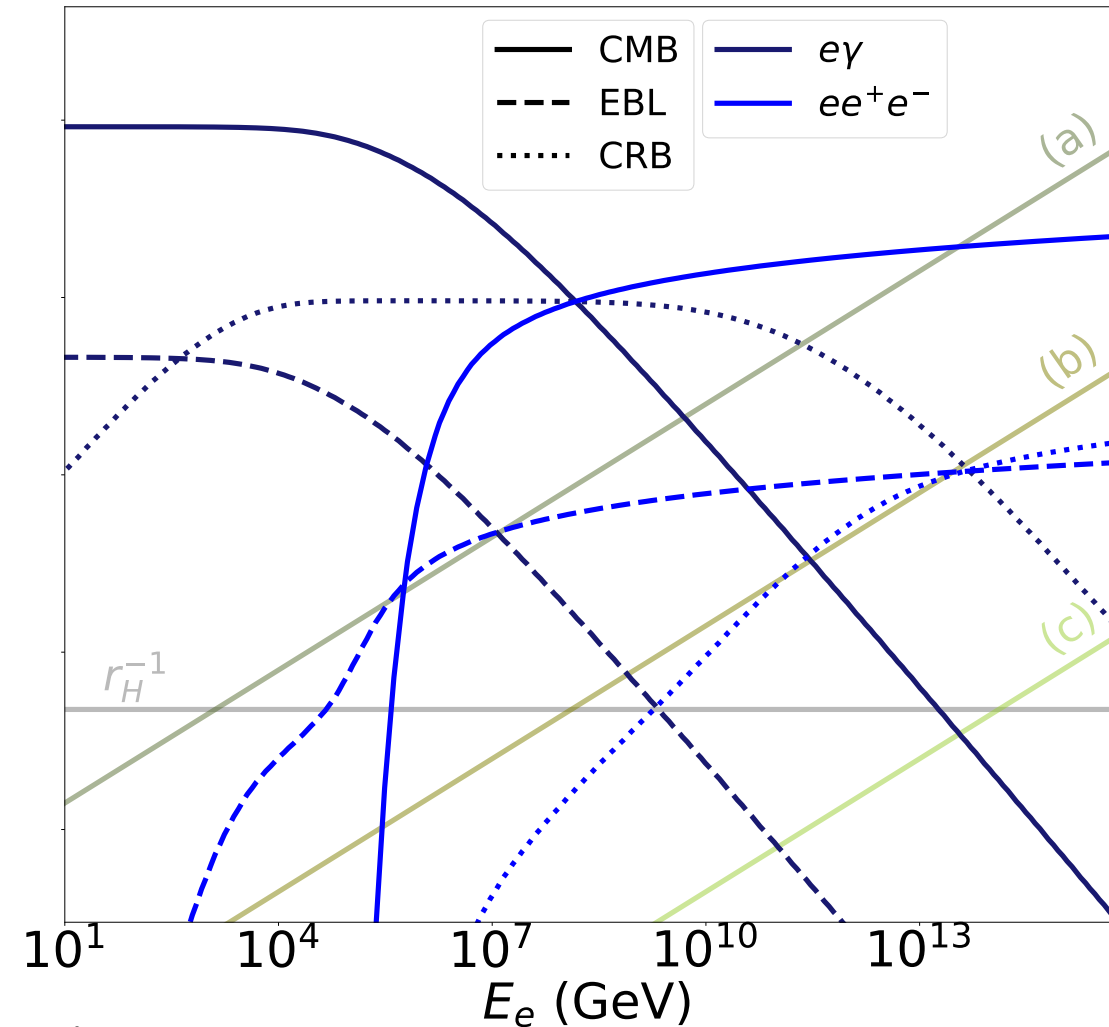
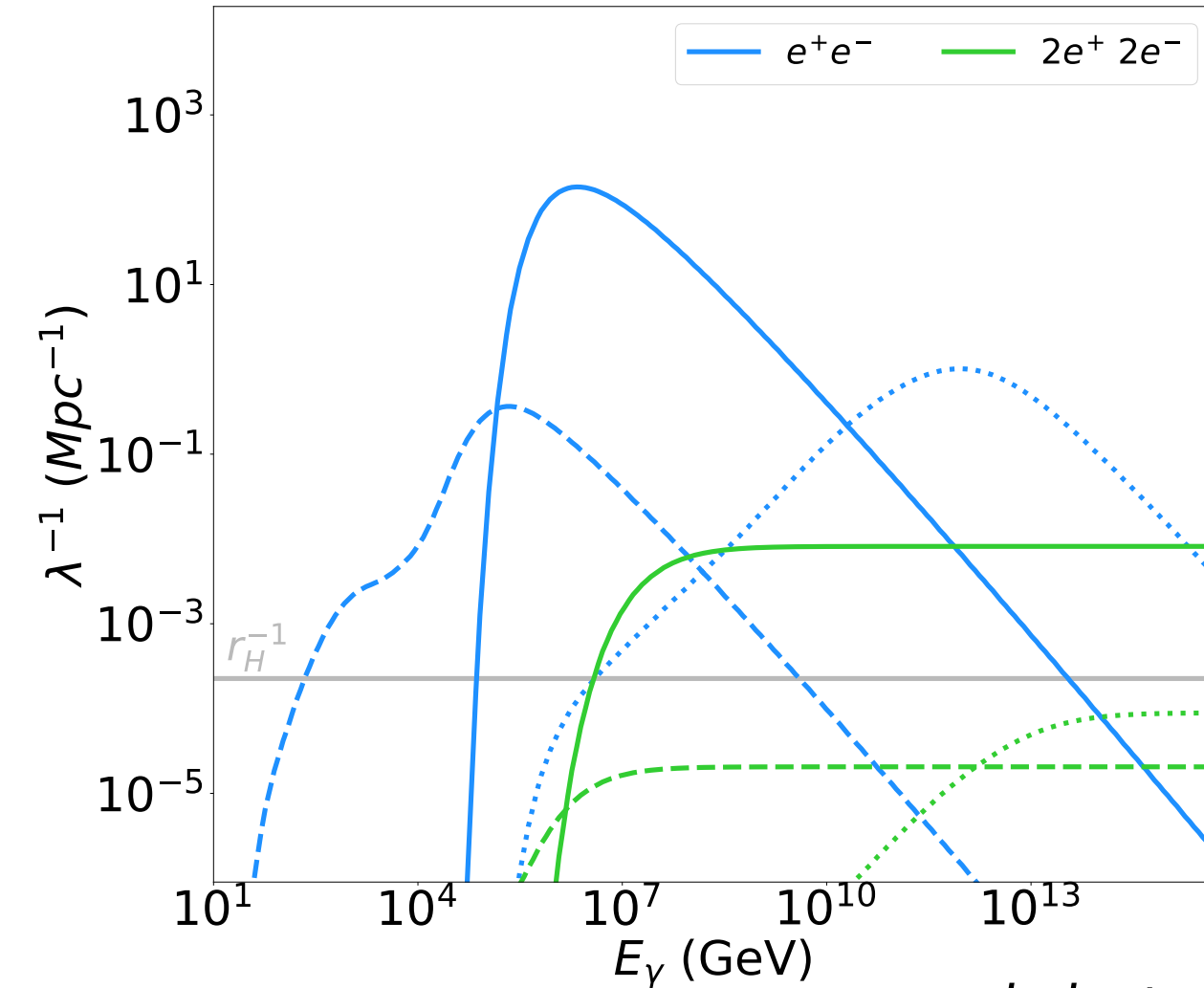
electromagnetic cascades – cosmological rates

11

cosmic radio background (CRB)

cosmic microwave background (CMB)

extragalactic background light (EBL)

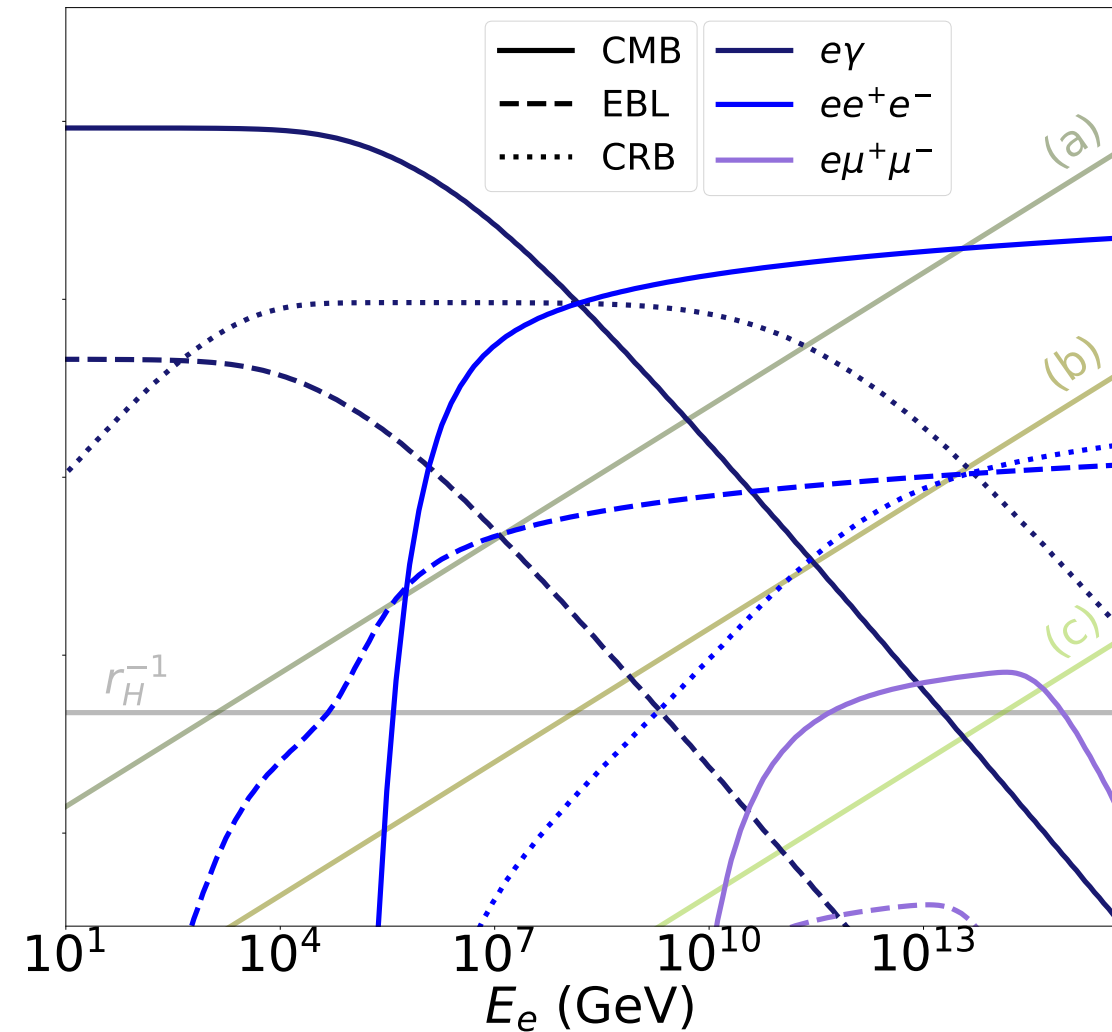
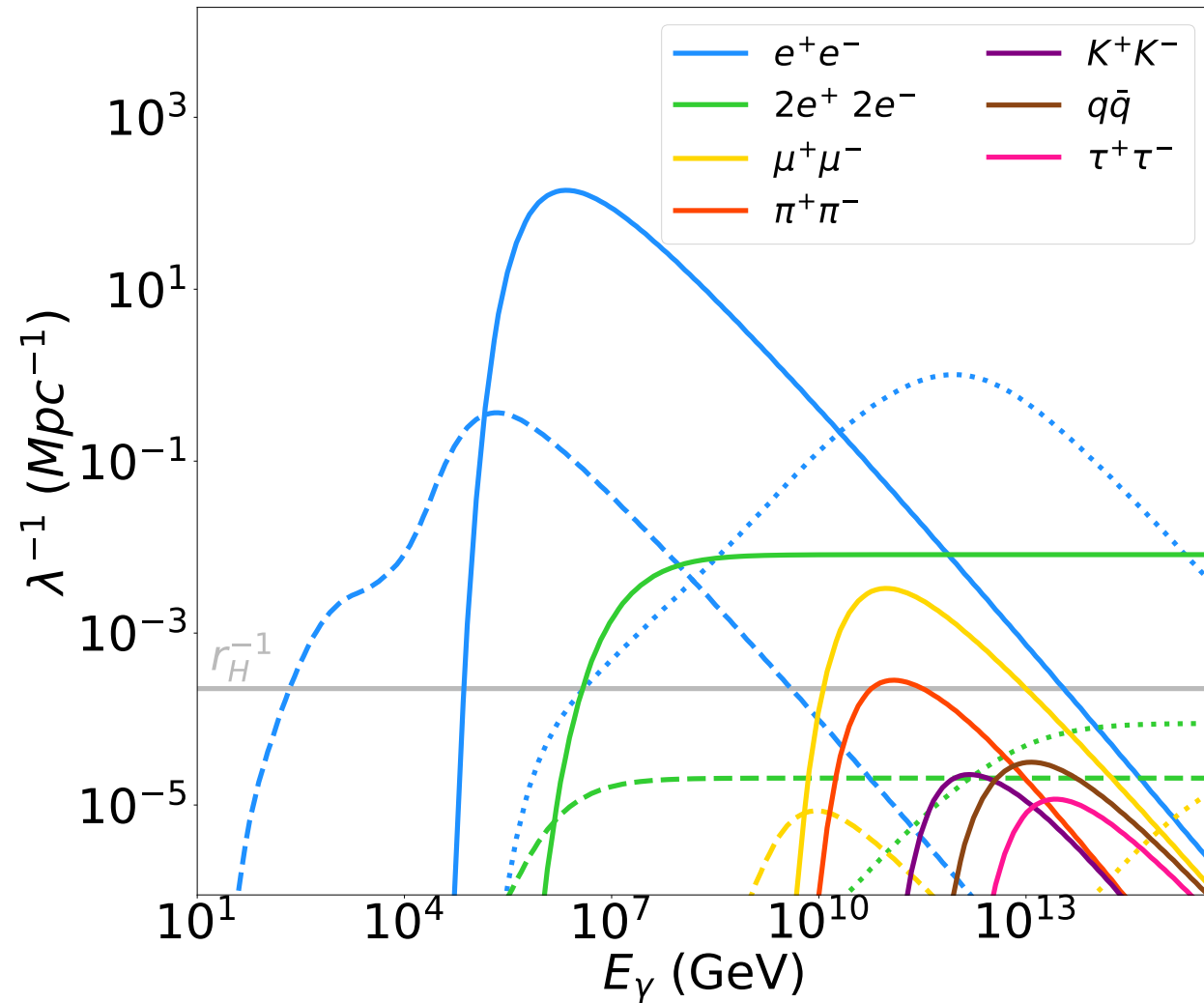


usual electromagnetic processes...

electromagnetic cascades – new cosmological rates

12

(Di Marco, Alves Batista, Sánchez-Conde, 2025)

