What do we know about the propagation of astroparticles in the intergalactic medium?

2025.02.10, IFPU Focus Week: IGMF

Jonathan Biteau

Extragalactic astroparticles

My main research interests

- ❑ Non-thermal and thermal extragalactic sources
- ❑ Propagation in the intergalactic medium
- ❑ Detection on Earth

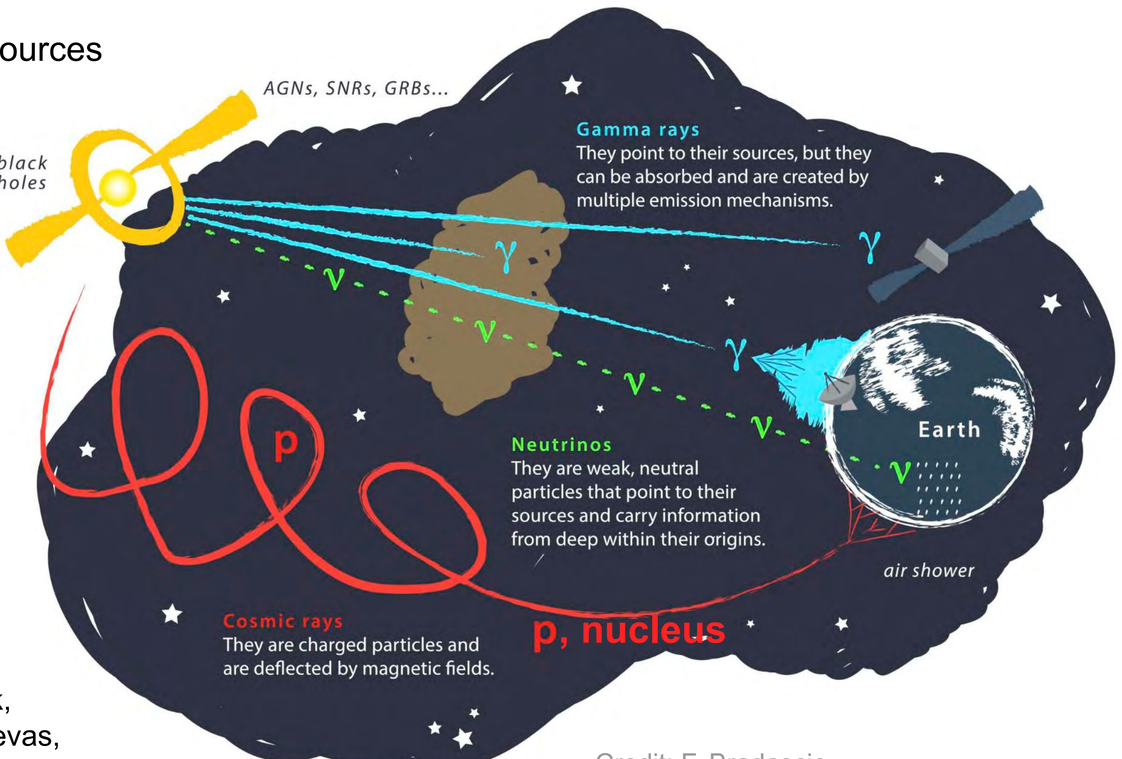
Collaborations

- ❑ H.E.S.S. (‘10-’13)
- ❑ VERITAS (‘13-’15)
- ❑ Auger (‘15-’26)
- ❑ CTAO (‘10-X), incl. NectarCAM (‘15-X)

Some close collaborators on topics related to this talk

Q. Luce (‘18), S. Marafico (PhD ‘21),
L. Gréaux (PhD ‘24), B. Biasuzzi (postdoc),
A. Condorelli (postdoc).

+ special thanks to: M. Meyer, E. Pueschel, I. Vovk,
O. Deligny, D. Harari, R. Adam, D. Williams, M. Nievas,
T. Hassan, J. Becker-Tjus, K.H. Kampert, C. Bérat



Credit: F. Bradascio

Intro

astroparticles & cosmic backgrounds

The physics of propagation

radiative and catastrophic losses

deflections, delays and spreads

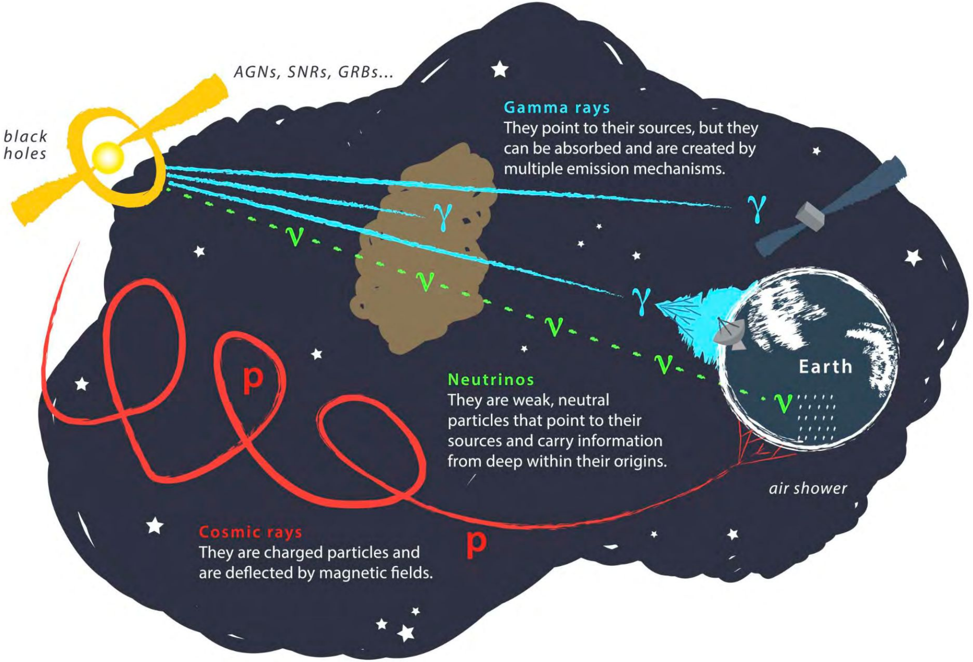
Inferences from observations

TeV gamma rays

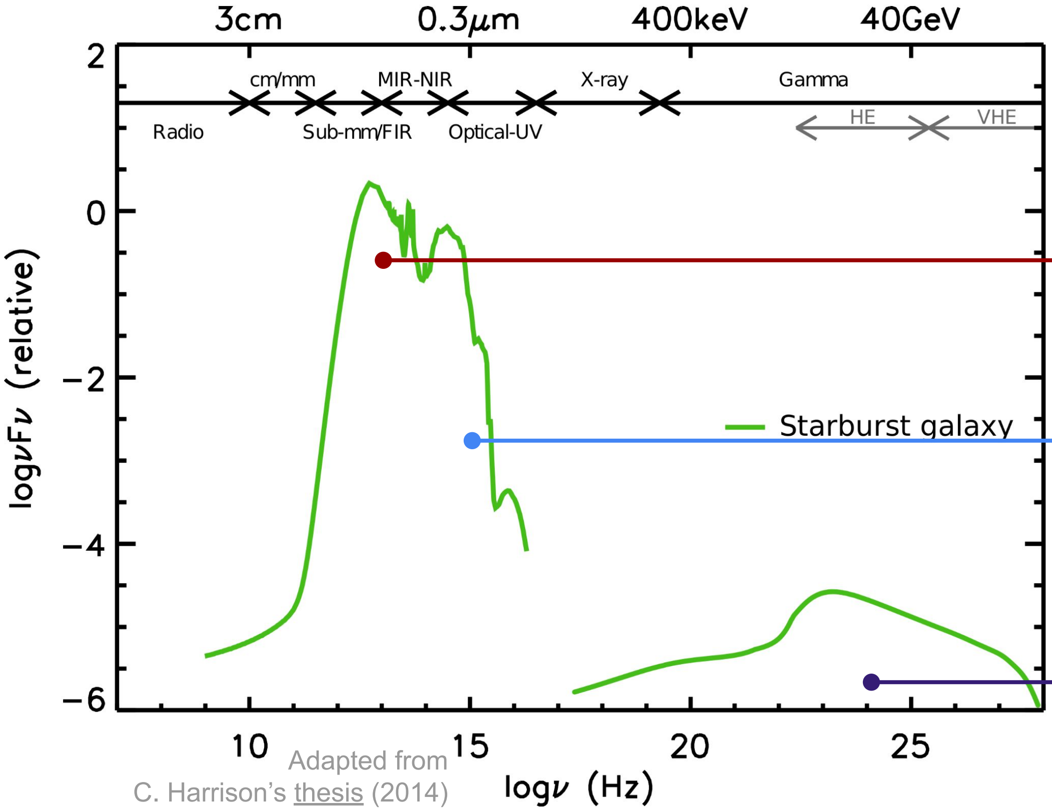
EeV nuclei

Outro

summary & open questions



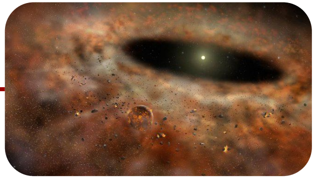
Broad-band spectra of the sources



Adapted from C. Harrison's thesis (2014)

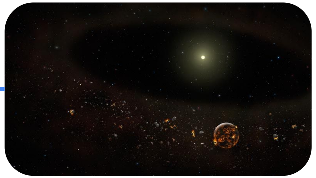
Interstellar dust

Credits: Gemini Obs./AURA/Cook



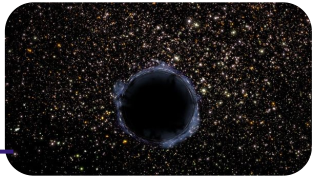
Light-weight long-lived stars

Credits: Gemini Obs./AURA/Cook



Massive short-lived stars

Credits: NASA/ESA/Bacon



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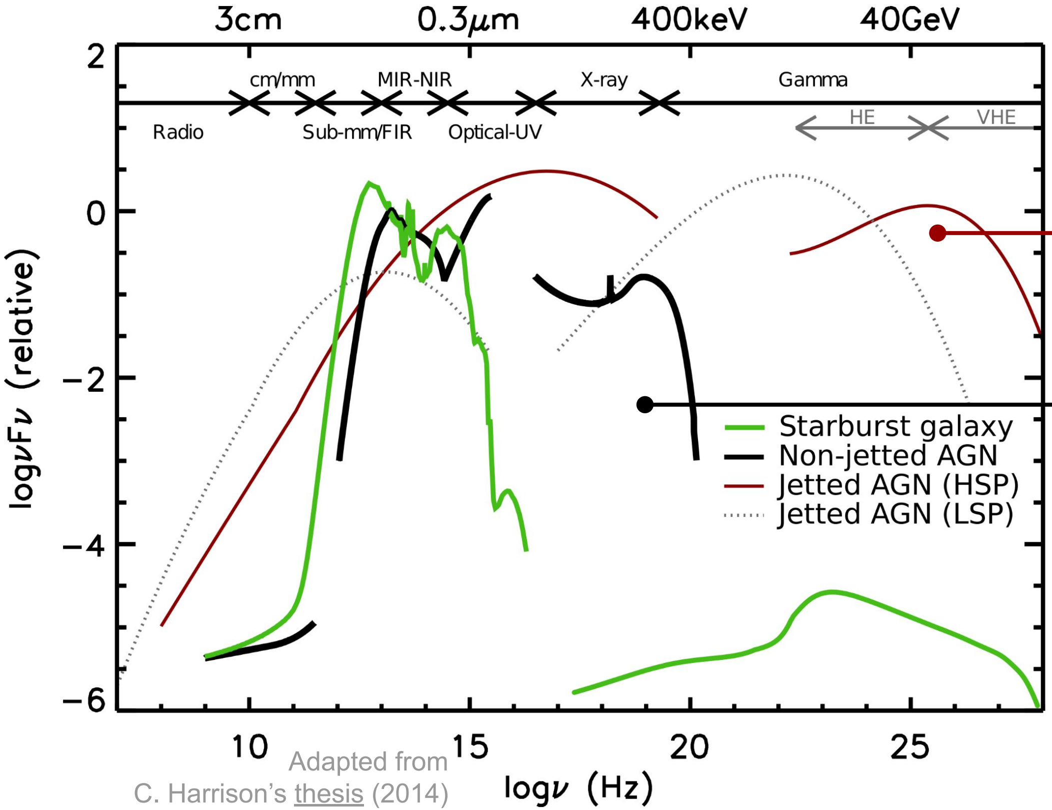


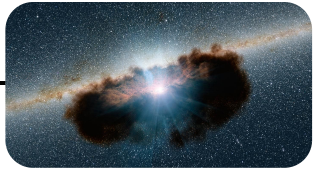
Adapted from
C. Harrison's thesis (2014)

Jetted AGN

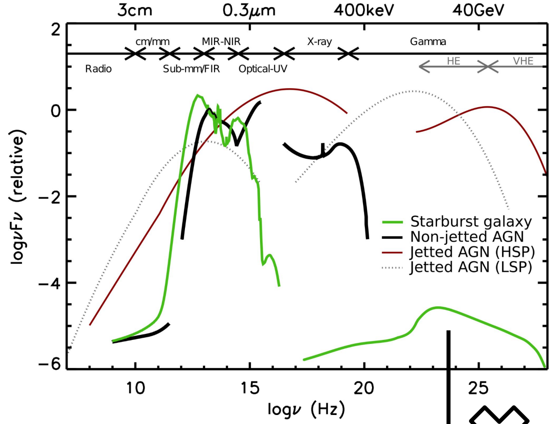
Credits: ESA/NASA/AVO/Padovani

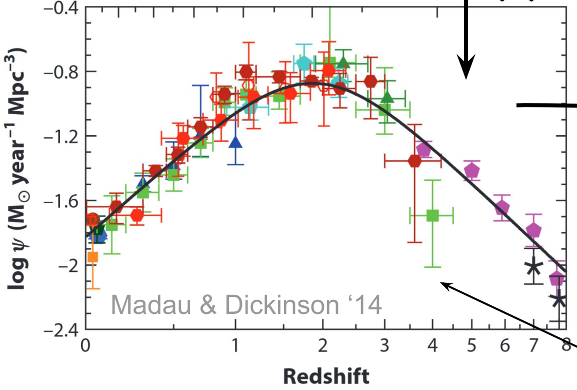
Non-jetted AGN

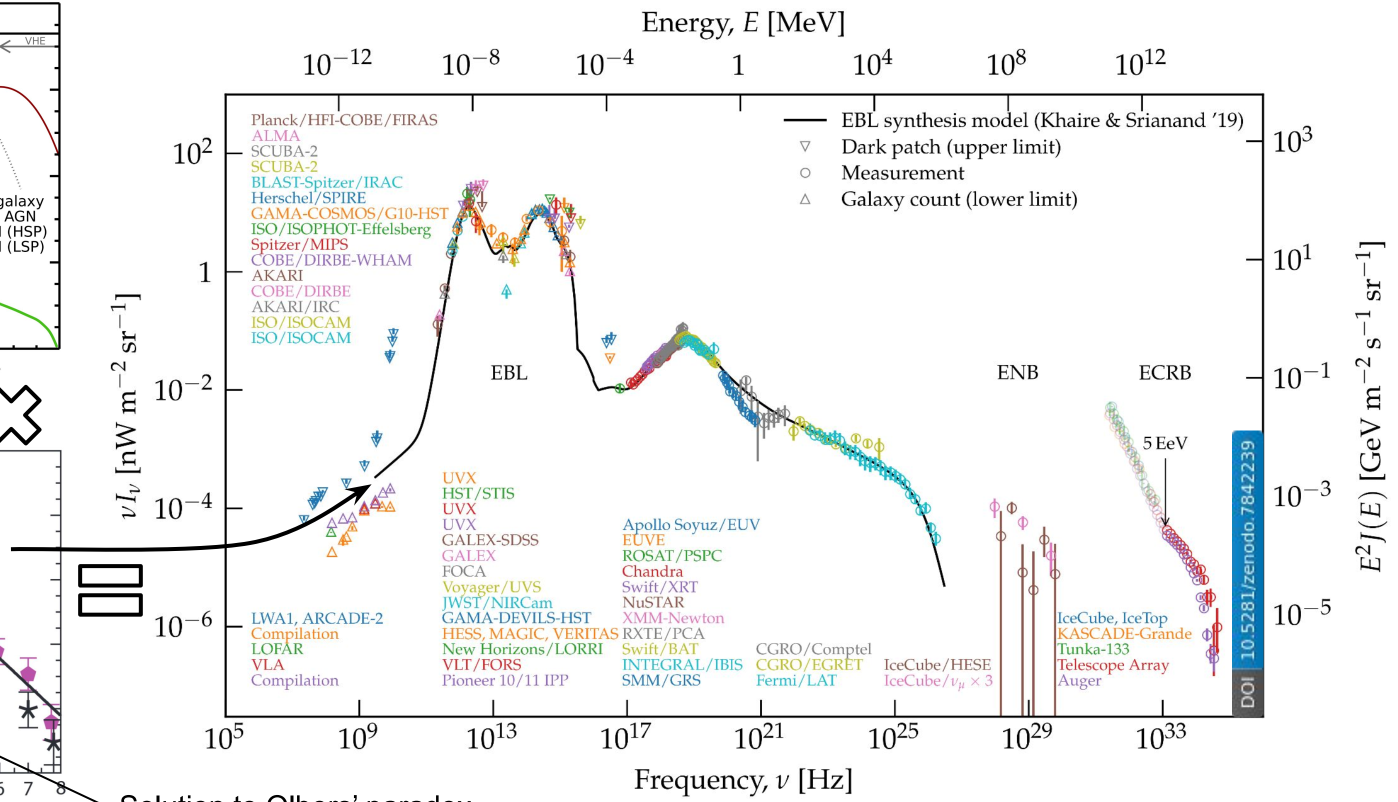
Credits: NASA/JPL-Caltech



Synthesis models of all galaxies

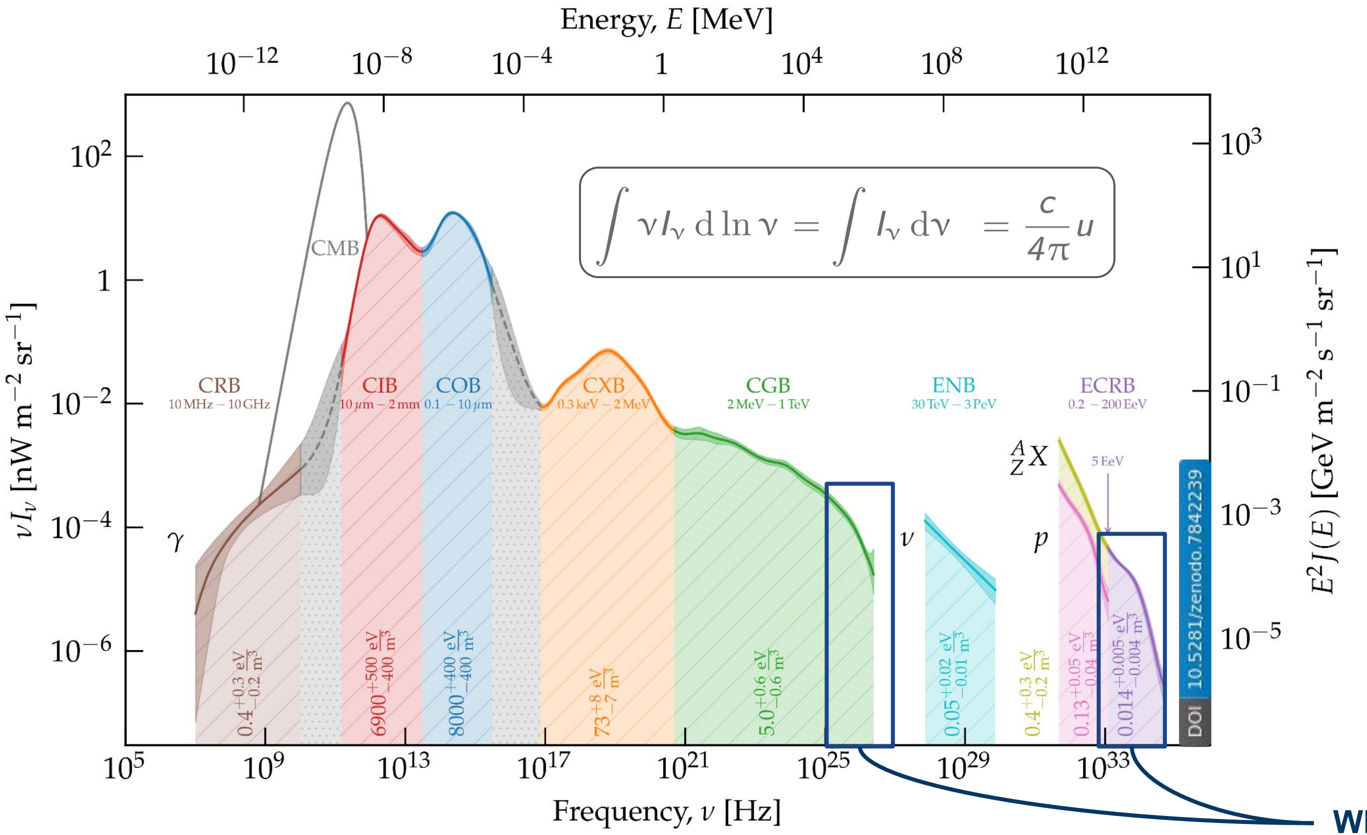


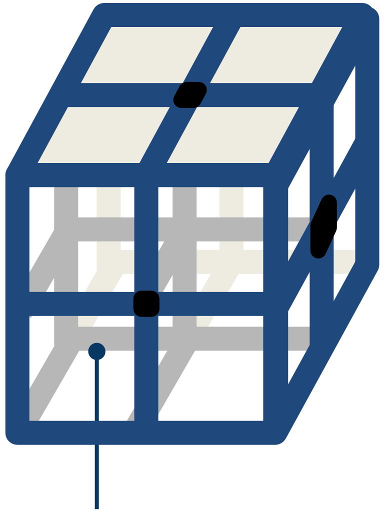




Solution to Olbers' paradox

Their accumulated contributions today





Where propagation matters

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TeV gamma rays

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$$
\begin{aligned}
\frac{\partial n_l}{\partial t} &= \sum_{j=1}^{3} \frac{\partial}{\partial x^j} \left[\left(D_{jk} \cdot \frac{\partial}{\partial x^k} \right) n_l \right] - \sum_{j=1}^{3} \frac{\partial}{\partial x^j} \left[u^j \cdot n_l \right] + \frac{\partial}{\partial p} \left[p^2 \, D_{pp} \, \frac{\partial}{\partial p} \left(\frac{n_l}{p^2} \right) \right] \\
&- \frac{\partial}{\partial p} \left[\dot{p} \, n_l - \frac{p}{3} \left(\nabla \cdot \vec{u} \right) n_l \right] + \sum_{j>l} \frac{v_l}{c} \, n_0 \int dp' \, \sigma_{j \to l}(p, p') \, n_j(p') \\
&- \frac{n_l}{\tau} + Q_l(p) \, .
\end{aligned}
$$

The diffusion-loss equation (Fokker-Planck)

Starting from the Vlasov equation (e.g. review by Becker-Tjus & Merten ‘20)

- ❏ Test particle approach
- ❏ Stationary magnetic field
- ❏ Isotropy in momentum phase space

n ≡ differential number density in phase space

$$
\begin{aligned}
\frac{\partial n_l}{\partial t} \quad = \quad & \sum_{j=1}^{3} \frac{\partial}{\partial x^j} \left[\left(D_{jk} \cdot \frac{\partial}{\partial x^k} \right) n_l \right] - \sum_{j=1}^{3} \frac{\partial}{\partial x^j} \left[u^j \cdot n_l \right] + \frac{\partial}{\partial p} \left[p^2 \, D_{pp} \, \frac{\partial}{\partial p} \left(\frac{n_l}{p^2} \right) \right] \\
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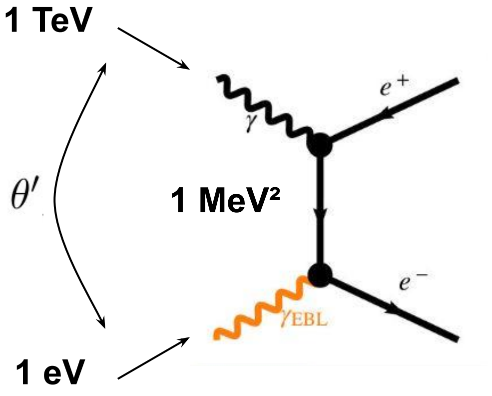
- \quad & \frac{n_l}{\tau} + Q_l(p) \, .
\end{aligned}
$$

Gamma-ray catastrophic losses: pair production on COB/CIB



Optical depth $\tau(E,z) = \int_0^z \mathrm{d}z' \, \frac{\partial L}{\partial z'} \Gamma_{\gamma\gamma}^{-1}(E(1+z'), z')$

Light travel distance (ΛCDM)

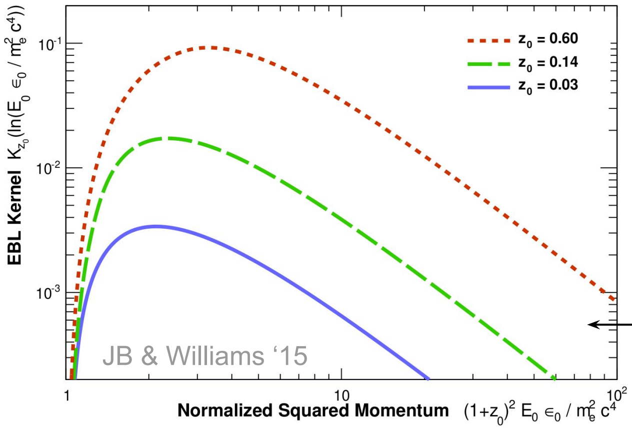
$$\frac{\partial L}{\partial z} = \frac{c}{H_0} \frac{1}{1+z} \frac{1}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}$$

Mean free path (photon density, Breit-Wheeler cross section)

$$\Gamma_{\gamma\gamma}^{-1}(E', z) = \int_0^{+\infty} \mathrm{d}\epsilon \, \frac{\partial n}{\partial \epsilon} \int_{-1}^{1} \mathrm{d}\mu \, \frac{1-\mu}{2} \sigma_{\gamma\gamma}\left[E', \epsilon, \mu\right]$$

where $\mu = 1 - \cos\theta'$

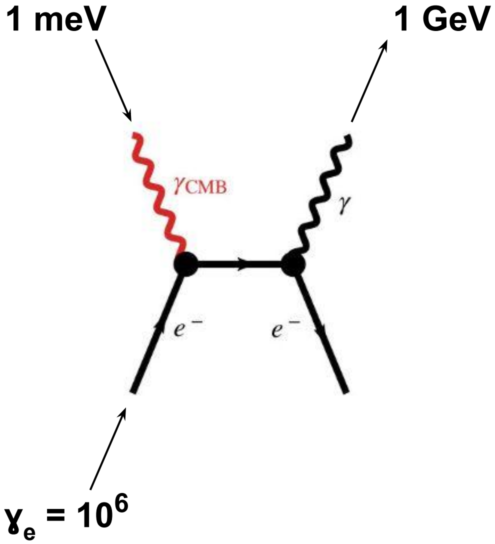
$\rightarrow \Gamma_{\gamma\gamma}(1\,\mathrm{TeV}, z = 0.2) \approx 250\,\mathrm{Mpc}$



Cross-section integrated over the line of sight

Relevant threshold for gamma-rays:
***E* ~ 100 GeV** ↔ ϵ ~ 10 eV (UV bckgd)

