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magnetic horizons of ultra-high energy cosmic rays

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Particles & Nuclei International Conference
Hamburg
26/08/2014

UHECRs: open questions

- ✦ where do they come from?
- ✦ what is their chemical composition?
- ✦ what are the acceleration processes?
- ✦ is there a maximum energy that they can reach?
- ✦ can we see hint of new physics through their interaction?

diffusion of CRs in an expanding universe

Berezinsky & Gazizov ApJ 643 (2006) 8

diffusion equation

$$\frac{\partial}{\partial t}n(E,\vec{r},t) - b(E,t)\frac{\partial}{\partial E}n(E,\vec{r},t) + 3H(t)n(E,\vec{r},t) - n(E,\vec{r},t)\frac{\partial}{\partial E}b(E,t) - \frac{D(E,t)}{a^2(t)}\nabla^2 n(E,\vec{r},t) = \frac{Q(E,t)}{a^3(t)}\delta^3(\vec{r}-\vec{r_g})$$

number density

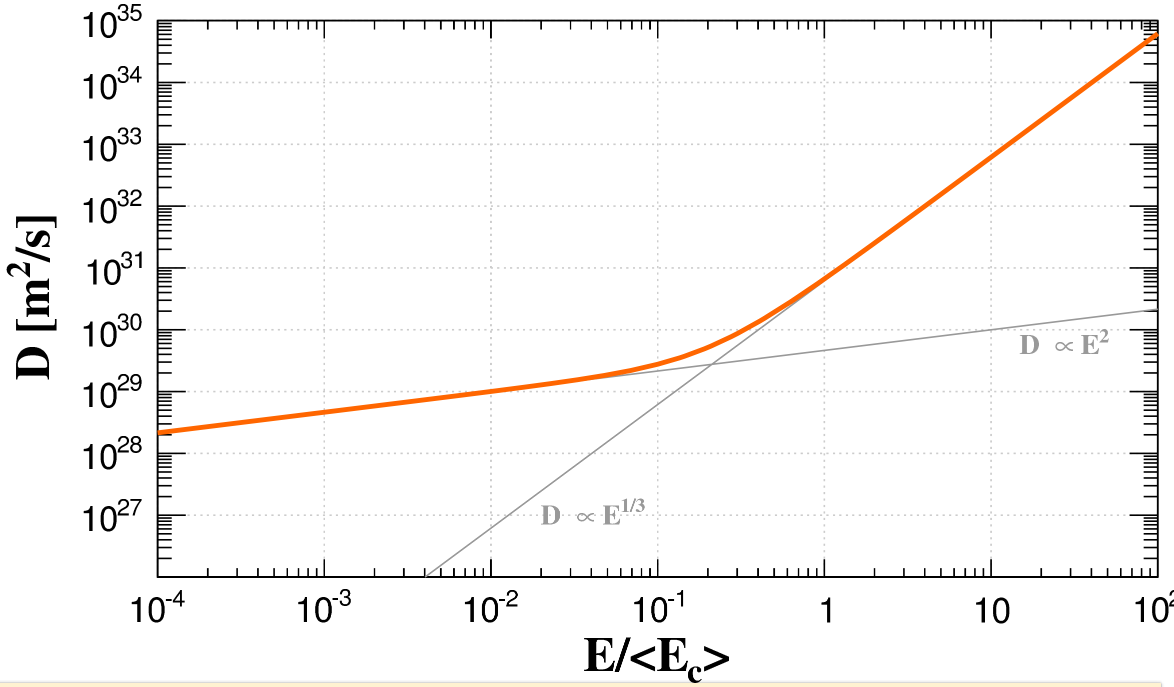
energy losses

diffusion coefficient

source term

diffusion coefficient

$$D(E,z,B) = \frac{c l_c}{3}\left[a_L\left(\frac{E}{E_c}\right)^{\frac{1}{3}} + a_H\left(\frac{E}{E_c}\right)^2\right]$$



source term

spectral index

$$Q(E,z) = \frac{\xi_Z f(z) E^{-\gamma}}{\cosh\left(\frac{E}{E_{max}}\right)}$$

- ✦ diffusion coefficient is an approximation
- ✦ ideally D is calculated from the power spectrum of a realistic magnetic field scenario
- ✦ source can also have an exponential or sharp cutoff
- ✦ Ec is the critical energy, energy at which the Larmor radius is equal to the coherence length of the magnetic field

the cosmic ray spectrum

sources spectrum

$$j_t(E,B) = \sum_{i=1}^{N_s} j_s(E) = \frac{c}{4\pi}\int_0^{z_{max}} dz \left|\frac{dt}{dz}\right| Q(E_g(E,z),z)\frac{dE_g}{dE} \overbrace{\boxed{\sum_{i=1}^{N_s}\frac{\exp\left(-\frac{r_i^2}{4\lambda^2}\right)}{(4\pi\lambda^2)^{\frac{3}{2}}}}}^{F}$$

Syrovatskii variable

energy losses

generation energy

$$\frac{dE_g}{dE} = (1+z)\exp\left(\int_0^z dz' \left|\frac{dt'}{dz'}\right| \frac{\partial}{\partial E_g} b(E_g,z')\right)$$

redshift evolution

$$\left|\frac{dt}{dz}\right| = \frac{1}{H_0(1+z)}\frac{1}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

