probing intergalactic magnetic fields

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intergalactic magnetic fields (IGMFs)

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?

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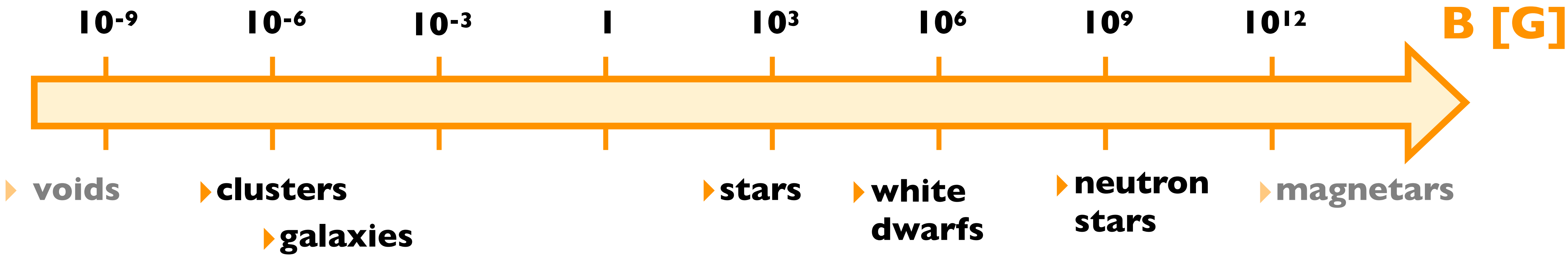
- **astrophysical mechanisms:** during structure formation (e.g. Biermann battery, ...)
- **primordial mechanisms**: large-scale cosmological processes such as inflation, EW phase transition, QCD phase transition, ...

intergalactic magnetic fields (IGMFs)



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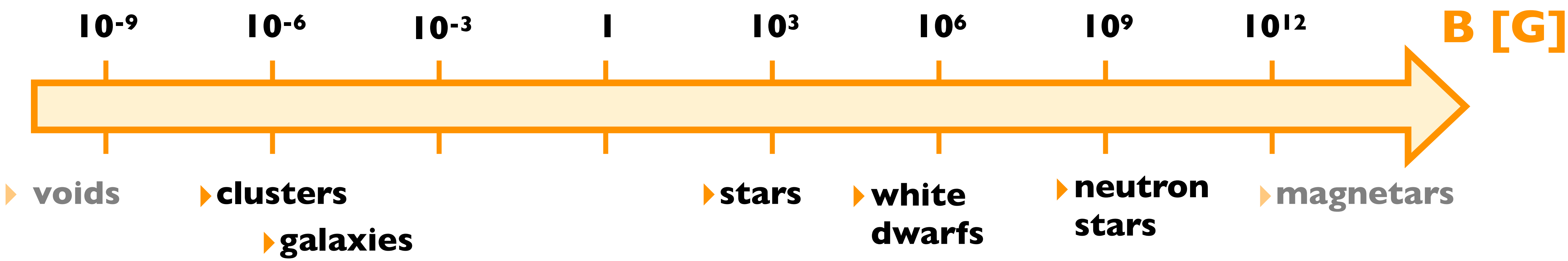

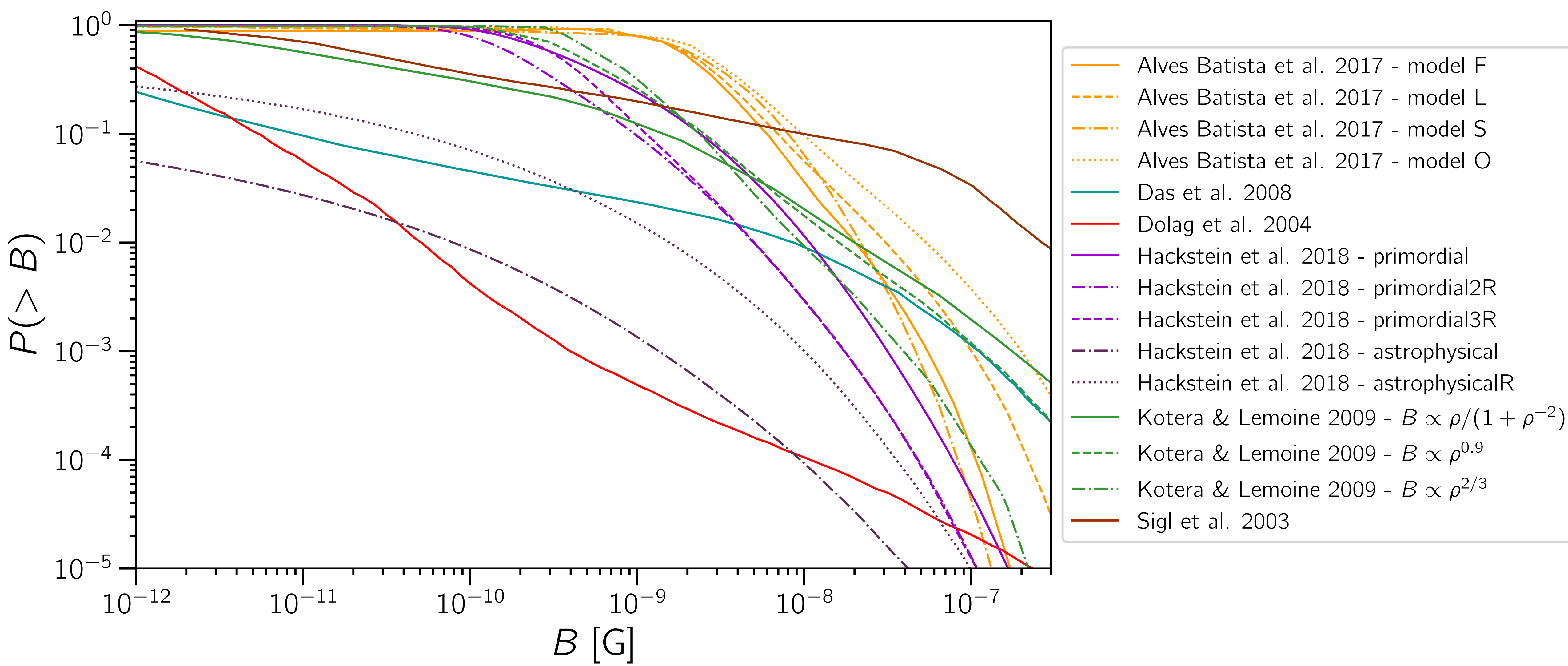

Alves Batista et al. Front. Astron. Space Sci. 6 (2019) 23.

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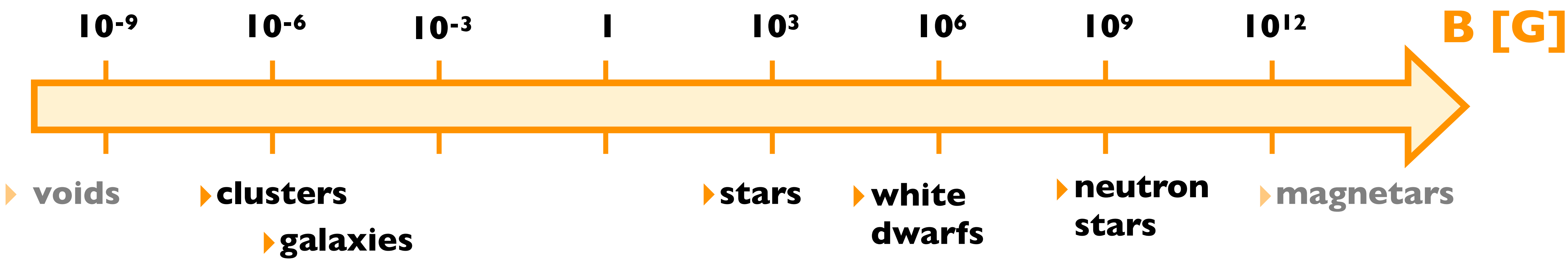

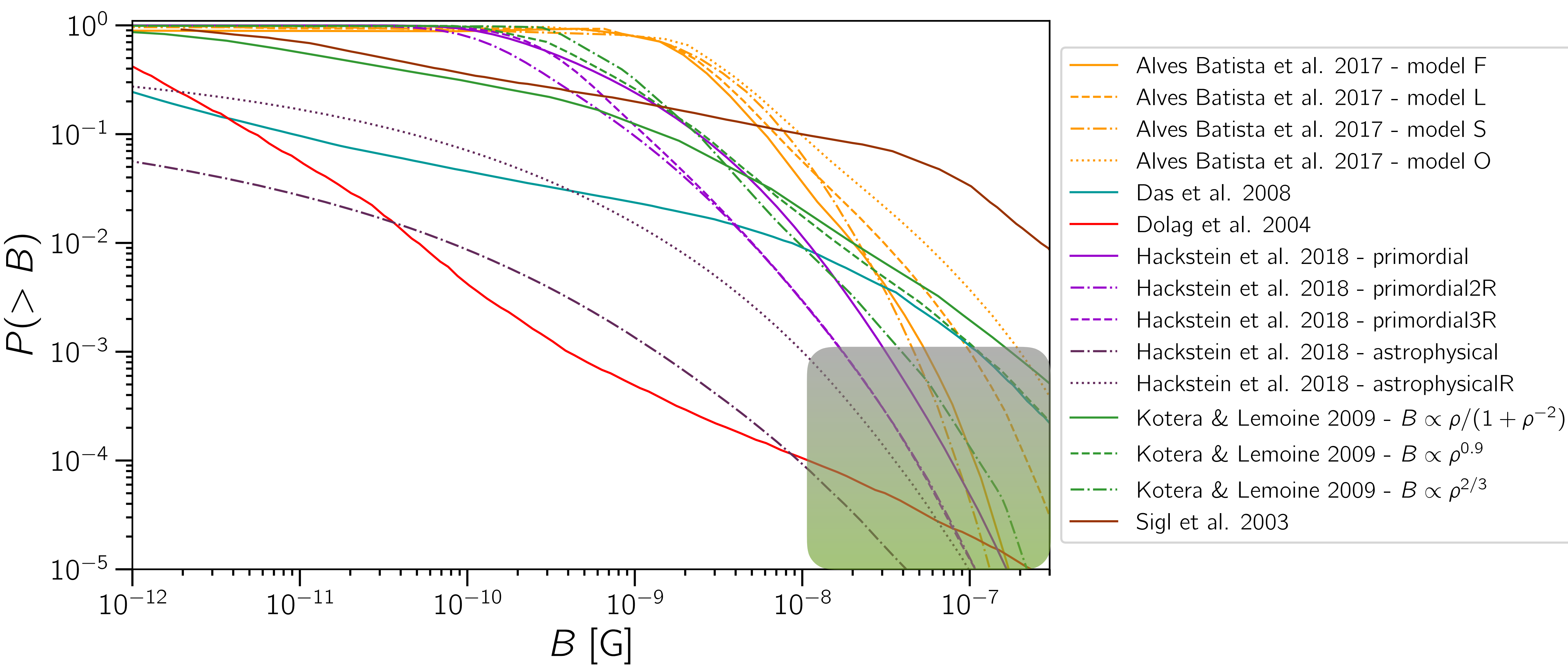

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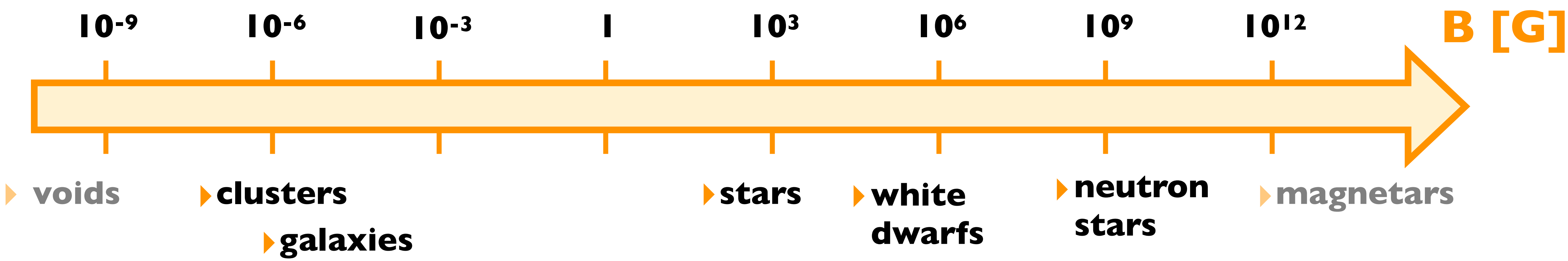

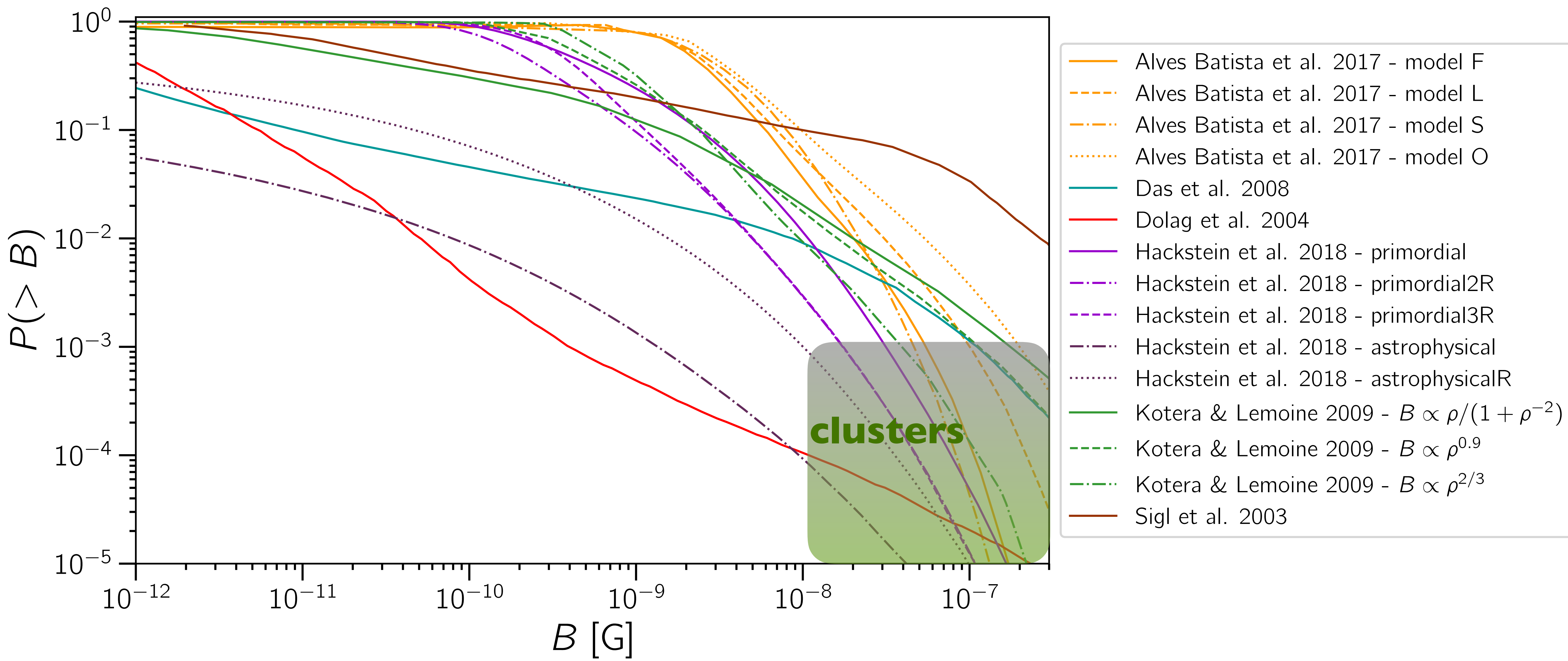

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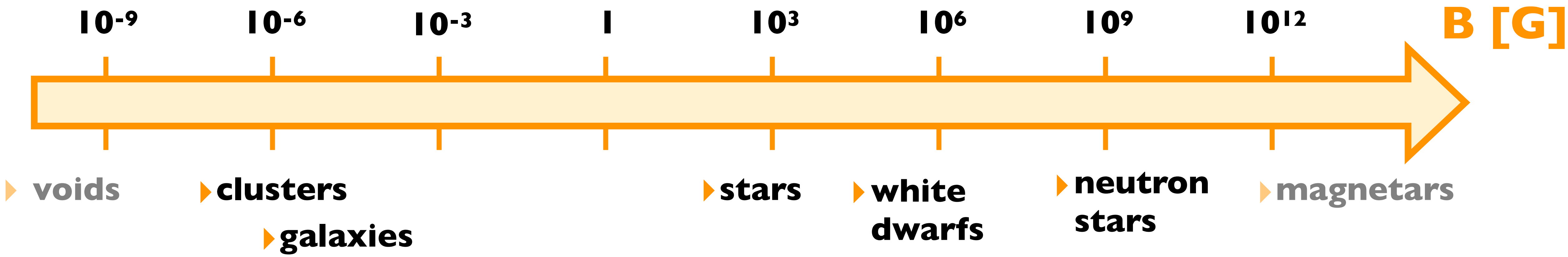

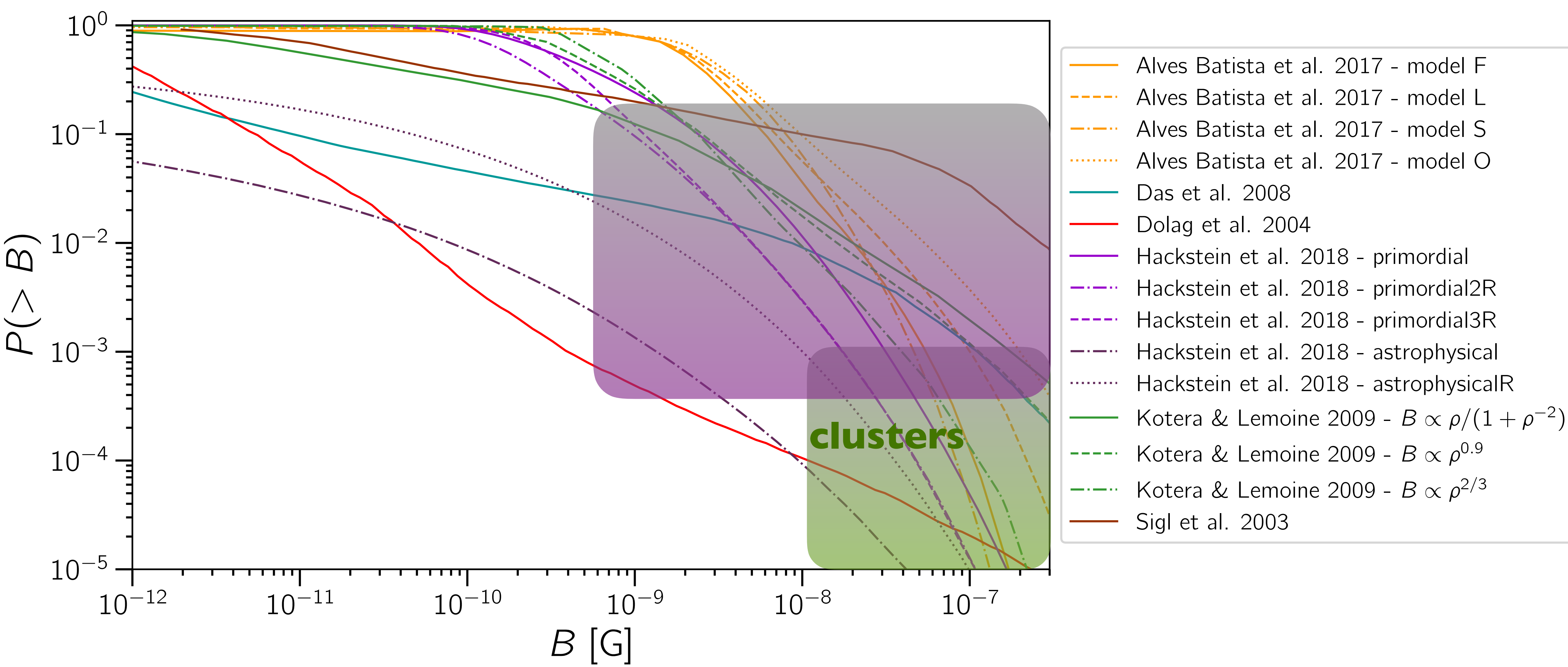

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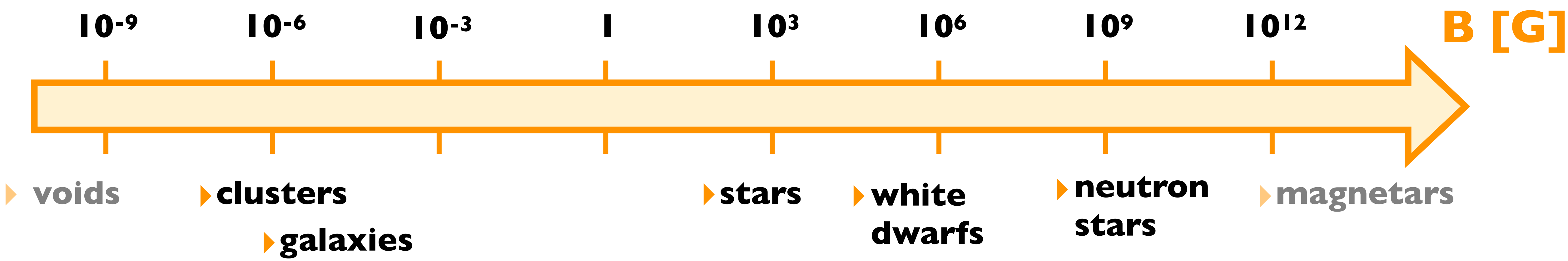

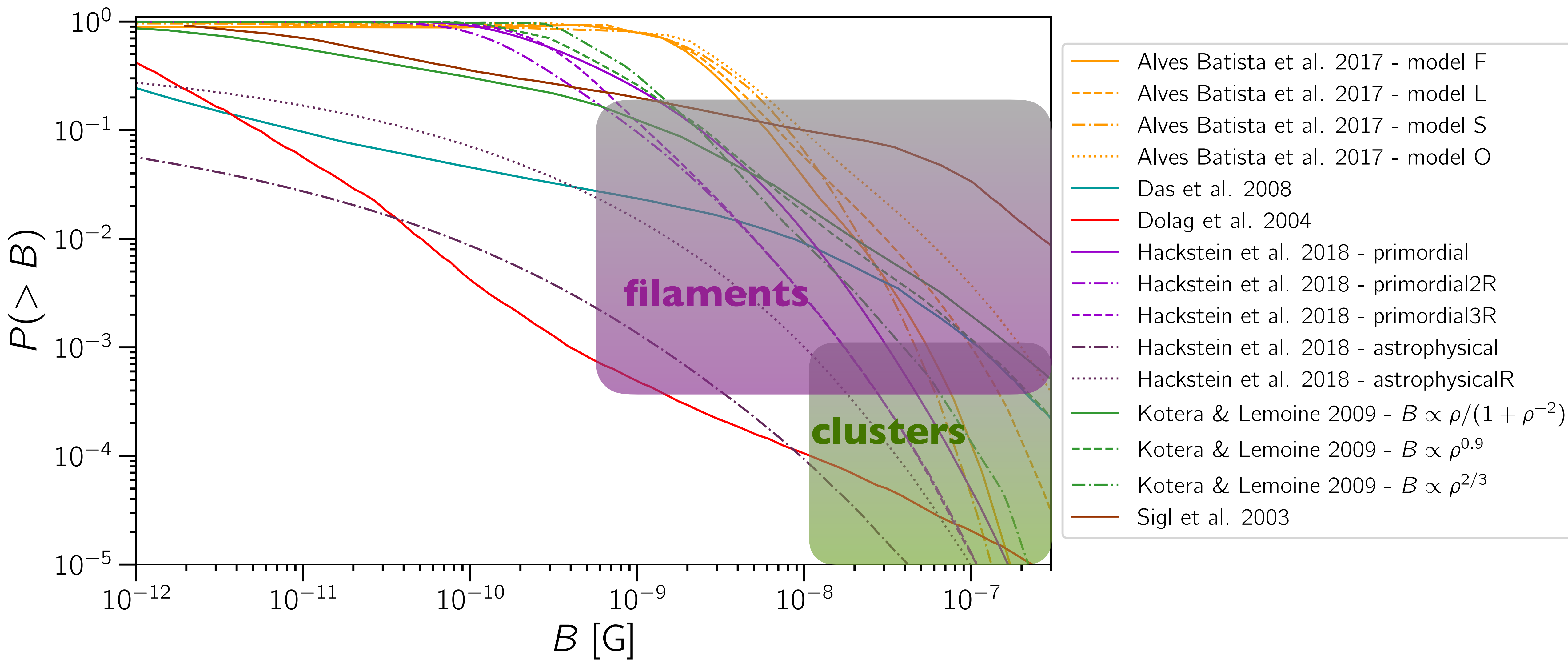

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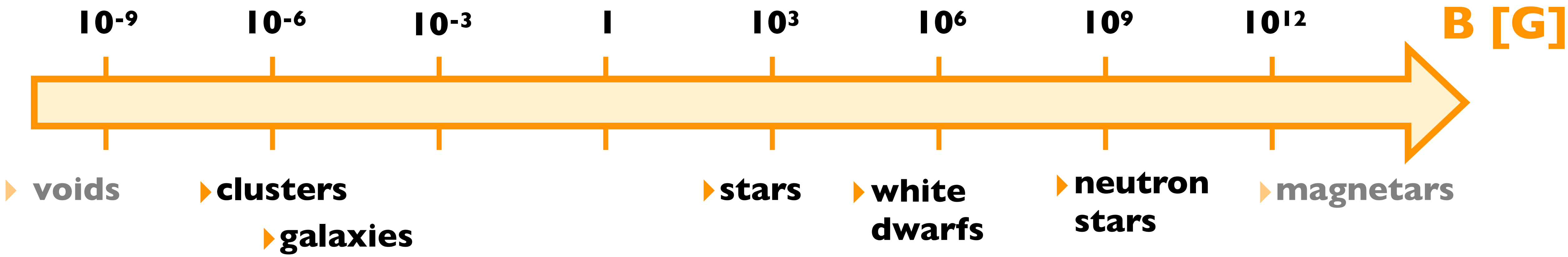

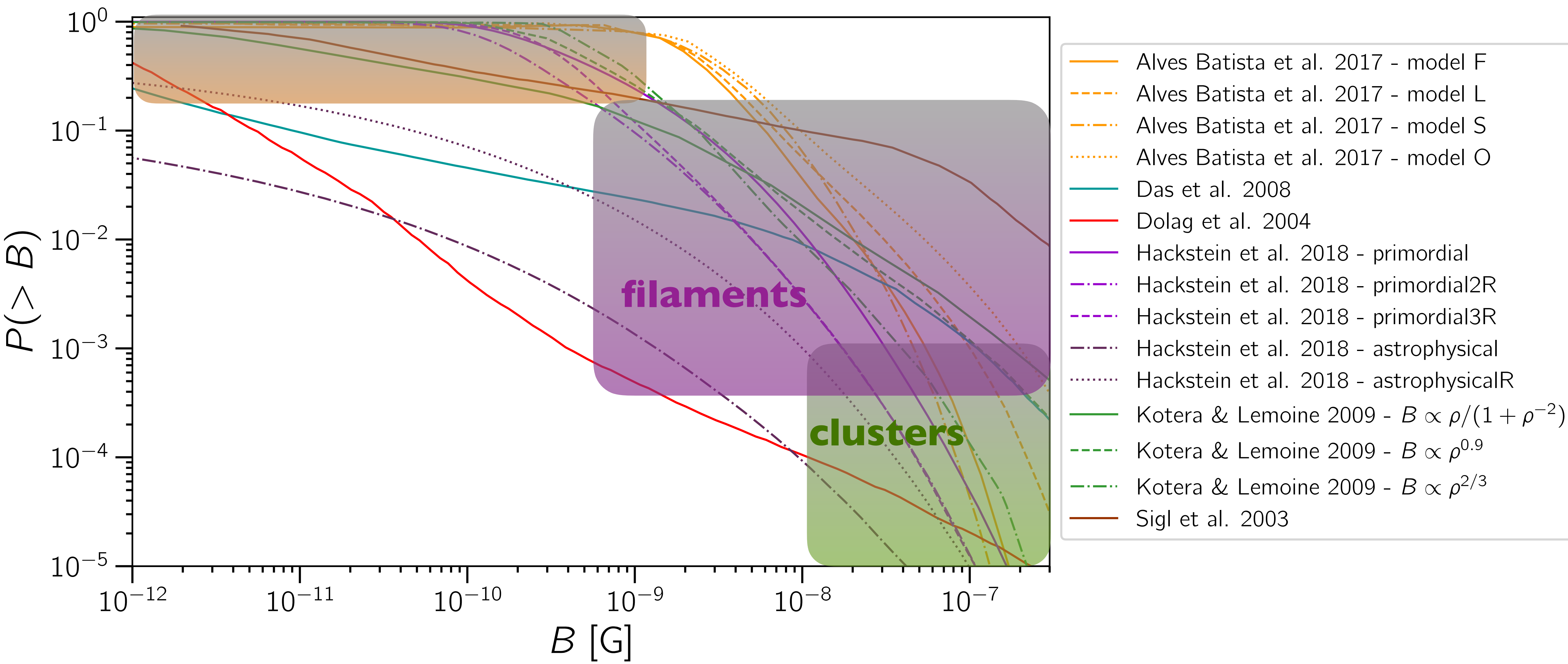

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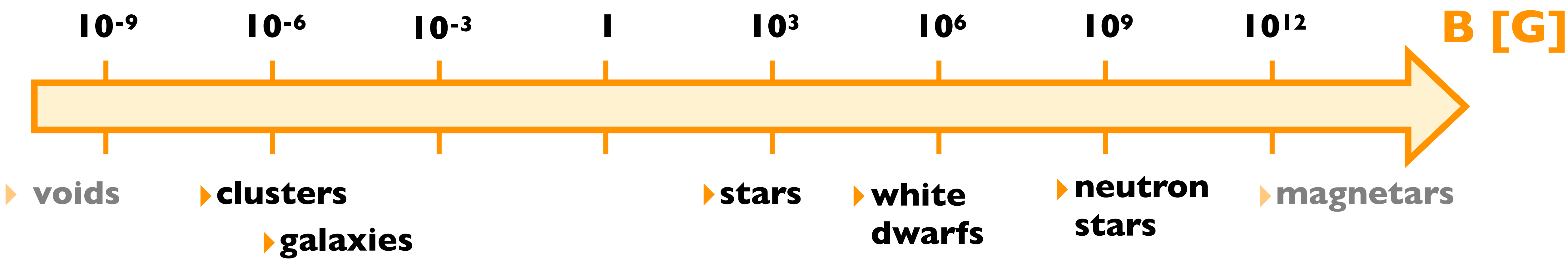

