On sources of ultra-high energy cosmic rays

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Outline:

1. General constraints: 'the sources at the sources'
2. Spectrum, deflection, apparent density: 'the sources on the detectors'
3. Anisotropies (vs chemical composition)

Motivations

→ chemical composition, or rigidity E/(eZ) at a given energy, controls all the phenomenology at ultra-high energies:

(1) sources of 10^{20}V are much more extreme than sources of 10^{18}V particles:

… e.g., a few candidate sources for 10^{20}eV protons vs *dozens* of candidate sources of 10^{20}eV iron…

(2) light particles leave stronger signatures of their sources:

… e.g., anisotropies at ultra-high energies with deflections of a few deg, vs large deflections for iron-like primaries

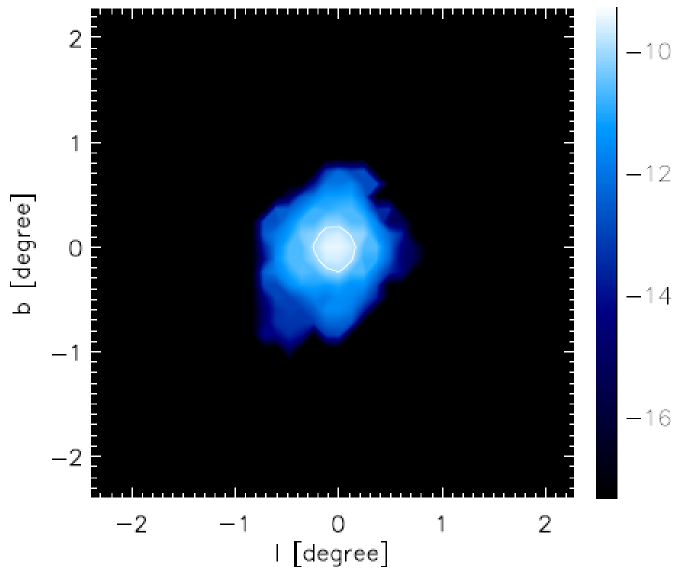
… e.g., secondary photons and neutrino signals

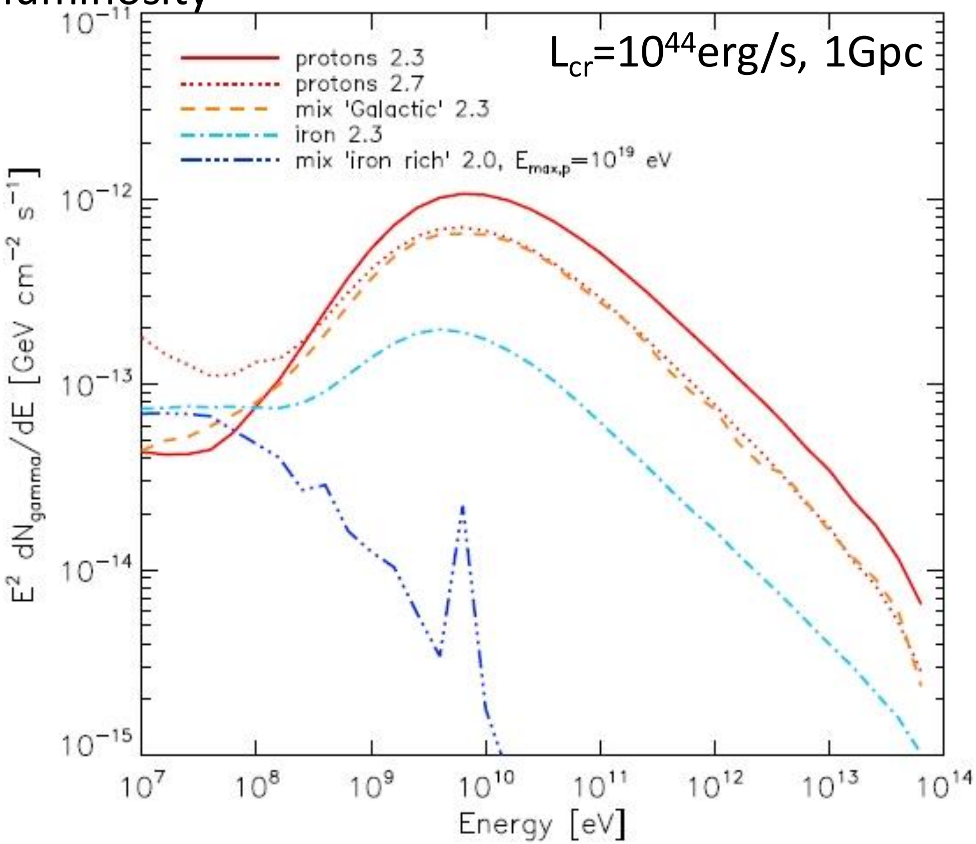
GeV photon halo from a UHECR source

→ a possible signature of UHECR acceleration: a gamma-ray halo / secondary flux from a powerful source, from synchrotron radiation of secondary electrons (Aharonian 02, Gabici & Aharonian 05, Kotera+ 11):

$N + \gamma_{CMB/IRB} \rightarrow$ e.m. cascade down to GeV-TeV
electron synchrotron to GeV

→ detection with CTA requires a large CR luminosity of protons above 10^{19}eV:
$L_{cr} \sim 10^{46}$ erg/s for a distance 1Gpc...





see also Essey+ 10,11, Murase+ 12

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… e.g., secondary photons and neutrino signals

Acceleration – a luminosity bound

<u>A generic case:</u> acceleration in an outflow

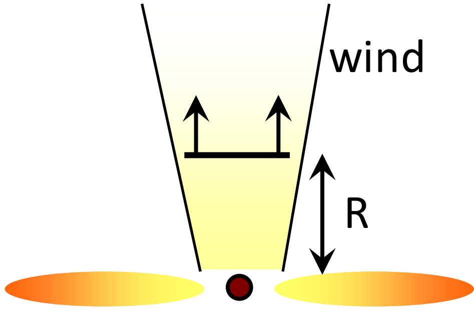
(e.g. Lovelace 76, Norman+ 95, Blandford 00, Waxman 05, Aharonian+ 02, Lyutikov & Ouyed 05, Farrar & Gruzinov 09, M.L. & Waxman 09)

$\rightarrow$ acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm g}$

A >> 1, A ~ 1 at most:

- for non-relativistic Fermi I, $A \sim (t_{\rm scatt}/t_{\rm g}) / \beta_{\rm sh}^2$

$\rightarrow$ time available for acceleration (comoving frame): $t_{\rm dyn} \approx \dfrac{R}{\beta\Gamma c}$



$\rightarrow$ maximal energy: $t_{\rm acc} \leq t_{\rm dyn} \Rightarrow E_{\rm obs} \leq \mathcal{A}^{-1} ZeBR/\beta$

$\rightarrow$ 'magnetic luminosity' of the source: $L_B = 2\pi R^2\Theta^2 \dfrac{B^2}{8\pi}\Gamma^2\beta c$

$\rightarrow$ lower bound on total luminosity: $L_{\rm tot} \geq 0.65\times 10^{45}\,\Theta^2\Gamma^2\mathcal{A}^2\beta^3 Z^{-2}E_{20}^2\,{\rm erg/s}$

10^{45} ergs/s is robust: for $\beta \rightarrow 0$, $\mathcal{A}^2\beta^3 \geq 1/\beta \geq 1$

for $\Theta\Gamma \rightarrow 0$, $L_{\rm tot} \geq 1.2\times 10^{45}\,\mathcal{A}\beta\dfrac{\kappa}{r_{\rm L}c}Z^{-2}E_{20}^2\,{\rm erg/s}$

<u>Lower limit on luminosity of the source:</u> $L_{\rm tot} > 10^{45}\,Z^{-2}\,{\rm erg/s}$

low luminosity AGN: $L_{\rm bol} < 10^{45}$ ergs/s

Seyfert galaxies: $L_{\rm bol} \sim 10^{43}$-10^{45} ergs/s

high luminosity AGN: $L_{\rm bol} \sim 10^{46}$-10^{48} ergs/s

gamma-ray bursts: $L_{\rm bol} \sim 10^{52}$ ergs/s

$\Rightarrow$ only most powerful AGN jets, GRBs or young magnetars for UHE protons...
... many (many) others for heavy nuclei?

