

On the verge of discovering ultra-high-energy accelerators?

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with significant inputs from Quentin Luce & Sullivan Marafico*

As part of the ANR & DFG funded project: Multi-messenger probe of Cosmic-Ray Origins ([MICRO](#))

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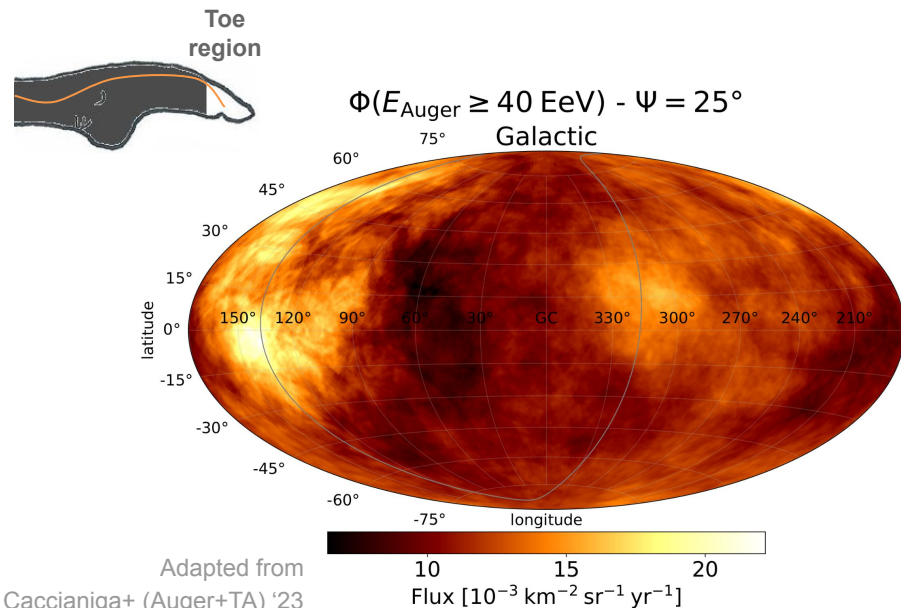
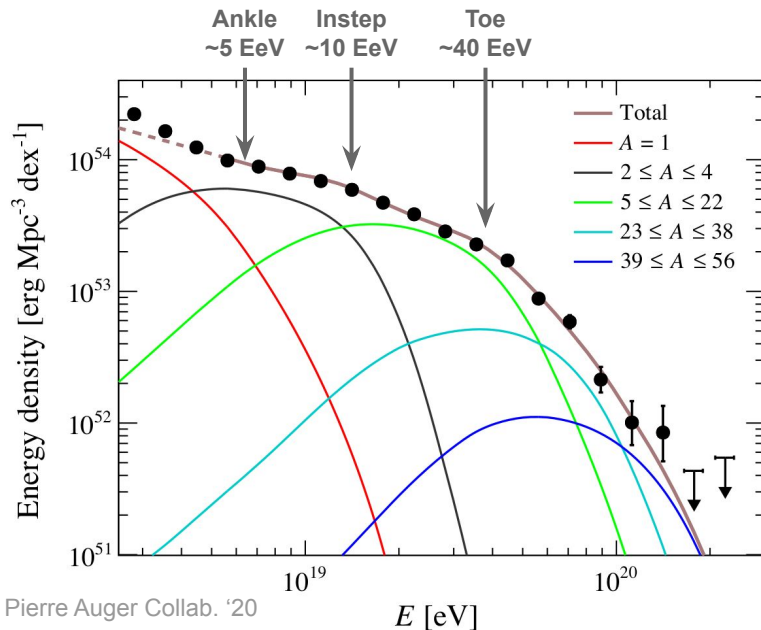
The quest for UHECR origins

Full-sky spectral and composition observables

→ accounting for propagation, constrain UHECR **production rate per unit matter**: $n_{\text{src}} \times \dot{\mathcal{E}}_{\text{UHECR}}$ or $\dot{n}_{\text{src}} \times \mathcal{E}_{\text{UHECR}}$

Anisotropy observables

→ break down the flux vs arrival direction: **pinpoint sources** provided magnetic deflections under control



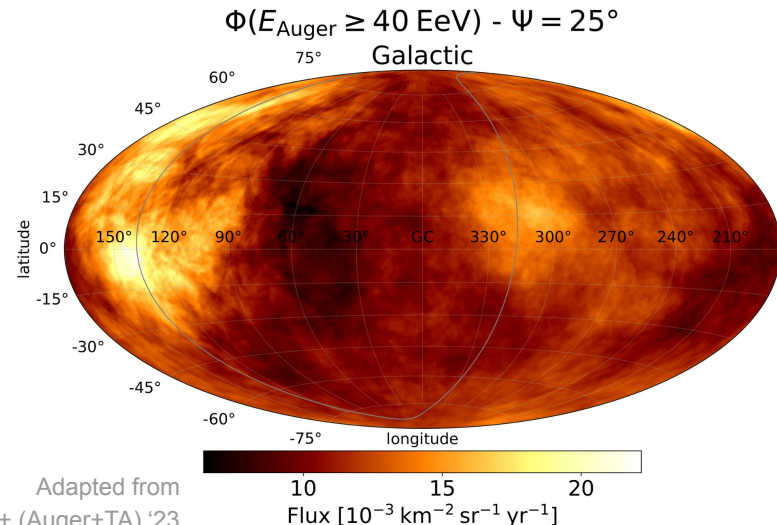
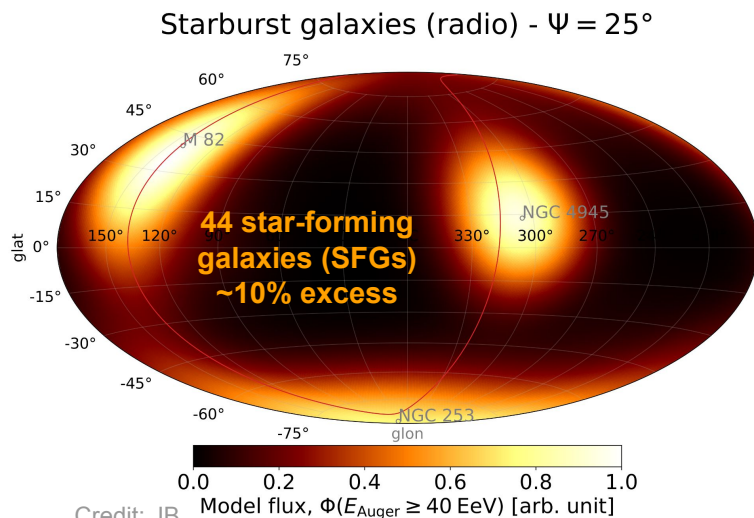
Status of anisotropies in the toe region

Cross-correlation with 44 starbursts, accounting for propagation: evidence of anisotropy in the toe region

Pierre Auger Obs. + Telescope Array Arrival Directions: 4.6σ (Auger + TA, ICRC 2023)

Pierre Auger Obs. Arrival Directions + Spectrum + Composition: 4.5σ (Auger, JCAP 2023)

Why starbursts? Why anisotropic fraction $\sim 10\%$?
Why Gaussian angular scale $\theta \approx 15^\circ$ ($\Leftrightarrow$ top-hat $\Psi \sim 25^\circ$)?