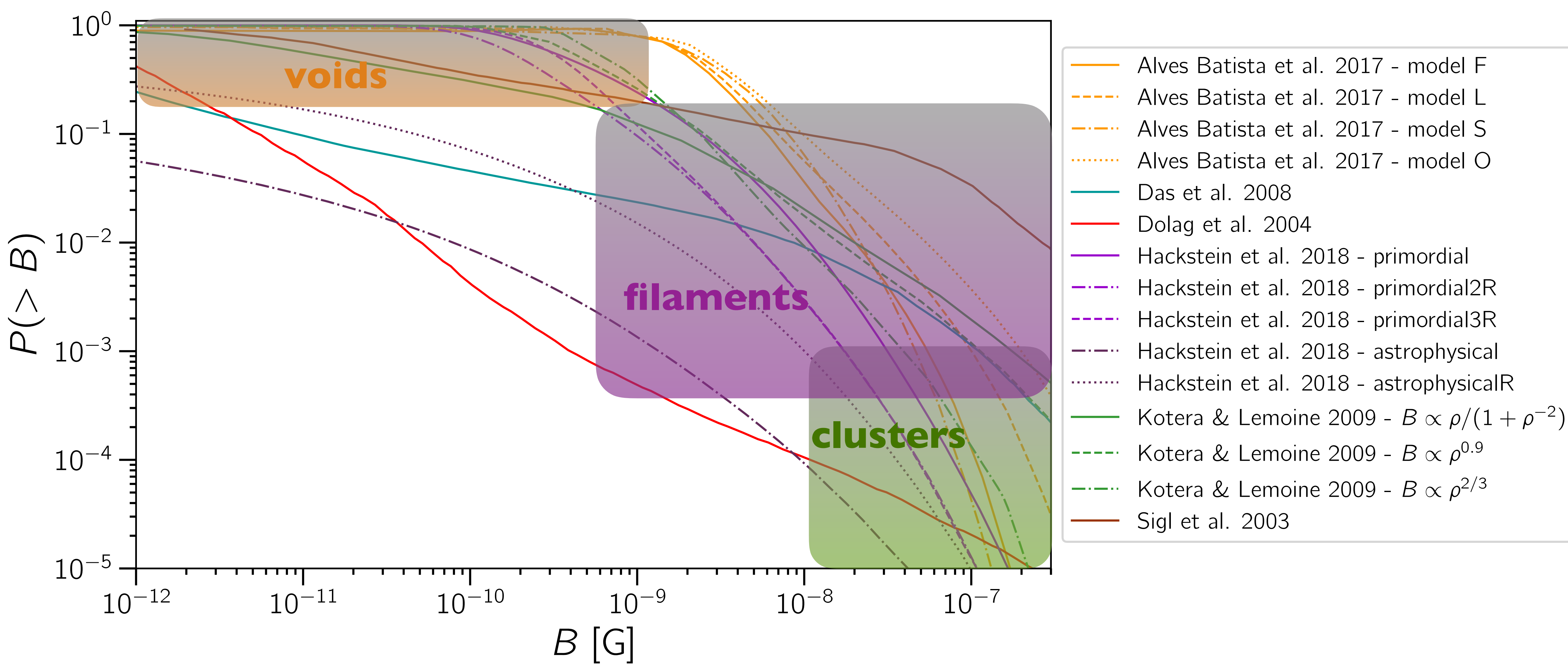

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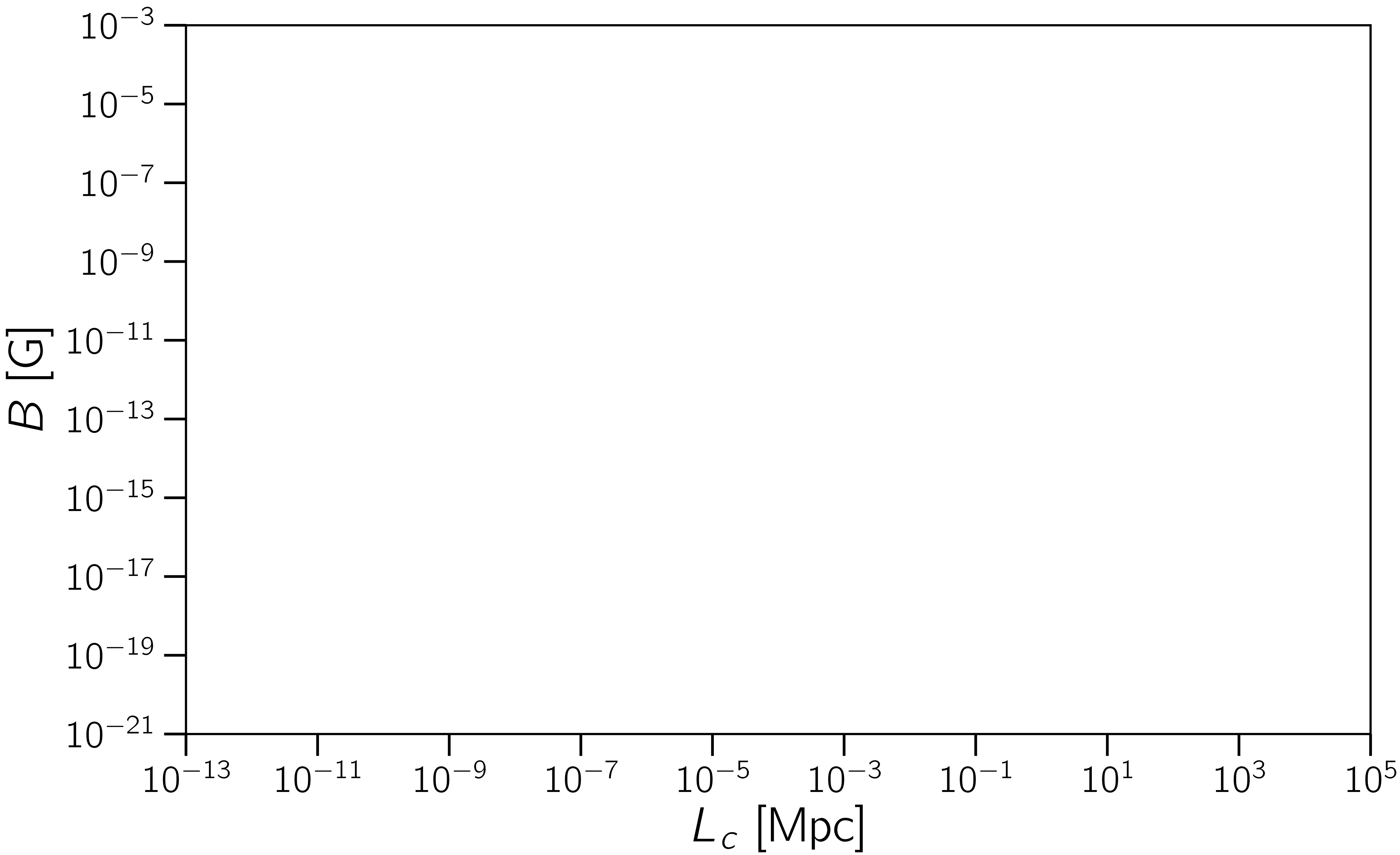
constraints on IGMFs



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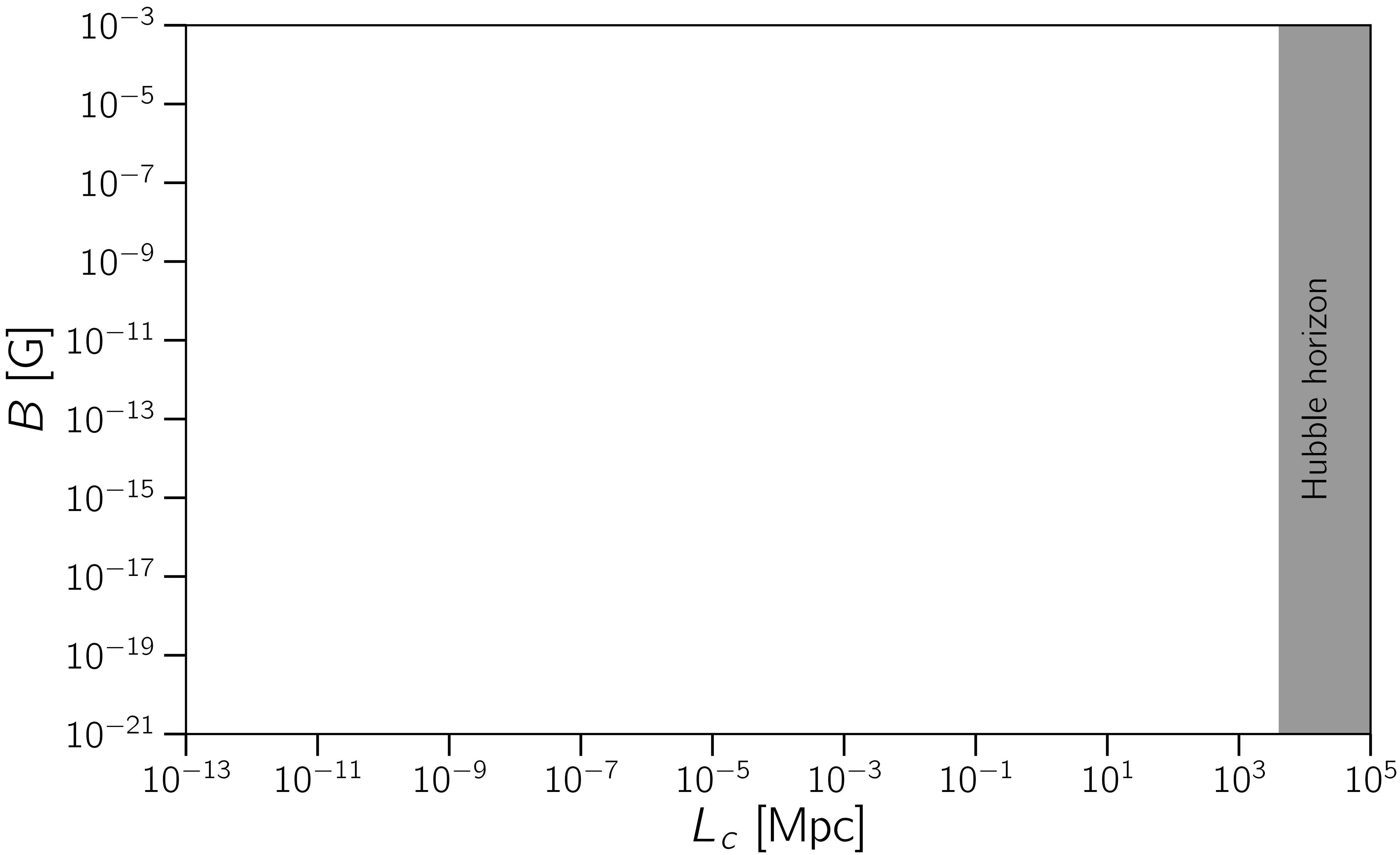

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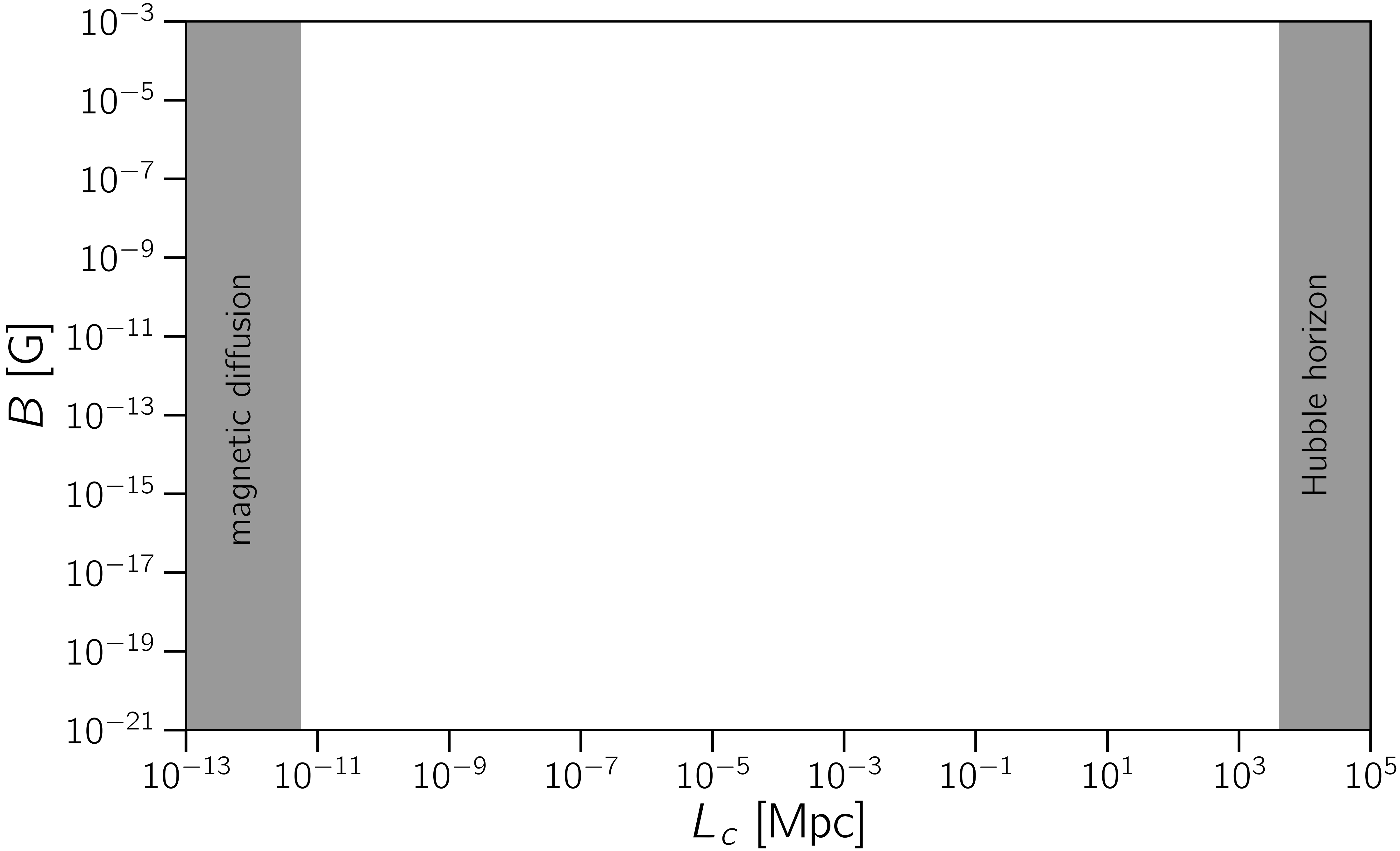

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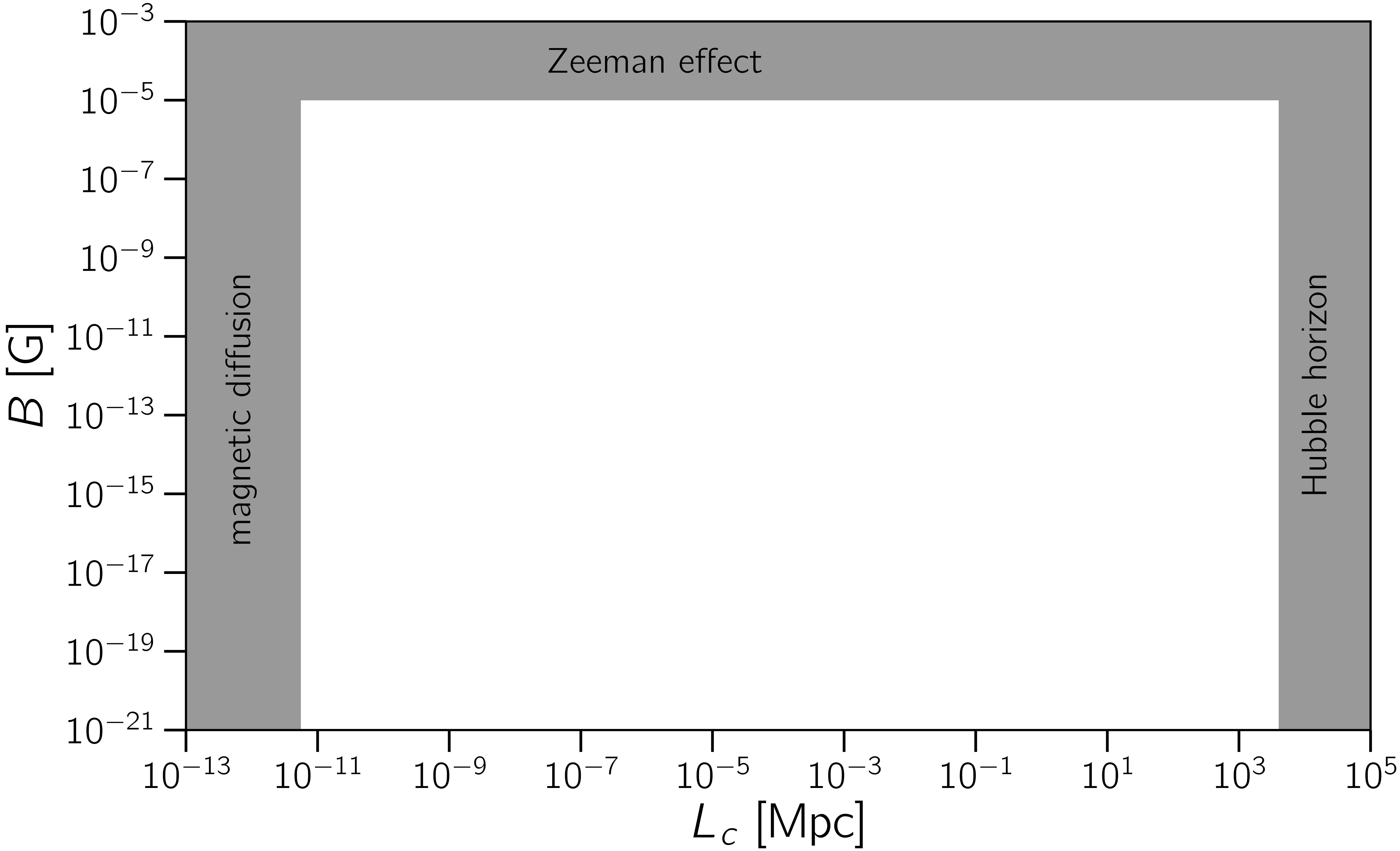

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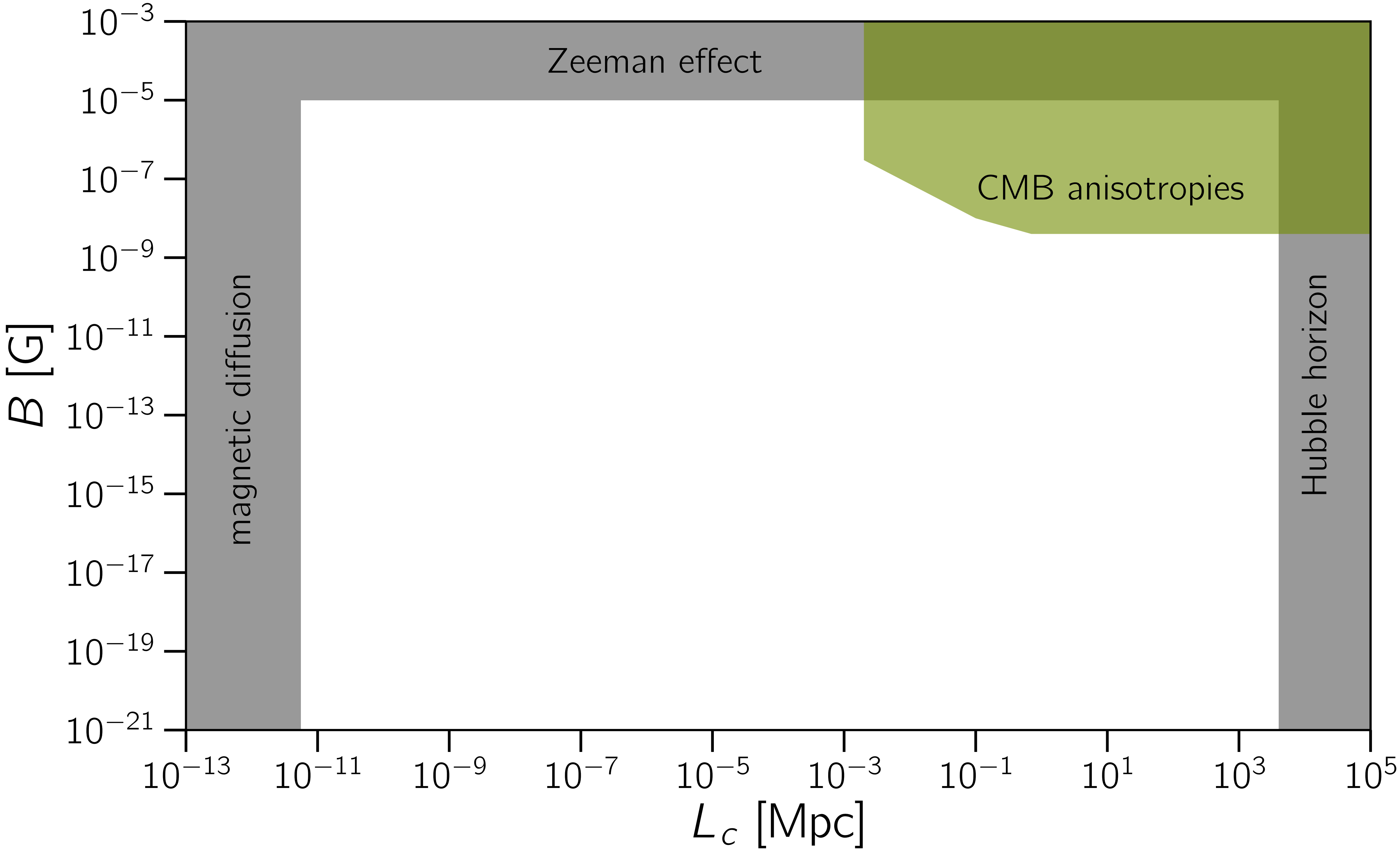

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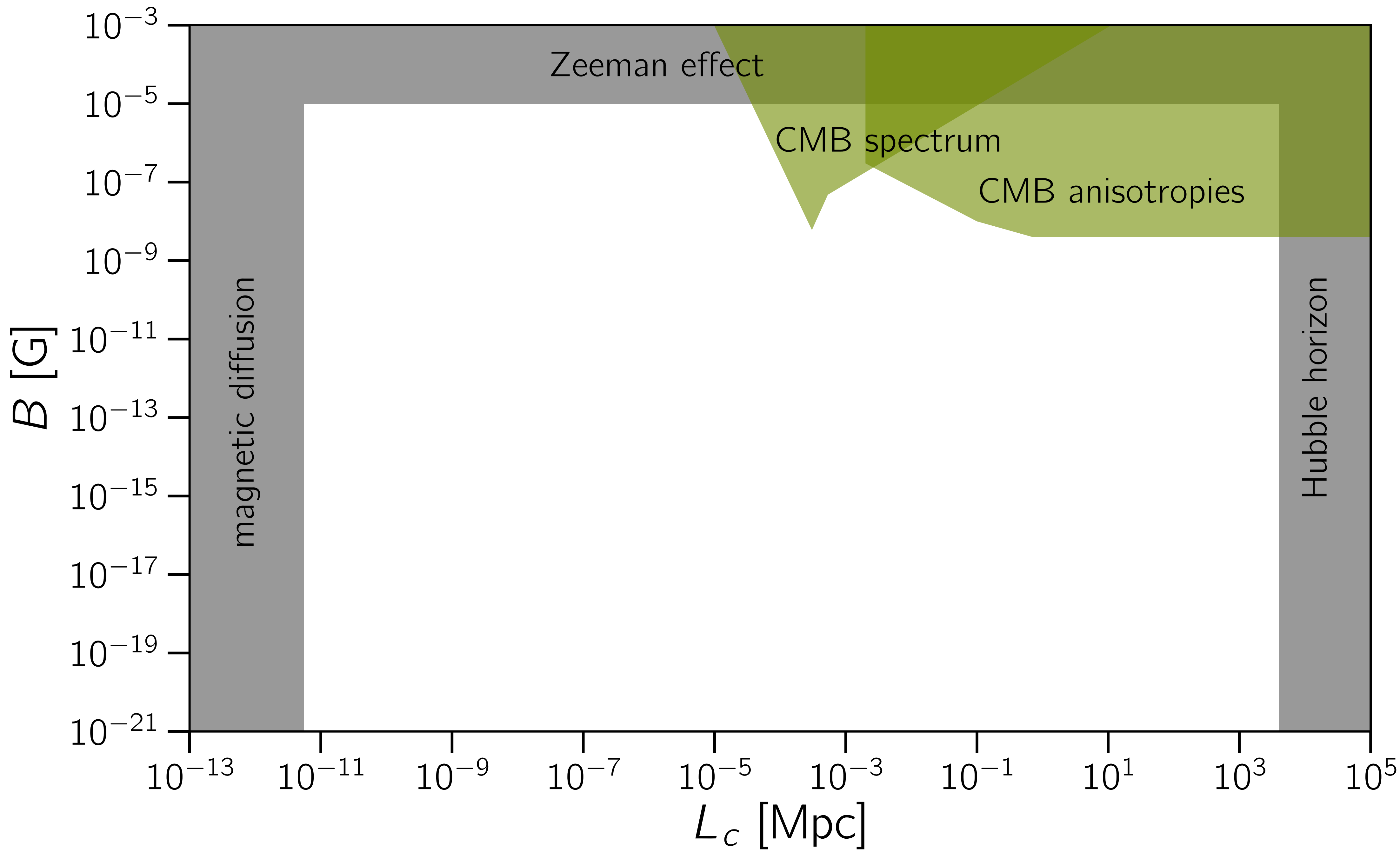

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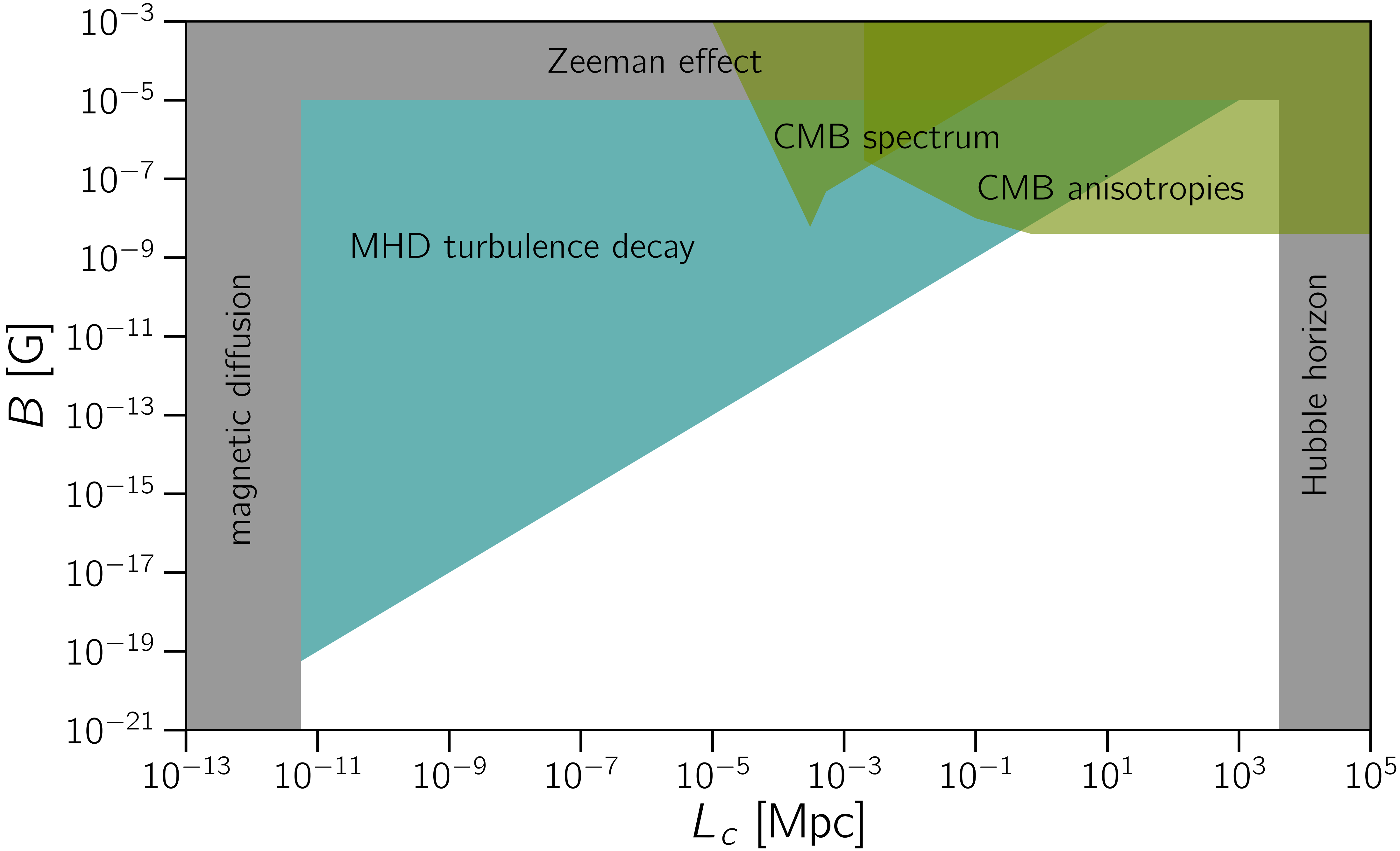

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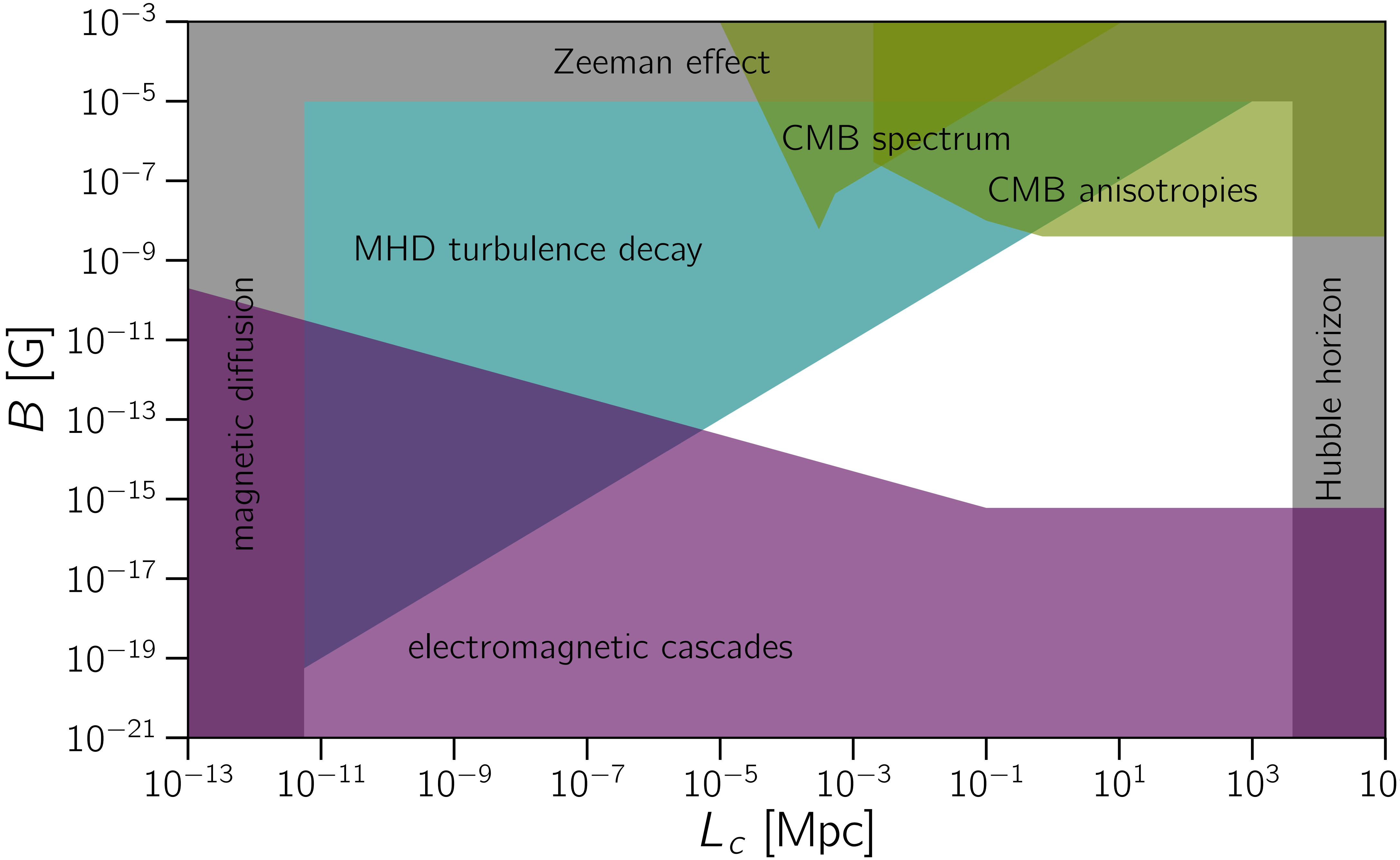

propagation picture

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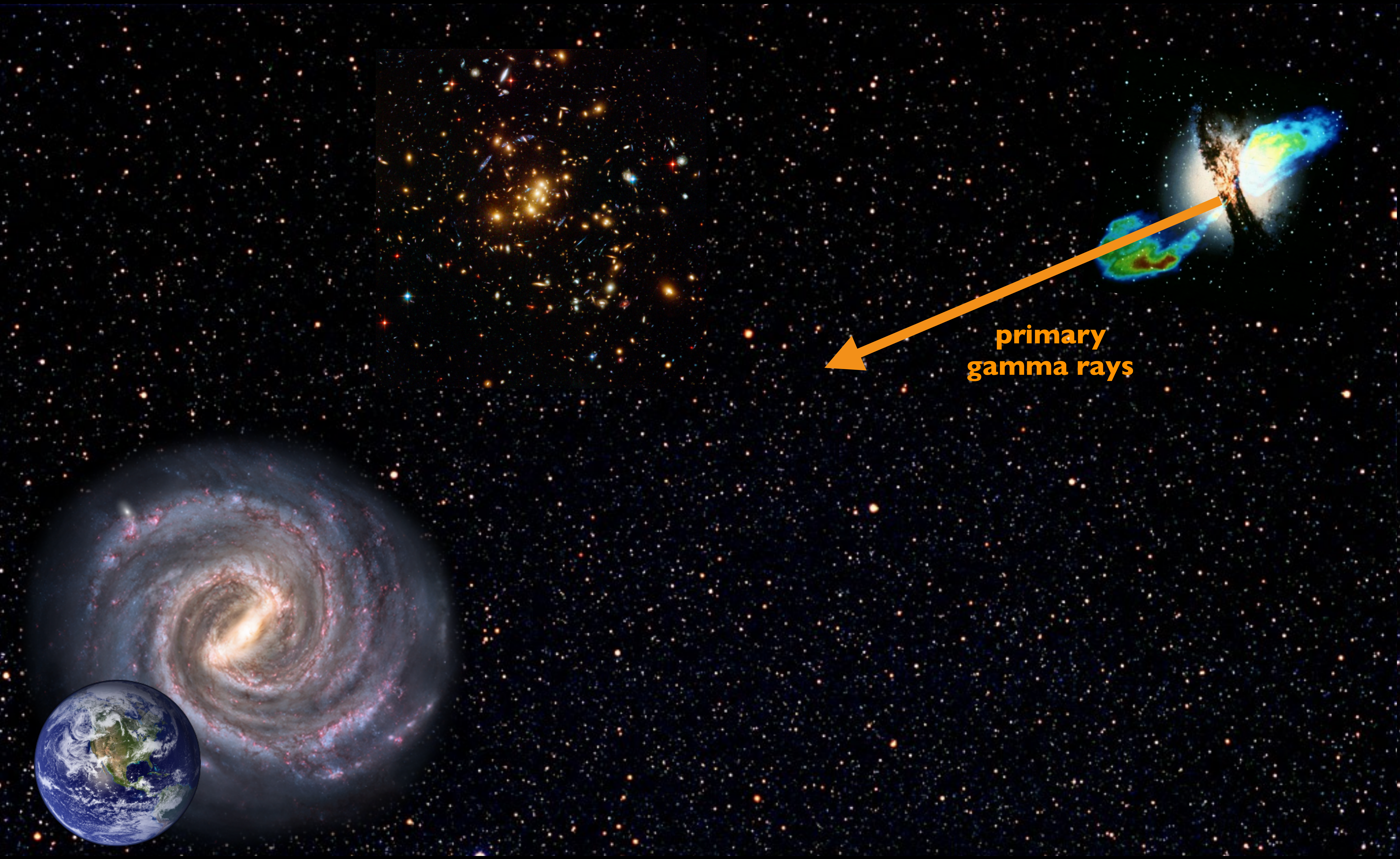

