

COMPOSITION

NAME Michael Unger

SUBJECT OVERVIEW

100 Sheets (200 Pages)
9 3/4" x 7 1/2" (24.7 cm x 19.0 cm)

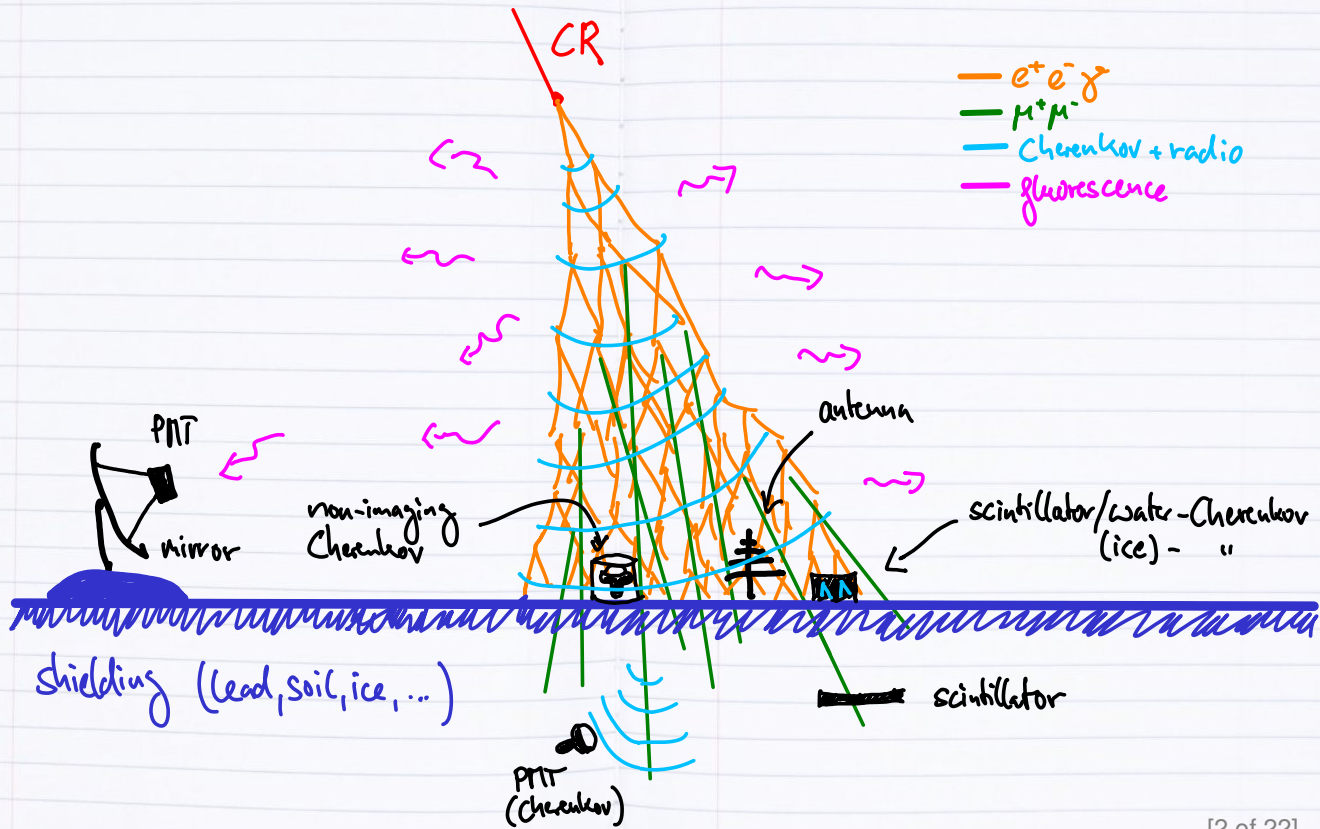
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SEWN
PAGES

GRAPH RULED
(5 SQUARES PER INCH)