General principles of particle acceleration

Standard lore:

→ Lorentz force: $$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right)$$

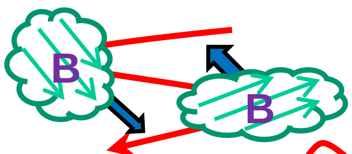
Ideal MHD: $\boldsymbol{E}_{|\mathrm{p}} \simeq 0$ in plasma rest frame

→ ***E*** field is 'motional', i.e. if plasma moves at velocity $\boldsymbol{v}_\mathrm{p}$: $\boldsymbol{E} \simeq -\frac{\boldsymbol{v}_\mathrm{p}}{c}\times\boldsymbol{B}$

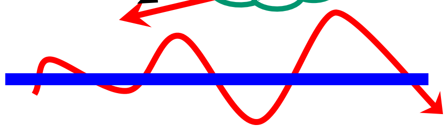
→ need some force or scattering to push particles across *B*

→ lower bound to acceleration timescale: $t_\mathrm{acc} = \frac{p}{\beta_\mathrm{p} eB} = \frac{t_\mathrm{g}}{\beta_\mathrm{p}}$

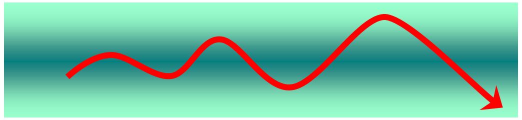
→ examples: - turbulent Fermi acceleration



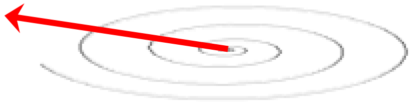
- Fermi acceleration at shock waves



- acceleration in sheared velocity fields

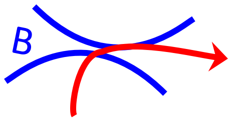


- magnetized rotators

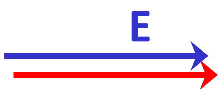


Beyond MHD:

→ examples: - reconnection



- gaps

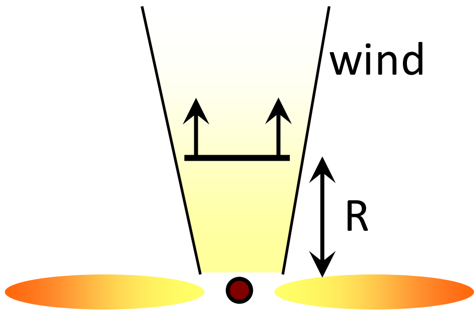


Acceleration – a luminosity bound

(e.g. Lovelace 76, Norman+ 95, Blandford 00, Waxman 05, Aharonian+ 02, Lyutikov & Ouyed 05, Farrar & Gruzinov 09, M.L. & Waxman 09)

A generic case: acceleration in an outflow

→ acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm g}$



→ **A >> 1 in most acceleration scenarios:**

e.g. in Fermi-type, **A ~ interaction time / energy gain**

sub-relativistic Fermi I: $\mathcal{A} \sim (t_{\rm scatt}/t_{\rm g})/\beta_{\rm sh}^2$
and $t_{\rm scatt} > t_{\rm g}$ (saturation: Bohm regime!)

sub-relativistic stochastic: $\mathcal{A} \sim (t_{\rm scatt}/t_{\rm g})/\beta_{\rm A}^2$

sub-relativistic reconnection flow: $\mathcal{A} \sim 10/\beta_{\rm A}$ (on reconnection scales)

relativistic Fermi I: $\mathcal{A} \sim t_{\rm scatt}/t_{\rm g}$ in shock frame, much more promising?

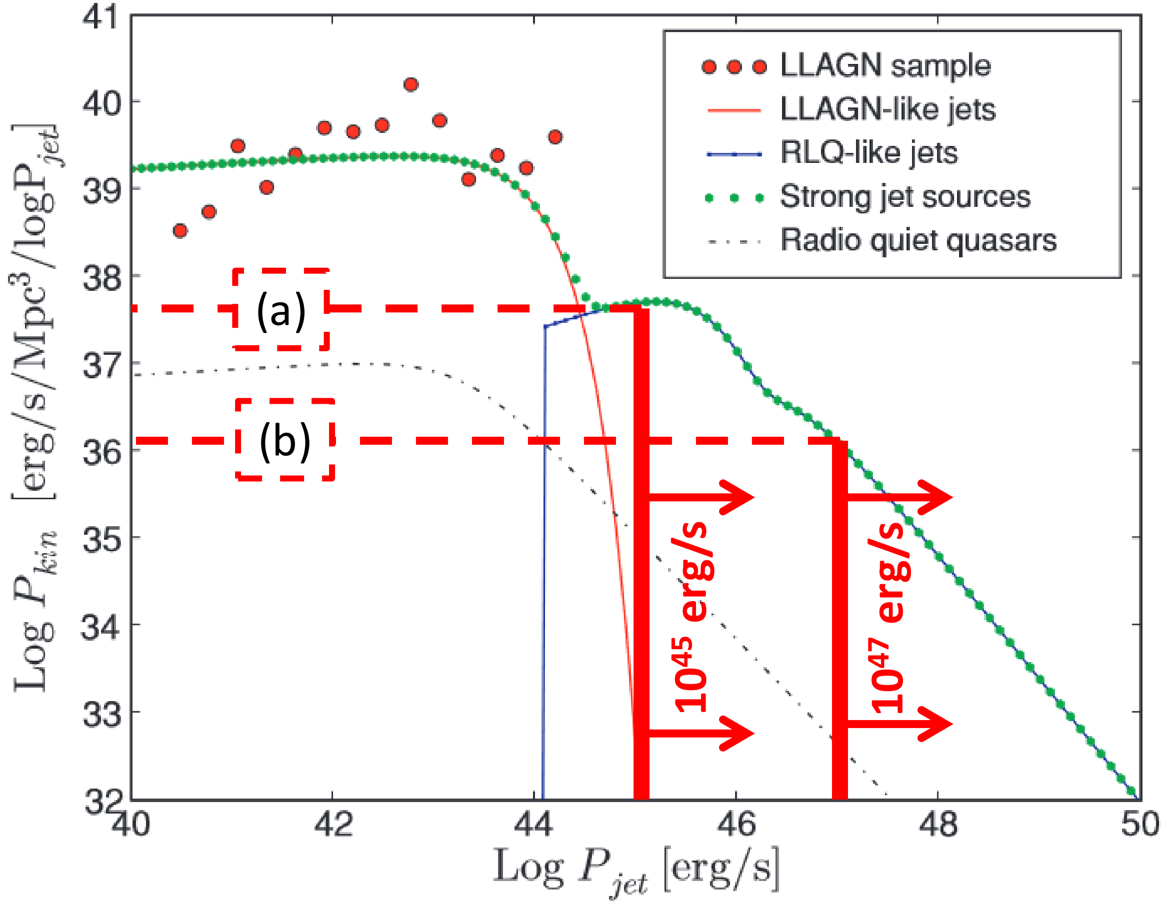
relativistic reconnection: $\mathcal{A} \sim 10$ (on reconnection scales)