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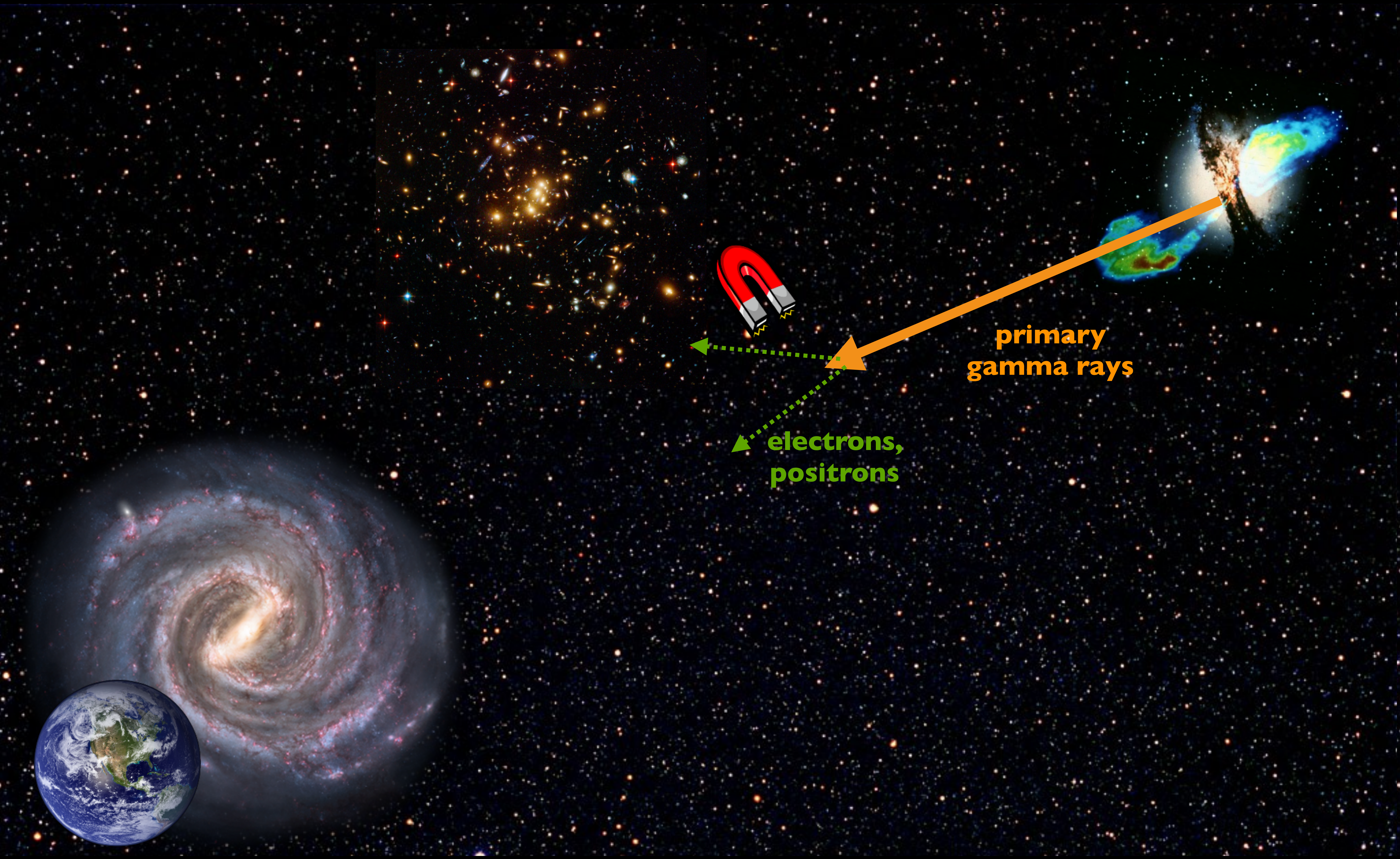

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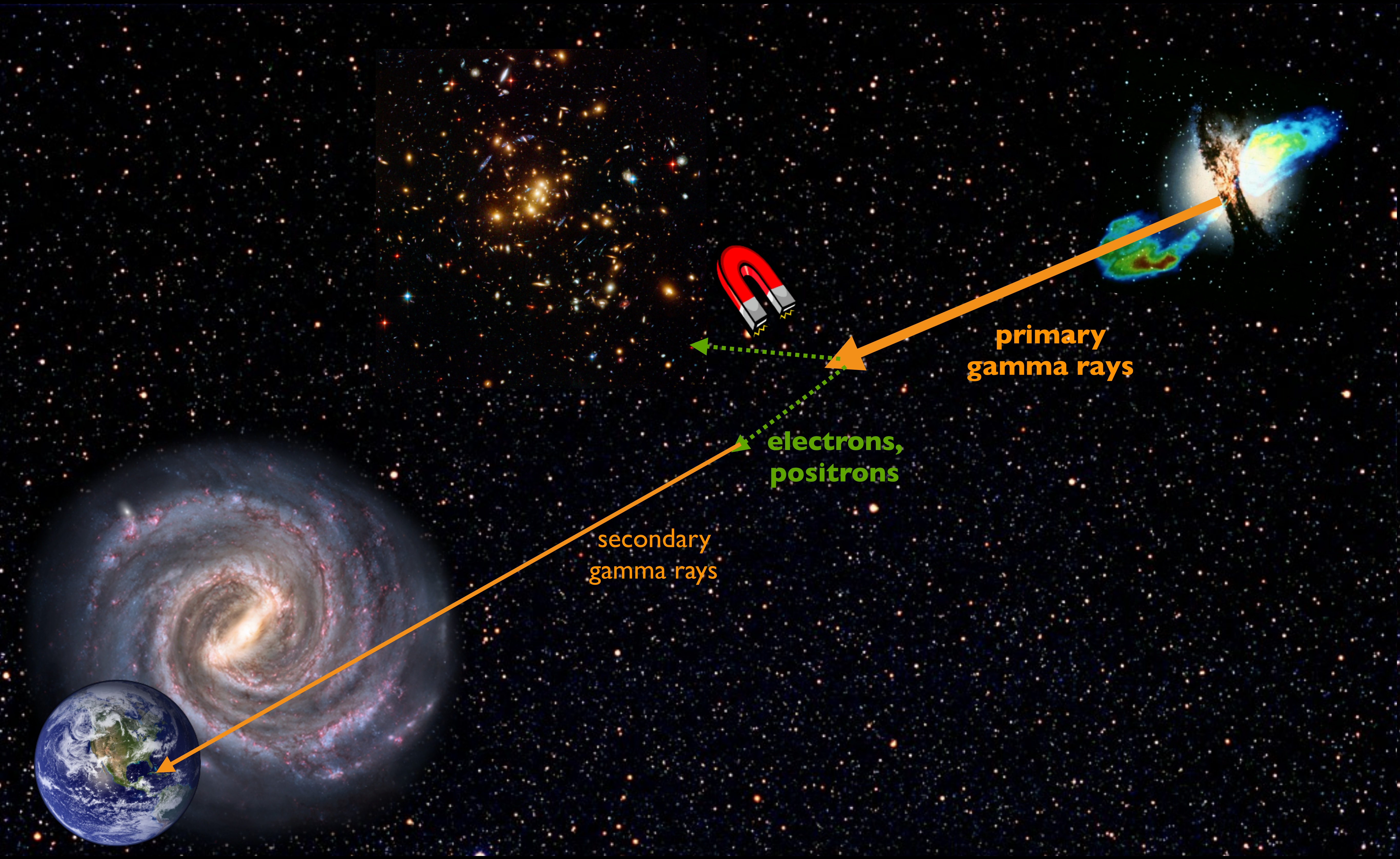

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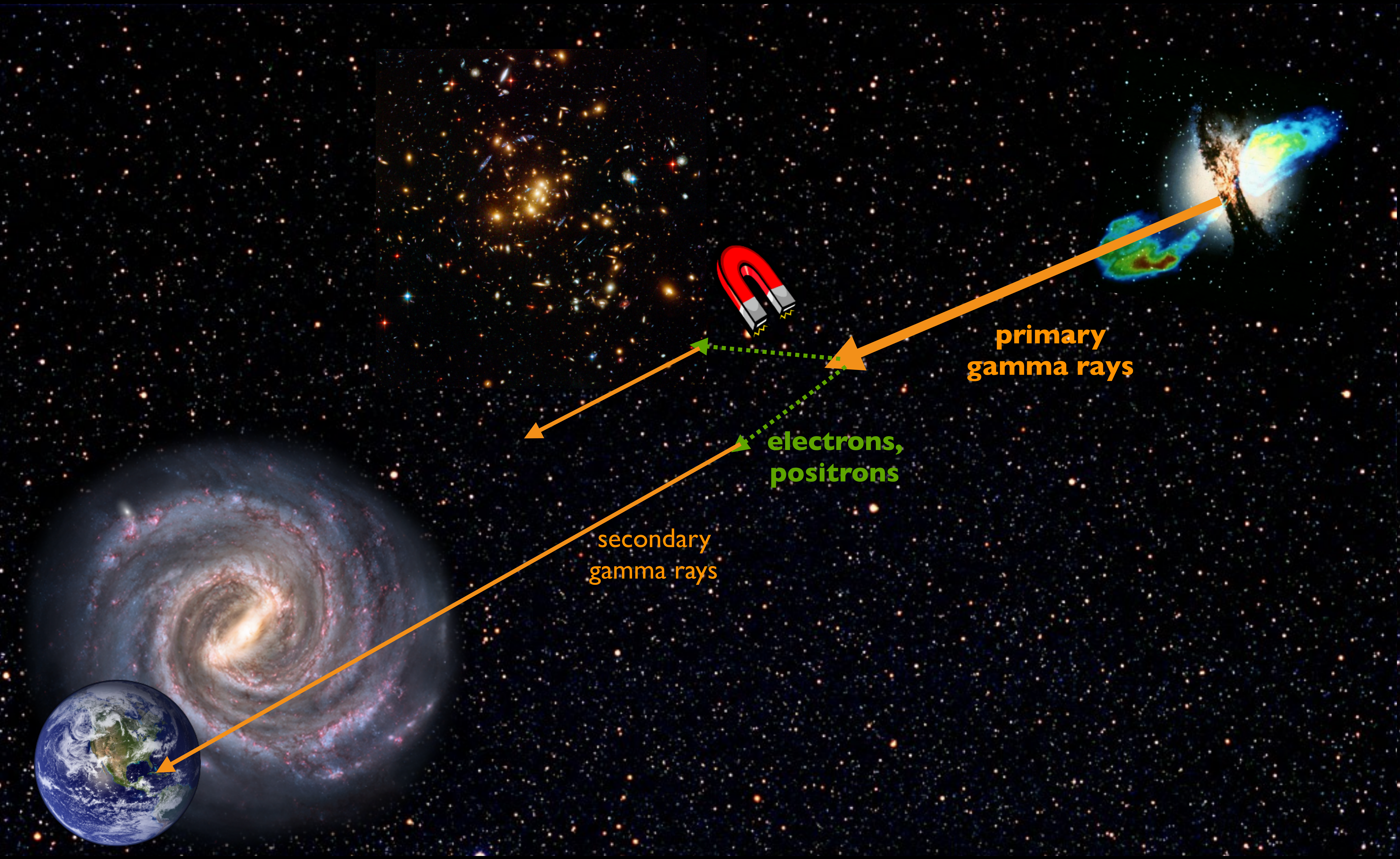

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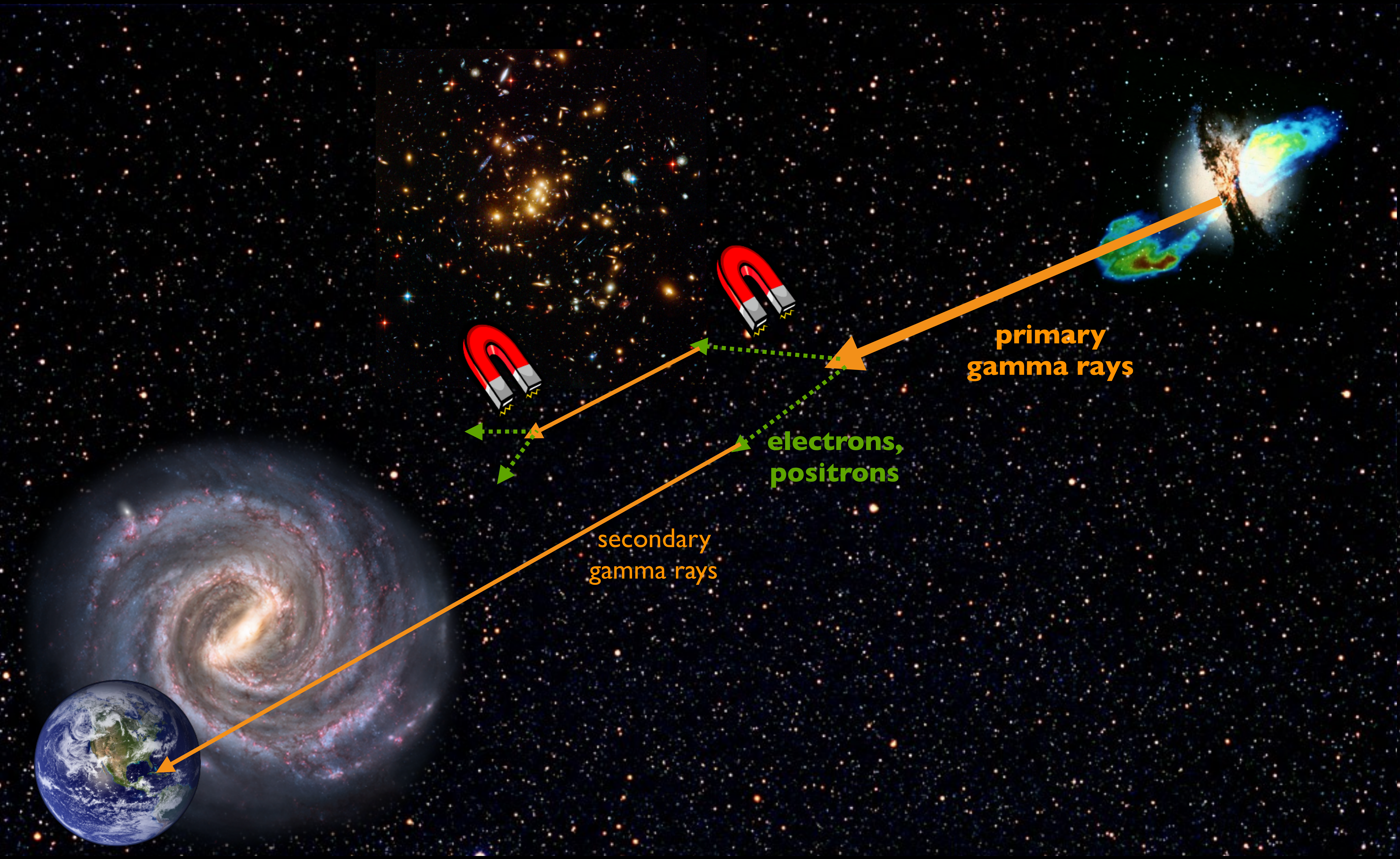

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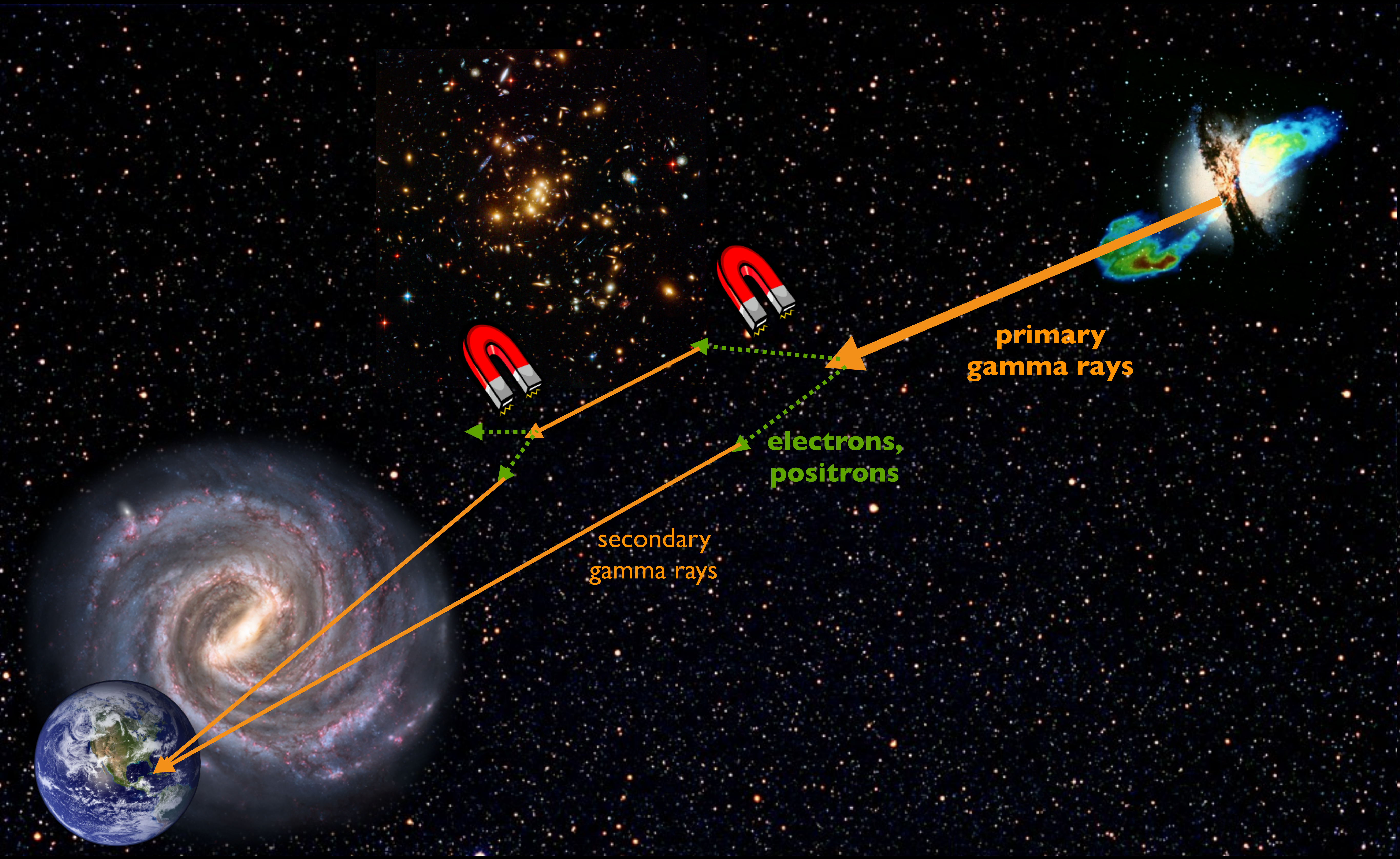
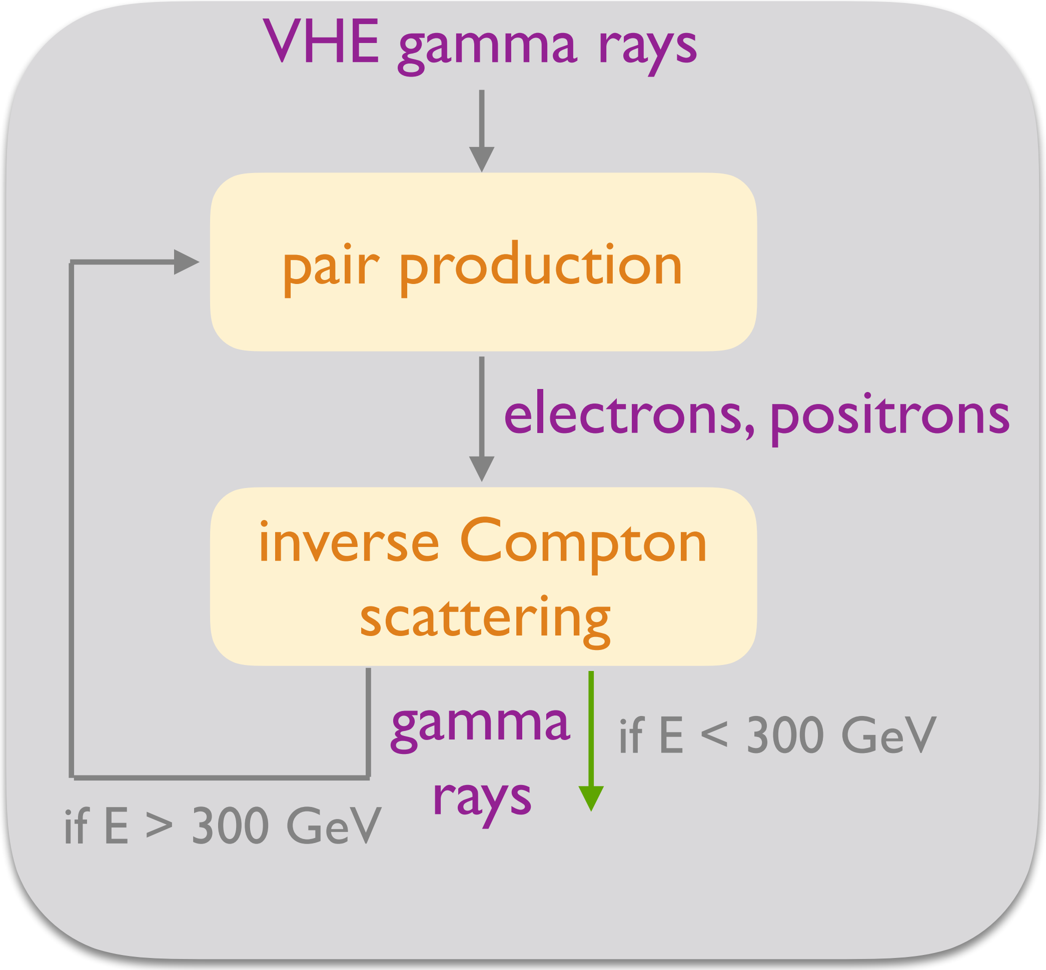


electromagnetic cascades

- pair production: $\gamma + \gamma_{\rm bg} \rightarrow e^{+} + e^{-}$
- inverse Compton scattering: $e^{\pm} + \gamma_{\rm bg} \rightarrow e^{\pm} + \gamma$
- synchrotron emission
- adiabatic losses due to the expansion of the universe
- at higher energies: double pair production, triplet pair production
- background photon fields: CMB and EBL at ~TeV energies



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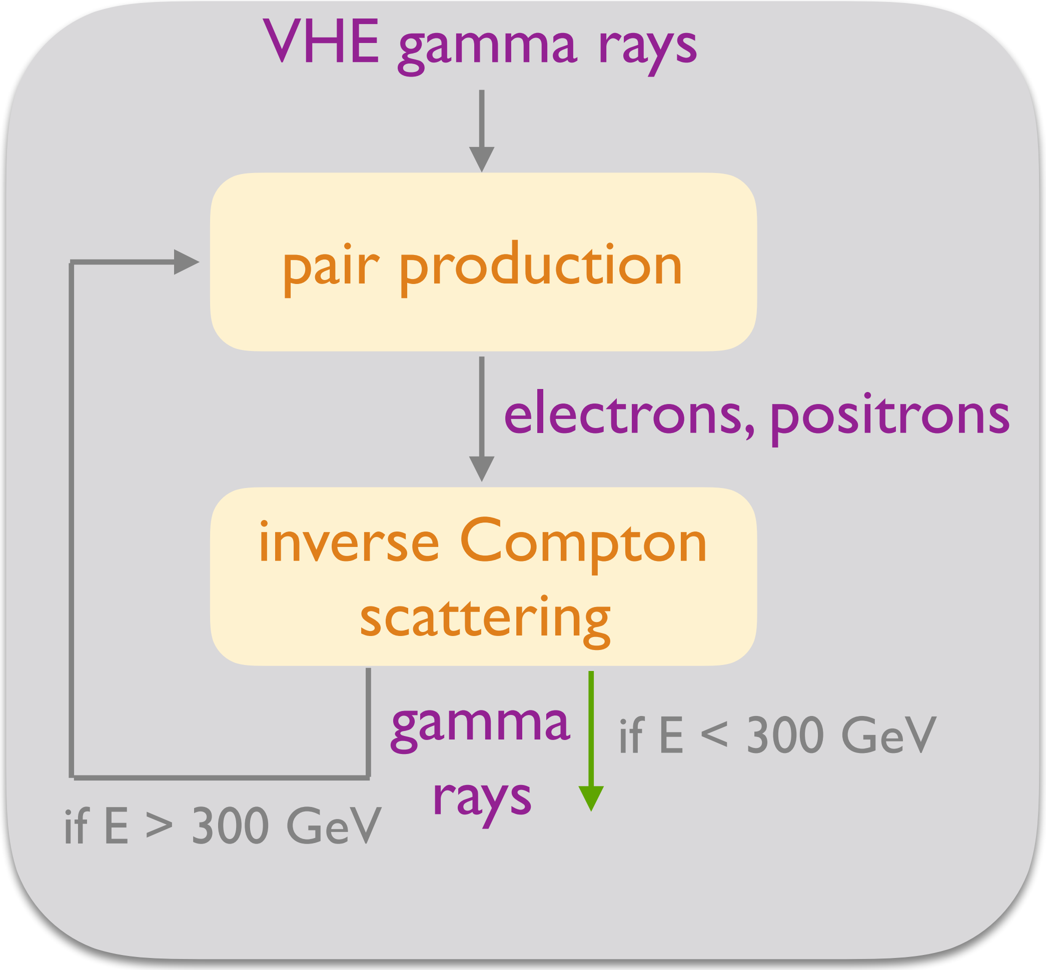

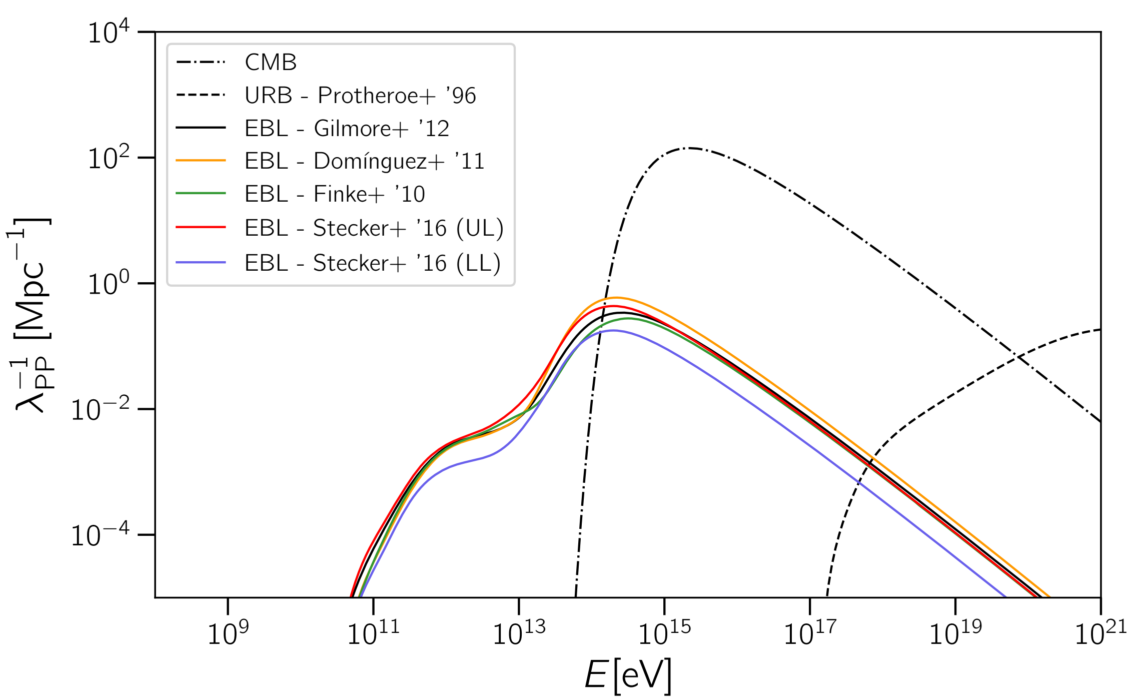

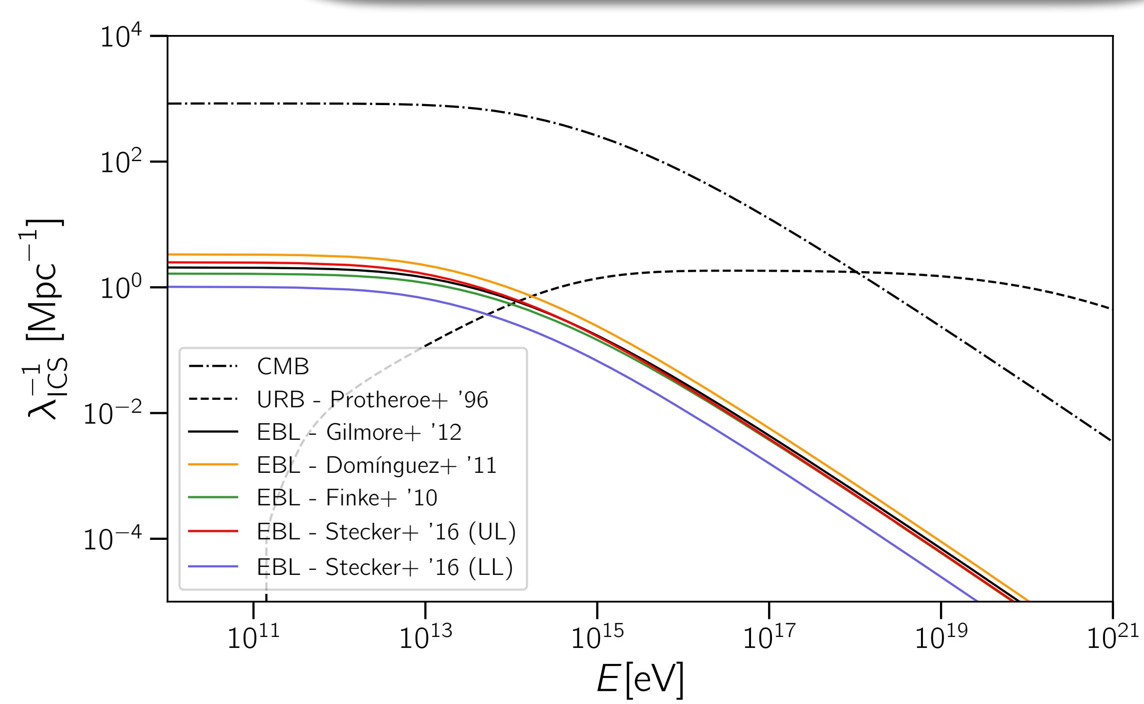

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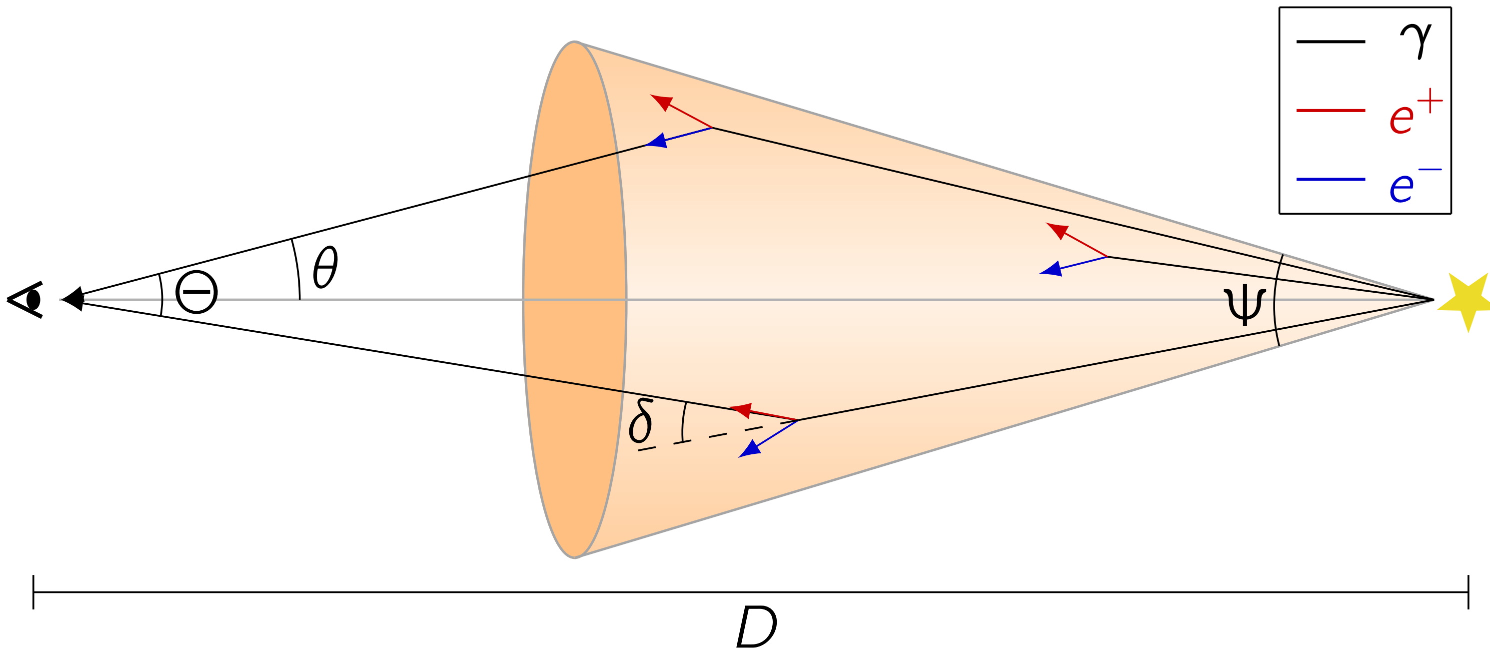

the charged component of the cascade is sensitive to the **strength** and **structure** of intervening magnetic fields

observational strategies

- strategy 1: point-like sources will appear extended → haloes
- strategy 2: secondary gamma rays will arrive with a delay with respect to the primaries → adequate for transients
- strategy 3: the combination of 1 and 2 lead to spectral changes

strategy 1: pair haloes

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theoretical prediction

$$\Theta(E,z) = \begin{cases} 5.0^\circ (1+z)^{-2}\, \tau^{-1} \left(\frac{100\ \text{GeV}}{E}\right) \left(\frac{B}{\text{fG}}\right) & L_c \gg \lambda_{ICS} \\ 7.0^\circ (1+z)^{-1/2}\, \tau^{-1} \left(\frac{100\ \text{GeV}}{E}\right)^{-\frac{3}{4}} \left(\frac{B}{\text{fG}}\right) \left(\frac{L_c}{\text{kpc}}\right)^{\frac{1}{2}} & L_c \ll \lambda_{ICS}, \end{cases}$$

