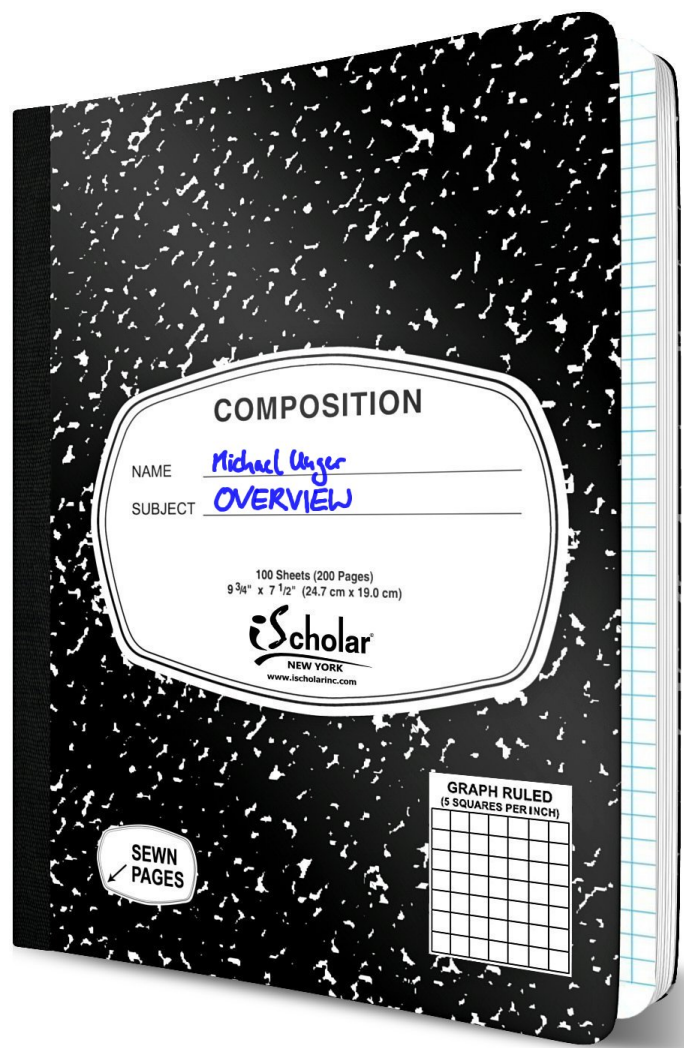
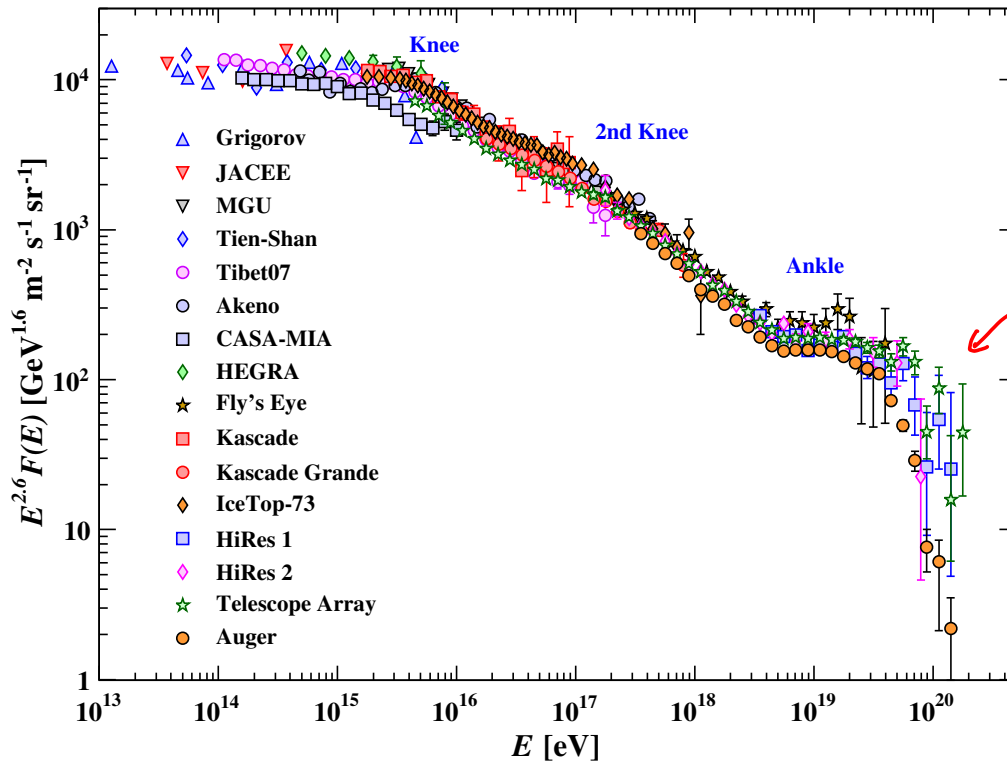




Energy Spectrum of Cosmic Rays ($E > 10^{13}$ eV)

