multimessenger constraints on intergalactic magnetic fields

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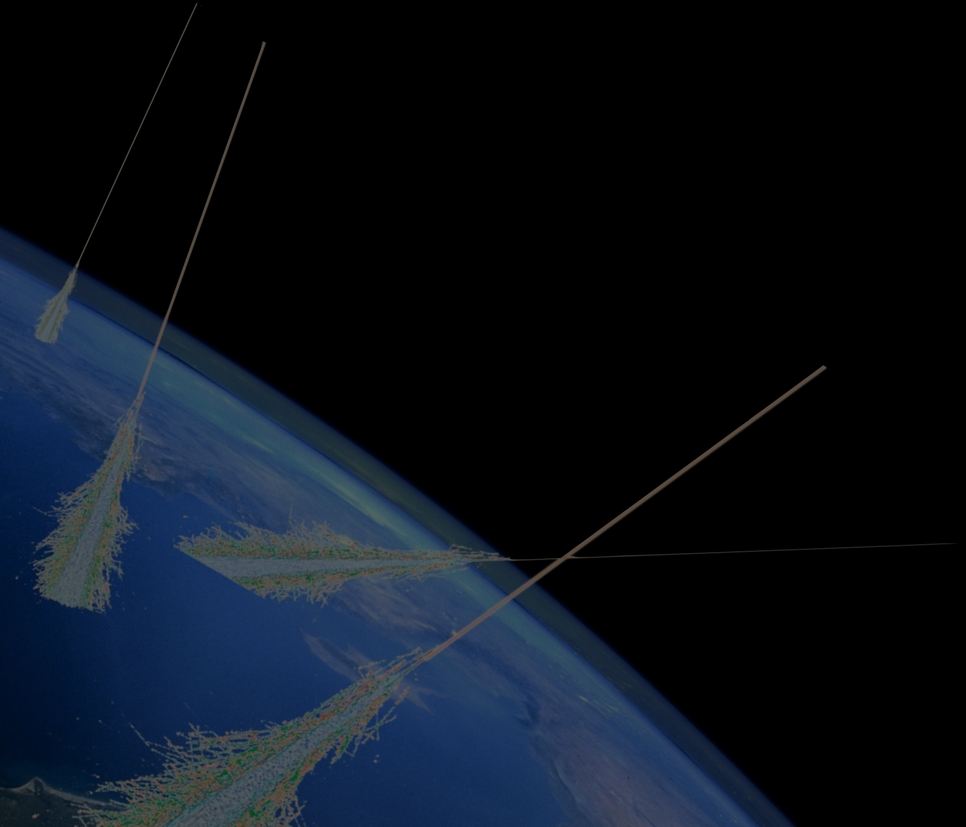
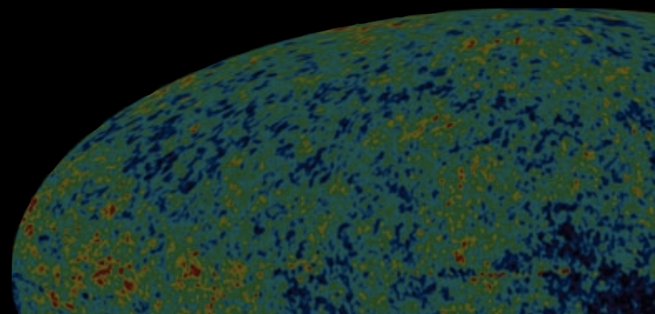


Trieste
November 8, 2023

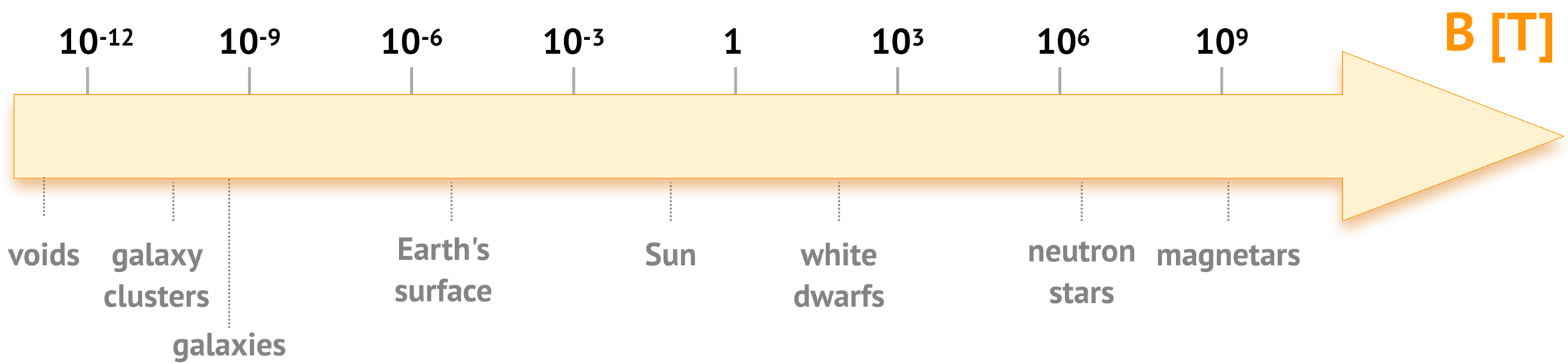


structure of this talk

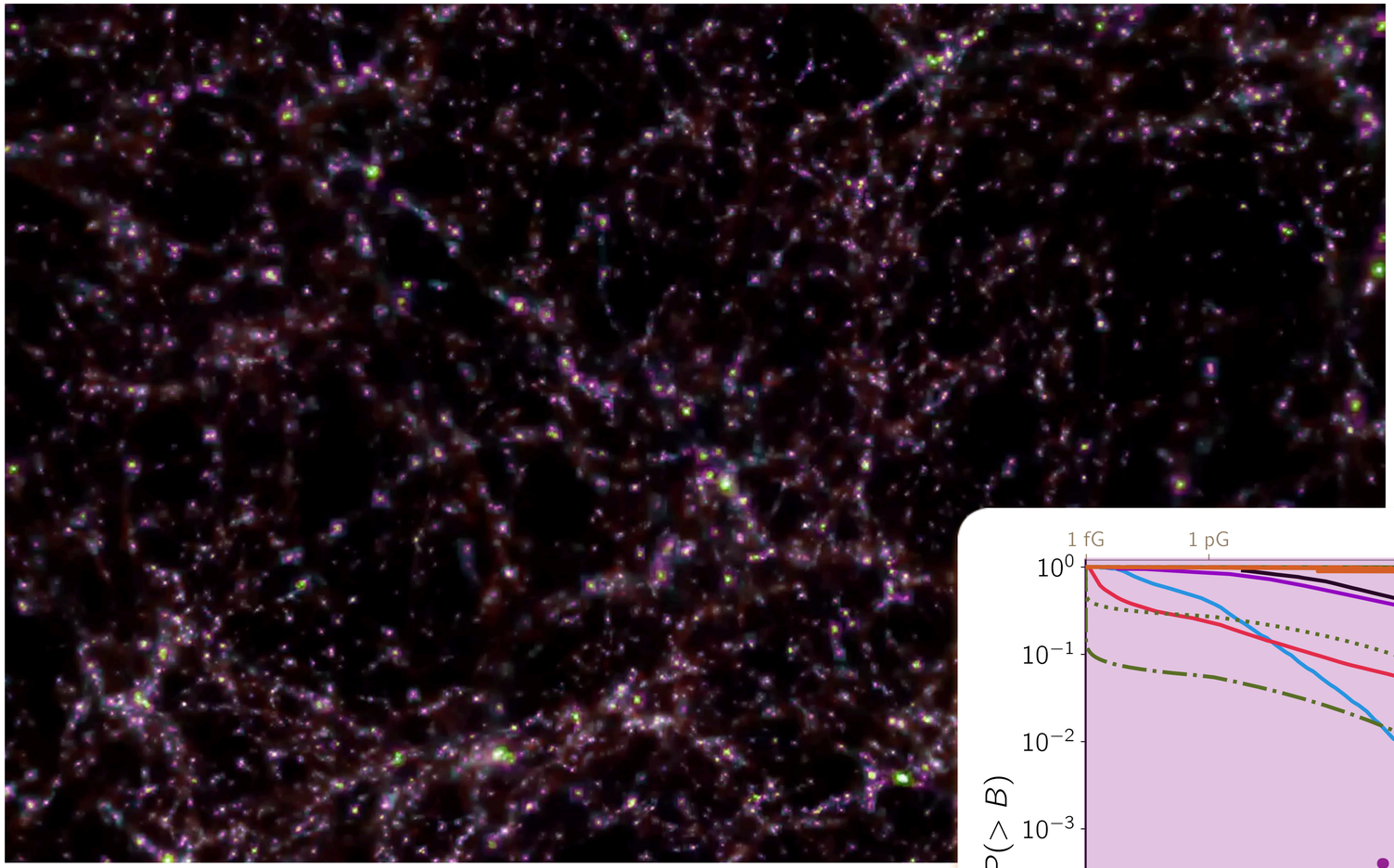
- **cosmic magnetic fields**
  - large-scale structure
  - magnetogenesis
  - current constraints
- **propagation of cosmic messengers**
  - overview
  - modelling
- **constraints with gamma rays**
  - strategies
  - detectability & parameter space
  - prospects for CTA
  - helical IGMFs
- **constraints with UHECRs**
  - strategy
  - current constraints
  - helical IGMFs
- **constraints with multiple messengers**
  - general idea
  - constraints from TXS 0506+056
- **plasma instabilities**
  - role in electromagnetic cascades
  - phenomenological signatures
- conclusions & outlook

cosmic magnetic fields

magnetic fields in the universe



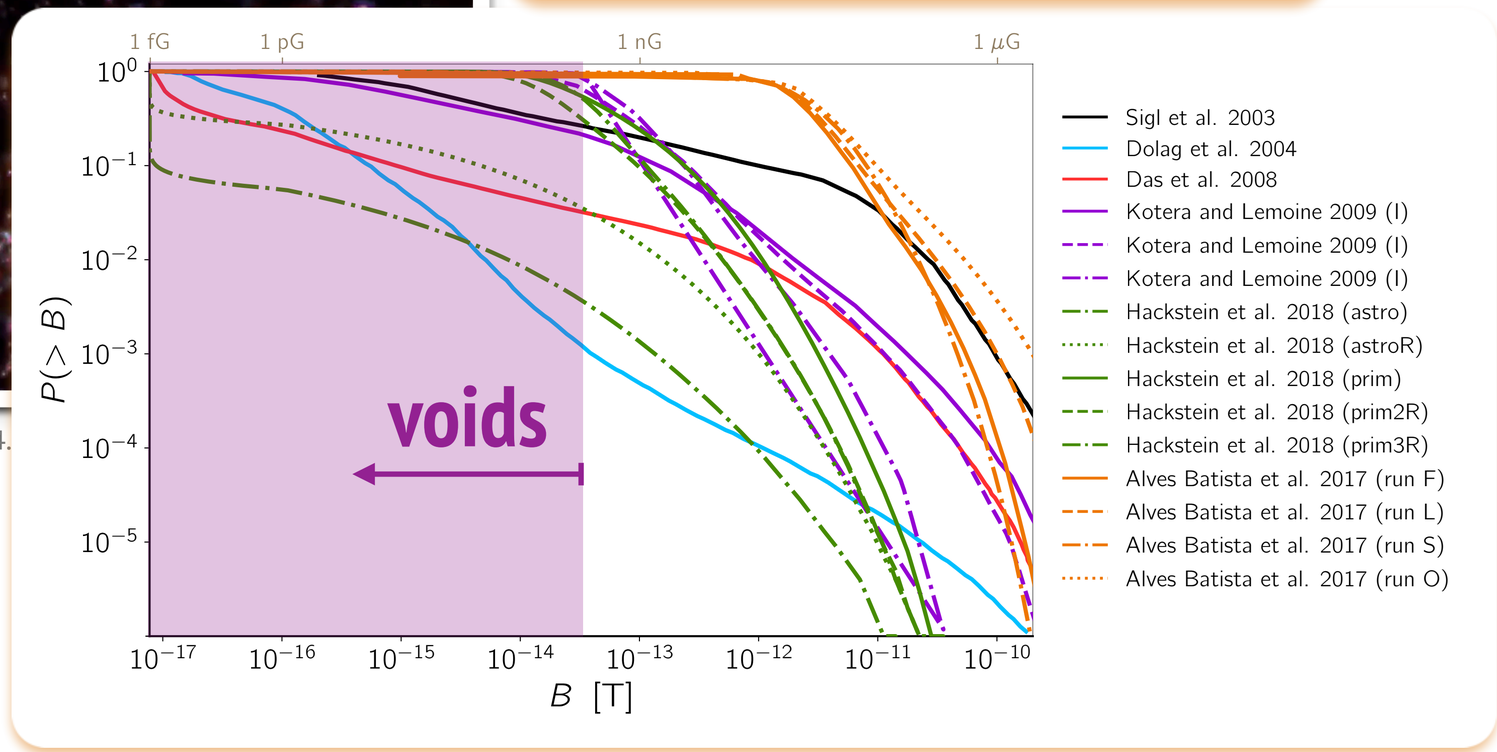
magnetic fields in the large-scale structure of the universe



Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.

magnetic fields in voids are the most uncertain

contribution of voids dominate over cosmological distances



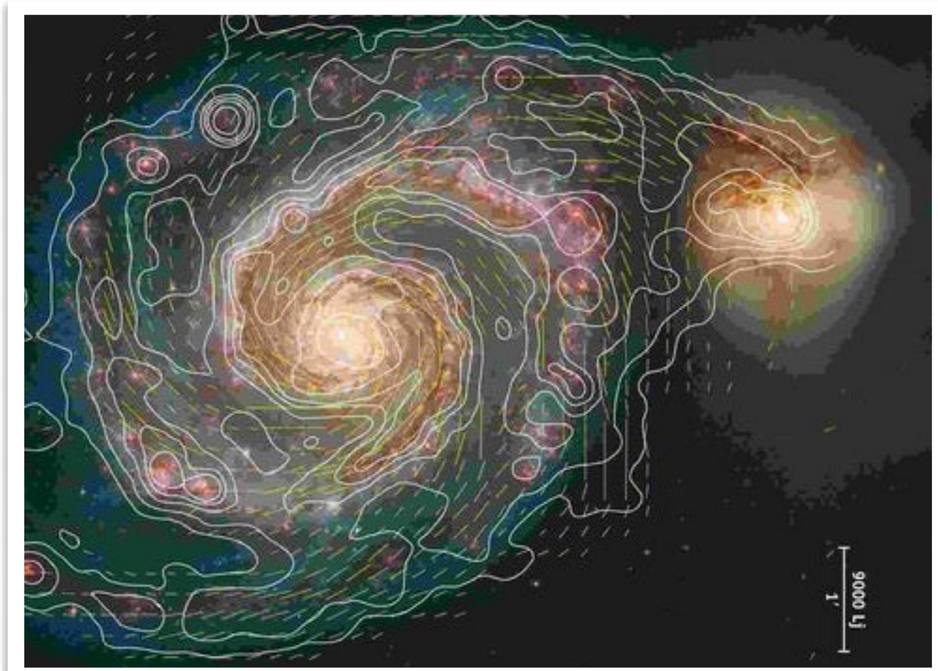
properties of magnetic fields

- regular vs. (near-)stochastic component
- superposition of stochastic components is usually a good description
- stochastic component
  - **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**: $H_B = \int_V \vec{A}(\vec{r}) \cdot \vec{B}(\vec{r}) \,\mathrm{d}^3 r$
- all of these properties can be important

cosmic magnetic fields

- magnetic fields in galaxies have strengths of ~10^{-10} T
- to explain these observations, pre-existing seed magnetic fields are required
- dynamos can amplify these fields
  - MHD induction equation:

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



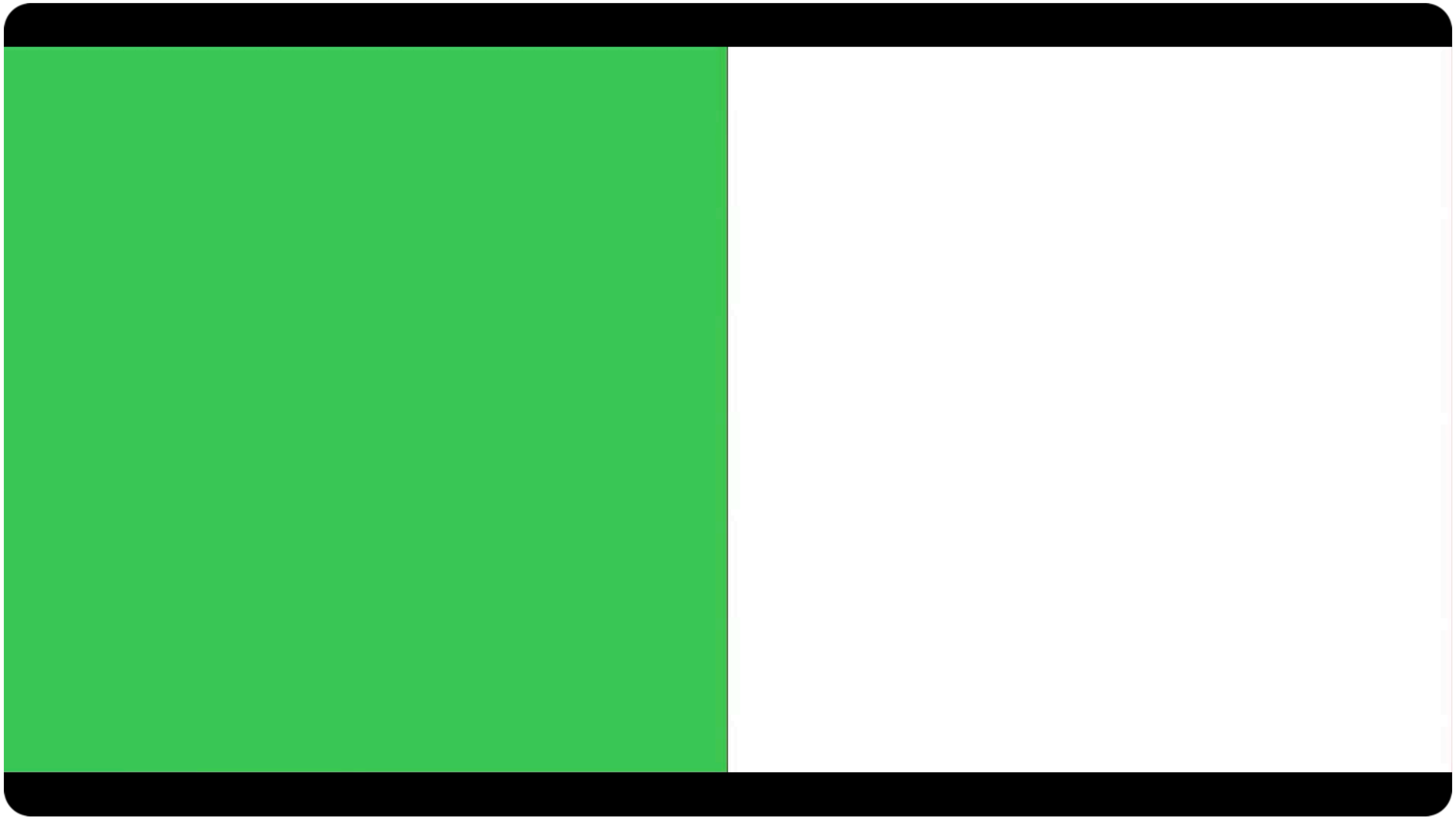
- **how did the seed magnetic fields originate?**
  - astrophysical vs. cosmological origin