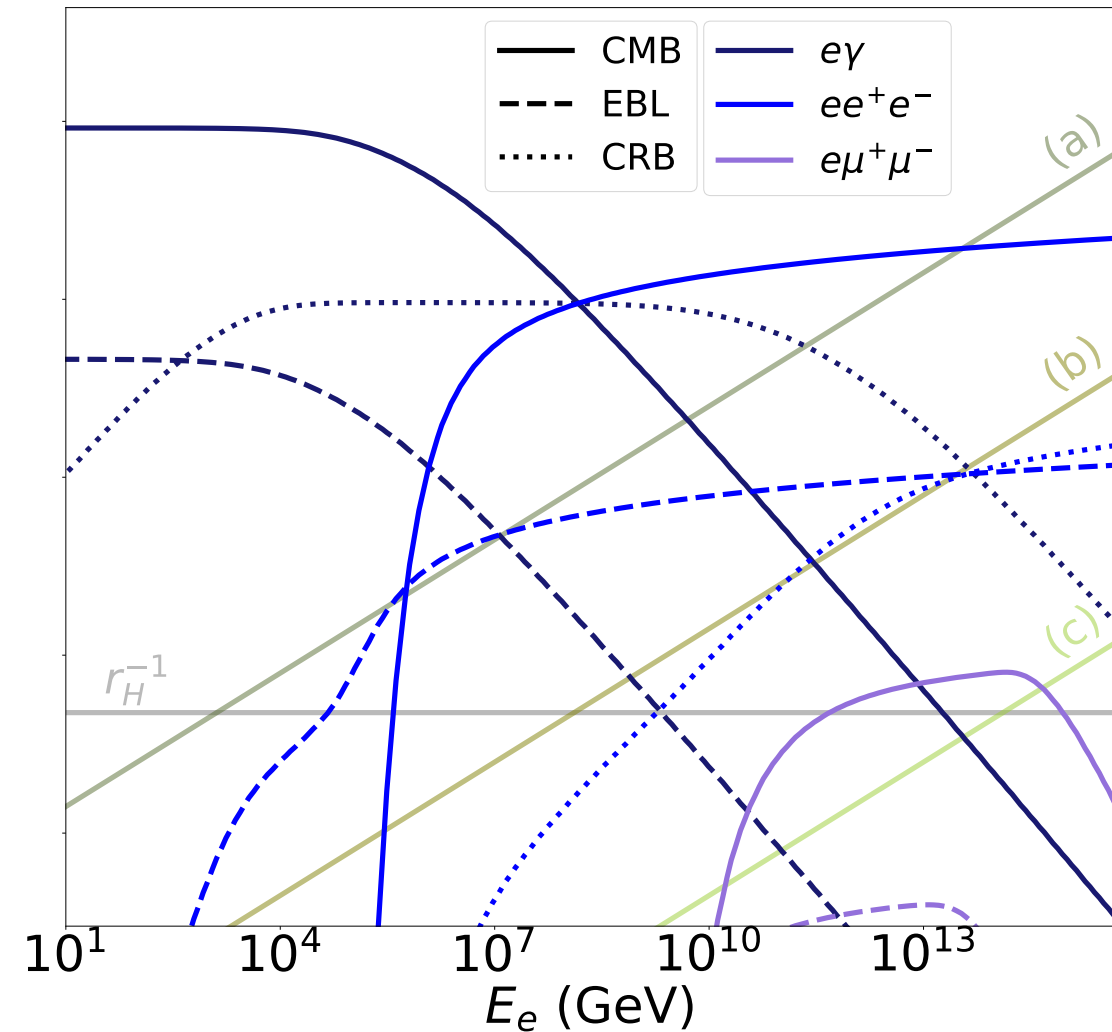
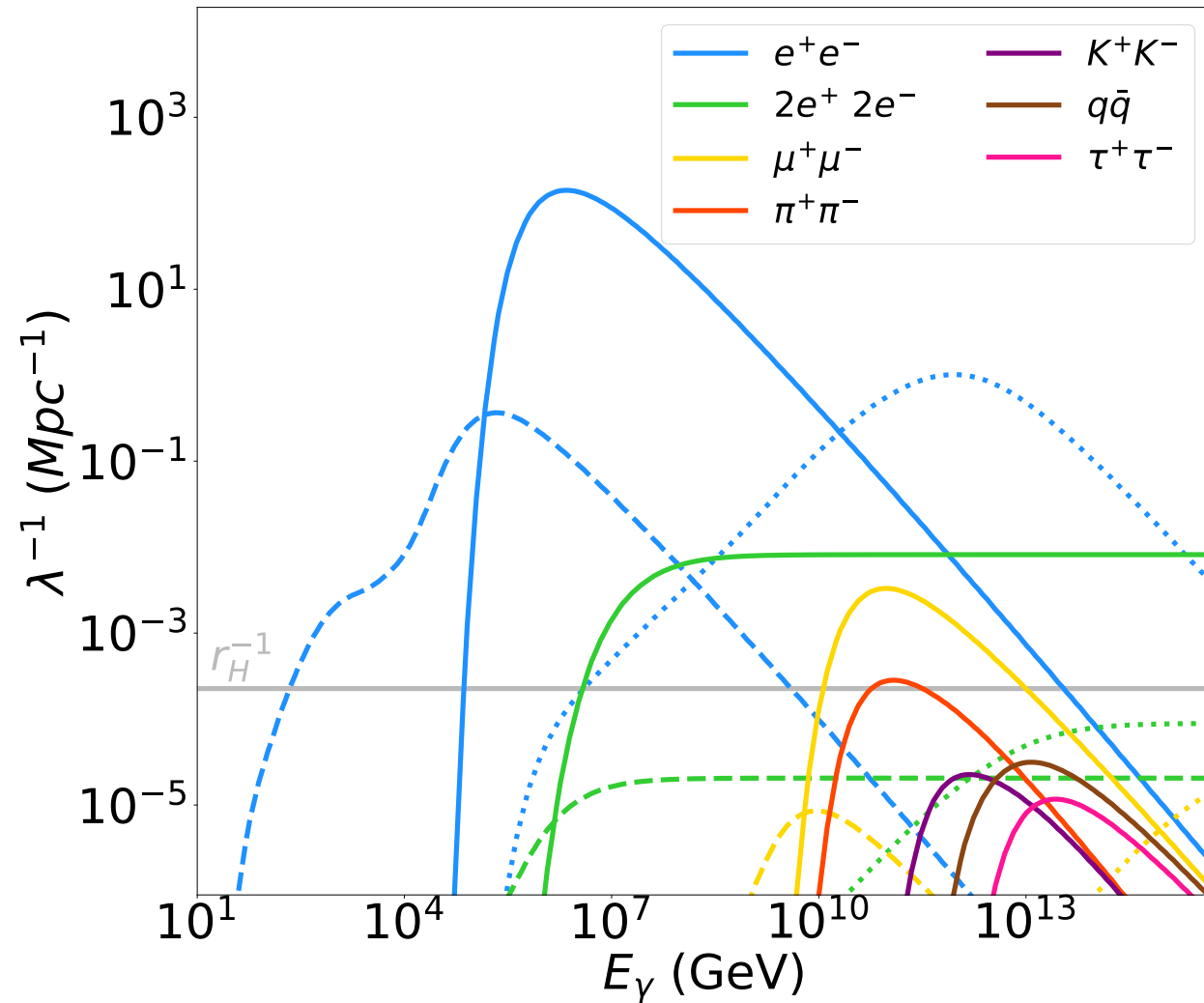


.... and high-s processes...

electromagnetic cascades – new cosmological rates

13

(Di Marco, Alves Batista, Sánchez-Conde, 2025)



for energies $> 10^{18} \text{ eV}$ muon productions on CMB!

these scenarios in CRPropa

- new decay plugin:

CRPYTHIAxDecays

(synergy between CRPropa & PYTHIA)

- new interaction plugins:

EMMuonPairProduction

EMChargedPionPairProduction

EMTauonPairProduction

EMElectronMuonPairProduction

MC code to simulate
astroparticle propagation!

CRPropa

(Alves Batista+, 2022)

MC event generator
for **high-energy**
physics collisions!



PYTHIA

(Bierlich+, 2022)



simulations – gamma-ray propagation

15

sources characterised by $E_{\text{mono},\gamma} > 10^{18} \text{ eV}$ and $z > 0.1$

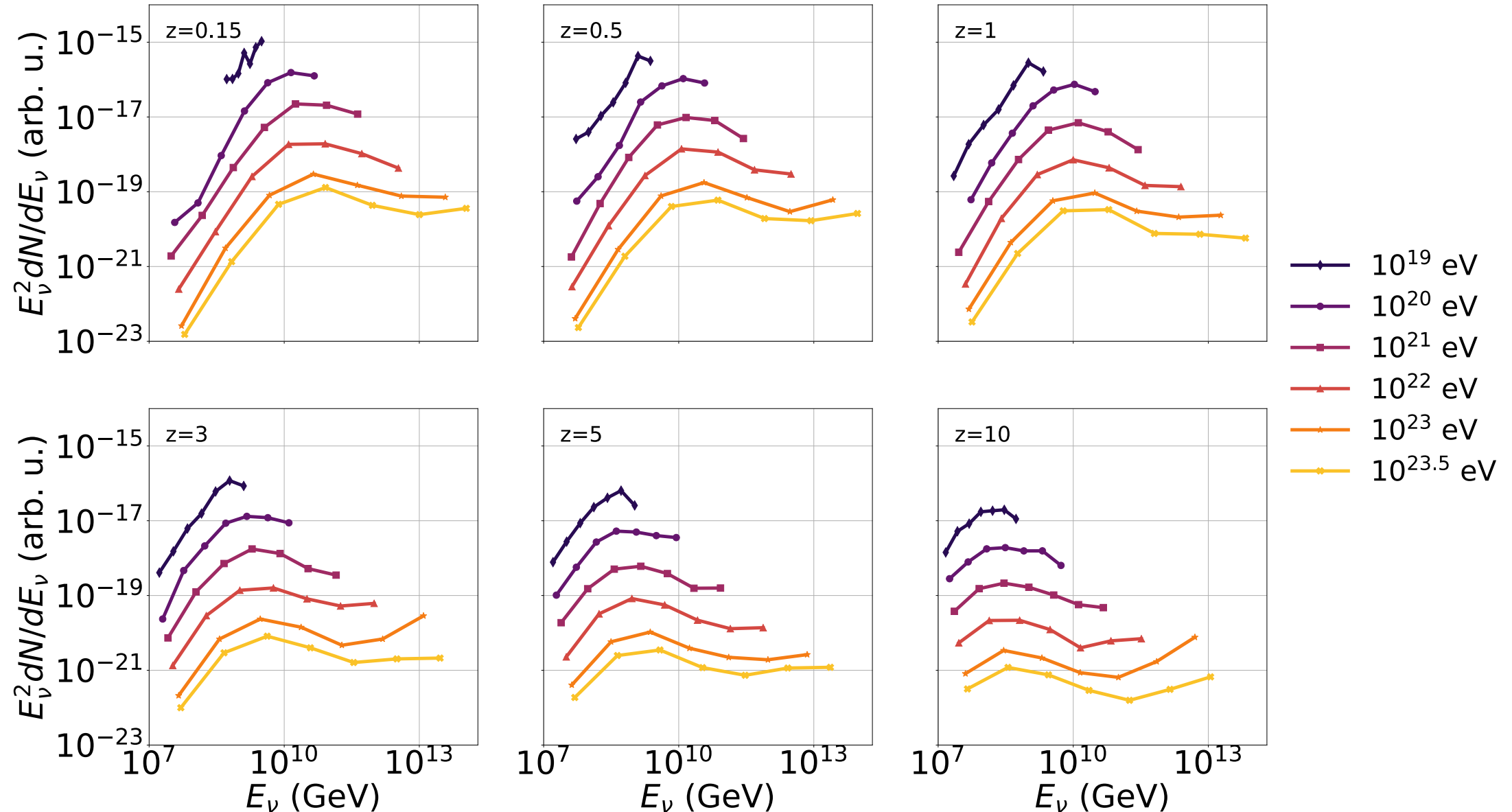


observables about the emerging
neutrinos with $E_\nu > 10 \text{ PeV}$



mono sources – emerging ν energy spectra

16

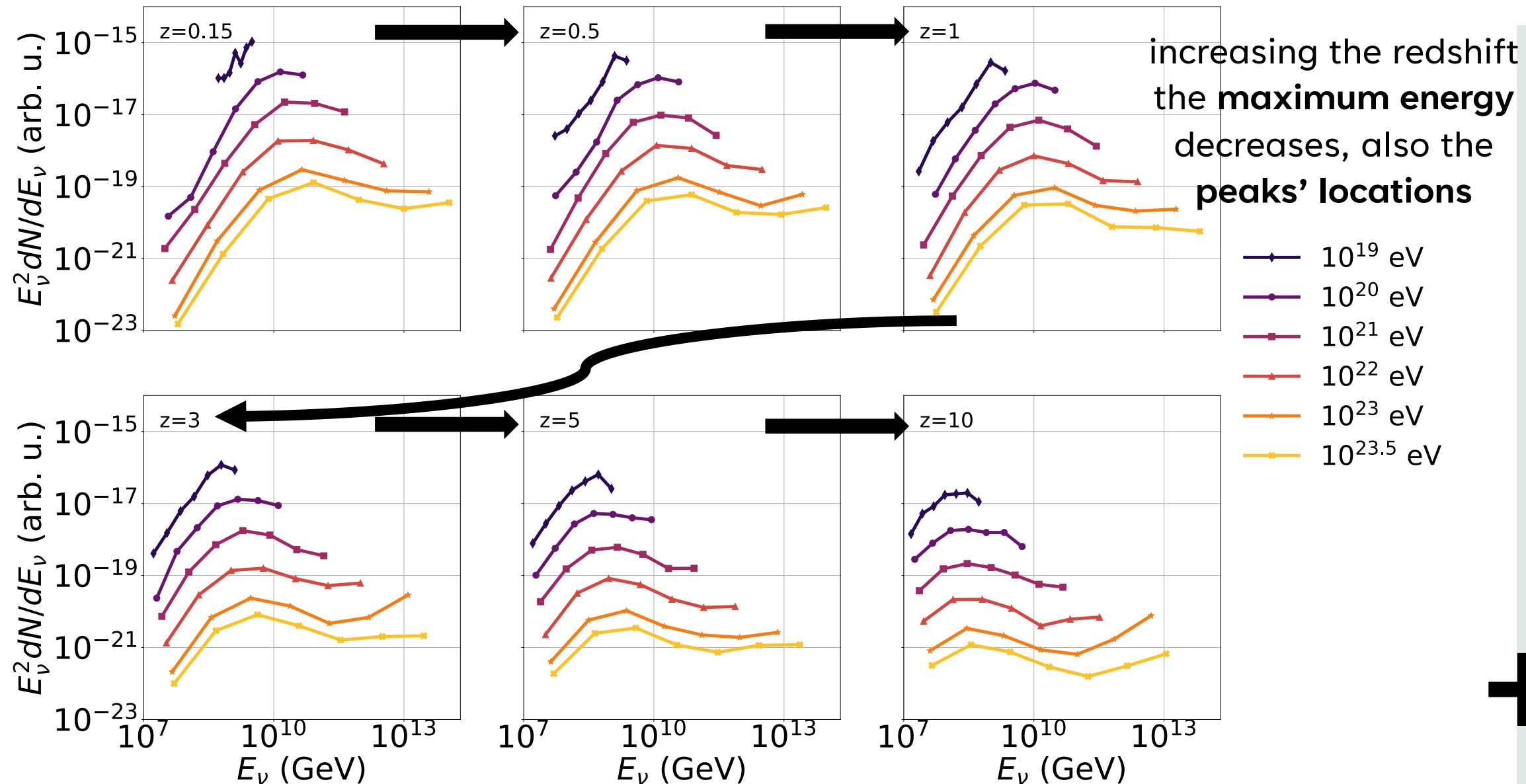


(Di Marco, Alves Batista, Sánchez-Conde, 2025)



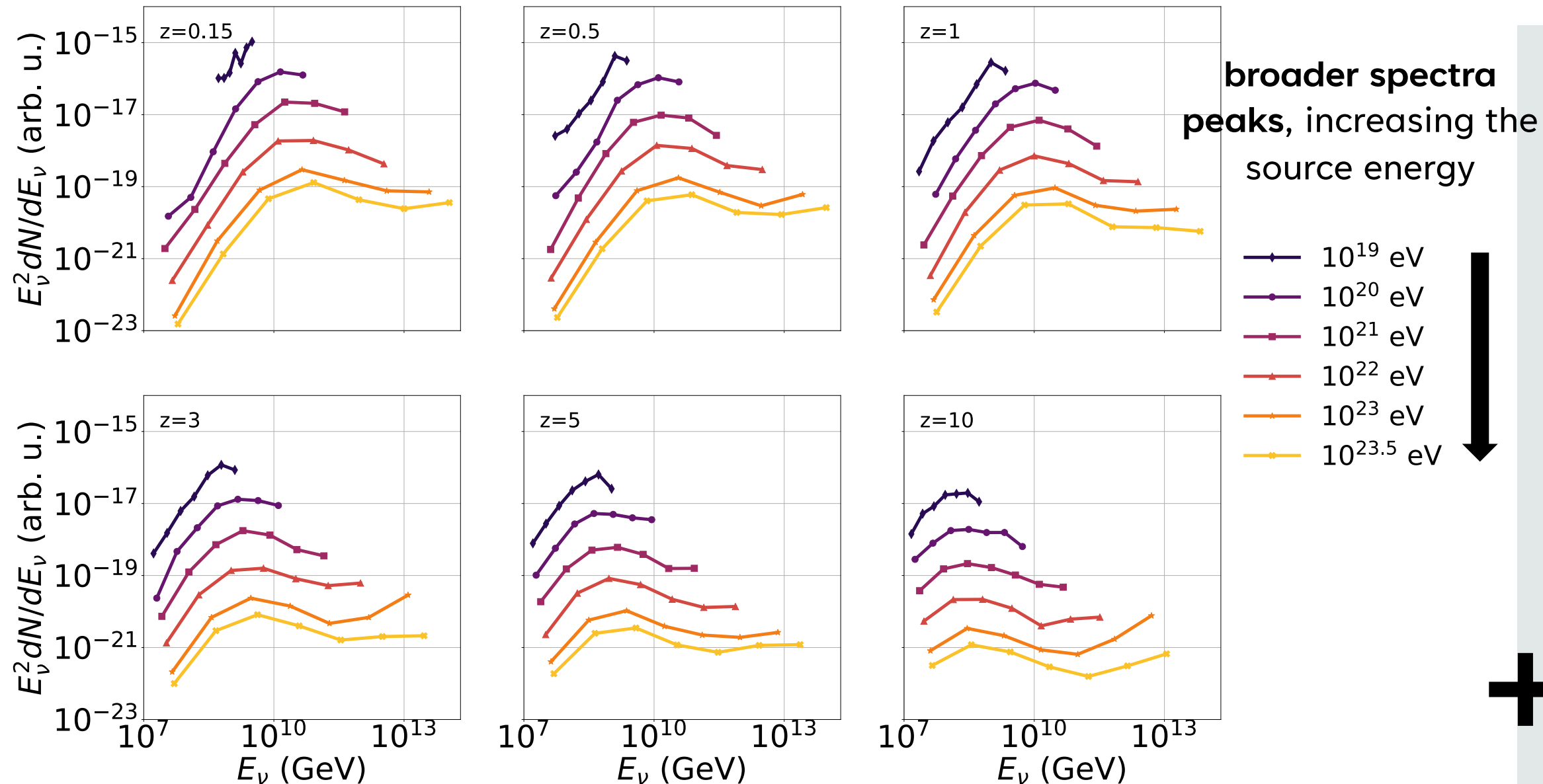
mono sources – emerging ν energy spectra

17



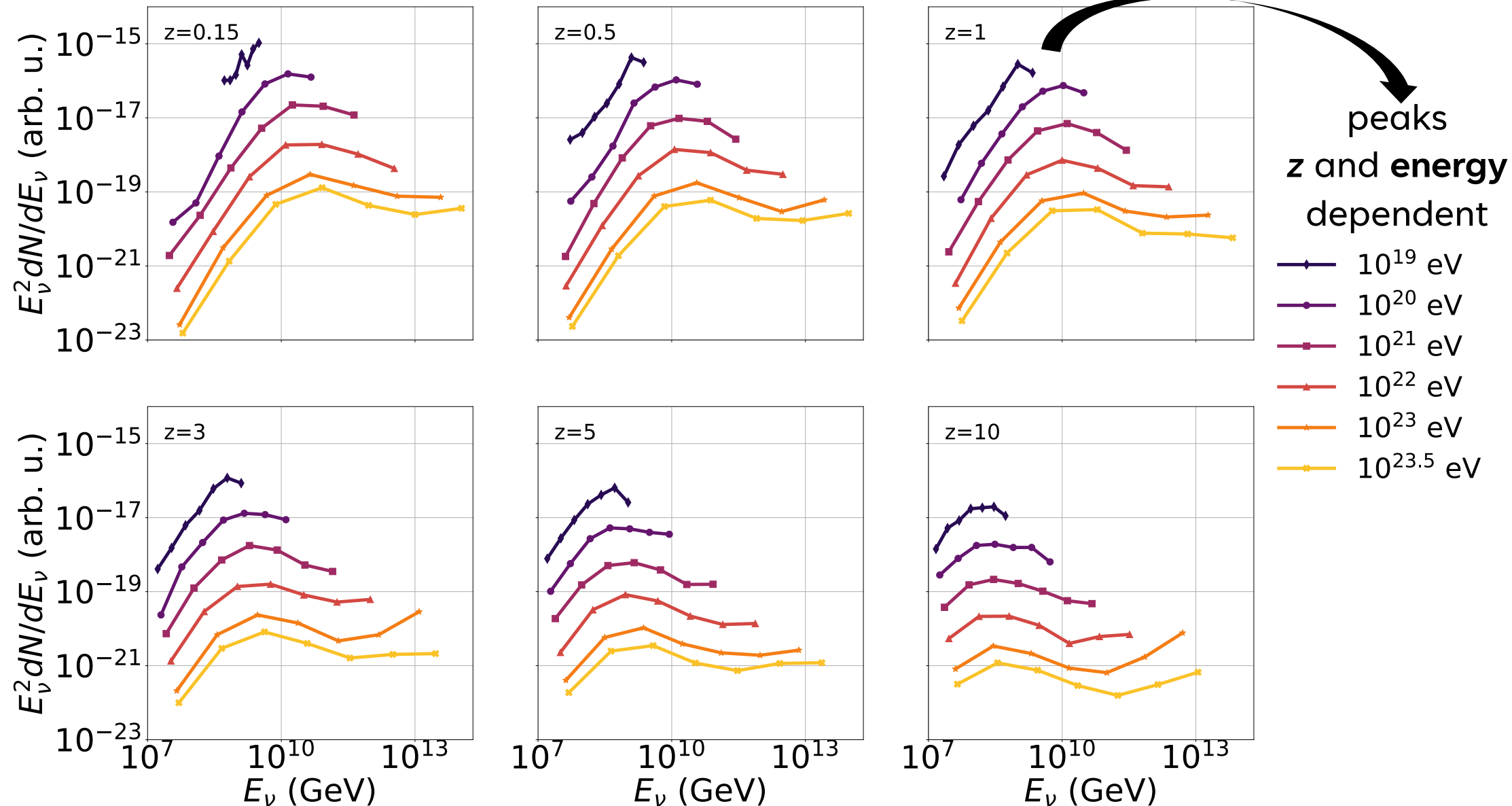
mono sources – emerging ν energy spectra

