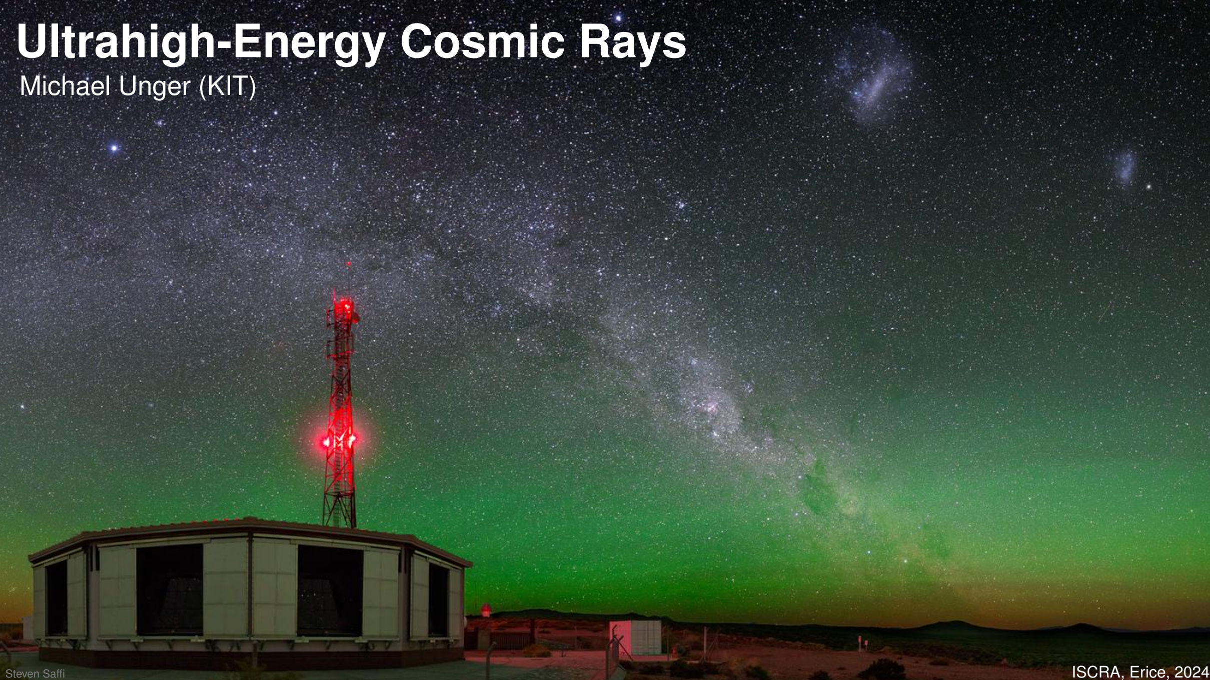
Ultrahigh-Energy Cosmic Rays

Michael Unger (KIT)



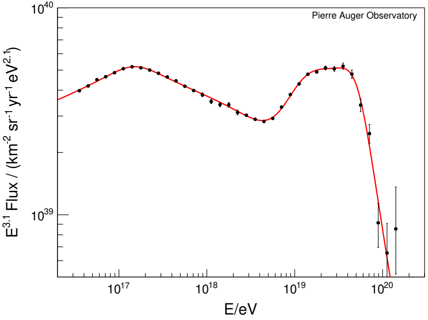
Steven Saffi

Ultrahigh-Energy Cosmic Rays

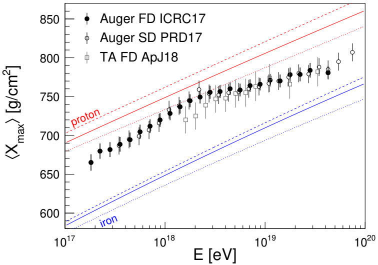
- Air Shower Physics
  (electromagnetic and hadronic showers, shower maximum, muons in air showers)
- Detection Techniques
  (particles, fluorescence- and Cherenkov-light, radio)
- **Key Observations (and their Interpretation)**
  (anisotropies, mass, spectrum, Peters cycle, propagation, cosmic magnetic fields)

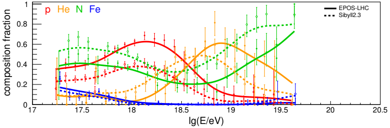
Key UHECR Observations

energy spectrum

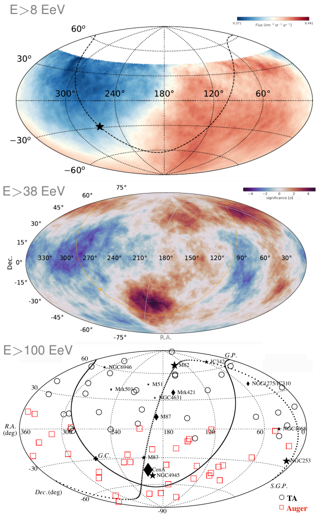


mass composition



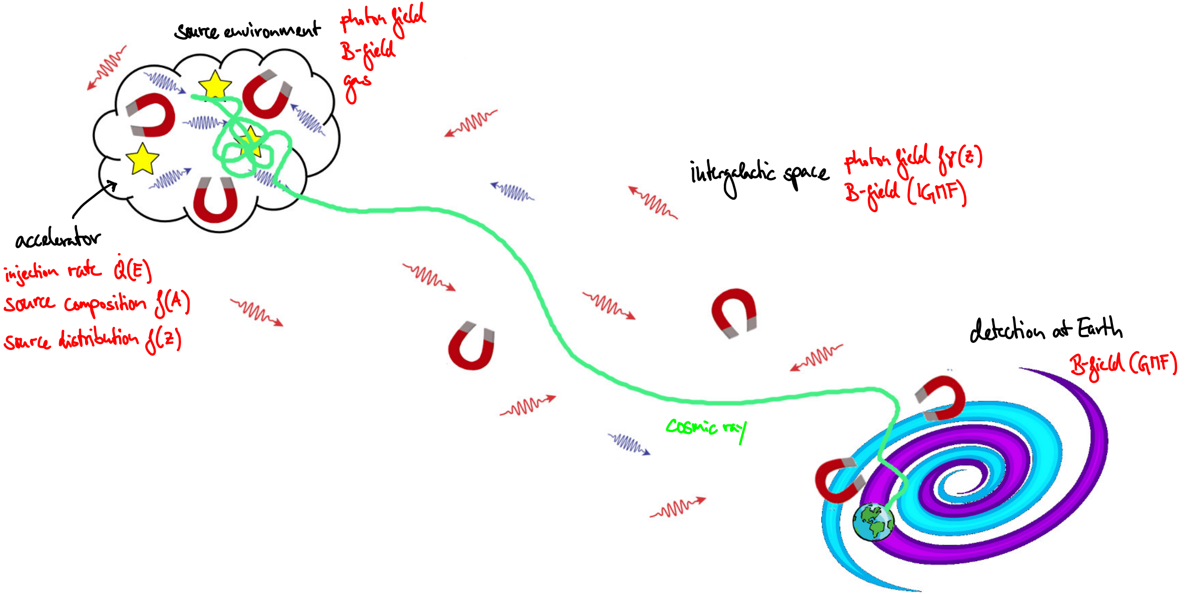


arrival directions



AND: Neutral UHE messengers (photons, neutrons, neutrinos), Hadronic Interactions (p+air cross section, muons in air showers), BSM Physics (LIV, SHDM, anitons, monopoles), ...

Extragalactic Cosmic-Ray Propagation



Greisen, Zatsepin, Kuzmin Cutoff (GZK)

$p+\gamma_{CMB} \rightarrow p+\pi^0$ or $n+\pi^+$

Penzias & Wilson 1965 (Nobel 1978)

VOLUME 16, NUMBER 17 PHYSICAL REVIEW LETTERS 25 APRIL 1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

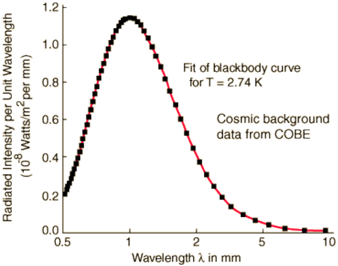
UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min

P. N. Lebedev Physics Institute, USSR Academy of Sciences

Submitted 26 May 1966

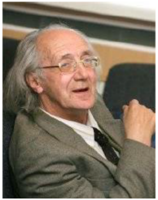
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966



at peak:

$E_\gamma = h\cdot\nu_{max}$

$\approx 10^{-3}\,\text{eV}$



Greisen, Zatsepin, Kuzmin Cutoff (GZK)

$$p_{CR} + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ \, \bar{\nu}_\mu \, \nu_e$$

$$\Delta^+ \rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma\gamma$$

Cosmogenic photons and neutrinos !!

Greisen, Zatsepin, Kuzmin Cutoff (GZK)

$$p_{CR} + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ \, \bar{\nu}_\mu \, \nu_e$$

$$\Delta^+ \rightarrow p + \pi^0, \quad \pi^0 \rightarrow \gamma\gamma$$

Cosmogenic photons and neutrinos !!

Reminder:

- 4-vectors: $\hat{p} = (E, \vec{p})$
- invariant mass: $\hat{p}^2 = m^2$ $(c=1)$
- scalar product: $\hat{p}_1 \cdot \hat{p}_2 = E_1 E_2 - \vec{p}_1 \vec{p}_2$

4-momentum conservation:

$$(\hat{p}_p + \hat{p}_\gamma)^2 = (p_n + p_\pi)^2 \overset{\text{at rest}}{=} (m_p + m_\pi)^2$$

$$= \hat{p}_p^2 + 2\hat{p}_p \hat{p}_\gamma + \hat{p}_\gamma^2 = m_p^2 + 2\,(E_p, \vec{p}_p)(E_\gamma, \vec{p}_\gamma) + 0$$

$$= m_p^2 + 4 E_p E_\gamma$$

using $|\vec{p}_p| = \sqrt{E_p^2 - m_p^2} \approx E_p$, $|\vec{p}_\gamma| = E_\gamma$

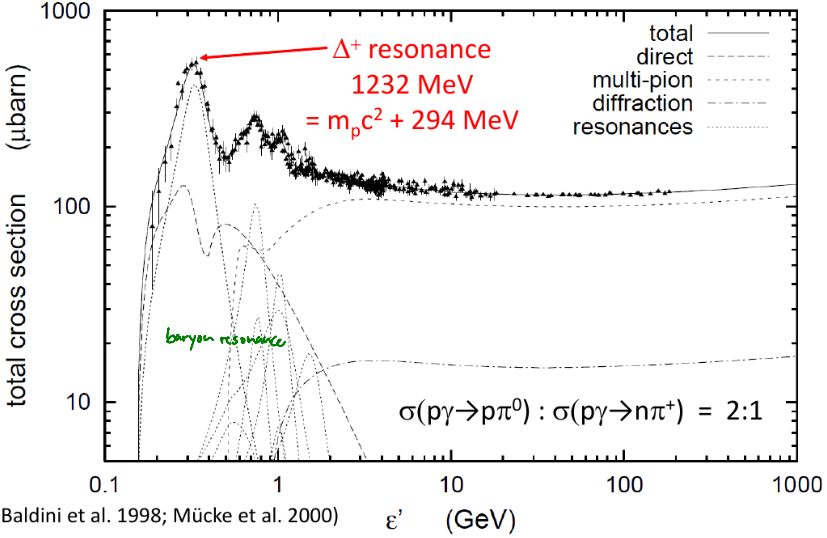
head-on collision

$$\boxed{E_{GZK} = \frac{(m_n + m_\pi)^2 - m_p^2}{4 E_\gamma} = 7 \cdot 10^{19}\,\text{eV}}$$

$\Leftrightarrow$ flux suppression ?!?

