7th International Symposium on Ultra High Energy Cosmic Rays (UHECR)

Closing the Net on Transient Sources of Ultra-High Energy Cosmic Rays

J. Biteau, J. Bregeon, A. Condorelli, O. Deligny, S. Marafico

Based on:

*Biteau, **ApJS** 256, 15 (2021)*

*Luce, Marafico, Biteau, Condorelli, Deligny, **ApJ** 936, 62 (2022)*

*Condorelli, Biteau, Adam, **ApJ** 957, 80 (2023)*

*Marafico, Biteau, Condorelli, Deligny, Bregeon, **ApJ** 972, 1 (2024)*

anr agence nationale de la recherche AU SERVICE DE LA SCIENCE

DFG Deutsche Forschungsgemeinschaft

MICRO

As part of the ANR & DFG funded project: MultI-messenger probe of Cosmic-Ray Origins (MICRO)

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DE PIs: K.-H. Kampert (Bergischen Univ. Wuppertal), J. Becker-Tjus (Ruhr Univ. Bochum)

Olivier Deligny

cnrs IN2P3 Les deux infinis

IJCLab Irène Joliot-Curie

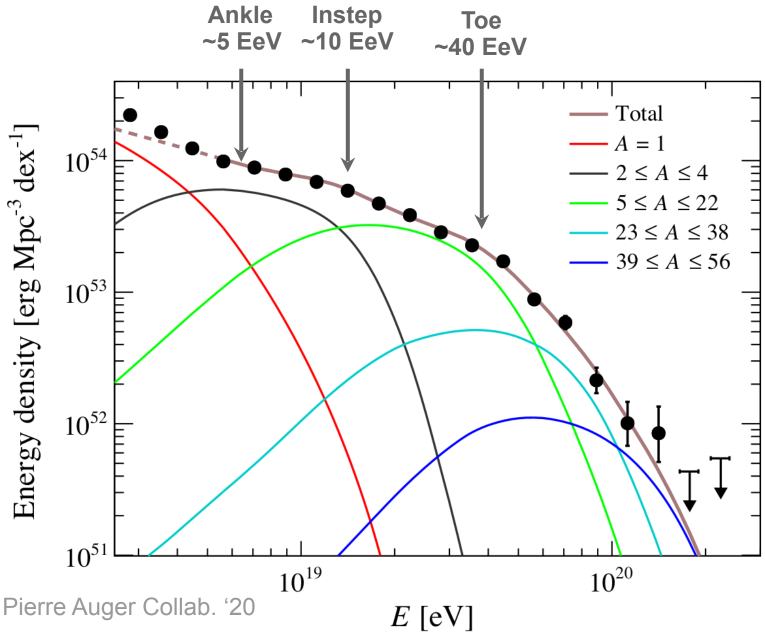
The quest for UHECR origins

Full-sky spectral and composition observables

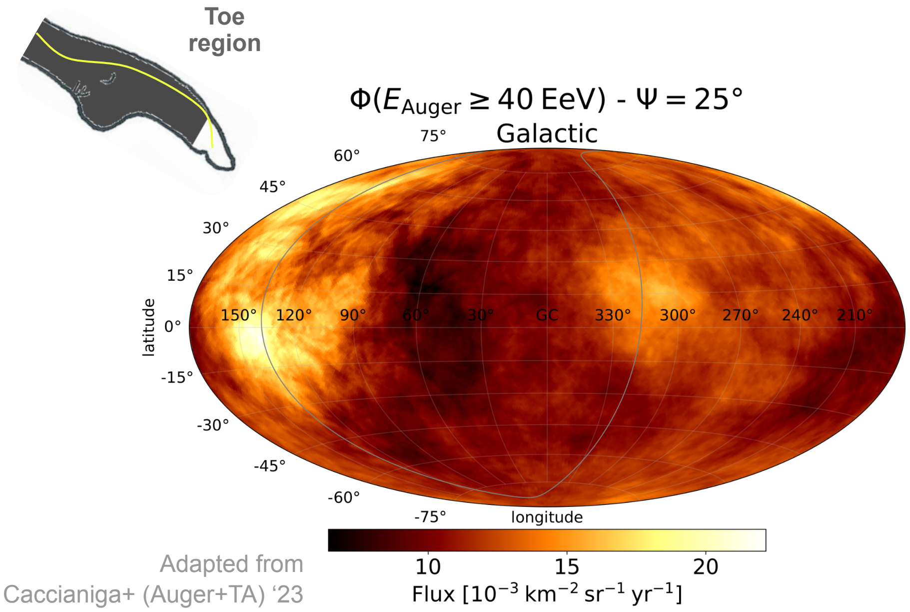
➔ Constrain UHECR **production rate per unit matter:** $n_{\rm src} \times \dot{\mathcal{E}}_{\rm UHECR}$ or $\dot{n}_{\rm src} \times \mathcal{E}_{\rm UHECR}$

Anisotropy observables

➔ Break down the flux vs arrival direction



Pierre Auger Collab. '20



Adapted from
Caccianiga+ (Auger+TA) '23

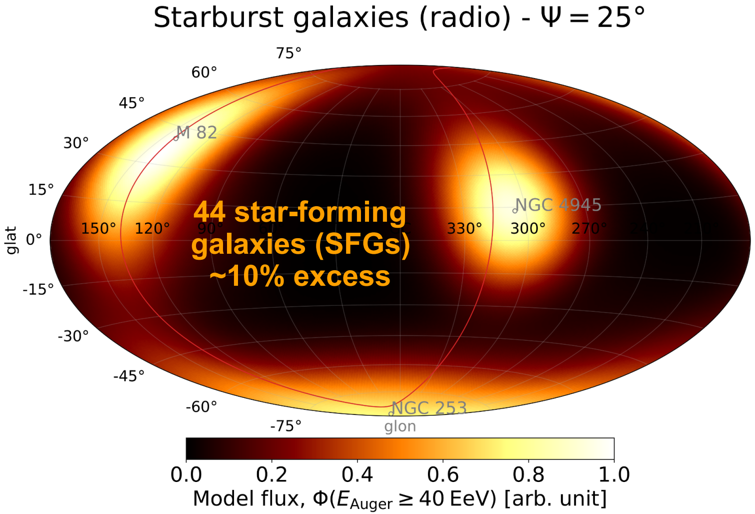
Status of anisotropies @UHE

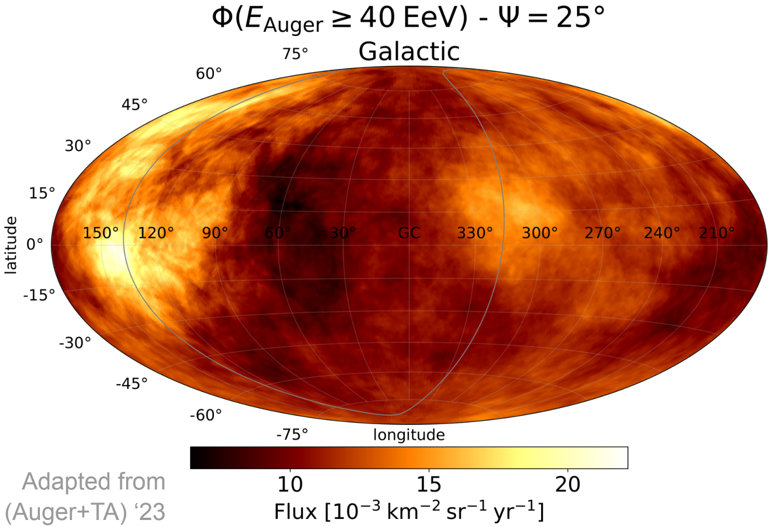
Cross-correlation with 44 starbursts: evidence of anisotropy in the toe region

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 ~ 10%?
Why Gaussian angular scale θ ≈ 15° (⇔ top-hat Ψ ~ 25°)**?**



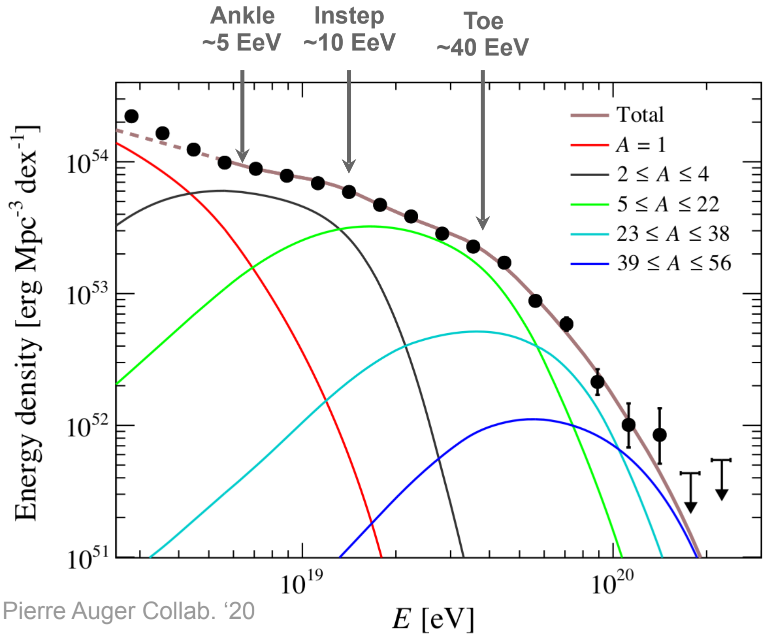


Adapted from Caccianiga+ (Auger+TA) ‘23

Mass composition

Reservoir of heavy elements?
➔ Accelerators located close to exceptional sources of nuclei, e.g. of nucleosynthesis or direct synthesis

➔ Reacceleration of PeV CRs



Pierre Auger Collab. ‘20

➔ Metallicity poorly constrained (p secondaries/primaries?)