… comparing $t_{\rm acc}$ and $t_{\rm dyn}$ bounds the luminosity of the source to reach UHE:

$$L_{\rm tot} \geq 0.65 \times 10^{45}\, \Theta^2 \Gamma^2 \mathcal{A}^2 \beta^3 Z^{-2} E_{20}^2\ {\rm erg/s}$$

Radio-galaxies – luminosity function

Körding+ 07: energy input of radio-galaxies



(a): energy input of 10^{45} erg/Mpc^3/yr… density 0.5 10^{-7} Mpc^{-3}

(b): energy input of 3 10^{43} erg/Mpc^3/yr… density 10^{-11} Mpc^{-3}

… to match the flux above 10^{19} eV: input rate needed 10^{44} erg/Mpc^3/yr (Katz+ 09)

Extreme acceleration, but also high output

Energy output of a source:

→ to match the flux above 10^{19} eV, $\dot{u}_{\rm UHECR} \sim 10^{44}\,{\rm erg/Mpc^3/yr}$ (Katz+ 10)

→ per source, assuming it is steady: $L_{\rm UHECR} \sim 10^{43}\, n_{-7}^{-1}\,{\rm erg/s}$ $(n\,{\rm in\,Mpc^{-3}})$

→ per transient source: $E_{\rm UHECR} \approx 10^{50}\,{\rm erg}\ \dot{n}_{-6}^{-1}$ $(\dot{n}\,{\rm in\,Mpc^{-3}yr^{-1}})$

e.g.: → radio-galaxies with L > 10^{45} erg/s, a few % efficiency

→ for the whole radio-galaxy population, nL ~ 3 10^{47} erg/Mpc^3/yr, typically from sources with L ~ 10^{43} erg/s…

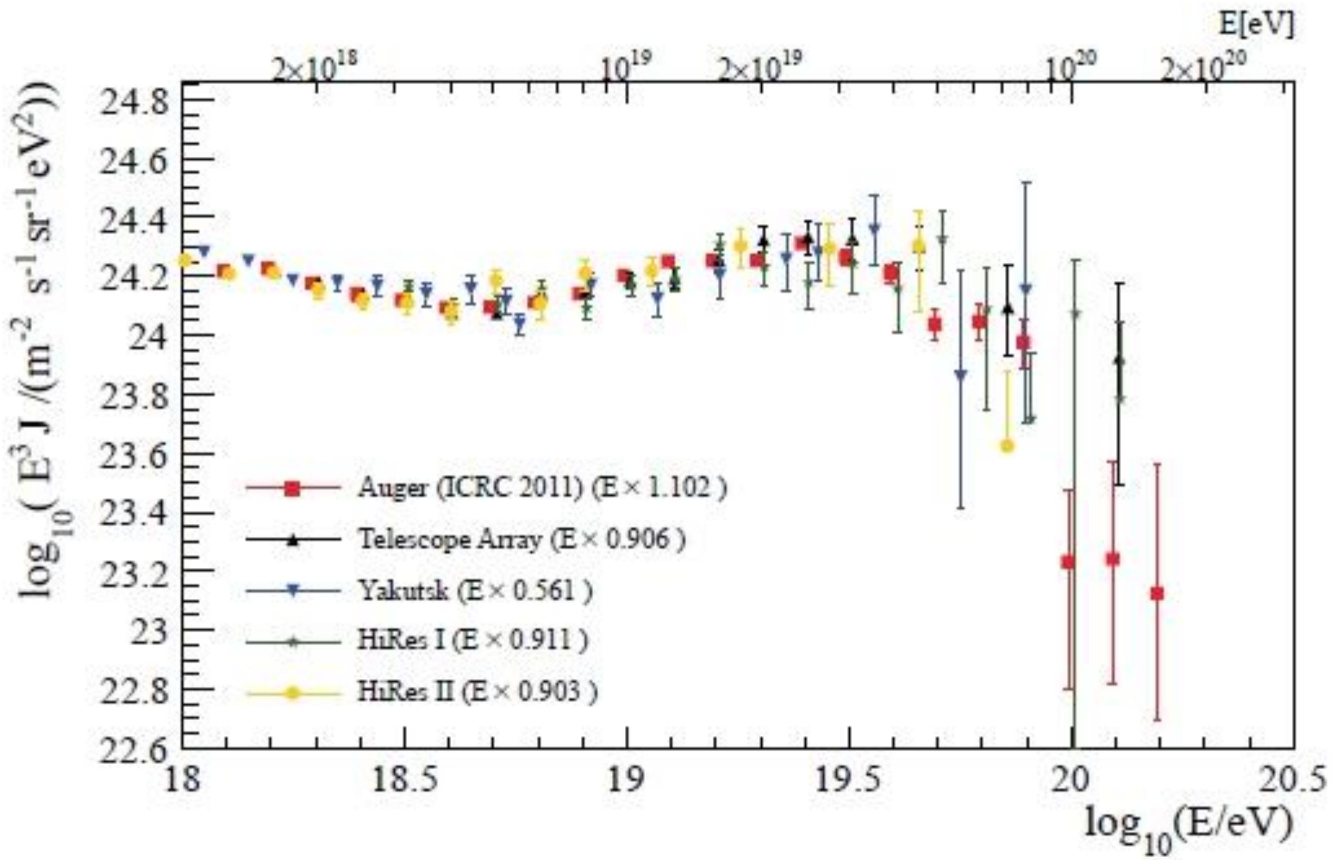
… if injecting CNO to match flux at 10^{19}eV and if metallicity is ~solar, requires an overall efficiency in high energy CR of a few percent!

if one wants nuclei at >E to circumvent luminosity bound, accounting for the protons accelerated to >E/Z requires an energy input higher by M_p/M_Z …
for reference, solar composition means:

$$\left.\frac{M_{\rm H}}{M_{\rm CNO}}\right|_\odot \sim 70,\quad \left.\frac{M_{\rm H}}{M_{\rm Si-group}}\right|_\odot \sim 1000,\quad \left.\frac{M_{\rm H}}{M_{\rm Fe-group}}\right|_\odot \sim 500$$

