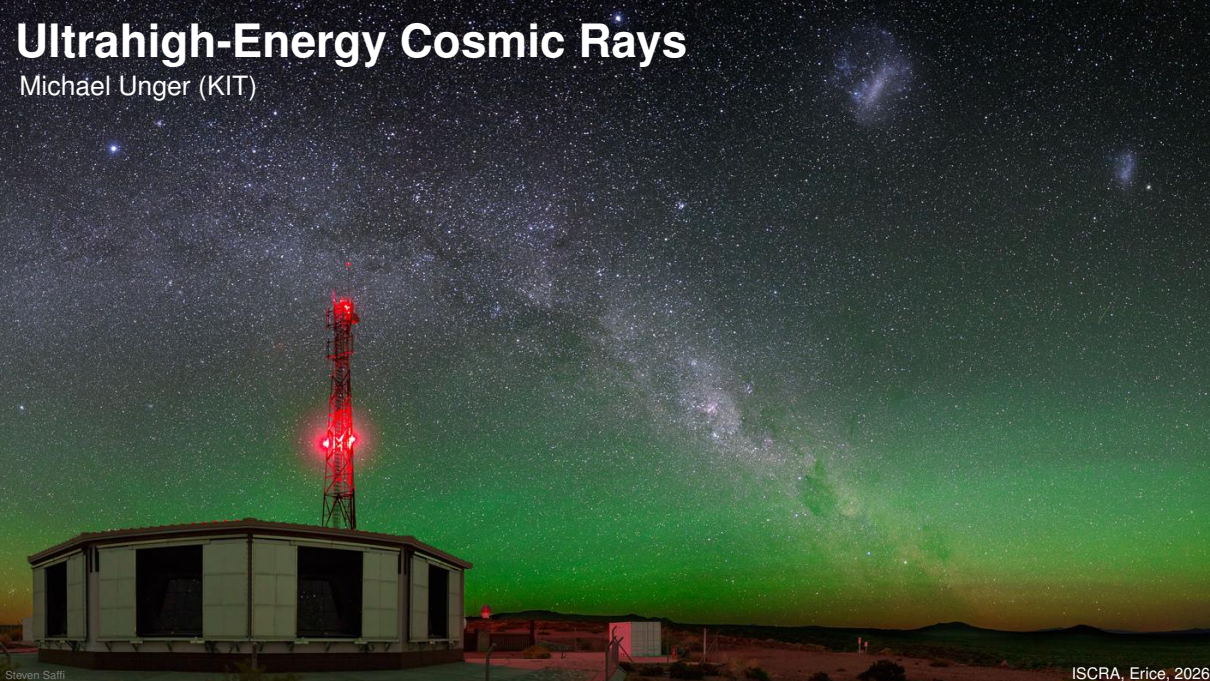
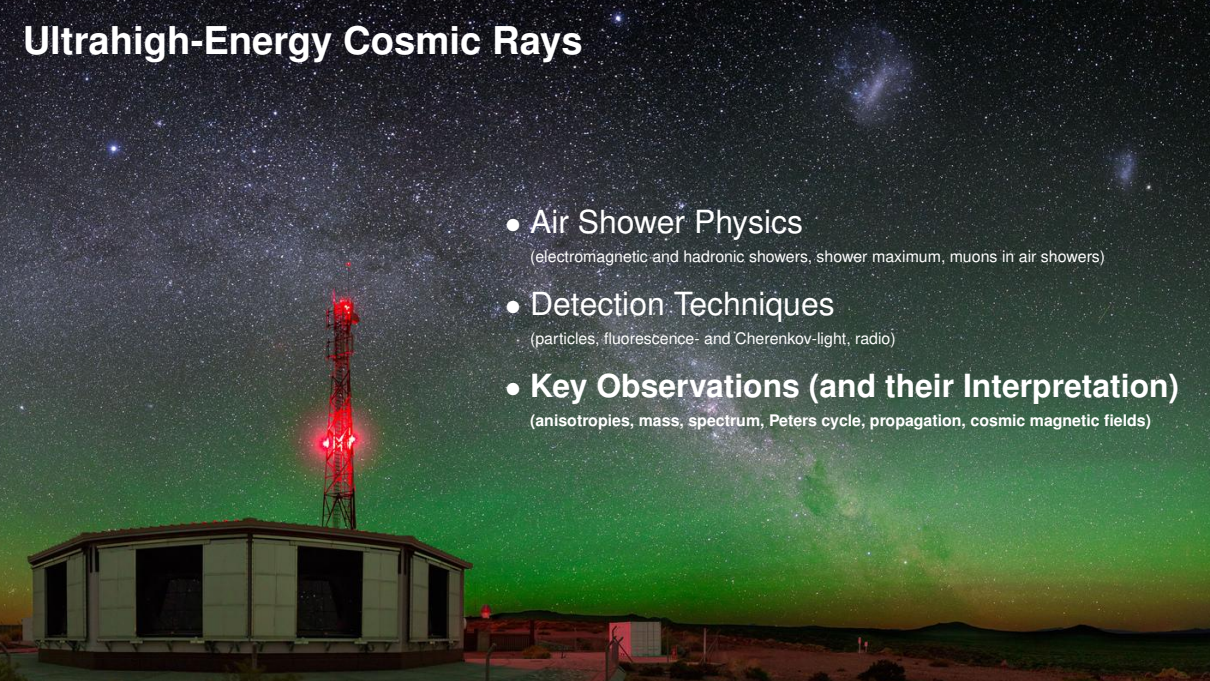


Ultrahigh-Energy Cosmic Rays

Michael Unger (KIT)



Ultrahigh-Energy Cosmic Rays

A night sky with a vibrant green aurora borealis. In the lower-left foreground, there is a white, octagonal building with large windows. A tall, red-lit radio telescope structure stands behind it. The sky is filled with stars and the Milky Way galaxy is visible.

- **Air Shower Physics**

(electromagnetic and hadronic showers, shower maximum, muons in air showers)

- **Detection Techniques**

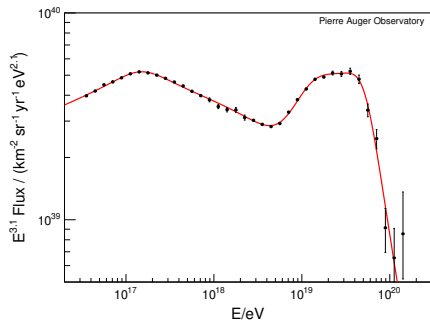
(particles, fluorescence- and Cherenkov-light, radio)

- **Key Observations (and their Interpretation)**

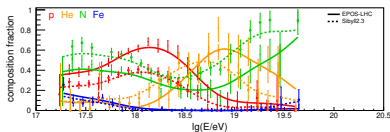
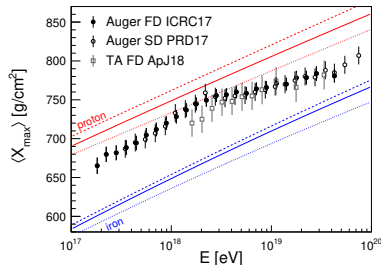
(anisotropies, mass, spectrum, Peters cycle, propagation, cosmic magnetic fields)

Key UHECR Observations

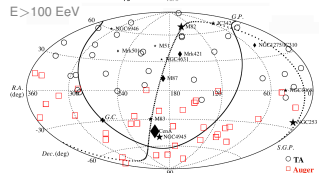
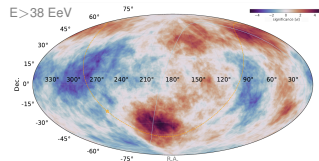
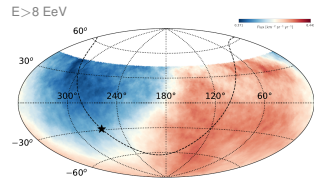
energy spectrum



mass composition

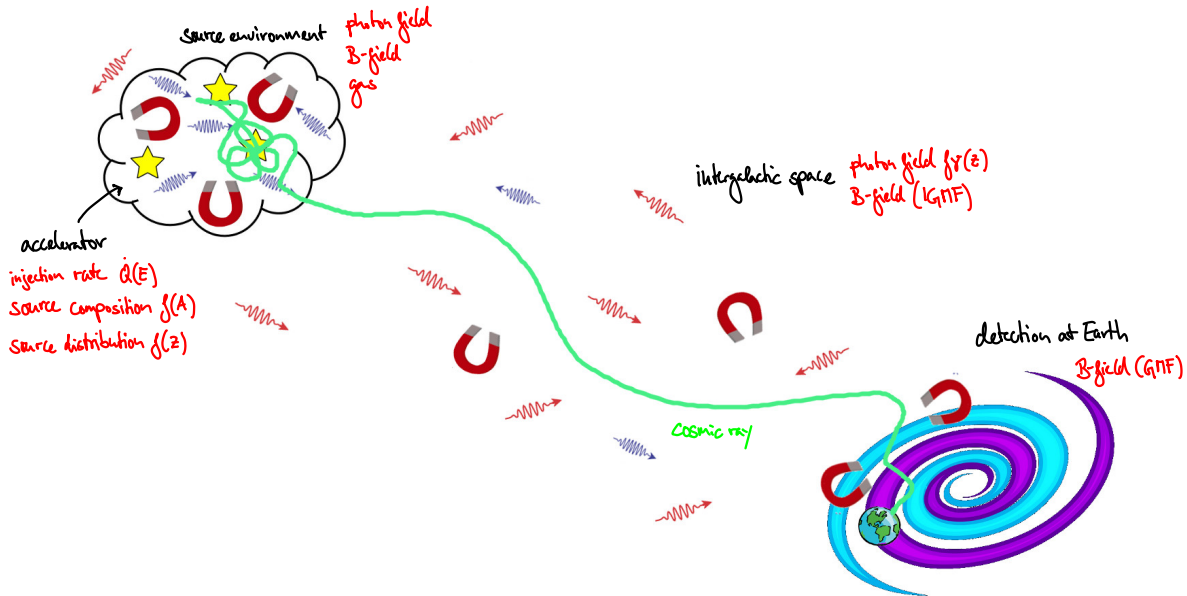


arrival directions

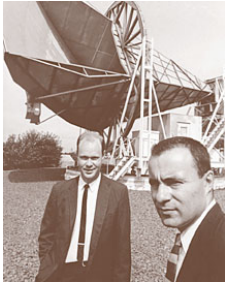


AND: Neutral UHE messengers (photons, neutrons, neutrinos), Hadronic Interactions (p+air cross section, muons in air showers), BSM Physics (LIV, SHDM, anitons, monopoles), ...

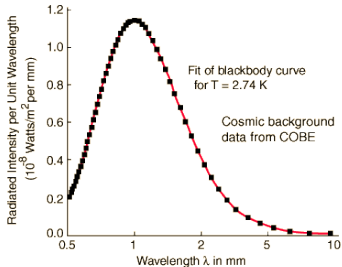
Extragalactic Cosmic-Ray Propagation



Greisen, Zatsepin, Kuzmin Cutoff (GZK)



Penzias & Wilson 1965 (Nobel 1978)



at peak:

$$E_{\gamma} = h \cdot \nu_{\text{max}} \\ \approx \underline{\underline{10^{-3} \text{ eV}}}$$

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

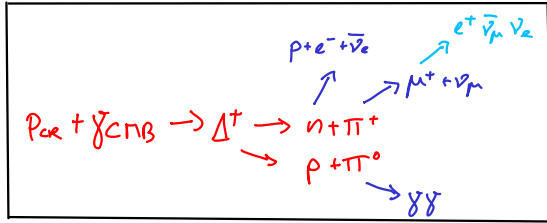
P. N. Lebedev Physics Institute, USSR Academy of Sciences

Submitted 26 May 1966

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

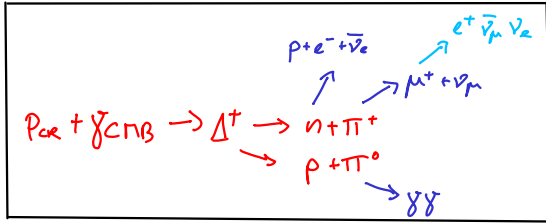


Greisen, Zatsepin, Kuzmin Cutoff (GZK)



Cosmogenic photons
and neutrinos !!

