Highest Energy Cosmic Rays as Messengers of the Mirror World

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in collaboration with

Z. Berezhiani and R. Biondi

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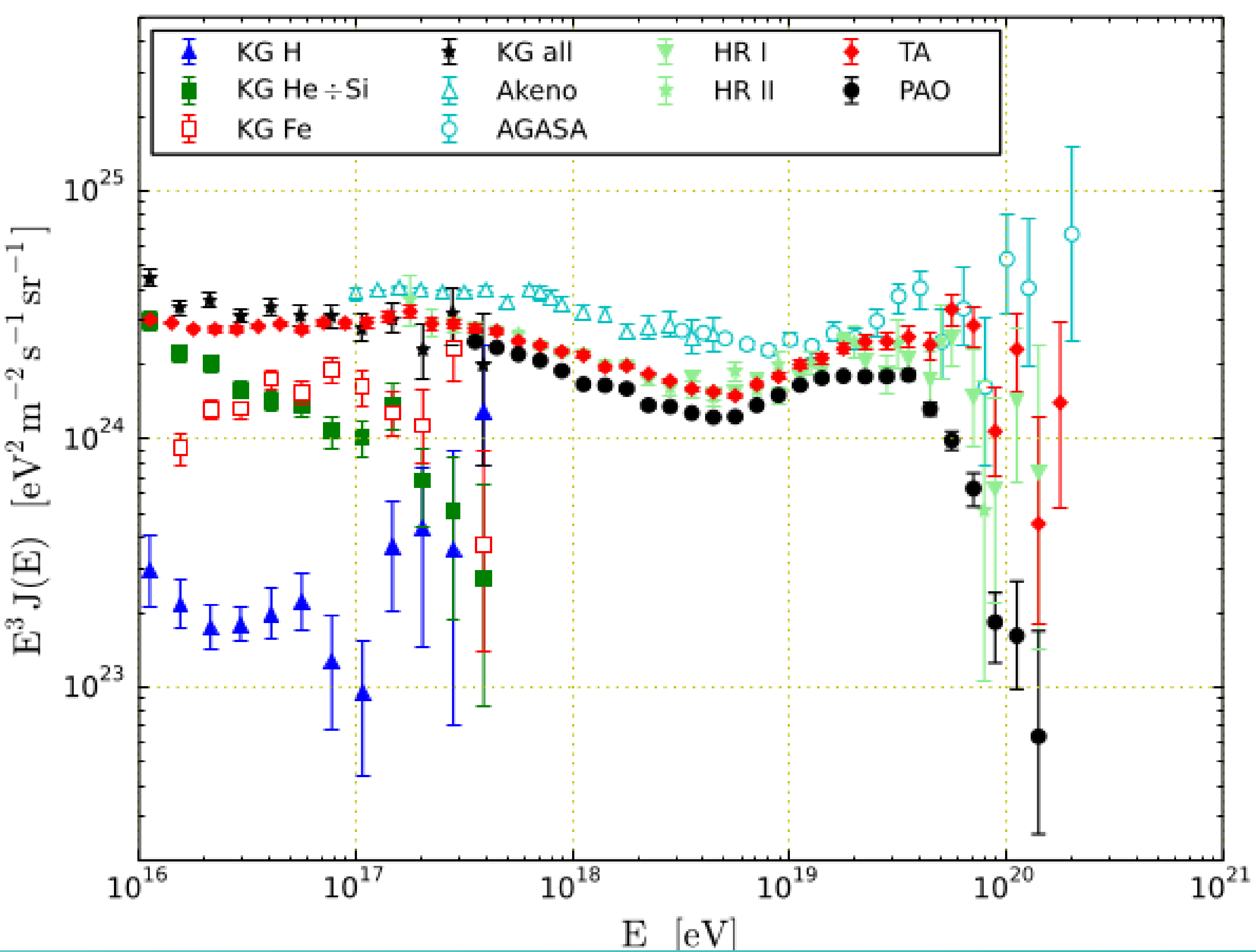
Problems

- Sources of *UHECRs*.
  Acceleration up to *E>100 EeV*.
  Lack of point-like ones close to the Earth (especially with $E > E_{GZK}$).
  Anisotropy of arrival directions is small. Strong magnetic fields?
- Mass composition of *UHECRs*.
  Protons? **He**? Heavy nuclei up to **iron**? A mixture of *UHE* nuclei?
- Survival on traveling long distances through *CMB* and *EBL*.
  Protons: energy losses due to $p+\gamma \Rightarrow e^{+} + e^{-} + p$ $(\pi^{\pm,0} + X)$
  ⇨ secondary *e.m.*-cascades and high energy ν's .
  Nuclei: photodisintegration $A+\gamma_{CMB} \Rightarrow A'$ mostly via ***GDR*** at $\Gamma_A \sim \frac{E_{GDR}}{k\,T_{CMB}}$.
- Treatment of data (*EAS, muons, radio, neutrinos*).
  MC simulation programs rely on **extrapolations** of hadronic interaction models to very high energies, well beyond the ***LHC*** energy scale. Cross-sections of *πA-* and *KA-*scatterings are important.

Observations: EAS



Detectors:

PAO and TA
HiRes, Akeno, AGASA, Yakutsk, KASCADE, IceTop, EAS-TOP, LHAASO

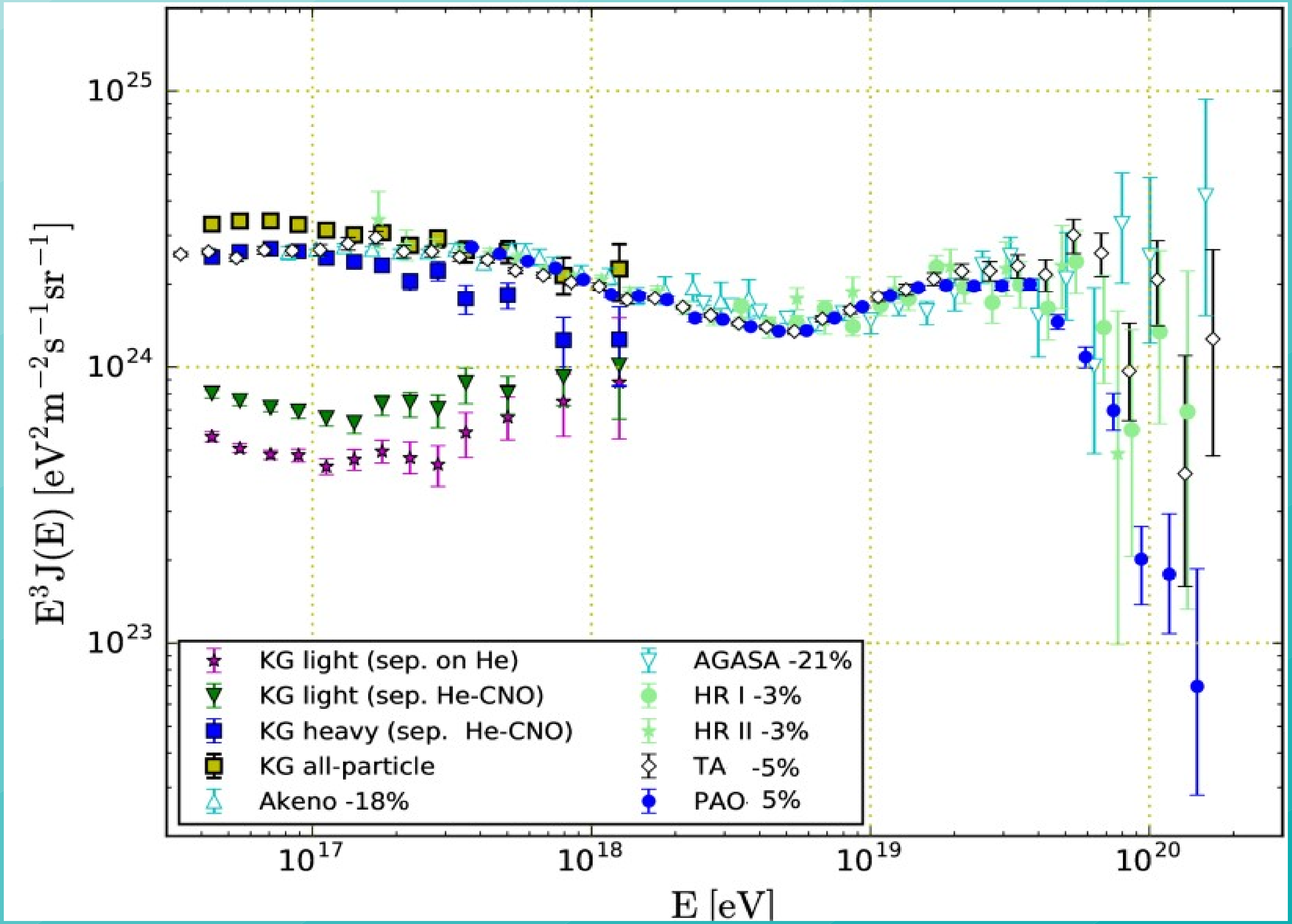
Discrepancies are noticeable, but systematic errors are also large:

$$PAO: \quad \frac{\Delta E}{E} \simeq 14\,\%$$

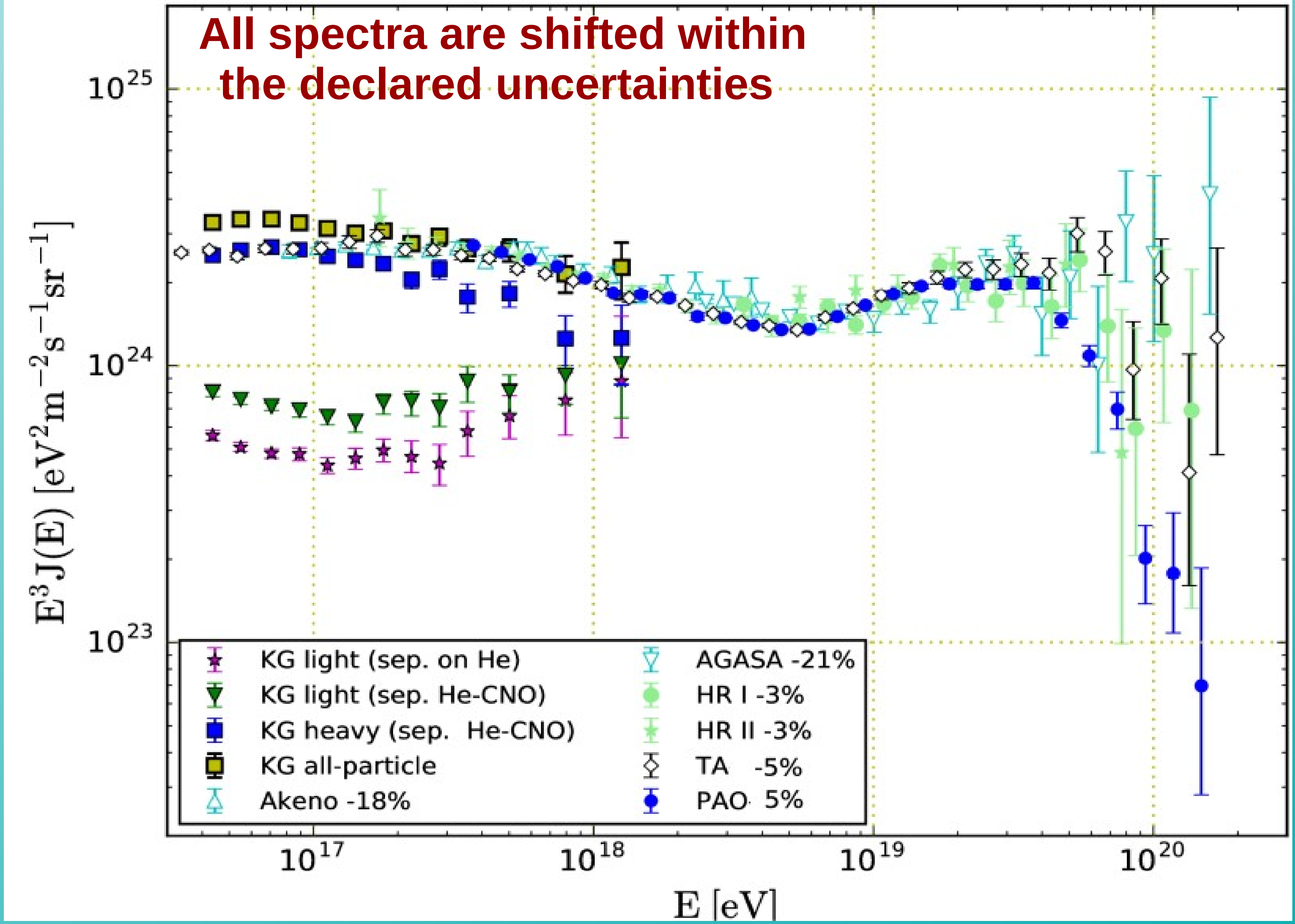
$$TA: \quad \frac{\Delta E}{E} \simeq 21\,\%$$

Fluorescence Detectors (**FD**), **surface** scintillation detectors (**SD**), Water Cherenkov (**WC**) detectors, muon detectors, radio antennas.

