Observational Constraints on Cosmic-Ray Escape from Ultra-High Energy Accelerators

O. Deligny

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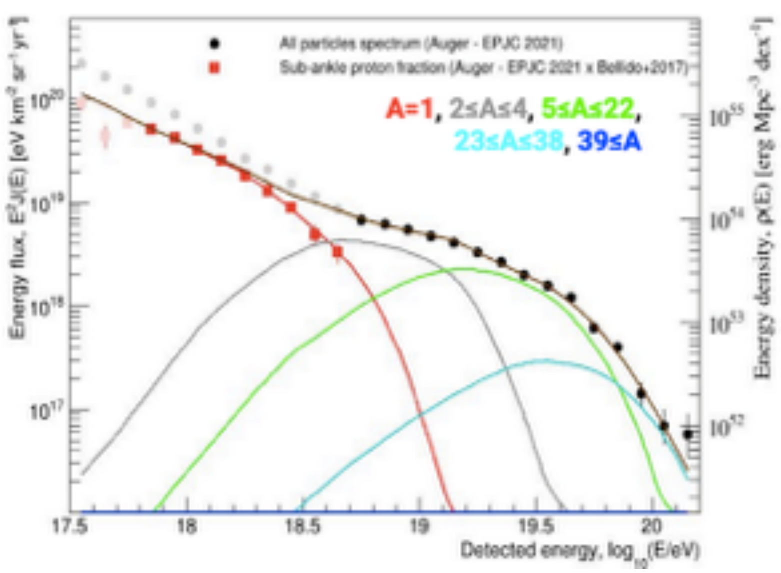
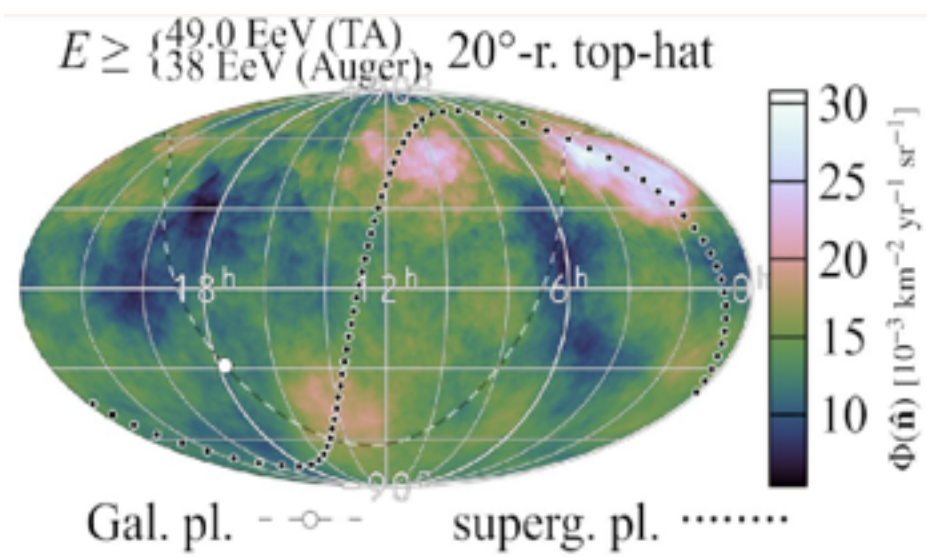
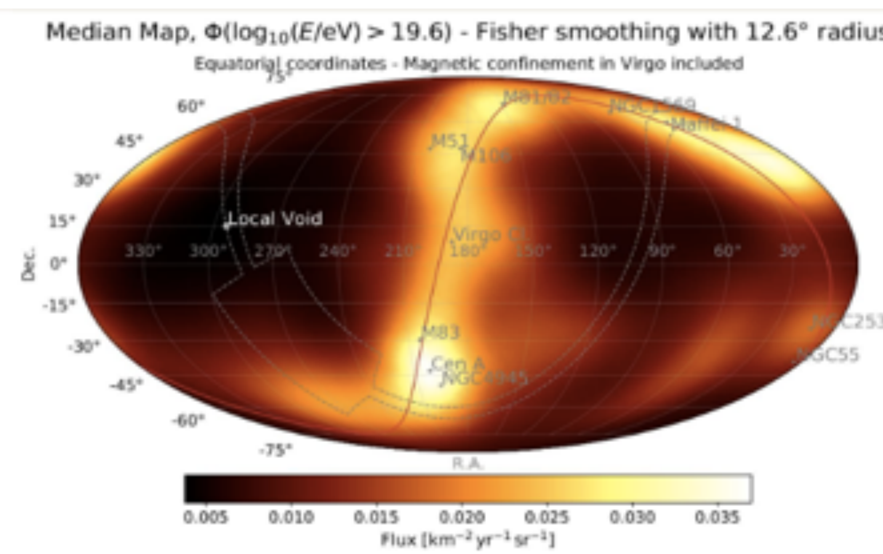
Contribution based on Luce et al. **ApJ 936 32 (2022)** *and* Marafico et al. in prep.







CRIS 2022
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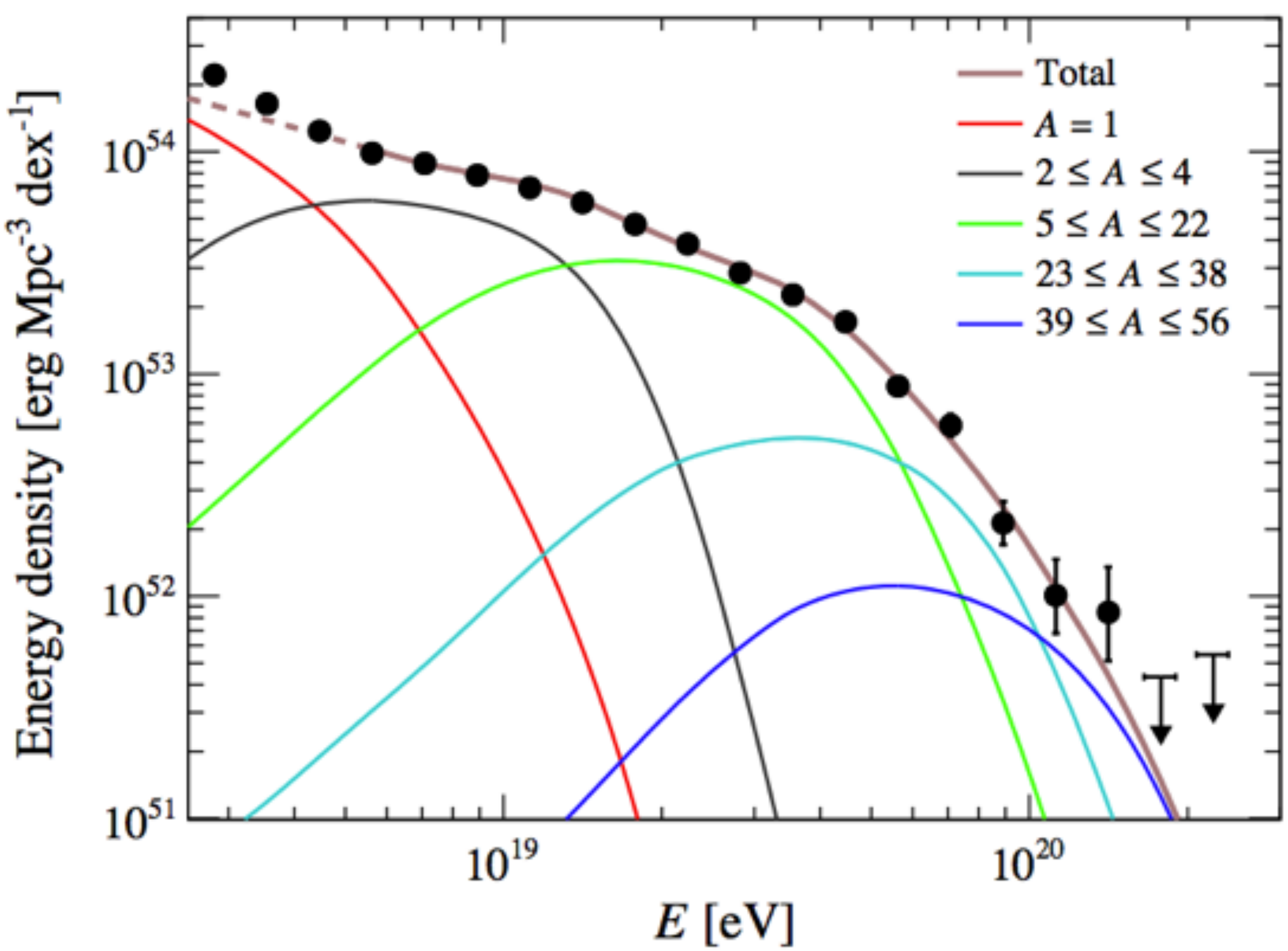
Astrophysical picture of Auger data at UHE

[PRL 125 (2020) 121106]



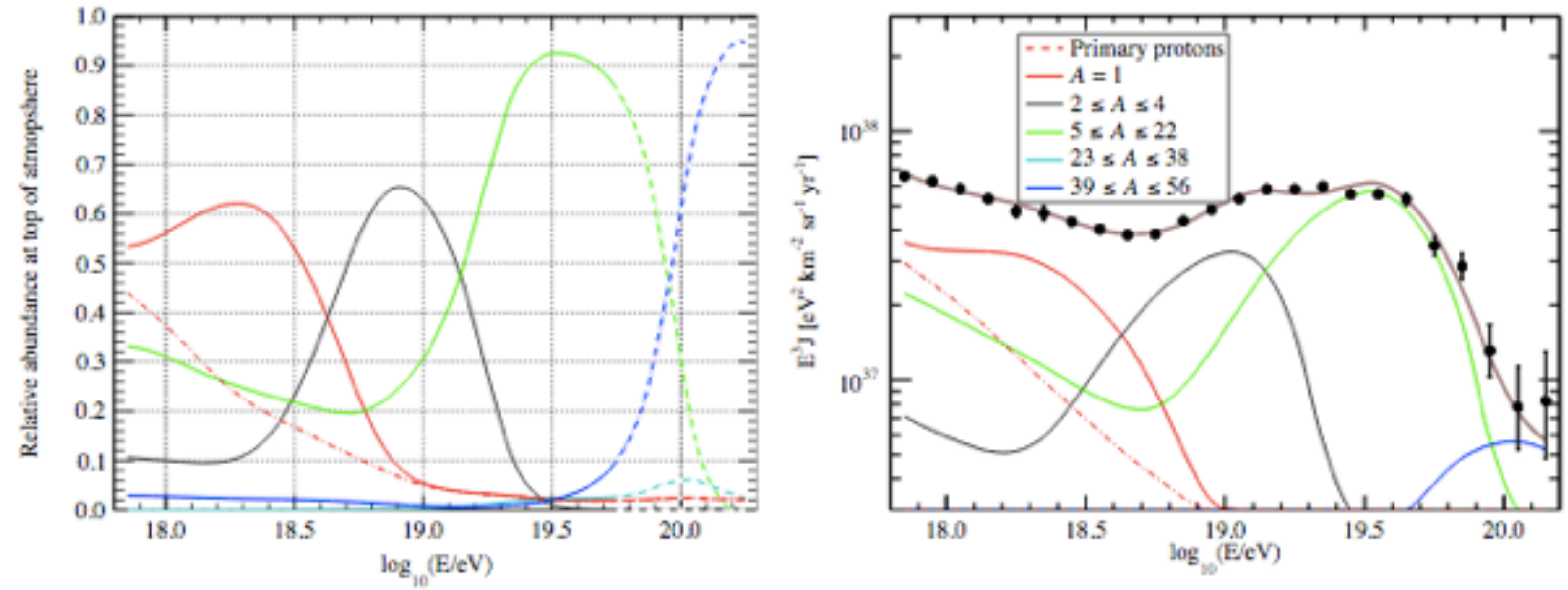
- Hard ejected spectra (quasi mono-elemental fluxes at UHE)
- Energy cutoff ~5Z EeV
- Steepening above ~50 EeV: combination of the maximum energy of acceleration of the heaviest nuclei at the sources and the GZK effect
- Steepening above ~10 EeV: interplay between the flux contributions of He and CNO injected at the source with their distinct cutoff energies, shaped by photodisintegration during the propagation
- Luminosity density ($E^2 q_{\rm gen}(E)$): $6\ 10^{44}$ erg Mpc^{-3} yr^{-1}

Ankle feature?