➔ Material from (high-mass) stars He/Heavy nuclei (Marafico+ ‘24)

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

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 (0.30 ± 0.05 stat. ± 0.10 sys. vs 0.53 ± 0.09)
Lodders 09, Zhang, Murase, Oikonomou ‘17

Starbursts host more frequent stellar explosions…

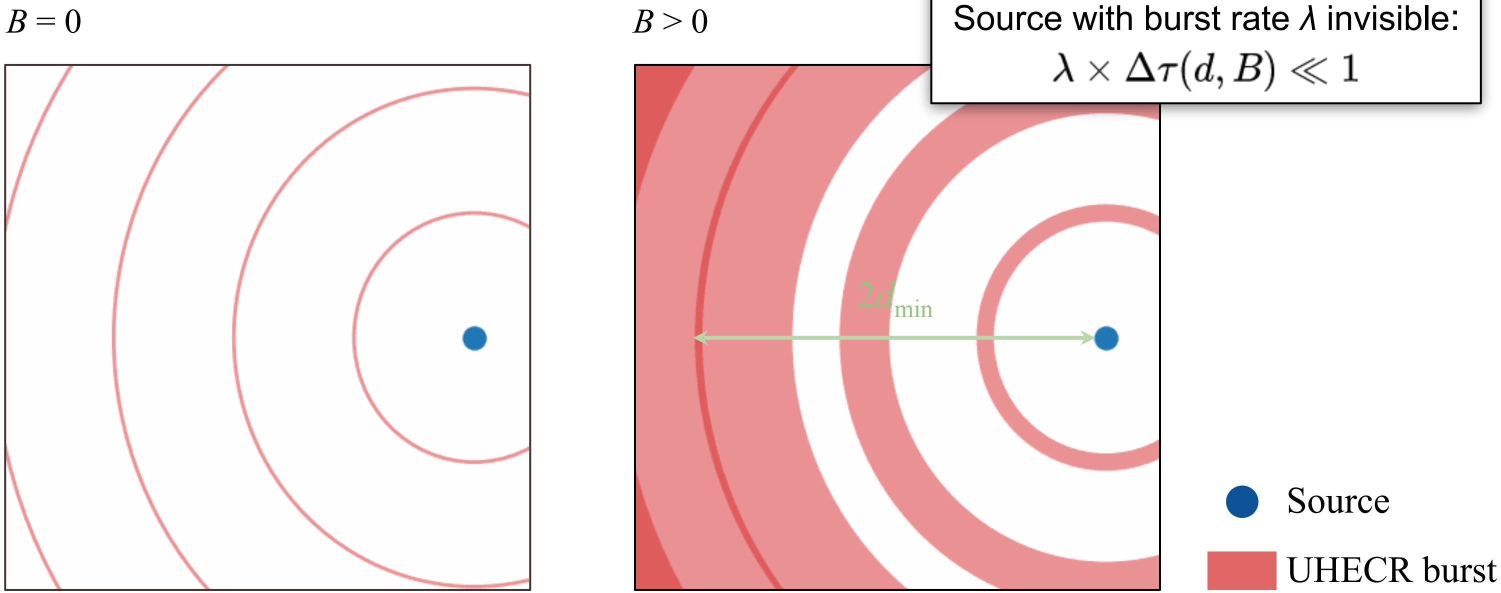
Just a tracer of SFR or stellar mass *M**

➔ SFR/M* tracer of cataclysmic events, death of massive stars

➔ Transient scenario by essence

Source with burst rate λ invisible:

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



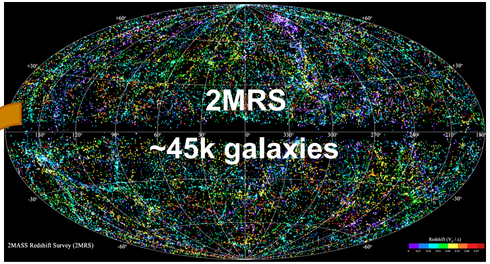
Credit: S. Marafico

Mapping out stellar matter in the GZK horizon

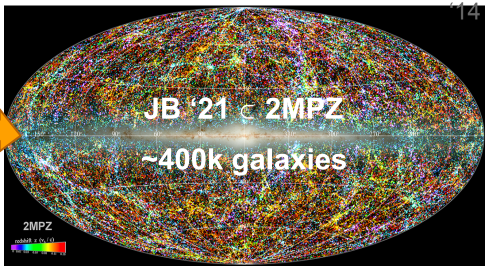
(2MASS Photometric *z* catalog ∩ WISE) ✖ HyperLEDA (Biteau, ApJS ‘21)

Near IR flux-limited sample mapping both SFR and stellar mass over 90% of the sky

Credits: 2MRS, Huchra+ ‘12

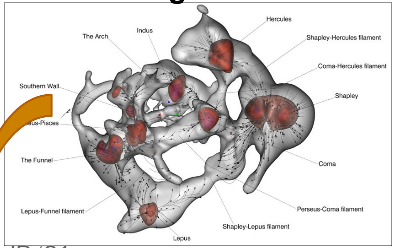


Credits: 2MPZ, Bilicki & Jarret ‘14



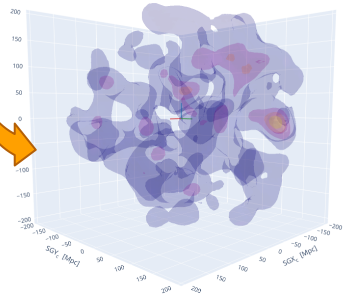
Cosmic V-web, Pomarède+ 2017

~8k galaxies



JB ‘21

~400k galaxies



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

➔ Completeness in M_*: 50% at d_{max} (× 2 wrt 2MRS)

➔ Distances estimated with a 50 − 50 ratio of spectroscopic and photometric measurements

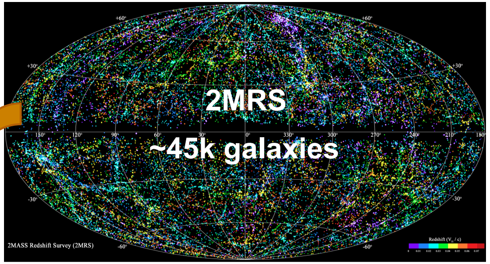
➔ Greatest granularity to date of the density of matter in the entire 350-Mpc radius volume

➔ >100 Mpc, convergence of SFR and M_* densities towards measurements of deep-fields values

Mapping out stellar matter in the GZK horizon

(2MASS Photometric *z* catalog ∩ WISE) ✖ HyperLEDA (Biteau, ApJS '21)

Credits: 2MRS, Huchra+ '12



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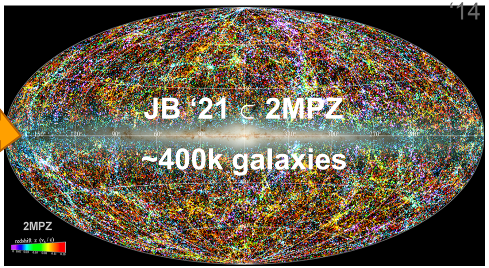