Neronov & Semikoz. PRD 80 (2009) 123012. arXiv:0910.1920

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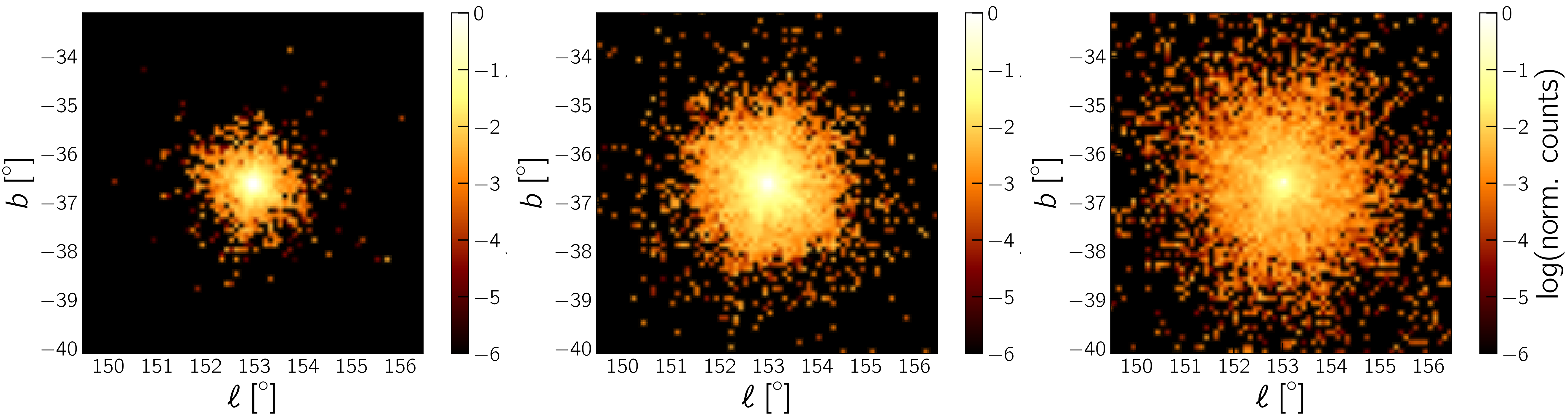
B = 10^{-17} G | B = 10^{-16} G | B = 10^{-15} G



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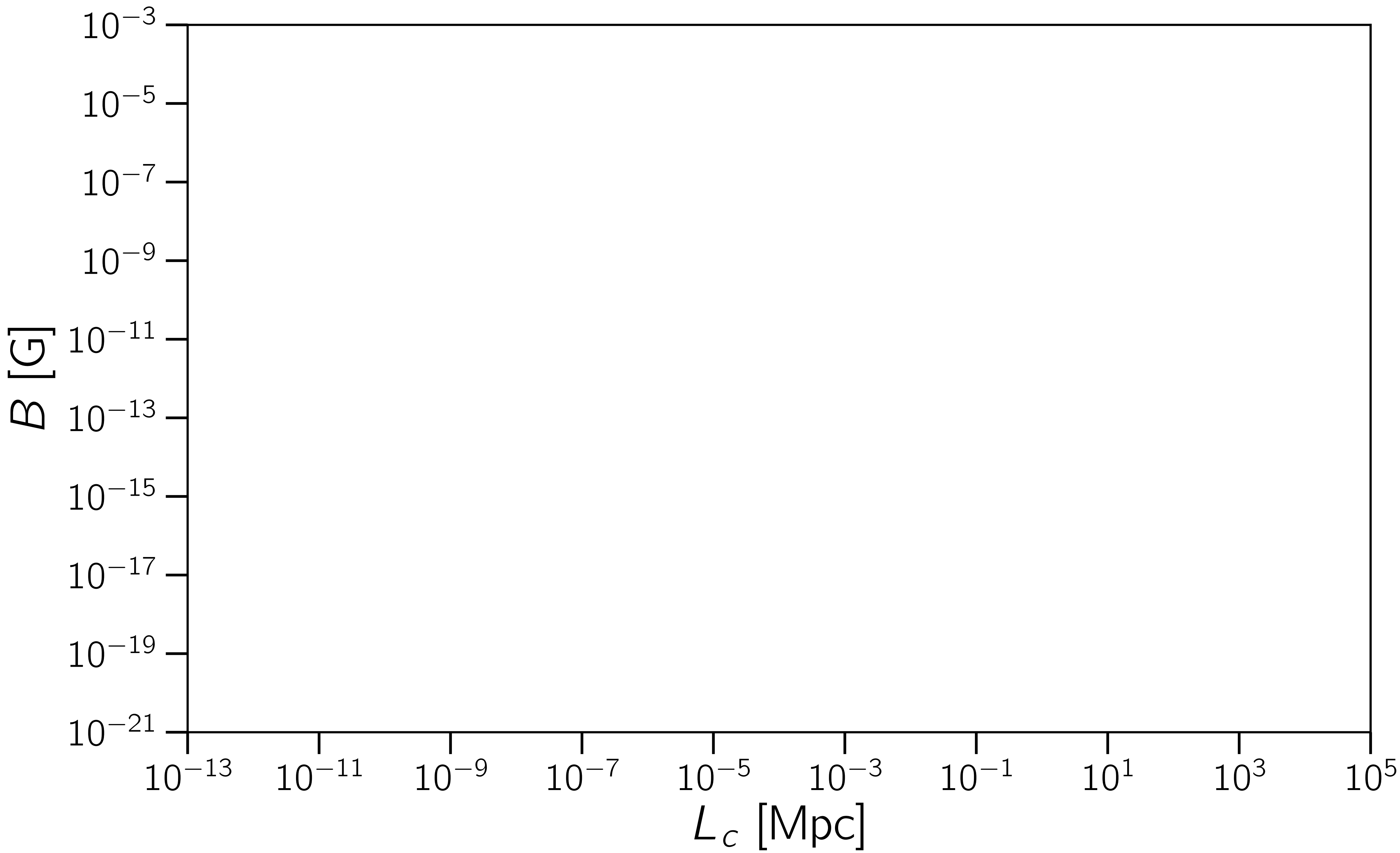

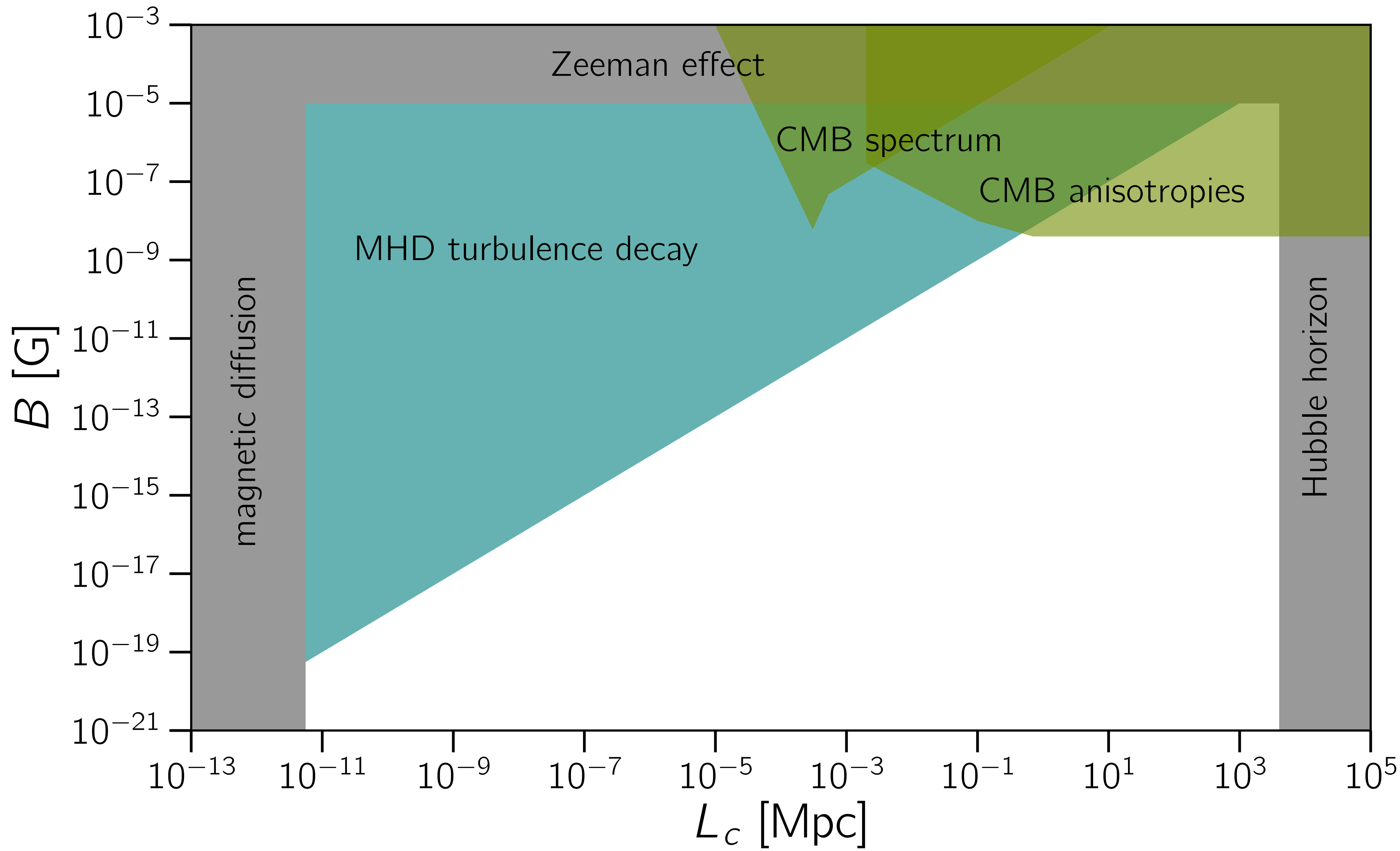
Zeeman effect
CMB spectrum
CMB anisotropies
MHD turbulence decay
magnetic diffusion
Hubble horizon
B [G]
L_c [Mpc]
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-13}
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10^{5}

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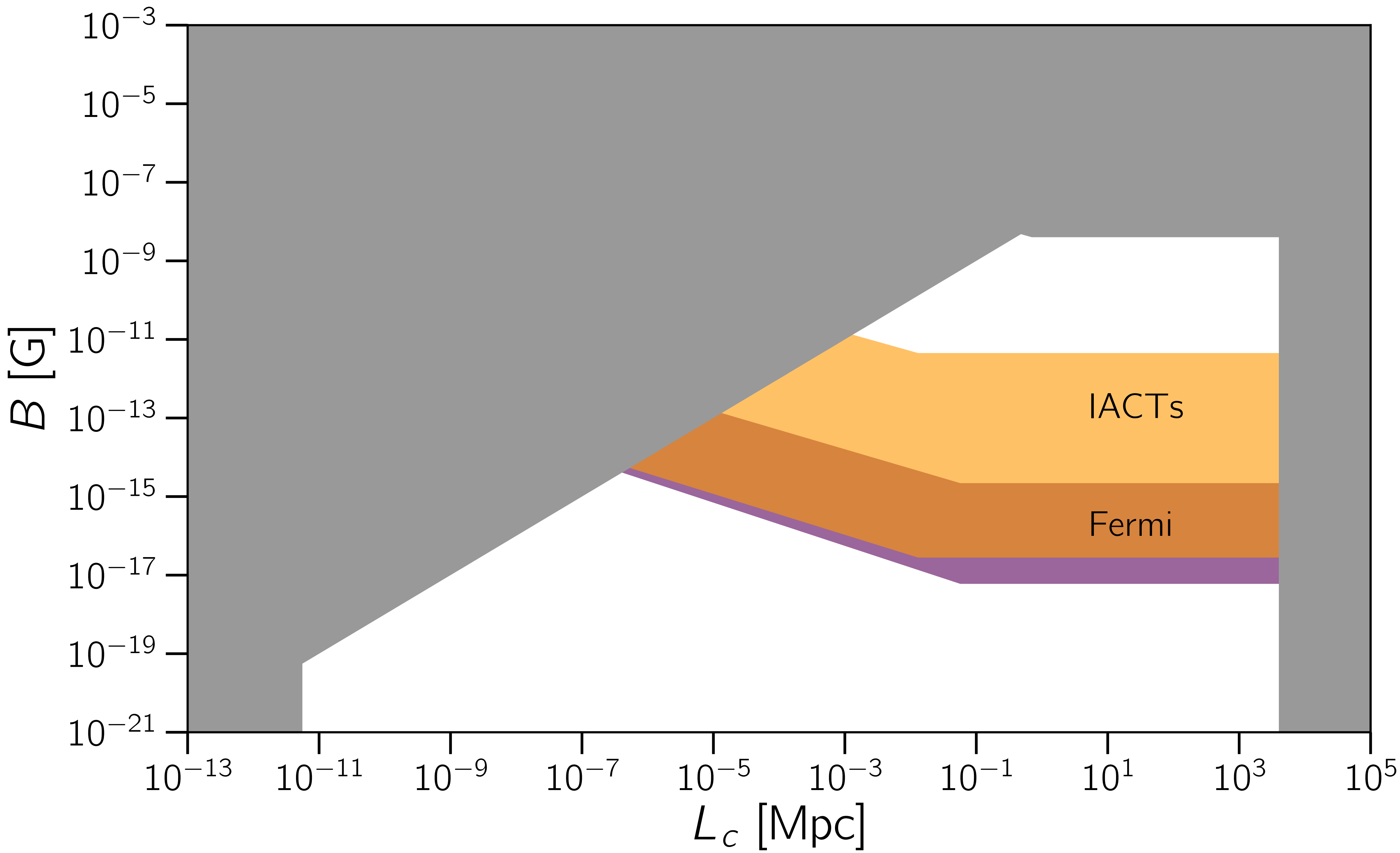
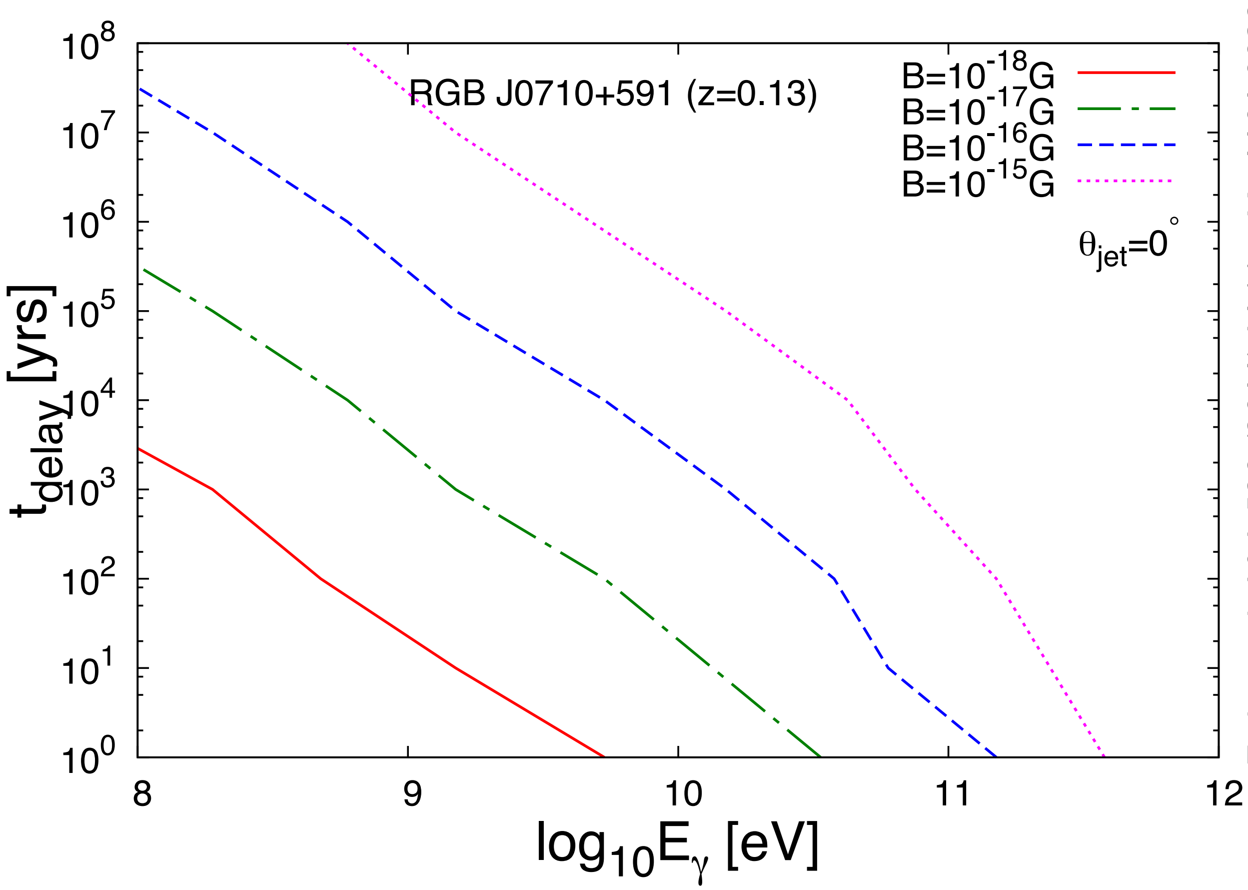


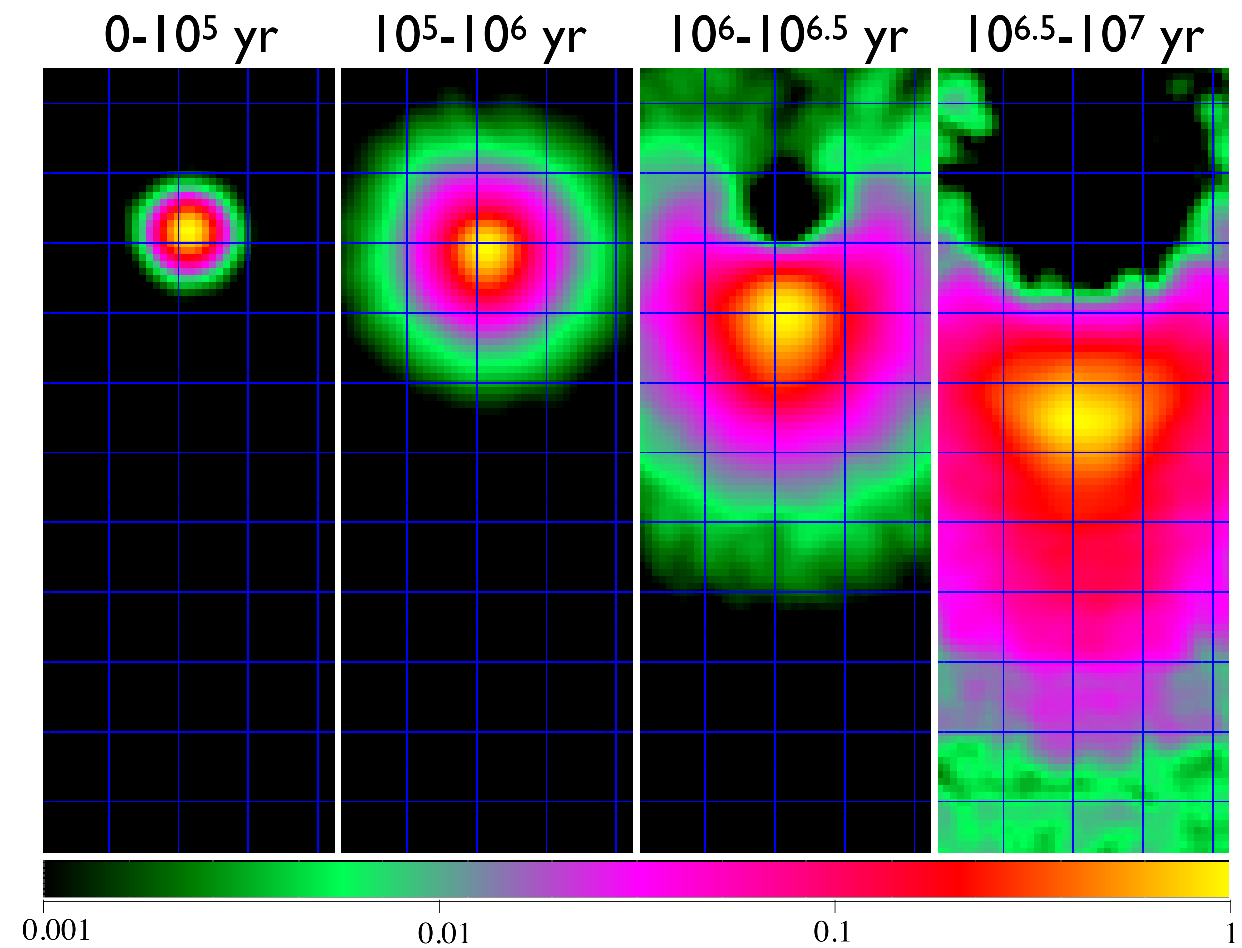
theoretical prediction

$$\Delta t = \begin{cases} 30(1+z)^{-3}(1-\tau^{-1})\left(\frac{E}{100\ \mathrm{GeV}}\right)^{-\frac{5}{2}}\left(\frac{B}{\mathrm{aG}}\right)^{2}\ \mathrm{yr} & L_c \gg \lambda_{ICS} \\ 0.6\,(1-\tau^{-1})\left(\frac{E}{100\ \mathrm{GeV}}\right)^{-2}\left(\frac{B}{\mathrm{aG}}\right)^{2}\left(\frac{L_c}{\mathrm{kpc}}\right)\ \mathrm{yr} & L_c \ll \lambda_{ICS}, \end{cases}$$

Neronov & Semikoz. PRD 80 (2009) 123012. arXiv:0910.1920



Taylor et al. A&A 529 (2011) A144. arXiv:1101.0932



Neronov et al. ApJL 719 (2010) 130. arXiv:1002.4981

strategy 2: time delays

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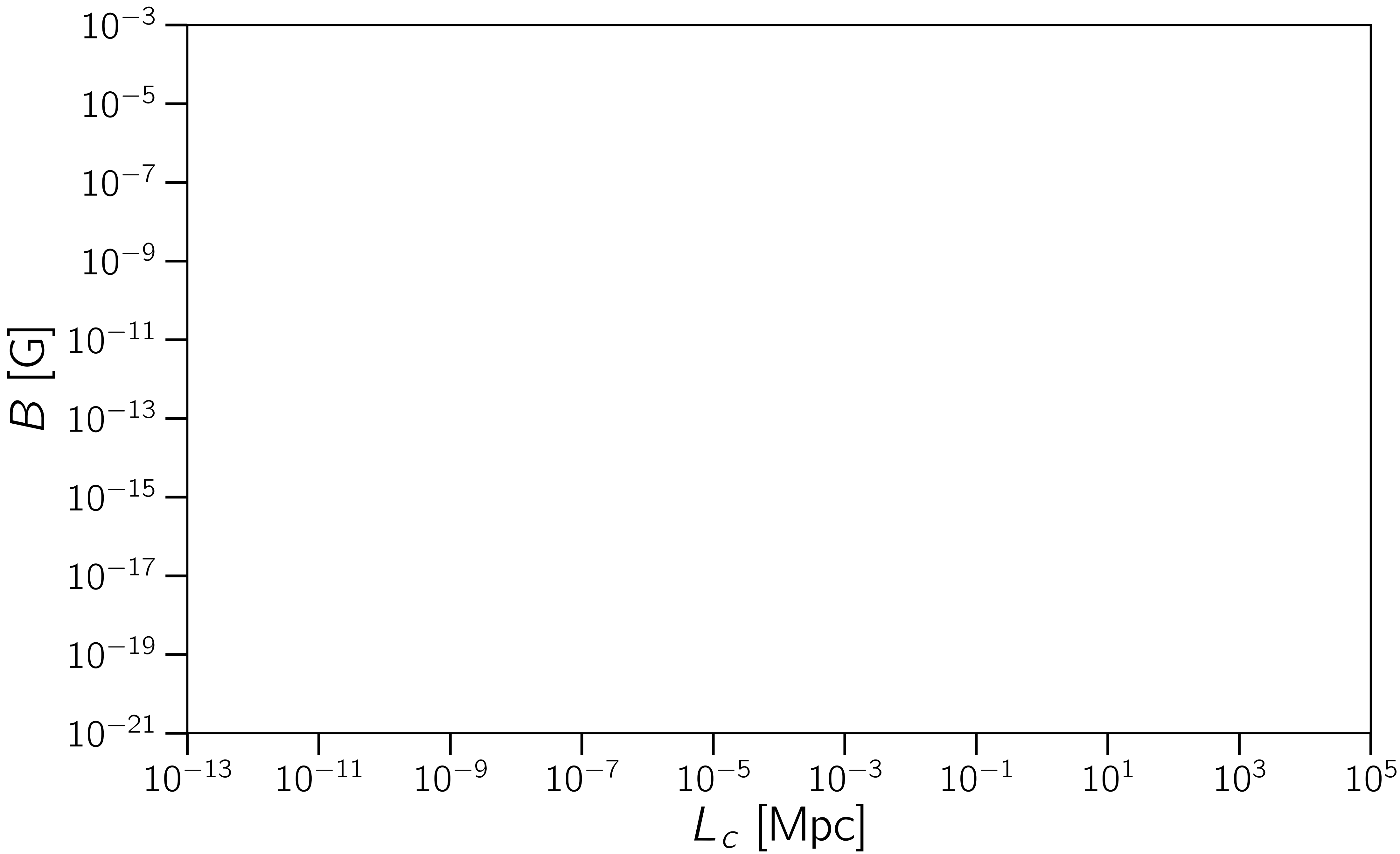

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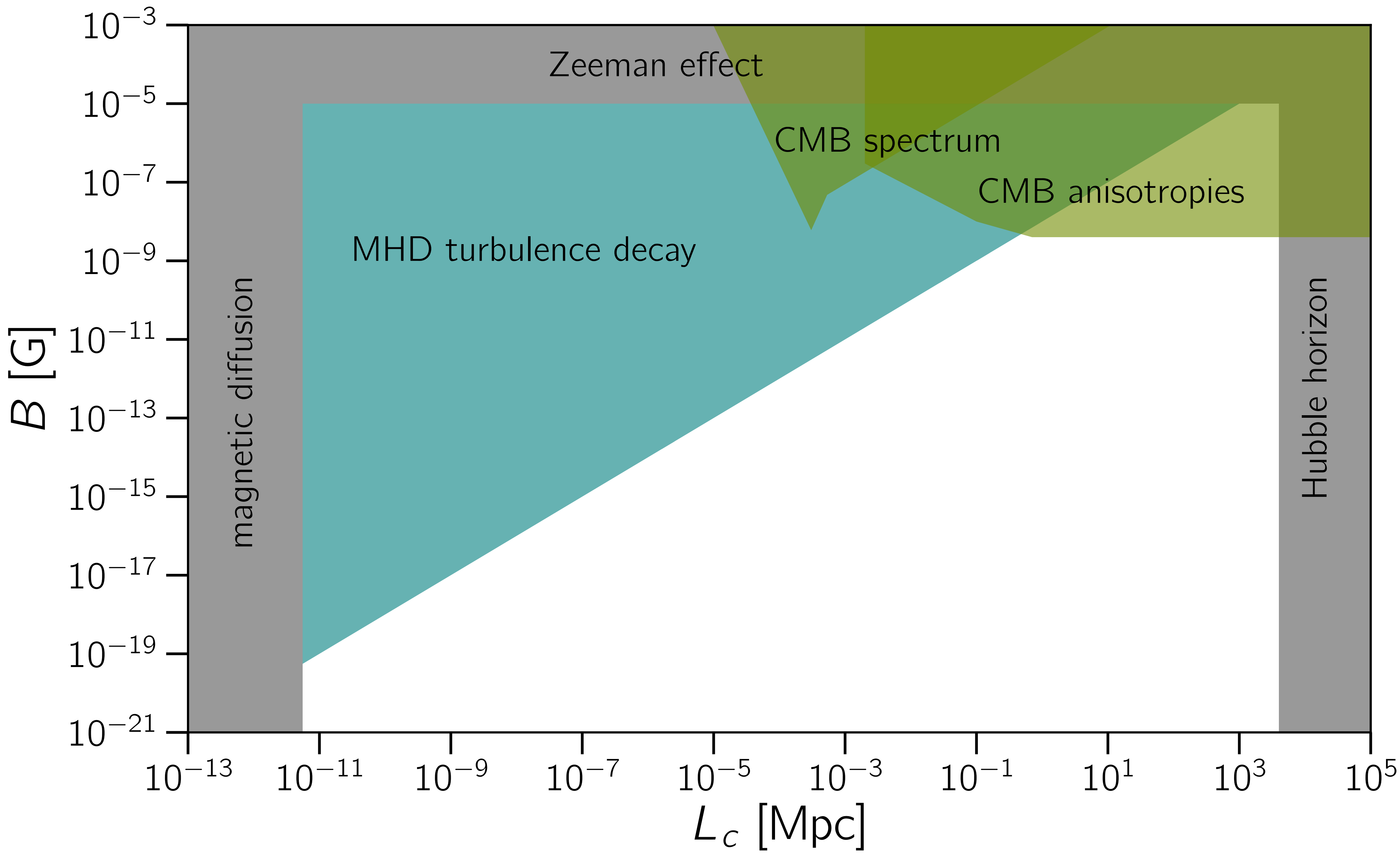