fundamental questions

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

cosmic magnetogenesis

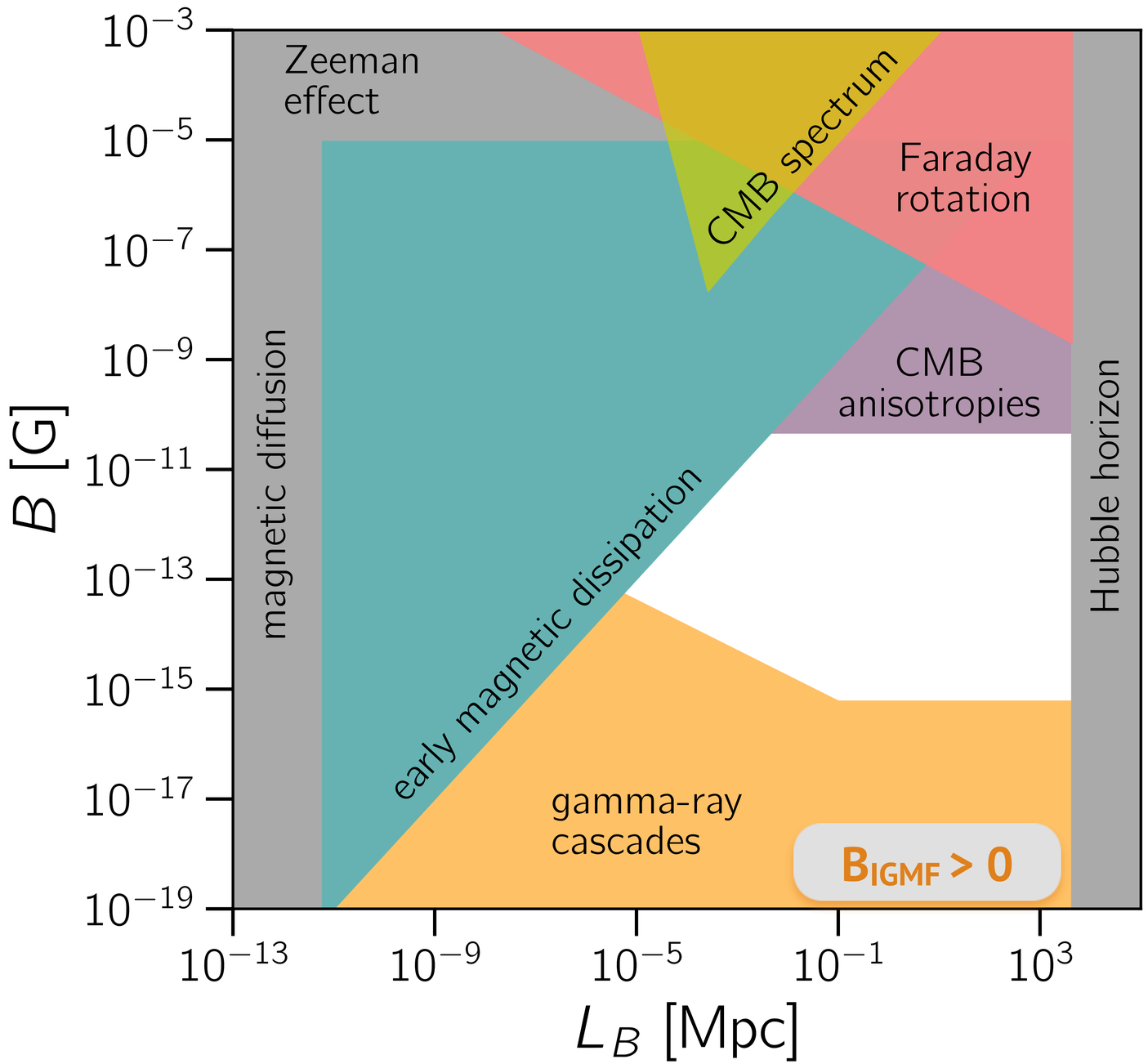
- **astrophysical mechanisms:** during structure formation (e.g. Biermann battery, ...)
- **primordial mechanisms**: large-scale cosmological processes such as inflation, EW or QCD phase transition, ...



Credits: Franco Vazza

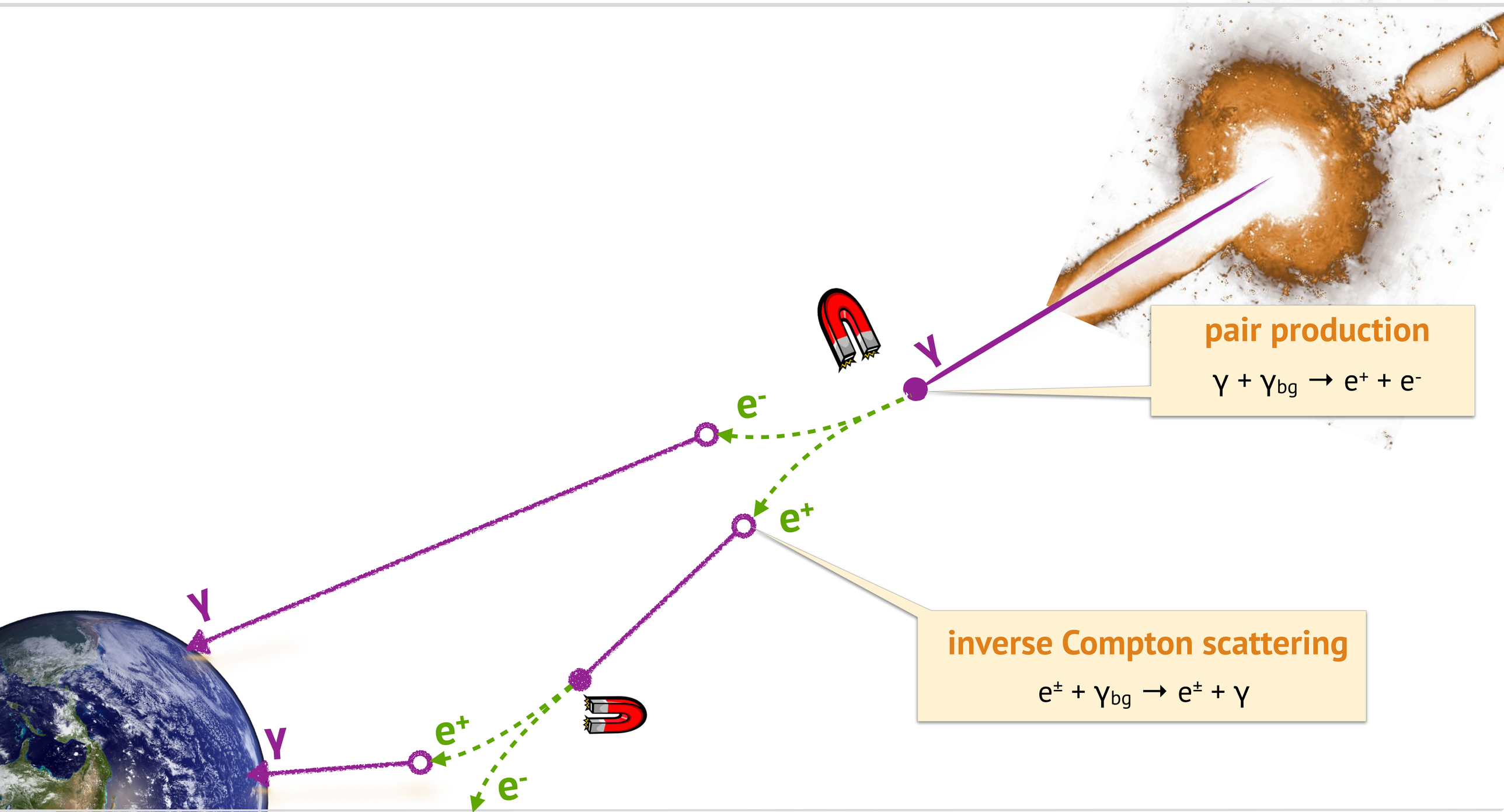
IGMF constraints

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

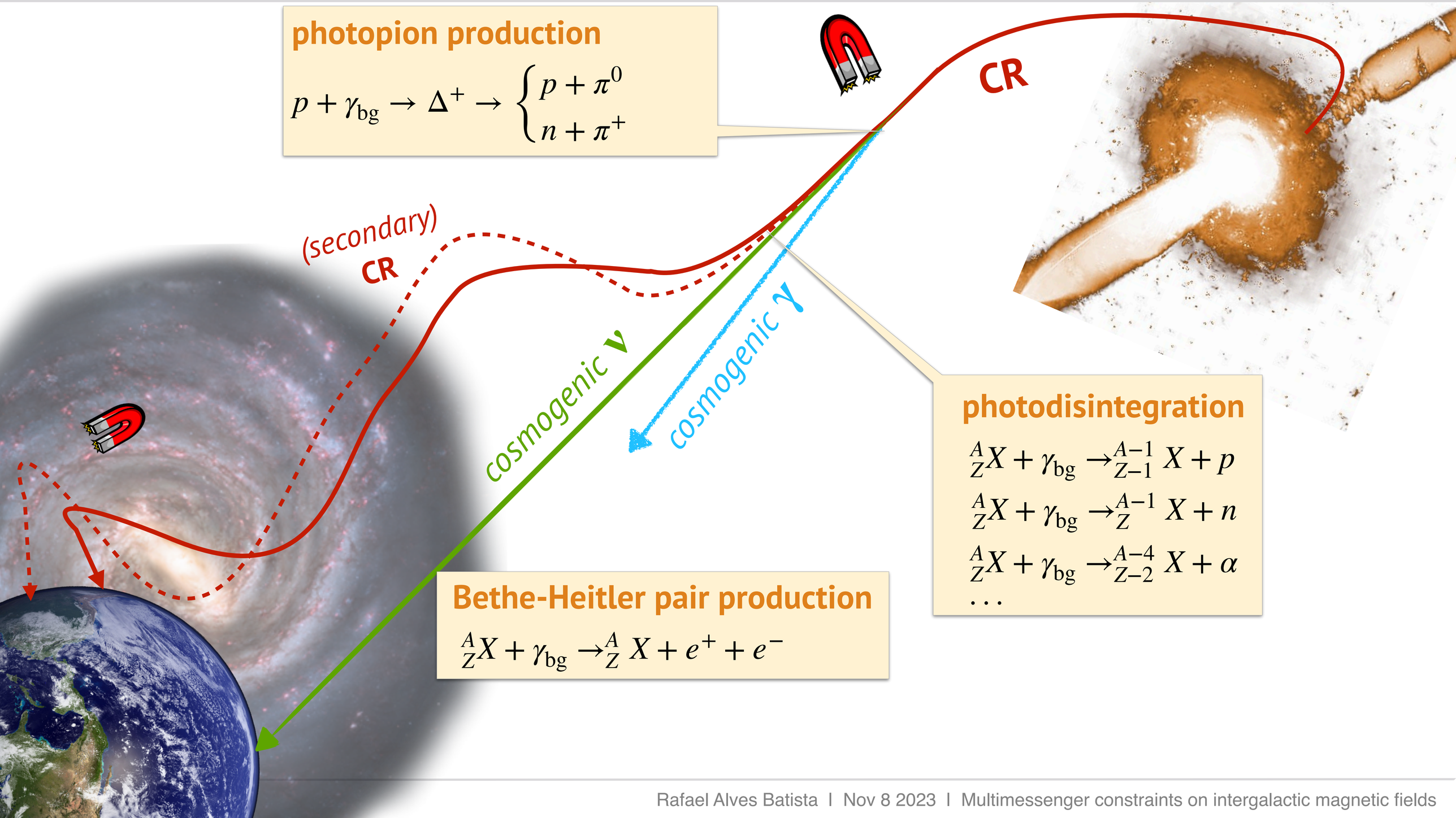


cosmic messengers: propagation

multimessenger propagation picture: gamma rays



multimessenger propagation picture: cosmic rays



photopion production

$$p + \gamma_{\rm bg} \to \Delta^+ \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

photodisintegration

$$^{A}_{Z}X + \gamma_{\rm bg} \to ^{A-1}_{Z-1}X + p$$

$$^{A}_{Z}X + \gamma_{\rm bg} \to ^{A-1}_{Z}X + n$$

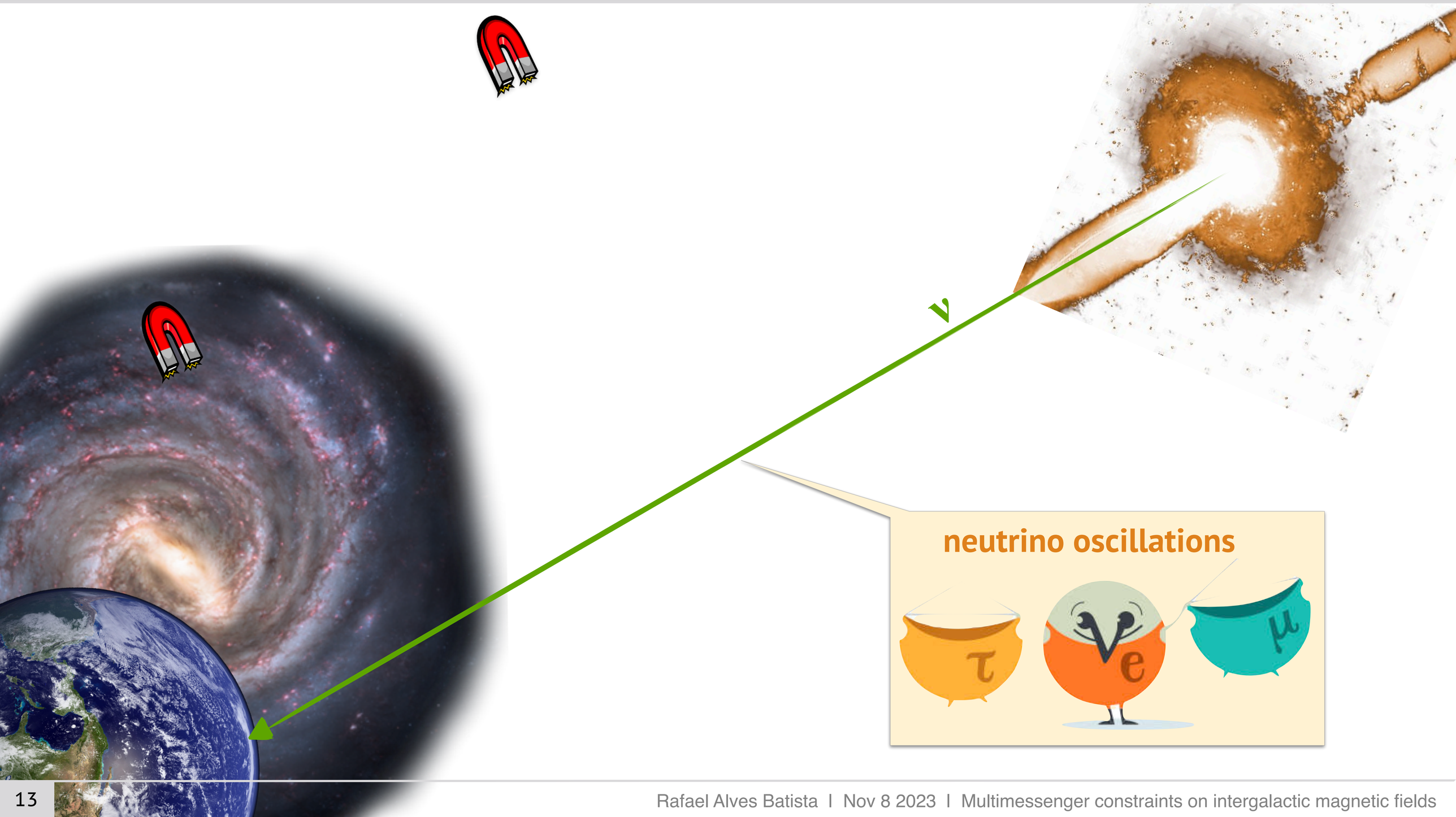
$$^{A}_{Z}X + \gamma_{\rm bg} \to ^{A-4}_{Z-2}X + \alpha$$

