The UHECR science after 15 years of operation of the Pierre Auger Observatory

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i) Ultra-High Energy Cosmic rays

ii) The Pierre Auger Observatory

iii) Extragalactic cosmic rays

iv) Galactic/extragalactic cosmic rays

v) Outlook

Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives — Dec. 2020, Kyoto, Japan

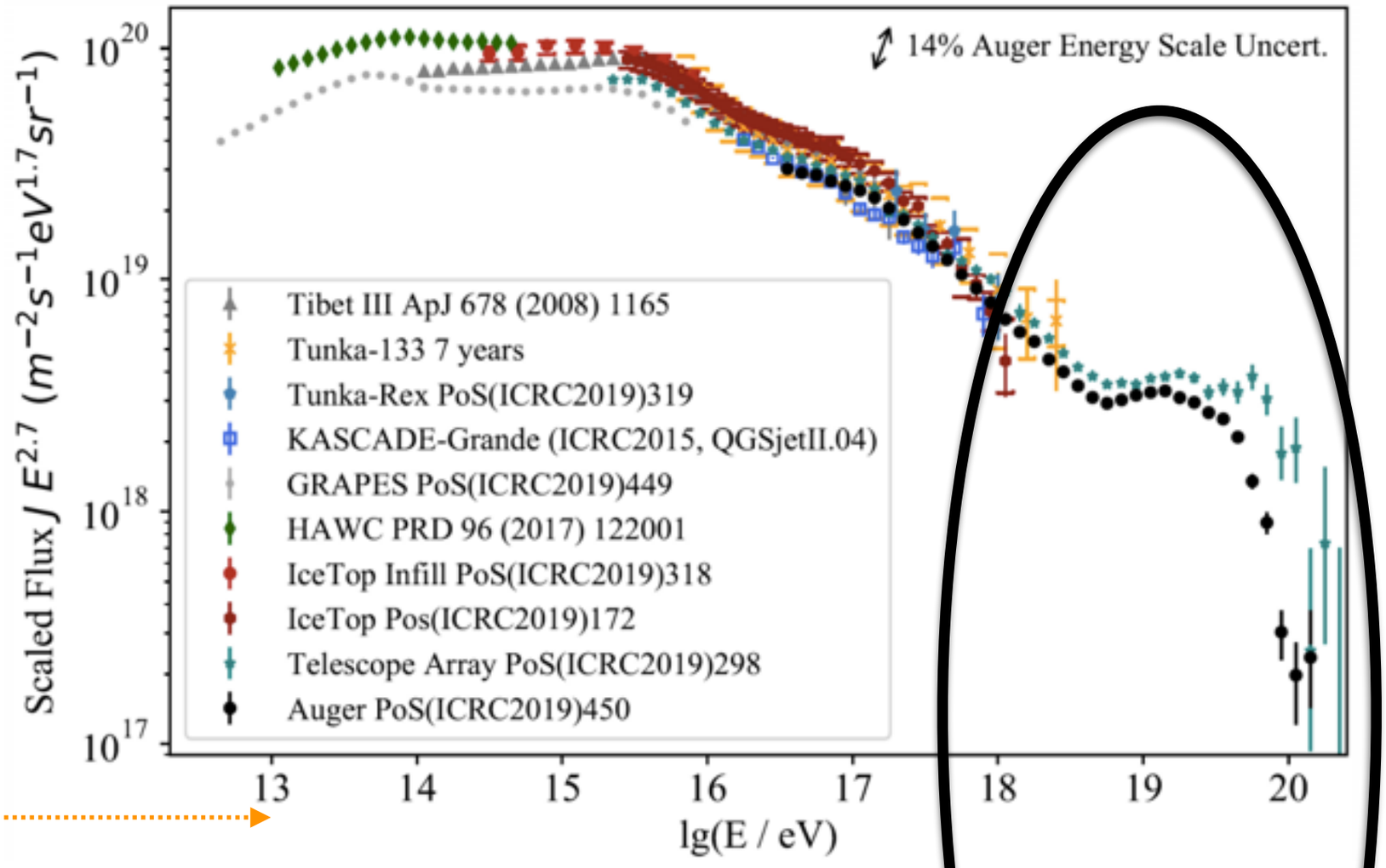
i) Ultra-High Energy Cosmic rays

All-particle Energy Spectrum by Air-Shower Arrays

[Compilation: F. Schroder]

Non-thermal processes from GeV to ZeV

Sources ?



radio IR visible UV X γ

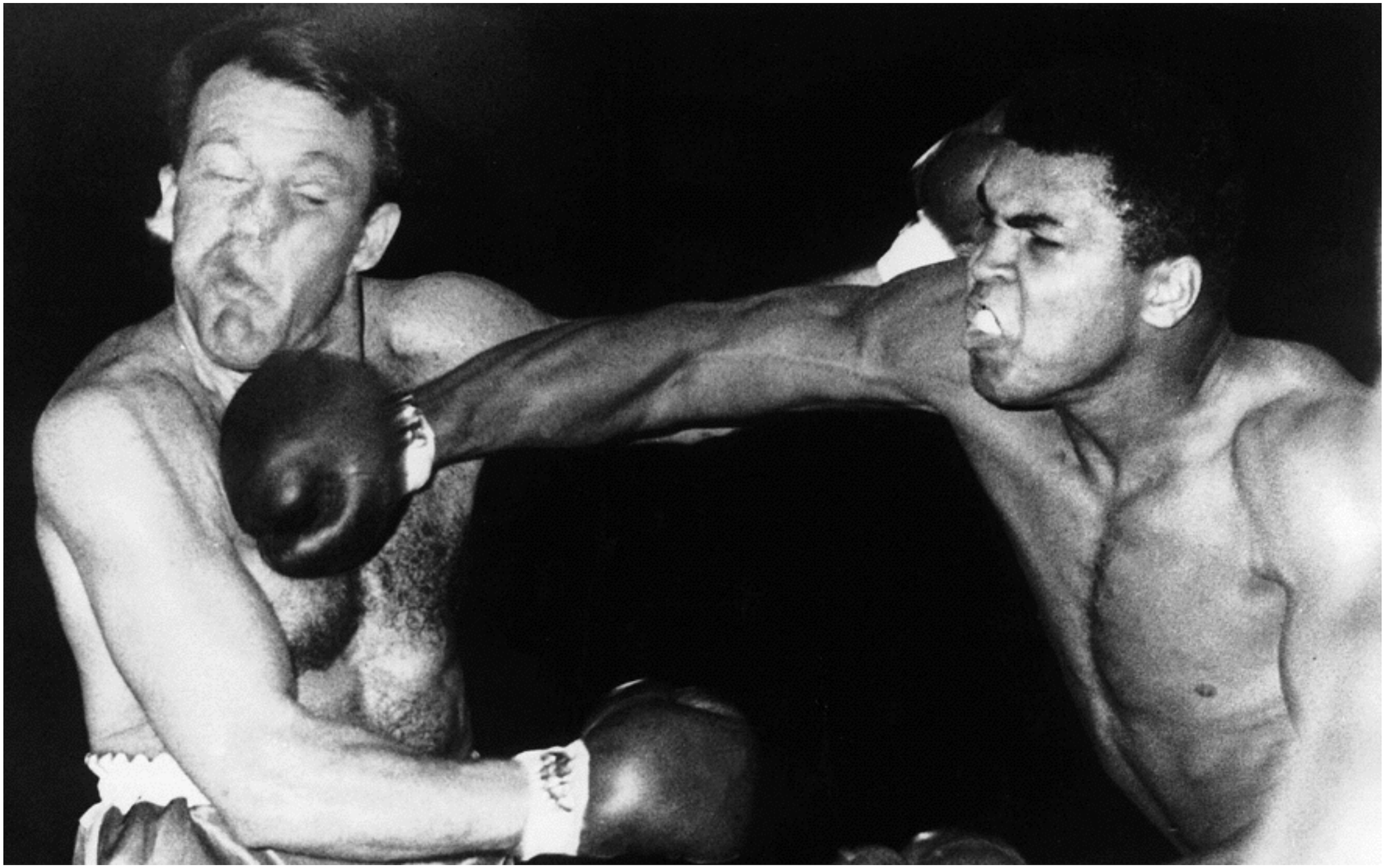
meV … eV … keV … MeV … GeV … TeV … PeV … EeV … ZeV

Photons : astronomy

Charged particles : e, p, He, …, Fe — fully ionized nuclei

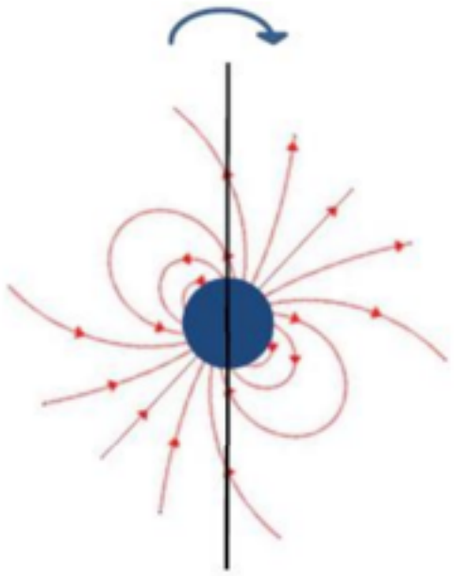
Neutrinos

10^{20} eV!

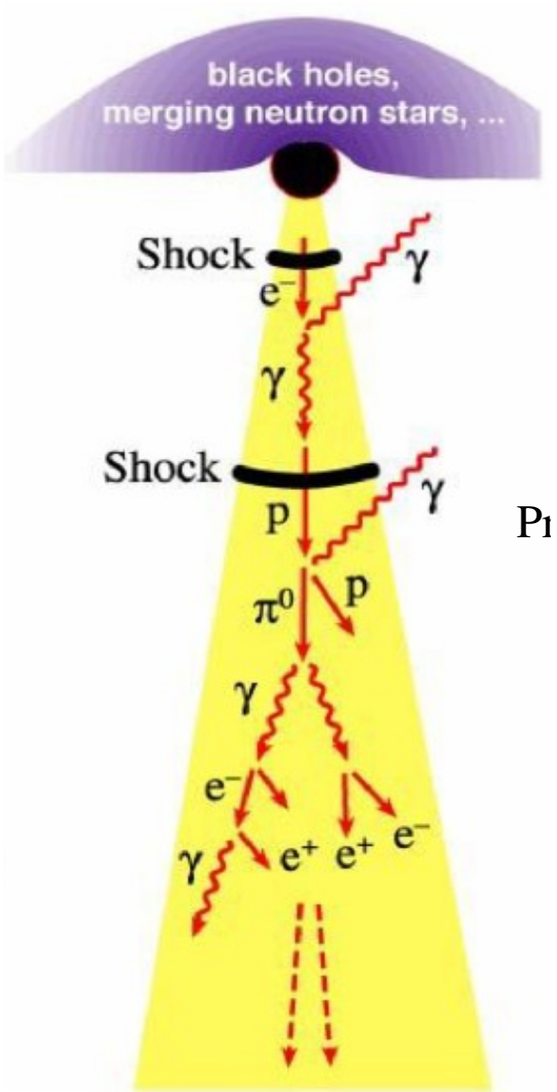


Cosmic accelerators?

rotating **B**

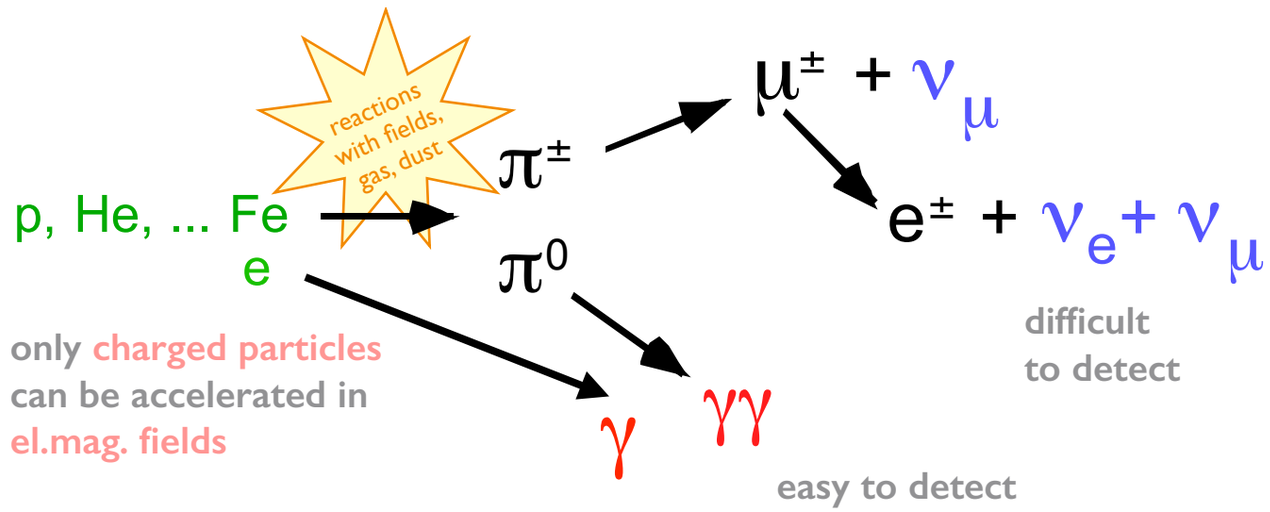


turbulent **B**



P_1

multi-messenger cascade



"multi-messenger astrophysics"

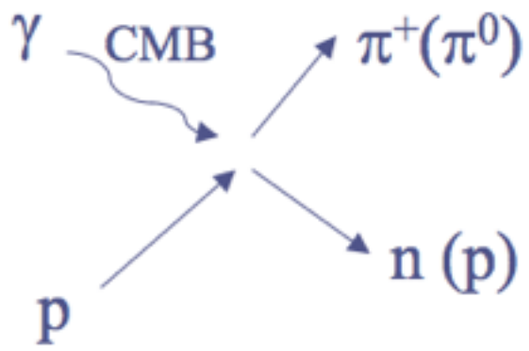
but gamma rays are currently the most "productive" messengers.