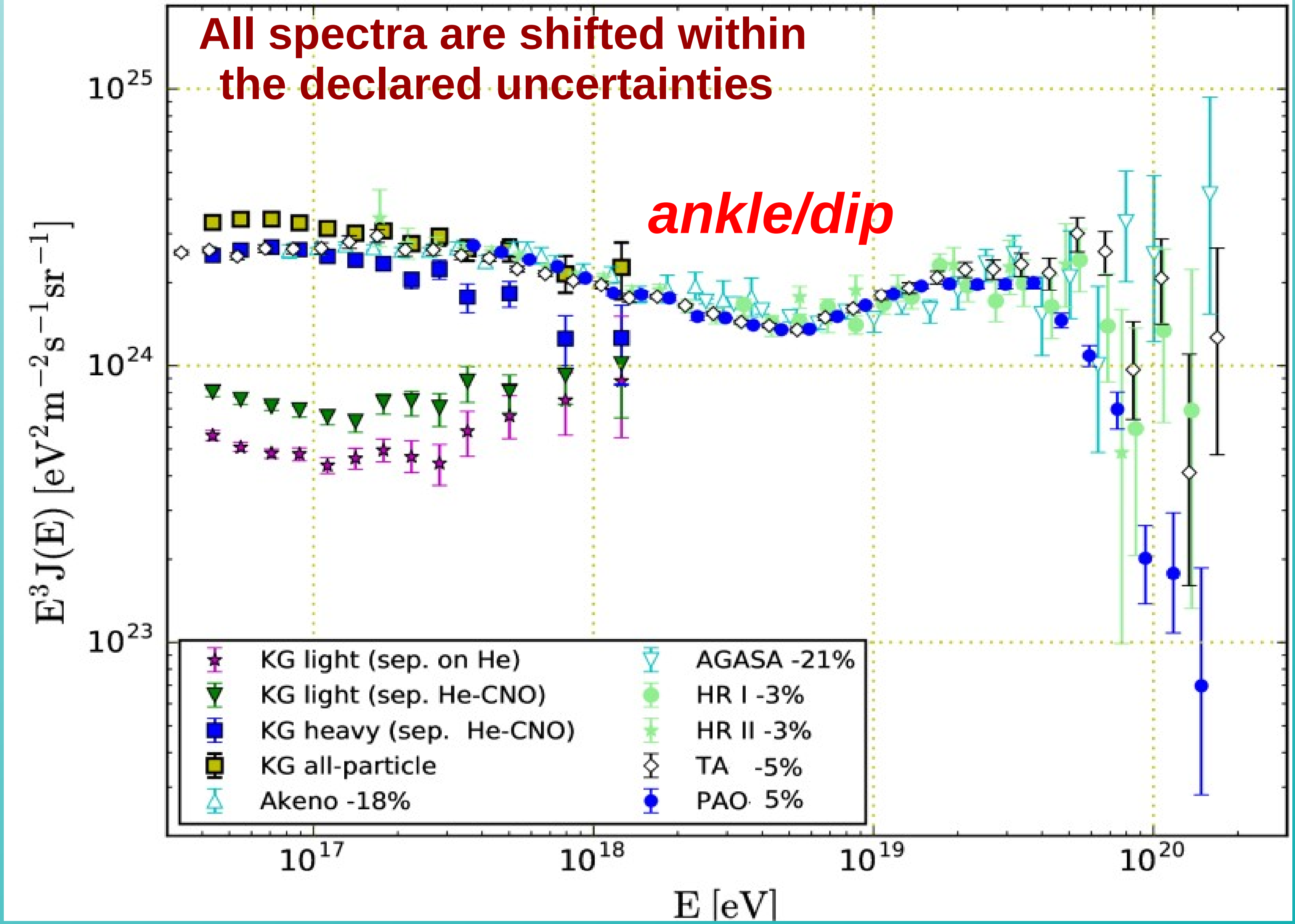
Shifted spectra



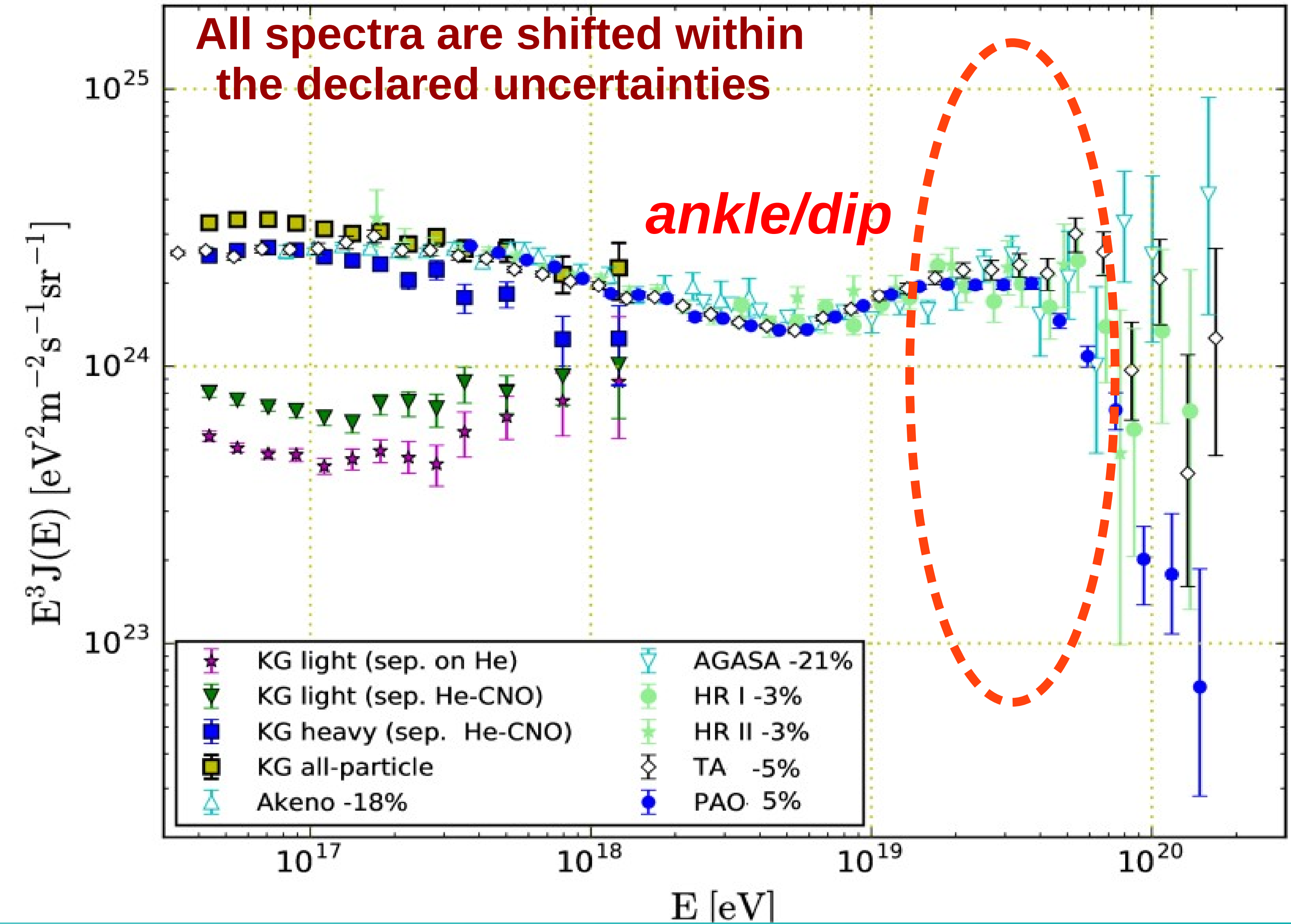
Shifted spectra



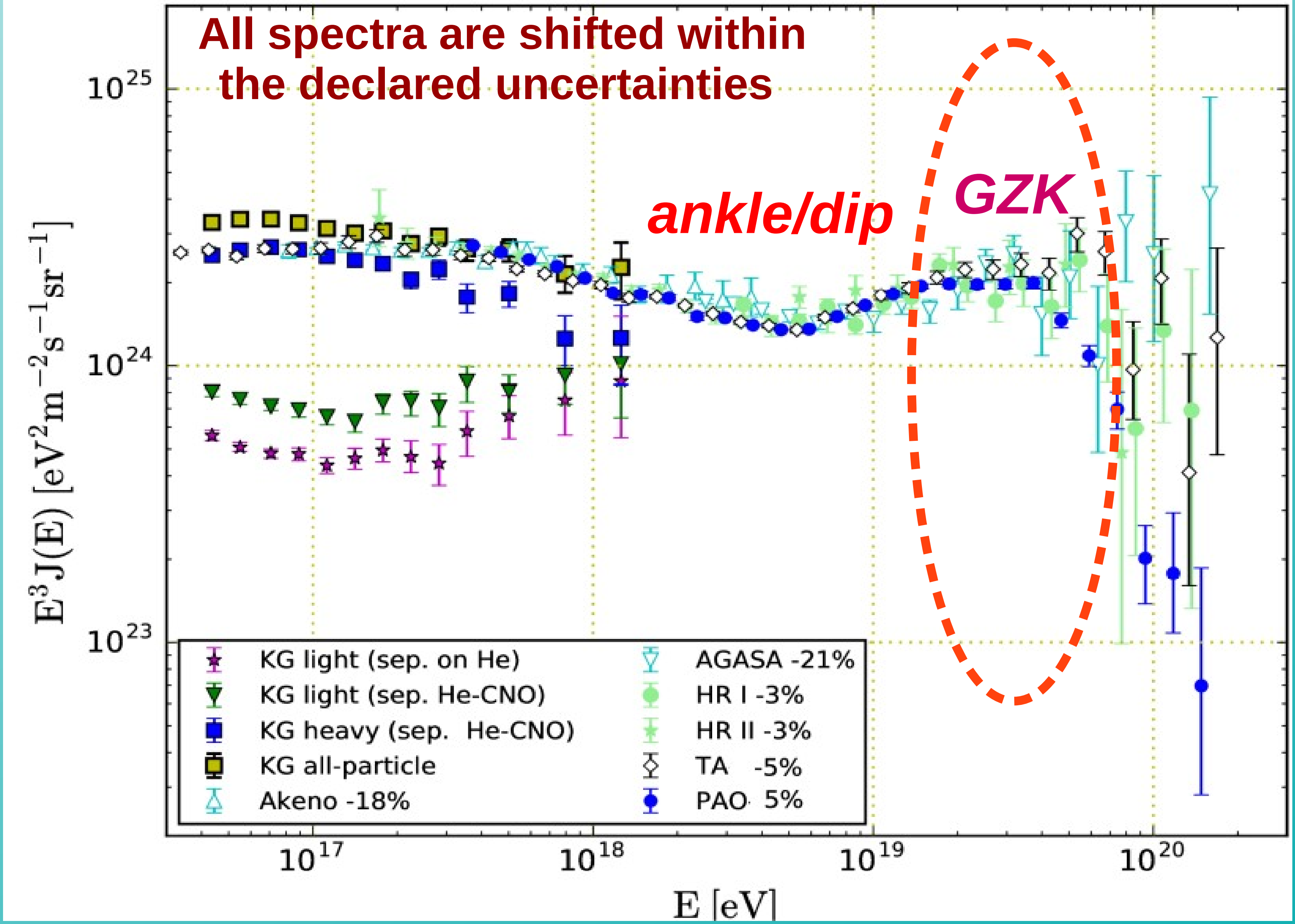
Shifted spectra



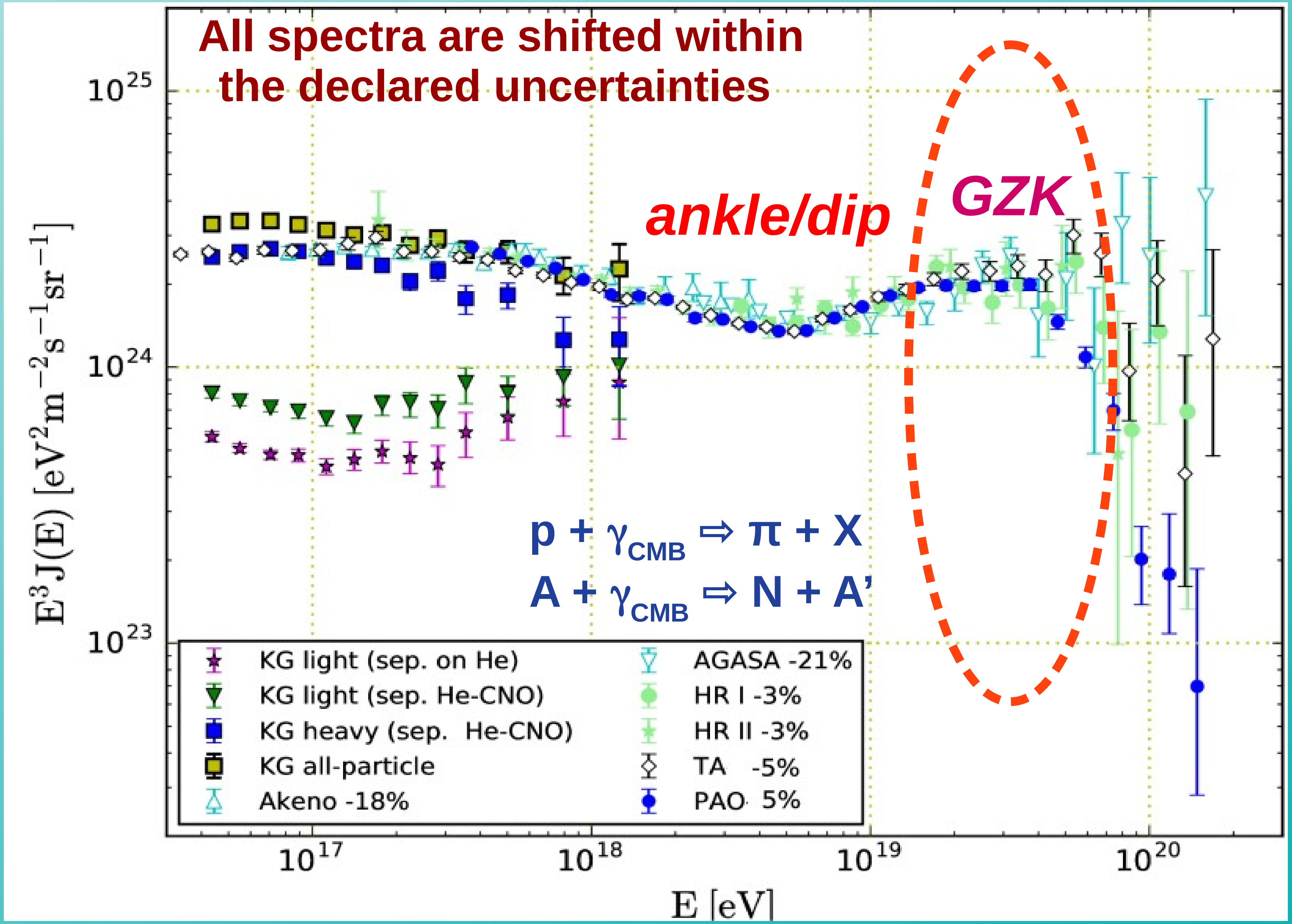
Shifted spectra



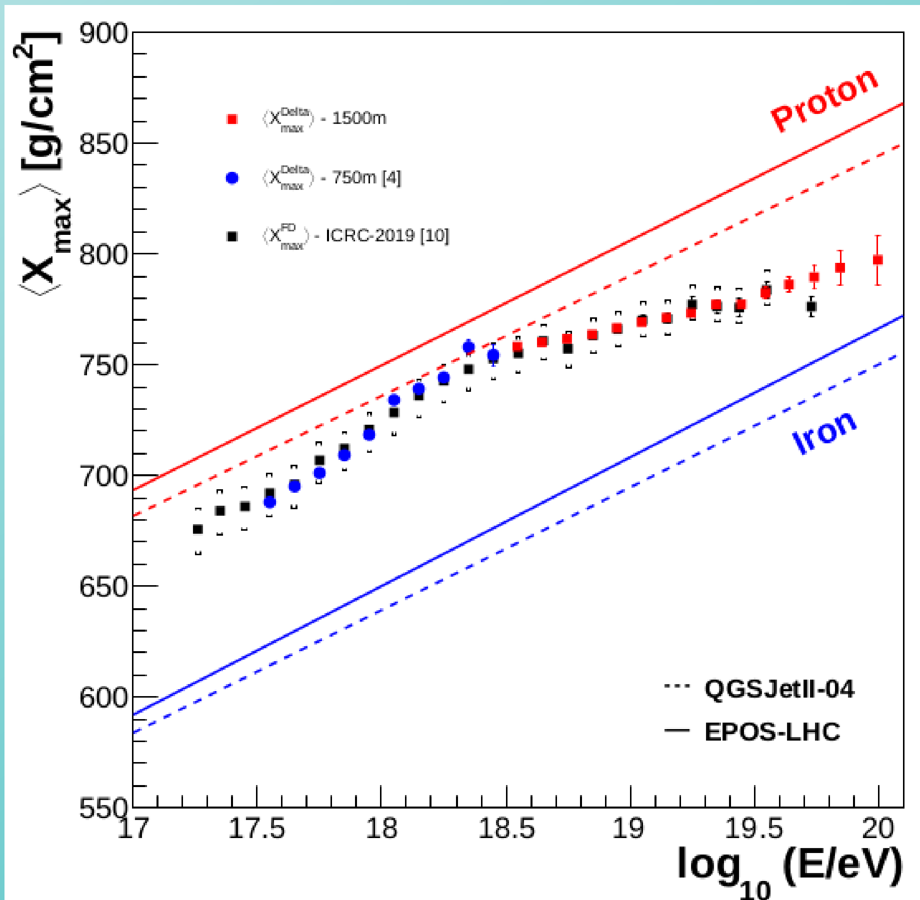
Shifted spectra

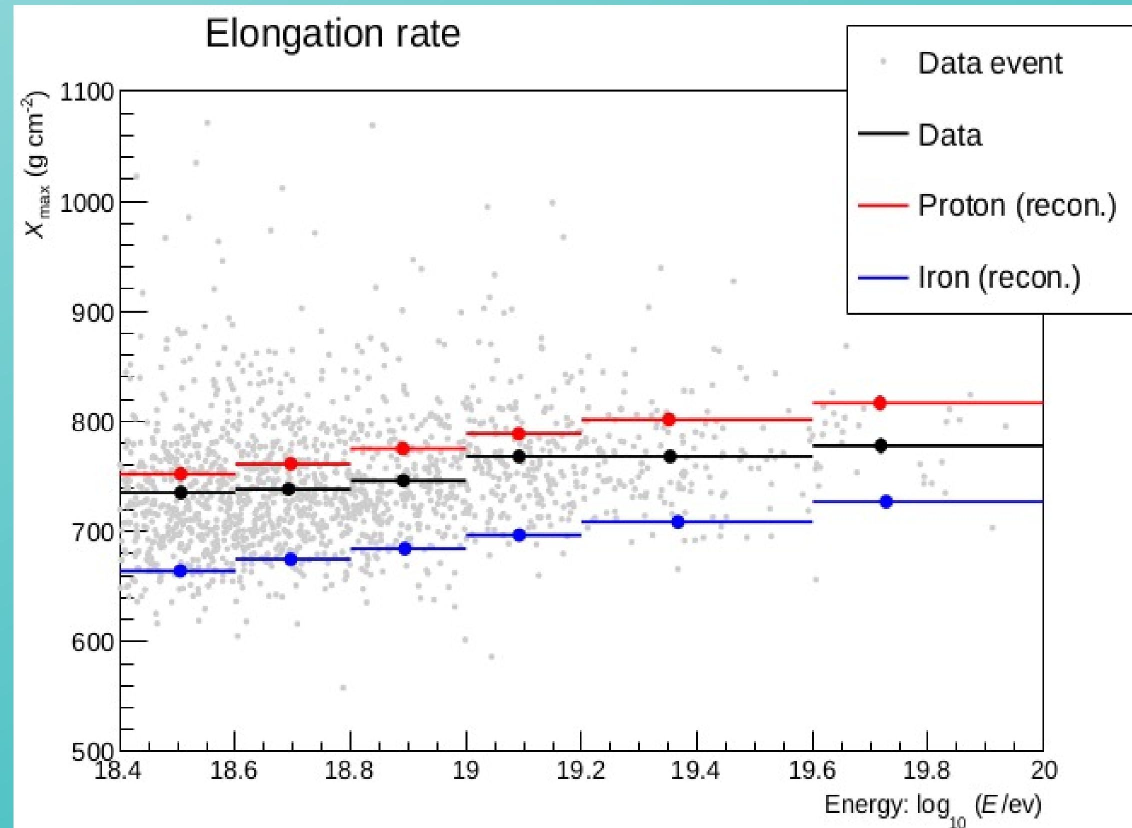


Shifted spectra



Mass composition





PAO, *arXiv:190909073*

36th ICRC 2019

TA, *PoS (ICRC2019) 191*

R.U. Abbasi et all, arXiv:1808.03680

no significant energy dependence

<ln A> = 2.0 ± 0.1(stat.) ± 0.44(syst.)

Northern sky vs. southern

Spectra of ***UHECRs*** and their chemical compositions measured by ***TA*** and ***PAO*** detectors in the northern and southern hemispheres are different.

Data of ***Akeno-AGASA*** and ***Yakuts*** just add to the difference.

The problem does not reduce just to statistic and systematic uncertainties.

At large scales extragalactic ***CR*** sources should be the same.

⇨ Nearby sources.

They should be bright and powerful in all e.-m. radiations.

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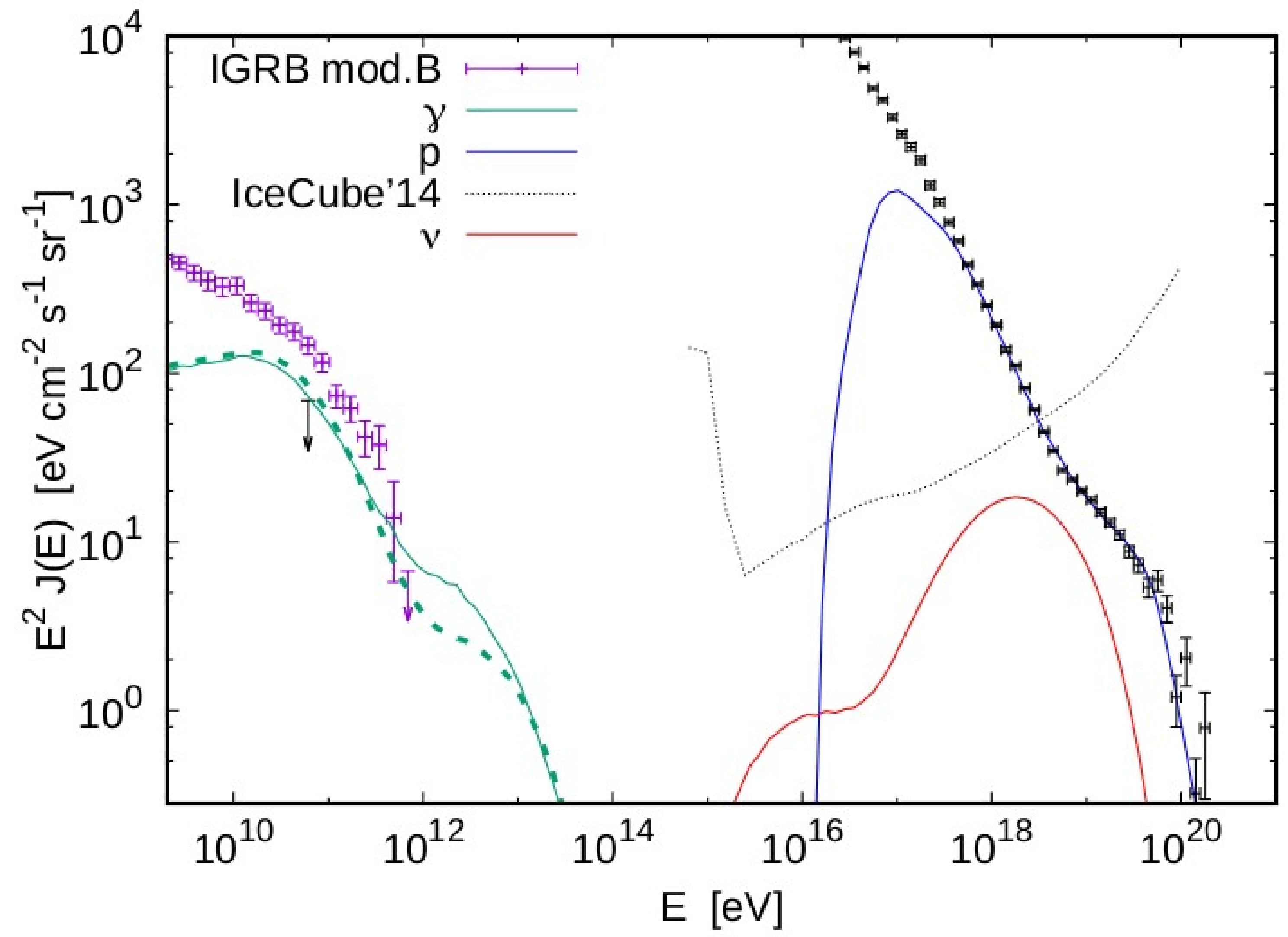
The problem does not reduce just to statistic and systematic uncertainties.

