Observational constraints on transient accelerators of ultra-high energy cosmic rays

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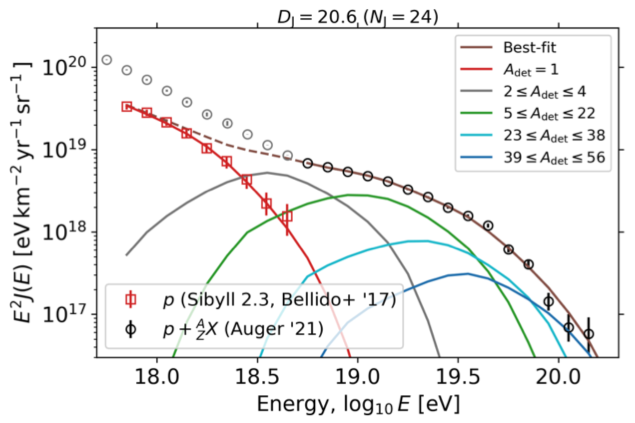
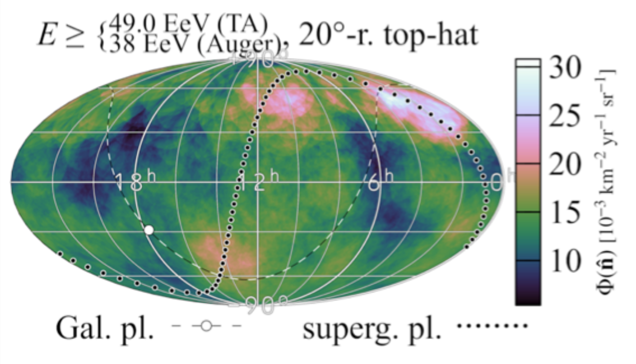
Motivation



- UHECR spectrum $\longrightarrow$ constraints on the emissivity of the candidate sources.
- Propagation effects $\longrightarrow$ UHECRs are coming from nearby Universe.

Motivation



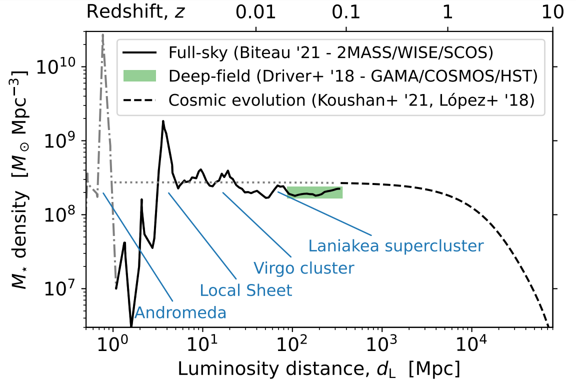
- UHECR spectrum ⟶ constraints on the emissivity of the candidate sources.
- Propagation effects ⟶ UHECRs are coming from nearby Universe.
- Correlation with a starburst catalogue contributing only to 10% of the flux[a]. What about the remaining 90%?

[a] L. Caccianiga for the Auger-TA working group, ICRC2023

☛ Studying the plausible UHECR sources in the nearby Universe in a transient scenario.

Combined fit using a complete catalogue of the nearby Universe

- Catalogue of 400,000 galaxies [1] in the nearby Universe (≤ 350 Mpc).
- Assuming that UHECR production rate follows a tracer (SFRD or $M_\star$ density).



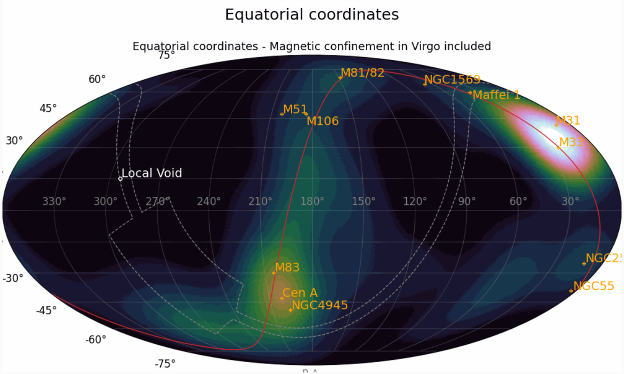
- Discrete: Compute the flux for each galaxy from the catalogue proportional to their tracer.
- Continuous: Compute the flux from $z = 0.08$ to $z = 2.5$ (isotropic background).
- Able to reproduce spectrum and composition + arrival direction map.

