multimessenger constraints on intergalactic magnetic fields

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NPAC Seminar
16-Dec-2021

motivation for this talk

multimessenger astrophysics & intergalactic magnetic fields

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intergalactic magnetic fields (IGMFs)

definitions

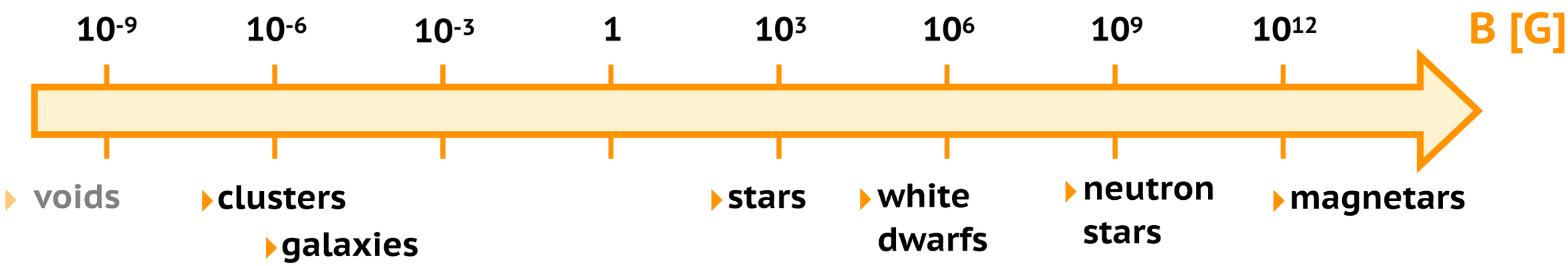
- **galactic** → in any galaxy
- **Galactic** → in the Milky Way
- **extragalactic** → outside our own galaxy
- **intergalactic** → between galaxies

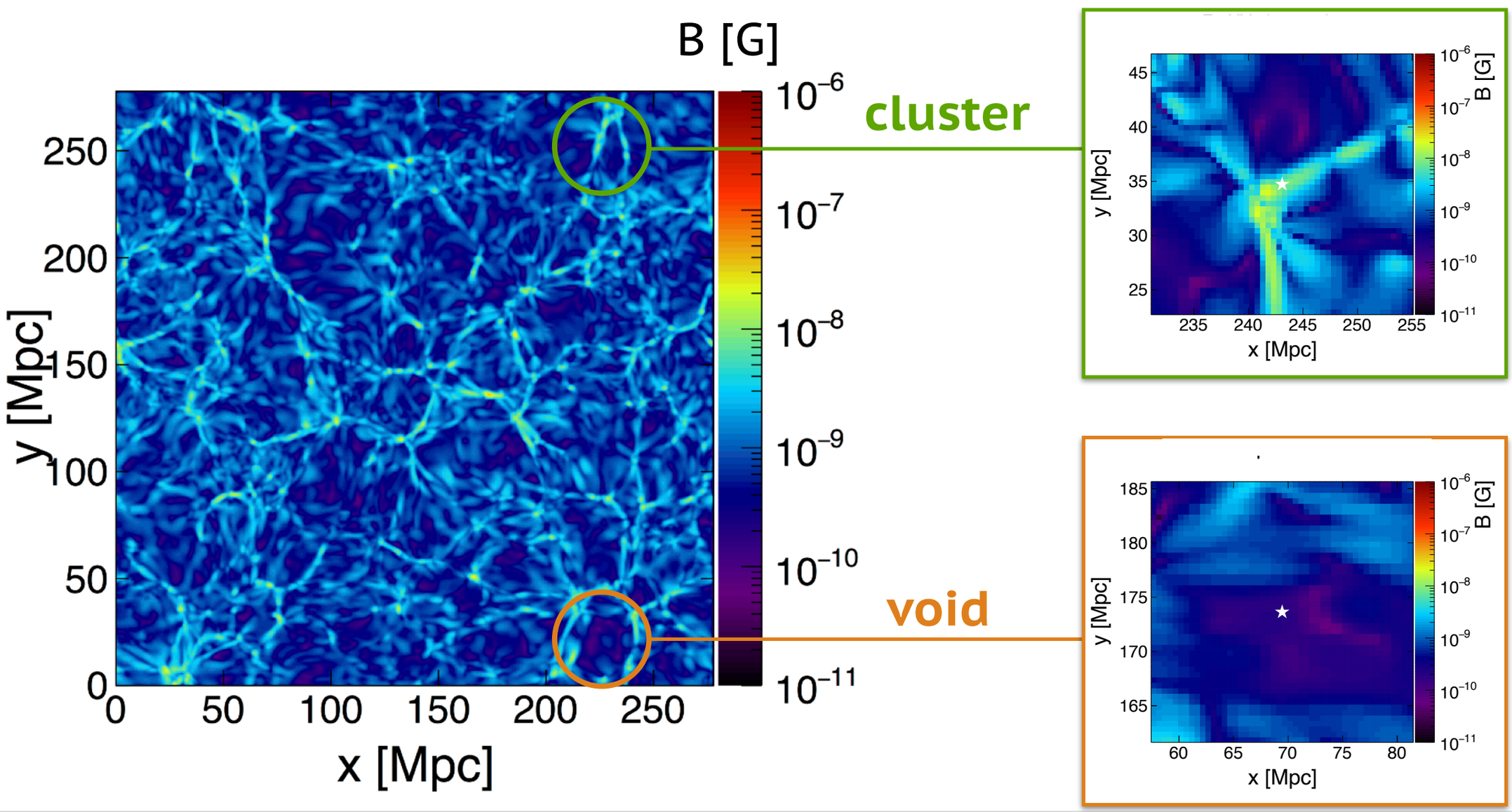
what are IGMFs?

how did cosmic magnetic fields originate?

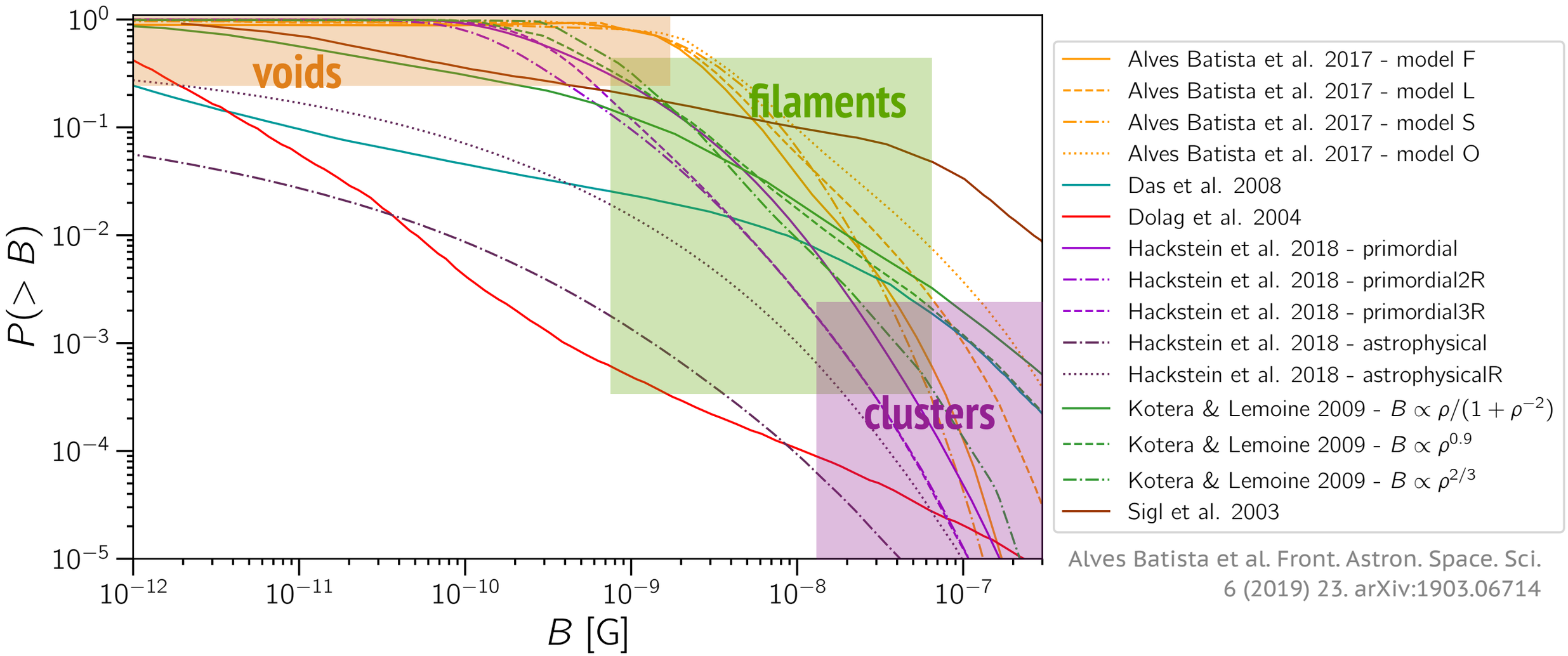
how are they distributed?

magnetic fields in the universe





the magnetised cosmic web



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

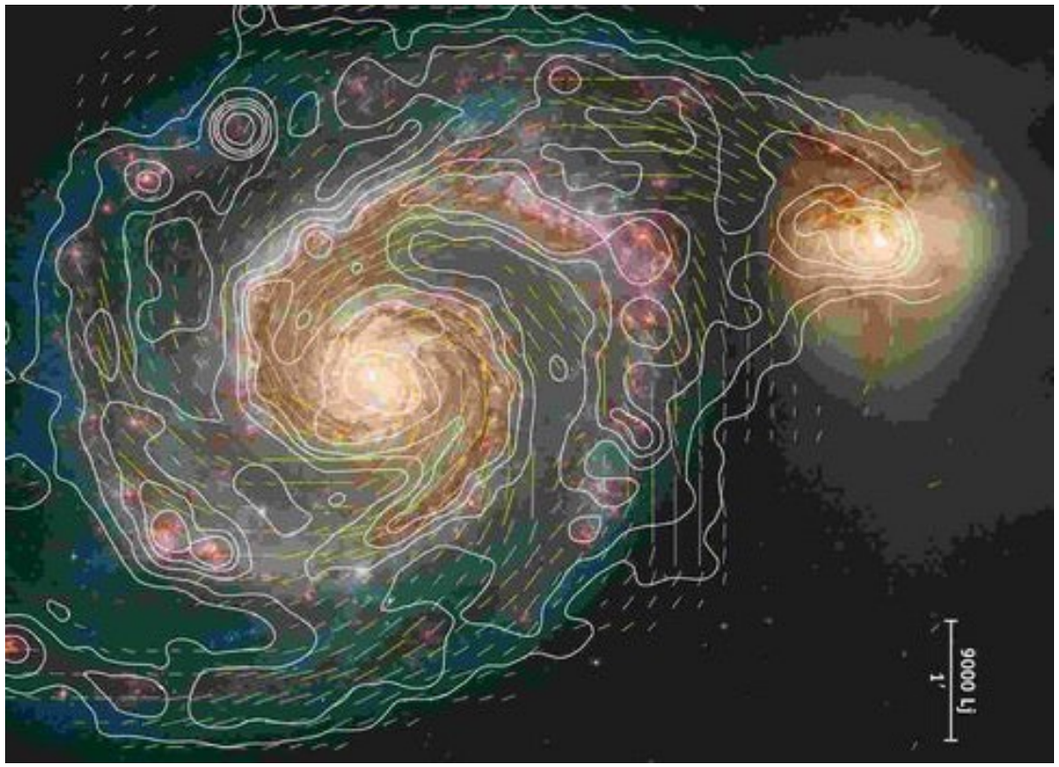
magnetic-field properties

- the magnetic fields is usually approximated by a superposition of (nearly-)stochastic components
- **strength**: $B^2 \equiv B_{\rm rms}^2 = \frac{1}{V}\int_V \left|\vec{B}(\vec{r})\right|^2 \mathrm{d}^3 r$
- **power spectrum**: $M_k \propto k^{\alpha_B - 1}$
- **coherence length**: $L_B = \frac{2\pi \int k^{-1} M_k \, \mathrm{d}k}{\int M_k \, \mathrm{d}k}$
- **helicity**: $H_B = \int_V \vec{A}(\vec{r}) \cdot \vec{B}(\vec{r}) \, \mathrm{d}^3 r$
- **structure of the field**

- in principle, none of these properties are necessarily small, such that all of them need to be taken into account in the models

magnetic fields in the universe

- magnetic fields in galaxies have ~ μG strengths
- to explain these observations, pre-existing **seed fields** are required
- dynamos can amplify (weak) seed fields
- **how did the seed fields originate?**
- but if the seed field is strong (B > 10 pG), adiabatic compression alone explains observations



- MHD induction equation

$$\frac{\partial \vec{B}}{\partial t} = \boxed{\vec{\nabla} \times \left(\vec{v} \times \vec{B} \right)} + \eta \nabla^2 \vec{B}$$

amplification

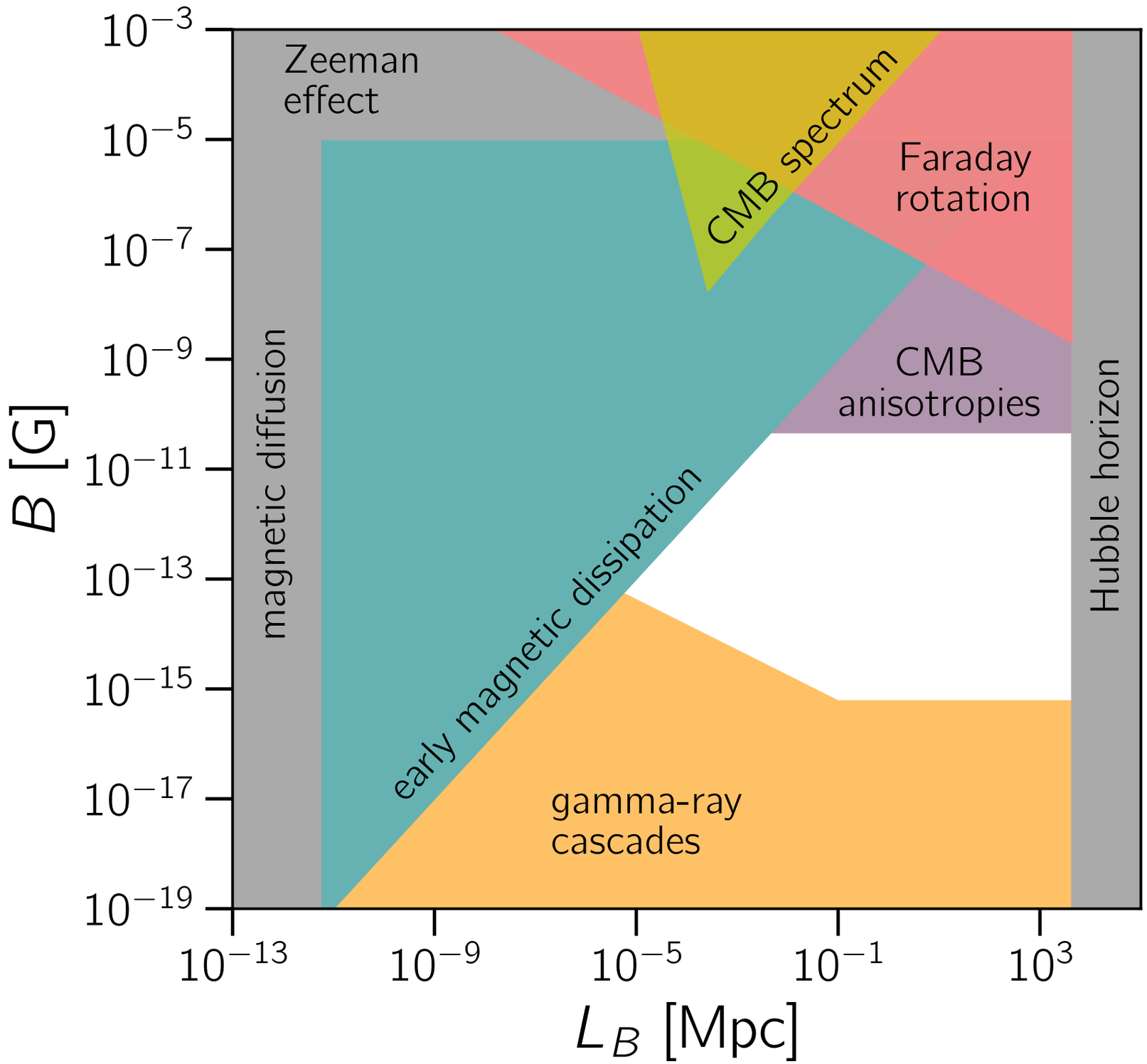
intergalactic magnetic fields

fundamental questions

- how were they produced?
- what is their role in the evolution of the universe?
- how strong are they?
- what is their power spectrum?
- what are their topological properties?

- **astrophysical mechanisms:** during structure formation (e.g. Biermann battery, ...)
- **primordial mechanisms**: large-scale cosmological processes such as inflation, EW phase transition, QCD phase transition, ...

intergalactic magnetic fields (IGMFs)



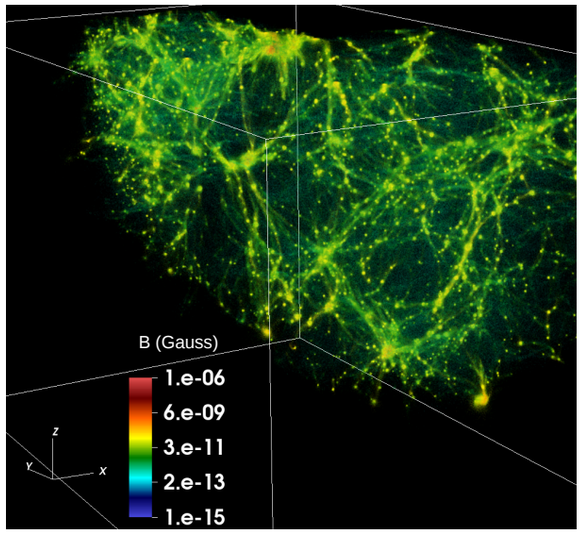
on the importance of IGMFs for multimessenger studies

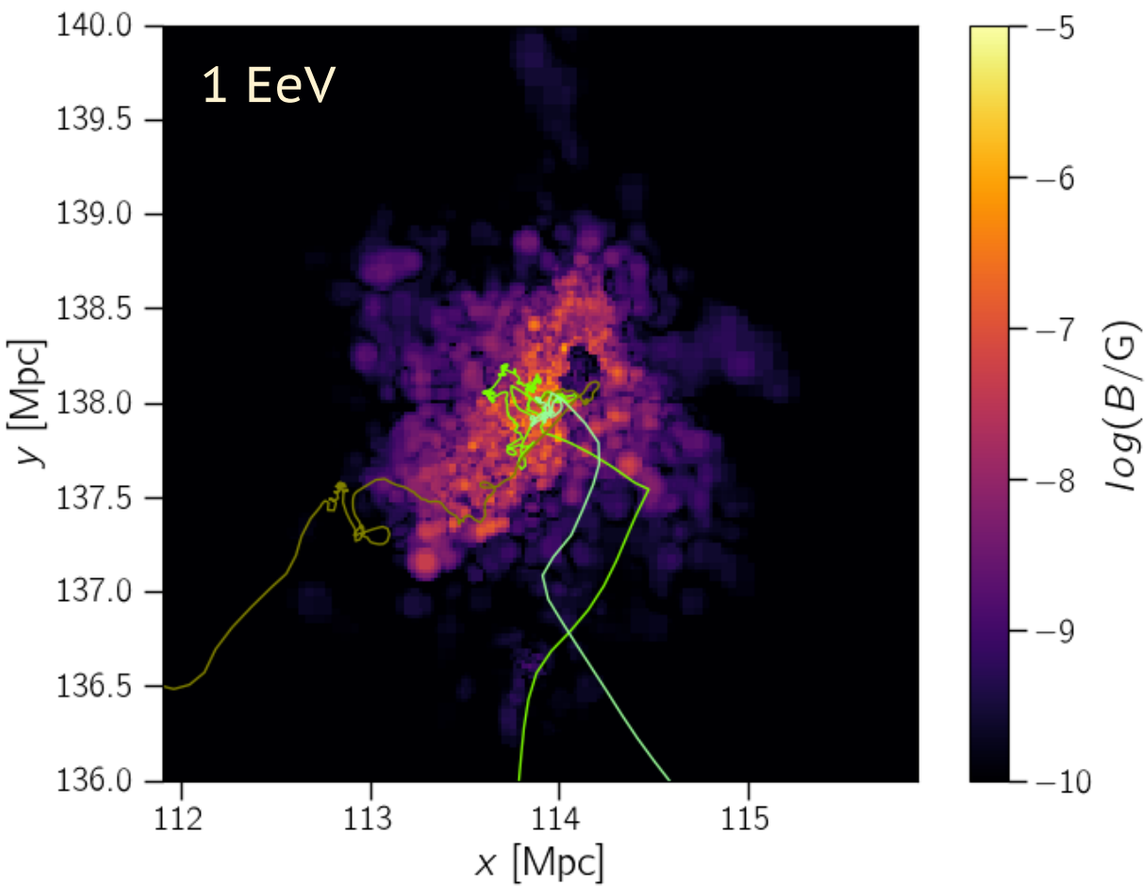
an example: high-energy emission by clusters of galaxies

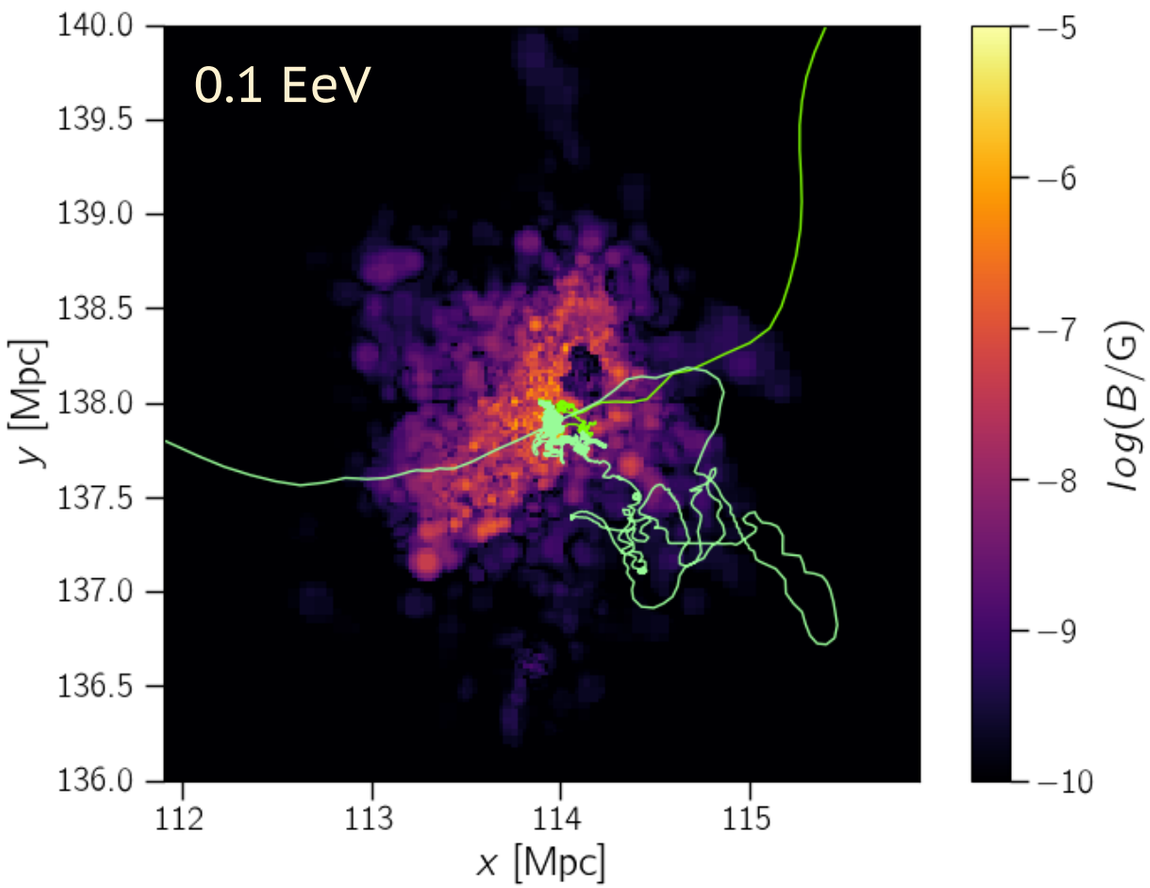
CRs wandering in the intracluster medium

Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. MNRAS 507 (2021) 1762. arXiv:2101.07702

- high-energy neutrinos are produced via hadronic processes
- cosmic rays are affected by magnetic fields
- CR interactions are more frequent if magnetic fields are strong