Radiative losses of $e^+ e^-$: inverse Compton on CMB



Generation 1: TeV gamma-ray

$$\Gamma_{\gamma\gamma}(1\,\mathrm{TeV}, z = 0.2) \approx 250\,\mathrm{Mpc}$$

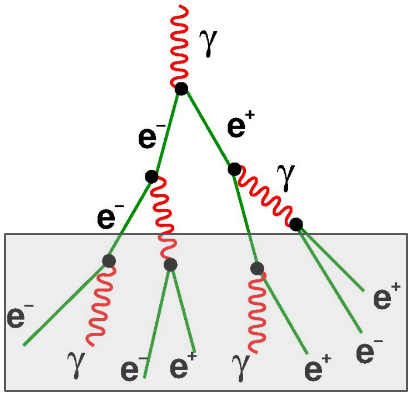
Generation 2: pair $e^+ e^-$

- Diffuse in $\langle B^2 \rangle$
  $r_L(\gamma_e = 10^6) \approx 0.5\,\mathrm{Mpc}(B_{IGM}/10^{-15}\,\mathrm{G})^{-1}$
- Excite electrostatic instability of beam (~ 10^{-22} cm^{-3}) / intergalactic plasma (~ 10^{-7} cm^{-3})
  - ➔ <u>Inefficient *E*-loss mechanism</u> due to
    - ◆ background MeV e^- (Yang+ *ApJ* '24)
    - ◆ non-linear feedback (Alawashra & Pohl *ApJ* '24)
    - ◆ $B > 10^{-17}$ G $(\lambda_B/1\,\mathrm{pc})^{-1/2}$ (Alawashra & Pohl *ApJ* '22)
- Inverse Compton on CMB photons
  $\Gamma_{e\gamma}(\gamma_e = 10^6) \approx 0.75\,\mathrm{Mpc}$

Generation 3: GeV gamma-ray → stop

$$E_1 = \frac{4}{3}\gamma_e^2 \epsilon_{\mathrm{CMB}} \approx 1\,\mathrm{GeV}\left(\frac{E_0}{1\,\mathrm{TeV}}\right)^2$$

em cascade



4th generation if
E_0 ~ 10 TeV (plausible)

5th generation if
E_0 ~ 100 TeV
→ unobserved &
Klein-Nishina suppressed

Continuous losses of protons: p-ɣ on the CMB

$$p + \gamma \to p + e^+ + e^-$$
$$\to p + \pi^0$$
$$\to n + \pi^+$$

Threshold for π photoproduction

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

Note: p @ 50 EeV → *unobserved*

Center of mass

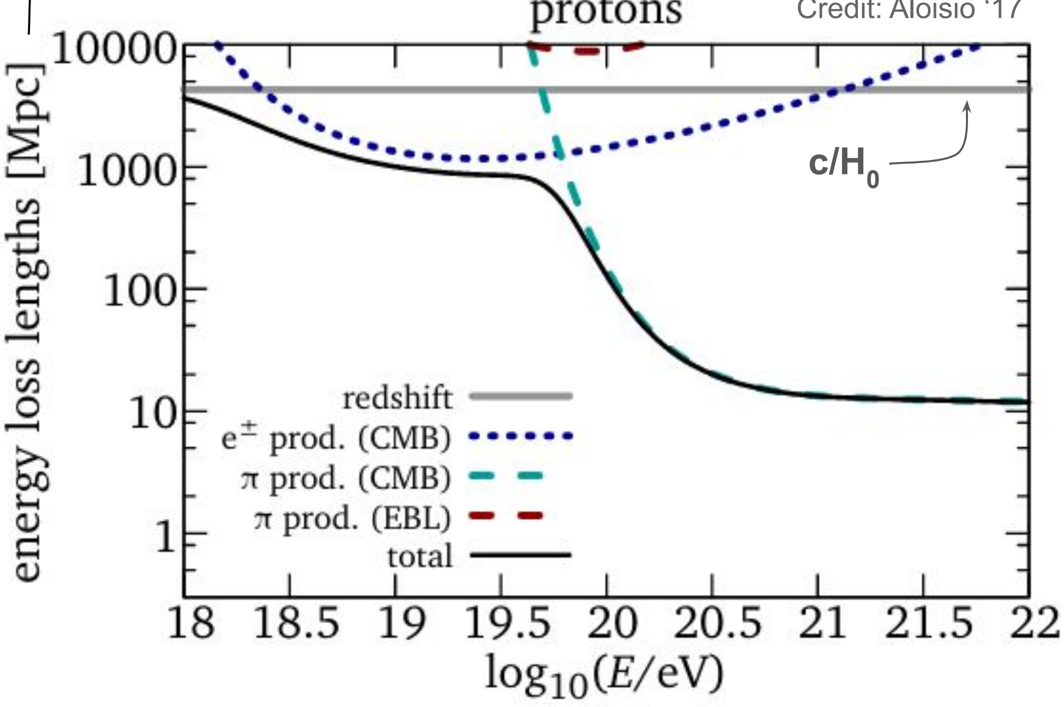
(50 EeV x 1 meV)$^{1/2}$ ~ 0.2 GeV

Neutron = proton in the IGM

$\gamma c\tau$ ~ 10 kpc x (E / 1 EeV)

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

Credit: Aloisio '17



Catastrophic losses of nuclei: photo-erosion/disintegration

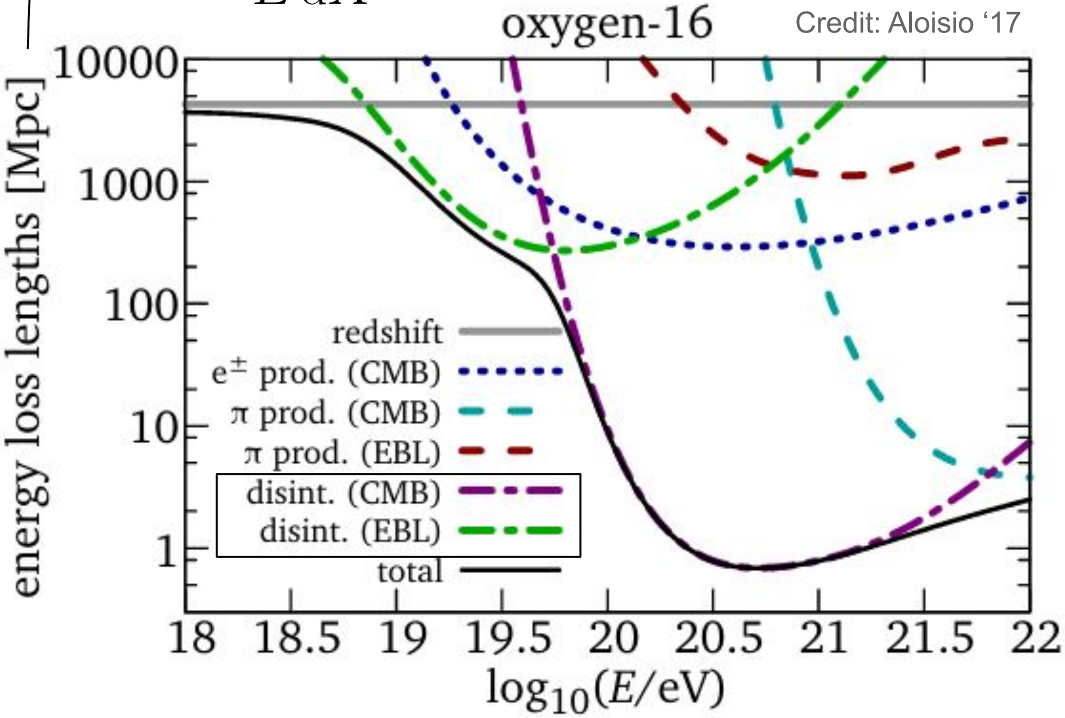
$$^{A}_{Z}X + \gamma \rightarrow ^{A-a-b}_{Z-b}Y + an + bp$$

Photo-erosion driven by

- ϵ_γ' ~ 10 MeV: giant dipole resonance
  $\rightarrow \lambda_\gamma$ ~ 0.5 mm (CMB) for E_X/A ~ 2 EeV
- ϵ_γ' ~ 30 MeV: quasi-deuteron process
- ϵ_γ' > 150 MeV: baryon resonance
  $\rightarrow \lambda_\gamma$ ~ 30 μm (CIB) for E_X/A ~ 2 EeV

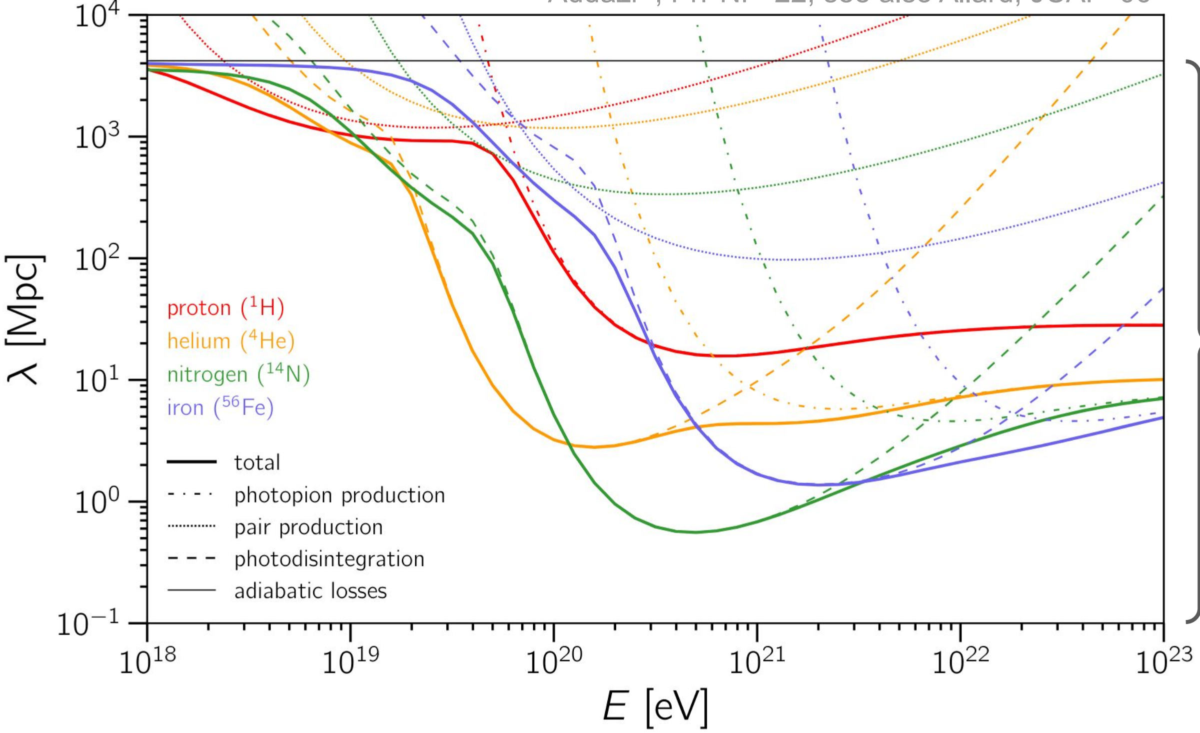
Lower energy nuclei and protons
→ with Lorentz boost nearly conserved

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

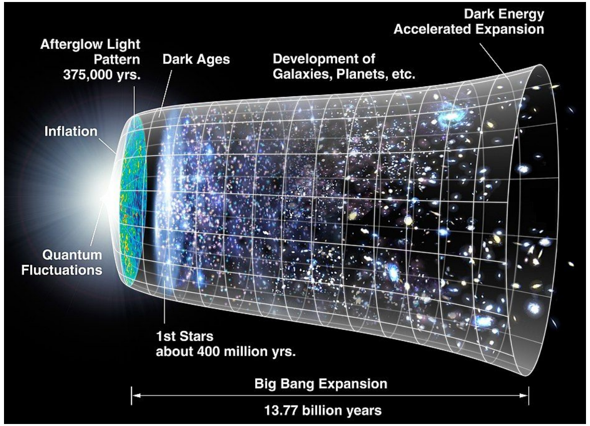


Cosmic-ray propagation on extragalactic scales

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



D_T ~ 14 Gyr



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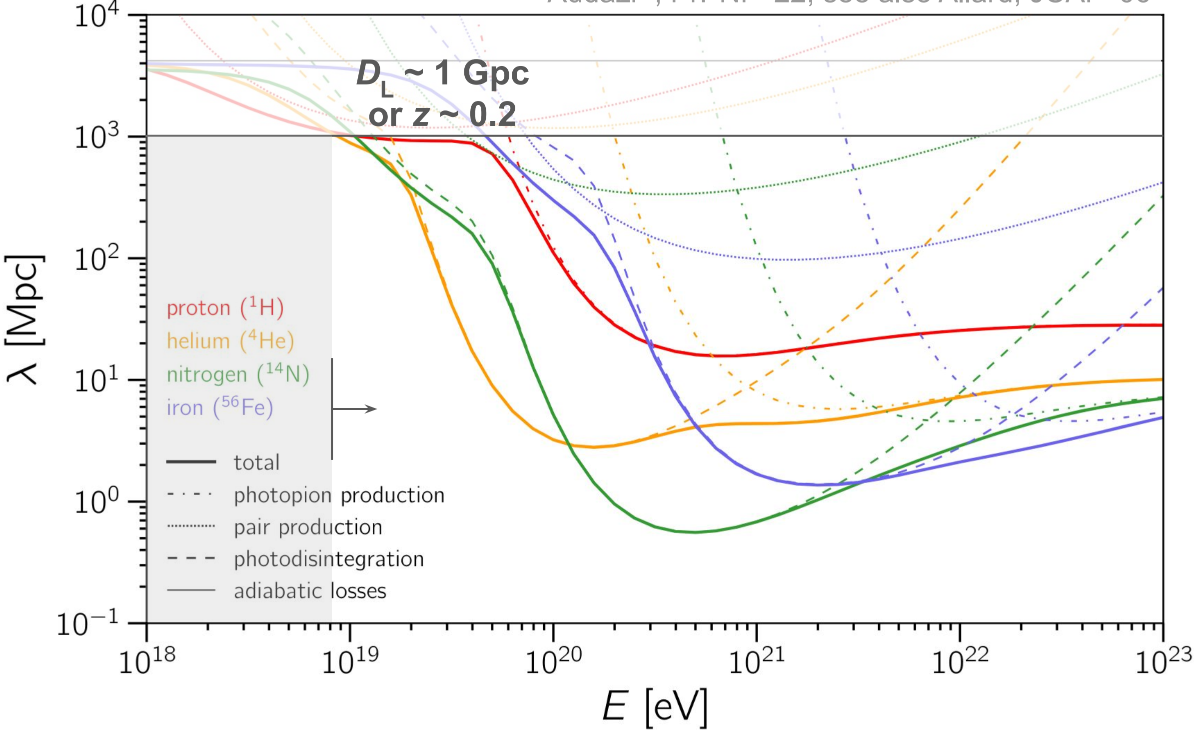
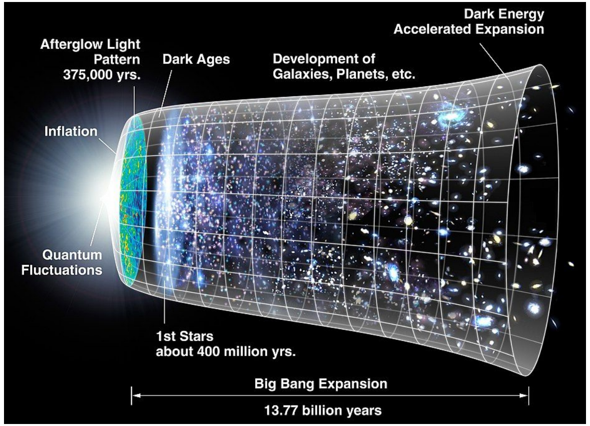


D_L ~ 1 Gpc
or D_T ~ 2.5 Gyr



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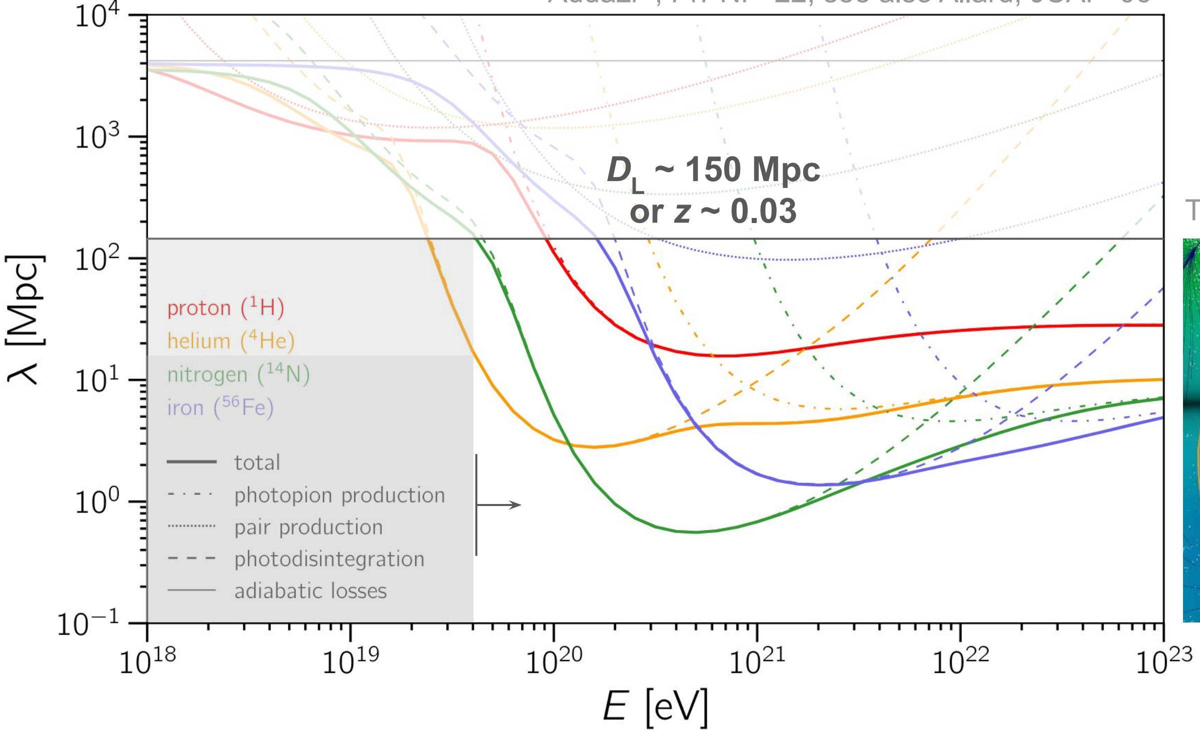
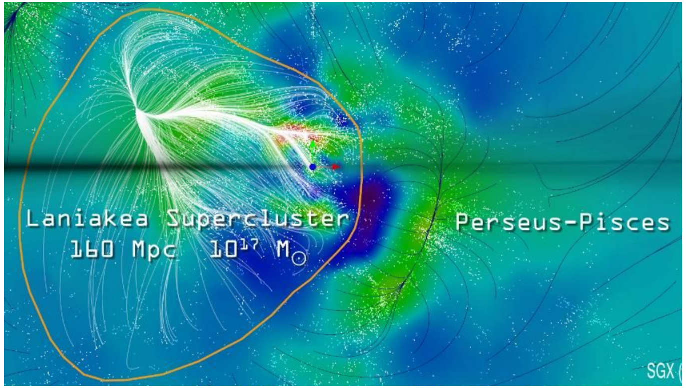


Tully+, Nature ‘14



Cosmic-ray propagation on extragalactic scales

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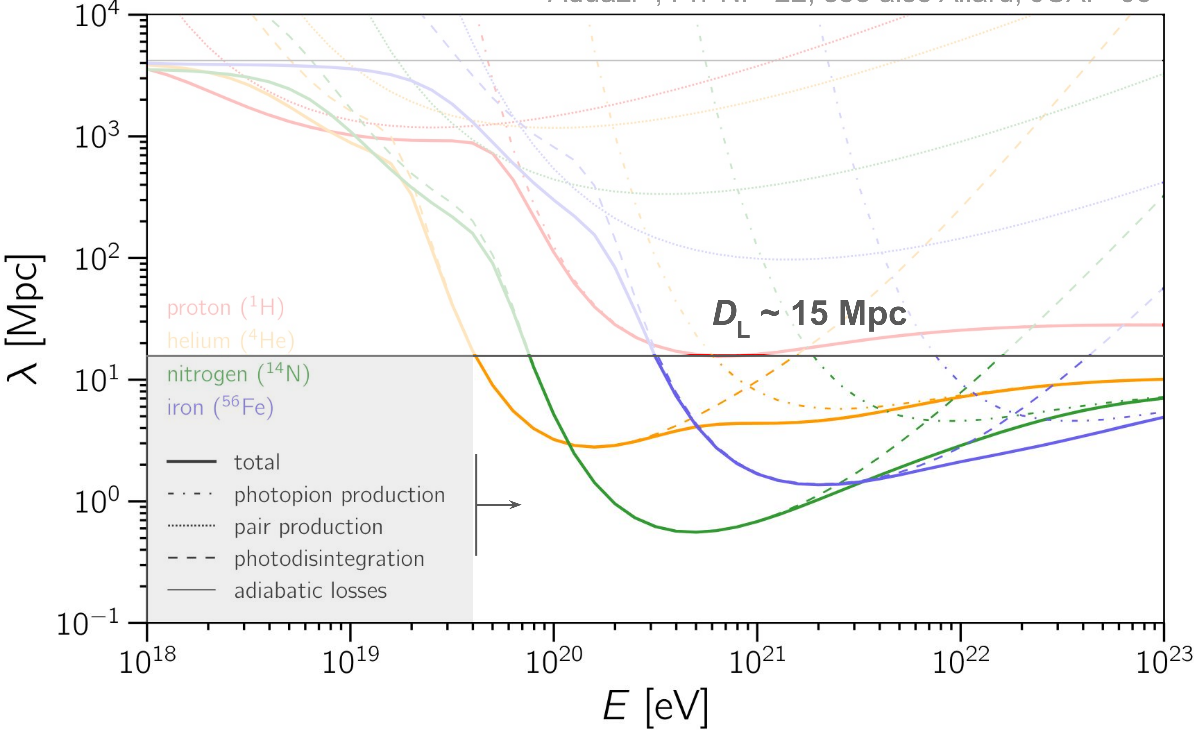
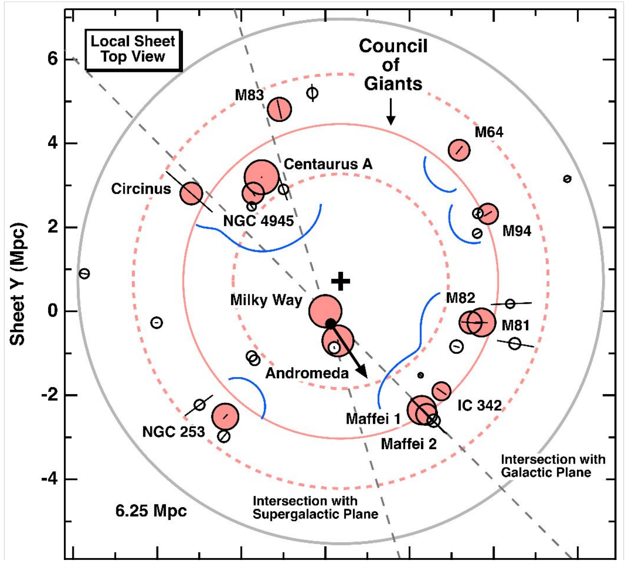


McCall, MNRAS '14



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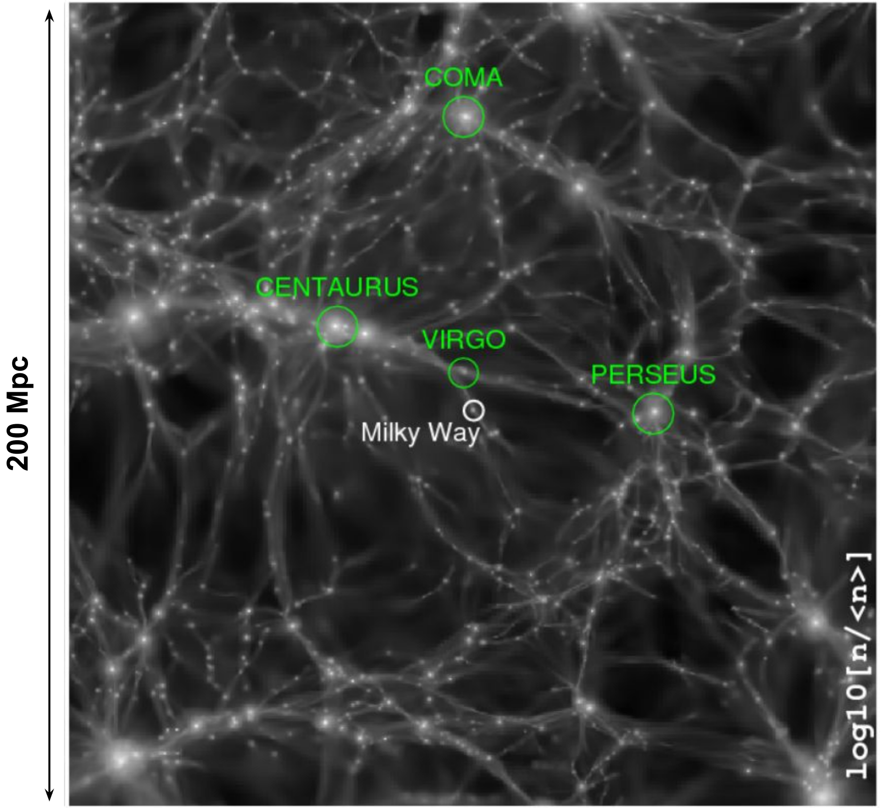
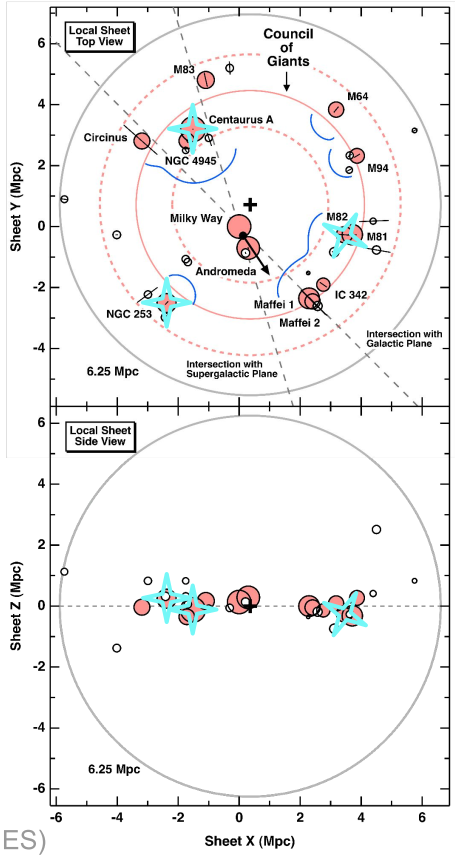
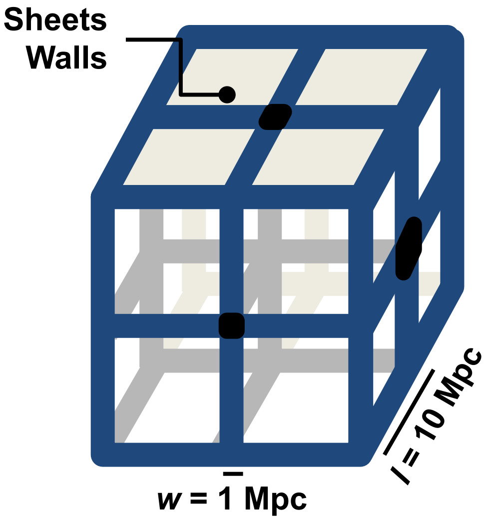
Cosmic web: relevant scales

