Horizon of UHECRs in Galaxy Clusters

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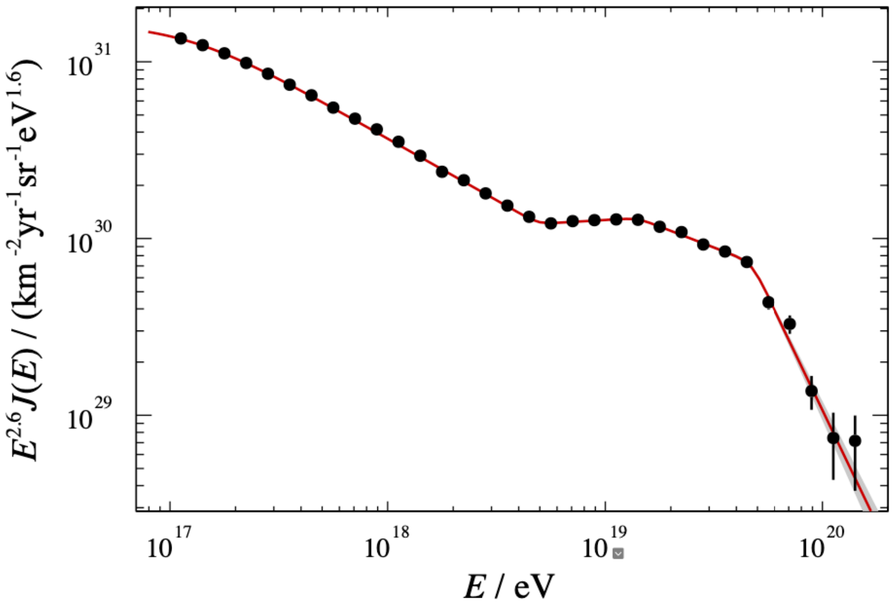
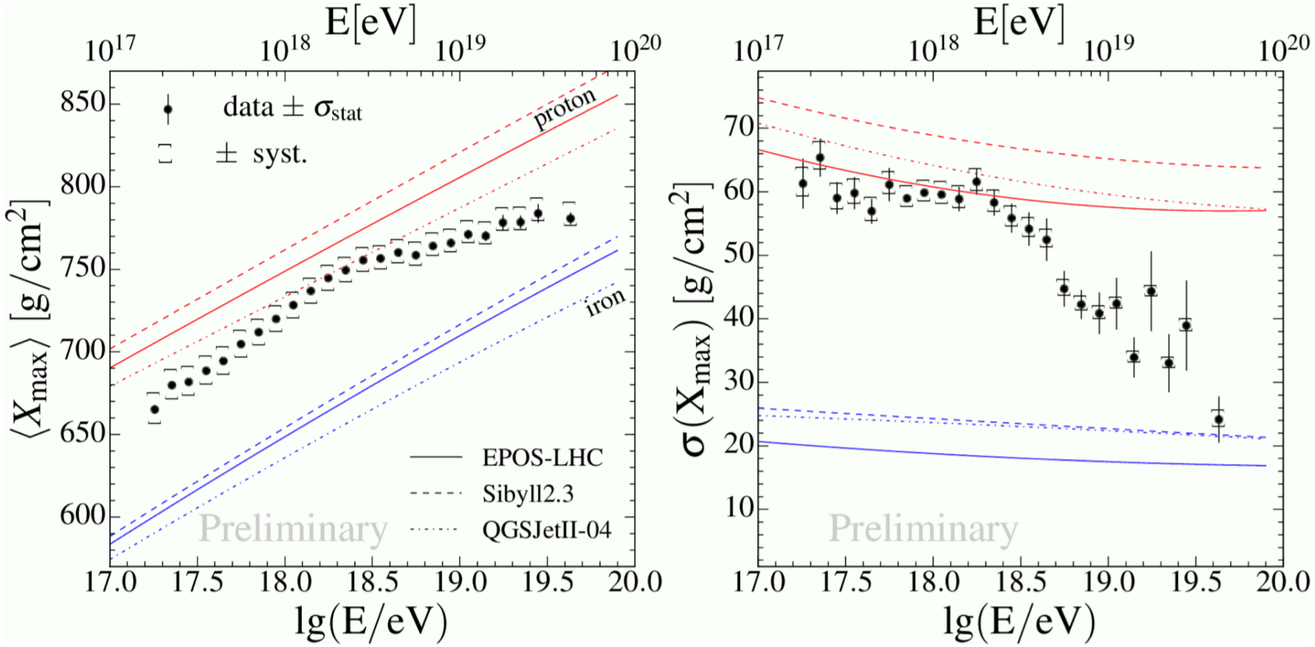
Outline

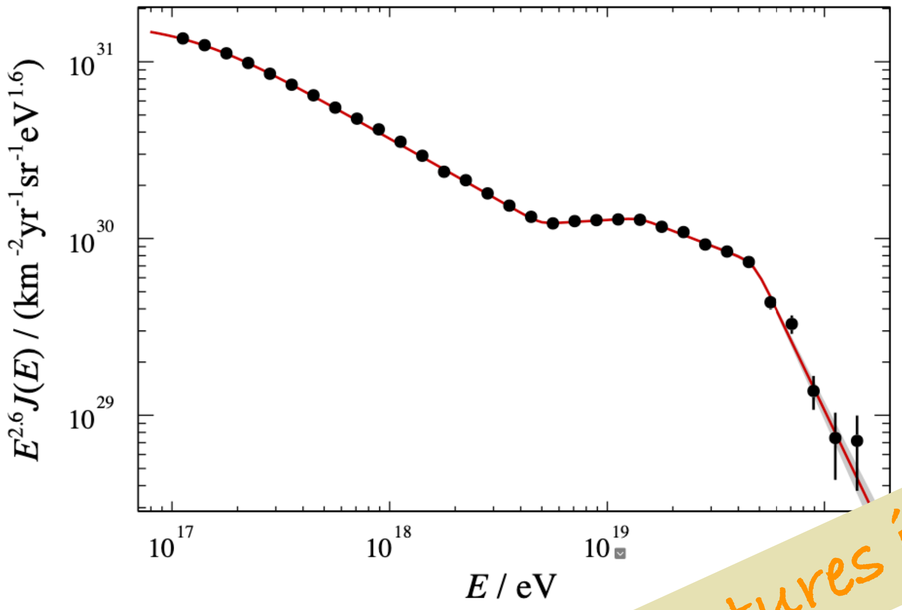
- Motivation: astrophysical interpretation of UHECRs measurements
- Details of the Clusters' environment
- Propagation of UHECRs in Galaxy Clusters
- Conclusions and future perspectives

UHECRs measurements

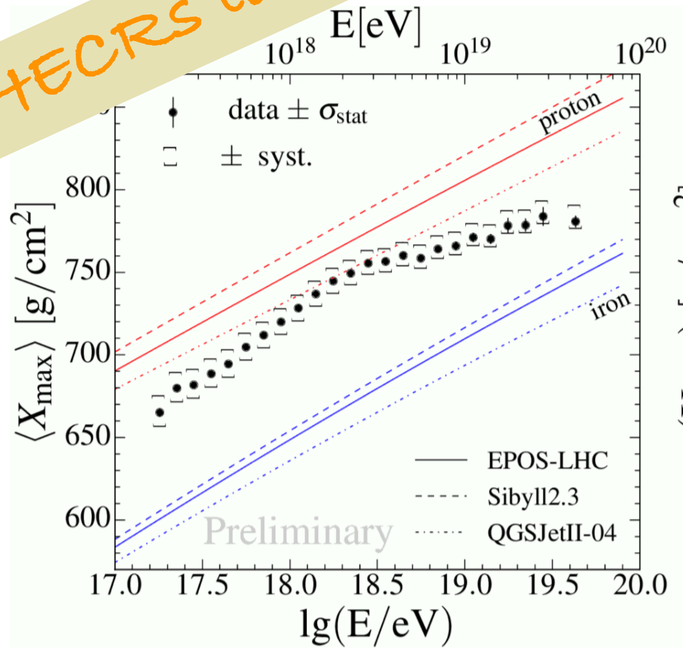


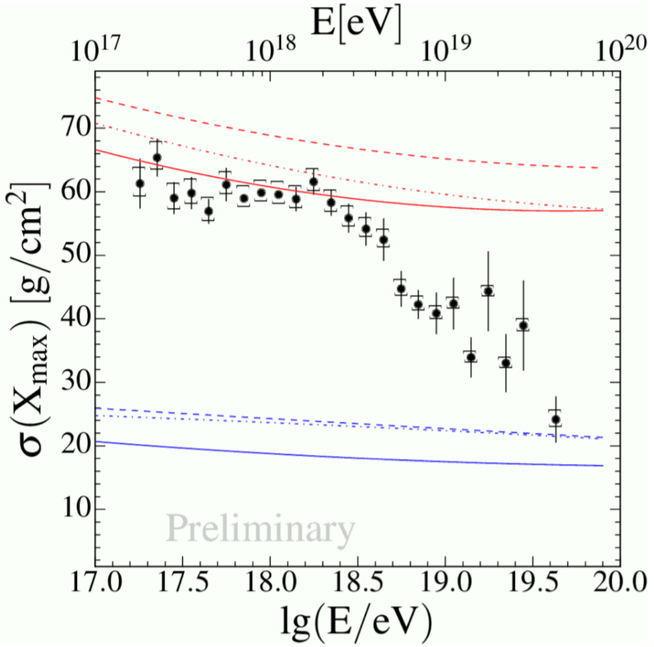


UHECRs measurements



It is possible to link features in the UHECRs to astrophysical processes?