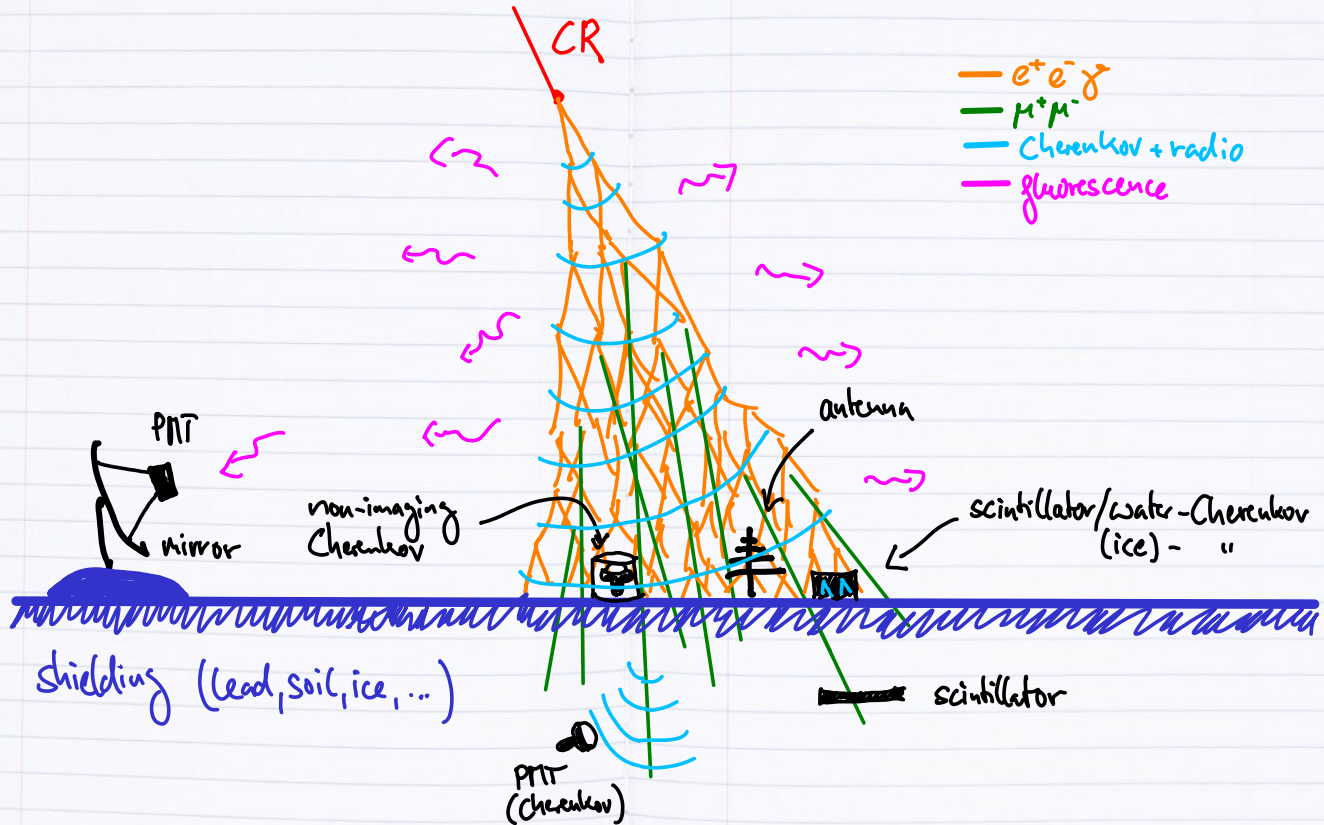


$$E_{\text{lab}} > 10^{20} \text{ eV}$$

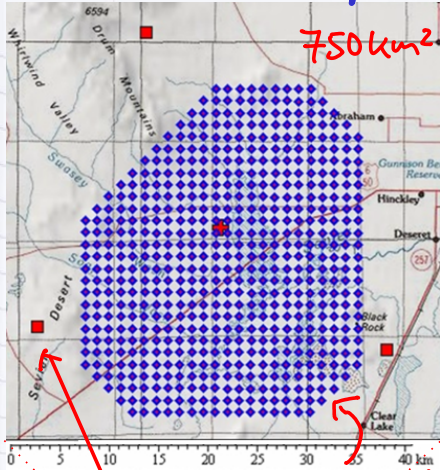
$$\sqrt{s} > 400 \text{ TeV}$$

$$L \sim \frac{1}{\text{km}^2 \text{ century}}$$

Air Shower Measurements

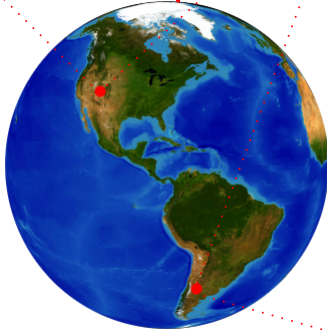


Telescope Array

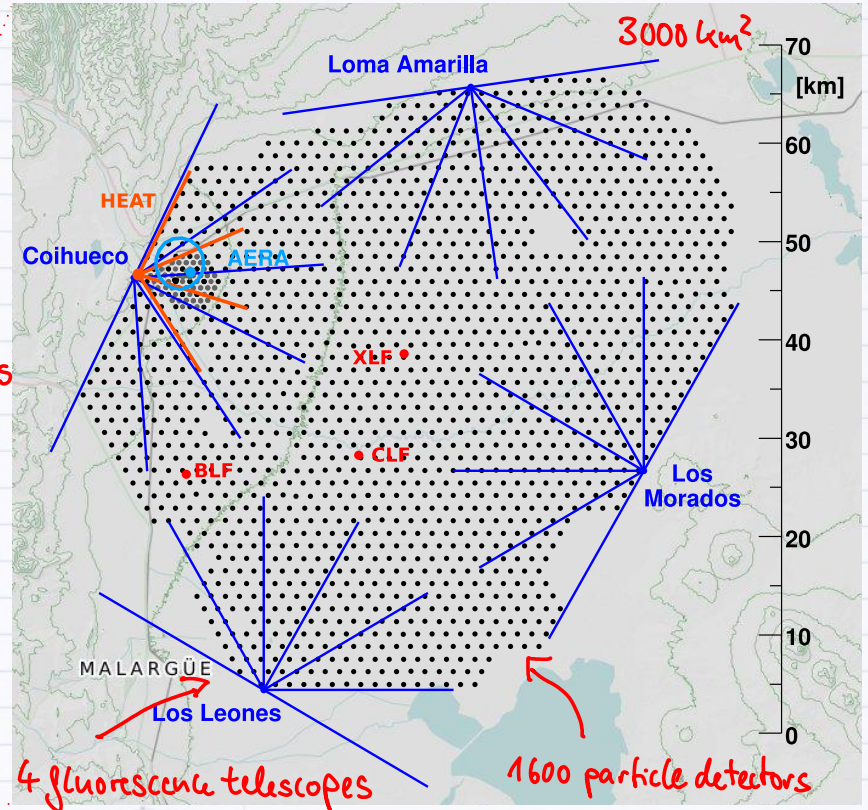


3 fluorescence telescopes

507 particle detectors



Pierre Auger Observatory



4 fluorescence telescopes

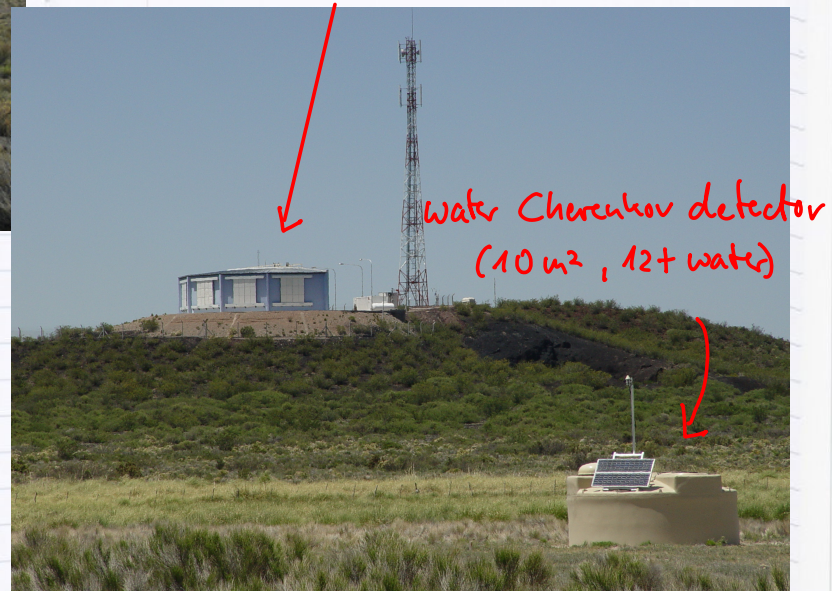
1600 particle detectors

Telescope Array



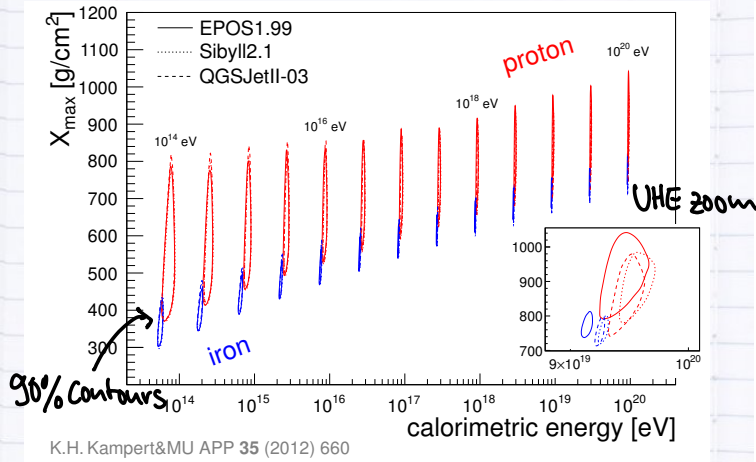
Pierre Auger Observatory

← air fluorescence telescope



Mass Estimate: a) X_{max}

(fluorescence detectors, non-imaging $\checkmark$, radio)



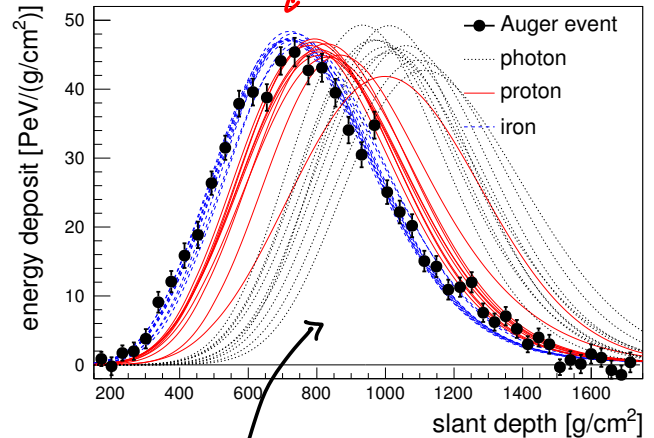
$$\langle X_{max} \rangle \sim D_{10} (\log E - \log A)$$

energy

mass

Longitudinal development:

shower maximum X_{max}



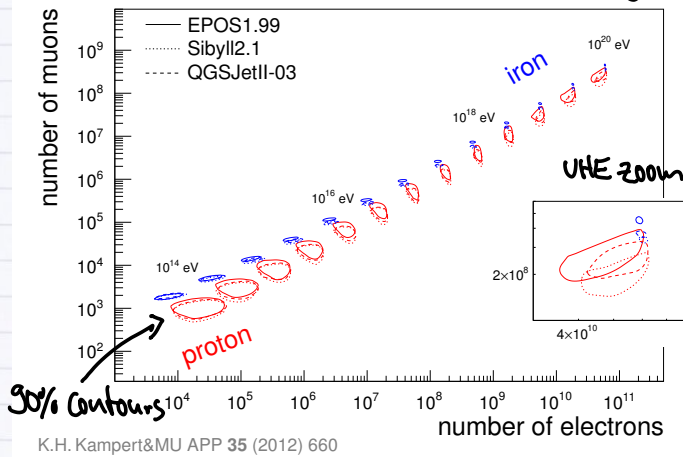
area: calorimetric energy

$$E_{cal} = \int dE/dX \, dX \gtrsim (0.85 \pm 0.05) E_{tot} \quad (E \geq 10^{18} \text{ eV})$$

Mass Estimate: b) N_e / N_μ

(particle detectors)

($x_{\text{ground}} = 800 \text{ g/cm}^2$)

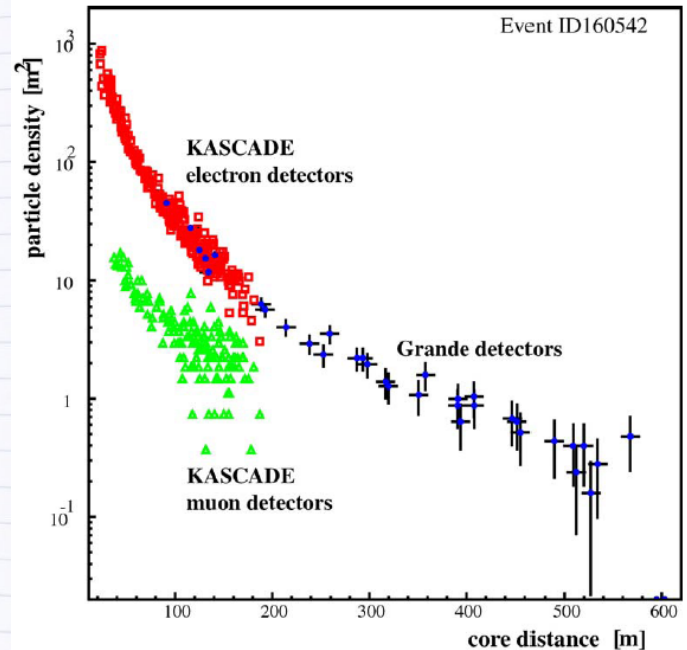


$$N_\mu \sim A \cdot (E/A)^\beta$$

$$N_e \sim e^{-\frac{x_{\text{ground}} - x_{\text{max}}}{\lambda}}$$

$$\sim \exp(-(x_{\text{ground}} - D_{10}(\log E - \log A))/\lambda)$$

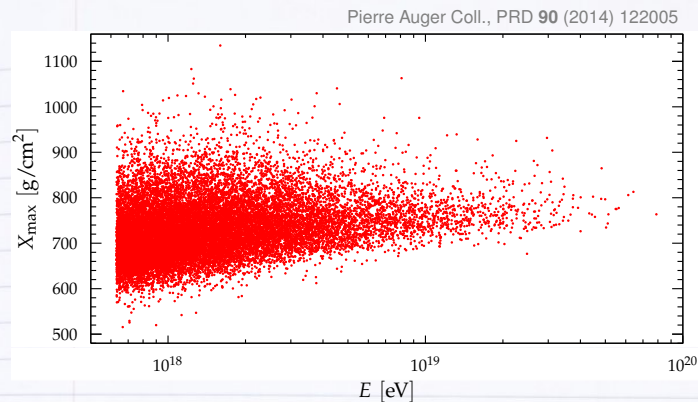
lateral distribution:



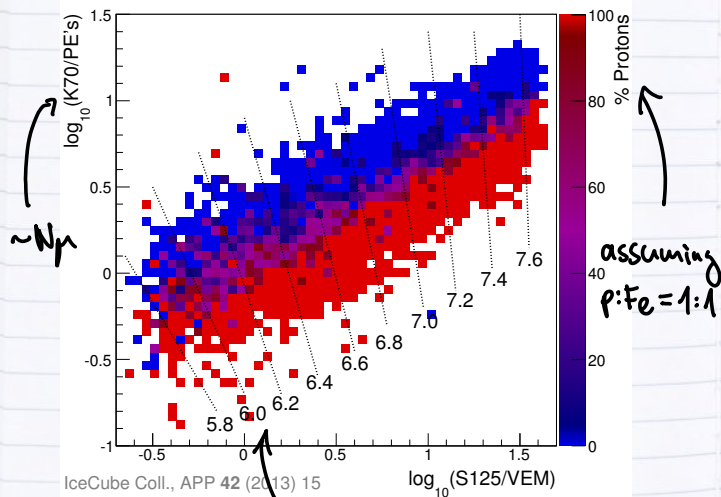
integral $\rightarrow$ total number of particles: N
or
shower size at certain distance: S_r

Examples

Auger fluorescence →



IceCube surface detector vs. in-ice

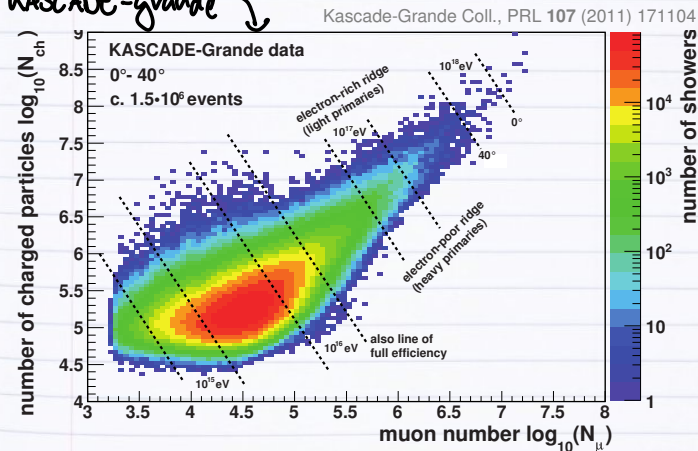


IceCube Coll., APP **42** (2013) 15

$\log(E/\text{GeV})$

$\sim S_e(125m)$

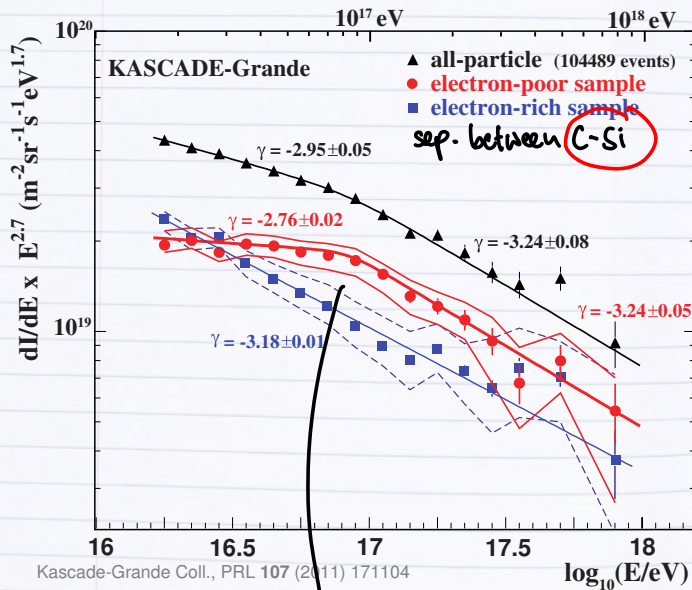
KASCADE-Grande ↓



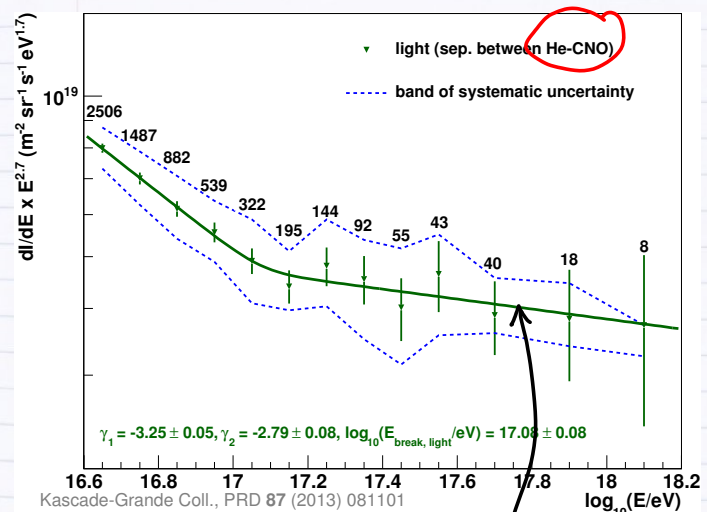
"Iron knee" and "proton ankle"

(KASCADE-Grande)

"K-parameter" method: a) "rotate" N_{ch} - N_p diagram to E - k ($k \sim \log N_{ch}/N_p \sim \log A$)
 b) measure flux for different cuts in k



$E_{\text{break}} \sim 10^{16.9} \text{ eV} \Leftrightarrow E_{\text{max}}^p \approx E_{\text{break}}/26 = 3 \cdot 10^{15} \text{ eV} ?!$

