Propagation of astroparticles: a multimessenger view

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structure of this talk

part 1

UHECR propagation
UHECR astronomy
cosmogenic neutrinos and photons
high-energy particles from galaxy clusters

part 2

gamma-ray propagation
intergalactic magnetic fields (IGMFs)
multimessenger method for IGMF constraints
plasma instabilities: propagation effects

part 1

propagation of ultra-high-energy cosmic rays

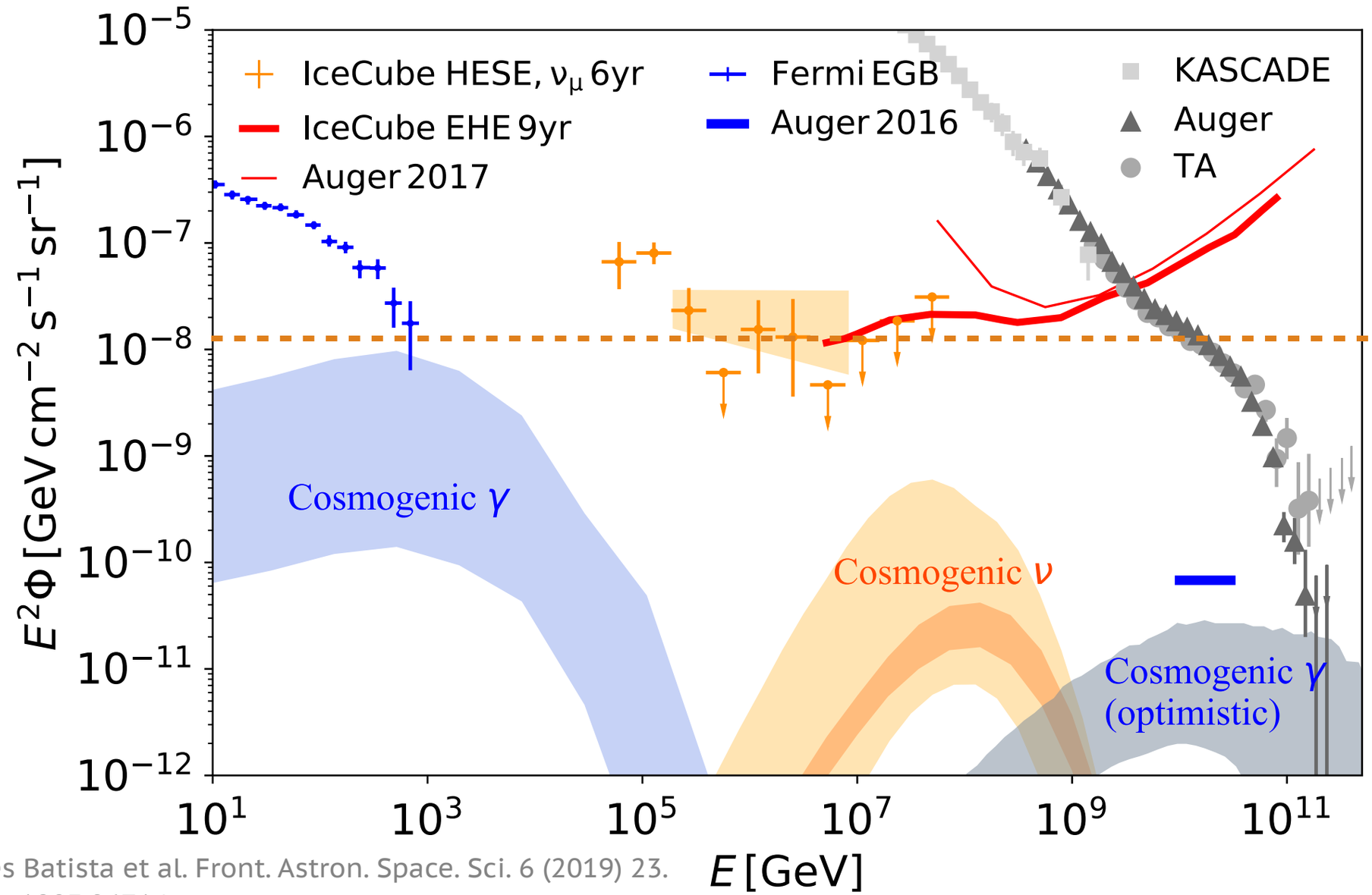
ultra-high-energy cosmic rays (UHECRs)

cosmogenic neutrinos and photons

the CRPropa framework

uncertainties in UHECR propagation

the multimessenger landscape at high energies



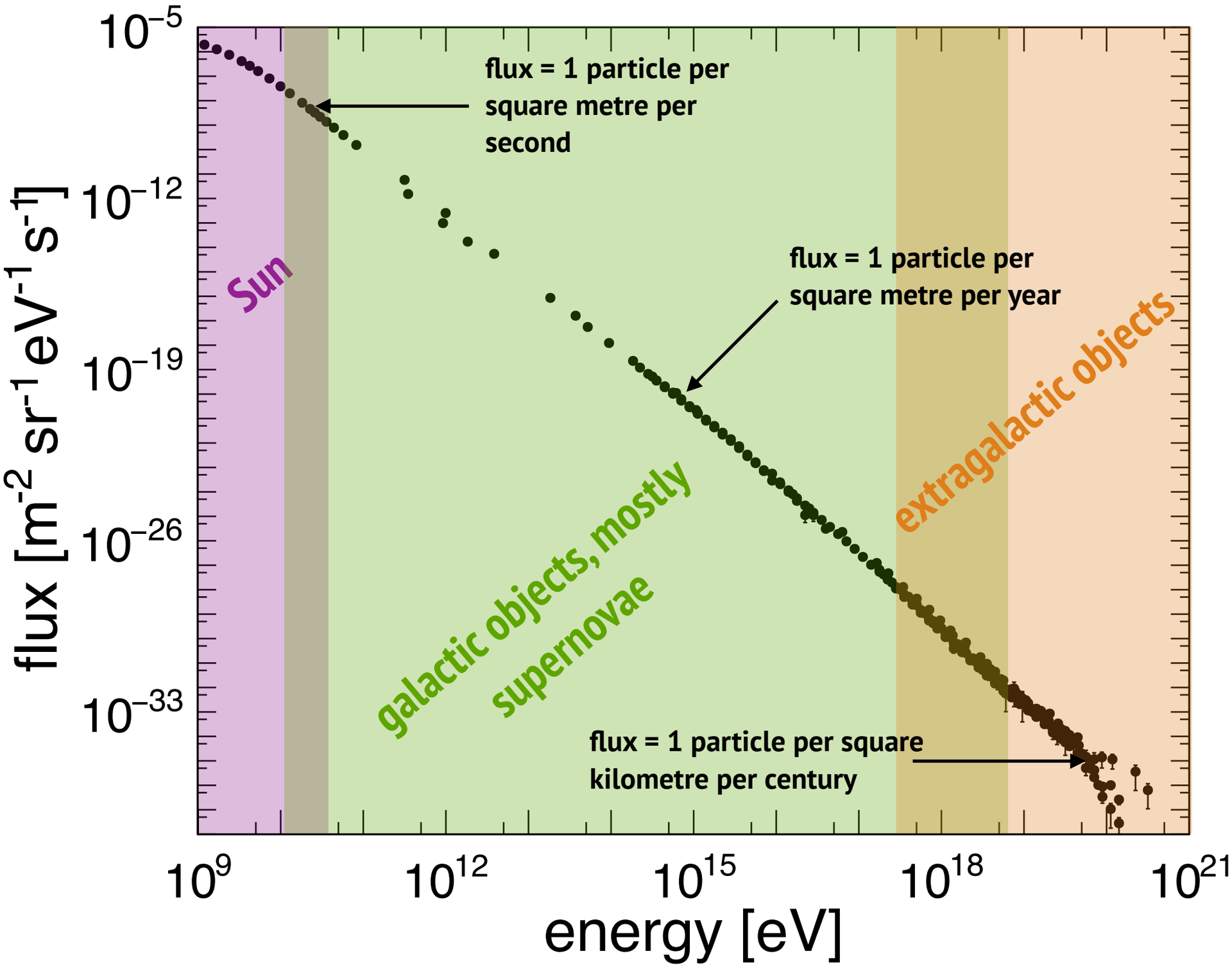
fluxes are comparable!

common origin?

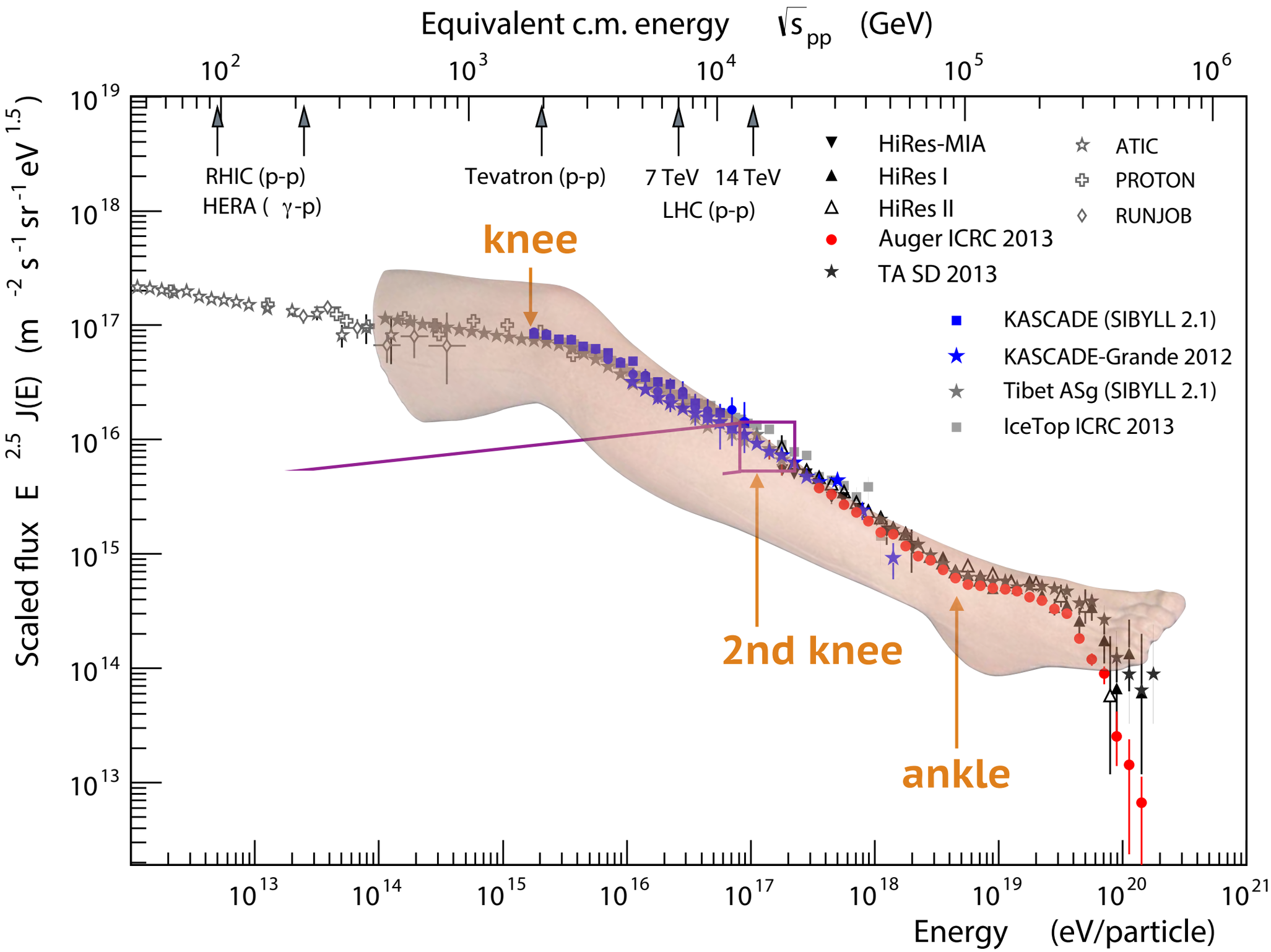
Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

CRs are the key to unveil the non-thermal (ultra-)high-energy universe

the cosmic-ray spectrum



anatomy of the cosmic-ray spectrum



UHECRs

fundamental questions

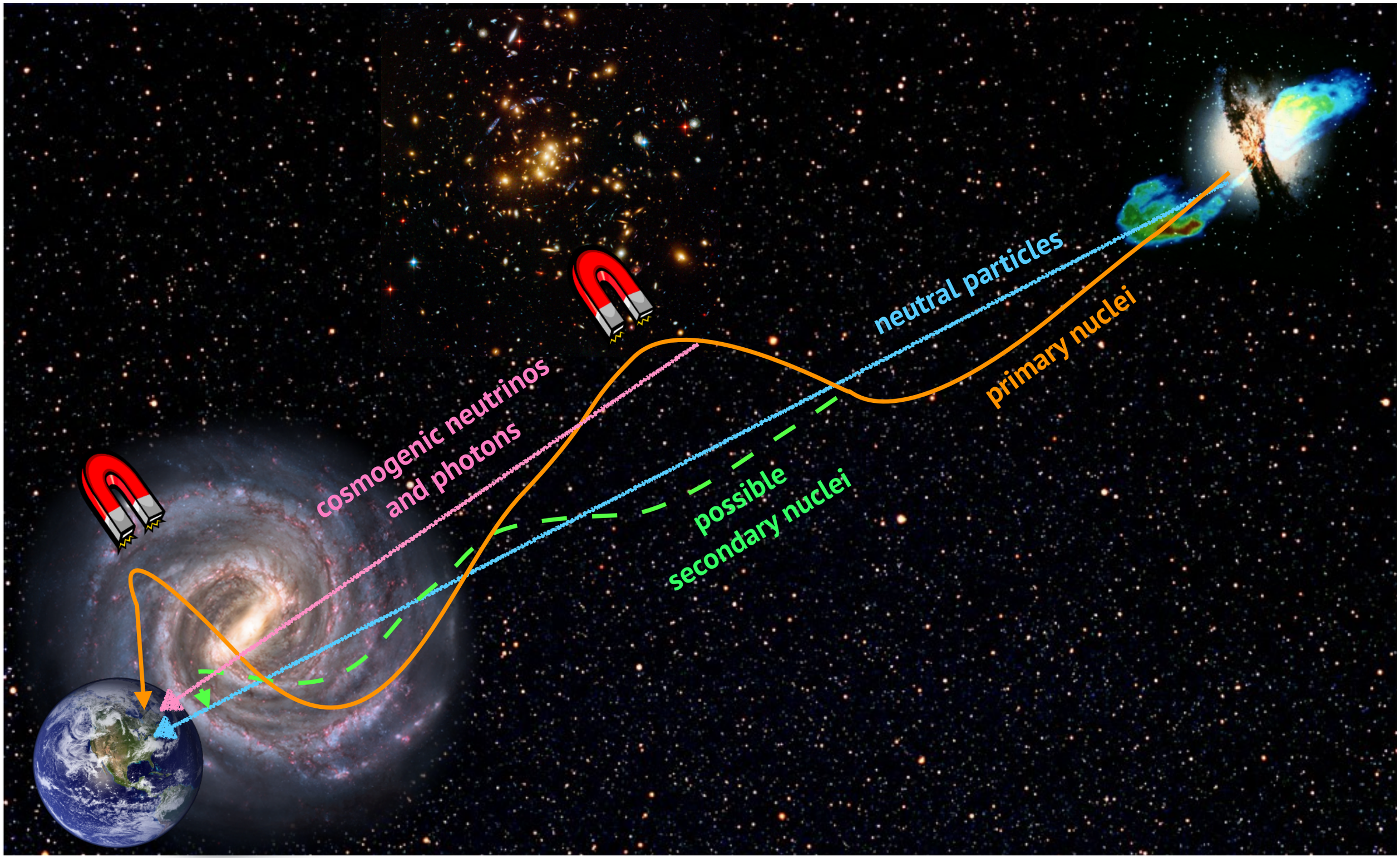
- where do they come from?
- what are they made of?
- how are they accelerated?

some problems

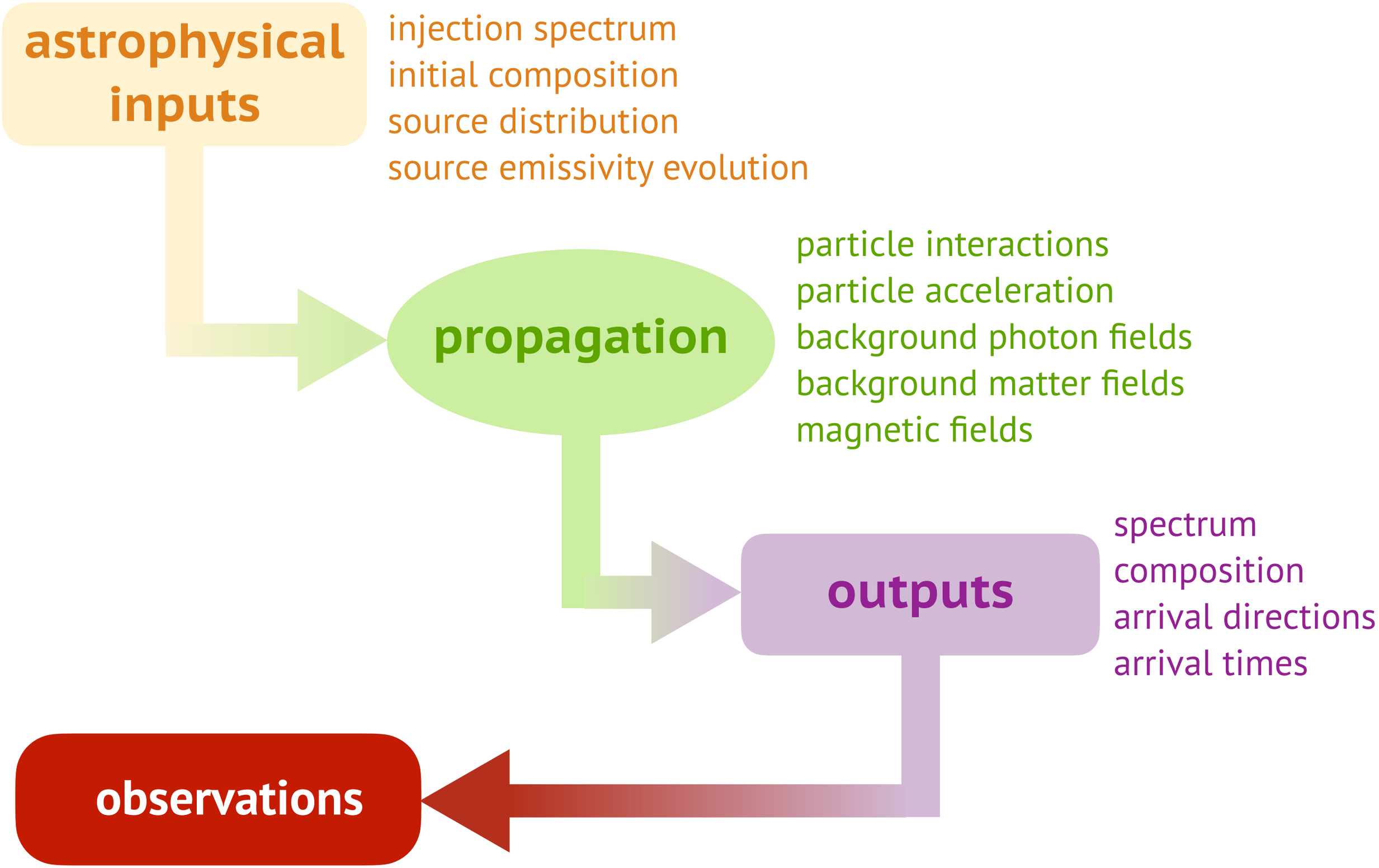
- what is the maximal energy UHECRs can reach?
- why do we see a flux suppression at 40 EeV?
- where does the transition between galactic and extragalactic cosmic rays take place?
- can we do UHECR astronomy?

how do ultra-high-energy cosmic rays propagate?

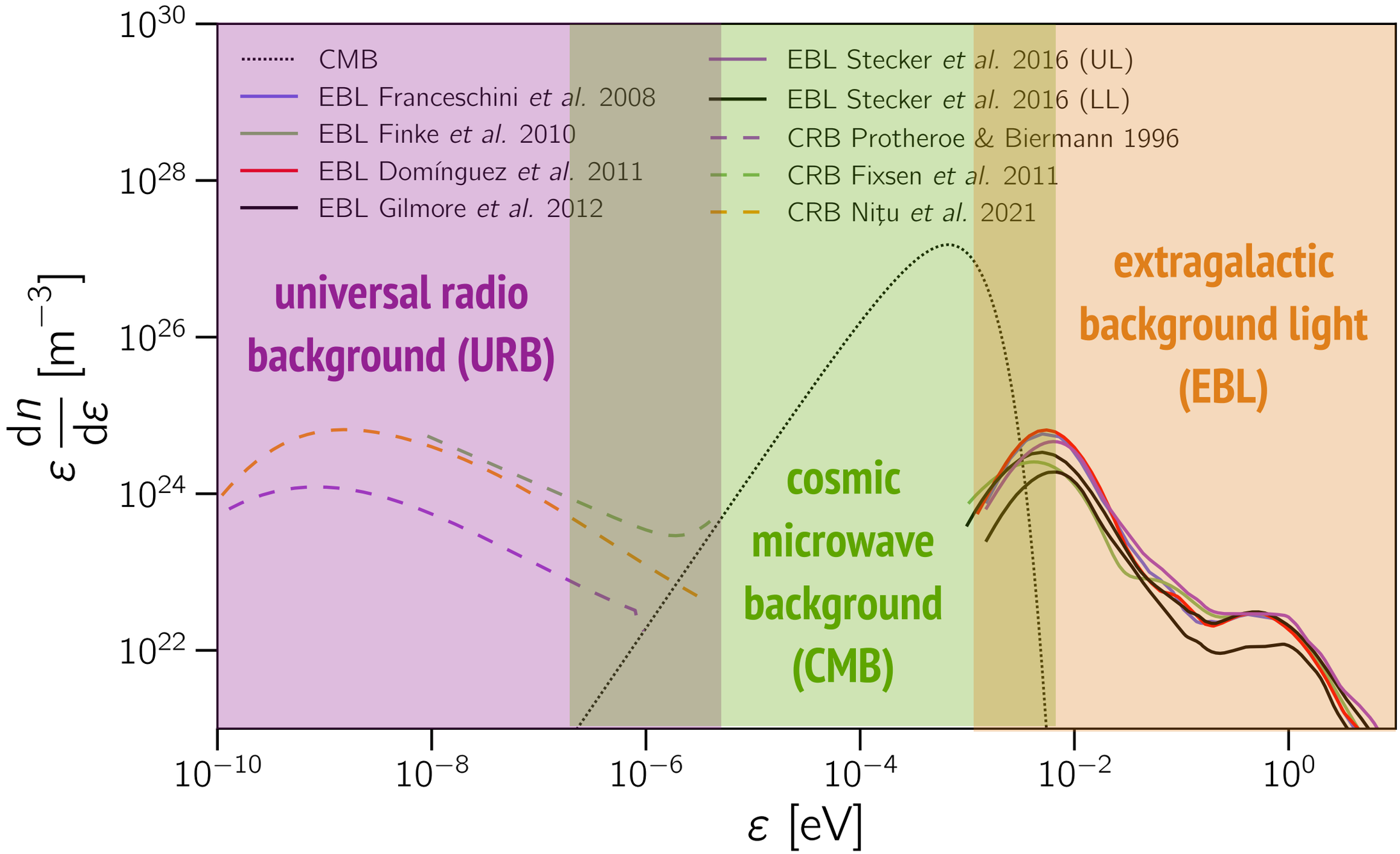
UHECR propagation picture



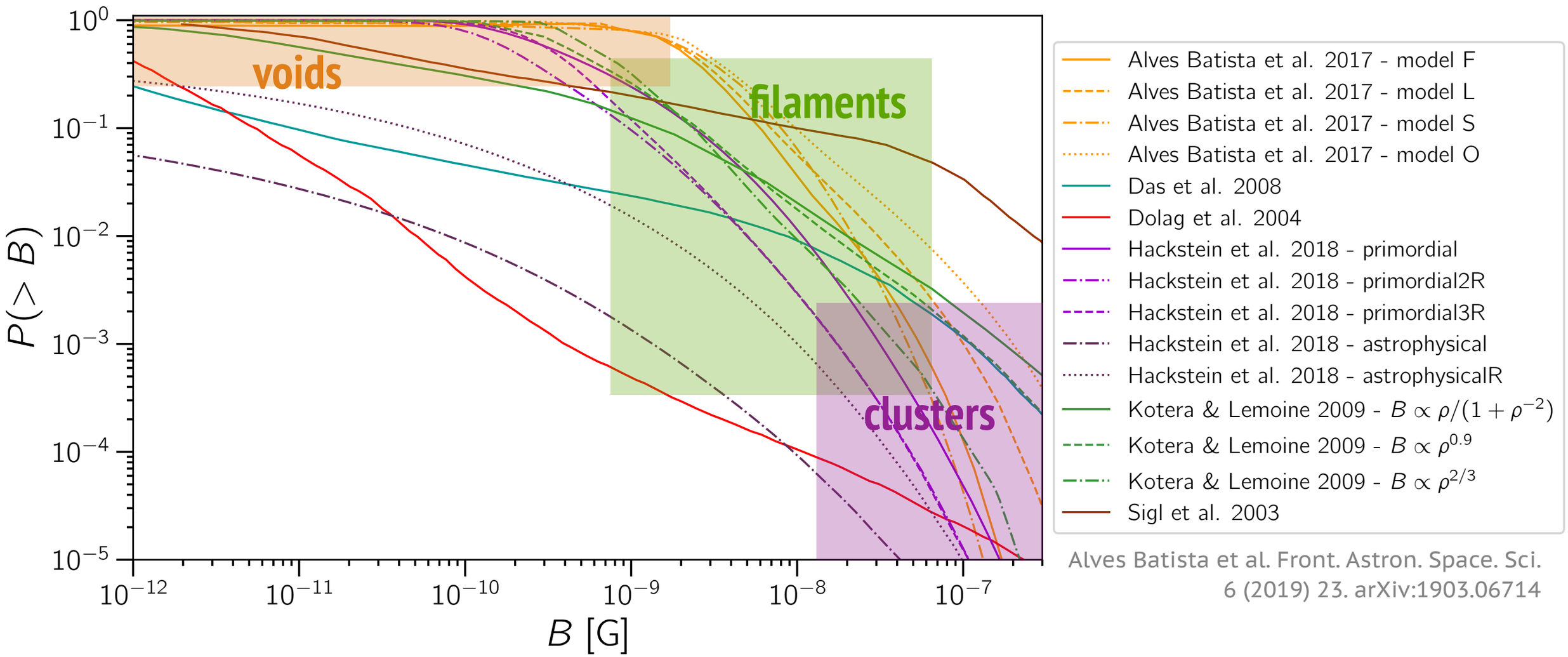
recipes for astroparticle propagation



INGREDIENTS: cosmological radiation fields



INGREDIENTS: cosmic magnetic fields



Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

UHECR propagation: interactions

photopion production

$p + \gamma_{bg} \rightarrow p + \pi^0$

$\pi^0 \rightarrow \gamma + \gamma$

$p + \gamma_{bg} \rightarrow n + \pi^+$

$\pi^+ \rightarrow \nu_\mu + \mu^+$

(similar for nuclei) $\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

Bethe-Heitler pair production

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A,Z) + e^- + e^+$

photodisintegration

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1,Z) + n$

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1,Z\text{-}1) + p$

...