UHECRs sources

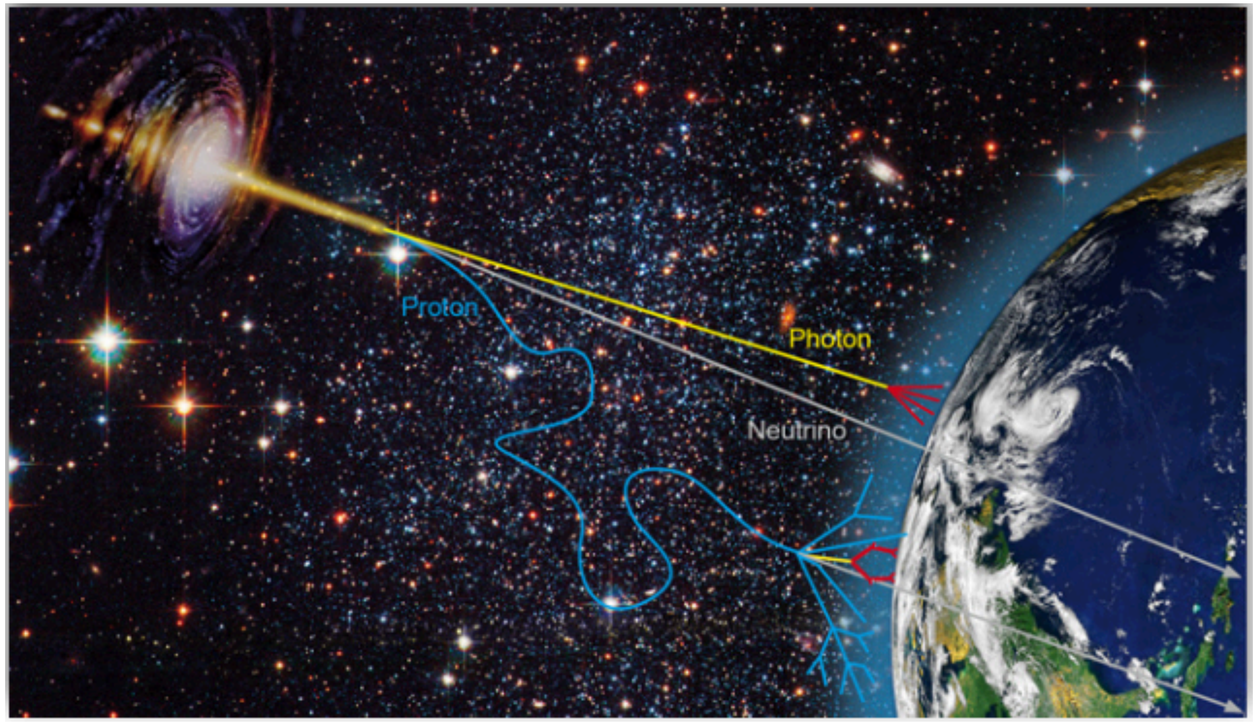
Connection of observables at Earth to theoretical models including UHECR properties –> Propagation of UHECRs

Several codes for UHECR propagation available:

✳SimProp (Aloisio et al., JCAP 2017)

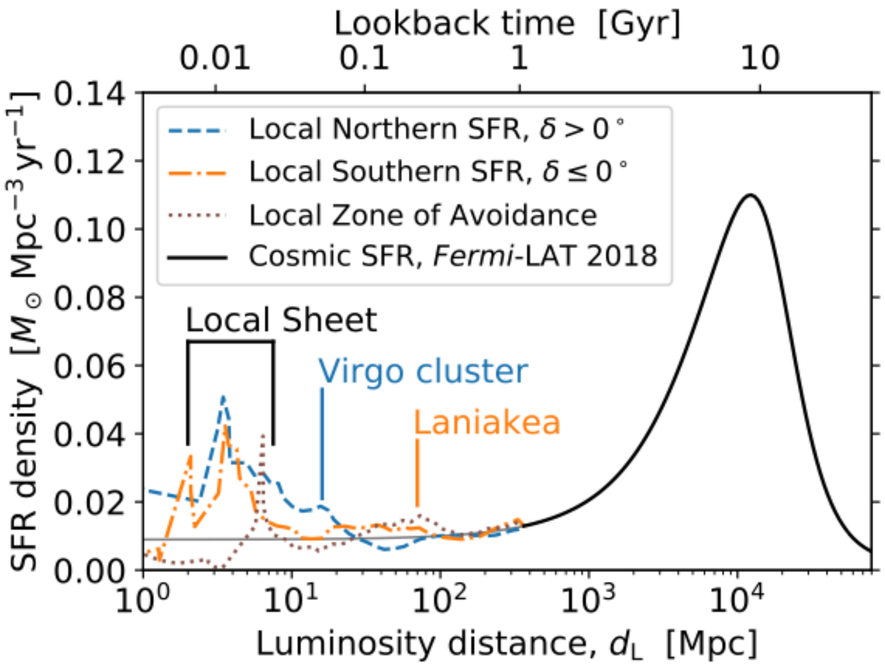
✳ CRPropa (Alves Batista et al., JCAP 2016)

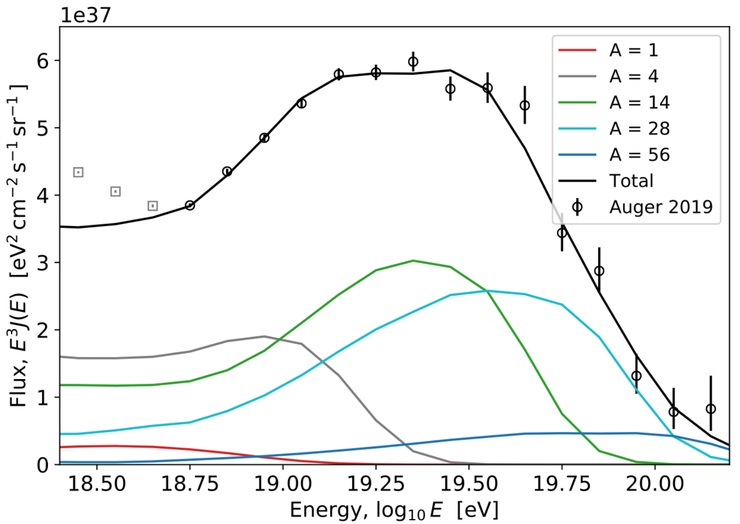
Combining two or more UHECRs observables it is possible to infer something about the sources of UHECRs –> See @Sullivan's talk!

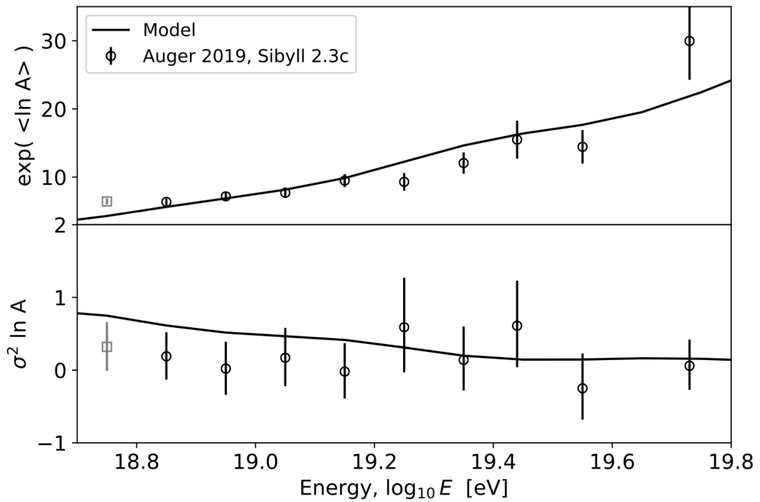


Motivation

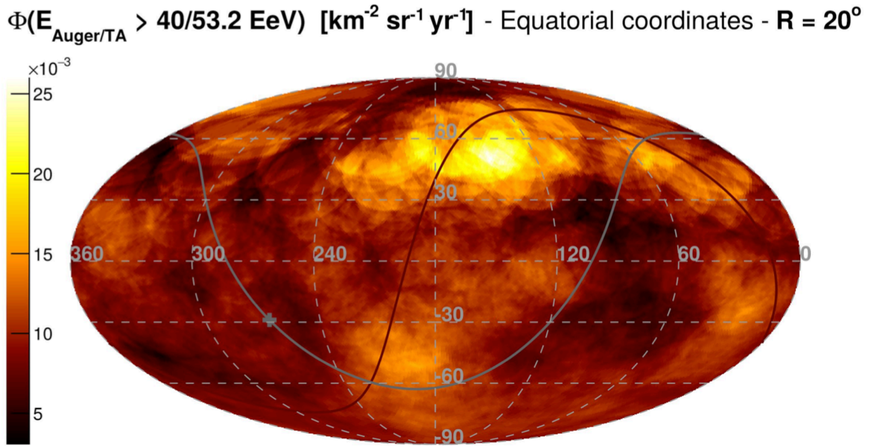
- Assumption: UHECR production rate follows matter (ex: Star Formation Rate)
- Fit of energy spectrum and composition using a catalogue which reconstructs the 3D distribution of the most extreme sources in the Universe.

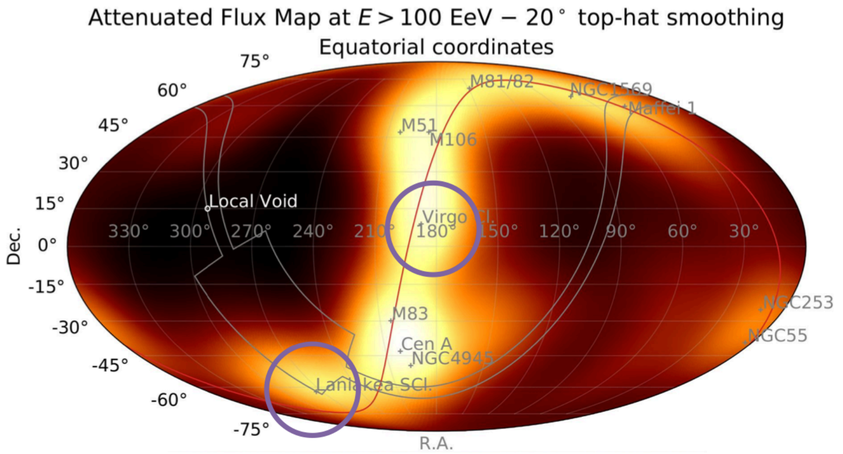






Motivation

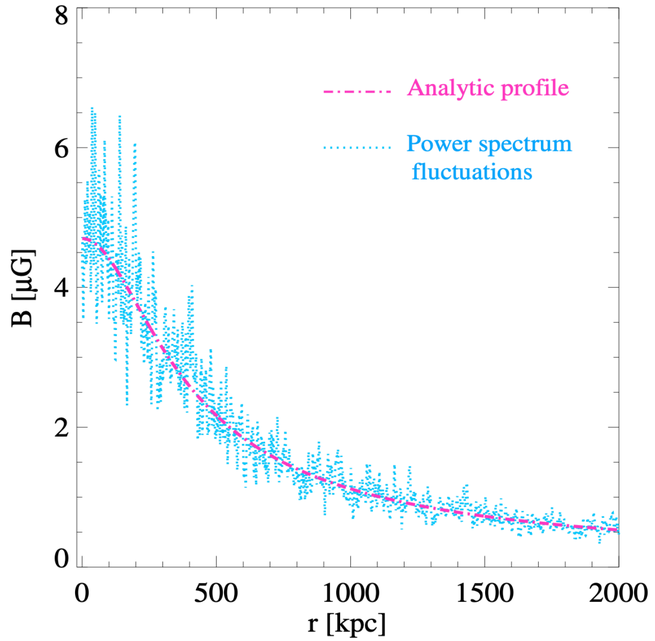




Why don't we see nearby clusters or superclusters?

