~~What are the sources~~

On ~~of~~ ultra-high energy cosmic rays ~~?~~

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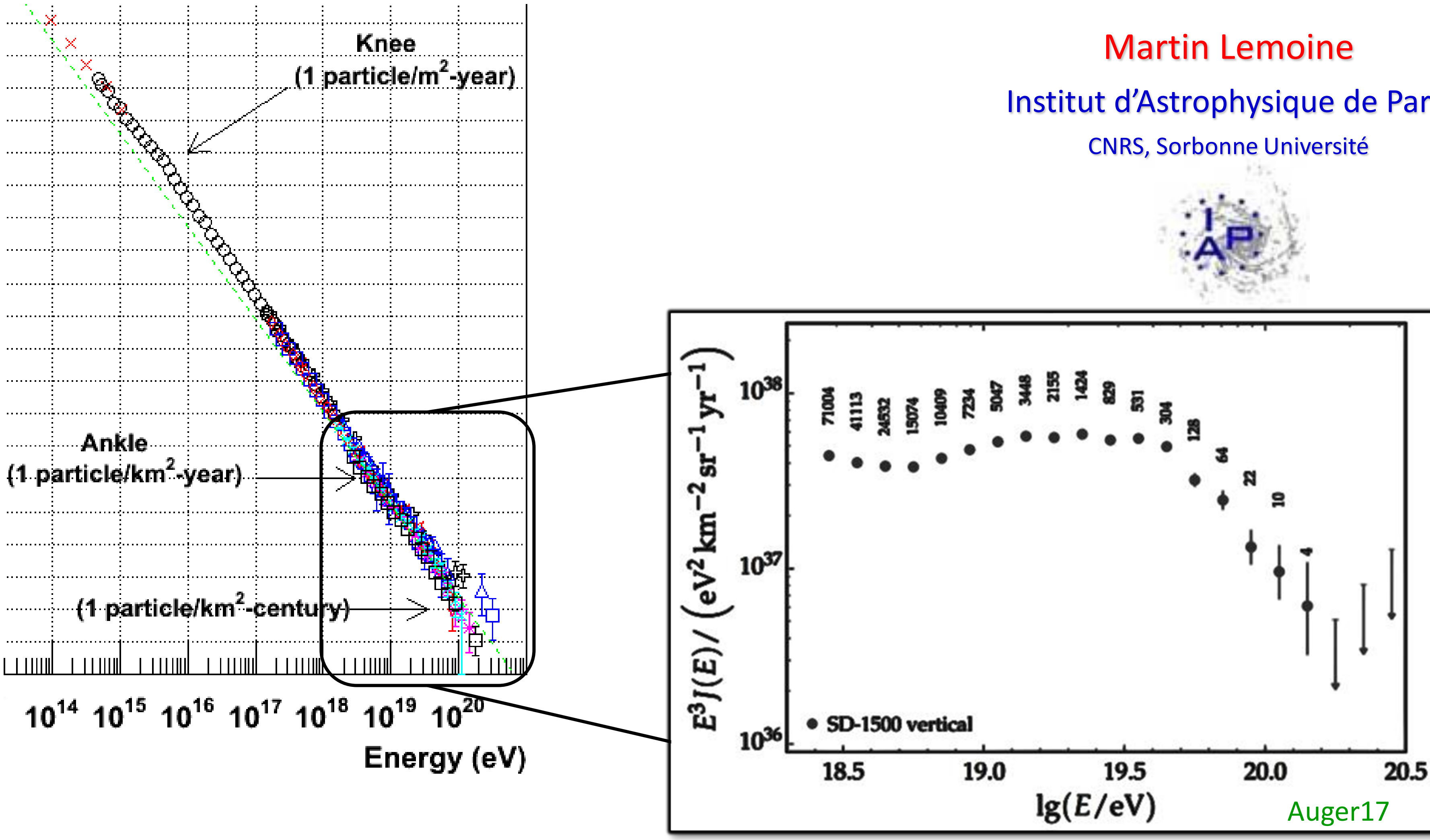

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General principles of particle acceleration