nuclear decay

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A\text{-}4,Z\text{-}2) + \alpha$

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A,Z\text{+}1) + e^- + \underline{\nu_e}$

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A,Z\text{-}1) + e^{-+} + \nu_e$

$\text{nucleus}(A,Z)^* \rightarrow \text{nucleus}(A,Z) + \gamma$

nucleus-nucleus interactions

$p + p_{bg} \rightarrow \pi^0, \eta^0, \pi^+, \pi^-$

$\pi^0 \rightarrow \gamma + \gamma$

$\eta^0 \rightarrow \gamma + \gamma$

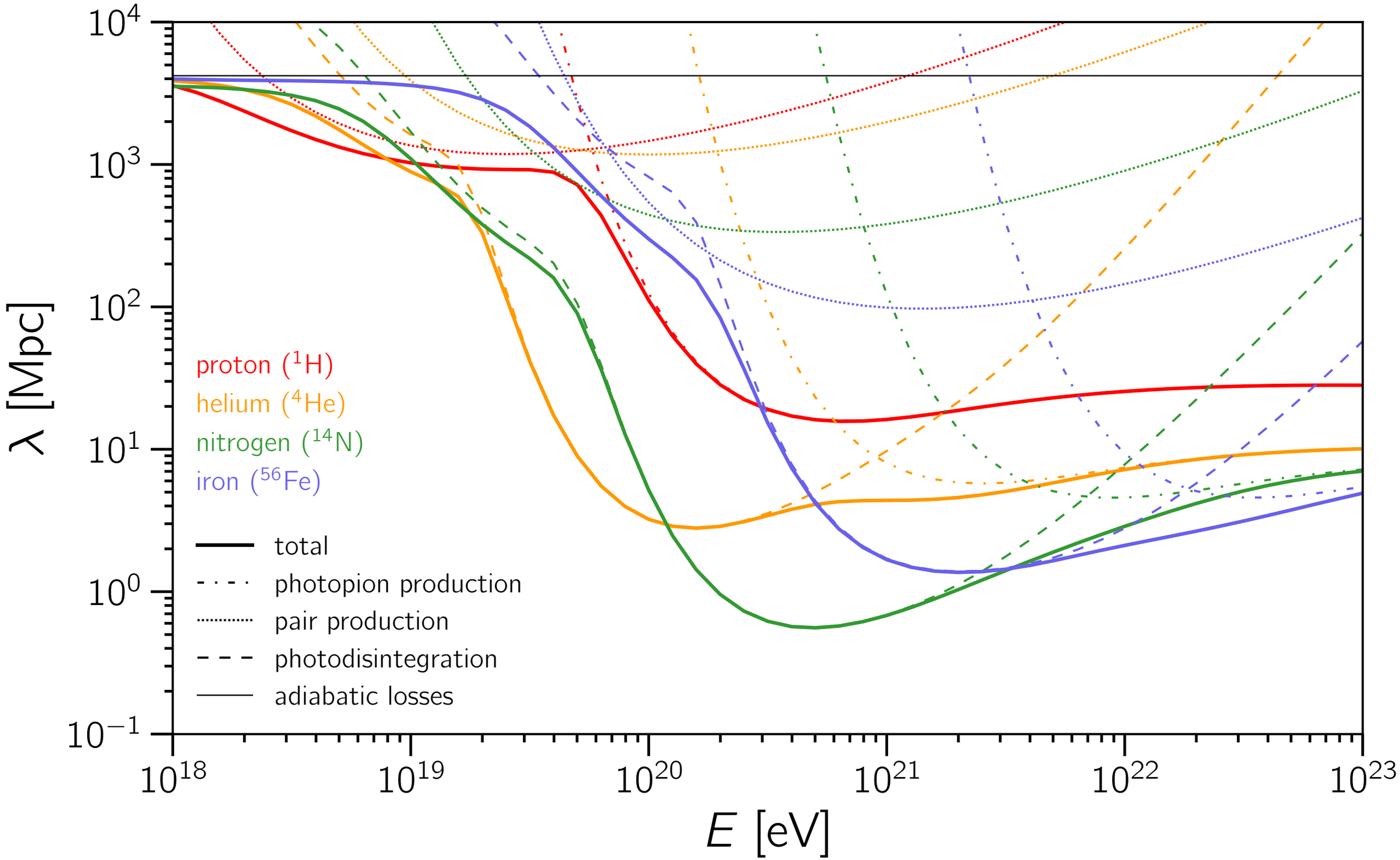
$\pi^+ \rightarrow \nu_\mu + \mu^+$

$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

$\pi^- \rightarrow \underline{\nu_\mu} + \mu^-$

(similar for nuclei) $\mu\text{-} \rightarrow e^- + \underline{\nu_e} + \nu_\mu$

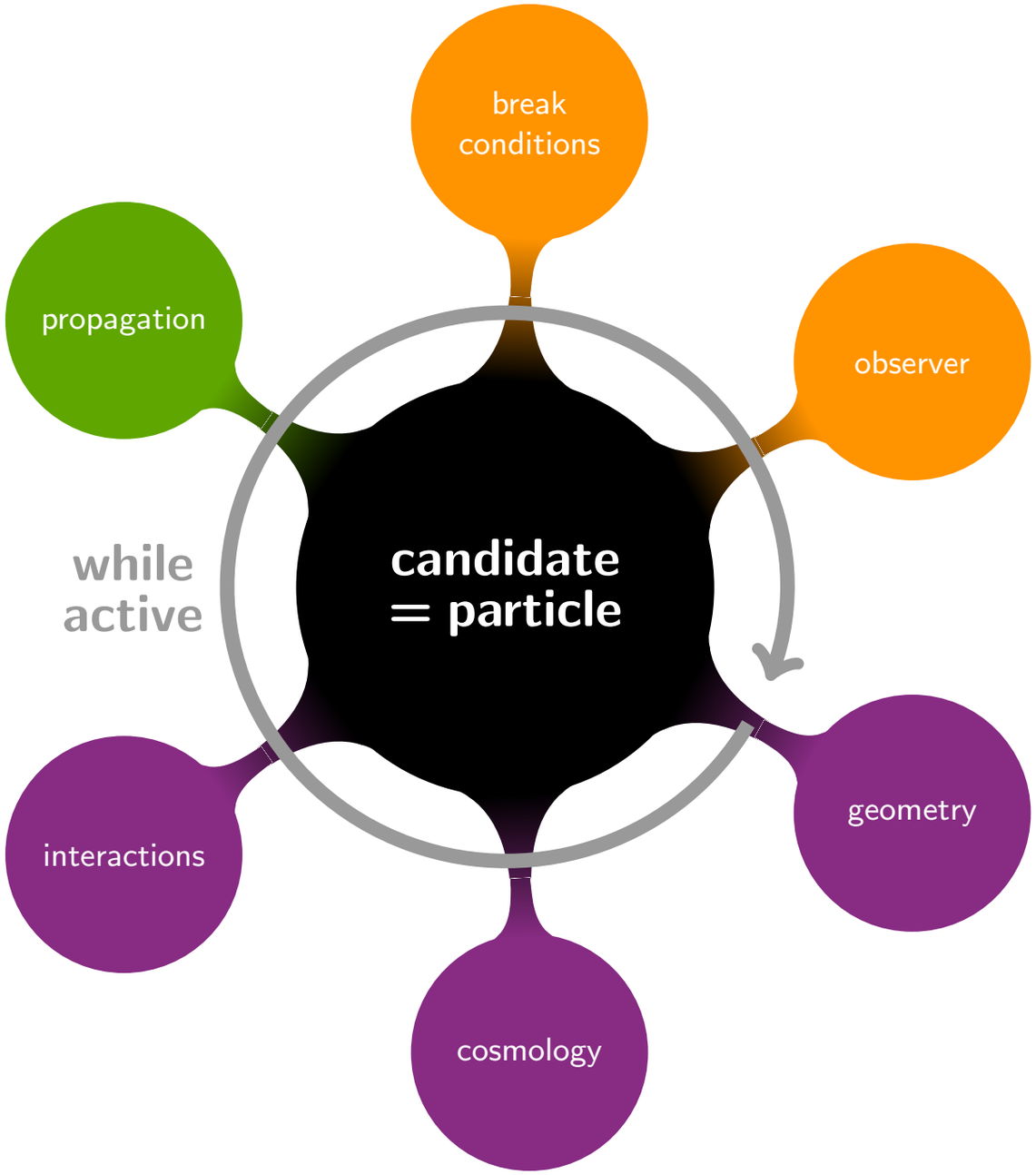
ingredients for UHECR propagation: interactions



CRPropa: an overview

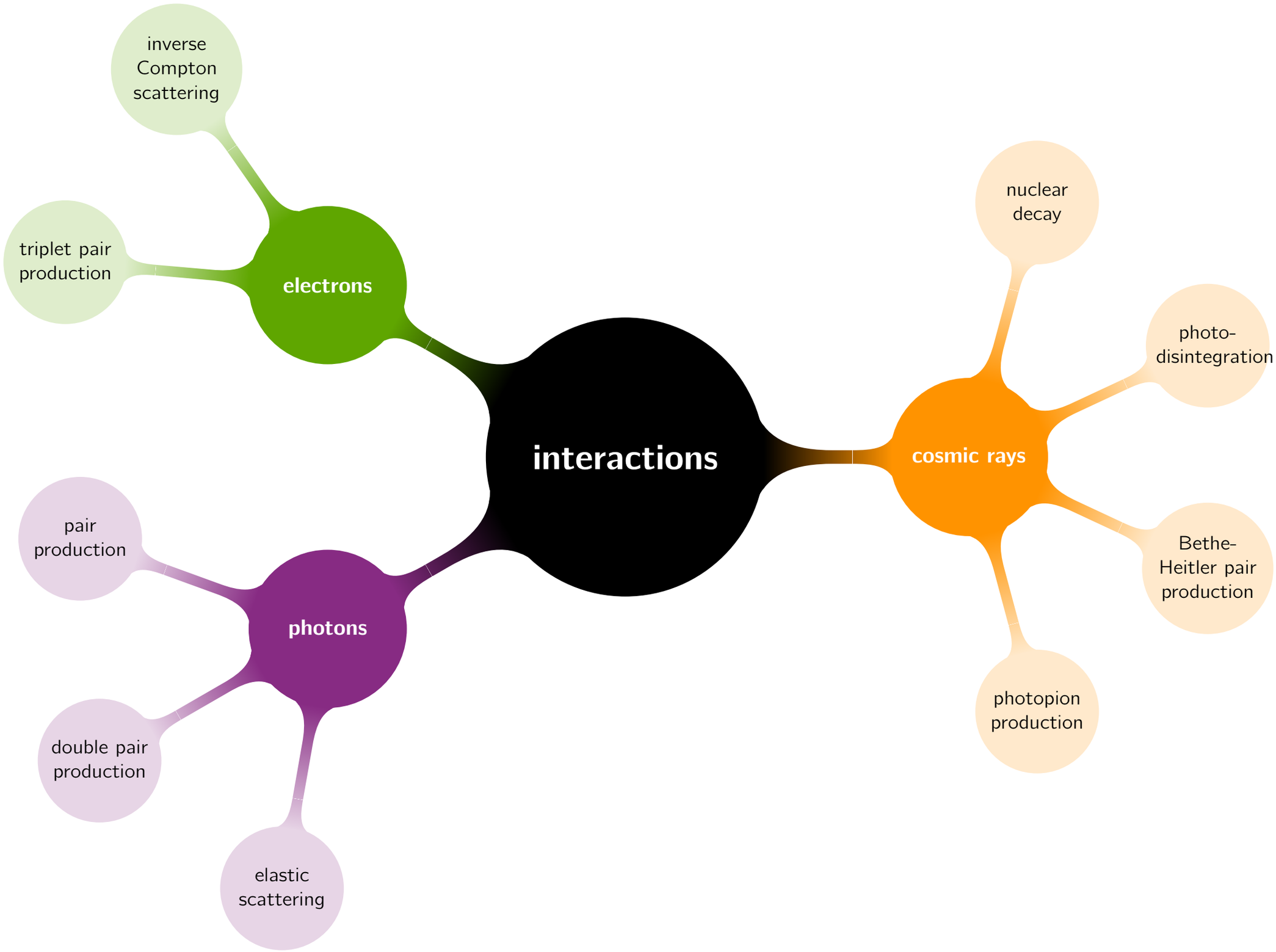
Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142

- publicly available Monte Carlo code
- modular structure
- propagation of cosmic rays, gamma rays, neutrinos
- galactic and extragalactic propagation
- modular structure
- parallelisation with OpenMP
- development on Github: https://github.com/CRPropa/CRPropa3
- **CRPropa 3.2 coming out very soon!**

