cosmic magnetism through the lens of gamma rays

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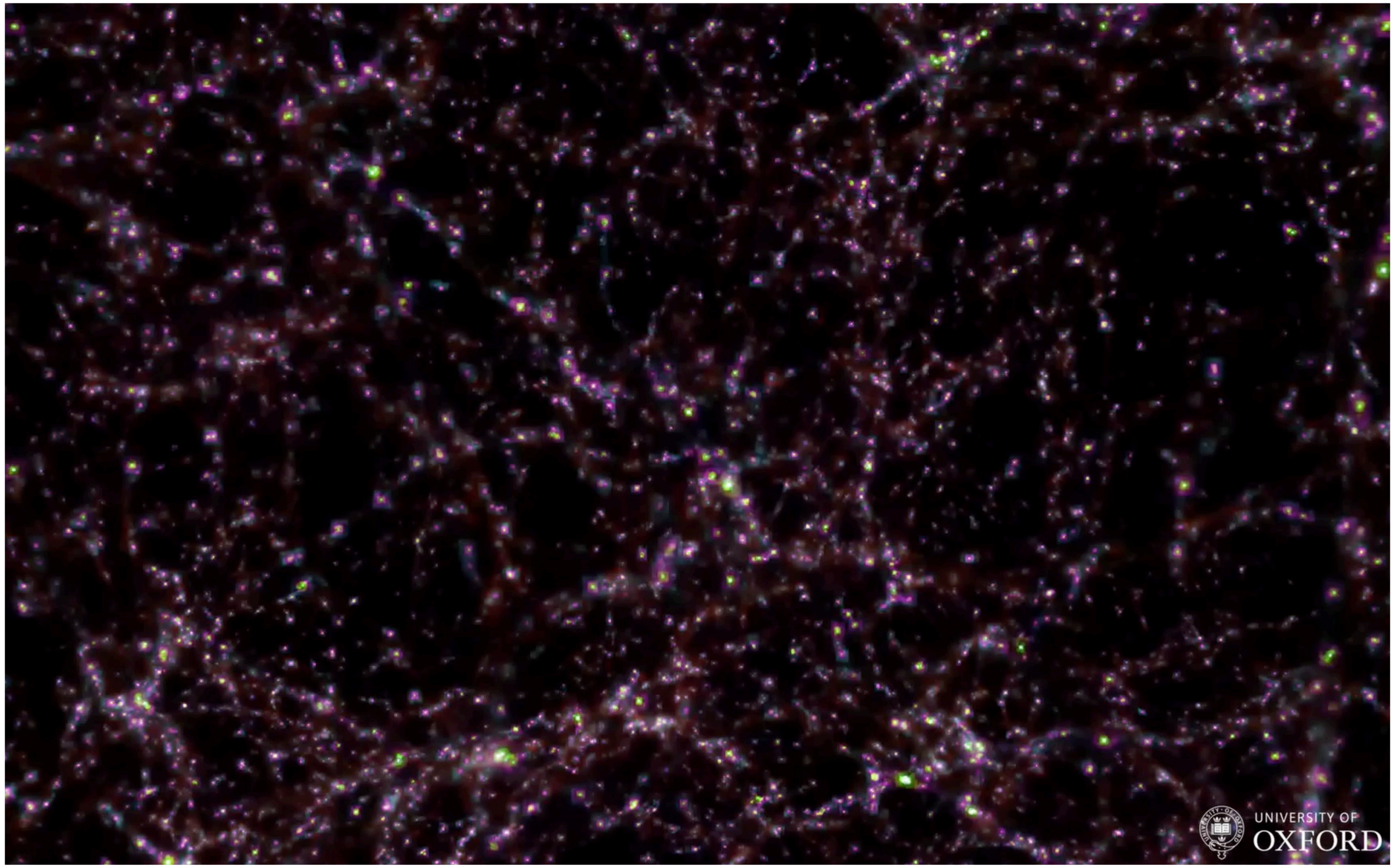
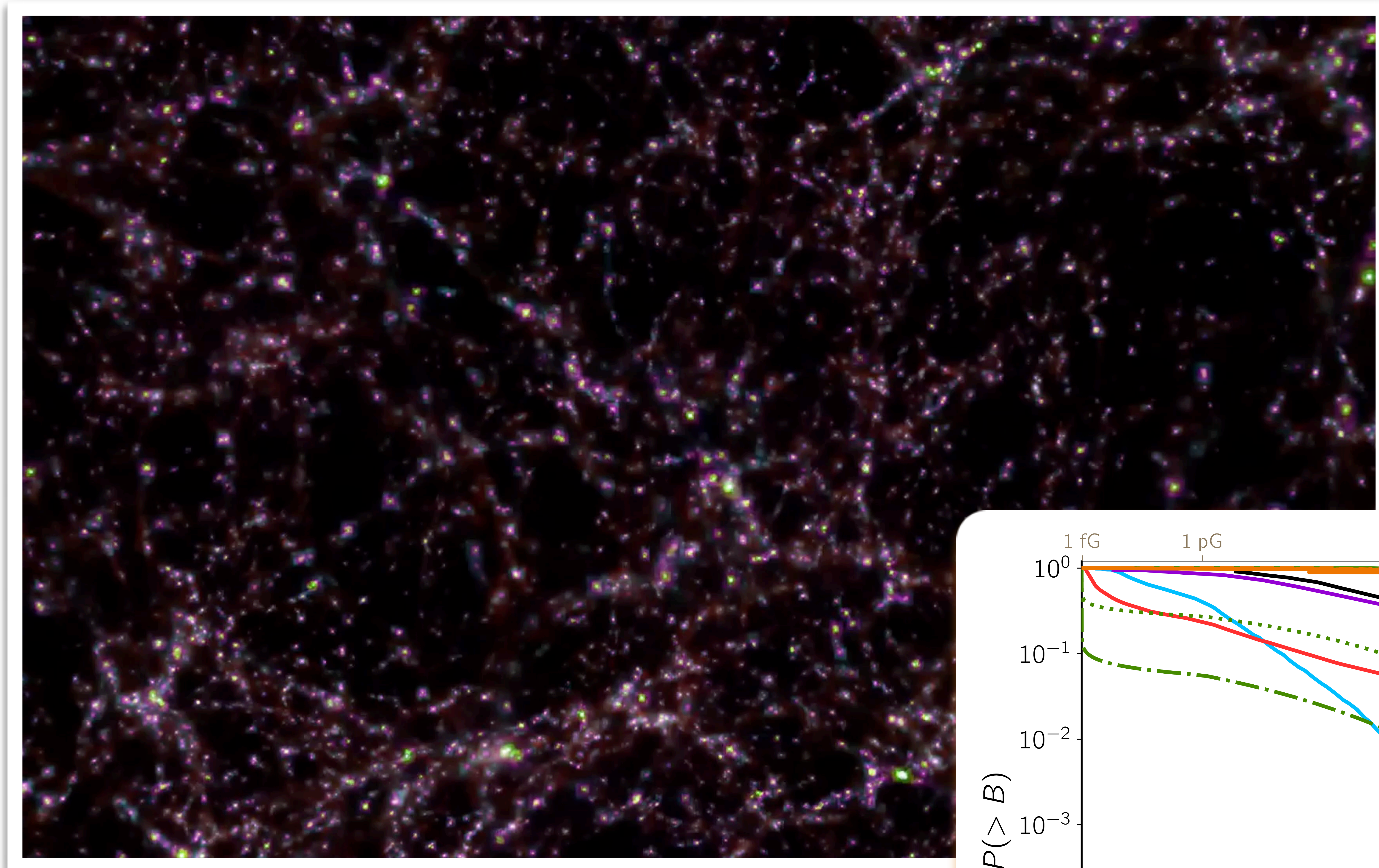
Cosmic Magnetism in Voids and Filaments
24 January 2023
Bologna

cosmic magnetic fields



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

cosmic magnetic fields



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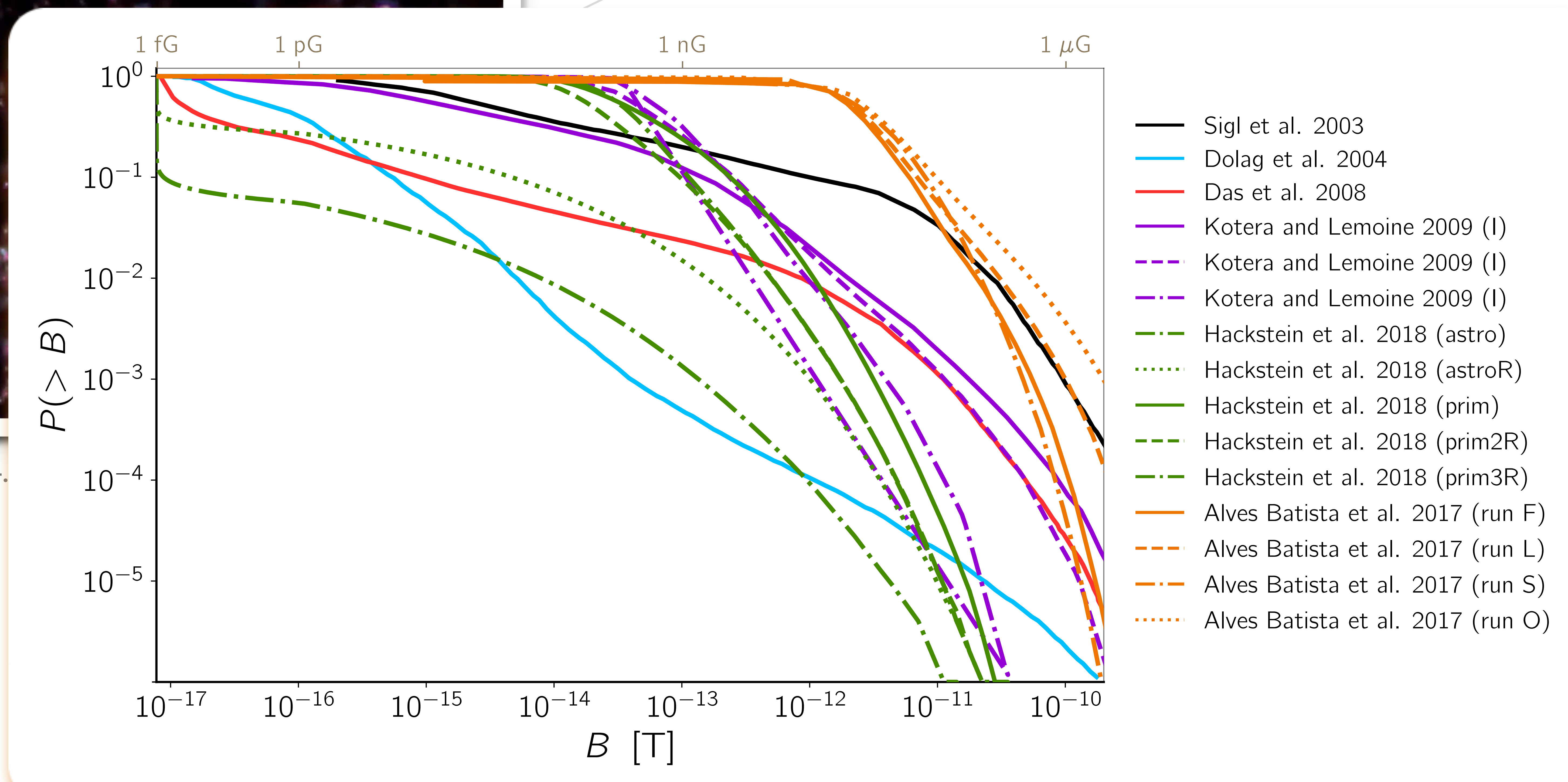

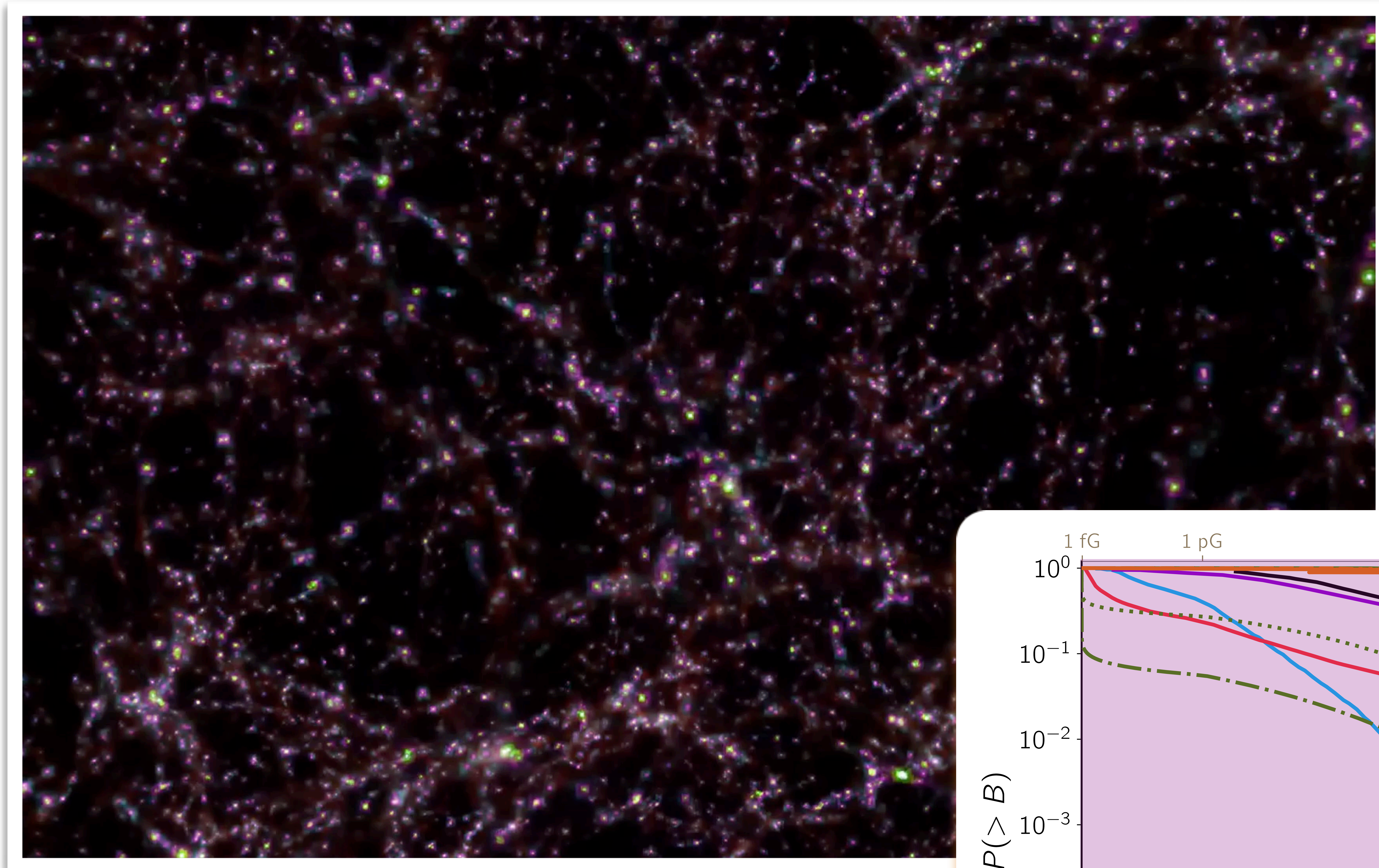

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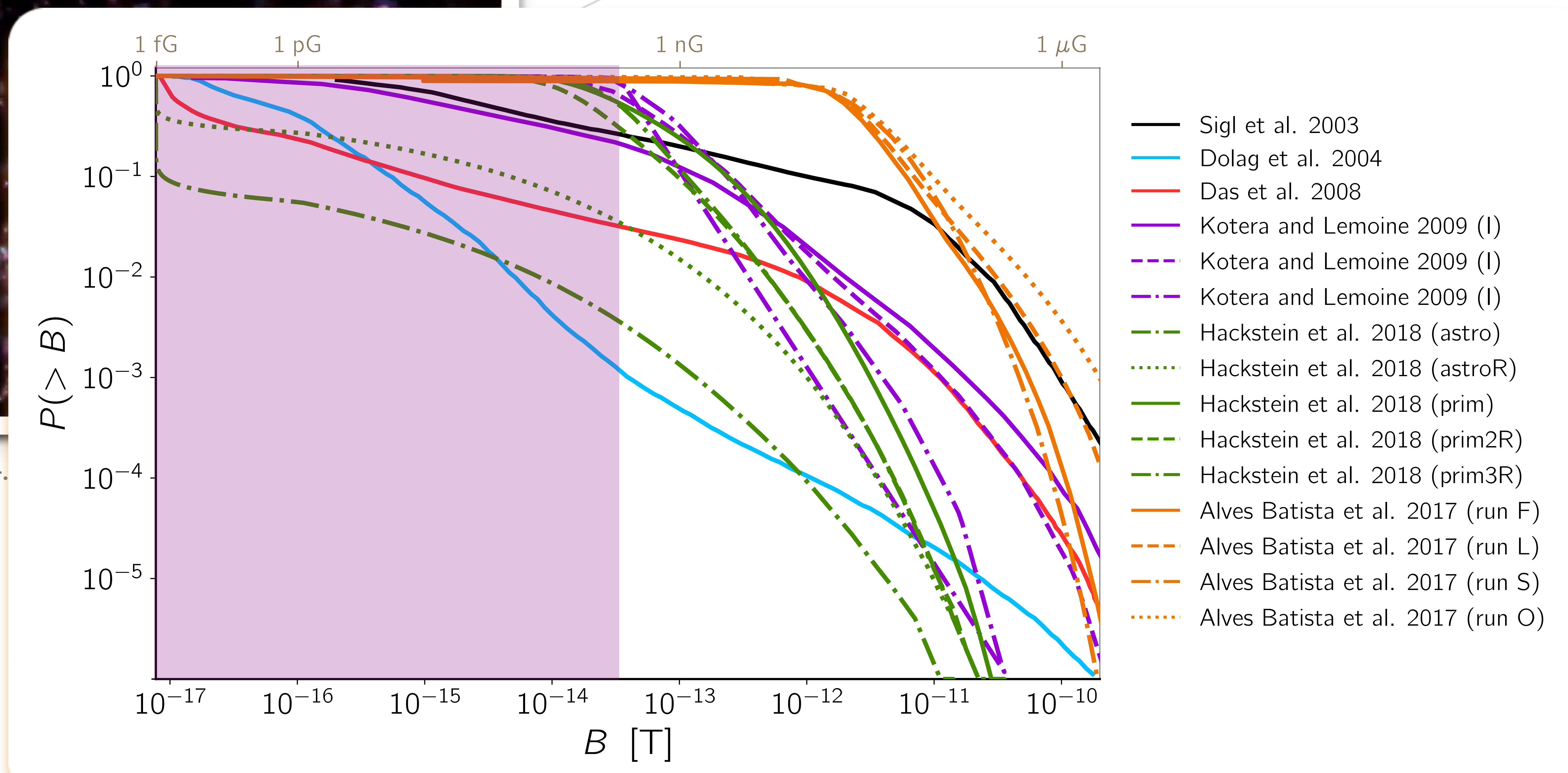

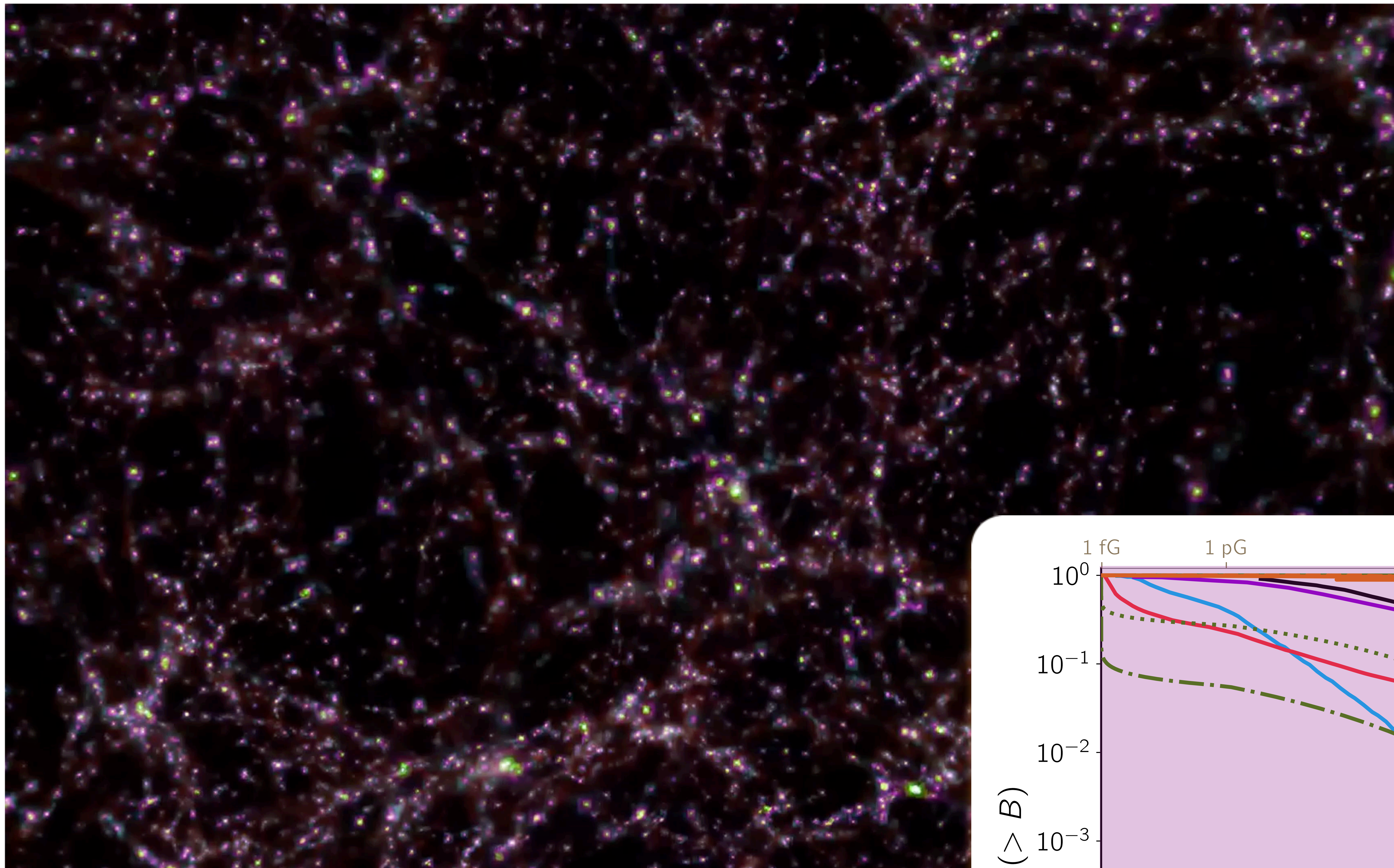

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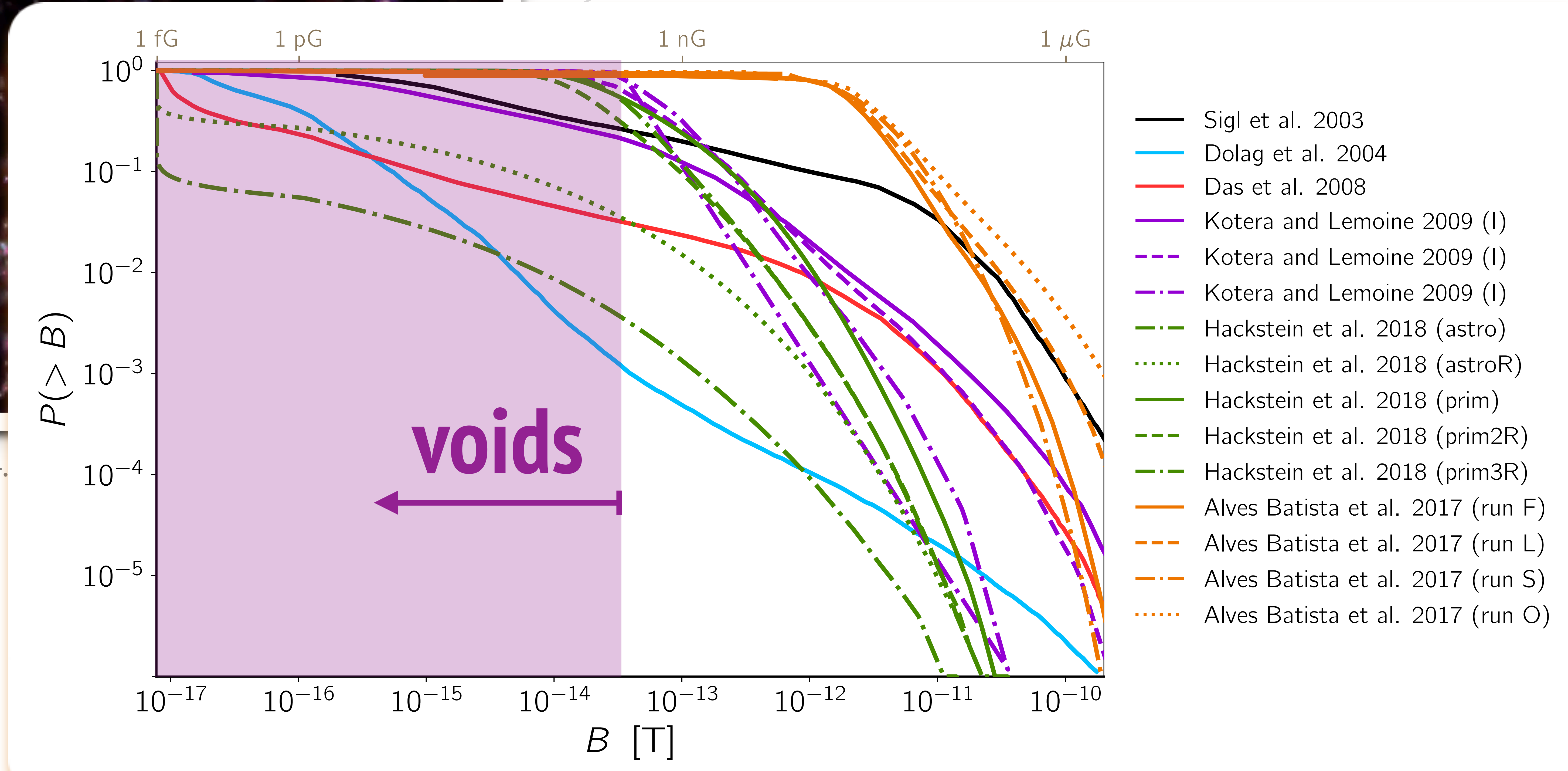

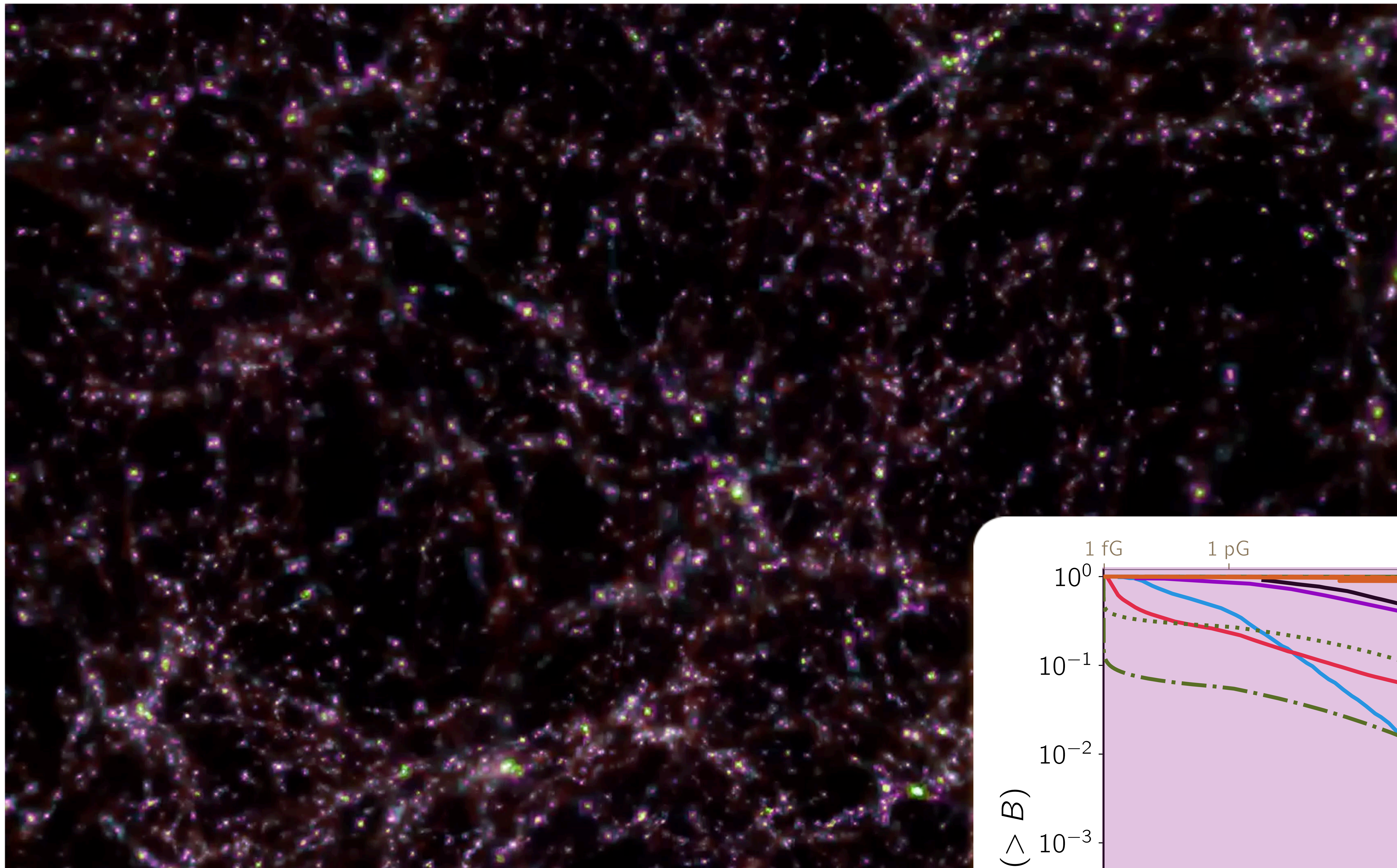

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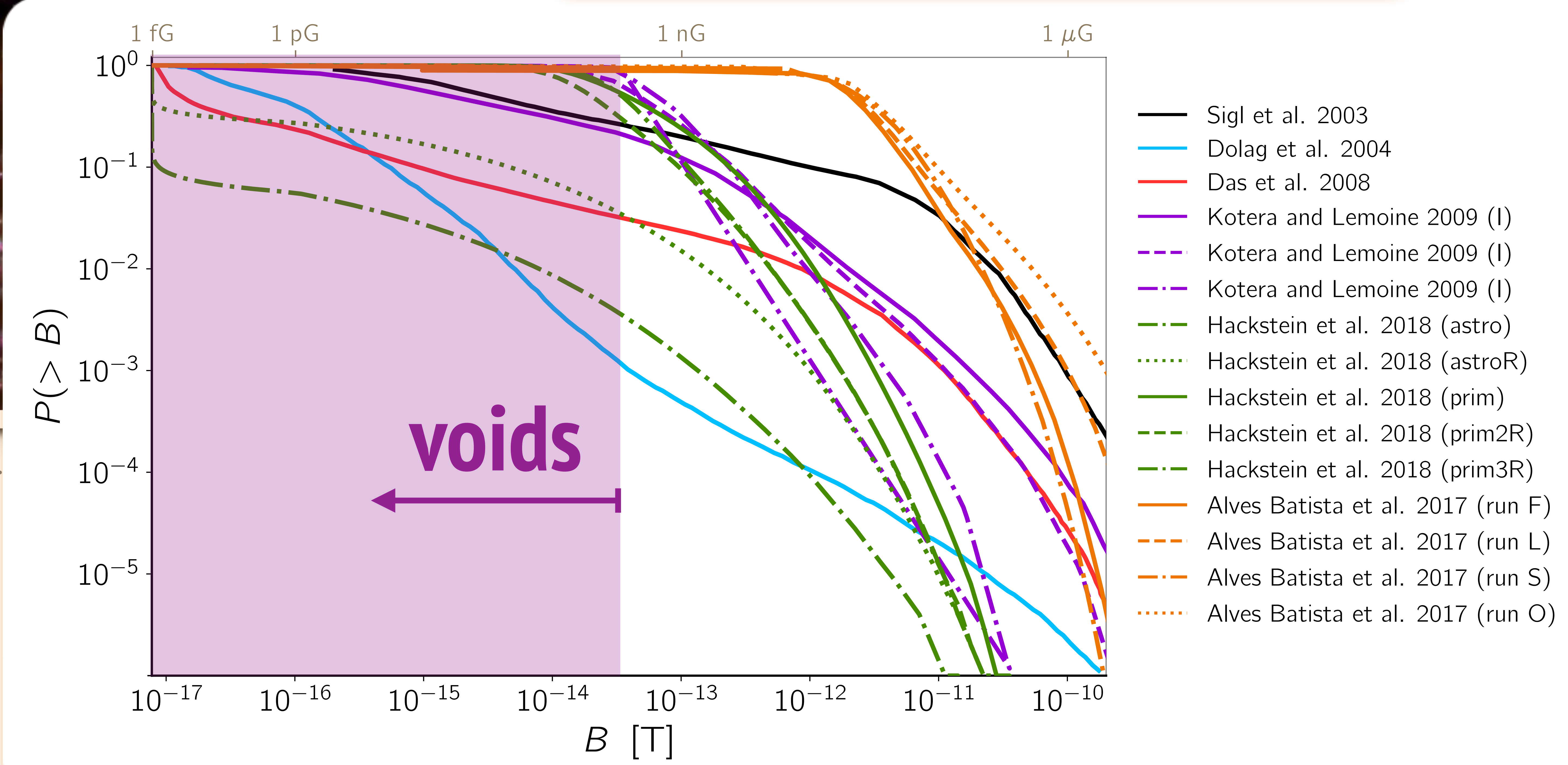
contribution of voids dominate over cosmological distances



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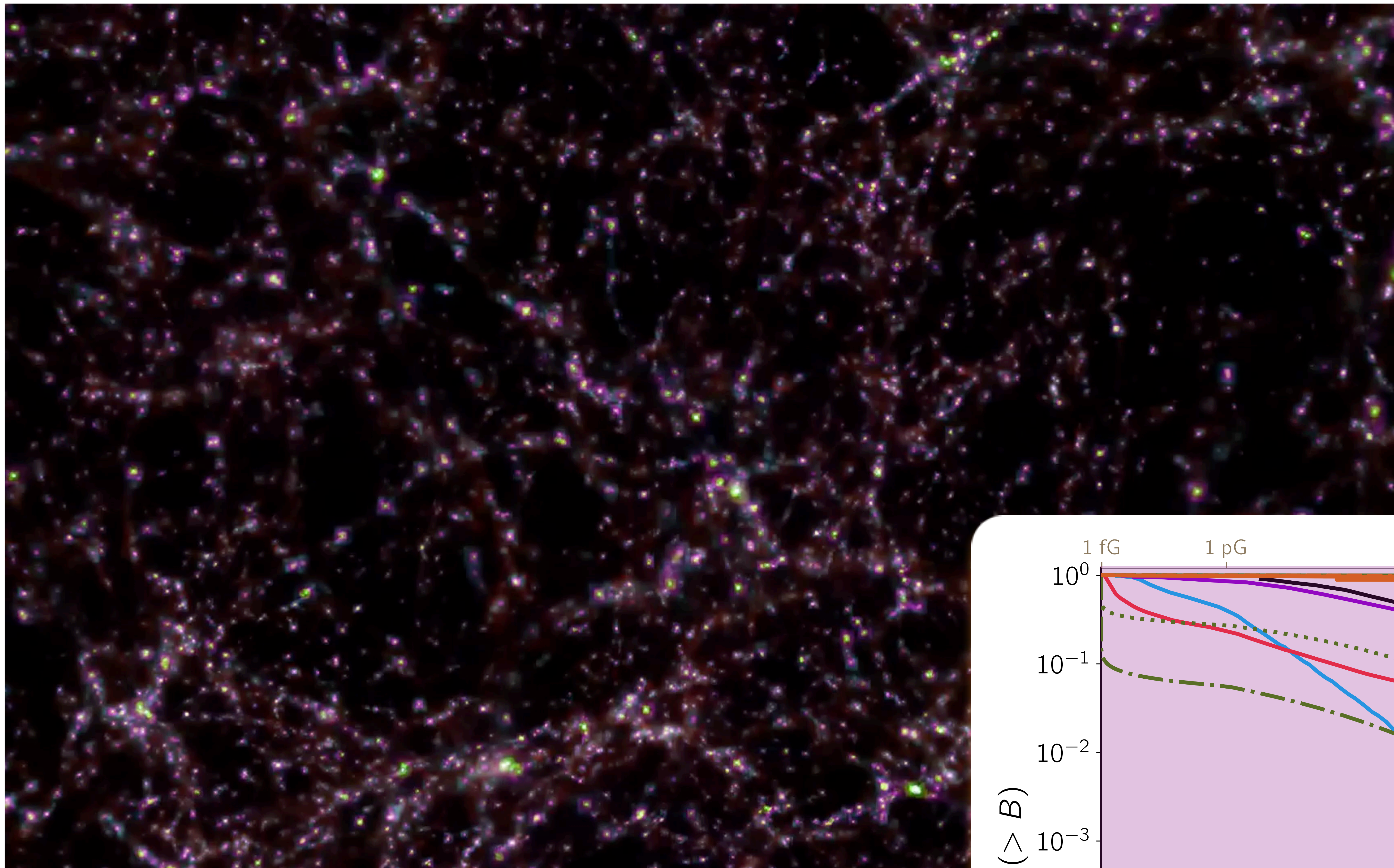

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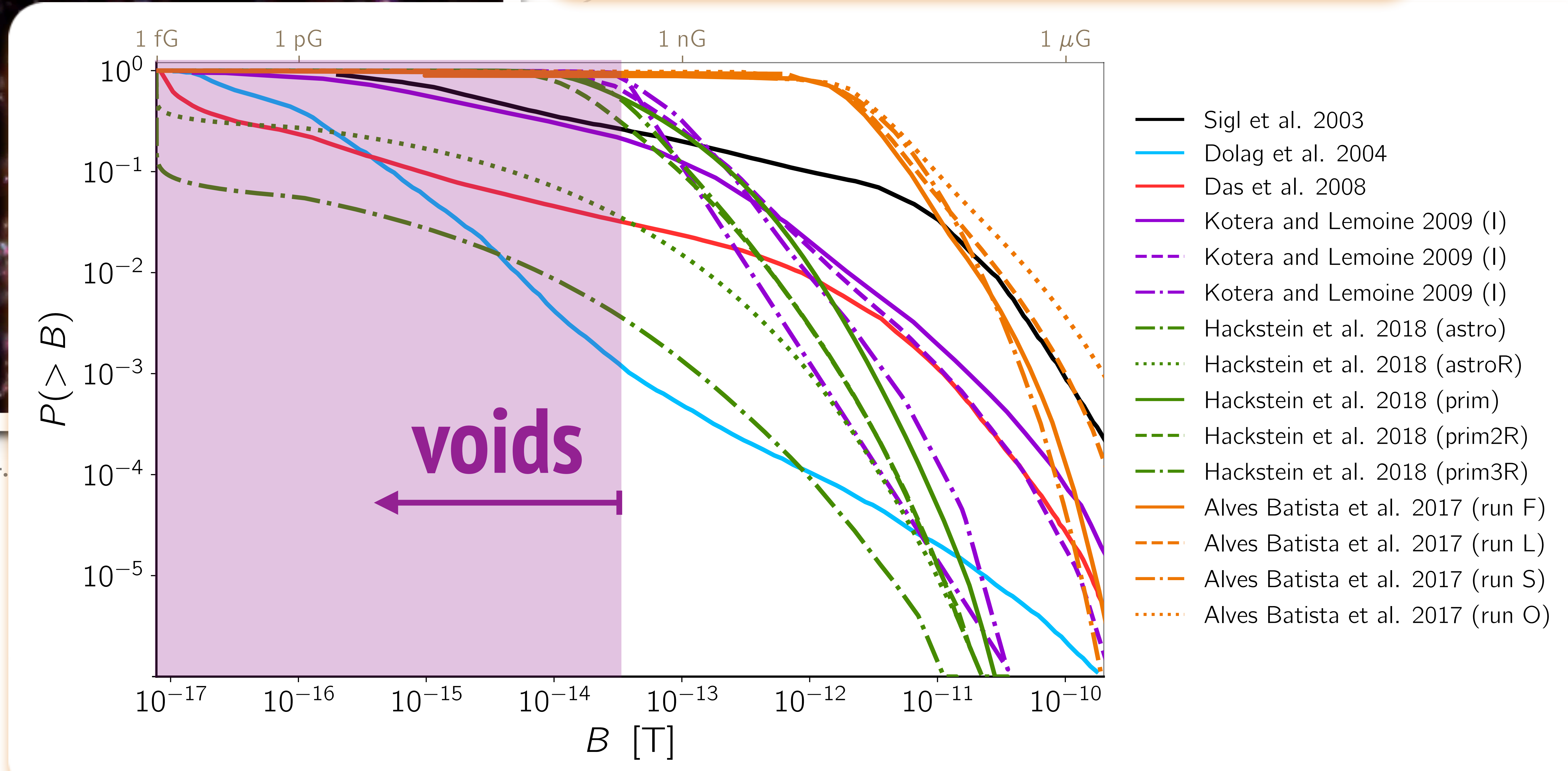
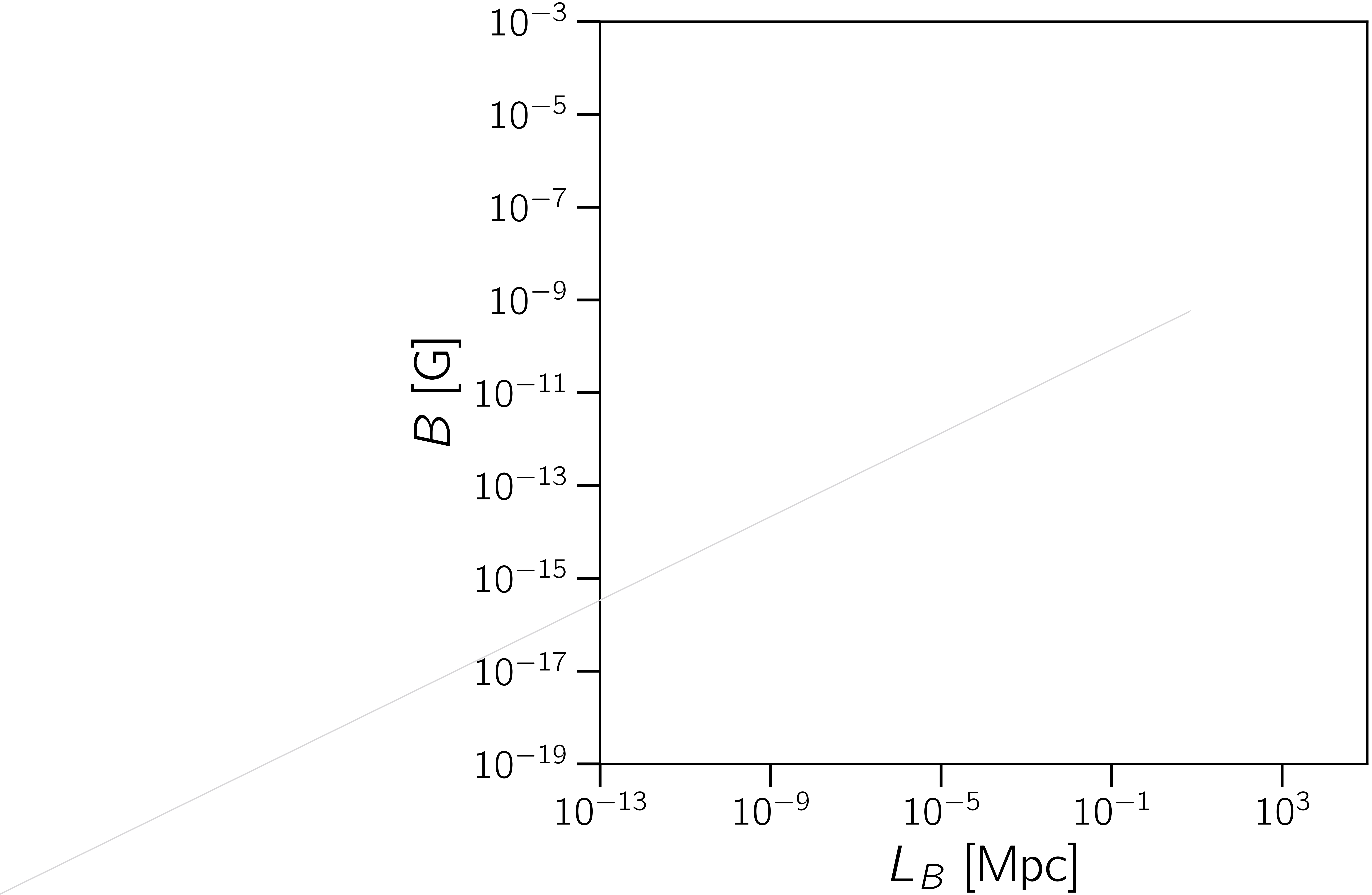
magnetic fields in voids are the most uncertain

contribution of voids dominate over cosmological distances



propagation ingredients: cosmic magnetic fields

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



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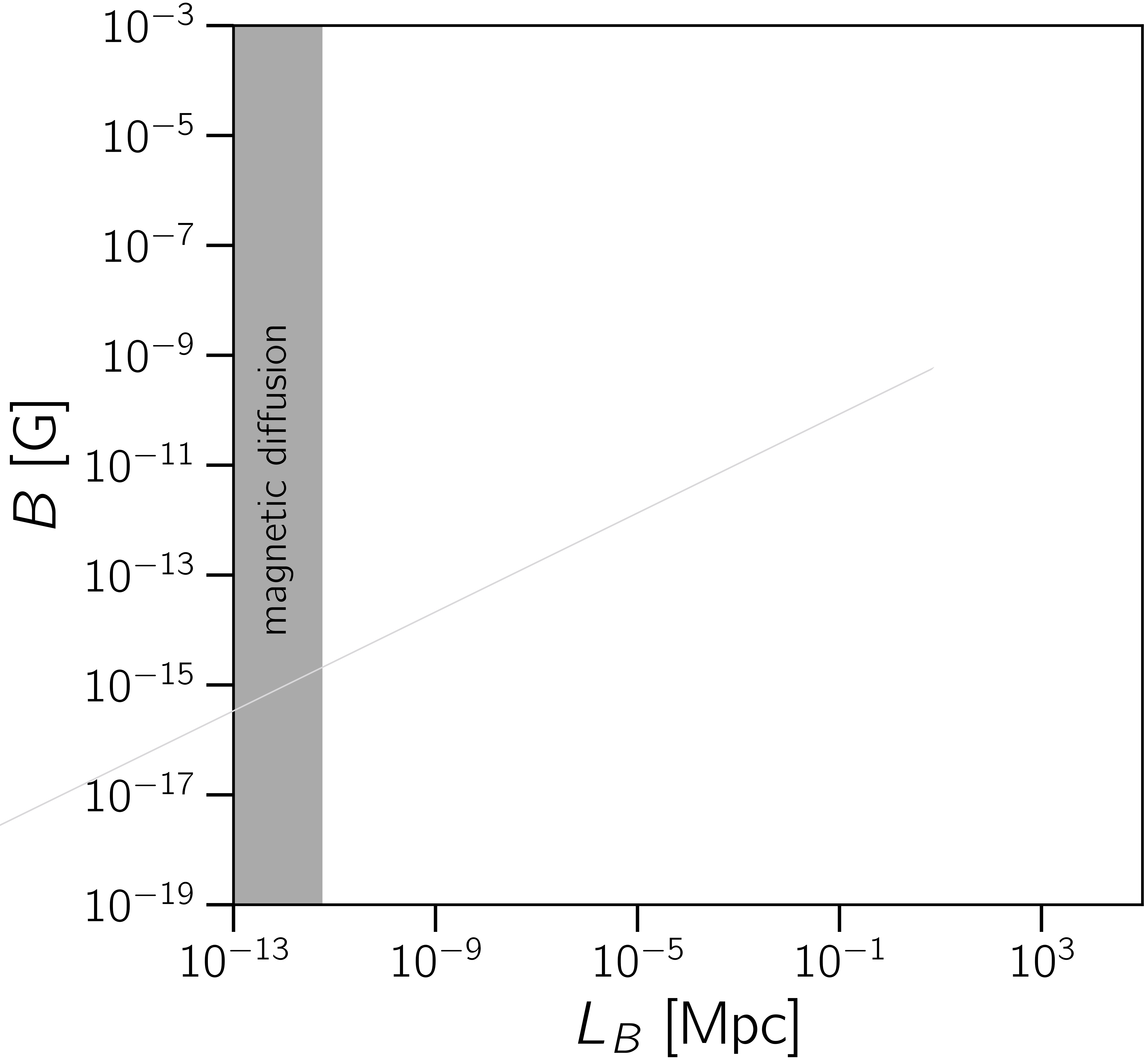

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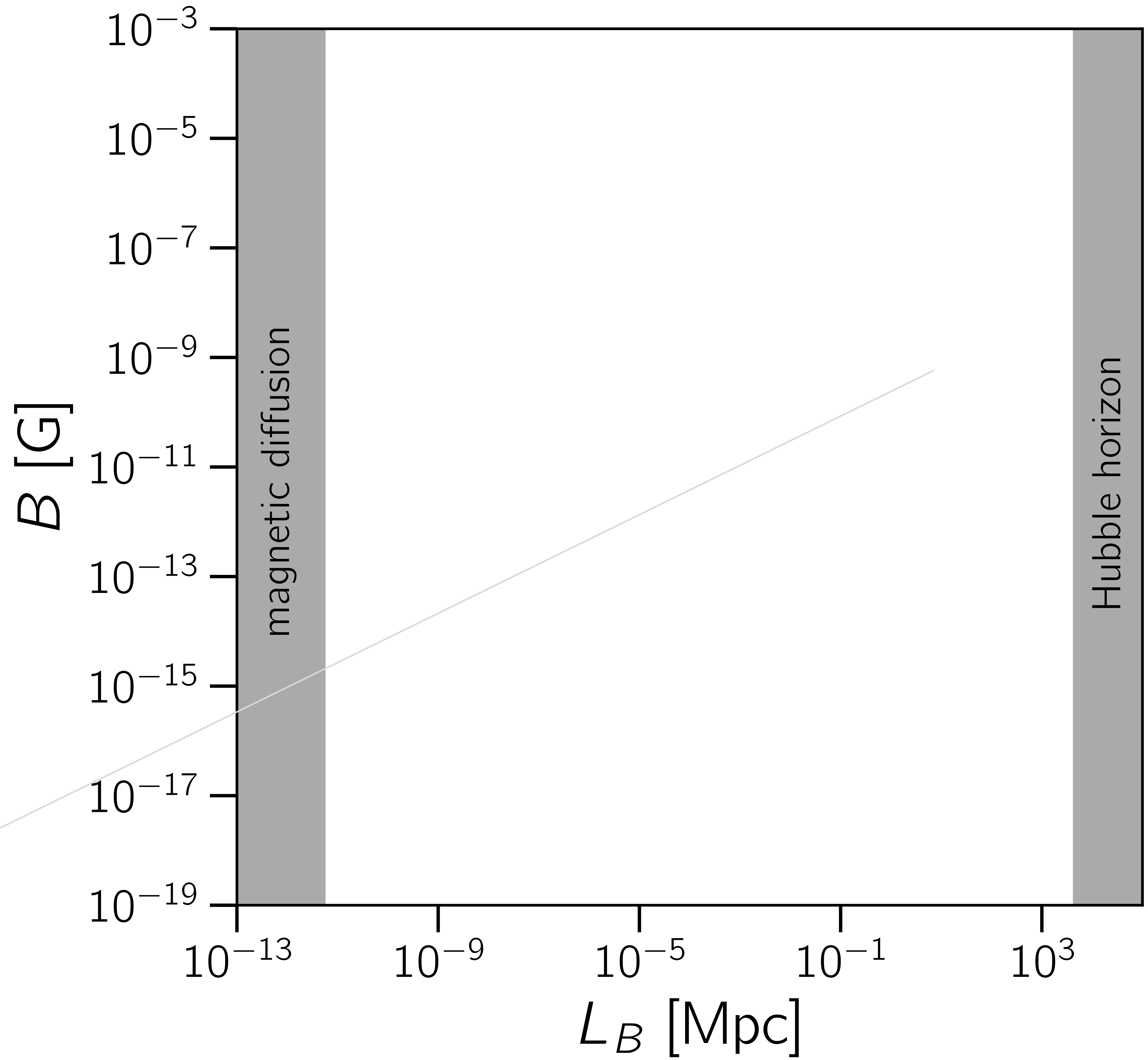

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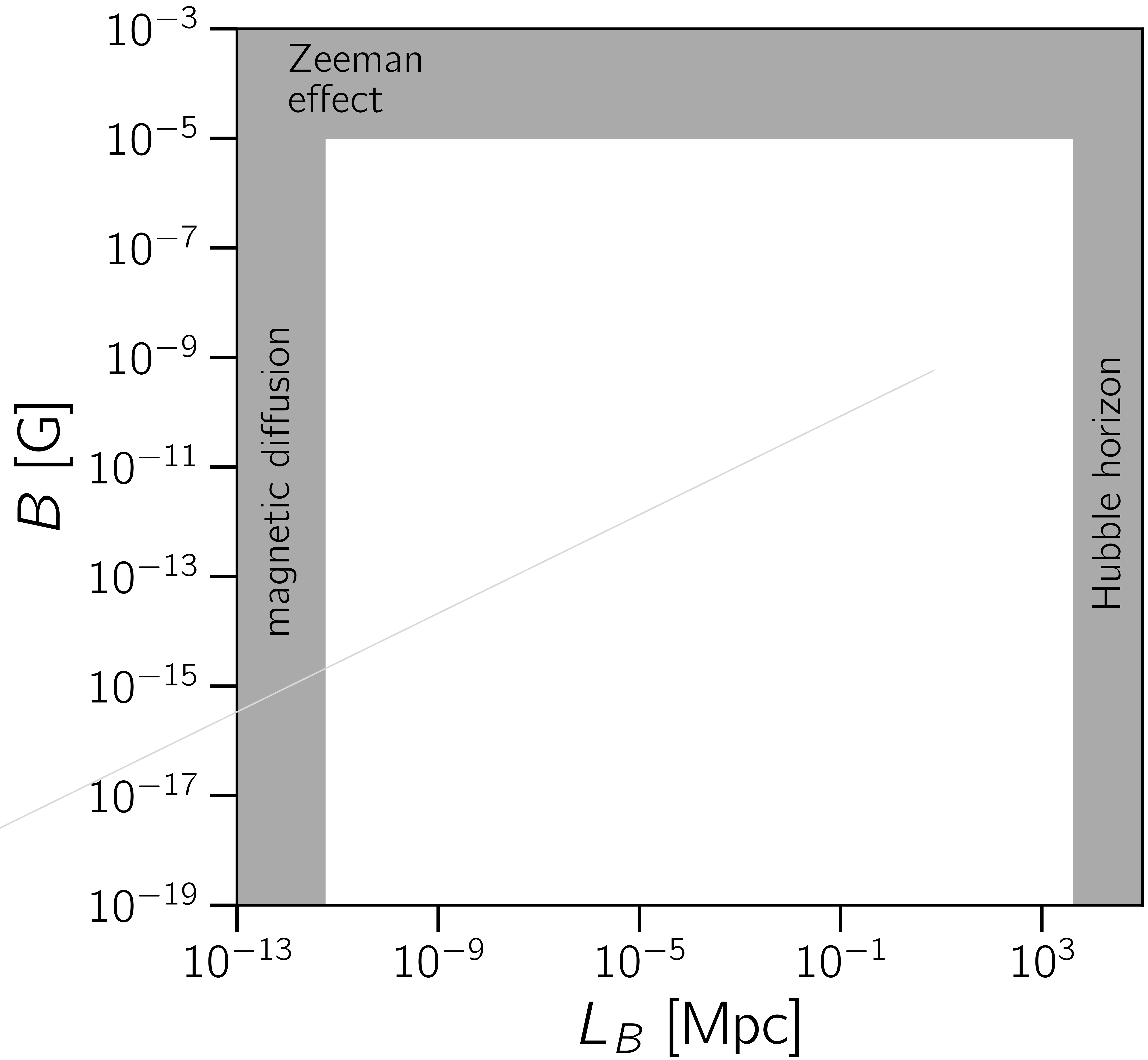

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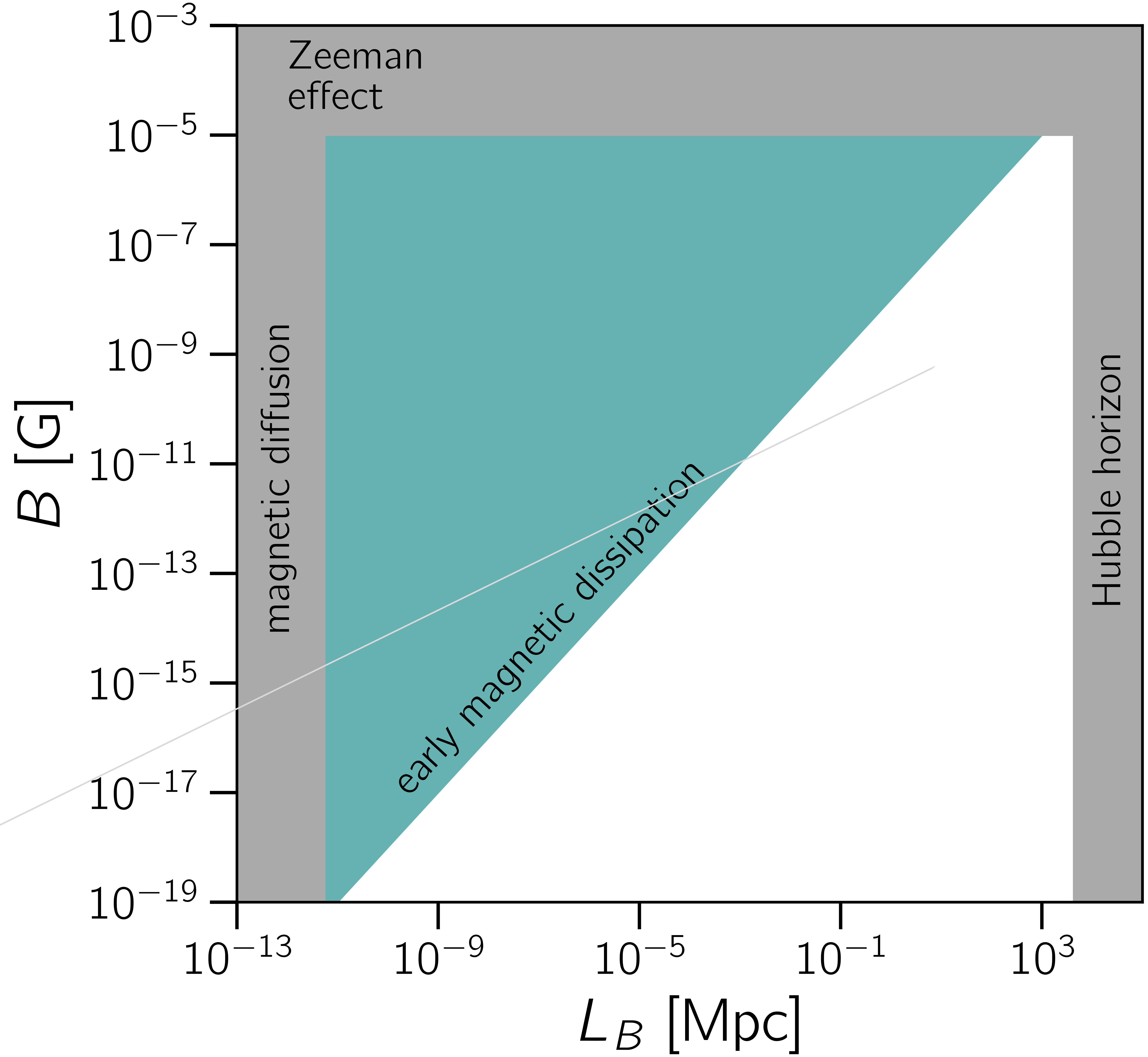