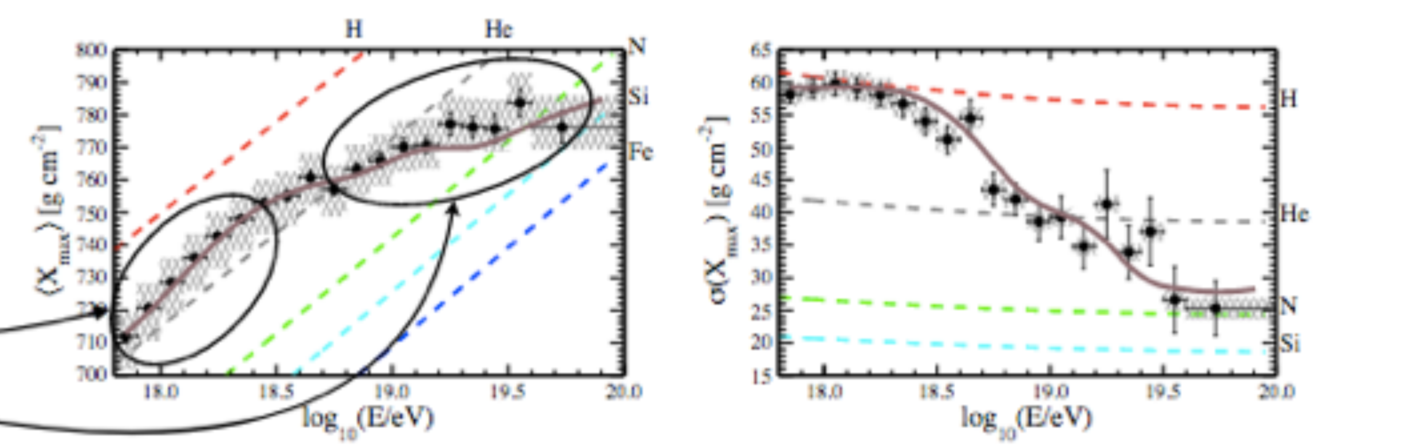
[E. Guido (Auger Collab.), ICRC2021]

EG components (at the sources)	Low energy	High energy
$\mathcal{L}_0$ $[10^{45}$ erg Mpc^{-3} yr$^{-1}]$	17.0	0.45
γ	3.49 ± 0.02	-1.98 ± 0.10
$\log_{10}(R_{\rm cut}/{\rm V})$	24 (lim.)	18.16 ± 0.01
$I_{\rm H}$ (%)	49.87	0.0
$I_{\rm He}$ (%)	10.92	28.60
$I_{\rm N}$ (%)	36.25	69.05
$I_{\rm Si}$ (%)	0.0	0.0
$I_{\rm Fe}$ (%)	2.96	2.35
D_J (N_J)	60.1 (24)	
$D_{X_{\max}}$ $(N_{X_{\max}})$	554.8 (329)	
D (N)	614.9 (353)	

Predicted fluxes at Earth

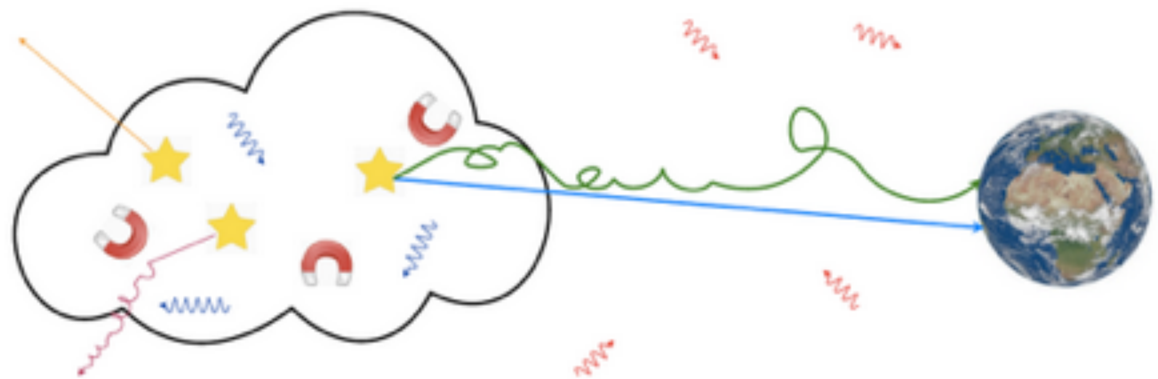


- **Low energy:** mixed composition dominated by H and N
- **High energy:** increasingly heavier mass composition, mass groups not much superposed



Alternative: Acceleration vs emission spectral index

➡ The role of in-source interactions

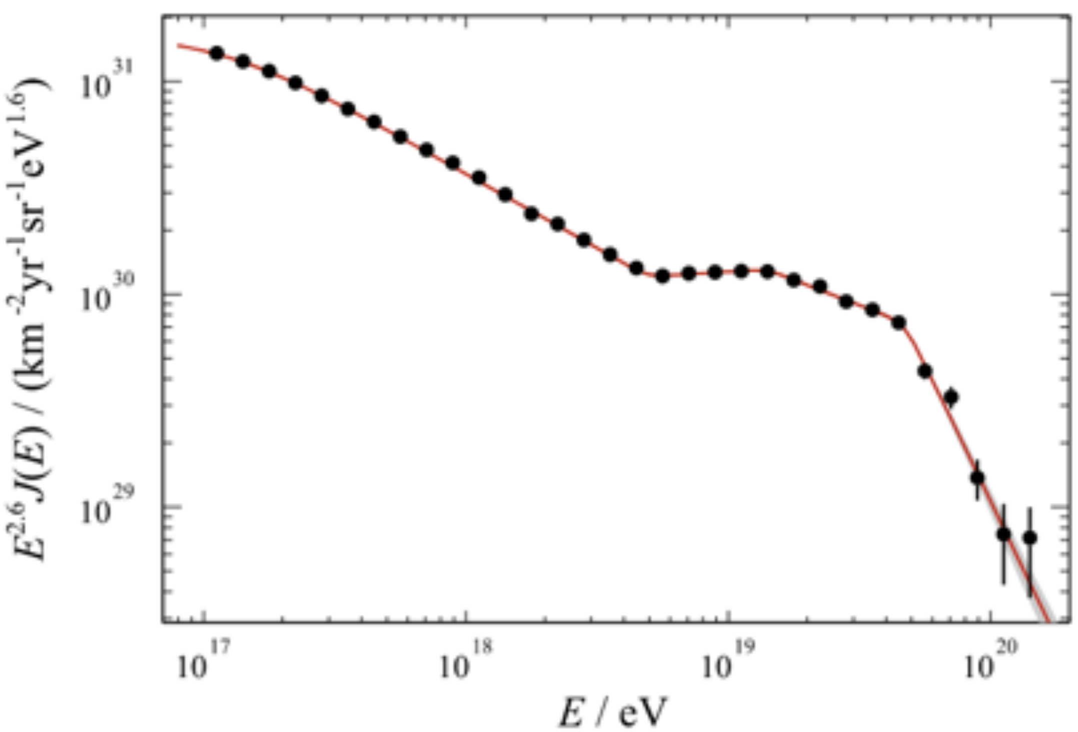


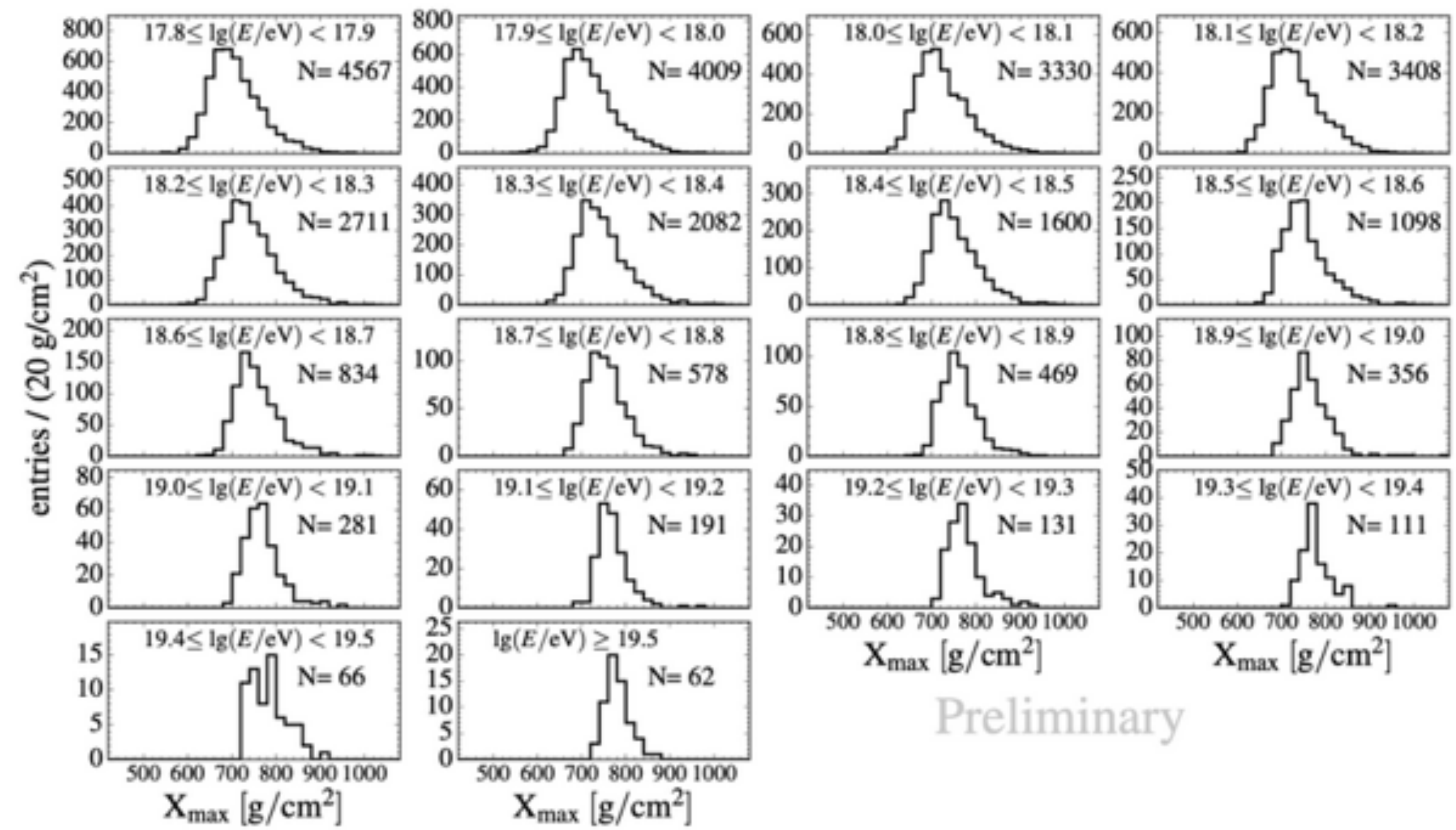
- Accelerated particles confined in the environment surrounding the source;
- Presence of photon and gas density;
- High energy particles–> escape with no interaction;
- Low energy particles –> Pile-up of nucleons at lower energies.

Interactions at the source already discussed in:

✓Unger, M., Farrar, G. R., & Anchordoqui, L. A. 2015, PhRvD, 92, 123001
✓Globus, N., Allard, D., & Parizot, E. 2015, PhRvD, 92, 021302
✓Biehl, D., Boncioli, D., Fedynitch, A., & Winter, W. 2018, A&A, 611, A101
✓Zhang, B. T., Murase, K., Kimura, S. S. Et al., P. 2018, PhRvD, 97, 083010
✓Fang, K., & Murase, K. 2018, Nature Phys., 14, 396
✓Supanitsky, A. D., Cobos, A., & Etchegoyen, A. 2018, PhRvD, 98, 103016
✓Boncioli, D., Biehl, D., & Winter, W. 2019, ApJ, 872, 110
✓Condorelli, A., Boncioli, D., Peretti., E., & Petrera, S., *PoS* ICRC2021 (2021) 959

Ingredients of the combined fit



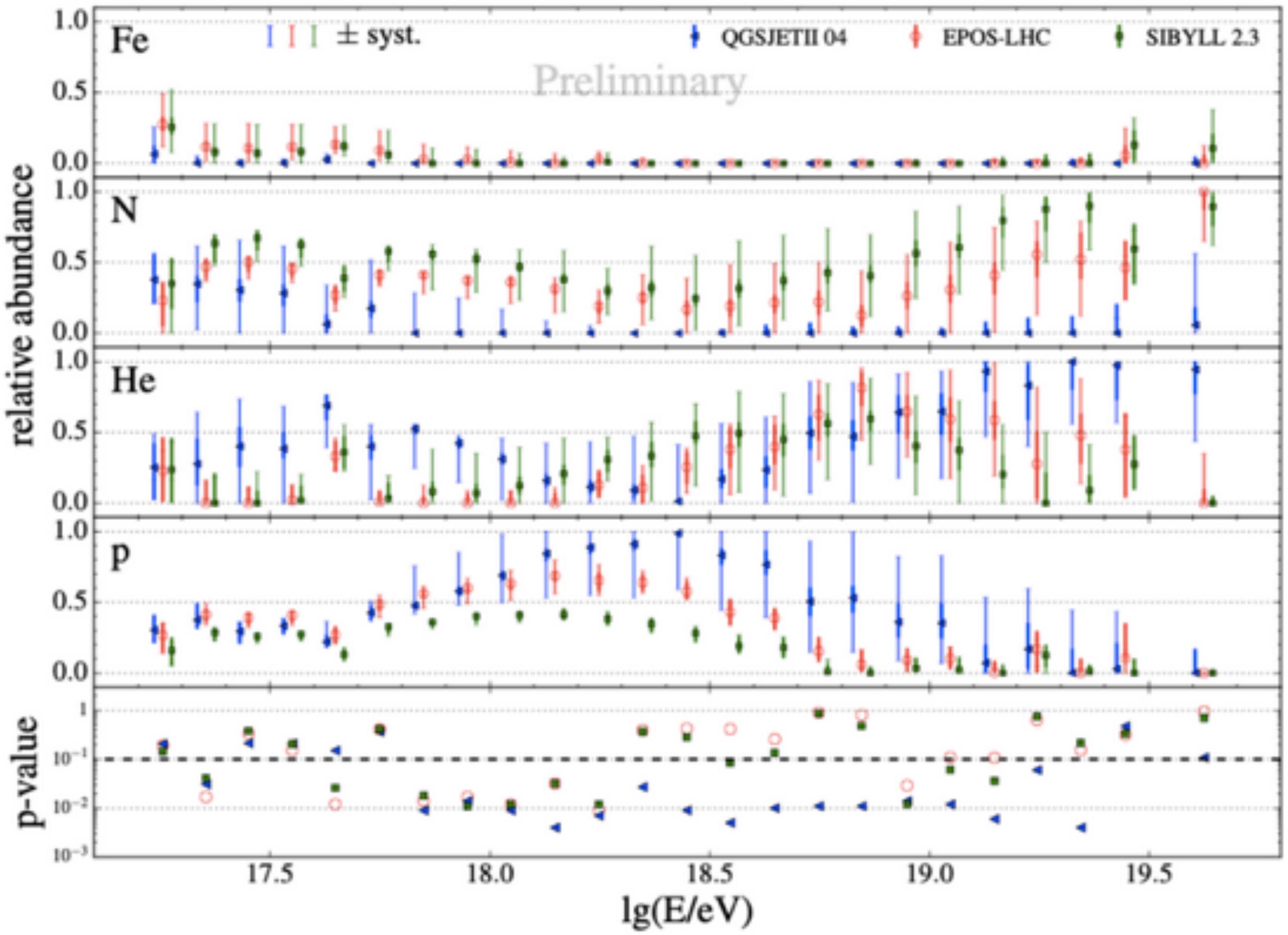


- Model:
$$J(E) = \frac{c}{4\pi} \sum_{A,\,A'} \iint \mathrm{d}z\, \mathrm{d}E' \left| \frac{\mathrm{d}t}{\mathrm{d}z} \right| S(z)\, q_{A'}(E')\, \frac{\mathrm{d}\eta_{AA'}(E, E', z)}{\mathrm{d}E}$$