[1] J. Biteau (2021) Astrophys. J. Suppl. 256

Contribution for each galaxy in a transient scenario

☛ Each galaxy contributes with a number of bursts N given by:

$$N = \Delta\tau \cdot k \cdot s$$



With

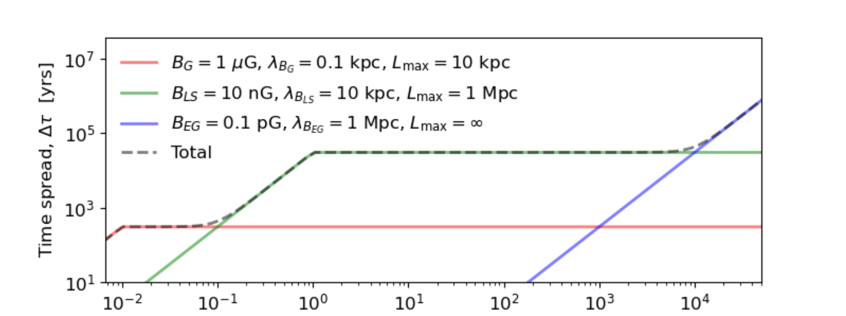
- s is the tracer.
- $\Delta\tau$ is the time spread induced by magnetic fields.
- k is a parameter such as $k \cdot s$ is the the burst rate.

☛ N is randomized $\longrightarrow$ 100 realizations $\longrightarrow$ median map.

Magnetic field and time spread

- Magnetic fields contribute not only in deflection but also on time delays.
- The time spread is computed assuming small-angle scattering:

$$\frac{\Delta\tau}{4.4\times 10^3\ \text{yr}} = \left(\frac{B}{10\ \text{nG}}\right)^2 \left(\frac{R}{10\ \text{EV}}\right)^{-1} \left(\frac{d}{1\ \text{Mpc}}\right)^2 \left(\frac{\lambda_B}{10\ \text{kpc}}\right) \tag{1}$$

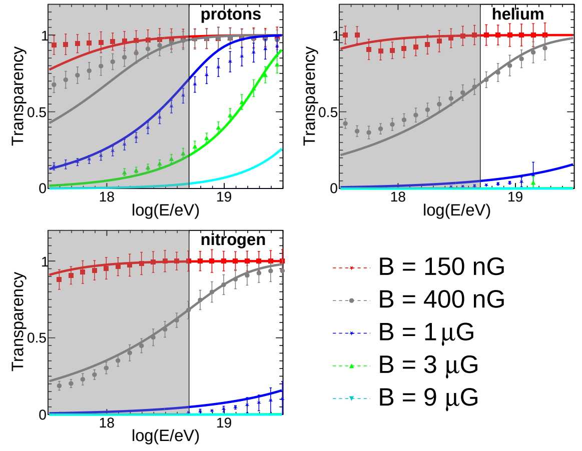


- $\Delta\tau$ large $\longrightarrow$ make a transient event quasi-persistent for far-enough source.

Propagation in galaxy clusters

☛ Galaxy clusters ⟶ how do they affect UHECR propagation? In [2]:

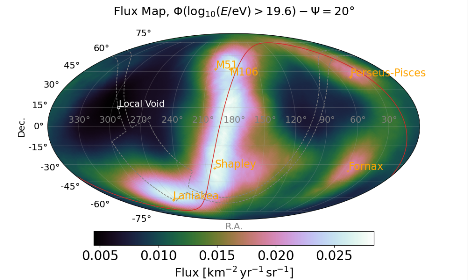
- Modelling on the environment under the assumption of self-similarity.
- Propagation in the environment.
- Universal parametrization of the transparency.
- Take-home message: galaxy clusters are very opaque environment for UHECR nuclei ⟶ effect to be taken into account!