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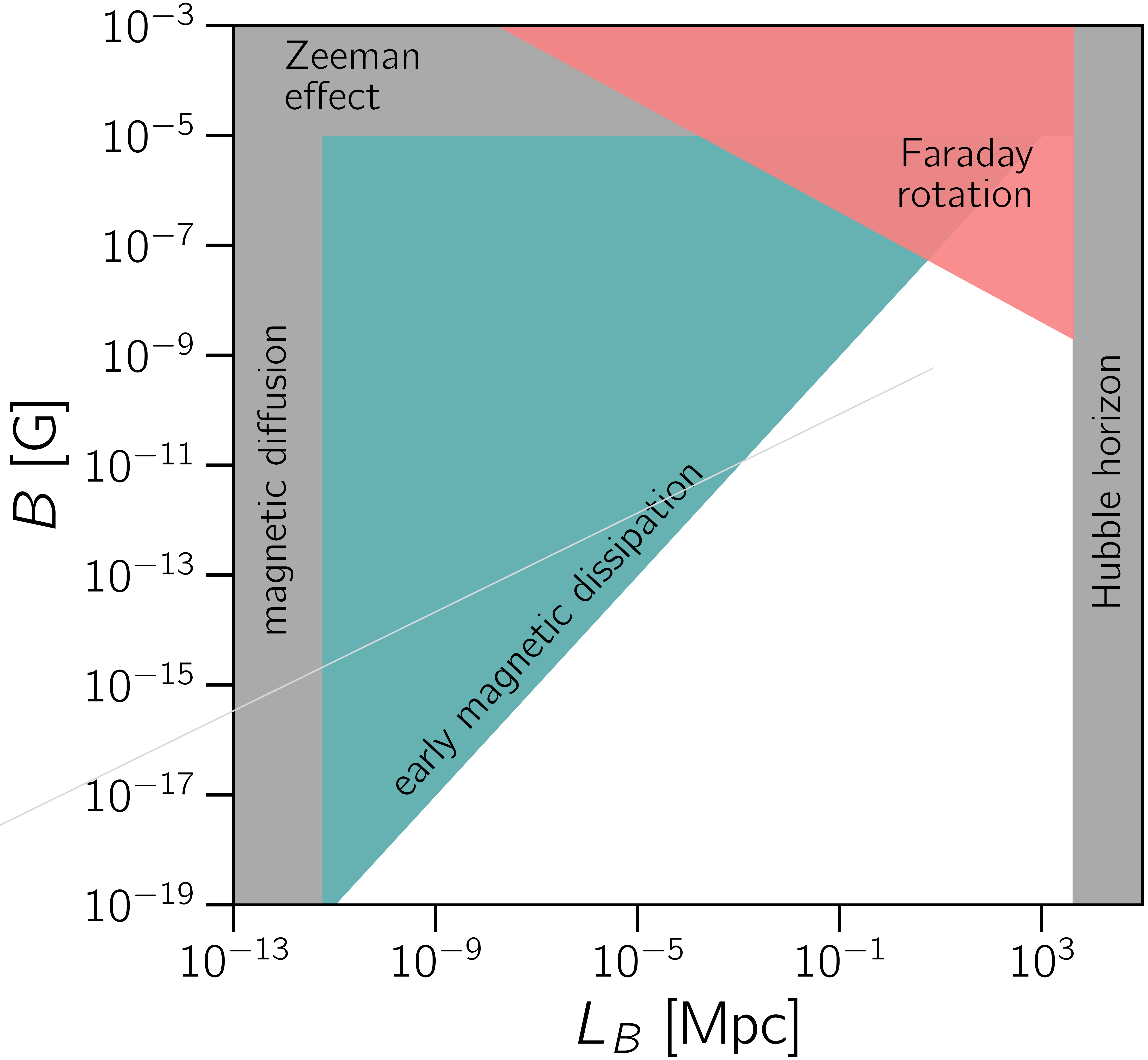

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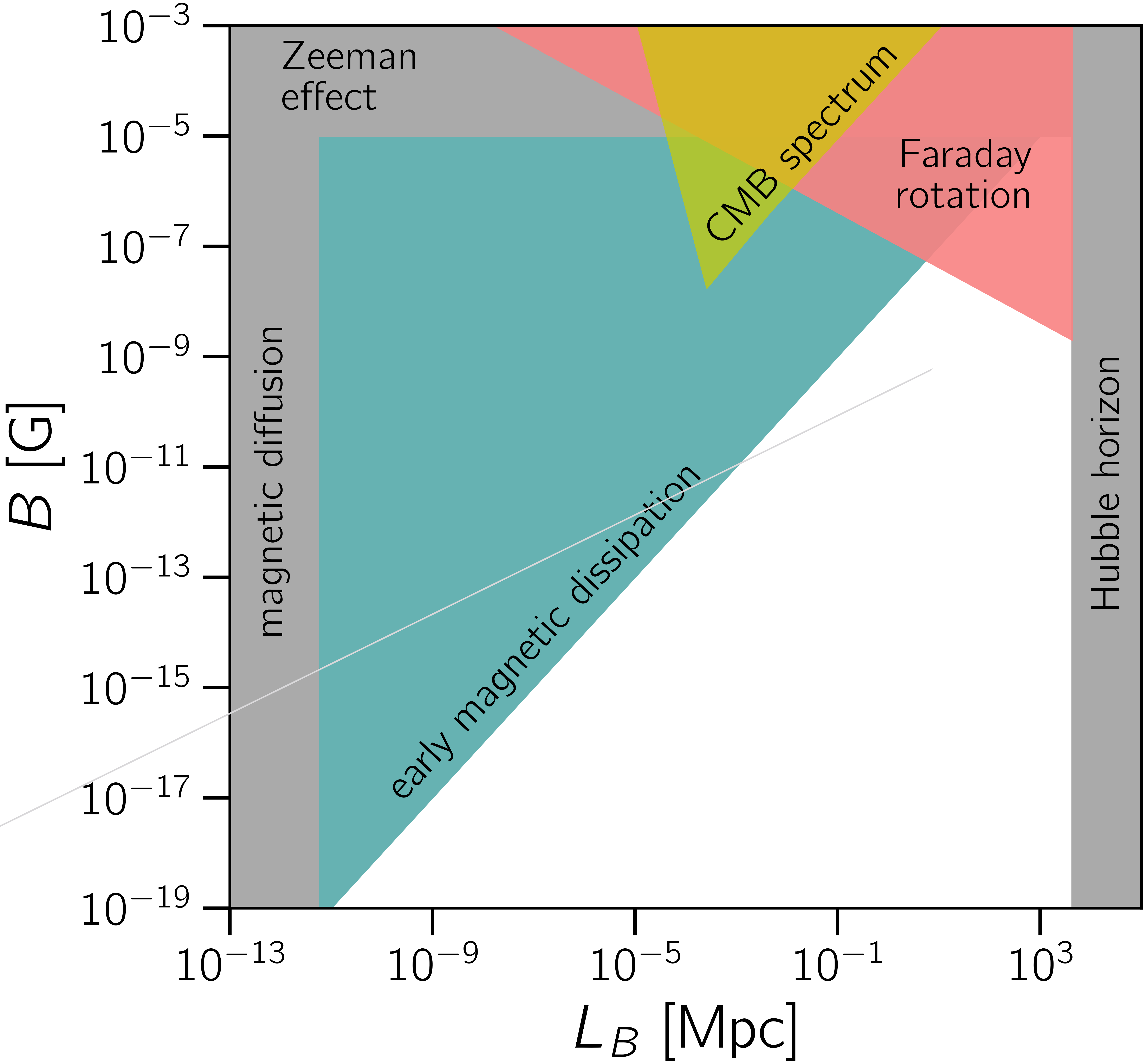

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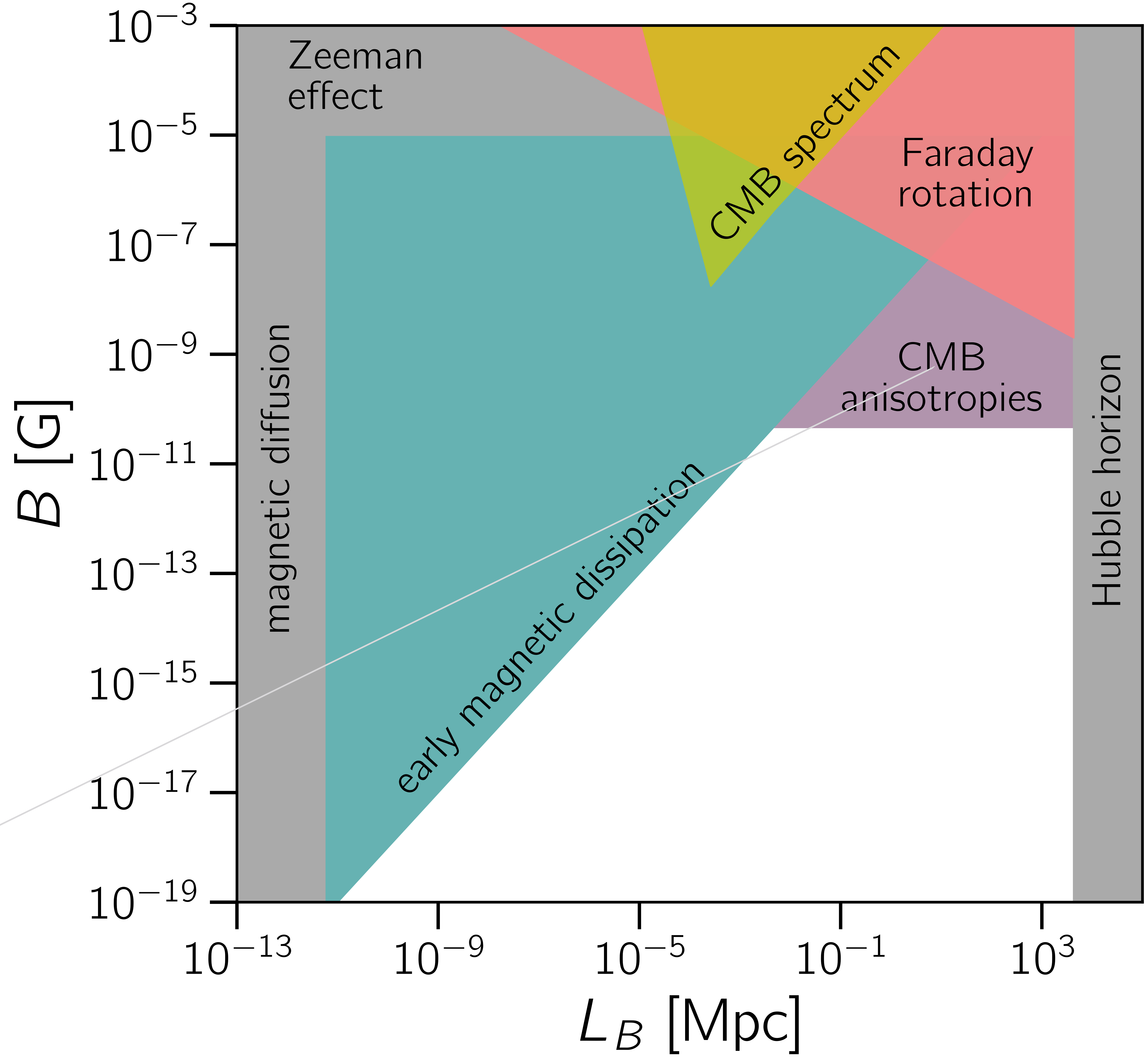

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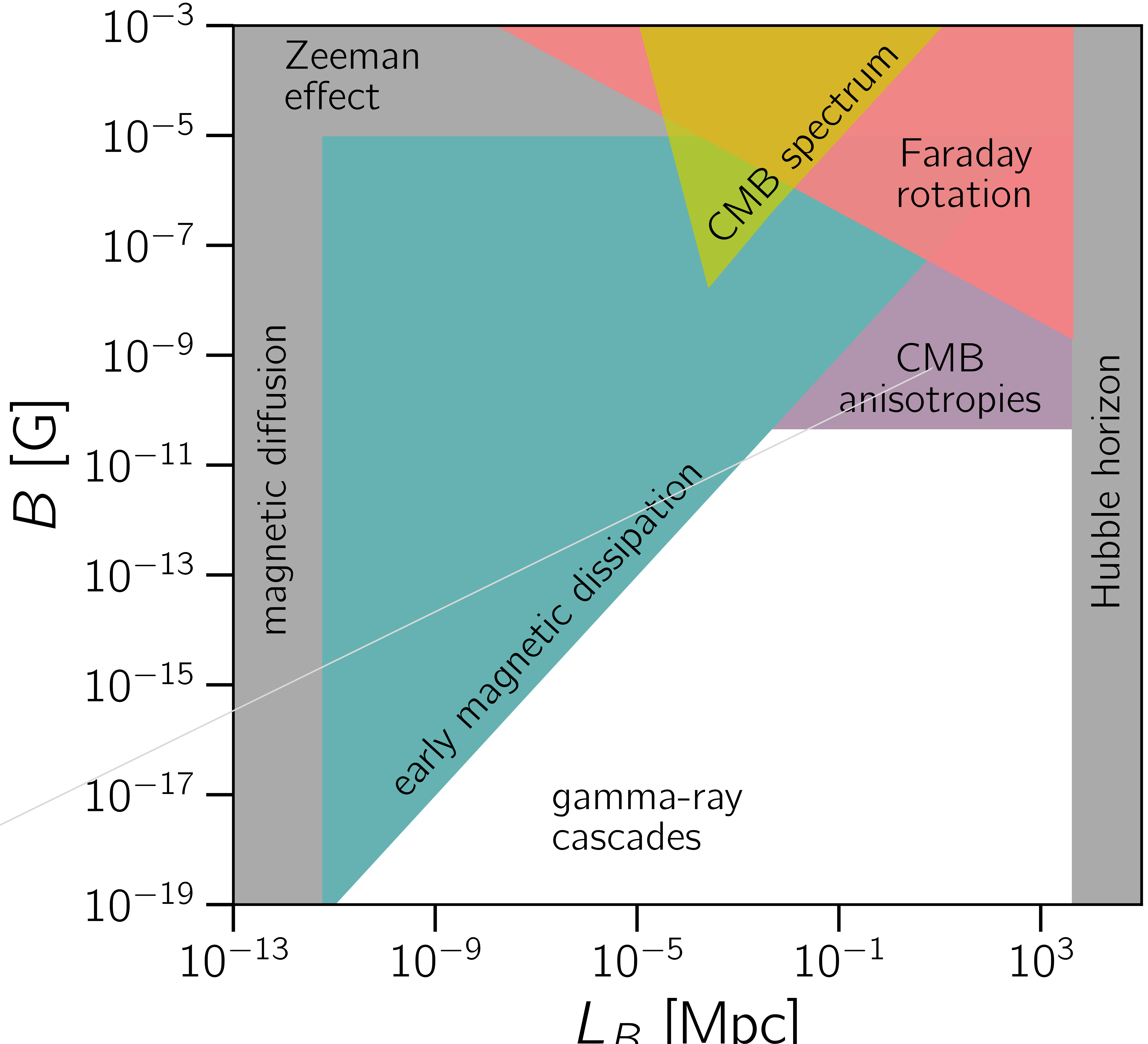

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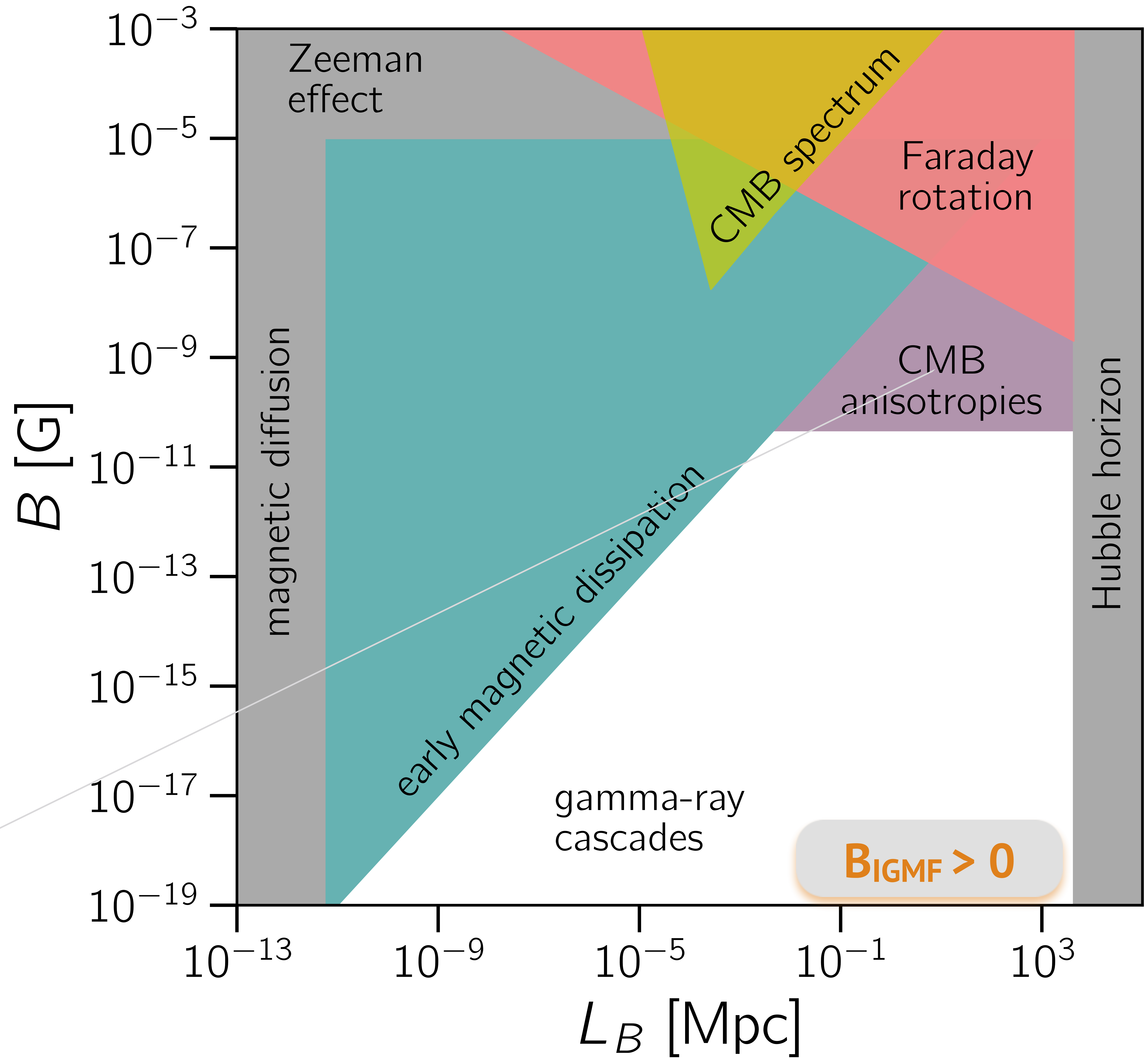
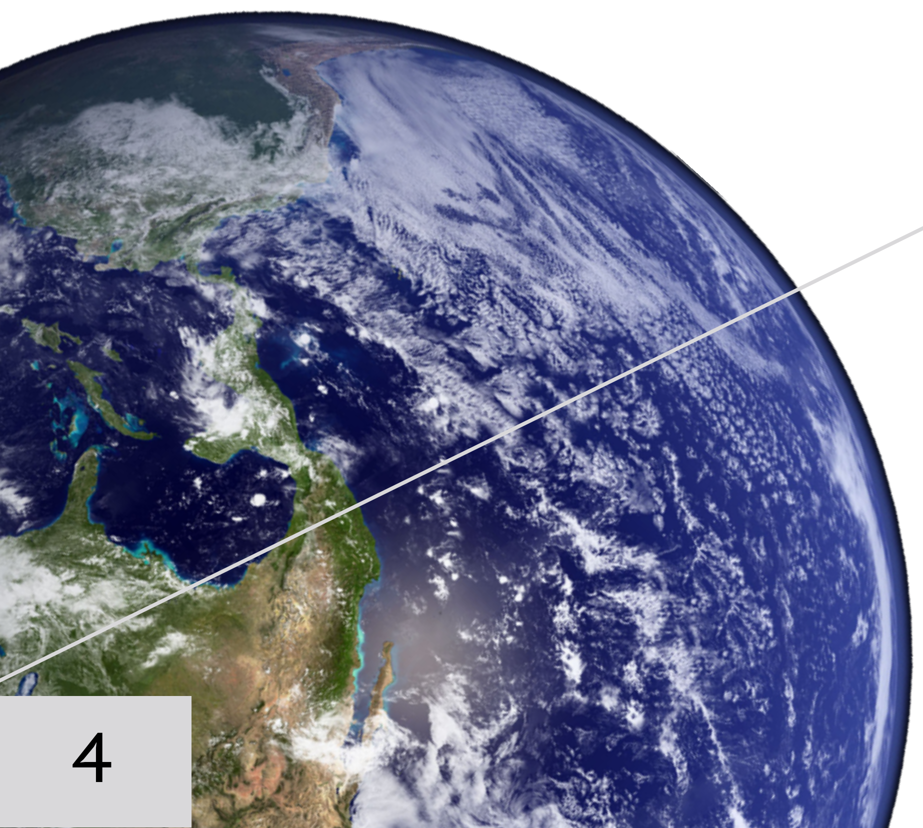


propagation picture




γ


γ
pair production
γ + γbg → e+ + e-

pair production

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


γ
e-
e+
pair production
γ + γbg → e+ + e-

γ
e-
e+
pair production
$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$
inverse Compton scattering
$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$


γ
e-
e+
γ
pair production
γ + γbg → e+ + e-
inverse Compton scattering
e± + γbg → e± + γ

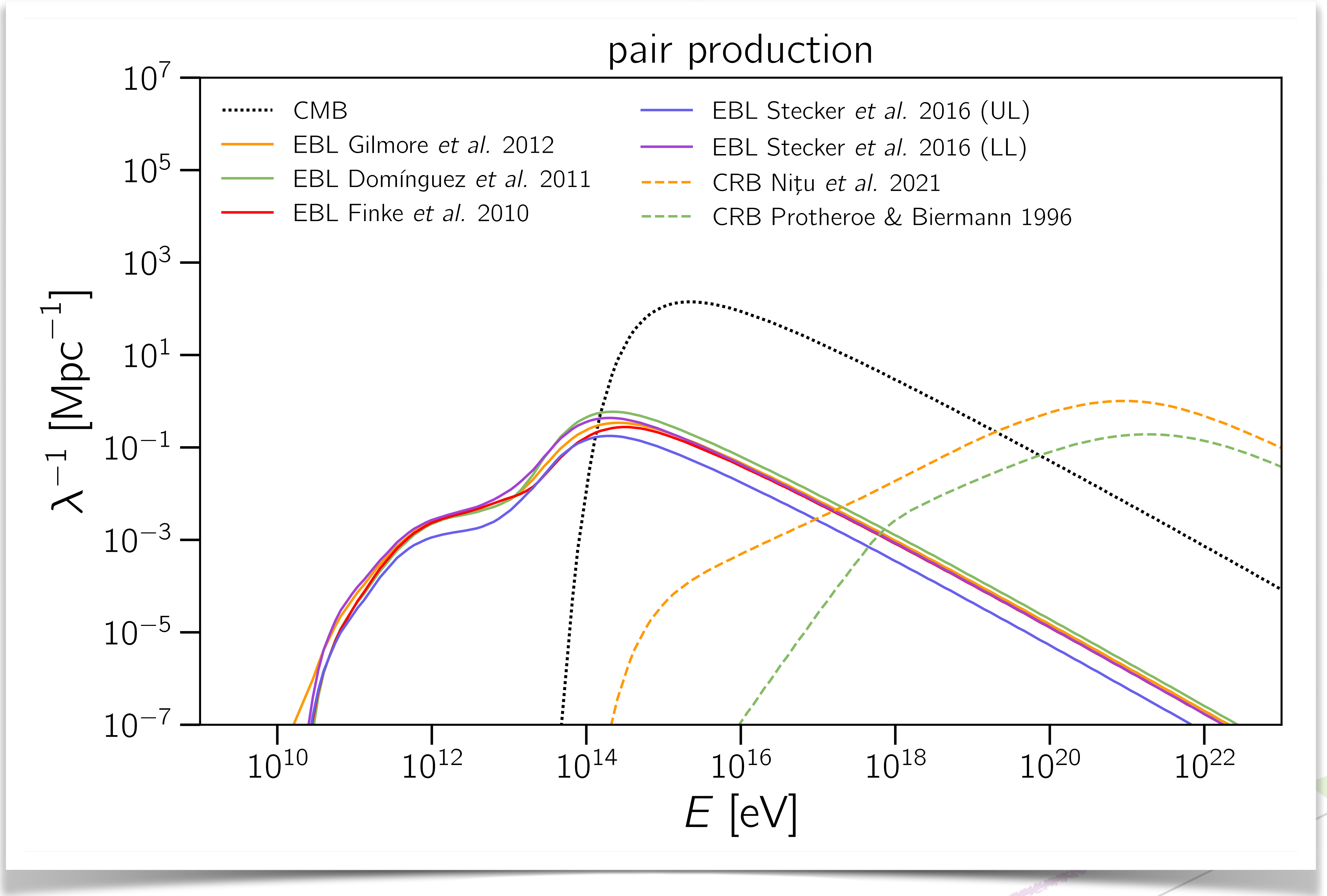
propagation picture

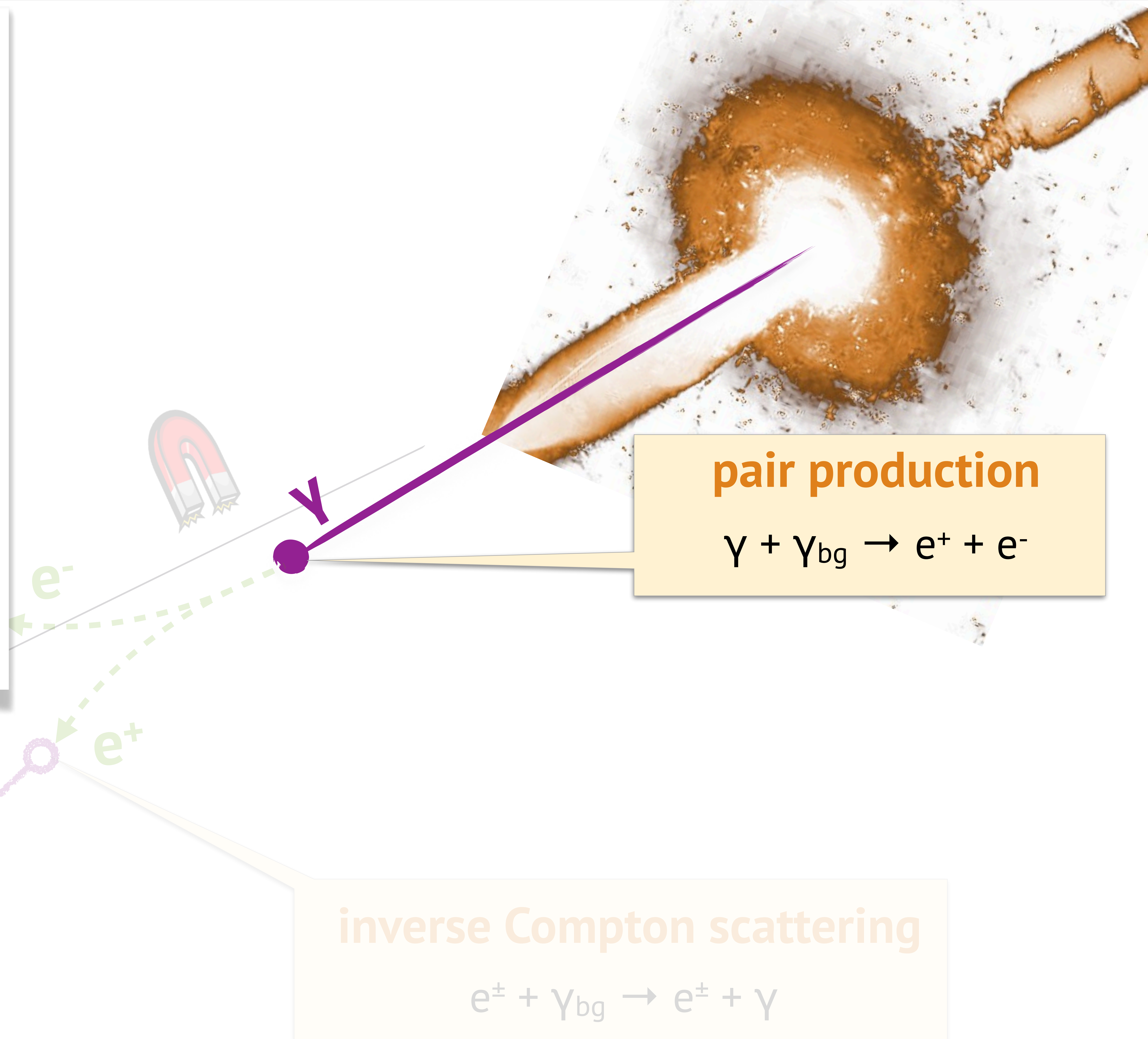
propagation picture


γ
e-
e+
γ
e+
e-
γ
pair production
$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$
inverse Compton scattering
$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$


γ
pair production
γ + γbg → e+ + e-
e-
e+
γ
γ
e+
e-
inverse Compton scattering
e± + γbg → e± + γ

interactions: pair production





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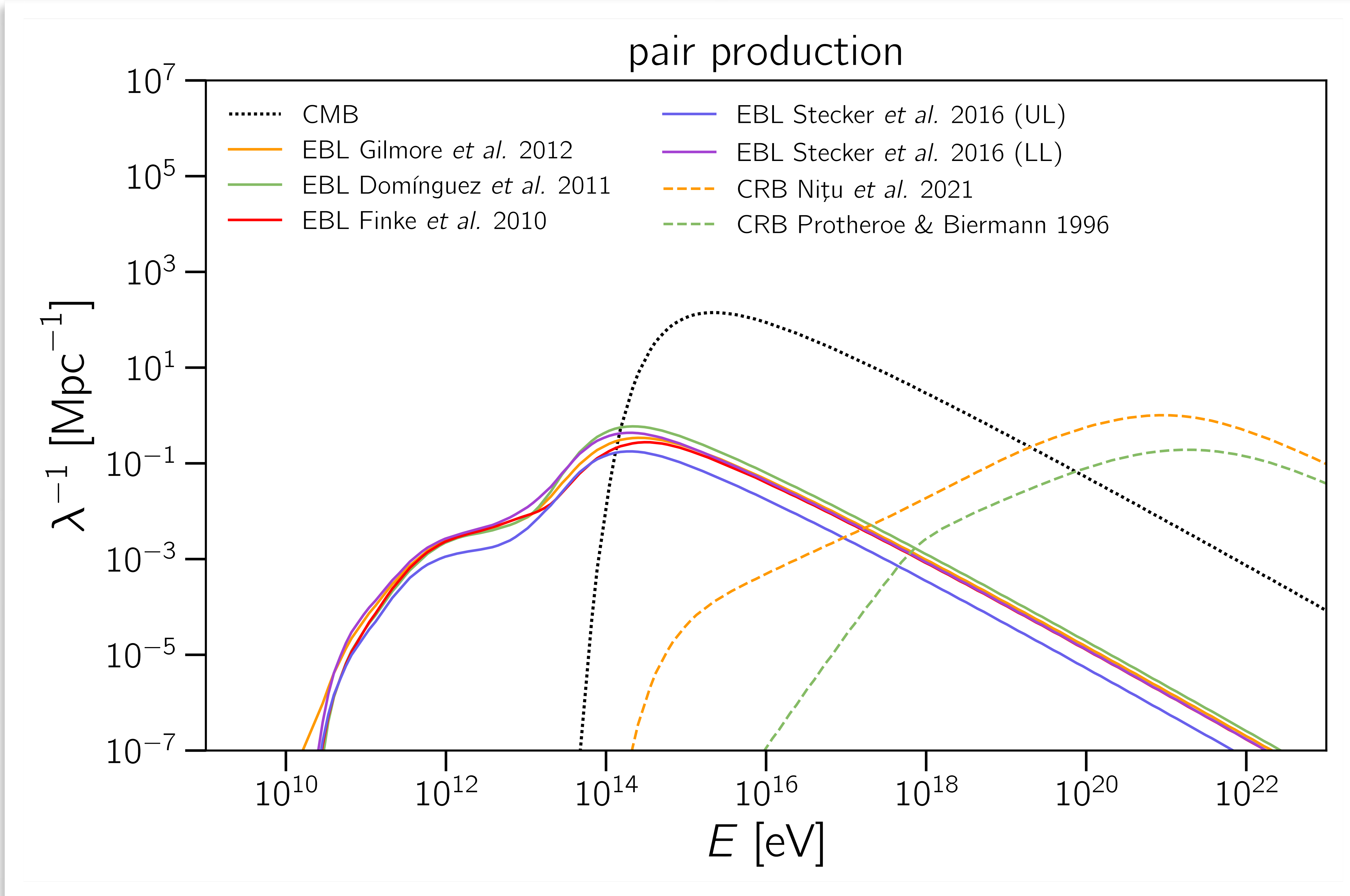
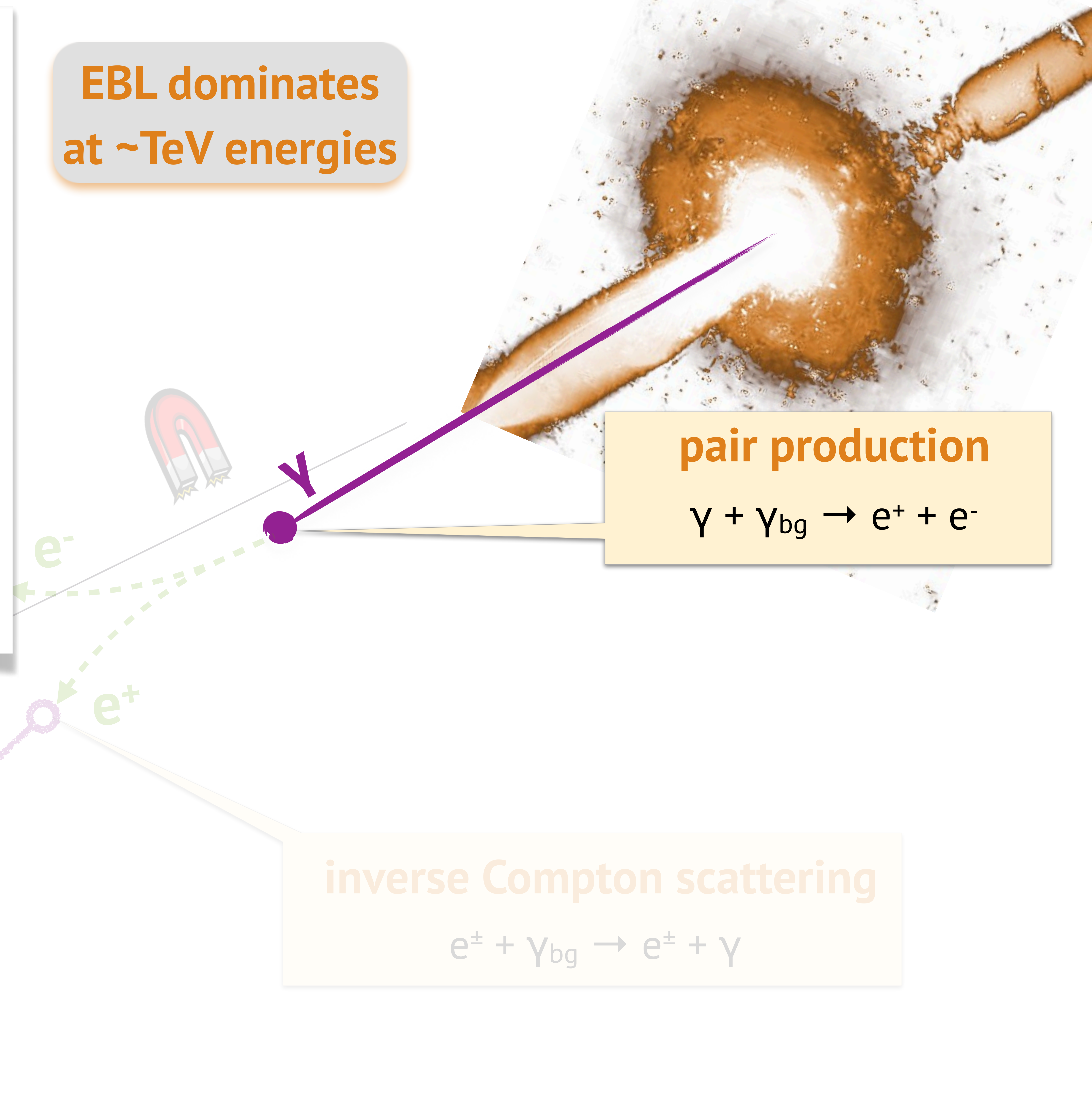
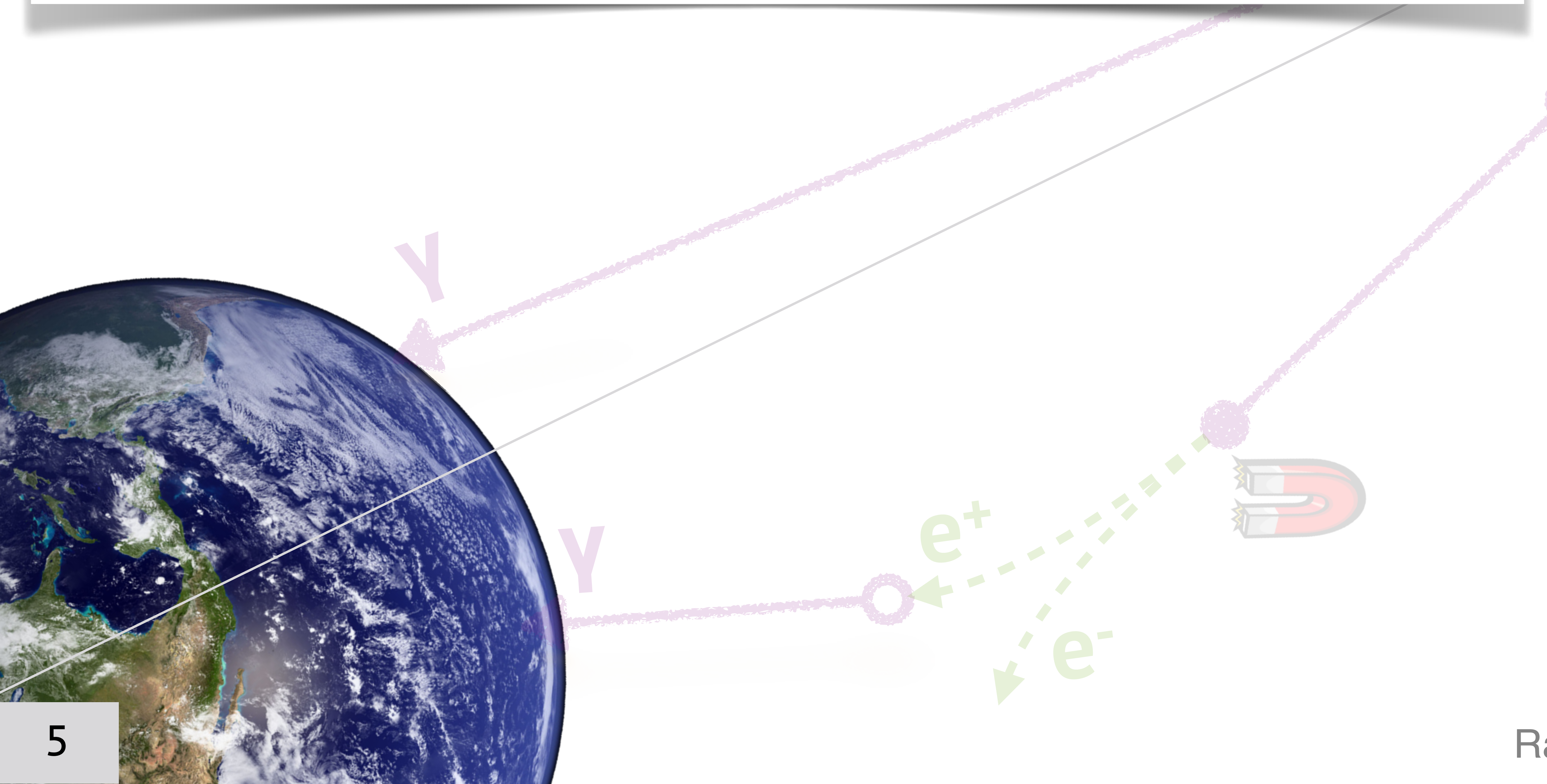


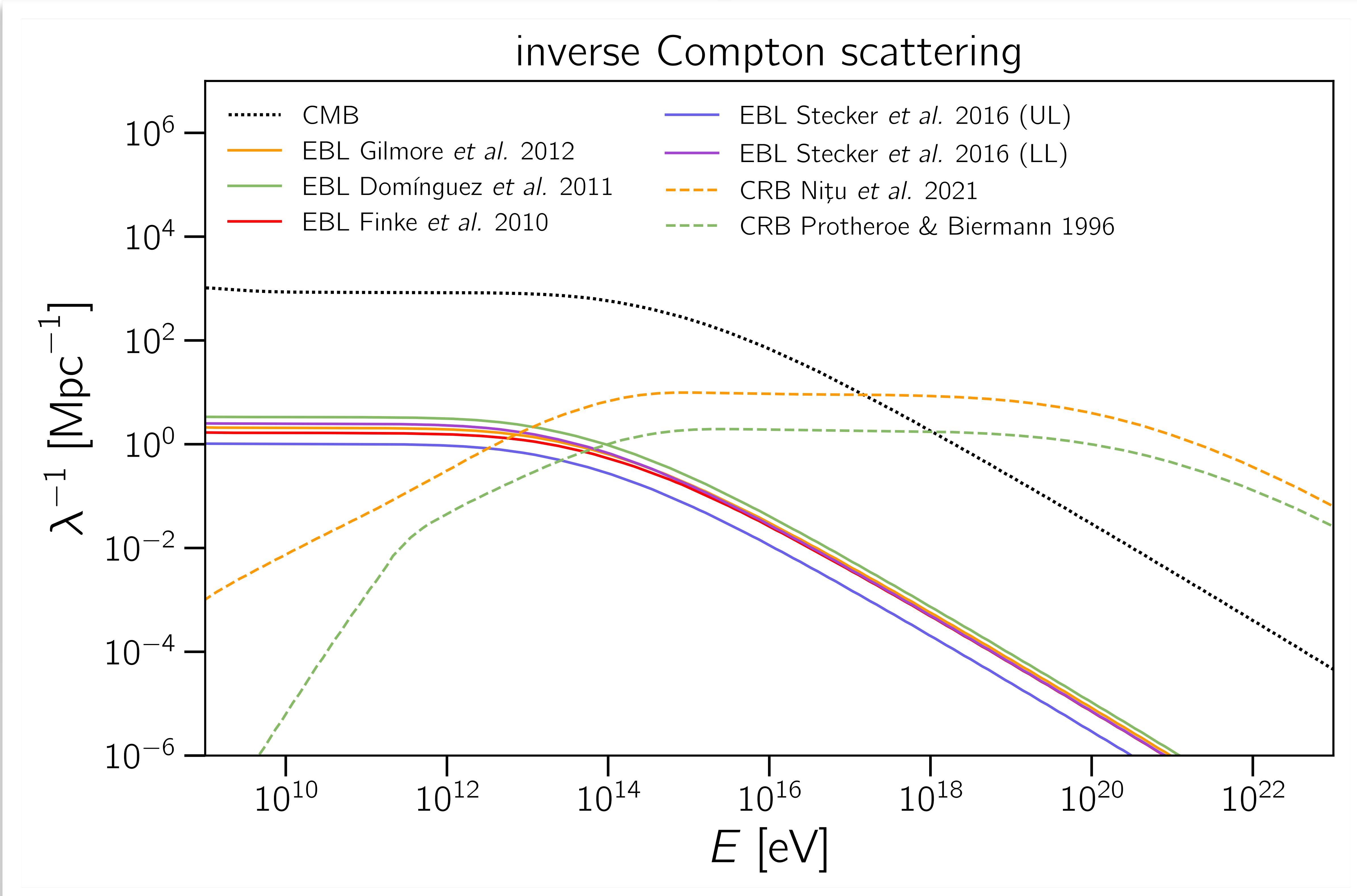




interactions: inverse Compton scattering

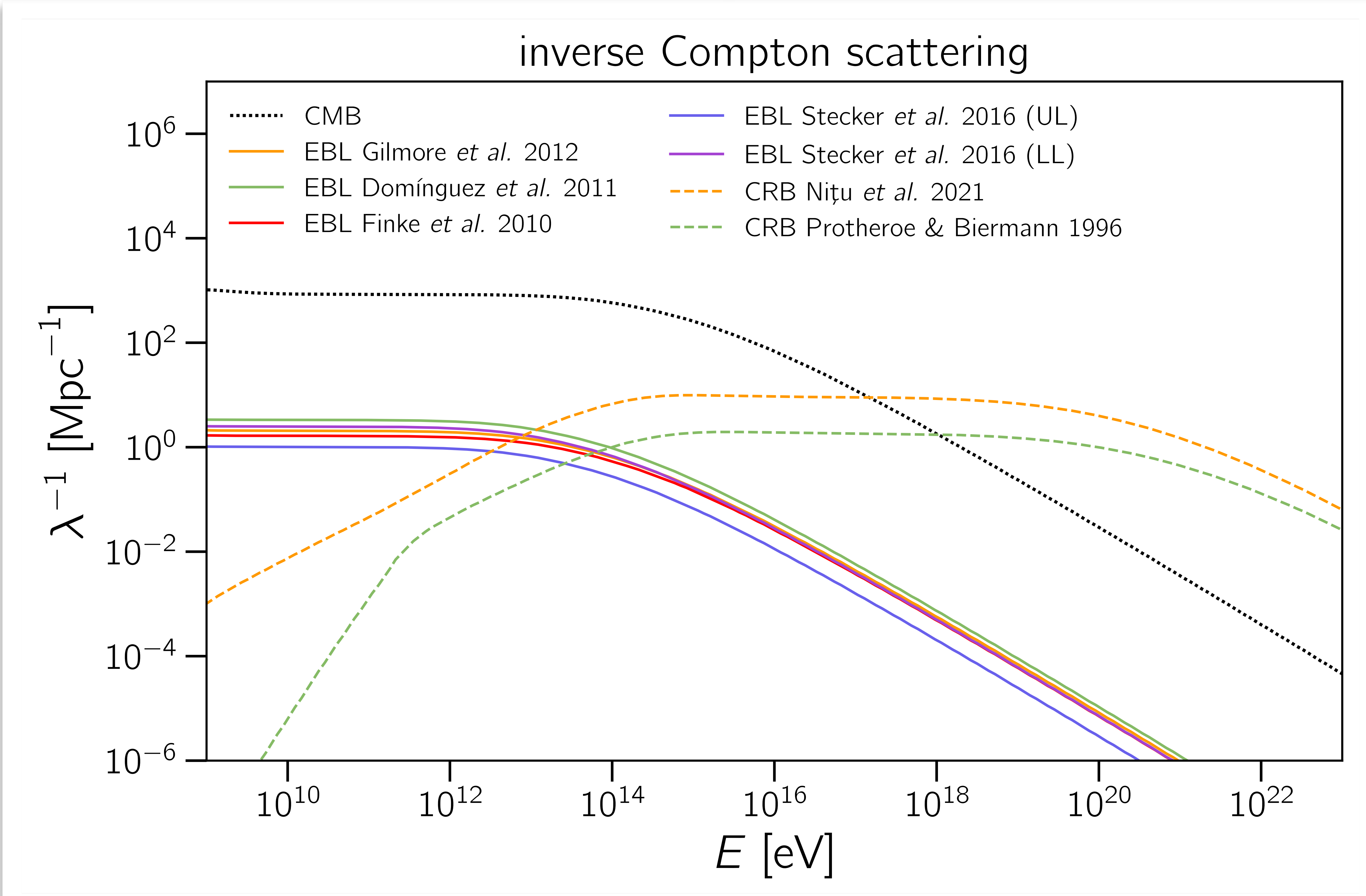
inverse Compton scattering

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

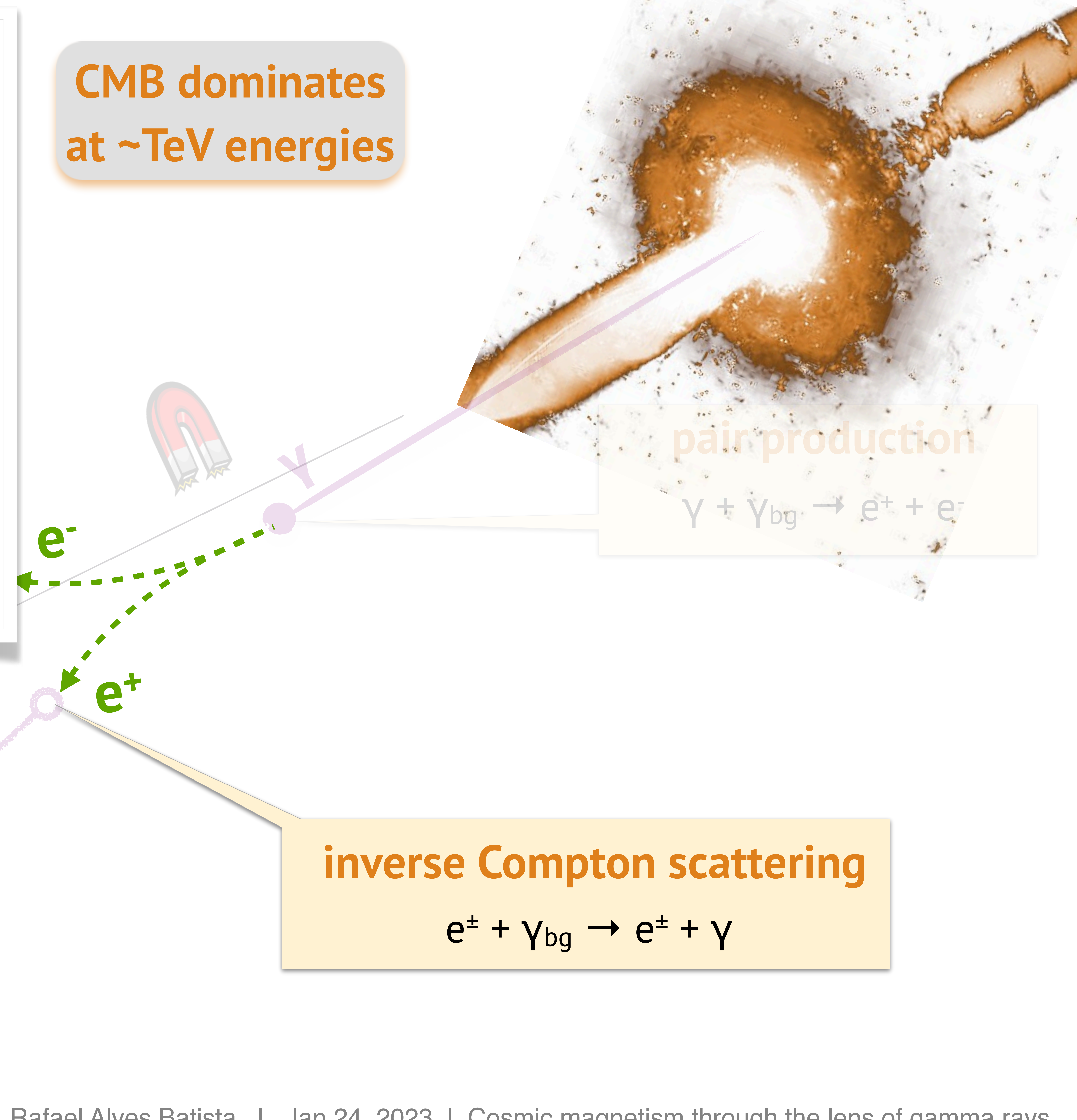


inverse Compton scattering

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



CMB dominates at ~TeV energies



inverse Compton scattering

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

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- **sources**

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  - blazars

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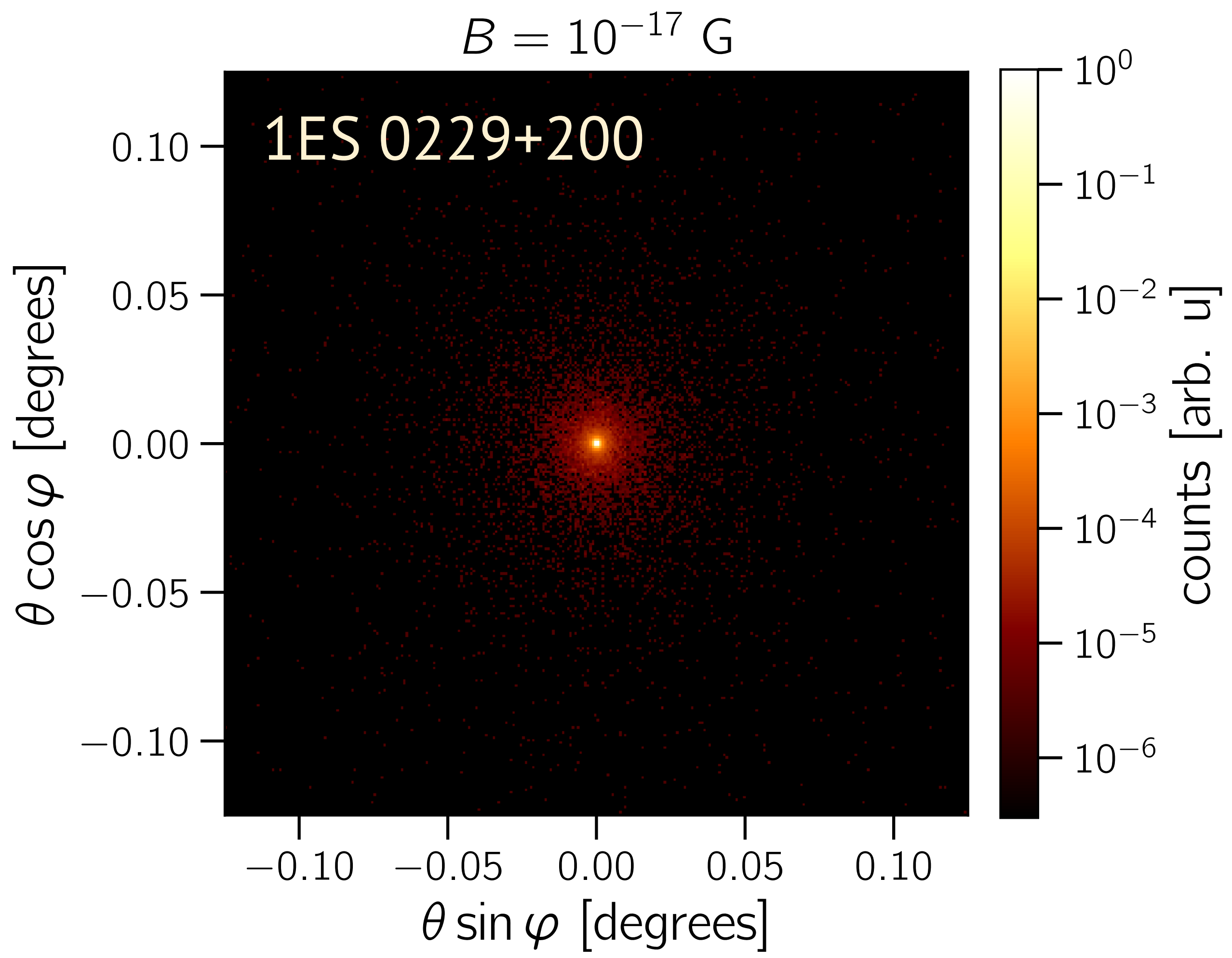
  - knowledge of of HE emission
  - known time emission profile

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

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



$B = 10^{-17}$ G
1ES 0229+200
$\theta \cos\varphi$ [degrees]
$\theta \sin\varphi$ [degrees]
counts [arb. u]

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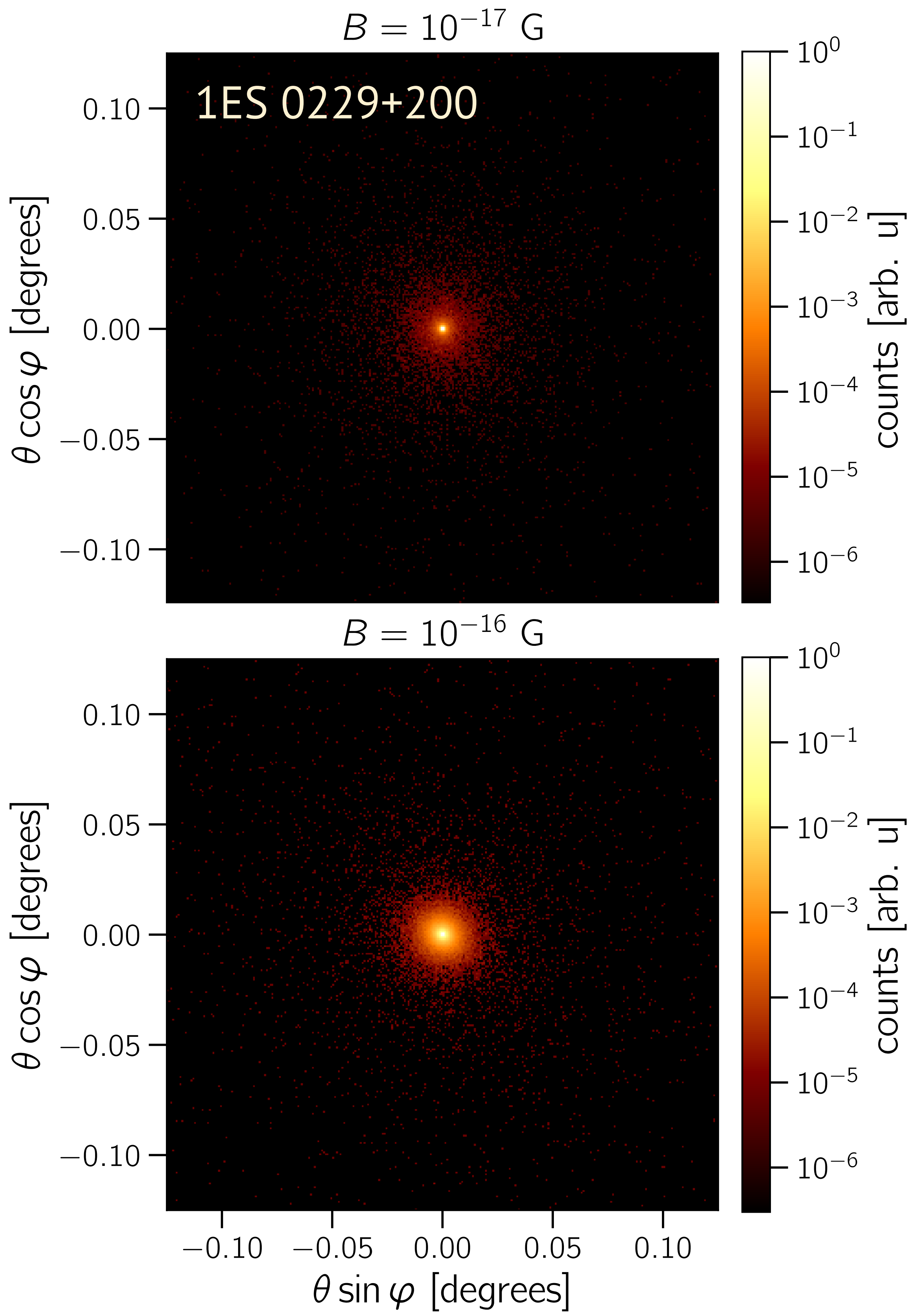