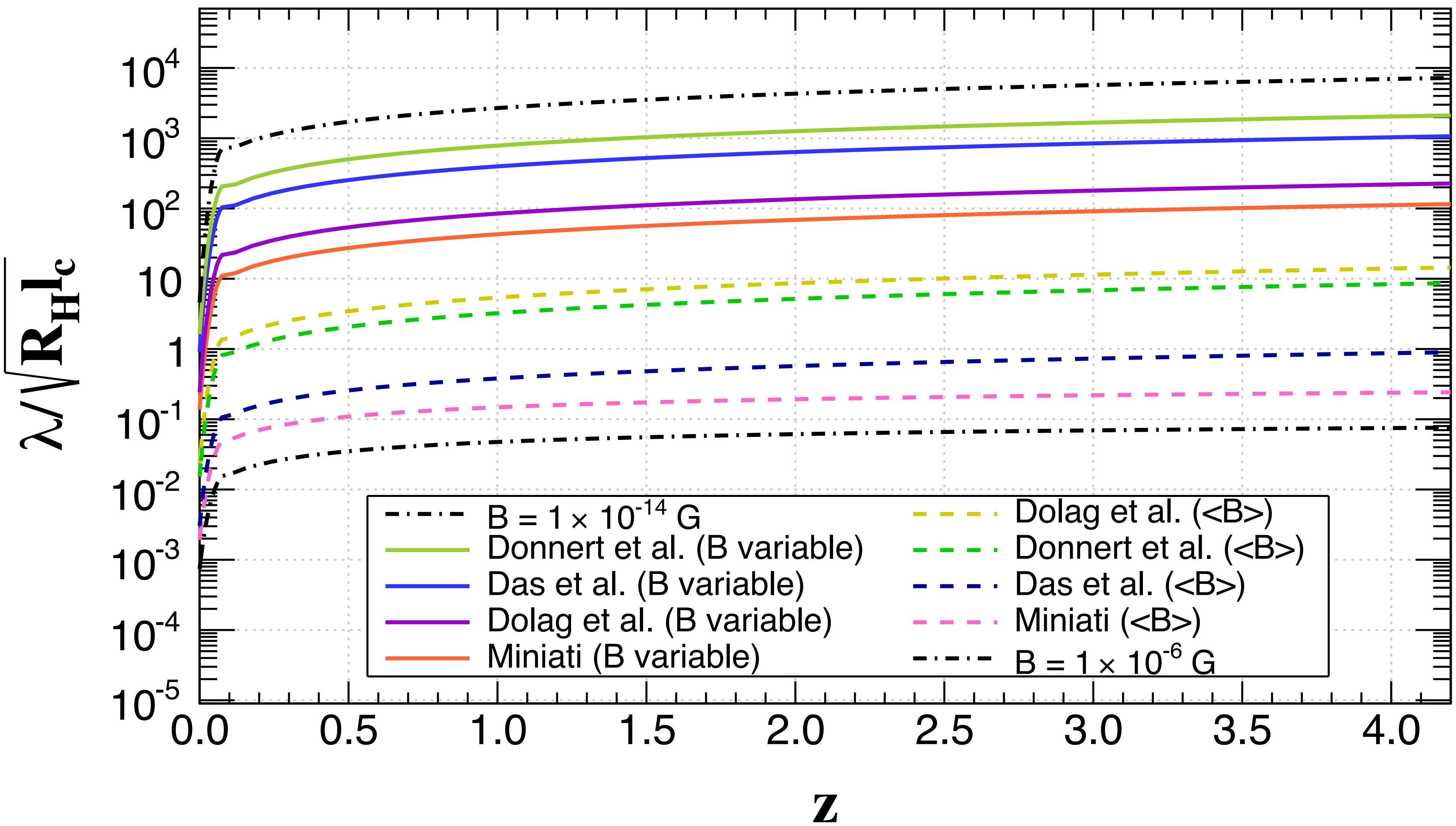
ΛCDM

Syrovatskii variable

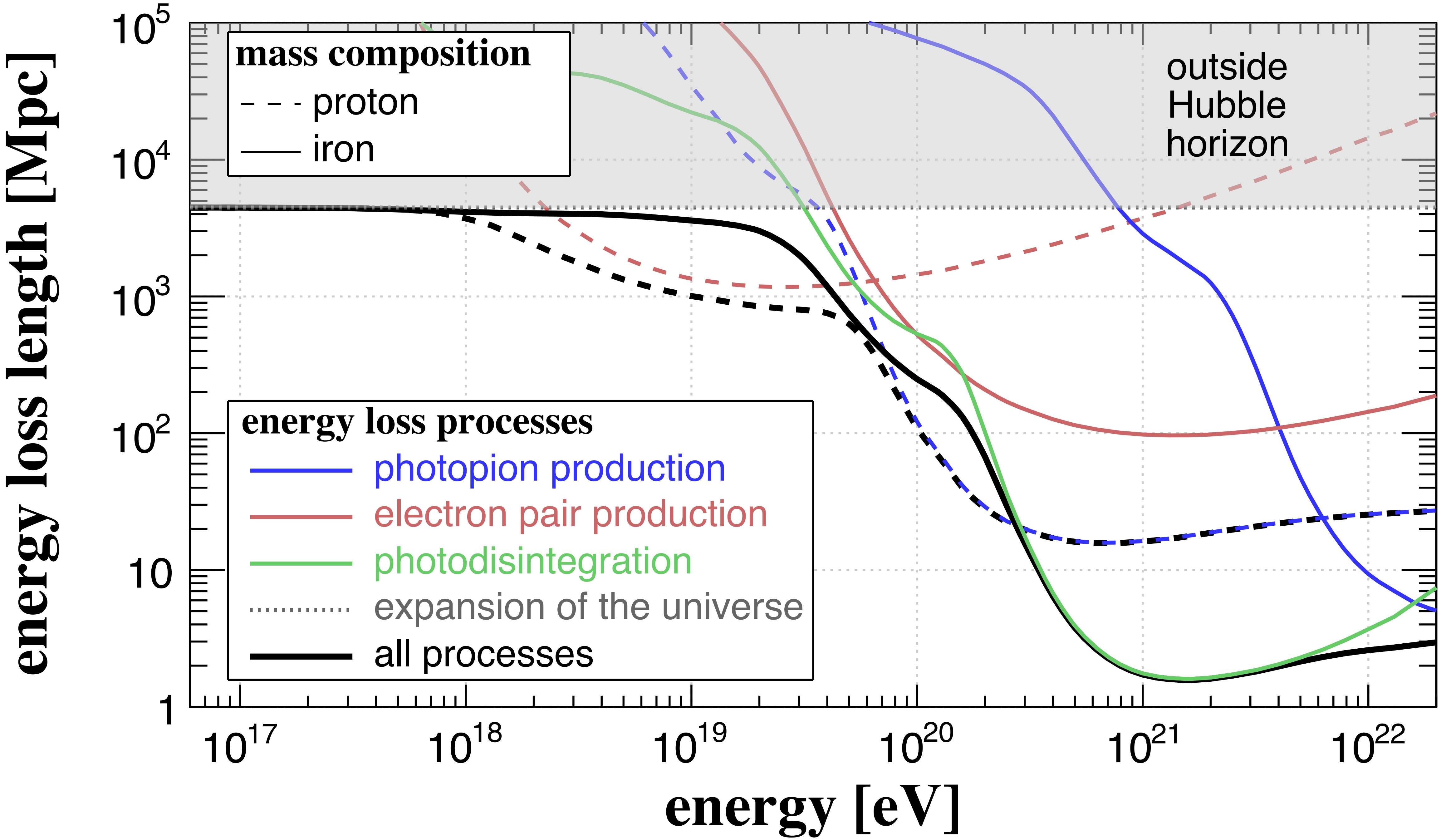
$$\lambda(E,z,B) = \sqrt{\int_0^z dz' \left|\frac{dt}{dz'}\right| \frac{D(E_g,z',B)}{a^2(z')}}$$

- ✦ spectrum depends on source distance
- ✦ the interaction term b describes all the interaction energy losses, but not adiabatic ones
- ✦ Syrovatskii variable written this way can be translated into the magnetic horizon
- ✦ if F=1 the propagation does not depend on the modes of propagation and the spectrum will be universal → propagation theorem