Cosmic V-web, Pomarède+ 2017

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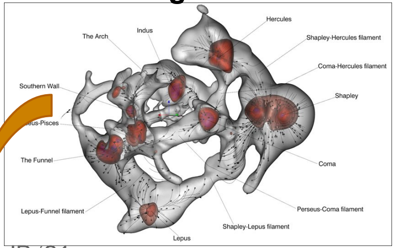
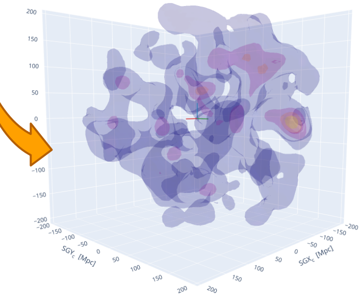
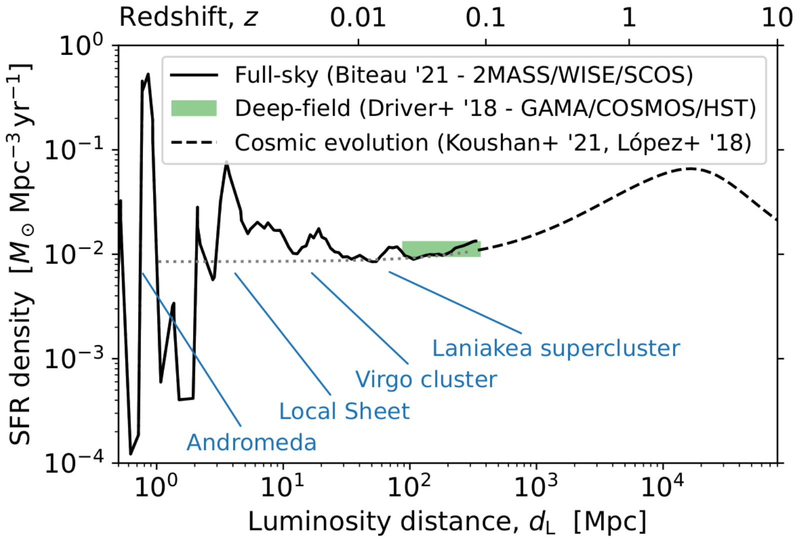


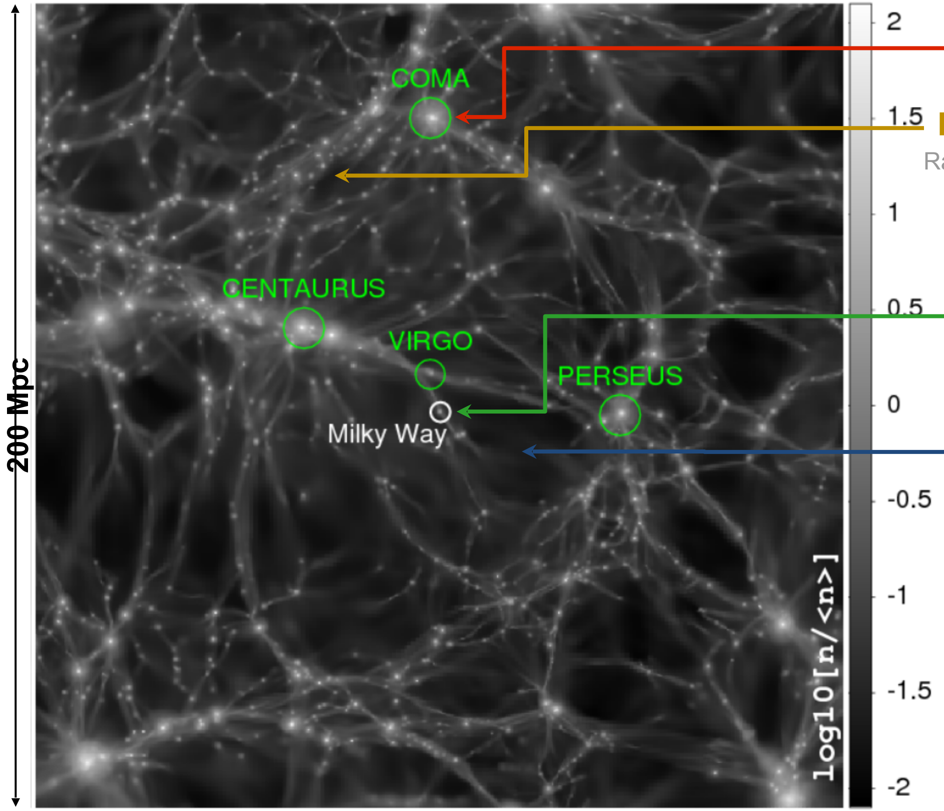
JB '21

~400k galaxies





Magnetic fields



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

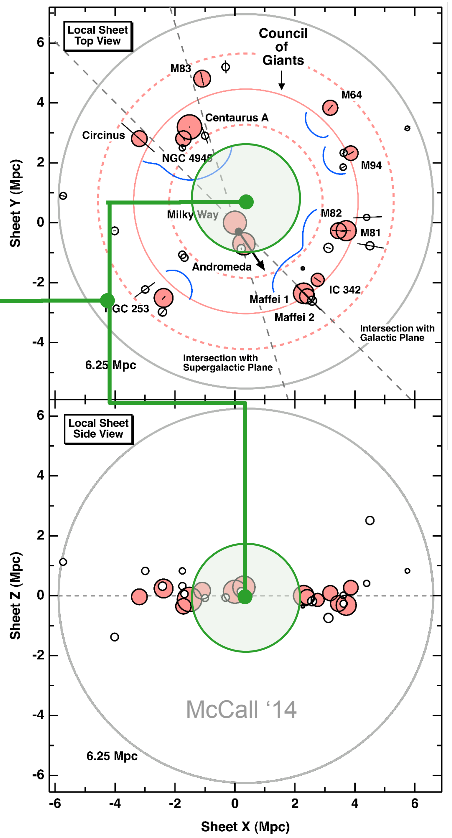
Cluster: *B* ~ 1-10 μG
e.g. Bonafede+ '10

Filament: *B* ~ 10-100 nG
Radio and X- ray stacking of galaxy filaments, Vernstrom+ '21, Faraday rotation, Carretti+ '22

Sheet: *B*?

Void: *B* < 10 pG
Jedamzik & Saveliev '19, Vazza+ '17

Our location:
The Local Sheet
Assume warm-hot plasma with properties similar to those of clusters turbulent B field filling the Local Group with λ ~ $\lambda_{clusters}$ and B_{rms} to be determined



Magnetic fields

Galaxy clusters: B ~ 1-10 μG

➔ Calorimeters for UHE nuclei (Dolag+ 09, Kotera+09, Harari+16, Fang & Murase 18, Condorelli+, ApJ '23)

➔ **Turn OFF** bright X-ray clusters (~~Virgo~~, ~~Perseus~~, ~~Coma~~)

Galaxy filaments: B ~ 10-100 nG

➔ **Transparent** to UHE nuclei (Condorelli+, ApJ '23)

➔ No need for specific treatment

Voids: B < 10 pG

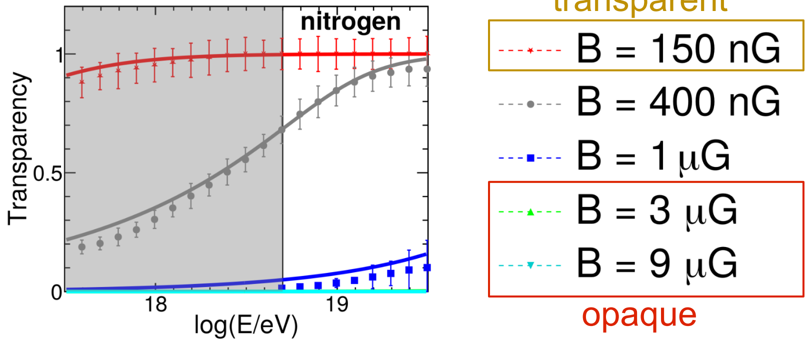
➔ Too low to have a sizeable impact on UHECRs within GZK horizon

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

➔ **Translucent**, w/ angular spread $\boldsymbol{\theta_{\mathrm{obs,\,UHECR}}} \sim \boldsymbol{\Delta\theta_{\mathrm{Local\ Sheet}}}$

➔ Time spread → $\boldsymbol{d_{\min}}$ **= extent of $\boldsymbol{B_{\mathrm{Local\ Sheet}}}$ ~ few Mpc**

Condorelli, Biteau, Adam, ApJ 23



The Milky Way (Jansson & Farrar '12)

➔ $\boldsymbol{\Delta\tau_{\mathrm{MW}}} \ll \boldsymbol{\Delta\tau_{\mathrm{Local\ Sheet}}}$, $\boldsymbol{\Delta\theta_{\mathrm{MW}}}$ accounted for

