Cosmic-ray astronomy at the highest energies

Ground- and space-based detection principles, recent highlights and future projects

Jonathan Biteau – Journée SFP Astropart. & MM – 2025.03.20

From Hillas, 20 years ago… *pre Pierre Auger Observatory era*

Component A

fully ionized <u>H, He, … , Fe</u>

with a slope γ ~ 2.7

up to

R_A ~ 3 PV

- $Z_{\mathrm{H-He}} e R_A = 3 - 6\,\mathrm{PeV} \equiv E_{\mathrm{1st\ knee}}$
- $Z_{\mathrm{Fe}} e R_A \approx 100\,\mathrm{PeV} \equiv E_{\mathrm{2nd\ knee}}$
-

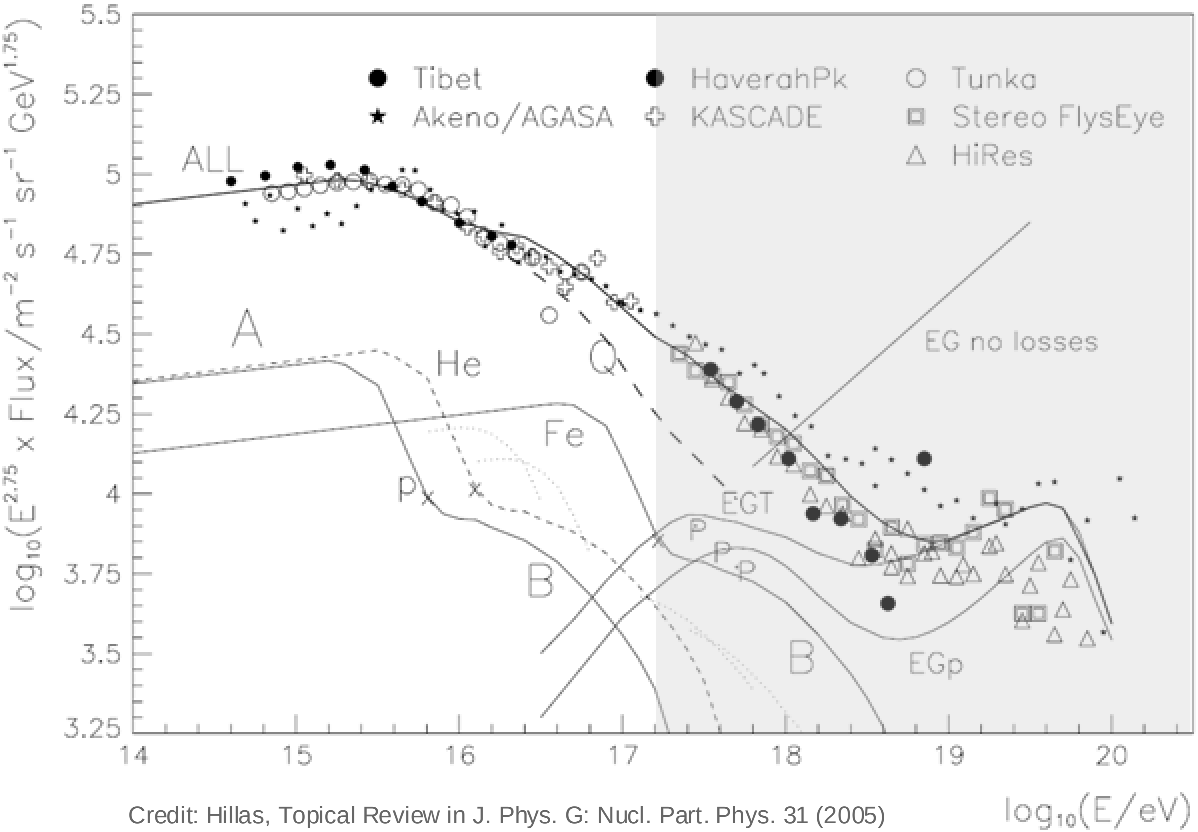
<u>**Component B**</u>

Something still has to be added to the ‘KASCADE’ component ‘A’

M. Hillas (2005)

<u>**Component C**</u>

- H only ~ dip of Berezinsky+ ‘04
- H and He (no heavier nuclei)



Credit: Hillas, Topical Review in J. Phys. G: Nucl. Part. Phys. 31 (2005)

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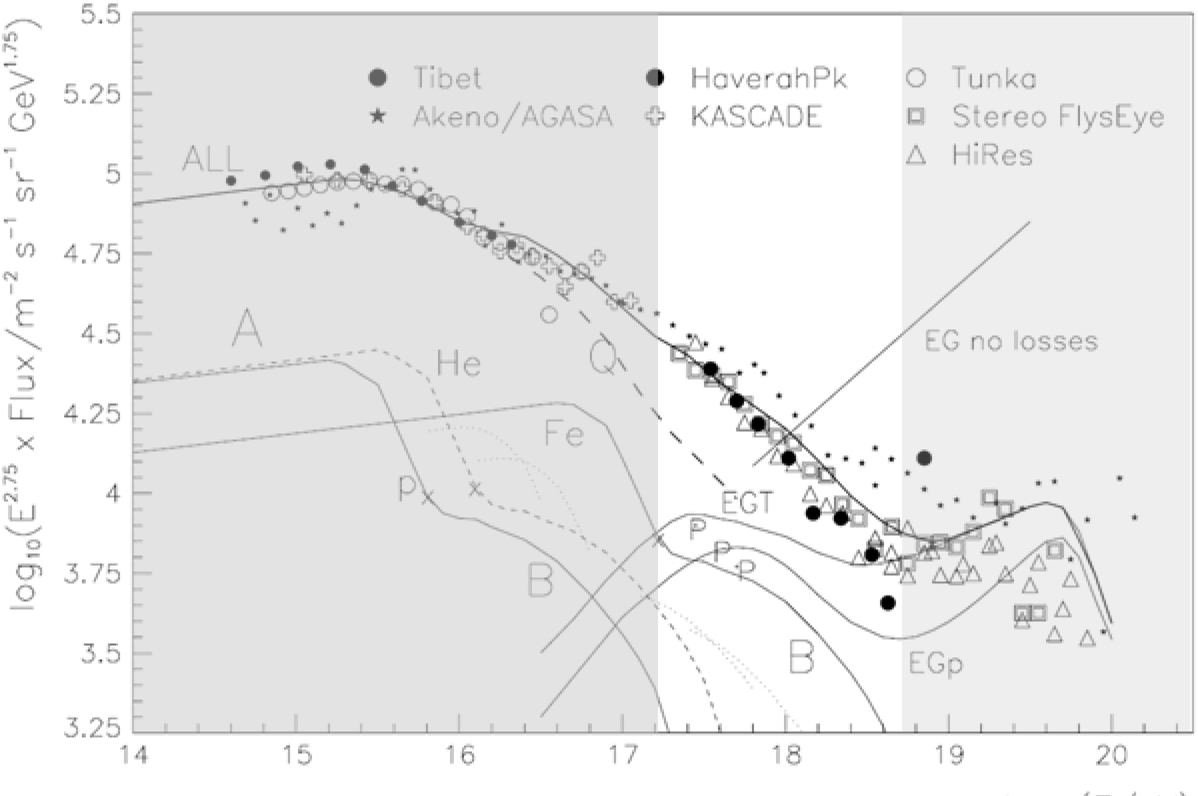

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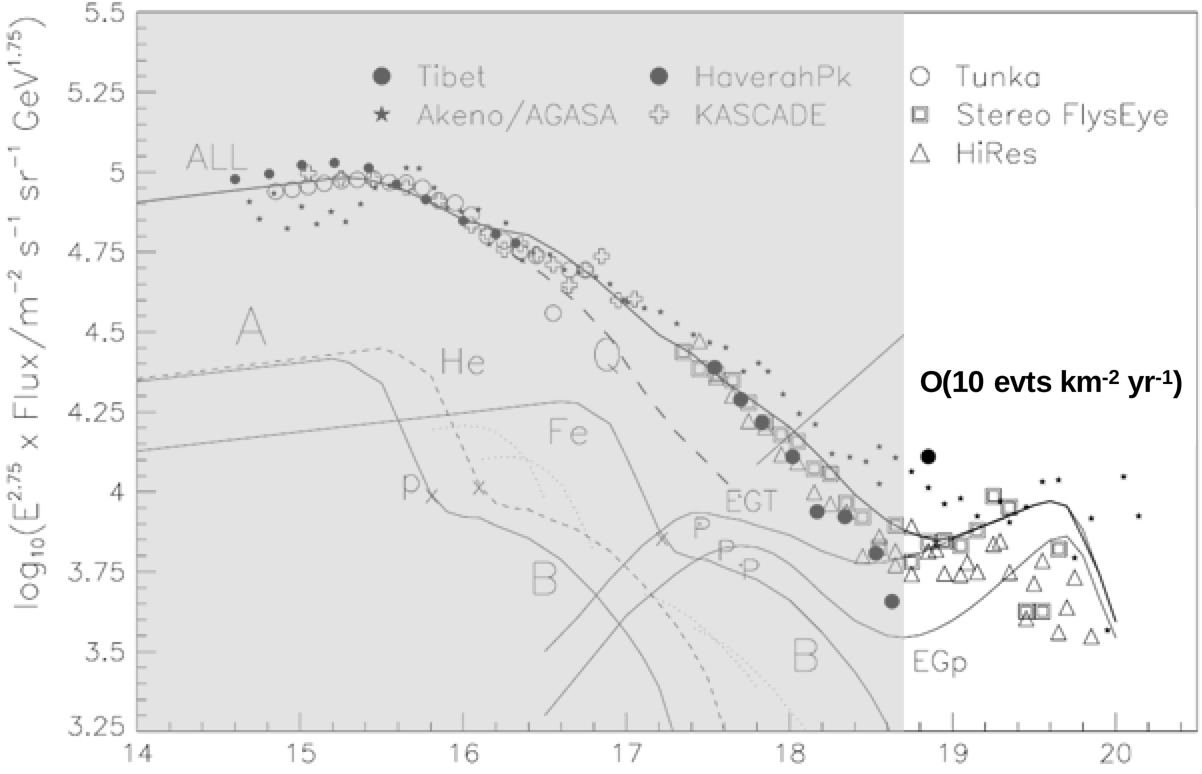
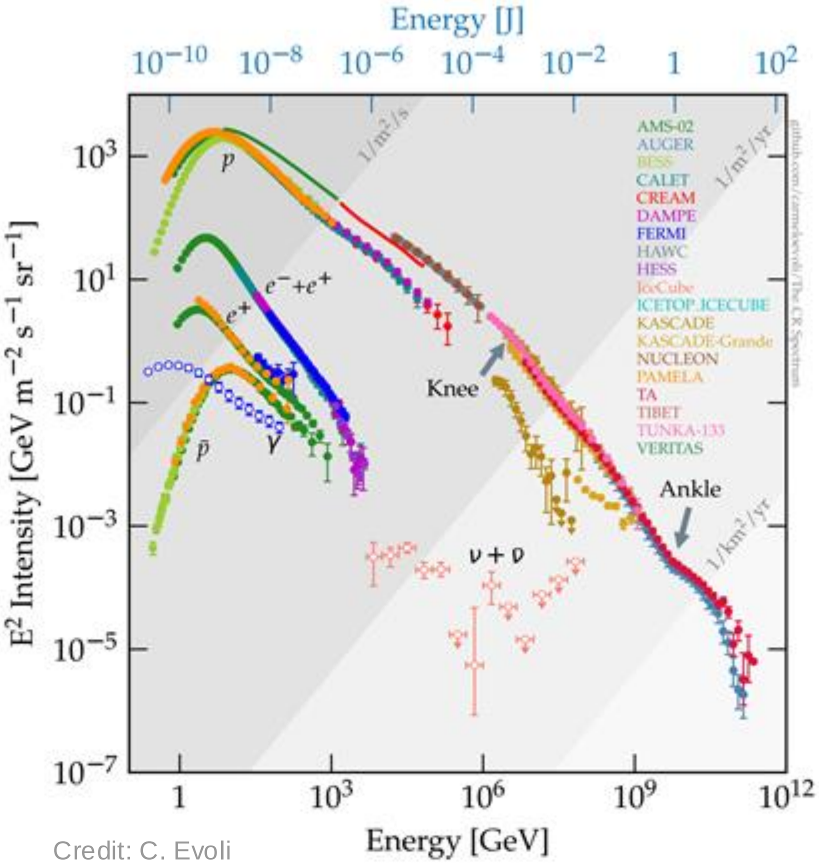
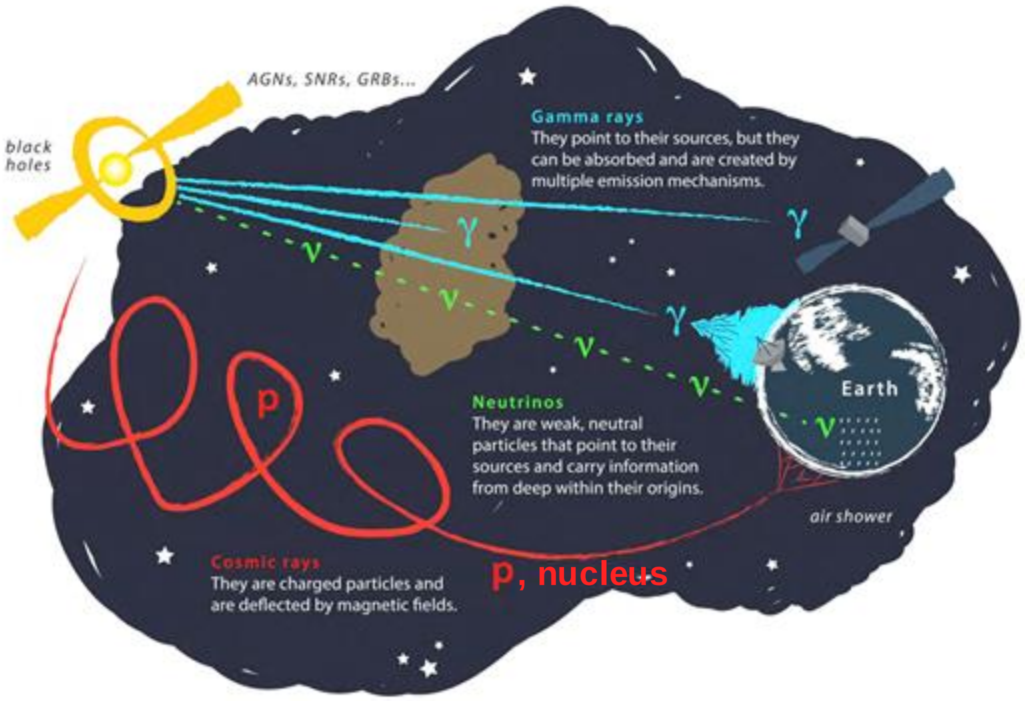


$\log_{10}(E/\mathrm{eV})$

Credit: Hillas, Topical Review in J. Phys. G: Nucl. Part. Phys. 31 (2005)

Today's picture: all astroparticles



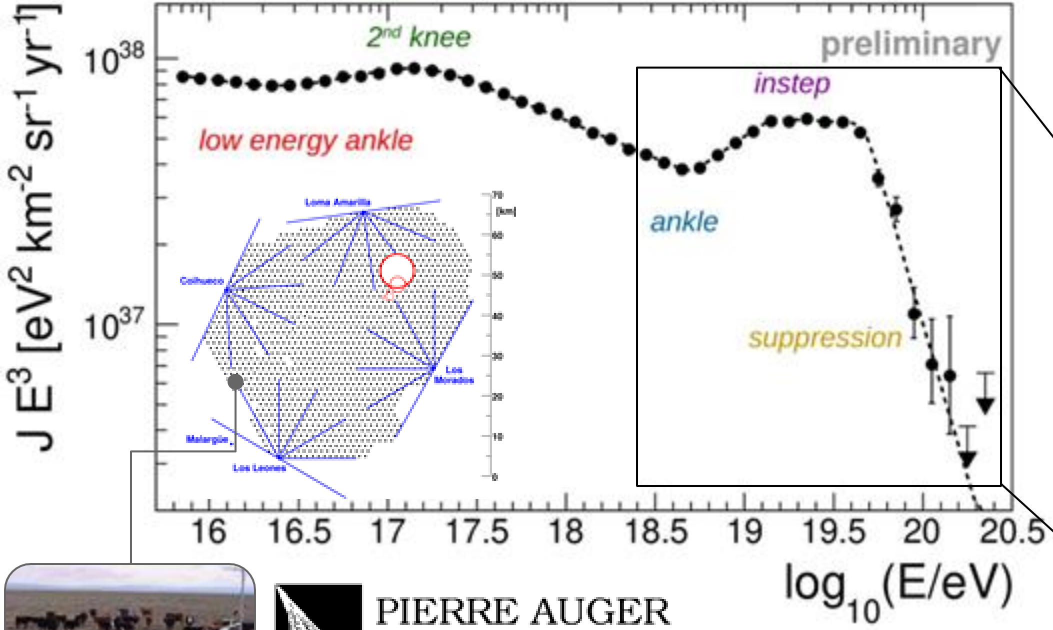


Credit: C. Evoli

Credit: M. Ahlers & F. Halzen

Today's picture: cosmic rays at the highest *E*

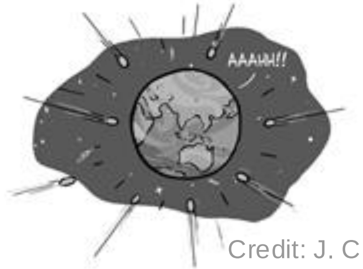
Auger Coll; PRD '20, PRL '20,
EPJC '21, PoS(ICRC2023) by Brichetto



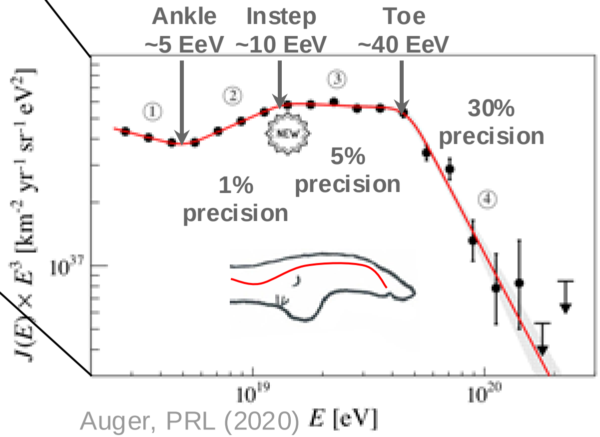
PIERRE AUGER
OBSERVATORY

Who Is Shooting Superfast Particles at the Earth?

In Which You Learn That Space
Is Full of Tiny Bullets



Credit: J. Cham
& D. Whiteson



Auger, PRL (2020)

I. Spectrum & nuclear composition

How to measure them, where do we stand, why does it matter

II. Anisotropy searches at the highest *E*

Why do we try, what do we see, the sources within reach?

III. The extragalactic cosmic-ray background

Next observational and phenomenological frontiers

Detection principles

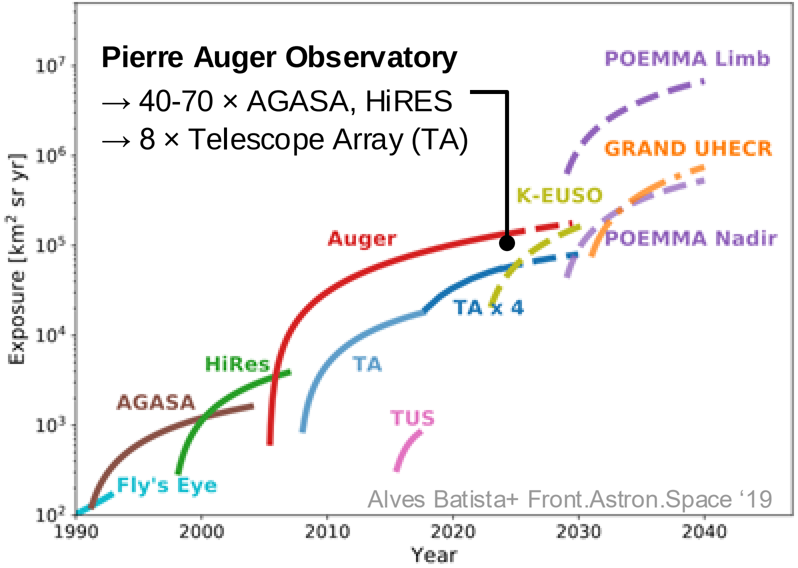
Shower particle sampling: water Cherenkov (Č) or plastic scintillator

Luminescence (calorimetric): fluorescence (isotropic) rather than Č

Radio emission: ~100 MHz pulse driven by geomagnetic effect

→ **key quantity: Exposure =** $\boldsymbol{A_{\mathrm{eff}} \times \Omega \times T}$

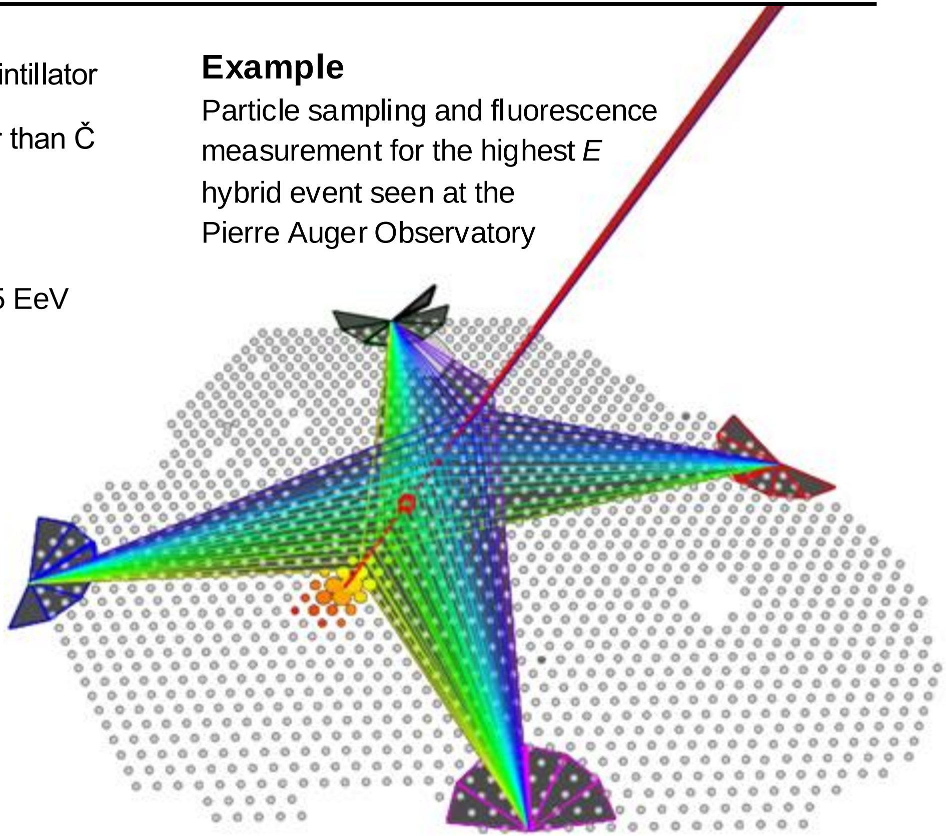
Auger Phase 1 (2004-2021) ~80,000 km² yr sr, i.e. ~150k at E > 5 EeV



Alves Batista+ Front.Astron.Space '19

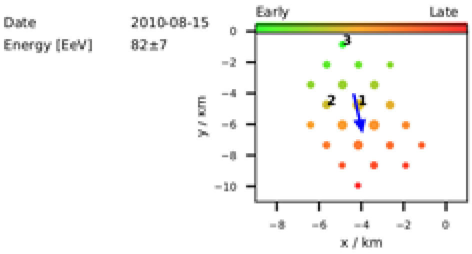
Example

Particle sampling and fluorescence measurement for the highest E hybrid event seen at the Pierre Auger Observatory



Auger Coll., ApJS 2023

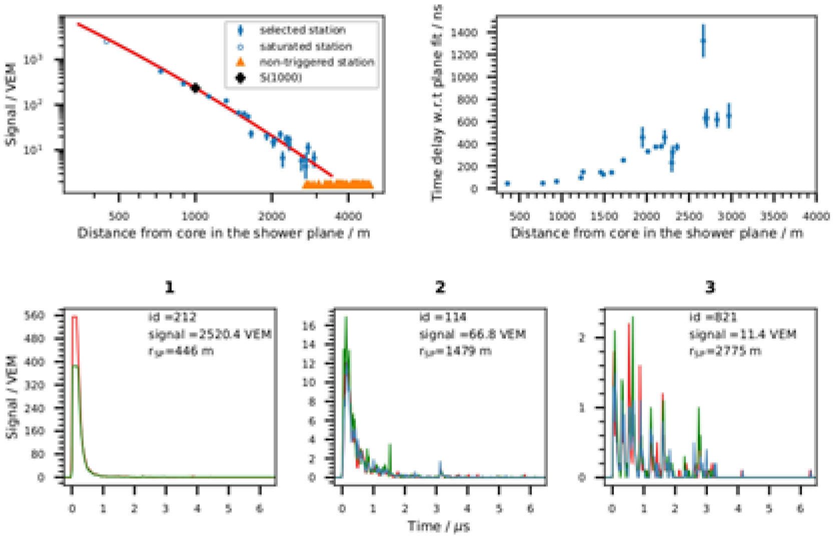
Event reconstruction: surface detector (SD)