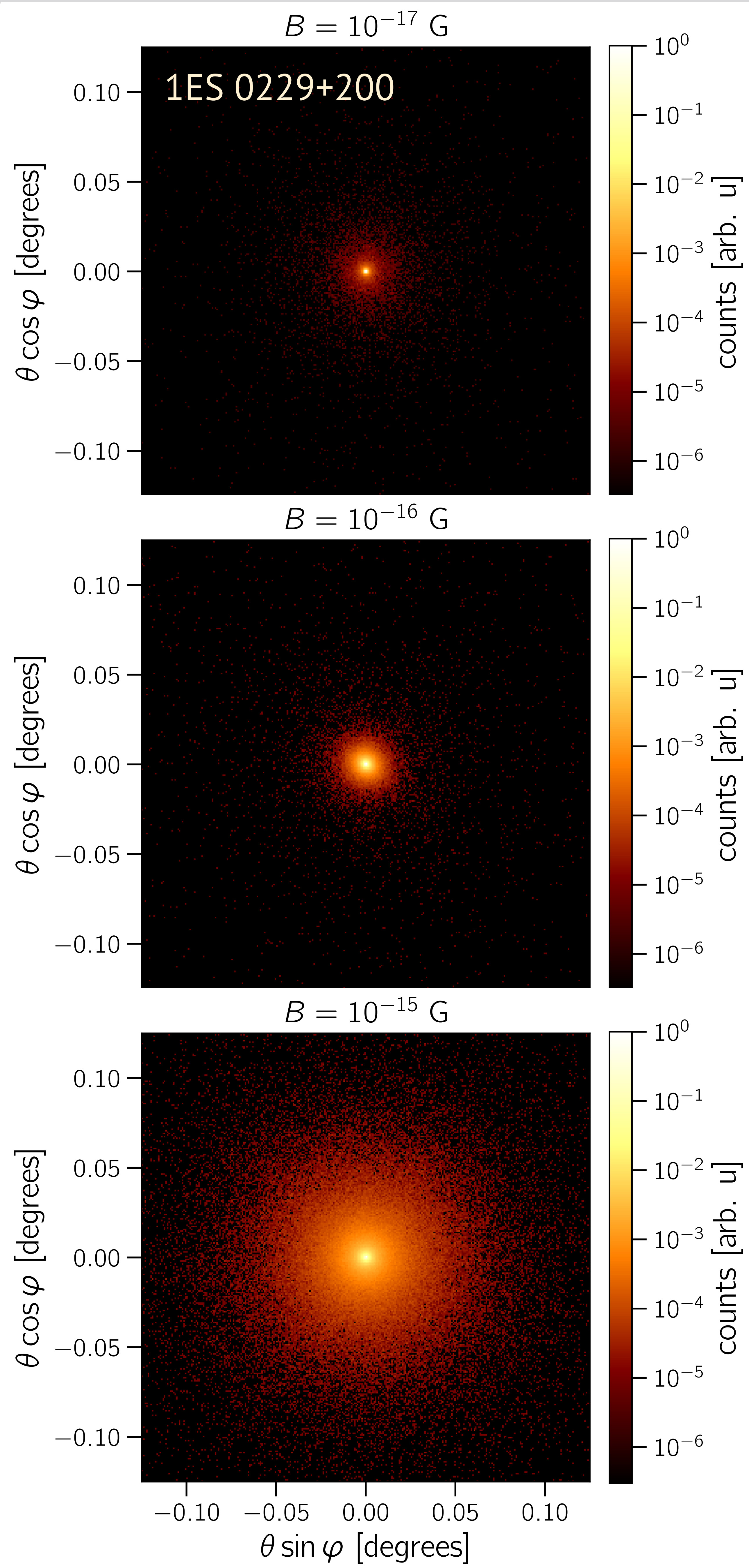

$B = 10^{-17}$ G
1ES 0229+200
$B = 10^{-16}$ G
$B = 10^{-15}$ G
$\theta \cos\varphi$ [degrees]
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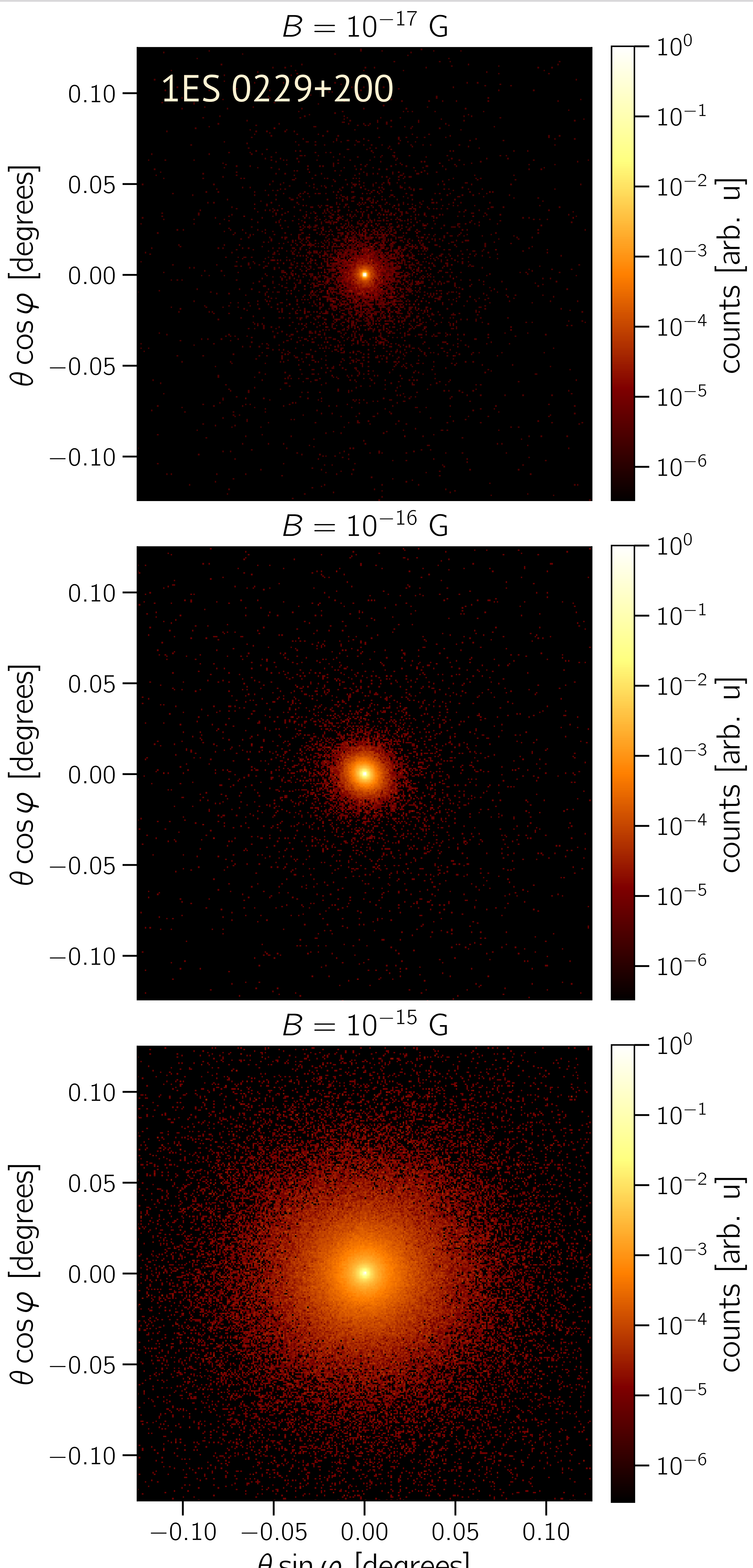

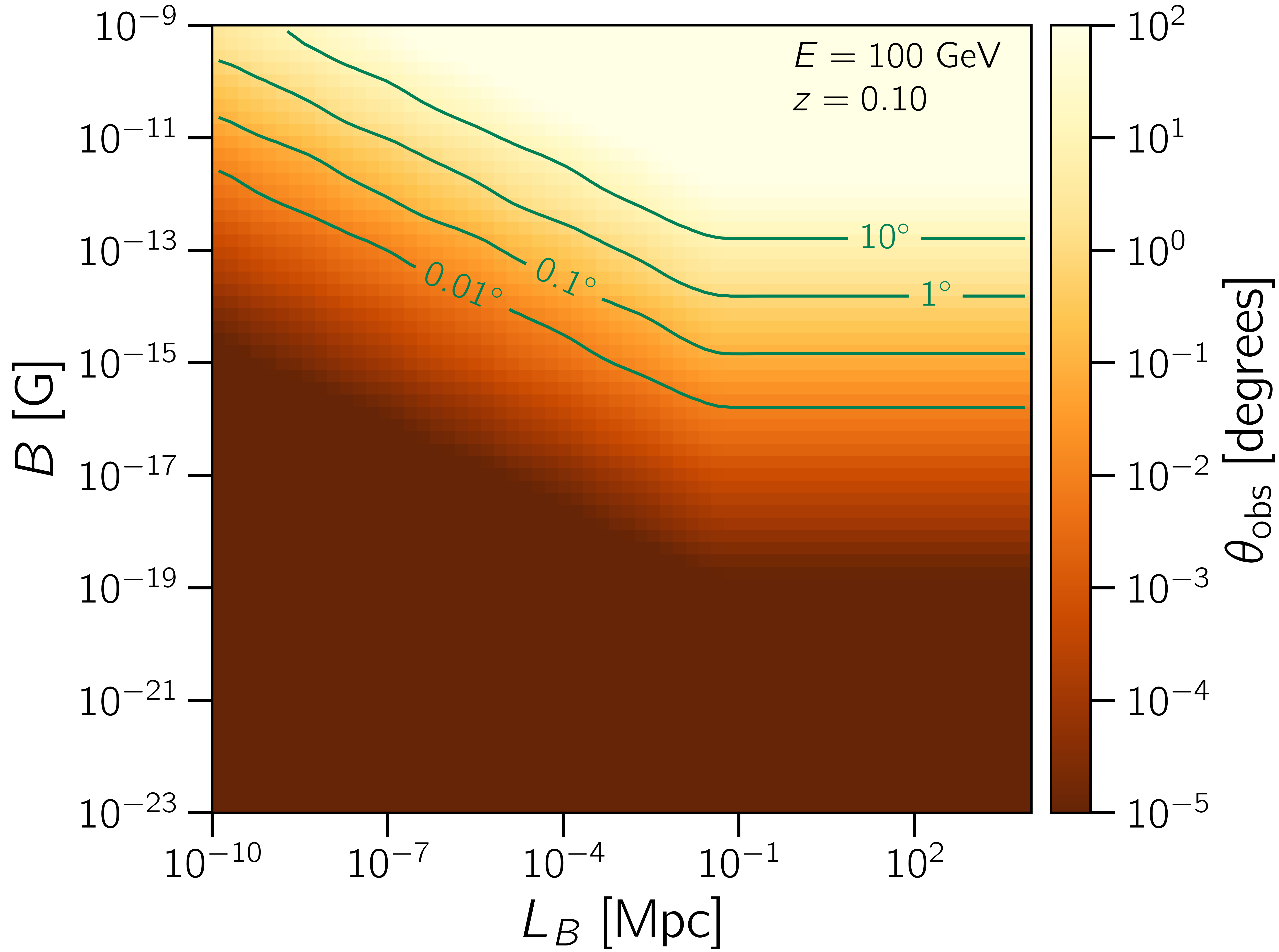

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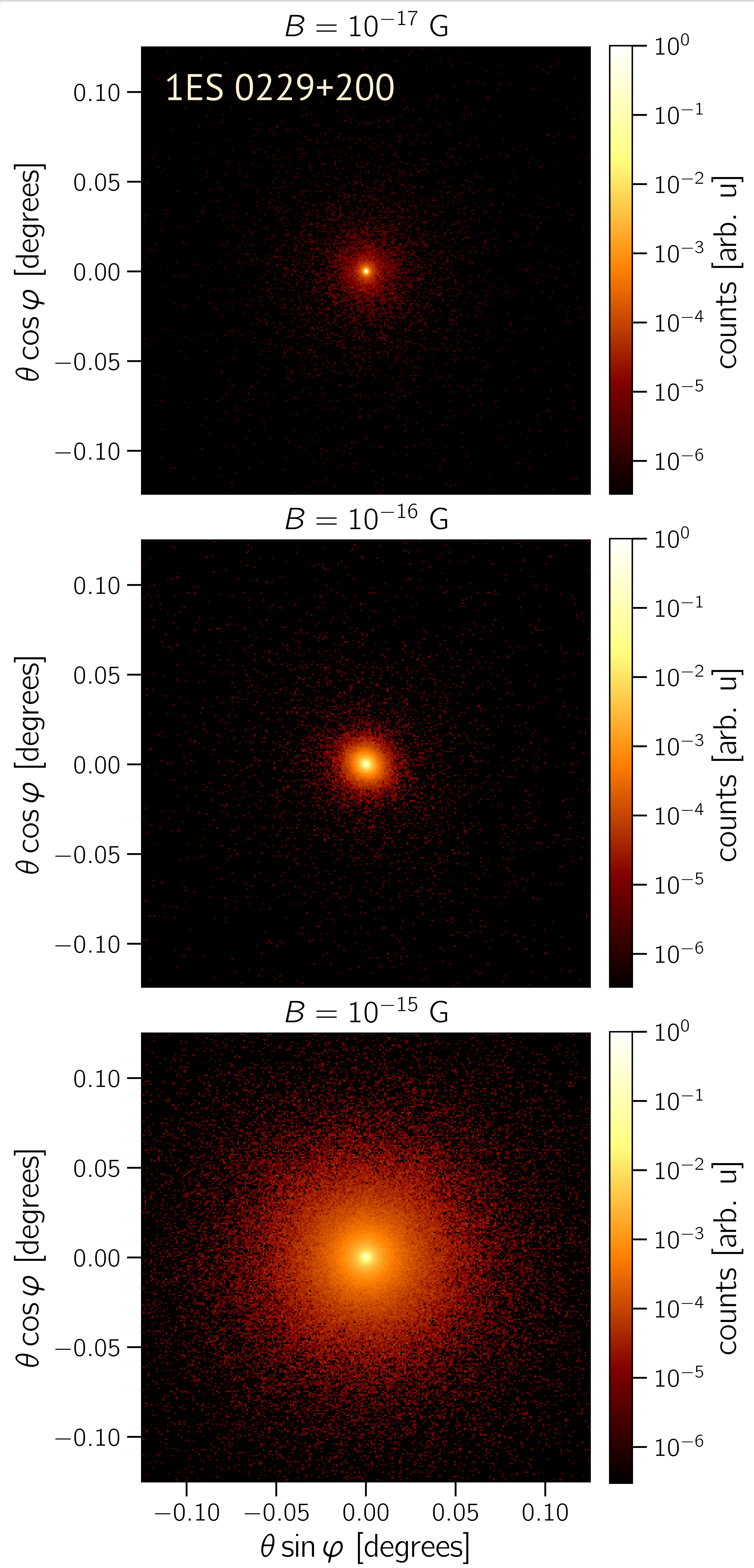

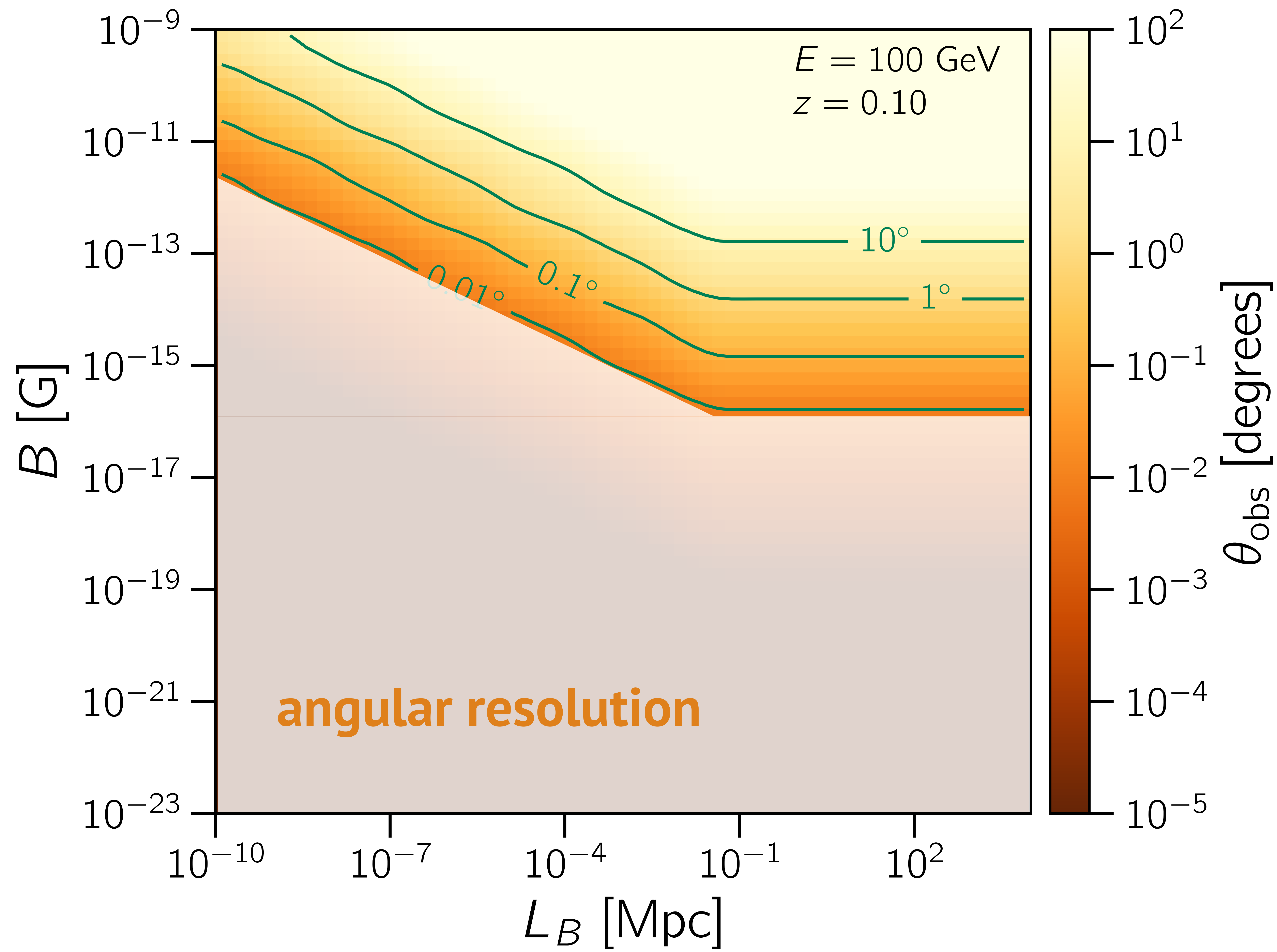

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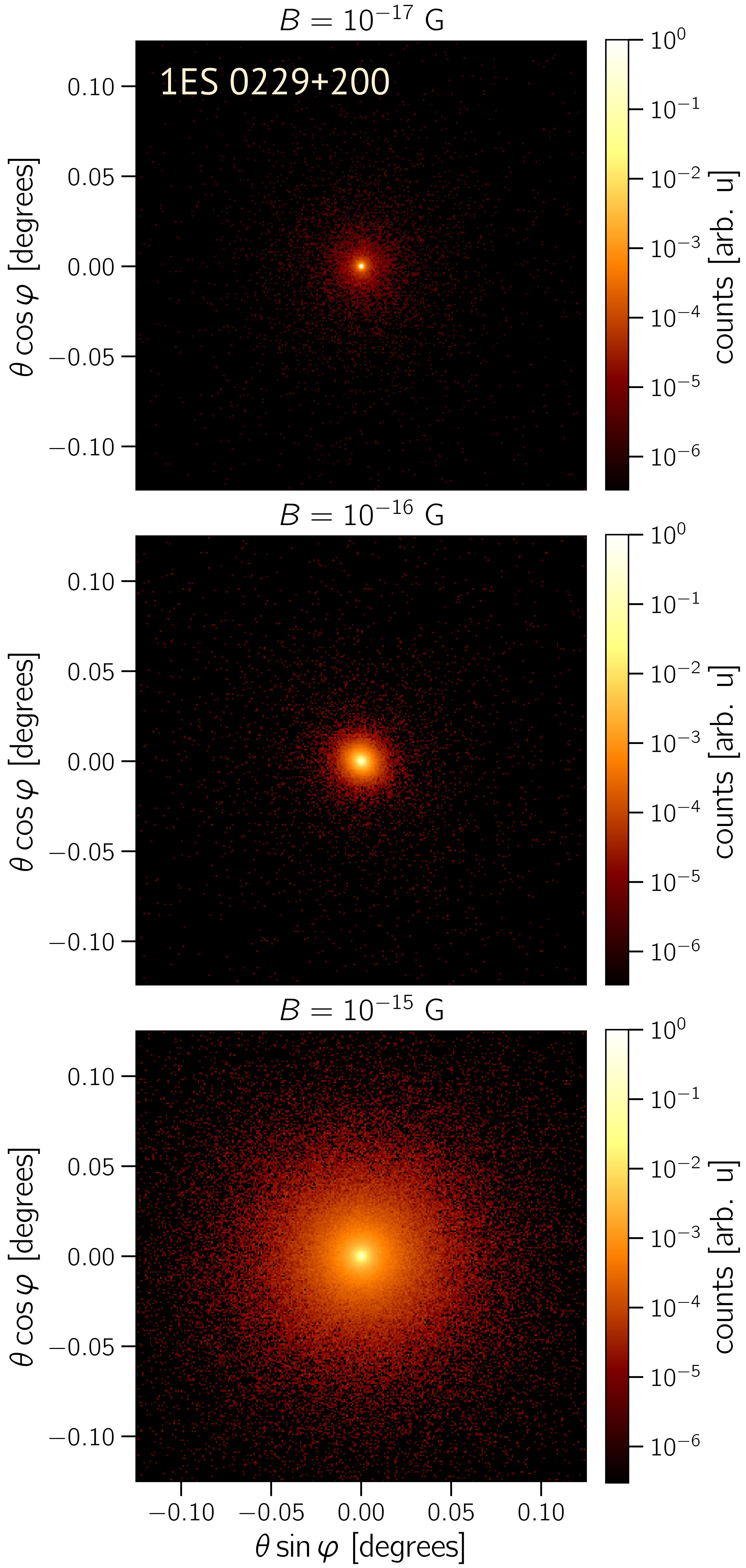

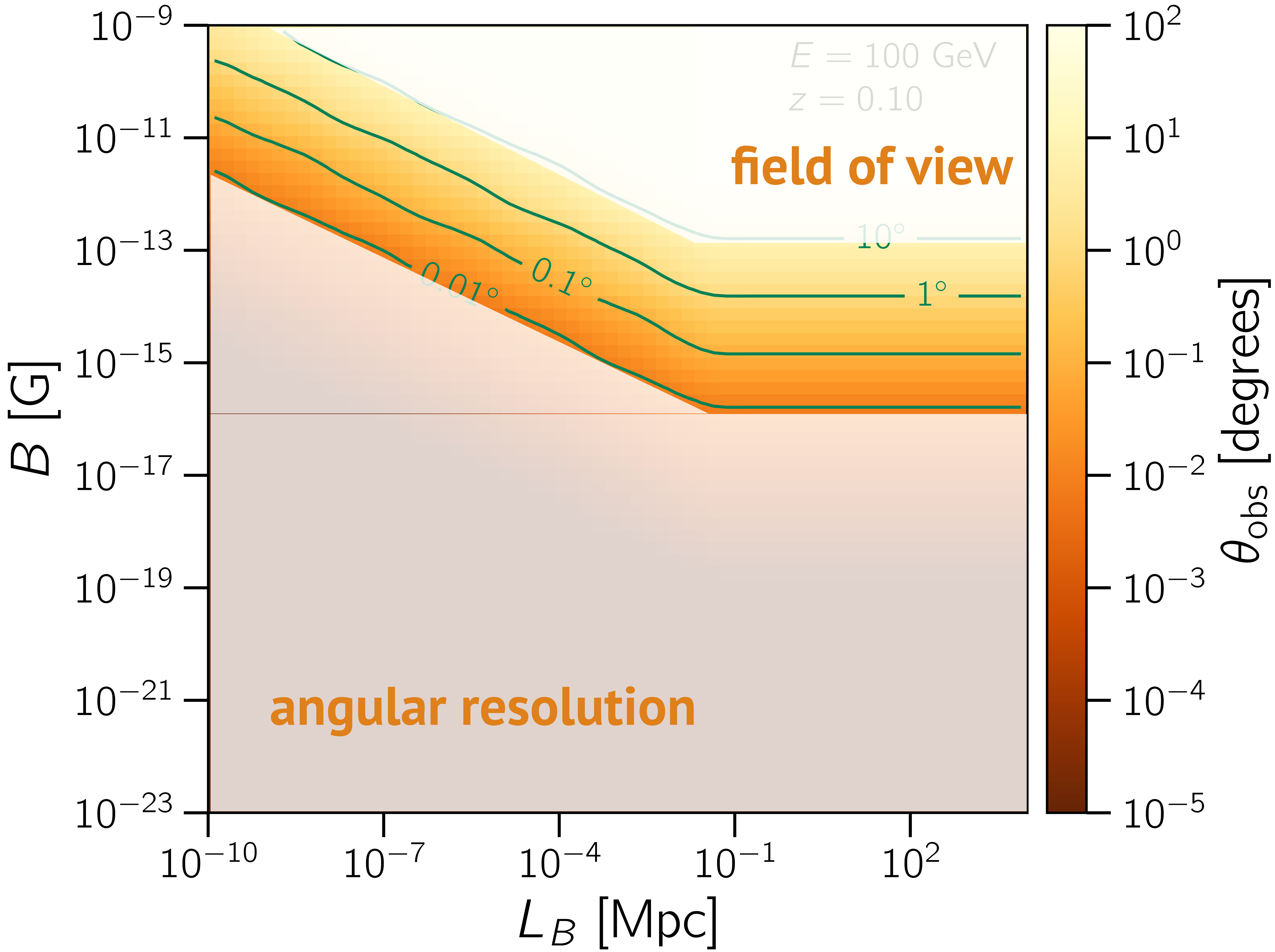

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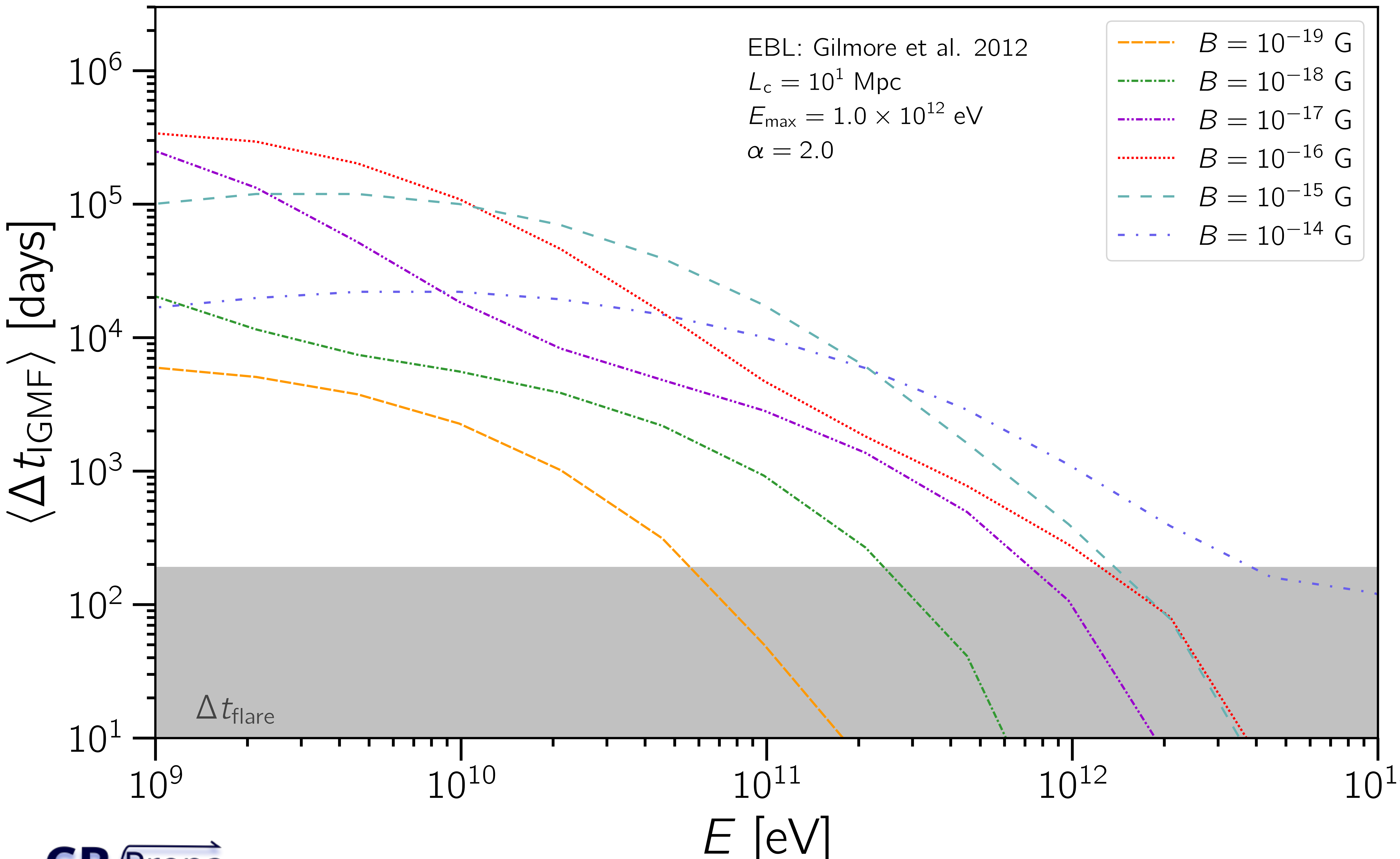
observational strategies: time delays (a.k.a. pair echoes)

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

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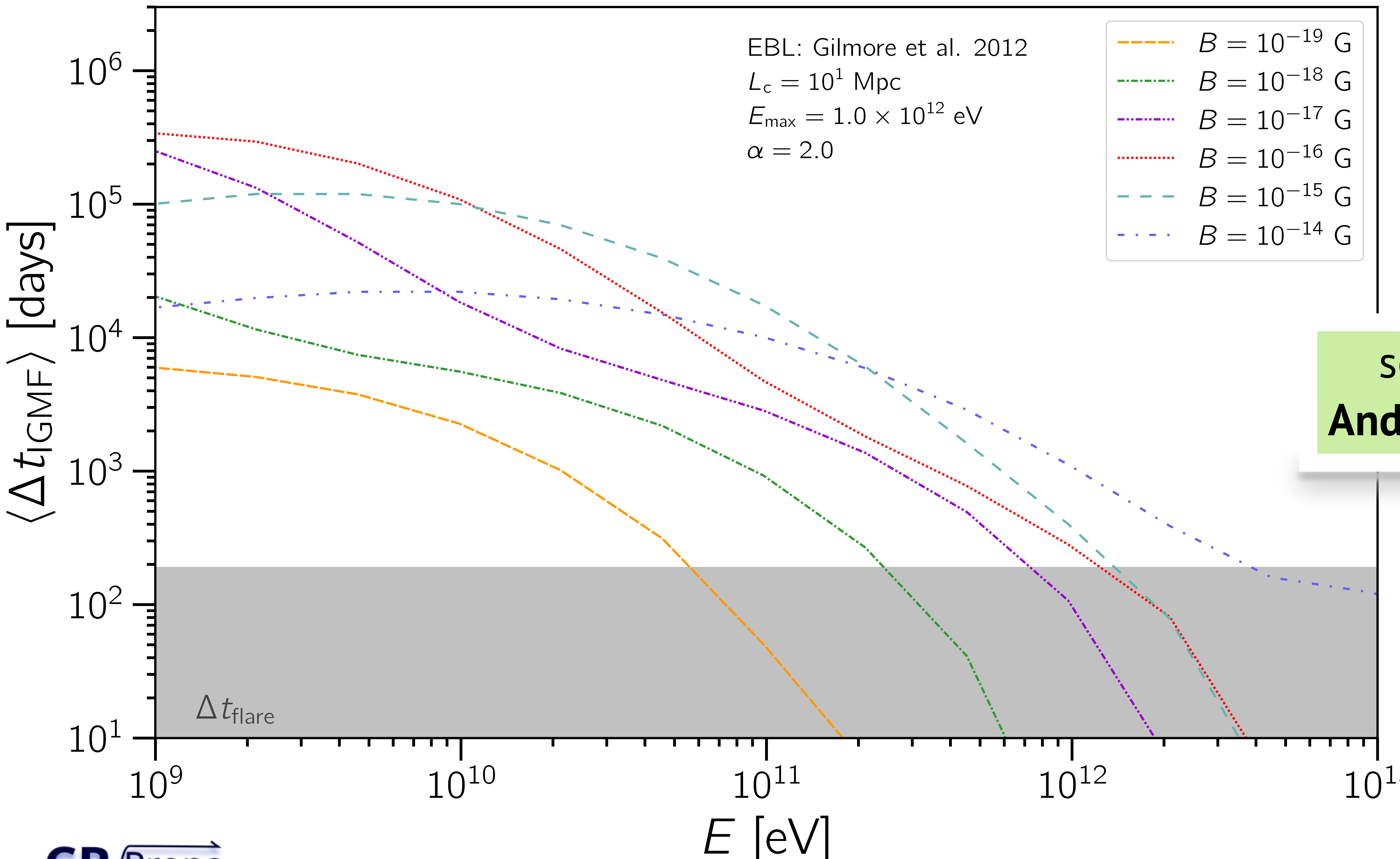

see talk by
Andrey Saveliev

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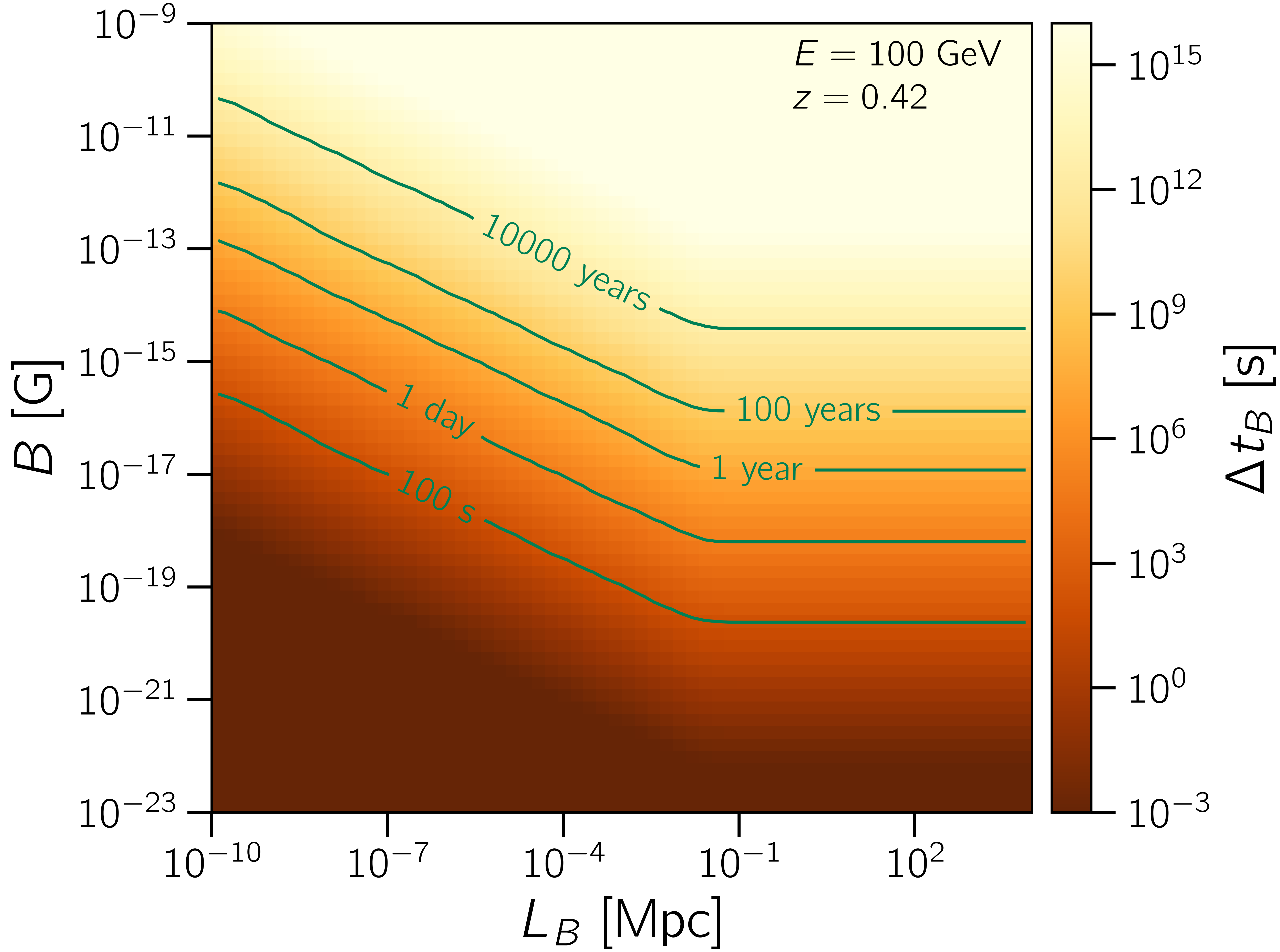

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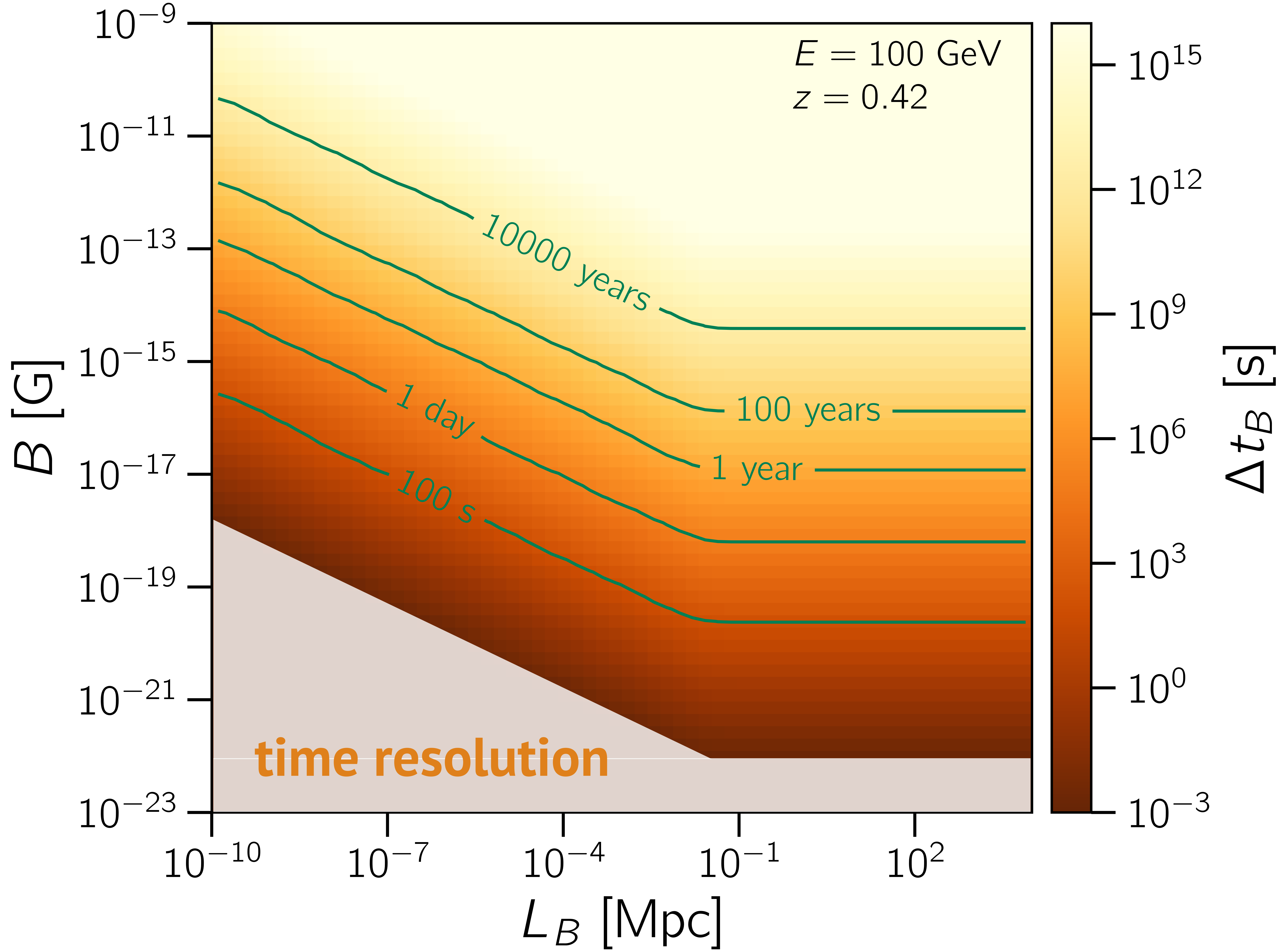

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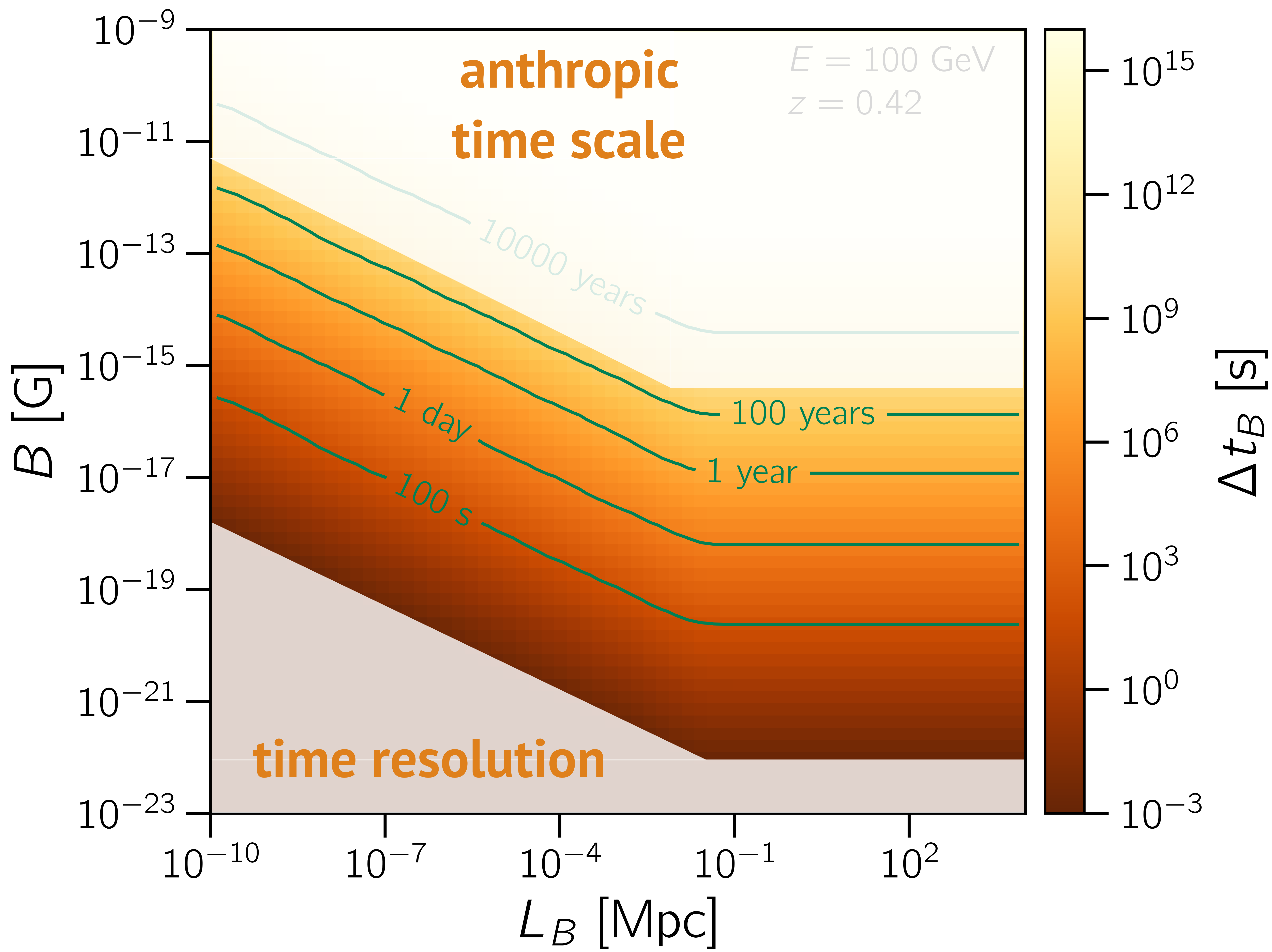

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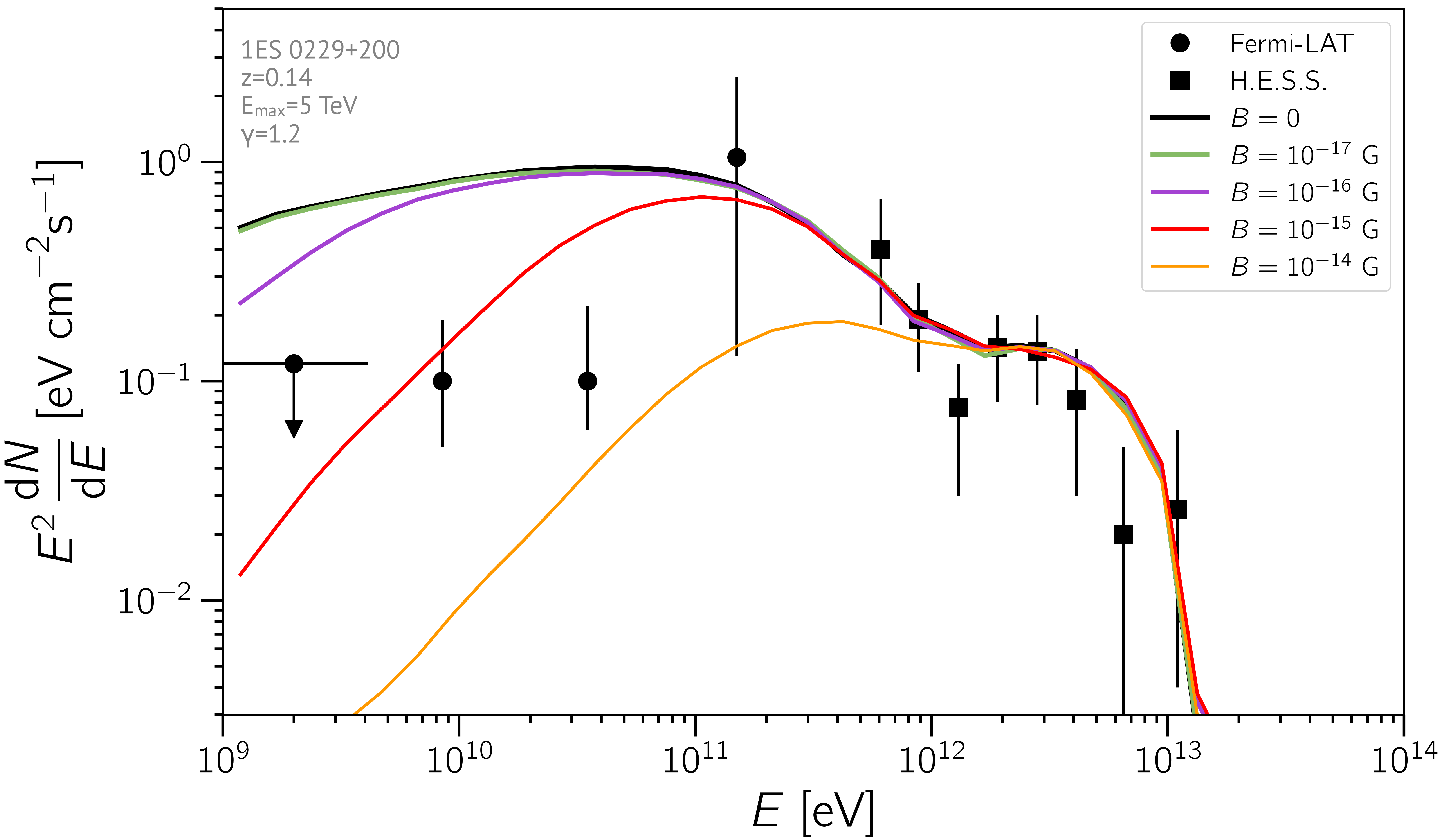

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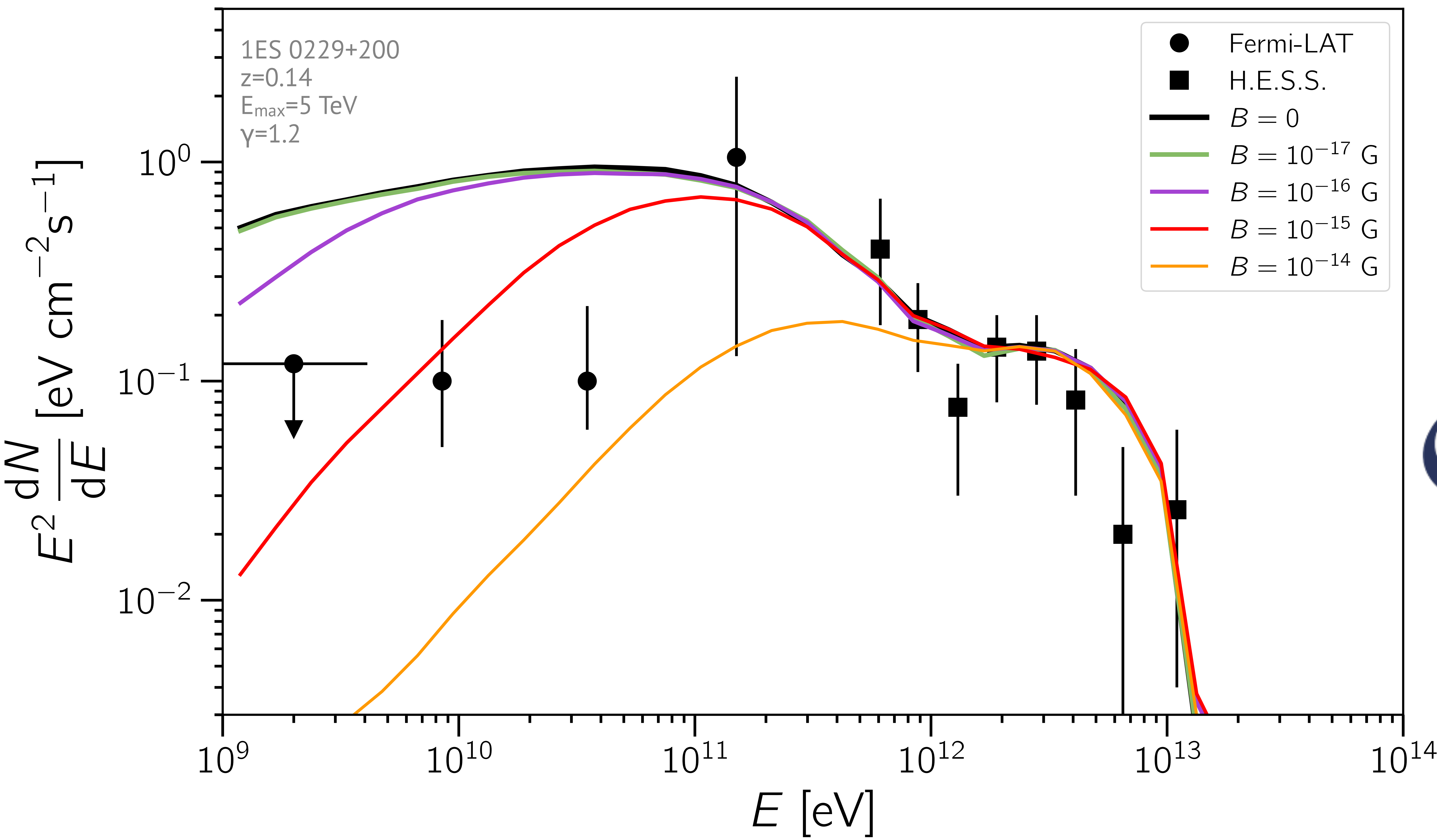

cherenkov telescope array

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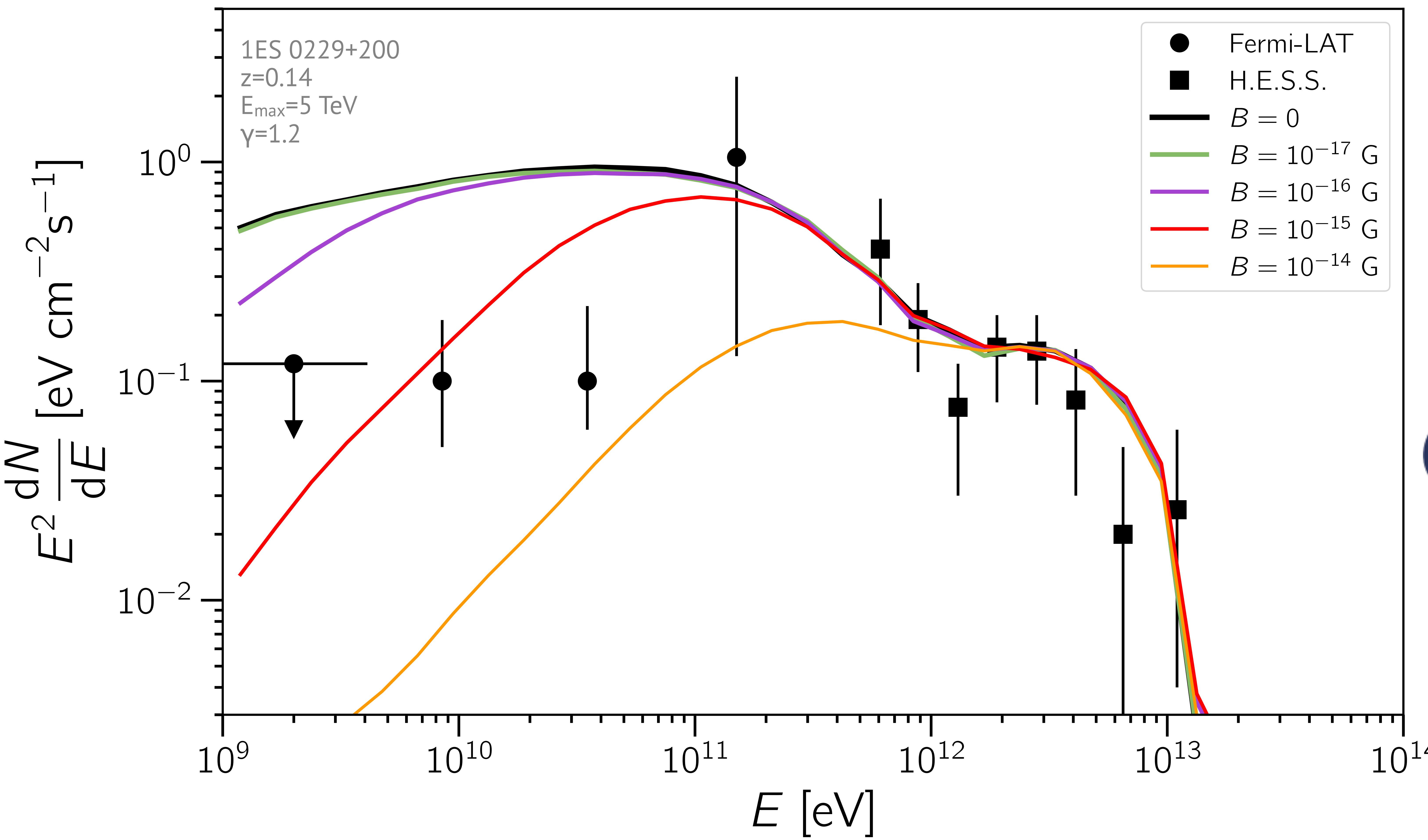