Standard lore:

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

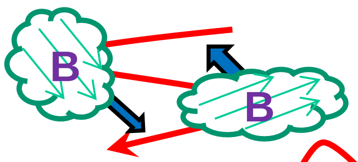
Ideal MHD: $\boldsymbol{E}_{|\mathrm{p}} \simeq 0$ in plasma rest frame

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

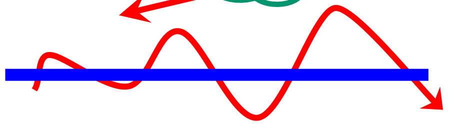
→ need some force or scattering to push particles across *B*

→ lower bound to acceleration timescale: $t_\mathrm{acc} = \dfrac{p}{\beta_\mathrm{p} e B} = \dfrac{t_\mathrm{g}}{\beta_\mathrm{p}}$

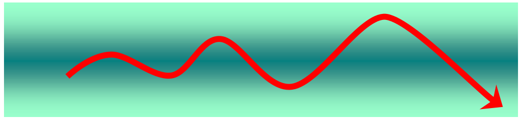
→ examples: - turbulent Fermi acceleration



- Fermi acceleration at shock waves

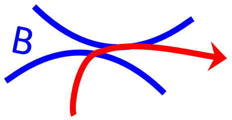


- acceleration in sheared velocity fields

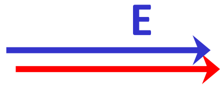


Beyond MHD:

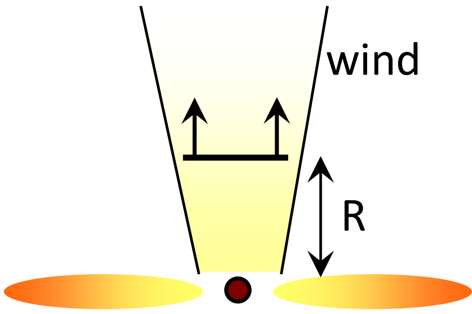
→ examples: - reconnection



- gaps



Acceleration – a luminosity bound



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 $t_{scatt} > t_g$ (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?

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

$$L_{\rm tot} \geq 0.7 \times 10^{45}\ \Theta^2\Gamma^2\beta^3\,\mathcal{A}^2 Z^{-2} E_{20}^2\,{\rm erg/s}$$

low lum. AGN: $L_{bol} << 10^{45}$ ergs/s
high lum. AGN: $L_{bol} \sim 10^{46}$-10^{48} ergs/s

Crab pulsar: $L_{bol} \sim 10^{39}$ ergs/s
high lum. GRBs: $L_{bol} \sim 10^{52}$ ergs/s

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~10 events above 100EeV

→ **source density:** $n_{\rm s} \gtrsim 10^{-6} - 10^{-4}\,{\rm Mpc}^{-3}$

→ $n_{\rm s} \gtrsim 10^{-6}\,{\rm Mpc}^{-3}$: at least one source within GZK sphere (radius 100Mpc)

→ $n_{\rm s} \gtrsim 10^{-4}\,{\rm Mpc}^{-3}$: Auger16, from lack of multiplets…
… assumes small magnetic deflection

→ note: n_s corresponds to actual density for steady sources…
and $n_{\rm s}(E) \simeq \dot{n}_{\rm s}\,\Delta t$ for transient sources, *e.g.*

$$\dot{n}_{\rm GRB} \sim 10^{-9}\,/{\rm Mpc}^3 \qquad \Delta t \sim 10^4 - 10^5\,E_{20}^{-2} D_{100{\rm Mpc}}^2\,{\rm yr}$$

→ **energy output:**

→ **anisotropies:** S

→ **composition:**

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Extreme acceleration, but also high output

Energy output of a source:

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

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

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

e.g.: → high-luminosity GRBs: $E_{\rm UHECR/GRB} \approx 10^{53}\,{\rm erg} \sim 10\,E_{\gamma/GRB}$

→ protons from radio-galaxies with L > 10^{45} erg/s: ***a few percent 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:

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

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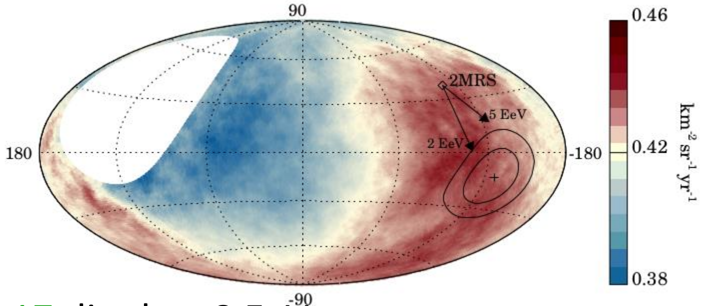
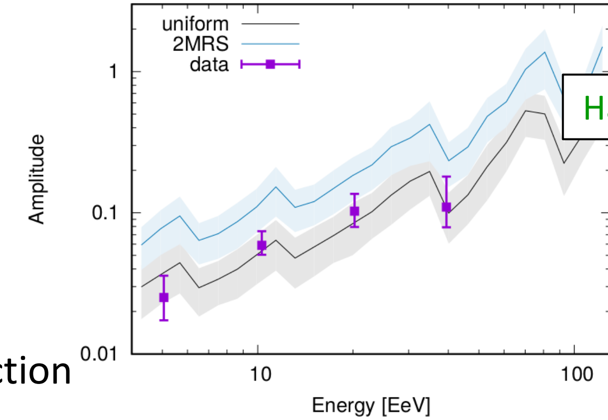
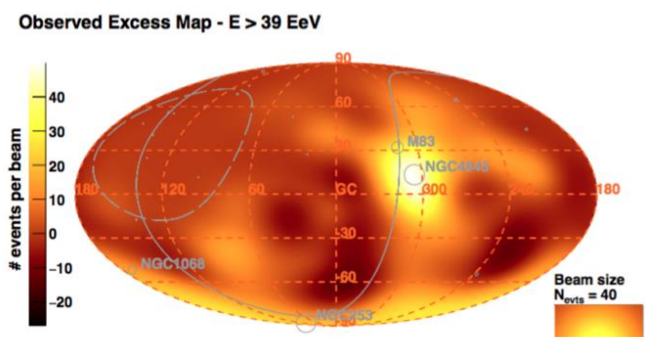
Anisotropies at UHE

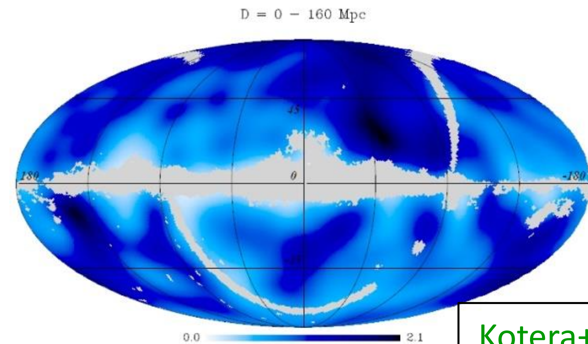




Harari+15

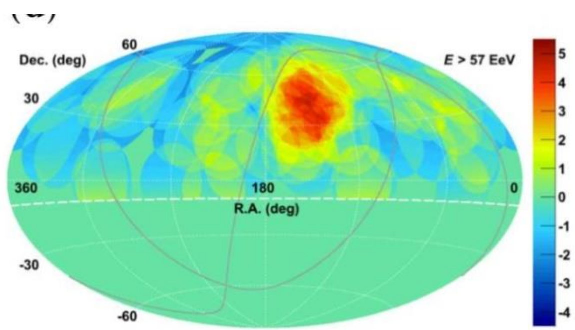
☆ Auger 17 dipole > 8 EeV…
expected for local LSS contribution with large magnetic deflection





Kotera+ML 08

☆ Auger 17 ‘hotspot’ >40 EeV… correlation with LSS…
expected for weak deflection at UHE… anisotropy corresponds to 10% of particles with ~10° deflection