Photo-Pion Production

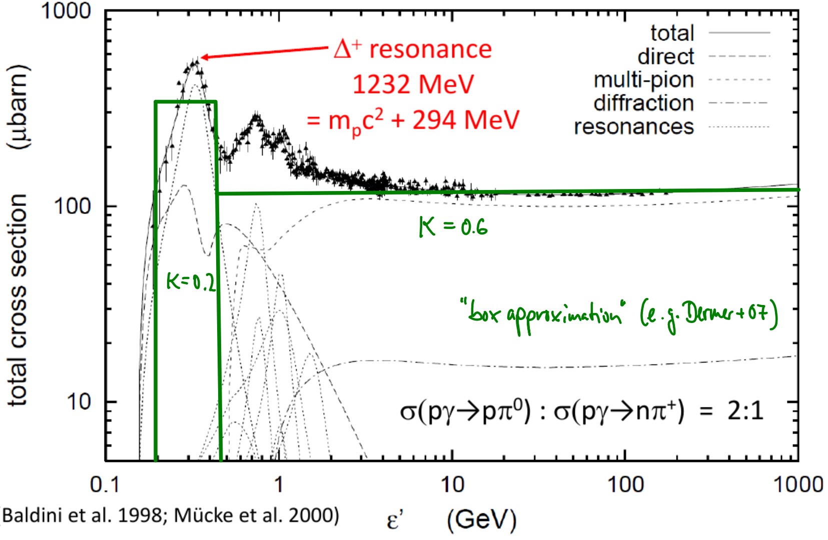
proton at rest



(Baldini et al. 1998; Mücke et al. 2000)

Photo-Pion Production

proton at rest



(Baldini et al. 1998; Mücke et al. 2000)

Photo-Pion Production

- interaction length:

  $$\lambda = (\sigma \cdot n)^{-1}$$ (σ: cross section, n: number density)

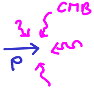
  e.g. $n_{CMB} = 400/cm^3$, $\sigma_{photopion} \approx 0.35\,mb$ $\rightarrow$ $\lambda \approx 2\,Mpc$

- inelasticity: relative energy loss per interaction: $\kappa \approx m_\pi/(m_p + m_\pi) = 0.125$

- energy loss length: $\chi = -c\left(\frac{1}{E}\frac{dE}{dx}\right)^{-1} = \frac{\lambda}{\kappa} \approx 20\,Mpc$ $\left(\frac{1}{E}\frac{\Delta E}{\Delta x} = -\frac{1}{E}\,\frac{\kappa \cdot E}{\lambda}\right)$

  $\Rightarrow$ GZK sphere: high energy particles must be produced "nearby"

- full calculation: integrate $\sigma(\varepsilon')$ over photon energy spectrum $n(\varepsilon)$ and isotropic photon directions



Lorentz-trafo to p rest frame:

$$\varepsilon' = \Gamma\,\varepsilon\,(1 - \beta_p \cos\theta)$$

using box approximation $\chi \approx \frac{13.7\,Mpc}{e^{-Y}(1+Y)}$ $\quad Y = 4 \cdot 10^{20}\,eV/E$

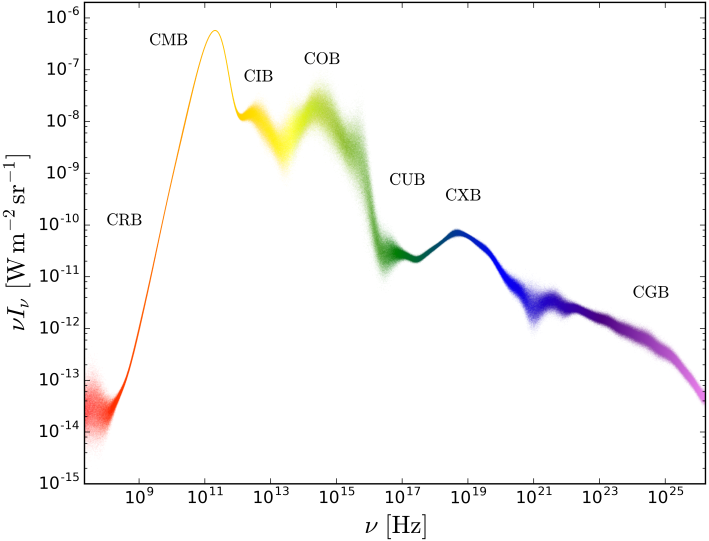
Extragalactic Photon Fields

spectral energy distribution $\nu I_\nu \equiv \nu \frac{dI}{d\nu} \sim E^2 \frac{dn}{dE}$

- extragalactic background light "EBL"
  starformation + AGN (redshifted)

- $\nu_{EBL}^{peak} \approx 10^2 \nu_{CMB}^{peak}$

$\Rightarrow$ threshold $\sim 10^{-2} E_{GZK} \approx 10^{18}$ eV



arXiv:1802.03694

Pair Production and Adiabatic Loss

- $p + \gamma \rightarrow p + e^+ + e^-$
- inelasticity: $\quad \kappa_{e^+e^-} = \dfrac{2m_e}{m_p + 2m_e} \approx 10^{-3}$
- $\dfrac{\kappa_\pi \sigma_\pi}{\kappa_{e^+e^-} \sigma_{e^+e^-}} = 100 \quad \Rightarrow \chi_{e^+e^-} = 100\, \chi_\pi$

$$E_{e^+e^-} = \frac{(m_p + 2m_e)^2 - m_p^2}{4E_\gamma} = 5 \cdot 10^{17}\, eV$$

(replace m_π with $2m_e$ in GZK equation)

Pair Production and Adiabatic Loss

- $p + \gamma \rightarrow p + e^+ + e^-$

- inelasticity: $K_{e^+e^-} = \frac{2m_e}{m_p + 2m_e} \approx 10^{-3}$

- $\frac{K_\pi \sigma_\pi}{K_{e^+e^-} \sigma_{e^+e^-}} = 100 \Rightarrow \chi_{e^+e^-} = 100\, \chi_\pi$

$$E_{e^+e^-} = \frac{(m_n + 2m_e)^2 - m_p^2}{4E_\gamma} = 5 \cdot 10^{17}\, eV$$ (replace m_π with $2m_e$ in GZK equation)

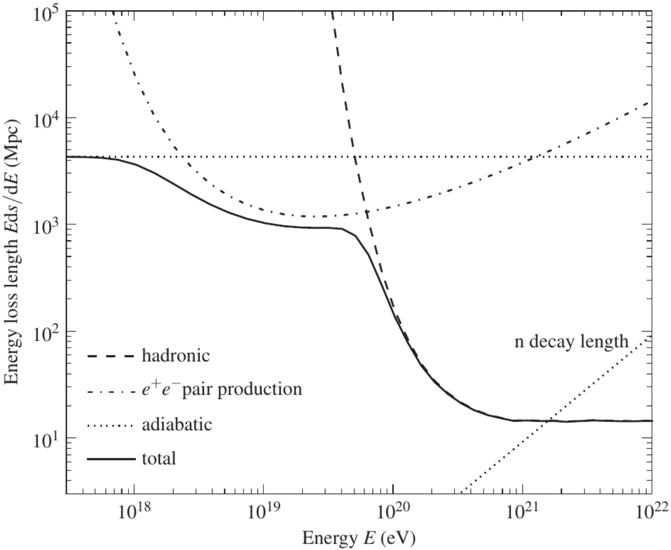
$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0}$

- expansion of universe: (z: redshift)

$z = \frac{H_0 \cdot D}{c}$ $\quad H_0 \approx \frac{70\, km/s}{Mpc}$

$$E_{earth} = E_{source} / (1 + z_{source}) \quad \underset{z=0}{\leftrightarrow} \quad \frac{1}{E}\frac{dE}{dt} = -H_0 \quad \leftrightarrow \quad \chi = c/H_0 \approx 4\, Gpc$$

Energy Loss of Protons (z=0)



Gaisser, Engel & Resconi, “Cosmic Rays & Particle Physics”

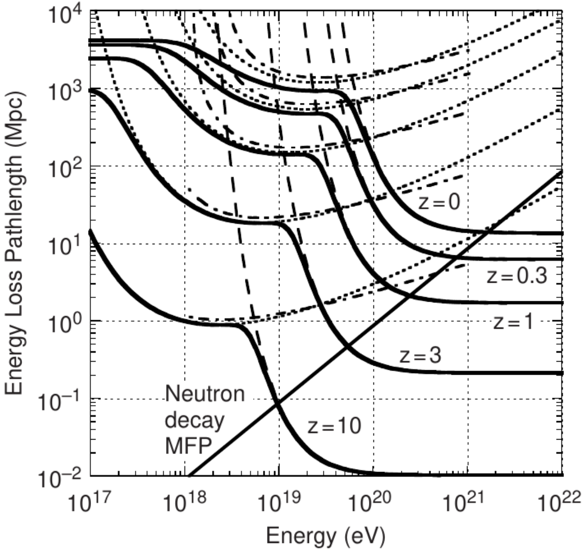
Energy Loss of Protons

cosmological distances:

CMB temperature: $T(z) = T_0\,(1+z)$

CMB density: $n(z) = n_0\,(1+z)^3$

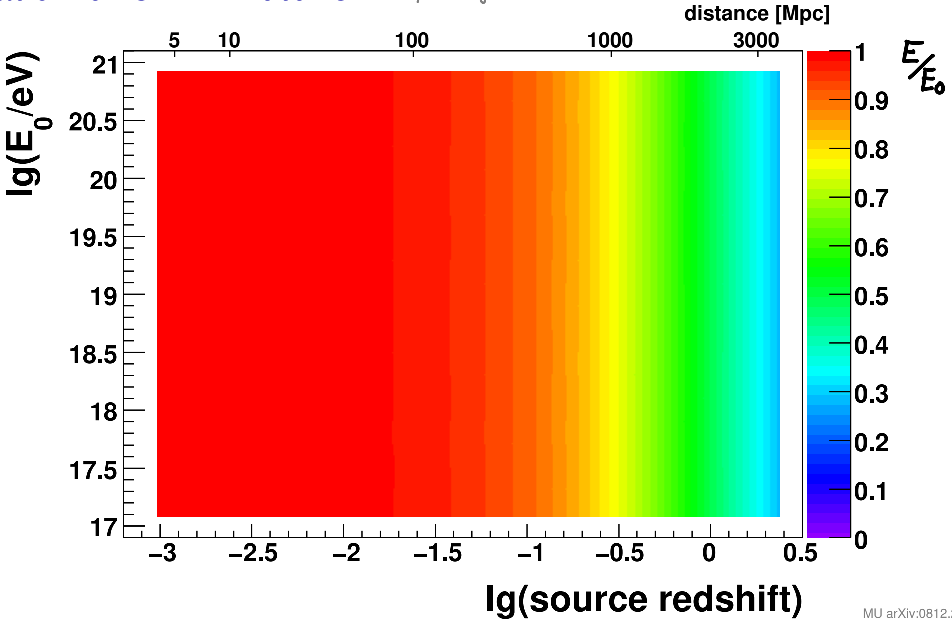
$$\Rightarrow \chi(E,z) = (1+z)^{-3}\,\chi((1+z)\cdot E, 0)$$



Dermer & Menon, "High Energy Radiation from Black Holes"

Propagation of UHE Protons

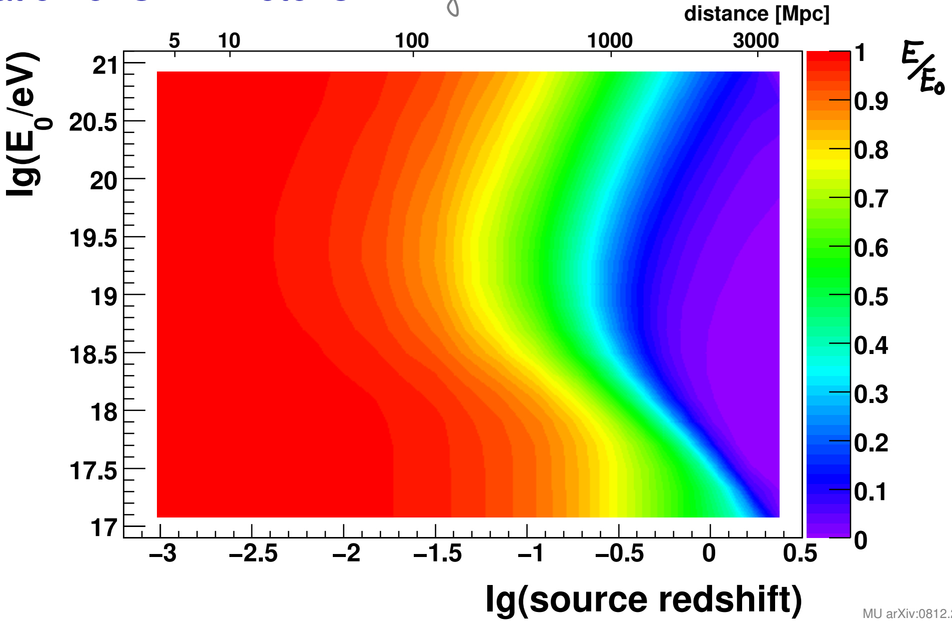
only redshift



MU arXiv:0812.2763

Propagation of UHE Protons

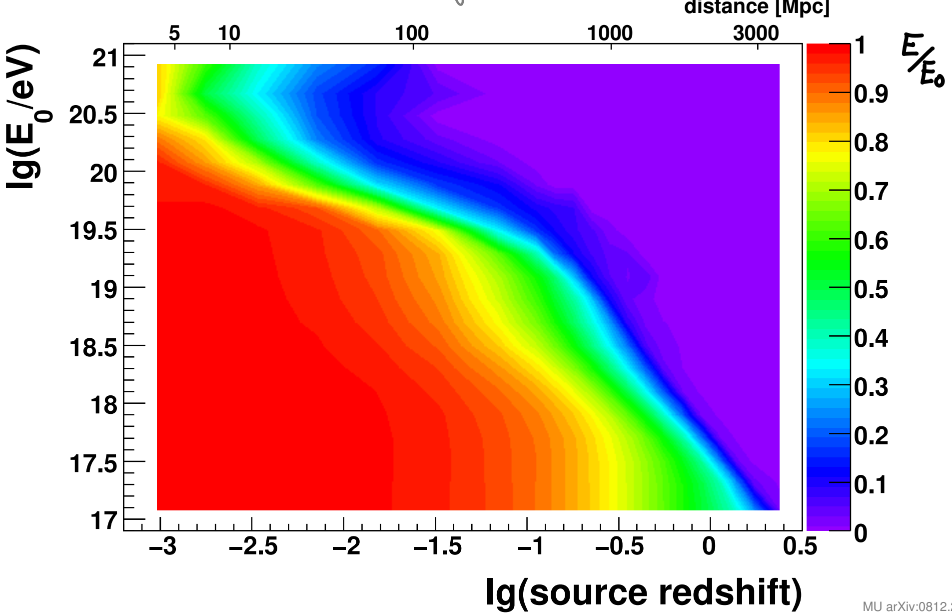
redshift + e⁺e⁻



MU arXiv:0812.2763

Propagation of UHE Protons

redshift + e^+e^- + photo-pion



MU arXiv:0812.2763

Propagation of UHE Nuclei

$(A,Z)+\gamma \to (A',Z') + (Z-Z')p + (A-A'-(Z-Z'))n$

(d, t, He, ... emission also possible)