Motivation

Study the propagation of UHECRs in Galaxy Clusters' environment!



$$\frac{L_{eff}}{L}(E,Z) \simeq \cos\theta \simeq 1 + \frac{\theta^2}{2} \simeq 65\left(\frac{10^{20}\ \mathrm{eV}}{E}\right)^2\left(\frac{L}{1\ \mathrm{Mpc}}\right)\left(\frac{L_{coh}}{10\ \mathrm{kpc}}\right)\left(\frac{B}{1\ \mu\mathrm{G}}\right)^2\left(\frac{Z}{26}\right)^2$$

Possible trapping due to clusters' magnetic field!

A. Bonafede et al., A&A 513, A30 (2010)

D. Hooper, et al., Phys. Rev. D **77**, 103007

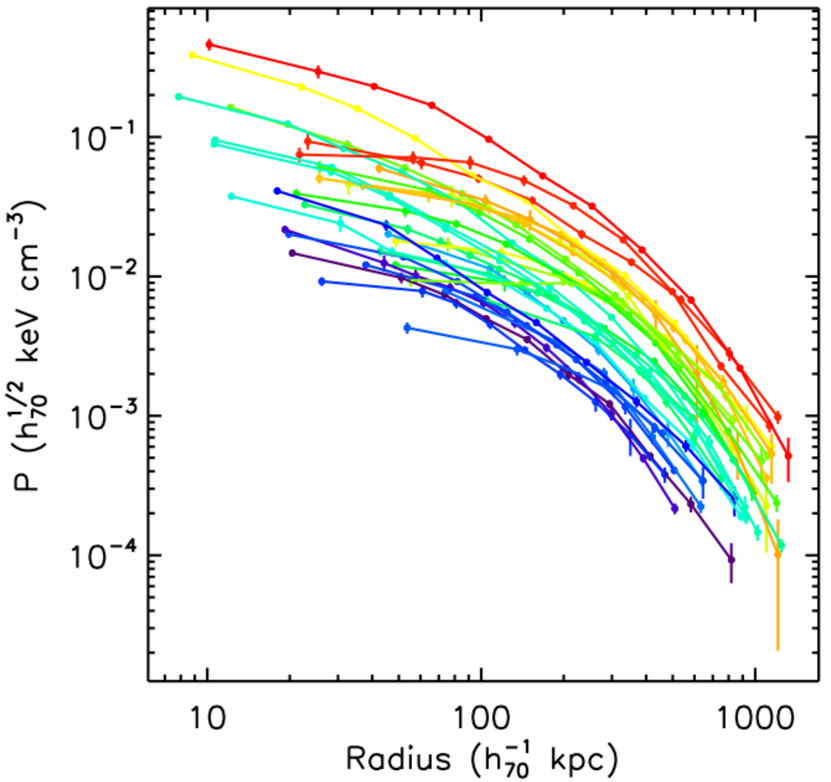
The universal galaxy cluster pressure profile

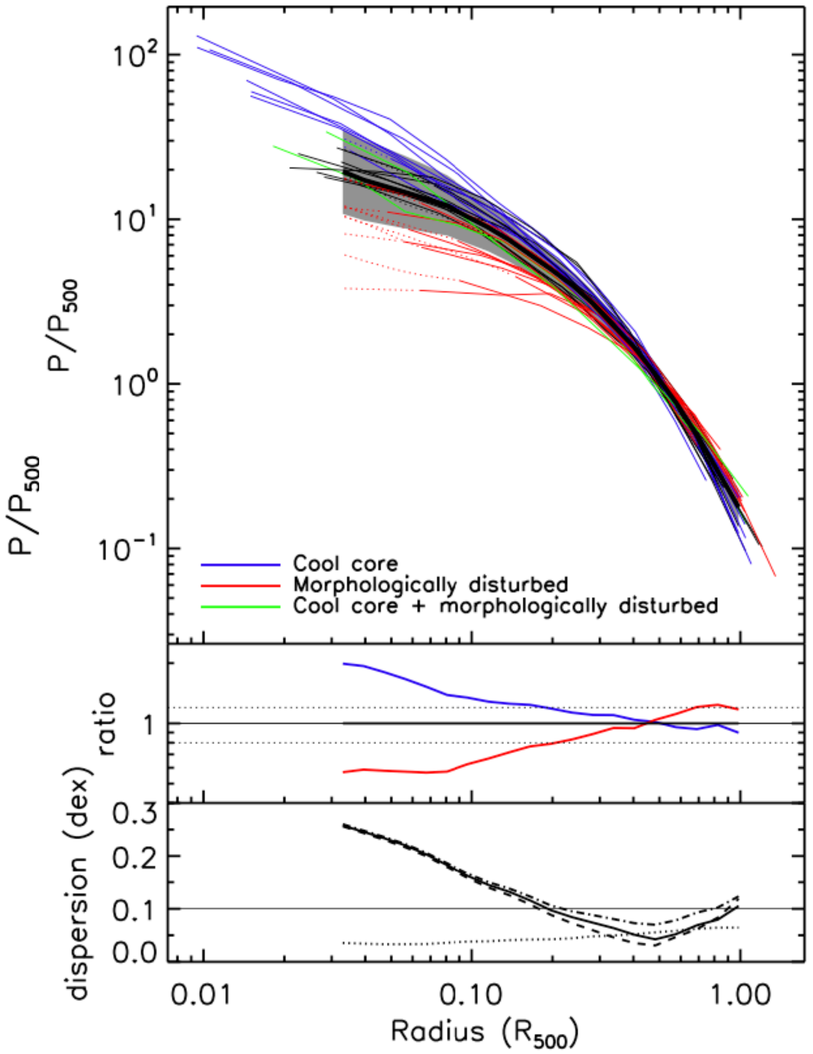
- Self-similarity: approximation all their properties depend only on mass and redshift;
- (M, z) –> pressure profile for any cluster.

$$P(r) = \frac{P_0 \cdot P_{500} \cdot f(M,z)}{(x/r_p)^{\gamma} \cdot (1 + (x/r_p)^{\alpha})^{\frac{\beta-\gamma}{\alpha}}}$$

with P_0 normalisation factor

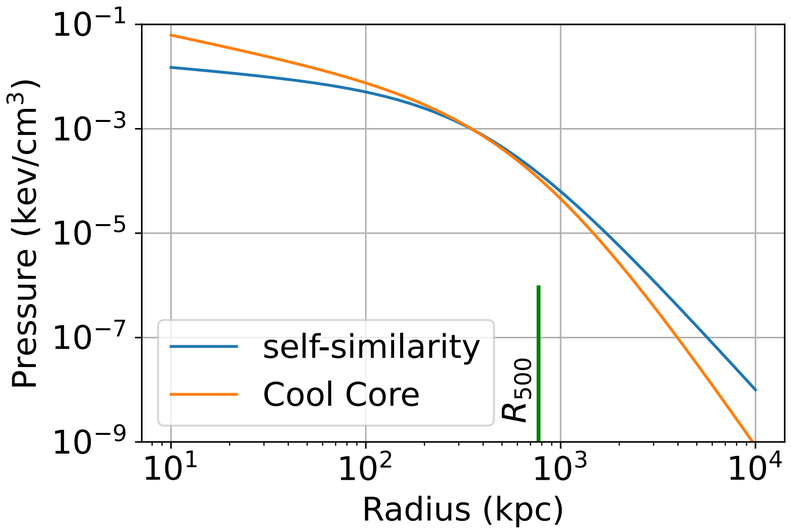
α, β, γ and r_p are fitted parameters.

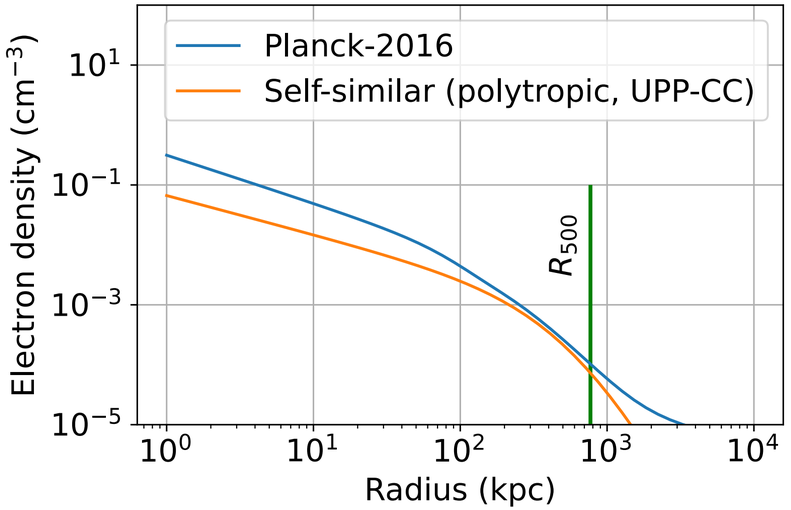


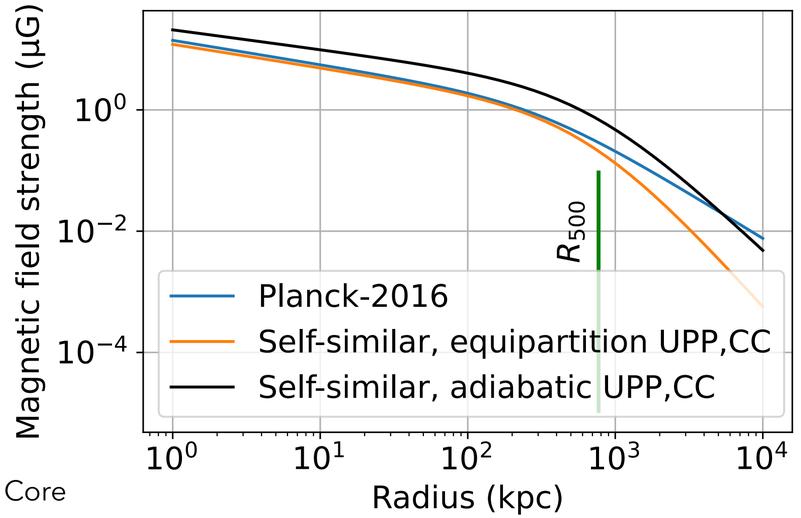


Arnaud et al, A&A 517, A92 (2010).