18



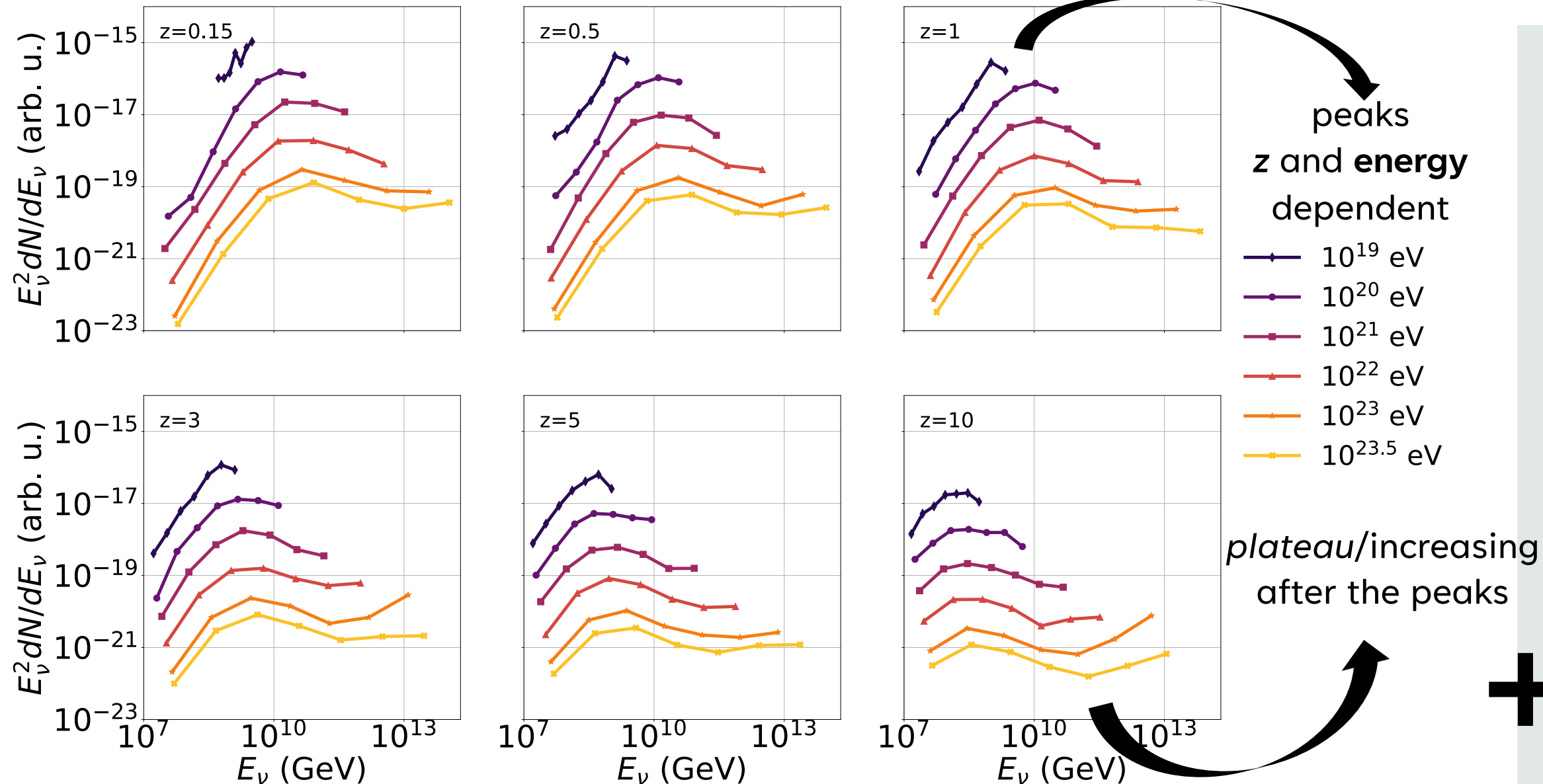
mono sources – emerging ν energy spectra

19



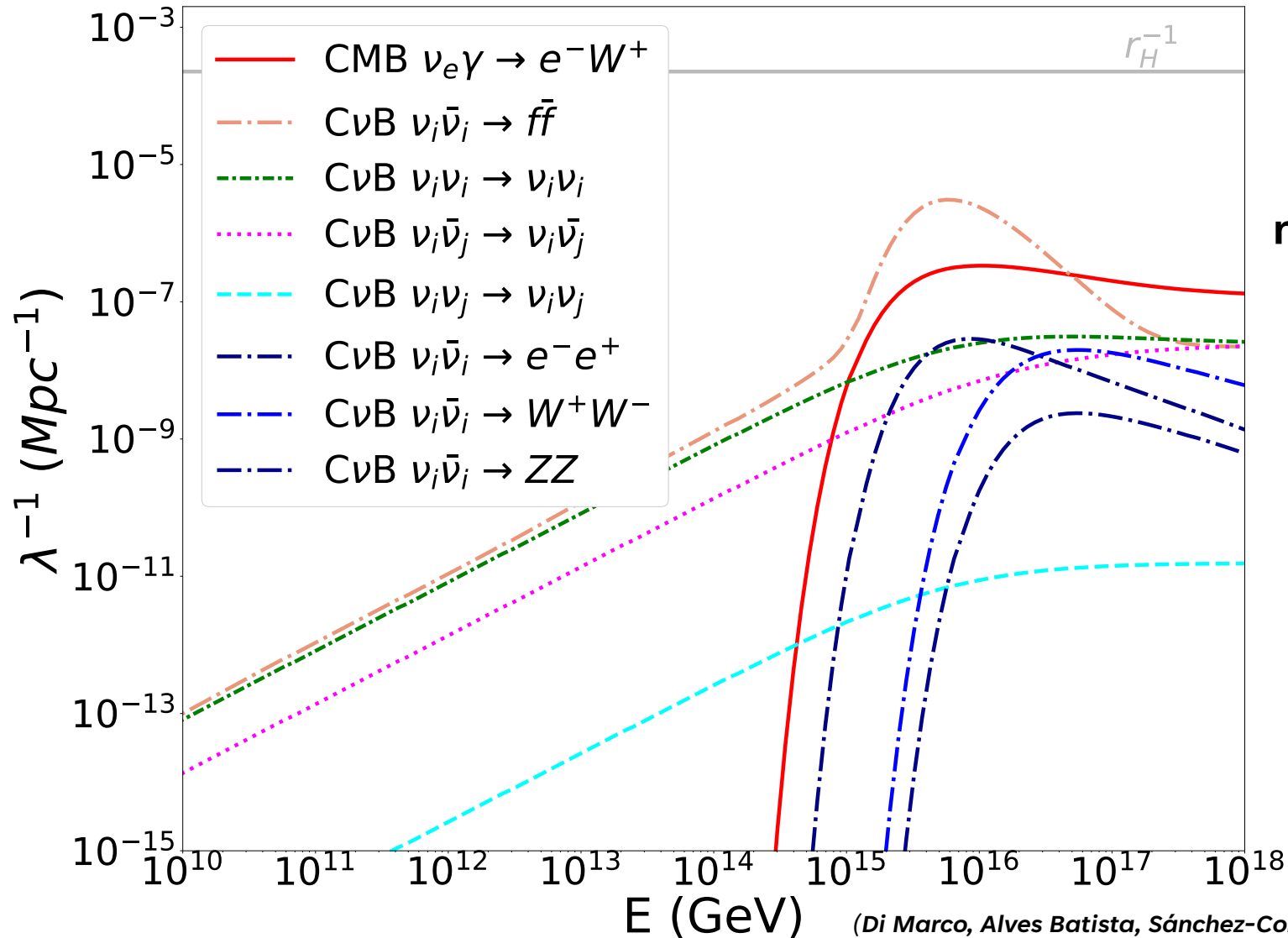
mono sources – emerging ν energy spectra

20



μ s: emerging ν energy spectra - propagation

21

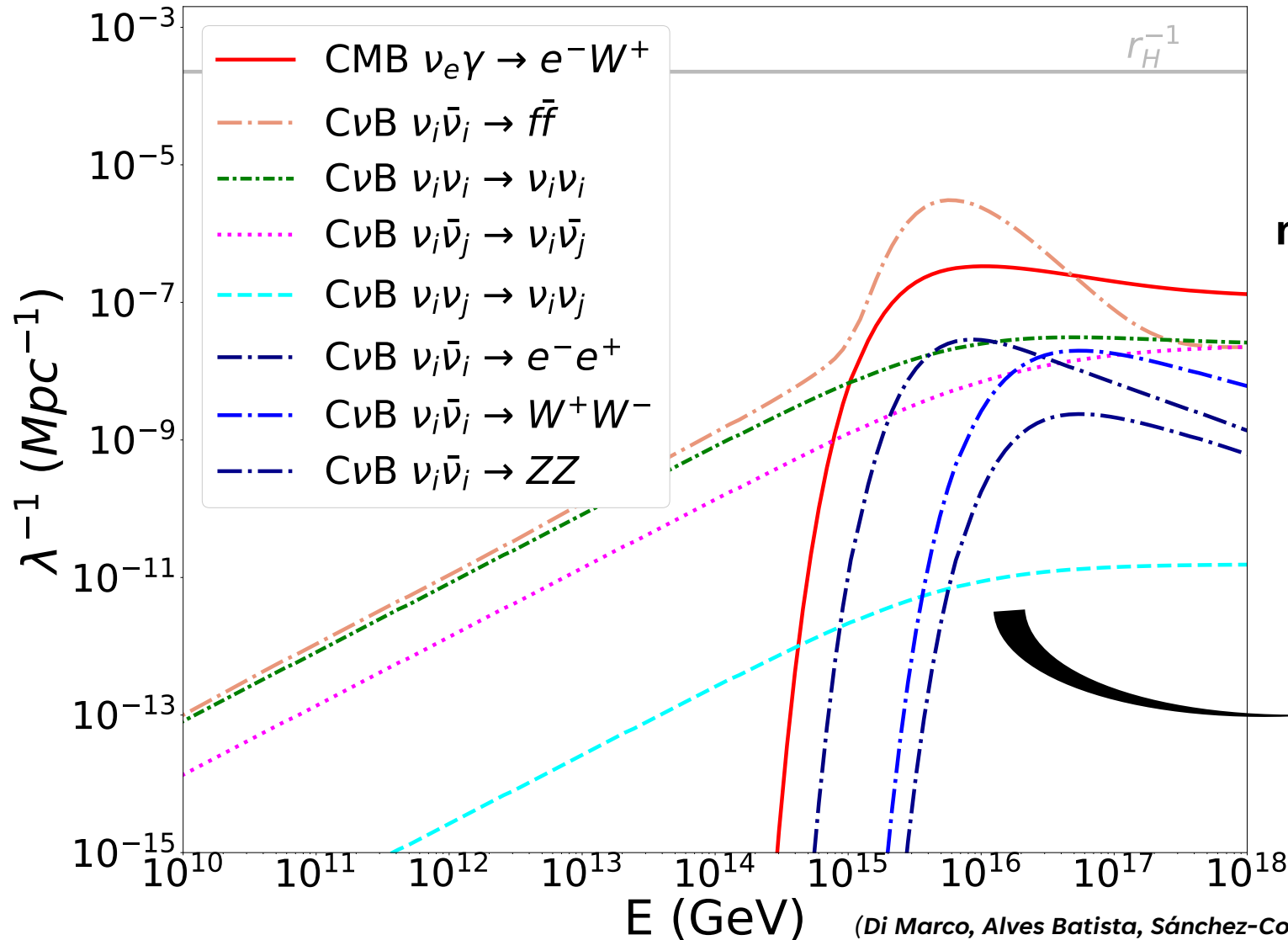


NOT included in this work,
however:
**potential interactions with
neutrino/photons backgrounds**



μ s: emerging ν energy spectra - propagation

22



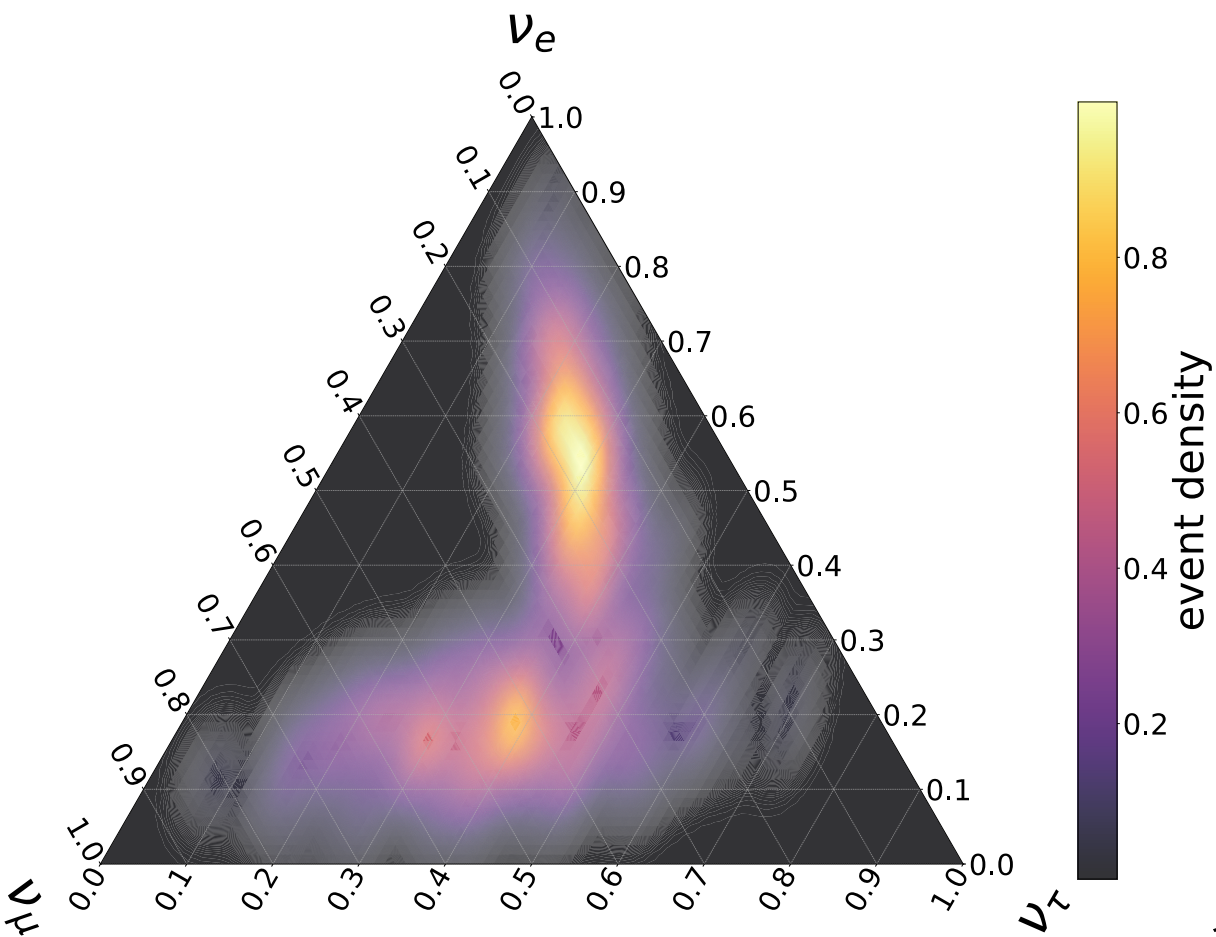
NOT included in this work,
however:
**potential interactions with
neutrino/photons backgrounds**

rates for massless
neutrinos, at $z=0$!