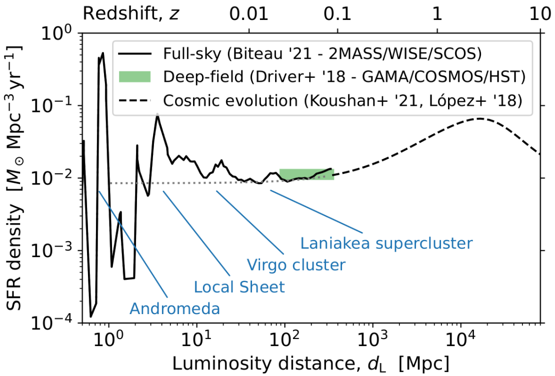
➔ Test of coherent deflections with 1 model

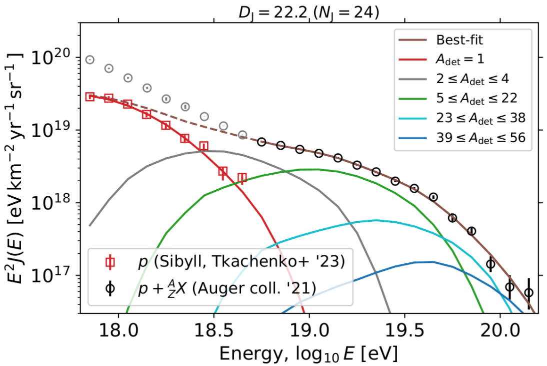
$$\Delta\theta = 10^\circ \times \left(\frac{B}{10\,\mathrm{nG}}\right)\left(\frac{R}{5\,\mathrm{EV}}\right)^{-1}\left(\frac{d}{2\,\mathrm{Mpc}}\right)^{1/2}\left(\frac{\lambda_B}{10\,\mathrm{kpc}}\right)^{1/2}.$$

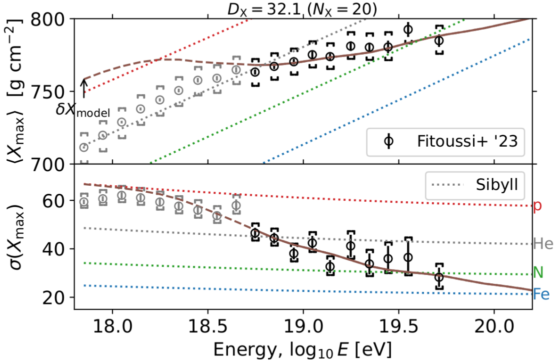
$$\Delta\tau = 70\,\mathrm{kyr} \times \left(\frac{B}{10\,\mathrm{nG}}\right)^2\left(\frac{R}{5\,\mathrm{EV}}\right)^{-2}\left(\frac{d}{2\,\mathrm{Mpc}}\right)^2\left(\frac{\lambda_B}{10\,\mathrm{kpc}}\right).$$

Transient model of UHECR sky

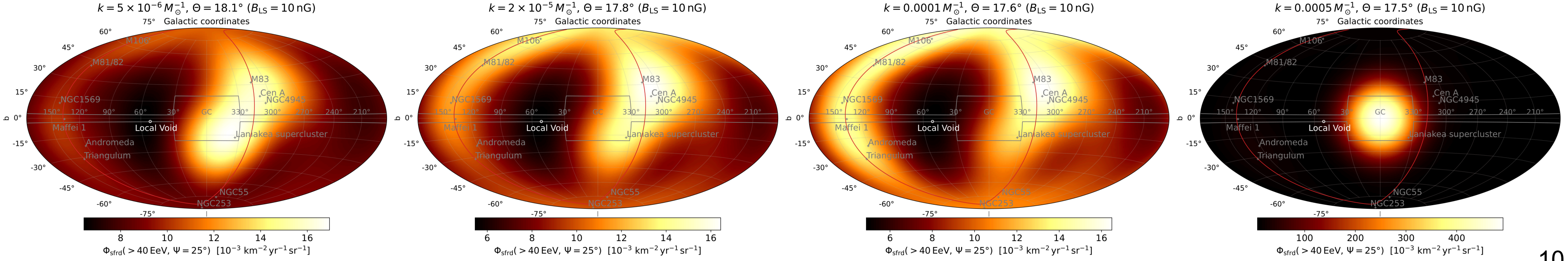
Spectral & composition model (see also Luce+ ApJ '22)







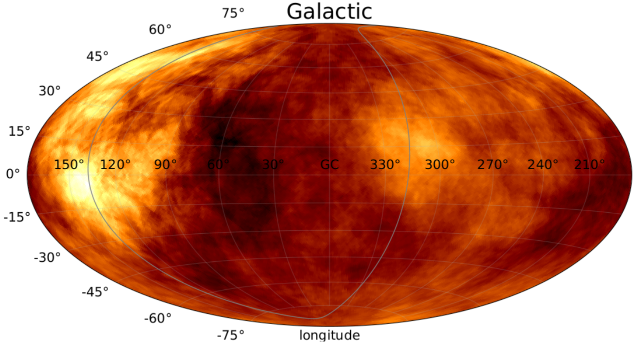
Increasing value of burst rate per star-formation unit *k*, for a given *B*-field in the Local Sheet



Closing the Net on UHECR Transient Sources

Auger + TA data

Credits: L. Caccianiga for Auger & TA

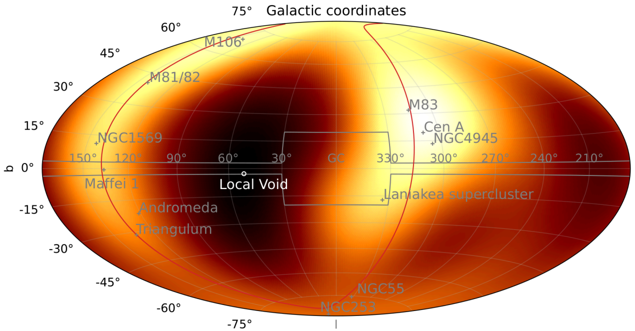


UHECR Model ≈ UHECR Data

$\Delta\theta(\mathrm{hotspot}_{\mathrm{model}}, \mathrm{hotspot}_{\mathrm{data}}) < 40°$

Best-match transient scenario

Credits: Marafico, JB+ '24



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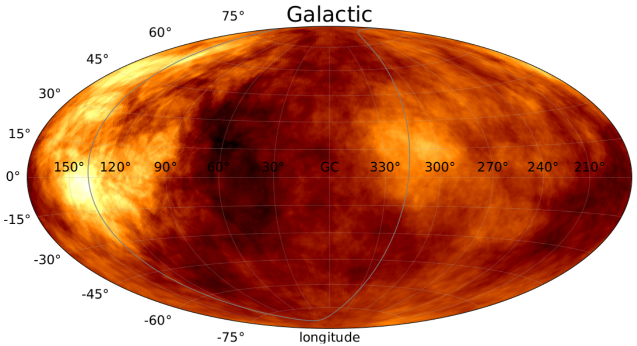

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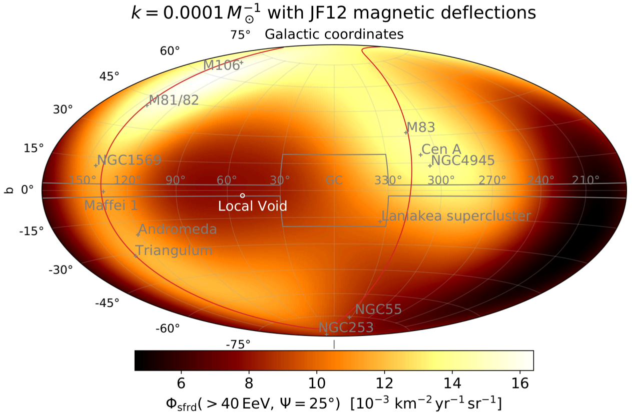

Closing the Net on UHECR Transient Sources

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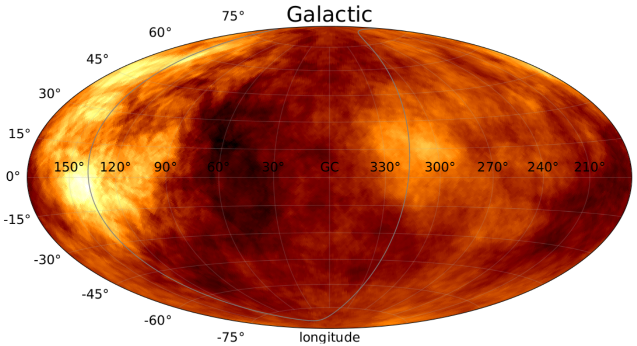