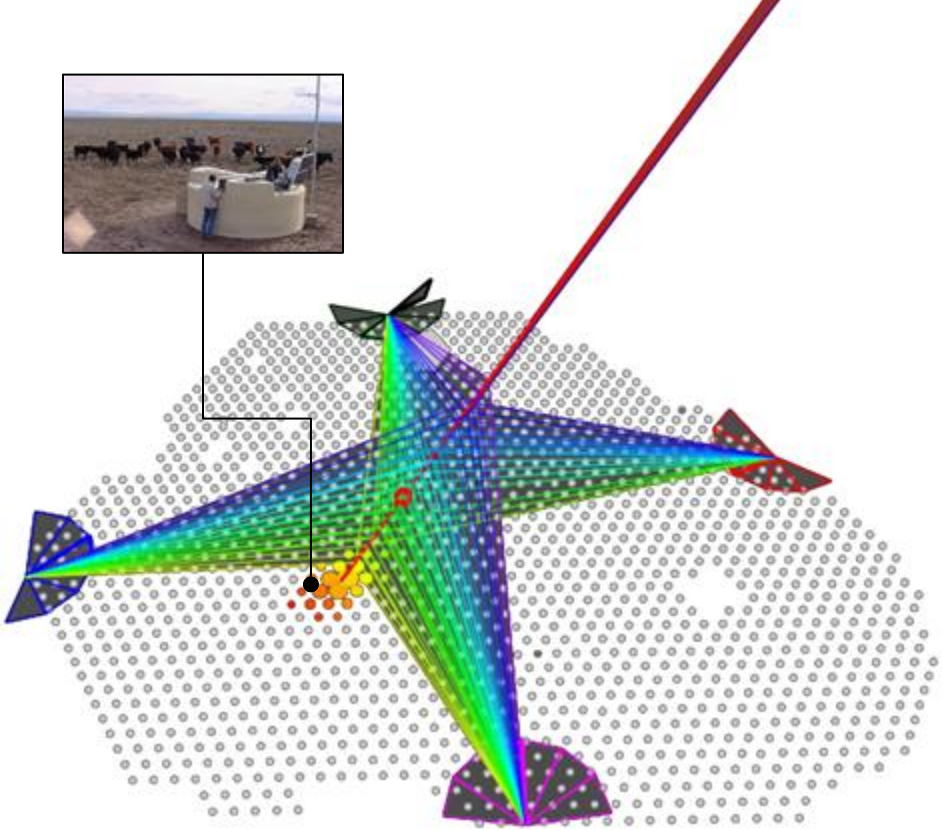


Above the ankle:

$\Delta E/E < 15\%$

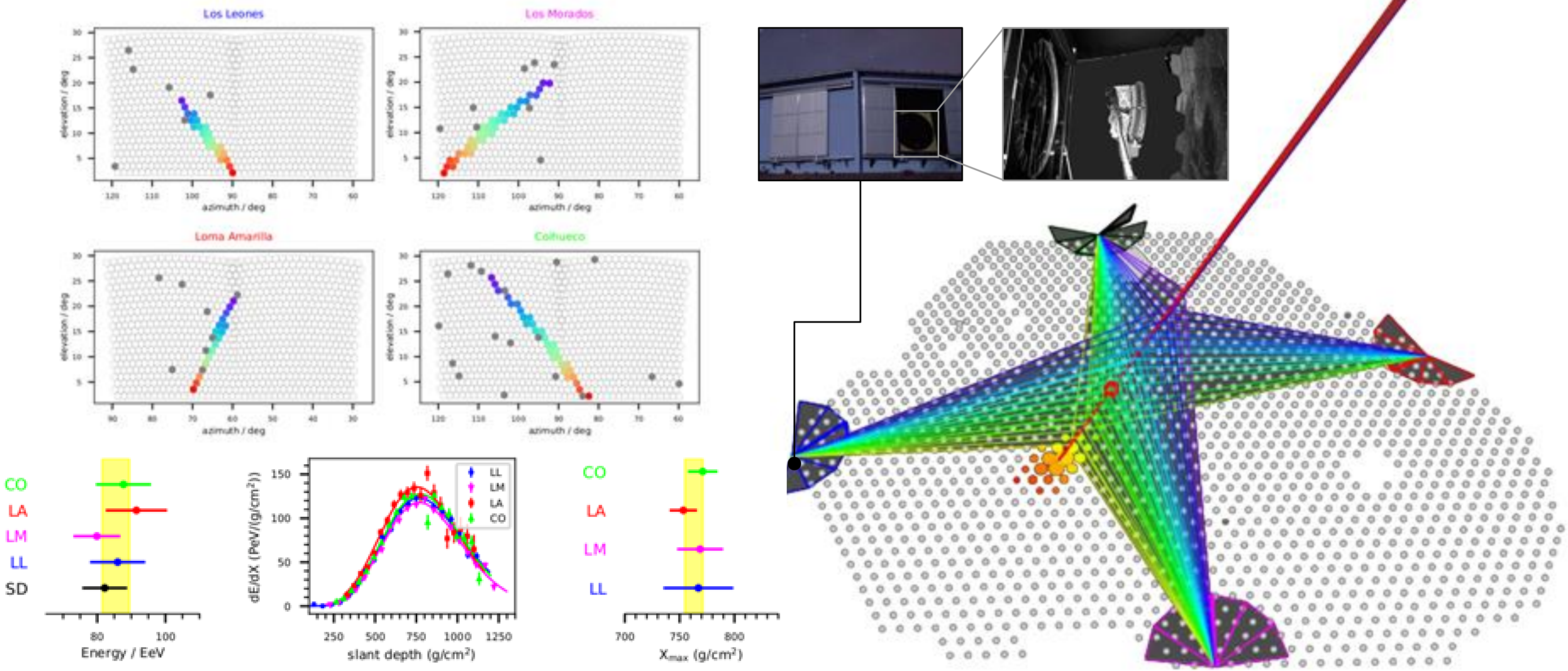
$\Delta\theta \sim 1°$





Auger Coll., ApJS 2023

Event reconstruction: fluorescence detector (FD)



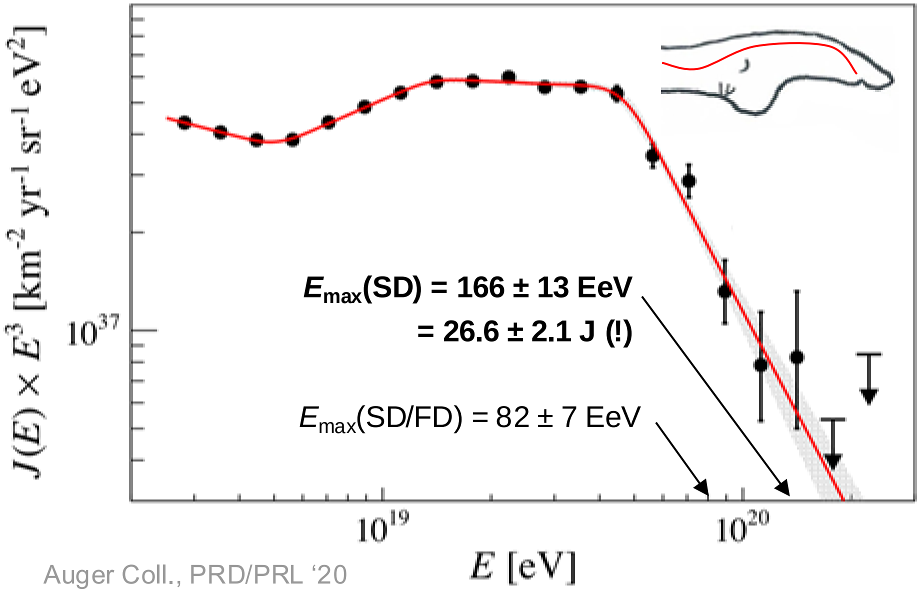
Auger Coll., ApJS 2023

Cosmic-ray spectrum at the highest energies

Energy estimation

at the Pierre Auger Observatory

Data-driven: cross-calibration of SD signal with FD calorimetry



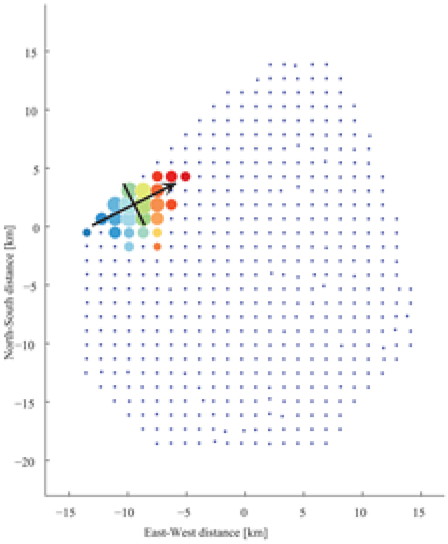
Auger Coll., PRD/PRL '20

Energy estimation

at the Telescope Array

Monte-Carlo based + data-driven correction

E_{max}(TA) = 244 ± 29 EeV



TA, Science (2023)

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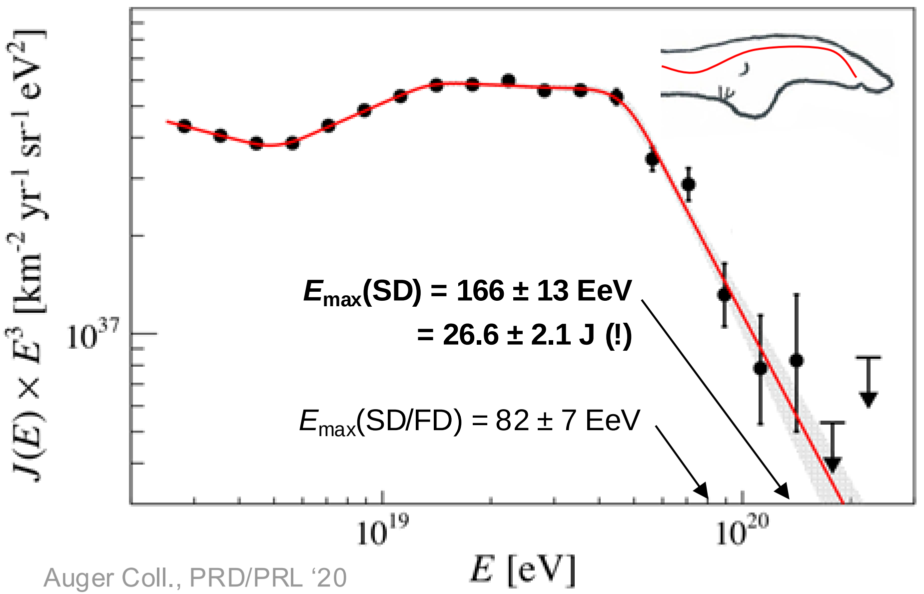


Auger Coll., PRD/PRL '20

Energy estimation

at the Telescope Array

Monte-Carlo based + data-driven correction

E_{max}(TA) = 244 ± 29 EeV ↔ E_{max}(SD) ≃ 150 ± 20 EeV

TA, Science (2023)

Shower slant depth: a proxy for $^{\boxed{A}}_{Z}X$

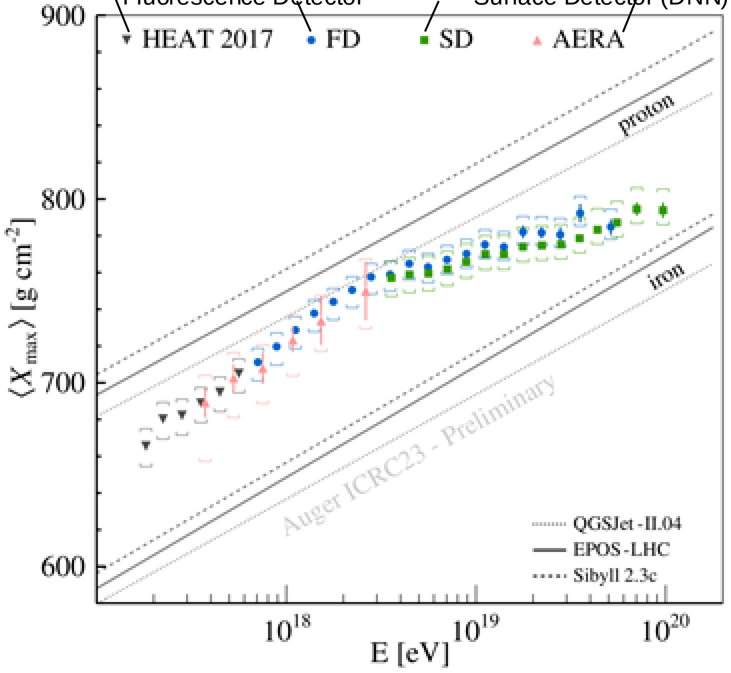
Independent measurements of $X_{max} \propto \ln(E\ /\ A)$ at the Pierre Auger Observatory

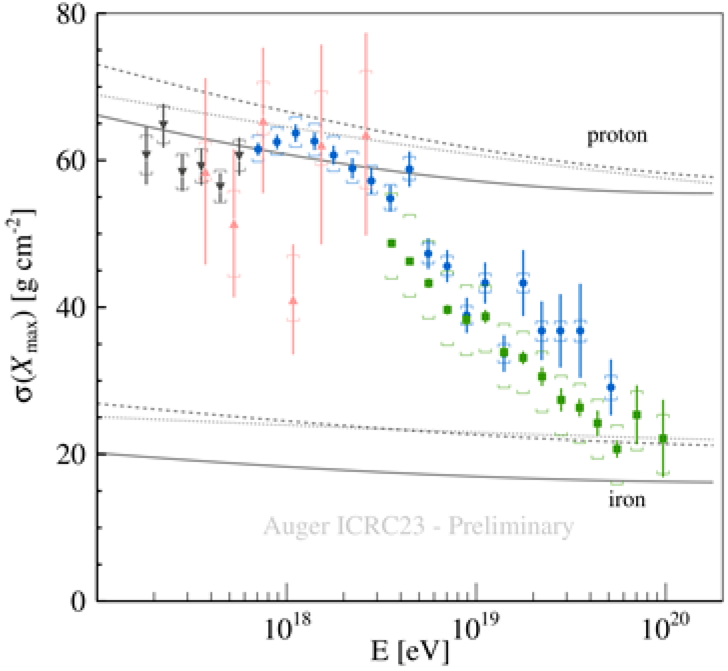
High Elevation Auger Telescopes (low *E*)

Auger Engineering Radio Array (Auger Coll., PRD/PRL '24)

Fluorescence Detector

Surface Detector (DNN)

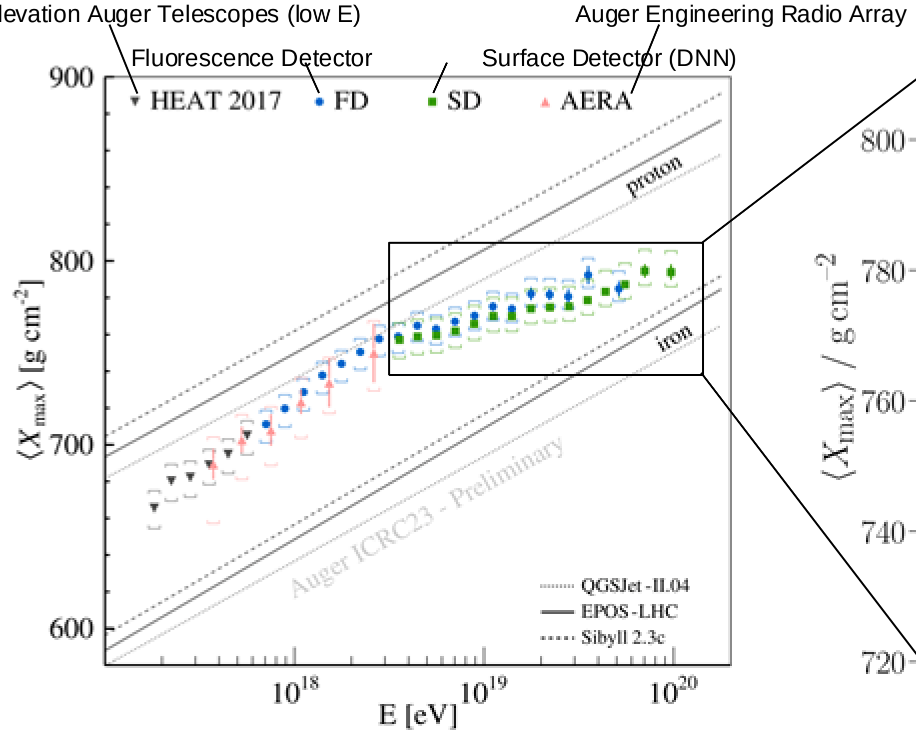


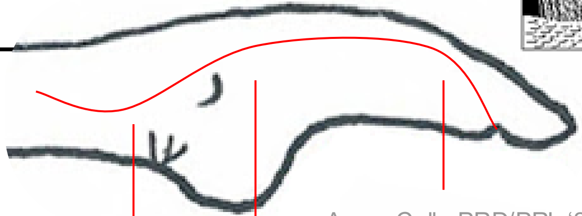


Auger Coll., PoS(ICRC23) by Salamida

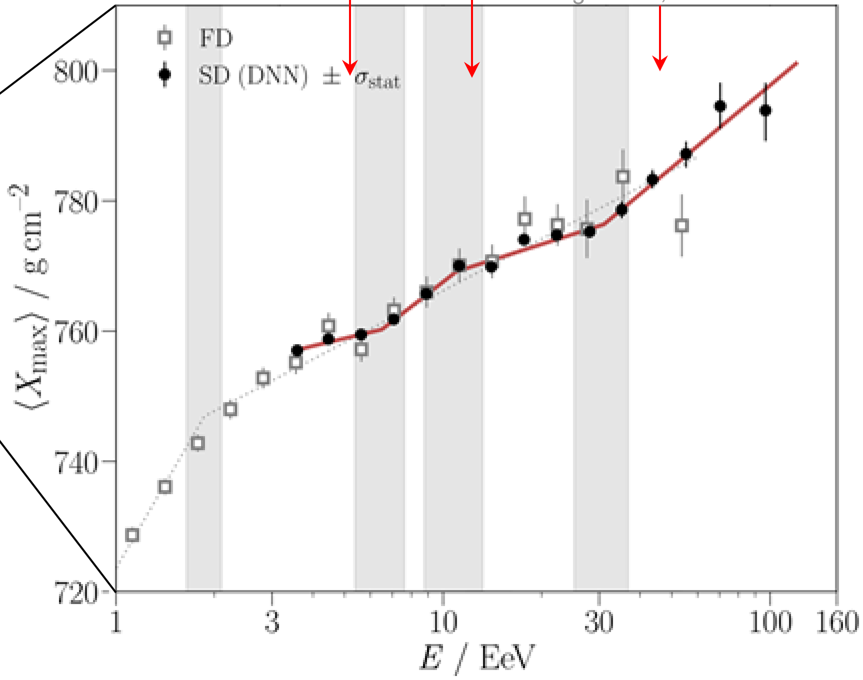
Shower slant depth: a proxy for $^{\boxed{A}}_{Z}X$