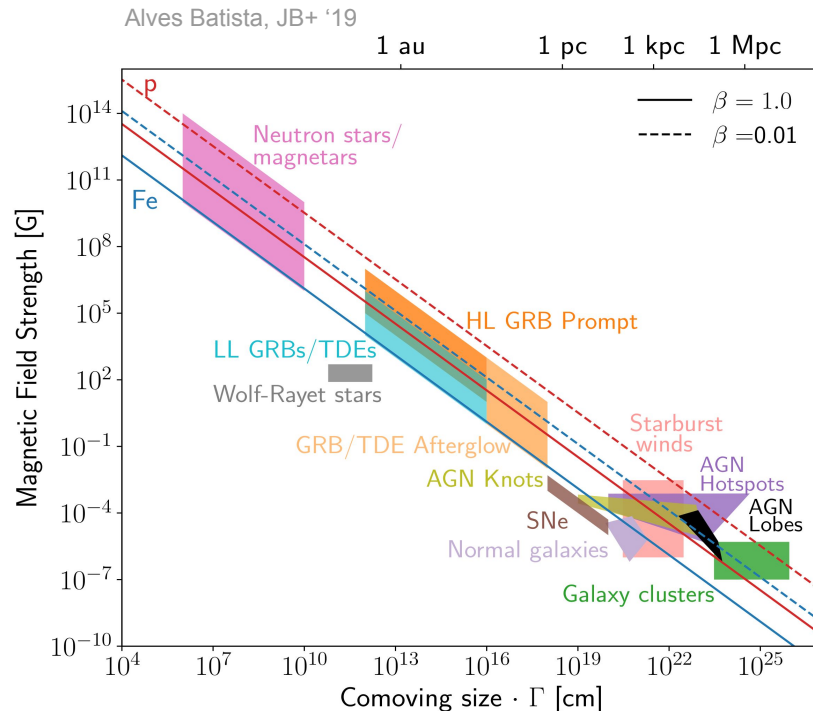
Starbursts host more frequent stellar explosions...

Why would UHECR sources be transient?

→ Hillas-Lovelace-Waxman: high-luminosity sources

Hillas criterion, $B \times (r \times \Gamma) \times \beta_{\text{shock}} > (E / Ze)$,
neatly reformulated as:

$$L_B > \frac{\Gamma^2}{\beta} \frac{R^2}{\Omega_{\text{vac}}} \\ > 6.6 \cdot 10^{43} \text{ erg s}^{-1} \times \left(\frac{\Gamma^2/\beta}{100} \right) \left(\frac{R}{5 \text{ EV}} \right)^2$$



Starbursts host more frequent stellar explosions...

Why would UHECR sources be transient?

- Hillas-Lovelace-Waxman: high-luminosity sources
- Composition: material from (high-mass) stars

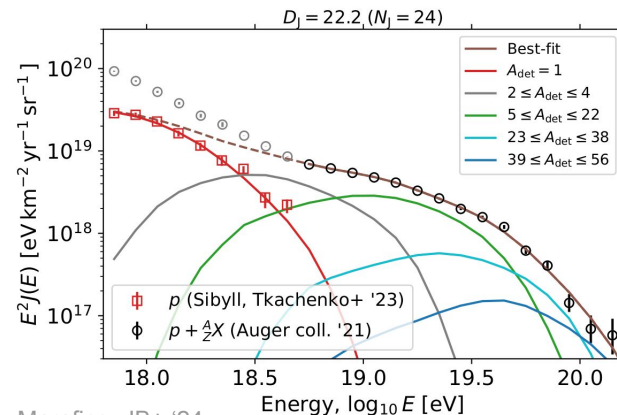
Helium / Heavy nuclei proportion (Marafico, JB+ '24)

$$\left. \frac{M(\text{He})}{M(\text{C} - \text{Fe})} \right|_{\text{UHECR}} = 0.21 \pm 0.05_{\text{stat.}} \pm 0.06_{\text{sys.}}$$

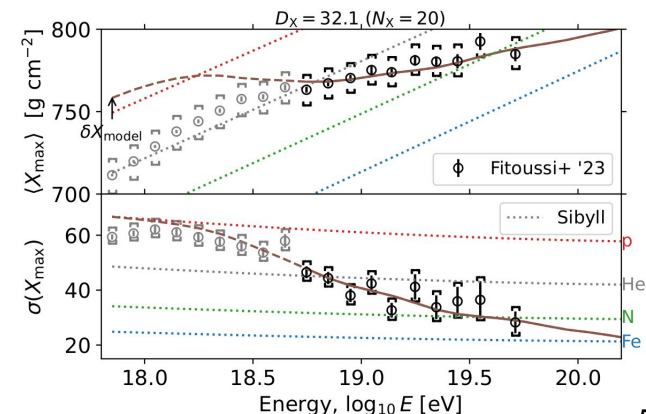
would be 18 ± 2 if ISM picked-up material

+ good agreement of heavy to intermediate-mass nuclei with composition of massive stars stripped of their H-He envelopes