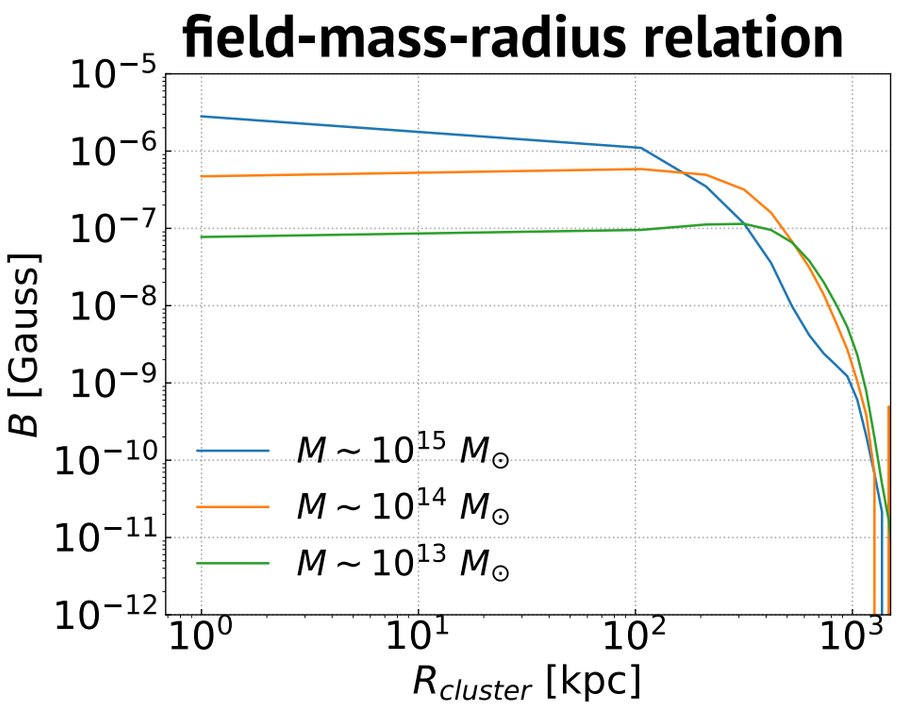


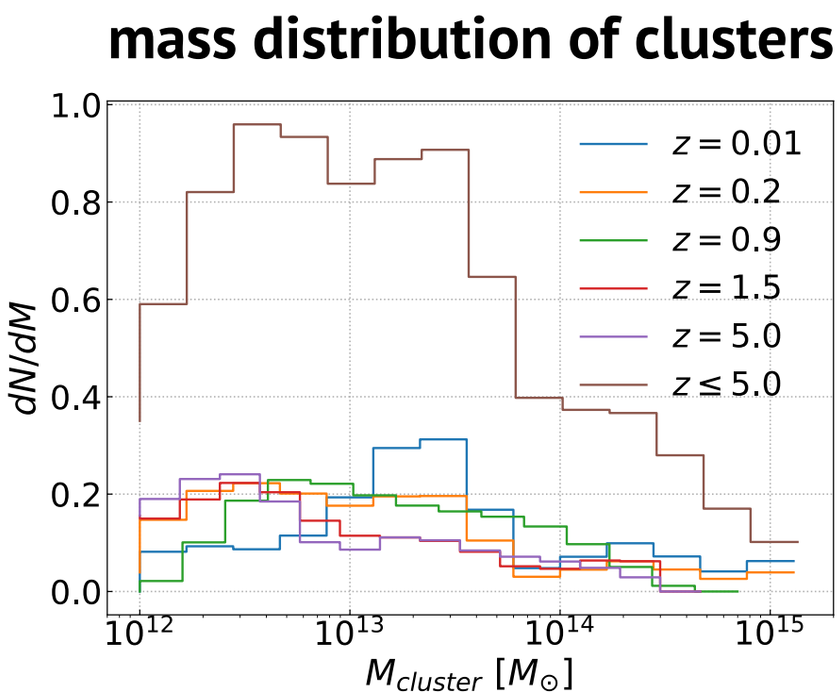


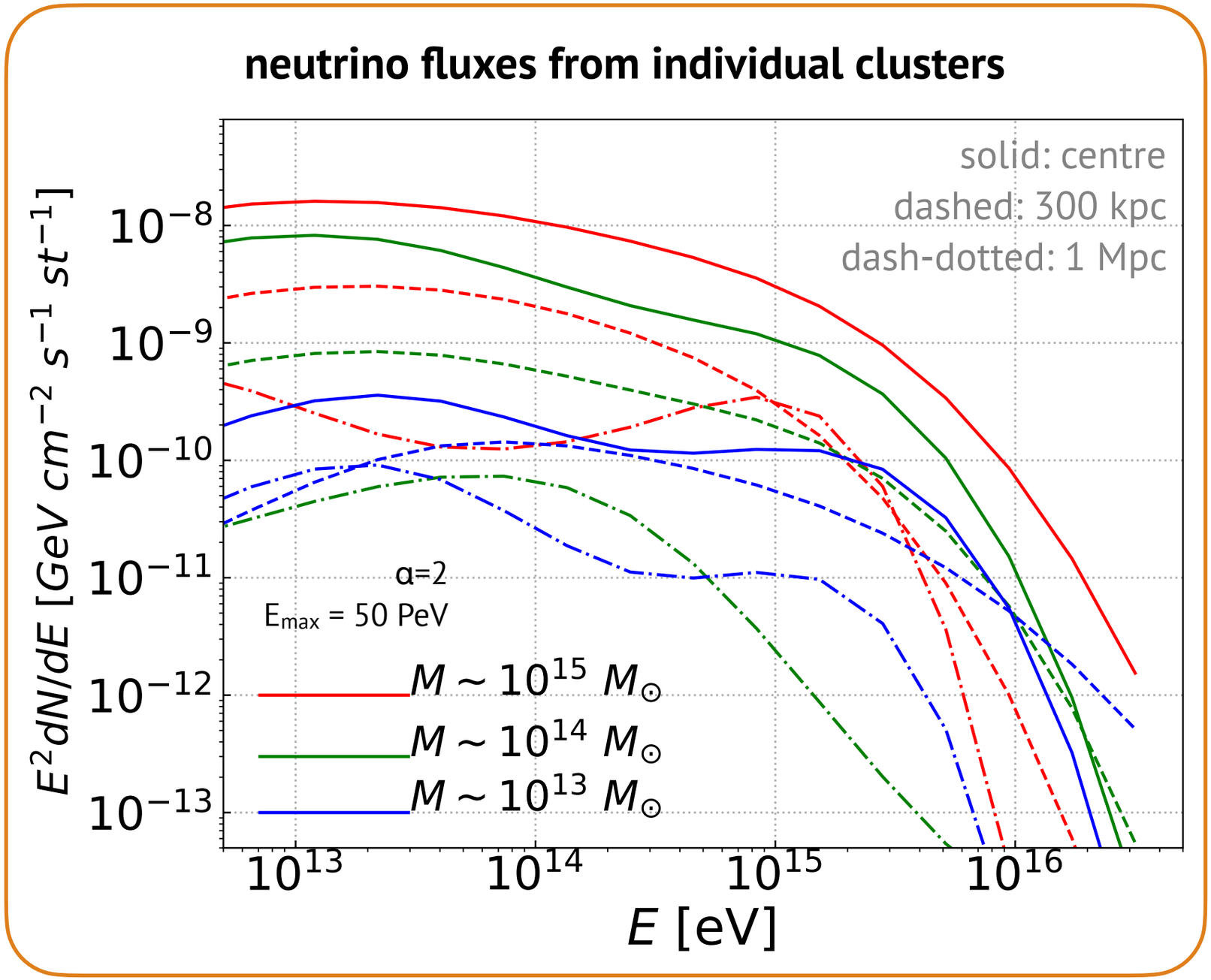


neutrinos from clusters: the role of magnetic fields

Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. MNRAS 507 (2021) 1762. arXiv:2101.07702

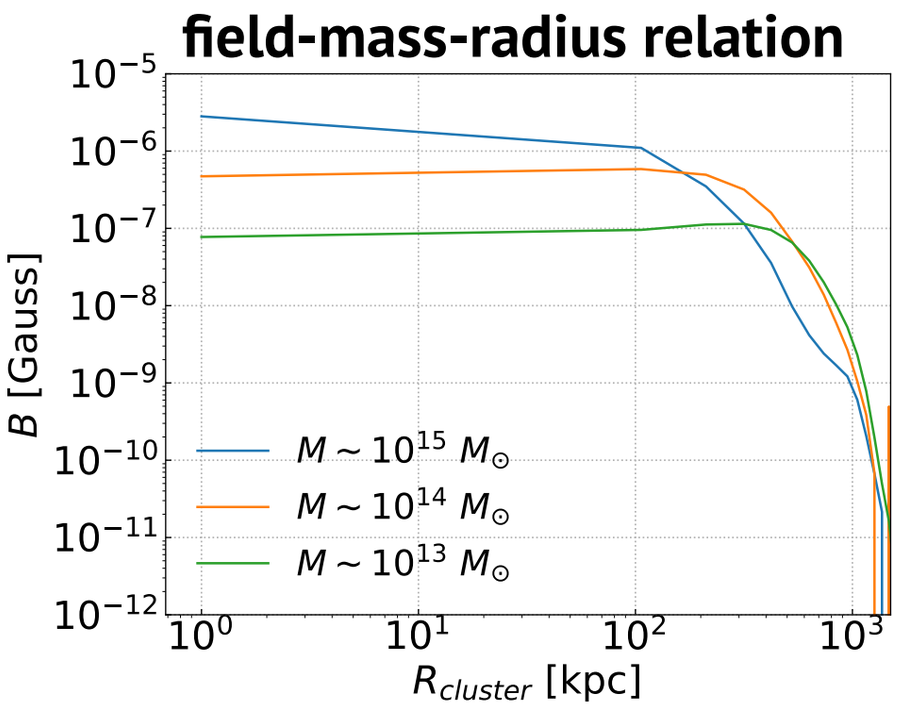


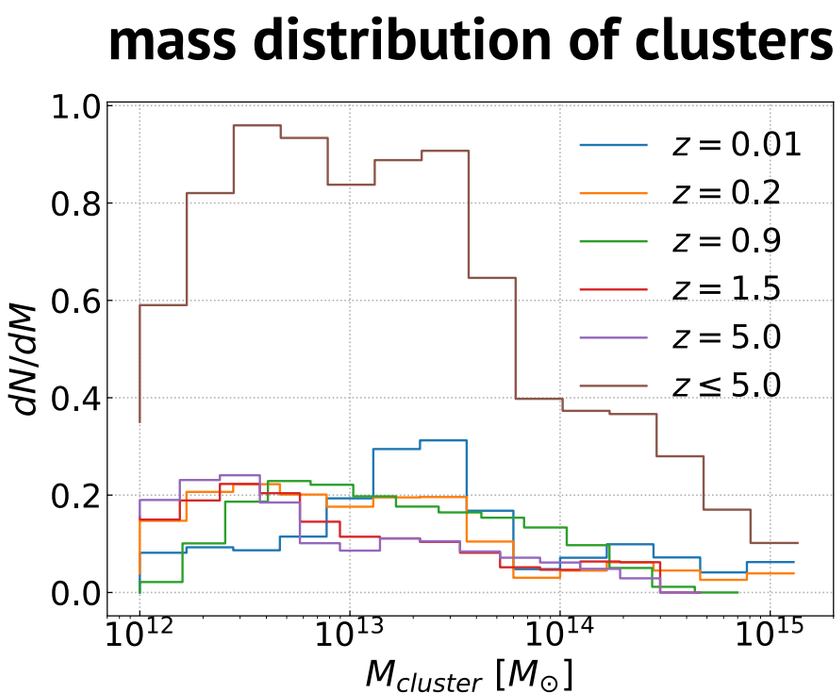


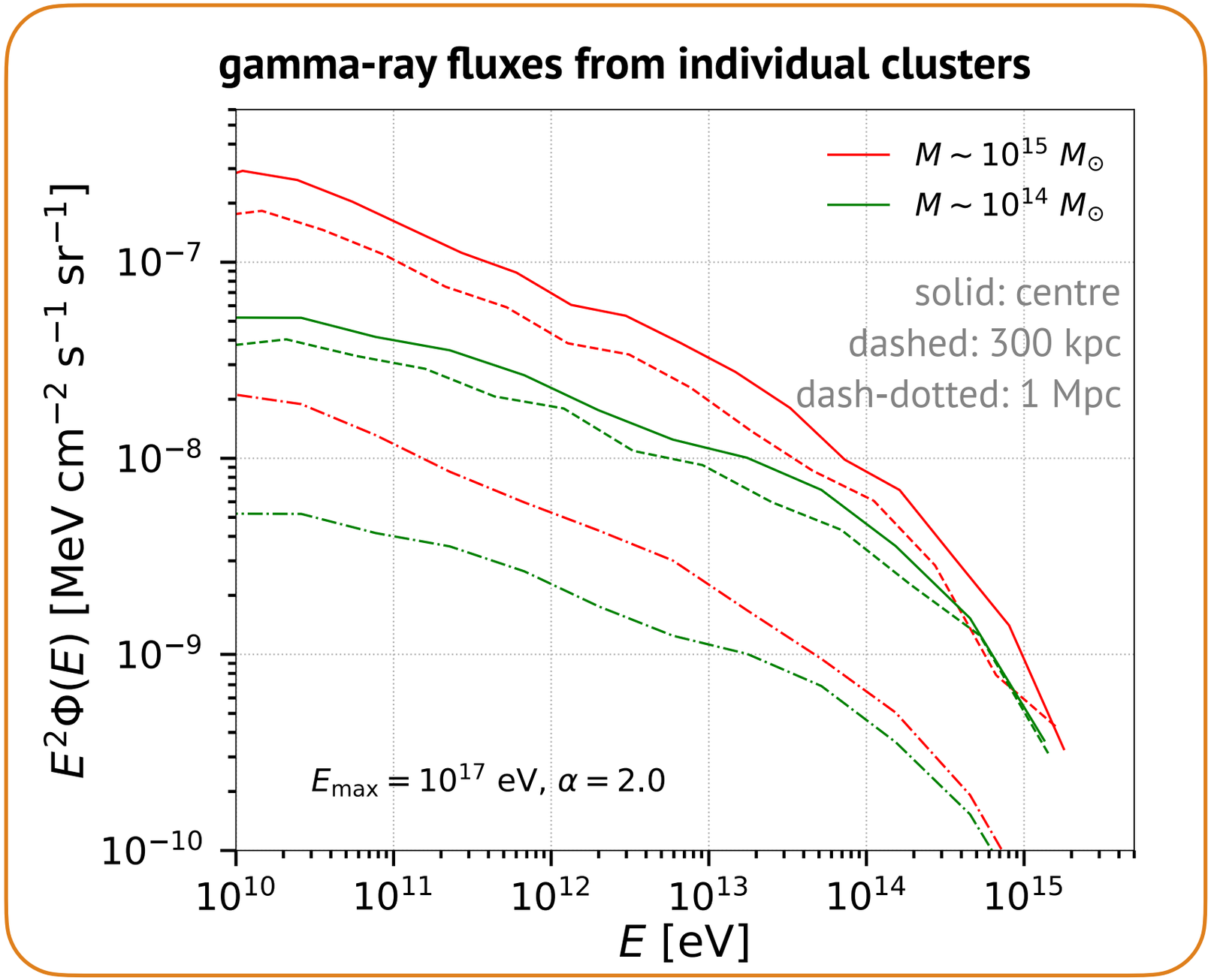


gamma rays from clusters: the role of magnetic fields

Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. arXiv:2112.XXXXX







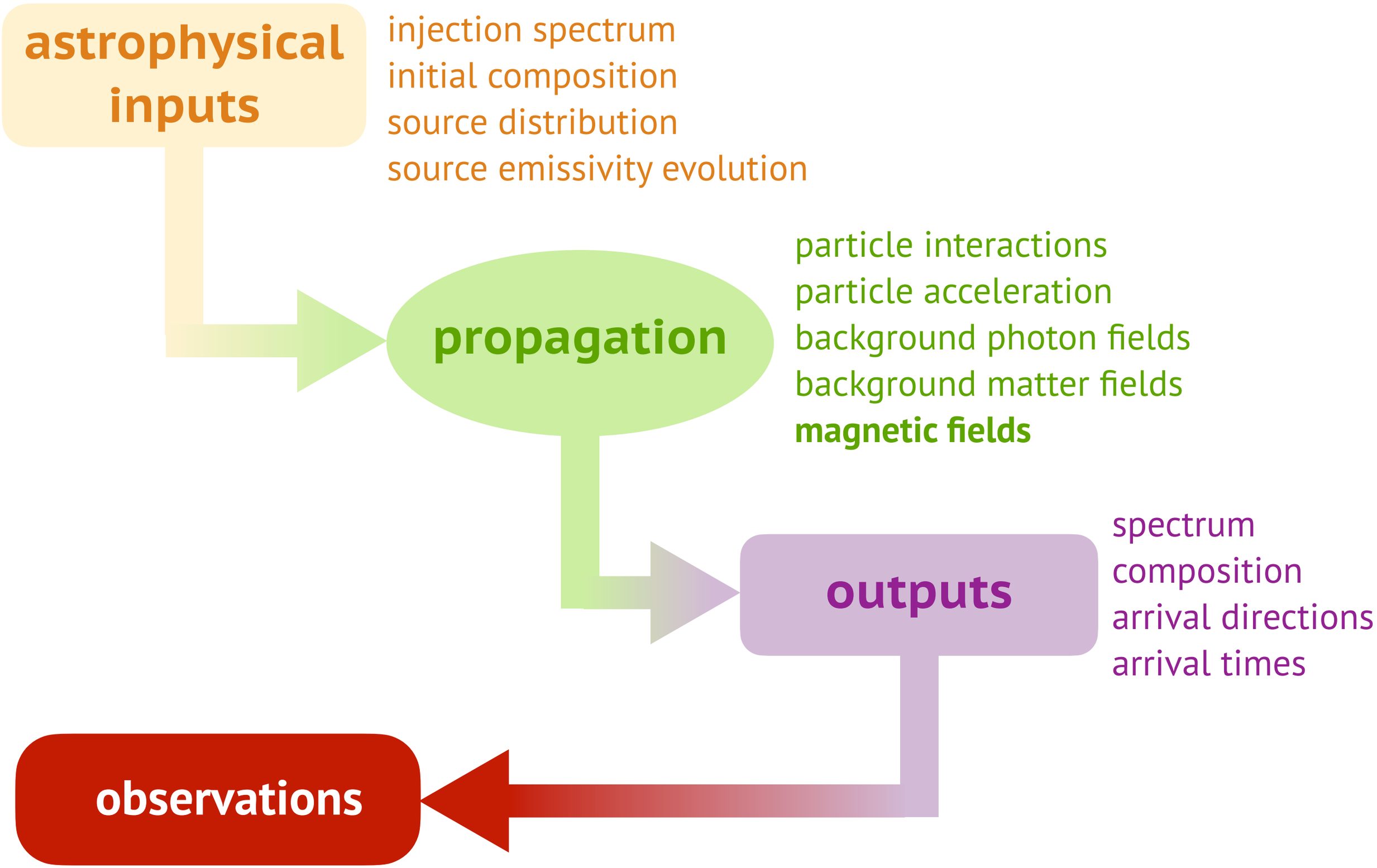
particle propagation in the cosmos

how do high-energy particles propagate over cosmological distances?

what is the role of magnetic fields in their propagation?

how to model all this?

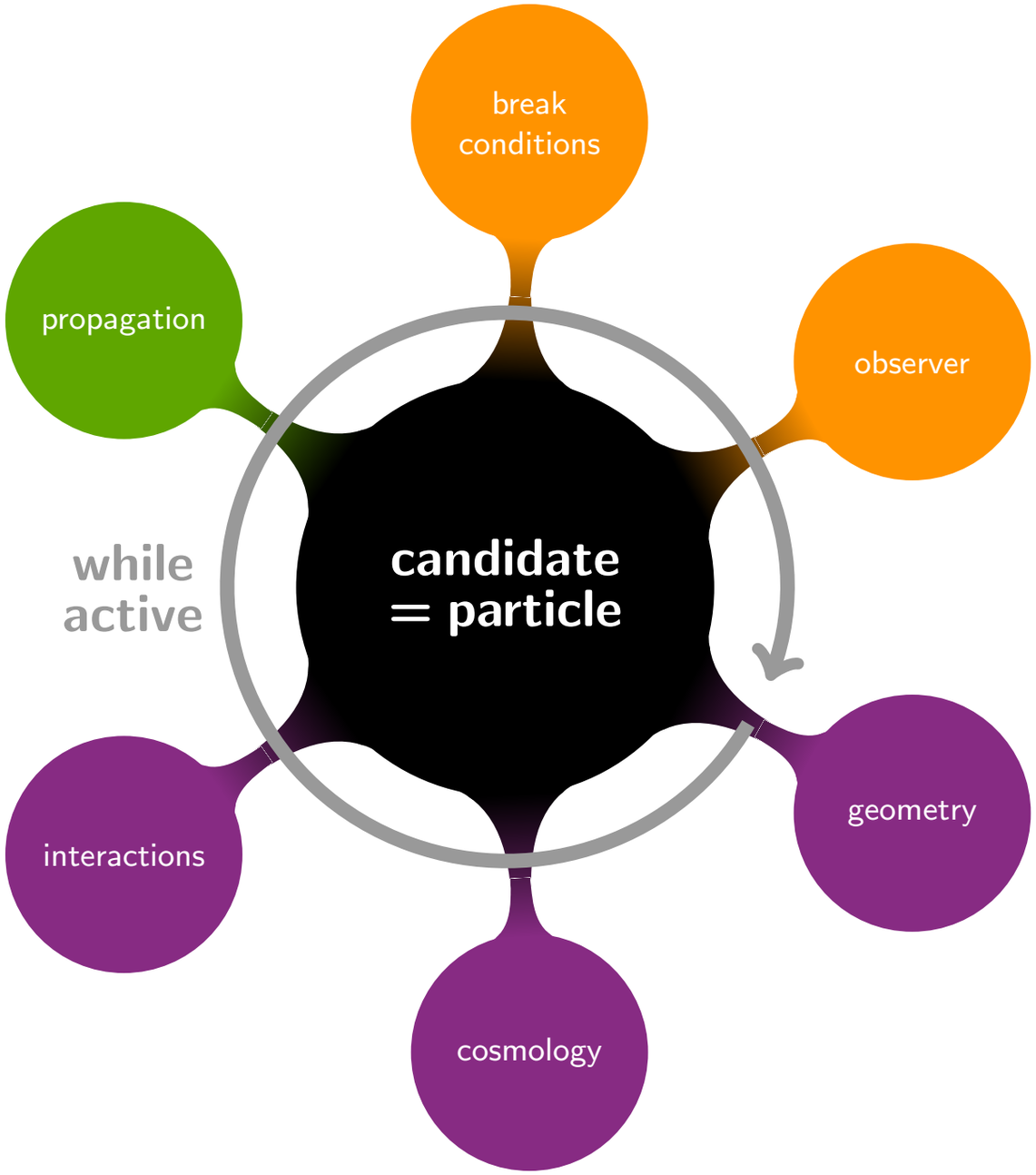
recipes for astroparticle propagation



CRPropa astroparticle simulation framework: CRPropa

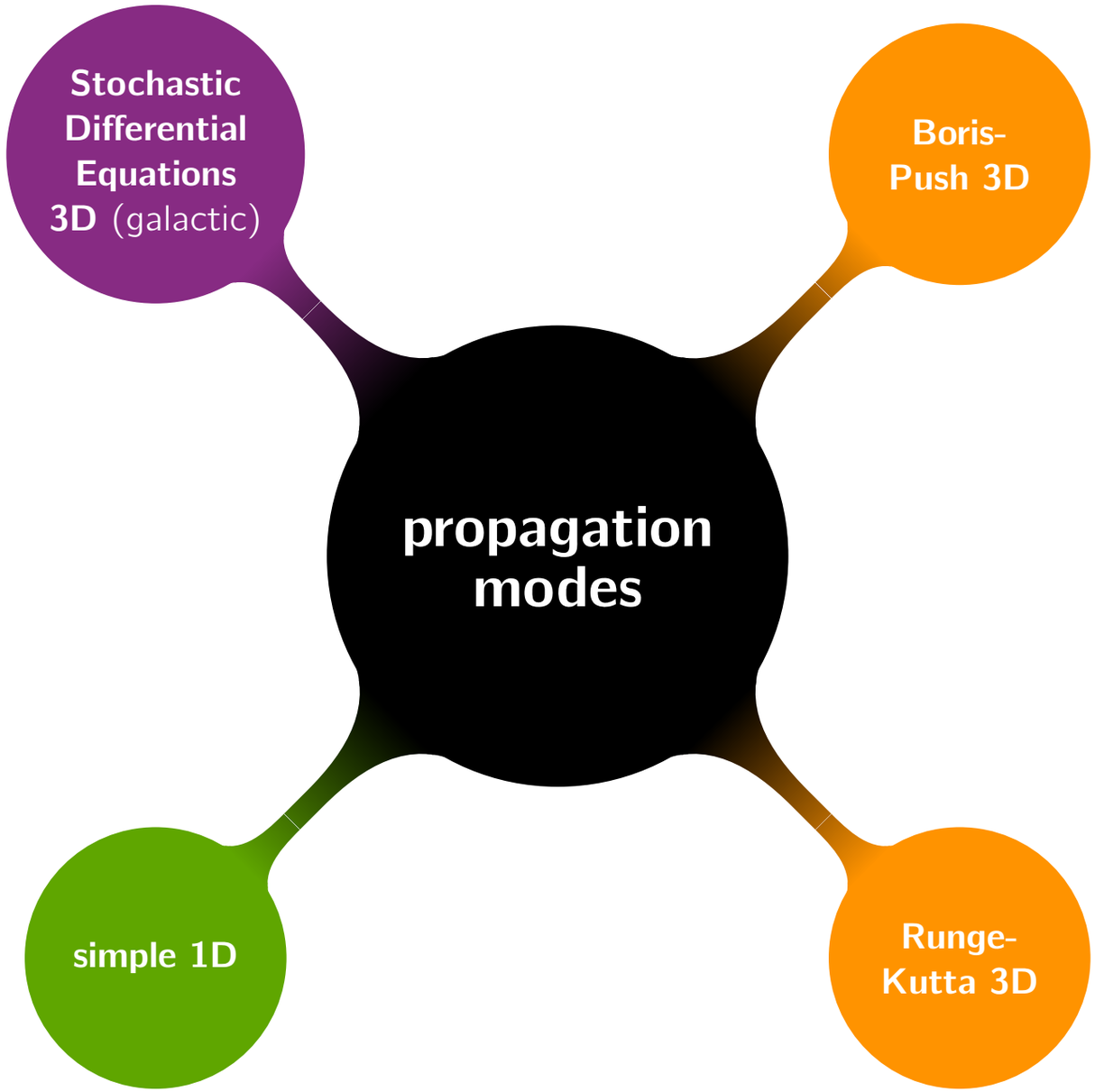
Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142
Alves Batista et al. PoS (ICRC2021) 978. arXiv:2107.01631