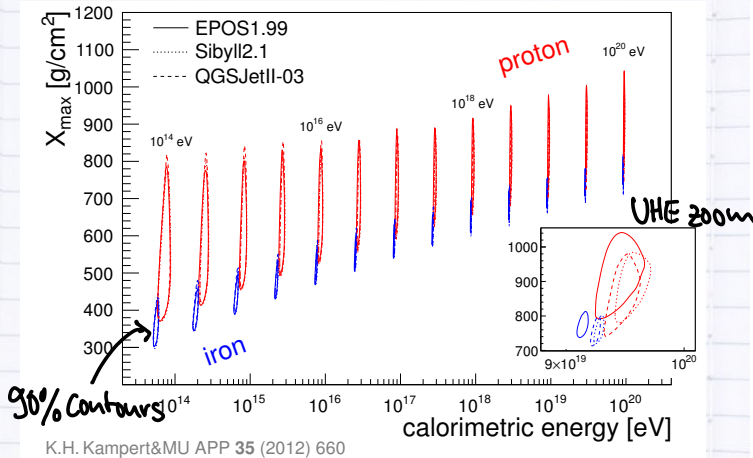


Air Shower Measurements

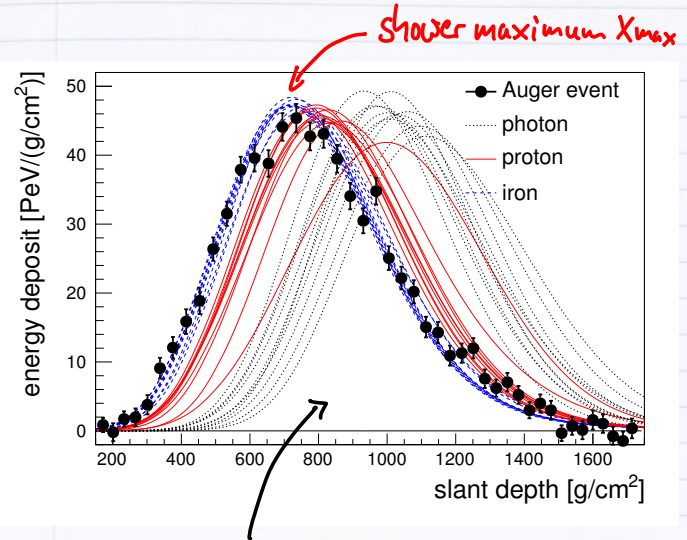


Mass Estimate: a) X_{max}

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



longitudinal development:



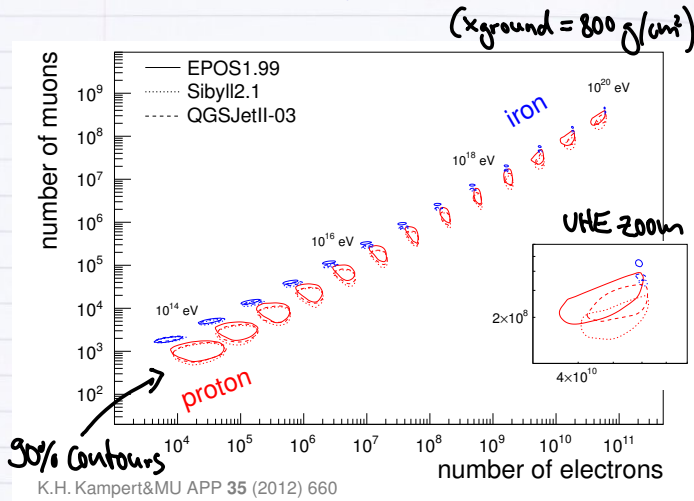
$$\langle X_{max} \rangle \sim D_{10} (\log E - \log A)$$

mass
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)

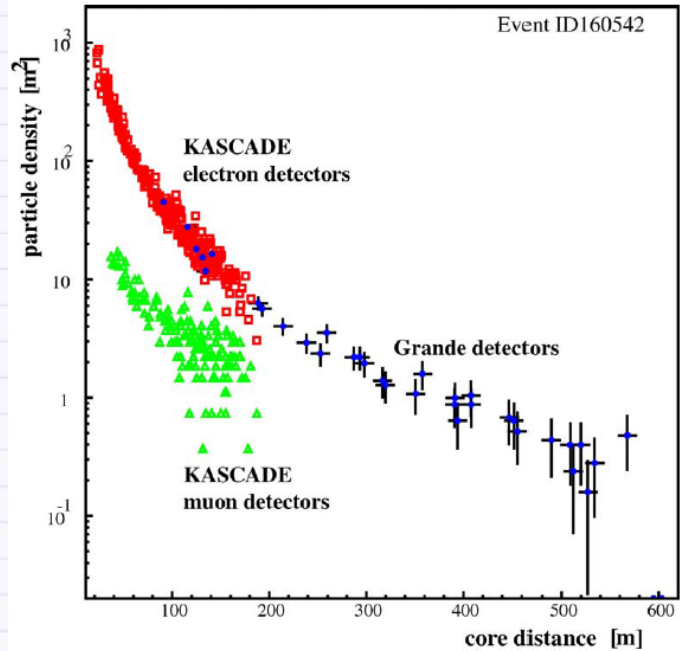


$$N_\mu \sim A \cdot (E/A)^\beta$$

$$N_e \sim e^{-\frac{X_{ground} - X_{max}}{\Lambda}}$$

$$\sim \exp\left(-\frac{(X_{ground} - D_{10}(\log E - \log A))}{\Lambda}\right)$$

Lateral distribution:



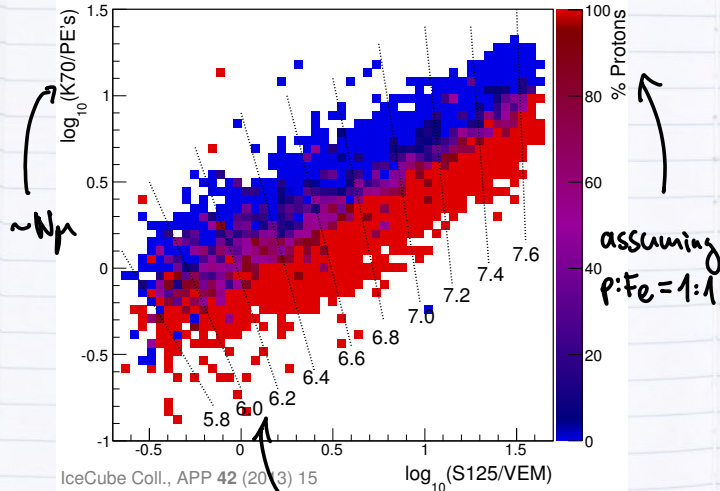
integral \rightarrow total number of particles: N
or