Greisen, Zatsepin, Kuzmin Cutoff (GZK)



Cosmogenic photons
and neutrinos !!

Reminder:

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

4-momentum conservation:

at rest

$$\begin{aligned}
 (\hat{p}_p + \hat{p}_\gamma)^2 &= (p_n + p_\pi)^2 = (m_p + m_\pi)^2 \\
 &= \hat{p}_p^2 + 2\hat{p}_p \hat{p}_\gamma + \hat{p}_\gamma^2 = m_p^2 + 2(E_p, \vec{p}_p)(E_\gamma, \vec{p}_\gamma) + 0 \\
 &= m_p^2 + 4E_p E_\gamma
 \end{aligned}$$

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

$\Leftrightarrow$ flux suppression ?!?

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

Photo-Pion Production

proton at rest

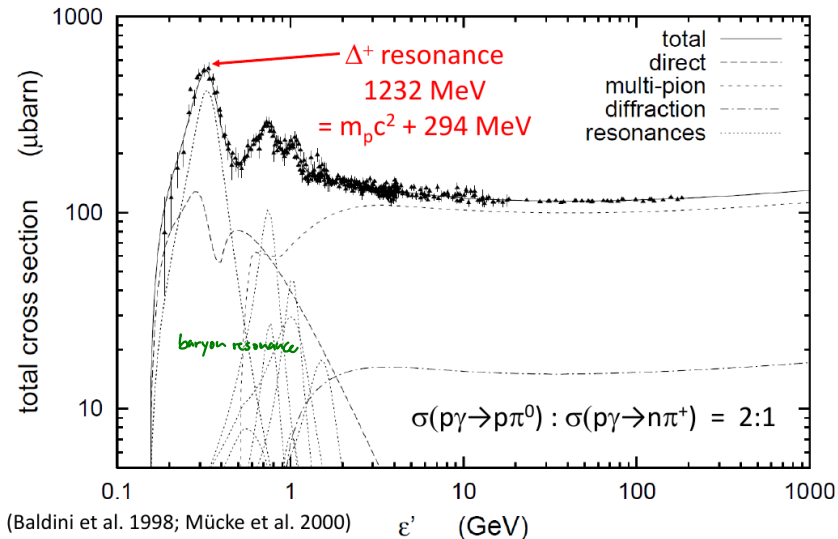


Photo-Pion Production

proton at rest

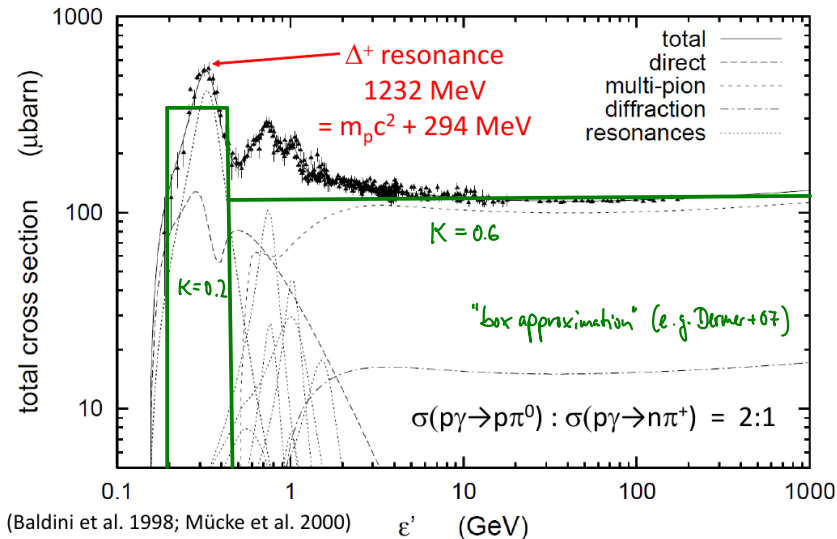


Photo-Pion Production

- interaction length:

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

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

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

- energy loss length: $\chi = -c \left(\frac{1}{E} \frac{dE}{dx} \right)^{-1} = \frac{\lambda}{K} \approx 20 \text{ Mpc} \quad \left(\frac{1}{E} \frac{dE}{dx} = -\frac{1}{E} \frac{K \cdot E}{\lambda} \right)$

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

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



Lorentz-rafo to p rest frame:

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

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

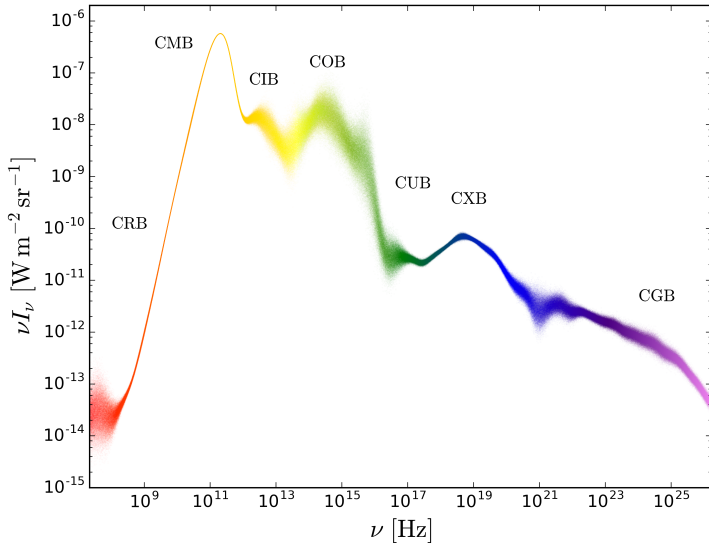
Extragalactic Photon Fields

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)

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

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



Pair Production and Adiabatic Loss

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

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

- $\frac{K_{\pi^0} \sigma_{\pi^0}}{K_{e^+e^-} \sigma_{e^+e^-}} = 100 \Rightarrow \chi_{e^+e^-} = 100 \chi_{\pi}$

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

Pair Production and Adiabatic Loss

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

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- expansion of universe: (z : redshift)

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

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

$$E_{\text{earth}} = E_{\text{source}} / (1 + z_{\text{source}})$$

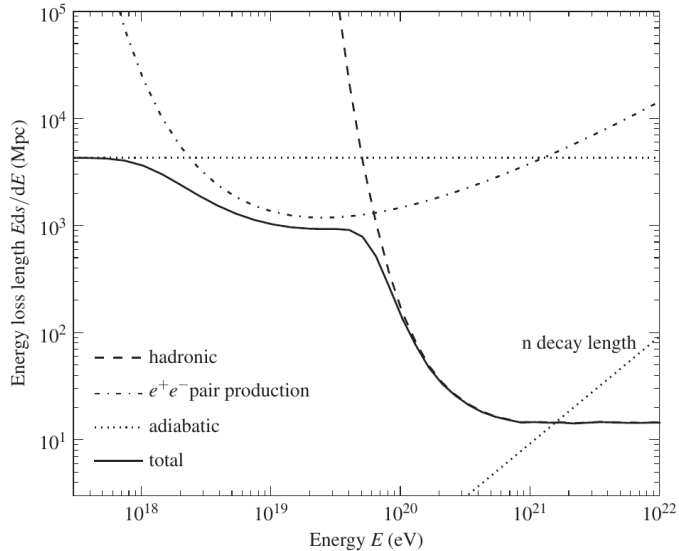
$$\leftrightarrow_{z=0}$$

$$\frac{1}{E} \frac{dE}{dt} = -H_0$$

$$\leftrightarrow$$

$$\chi = \frac{c}{H_0} \approx 4 \text{ Gpc}$$

Energy Loss of Protons ($z=0$)



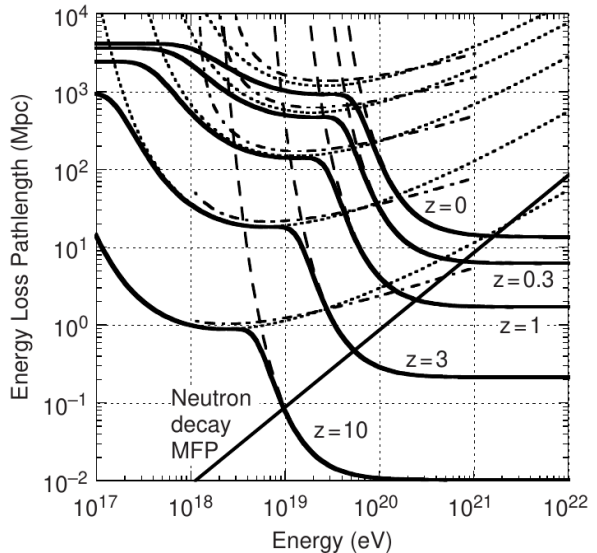
Energy Loss of Protons

cosmological distances:

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

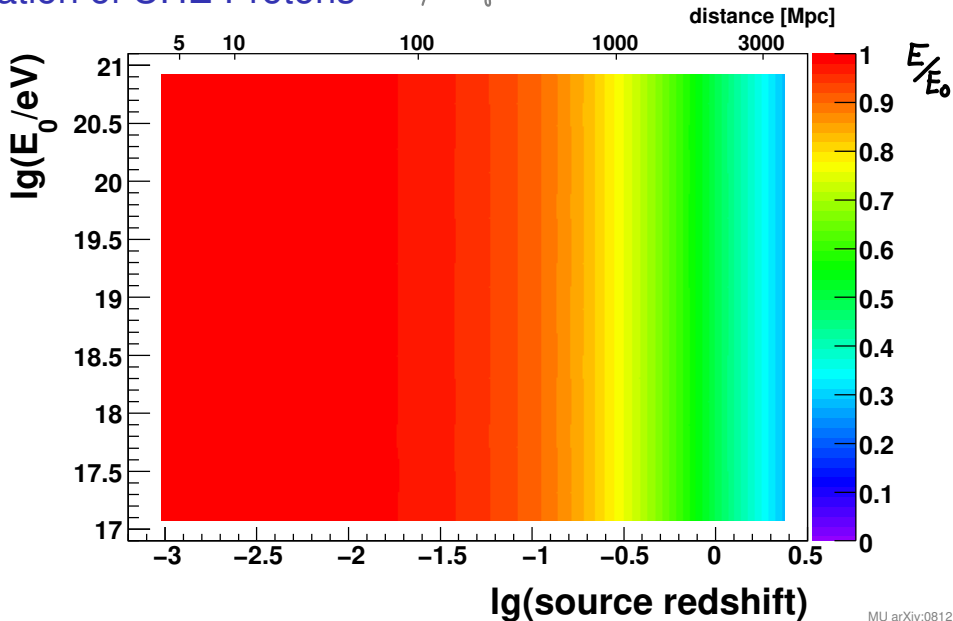
CMB density: $n(z) = n_0 (1+z)^3$

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



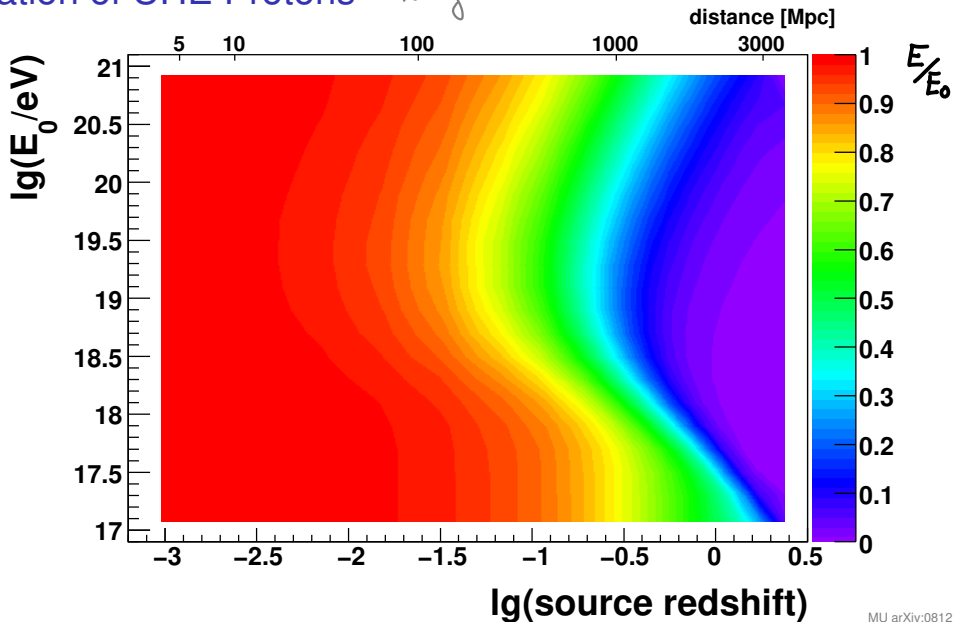
Propagation of UHE Protons

only redshift



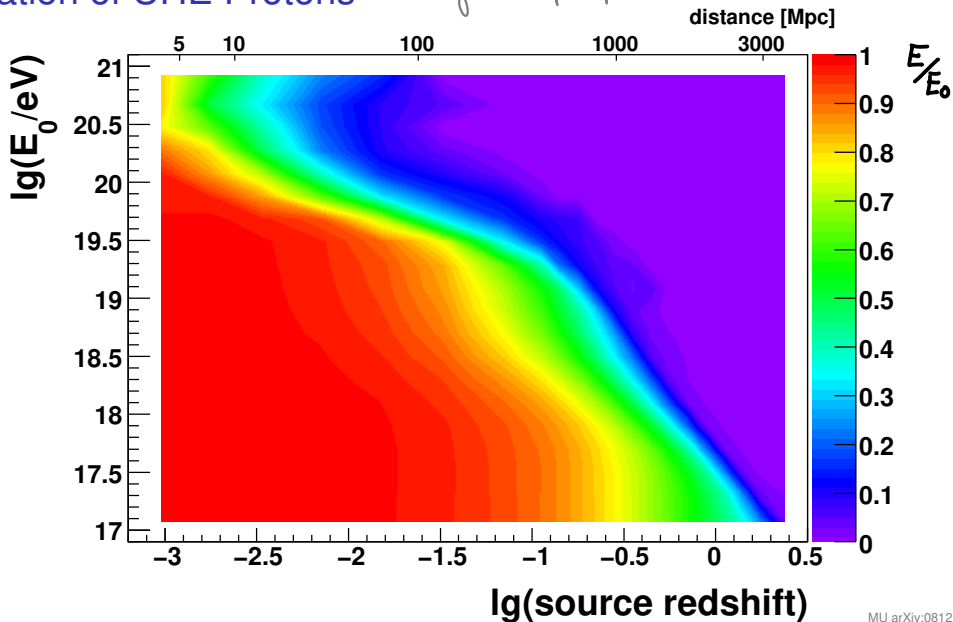
Propagation of UHE Protons

redshift + e^+e^-

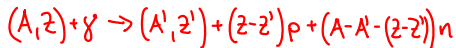


Propagation of UHE Protons

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



Propagation of UHE Nuclei



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

- giant dipole resonance (GDR)

collective oscillation of all p vs. all n

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

- quasi deuteron scattering (QD)

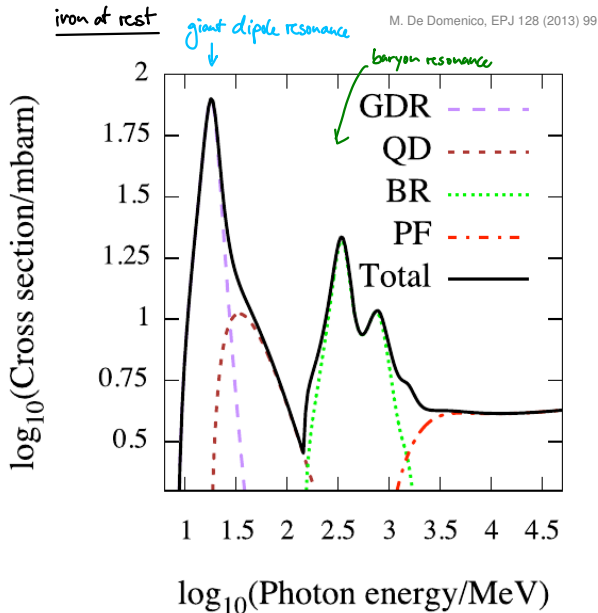
scattering with n+p pair $\rightarrow$ p+n emission

- baryon resonances (BR)

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

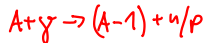
- photo fragmentation (PF)

nucleus breakup



Propagation of UHE Nuclei

- Inelasticity of GDR:



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

$\Rightarrow K(\text{He}) = 0.25, K(\text{Fe}) = 0.018$

- cross section:

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

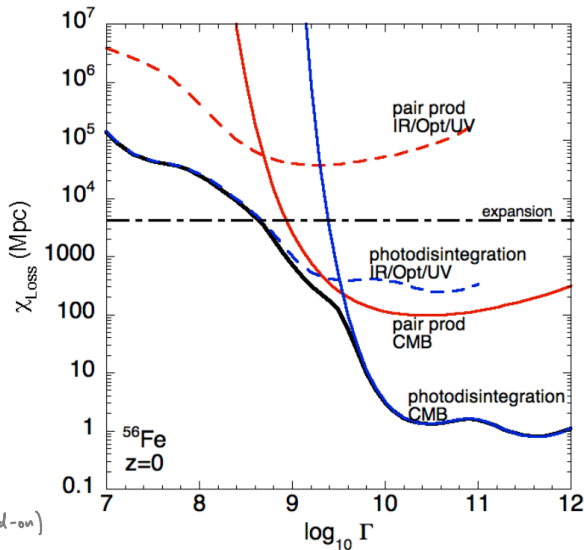
$\sigma_{\text{Fe}} \approx 30 \text{ mb} \Rightarrow \frac{\chi_{\text{Fe}}}{\chi_{\text{p}}} \approx \frac{(\sigma_{\pi} K_{\pi})_{\text{p}}}{(\sigma_{\text{GDR}} \cdot K_{\text{GDR}})_{\text{Fe}}} \approx 0.1$

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

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

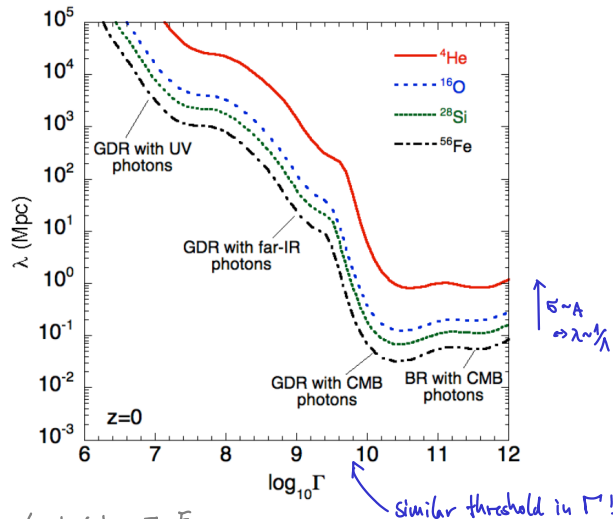
$$\Gamma_{\text{GDR}} = \frac{E}{A \cdot m_p} = \frac{E'_{\text{GDR}}}{2 \cdot E} \approx \frac{20 \text{ MeV}}{2 \cdot 10^{-3} \text{ eV}} = 10^{10} \text{ (head-on)}$$

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

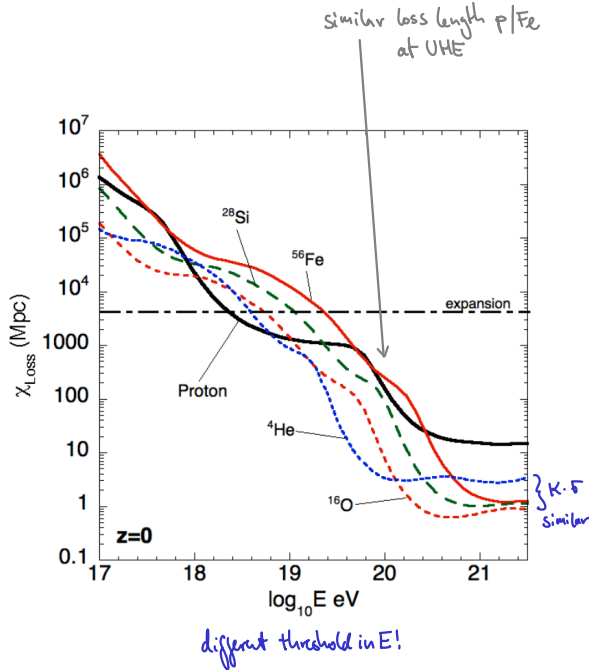


Propagation of UHE Nuclei

D.Allard APP 39 (2012) 33

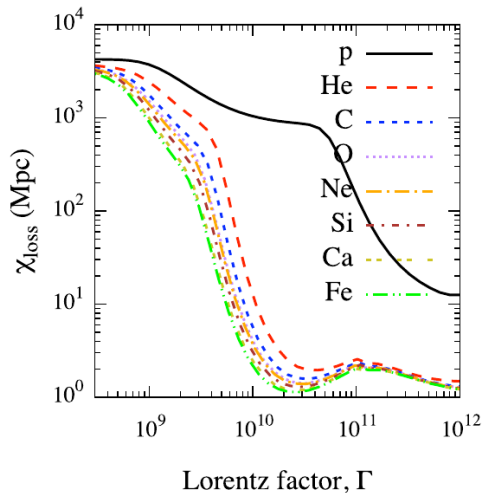
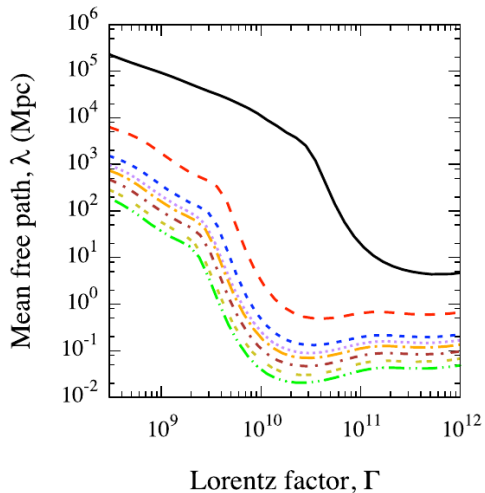