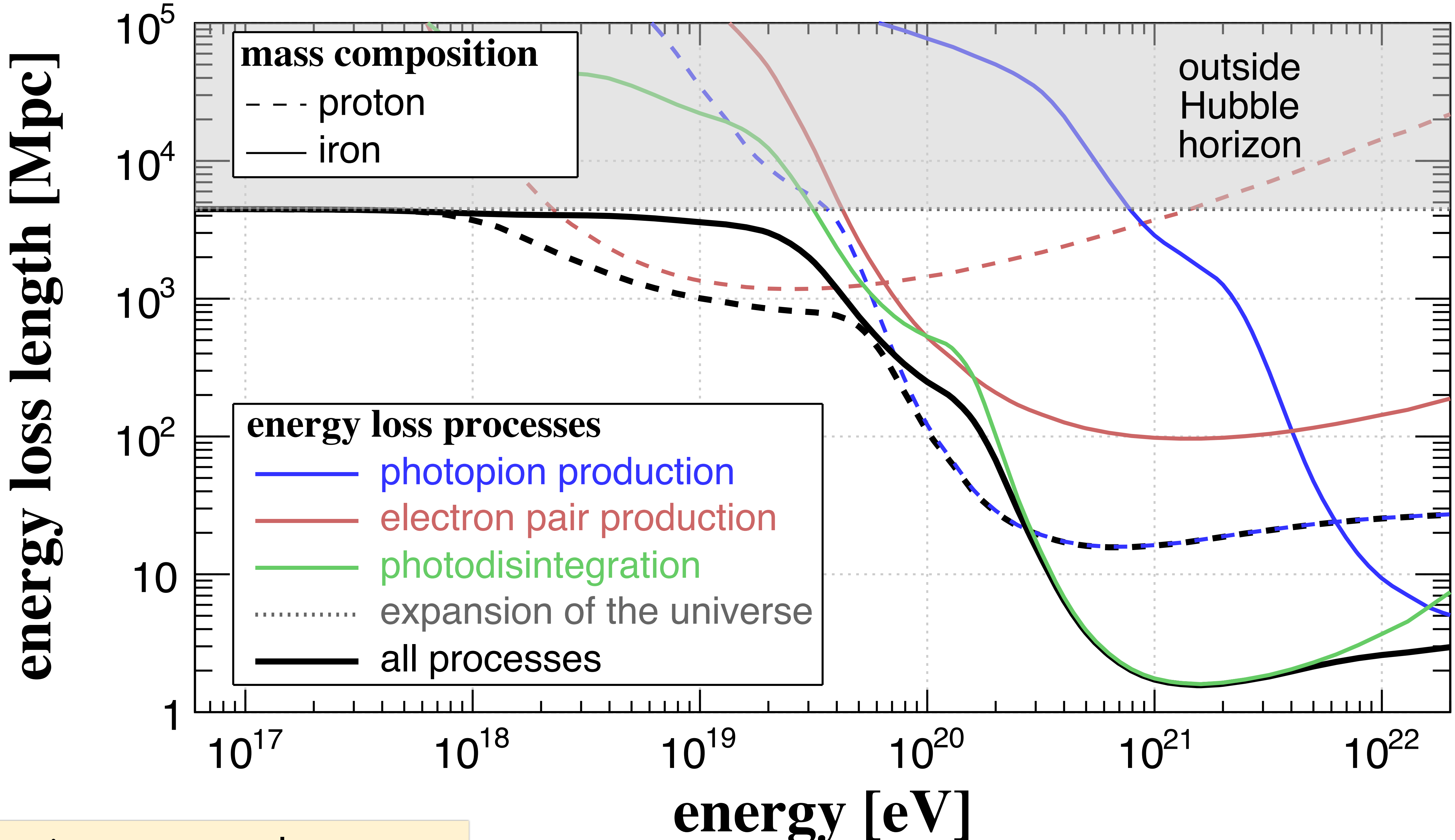
Syrovatskii variable



energy loss processes

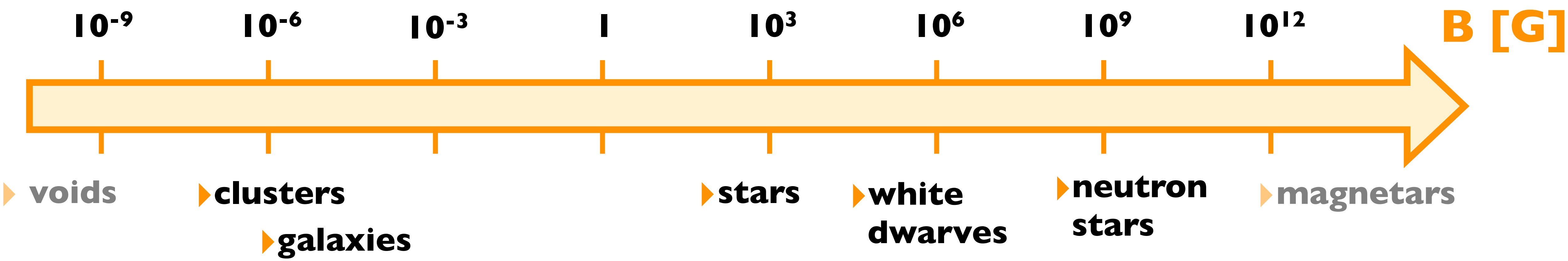


energy loss processes



interaction energy losses are small for E < Z EeV → neglected in this work

cosmic magnetic fields



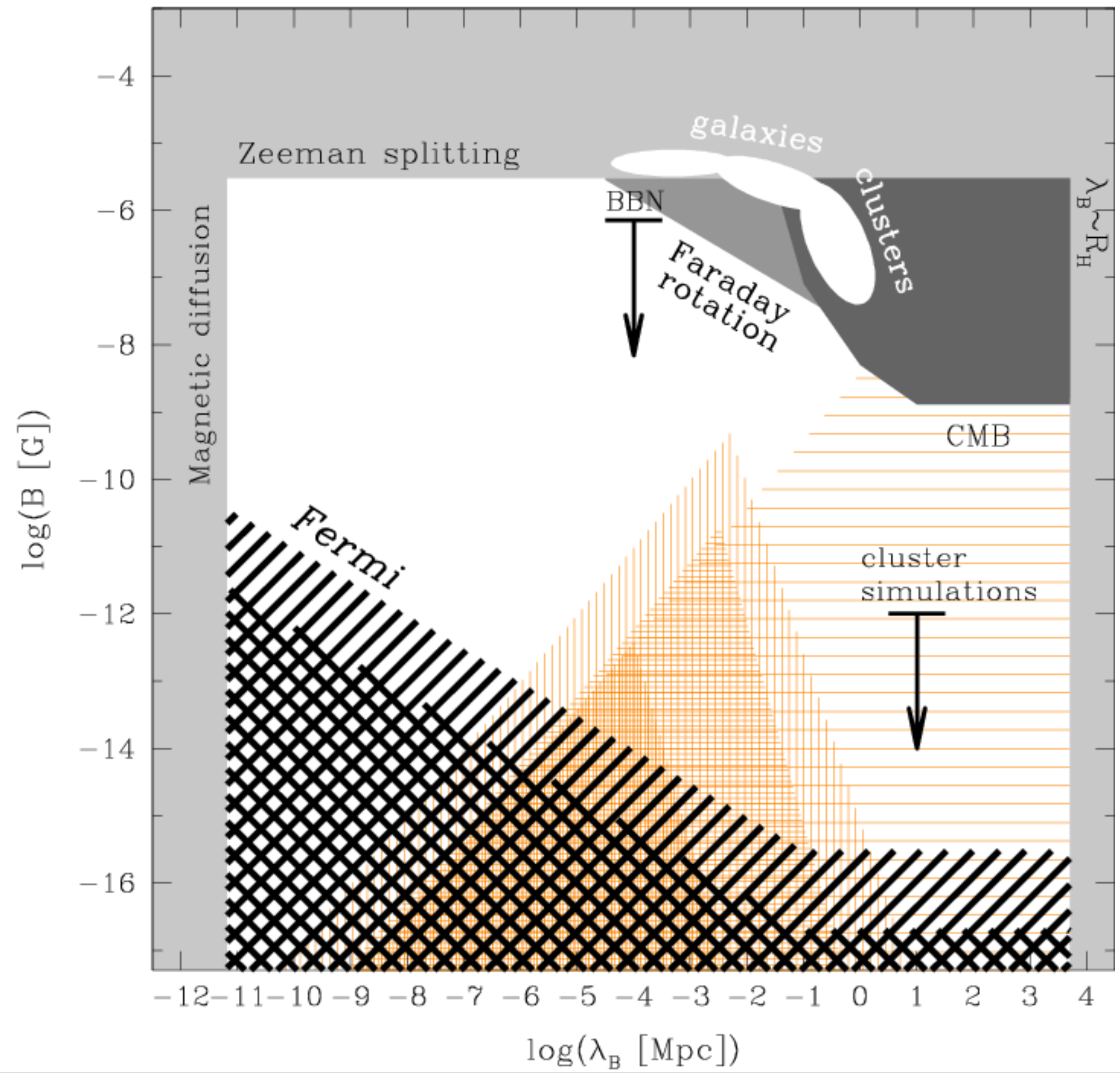
overview

✦ are there cosmological magnetic fields?

✦ how are magnetic fields created?

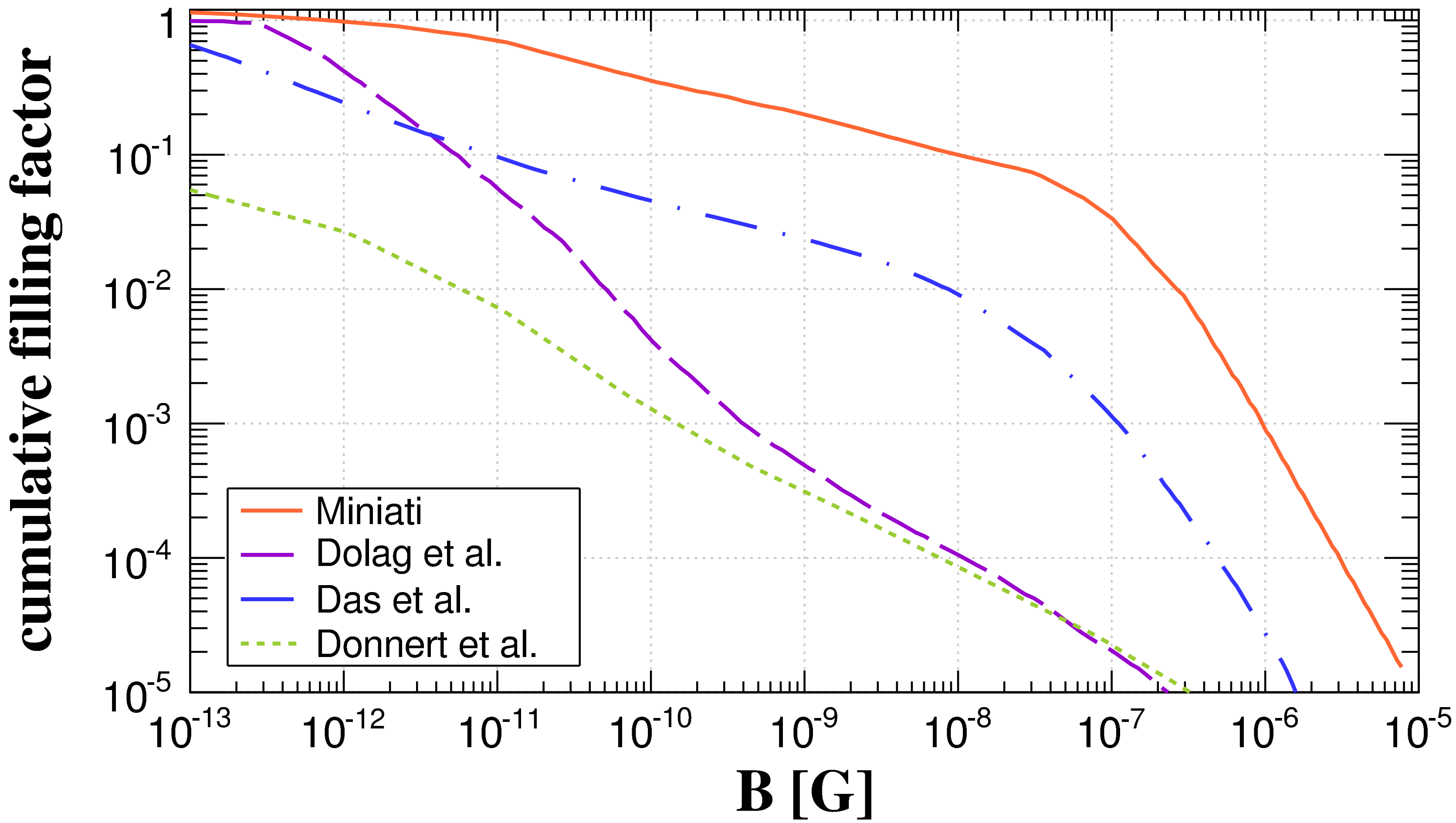
- astrophysical (Biermann battery)
- cosmological (inflation, phase transitions, etc)

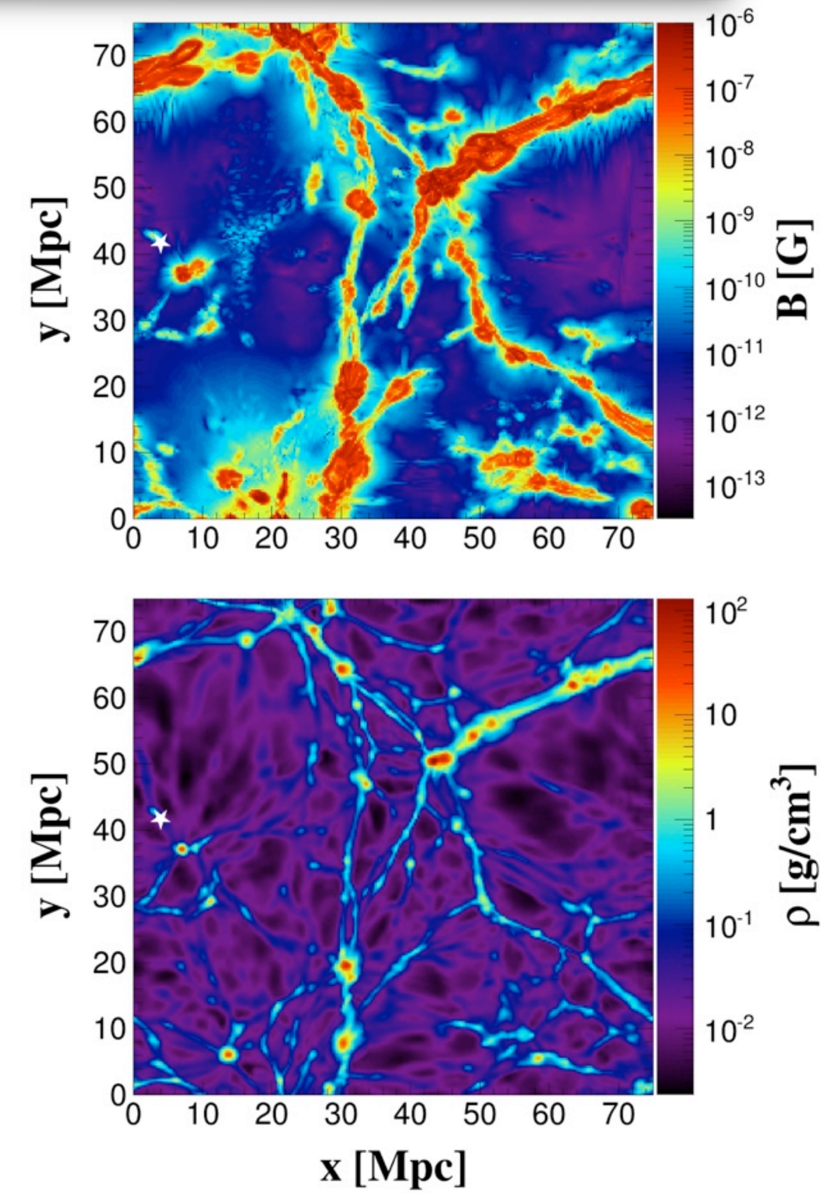
✦ lower limit: electromagnetic cascades (?)