- Standard combined fit above $10^{18.7}$ eV

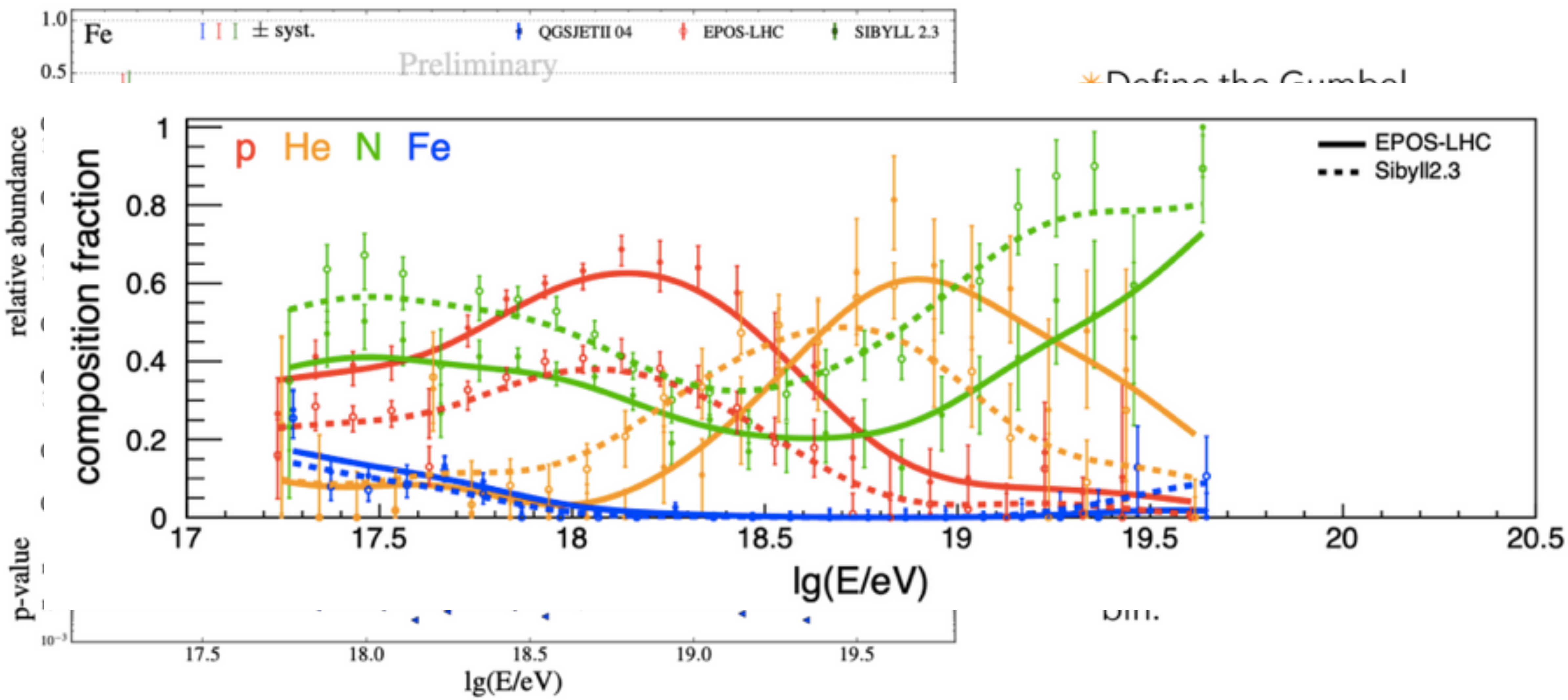
- $< 10^{18.7}$eV: protons alone as the low-energy counterpart of in-source interactions
➡ ++ **No need to model** the « high-energy Galactic component »

Proton flux



- Define the Gumbel distribution of a set of four masses (H, He, N, Fe);
- Including detector effects;
- Find the best fit fractions with respect to the chosen set of Gumbel distributions;
- Analysis independent bin to bin.

Proton flux



➡ Proton flux as total flux weighted by proton fraction

The generic model

- Emission of five representative masses: H, He, N, Si and Fe
- Ejected flux for each mass: exponentially-broken power law

$$q_{A_i}(E) = q_{0A_i}\left(\frac{E}{E_0}\right)^{-\gamma_A} f_{\rm supp}(E, Z_{A_i}), \qquad q_{\rm p}(E) = q_{0{\rm p}}\left(\frac{E}{E_0}\right)^{-\gamma_{\rm p}} f_{\rm supp}(E, Z_{\rm p}), \qquad f_{\rm supp}(E, Z) = \begin{cases} 1 & \text{if } E \leqslant E^Z_{\max}, \\ \exp(1 - E/E^Z_{\max}) & \text{otherwise.} \end{cases}$$

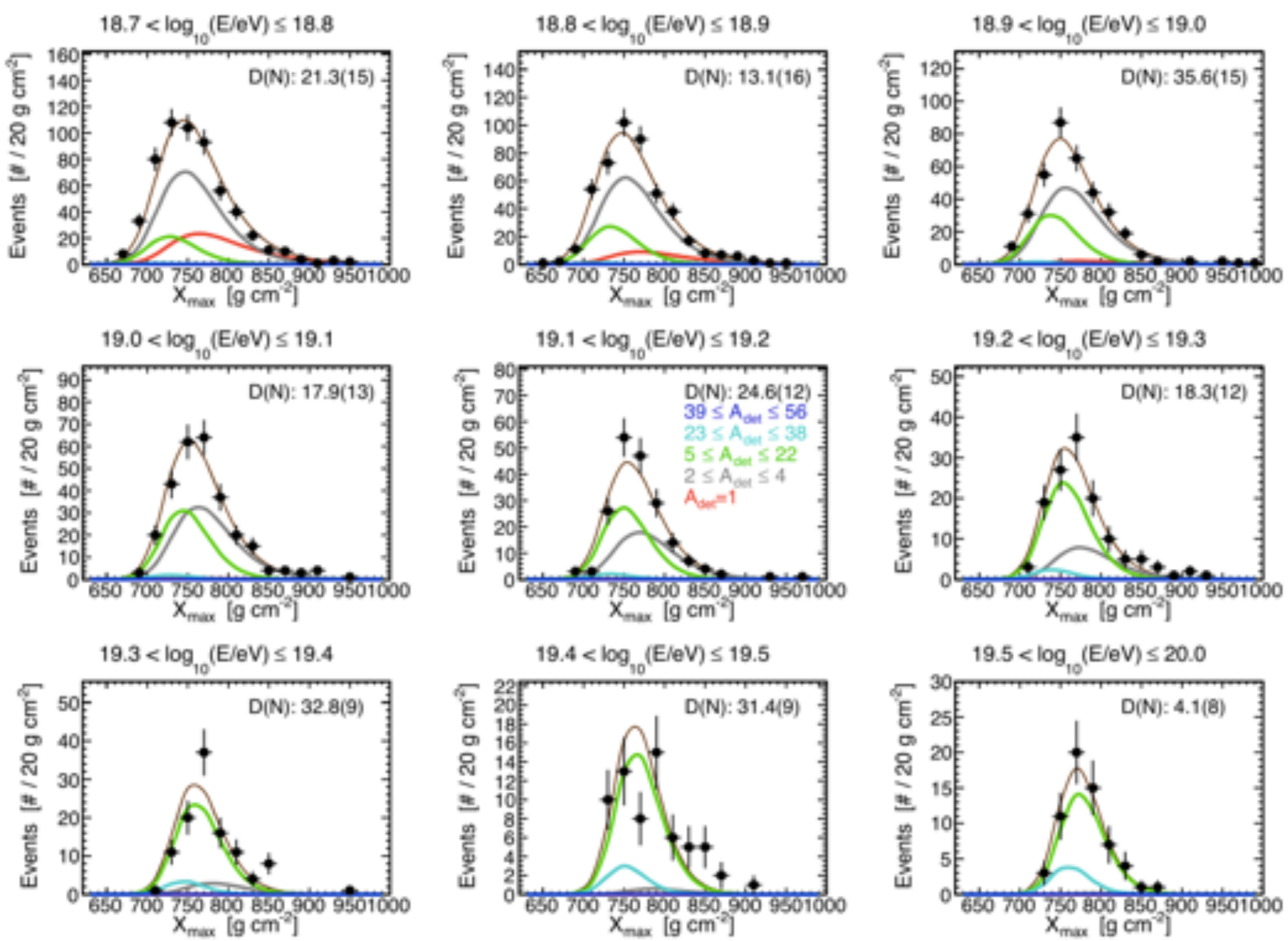
- Ejected flux are propagated using SimProp
- Goodness-of-fit: sum of spectrum and $X_{\max}$ deviances
- UHECR luminosity density traced by the density of baryonic matter over cosmic time [Madau & Dickinson 2014], with local overdensity [McCall 2014] — Correction factor inferred by Condon et al. 2019:

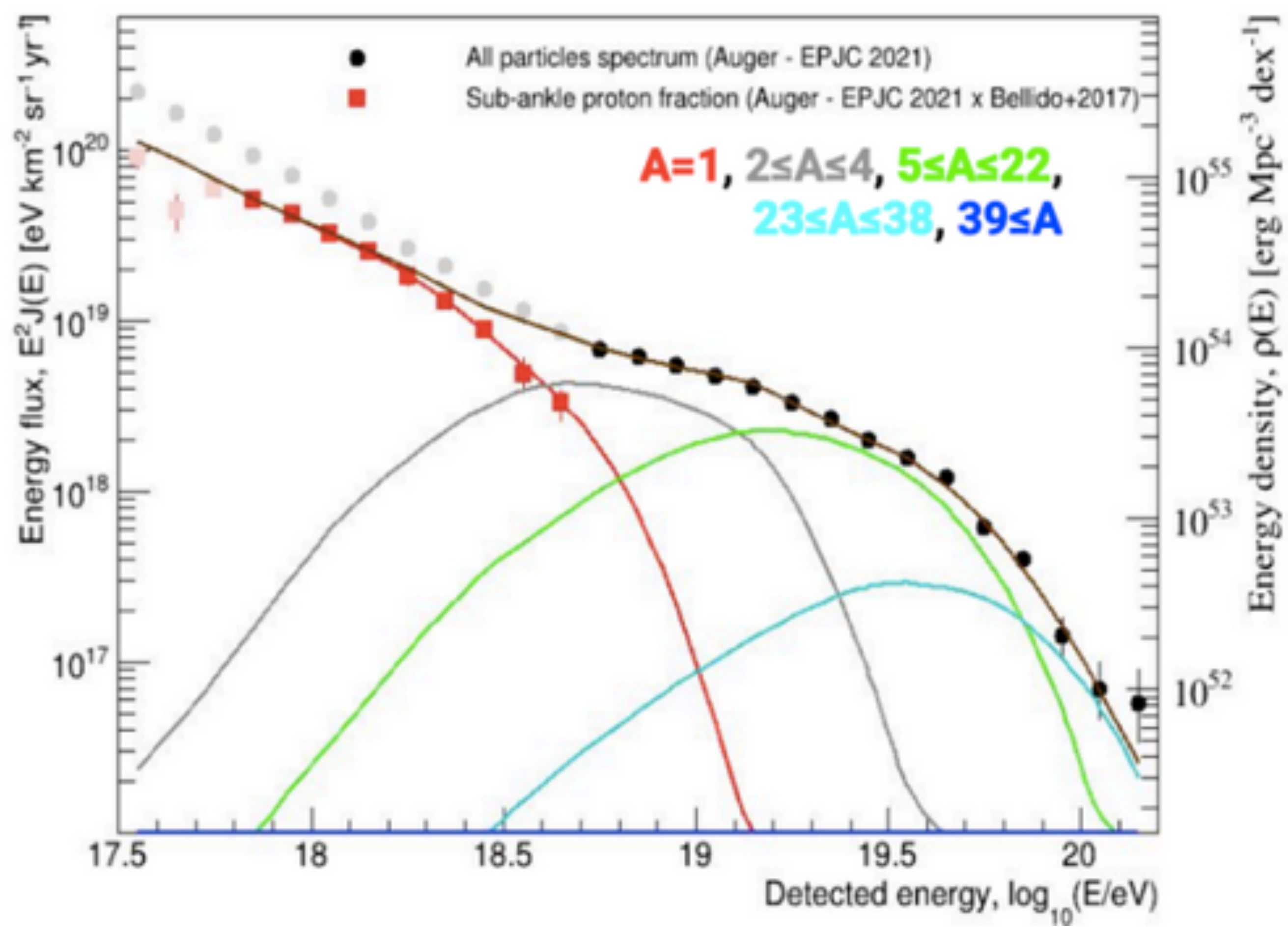
$$\frac{\delta\rho(r)}{\bar{\rho}} = 1 + \left(\frac{r}{r_0}\right)^{-\alpha}.$$

- xGal magnetic fields: fG<B<nG — ~pG here, ie negligible
- EBL: Gilmore, TALYS cross sections, EPOS-LHC & Sibyll2.3