Ultra-high energy cosmic ray spectrum

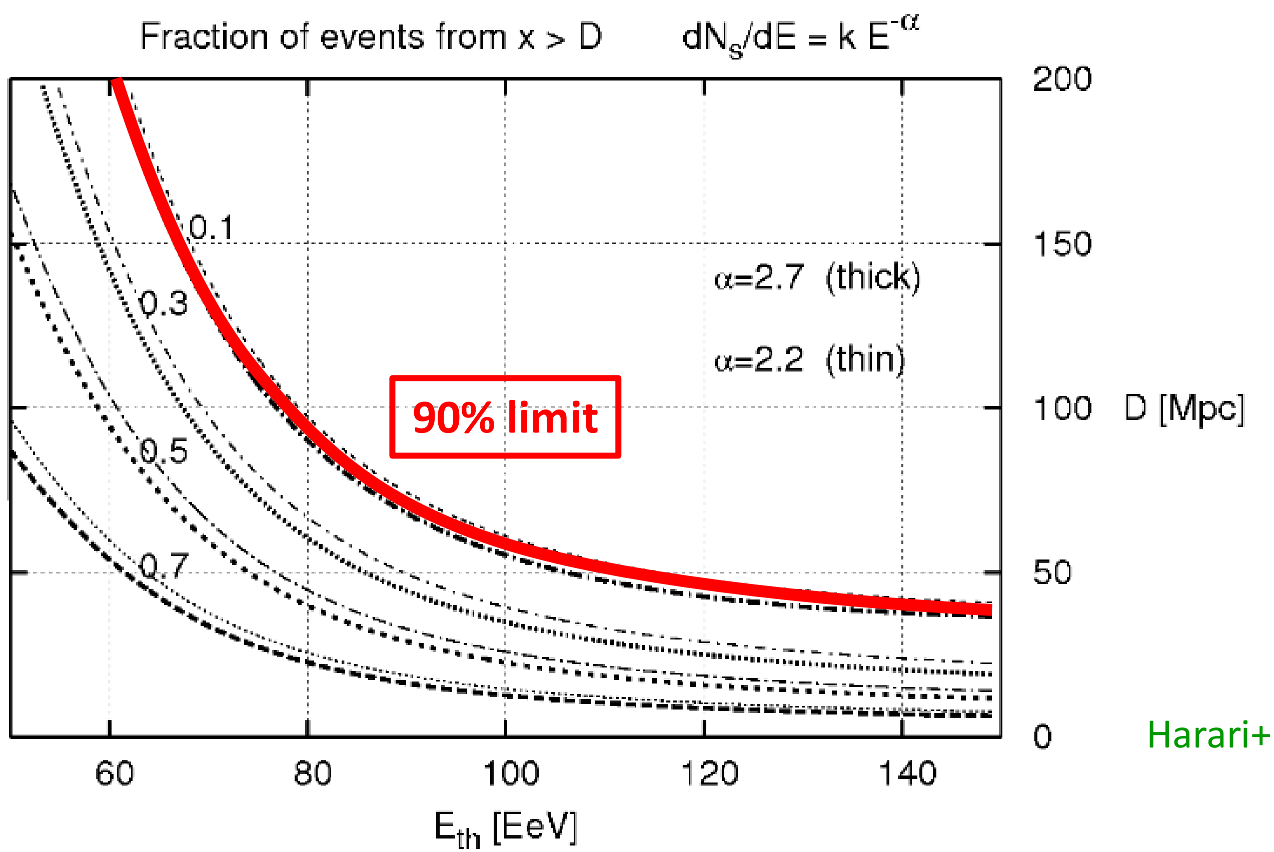
Fukushima 13



→ above ~5 10^{19} eV, the CMB becomes opaque to UHE protons due to pion production, with energy loss length ~ 100Mpc … and to nuclei through photodisintegration…

→ matches well the cut-off seen by HiRes, Auger, TA at high energies…
… but this cut-off could also represent the maximal energy at accceleration…

Greisen-Zatsepin-Kuzmin cut-off



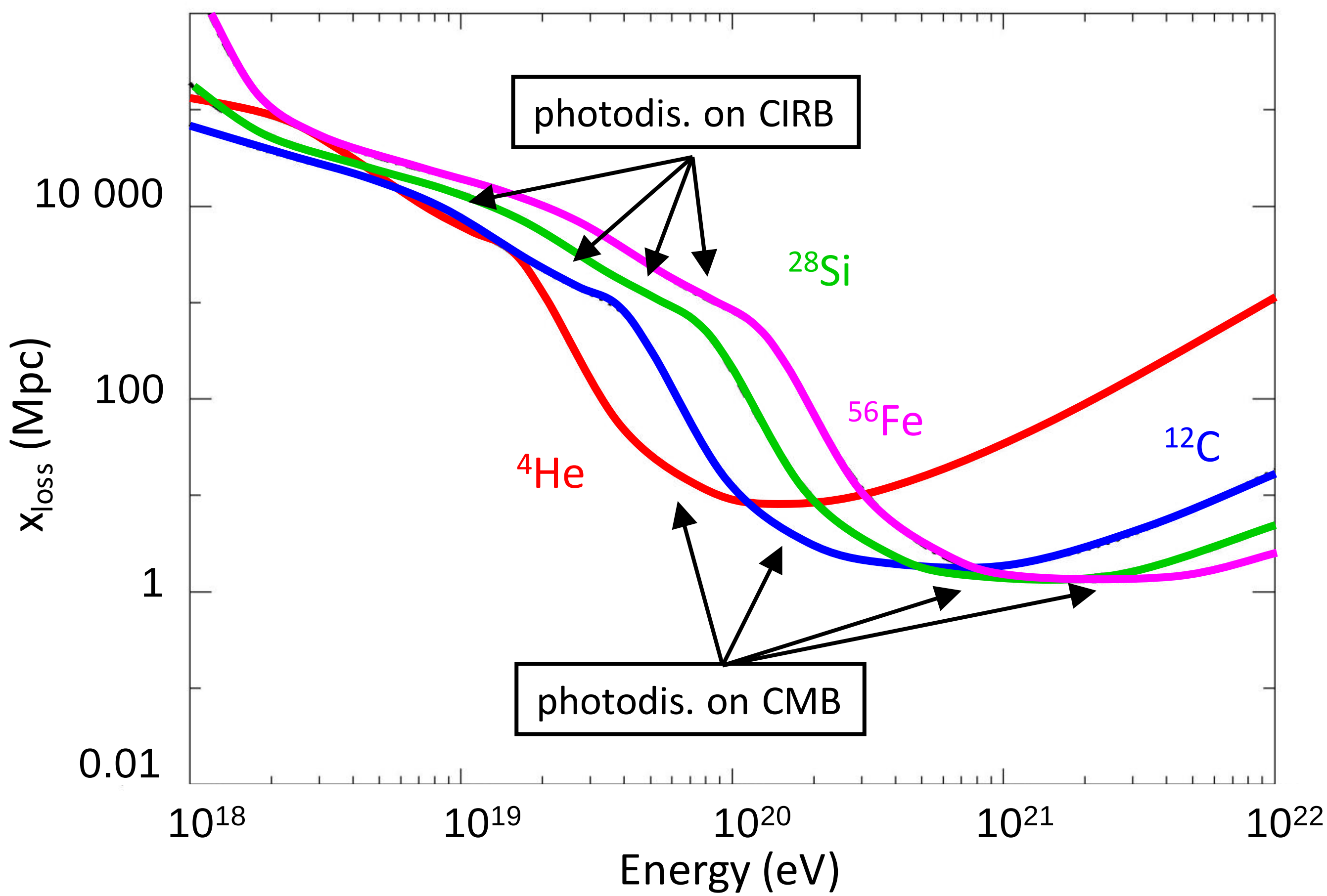
Harari+ 06

→ at 6 10^{19} eV, 90% of protons come from within 200Mpc…

→ at 10^{20} eV, 90% of protons come from within 60Mpc…

Nuclei : photodisintegration losses

Bertone+ 02



→ iron horizon is comparable to that of protons... while intermediate mass nuclei are more fragile, with smaller horizons...