- giant dipole resonance (GDR)

  collective oscillation of all p vs. all n

  mostly $A+\gamma \to (A-1) + n/p$

- quasi deuteron scattering (QD)

  scattering with n+p pair → p+n emission

- baryon resonances (BR)

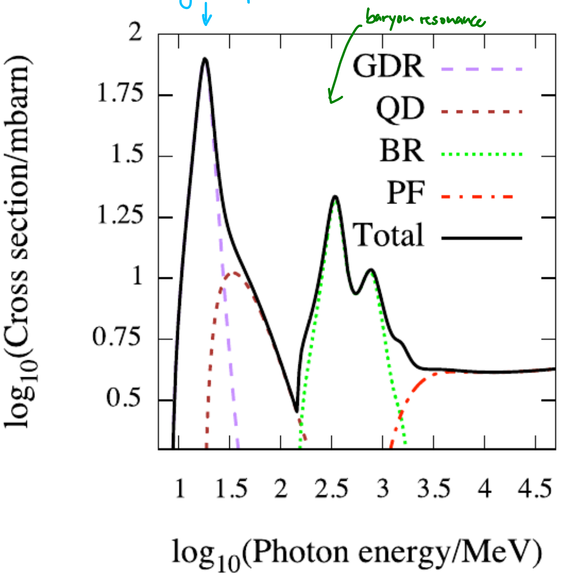
  photo-pion with nucleon $\langle N_{n/p}\rangle \approx 6$ (+π-production!)

- photo fragmentation (PF)

  nucleus breakup

iron at rest

M. De Domenico, EPJ 128 (2013) 99



Propagation of UHE Nuclei

D.Allard APP 39 (2012) 33

- Inelasticity of GDR:

  $A + \gamma \to (A-1) + n/p$

  $\Rightarrow$ energy loss per interaction: $\kappa \sim \frac{1}{A}$

  $\Rightarrow \kappa(He) = 0.25\,,\ \kappa(Fe) = 0.018$

- cross section:

  $\sigma_{GDR} \sim A \ \Rightarrow\ \kappa \cdot \sigma \approx \text{const}\,!$ Same for all A!

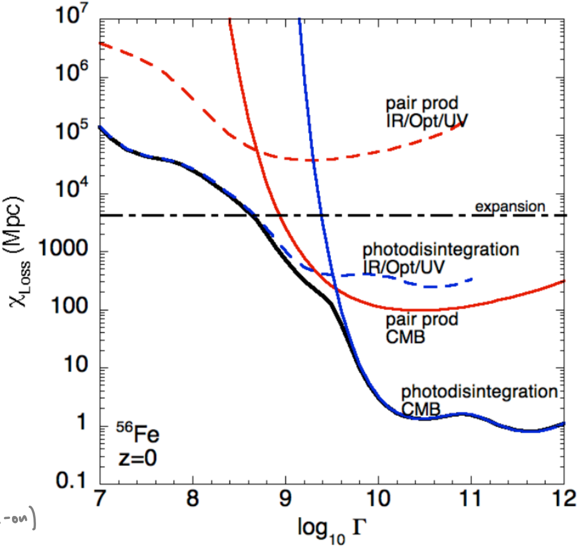
- $\sigma_{Fe} \approx 30\,\text{mb} \ \Rightarrow\ \frac{\chi_{Fe}}{\chi_p} \approx \frac{(\sigma_\pi \kappa_\pi)_p}{(\sigma_{GDR} \cdot \kappa_{GDR})_{Fe}} \approx 0.1$

- $\varepsilon'_{GDR} \approx 20\,\text{MeV}$ in nucleus rest frame. Same for all A!

  $\Rightarrow$ same Lorentz-boost needed for all nuclei

  $\Gamma_{GDR} = \frac{E}{A \cdot m_p} = \frac{\varepsilon'_{GDR}}{2\,\varepsilon} \approx \frac{20\,\text{MeV}}{2 \cdot 10^{-3}\,\text{eV}} = 10^{10}$ (head-on)

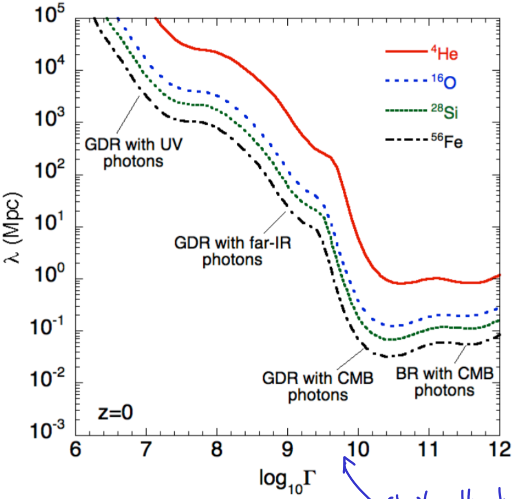
  $\Rightarrow$ cosmic coincidence $\quad E^{p}_{\text{photo-}\pi} \approx E^{Fe}_{GDR}$ (threshold energies in full calculation $\Rightarrow$ see next page)



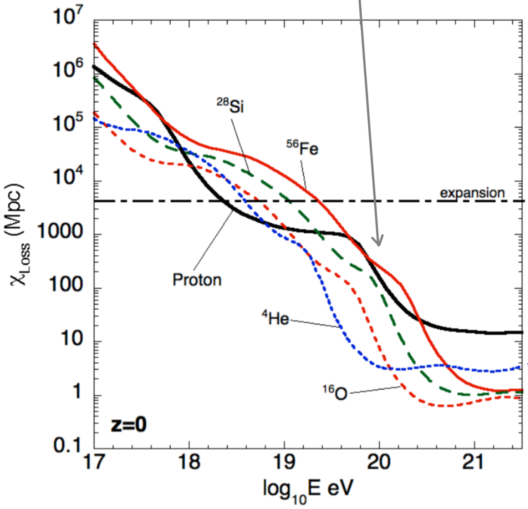
Propagation of UHE Nuclei

D.Allard APP 39 (2012) 33

similar loss length p/Fe at UHE



$\sigma \sim A$
$\Leftrightarrow \lambda \sim 1/A$



$\}$ K·σ similar

Lorentz-factor $\Gamma = E/A \cdot m_p$

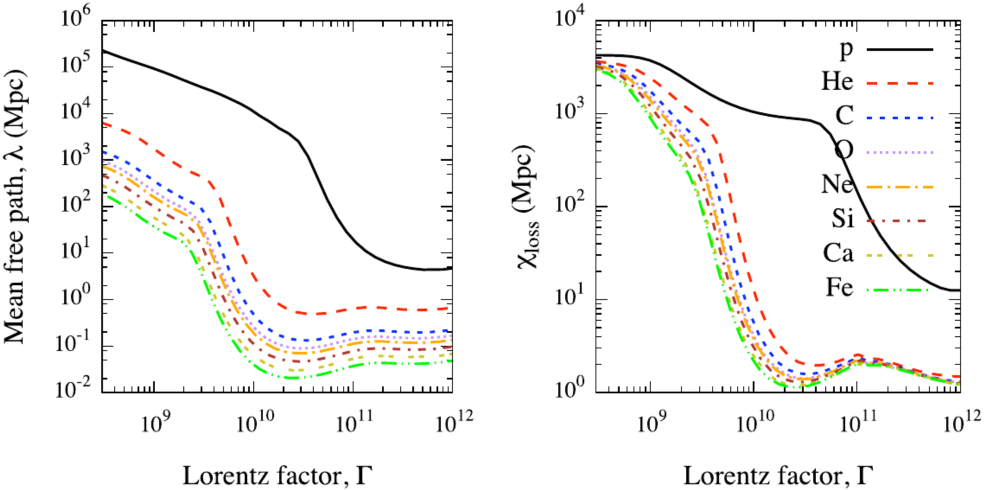
similar threshold in Γ!

different threshold in E!

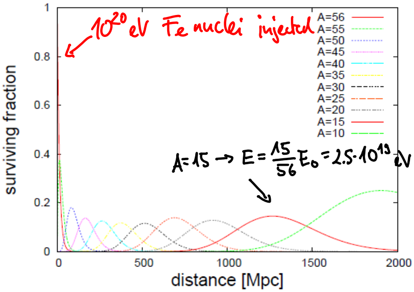
Propagation of UHE Nuclei

(variation of previous slide)

M. De Domenico, EPJ 128 (2013) 99



Propagation of UHE Nuclei



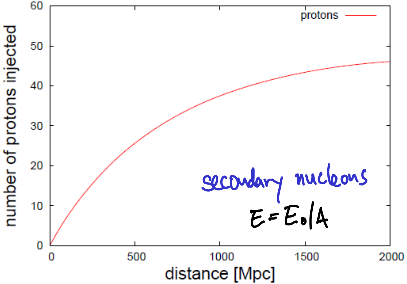
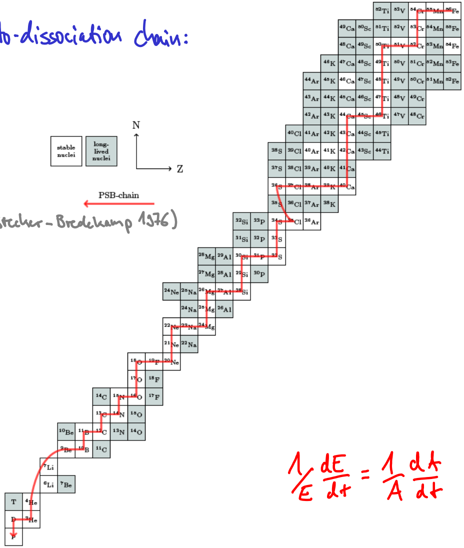


photo-dissociation chain:



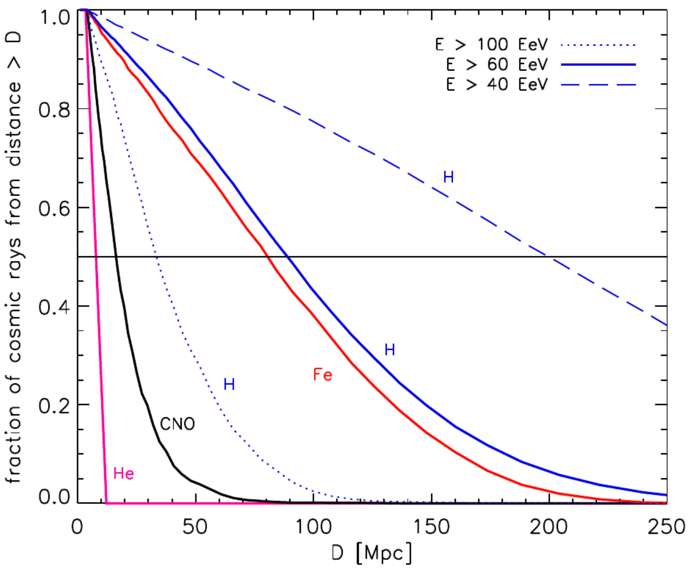
(Puget-Stecker-Bredekamp 1976)

$$\frac{1}{E}\frac{dE}{dt} = \frac{1}{A}\frac{dA}{dt}$$

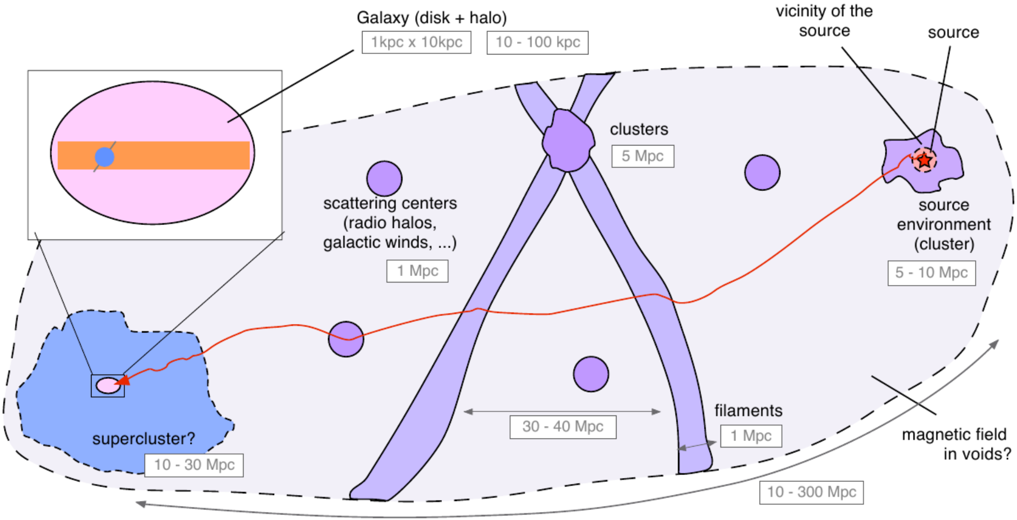
A. Taylor et al., Phys.Rev. **D77** (2008) 103007 and **D82** (2010) 123005

"GZK Sphere"

K. Kotera & A.V. Olinto ARAA 49 (2011) 119

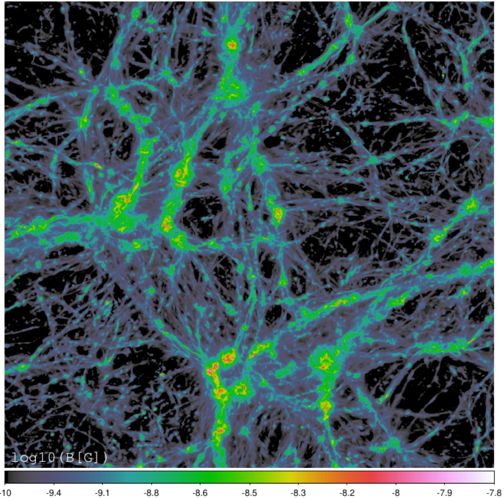


Extra- and Intergalactic Magnetic Fields

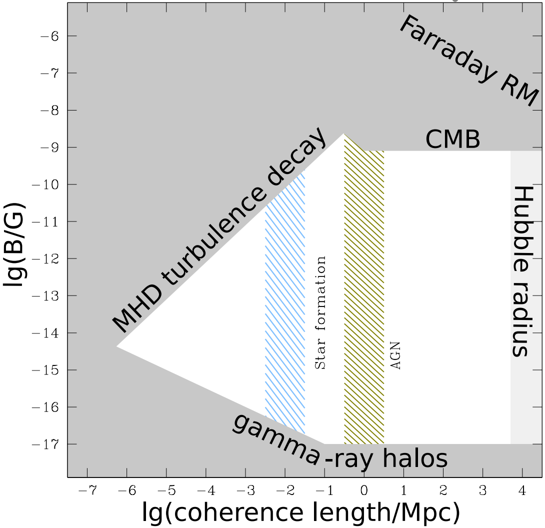


K. Kotera & A.V. Olinto ARAA 49 (2011) 119 limits (dashed: range for astrophysical origin in galaxies)

50Mpc



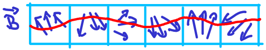
Projected (density weighted) magnetic field intensity for our 2400^3 simulation of a $(50\ \mathrm{Mpc})^3$ volume at $z = 0$.



Vazza et al. MNRAS 445 (2014) 3706

Durrer&Neronov, AAR **21** (2013) 62

Propagation Through the IGMF



$R_L > \lambda_c$

random walk in angle

- small-angle scattering for $r_L > \lambda_c$ (coherence length λ_c) $\Rightarrow$ see lecture 4

- standard deviation of deflection $\theta_{rms} = \sqrt{\langle \Delta\theta^2 \rangle}$

$$\underline{\theta_{rms} \approx 3.5^\circ \left(\frac{B}{nG}\right) \left(\frac{10^{20}\,V}{R}\right) \left(\frac{d}{100\,Mpc}\right)^{1/2} \left(\frac{\lambda_c}{1\,Mpc}\right)^{1/2}}$$

$\Rightarrow$ proton astronomy at UHE!

(maybe even carbon-astronomy if $B = 10^{-10}\,G$)

- corresponding average time delay wrt ballistic @ $v = c$

$$\underline{\langle t \rangle = 3 \cdot 10^5\,yr \left(\frac{B}{nG}\right)^2 \left(\frac{10^{20}\,V}{R}\right)^2 \left(\frac{d}{100\,Mpc}\right)^2 \left(\frac{\lambda_c}{1\,Mpc}\right)}$$

$\Rightarrow$ coincident detection of CR, γ, ν needs steady sources $> \langle t \rangle$

- magnetic horizon: $t < 1/H_0$ (Hubble time 14 Gyr)

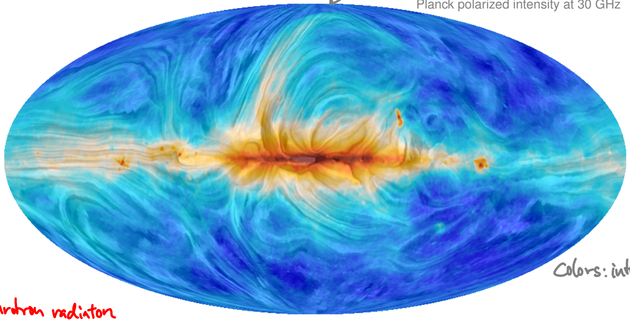
$$\underline{R \lesssim \left(\frac{B}{nG}\right) \left(\frac{\lambda_c}{1\,Mpc}\right)^{1/2} \left(\frac{d}{70\,Mpc}\right) 10^{18}\,V}$$

$\Rightarrow$ low-rigidity horizon

Galactic Magnetism

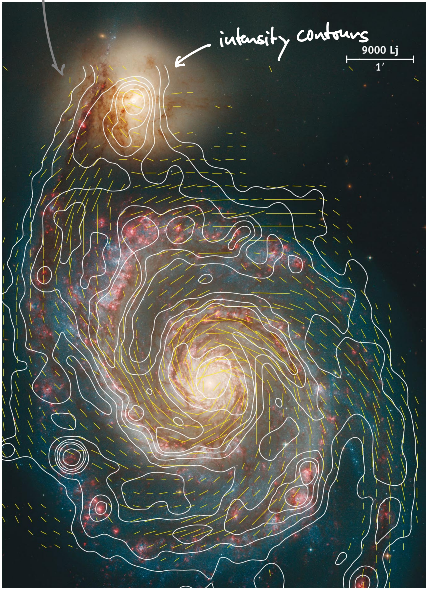
projected magnetic field orientation inferred from polarization

Planck polarized intensity at 30 GHz

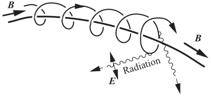


Colors: intensity

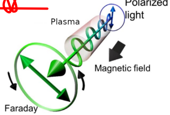
M51 (HST, MPIfR)

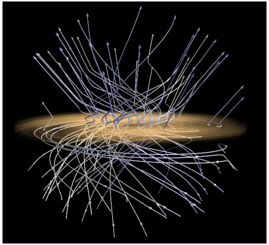


synchrotron radiaton



Faraday effect

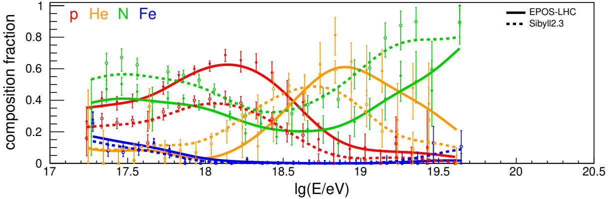


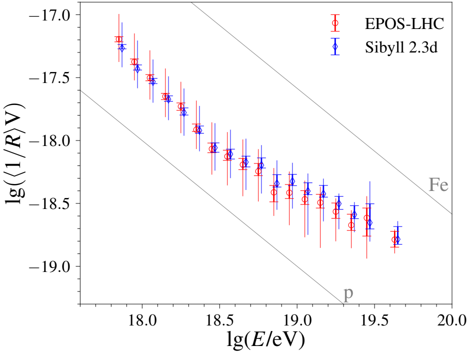


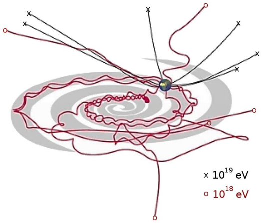
Jansson&Farrar 2012

galactic magnetic field model

Cosmic-Ray Deflections







D. Harari

- Larmor radius of charged particle in B-field

$$r = 1.1\,\mathrm{kpc}\,\frac{R/10^{18}\,\mathrm{V}}{B/\mu\mathrm{G}}$$

- rigidity

$$R = \frac{cp}{eZ} \overset{e=c=1}{=} \frac{E}{Z}$$

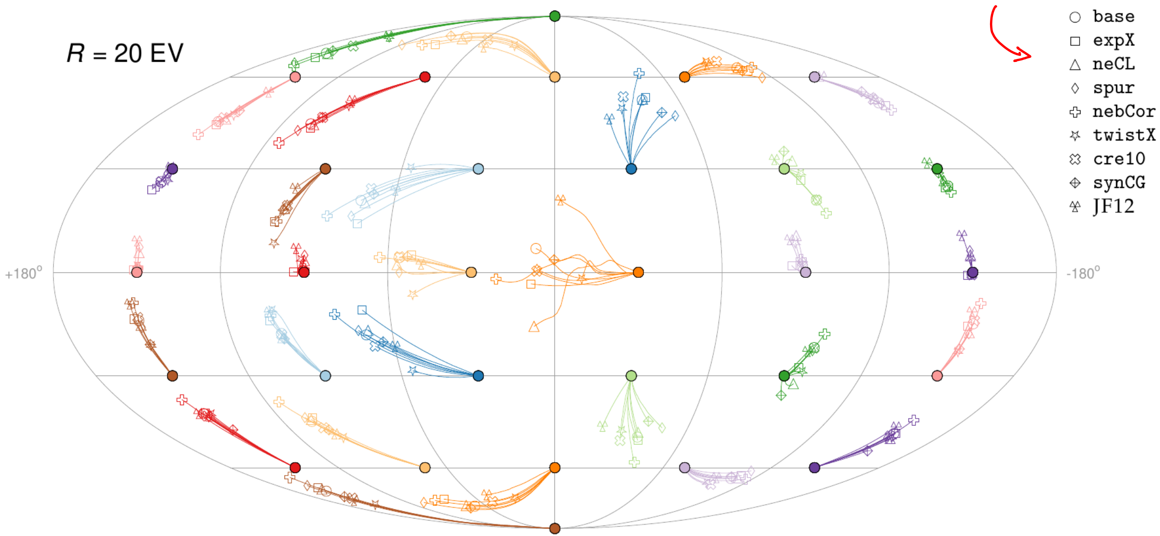
- typical GMF deflections (JF12)

$$\theta_{\mathrm{coh}} \sim 3^\circ \left(\frac{R}{10^{20}\,\mathrm{V}}\right)^{-1}$$

Pierre Auger Coll. 2014, O. Tkachenko for Snowmass 2205.05845

Deflections at 20 EV (backtracking)

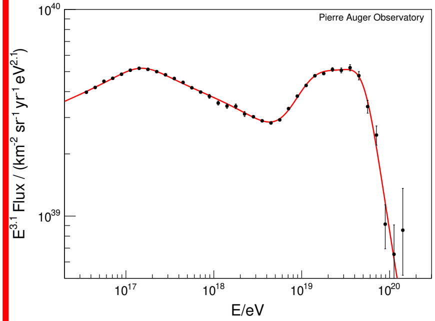
different models of the galactic magnetic field