Results

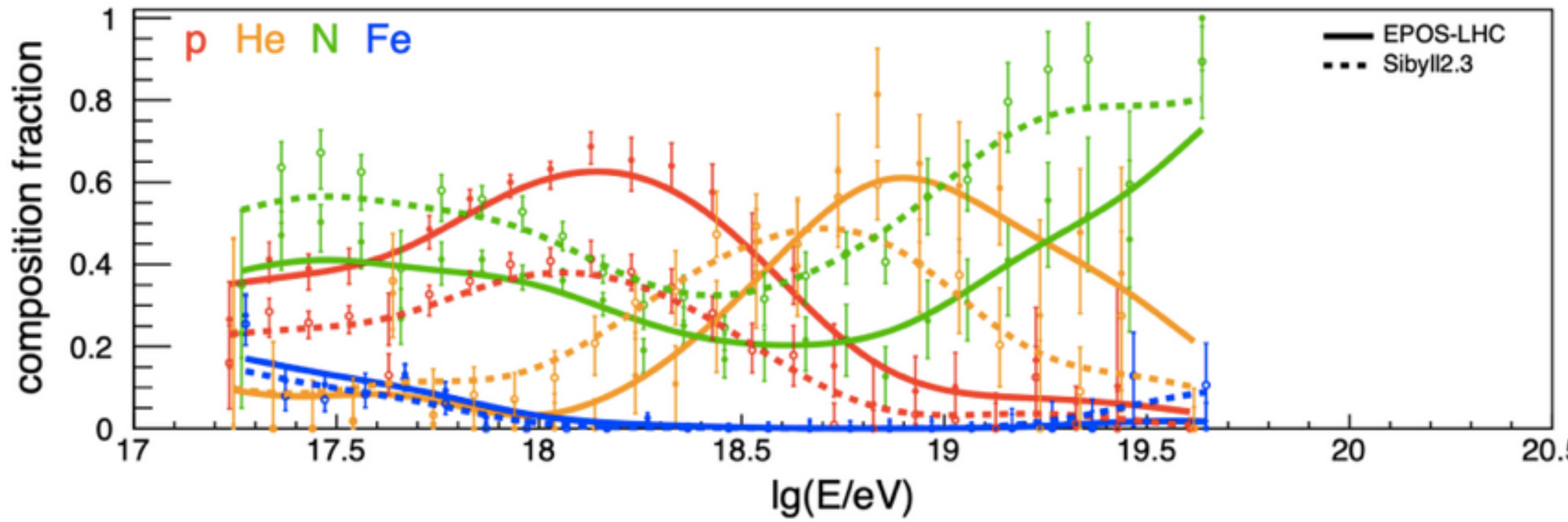
Scenario	$\gamma_{\rm p}$	γ_A	$\log_{10} E_{\max}$ [eV]	$\bar{\mathcal{L}}_{\rm p}/\mathcal{L}_0$	$\bar{\mathcal{L}}_{\rm He}/\mathcal{L}_0$	$\bar{\mathcal{L}}_{\rm N}/\mathcal{L}_0$	$\bar{\mathcal{L}}_{\rm Si}/\mathcal{L}_0$	$\bar{\mathcal{L}}_{\rm Fe}/\mathcal{L}_0$	D/ndf
$\gamma_{\rm p} = \gamma_A$	γ_A	-1.54 ± 0.10	18.19 ± 0.01	0.63 ± 0.07	1.4 ± 0.1	3.1 ± 0.1	0.34 ± 0.21	0.12 ± 0.02	862.7/126
$\gamma_{\rm p} \neq \gamma_A$	3.24 ± 0.10	-0.46 ± 0.03	18.35 ± 0.01	5.5 ± 0.2	1.7 ± 0.1	2.95 ± 0.06	0.62 ± 0.21	0.00 ± 0.19	236.8/125

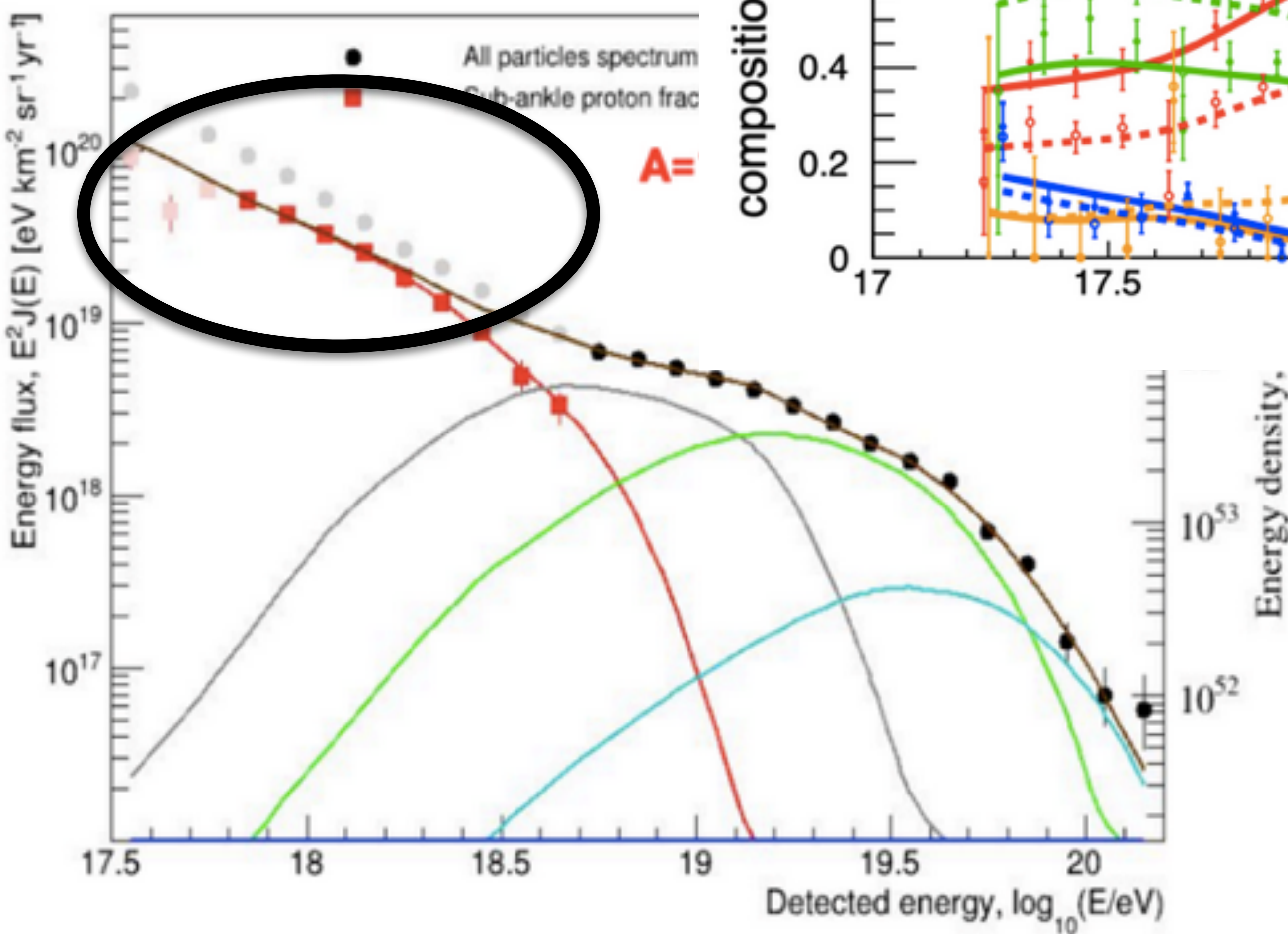




- Emission spectra in $E^{+0.5}$ (nuclei) and $E^{-3.5}$ (protons): extreme values?
- NB: $E^{-3.5}$ (protons) obtained if all protons are ejected ($E_{\max}/2$)
- Results stable against systematics in E, $X_{\max}$, hadronic interaction models, EBL models, redshift evolution of UHECR luminosity

« B-component? » (Hillas)



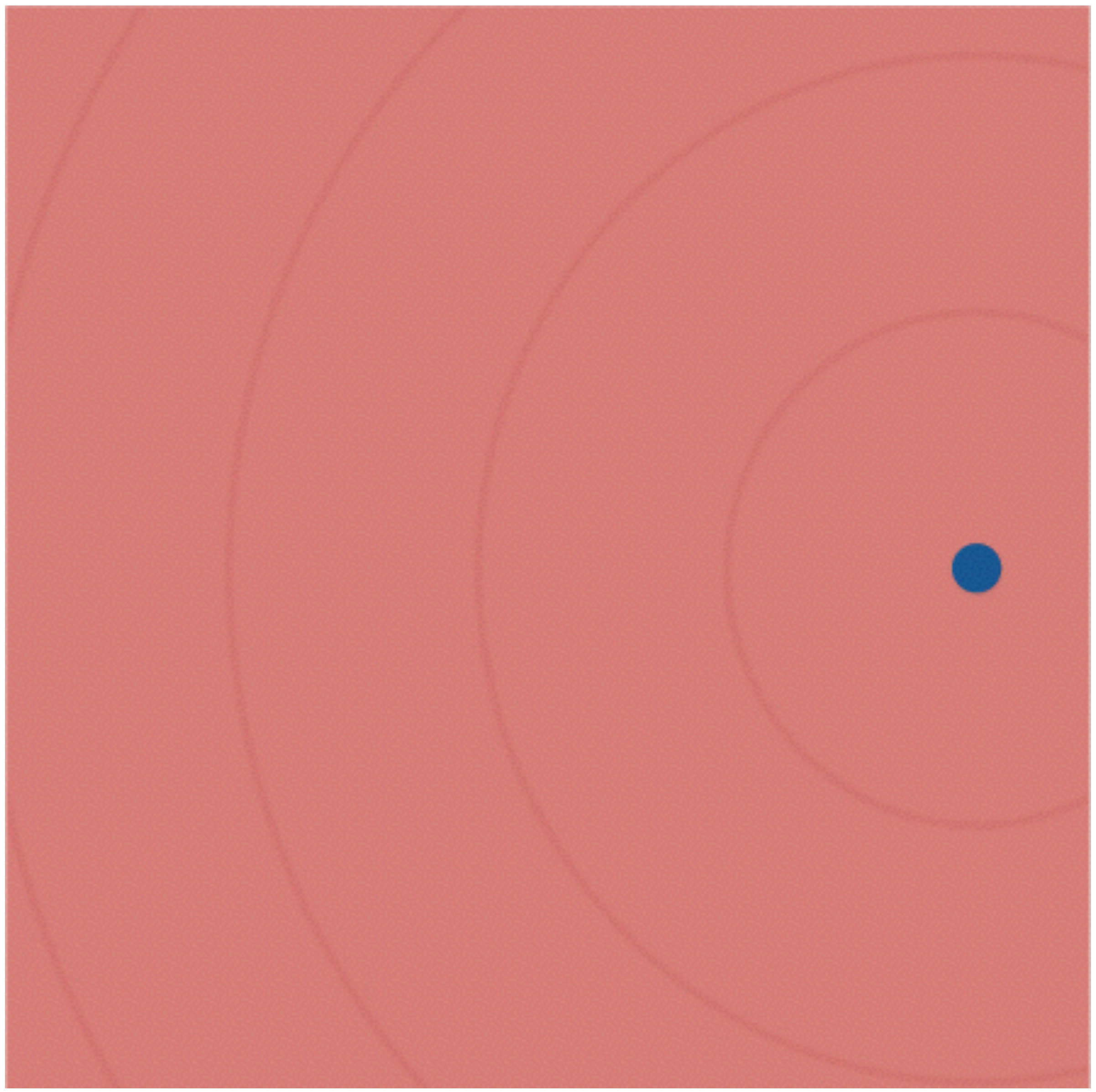


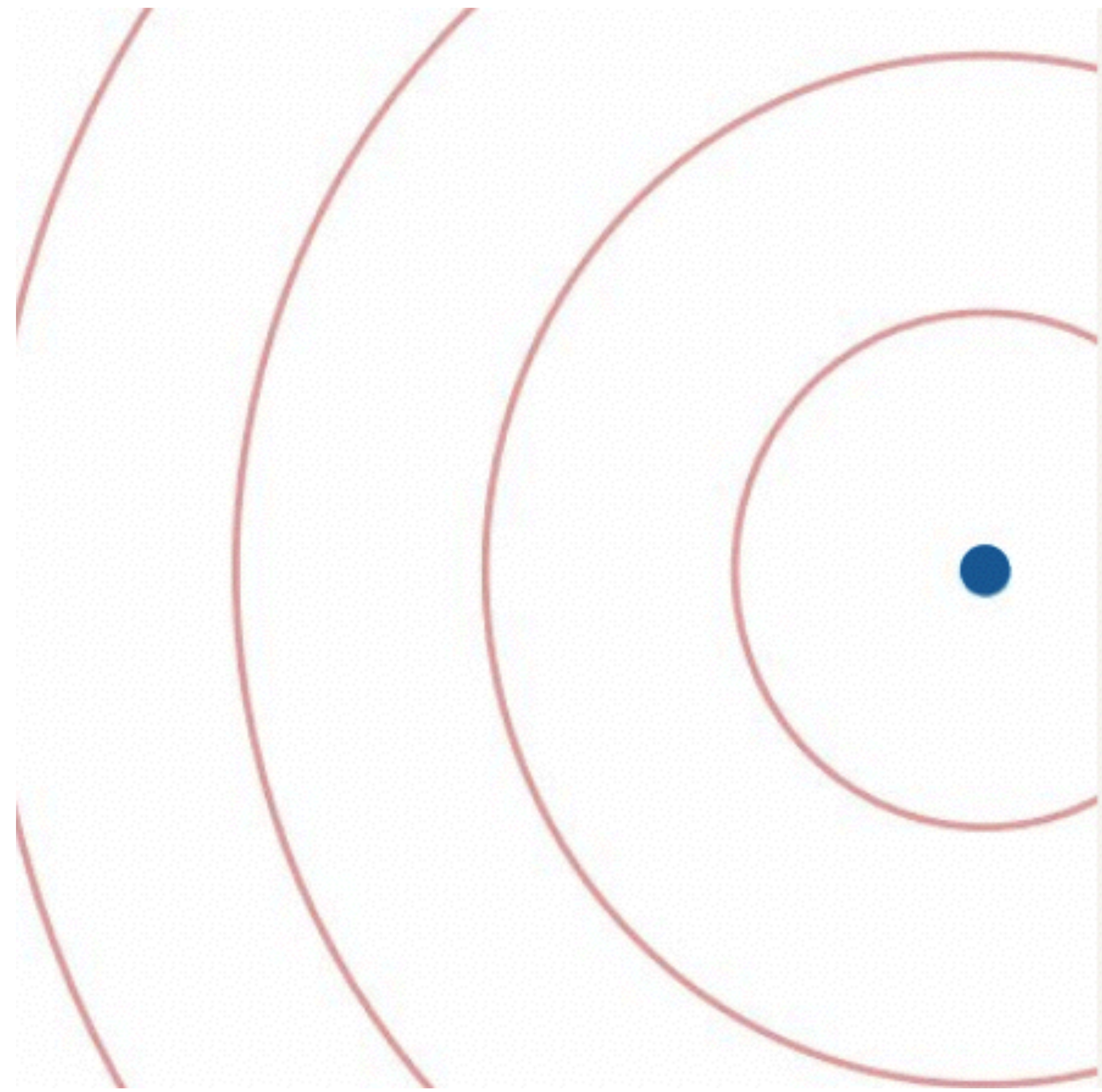
- Energy density of B-component compatible with 10^{50} erg every million years for residence times of EV particles

➡B-component as an old event in the Galaxy, similar to UHECR (transient) sources?

