Ring closing on transient accelerators of ultra-high energy cosmic rays

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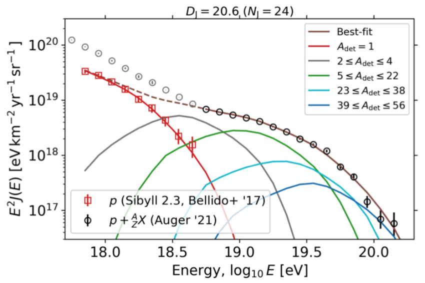
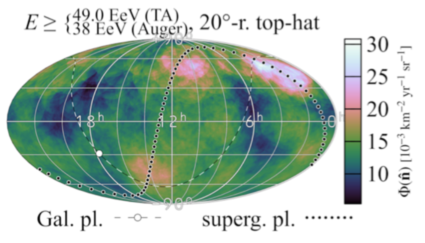
Observational constraints

Pierre Auger Collaboration, PRL 125 (2020) 121106



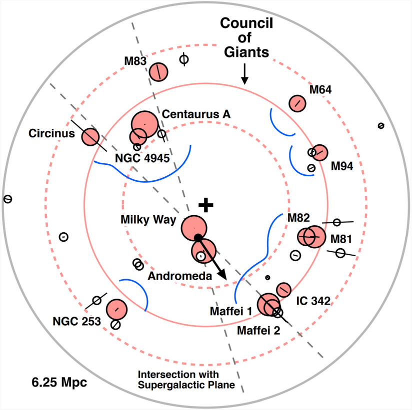
Pierre Auger and Telescope Array Collaborations, ICRC 2023



- Emissivity constrained by spectrum and composition data
- Correlation with starburst galaxies contributing only to ~10% of the flux. What about the remaining 90%?
- Starburst galaxies responsible for ~15% of the SFR for $z < 2$

SFR, Council of Giants and SBG correlation

☛ Assumption: SFR or $M_\star$ as tracers of UHECR production rate

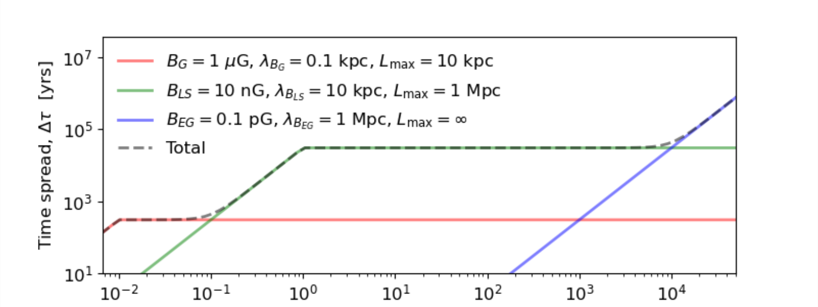


☛ Transient sources?

Transient sources and magnetic-fields induced time spread

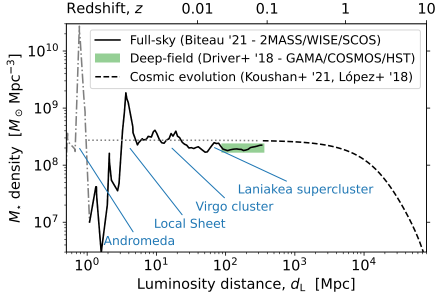
- Impact of **B** on UHECRs: deflections *and* time spread in arrivals
- Assuming small-angle scattering:

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



UHECR-source model

- ☛ Catalogue of ~ 400,000 galaxies[1] within 350 Mpc

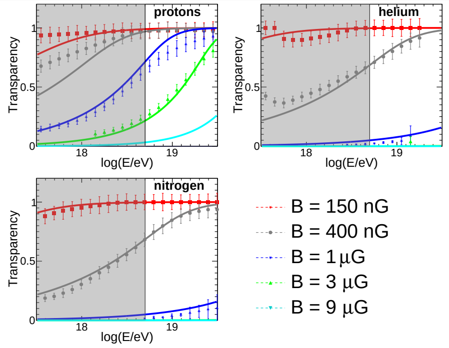


- ☛ UHECR flux contribution of each foreground galaxy ∝ to its SFR or $M_\star$
- ☛ Isotropic background from $z = 0.08$ to $z = 2.5$
- ☛ Best match of spectrum and composition data + arrival direction map

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

Propagation in galaxy clusters

☛ Galaxy clusters: very opaque environments for UHECR nuclei:[2]



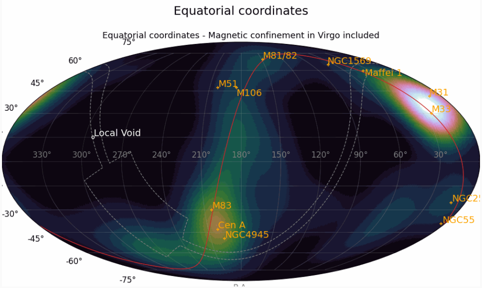
- Modelling of the environment under the assumption of self-similarity
- Propagation in the cluster environments
- Rigidity-dependent escape time much longer than age of clusters