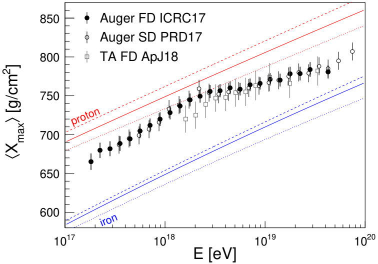
MU & G.R. Farrar, arXiv:2311.12120

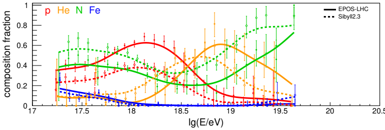
Key UHECR Observations

energy spectrum



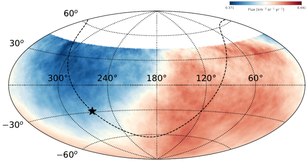
mass composition



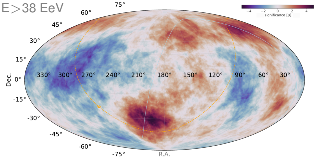


arrival directions

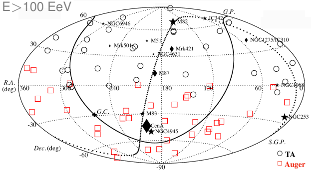
E>8 EeV



E>38 EeV



E>100 EeV



End of GCR Spectrum – Escape? → see also lecture by Jörg Hörandel

Larmor radius of charge Z in magnetic field B:

$$R_L = 1.1\ \text{kpc}\ \frac{(E/Z)/10^{18}\,\text{eV}}{B/\mu G}$$

- coherent magnetic field in galaxy:

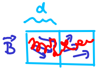
  $H \approx 500\,\text{pc}$, $\langle B \rangle \lesssim 1\,\mu G$

  $$R_L = H \Rightarrow E = \begin{cases} 5\cdot 10^{17}\,\text{eV} & Z=1 \quad (p) \\ 1\cdot 10^{19}\,\text{eV} & Z=26 \quad (Fe) \end{cases}$$

  $\Rightarrow$ free streaming out of Galaxy

- turbulent magnetic field

  coherence length $d \lesssim 100\,\text{pc}$

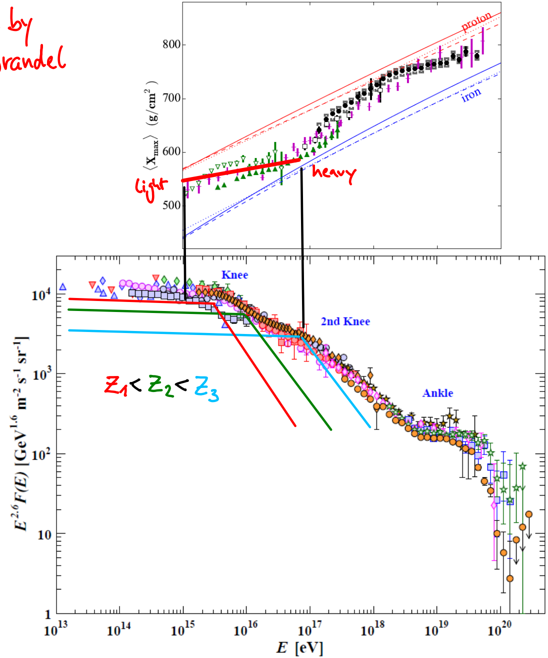


$R_L < d$

$R_L > d$

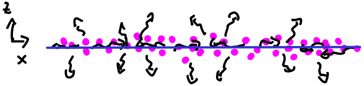
$\Rightarrow$ change of diffusion coefficient D

$\Rightarrow$ change of $\tau_{esc} \sim \frac{1}{D}$



End of GCR Spectrum – E_{max} ?

• problem with escape model: anisotropy



$J_x > J_z \leftrightarrow$ not observed!

• maximum energy in shock acceleration ?

$E_{max} \gtrsim 10^{14} \cdot Z \cdot eV$

$\Rightarrow$ same phenomenology as escape model:

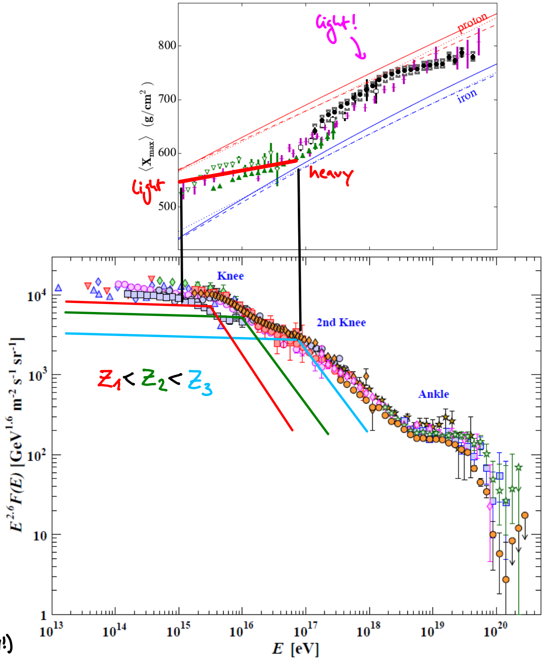
Superposition of "Knees" $\sim E \cdot Z$

"Peters Cycle"
(B. Peters 1961)

• can CRs with $E > 10^{18}$ eV be galactic ?

Composition $\rightarrow \approx p$

$\rightarrow R_L \gg H$!! $\Rightarrow$ extragalactic (otherwise huge anisotropy!)



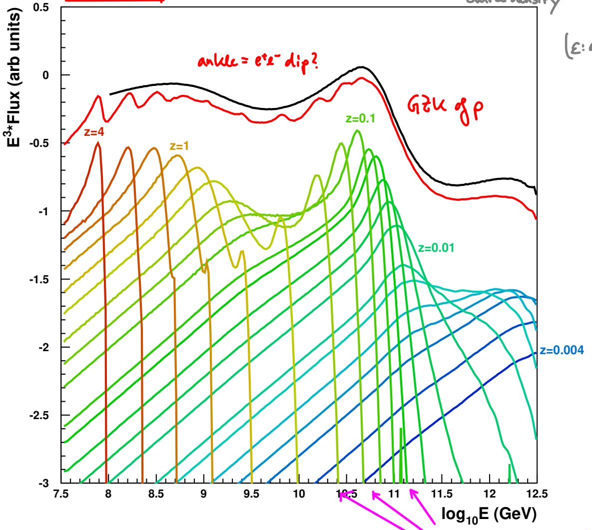
Extragalactic Protons

without cosmological corrections: (see CRPP Eq. (10.23))

$$\boxed{\phi(\varepsilon) \sim \int \frac{dN_{inj}}{dE\,dt}(E(\varepsilon))\, \underbrace{n_{src}}_{\text{source density}} \left|\frac{dE}{d\varepsilon}\right| \frac{1}{4\pi R^2}\, \underbrace{R^2\, dR\, d\Omega}_{\text{Volume}}}$$

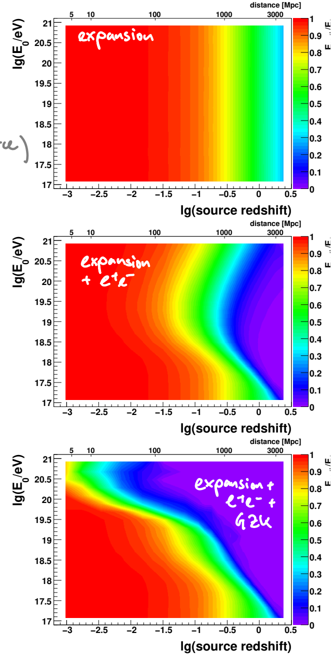
(ε: at Earth E: at source)

"dip model"



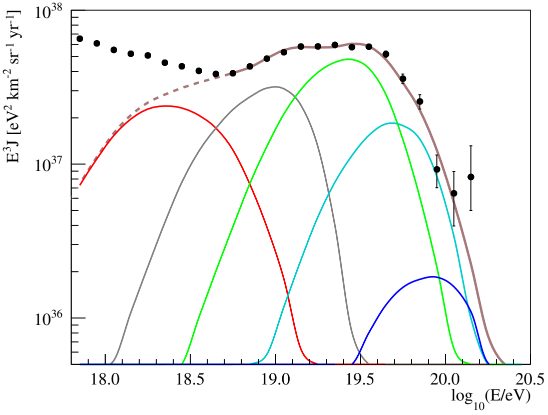
D. Bergman, 29th ICRC 2005

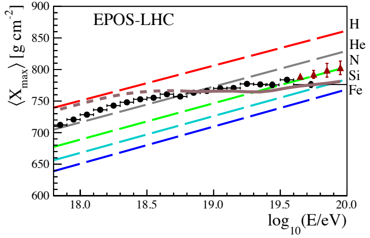
sources from different redshift shells

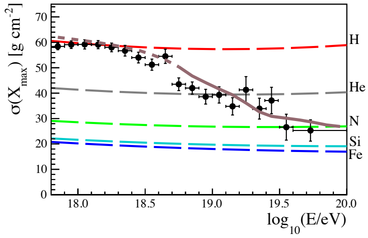


Maximum Rigidity Model, Peters Cycle?

energy spectrum at source $\propto (E/Z)^{-\gamma}$



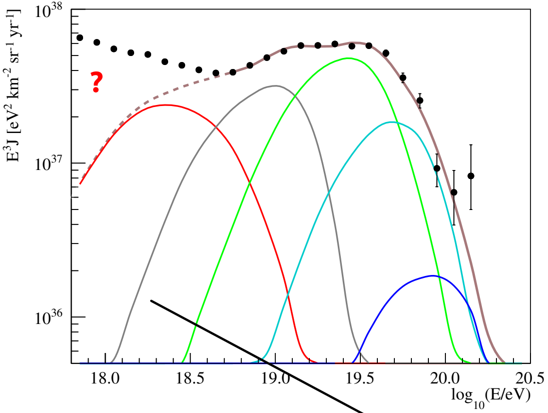


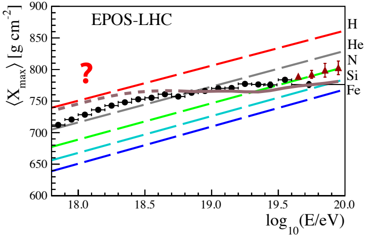


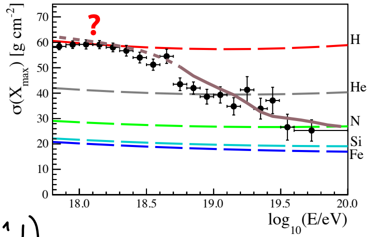
A. Castellina for the Auger Coll. ICRC19 and JCAP **1704** (2017) 038

Maximum Rigidity Model, Peters Cycle?

energy spectrum at source $\propto (E/Z)^{-\gamma}$



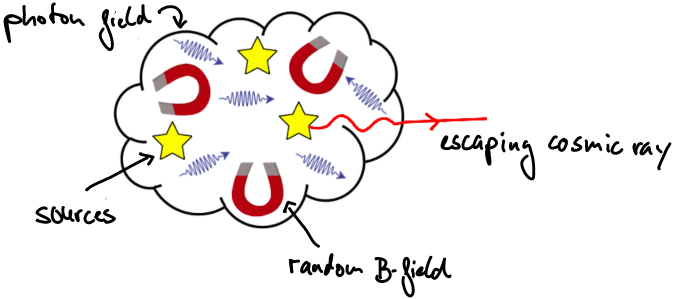


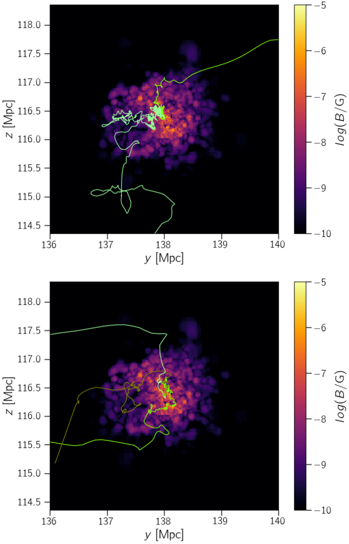


very hard spectrum ($E^{-1...+1}$!)

A. Castellina for the Auger Coll. ICRC19 and JCAP **1704** (2017) 038

Photonuclear Interactions in Source Environment?