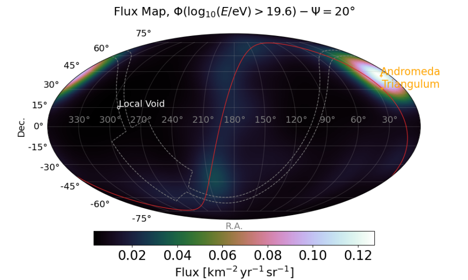


[2] A. Condorelli, J. Biteau and R. Adam., submitted to *ApJ*

Exploring the plausible range of k

Scan over a range of k to reproduce the observed sky map.

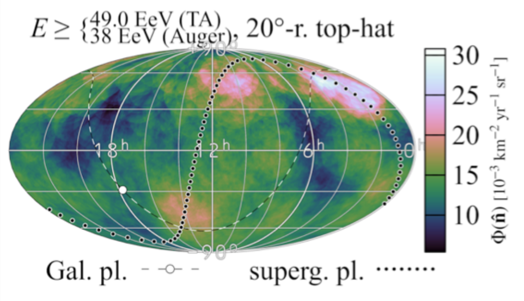


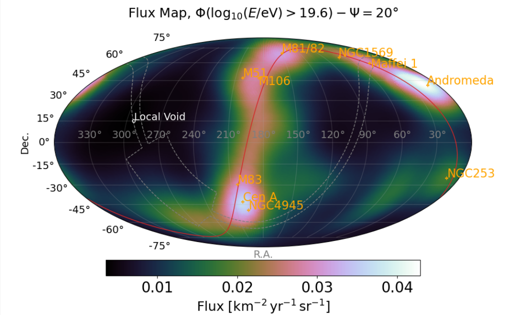


- low value of k ($3 \cdot 10^{-17}$ $M_\odot^{-1}$ yr^{-1}): filter the nearby sources.
- Sky map dominated by sources at distances ≥ 10 Mpc.

- high value of k ($1 \cdot 10^{-13}$ $M_\odot^{-1}$ yr^{-1}): contribution from nearby sources.
- Sky map dominated by the Andromeda Galaxy (not seen in data).