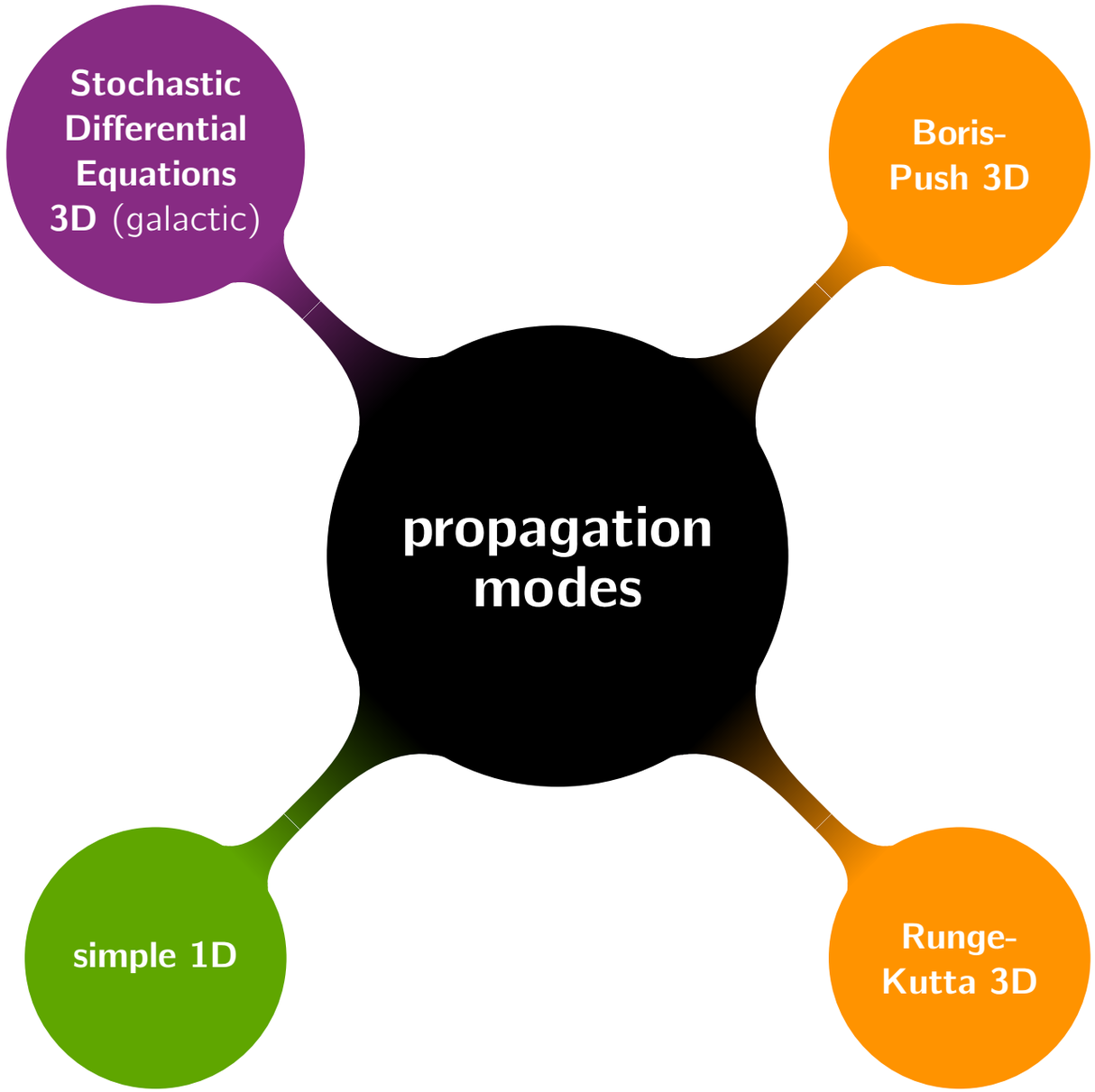


crpropa.desy.de

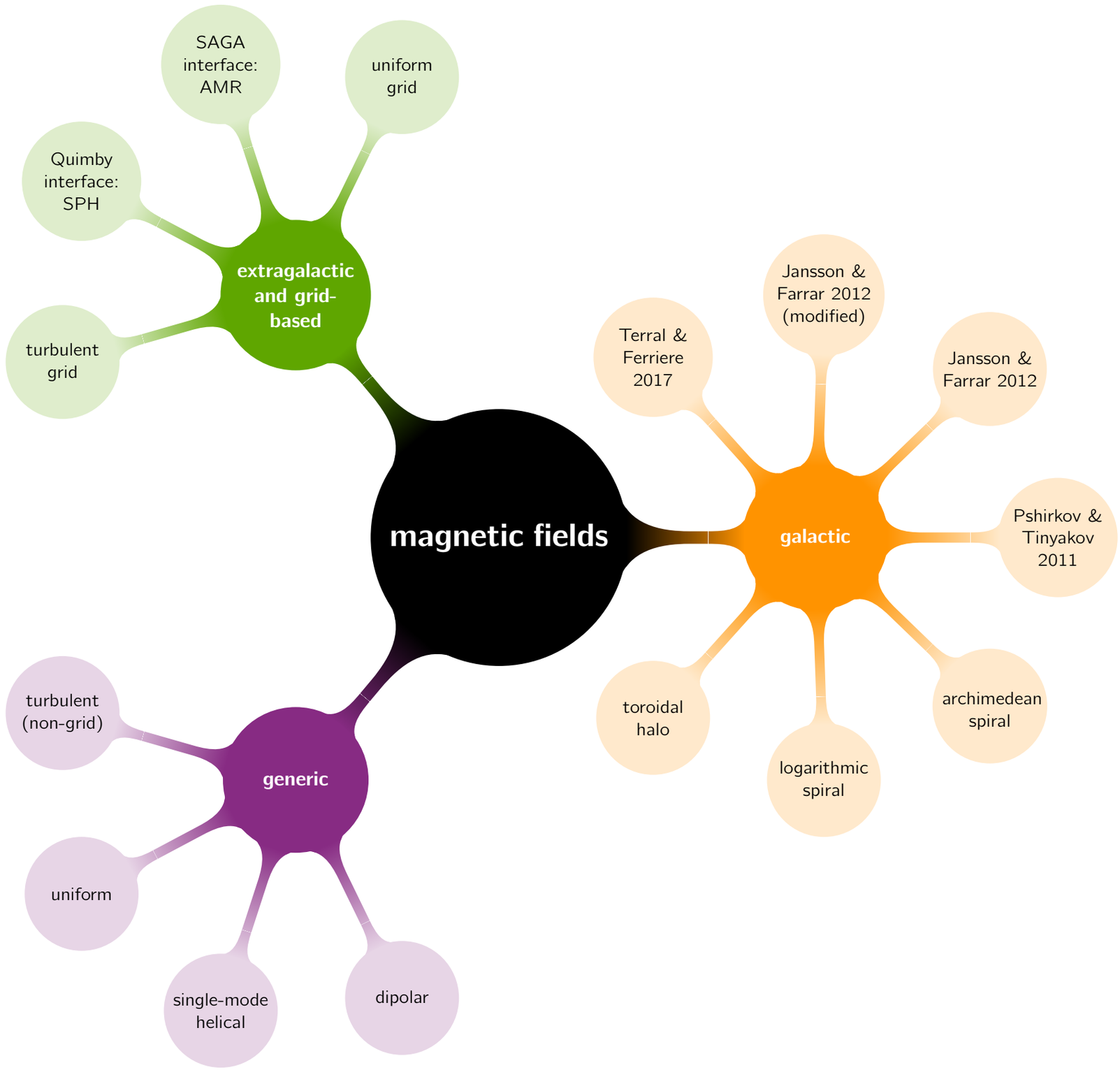
CRPropa: interactions



CRPropa: propagation modes



CRPropa: magnetic fields

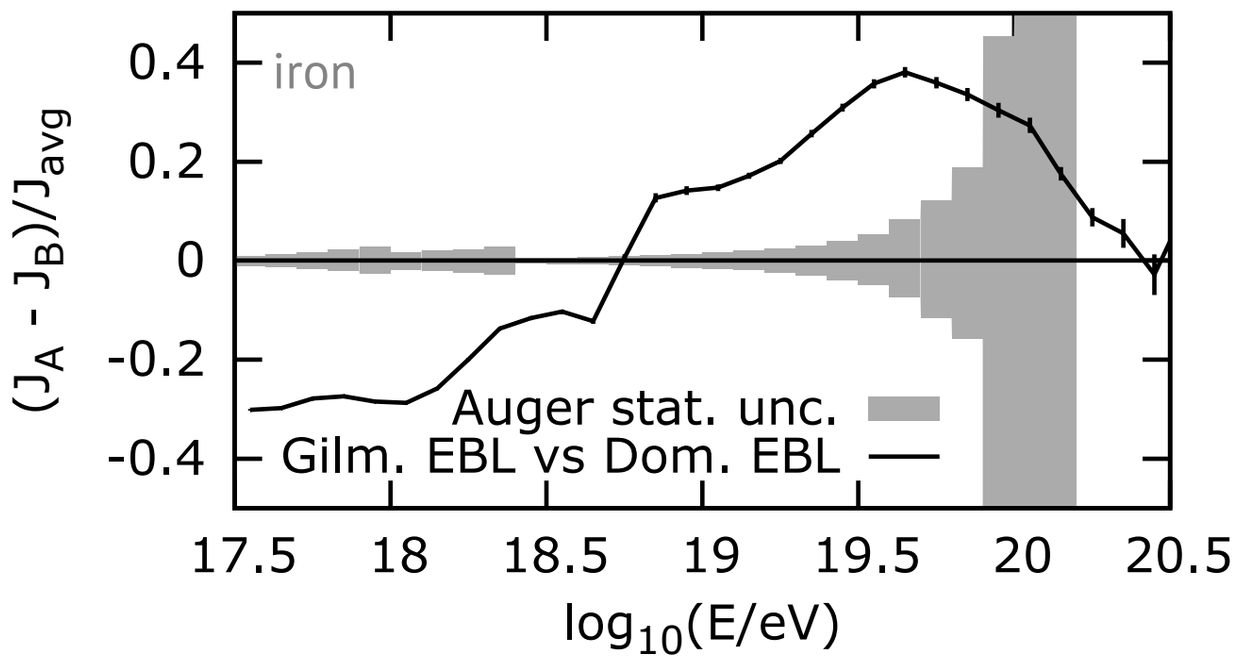


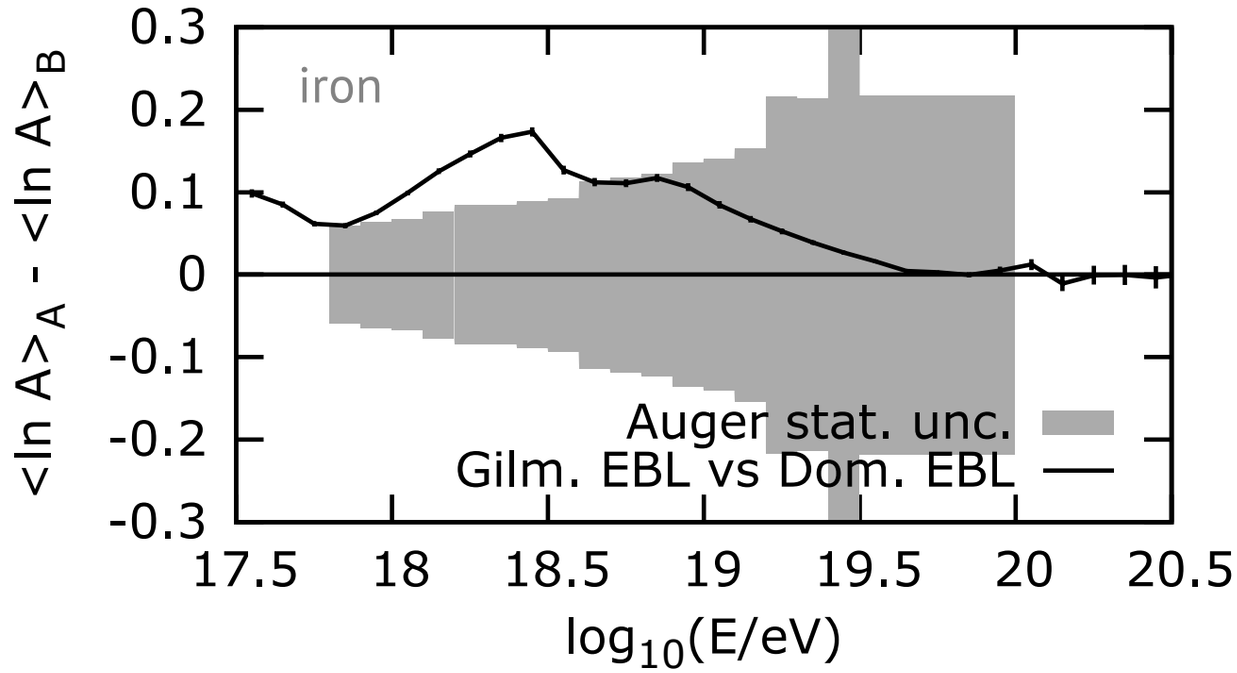
what are the relevant uncertainties for UHECR propagation?

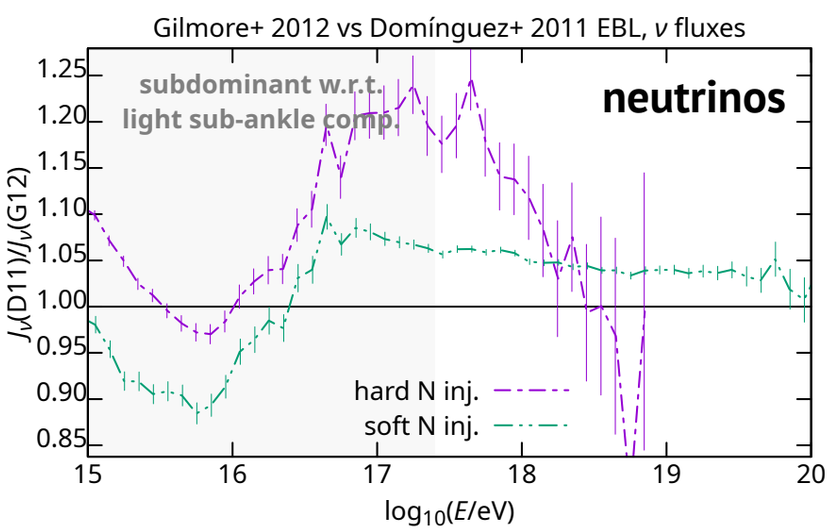
UHECR propagation uncertainties: EBL model

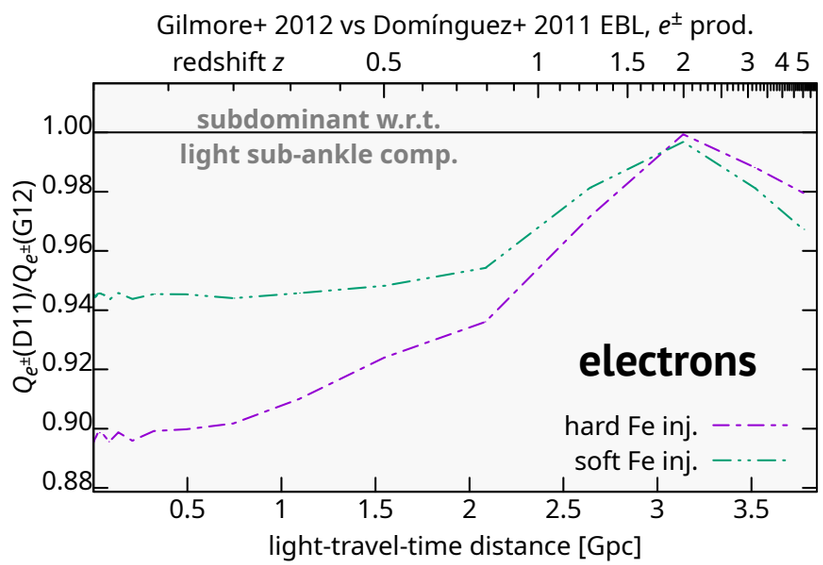
Alves Batista, Boncioli, di Matteo, van Vliet, Walz. JCAP 10 (2015) 063. arXiv:1508.01824

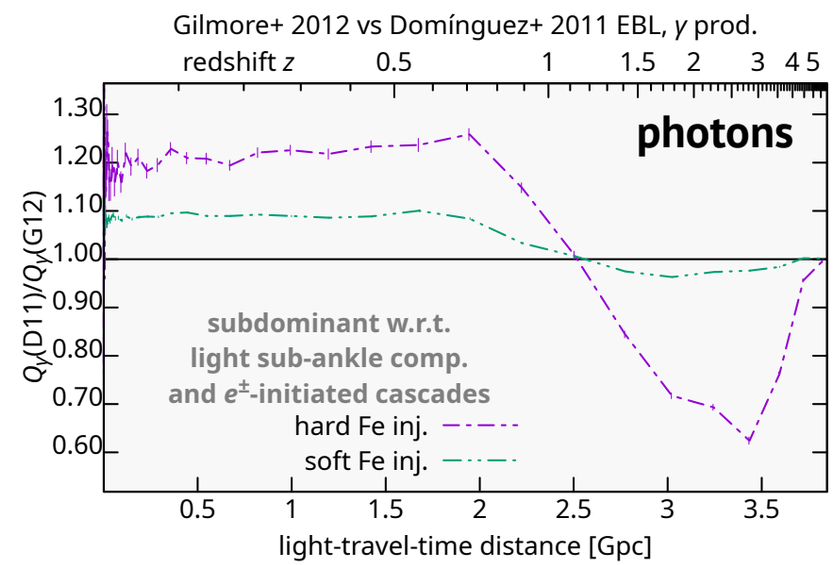
Alves Batista, Boncioli, di Matteo, van Vliet. JCAP 05 (2019) 006. arXiv:1901.01244







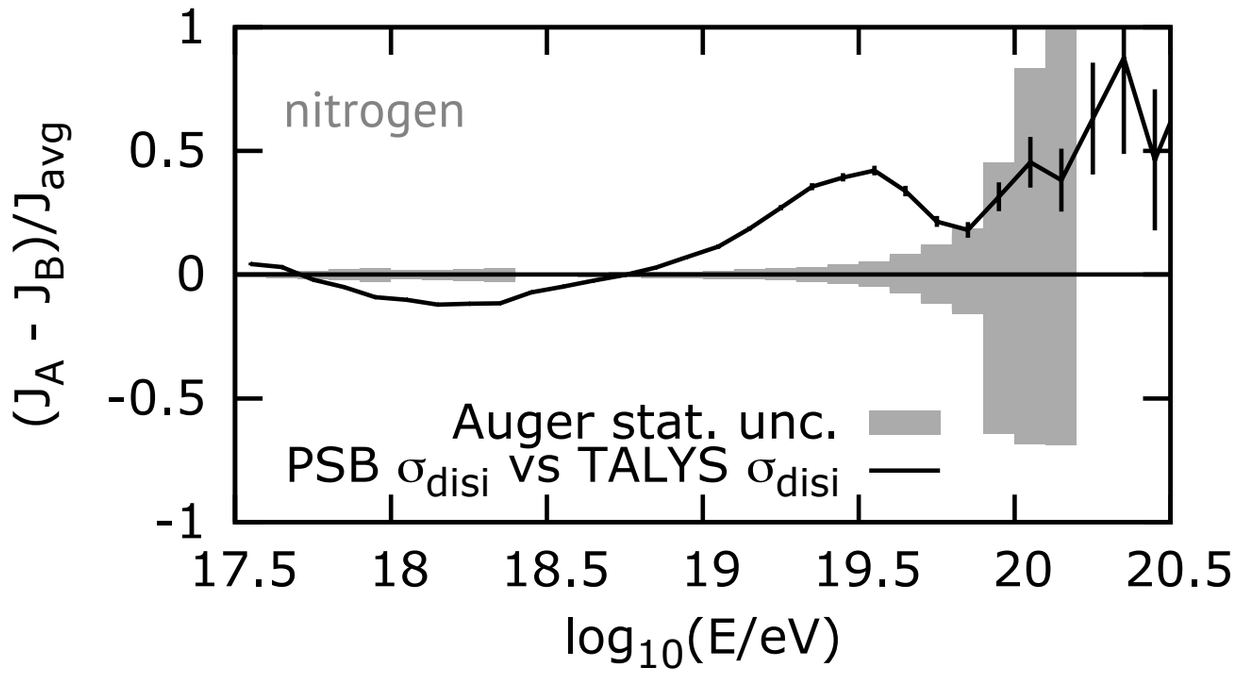


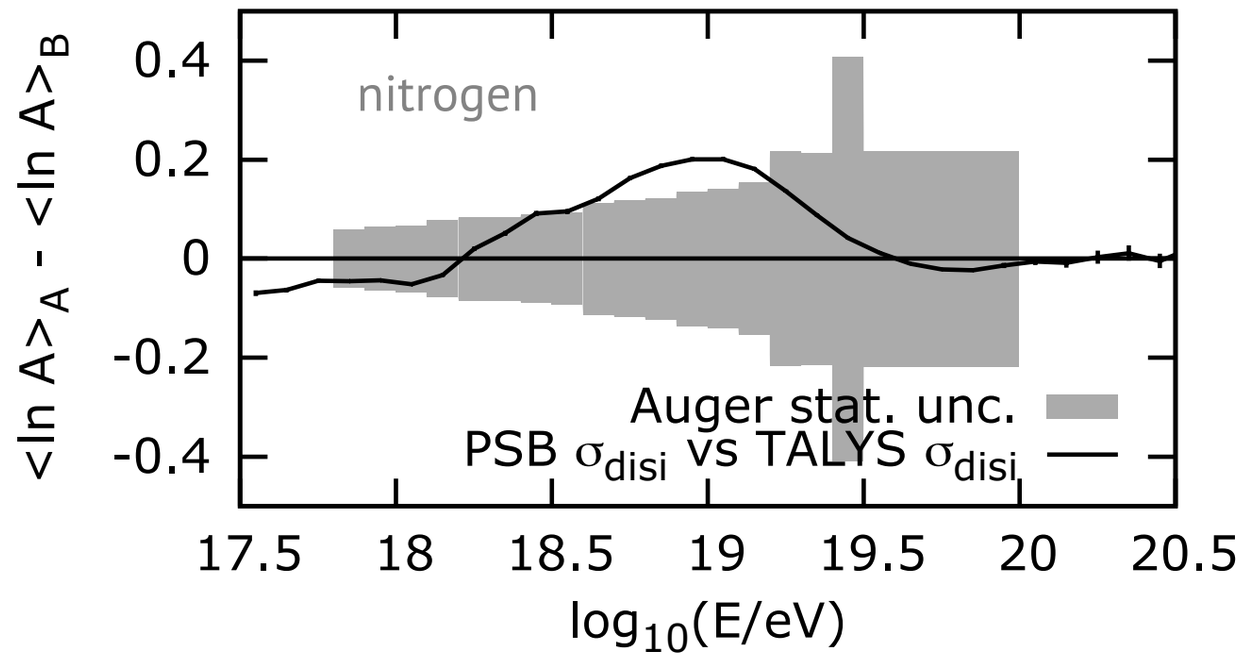


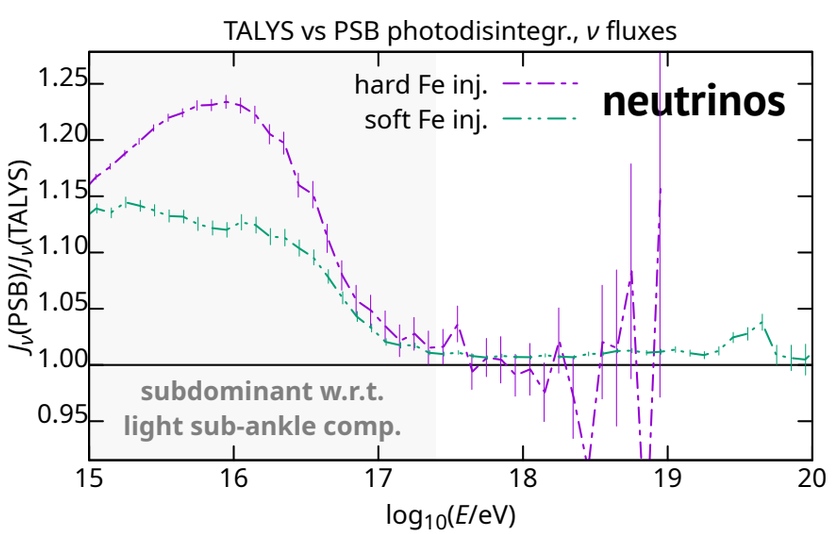
UHECR propagation uncertainties: photodisintegration

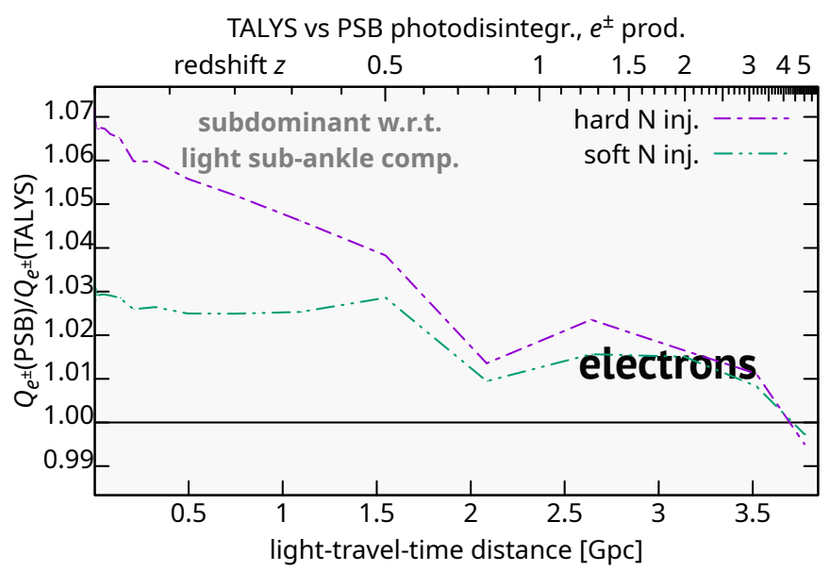
Alves Batista, Boncioli, di Matteo, van Vliet, Walz. JCAP 10 (2015) 063. arXiv:1508.01824

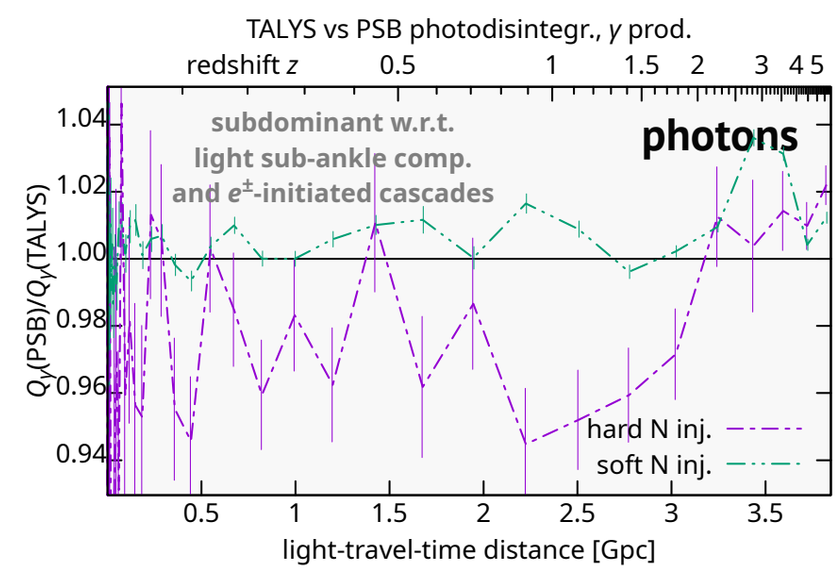
Alves Batista, Boncioli, di Matteo, van Vliet. JCAP 05 (2019) 006. arXiv:1901.01244







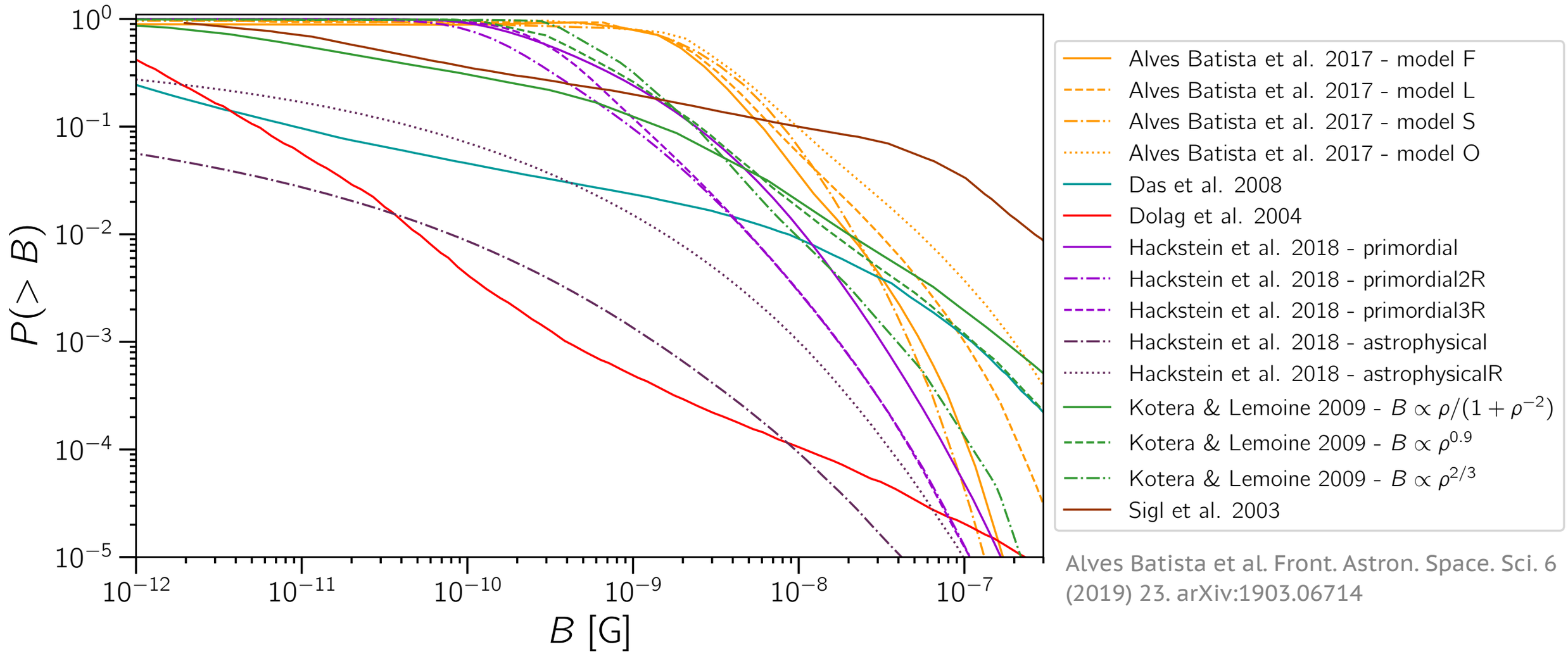




what are the prospects for UHECR astronomy?

the effects of magnetic fields

UHECR astronomy?