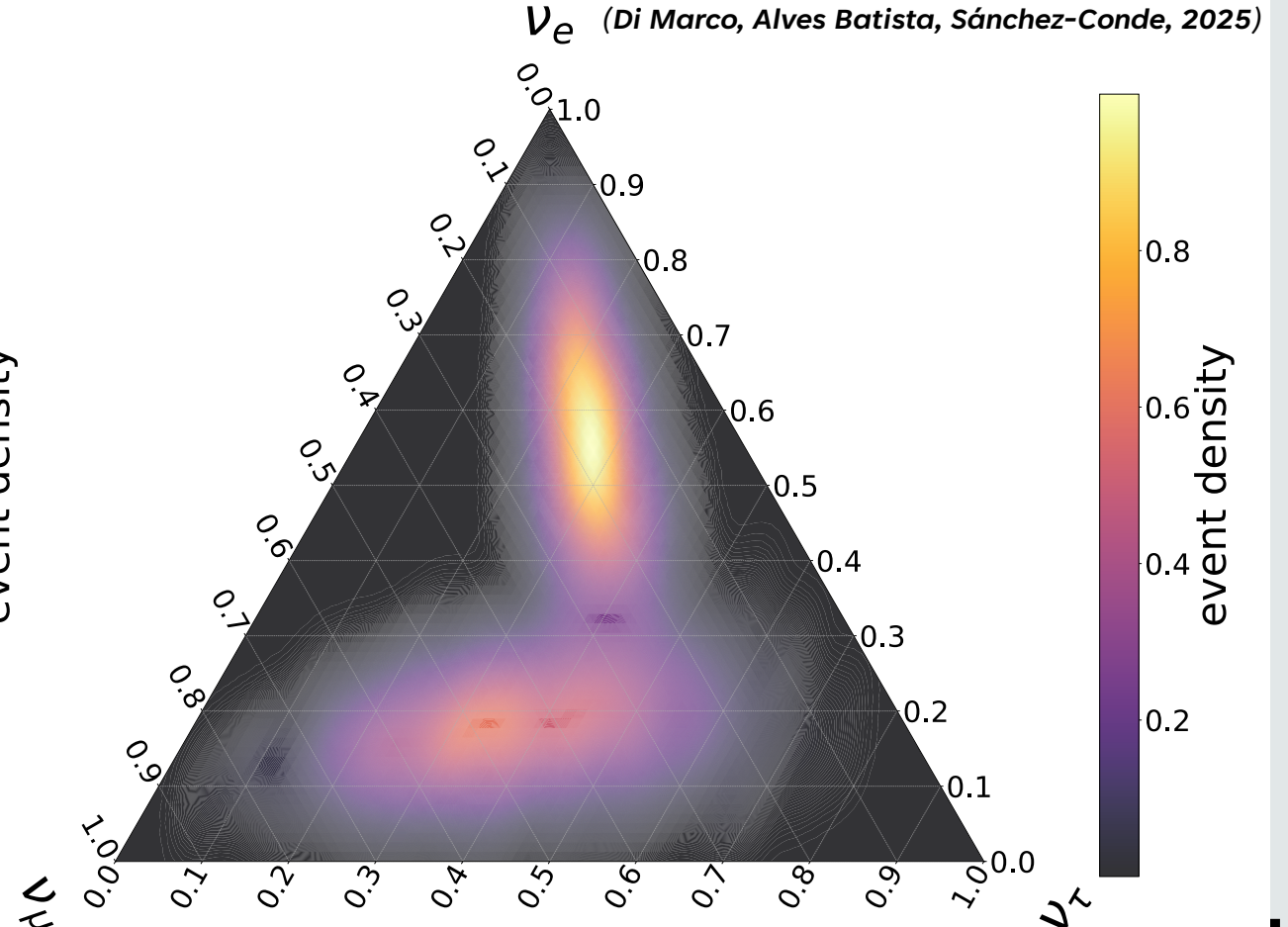


mono sources – flavour probabilities

23



$E_\gamma = 10^{20} \text{ eV}, z = 0.15$



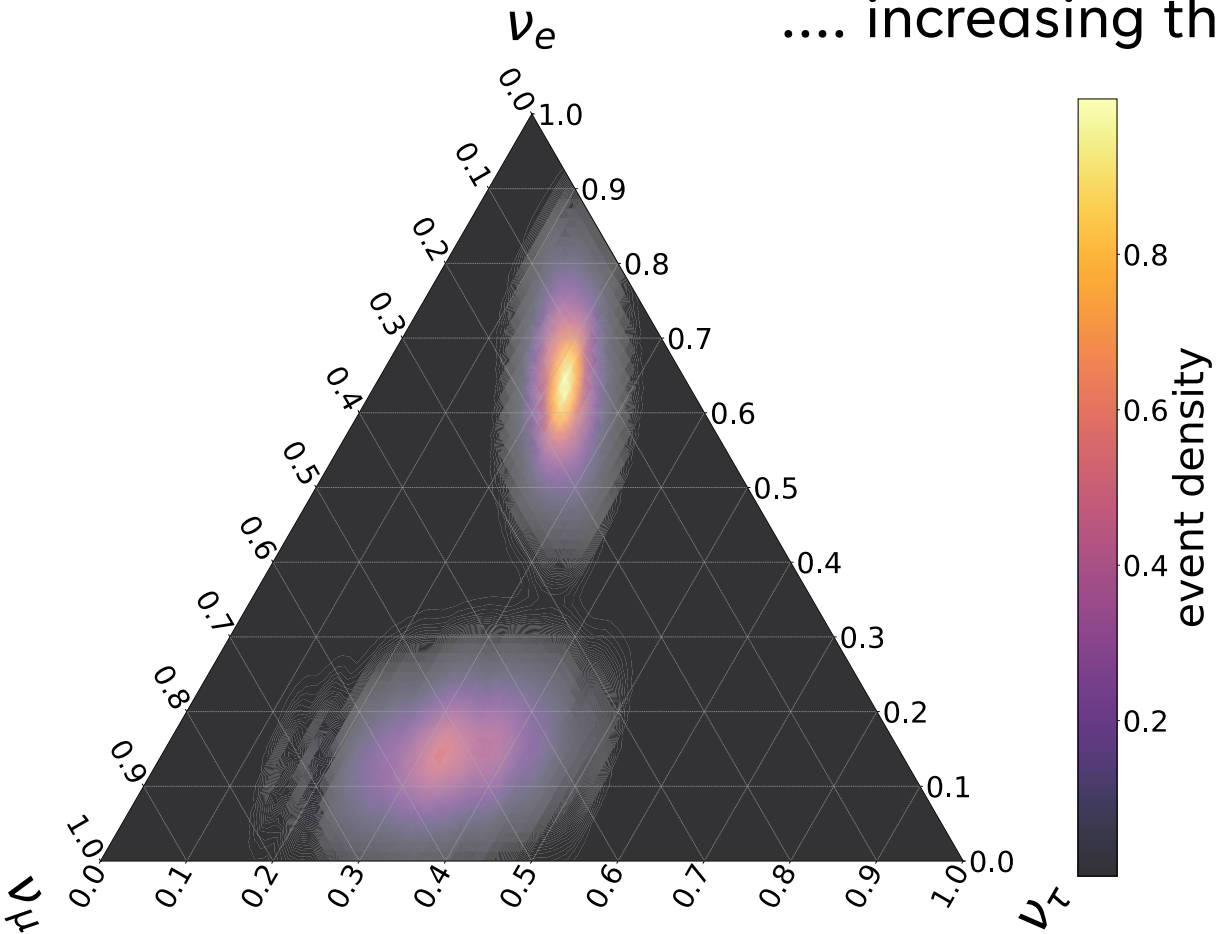
$E_\gamma = 10^{22} \text{ eV}, z = 0.15$

[Neurthino](#) code with the last NuFit-6.0 parameters, «propagating probabilities»

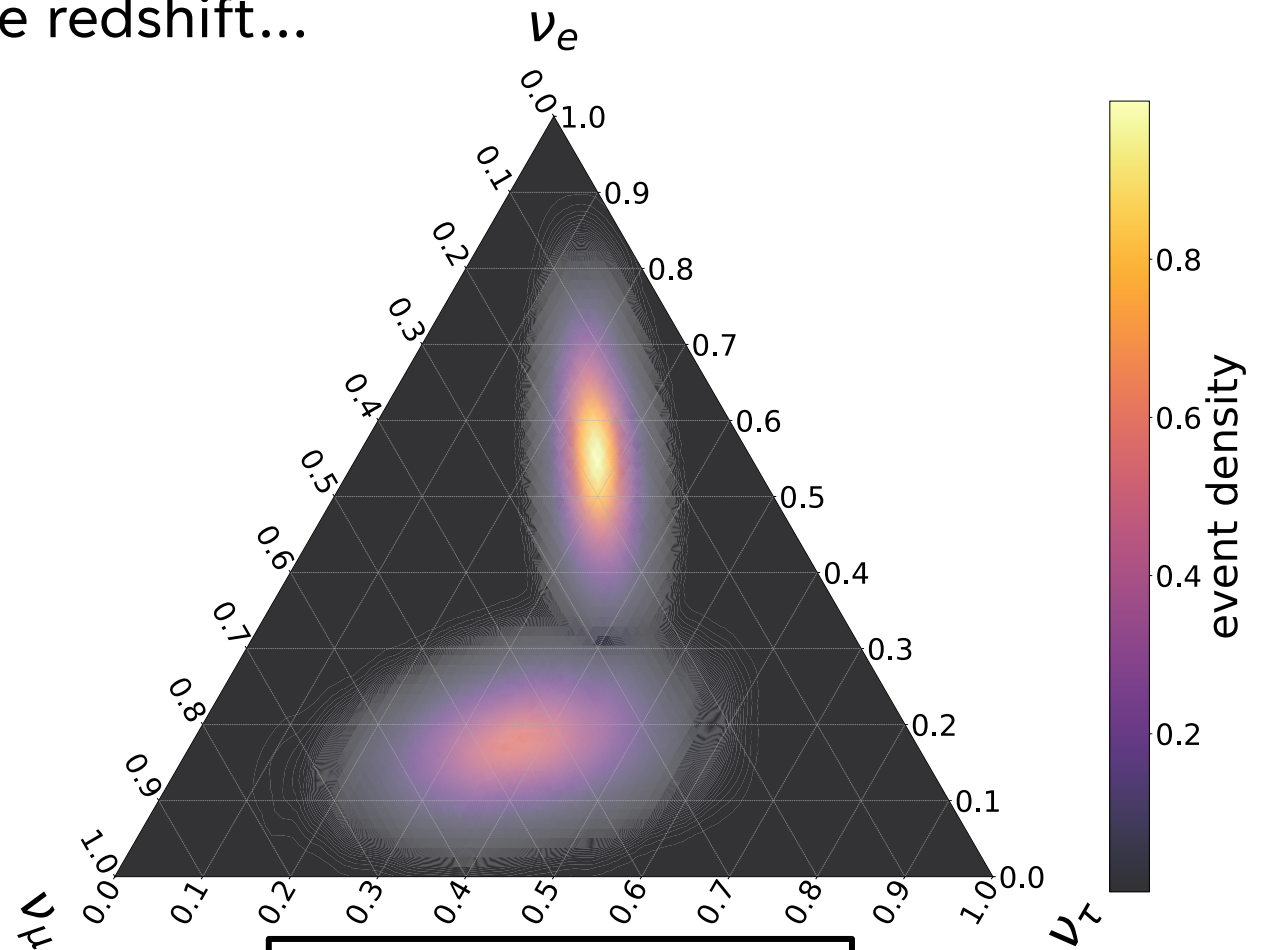
mono sources – flavour probabilities

24

.... increasing the redshift...



$$E_\gamma = 10^{20} \text{ eV}, z = 10$$



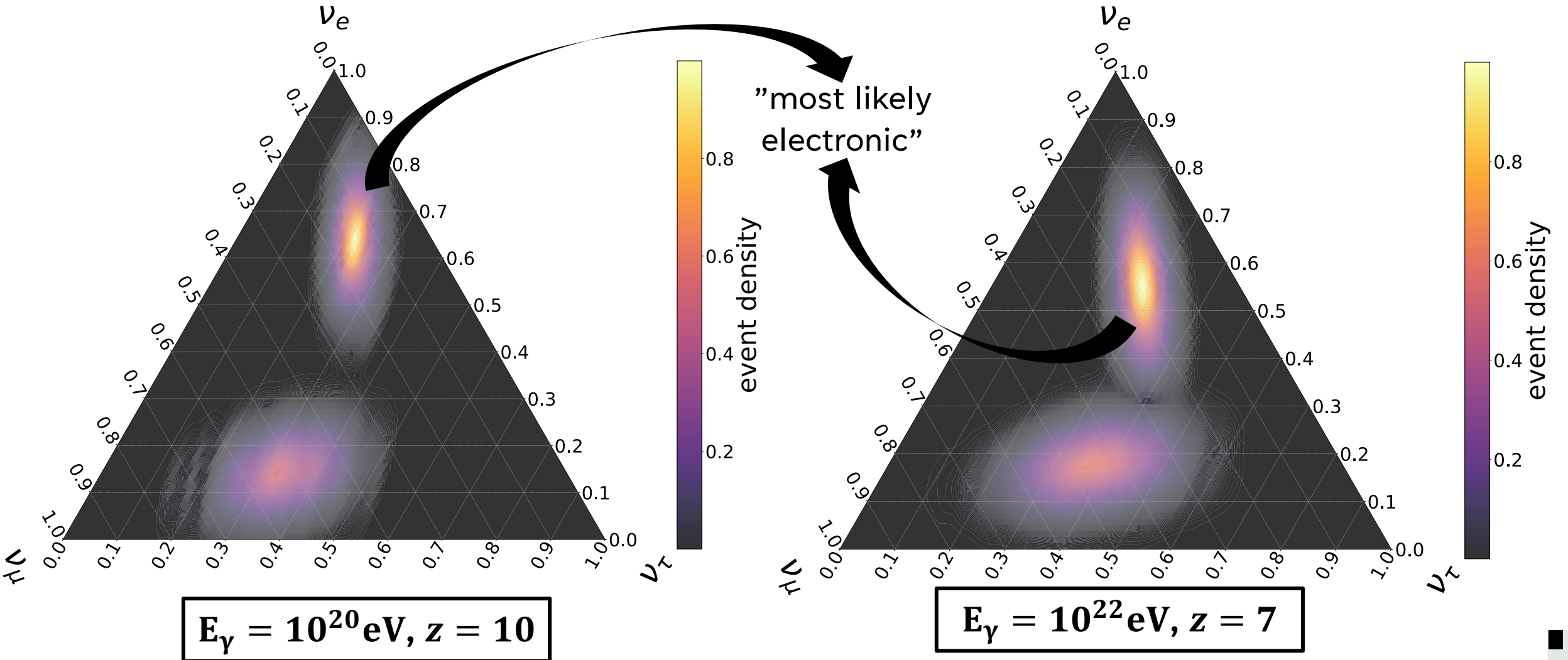
$$E_\gamma = 10^{22} \text{ eV}, z = 7$$

.... more well-defined shapes!

(Di Marco, Alves Batista, Sánchez-Conde, 2025)