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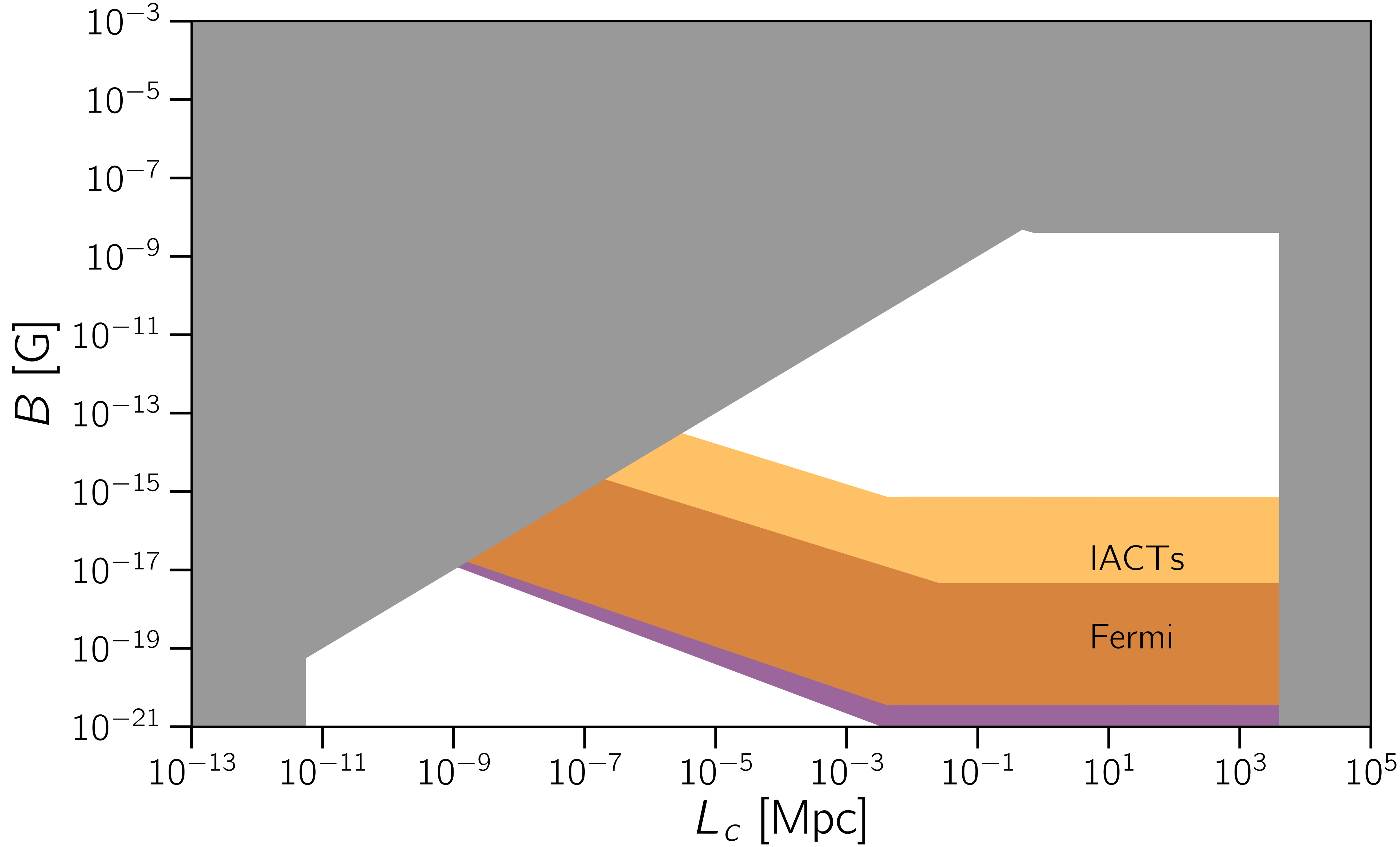
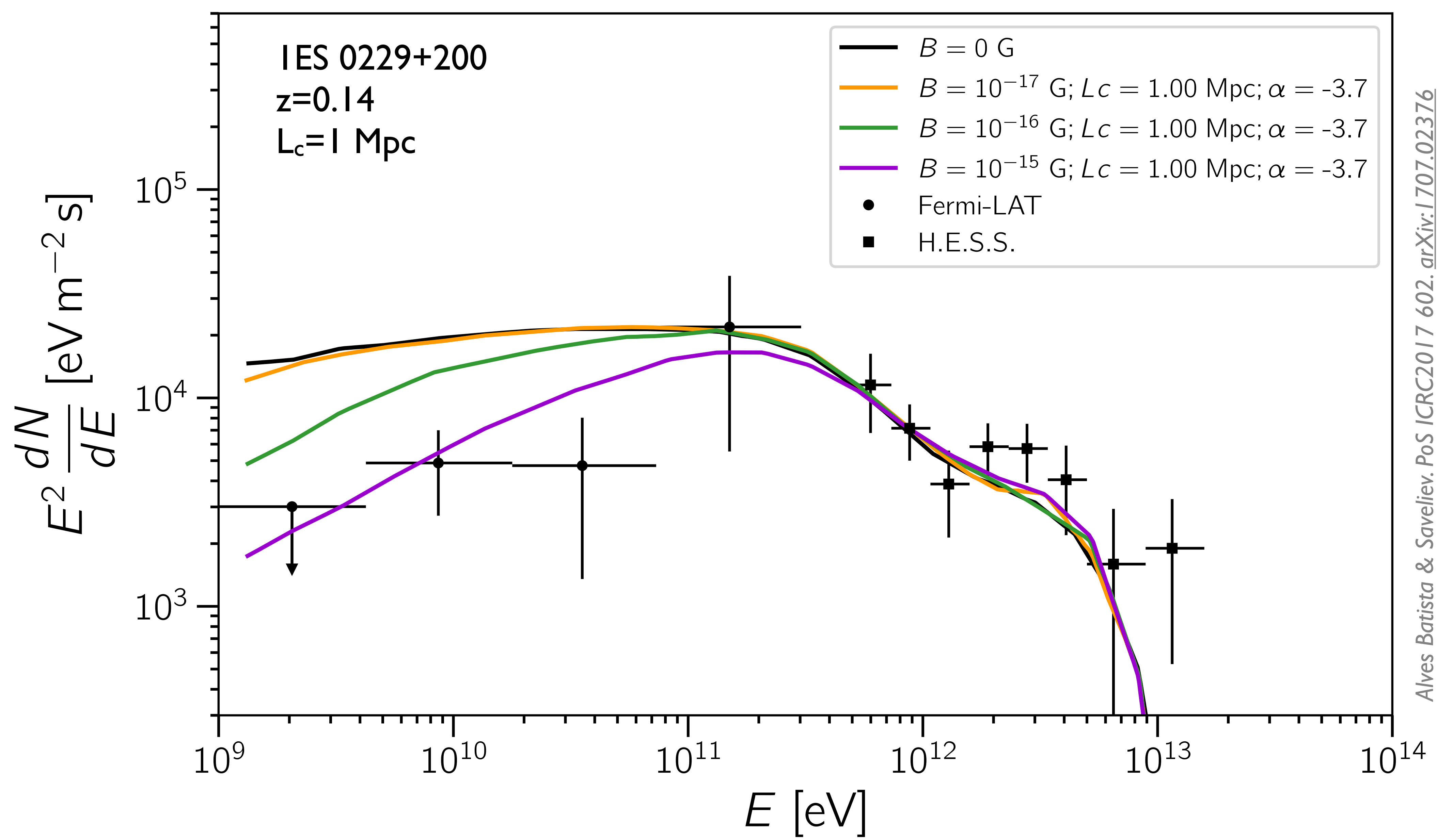
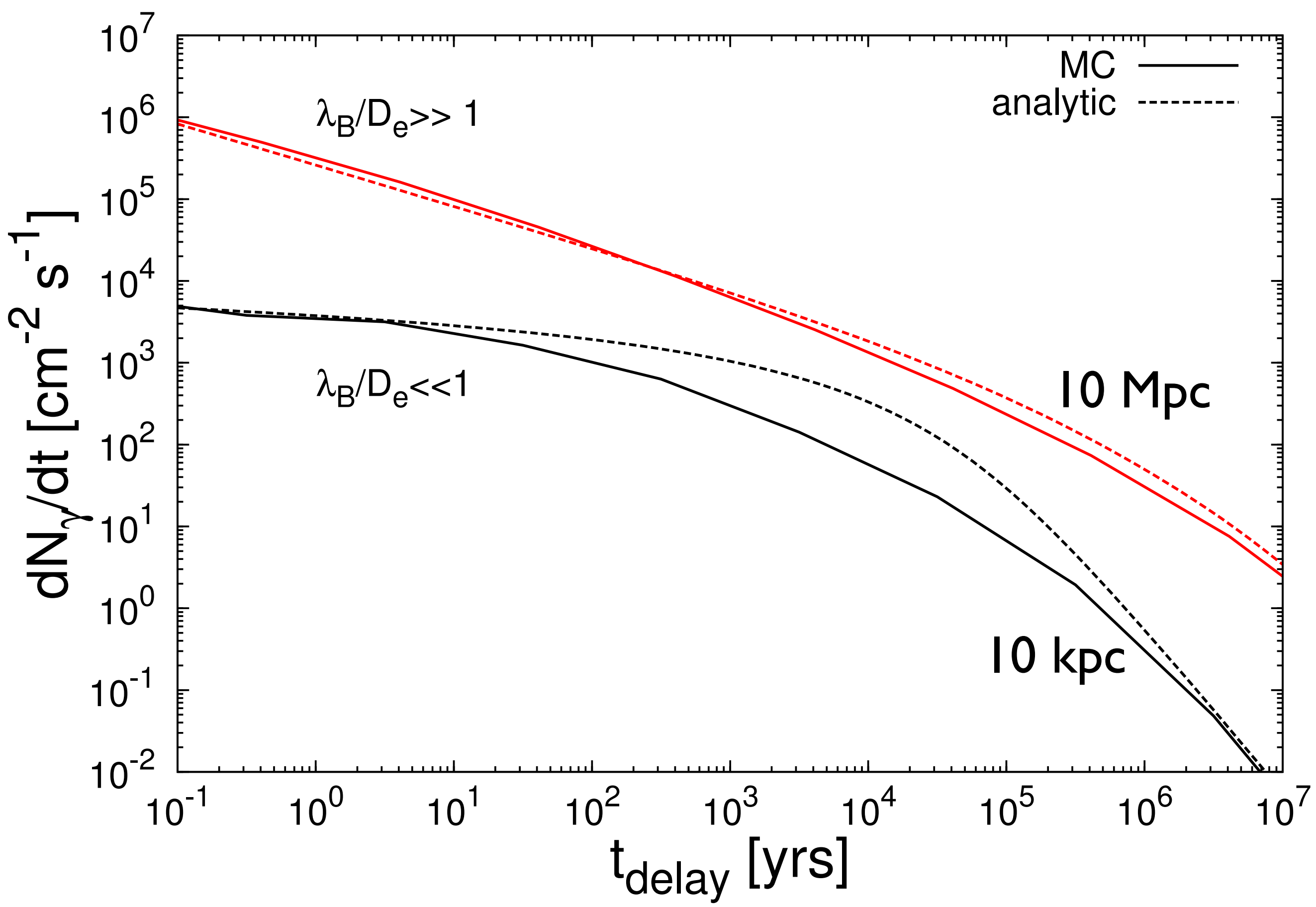


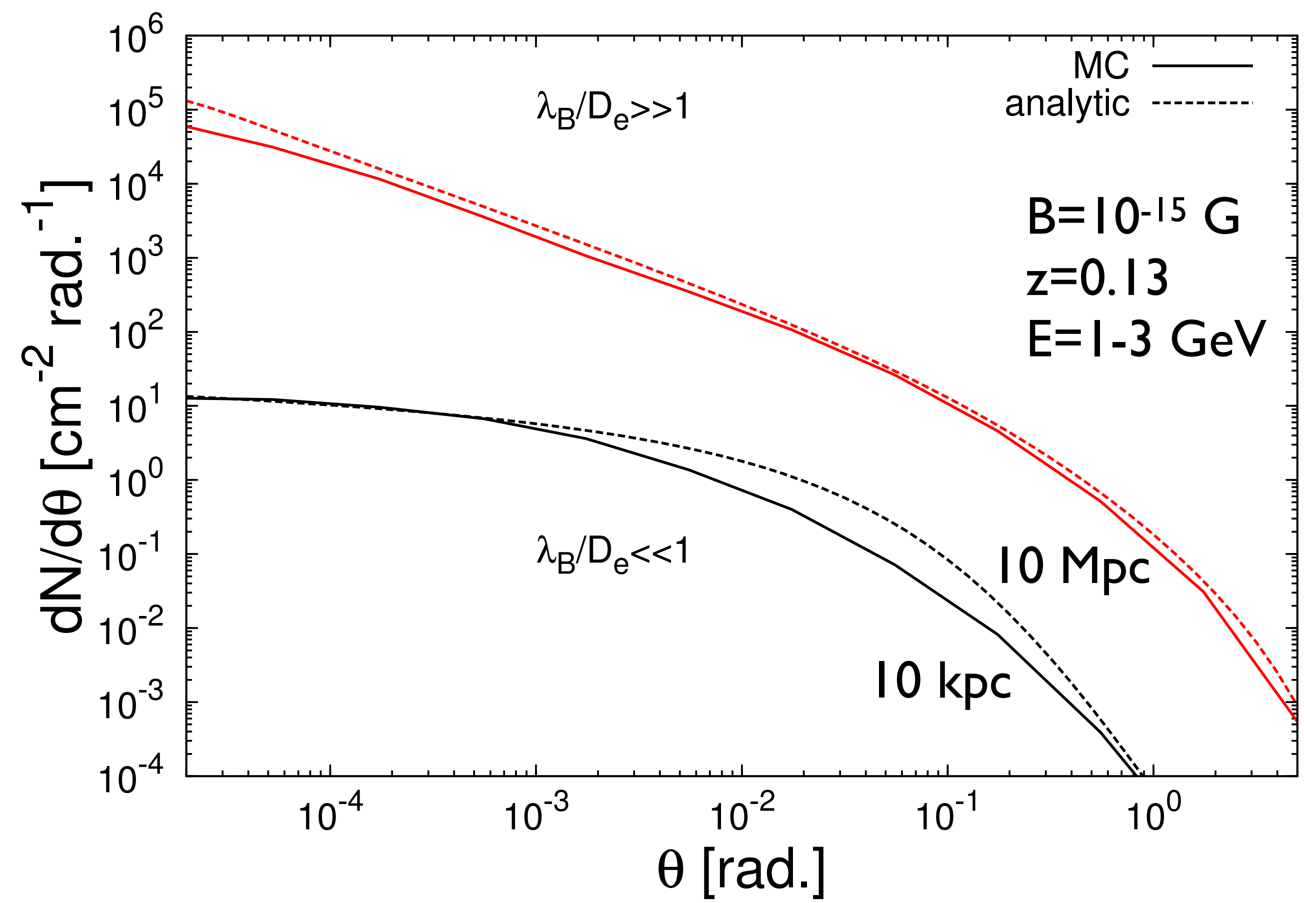


Alves Batista & Saveliev. PoS ICRC2017 602. arXiv:1707.02376

constraining the coherence length

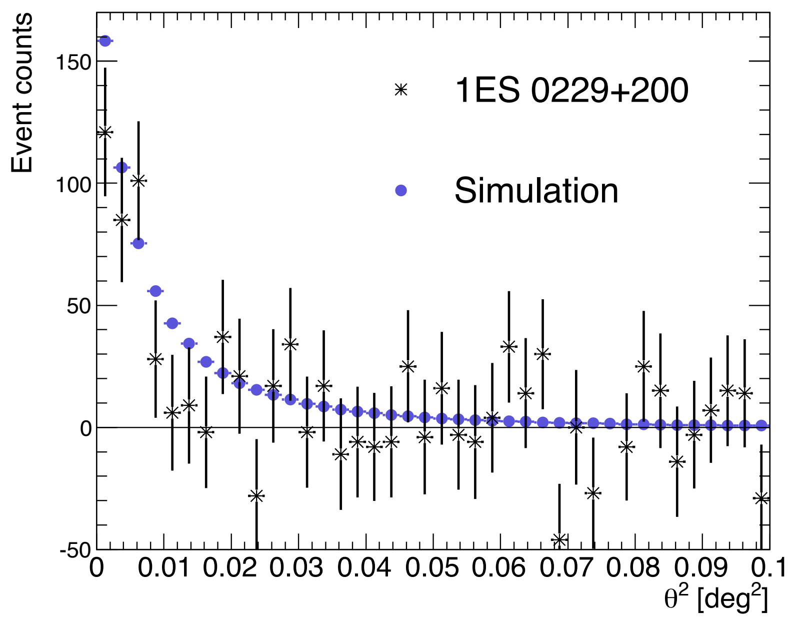
Neronov et al. A&A 554 (2013) A31. arXiv:1307:2753





a few results: IGMF constraints

VERITAS Collab. ApJ 835 (2017) 288. arXiv:1701.00372



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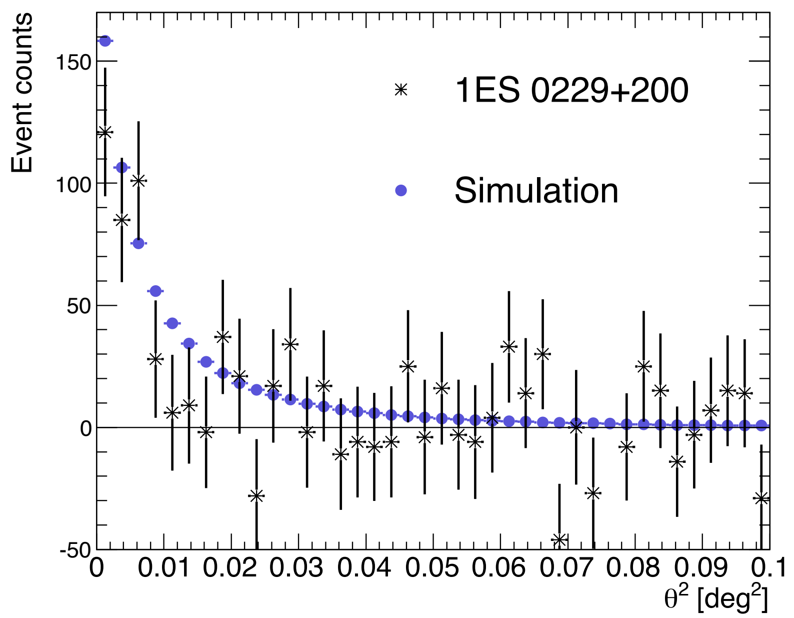

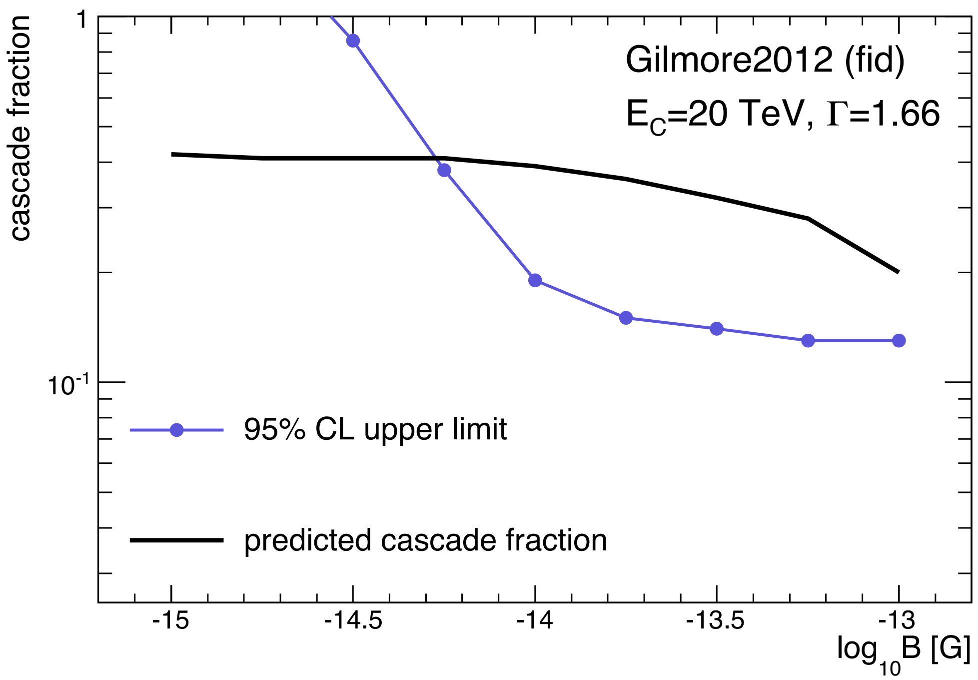

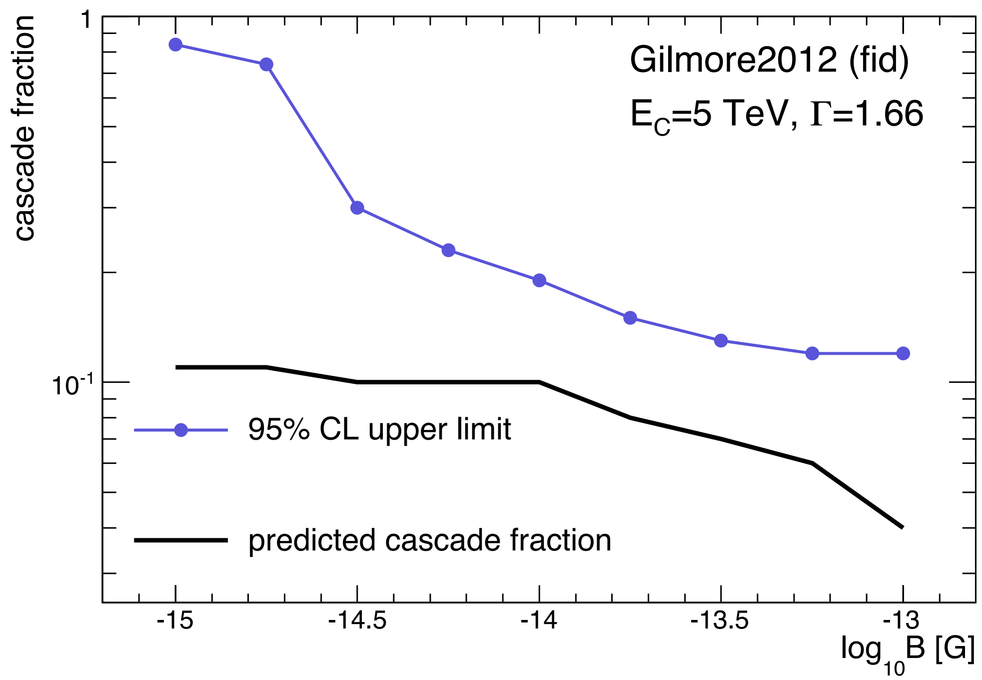

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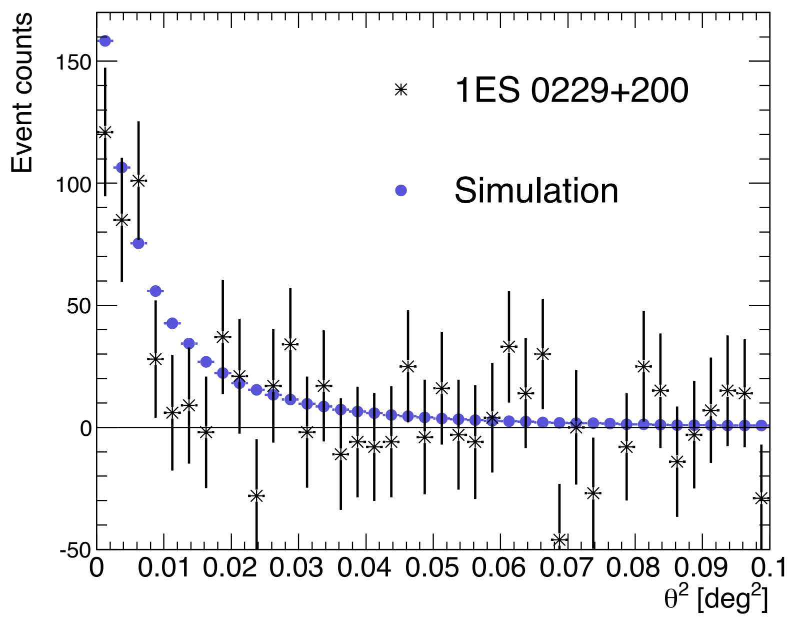
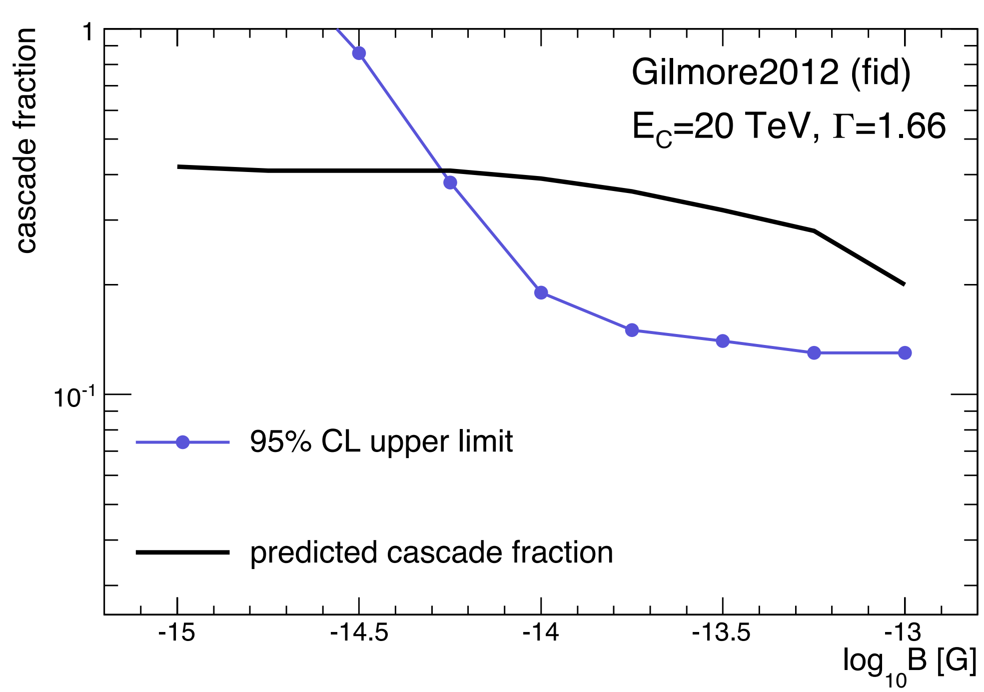
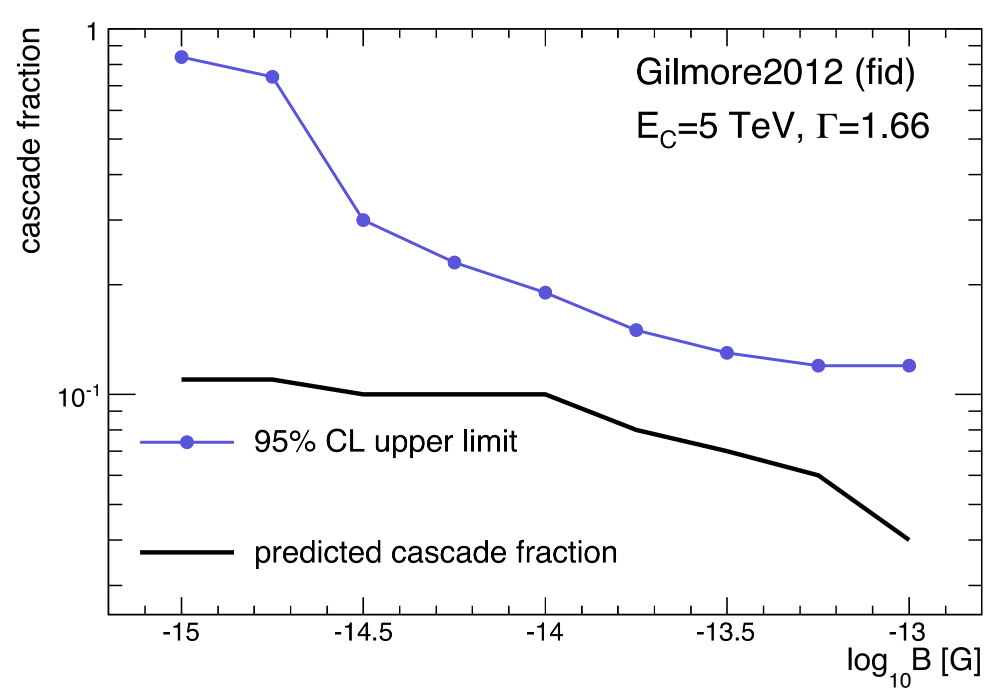


Table 3
The 95% Confidence Level Exclusion Ranges on the IGMF Strength for each Set of Model Assumptions

Γ	E_C (TeV)	EBL Model	IGMF Excluded (G)
1.660	10	Gilmore2012 (fid)	5.5×10^{-15}–7.4×10^{-14}
1.460	10	Gilmore2012 (fid)	4.5×10^{-15}–1.0×10^{-13}
1.860	10	Gilmore2012 (fid)	non-constraining
1.660	5	Gilmore2012 (fid)	non-constraining
1.660	20	Gilmore2012 (fid)	5.4×10^{-15}–1.0×10^{-13}
1.660	10	Franceschini2008	9.1×10^{-15}–5.6×10^{-14}





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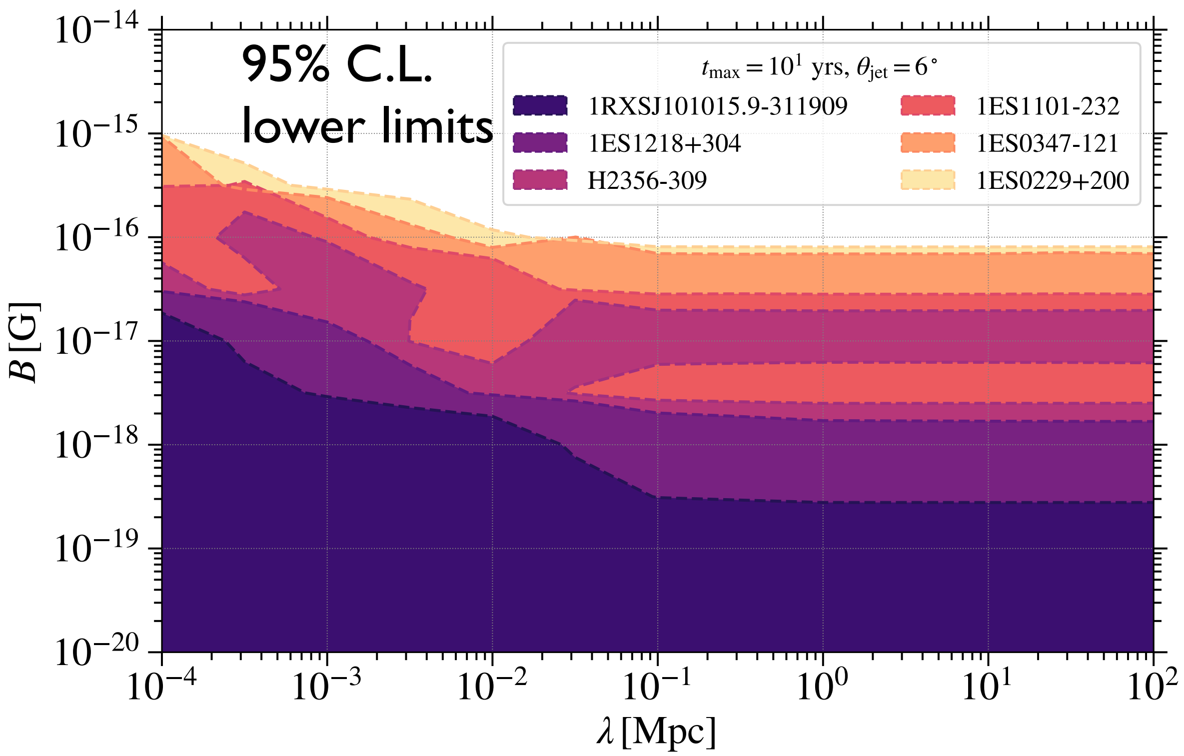
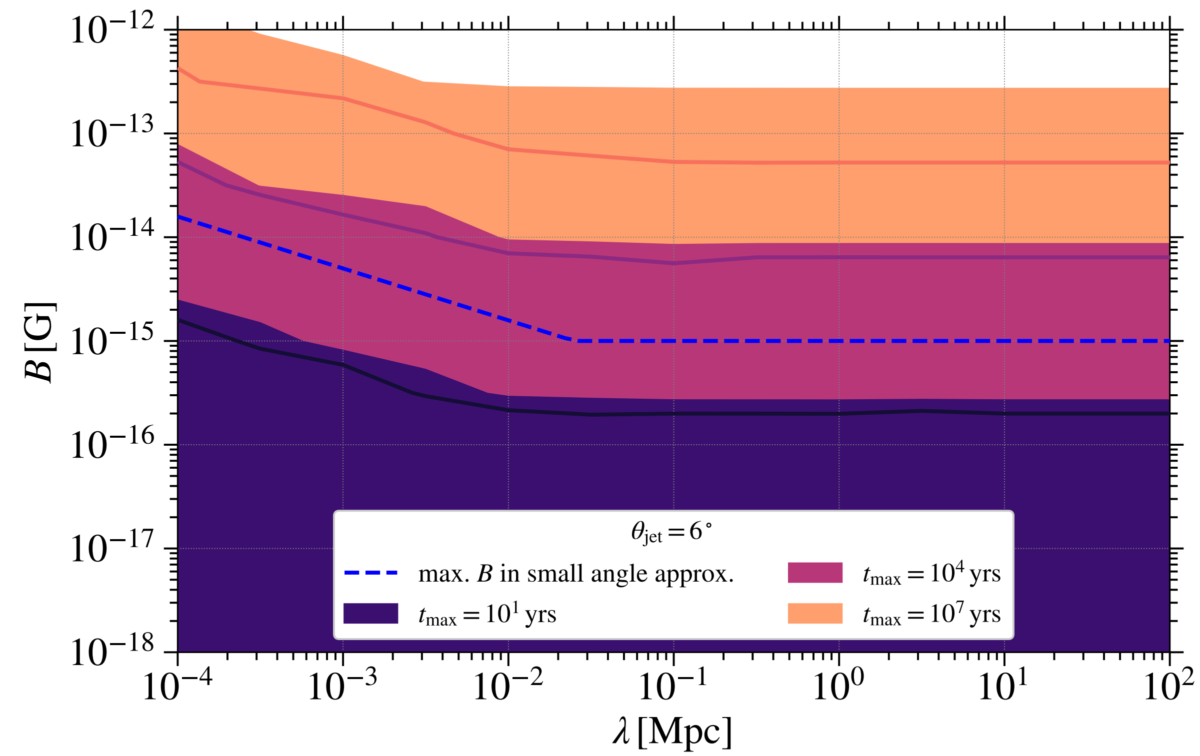
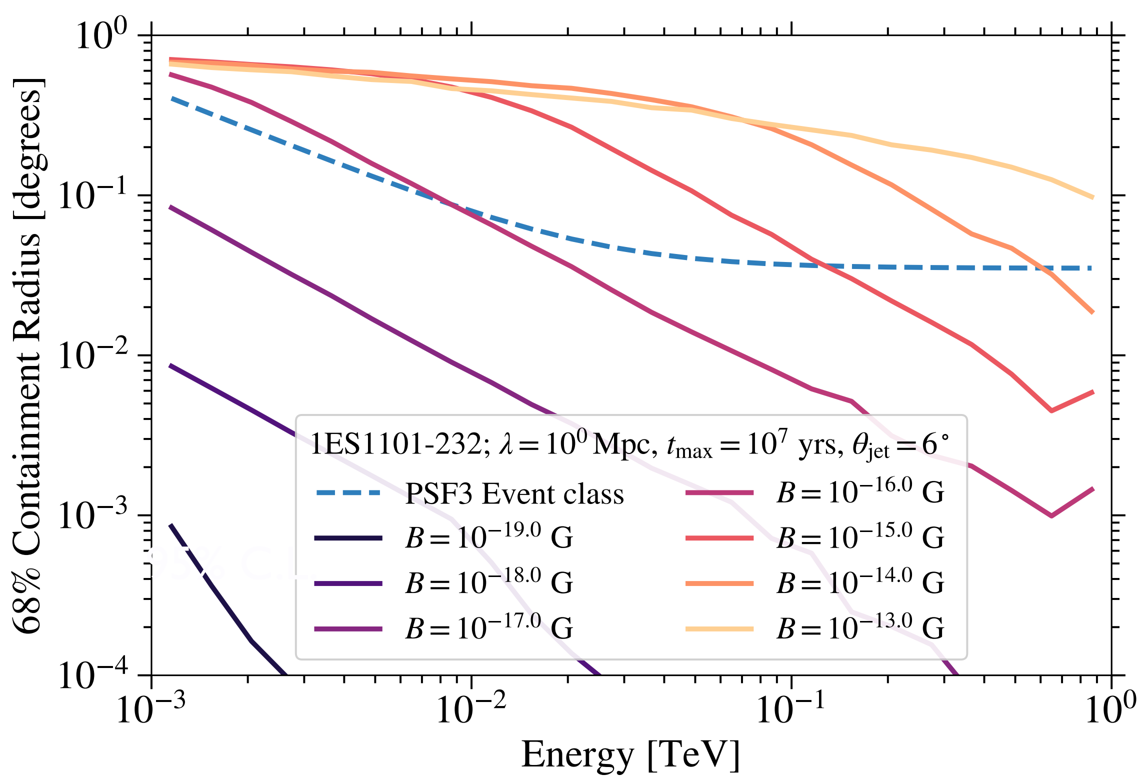
Fermi-LAT Collaboration & Biteau. arXiv:1804.08035