- 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!**

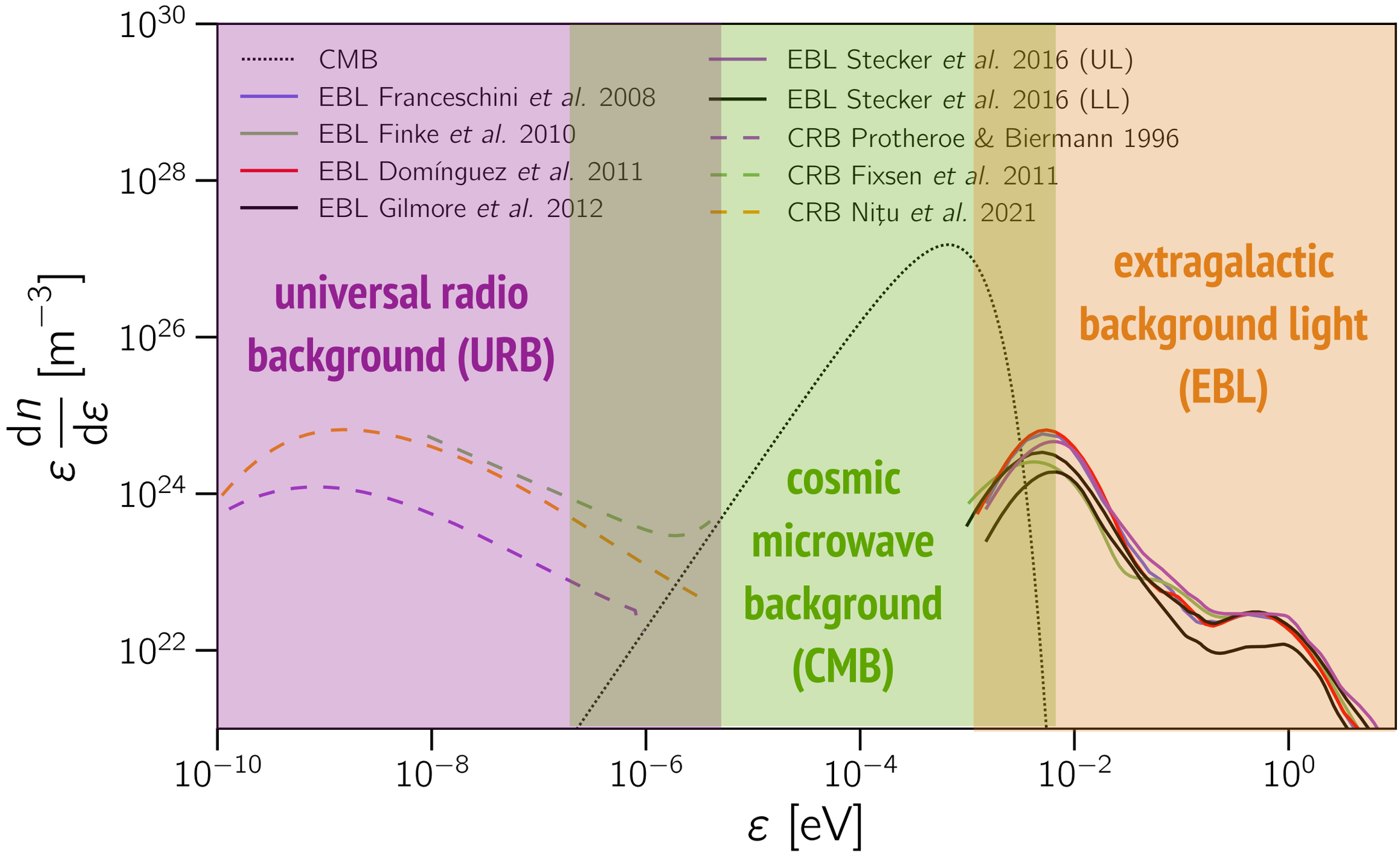


crpropa.desy.de

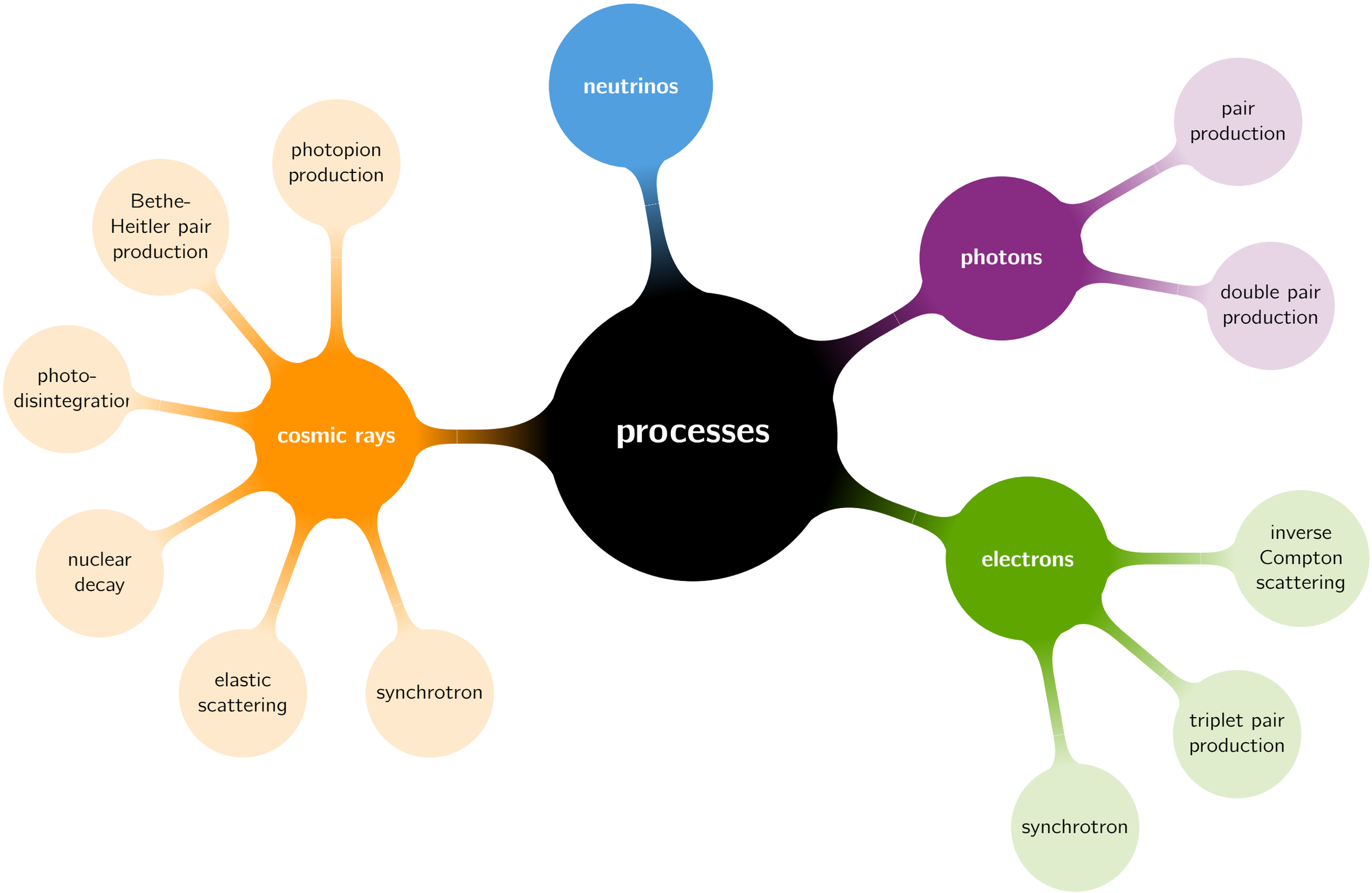
CRPropa: propagation modes



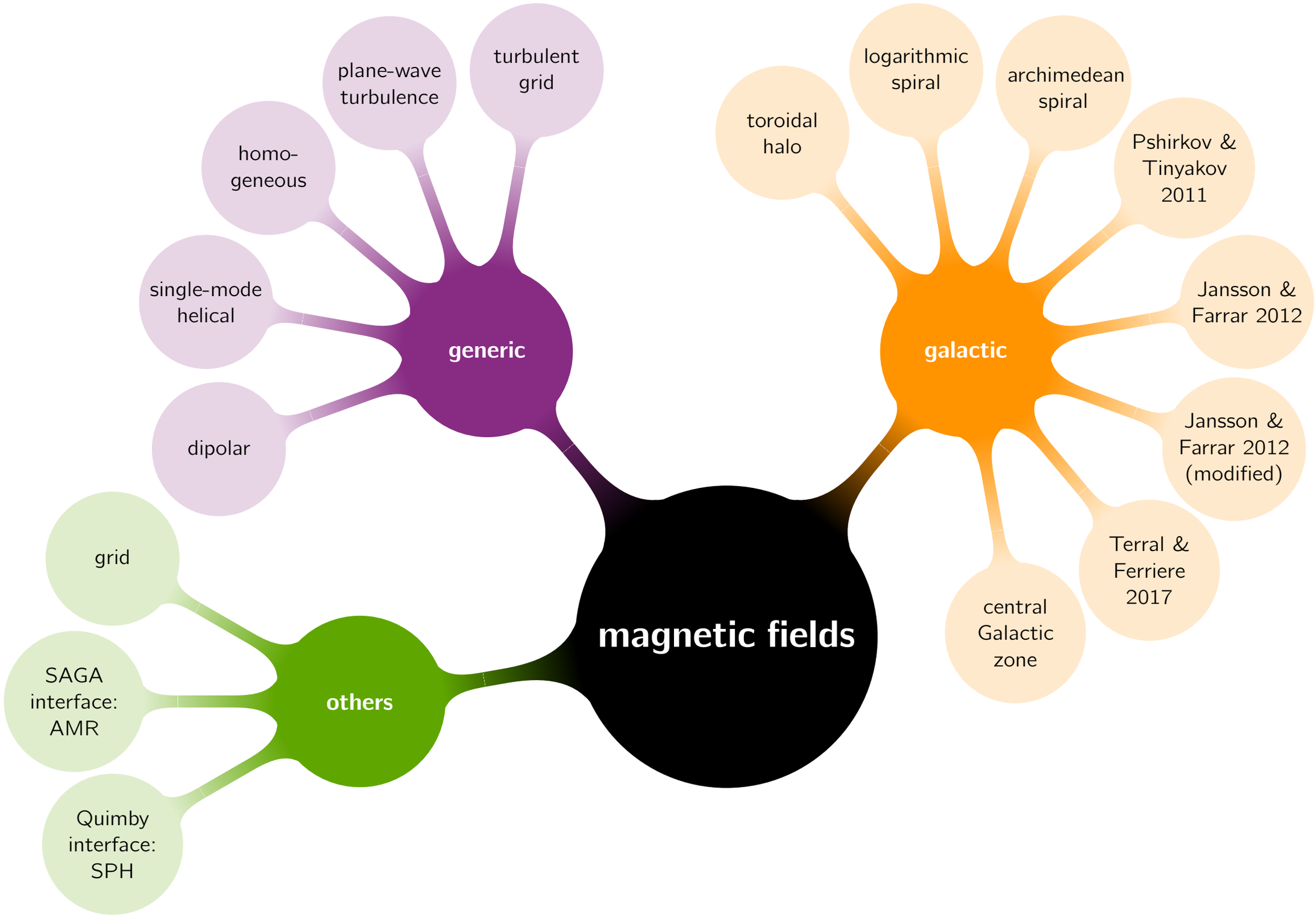
cosmological radiation fields



CRPropa: interactions and energy losses

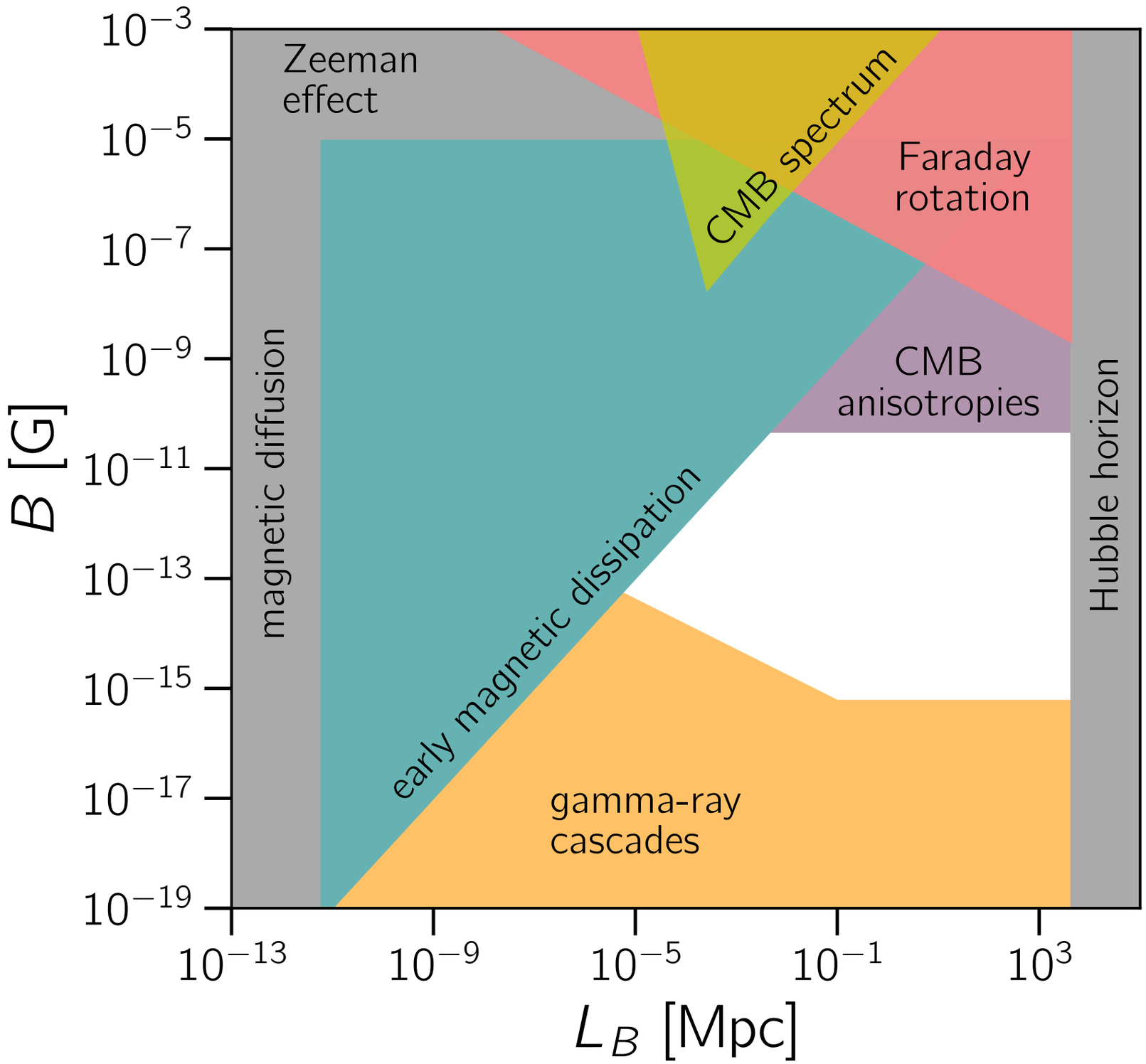


CRPropa: magnetic fields

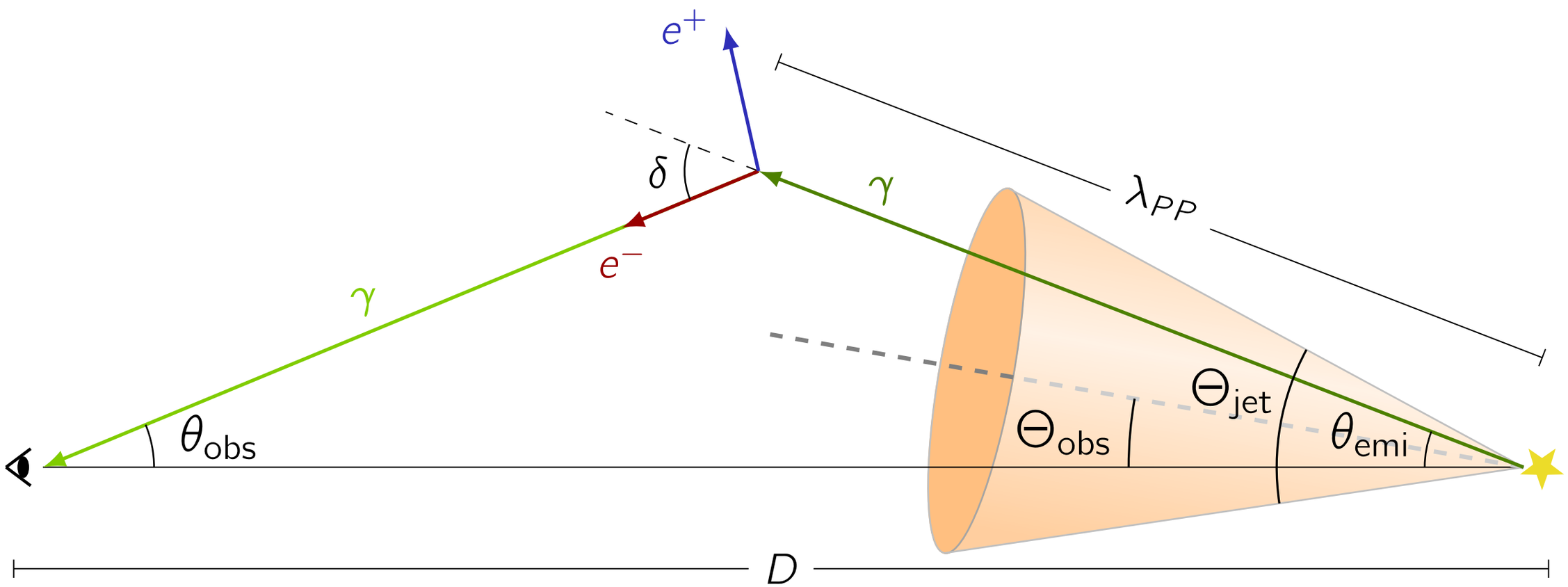


constraining IGMFs with high-energy gamma rays

intergalactic magnetic fields (IGMFs)



gamma-ray propagation and IGMFs

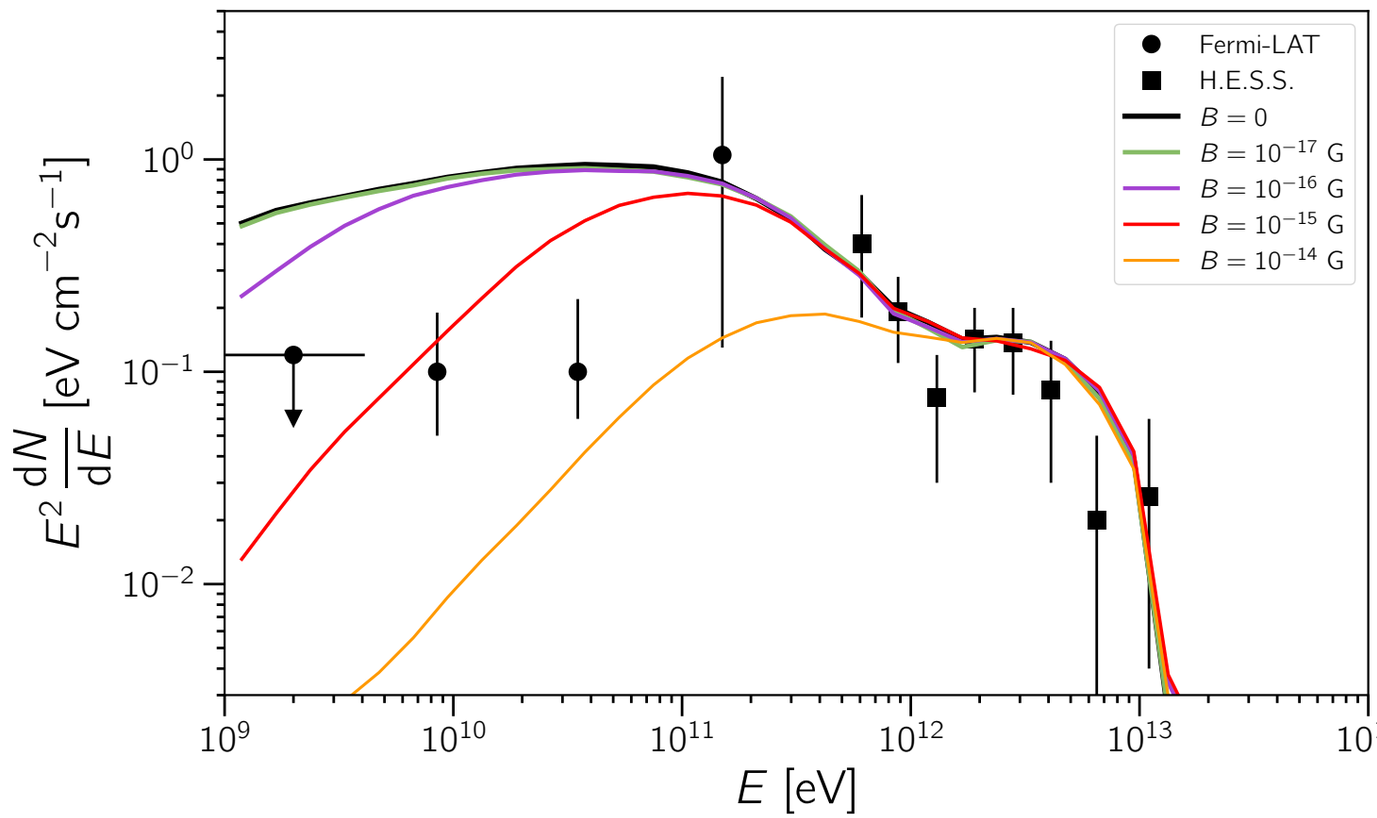


observational strategies

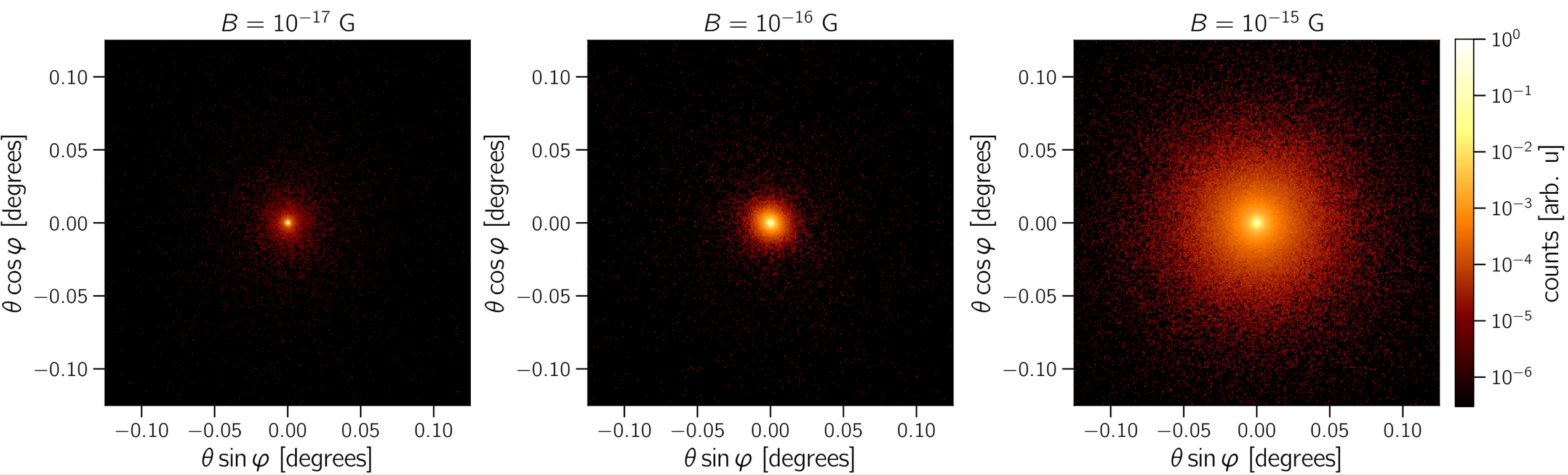
- **strategy 1:** point-like sources will appear extended
- **strategy 2:** secondary gamma rays will arrive with time delays
- **strategy 3:** combination of 1 and 2 → spectral changes

IGMF constraints with gamma rays

Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020

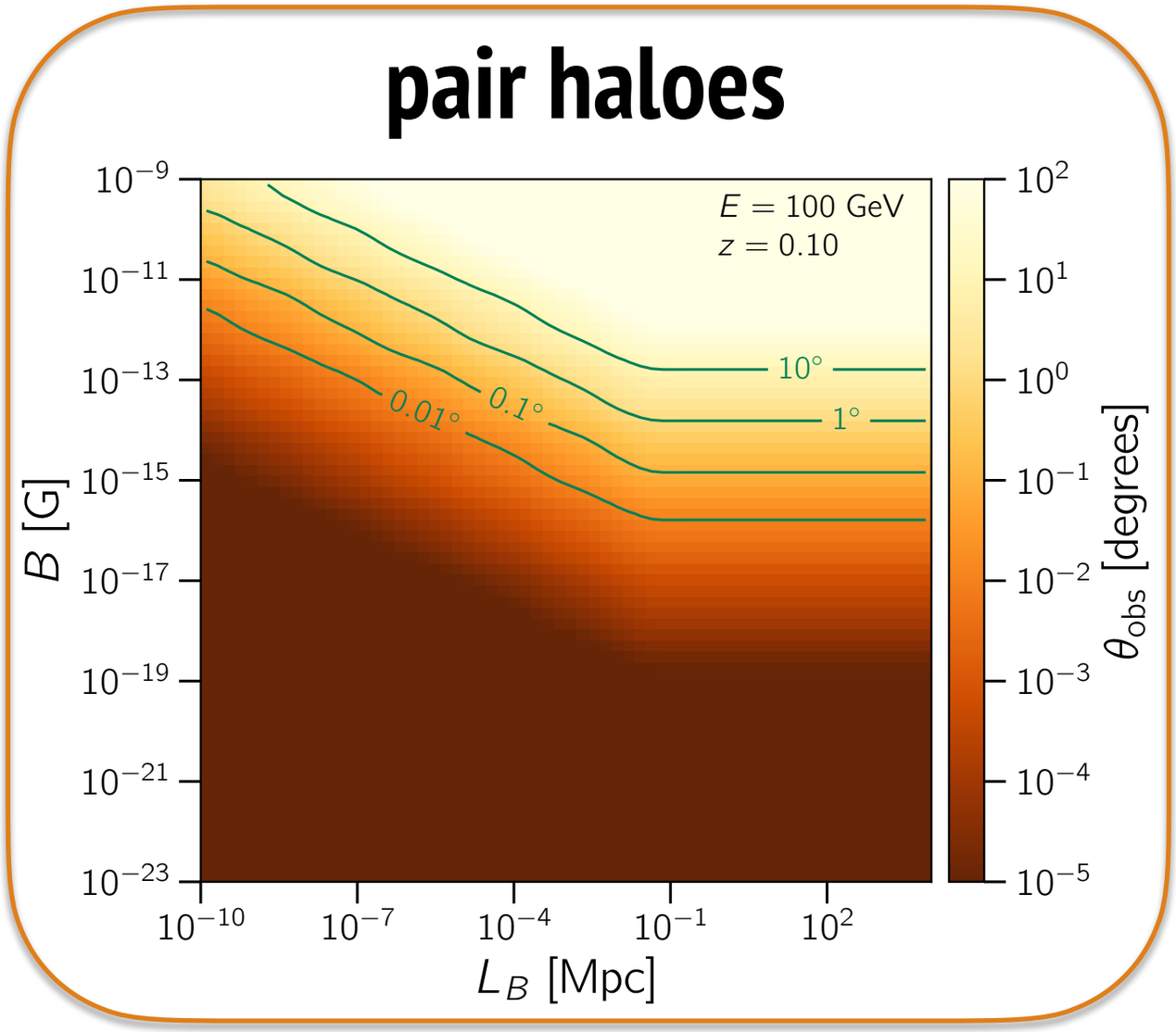


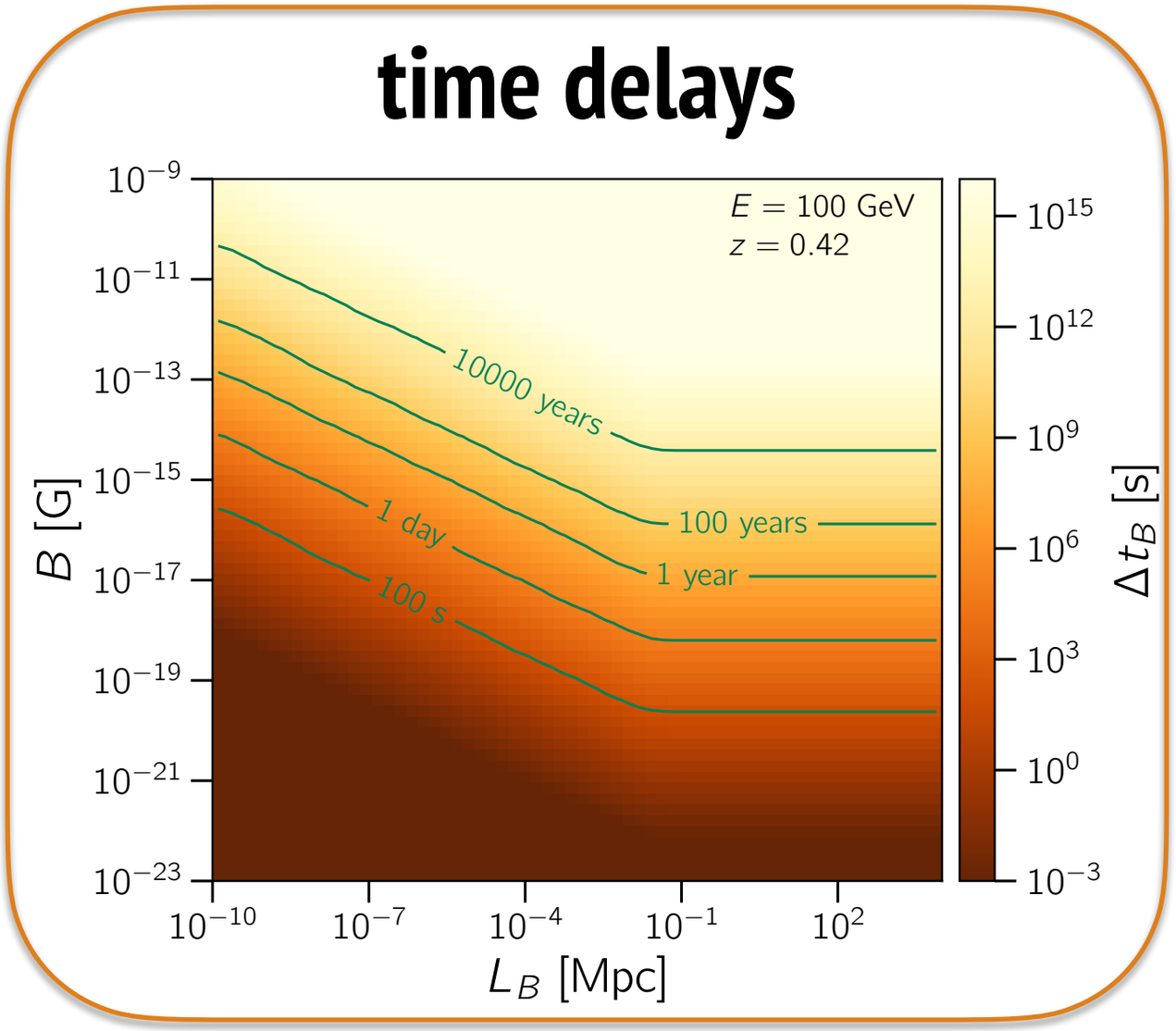
blazar: 1ES 0229+200
z=0.14
Emax=5 TeV
α=2



gamma-ray constraints on IGMFs

Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020

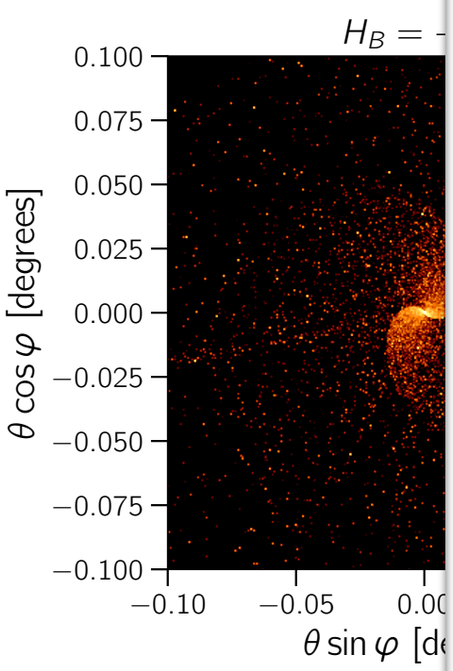




the effect of helicity

Alves Batista, Saveliev, Sigl, Vachaspati. PRD 94 (2016) 083005. arXiv:1607.00320

- helical mag … enesis (right-hande
- helicity is a
- signatures o … urce)



counts [arb. u]