Independent measurements of X_{max} at the Pierre Auger Observatory



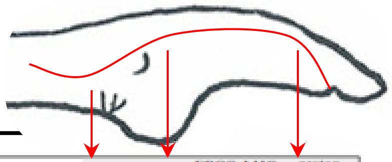


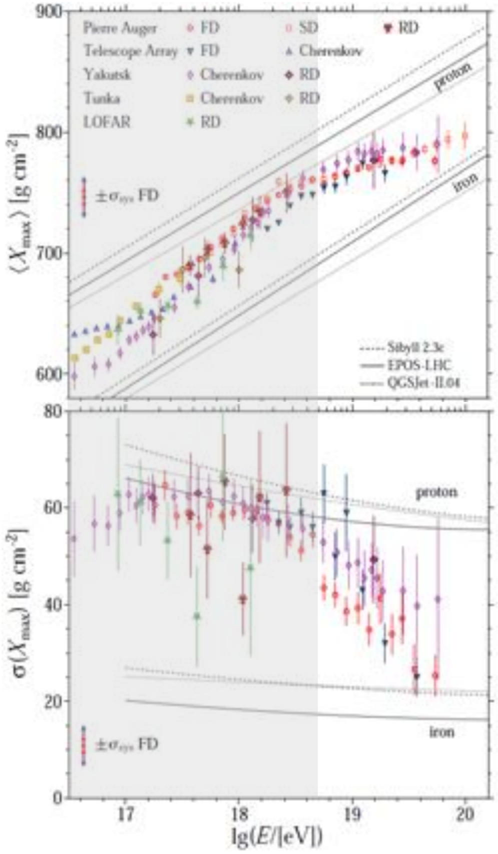
Auger Coll., PRD/PRL ‘25



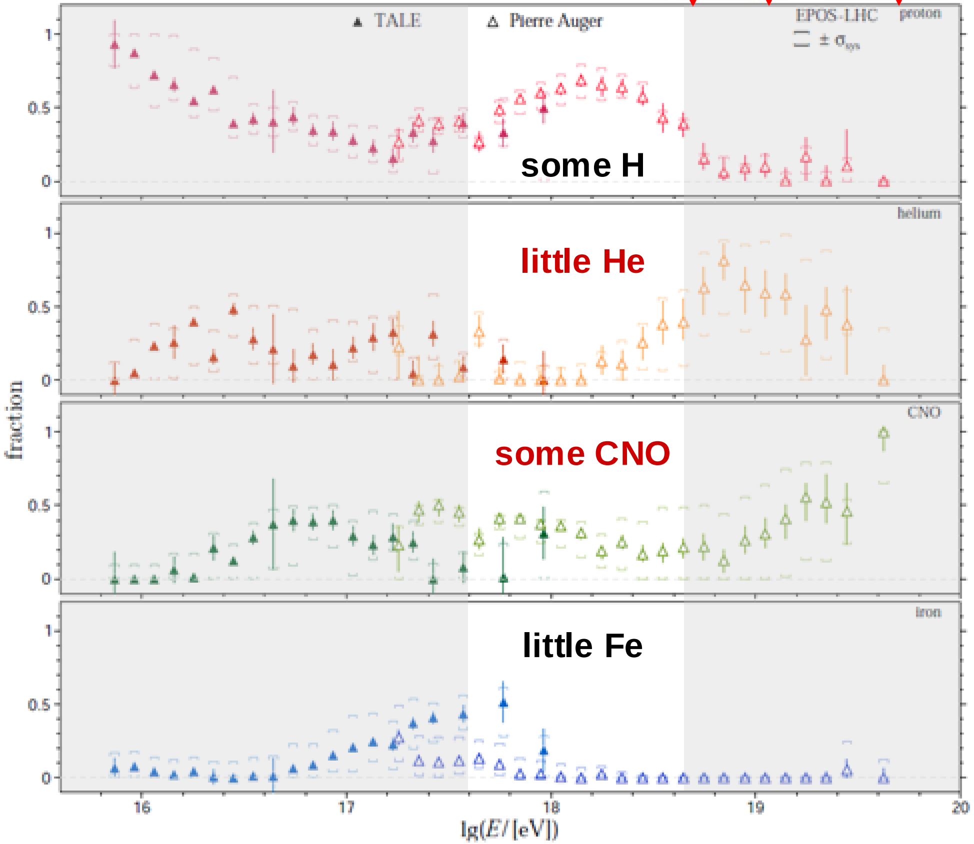
Auger Coll., PoS(ICRC23) by Salamida

Today's picture on $^{\boxed{A}}_{Z}X$

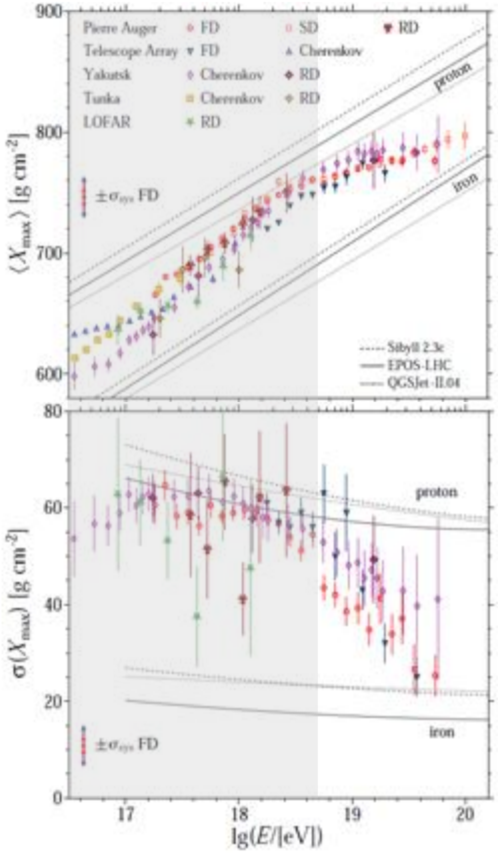




Credit: Coleman+,
Astropart. Phys. '22



Today's picture on $^{A}_{Z}X$



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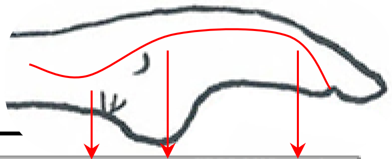
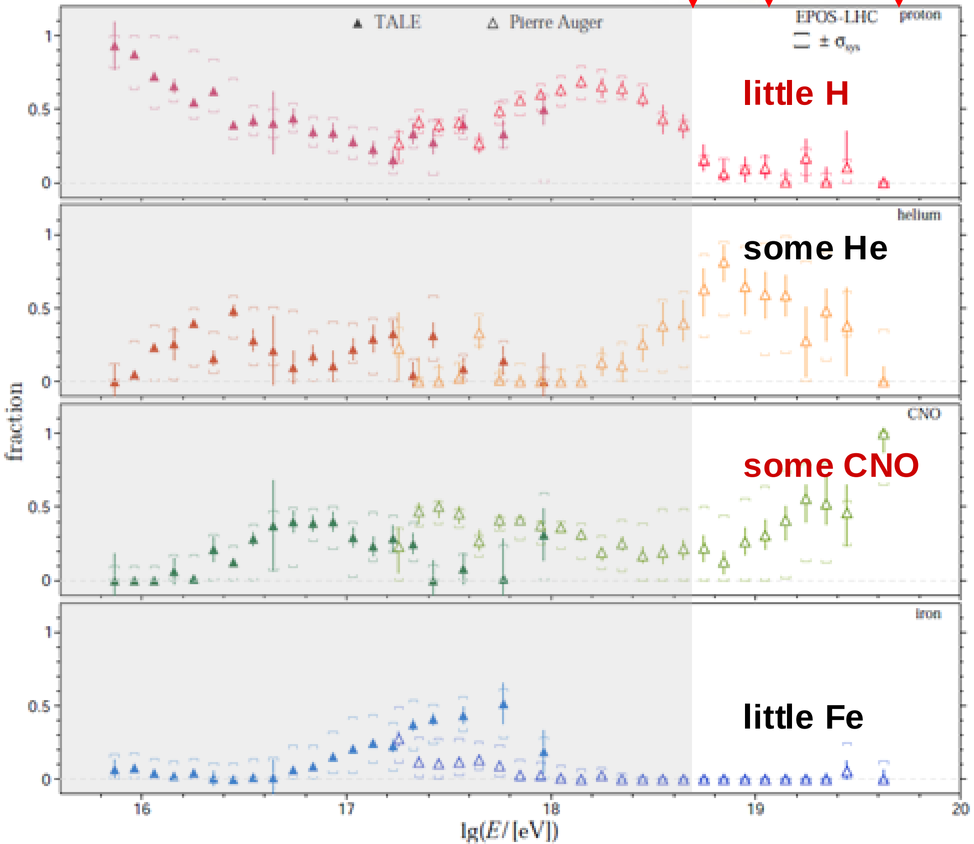
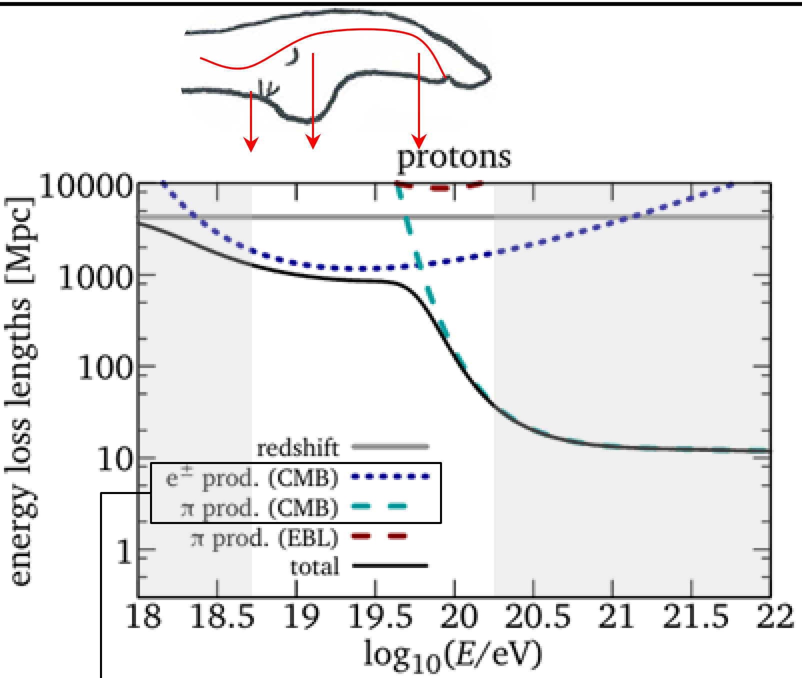
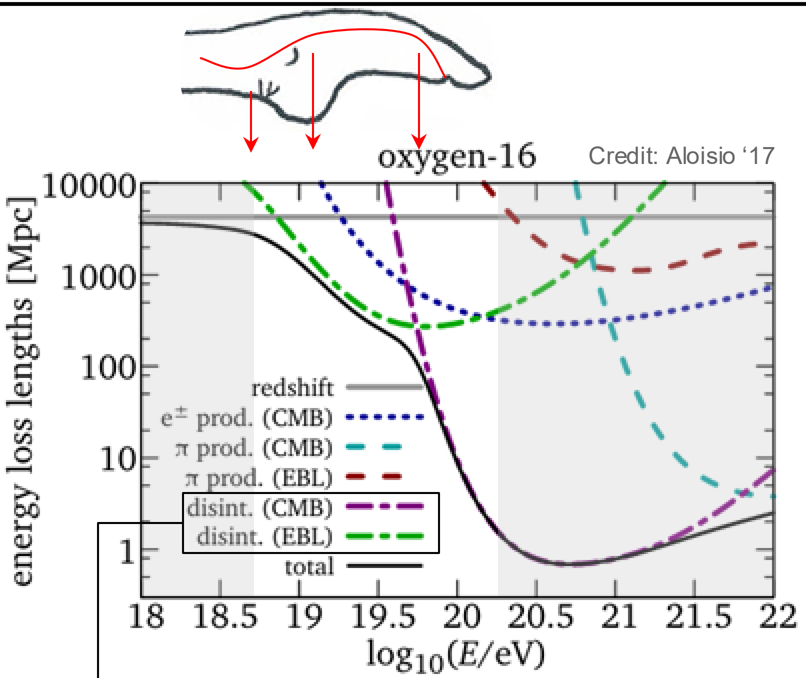




Composition impact on energy loss length



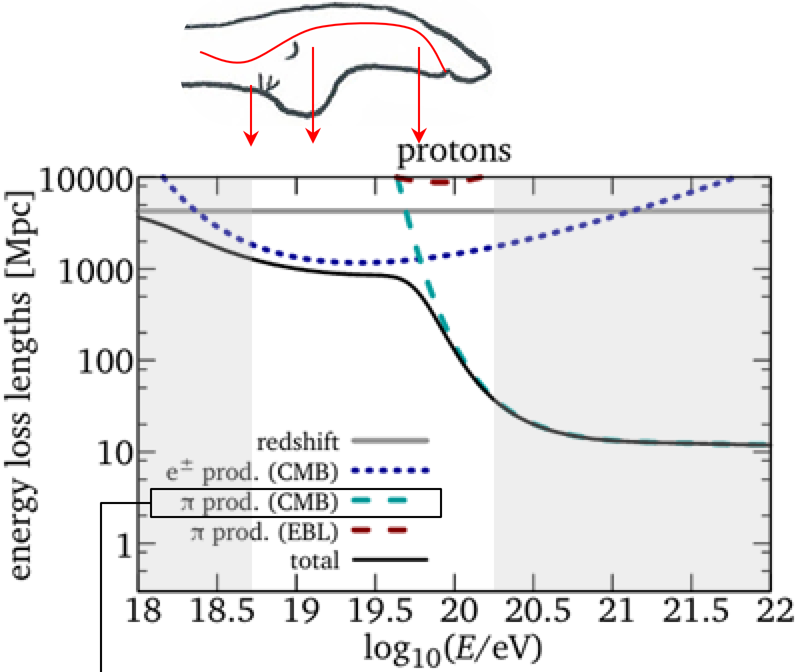
$$
\begin{aligned}
p + \gamma &\to p + e^+ + e^- \\
&\to p + \pi^0 \\
&\to n + \pi^+
\end{aligned}
$$

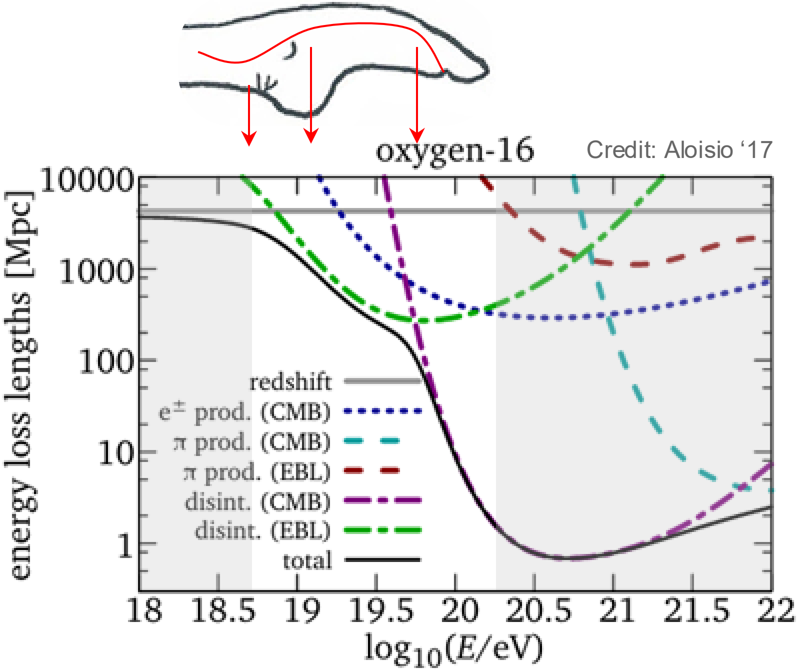


Credit: Aloisio ‘17

$$ {}^{A}_{Z}X + \gamma \to {}^{A-a-b}_{Z-b}Y + an + bp $$

Composition impact on energy loss length





Credit: Aloisio ‘17

$$
\begin{aligned}
p + \gamma &\rightarrow p + e^+ + e^- \\
&\rightarrow p + \pi^0 \\
&\boxed{\rightarrow n + \pi^+}
\end{aligned}
$$

$$
\begin{aligned}
&\pi^+ \rightarrow e^+ + 3\nu \\
&\text{with } E_\nu \approx E_p/20 \\
&\quad = 250\,\mathrm{PeV} \times \left(\frac{E_p}{5\,\mathrm{EeV}}\right)
\end{aligned}
$$

⟵ **MM channel: ν - CR**

I. Spectrum & nuclear composition

How to measure them, where do we stand, why does it matter

II. Anisotropy searches at the highest *E*

Why do we try, what do we see, the sources within reach?

III. The extragalactic cosmic-ray background

Next observational and phenomenological frontiers

Combining observables to search for UHECR origins

Fit of synthetic model of source population

to spectrum and composition data

Spectral and composition observables integrated over the sphere
→ constrain **energy injection rate** & **composition at escape from the sources**

Ankle at > 5 EeV marks the transition to a **purely extragalactic origin**,
with the onset of He nuclei

Observed spectral features: **instep at 10-15 EeV**, **toe at 40-50 EeV**

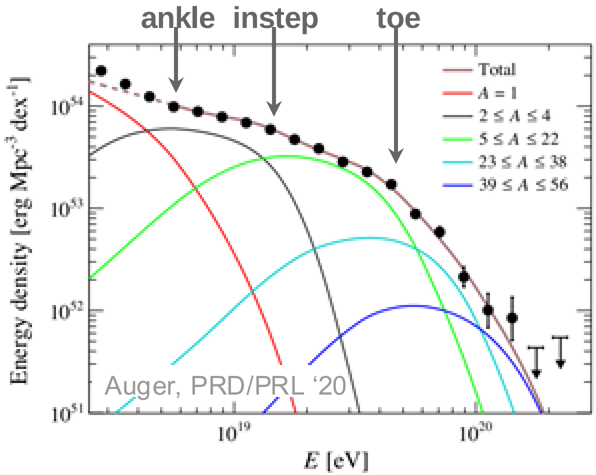
→ markers of ~Peters cycle (**acceleration up to $E_{max}(Z) \sim Z \times 5$ EeV**)

→ hard nuclear emission at sources (**$dN/dE \propto E^{\pm 1}$** vs E^{-2}, explained e.g. by escape from magnetized region within the sources)

→ reservoir of heavy elements? Accelerated material with heavy nuclei, that is little H and He with respect to the interstellar medium.

Anisotropy observables

→ break down the flux (and composition) vs **arrival direction**: **pinpoint sources? if cosmic magnetism does not prevent it!**



Energy injection rate

$$\dot{Q}(E > 0.6\,\mathrm{EeV}) = 1.1 \times 10^{45}\,\mathrm{erg\,yr^{-1}\,Mpc^{-3}}$$

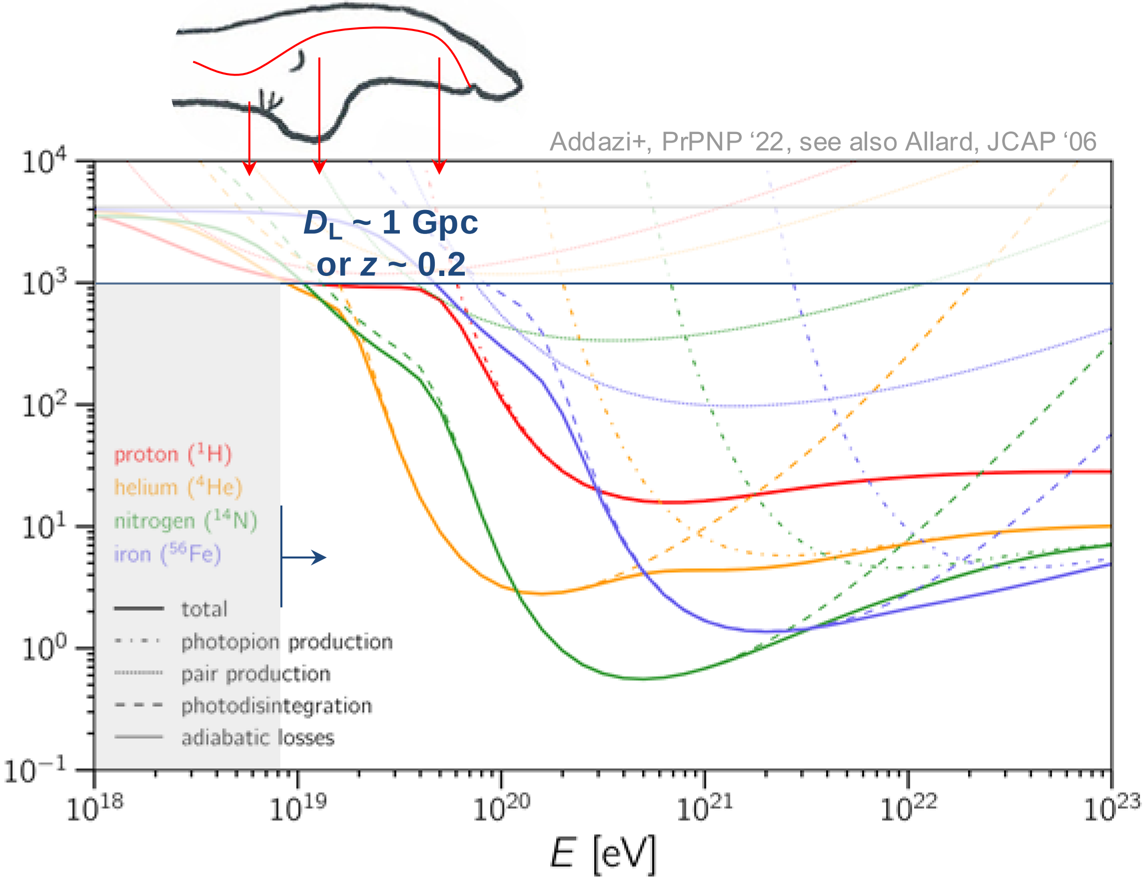
Composition at the sources

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

vs $$\left| \frac{M(\mathrm{He})}{M(\mathrm{C{-}Fe})} \right|_{\mathrm{ISM}} = 18 \pm 2$$

Luce, Marafico, JB+ ApJ '22 & Marafico, JB+, ApJ '24

UHECR propagation on extragalactic scales

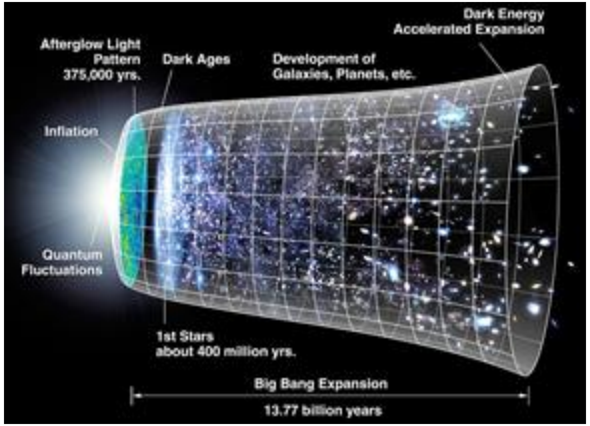


Addazi+, PrPNP '22, see also Allard, JCAP '06

For nuclei:

$$ {}^{A}_{Z}X + \gamma \rightarrow {}^{A-a-b}_{Z-b}Y + an + bp $$

D_L ~ 1 Gpc
or D_T ~ 2.5 Gyr



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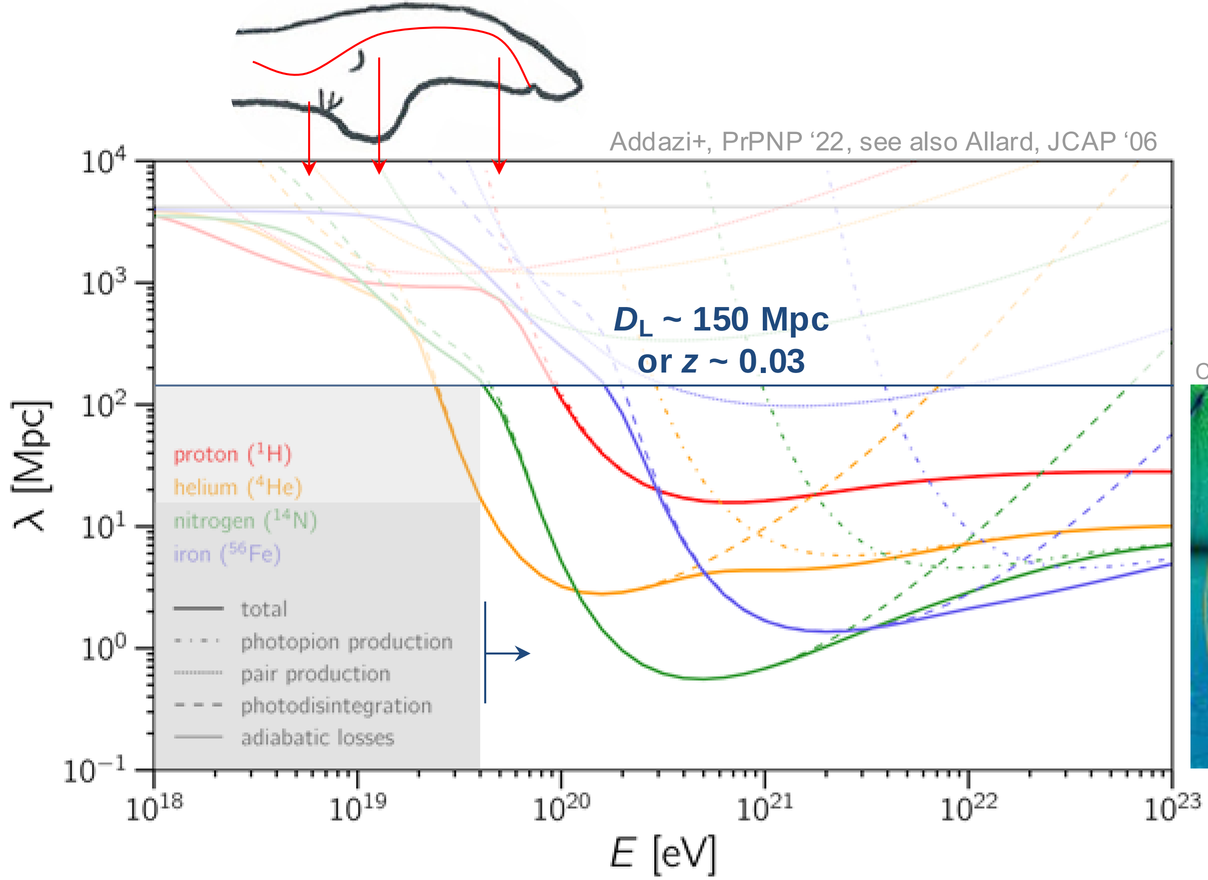

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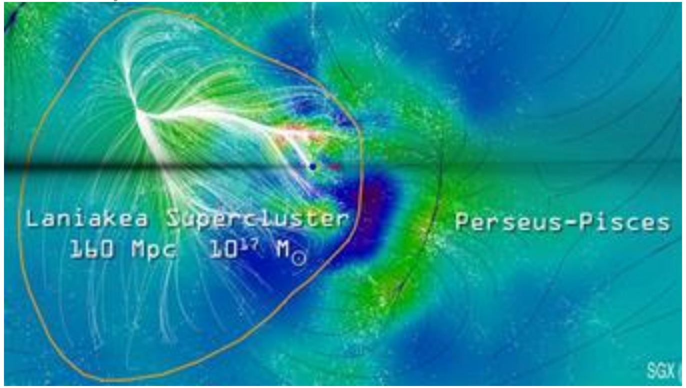
Credit: Tully+, Nature '14



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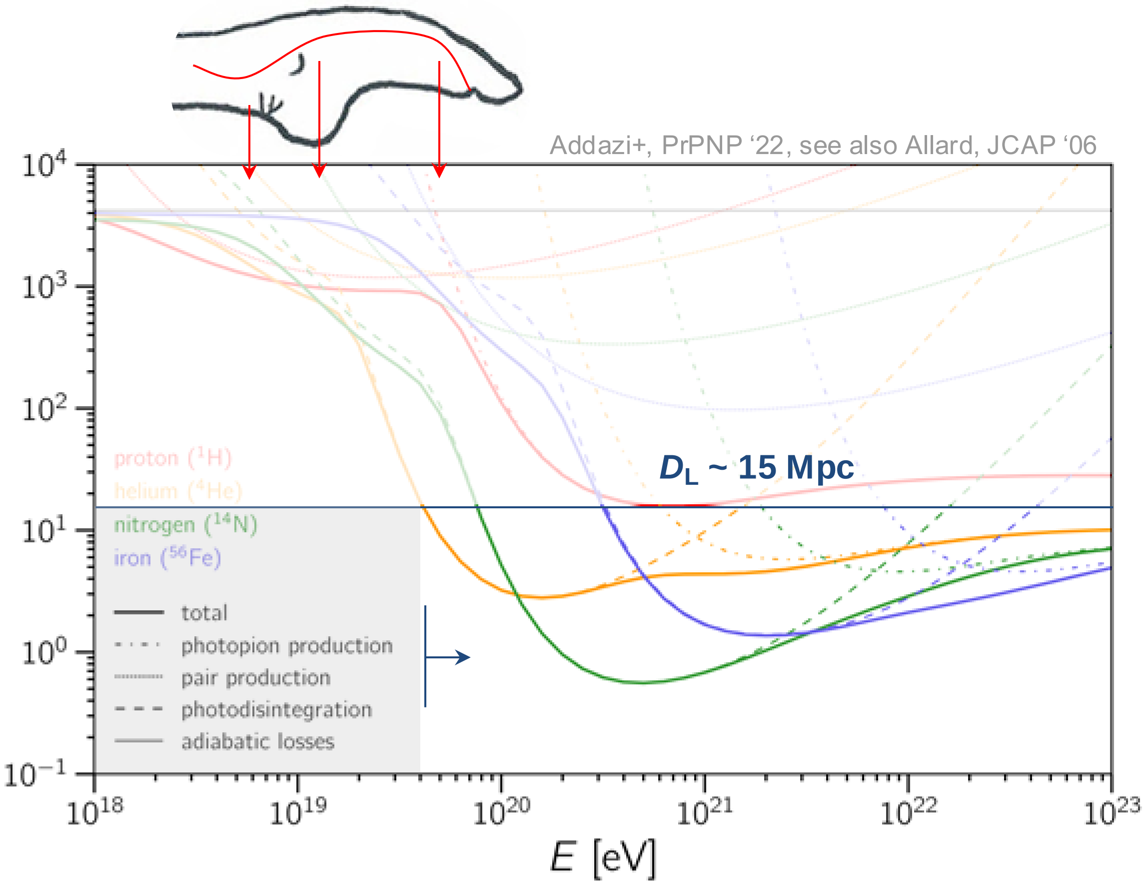

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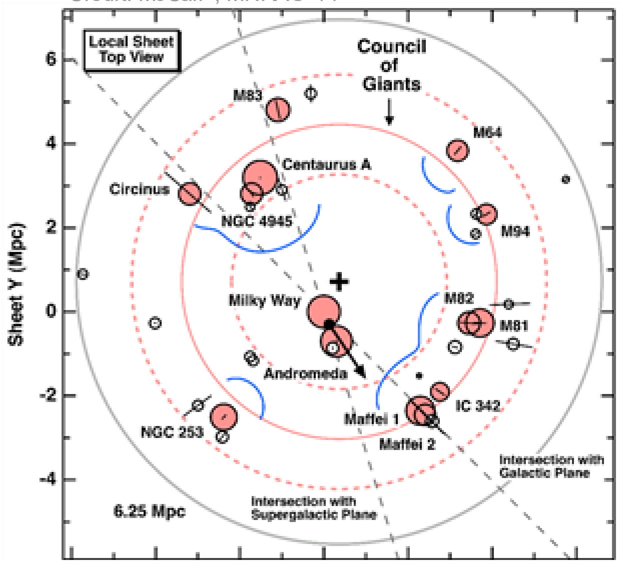
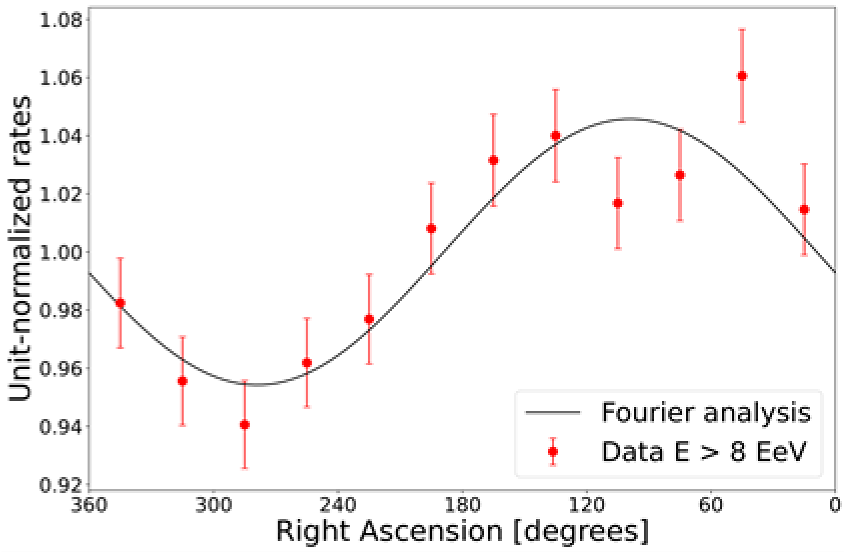