Lorentz-factor $\Gamma = \frac{E}{A \cdot m_p}$



Propagation of UHE Nuclei *(variation of previous slide)*

M. De Domenico, EPJ 128 (2013) 99



Propagation of UHE Nuclei

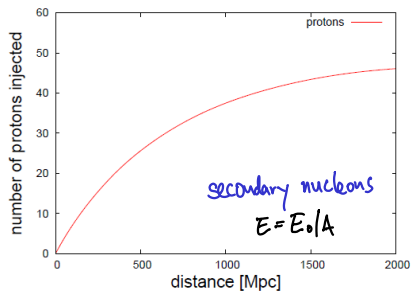
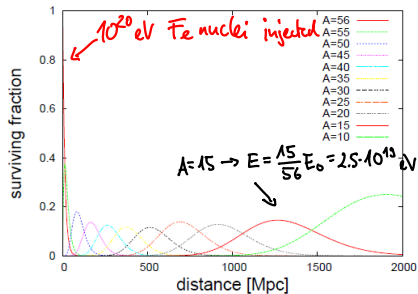
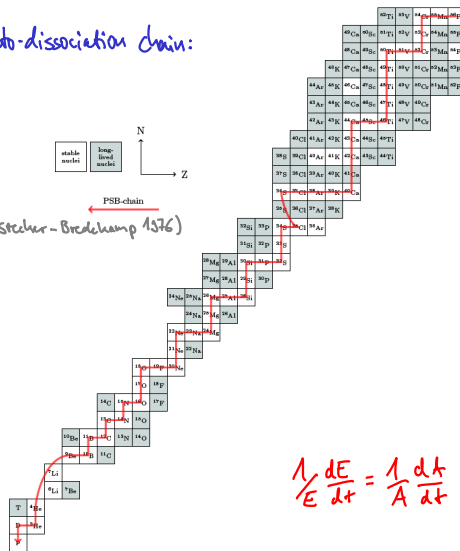


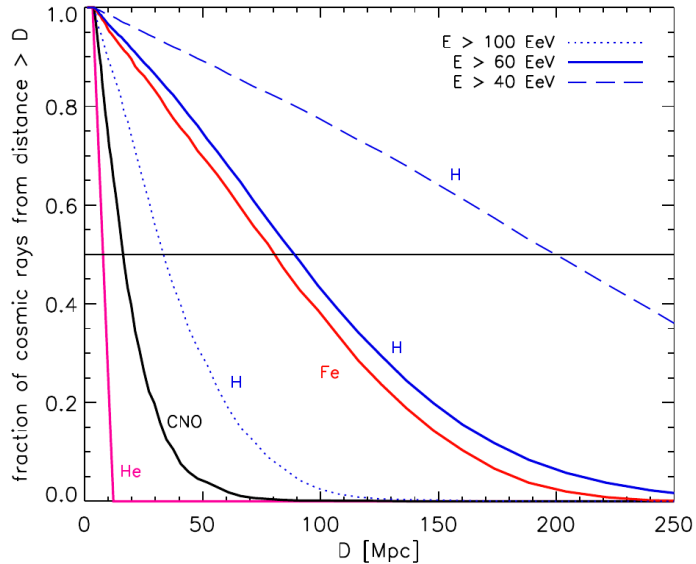
photo-dissociation chain:
(Puget-Stecher-Bredekamp 1976)



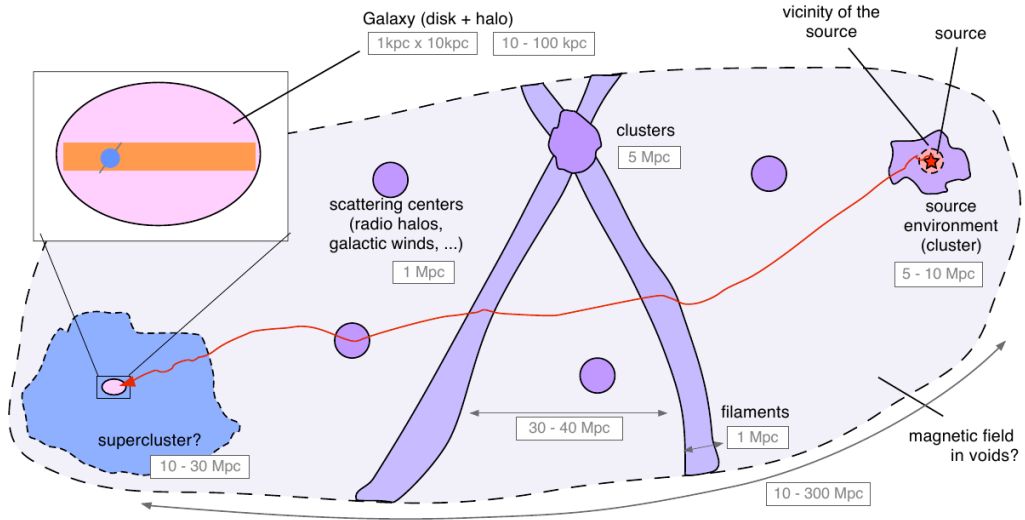
$$\frac{1}{E} \frac{dE}{dt} = \frac{1}{A} \frac{dA}{dt}$$

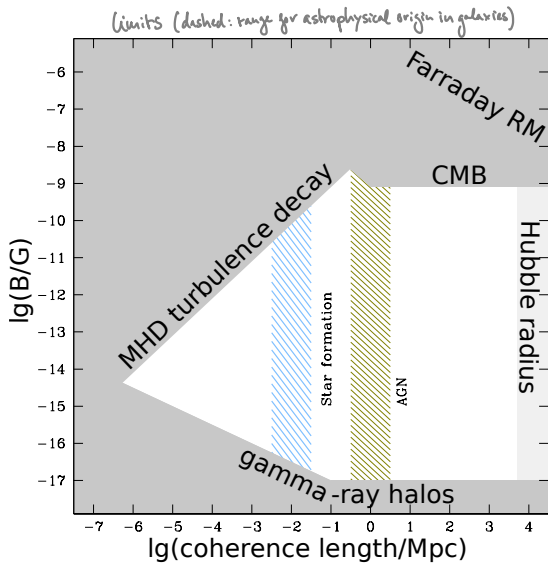
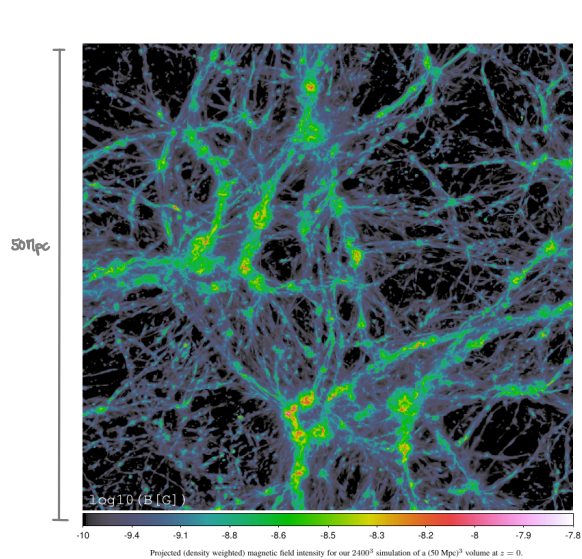
“GZK Sphere”

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



Extra- and Intergalactic Magnetic Fields





Propagation Through the IGMF



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

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

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

$\Rightarrow$ proton astronomy at UHE!

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

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

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

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

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

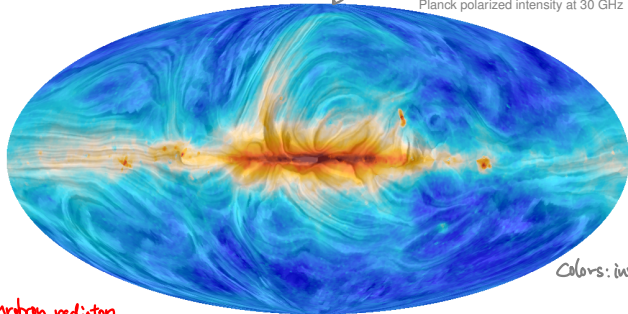
$$R \lesssim \left(\frac{B}{nG} \right) \left(\frac{\lambda_c}{1 \text{ Mpc}} \right)^{1/2} \left(\frac{d}{70 \text{ Mpc}} \right) 10^{18} V$$

$\Rightarrow$ low-rigidity horizon

Galactic Magnetism

projected magnetic field orientation inferred from polarization

Planck polarized intensity at 30 GHz



Colors: intensity

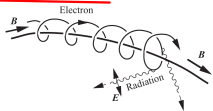
M51 (HST, MPIIR)



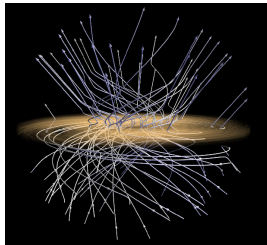
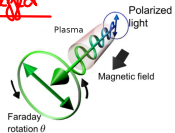
intensity contours

9000 LJ
1'

Synchrotron radiation



Faraday effect

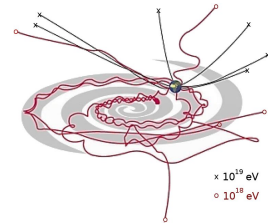
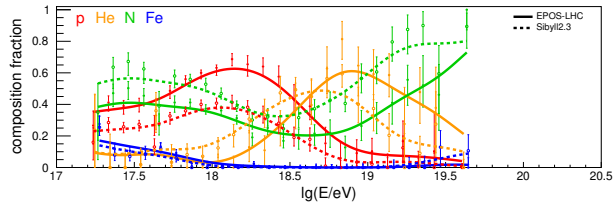


Galactic
magnetic
field model



Jansson&Farrar 2012

Cosmic-Ray Deflections



D. Harari

- Larmor radius of charged particle in B-field

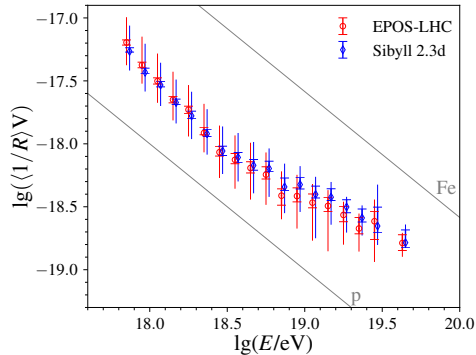
$$r = 1.1 \text{ kpc} \frac{R/10^{18} \text{ V}}{B/\mu\text{G}}$$

- rigidity

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

- typical GMF deflections (JF12)

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

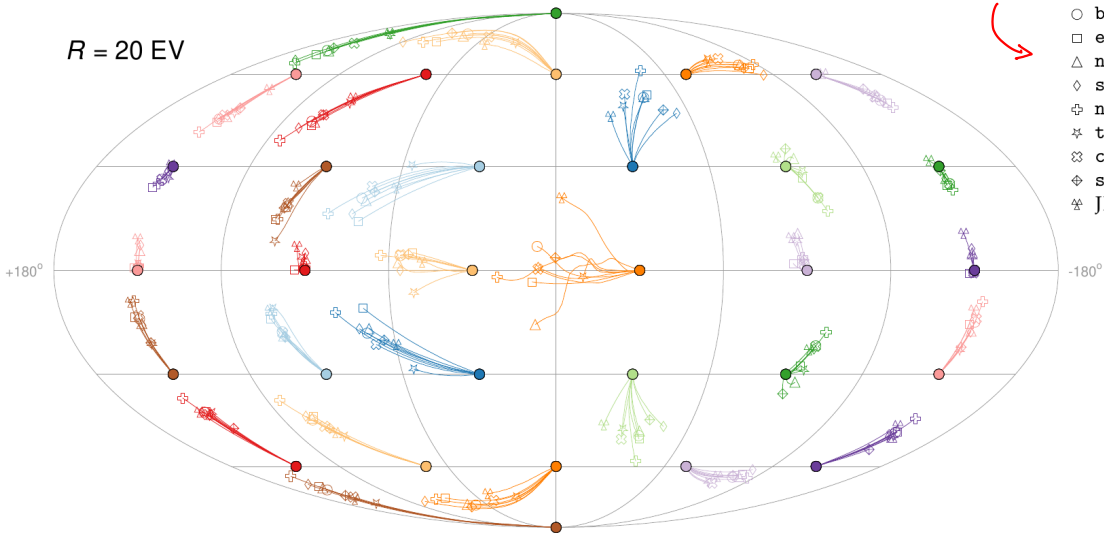


Deflections at 20 EV (backtracking)

different models of the
galactic magnetic field

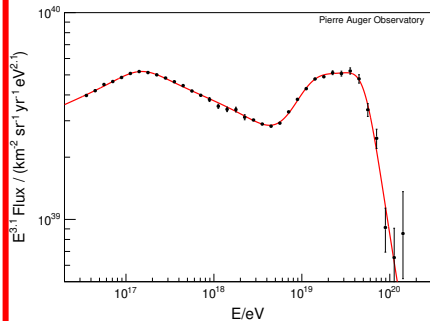
$R = 20 \text{ EV}$

- base
- expX
- △ neCL
- ◇ spur
- ⊕ nebCor
- ✱ twistX
- ⊗ cre10
- ⊕ synCG
- ✱ JF12