γ,ν

point back to sources
(good for astronomy)
but serious backgrounds

$\langle E \rangle$ $\langle E^2 \rangle$ Constraints from the Auger Observatory?

GZK cutoff

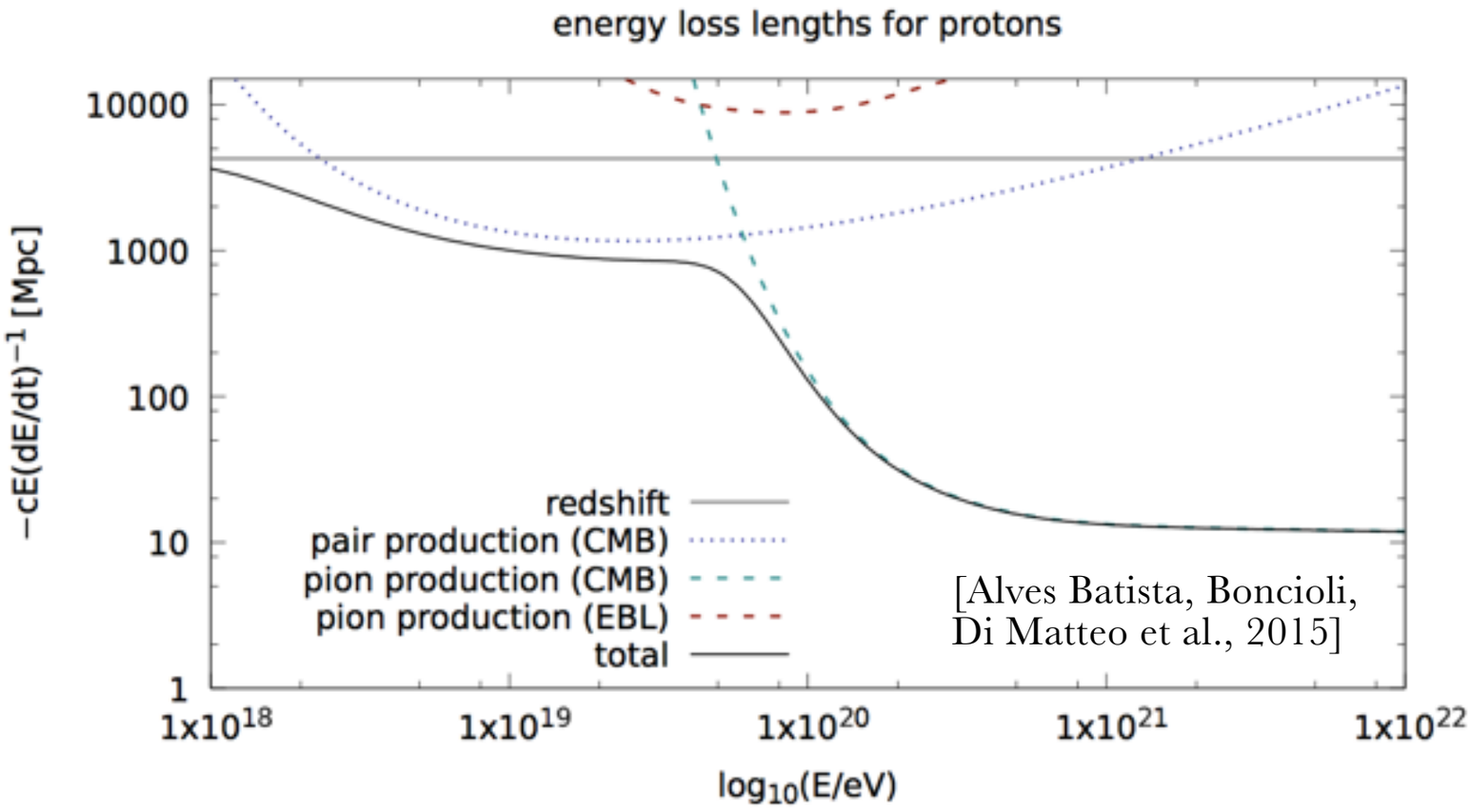


Example with protons

$$\varepsilon_\gamma > \frac{m_\pi m_p}{\varepsilon_p} \sim 10^{-3}\,\varepsilon_{20}^{-1}\ \text{eV} \Rightarrow \quad n_\gamma \sim \frac{400}{\text{cm}^3}\exp\left[1-\frac{3}{\varepsilon_{20}}\right]$$

$$\lambda_E \sim \frac{m_p}{m_\pi}\frac{1}{n_\gamma \sigma_{p\pi}}$$

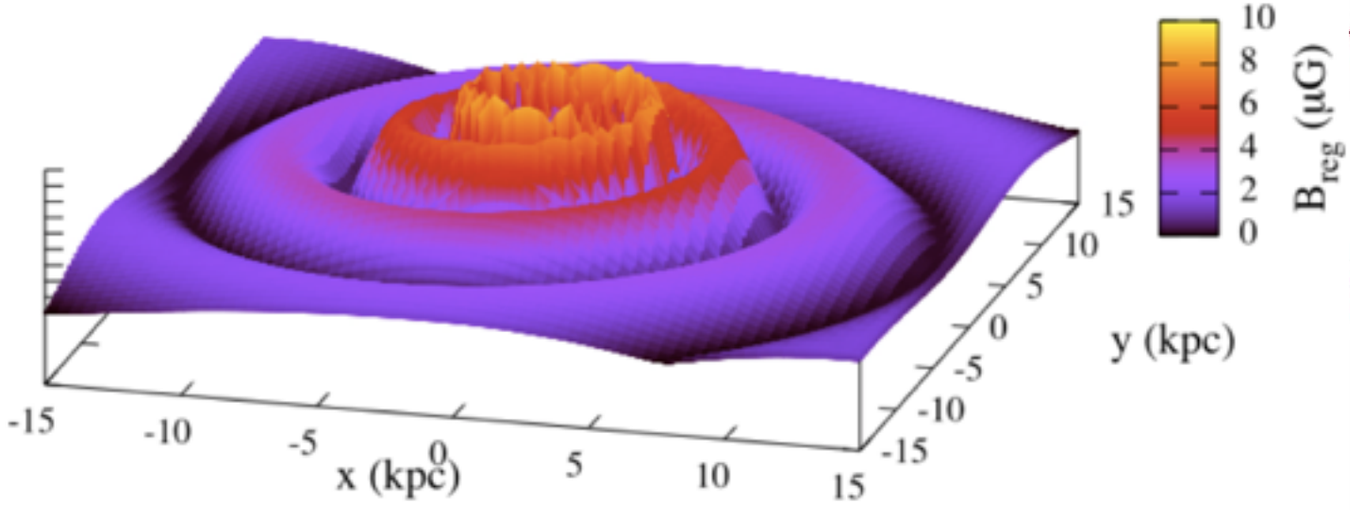
$$\sim 11\exp\left[\frac{3}{\varepsilon_{20}}-1\right] \quad \text{Mpc}$$



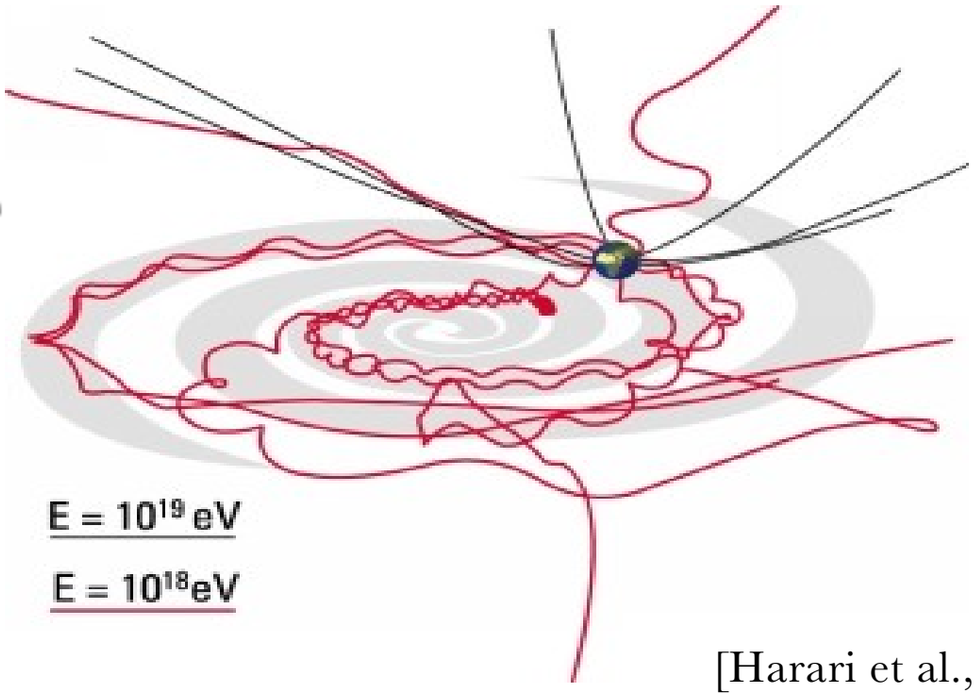
Almost same conclusions for nuclei (photo-disintegration)

➡ Reduction of the CR horizon at UHE

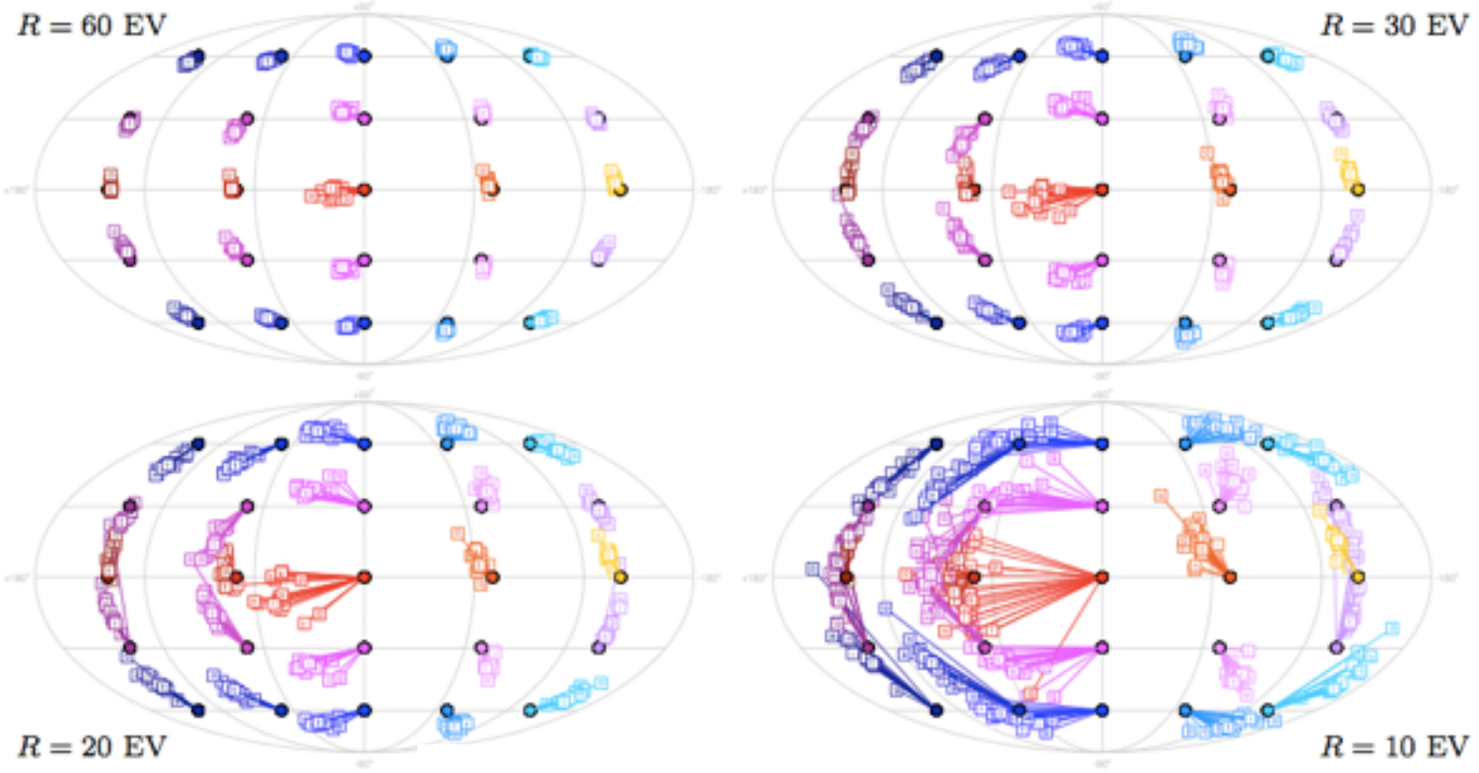
Magnetic deflections



[Jansson & Farrar 2012]