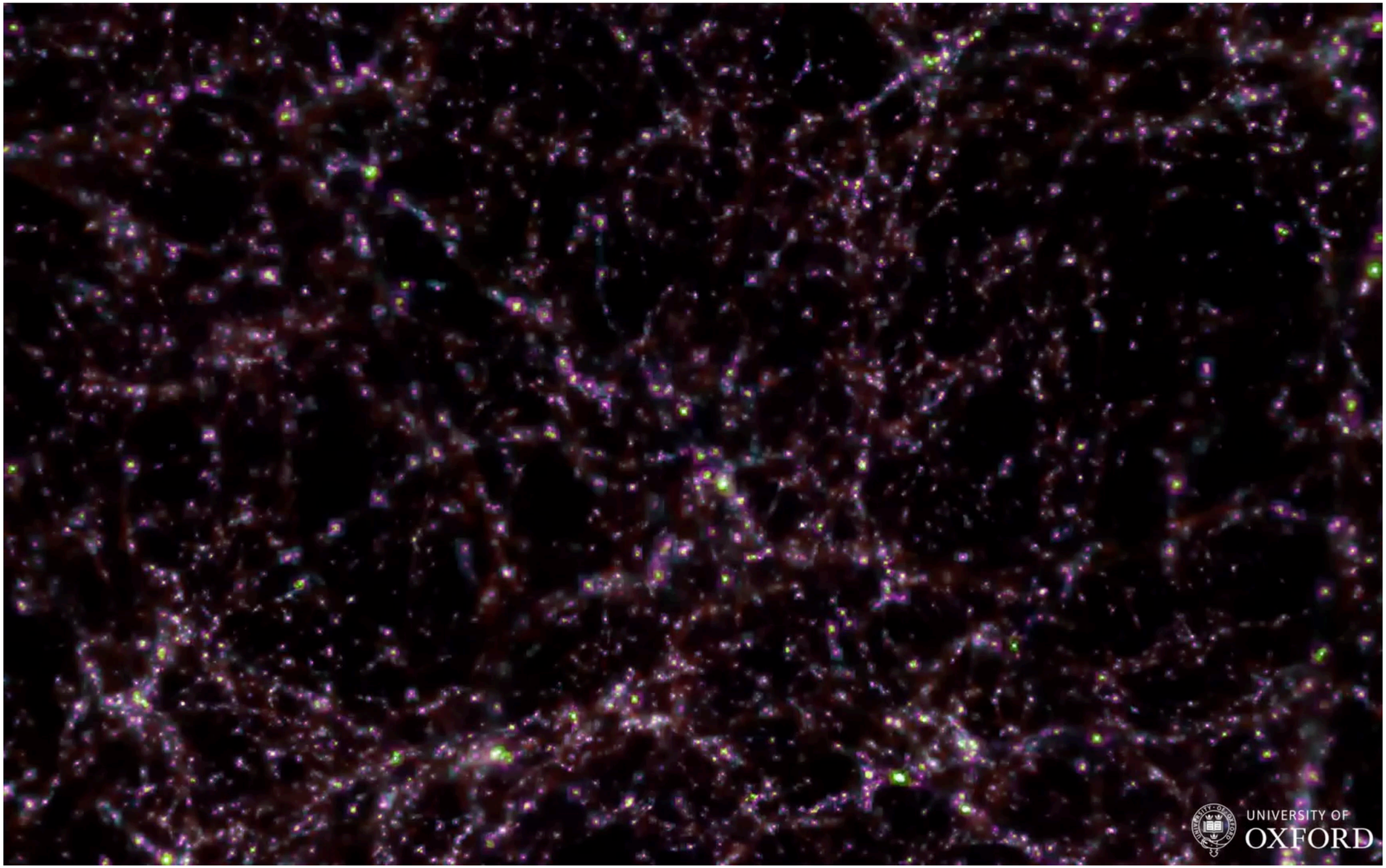


Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

- cosmological simulations of the cosmic web give VERY different results
- power spectrum of magnetic fields affects UHECR astronomy
- **we know nothing about extragalactic magnetic fields**
- **...but we can set limits**

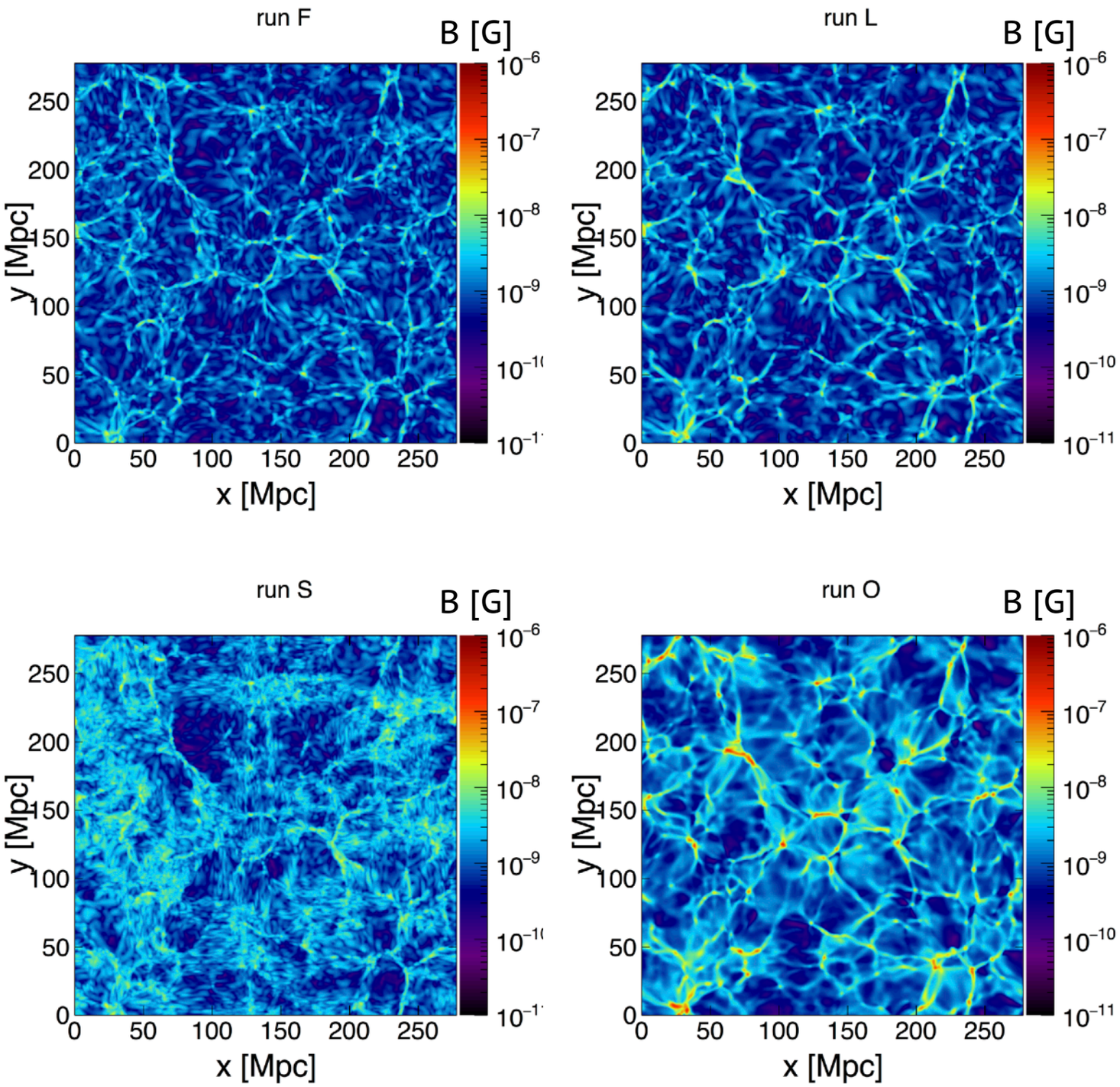
UHECR astronomy prospects: MHD simulations

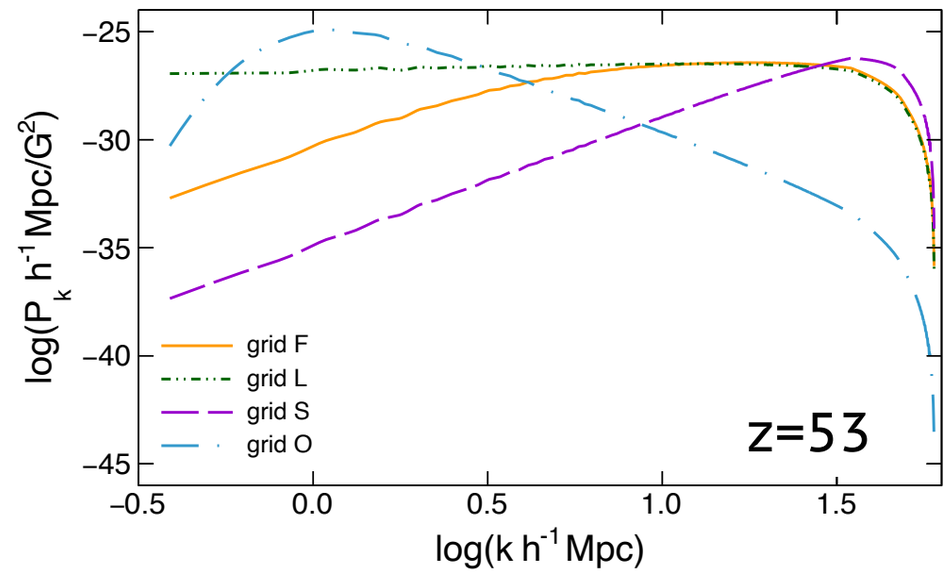
Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

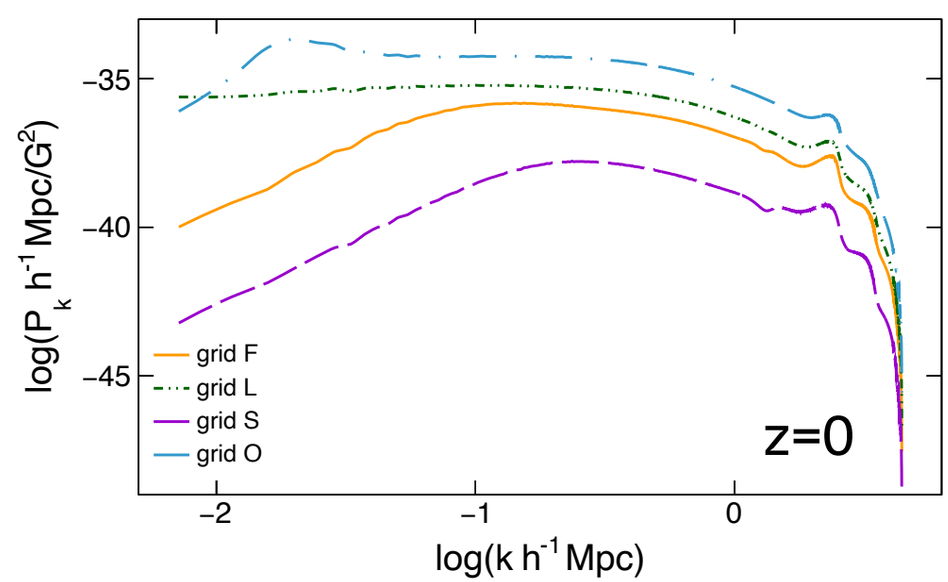


UHECR deflections in extragalactic magnetic fields

Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869







UHECR deflections in extragalactic magnetic fields

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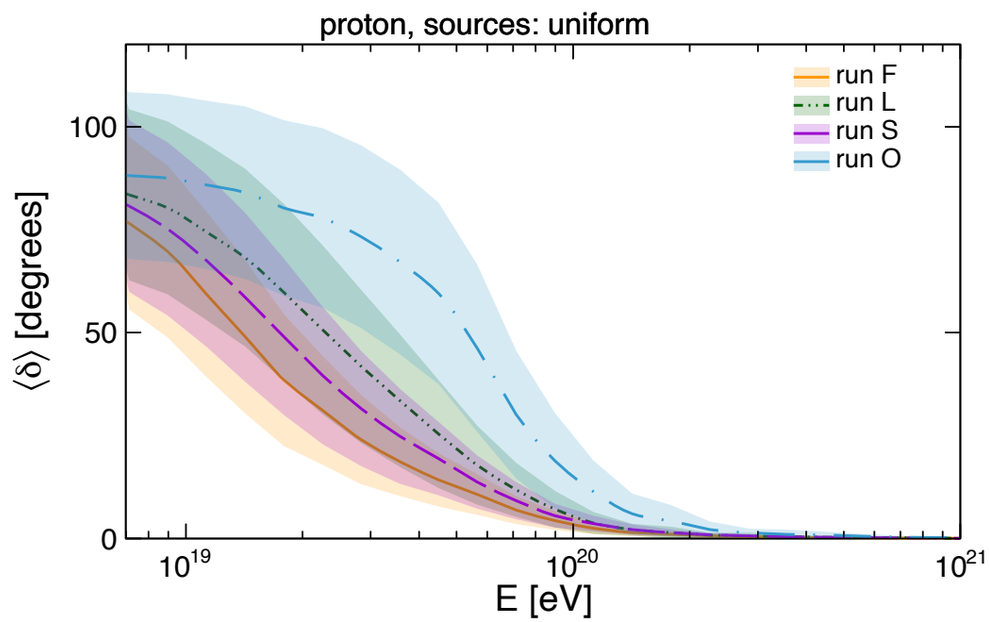
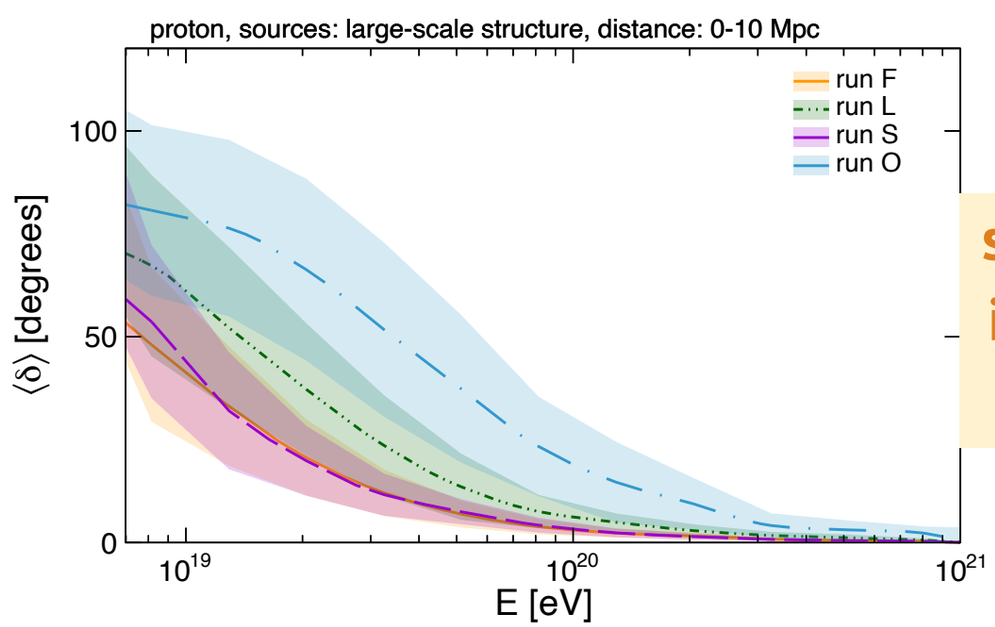
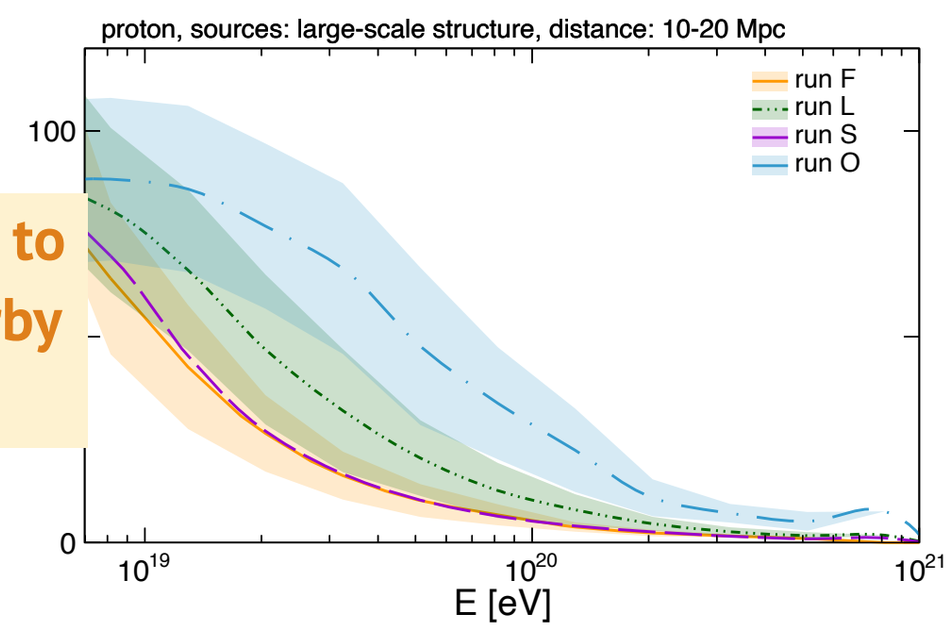




still possible to identify nearby sources!



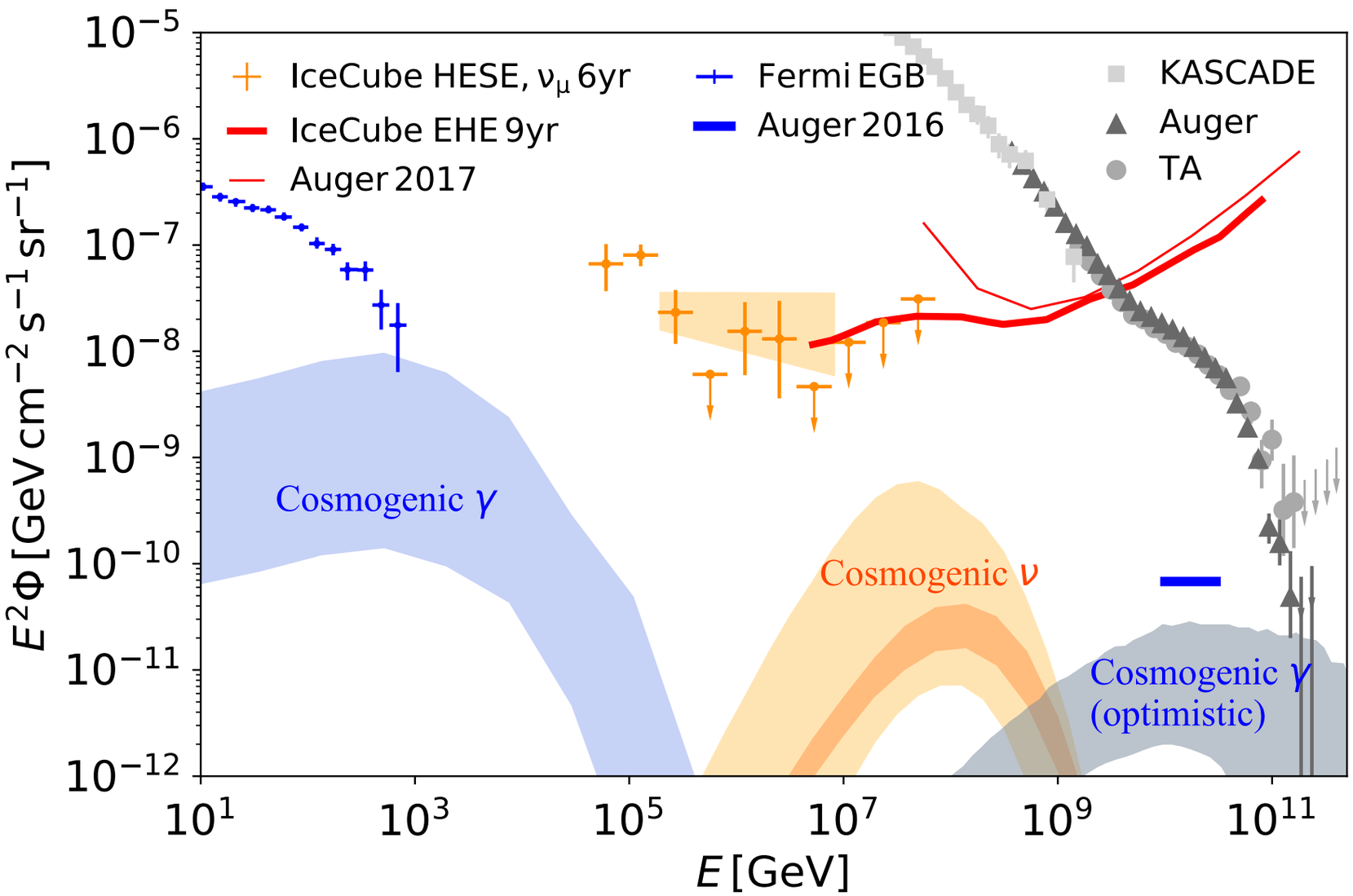
In the worst case scenario UHECR astronomy is not impossible -- but it is not very easy either.

use multiple messengers

cosmogenic neutrinos and photons

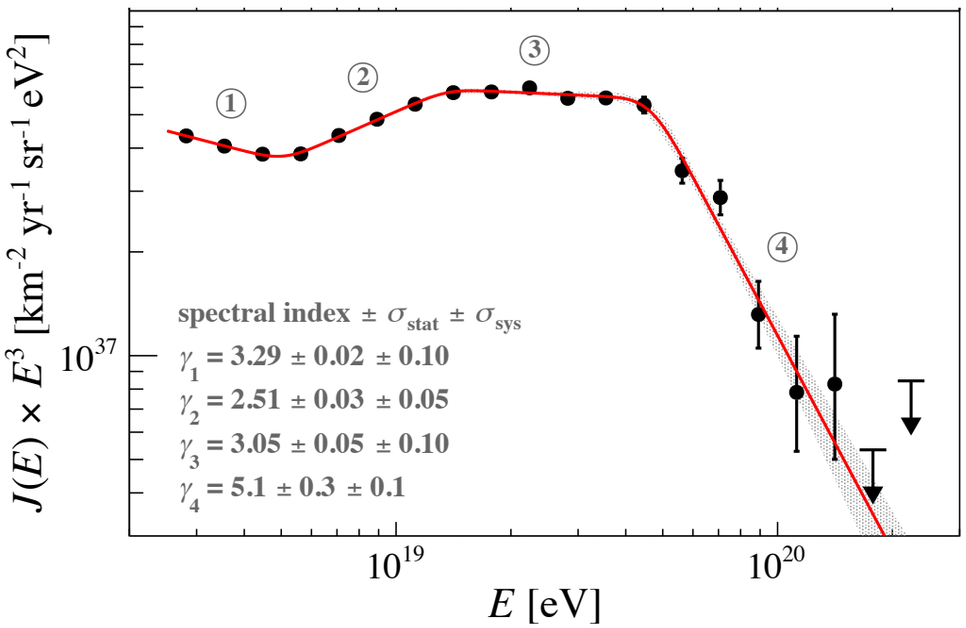
diffuse neutrinos and photons

EeV CRs, **PeV neutrinos**, **TeV gamma rays**:
is there a **cosmogenic** connection?