Virgo Cluster







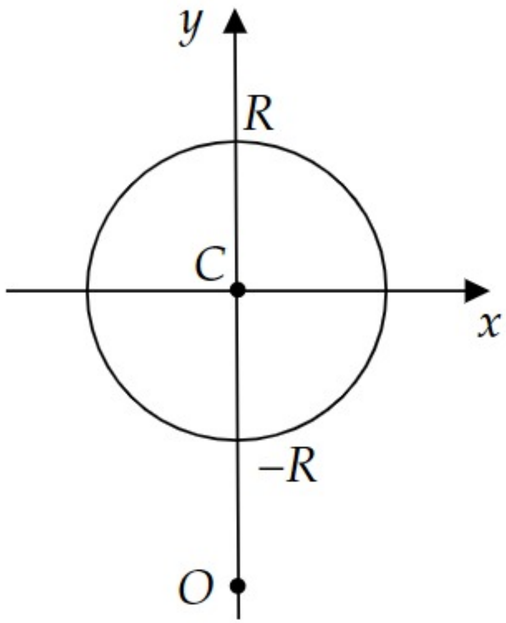
*UPP,CC = Universal Pressure Profile for Cool Core

Planck collaboration, A&A 596, A101 (2016)

R. Adam et al, A&A 644, A70 (2020)

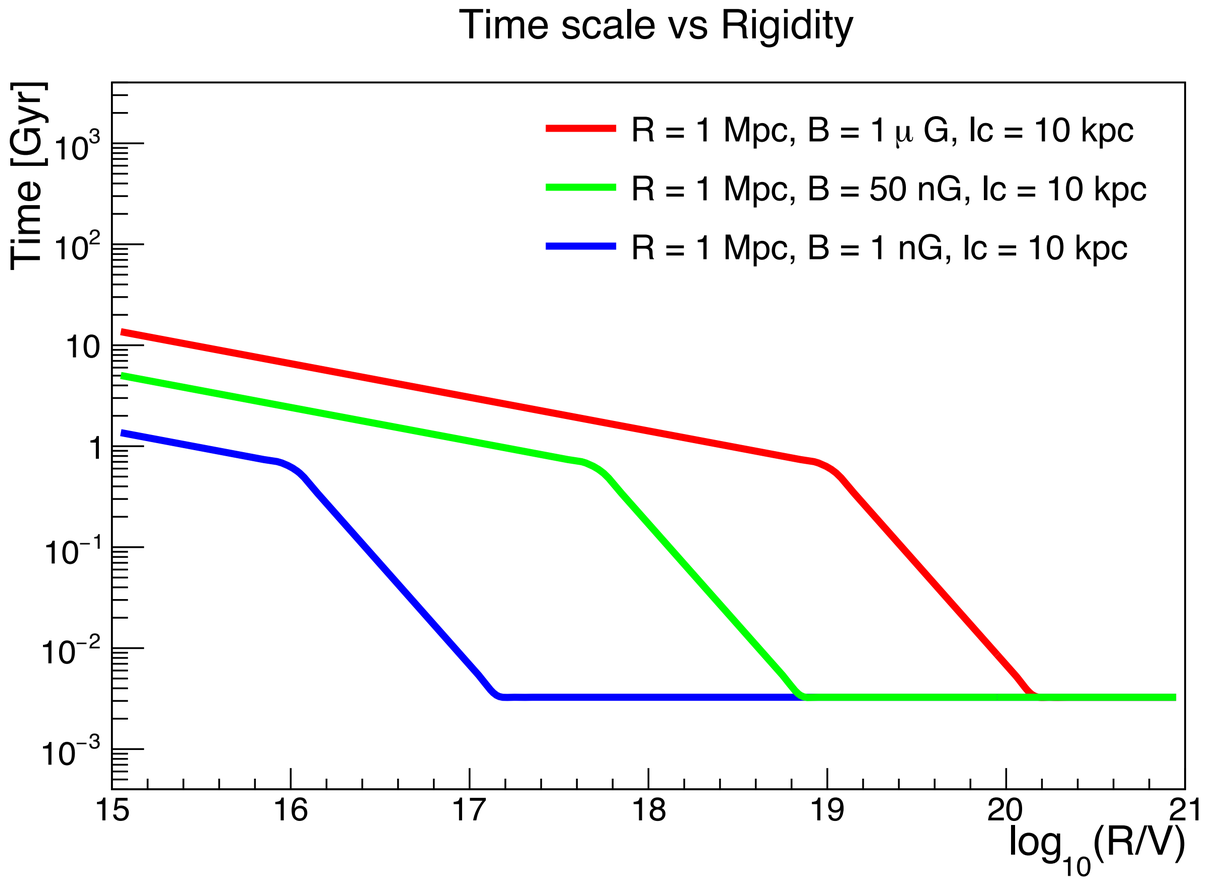
Source-propagation in Galaxy Clusters

- Propagation in source computed using SimProp;
- Computation of interaction and diffusion times;
- Inclusion of magnetic field effect on propagation; New!
- Including radial dependence. New!



$R = 1\,Mpc$

Diffusion and interaction times



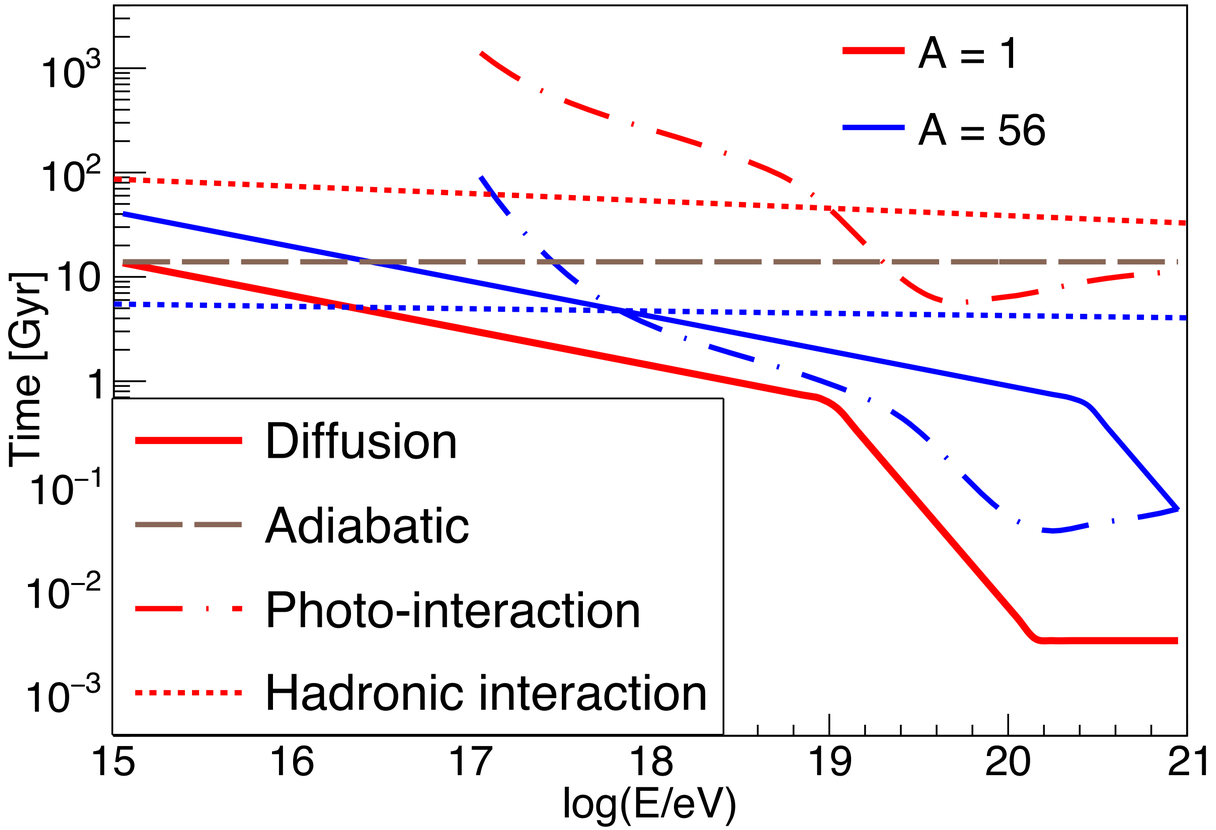
Diffusion

$$\tau_D = \frac{R^2}{D}$$

Depends on the slope in energy and on the coherence lenght l_c

P. Subedi et al, 2017 ApJ 837 140

Diffusion and interaction times



Interactions with CMB and EBL:

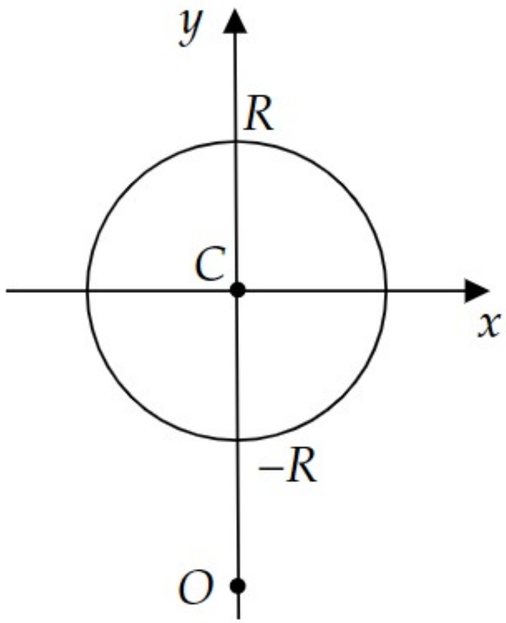
$$\frac{1}{\tau} = \frac{1}{2\Gamma^2} \int_{\epsilon'_{\min}}^{2\Gamma\epsilon} \int_{\epsilon=0}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} \, \mathrm{d}\epsilon \, \sigma(\epsilon') \epsilon' \, \mathrm{d}\epsilon'$$

Interactions with protons and helium nuclei:

$$\tau = (n_{ICM} \cdot \sigma \cdot c)^{-1}$$

Procedure for escape:

- Fixed number of steps for each particles



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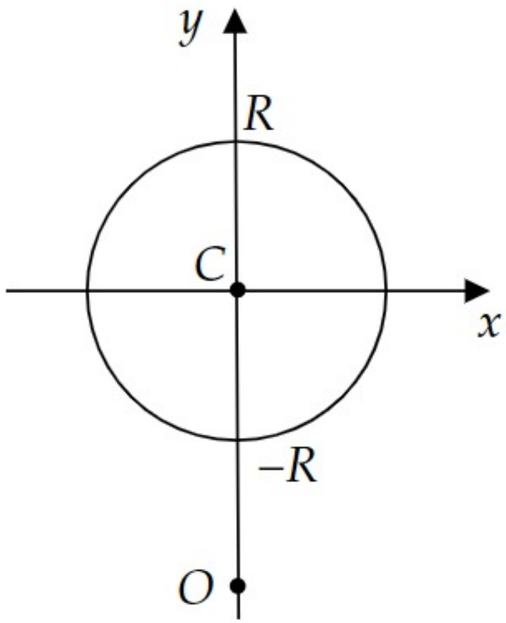
Procedure for escape:

- Fixed number of steps for each particles
- Propagation from $y \in [-R, R]$ to $-R$



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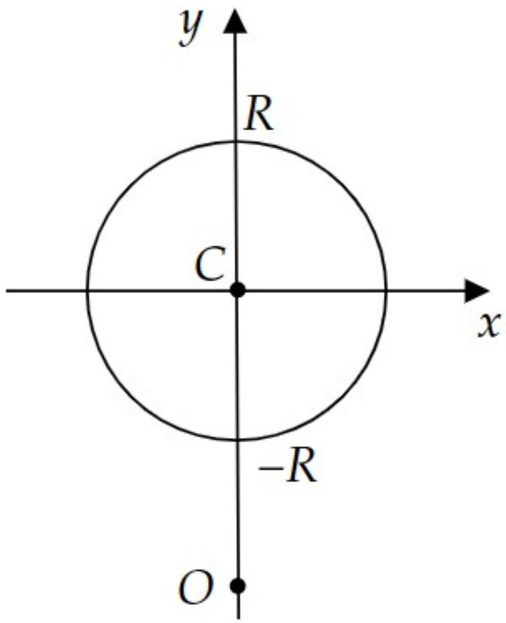

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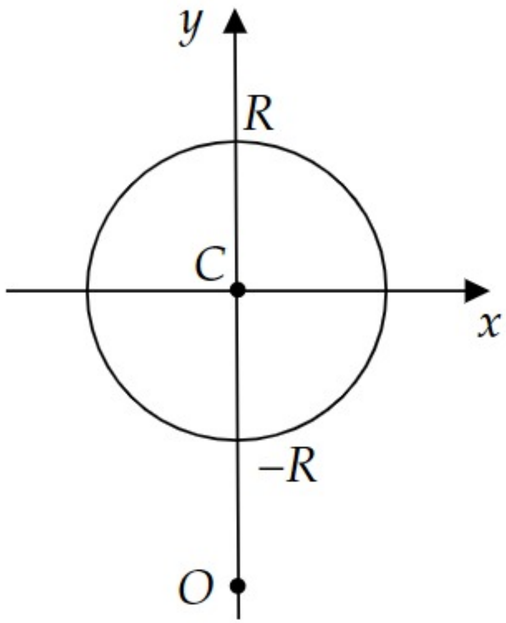
- If, at step n> n_stepmax, the diffusion time is shorter that the interaction times, particle escape



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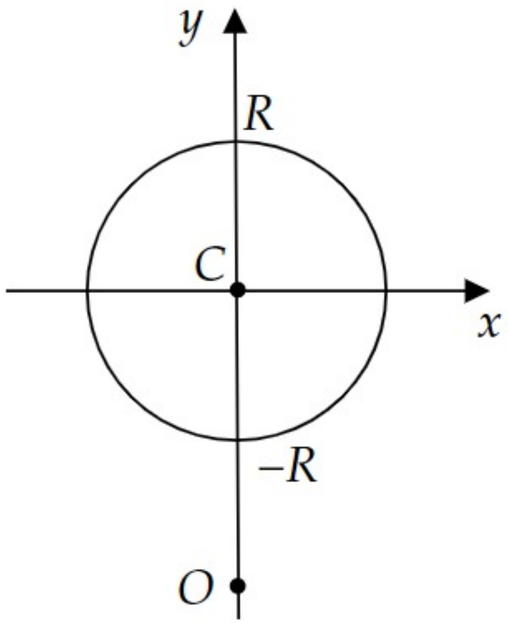
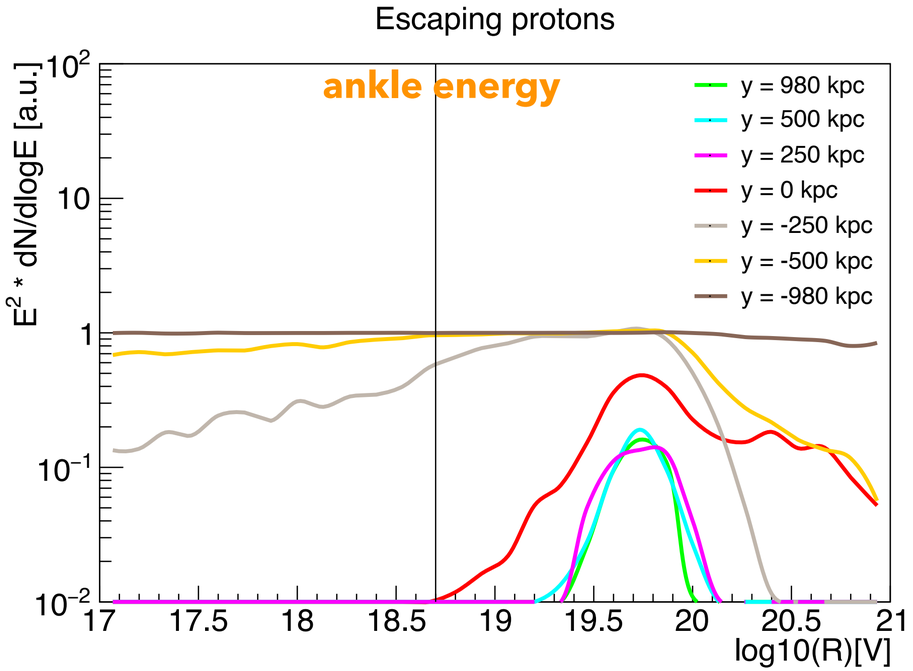
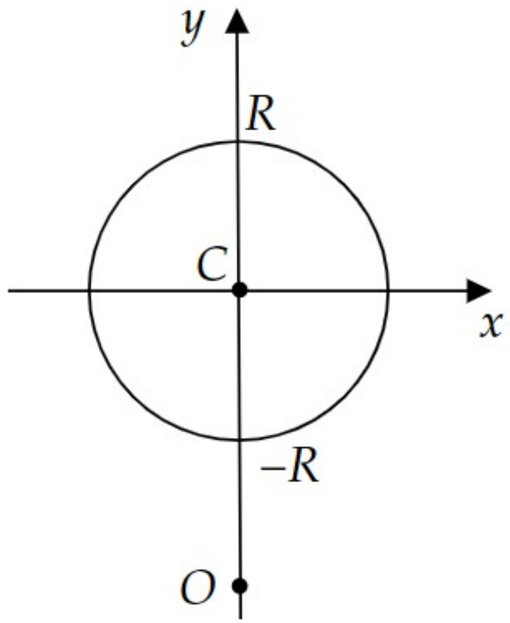
- If, at step n> n_stepmax, the diffusion time is shorter that the interaction times, particle escape
- If a particle is propagated and it reach a time in the source > time of the Universe: particle is trapped!



$R = 1\,Mpc$

Parametrizing the escaping flux

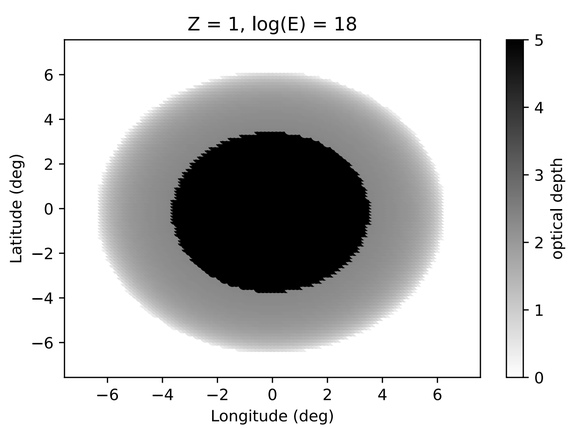


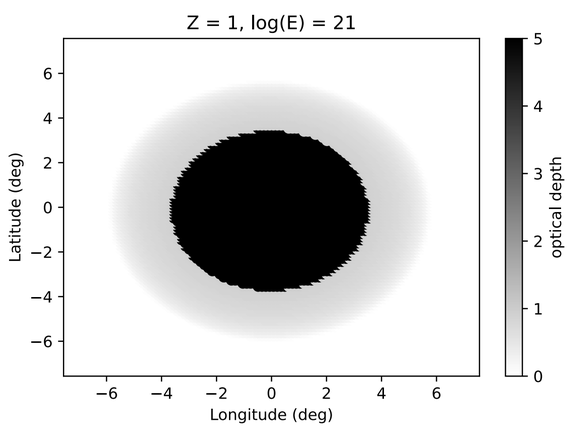


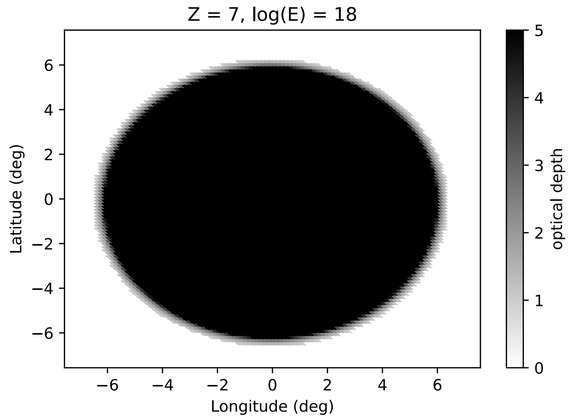
$R = 1\,Mpc$

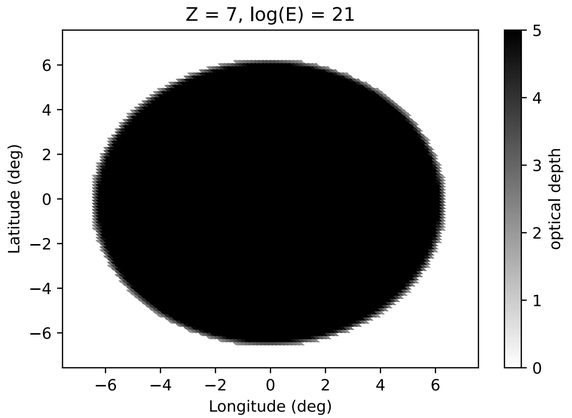
- Inject protons with $\Phi \propto E^{-2}$
- Simulate Virgo environment
- Parametrize the escaping flux as a function of the injection point