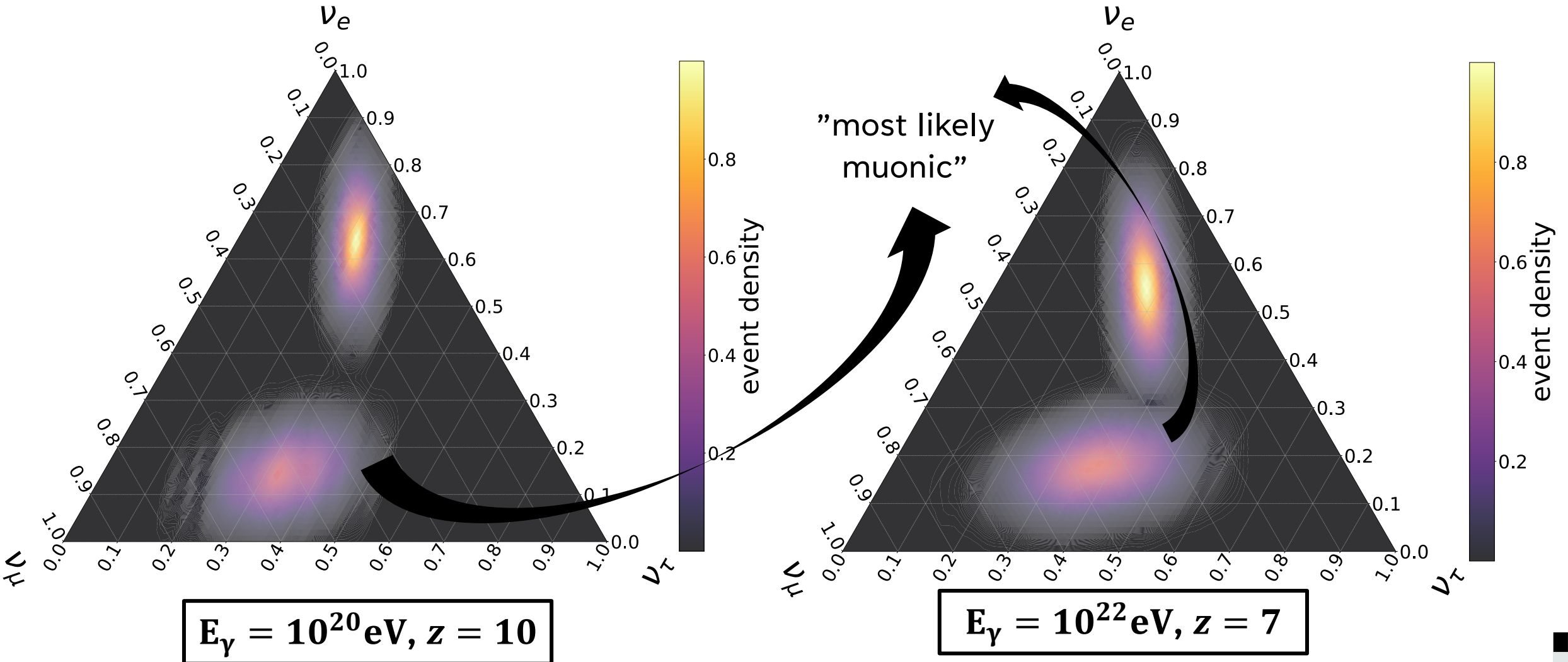
mono sources – flavour probabilities

25



mono sources – flavour probabilities

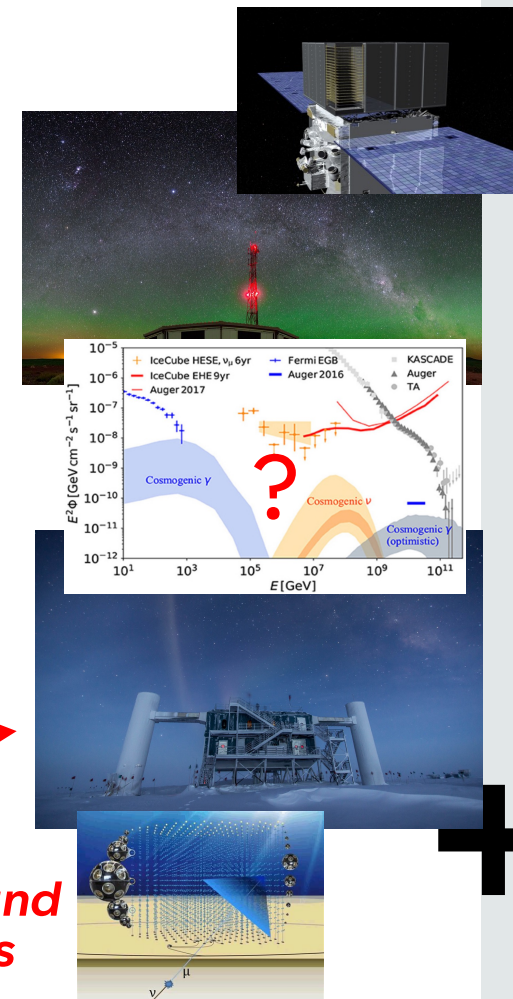
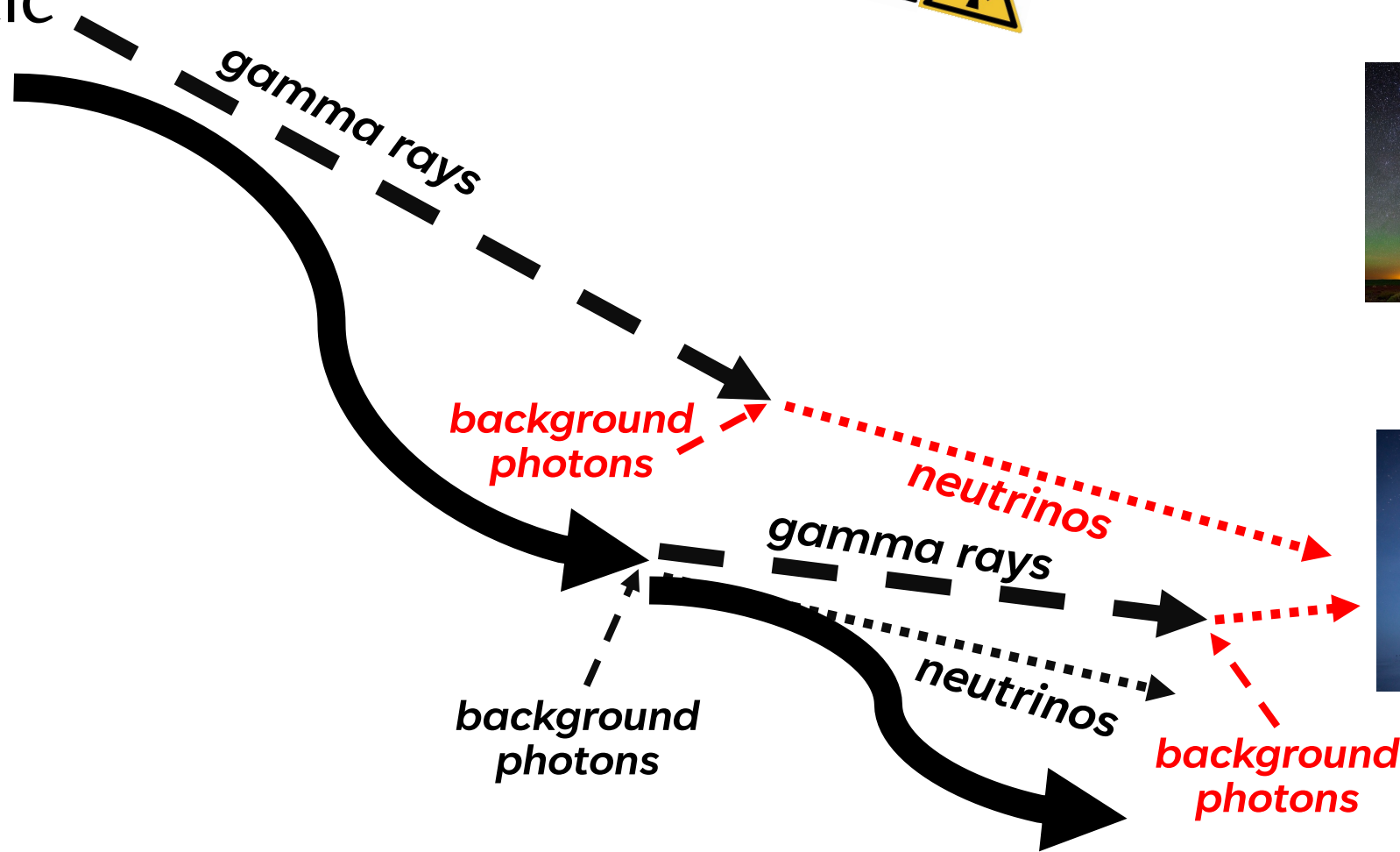
26



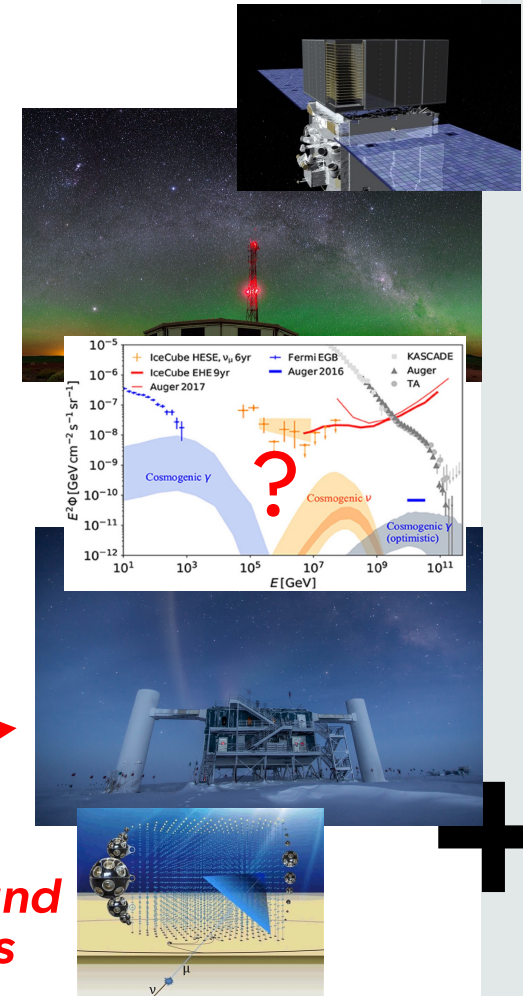
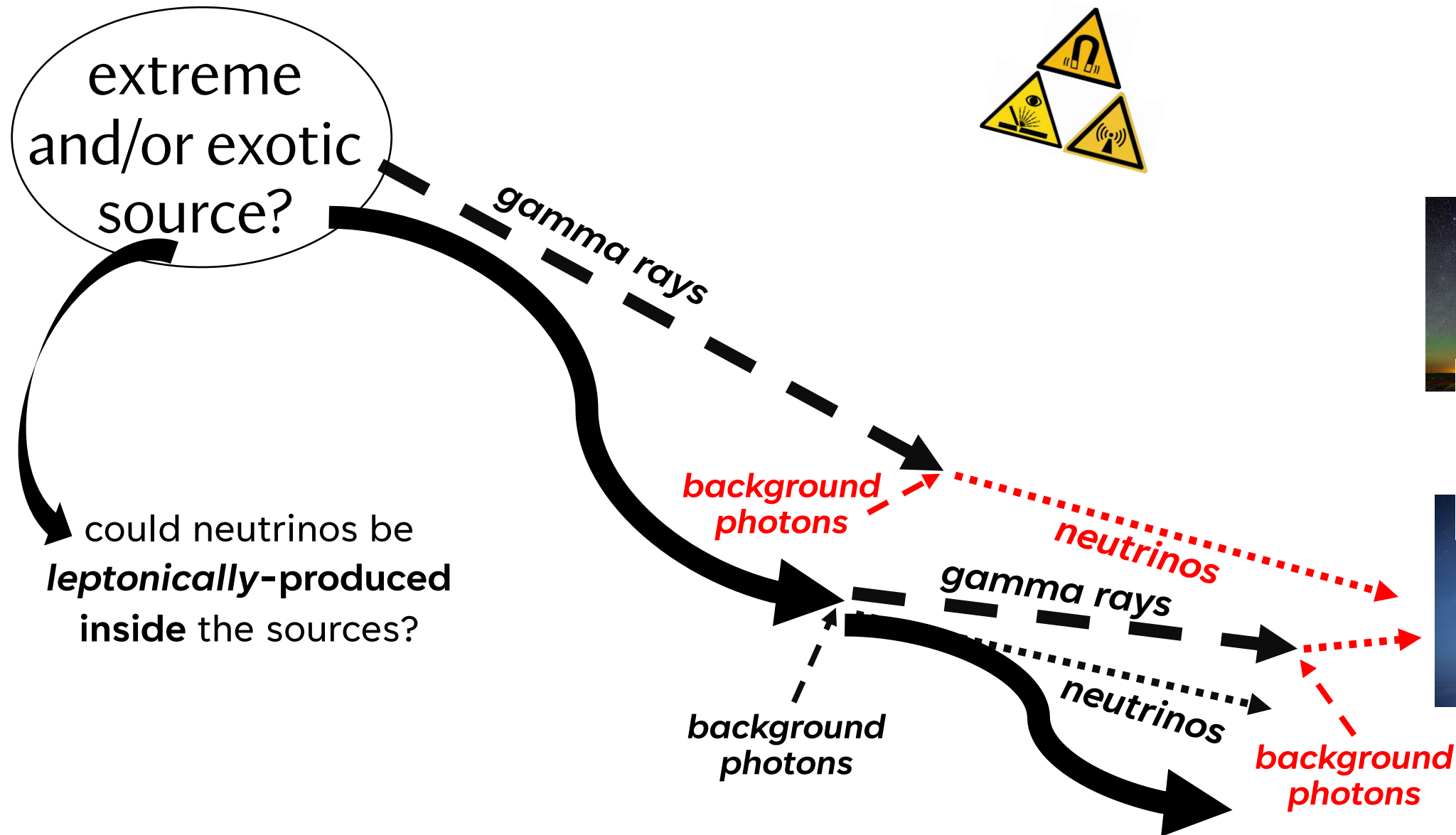
neutrino & γ -ray fluxes – in propagation (so far)

27

extreme
and/or exotic
source?



neutrino & γ -ray fluxes – at sources?



➡ could neutrinos be ***leptonically-produced*** inside the sources?

neutrino & γ -ray fluxes – in active galaxy?

29



gamma rays

background photons

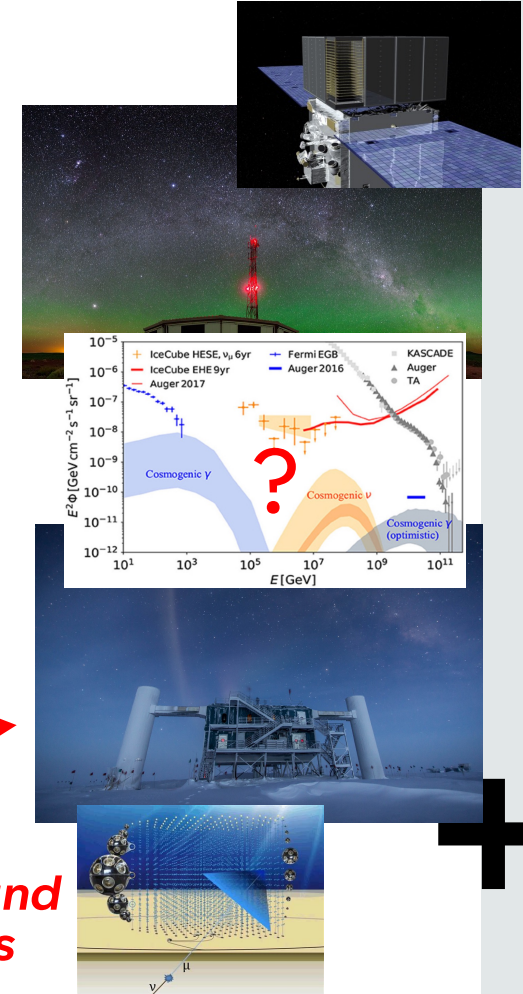
neutrinos

gamma rays

neutrinos

background photons

could neutrinos be
leptonically-produced
inside sources?



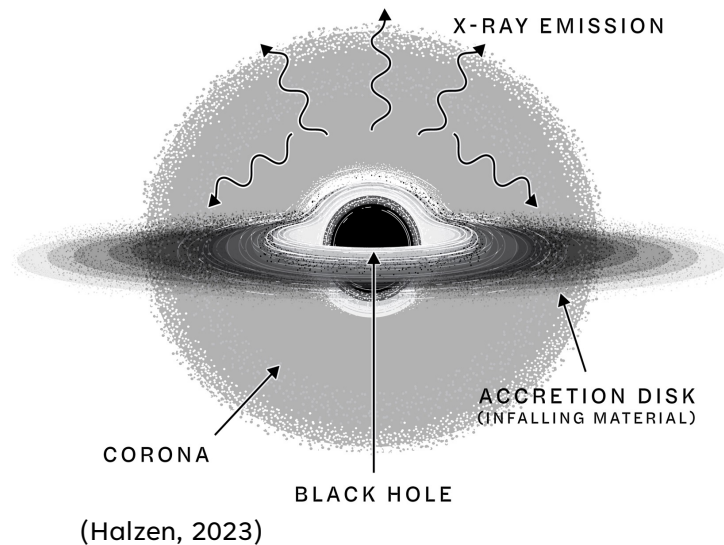
leptonic ν production – in active galaxies?

30

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*

*E-mail: analysis@icecube.wisc.edu.



We report three searches for high energy neutrino emission from astrophysical objects using data recorded with IceCube between 2011 and 2020. Improvements over previous work include new neutrino reconstruction and data calibration methods. In one search, the positions of 110 a priori selected gamma-ray sources were analyzed individually for a possible surplus of neutrinos over atmospheric and cosmic background expectations. We found an excess of 79^{+22}_{-20} neutrinos associated with the nearby active galaxy NGC 1068 at a significance of 4.2σ . The excess, which is spatially consistent with the direction of the strongest clustering of neutrinos in the Northern Sky, is interpreted as direct evidence of TeV neutrino emission from a nearby active galaxy. The inferred flux exceeds the potential TeV gamma-ray flux by at least one order of magnitude.

(Abbasi+, 2024)



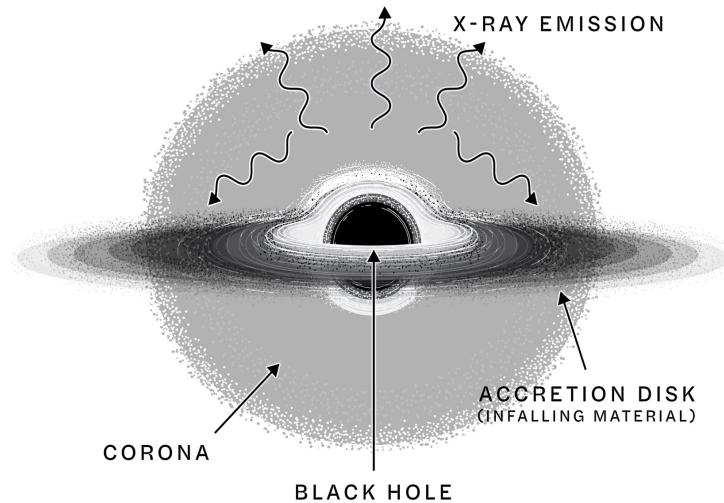
leptonic ν production – in active galaxies?

31

Evidence for neutrino emission from the nearby active galaxy NGC 1068

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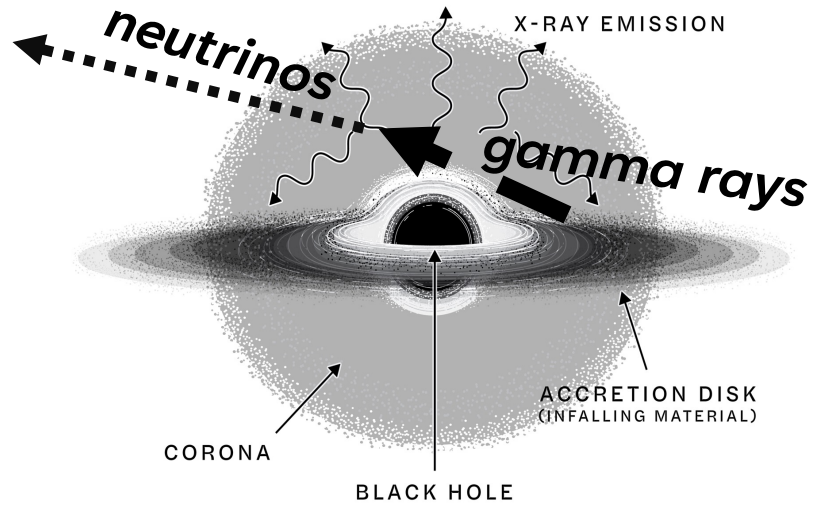
hadronic models trying to explain:
- *neutrino excess*
- *absence of TeV gamma rays*