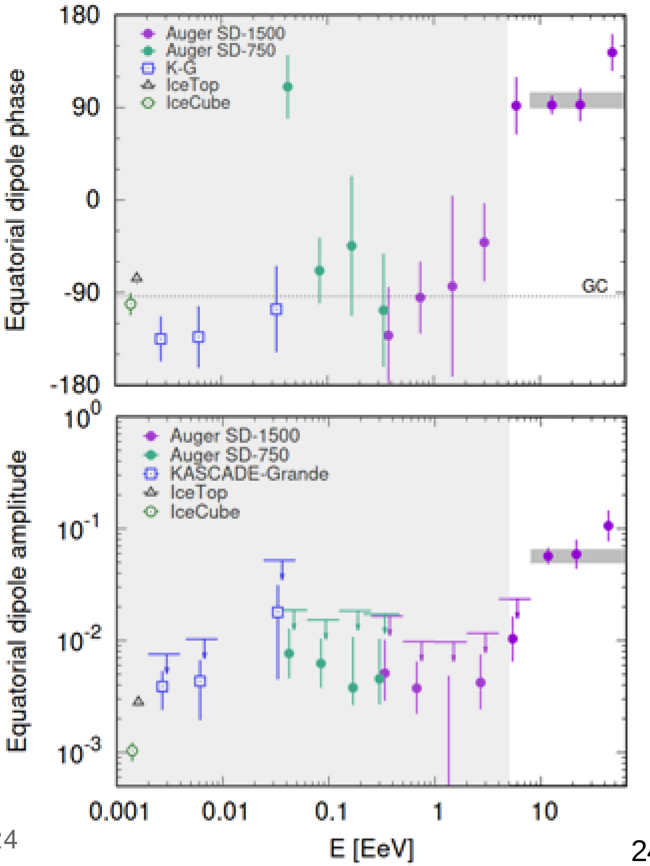
Arrival-direction modulation on large angular scales

Modulation of the event rate as a function of R.A.

or of the difference between events from East and West

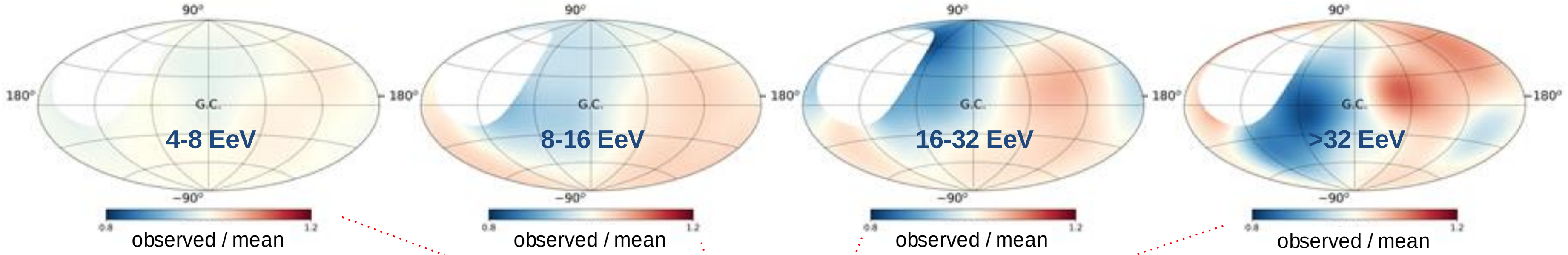
Exposure of the array nearly uniform in right ascension
→ modulation = robust observable for the phase and amplitude
of the first spherical harmonic (equatorial component of the dipole)





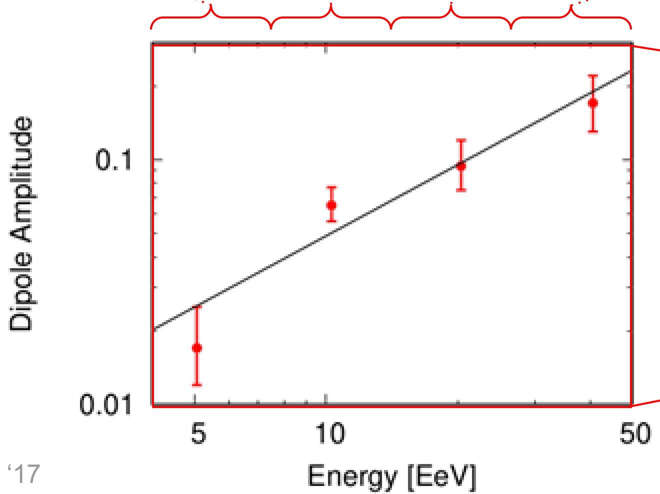
Auger, ApJ ‘24

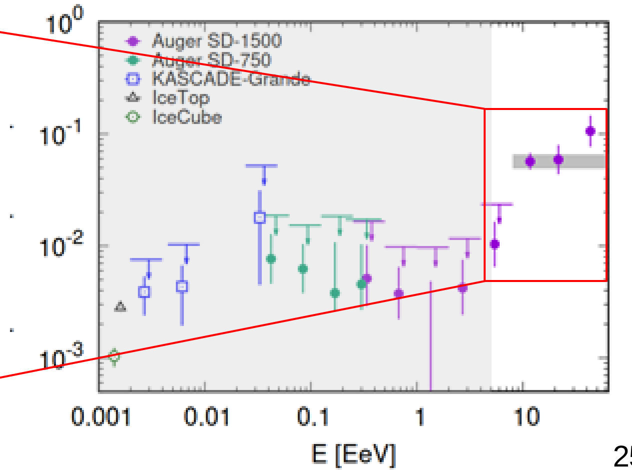
Observed arrival directions from the ankle to the toe



Modulation in R.A. >8 EeV significant at 6.8σ

well modeled by a dipole ~ 115° away from the Galactic center, in line with extragalactic distribution of luminous matter within ~100 Mpc





Auger Coll., ApJ ‘24/ ‘20 / ‘18, Science ‘17

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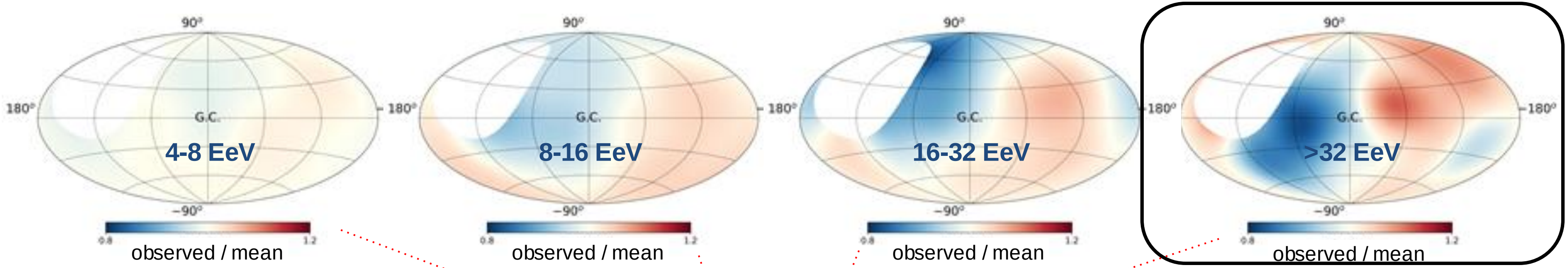

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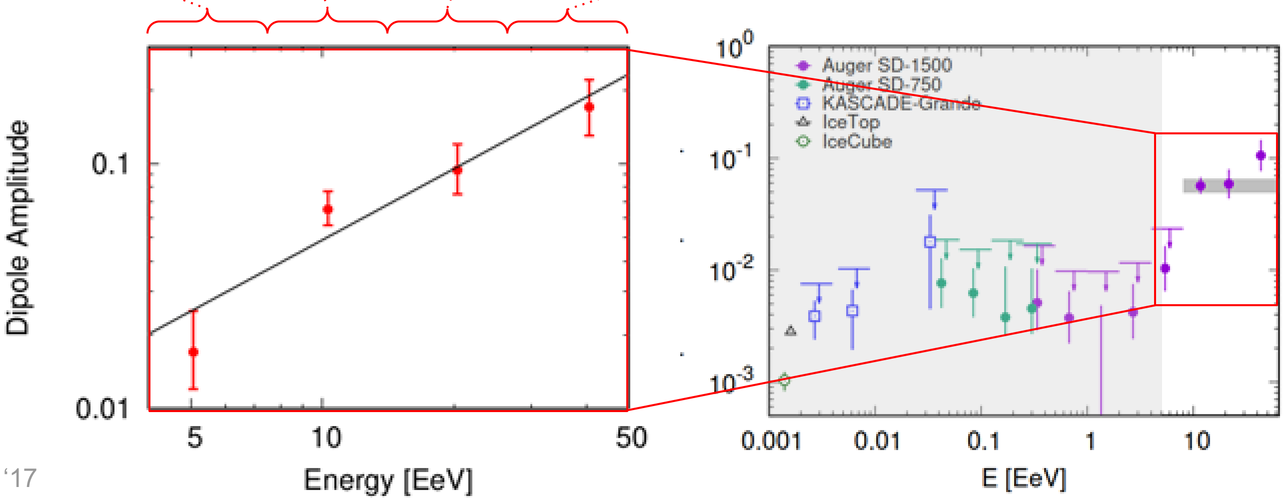
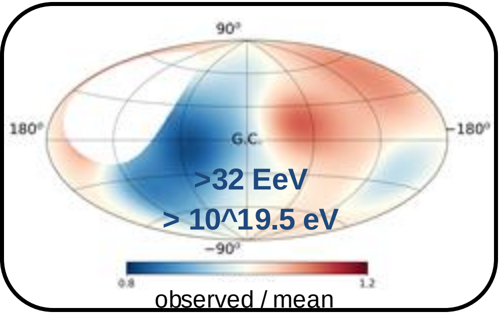


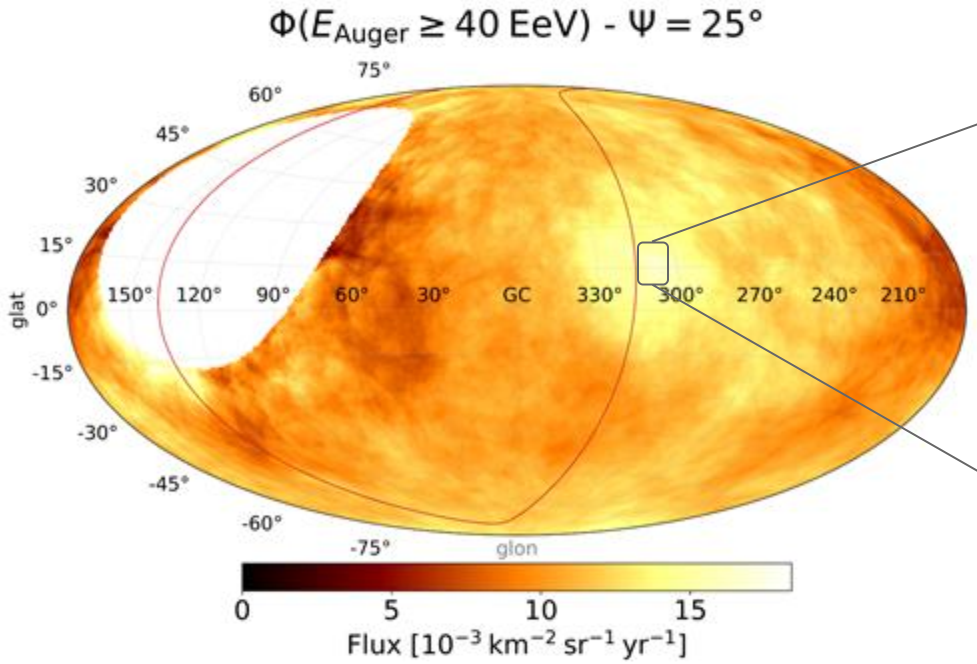
Auger Coll., ApJ '24/ '20 / '18, Science '17

Status of anisotropies in the toe region



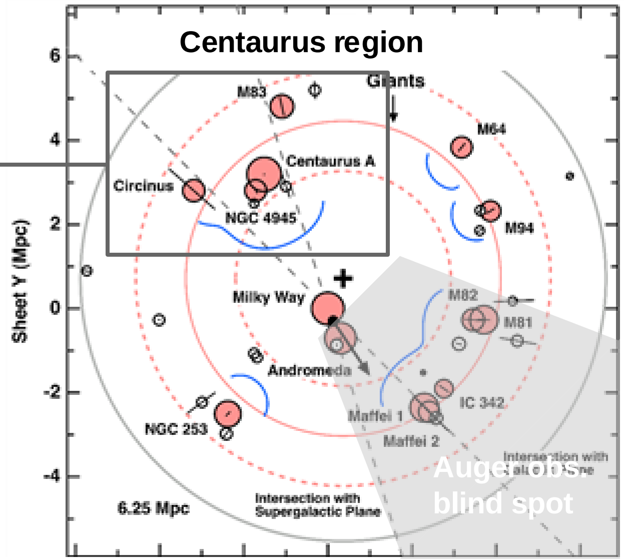
Arrival directions of events > 32 EeV up to Dec. 2020

~ 4σ excess in model-independent analysis (Centaurus region),
dataset publicly available at DOI 10.5281/zenodo.6759610



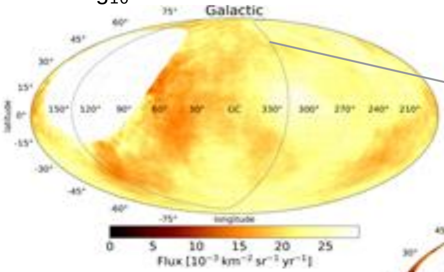
Auger coll., ApJ '22

Credit: McCall+, MNRAS '14

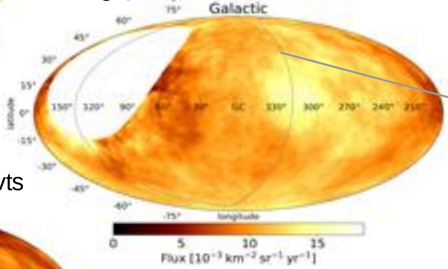


Status of anisotropies in the toe region

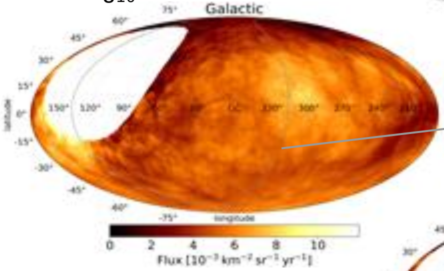
log$_{10}$ *E*/eV > 19.5: ~3000 evts



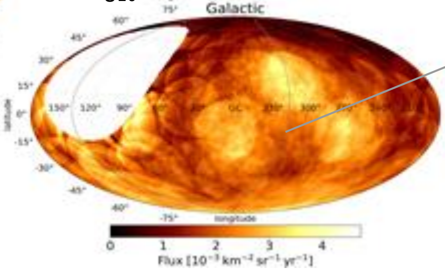
log$_{10}$ *E*/eV > 19.6: ~1500 evts



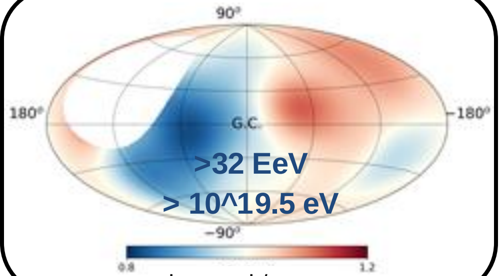
log$_{10}$ *E*/eV > 19.7: ~700 evts



log$_{10}$ *E*/eV > 19.8: ~300 evts

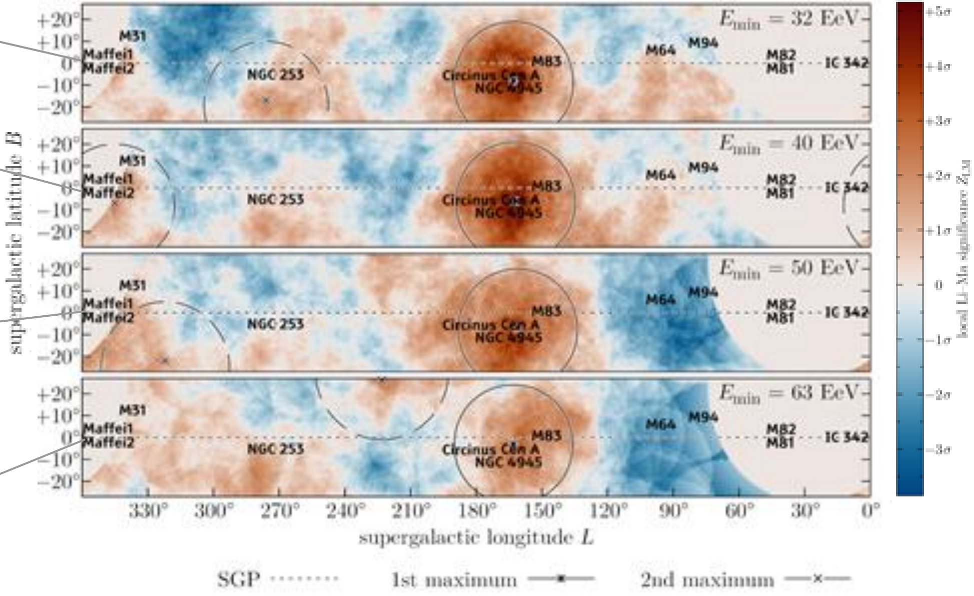


Auger Coll., ApJ ‘22



Auger Coll., accepted in ApJ
(arXiv:2407.06874)

Auger Coll., ApJ ‘24

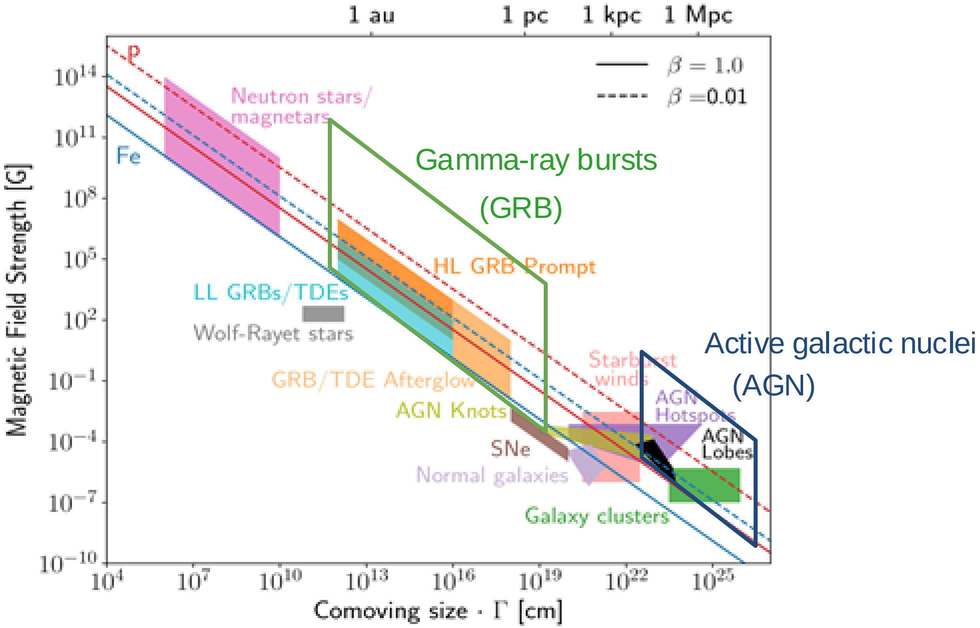


Which sources to explain the Centaurus region excess?

Hillas: only the highest-energy

Confinement, i.e. large B-field, size, and shock velocity:

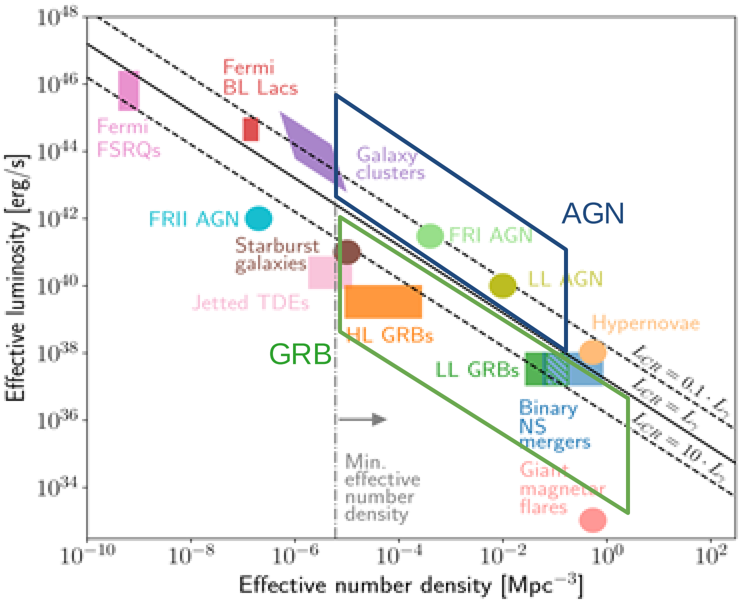
$B \times (r \times \Gamma) \times \beta_{shock} > E / Ze$



Arrival directions: only the numerous

No significant self-clustering above flux suppression:

number density > 10^{-5} / Mpc³ (if deflections < 30°)



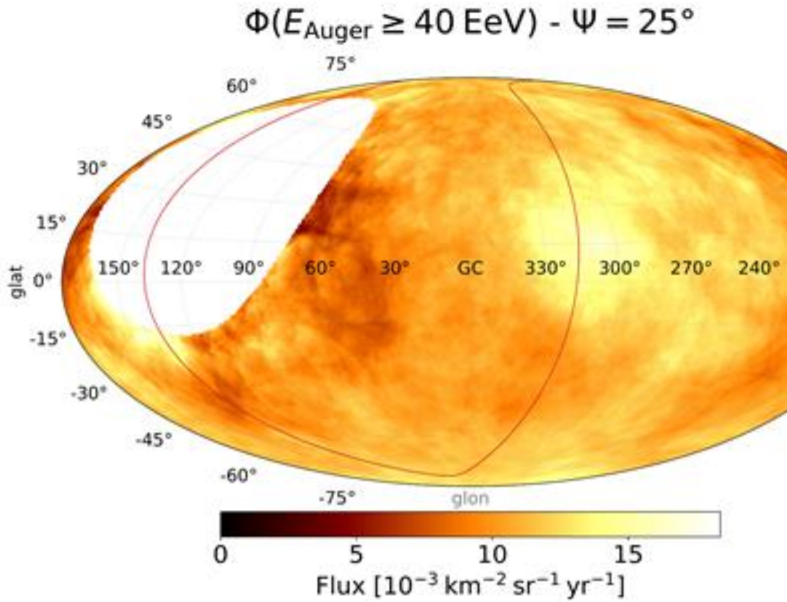
Alves Batista+, Front.Astron.Space Sci. '19

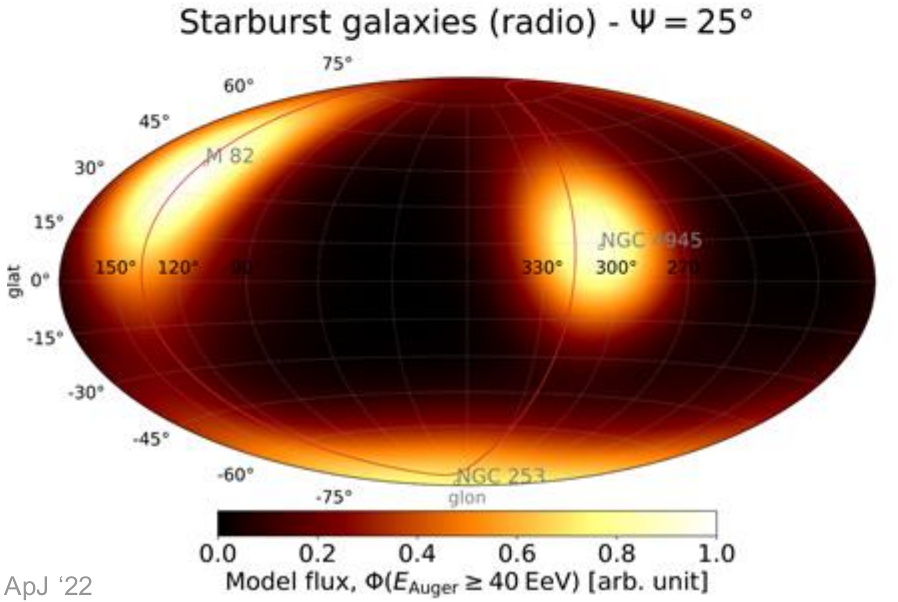
Status of anisotropies in the toe region

Arrival directions of events > 32 EeV up to Dec. 2020: best template model

~ 3.8σ exclusion of isotropy with **10% XS** from **44 brightest star-forming galaxies < 150 Mpc** (Auger, ApJ '22, ApJL '18)

~ 4.6σ exclusion when including Northern complementary data (Auger Coll. + Telescope Array Coll., PoS(ICRC2023) by Caccianiga)





Auger coll., ApJ '22

Mapping out star formation in the CR horizon

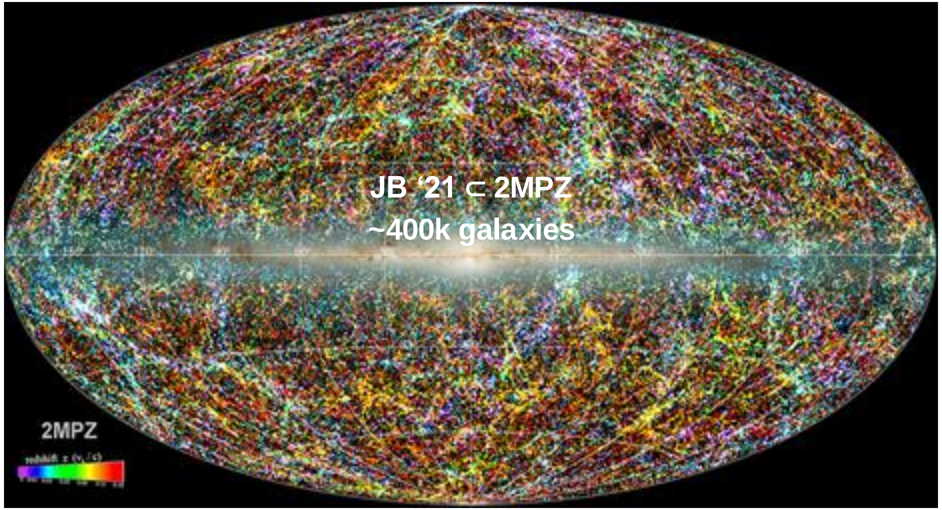
(2MASS Photometric *z* catalog ∩ WISE) ✕ HyperLEDA (JB, ApJS '21)