- Additional observable to probe transient scenarios of UHECRs: arrival directions

Steady state/Transient state





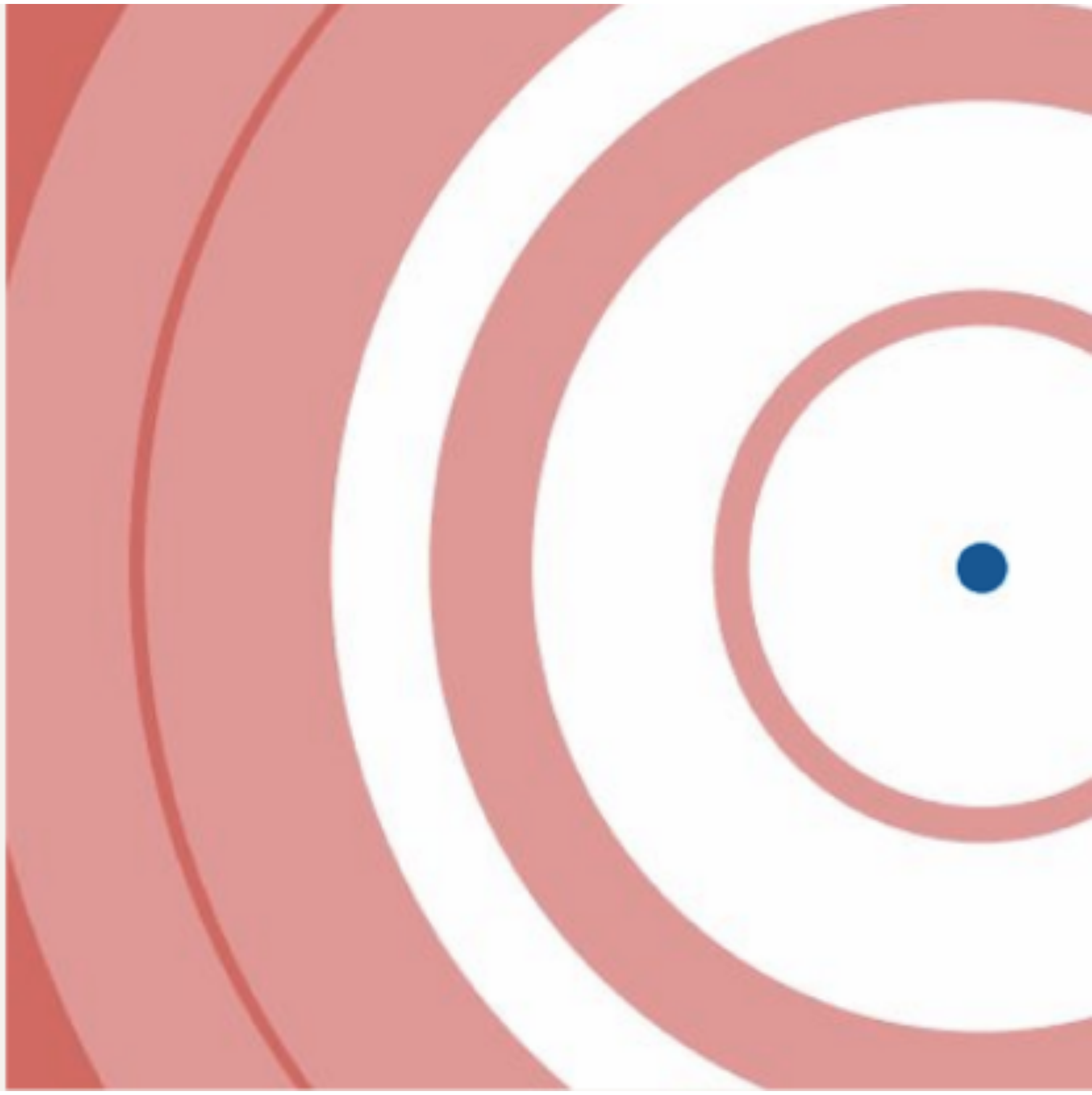
From transient to steady states

- Transient scenario
  - UHECRS produced per burst lasting a time ε

    Source bursting

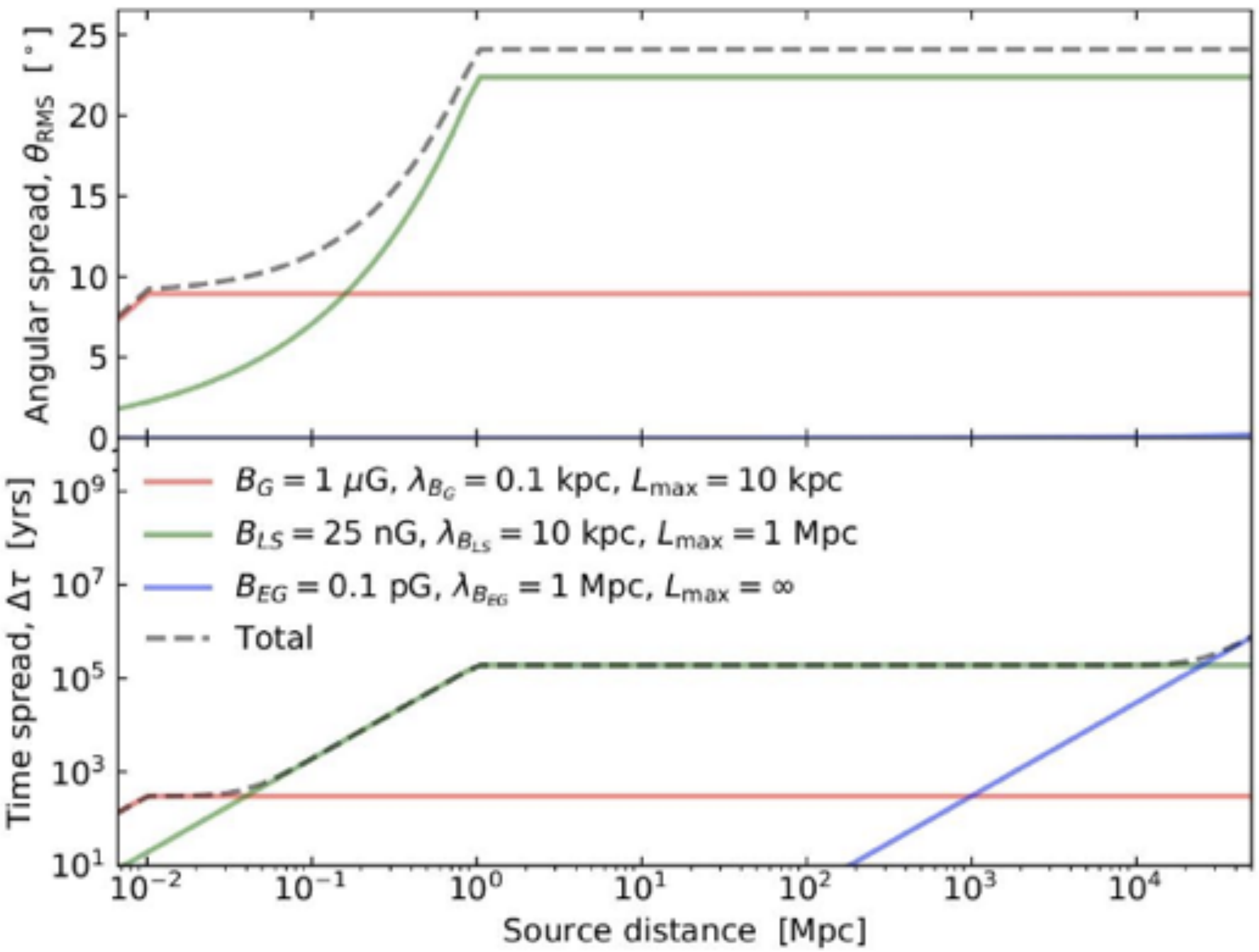
    UHECR burst

- Magnetic field
  - Time spread of the burst induced by the magnetic field

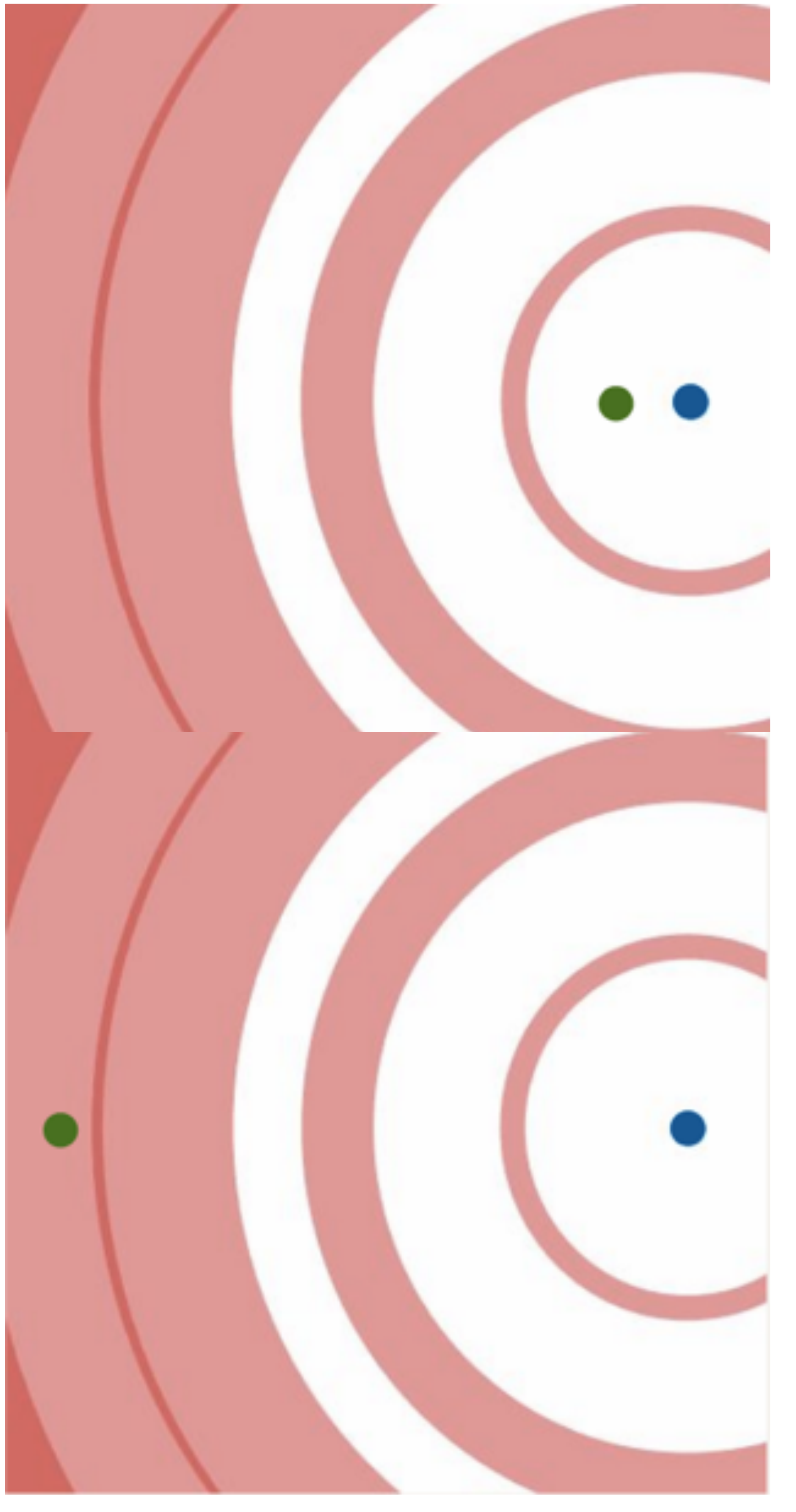


Time delay from magnetic fields

- ➔ Galactic magnetic field (JF12)
  - Strength $B_G = 1\ \mu G$
  - Coherence length $\lambda_G = 0.1$ kpc
  - Size $L_{max} = 10$ kpc
- ➔ **Local Sheet magnetic field**
  - Strength $B_G = [10; 25]$ nG (at least few nG, **consistent with MHD simulation,** considering primordial origin)
  - Coherence length $\lambda_G = 10$ kpc
  - Size $L_{max} = 1$ Mpc
- ➔ Extragalactic magnetic field
  - Strength $B_G = 0.1$ pG
  - Coherence length $\lambda_G = 1$ Mpc
  - Size $L_{max} = \infty$