At large scales extragalactic ***CR*** sources should be the same.
⇨ Nearby sources.
They should be bright and powerful in all e.-m. radiations.

But we do not see them!

γ-rays and ν's constraint



Pure proton composition is constrained by the ***Fermi-LAT*** **IGRB** measurements.

Local ***"fog"*** of sub-ankle *UHECR* sources.

R.-Y.Liu, A.M.Taylor, X.-Y.Wang, F.A.Aharonian, *Phys. Rev. D 94, 043008 (2016)*
V.Berezinsky, A.G., O.Kalashev. *Astropart. Phys. 84 (2016) 52*

Mirror world

In 1956 李政道 (*Tsung-Dao Lee*) and 楊振寧 (*Yang Chen-Ning*) noticed that the P-parity conservation in weak interactions may be violated: *"Question of Parity Conservation in Weak Interactions", Phys. Rev. 104 (1956) 254–258* .

吴健雄 (*Chien-Shiung Wu*) with colleagues checked the idea and found parity non-conservation in β-decays of Co^{60}.

⇒ *T.D. Lee* and *C.N. Yang* were awarded the Nobel Prize in 1957.

Later, in 1956 the *V-A theory* of weak interactions was established (*Feynman* and *Gell-Mann*).

Restoration of symmetry

exhibit asymmetrical behavior with respect to the right and the left. If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry. If this is the case, it should be pointed out, there must exist two kinds of protons p_R and p_L, the right-handed one and the left-handed one. Furthermore, at the present time the protons in the laboratory must be predominantly of one kind in order to produce the supposedly observed asymmetry, and also to give rise to the observed Fermi-Dirac statistical character of the proton. This means that the free oscillation period between them must be longer than the age of the universe. They could therefore both be regarded as stable particles. Furthermore, the numbers of p_R and p_L must be separately conserved. However, the interaction between them is not necessarily weak. For example, p_R and p_L could interact with the same electromagnetic field and perhaps the same pion field. They could then be separately pair-produced, giving rise to interesting observational possibilities.

In such a picture the supposedly observed right-and-left asymmetry is therefore ascribed not to a basic non-invariance under inversion, but to a cosmologically local preponderance of, say, p_R over p_L, a situation not unlike that of the preponderance of the positive proton over the negative. Speculations along these lines are extremely interesting, but are quite beyond the scope of this note.

Right in their first paper *T.D. Lee & C.N. Yang* *suggested* that symmetry may restore.

T.D.Lee Ch.N.Yang

"Imagination is more important than knowledge..."
A. Einstein

Mirror matter

- KOP: I.Yu. Kobzarev, L.B. Okun, I.Ya. Pomeranchuk,
  Sov. J. Nucl. Phys. 3 (1966) no.6, 837-841.
  ⇨ Mirror particles may interact with our particles only via gravity.

- Our: $G = SU(3)\times SU(2)\times U(1)$; Mirror: $G' = SU(3)'\times SU(2)'\times U(1)'$
  $G\times G'$ ⇨ $\mathcal{L}_{tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{mix}$ $G \Leftrightarrow G'$ The same (twin) particles.

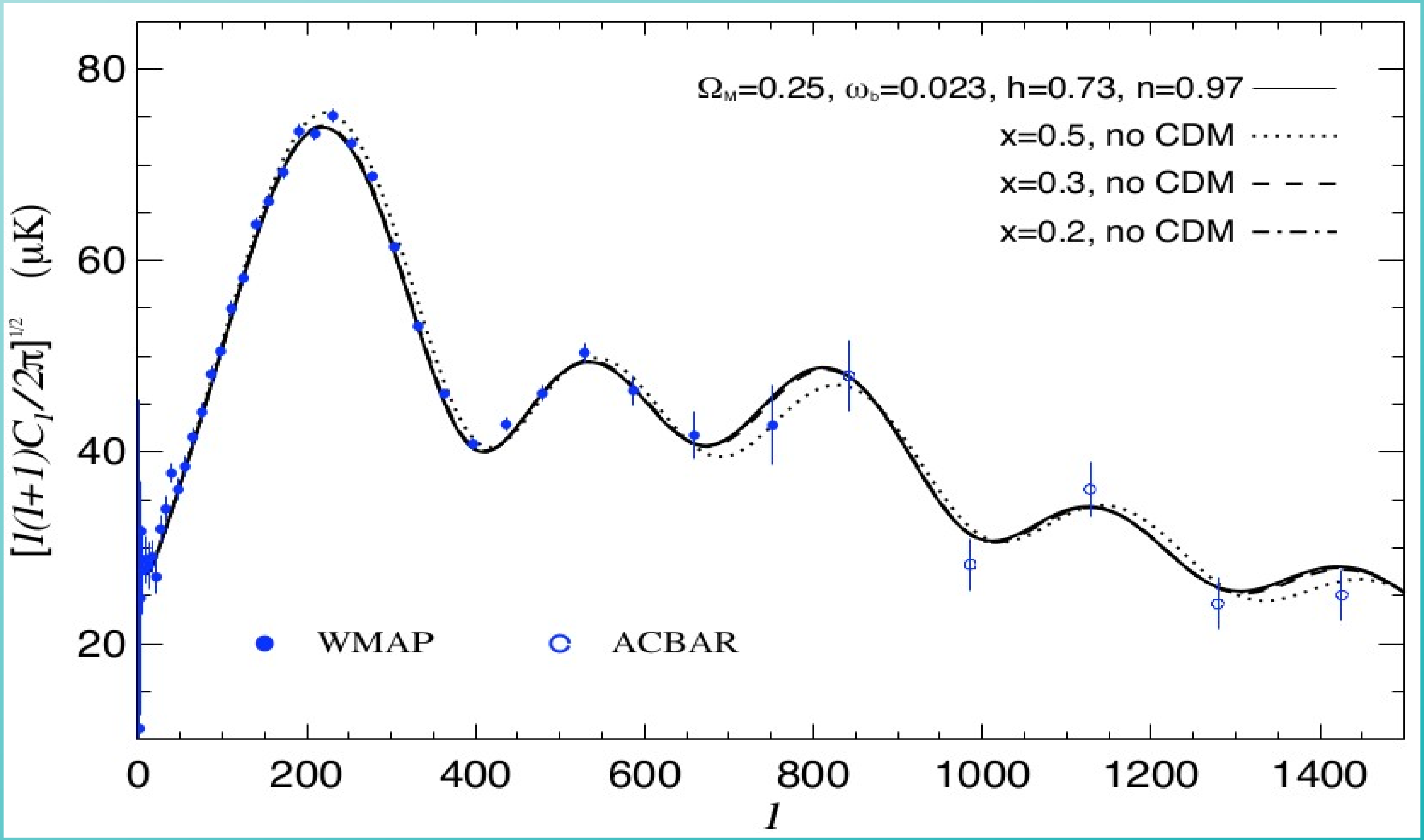
- Kinetic mixing $\gamma \Leftrightarrow \gamma'$ and/or gauge heavy bosons that couple to both sectors.

- Mirror matter is (partially?) the ***DM.***

- Cosmology:
  - MW was born with $T' < T$,
  - $\mathcal{L}_{mix}$ is very weak (otherwise only gravitational interactions),
  - $T' / T = const$ during expansion of the universe,
  - $T' / T < 0.5$ to be in accordance with **BBN**.
  - more severe cosmological constrain, $T' / T < 0.2$,
  - implies mirror matter is 25%H' + 75%^{4}He'.

- Mirror matter behaves as CDM.
  WMAP/Planck data, *BAO*, *Ly-α* are OK, if $T'/T \lesssim 0.2$.

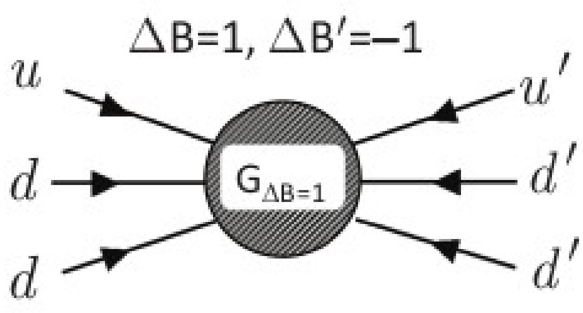
CMB power spectrum



Z.Berezhiani, P.Ciarcelluti, D.Comelli and F.L.Villante,
Int.J.Mod.Phys. D14 (2005) 107-120

O-M oscillations ($\mathcal{L}_{mix}$)

- Massive neutral particles with equal masses may oscillate, violating ***B***- and ***L***-conservation laws, e.g. *ν* to *sterile ν*.
- *n* ⇔ *n'* comes from a six-fermions effective operator



$\frac{1}{M^5}(udd)(u'd'd')$, where *M* is the scale of some new interaction. It violates both *B* and *B'*, but conserves *B* + *B'* (in contrast to n⇔ $\bar{n}$, with ΔB=2. Nuclei remain stable.

$$\epsilon = \langle n | (udd)(u'd'd') | n' \rangle \sim \frac{\Lambda_{QCD}^6}{M^5} \sim \left(\frac{10\,TeV}{M} \right)^5 \times 10^{-15}\,eV$$

- *n* ⇔ *n'* oscillation can be as fast as $\tau_{nn'} = \frac{1}{\epsilon} \sim 1\,s$

  Z.Berezhiani, *Phys.Rev.Lett. 96 (2006) 081801*

Suppression by magnetic fields

n ⇔ n' oscillation may be suppressed due to interactions with different magnetic fields in our and mirror worlds

$$H = \begin{pmatrix} m_n + \mu_n \boldsymbol{B} \cdot \sigma & \epsilon \\ \epsilon & m_n + \mu_n \boldsymbol{B}' \cdot \sigma \end{pmatrix}$$

For relativistic neutrons $\boldsymbol{B}_\perp$ and $\boldsymbol{B}_\perp'$ are enhanced by Lorentz-factor $\Gamma = E / m_n$. If $E_n \sim 100$ *EeV*, $\Gamma \approx 10^{11}$, and $B_\perp = \Gamma \cdot B$.

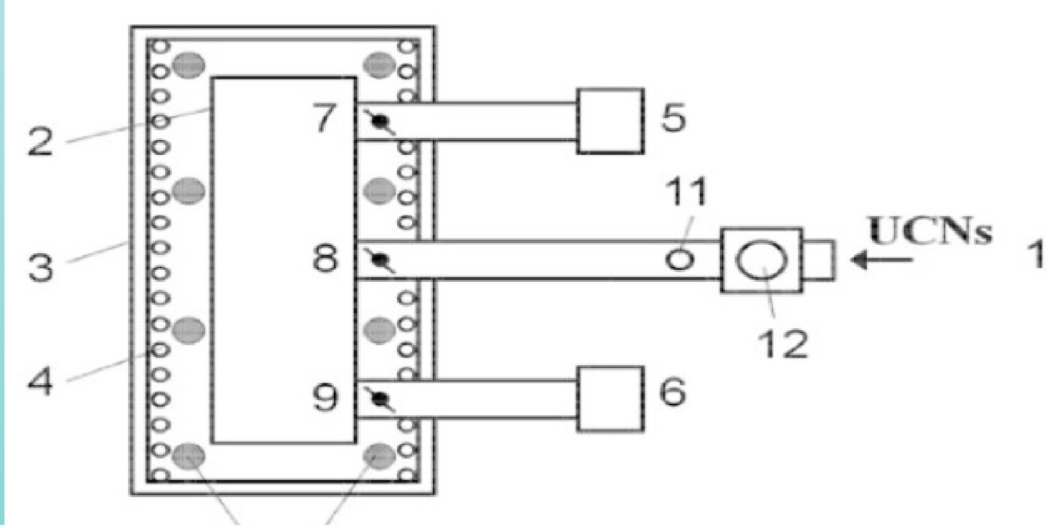
The average oscillation probability

$$P_{nn'}(E) = \frac{1}{2 + q(E)}, \quad q(E) \approx 0.45 \times \left(\frac{\tau_{nn'}}{1\,s}\right)^2 \times \left(\frac{\Delta B_\perp}{1\,fG}\right)^2 \times \left(\frac{E}{100\,EeV}\right)^2.$$

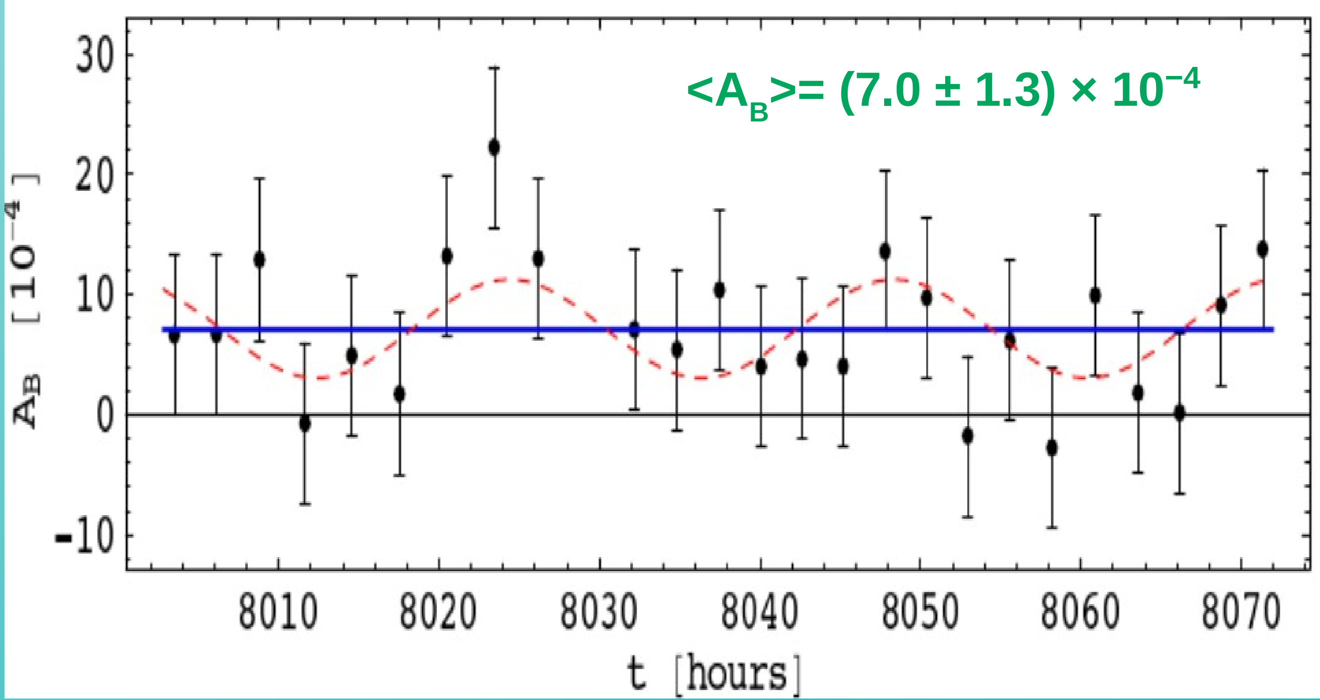
Oscillation is suppressed by large $\Delta B_\perp$ and at $E \gg 100$ *EeV*.

At low energies mirror neutron production is suppressed by ***CMB'*** spectrum. Mirror *EBL'* is unknown.

Search for n⇔n' oscillation



Z. Berezhiani & *F. Nesti*, *Eur. Phys. J. C72 (2012) 1974*



190 l beryllium plated **UCN** trap for ***ILL***

- Fill the trap with ***UCN***
- Close the valve
- Wait for T_s (*300 s* ...)
- Open the valve
- Count survived neutrons

Repeat this for different orientation and values of magnetic field.