[Harari et al., 1999]



[Unger & Farrar 2017]

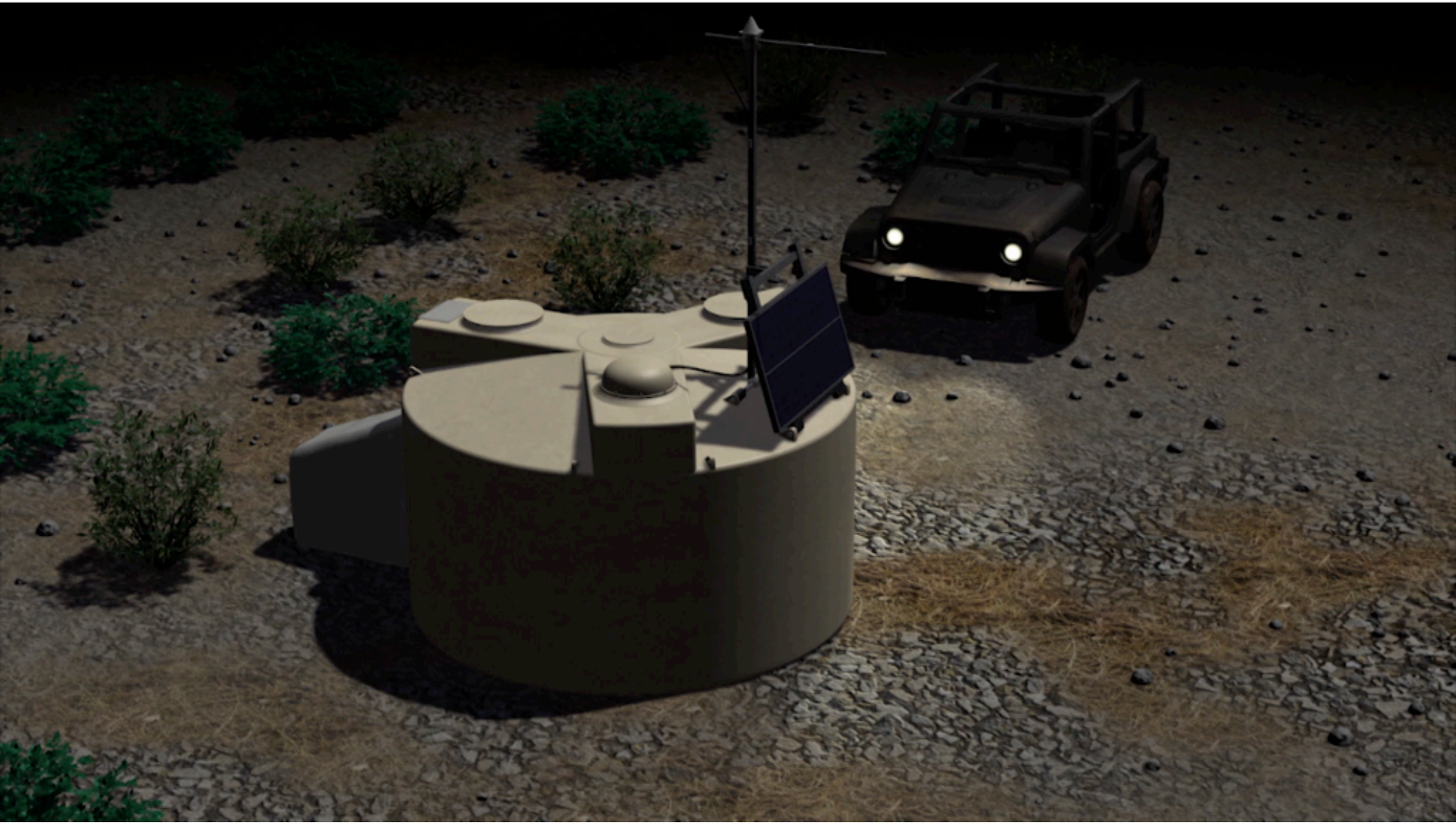
At UHE, CRs may be rigid enough to point back to their sources within a few degrees

+ Reduced horizon

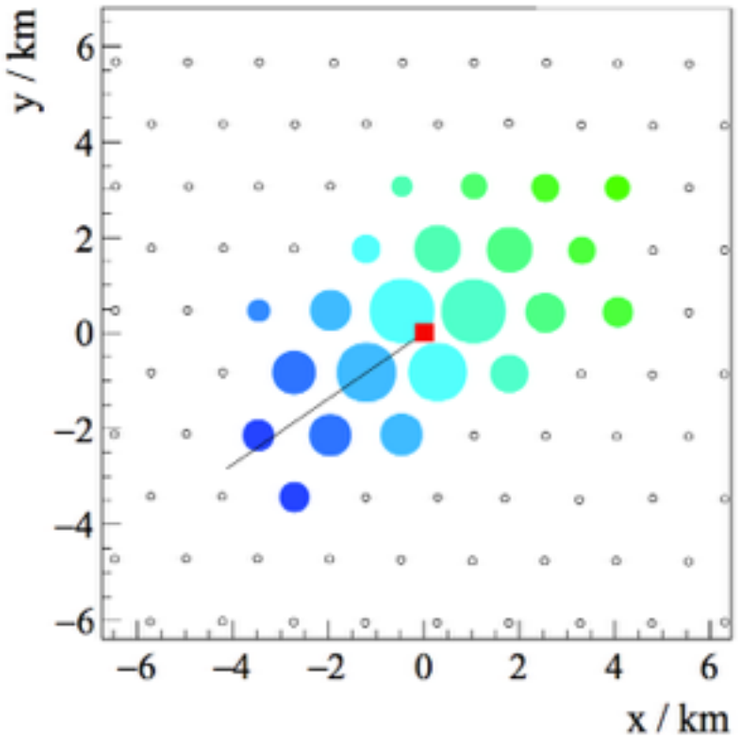
➡ Possibility to identify nearby sources?

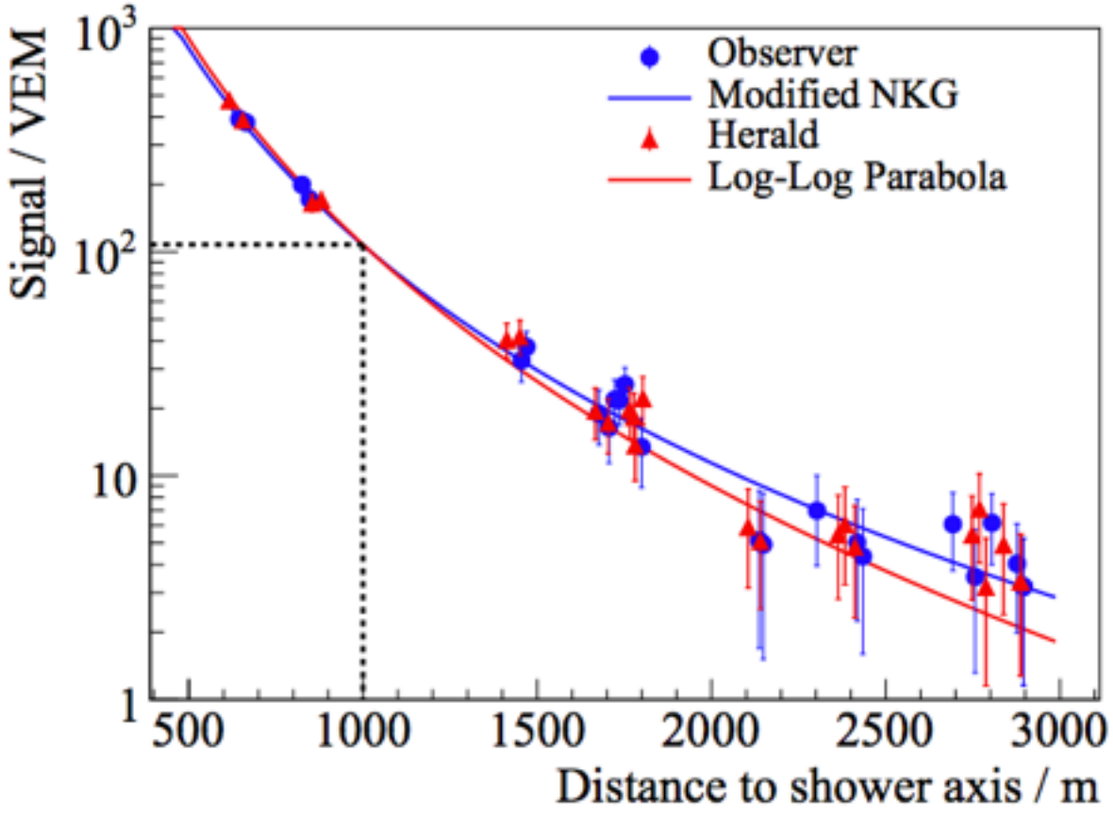
ii) The Pierre Auger Observatory

Surface Detectors (3000 km^2)



Lateral profile reconstruction





EAS footprint at ground

⇒ lateral sampling

+ Arrival direction < ~1°

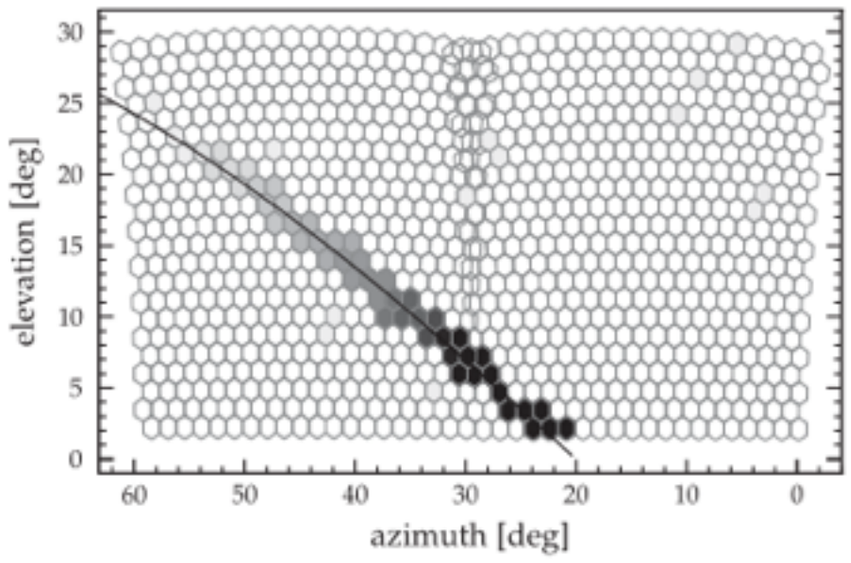
+ 100% duty cycle

- Energy estimate resorting to hadronic models

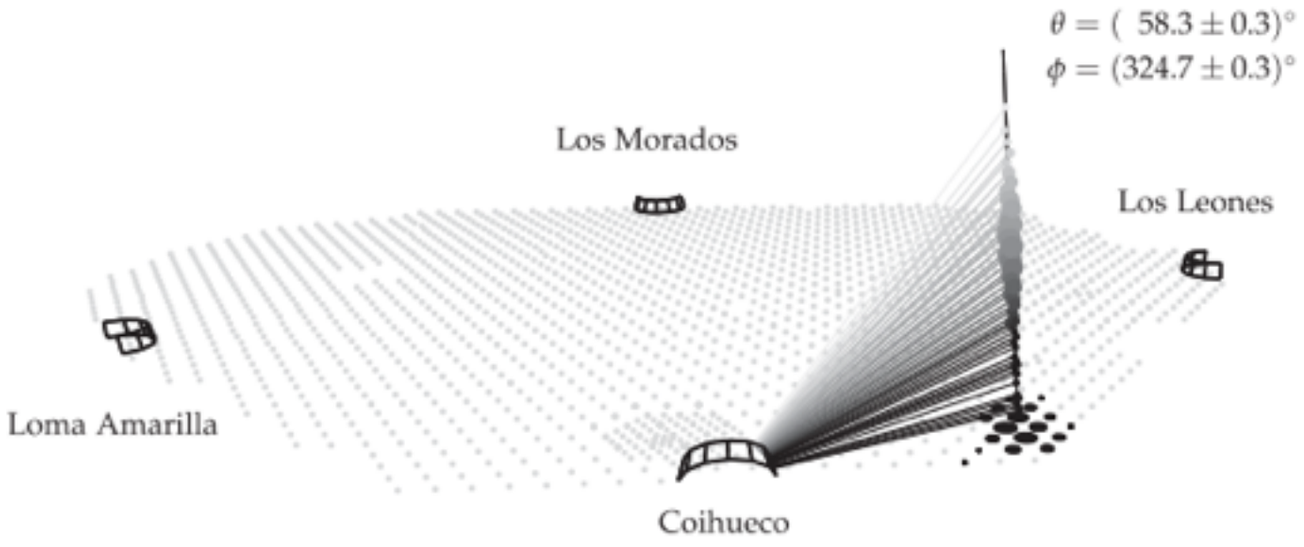
- Mass?