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

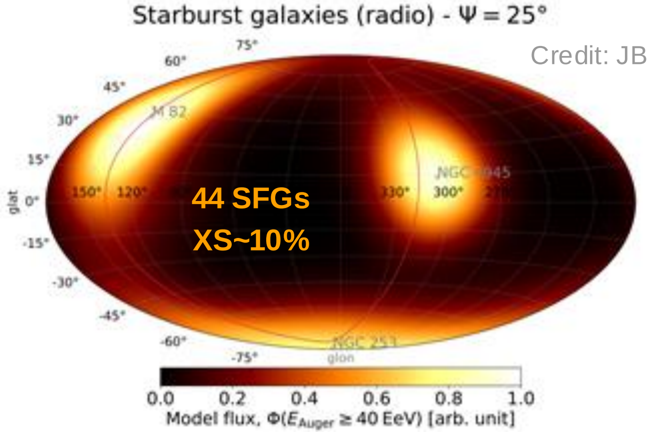
Distances: 50 / 50 photometric / spectroscopic (cosmic distance ladder)

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

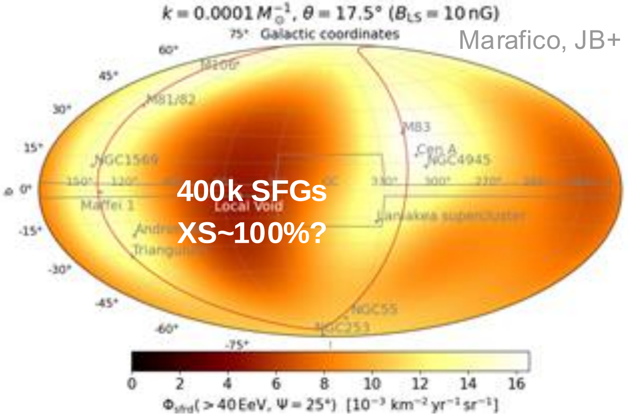
MM channel: IR - GW - CR Credits: 2MPZ, Bilicki & Jarret '14



Credit: JB



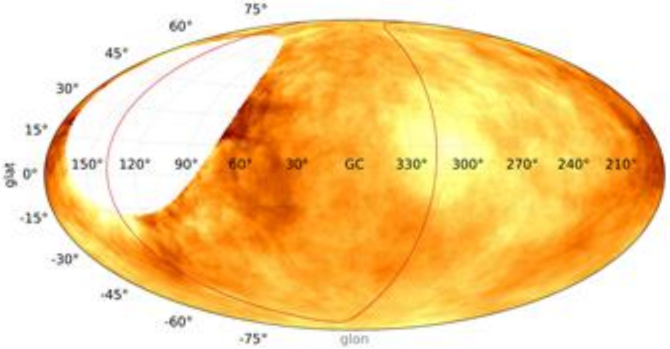
Marafico, JB+ '24



Candidate ultra-high-energy sources

Auger + TA data

Credits: L. Caccianiga for Auger & TA

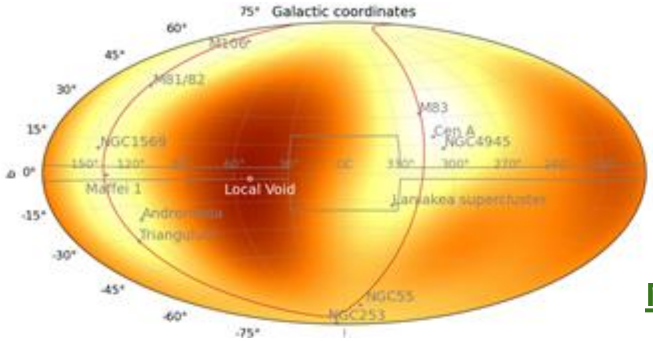


UHECR Model ≈ UHECR Data ⟶

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

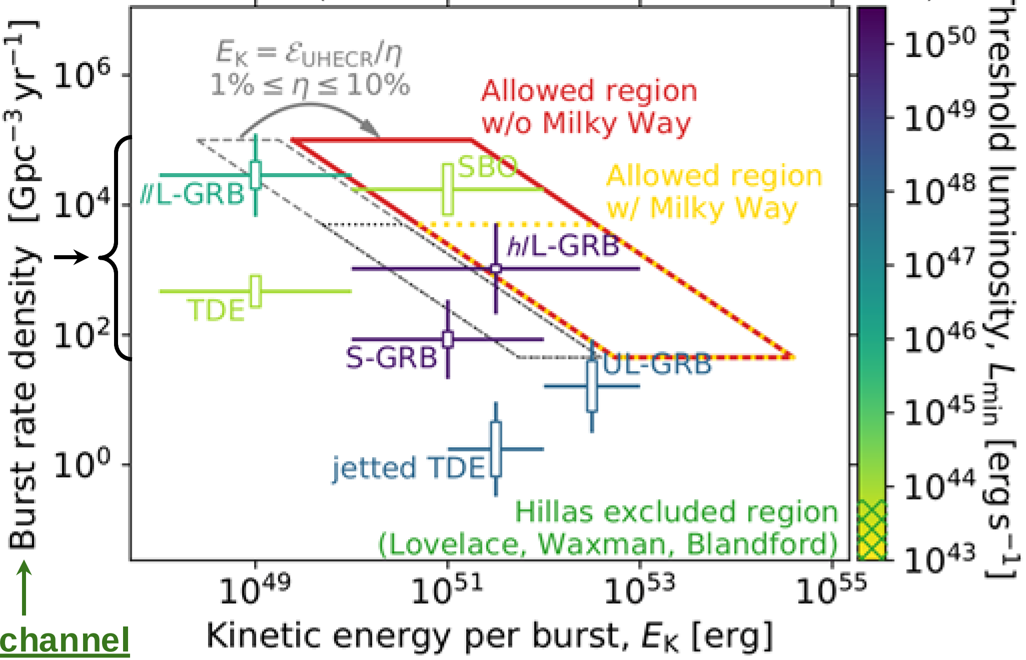
Best-match transient scenario

Credits: Marafico, JB+ '24



X-ray transient rate: ~~TDE~~, ~~Short GRB~~, **Long GRB**

in line with models of particle acceleration at mildly relativistic internal shocks (Globus, Allard, Mochkovitch, Parizot, MNRAS 2015)



MM channel

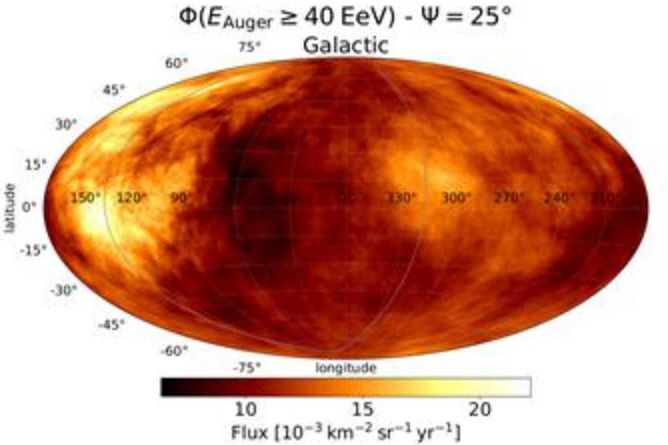
X-rays - CR

Marafico, JB, Condorelli, Deligny, Bregeon, **ApJ '24**

Impact of magnetic fields?

Auger + TA data

Credits: L. Caccianiga for Auger & TA



Elephant in the room: cosmic magnetic fields

Impact of *B* field in voids, sheets, filaments, clusters

→ order-of-magnitude estimates (e.g. Condorelli, JB, Adam, ApJ '23)

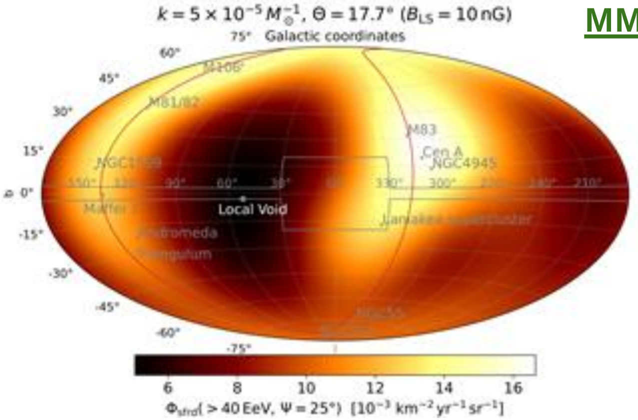
Impact of *B* field of the Milky Way

→ models still incomplete (e.g. Jansson & Farrar, ApJ '12 vs Korochkin, Semikoz, Tinyakov, A&A '25)

→ no study able to jointly model the dipole > 8 EeV and excesses > 40 EeV (see Allard, Aublin, Baret, Parizot, A&A '22 & '24)

Best-match transient scenario

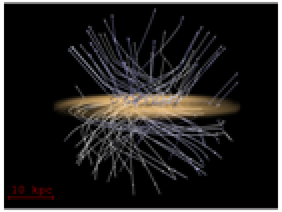
Credits: Marafico, JB+ '24

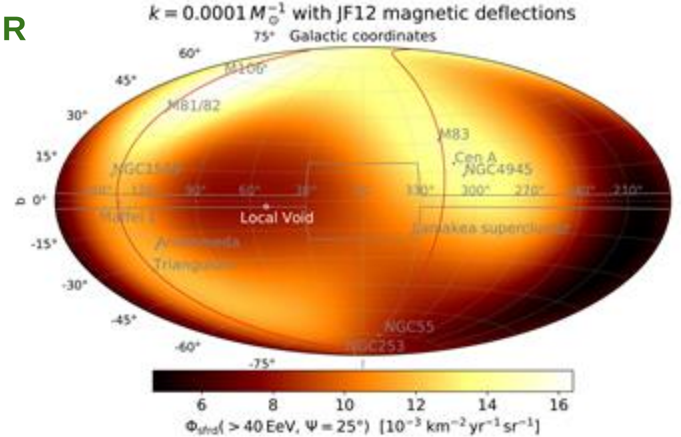


MM channel: radio - CR

Regular $B_{\text{Milky Way}}$

Jansson & Farrar '12





I. Spectrum & nuclear composition

How to measure them, where do we stand, why does it matter

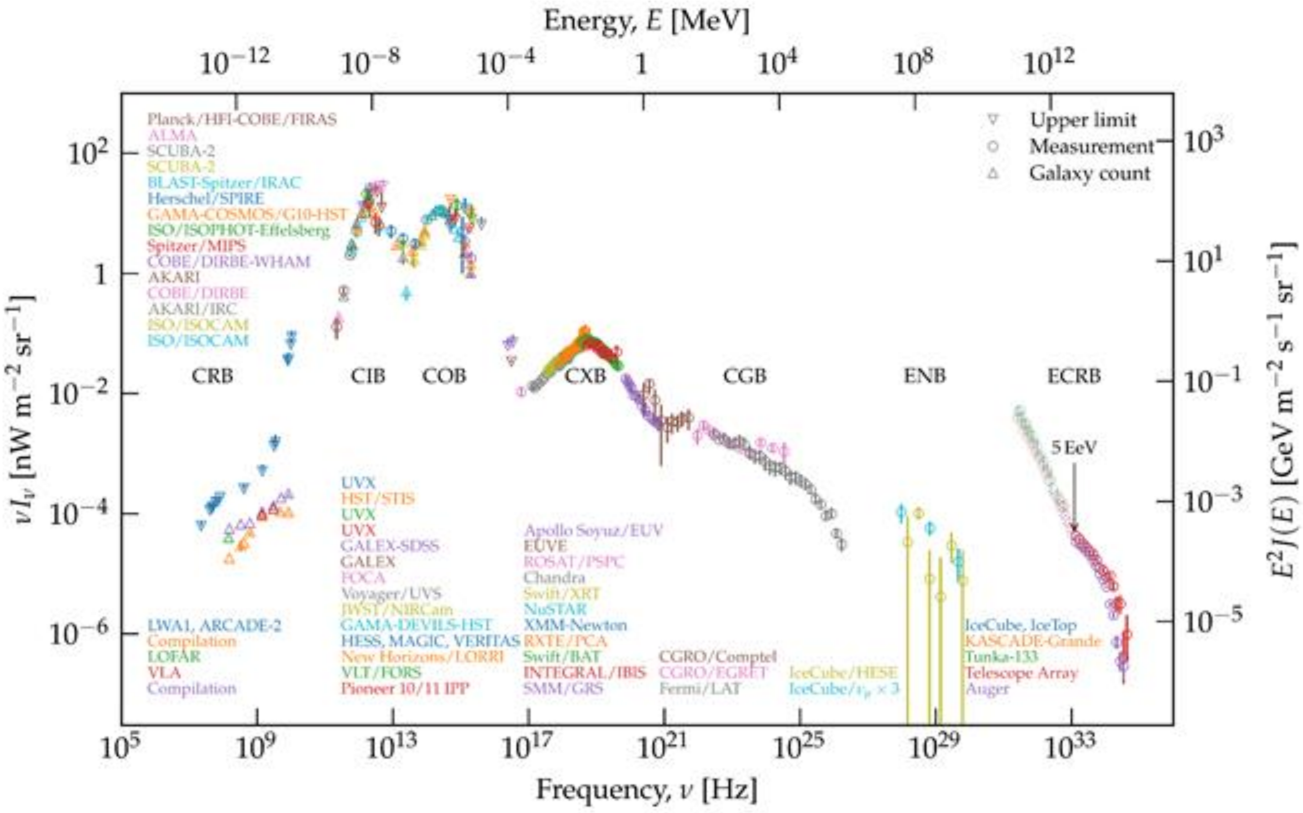
II. Anisotropy searches at the highest *E*

Why do we try, what do we see, the sources within reach?

III. The extragalactic cosmic-ray background

Next observational and phenomenological frontiers

The extragalactic background from radio *λ* to ultra-high *E*



CR > 100 PeV

Radio signal

→ GRAND

E ~ 0.1-1 EeV

Fluo. signal

→ K-EUSO

E > 50 EeV

→ (POEMMA?)

Part. sampling

→ AugerPrime

E ~ 0.1-100 EeV

→ (GCOS?)

The extragalactic background from radio *λ* to ultra-high *E*

MM synergies

Radio

B-fields

→ SKAO

O, X-rays

Transients

→ LSST

→ SVOM

IR (GW)

Galaxy mapping

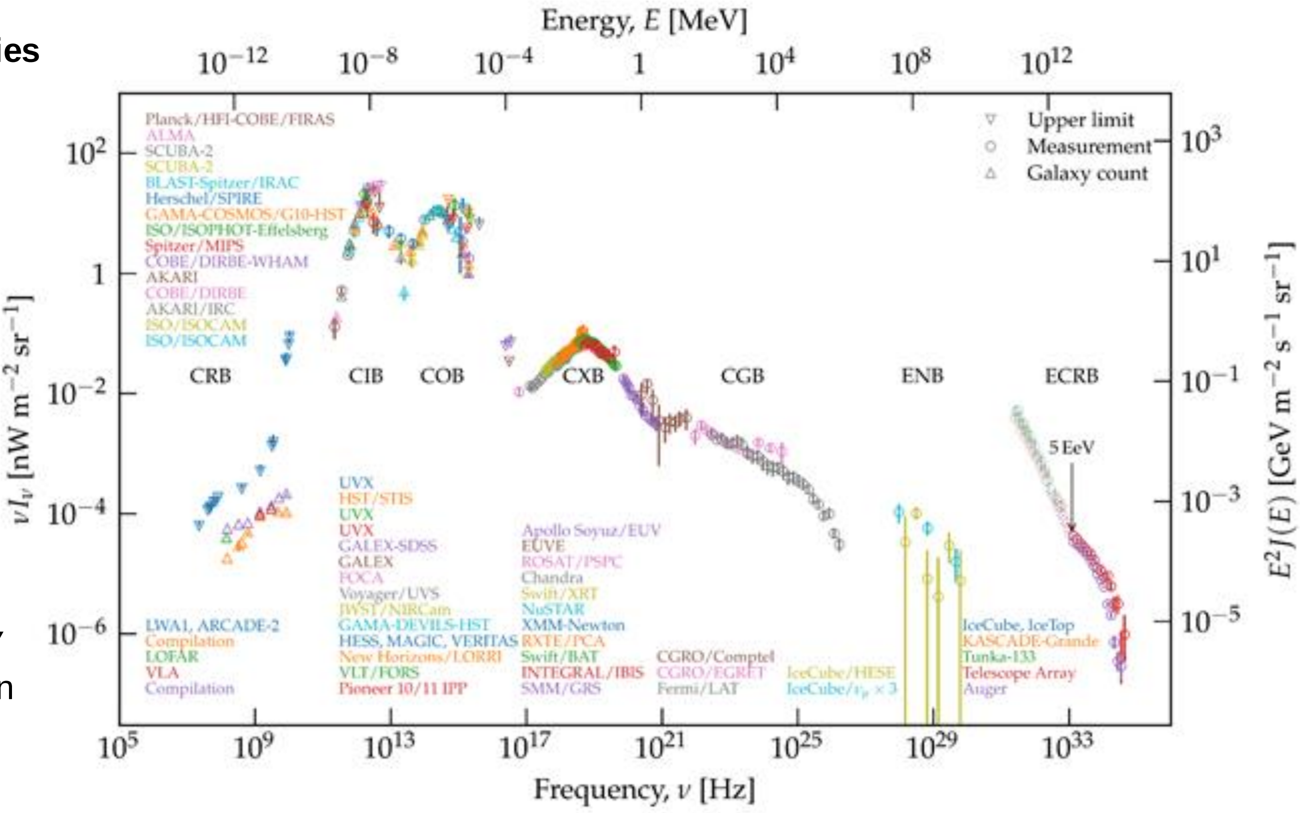
→ Euclid

***ν* > 100 PeV**

Smoking gun

→ KM3Net

→ GRAND



CR > 100 PeV

Radio signal

→ GRAND

E ~ 0.1-1 EeV

Fluo. signal

→ K-EUSO

E > 50 EeV

→ (POEMMA?)

Part. sampling

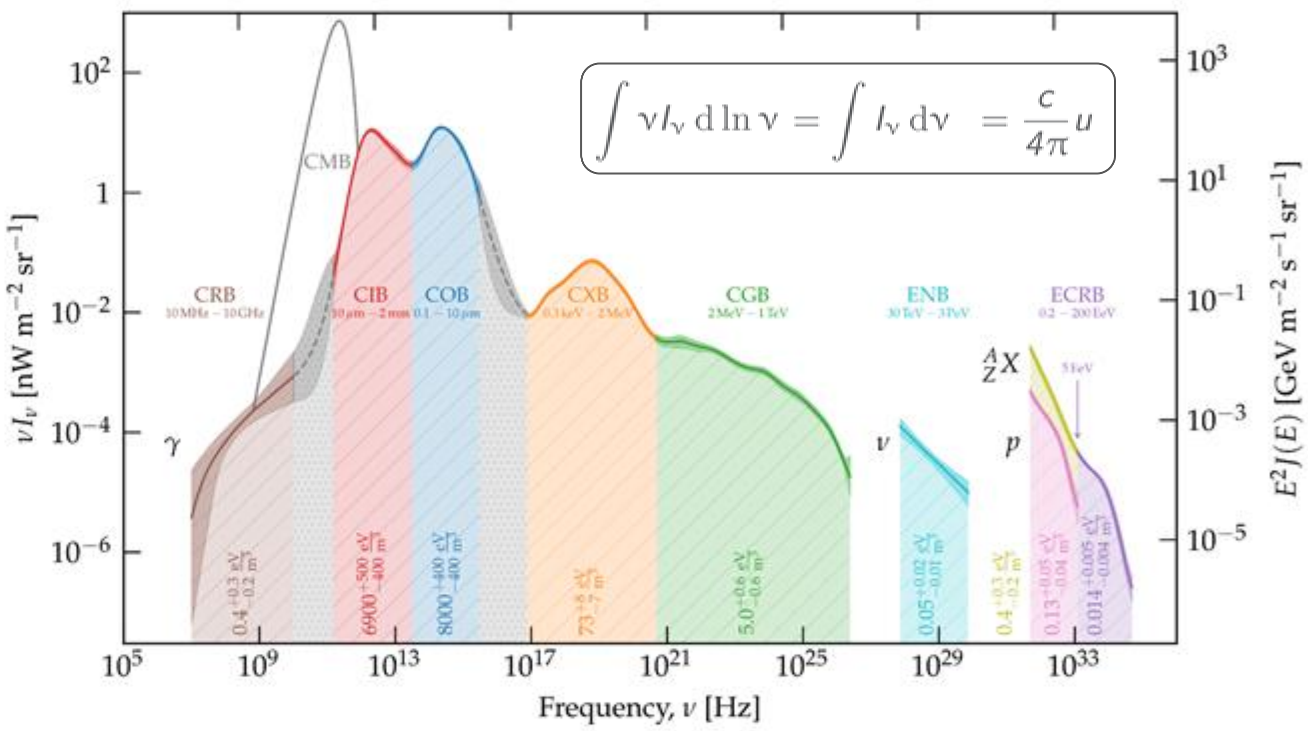
→ AugerPrime

E ~ 0.1-100 EeV

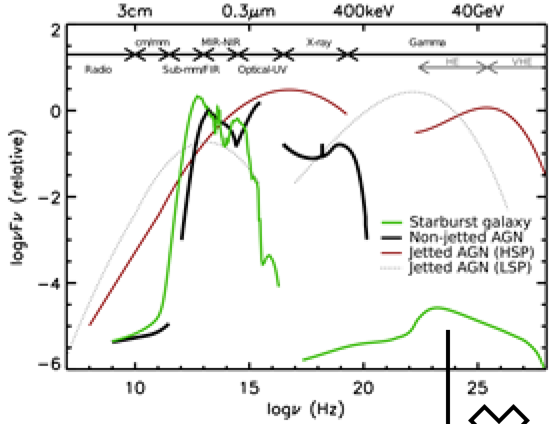
→ (GCOS?)

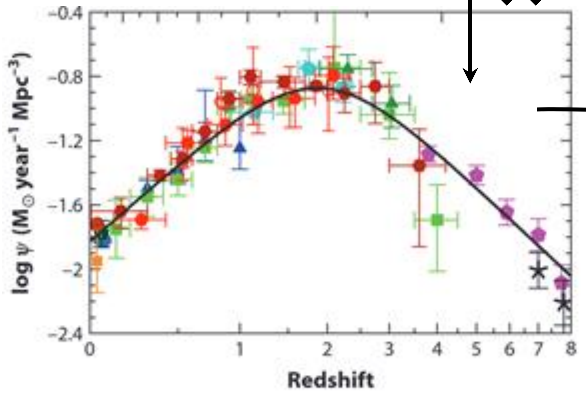
The multi-messenger extragalactic spectrum

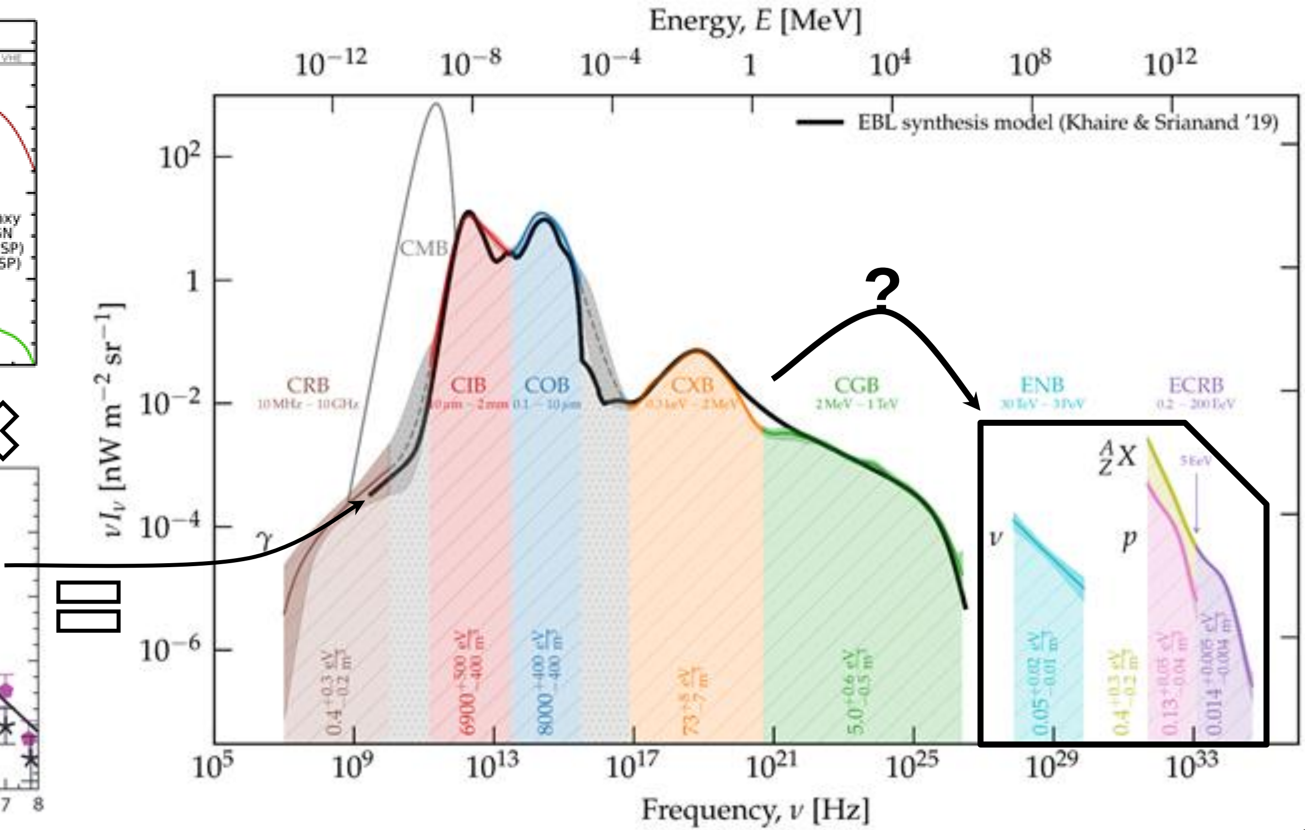
How to constrain the **populations of hadronic emitters** and the mechanisms at play in **hadronic accelerators**?
→ likely from what we learned about the **populations of photon emitters**



Model for the particles of the extragalactic spectrum?