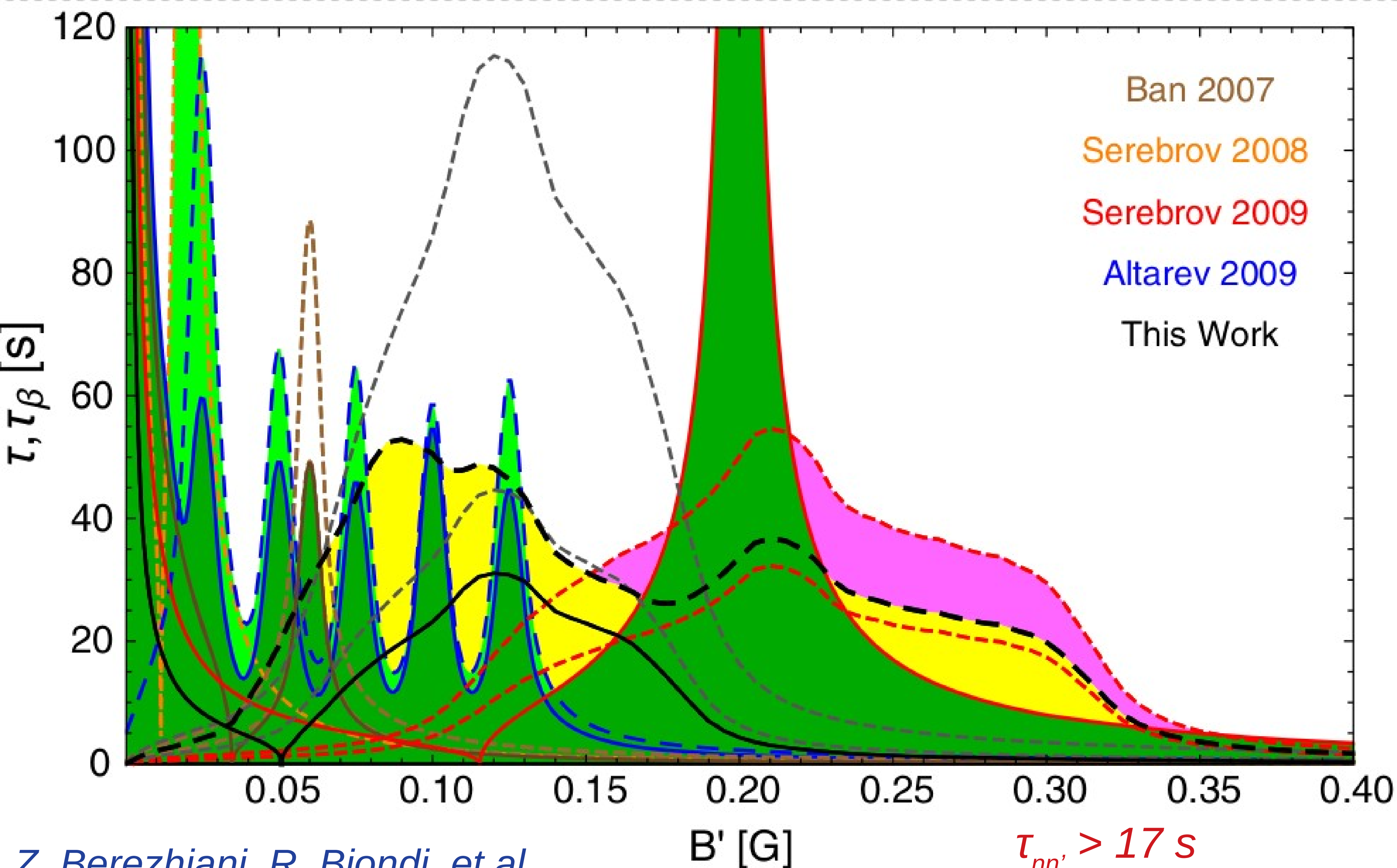
$$A_B = \frac{N_B - N_{-B}}{N_B + N_{-B}}$$

χ^2/dof = 0.9 ⇨ ***5.2σ***

$T_{nn'} \sim 2 - 10\ s$

$B' \sim 0.1\ G$

Limit on n-n' oscillation time

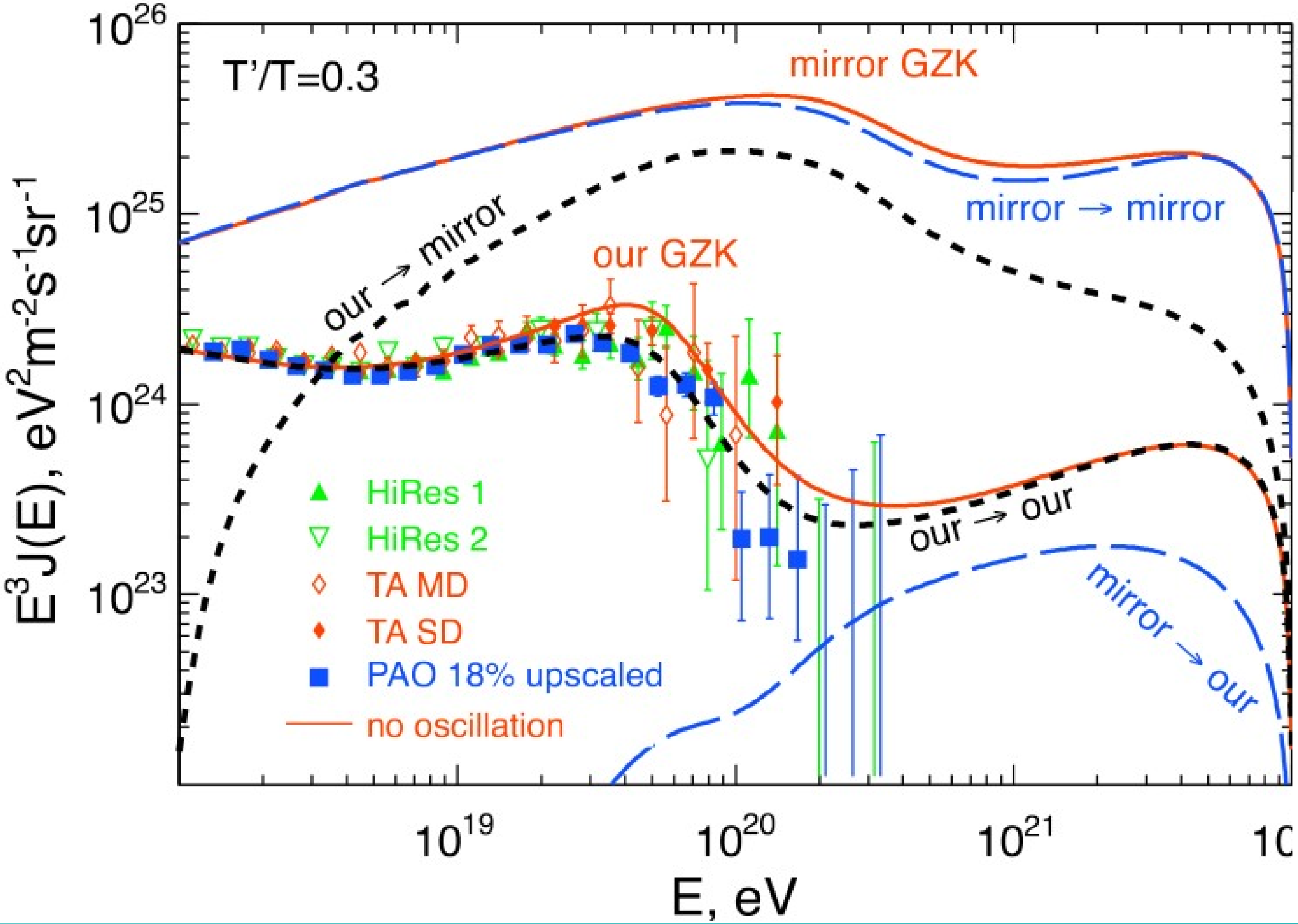


Z. Berezhiani, R. Biondi, et al
Eur. Phys. J. C78 (2018) no. 9, 717

$\tau_{nn'} > 17$ s
0.08 G $\leq B' \leq 0.17$ G

n-n' oscillation in universe

High-energy neutrons are produced in the universe in p+γ→**n**+X interactions with CMB at energies above the GZK-cutoff.



$$\frac{n'_{CMB}}{n_{CMB}} \propto \left(\frac{T'_{CMB}}{T_{CMB}}\right)^3 \ll 1$$

p' ans He' may travel 100 times larger distances in CMB'.

But production of n', and hence of n is low.

So our **HE** p's may disappear to the MW

Z.Berezhiani & A.G., Eur. Phys. J. C 72, 2111 (2012)

Equations

Approximation: a set of coupled integro-differential equations

$$\frac{\partial n_i(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[\Gamma \beta_i(\Gamma,t)\, n_i(\Gamma,t)\right] + \mathfrak{D}_i(\Gamma,t)\, n_i(\Gamma,t) = Q_i(\Gamma,t)$$

$n_i(\Gamma,t)$ are *$dN_i(\Gamma,t)/d\Gamma dV$*, ***i*** = *p*, *p'*, *He*, *He'* ***Γ*** is Lorentz-factor

$$Q_i(E,z) = Q_{0,i} \times (1+z)^m \times \left(\frac{E}{E_0}\right)^{-\gamma_g} \times \exp\left(-\frac{E}{E_{\mathrm{cut},i}}\right)$$

source generation functions

$$\beta_i(\Gamma,t) = \frac{1}{\Gamma}\frac{d\Gamma}{dt}(\Gamma,t)$$

average energy loss of particle i on CMB + EBL

$$\begin{aligned}
\beta_p(\Gamma,z) &= H(z) + \beta_p^{ee} + \beta_p^{pX} + (1-P_{n'n})\,\beta^{nX} \\
\beta_{\mathrm{He}}(\Gamma,z) &= H(z) + \beta_{\mathrm{He}}^{ee}, \\
\mathfrak{D}_p(\Gamma,z) &= \frac{dP^{nX}}{dt}(\Gamma,z), \\
\mathfrak{D}_{\mathrm{He}}(\Gamma,z) &= -\frac{dP^{\mathrm{He}}}{dt}(\Gamma,z),
\end{aligned}$$

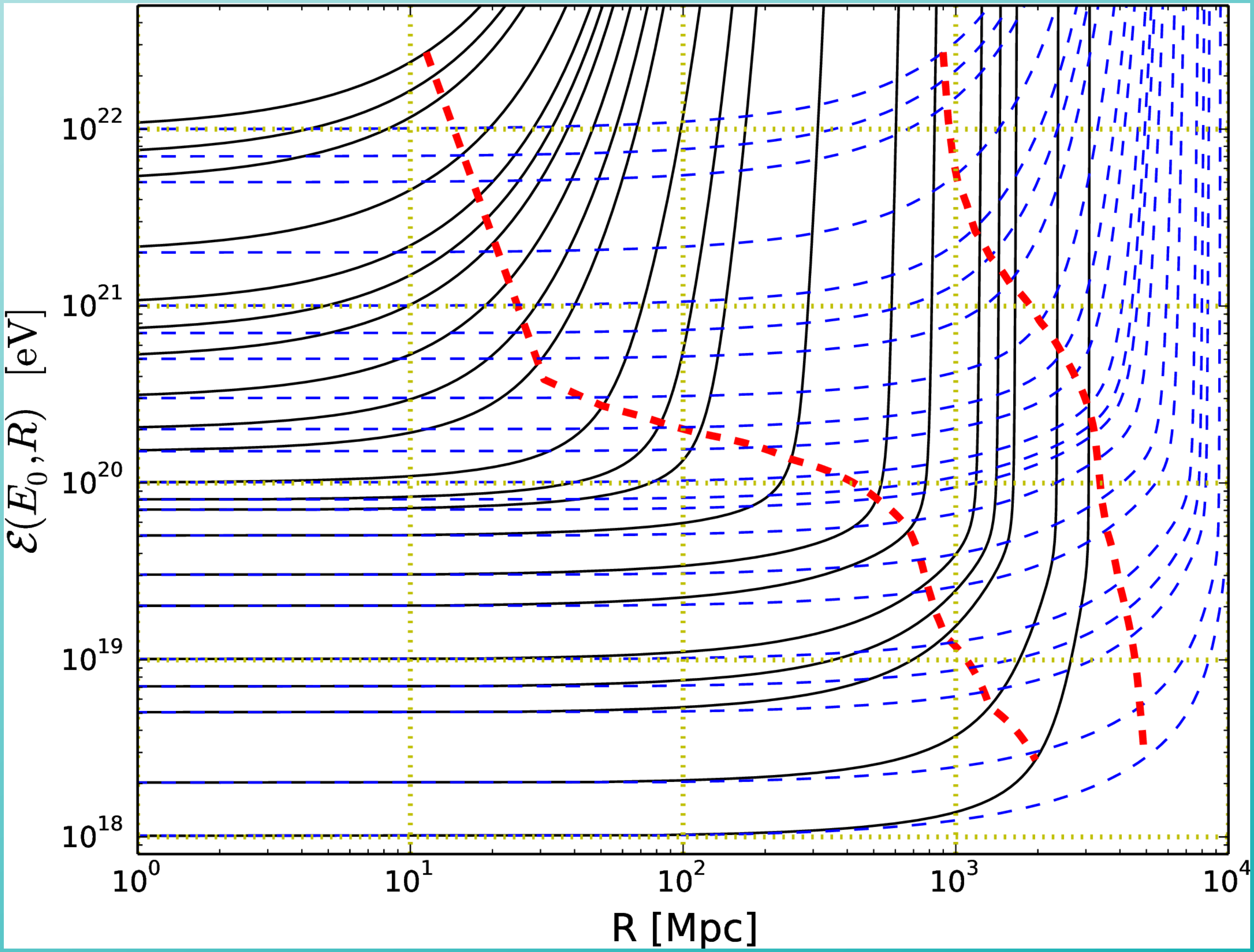
$$H(z) = H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$$

p ⇔ p'; He ⇨ p;

He' ⇨ p;
He' ⇨ p' ⇨ p

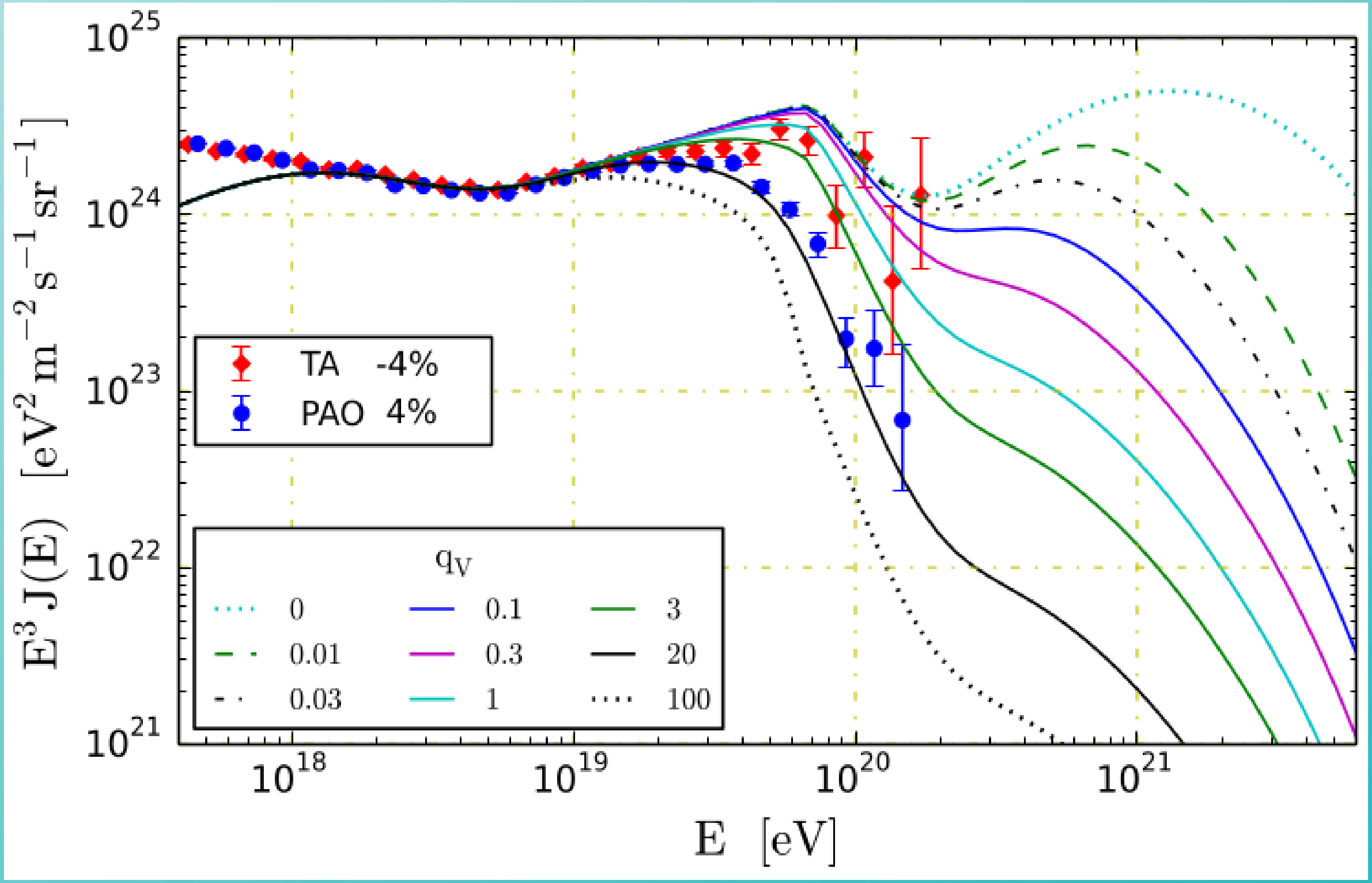
$$P_{nn'}(E) = \frac{1}{2+q(E)},\; q(E) \approx 0.45 \times \left(\frac{\tau_{nn'}}{1\,s}\right)^2 \times \left(\frac{\Delta B_\perp}{1\,fG}\right)^2 \times \left(\frac{E}{100\,EeV}\right)^{2.}$$

Proton characteristic lines



$$\frac{T_{CMB'}}{T_{CMB}} = 0.2$$

Neutron oscillations in voids



Most energetic ***CRs*** should arrive from voids.