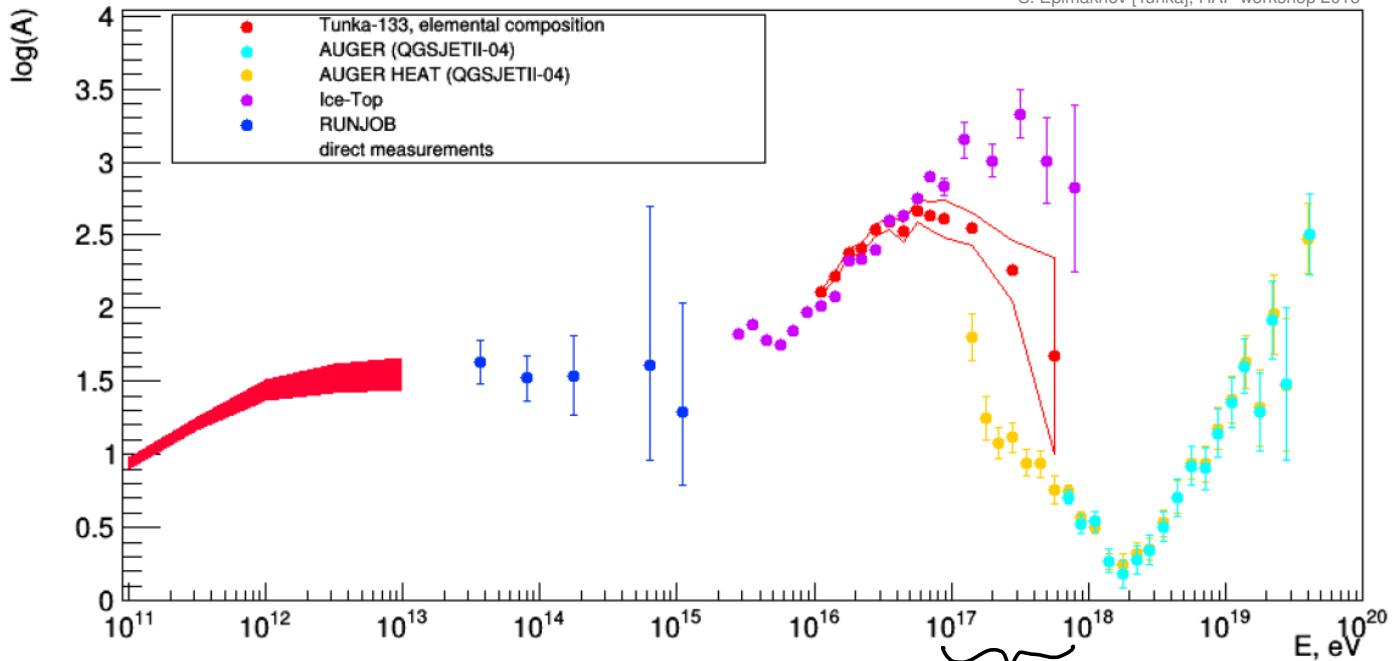


transition to light, extragal component?

Overview of recent "low-energy" results

(new LOFAR data is between Auger + Tunka)

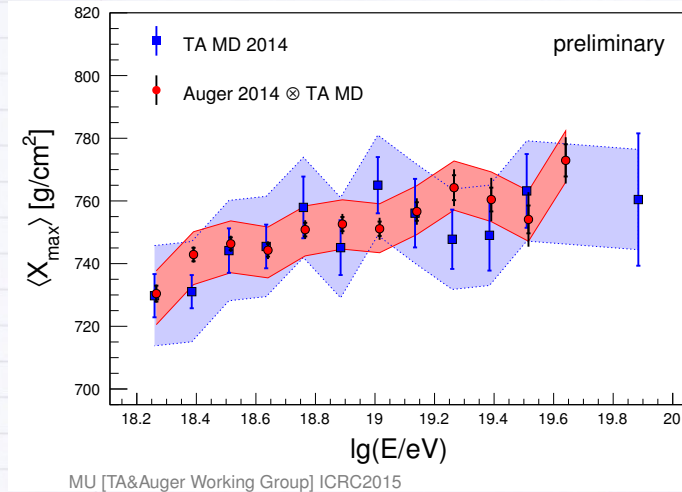
S. Epimakhov [Tunka], HAP workshop 2015



$$\ln A = \sum f_i \ln A_i \sim \langle X_{\max} \rangle$$

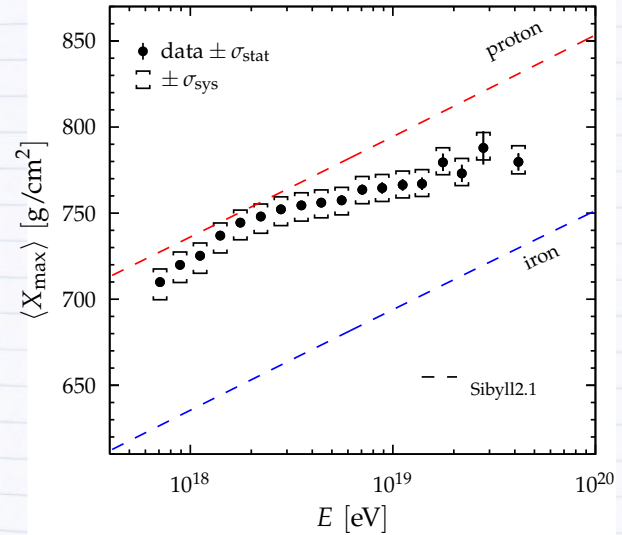
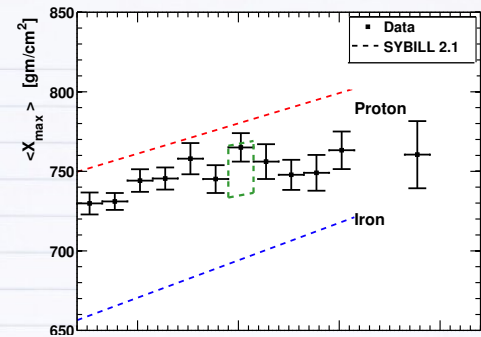
large discrepancies in presumed
region of gal. to egl. CRs ☹️

Composition at Ultrahigh Energies (fluorescence detector results)



$$\langle \Delta_{\max} \rangle = 2.9 \pm 2.7 (\text{stat.}) \pm 18 (\text{syst.})$$

$\Rightarrow$ ok! 😊



Interpretation of $X_{\max}$ Distributions

(using 4 representative masses: p/He/N/Fe)

$\log(E/eV) = 17.8-17.9$

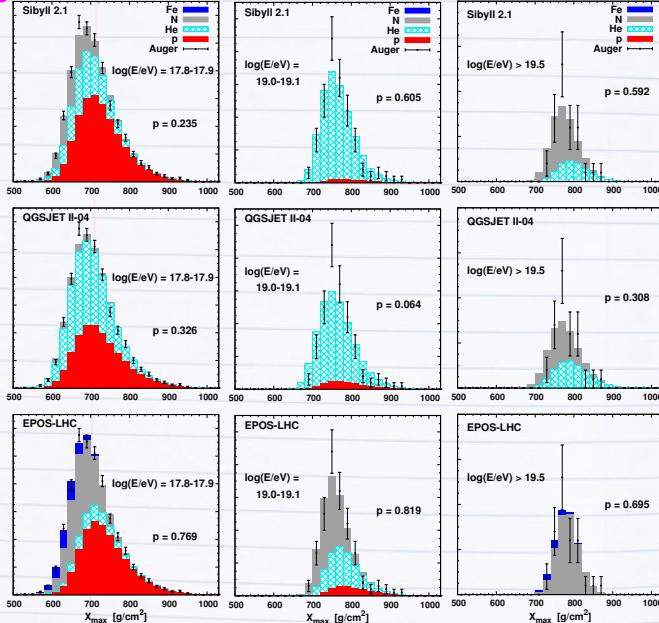
$19.0-19.1$

>19.5

SIBYLL

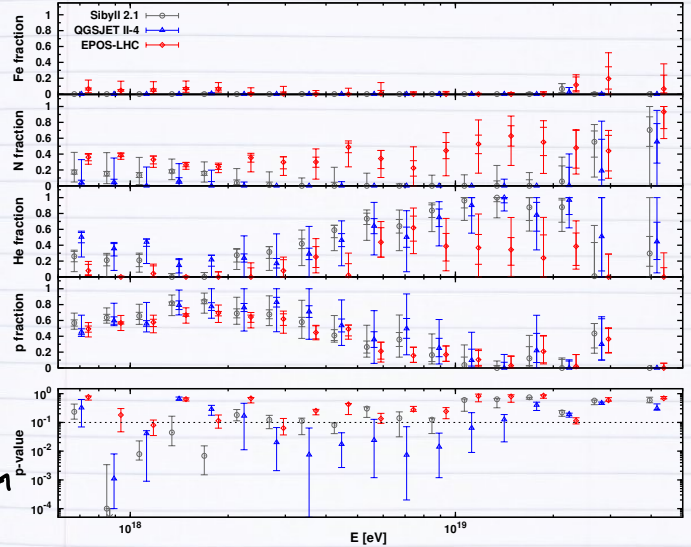
QGSJET II-04

EPOS



fitted fractions:

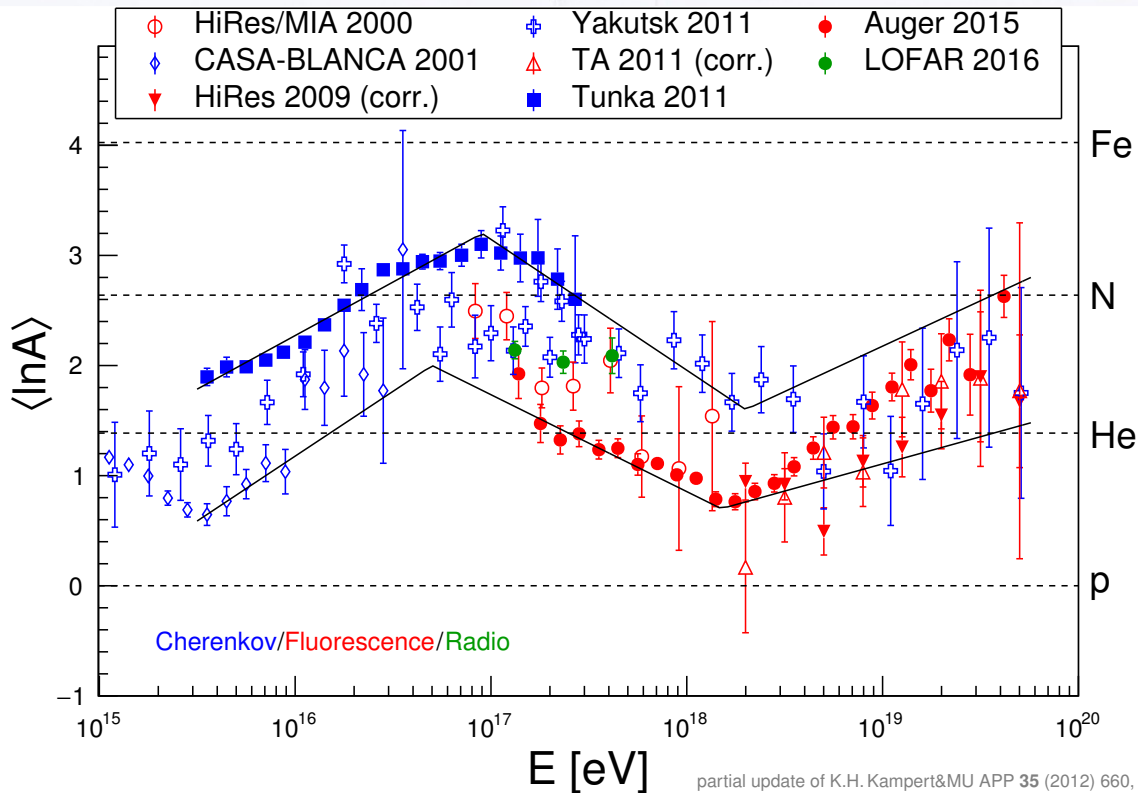
Pierre Auger Coll., PRD 90 (2014) 12, 122006



fit probability (bad fits with QGSjetII-04)

Zig-Zag Plot

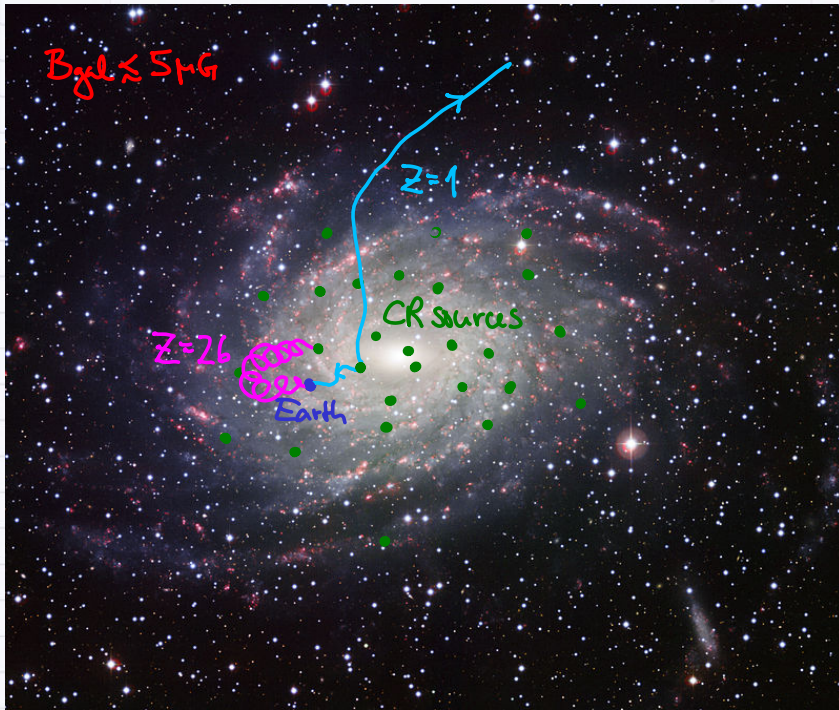
(only X_{max} measurements)



partial update of K.H. Kampert & MU APP 35 (2012) 660, (EPOS1.99)

exp. syst. typically $\geq \pm 10\%$ / $\text{cm}^2 \leftrightarrow \pm 0.4$ in $\langle \ln A \rangle$

Low-Mass Galactic CRs at EeV?