Neronov,Vovk. Science 328 (2010) 73

cosmological simulations: magnetic fields





F. Miniati. MNRAS 337 (2002) 199

K. Dolag *et al.* JCAP 01 (2005) 09

S. Das *et al.* ApJ 682 (2008) 29

Donnert *et al.* MNRAS 392 (2009) 1008

	Miniati	Dolag et al.	Das et al.	Donnert et al.
<B> [G]	1.8×10^{-8}	5.5×10^{-11}	1.2×10^{-9}	6.3×10^{-11}
B_{rms} [G]	1.7×10^{-7}	1.5×10^{-8}	5.7×10^{-8}	1.7×10^{-8}

magnetic suppression

suppression factor

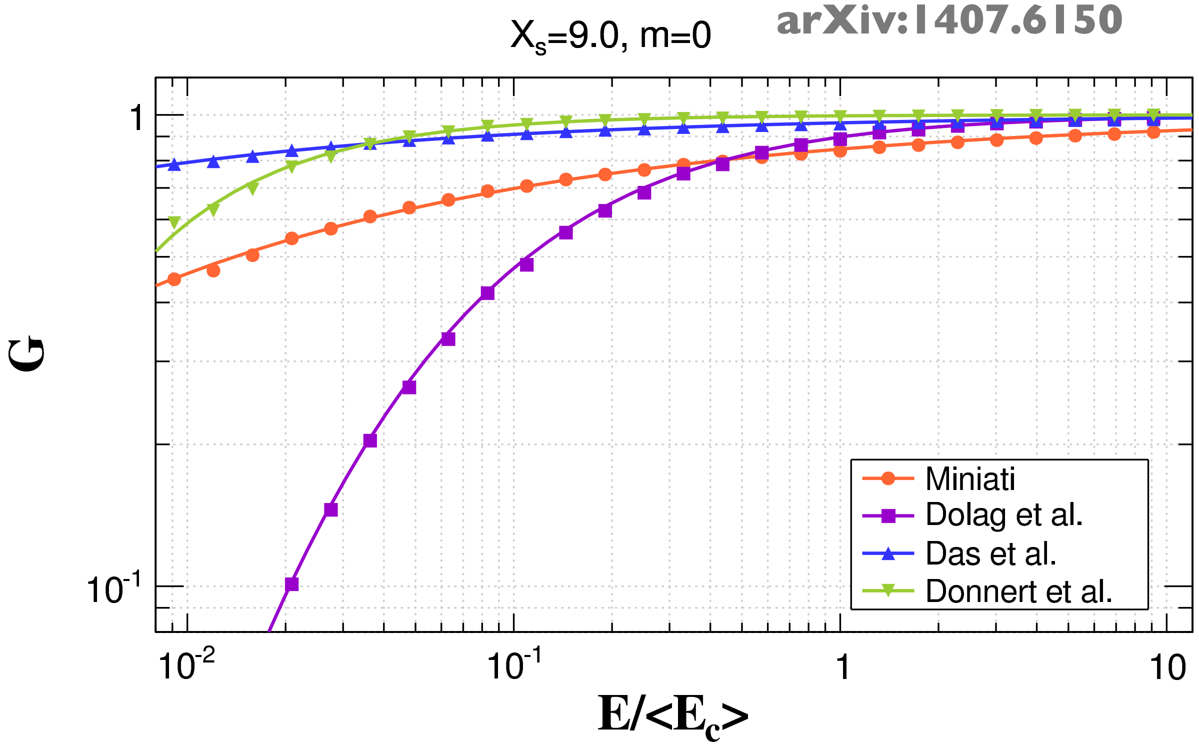
$$G(x) = \frac{j(E)}{j_0(E)} = \exp\left[-\frac{(aX_s)^\alpha}{x^\alpha + bx^\beta}\right]$$

Mollerach & Roulet
JCAP 10 (2013) 013

critical energy

$$E_c(z,B) = cZeB(z)l_c(z) \approx 0.9Z\left(\frac{B}{\mathrm{nG}}\right)\left(\frac{l_c}{\mathrm{Mpc}}\right)\ \mathrm{EeV}$$

RAB & Sigl.
arXiv:1407.6150



- ✦ expression to "fit" magnetic suppression at "lower" energies first used by Mollerach & Roulet
- ✦ propagation time of cosmic rays comparable to the Hubble radius
- ✦ α, β, a and b are taken from the best fit of G

magnetic suppression

suppression factor

$$G(x) = \frac{j(E)}{j_0(E)} = \exp\left[-\frac{(aX_s)^\alpha}{x^\alpha + bx^\beta}\right]$$

universal spectrum

$$X_s = \frac{d_s}{\sqrt{R_H l_c}}$$

$$x \equiv \frac{E}{\langle E_c \rangle}$$

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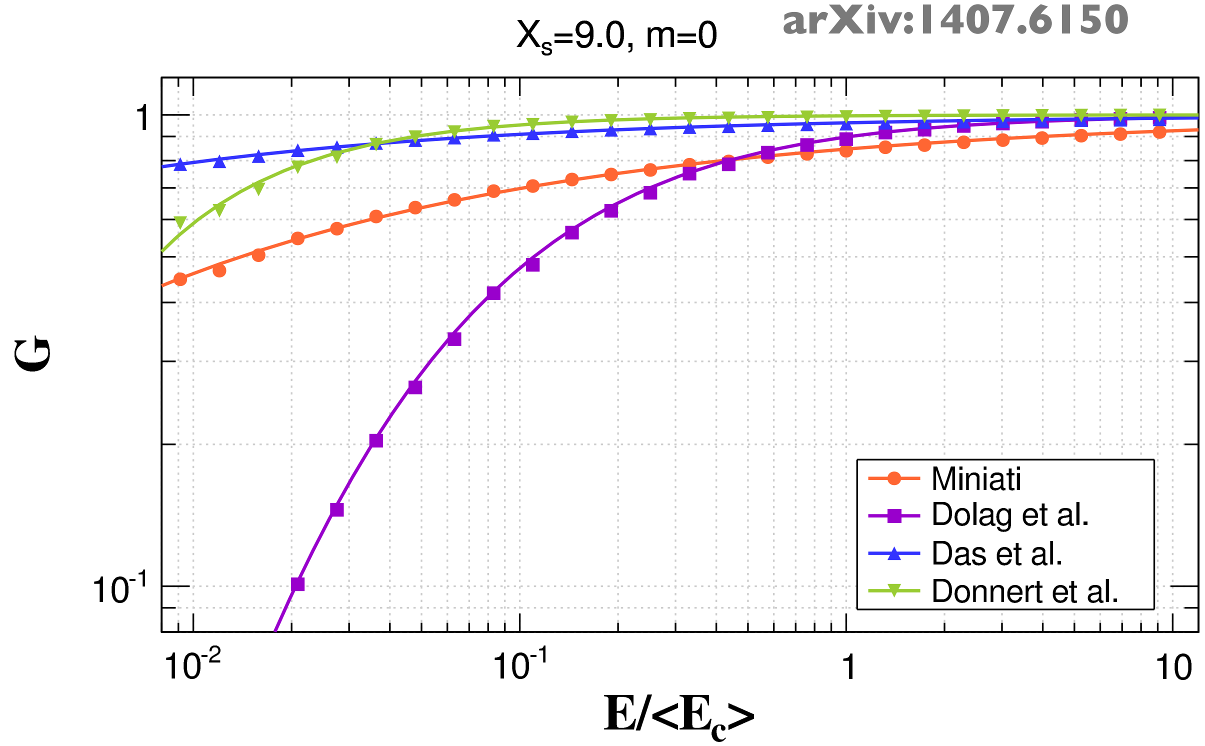

magnetic suppression

suppression factor

$$G(x) = \frac{j(E)}{j_0(E)} = \exp\left[-\frac{(aX_s)^\alpha}{x^\alpha + bx^\beta}\right] \qquad X_s = \frac{d_s}{\sqrt{R_H l_c}}$$

universal spectrum

$$x \equiv \frac{E}{\langle E_c \rangle}$$

average source separation

coherence length of the field

Mollerach & Roulet
JCAP 10 (2013) 013

critical energy

$$E_c(z,B) = cZeB(z)l_c(z) \approx 0.9Z \left(\frac{B}{\mathrm{nG}}\right)\left(\frac{l_c}{\mathrm{Mpc}}\right)\ \mathrm{EeV}$$