$$\ldots$$

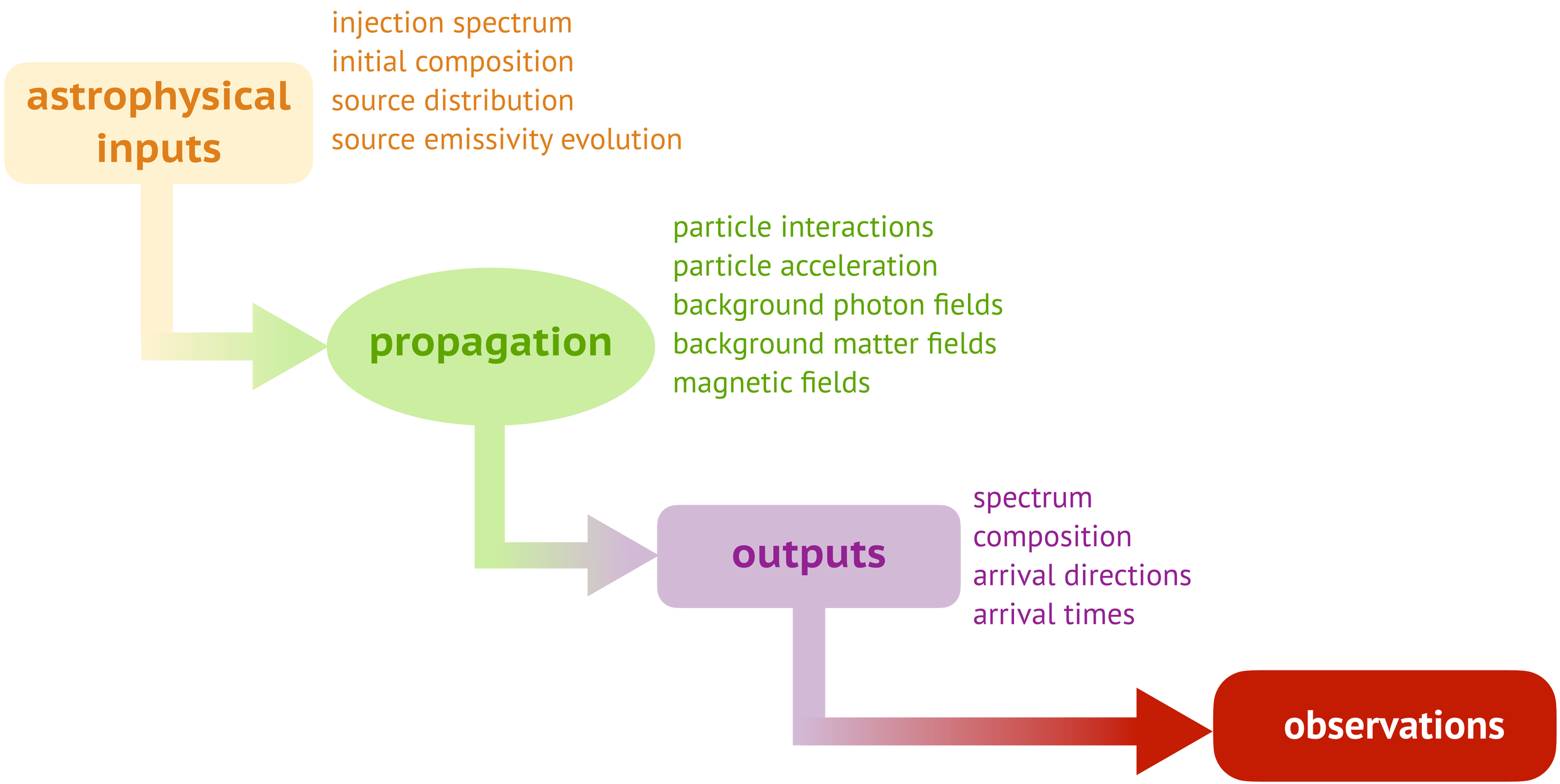
Bethe-Heitler pair production

$$^{A}_{Z}X + \gamma_{\rm bg} \to ^{A}_{Z}X + e^+ + e^-$$

multimessenger propagation picture: neutrinos

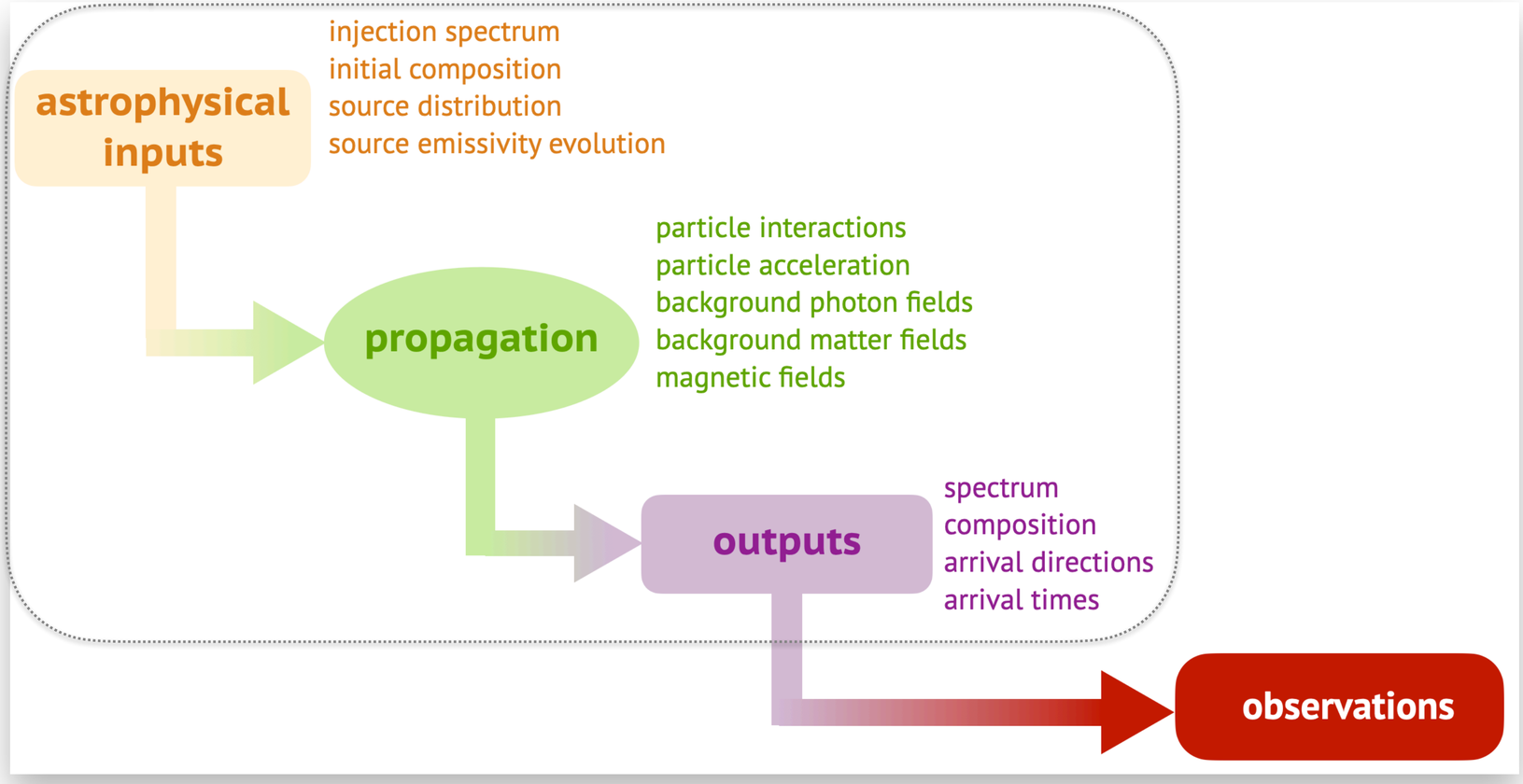


recipe for propagating astroparticles



modelling the propagation

Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142
Alves Batista et al. JCAP 09 (2022) 035. arXiv:2208.00107



https://github.com/CRPropa/CRPropa3

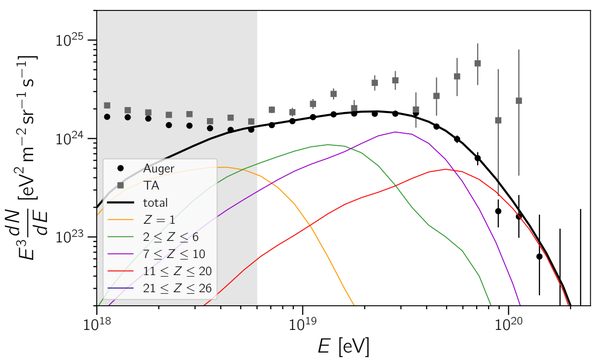
CRPropa

- mixing all ingredients → interpret (fit) observations based on models
- this should be done ***self-consistently for all messengers***
- need to ***scan full parameter space*** of uncertainties

simulation framework

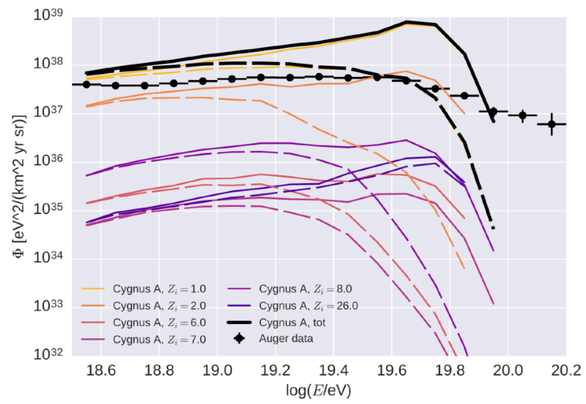
the CRPropa framework: applications

fit UHECR measurements



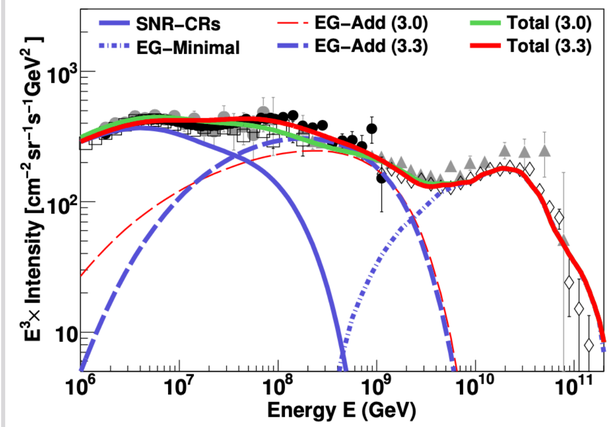
Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

test UHECR source models



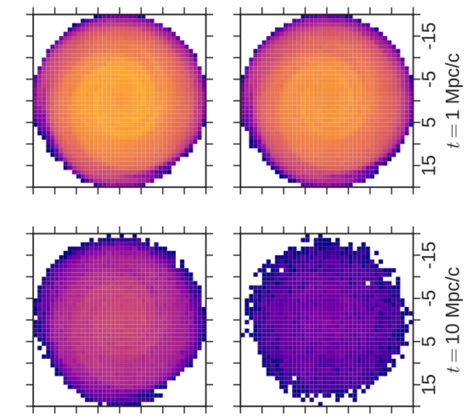
Eichmann et al. JCAP 02 (2018) 036. arXiv:1701.06792

transition G-EG CRs



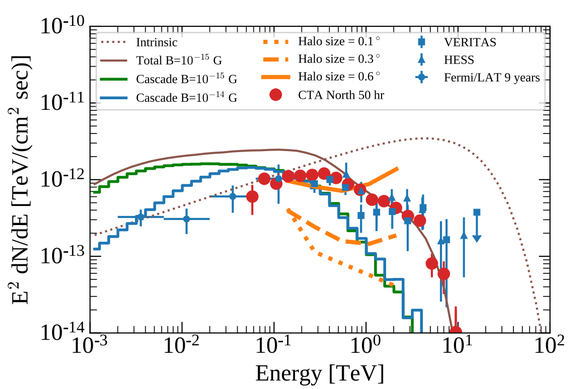
Thoudam et al. Astron. Astrophys. 595 (2016) A33. arXiv:1605.03111

diffusion of Galactic CRs



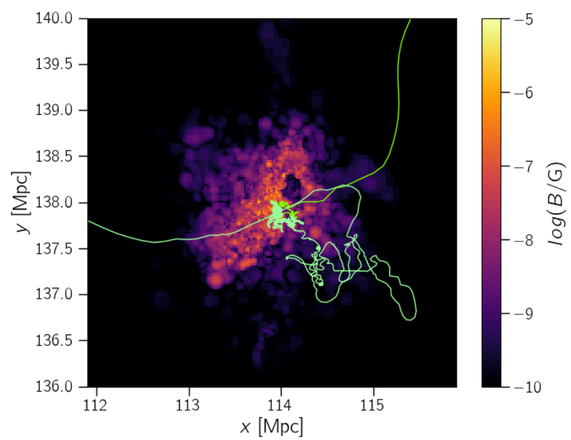
Merten et al. JCAP 06 (2016) 046. arXiv:1704.07484

gamma rays + IGMFs



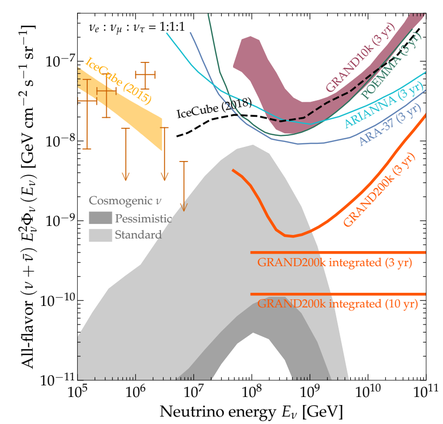
CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

neutrinos from galaxy clusters



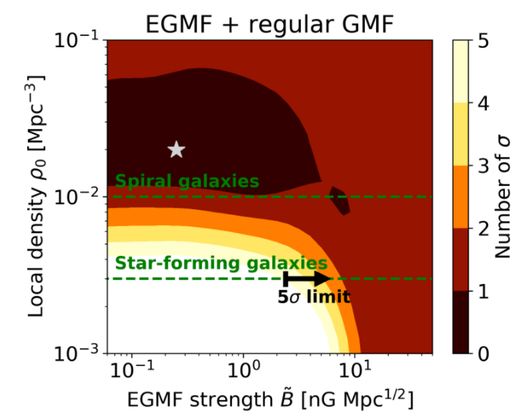
Hussain, Alves Batista, de Gouveia Dal Pino. arXiv:2101.07702

cosmogenic neutrinos



GRAND Collaboration. Science China Phys 63 (2020) 219501. arXiv:1810.09994

EGMF constraints



van Vliet, Palladino, Taylor, Winter. MNRAS 510 (2022) 1289. arXiv:2104.05732

... and much more!

constraining IGMFs: gamma rays

measuring IGMFs with gamma rays

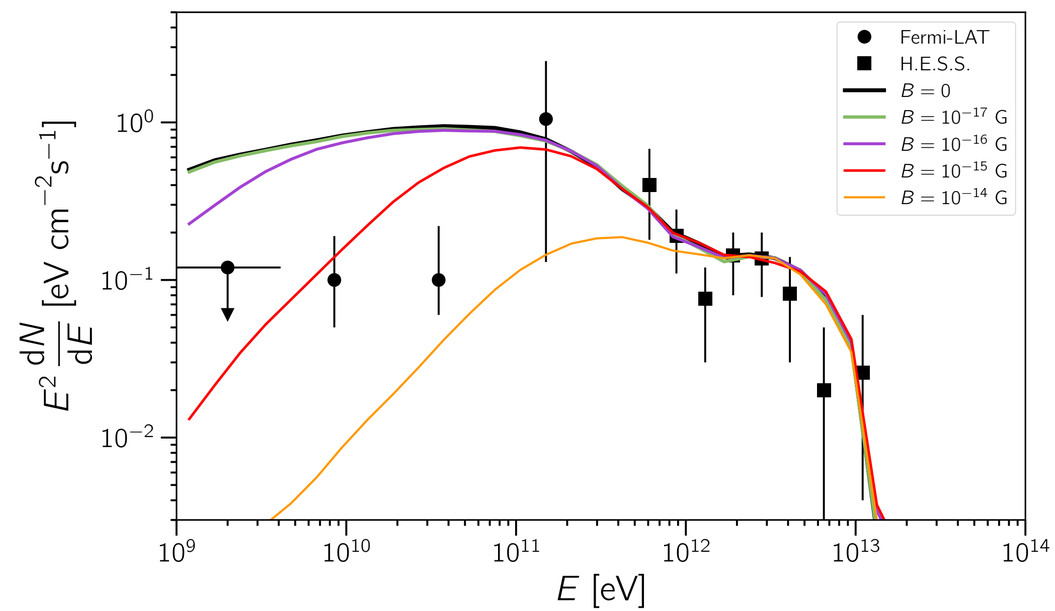
observational strategies

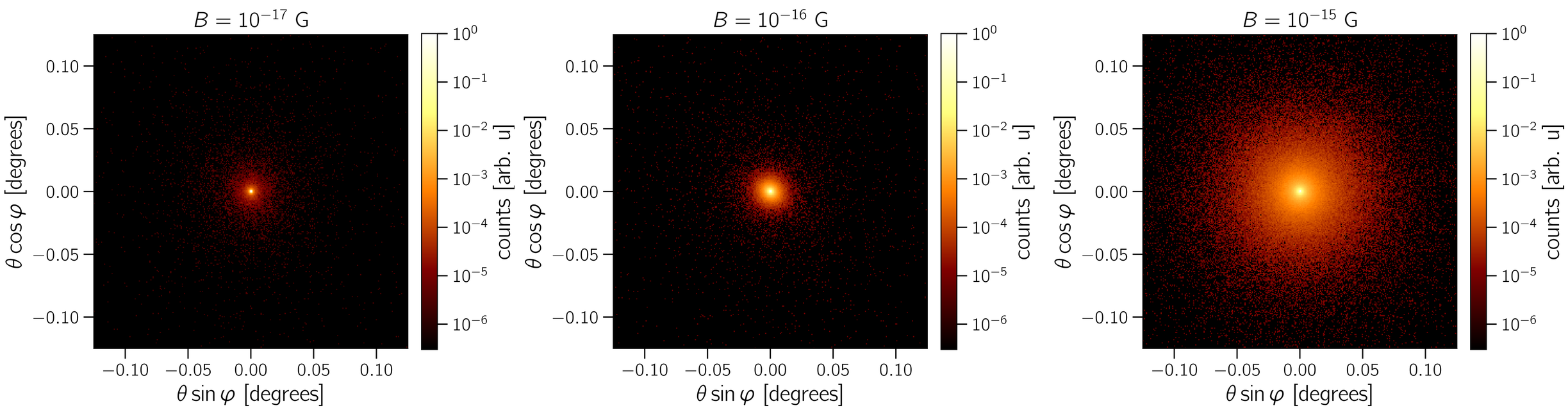
- **strategy 1:** point-like sources will appear extended
- **strategy 2:** secondary gamma rays will arrive with time delays
- **strategy 3:** combination of 1 and 2 → spectral changes

an example: an extreme blazar

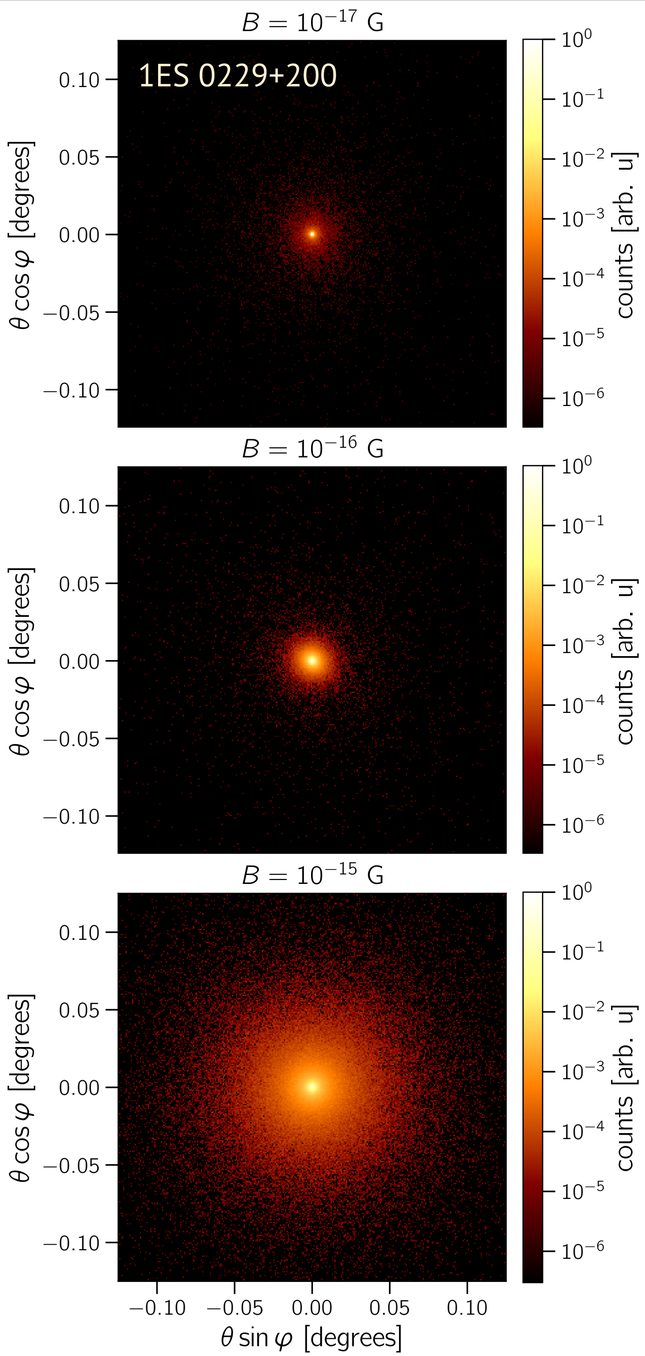
Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020

