Indirect measurements of cosmic rays — Review

O. Deligny (CNRS/IN2P3 - IPN Orsay)

i) Cosmic rays

ii) Extensive air showers

iii) Galactic cosmic rays : anisotropy implications

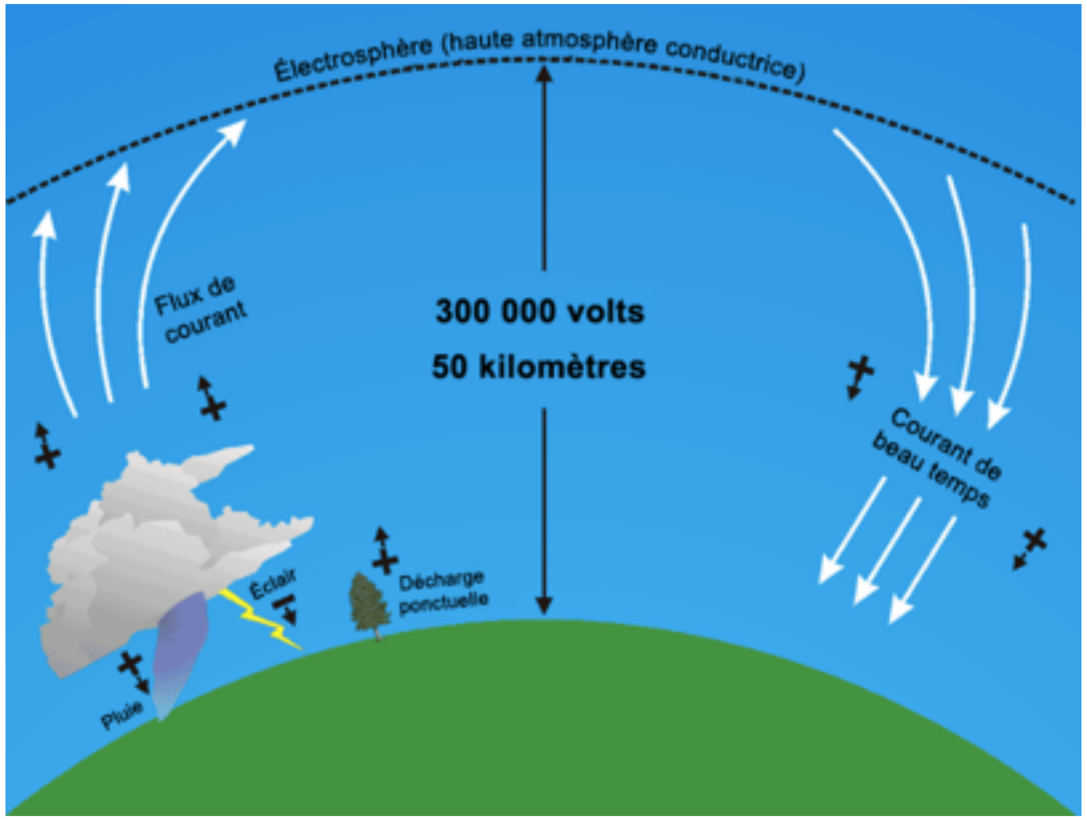
iv) Extragalactic cosmic rays

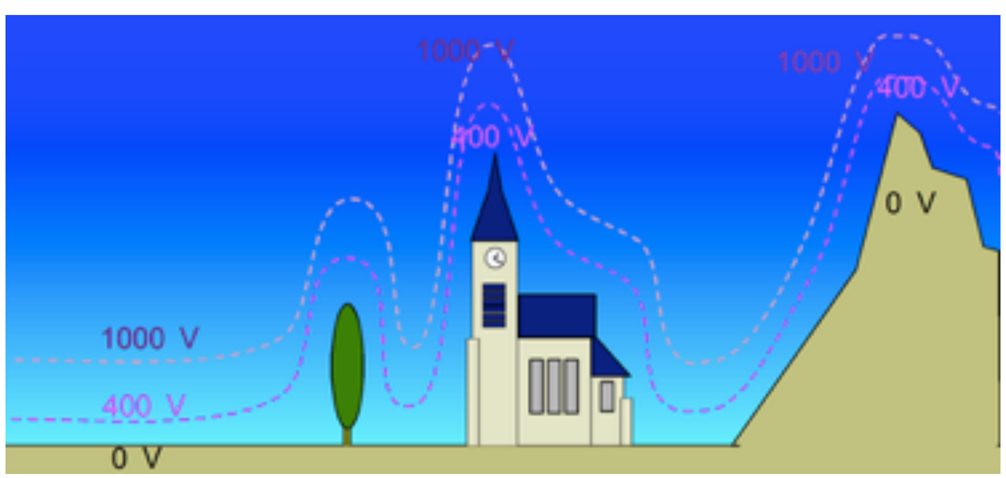
v) Galactic/extragalactic cosmic rays

COSPA meeting — Oct. 2019

i) Cosmic rays

Atmospheric electricity

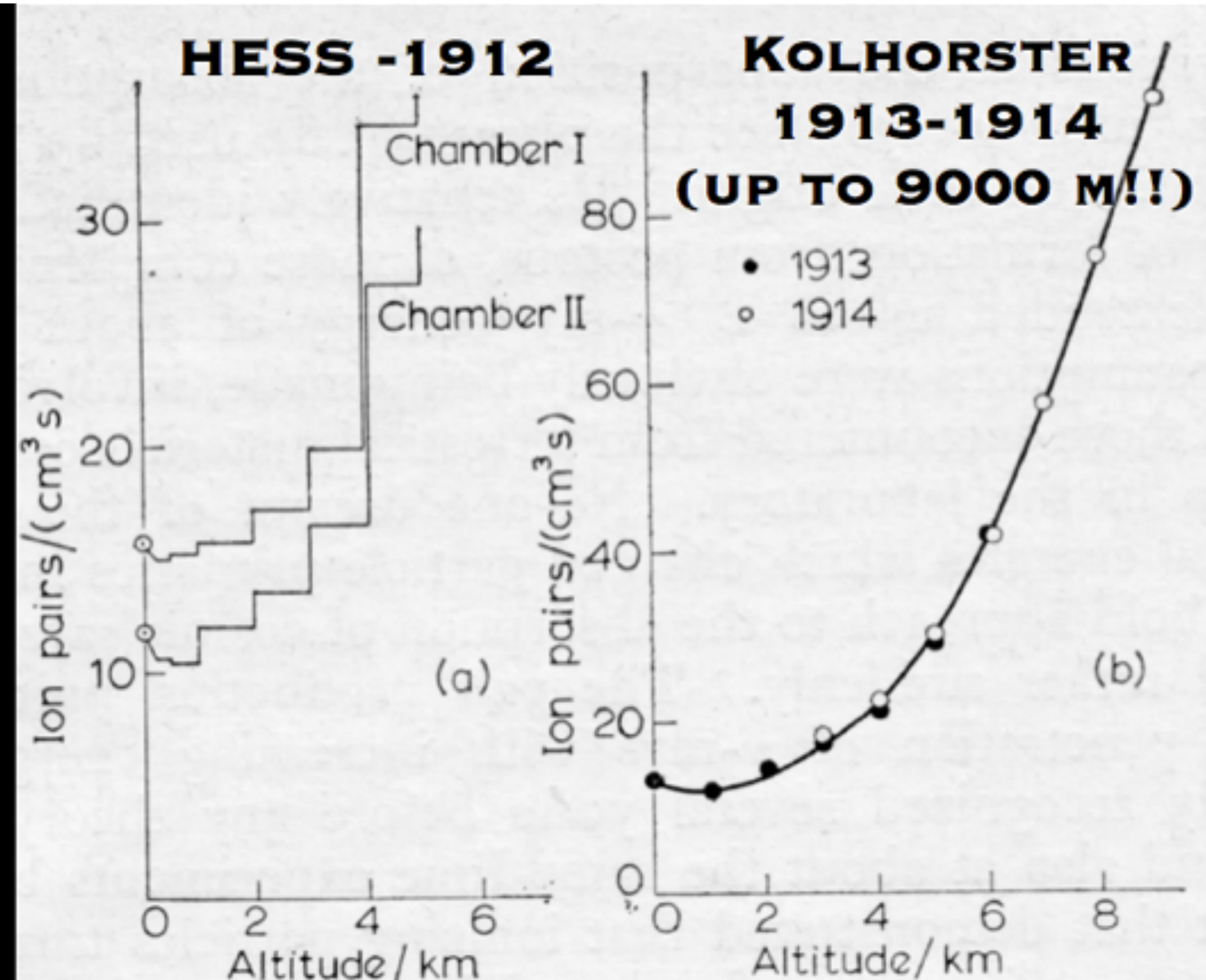




- Clear weather: electrical potential of 100 V/m at ground level
- Equipotential bypassing conductive obstacles (human body: $5\ 10^4$ Ohm)
- Negative potential: Earth's surface powered by electrons by lightning - Positive electrode: ionosphere
- Discharge of the Earth in ~a day: ionic drift rate ~1 cm/s
- Central question at the beginning of the XXth century: origin of ions in the atmosphere?

➡Radioactivity at the origin of the low conductivity of the air?

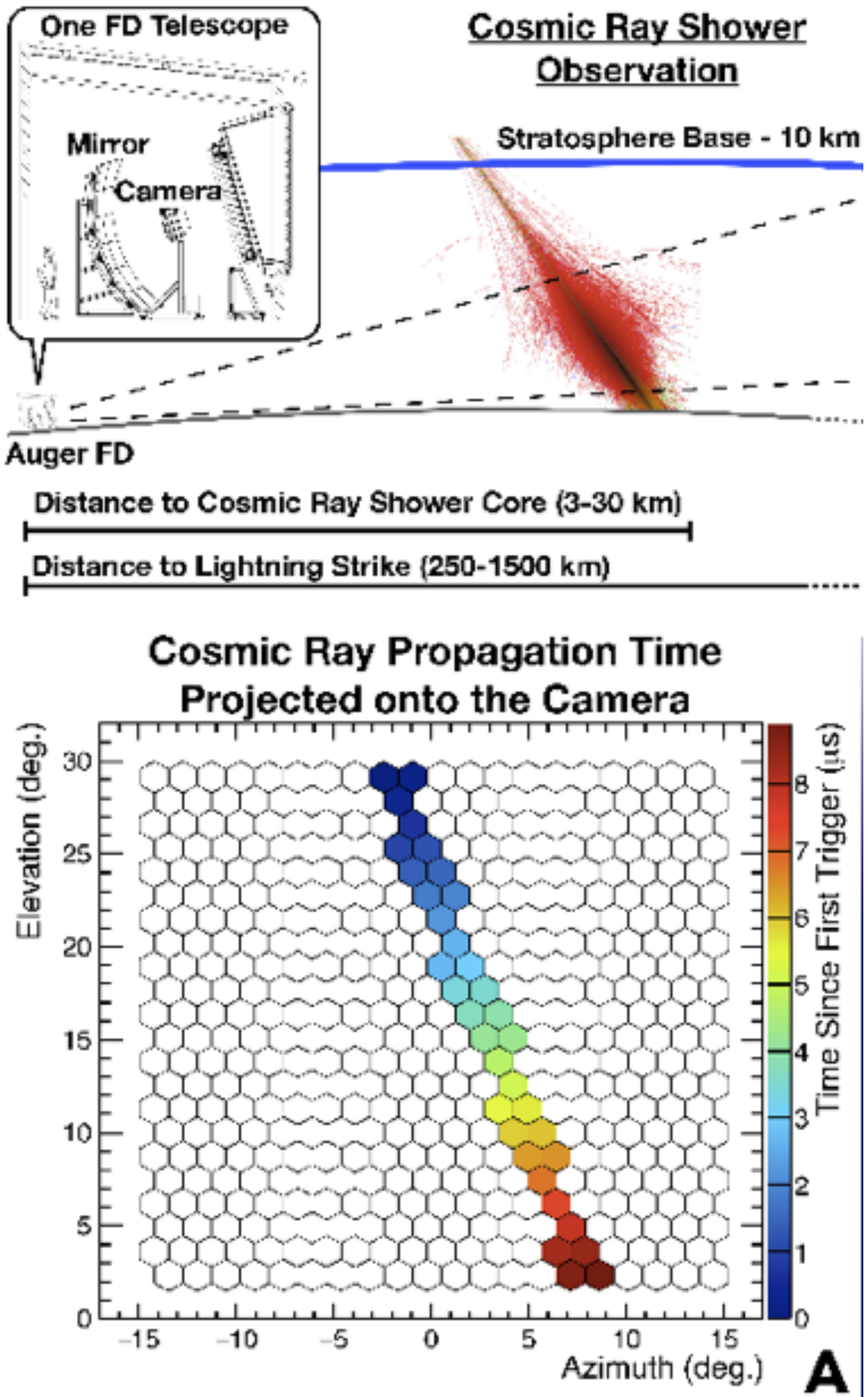
From atmospheric electricity to CR discovery



Intensity of the ionizing radiation first decreased as the balloon went up and then increased

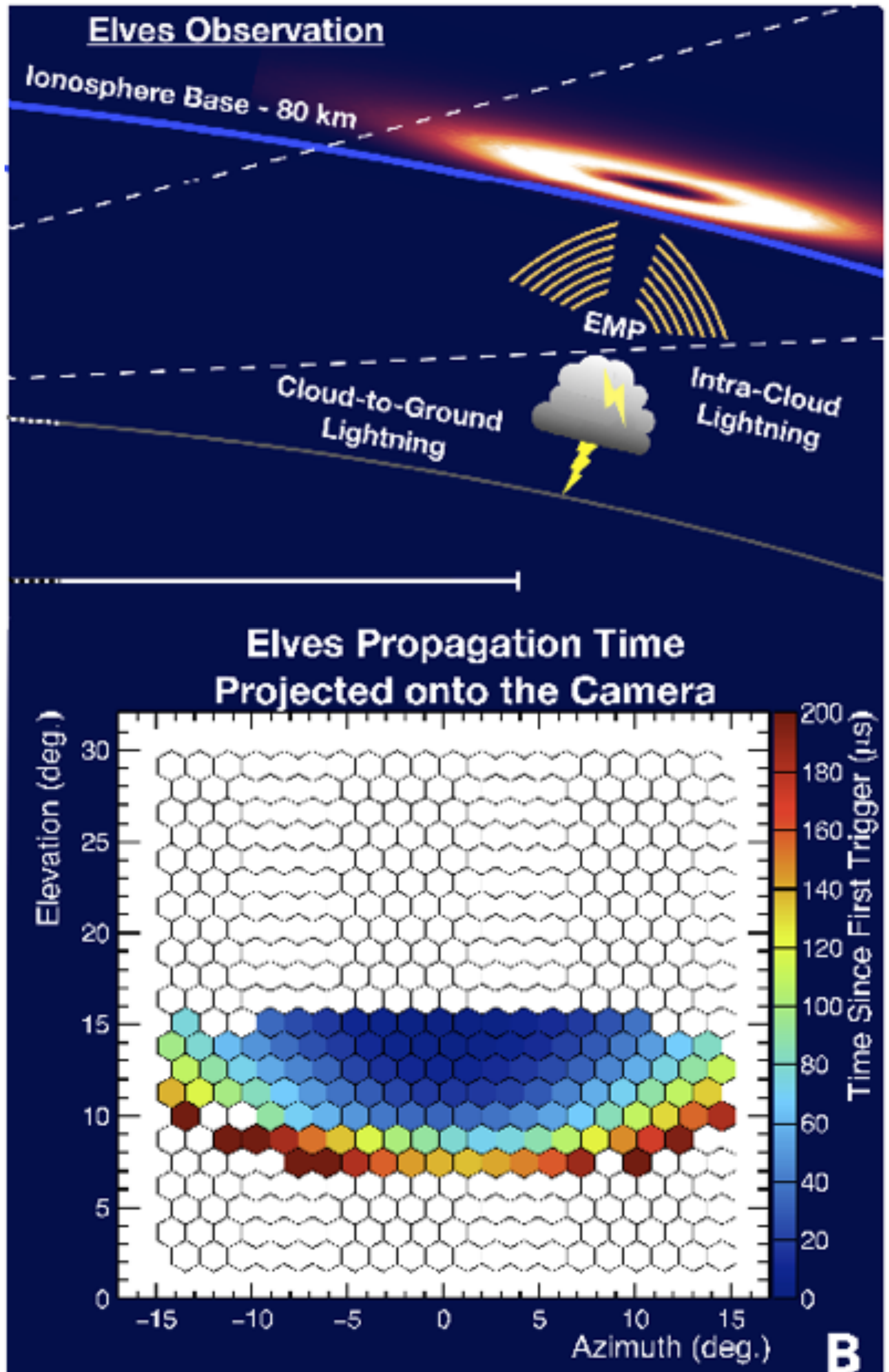
"The only possible way of interpret my findings was to conclude to the existence of a hitherto unknown and very penetrating radiation, coming from above and probably of extra-terrestrial origin" [V. Hess 1912]

From contemporary CR studies to atm. electricity



- Development of the electromagnetic cascade
- Production of ionisation electrons left after the passage of the e.m. cascade
- Excitation of nitrogen molecules due to ionisation electron collisions
- Production of fluorescence light through the de-excitation
- Enough detectable fluoresce light above ~10^{17} eV

ELVES: Emission of Light and Very Low Frequency perturbations due to Electromagnetic Pulse Sources



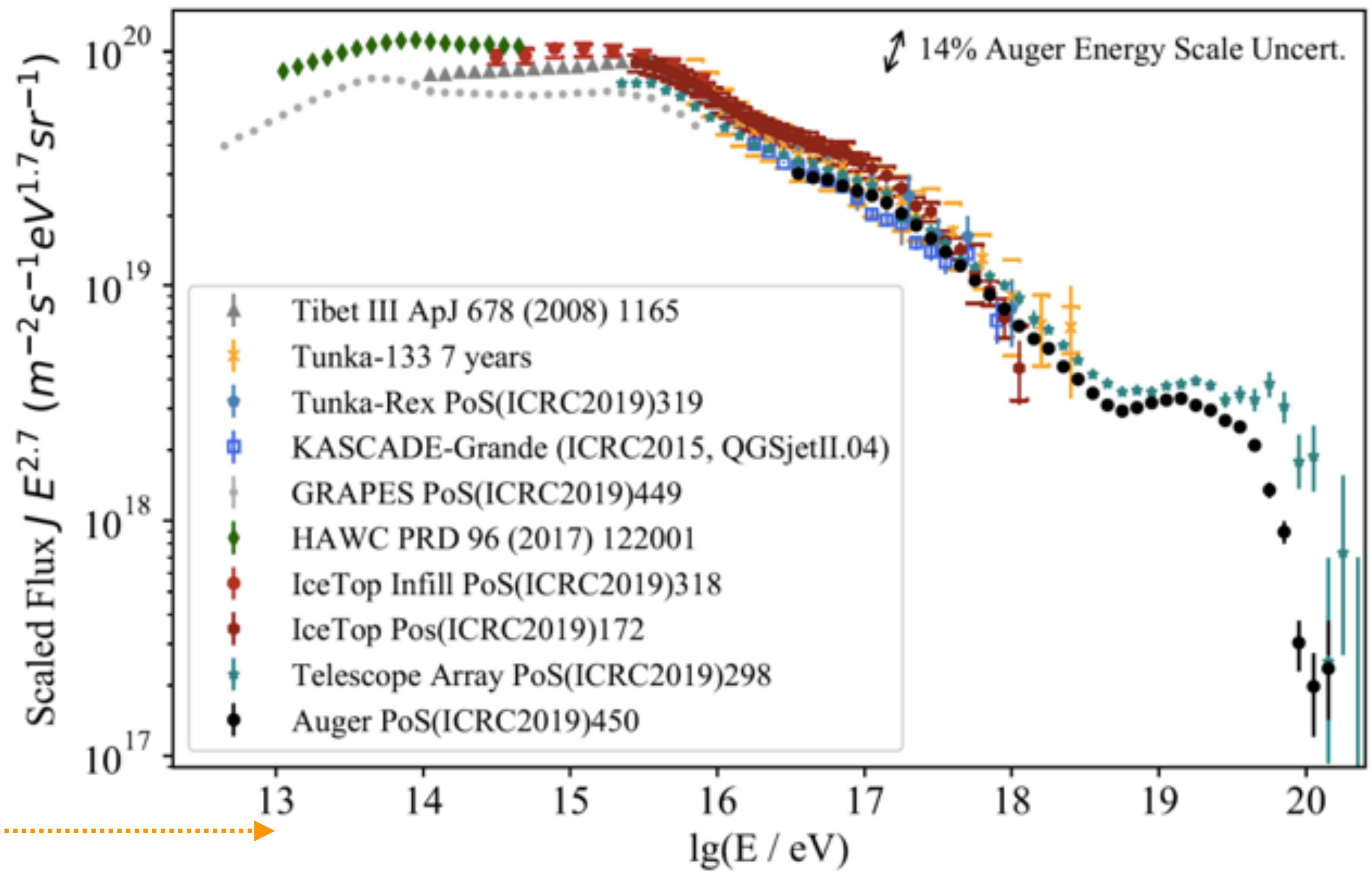
- Occurring in the ionosphere 100 km above the ground over thunderstorms
- Excitation of nitrogen molecules due to electron collisions (electrons energized by the EMP caused by a discharge from a thunderstorm)
- Red hue radiation
- Dim, flattened, expanding glow around 400 km in diameter lasting typically 1 ms
- Auger Observatory: observational footprint including the Córdoba region, known for some of the most energetic and destructive convective thunderstorm systems in the world [Auger Collab. Submitted to Earth and Space Science]
- Possibility to further the understanding/ modeling of mechanisms governing the production of the most intense lightning

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

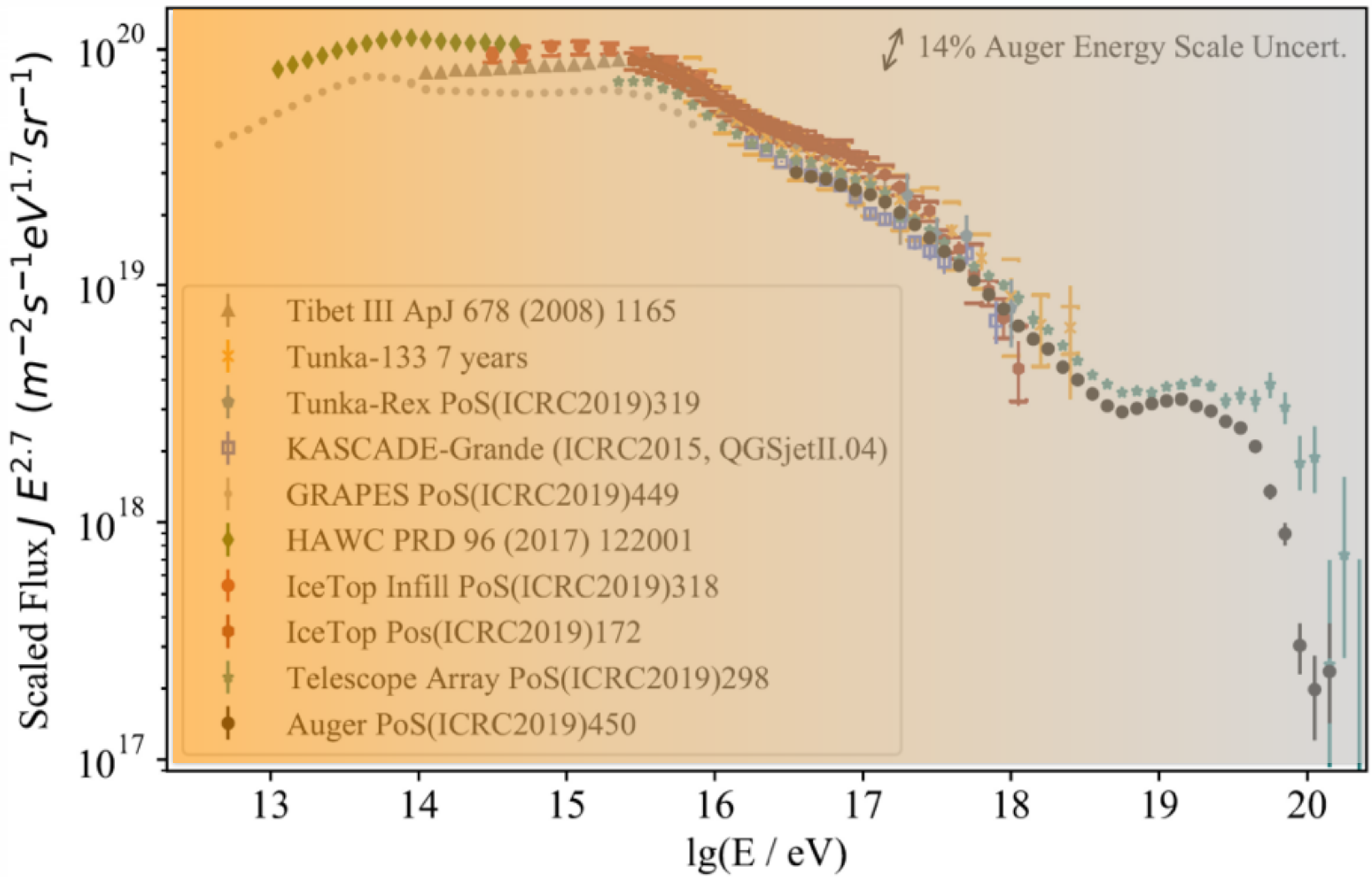
. . . . . .