→ in practice: **expect either protons or heavy (Si-Fe-?) nuclei at the highest energies**

Propagation – transport in extra-galactic magnetic fields

Ultra-high rigidities: $r_{\rm L} \simeq 100\,{\rm Mpc}\,Z^{-1}\left(\frac{E}{10^{20}{\rm eV}}\right)\left(\frac{B}{1\,{\rm nG}}\right)^{-1}$

if B follows large scale structure:

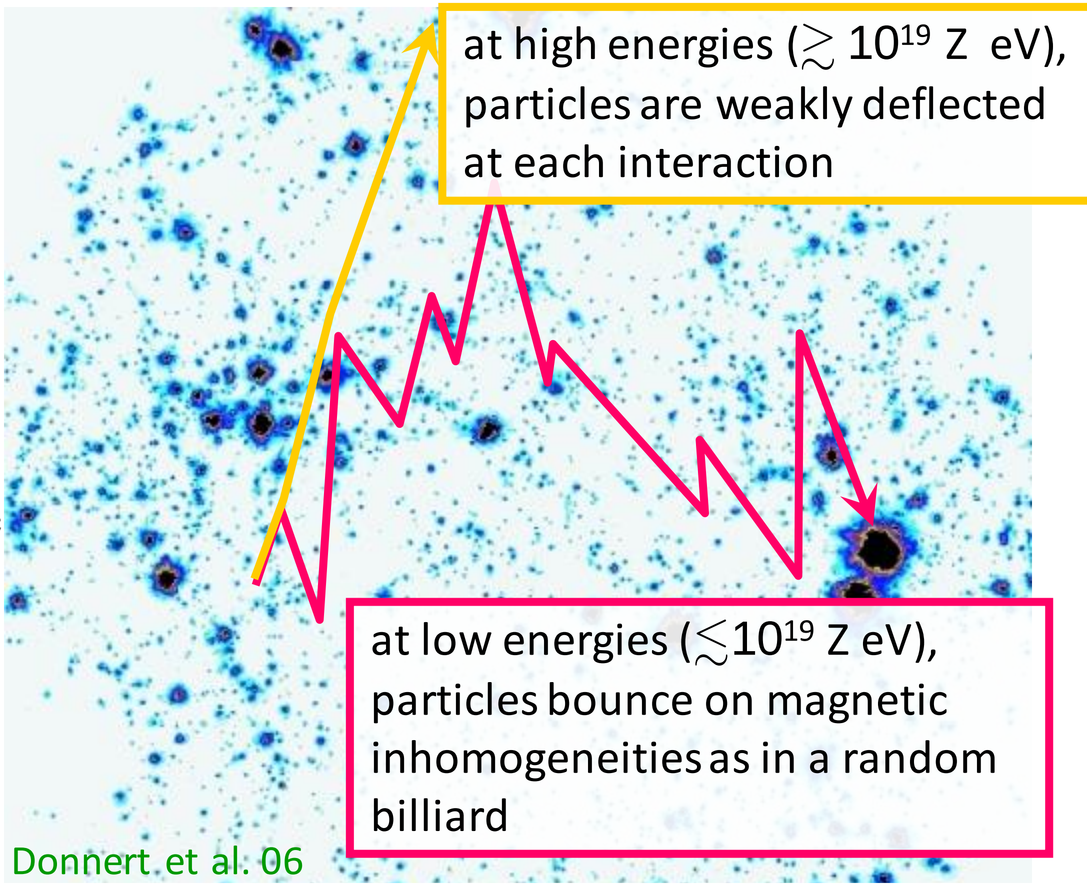
$\rightarrow$ particles of different energies probe different structures...

$\rightarrow$ at high energies, few interactions with small deflection:

$$\delta\theta_i \sim 1.7^\circ Z E_{20}^{-1} B_{-8} \lambda_{100{\rm kpc}}^{1/2} R_{1{\rm Mpc}}^{1/2}$$

per interaction, with typical mfp ~ 30Mpc (Kotera & ML 08)

$\Rightarrow$ a few deg total at Z 10^{20} eV over 100 Mpc...



$\rightarrow$ deflection in Galactic magnetic field: a few degrees at Z 10^{20} eV, with direction dependent magnitude...

Expected angular deflection

Integrating over all sources at a given energy:

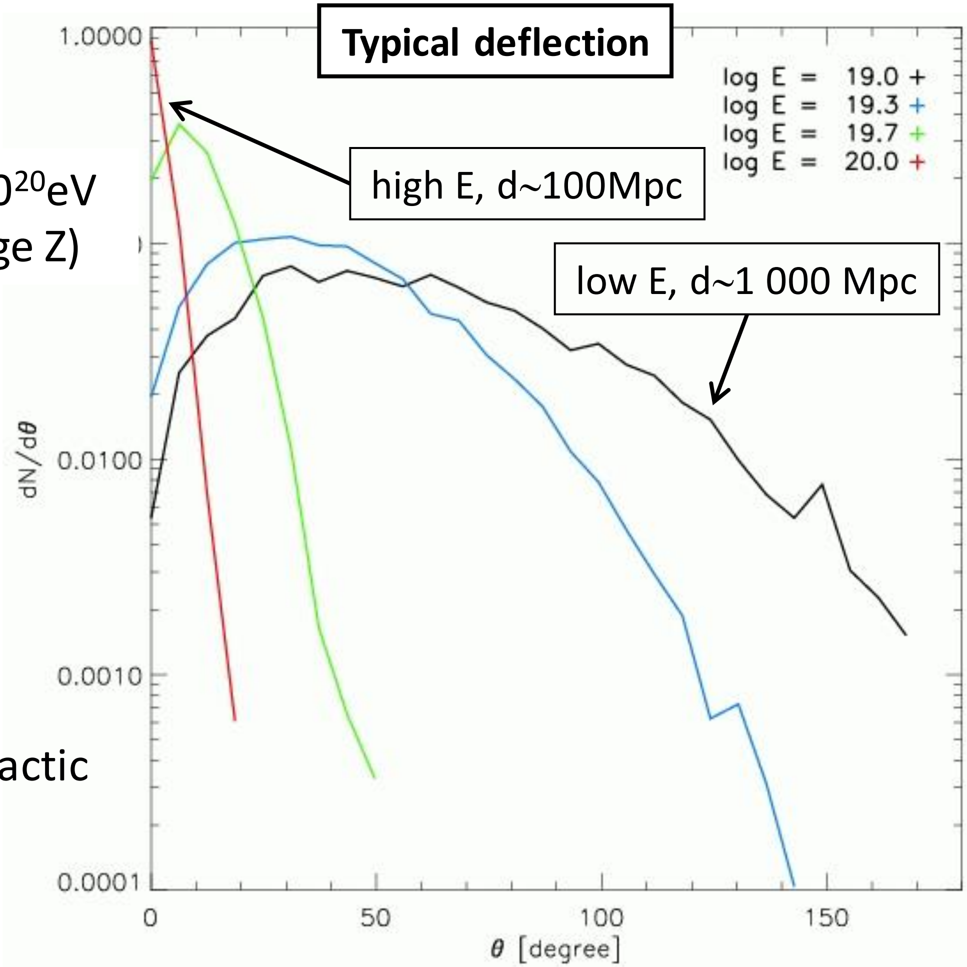
→ note that most of the flux comes from $l_{max}(E)$ (→ Olbers' paradox!)