NGC 6744, Wikipedia

- gyro radius of relativistic charge in B-field:

$$R = 1.1 \text{ kpc} \frac{E/10^{18} \text{ eV}}{Z \cdot B/\mu\text{G}}$$

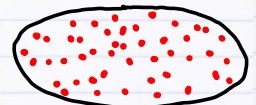
$$\rightarrow R_{18}^1 \lesssim 0.2 \text{ kpc}, R_{18}^{26} \lesssim 0.01 \text{ kpc}$$

- Galaxy: $h \sim 0.3 \text{ kpc}$, $r \sim 15 \text{ kpc}$

$\Rightarrow$ CR arrival directions at 10^{18} eV :



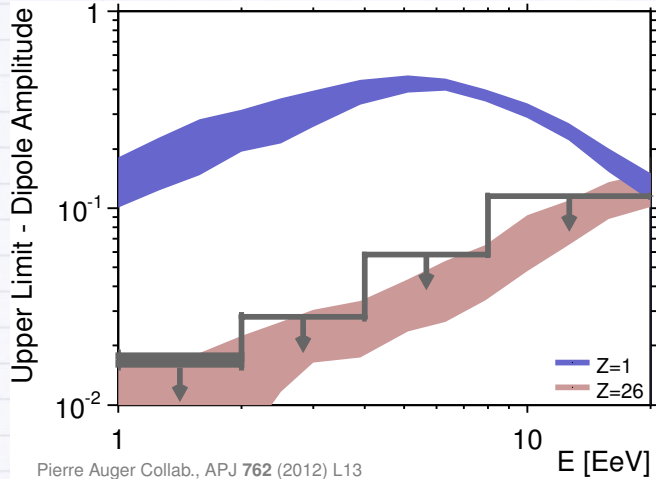
Z=1



Z=26

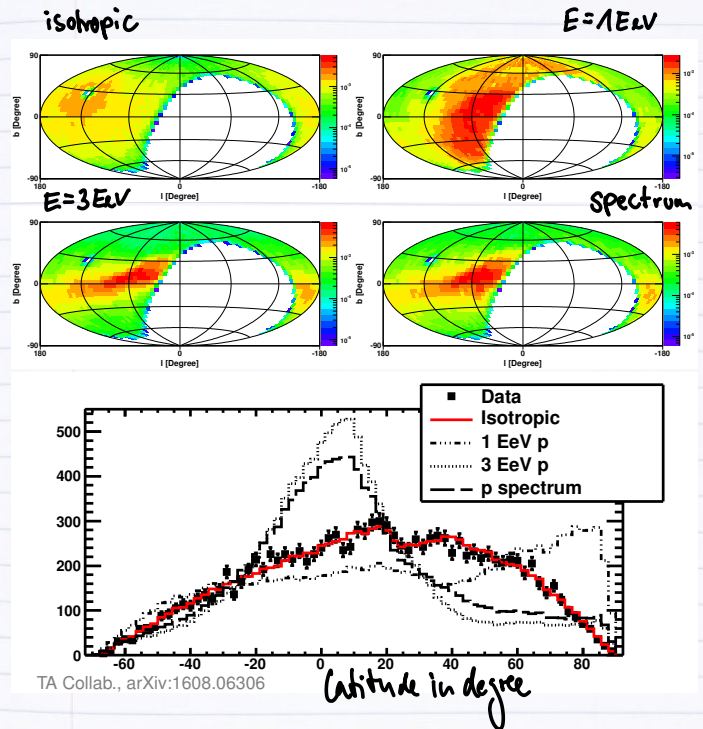
Low-Mass Galactic CRs at EeV?

Auger dipole amplitude limits:

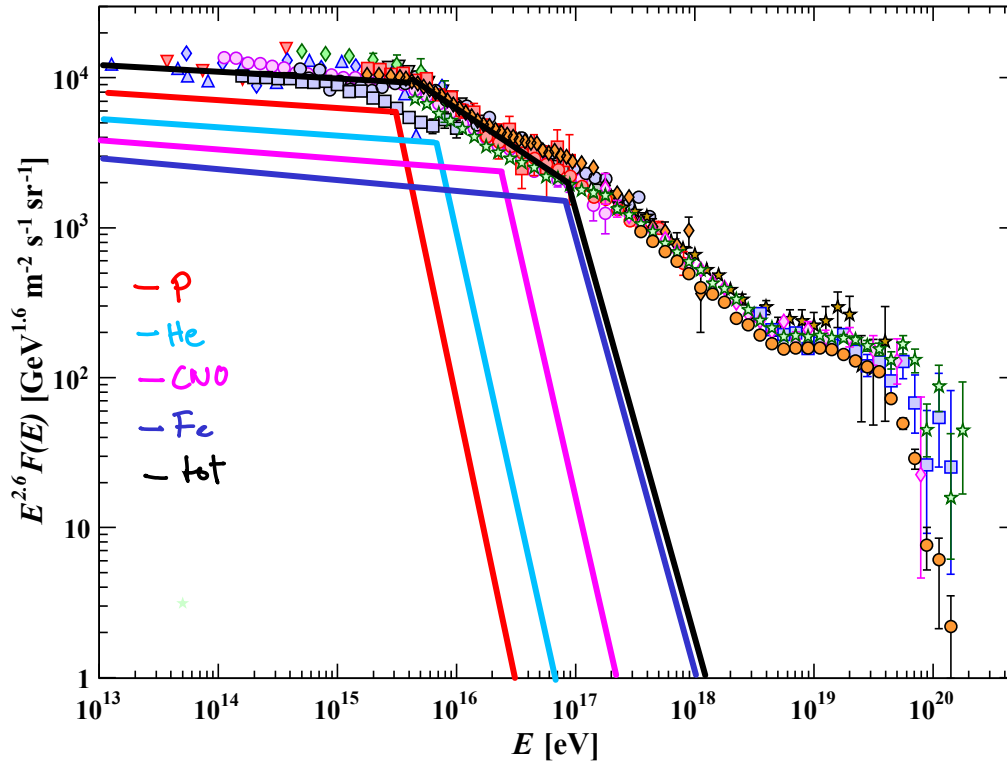


answer: **No!** → if light, then extragalactic!

TA Latitude distribution:



The End of the Galactic Cosmic Ray Spectrum



maximum energy and/or leakage $\sim Z \cdot E$

End of galactic Component?

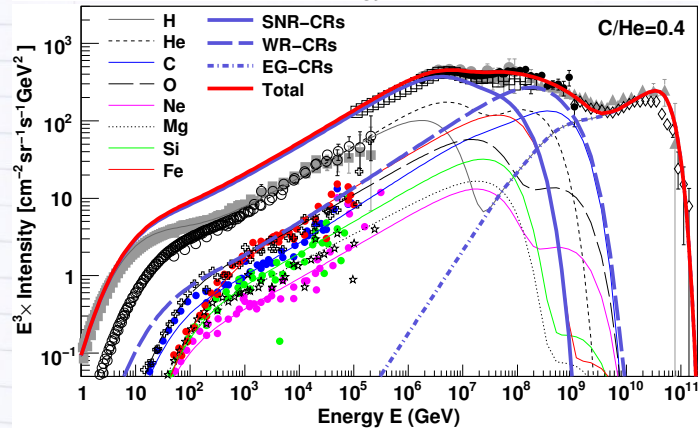
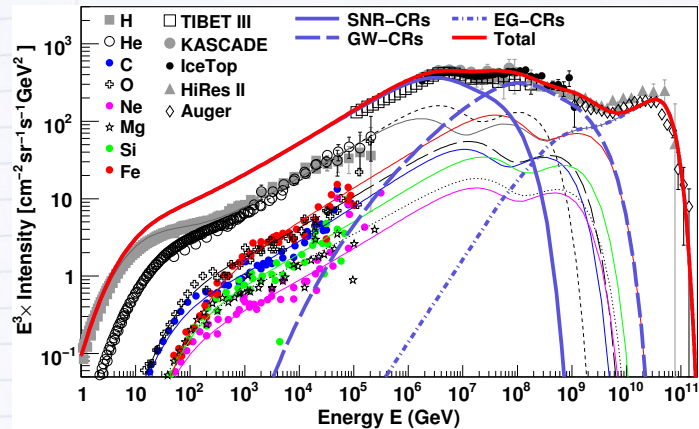
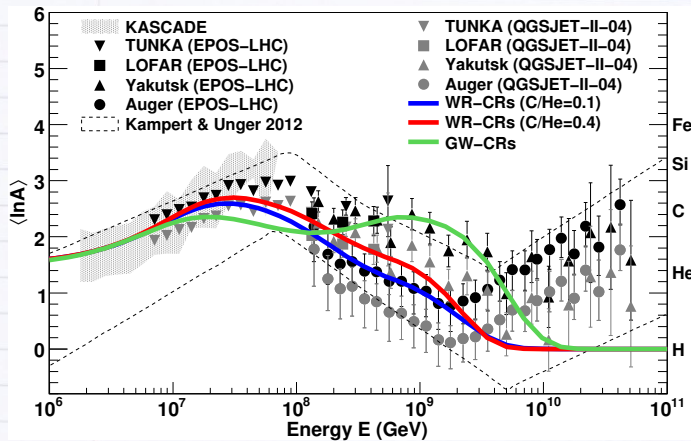
→ SNR $E_{\text{max}} = \text{few } Z \cdot 10^{15} \text{ eV} ?$

→ additional galactic component?

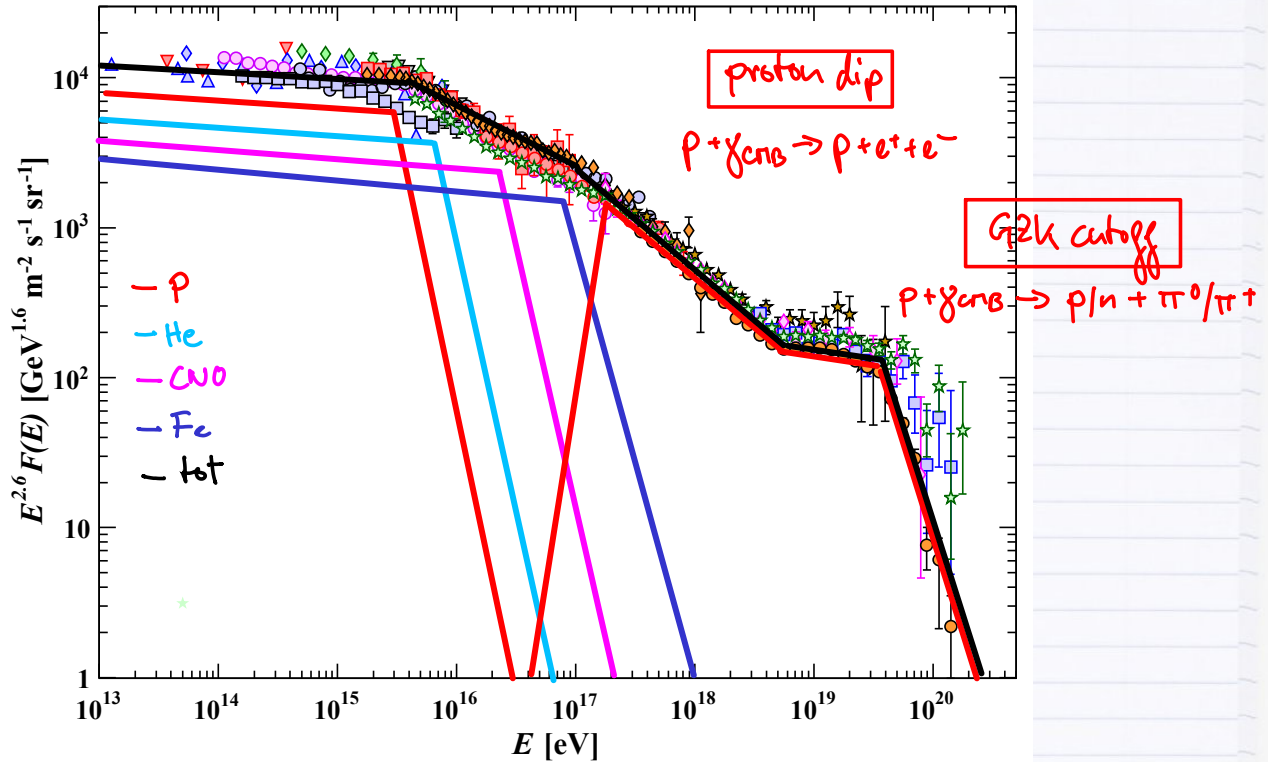
→ Wolf-Rayet stars?