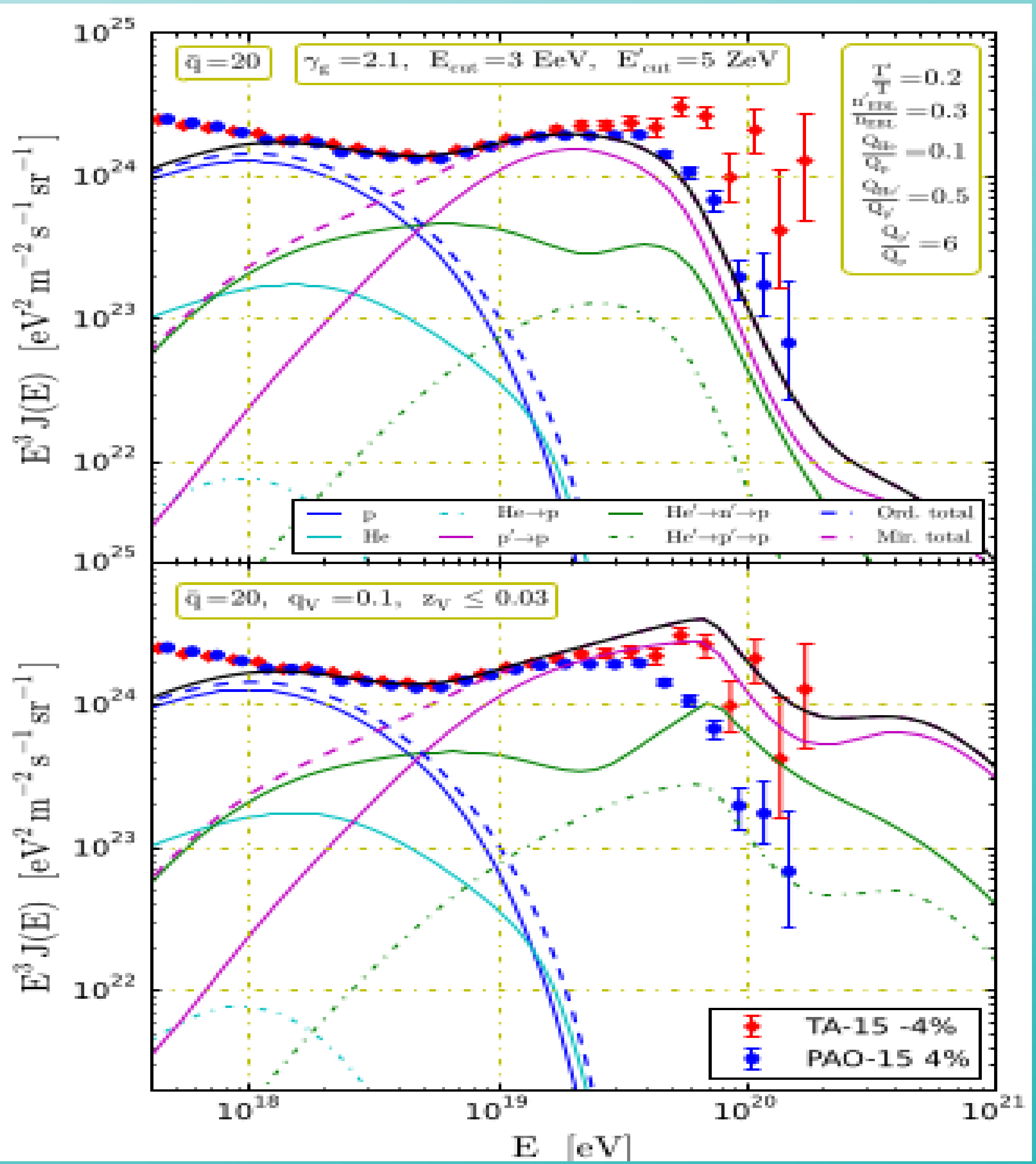
They must be **protons**.

The number of voids and their properties are more favorable in the *northern* sky.

Higher statistics at $E > E_{GZK}$, and especially at $E \gtrsim$ *100 EeV*, is needed.

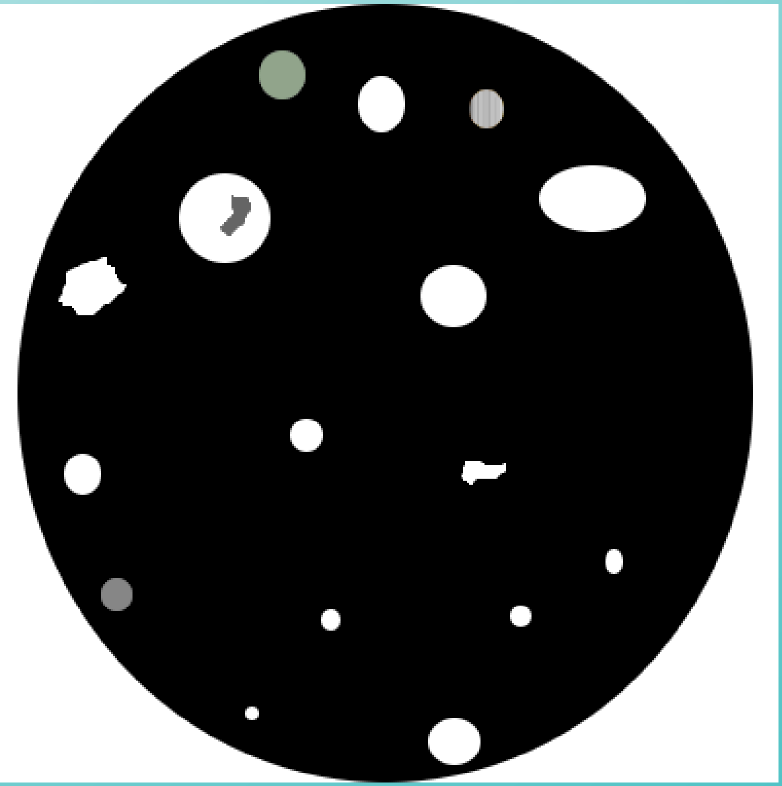
Z.Berezhiani, R.Biondi, A.G., to be published

Mirror EBL



- Unfortunately, n'_{EBL} is completely unknown, but it is important.
- The ratio He'/H' may vary.
- The highest energy **CRs** are protons, arising in the vicinity of the Earth from voids. They are produced via oscillations from mirror neutrons.
- These protons do not overproduce ***γ**-rays* and ***ν***-fluxes.
- All nuclei at such high energies are photodisintegrated.

Looking through a strainer

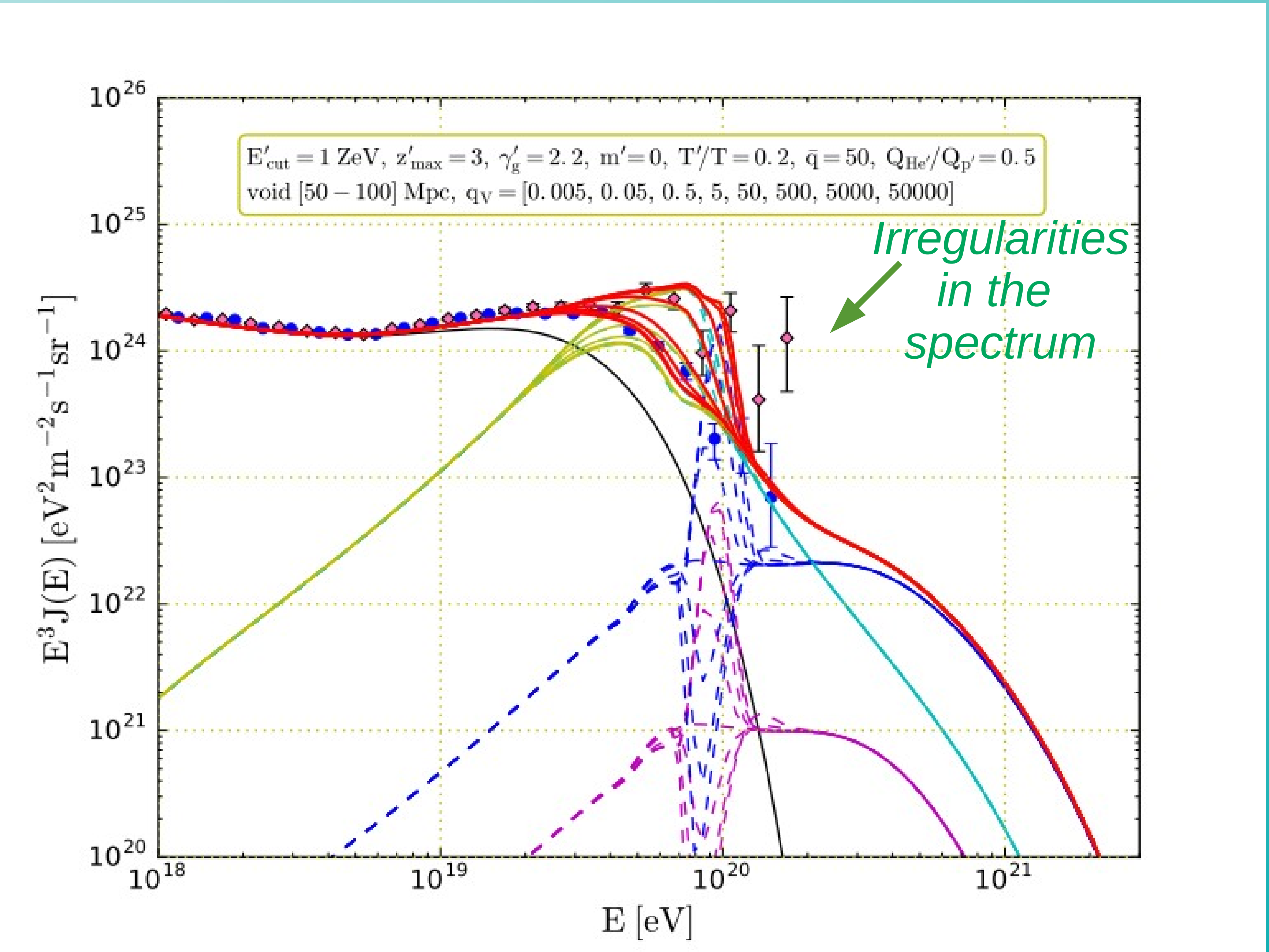


At highest energies we look at distant powerful mirror ***CR*** sources through a kind of “strainer” with voids as *irregular holes* of different sizes and properties. By chance, there are more voids in our hemisphere. It makes the southern and northern skies so different.

We are to better study the matter (actually, the magnetic fields) distribution.

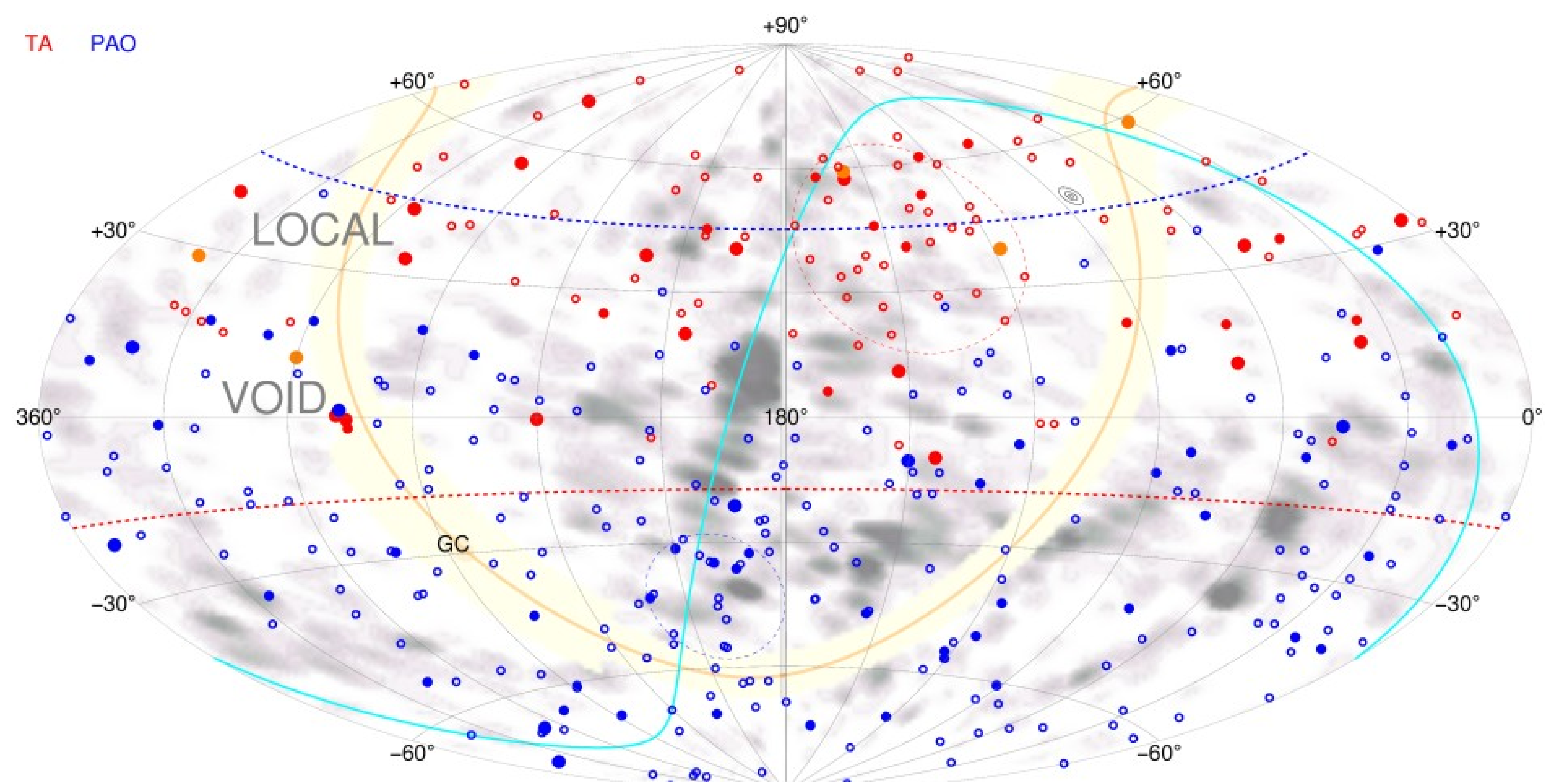
At lower energies the discrepancy disappears.

Contributions from distant voids



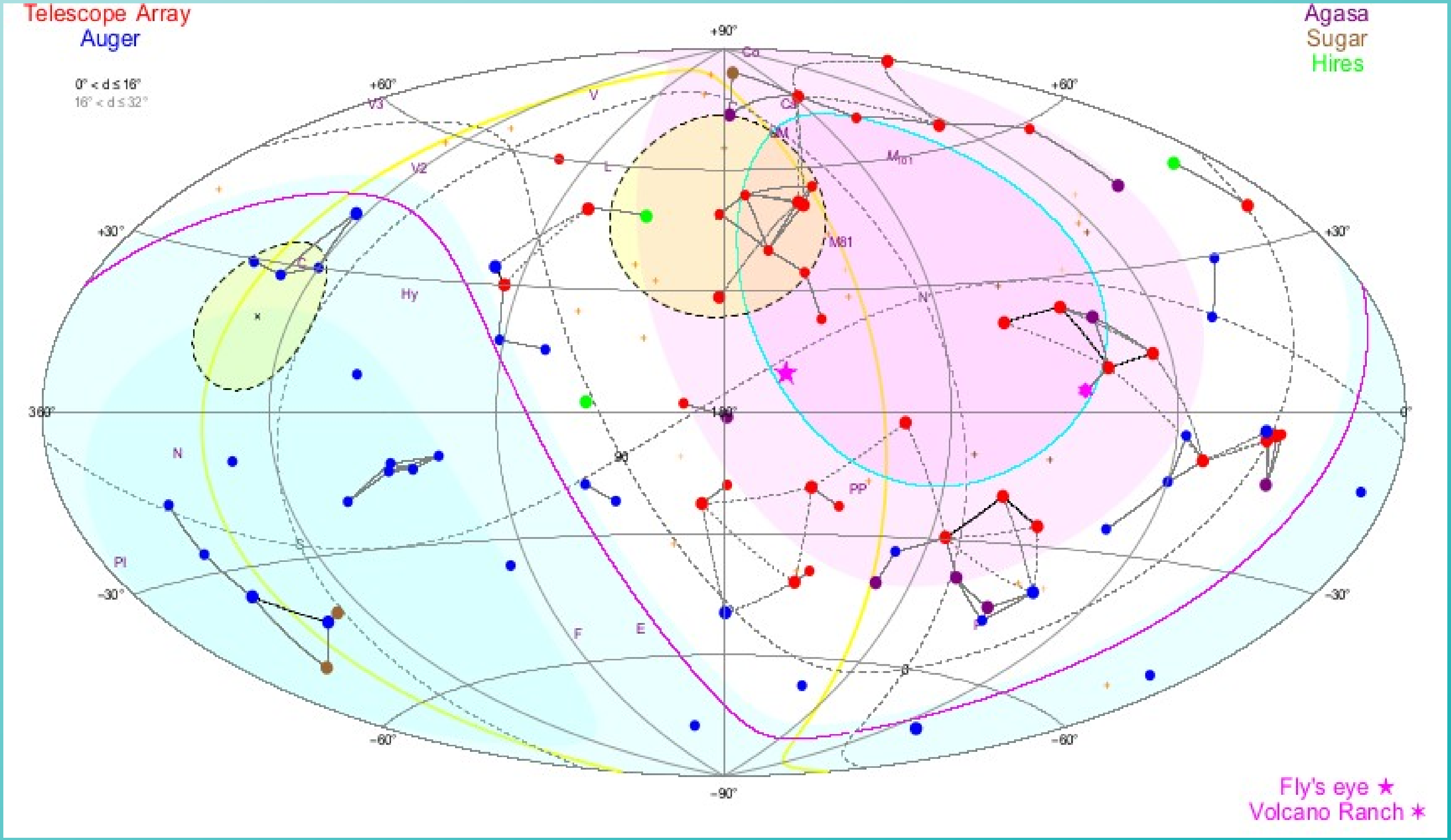
UHECR sources

TA 2008-14 • E > 100 EeV (#18), • 79 ÷ 100 EeV, ◦ 57 ÷ 79 EeV



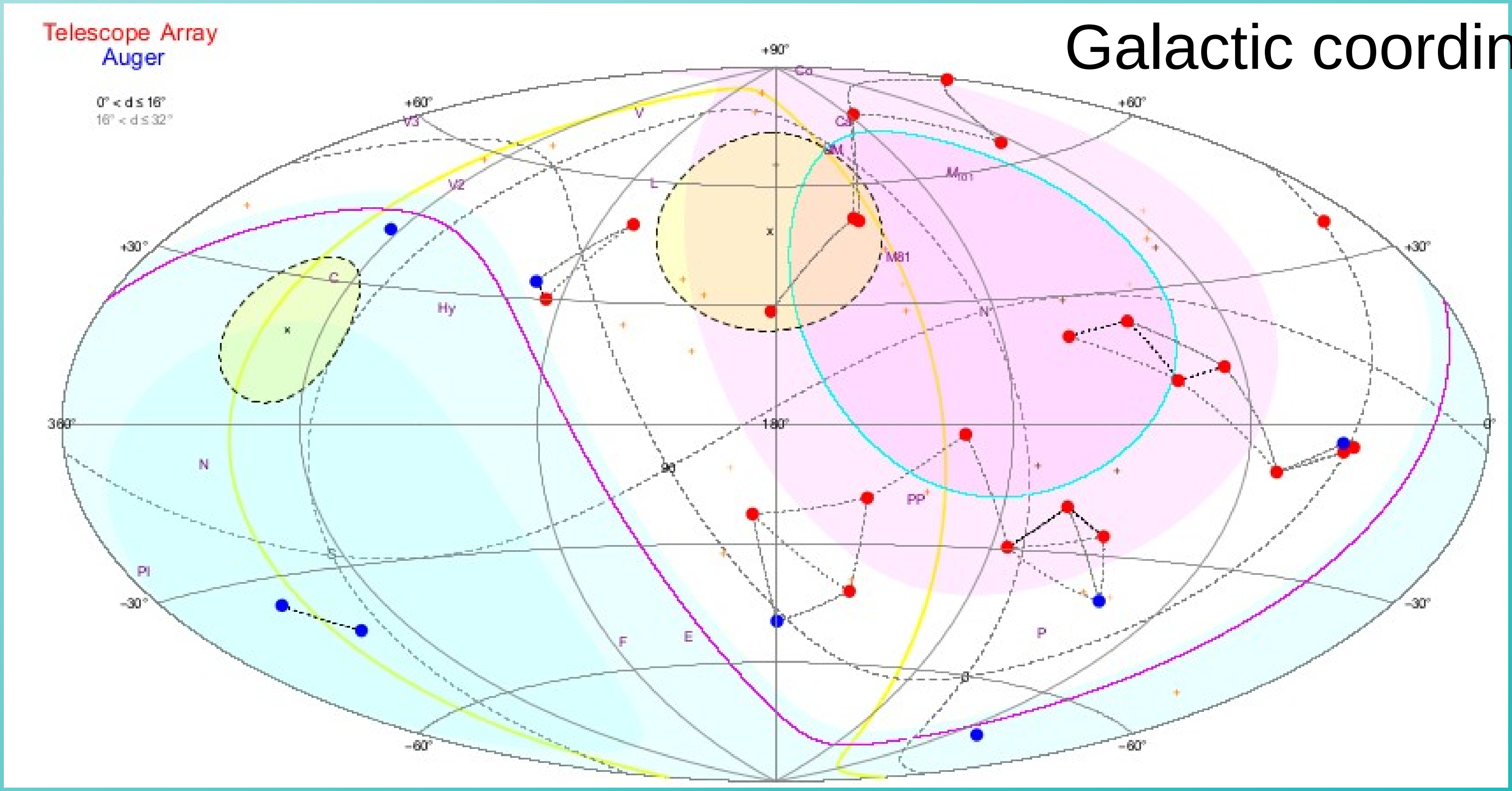
PAO 2008-14 • E > 100 EeV (#8), • 79 ÷ 100 EeV , ◦ 57 ÷ 79 EeV
rescaling: $E_r = 1.1 \times E$

Arrival directions of E>80 EeV



Galactic coordinates

E>100 EeV events



TA registered 23 events with *E>100 EeV*, while **PAO** has just 18 events of such high energy. Note that **PAO** is larger and works longer. But the southern sky looks more isotropic.