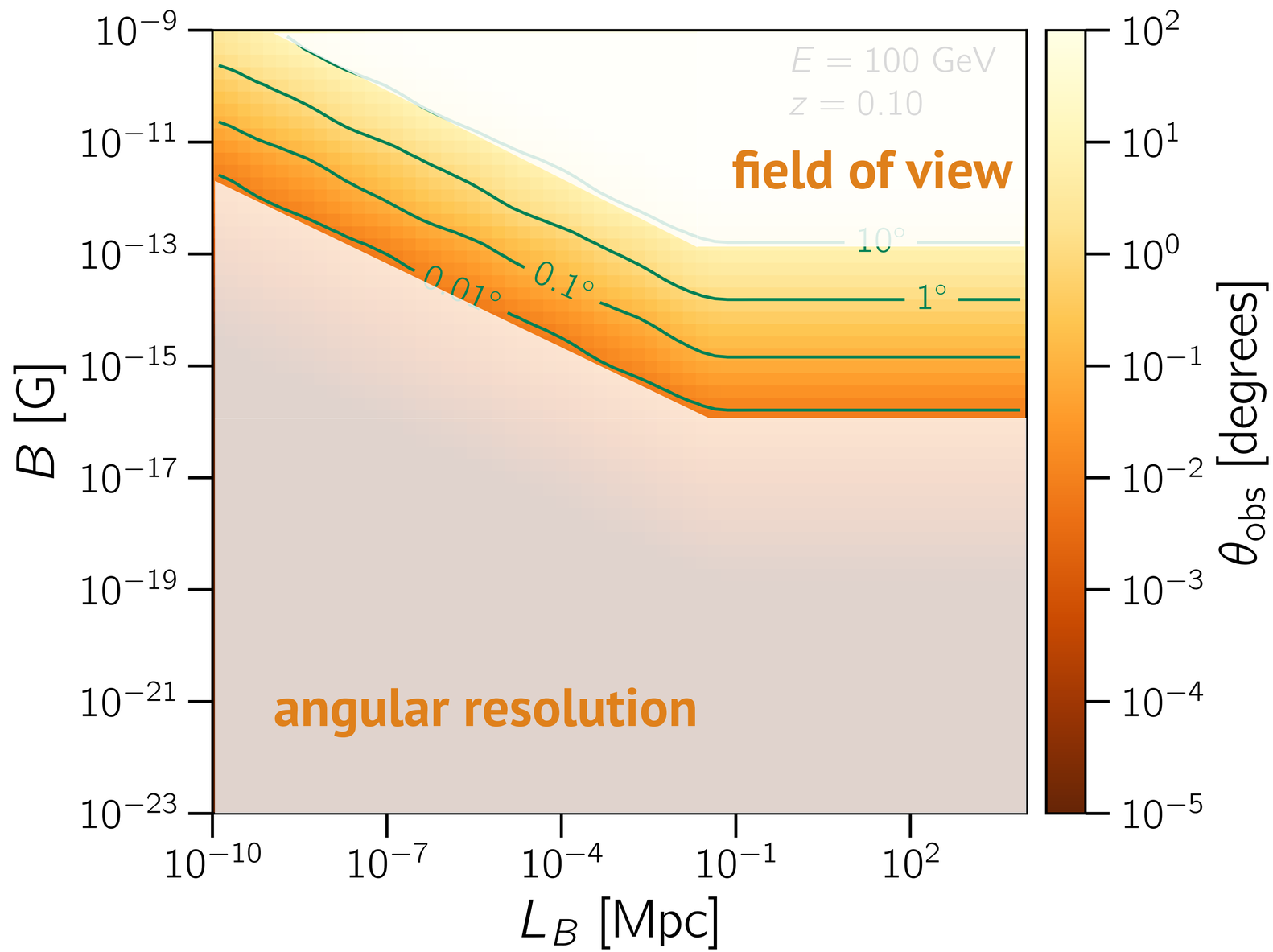
- haloes around sources
- haloes are energy-dependent
- example: 1ES 0229+200 (z=0.14)





observational strategies: extended emission (a.k.a. pair haloes)

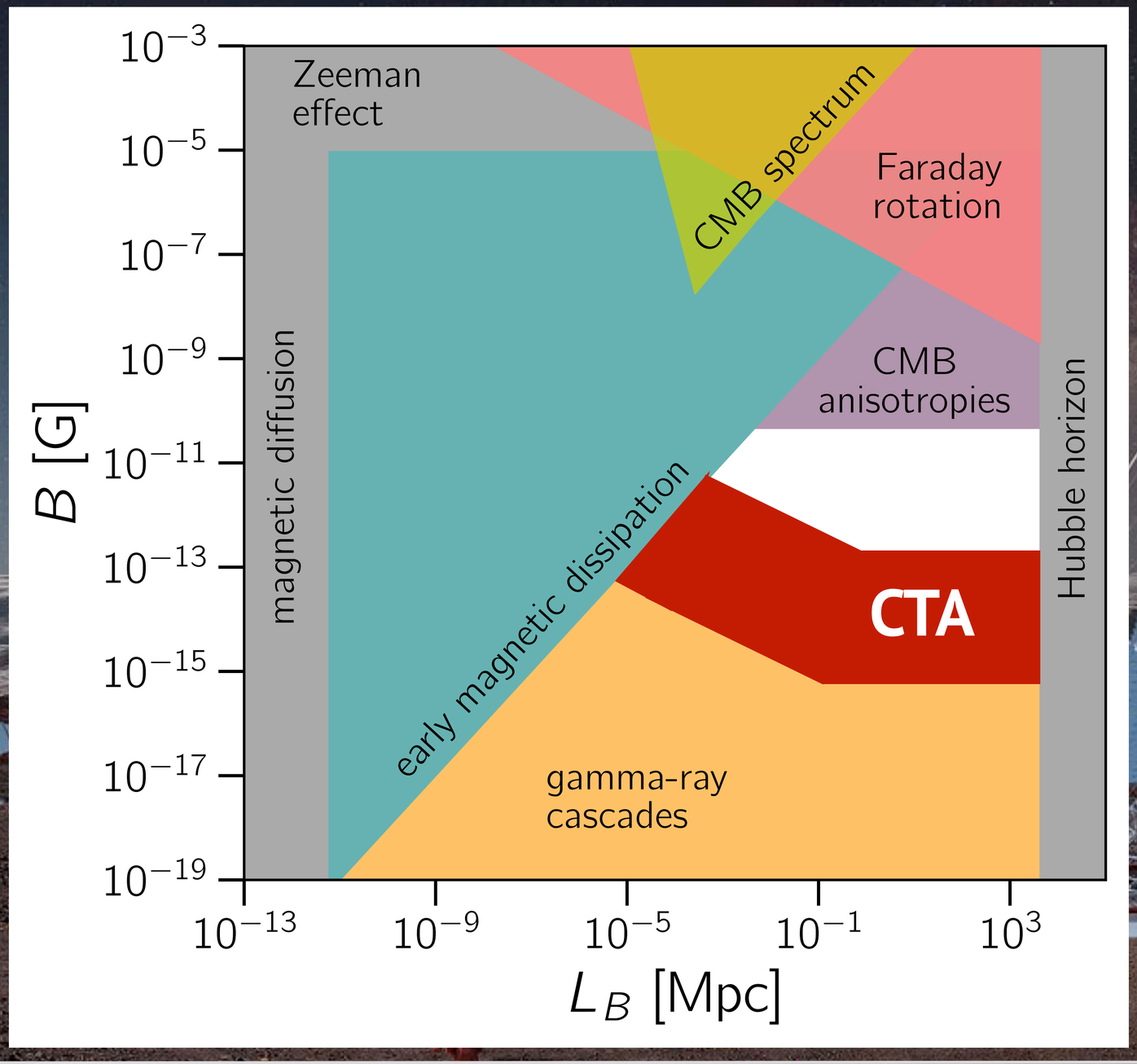


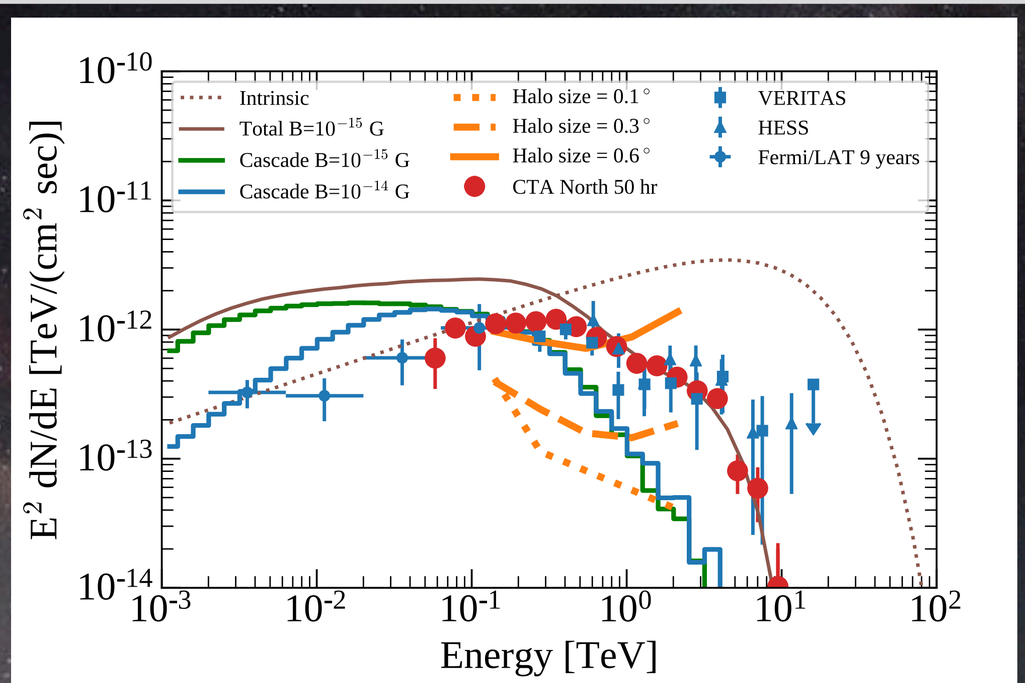


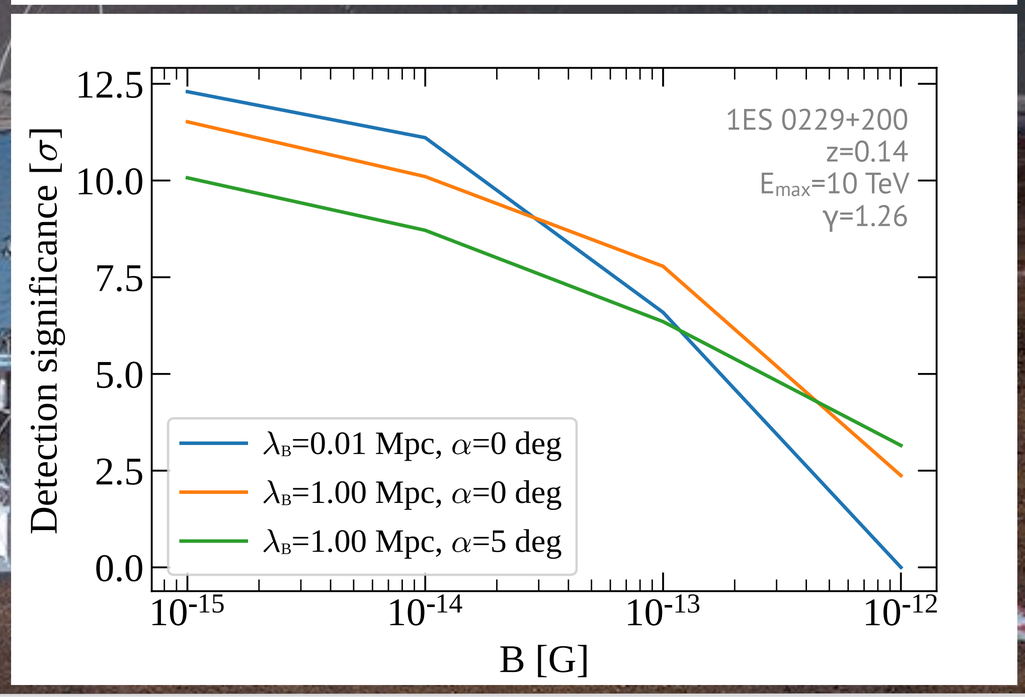
Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020