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

. . . .

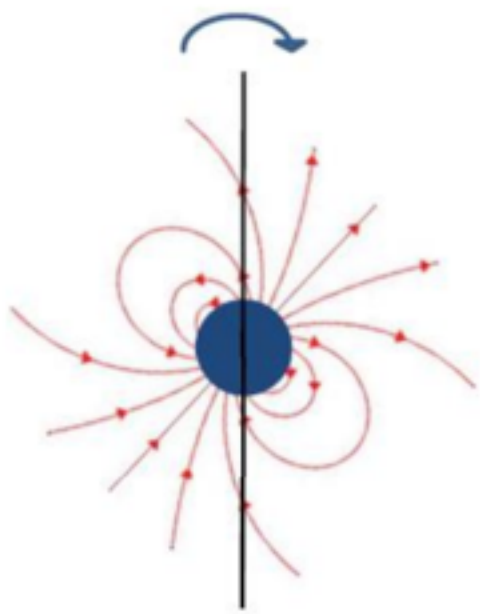
Neutrinos

Galactic/extragalactic origin



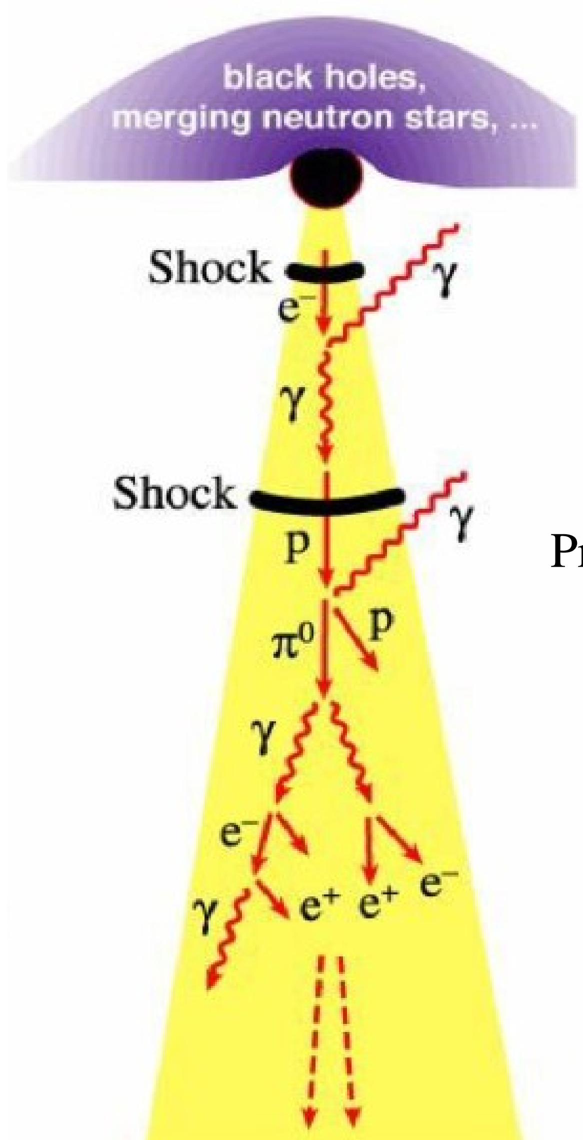
Cosmic accelerators

rotating **B**



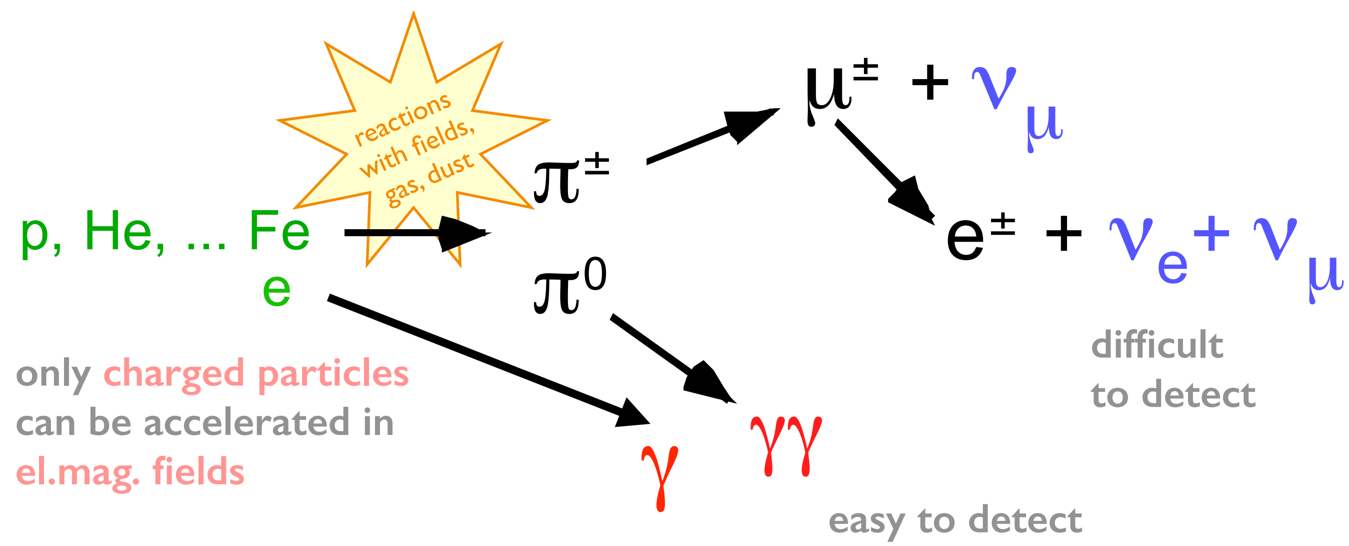
$\langle E \rangle$

turbulent **B**



$\langle E^2 \rangle$

multi-messenger cascade



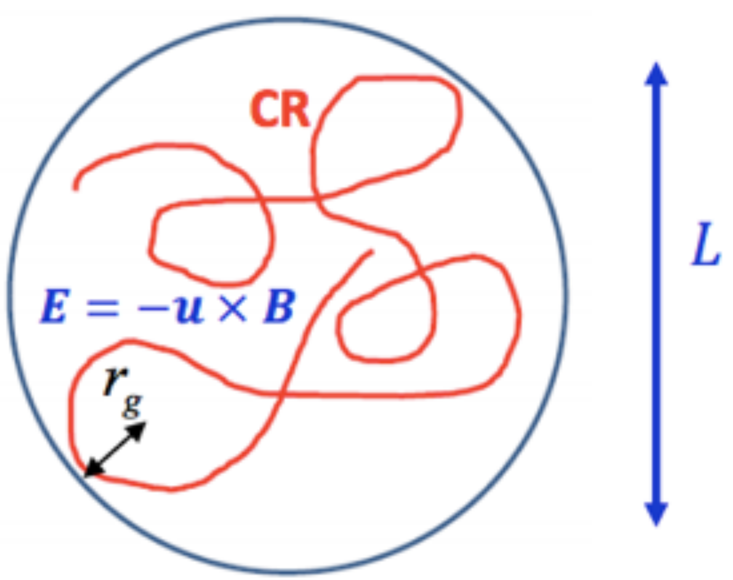
"multi-messenger astrophysics"

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

γ,ν

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

Hillas criterium — Diffusive shock acceleration



1/ Spatial confinement: Larmor radius< size of the plasma

$$r_g = \frac{T}{cB} \quad \leftarrow \text{energy}$$

$$T < cBL$$

2/ Acceleration by an electric field: $E = -u \times B$ (u: speed of the thermic plasma)

Maximal gain: $L \times$ maximum of **E** $\quad T < uBL$

Hillas maximal attainable energy:
($\times$ electric charge Z)

$$T = \left(\frac{u}{c/3}\right)\left(\frac{B}{10\ \mu\text{G}}\right)\left(\frac{L}{3\text{kpc}}\right) 10\ \text{EeV}$$

upstream | shock | downstream

u_1 → | shock | u_2 →

Diffusion coefficient D_1 | | Diffusion coefficient D_2

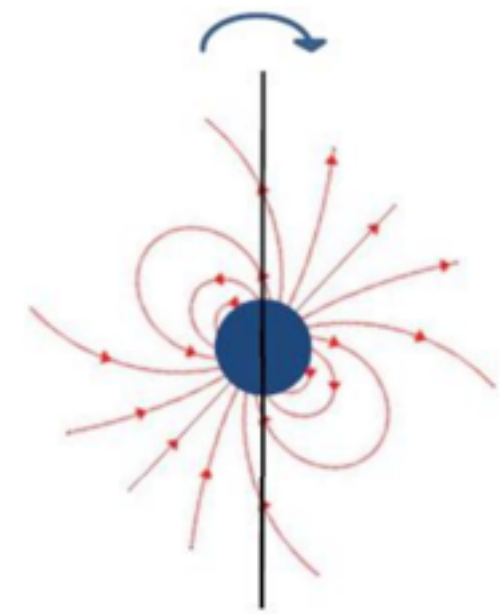
Maximal attainable energy: $$T = \frac{3}{4}\left(\frac{D_1}{D_{Bohm}}\right)^{-1} u_1 BL \iff T = \frac{1}{4}\left(\frac{\lambda}{r_g}\right)^{-1} u_1 BL$$

Source candidates

Galactic: SNRs

- u=5000 km s^{-1}, B=300 μG, L=1 pc
  $T_{\mathrm{max}} \sim Z\ 10^{15}$ eV
- Power law spectrum for DSA
- Energetics required to fuel the observed CR intensity: ~1.5 10^{50} erg
  - ~1/6 of 10^{51} erg in 3 SN explosions per century [Baade & Zwicky'34]
    - Equipartition of the dissipated energy: 1/3 eaten by CR acceleration
    - Efficiency of the acceleration ~ 50%

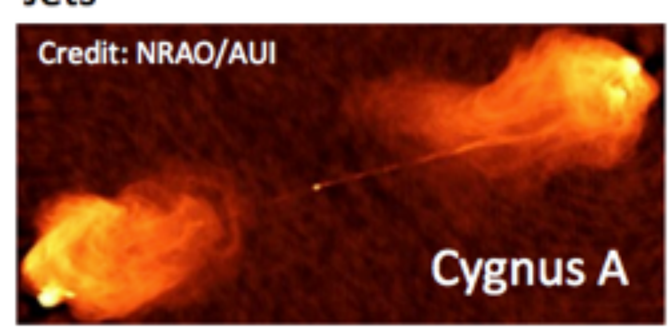
Extragalactic?



$u = \Omega R$

$T = B\Omega R^2$ =10^{19} eV for B=10^{15}G R=10km Ω=1 s^{-1} (magnetar)

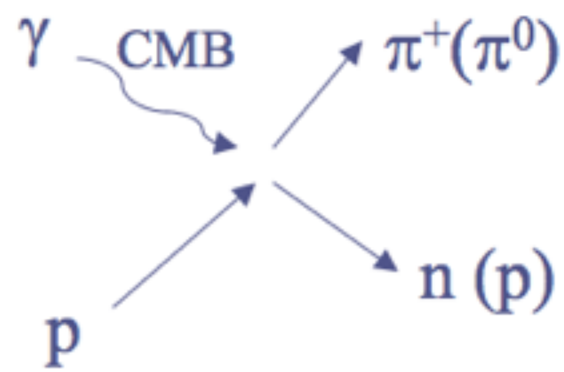
Jets



$u \sim c$
B = 300 μG
R = 10 kpc

T =10^{21} eV

GZK cutoff

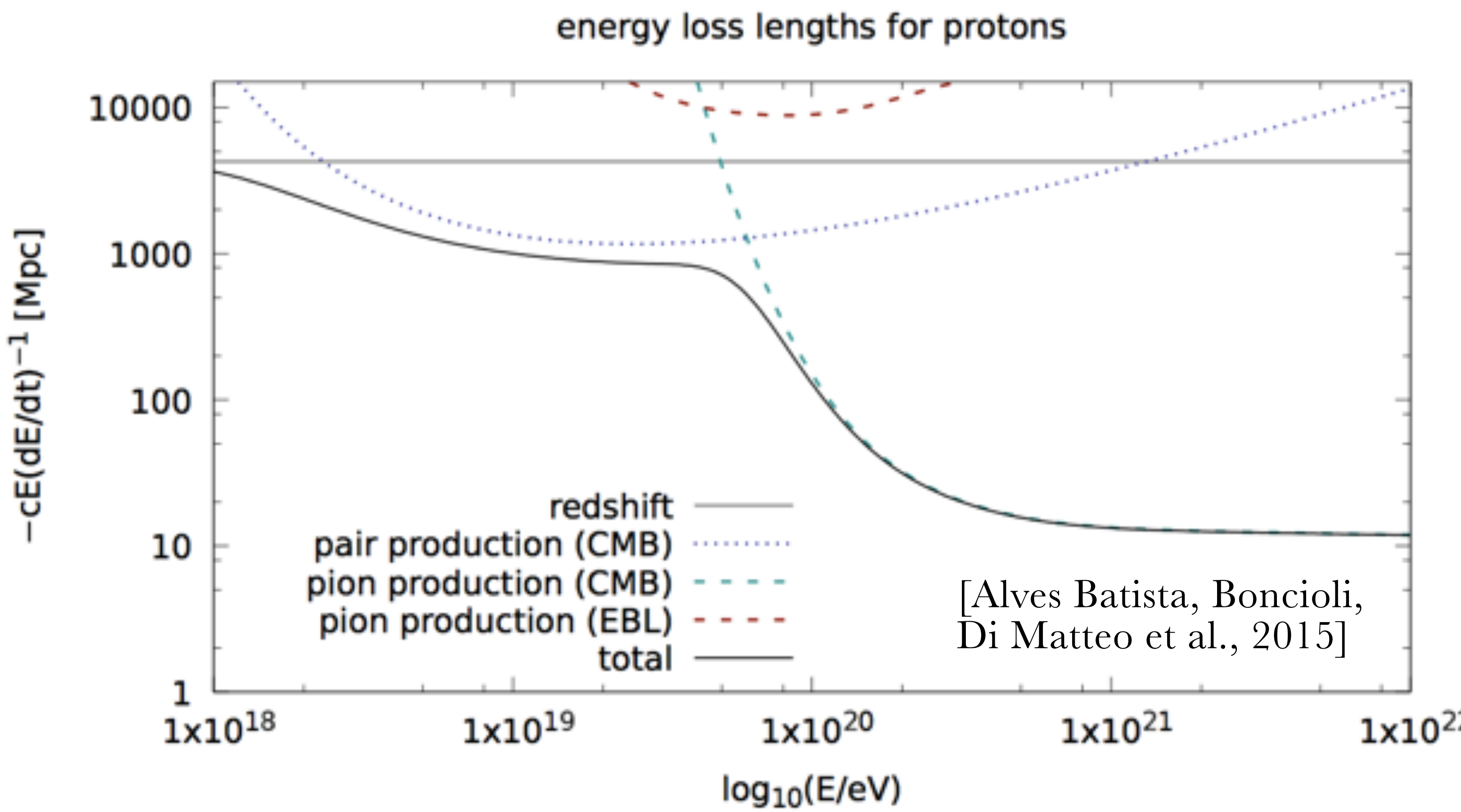


Example with protons

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

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

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

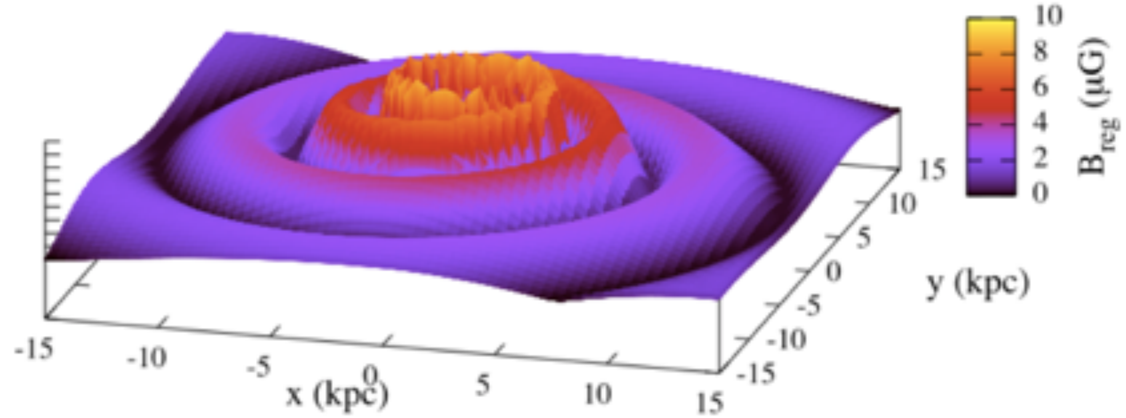


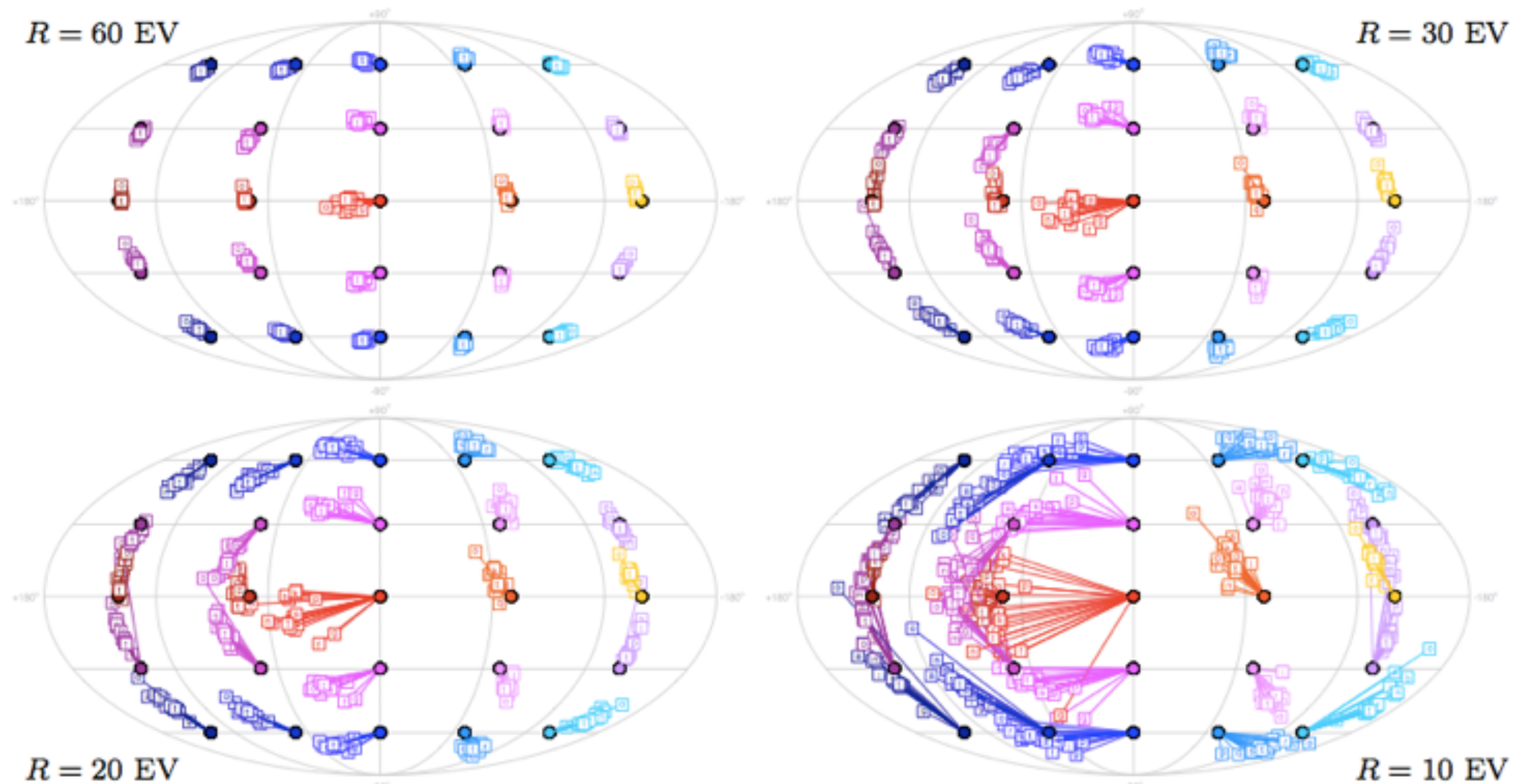
[Alves Batista, Boncioli, Di Matteo et al., 2015]

Almost same conclusions for nuclei (photo-disintegration)