[2] A. Condorelli et al., arXiv:2309.04380; D. Harari et al., JCAP 08 (2016) 010

Contribution of each galaxy in a transient scenario

☛ Stochastic number of bursts of each foreground galaxy:

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

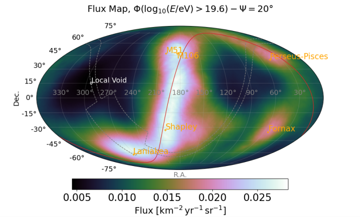


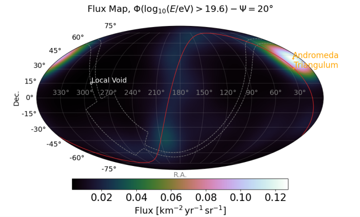
- s: tracer
- $\Delta\tau$: time spread induced by magnetic fields
- k: parameter such as $k \cdot s$ is the the burst rate

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

Exploring the plausible range of k

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





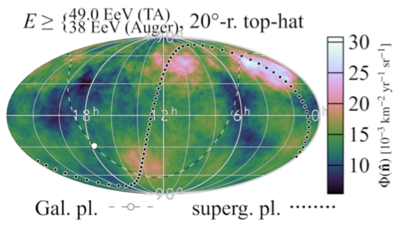
☛ Low value of k ($3 \cdot 10^{-17}\ \mathrm{M}_\odot^{-1}\ \mathrm{yr}^{-1}$):

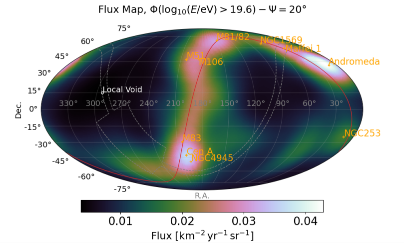
- Nearby sources filtered
- Sky map dominated by sources at distances ≥ 10 Mpc

☛ High value of k ($1 \cdot 10^{-13}\ \mathrm{M}_\odot^{-1}\ \mathrm{yr}^{-1}$):

- Contribution from nearby sources
- Sky map dominated by the Andromeda Galaxy

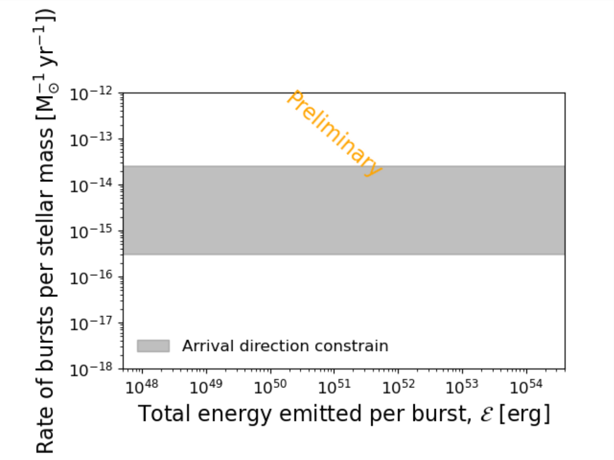
Best k





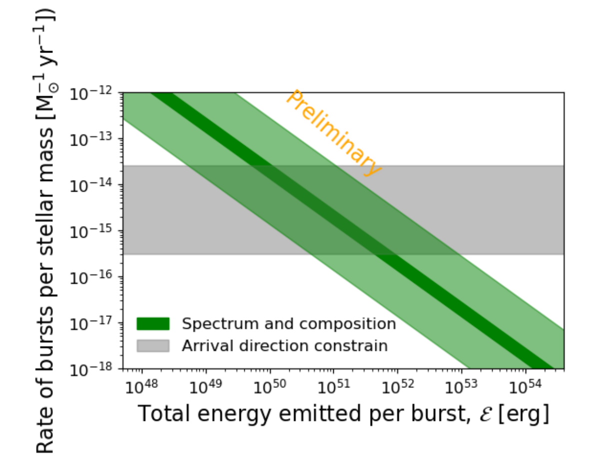
- Best value: $k = 1 \cdot 10^{-15}\ \mathrm{M}_\odot^{-1}\ \mathrm{yr}^{-1}$
- Possible range of k obtained within a range of Local Sheet magnetic fields
- SBG correlation (10% signal) indeed explained by transient events traced by SFR or $M_\star$