UHECR measurements

spectrum

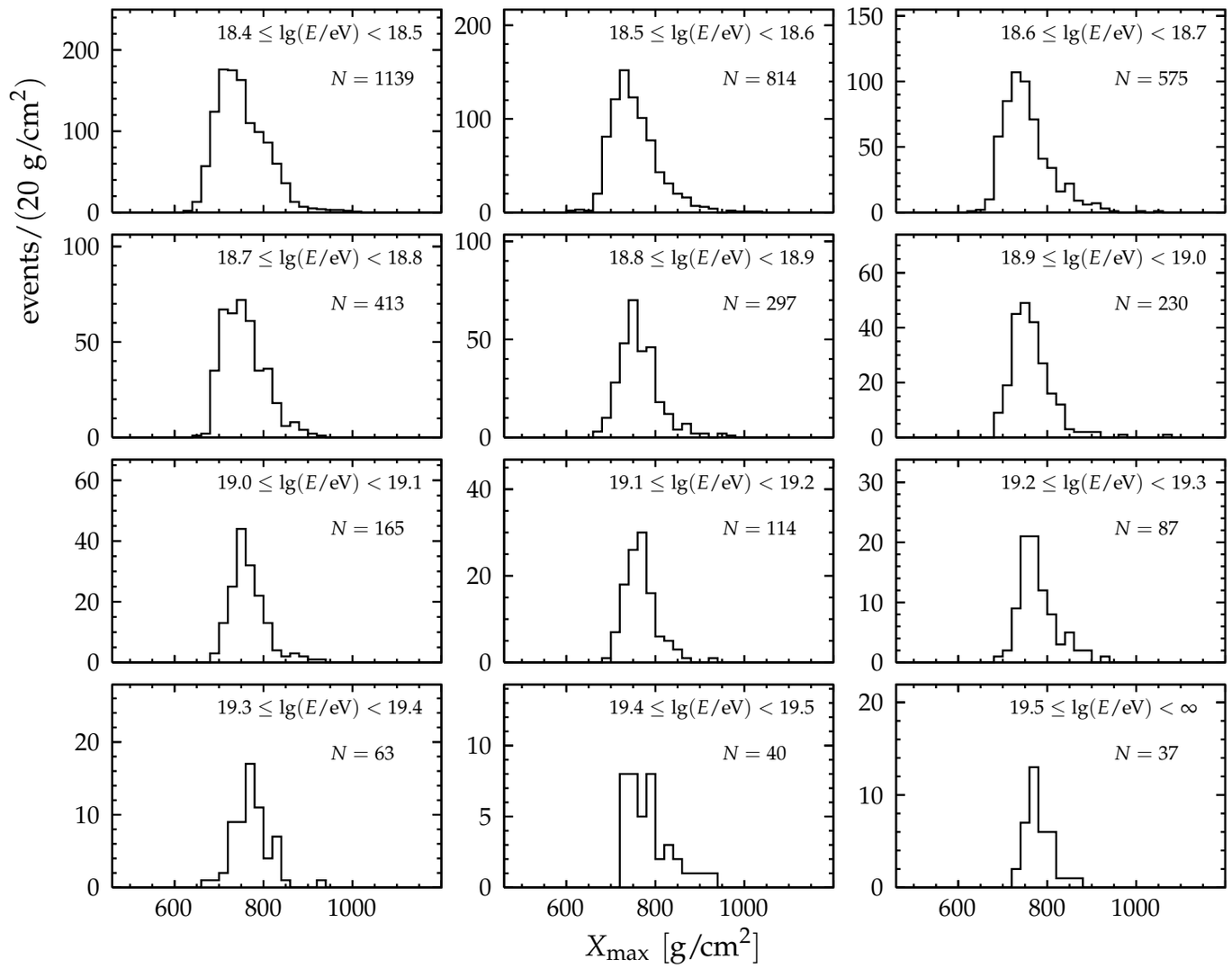


Pierre Auger Collaboration. Phys. Rev. Lett. 125 (2020) 121106. arXiv:2008.06488

combined spectrum-composition fit

observations at Earth (=after intergalactic propagation)

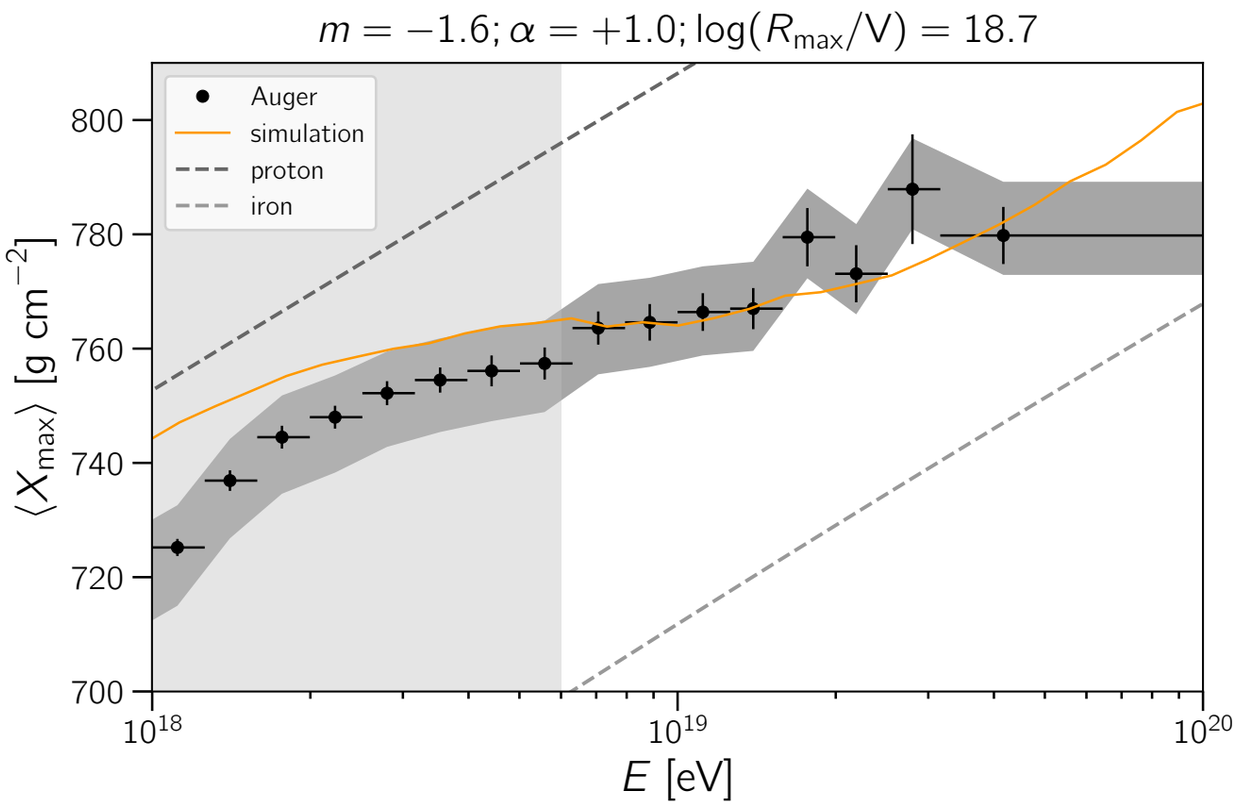
composition

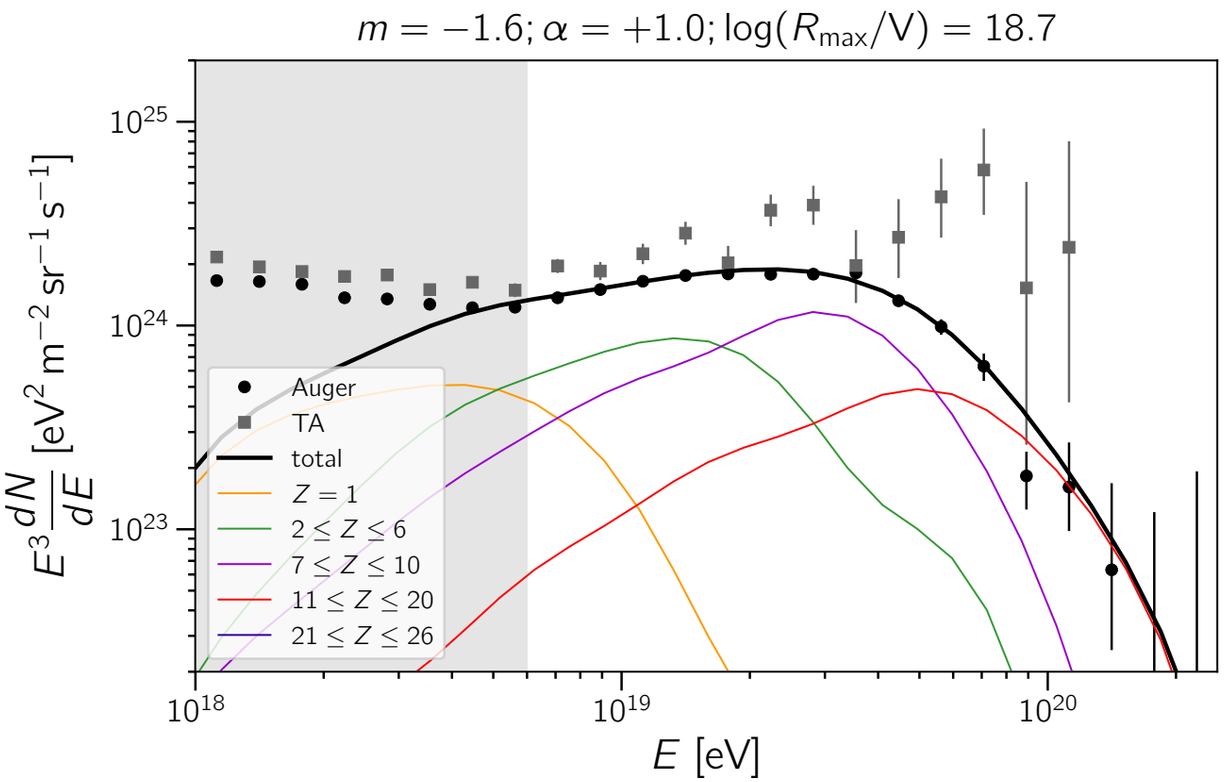


Pierre Auger Collaboration. Phys. Rev.D 90 (2014) 122005. arXiv:1409.4809

interpreting the data: spectrum-composition fit

Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879





CRPropa simulations with all relevant interactions

fit to Auger data (2017)

uniform source distribution up to z_{max}=1

five nuclear species: H, He, N, Si, Fe

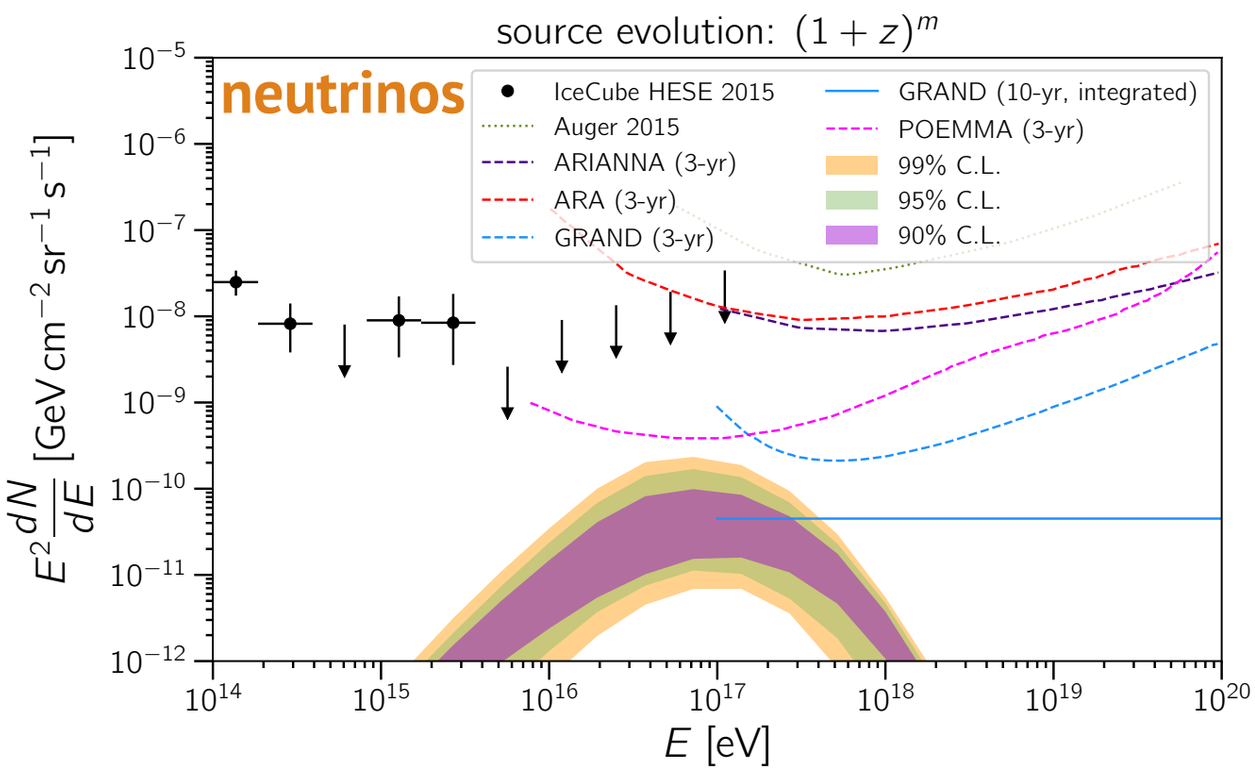
CR injection: power-law with exponential cut-off

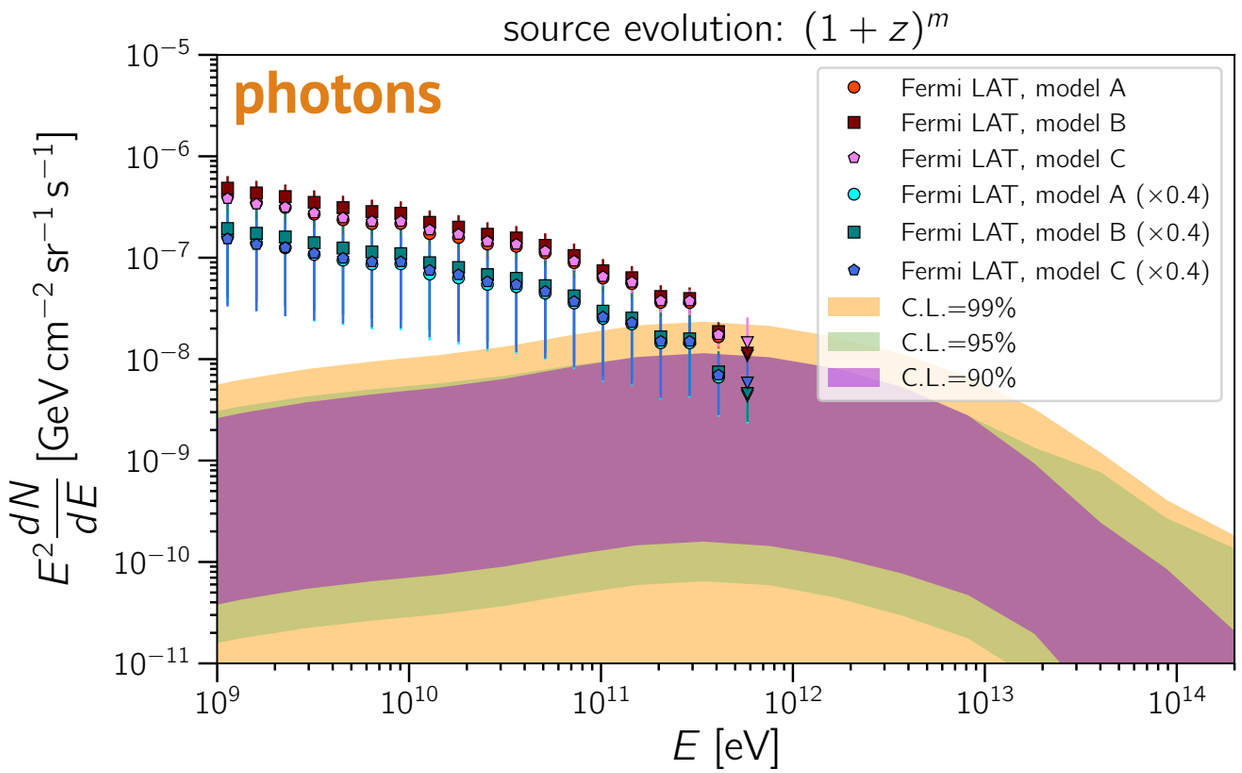
cosmological evolution of sources: $(1+z)^m$

fit favours negative source evolution with hard injection spectra dominate by CNO nuclei

interpreting the data: cosmogenic neutrinos and photons

Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879





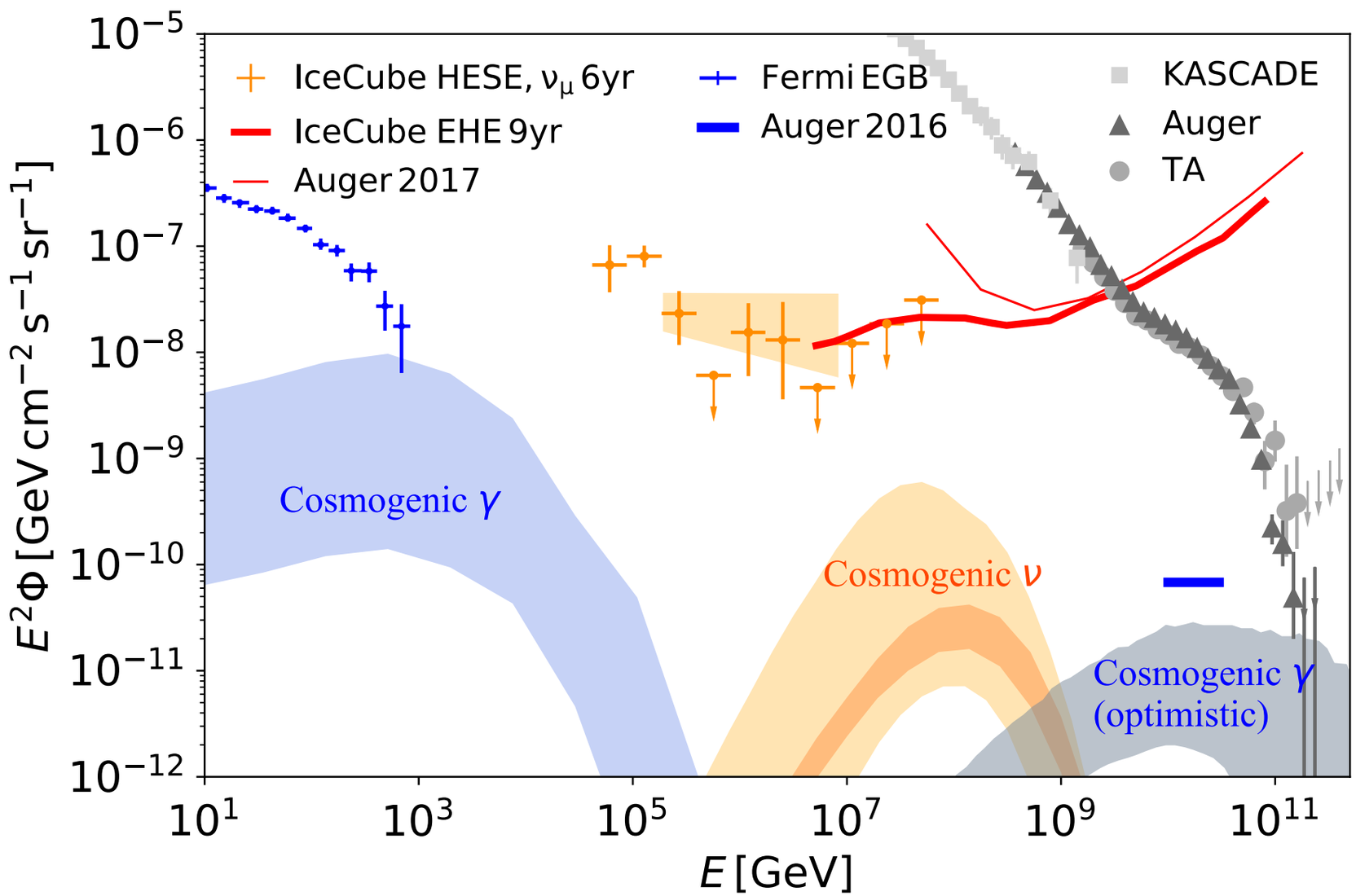
- these are **pessimistic estimates** (z_{max}=1)
- there are uncertainties due to photodisintegration uncertainties, hadronic interaction models [Heinze et al. 2019]
- magnetic fields may increase this flux [Wittkowski & Kampert 2019]
- even so, UHECR data does not seem to explain the diffuse neutrino and gamma-ray fluxes

diffuse neutrinos and photons

EeV CRs, **PeV neutrinos**, **TeV gamma rays**:

is there a **cosmogenic** connection? → **not clear**

is there a **source** connection?

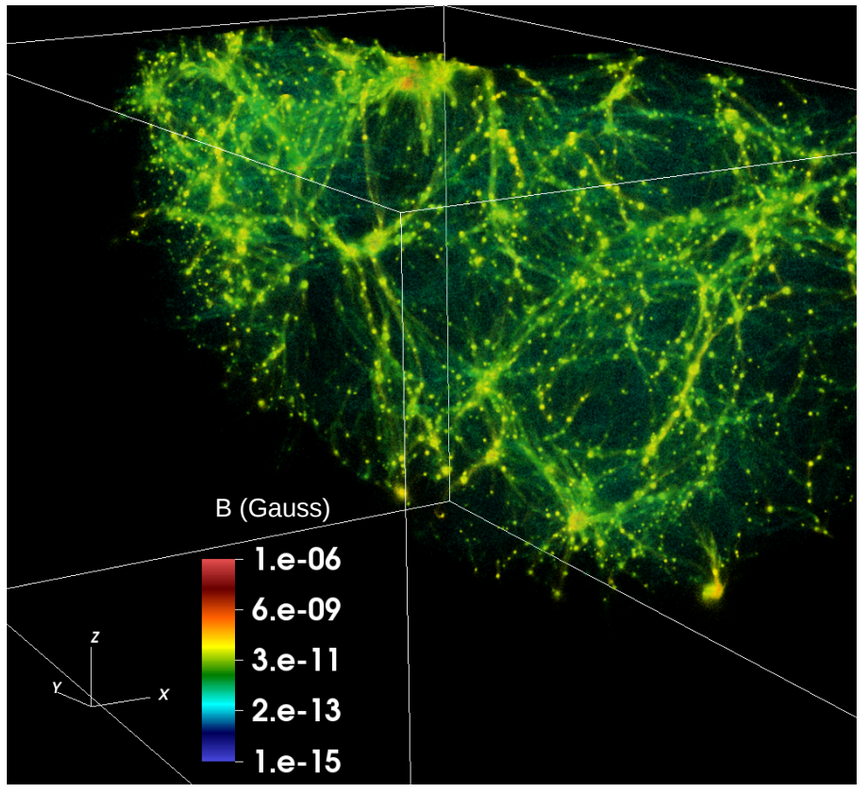


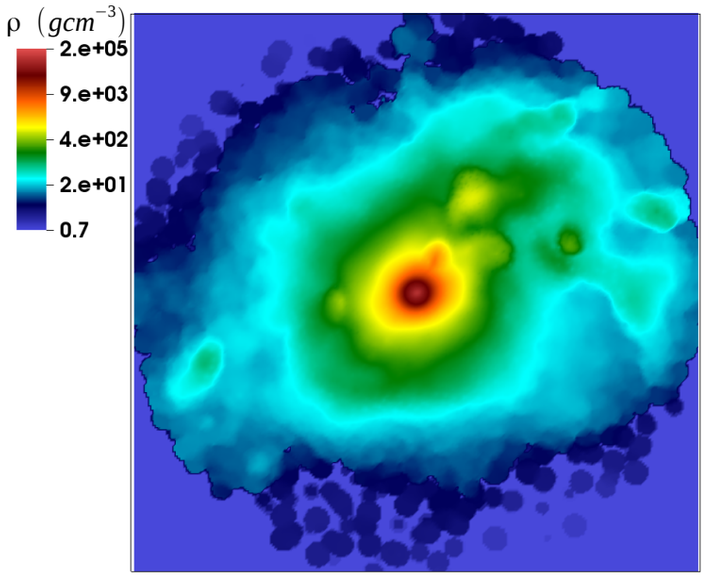
CR propagation in galaxy clusters

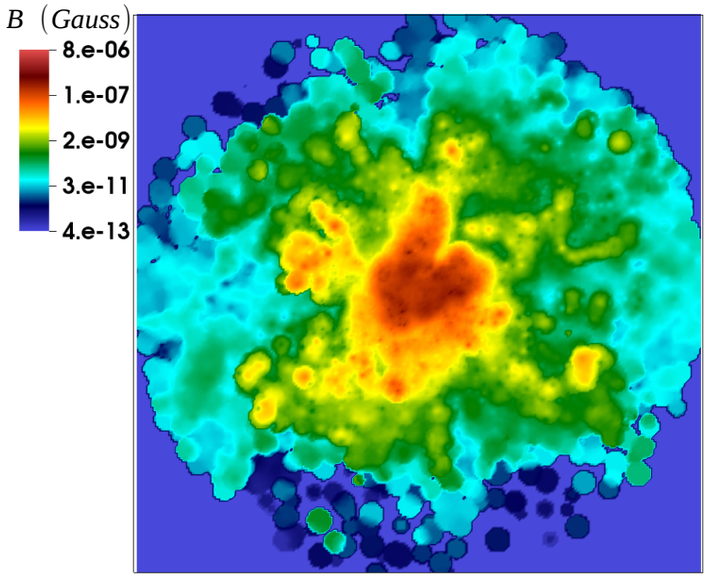
cosmological simulations of structure formation