➡ Reduction of the CR horizon at UHE

Magnetic deflections

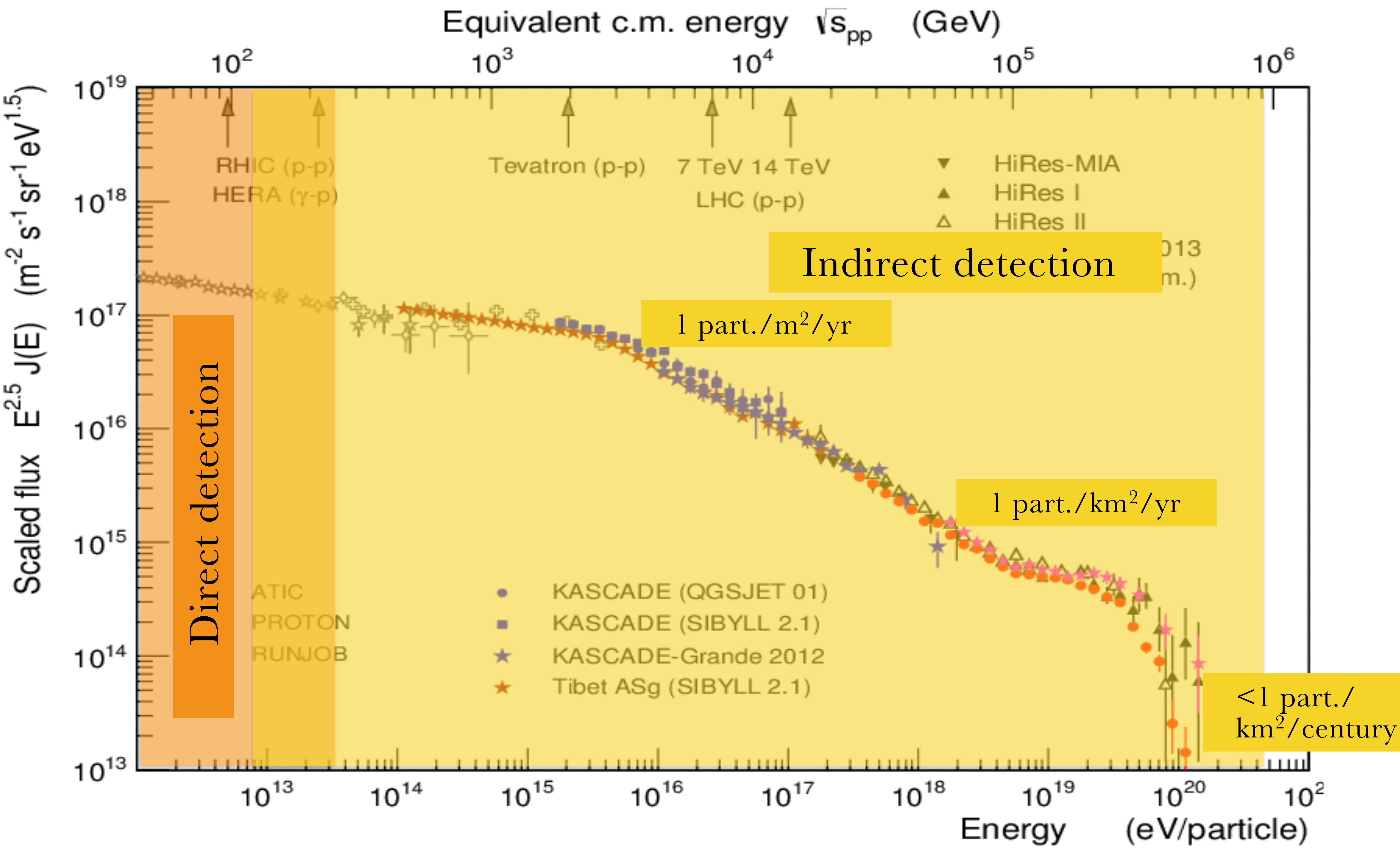




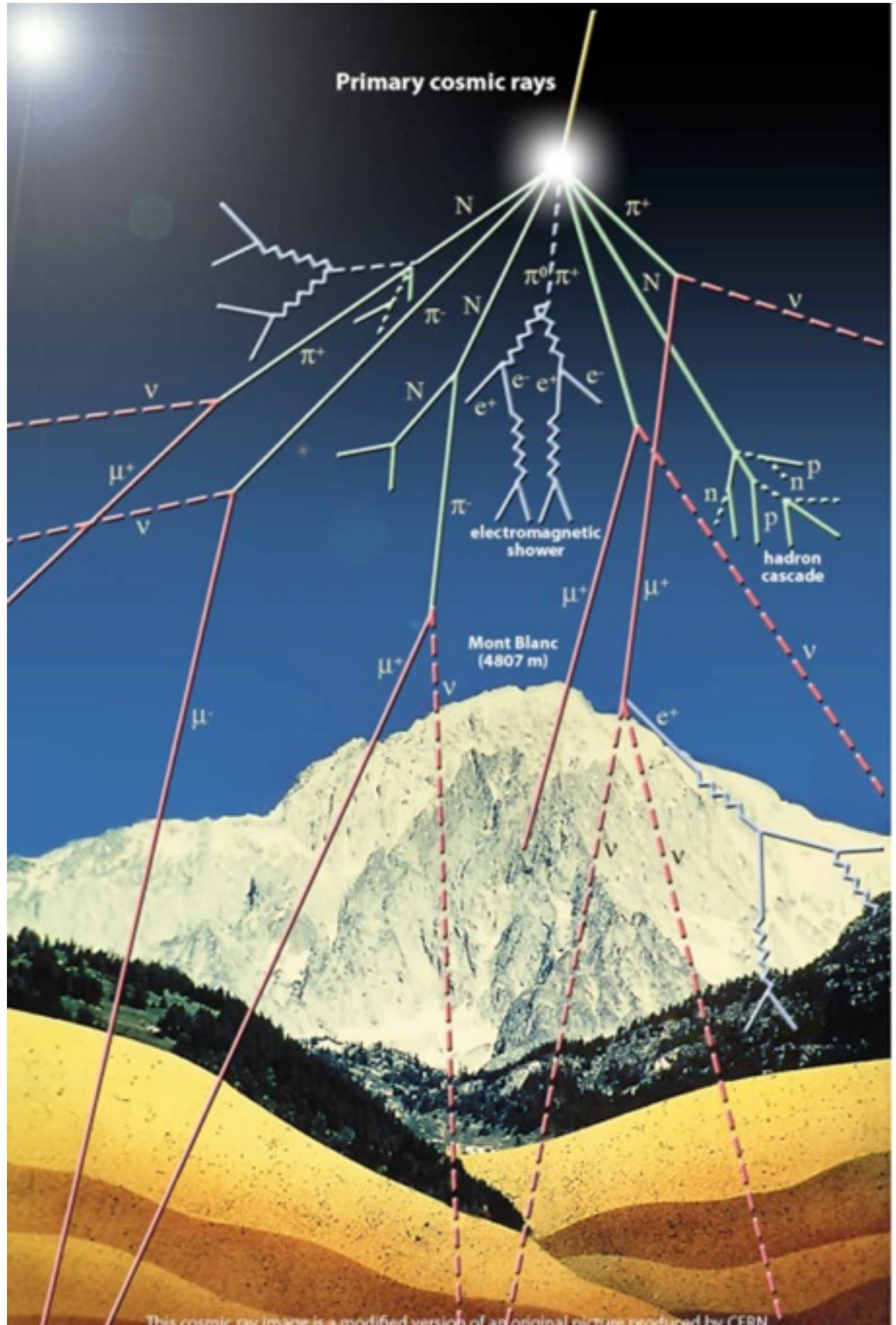
[Unger & Farrar 2017]

ii) Extensive air showers

Cosmic ray detection

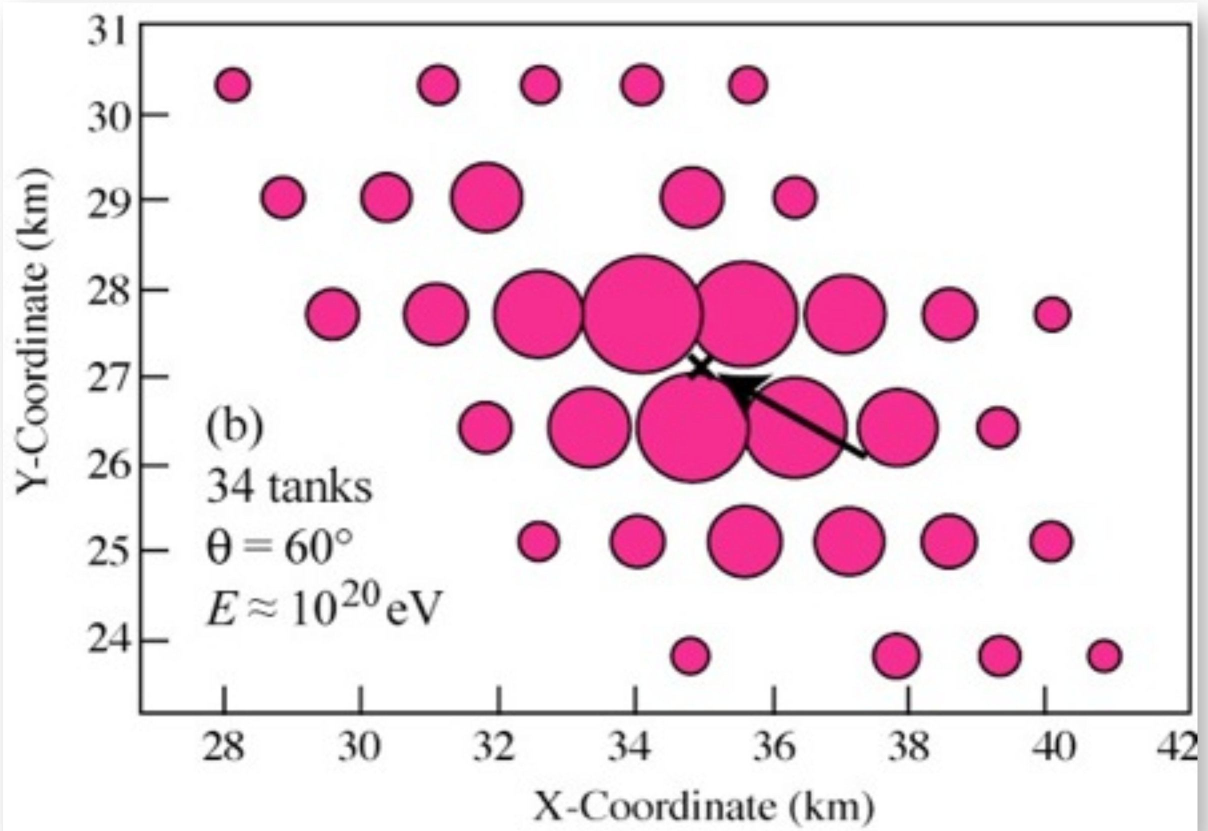


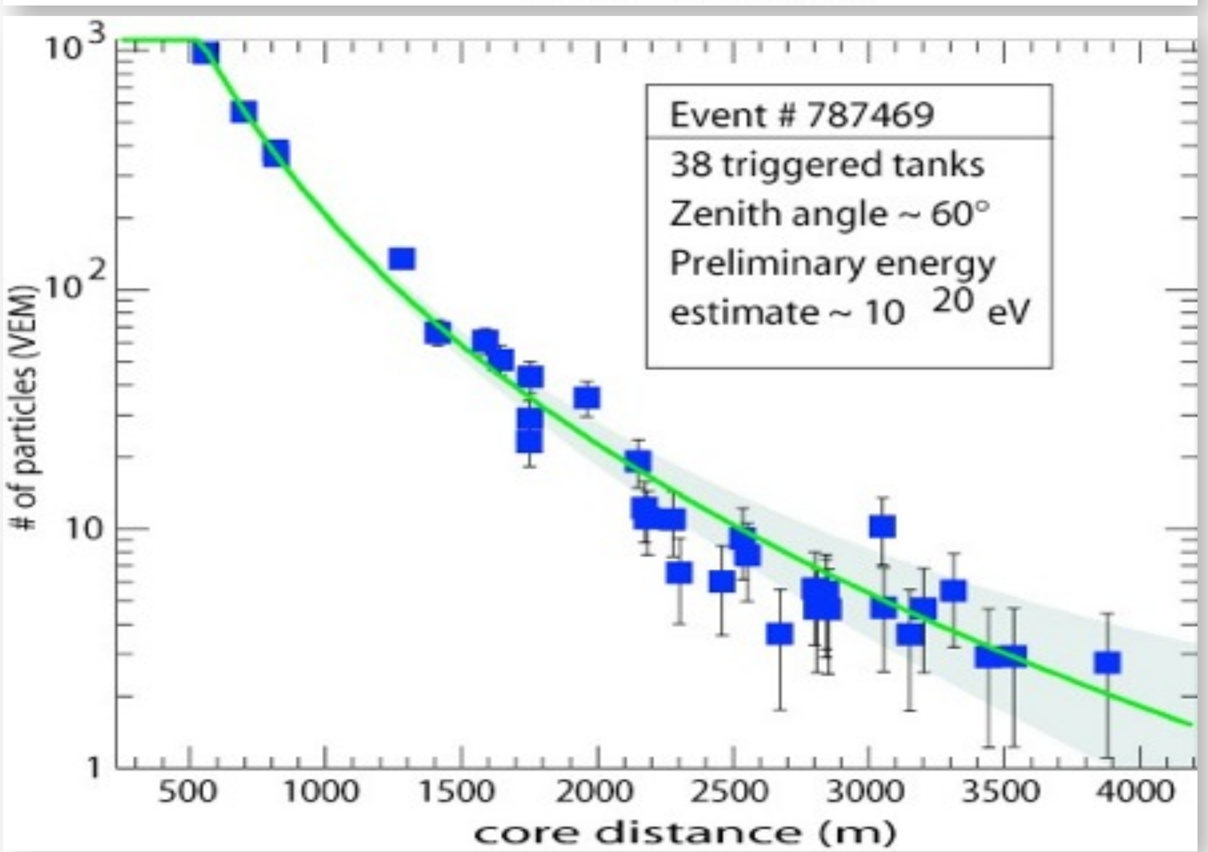
Extensive air showers



Ground array detectors

EAS reconstruction





EAS footprint at ground

⇒ lateral sampling

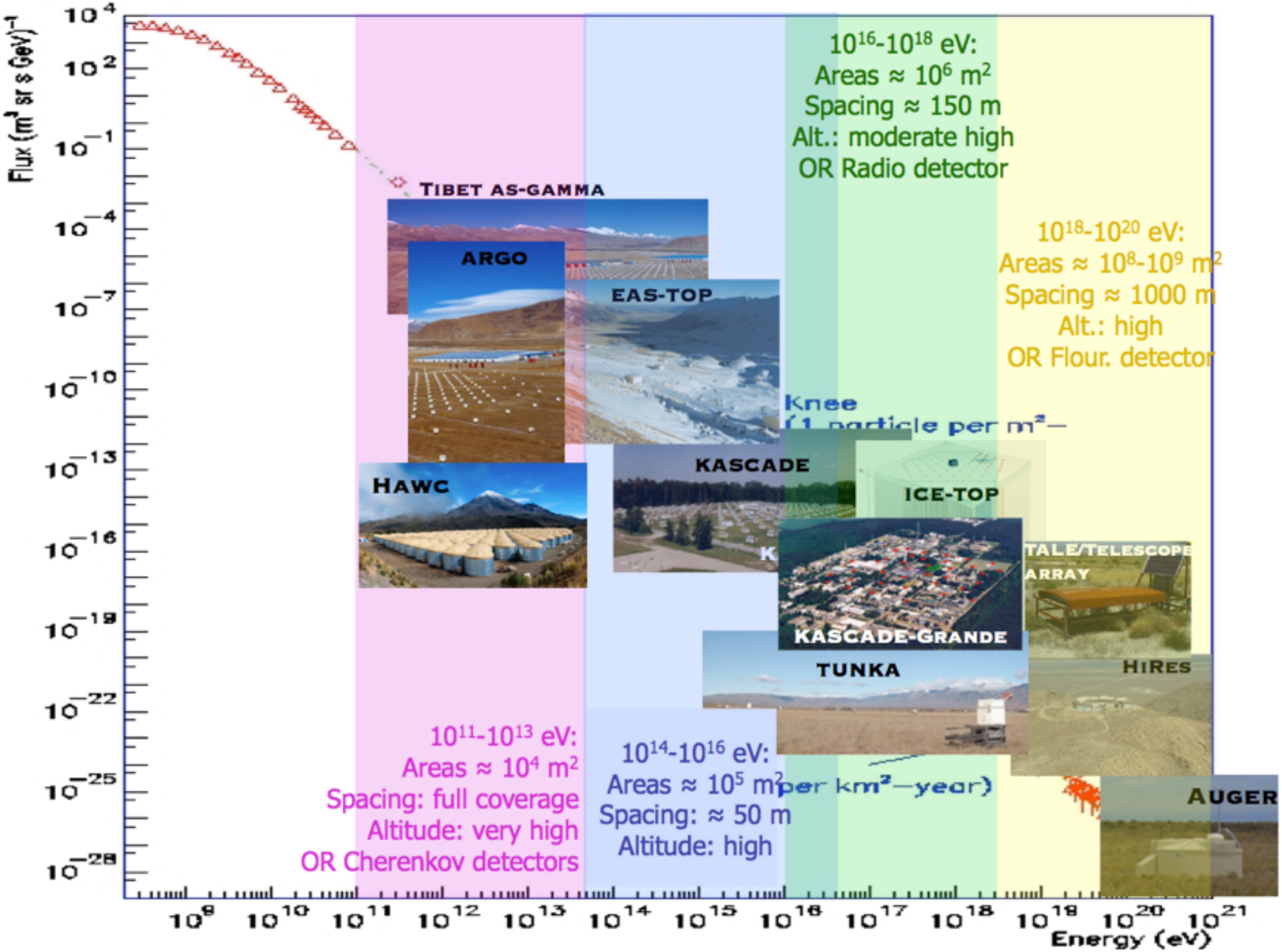
+ Arrival direction < ~1°

+ 100% duty cycle

- Energy estimate resorting to hadronic models

- Mass?