Constraints on transient UHECR sources



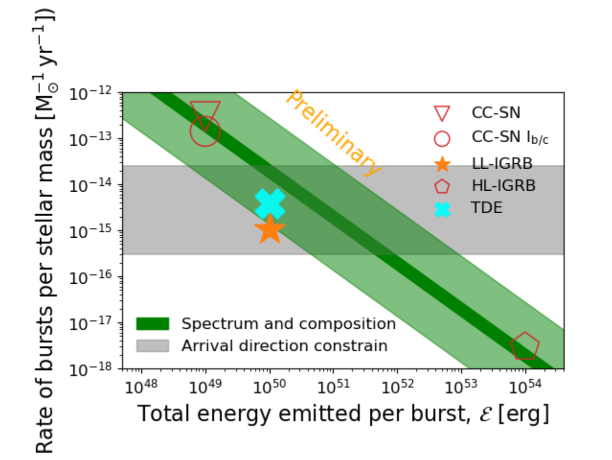
☛ Burst rate constrained by sky maps

Constraints on transient UHECR sources



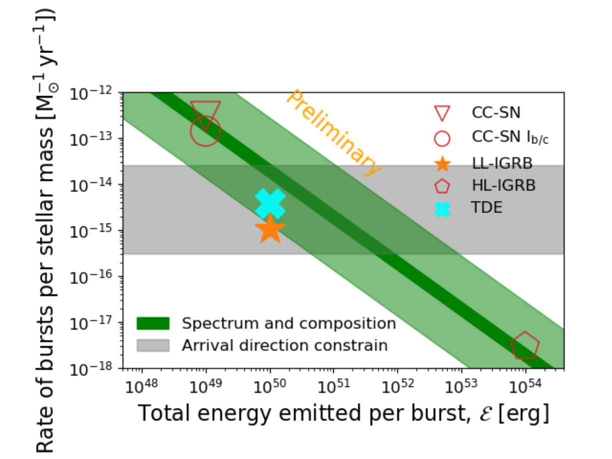
- ☛ Burst rate constrained by sky maps
- ☛ Energetic budget constrained by spectrum and composition data

Constraints on transient UHECR sources



- ☛ Burst rate constrained by sky maps
- ☛ Energetic budget constrained by spectrum and composition data
- ☛ Suitable source candidates: LL-lGRB and TDE

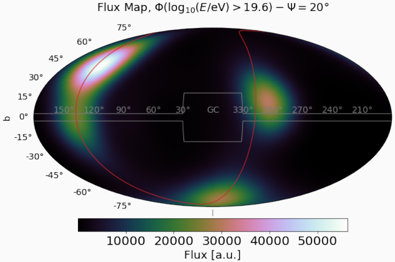
Constraints on transient UHECR sources



Thanks for your attention

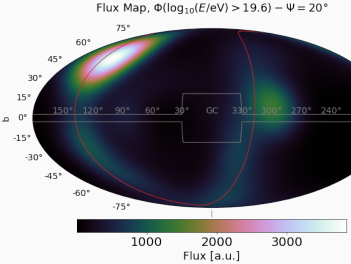
BACK-UP

Including coherent deflections



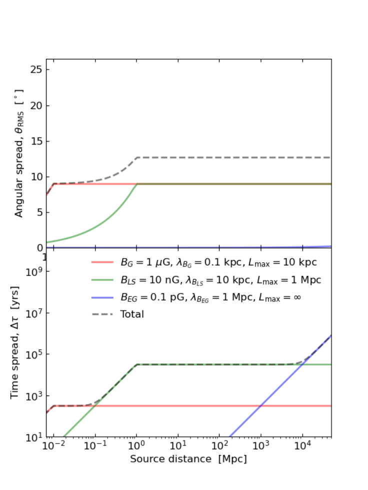
- GMF model: JF12;
- Force-brutal backtracking accounting for (de)magnification effects
- Fraction of He from < 5 Mpc sources such as 3% of He in total (up to 10%, depending on hadronic interaction model, in the latest Auger report)

Including coherent deflections



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

Magnetic fields and angular spread



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

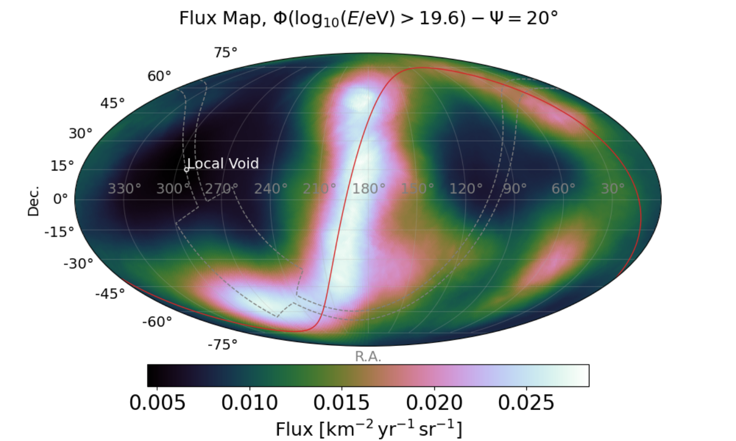
Chosen values of the magnetic fields

- Galactic magnetic field: 1 μG (JF12), $\lambda_c = 100$ 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, $\lambda_c = 10$ 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)).

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]