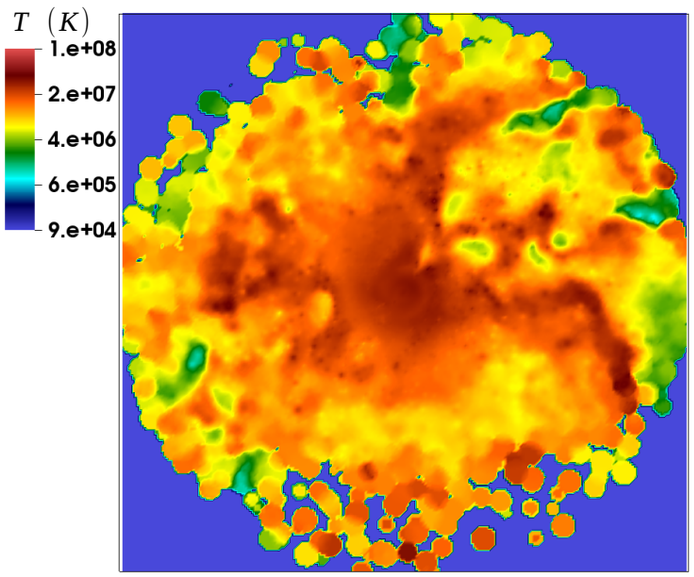
Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. arXiv:2101.07702

- use cosmological simulations of structure formation ~(130 Mpc)^3
- selected representative clusters of different masses
- CRPropa simulations
- consider all CR interactions with cluster photon fields, gas, etc.
- compute flux of neutrinos (CRs will be trapped)



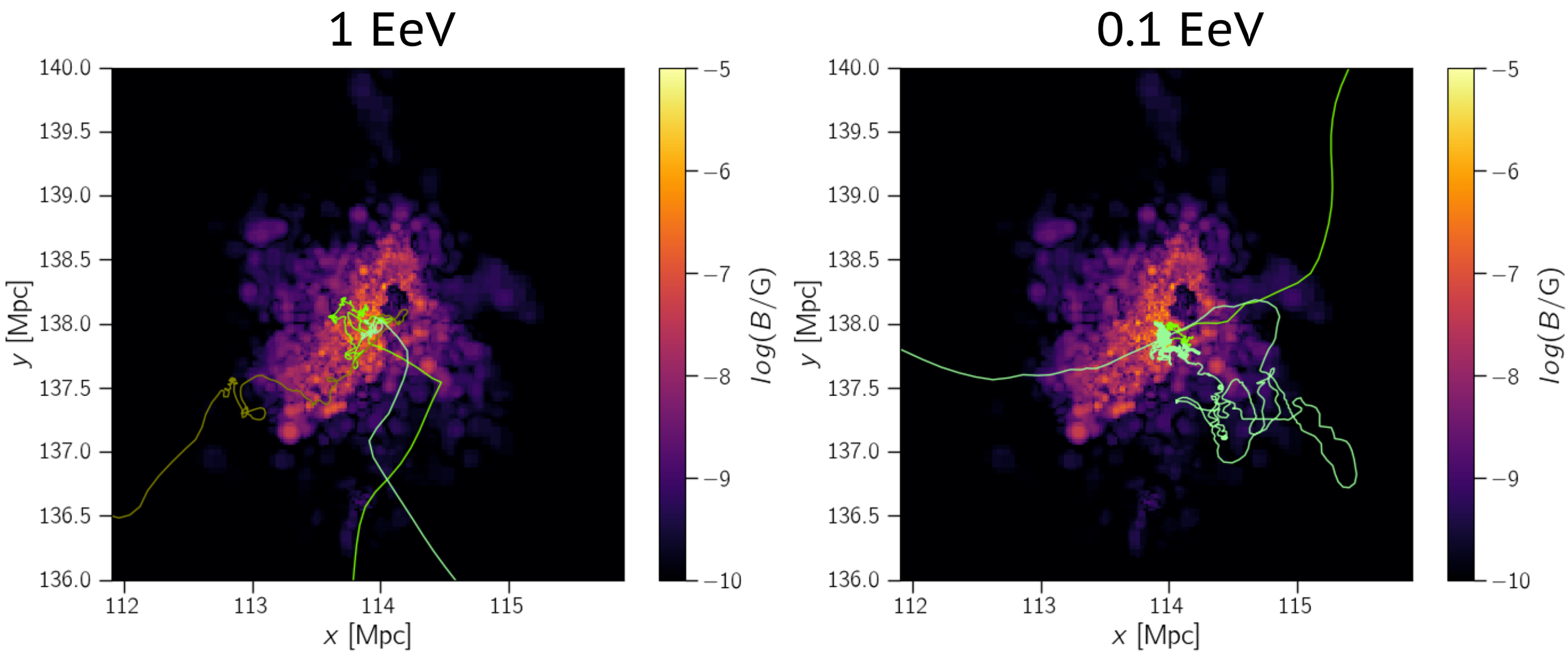






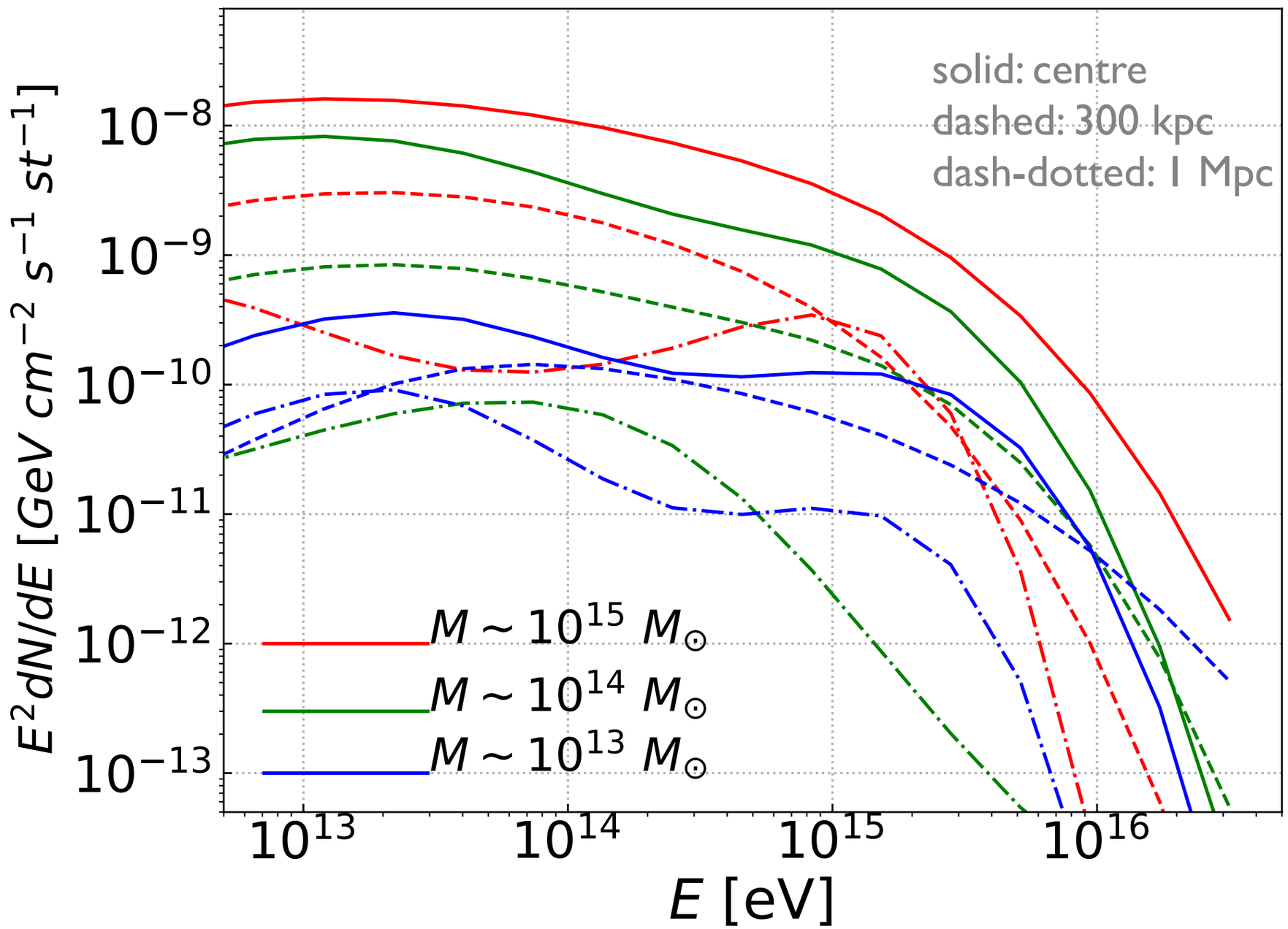
CR propagation in clusters

Alves Batista, de Gouveia Dal Pino, Dolag, Hussain. Proceedings IAU Focus Meeting FM8. arXiv:1811.03062



diffuse neutrino fluxes

Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. arXiv:2101.07702



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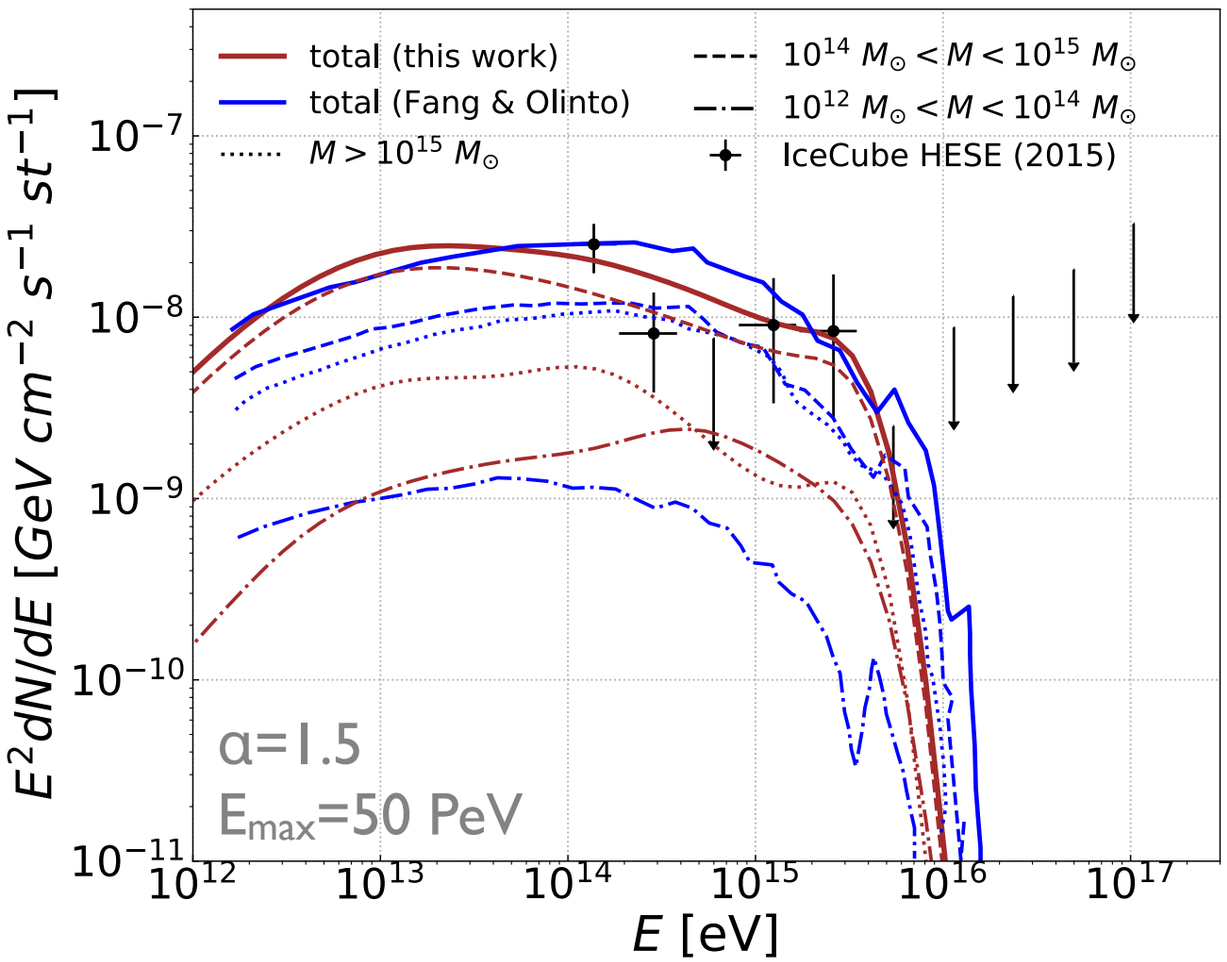
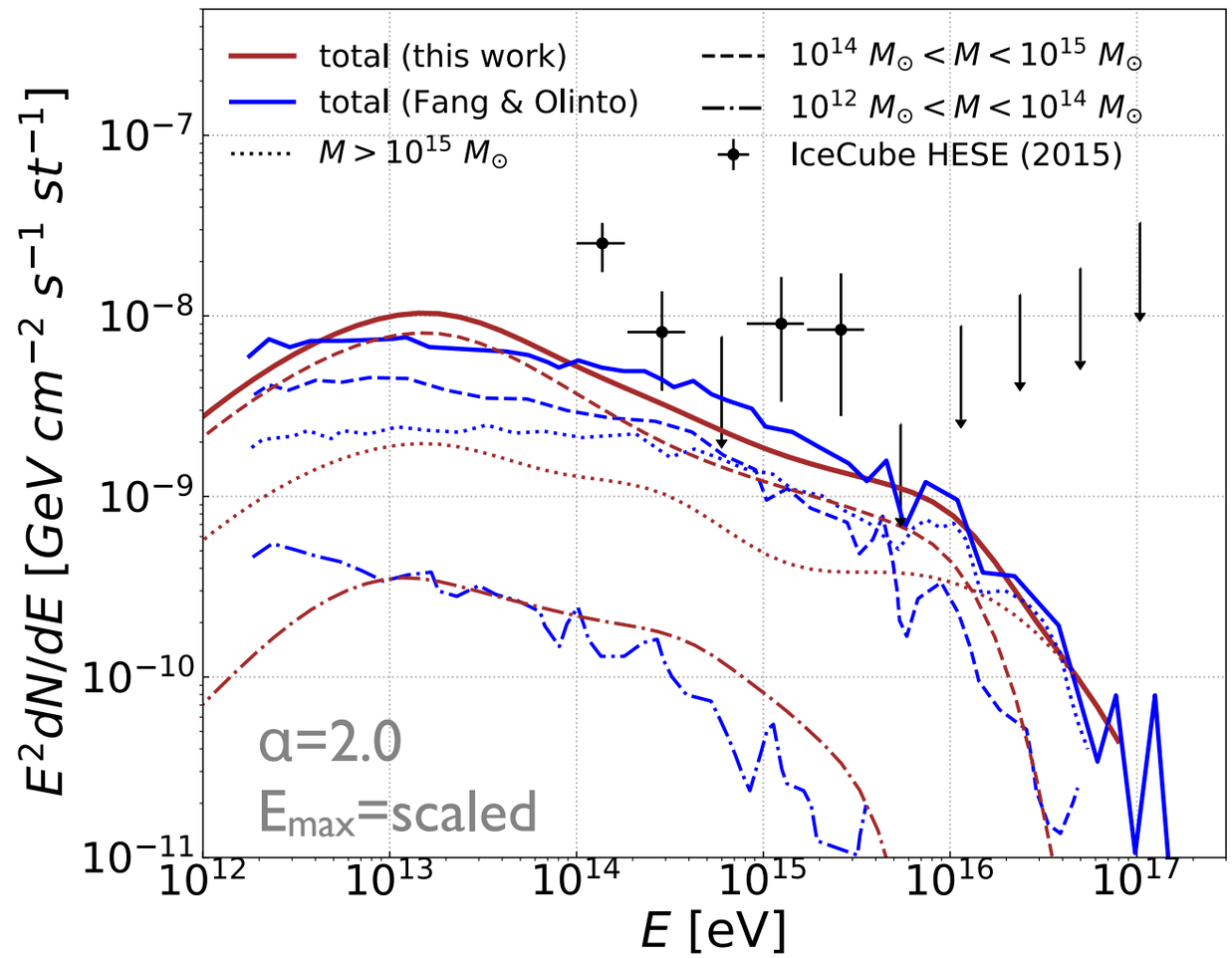
Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. arXiv:2101.07702





$$E_{\rm max} = 2.8 \times 10^{18} \left(\frac{M_{\rm cluster}}{10^{15} M_\odot}\right)^{2/3} \left(\frac{B_{\rm cluster}\ {\rm G}}{10^{-6}\ {\rm G}}\right)\ {\rm eV}$$

structure of this talk

part 1

UHECR propagation
UHECR astronomy
cosmogenic neutrinos and photons
high-energy particles from galaxy clusters

part 2

gamma-ray propagation
intergalactic magnetic fields (IGMFs)
multimessenger method for IGMF constraints
plasma instabilities: propagation effects

part 2

propagation of high-energy gamma rays

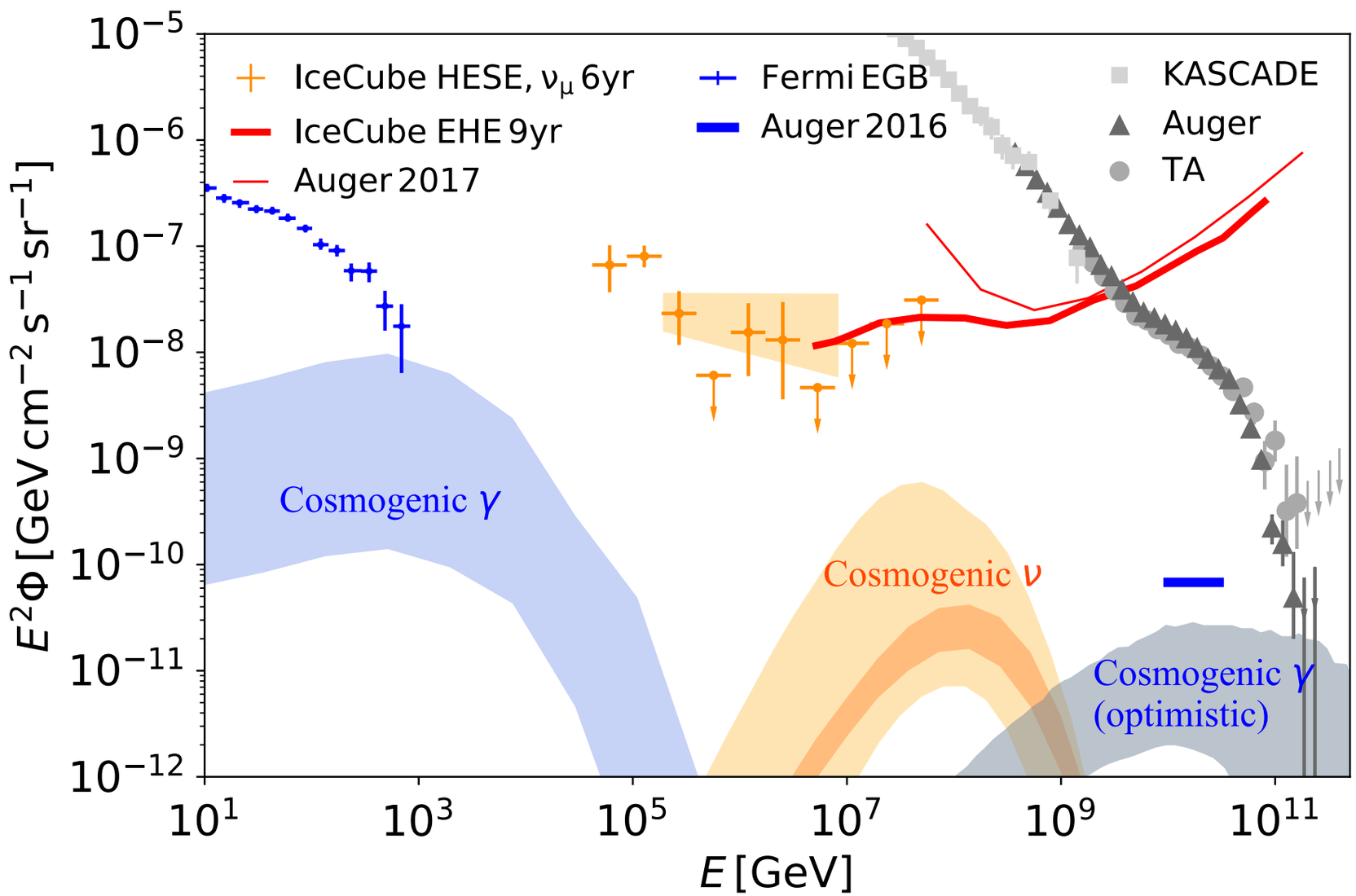
high-energy gamma rays rays

intergalactic magnetic fields

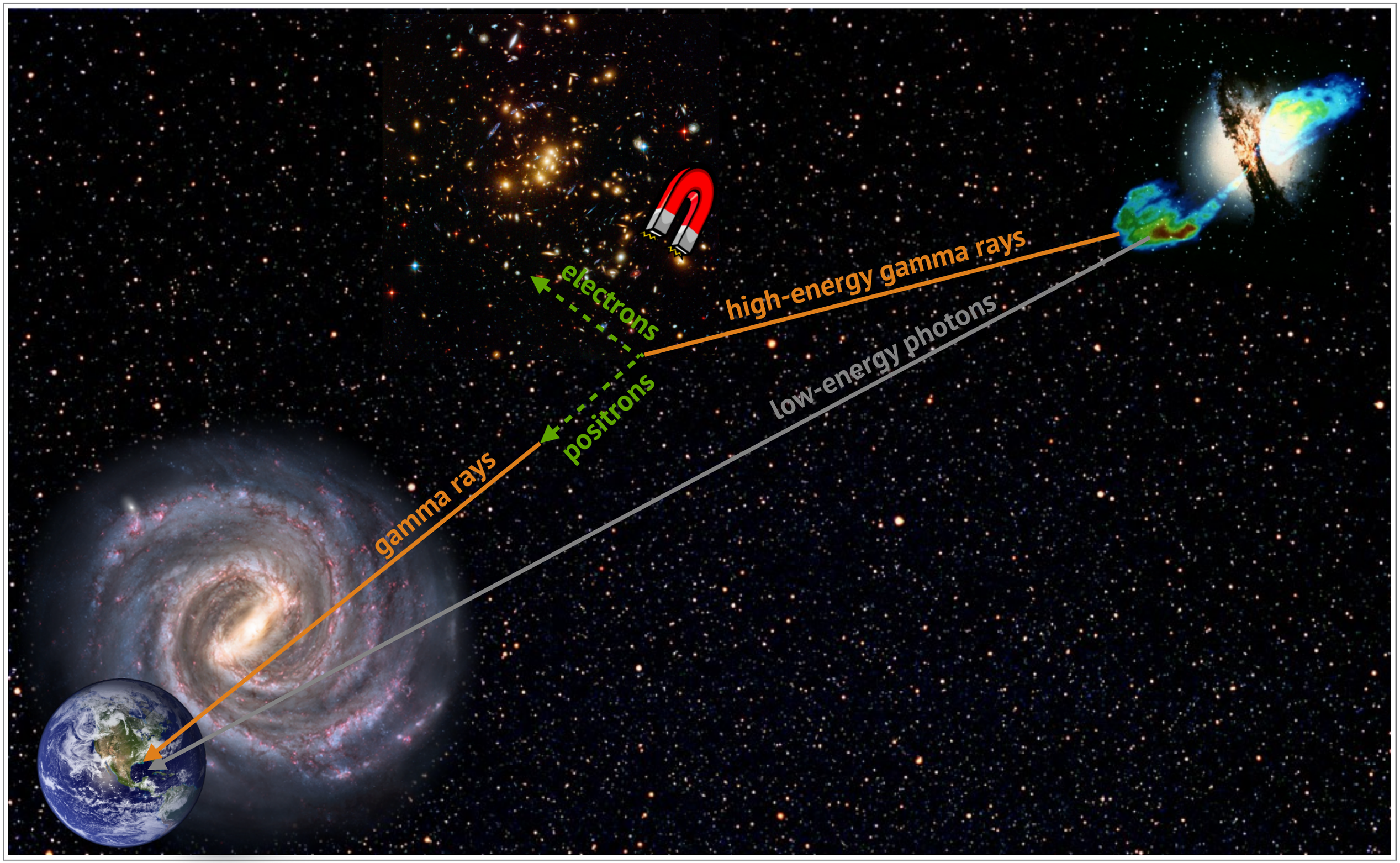
axion-like particles

diffuse neutrinos and photons

why is the cosmogenic gamma-ray flux (~TeV) not similar to the neutrino flux (~PeV)? → **intergalactic propagation**



gamma-ray propagation picture



gamma-ray propagation: interactions

pair production

$\gamma + \gamma_{bg} \rightarrow e^- + e^+$

double pair production

$\gamma + \gamma_{bg} \rightarrow e^- + e^+ + e^- + e^+$

inverse Compton scattering

$e^+ + \gamma_{bg} \rightarrow e^+ + \gamma$

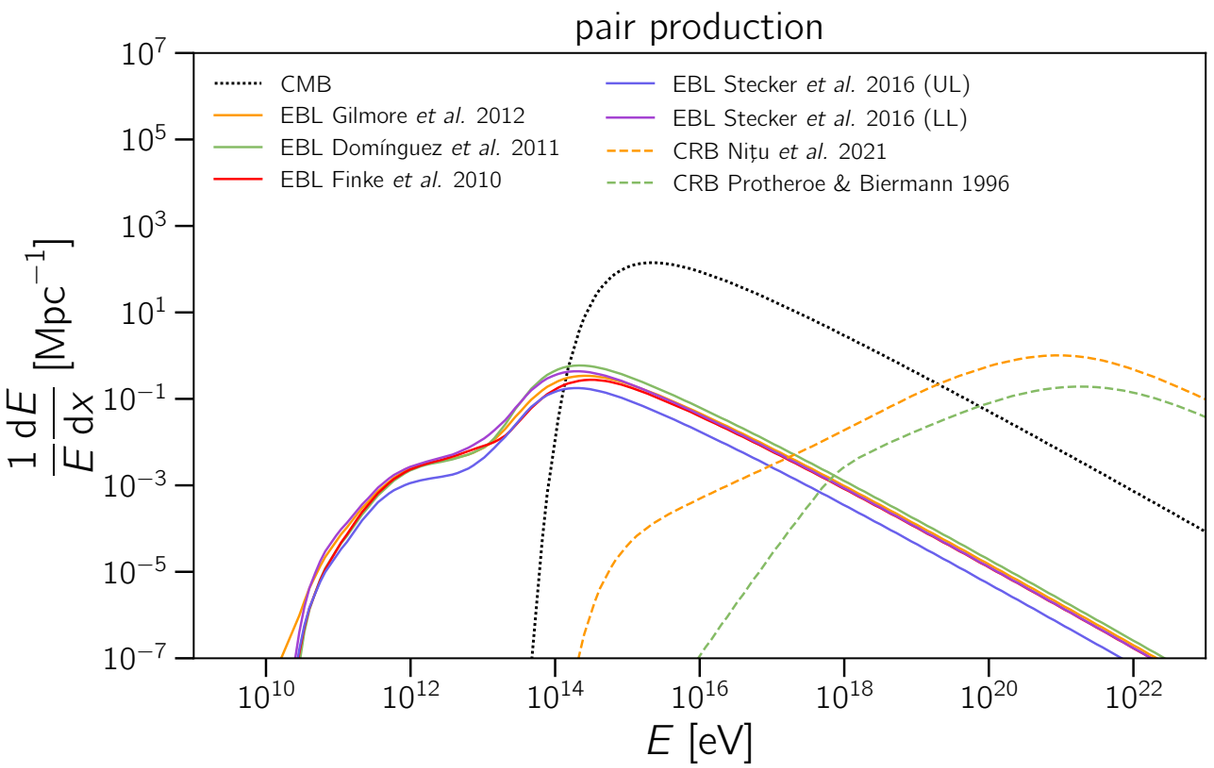
$e^- + \gamma_{bg} \rightarrow e^- + \gamma$