constraining IGMFs with the Cherenkov Telescope Array

CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

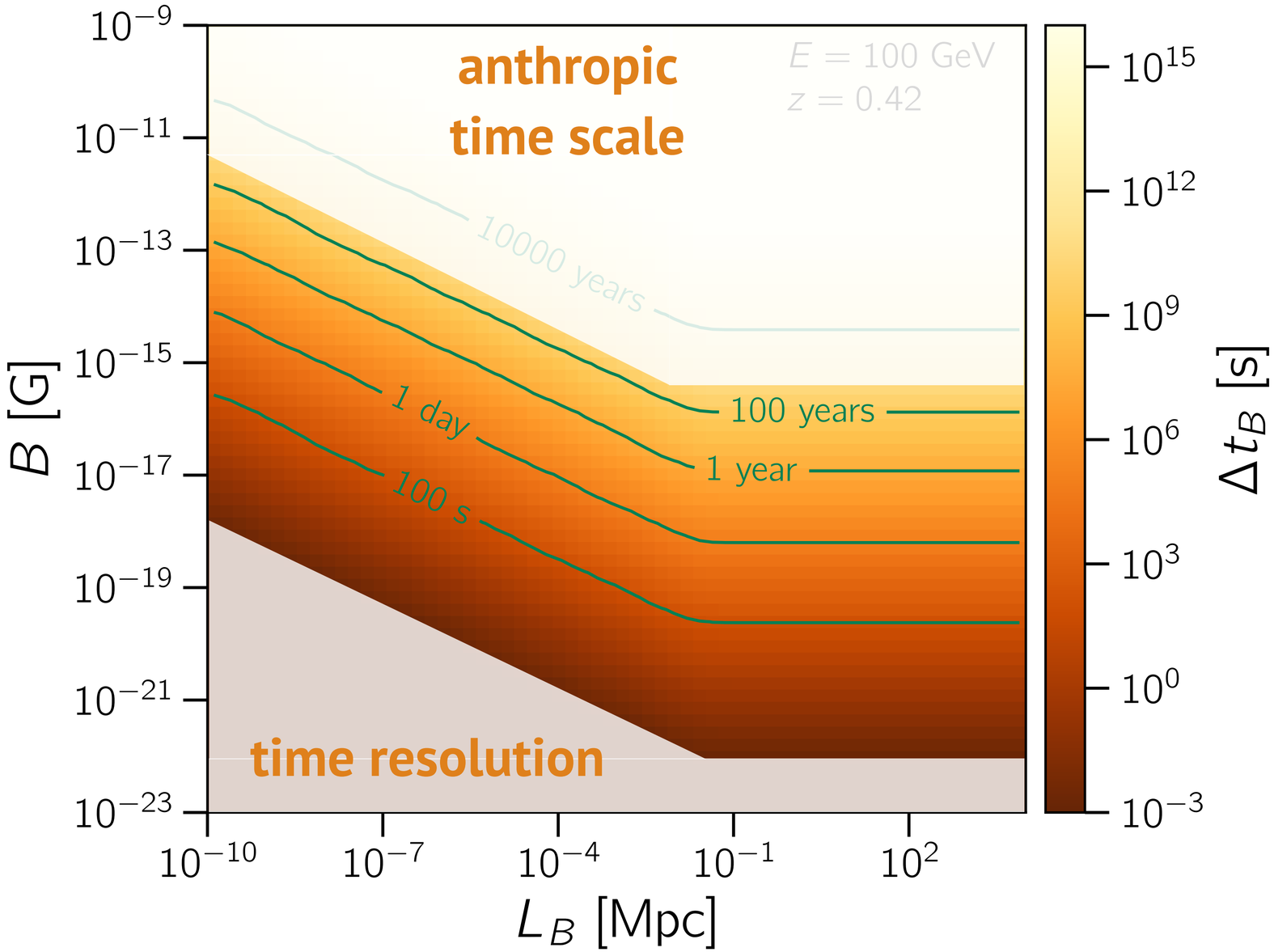






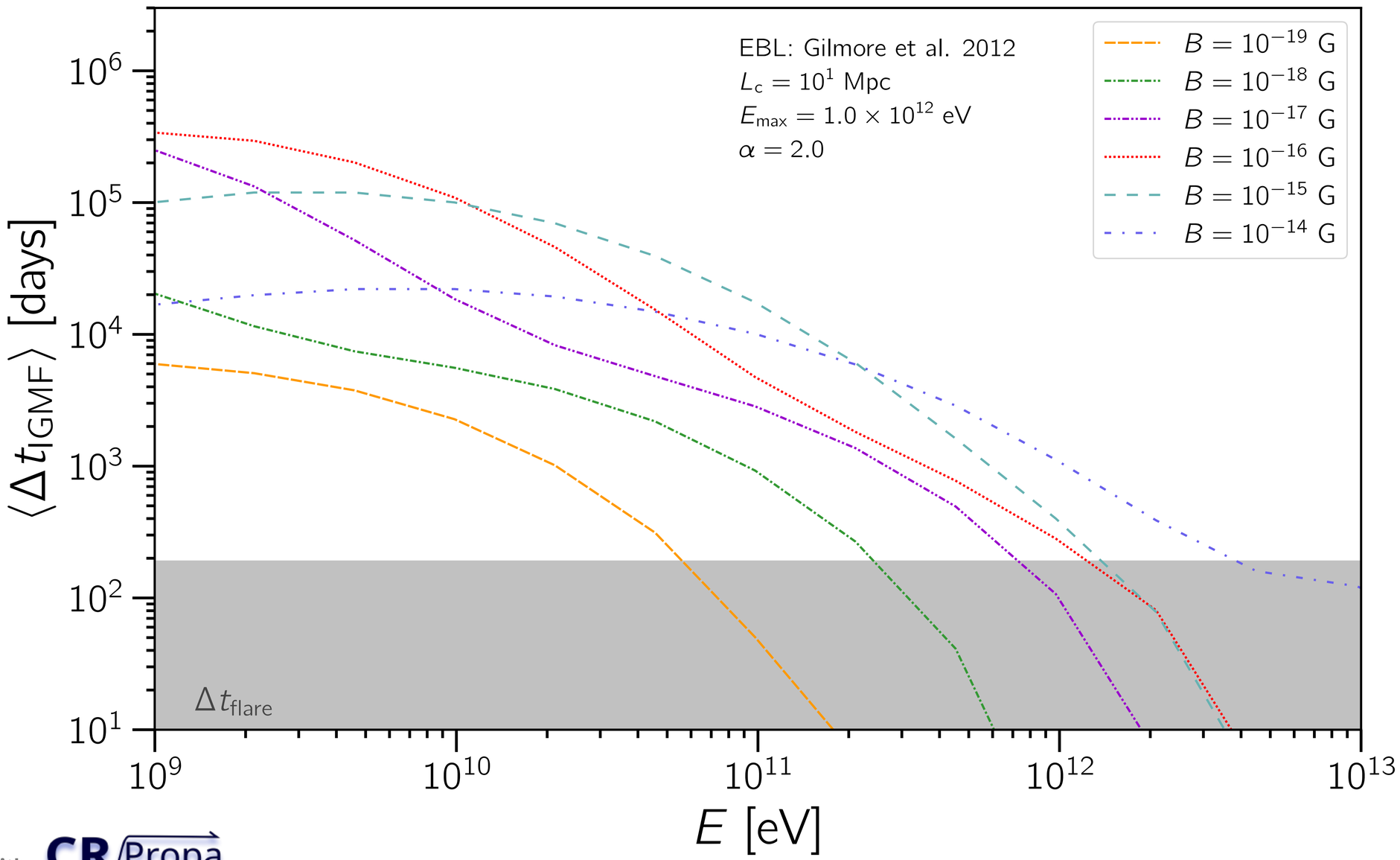
observational strategies: time delays (a.k.a. pair echoes)

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



observational strategies: time delays (a.k.a. pair echoes)

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



simulations performed with CRPropa

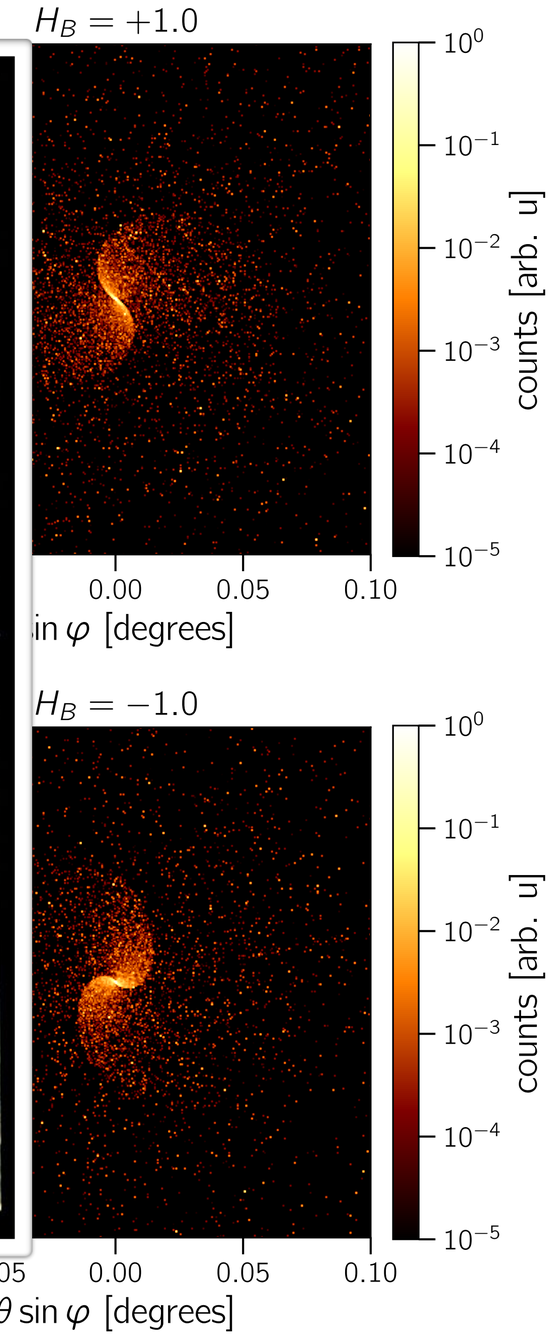
Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142

Alves Batista et al. JCAP 09 (2022) 035. arXiv:2208.00107

helical magnetic fields: gamma-ray signatures

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

- helical magnetic f
  handed) leptogene
  prior to the EW pha
- helicity: $\mathscr{H} = \int d^3r$
- if helical magnetic
  asymmetry is natur
- helicity is approxin
  could be (mostly) u

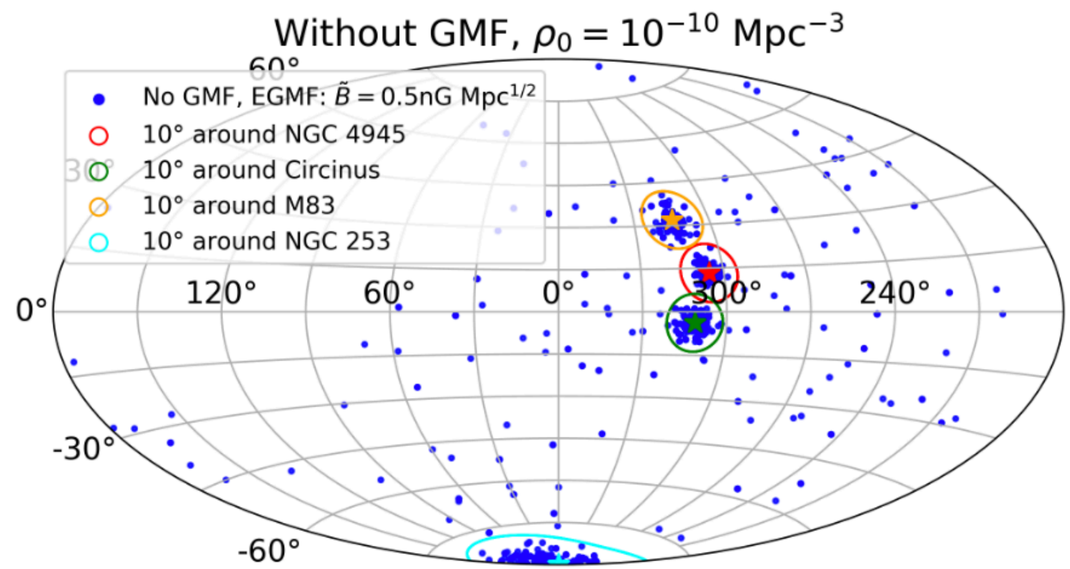


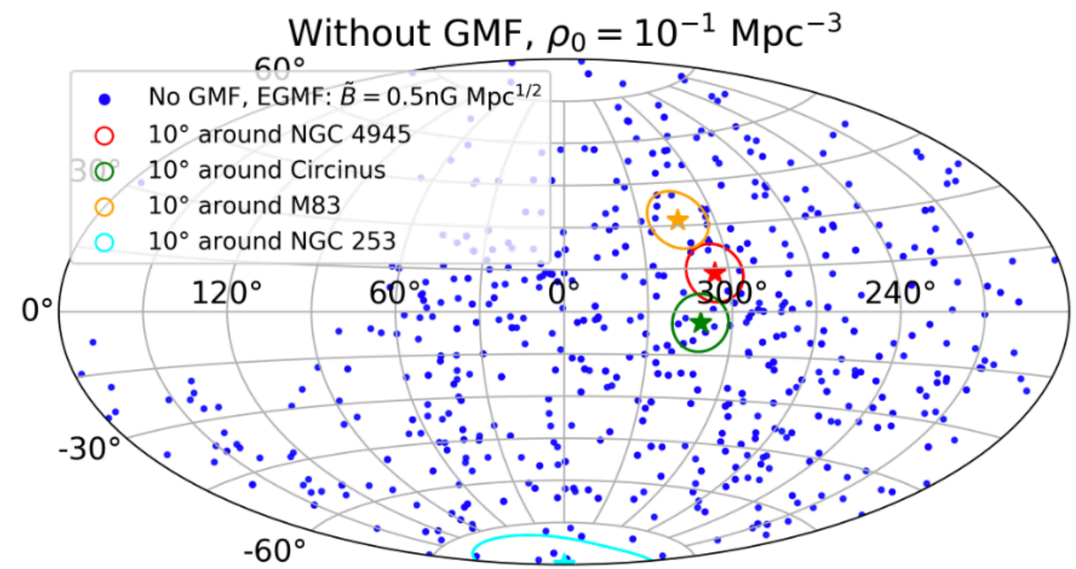
Batchelor spectrum α=1.5
L_B=200 Mpc z=0.08

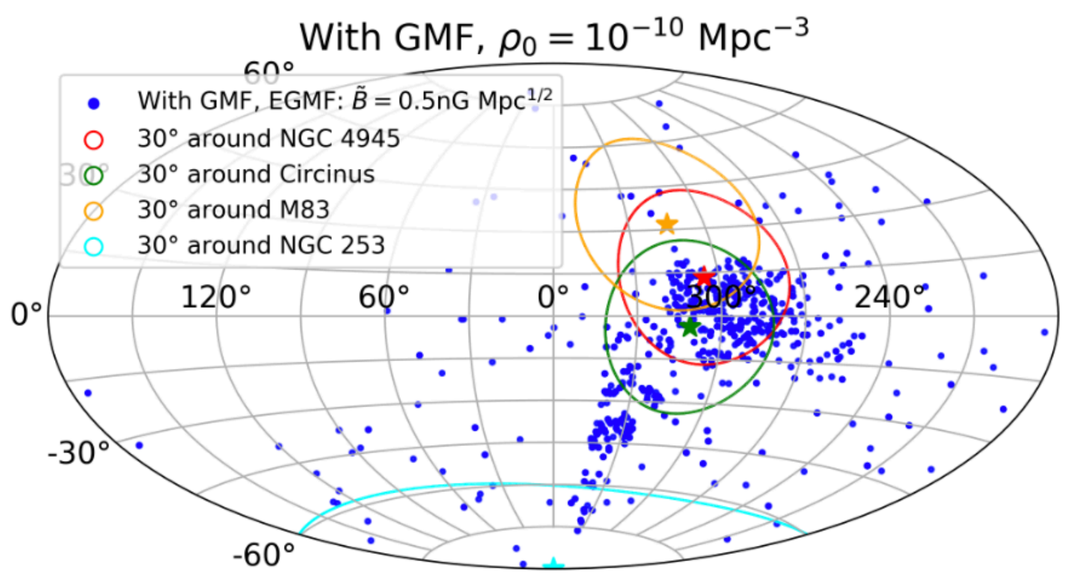
constraining IGMFs: (ultra-high-energy) cosmic rays

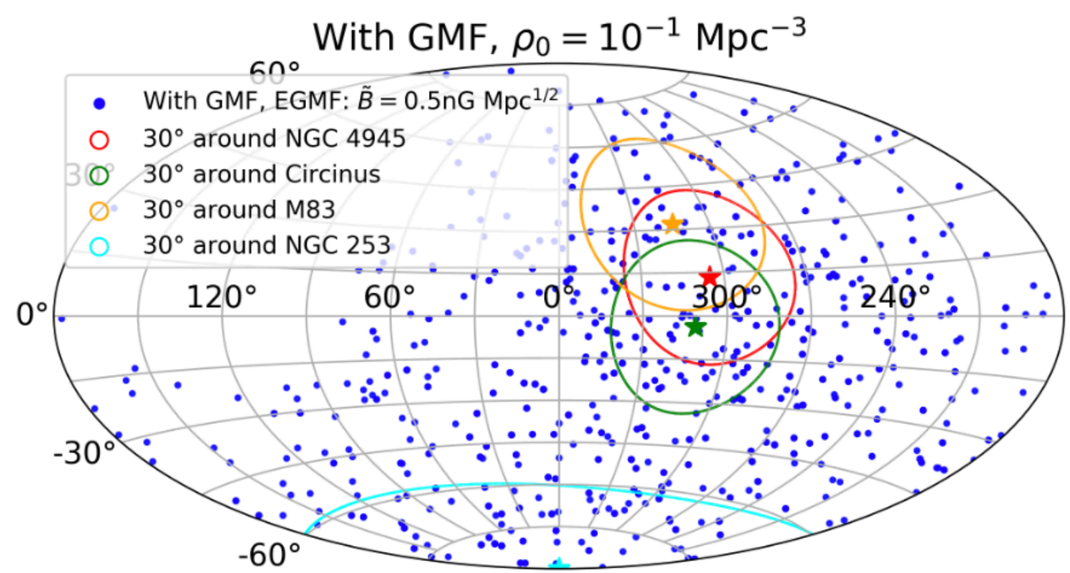
constraining IGMFs with UHECRs

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







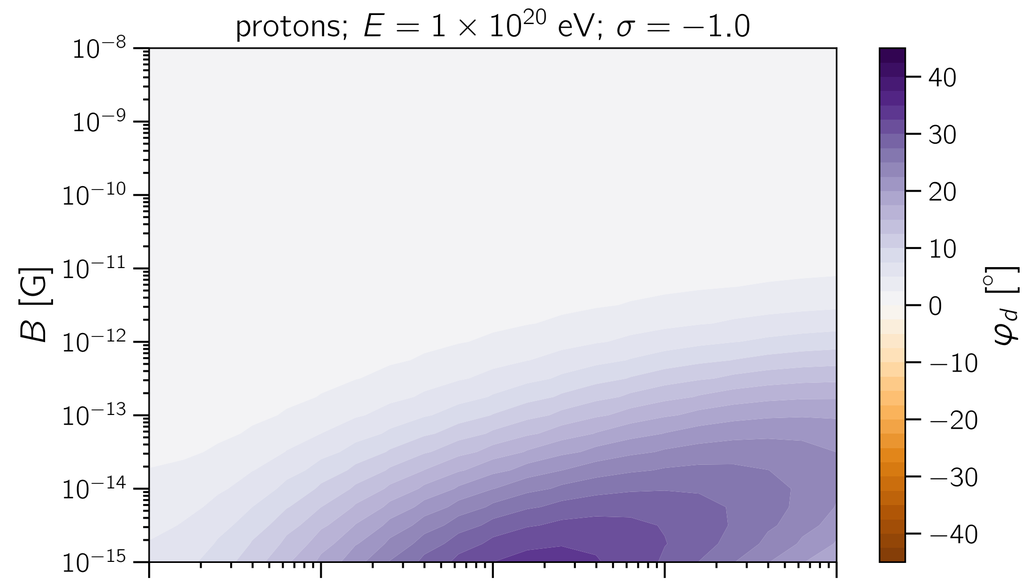


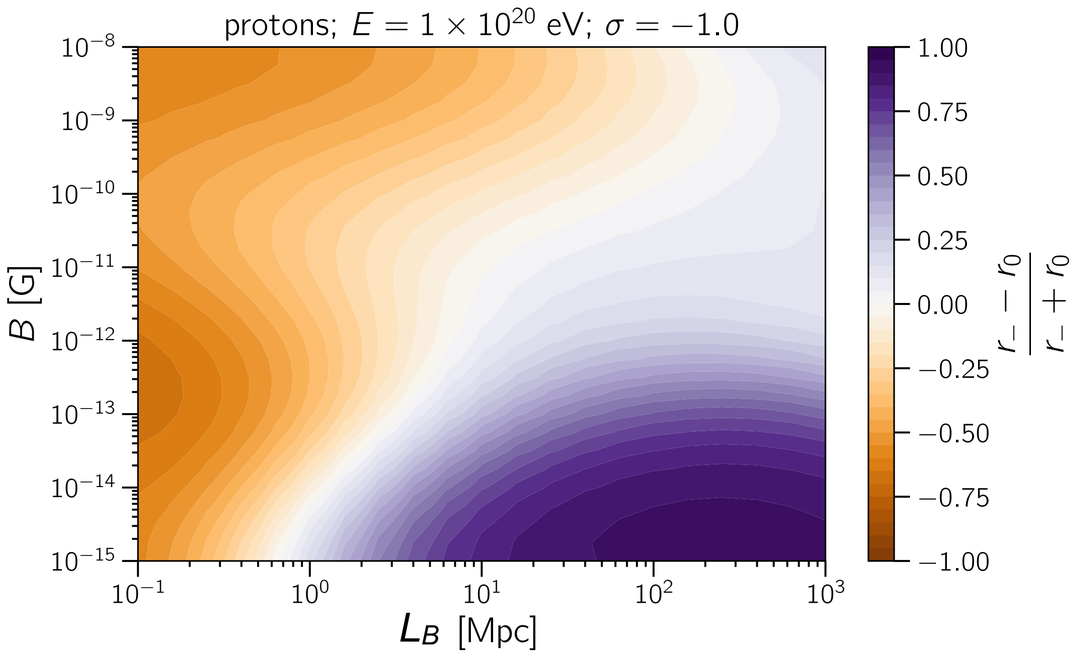
constraining the helicity of IGMFs with UHECRs