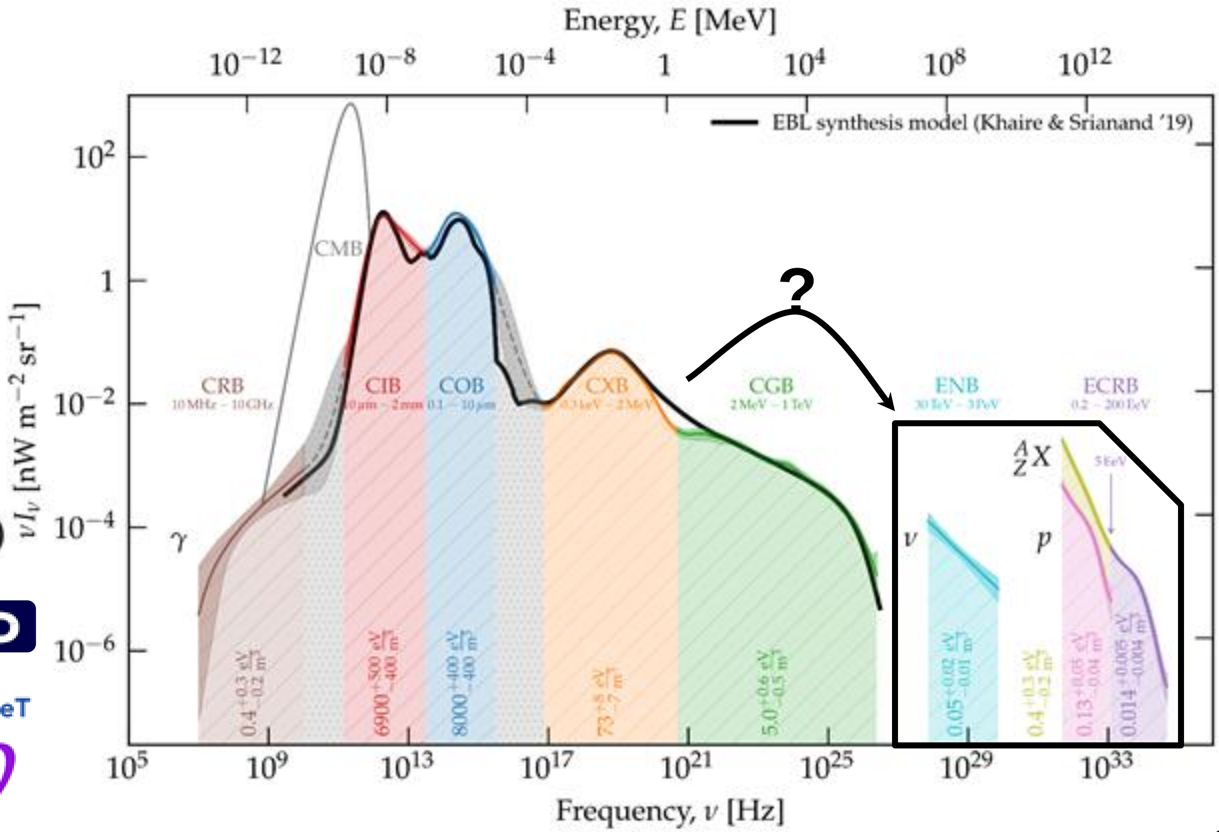




Model for the multi-messenger extragalactic spectrum

Ingredients

- Refined photon model
- Refined 3D catalog of baryonic matter
- 3D to 4D: $\mathbb{R}^3$ + time
  → transients



Backup

Clarification on energetics

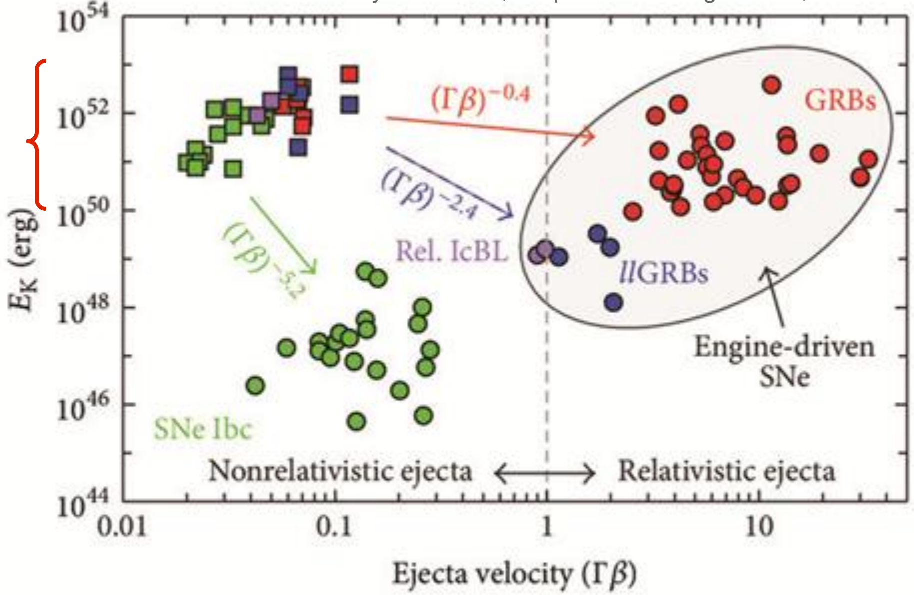
Common in literature

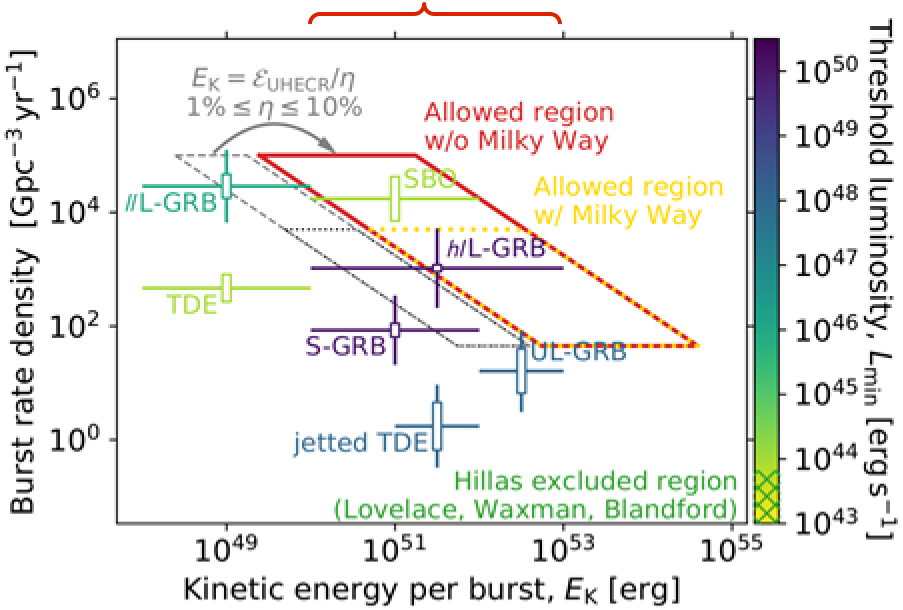
➔apparent local rate ✕ isotropic-equivalent energy (beaming corrected - often based on gamma-ray flux)

This work

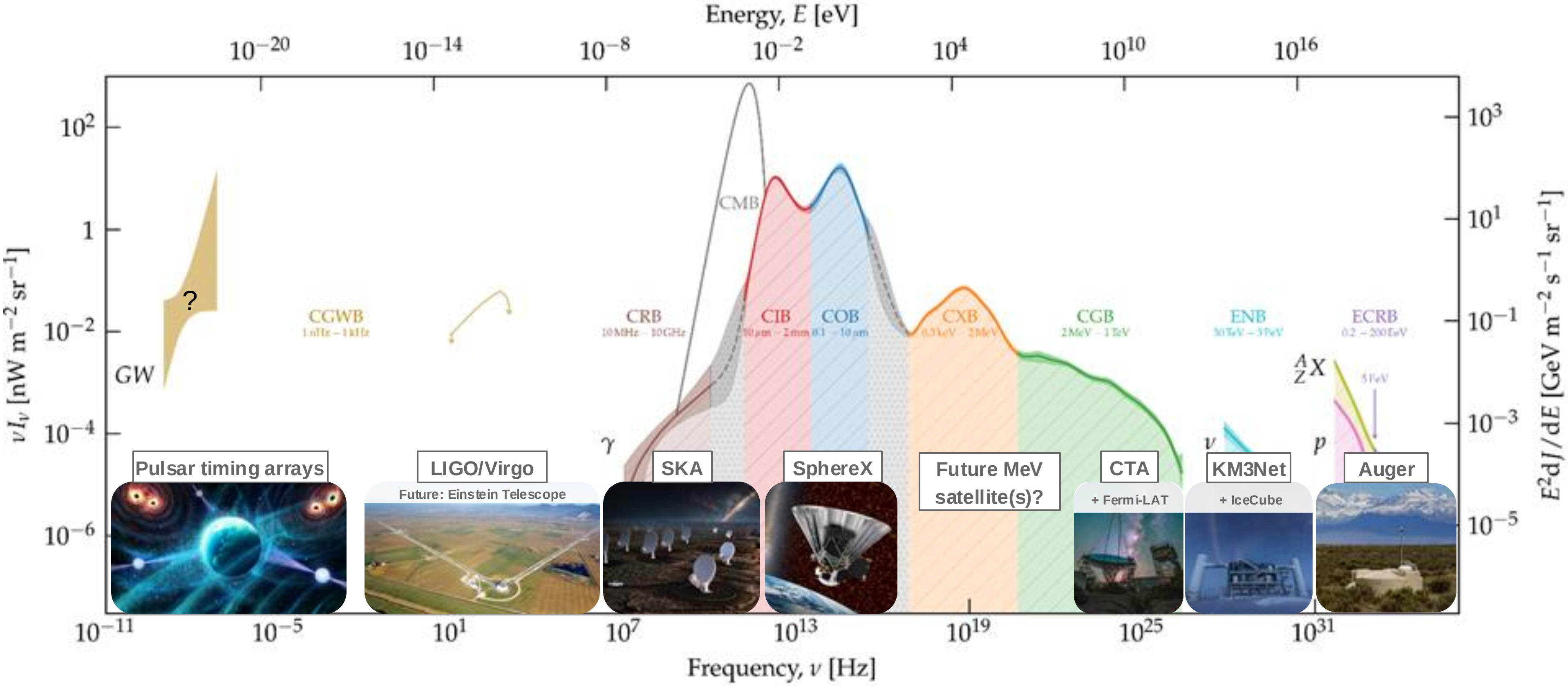
➔true local rate (beaming corrected) x true energies (based on expected kinetic energies)

Credits: review by Cano+ ‘17, adapted from Margutti+ ‘13, ‘14

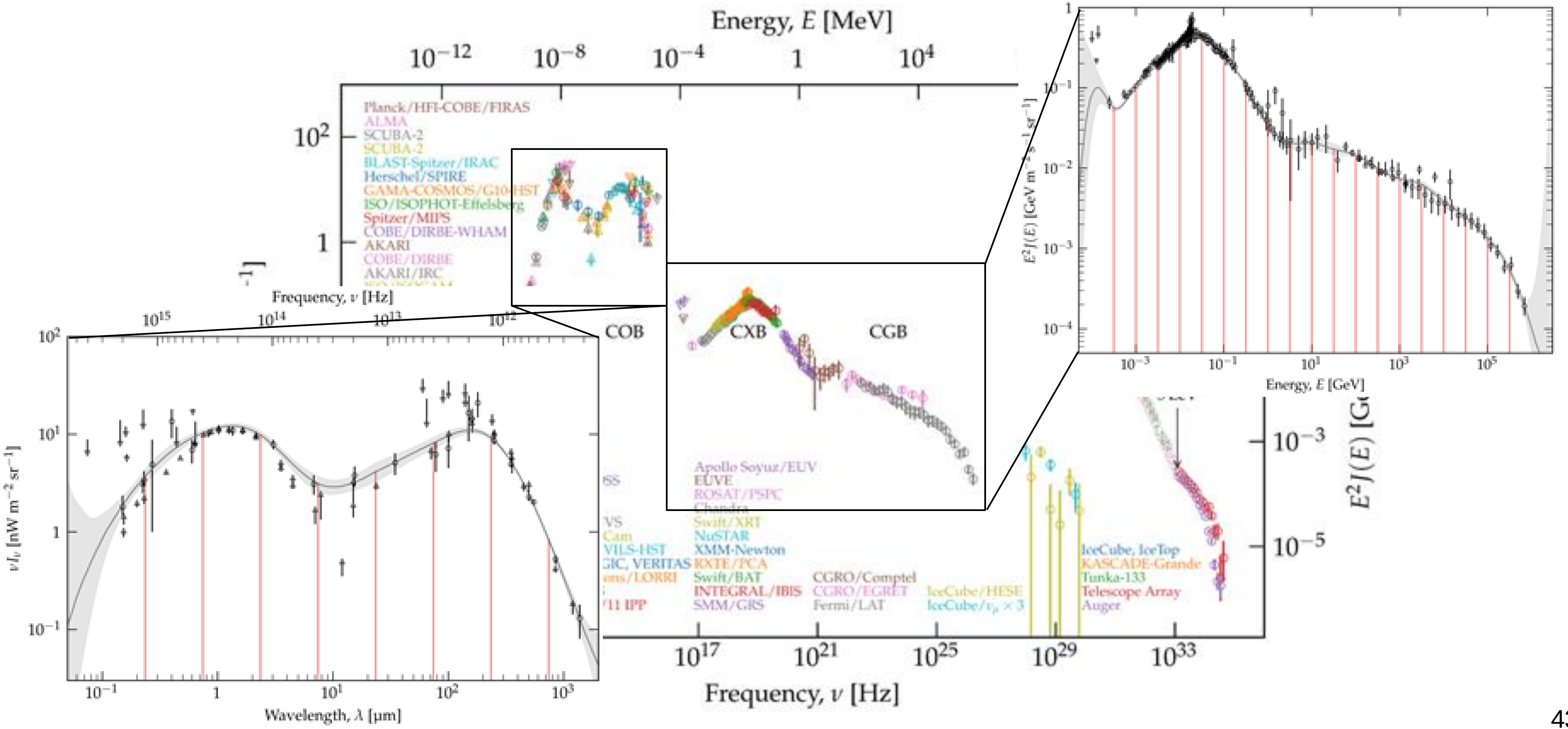




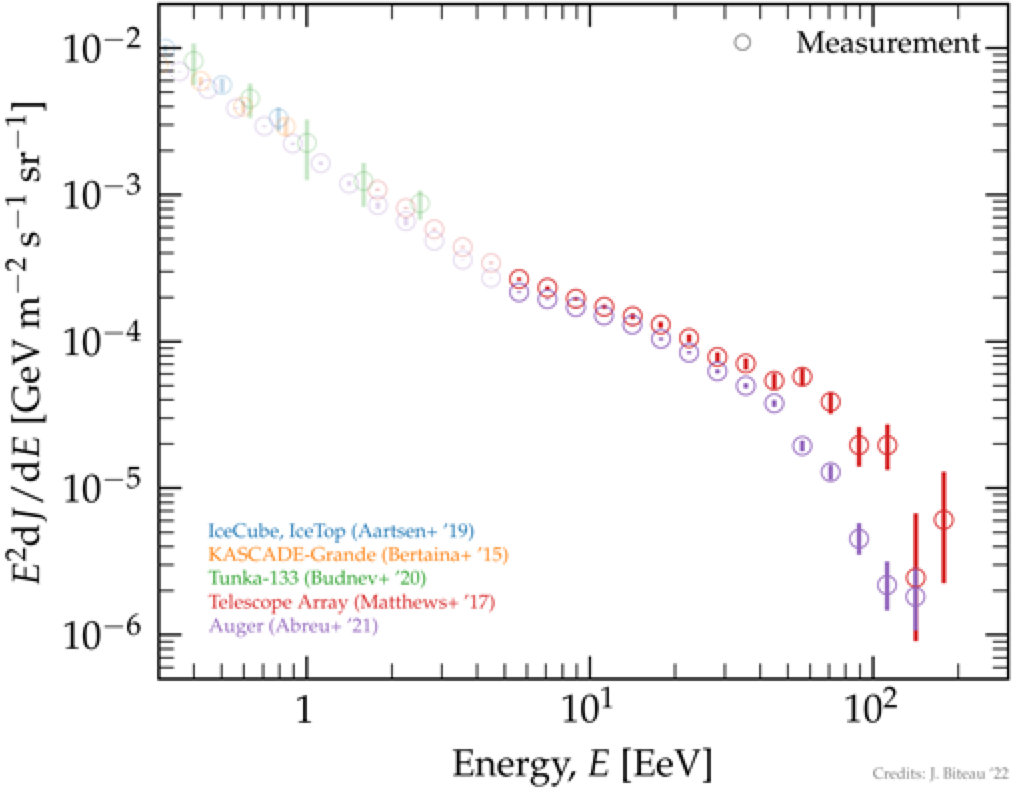
What remains: the multi-messenger extragalactic spectrum



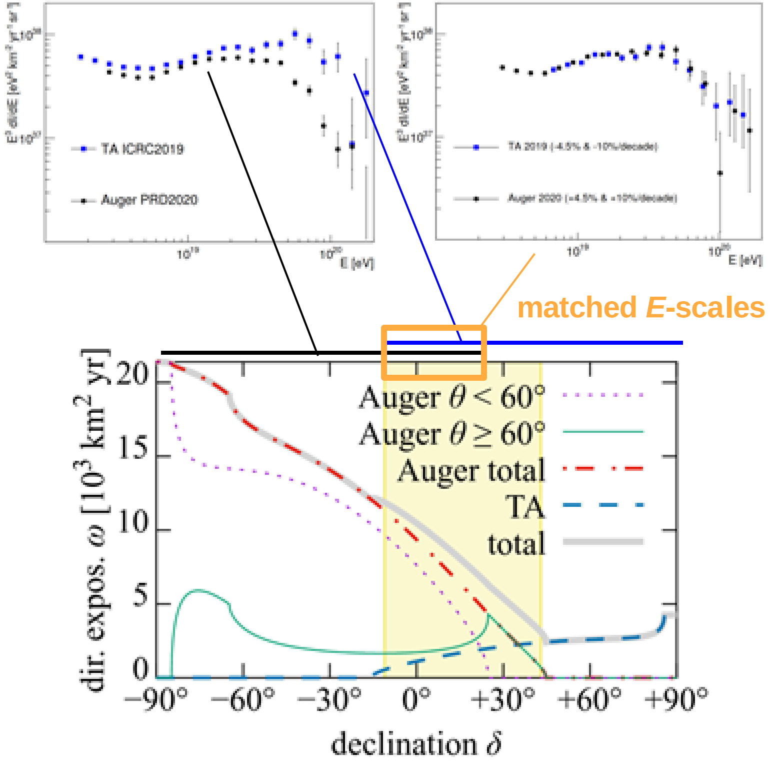
Spline fit of the multi-messenger extragalactic spectrum



The UHECR Background



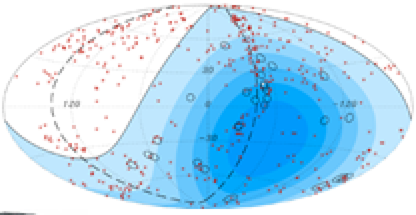
Credits: Tsunesada+ '21



Credits: Tinyakov+ '21

Some landmarks in Auger anisotropy studies

Auger, Science 2007



First steps: hint

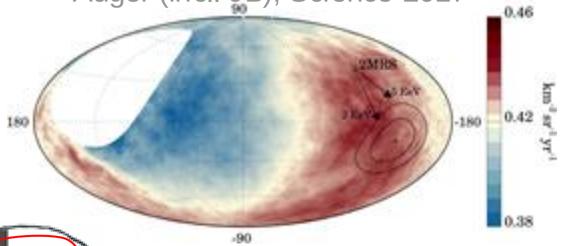
20 out of 27 evts within 3°

of nearby galaxies → ~3σ

10 evts in particular clustered in the Centaurus region

~ 27 evts ≥ 57 EeV

Auger (incl. JB), Science 2017



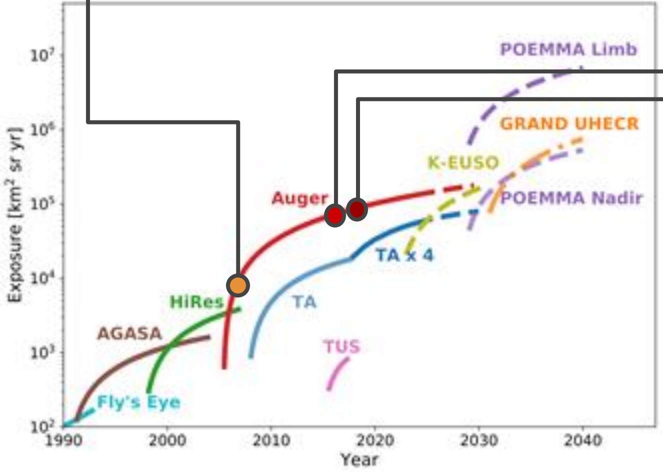
Maturity: discovery

6σ dipolar-like flux

In line with nearby galaxy stellar mass distribution (2MRS)

~ 32,000 evts ≥ 8 EeV

Alves Batista+ (incl. JB) ‘19



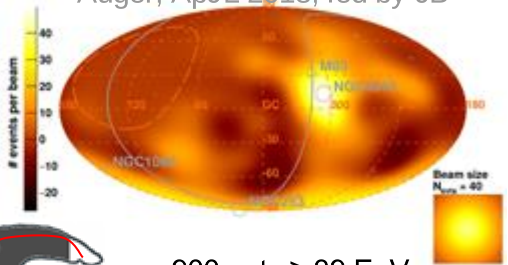
Revival: a trail?