Fluorescence Detectors

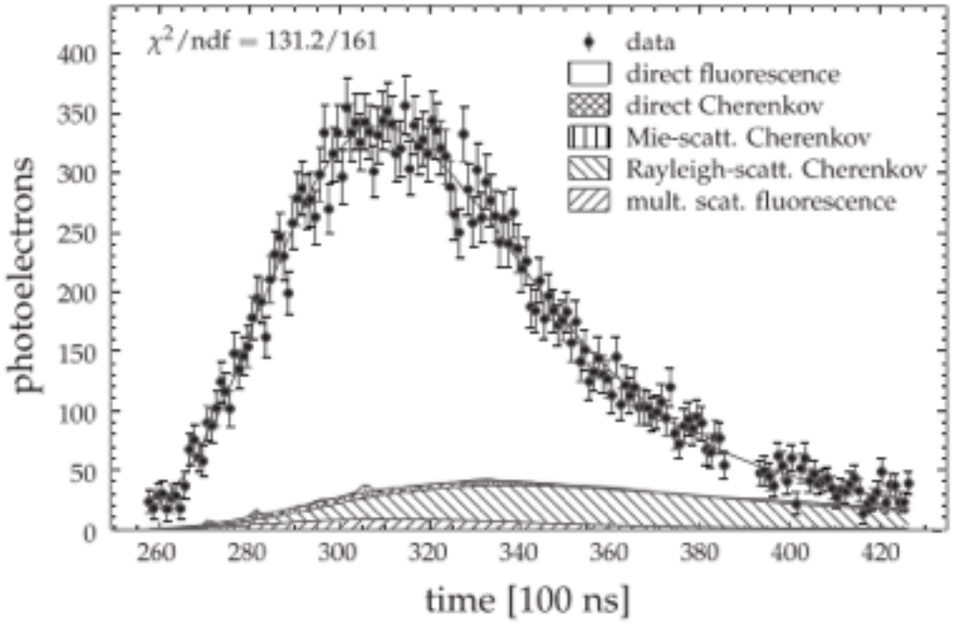
Longitudinal profile reconstruction



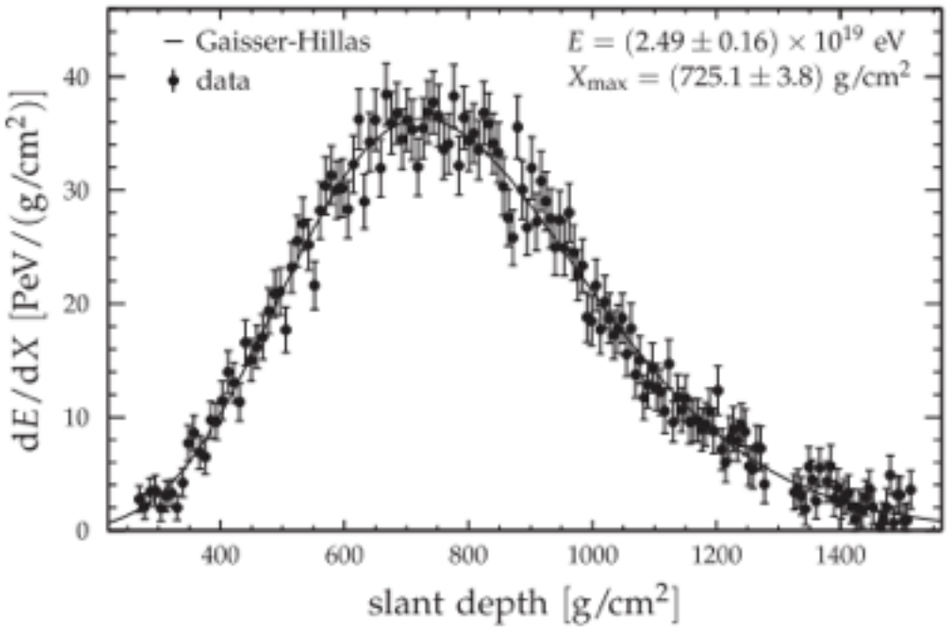
(a) Camera view. The timing of the pixel pulses is denoted by shades of gray (early = light, late = dark). The line shows the shower detector plane.



(b) Event geometry. Pixel viewing angles are shown as shaded lines and the shower light and surface detector signals are illustrated by markers of different size in logarithmic scale.



(c) Detected photoelectrons (dots) and the fitted contributions from components of the shower light (open and hatched areas).



(d) Longitudinal profile (dots) and Gaisser-Hillas function (line).

iii) Extragalactic cosmic rays

Extragalactic origin

Laniakea: Norma (attractor) + Pavo-Indus + Virgo supercluster (Virgo cluster + Local sheet)

Local sheet : 10-15 Mpc diameter, 0.5 Mpc height, with a void region ~70 Mpc North in supergalactic coordinates

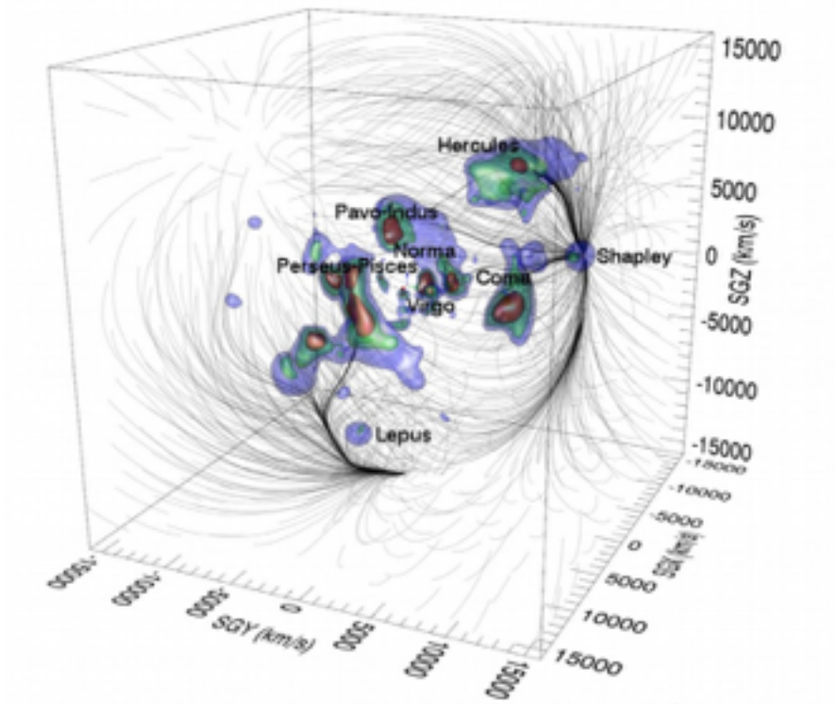
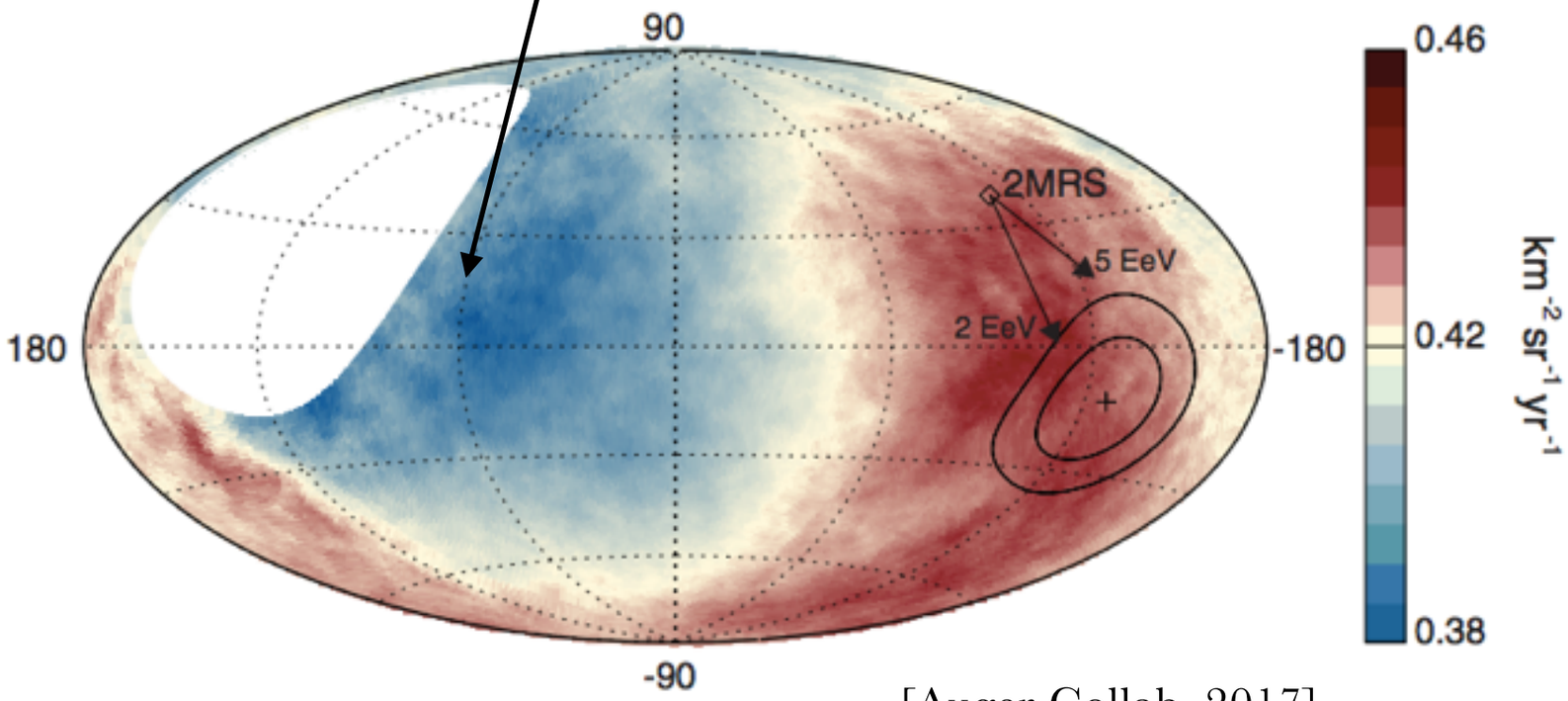


Fig. ED 1. — Structure within a cube extending 16,000 km s^{-1} (~200 Mpc)

Tully, Courtois, Hoffman, Pomarède, Nature 2014

Direction of the local void



[Auger Collab. 2017]