RAB & Sigl.
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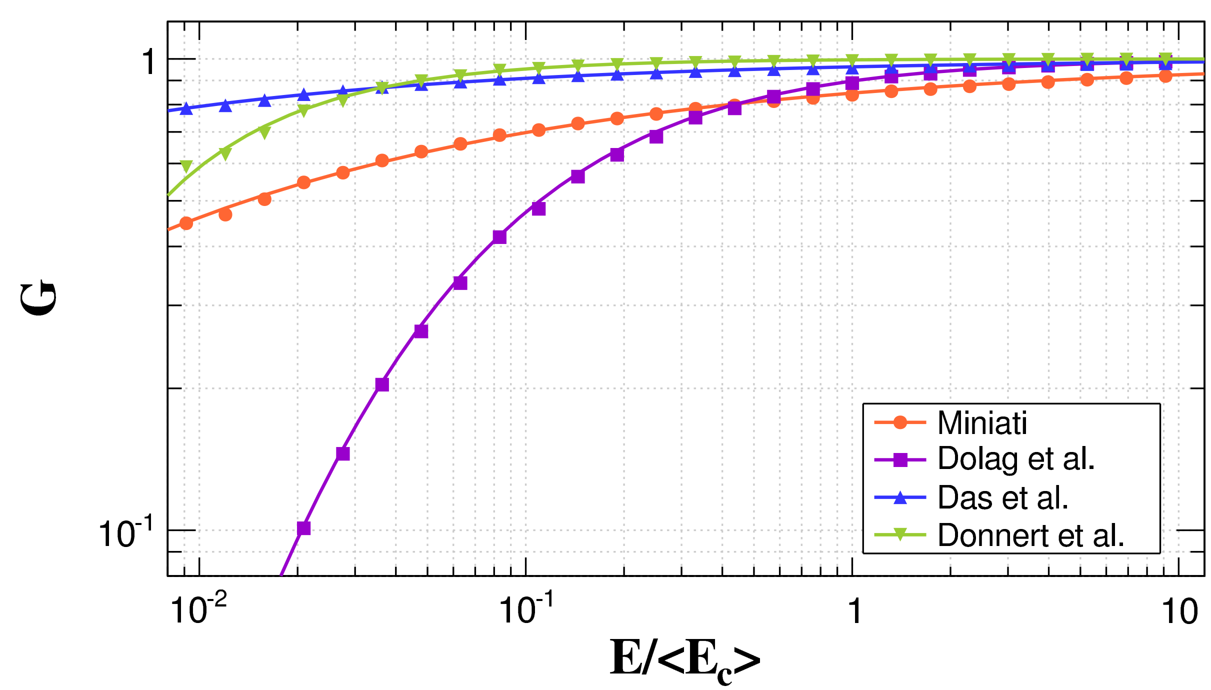
X_s=9.0, m=0



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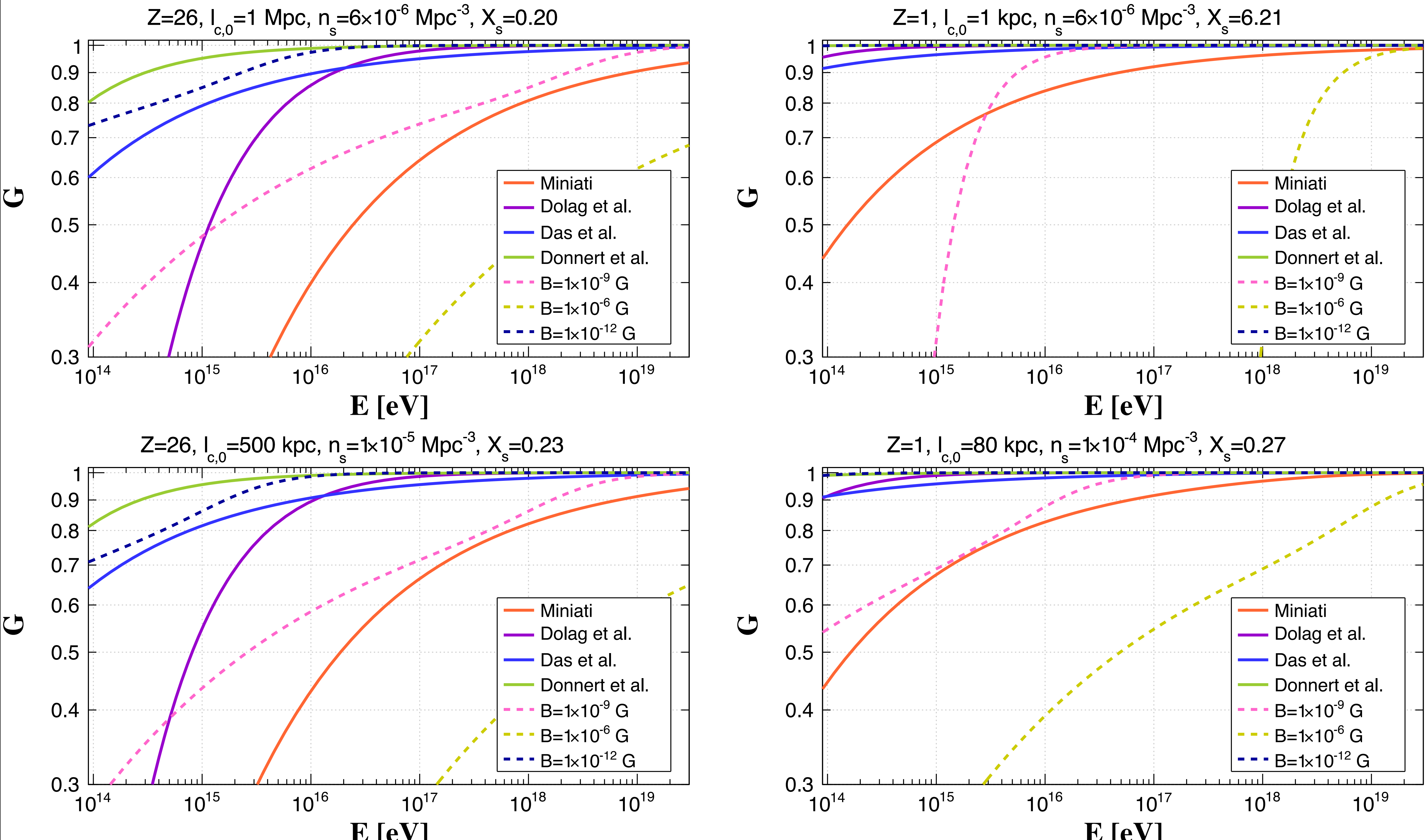
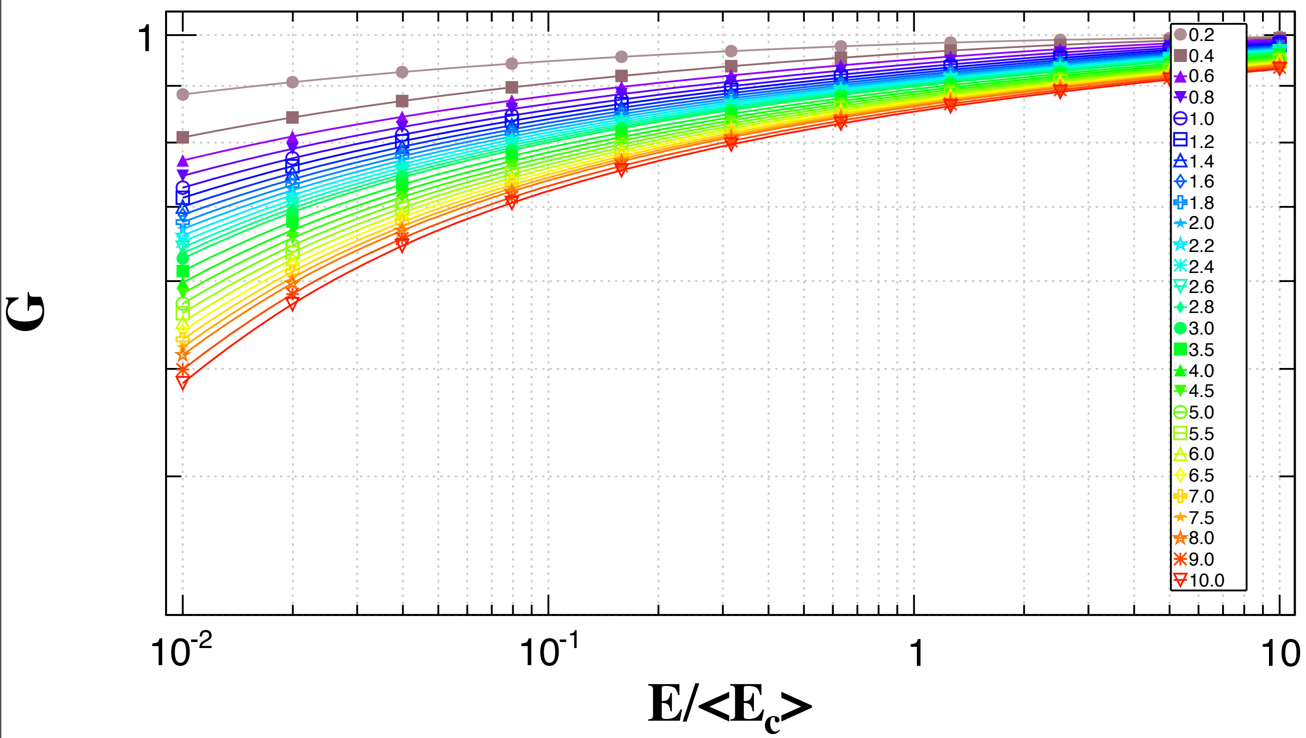
magnetic suppression: examples