$B=10^{-15}$ G
Batchelor spectrum
L_B=200 Mpc

z=0.08

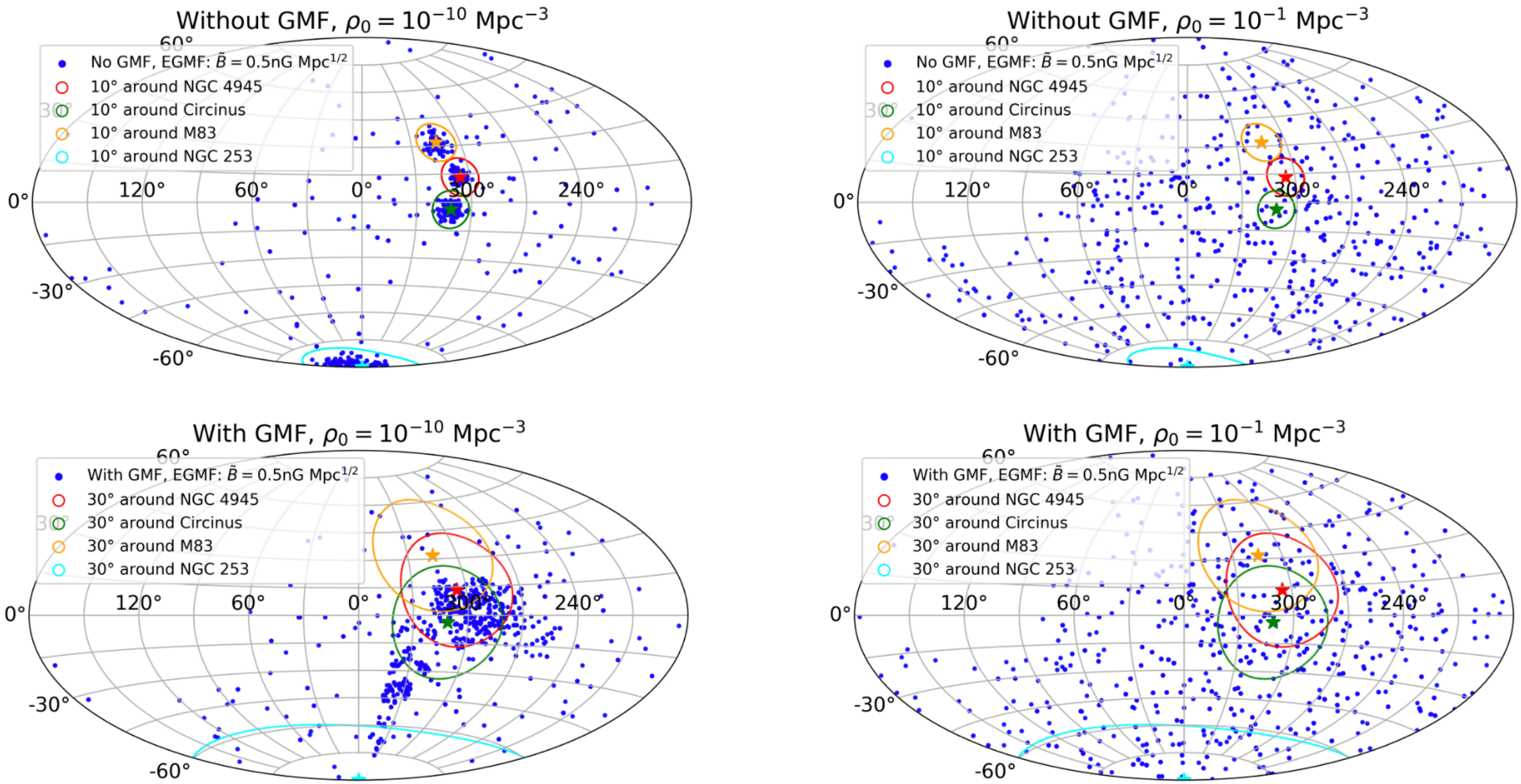
gamma-ray constraints on IGMFs

- most common method for probing IGMFs in the voids
- **common shortcomes**:
  . simplified treatment of particle interactions;
  . intrinsic source spectrum is fixed (should be inferred together with IGMF)
  . oversimplified IGMF models
- **other possible problems**: plasma instabilities may quench the electromagnetic cascades

constraining IGMFs with ultra-high-energy cosmic rays

IGMF constraints from UHECRs

van Vliet, Palladino, Taylor, Winter. MNRAS (2021). arXiv:2104.05732



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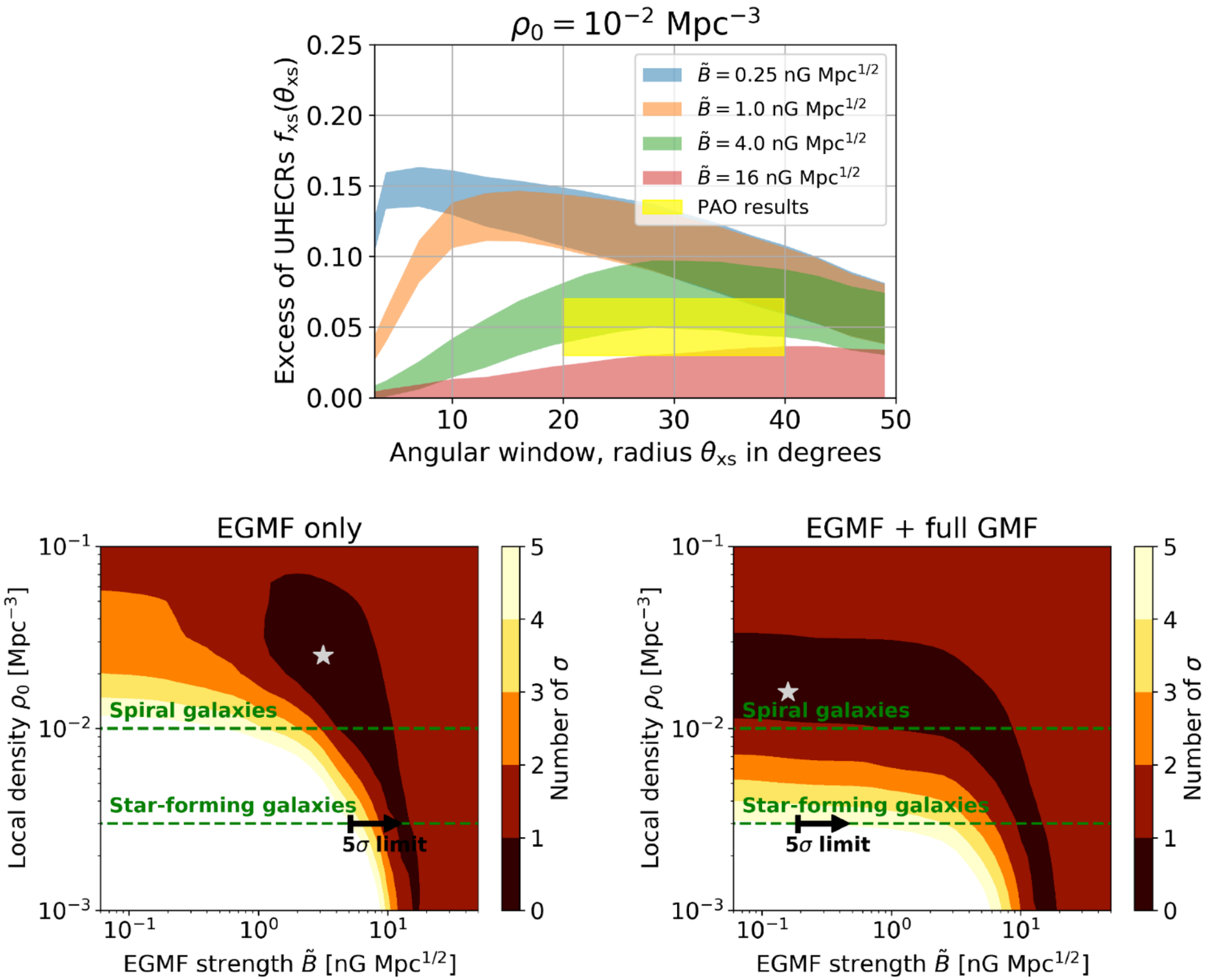


cosmic-ray signatures of helical IGMFs

Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182

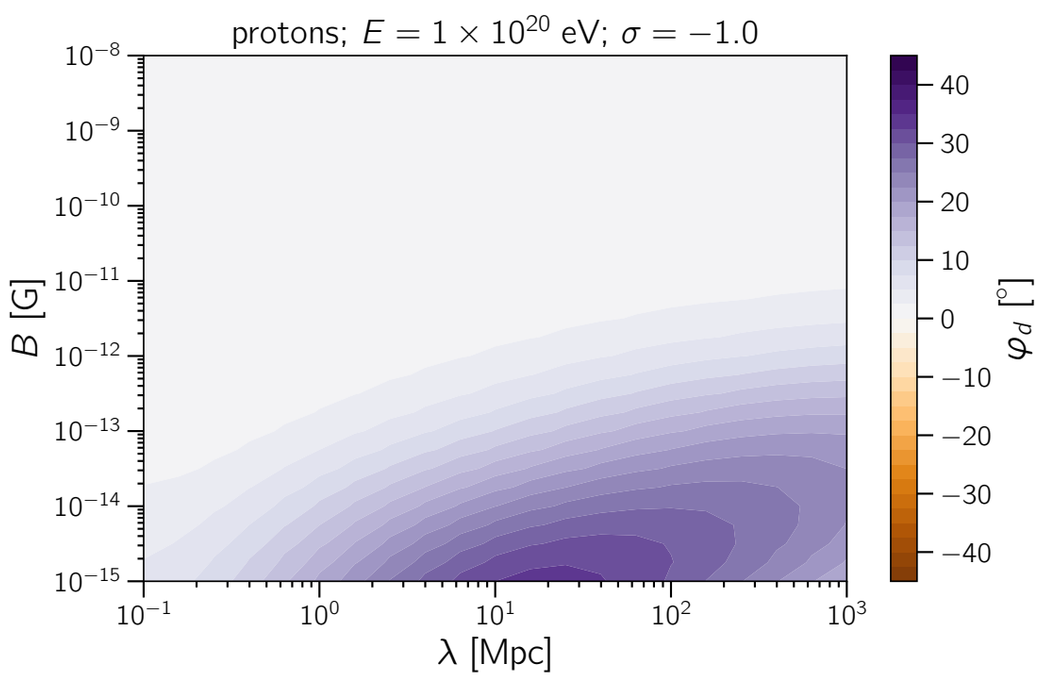
general idea

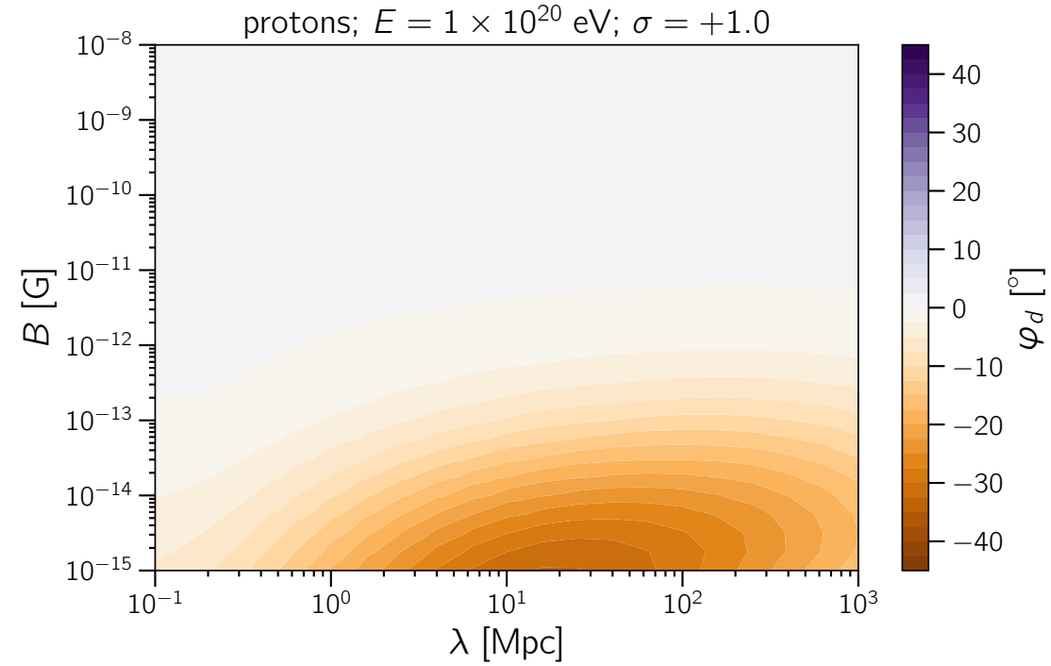
- UHECRs can be used to constrain helicity
- select UHECR sources at approximately the same distance from Earth
- perform harmonic analysis
- dipole direction (ϕ_d) → sign of the helicity;
- dipole-to-quadrupole ratio (r) → absolute value

cosmic-ray signatures of helical IGMFs

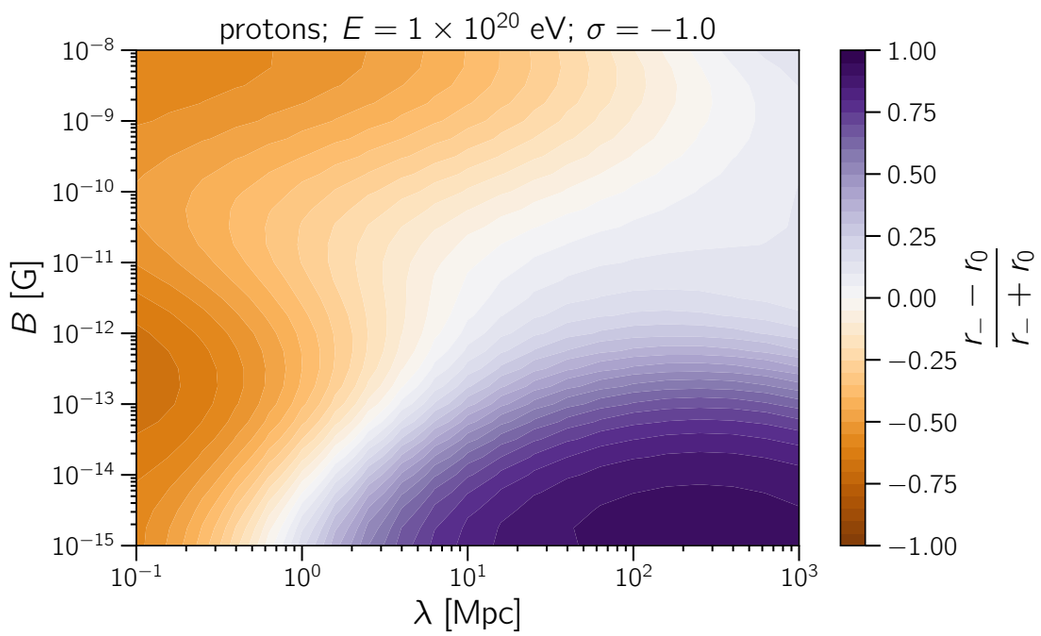
Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182

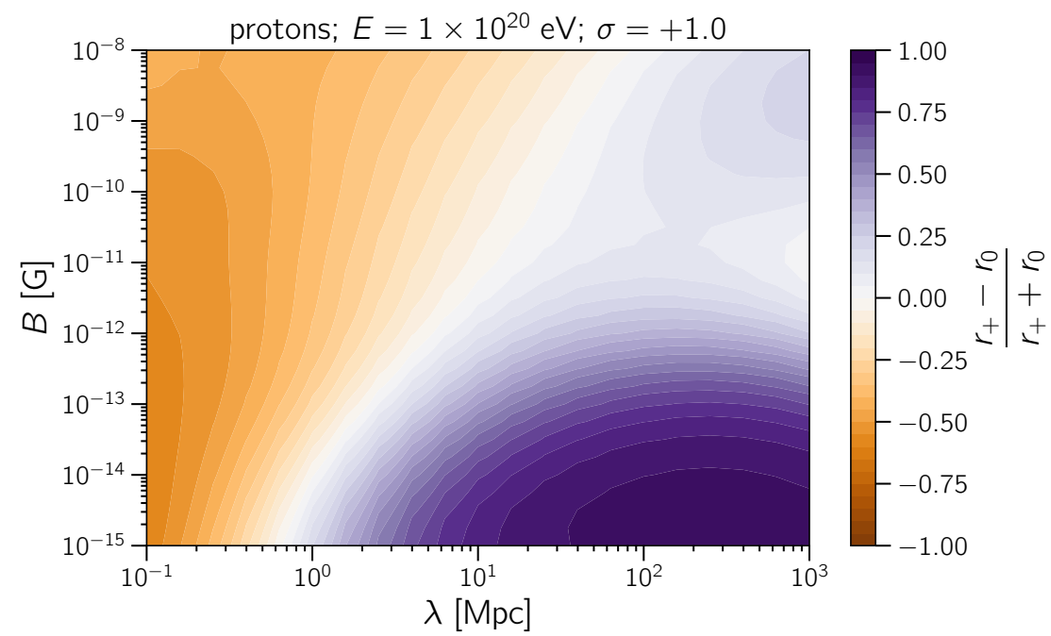
sign





absolute value





IGMF constraints from UHECRs

- UHECR sources are unknown
- **general constraints shortcomes**:

  . variations in the relative contribution of each UHECR source may interfere with result

  . other propagation uncertainties (interactions) are correlated with IGMF constraints
- **helicity constraints shortcomes**:

  . toy model with simple single-mode magnetic fields

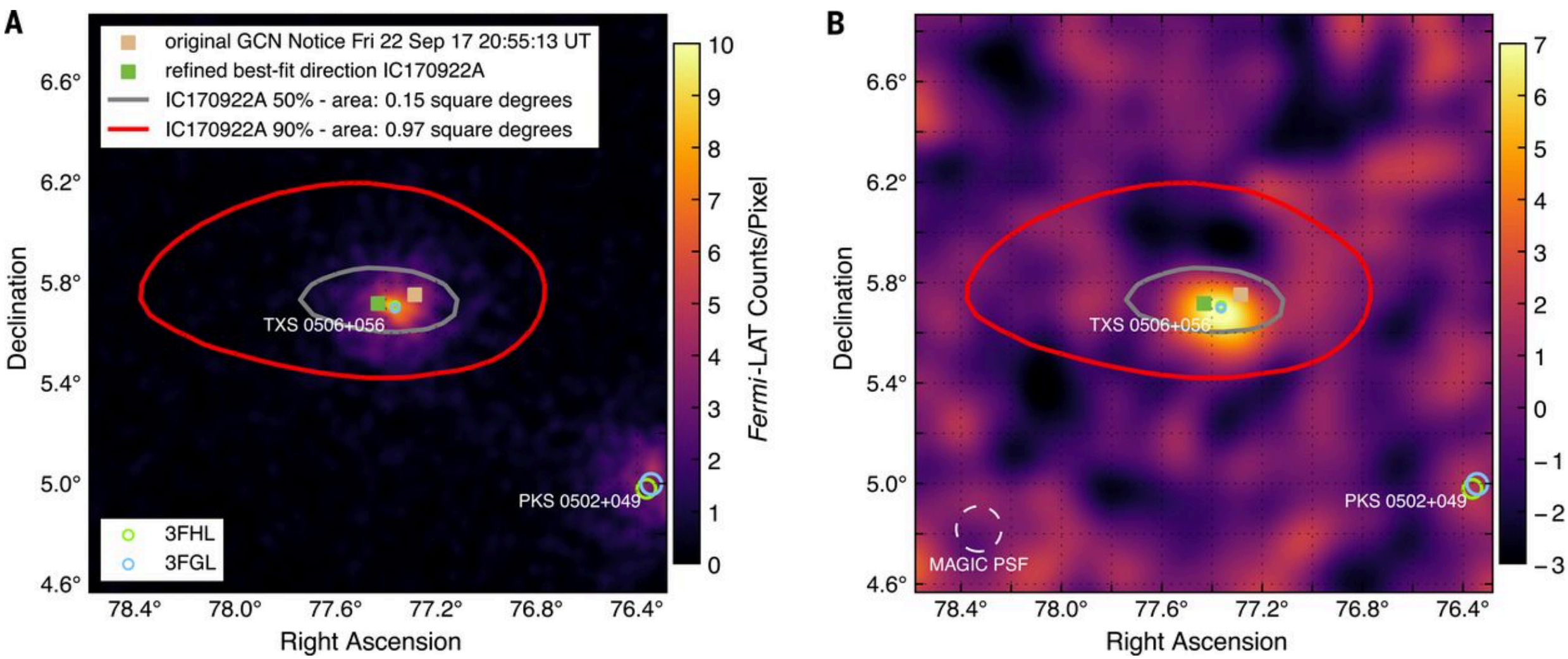
  . for realistic fields anisotropy patterns might vanish

gamma rays + neutrinos

a multimessenger method for constraining IGMFs

TXS 0506+056: the first cosmic neutrino source

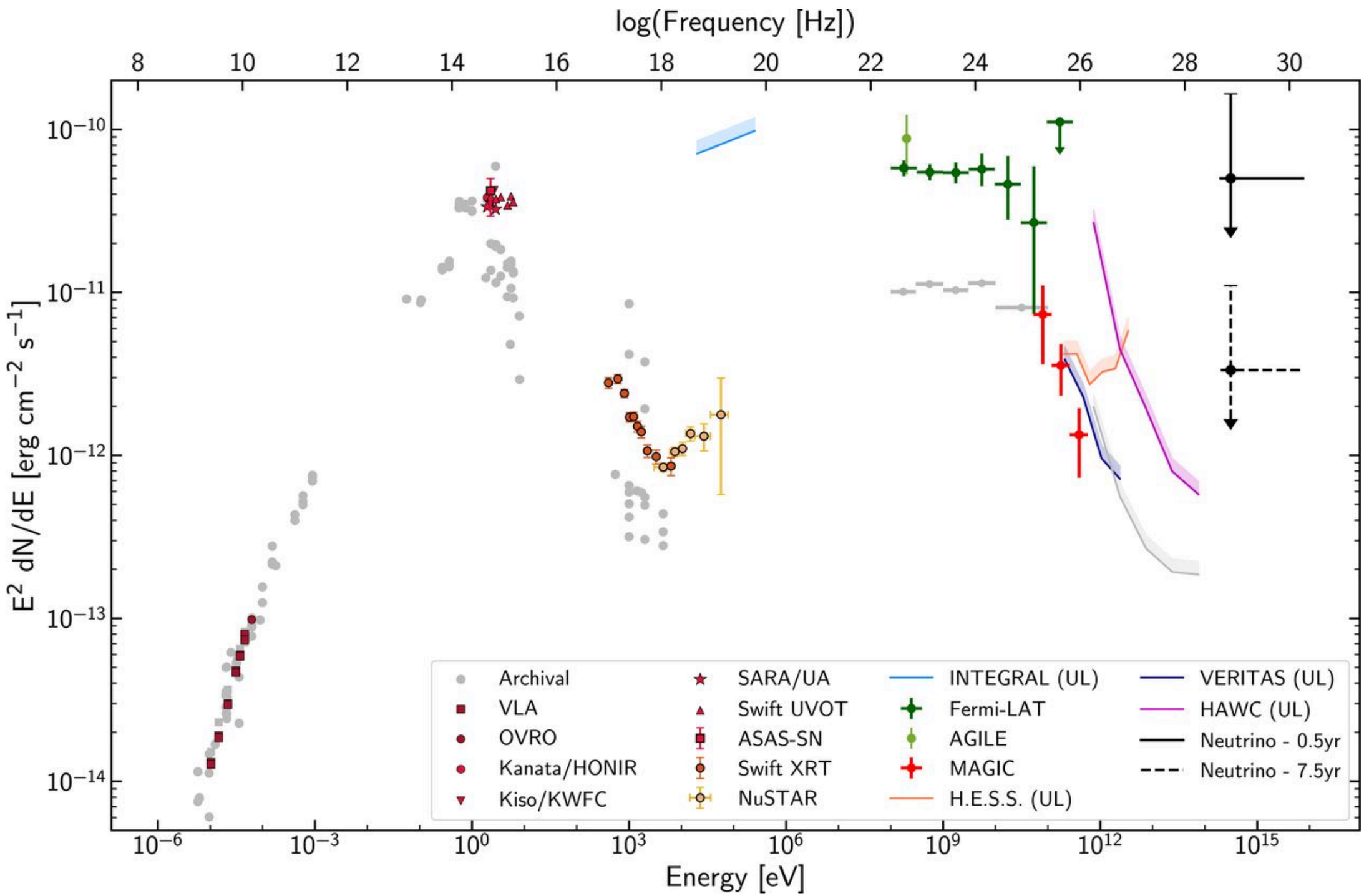
(possibly)



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

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

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

constraining IGMFs with TXS 0506+056

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

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

general idea

- neutrino flare could emit high-energy gamma rays
- high-energy gamma rays are attenuated by the EBL
- cascade component retains information of primary spectrum

intrinsic gamma-ray spectrum

$$\frac{dN}{dE} = J_0 \left[E^{-\alpha_l} \exp\left(-\frac{E}{E_{max,l}}\right) + \eta E^{-\alpha_h} \exp\left(-\frac{E}{E_{max,h}}\right) \right]$$

(phenomenological model = how it appears)

method

- run simulations with CRPropa
- fit intrinsic spectrum (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

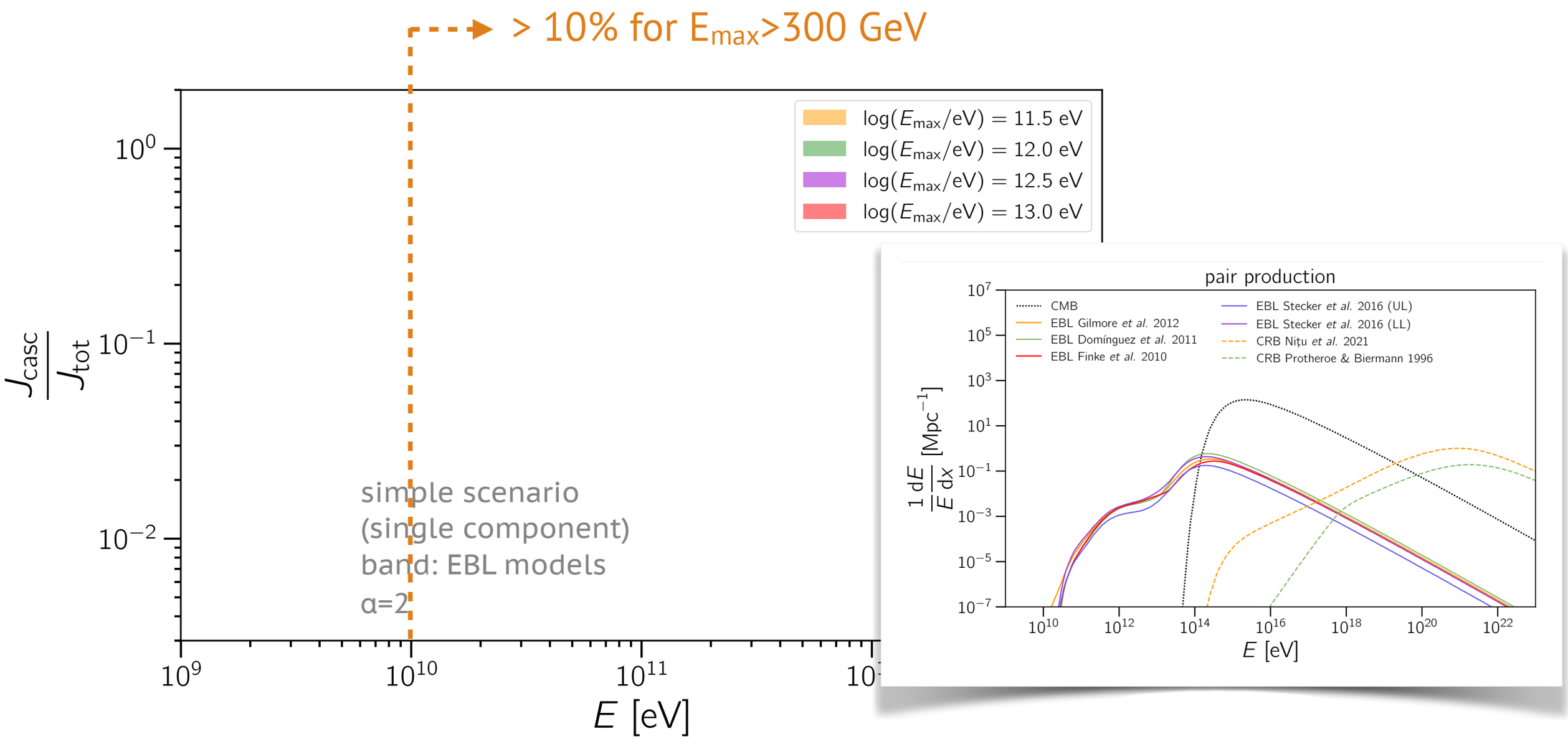
IGMFs and TXS 0506+056: cascade component

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

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

is there a cascade contribution?