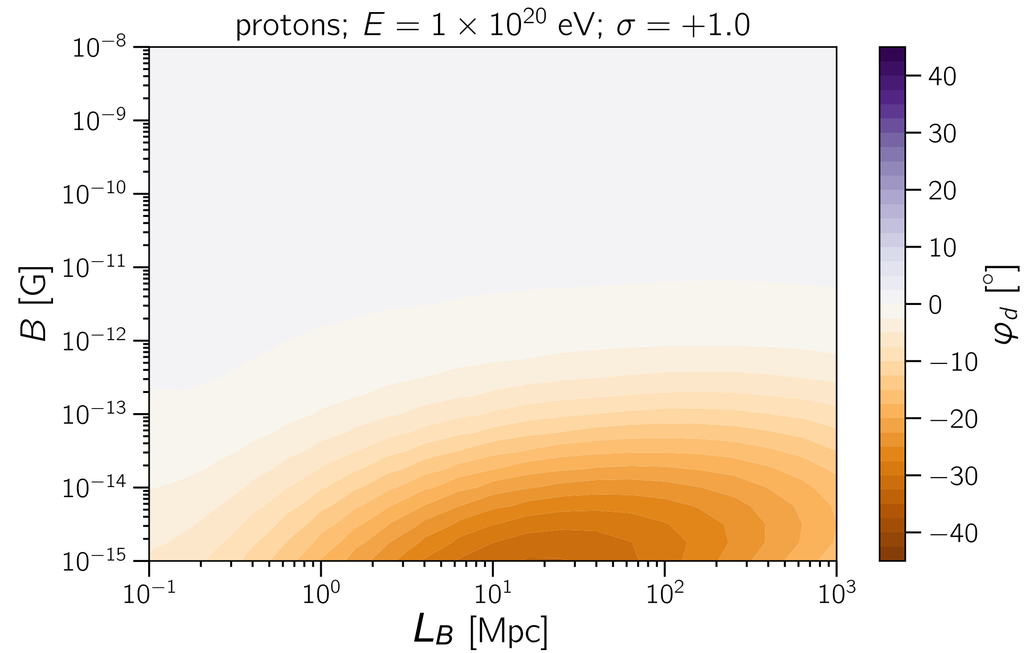
Alves Batista & Saveliev. JCAP 03 (2019) 011. arXiv:1808.04182

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) → helicity sign
- dipole-to-quadrupole ratio (r) → absolute value







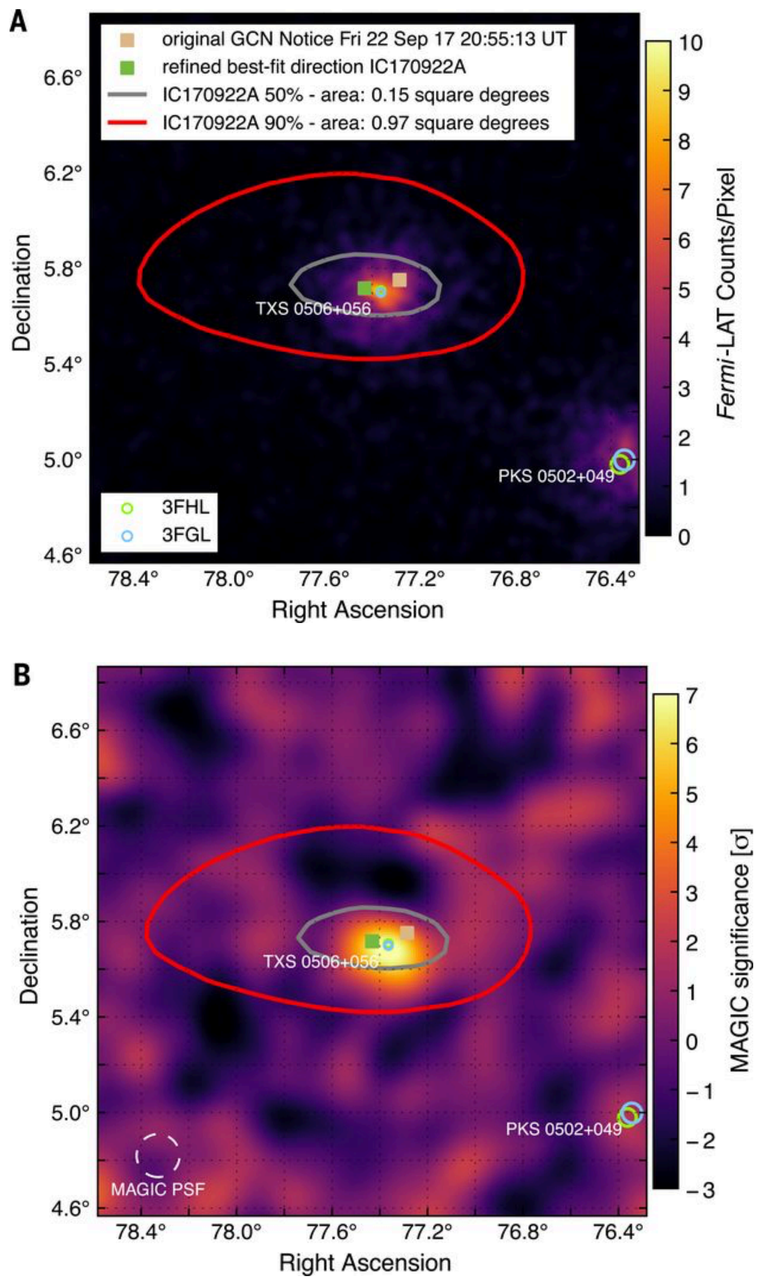
constraining IGMFs: multimessenger

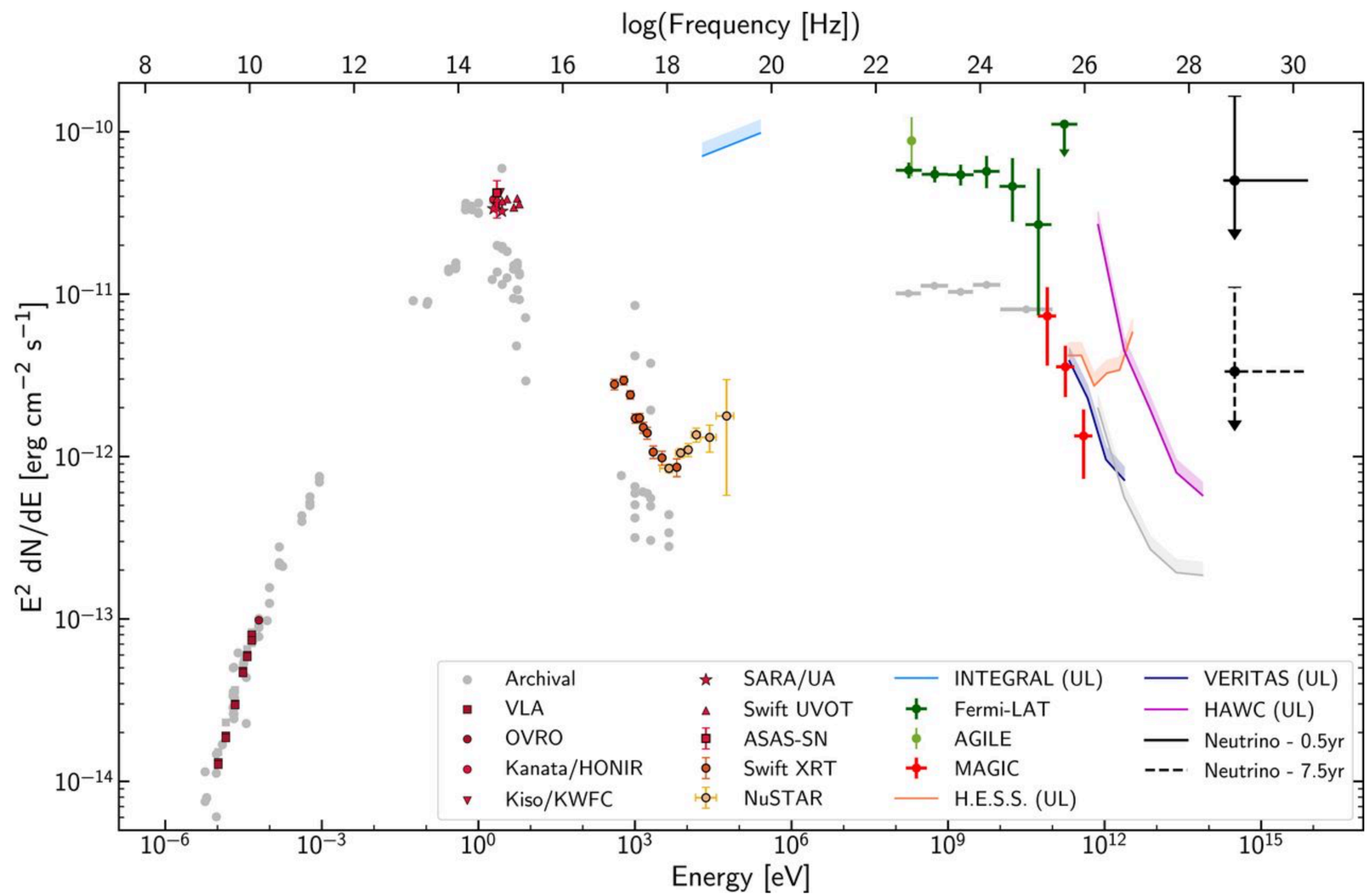
gamma rays
+
neutrinos

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

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

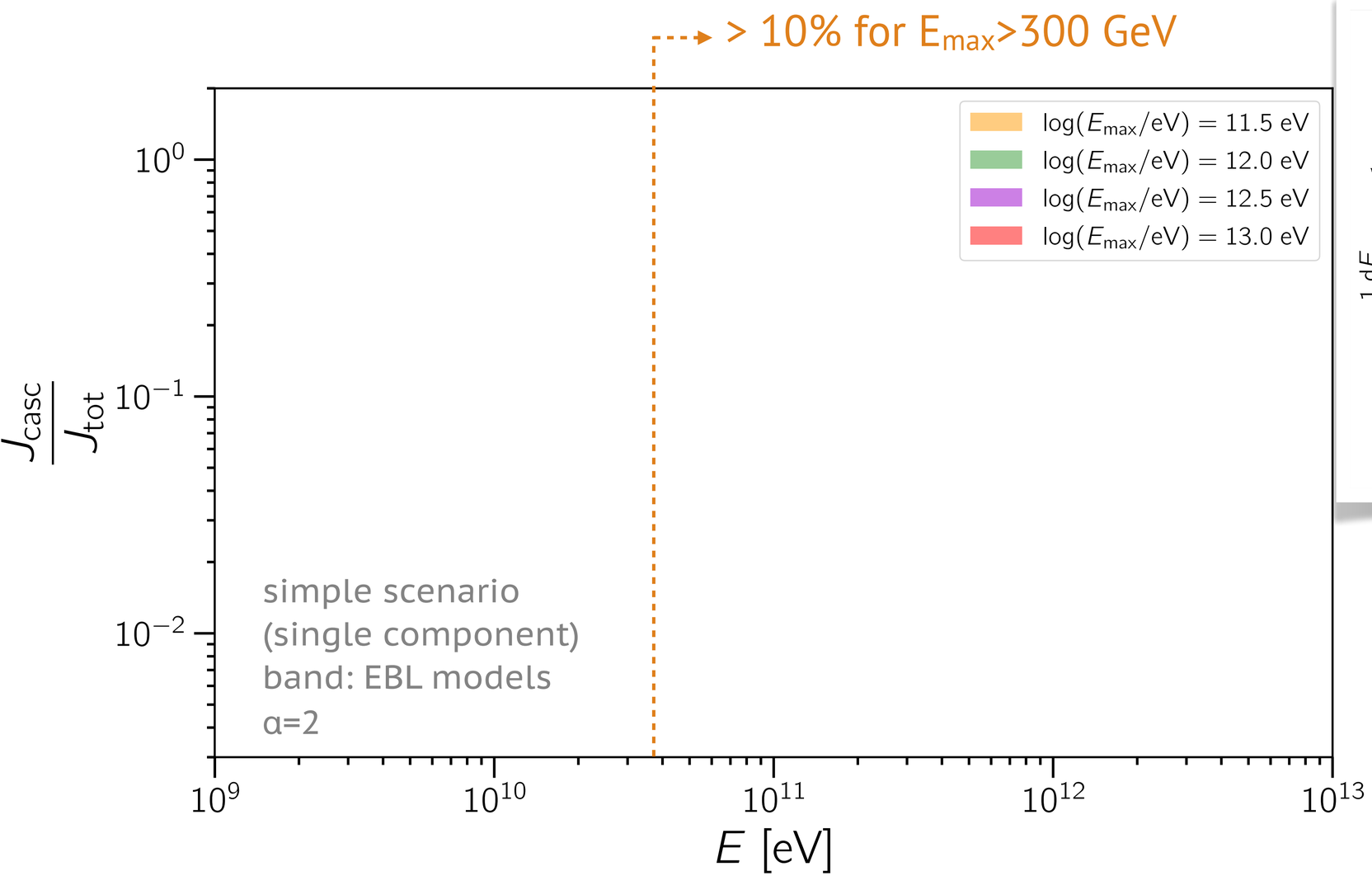
intrinsic gamma-ray spectrum

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

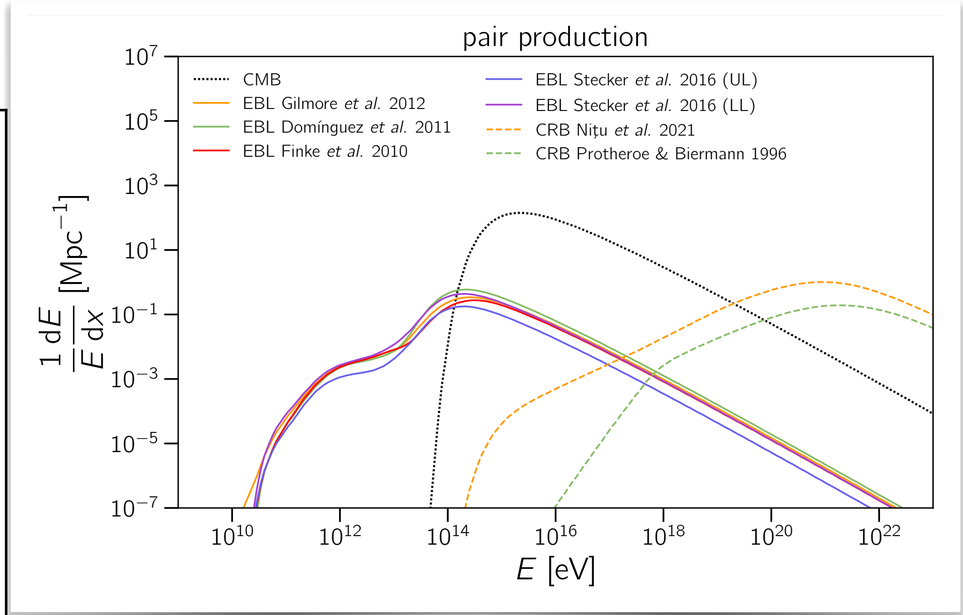
(phenomenological model = how it appears)

- 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

is there a cascade contribution?