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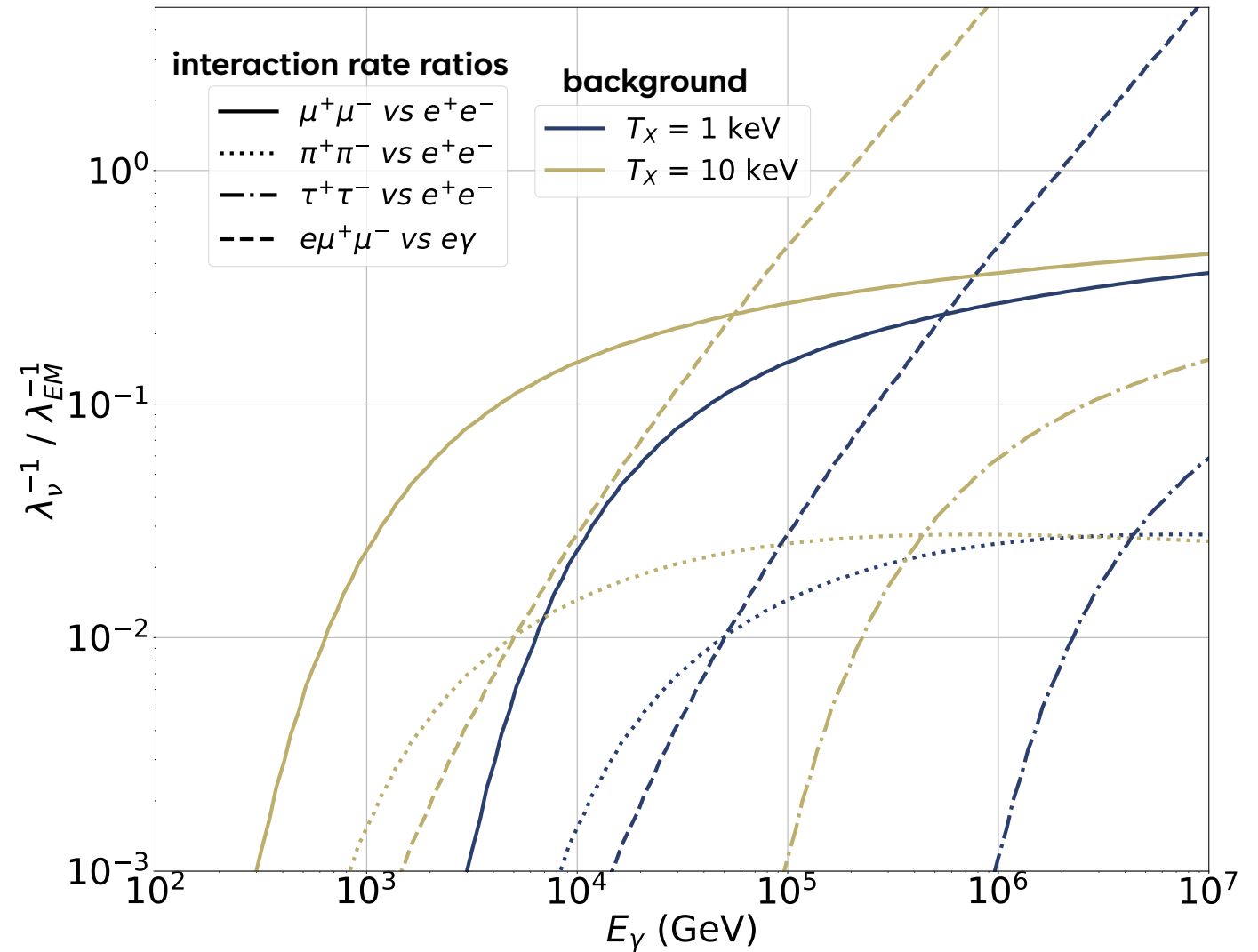
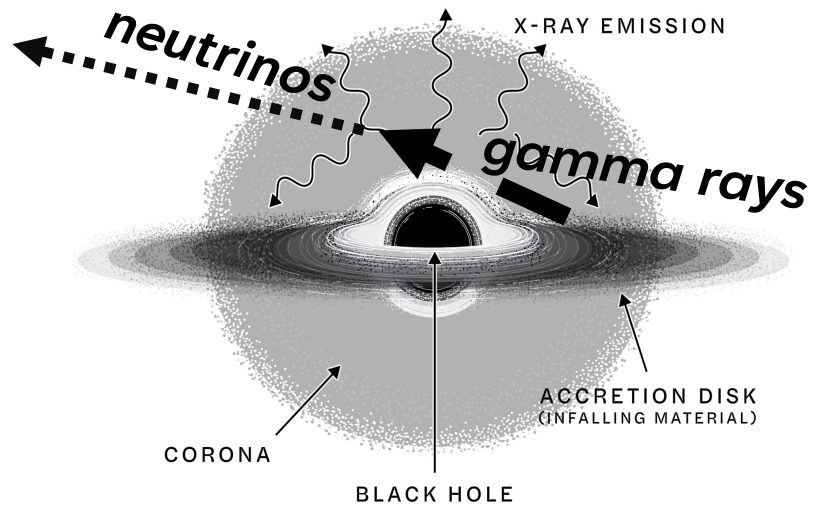
leptonic ν production – in hot corona

32



leptonic ν production – rates in corona

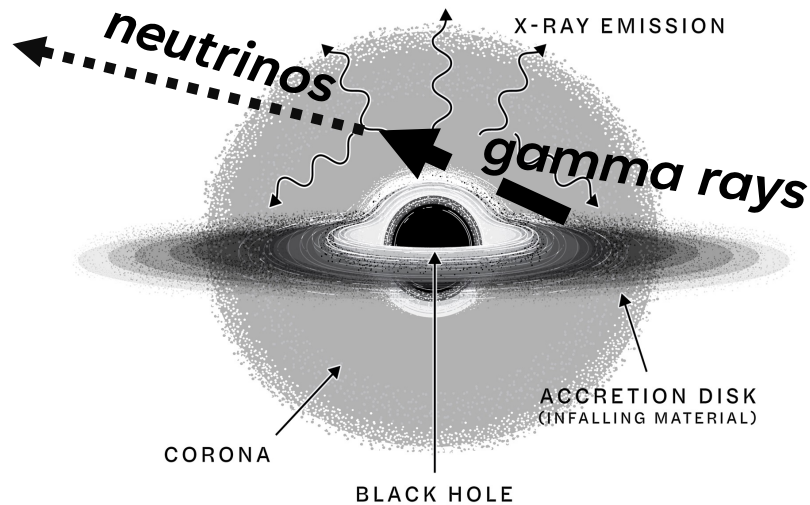
33



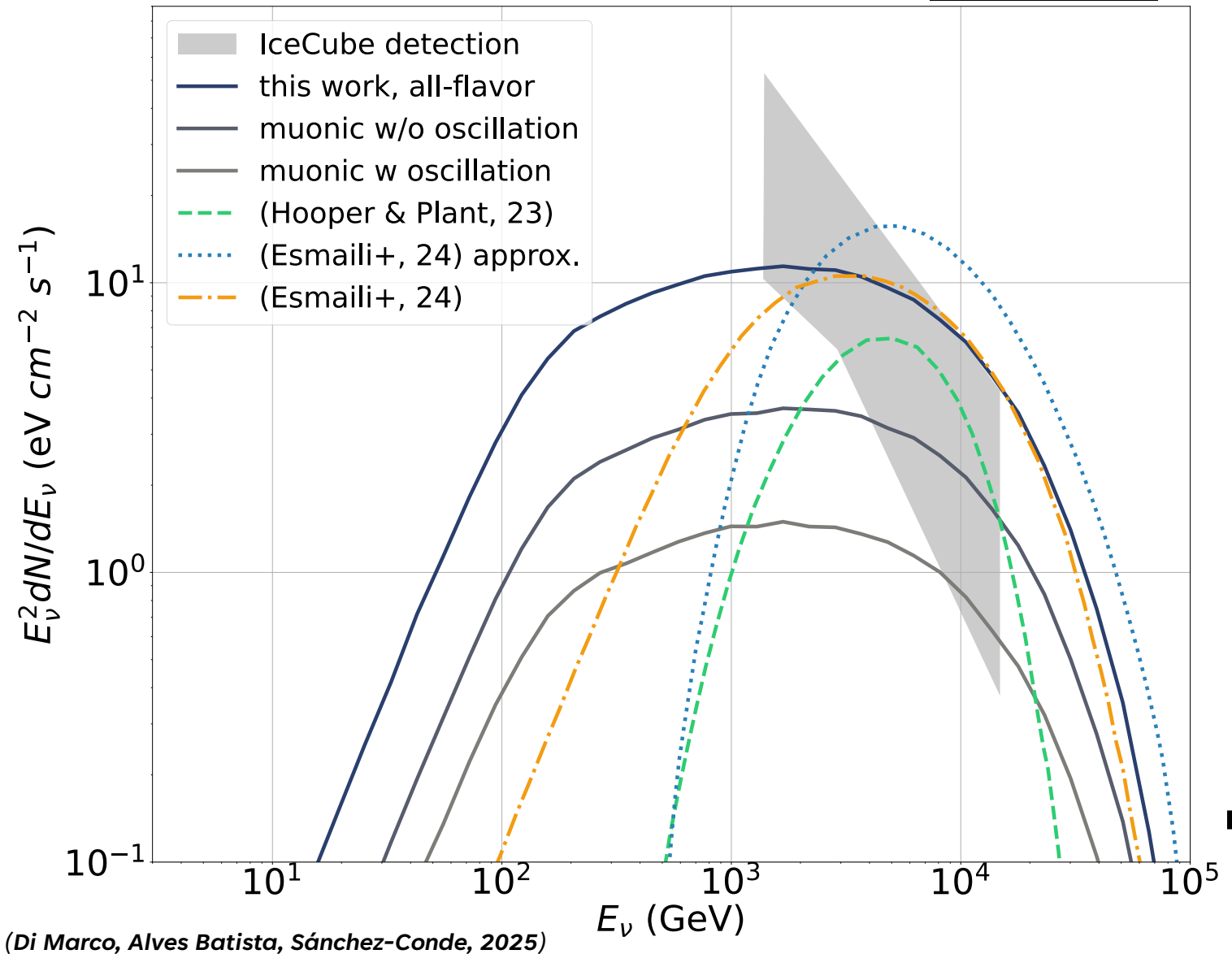
(Di Marco, Alves Batista, Sánchez-Conde, 2025)

leptonic ν production – energy spectra

34



(just by considering **electron** and **muon pair production** processes)



concluding with some prospects

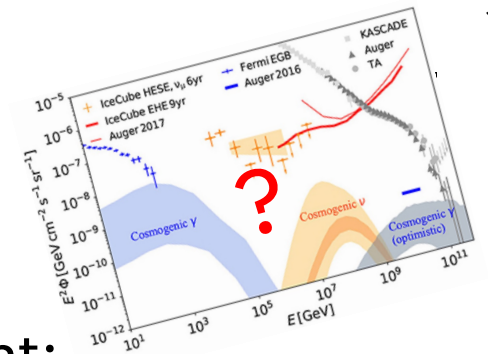
in science:

heavy leptons and hadrons production in EM cascades might:

- **alter** expected gamma-ray and neutrino balance;
(*cosmogenic?* exotic physics searches, e.g. dark matter?)
- **leptonically produce** neutrino in source, e.g. AGNs;

in simulation framework:

synergy between CRPropa & PYTHIA simulation codes,
(useful in other frameworks?)



$$\chi \rightarrow \begin{cases} q\bar{q} \\ gg \\ \dots \end{cases} \rightarrow p, e, \gamma, \nu$$



concluding with some prospects

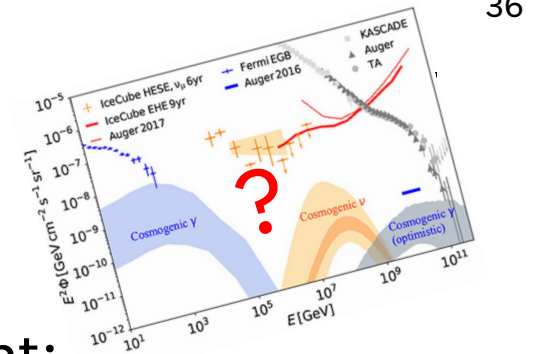
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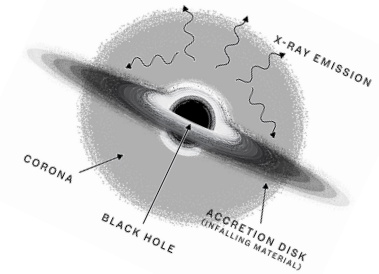
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concluding with some prospects

in science:

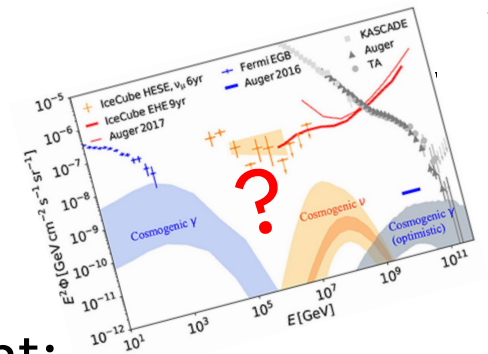
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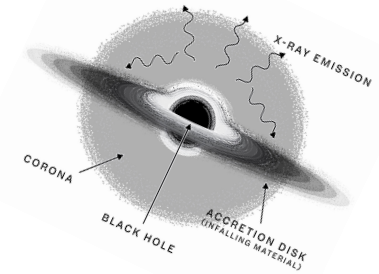
in simulation framework:

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CRPropa



$$\chi \rightarrow \begin{cases} q\bar{q} \\ gg \\ \dots \end{cases} \rightarrow p, e, \gamma, \nu$$



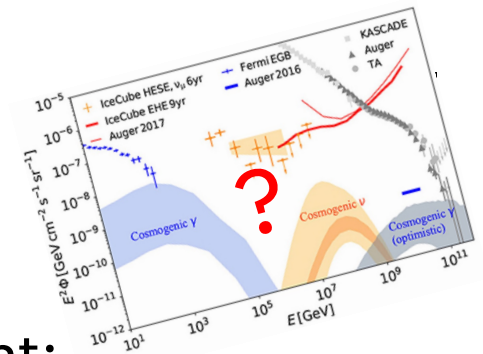
concluding with some prospects

38

in science:

heavy leptons and hadrons production in EM cascades might:

- **alter** expected gamma-ray and neutrino balance;
(*cosmogenic?* exotic physics searches, e.g. dark matter?)
- **leptonically produce** neutrino in source, e.g. AGNs;



$$\chi \rightarrow \begin{cases} q\bar{q} \\ gg \\ \dots \end{cases} \rightarrow p, e, \gamma, \nu$$

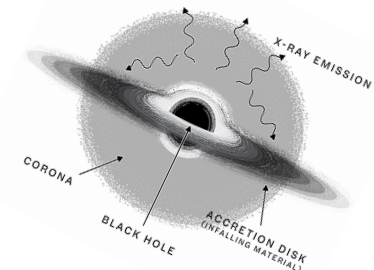
in simulation framework:

synergy between CRPropa & PYTHIA simulation codes,
(useful in other frameworks?)

CRPropa ↔



thank you! 😊



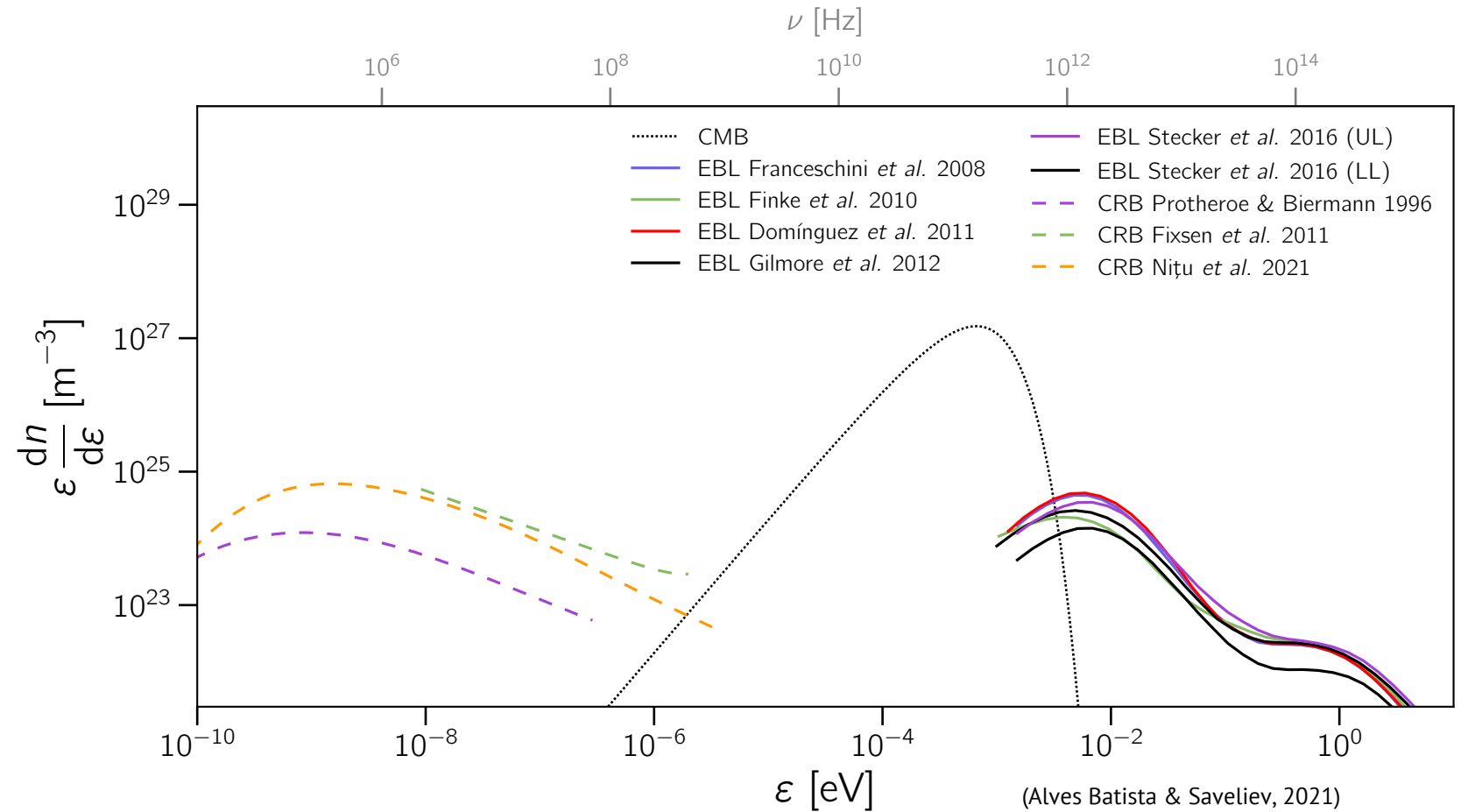
backup slides...



cosmological background photons

primordial: **cosmic
microwave background
(CMB)**

astrophysical:
**cosmic radio background
(CRB), extragalactic
background light
(EBL)**