see also Zhang, Murase, Oikonomou '17



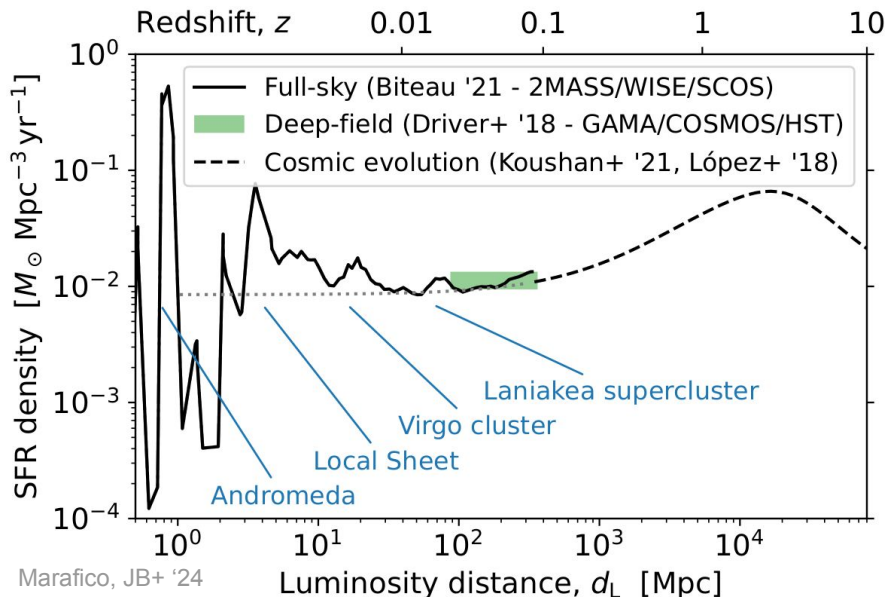
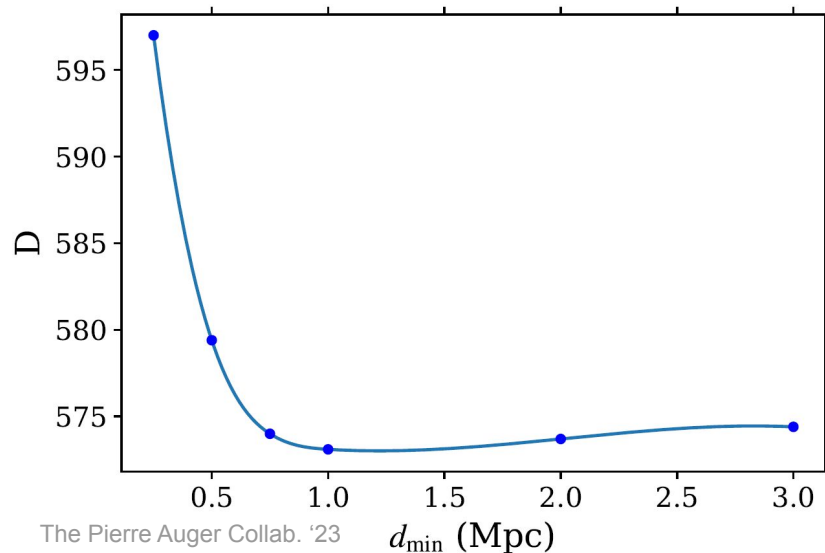
Marafico, JB+ '24



Starbursts host more frequent stellar explosions...

Why would UHECR sources be transient?

- Hillas-Lovelace-Waxman: high-luminosity sources
- Composition: material from (high-mass) stars
- Minimum distance: for an observer in a large-scale B -field

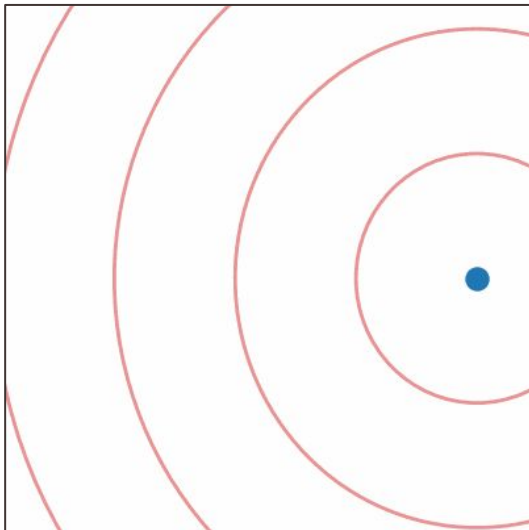


Starbursts host more frequent stellar explosions...

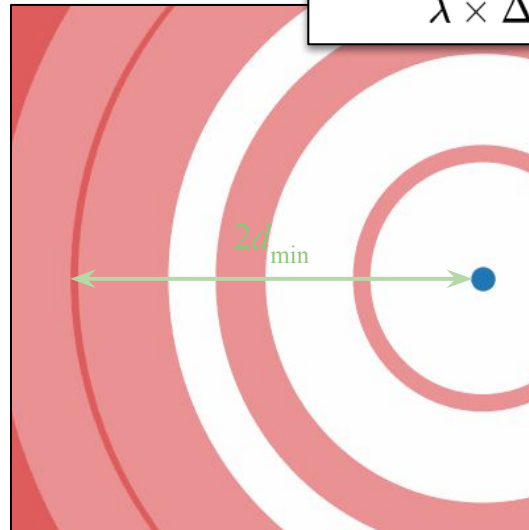
Why would UHECR sources be transient?

- Hillas-Lovelace-Waxman: high-luminosity sources
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- Minimum distance: for an observer in a large-scale B -field

$B = 0$



$B > 0$



Source with burst rate λ invisible:

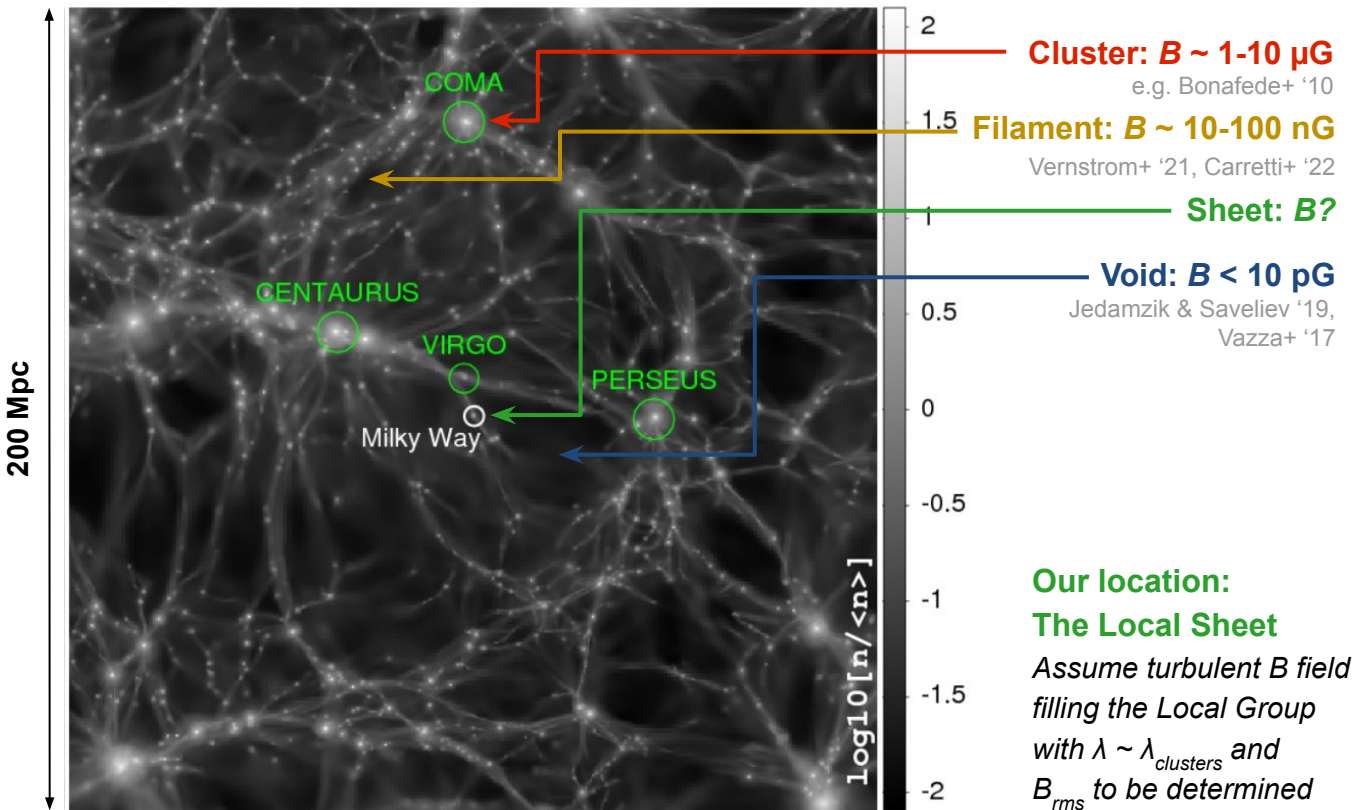
$$\lambda \times \Delta\tau(d, B) \ll 1$$