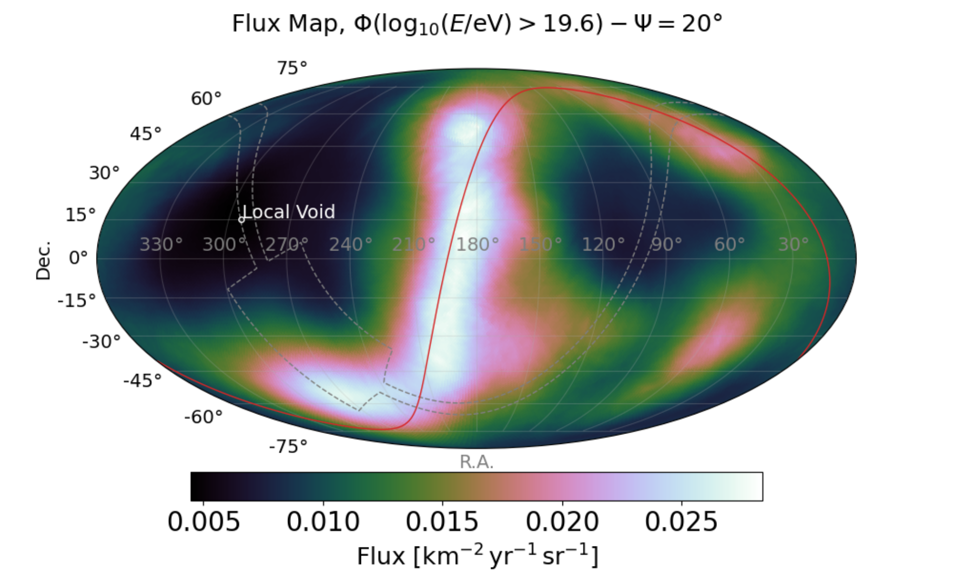
Best k





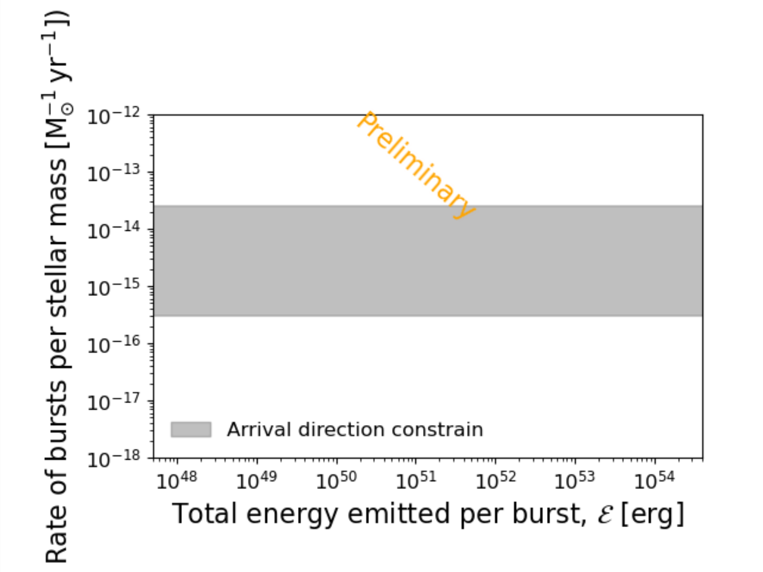
- The best map is obtained for a value of $k = 1 \cdot 10^{-15}\ \mathrm{M}_\odot^{-1}\ \mathrm{yr}^{-1}$.
- A range of k is plausible for matching the observations.

Best k



Flux Map, Φ(log10(E/eV) > 19.6) − Ψ = 20°
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Dec.
Local Void
330°
300°
270°
240°
210°
180°
150°
120°
90°
60°
30°
R.A.
0.005
0.010
0.015
0.020
0.025
Flux [km−2 yr−1 sr−1]

Constraints on UHECR sources



☛ The experimental skymaps constrains the burst rate.

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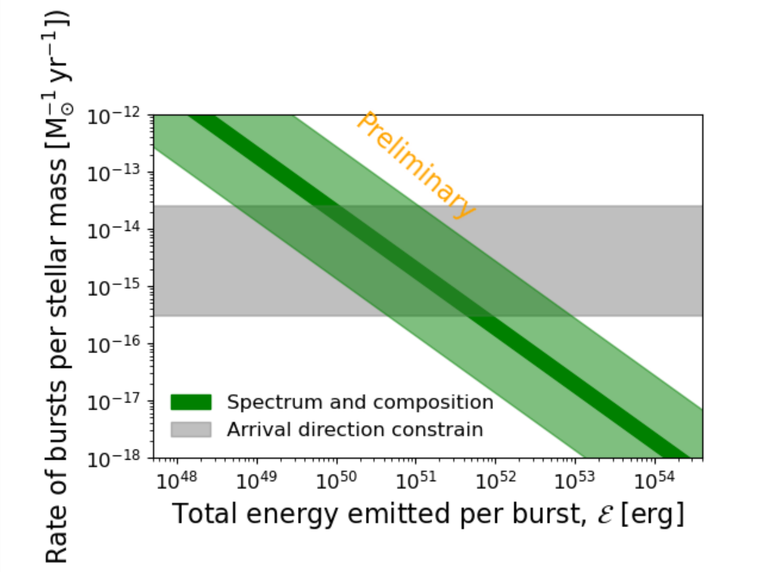

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- ☛ Spectrum and composition constrain the energetic budget.