shower size at certain distance: S_r

Examples

Auger fluorescence →

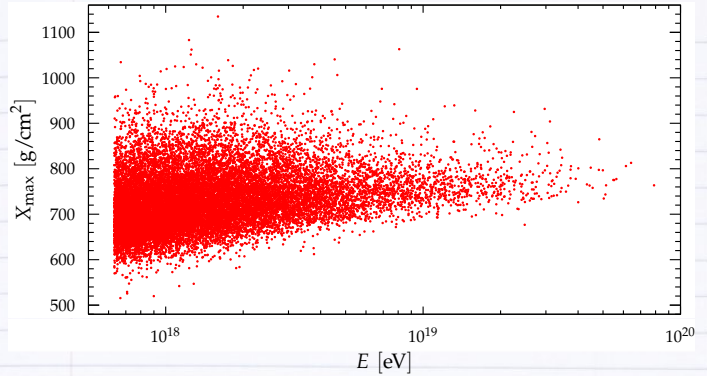
IceCube surface detector vs. in-ice



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

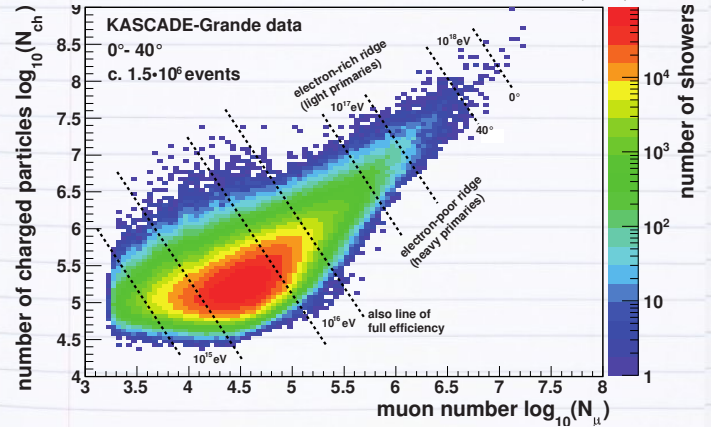
$\sim S_e(125\text{m})$

Pierre Auger Coll., PRD 90 (2014) 122005



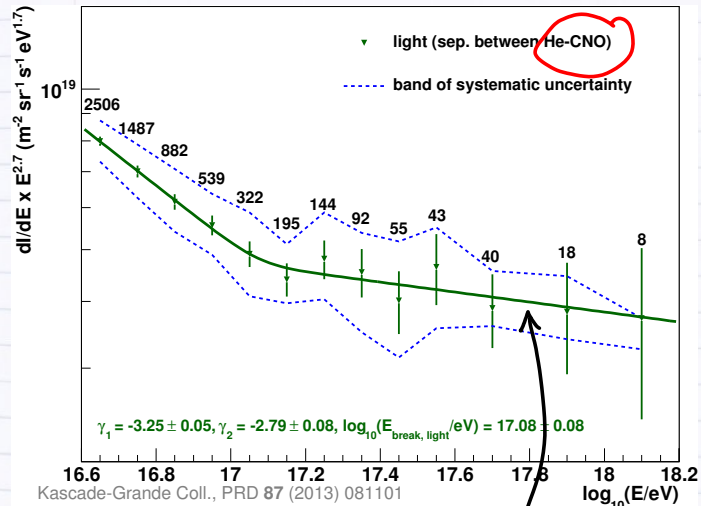
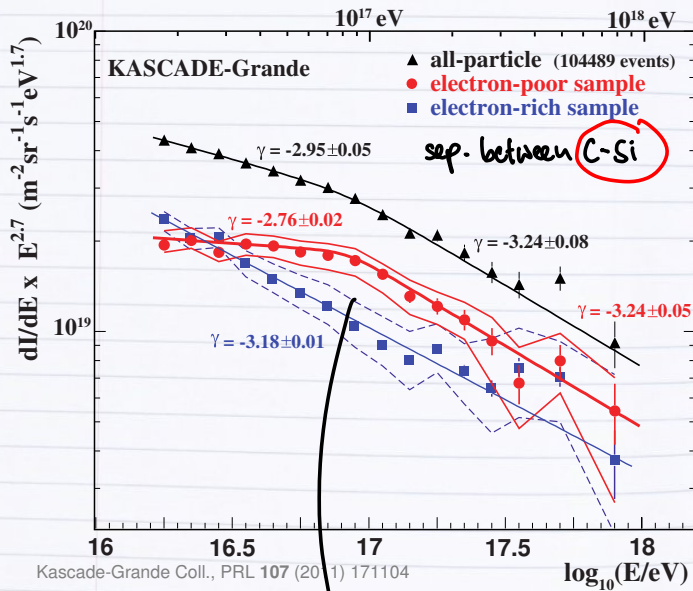
KASCADE-Grande ↓