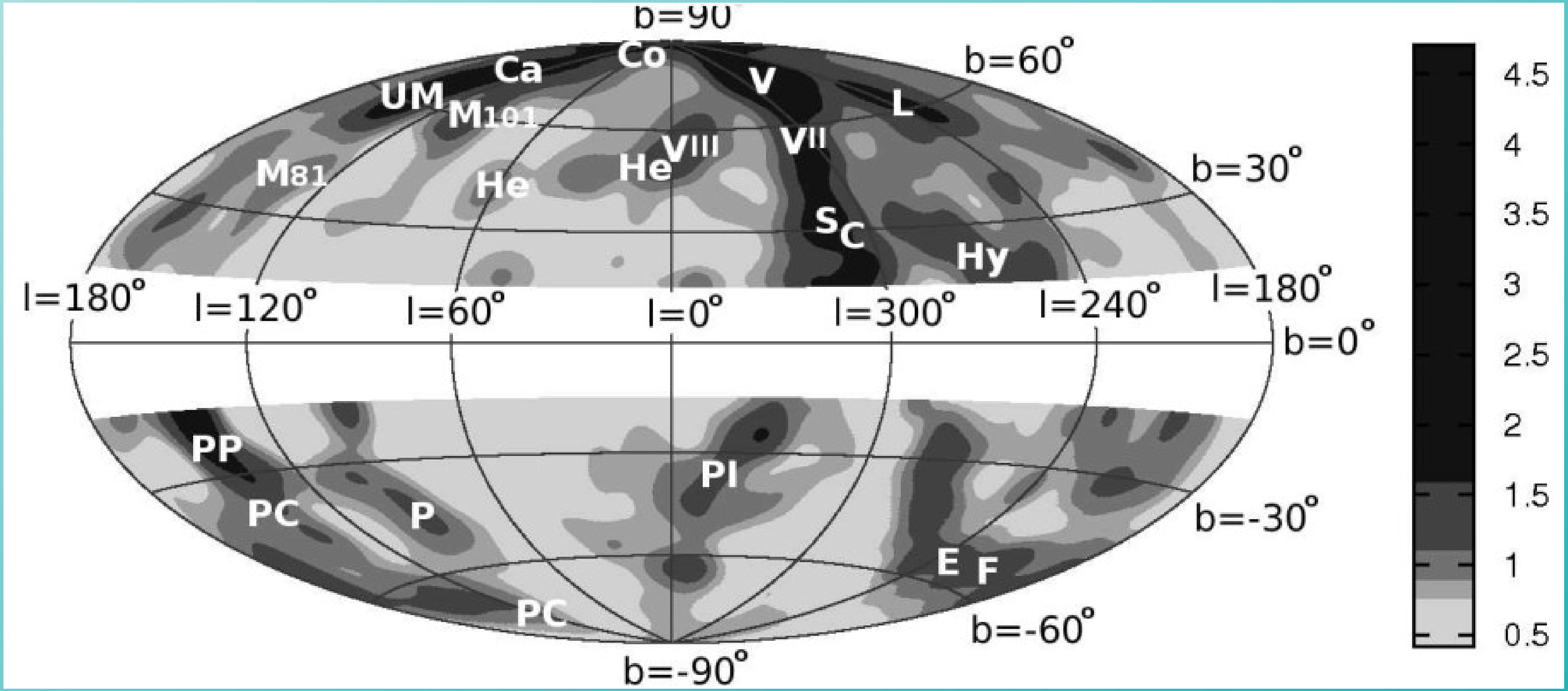
CONCLUSIONS

- Observation of ***CRs*** with energies $E > E_{GZK} \simeq 60\ EeV$ suggests that their sources are close to us. Small anisotropy of arrival directions means the sources are numerous or allows for strong magnetic fields.
- Events with $E > 100\ EeV$ hardly can be (heavy) nuclei. But protons may survive the traveling large distances in ***CMB***.
- Absence of such sources may be explained if they are hidden in the mirror world. Then ***UHECRs*** appear due to mirror neutrons conversion to our protons not far from us.
- Conversions via $n' \Leftrightarrow n$ oscillation should occur where both our and mirror magnetic fields are weak, most likely in voids.
- The model predicts the light, mostly ***p***, composition of ***CRs*** at highest energies and the correlation of arrival directions with voids.
- The local excess of voids in the northern sky explains the differences between ***PAO*** and ***TA*** spectra.

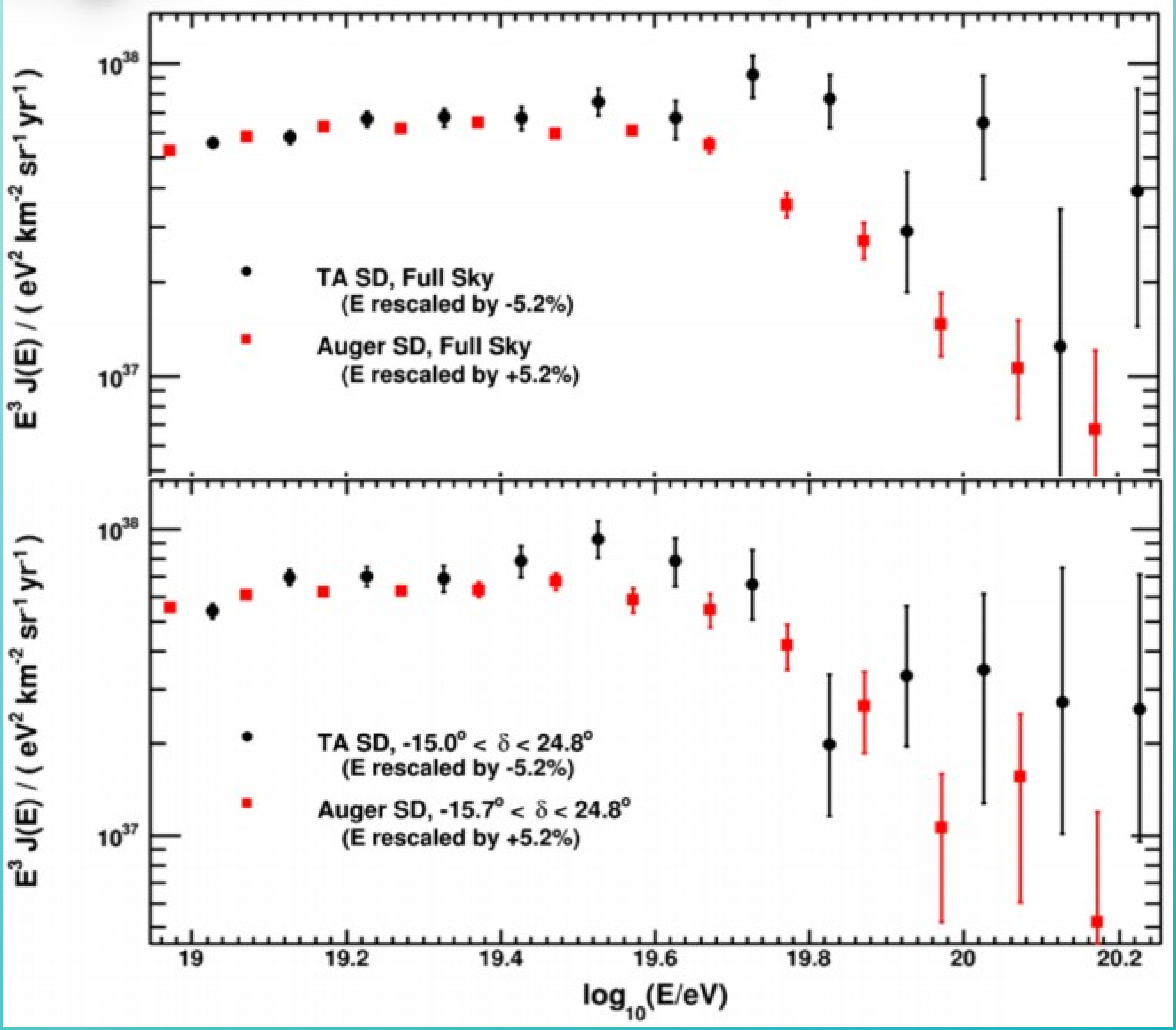
Thank you!

Back up slides

Where UHECRs come from?

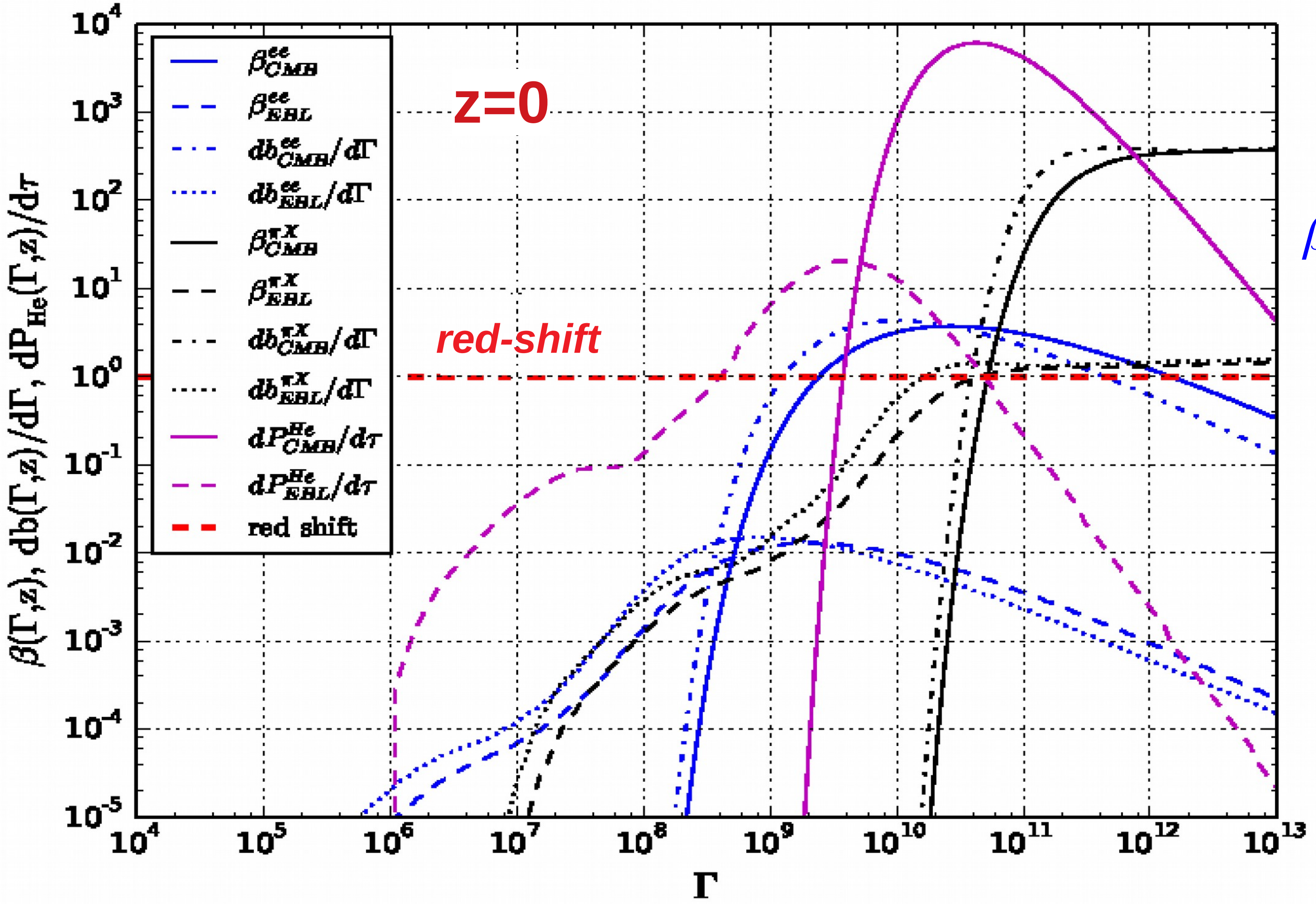


PAO&TA spectra



Spectra get similar for the same regions of the sky.

Proton and He energy losses



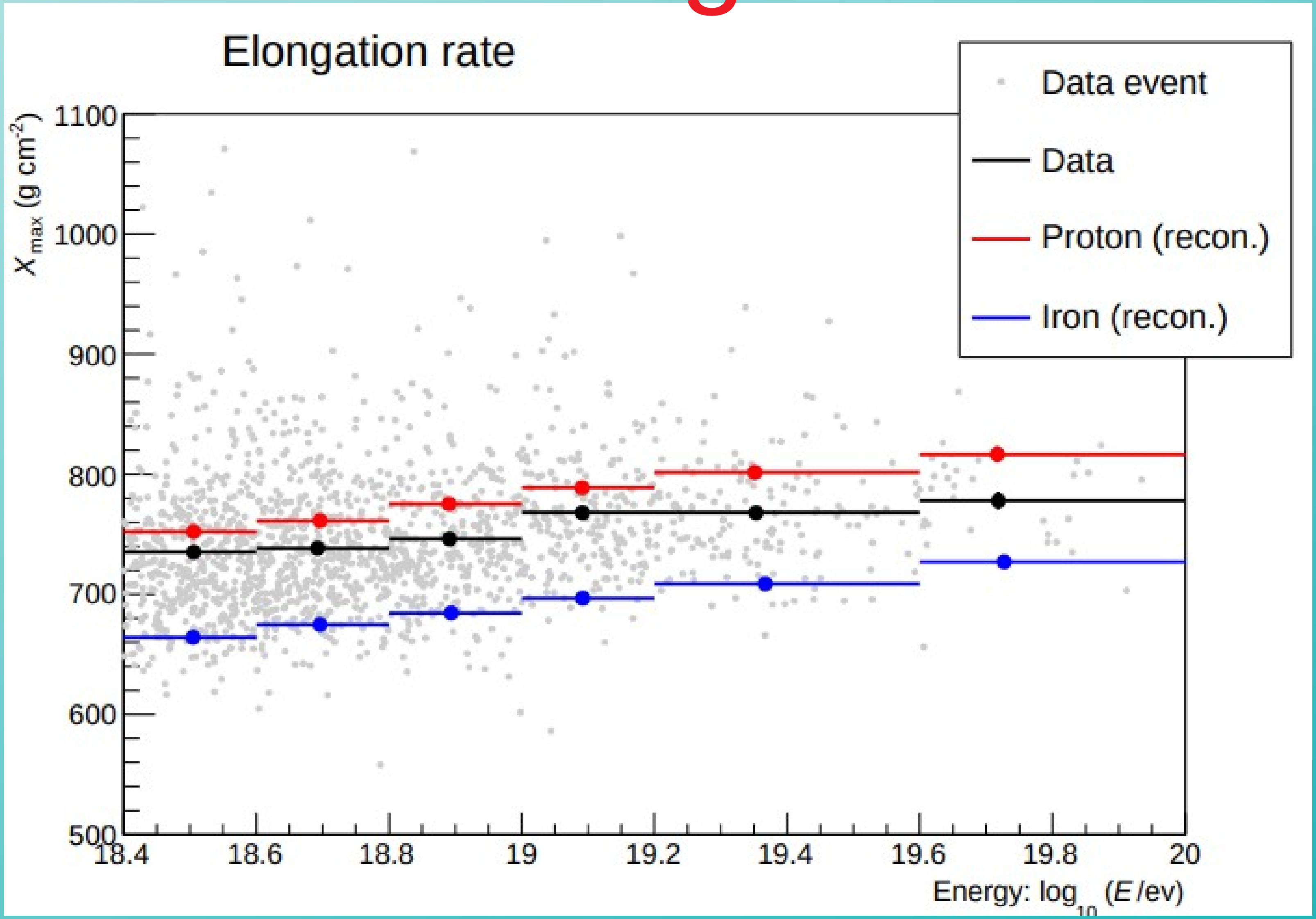
EBL & CMB

$$\beta^{ee}(E) = \frac{1}{E}\frac{dE}{d\tau}(E)$$

$$d\tau = H(t)\,dt = $$
$$= d\ln(1+z)$$

Γ = E/M is Lorentz-factor

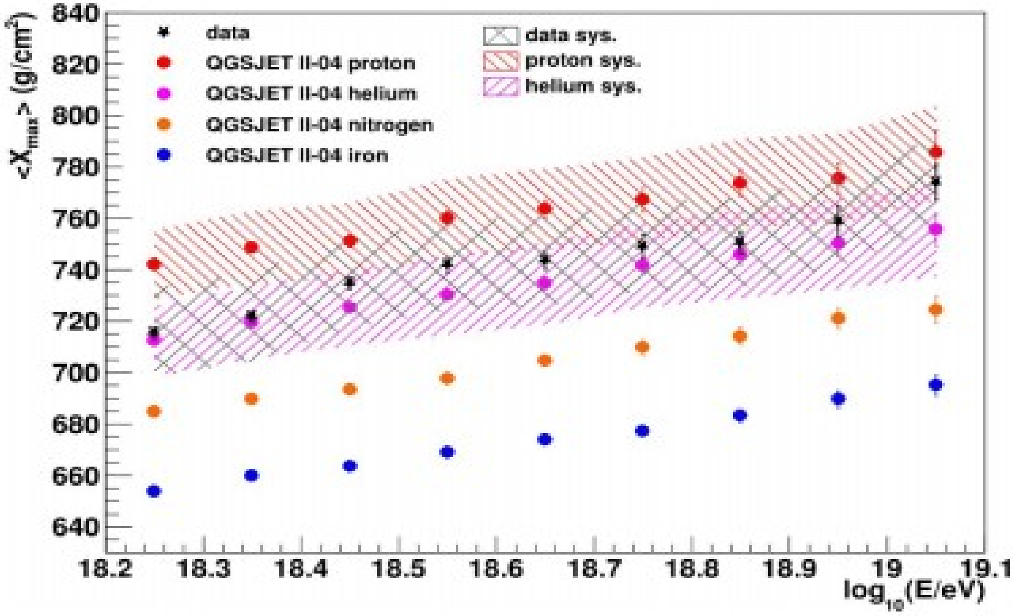
TA elongation rate



D.R. Bergman & T.A. Stroman, ICRC 2019

“We find that for all hadronic models considered, the data collected is consistent with a chiefly light UHECR composition”.