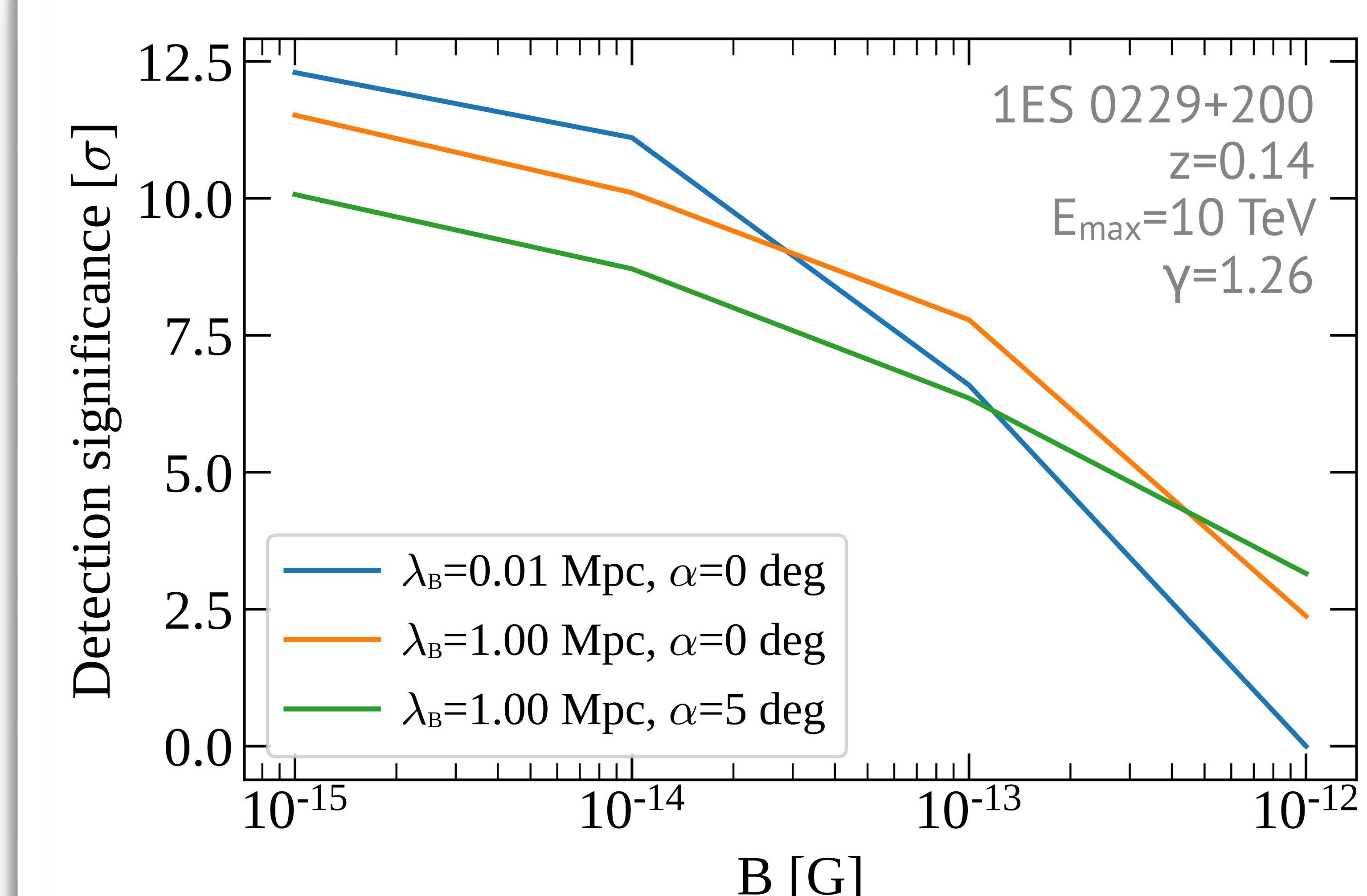

CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

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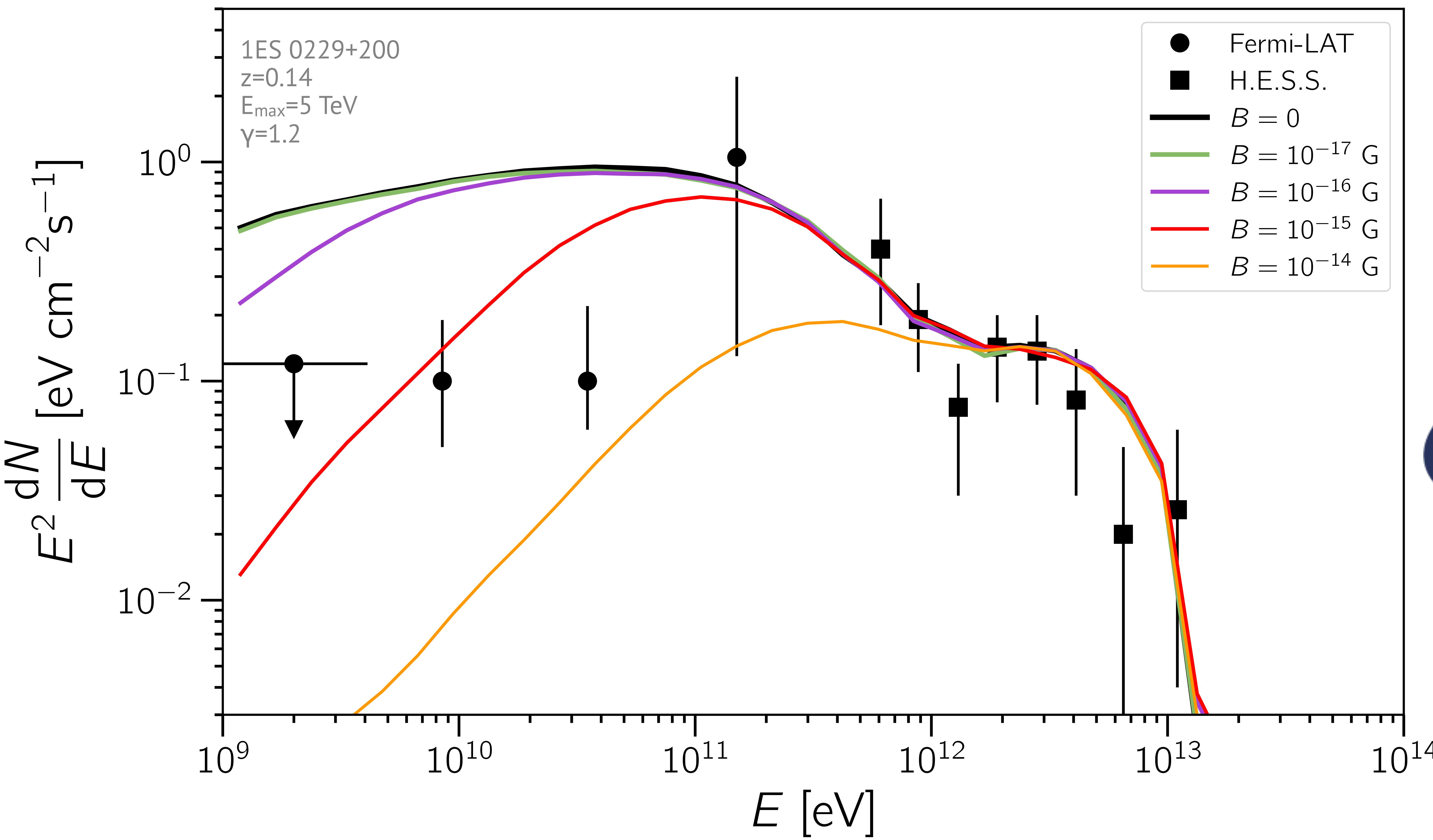
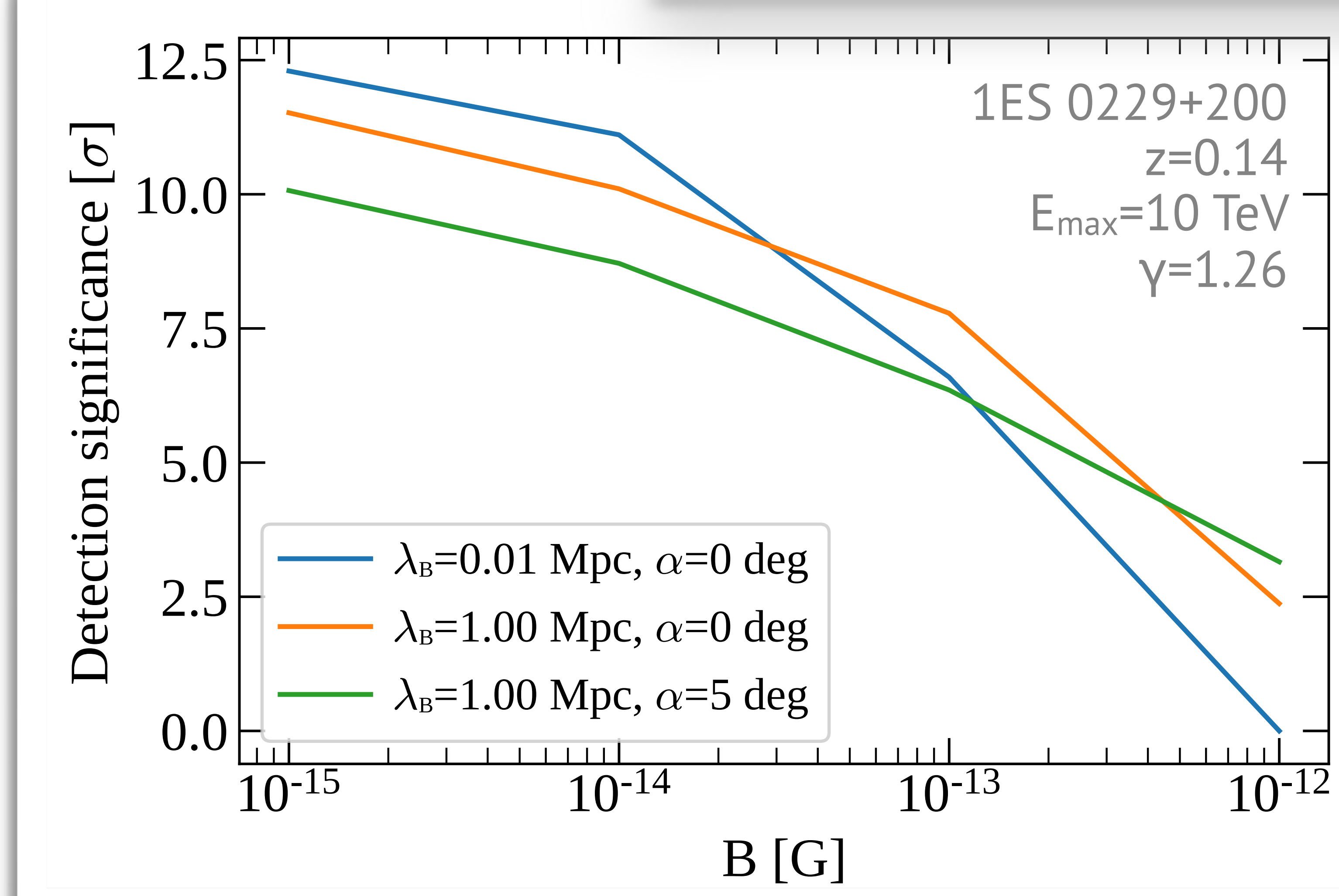


cherenkov telescope array

see talk by
Jonathan Biteau



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(selected) gamma-ray constraints on IGMFs

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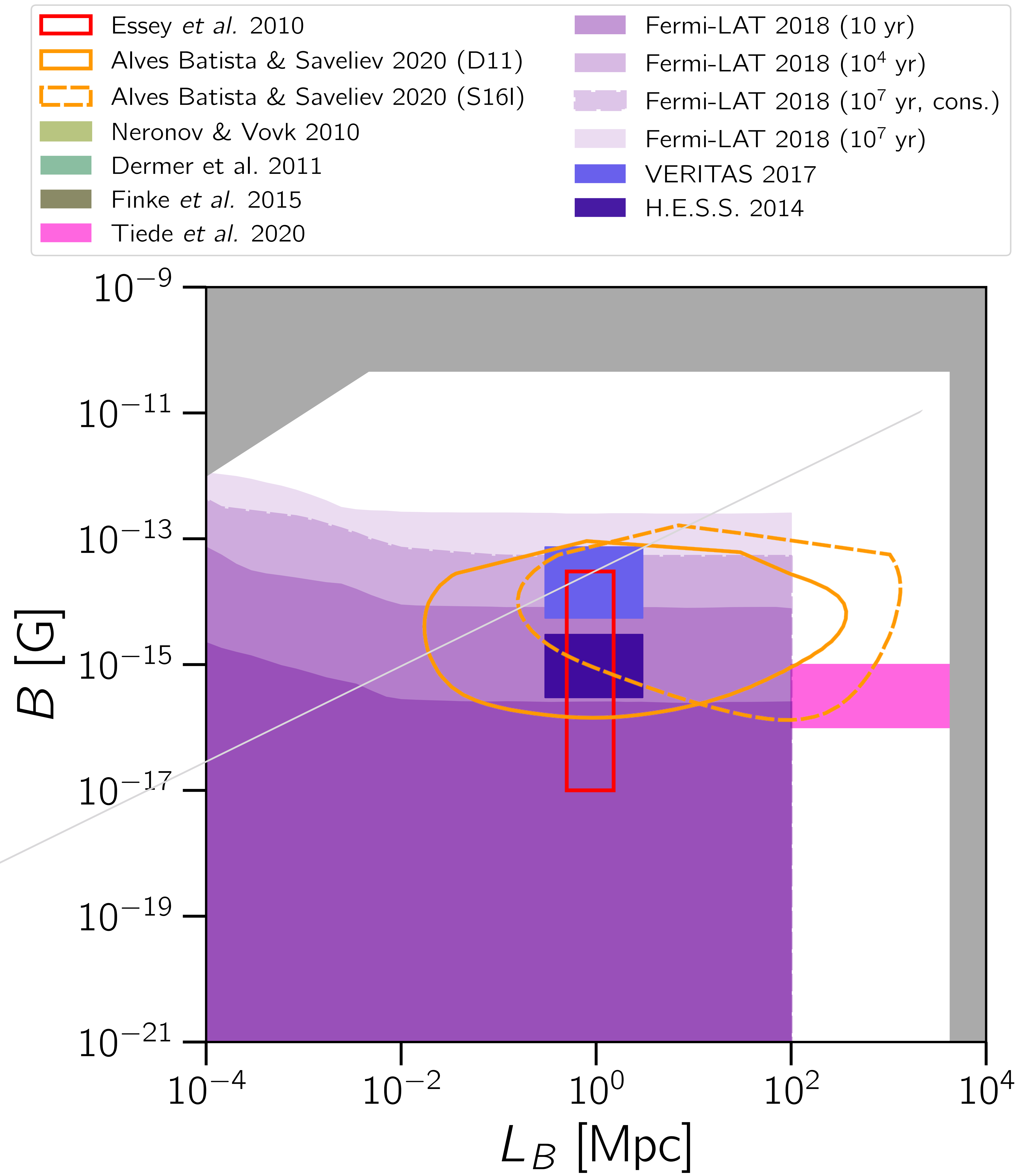

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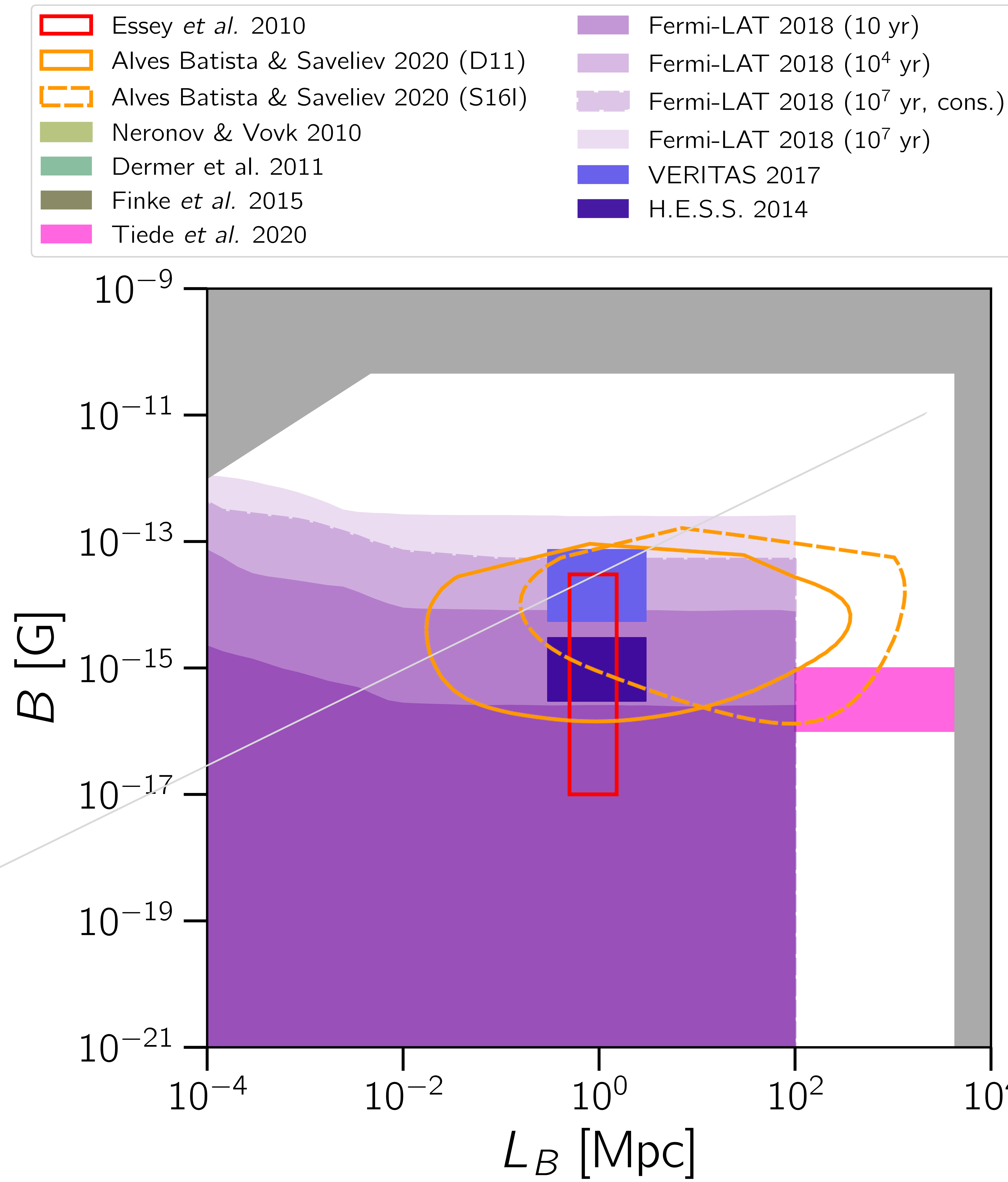

results highly **model-dependent**

pair production
$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$
inverse Compton scattering
$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$
γ
e-
e+
γ
γ
e+
e-

building a model

model


pair production
γ + γbg → e+ + e-
inverse Compton scattering
e± + γbg → e± + γ
γ
e-
e+
γ
γ
e+
e-


model
astrophysical inputs (source)
pair production
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γ
e^-
e^+
γ
γ
e^+
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model
spectrum
temporal properties
related messengers
astrophysical inputs (source)
pair production
γ + γbg → e+ + e-
inverse Compton scattering
e± + γbg → e± + γ
γ
e-
e+
γ
γ
e+
e-

building a model

model

spectrum
temporal properties
related messengers

astrophysical inputs (source)

particle acceleration
particle interactions
magnetic fields

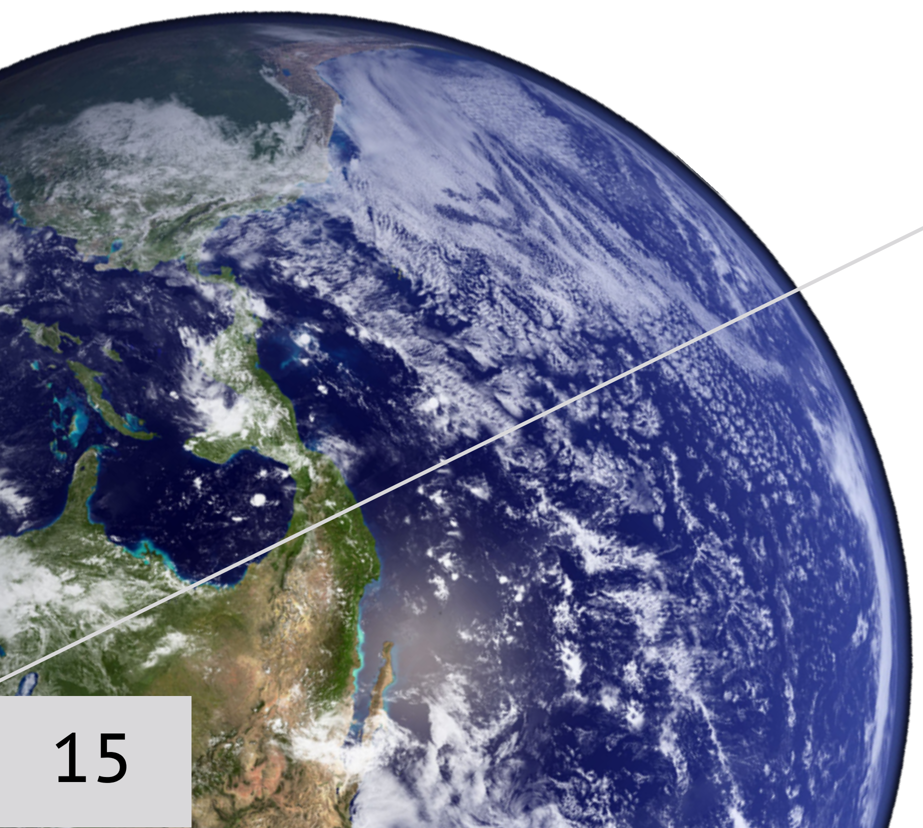
propagation details

building a model


model
astrophysical inputs (source)
spectrum
temporal properties
related messengers
propagation details
particle acceleration
particle interactions
magnetic fields
observables
energy spectrum
arrival directions
arrival times
pair production
γ + γbg → e+ + e-
inverse Compton scattering
e± + γbg → e± + γ
γ
e-
e+

building a model

- **uncertainties**
  - EBL
  - IGMF distribution
  - source properties
  - ...
- **other effects?**



modelling electromagnetic cascades: a numerical strategy

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modelling electromagnetic cascades: a numerical strategy

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modelling electromagnetic cascades: a numerical strategy

Δx

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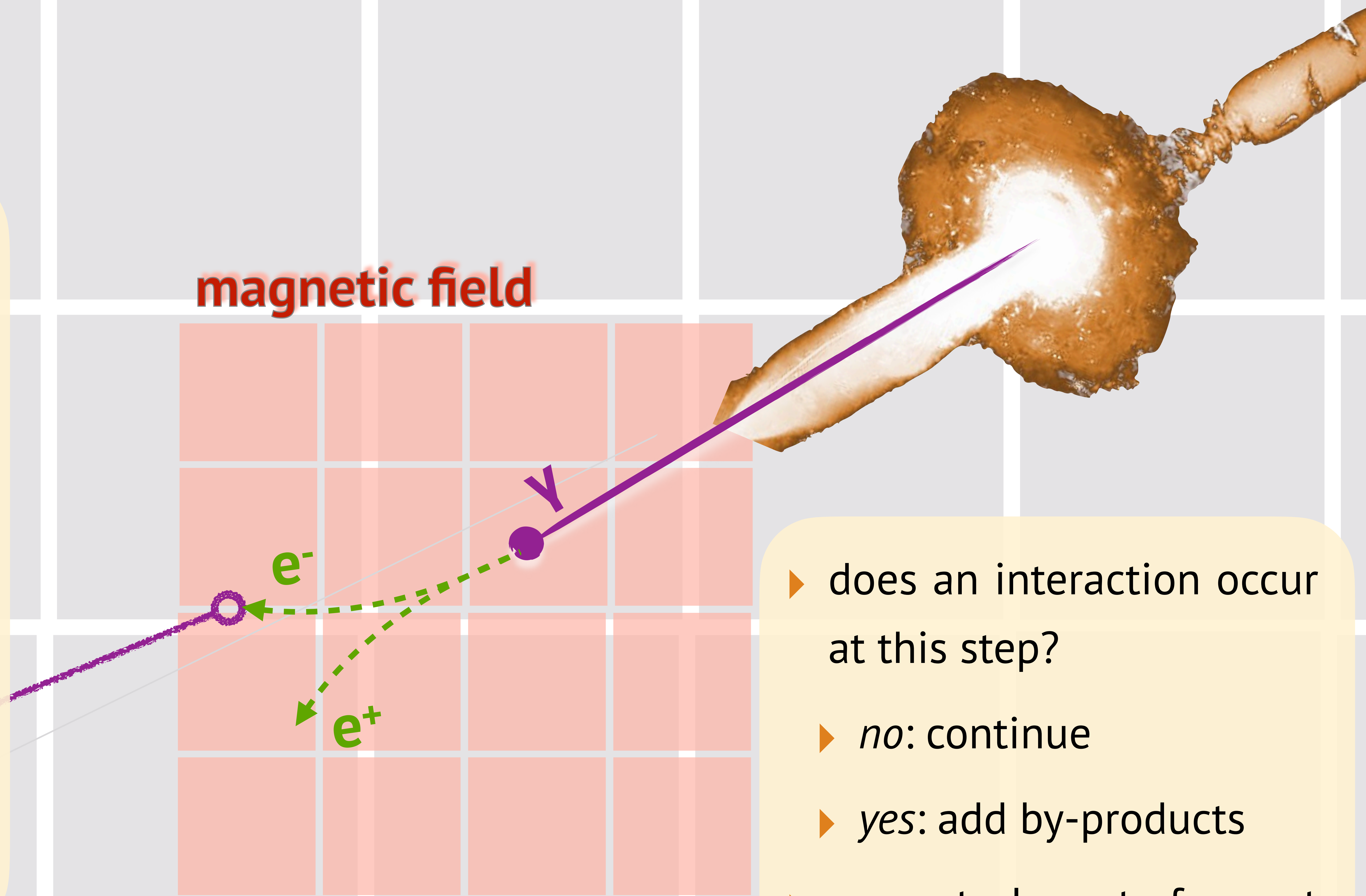
  - large: speed up simulation



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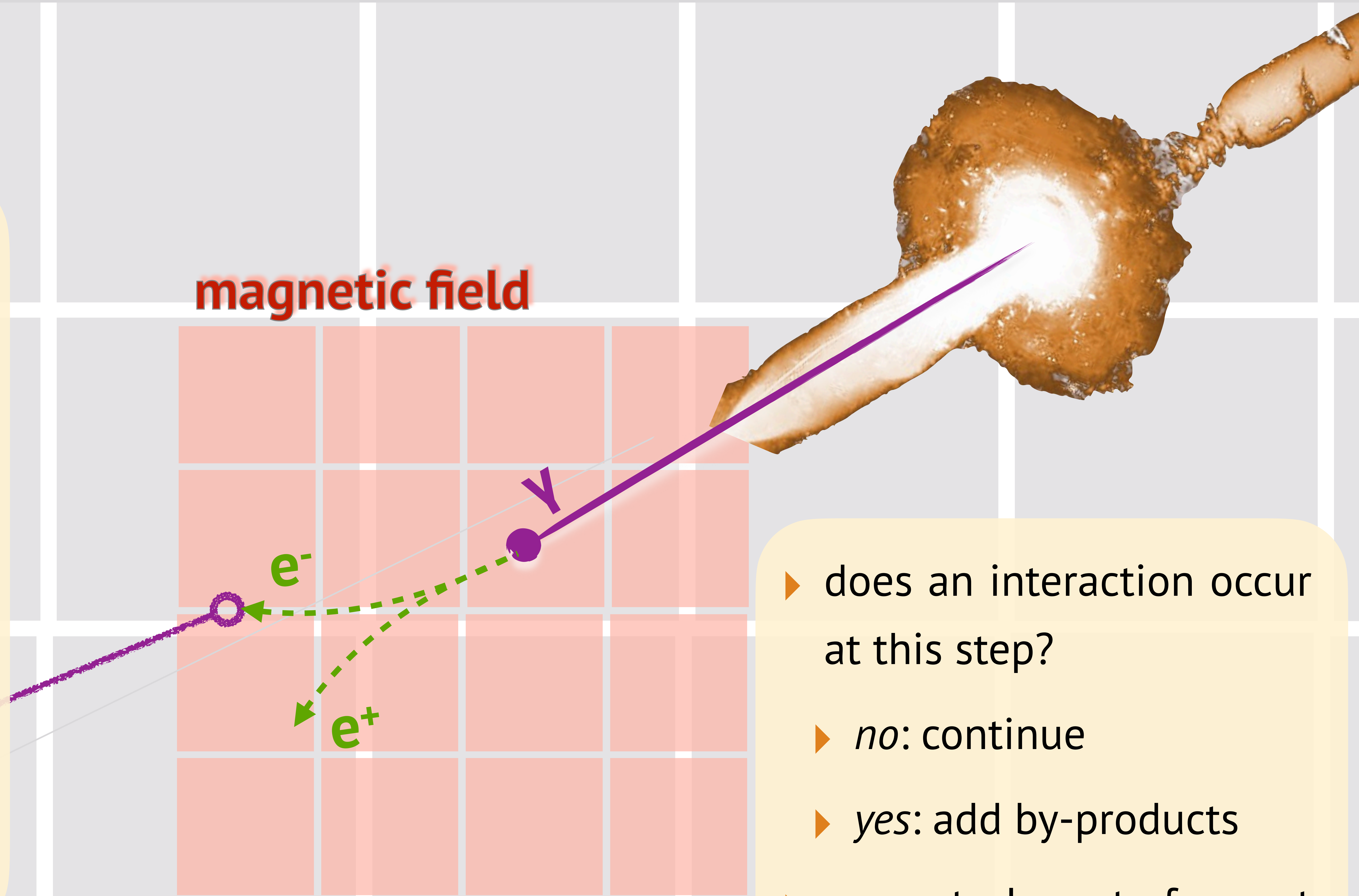

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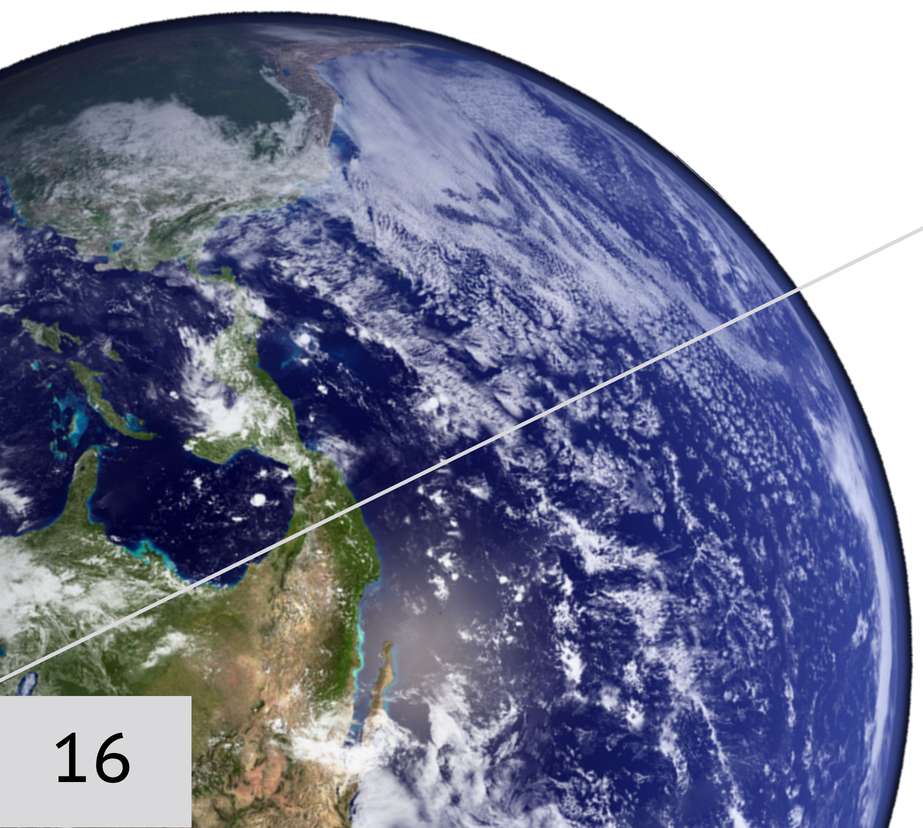
plasma instabilities: do they quench electromagnetic cascades?




γ
pair production
γ + γbg → e⁺ + e⁻

plasma instabilities: do they quench electromagnetic cascades?

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

inverse Compton scattering

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see talk by
Mahmoud Alawashra

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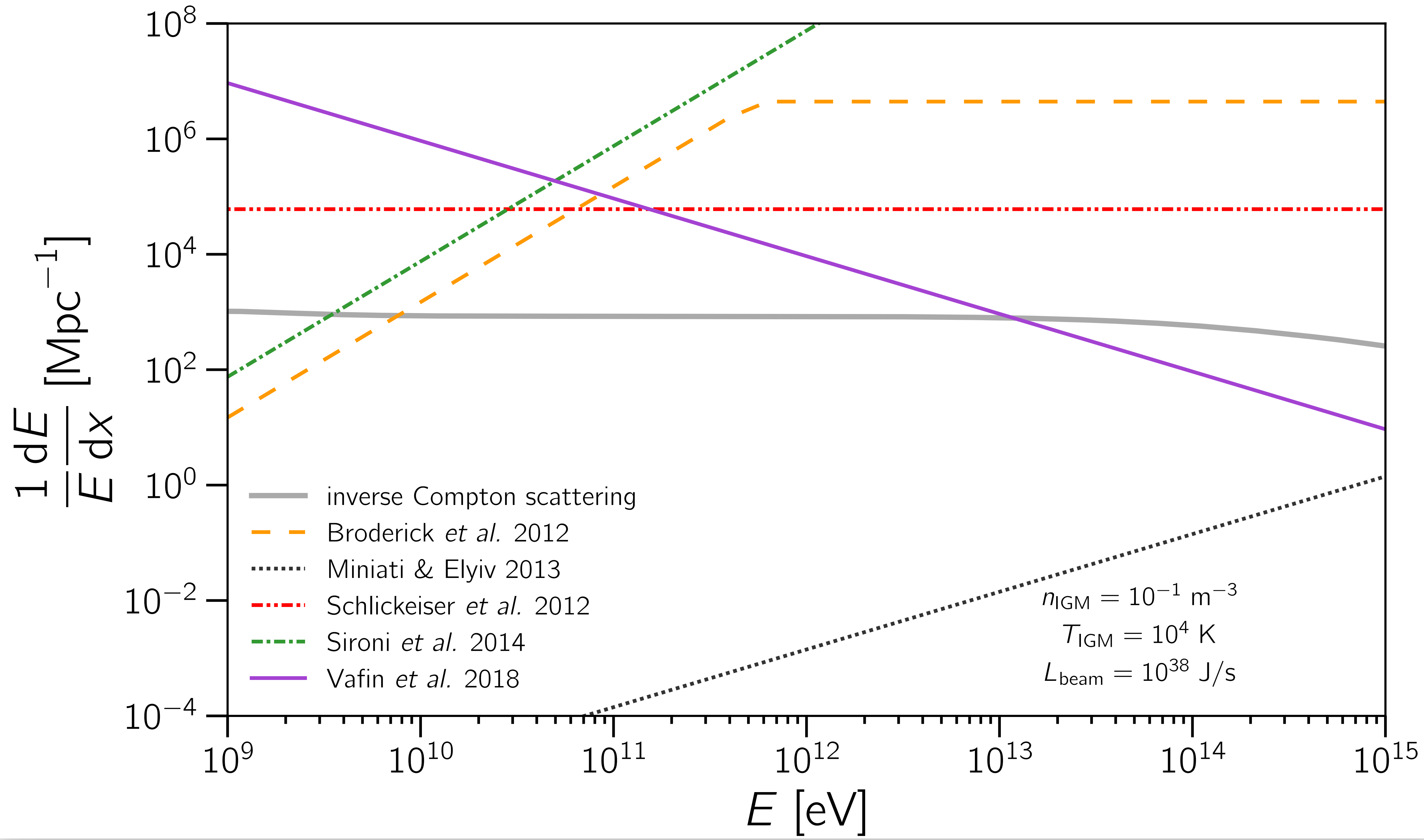

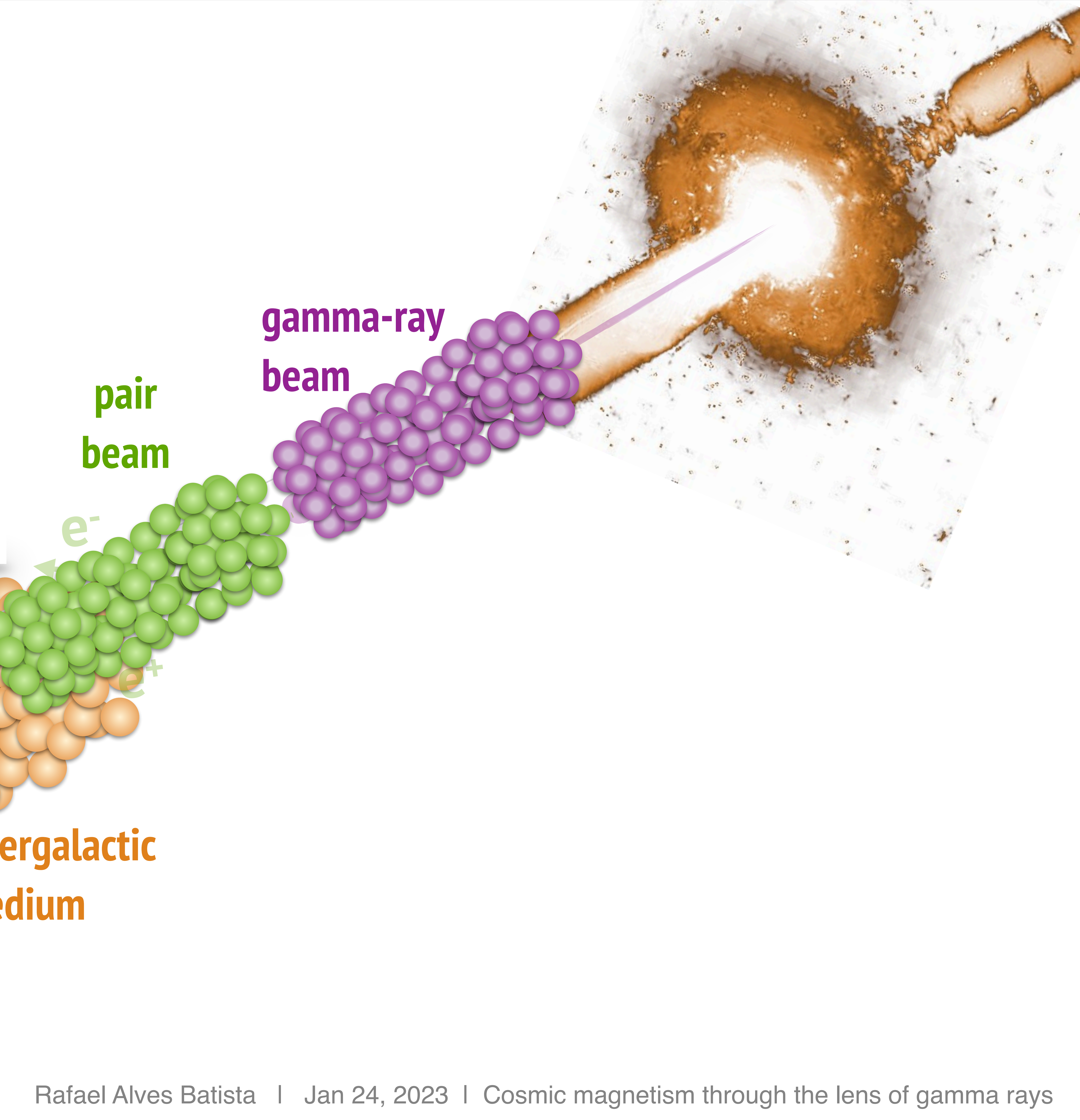

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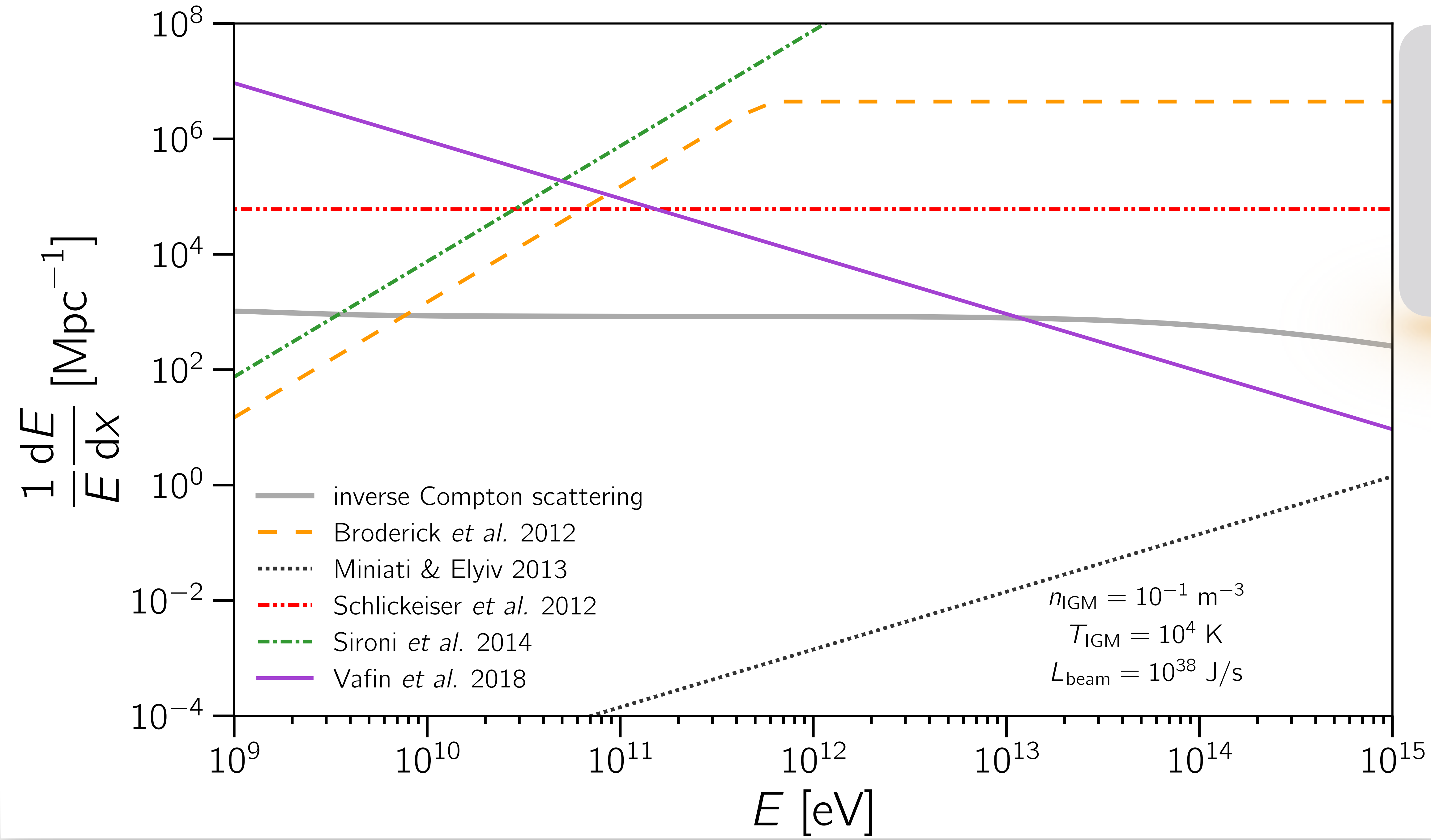

implemented in the GRPLINST module for CRPropa

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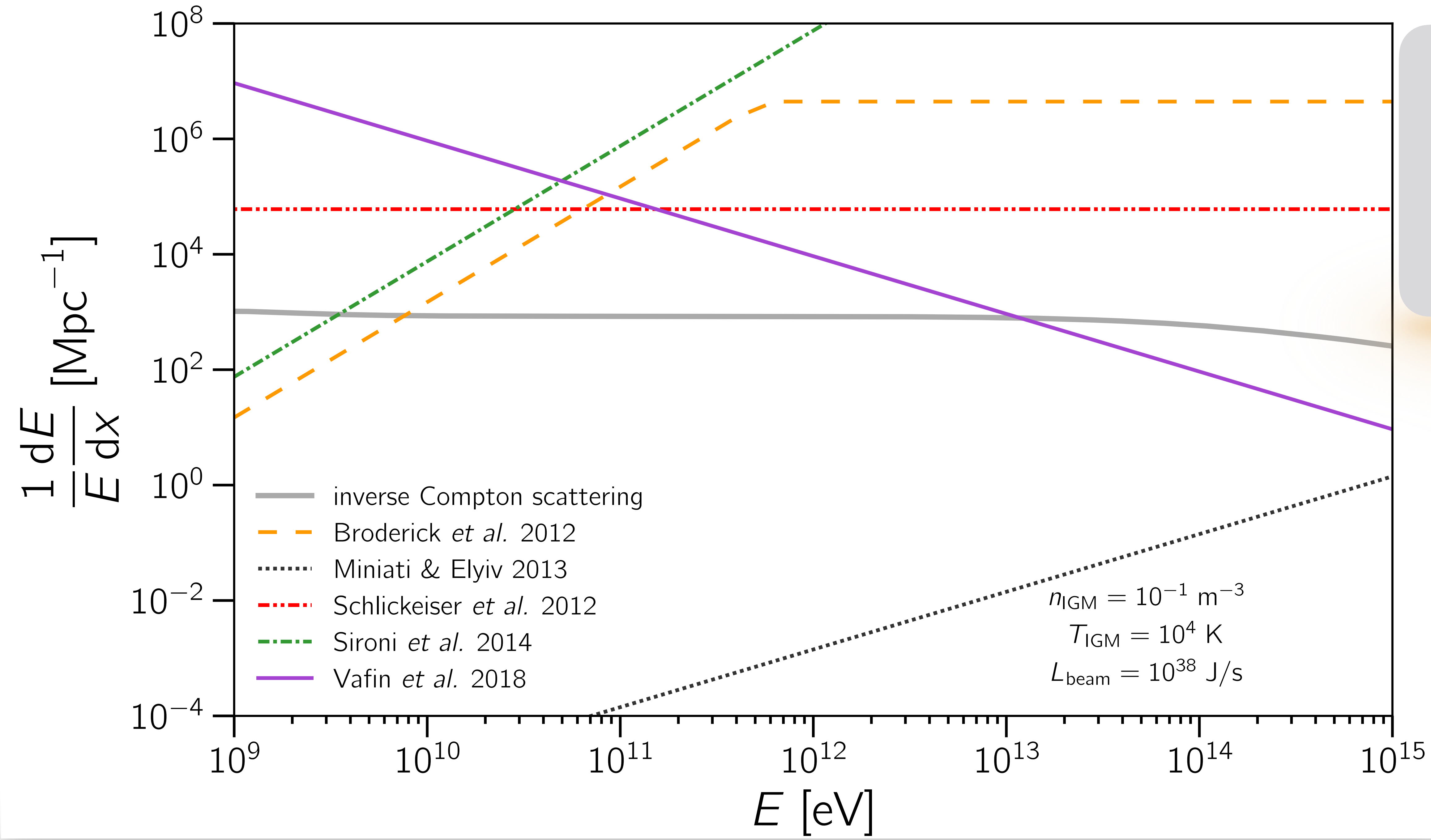

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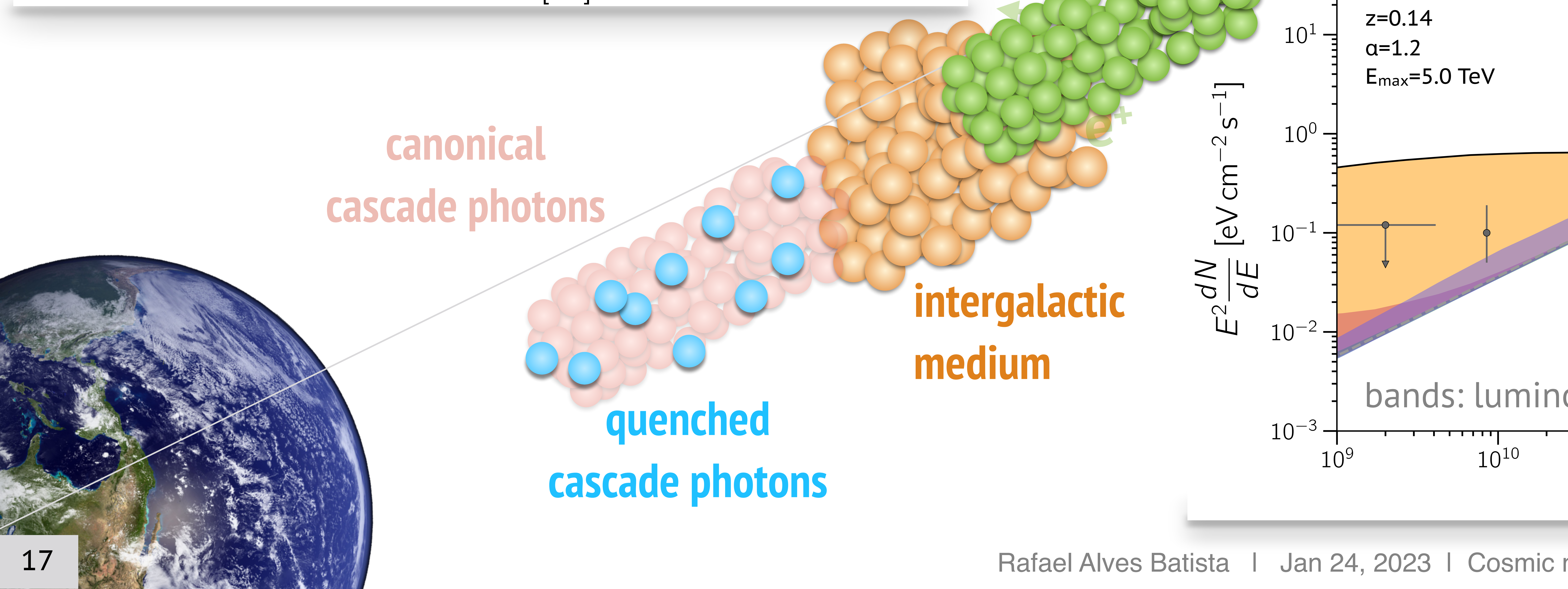

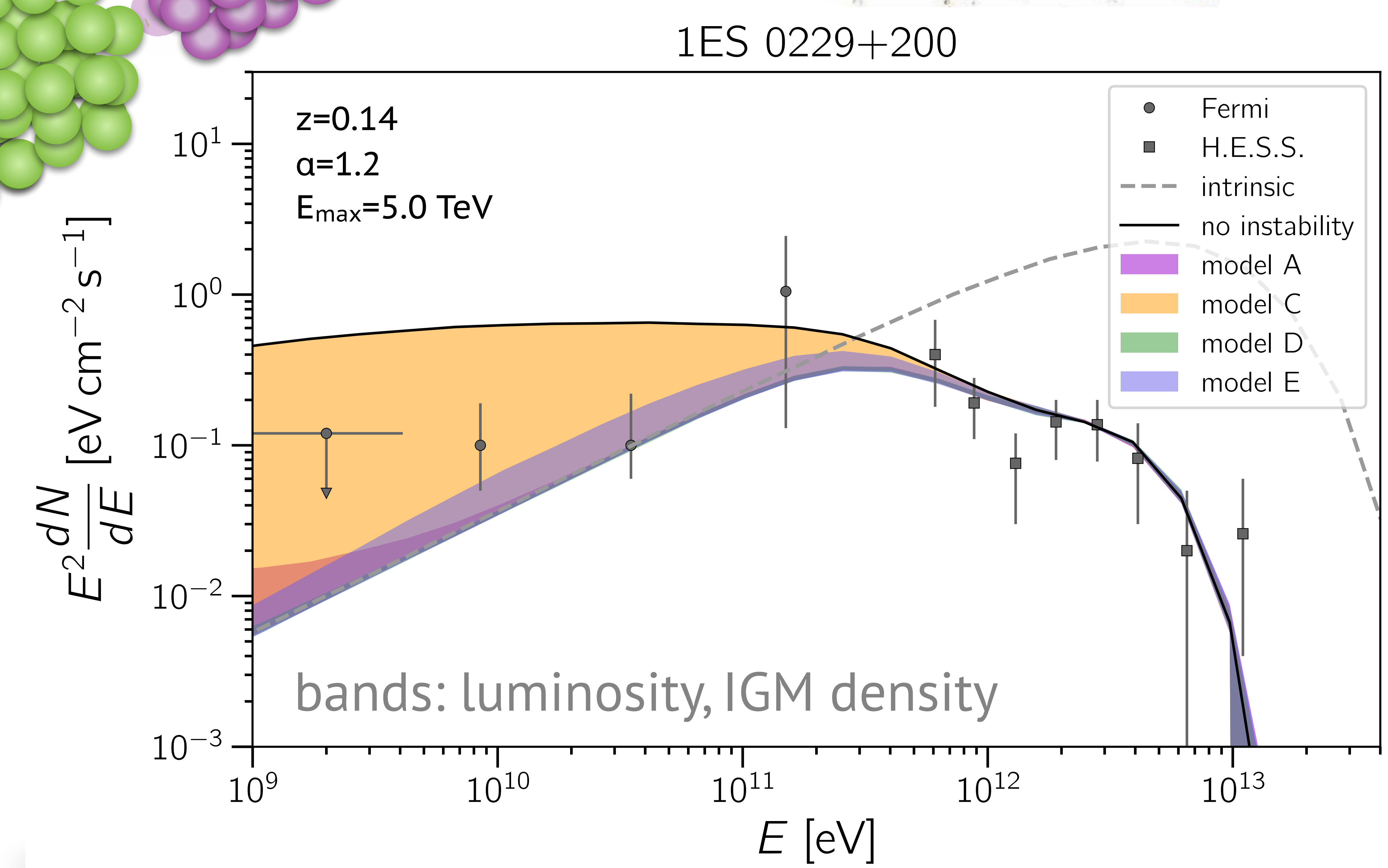

- helicity: $\mathscr{H} = \int d^3r \overrightarrow{A} \cdot \overrightarrow{B}$
- helicity is approximately conserved → helical IGMFs in voids could be (mostly) undisturbed → window to early universe
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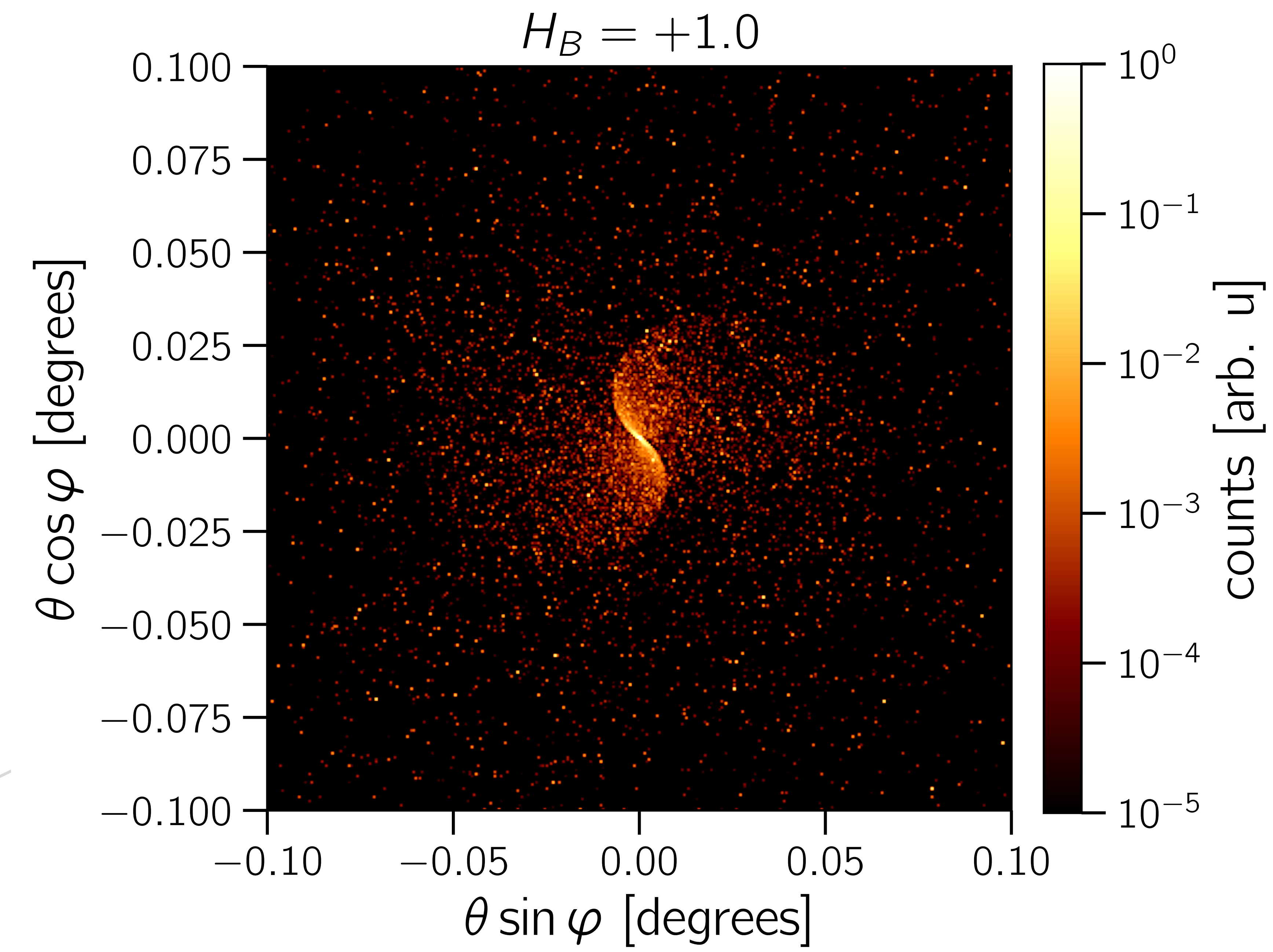