→ re-acceleration at gal. wind termination shock?

→ ... ?

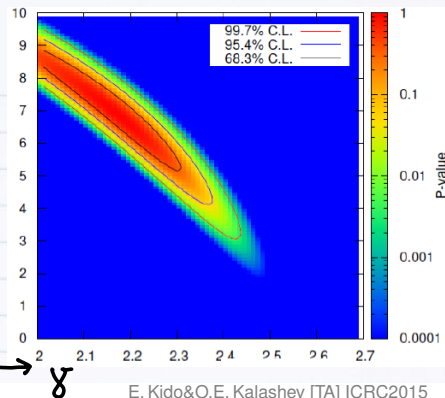


Extragalactic Protons

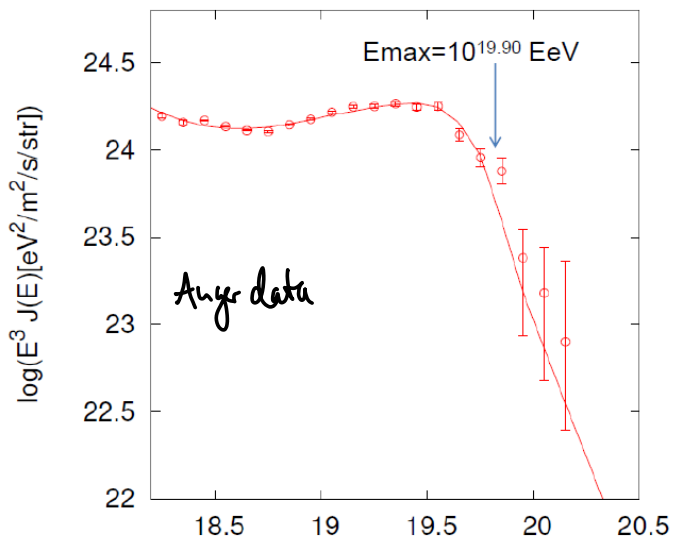


The proton-dip model (composition: >80% proton)

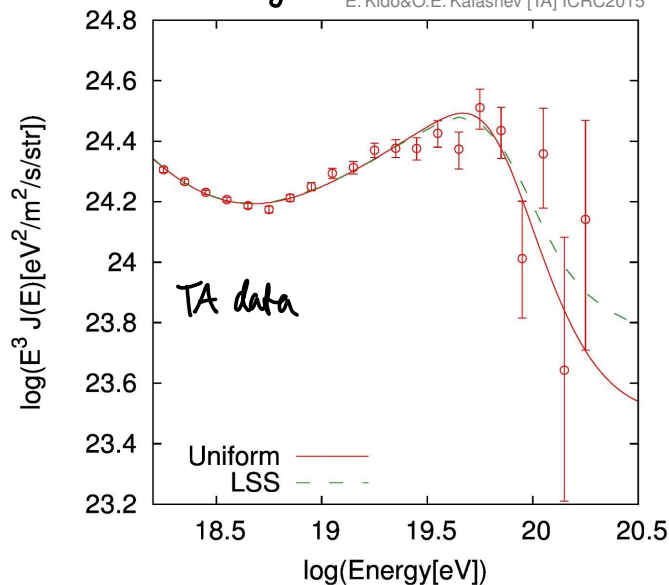
- minimal parameters:
- Source evolution e.g. $\sim (1+z)^m$
 - Spectrum at injection $\sim E^{-\gamma}$
 - if needed: $E_{\max}$



E. Kido & O.E. Kalashev [TA] ICRC2015

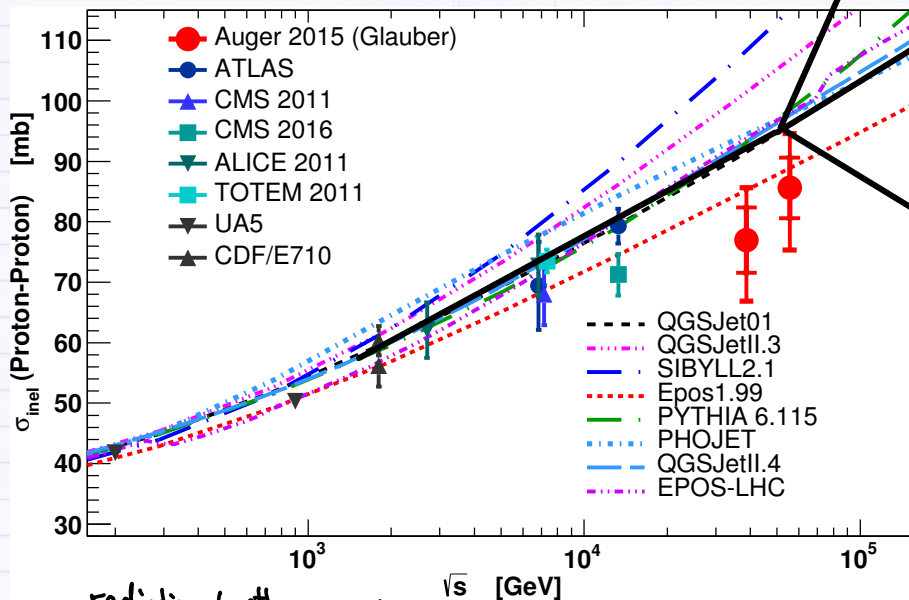


E. Kido & O.E. Kalashev [TA] ICRC2015



Can x_{max} be reconciled with the dip model?

are shower physics wrong at ultra-high energies?



update of R. Ulrich [Pierre Auger Coll.] ICRC2015

$$\langle x_{max} \rangle \sim \lambda_p + X_0 \ln(E/2N\epsilon_0)$$

interaction length $\sim 1/\sigma_{air}$

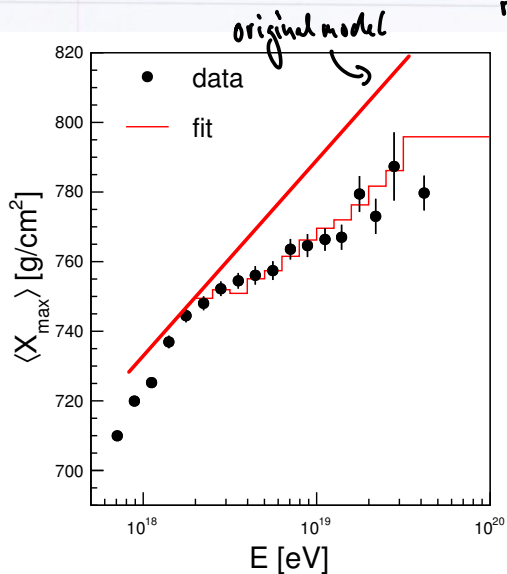
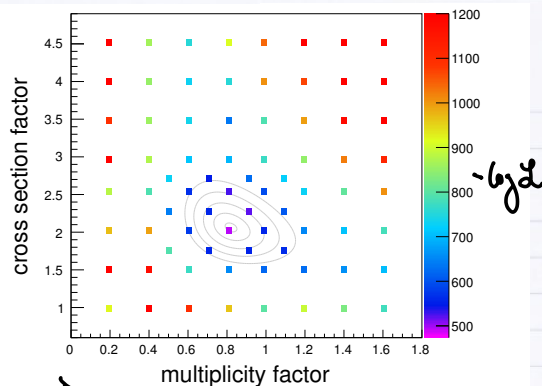
multiplicity

$$\sigma(x_{max})^2 \sim \lambda_p^2 + \left(X_0 \frac{\sigma(N)}{N} \right)^2$$

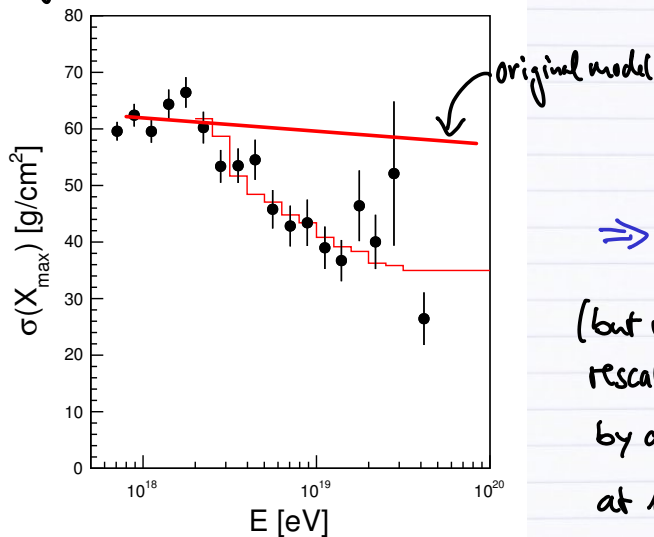
Can $X_{\max}$ be reconciled with the dip model?

→ exotic hadronic interactions?

e.g. linear rescaling of cross section and multiplicity above $10^{18.3}$ eV (AGSjet11-04)



rescaling at $10^{18.3}$ eV

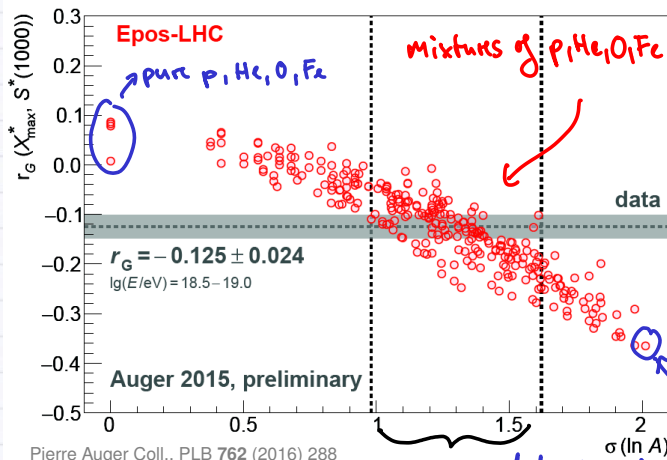


⇒ Works!!

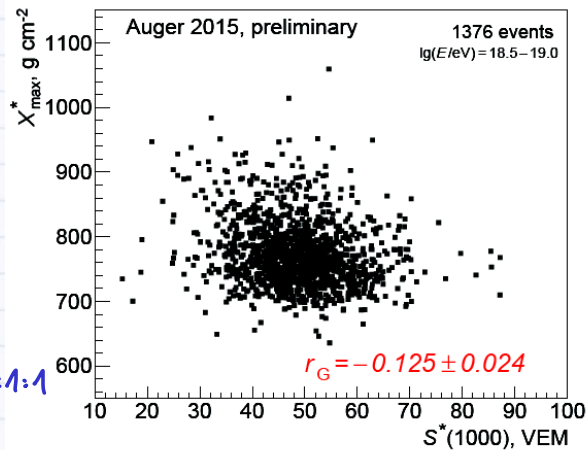
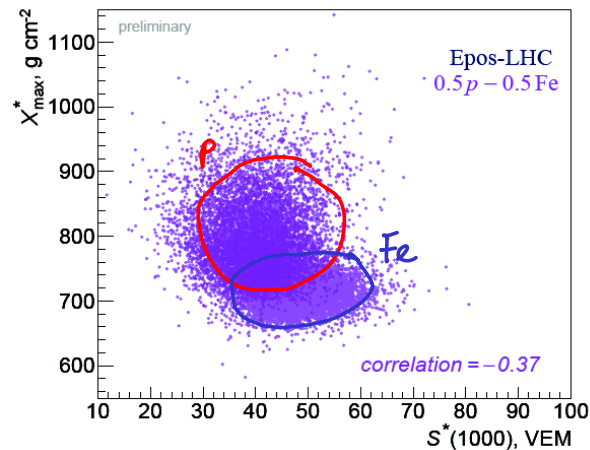
(but very exotic...
rescaling of $\sigma_{p\text{-air}}$
by a factor of 2
at $10^{18.3}$ eV!)

A Model-Independent Test of Composition

- correlation of $X_{\max}$ and ground signal
- pure composition: $r \geq 0$
- mixed composition: $r < 0$
- holds for all models + ad-hoc modifications (incl. the one from the previous slide)

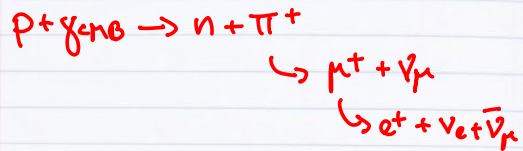


$\Rightarrow$ data is mixed composition!