KASCADE-Grande Coll., PRL 107 (2011) 171104



"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

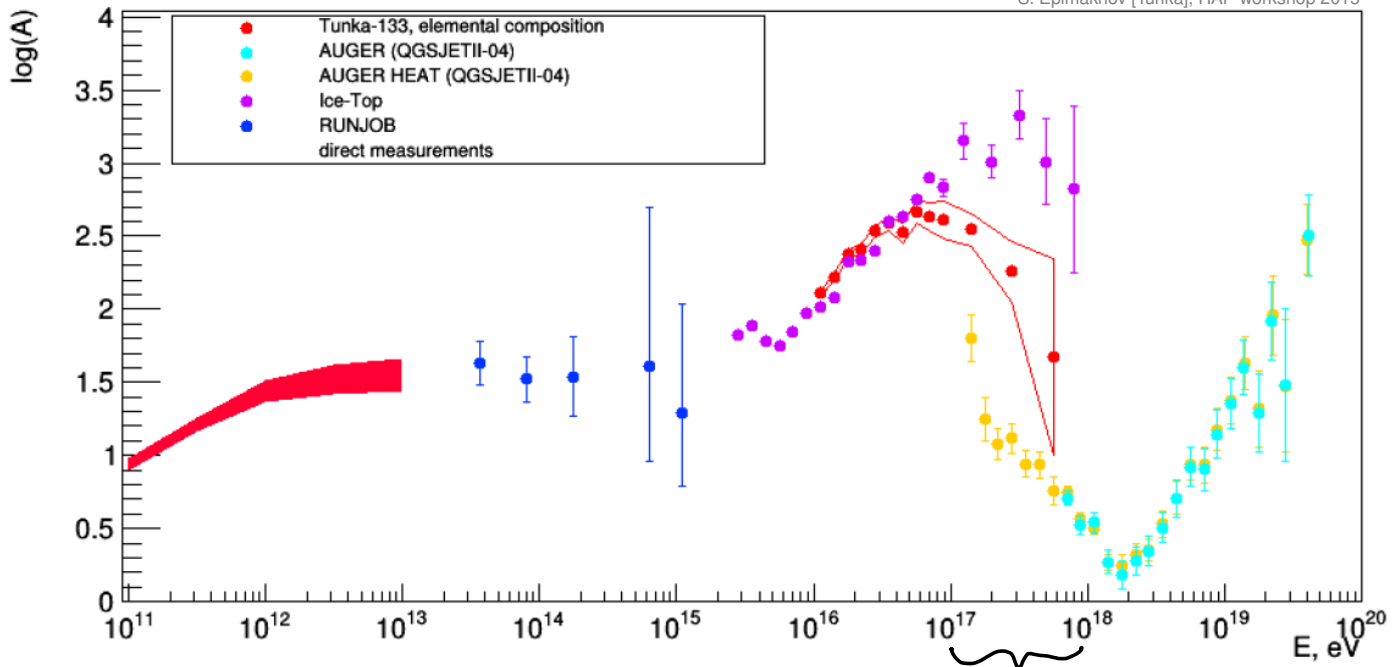


$E_{break} \sim 10^{16.9} \text{ eV} \leftrightarrow E_{max} \hat{\sim} E_{break}/26 = 3 \cdot 10^{15} \text{ eV} ?!$

transition to light, extragal component?

Overview of recent "low-energy" results (new LOFAR data is between Auger + Tunka)

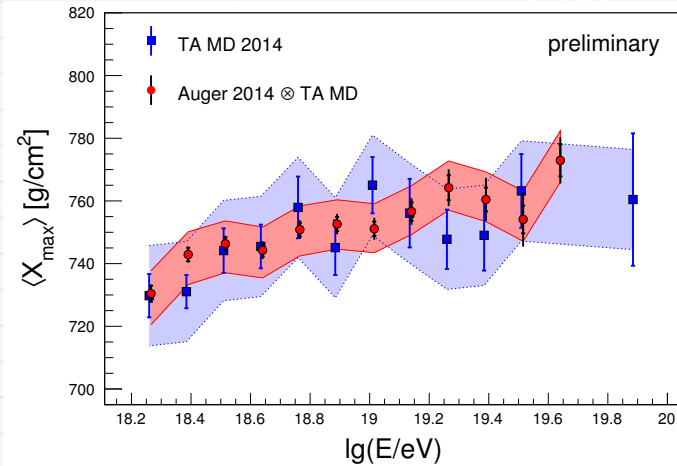
S. Epimakhov [Tunka], HAP workshop 2015



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

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

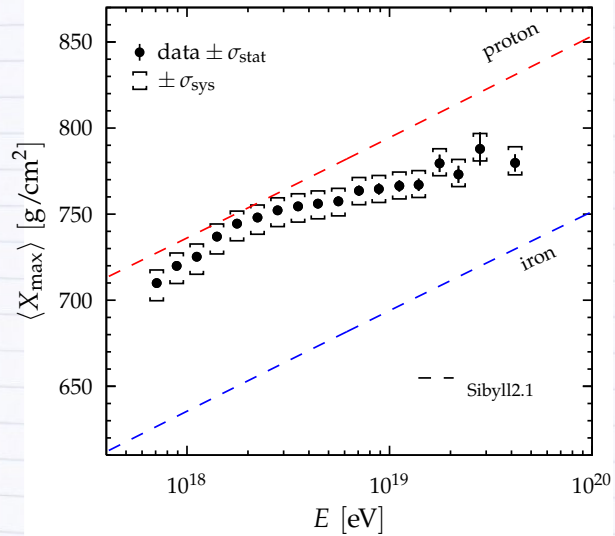
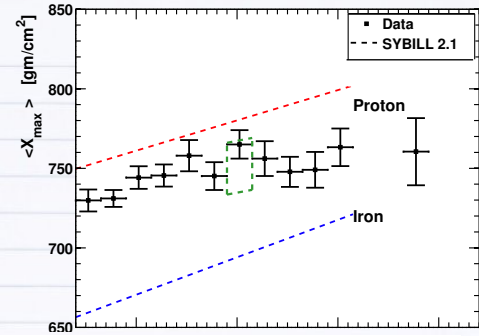
Composition at Ultrahigh Energies (fluorescence detector results)