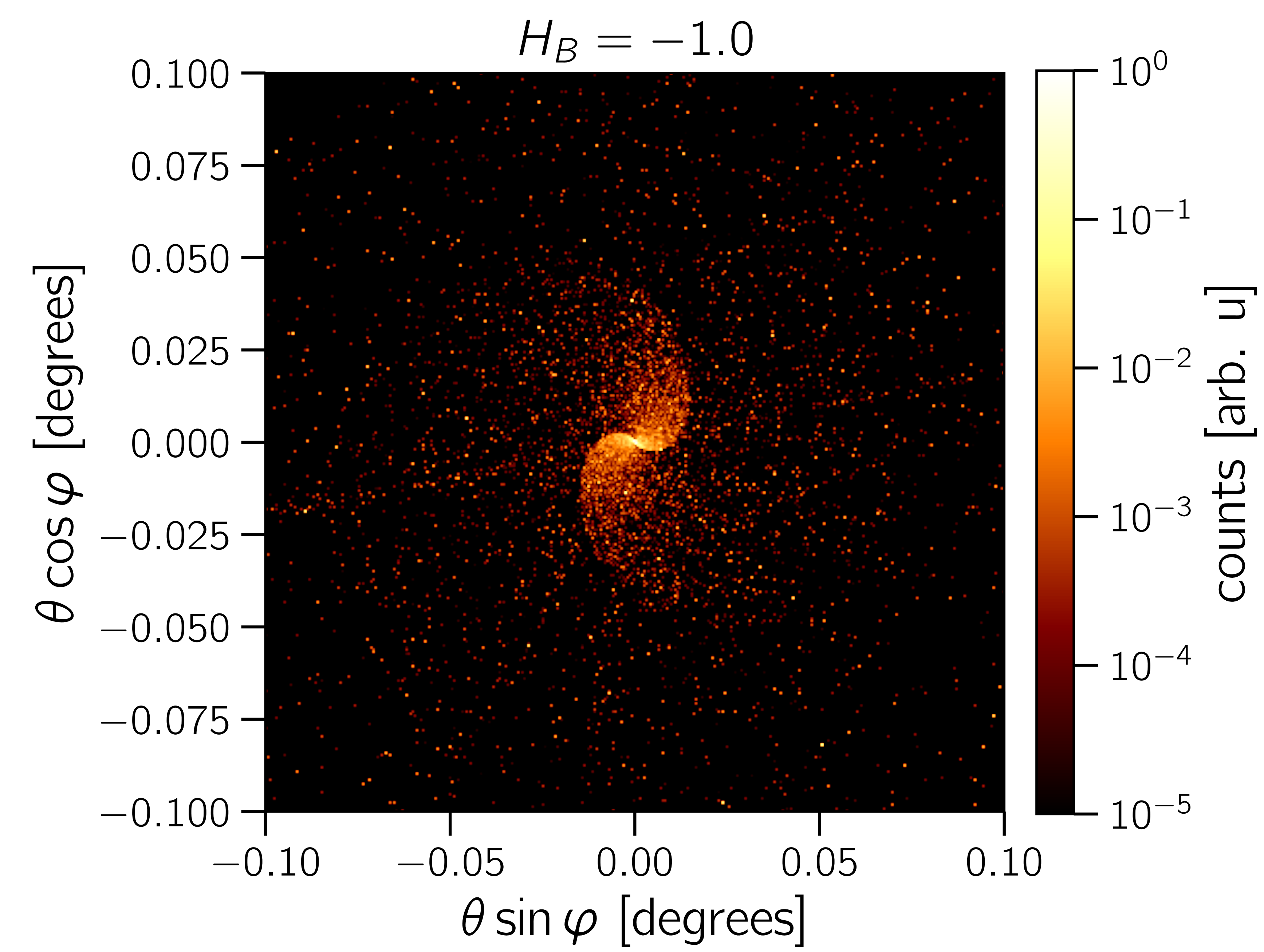

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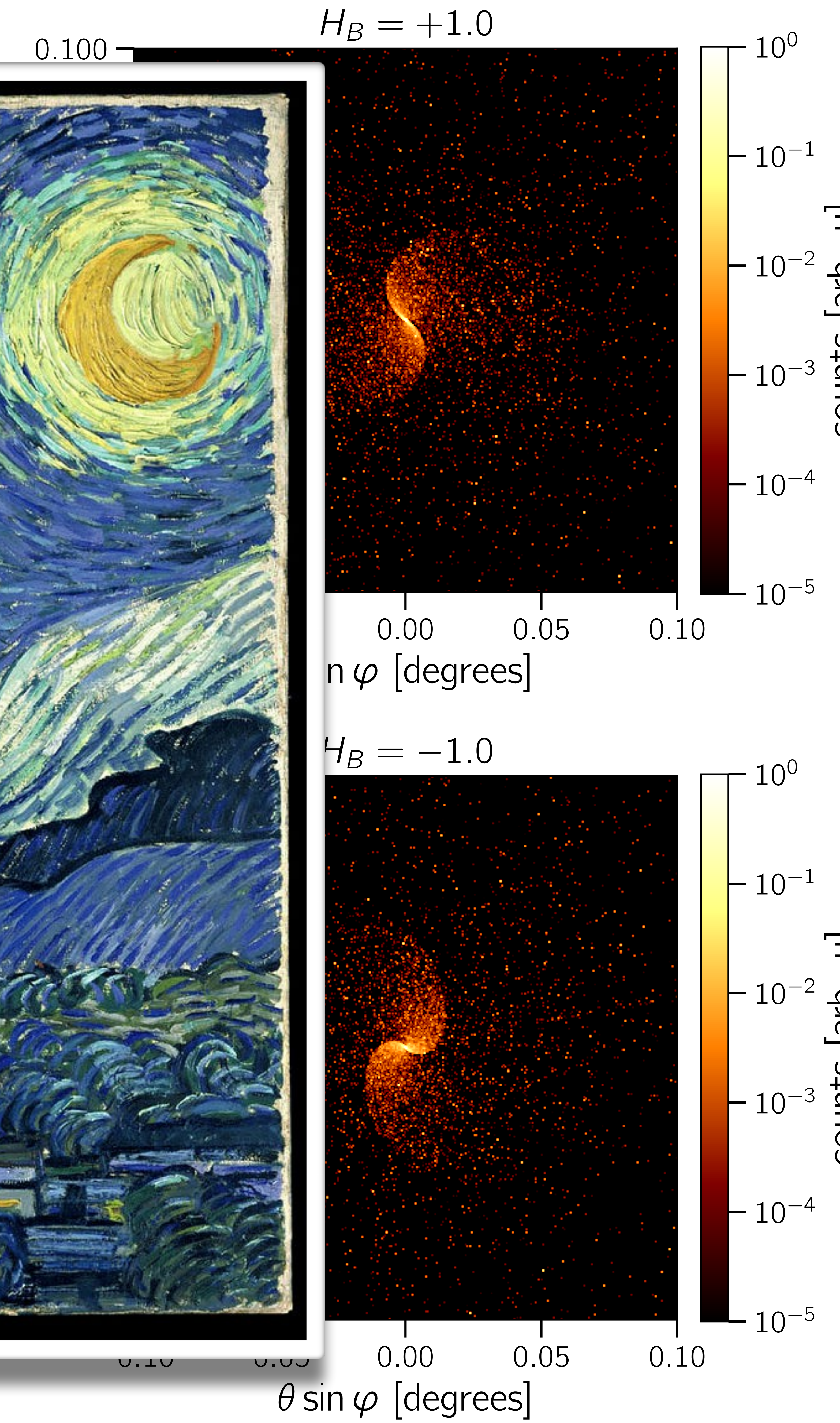
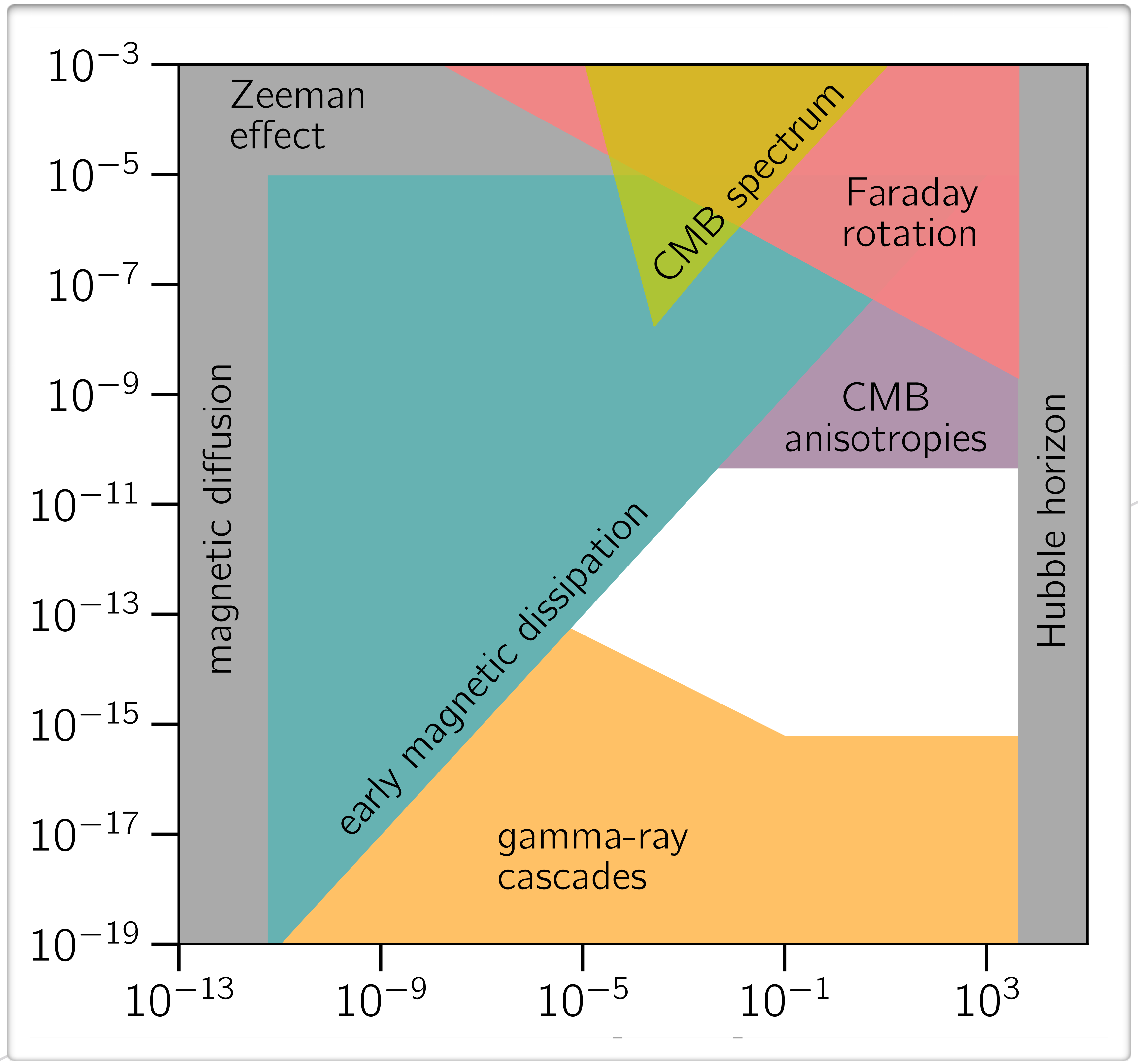
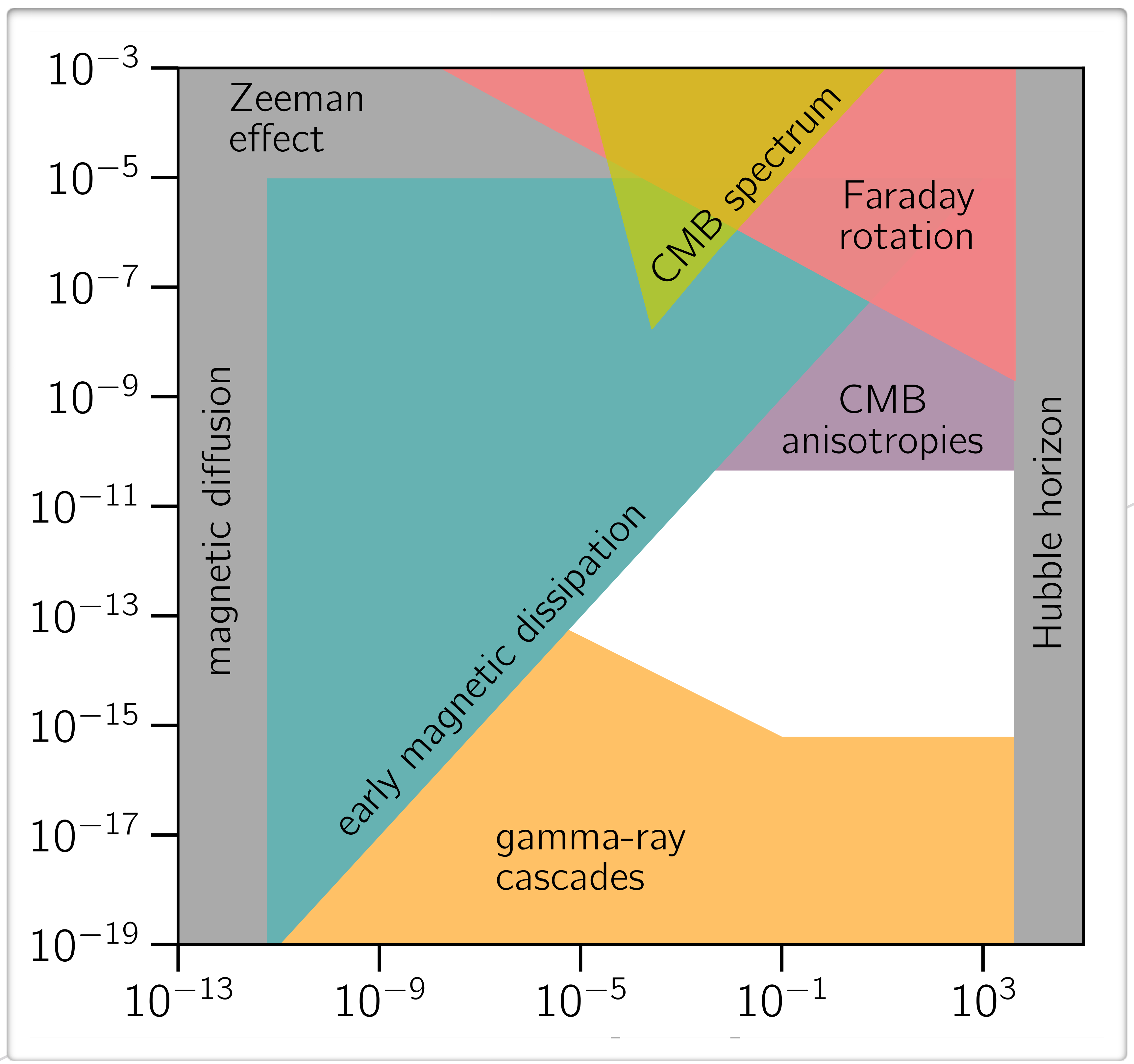


gamma-ray constraints on IGMFs: *quo vadis*?

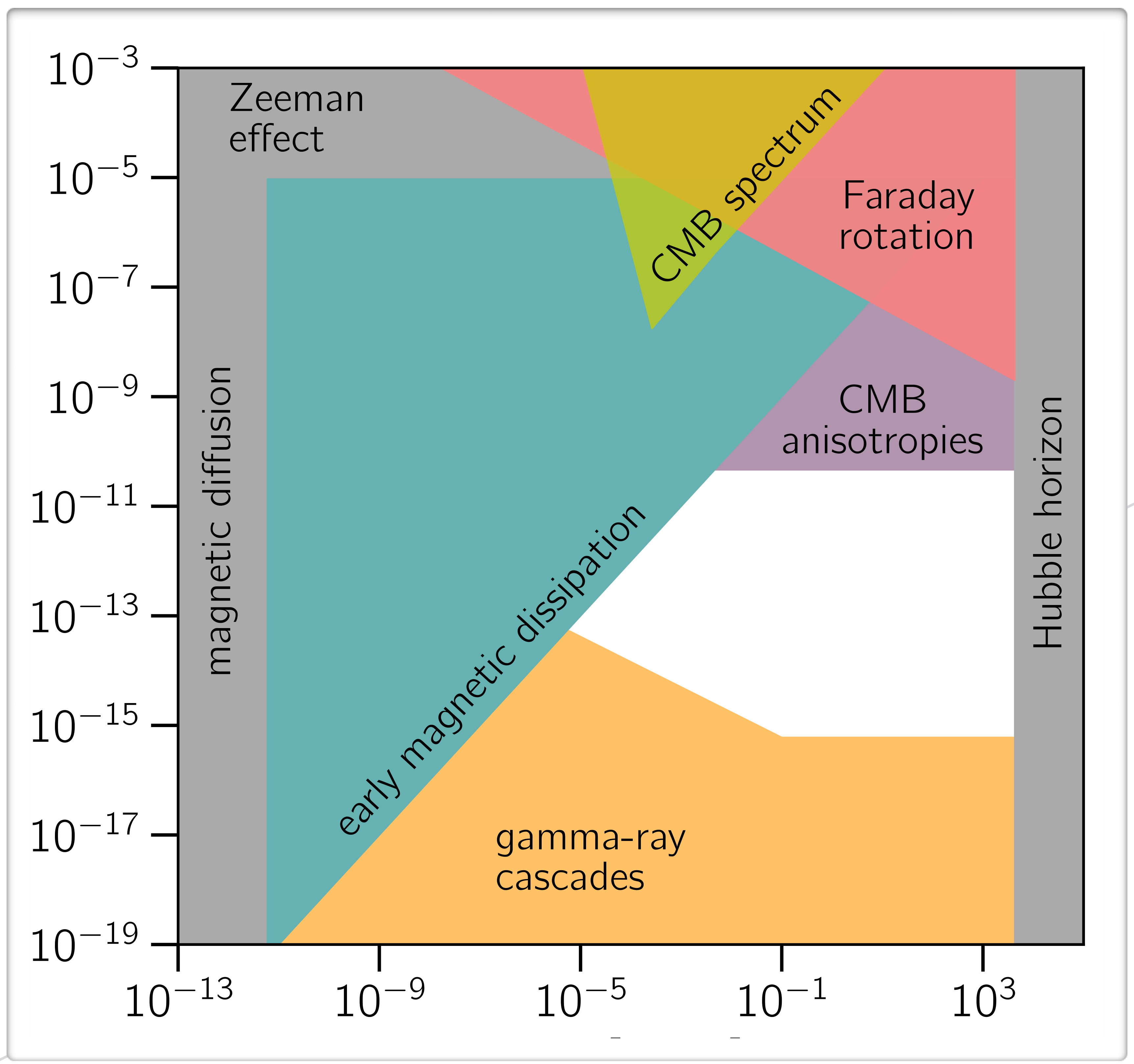


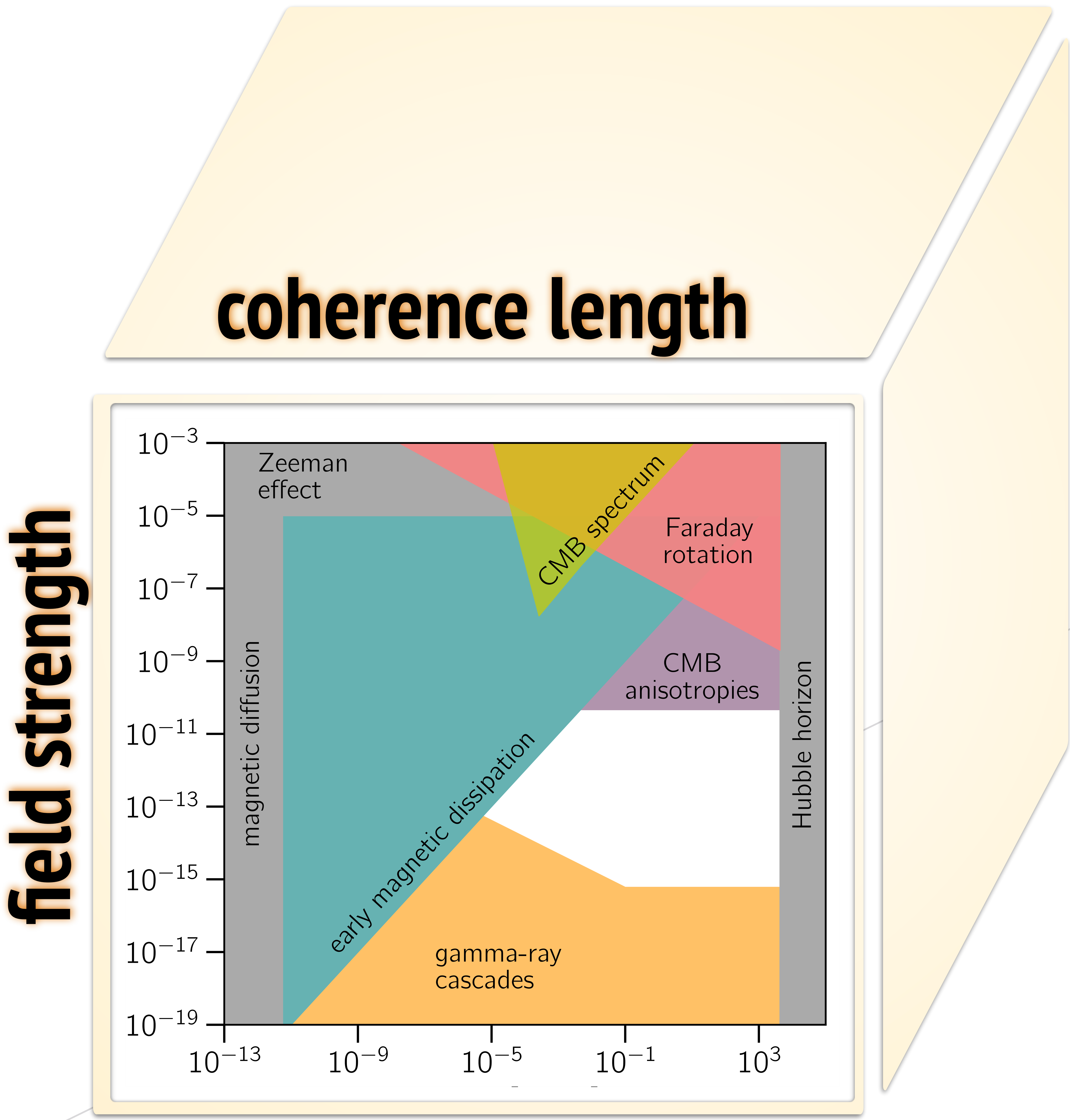
field strength



coherence length

field strength




coherence length
field strength
Zeeman effect
CMB spectrum
Faraday rotation
CMB anisotropies
magnetic diffusion
early magnetic dissipation
gamma-ray cascades
Hubble horizon
10^{-3}
10^{-5}
10^{-7}
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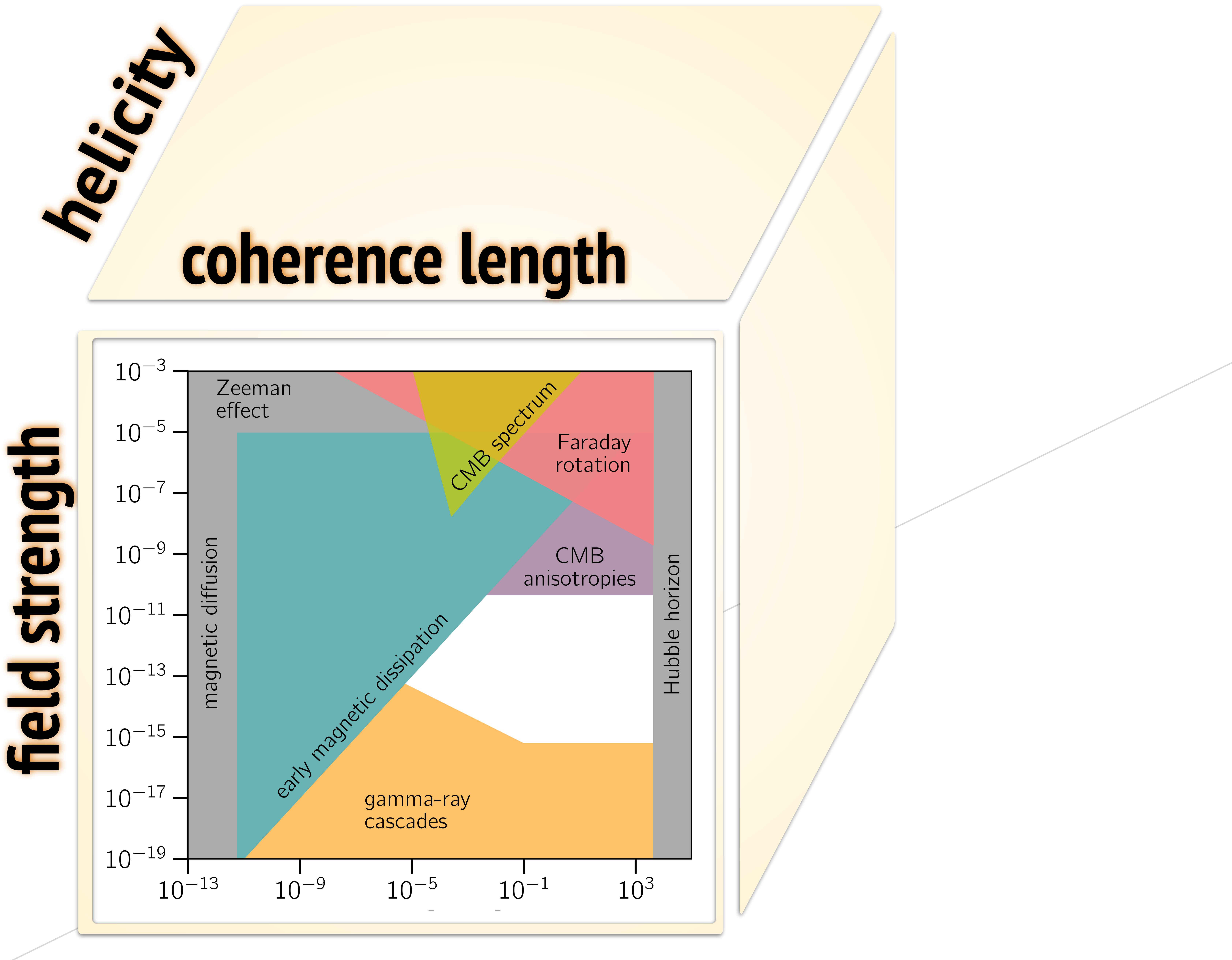

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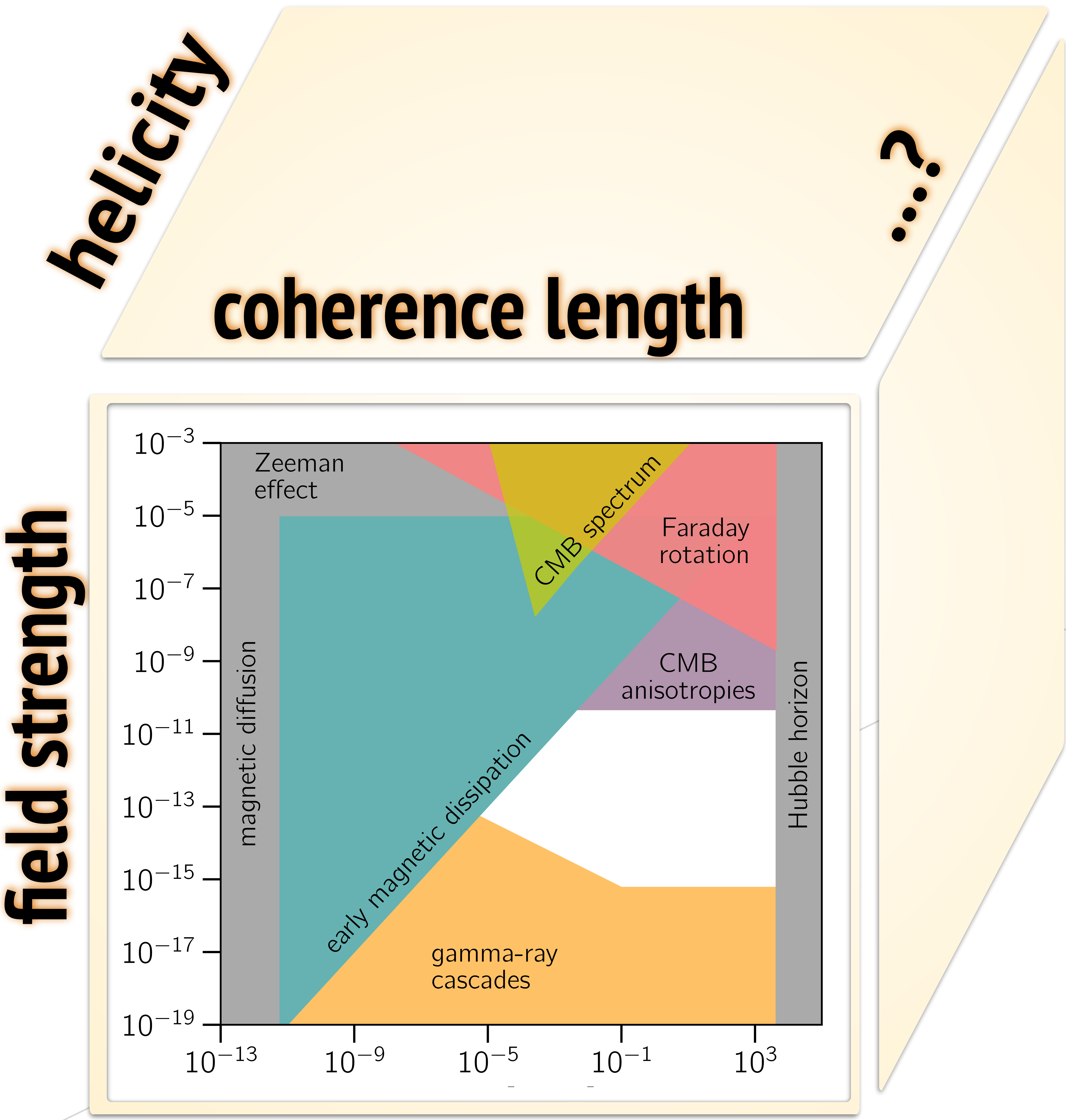

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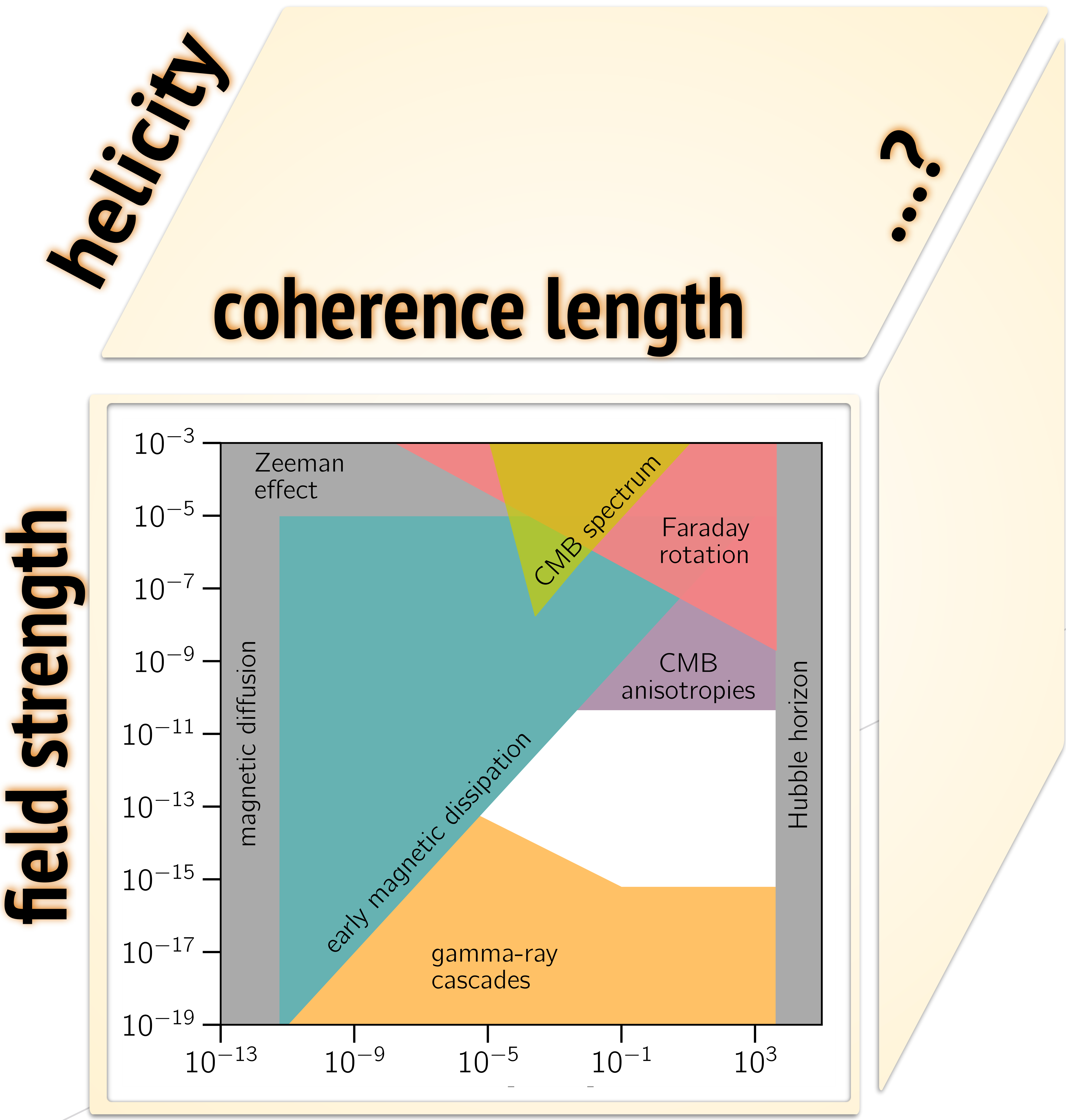


large-scale distribution
vs.
"statistical" properties

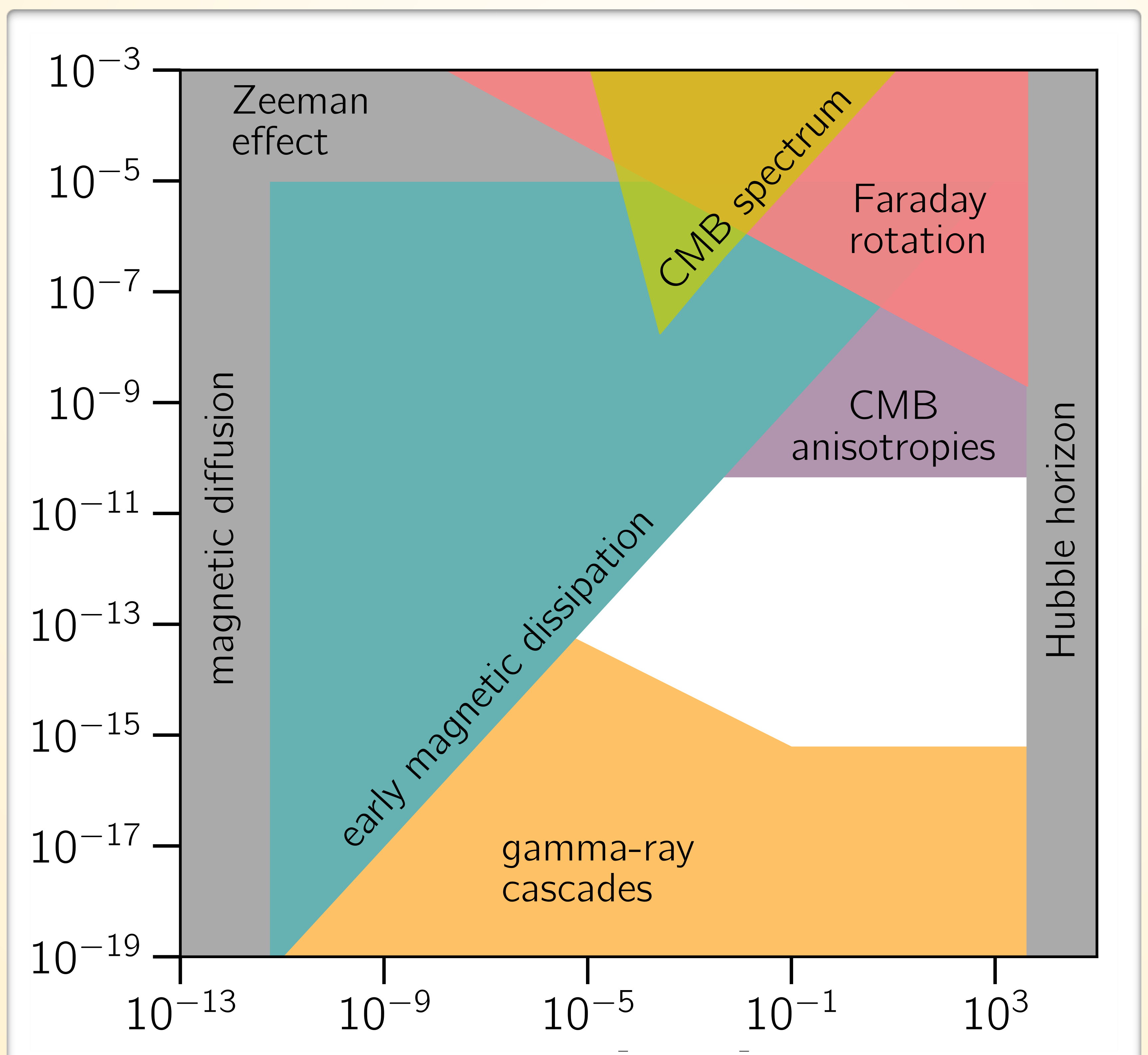
gamma-ray constraints on IGMFs: *quo vadis*?

helicity

coherence length

...?

field strength



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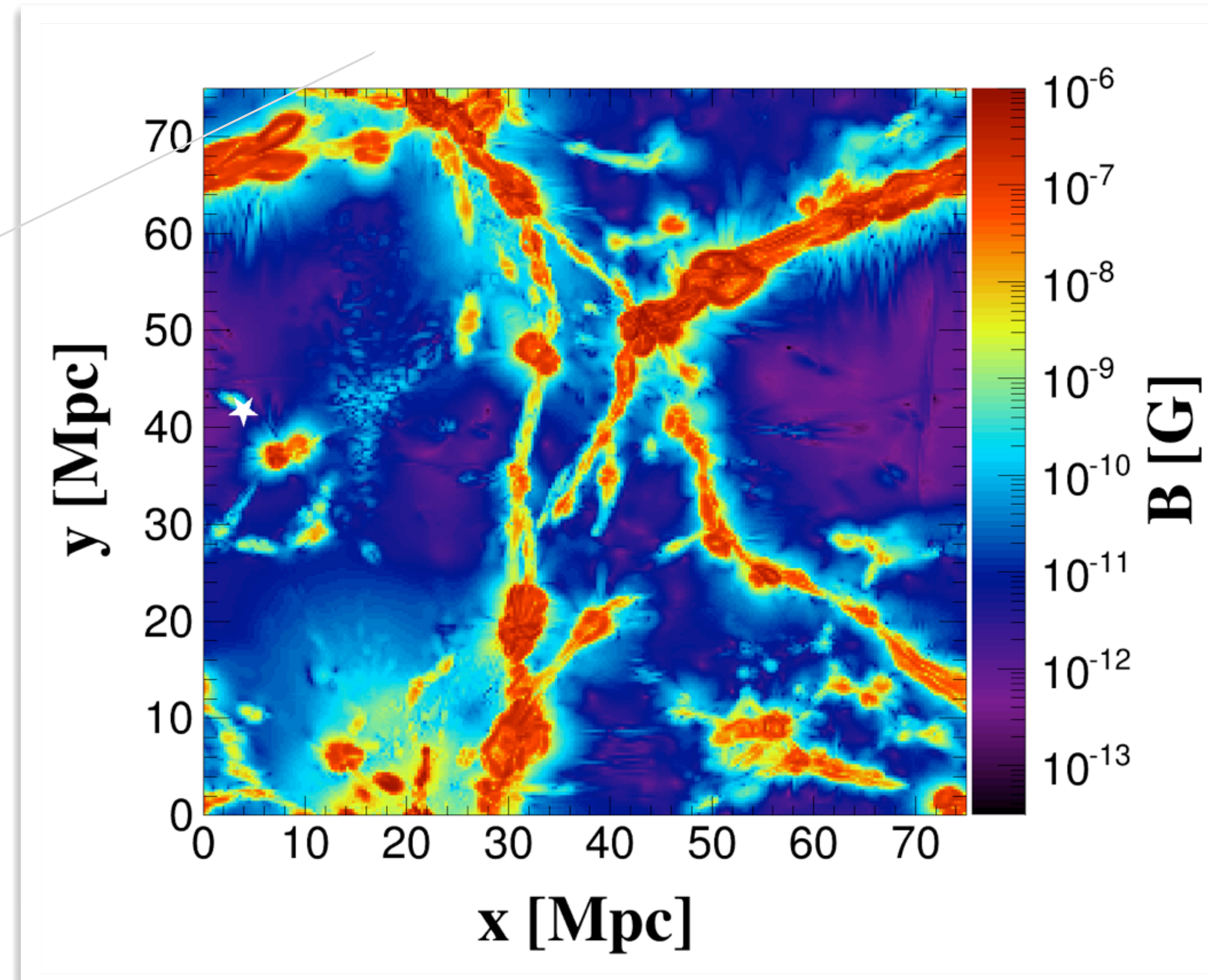

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propagation model

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gamma-ray observations

propagation model

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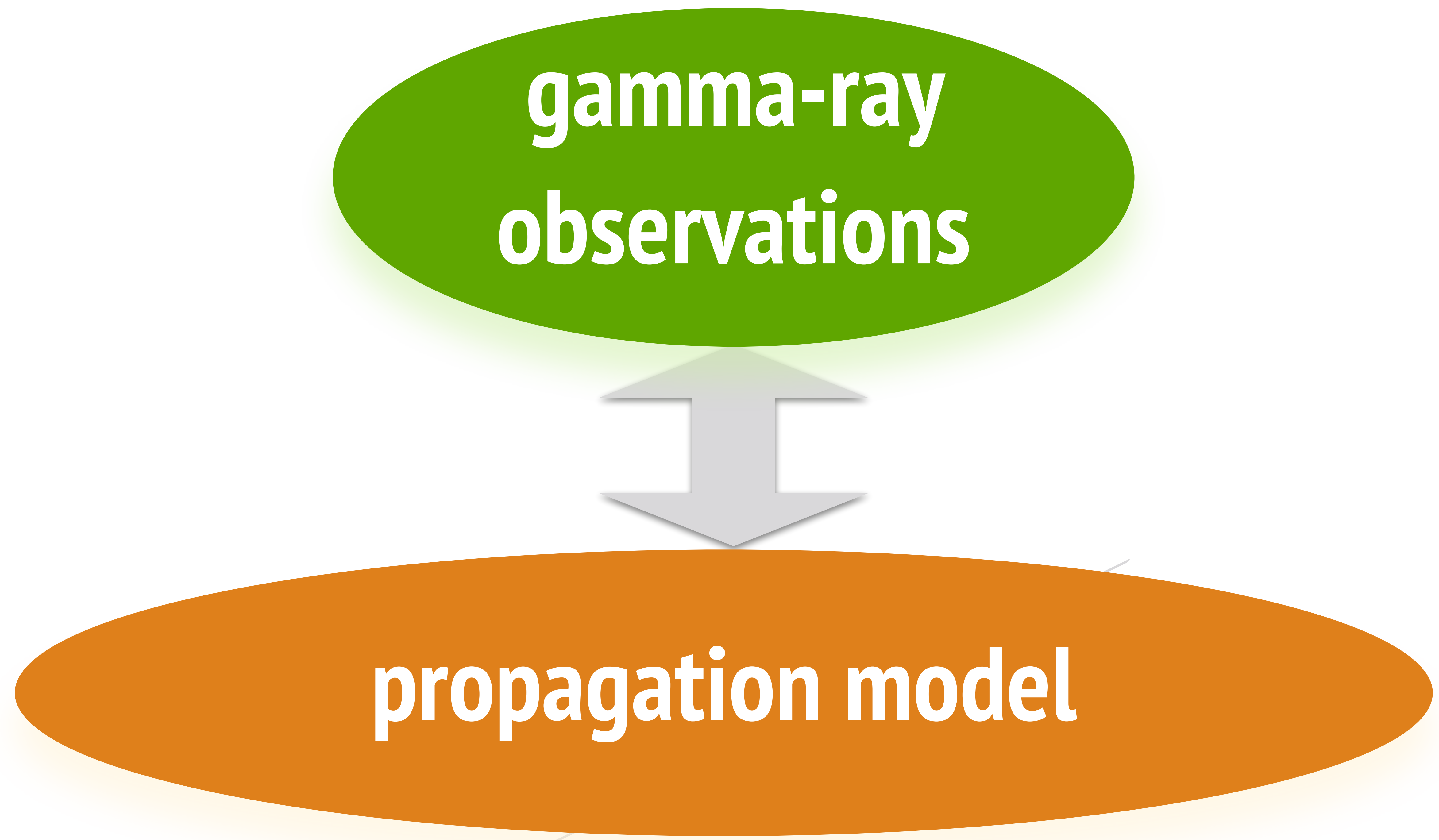
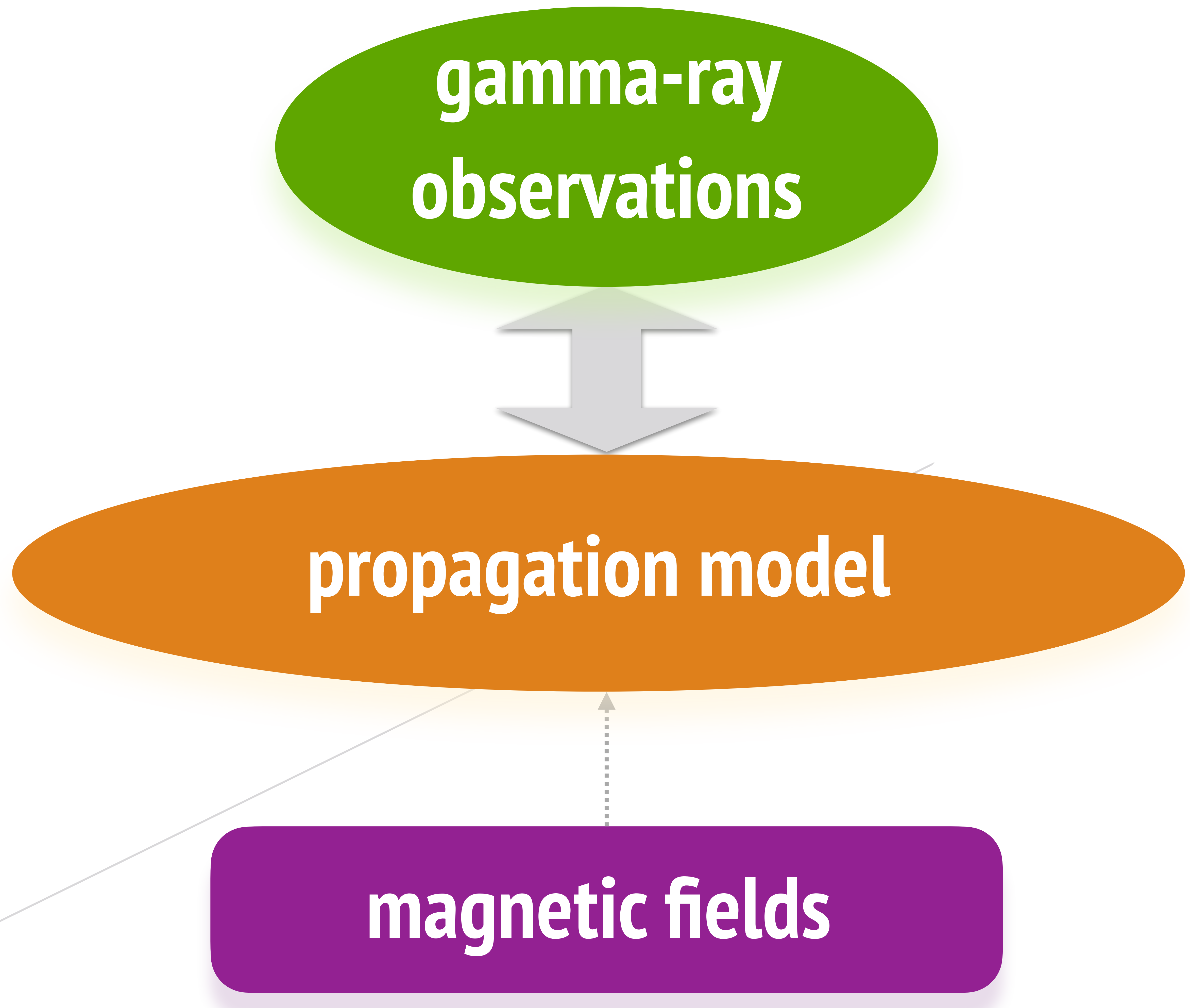
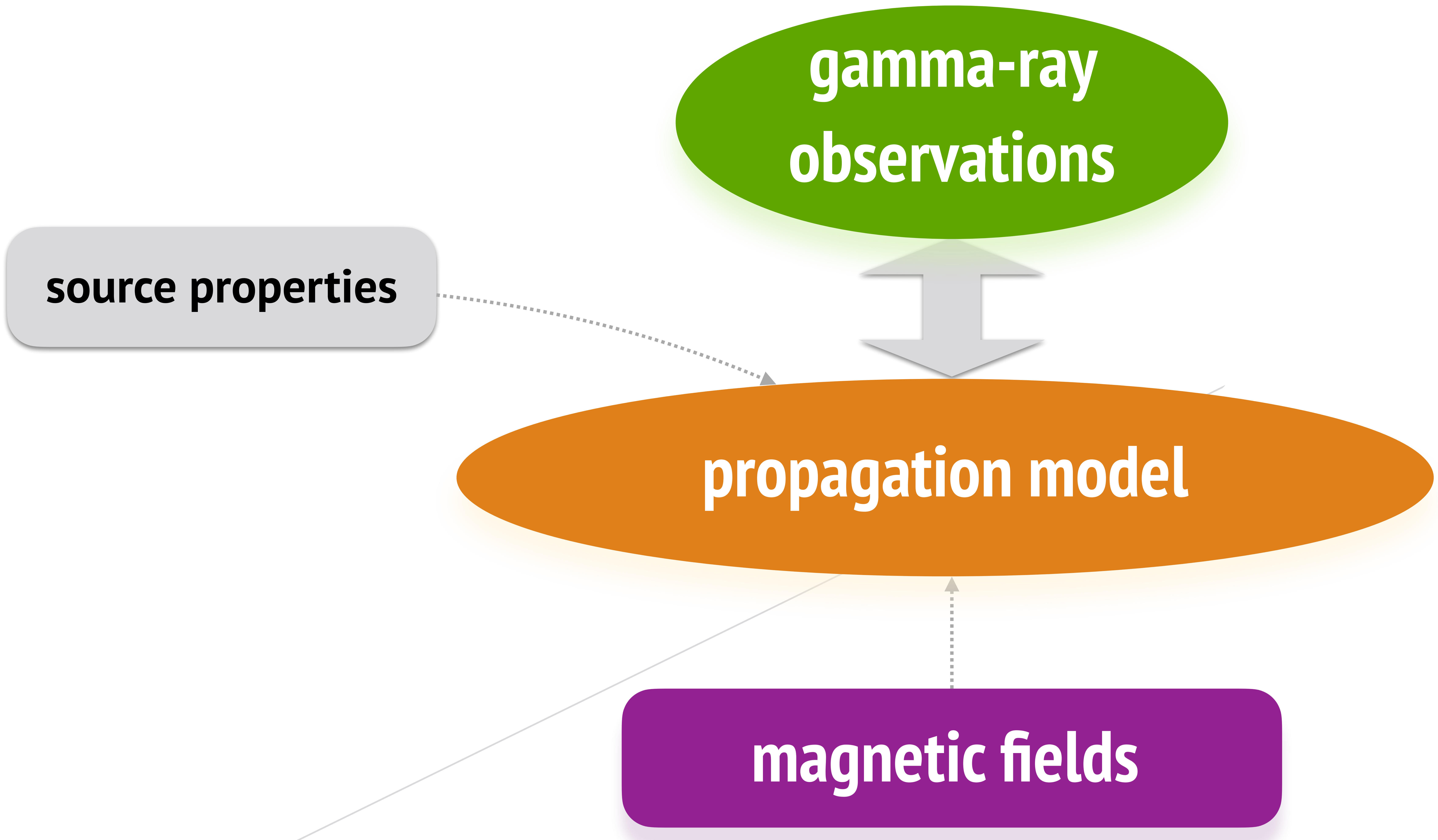



gamma-ray observations
propagation model
magnetic fields


gamma-ray
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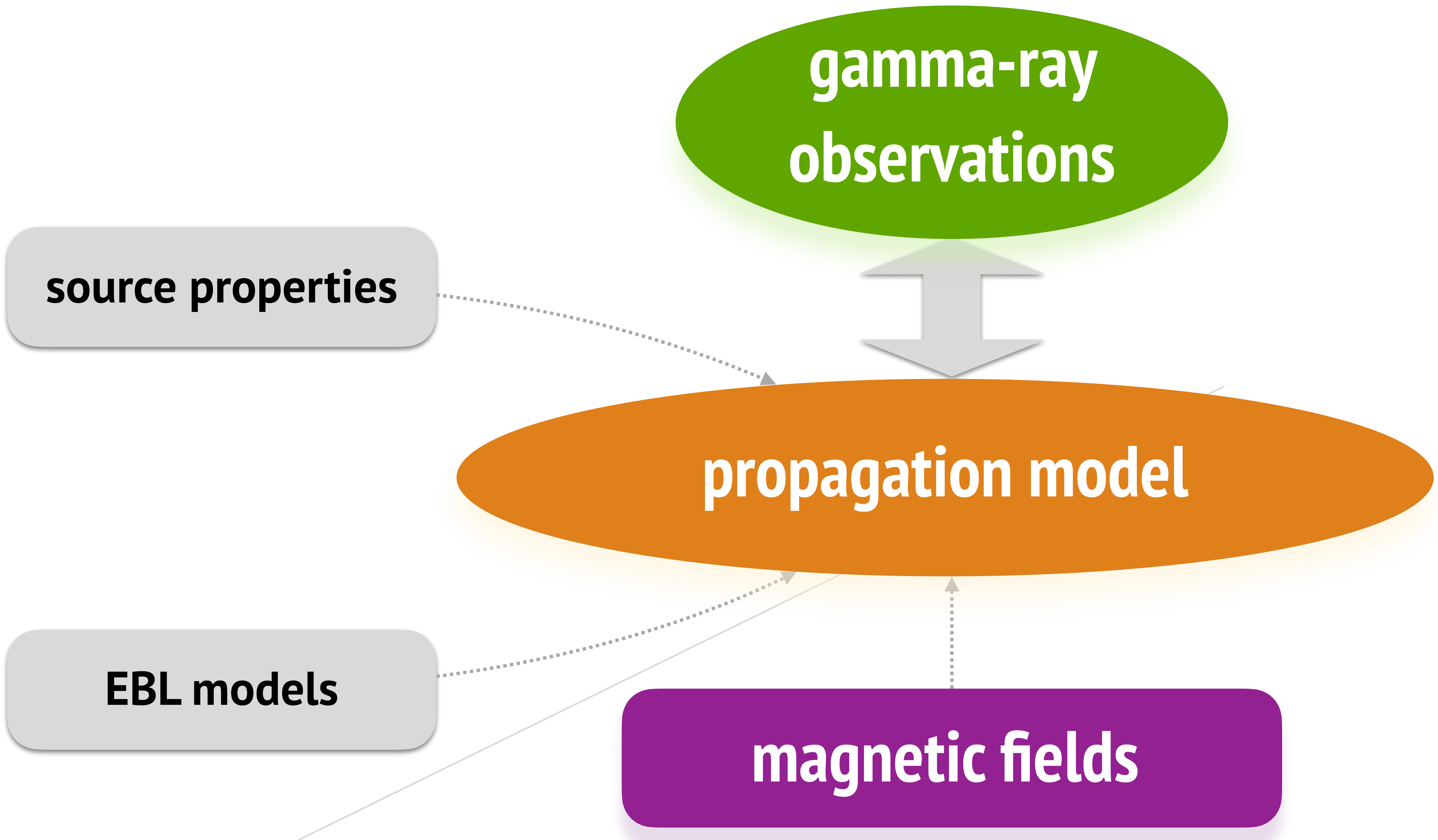
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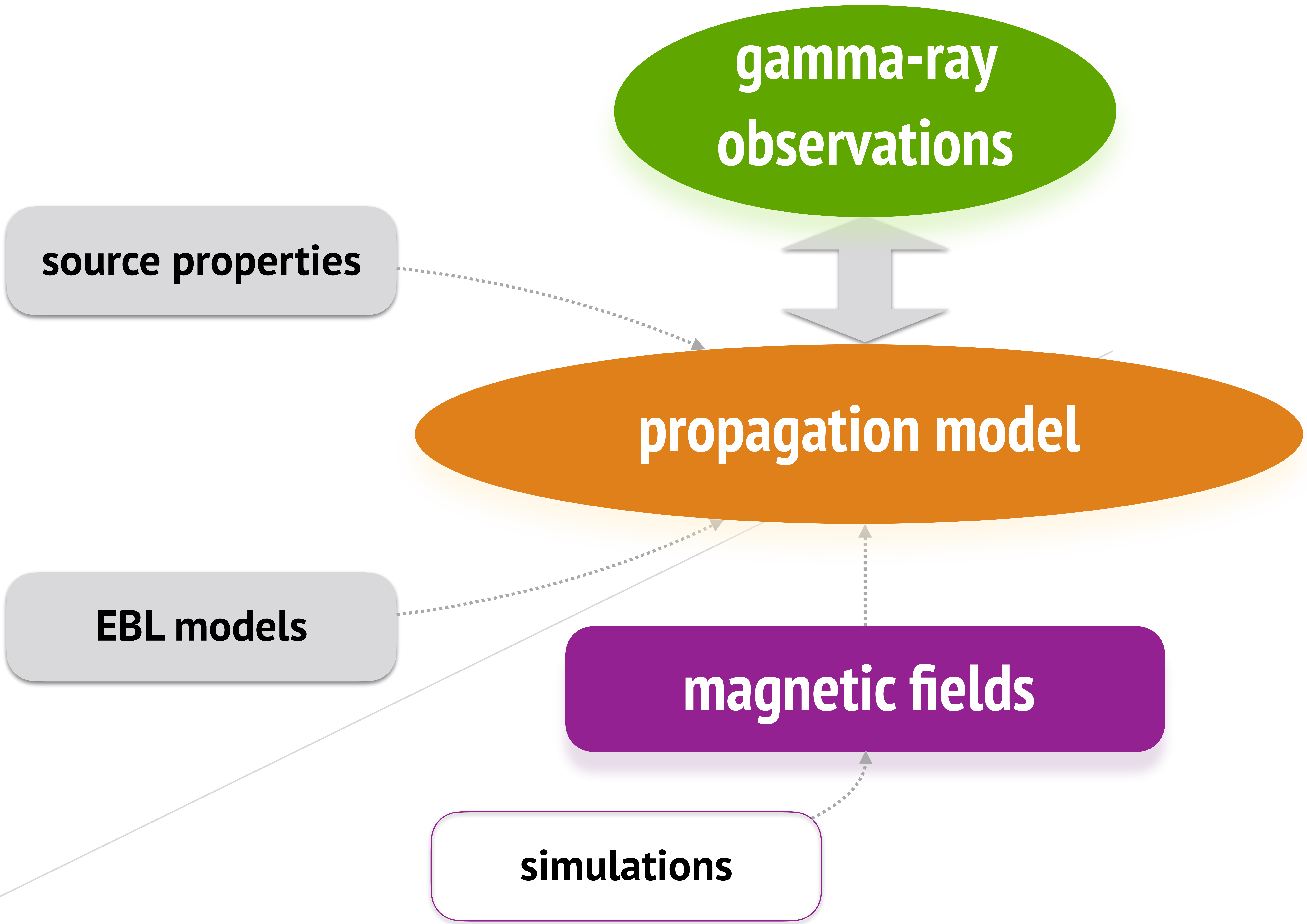