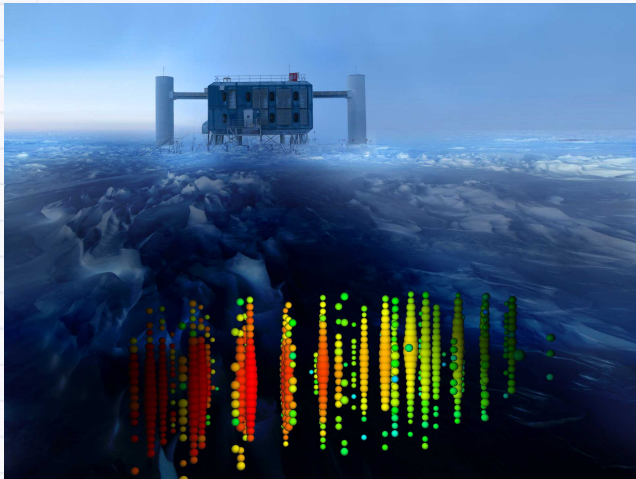


Clues from Secondary Particles

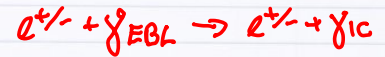
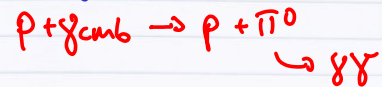
cosmogenic neutrinos



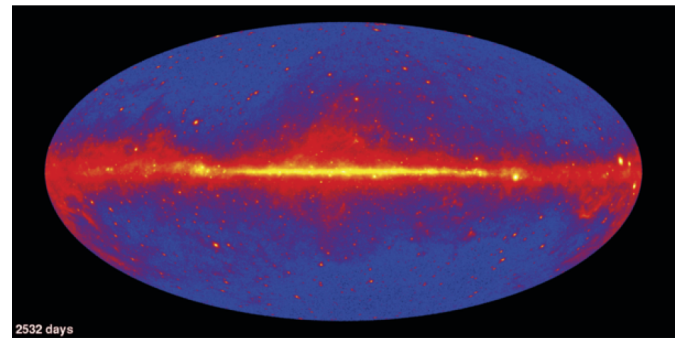
IceCube Neutrino Observatory



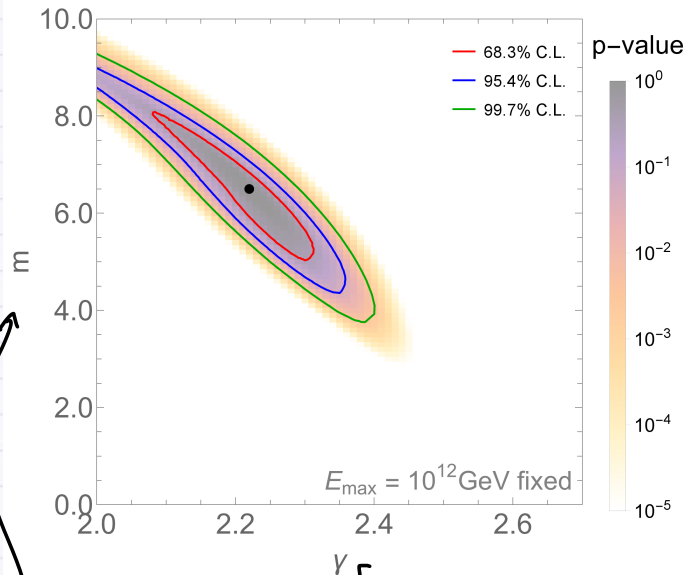
cosmogenic photons:



Fermi LAT γ -ray sky



Dip Model vs. Secondaries

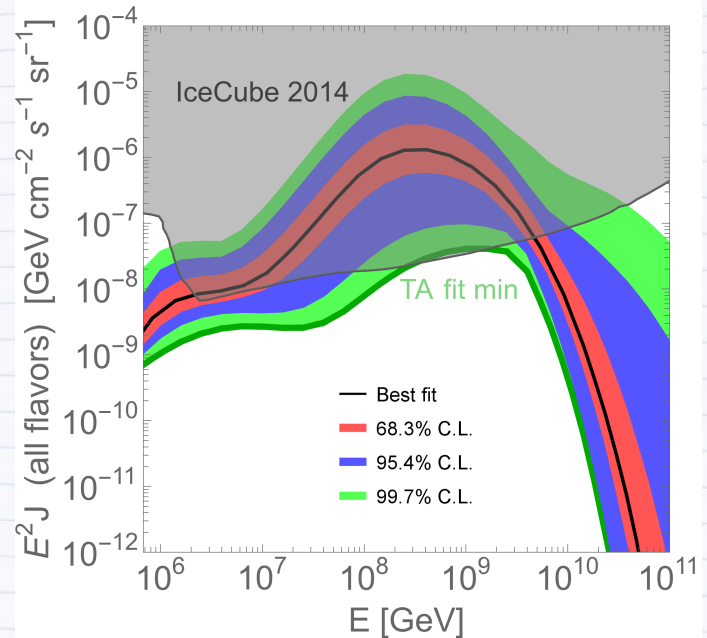


J. Heinze et al. ApJ 825 (2016) 122

source evolution $\sim (1+z)^m$, spectrum $\sim E^{-8}$

$\Rightarrow$ very strong source evolution needed to fit spectrum $\Rightarrow$ too many neutrinos

a) neutrinos from photopion production (ν_{GZK})

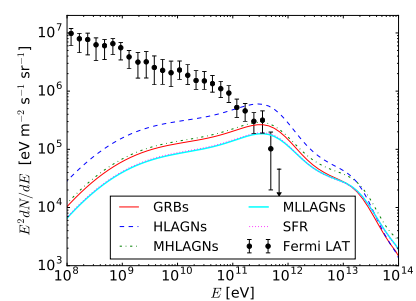
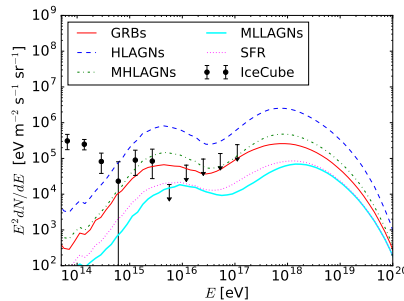
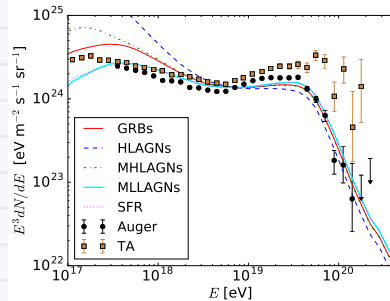
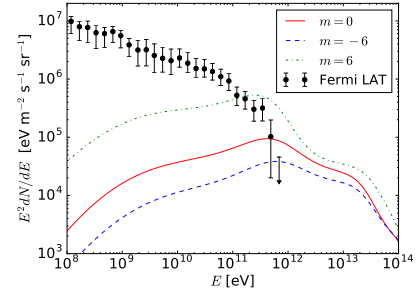
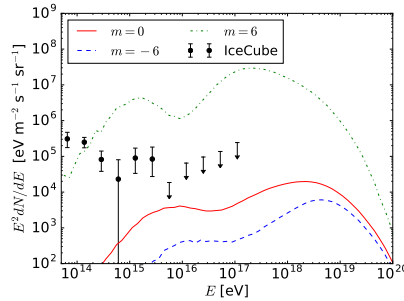
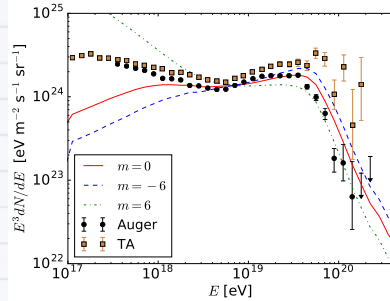


Dip Model vs. Secondaries

A. van Vliet, arXiv:1609:03336

b) ν_{QEK} and photons from $p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-$

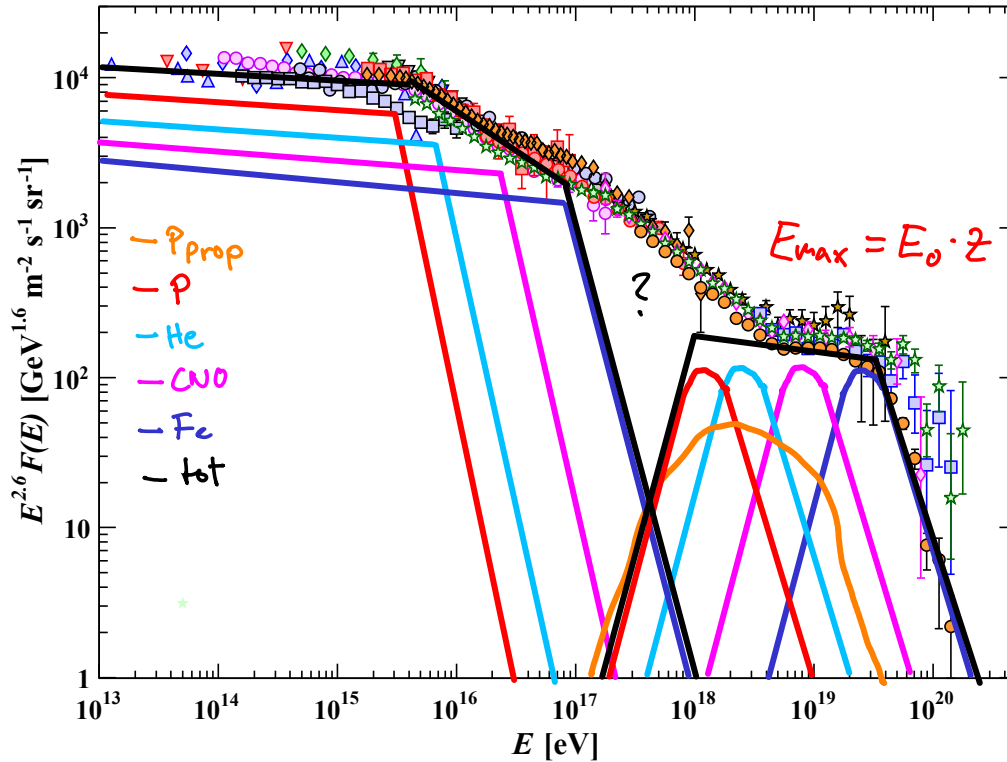
↓
emg. cascade



(see also IceCube Coll. arXiv:1607.05886; R.-Y. Liu et al., PRD **94** (2016) 043008; V. Berezhinsky et al, APP **84** (2016) 52; A.D. Supanitsky PRD **94** (2016) 063002; E. Gavish, D. Eichler ApJ **822** (2016) 56, ...)

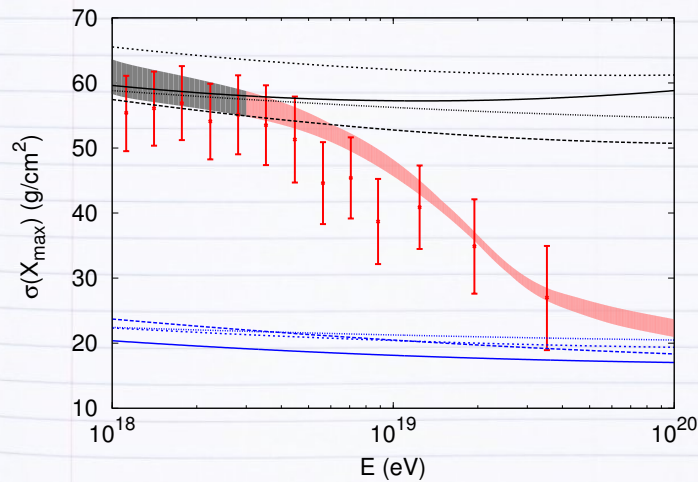
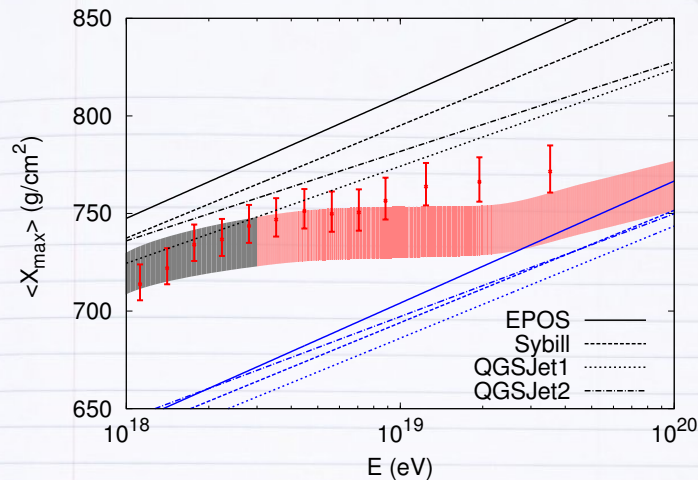
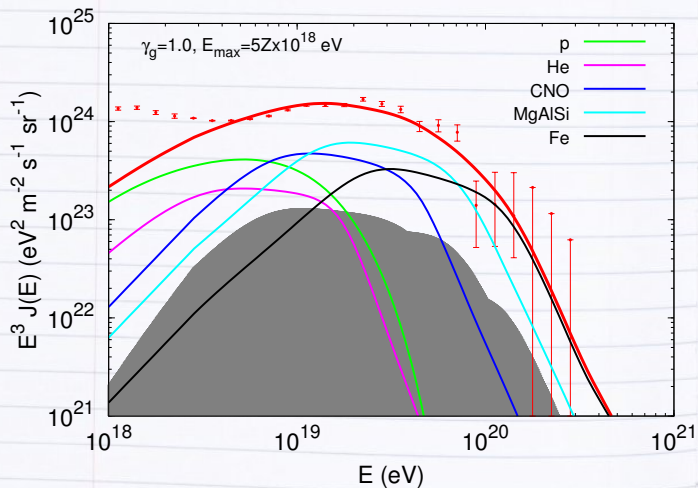
⇒ sources of UHECR p strongly constrained!