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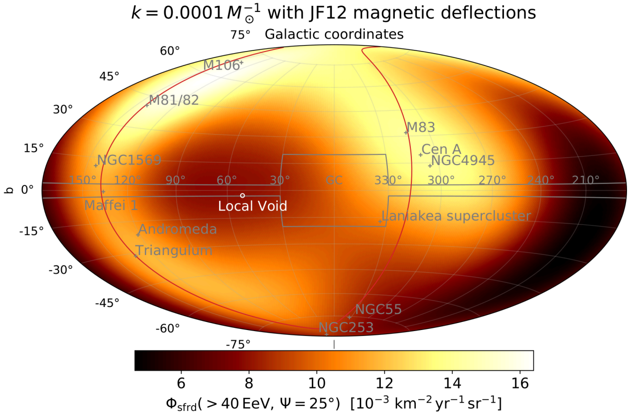
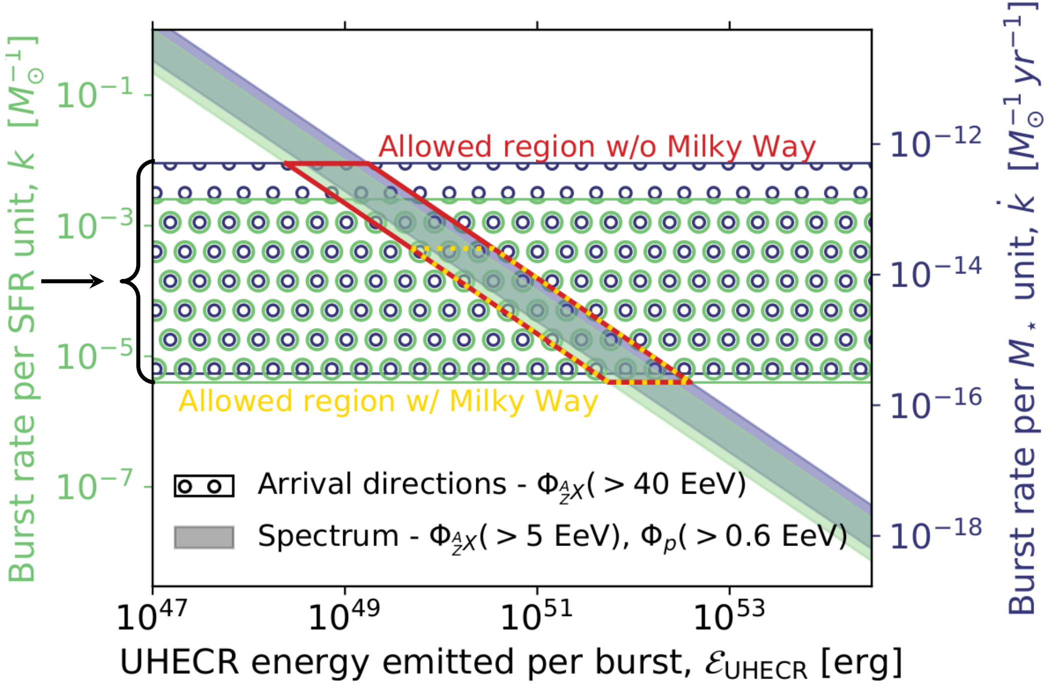


Solution with at least 1 Northern & Southern hotspot found for

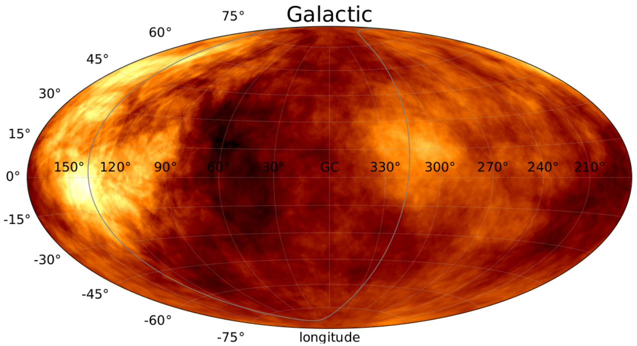
Local Sheet $B_{\rm rms}$ = 0.5 - 20 nG



Closing the Net on UHECR Transient Sources

Auger + TA data

Credits: L. Caccianiga for Auger & TA



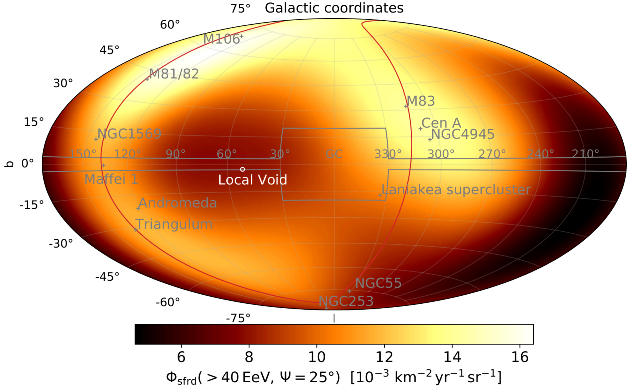
UHECR Model ≈ UHECR Data

$\Delta\theta(\text{hotspot}_{\text{model}}, \text{hotspot}_{\text{data}}) < 40°$