● Source

■ UHECR burst

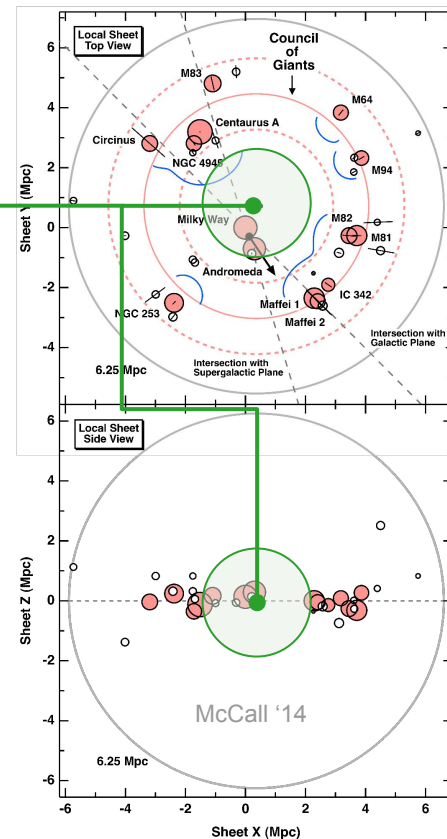
Credit: S. Marafico

Magnetic fields and where to find them



Credit: Hackstein+ 2018 (Cosmic V-web constrained sim. / CLUES)

Our location:
The Local Sheet
 Assume turbulent B field
 filling the Local Group
 with $\lambda \sim \lambda_{\text{clusters}}$ and
 B_{rms} to be determined



Magnetic fields and where to find them

Galaxy clusters: $B \sim 1\text{-}10 \mu\text{G}$

- Calorimeters for UHE nuclei (Condoirelli, JB, Adam, ApJ '23)
- Turn OFF bright X-ray clusters (**Virgo**, **Perseus**, **Goma**)

Galaxy filaments: $B \sim 10\text{-}100 \text{ nG}$

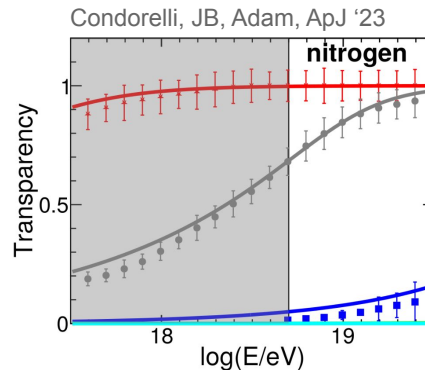
- Transparent to UHE nuclei (Condoirelli, JB, Adam, ApJ '23)
- No need for specific treatment

Voids: $B < 10 \text{ pG}$

- Too low to have a sizeable impact on UHECRs within GZK horizon (see Pierre Auger Collab. '24)

The Local Sheet: $B \sim B_{\text{filaments}}?$

- Translucent, w/ angular spread $\theta_{\text{obs, UHECR}} \sim \Delta\theta_{\text{Local Sheet}}$
- Time spread $\rightarrow d_{\text{min}} = \text{extent of } B_{\text{Local Sheet}} \sim \text{few Mpc}$



transparent

--- $B = 150 \text{ nG}$

--- $B = 400 \text{ nG}$

--- $B = 1 \mu\text{G}$

--- $B = 3 \mu\text{G}$

--- $B = 9 \mu\text{G}$

opaque

The Milky Way (Jansson & Farrar '12)

- $\Delta\tau_{\text{MW}} \ll \Delta\tau_{\text{Local Sheet}}$, $\Delta\theta_{\text{MW}}$ accounted for
- Test of coherent deflections with 1 model

$$\Delta\theta = 10^\circ \times \left(\frac{B}{10 \text{ nG}}\right) \left(\frac{R}{5 \text{ EV}}\right)^{-1} \left(\frac{d}{2 \text{ Mpc}}\right)^{1/2} \left(\frac{\lambda_B}{10 \text{ kpc}}\right)^{1/2}$$

$$\Delta\tau = 70 \text{ kyr} \times \left(\frac{B}{10 \text{ nG}}\right)^2 \left(\frac{R}{5 \text{ EV}}\right)^{-2} \left(\frac{d}{2 \text{ Mpc}}\right)^2 \left(\frac{\lambda_B}{10 \text{ kpc}}\right)$$

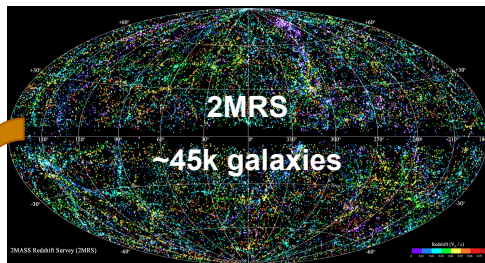
Mapping out stellar matter in the GZK horizon

(2MASS Photometric z catalog $\cap$ WISE) $\times$ HyperLEDA (JB, ApJS '21)

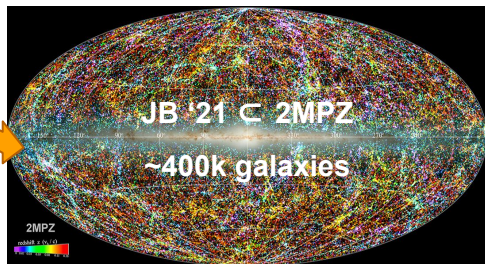
Catalog of 400k galaxies out to $d_{\max} = 350$ Mpc