☆ Telescope Array 14 hot spot >57EeV

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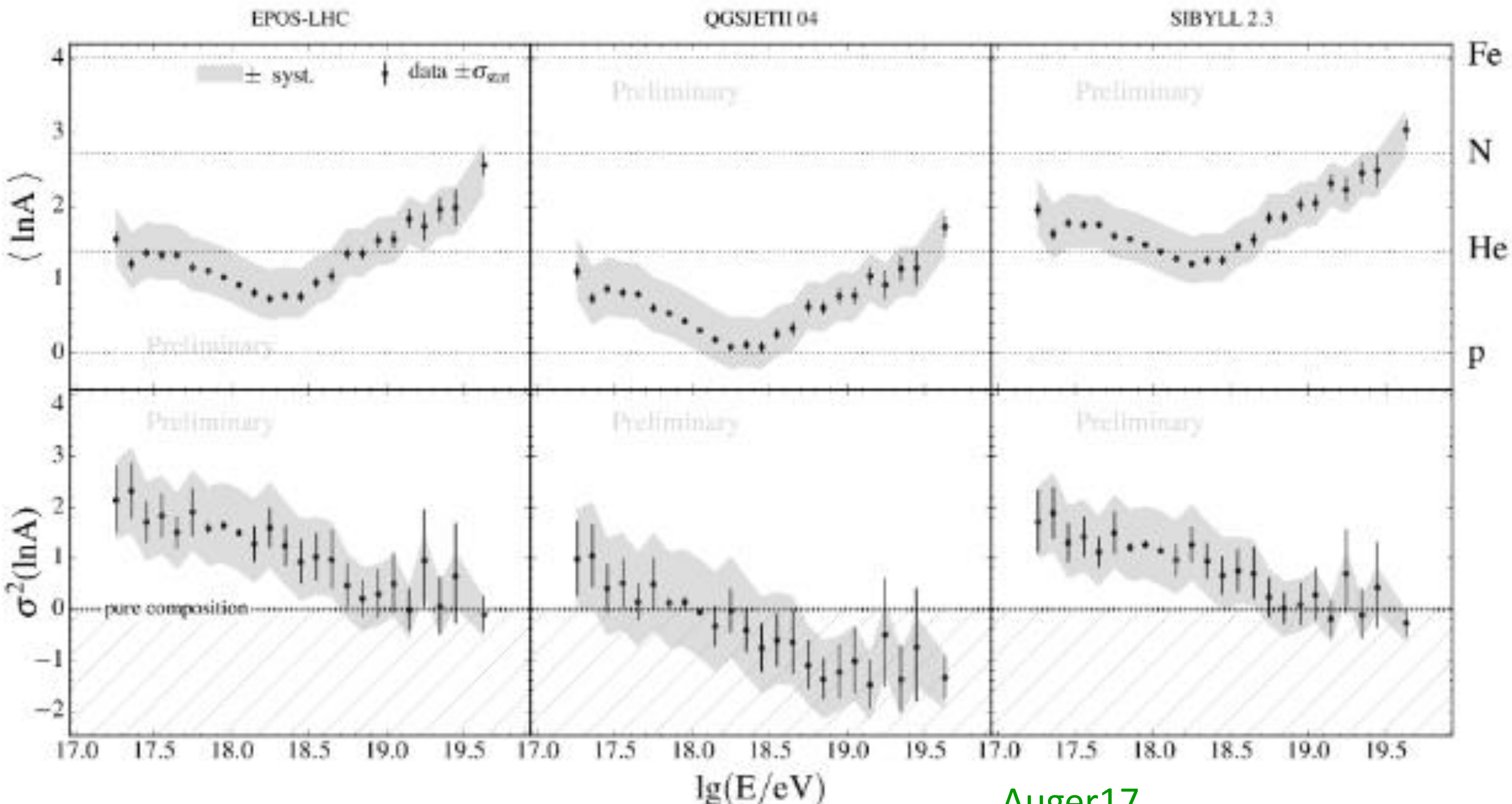
Chemical composition at UHE