TeV emitter



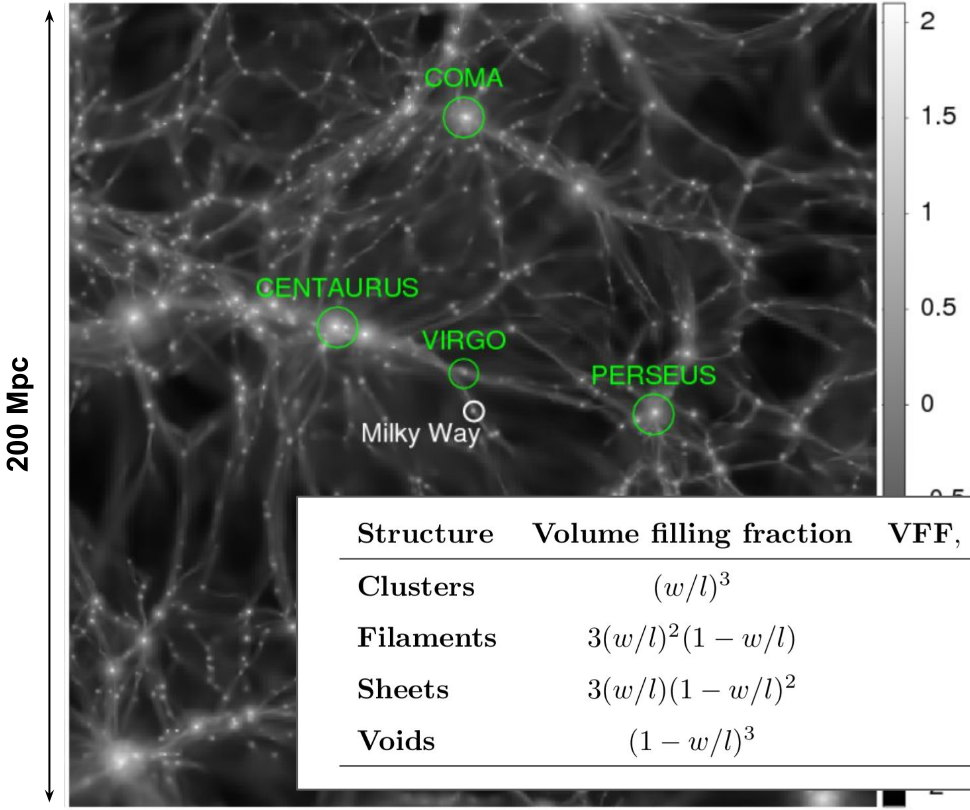
Credit: Hackstein+ *MNRAS* '18 (Cosmic V-web constrained sim. / CLUES)



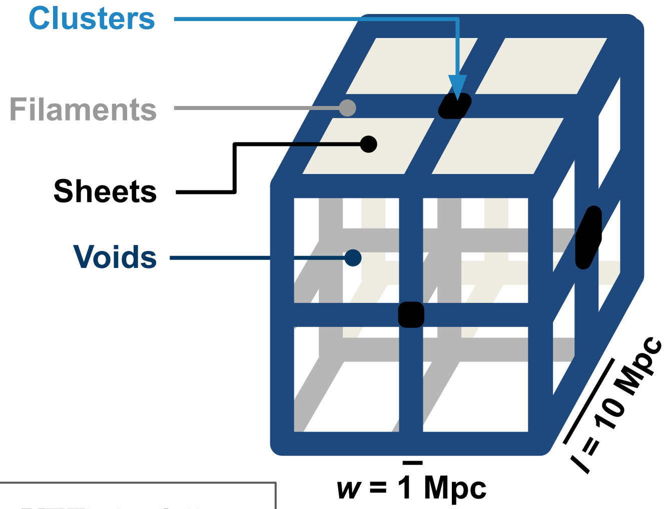


Credit: McCall *MNRAS* '14 (The Council of Giants)

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%

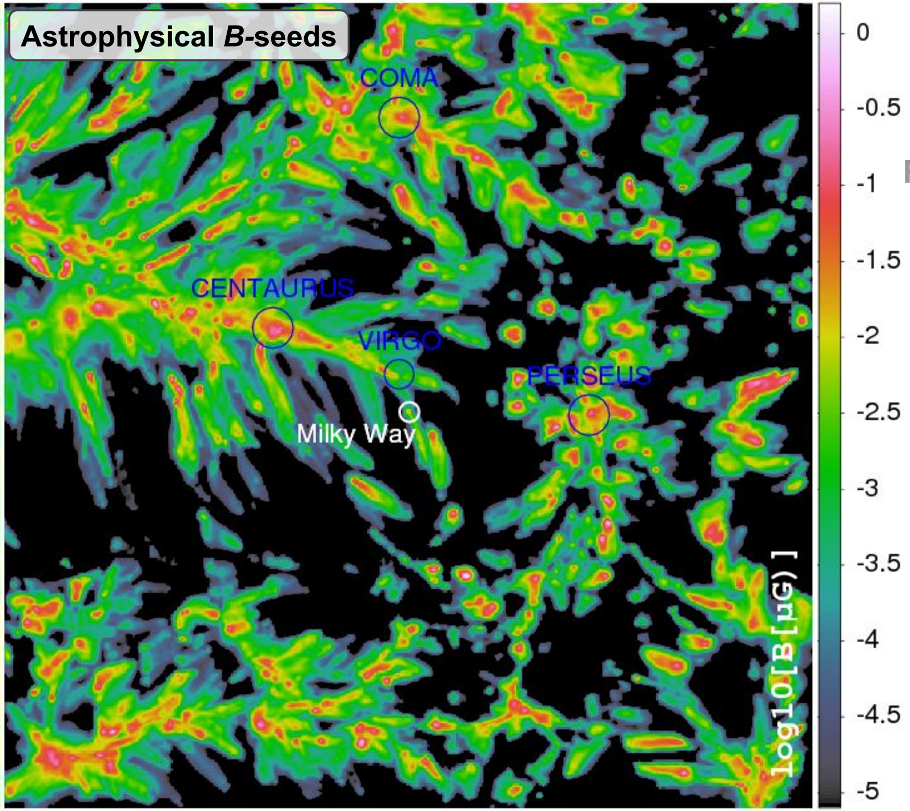


Credit: Oei+ *A&A* '22

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

Cosmic web: magnetic fields

200 Mpc



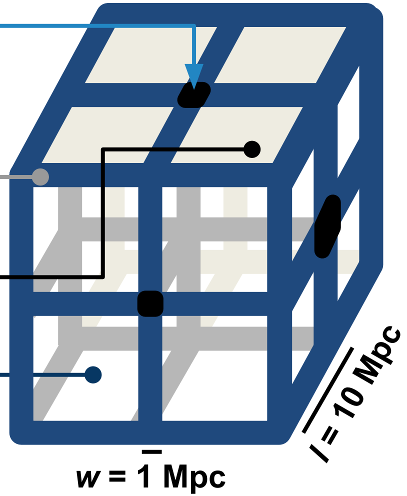
Credit: Hackstein+ *MNRAS* '18 (Cosmic V-web constrained sim. / CLUES)

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

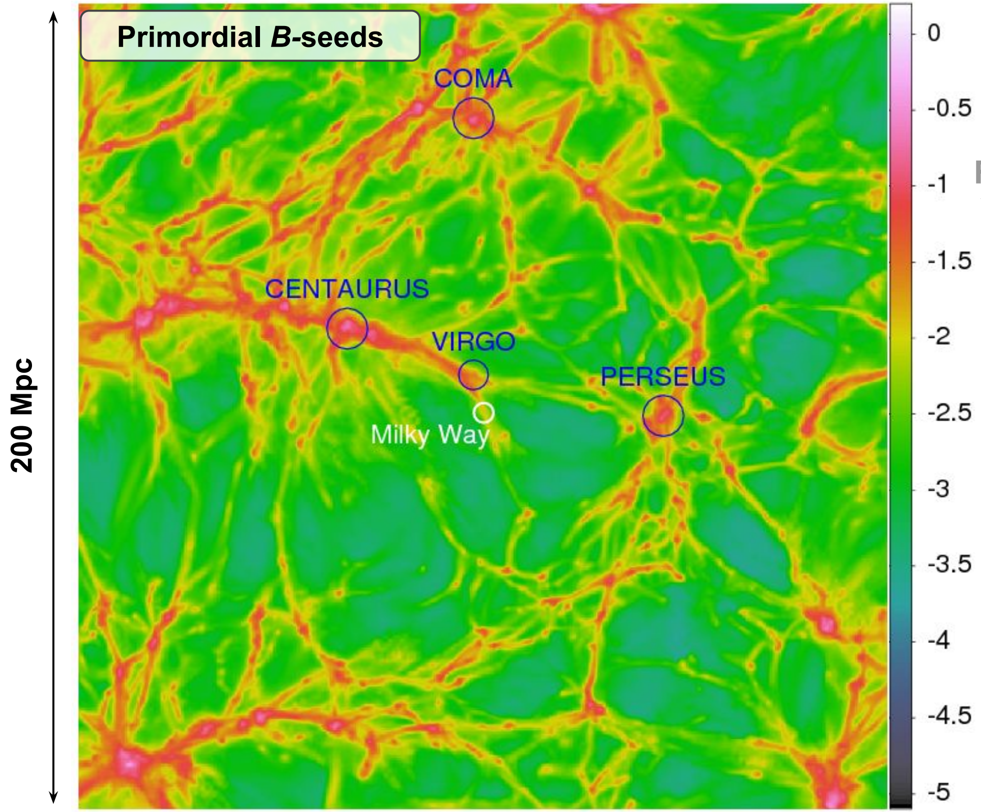
Filaments: *B* ~ 10-100 nG
Vernstrom+ '21, Carretti+ '22

Sheets: *B* ~ 1-10 nG?

Voids: *B* < 10 pG
Jedamzik & Saveliev '19



Cosmic web: magnetic fields



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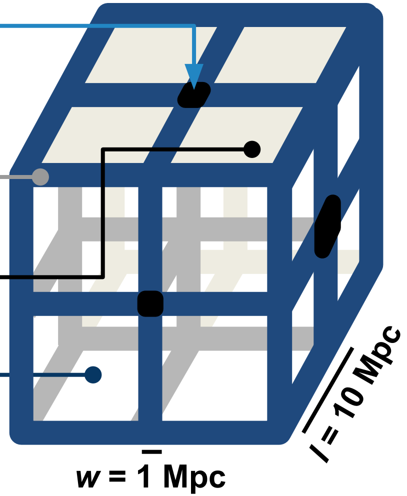
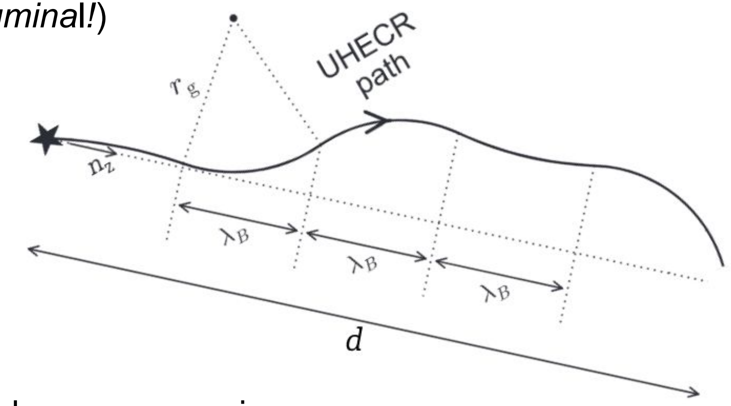


Credit: Hackstein+ *MNRAS* '18 (Cosmic V-web constrained sim. / CLUES)

Cosmic-ray propagation in a turbulent magnetic field

- ❏ From first principles, assuming a quasi-static turbulent *B*-field: $\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}s} = \hat{\boldsymbol{n}} \ , \quad \frac{\mathrm{d}\hat{\boldsymbol{n}}}{\mathrm{d}s} = \left(\frac{Ze|\boldsymbol{B}|}{E}\right) \hat{\boldsymbol{n}} \times \hat{\boldsymbol{b}} \ .$
- ❏ Treatment of propagation using stochastic differential equation
  (see Achterberg+ ‘99, Marafico’s thesis - chap. 6, App. B)
- ❏ Signal delayed by τ_{del}, temporally spread by $\Delta\tau = \tau_{\mathrm{del}} \sqrt{2}$ (*superluminal!*)
- ❏ Angularly spread by $\Delta\theta$

Credit: Bray & Scaife *ApJ* ‘18



$$\Delta\tau = \frac{\sqrt{2}\lambda_B}{9c}\left(\frac{cBd}{R}\right)^2$$

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

$$\Delta\theta = \frac{2}{3}\frac{cB\sqrt{\lambda_B d}}{R}$$

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

} ultra-high energy cosmic rays in the Local Sheet

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 $\theta_{\text{obs, UHECR}} \sim \Delta\theta_{\text{Local Sheet}}$

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

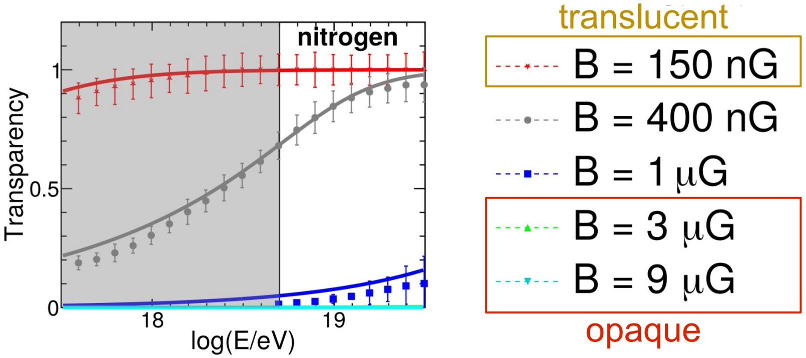
Galaxy filaments: *B* ~ 10-100 nG

➔ **Translucent** to UHE nuclei

➔ No need for specific treatment

Galaxy clusters: *B* ~ 1-10 μG

➔ Calorimeters for UHE nuclei



Condorelli, JB, Adam, ApJ '23

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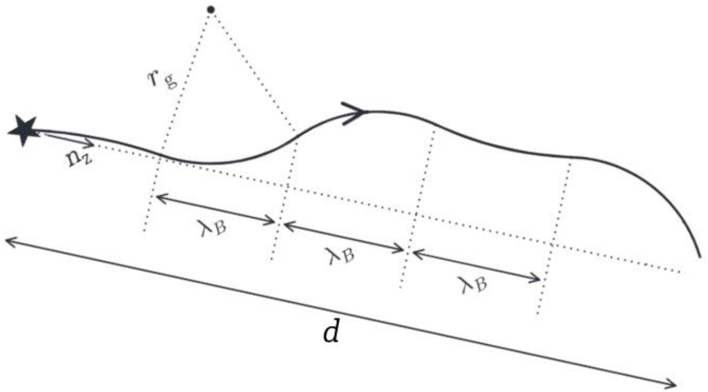
- ❑ Angularly spread by $\Delta\theta$

Credit: Bray & Scaife *ApJ* '18



$$\Delta\tau = \frac{\sqrt{2}\lambda_B}{9c}\left(\frac{cBd}{R}\right)^2$$

$$= 100\,\mathrm{kyr} \times \left(\frac{B}{10^{-15}\,\mathrm{G}}\right)^2 \left(\frac{R}{0.5\,\mathrm{TeV}}\right)^{-2} \left(\frac{d}{0.75\,\mathrm{Mpc}}\right)^2 \left(\frac{\lambda_B}{0.1\,\mathrm{Mpc}}\right)$$

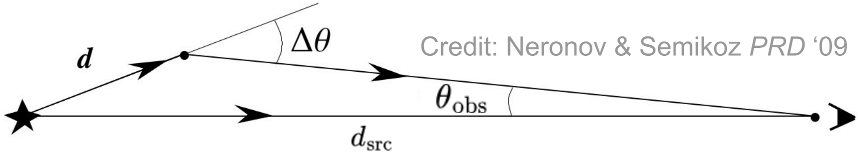
$$\Delta\theta = \frac{2}{3}\frac{cB\sqrt{\lambda_B d}}{R}$$

$$= 20^\circ \times \left(\frac{B}{10^{-15}\,\mathrm{G}}\right) \left(\frac{R}{0.5\,\mathrm{TeV}}\right) \left(\frac{d}{0.75\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{\lambda_B}{0.1\,\mathrm{Mpc}}\right)^{1/2}$$

} electrons from TeV gamma-rays in voids

Cosmic-ray propagation in a turbulent magnetic field

- From first principles, assuming a quasi-static turbulent *B*-field: $\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}s} = \hat{\boldsymbol{n}} \quad , \quad \frac{\mathrm{d}\hat{\boldsymbol{n}}}{\mathrm{d}s} = \left(\frac{Ze|\boldsymbol{B}|}{E}\right) \hat{\boldsymbol{n}} \times \hat{\boldsymbol{b}} \,.$
- Treatment of propagation using stochastic differential equation
  (see Achterberg+ '99, Marafico's thesis - chap. 6, App. B)
- Signal delayed by $\tau_{\rm del}$, temporally spread by $\Delta\tau = \tau_{\rm del}\sqrt{2}$
- Angularly spread by $\Delta\theta$



Credit: Neronov & Semikoz *PRD* '09

$$\Delta\tau = \frac{\sqrt{2}\lambda_B}{9c}\left(\frac{cBd}{R}\right)^2$$

$$= 100\,\mathrm{kyr} \times \left(\frac{B}{10^{-15}\,\mathrm{G}}\right)^2 \left(\frac{R}{0.5\,\mathrm{TeV}}\right)^{-2} \left(\frac{d}{0.75\,\mathrm{Mpc}}\right)^2 \left(\frac{\lambda_B}{0.1\,\mathrm{Mpc}}\right)$$

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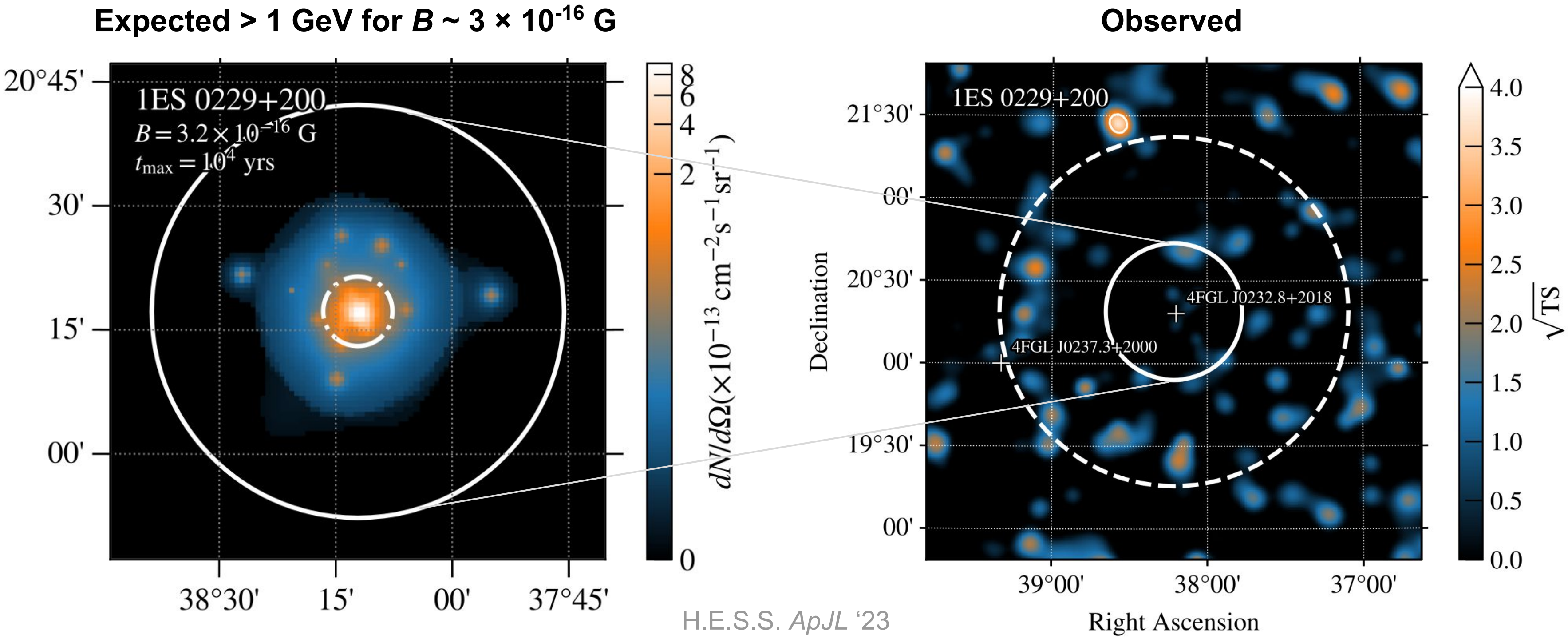
} electrons from TeV gamma-rays in voids

secondary gamma-rays from these electrons

$$\theta_{\rm obs} \approx \Delta\theta \times \frac{d}{d_{\rm src} - d}$$

$$\approx 1' \times \left(\frac{\Delta\theta}{20^\circ}\right) \left(\frac{d}{0.75\,\mathrm{Mpc}}\right) \left(\frac{d_{\rm src}}{1\,\mathrm{Gpc}}^{-1}\right)$$

Voids


Expected > 1 GeV for *B* ~ 3 × 10^-16 G
1ES 0229+200
B = 3.2 × 10^-16 G
t_max = 10^4 yrs
20°45'
30'
15'
00'
38°30'
15'
00'
37°45'
dN/dΩ(×10^-13 cm^-2 s^-1 sr^-1)
8
6
4
2
0
Observed
1ES 0229+200
21°30'
00'
20°30'
00'
19°30'
00'
4FGL J0232.8+2018
4FGL J0237.3+2000
Declination
39°00'
38°00'
37°00'
Right Ascension
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
√TS
H.E.S.S. ApJL '23

Intro

astroparticles & cosmic backgrounds

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deflections, delays and spreads

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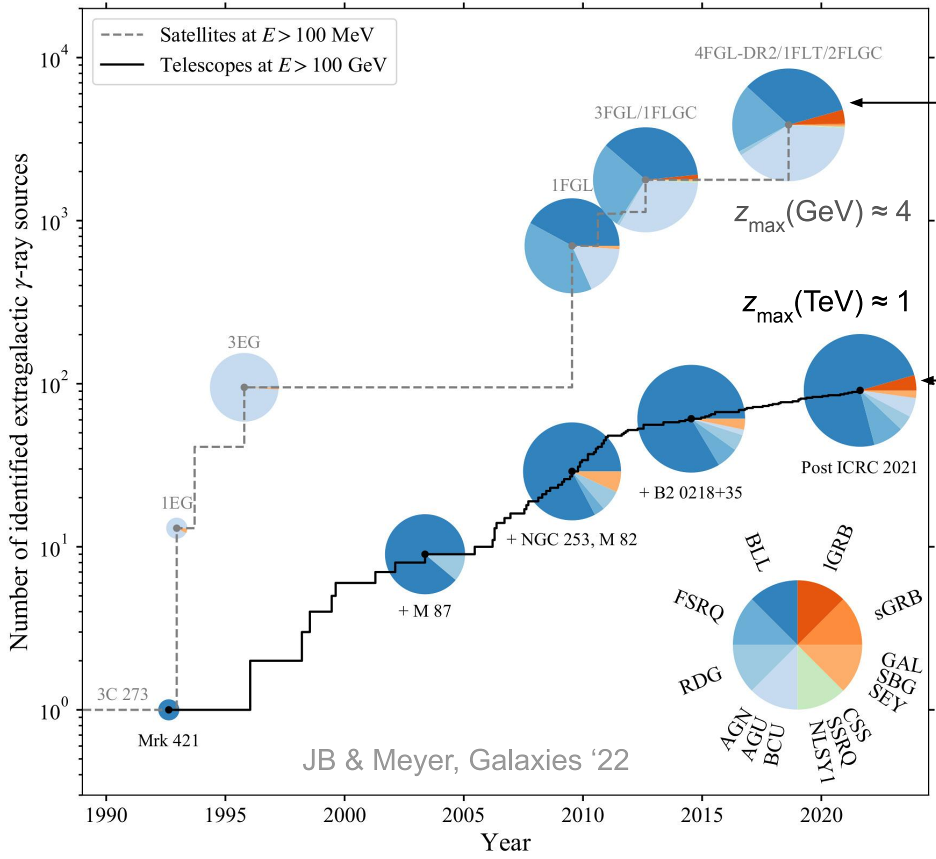
TeV gamma rays

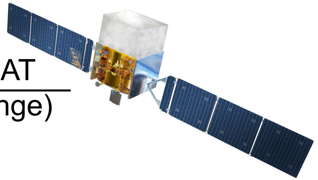
EeV nuclei

Outro

summary & open questions

Known extragalactic sources of gamma rays

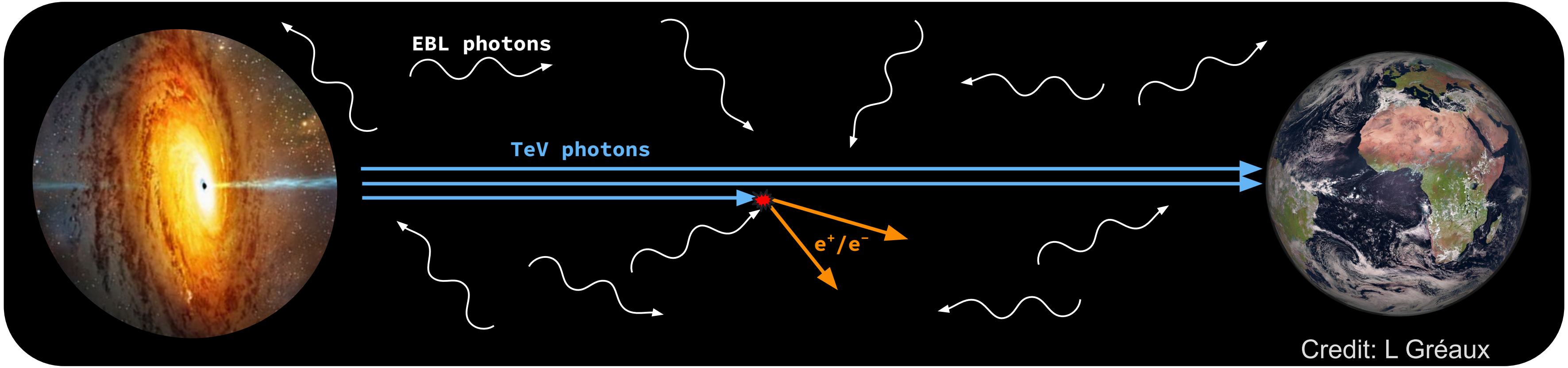


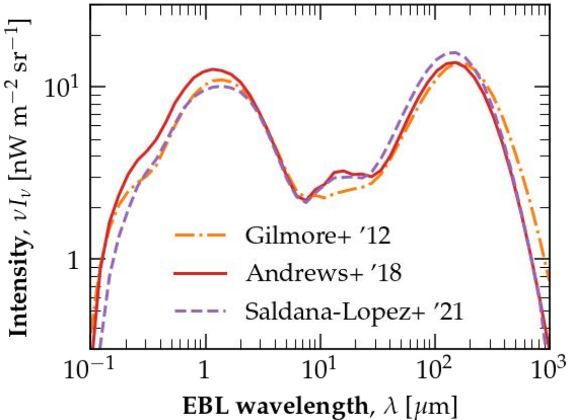


Fermi-LAT
(GeV range)

HESS, MAGIC, VERITAS
(TeV range)

Signature of the COB/CIB in gamma-ray spectra



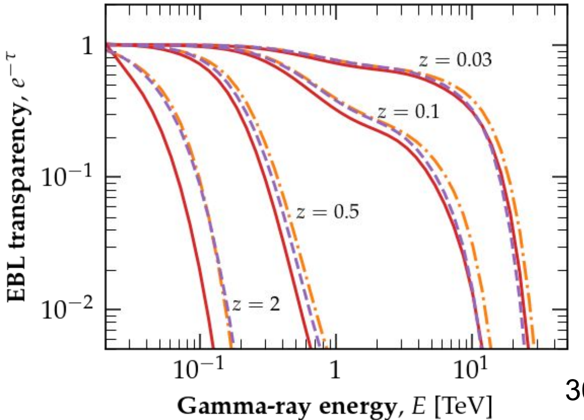


TeV gamma-ray suppression

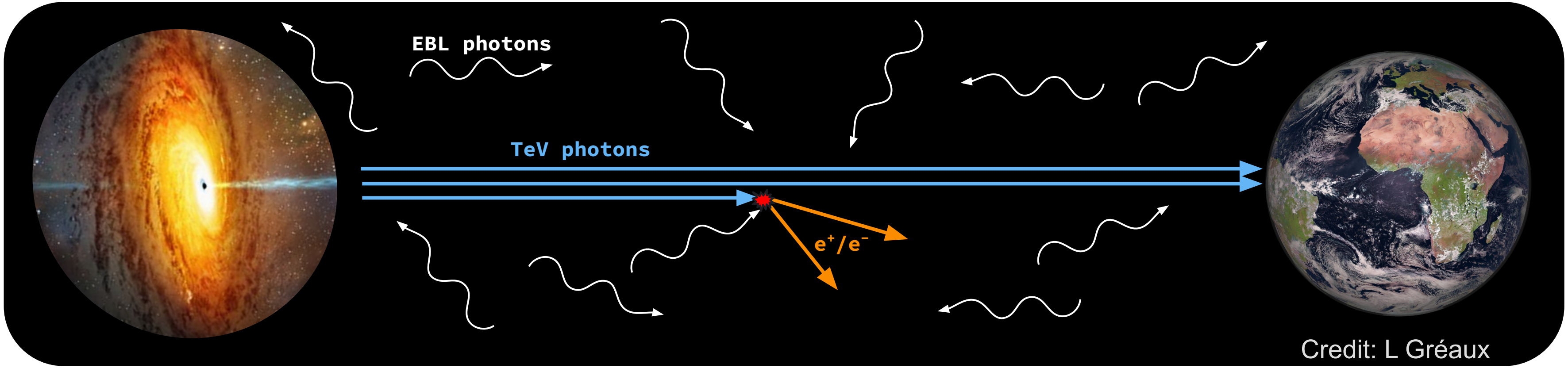
$$\Phi_{\rm obs} = \Phi_{\rm int} \times e^{-\tau}$$