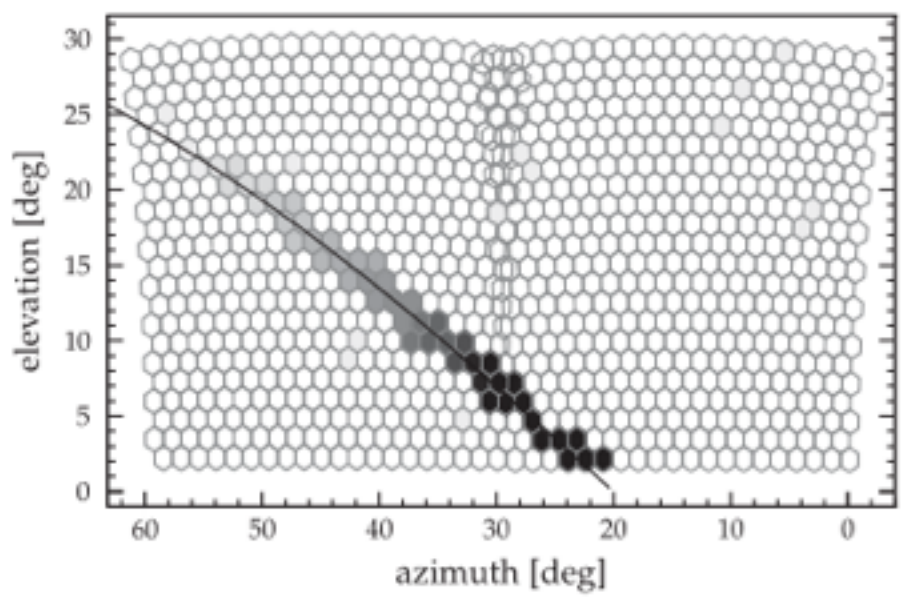
Cosmic-ray observatories



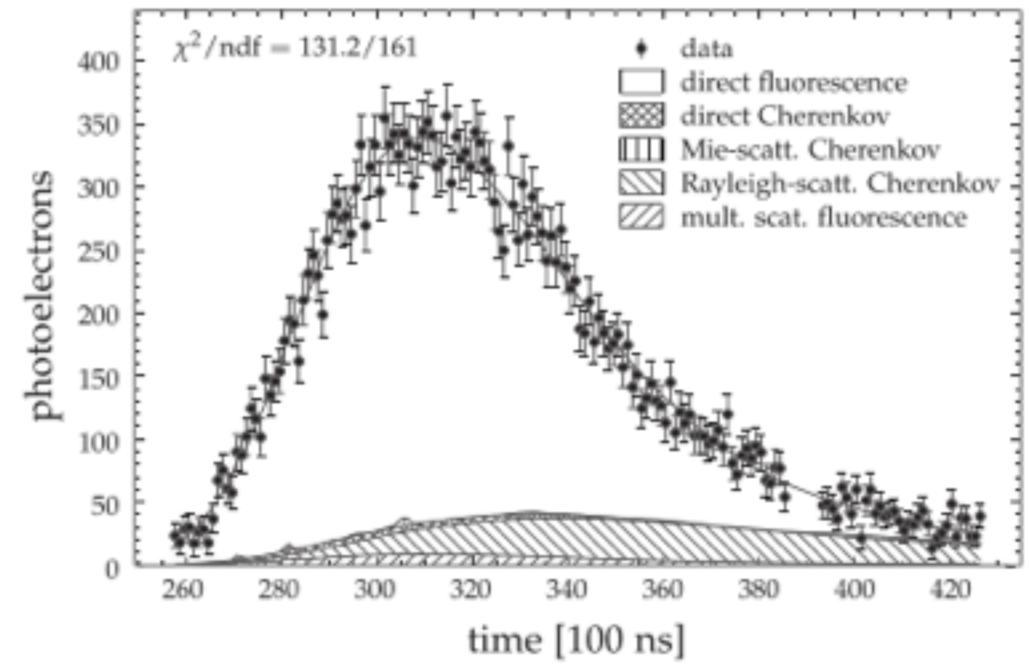
Fluorescence detectors > 10^{17} eV

Fluorescence detectors > 10^{17} eV

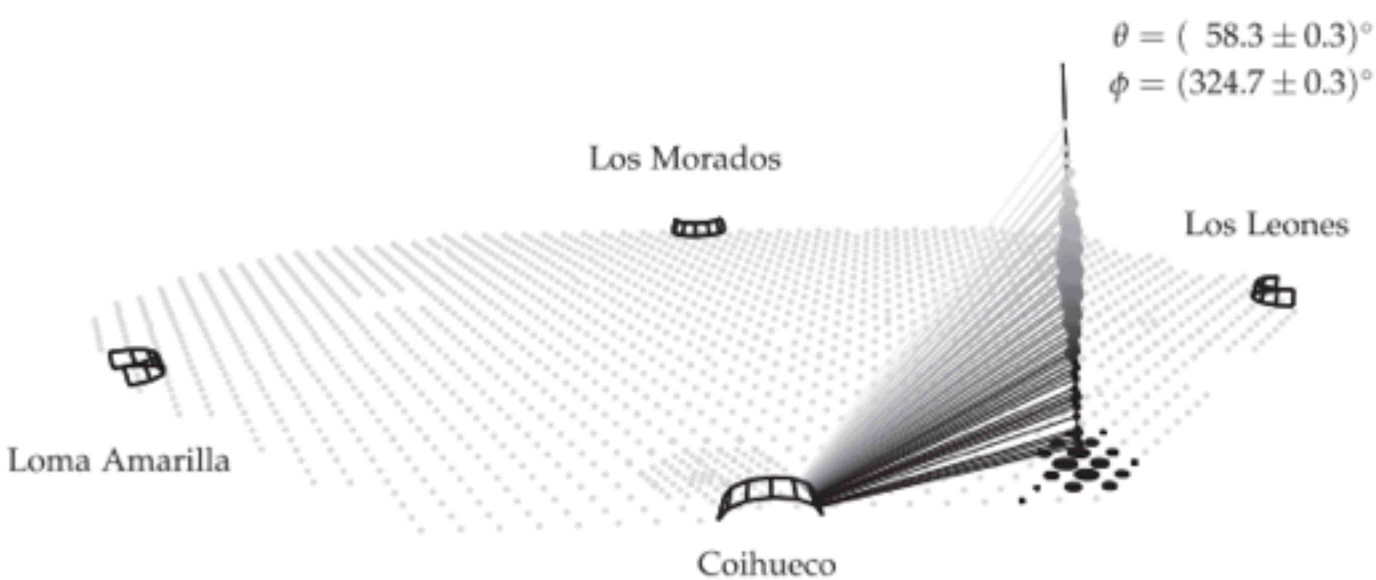
Fluorescence detectors > 10^{17} eV



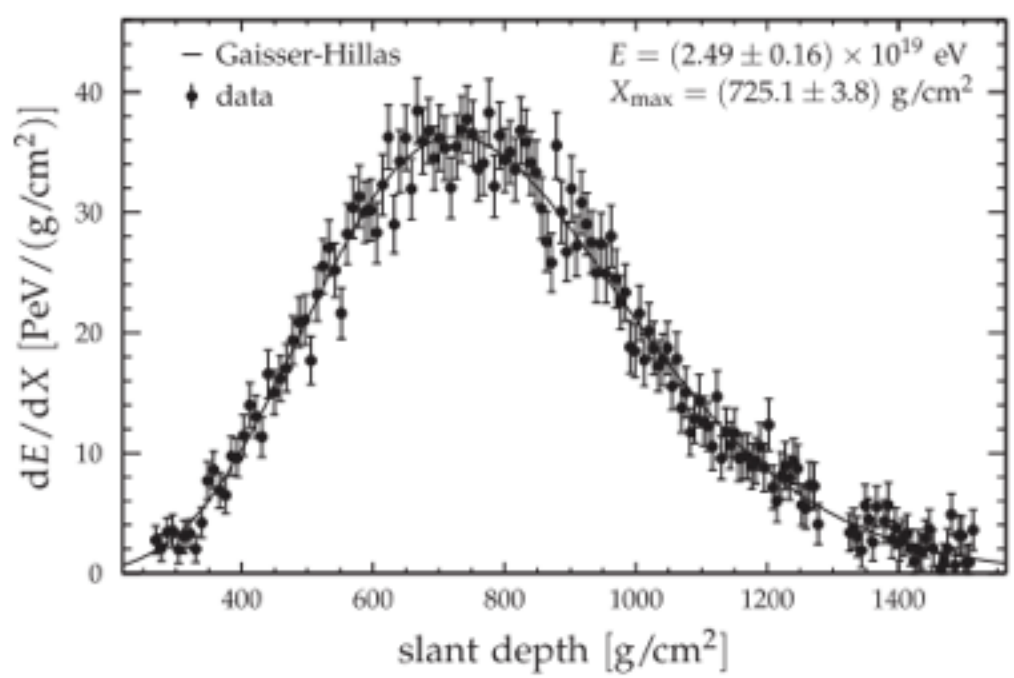
(a) Camera view. The timing of the pixel pulses is denoted by shades of gray (early = light, late = dark). The line shows the shower detector plane.



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



(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.



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

***iii*) Galactic cosmic rays : anisotropy implications**

All extragalactic?

THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics

VOL. 47, No. 11 JUNE 1, 1935 SECOND SERIES

An Apparent Effect of Galactic Rotation on the Intensity of Cosmic Rays

ARTHUR H. COMPTON, *University of Chicago and Oxford University* AND IVAN A. GETTING, *Oxford University*

(Received April 12, 1935)

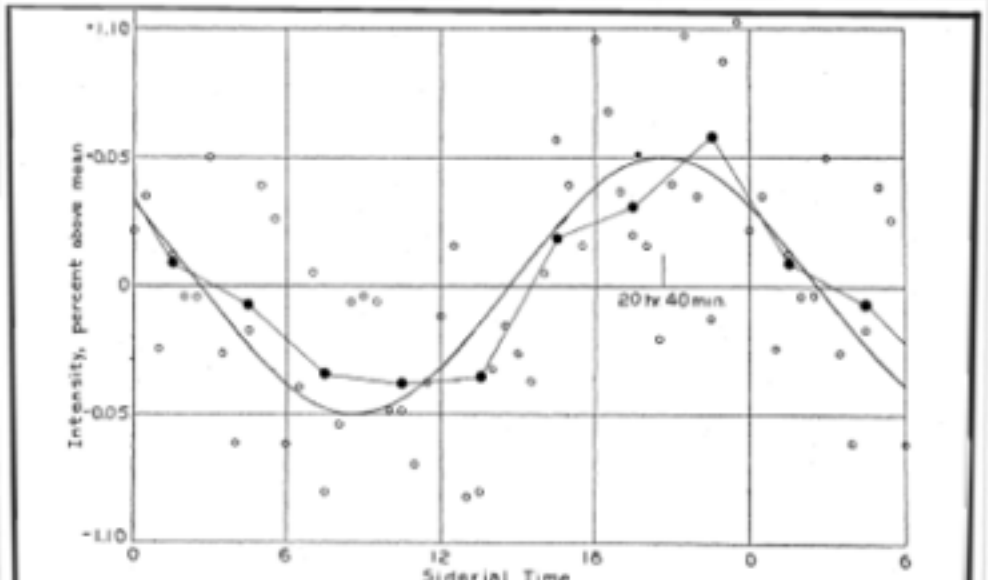
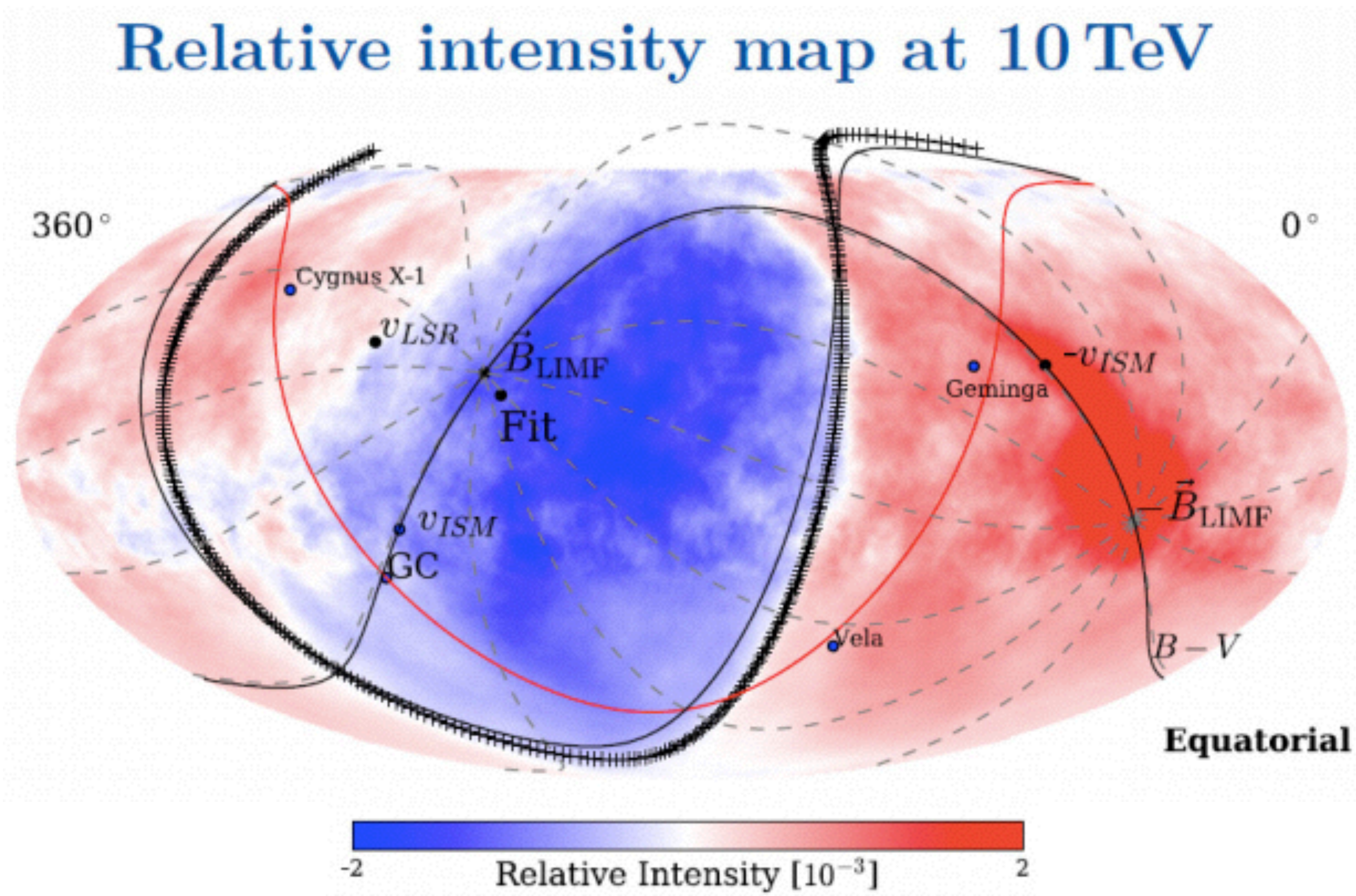


FIG. 2. Percentage variation in intensity of the cosmic rays with sidereal time. Curve, predicted effect due to galactic rotation. Data, Hess and Steinmaurer; open circles, half-hour means; solid circle, 3-hour means.

While we must await some such measurements before we can consider the effect due to the rotation of the galaxy as established, the quantitative agreement with the predictions as shown in Fig. 2 gives a strong presumption in its favor. Its existence would imply that an important part of the cosmic rays originates outside of our galaxy. If its magnitude is found to be as great as we have predicted, it will imply that practically all the cosmic radiation has an extragalactic origin.

Observations @ TeV—PeV

IceCube/HAWC [ICRC 2019]

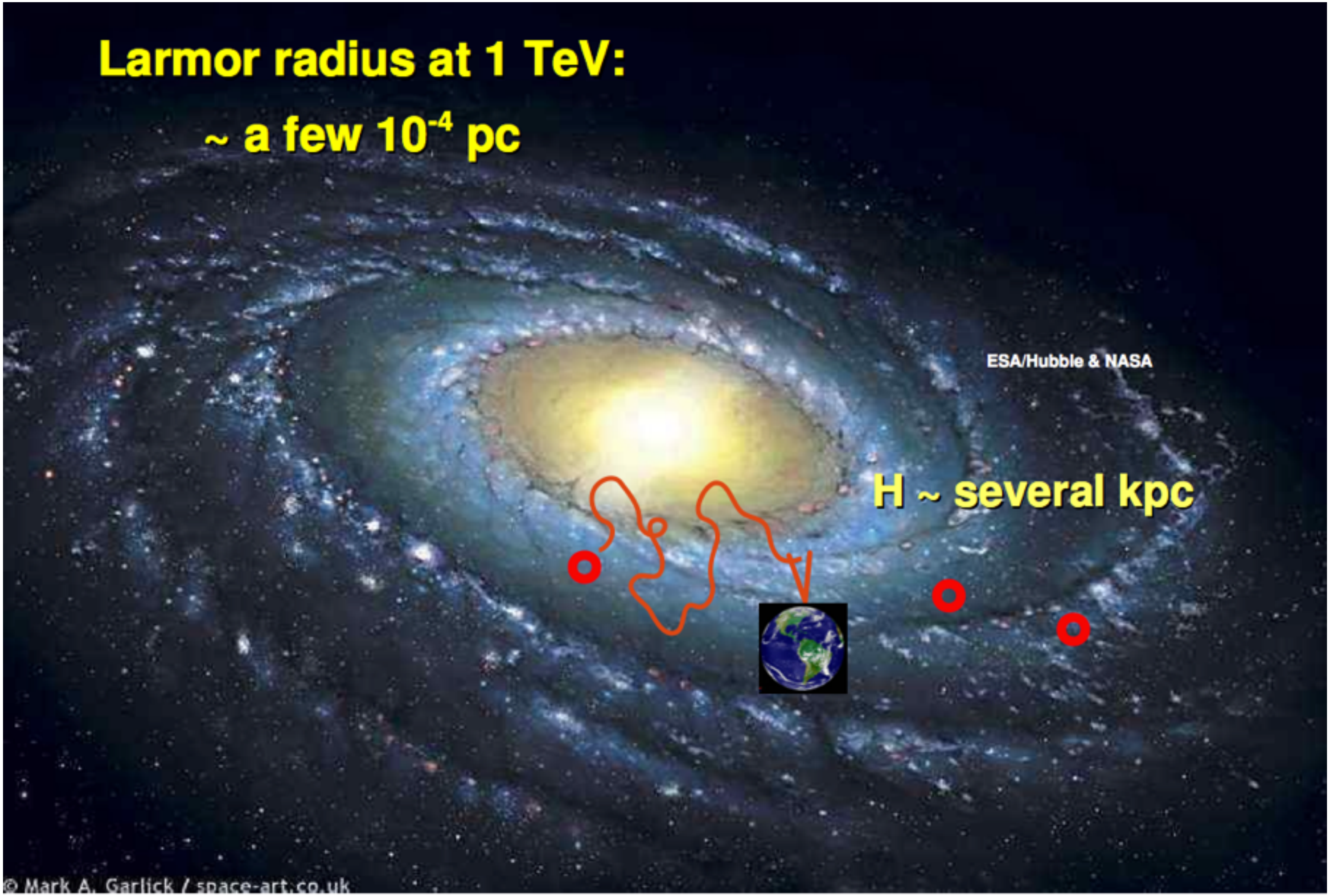


- Challenge: control the directional exposure down to anisotropy contrasts of ~10^{-3} — 10^{-4} (variations of atmospheric conditions, long-term performances of the detectors, …)

- Data-driven estimation of the directional exposure

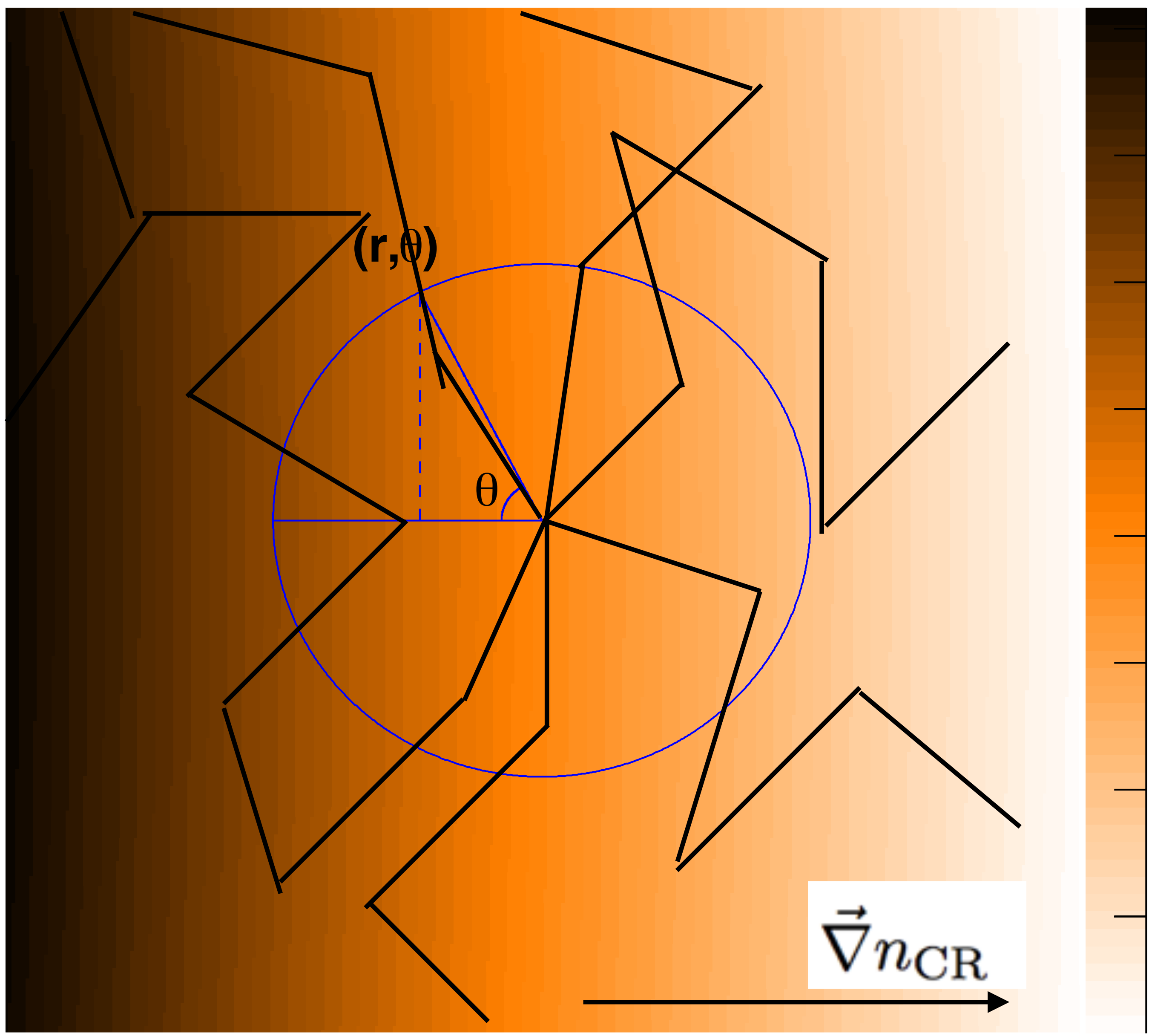
➡ Loss of sensitivity
➡ Loss of the a_{l0} moments
➡ Loss of the declination component of the dipole

Diffusion des rayons cosmiques Galactiques



Diffusion = Dipole anisotropy

$$|\delta| = \frac{\phi_{\max} - \phi_{\min}}{\phi_{\max} + \phi_{\min}} = \frac{\phi(\vec{r}+\vec{\lambda}) - \phi(\vec{r}-\vec{\lambda})}{\phi(\vec{r}+\vec{\lambda}) + \phi(\vec{r}-\vec{\lambda})} \simeq \frac{2\lambda|\nabla\phi(\vec{r})|}{2\phi(\vec{r})} = \frac{3D}{c}\frac{|\nabla\phi(\vec{r})|}{\phi(\vec{r})}$$