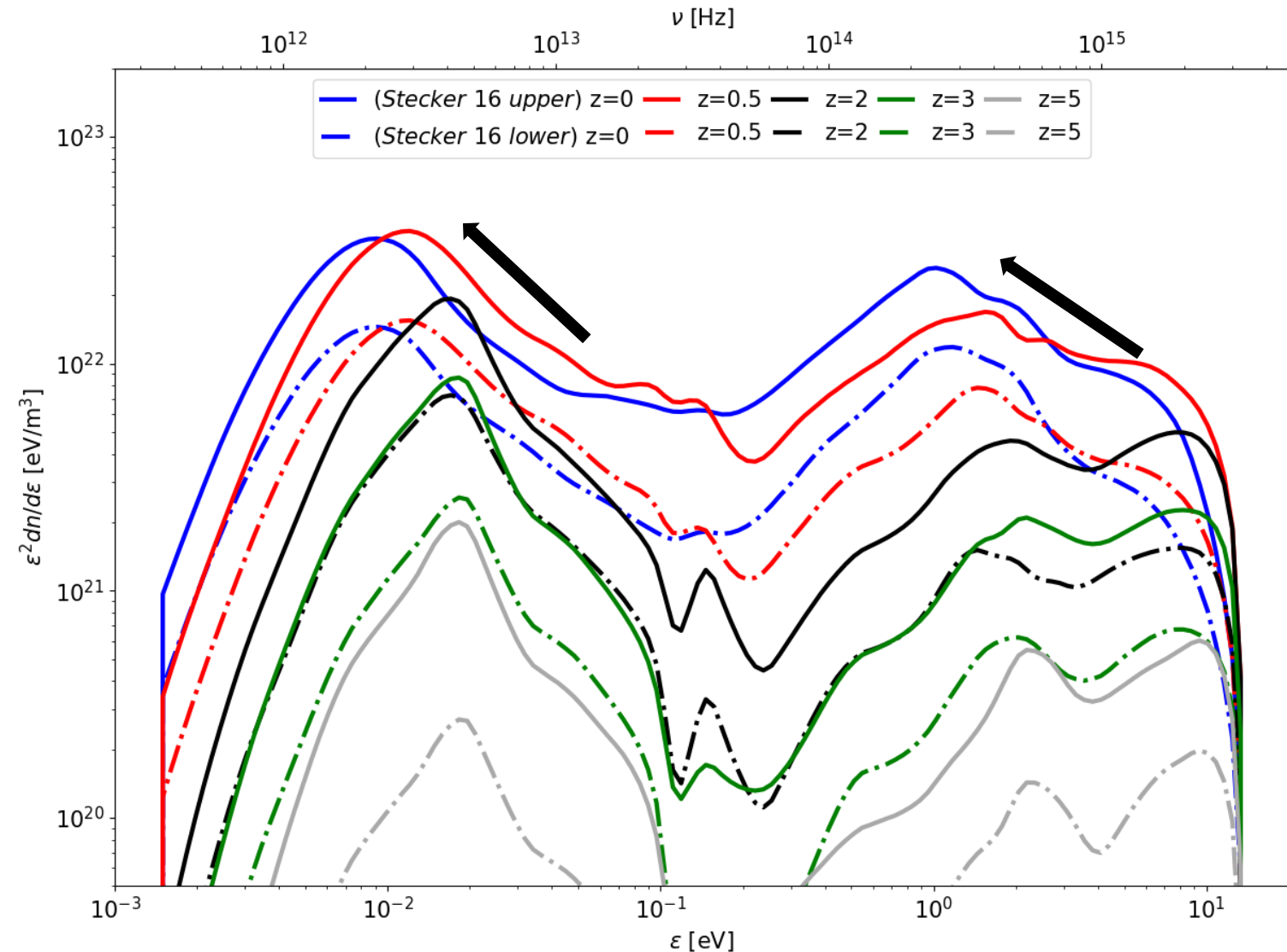
EBL with redshift

41

evolution trace of
extragalactic
sources' emission
between the IR to the UV

(- largely uncertain at
higher redshifts

- lots of models)

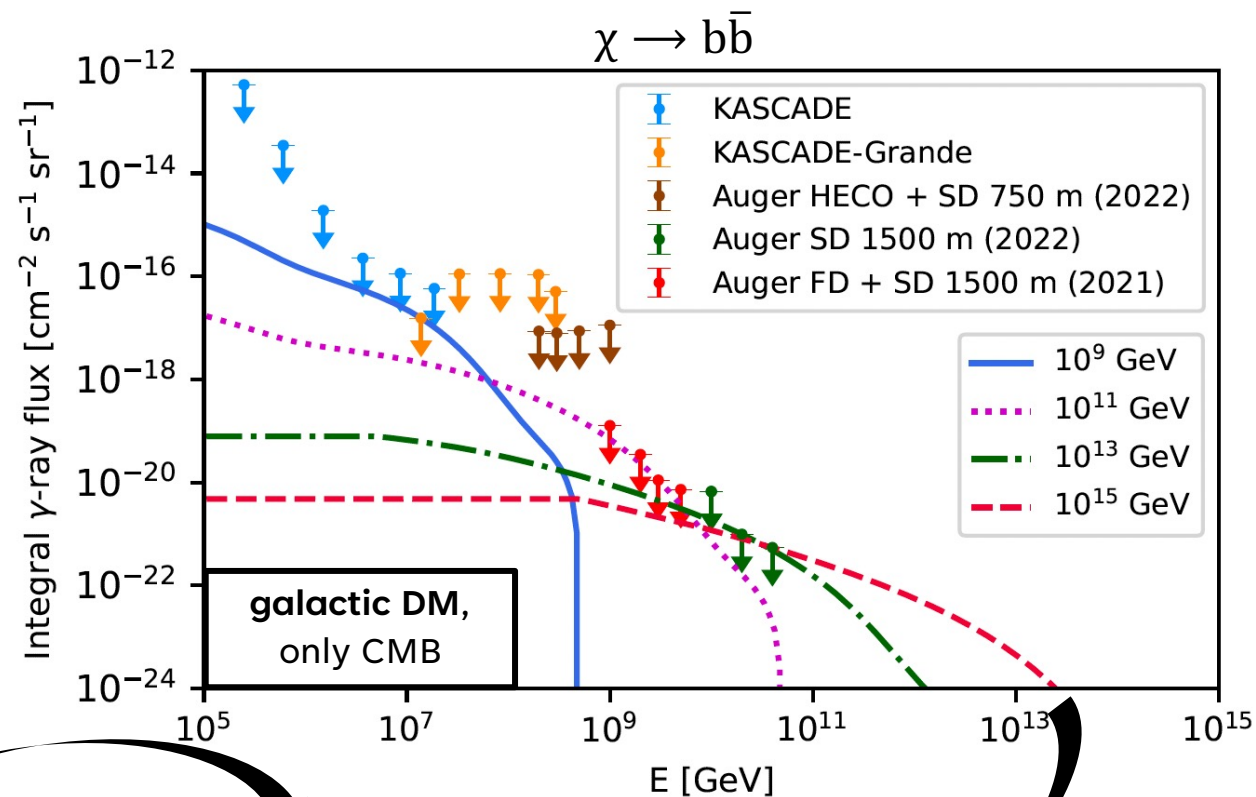
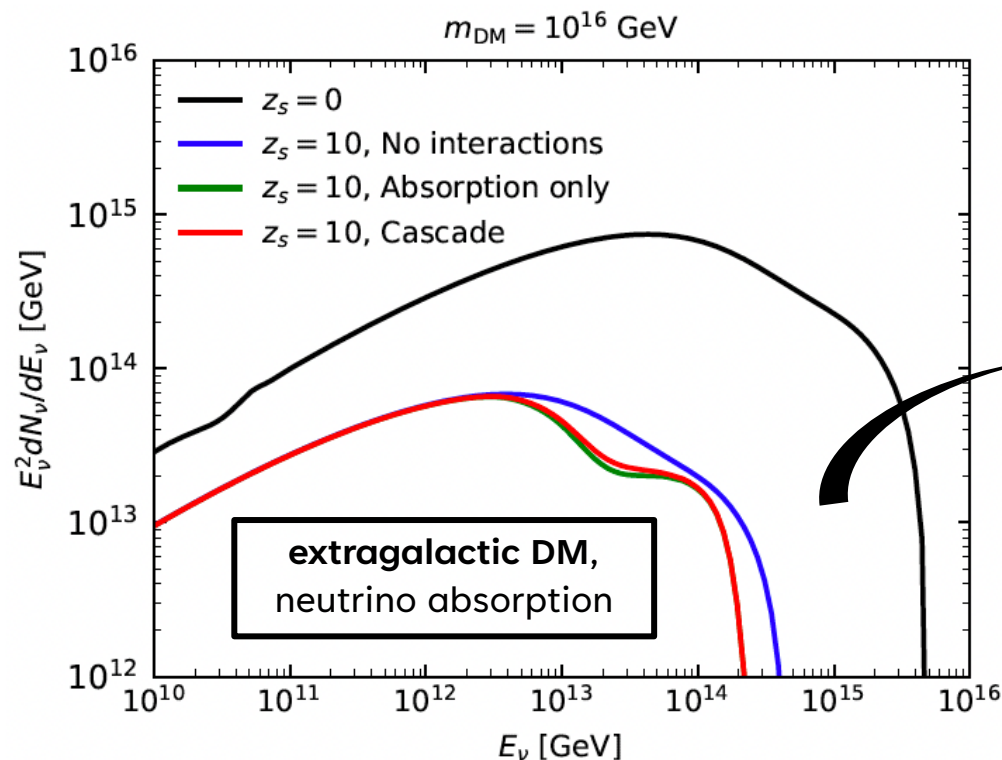


neutrino & γ -ray fluxes – super heavy dark matter

42

lifetime $\tau_\chi \gg 10^{10}$ yr
mass $10^7 \lesssim M_\chi \lesssim 10^{16}$ GeV

$$\chi \rightarrow \begin{cases} q\bar{q} \\ gg \rightarrow p, e, \gamma, \nu \\ \dots \end{cases}$$



*leptonically-produced
neutrinos during
propagation of gamma rays?*

neutrino & γ -ray fluxes – cosmic string

43

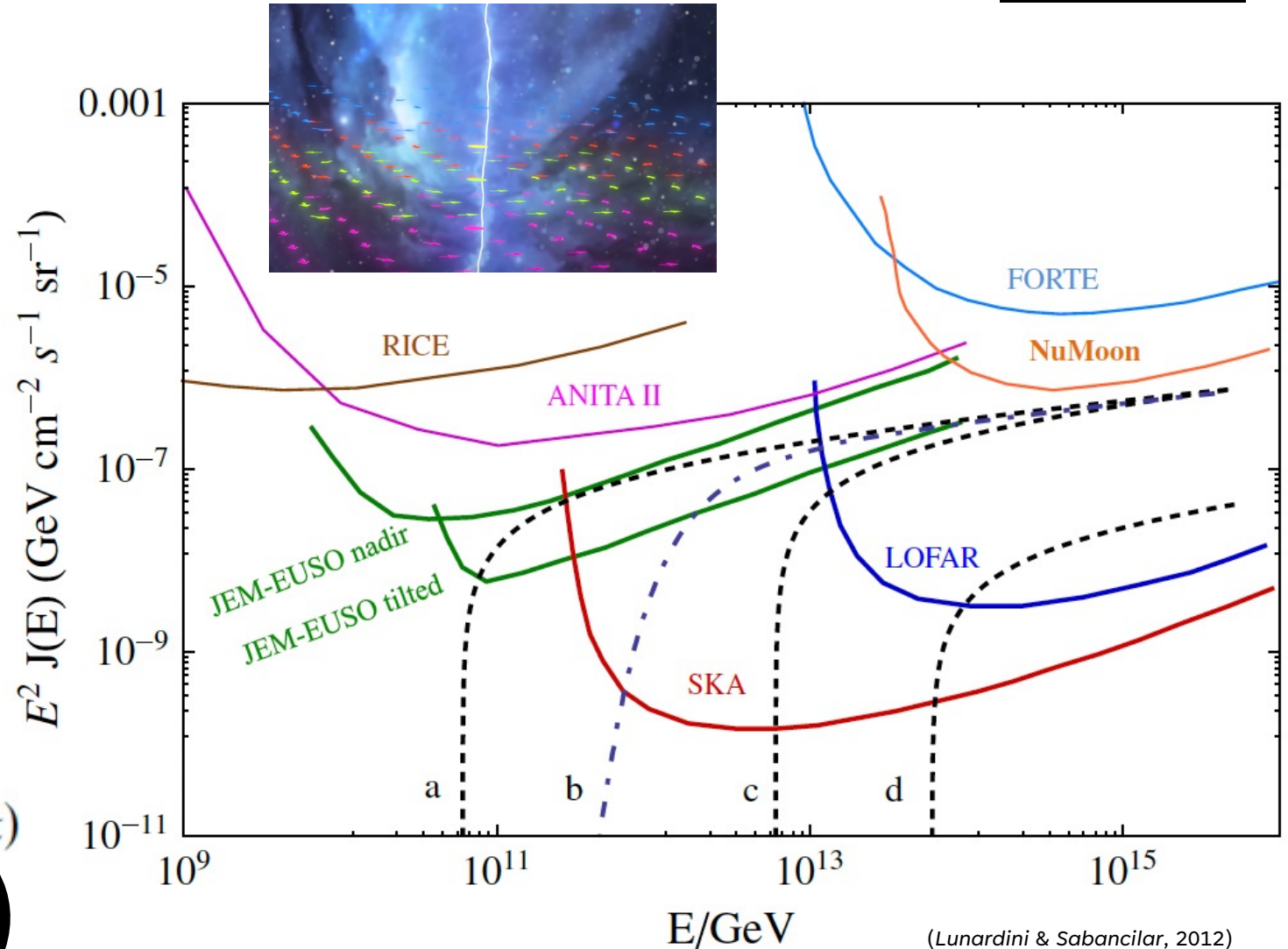
expected fluxes depending on:

- moduli coupling
- kinks "sharpness"
- (neutrino masses)

EM cascade energy density:

$$\omega_{\text{cas}} = \frac{1}{2} f_{\pi} \int \frac{dt}{(1+z)^4} n(L, t) dL dP(k)$$

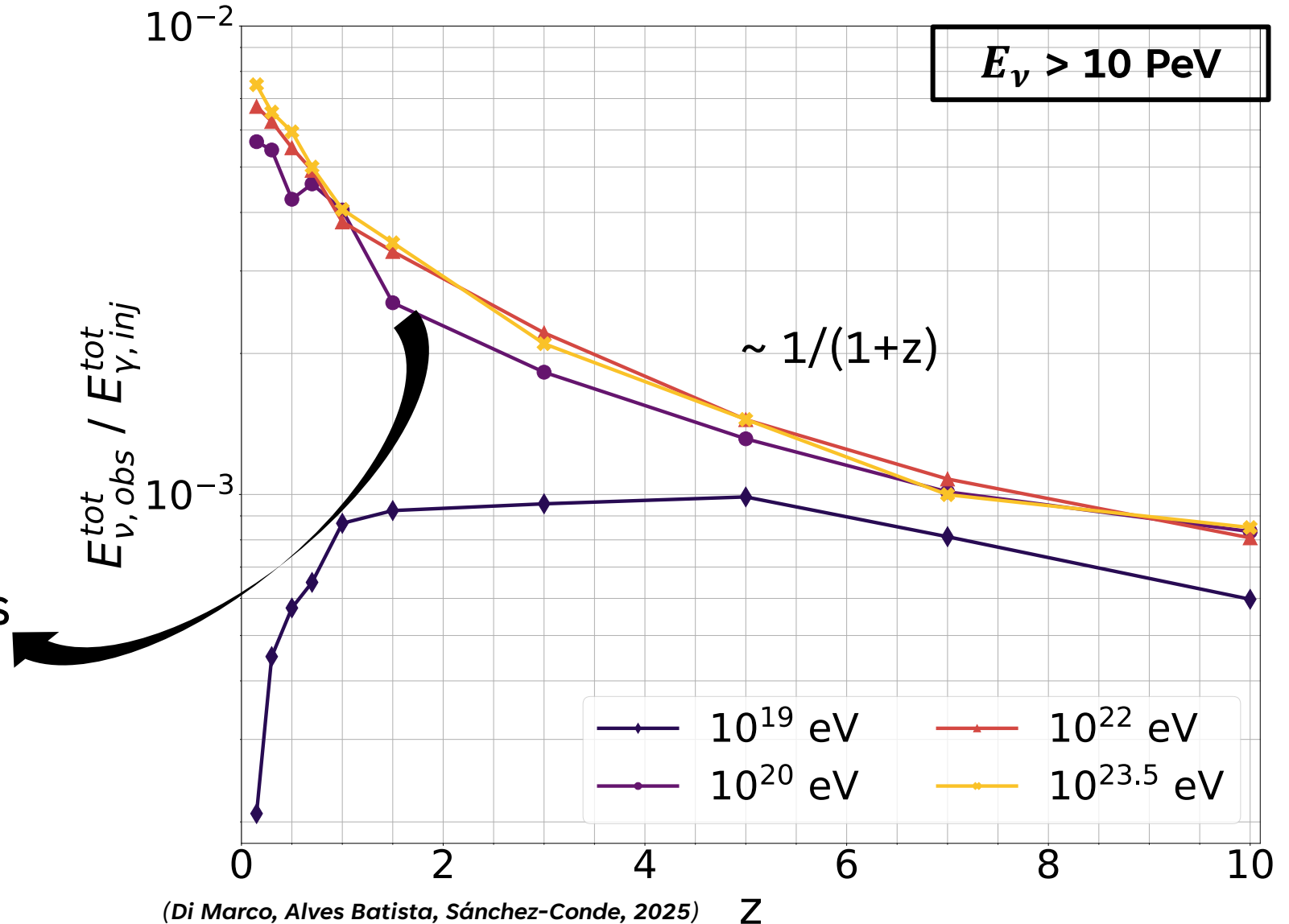
neutrinos?