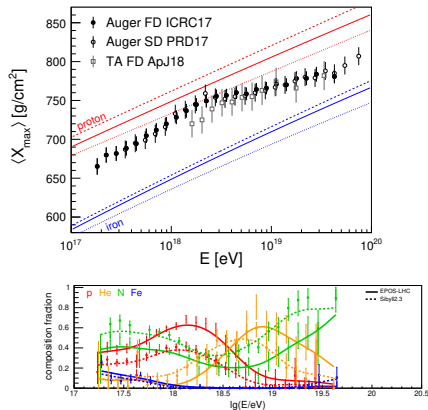


Key UHECR Observations

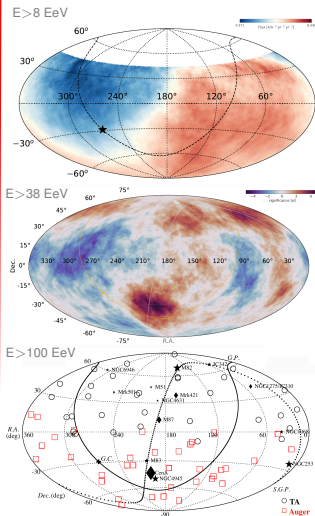
energy spectrum



mass composition



arrival directions



End of GCR Spectrum - Escape? $\rightarrow$ see also lecture by Jörg Hörandel

Larmor radius of charge Z in magnetic field B :

$$R_L = 1.1 \text{ kpc} \frac{(E/Z) / 10^{19} \text{ eV}}{B / \mu\text{G}}$$

• coherent magnetic field in galaxy:

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

$$R_L = H \Rightarrow E = \begin{cases} 5 \cdot 10^{17} \text{ eV} & Z=1 \text{ (p)} \\ 1 \cdot 10^{13} \text{ eV} & Z=26 \text{ (Fe)} \end{cases}$$

$\Rightarrow$ free streaming out of Galaxy

• turbulent magnetic field

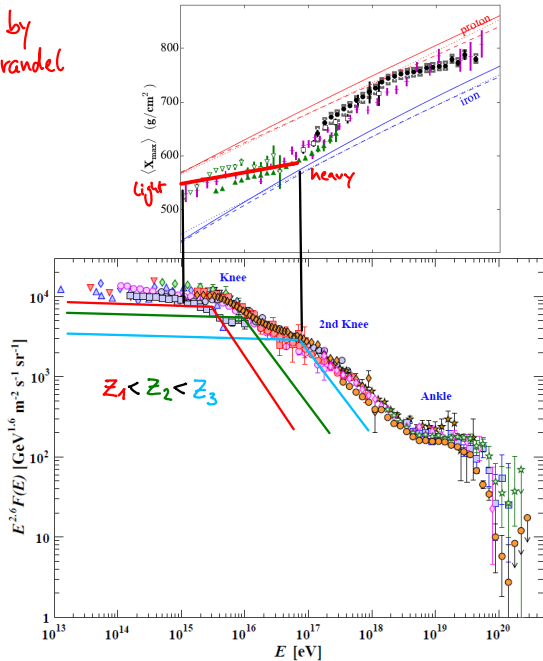
coherence length $d \lesssim 100 \text{ pc}$



$\Rightarrow$ change of diffusion coefficient D

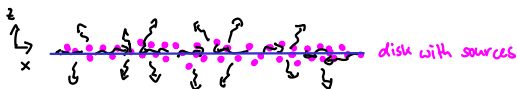


$\Rightarrow$ change of $\tilde{\tau}_{\text{esc}} \sim \frac{1}{D}$



End of GCR Spectrum - E_{max} ?

- problem with escape model: anisotropy



$J_x > J_z \leftrightarrow$ not observed!

- Maximum energy in shock acceleration?

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

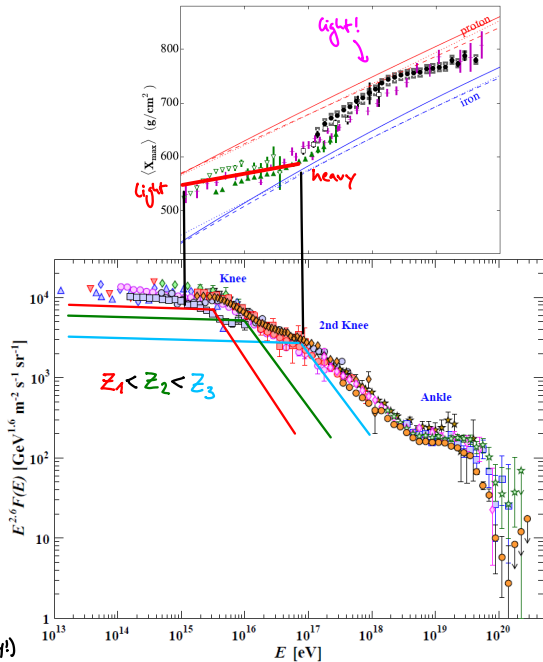
$\Rightarrow$ same phenomenology as escape model:

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

- can CRs with $E > 10^{18} \text{ eV}$ be galactic?

Composition $\rightarrow \approx p$

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



Extragalactic Protons

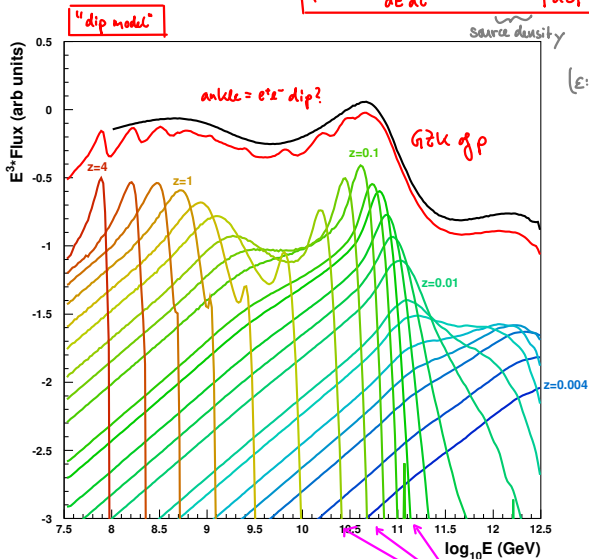
without cosmological corrections: (see CRPP Eq. (10.23))

$$\Phi(E) \sim \int \frac{dN_{inj}}{dE dt} (E(\epsilon)) n_{src} \left| \frac{dE}{d\epsilon} \right| \frac{1}{4\pi R^2} R^2 dR d\Omega$$

source density

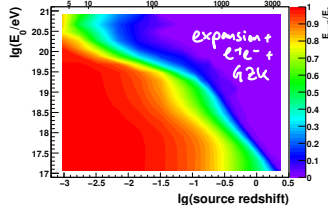
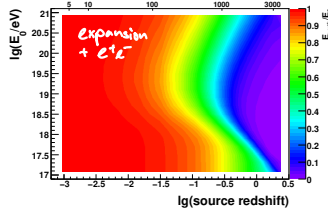
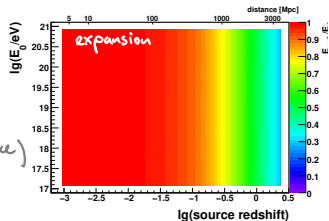
Volume

(ϵ : at Earth E : at source)



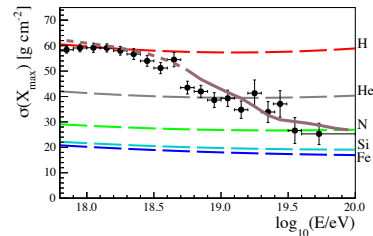
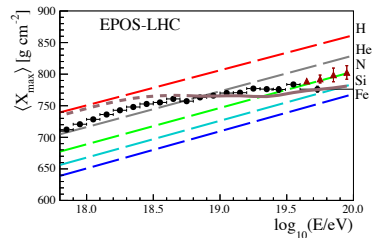
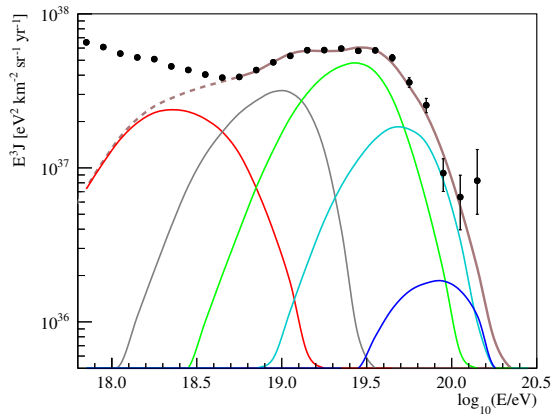
D. Bergman, 29th ICRC 2005

sources from different redshift shells



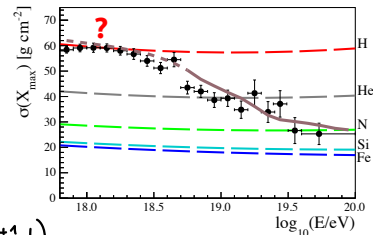
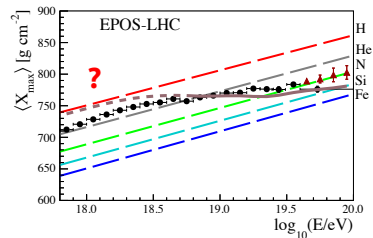
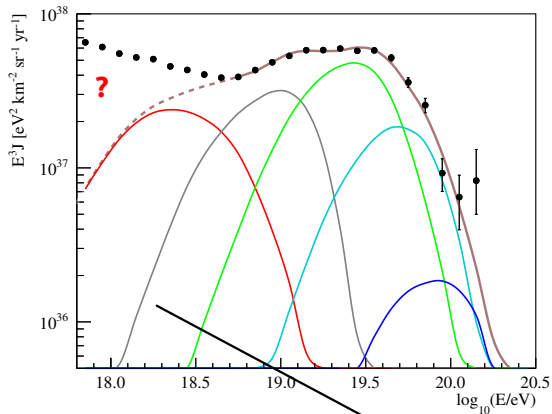
Maximum Rigidity Model, Peters Cycle?

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



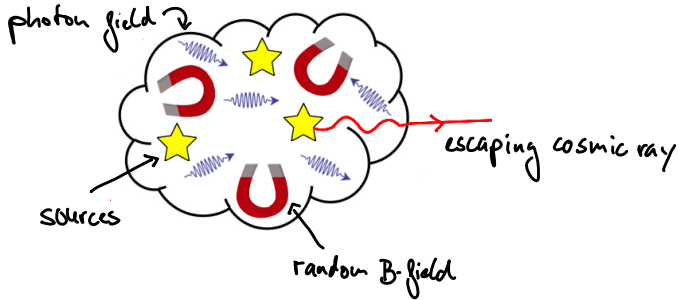
Maximum Rigidity Model, Peters Cycle?