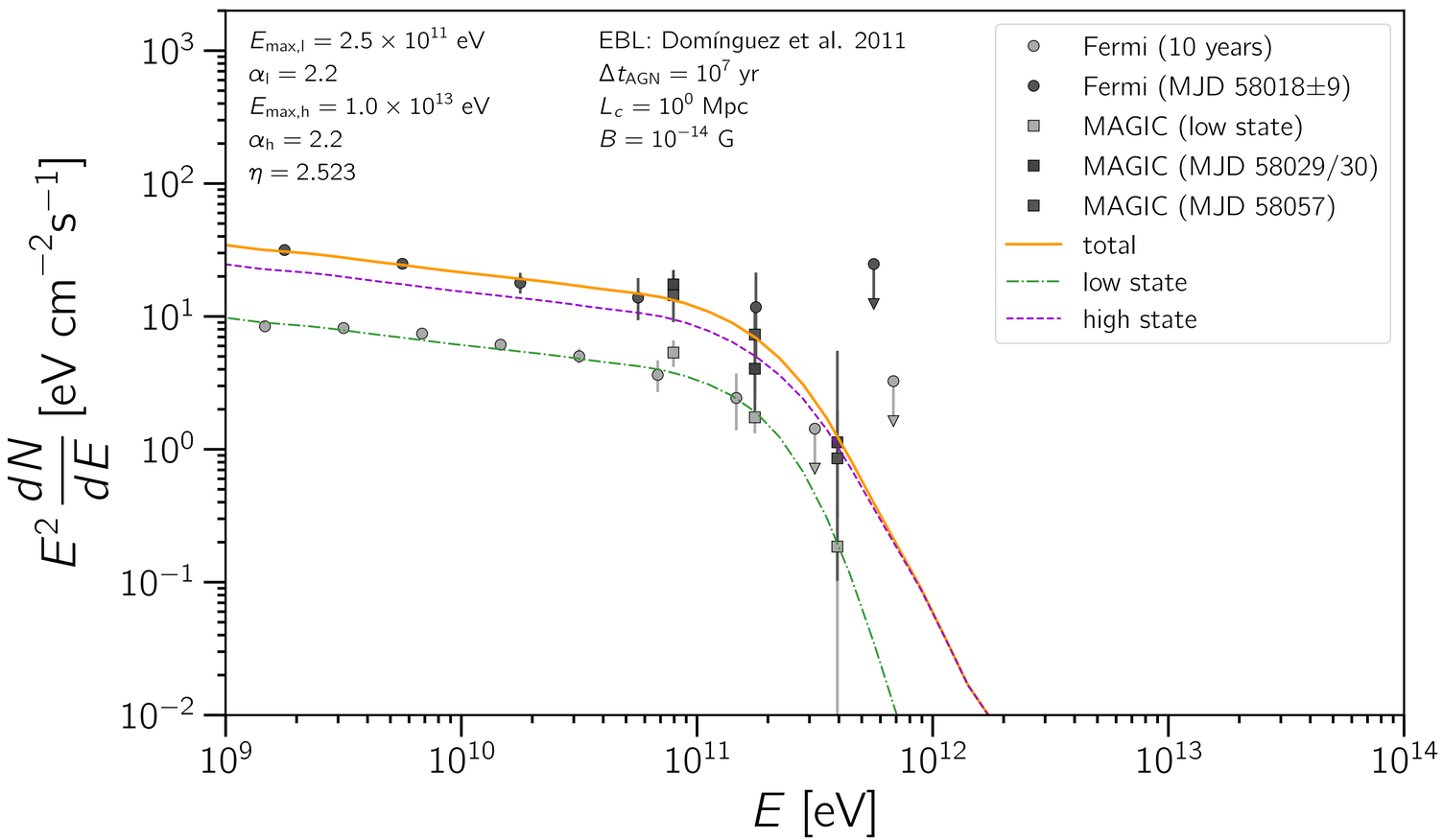
MAGIC observes ~400 GeV events

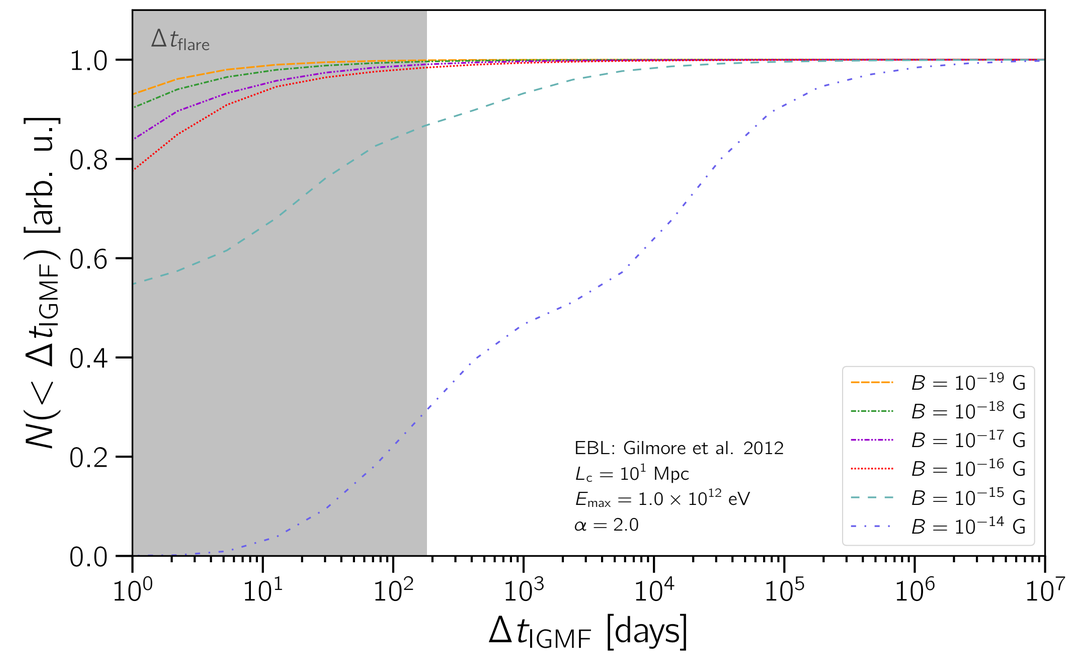


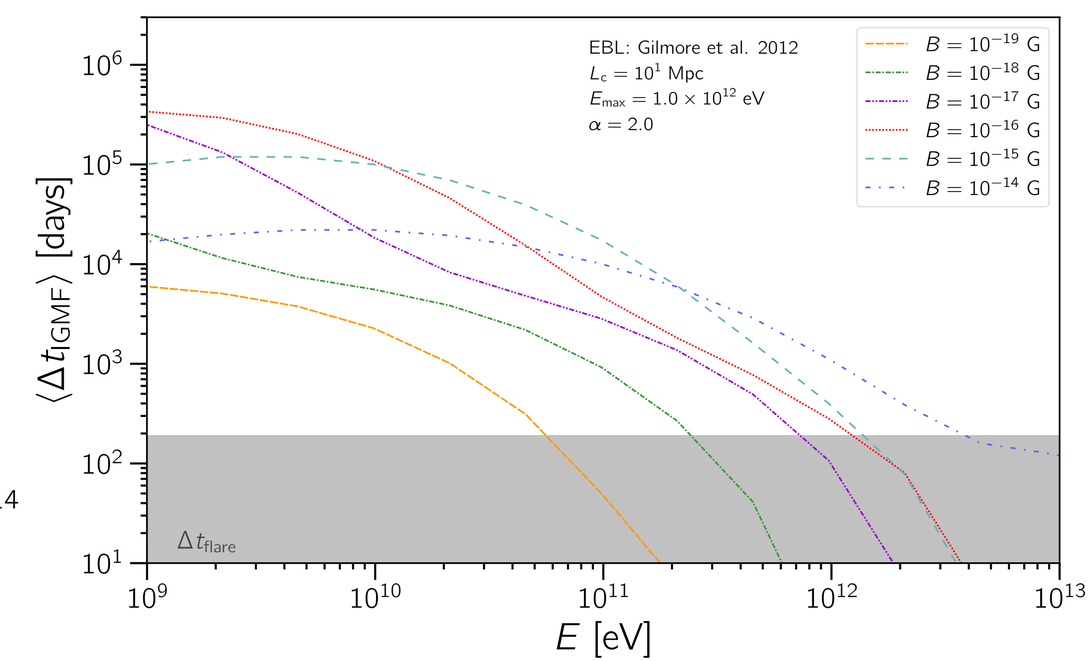
IGMFs and TXS 0506+056: fitting the data

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

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



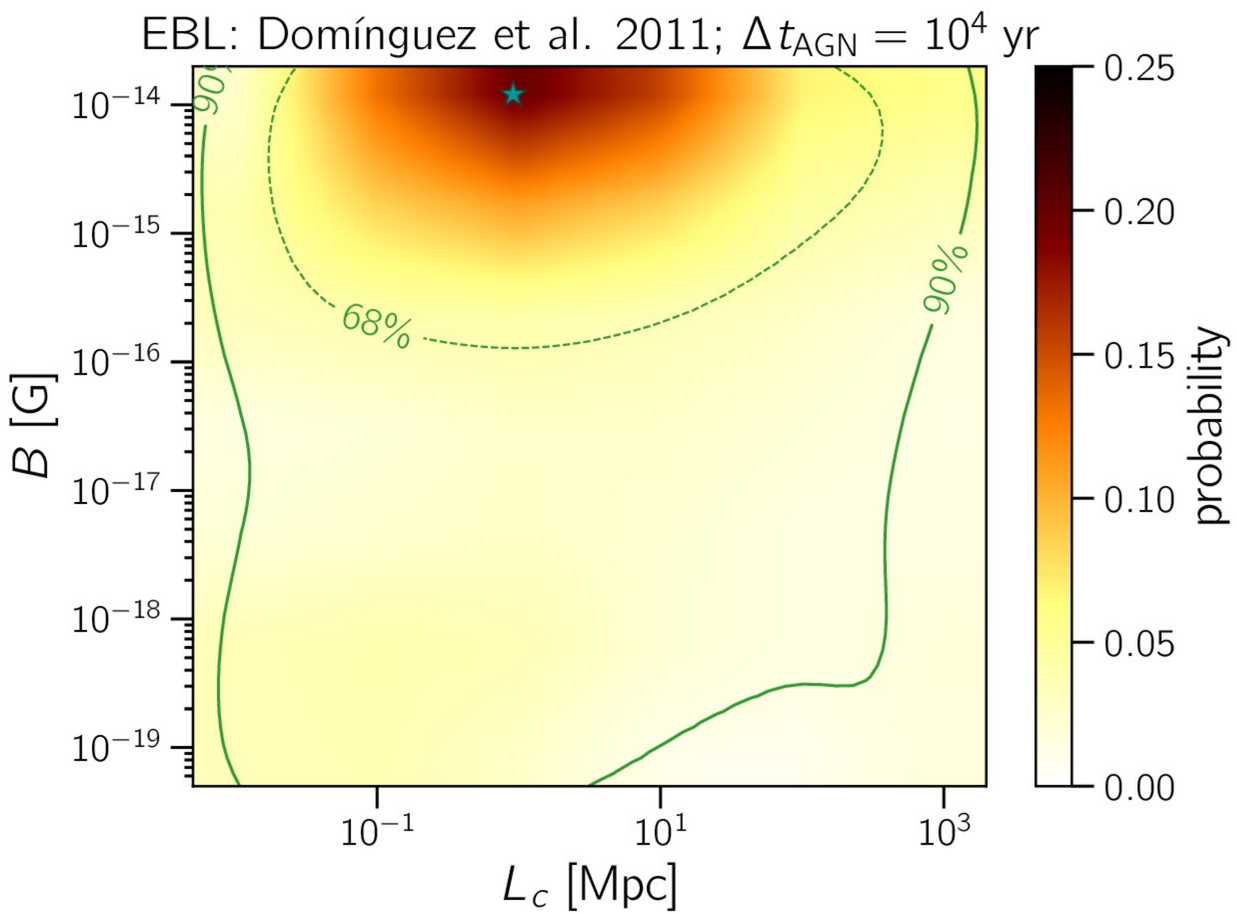


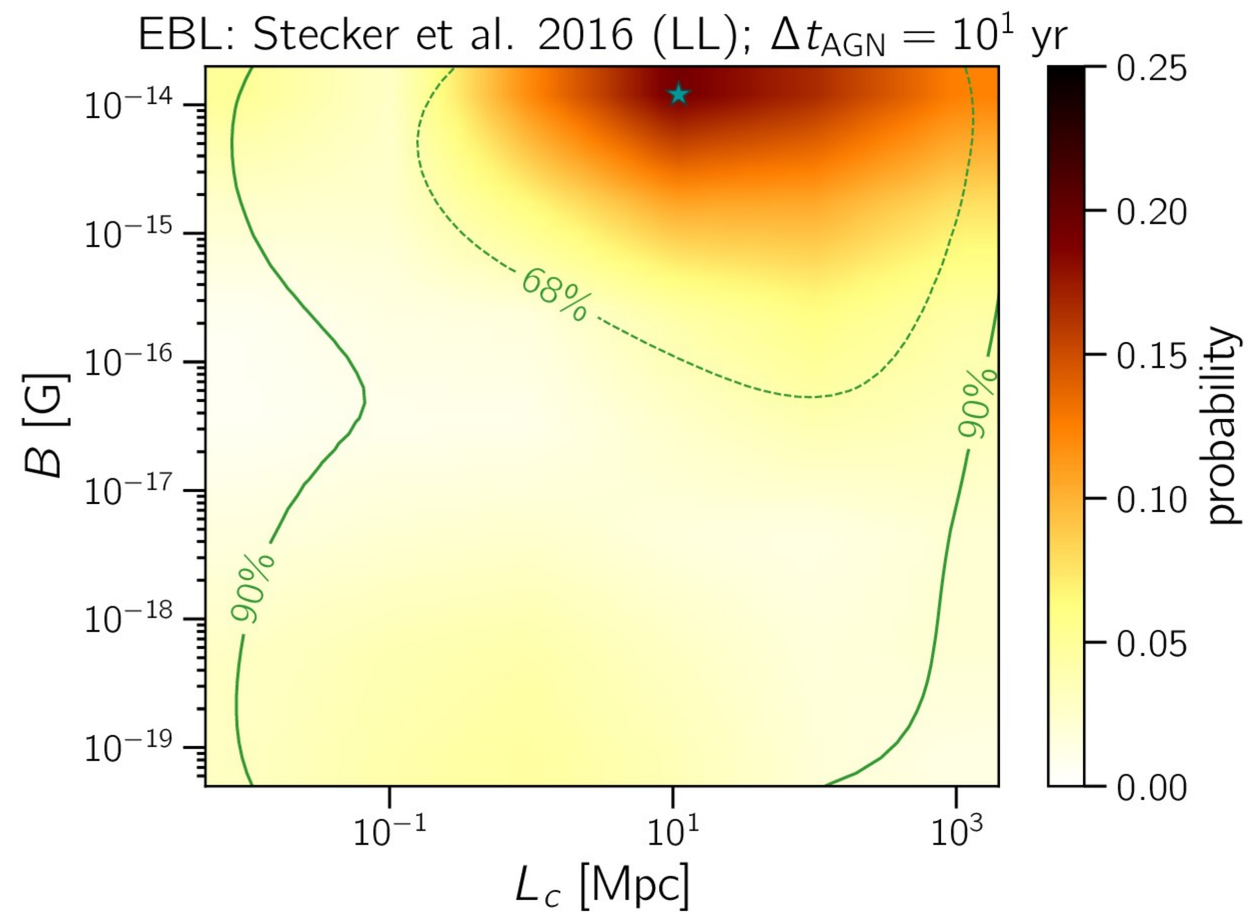


IGMFs and TXS 0506+056: fitting the data

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

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

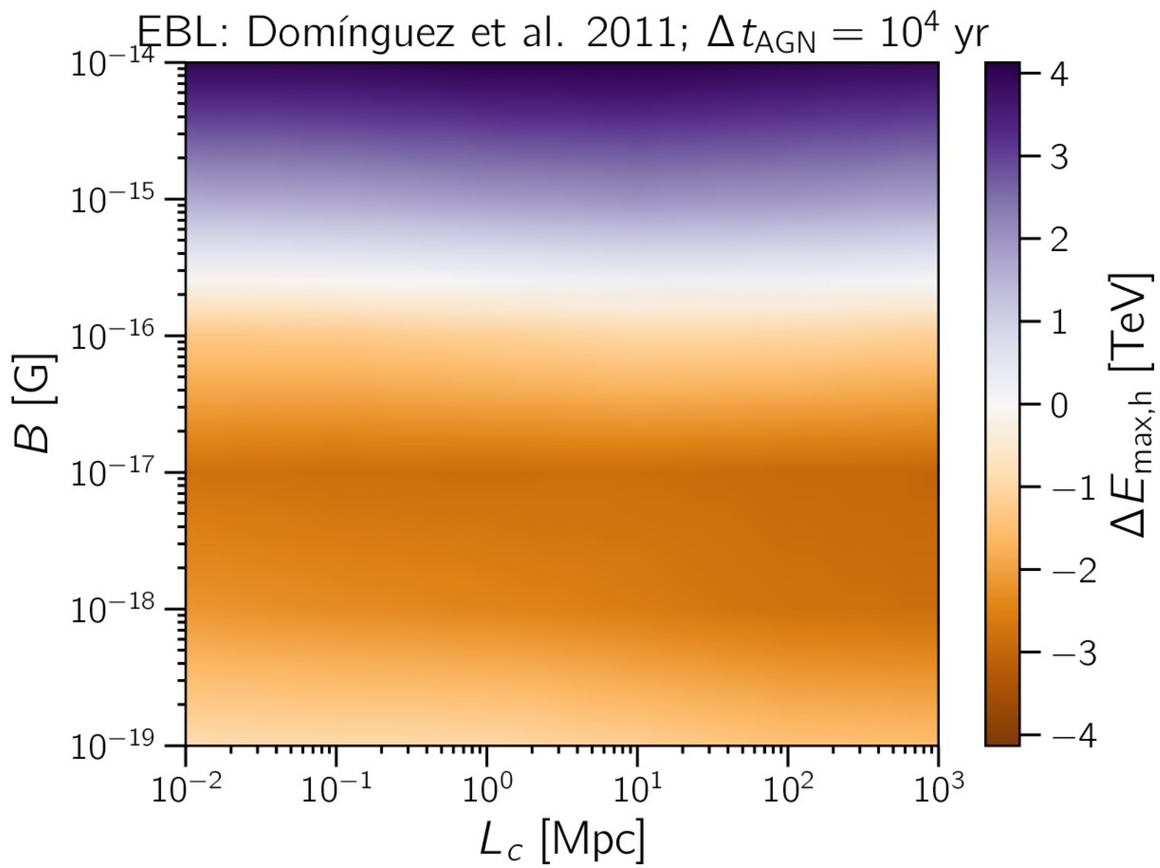


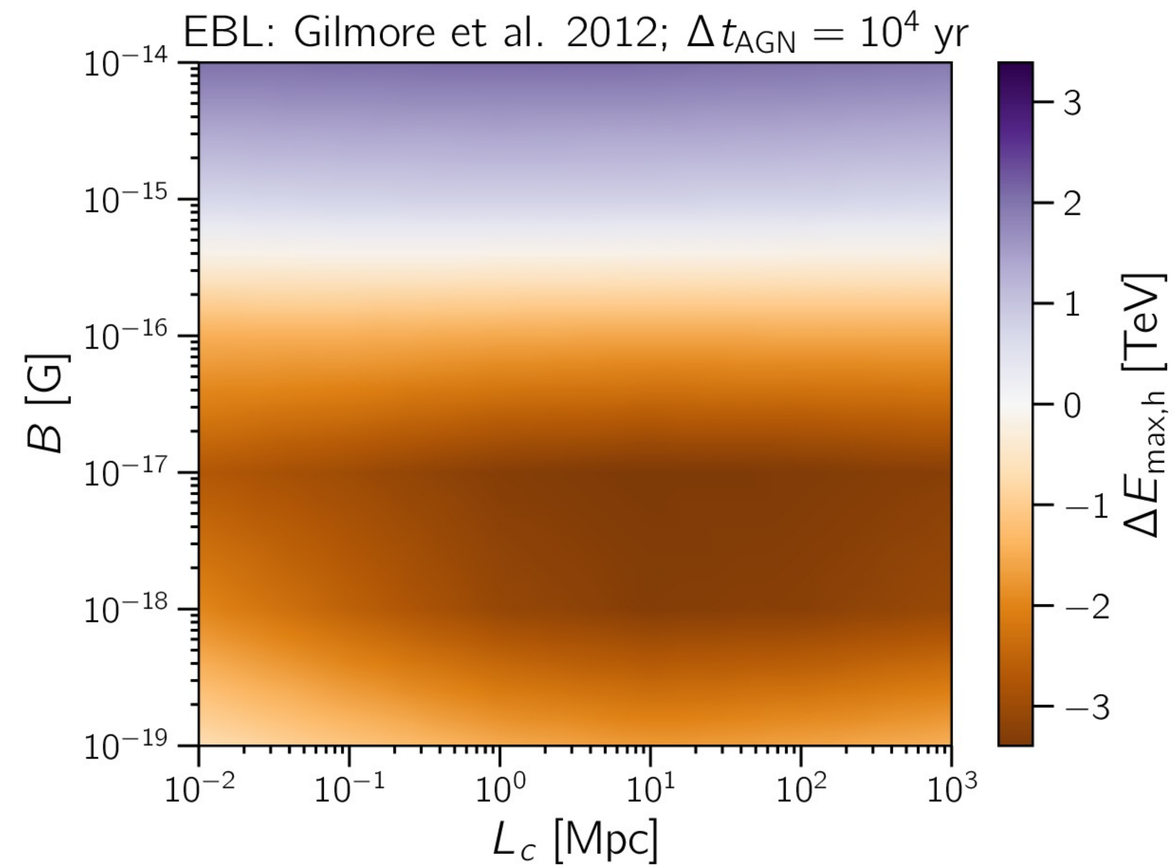


do IGMFs affect the reconstructed intrinsic gamma-ray spectrum?