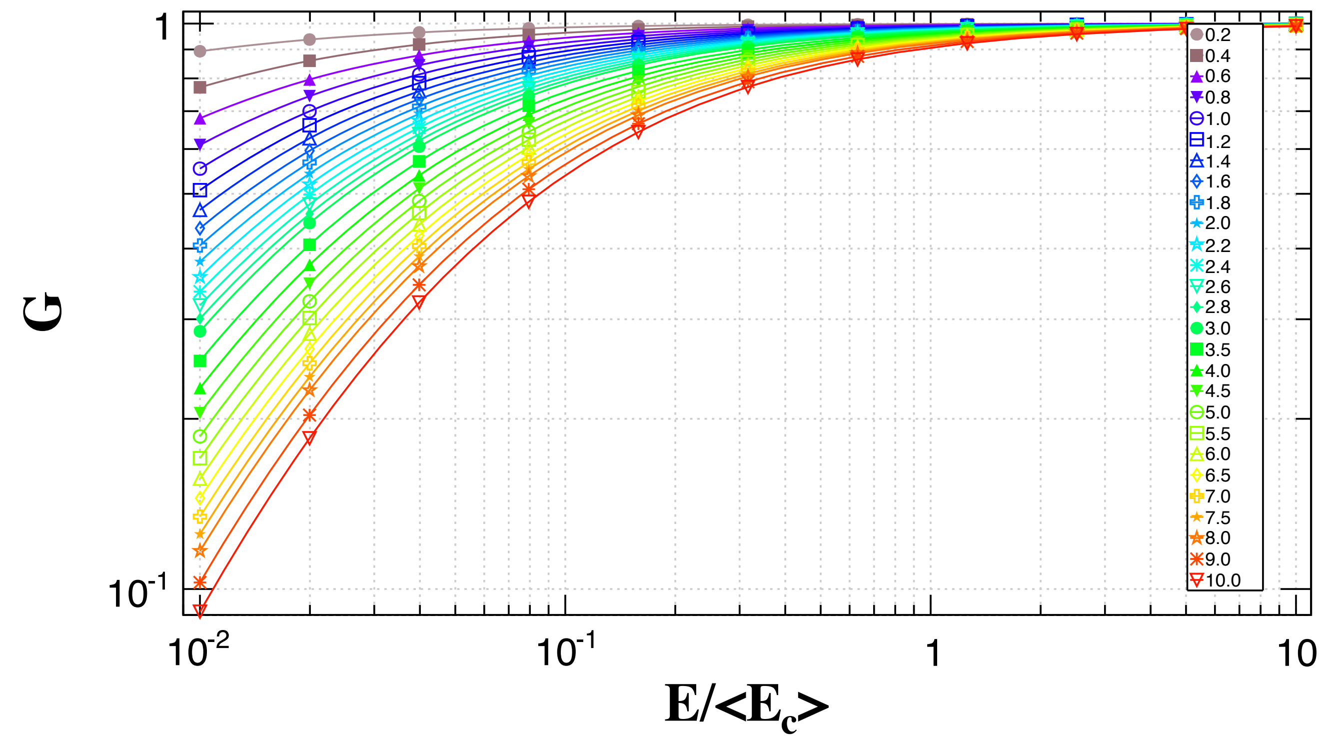


magnetic suppression: examples

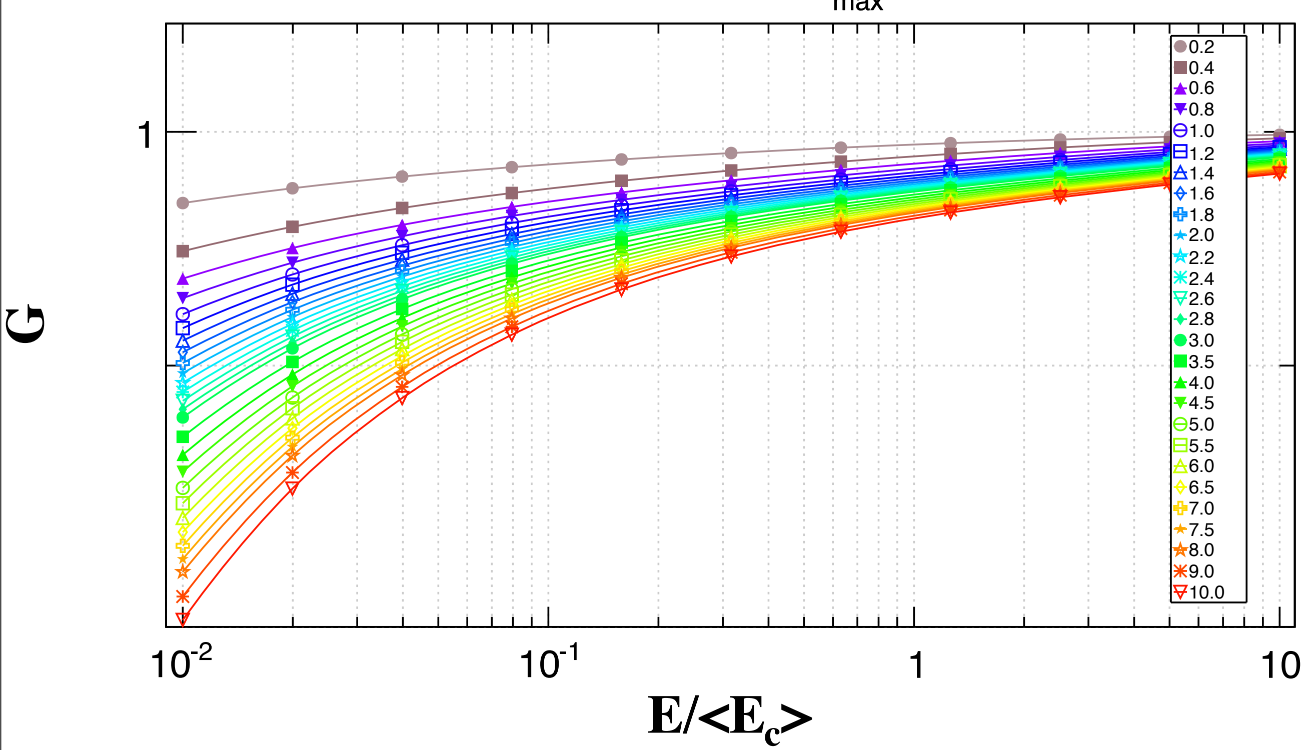
Miniati - m=1, γ=2.0, z_{max}=4.0



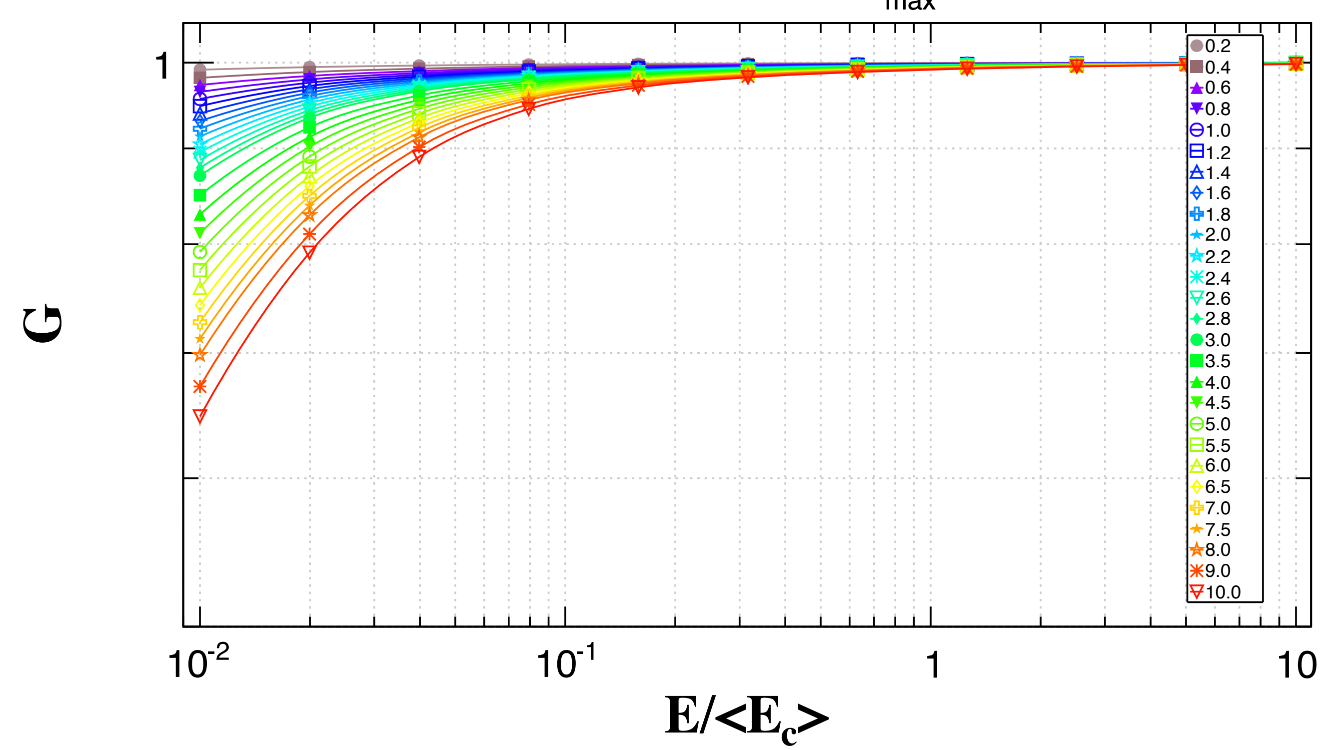
Dolag et al. - m=1, γ=2.0, z_{max}=4.0



Das et al. - m=1, γ=2.0, z_{max}=4.0



Donnert et al. - m=1, γ=2.0, z_{max}=4.0



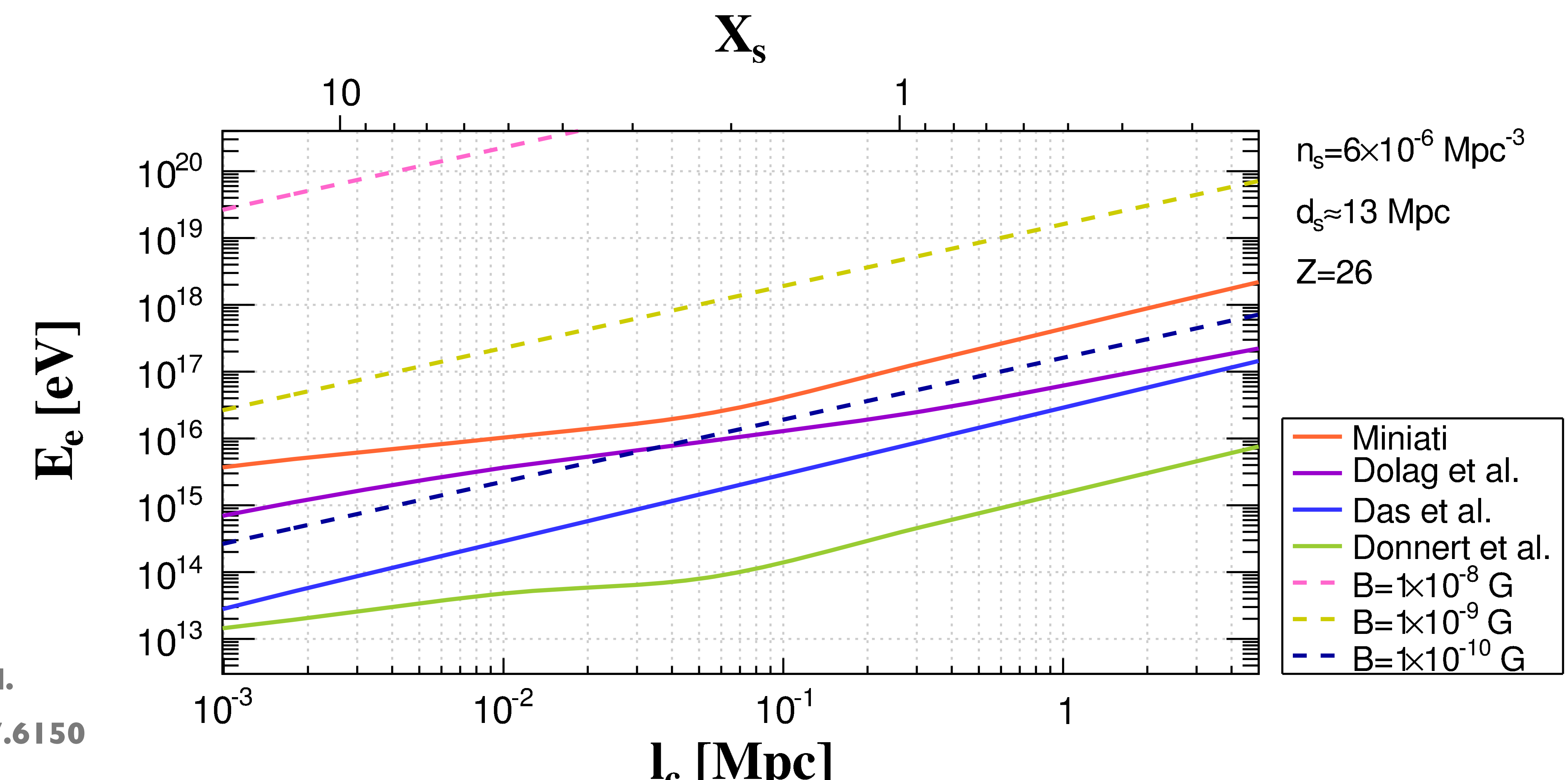
magnetic suppression: upper limit

✦ $G(E_e)$ = 1/e : suppression of the flux to 1/e of its former value

$$E_e^{\alpha} + bE_e^{\beta}\langle E_{c,0}\rangle^{\alpha-\beta} = (aX_s\langle E_{c,0}\rangle)^{\alpha}$$

✦ suppression start to become pronounced for E<10^{17} eV for heavy nuclei

✦ extragalactic CR spectrum extends to lower energies → dominate by contribution of other source populations