Testing the transient scenario for UHECRs

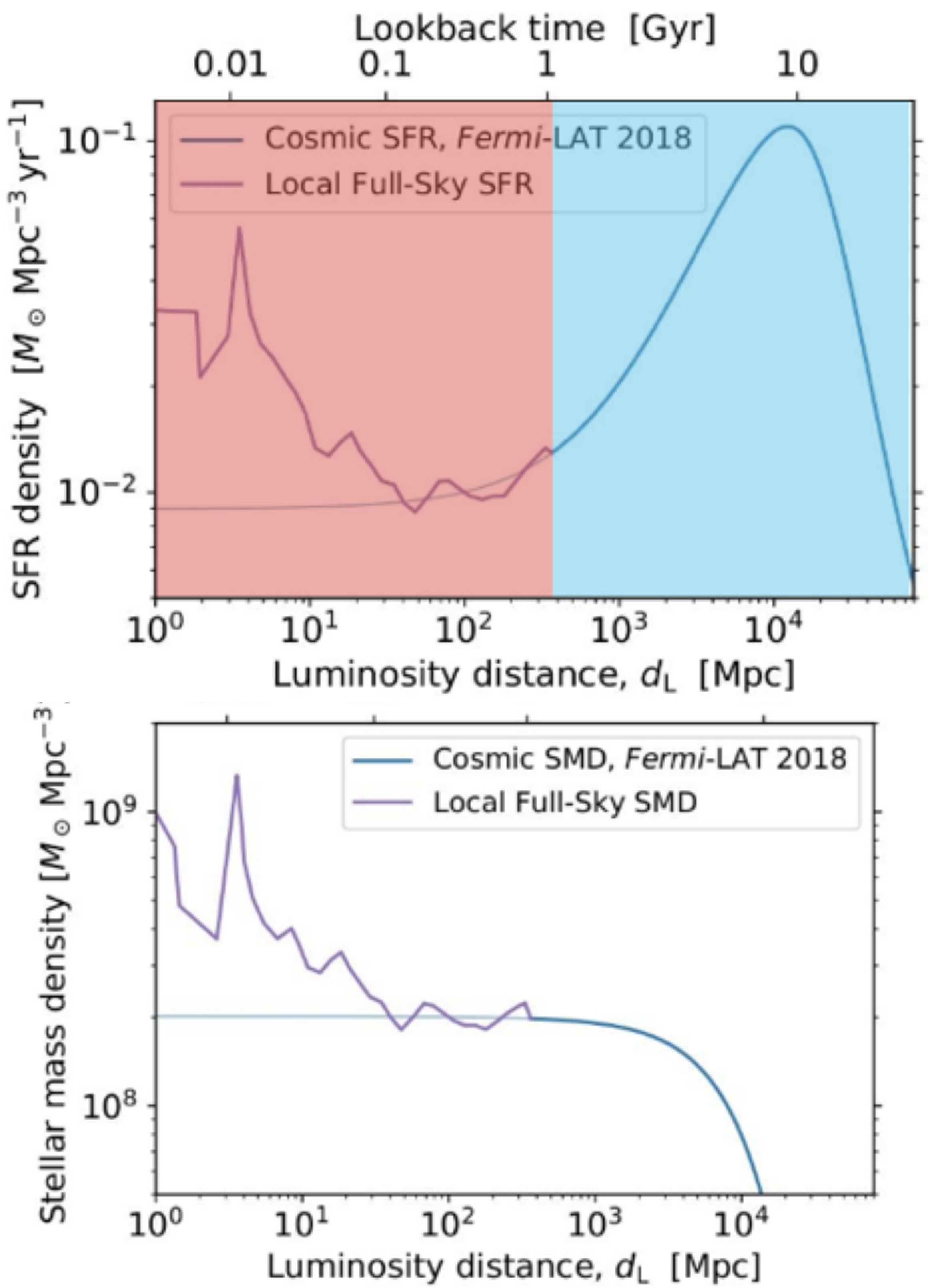


- ➔ The probability to observe a source is given by a Poisson distribution of parameter:

  $$\mathbf{N = k \times \Delta\tau \times s_{Gal}}$$

- ➔ Poisson parameter:
  - $\Delta\tau$ is the time spread (magnetic field)
  - s_{Gal} is the SFR/stellar mass of the galaxy
  - ***k* is a new parameter**
  - $k \times s_{Gal}$ is the burst rate
  - $[k] = \mathbf{M_\odot^{-1}}$ (SFRD) **|** $[k] = \mathbf{M_\odot^{-1}\,yr^{-1}}$(SMD)

The term S_{Gal}



Catalog of 400,000 galaxies:
Biteau, ApJS 256 (2021)

a near-infrared flux-limited sample to map both stellar mass and star formation rate (SFR) over the full sky

➔ **Discrete:** Compute the flux for **each galaxy** from the catalogue (~400 000) proportional to their SFR/Stellar mass

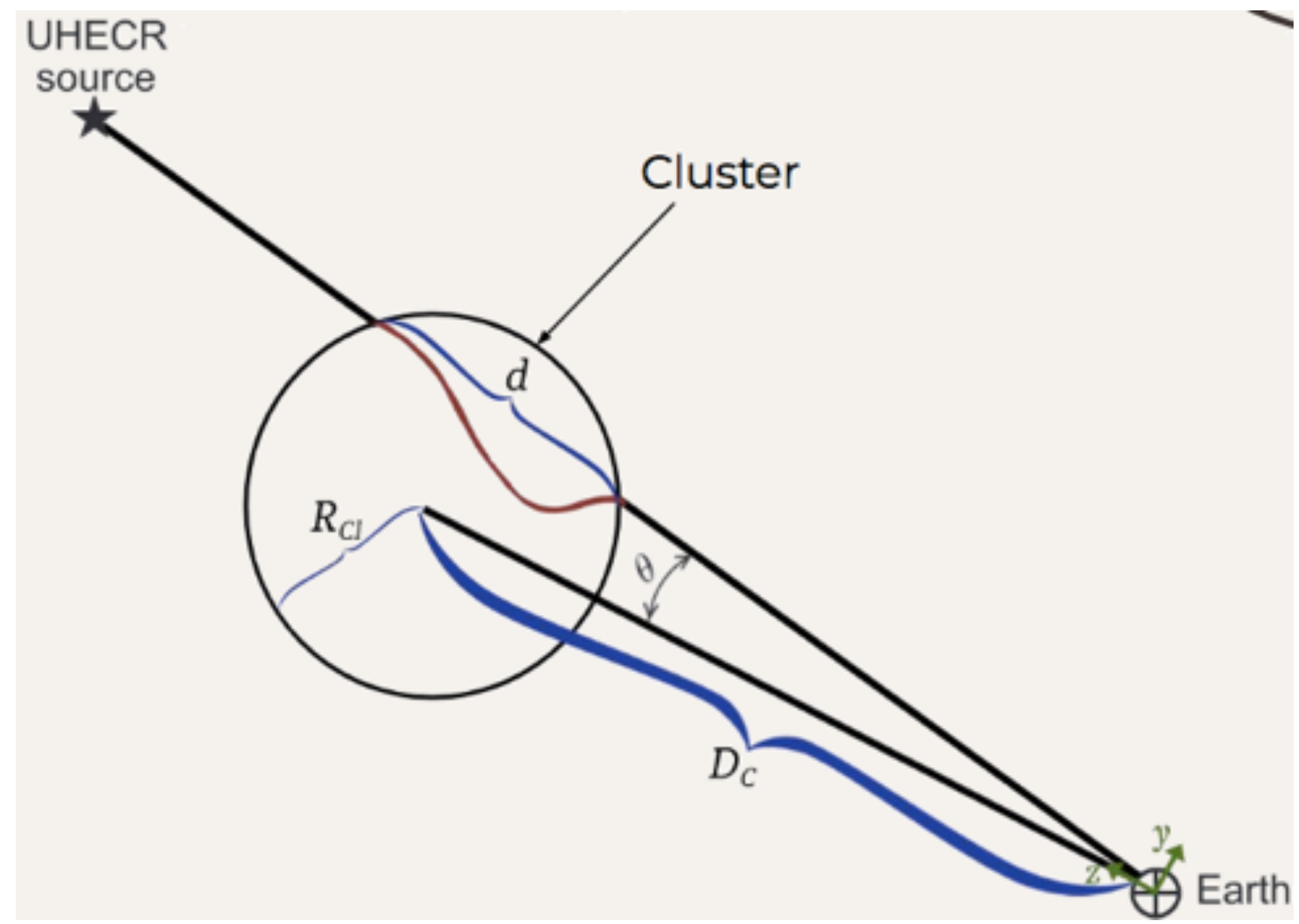
➔ **Continuous:** Compute the flux as before, from z=0.08 to z=2.5 **(isotropic background)**

➔ **Arrival direction map:**
Sum the contributions of all galaxies and isotropic background within one pixel