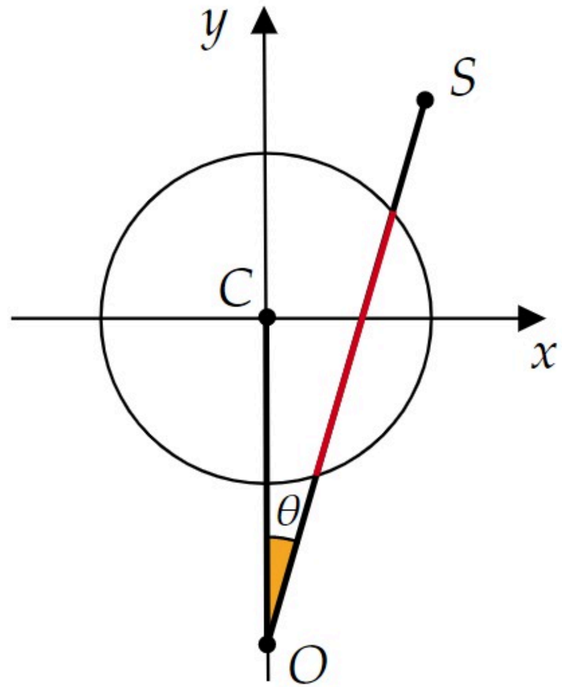
Filtering







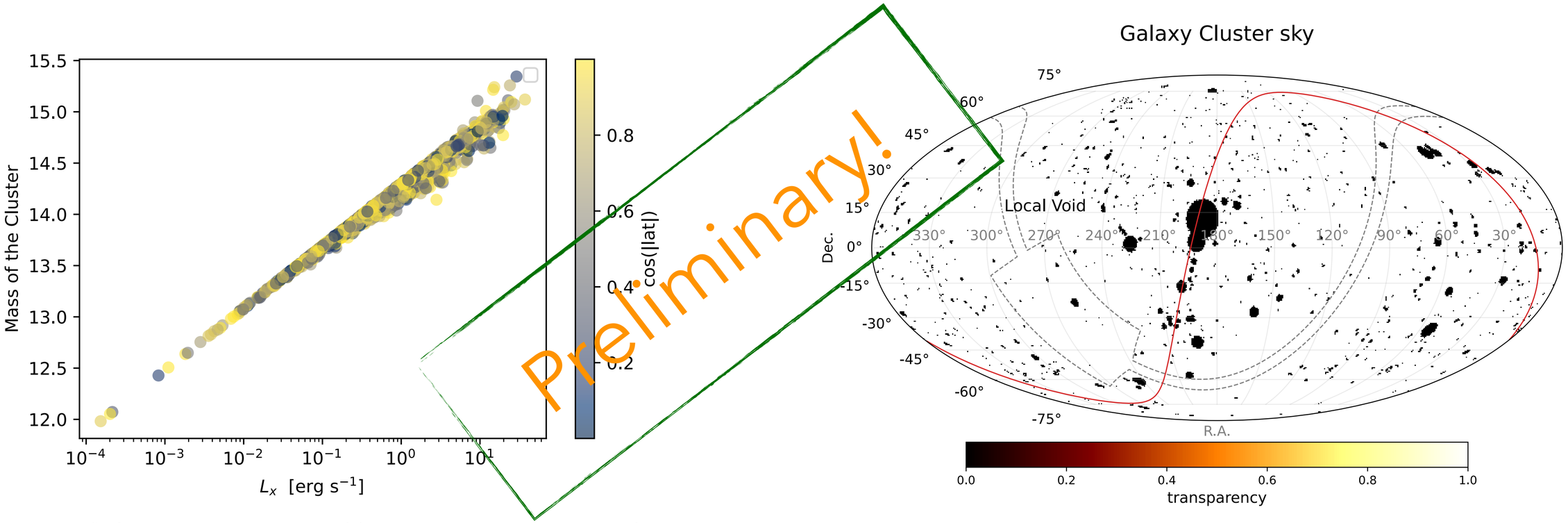




$= 1\,Mpc$

We should not see Virgo Cluster!

Catalogue



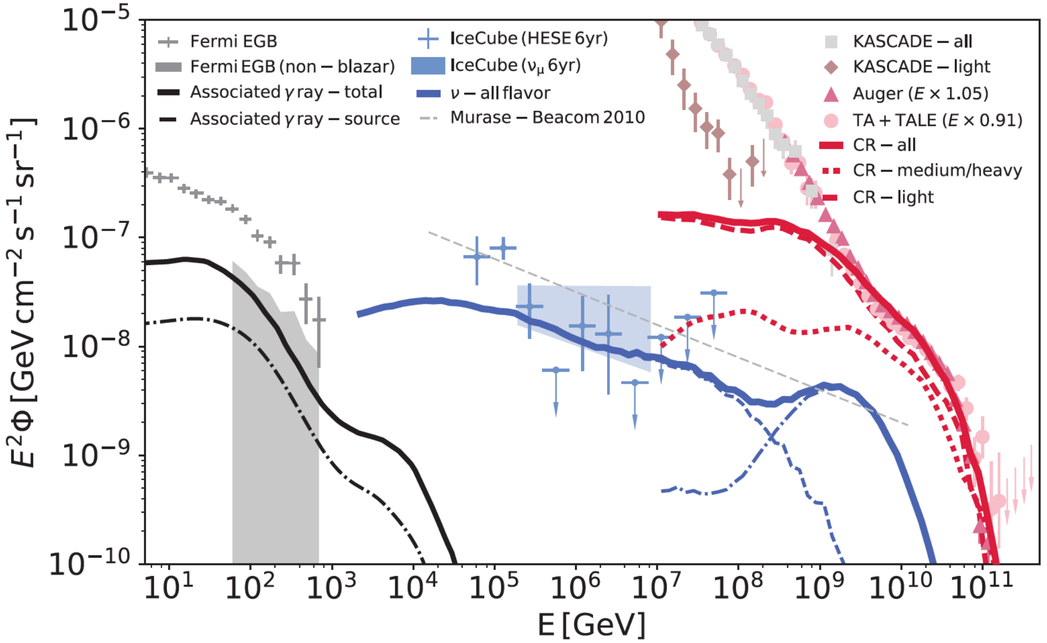
Mass of clusters as measured by NORAS, REFLEX and CIZA. The color bar represent different the latitude of the observed clusters.

Summary and future perspectives

- ☑ Modelling the environment of Galaxy Cluster;
- ☑ Computing the propagation in the magnetised environment;
- ☑ Parametrising the escaping primary fluxes;
- ☑ Possibility to connect the parameter at the source to the fitted parameter at Earth;

Future perspectives

- ☐ Universal parametrisation for Clusters;
- ☐ Compute the secondary fluxes (neutrinos, gamma);
- ☐ Perform a fit of spectrum, composition and arrival directions.

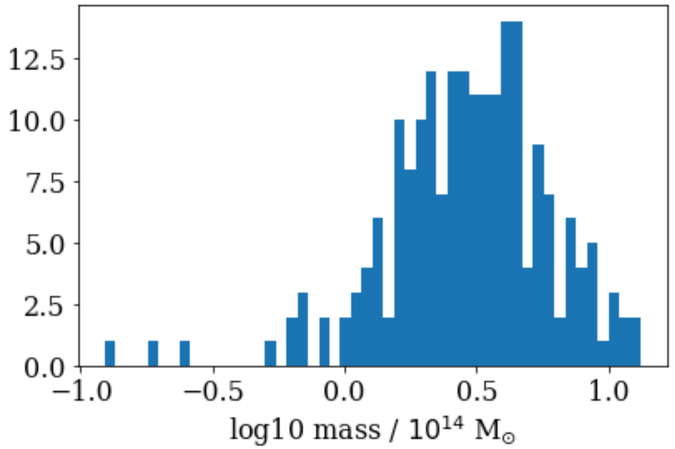


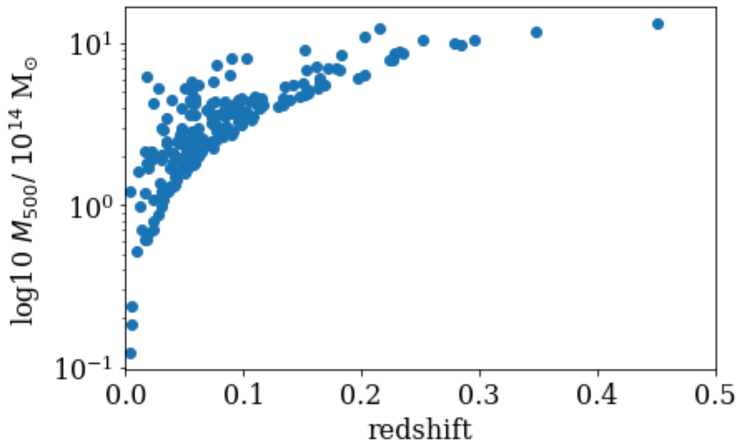
K.Fang and K. Murase, Nature Phys. 14 (2018) 396

Thanks for your attention!

Backup slides

Distribution in mass and redshift of the sample





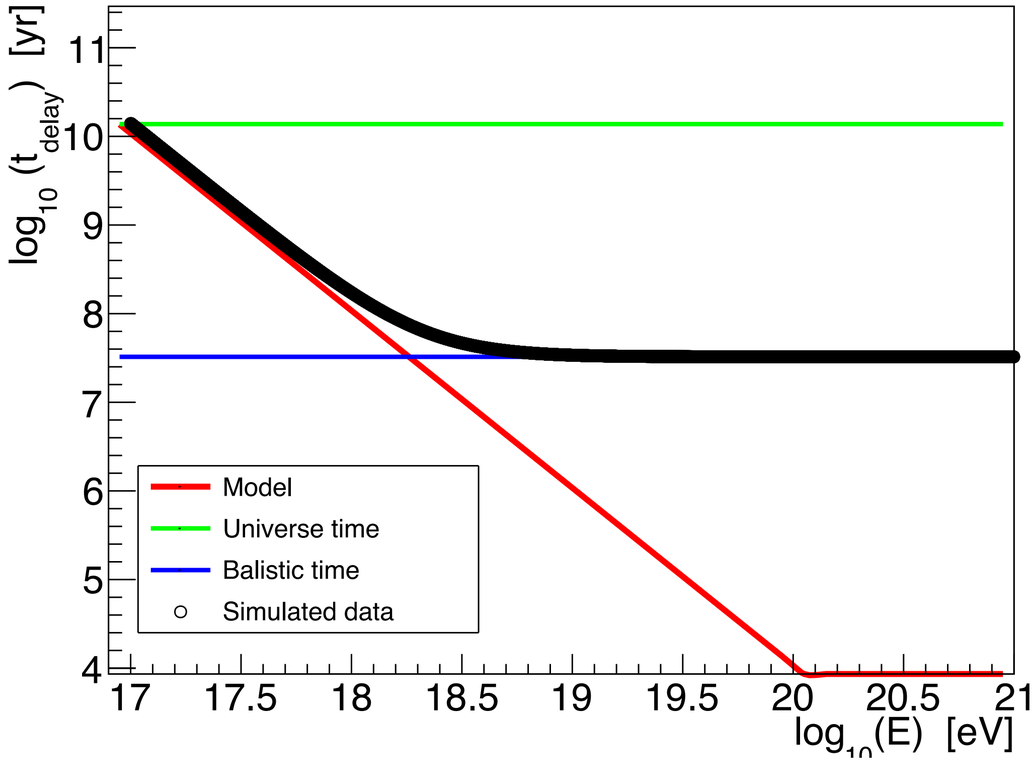
Performing a scan between 10^14 and 10^15 solar masses corresponds to values of the magnetic field at the center of the cluster between 3 and 8 micro Gauss.