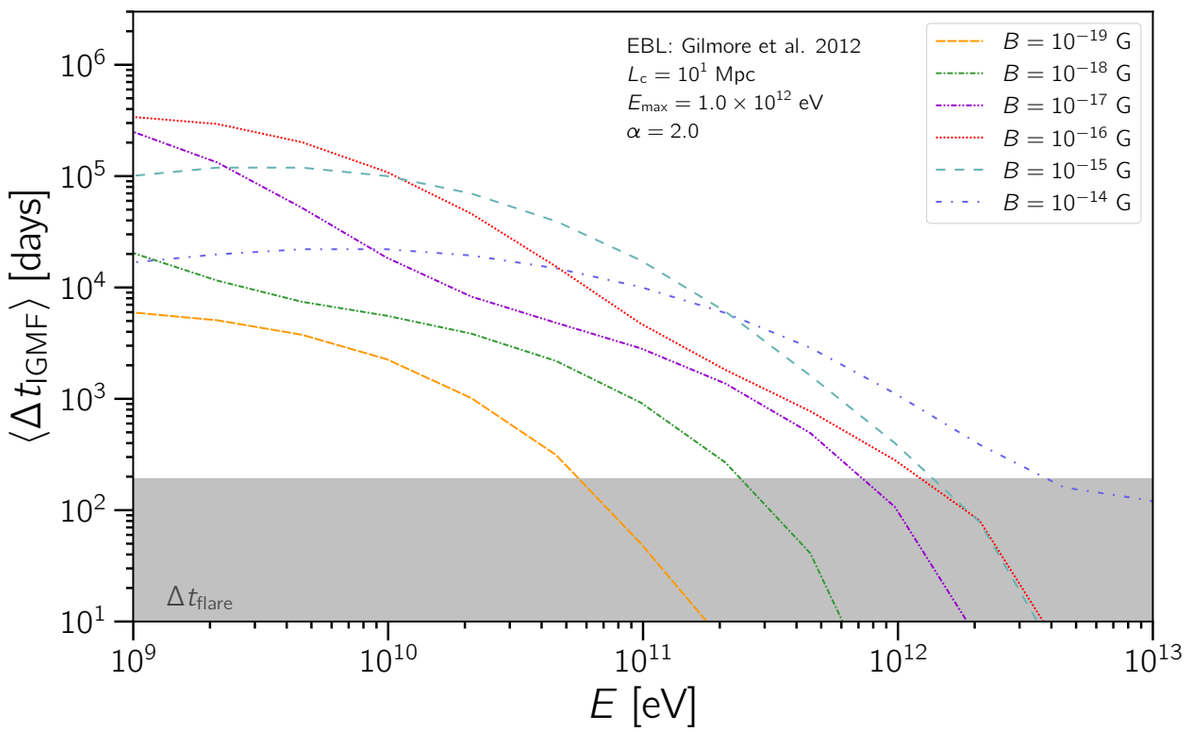
MAGIC observes
400 GeV events

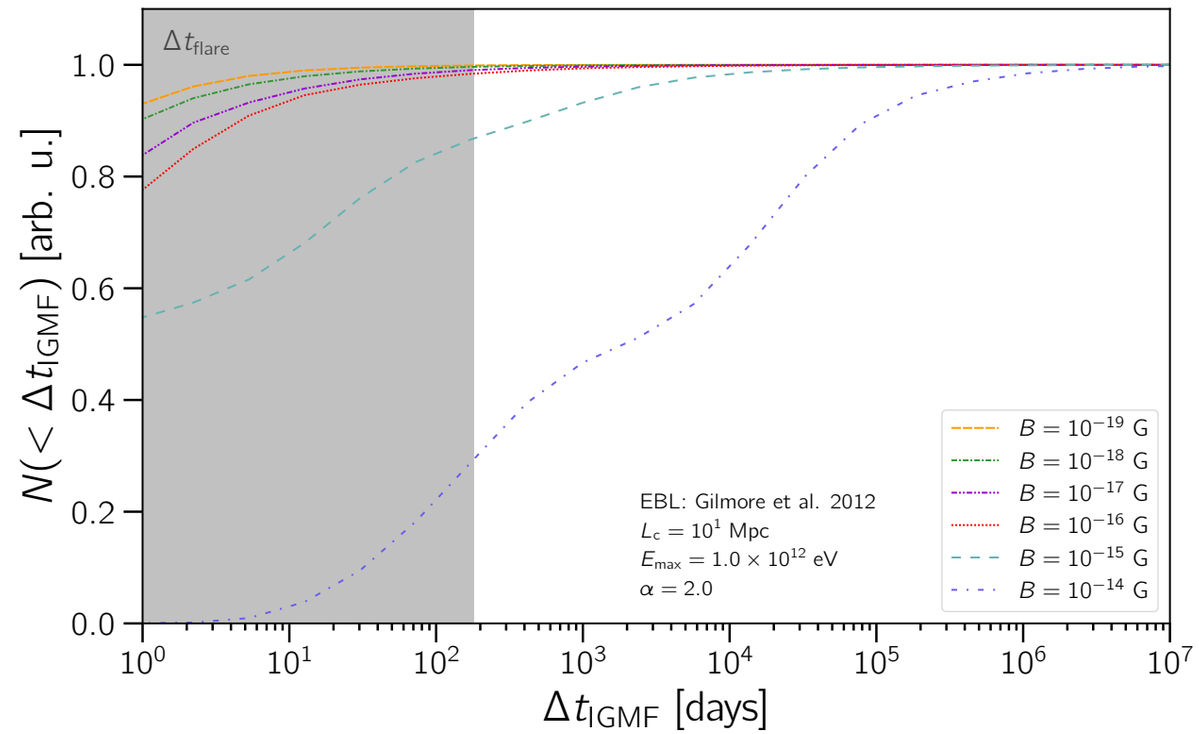


IGMFs and TXS 0506+056: time delays

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

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



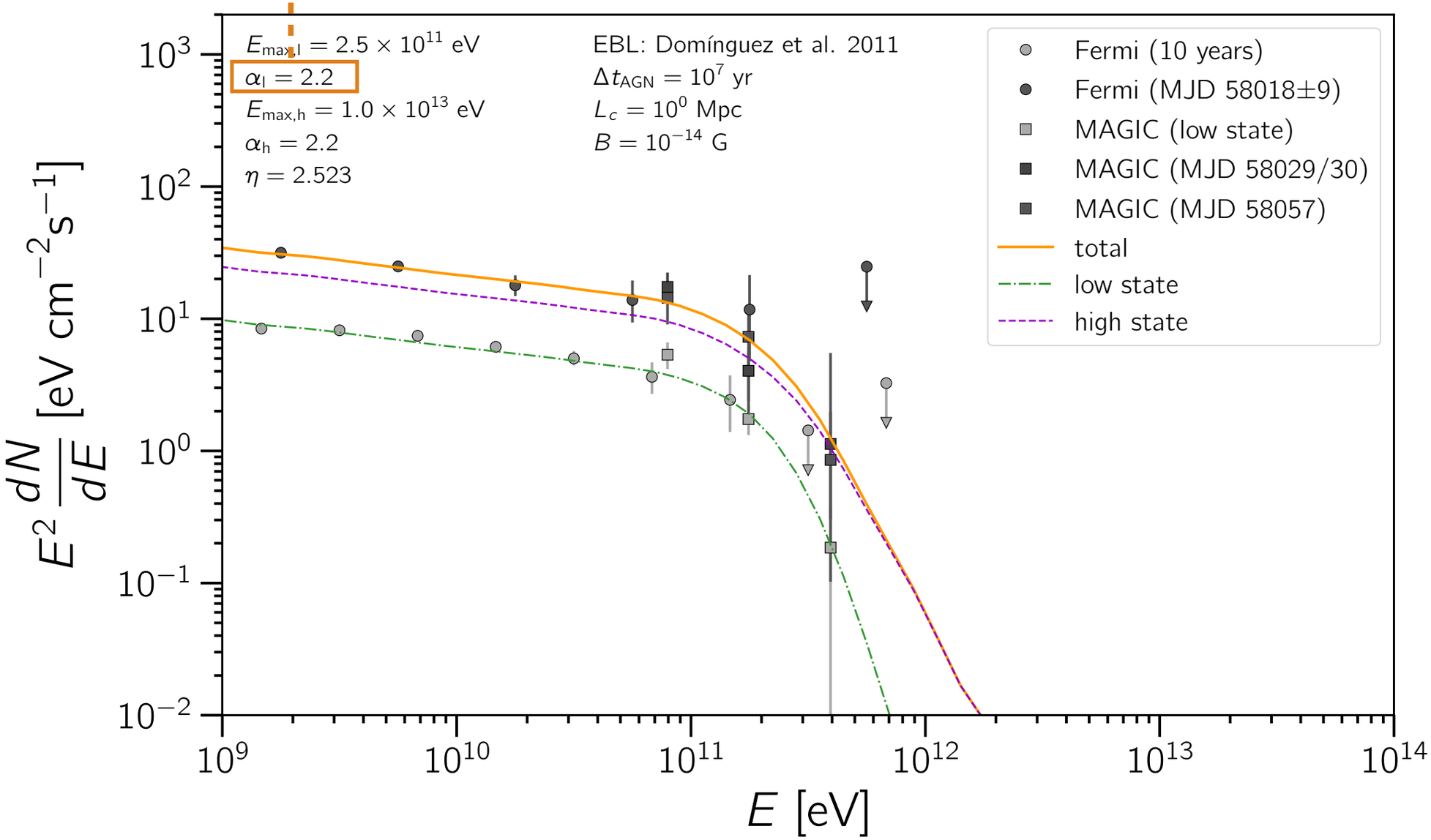


IGMFs and TXS 0506+056: fitting the data

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

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

approximately the same regardless of the magnetic field



IGMFs and TXS 0506+056: fitting the data

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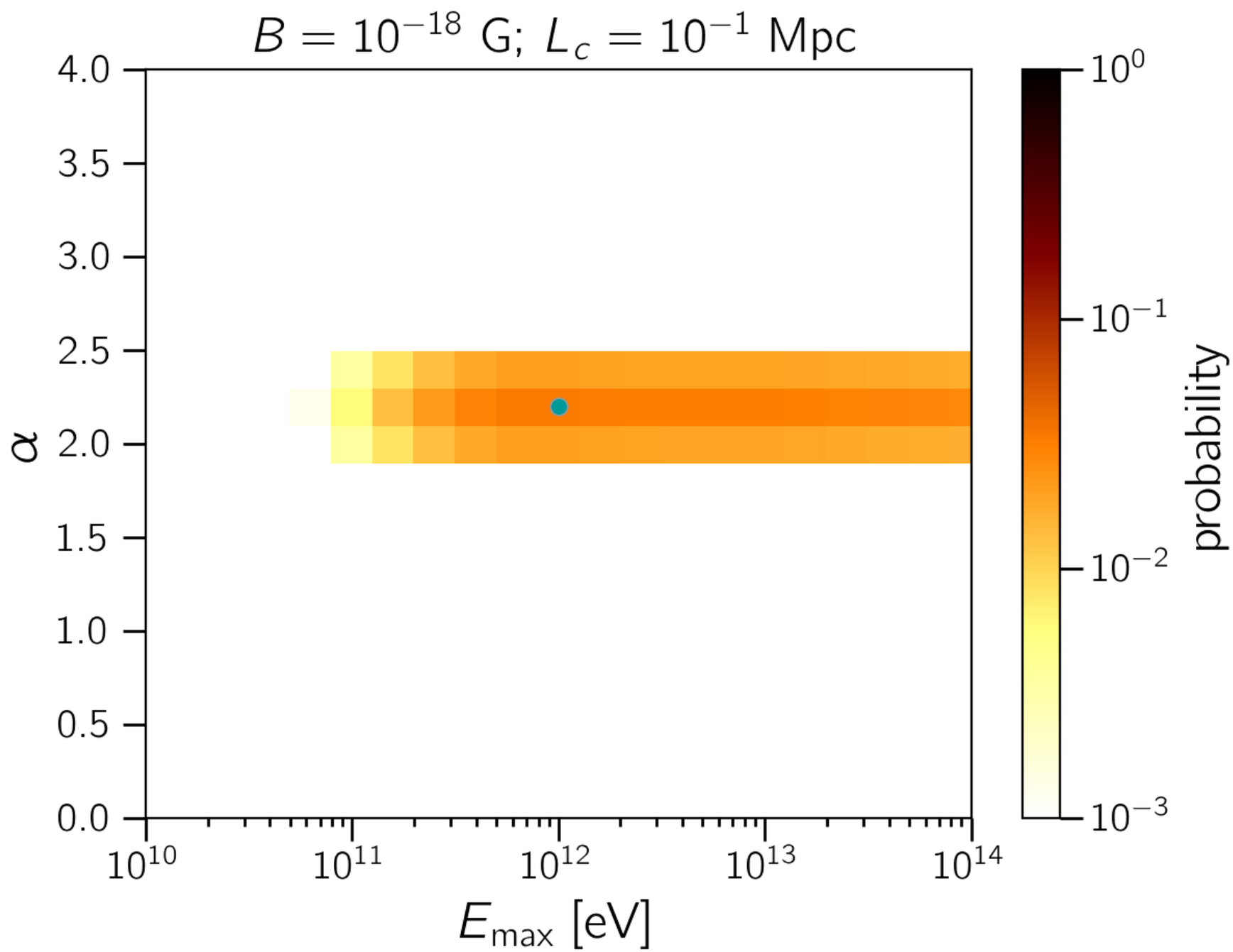

constraining IGMFs with TXS 0506+056

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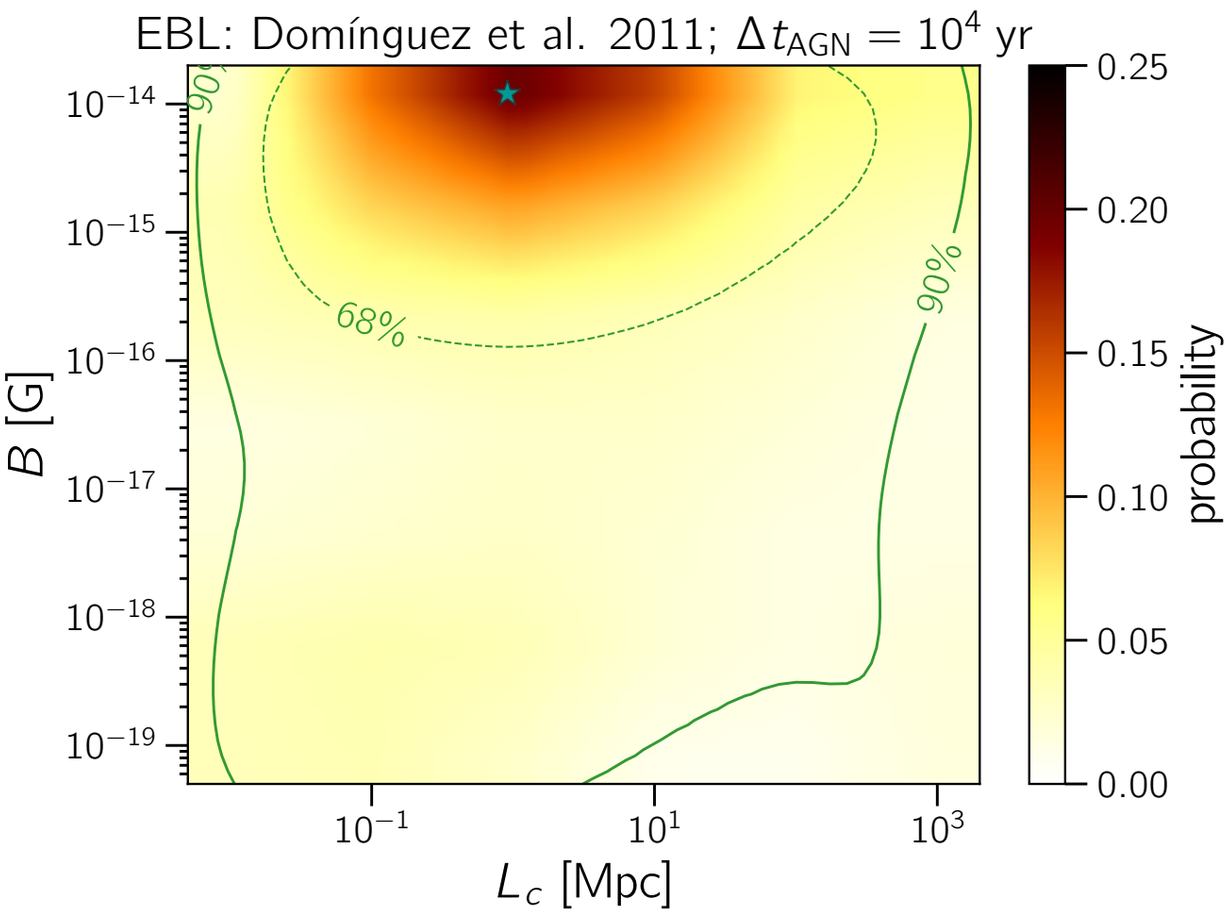
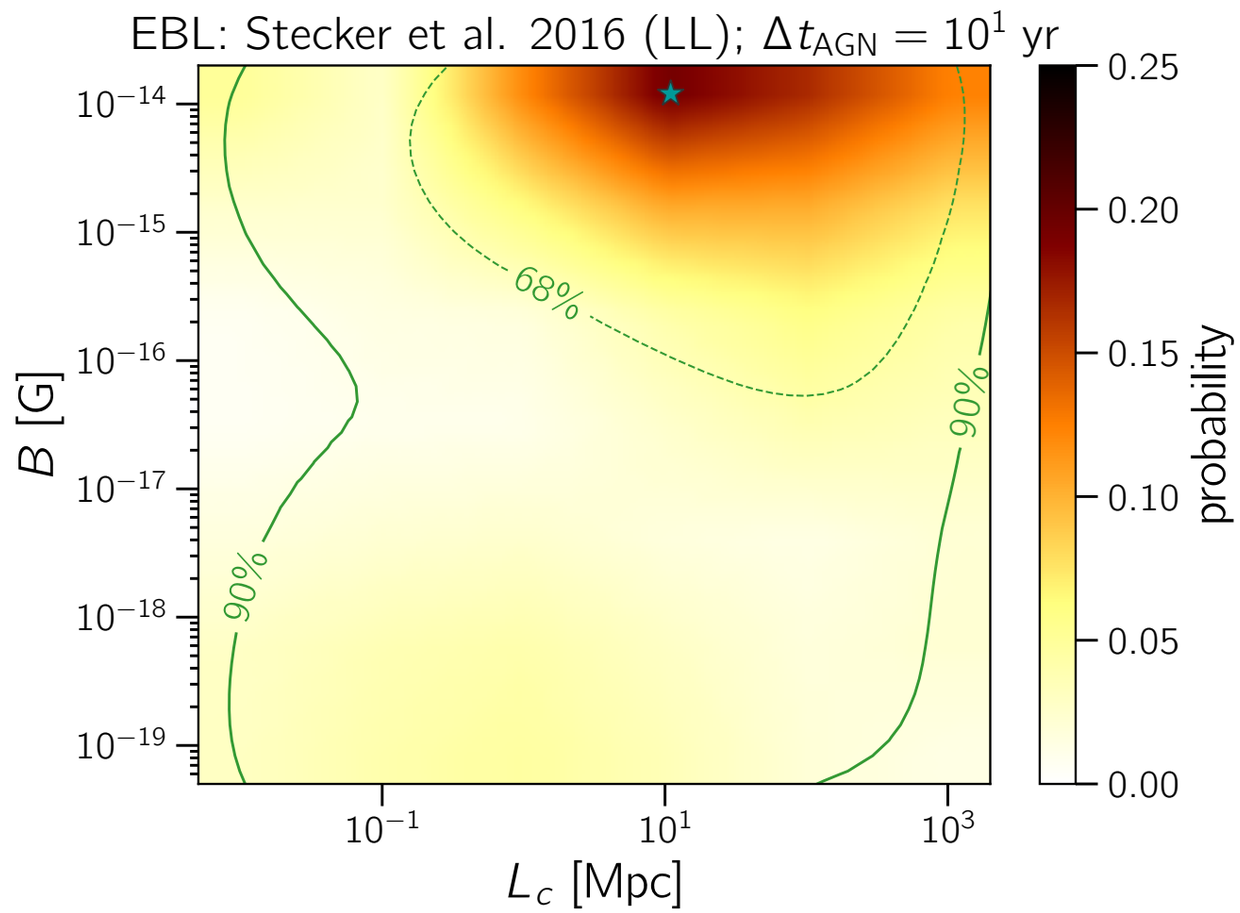
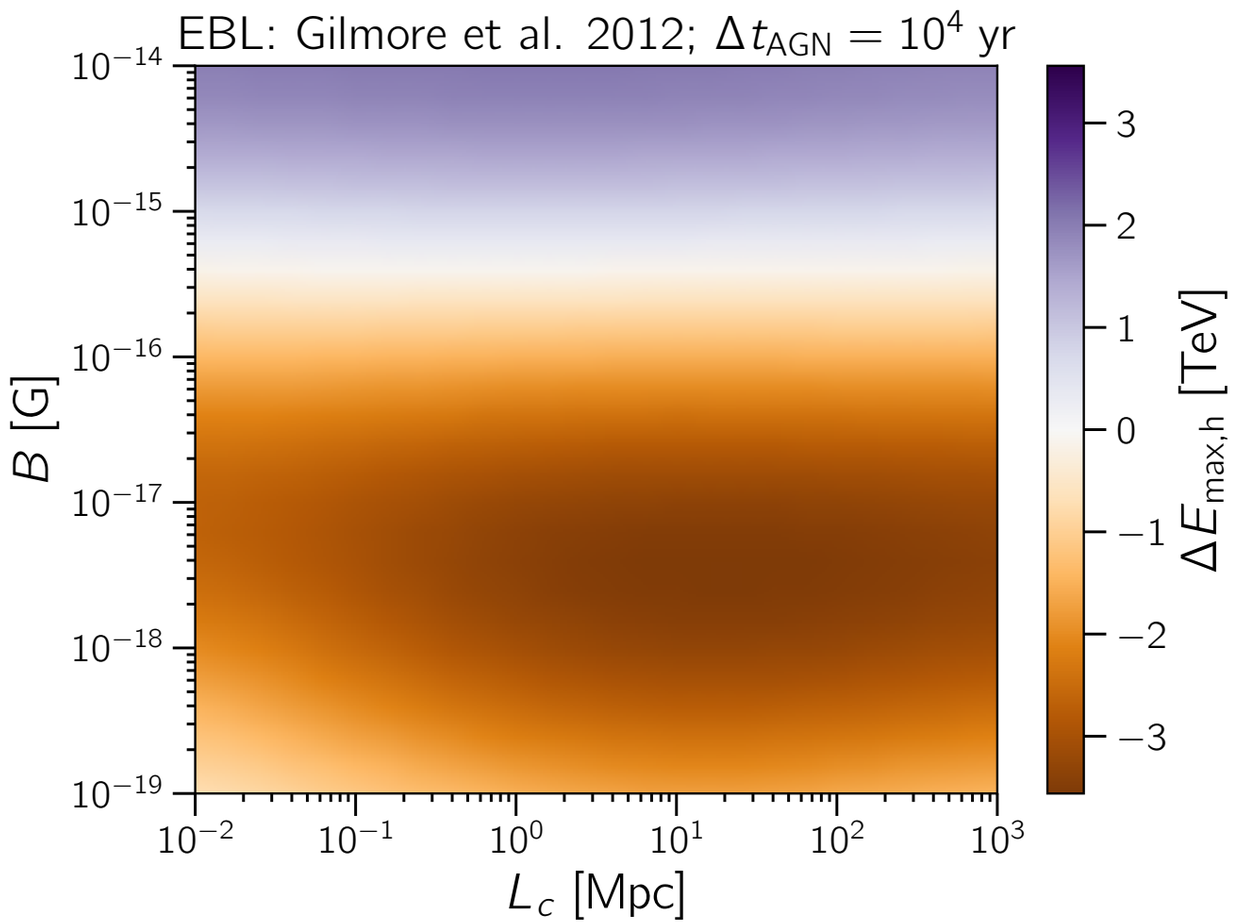
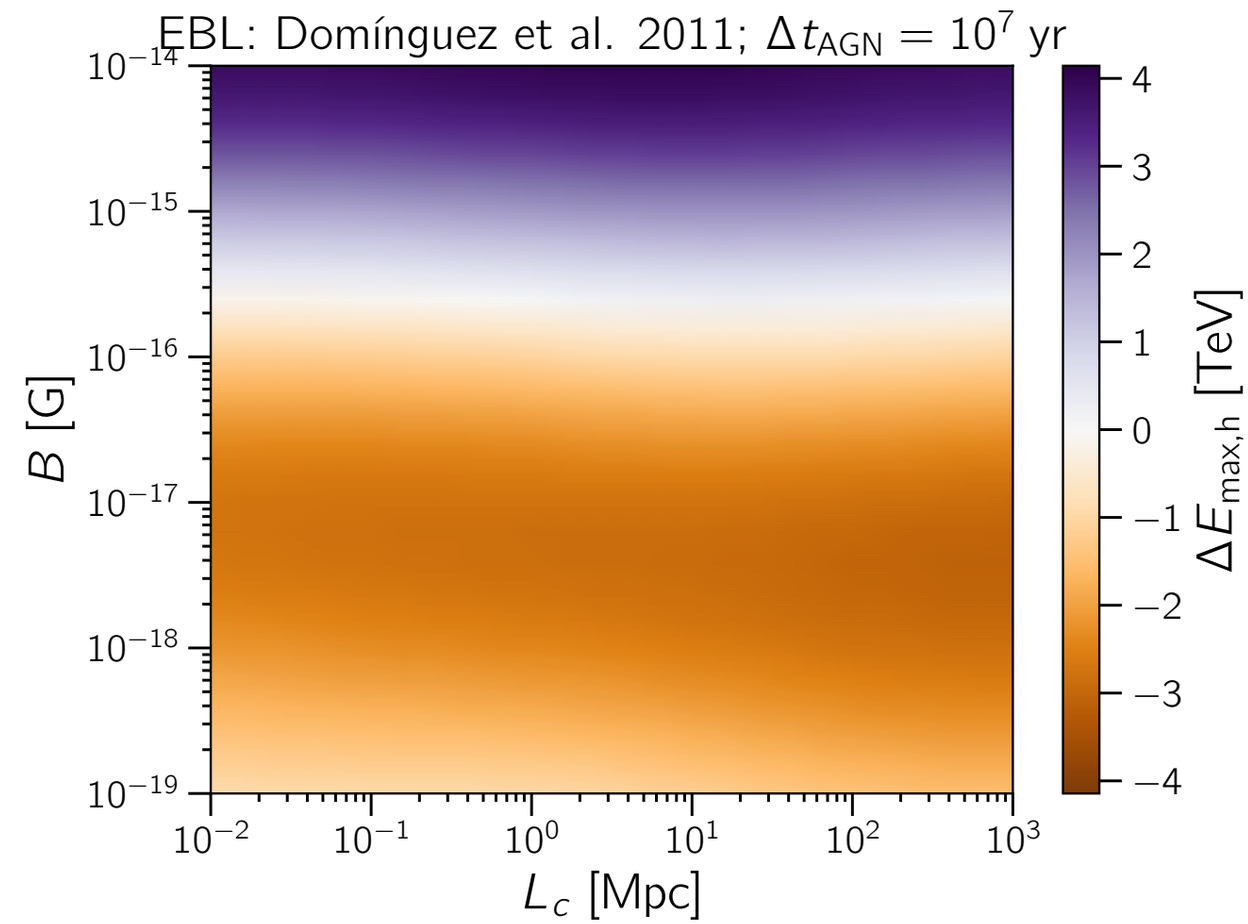