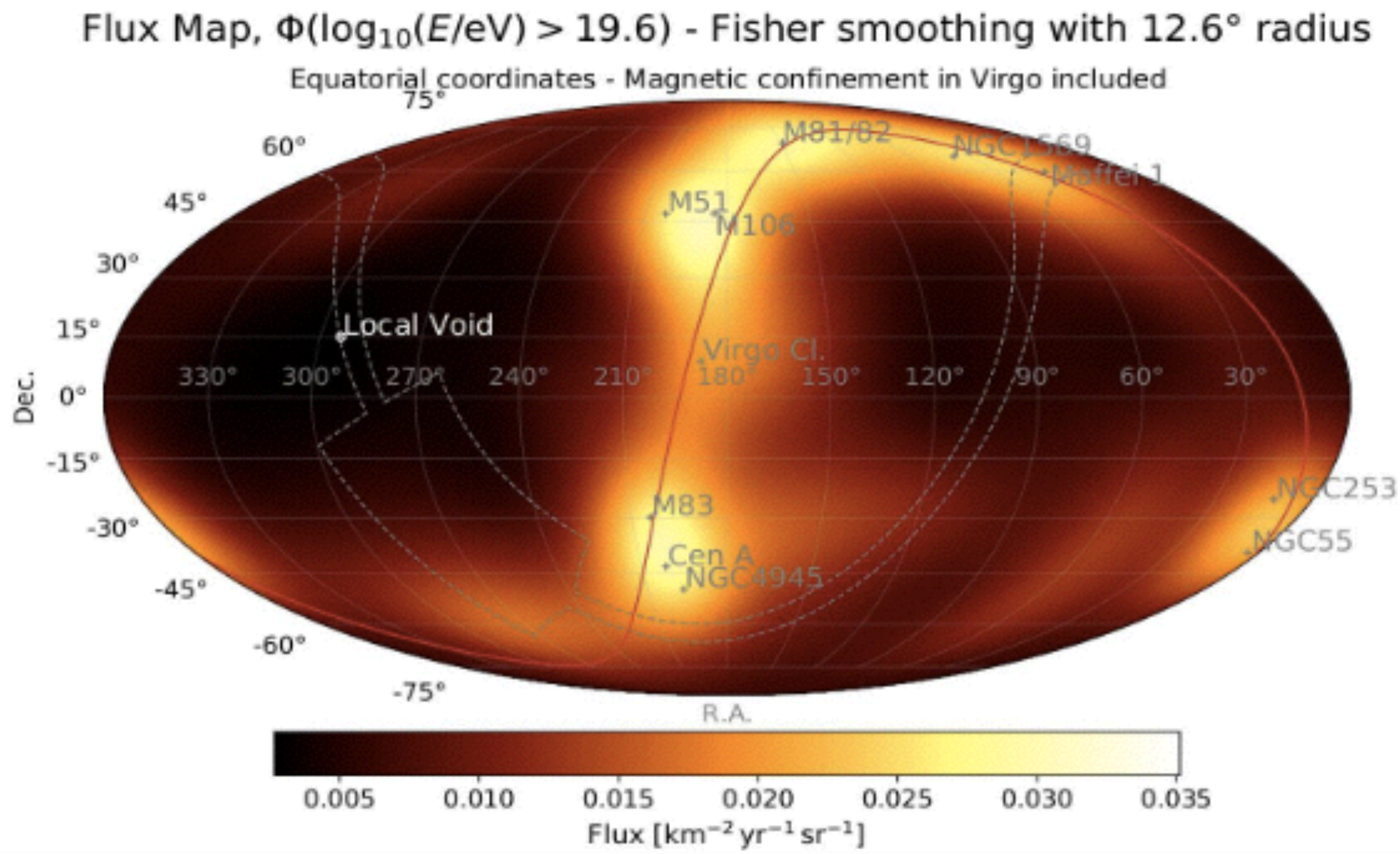
➔ Do a smoothing

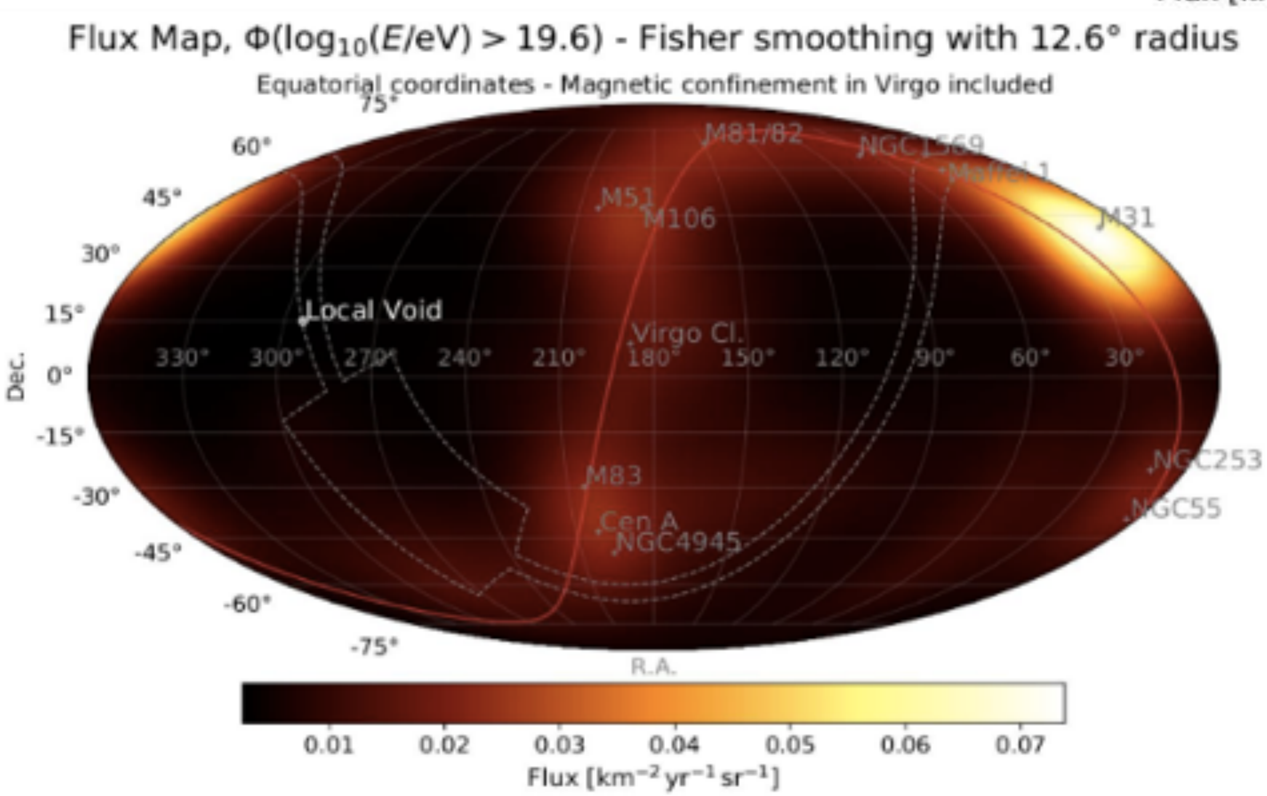
UHECR « horizon » in clusters

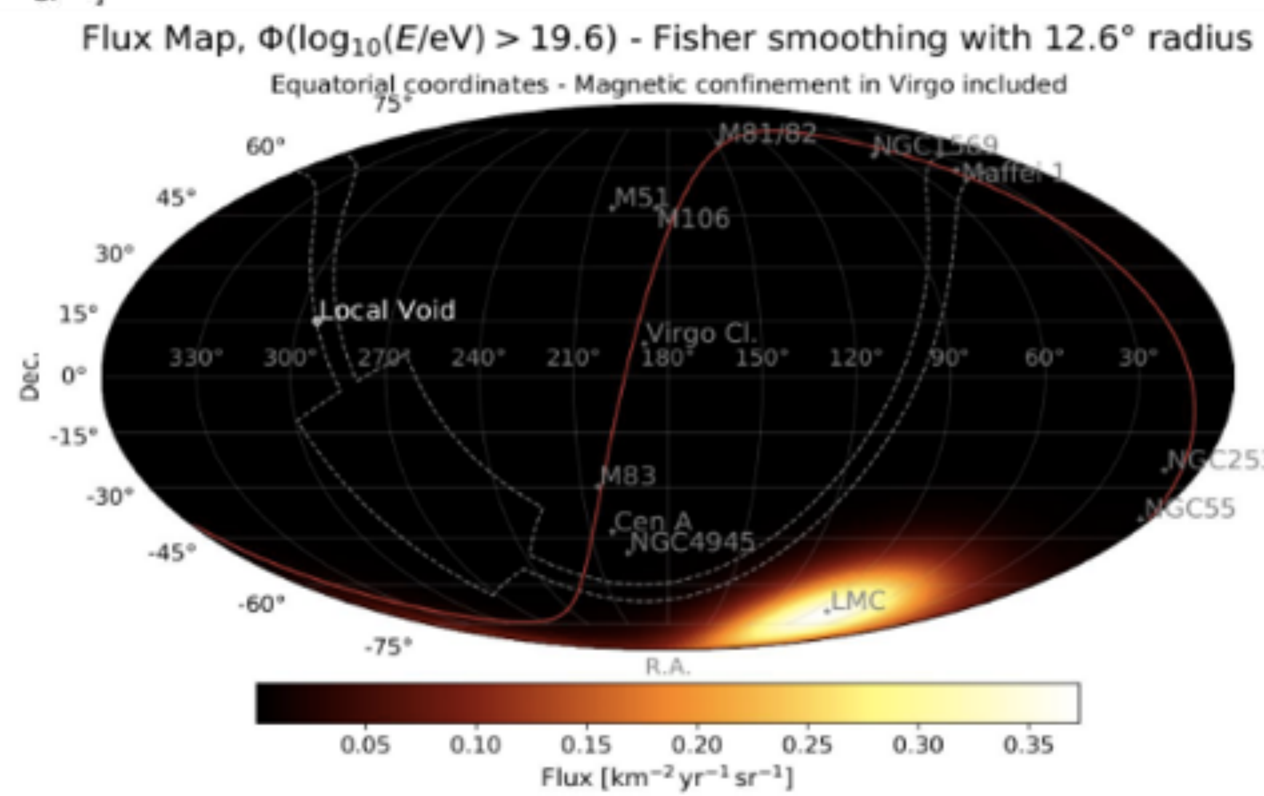
- <B> in Coma from RM: 2 μG over 1 Mpc^3 [Bonafede et al., A&A 513 (2010) A30]
- Scaling laws available
- <B> + interactions in clusters: $t_{\rm escape} > t_{\rm loss}$ possible
- Some clusters may not contribute to the UHECR flux!



Horizon applied to local clusters (GZK sphere)

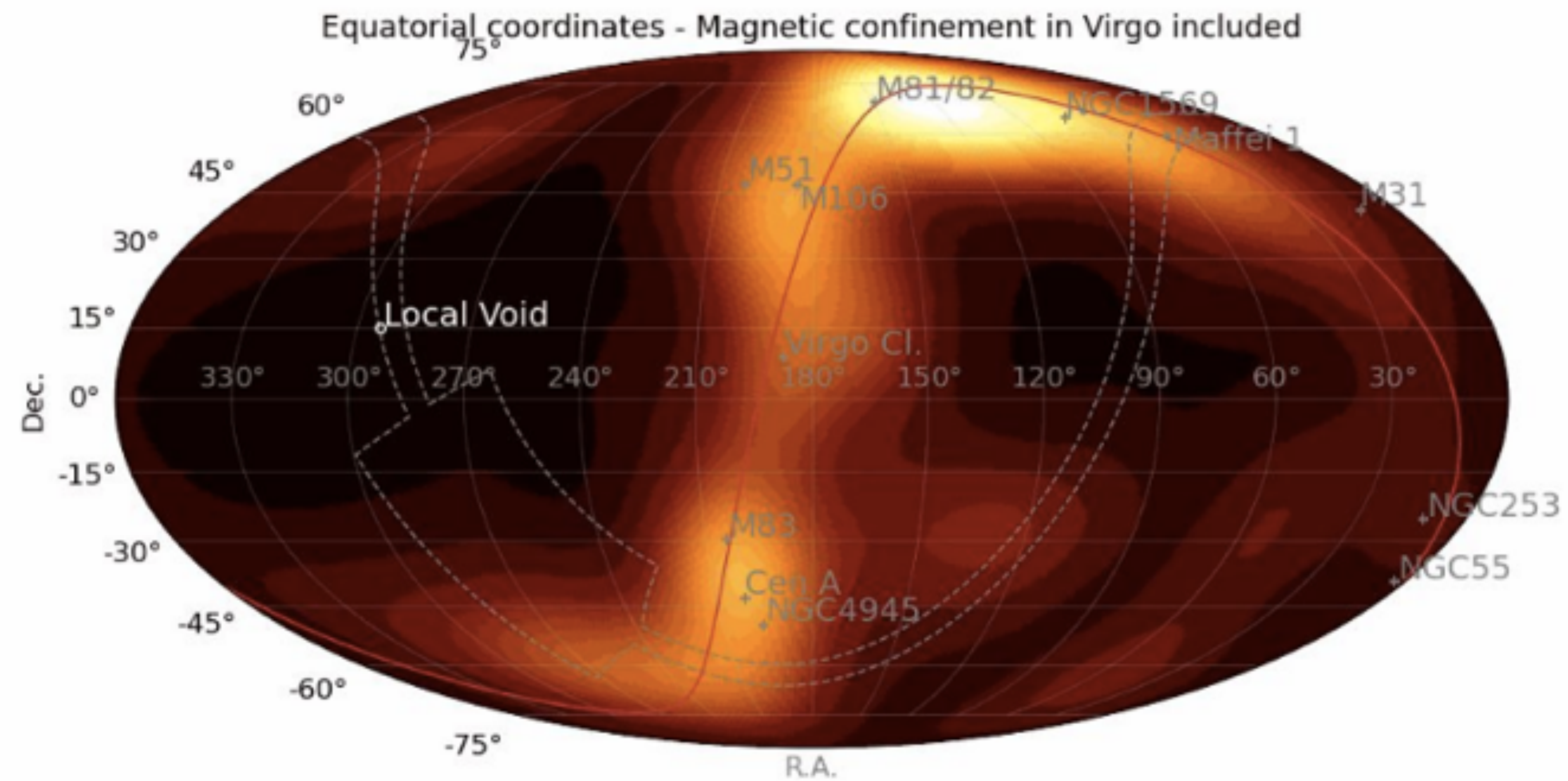






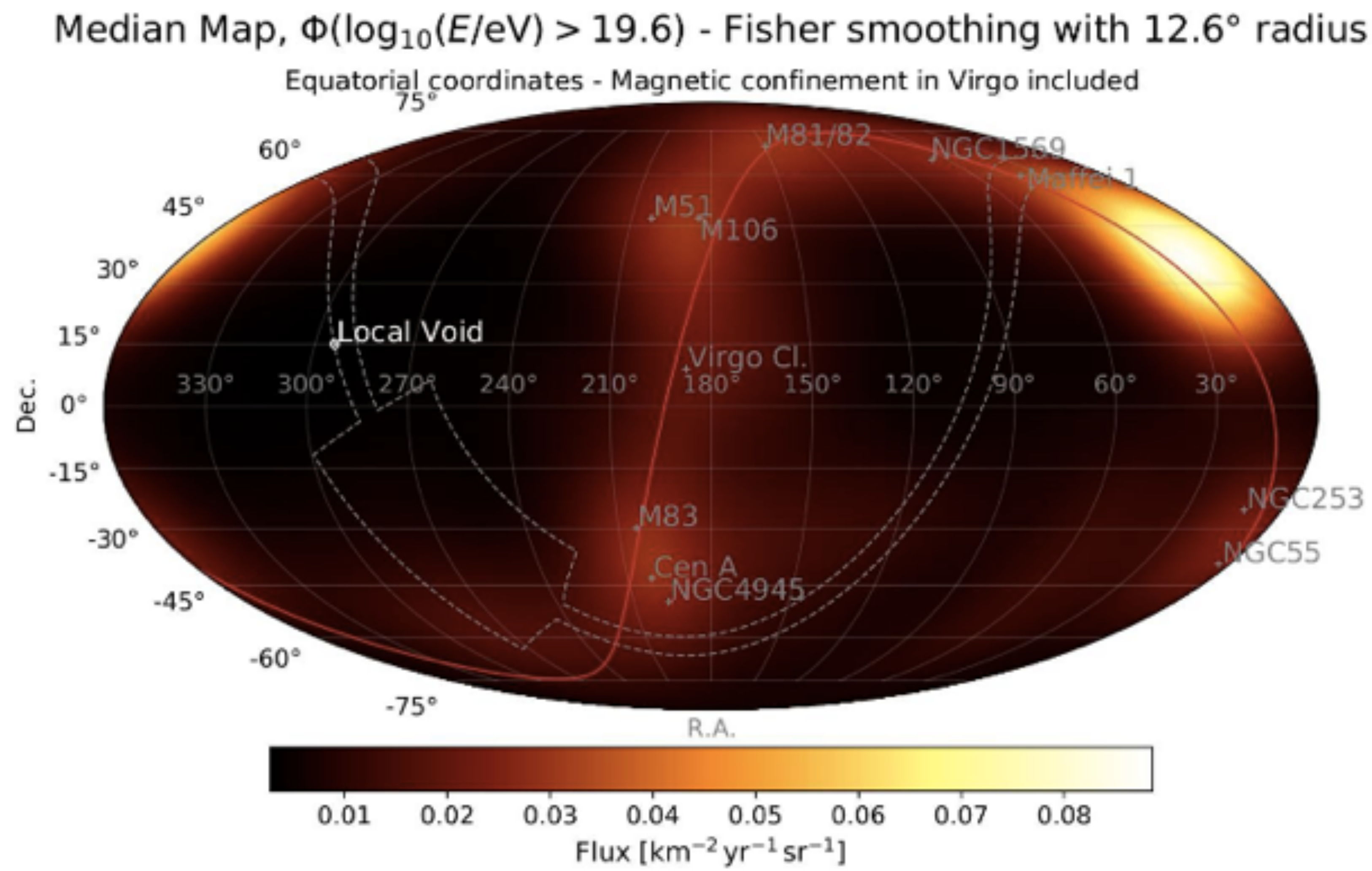
Random realizations governed by k

- For a given k, **N** (number of burst) is drawn at random for each galaxy.
- 100 maps are made
- Here, $\boldsymbol{k}$**=10^{-5} M$_{\odot}^{-1}$**



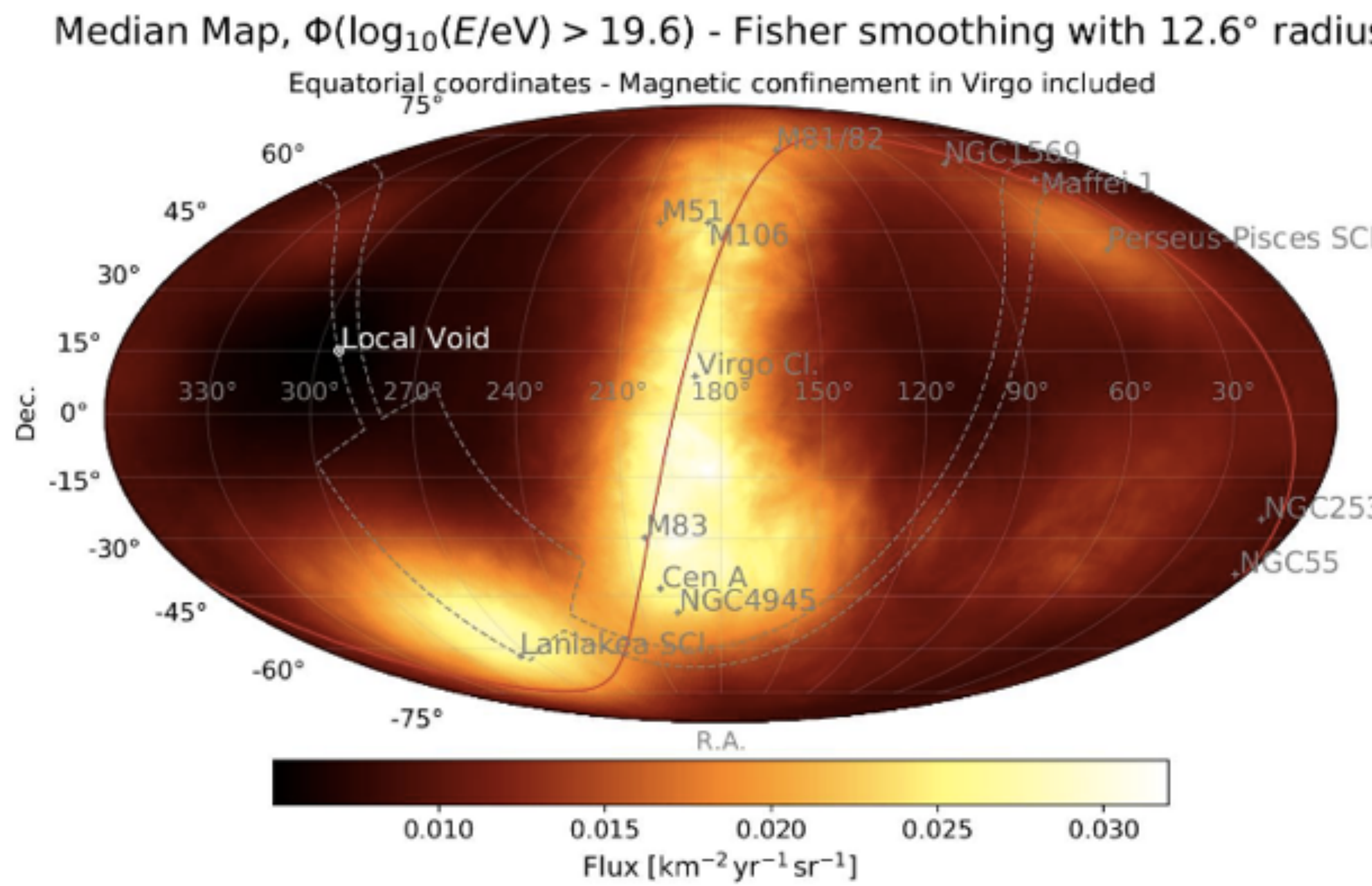
Median (SFR) map — High k

- ➔ Here, $k=10^{-4}\ M_\odot^{-1}$
- ➔ Median map
- ➔ Council of Giants contributes
- ➔ Nearby galaxies as Andromeda dominate the UHECR sky