Magnetic field in the source

Charged particle moving through a uniform magnetic field undergoes an angular deflection upon traversing a distance, Lcoh, of $\alpha = \frac{L_{coh}}{R_L}$

A particle traversing a distance, L, suffers an overall angular deflection given by

$$\theta(E,Z) \simeq \left(\frac{L}{L_{coh}}\right) \alpha$$

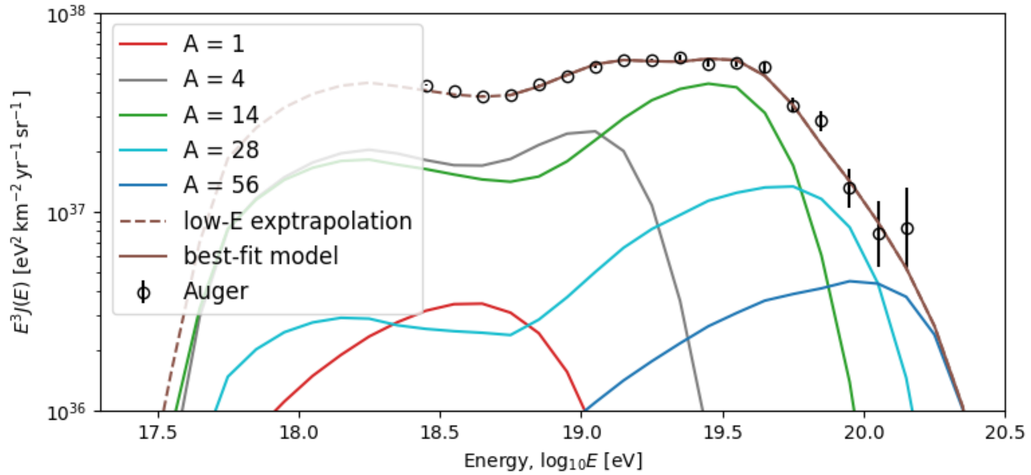


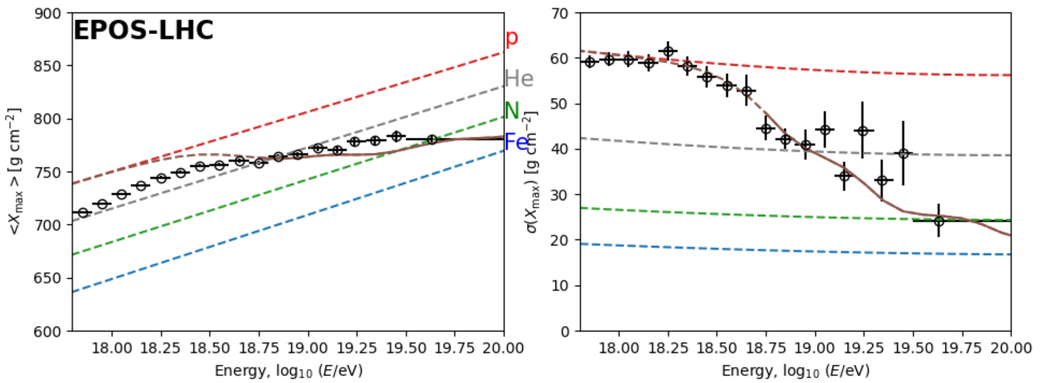
$$\frac{L_{eff}}{L}(E,Z) \simeq \cos\theta \simeq 1 + \frac{\theta^2}{2} \simeq 65\left(\frac{10^{20}\ \text{eV}}{E}\right)^2\left(\frac{L}{1\ \text{Mpc}}\right)\left(\frac{L_{coh}}{10\ \text{kpc}}\right)\left(\frac{B}{1\ \mu\text{G}}\right)^2\left(\frac{Z}{26}\right)^2$$

EG propagation and comparison to data

Combined fit code capable to:

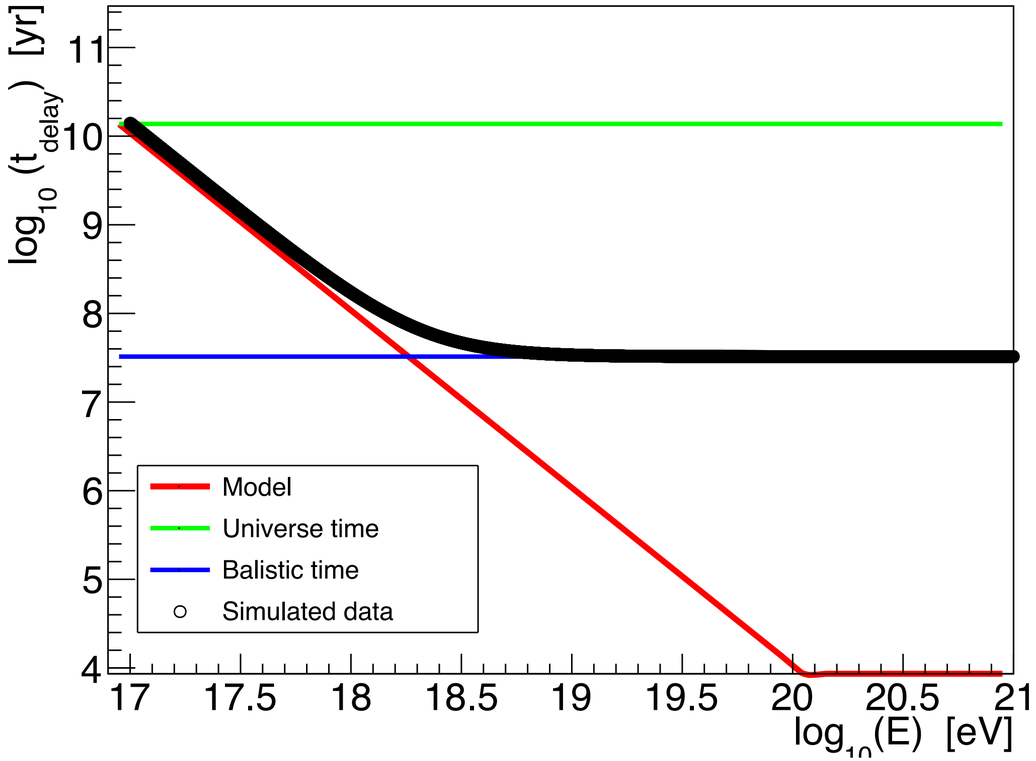
- Use a 5D tensor, coming from SimProp simulations, to compute the extra-galactic propagation;
- Fit simultaneously energy spectrum and mass observables (lnA, mean Xmax or Xmax distributions) above the ankle;
- Producing sky maps;