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

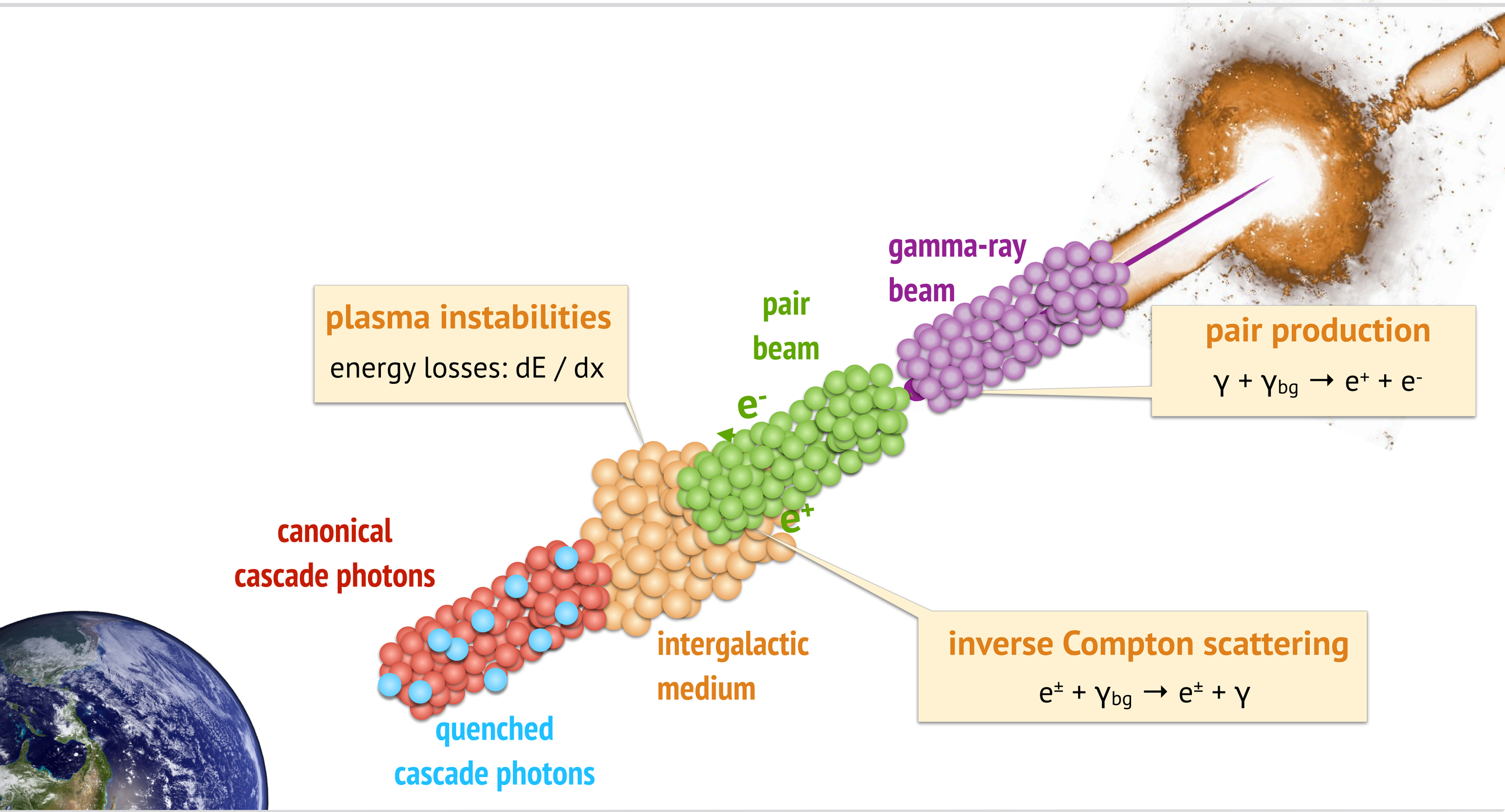
Saveliev, Alves Batista. MNRAS 500 (2021) 2188. arXiv:2009.09772





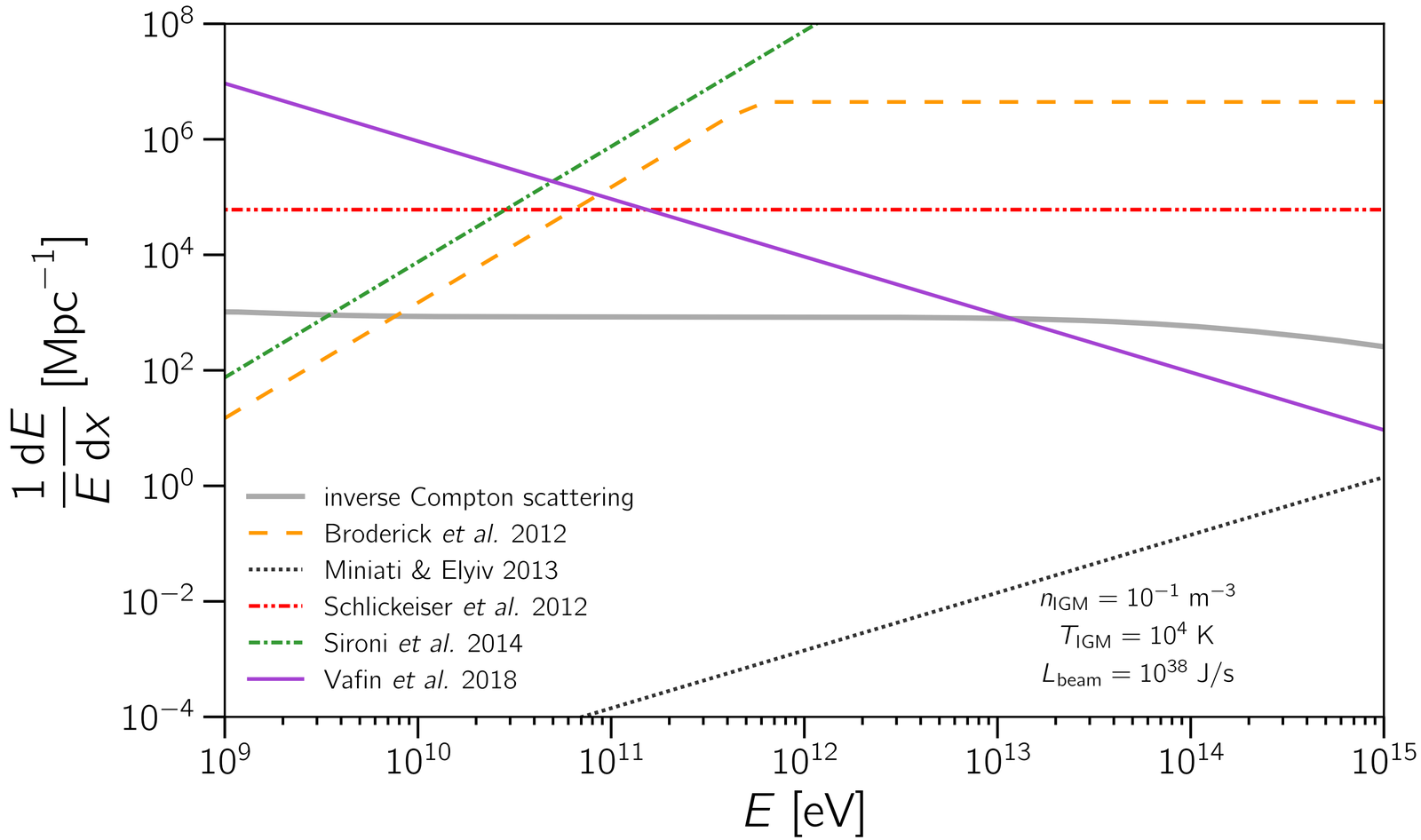
IGMF constraints and plasma instabilities

plasma instabilities: do they quench electromagnetic cascades?



plasma instabilities and electromagnetic cascades

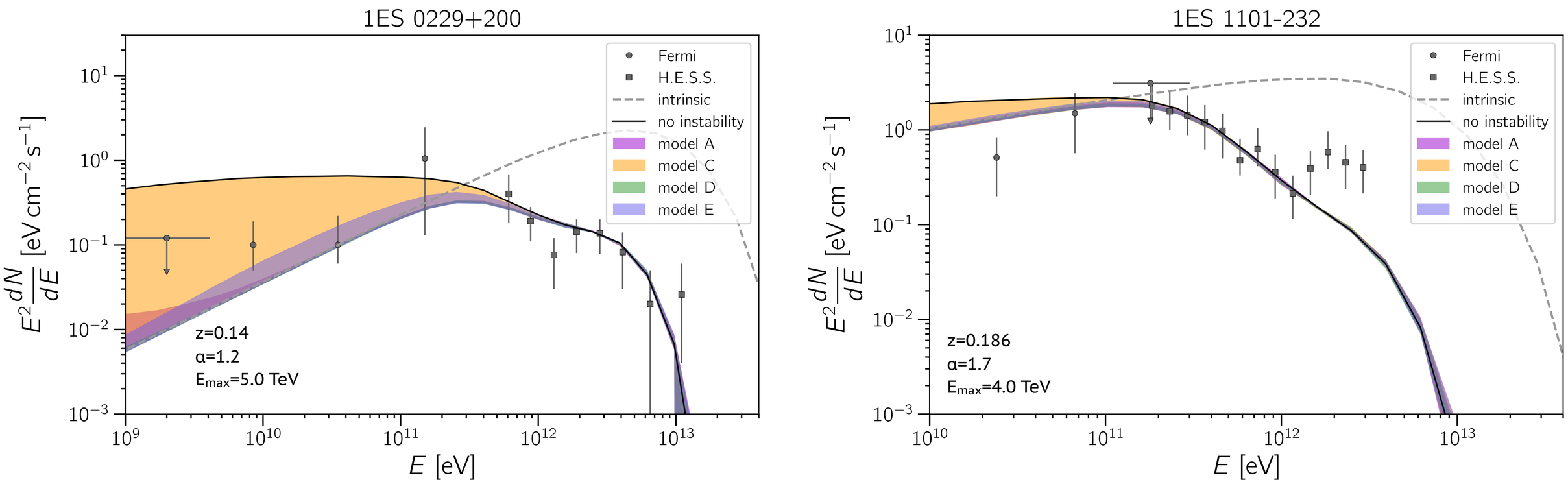
Alves Batista, Saveliev, de Gouveia Dal Pino. MNRAS 489 (2019) 3836. arXiv:1904.13345



- 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

plasma instabilities: effects on the spectrum of TeV blazars

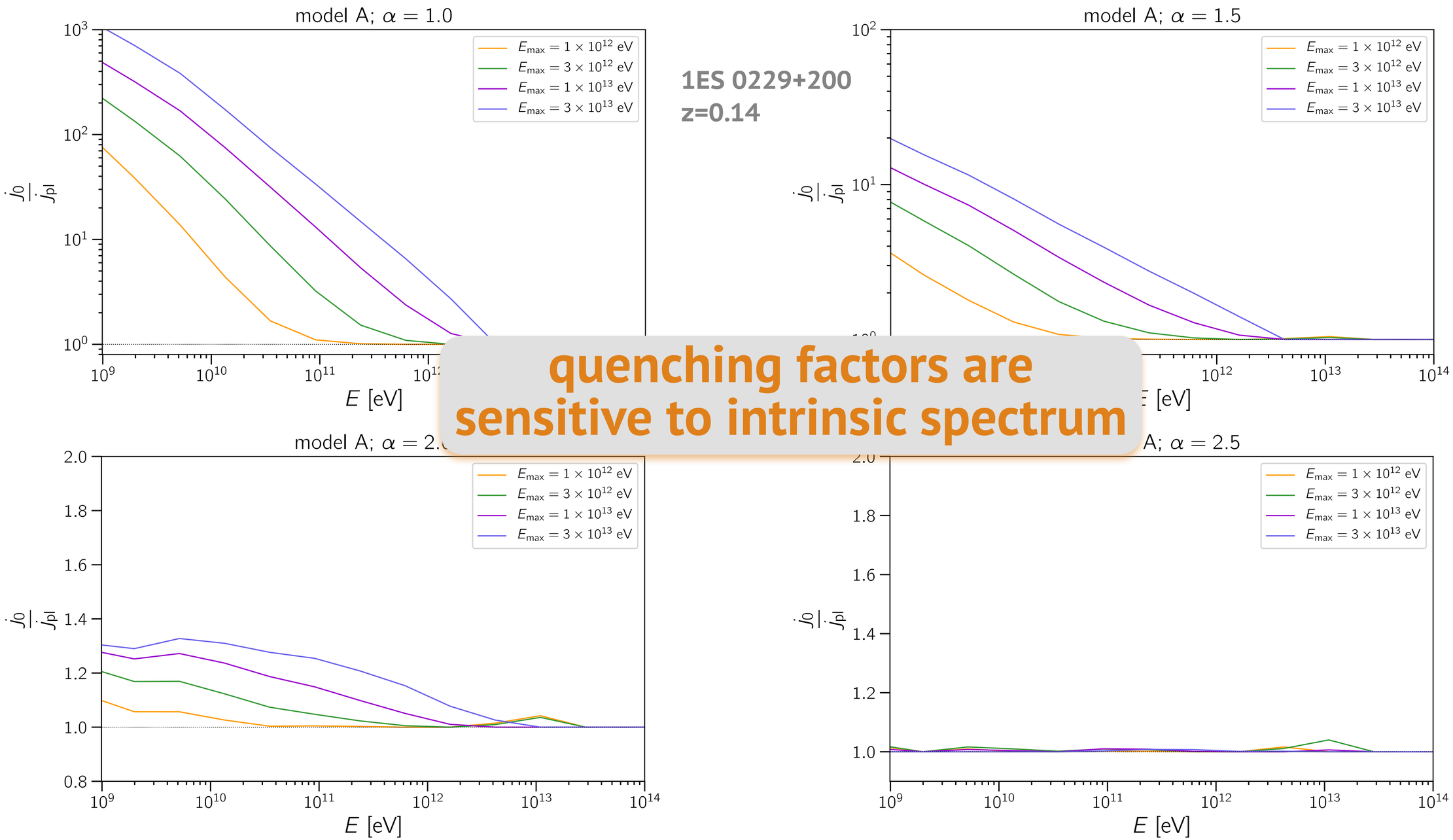
Alves Batista, Saveliev, de Gouveia Dal Pino. MNRAS 489 (2019) 3836. arXiv:1904.13345



bands encompass: luminosity, IGM density

plasma instabilities: quenching factors

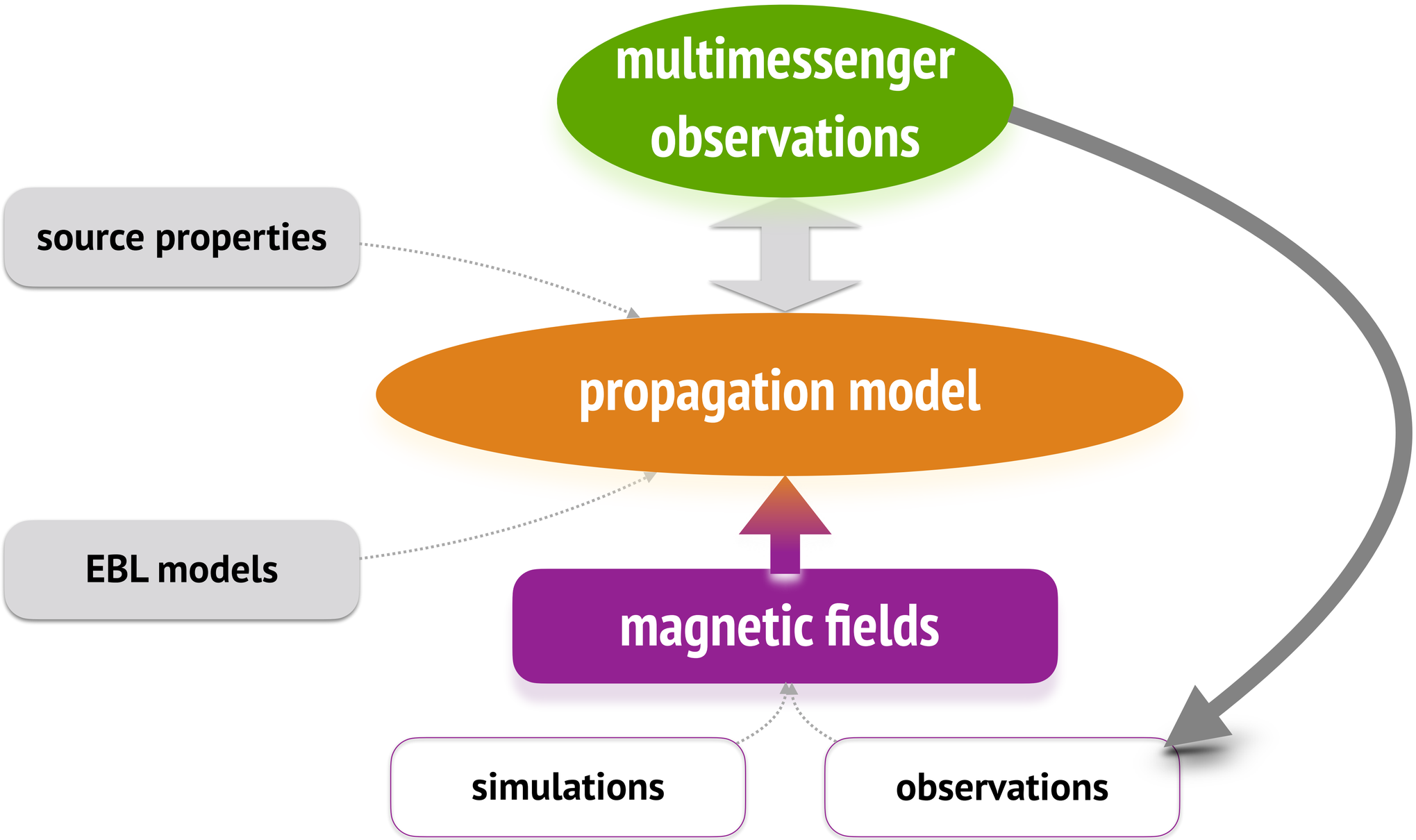
Alves Batista, Saveliev, de Gouveia Dal Pino. MNRAS 489 (2019) 3836. arXiv:1904.13345



quenching factors are sensitive to intrinsic spectrum

conclusions & outlook

multimessenger constraints on IGMFs: *quo vadis*?



conclusions & outlook

- there are many constraints on IGMFs, but results are not completely conclusive
- most works suggest B is in the range ~ 10^{-17} - 10^{-14} G
- first ever constraints on the coherence length rather weak, between ~30 kpc and 300 Mpc
- magnetic power spectrum affect gamma-ray propagation → constraints on magnetogenesis
- helical fields have unique signatures in gamma rays: spiral-like patterns → topological properties of IGMFs can be probed with VHE gamma rays
- the impact of plasma instabilities on the spectra of blazars seems small
- combined with Fermi, CTA may provide the best constraints on IGMFs via simultaneous GeV-TeV observations and improve the constraints on the parameter space of B-L_B

thank you 😊