MU [TA&Auger Working Group] ICRC2015

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

⇒ ok! 😊



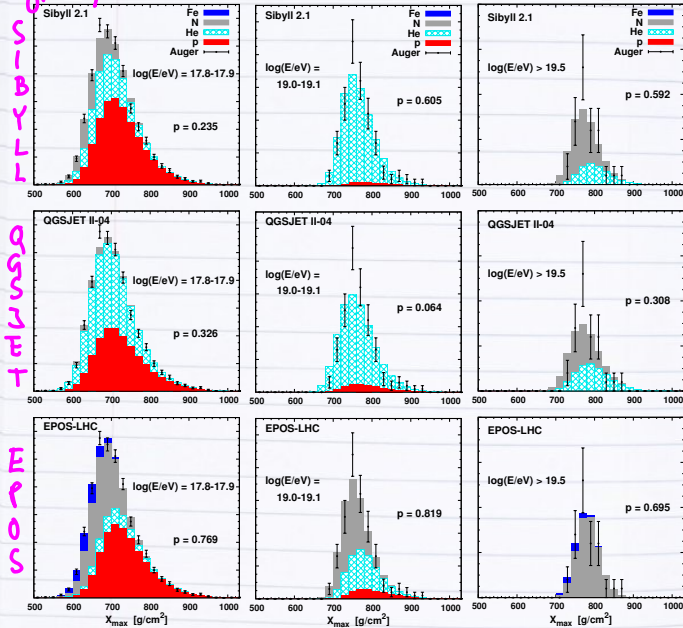
Interpretation of X_{max} Distributions

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

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

19.0-19.1

>19.5



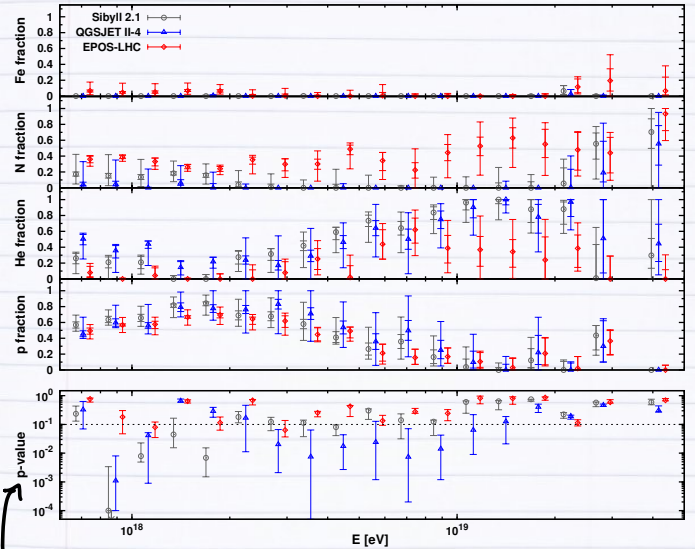
SIBYLL

QGSJET

EPOS

fitted fractions:

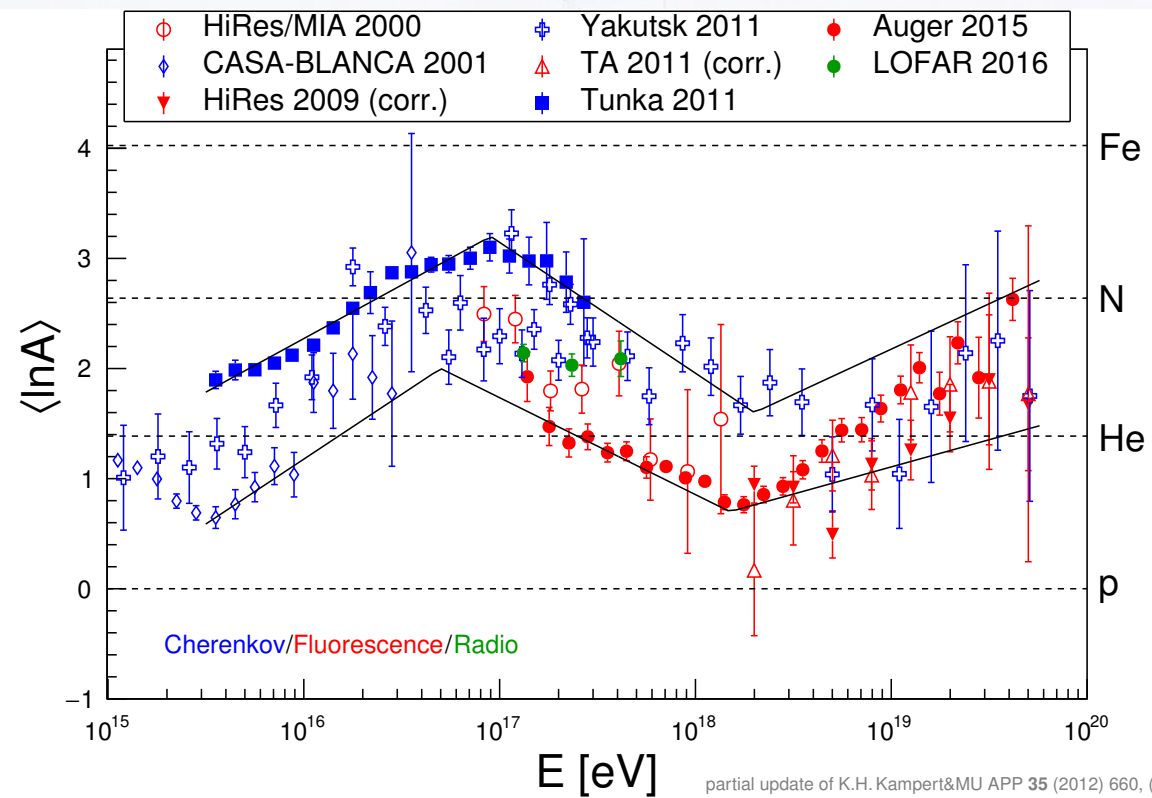
Pierre Auger Coll., PRD 90 (2014) 12, 122006



fit probability (bad fits with QGSJET II-04)

Zig-Zag Plot

(only Xmax measurements)



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

End of Galactic Component?