RAB & Sigl.
arXiv:1407.6150

the “hard spectra problem”

✦ combined spectrum-composition fits of Auger data suggest hard spectral index ($\gamma < 2$) (Taylor ’13, Aloisio+ ’13)

✦ this problem, obviously, does not exist when fitting TA data since the composition is compatible with protons

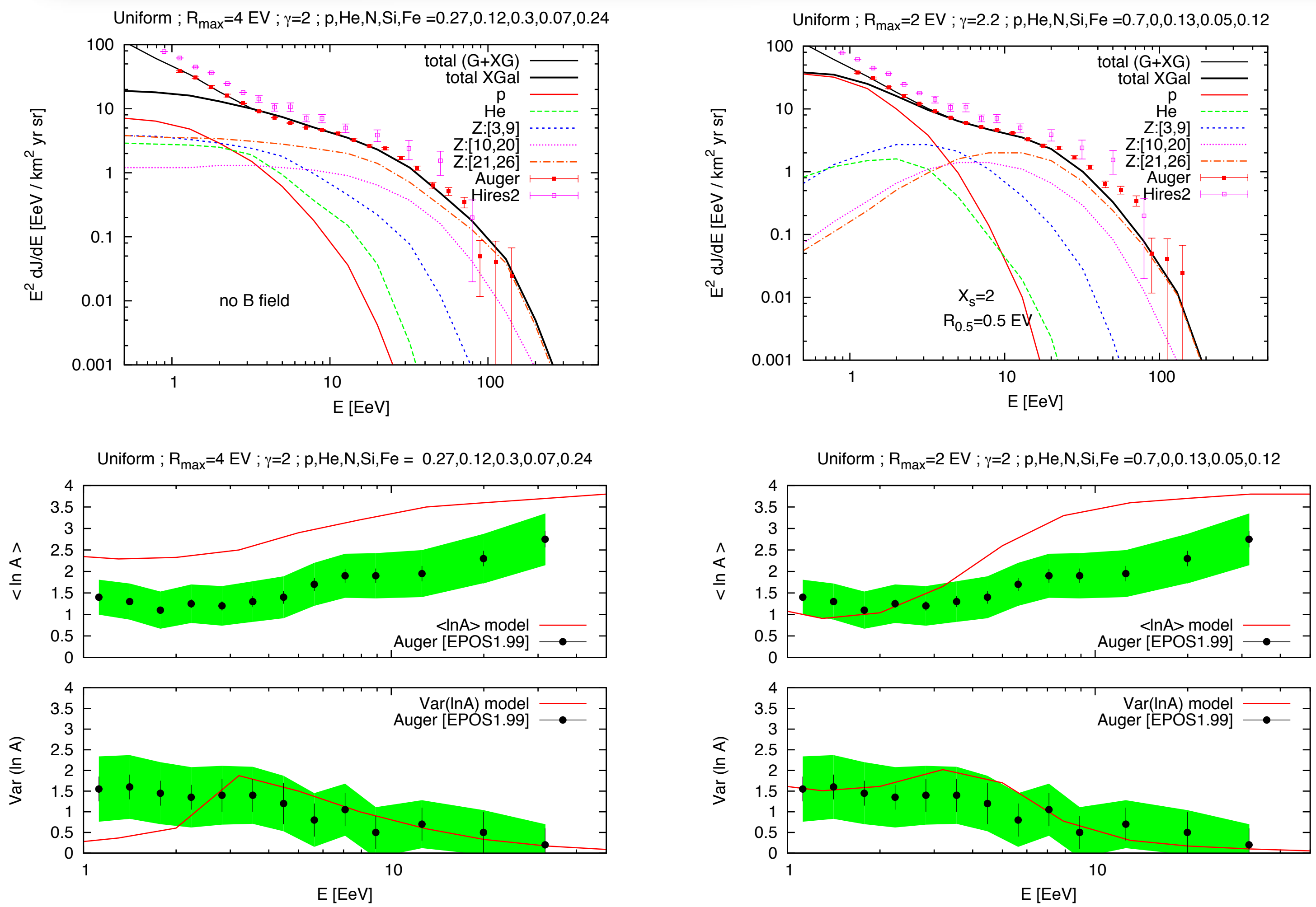
✦ standard shock acceleration mechanism → $\gamma \approx 2$

✦ hard spectral indexes are compatible with acceleration by magnetars (Arons ’03), young pulsars (Fang+ ’12), ...

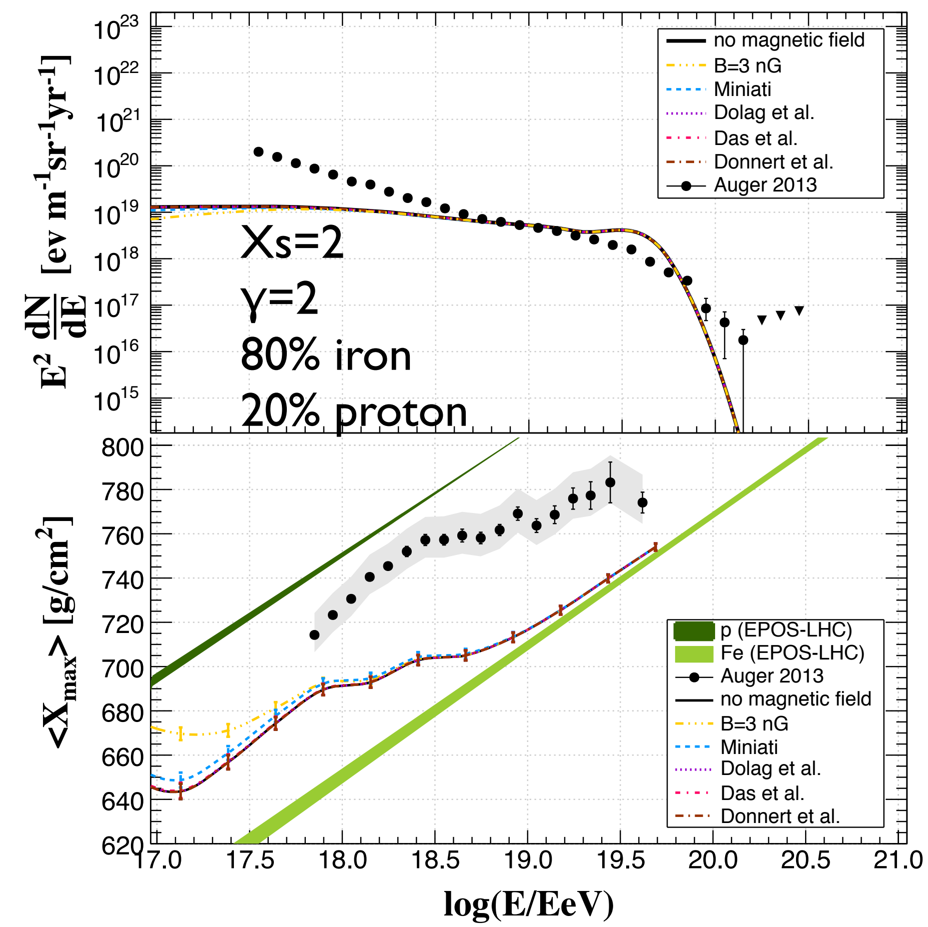
✦ lower energy magnetic suppression (Lemoine ’05, Aloisio & Berezinsky ’05)→ hard spectral indexes not needed (Mollerach & Roulet ’13)