→ Telescope Array sees a proton (/light) – like composition…

→ Auger observes a shift from light to mixed/intermediate, from EeV to UHE…



Auger17

A key question: the chemical composition

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

(1) sources of E/eZ = 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…

$$L_{\rm tot} \gtrsim 10^{45}\,{\rm erg/s}\;\mathcal{A}^2\;\left(E_{20}/Z\right)^2$$

… for CNO composition, possible sources: powerful radio-galaxies, relativistic supernovae (low luminosity GRB)…

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

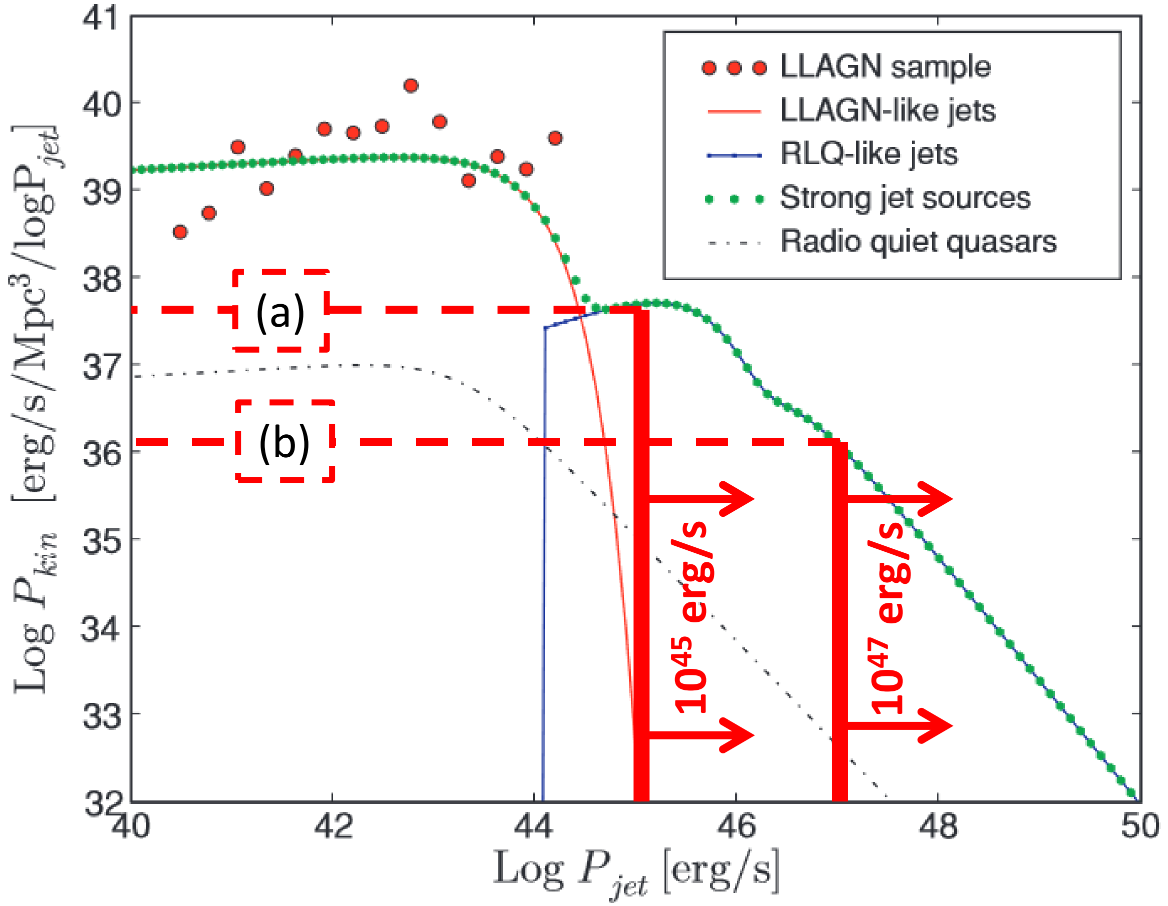
… e.g., anisotropies at ultra-high energies with deflections of a few deg, vs large deflections for iron-like primaries

… e.g., secondary photons and neutrino signals

⟹ do protons exist at GZK energies ? … search for ultra-rigidity particles!