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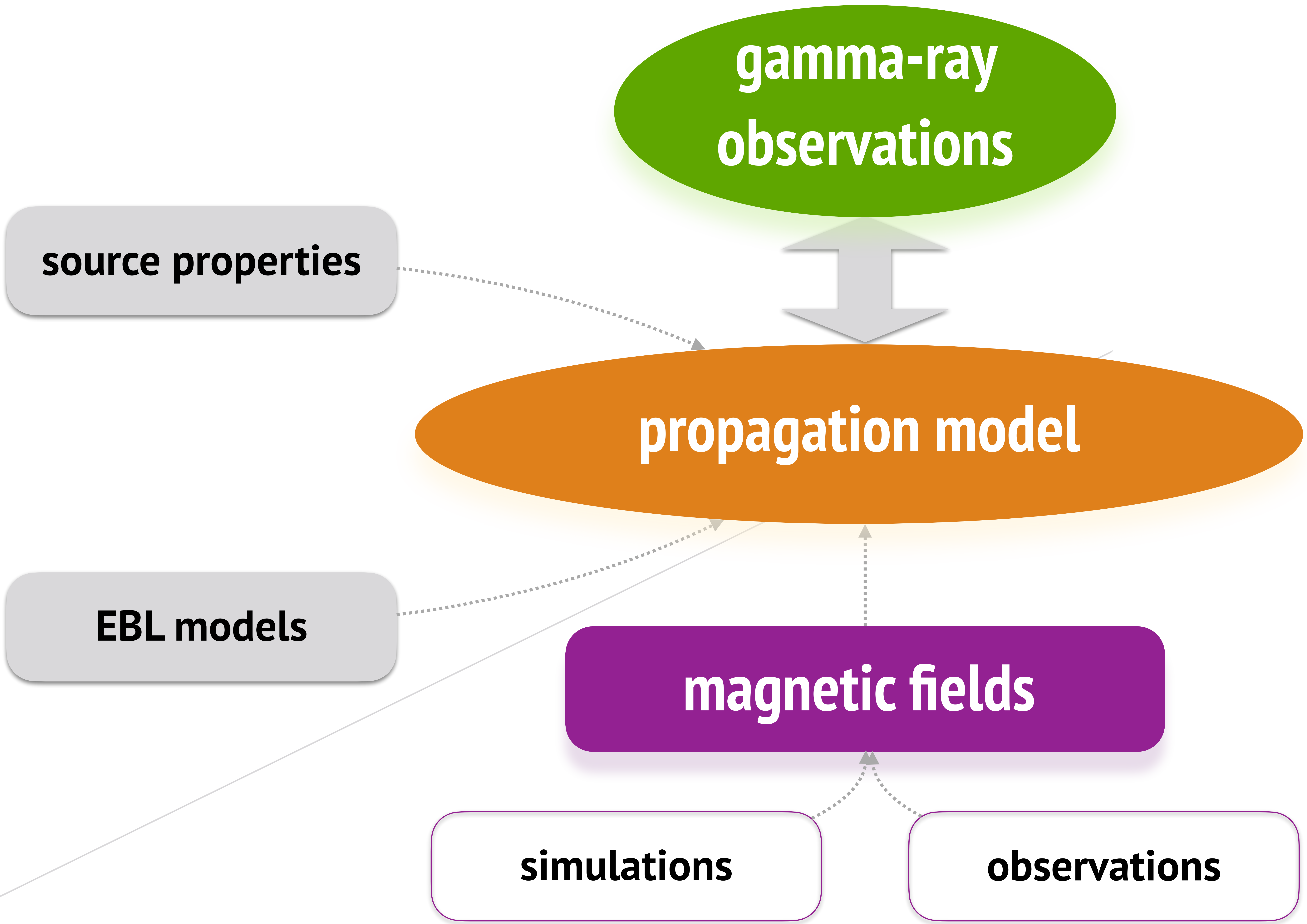

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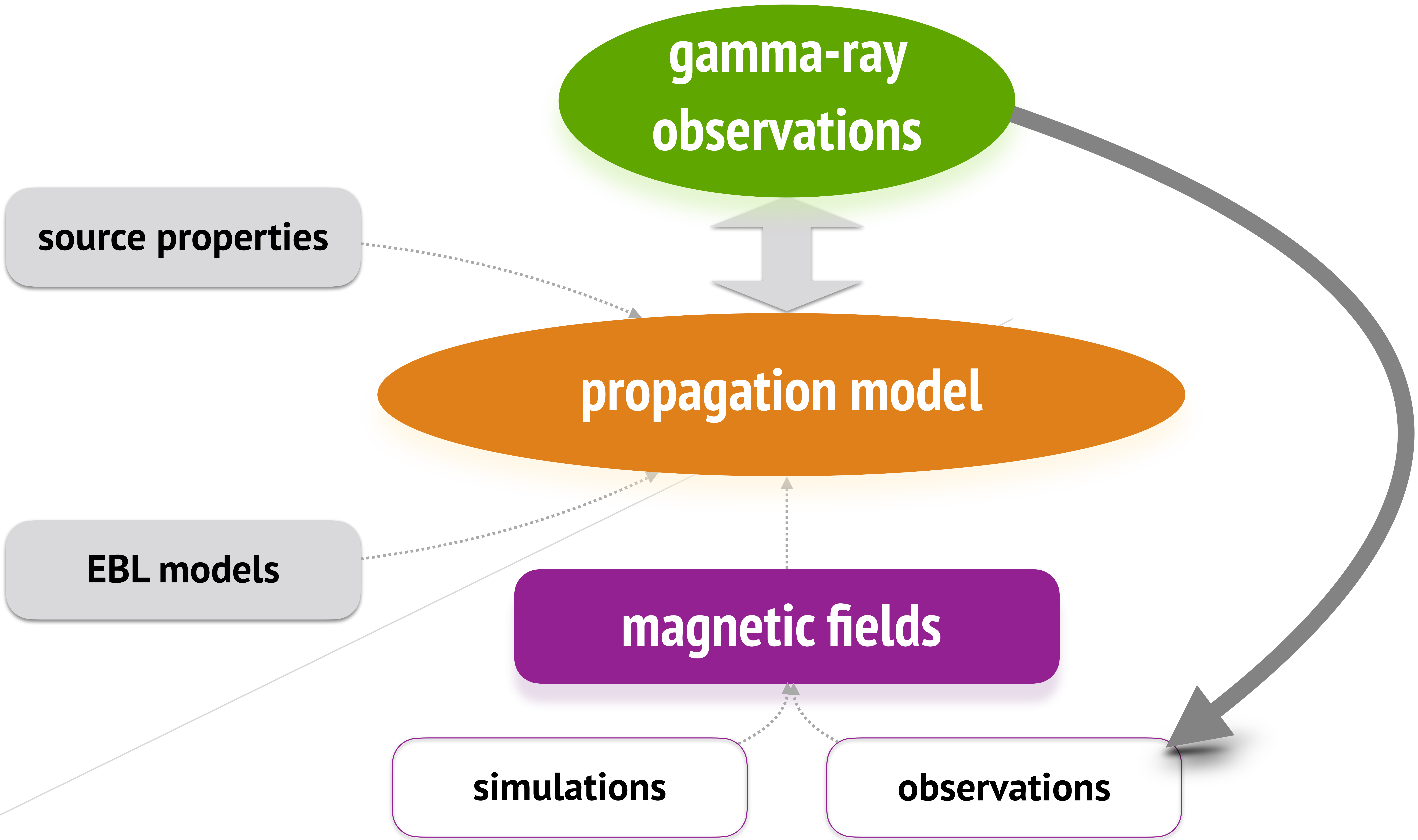

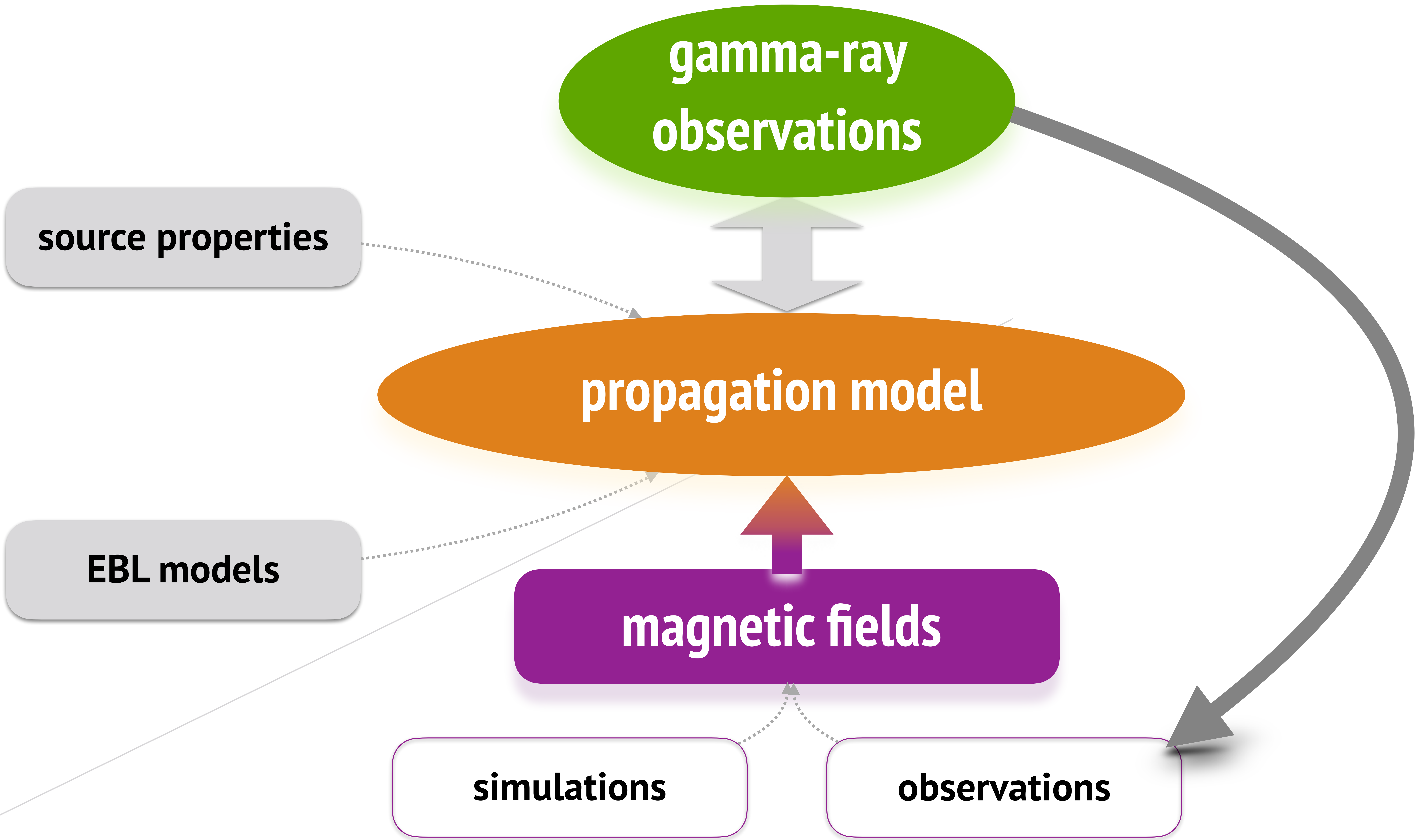
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  - IGMF constraints are just as good as the models used to derive them
  - *(the devil is in the details)*
- other effects such as **plasma instabilities** could be important

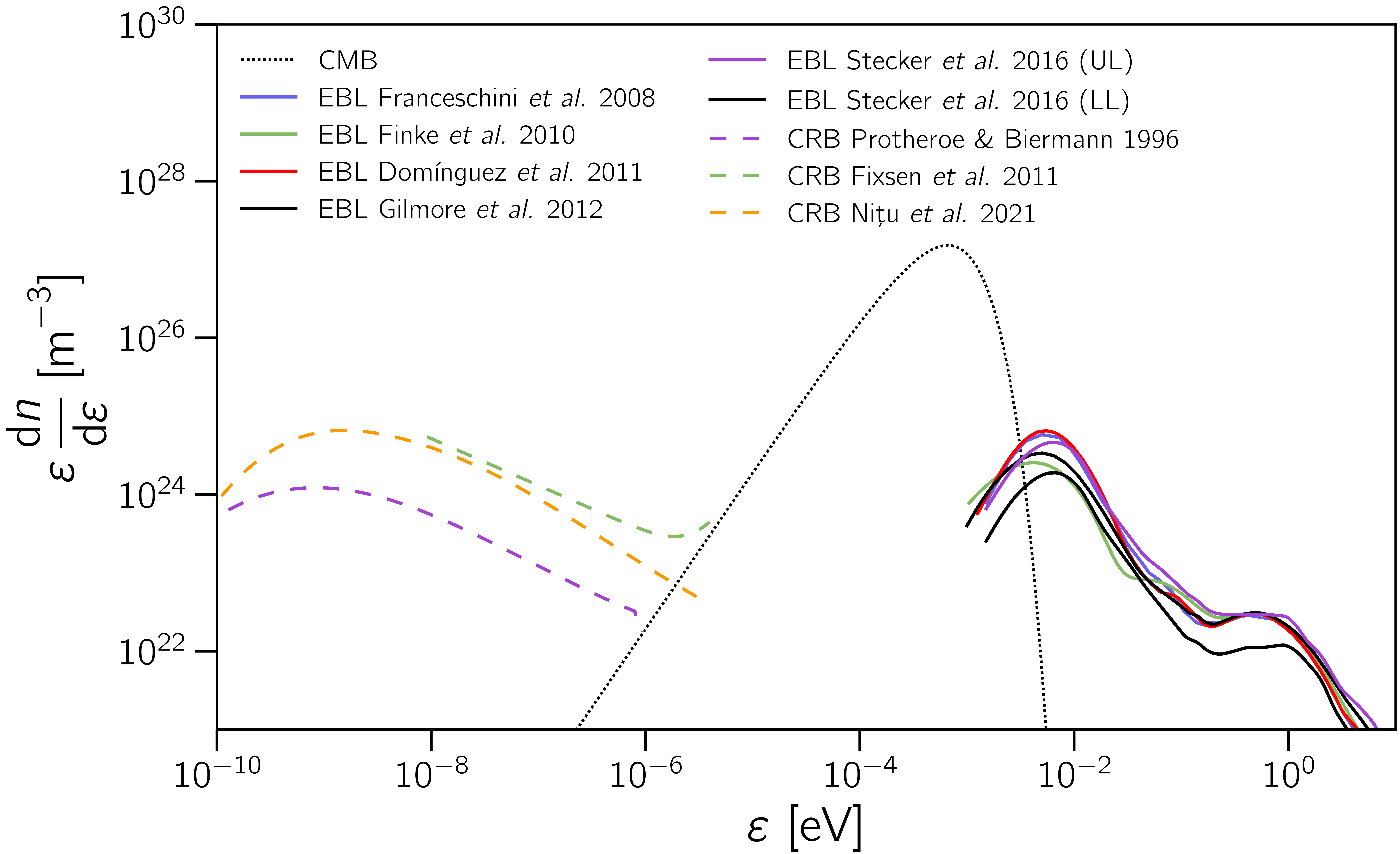
thank you 😊

"la Caixa" Foundation

MARIE CURIE ACTIONS

European Commission

back-up slides


CMB
EBL Franceschini et al. 2008
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EBL Stecker et al. 2016 (UL)
EBL Stecker et al. 2016 (LL)
CRB Protheroe & Biermann 1996
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10^{30}
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$\varepsilon \frac{dn}{d\varepsilon}$ [m^{-3}]
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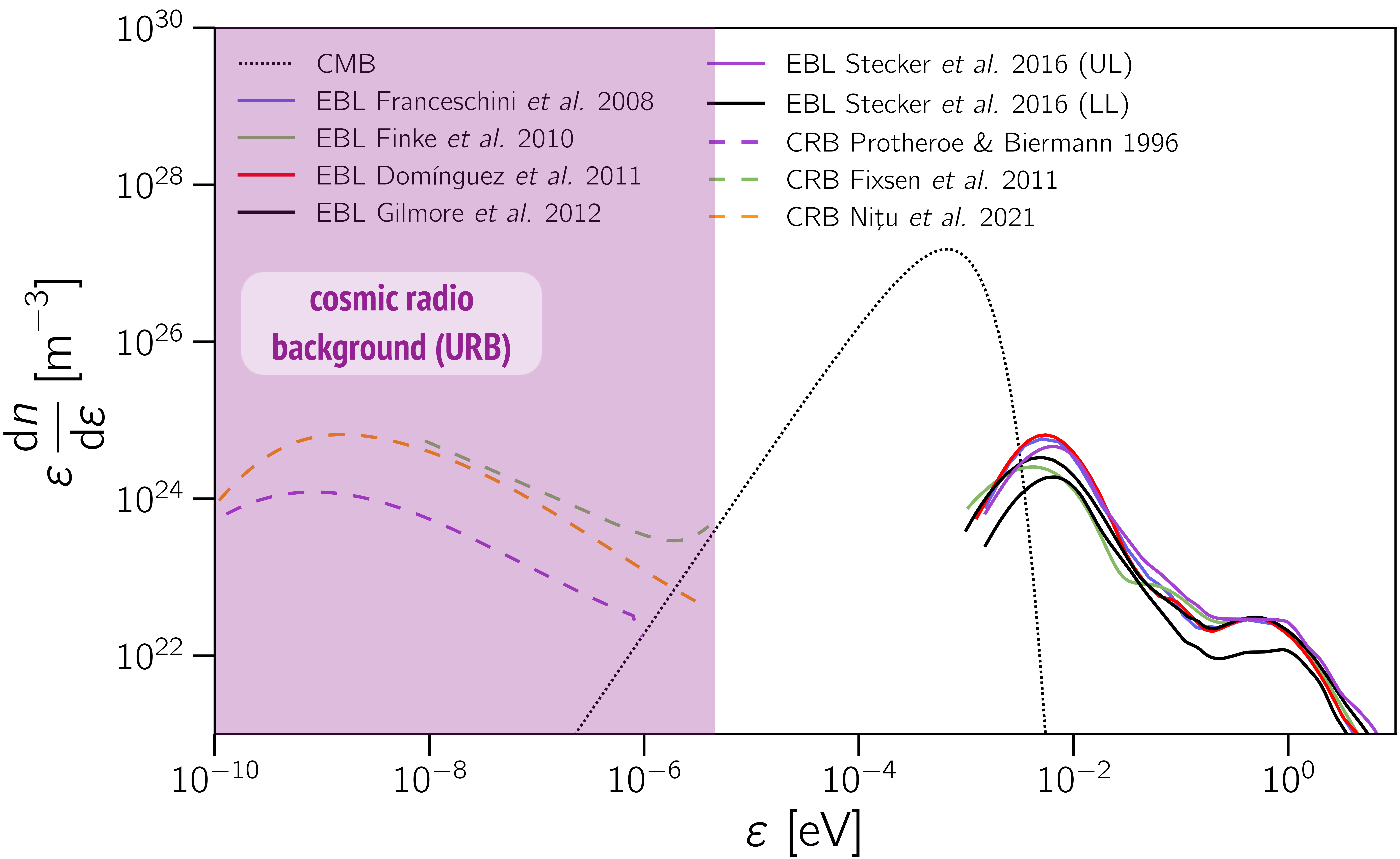
ε [eV]



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cosmic radio background (URB)
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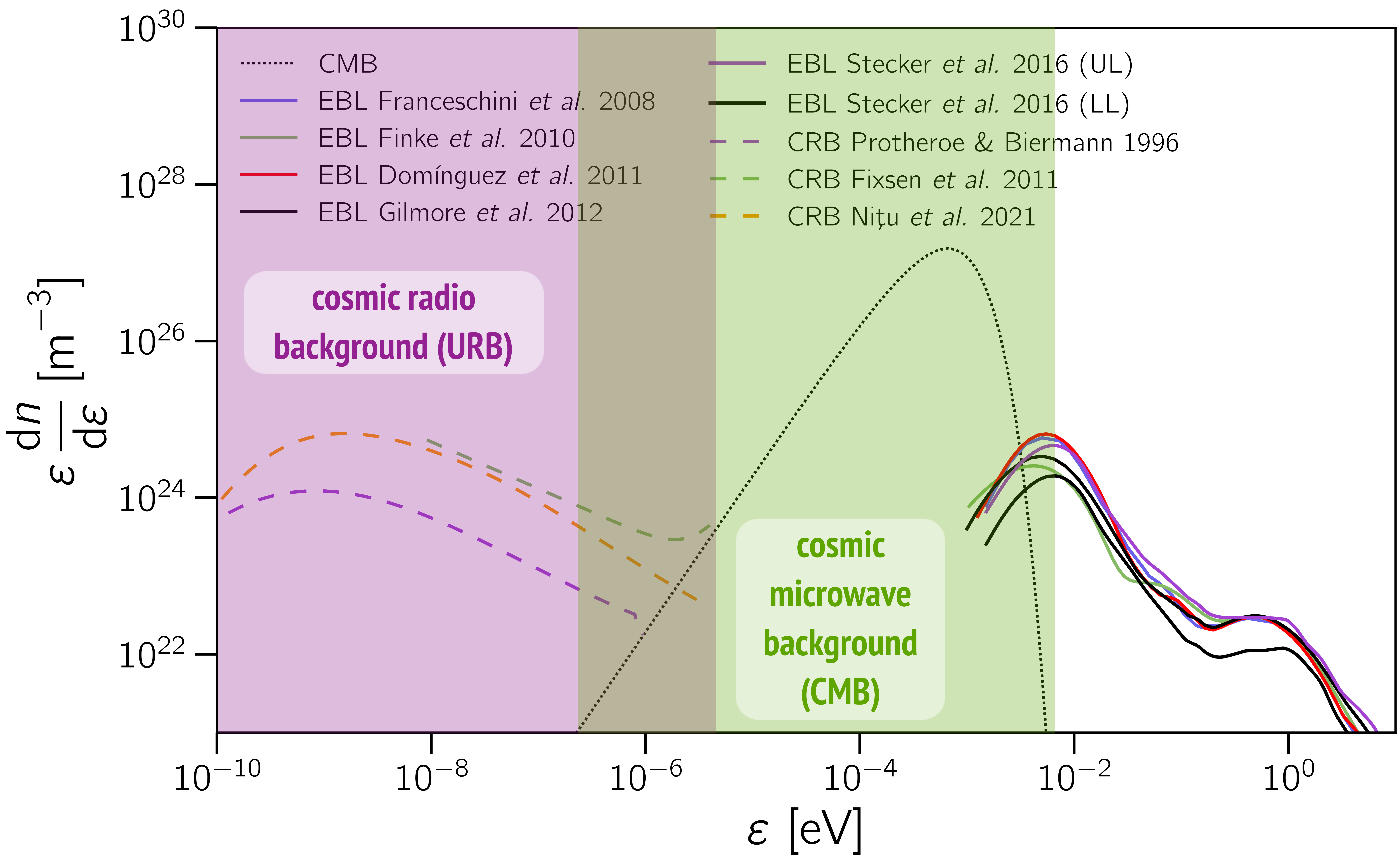
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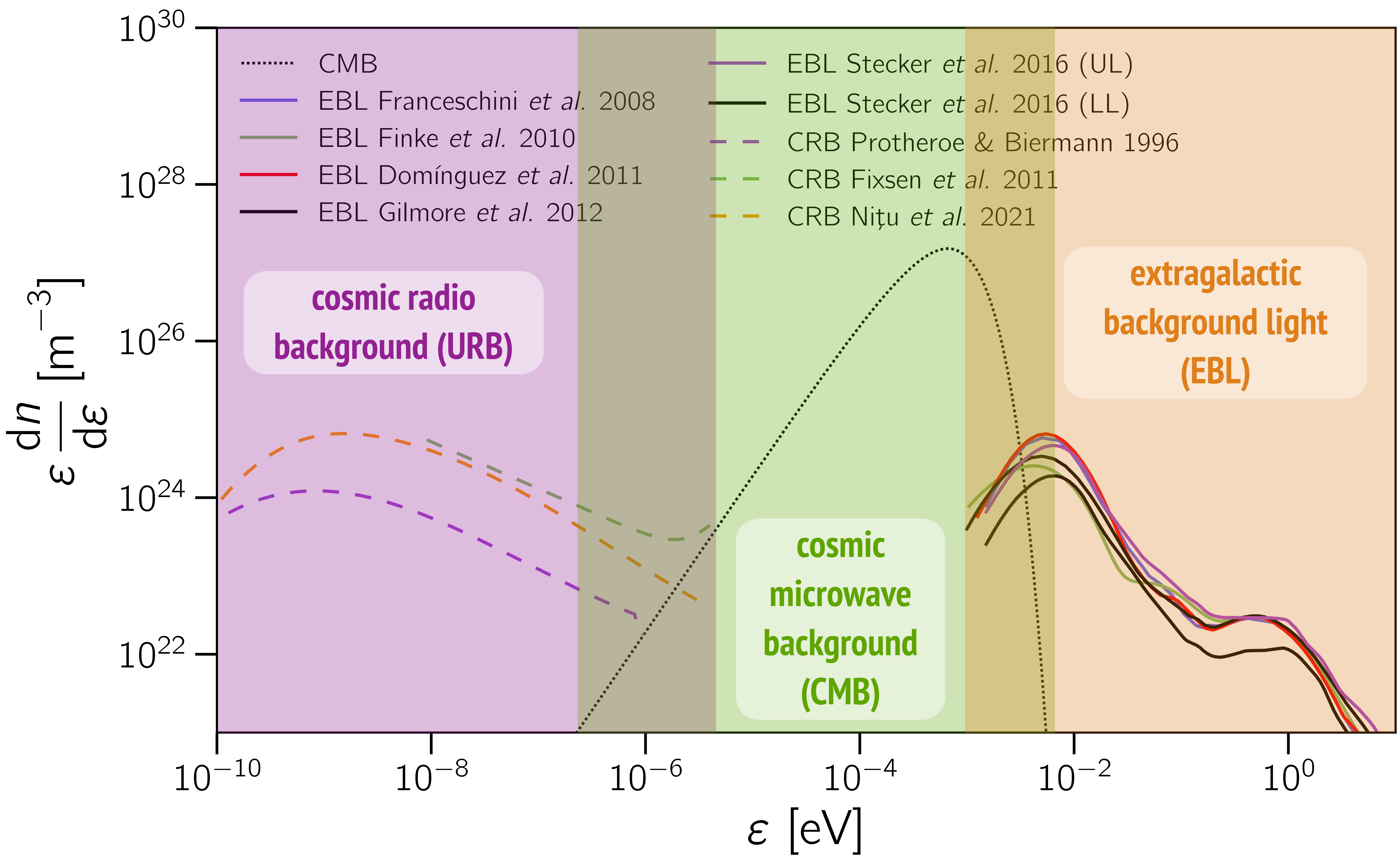
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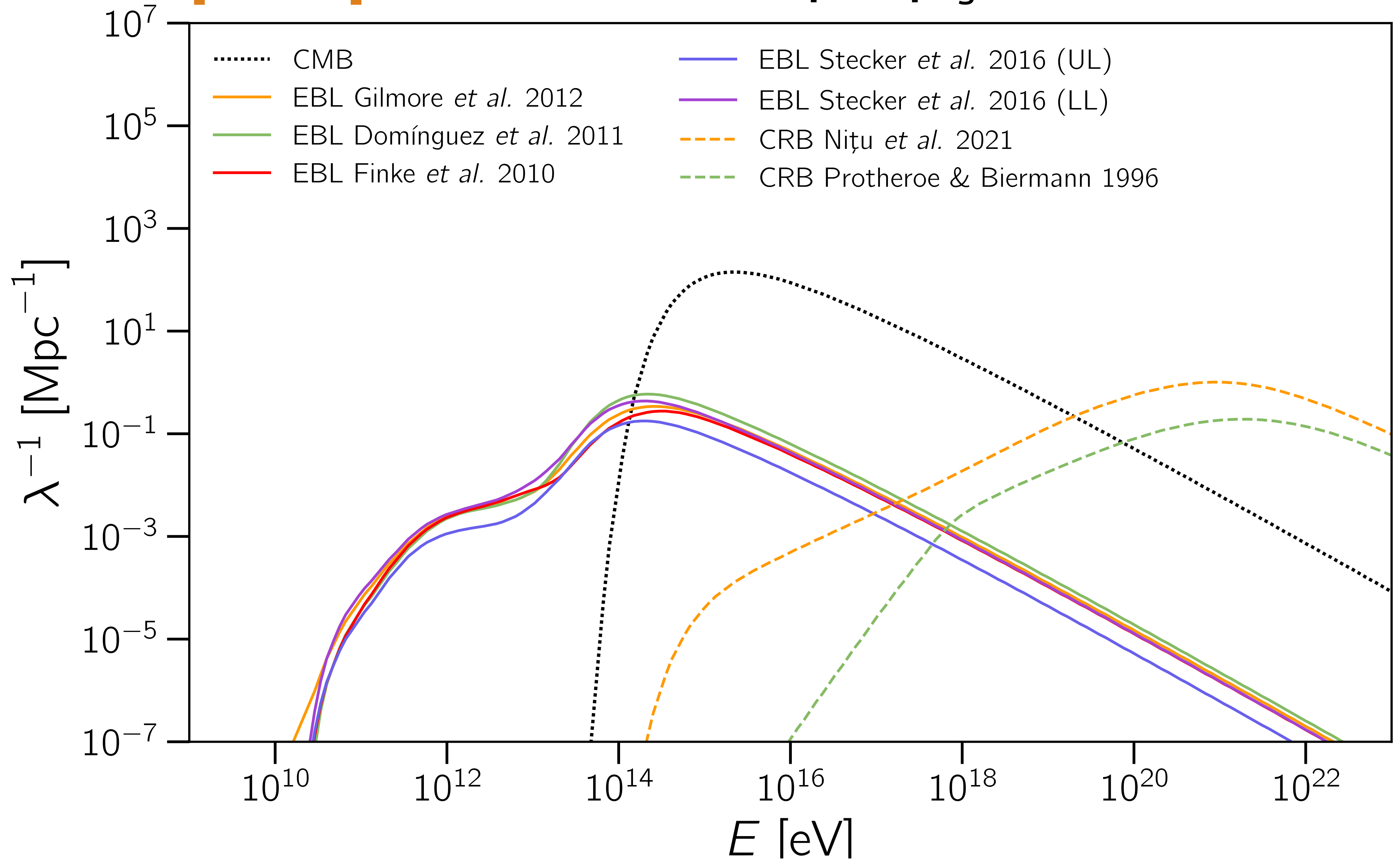
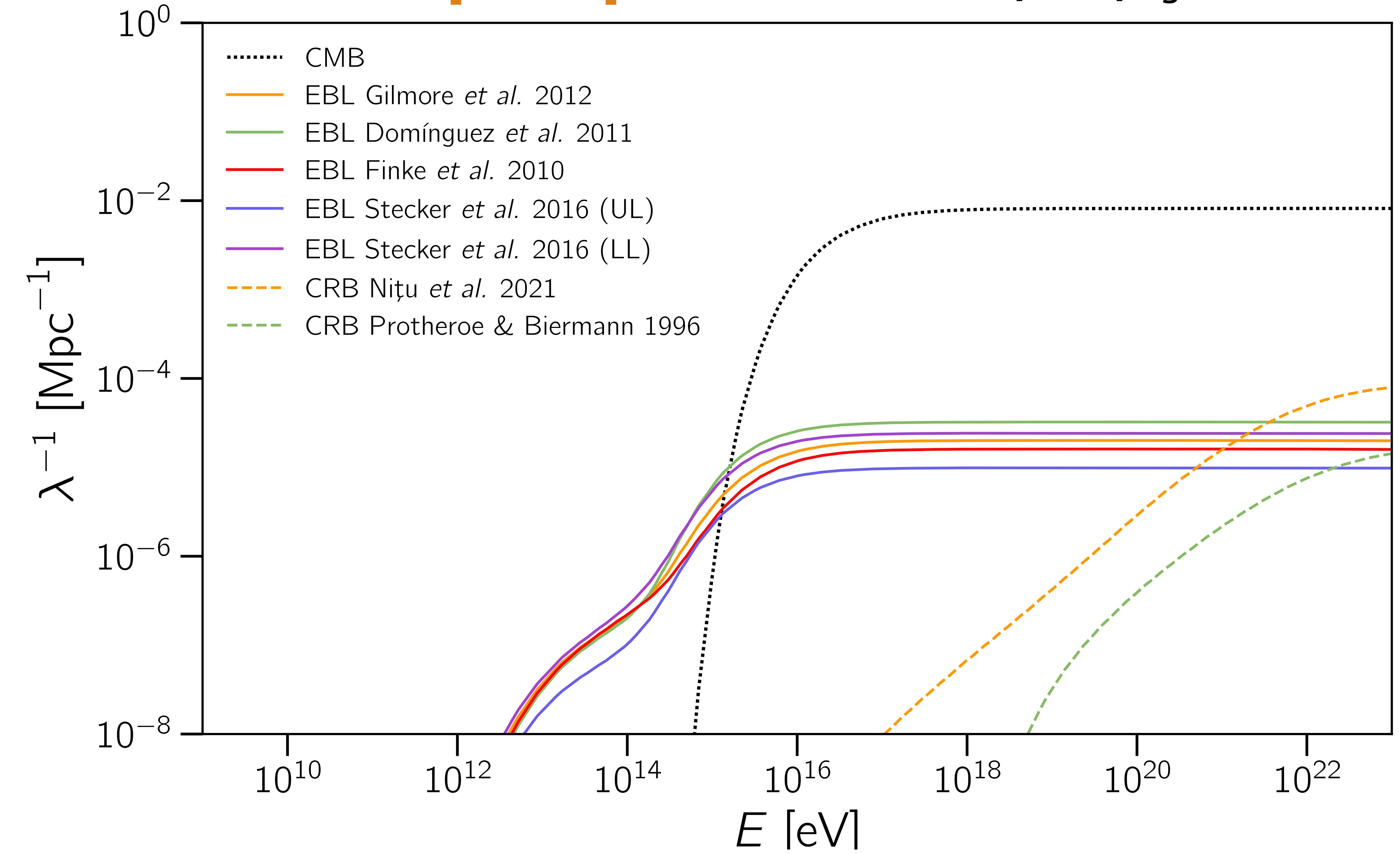
gamma rays: interactions during cosmological propagation

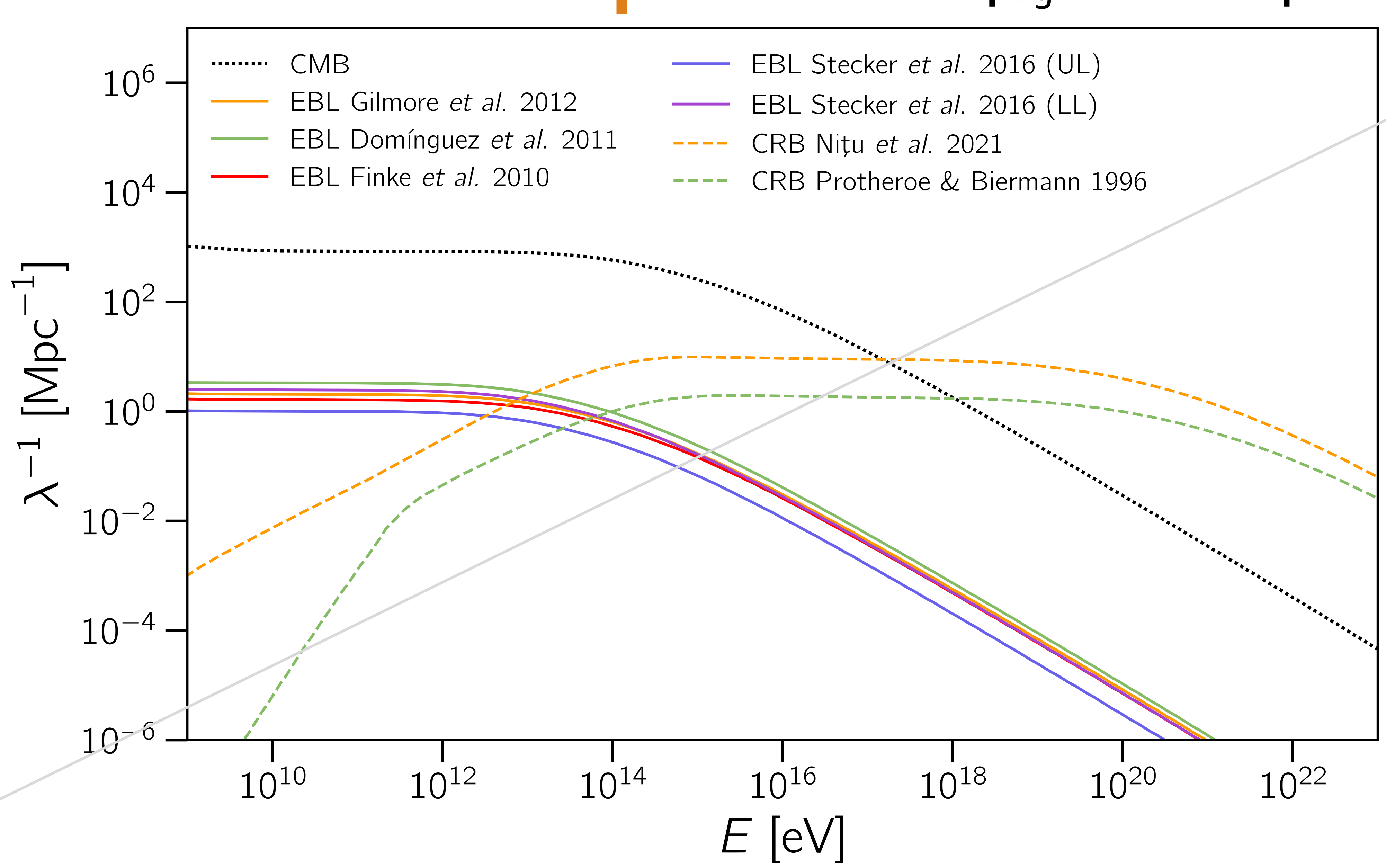
pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+$



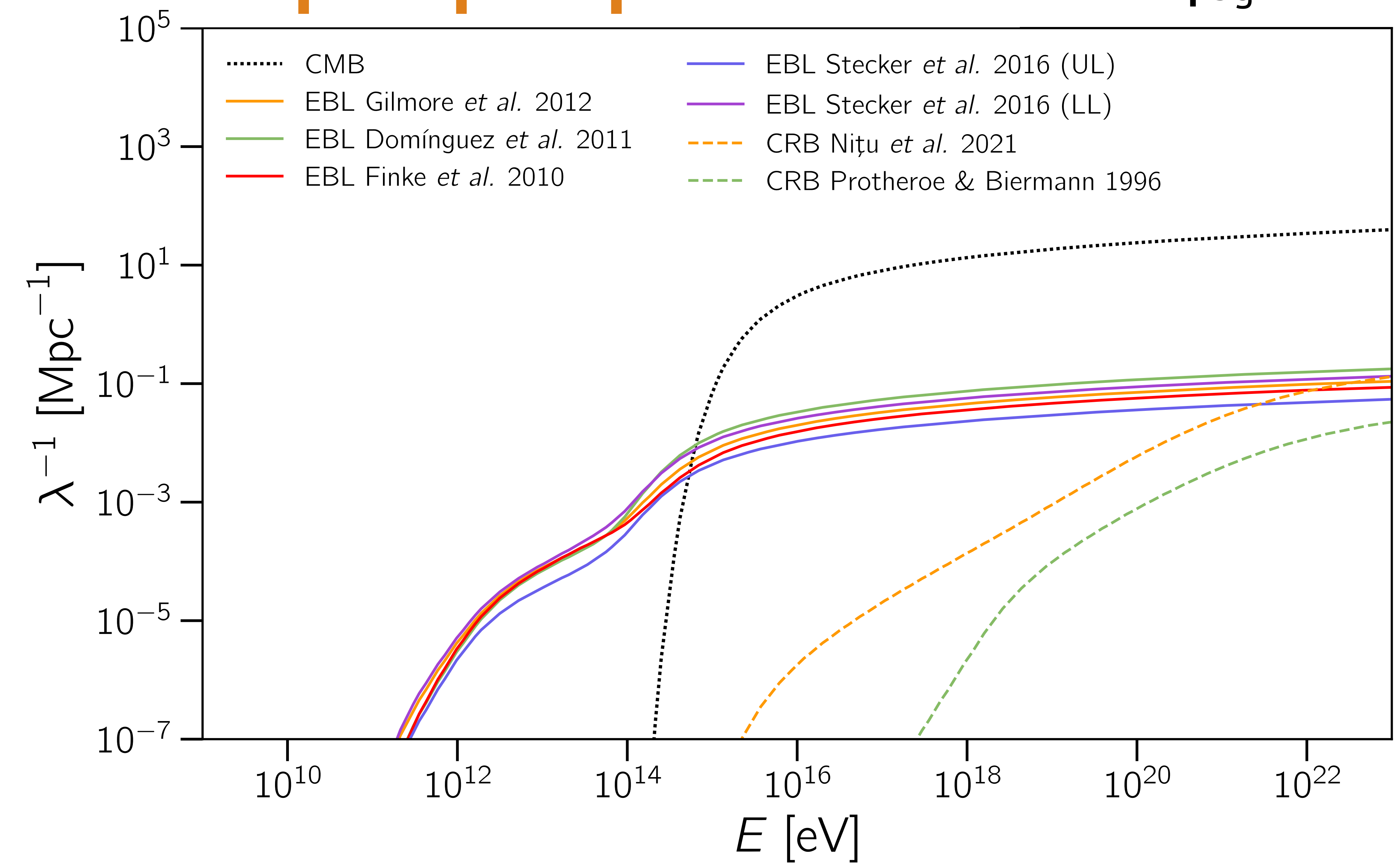
double pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+ + e^- + e^+$



inverse Compton $e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$



triplet pair production $e^\pm + \gamma_{bg} \rightarrow e^\pm + e^- + e^+$



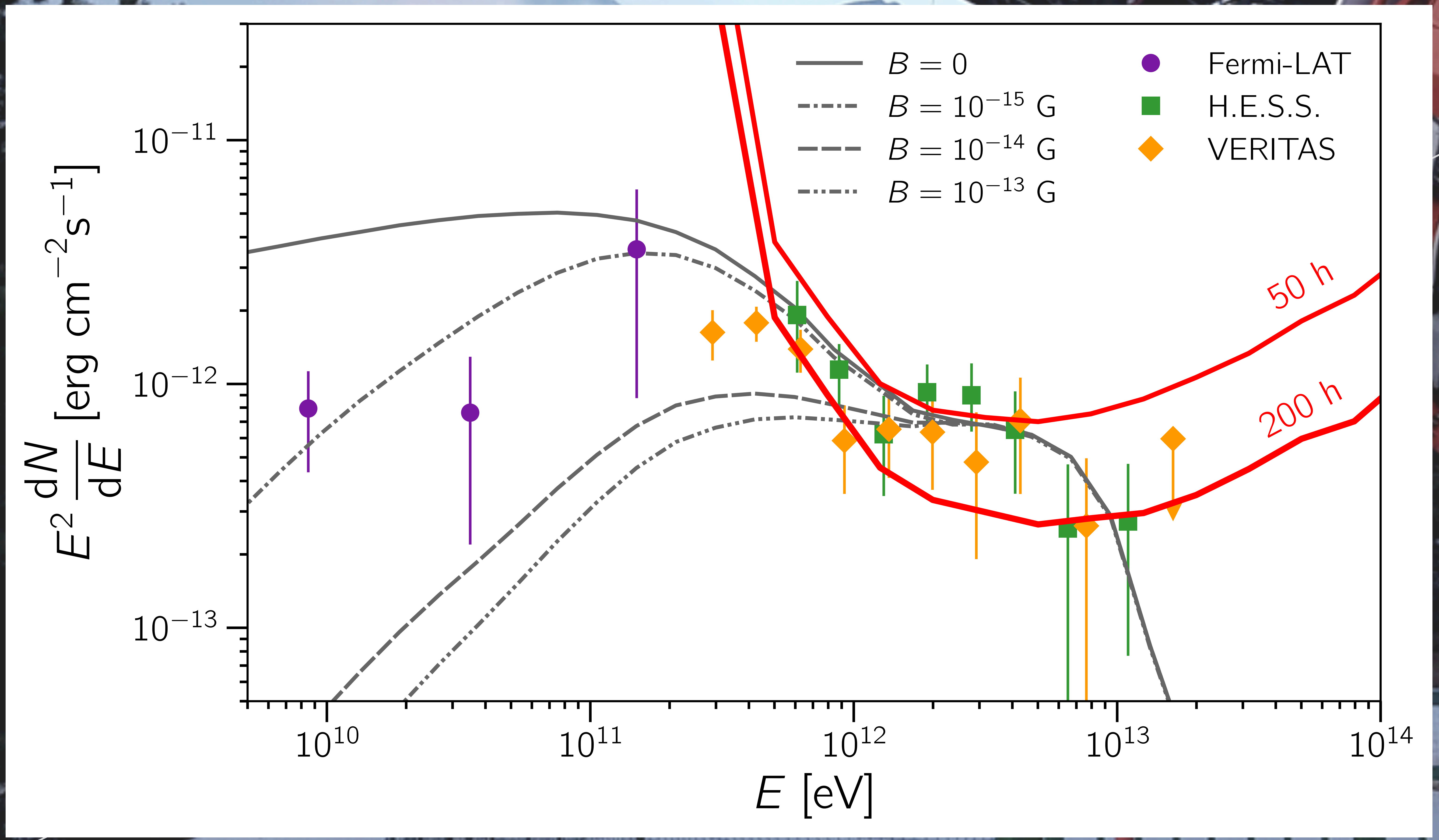
constraining IGMFs with the ASTRI Mini-Array

Vercellone et al. JHEAp 35 (2022) 1. arxiv:2208.03177

Mini-Array

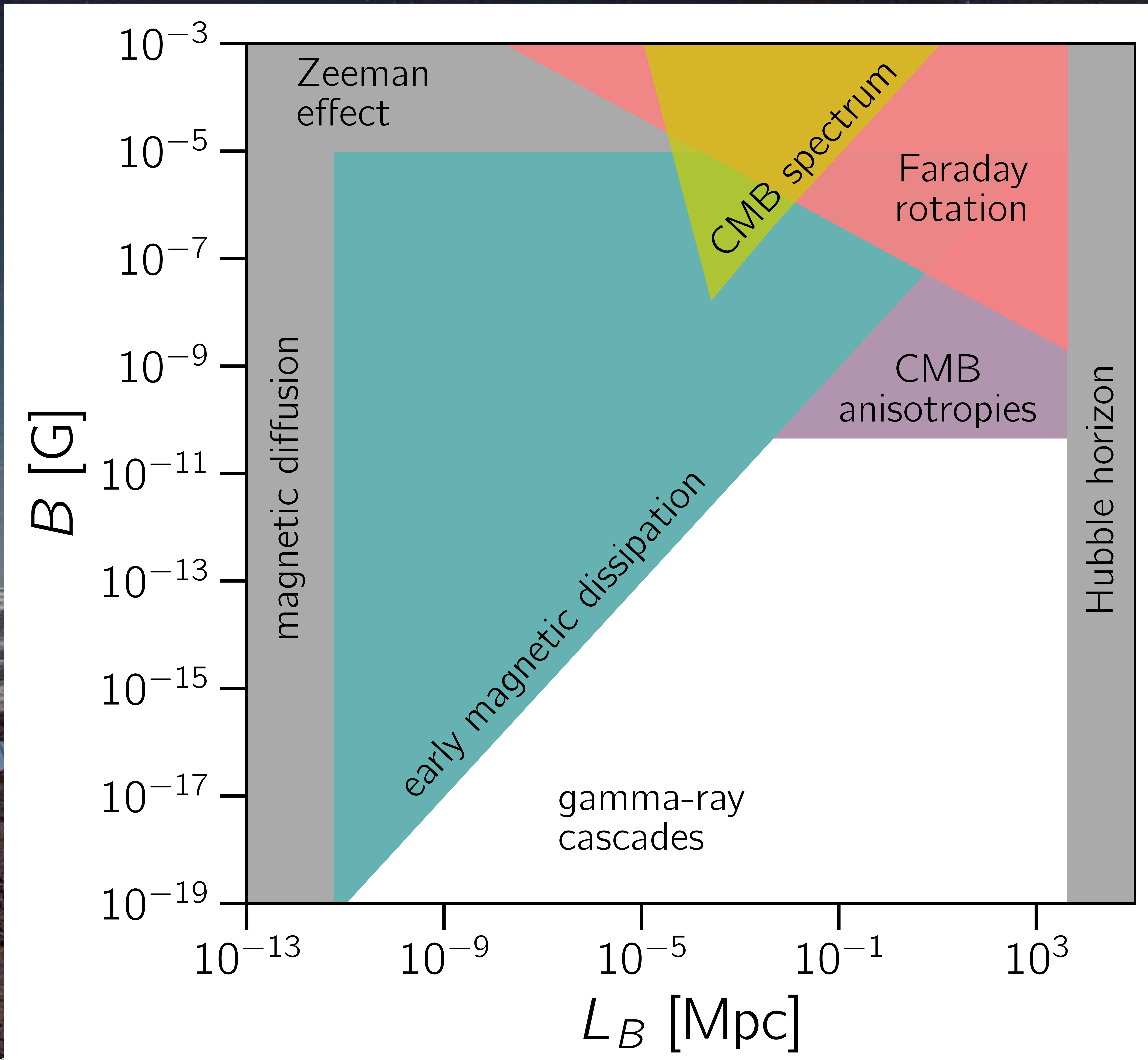
constraining IGMFs with the ASTRI Mini-Array

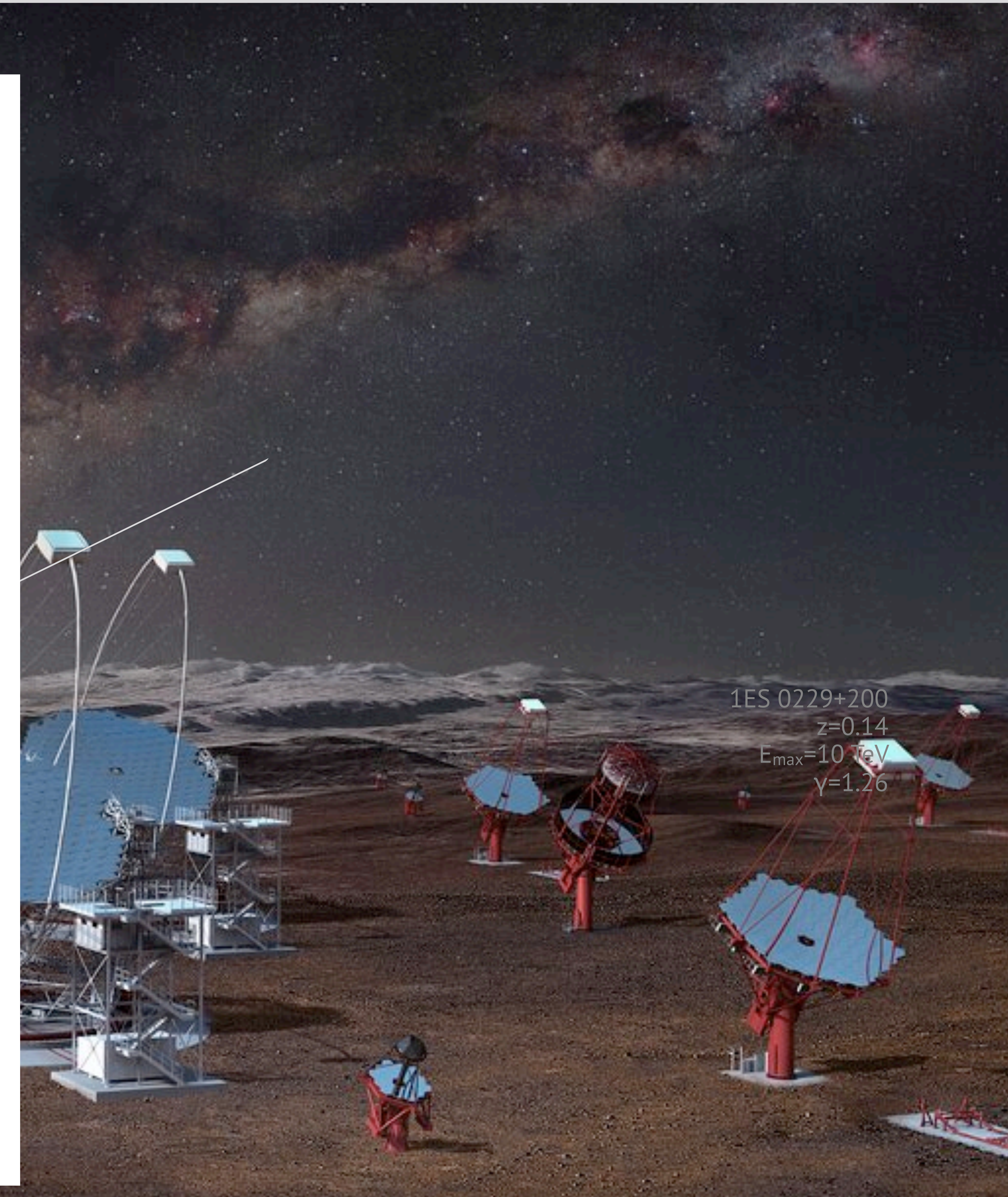
Vercellone et al. JHEAp 35 (2022) 1. arxiv:2208.03177



probing IGMFs with the Cherenkov Telescope Array (CTA)

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





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cta cherenkov telescope array

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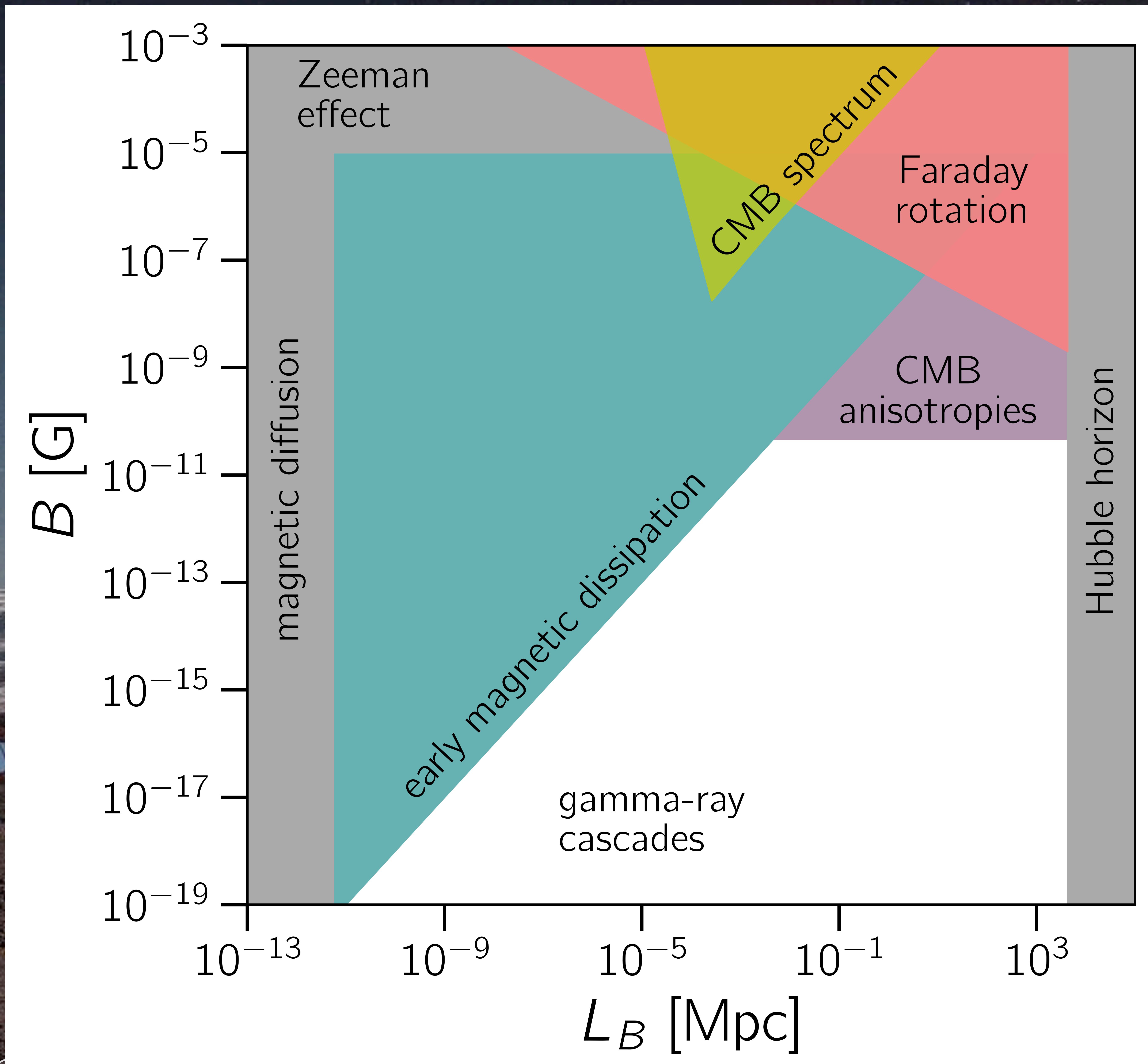