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

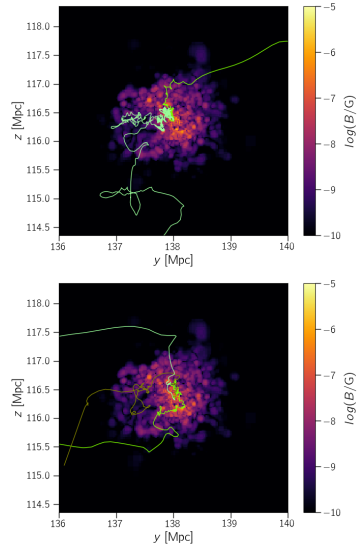


very hard spectrum ($E^{-1...+1}$!)

Photonuclear Interactions in Source Environment?



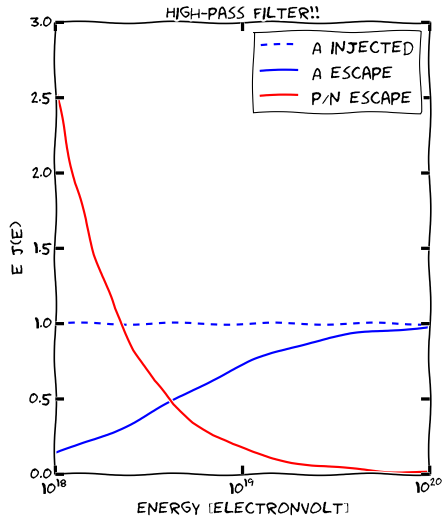
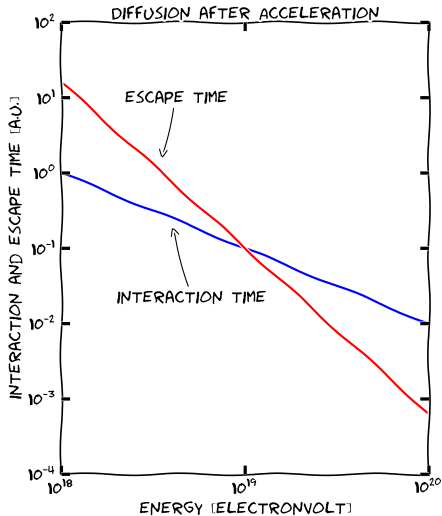
MU, G. Farrar, L. Anchordoqui, PRD **92** (2015) 123001 and M. Muzio, MU, G. Farrar arXiv:1906.06233
see also Globus+15, Biel+17, Kachelriess+17, Supanitsky+18



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

Photonuclear Interactions in Source Environment?

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

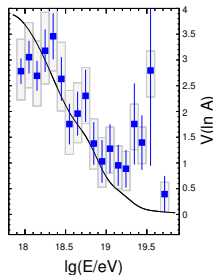
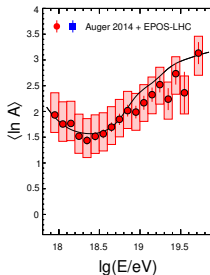
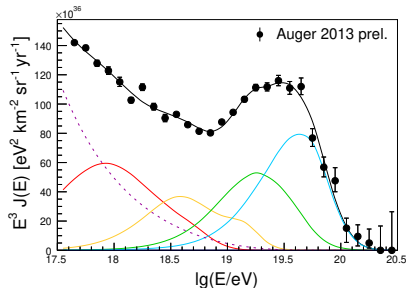
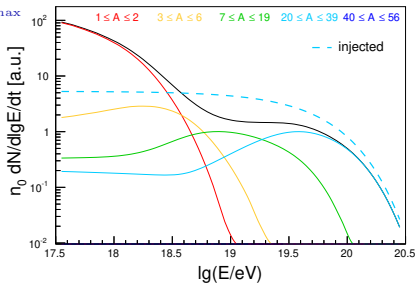


Single Mass + Photonuclear Interactions in Source Environment

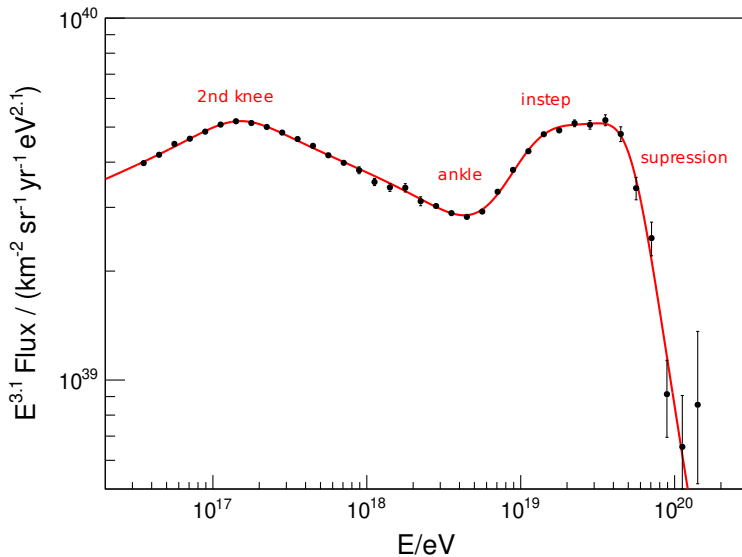
Fiducial Scenario $+1\sigma_E -1\sigma_{X_{\max}}$

^{29}Si injected, escaping
flux at source

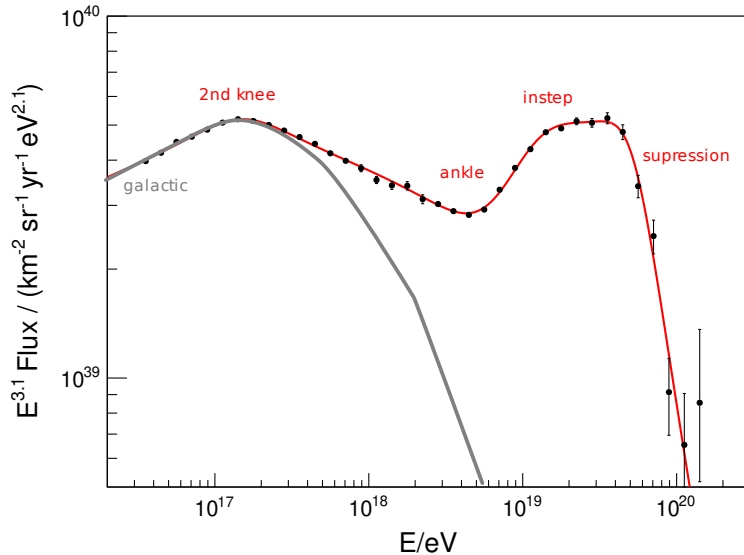
flux and composition
at Earth



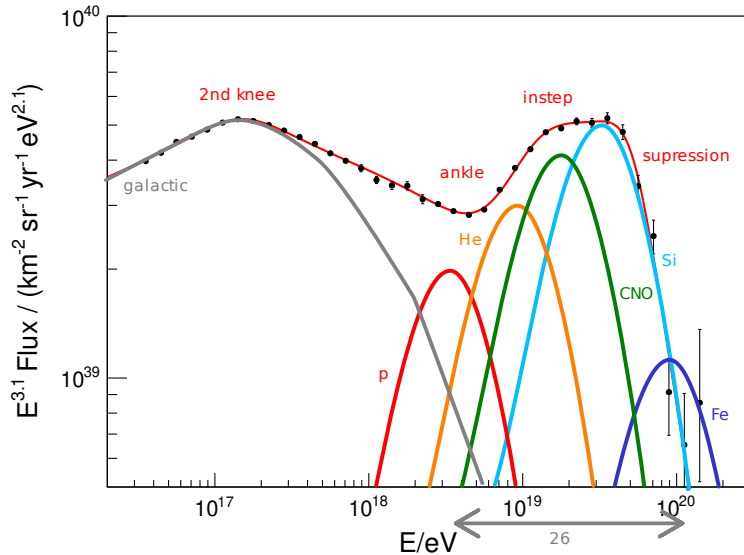
Interpretation of the UHE Spectrum and Mass (schematically)



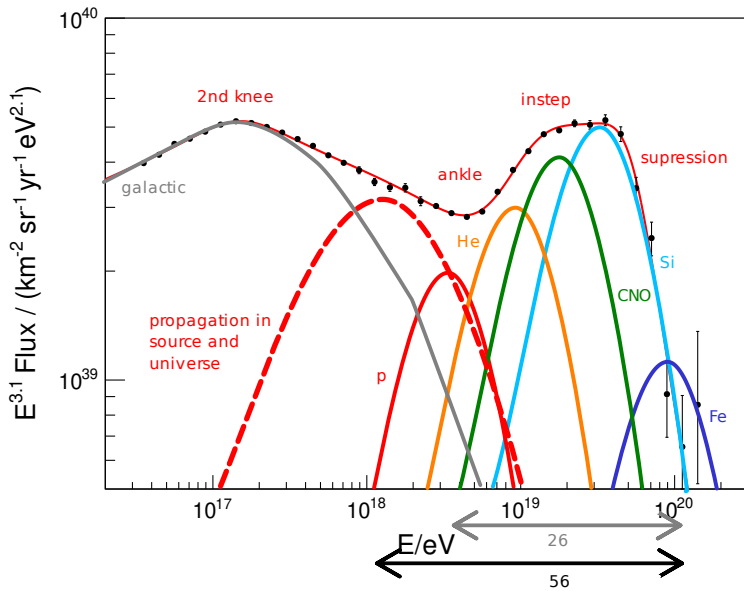
Interpretation of the UHE Spectrum and Mass (schematically)



Interpretation of the UHE Spectrum and Mass (schematically)

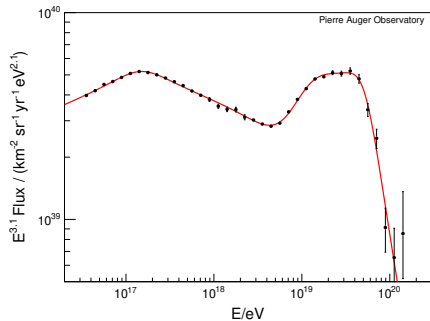


Interpretation of the UHE Spectrum and Mass (schematically)

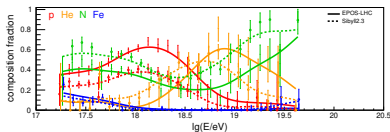
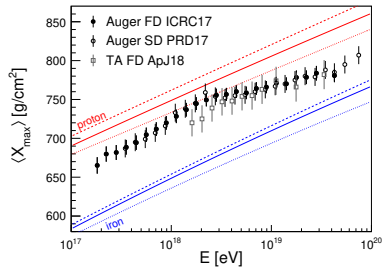


Key UHECR Observations

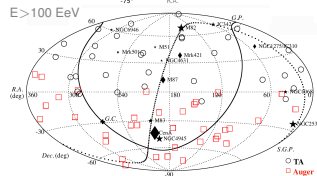
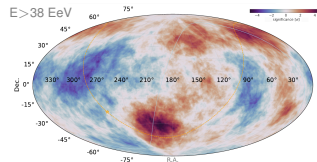
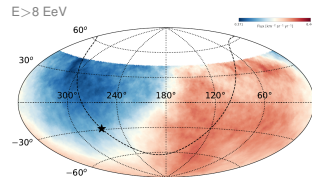
energy spectrum



mass composition



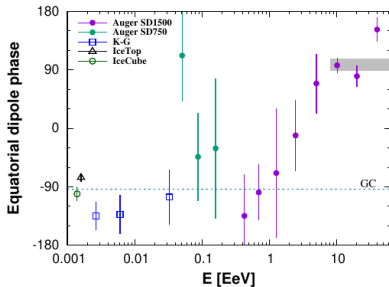
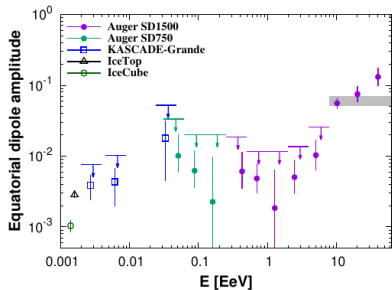
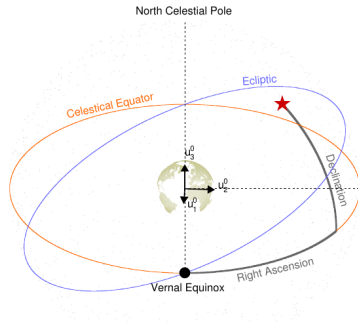
arrival directions