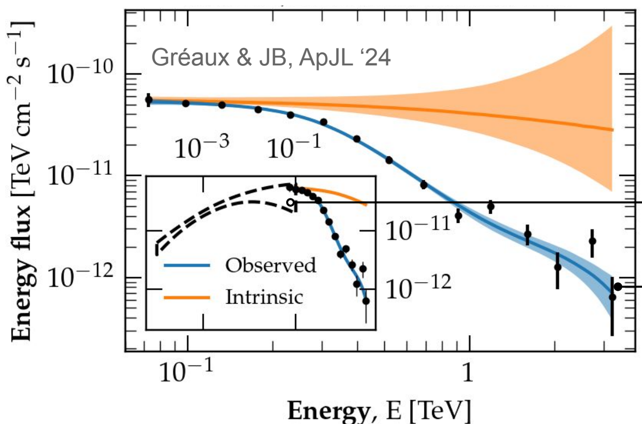
with

$$\tau(E_\gamma, z_0) = \int_0^{z_0} \mathrm{d}z \, \frac{\partial L}{\partial z}(z) \int_0^\infty \mathrm{d}\epsilon \, \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} \mathrm{d}\mu \, \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E_\gamma(1+z), \epsilon, \mu)$$



Signature of the COB/CIB in gamma-ray spectra





TeV gamma-ray suppression

$$\Phi_{\mathrm{obs}} = \Phi_{\mathrm{int}} \times e^{-\tau}$$

Fermi-LAT
(GeV range)

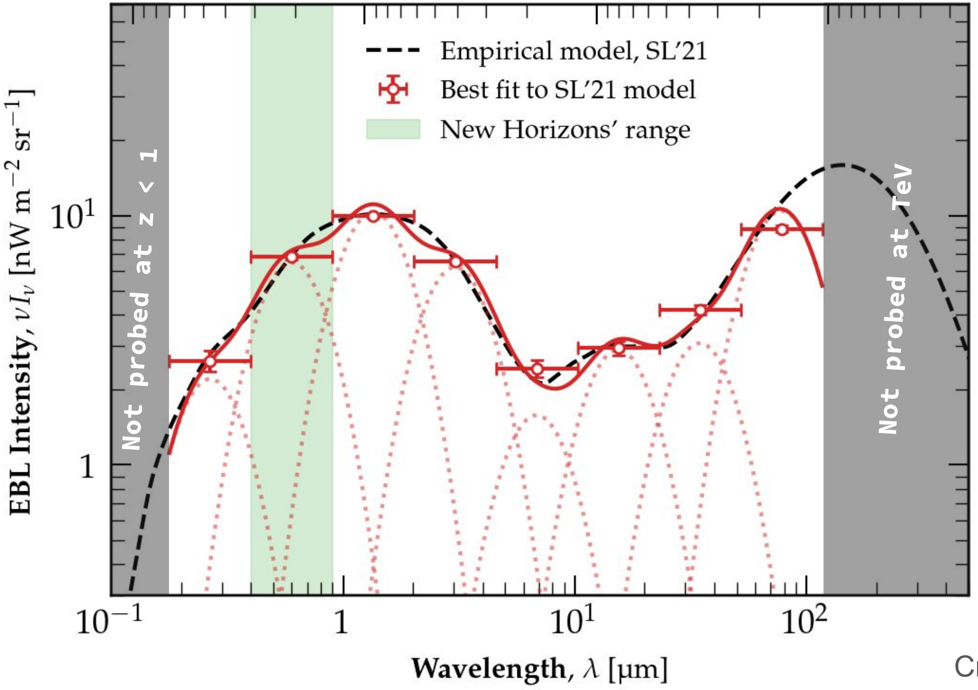
HESS, MAGIC, VERITAS
(TeV range)

Dataset and analysis

Gréaux, JB, Nievas Rosillo, **ApJL 2024**

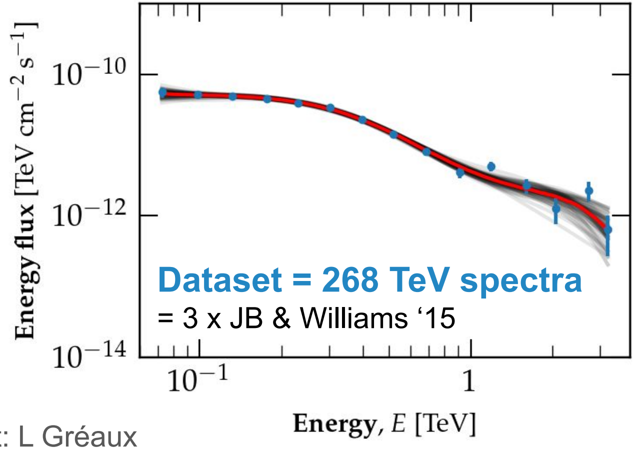
Parameters: α (EBL), Θ (intrinsic spectra)

$$\phi_{\rm m}(E, z, \Theta, a) = \phi_{\rm ELP}(E, \Theta) \times e^{-\tau_{\rm m}(E,z,a)} \quad \text{with} \quad \phi_{\rm ELP}(E, \Theta) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\log\left(\frac{E}{E_0}\right)} e^{-\lambda E}$$



Marginalization:

$$\mathbf{Pr}(a|\mathcal{D}) = \int \mathrm{d}\Theta\, \mathbf{Pr}(a, \Theta|\mathcal{D})$$



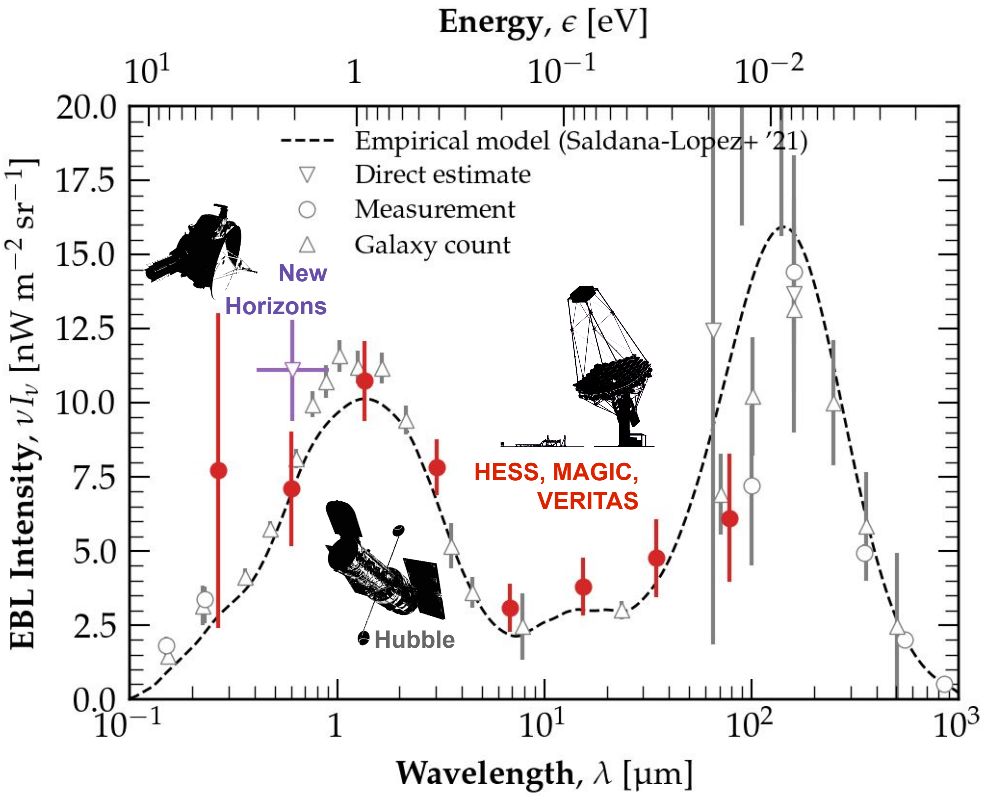
Dataset = 268 TeV spectra

= 3 x JB & Williams ‘15

Credit: L Gréaux

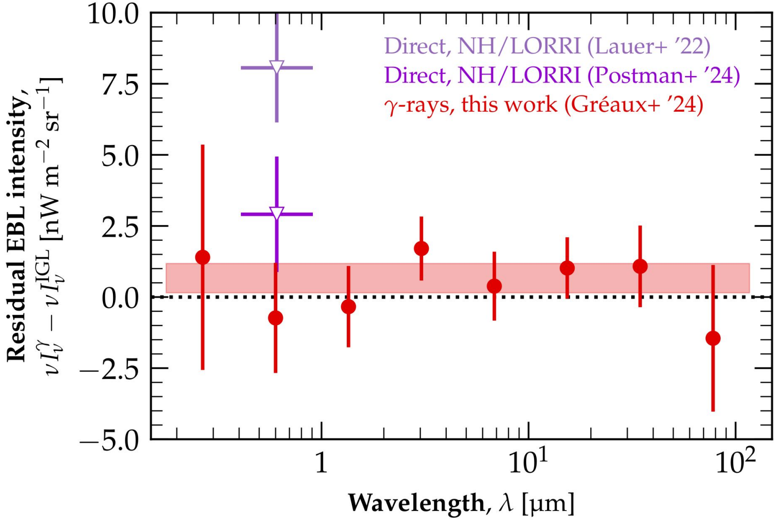
The cosmological optical convergence

Gréaux, JB, Nievas Rosillo, **ApJL 2024**



Good match: probe of H_0 within ± 10%

as $\tau_{\gamma\gamma} \propto I_{EBL} \times c / H_0 = (1+f_{diff}) \times I_{IGL} \times c / H_0$



Search for the $e^+ e^-$ reprocessed energy

Discovery of extreme TeV blazars in 2006

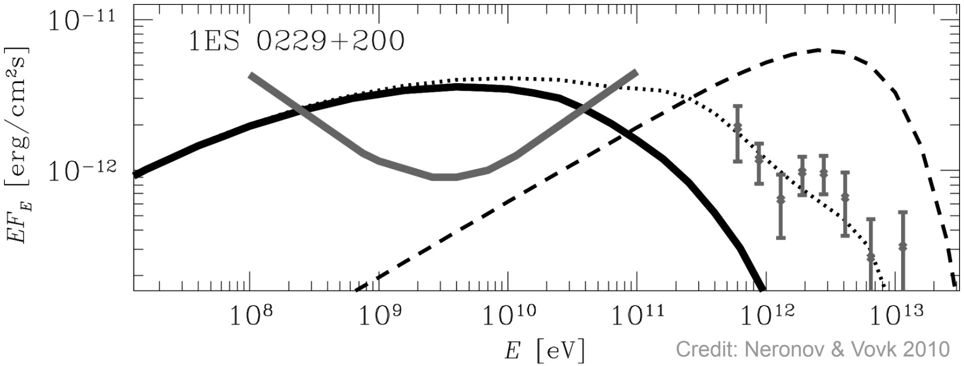
Hard TeV photon spectrum when corrected for absorption

Intrinsic emission expected to be faint in the GeV band

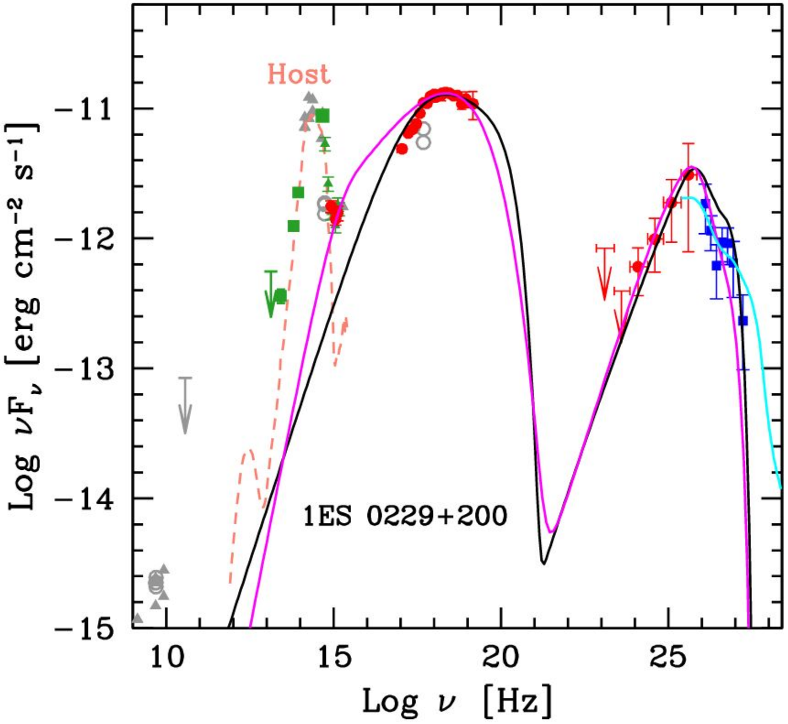
Reprocessed emission?

None in 2010 within point spread function

⇒ **minimum *B*-field needed to spread out the signal**



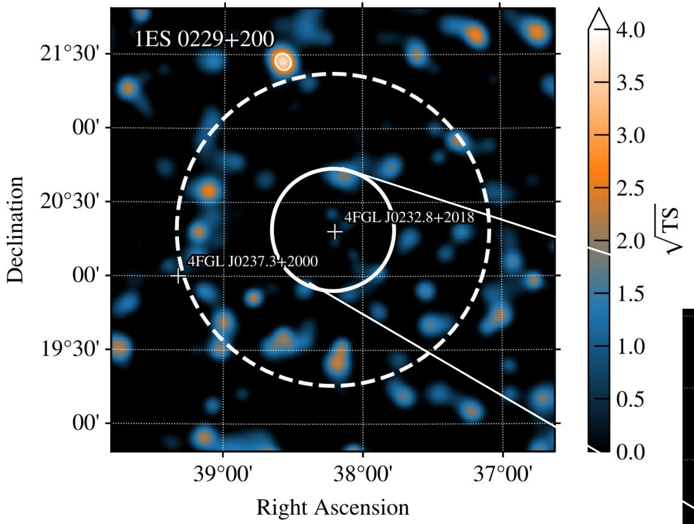
Credit: Neronov & Vovk 2010



Credit: JB+ 2020

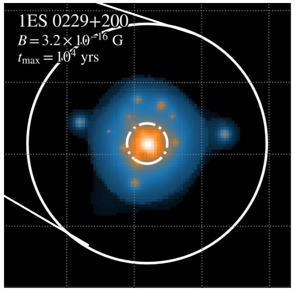
Search for the e⁺ e⁻ reprocessed energy

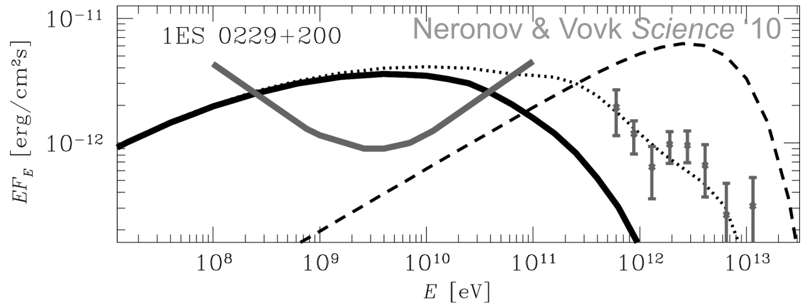
Observed

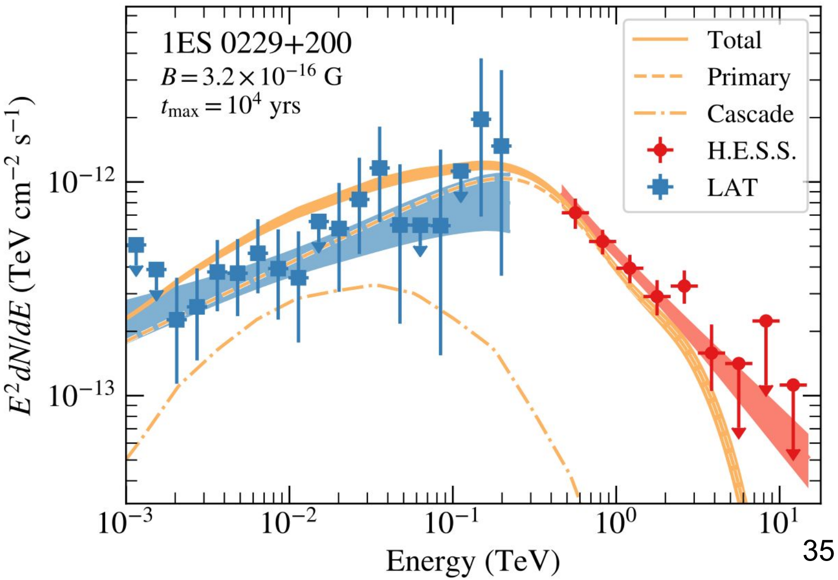


H.E.S.S. *ApJL* '23

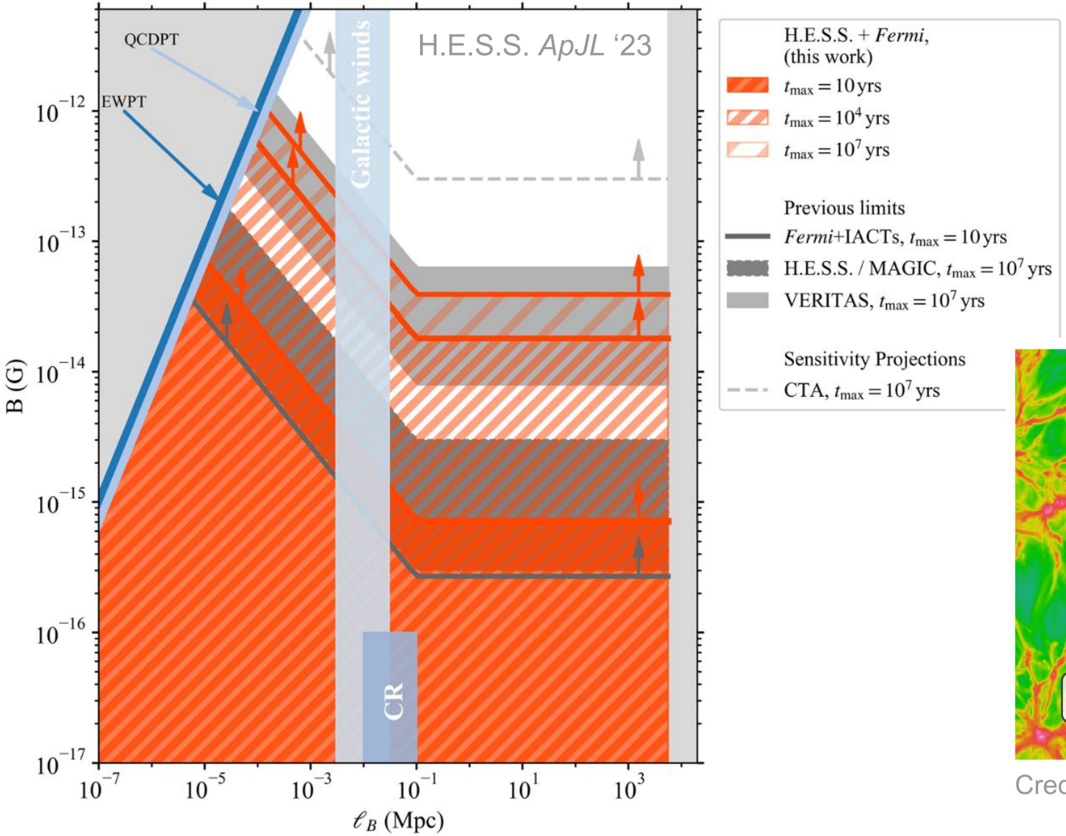
Expected for $B \sim 3 \times 10^{-16}$ G







Constraints on magnetic fields in voids

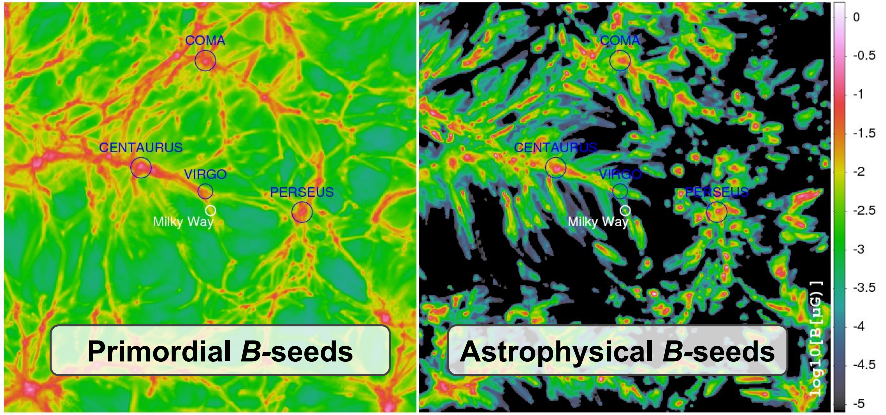


Status and expectations

Current-generation: B > 10-100 fG,
CTAO discovery at 5σ up to 300 fG (CTAO *JCAP* ‘21)

Patchy B-field generation models disfavored:
VFF < 0.67 excluded at 95% C.L. (Tjemsland+ *ApJ* ‘24)

Primordial ↗ - Astrophysical ↘



Credit: Hackstein+ *MNRAS* ‘18

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EeV nuclei

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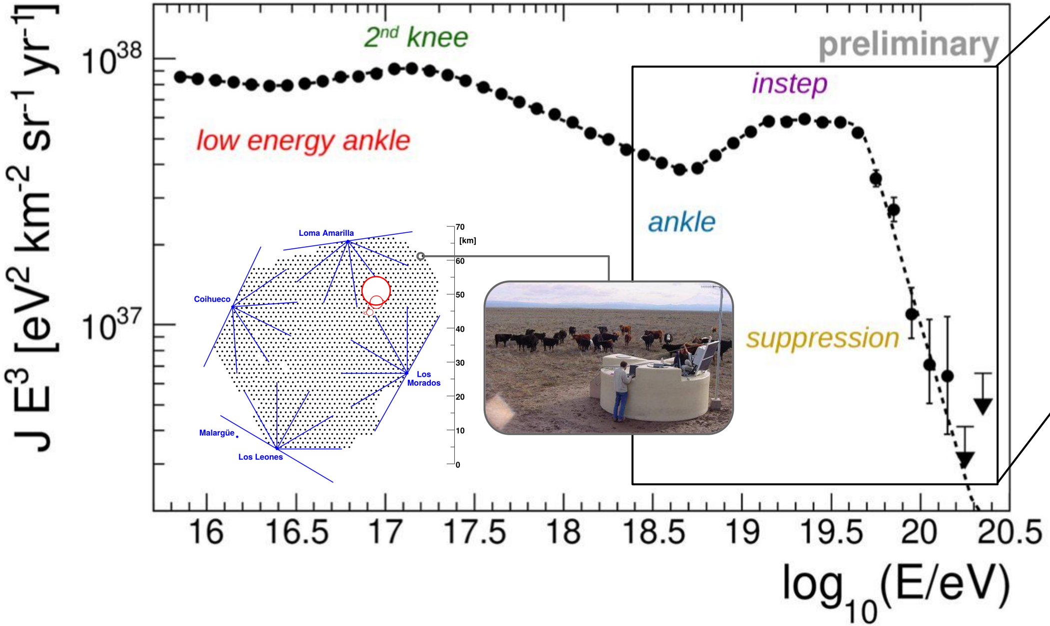
The quest for UHECR origins

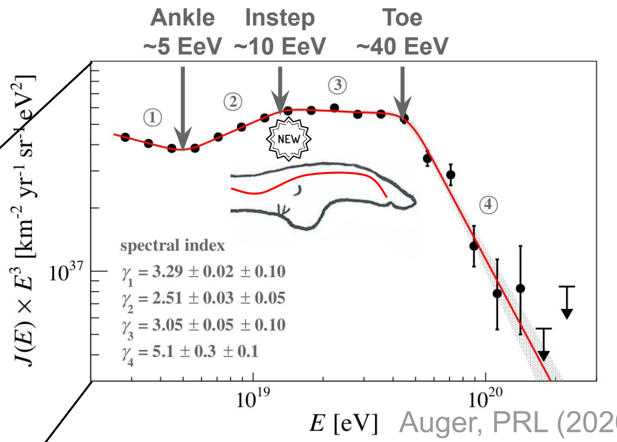
Ultra-high energy cosmic rays (UHECRs)

Long thought to be of **extragalactic origin > 5 EeV** (0.8 J!), marking the **ankle**

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

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



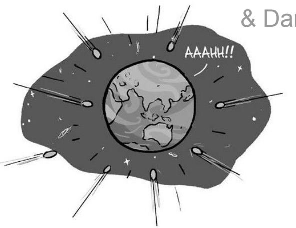


Auger, PRL (2020)

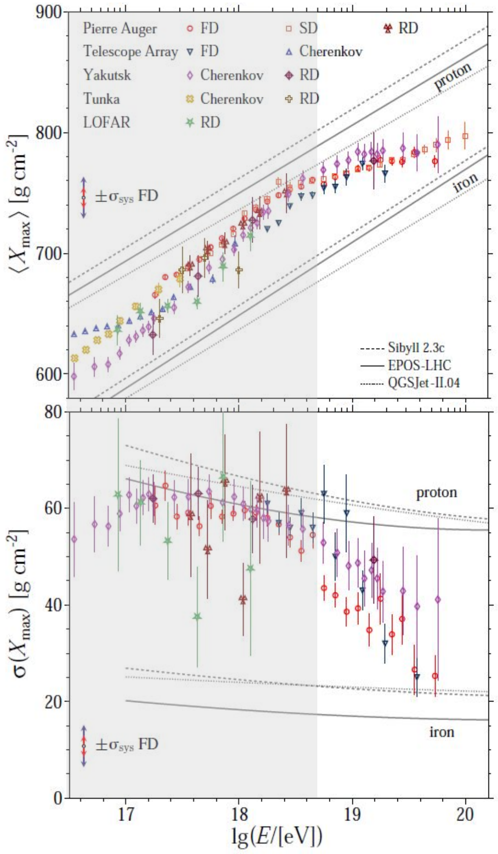
Who Is Shooting Superfast Particles at the Earth?