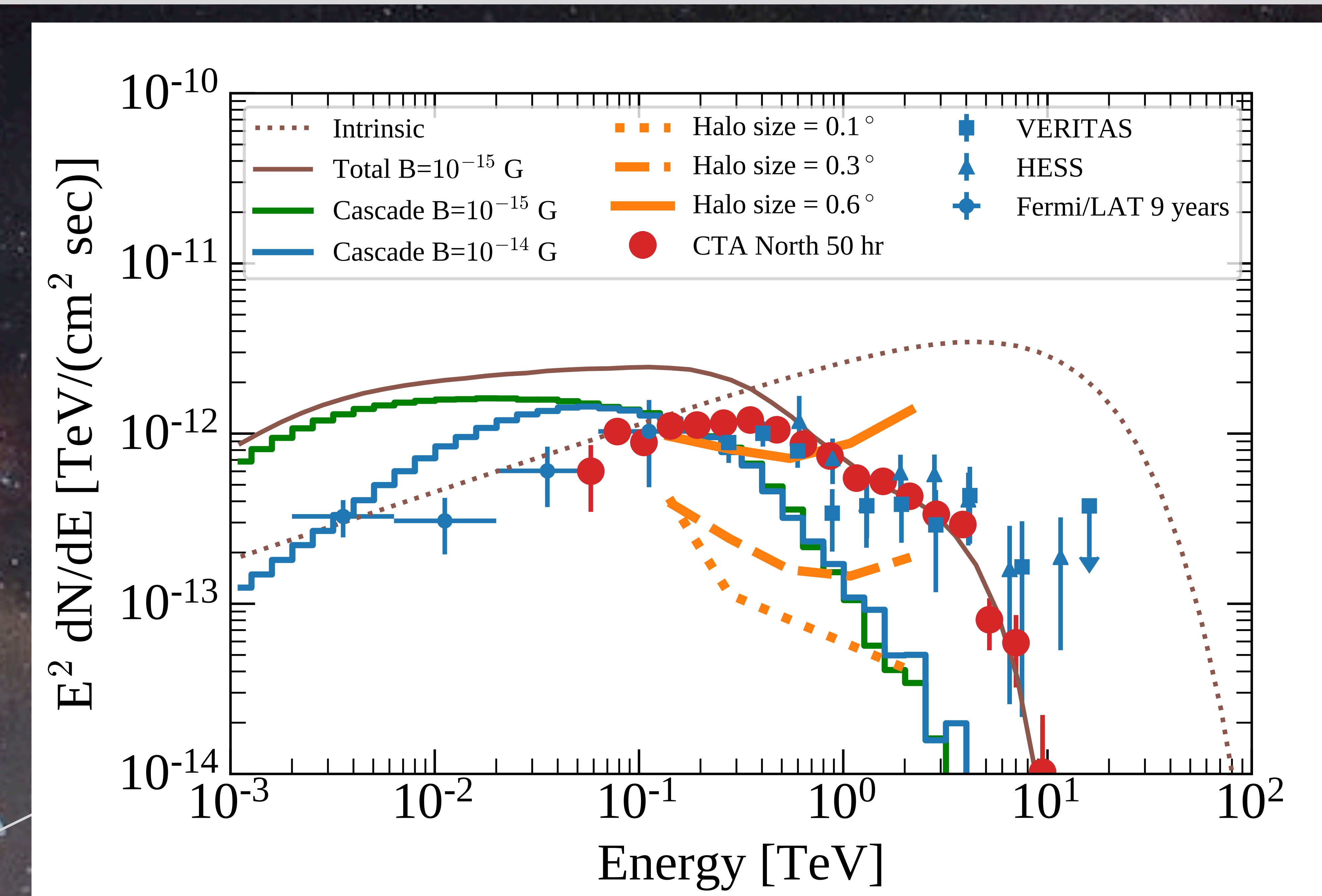

1ES 0229+200
z=0.14
E_{max}=10 TeV
γ=1.26

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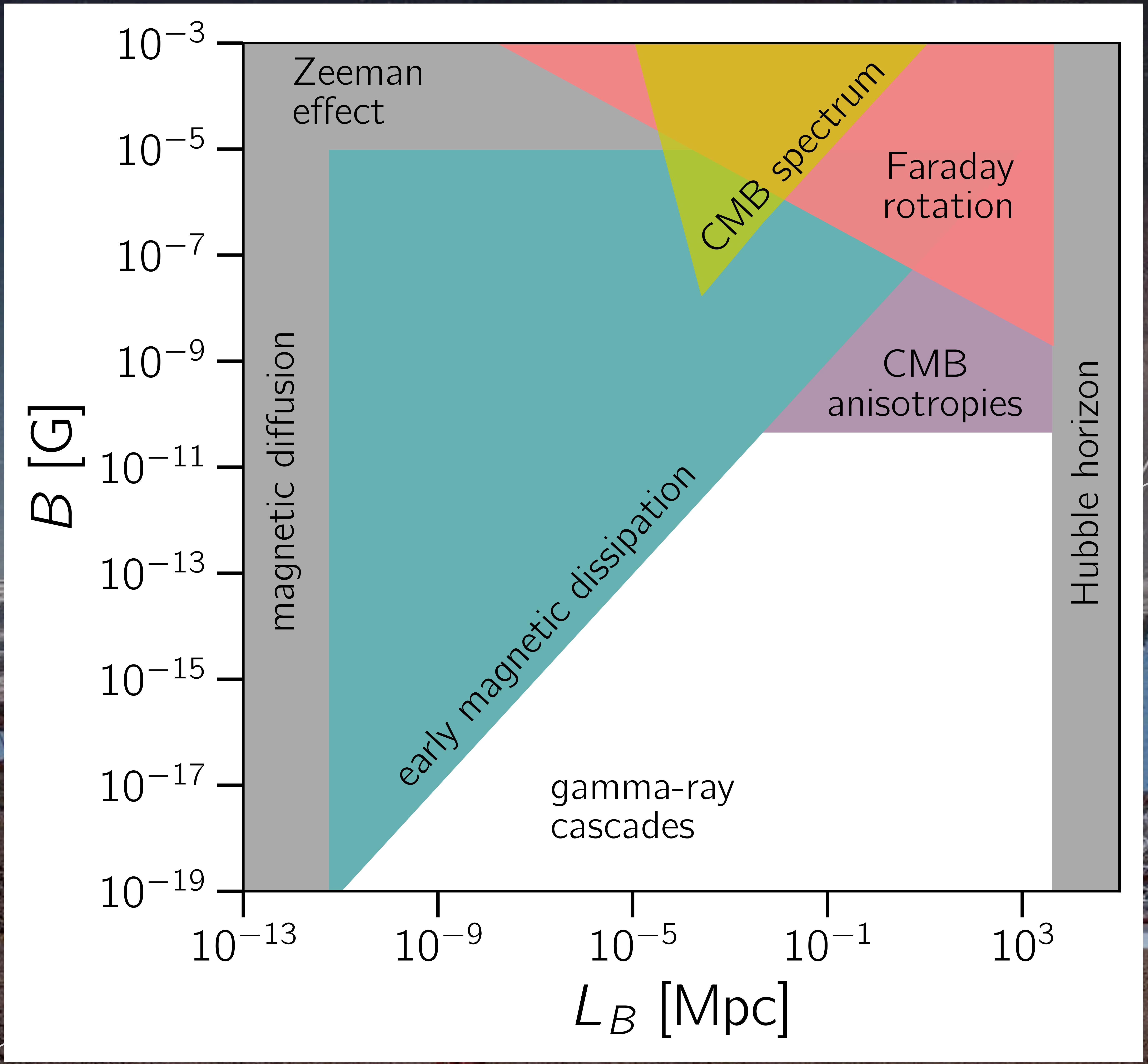
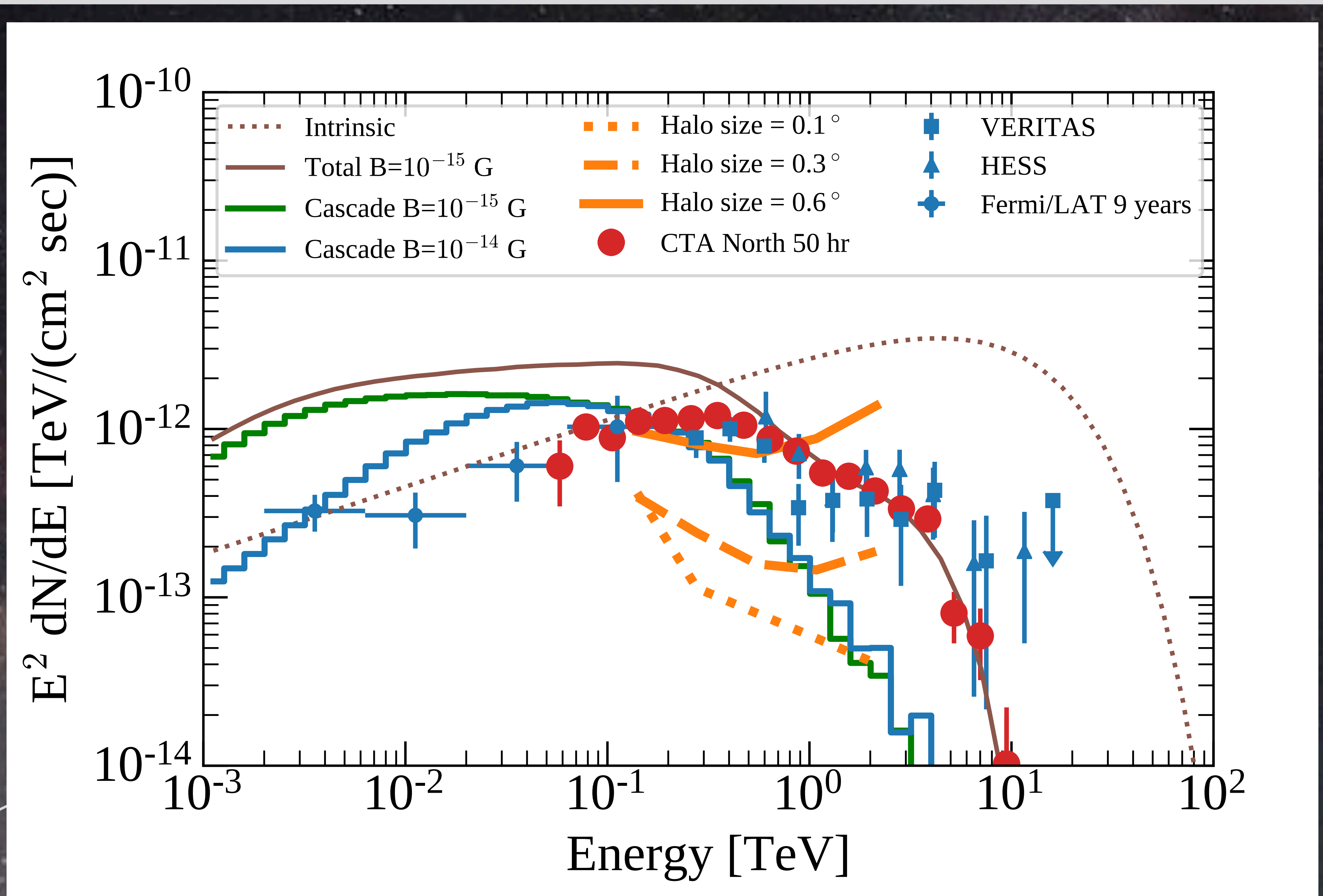
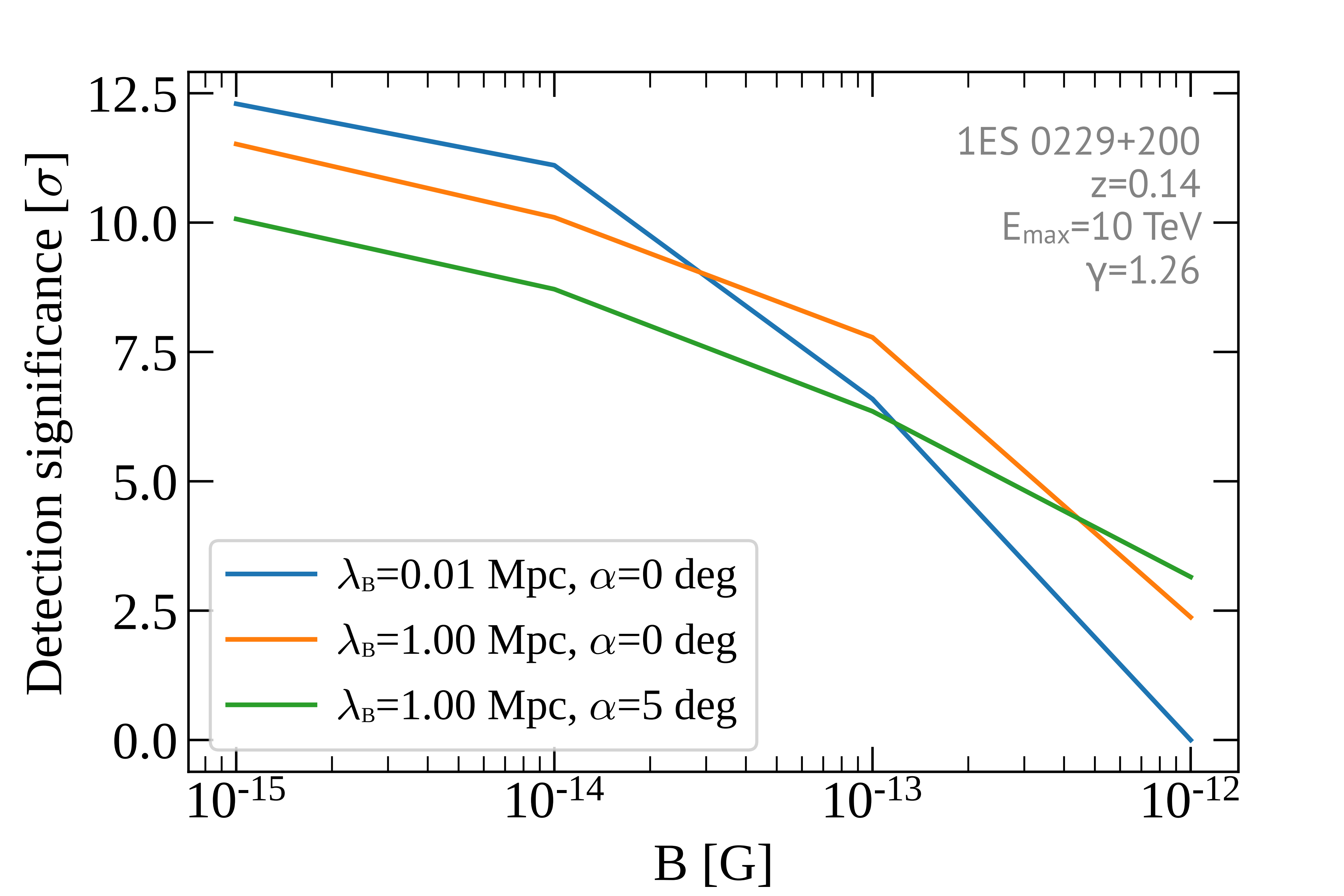
CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349







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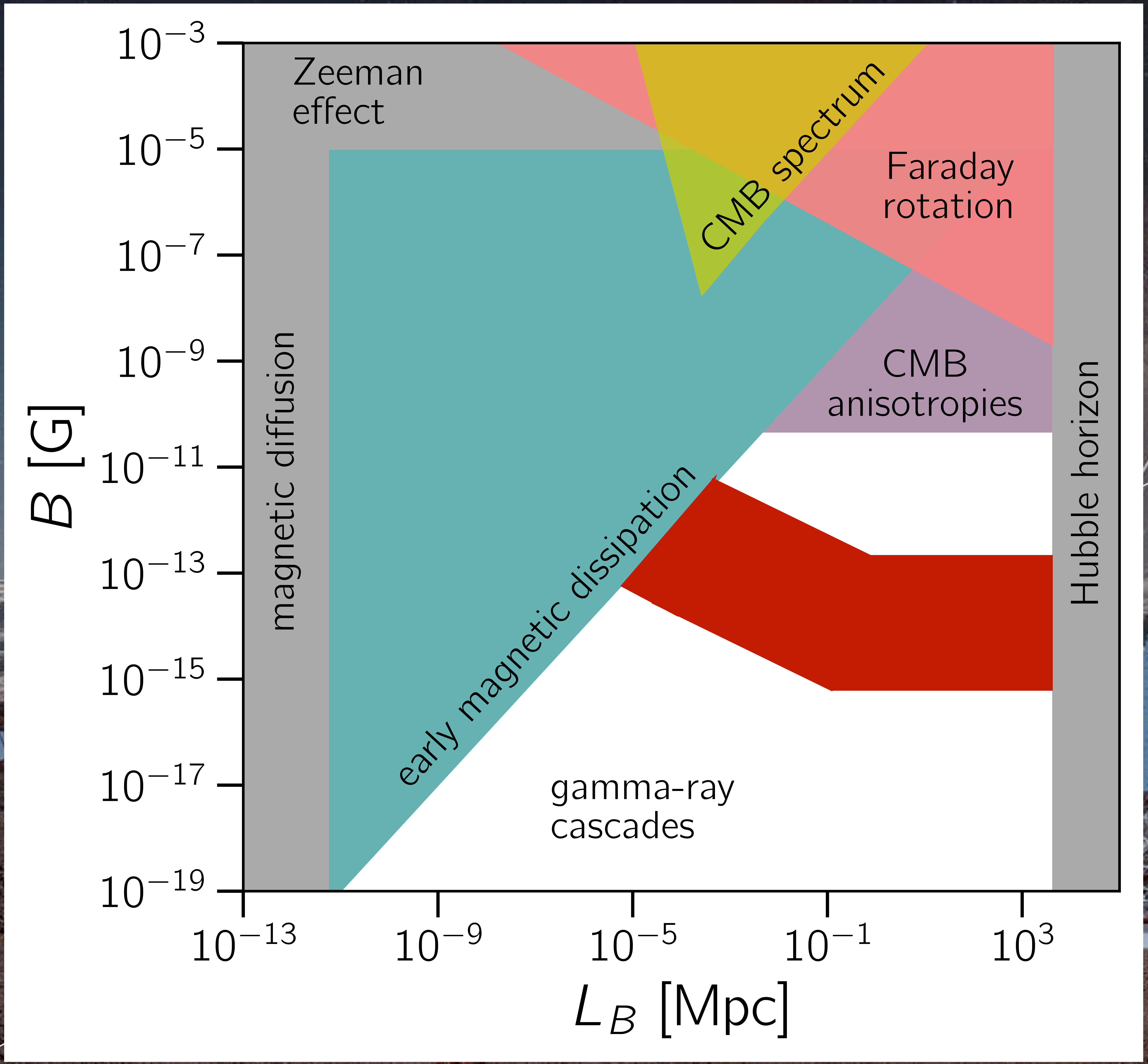

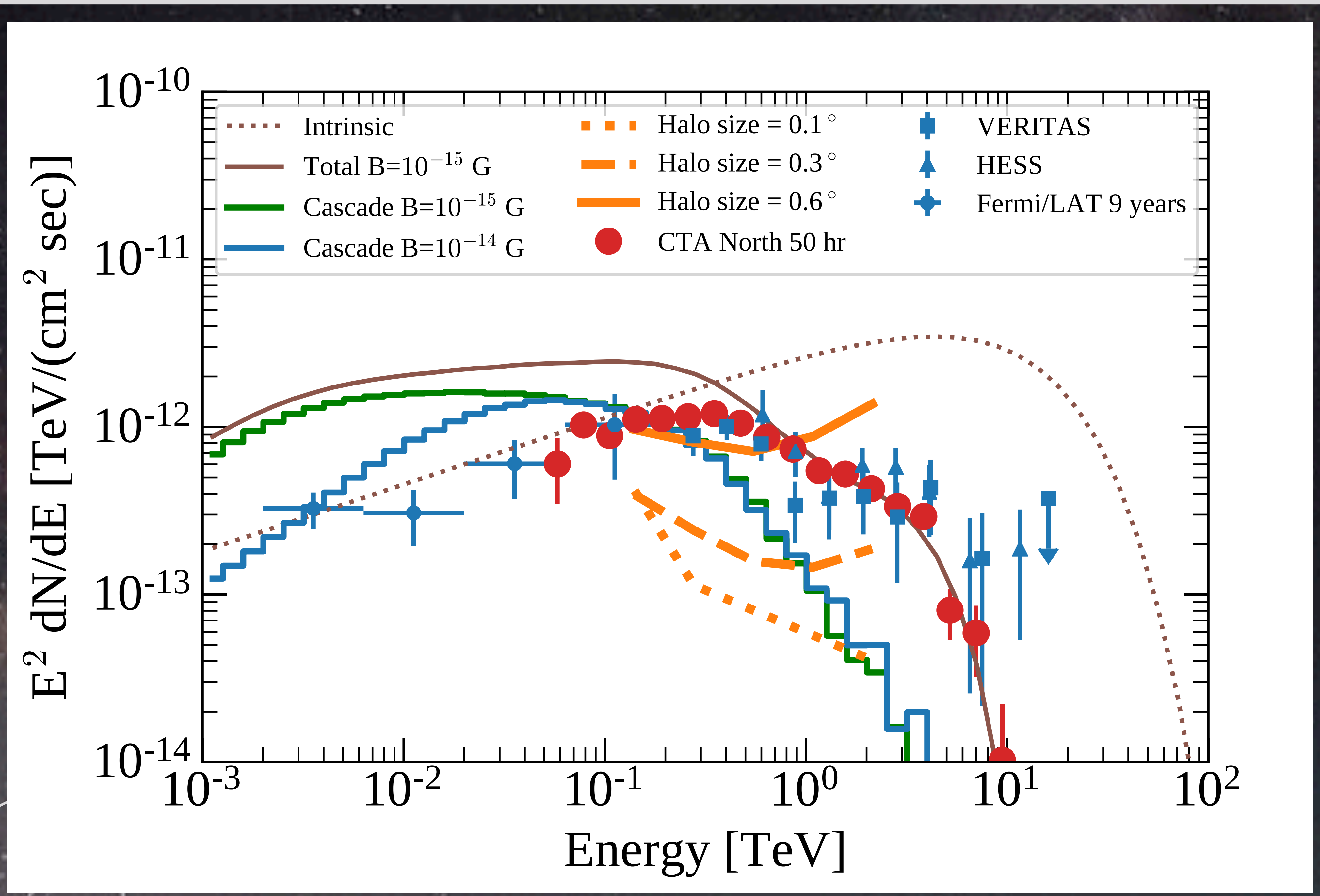

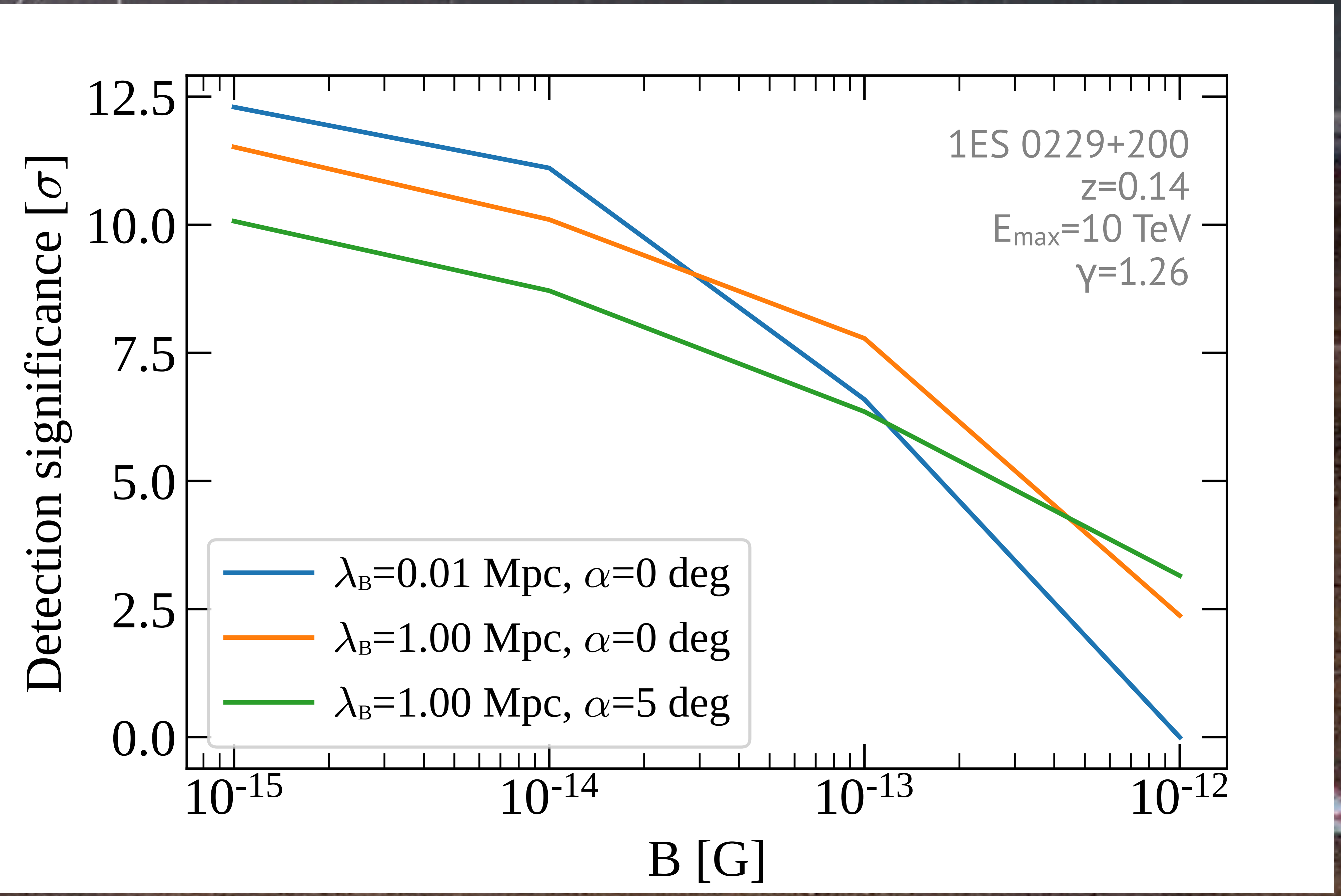

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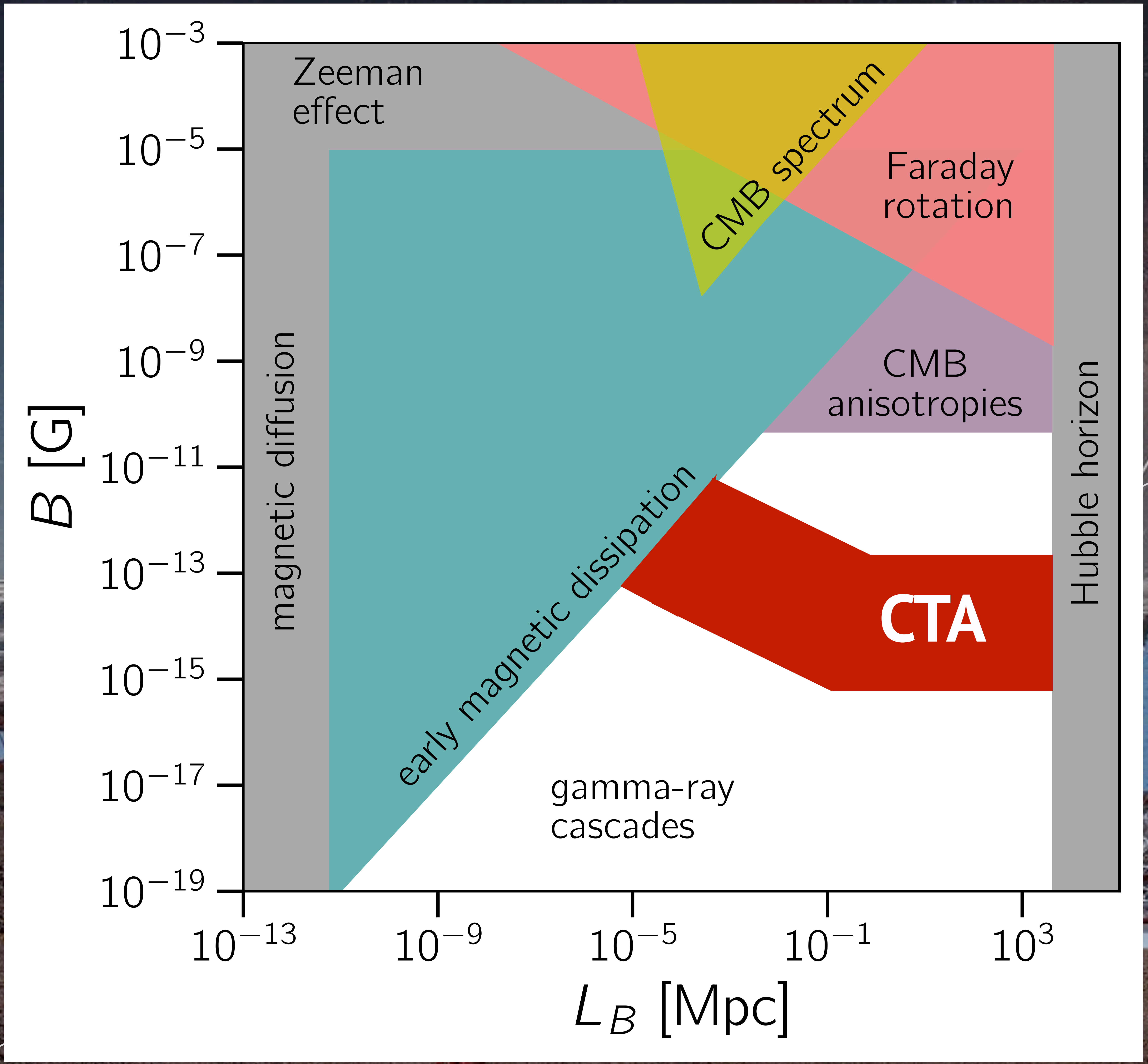
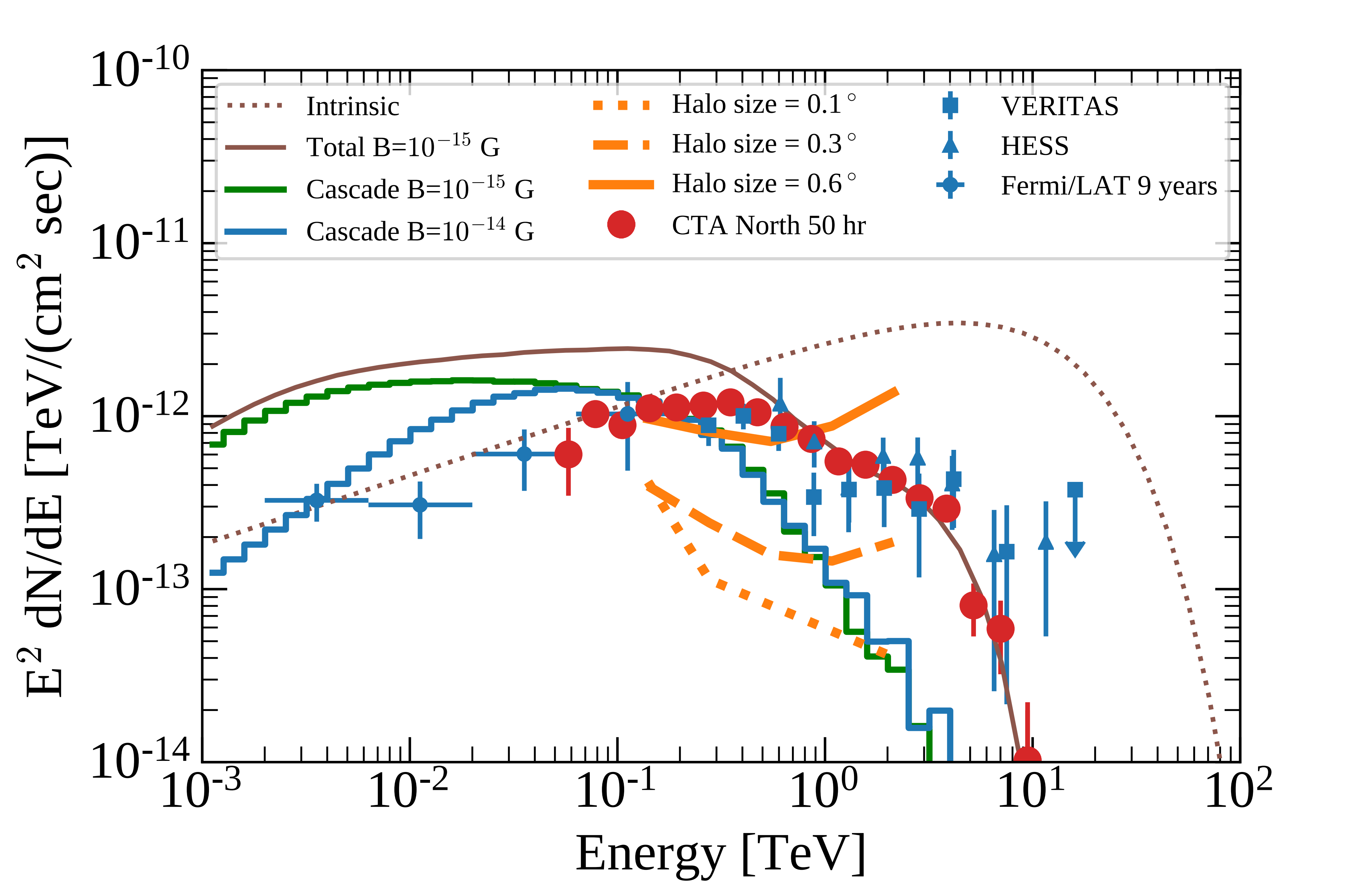
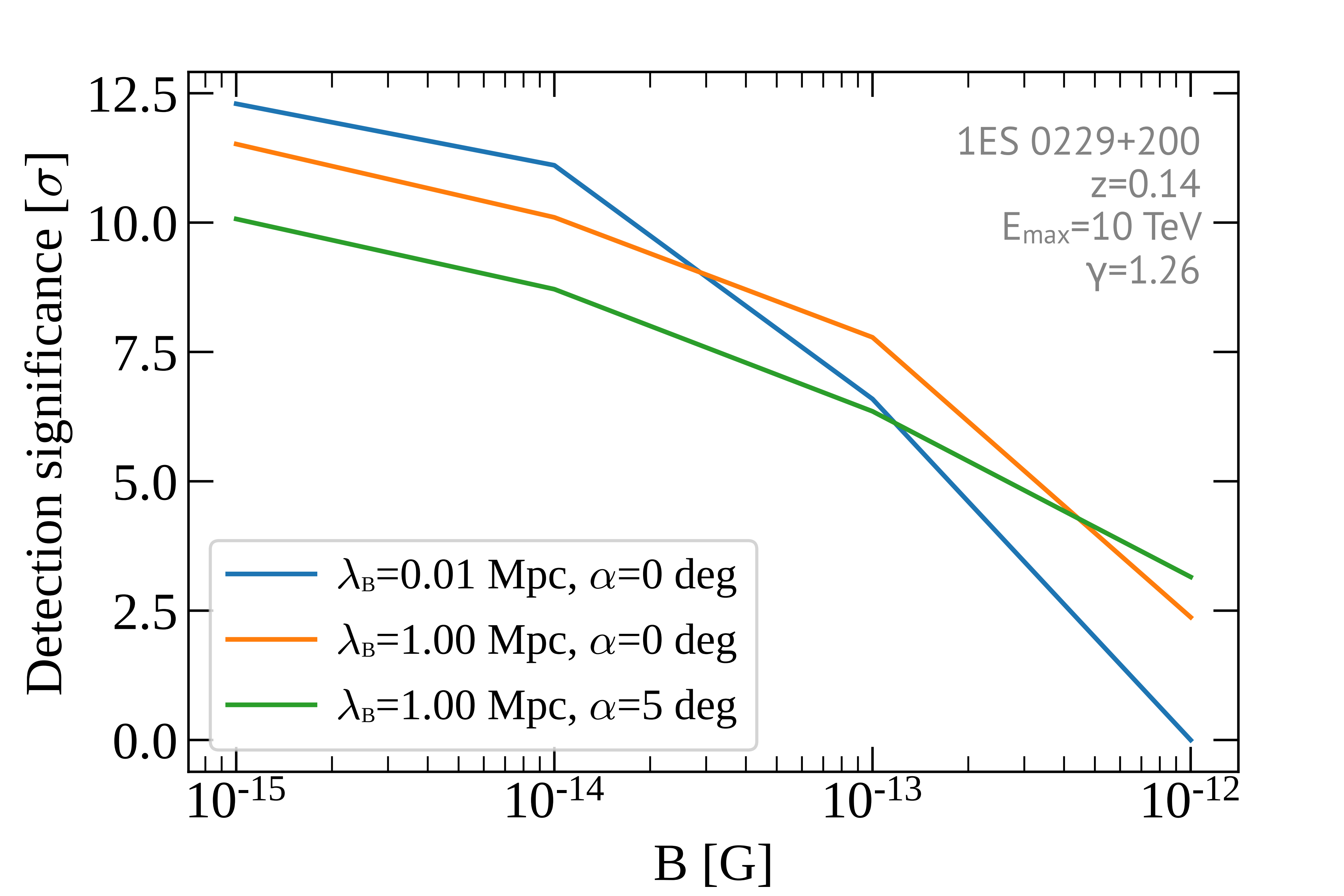




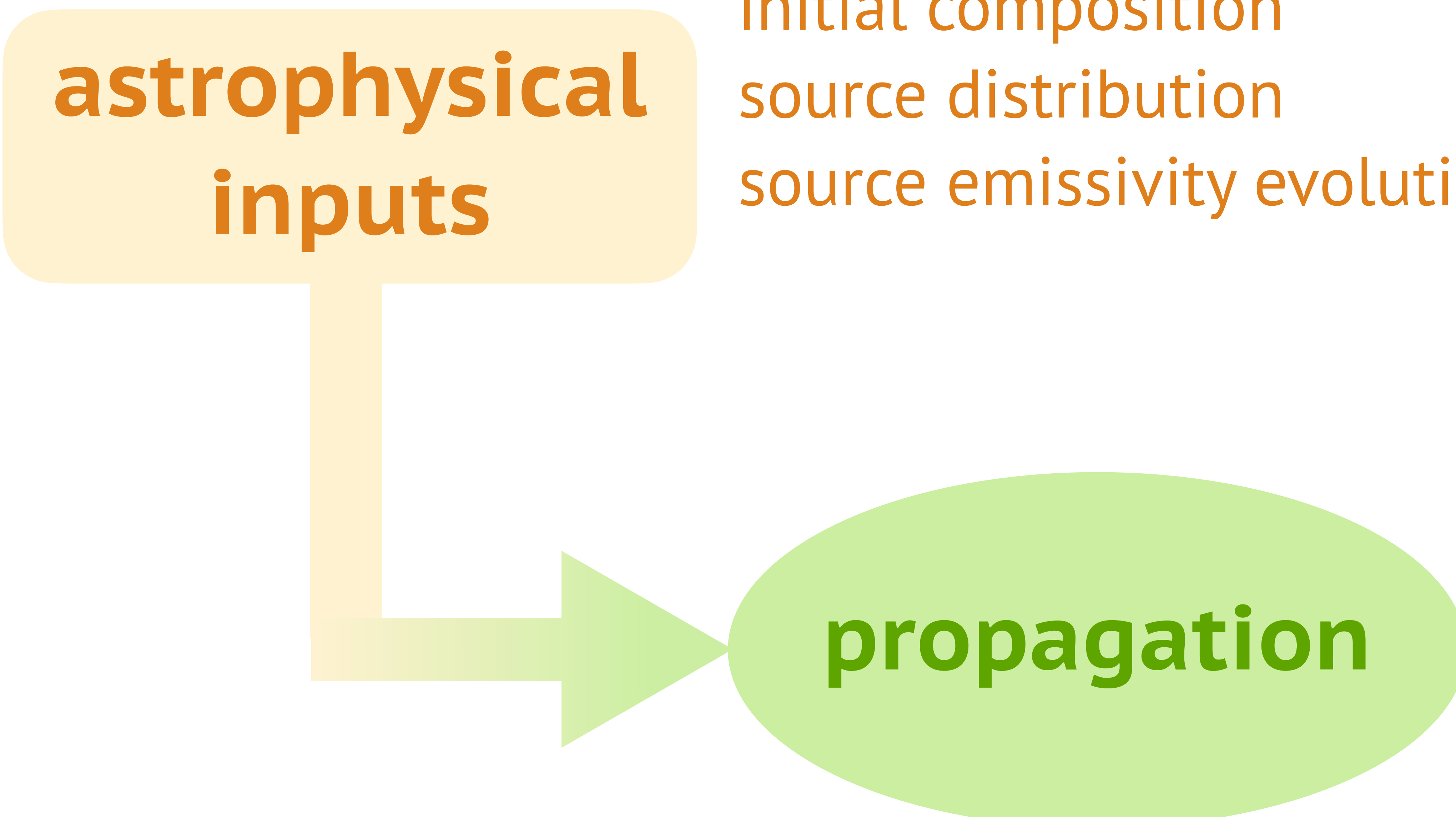


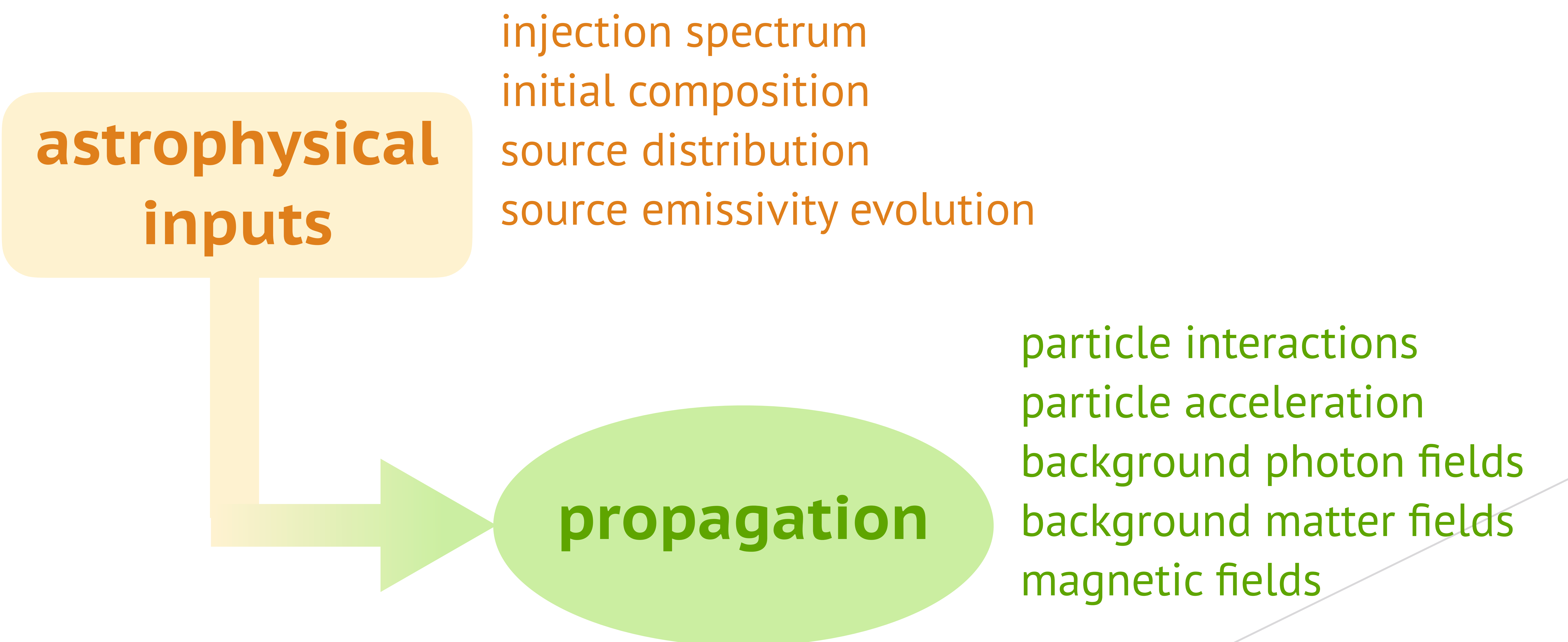
astrophysical inputs

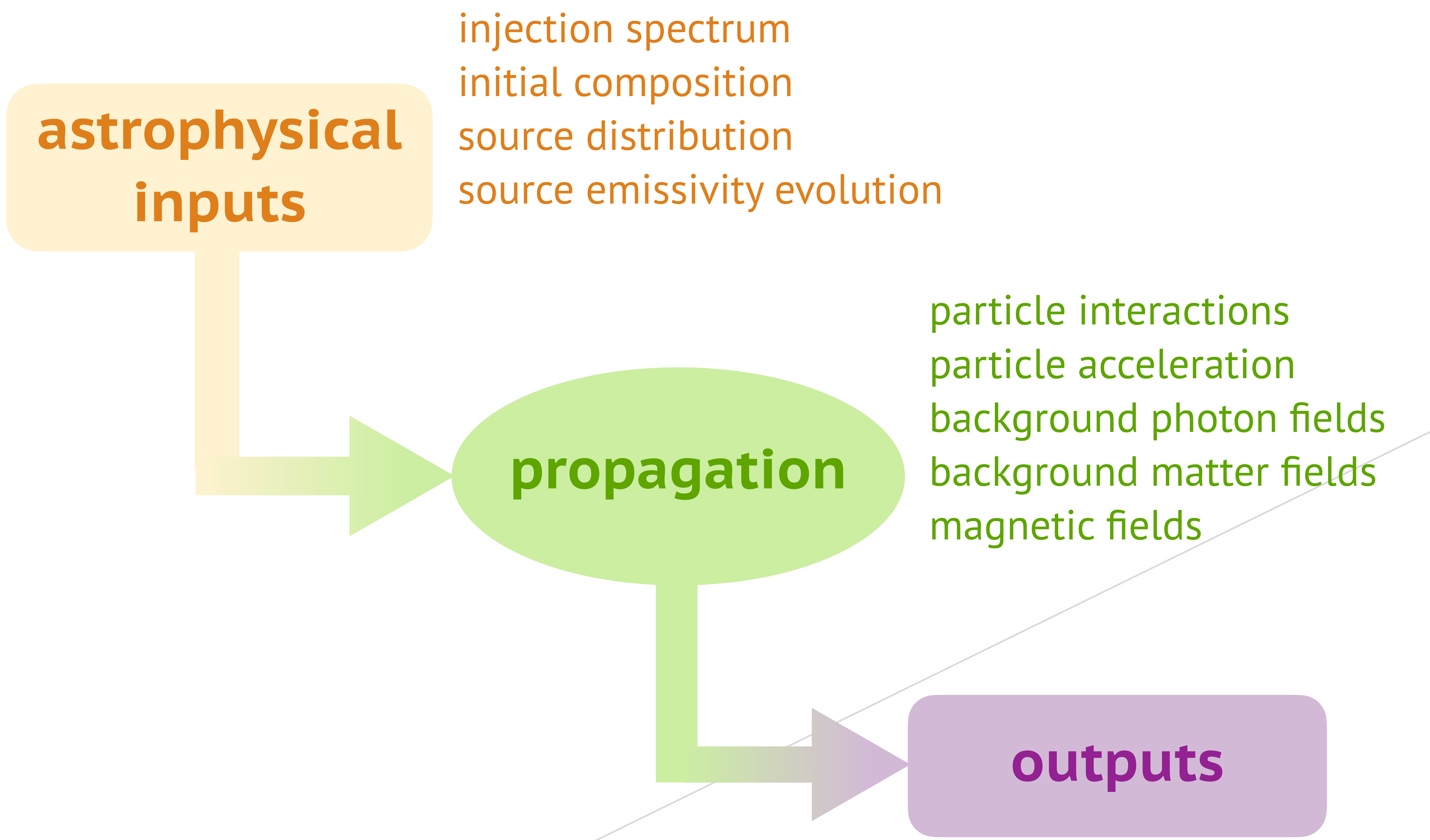
astrophysical inputs

- injection spectrum
- initial composition
- source distribution
- source emissivity evolution

injection spectrum
initial composition
source distribution
source emissivity evolution




injection spectrum
initial composition
source distribution
source emissivity evolution
astrophysical inputs
particle interactions
particle acceleration
background photon fields
background matter fields
magnetic fields
propagation


astrophysical inputs
injection spectrum
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propagation
particle interactions
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outputs

astrophysical inputs

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propagation

- particle interactions
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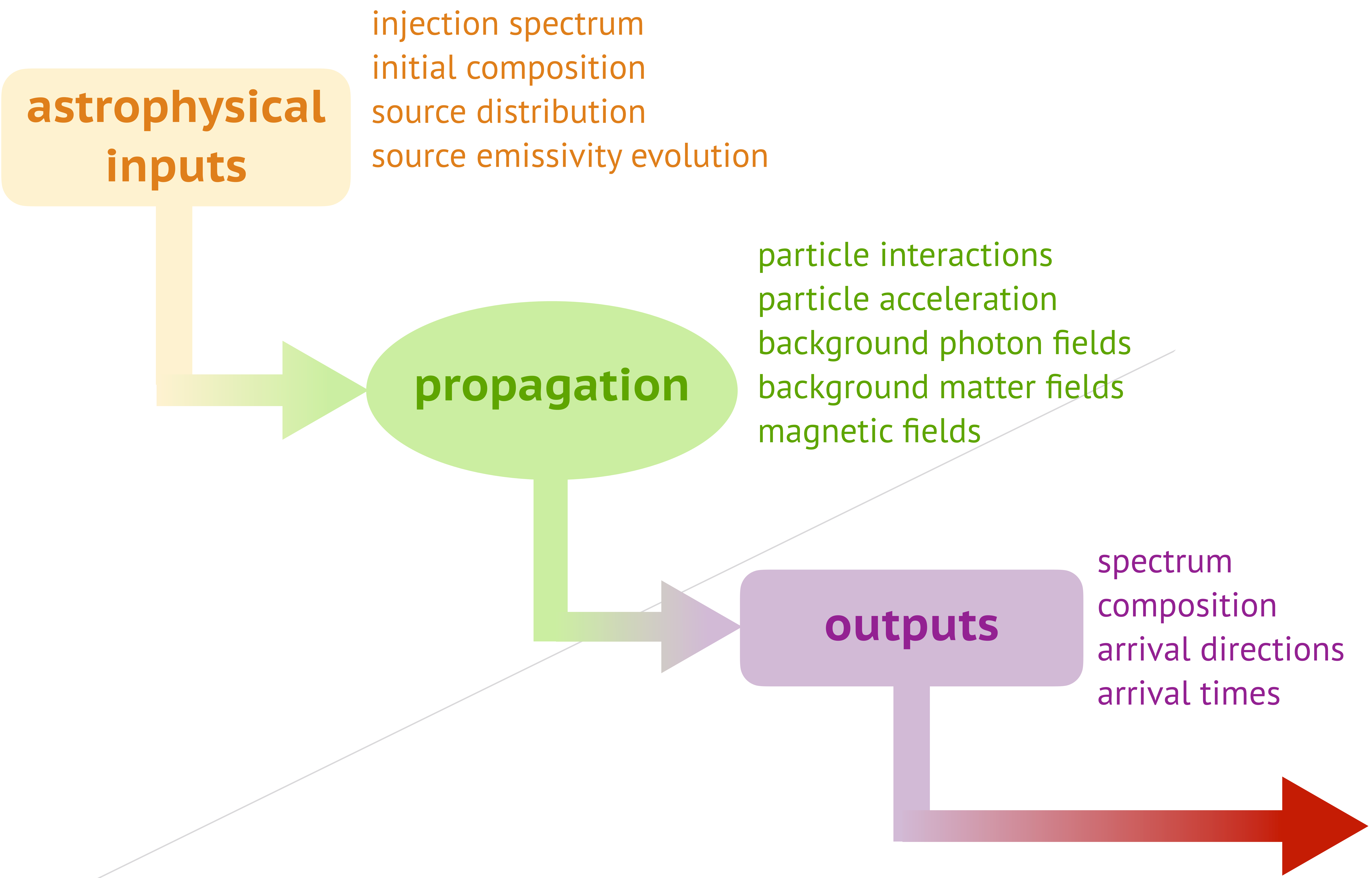
- background photon fields
- background matter fields
- magnetic fields

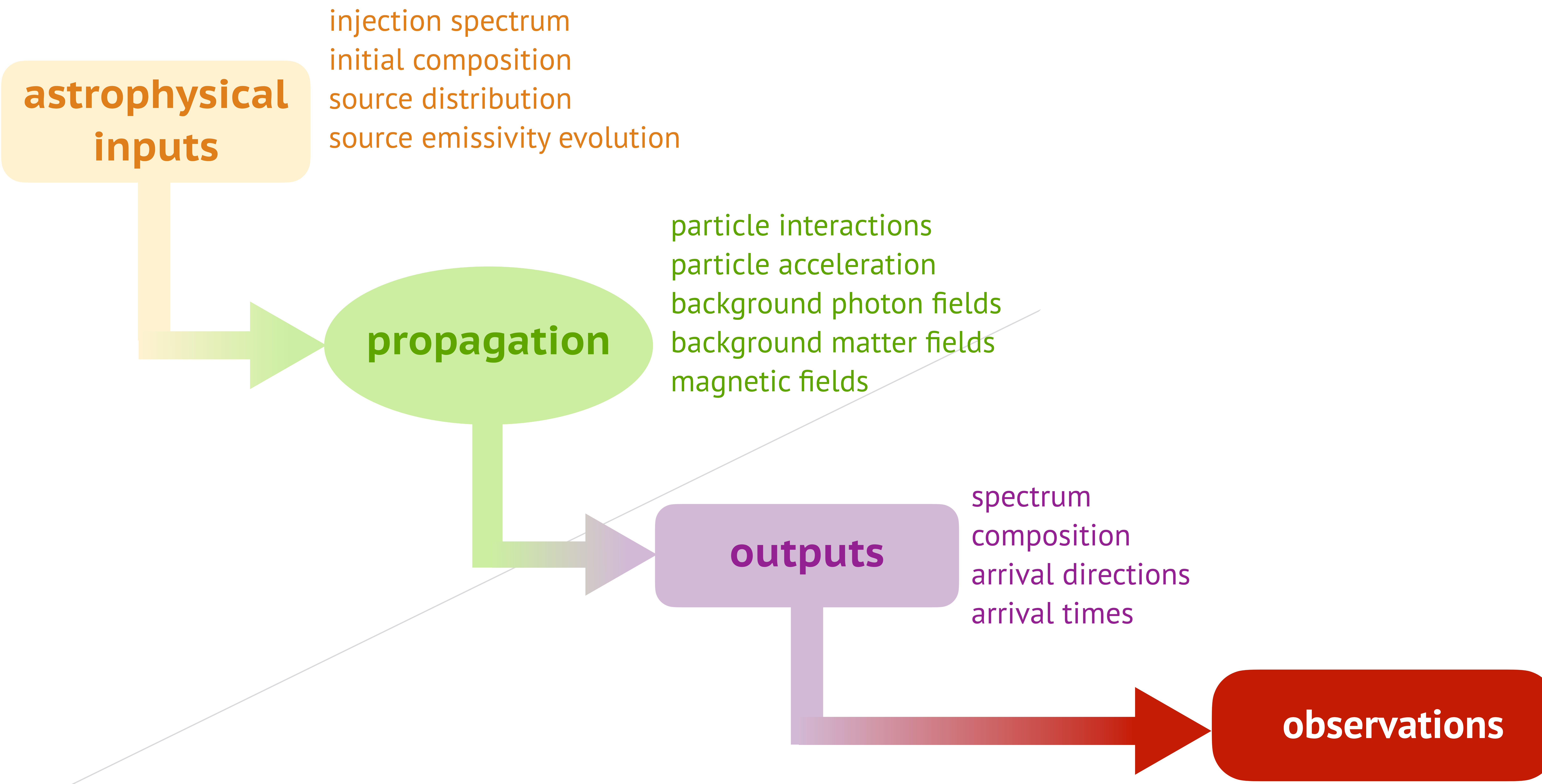
outputs

- spectrum
- composition
- arrival directions
- arrival times

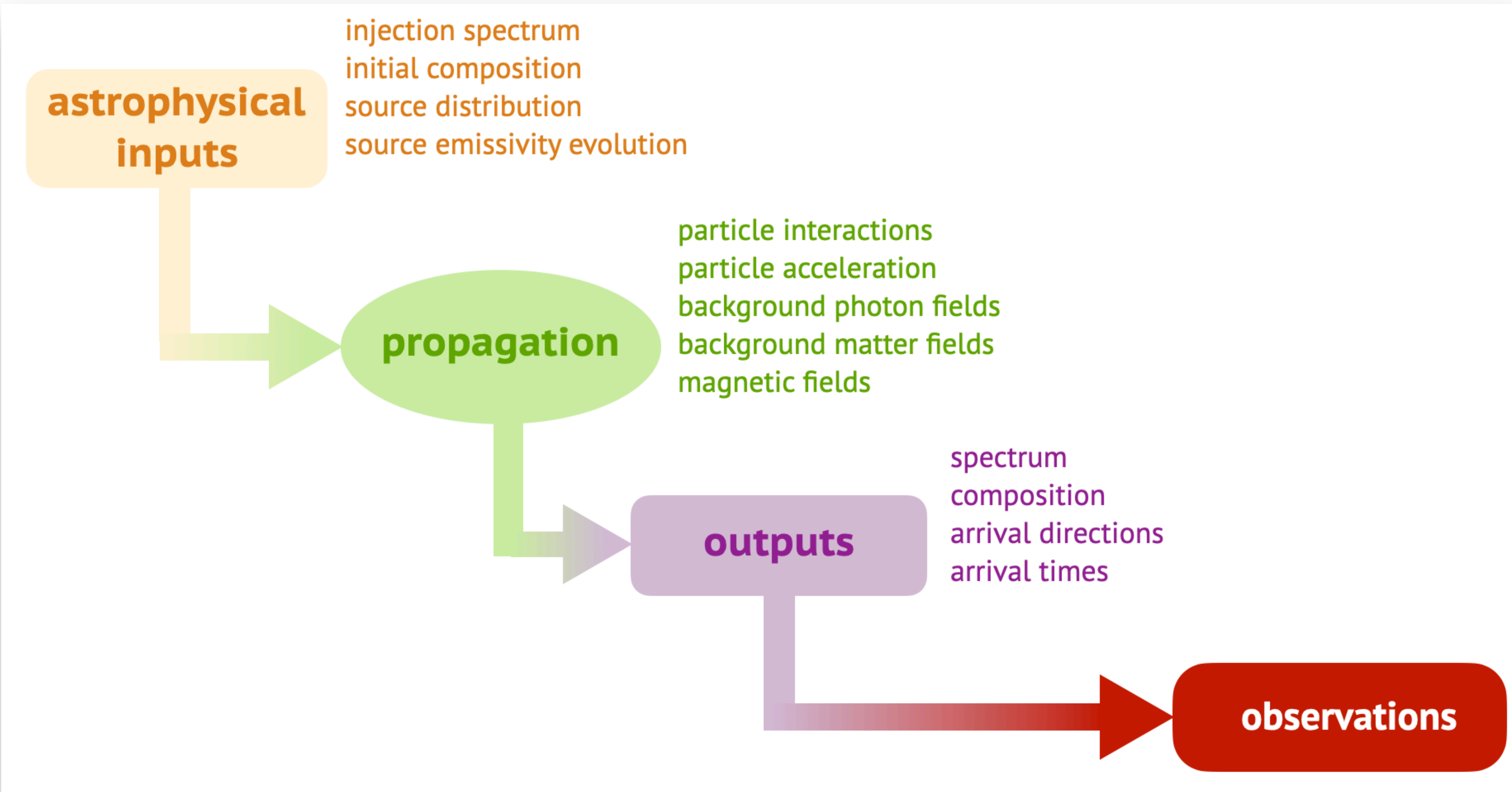
cookbook for astroparticle transport



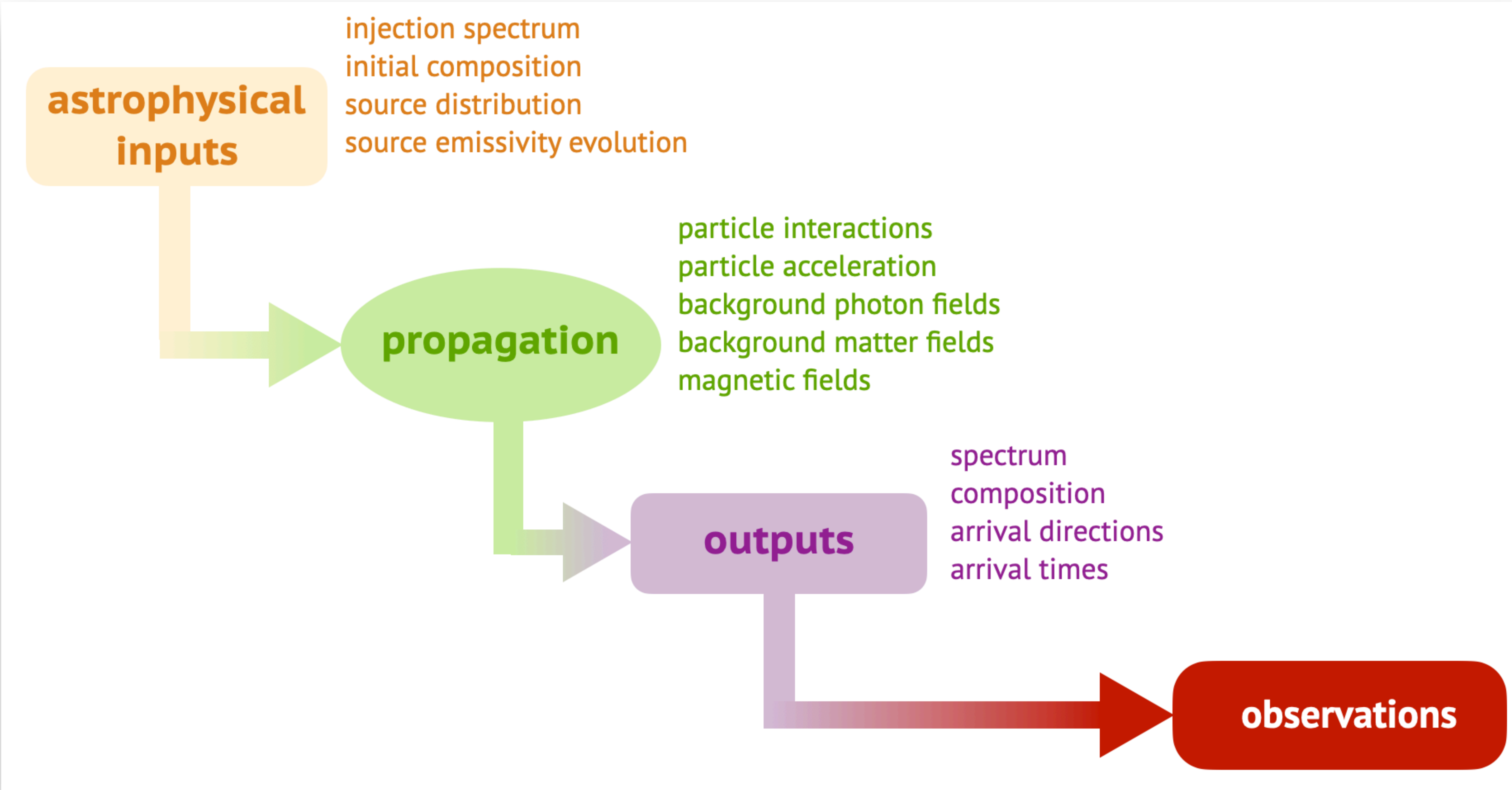
cookbook for astroparticle transport



modelling the propagation of high-energy cosmic messengers

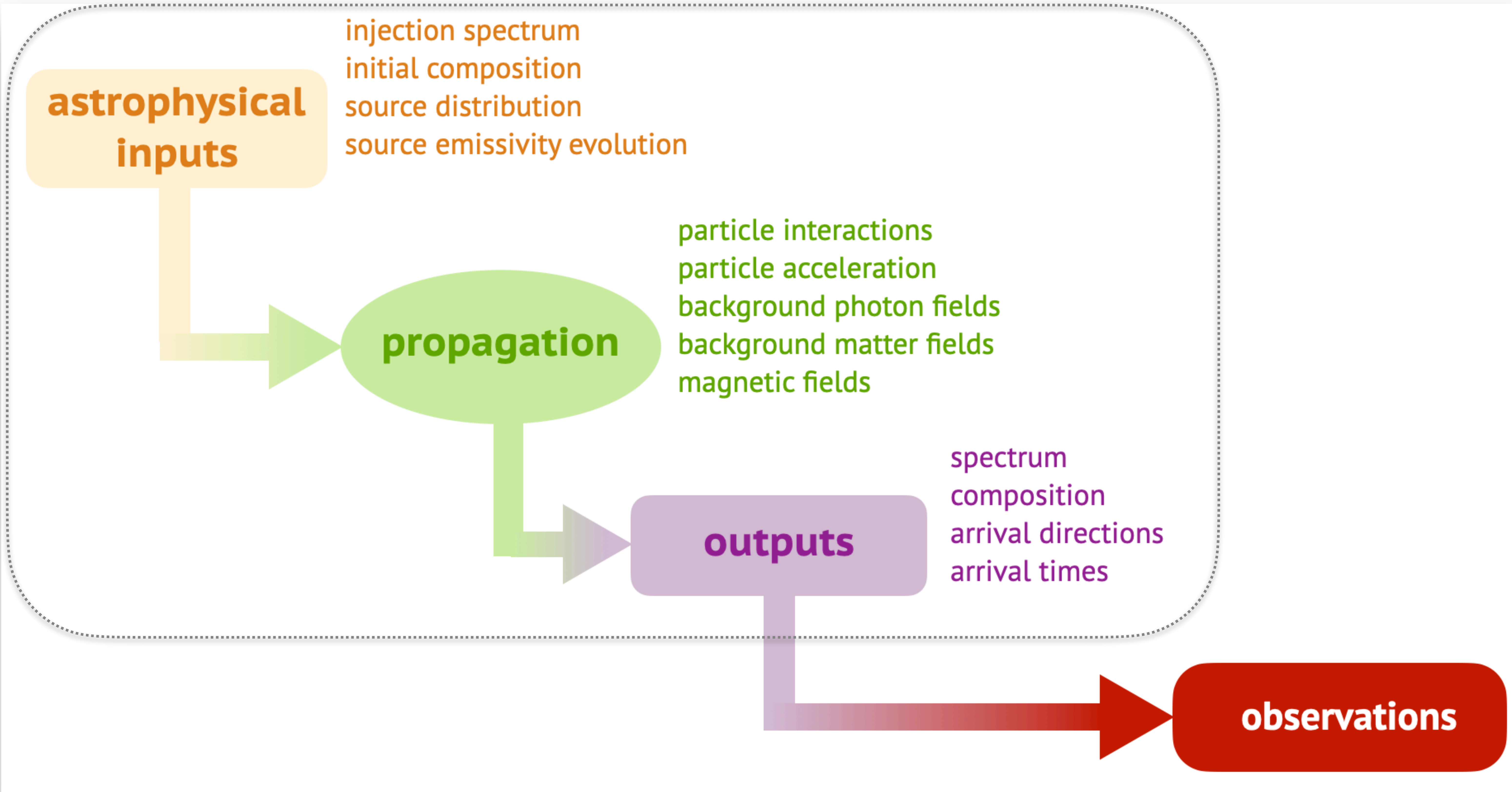


modelling the propagation of high-energy cosmic messengers



- mixing all ingredients → interpret (fit) observations based on models

modelling the propagation of high-energy cosmic messengers



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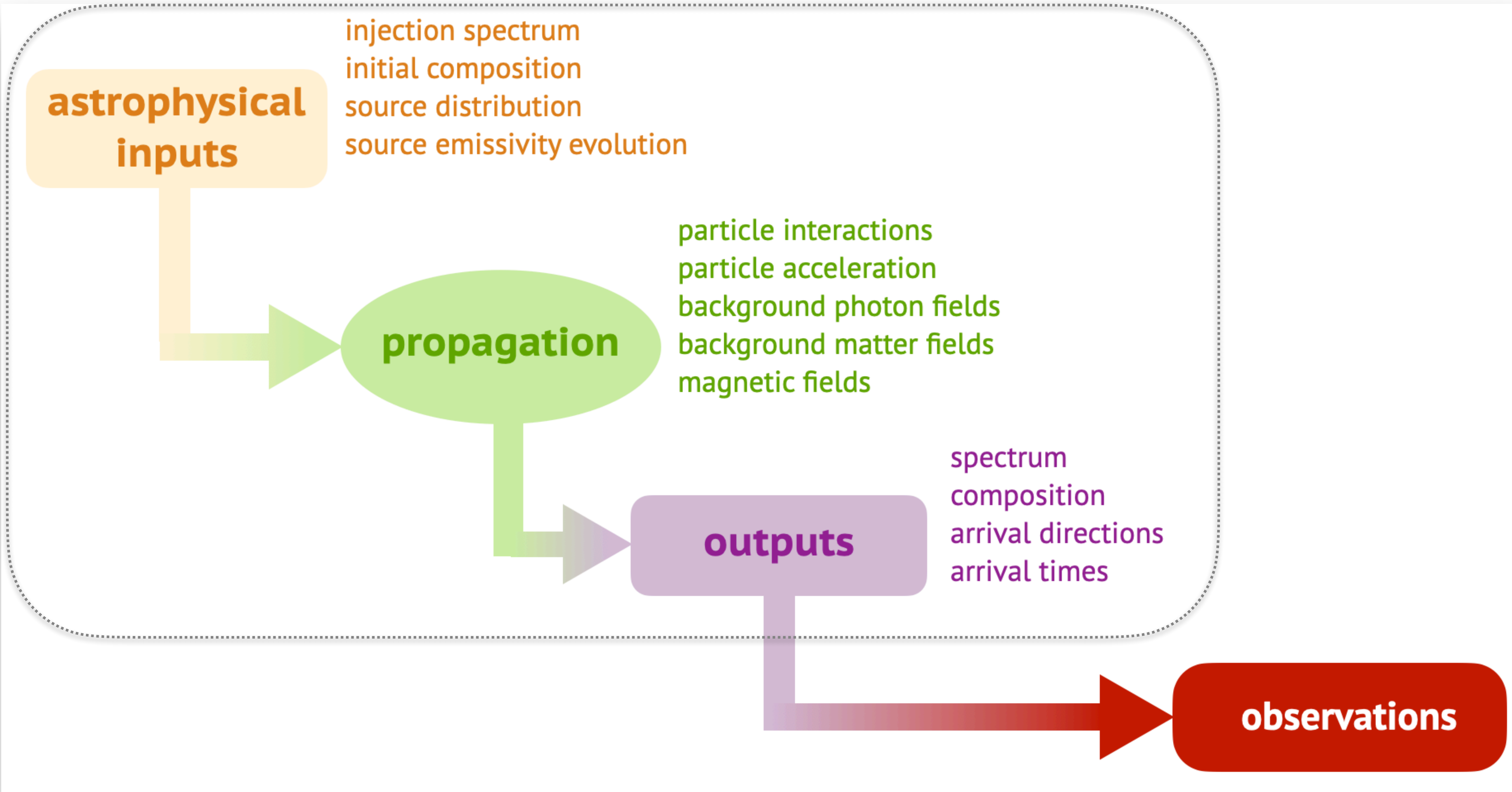