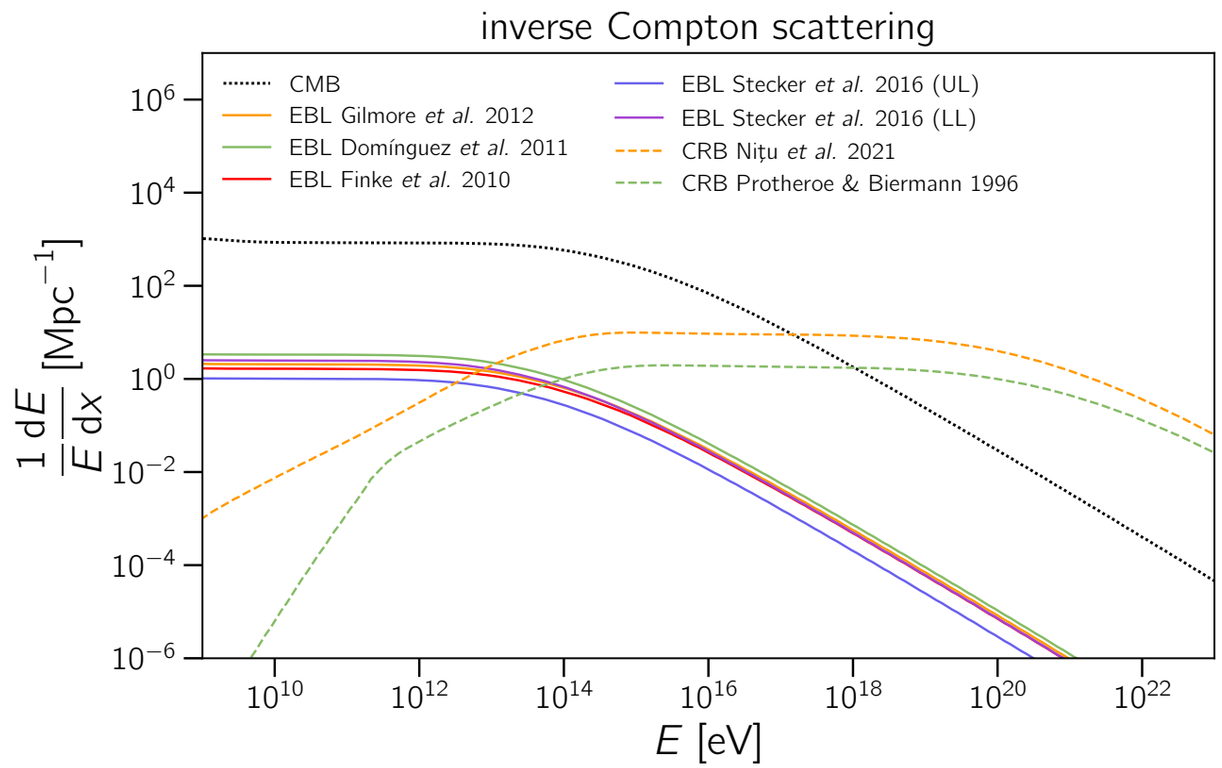
triplet pair production

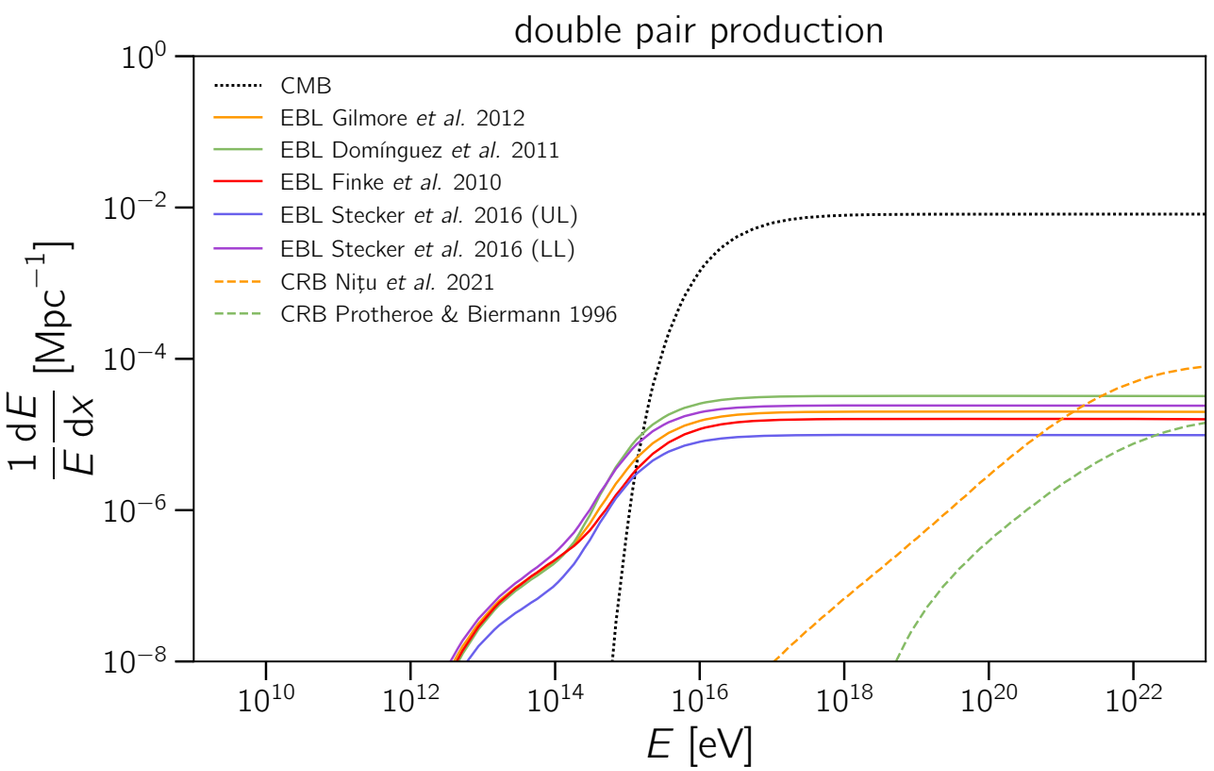
$e^+ + \gamma_{bg} \rightarrow e^+ + \gamma$

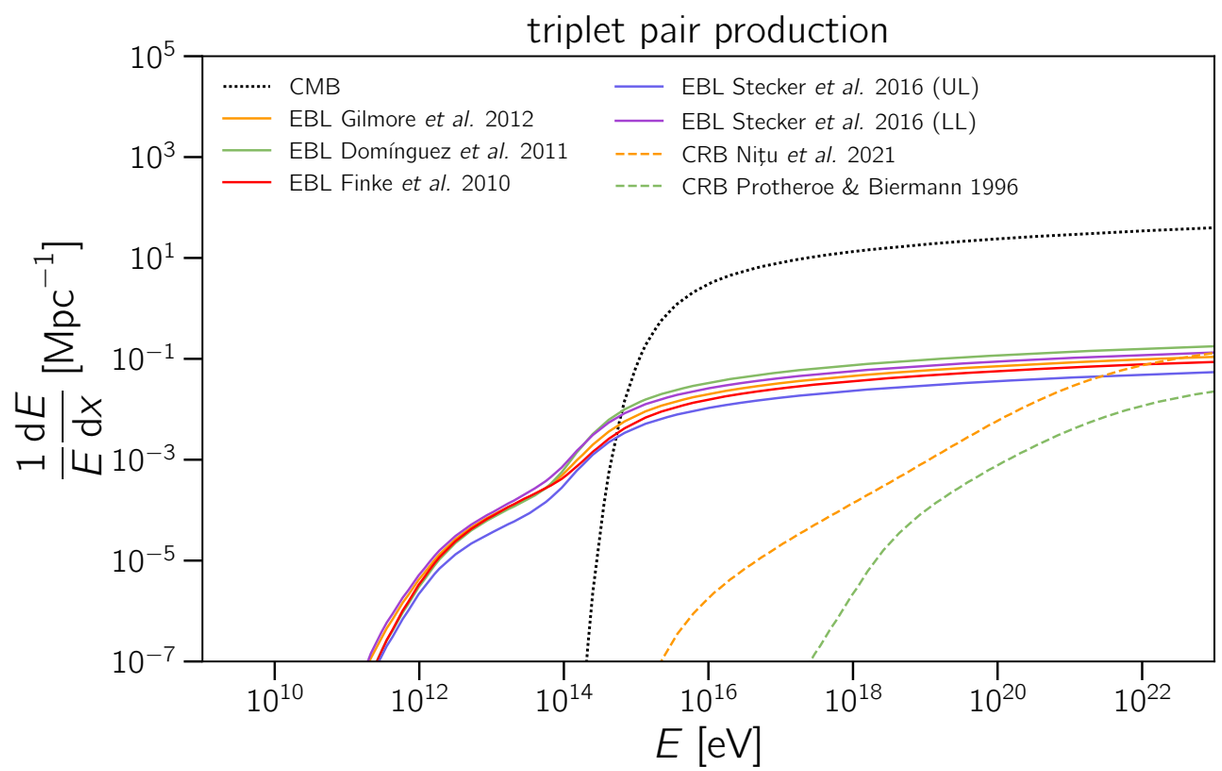
$e^- + \gamma_{bg} \rightarrow e^- + \gamma$

gamma-ray propagation: interactions







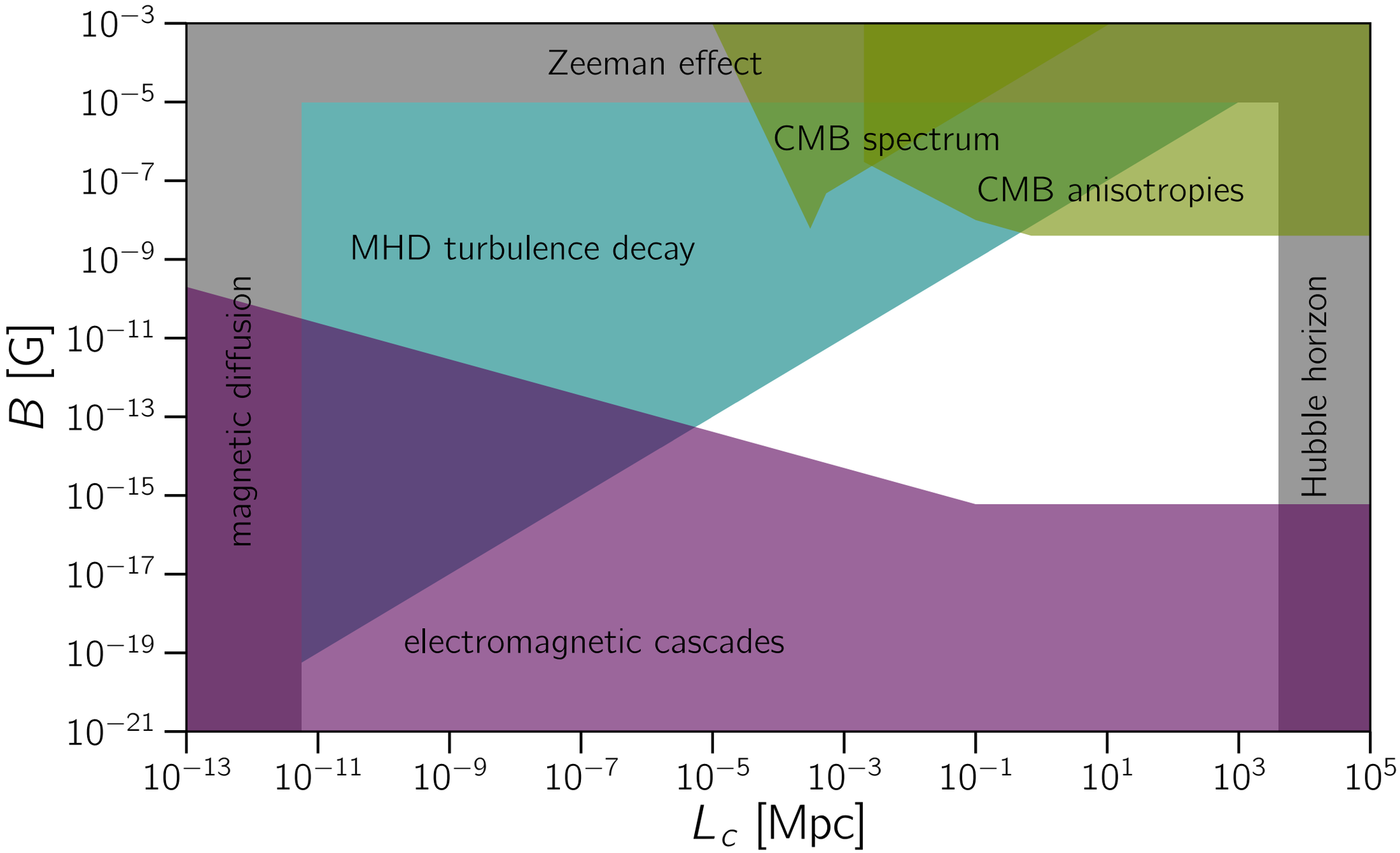


constraining IGMFs with gamma rays

how did magnetic fields originate in the Universe?

what are the properties of intergalactic magnetic fields?

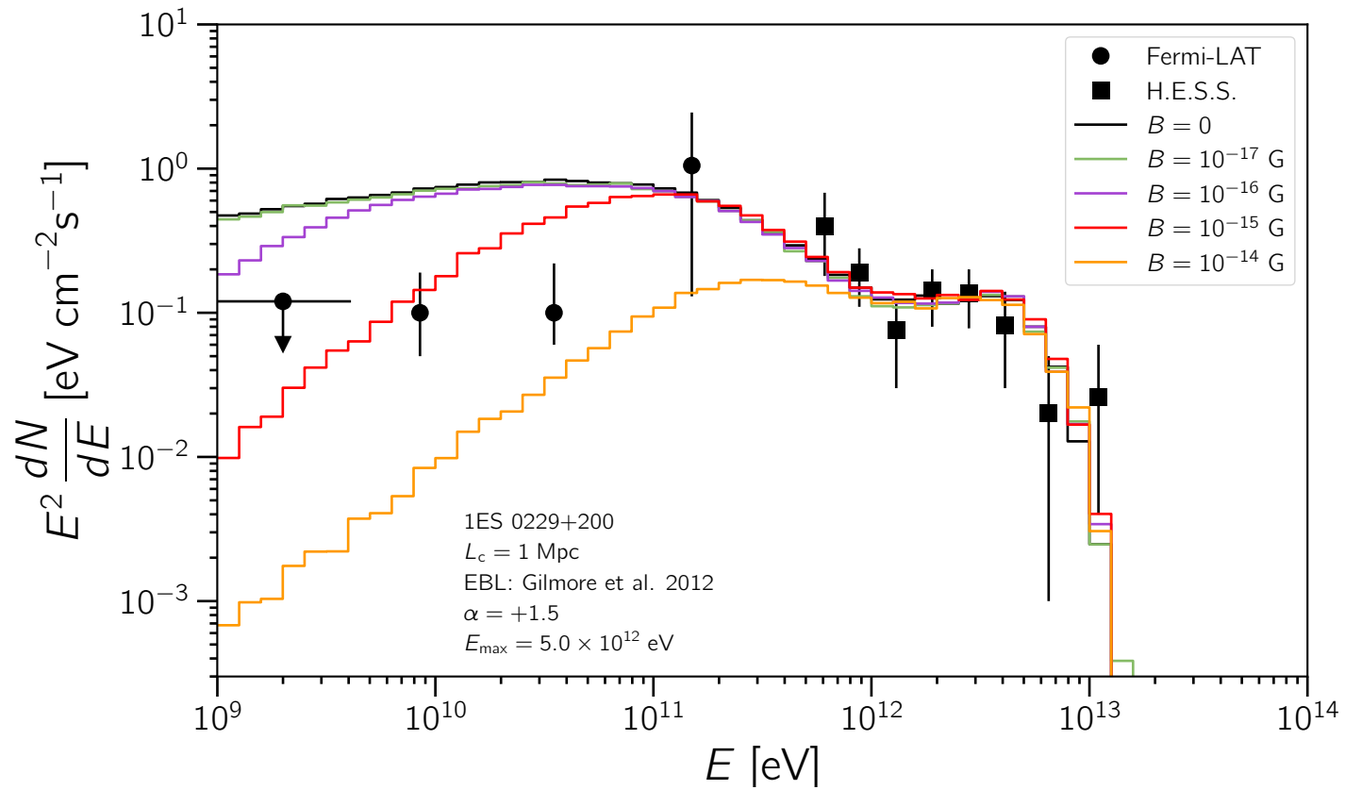
intergalactic magnetic fields (IGMFs)

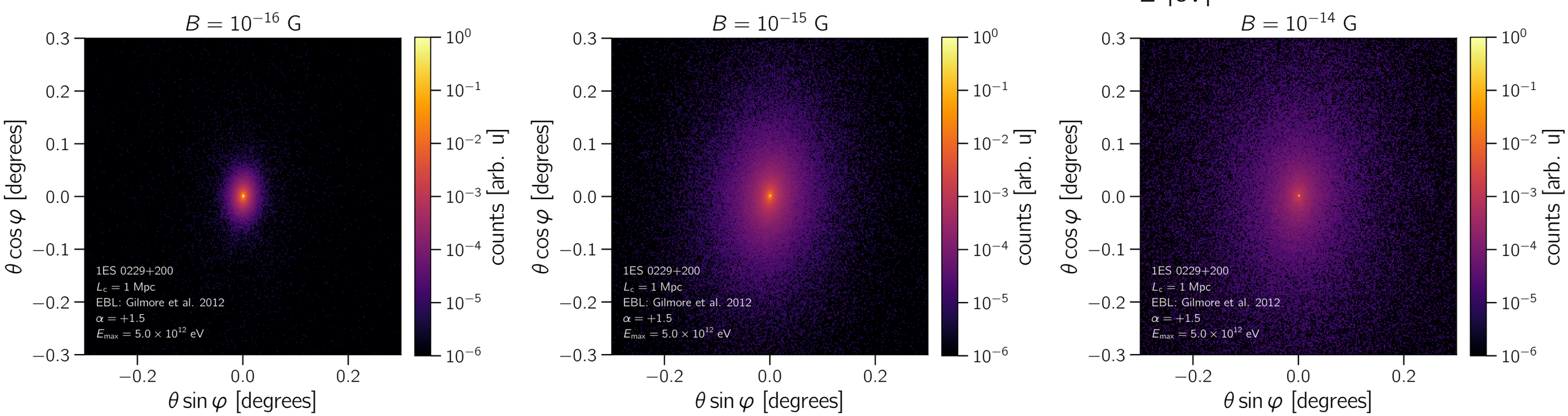


electromagnetic cascades and IGMFs

observational strategies

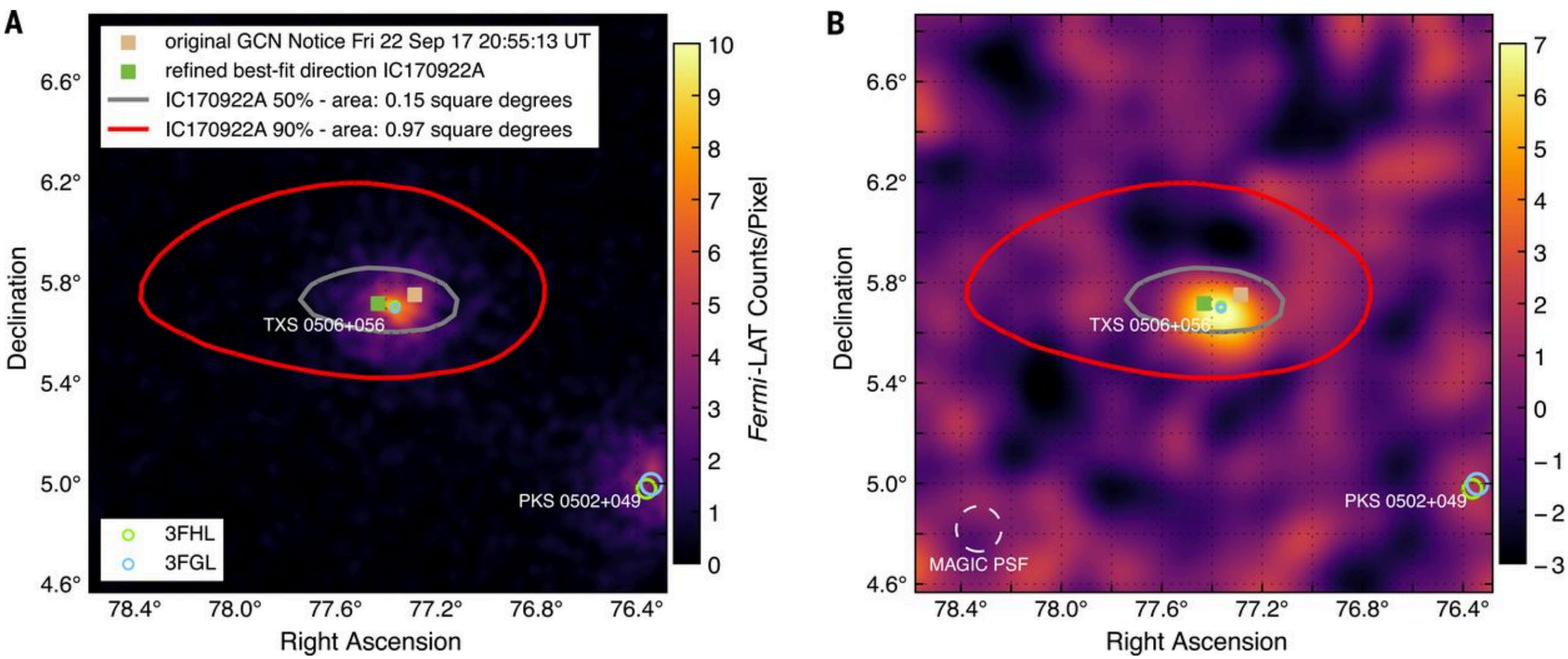
- strategy 1: point-like sources will appear extended
- strategy 2: secondary gamma rays will arrive with time delays
- strategy 3: combination of 1 and 2
  → spectral changes