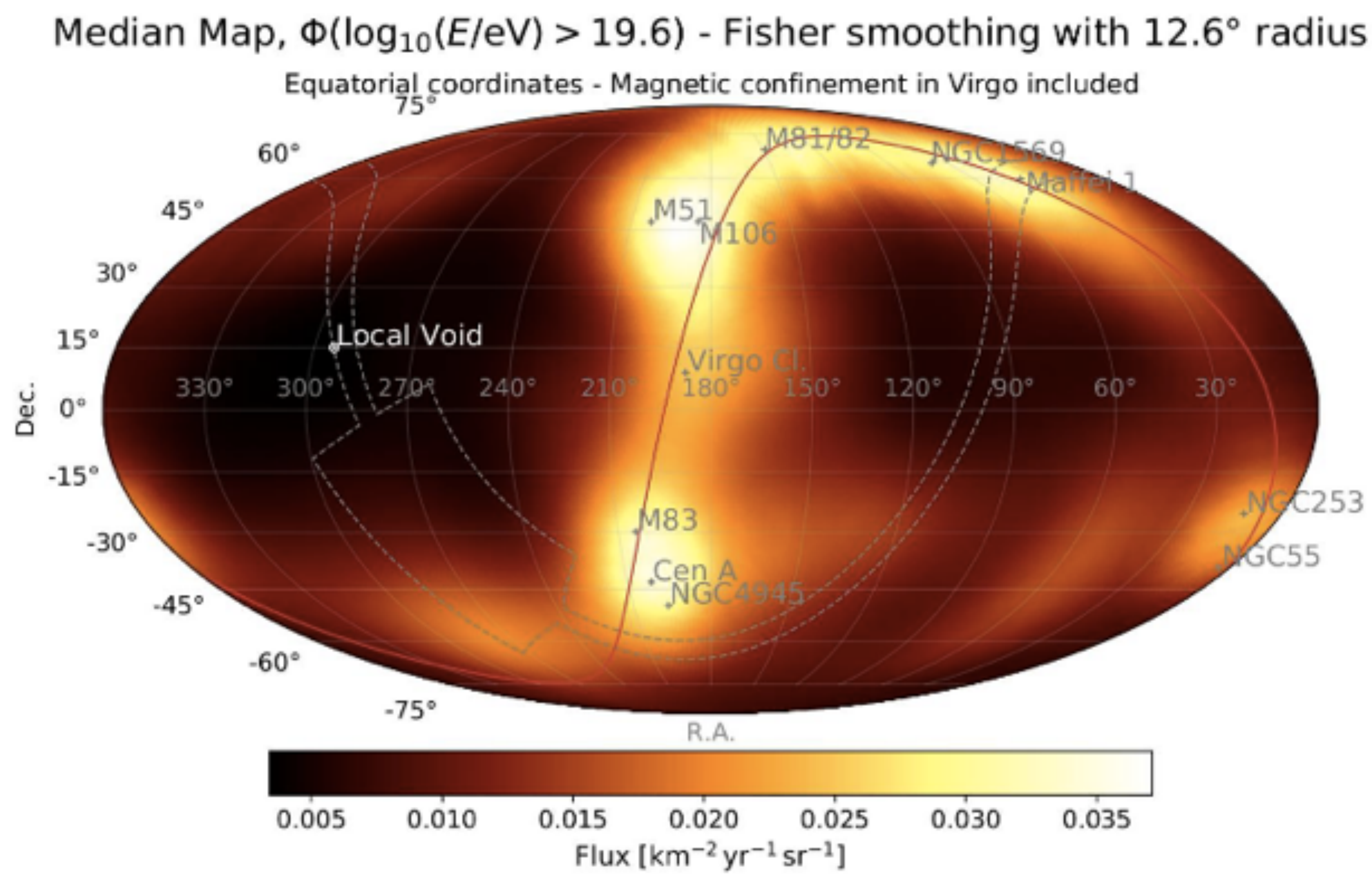
Median (SFR) map — Small *k*

- ➔ Here, ***k*=10^{-7} M$_{\odot}^{-1}$**
- ➔ Median map
- ➔ Council of Giants **does not** contribute !
- ➔ Dominated by far-away clusters/superclusters



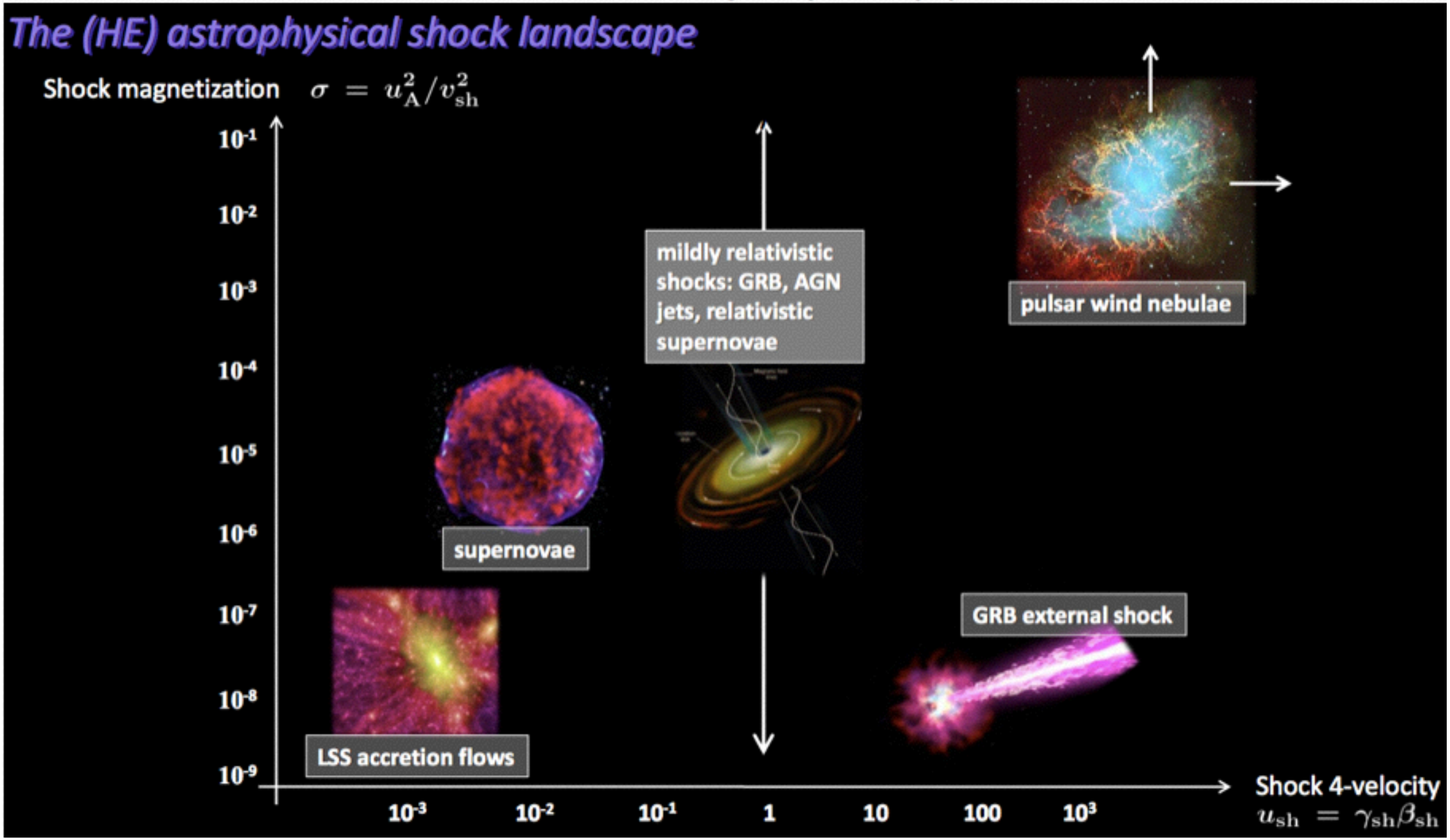
Median (SFR) map — Best k

- Here, k=10^{-5} $M_{\odot}^{-1}$
- Median map
- Council of Giants contributes
- No contribution from very close galaxies



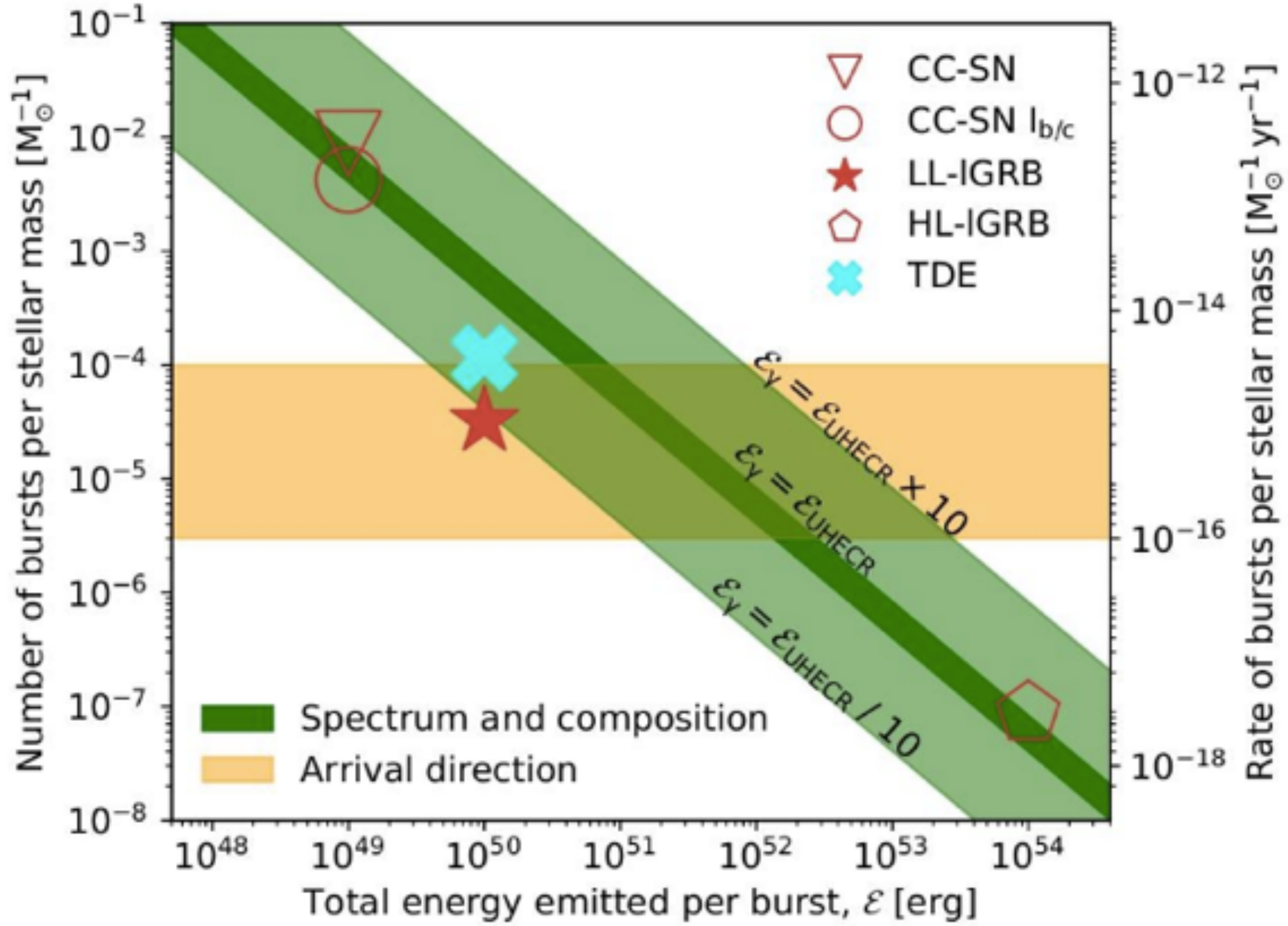
The UHE landscape

Credits: M. Lemoine, Paris-Saclay Astroparticle Symposium 2021



Constraints on sources

- SFRD scenario:
  - Core Collapse supernova (CC-SN)
  - CC-SN type Ib/c
  - Low luminosity lGRB (LL-lGRB)
  - High luminosity lGRB(HL-lGRB)
- SMD scenario:
  - Tidal Disruption Event (TDE)
- Two sources reach the two requirements:
  - LL-lGRB
  - TDE



Summary

- Source environments: key to understand UHECRs