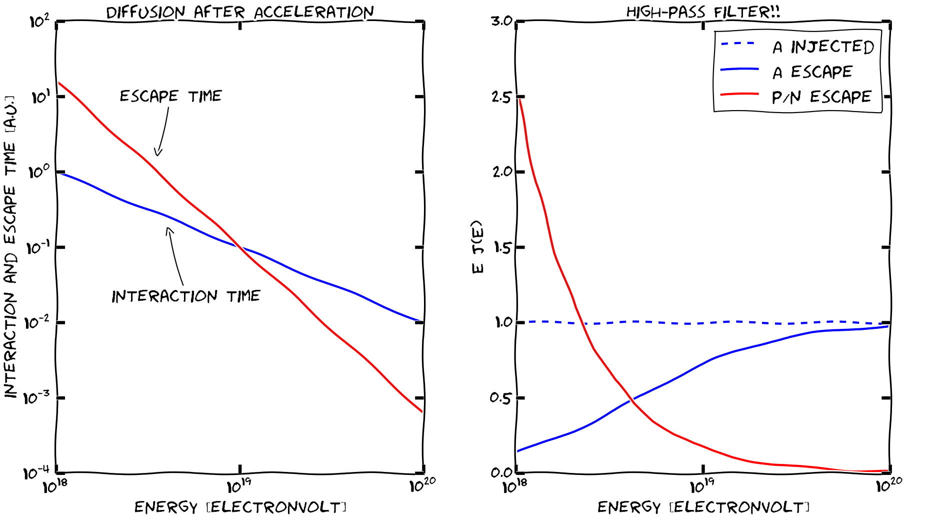


MU, G. Farrar, L. Anchordoqui, PRD **92** (2015) 123001 and M. Muzio, MU, G. Farrar arXiv:1906.06233
see also Globus+15, Biel+17, Kachelriess+17, Supanitsky+18

Virgo Cluster sim., R.A. Batista et al, arXiv:1811.03062

Photonuclear Interactions in Source Environment?

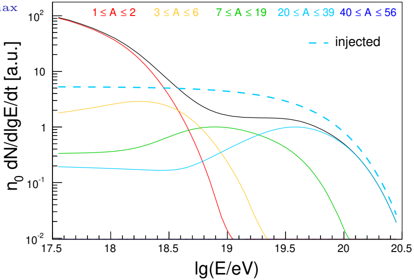
analytic example: full spallation of nucleus A, diffusion $\tau_{\mathrm{esc}} \propto E^{\alpha}$, $\tau_{\mathrm{int}} \propto E^{\beta}$



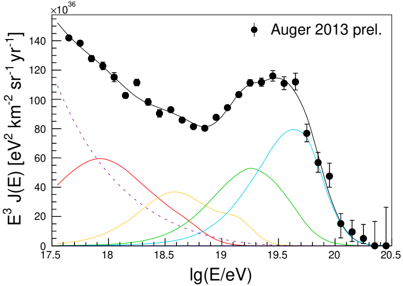
Single Mass + Photonuclear Interactions in Source Environment

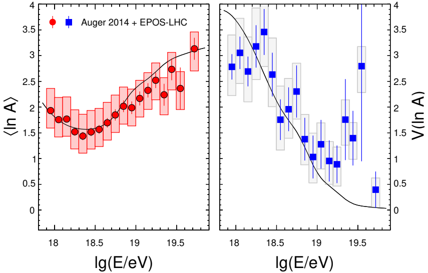
Fiducial Scenario $+1\sigma_{\mathrm{E}}\ -1\sigma_{\mathrm{X_{max}}}$

^{29}Si injected, escaping flux at source



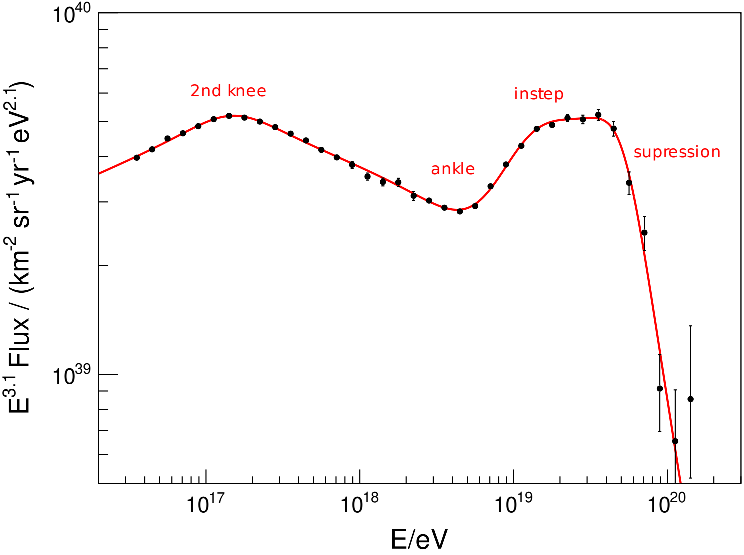
flux and composition at Earth



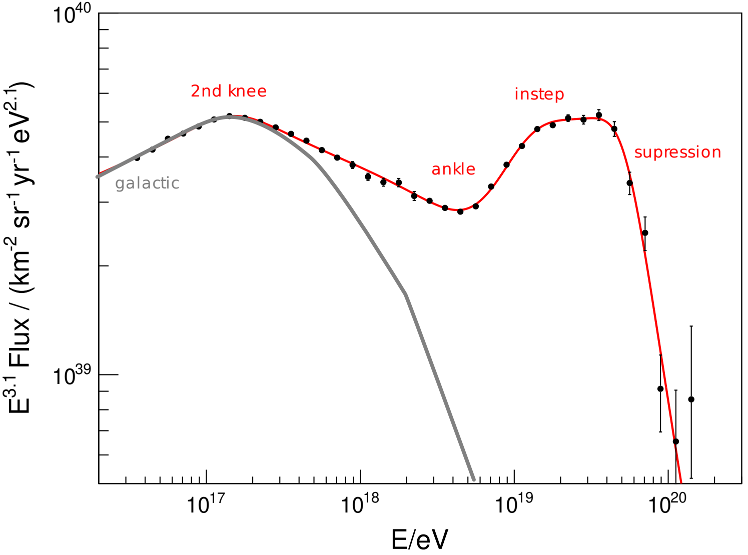


MU, G. Farrar, L. Anchordoqui, PRD **92** (2015) 123001

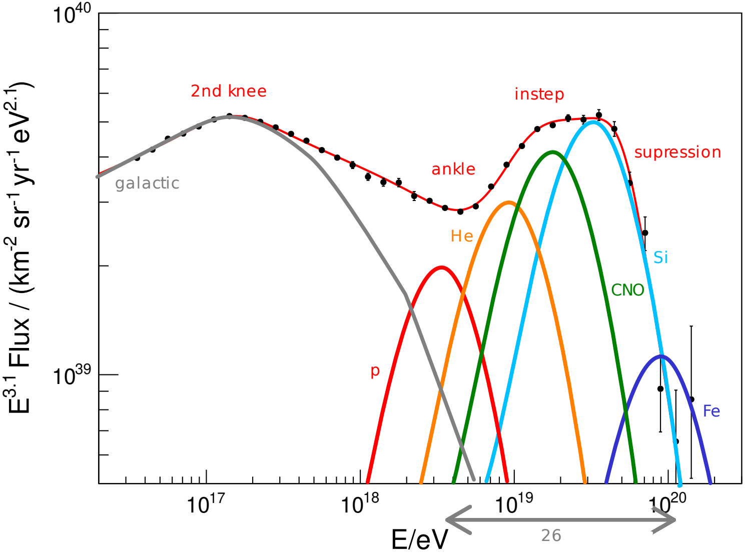
Interpretation of the UHE Spectrum and Mass (schematically)



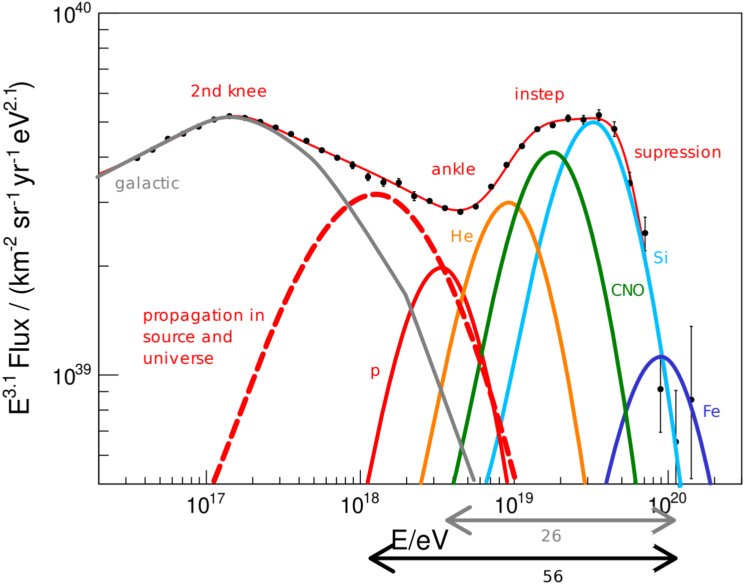
Interpretation of the UHE Spectrum and Mass (schematically)



Interpretation of the UHE Spectrum and Mass (schematically)



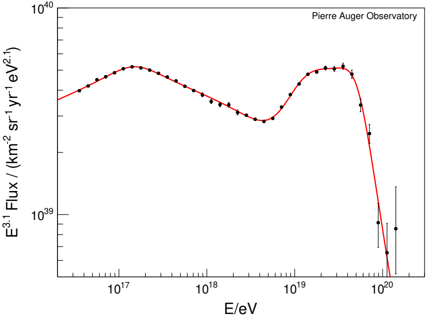
Interpretation of the UHE Spectrum and Mass (schematically)



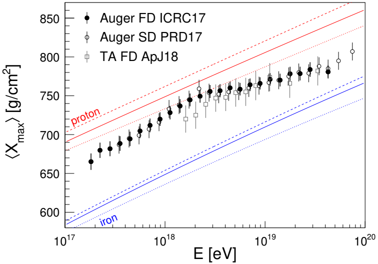
Key UHECR Observations

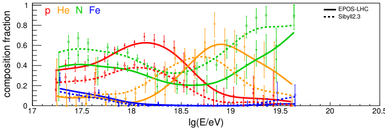
See also lecture by Teresa Bister

energy spectrum



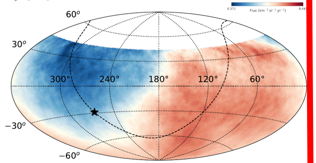
mass composition



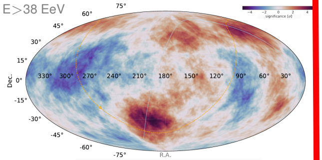


arrival directions

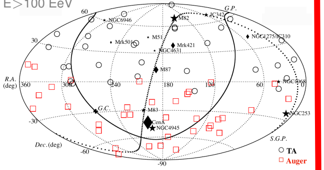
E>8 EeV



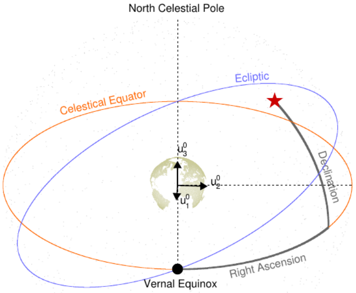
E>38 EeV



E>100 EeV

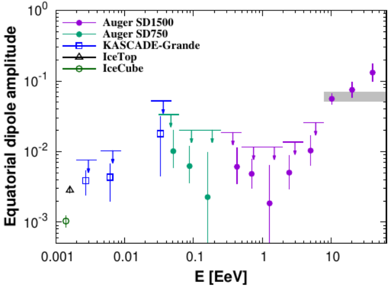


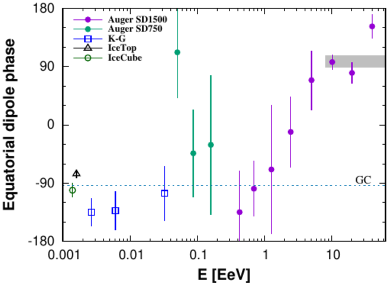
Large-Scale Anisotropy



intensity on sphere: $I(\vec{n}) = \frac{I_0}{4\pi}\left(1 + \delta I(\vec{n})\right)$

dipolar anisotropy: $\delta I = \vec{d}\,\vec{n}$ direction $\vec{u}_d$, amplitude $d = |\vec{d}\,|$



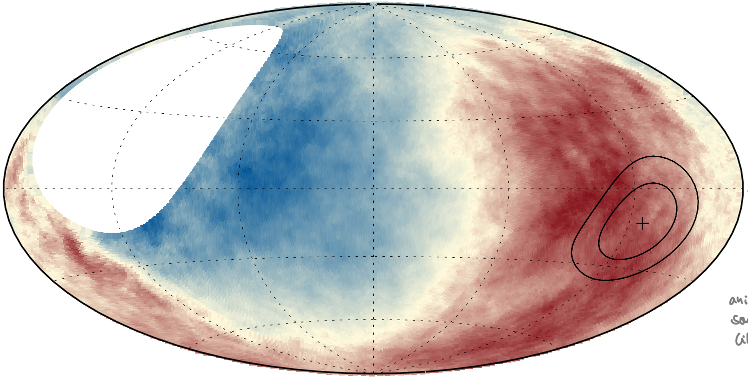


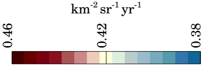
← ≈ 180° away from galactic center!