✦ if this suppression sets in below 10^{18} eV hard spectral indexes are still needed

the “hard spectra problem”



Mollerach & Roulet JCAP 10 (2013) 013



simulations done with CRPropa 3.0

RAB *et al.* arXiv:1307.2643

- ✦ strong suppression → softer spectral indexes (compatible with Fermi acceleration)
- ✦ with realistic models of extragalactic magnetic fields → hard spectral indexes still required
- ✦ weak suppression → contribution of far away sources may be relevant below 1 EeV
- ✦ local sources may dominate → 3D simulations with full Monte Carlo approach may be needed

conclusions

✦ analytical calculation of the cosmic ray spectrum below ~ Z x 10^{18} eV considering inhomogeneous magnetic fields from cosmological simulations

✦ we have obtained a parametrization of the suppression due to the magnetic horizon of the particles assuming several models of extragalactic magnetic field

✦ the extragalactic CR spectrum extends down to low energies

✦ magnetic suppression was postulated to explain the hard spectral index problem

✦ our results indicate that in realistic magnetic field scenarios the magnetic suppression would set in at very low energies → hard spectral indexes still required

✦ caveat: effects of nearby sources → 3D simulations needed (how reliable are the models for the extragalactic magnetic field?)

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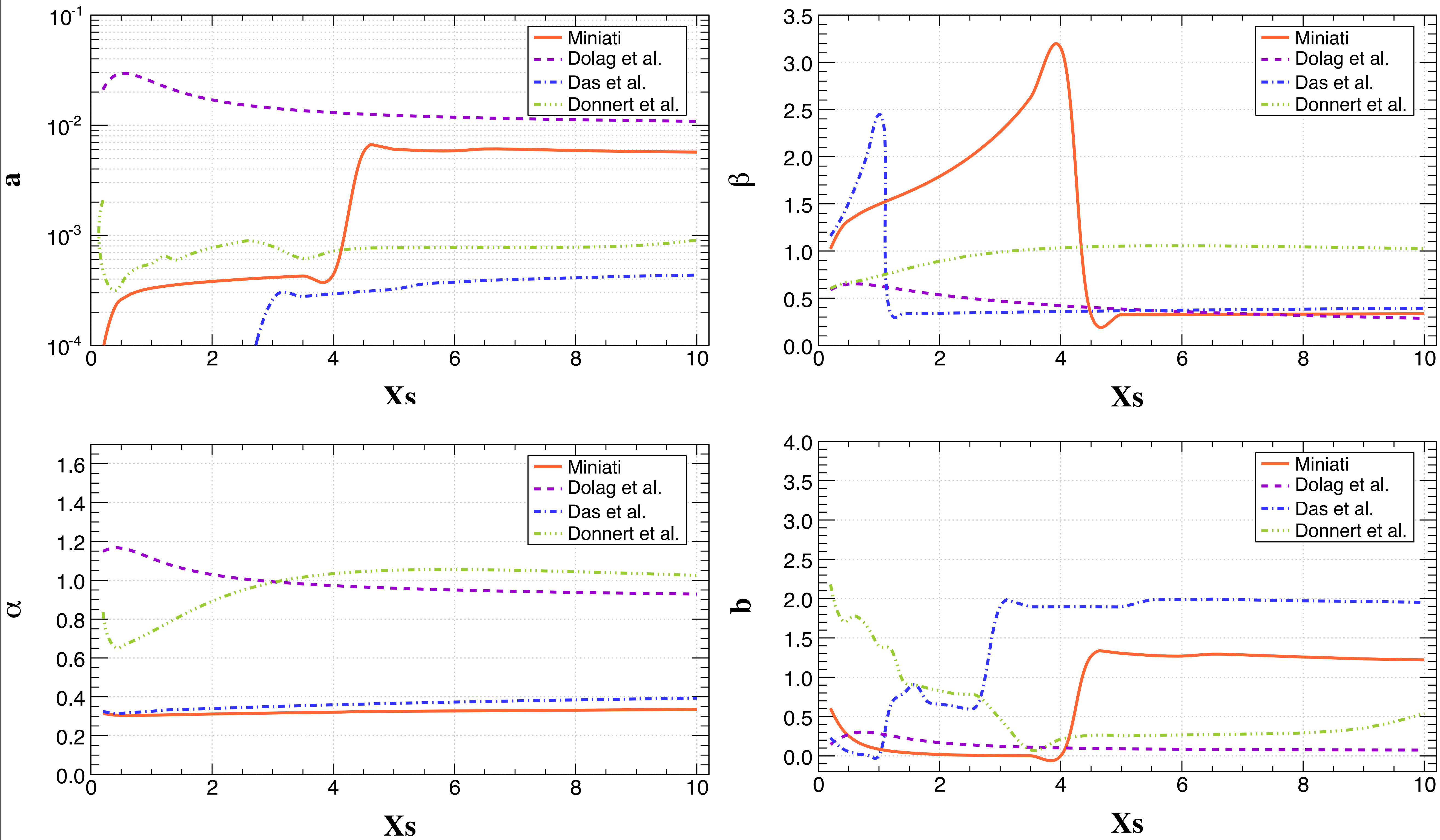
Thank you!

backup slides

best fit parameters



energy loss and interaction processes

photopion production

$$p + \gamma \to \Delta^+ \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

- mean free path for nuclei written as a function of the mfp for protons and neutrons

photodisintegration

- tabulated cross sections

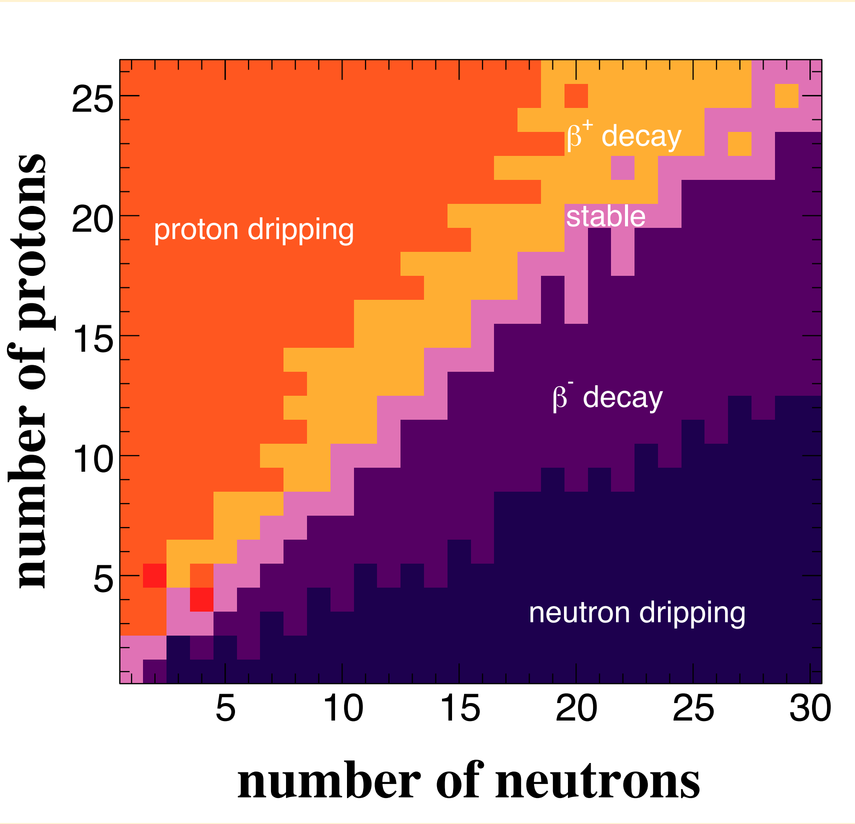
$$\frac{1}{\lambda(\Gamma)} = \int_{E_{min}}^{E_{max}} n(\epsilon, z)\bar{\sigma}(\epsilon'_{max} = 2\Gamma\epsilon)d\epsilon$$

expansion of the universe

$$\frac{dt}{dz} = \frac{1}{H_0}\frac{1}{1+z}\frac{1}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

$$E = \frac{E_0}{1+z}$$

nuclear decay



pair production

$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

the MHD simulations

- ✦ Miniati: Biermann battery rescaled to match B in galaxy clusters
- ✦ Das *et al.*: magnetic field estimated directly from properties of the gas (e.g. vorticity, energy density)
- ✦ Dolag *et al.*: seed field at high redshift with B matching measured values for galaxy clusters
- ✦ Donnert *et al.*: similar to Dolag *et al.*, with magnetic pollution at low redshifts