a multimessenger method for constraining IGMFs

TXS 0506+056: the first cosmic neutrino source



IceCube Collaboration. Science 361 (2018) 147. arXiv:1807.08794

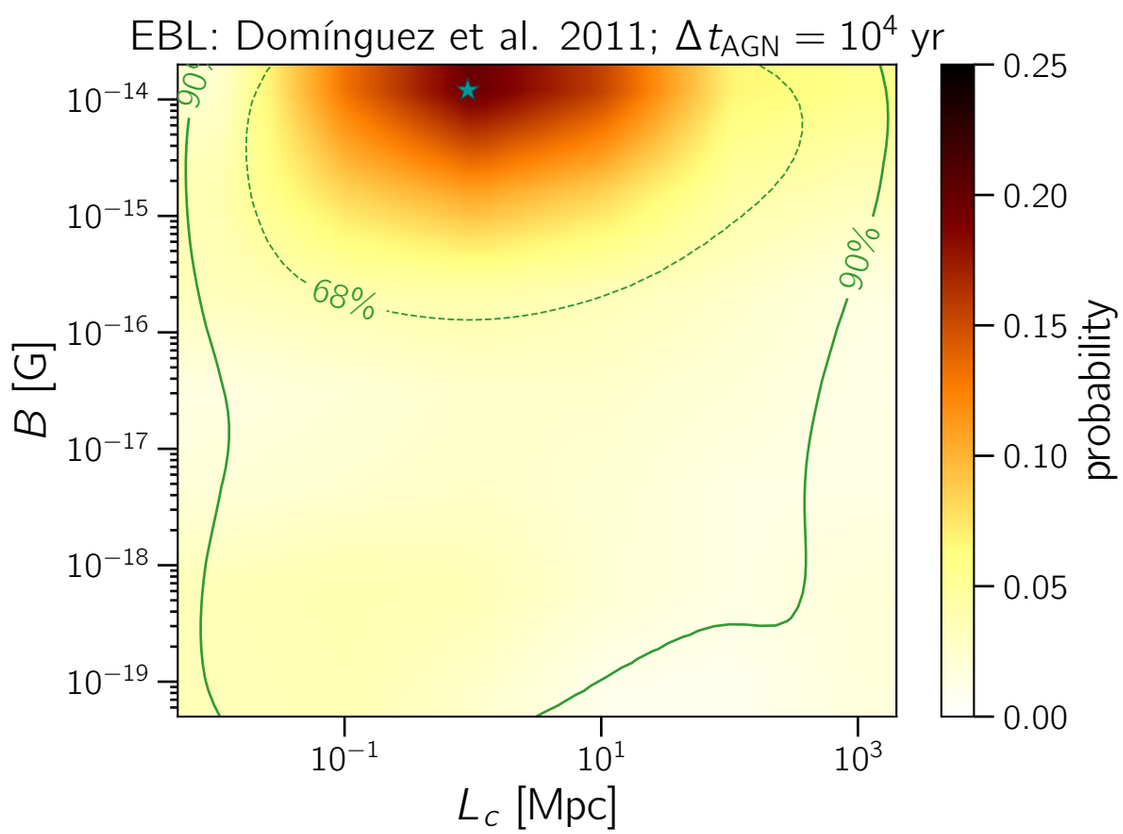
IceCube Collaboration. Science 361 (2018) eaat1378. arXiv:arXiv:1807.08816

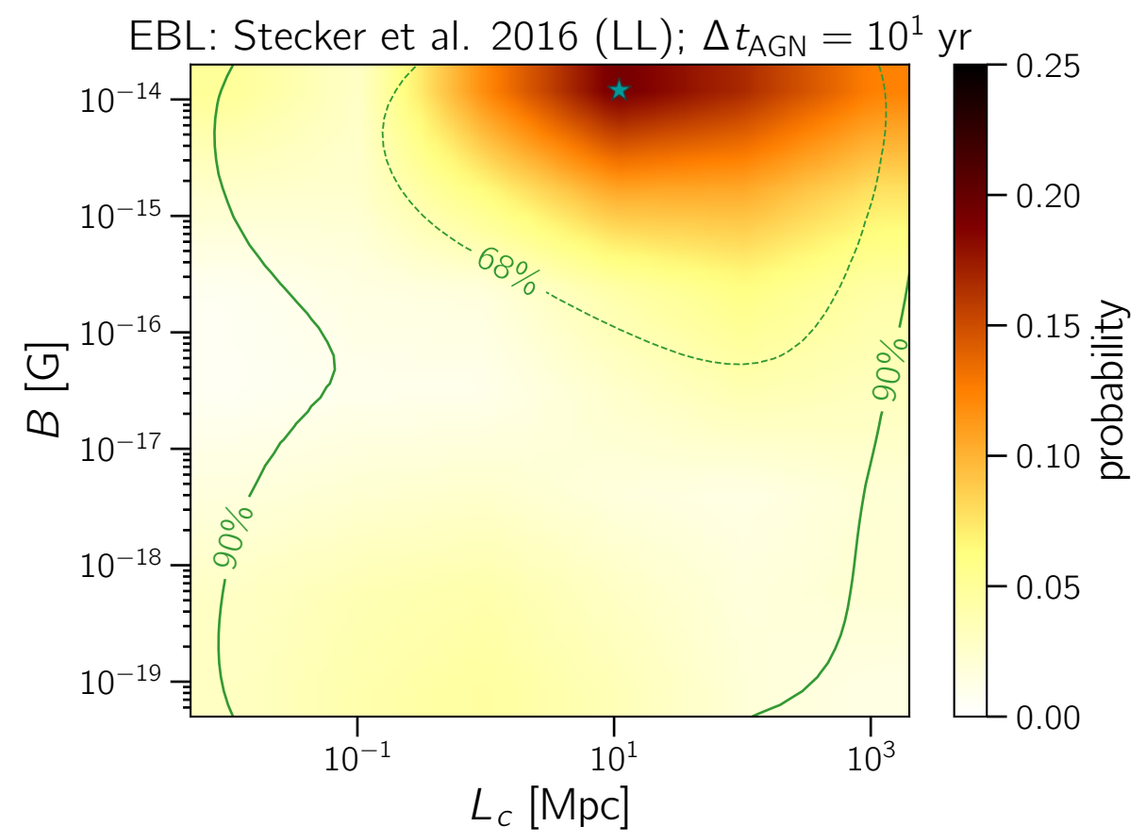
multimessenger constraints on IGMFs

Alves Batista & Saveliev. ApJL 902 (2020) L11. arXiv:2009.12161

general idea

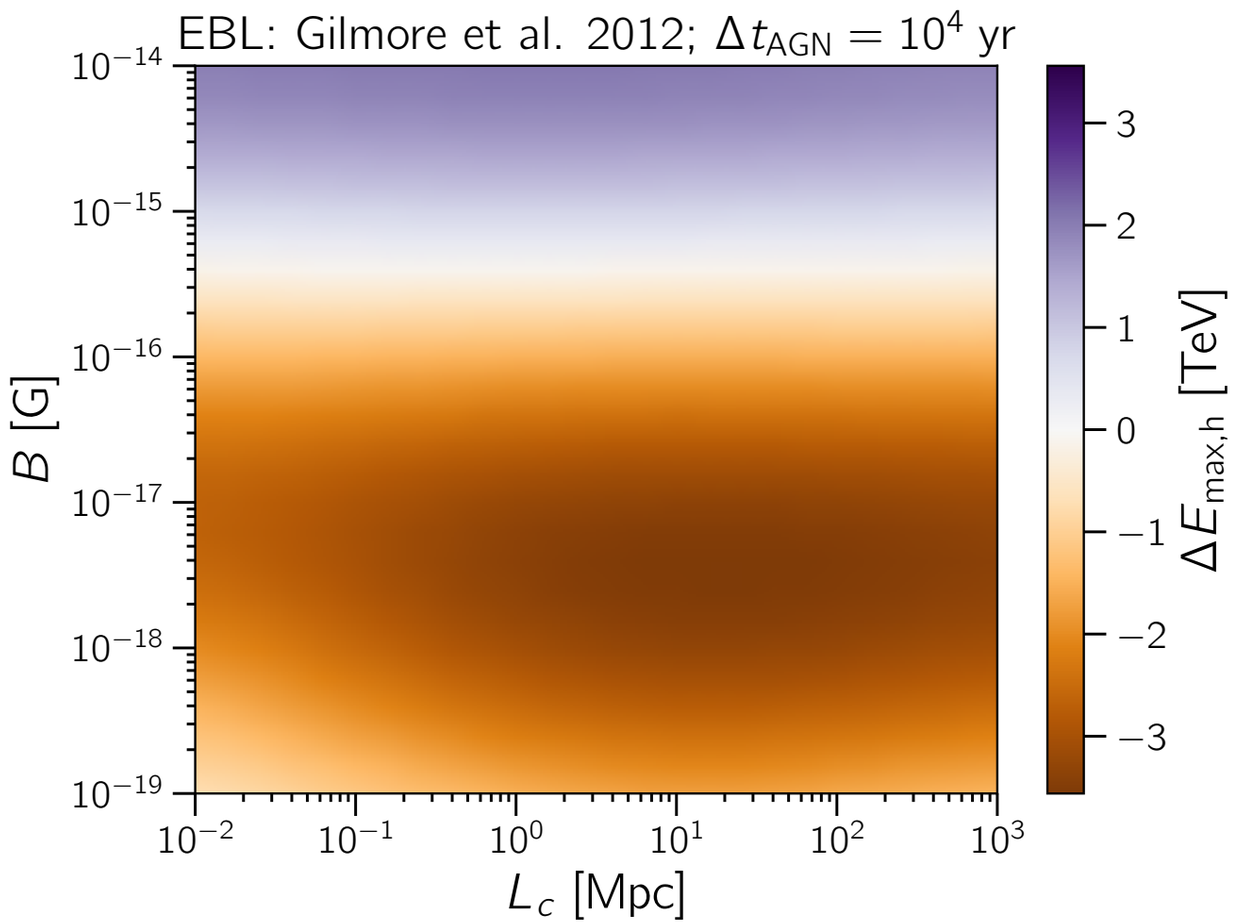
- neutrino flare may be a gamma-ray flare
- fit CRPropa simulations for (α_l, $E_{max,l}$, α_h, $E_{max,h}$, η, J_0) for each (B, L_c)
- maximise likelihood for pairs (B, L_c)
- assume AGN active over Δt_{AGN}~10, 10^4, 10^7 yr

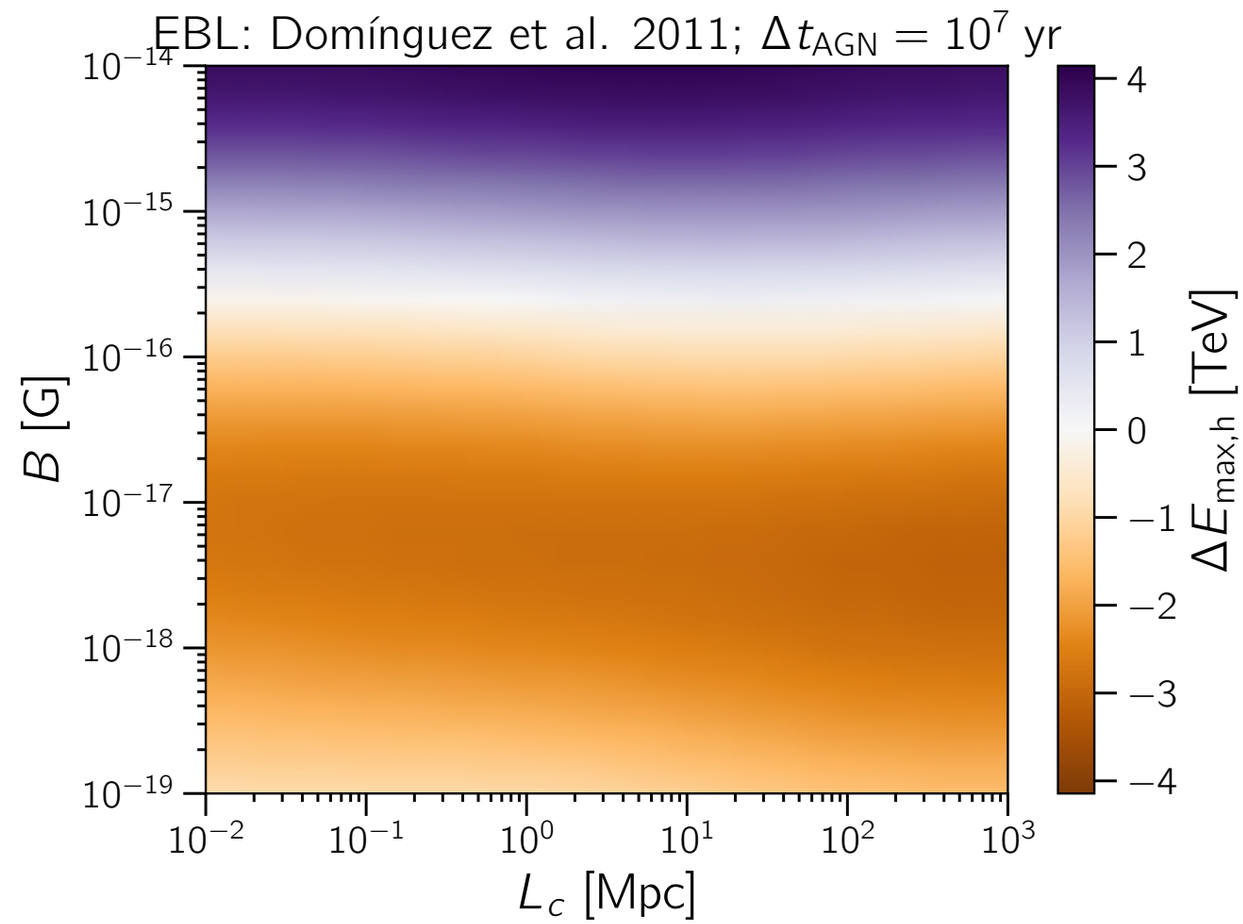




IGMF effects on TXS 0506+056: maximum gamma-ray energy

Saveliev, Alves Batista. MNRAS 500 (2021) 2188. arXiv:2009.09772





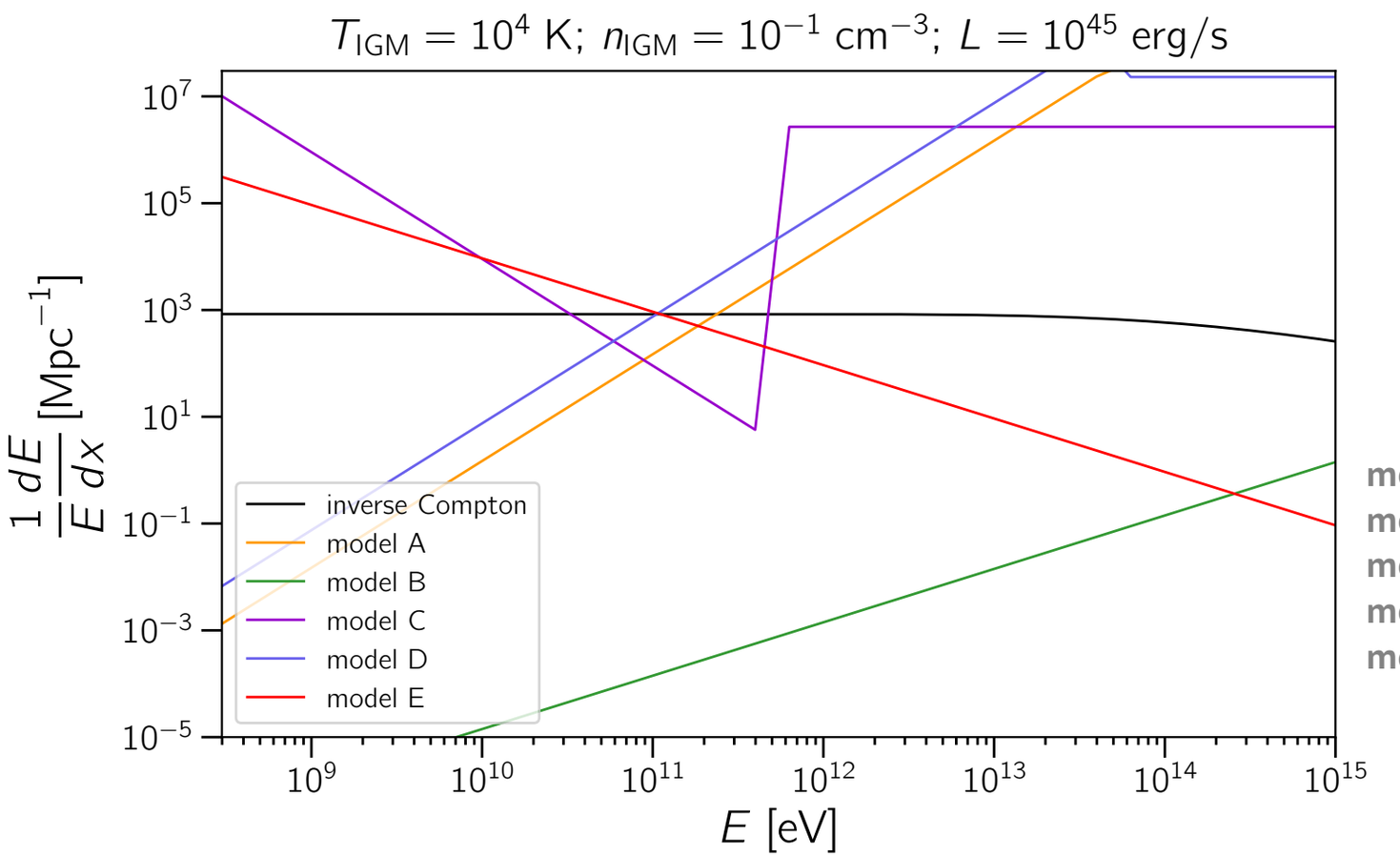
do plasma instabilities quench electromagnetic cascades?

do plasma instabilities quench electromagnetic cascades?

Alves Batista, Saveliev, de Gouveia Dal Pino. MNRAS 489 (2019) 3836. arXiv:1904.13345

general idea

- plasma instabilities depend on the temperature and density of intergalactic medium, and on the luminosity of the blazar beam
- effect can be approximated as a cooling term for electrons
- **grplinst:** a **CRPropa** plugin to account for plasma instability effects on gamma-ray cascades https://github.com/rafaelab/grplinst



model A: Broderick et al. ApJ 752 (2012) 22. arXiv:1106.5494
model B: Miniati & Elyiv. ApJ 770 (2013) 54. arXiv:1208.1761
model C: Schlickeiser et al. ApJ 758 (2012) 102.
model D: Sironi & Giannios. ApJ 787 (2014) 49. arXiv:1312.4538
model E: Vafin et al. ApJ 857 (2018) 43. arXiv:1803.02990

do plasma instabilities quench electromagnetic cascades?

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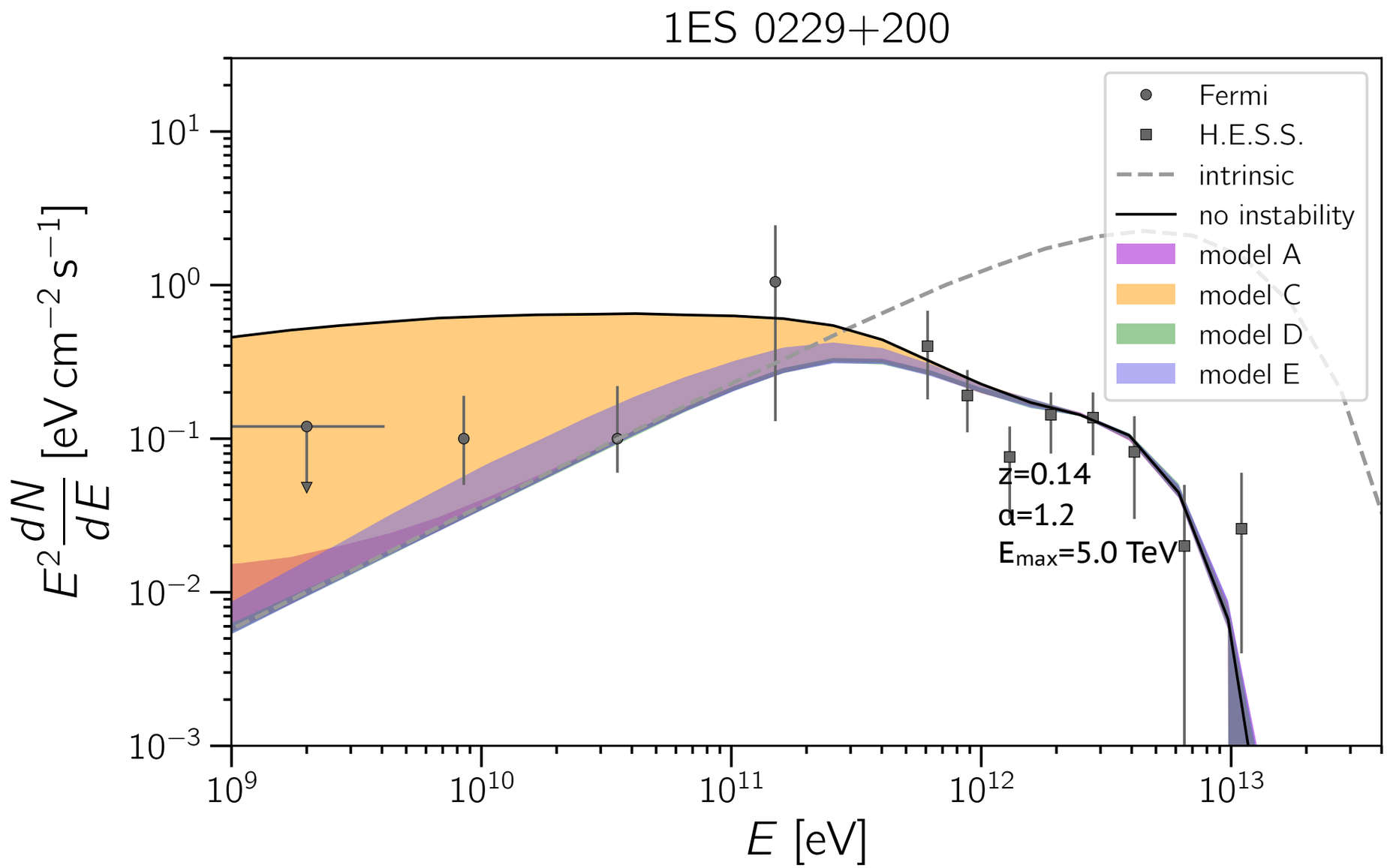

summary and outlook

summary & outlook

part 1

- UHECR propagation contains many uncertainties
- magnetic fields may make UHECR astronomy difficult (but not impossible)
- to interpret the UHECR data requires a self-consistent framework and detailed simulations
- **multiple messengers** seem to be the way to study the ultra-high-energy Universe!
- detection of cosmogenic neutrinos possible in the future
- cluster of galaxies are an important contribution to the diffuse neutrino flux

part 2

- first ever (weak) constraints on the coherence length: between ~100 kpc and 300 Mpc
- magnetic power spectrum may affect gamma-ray propagation → constraints on magnetogenesis models
- plasma instabilities: no major problems for IGMF constraints