IGMF effects on TXS 0506+056: maximum gamma-ray energy

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





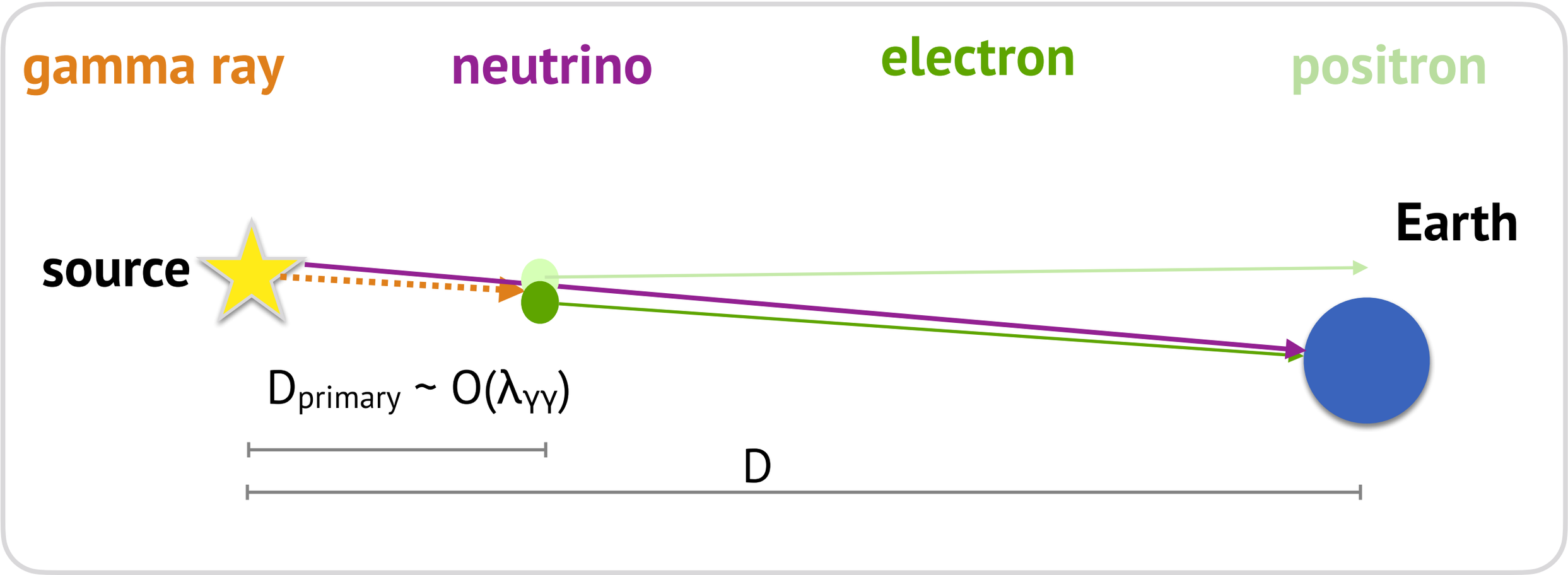
motivation for this talk

a note on neutrinos and IGMFs

on the importance of magnetic fields for multimessenger studies

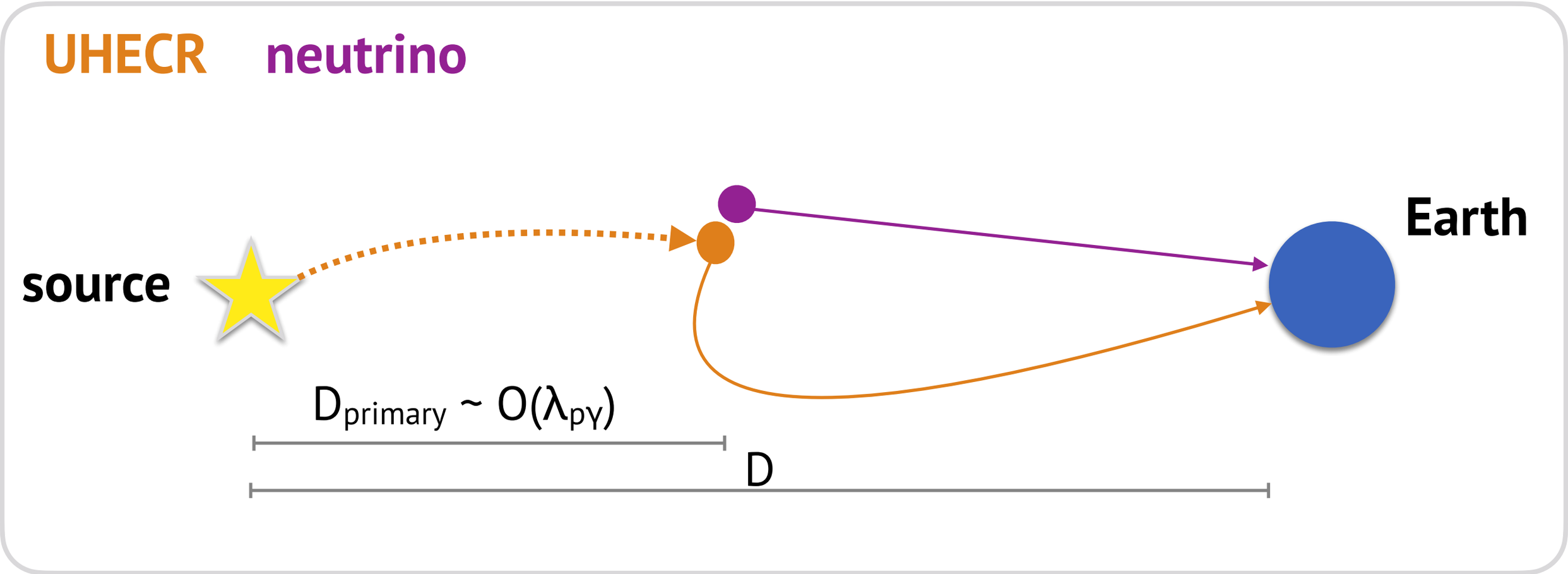
how to enrich the science case of a neutrino telescope?

(source) neutrino--gamma-ray correlations



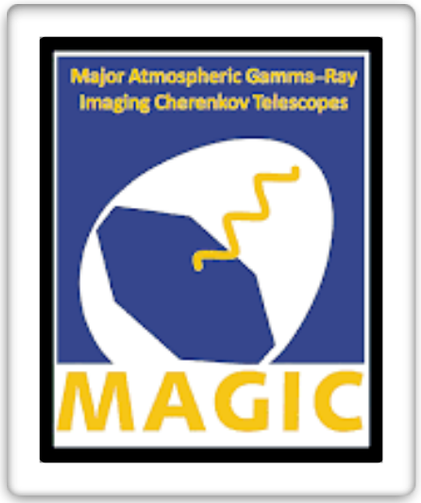
- time delays and angular correlations between a source emitting neutrinos and gamma rays simultaneously depend on IGMFs

(cosmogenic) neutrino-UHECR correlations



- time delays and angular correlations between UHECRs and cosmogenic neutrinos depend on IGMF (and GMF)

IGMFs: "free lunch" for neutrino and gamma-ray observatories



concluding remarks

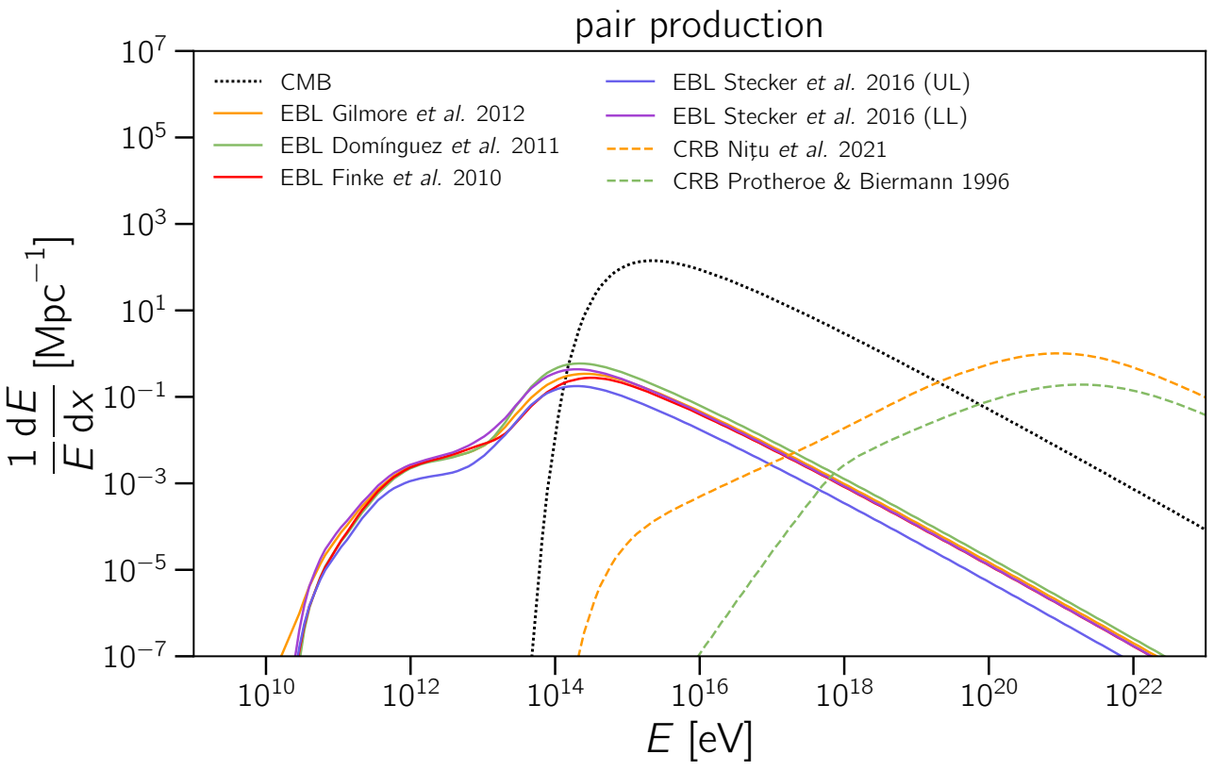
summary and outlook

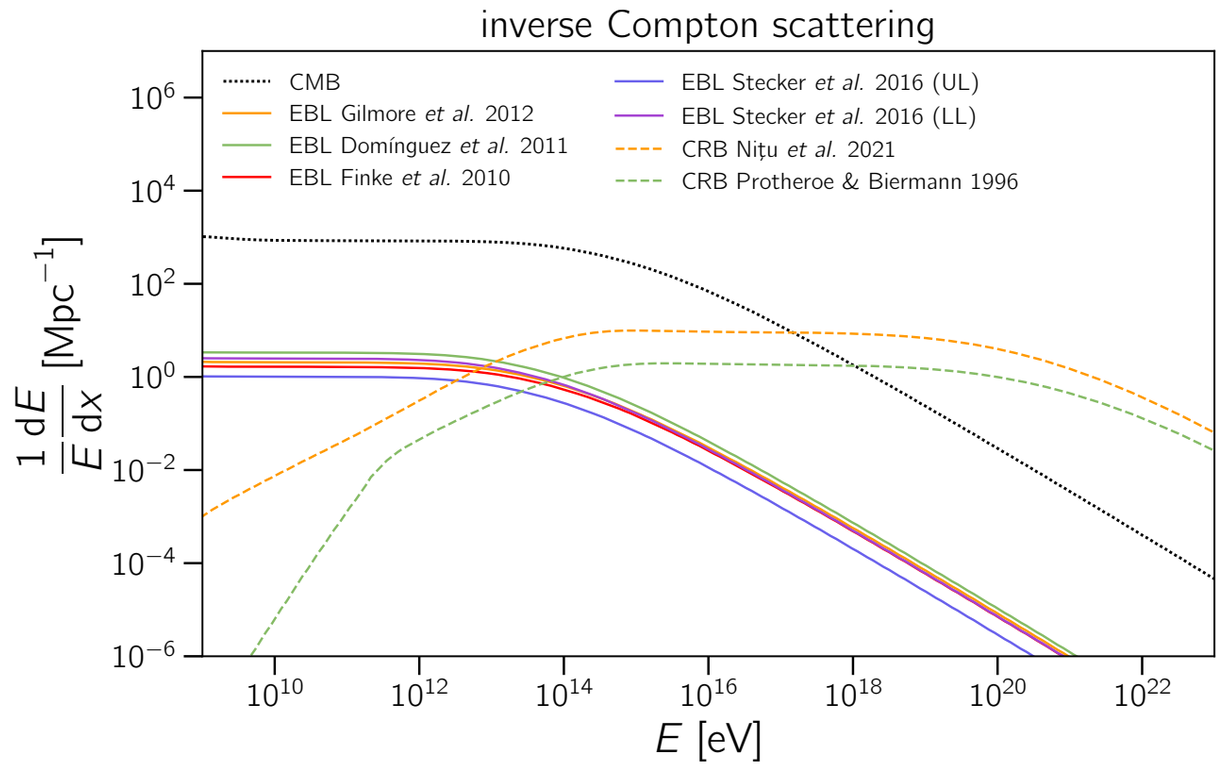
- we know next to nothing about IGMFs
- common methods to constrain IGMFs still leave a large portion of the parameter space open
- gamma rays (through electromagnetic cascades) and UHECRs are valuable high-energy probes of IGMFs
- properties of magnetic fields such as helicity are often neglected and may severely interfere with the results of analyses
- IGMFs (specifically in the intracluster medium) are determinant for the neutrino and gamma-ray fluxes produced by galaxy clusters
- multimessenger studies require knowledge of intervening magnetic fields *OR* these fields have to be shown to be small
- can we draw *unambiguous* conclusions from multimessenger studies with neutrinos + HE gamma rays or neutrinos and UHECRs? **NO!!** (unless IGMFs are shown to be negligible)

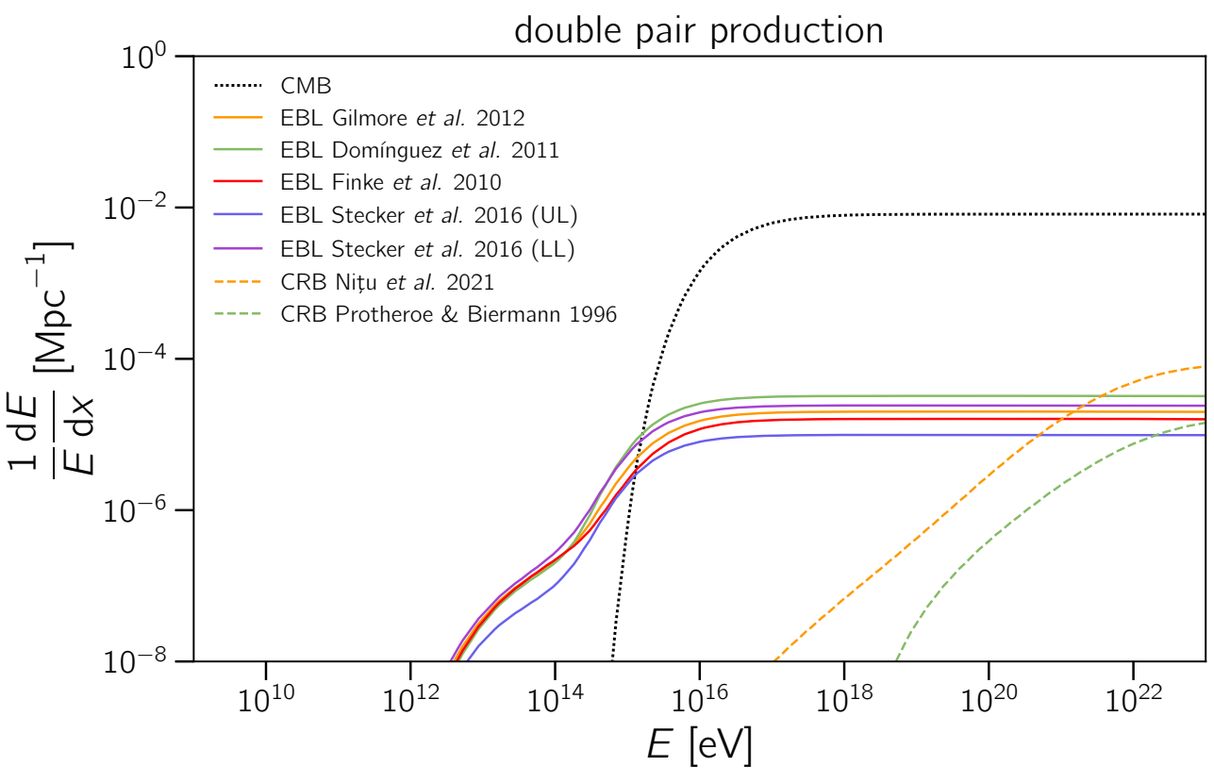
back-up slides

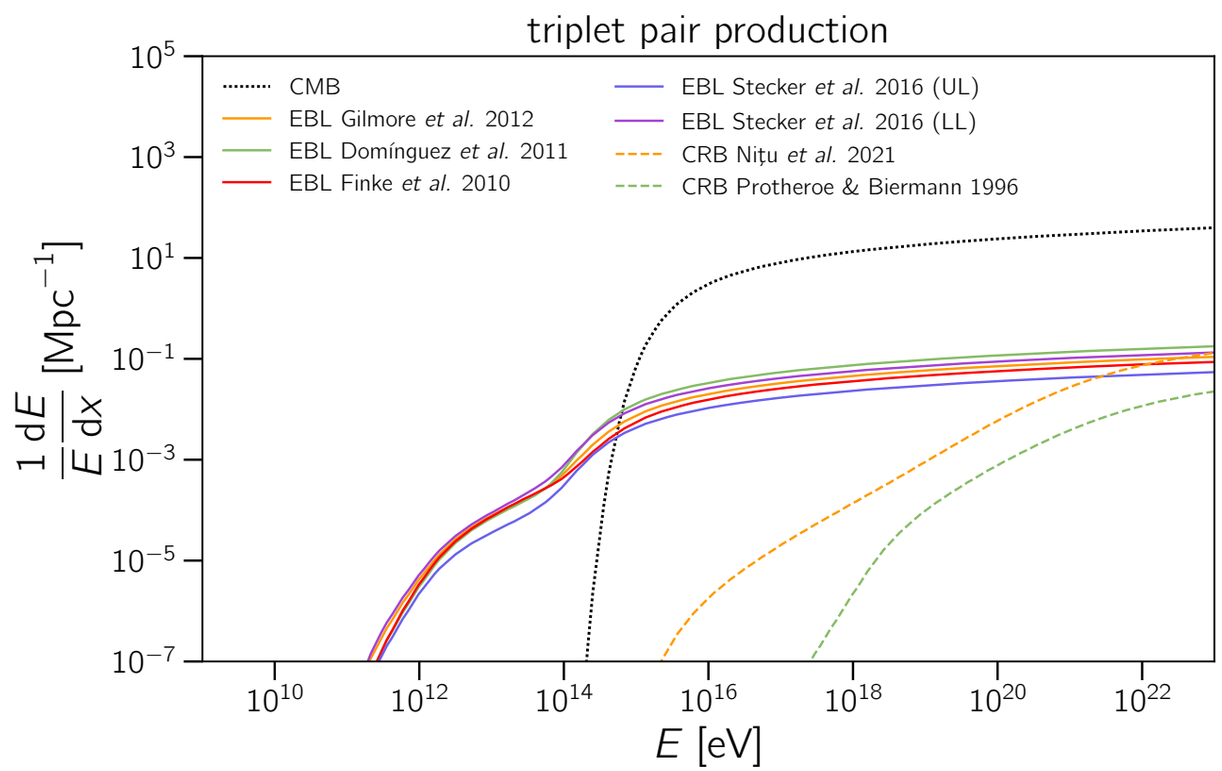
interactions

electromagnetic interactions









constraining IGMFs with TXS 0506+056

constraining IGMFs with TXS 0506+056

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

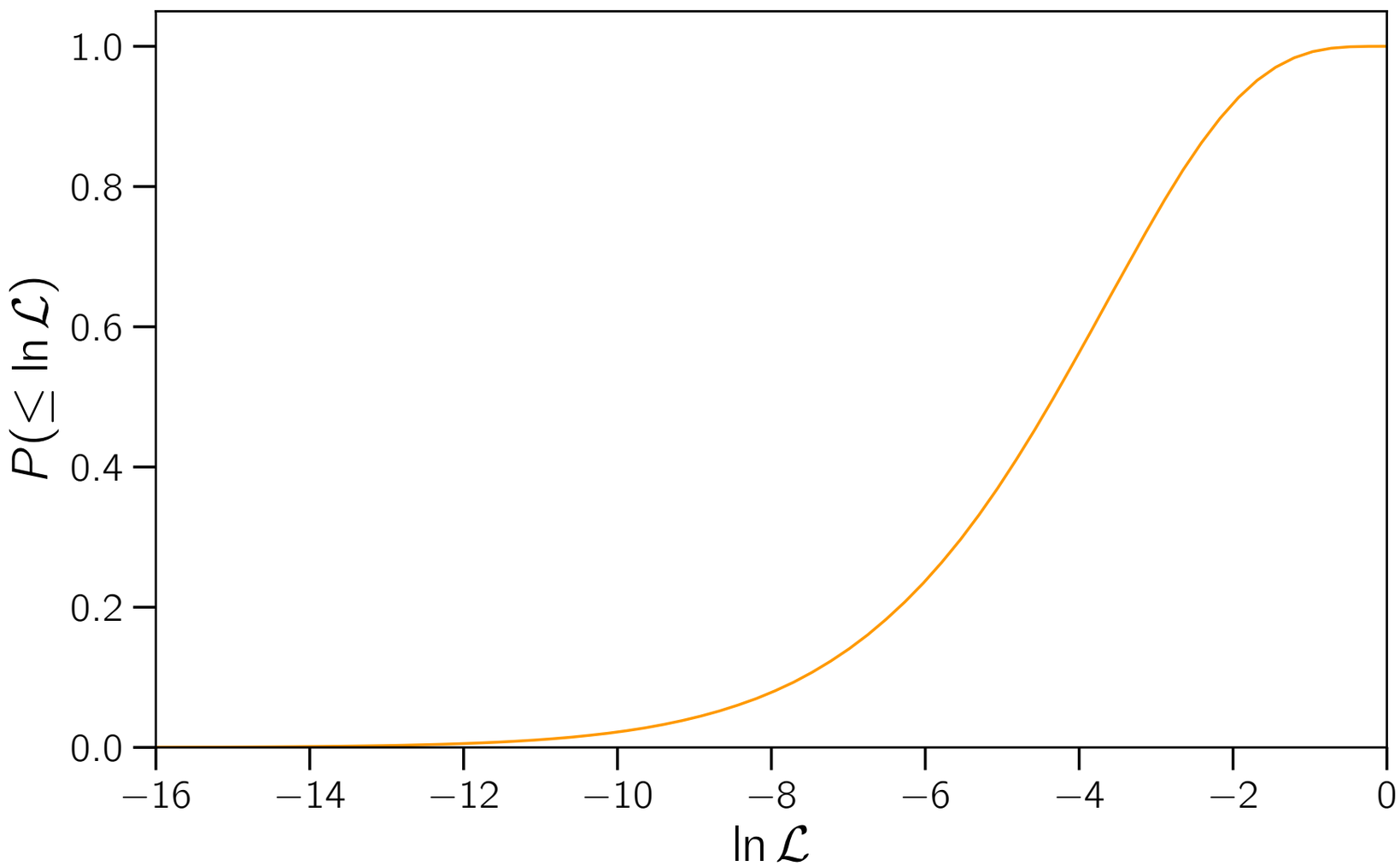
EBL	$\Delta t_{\rm AGN}$ [yr]	$\log(L_{\rm c}/{\rm Mpc})$	$\log(B/{\rm G})$
S16l	10^1	$1.0^{+1.3}_{-1.6}$	$-15.3^{+1.0}_{-2.7}$
S16l	10^4	$1.0^{+1.3}_{-1.6}$	$-15.2^{+0.9}_{-2.7}$
S16l	10^7	$1.0^{+1.3}_{-1.6}$	$-15.2^{+0.9}_{-2.7}$
S16u	10^1	$0.2^{+2.1}_{-1.6}$	$-15.4^{+1.1}_{-2.5}$
S16u	10^4	$0.0^{+2.4}_{-1.4}$	$-15.2^{+0.9}_{-2.3}$
S16u	10^7	$-0.1^{+2.3}_{-1.3}$	$-15.2^{+0.9}_{-2.6}$
G12	10^1	$0.5^{+1.6}_{-1.7}$	$-15.8^{+1.3}_{-2.4}$
G12	10^4	$0.6^{+1.6}_{-1.7}$	$-15.6^{+1.2}_{-2.6}$
G12	10^7	$0.6^{+1.6}_{-1.7}$	$-15.6^{+1.2}_{-2.6}$
D11	10^1	$0.2^{+1.5}_{-1.3}$	$-15.4^{+1.0}_{-2.5}$
D11	10^4	$0.1^{+1.5}_{-1.3}$	$-15.3^{+1.0}_{-2.6}$
D11	10^7	$0.1^{+1.5}_{-1.3}$	$-15.3^{+1.0}_{-2.6}$

fitting the low-state of TXS 0506+056

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

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

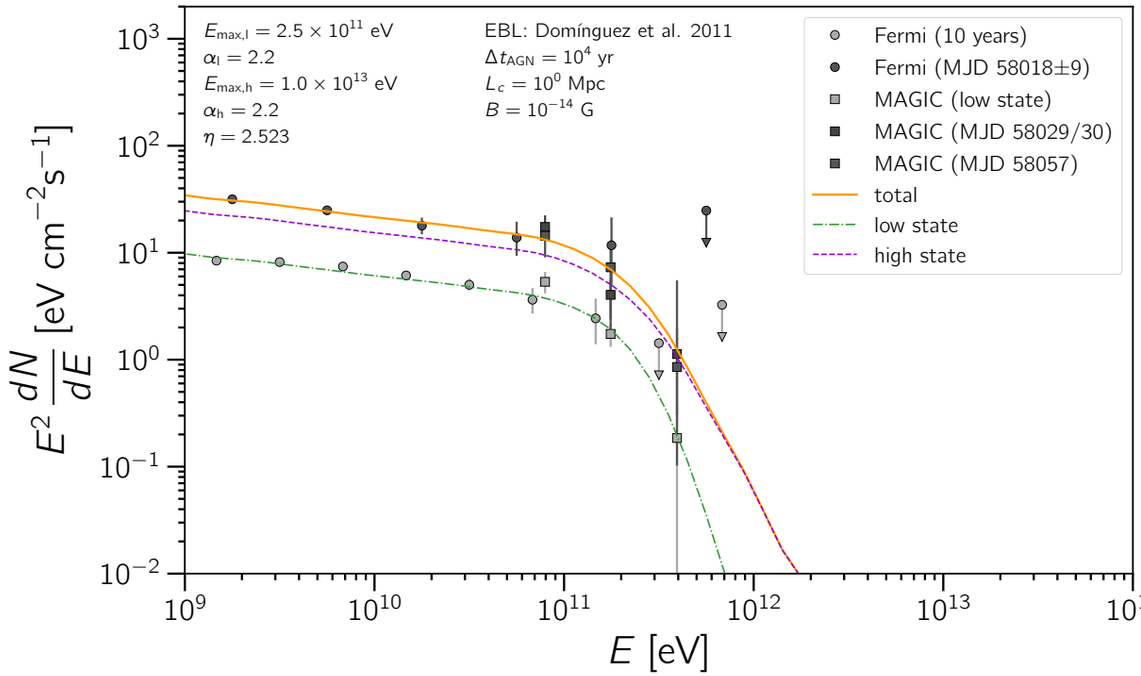
- for the low state, we keep only pairs of (α_l, $E_{max,l}$) for which the p-values are < 10^{-3}
- in any case, α_l = 2.2 and $E_{max,l} \leqslant$ 250 GeV does not vary significantly