4σ evidence for ~10% excess from nearby starbursts (23 brightest)

Now 4.5σ

Auger, JCAP ‘24

Auger, ApJL 2018, led by JB

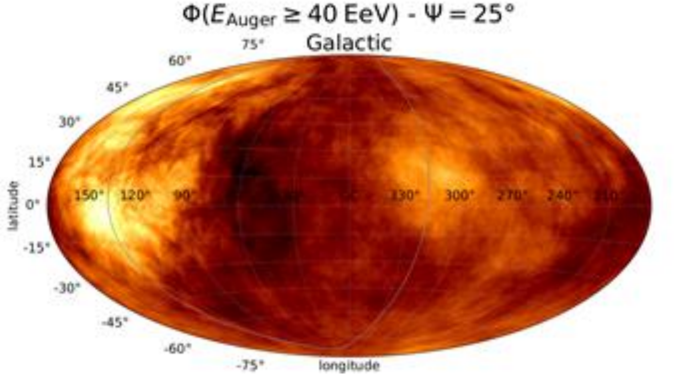


~ 900 evts ≥ 39 EeV

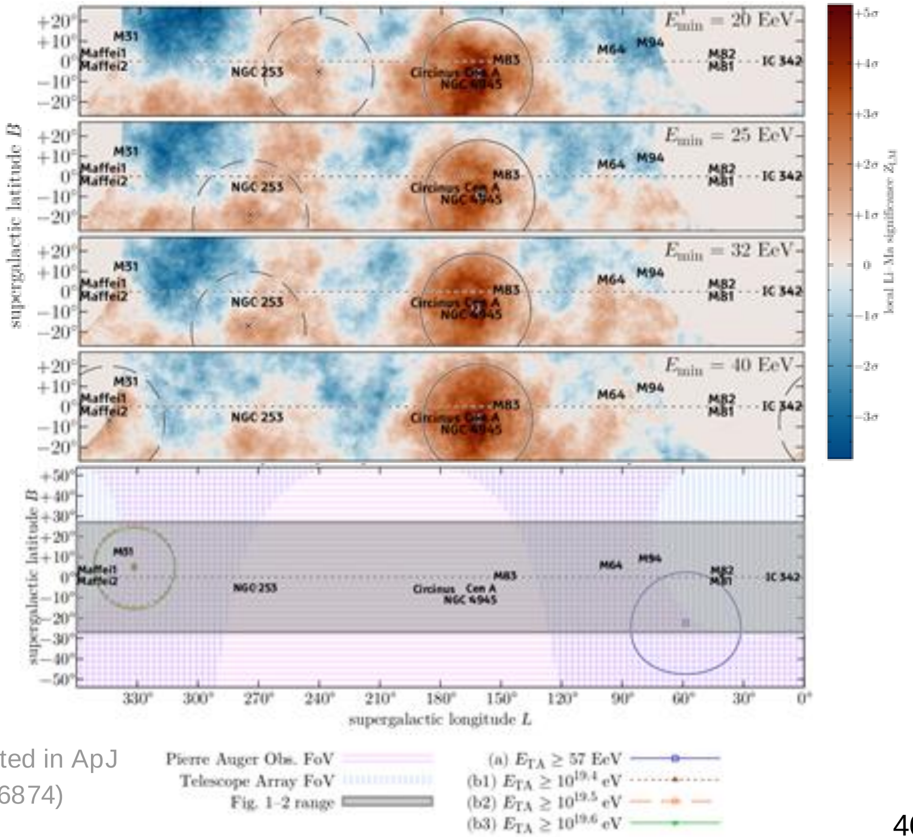
Status of the TA hotspots

Auger + TA data

Credits: L. Caccianiga for Auger & TA



	Telescope Array		Pierre Auger Observatory	
	E_{min}	$\frac{\Phi_{\mathrm{in}}}{\Phi_{\mathrm{out}}}$	E_{min}	$\frac{\Phi_{\mathrm{in}}}{\Phi_{\mathrm{out}}}$
(a)	57 EeV	$2.44^{+0.44}_{-0.39}$	44.6 EeV	$0.84^{+0.31}_{-0.25}$
(b1)	$10^{19.4}$ eV	$1.58^{+0.17}_{-0.16}$	20.5 EeV	$0.93^{+0.12}_{-0.11}$
(b2)	$10^{19.5}$ eV	$1.70^{+0.22}_{-0.20}$	25.5 EeV	$0.90^{+0.15}_{-0.14}$
(b3)	$10^{19.6}$ eV	$1.83^{+0.31}_{-0.27}$	31.7 EeV	$1.04^{+0.21}_{-0.19}$



Auger Coll., accepted in ApJ (arXiv:2407.06874)

Continuous losses of protons: p-ɣ on the CMB

$$\begin{aligned} p + \gamma &\to p + e^+ + e^- \\ &\to p + \pi^0 \\ &\to n + \pi^+ \end{aligned}$$

Threshold for π photoproduction

$2m_p\, m_\pi$ / 4ϵ ~ **50 EeV** x (λ / 1 mm)

Note: p @ 50 EeV → <u>unobserved</u>

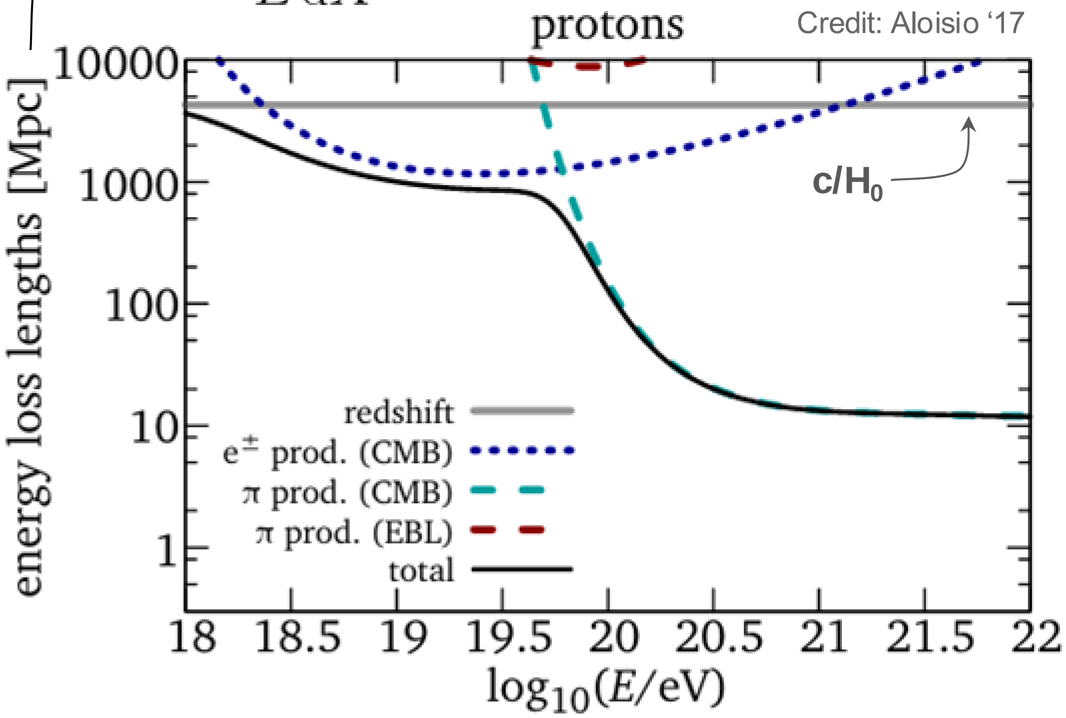
Center of mass

(50 EeV x 1 meV)$^{1/2}$ ~ 0.2 GeV

Neutron = proton in the IGM

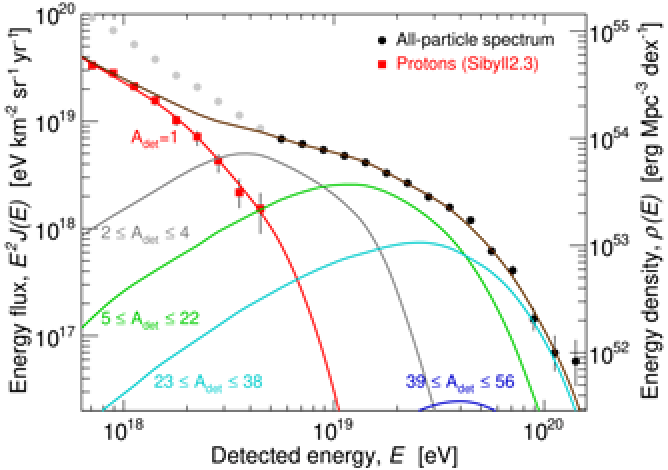
ɣcτ ~ 10 kpc x (*E* / 1 EeV)

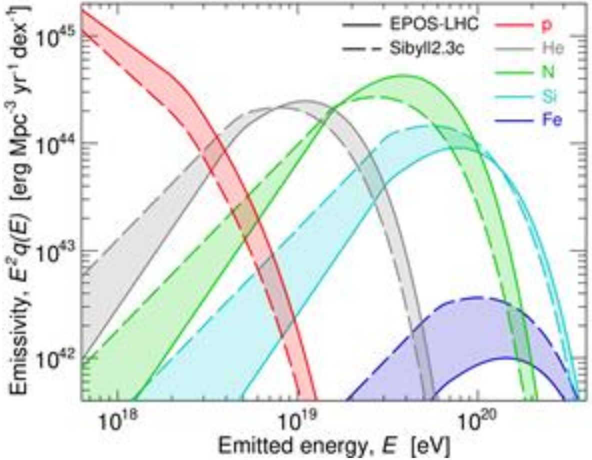
$$\chi^{-1} = \frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}X}$$



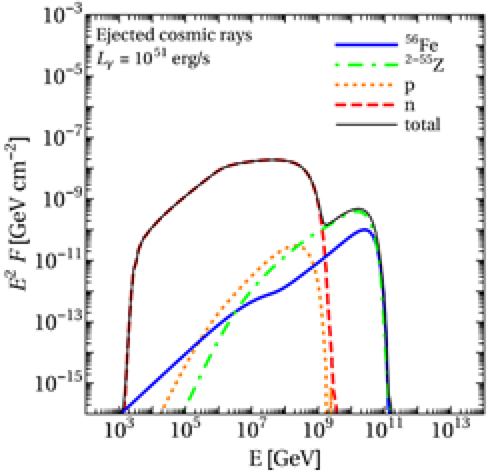
Escape spectrum: neutrons

Luce, Marafico, JB+ ApJ '22





Biehl+ A&A '18



Catastrophic losses of nuclei: photo-erosion/disintegration

$$\boxed{{}^{A}_{Z}X + \gamma \rightarrow {}^{A-a-b}_{Z-b}Y + an + bp}$$

Photo-erosion driven by

- ❑ ϵ_γ' ~ 10 MeV: giant dipole resonance

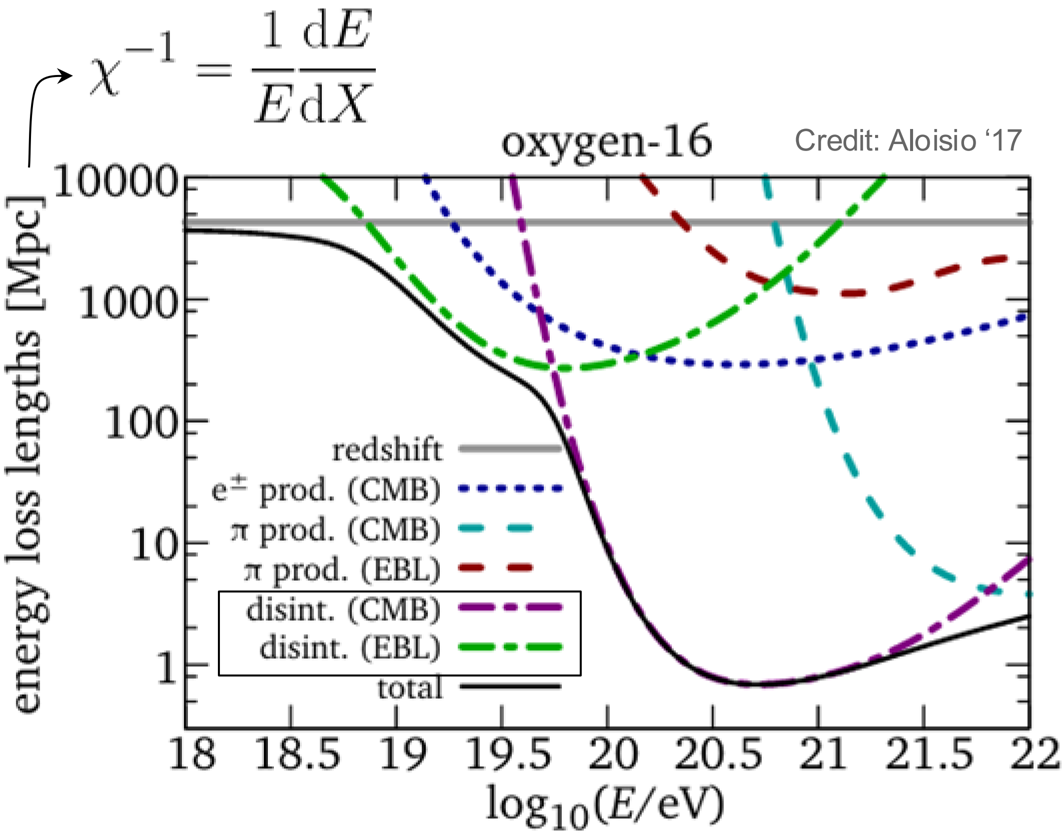
→λ_γ ~ 0.5 mm (CMB) for E_X/A ~ 2 EeV

- ❑ ϵ_γ' ~ 30 MeV: quasi-deuteron process
- ❑ ϵ_γ' > 150 MeV: baryon resonance

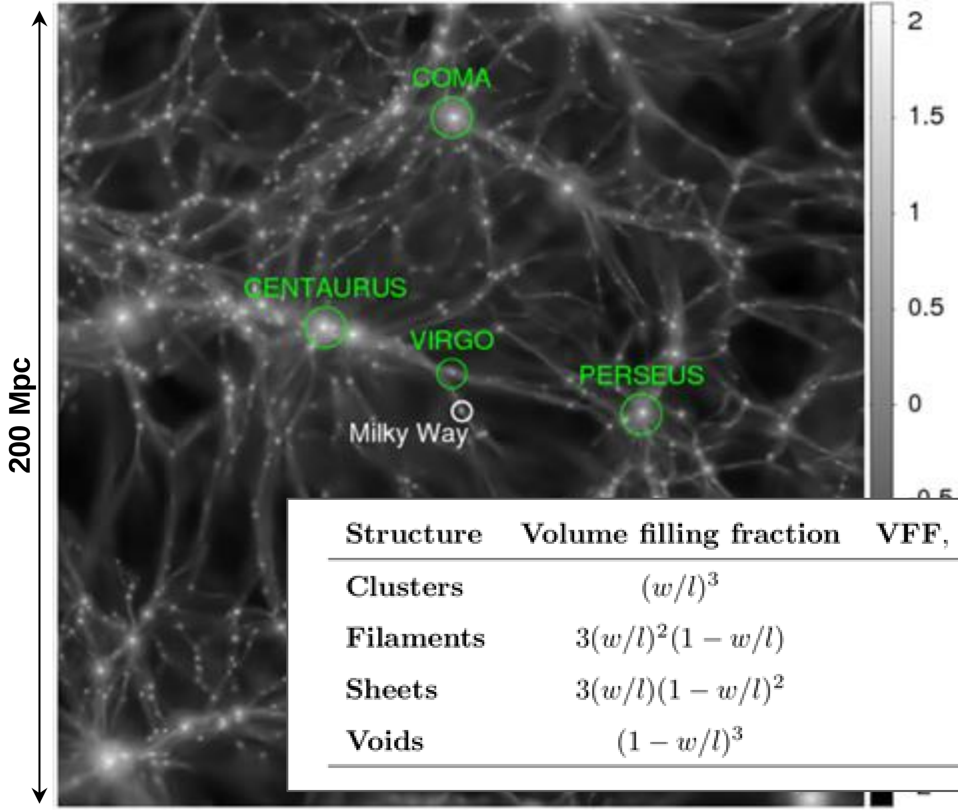
→λ_γ ~ 30 μm (CIB) for E_X/A ~ 2 EeV

Lower energy nuclei and protons

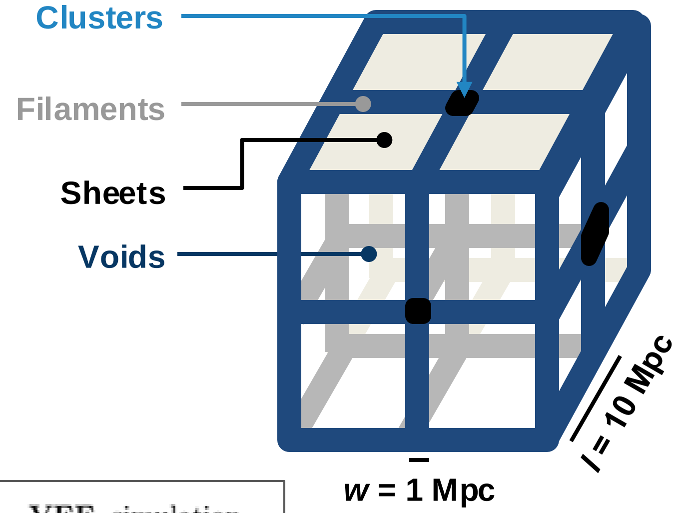
→ with Lorentz boost nearly conserved



Cosmic web: volume filling fraction



Structure	Volume filling fraction	VFF, cubic $w/l = 0.1$	VFF, simulation
Clusters	$(w/l)^3$	0.1%	0.5%
Filaments	$3(w/l)^2(1-w/l)$	2.7%	5%
Sheets	$3(w/l)(1-w/l)^2$	24.3%	18%
Voids	$(1-w/l)^3$	72.9%	76%

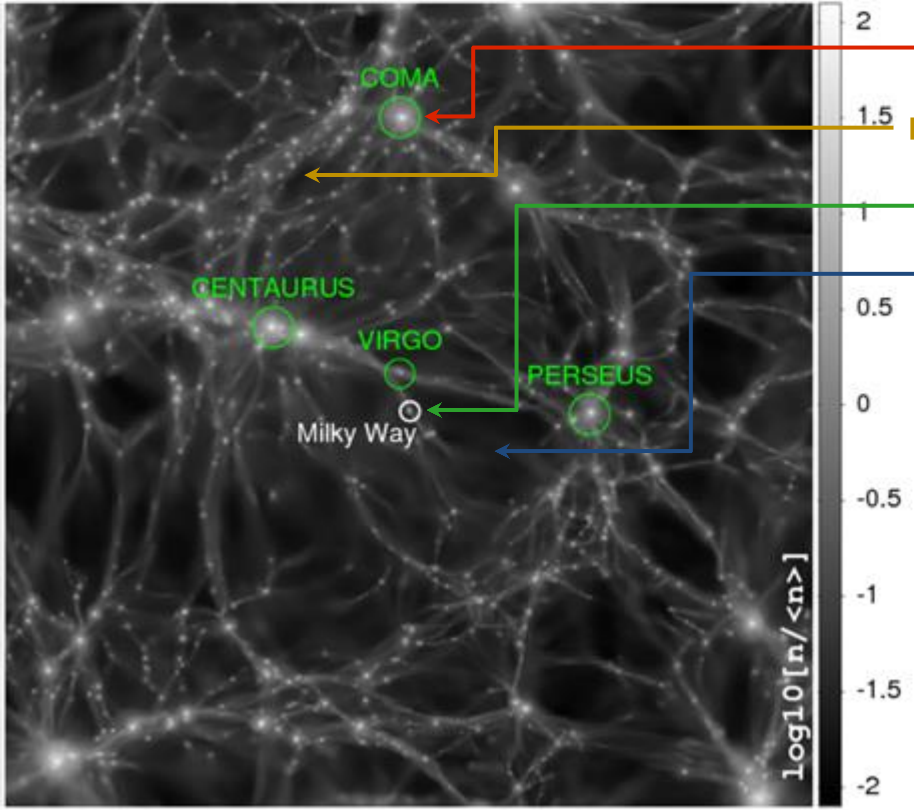


Credit: Oei+ *A&A* ‘22

Credit: Hackstein+ *MNRAS* ‘18 (Cosmic V-web constrained sim. / CLUES)

Magnetic fields and where to find them

200 Mpc



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

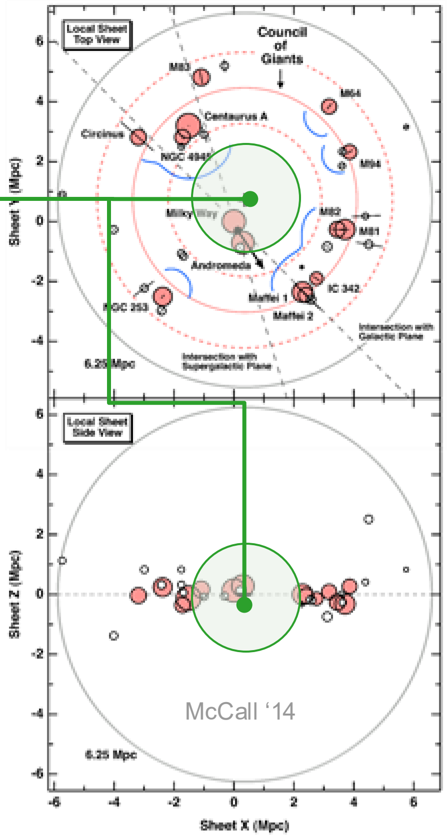
Cluster: *B* ~ 1-10 μG
e.g. Bonafede+ '10

Filament: *B* ~ 10-100 nG
Vernstrom+ '21, Carretti+ '22

Sheet: *B?*

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

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



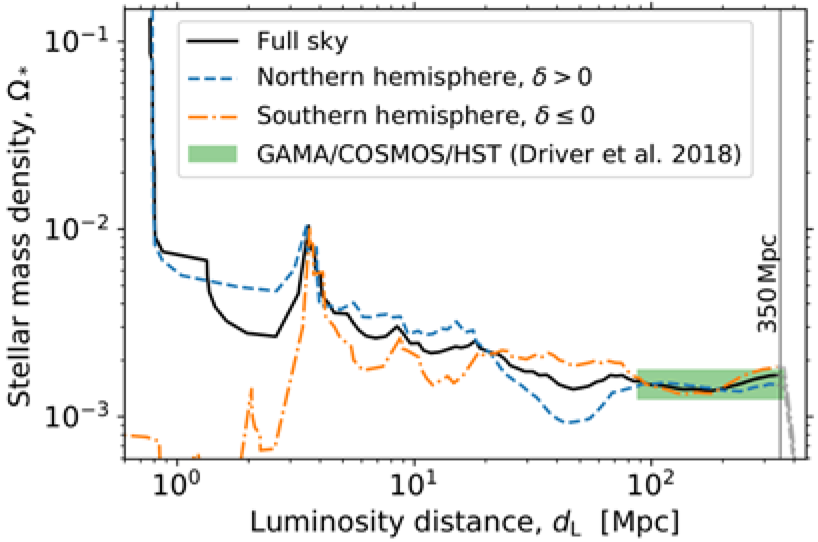
McCall '14

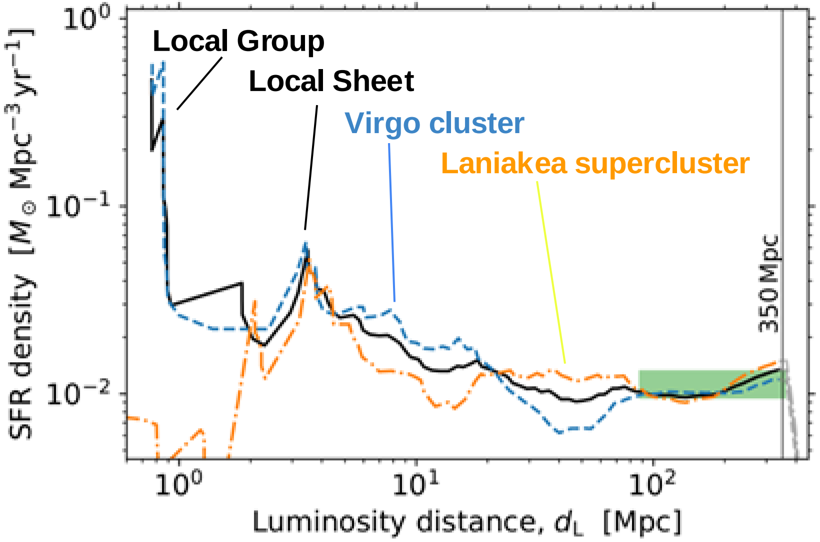
Validation: do we grasp all $M_\star$ and SFR?

1D visualization vs *d* out to 350 Mpc (vs 135 Mpc in Karachentsev+ 2018)

→ **Full-sky** plateau beyond 100 Mpc matches **deep-field observations** (Driver+ 2018)

→ **Northern** matches **Southern** hemisphere beyond 100 Mpc: negligible N/S dipole ~ isotropic regime





DOI 10.5281/zenodo.5118697

3D visualization out to 350 Mpc (see interactive figures of the Local Superclusters, Local Clusters and Local Sheet)

→ Good agreement with V-web from Cosmicflows (Hoffman+ 2017, Dupuy +2019) on supercluster scales

EeV cosmic rays in the cosmic web

Condorelli, JB, Adam, **ApJ ‘23**

Voids: B < 10 pG

➔Too low to have a sizeable impact within cosmic-ray horizon

(see Pierre Auger Collab. ‘24)

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

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

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

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

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

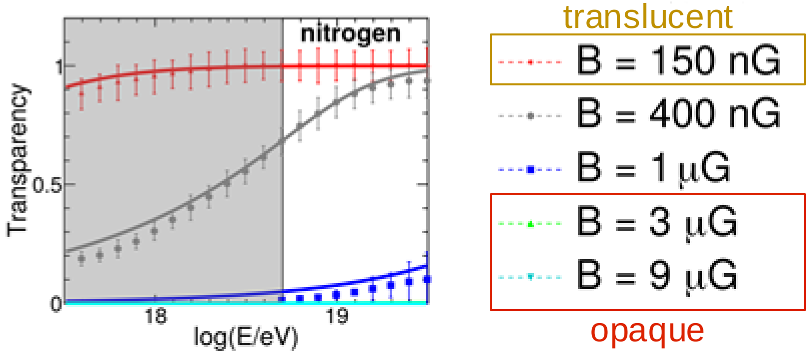
Galaxy filaments: B ~ 10-100 nG

➔**Translucent** to UHE nuclei

➔No need for specific treatment

Galaxy clusters: B ~ 1-10 μG

➔Calorimeters for UHE nuclei



Condorelli, JB, Adam, ApJ ‘23

Starbursts host more frequent stellar explosions…

Marafico, JB+, **ApJ '24**

Why would UHECR sources be transient?