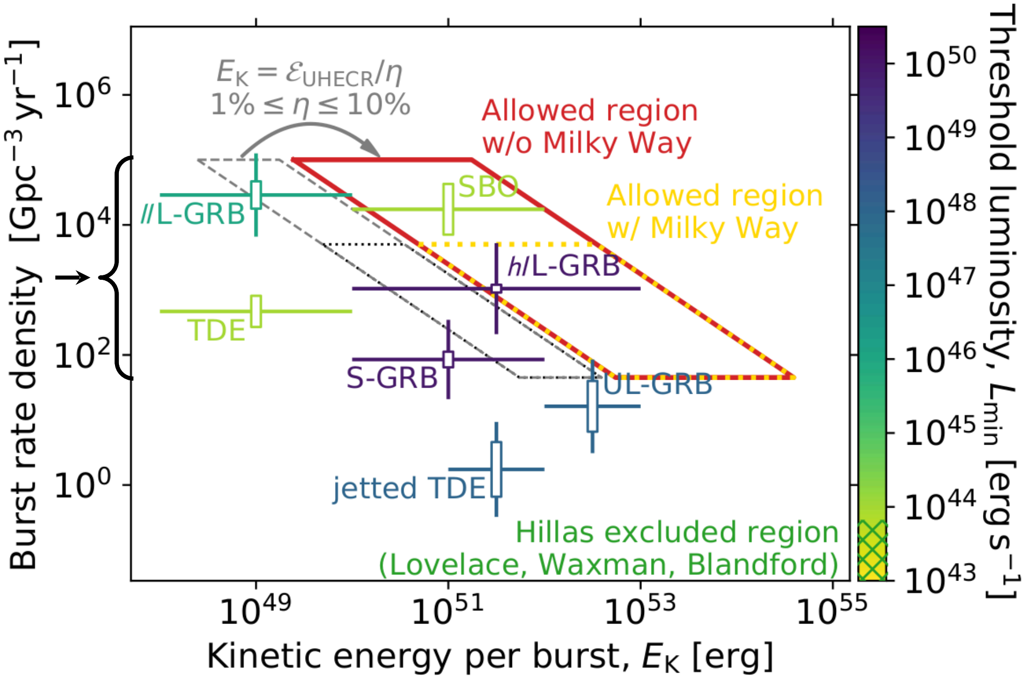
Best-match transient scenario

Credits: Marafico, JB+ '24

$k = 0.0001\,M_{\odot}^{-1}$ with JF12 magnetic deflections



X-ray transient rate vs kinetic energy

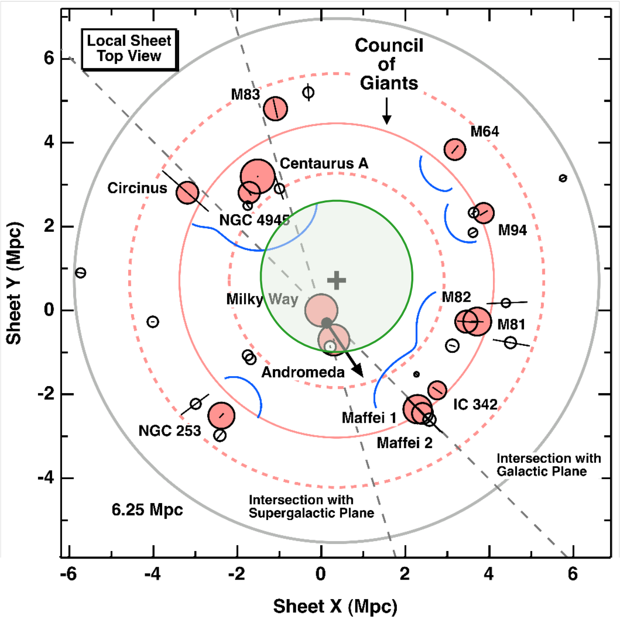


Conclusions

Marafico, Biteau, Condorelli, Deligny, Bregeon, **ApJ 972, 1 2024**

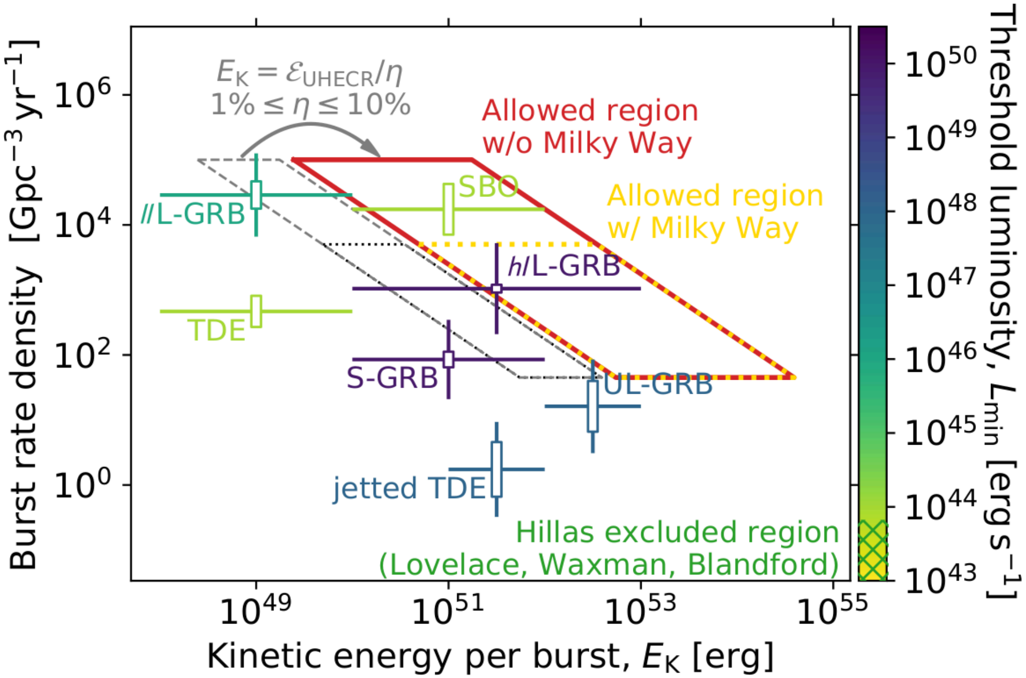
Local Sheet B_{rms} = 0.5 - 20 nG

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



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

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



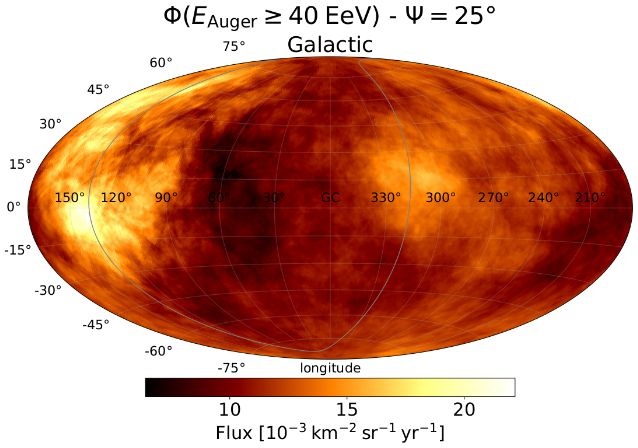
Backup

Contrast in the Centaurus region

Marafico, Biteau, Condorelli, Deligny, Bregeon, **ApJ 972, 1 2024**

Auger + TA data

Credits: L. Caccianiga for Auger & TA



Best-match transient scenario

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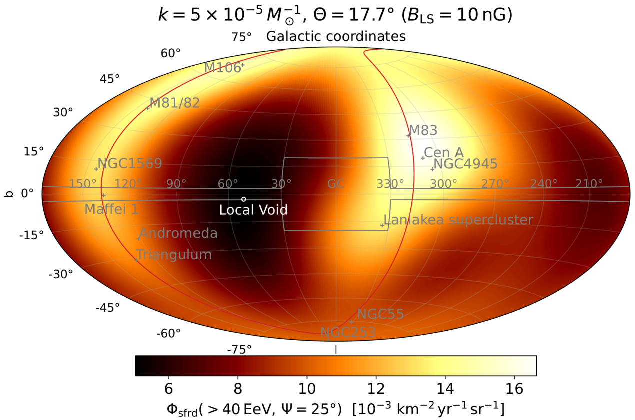
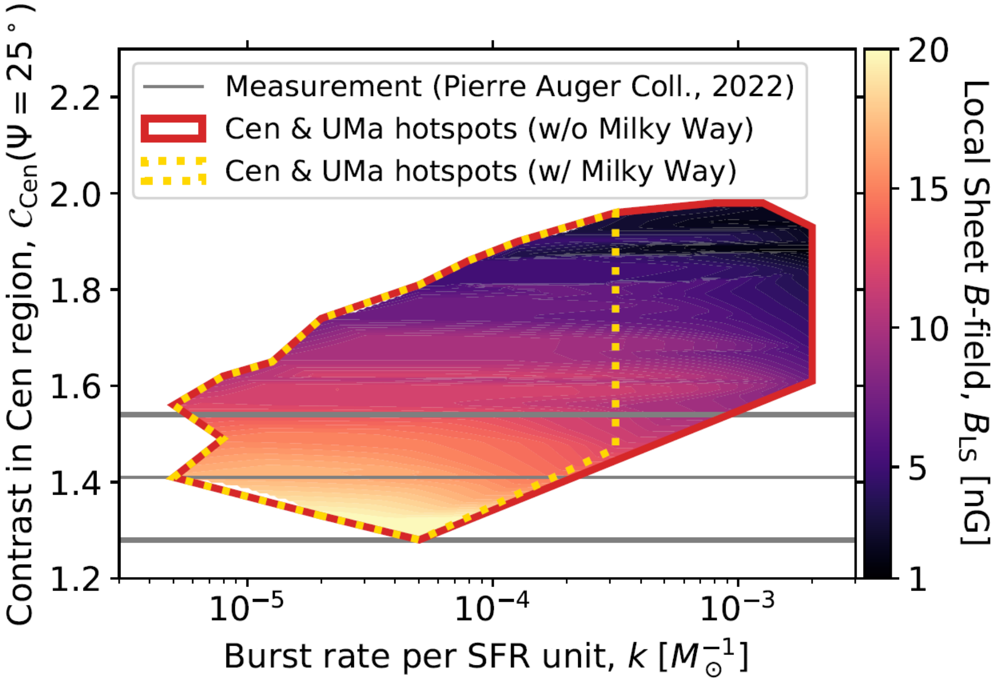




Properties of the stellar-sized X-ray transients

Type	Beam angle deg	$\log_{10} E_{\rm K}$ [erg]	Reference	$\log_{10} L_{\rm min}$ [erg s^{-1}]	$\log_{10} \dot{n}_{\rm obs}$ [Gpc^{-3} yr^{-1}]	Reference	$\log_{10} \dot{n}_{\rm true}$ [Gpc^{-3} yr^{-1}]
*ll*L-GRBs	5 – 20	48 – 50	Cano et al. (2017)	46	2.64 ± 0.21	Sun et al. (2015)	4.5 ± 0.6
SBOs	–	50 – 52	Waxman & Katz (2017)	44	4.24 ± 0.39	Sun et al. (2015)	4.2 ± 0.4
*hl*L-GRBs	1 – 5	50 – 53	Cano et al. (2017)	50	-0.10 ± 0.06	Sun et al. (2015)	3.0 ± 0.7
TDEs	–	48 – 50	Cendes et al. (2022)	44	2.67 ± 0.24	Sun et al. (2015)	2.7 ± 0.2
S-GRBs	5 – 20	50 – 52	Laskar et al. (2022)	50	0.12 ± 0.12	Sun et al. (2015)	1.9 ± 0.6
UL-GRBs	5 – 20	52 – 53	Beniamini et al. (2015)	48	-0.61 ± 0.39	Prajs et al. (2017)	1.2 ± 0.7
Jetted TDEs	5 – 20	51 – 52	Cendes et al. (2022)	48	-1.58 ± 0.42	Sun et al. (2015)	0.2 ± 0.7

NOTE—In column 8, the true rate density of bursts $\dot{n}_{\rm true} = f_{\rm b}^{-1} \dot{n}_{\rm obs}$ is determined from the rate observed in soft and hard X-rays, $\dot{n}_{\rm obs}$ (column 6), above a luminosity threshold $L_{\rm min}$ (column 5). The true rate density also accounts for the beaming correction factor of the relativistic component, $f_{\rm b} = 1 - \cos\theta_{\rm jet}$, where $\theta_{\rm jet}$ is the two-sided jet opening angle, or beam angle (column 2). The latter is taken as 90° for non-collimated outflows from SBOs and TDEs.