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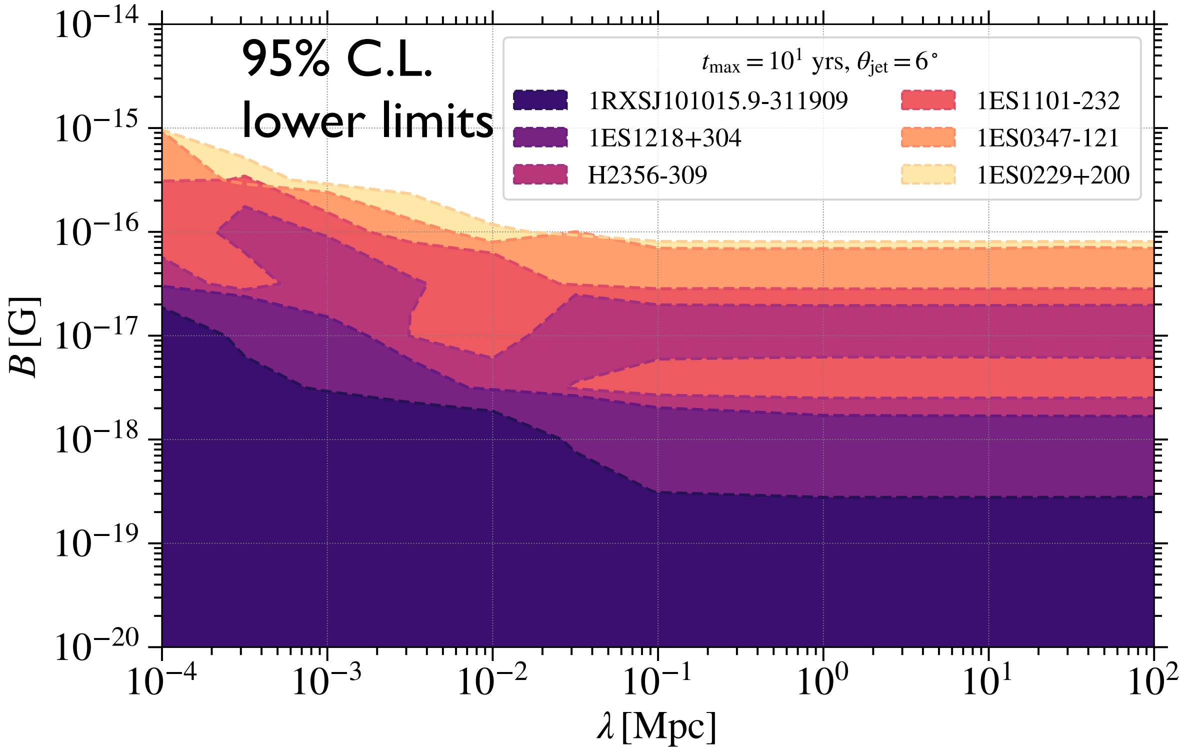
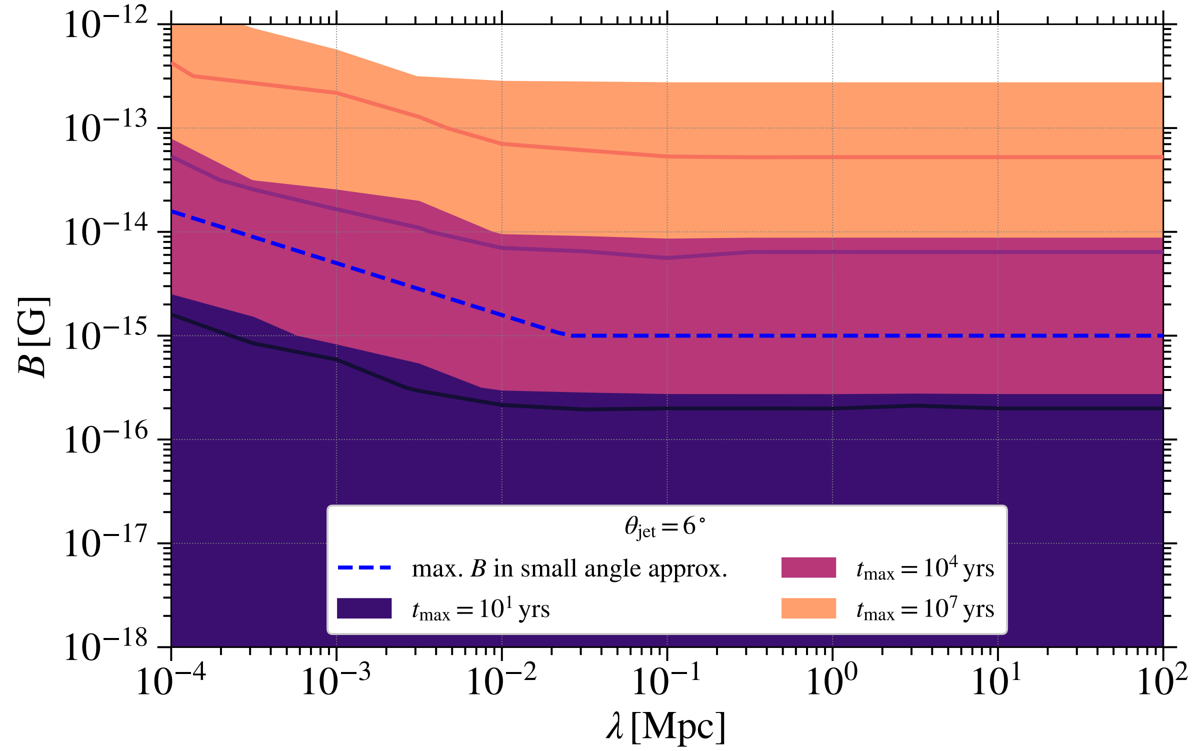
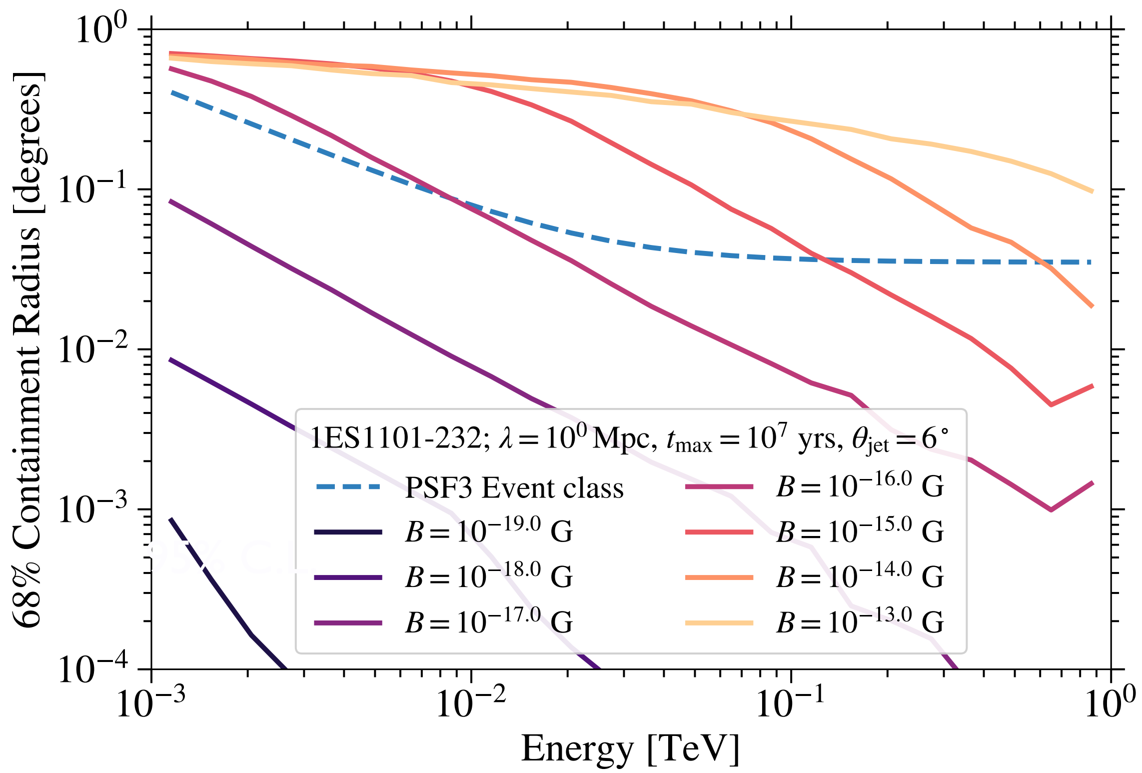
Fermi-LAT Collaboration & Biteau. arXiv:1804.08035



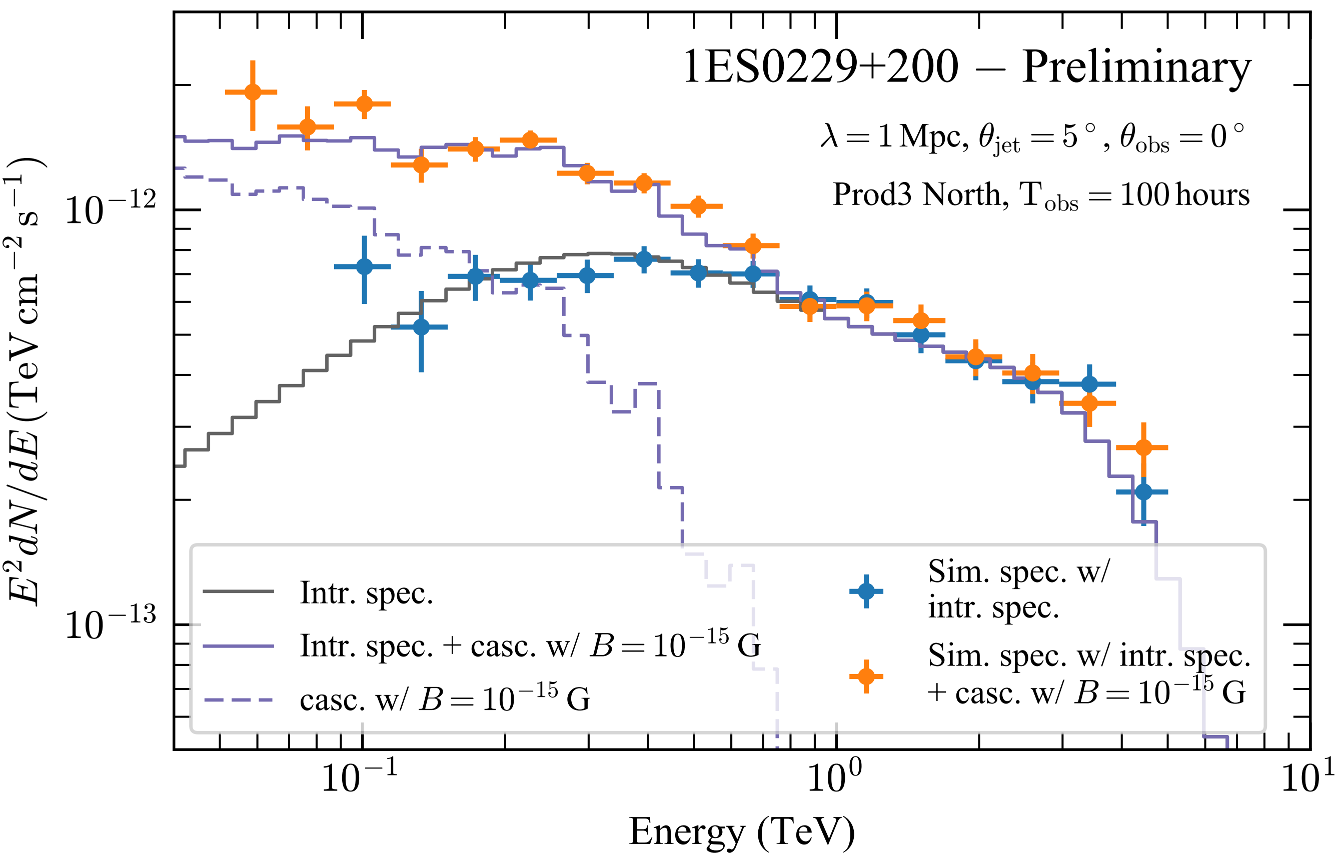


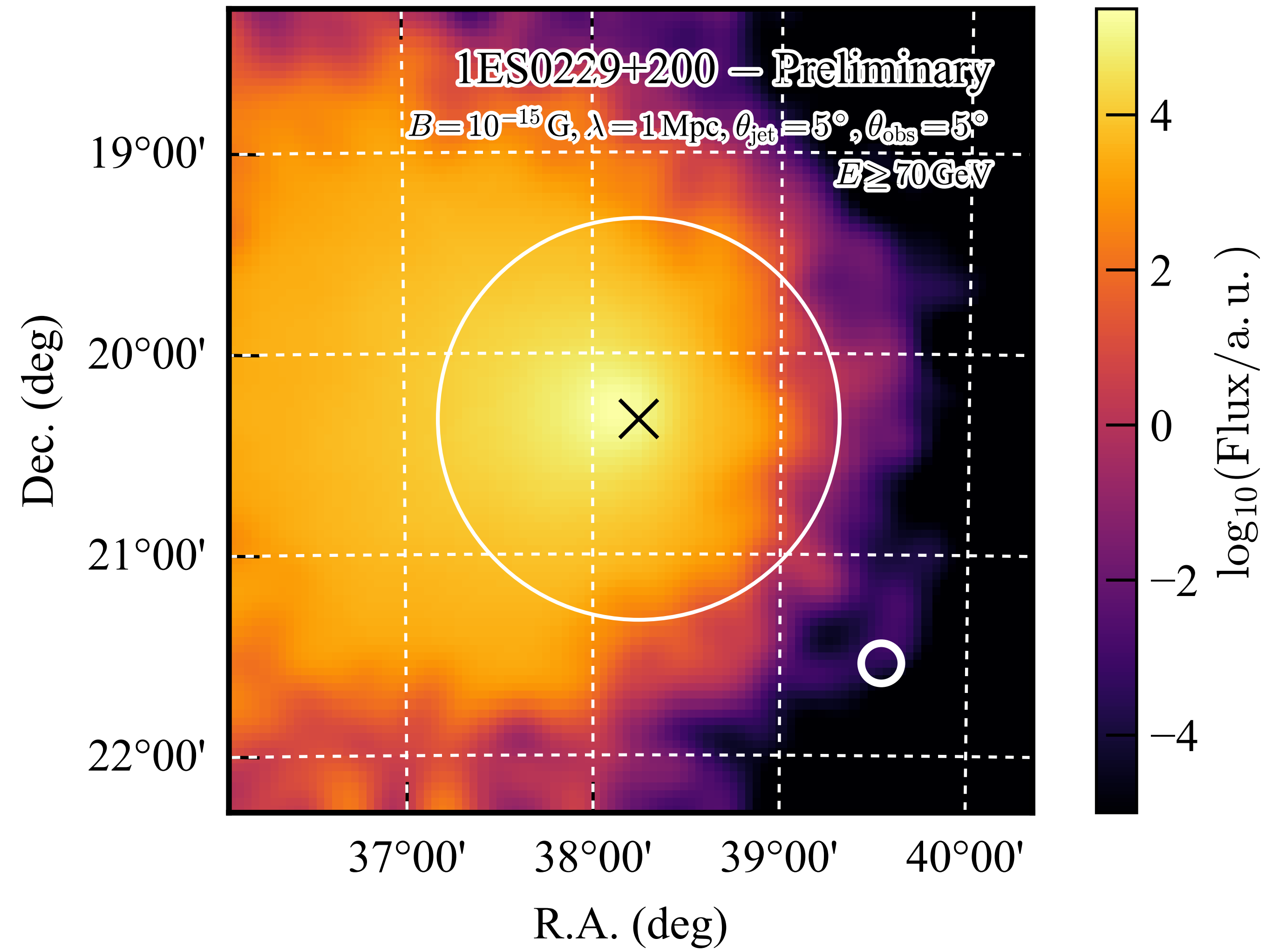


no evidence for extended emission in neither individual sources nor in the stacked samples

IGMF constraints with CTA

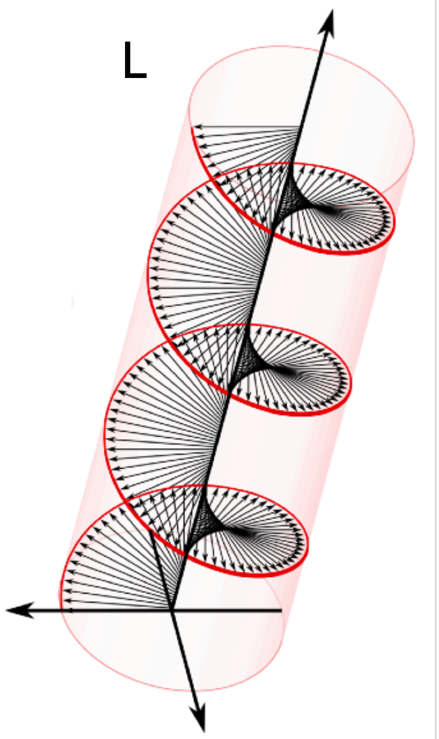
F. Gaté et al. for the CTA Consortium. Proc. ICRC 2017. arXiv:1709.04185

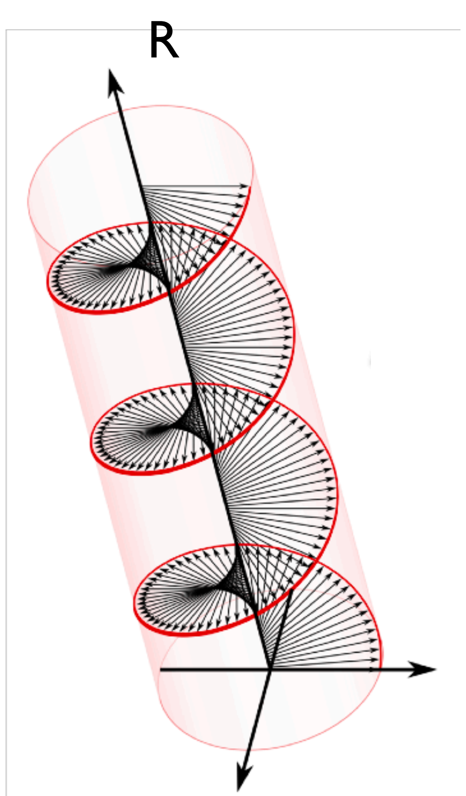




see talk by M. Meyer

helical IGMFs

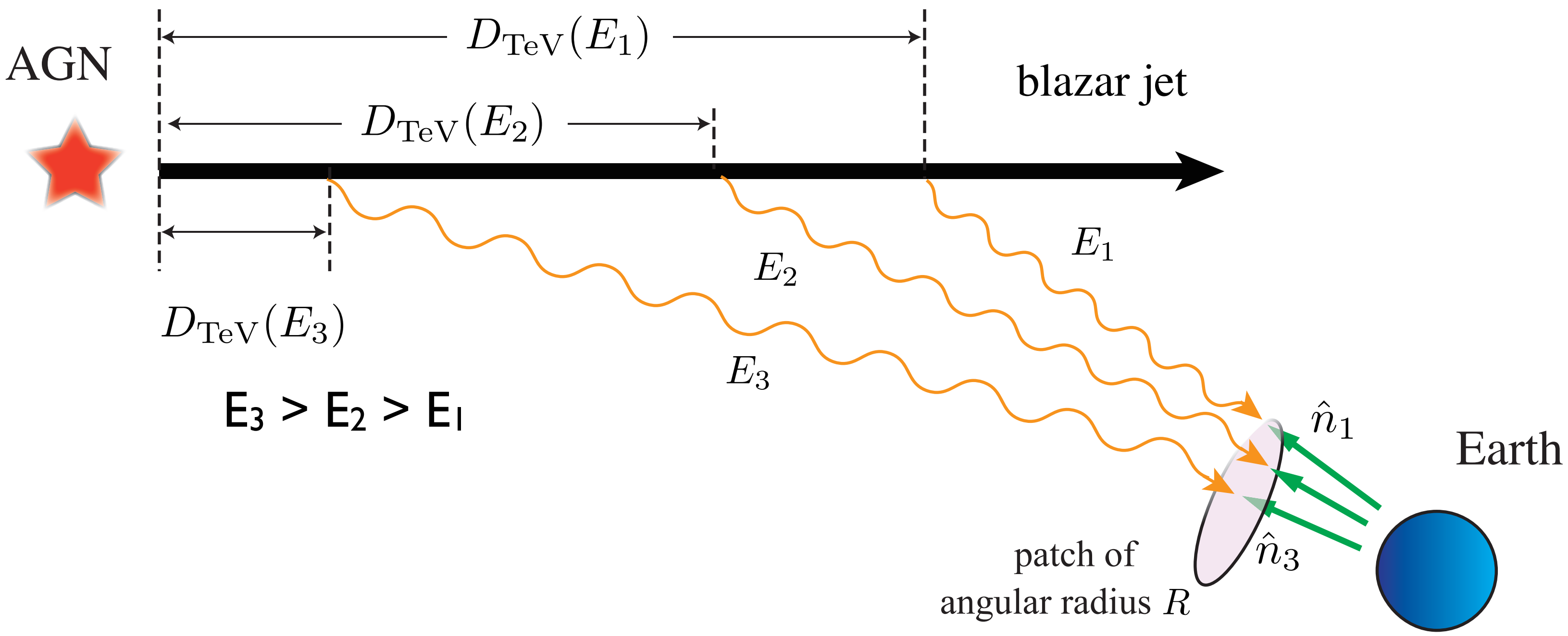




- helicity: $\mathscr{H} = \int d^3 r \vec{A} \cdot \vec{B}$
- helical magnetic fields may be related to baryogenesis (left-handed) leptogenesis (right-handed) if they were generated prior to the EW phase transition
- helicity is a conserved quantity
- signatures of helical fields can be searched in gamma rays using parity-odd correlators → all sky searches *[Tashiro+ 2014, Chen+ 2015, Tashiro & Vachaspati 2015]*
- morphology of blazar pair haloes enables the measurement of the helicity integrated along the line of sight *[Long & Vachaspati 2015; Alves Batista+ 2016]*

helical IGMFs

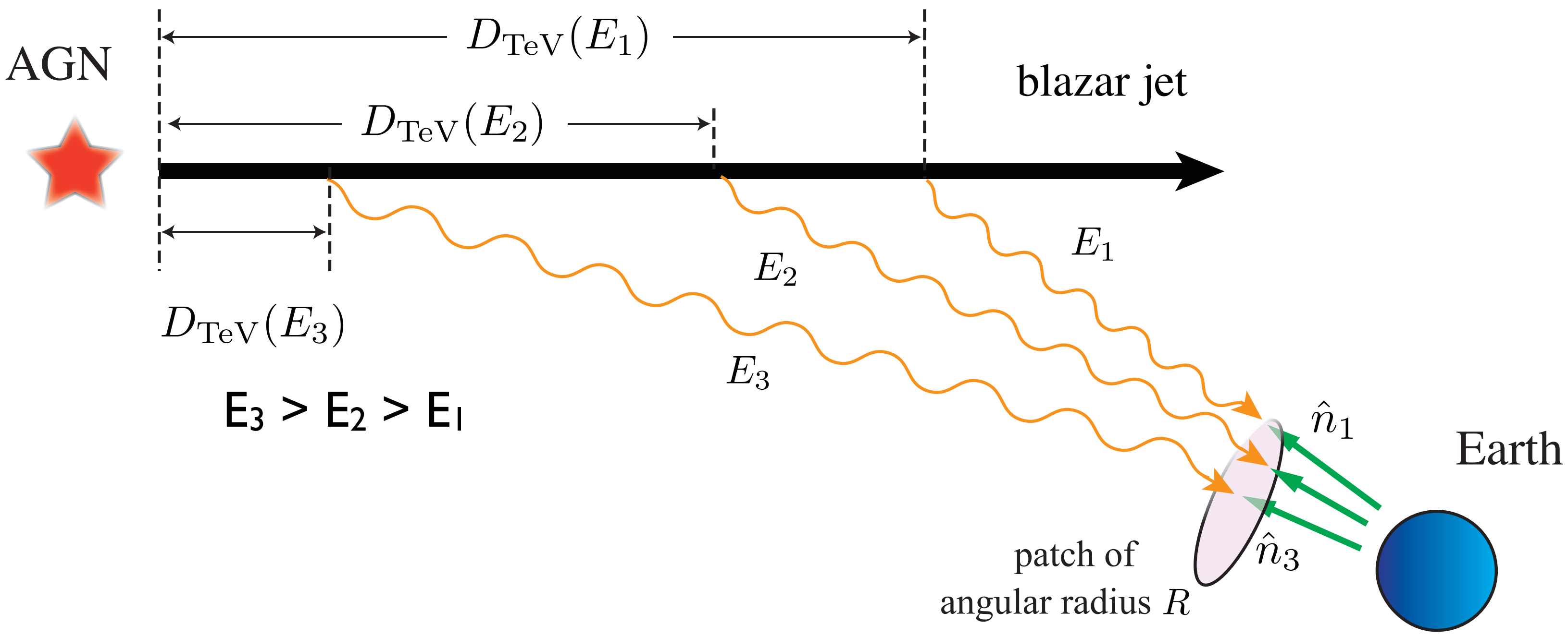
Tashiro et al. MNRAS Lett. 445 (2014) L41. arXiv:1310.4826



$E_3 > E_2 > E_1$

helical IGMFs

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



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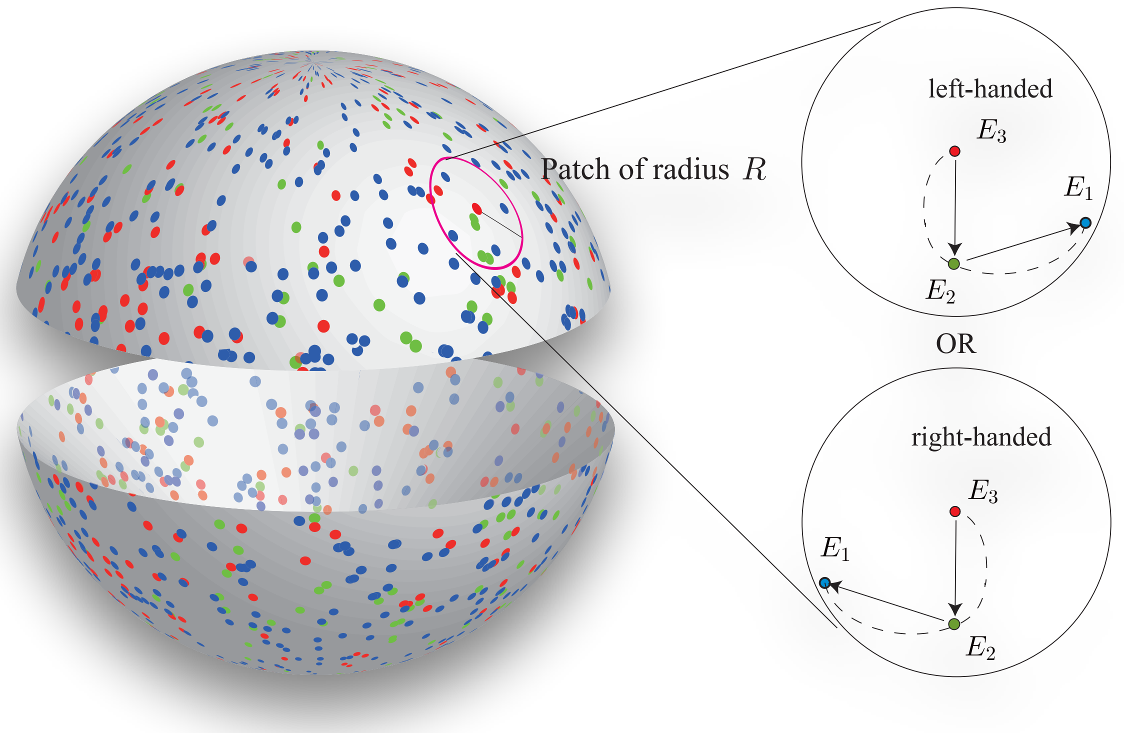

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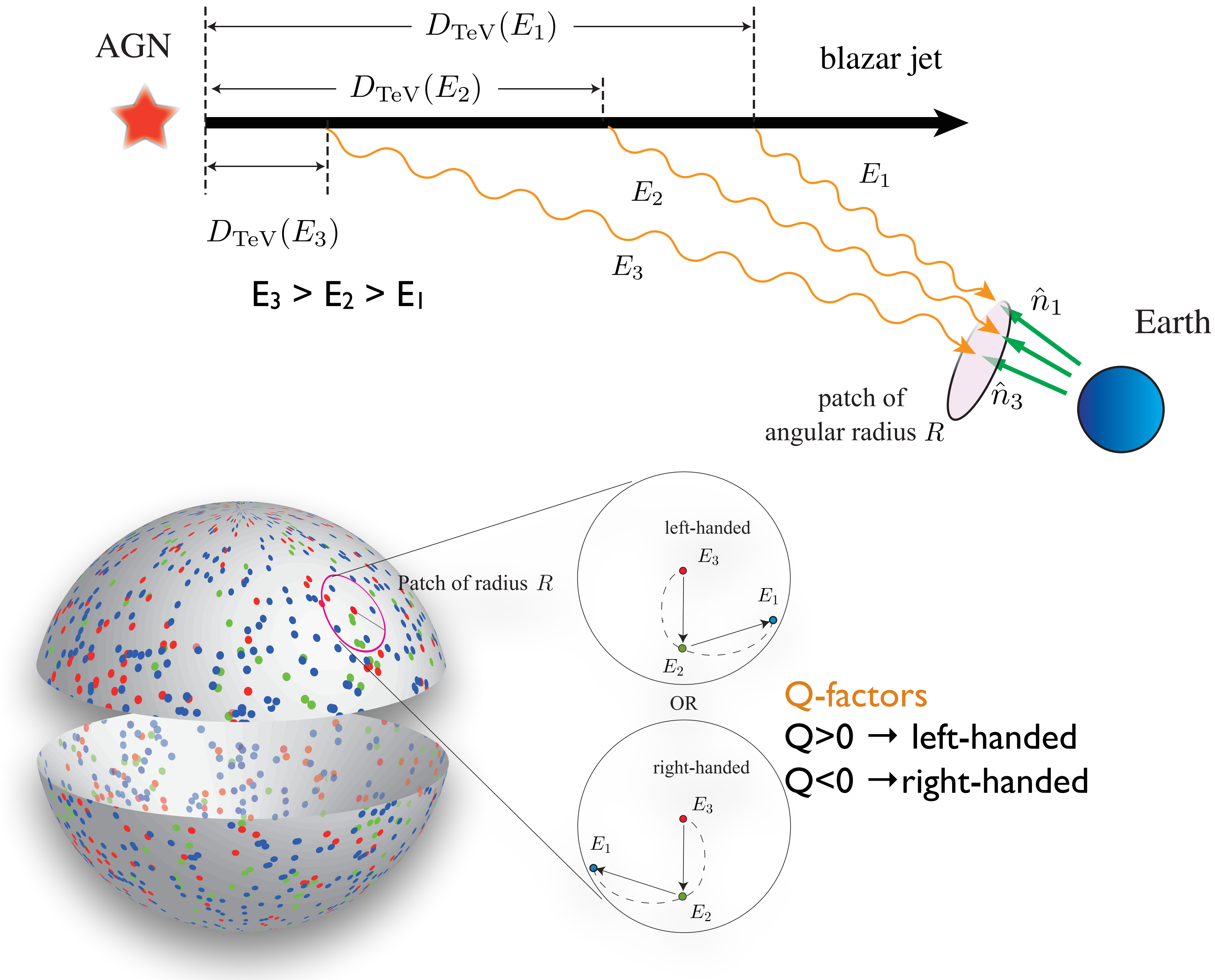
Tashiro et al. MNRAS Lett. 445 (2014) L41. arXiv:1310.4826