Completeness in stellar mass: 50% at $d_{\max}$ ($\times 2$ wrt 2MRS)

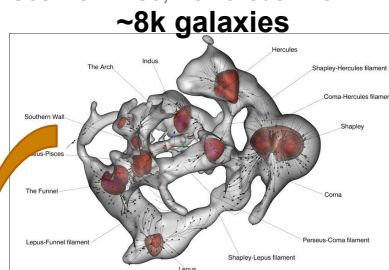
Credits: 2MRS, Huchra+ '12



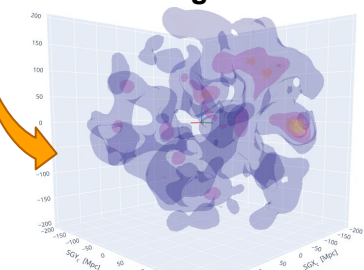
Credits: 2MPZ, Bilicki & Jarret '14



Cosmic V-web, Pomarède+ 2017

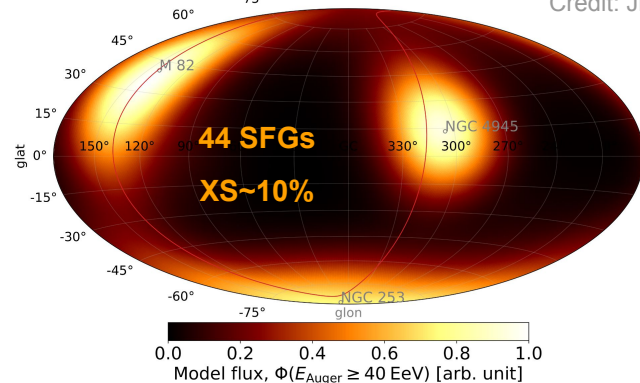


JB '21 ~400k galaxies



Starburst galaxies (radio) - $\Psi = 25^\circ$

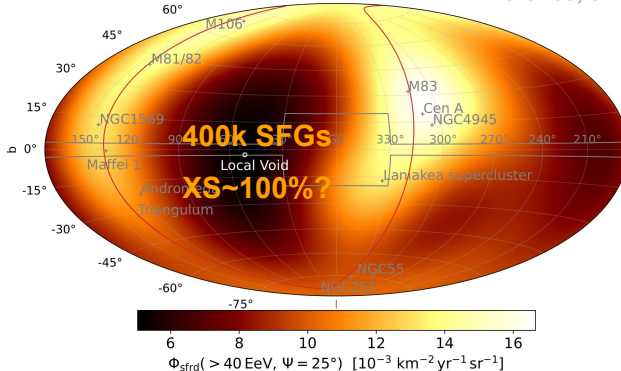
Credit: JB



$k = 5 \times 10^{-5} M_{\odot}^{-1}$, $\Theta = 17.7^\circ$ ($B_{\text{LS}} = 10 \text{ nG}$)

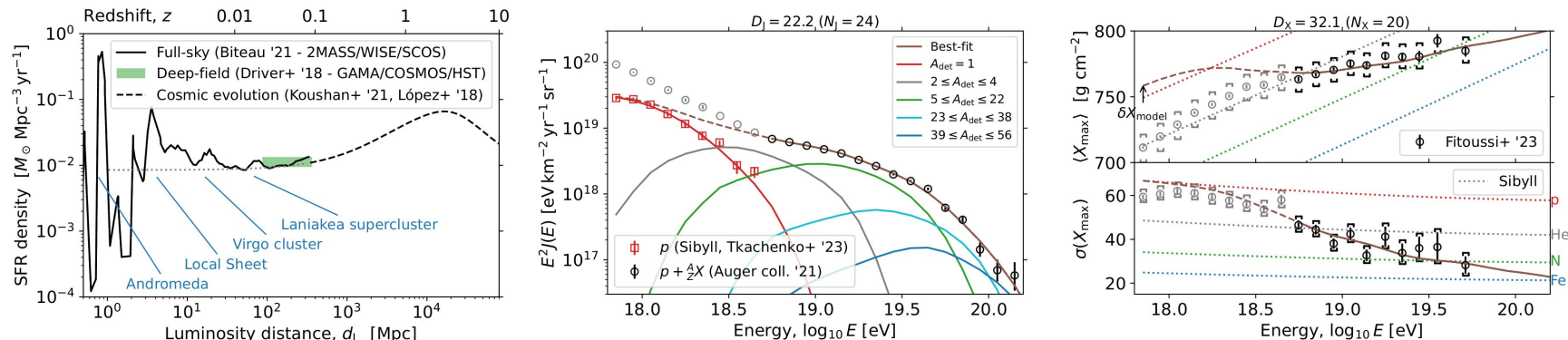
Galactic coordinates

Marafico, JB+ '24

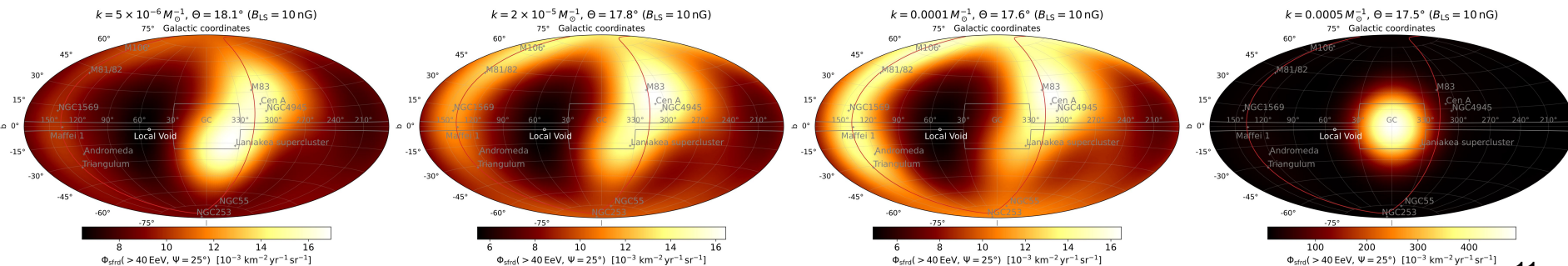


DOI [10.5281/zenodo.11440864](https://doi.org/10.5281/zenodo.11440864)

Spectral & composition model (see also Luce+ ApJ '22)