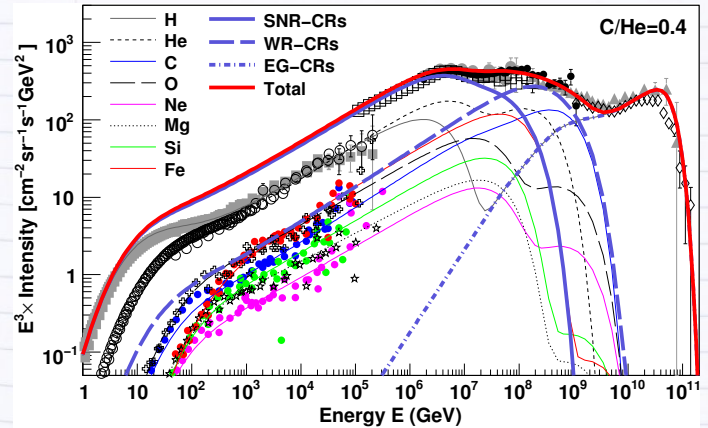
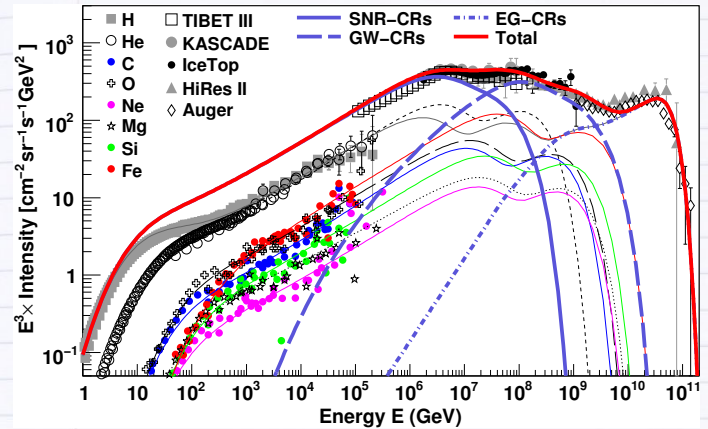
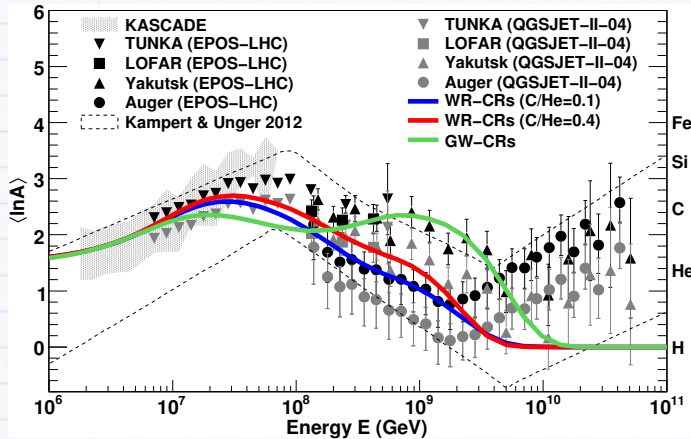
→ SNR $E_{max} = \text{few } Z \cdot 10^{15} \text{ eV}?$

→ additional Galactic component?

→ Wolf-Rayet stars?

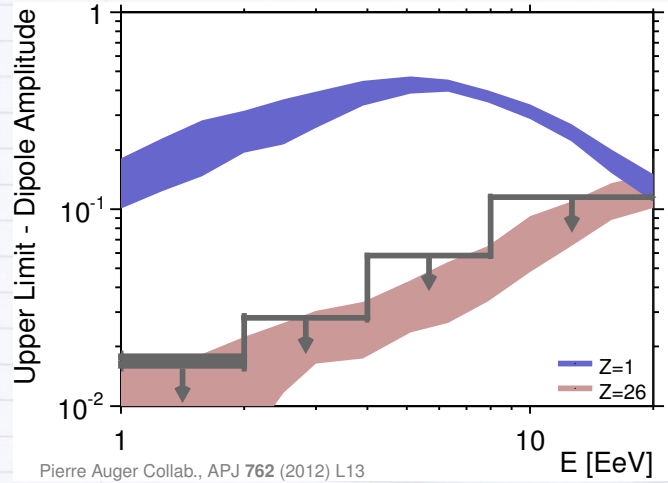
→ re-acceleration at Gal. wind termination shock?

→ ... ?