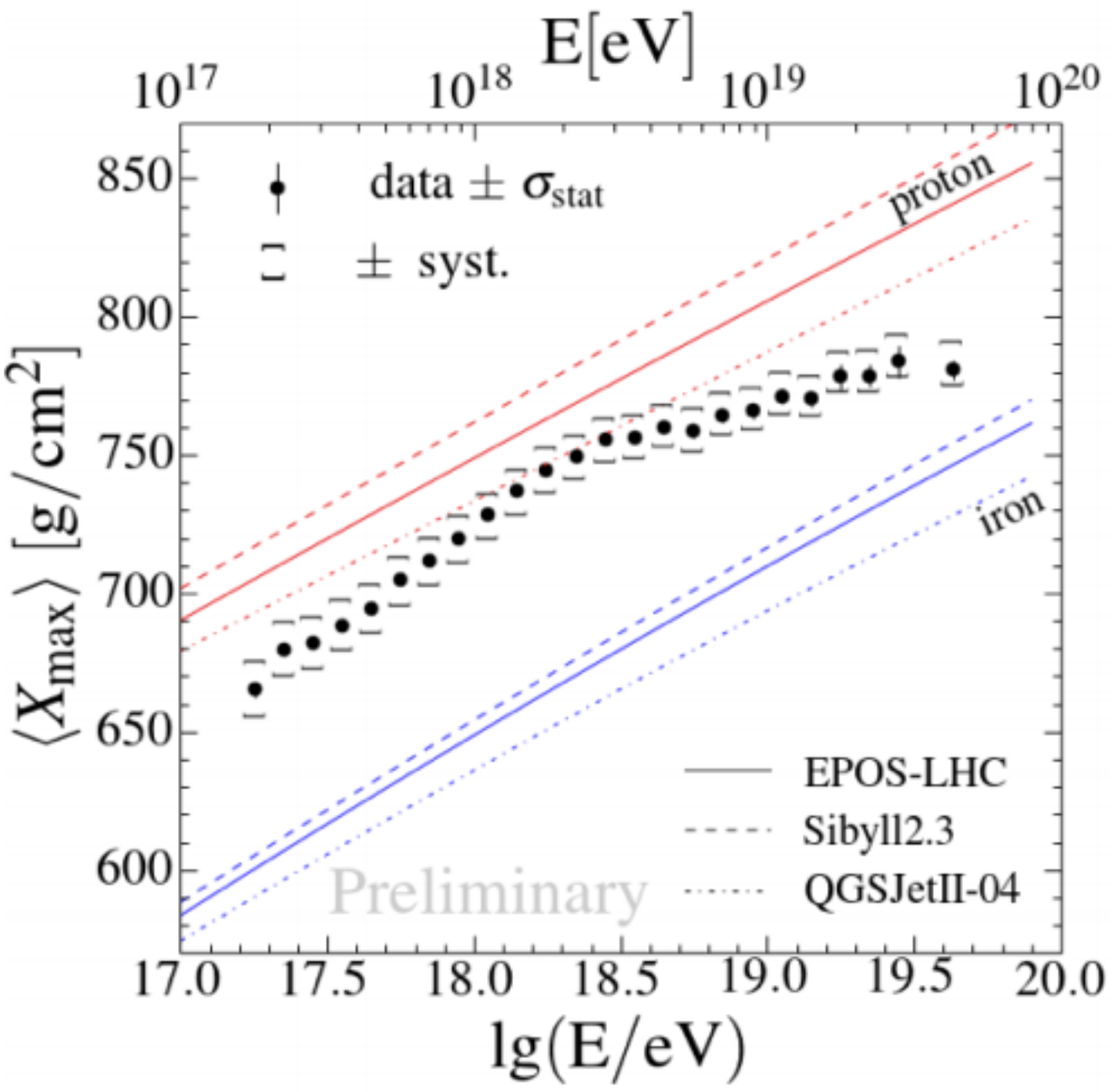
Accounting GMF deflections

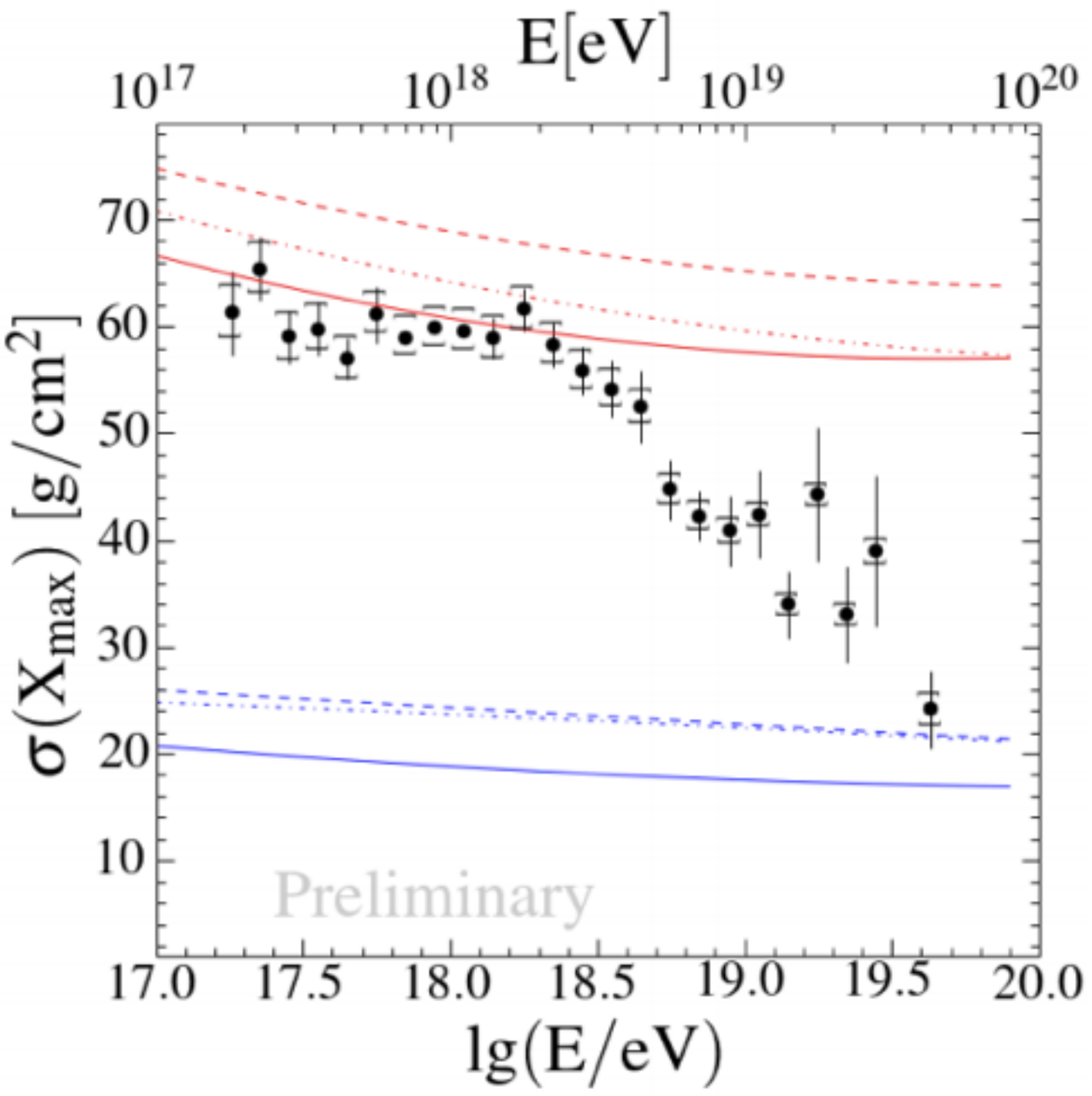
[Jansson and Farrar ApJ 757 (2012) 14]

Z ~ 1.7 – 5 at 10 EeV → E/Z ~ 2 – 5 EeV

[Auger Coll. PRD 90 (2014) 122006]

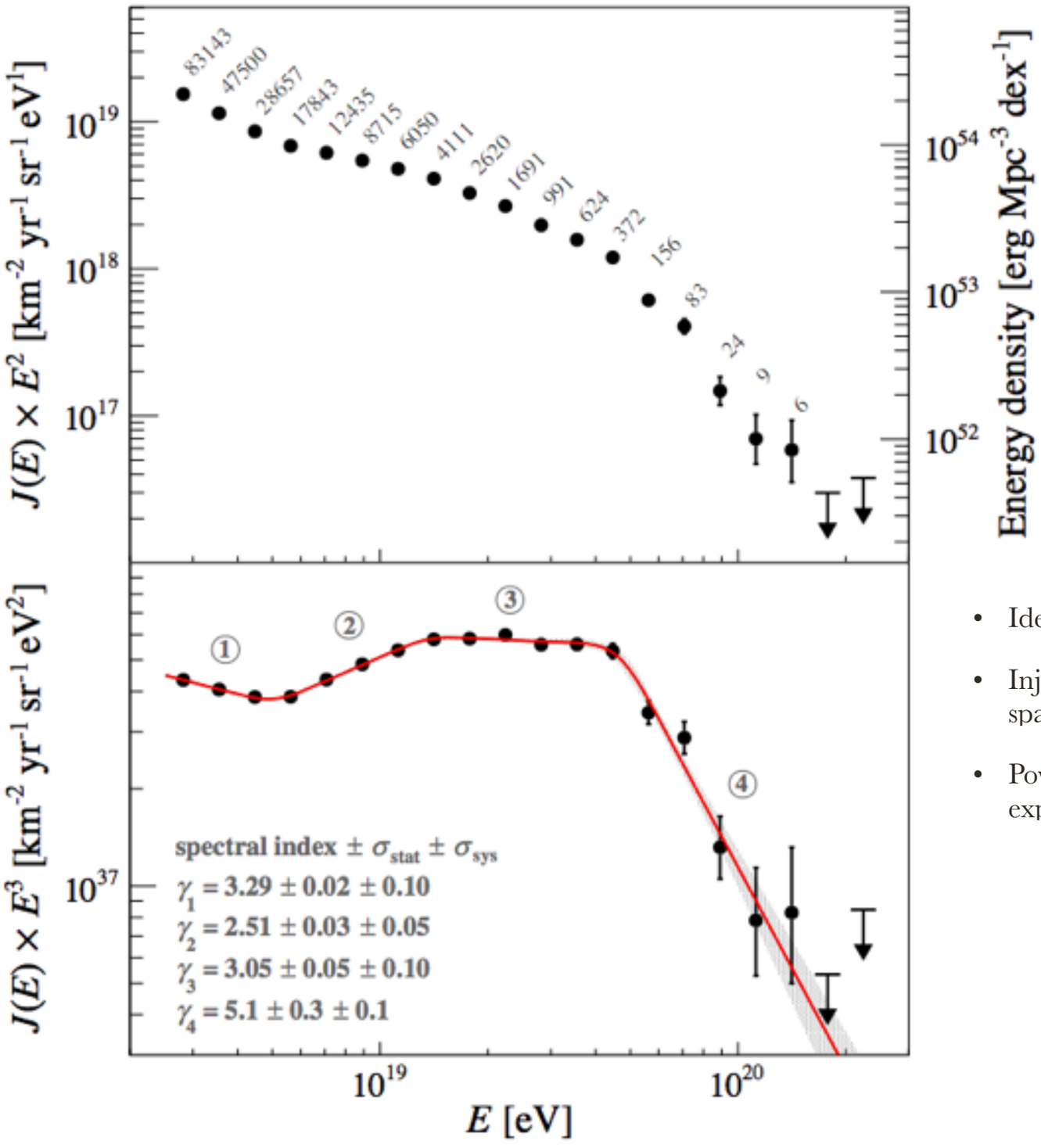
Mass composition — X_{max} moments





[Auger Collab. 2019]

Extragalactic cosmic rays



✦ **Rigidity-dependent**
maximum acceleration energy at the sources (X_{max} measurements)

➡ Astrophysical scenario to fit > $10^{18.7}$ eV both the energy spectrum and the X_{max} measurements:

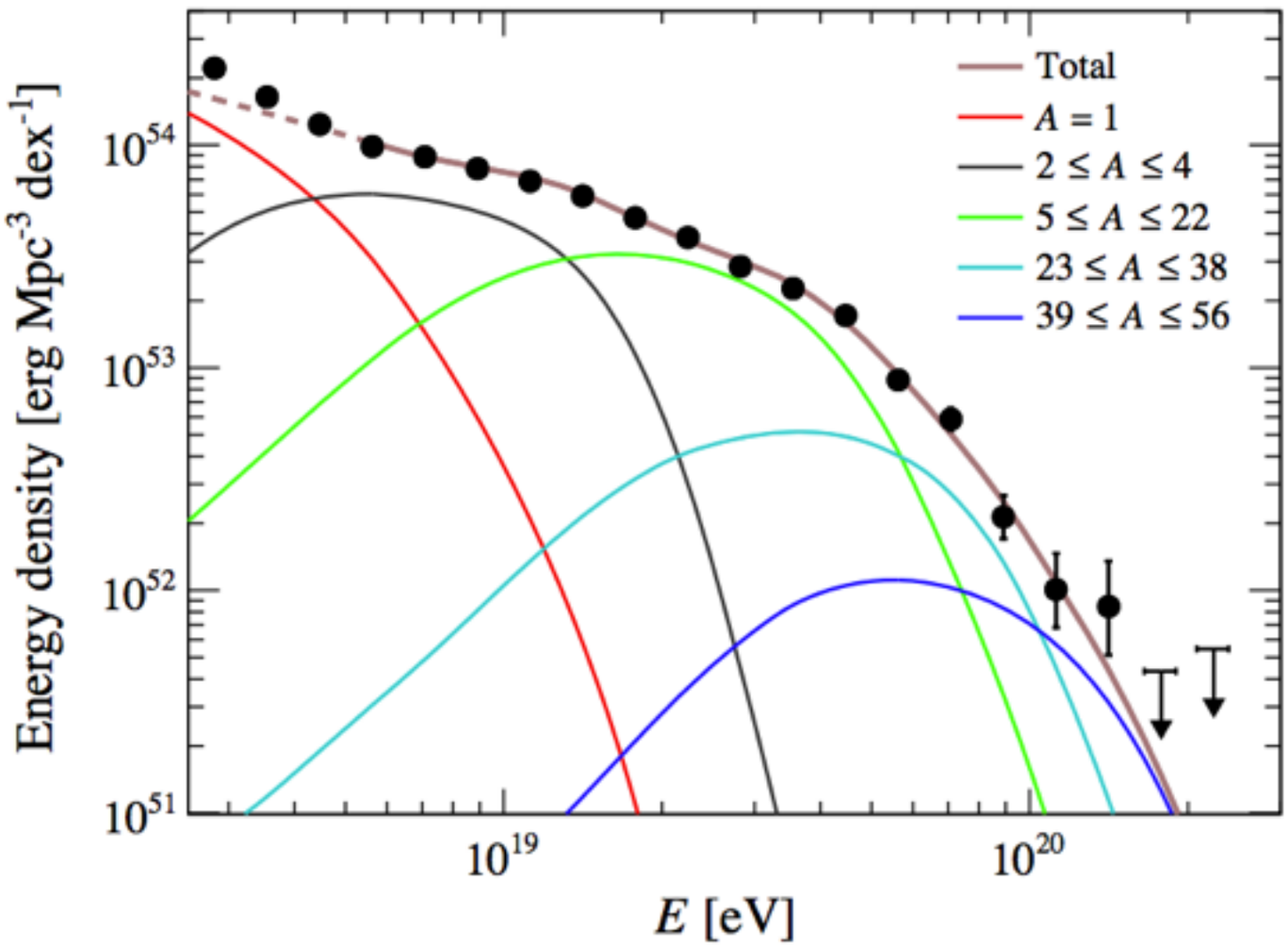
- Identical sources homogeneously distributed in a comoving volume
- Injection consisting only of ^{1}H, ^{4}He, ^{14}N, ^{56}Fe (approximately equally spaced in ln$A$)
- Power-law spectrum at the sources with rigidity-dependent broken exponential cutoff:

$$\frac{dN_{inj,i}}{dE} = \begin{cases} J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{cut} \\ J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{cut}}\right), & E/Z_i > R_{cut} \end{cases}$$