Large-Scale Anisotropy

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

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

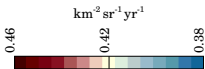
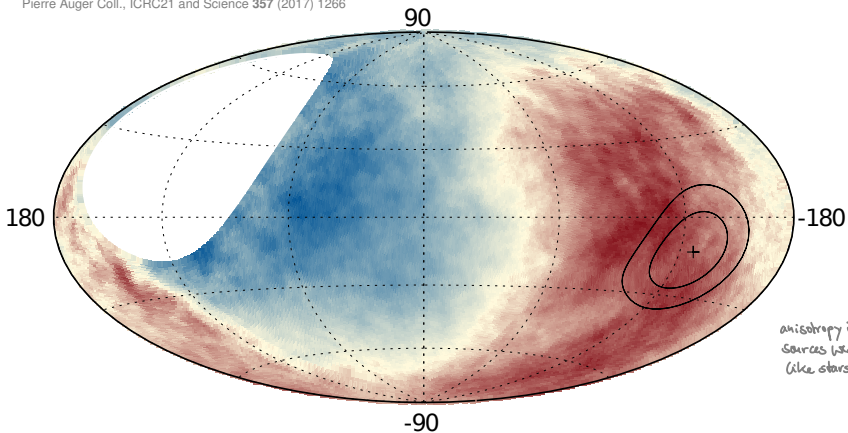


← ~180° away from galactic center!

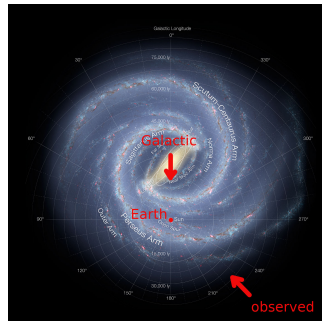
← direction of galactic center

Dipolar Anisotropy of UHECRs ($E > 8 \text{ EeV}$)

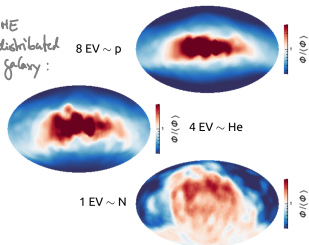
Pierre Auger Coll., ICRC21 and Science **357** (2017) 1266



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

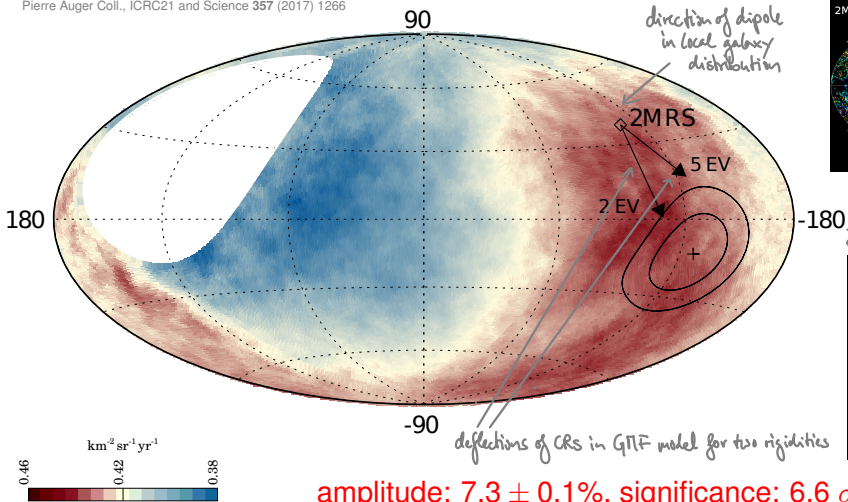


anisotropy if UHE
sources were distributed
like stars in galaxy:

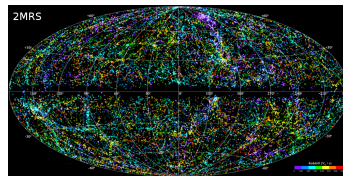


Dipolar Anisotropy of UHECRs ($E > 8 \text{ EeV}$)

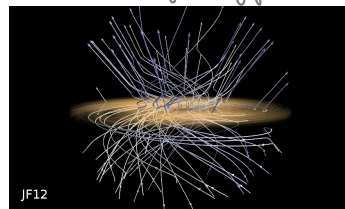
Pierre Auger Coll., ICRC21 and Science 357 (2017) 1266



2MRS galaxy catalogue

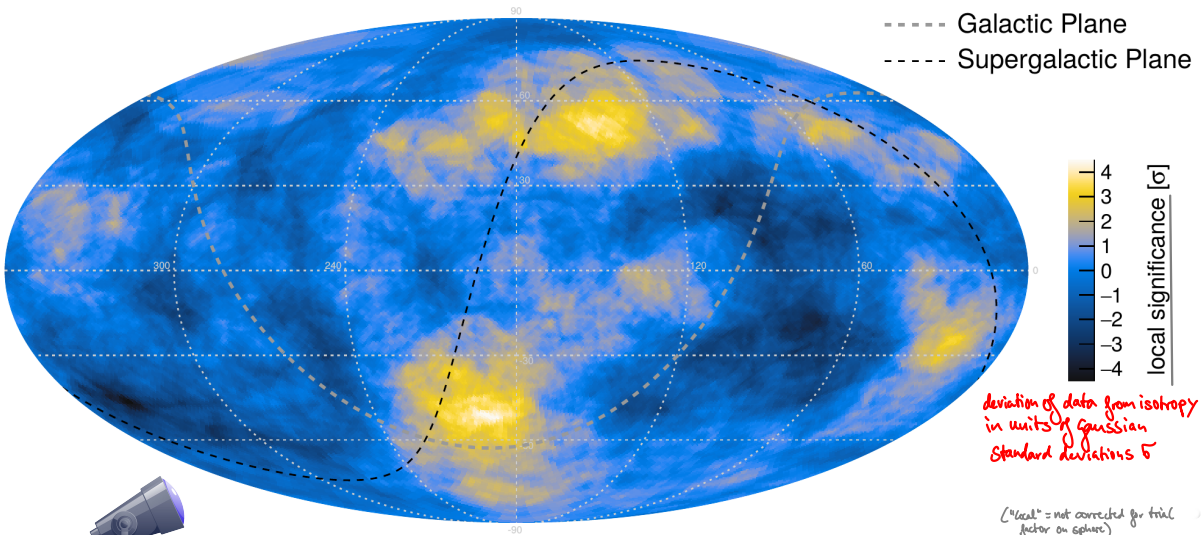


Jansson + Farrar 2012 galactic mag. field model:



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

Charged Particle Astronomy?



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

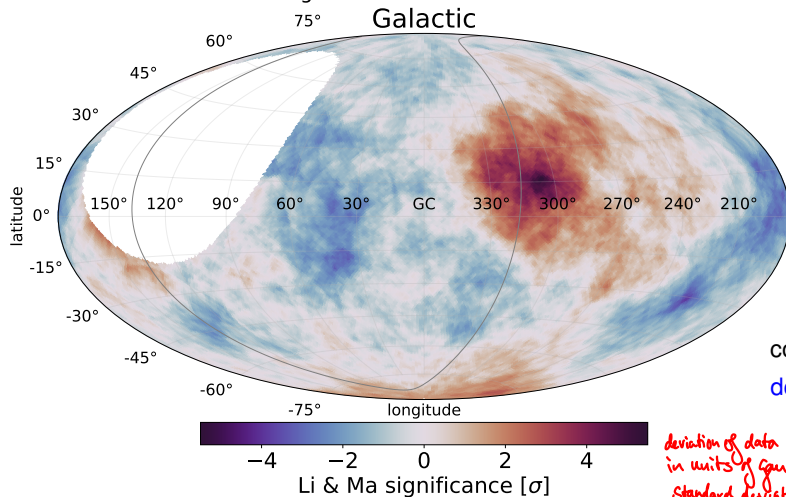
Auger&TA UHECR18



UHECR Sky as seen by the Pierre Auger Observatory

$\sigma(E_{\text{Auger}} \geq 41 \text{ EeV}) - \Psi = 24^\circ$

Galactic



code and dataset available at

[doi:10.5281/zenodo.6504276](https://doi.org/10.5281/zenodo.6504276)

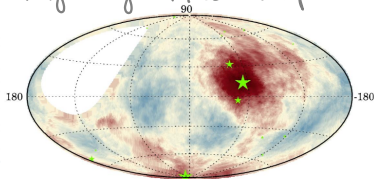
*deviation of data from isotropy
in units of gaussian
standard deviations σ*

post-trial p-value is 3%

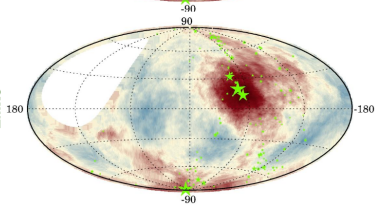
Correlation with Galaxy Catalogues ($E \gtrsim 40$ EeV)

Starburst Galaxies

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



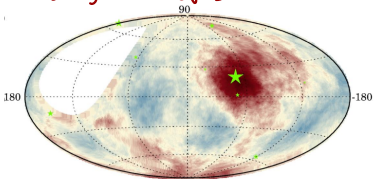
2MRS



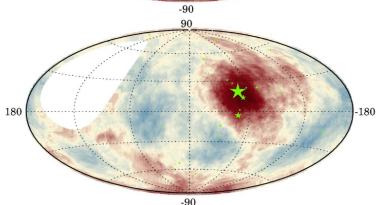
proxy for all galaxies

γ -emitting AGNs

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



Swift-BAT



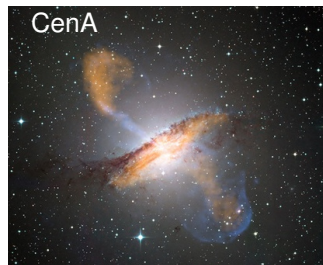
X-ray detected galaxies → all AGNs

starburst

NGC4945



CenA



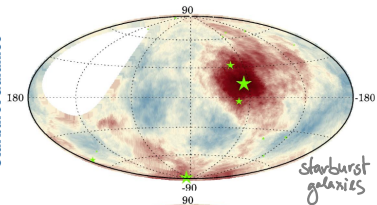
jetted AGN

Correlation with Galaxy Catalogues ($E_{\gamma} \gtrsim 40$ EeV)