A cosmographic view on stellar mass and star formation

410,761 galaxies out to 350 Mpc, distance at which 50% of $M*$ is below the 2MASS sensitivity limit

➔ Distances checked against those tabulated in the HyperLEDA database (cosmic-ladder estimates for about 4,000 nearby galaxies that are not in the Hubble flow, spectroscopic estimates for about half of the sample and 2MPZ photometric estimates for the other half)

➔ Galaxy-count decrease in the ZoA modeled with an empirical function of Galactic latitude, which provides incompleteness correction factors

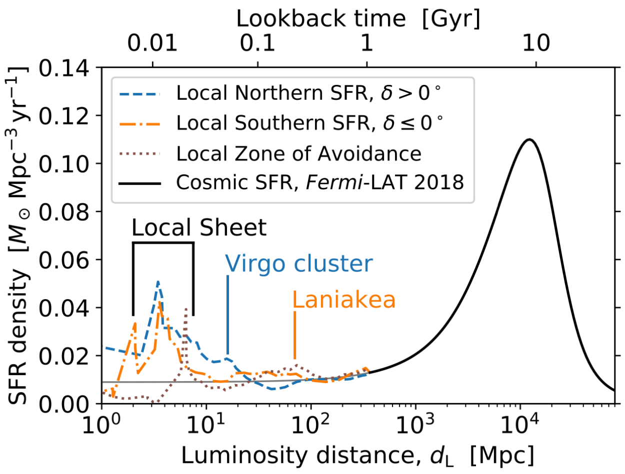
➔ Galaxy cloning close to the Galactic bulge, by filling of the ZoA with galaxies from mirrored regions above and below the Galactic plane

➔ Parameterization of the deep-field *M** function used to infer incompleteness correction factors vs luminosity distance

➔ SFR estimates by exploiting the relation between *M** and SFR for three morphological branches established with NIR and Halpha observations of galaxies in the Local Volume at distances smaller than 11 Mpc

➔ Morphological information available from HyperLEDA for about a third of the sample out to 350 Mpc; observed morphological distribution as a function of distance exploited to provide a statistical estimate of SFR for the remaining two thirds of the sample

➔ Correction factors for the SFR density



Stellar mass cosmographies

The 2 Micron All-Sky Survey (2MASS, Skrutskie+ 2006)

- Ground-based mosaic at near-IR wavelengths (J, H, K)
- 90% sky coverage, Zone-of-Avoidance excluded
- 1.6 million galaxies, based on their extension

→ K-band tracer of stellar mass M*, within ~0.1 dex provided distance measurements

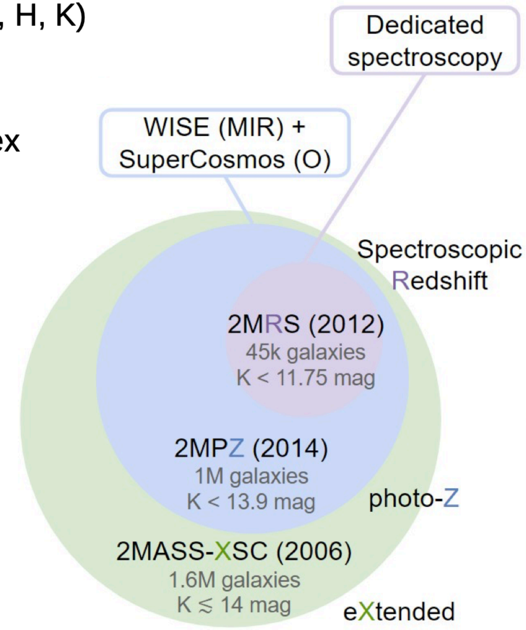
2MASS subsets with measured distances

- 2MASS redshift survey (2MRS, Huchra+ 2012):
  - → spectroscopy of the brightest
  - → limited to 140 Mpc at 50% M* completeness
- 2MASS photo-z catalog (2MPZ, Bilicki+ 2014):
  - → neural-net multi-band analysis: σ(d) = 12%
  - → limited to 350 Mpc at 50% M* completeness

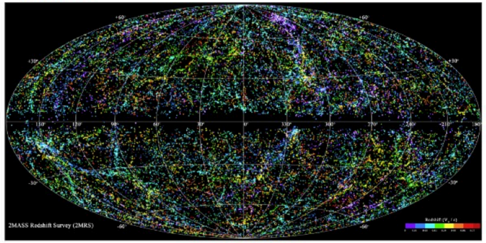
Limitations

- Spectro-z from **deep fields missing** from 2MRS
- Galaxies ≲ 20 Mpc not in Hubble flow

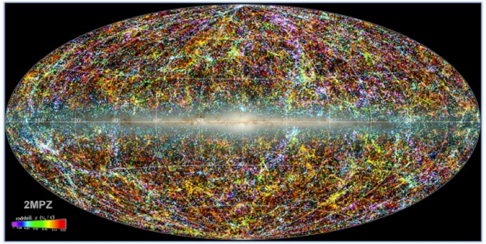
→ **nearby distances mis-estimated**



2MRS Credits: Huchra+ 2012



2MPZ Credits: M. Bilicki & T. Jarret 2014

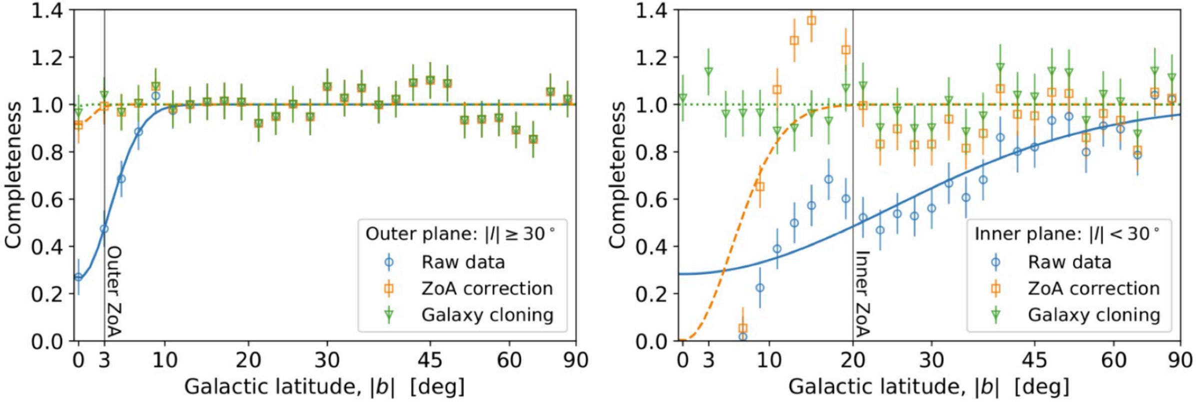


Galactic coordinates

Incompleteness in the Zone of Avoidance

- **Estimated based on galaxy counts in 100-300 Mpc (nearly isotropic distribution)**
- Equal area galactic latitude bins in inner and outer plane regions (|l|=30°)
- Cosmic variance estimated from bin-to-bin fluctuations at l > 45°

Biteau 2021

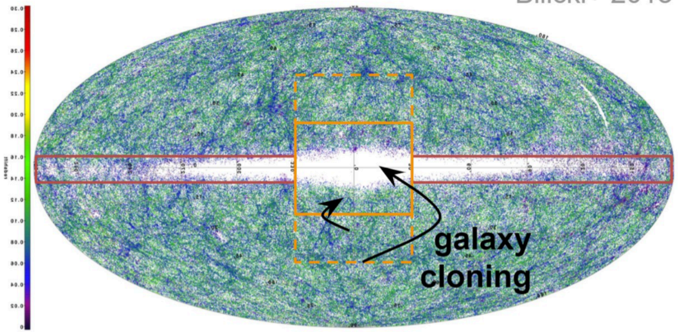


Corrections

Empirical Gaussian(sin b) fit used to infer galaxy weights:

- re-weighting sufficient in outer plane, insufficient in inner plane
- ZoA cut placed at ~50% incompleteness:
  l = 3° / 20° for outer / inner plane
- galaxy cloning (as in Lavaux & Hudson's 2M++ 2011) in ZoA region