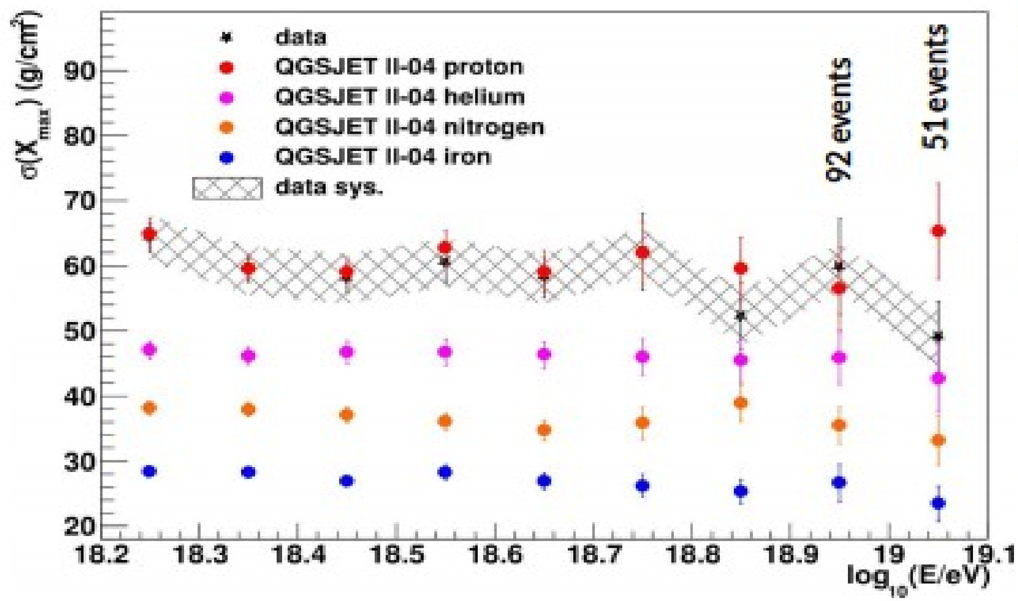
TA mass composition



< Xmax > along with predictions of QGSJET II-04 p, He, N and Fe

10 years data $10^{18.2}$ to $10^{19.1}$ eV
3560 events after the quality cuts

Systematic uncertainty on <Xmax> is 17 g/cm²
Xmax bias < 1 g/cm²
Xmax resolution = 17.2 g/cm²
Energy resolution = 5.7 %

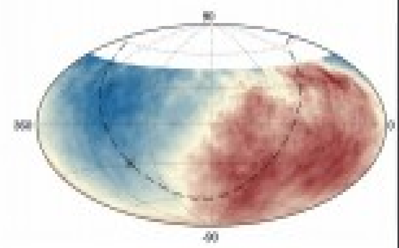


σ_{Xmax} along with predictions of QGSJET II-04 p, He, N and Fe
The measured data are compatible with the protons below 10^{19} eV.

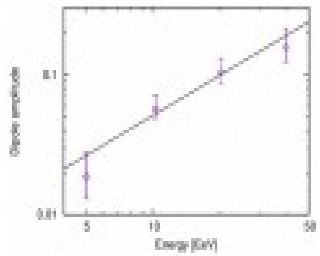
Quality cuts:
D_{border}>100m, FD track length > 10°, # FD good PMT > 11, SDP angle < 130°, FD track > 7us, Θ < 55°, Xmax in FOV, Good weather

PAO anisotropy

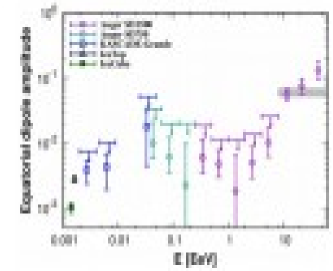
- the bin above 8 EeV has the most significant departure from isotropy, with $d = 0.066^{+0.012}_{-0.008}$ and 125° away from GC, indicative of an extragalactic origin



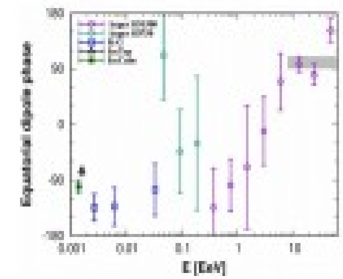
- above 4 EeV the dipole amplitude grows with energy



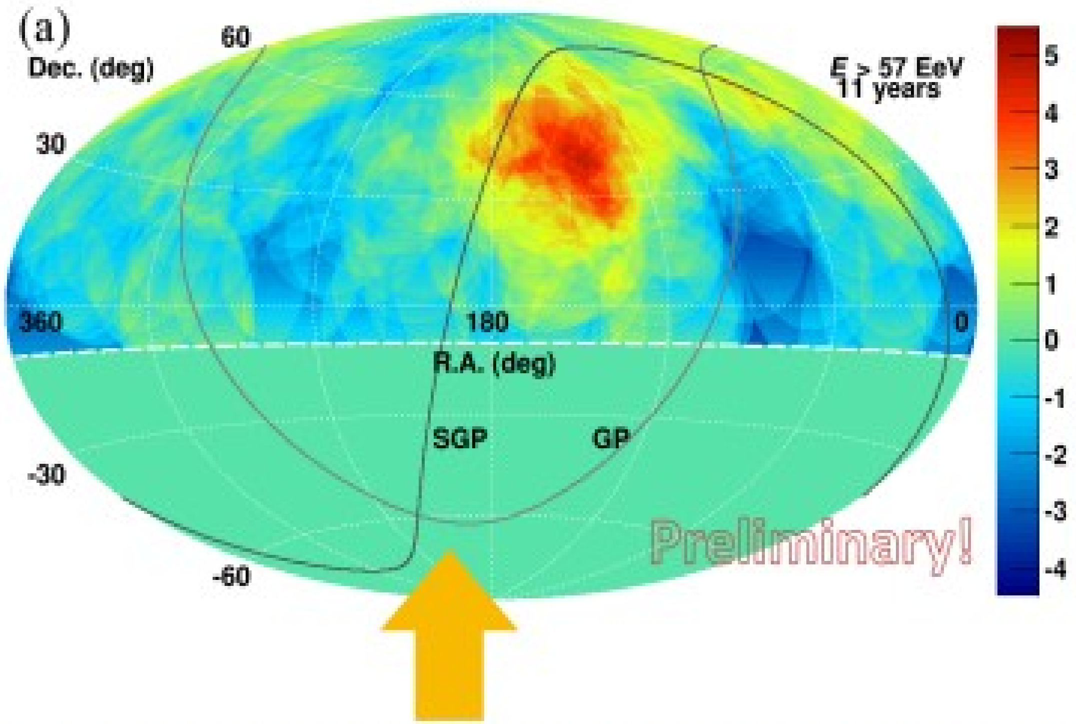
- below 8 EeV the amplitudes are not significant
  99% CL upper bounds on $d_\perp$ are at the level of 1 to 3%



- results on the right ascension phases suggest that the anisotropy has a predominantly Galactic origin below 1 EeV and a predominantly extragalactic origin above few EeV



TA hotspot



Original hotspot reported in 2014, from 5 years of data

Ap. J., 790, L21(2014)

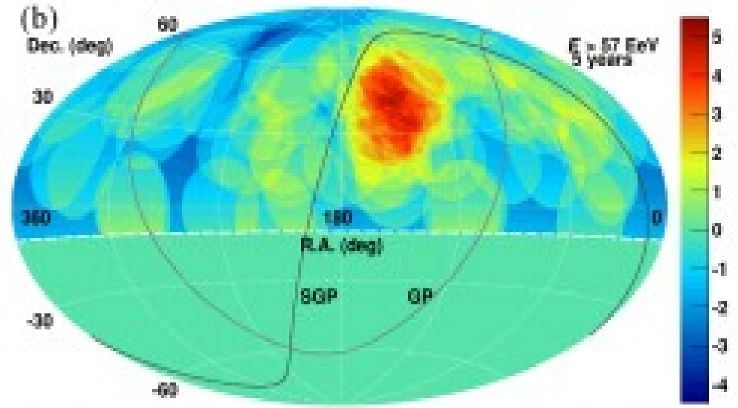
E > 57 EeV (Observed 72 events)

20° over-sampling circle

19 events fall in "Hotspot" centered at (146.7°, 43.2°)

(Expected = 4.5 events)

local significance 5.1σ, post trial significance 3.4σ



Hotspot from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

E > 57 EeV, in total 168 events

38 events fall in Hotspot (α=144.3°, δ=40.3°, 25° radius, 22° from SGP), expected=14.2 events

local significance = 5.1 σ, chance probability → 2.9σ

25° over-sampling radius shows the highest local significance (scanned 15° to 35° with 5° step)

Combined anisotropy cont.

Relatively low energies

$1\ \text{EeV} \le E < 3.2\ \text{EeV}$: **isotropic** flux → fraction of Galactic protons $\lesssim 10\%$ / $\le 1.3\%$ at 95% C.L. (Auger 2013, TA 2017)

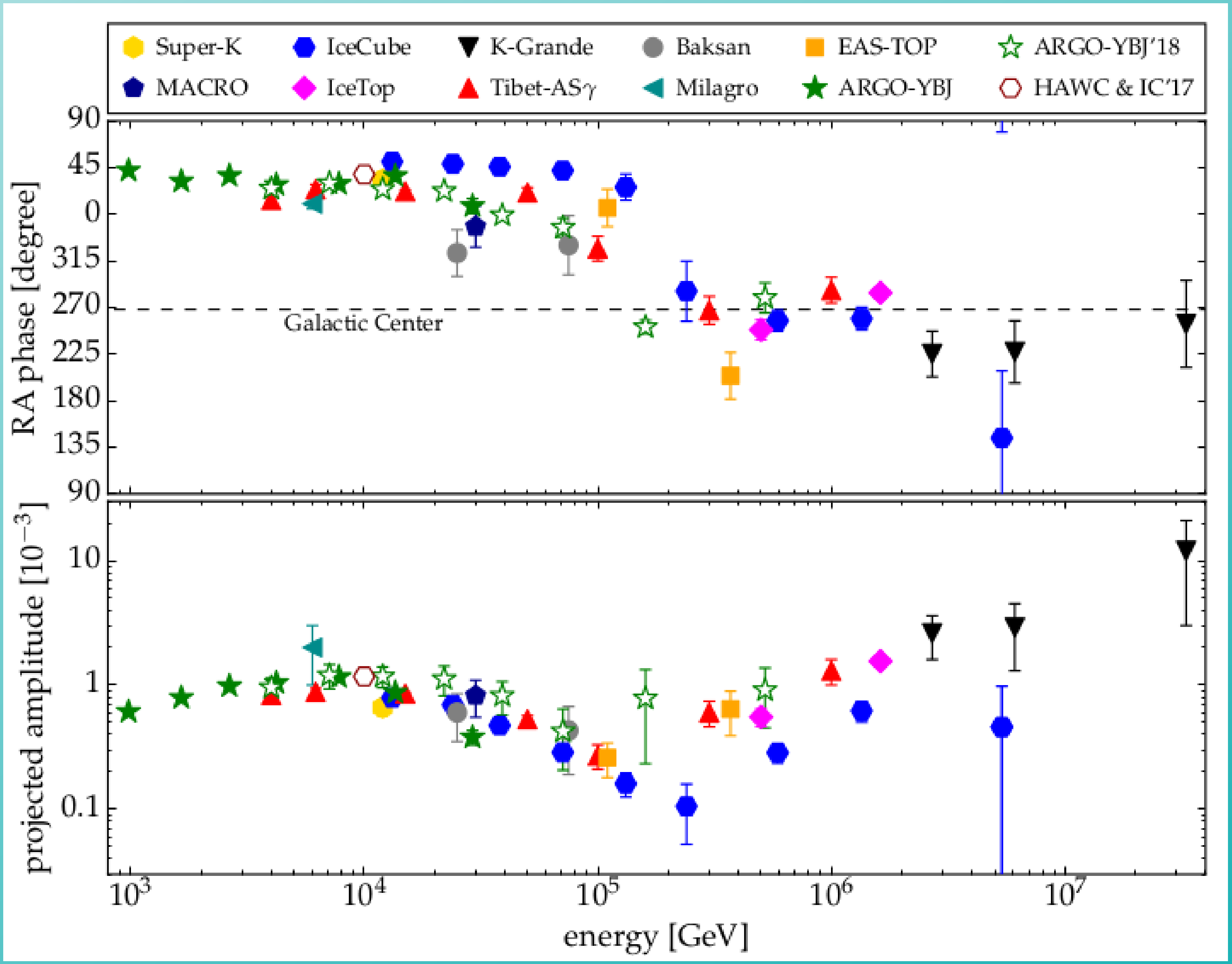
$E \ge 4\ \text{EeV}$: **dipole** moment $(5.5 \pm 0.8)\% \times \left(\frac{E}{10\ \text{EeV}}\right)^{0.8\pm0.2}$; no statistically significant quadrupole (Auger 2018)

The highest energies

$E \ge 39\ \text{EeV}$: indication of correlation with positions and fluxes of nearby **starburst galaxies** $(13^{+4}_{-3})^\circ$ smearing, plus $(90 \pm 4)\%$ isotropic background (Auger 2018) (TA 2018: not enough data to confirm or refute)

$16\ \text{EeV} \le E < 56\ \text{EeV}$ and $E \ge 56\ \text{EeV}$: indication of a **coldspot** and a **hotspot** (respectively) 28°-radius around $(9^h\ 15^m, +45^\circ)$ (Ursa Major/Lynx) in the northern hemisphere (TA 2018)

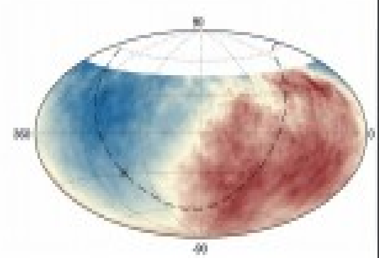
Dipole Anisotropy



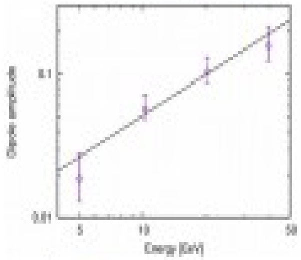
M. Ahlers, J. Phys. Conf. Ser. 1181 012004 (2019)

PAO anisotropy

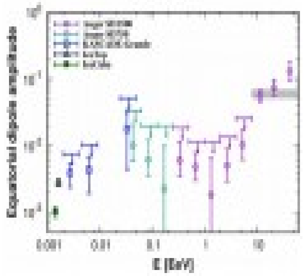
- the bin above 8 EeV has the most significant departure from isotropy, with $d = 0.066^{+0.012}_{-0.008}$ and 125° away from GC, indicative of an extragalactic origin



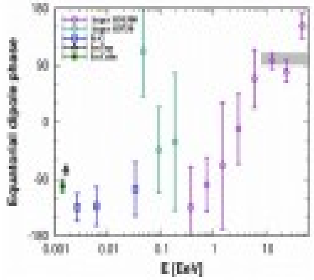
- above 4 EeV the dipole amplitude grows with energy



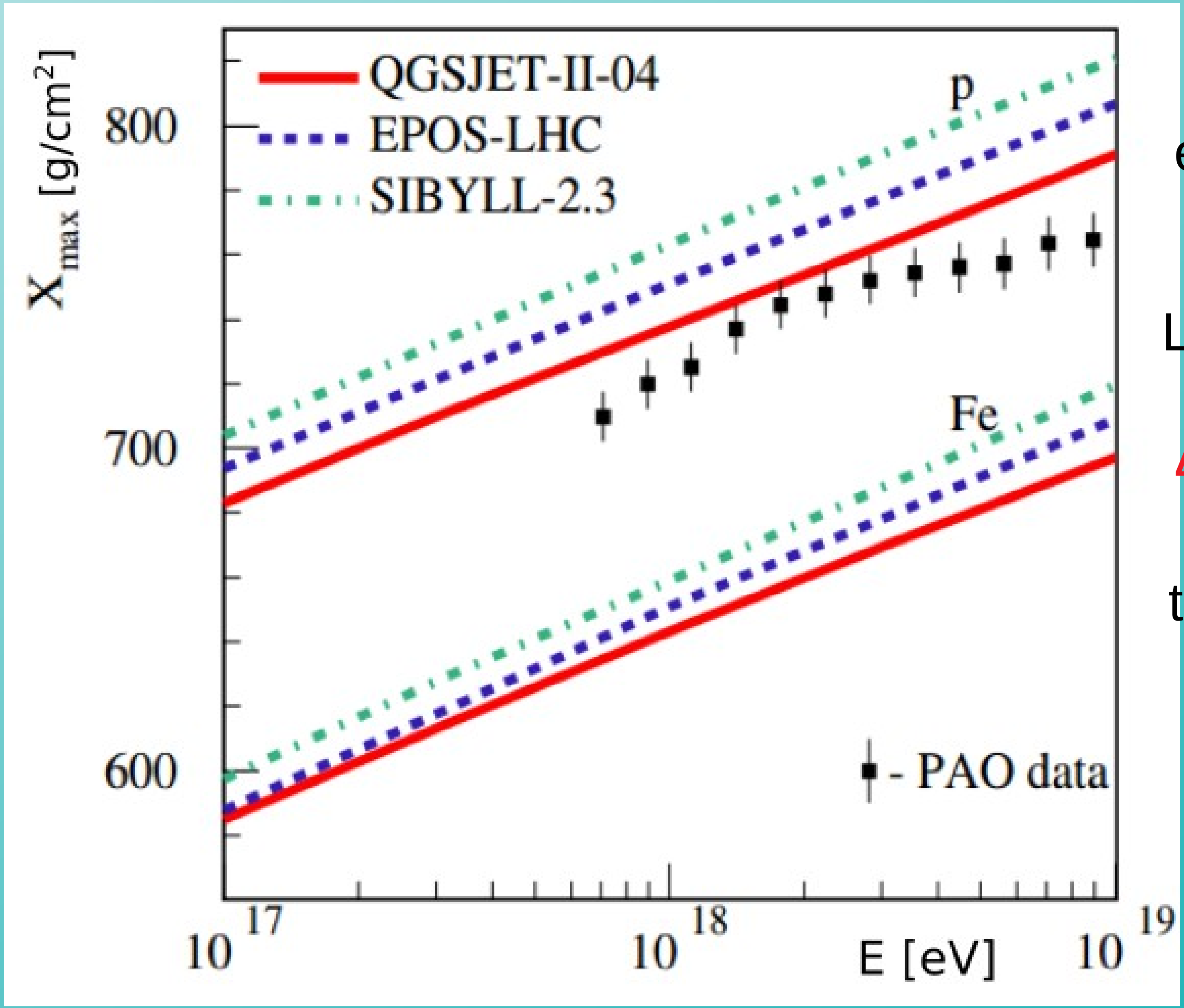
- below 8 EeV the amplitudes are not significant
  99% CL upper bounds on $d_\perp$ are at the level of 1 to 3%



- results on the right ascension phases suggest that the anisotropy has a predominantly Galactic origin below 1 EeV and a predominantly extragalactic origin above few EeV



Hadronic interaction models



At the highest energies differences between the depth predictions by the LHC-updated models

$\Delta X_{max} \simeq 40$ g/cm^2.