Mixed Composition Model



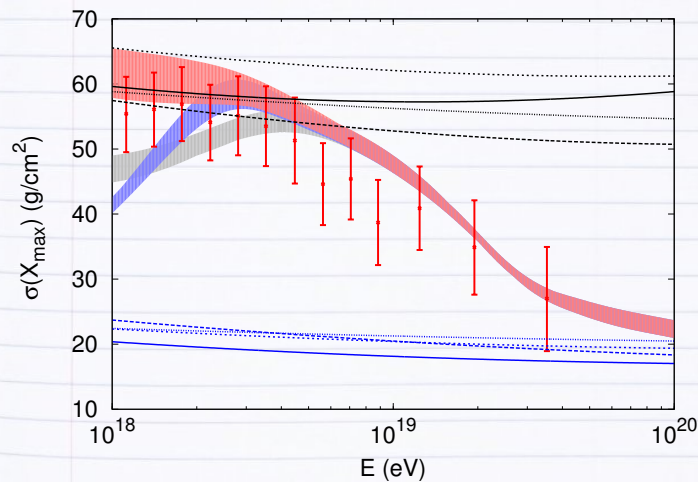
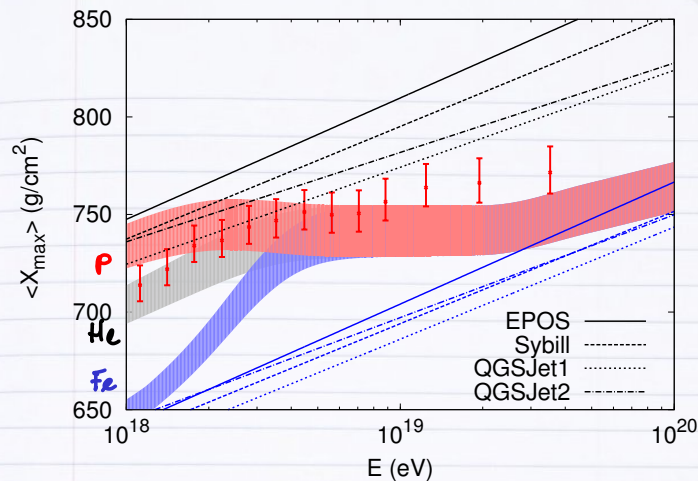
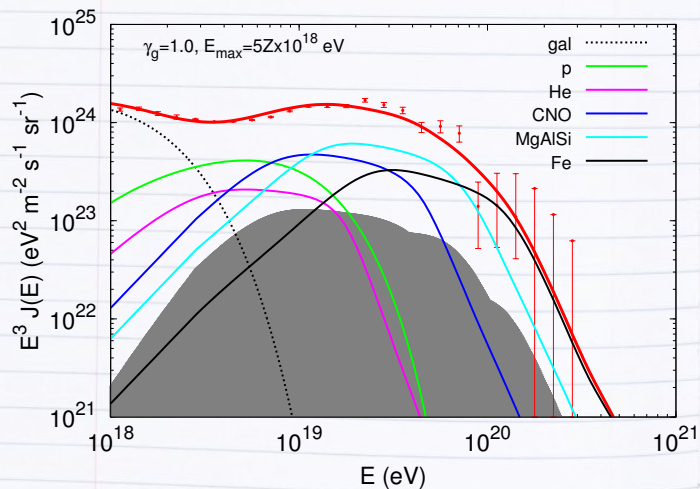
Mixed Composition Model

- $E_{\max} \sim Z$ 😊
- ad hoc composition fractions ☹️
- hard injection spectrum $g \approx 1$ 😬

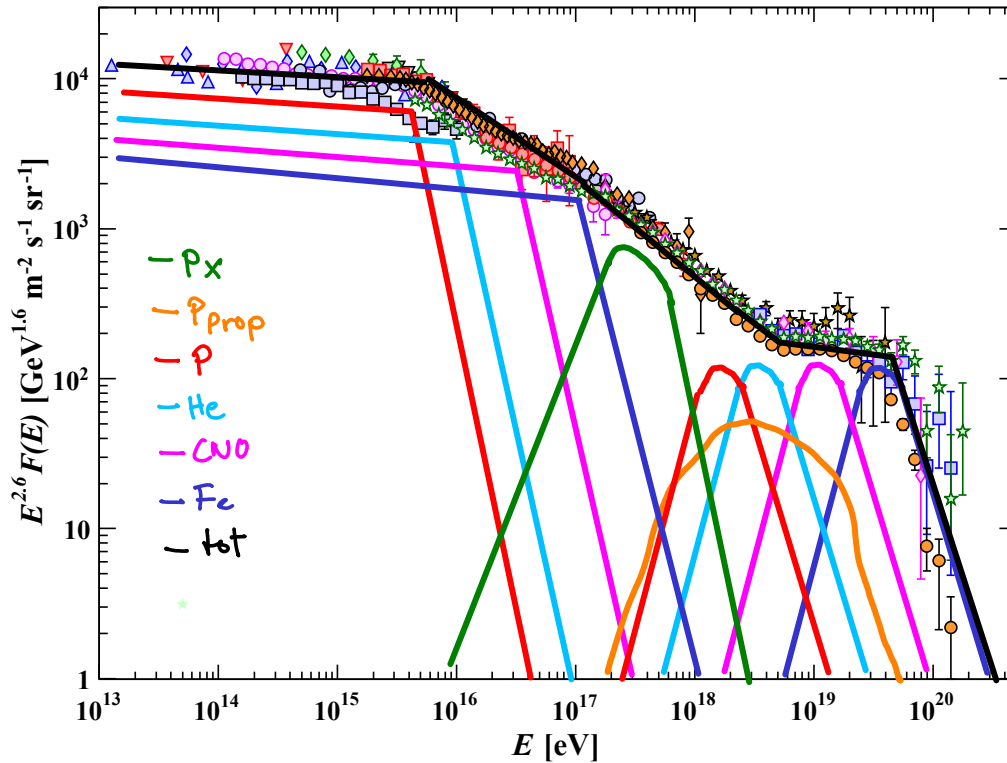


Mixed Composition Model

- $E_{\max} \sim Z$ 😊
- ad hoc composition fractions 😞
- hard injection spectrum $g \approx 1$ 😞
- ad hoc low-E light component 😞

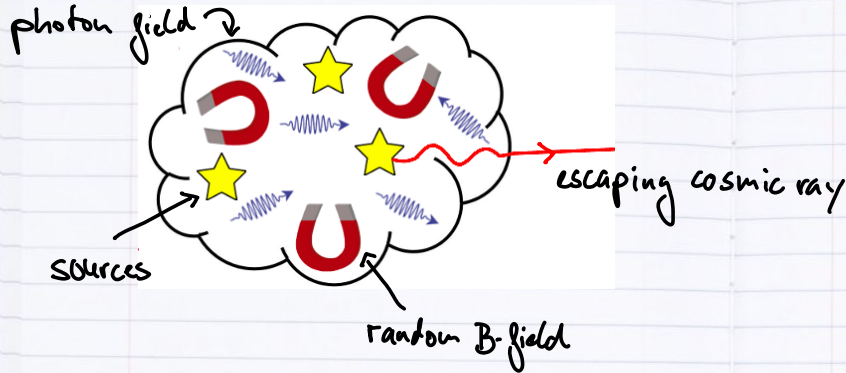


Where do the Missing Protons Come from?



Photoneuclear Interactions in Source Environment?

MU, G. Farrar & L. Anchordoqui PRD 92 123001



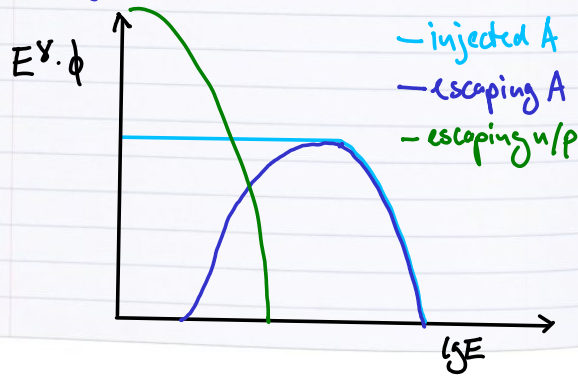
- diffusion:

$$\tau_{\text{esc}} \sim E^{-\alpha}$$

- interaction

$$\tau_{\text{int}} \sim E^{-\beta}$$

e.g. full spallation $A \rightarrow A \cdot n/p$

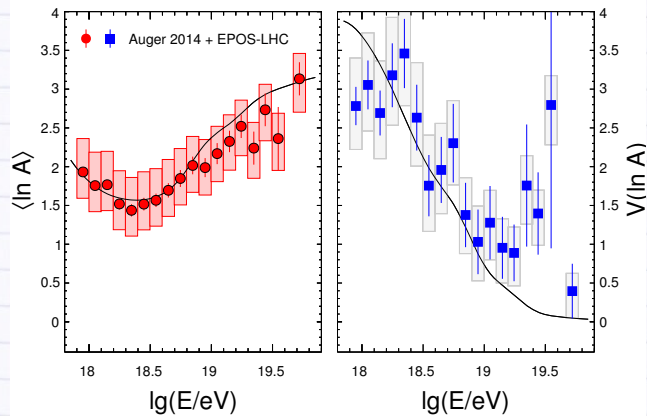
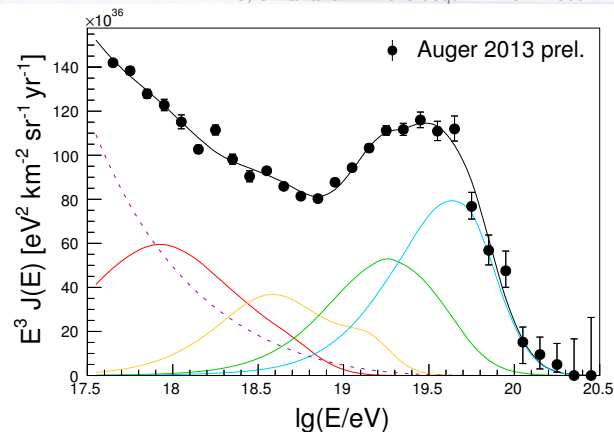
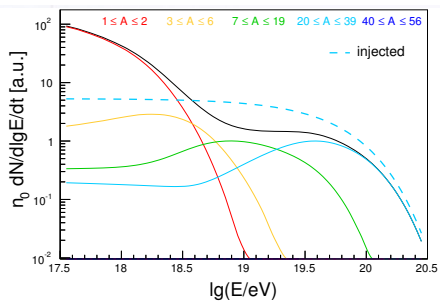
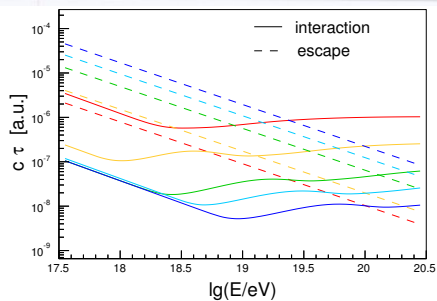
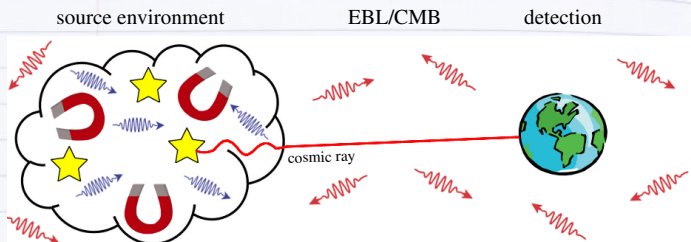


- fraction of escaping nuclei:

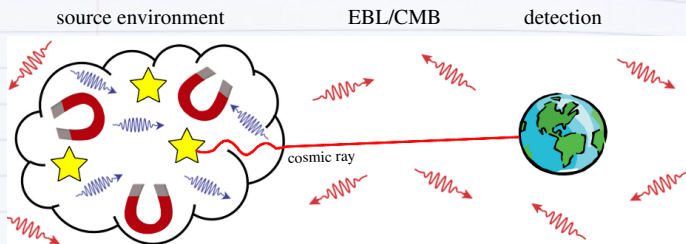
$$f_{\text{esc}} = (1 + \kappa E^{\alpha-\beta})^{-1}$$

Photoneuclear Interactions in Source Environment?