Bilicki+ 2013

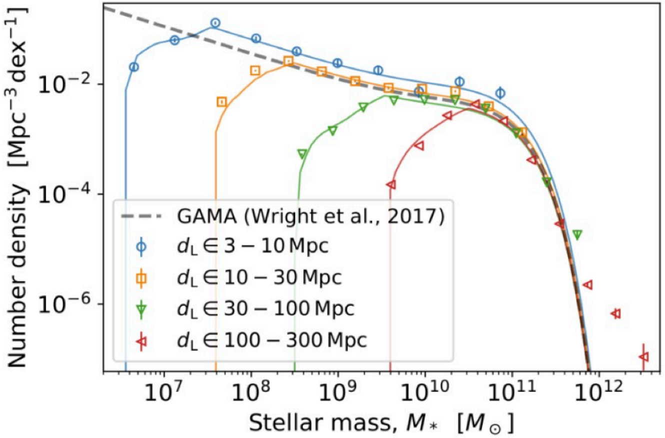


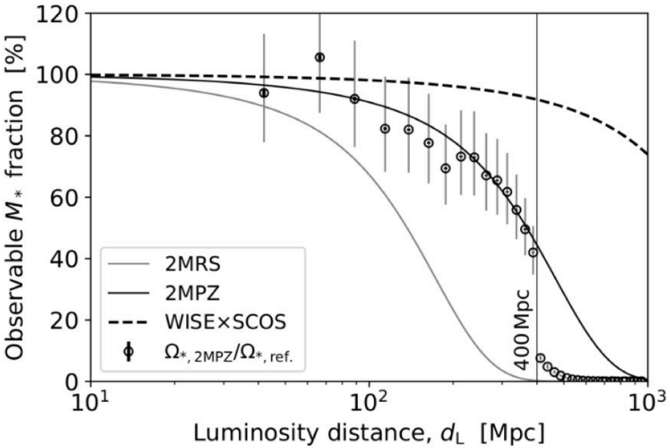
Incompleteness with increasing distance

Mass function

- Full-sky, including clones in the ZoA and weights as a function of galactic latitude
- Best-fit double Schechter from GAMA-field observations (Wright+ 2017) scaled to observed integral, accounting for local overdensity
- Low-mass end: (luminosity function) ⨉ (fraction of observable objects above 2MPZ sensitivity limit, provided distances)

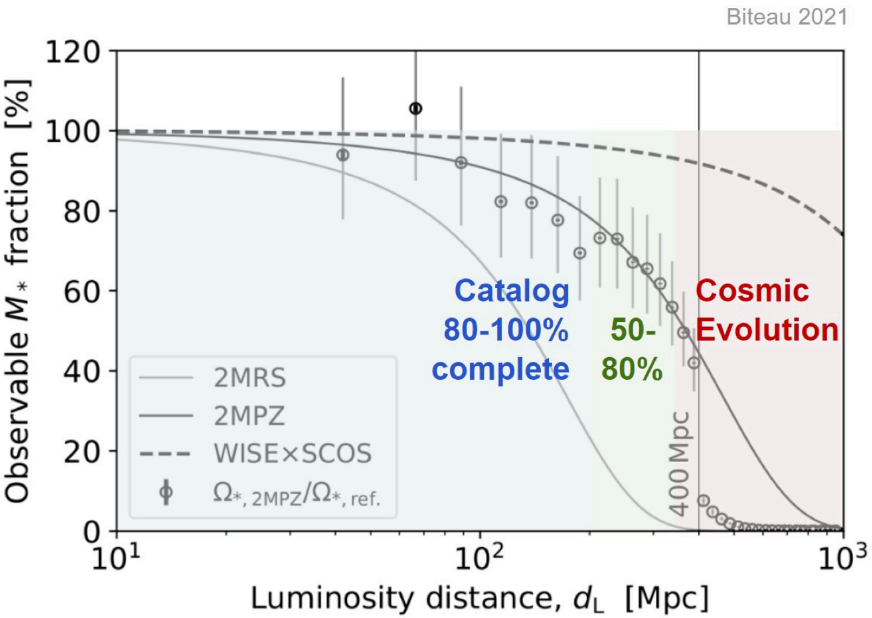
Biteau 2021

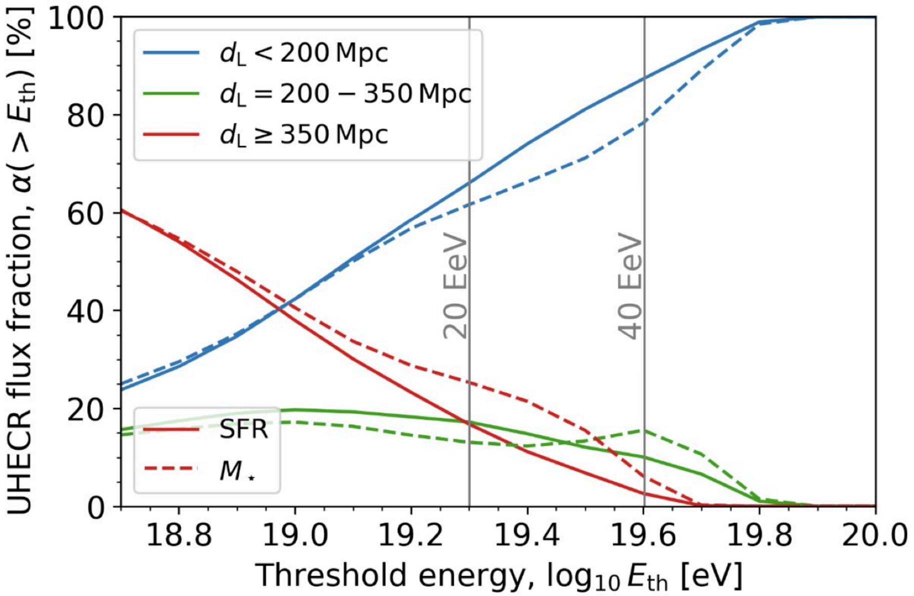




- **Completeness**
- From integral of (GAMA mass function) ⨉ M* above 2MPZ sensitivity limit: weights = completeness(d) ⨉ completeness(b) ∈ [0.26,1]
- → probed volume from 140 Mpc (2MRS) to 350 Mpc (2MPZ) at similar completeness: ⨉ 2.6 (distance), ⨉ 18 (volume)
- → further increase by ⨉ 4 (distance) to be expected if full WISE x SuperCOSMOS potential exploited

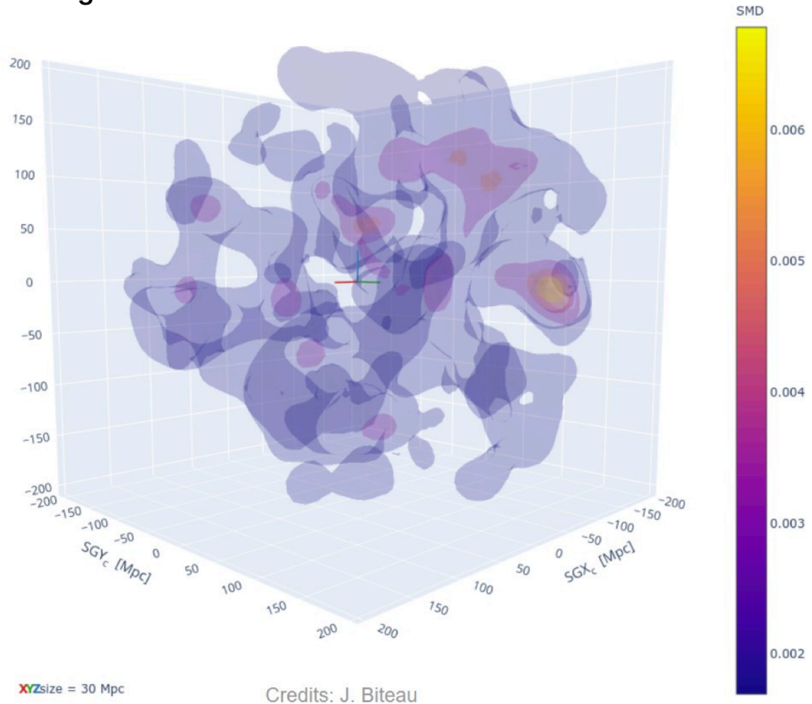
Fraction of UHECR signal from successive shells





Comparison: cosmographies (limited here to Cosmic V-web volume)

Stellar Mass Density [critical units]
Comoving radius < 250 Mpc - Smoothing: 15 Mpc
400000 galaxies



Credits: J. Biteau

Cosmic V-web, Pomarède+ 2017