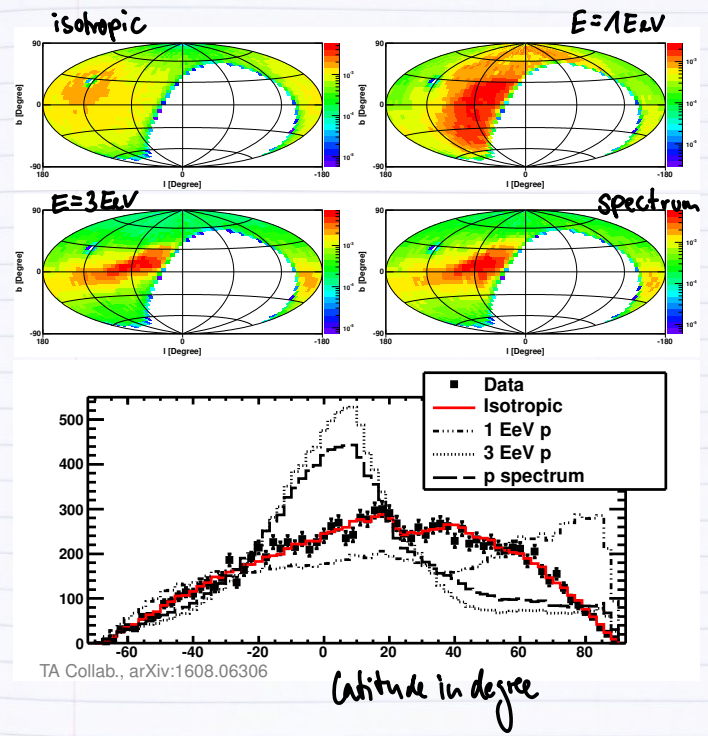
Low-Mass Galactic CRs at EeV?

Auger dipole amplitude limits:



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

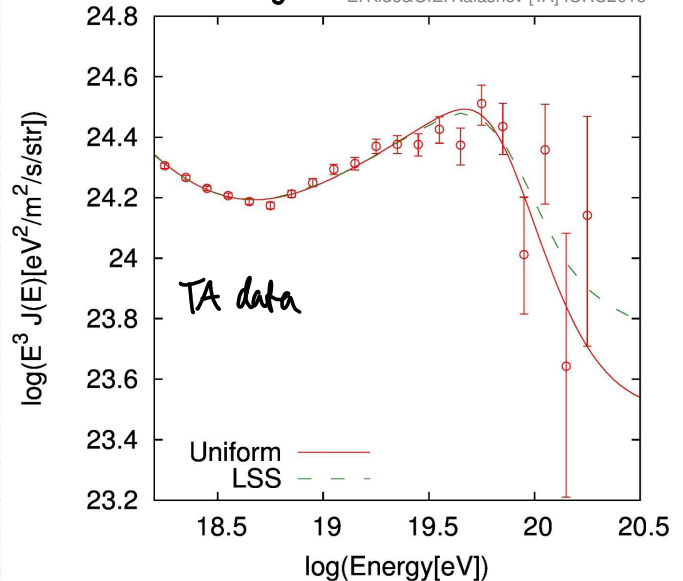
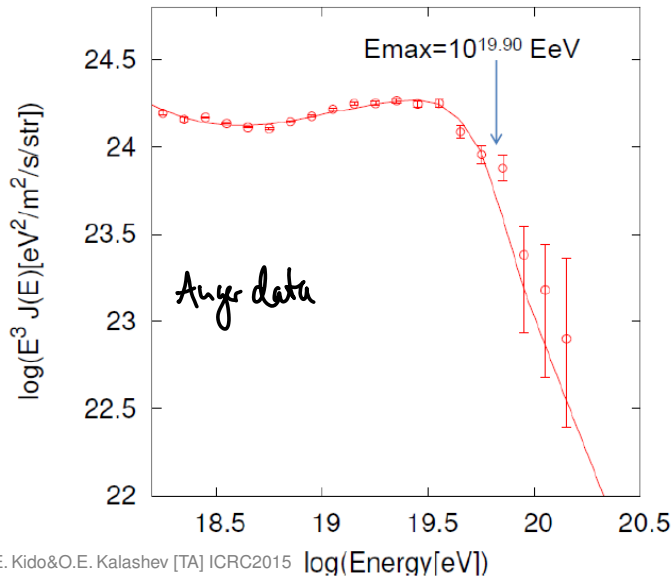
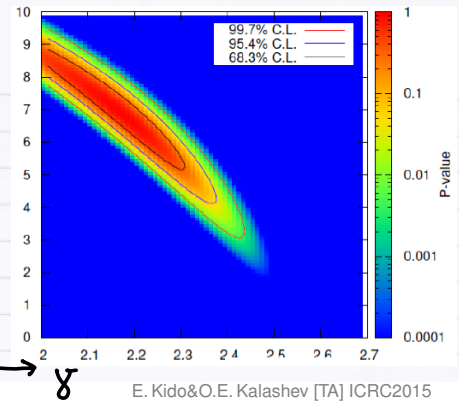
TA Latitude distribution:



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

origin of ankle: $p + \gamma_{crs} \rightarrow p + e^+ + e^-$

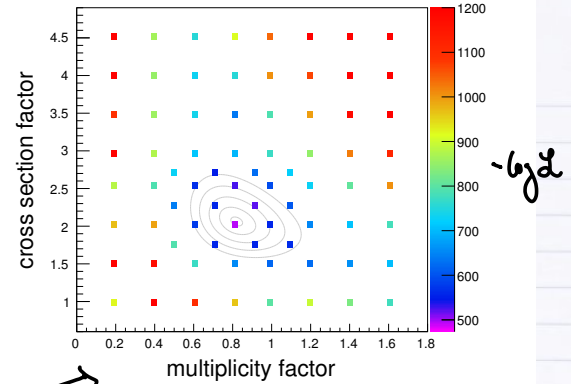
- parameters:
- Source evolution e.g. $\sim (1+z)^m$
 - Spectrum at injection $\sim E^{-\delta}$
 - if needed: E_{max}



How to reconcile with X_{max} ?