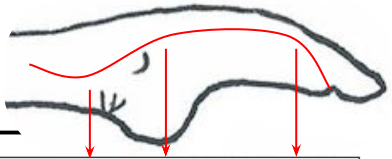
In Which You Learn That Space Is Full of Tiny Bullets

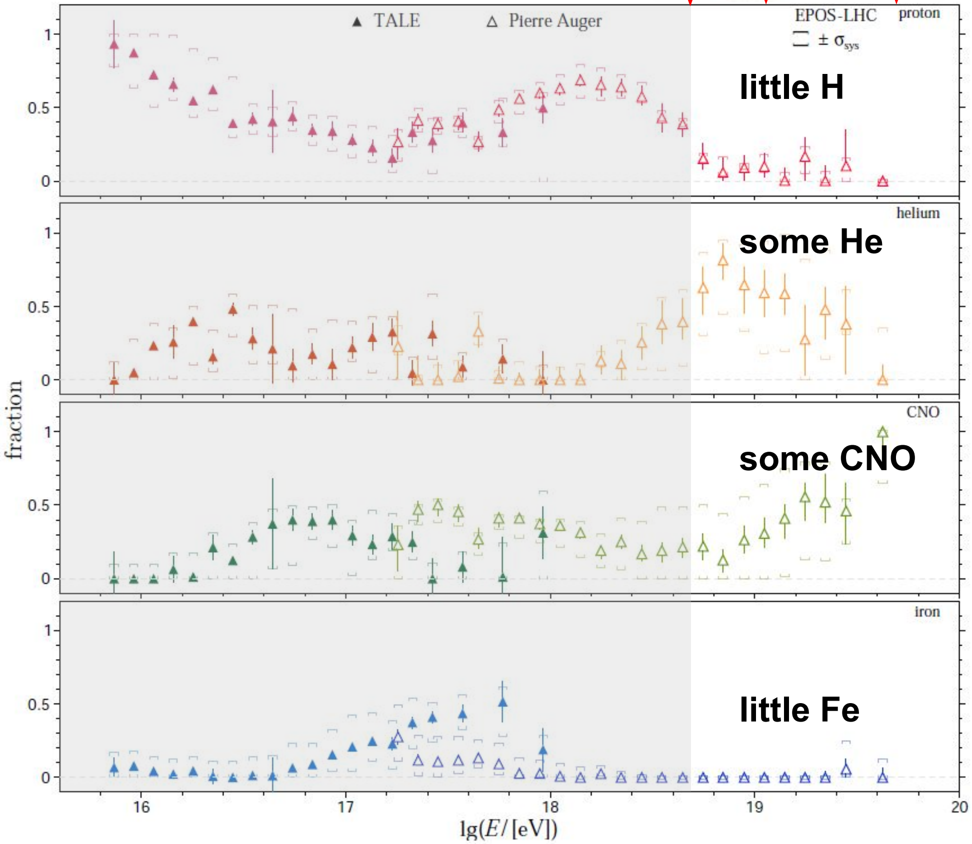
Credits: Jorge Cham & Daniel Whiteson



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







Coleman+, Astropart. Phys. '22

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
→ help constrain **source distance** distribution & source **escape spectrum**

Ankle at > 5 EeV (0.8 J!) marks the transition to a **purely extragalactic origin**, with the onset of He nuclei

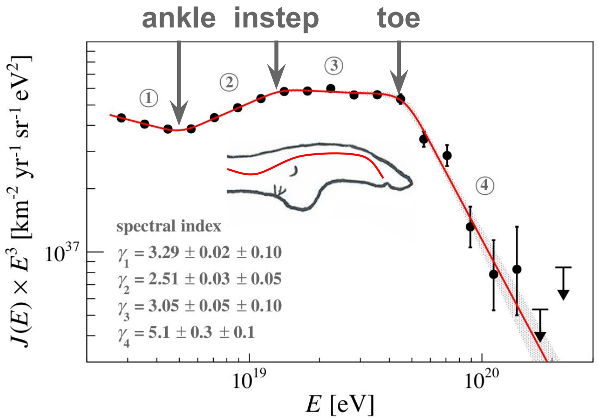
Observed spectral features: **instep at 10-15 EeV**, **toe at 40-50 EeV**
→ markers of ~Peters cycle (**acceleration up to $E_{max}(Z)$ ~ Z × 5 EeV**)

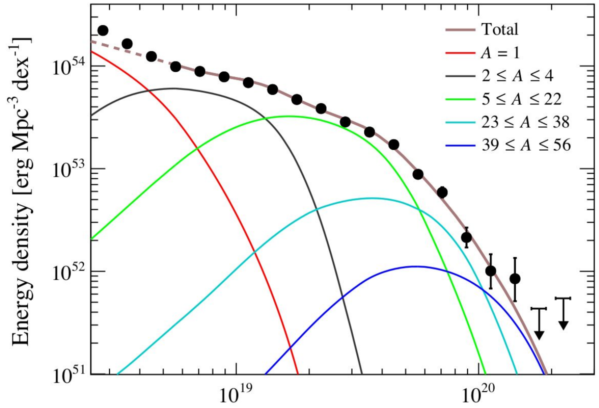
→ hard nuclear emission at sources (**$dN/dE \propto E^{\pm 1}$** vs E^{-2}, explained e.g. by escape from magnetized region within the sources)

→ reservoir of heavy elements? Accelerated material from exceptional metal sources / from sources low in H and He.

Anisotropy observables
→ break down the flux (and composition) vs **arrival direction**: **pinpoint sources?**

if cosmic magnetism does not prevent it!

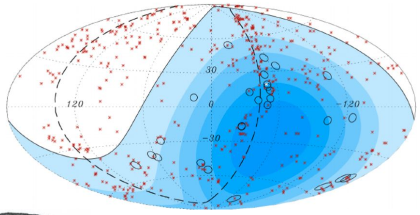


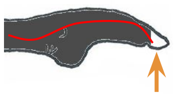


Auger Coll., PRD/PRL '20

Some landmarks in Auger anisotropy studies

Auger, Science 2007





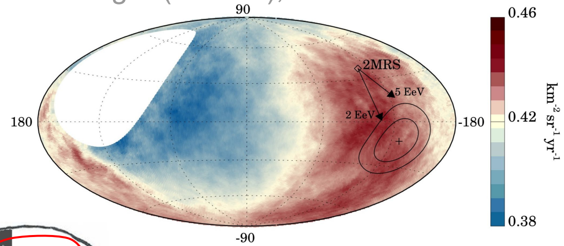
~ 27 evts ≥ 57 EeV

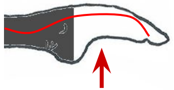
First steps: hint

20 out of 27 evts within 3° of nearby galaxies → ~3σ

10 evts in particular clustered in the **Centaurus region**

Auger (incl. JB), Science 2017





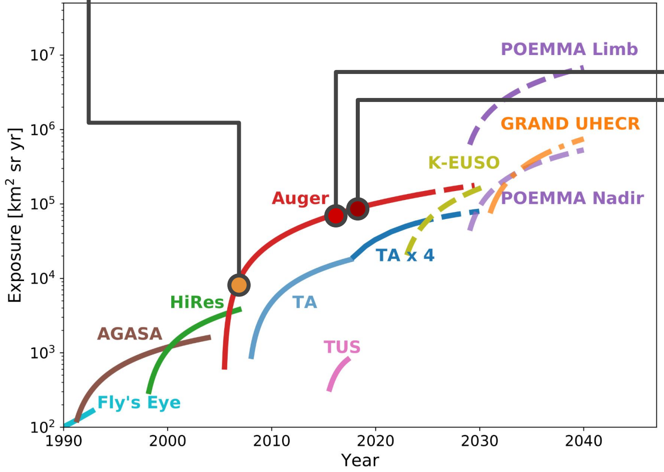
~ 32,000 evts ≥ 8 EeV

Maturity: discovery

6σ dipolar-like flux

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

Alves Batista+ (incl. JB) ‘19



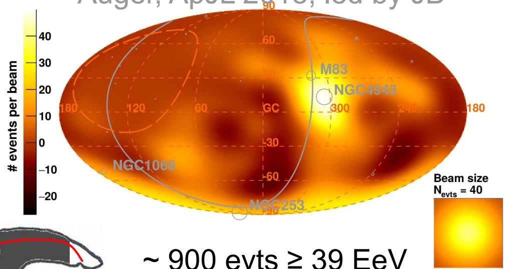
Revival: a trail?

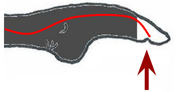
4σ evidence for ~10% excess from nearby **starbursts** (23 brightest)

Now 4.5σ

Auger, JCAP ‘24

Auger, ApJL 2018, led by JB





~ 900 evts ≥ 39 EeV

Starbursts host more frequent stellar explosions…

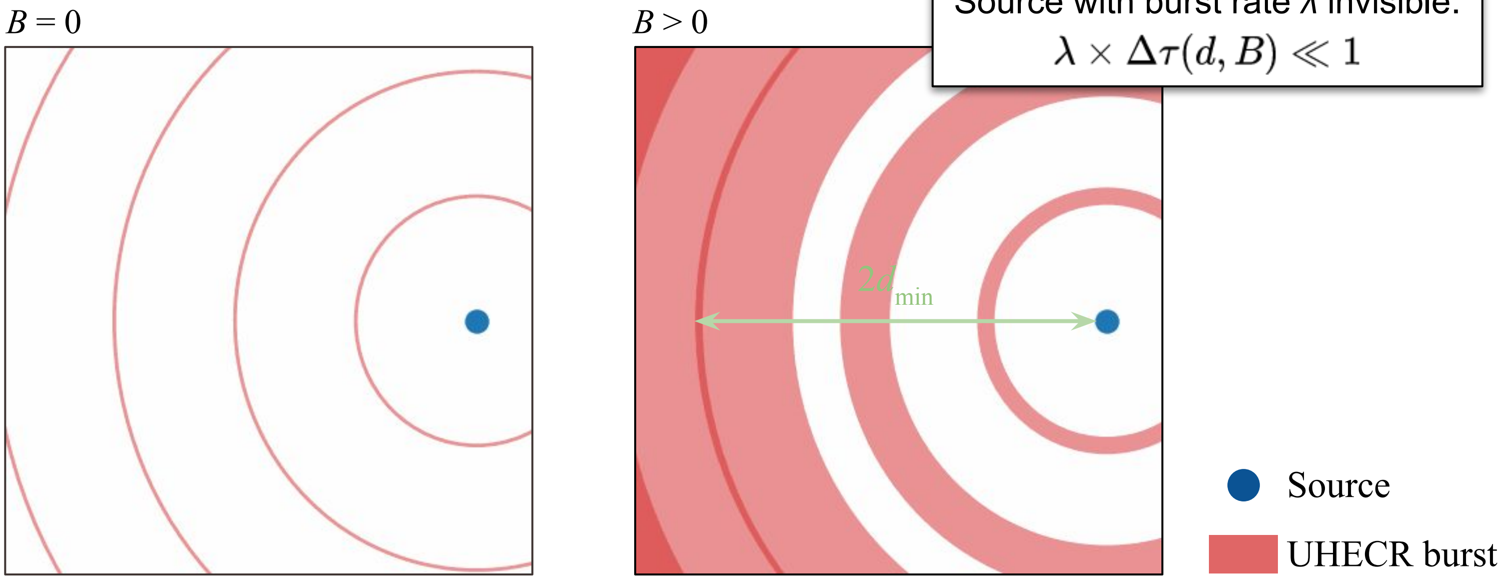
Marafico, JB+, **ApJ ‘24**

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

Mapping out stellar matter in the GZK horizon

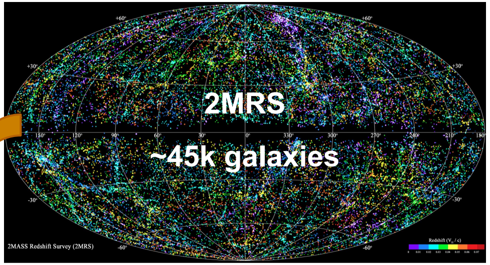
JB, **ApJ '21**

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

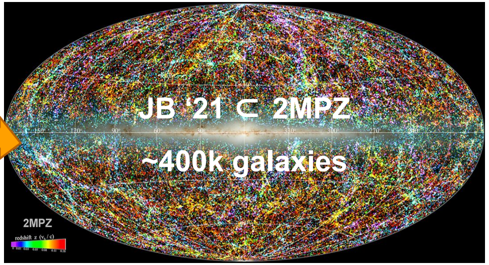
Catalog of 400k galaxies out to d_{max} = 350 Mpc

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

Credits: 2MRS, Huchra+ '12

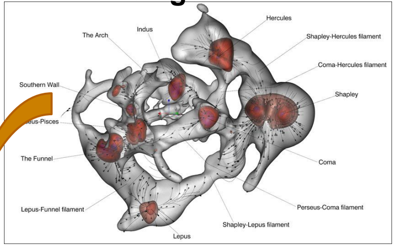


Credits: 2MPZ, Bilicki & Jarret '14

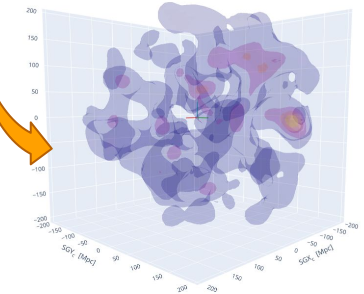


Cosmic V-web, Pomarède+ 2017

~8k galaxies

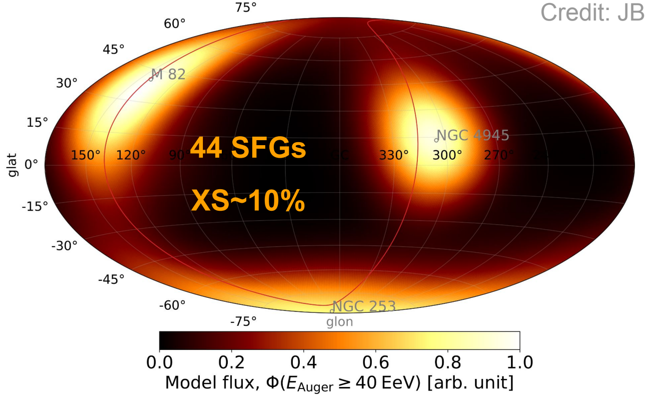


JB '21 **~400k galaxies**



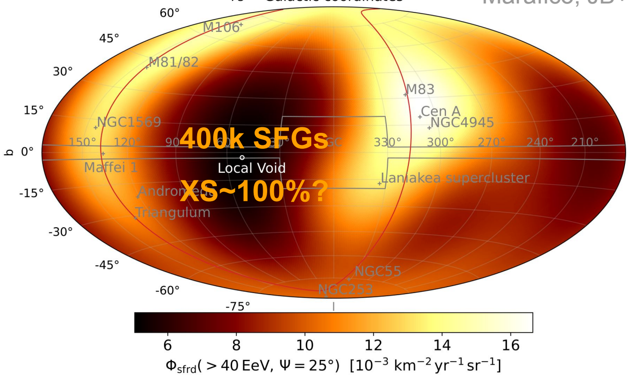
Starburst galaxies (radio) - Ψ = 25°

Credit: JB



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

Marafico, JB+ '24

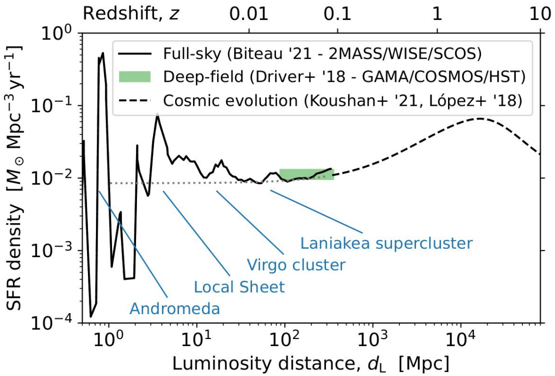


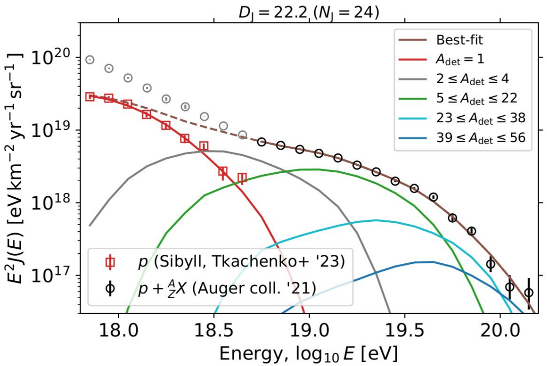
Transient model of UHECR sky

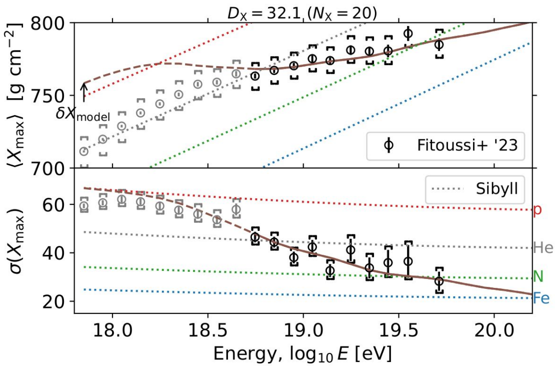
DOI 10.5281/zenodo.11440864

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

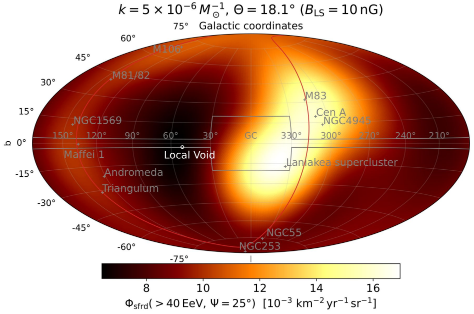
Spectral & composition model (see also Luce+ ApJ '22)

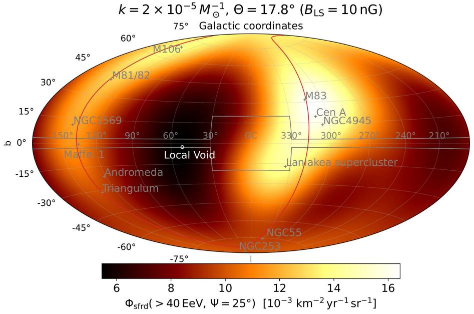


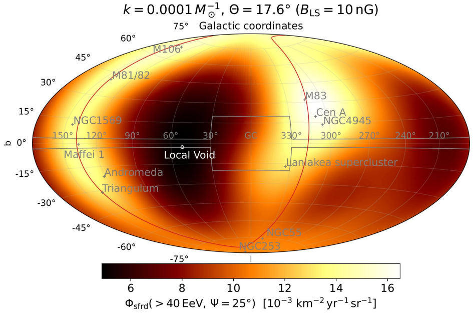


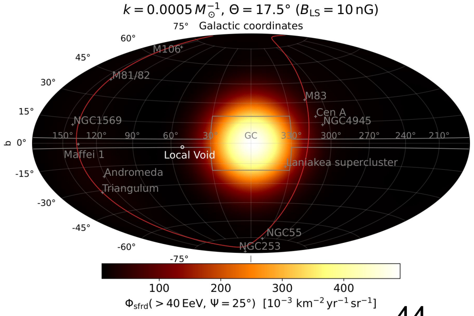


Increasing value of burst rate per star-formation unit *k*, for a given *B*-field in the Local Sheet







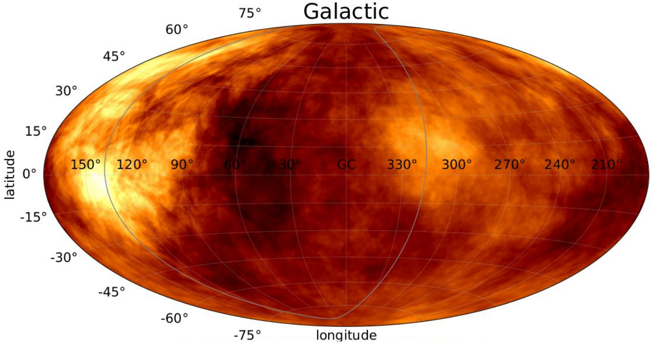


Candidate ultra-high-energy sources

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

Auger + TA data

Credits: L. Caccianiga for Auger & TA

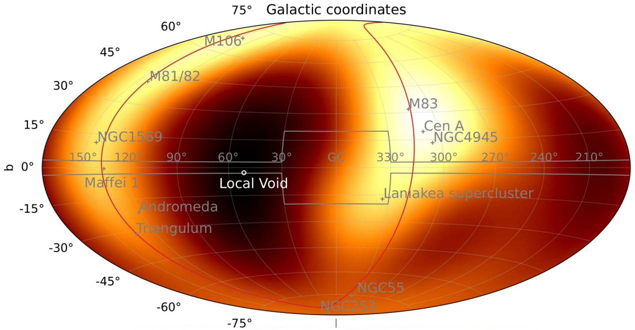


UHECR Model ≈ UHECR Data

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

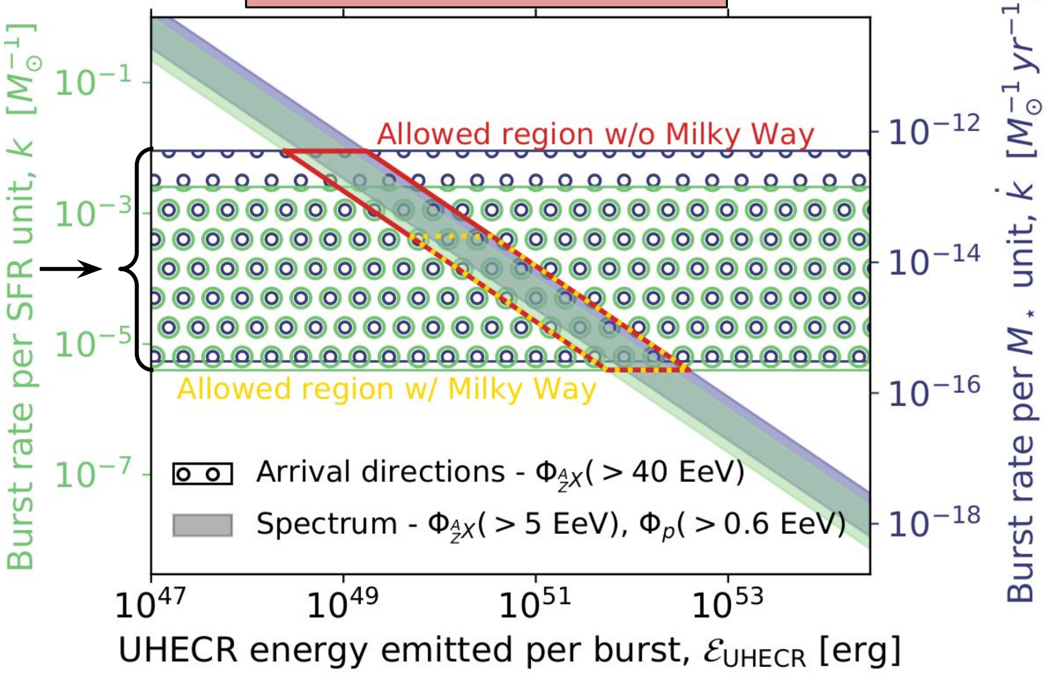
Best-match transient scenario

Credits: Marafico, JB+ '24



Solution with at least 1 Northern & Southern hotspot found for

Local Sheet B_{rms} = 0.5 - 20 nG



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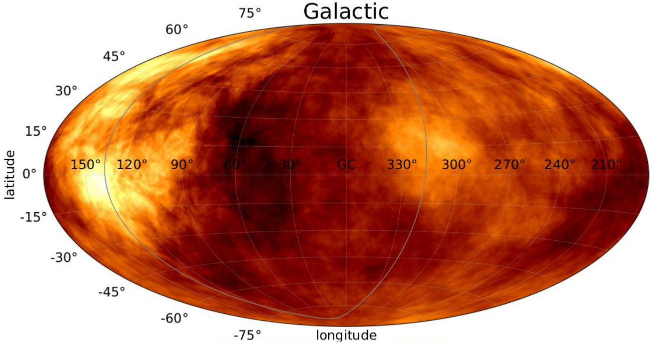

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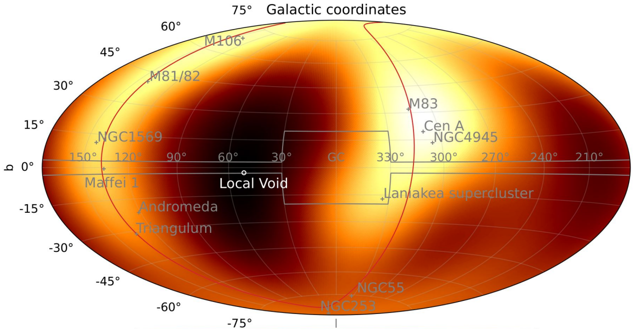
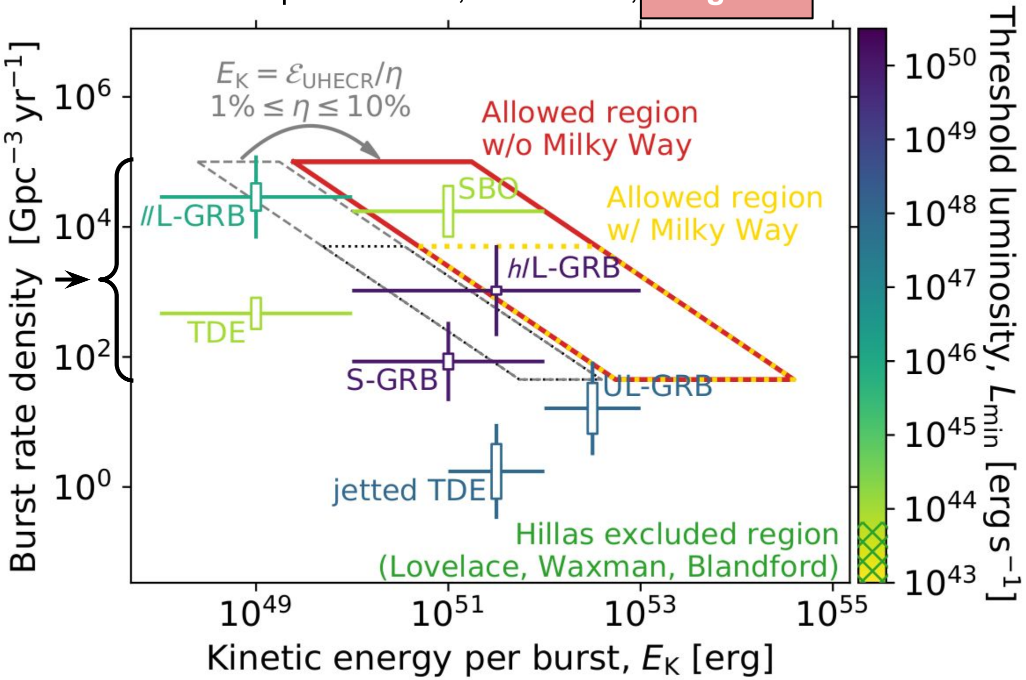


X-ray transient rate vs kinetic energy

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

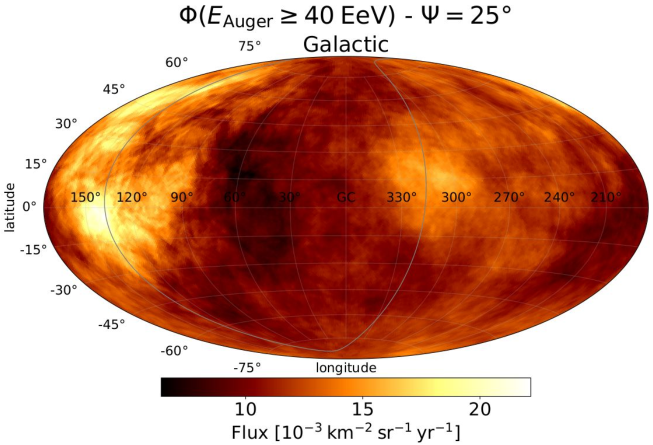


Coherent deflections in the Milky Way

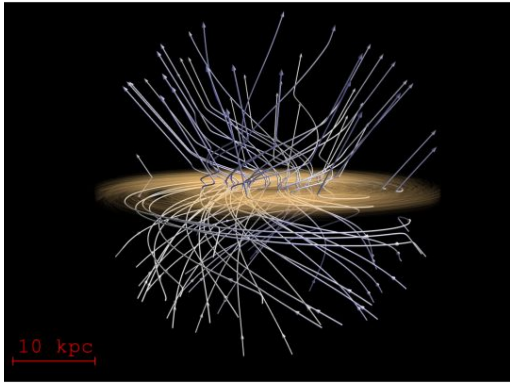
Marafico, JB, Condorelli, Deligny, Bregeon, **ApJ ‘24**

Auger + TA data

Credits: L. Caccianiga for Auger & TA

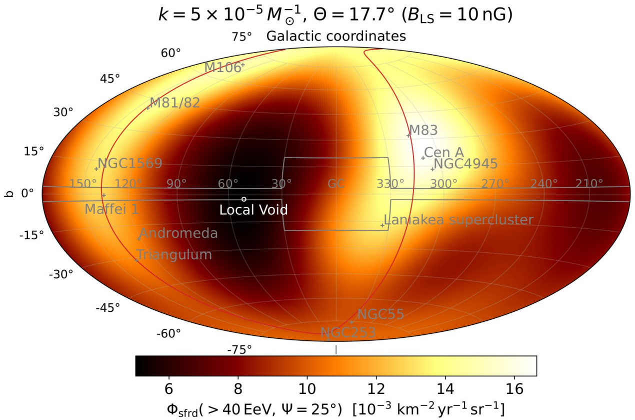


Credits: Farrar ‘15



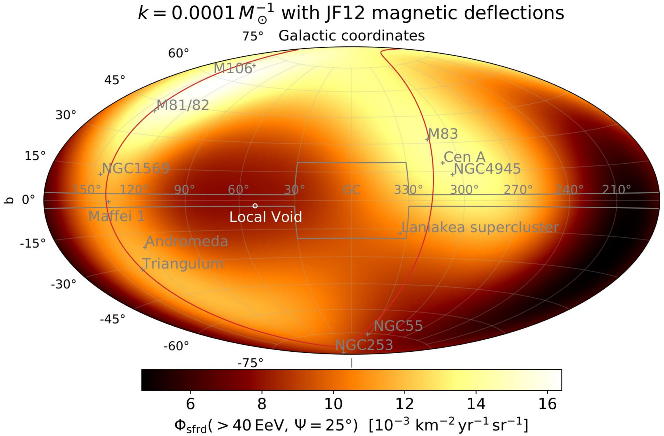
Best-match transient scenario

Credits: Marafico, JB+ ‘24



Regular $B_{\text{Milky Way}}$ →

Jansson & Farrar ‘12



Intro

astroparticles & cosmic backgrounds

The physics of propagation

radiative and catastrophic losses

deflections, delays and spreads

Inferences from observations

TeV gamma rays

EeV nuclei

Outro

summary & open questions

Conclusions and outlook: cosmic-ray propagation

- Measurement of the **cosmic-ray spectrum above the ankle (5 EeV)** with **1% precision up to instep (15 EeV), 5% up to the suppression (40 EeV) and 30% up to 100 EeV.**

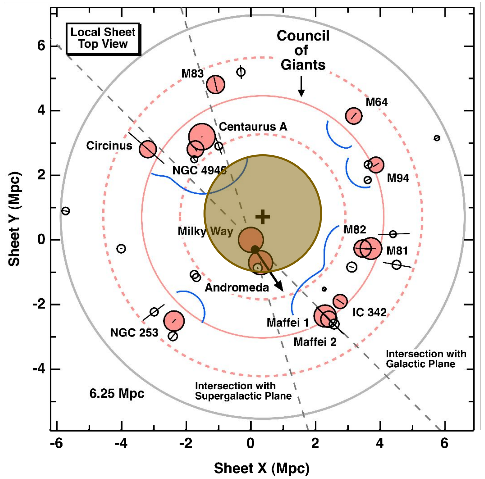
- Statistical **measurement of nuclear composition up to 40 EeV: *A*↗ as *E*↗** (from shower-depth moments), ongoing improvements with surface detectors
  → further room for improvement with **Auger Prime (radio signals, scintillators)**

- High-precision (*Z* ~ 7*σ*) of 6% **dipole above the ankle**, exciting prospects with ***Z* ~ 5*σ* (soon?)** for ***θ* ~ 20° anisotropy above the suppression**
  → observational confirmation of **extragalactic origin, which sources?**

- Propagation losses well constrained, **cosmic magnetism too poorly known**
  → although dipole and intermediate-scale anisotropies qualitatively reproduced, even the **best current models are unable to satisfactorily fit to both**

Local Sheet B_{rms} = 0.5 - 20 nG

Can it be measured through radio observations?