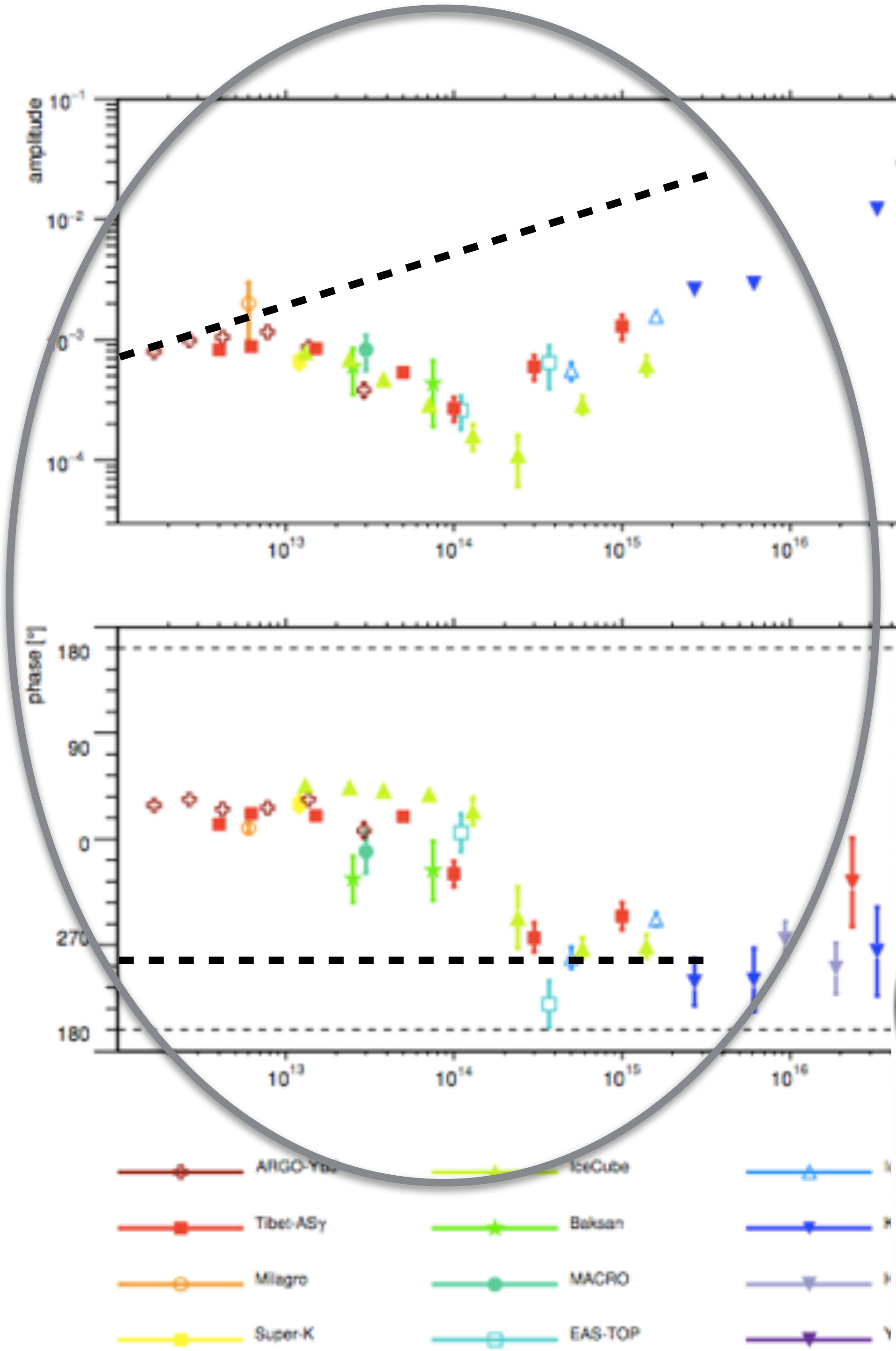


$$\vec{\delta} = \frac{3D}{c}\frac{\vec{\nabla} n_{\rm CR}}{n_{\rm CR}}$$

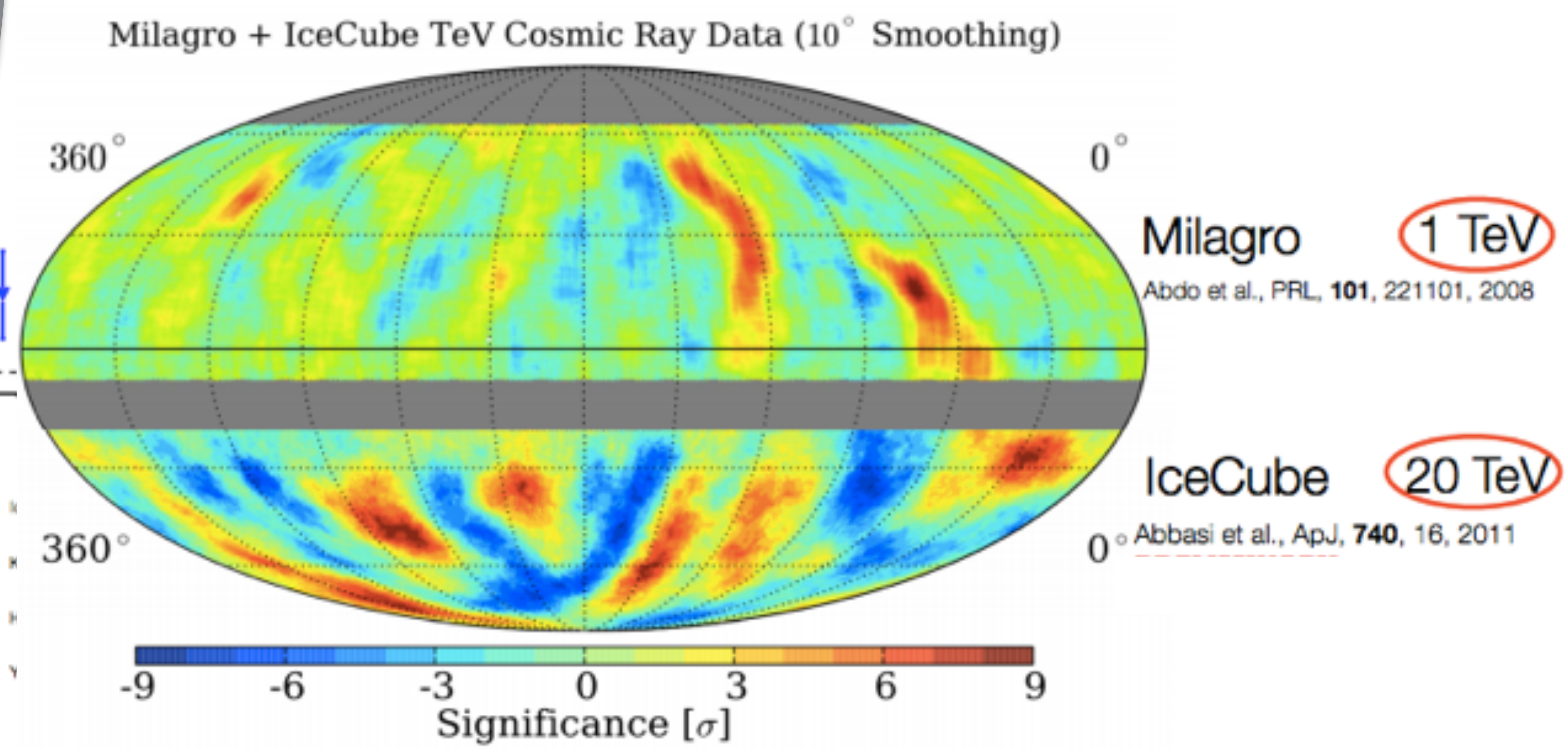
« sources = dipole »

(in average…)

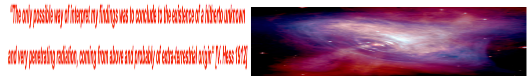
Observations



- Amplitude/direction in disagreement with diffusion ?
- Anisotropies beyond dipole !
  ➡ Much more complex picture



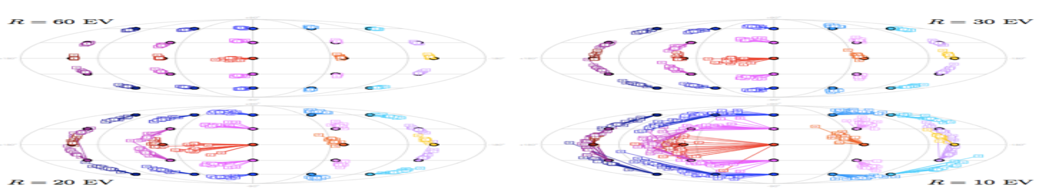
Dipole from anisotropic diffusion

- Liouville: 

- Boltzmann equation for f, considering the fluctuations of the turbulent field as perturbations

- Diffusion approximation ⇒ Fick laws for the moments of f: $$\langle \phi_{1i} \rangle = -\frac{1}{c} D_{ij} \frac{\partial \langle \phi_0 \rangle}{\partial x_j}$$

  ➡ Anisotropic diffusion:



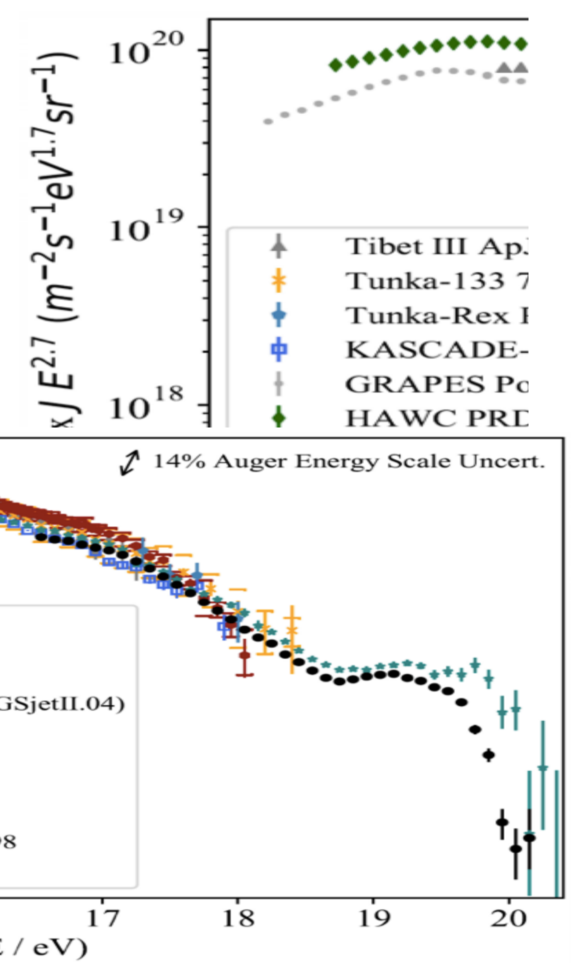
$$\vec{\delta} = \frac{3D}{c} \frac{\vec{\nabla} n_{\mathrm{CR}}}{n_{\mathrm{CR}}}$$

- Larmor radius much smaller than the coherence scale of the local **B**

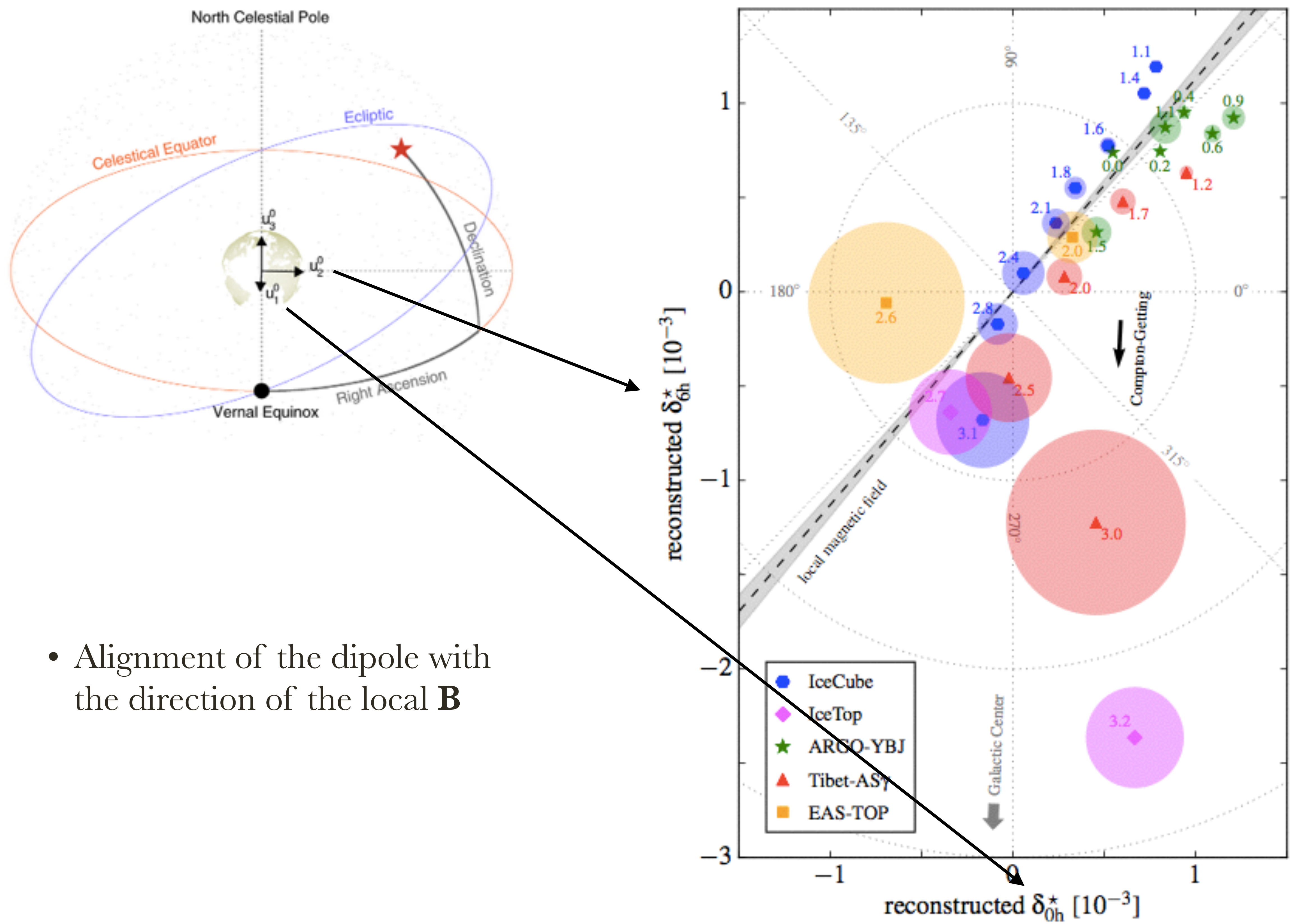
  - Diffusion tensor dominated by the first term

  - Projection of the gradient of density along the local **B**

[Ahlers 2016]



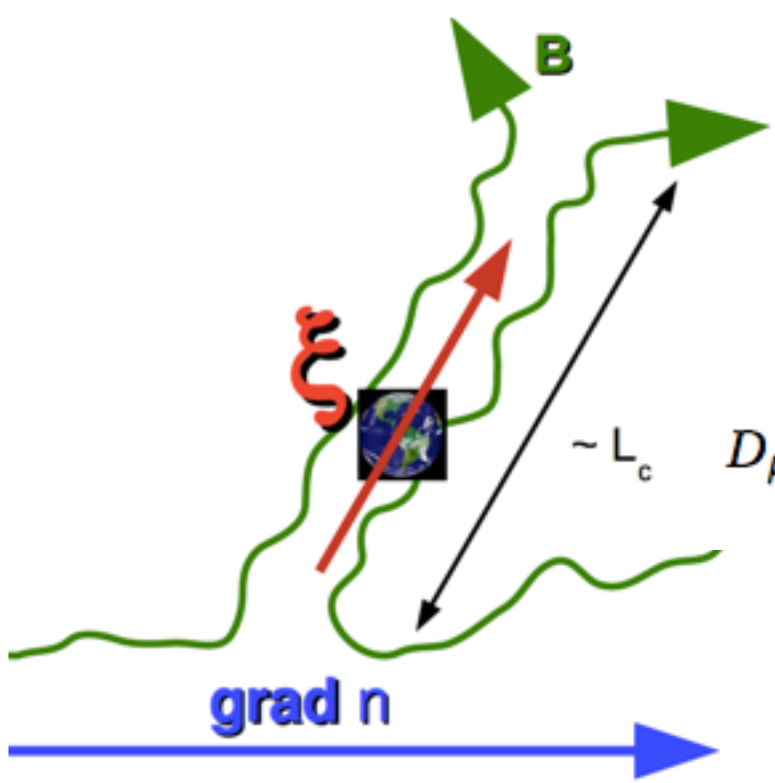
Signature of local environment?



- Alignment of the dipole with the direction of the local **B**

[Ahlers'2016]

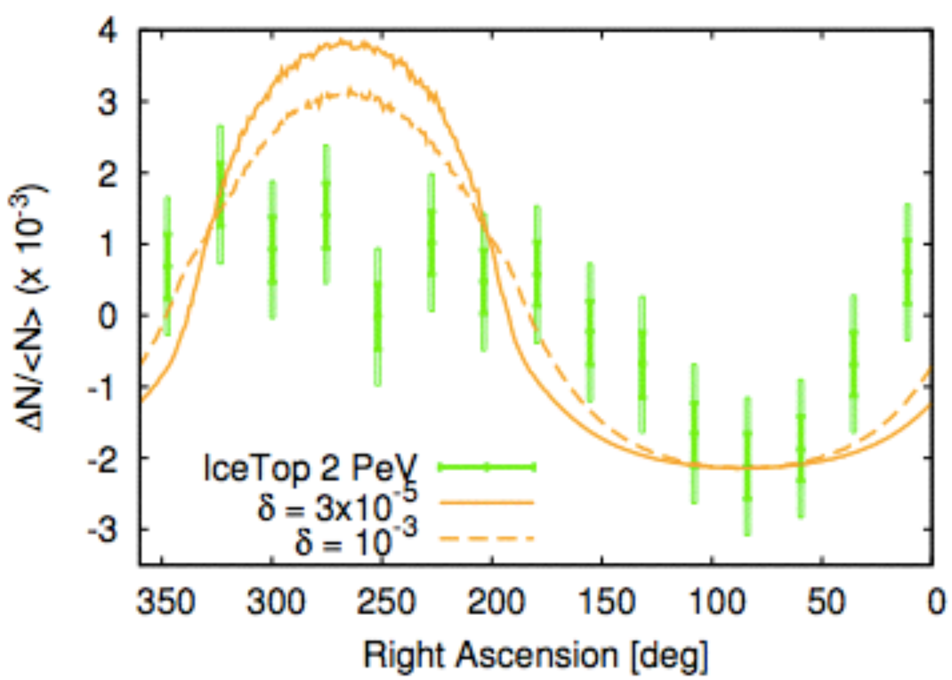
Constraining the local turbulence with dipole anisotropy?

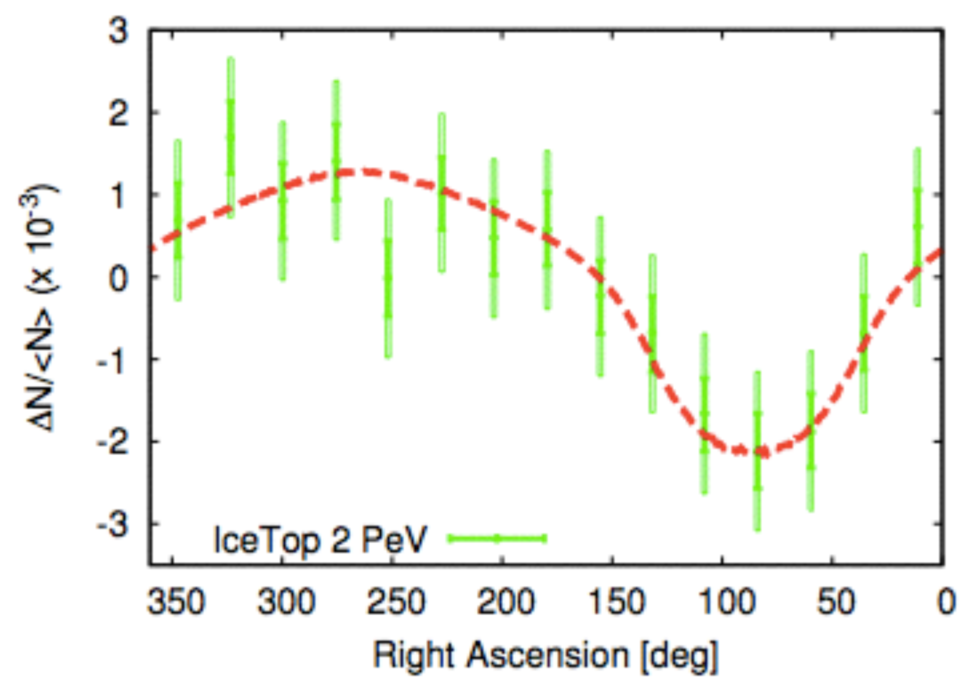


- Dipole shaped by local turbulence? [Giacinti & Kirk, 2017]
- Hyp. : turbulence scale ~ 10 parsecs
- Fokker-Planck formalism — diffusion coeff. related to the turbulence characteristics:

$$D_{\mu\mu} = \langle\omega\rangle^2(1-\mu^2)\int \mathbf{dk} \sum_{n=-\infty}^{\infty}\left(\frac{n^2 J_n^2(u)}{u^2}\mathscr{I}_{\mathrm{A}}(\mathbf{k}) + \frac{k_\parallel^2 J_n'^2(u)}{k^2}\mathscr{I}_{\mathrm{S,F}}(\mathbf{k})\right) R_n(k_\parallel v_\parallel - \Omega + n\langle\omega\rangle),$$

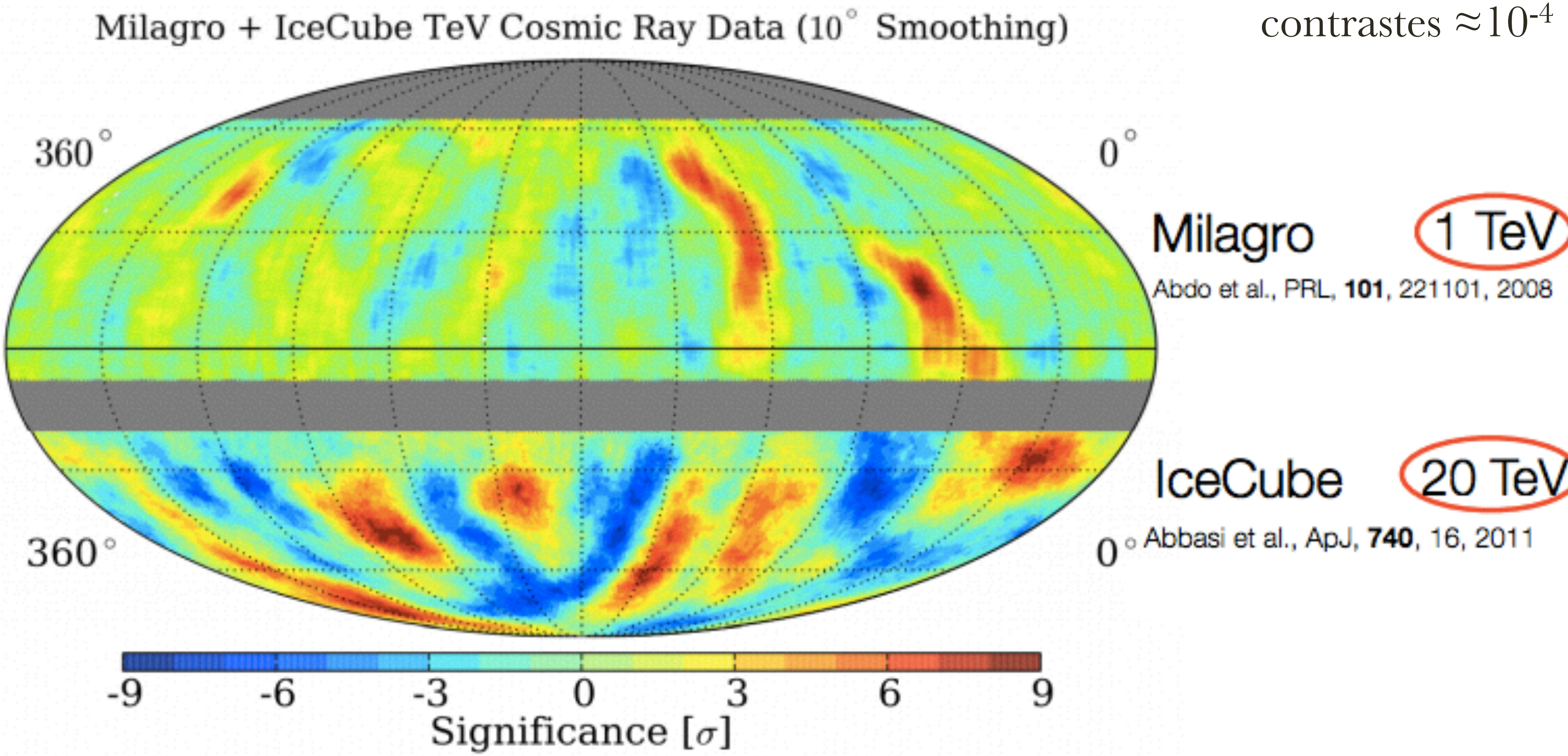
- Anisotropy non-exactly dipolar: $g(\mu) = -\frac{c}{2}\int_0^\mu \mathrm{d}\mu' \frac{1-\mu'^2}{D_{\mu'\mu'}}.$