$$F(<l) = \int_{r\leq l} d^3r\, n_{\rm source}\, \frac{\dot{N}_{\rm UHECR}}{4\pi r^2} = n_{\rm source}\dot{N}_{\rm UHECR} l$$

⇒ expect a few degrees for protons at 10^{20}eV
(… Z times more for heavy nuclei of charge Z)

⇒ near isotropy for $E \lesssim 3\ 10^{19}Z$ eV…
… small deflection above $5\ 10^{19}Z$ eV

→ deflection of similar magnitude in Galactic magnetic field…



Small angular deflection

→ at high E/Z ~ 10^{20} eV, expect only a few degree deflection over maximal distance:

$$\delta\theta \sim 2^\circ\ Z \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{d}{100\,\mathrm{Mpc}}\right)^{1/2}$$

(x uncertainty on B, λ)
(Waxman&Miralda-Escudé 96)

… small deflection gives rise to a significant time delay τ with respect to photon arrival time and dispersion of arrival times Δτ~τ:

$$\tau \sim 10^5\,\mathrm{yrs} \left(\frac{\delta\theta}{2^\circ}\right)^2 \left(\frac{d}{100\,\mathrm{Mpc}}\right)$$

(x uncertainty on B, λ)

… implying an apparent effective density for transient sources:

$$n_{\rm eff} = \dot n \Delta\tau \sim 10^{-4}\,\mathrm{Mpc}^{-3} \left(\frac{\dot n}{10^{-9}\,\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}}\right) \left(\frac{\Delta\tau}{10^5\,\mathrm{yrs}}\right)$$

… or 10s of sources in the GZK horizon at 10^{20}eV, but 10^7 sources in the Hubble volume …

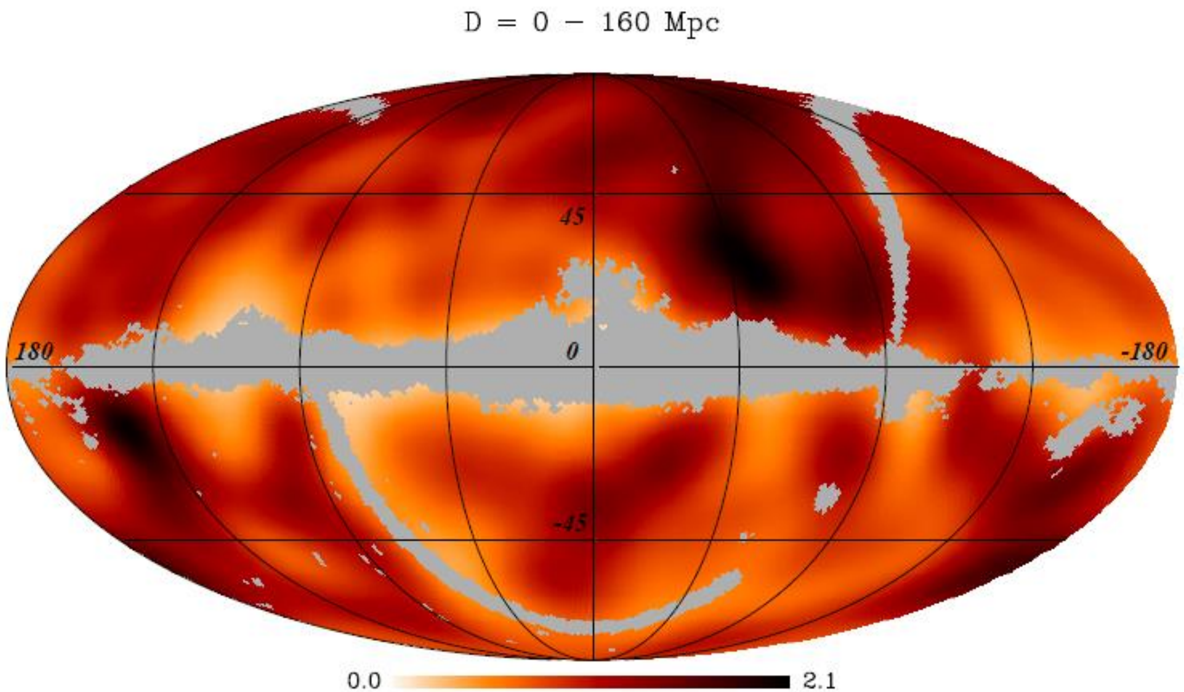
→ Auger 2013: absence of multiplets constrains the apparent density:

$$n \gtrsim 0.5 - 1 \times 10^{-4}\,\mathrm{Mpc}^{-3}$$

(assuming δθ<10° at >60EeV)

Small angular deflection and correlations to catalogs

→ **if sources follow large scale structure, correlations remain weak for energies > 50 EeV because of large integration depth (+deflection):**



Kotera+ML08

column density of galaxies in PSCz survey integrated up to 160Mpc

→ Kashti+Waxman 08, Oikonomou+13: need 300 events above 40EeV to achieve 99%cl for negligible angular deflection

→ Auger 15: no clear indication of correlation with large scale structure (600 events above 40EeV)

Large angular deflection

→ at low E/Z ~ 10^{18} eV, expect strong deflection and diffusion once d > l_{scatt}(E)…

… observational constraint on source density relaxed… 1 source within 50Mpc:

$$n \gtrsim 10^{-6}\,\mathrm{Mpc}^{-3}$$

… possible existence of a magnetic horizon (for steady sources only)

$$r_{\rm horizon} \sim \sqrt{c l_{\rm scatt}/H_0} \sim 60\,\mathrm{Mpc}\; l_{\rm scatt,1Mpc}^{1/2} < n^{-1/3}?$$

(ML 05, Aloisio+ 05)

... weak anisotropies if any: a weak dipole from nearby sources? (Harari+ 15)

Anisotropies

Auger, ICRC2015

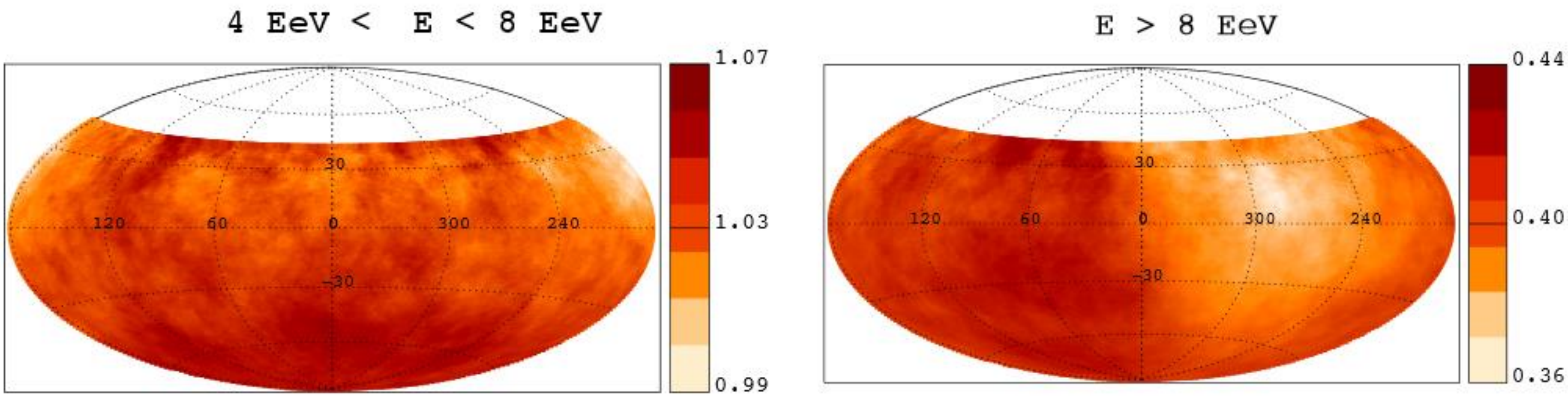


Figure 2: Sky map in equatorial coordinates of flux, in $km^{-2}\ yr^{-1}\ sr^{-1}$ units, smoothed in angular windows of 45° radius, for observed events with energies $4 < E < 8$ EeV (left) and $E > 8$ EeV (right).