- Emerging **synthesis population models of UHECR sources**, promising to solve a long-standing mystery (!), but in-source processes (acceleration, losses, escape) still underconstrained.
  → use **best-fit synthesis models to constrain *B*-fields** (in particular Galactic)**?**

Conclusions and outlook: gamma-ray propagation

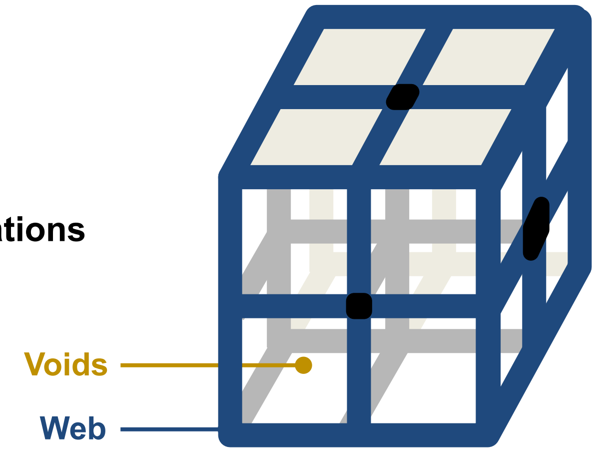
- Model-independent measurement of **Extragalactic Background Light**:
  O-IR backgrounds at $z = 0$ with **10-25% precision depending on λ**

- Precision on **Hubble constant:** 5% (model-dep.) to 10% (model-indep.)
  assuming no unresolved diffuse component in galaxy counts

  → could become relevant if Hubble tension not solved by **JWST observations**

- Probe of UV emissivity at high z (e.g. $z \sim 6$ in *Fermi*-LAT Science '18)
  room for improvement with archival and upcoming CTAO data?

  → timely in the **context of JWST observations**

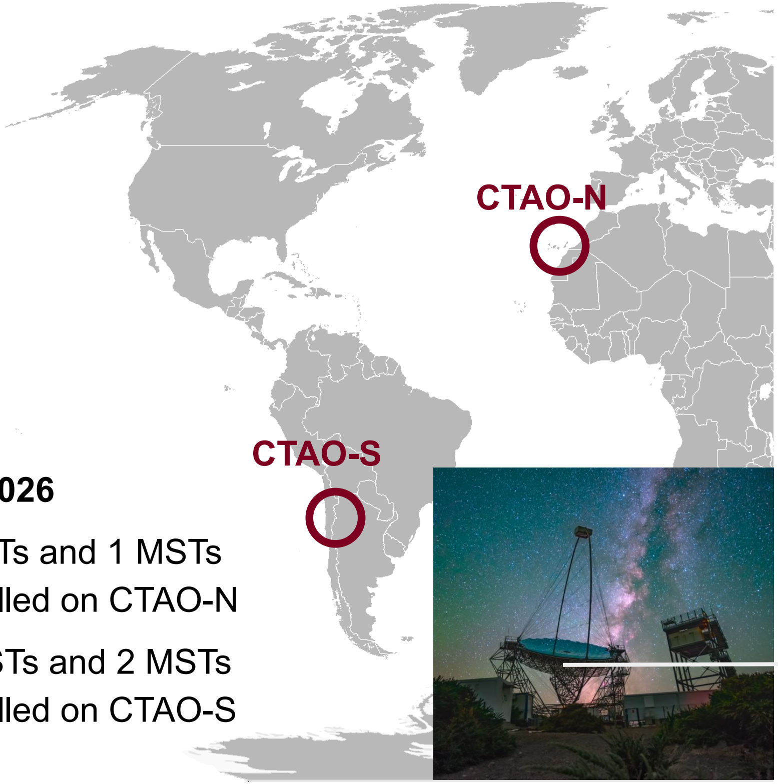


- opportunity to probe ***B*-field in voids** (and study the intergalactic plasma)
  little room left for plasma instabilities as main *E*-loss or *p*-diffusion mechanism

  → comparison with models goes in the direction of primordial origin of *B*-fields,
  but without clearly preferred mechanism and **without irrefutable observations** (!)

- growing body of studies of **cosmic-web impact** on propagation (e.g. Bondarenko+ *A&A* '22, Abdalla+ *MNRAS* '24)
  → timely in the **context of LSST and Euclid observations**

Game changer: The Cherenkov Telescope Array Observatory



By 2026

4 LSTs and 1 MSTs installed on CTAO-N

2 MSTs and 2 MSTs installed on CTAO-S

Backup

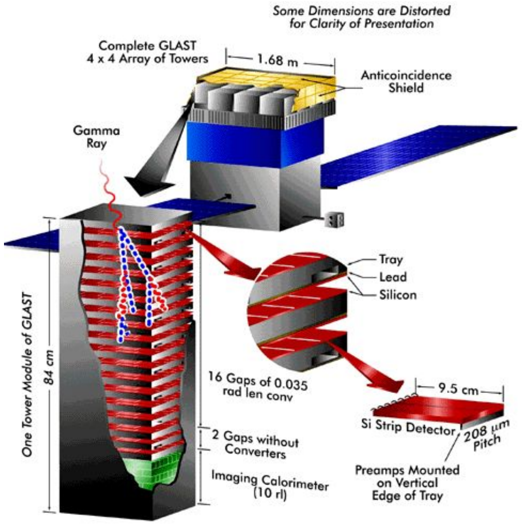
Detection of γ-rays near Earth

Satellite-based: 100 MeV - 1 TeV

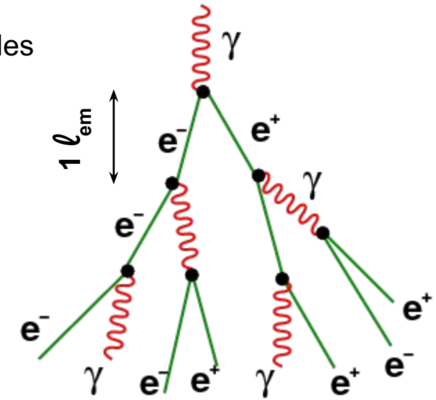
O(100%) duty cycle, ~ 550 km altitude

Tracker with SSDs, CsI(TI) with photodiodes

Lead experiment: *Fermi*-LAT



$15\ \ell_{em}$



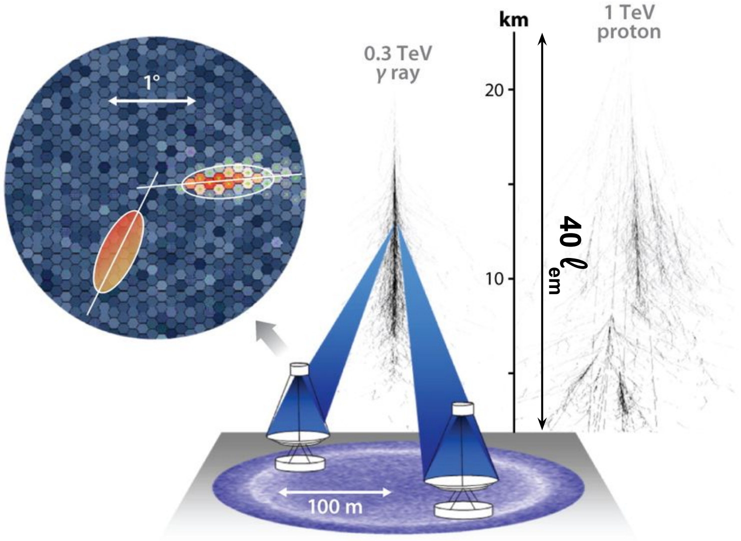
Performance > 10 GeV
energy resolution ~10-20%
angular resolution ~0.1°

Telescope-based: 100 GeV - 100 TeV

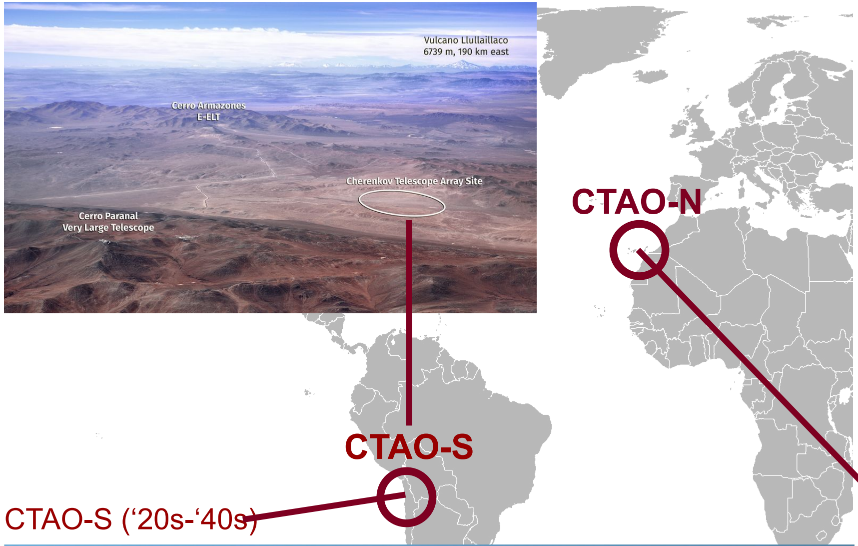
O(10%) duty cycle, ~ 2 km above sea level

Cameras with O(1000) PMTs and ns sampling

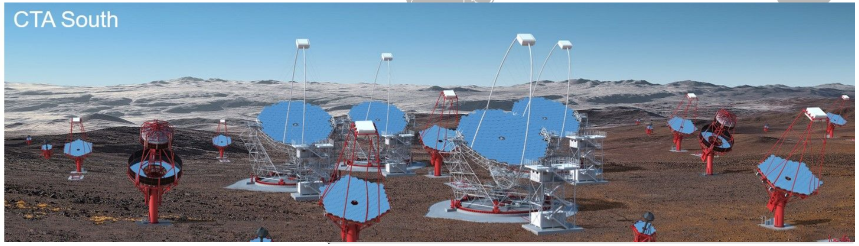
Lead experiments: HESS, MAGIC, VERITAS



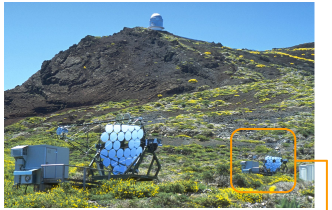
Game changer: The Cherenkov Telescope Array Observatory



CTAO-S (‘20s-‘40s)



HEGRA (‘90s)



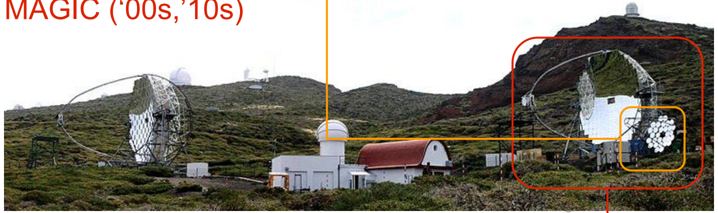
2 sites to access the entire sky w/ breakthrough performance

Sensitivity: 5-10× better than current

E-range: 0.02-200 TeV (vs 0.1-10 TeV)

E-resolution: <10% (vs <17%) >0.2 TeV

MAGIC (‘00s,’10s)



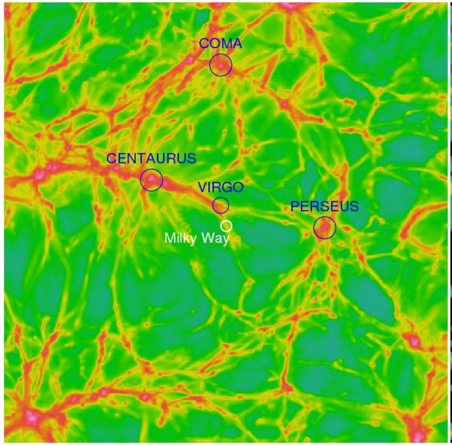
CTAO-N (‘20s-‘40s)

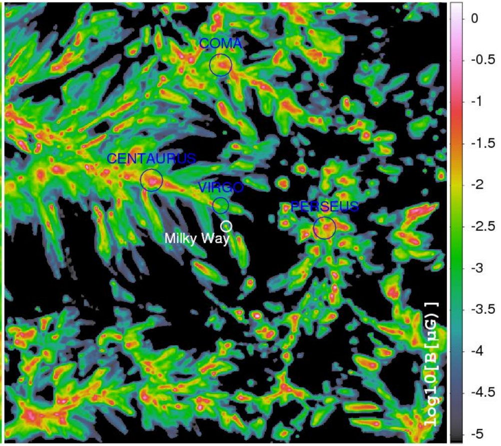
Magnetic fields in voids

Status and expectations

Current-generation (GeV+TeV - TeV extension): *B* > 10-100 fG

5σ CTA-discovery potential up to 300 fG





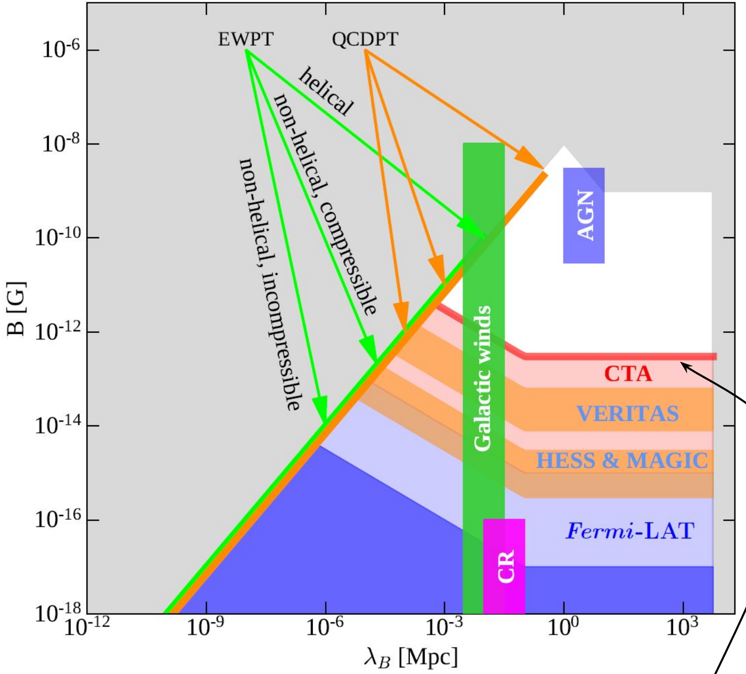
Credit: Hackstein+ 2018

Primordial origin simulation
B(void) < 1 nG

Astrophysical origin simulation
B(void) < 1 pG

In practice… largely unknown!

Credit: CTA Consortium 2021



1ES 0229+200 (*z*=0.14) up to E_{cut} = 10 TeV,
50h of CTAO-North to reach 5σ

What is known about the extragalactic background

Back-of-envelope estimates

Light from nucleosynthesis

$u_{\rm nucl} \approx \epsilon_\odot c^2 \int \psi_\star(t){\rm d}t \approx \underline{13,000}\,{\rm eV\,m^{-3}}$

where $\epsilon_\odot = L_\odot T_\odot/(M_\odot c^2) \approx 0.068\%$

Light from accretion

$u_{\rm accr} = \frac{\epsilon_{\rm accr}}{1-\epsilon_{\rm accr}} c^2 \int \psi_{\rm accr}(t){\rm d}t \approx \underline{1500\,{\rm eV}}\,{\rm m^{-3}}$

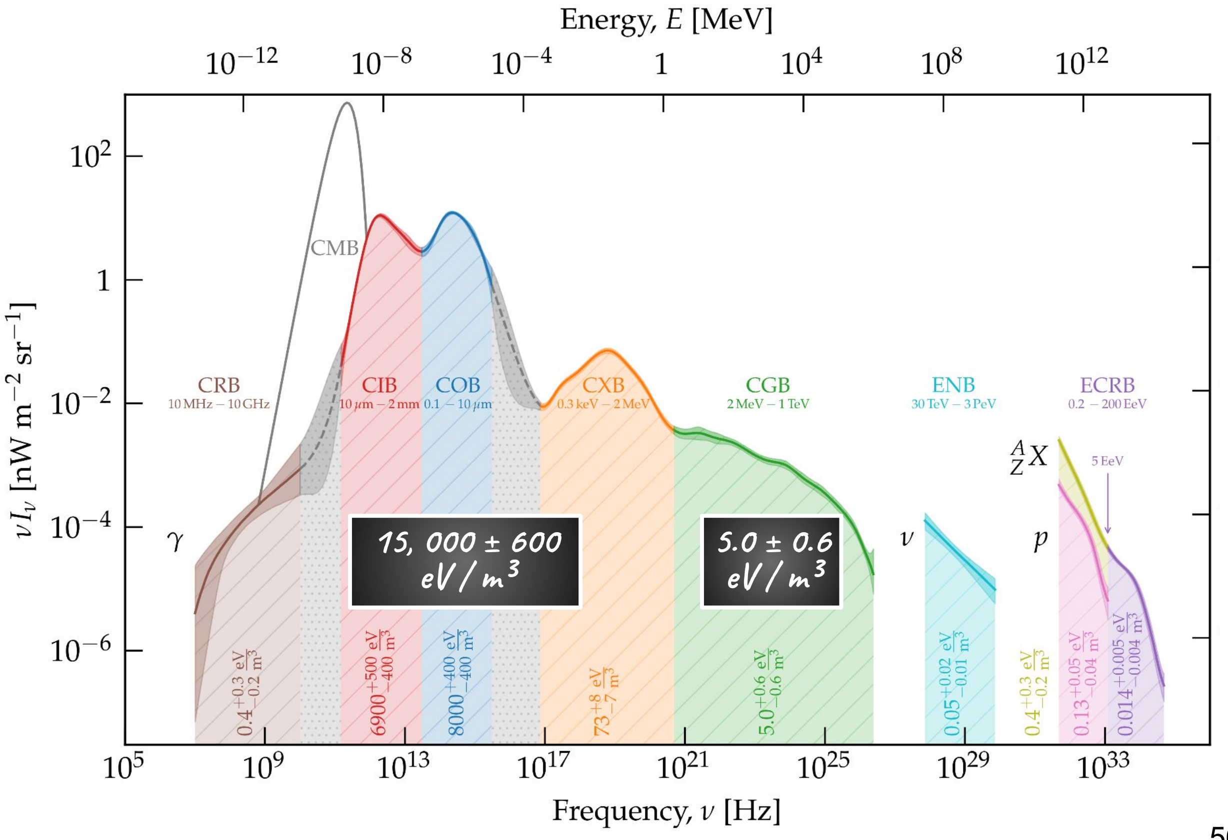
where $\epsilon_{accr} = 5.7 - 30.8\,\%$ and

$\psi_{\rm accr}/\psi_\star \approx 1/2000$ for a Chabrier IMF

Light from ejection

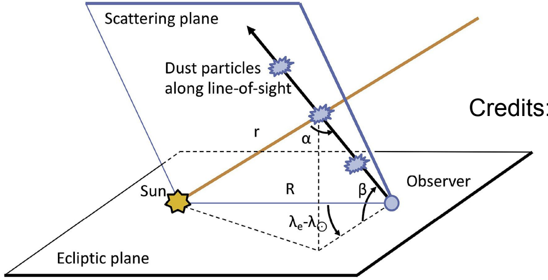
$u_{\rm jet} = \eta_{\rm jet} c^2 \int \psi_{\rm accr}(t){\rm d}t \approx \underline{4\,{\rm eV\,m^{-3}}}$

where $\eta_{\rm jet} = \eta_{\rm kin/accr} \times \epsilon_{\rm kin\to\gamma} \approx 0.04\%$
with $\epsilon_{\rm kin\to\gamma} \approx 10\,\%$ for AGNs and GRBs
and $\eta_{\rm kin/accr} \approx 0.4\,\%$ from Merloni & Heinz



Contaminants in the O/IR

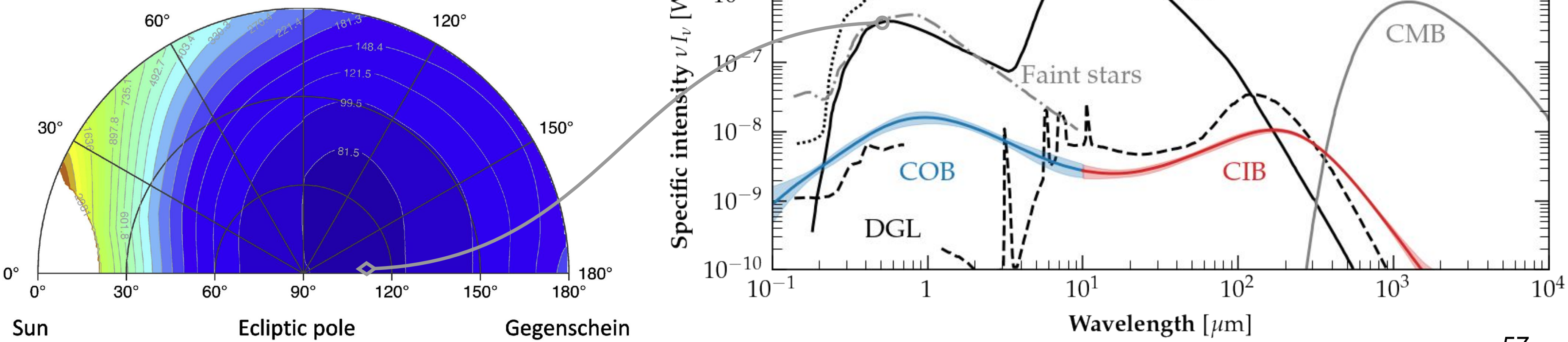
Zodiacal light, integrated star light, diffuse galactic light (cirrus)[1]