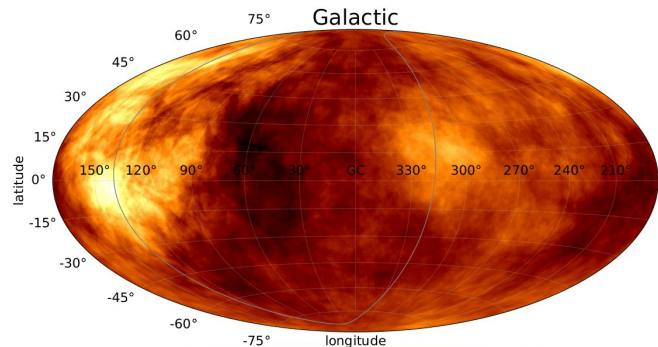
Increasing value of burst rate per star-formation unit k , for a given B -field in the Local Sheet



Candidate ultra-high-energy sources

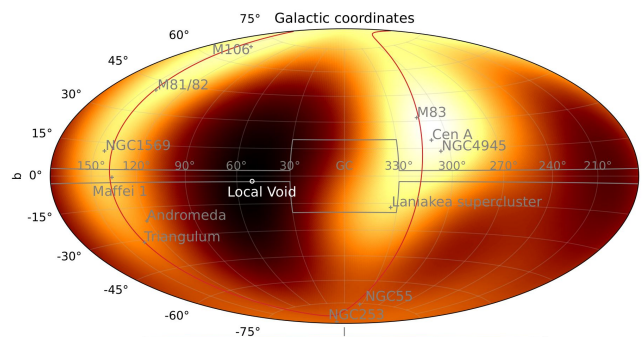
Marafico, JB, Condorelli, Deligny, Bregeon, **ApJ** (in press) 2024

Auger + TA data
Credits: L. Caccianiga for Auger & TA



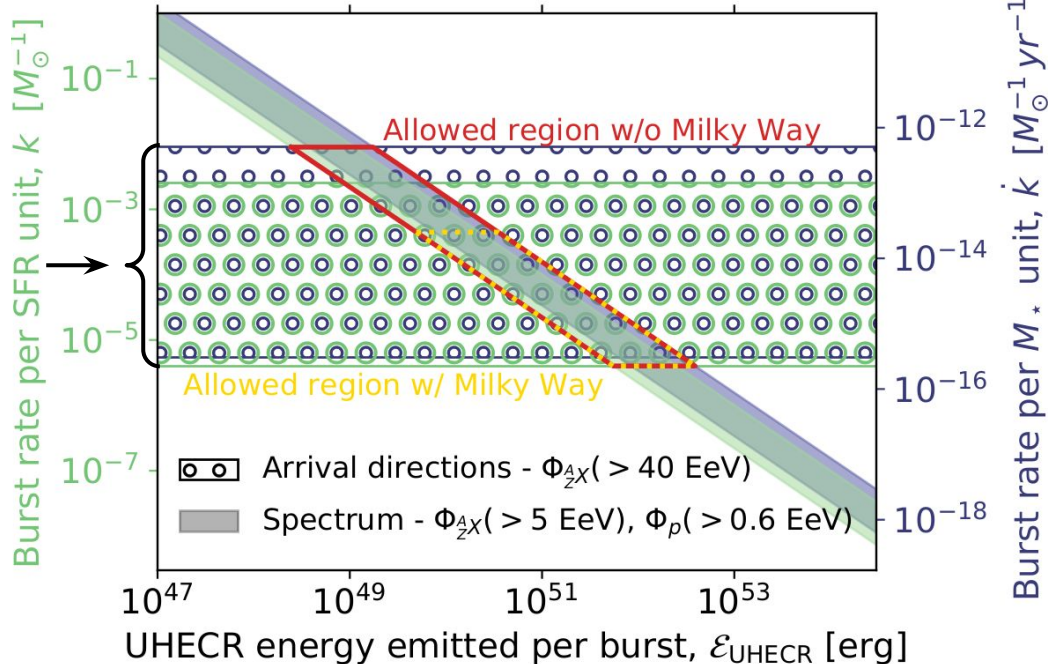
UHECR Model $\approx$ UHECR Data
 $\Delta\theta(\text{hotspot}_{\text{model}}, \text{hotspot}_{\text{data}}) < 40^\circ$

Best-match transient scenario
Credits: Marafico, JB+ '24



Solution with at least 1 Northern & Southern hotspot found for

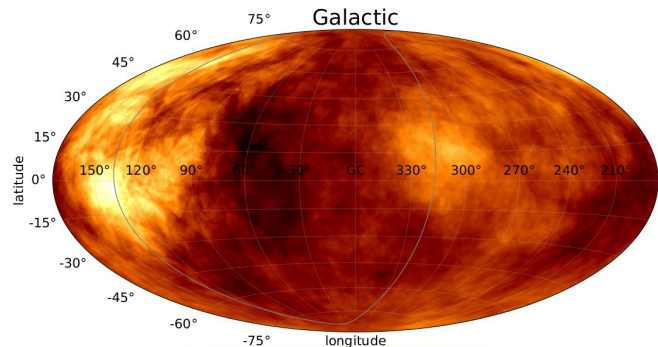
Local Sheet $B_{\text{rms}} = 0.5 - 20$ nG



Candidate ultra-high-energy sources

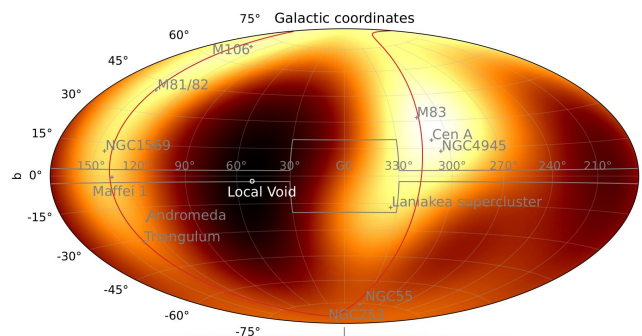
Marafico, JB, Condorelli, Deligny, Bregeon, **ApJ** (in press) 2024