➡ 6 free parameters: $(J_0, \gamma, R_{cut}, p_H, p_{He}, p_N)$; $p_{Fe} = 1 - p_H - p_{He} - p_N$

[Auger Collab. 2020]

Extragalactic cosmic rays



$$\rho_{\rm ener}(E_{\rm det}) = \int_{z_{\rm min}}^{z_{\rm max}} {\rm d}z \left|\frac{{\rm d}t}{{\rm d}z}\right| \sum_{A_{\rm inj}} E_{\rm inj}^2 q_{\rm gen}(E_{\rm inj}, A_{\rm inj})\, S(z) \left|\frac{{\rm d}E_{\rm inj}}{{\rm d}E_{\rm det}}\right|$$

- ✦ Hard ejected spectra
- ✦ Energy cutoff ~5Z EeV
- ✦ Steepening above ~50 EeV: combination of the maximum energy of acceleration of the heaviest nuclei at the sources and the GZK effect
- ✦ Steepening above ~10 EeV: interplay between the flux contributions of He and CNO injected at the source with their distinct cutoff energies, shaped by photodisintegration during the propagation
- ✦ Luminosity density ($E^2 q_{\rm gen}(E)$): 6 10^{44} erg Mpc^{-3} yr^{-1}

[Auger Collab. 2020]

Extragalactic gamma-ray sources

3FHL catalog
(*Fermi*-LAT, >50 GeV, < 250 Mpc)
[Ackermann *et al.*, 2016]

(leptonic processes preferred)

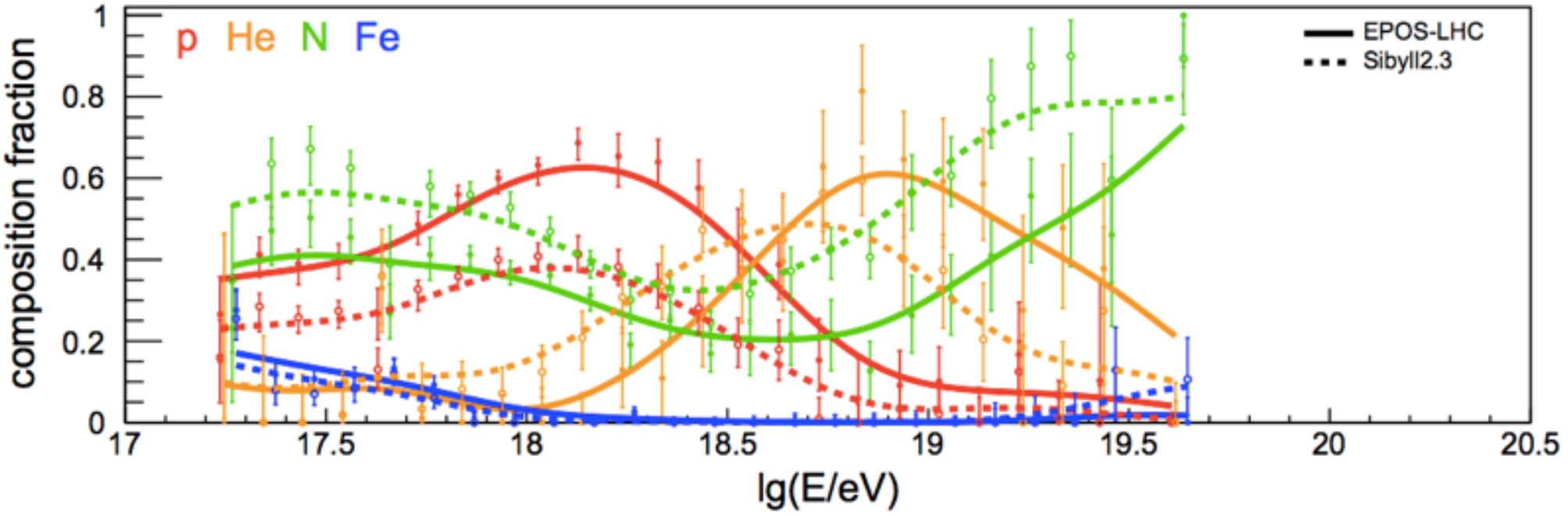
Selection by *Fermi*-LAT
(HCN survey) < 250 Mpc,
flux radio>0.3 Jy [Gao & Salomon, 2005]

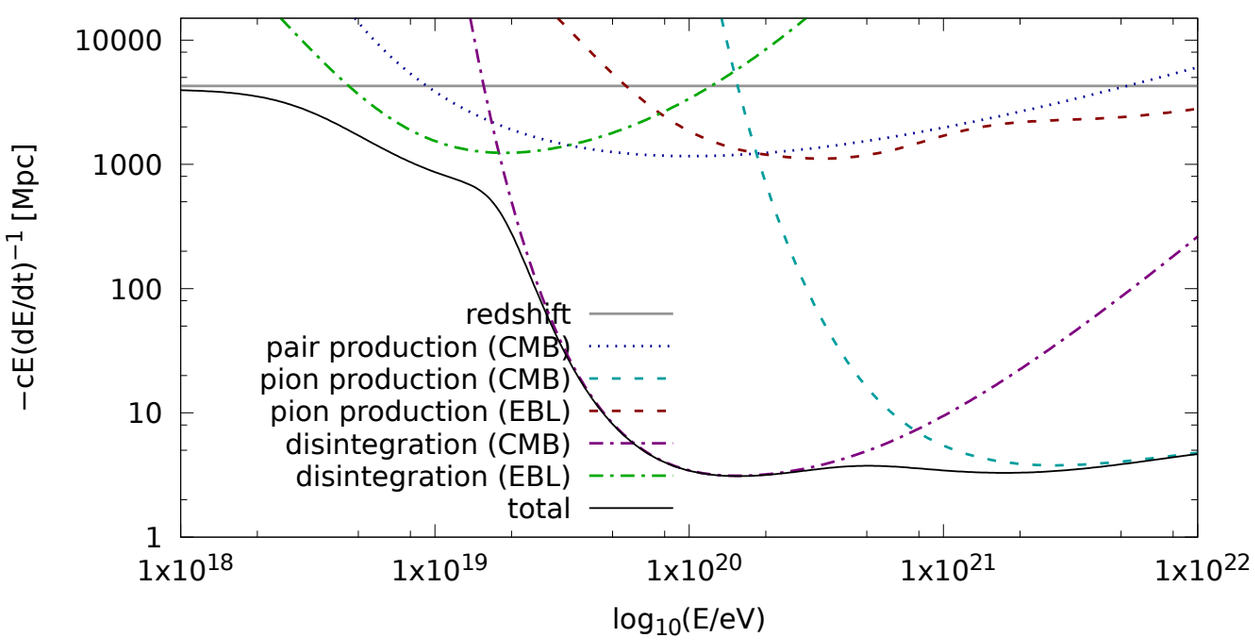
(hadronic processes preferred)

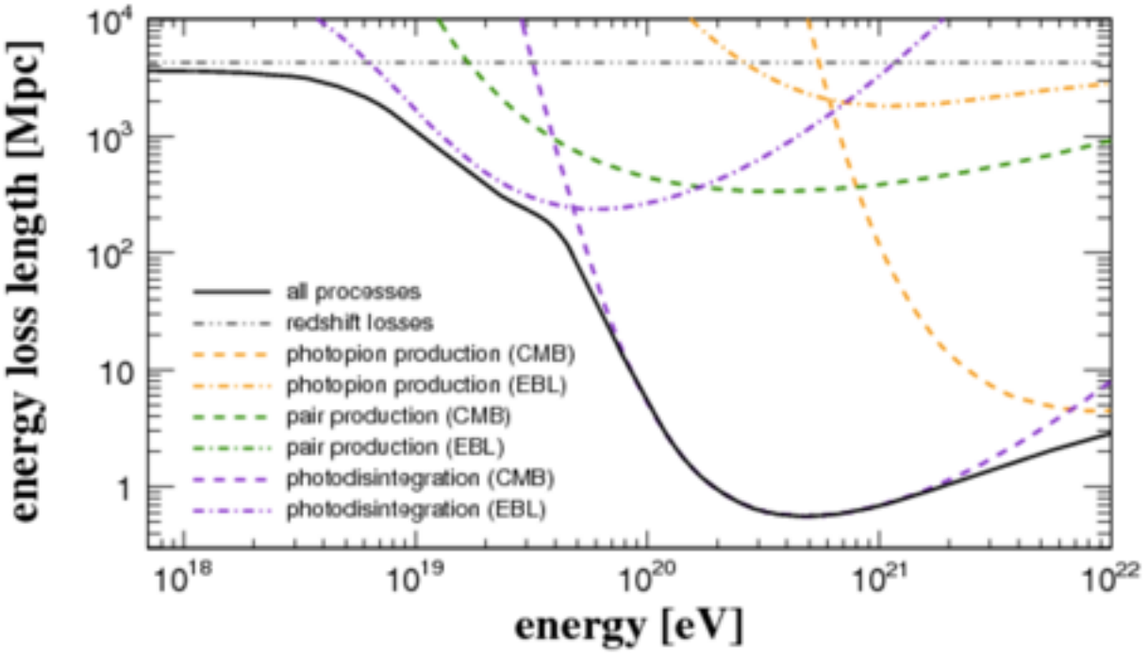
Hypothesis : CR flux ∝ non-thermal flux of photons