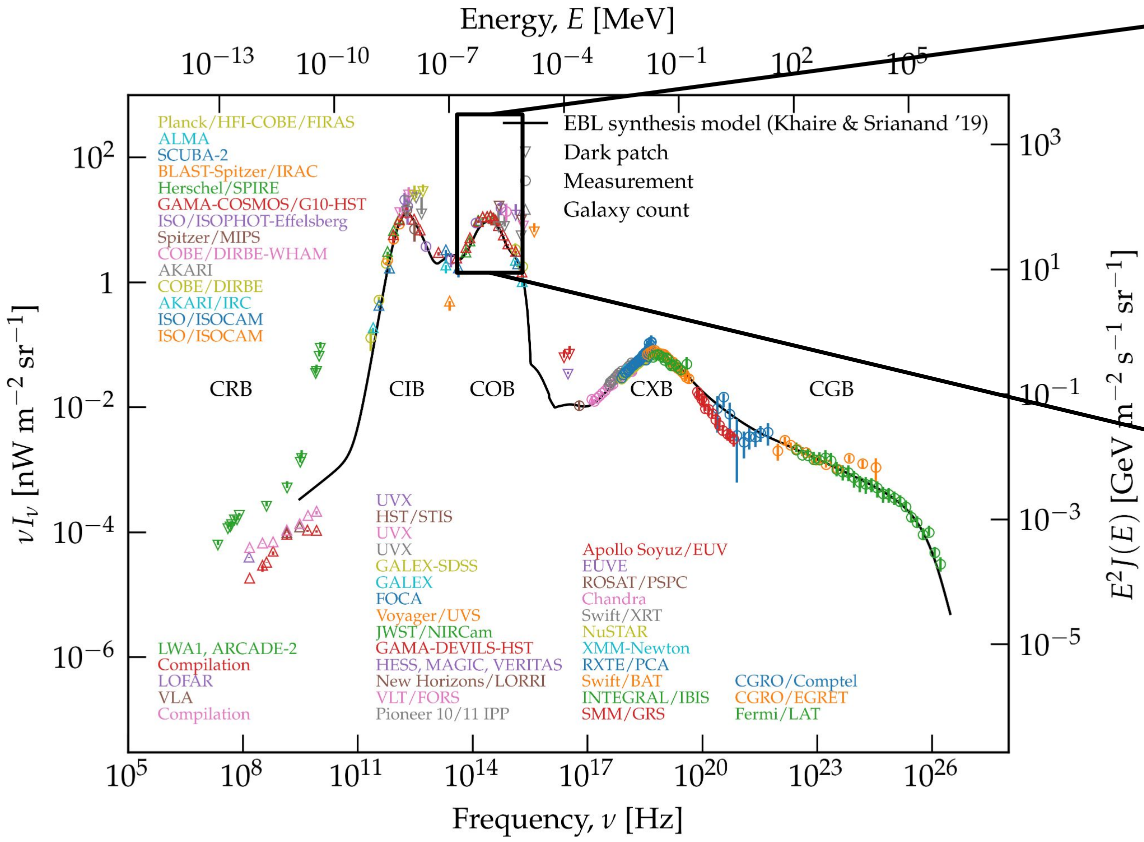
Credits: Lasue 2020

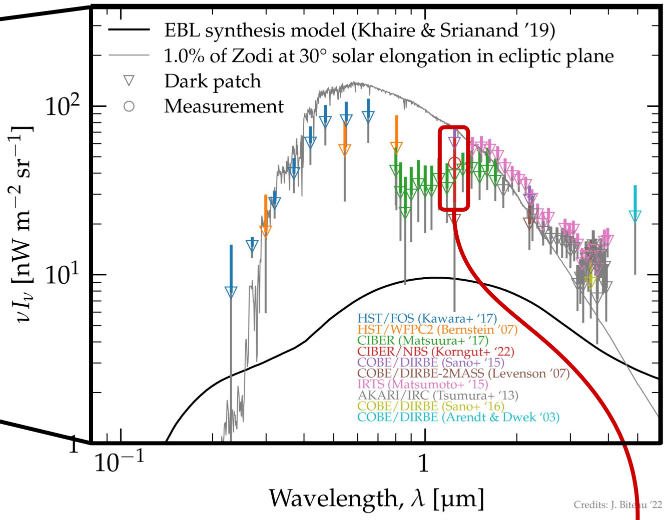
@ 0.55 µm

Credits: L. Gréaux
Adapted from Leinert '97 & JB '23



The light that remains once (all?) foregrounds are removed



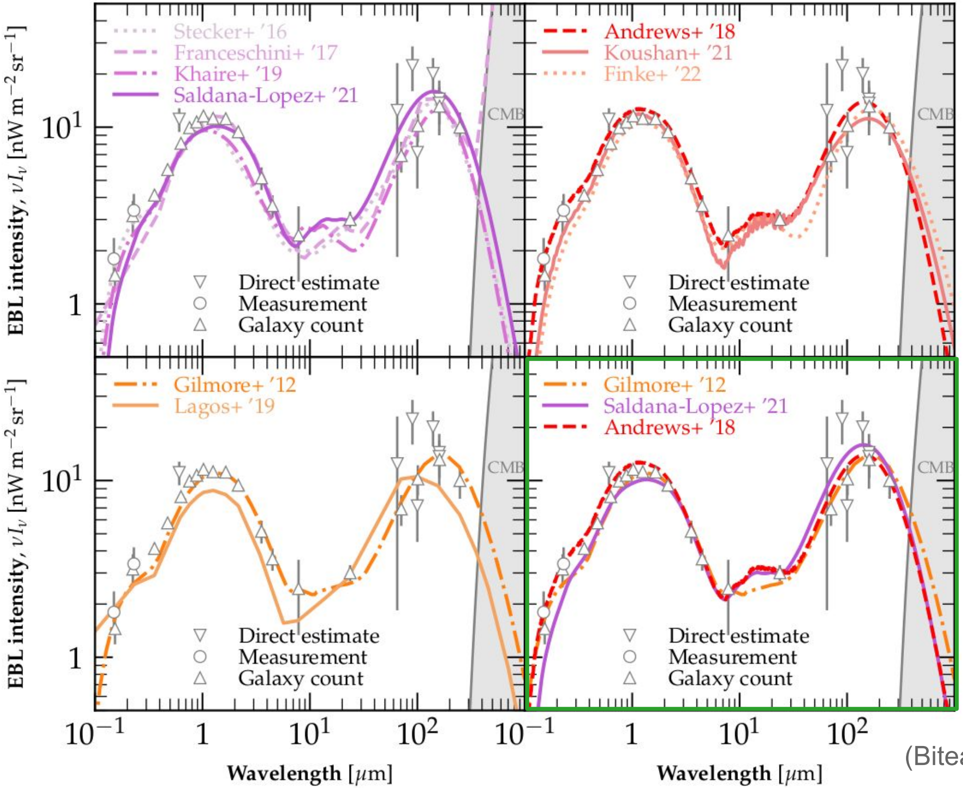


Dark-patch estimates in 0.3-5μm roughly consistent with 1% Zodi

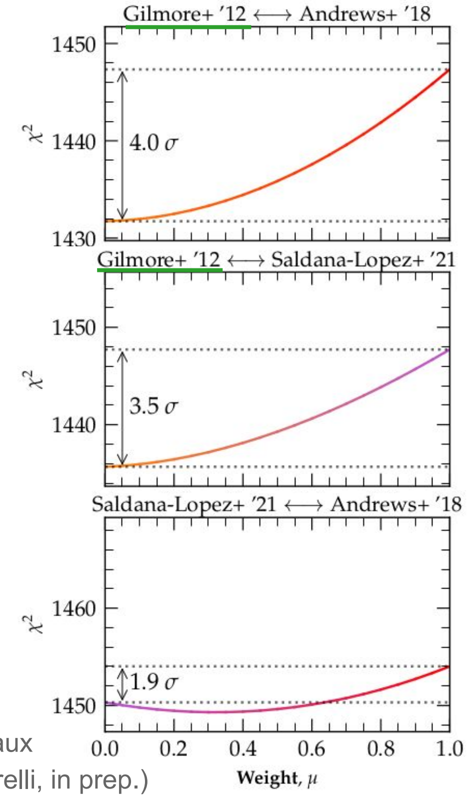
Ca-II absorption lines by CIBER
→ unaccounted for (Kelsall+ '98)
faint spherical Zodi component

Status of COB-CIB models: a TeV appraisal @ $z < 1$

Lowest tension with direct measurements and galaxy counts @ $z = 0$



Lowest tension with TeV ɣ rays



Credit: L. Gréaux
(Biteau, Gréaux, Condorelli, in prep.)

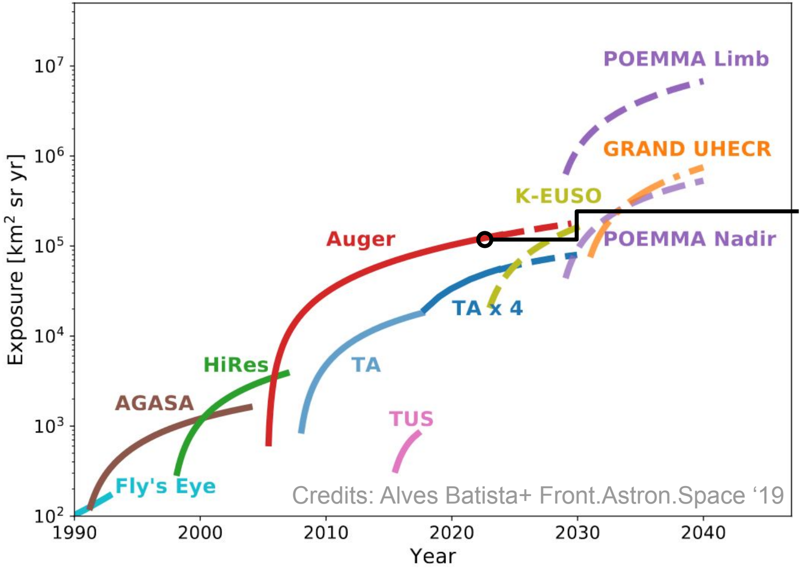
The largest cosmic-ray observatory ever built

The Pierre Auger Observatory

West Argentina at 1,400m a.s.l., **spread over 3,000 km²** (~ Luxembourg or Rhode Island)

1600 water Cherenkov detectors (12t each) to measure secondary particles in air showers
+ 27 fluorescence telescopes (440 px / cam) to image the air showers during dark time

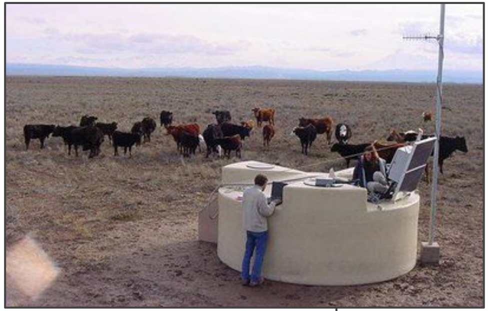
Phase 1 (2004-2021): ~150,000 events above the ankle over ~80,000 km² yr sr

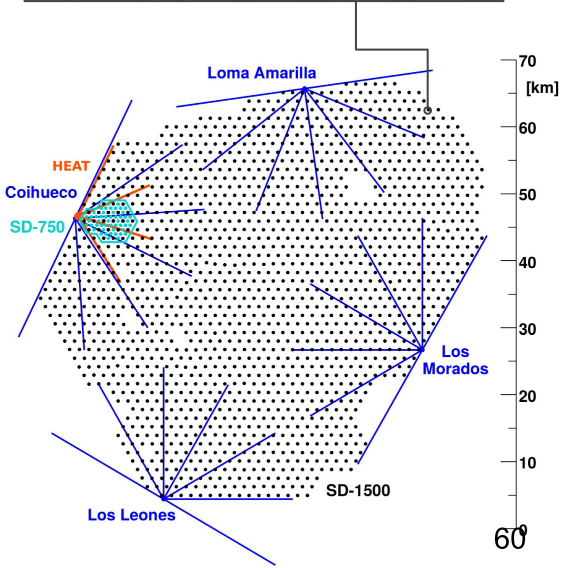


Exposure = $A_{eff} \times T$

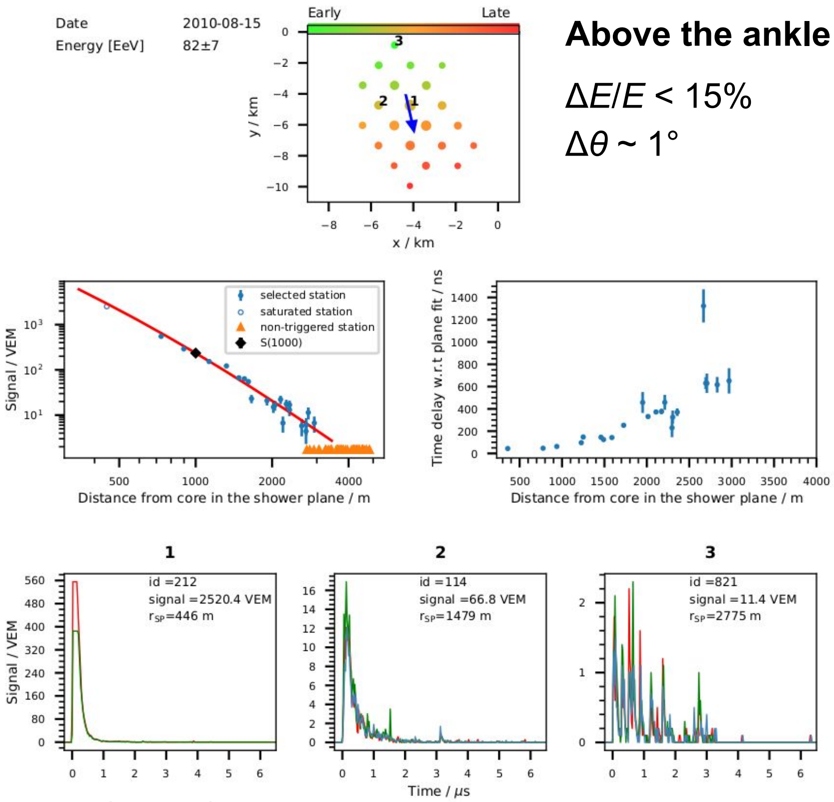
→ **40-70x larger than previous generation** experiments (AGASA, HiRES)

→ **8x larger than complementary Northern hemisphere** experiment (Telescope Array)





Event reconstruction: surface detector (SD)



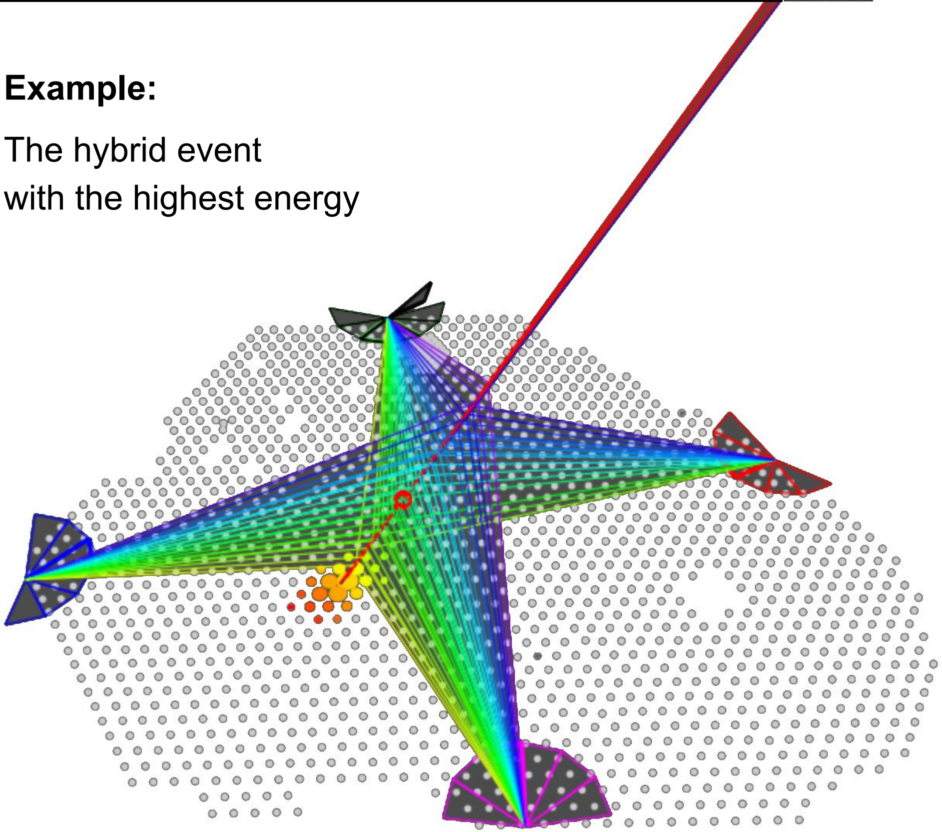
Auger Coll., ApJS 2023

Above the ankle:

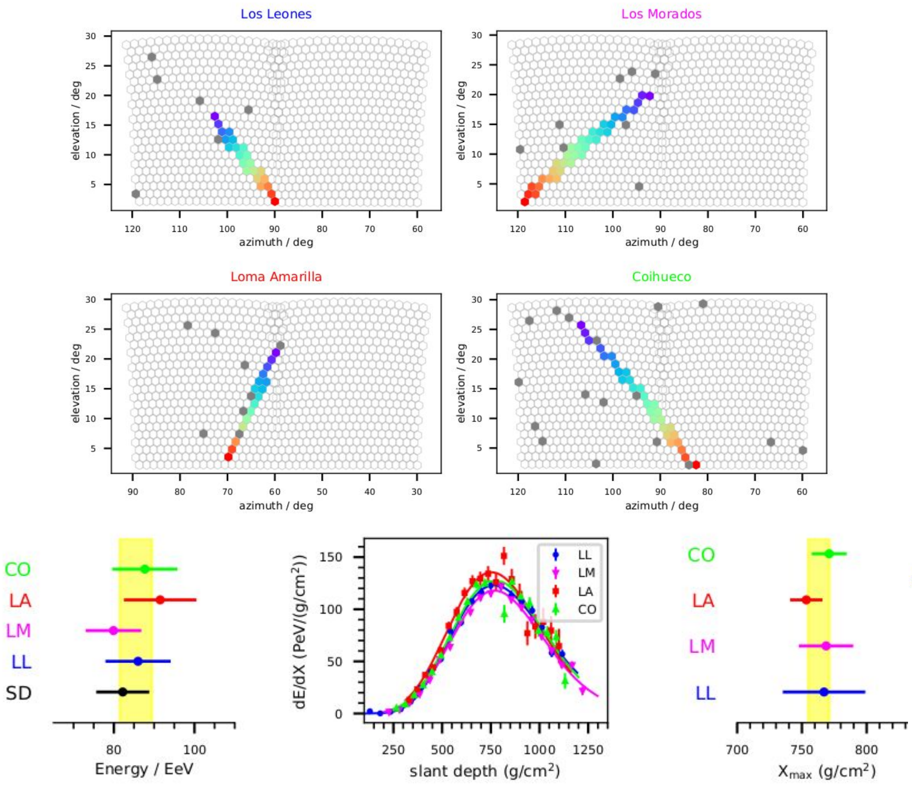
$\Delta E/E$ < 15%
$\Delta\theta$ ~ 1°

Example:

The hybrid event
with the highest energy

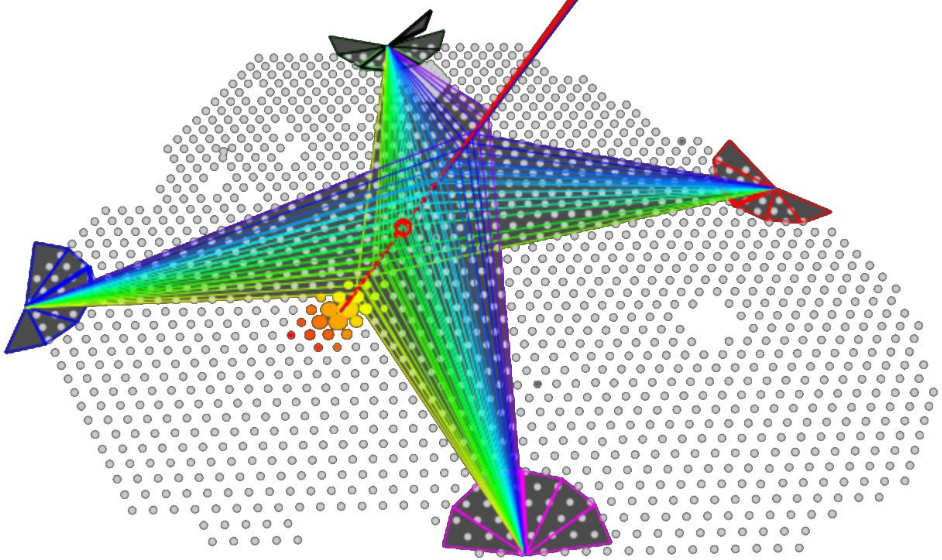


Event reconstruction: fluorescence detector (FD)



Example:

The hybrid event
with the highest energy



Auger Coll., ApJS 2023

UHECR propagation on extragalactic scales

 # evolution along propagation:

Aloiso, Berezinsky, Grigorieva (2013)

$$\frac{\partial n_{A_0}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_{A_0}(\Gamma,t) b_{A_0}(\Gamma,t)\right] + \frac{n_{A_0}(\Gamma,t)}{\tau^{\rm tot}_{A_0}(\Gamma,t)} = Q_{A_0}(\Gamma,t).$$

Energy losses: $e^{+/-}$ or π production

Absorption: photo-dissociation

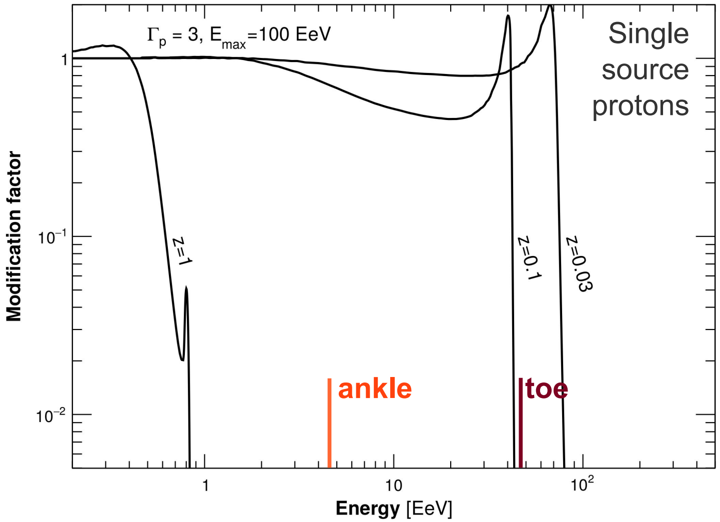
Injection: source or cascade

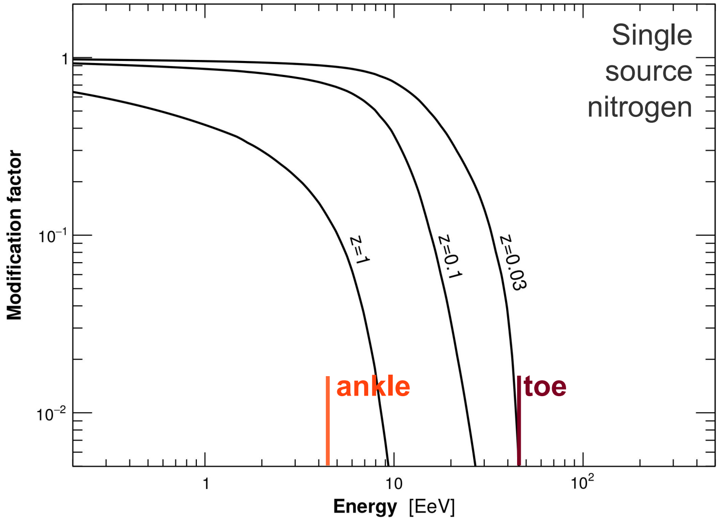
Propagation of protons

No absorption term → sharp wall at ~ 100 EeV for D ~ 100 Mpc, pile-up feature

Propagation of nuclei

Dominated by single-nucleon photo-dissociation → ~ exp. attenuation at ~20/50 EeV for D ~ 100/10 Mpc





Before the Pierre Auger Observatory

Component A

fully ionized H, He, … , Fe
with a slope $\gamma \sim 2.7$
up to $R_A \sim 3$ PV

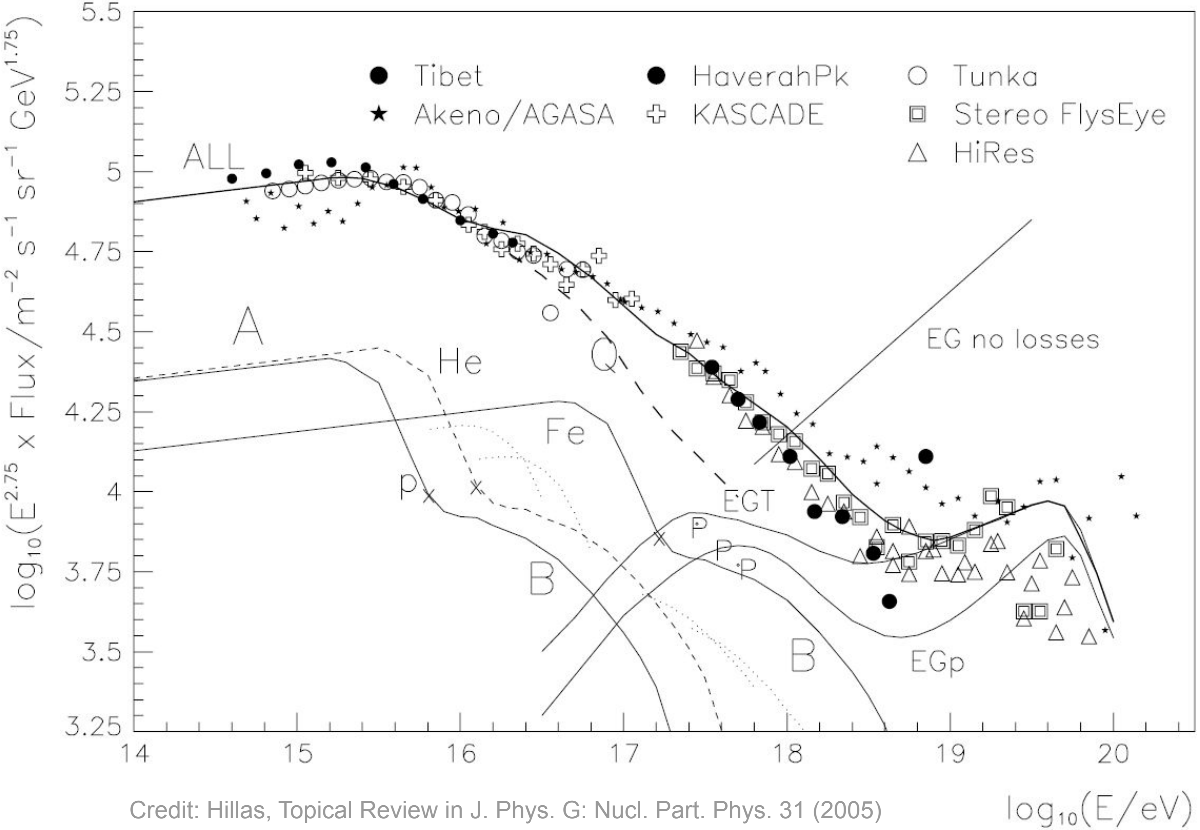
- $Z_{\mathrm{H-He}} e R_A = 3 - 6\,\mathrm{PeV} \equiv E_{\mathrm{1st\ knee}}$
- $Z_{\mathrm{Fe}} e R_A \approx 100\,\mathrm{PeV} \equiv E_{\mathrm{2nd\ knee}}$

Component B

Something still has to be added to the 'KASCADE' component 'A'
M. Hillas (2005)

Component C EGT = EGp + EGHe

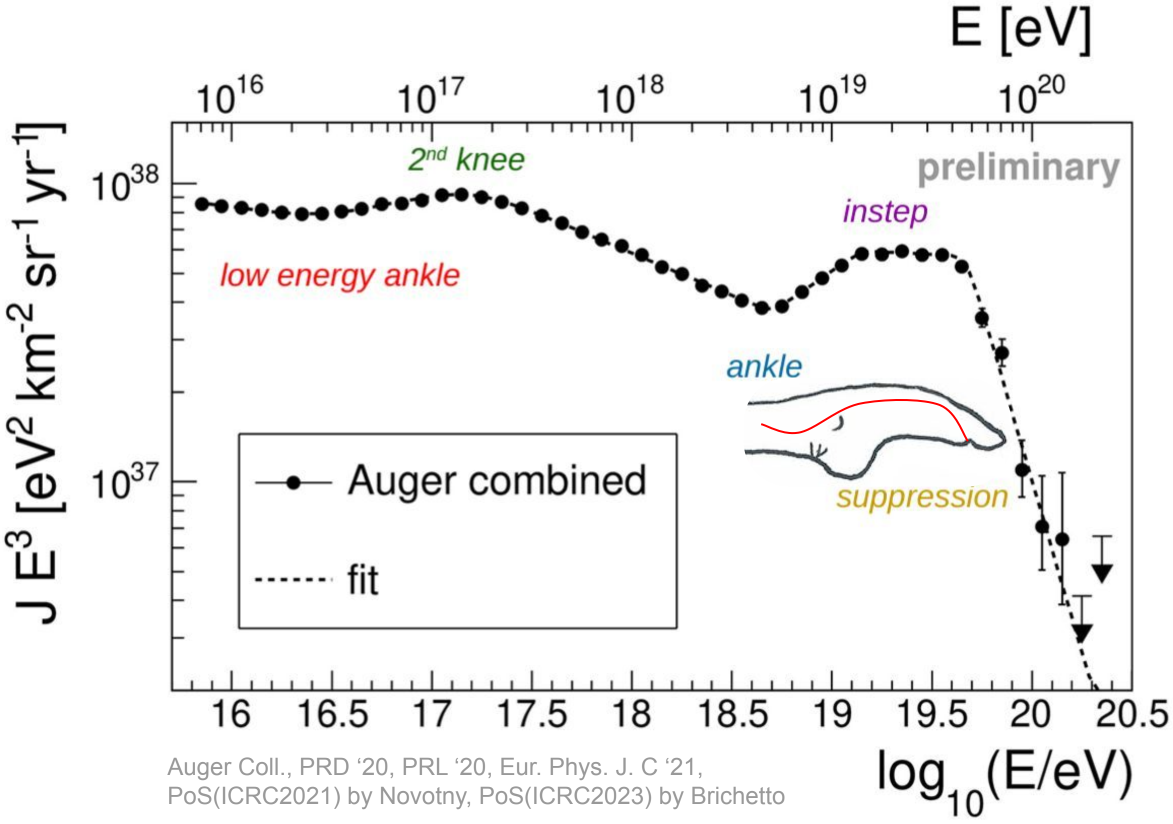
fully ionized H and He (~~heavier~~)
with absorption features due to extragalactic propagation



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

Today's picture

PIERRE AUGER OBSERVATORY



Auger Coll., PRD '20, PRL '20, Eur. Phys. J. C '21, PoS(ICRC2021) by Novotny, PoS(ICRC2023) by Brichetto

fit parameters (± stat. ± syst.)