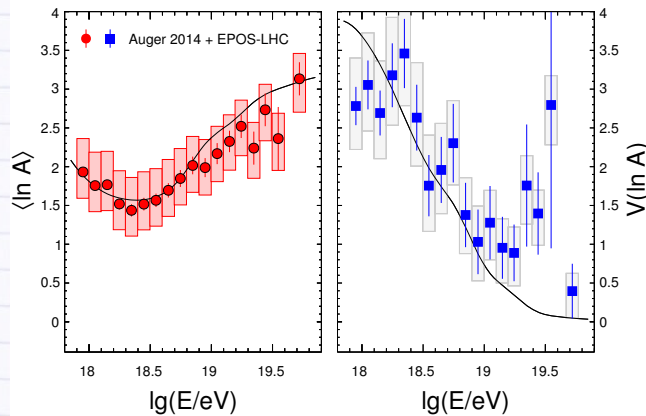
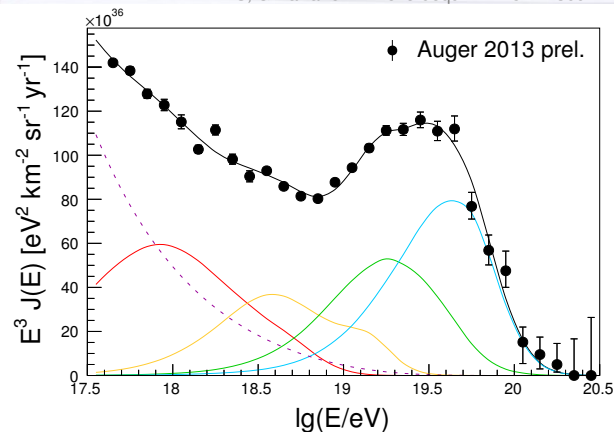
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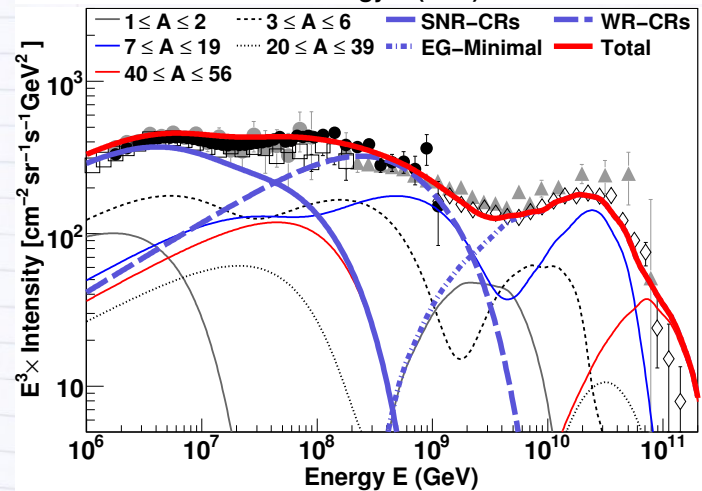
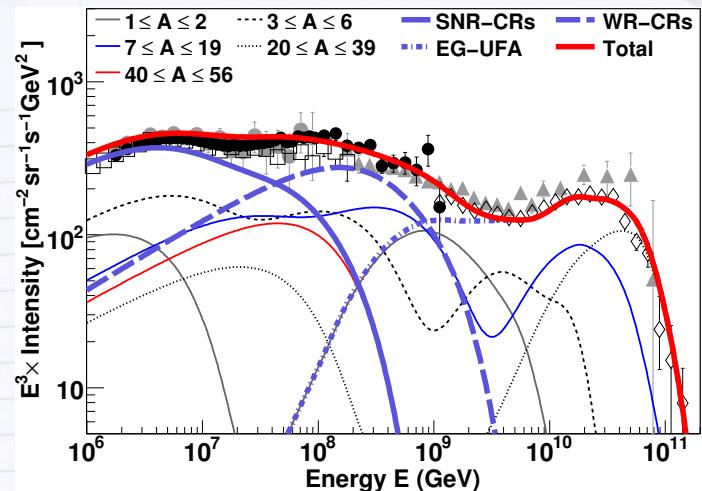
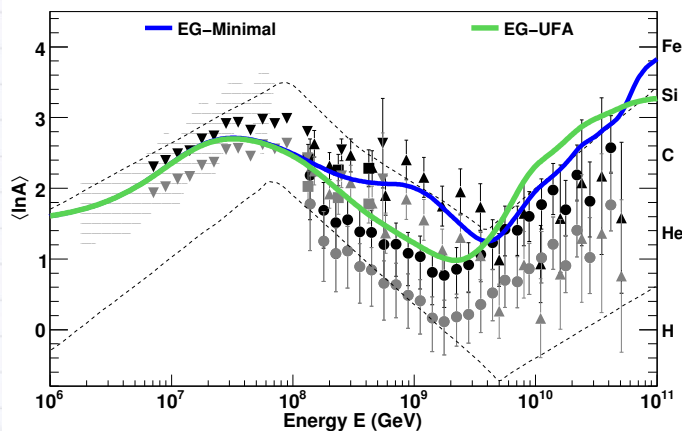
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- $E_{\text{max}} \propto Z$ 😊
- Composition: heavy or Gal. mix 😊
- hard injection spectrum $g \approx 1$ 😐
- low-E light component for free 😊
- next-gen ν observatories can probe model + parameters 😊
- additional degrees of freedom (escape + interaction lengths) 😐

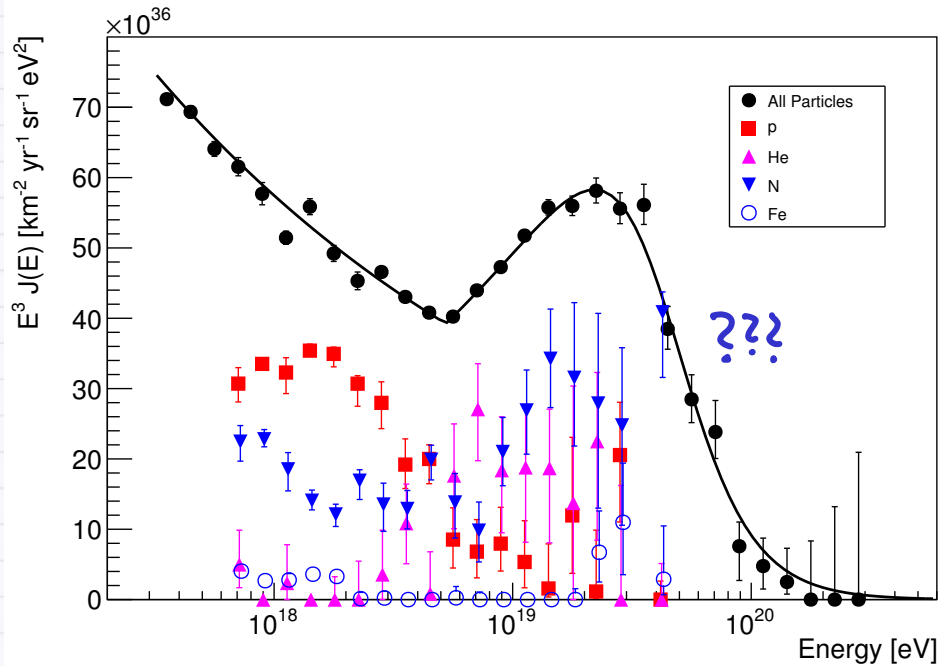


Conclusions so far

- measurements 10^{17} - 10^{18} eV quantitatively inconclusive
- CRs, ν s + γ s disfavor dip-model
- rigidity-dependent $E_{\max}$ can explain observations, but many models are possible
 $\Rightarrow$ need more + better data at UHE!



What happens at ultra-high energies?



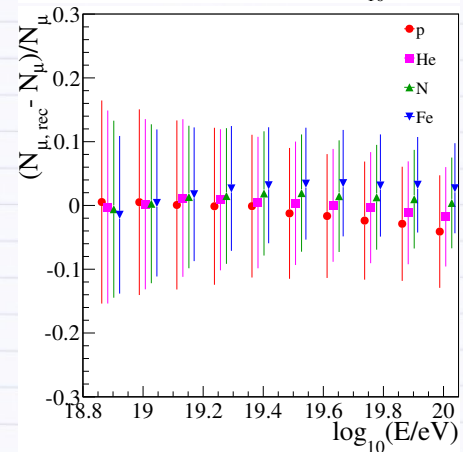
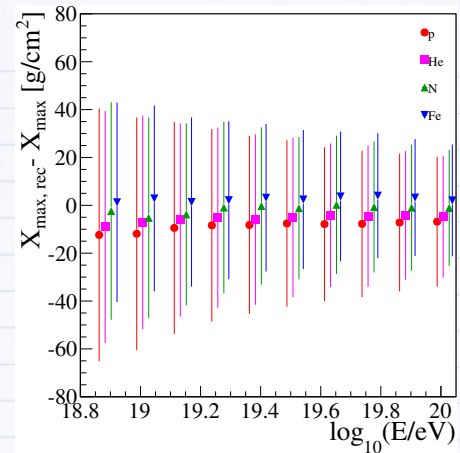
V. de Souza for the Pierre Auger Collaboration, Proc. UHECR14

AugerPrime

mass composition with 100% duty cycle



- origin of flux suppression?
- proton fraction at UHE?
- hadronic physics $\sqrt{s} \geq 140 \text{ TeV}$?



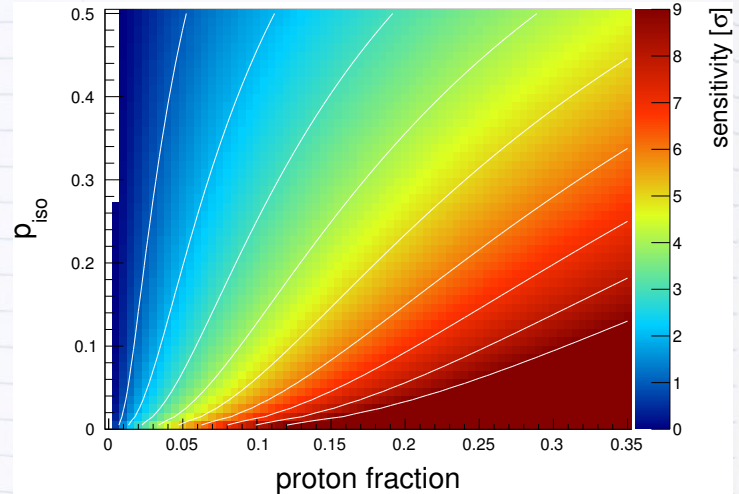
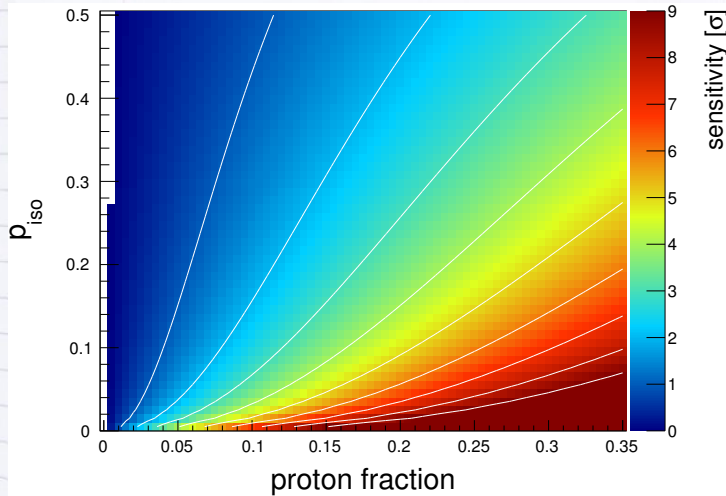
Charged Particle Astronomy?

↔ select low- z particles

Example: catalogue-based search:

no mass determination:

$$\frac{\langle P \rangle - \langle Fe \rangle}{\sigma} = 1.5 :$$





→ Cherenkov - fluorescence discrepancy?

- NUCHE at TALE!

- HiScore at Auger?

→ Northern hemisphere?

TAXt, but no composition at UHE

→ will LHA+ARLANNA help for CR comp.?
(or do they rather need CR input to
interpret what they will find?)

→ how can we push the γ -limits at
> 10¹⁶ eV further into the GZK range?

→ how to control model uncertainties
for surface-detector-based composition
studies ("muon discrepancy")?

→ how important are p₀ data from LHC?