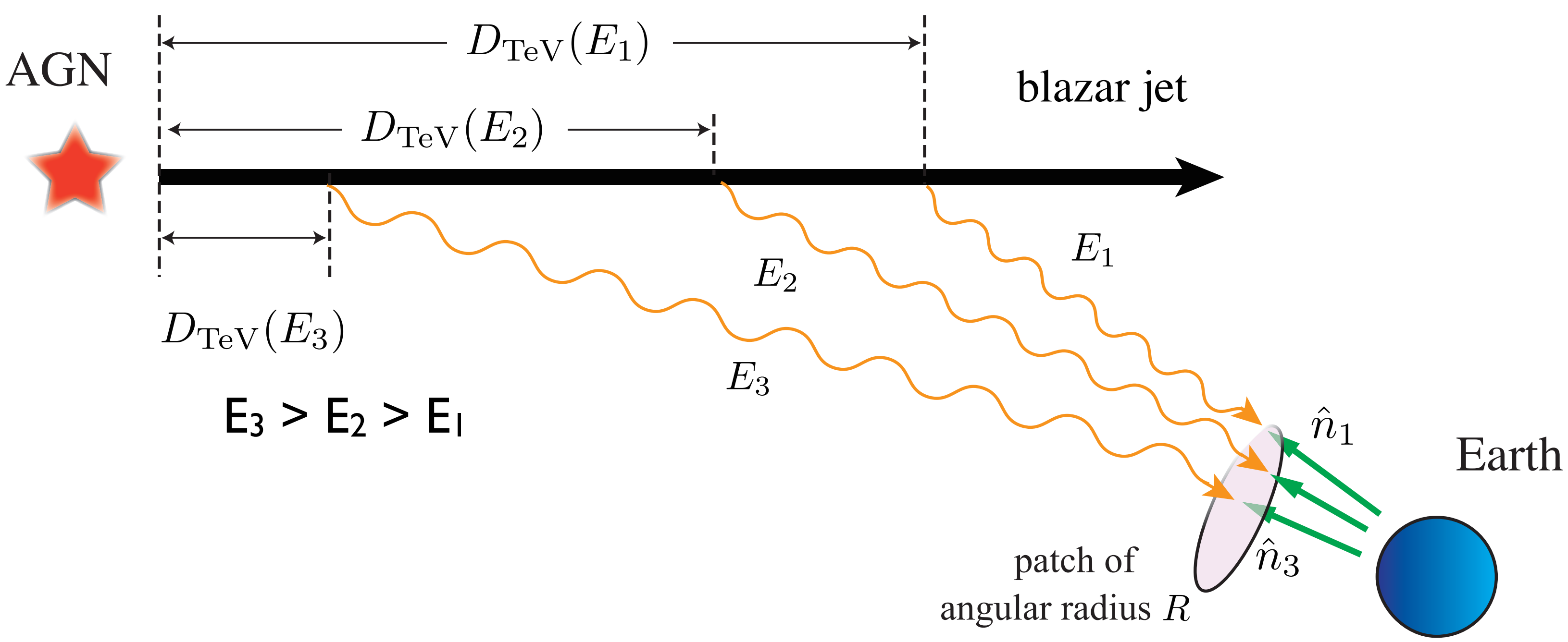


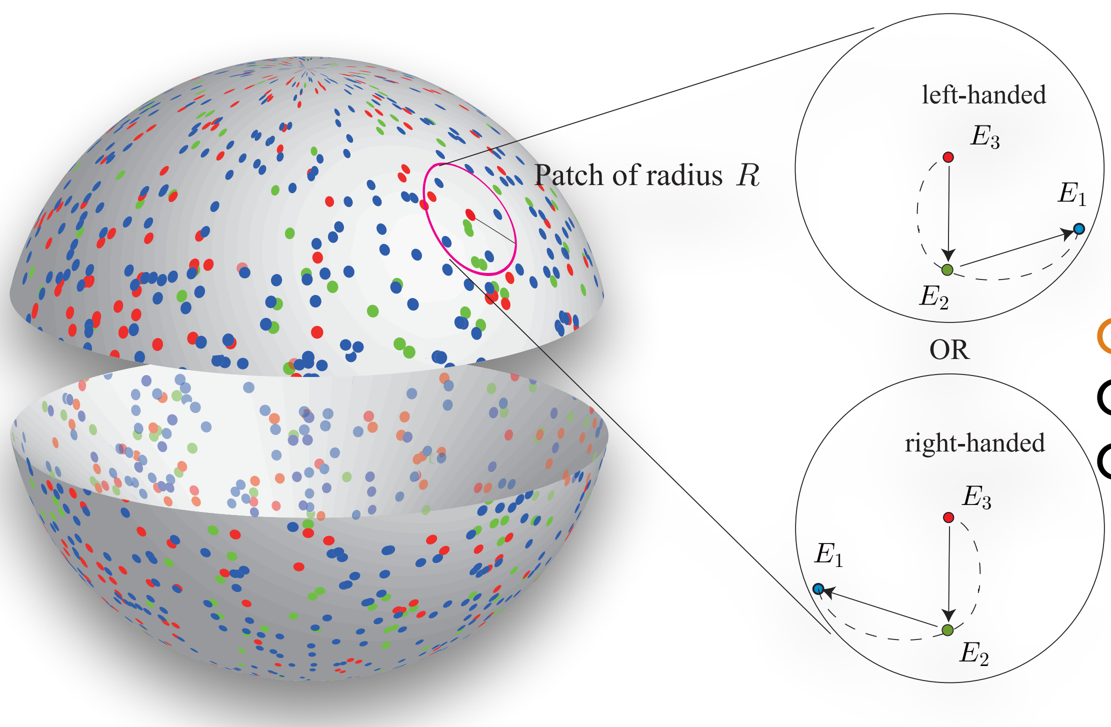
Q-factors

Q>0 → left-handed

Q<0 → right-handed

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





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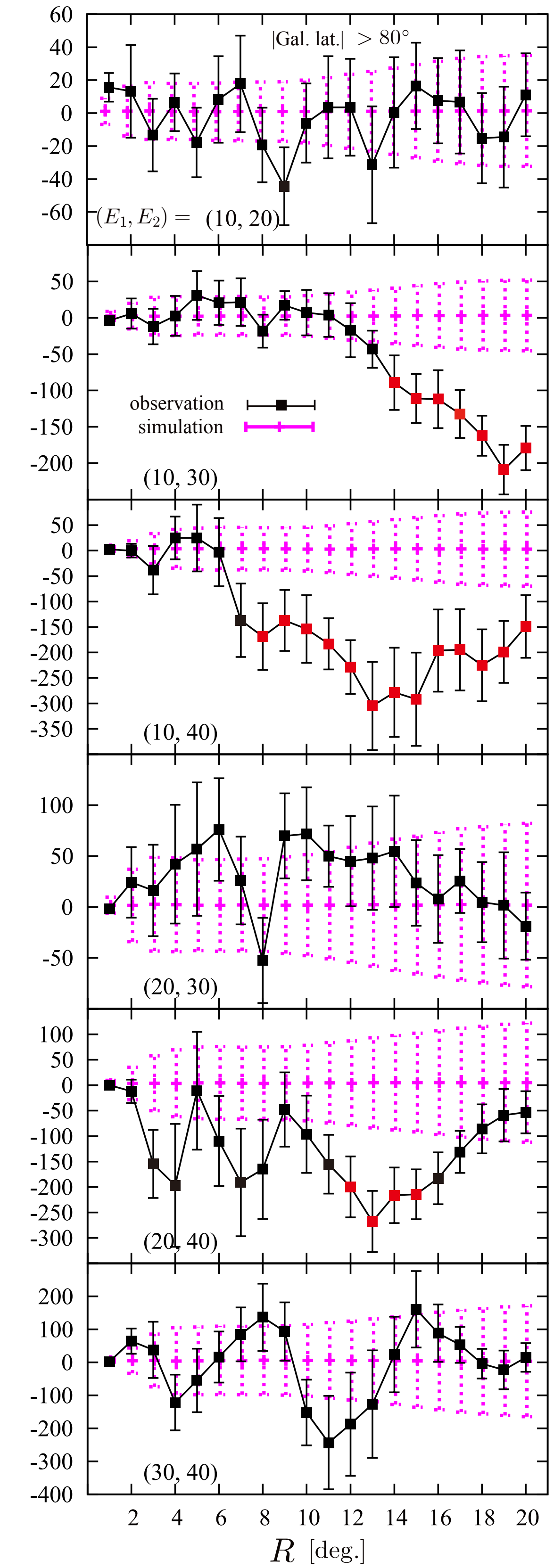
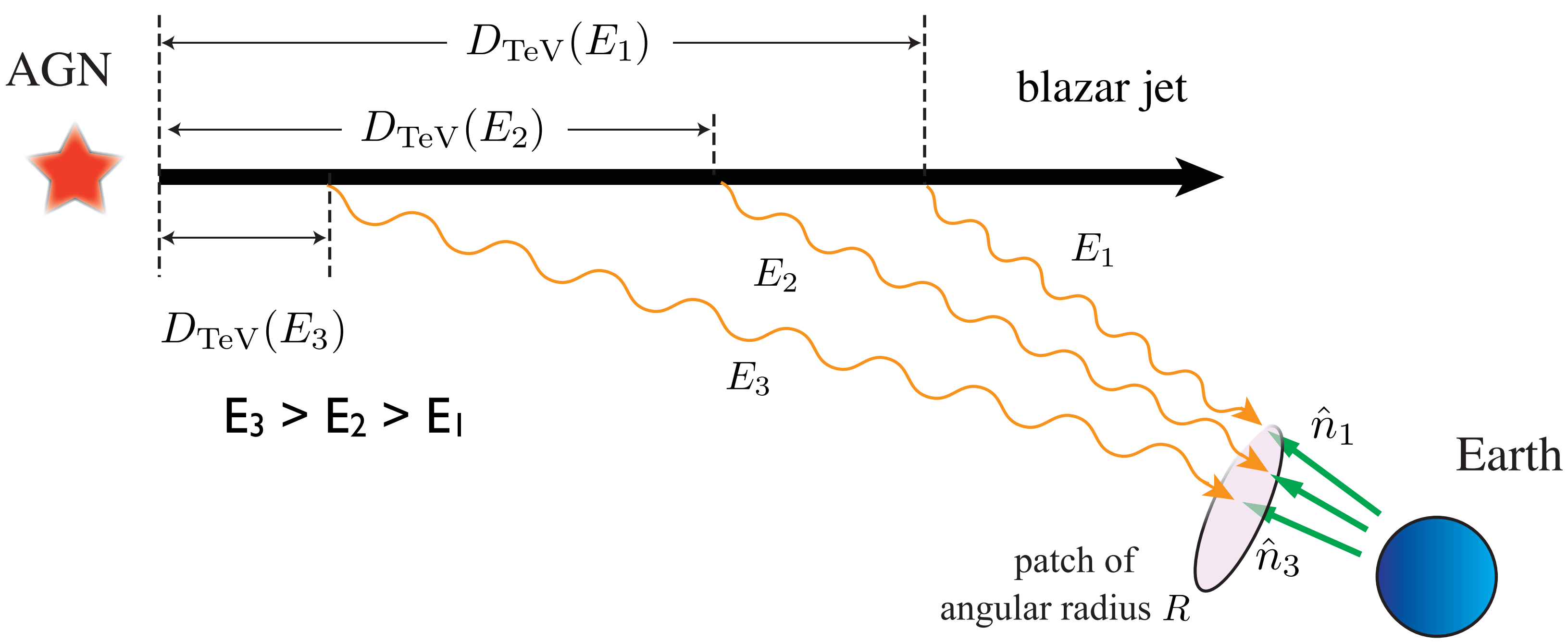
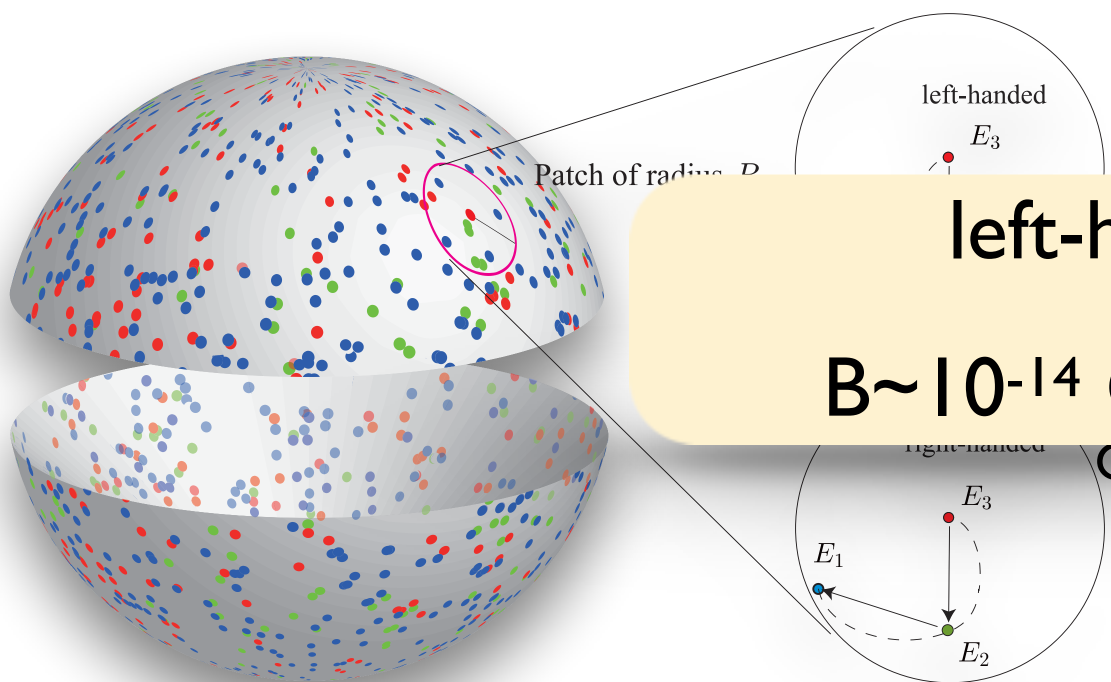


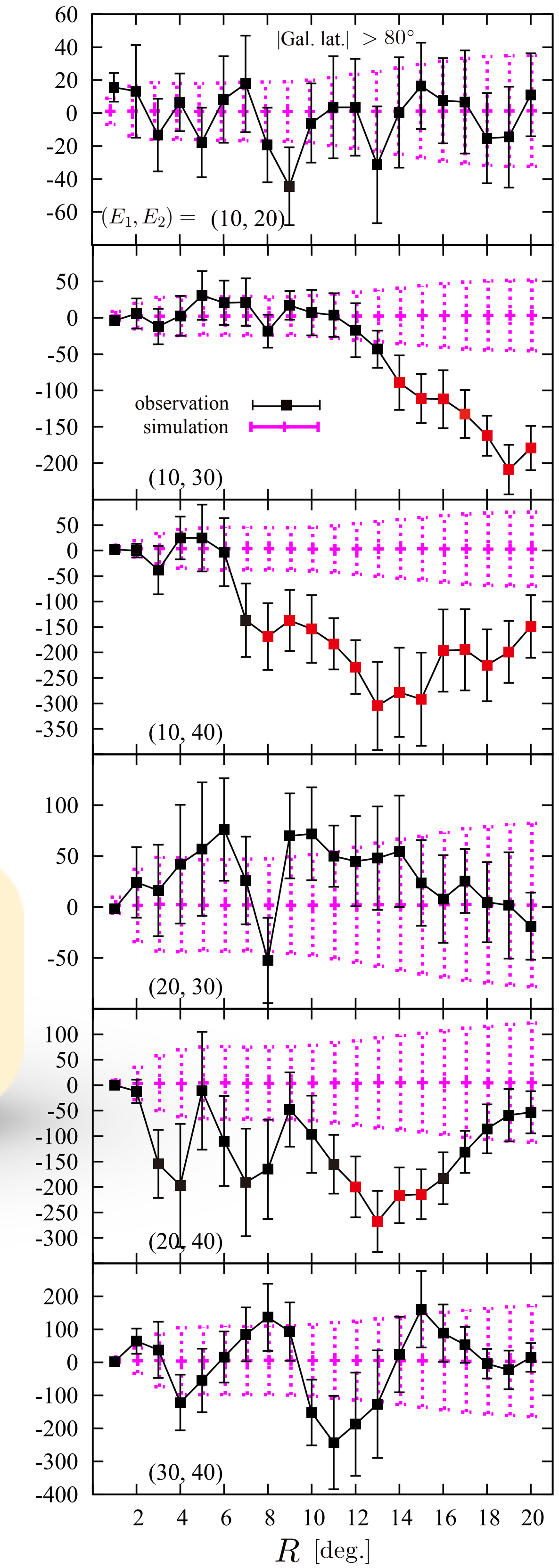
helical IGMFs

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



E3 > E2 > E1





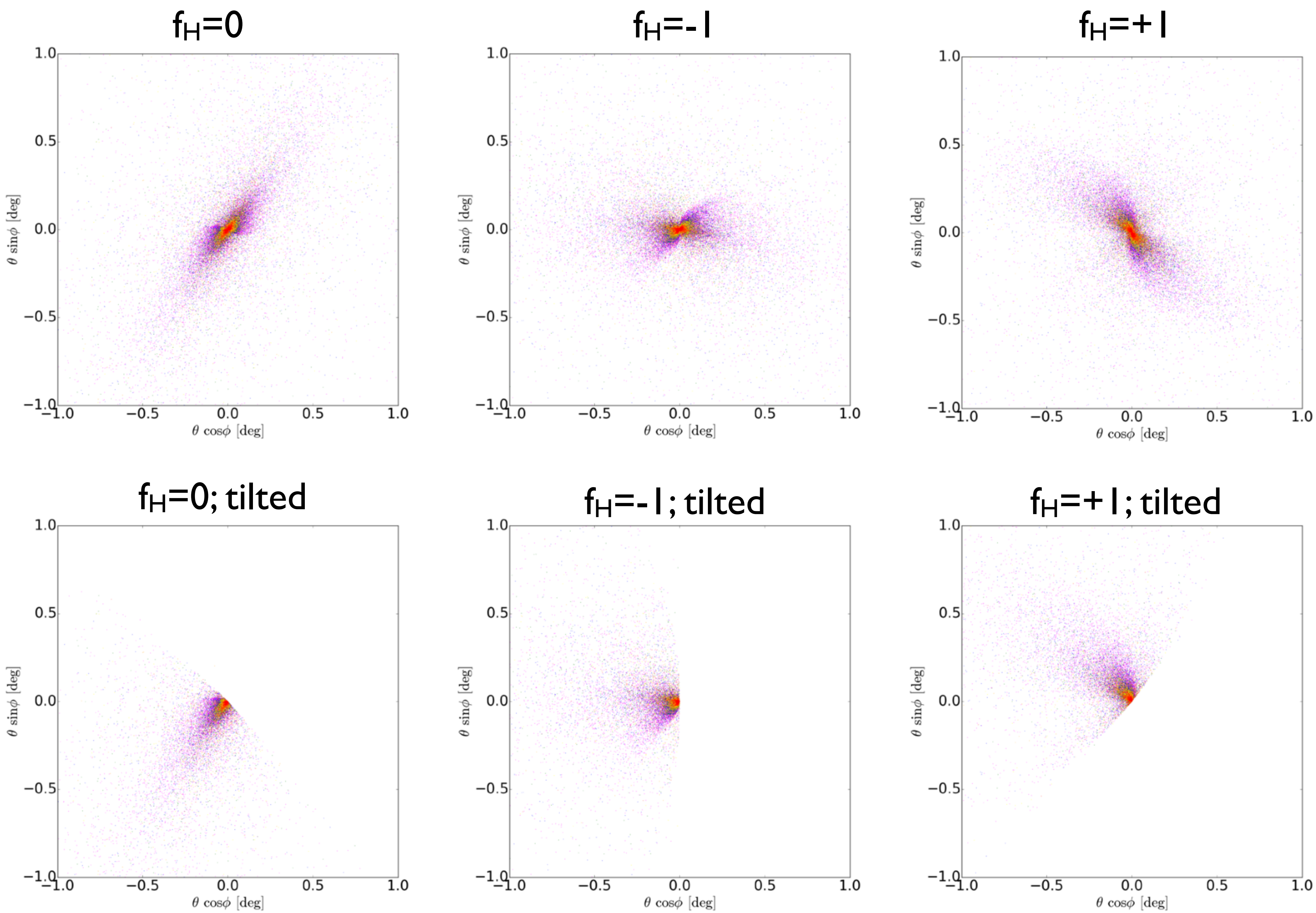
Q<0 →right-handed

left-handed IGMF

$B \sim 10^{-14}$ G at $L_c \sim 10$ Mpc

helical IGMFs

Alves Batista et al. PRD 94 (2016) 083005. arXiv:1607.00320



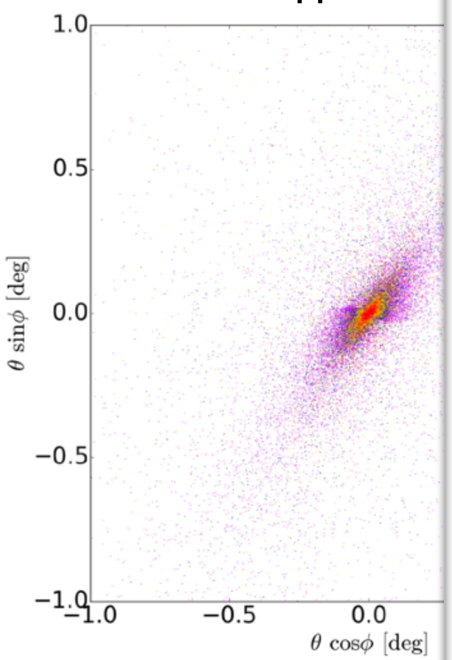
Batchelor spectrum
Lc = 100 Mpc
tilt angle: 5°
D=1 Gpc
B=1 fG
Ψ=5°

magenta: E=5-10 GeV
blue: E=10-15 GeV
green: E=15-20 GeV
yellow: E=20-30 GeV
orange: E=30-50 GeV
red: E=50-100 GeV

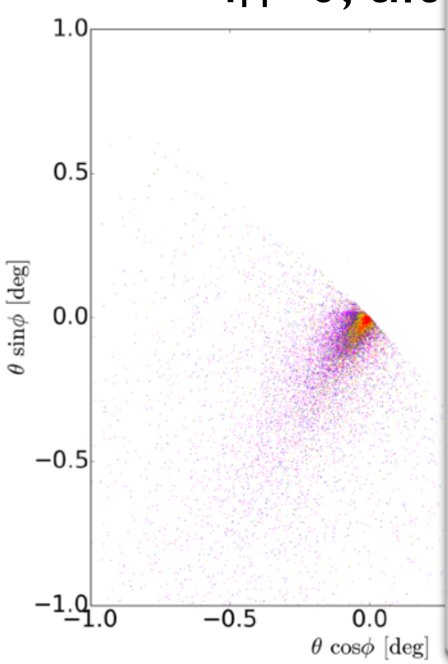
helical IGMFs

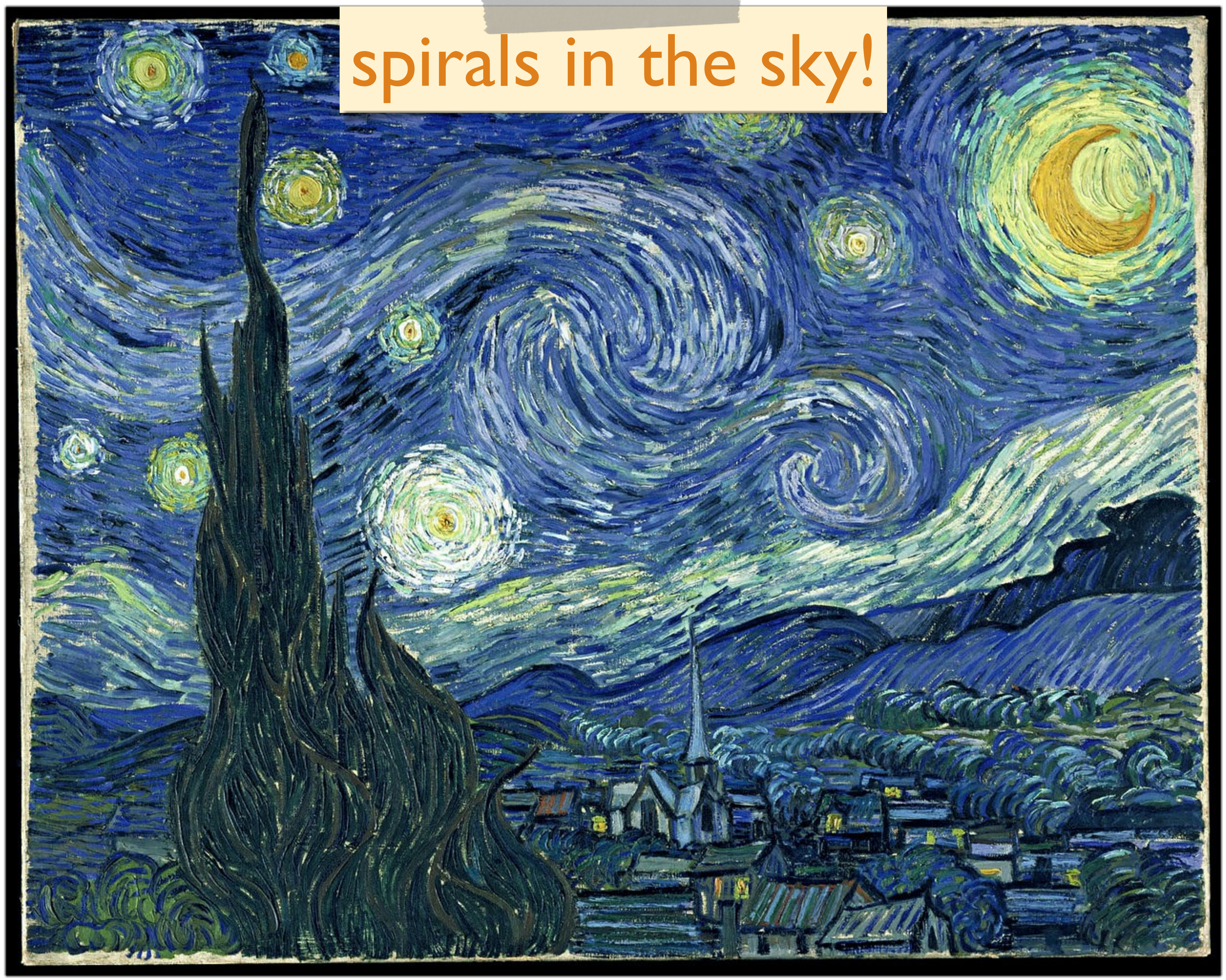
Alves Batista et al. PRD 94 (2016) 083005. arXiv:1607.00320

f_H=0



f_H=0; tilt





spirals in the sky!

helor spectrum
100 Mpc
ngle: 5°
Gpc
fG
°

enta: E=5-10 GeV
: E=10-15 GeV
n: E=15-20 GeV
w: E=20-30 GeV
ge: E=30-50 GeV
E=50-100 GeV

the 'missing haloes "problem"'

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

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

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[8] Department of Astronomy and Astrophysics, Berlin Institute of Technology, Hardenbergstrae 36, D-10623 Berlin, Germany

Received 2018 August 8; revised 2018 September 29; accepted 2018 October 1; published 2018 November 26

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

the 'missing haloes "problem"'

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plasma instabilities

- 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

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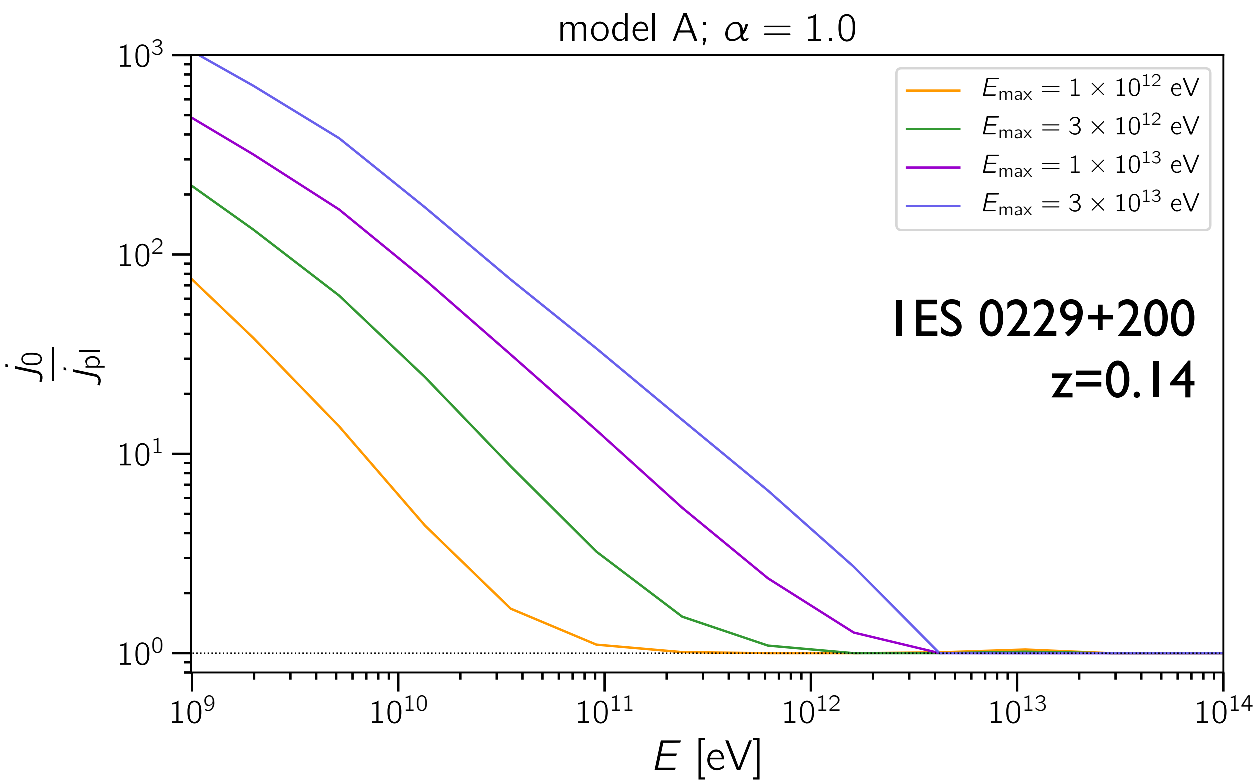

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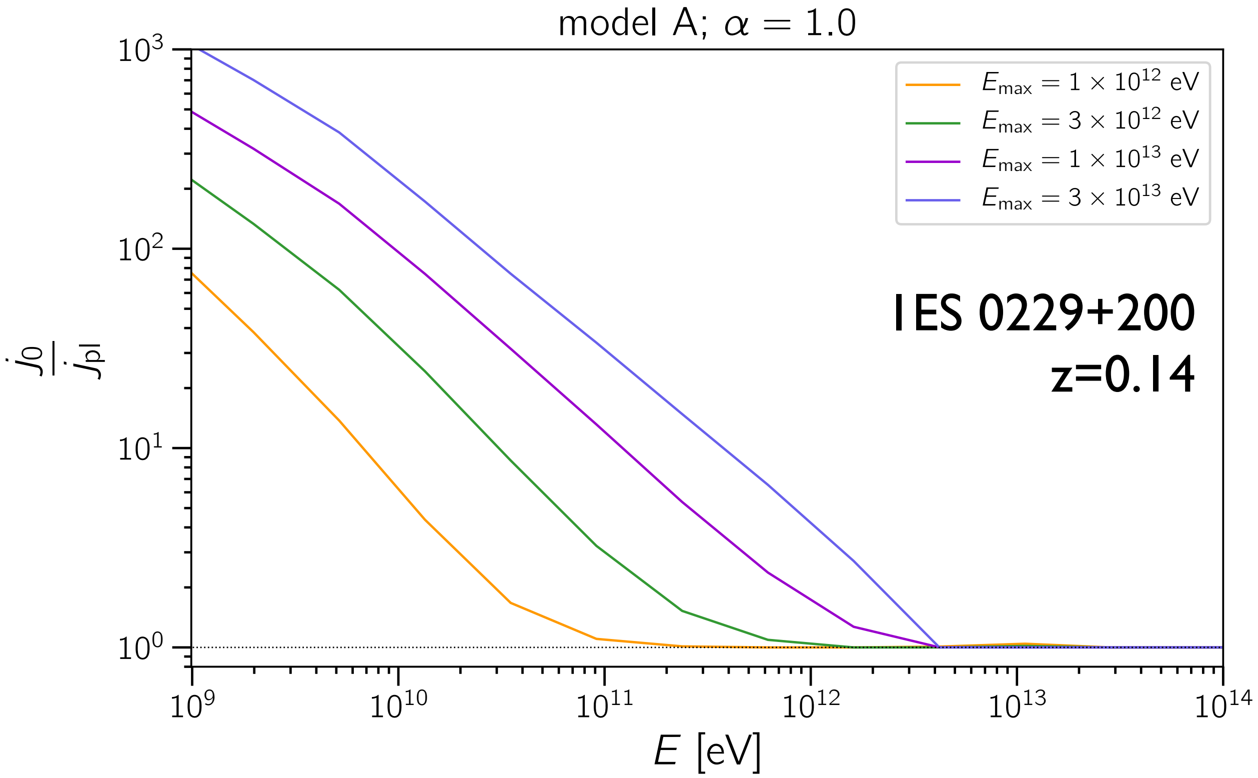

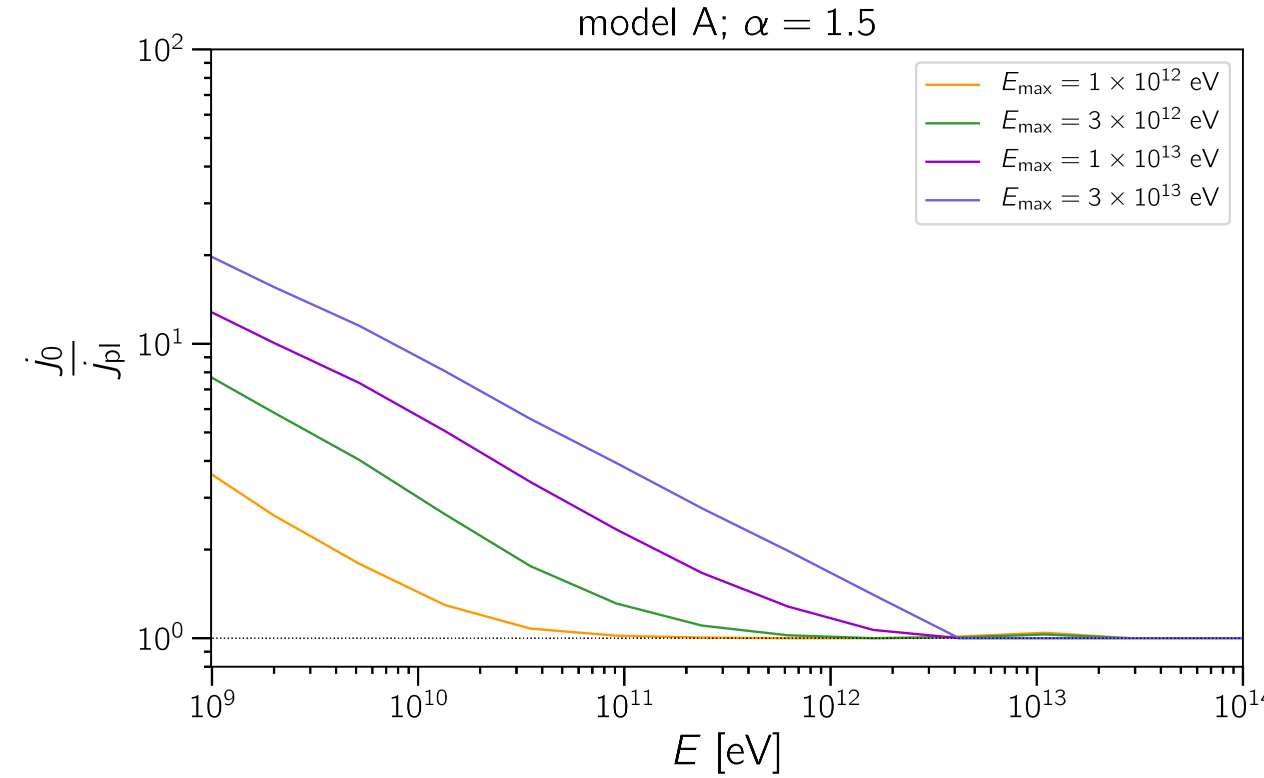

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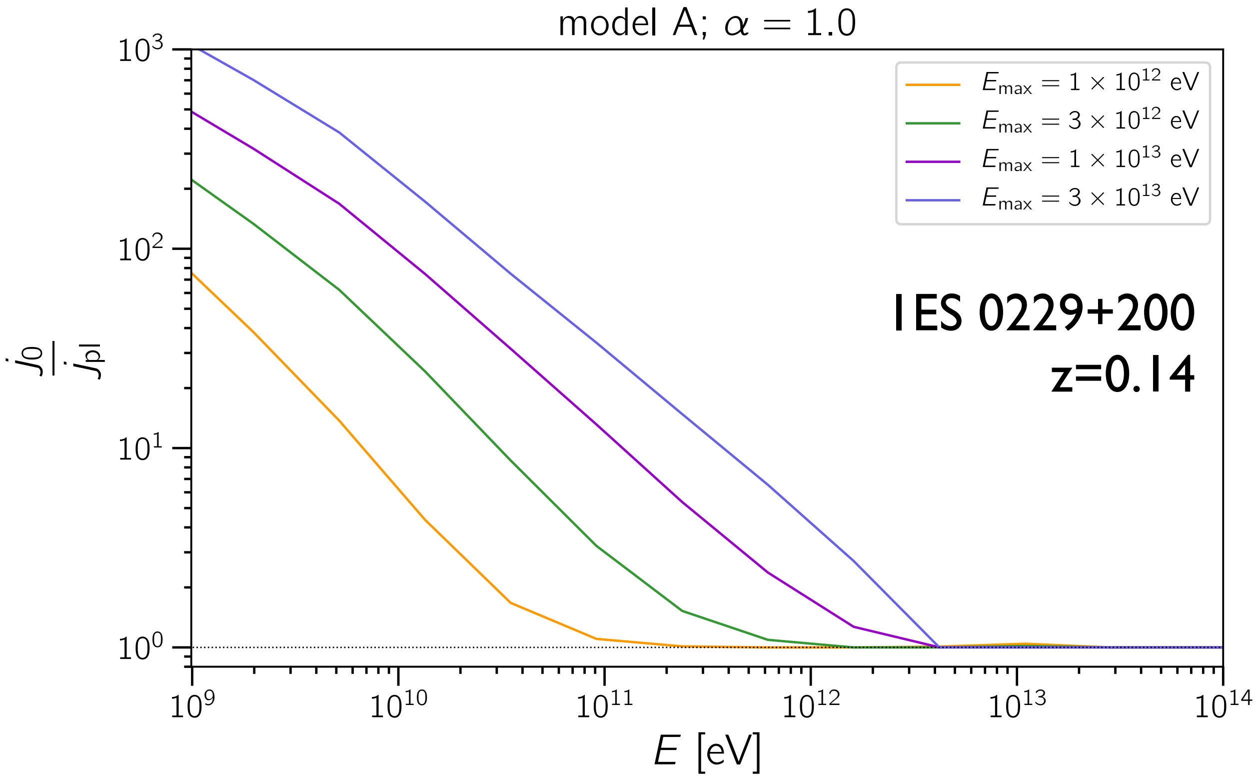