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

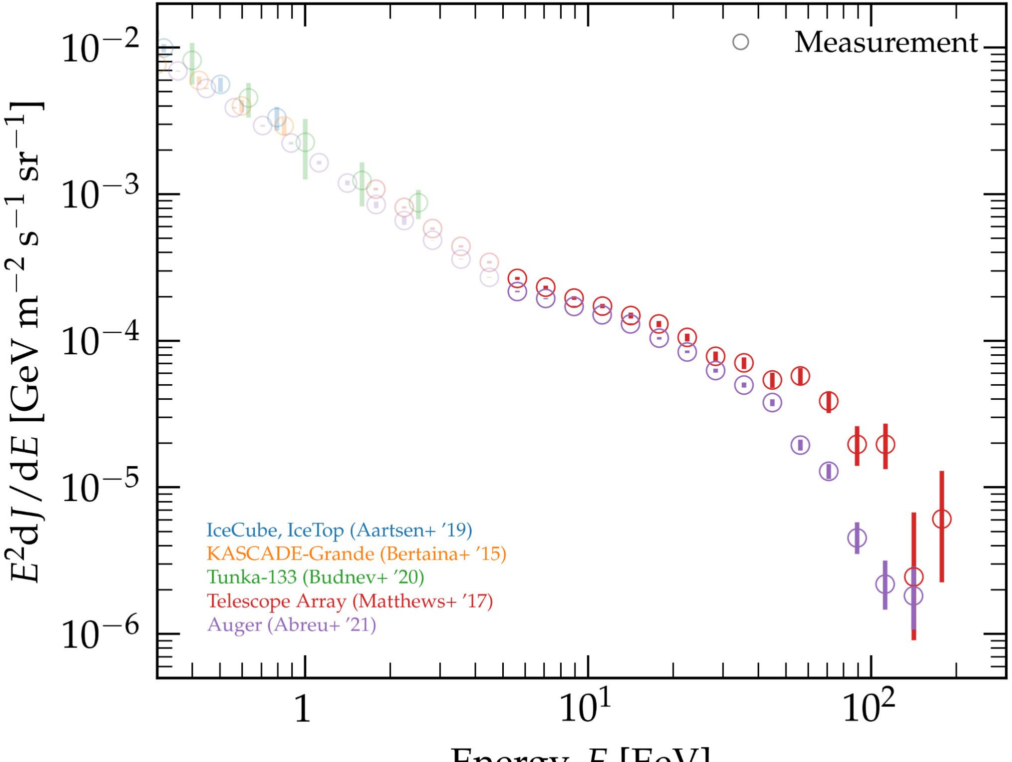
$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

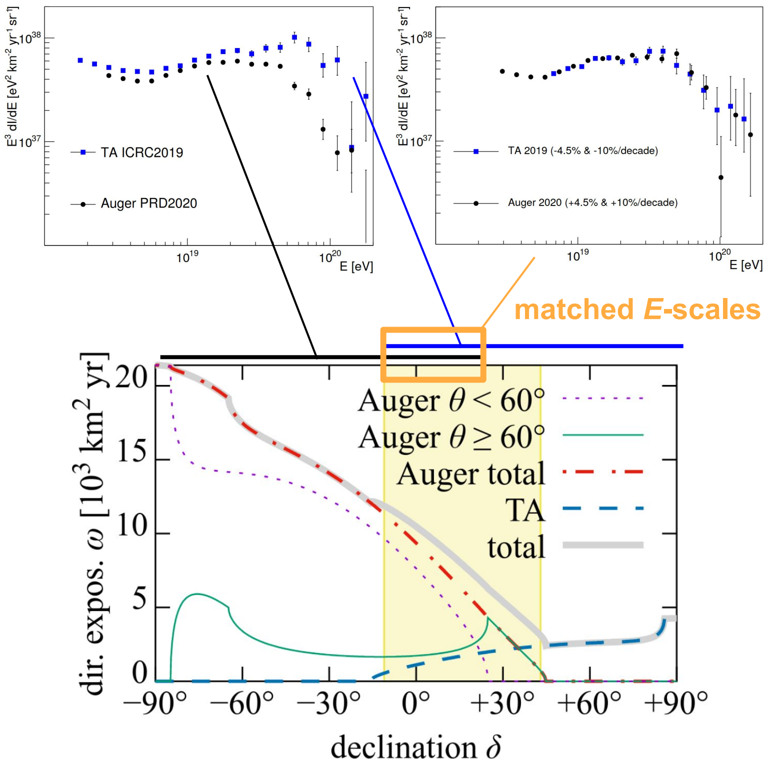
$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}\ km^{-2}\ sr^{-1}\ yr^{-1}\ eV^{-1}$

The UHECR Background



Credits: J. Biteau '22

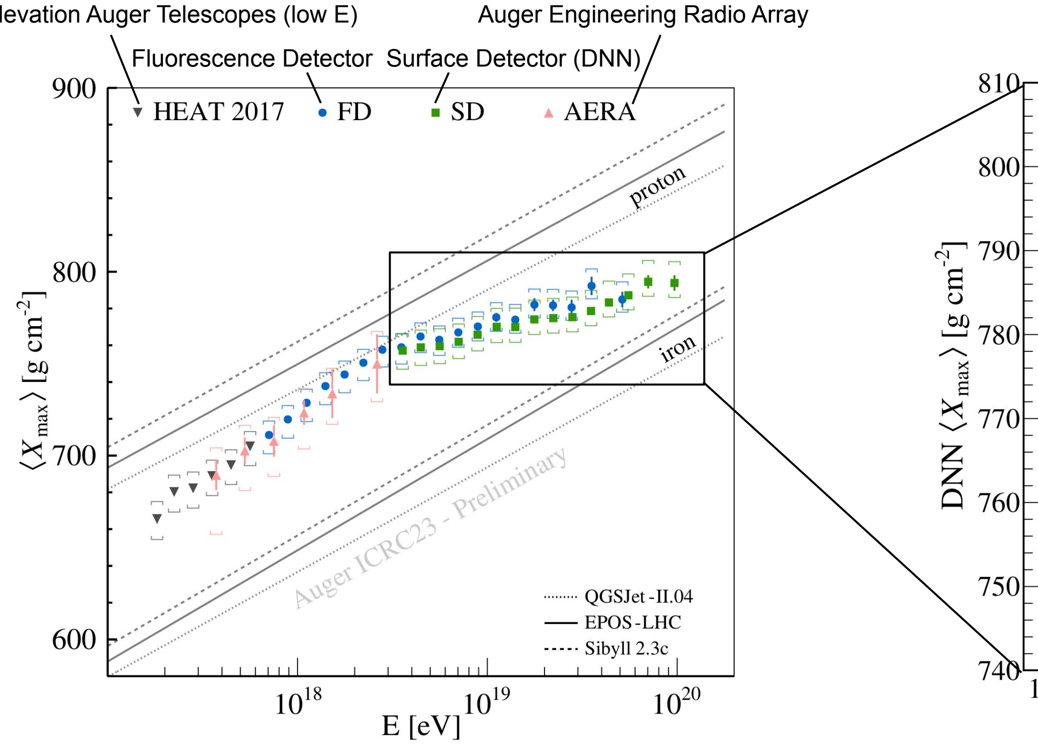
Credits: Tsunesada+ '21

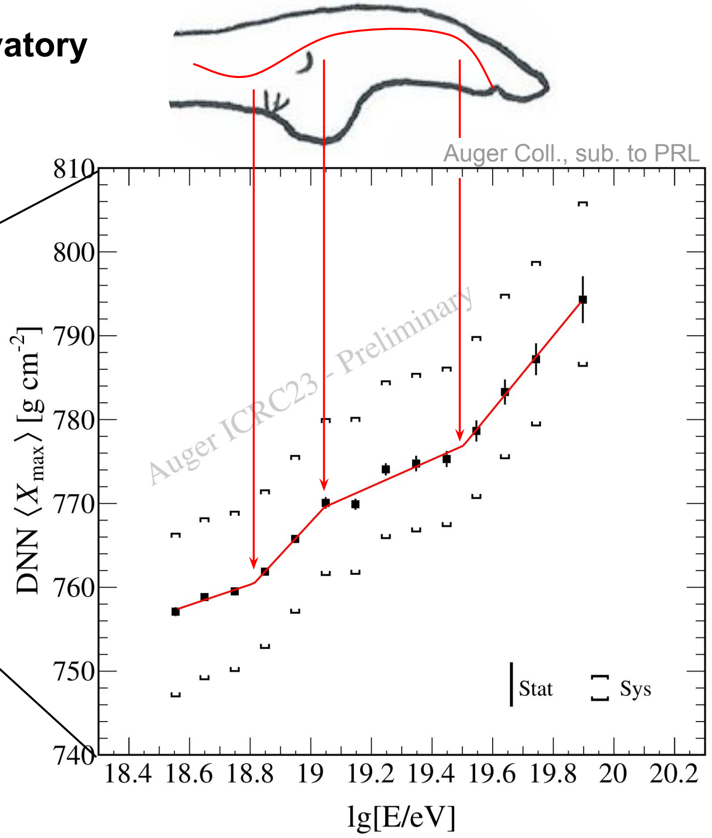


Credits: Tinyakov+ '21

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

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





Auger Coll., PoS(ICRC23) by Salamida

Plausible ultra-high energy accelerators

Hillas: only the highest-energy

Confinement, i.e. large B-field, size, and shock velocity:
$B \times (r \times \Gamma) \times \beta_{shock} > (E / Ze)$.

Hillas-Lovelace-Waxman: only the brightest

In an expanding plasma, magnetic luminosity:
$L_B > 3 \times 10^{44}$ erg/s $\times$ (E/Z / 10 EeV)² $\times$ (Γ^2/β_{shock} / 10).

Arrival directions: only the numerous

UHECR flux above the ankle:
number density x luminosity > 10^{30} UHECR / Mpc³ / s

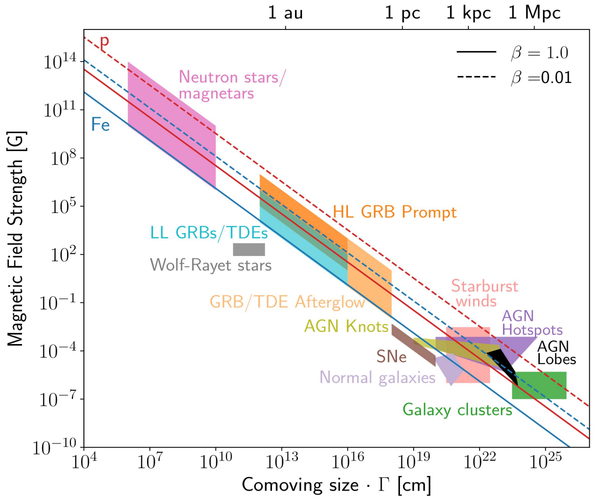
No significant self-clustering above flux suppression:
number density > 10^{-5} / Mpc³ (if deflections < 30°)

Work hypothesis: transient UHECR sources

Active Galactic Nuclei *vs* Gamma-ray bursts

Only the numerous, escape → low-luminosity preferred

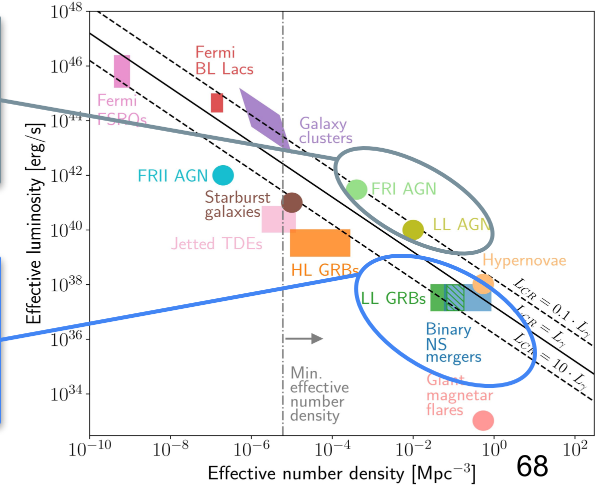
Only the brightest → constrains the min luminosity



Alves Batista+, Front.Astron.Space Sci. 6 (2019) 23

Jetted AGNs
· mostly hosted by elliptical galaxies
· traced by non-thermal emission (radio, X rays, γ rays)

Long GRBs
· mostly hosted by star-forming galaxies
· star-formation rate traced by thermal emission (UV, Hα, FIR)



Starbursts host more frequent stellar explosions…

Why would UHECR sources be transient?

➔ Hillas-Lovelace-Waxman: high-luminosity sources

➔ Composition: material from (high-mass) stars

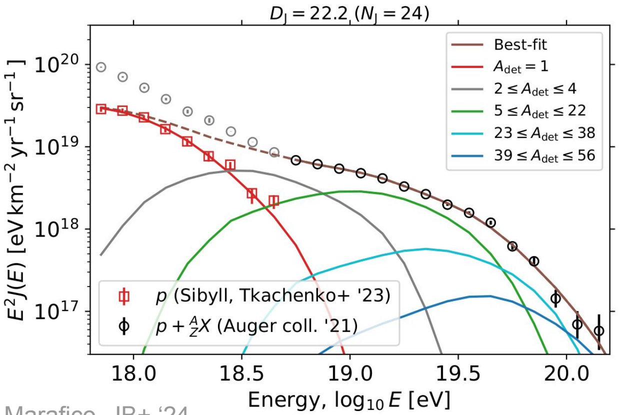
Helium / Heavy nuclei proportion (Marafico, JB+ '24)

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

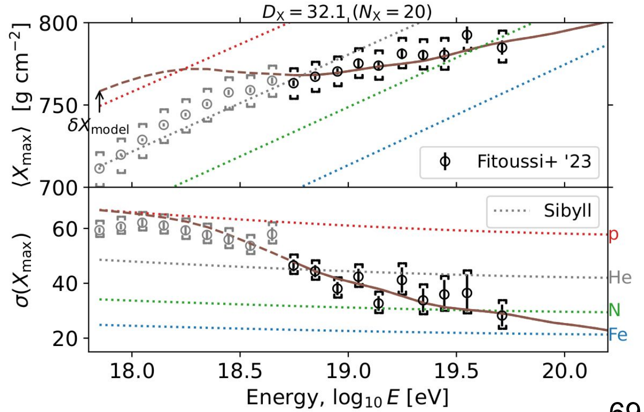
would be 18 ± 2 if ISM picked-up material

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

see also Zhang, Murase, Oikonomou '17



Marafico, JB+ '24



Exploiting the HyperLEDA database

Limitations of GLADE / MANGROVE
Mix of overlapping catalogs: risk of duplicate entries, possibly direction-dependent flux limit

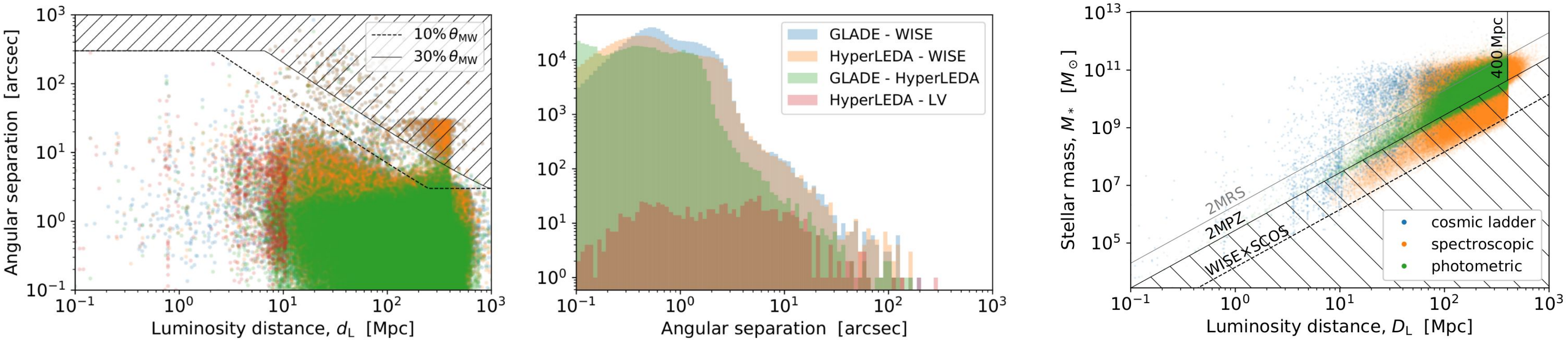
Fully exploiting distance databases
Local Volume (1k gal., *d* < 11 Mpc, Karachentsev+ 2018) and HyperLEDA (5M gal., Makarov+ 2014)

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



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)

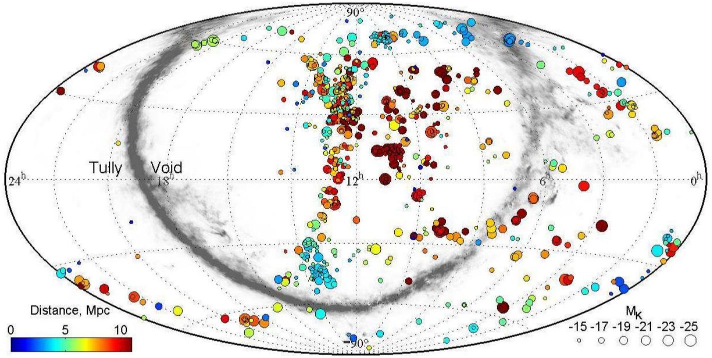
Main sequence of galaxies in the Local Volume?

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

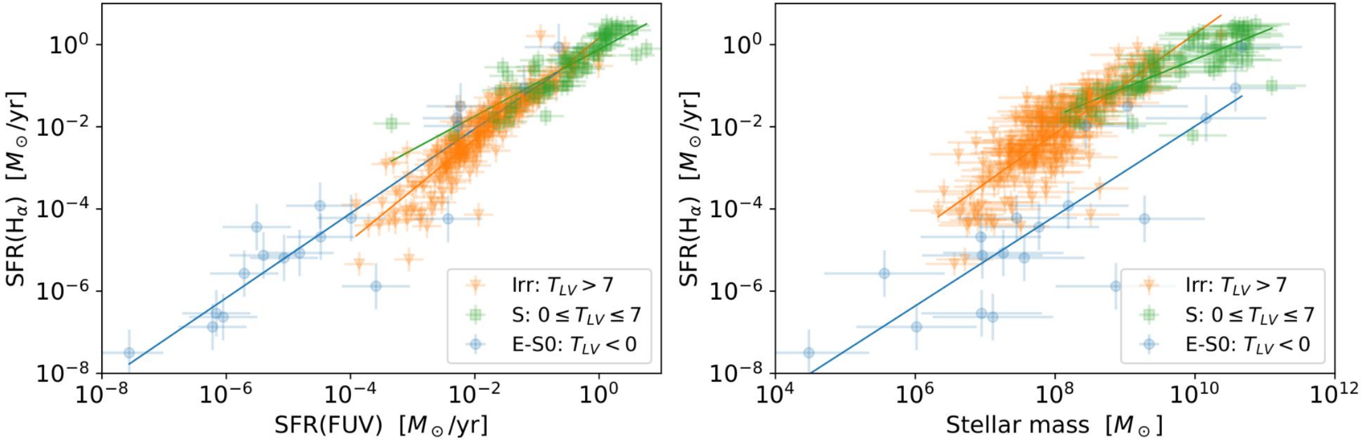
→ E-S0: linear (□ = 1.0-1.1 ± 0.10), i.e. no active star formation

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

→ Irr: super-linear (□ = 1.22 ± 0.04), active star formation <10 Myrs ago

Fit results with best morphological divide

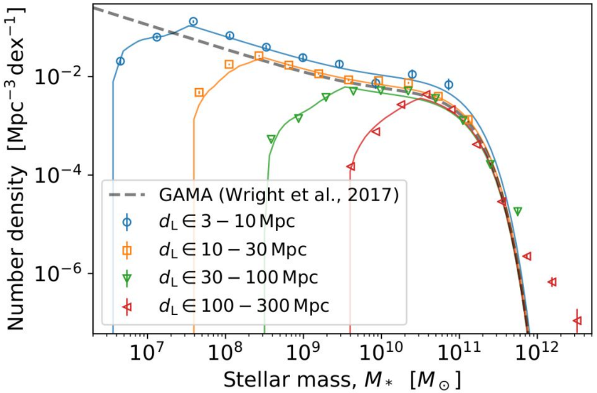
- KS-test p-value for Gaussian residuals ~ 5%, 4σ outliers → hidden variables (metallicity, environment)
- SFR dispersion of S: 0.24 dex (FUV-Hα), 0.34 dex (M_*-Hα)

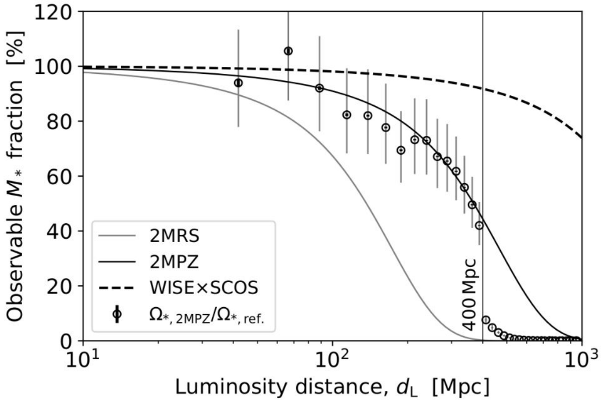


Incompleteness with increasing distance

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

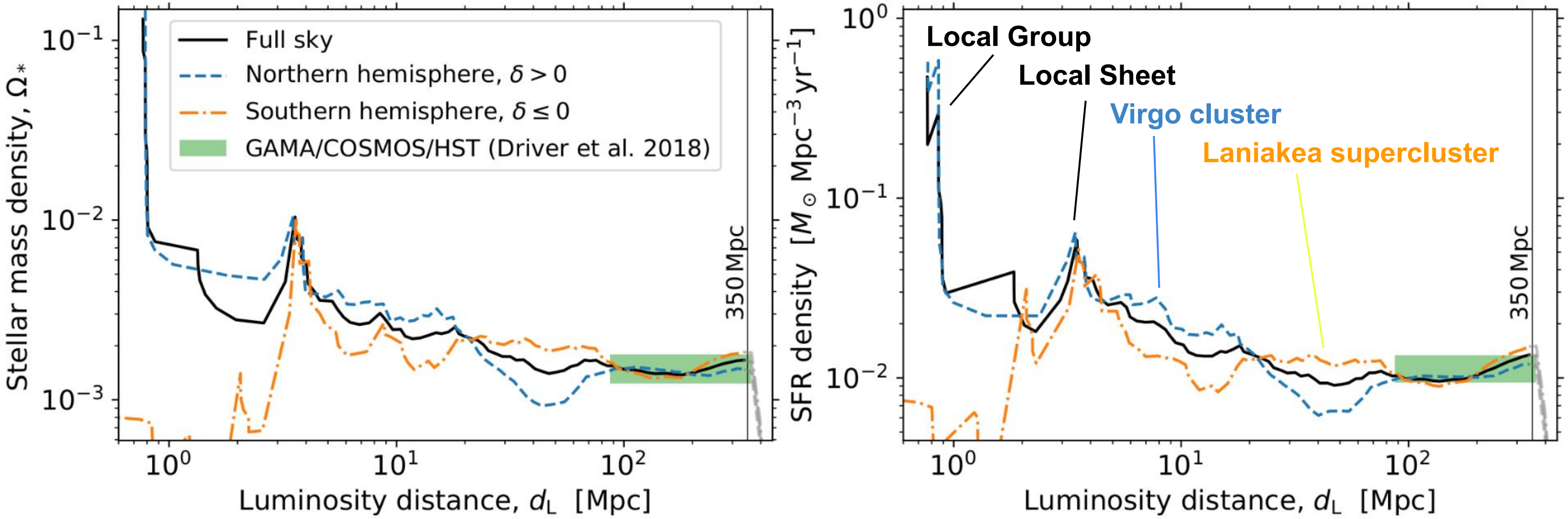
From integral of (GAMA mass function) ✕ M_* above 2MPZ sensitivity limit: weights = completeness(d) ✕ completeness(b) ∈ [0.26,1]
→ probed volume from 140 Mpc (2MRS) to 350 Mpc (2MPZ) at similar completeness: ✕ 2.6 (distance), ✕ 18 (volume)
→ further increase by ✕ 4 (distance) to be expected if full WISE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

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



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

SFR estimation in and out the Local Volume

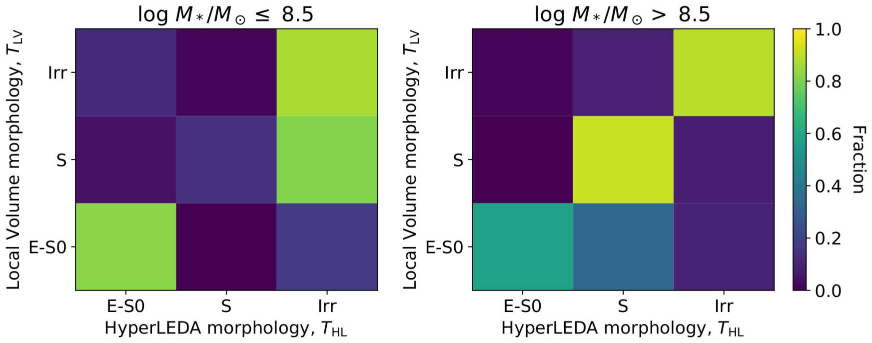
~700 galaxies with tabulated Local Volume morphology
- SFR(Hα) measured > SFR(Hα) from M_*, T_LV
→ UL / LL on SFR(Hα) if larger / lower SFR(Hα) from $M_\star$, T_LV

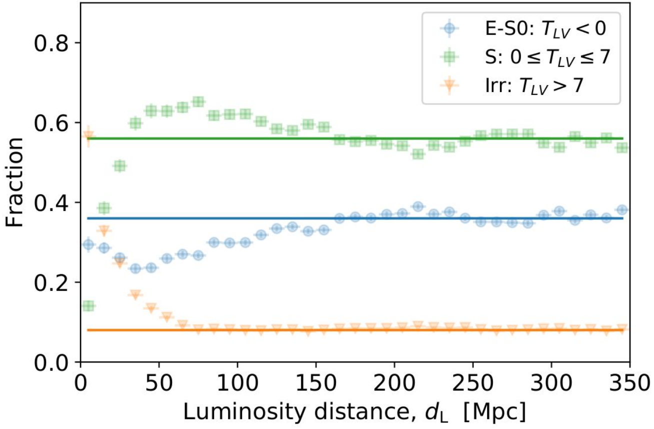
~150k galaxies with tabulated HyperLEDA morphology
- Exploit mapping of T_LV vs T_HL established in Local Volume
→ Irr / E-S0 confusion at 10-15% level
→ Mass-dependent Irr / S confusion
- SFR(Hα) from M_*, T_LV(T_HL)

~ 260k galaxies without morphological information
- Estimate average T_LV(T_HL) fraction assuming no selection bias
- Weighted average SFR(Hα) from M_*, T_LV(T_HL) for 3 morphologies

Correction for ionising fraction
- Account for ionising fraction f = 0.57 ± 0.21 (Hirashita+ 2003)
→ SFR(total) = SFR(Hα) / f - *Note: large systematic from uncertainty on f*

Incompleteness as a function of distance
- Weighted average of ∫ (GAMA mass function) × $M_\star$□: weights(d,b) ∈ [0.16,1]
→ under the assumption of constant weights vs d (partly wrong < 50 Mpc)

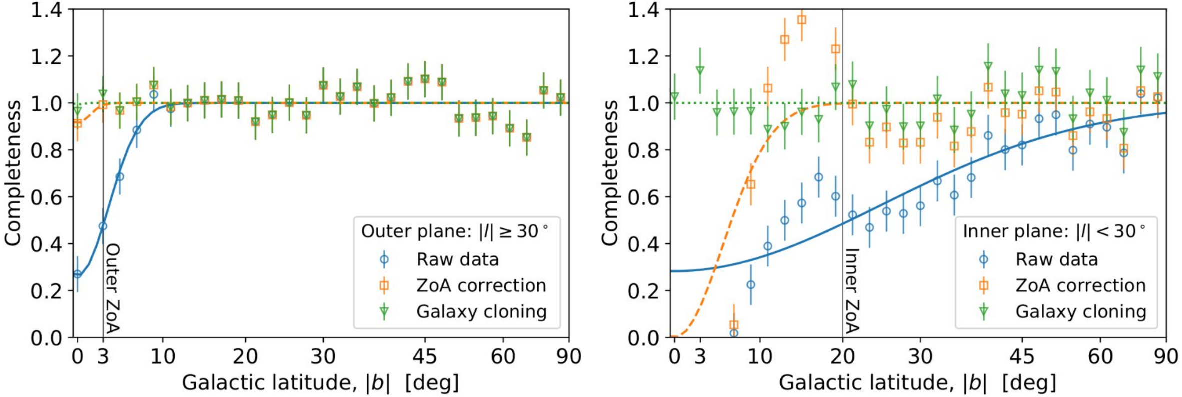




Incompleteness in the Zone of Avoidance

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