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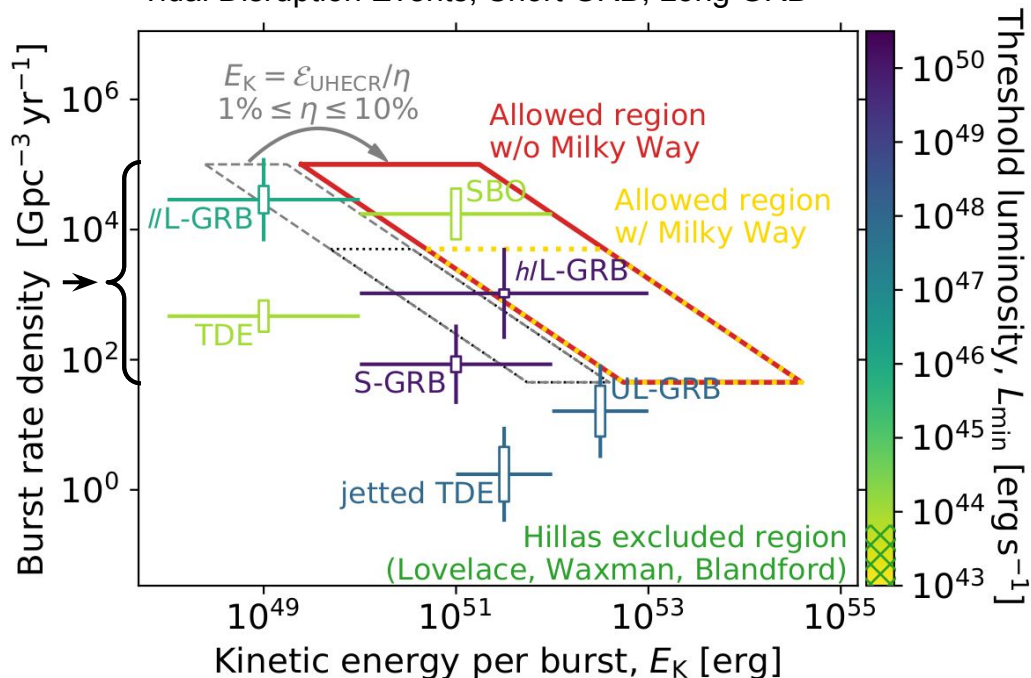
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X-ray transient rate vs kinetic energy

~~Tidal Disruption Events, Short GRB, Long GRB~~

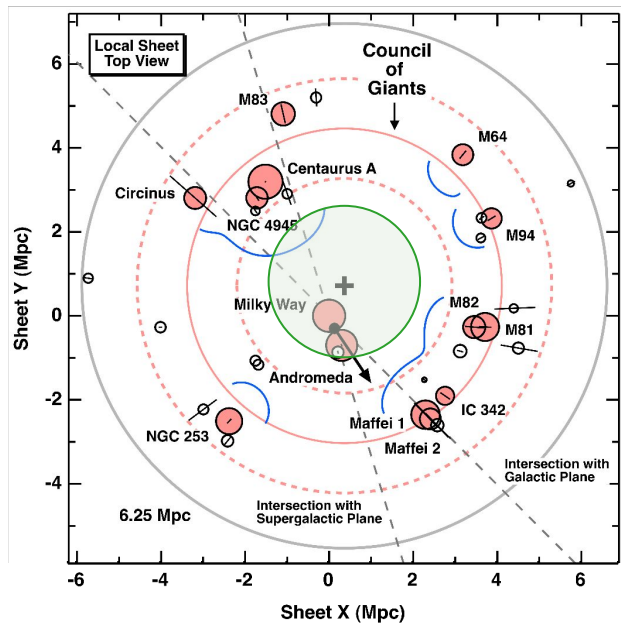


Conclusions

Marafico, JB, Condorelli, Deligny, Bregeon, *ApJ* (in press) 2024

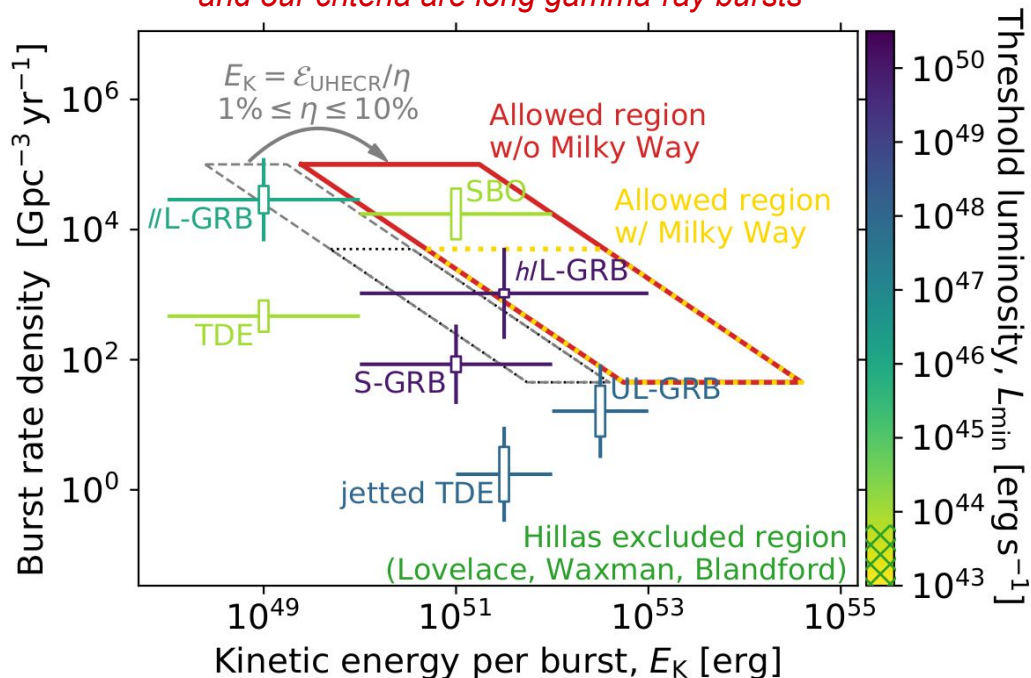
Local Sheet $B_{\text{rms}} = 0.5 - 20 \text{ nG}$

Whether LOFAR could already probe such a field
or whether SKAO could reveal it remains TBD



Transient rate = $50 - 30,000 \text{ Gpc}^{-3} \text{ yr}^{-1}$

The only stellar-sized transients that satisfy both Hillas' and our criteria are long gamma-ray bursts



[arXiv:2405.17179](https://arxiv.org/abs/2405.17179)