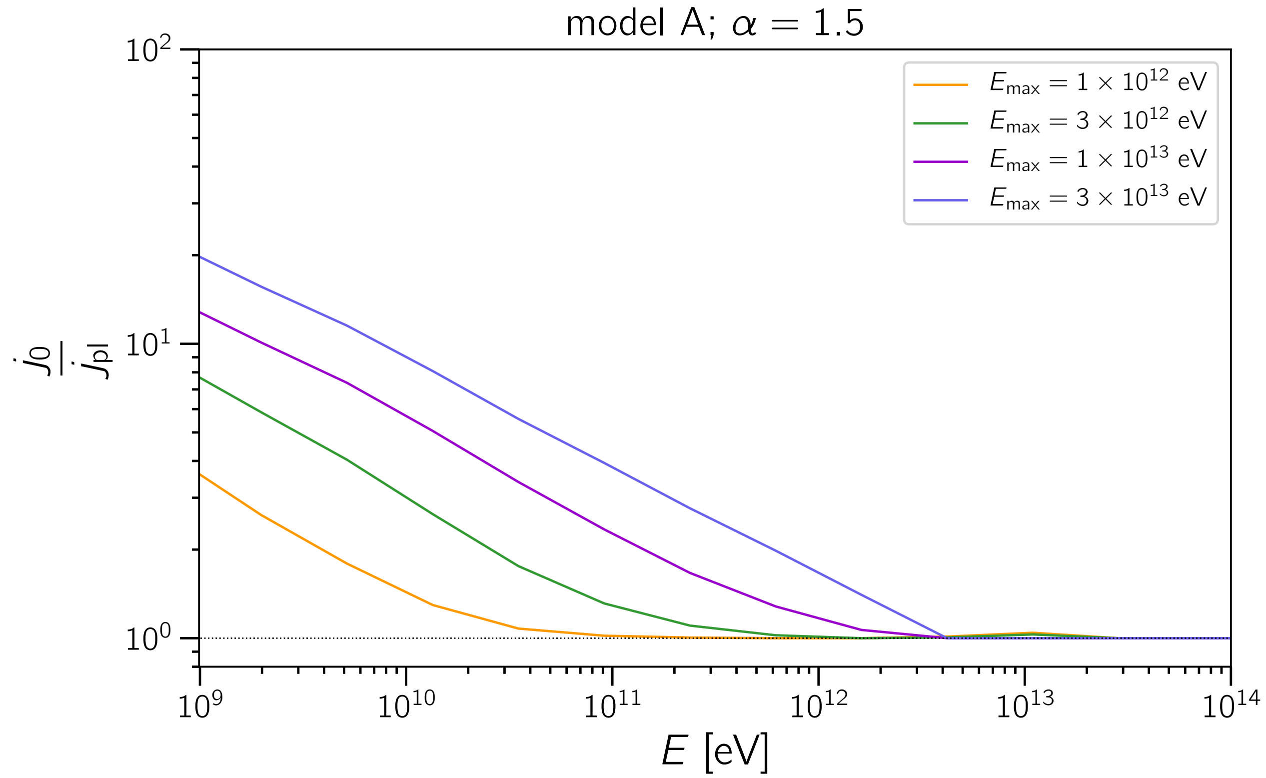

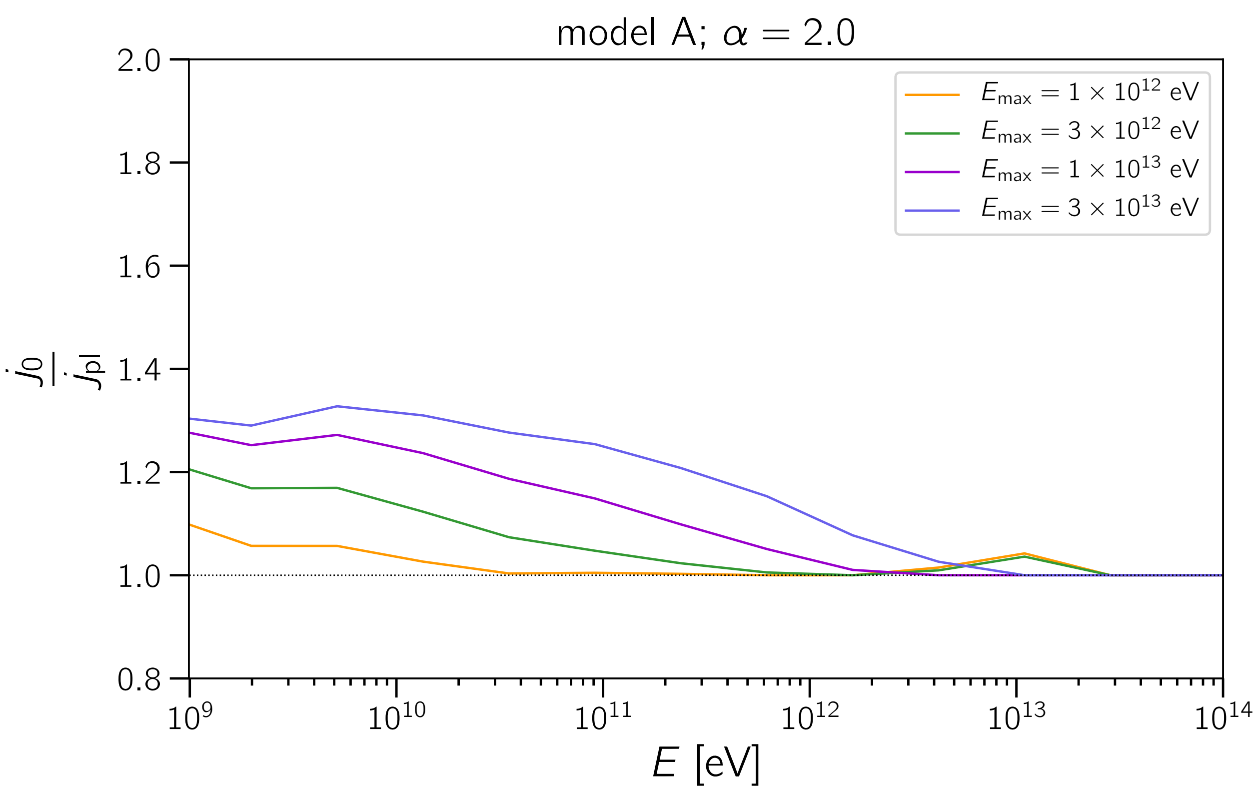

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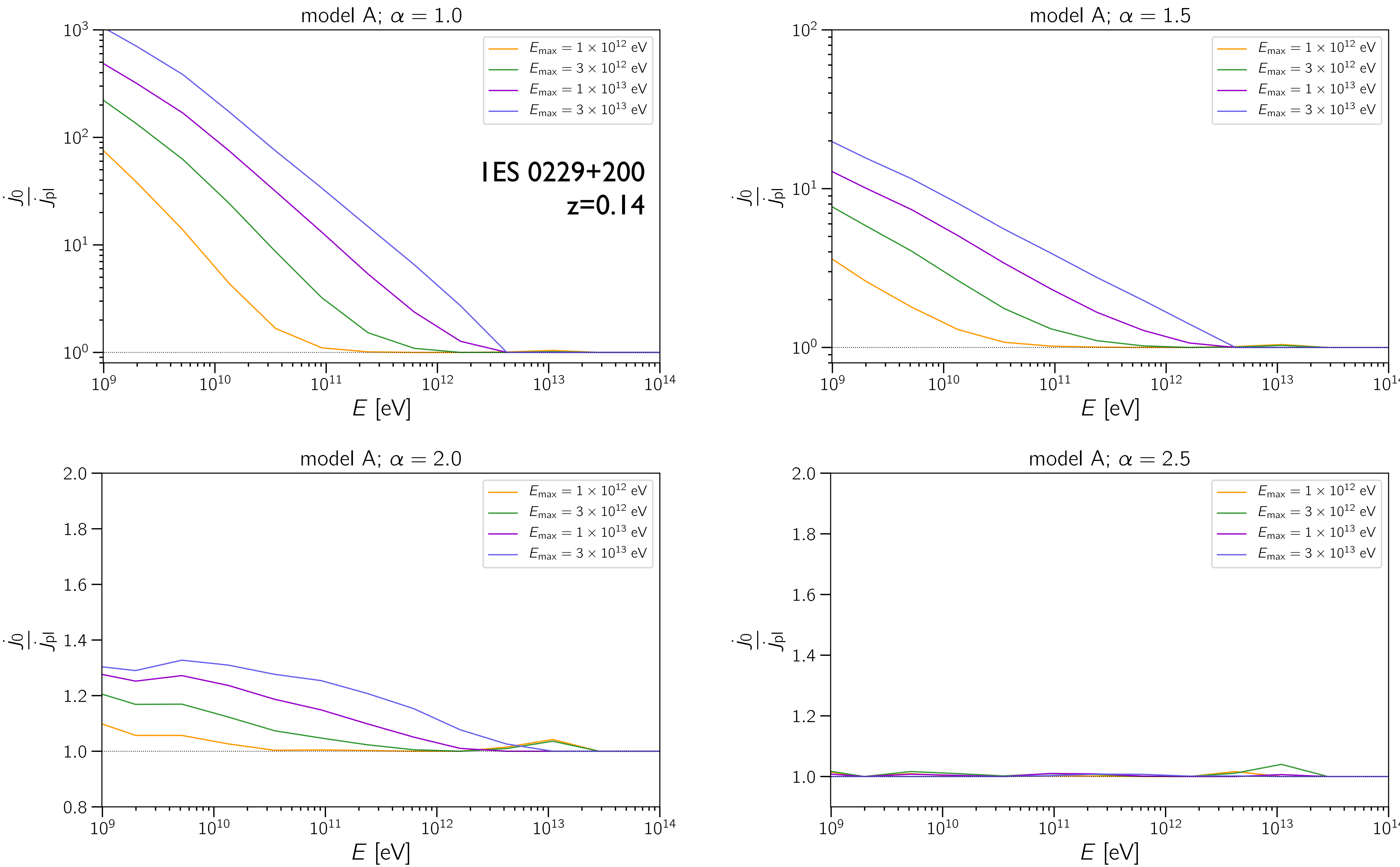

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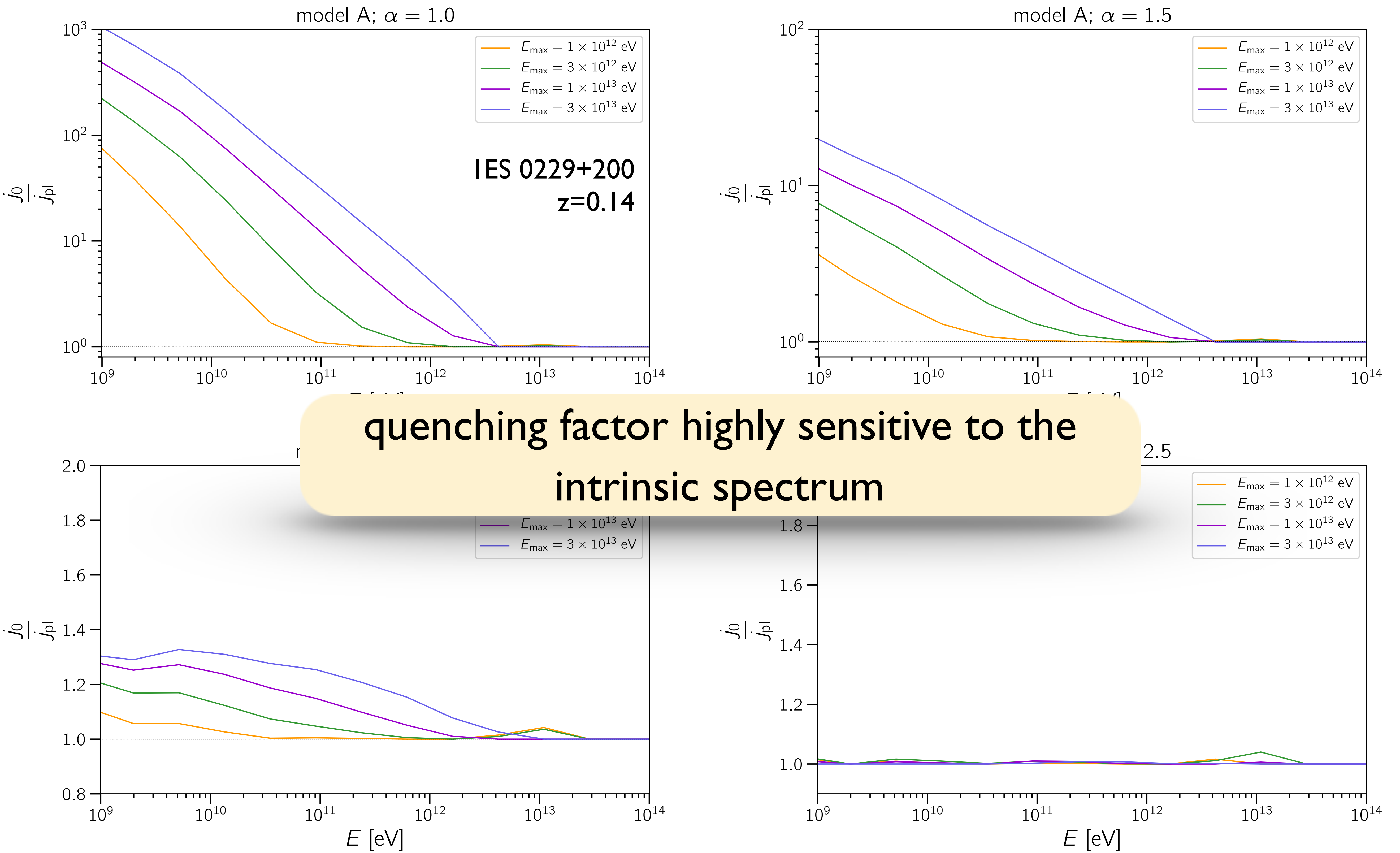
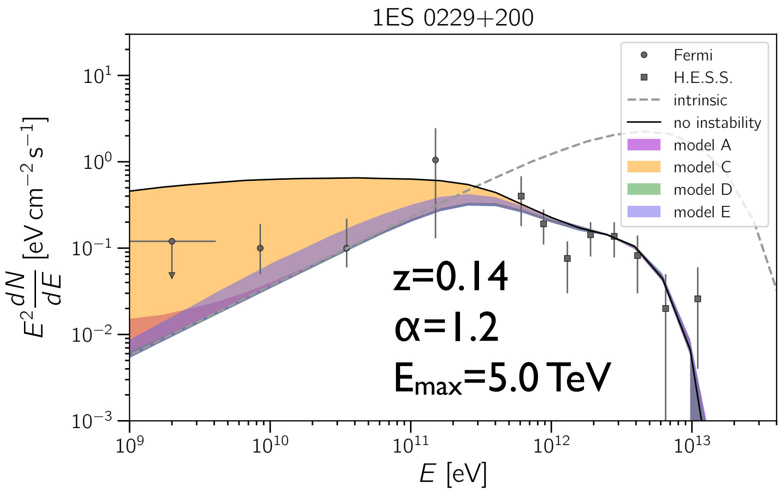
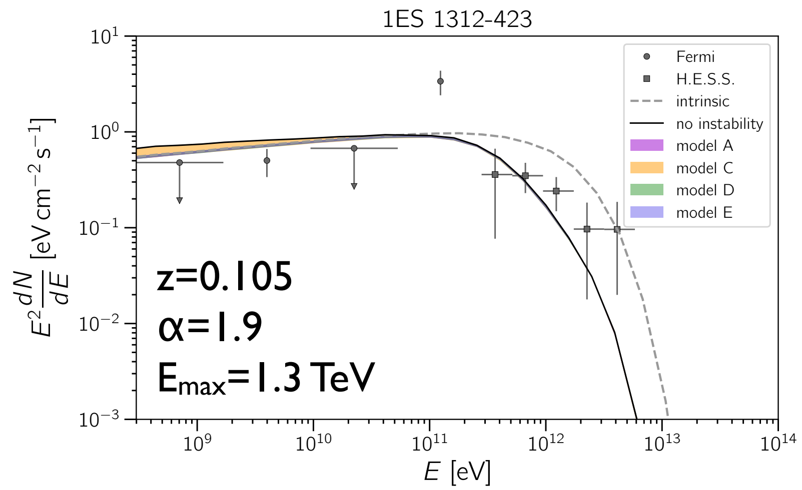


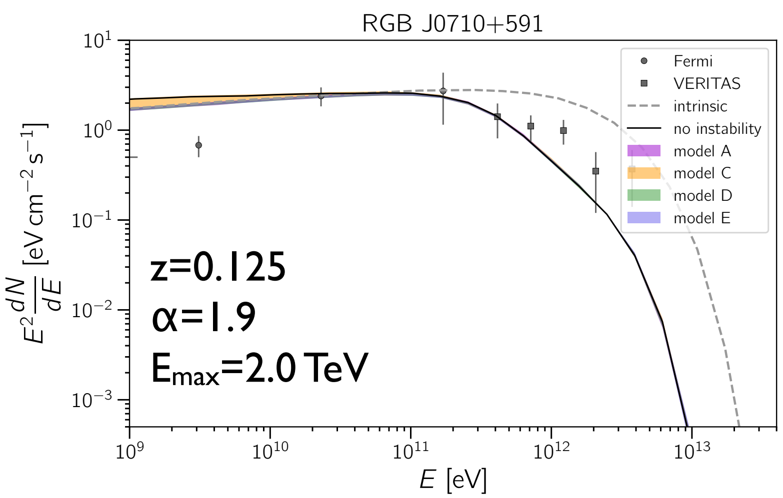
quenching factor highly sensitive to the intrinsic spectrum

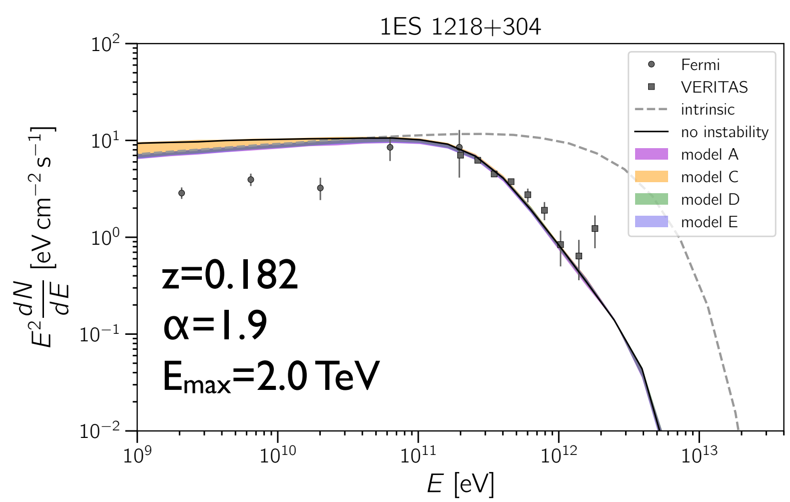
plasma instabilities

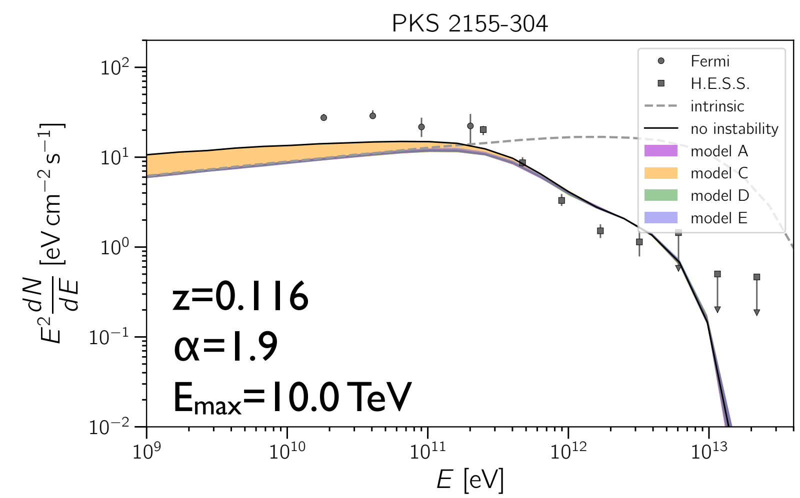
Alves Batista, Saveliev, de Gouveia Dal Pino. arXiv:1904.13345

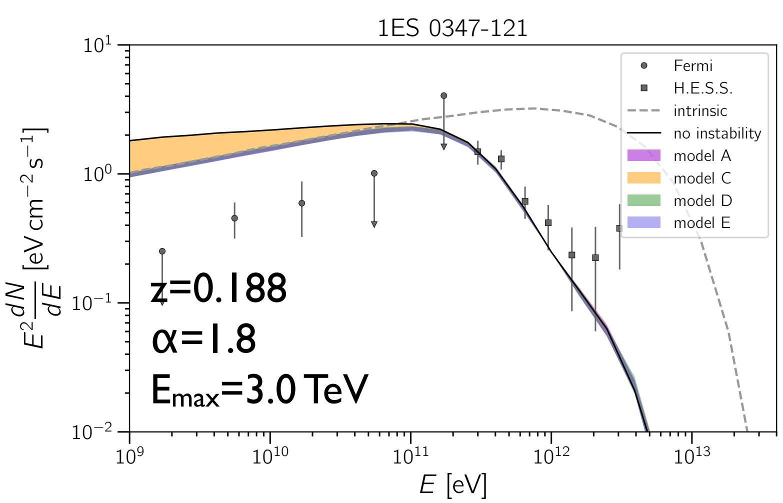


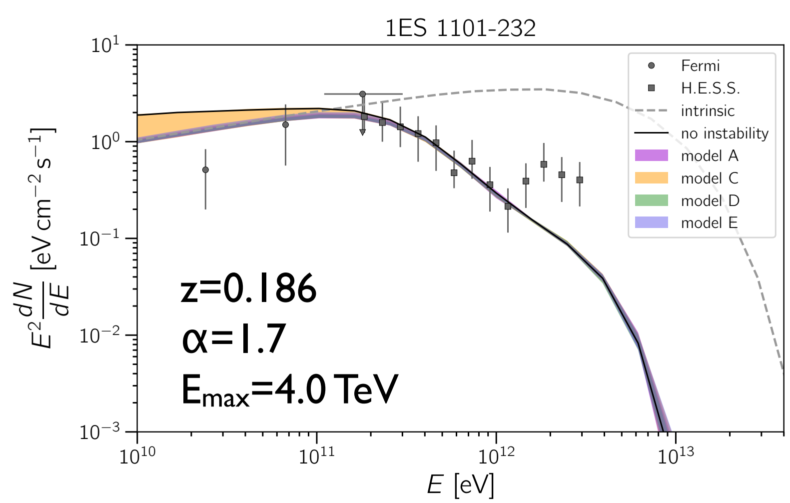


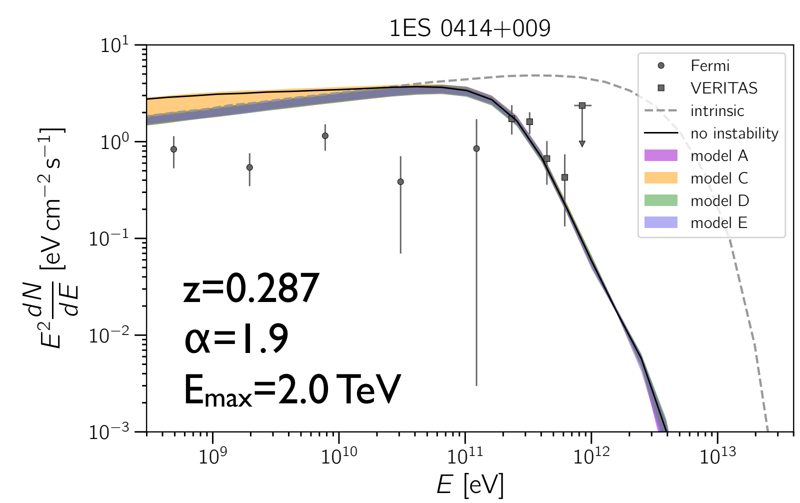






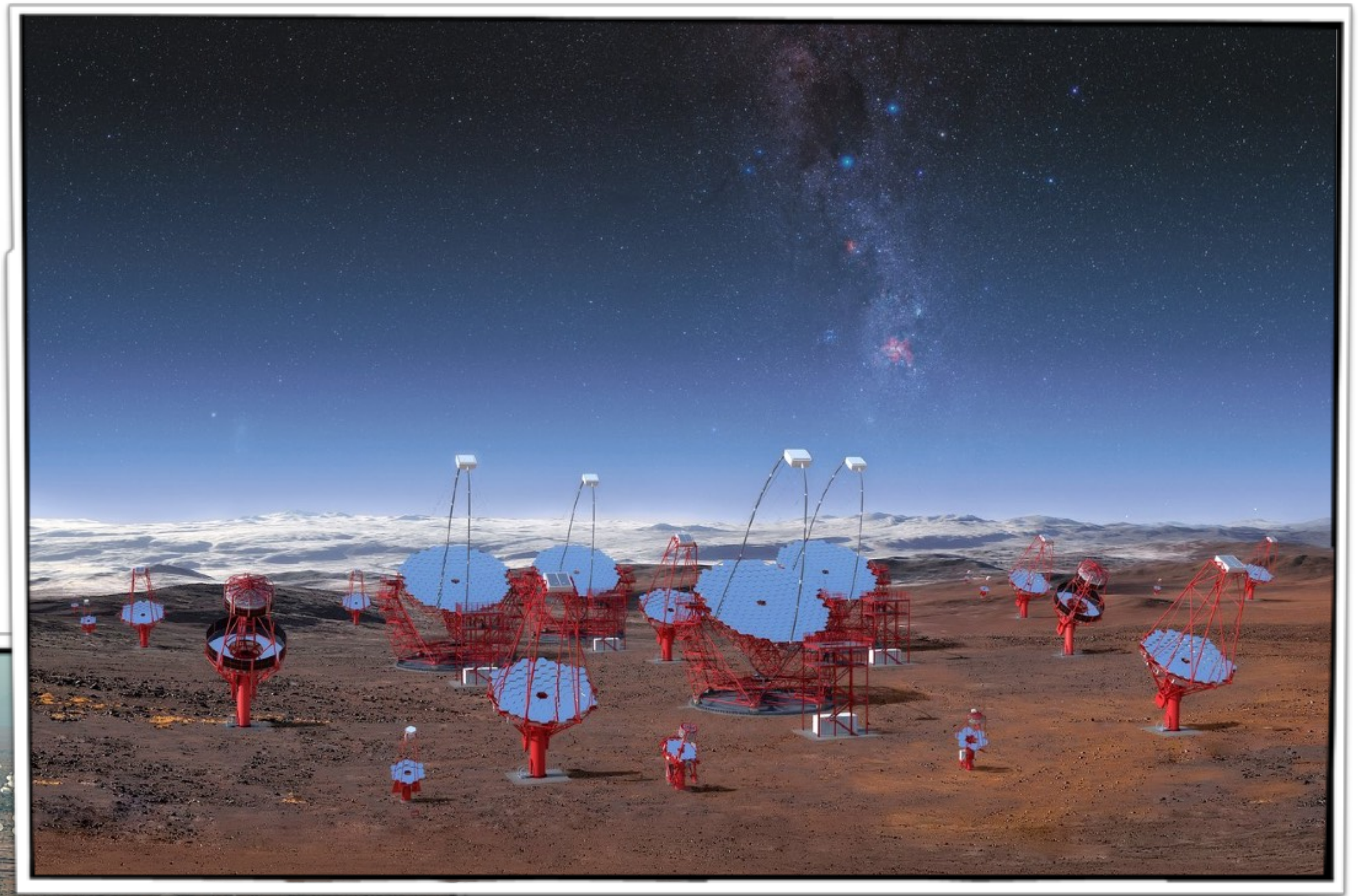






future experiments

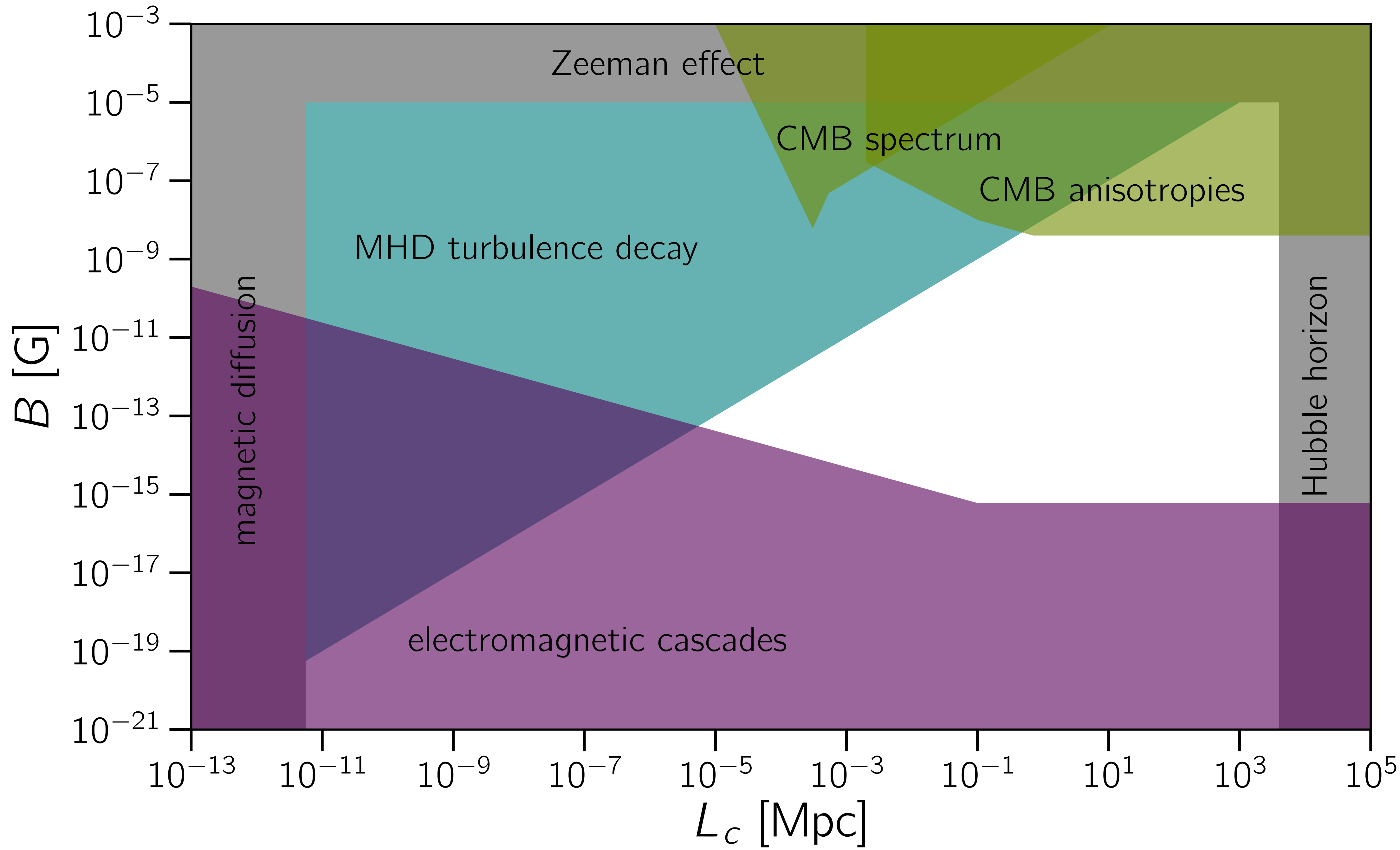
cta cherenkov telescope array



SKA SQUARE KILOMETRE ARRAY

where do we stand?

where do we stand?



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- understanding the EBL in detail is essential to model the propagation of VHE gamma rays
- 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

where do we stand?

- understanding the EBL in detail is essential to model the propagation of VHE gamma rays
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- 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_c

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