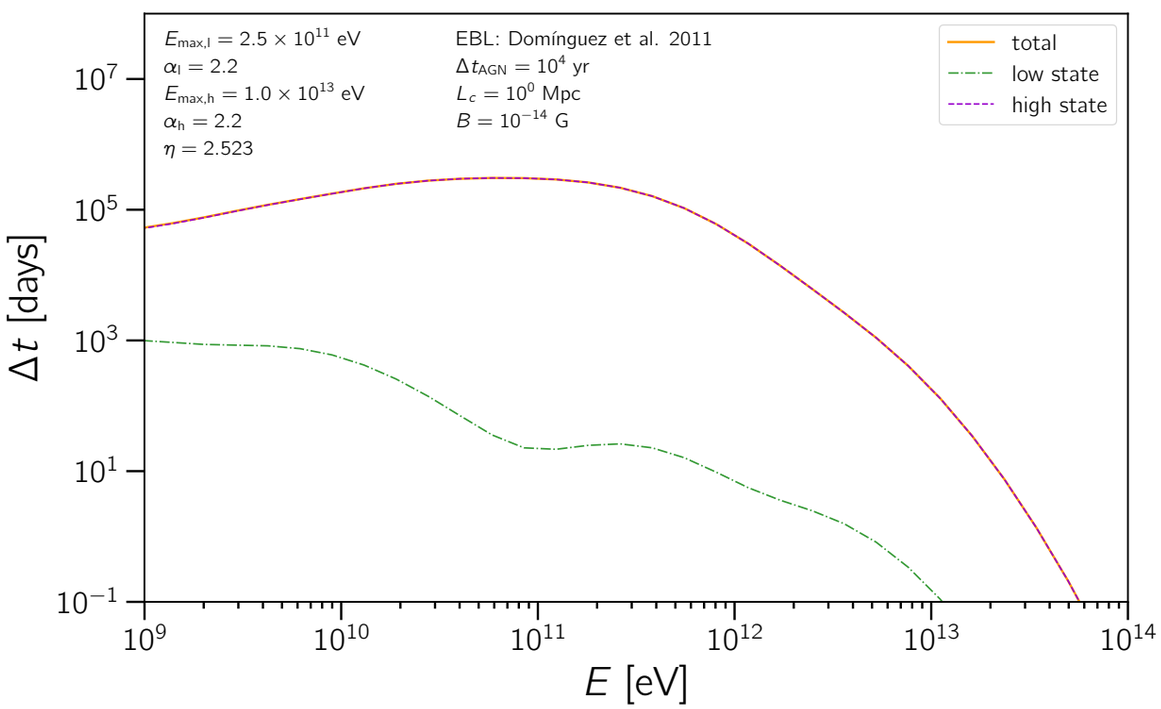


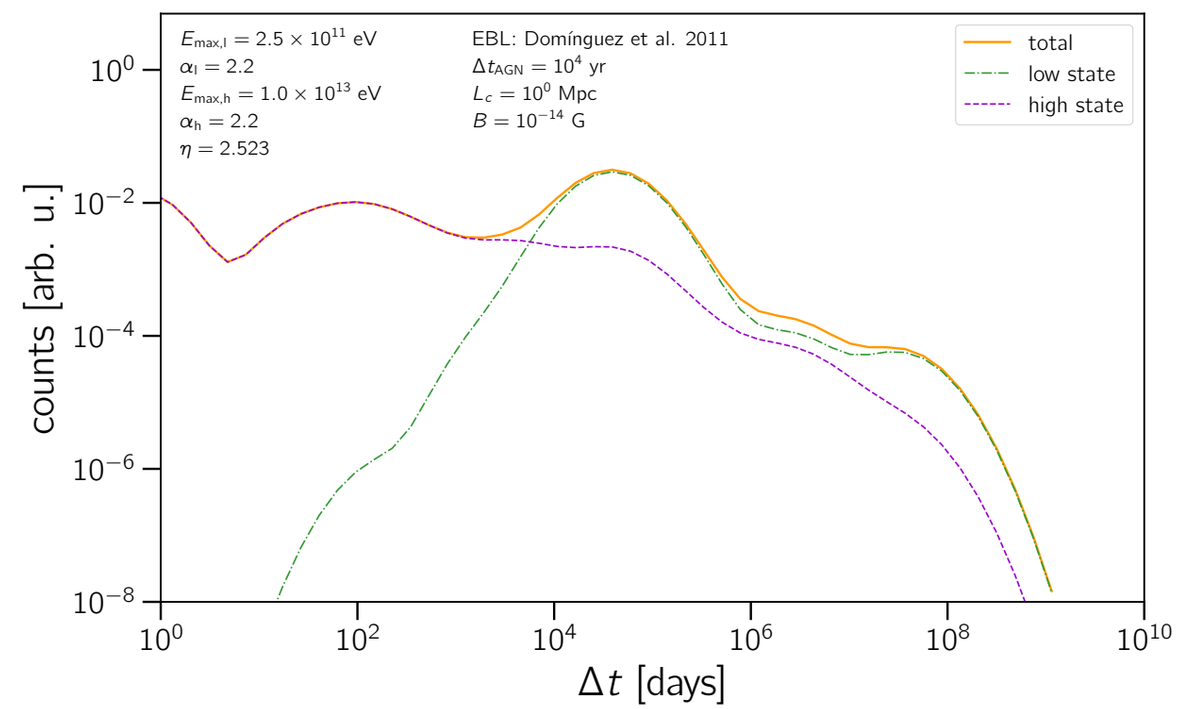
a complete example

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

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

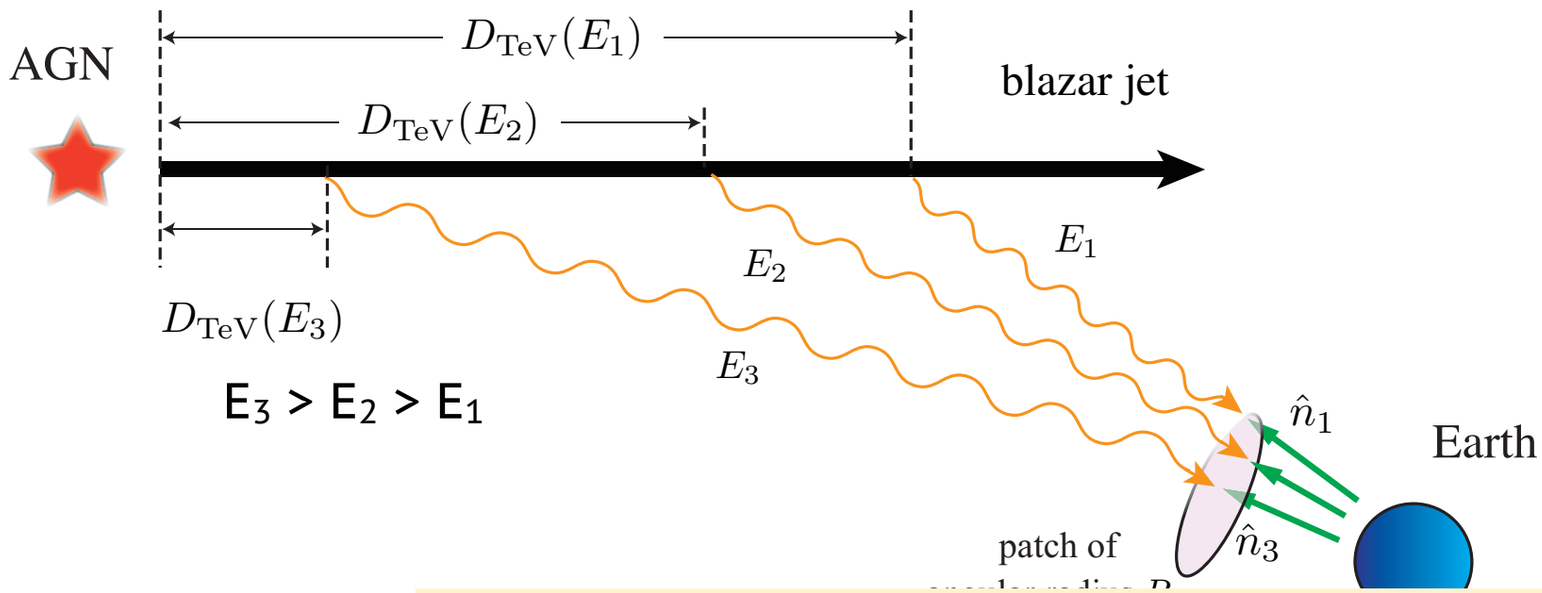




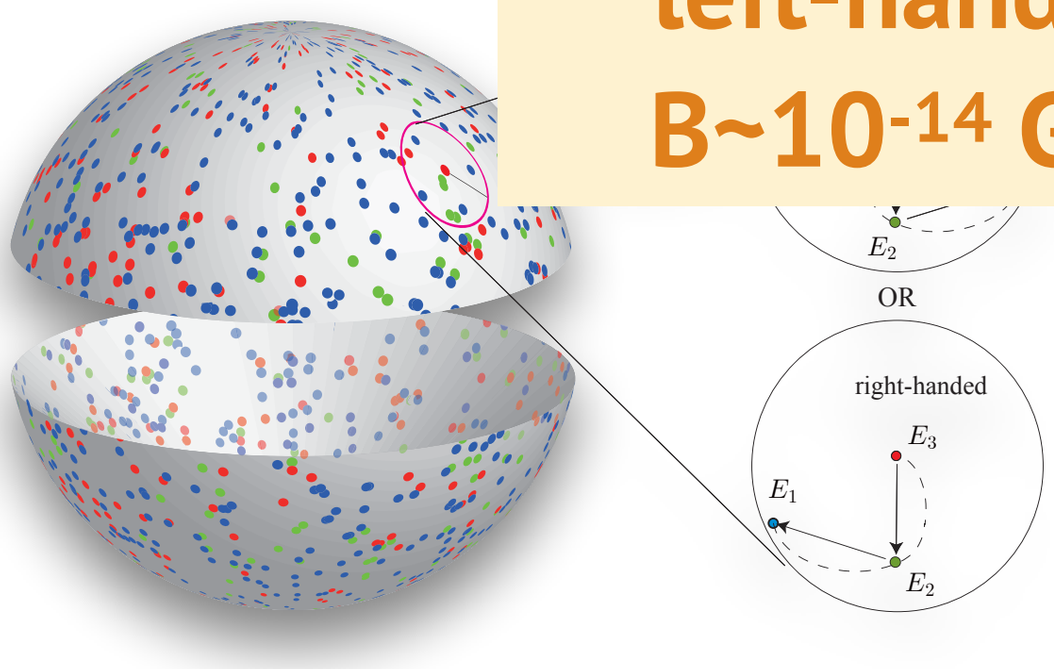


helical IGMFs

evidence for helical IGMFs?



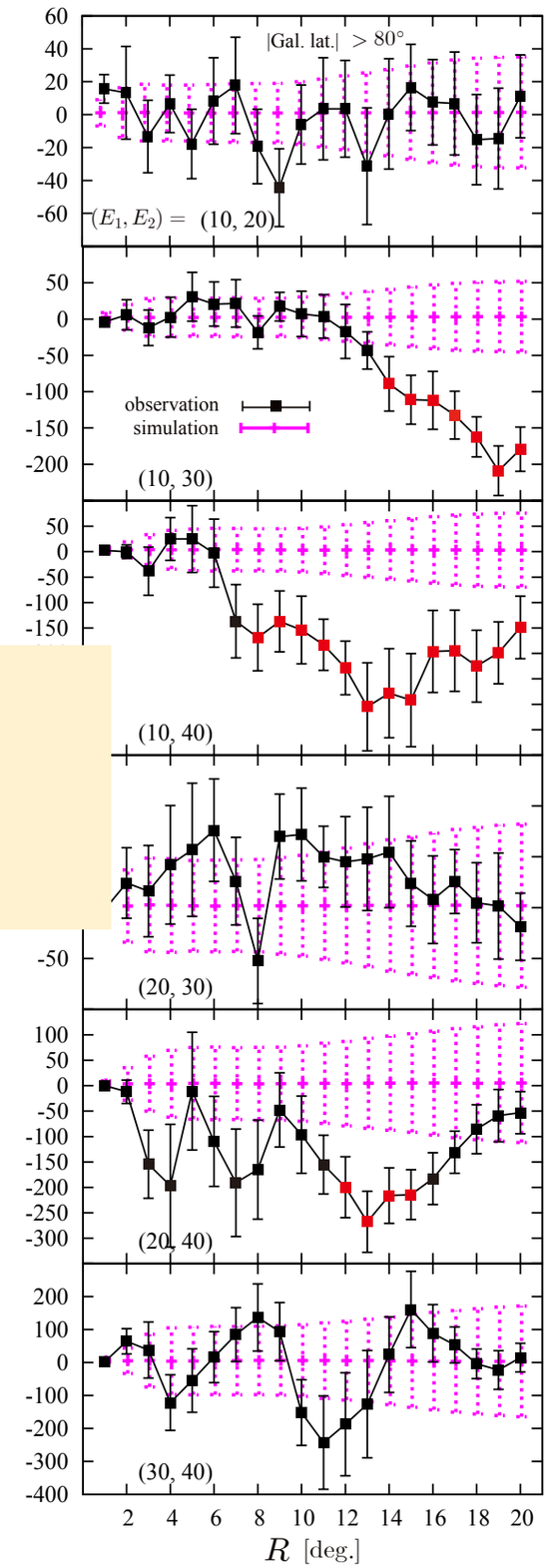
left-handed IGMFs with B~10^{-14} G at Lc~10 Mpc



Q-factors

Q>0 → left-handed

Q<0 →right-handed



Tashiro et al. MNRAS Lett. 445 (2014) L41. arXiv:1310.4826

UHECR constraints on the helicity of IGMFs

cosmic-ray signatures of helical IGMFs: analysis method

Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182

single-mode helical field

$$\vec{B} = B_0\sigma \sin\left(\frac{2\pi}{\lambda}z + \psi\right)\hat{x} + B_0 \cos\left(\frac{2\pi}{\lambda}z + \psi\right)\hat{y}$$

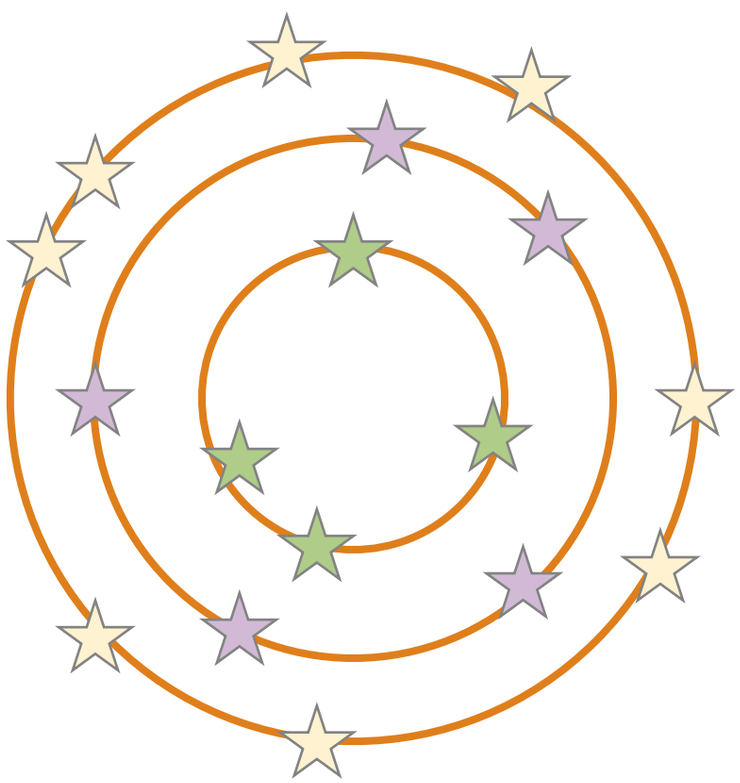
helicity parameter

coherence length

field strength

phase

source distribution



harmonic analysis

$$\Phi(\hat{n}) = \sum_{l=0}^{l_{max}} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\hat{n})$$

$$\Phi(\hat{n}) \approx \frac{\Phi_0}{4\pi}\left[1 + w_d \hat{d}\cdot\hat{n} + \frac{1}{2}\sum_{i,j} Q_{ij} n_i n_k j\right]$$

$$w_d = \frac{\sqrt{3}}{a_{00}}\sqrt{a_{10}^2 + a_{11}^2 + a_{1-1}^2}$$

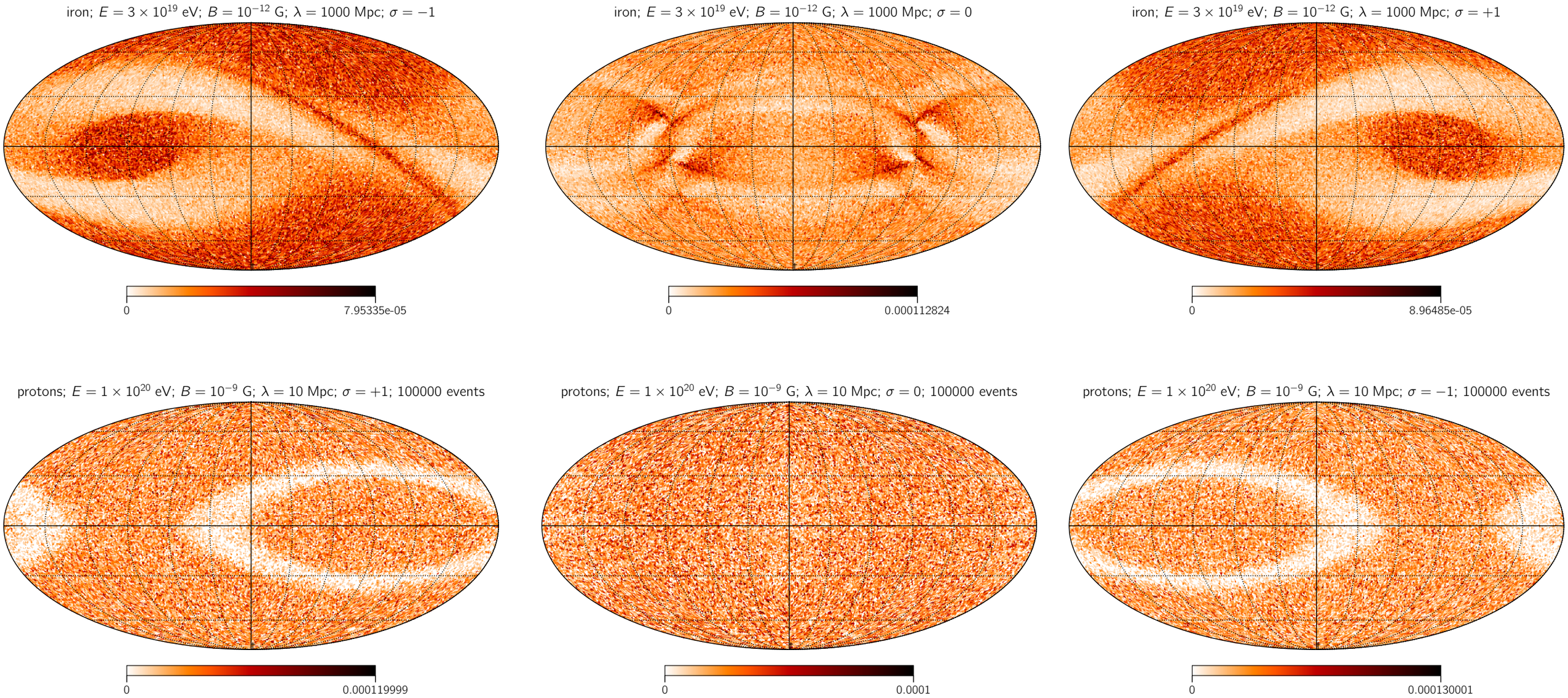
$$\theta_d = \arcsin\left(\frac{\sqrt{3}a_{10}}{a_{00}} w_d\right)$$

$$w_q = \frac{\lambda_{max} - \lambda_{min}}{2 + \lambda_{max} + \lambda_{min}}$$

$$\varphi_d = \arctan\left(\frac{a_{1-1}}{a_{11}}\right)$$

cosmic-ray signatures of helical IGMFs: skymaps

Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182

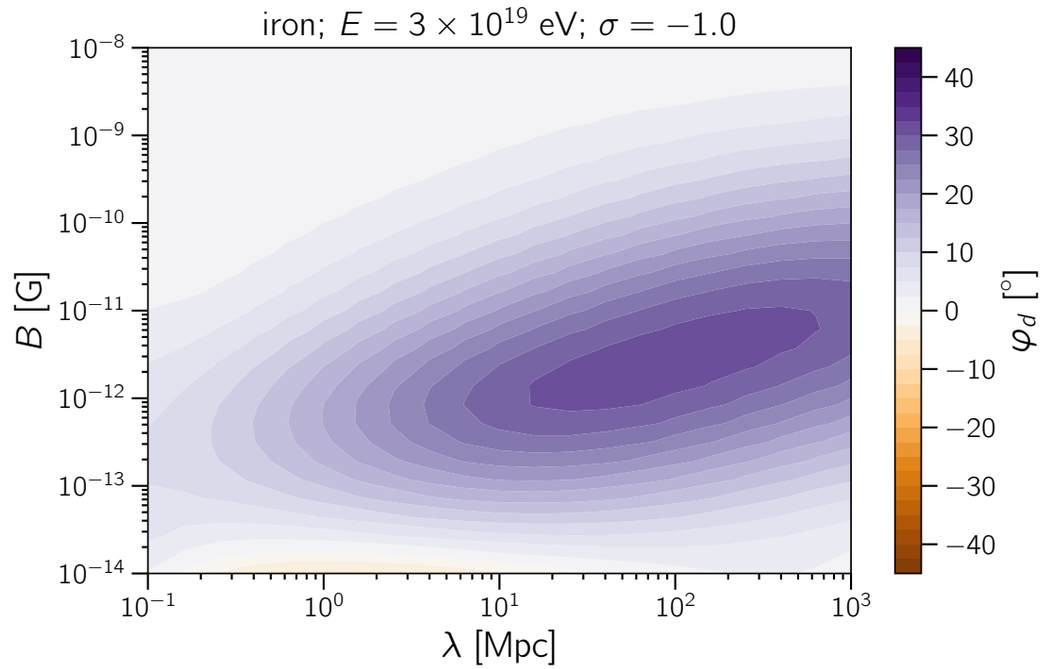


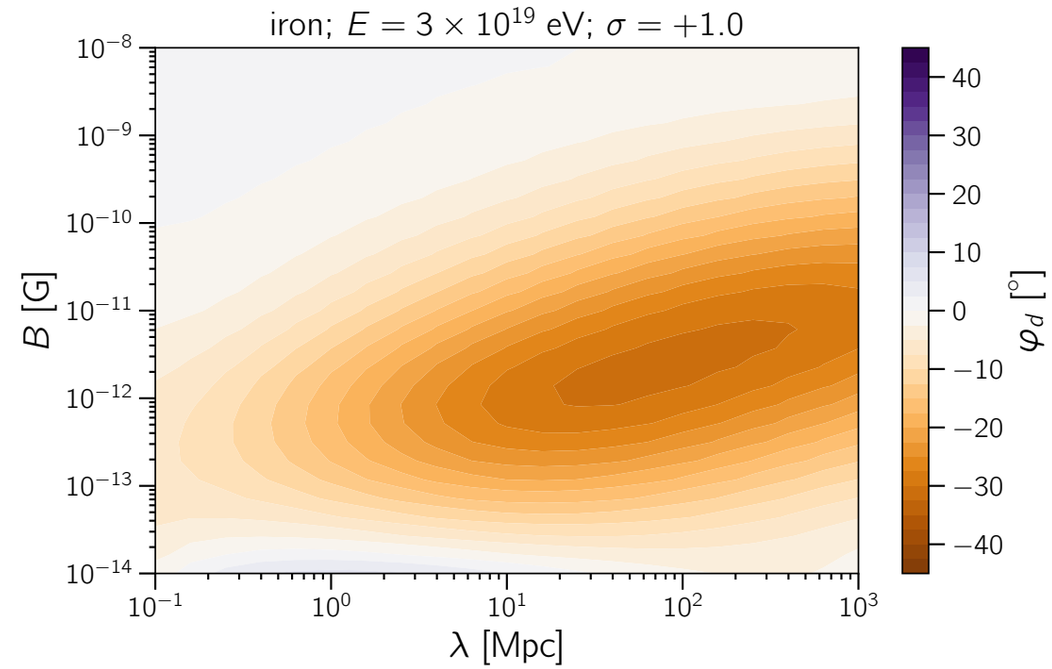
- toy model: single-mode field is likely not realistic
- single-mode field + hand-picked sources responsible for "artificial" pattern

constraints for UHE nuclei

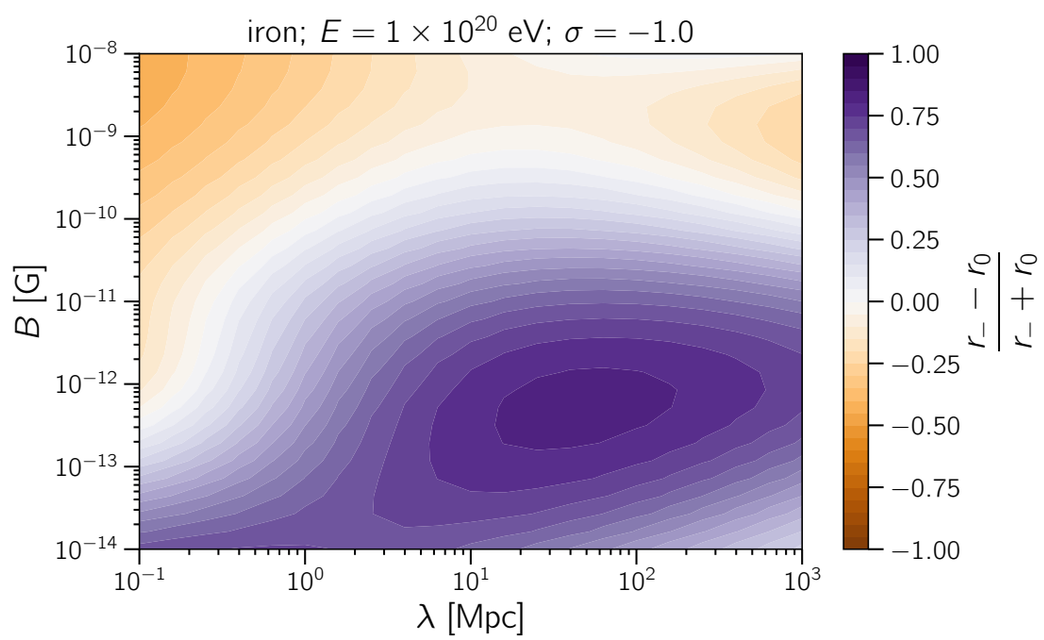
Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182

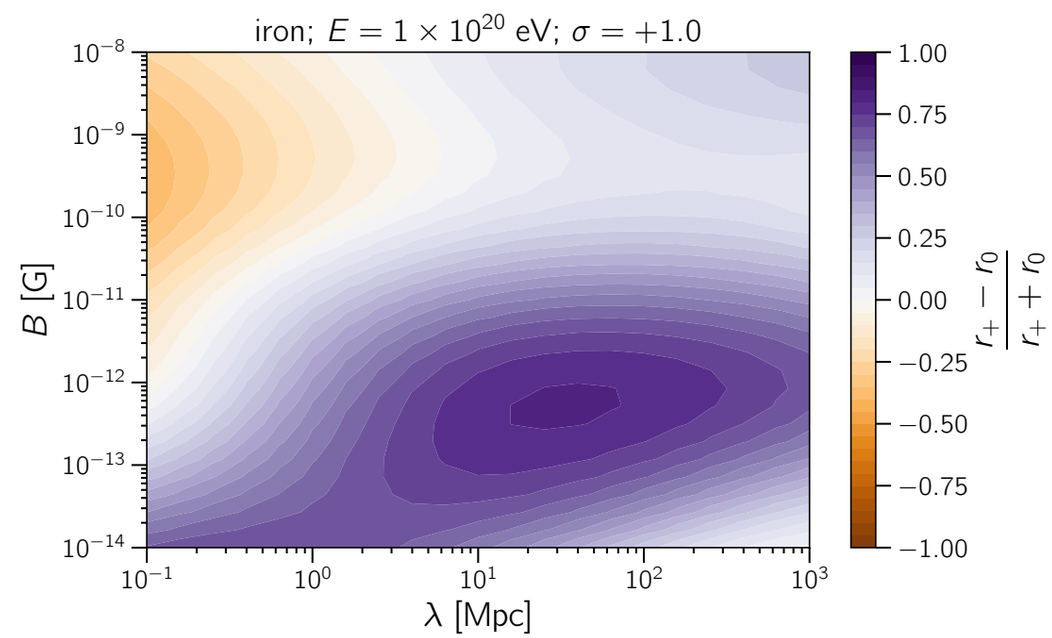
sign





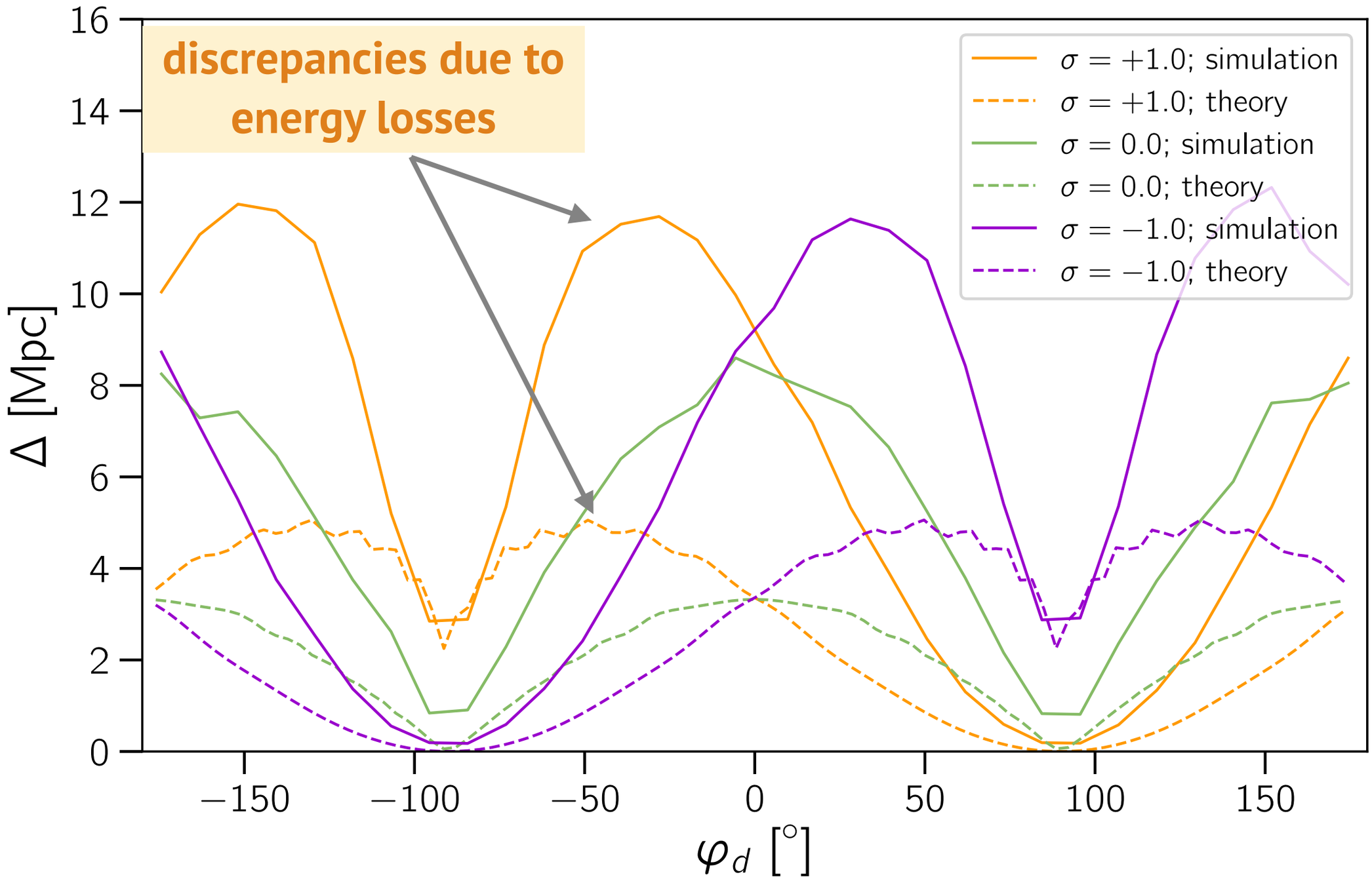
absolute value





predictions: numerical simulations vs. theory

Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182



effects of the galactic magnetic field

Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182

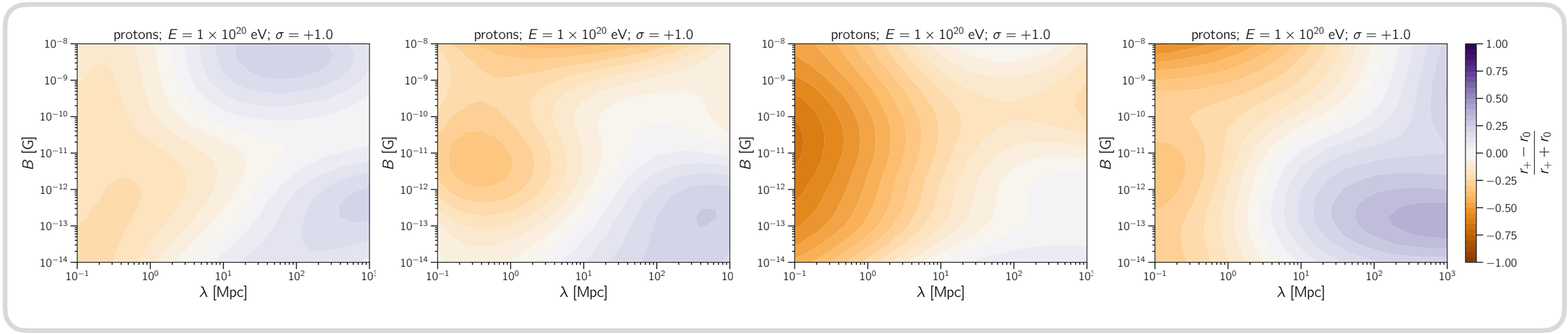
- we apply rotations to the default scenario (0)
- apply lensing technique to correct for the GMF
- we use the GMF model by Jansson & Farrar (2012)