It's 2 times higher than the experimental accuracy.

Why?

$\pi+A$ and $K+A$ interactions ⇨ μ's

TOTEM cross-sections

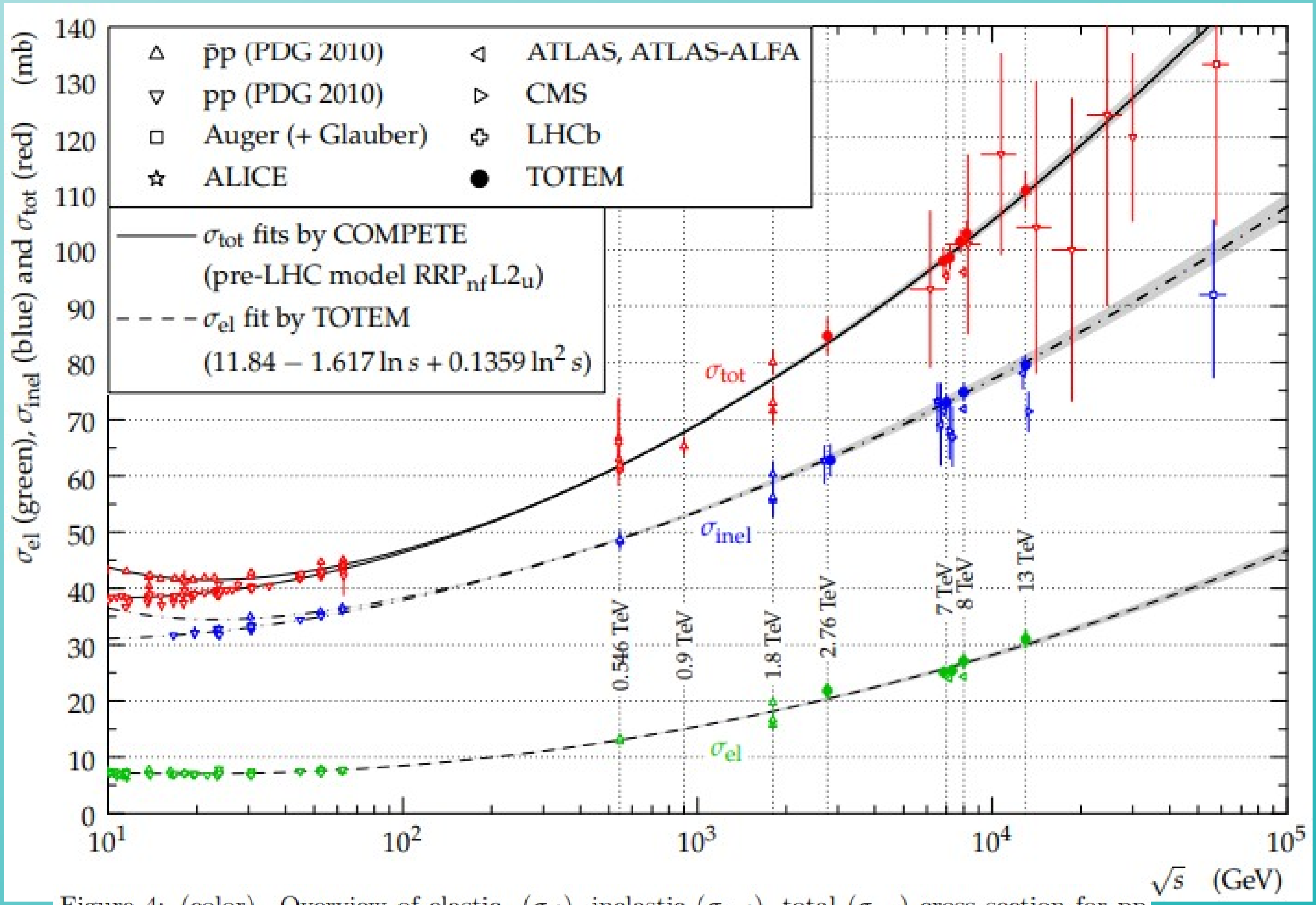
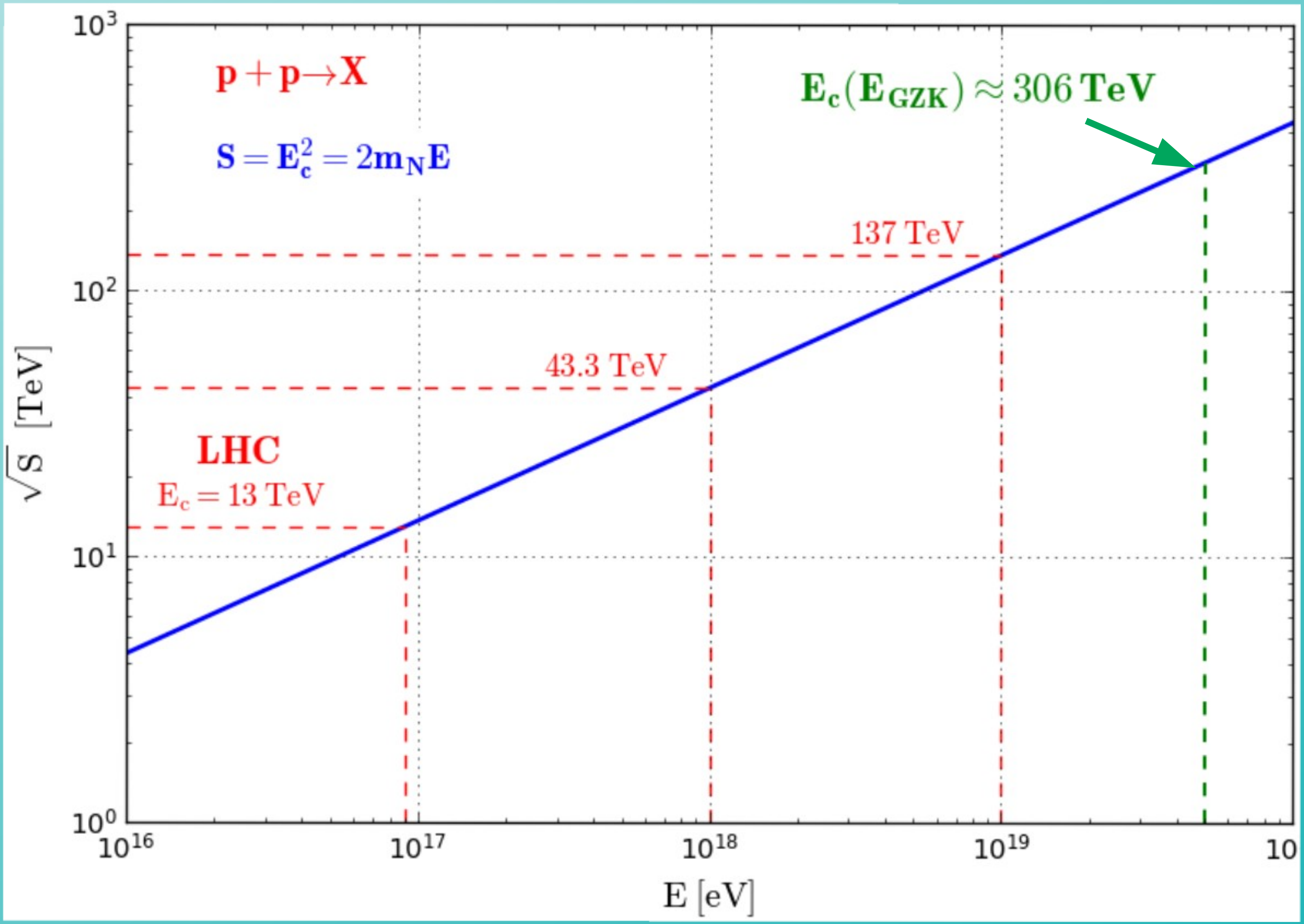


Figure 4: (color). Overview of elastic (σ_{el}), inelastic (σ_{inel}), total (σ_{tot}) cross section for pp and p$\bar{\text{p}}$ collisions as a function of $\sqrt{s}$, including TOTEM measurements over the whole energy range explored by the LHC [1, 2, 4–6, 10, 13, 22–31]. Uncertainty band on theoretical models and/or fits are as described in the legend. The continuous black lines (lower for pp, upper for p$\bar{\text{p}}$) represent the best fits of the total cross section data by the COMPETE collaboration [32]. The dashed line results from a fit of the elastic scattering data. The dash-dotted lines refer to the inelastic cross section and are obtained as the difference between the continuous and dashed fits.

E_c vs. E for pp-interactions

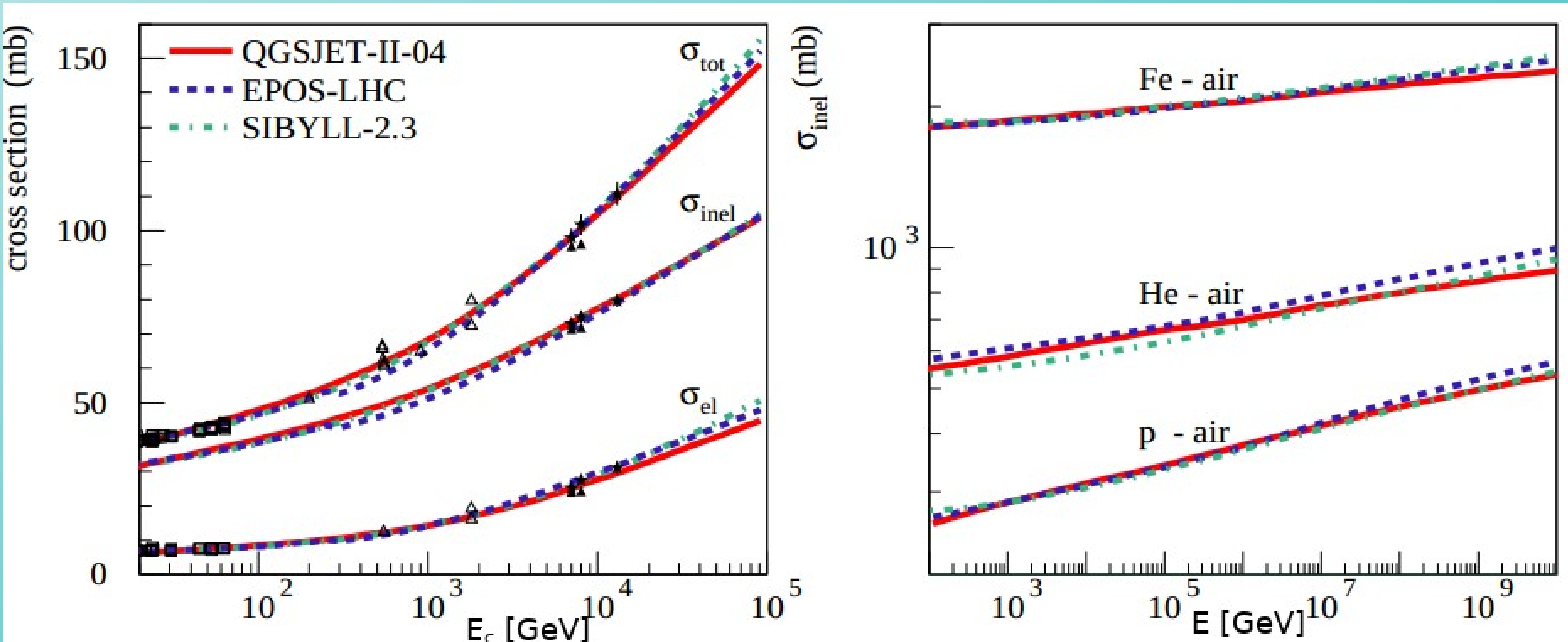


$R_{LHC} \approx 4.243$ km

$E_c \propto q \times B \times R$

We need **Super LHC** with **R ≃ 100 km** ! (if *B* remains the same).

LHC data

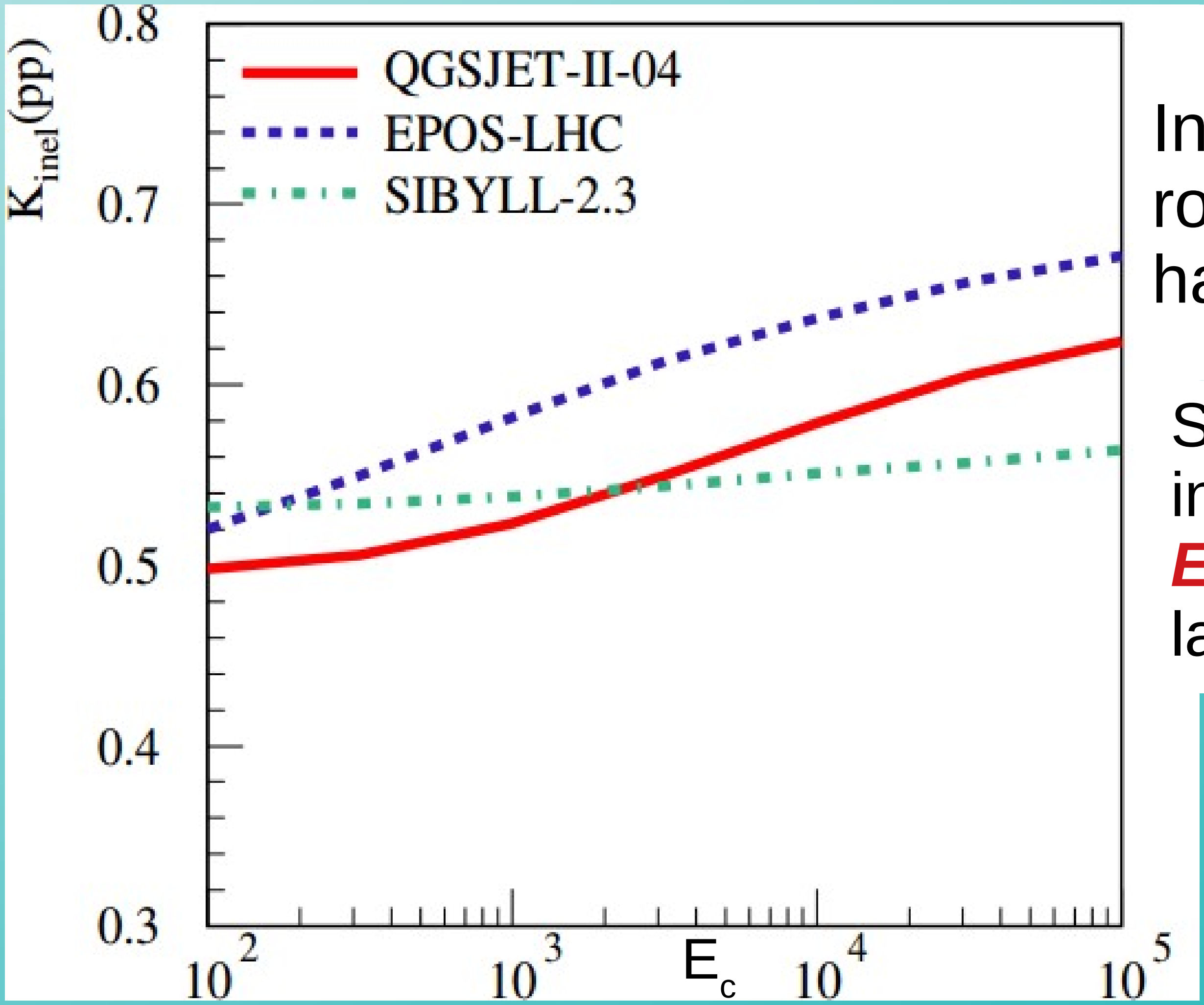


TOTEM and ***ATLAS*** data
compared to different models

Inelastic cross-sections calculated
with the same models

LHC provides a valuable information on the properties of high energy **pp**, **p**-**nucleus**, and **nucleus-nucleus** interactions.
S.Ostapchenko, *EPJ Web Conf. 210 (2019) 02001*

Inelasticity



Inelasticity plays a crucial role for ***MC*** simulations of hadron-hadron interactions.

Slow energy-rise of the inelasticity implies a larger ***EAS*** elongation rate ⇨ a larger X_{max} at high energies

Inelasticity of leading nucleons in ***pp***-collisions