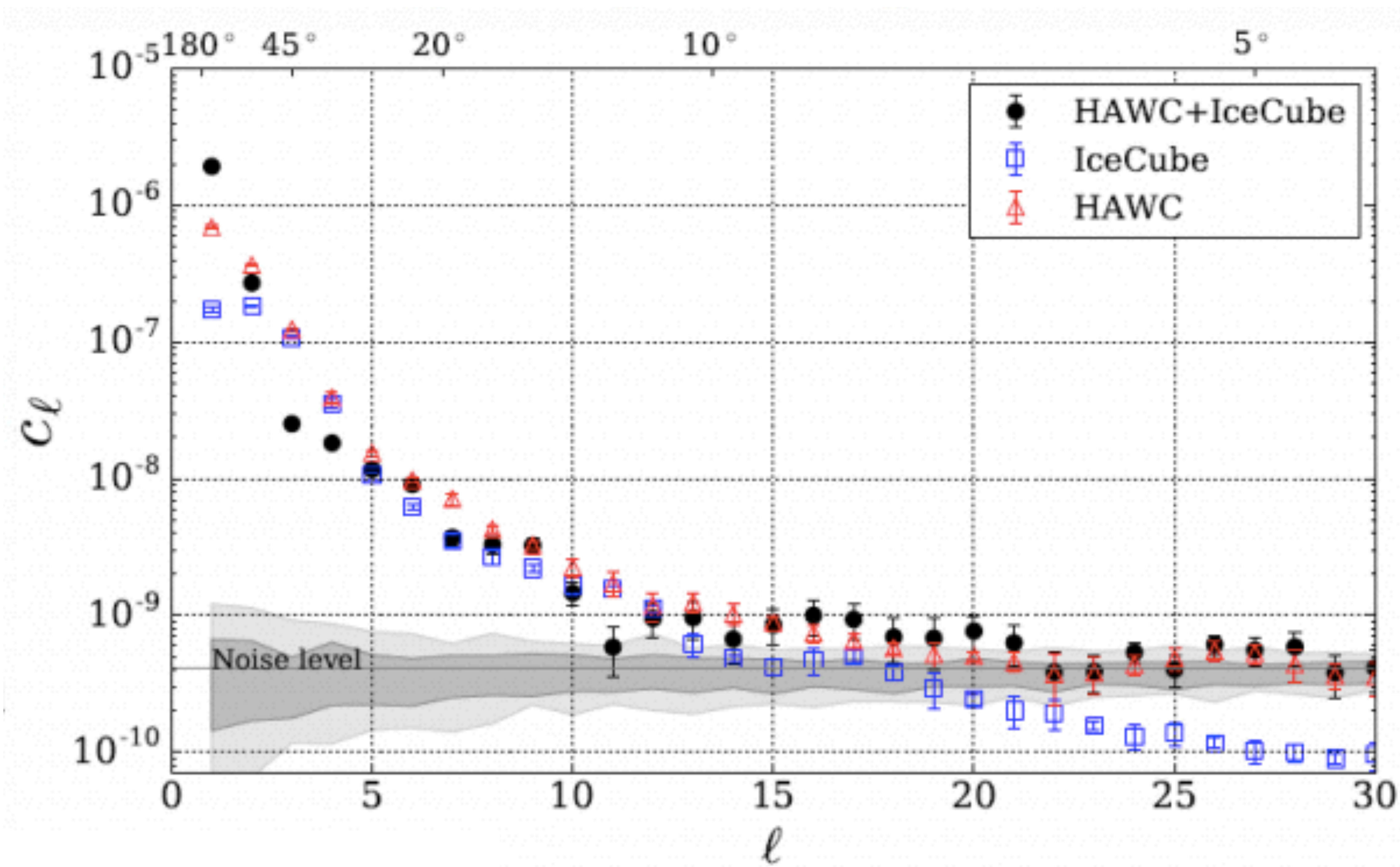
➡ Anisotropic power spectrum and broad resonance fonction preferred (incompressible turbulences)

Beyond the dipole



contrastes $\approx 10^{-4}$

Angular power spectrum



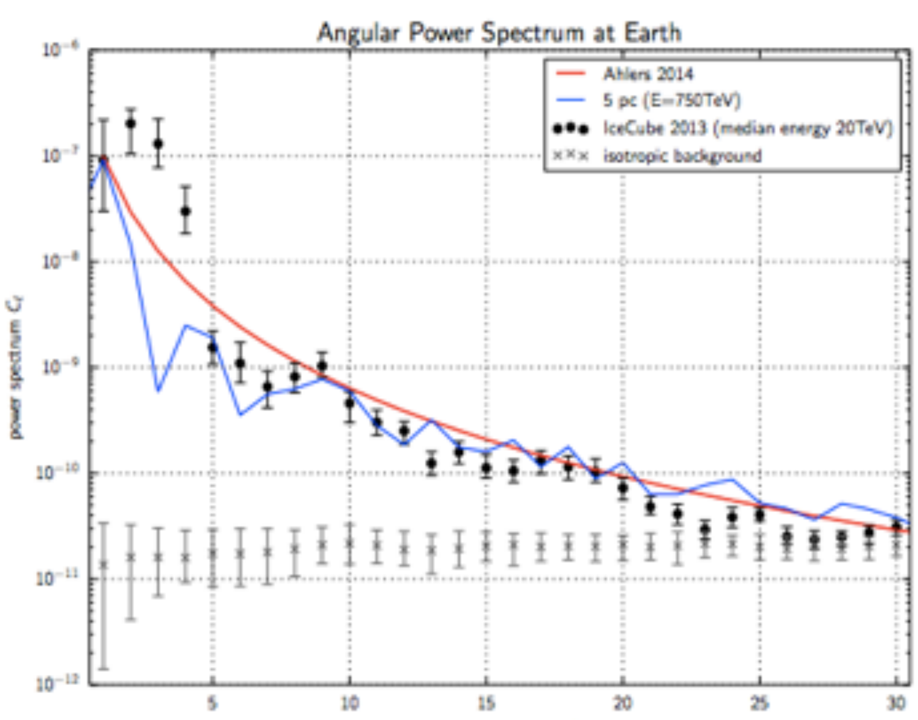
Last diffusion scattering sphere

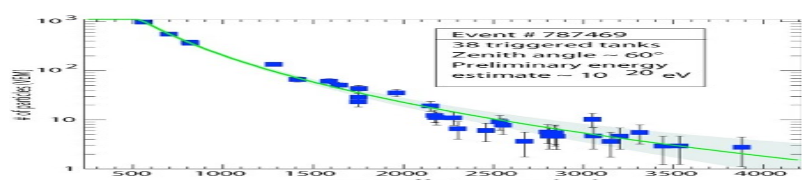
Probing the last diffusion scattering of an individual turbulence (no averaging process)
[Giacinti & Sigl, 2012, also Ahlers 2014]

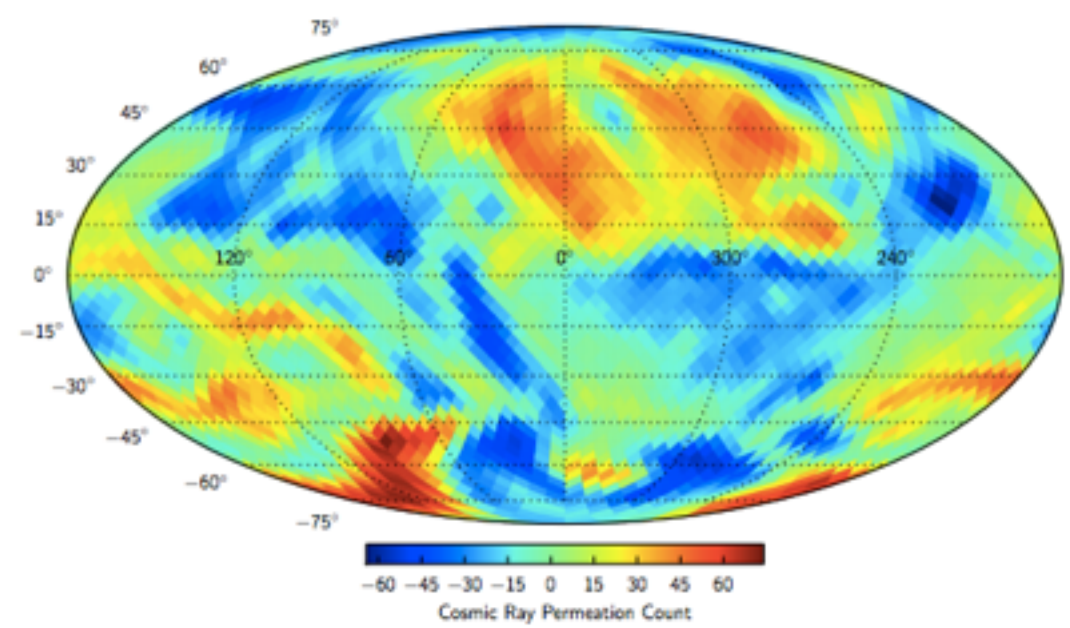
- Standard diffusion: $C_\ell^{\text{std}} = \frac{1}{4\pi}\int d\hat{\mathbf{p}}_1 \int d\hat{\mathbf{p}}_2\, P_\ell(\hat{\mathbf{p}}_1\hat{\mathbf{p}}_2)\langle f(\hat{\mathbf{p}}_1)\rangle\langle f(\hat{\mathbf{p}}_2)\rangle$
- Individual realization: $\langle C_\ell\rangle = \frac{1}{4\pi}\int d\hat{\mathbf{p}}_1 \int d\hat{\mathbf{p}}_2\, P_\ell(\hat{\mathbf{p}}_1\hat{\mathbf{p}}_2)\langle f(\hat{\mathbf{p}}_1) f(\hat{\mathbf{p}}_2)\rangle$

[Ahlers, Mertsch'2015]

- Boltzmann equation for *ff* for a configuration prepared in a dipolar state by diffusion:



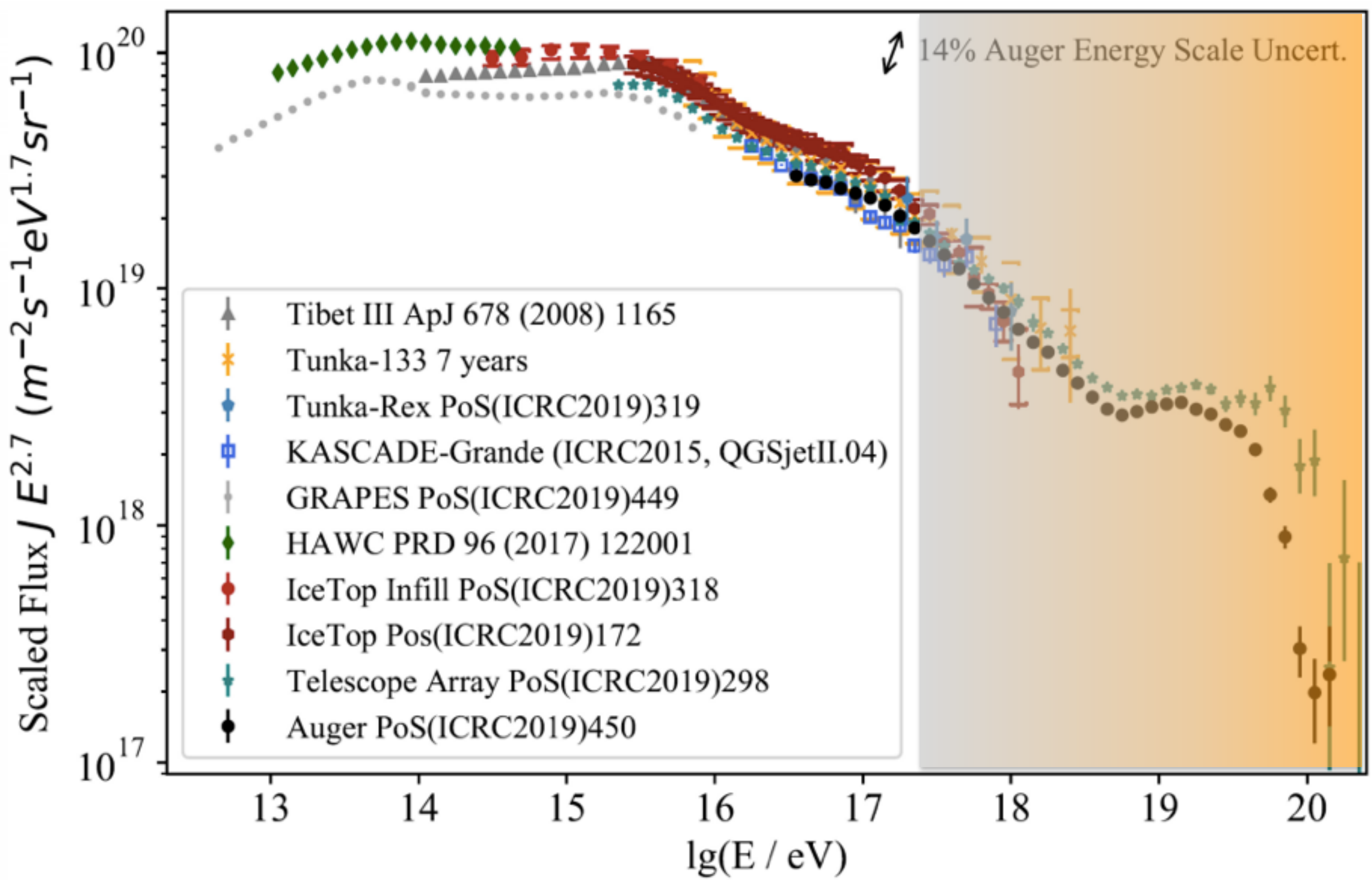




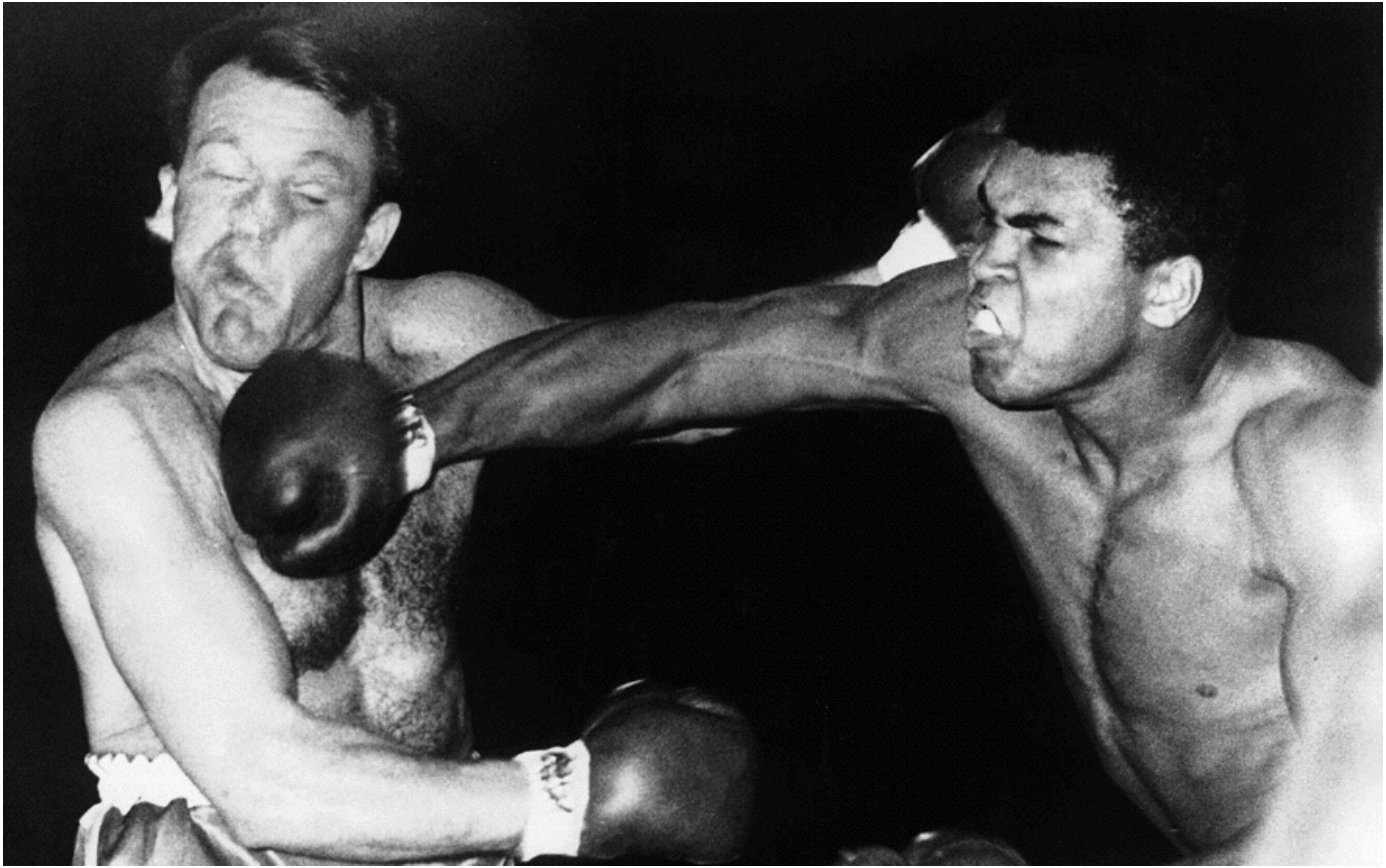
[López-Barquero+ 2016]

iv) Extragalactic cosmic rays

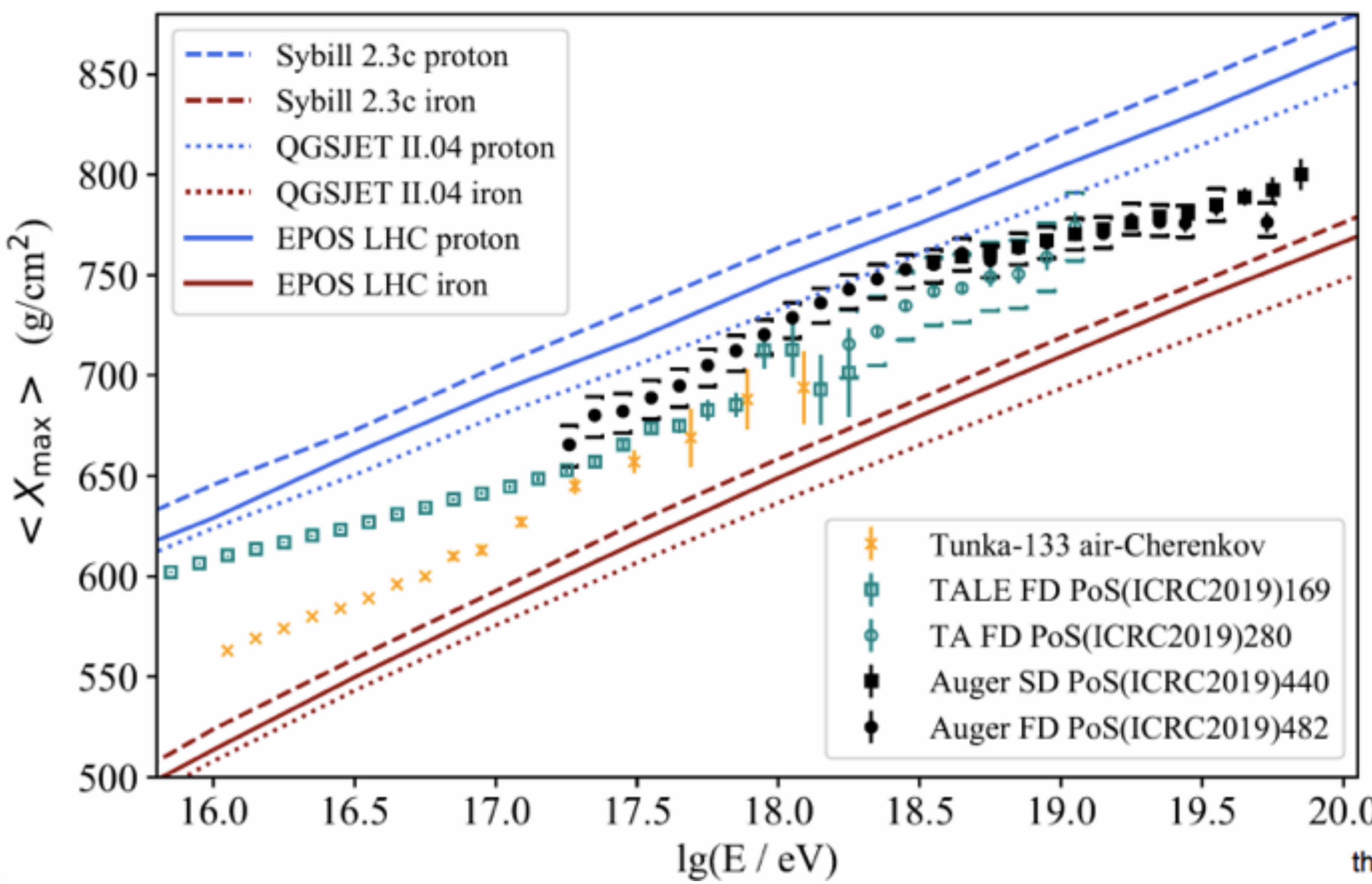
Extragalactic cosmic rays



10^{20} eV !