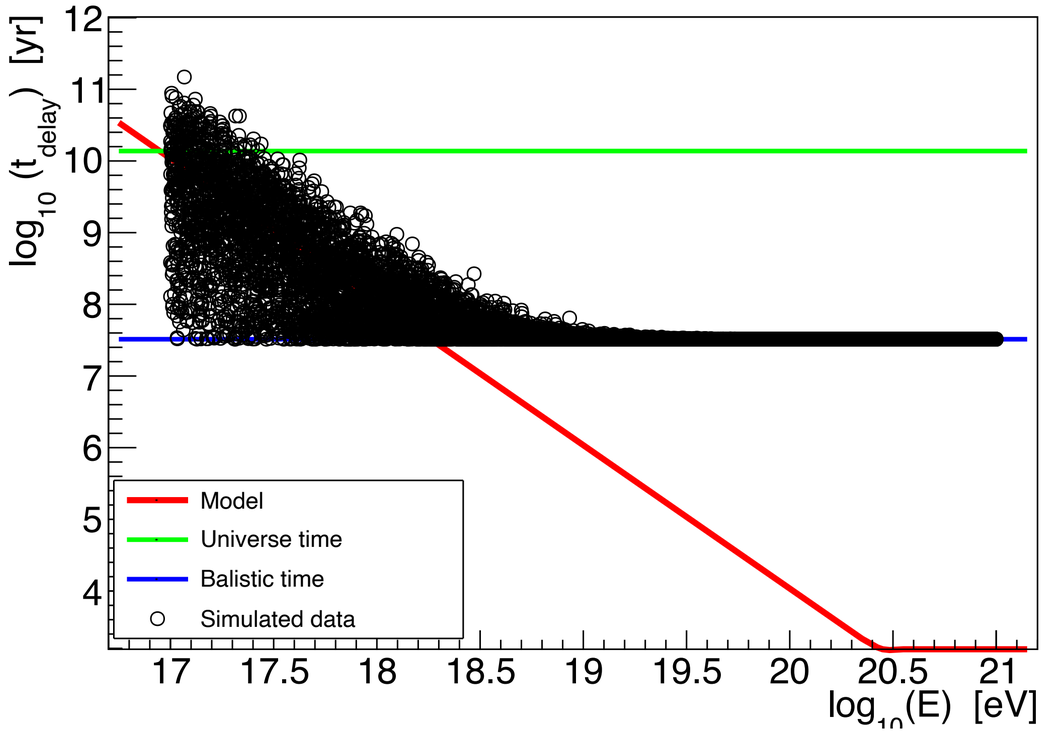


Magnetic field in the source

No randomisation

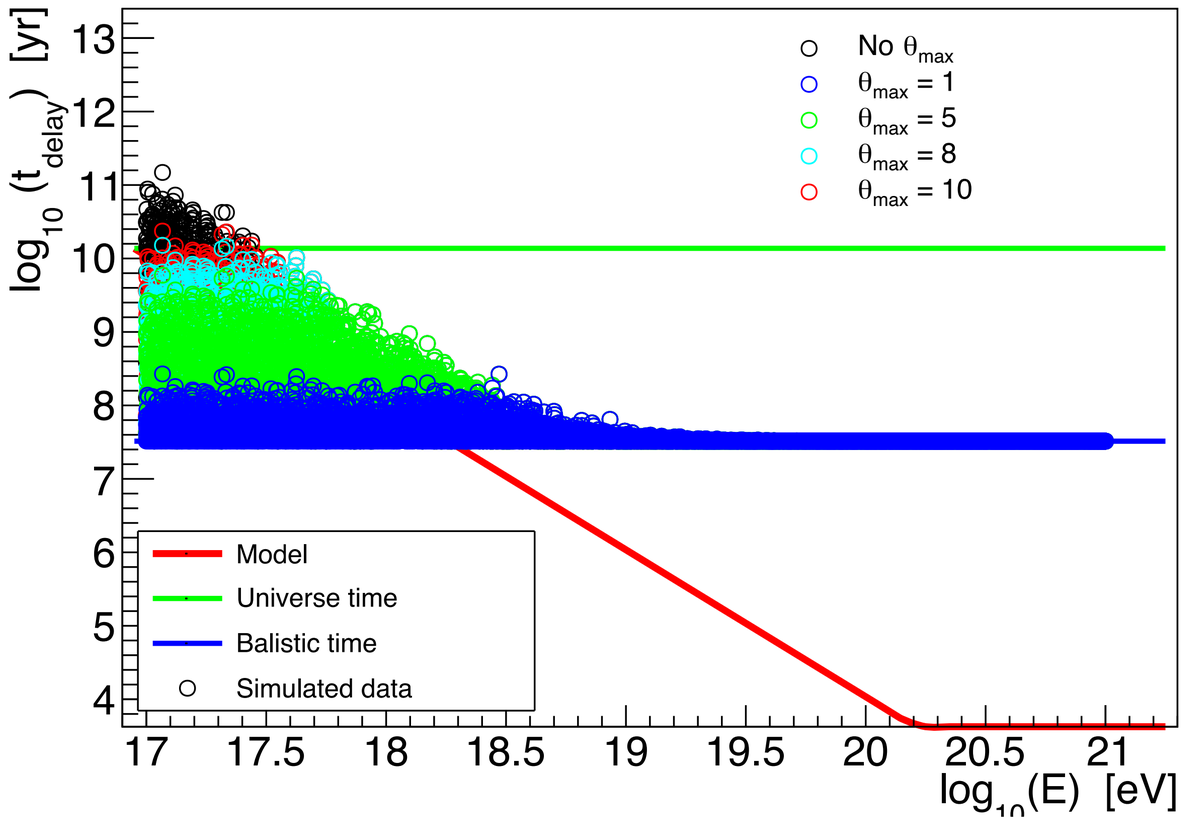


Randomisation



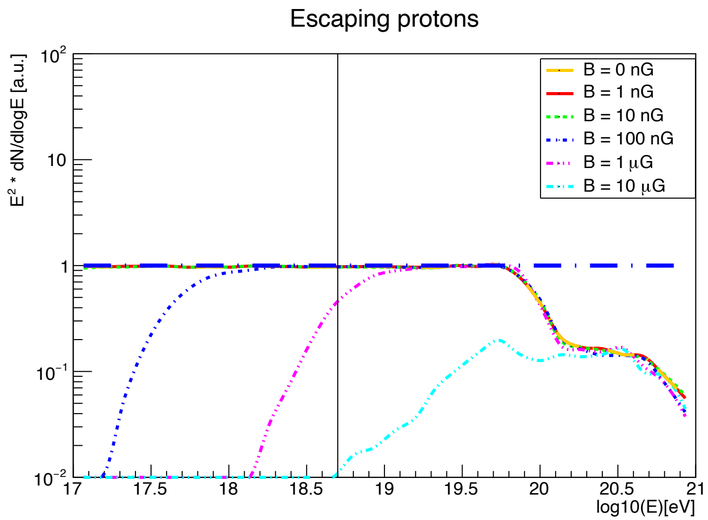
https://doi.org/10.1103/PhysRevD.59.023001

Small angle approximation is justified?

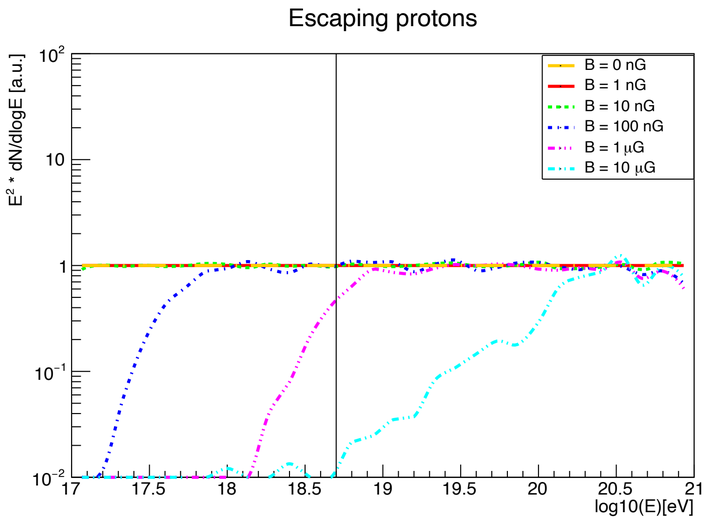


https://doi.org/10.1103/PhysRevD.59.023001

Injecting protons

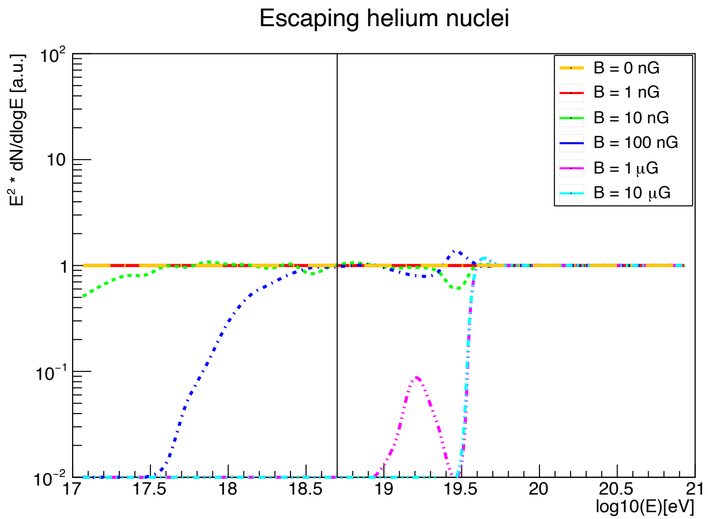


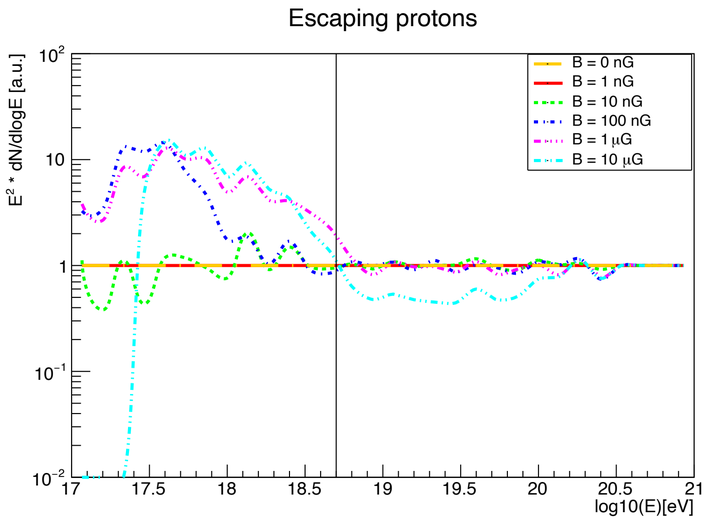
Normalized to the injection spectrum



Normalized to B = 0

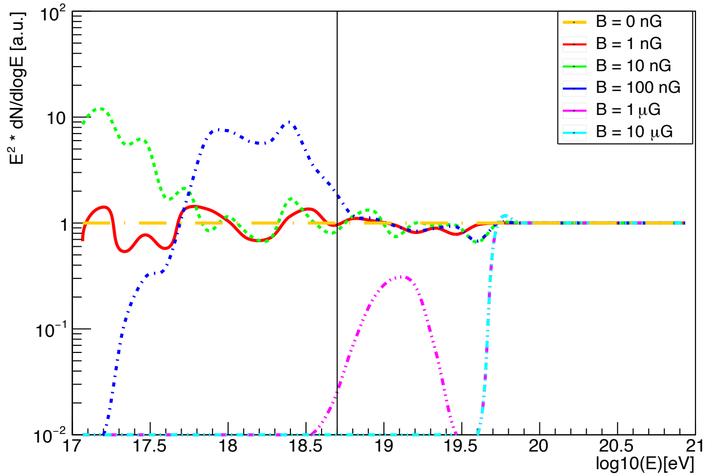
Injecting Helium



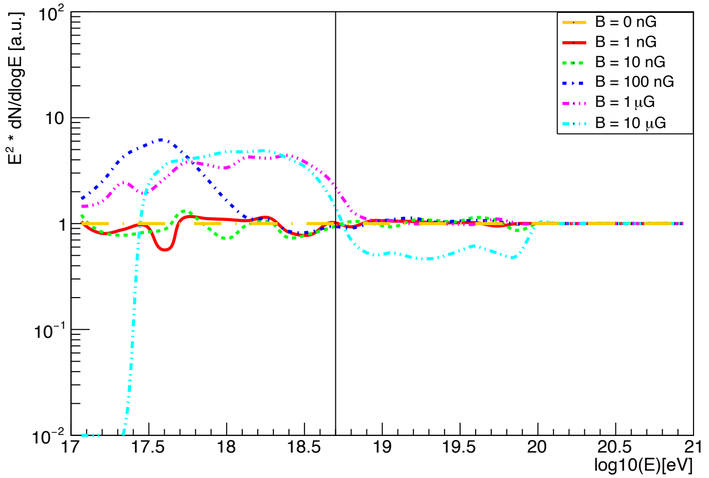


Injecting Nitrogen

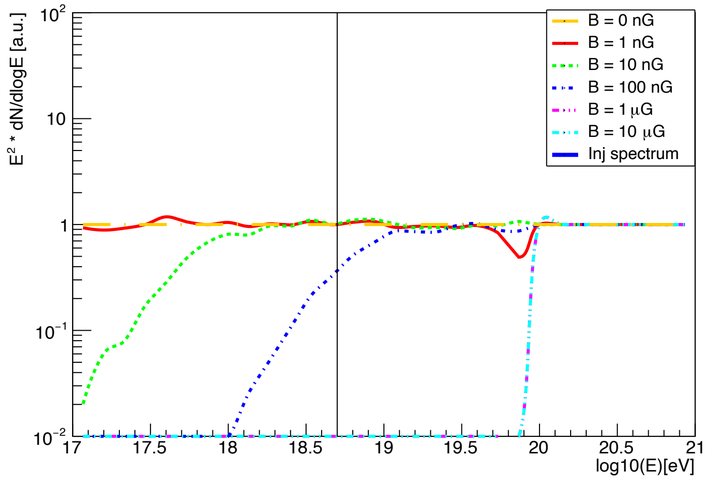
Escaping helium nuclei



Escaping protons



Escaping nitrogen nuclei



Injecting Silicon