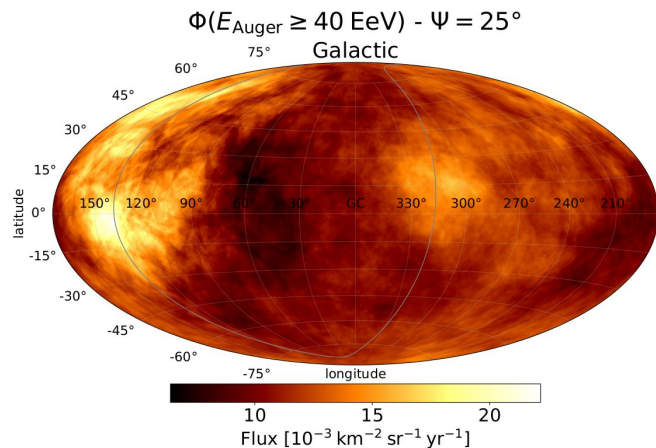
Backup

Jonathan Biteau

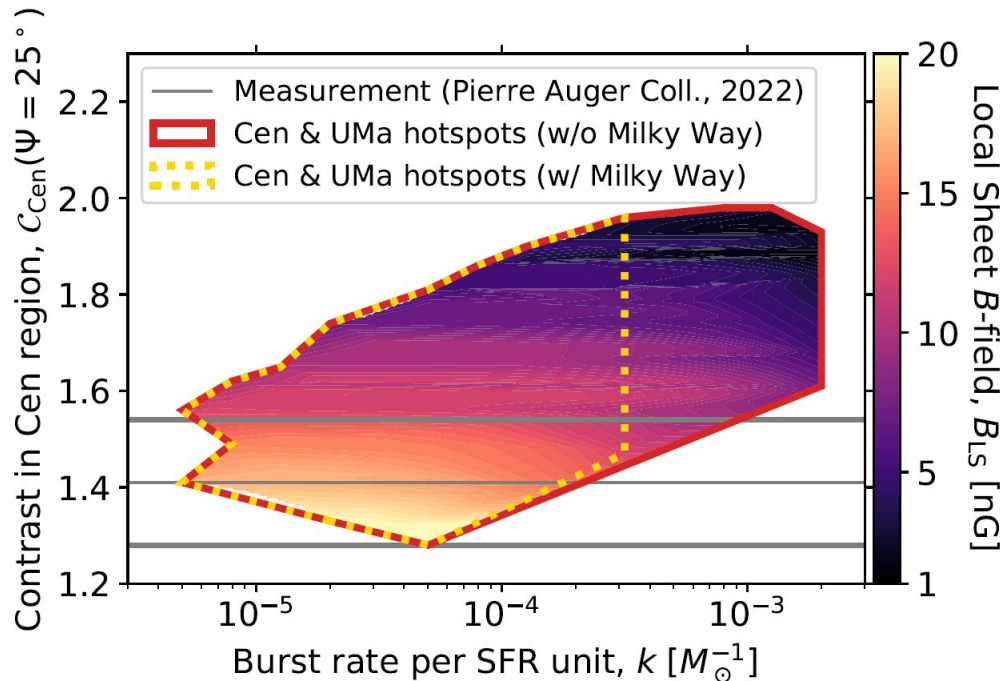
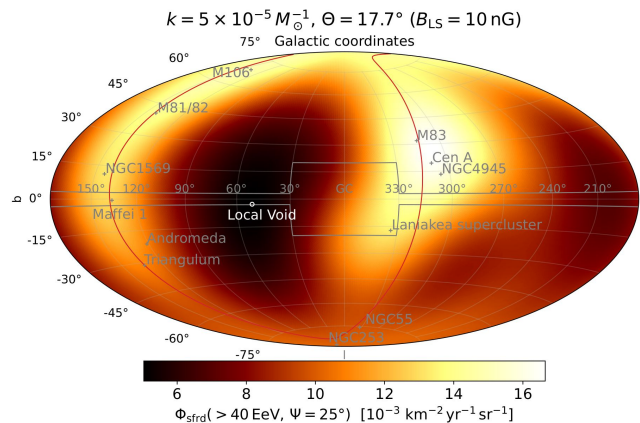
Contrast in the Centaurus region

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Auger + TA data
Credits: L. Caccianiga for Auger & TA



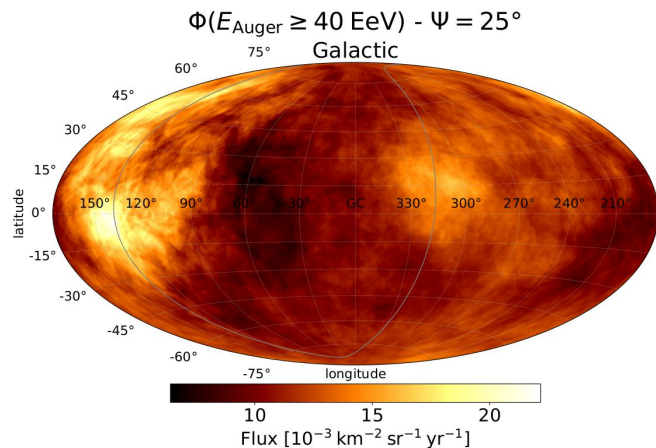
Best-match scenario
Credits: Marafico, JB+ '24



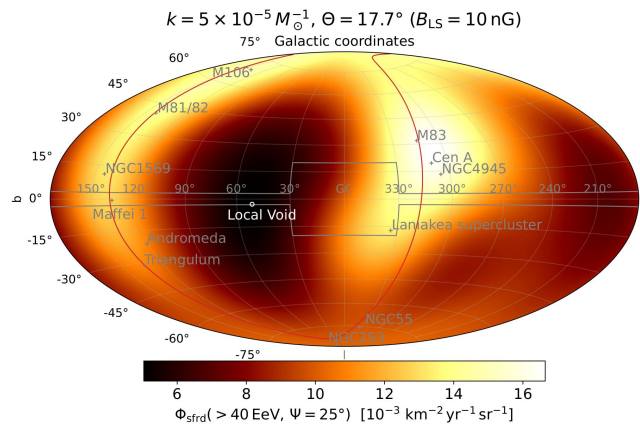
Coherent deflections in the Milky Way

Marafico, JB, Condorelli, Deligny, Bregeon, **ApJ** (in press) 2024

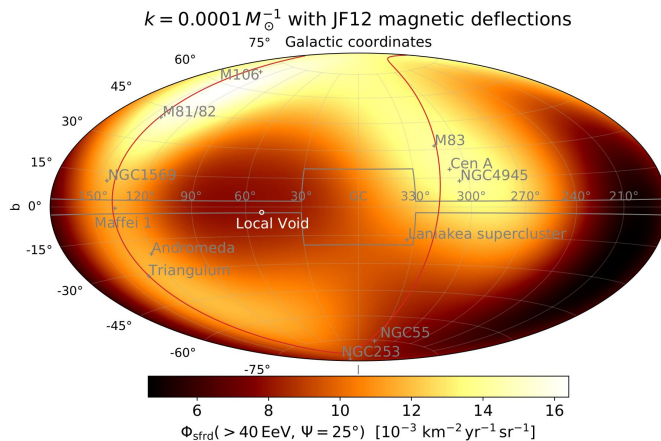
Auger + TA data
Credits: L. Caccianiga for Auger & TA



Best-match scenario
Credits: Marafico, JB+ '24



Regular B _{Milky Way}
from Jansson & Farrar '12



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