X_{max} from fluorescence, air-Cherenkov, rise time



[Compilation: F. Schroder]

Caveats:

energy scale uncertainties

some experiments have acceptance biases, but model lines are without bias

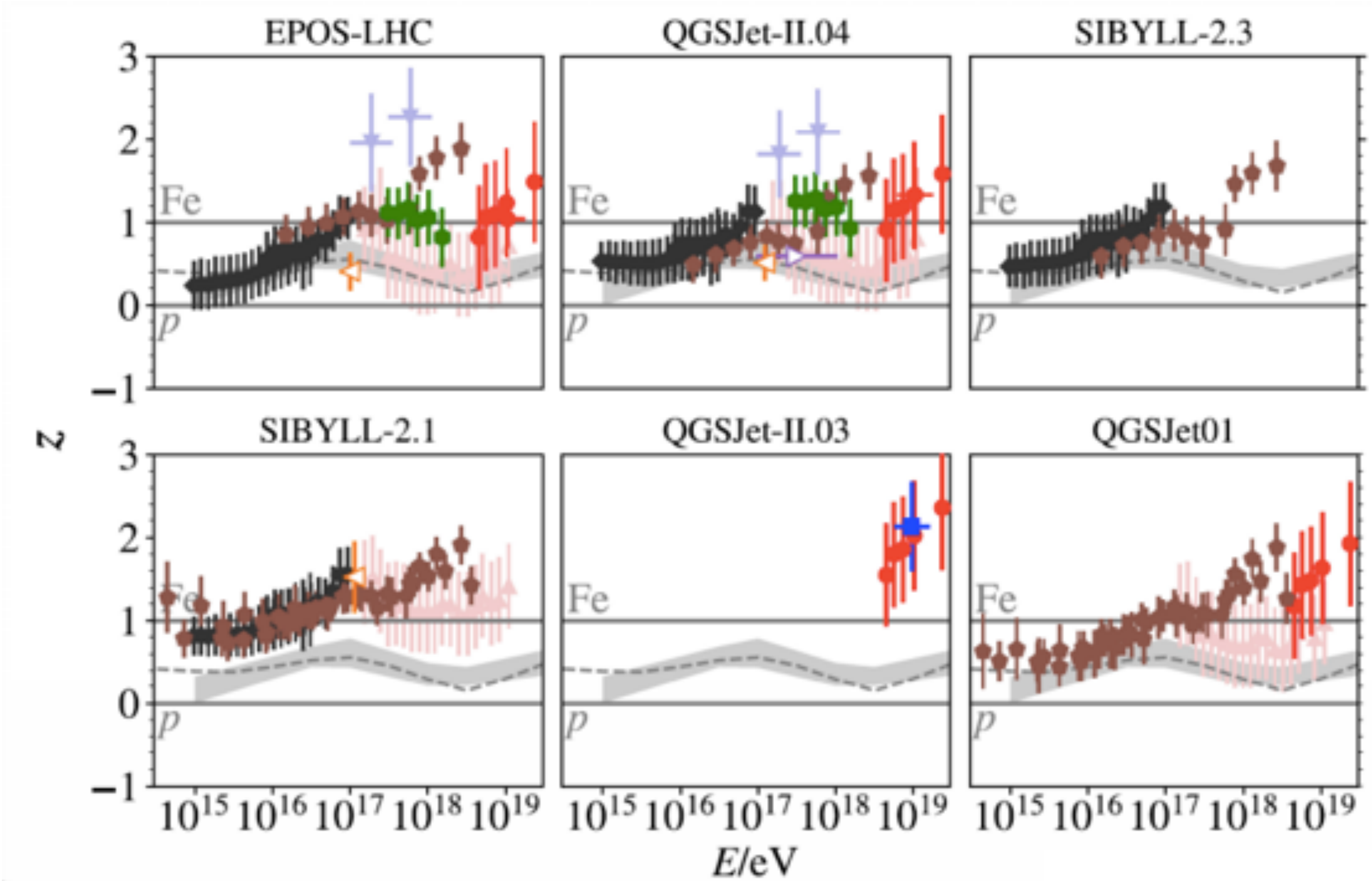
TA acceptance bias: 11 g/cm^2

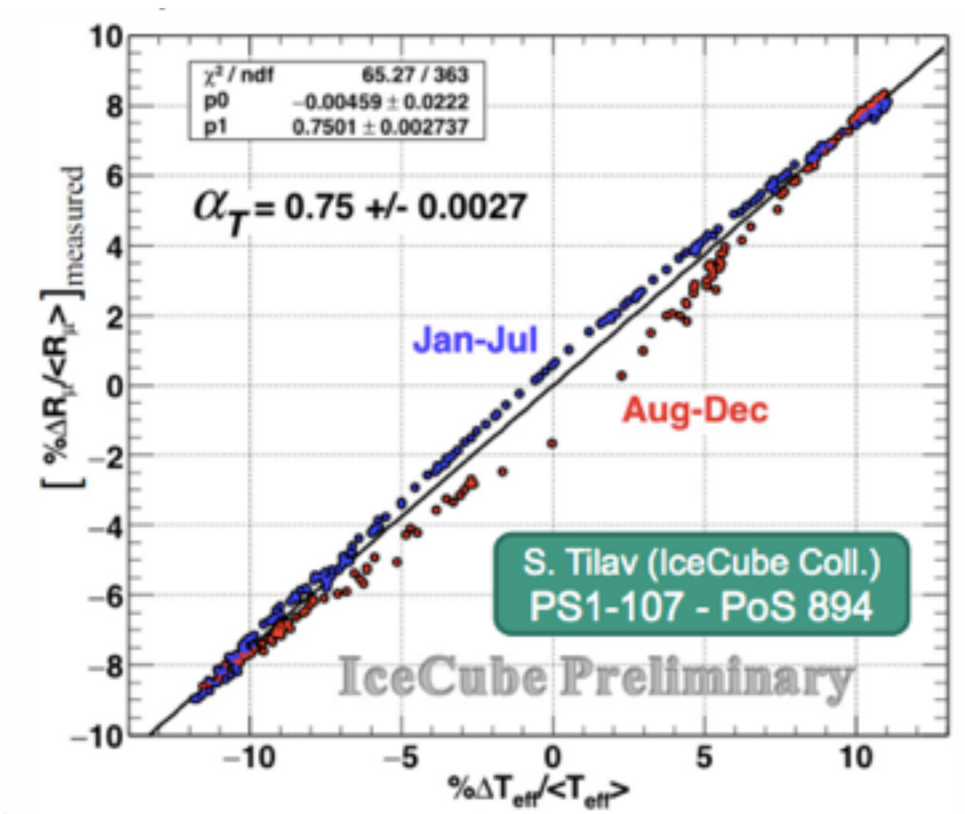
TALE bias not fully known

Tunka-133 biases and systematics not fully known

thanks to T. Pierog for model X_{max} values

Hadronic interaction models: X_{max} vs N_μ





[Cazon+ 2019]

- μ content stems from a multi-step cascade process, mostly driven by interactions of secondary pions and kaons with air

➡ properties of pion-air collisions over a wide range of energies

- X_{max} depends more strongly on the properties of the primary particle interaction with air nuclei

➡ Inelastic cross section and the forward spectra of the secondaries

➡ Maximally benefit from LHC

- Seasonal variations of muons in IceCube show non-linearity with effective atmospheric temperature

➡ pion-to-kaon ratio in air showers

Extragalactic origin

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

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

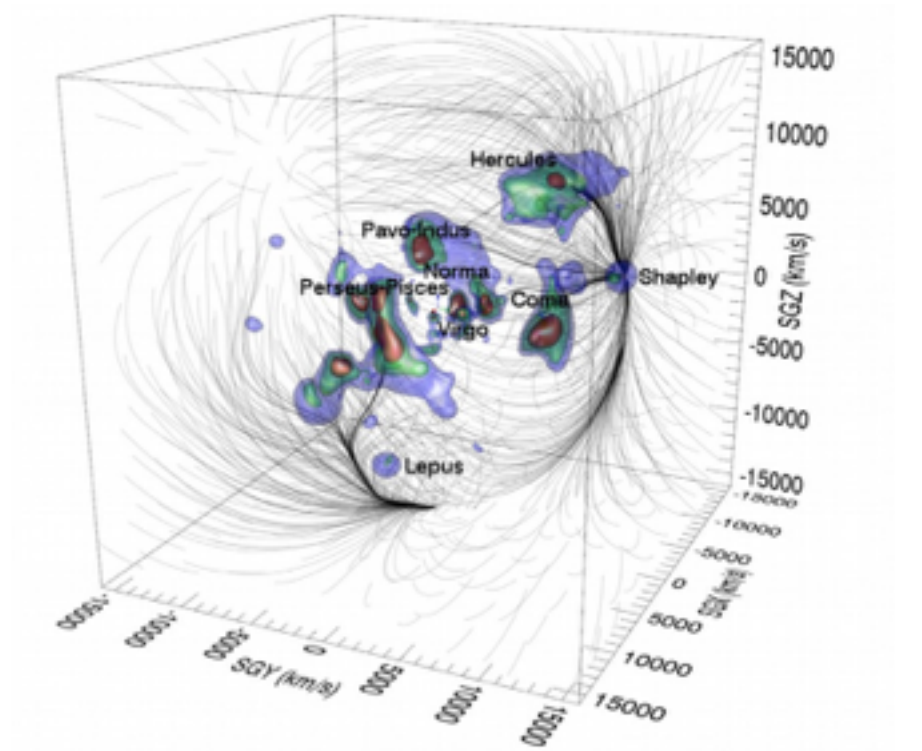
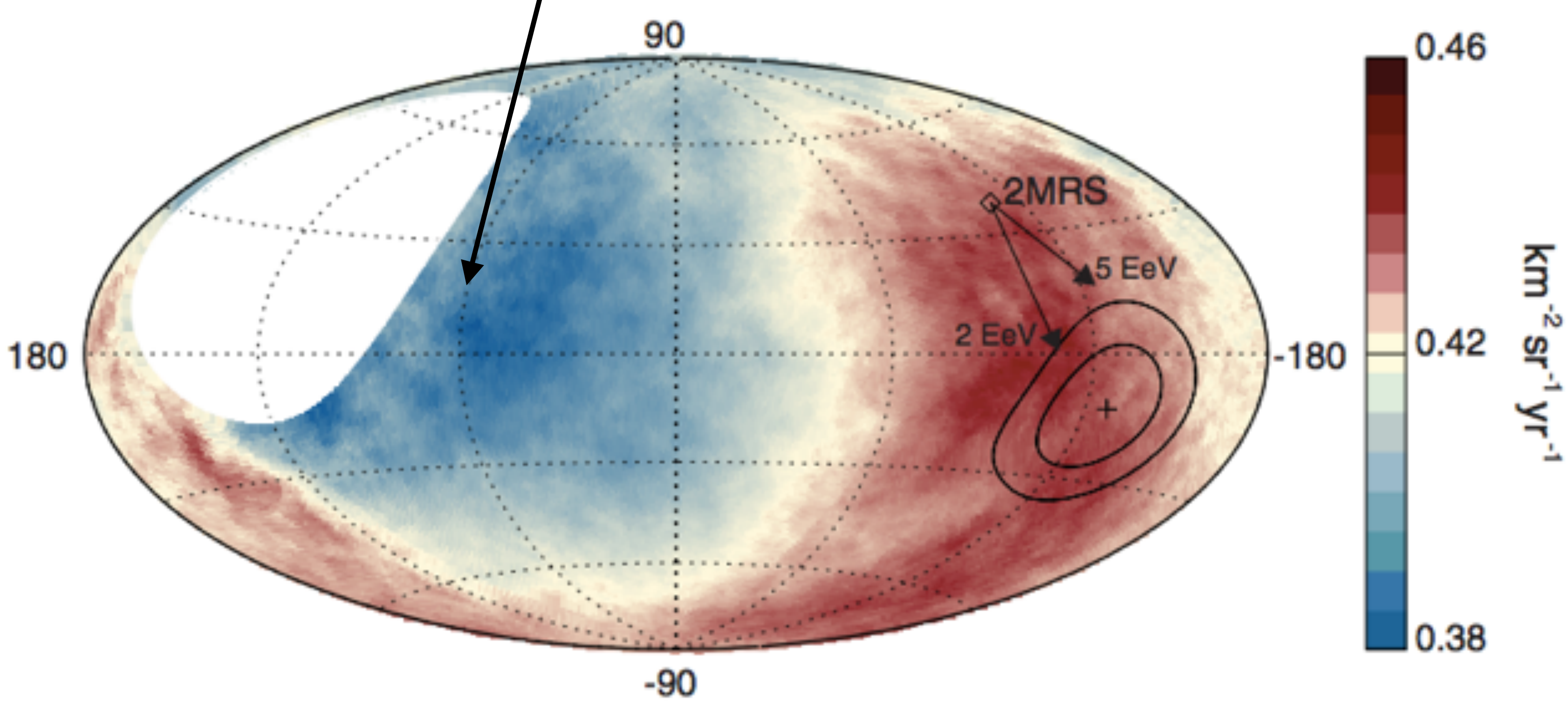


Fig. ED 1. — Structure within a cube extending 16,000 km s^{-1} (~200 Mpc)

Tully, Courtois, Hoffman, Pomarède, Nature 2014

Direction of the local void



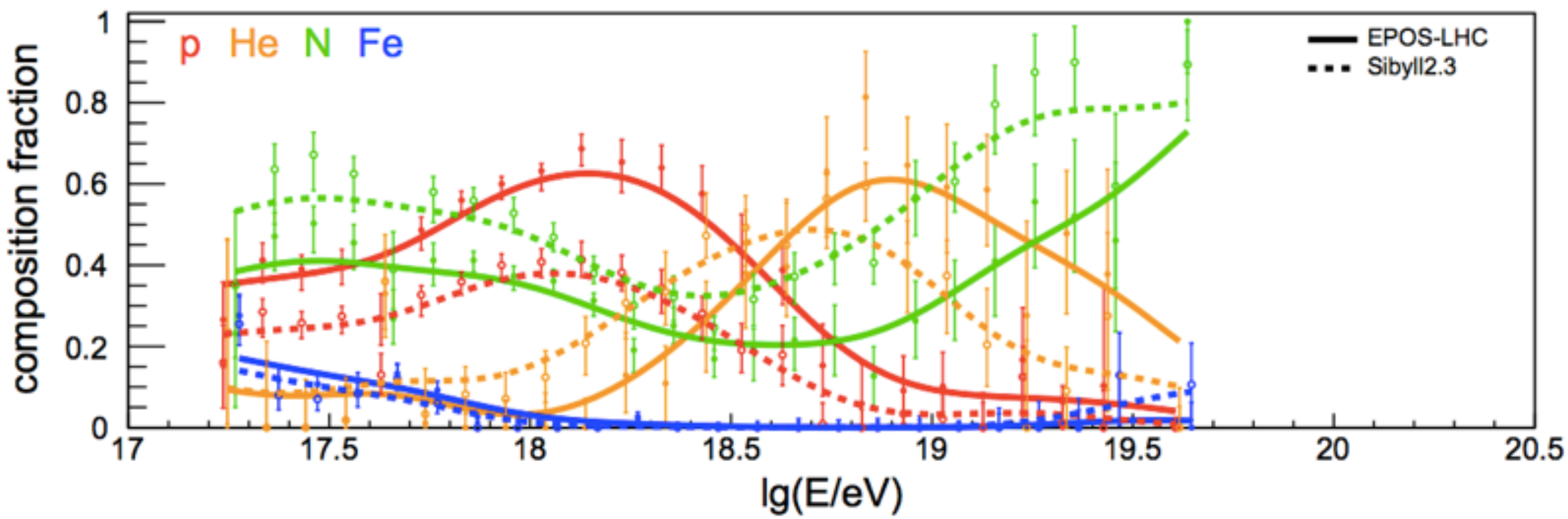
Accounting GMF deflections

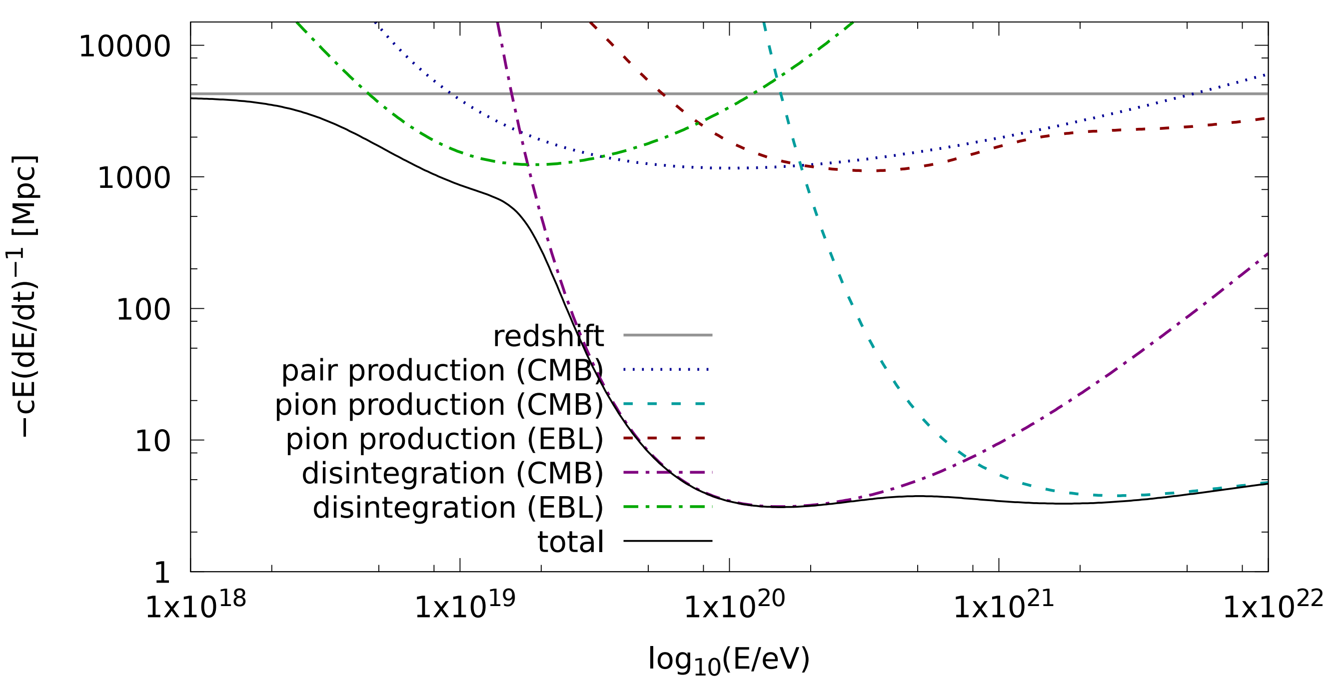
[Jansson and Farrar ApJ 757 (2012) 14]

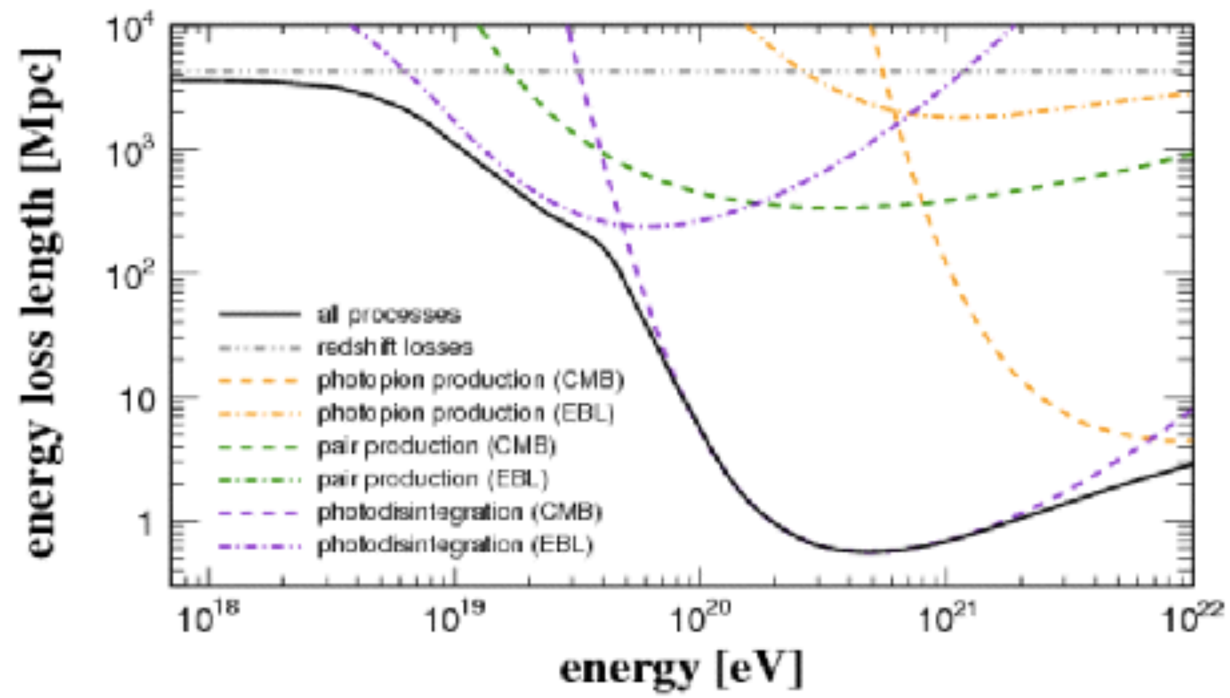
Z ~ 1.7 – 5 at 10 EeV ⟶ E/Z ~ 2 – 5 EeV

[Auger Coll. PRD 90 (2014) 122006]

Composition and horizons at UHE







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

☞ Limited horizons @ 30-40 EeV

Extragalactic gamma-ray sources

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

(leptonic processes preferred)

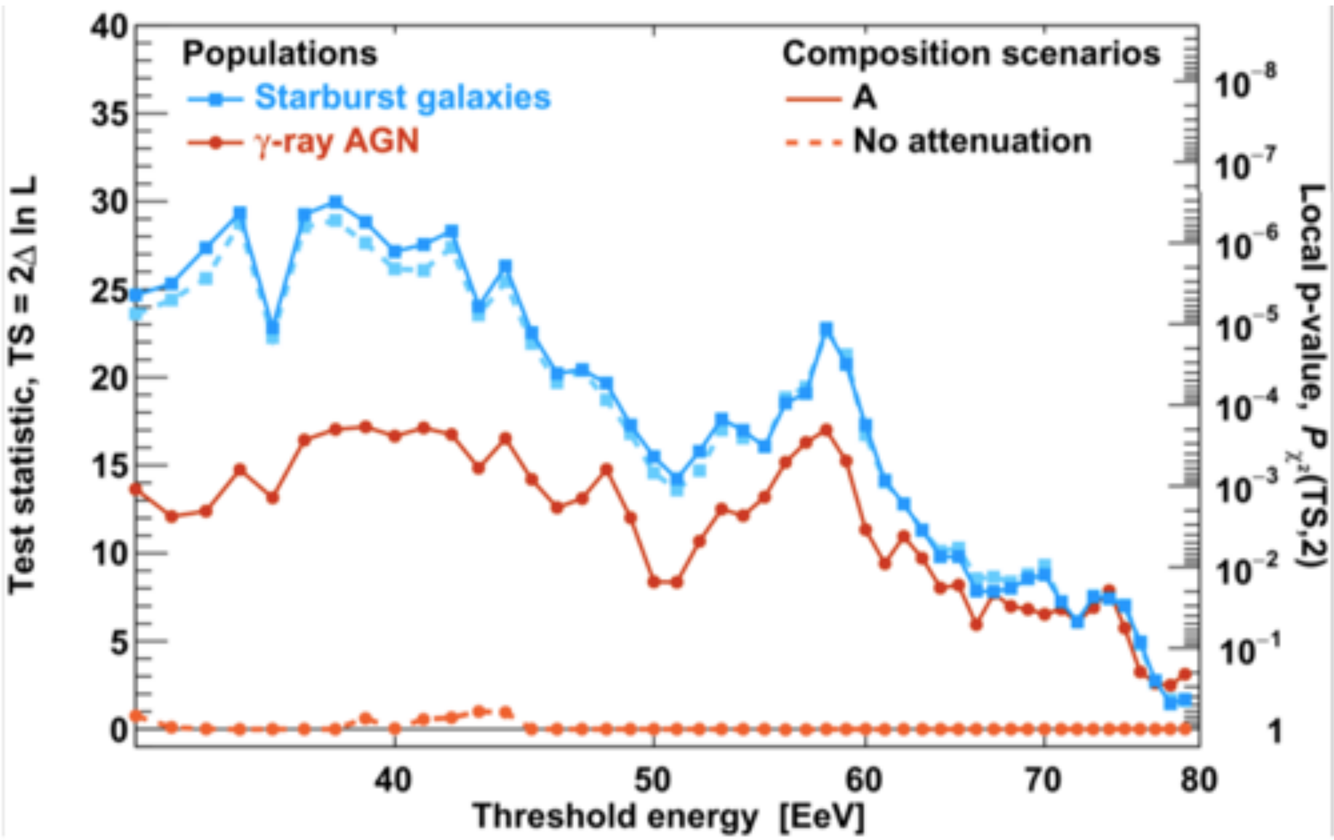
Selection by *Fermi*-LAT
(HCN survey) < 250 Mpc,
flux radio>0.3 Jy [Gao & Salomon, 2005]