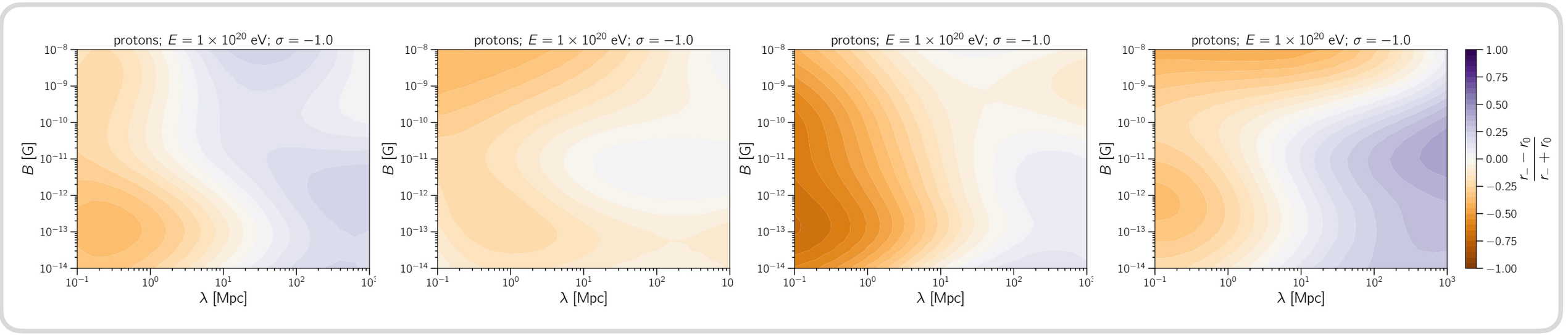
scenario	α [deg]	β [deg]	γ [deg]
0	0	0	0
1	-90	0	0
2	0	0	90
3	150	0	60

including the effects of the galactic magnetic field

Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182

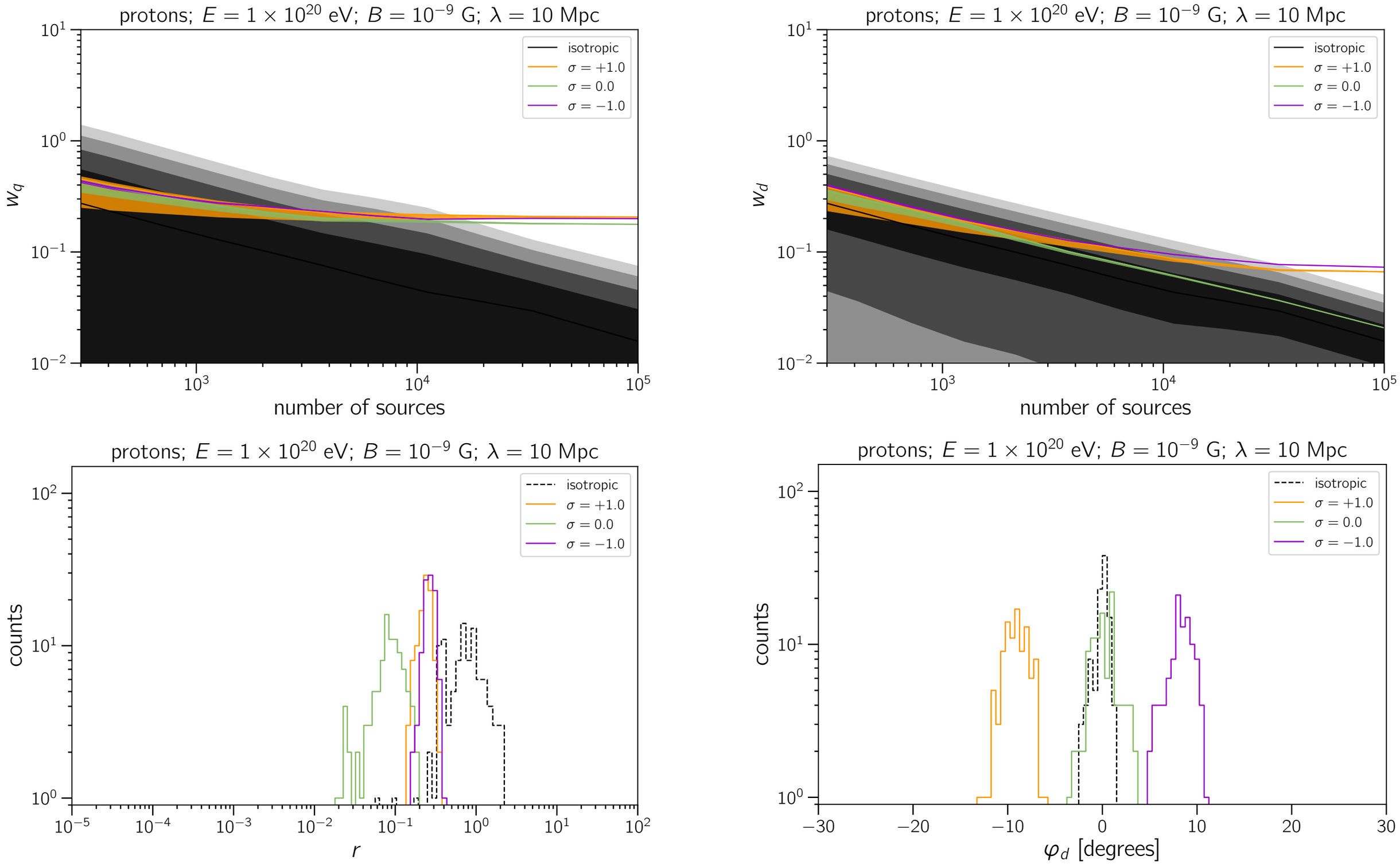
scenario 0 **scenario 1** **scenario 2** **scenario 3**





cosmic-ray signatures of helical IGMFs

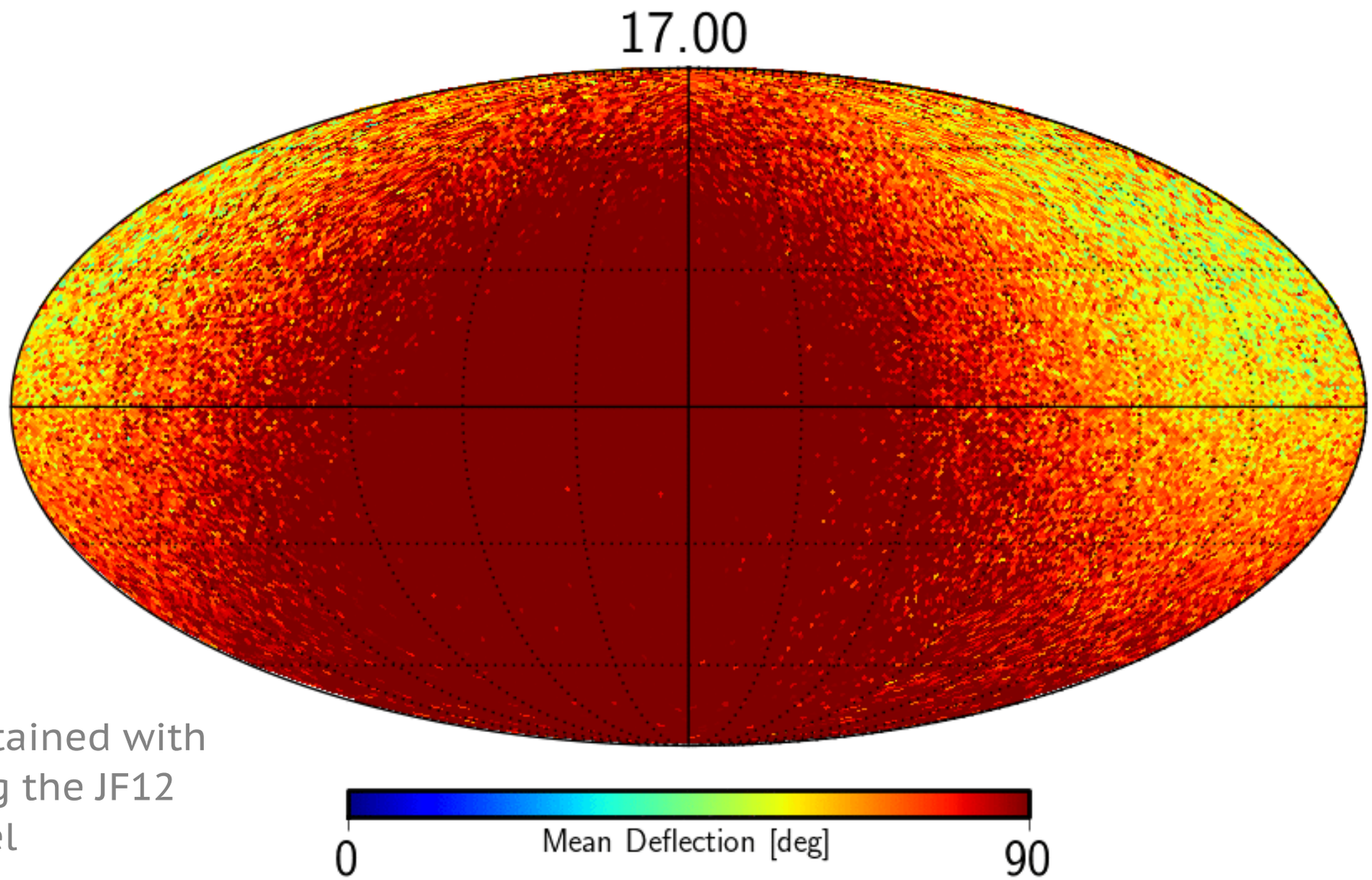
Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182



the galactic magnetic field

UHECRs and the galactic magnetic field

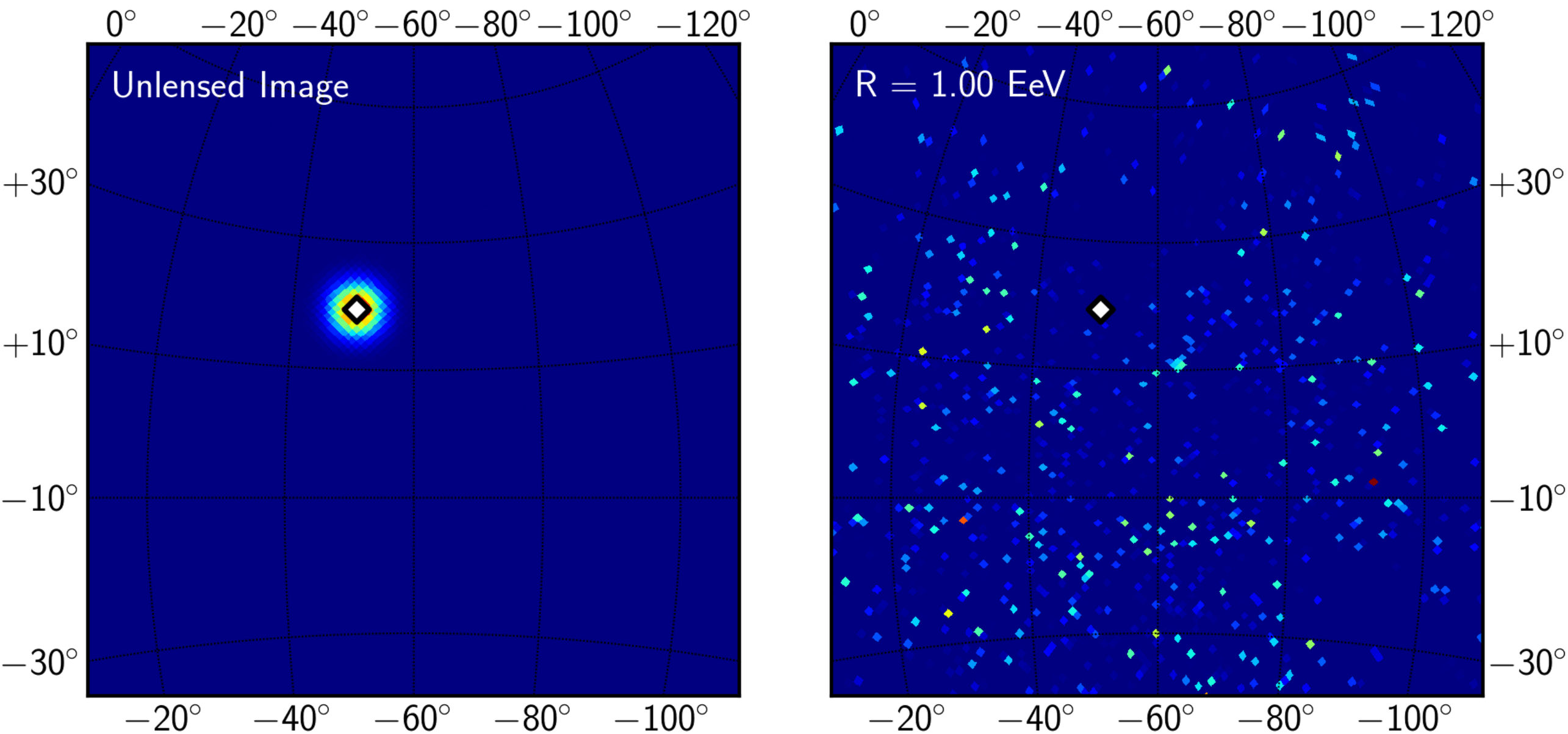
- widely-used GMF model: Jansson & Farrar '12 (JF12)
- this model is based on fits of synchrotron emission + Faraday rotation + polarisation measurements, but needs improvements!



simulations obtained with CRPropa using the JF12 model

UHECRs and the galactic magnetic field

- **Centaurus A**: assuming only galactic deflections and the complete JF12 field



do plasma instabilities compromise IGMF constraints?

the missing haloes "problem"

The Astrophysical Journal, 868:87 (17pp), 2018 December 1 https://doi.org/10.3847/1538-4357/aae5f2

Missing Gamma-Ray Halos and the Need for New Physics in the Gamma-Ray Sky

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Abstract

An intergalactic magnetic field (IGMF) stronger than 3×10^{-13} G would explain the lack of a bright, extended degree-scale, GeV-energy inverse Compton component in the gamma-ray spectra of TeV blazars. A robustly predicted consequence of the presence of such a field is the existence of degree-scale GeV-energy gamma-ray halos (gamma-ray bow ties) about TeV-bright active galactic nuclei, corresponding to more than half of all radio galaxies. However, the emitting regions of these halos are confined to and aligned with the direction of the relativistic jets associated with gamma-ray sources. Based on the orientation of radio jets, we align and stack corresponding degree-scale gamma-ray images of isolated Fanaroff–Riley class I and II objects and exclude the existence of these halos at overwhelming confidence, limiting the intergalactic field strength to $<10^{-15}$ G for large-scale fields and progressively larger in the diffusive regime when the correlation length of the field becomes small in comparison to 1 Mpc. When combined with prior limits on the strength of the IGMF, this excludes a purely magnetic explanation for the absence of halos. Thus, it requires the existence of novel physical processes that preempt the creation of halos, e.g., the presence of beam-plasma instabilities in the intergalactic medium or a drastic cutoff of the very high-energy spectrum of these sources.

Key words: BL Lacertae objects: general – gamma rays: diffuse background – gamma rays: general – infrared: diffuse background – plasmas – radiation mechanisms: nonthermal

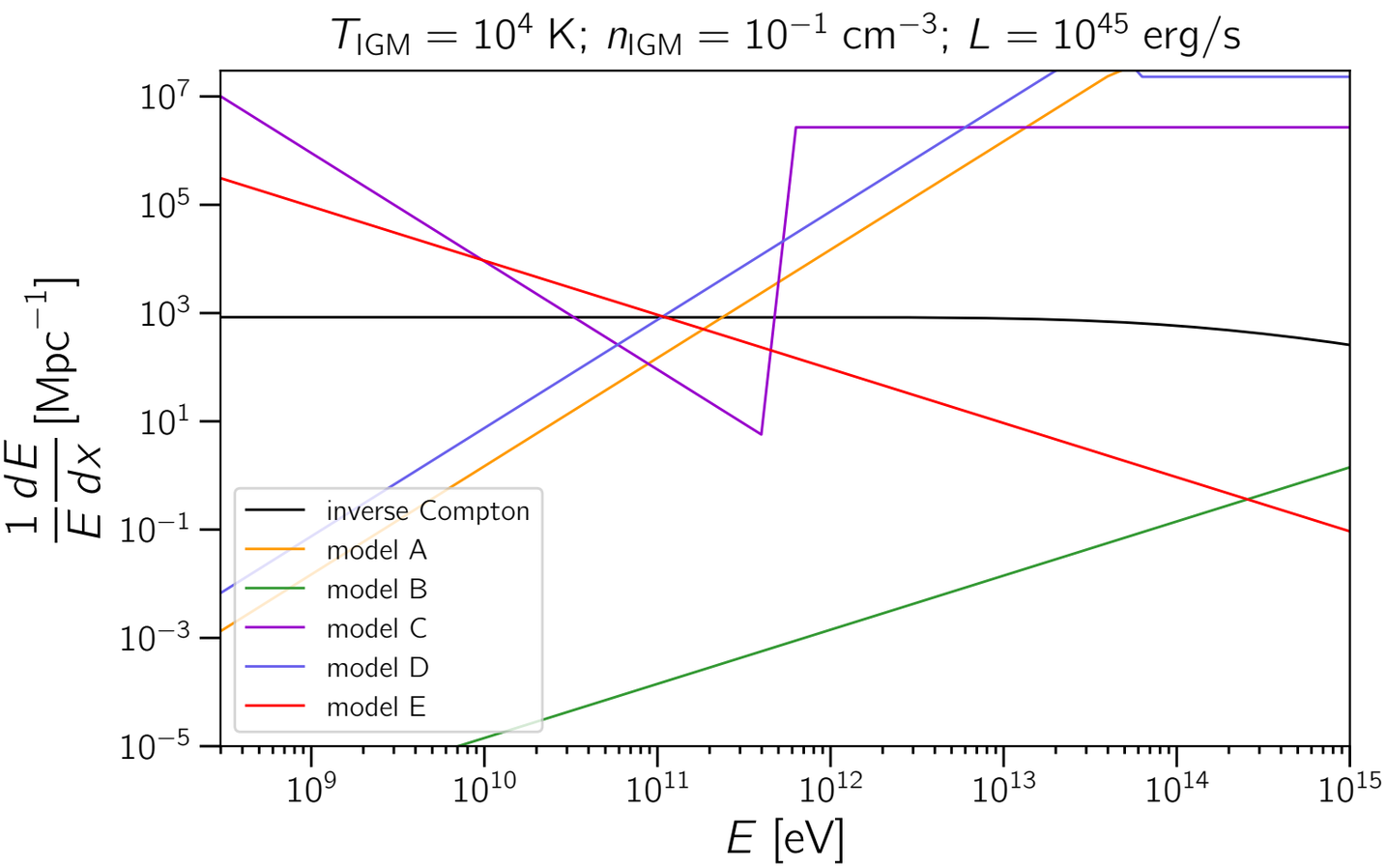
plasma instabilities in the intergalactic medium

- collective plasma phenomena: relevant if $n_{beam}\lambda_{pl}^3 \gg 1$
- skin depth: $\lambda_{pl} = \frac{2\pi c}{\omega_{pl}}$ with $\omega_{pl} = \sqrt{\frac{e^2 n_{IGM}}{\varepsilon_0 m_e}}$
- plasma instabilities may quench electromagnetic cascades → IGMF constraints unreliable(?) [Broderick+ 2012; Sironi & Giannios 2014; Schlickeiser+ 2012; Vafin+2018]
- the dominant instability determines if this effect affects the spectra of TeV blazars
- for instance, non-linear Landau damping may dominate → plasma instabilities do not play a significant role [Miniati & Elyiv 2013]
- IGMF constraints do not change strongly even if (the oblique) instabilities act → lower limit on B changes by ~ 10 [Yan+ 2019]
- instabilities may not compromise IGMF constraints, depending on the blazar spectrum and IGM parameters [Alves Batista+ 2019]

Broderick et al. ApJ 752 (2012) 22. arXiv:1106.5494
Schlickeiser et al. ApJ 758 (2012) 102.
Miniati & Elyiv. ApJ 770 (2013) 54. arXiv:1208.1761
Sironi & Giannios. ApJ 787 (2014) 49. arXiv:1312.4538
Vafin et al. ApJ 857 (2018) 43. arXiv:1803.02990
Yan et al. ApJ 870 (2019) 70. arXiv:1810.07013
Alves Batista, Saveliev, de Gouveia Dal Pino. arXiv:1904.13345

propagation of electromagnetic cascades: plasma instabilities

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



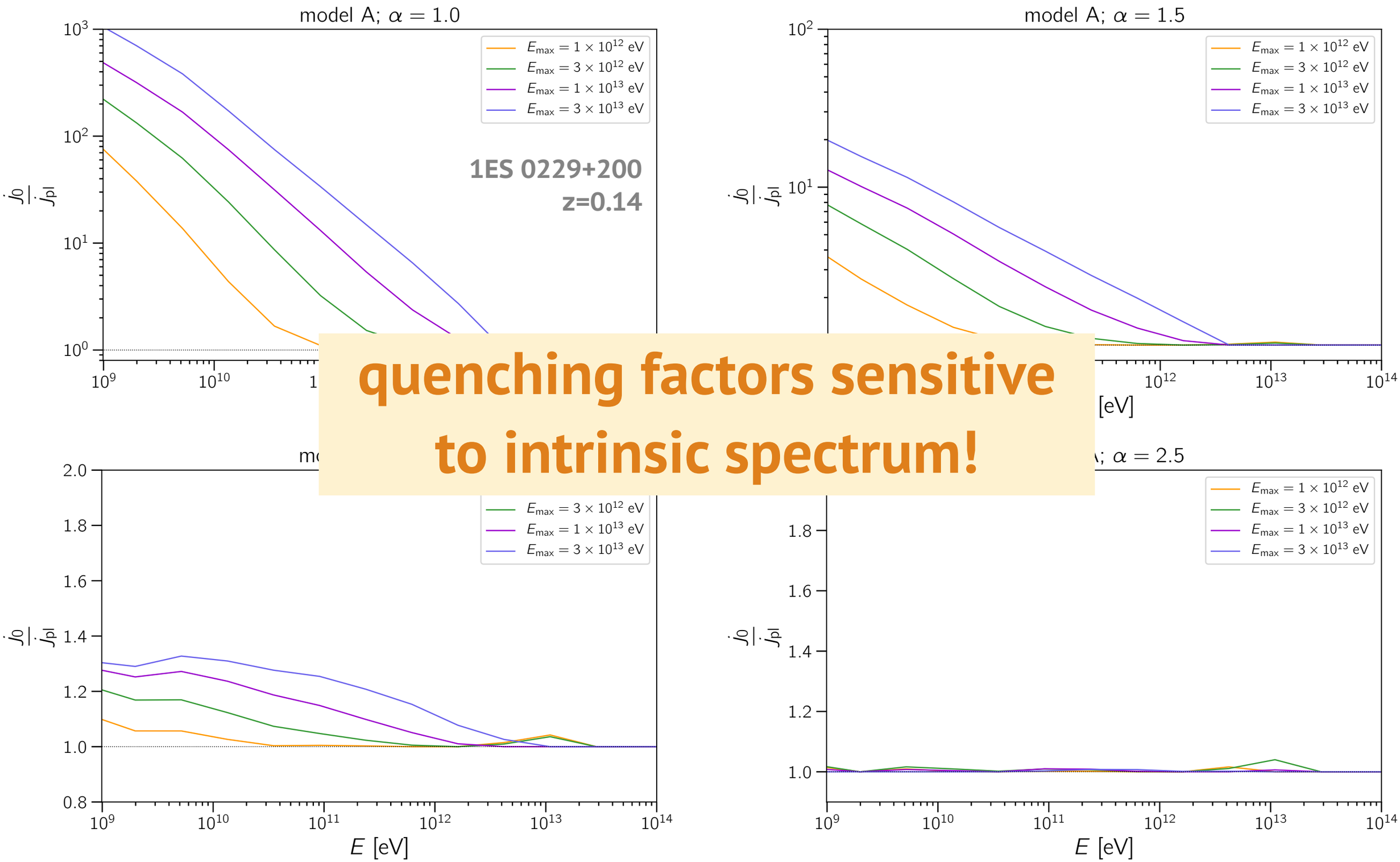
model A: Broderick et al. ApJ 752 (2012) 22. arXiv:1106.5494
model B: Miniati & Elyiv. ApJ 770 (2013) 54. arXiv:1208.1761
model C: Schlickeiser et al. ApJ 758 (2012) 102.
model D: Sironi & Giannios. ApJ 787 (2014) 49. arXiv:1312.4538
model E: Vafin et al. ApJ 857 (2018) 43. arXiv:1803.02990

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 propagation https://github.com/rafaelab/grplinst

plasma instabilities quenching factors

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



quenching factors sensitive to intrinsic spectrum!

effects on the spectrum of TeV blazars

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