➡ Calorimetric argument: natural for environments such that starburst galaxies

Composition and horizons at UHE



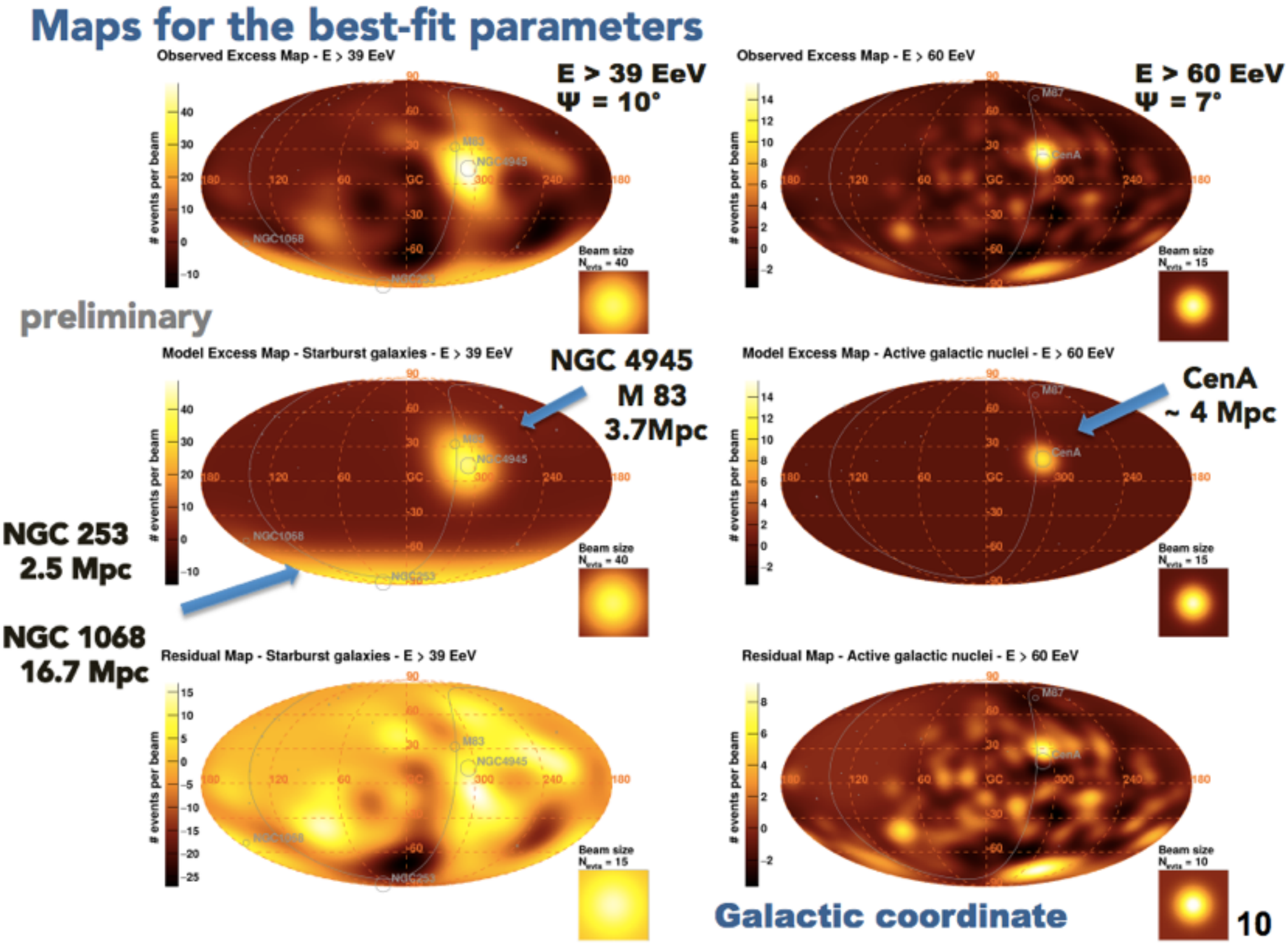




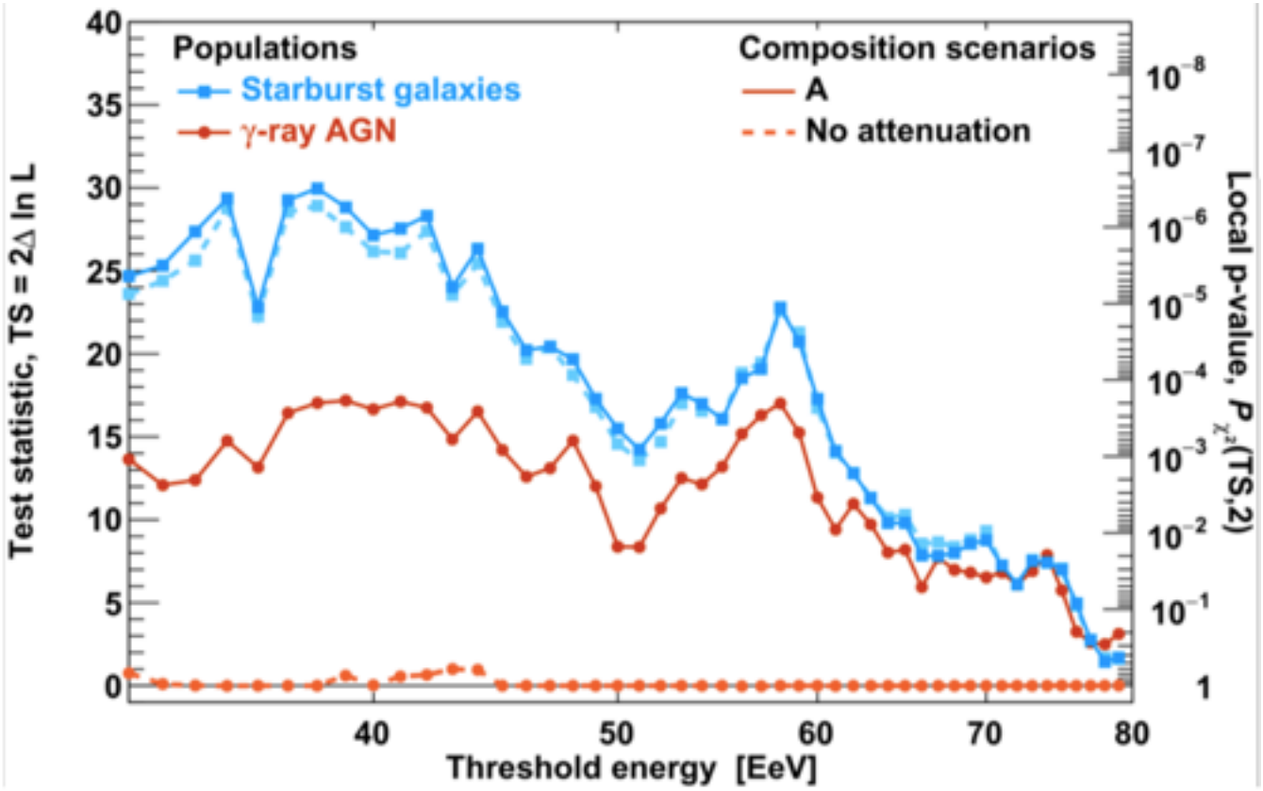
[Alves Batista, Boncioli, Di Matteo et al., JCAP10(2015)063]

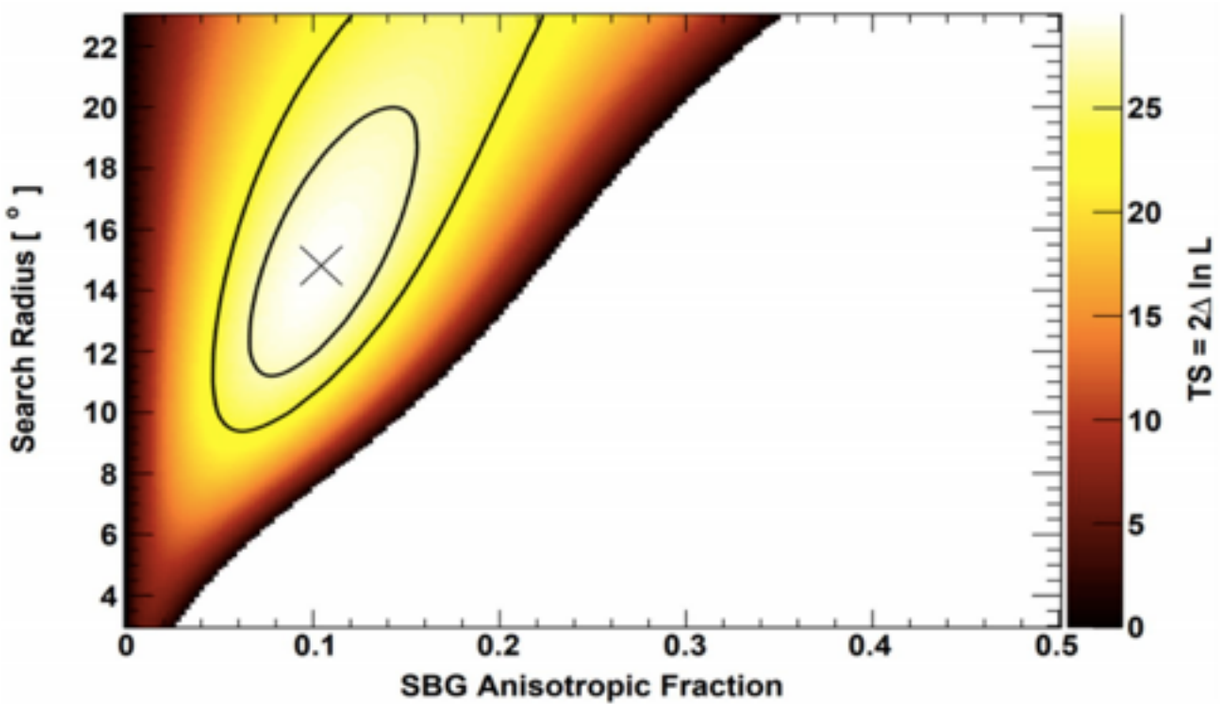
☞ Limited horizons @ 30-40 EeV

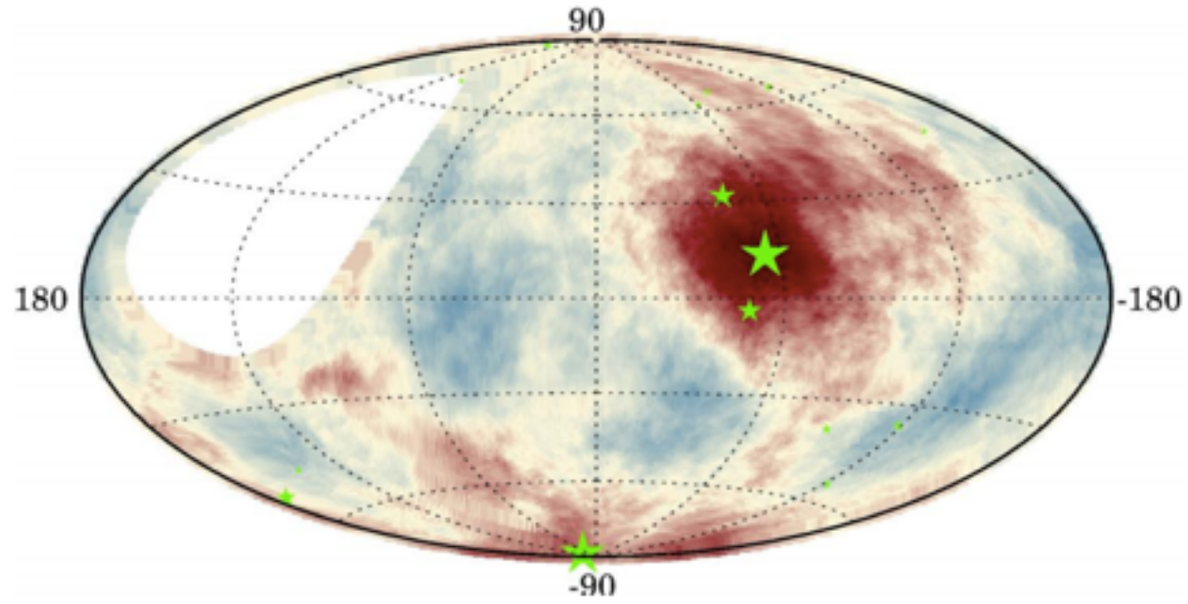
Sky maps


Maps for the best-fit parameters
Observed Excess Map - E > 39 EeV
E > 39 EeV
Ψ = 10°
events per beam
Beam size
N_evts = 40
preliminary
Observed Excess Map - E > 60 EeV
E > 60 EeV
Ψ = 7°
Beam size
N_evts = 15
Model Excess Map - Starburst galaxies - E > 39 EeV
NGC 4945
M 83
3.7Mpc
NGC 253
2.5 Mpc
NGC 1068
16.7 Mpc
Model Excess Map - Active galactic nuclei - E > 60 EeV
CenA
~ 4 Mpc
Residual Map - Starburst galaxies - E > 39 EeV
Residual Map - Active galactic nuclei - E > 60 EeV
Galactic coordinate
10