post-trial p-value

Starburst Galaxies

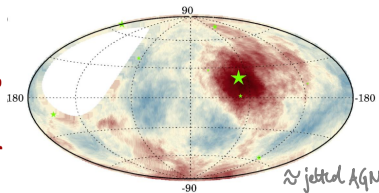
$$3 \times 10^{-5}$$



starburst galaxies

γ -emitting AGNs

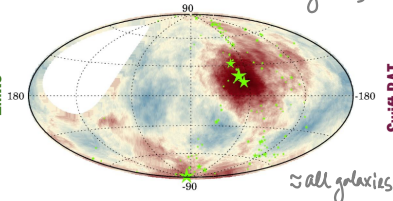
$$8 \times 10^{-4}$$



$\approx$ jetted AGN

2MRS

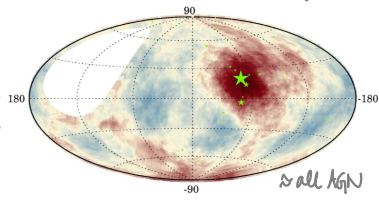
$$8 \times 10^{-4}$$



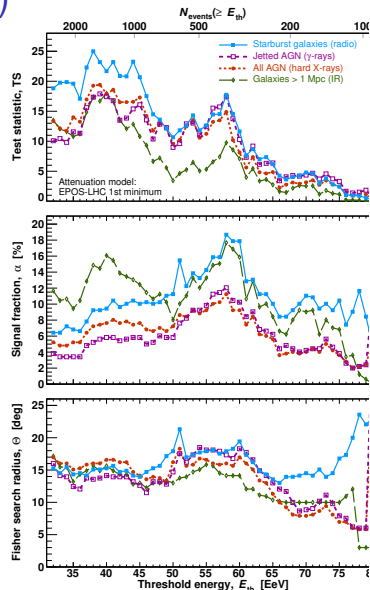
$\approx$ all galaxies

Swift-BAT

$$4 \times 10^{-4}$$



$\approx$ all AGN



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

5+ **OMG! Schon wieder!**

nature

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

VICE

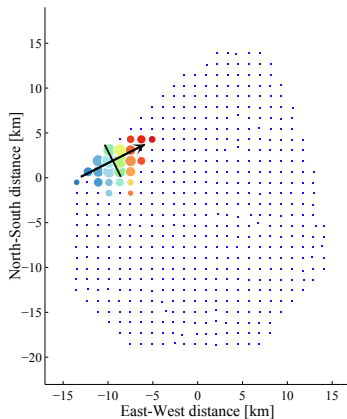
A Ray From Space Hit Earth with Such Incredible Power That Scientists Named It After a God

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

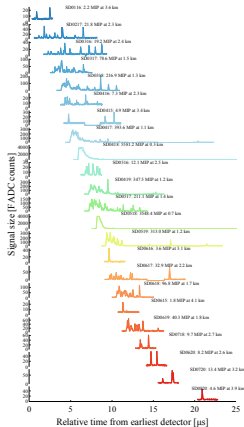
An extremely energetic cosmic ray observed by a surface detector array

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

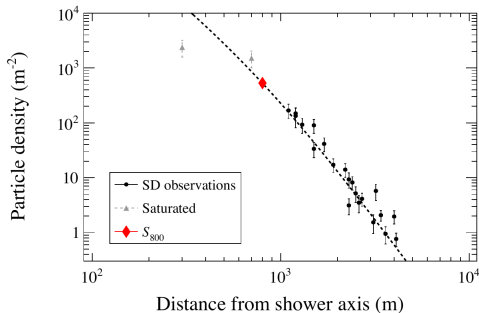
(A) Surface detector array of TA



(B) Date: 27 May 2021 Time: 10:35:56.474337 UTC

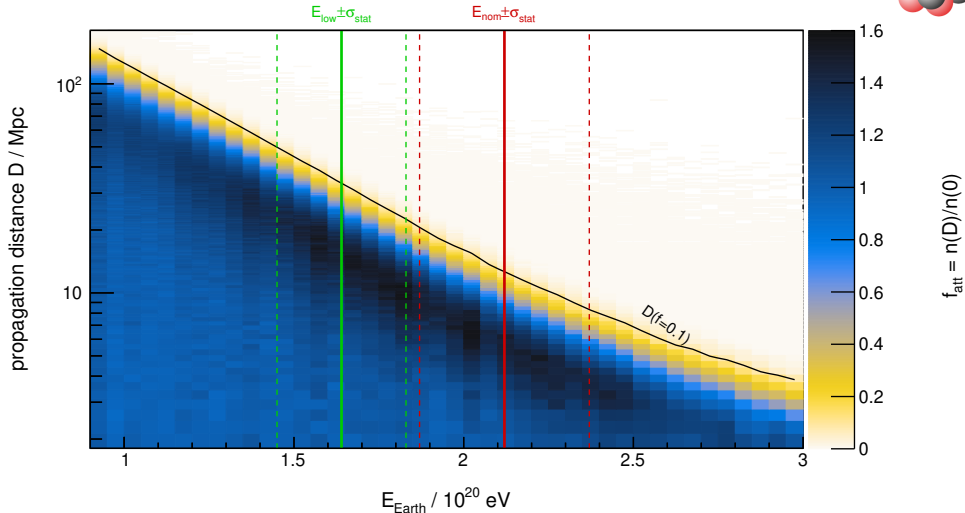
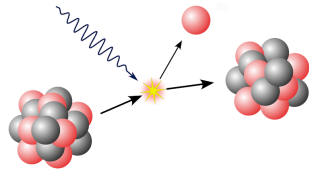


- $E = \left(2.44 \pm 0.29 \text{ (stat.)}^{+0.51}_{-0.76} \text{ (syst.)} \right) \times 10^{20} \text{ eV}$
- if Fe: $E_{\text{nom}} = (2.12 \pm 0.25) \times 10^{20} \text{ eV}$
- Fe at $-1\sigma_{\text{syst}}$: $E_{\text{low}} = (1.64 \pm 0.19) \times 10^{20} \text{ eV}$

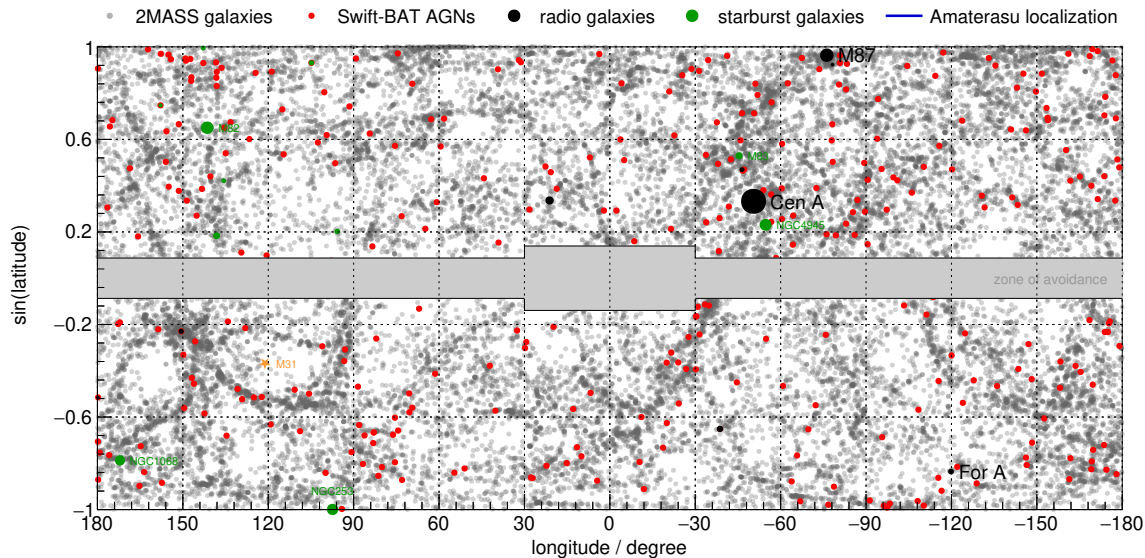


Propagation of Fe in Extragalactic Photon Fields

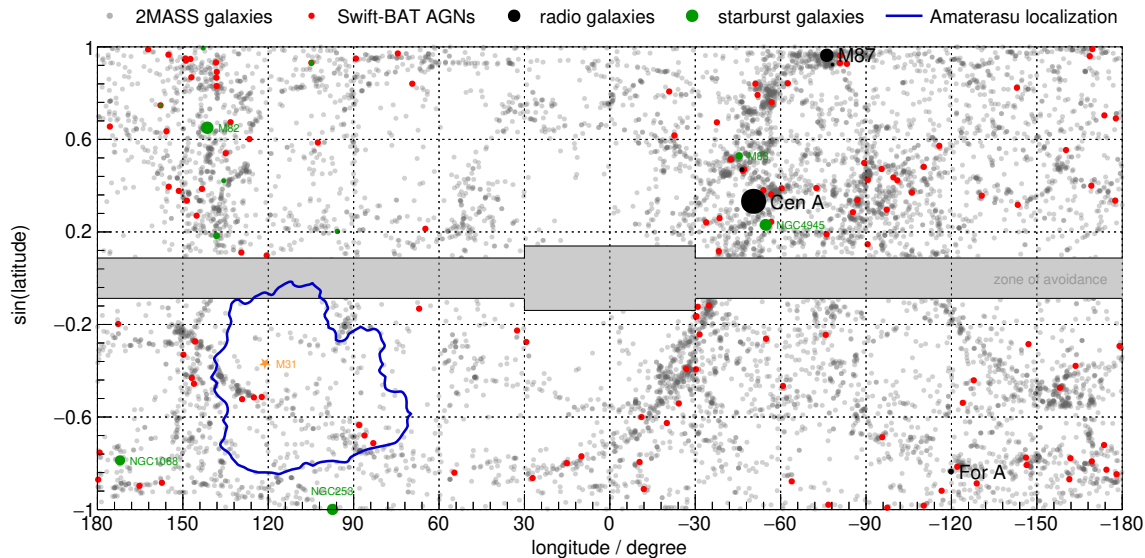
- horizon between 8 and 50 Mpc



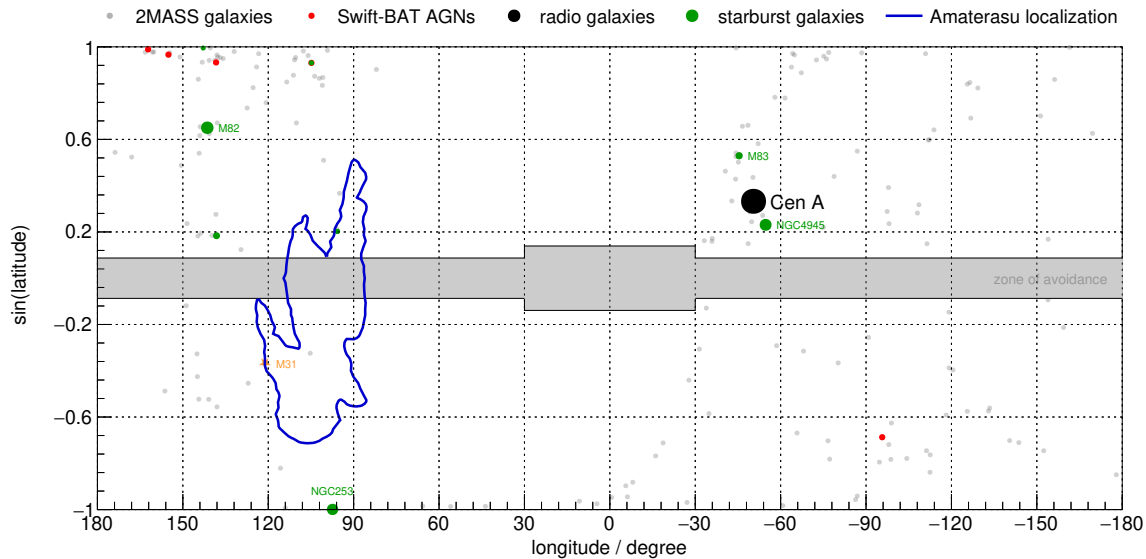
Distribution of galaxies up to D=150 Mpc



$E_{\text{low}} - 2\sigma$, $D_{0.1}=72$ Mpc



E_{nom} , $D_{0.1}=10$ Mpc



questions