Pierre Auger Observatory 2015 dipole above 8 EeV: amplitude 7%

Anisotropies

Auger, ICRC2015

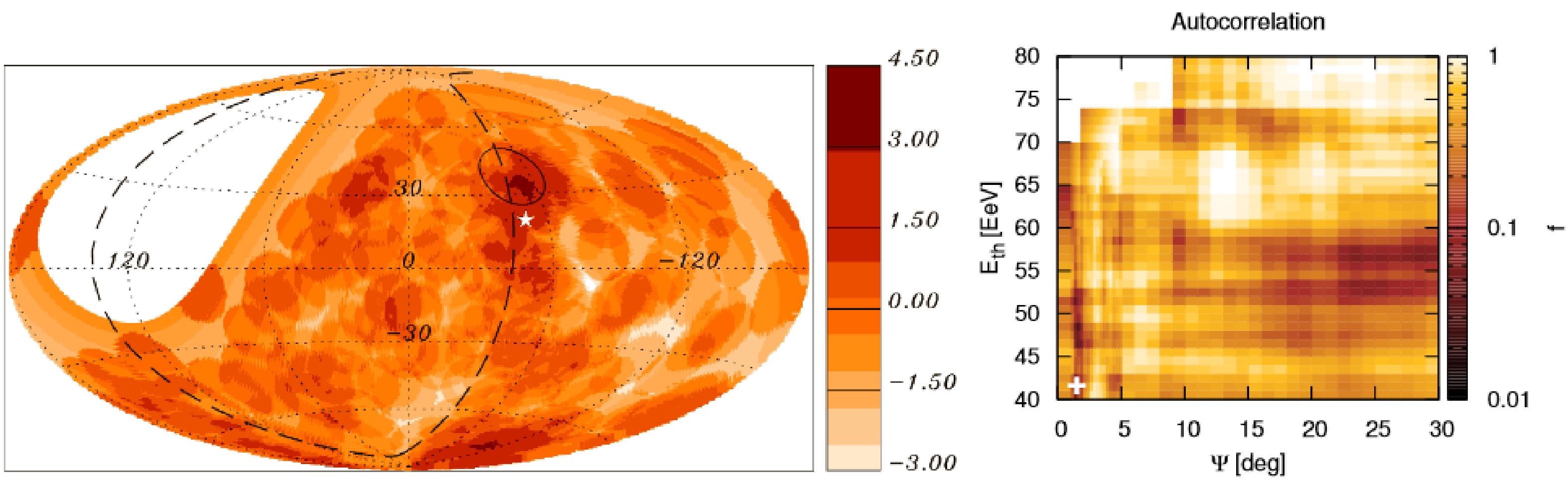
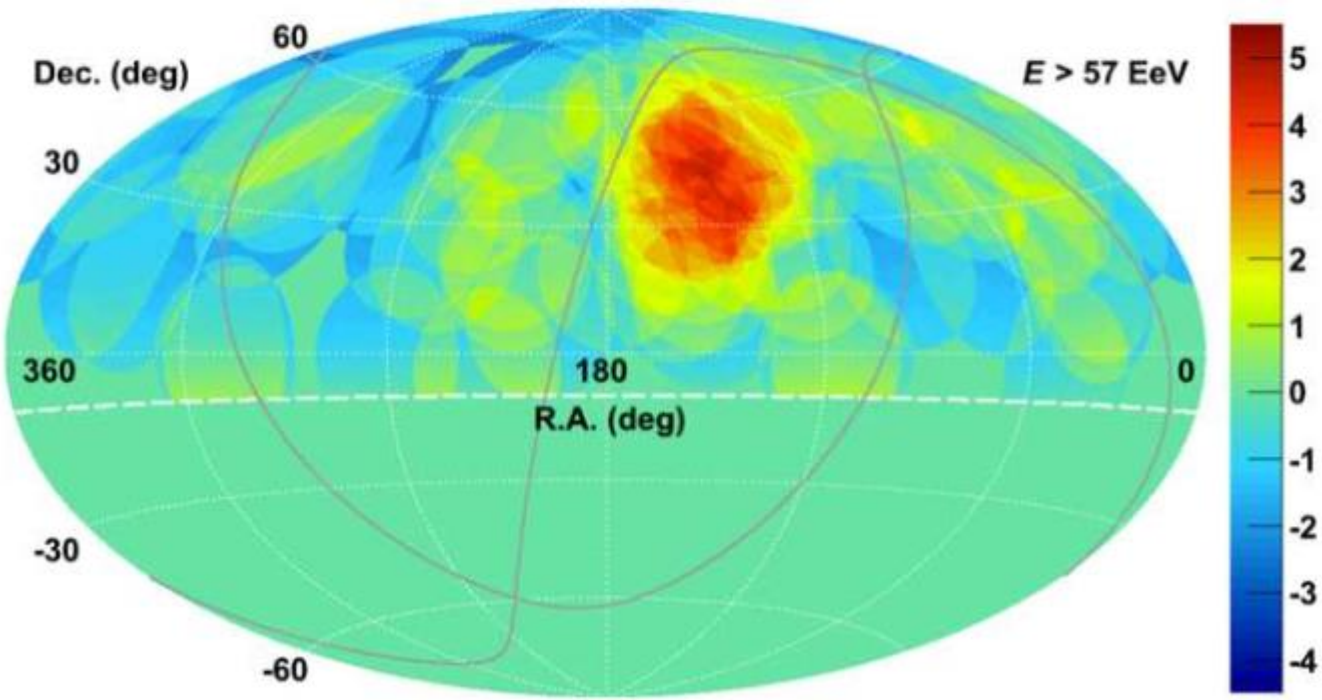


Figure 1: *Left*: map in galactic coordinates of the Li-Ma significances of excesses in 12°-radius windows for the events with $E \geq 54$ EeV. Also indicated are the Super-Galactic Plane (dashed line) and Centaurus A (white star). *Right*: Fraction f obtained in the autocorrelation of events versus ψ and E_{th}, white cross indicating the minimum.