Best matching: starburst galaxies







Post-trial significance: 4.5σ

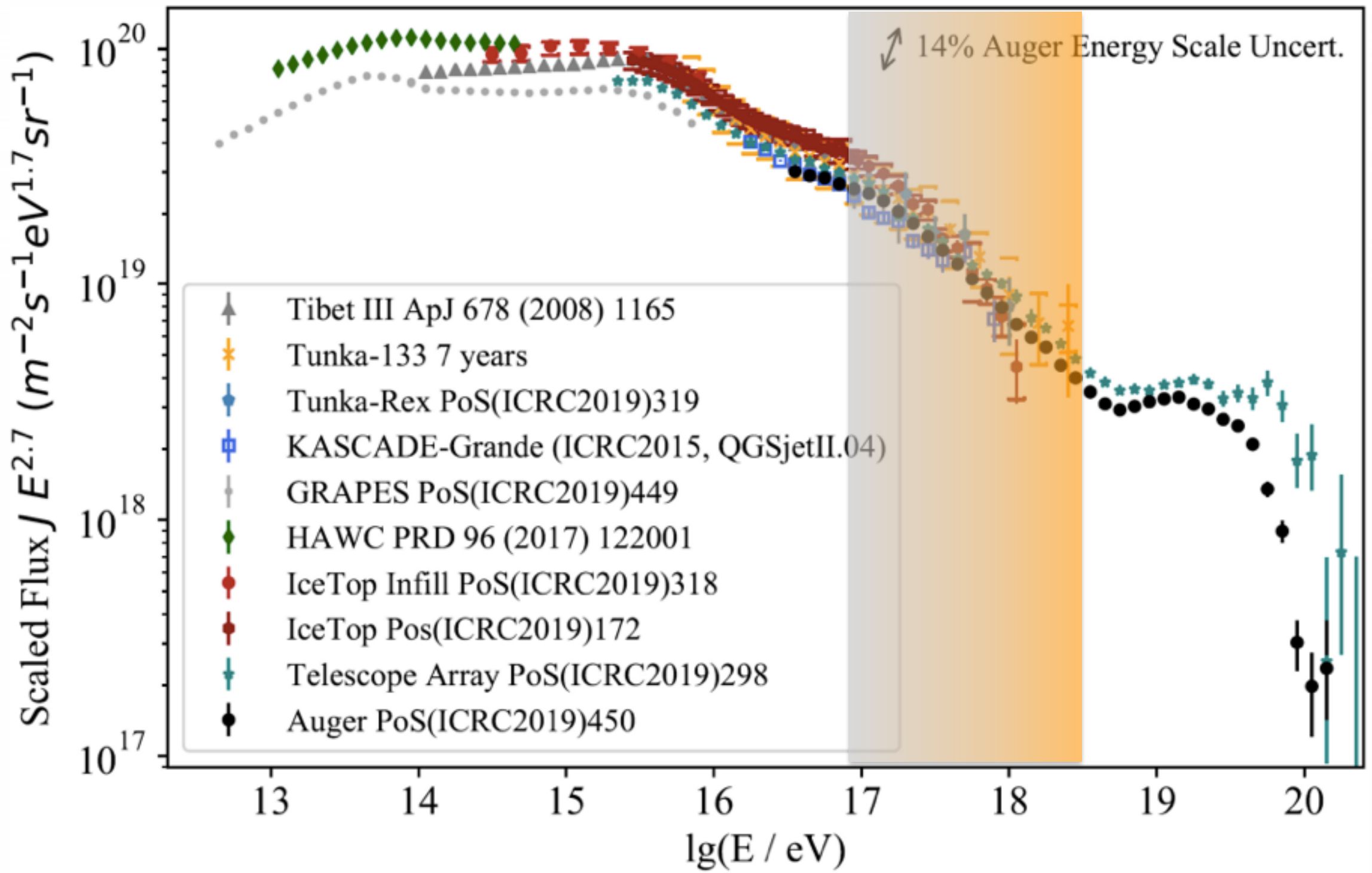
- SBGs : higher rate of cataclysmic events (GRBs, hypernovas, magnetars)
- Transient sources in all galaxies, SBGs being a good tracer of the proportionality between SFR and CR production?

[Auger Collab. 2019]

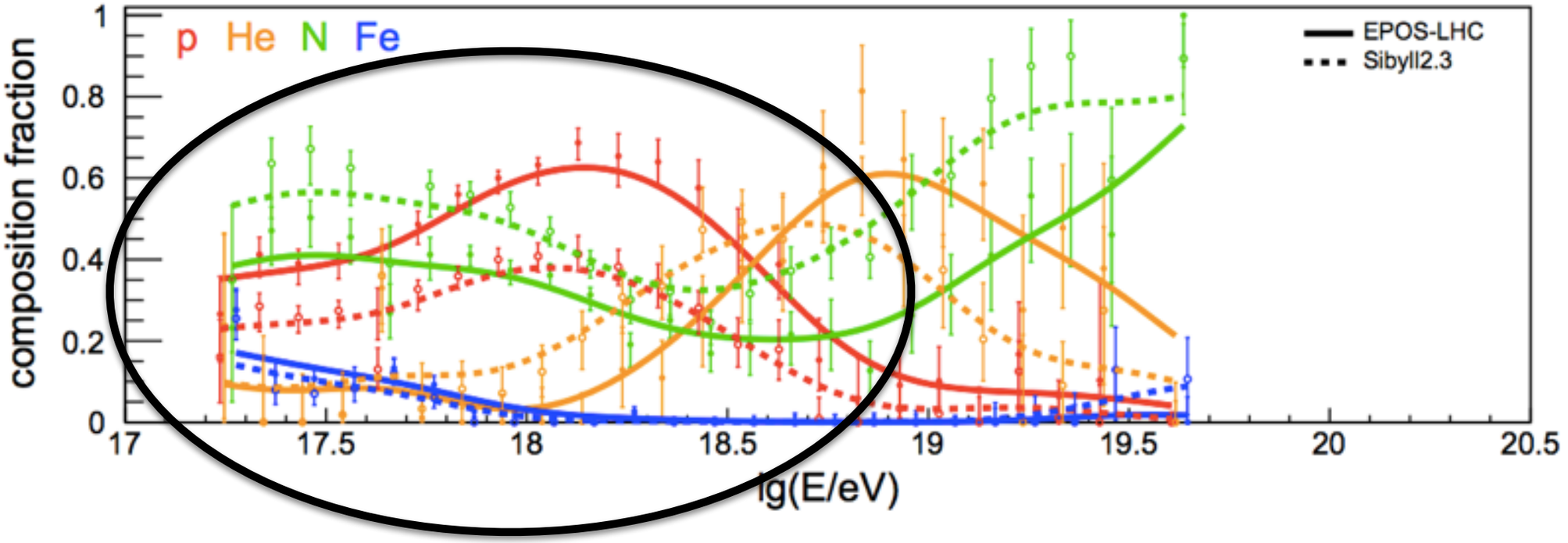
iv) Galactic/extragalactic cosmic rays

Galactic/extragalactic cosmic rays

[Compilation: Schroder 2019]



SNRs > 10^{17} eV?

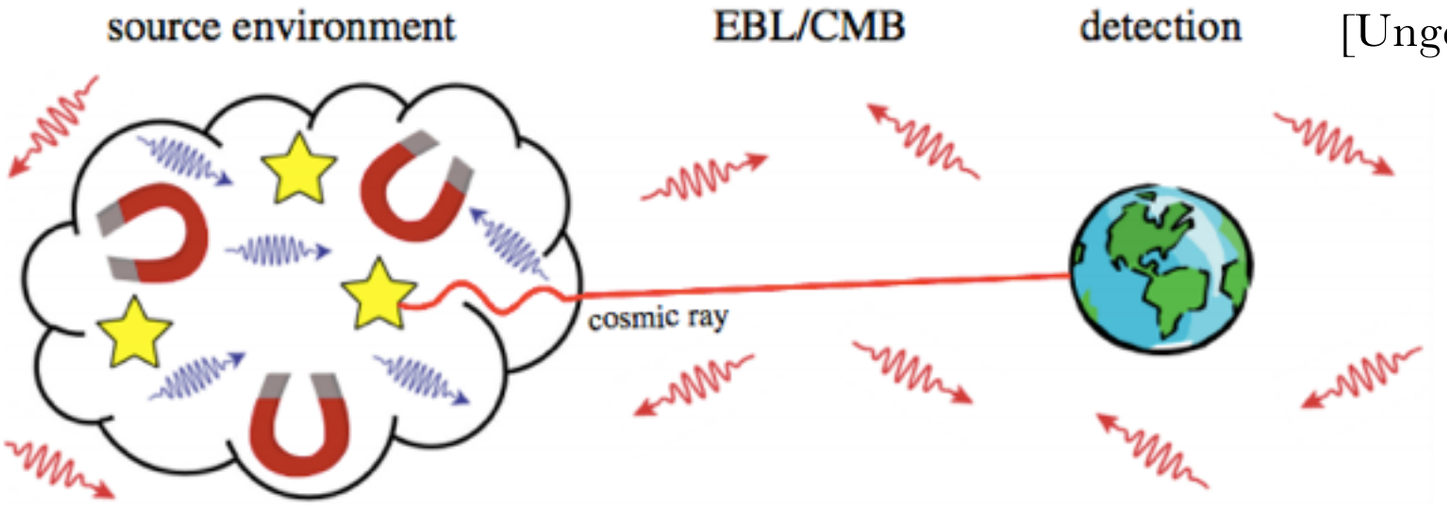


SNR paradigm : $E_{max} \sim 3Z\ 10^{15}$ eV

+ No Fe $<10^{18}$ eV

- p, He, CNO components?

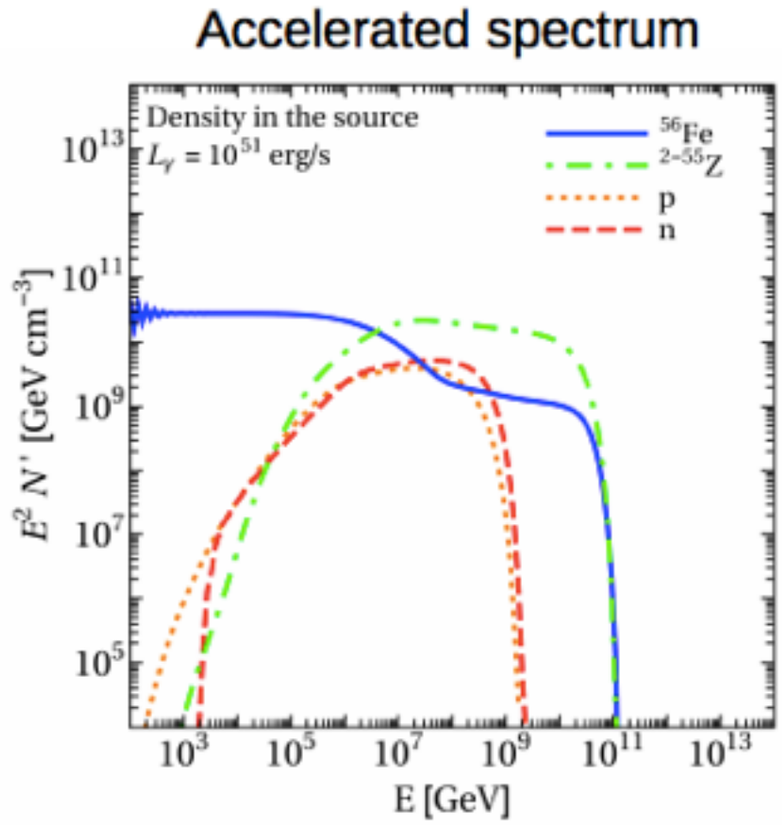
Extragalactic protons below the ankle energy

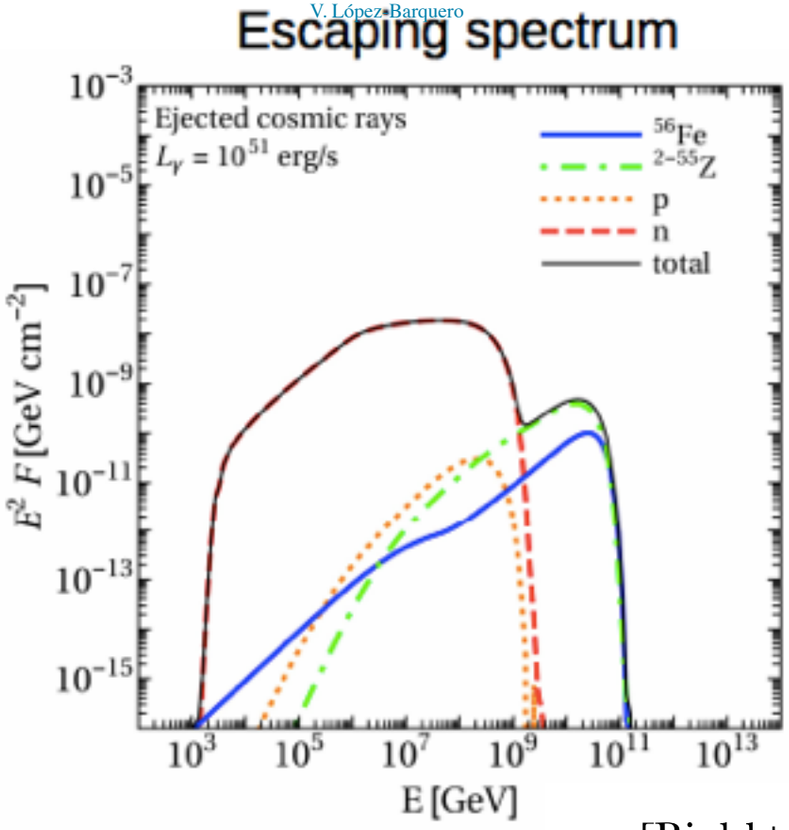


[Unger+ 2015]

Source environments such that:

- For efficient photo-disintegration, heavy cosmic rays are depleted and light secondary nucleons are produced
- Mostly high energy CR escape as their Larmor radius is large enough to reach the boundaries
- All neutrons escape as they are electrically neutral





[Biehl+ 2018]

v) Outlook

Outlook

- *What's your targeted physics in next decades?*
  - Identifying the UHECR sources
  - Understanding the 2nd knee-to-ankle energy range, key to understand the UHE one
- *What do we need to accomplish?*
  - Full-sky anisotropy analyses
  - Mass-discriminated anisotropy analyses
  - (Much) larger exposure…