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)

Acceleration to UHE in low luminosity GRBs

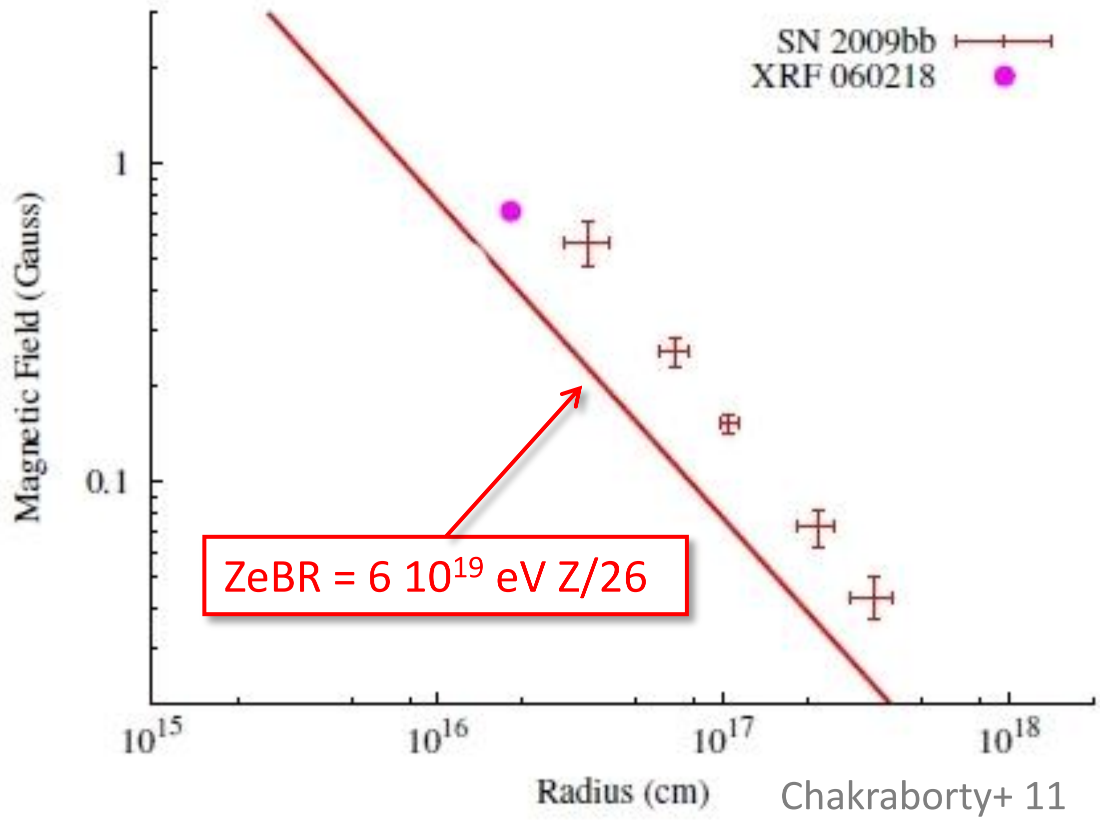
→ low luminosity GRBs, also associated to X-ray flashes, are interpreted as trans-relativistic supernovae with ejecta velocity $\gamma\beta \sim 1$ … the missing link to standard supernovae? possible sources of UHE nuclei (Wang+ 08,Chakaborty+ 11, Liu & Wang 12, Budnik+ 08)

energy budget : $\dot{n} \sim 10^{-7} - 10^{-6}\,/\mathrm{Mpc}^3/\mathrm{yr}$ $\quad E_\gamma \sim 10^{50}\,\mathrm{erg}$

max. energy: $E_{\rm max} \sim Z \times 10^{18} - 10^{19}\,\mathrm{eV}$ $\quad \Rightarrow$ **heavy nuclei at UHE**

Note:

Hillas bound assumes $\mathcal{A} \sim 1$



Chakraborty+ 11

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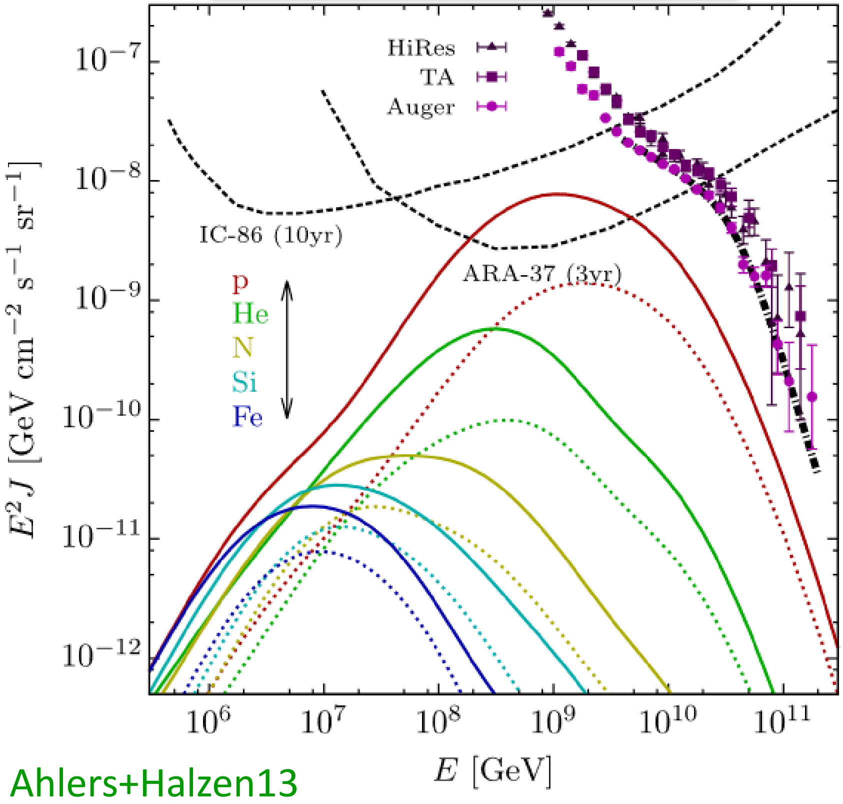
Diffuse secondary backgrounds

→ chemical composition vs multi-messengers astrophysics:

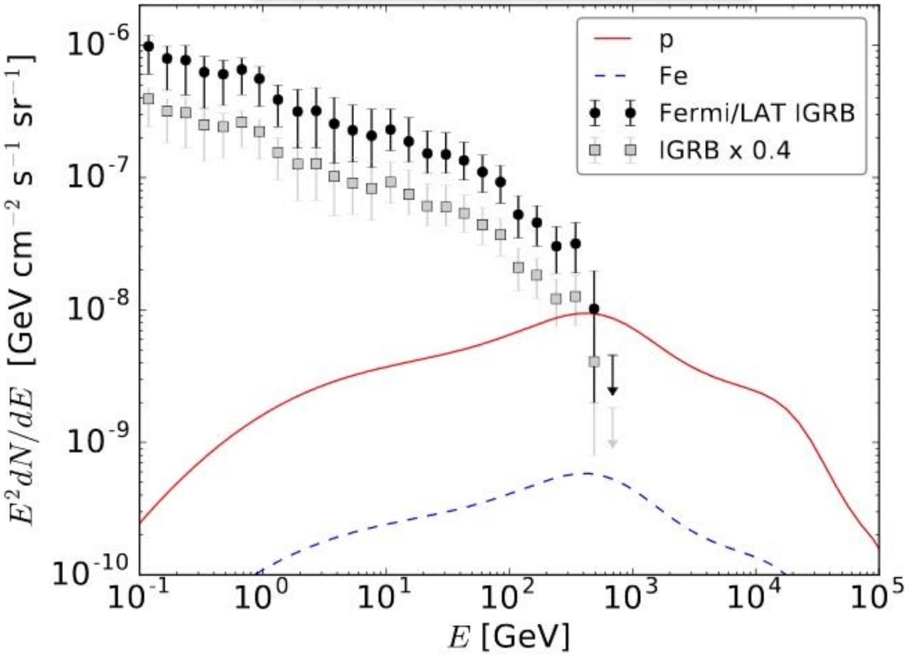
chemical composition can be tested through secondary neutrinos and photons