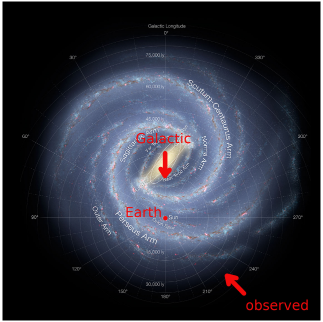
← direction of galactic center

Dipolar Anisotropy of UHECRs (E> 8 EeV)

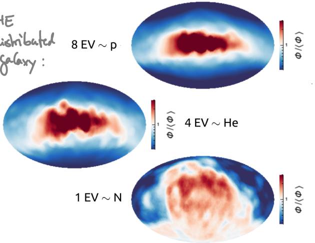
Pierre Auger Coll., ICRC21 and Science **357** (2017) 1266







anisotropy if UHE sources were distributed like stars in galaxy :

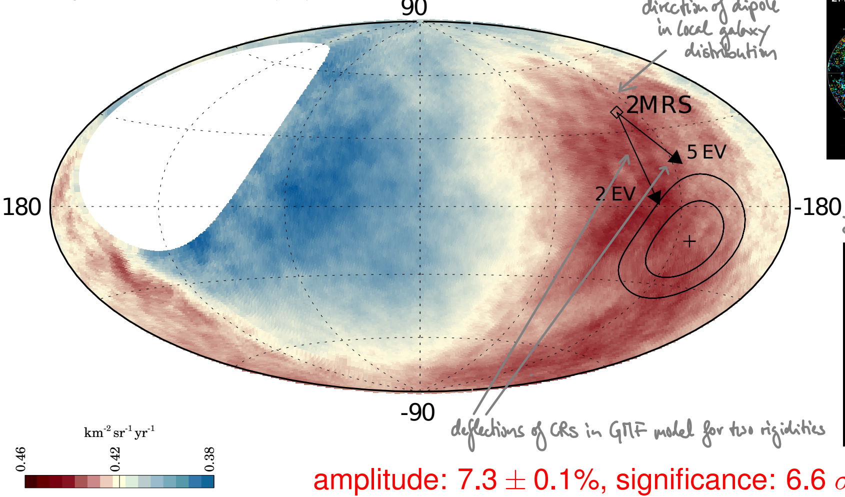


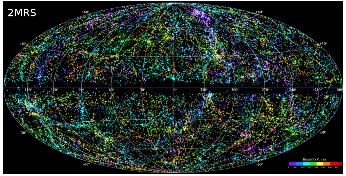
amplitude: $7.3 \pm 0.1\%$, significance: $6.6\ \sigma$

Dipolar Anisotropy of UHECRs (E> 8 EeV)

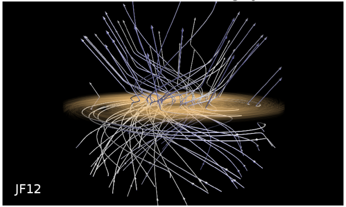
2MRS galaxy catalogue

Pierre Auger Coll., ICRC21 and Science **357** (2017) 1266



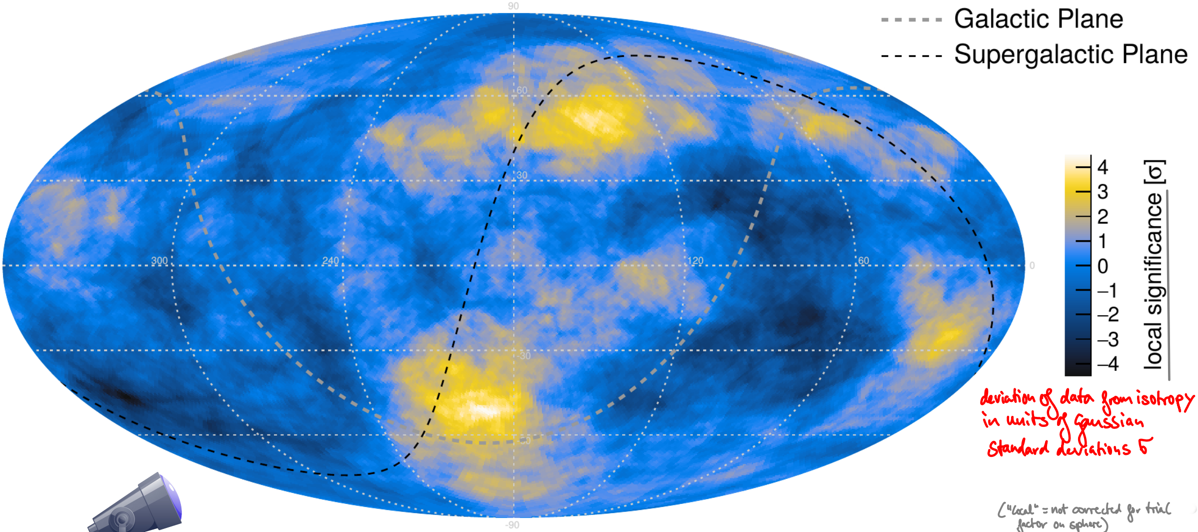


Jansson + Farrar 2012 galactic mag. field model:



amplitude: 7.3 $\pm$ 0.1%, significance: 6.6 σ

Charged Particle Astronomy?

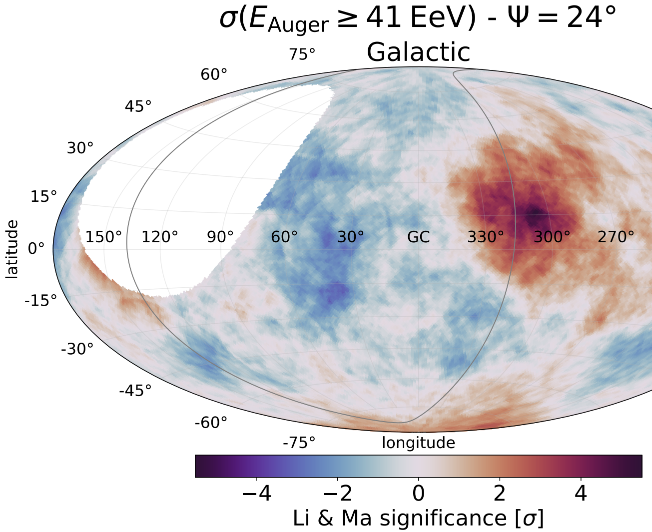


deviation of data from isotropy in units of Gaussian standard deviations σ

("local" = not corrected for trial factor on sphere)

Cosmic ray sky above 5×10^{19} eV (equatorial coordinates) Auger&TA UHECR18

UHECR Sky as seen by the Pierre Auger Observatory



code and dataset available at

doi:10.5281/zenodo.6504276

deviation of data from isotropy in units of Gaussian standard deviations σ

post-trial p-value is 3%

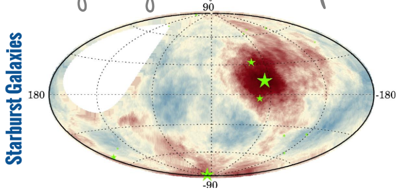
Pierre Auger Coll., ApJ 2022

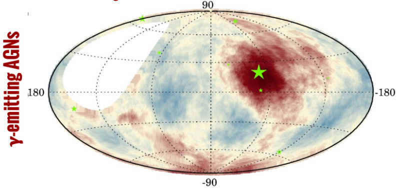
Correlation with Galaxy Catalogues (E$\gtrsim$ 40 EeV)

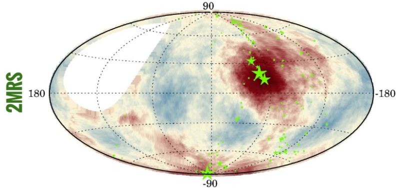
galaxies with large starforming activity
→ high rate of SNe, GRBs... → superwind

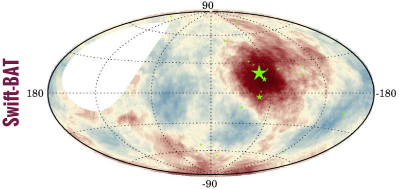
galaxies with an active nucleus around the central super-massive BH (AGN) + relativistic jets

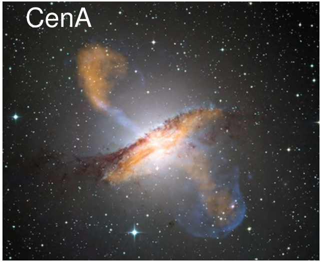
Starburst











proxy for all galaxies

X-ray detected galaxies → all AGNs

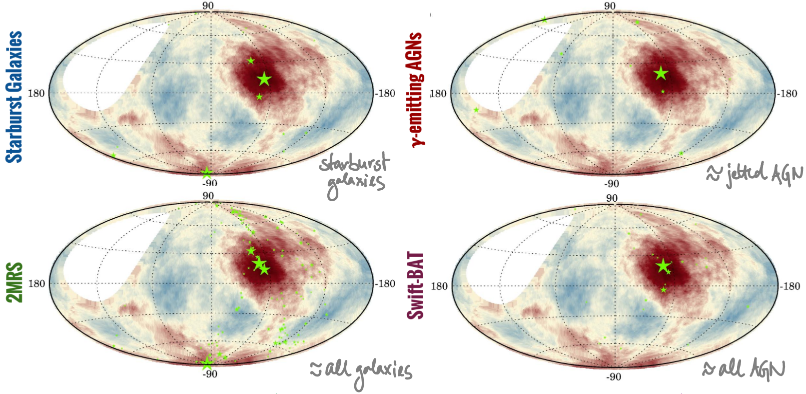
jetted AGN

Pierre Auger Coll., ApJ 2022 (p-values) ICRC19 (plots)

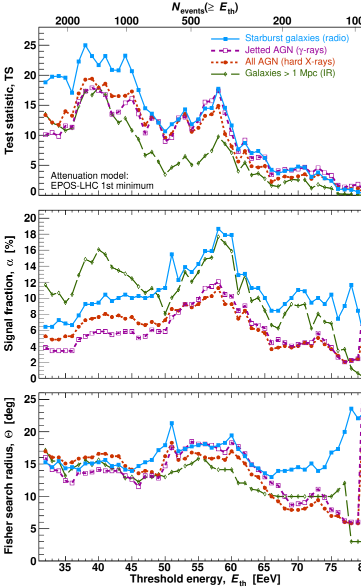
Correlation with Galaxy Catalogues ($E \gtrsim 40$ EeV)

post-trial p-value

3×10^{-5} 8×10^{-4}



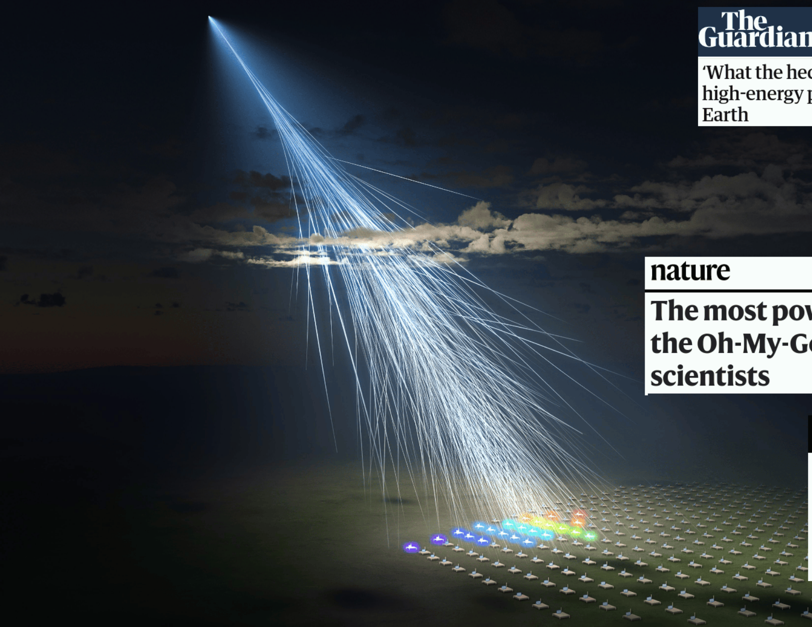
8×10^{-4} 4×10^{-4}



Pierre Auger Coll., ApJ 2022 (p-values) ICRC19 (plots)

isotropy rejected at $\sim 3.3 - 4.2\,\sigma$

Anisotropy at UHE: Localization of the “Amaterasu” Particle



The Guardian

‘What the heck is going on?’ Extremely high-energy particle detected falling to Earth

SPIEGEL Wissenschaft

Ultrahochenergetisches kosmisches Teilchen traf die Erde

OMG! Schon wieder!

nature

The most powerful cosmic ray since the Oh-My-God particle puzzles scientists

VICE

A Ray From Space Hit Earth with Such Incredible Power That Scientists Named It After a God

The source of the Amaterasu particle, named after the Japanese sun goddess, is a "big mystery."