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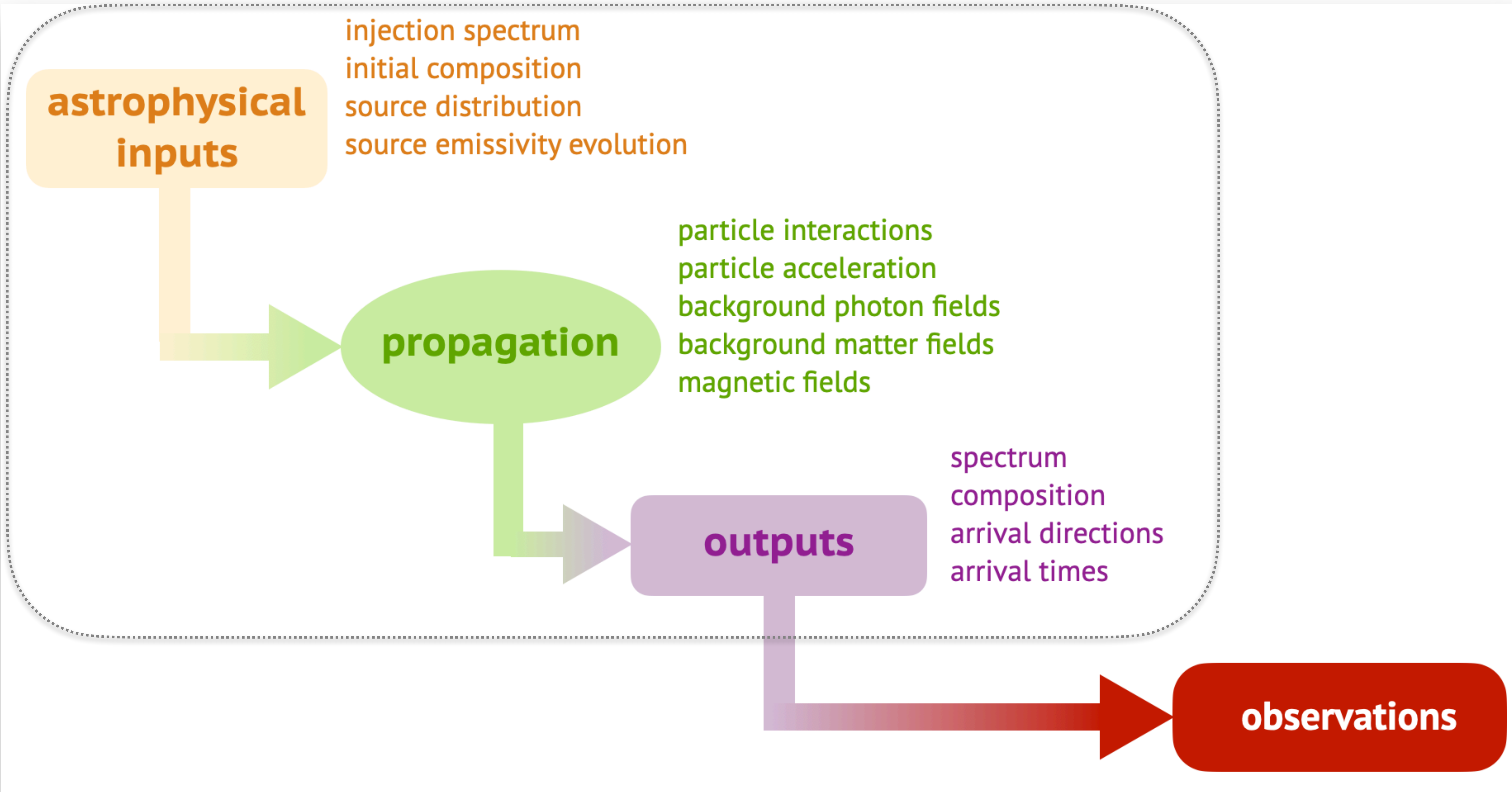

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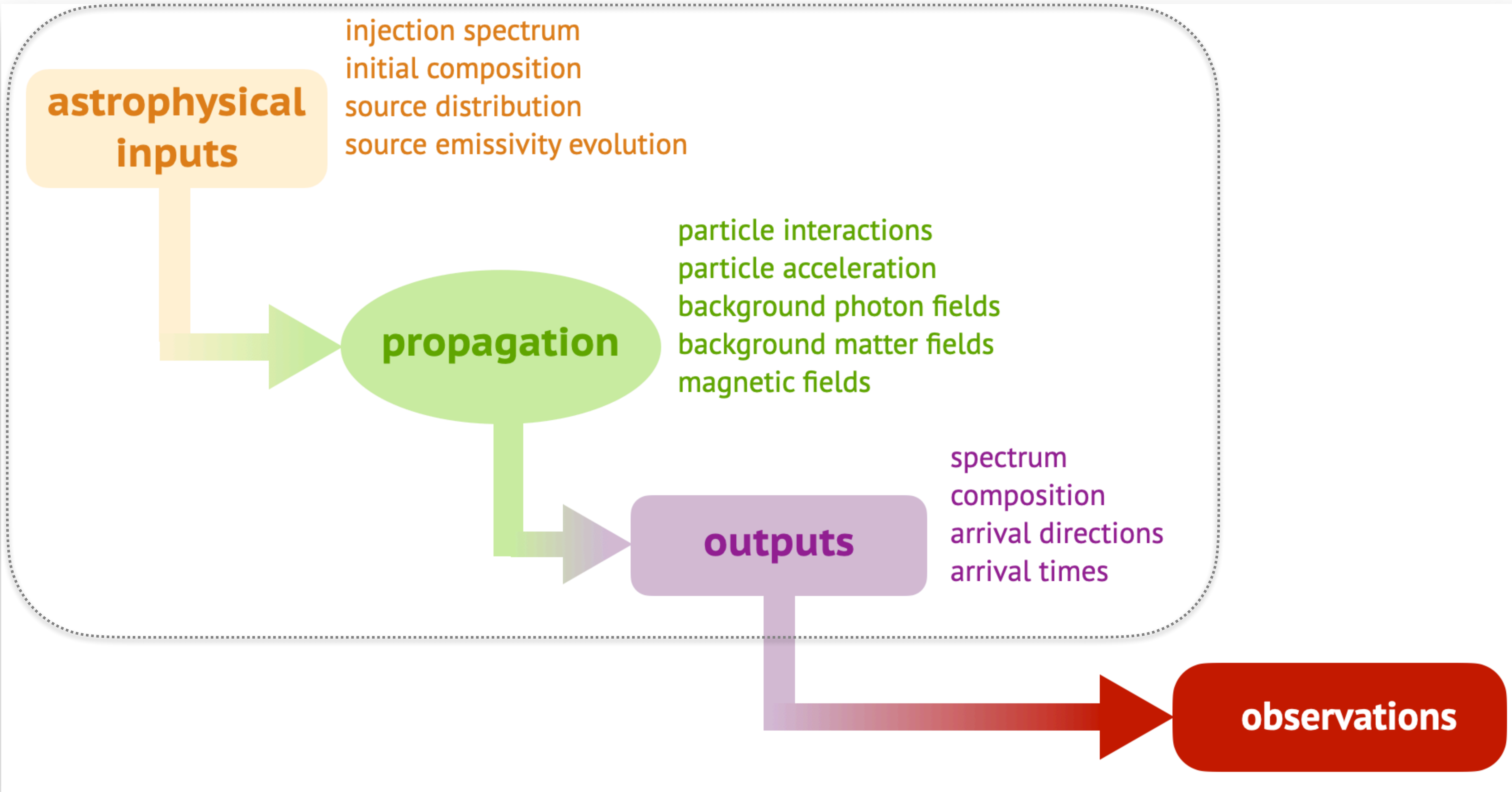

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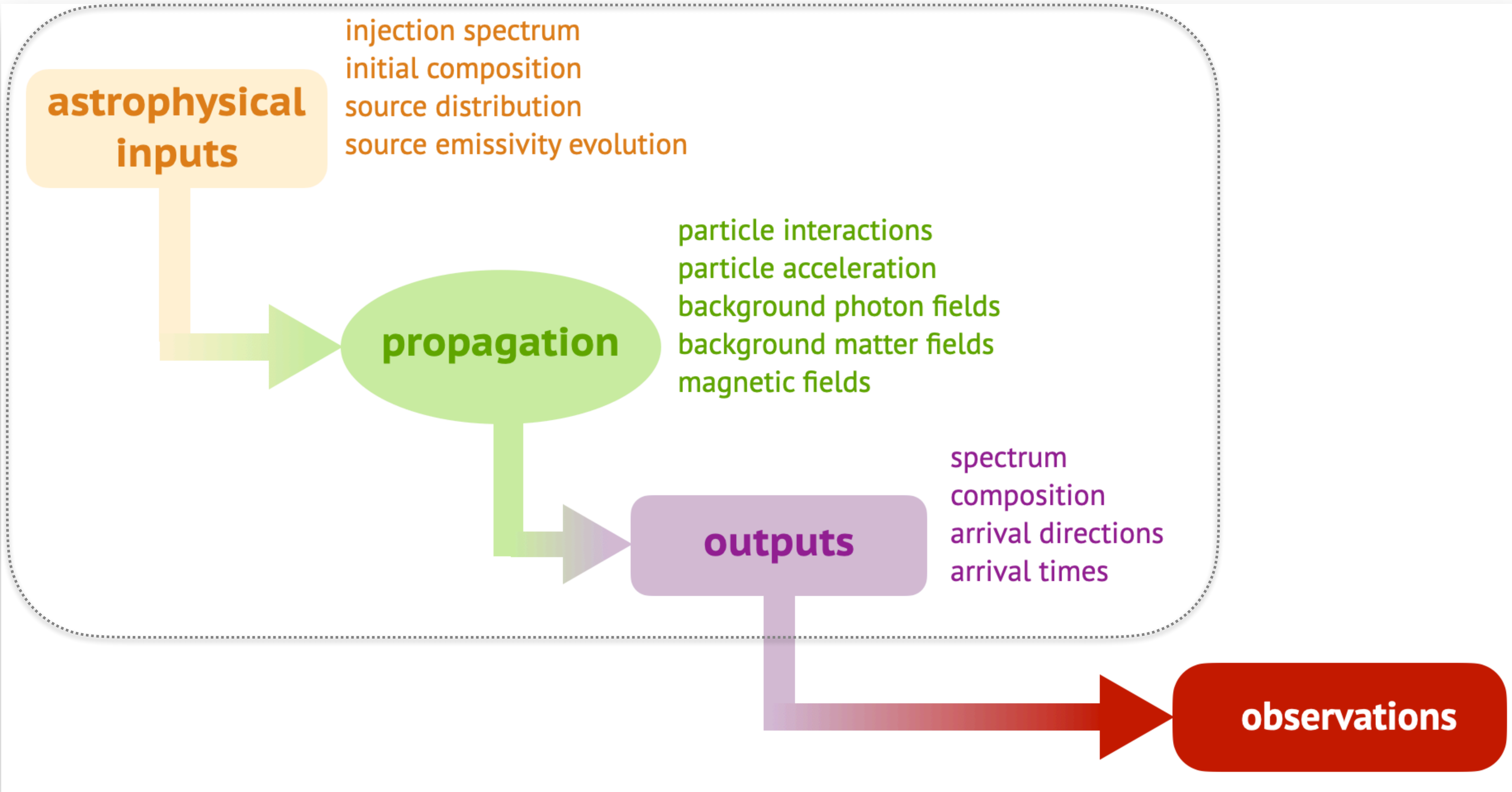

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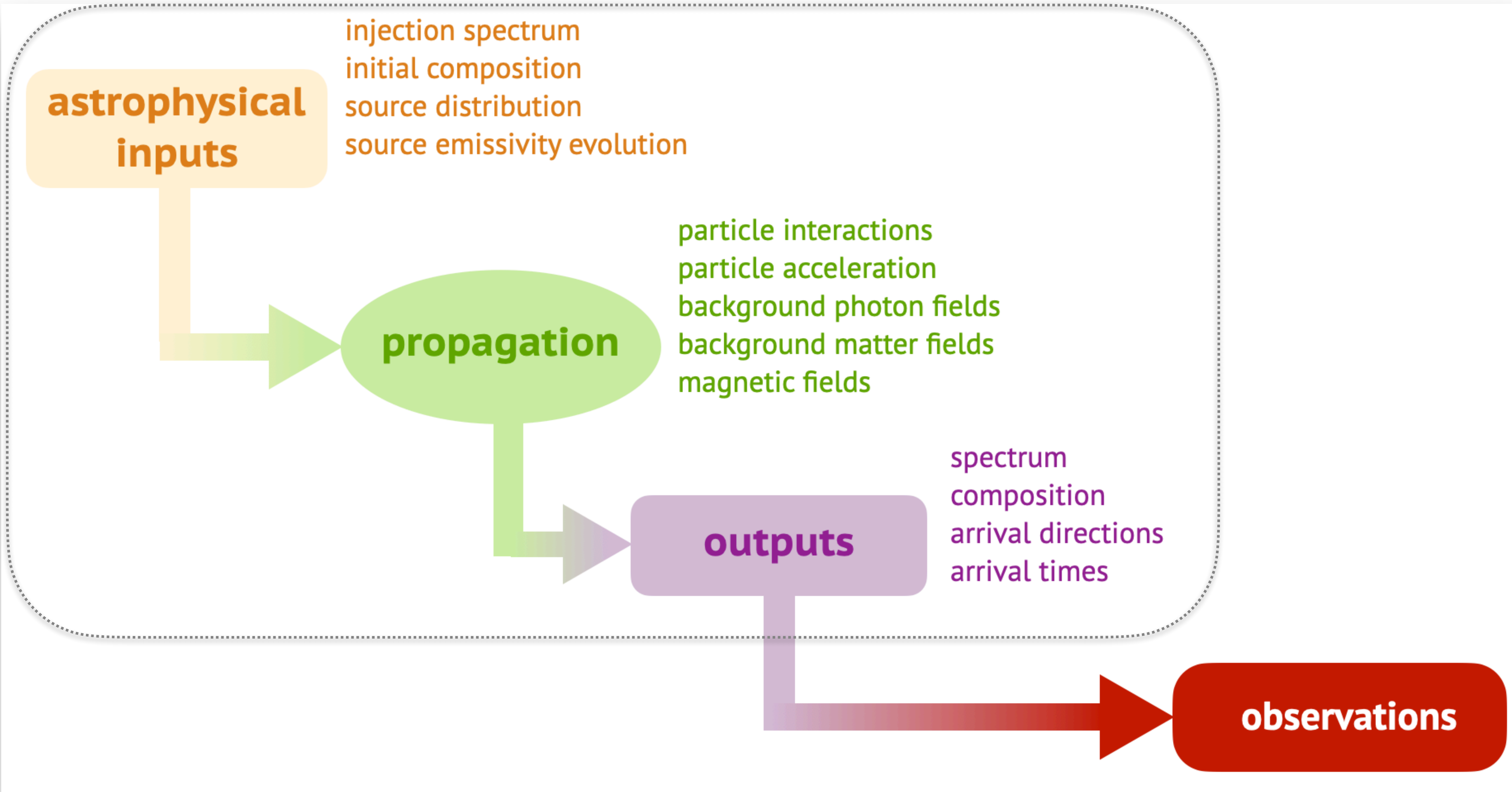
→ **multimessenger simulation framework**

modelling the propagation of high-energy cosmic messengers



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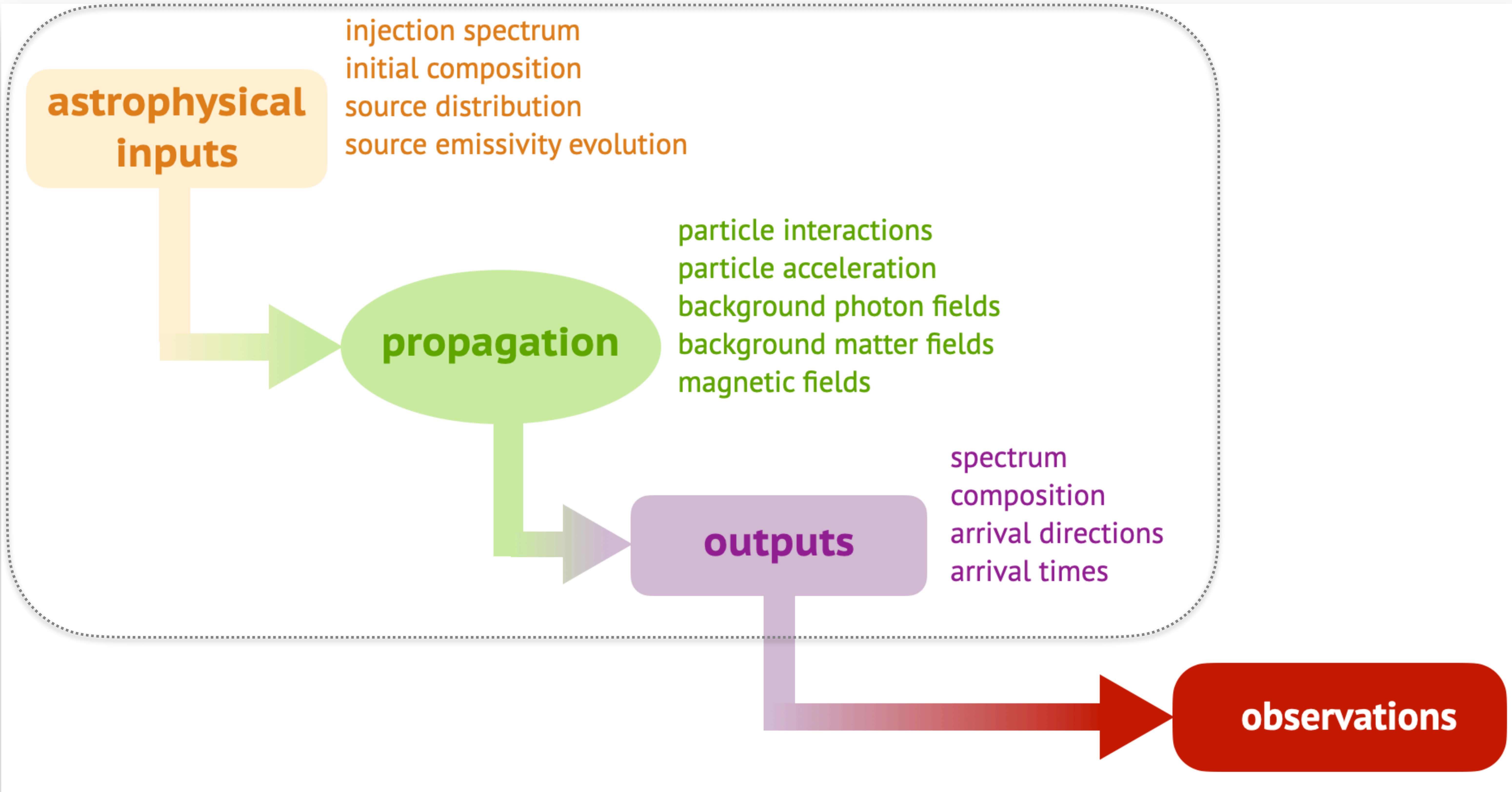

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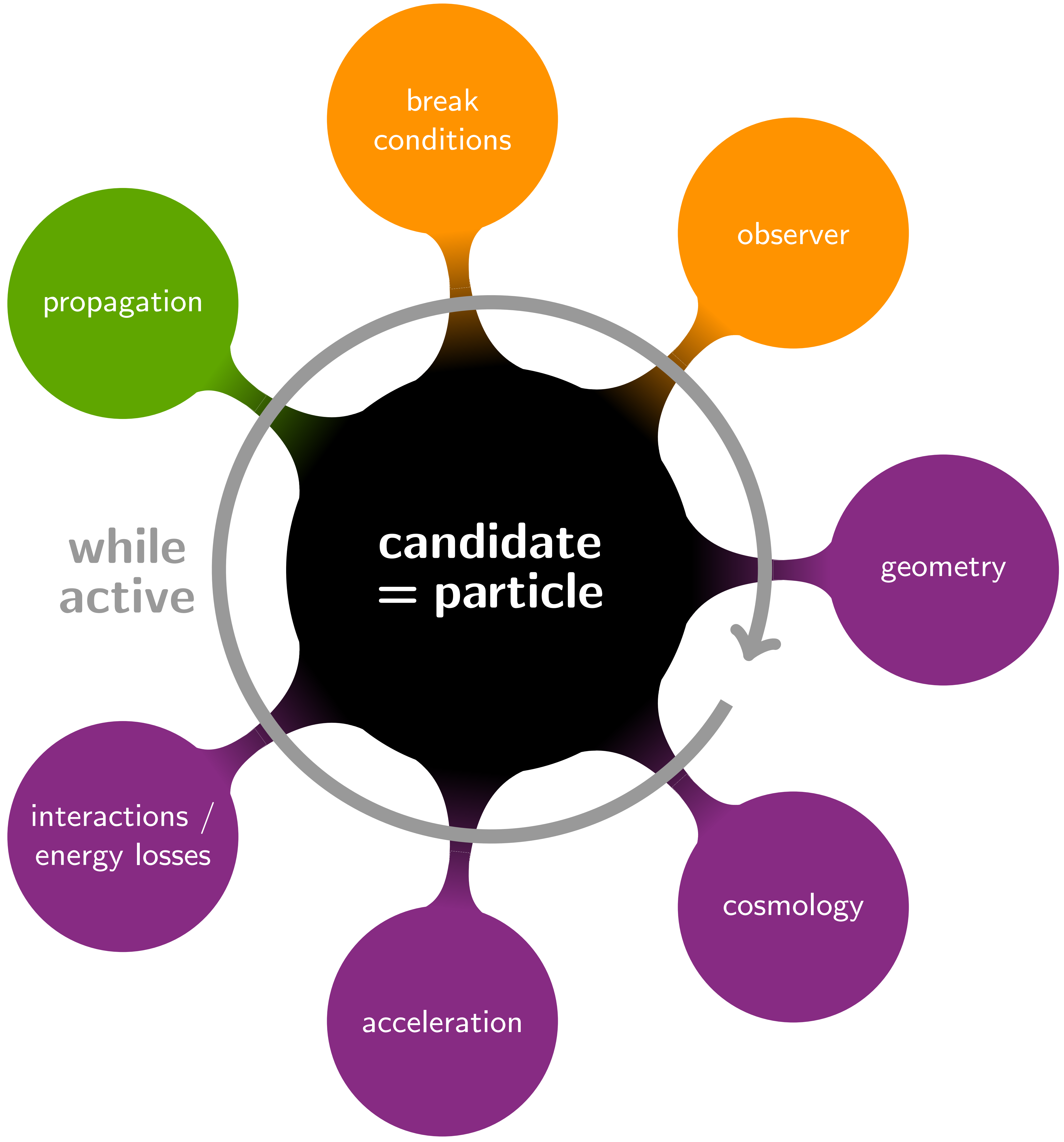
multimessenger simulation framework

CRPropa

the CRPropa framework for astroparticle propagation

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

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



crpropa.desy.de

CRPropa: interaction processes

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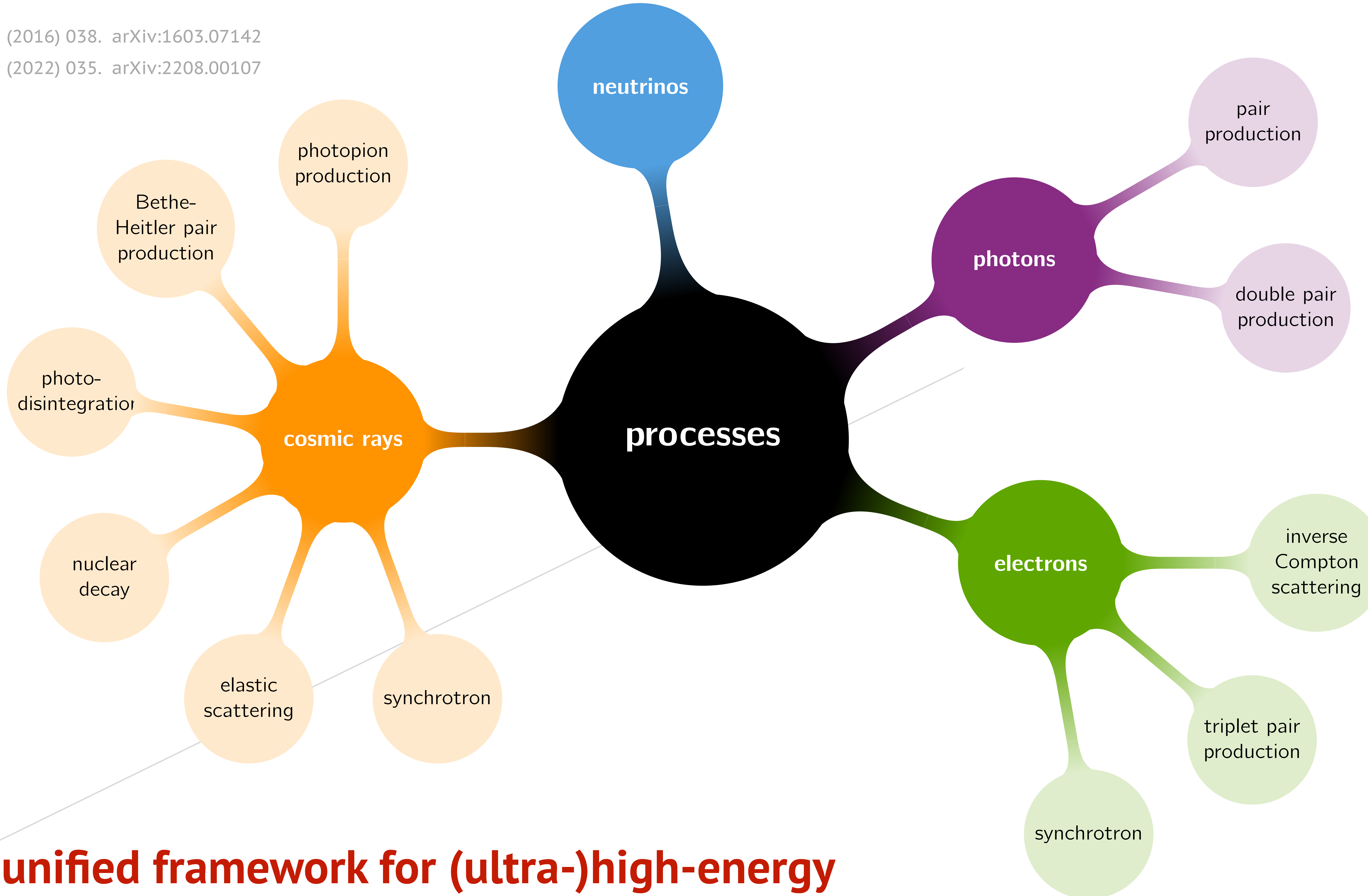

towards a unified framework for (ultra-)high-energy multimessenger studies

CRPropa: interaction processes

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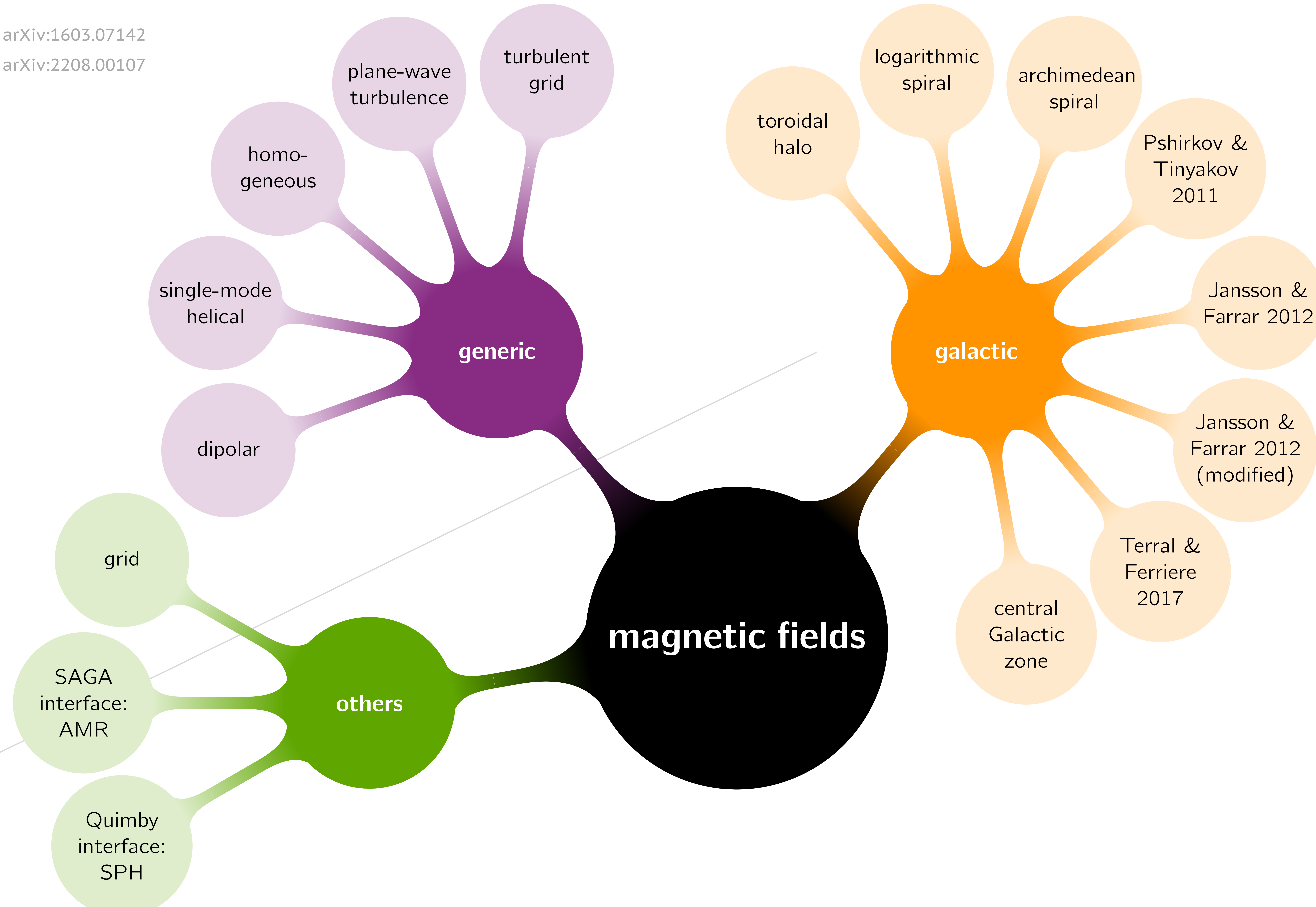

(some) computational tools for model building

Elmag https://elmag.sourceforge.net/

CRPropa https://crpropa.desy.de/

CECsi https://github.com/tfitoussi/CECsi

CRbeam https://github.com/okolo/mcray

(some) computational tools for model building

Elmag

https://elmag.sourceforge.net/

Kachelriess et al. Comp. Phys. Comms. 183 (2012) 1036. arXiv:1106.5508

Blytt et al. Comp. Phys. Comms. 252 (2019) 107163. arXiv:1909.09210

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

CECsi

https://github.com/tfitoussi/CECsi

Fitoussi et al. MNRAS 466 (2017) 3472. arXiv:1701.00654

CRbeam

https://github.com/okolo/mcray

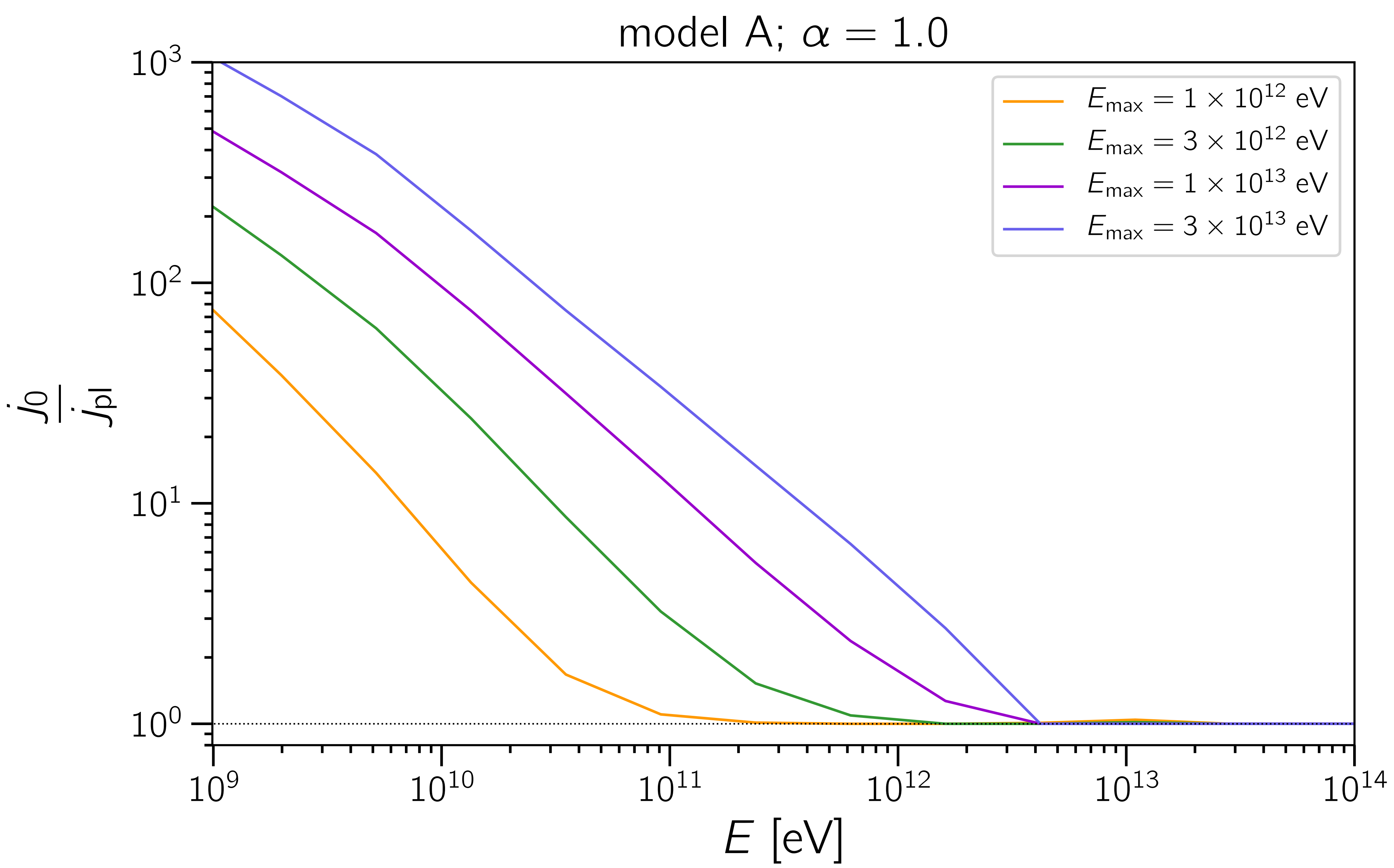
Kalashev et al. arXiv:2201.03996

- collective plasma phenomena relevant if: $n_{beam}\lambda_{pl}^3 \gg 1$
- skin depth: $\lambda_{pl} = \dfrac{2\pi c}{\omega_{pl}}$ $\omega_{pl} = \sqrt{\dfrac{e^2 n_{IGM}}{\varepsilon_0 m_e}}$
- 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]

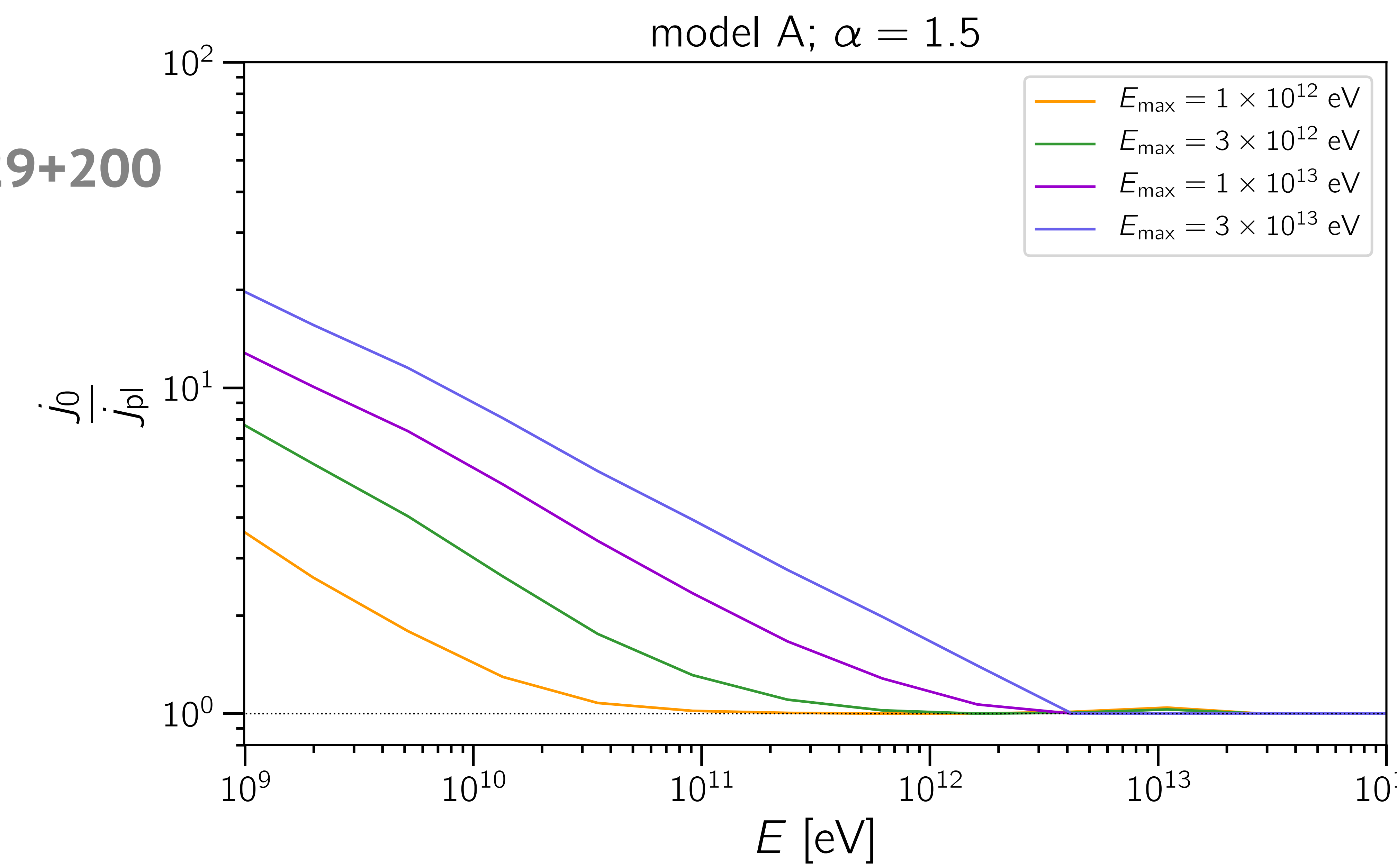
Broderick et al. ApJ 752 (2012) 22. arXiv:1106.5494
Schlickeiser et al. ApJ 758 (2012) 102.
Miniati & Elyiv. ApJ 770 (2013) 54. arXiv:1208.1761
Sironi & Giannios. ApJ 787 (2014) 49. arXiv:1312.4538
Vafin et al. ApJ 857 (2018) 43. arXiv:1803.02990
Yan et al. ApJ 870 (2019) 70. arXiv:1810.07013
Alves Batista,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

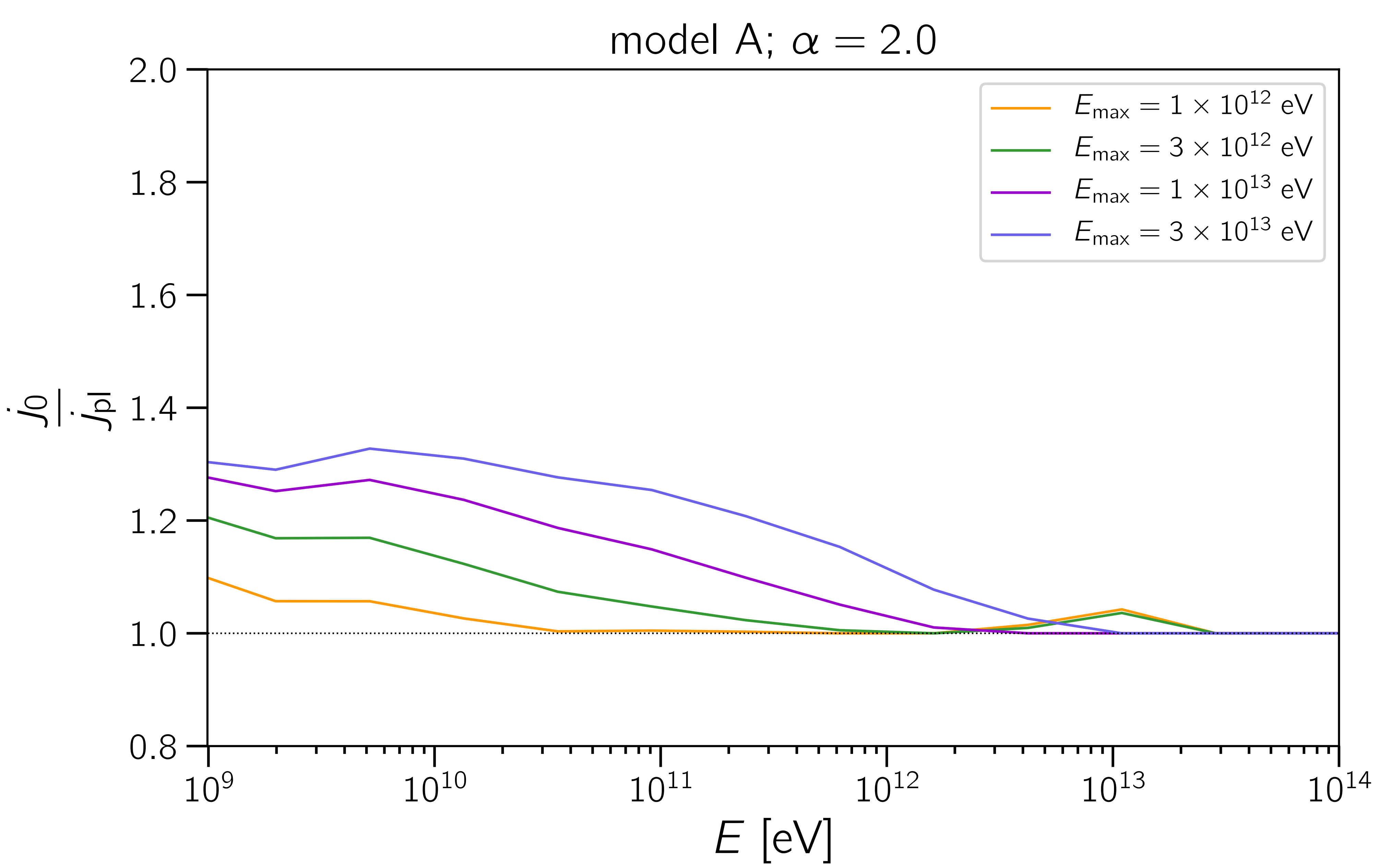
plasma instabilities: quenching factors

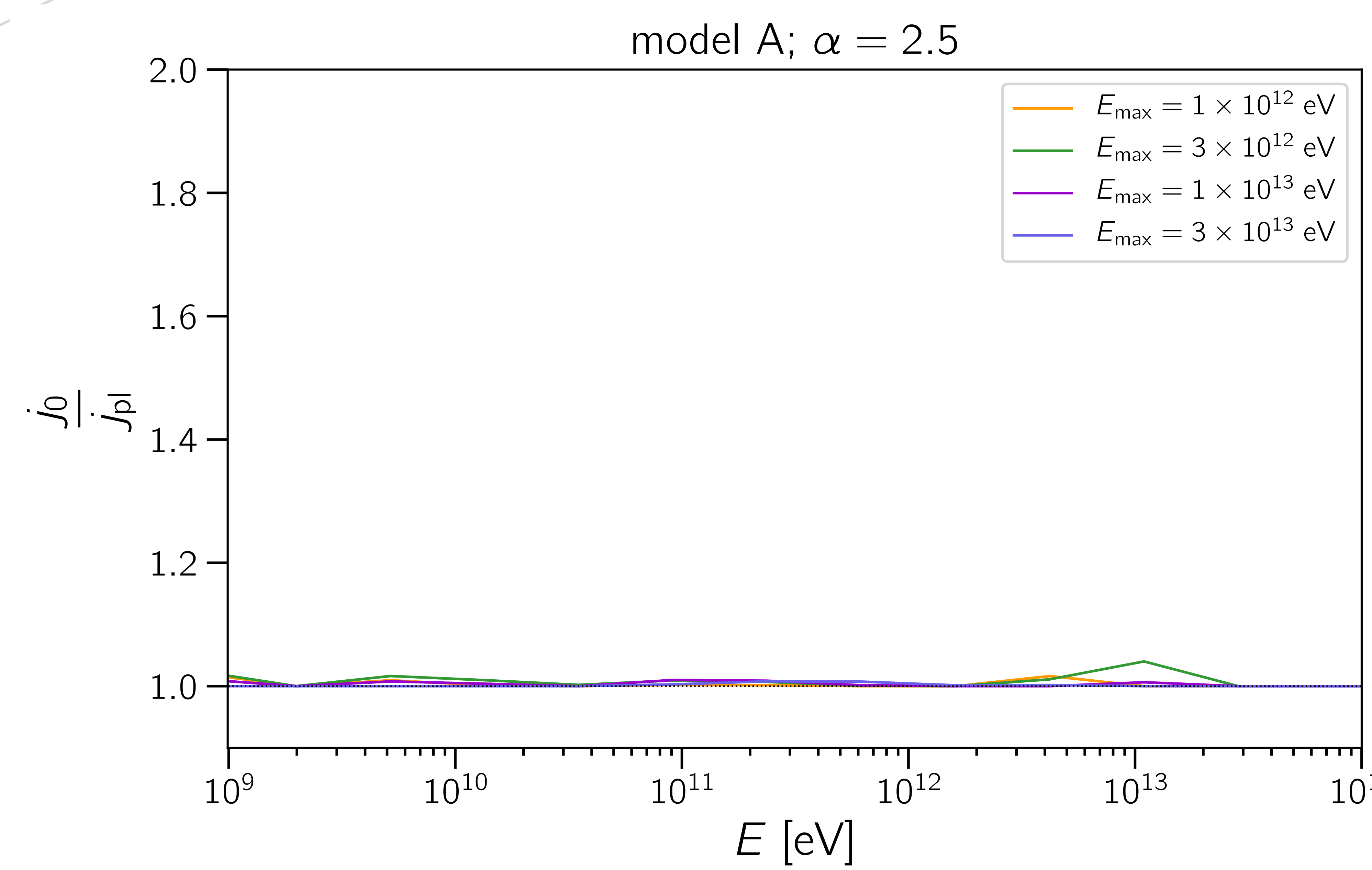
Alves Batista, Saveliev, de Gouveia Dal Pino. MNRAS 489 (2019) 3836. arXiv:1904.13345



1ES 0229+200
z=0.14







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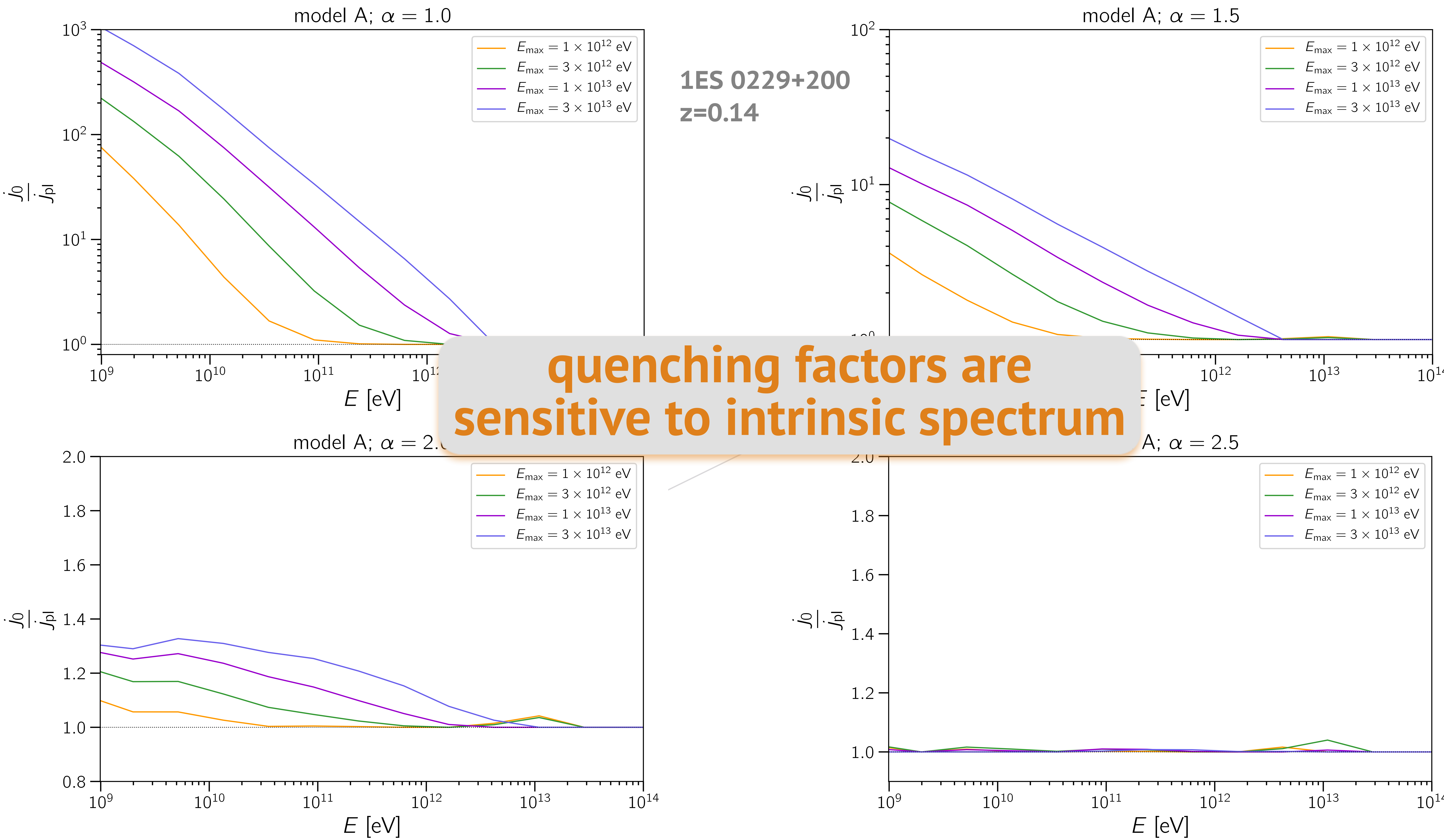

quenching factors are sensitive to intrinsic spectrum