secondary EeV neutrinos



Ahlers+Halzen13

secondary TeV photons



Van Vliet 17

⟹ pure proton composition in tension with secondary diffuse backgrounds

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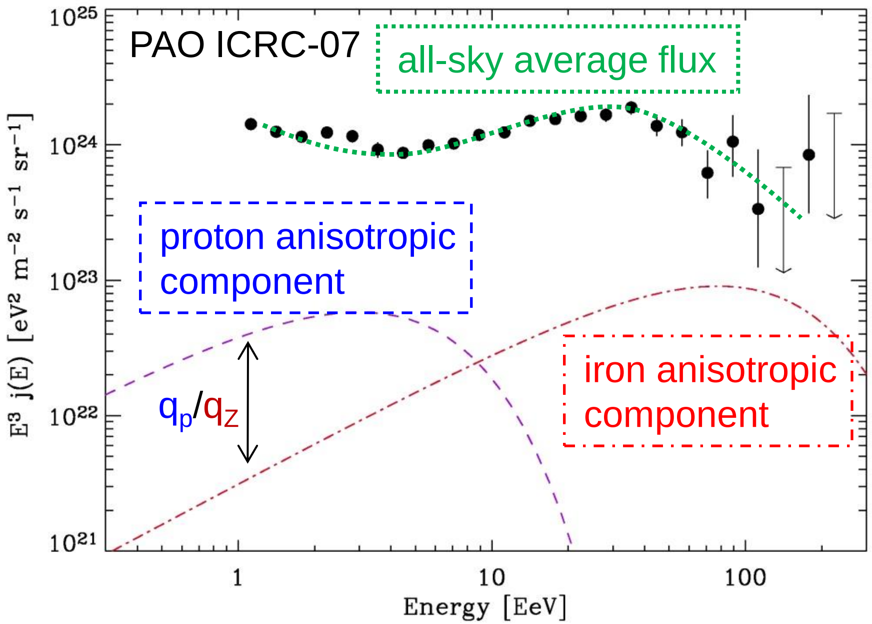
Anisotropies vs heavy composition at UHE

→ 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, Liu+13)



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

$$S/N|_p\,(E/Z) \quad \propto \quad \frac{N_p}{N_Z}\; S/N|_Z\,(>E)$$
$$\gg \quad S/N|_Z\,(>E)$$

⇒ if hot spots at >40-60 EeV 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...

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.): $(n\dot{E}) \sim 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$

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

… requires large energy output per source, with L_{UHECR}/L_{tot} ≈ few % or more, a strong constraint for acceleration scenarios

→ **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

e.g.: … long GRBs, most powerful Radio-Gals, or fast magnetars for p?
… low-luminosity GRBs, Radio-Gals … or else for CNO and heavier?

→ **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

… moving forward with multi-messenger astrophysics

→ **Pinpointing a source with clusters of UHECR:**

… 10-20 events within 10deg from closest sources at >80EeV energies, requires about >10 times the exposure of Auger … Rouillé d'Orfeuil+13

… what if the source is a transient?

→ **Pinpointing a source with secondary gamma-rays:**

… needs EeV γ-rays… or 10-100GeV γ from synchrotron of EeV electrons

… for CTA sensitivity: needs $L_{p,UHE} > 10^{46}\, D_{Gpc}^{2}$ erg/s at $D_{Gpc}>1$ …

Aharonian02, Kotera,Allard,ML11

… what if the source is a transient?

→ **Pinpointing a source with secondary neutrinos:**

… EeV neutrinos from closest sources…

… requires an all-sky number of 100 – 1000 EeV neutrino events… Fang+16

… what if the source is a transient?

→ **Deciphering the source with multi-messenger astrophysics + theory:**

… e.g. constraints on acceleration from multi-messenger data of TXS0506+056

… a long (and likely) way ahead…