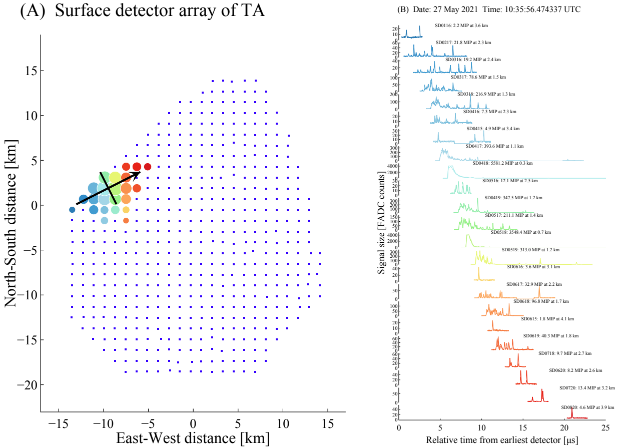
Science

HOME > SCIENCE > VOL. 382, NO. 6673 > AN EXTREMELY ENERGETIC COSMIC RAY OBSERVED BY A SURFACE DETECTOR ARRAY

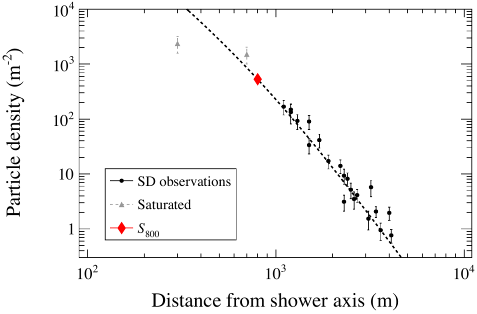
RESEARCH ARTICLE | ASTROPARTICLE PHYSICS

An extremely energetic cosmic ray observed by a surface detector array

TELESCOPE ARRAY COLLABORATION*†, R. U. ABBASI, M. G. ALLEN, R. ARIMURA, J. W. BELZ, D. R. BERGMAN, S. A. BLAKE, B. K. SHIN, I. J. BUCKLAND, [...], AND Z. ZUNDEL

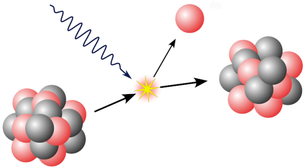


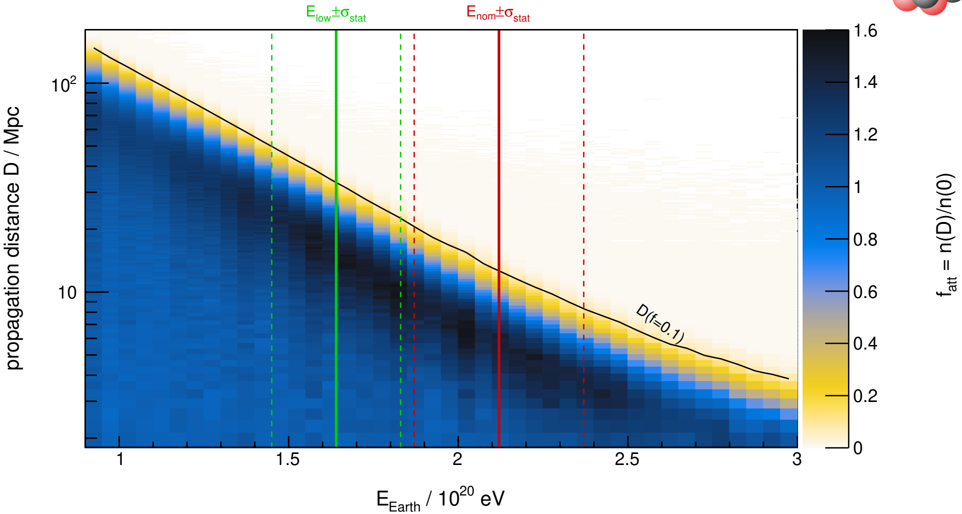
- $E = \left(2.44 \pm 0.29\,(\text{stat.})\,^{+0.51}_{-0.76}\,(\text{syst.})\right) \times 10^{20}$ eV
- if Fe: $E_{\text{nom}} = (2.12 \pm 0.25) \times 10^{20}$ eV
- Fe at $-1\sigma_{\text{syst.}}$: $E_{\text{low}} = (1.64 \pm 0.19) \times 10^{20}$ eV



Propagation of Fe in Extragalactic Photon Fields

- horizon between 8 and 50 Mpc





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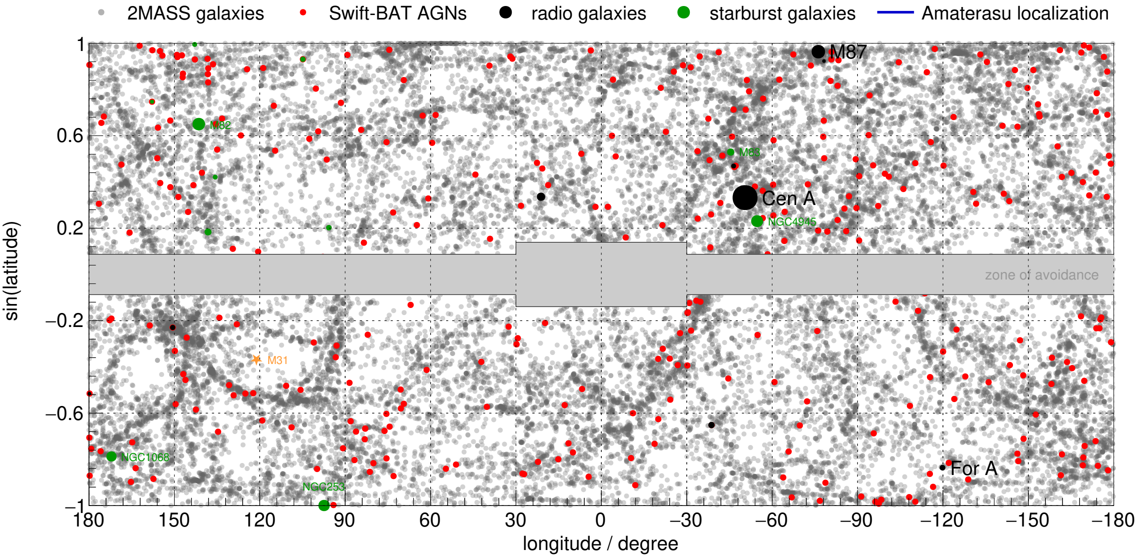
Distribution of galaxies up to D=150 Mpc



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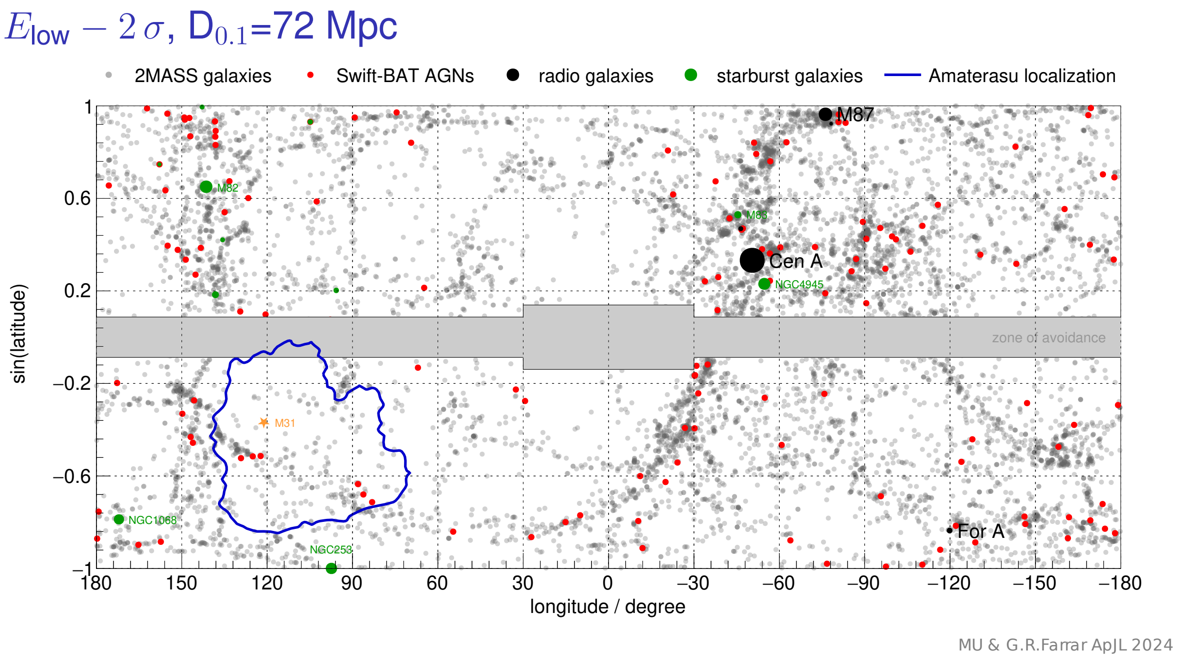

$E_{\text{low}} - 2\,\sigma$, D$_{0.1}$=72 Mpc
2MASS galaxies
Swift-BAT AGNs
radio galaxies
starburst galaxies
Amaterasu localization
M87
M82
M83
Cen A
NGC4945
zone of avoidance
M31
NGC1068
NGC253
For A
sin(latitude)
longitude / degree
1
0.6
0.2
−0.2
−0.6
−1
180
150
120
90
60
30
0
−30
−60
−90
−120
−150
−180
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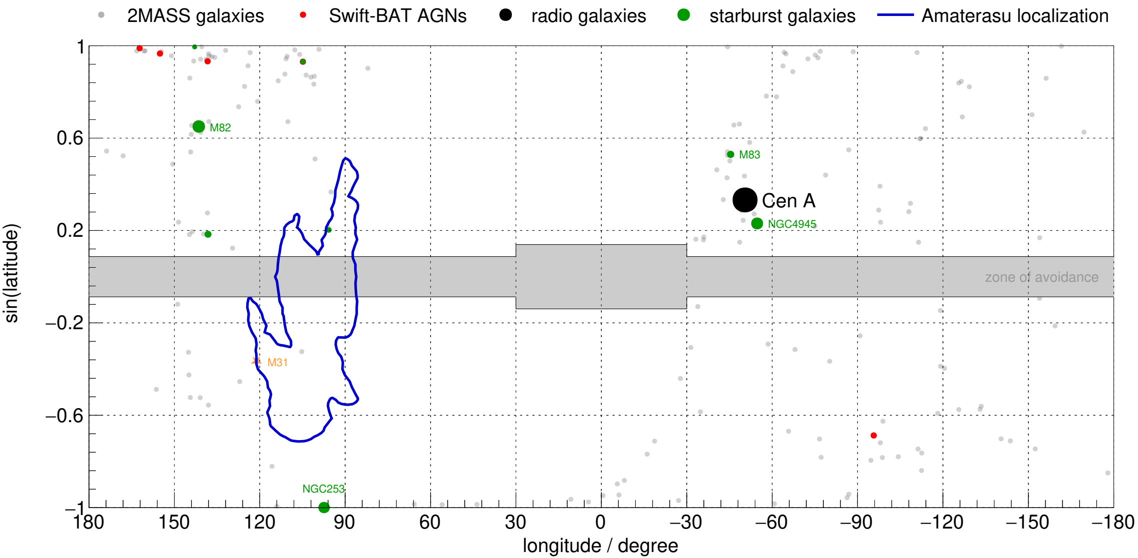
$E_{\rm nom}$, $D_{0.1}$=10 Mpc

→ see also posters by Nadine Bourrice and Luciana Dourado



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James Webb Space Telescope 2023
questions