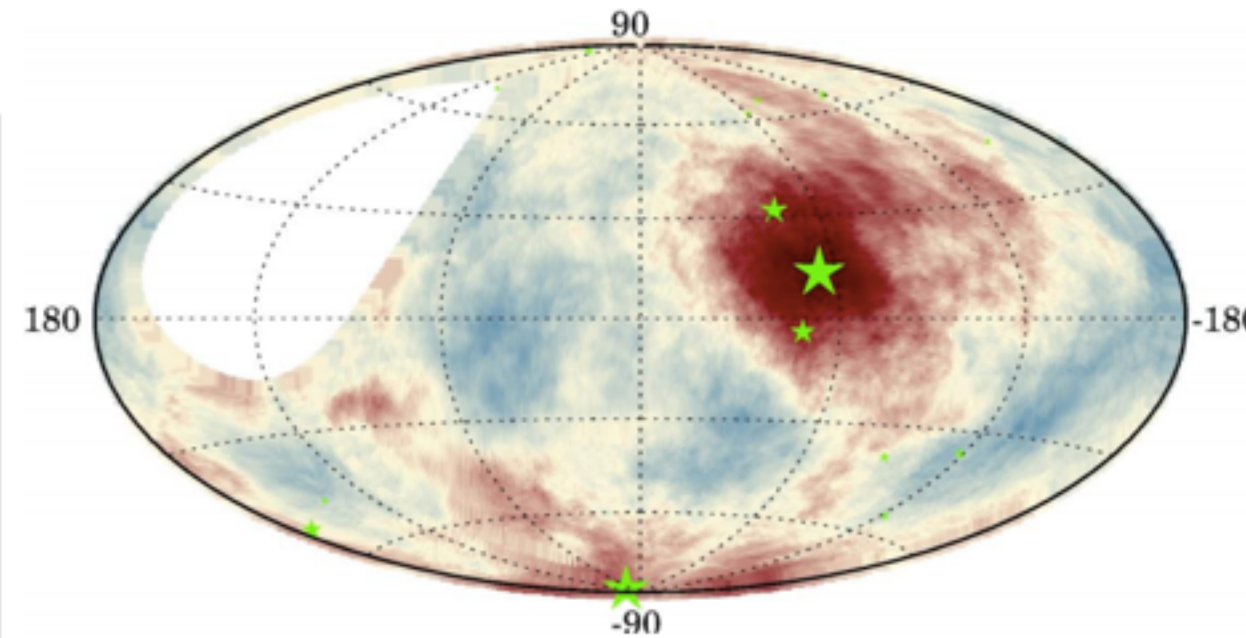
(hadronic processes preferred)

Hypothesis : CR flux ∝ non-thermal flux of photons

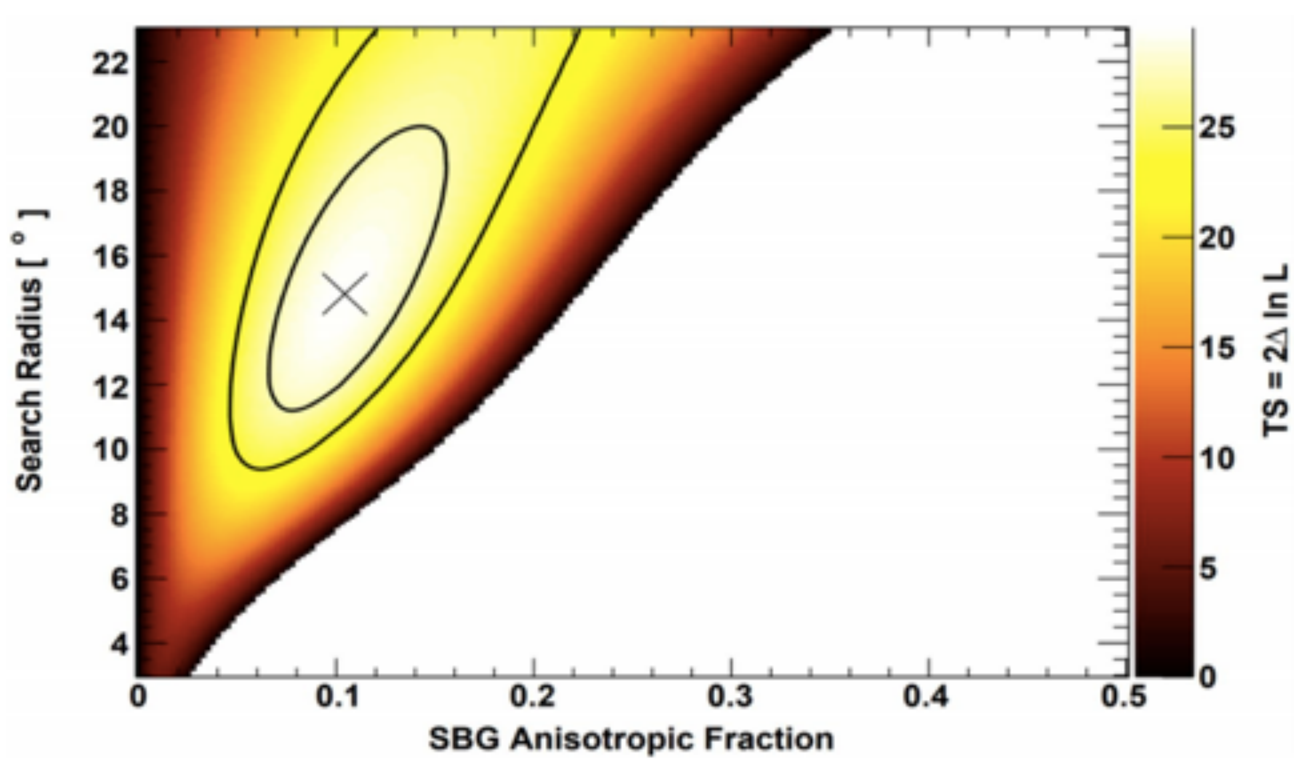
➡ Calorimetric argument: natural for environments such that starburst galaxies

Best matching: starburst galaxies





Post-trial significance: 4.5σ

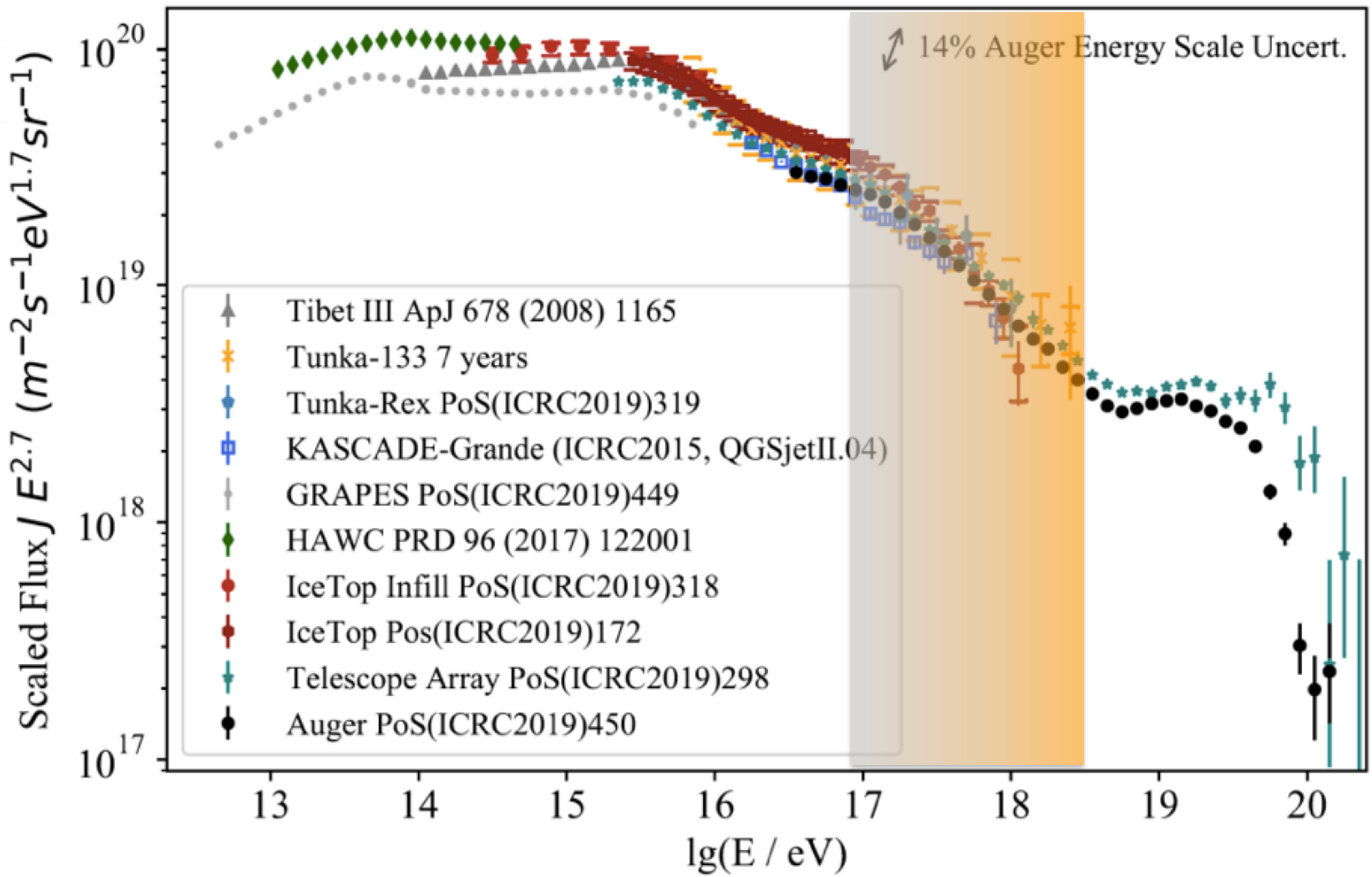


- SBGs : higher rate of cataclysmic events (GRBs, hypernovas, magnetars)
- Transient sources in all galaxies, SBGs being a good tracer of the proportionality between SFR and CR production?

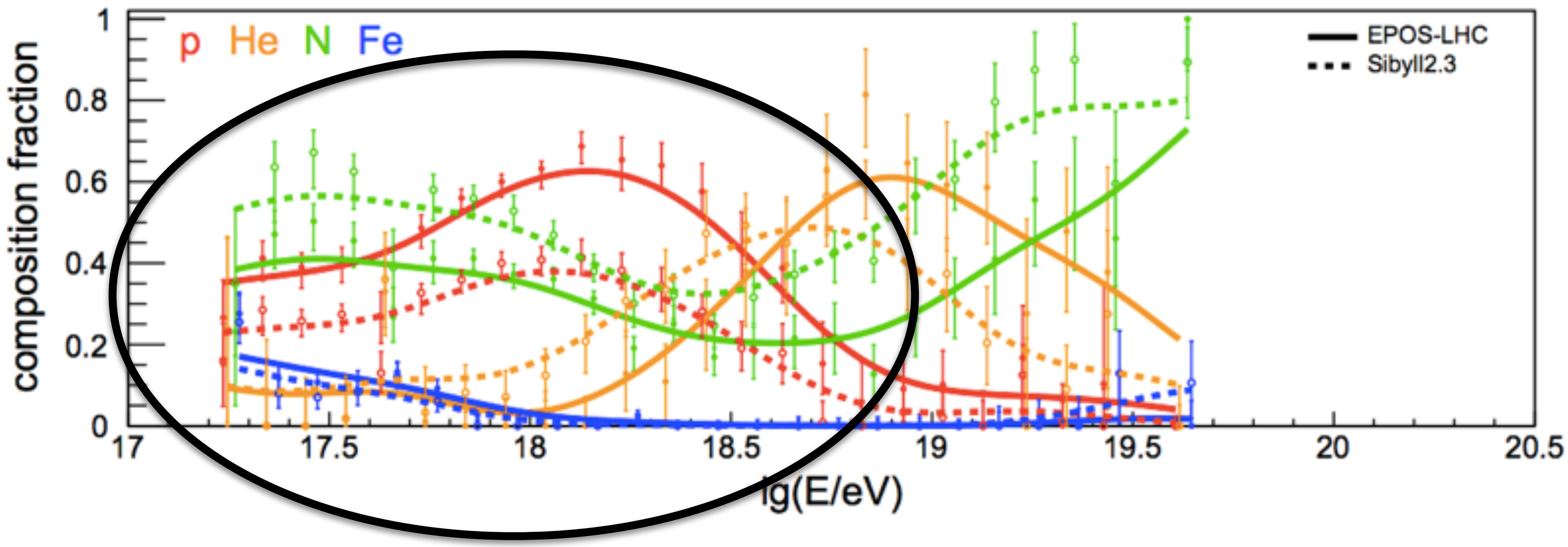
[Auger Collab. 2019]

v) Galactic/extragalactic cosmic rays

Galactic/extragalactic cosmic rays



SNRs > 10^{17} eV?

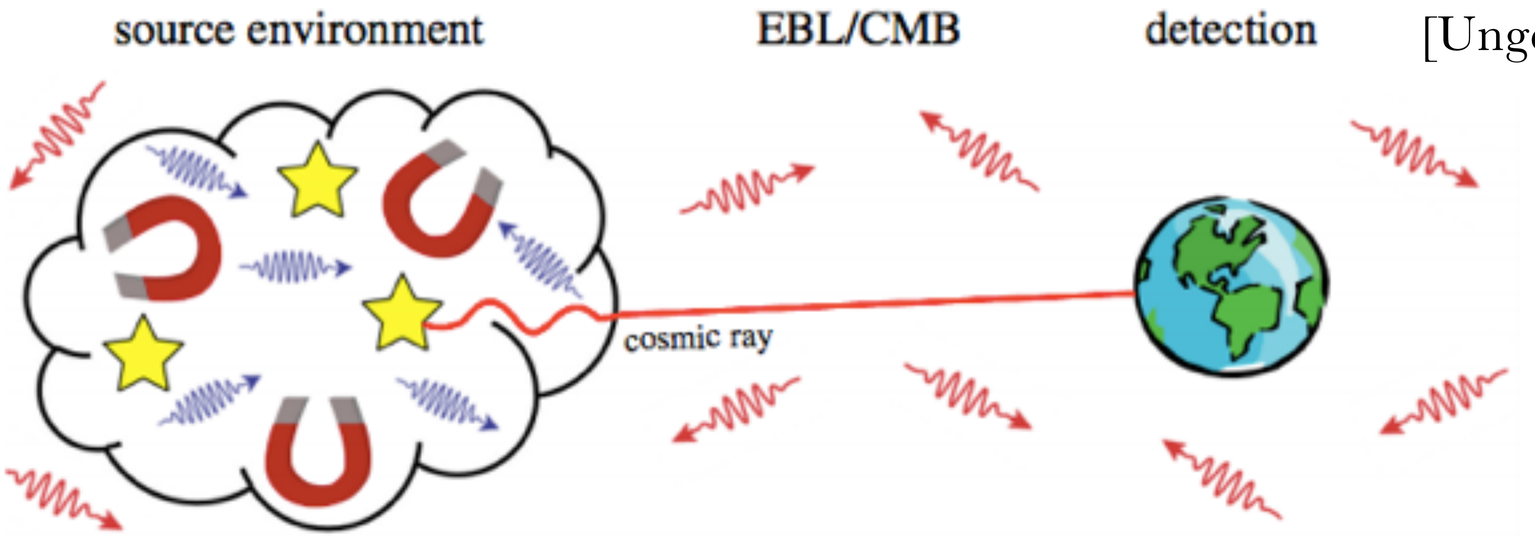


SNR paradigm : $T_{\max} \sim 3Z\, 10^{15}$ V

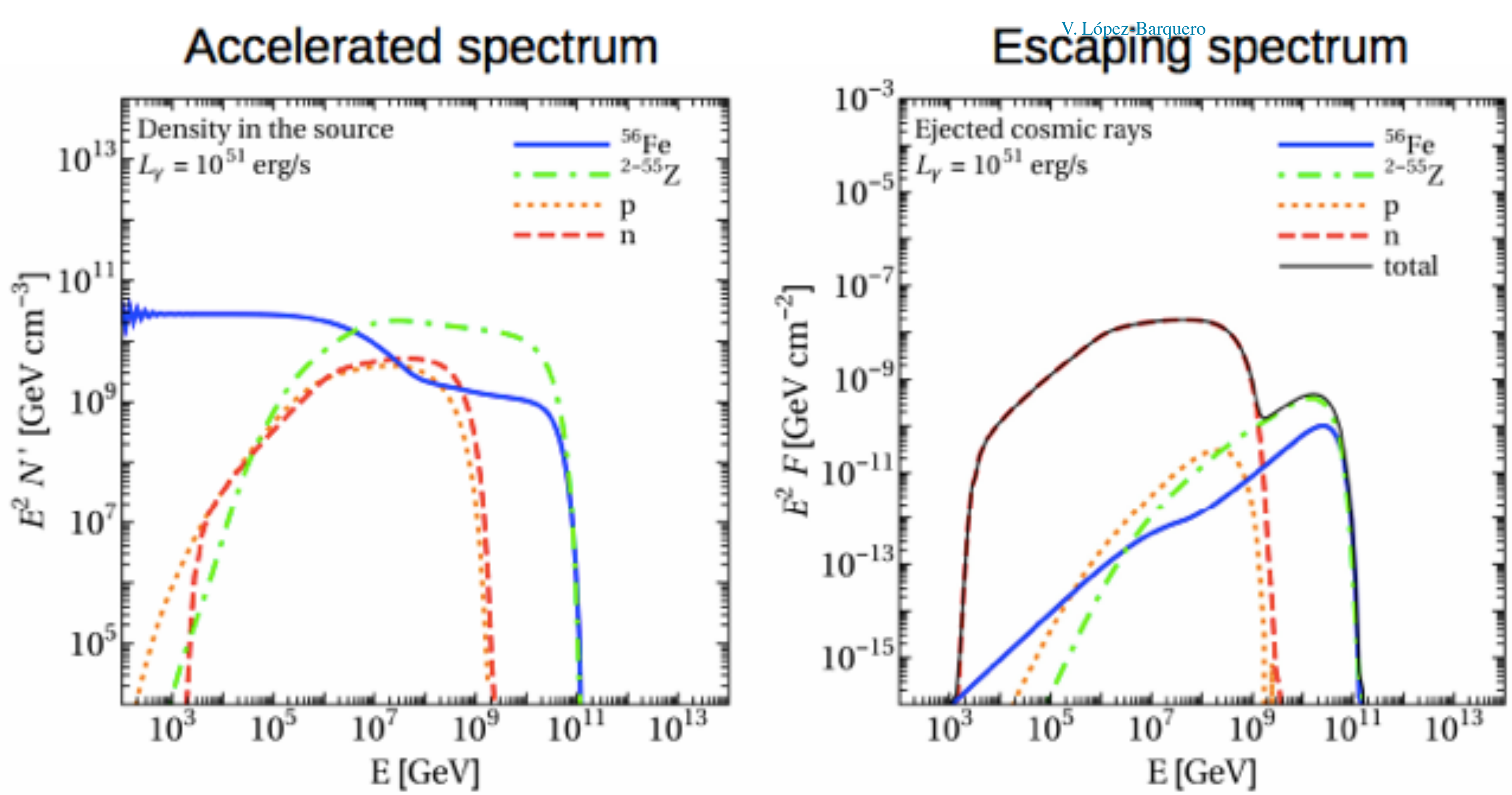
+ No Fe <10^{18} eV

- p, He, CNO components?

Extragalactic protons below the ankle energy



[Unger+ 2015]

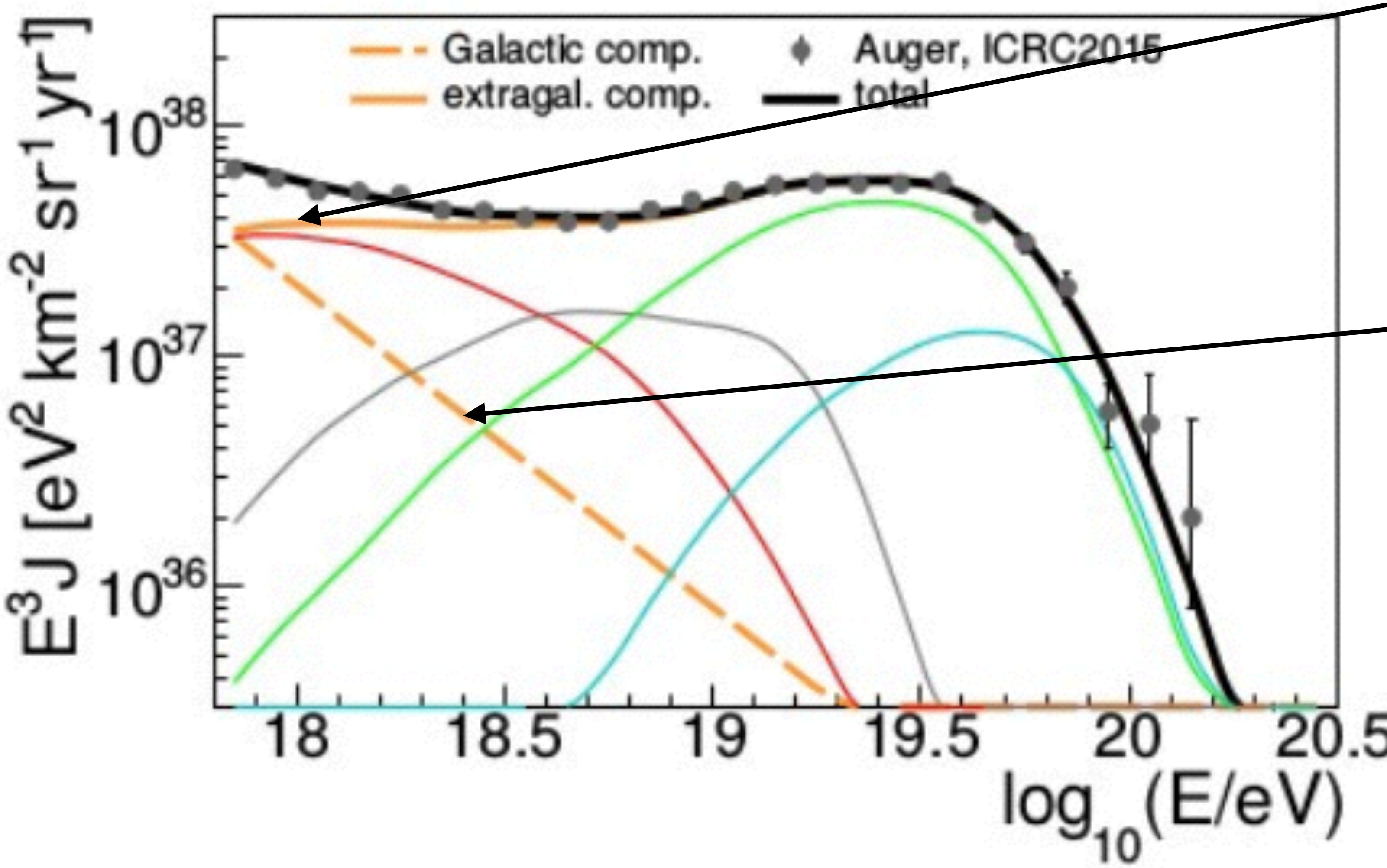


Source environments such that:

- 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]

Hillas' B component?



[Biehl+ 2018]

Extragalactic protons (in line with low anisotropies)

Hillas' B component:

Galactic « remnant » of a UHE transient event in the MW?

Summary

- Dipolar anisotropies fed by cosmic ray density gradient
  - *but* shaped by the local magnetic field
- Anisotropies beyond the dipole moment
  - due to the turbulence realization in the last scattering sphere
  - ➡ CR = tool to probe the local turbulence
- Extragalactic origin at UHE
  - Best tracer: starburst galaxies
  - Uncertainties on mass composition due to lack of knowledge in pion interactions