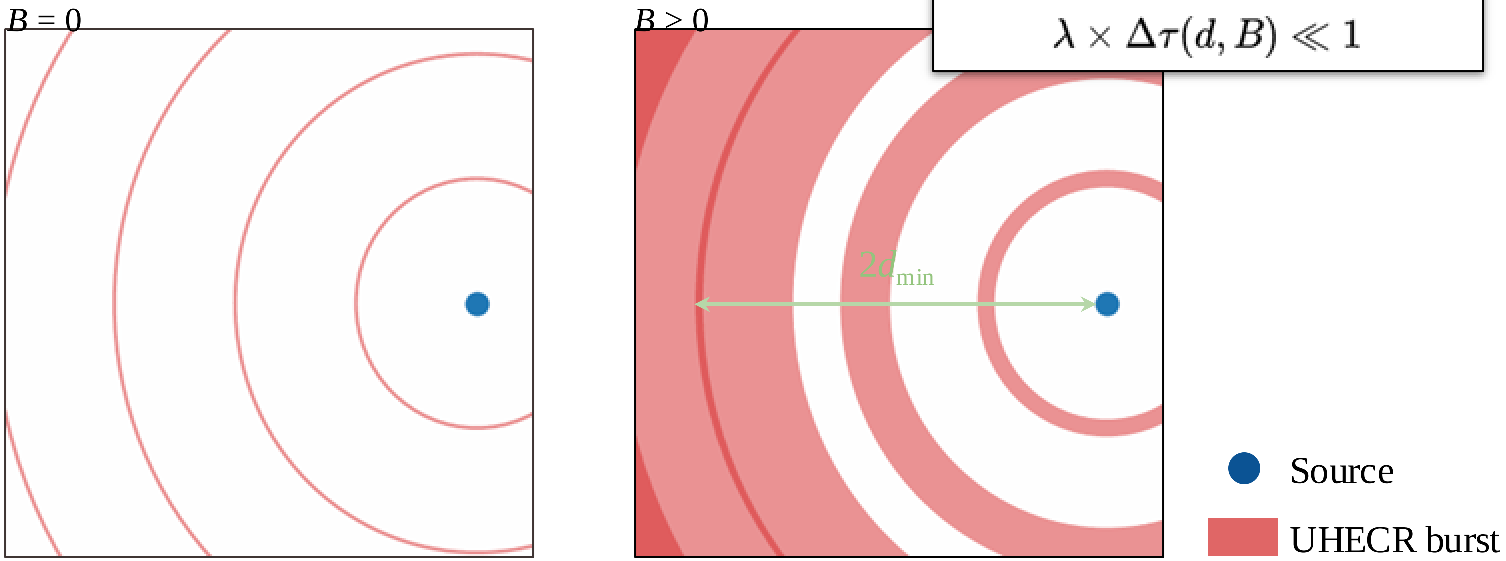
➔ Hillas-Lovelace-Waxman: high-luminosity sources

➔ Composition: H/He-poor material from (high-mass) stars

➔ Minimum distance: for an observer in a large-scale *B*-field

Source with burst rate λ invisible:

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



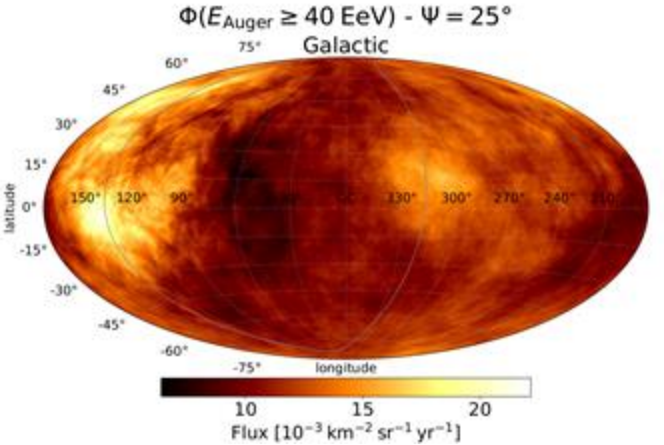
Credit: S. Marafico

Contrast in the Centaurus region

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

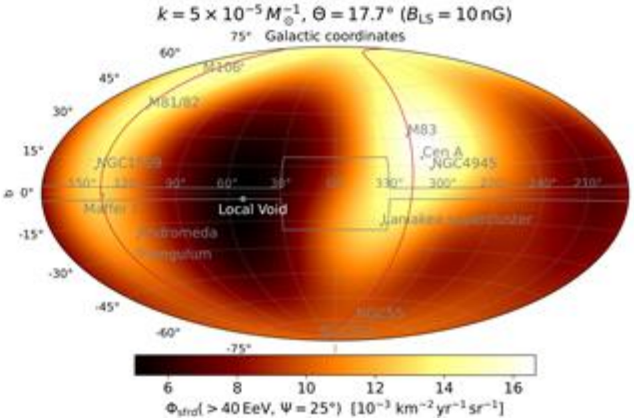
Auger + TA data

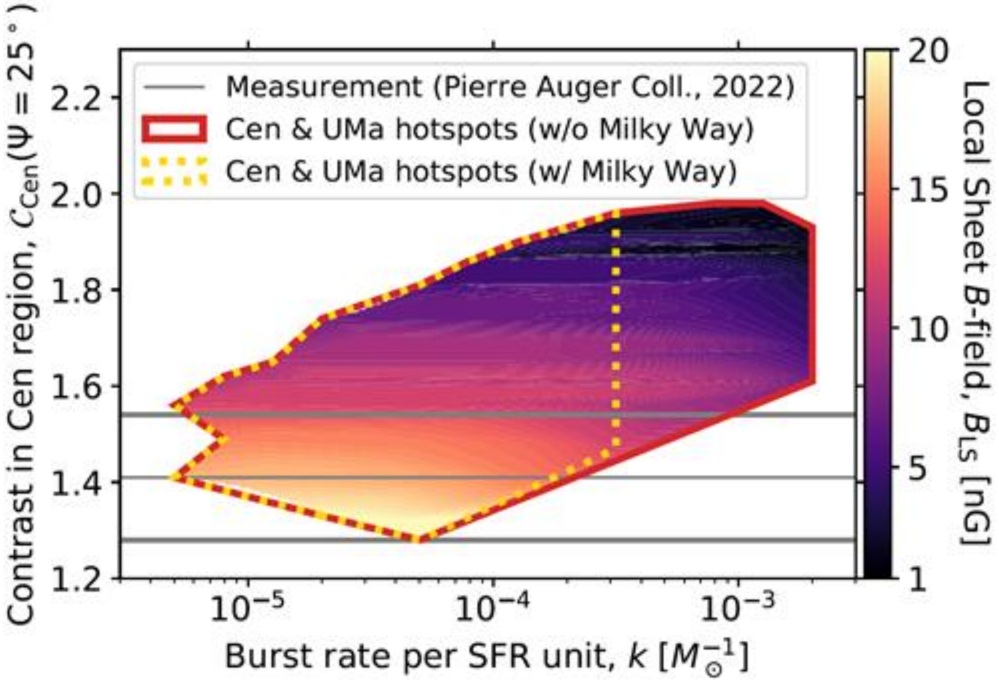
Credits: L. Caccianiga for Auger & TA



Best-match transient scenario

Credits: Marafico, JB+ '24



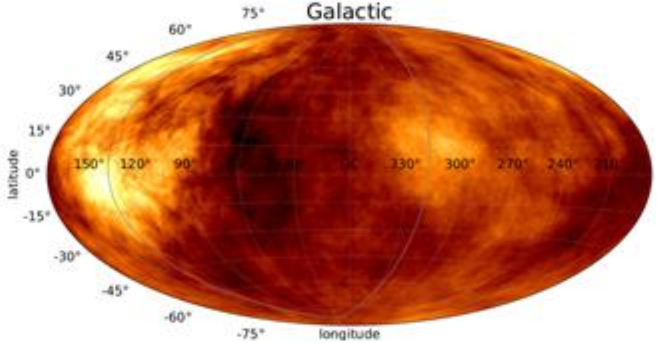


Candidate ultra-high-energy sources

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

Auger + TA data

Credits: L. Caccianiga for Auger & TA

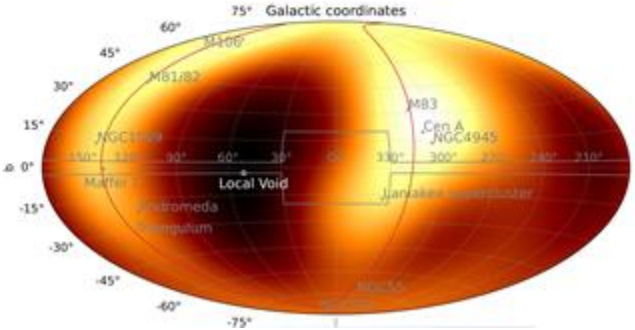


UHECR Model ≈ UHECR Data

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

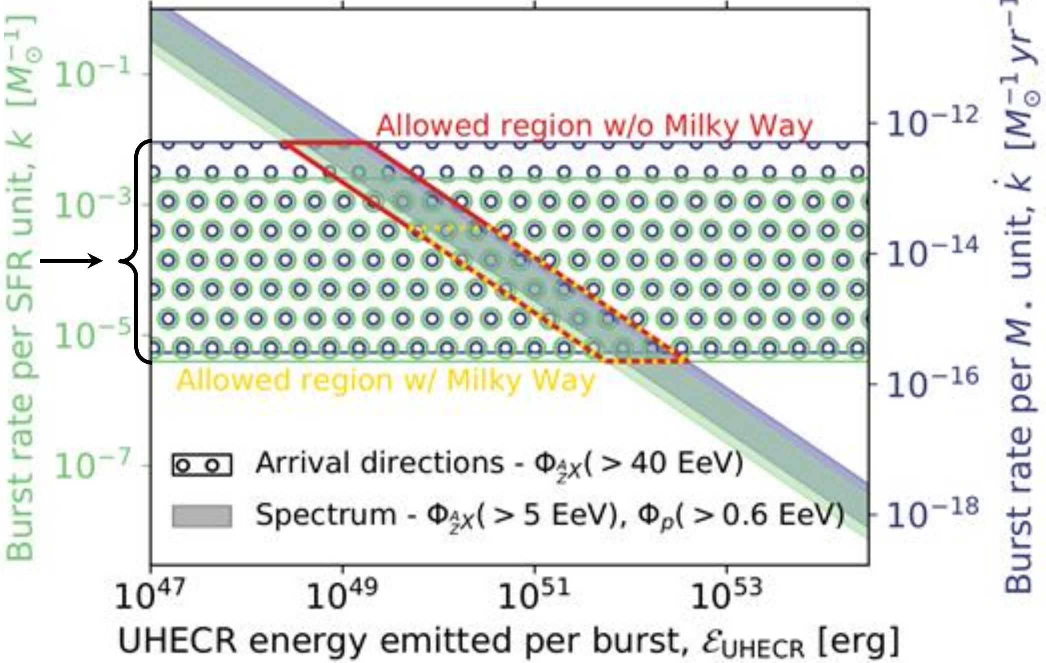
Best-match transient scenario

Credits: Marafico, JB+ '24



Solution with at least 1 Northern & Southern hotspot found for

Local Sheet B_{rms} = 0.5 - 20 nG

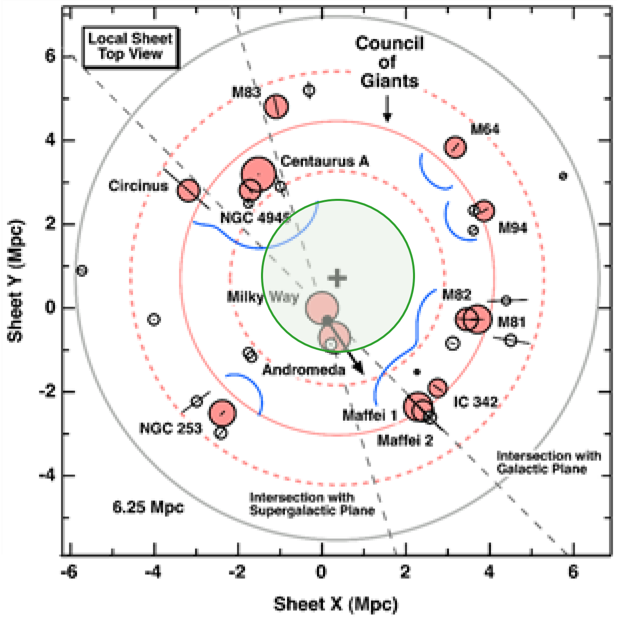


Conclusions

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

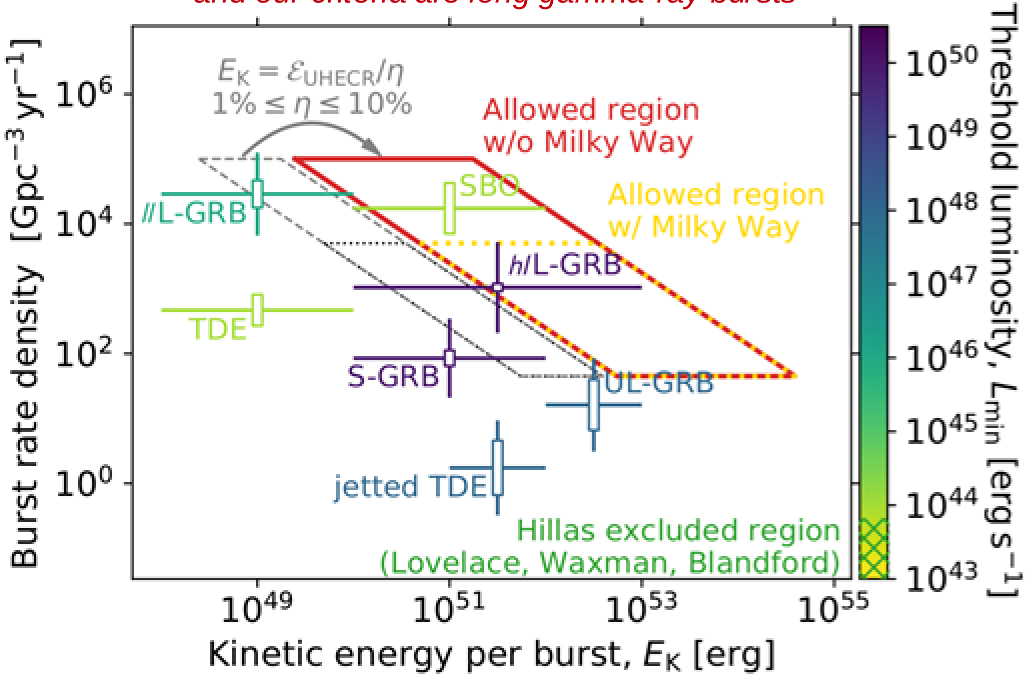
Local Sheet B_{rms} = 0.5 - 20 nG

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



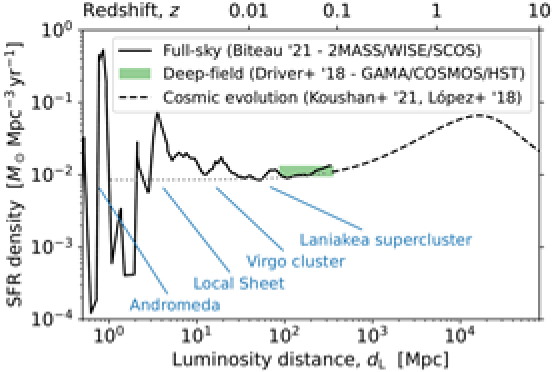
arXiv:2405.17179

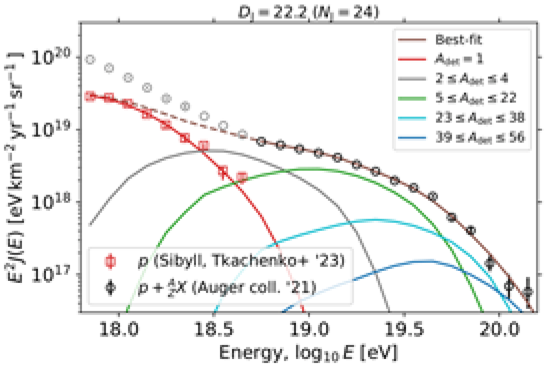
Transient model of UHECR sky

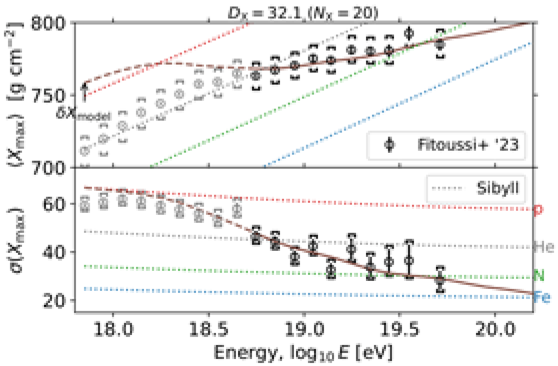
DOI 10.5281/zenodo.11440864

Marafico, JB, Condorelli, Deligny, Bregeon, **ApJ '24**

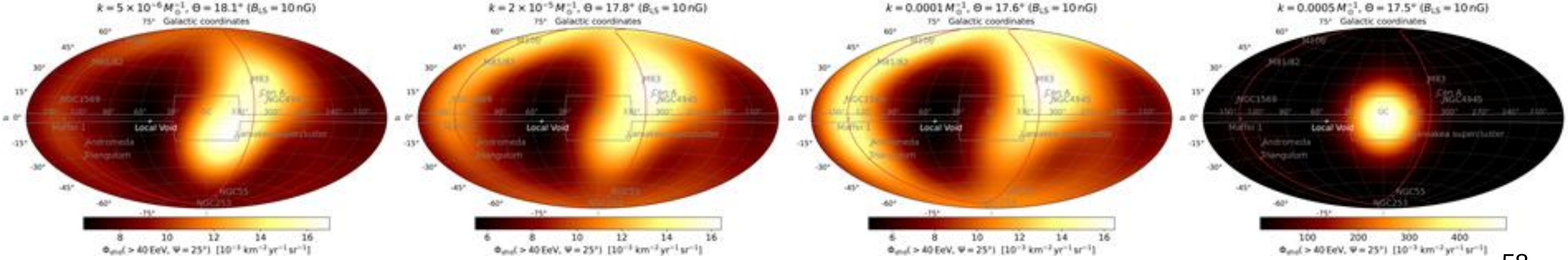
Spectral & composition model (see also Luce+ ApJ '22)







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



Observations in the Local Volume

Aim for volume limited sample to d < 11 Mpc or v_{LG} < 600 km/s

Distances based on usual cosmic-ladder estimates (supernovae, Cepheids, Tully-Fisher, Faber-Jackson) + tip of the red giant branch

→ avoid biases induced by peculiar motion, distance uncertainty: 5-25%

Information available from Karachentsev+ 2018

- $M_\star$: stellar mass from K band (1022/1029)
- T: de Vaucouleurs' morphology (1028/1029), special attention to dwarfs
- M(HI): atomic hydrogen mass, tracing gas (819/1029)
- SFR(FUV): mostly based on GALEX observations (647/1029)
- SFR(Hα): from literature & dedicated surveys (470/1029)

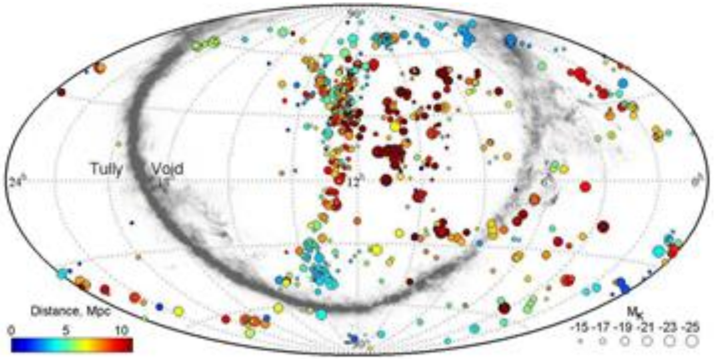
Main sequence of galaxies in the Local Volume?

SFR-M_* branch occupied by Irregular (Irr.) and Spiral (S.) galaxies

Small Magellanic Cloud
(ESO/VISTA VMC)

Antennae: NGC4038/4039
(ESA/Hubble)

Messier 83
(ESO)



Karachentsev+ 2013

Equatorial coordinates

Main sequence in the Local Volume

SFR tracers in the Local Volume

- **Hα: 5-10 Myrs** timescale, fraction of ionizing photons from young massive stars absorbed before being reprocessed into Hα
- **FUV: 100-300 Myrs** timescale, fraction of FUV photons from OB stars absorbed, often combined with total IR to estimate SFR

→ *both corrected for extinction, i.e. escape from the galaxy*

3 SFR-$M_\star$ branches

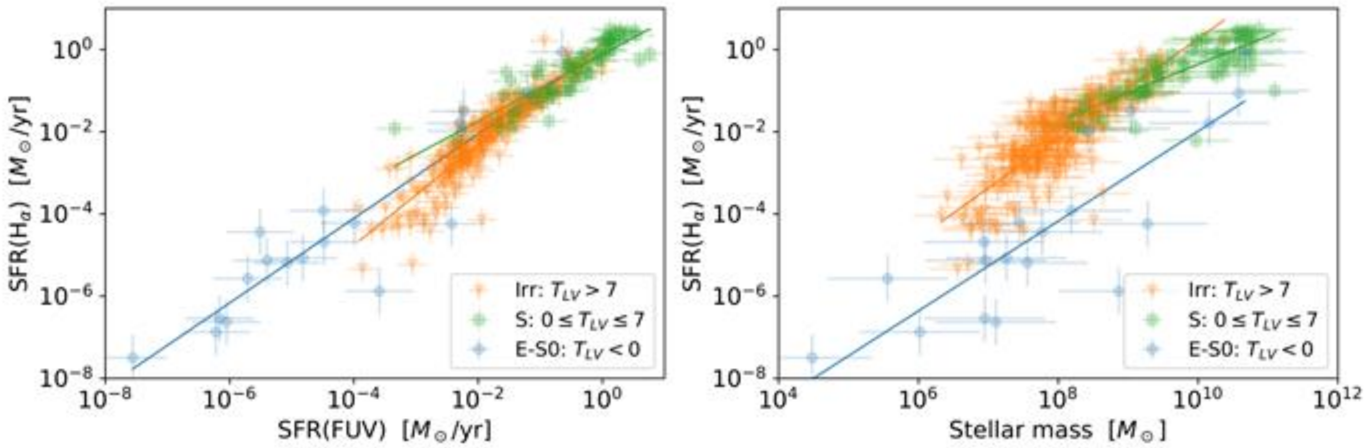
→ E-S0: linear (β = 1.0-1.1 ± 0.10), i.e. no active star formation

→ S: sub-linear (β = 0.81-0.69 ± 0.07), active star formation >10 Myrs ago

→ Irr: supe

Fit results with best morphological divide

- KS-test p-value for Gaussian residuals ~ 5%, 4σ outliers → hidden variables (metallicity, environment)
- SFR dispersion of S: 0.24 dex (FUV-Hα), 0.34 dex (M_*-Hα)



Exploiting the HyperLEDA database

Limitations of GLADE / MANGROVE

Mix of overlapping catalogs: risk of duplicate entries, possibly direction-dependent flux limit

Fully exploiting distance databases

Local Volume (1k gal., d < 11 Mpc, Karachentsev+ 2018) and HyperLEDA (5M gal., Makarov+ 2014)

Distance revision: cosmic ladder > spectro-z > photo-z

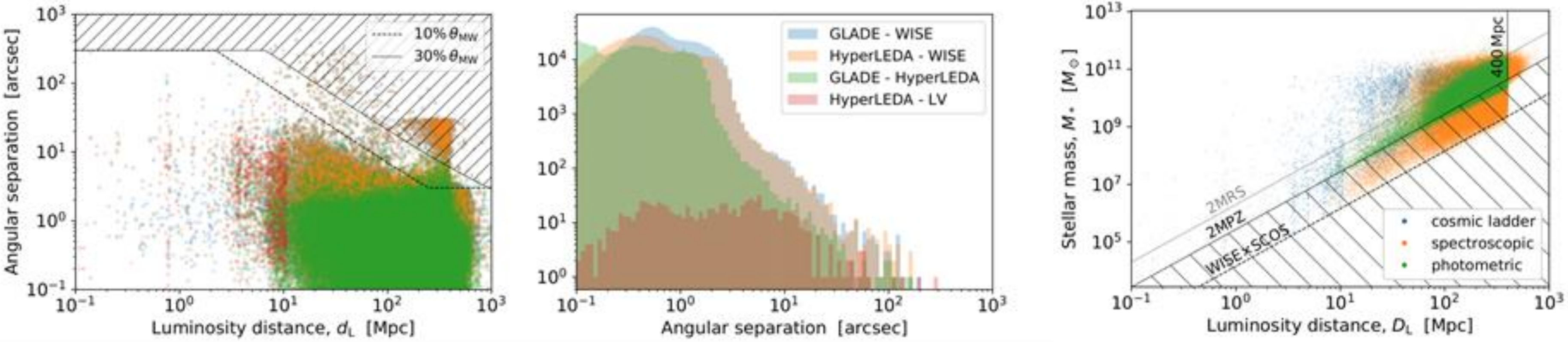
Cosmic-ladder distances for ~1k nearby objects, spectro-z x 4 → 200k/400k within 350 Mpc

Stellar mass estimates

K-band for Local Volume, W1-band otherwise, with $M_*/L = 0.6$ ($M_\odot/L_\odot$), i.e. Chabrier IMF

Association results

- 671,593 / 743,480 HyperLEDA pairings (others = 2MASS objects not in HyperLEDA)
- 361 duplicates removed
- 1,387 excluded entries:
  - dubious duplicates removed
  - jetted AGN from HyperLEDA



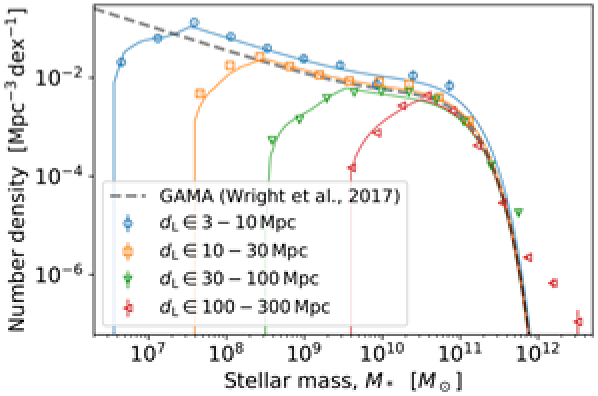
Incompleteness with increasing distance

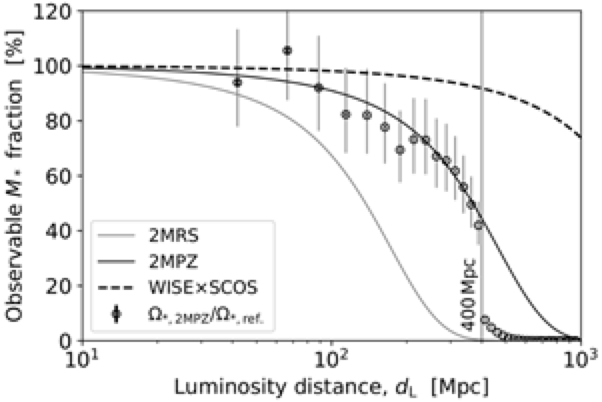
Mass function

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)





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)

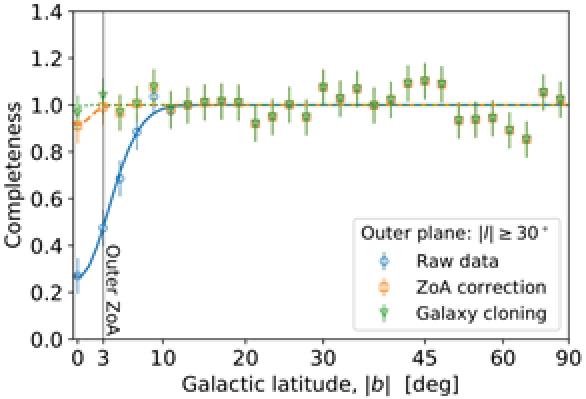
→ further increase by × 4 (distance) to be expected if full WISE x SuperCOSMOS potential exploited

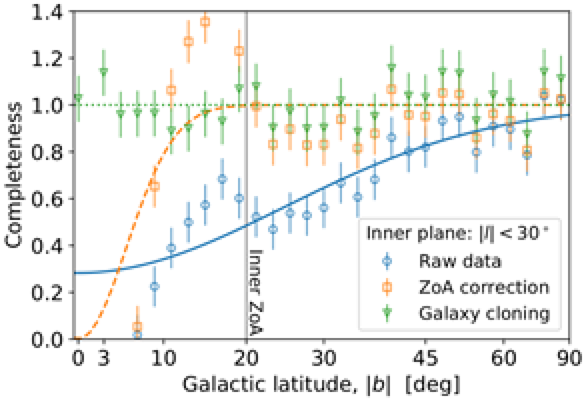
Incompleteness in the Zone of Avoidance

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°





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