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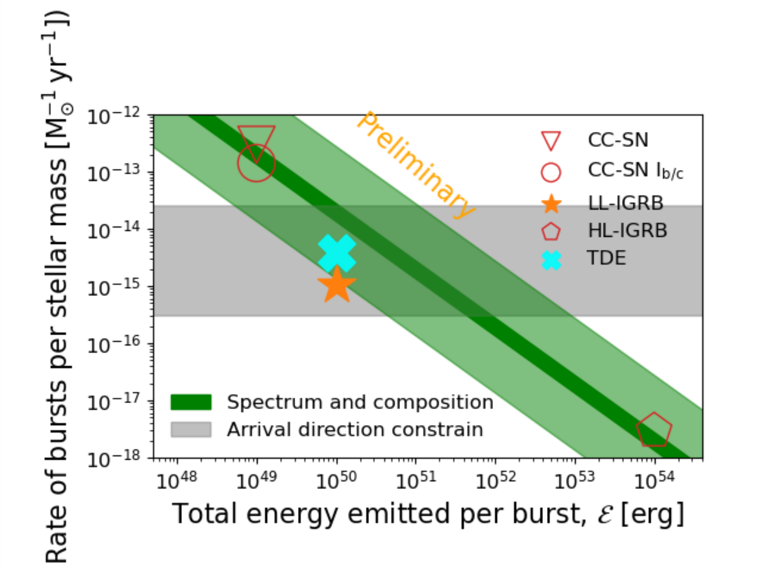
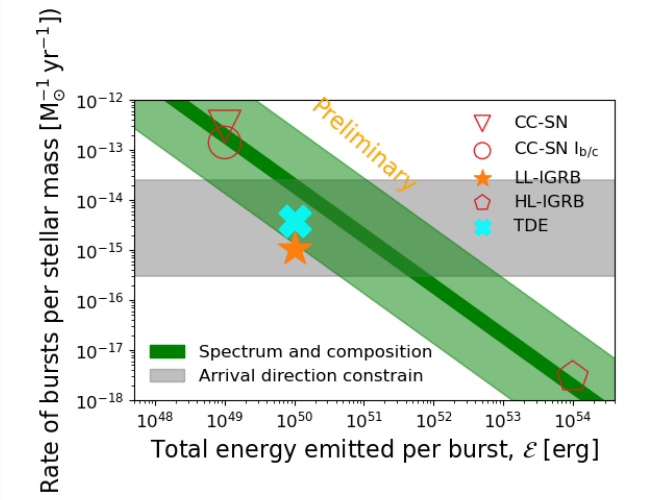


- ☛ The experimental skymaps constrains the burst rate.
- ☛ Spectrum and composition constrain the energetic budget.
- ☛ LL-lGRB and TDE are suitable candidate UHECR sources in a transient scenario.

Constraints on UHECR sources

Thanks for your attention!



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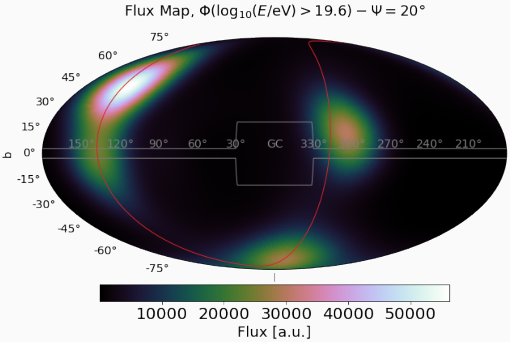
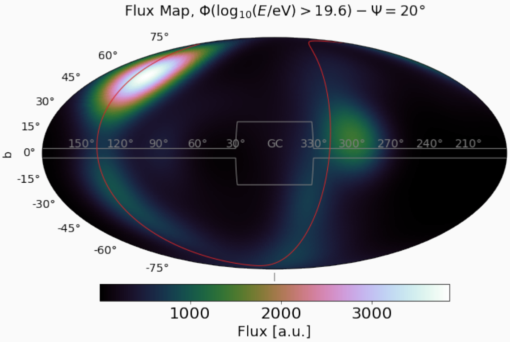
BACK-UP

Including coherent deflection



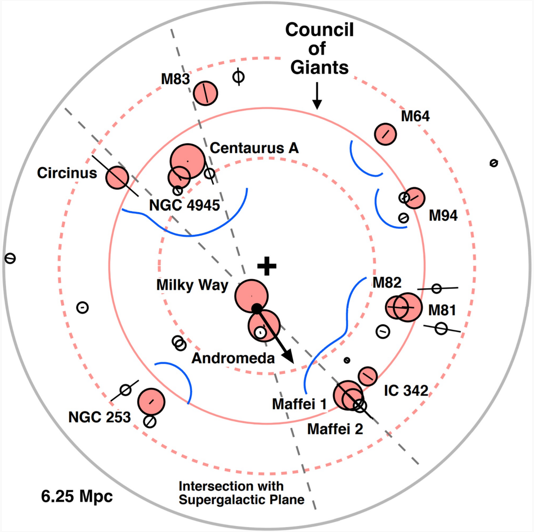
- GMF model: JF12;
- Force-brutal backtracking accounting for (de)magnification effects (agreeing with Farrar-Sutherland JCAP 05 (2019) 004)
- Fraction of He from < 5 Mpc sources such as 3% of He in total (up to 10%, depending on hadronic interaction model, in the latest Auger report at this conference)