Pierre Auger Observatory 2015 anisotropy map: consistent with isotropy…

… a slight excess close to Cen A direction, but significance not below 1%

Anisotropies

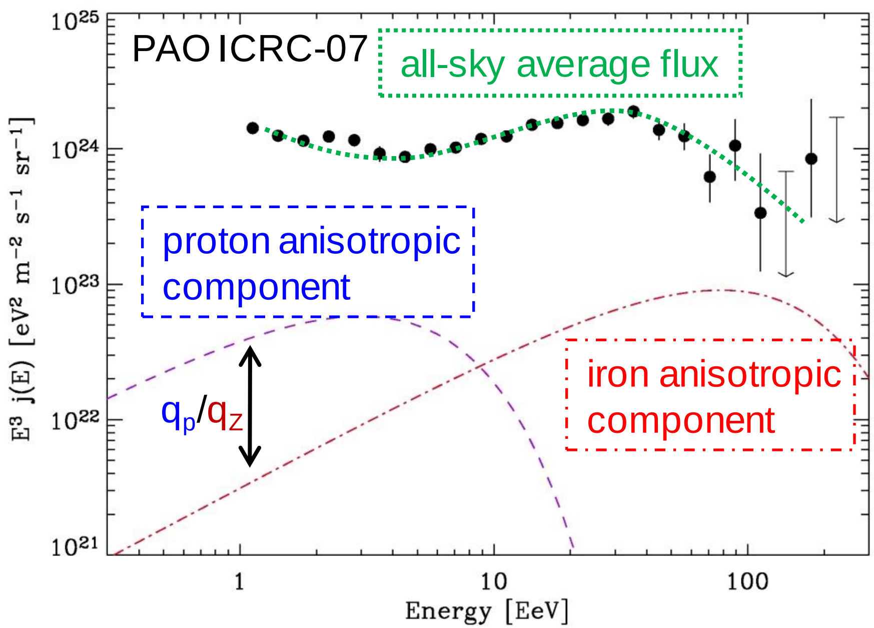


Telescope Array 2014 anisotropy map – Li-Ma excess significance:

… a hot-spot seen with a (post-trial) significance of 3.4 sigma…

Anisotropies vs heavy composition at UHE

→ if anisotropic signal >E is due to heavy nuclei, then one should detect a stronger anisotropy signal associated with protons of same magnetic rigidity at >E/Z eV...
argument independent of intervening magnetic fields... (M.L. & Waxman 09)



•injection shaped by rigidity, s=2:
$E_{max} \propto Z$
•composition: q_p/q_{Fe} = 1/0.06 as in sources of GCR

→ signal-to-noise at low energy vs that at high energy:

$$\mathrm{S/N}|_p\,(>E/Z) \simeq \underbrace{\underbrace{\alpha_{\mathrm{loss},Z}}_{>1}\;\underbrace{Z^{-0.85}}_{<1}\;\underbrace{\frac{N_p}{N_Z}}_{\gg 1}}_{\gg 1}\;\mathrm{S/N}|_Z\,(>E)$$

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→ if anisotropies are seen at >E, say >50 EeV, but not at any E/Z, with Z ~ 6-26, then the following assertions cannot hold simultaneously:

(1) the anisotropy signal at >E is real (=not a statistical accident)

(2) the composition at energies >E is heavy: O, Si, Fe...

(3) the sources have a "reasonable" metallicity N(Z>6)/N(Z=1) $\ll$ 1

⇒ if anisotropies are not statistical accidents, there exist GZK protons, or the source metallicity is extraordinarily large...

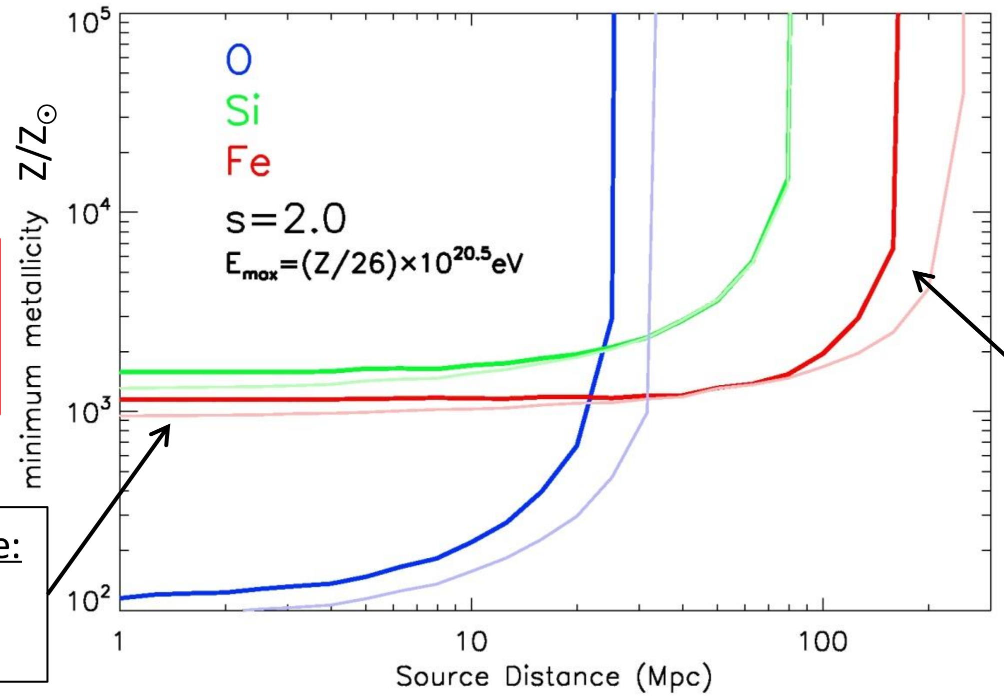
NB: does not depend on spectral index of injection spectrum...
only assumption: particle spectra are shaped by rigidity...

Anisotropies vs heavy composition at UHE

→ taking into account photodisintegration, nuclei with energy >2E produce protons with energy >E/Z, which add up to the anisotropy signal… Liu+ 13

$$\mathrm{S/N}|_p\,(>E/Z) \simeq Z^{-0.85} A \left[\frac{M_p}{M_Z} + 2^{1-s} f_{\rm photodis.}(>2E)\right] \mathrm{S/N}|_Z\,(>E)$$

minimum Z/Z_{solar} to ensure: $S/N_p\,(E/Z) < S/N_Z(E)$



Liu+ 13

close-by source:
no photo-dis.
Z → p

remote source:
secondary p's from photo-dis. of >2E nuclei produce anisotropies at E/Z

→ anisotropies at E could thus be produced by heavy nuclei ***only*** if the source metallicity:

if Fe at UHE: Z $\gtrsim$ 1000 $Z_\odot$; if Si at UHE: Z $\gtrsim$ 1600 $Z_\odot$; if O at UHE: Z $\gtrsim$ 100 $Z_\odot$

… sources with such high metallicities?

Summary

→ **(Robust) Constraints on the sources of ultra-high energy cosmic rays:**

→ highly powerful sources (from theory): $L \gtrsim 10^{45}\,\mathrm{erg/s}\;\; Z^{-2}\mathcal{A}^2 E_{20}^2$

→ injection rate (from exp.): $\dot{u} \sim 10^{44}\;\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$

→ large apparent density (from exp.): $n \gtrsim 10^{-6} - 10^{-4}\,\mathrm{Mpc^{-3}}$

→ **Composition controls the phenomenology of this field:**

→ experimentally: strong signatures from protons, weak signatures from heavies

→ theoretically: restricted landscape for proton sources, enlarged for heavies

→ **Existence of anisotropies at GZK energies (if confirmed) constrains composition:**

→ either protons at GZK, or an extremely metal-rich source with $Z > 100\,Z_o$