mono sources – energy fraction

most of the initial
energy absorbed,
less than 1% goes
into neutrinos

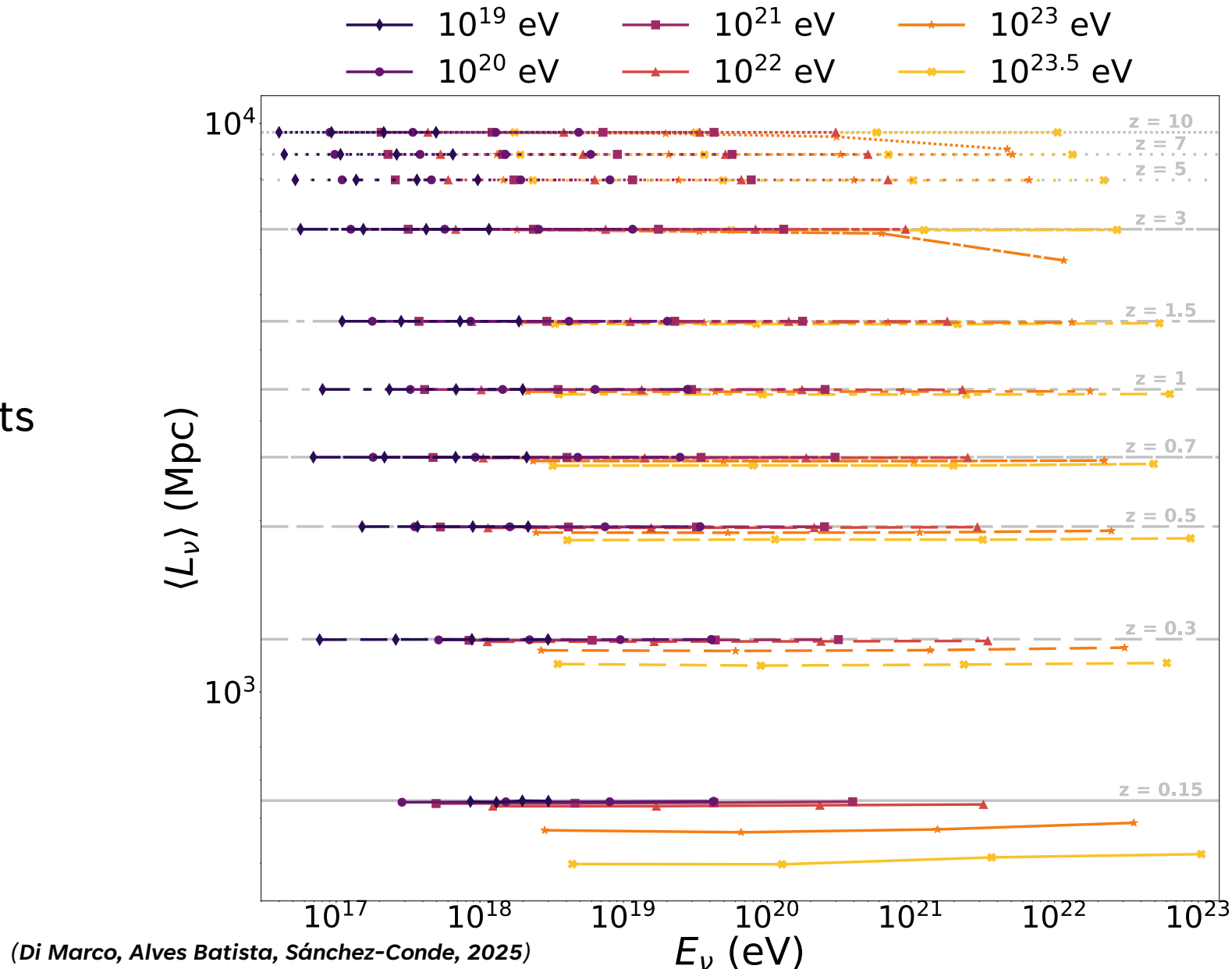
adiabatic energy loss
scaling



mono sources – ν distance travelled

45

in the highest energy
sources cascading effects
might happen

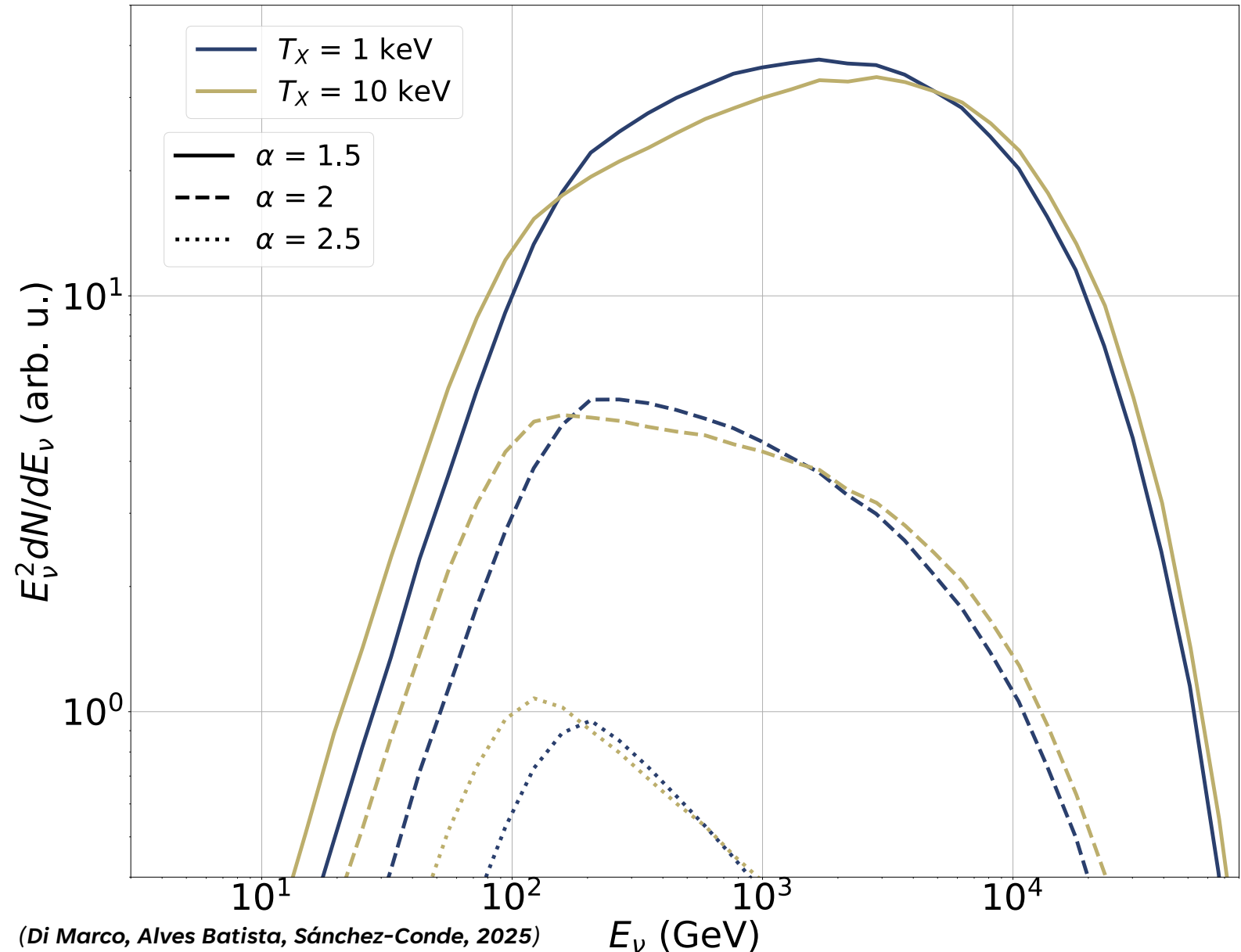


in source – ν energy spectra

46

including **only** muon
and electron pair
production & X-ray
background field

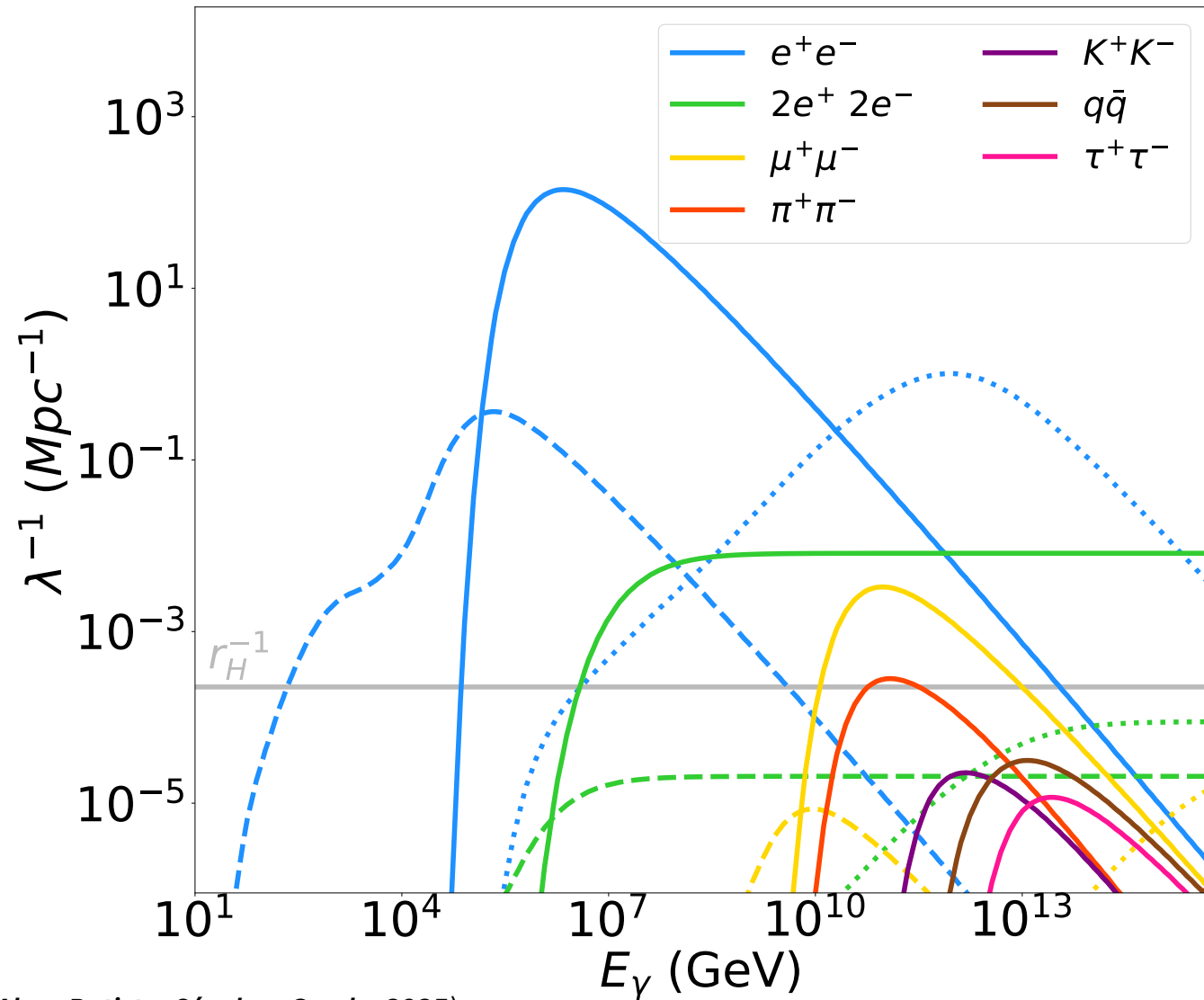
(computationally
expensive to add other
interactions and/or
trying to recreate the
AGN environment)



interaction rates - cosmological

47

computed tables at:
[EMCascadePlugins-data](#)



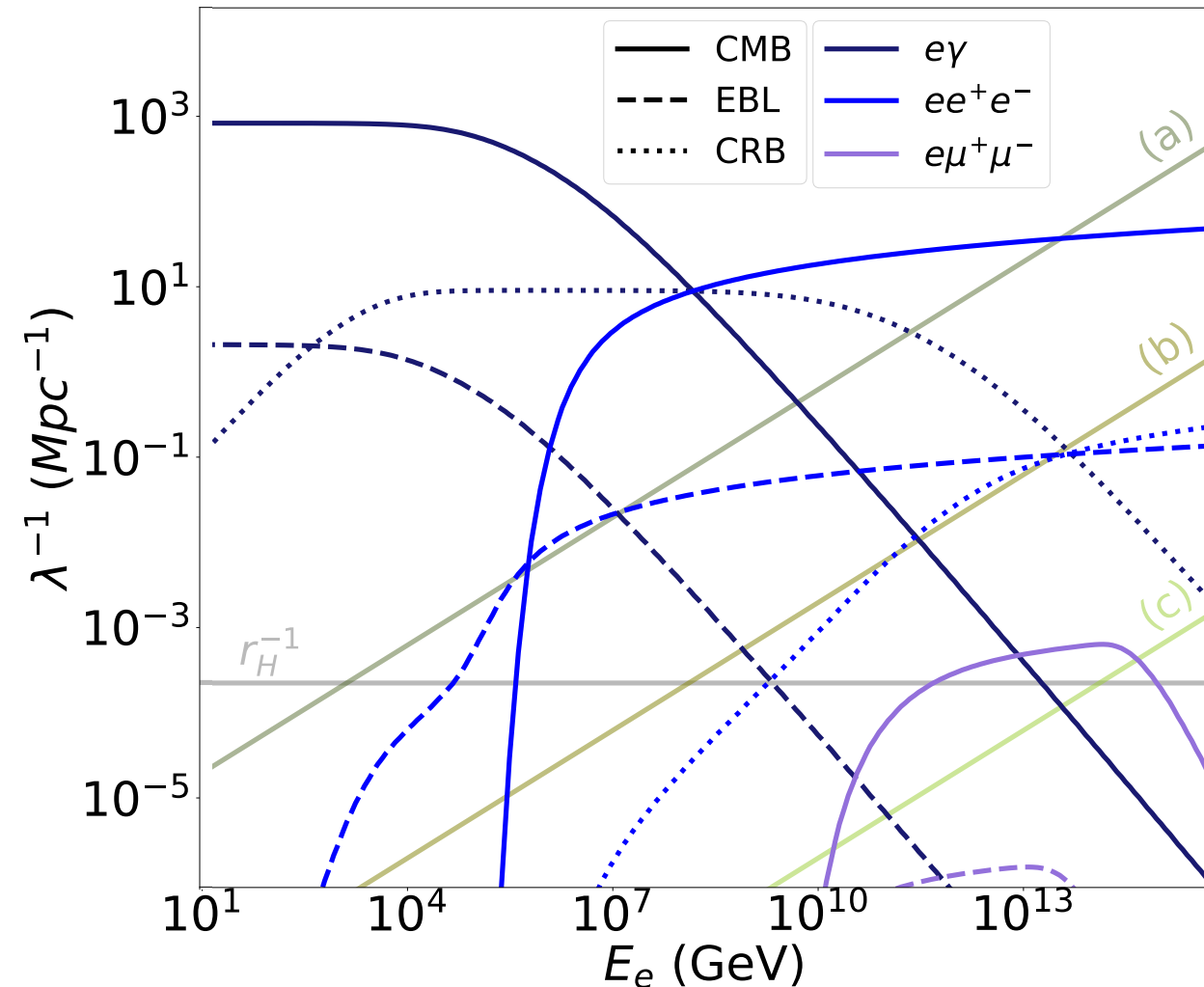
(Di Marco, Alves Batista, Sánchez-Conde, 2025)



interaction rates - cosmological

48

computed tables at:
[EMCascadePlugins-data](#)

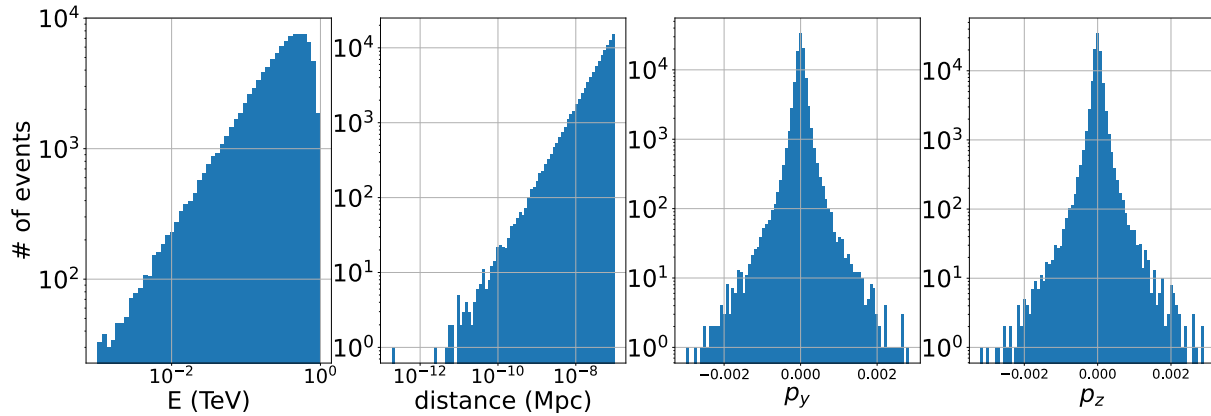


(Di Marco, Alves Batista, Sánchez-Conde, 2025)



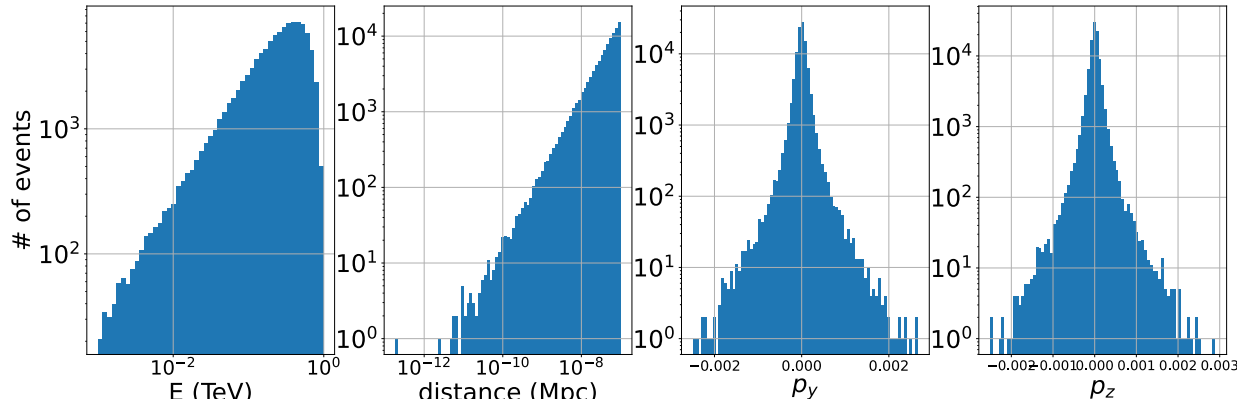
CRPYTHIAxDecays – muon decay

49



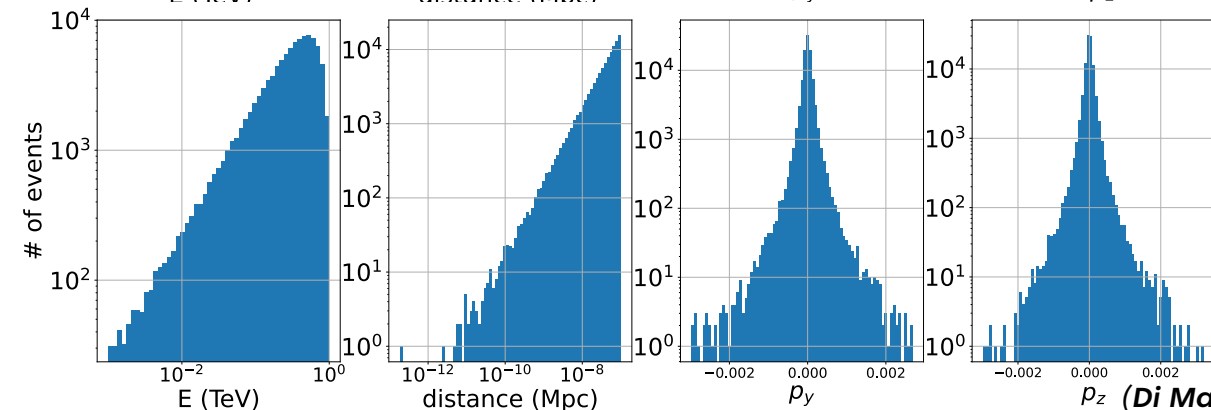
electrons

injecting $1e5$ muons of
1 TeV along the x-axis!



electronic
(anti)neutrinos

(angular correction ON)



muonic
neutrinos