Including coherent deflection

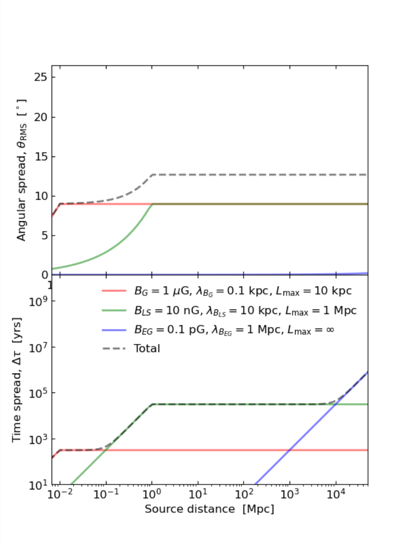


- GMF model: JF12;
- Force-brutal backtracking accounting for (de)magnification effects (agreeing with Farrar-Sutherland JCAP 05 (2019) 004)
- No Helium.

Local sheet


Council
of
Giants
M83
M64
Centaurus A
Circinus
NGC 4945
M94
Milky Way
M82
M81
Andromeda
IC 342
Maffei 1
NGC 253
Maffei 2
6.25 Mpc
Intersection with
Supergalactic Plane

Magnetic fields and angular spread

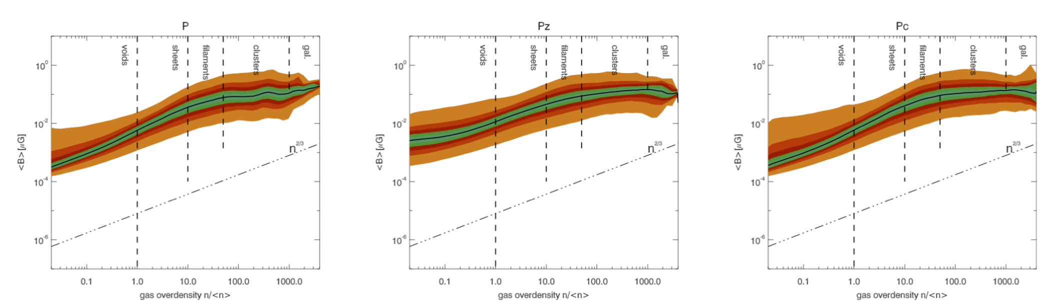


$$\frac{\Delta\theta}{3.4^\circ} = \left(\frac{B}{10\ \mathrm{nG}}\right)\left(\frac{R}{10\ \mathrm{EV}}\right)\left(\frac{d}{1\ \mathrm{Mpc}}\right)^{1/2}$$

$$\left(\frac{\lambda_B}{10\ \mathrm{kpc}}\right)^{1/2}$$

Chosen values of the magnetic fields

- Galactic magnetic field: 1 μG (JF12), λ_c = 100 pc (JF12), L_{max} = 10 kpc (size fo the galaxy).
- Local Sheet magnetic field: largely under-constrained. From MHD simulations (Donnert et al. 2018) $B \simeq 2 - 10$ nG, λ_c = 10 kpc (Donnert et al. 2018), L_{max} = 1 Mpc (radius of the Local Group).



Chosen values of the magnetic fields

- Extra-galactic magnetic field: Upper limits on extragalactic magnetic fields are set to tens of pG, for magnetic fields of primordial origin that would affect CMB anisotropies (Jedamzik & Saveliev 2019).
- Lower limits at the fG level have also been derived from the non-observation in the GeV range of gamma-ray cascades from TeV blazars (Neronov & Vovk 2010; Tavecchio et al. 2010; Ackermann et al. 2018)
- $\lambda_c = 1$ Mpc (Bray and Scaife, 2018)).