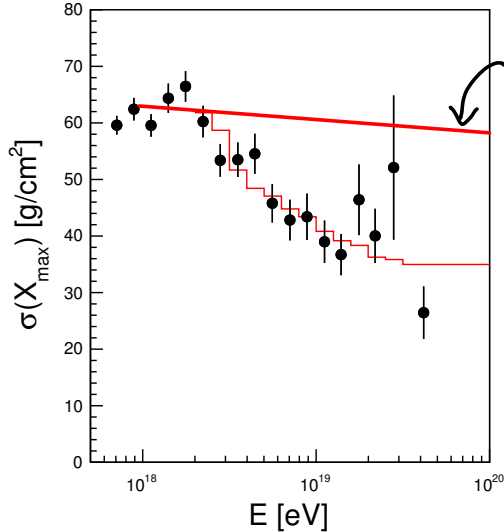
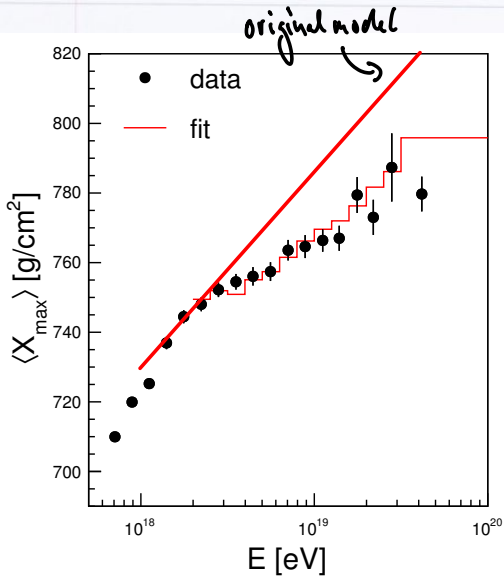
→ exotic hadronic interactions?

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



$-\log L$

rescaling at 10^{19} eV

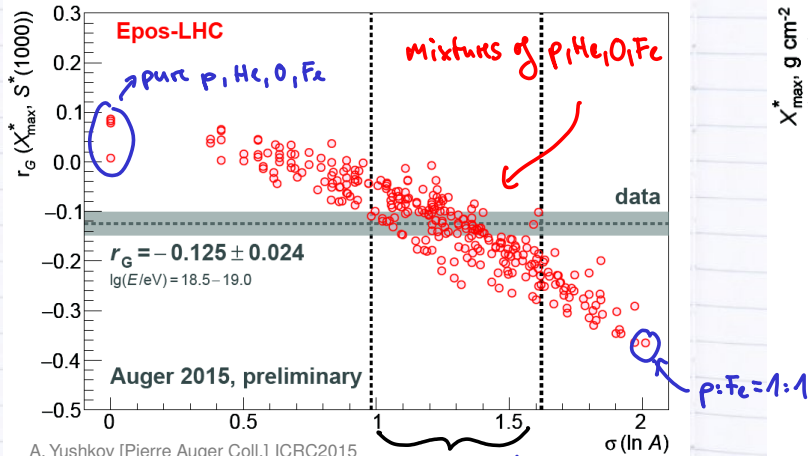
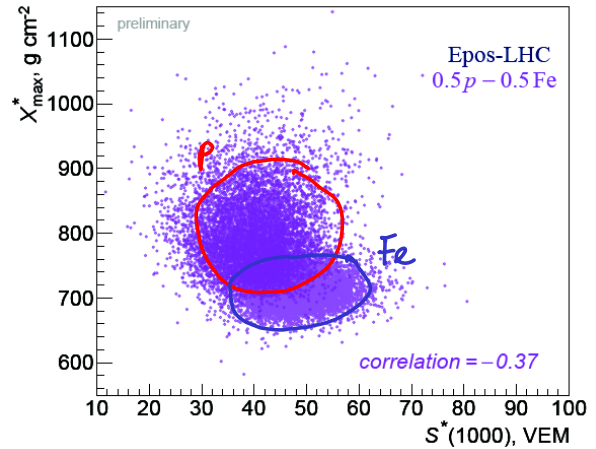


⇒ works!!

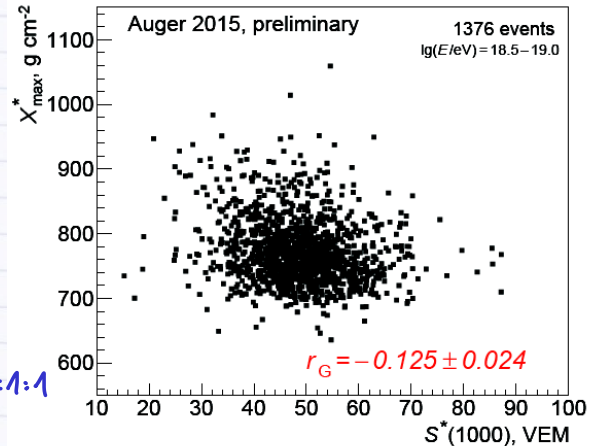
(but very exotic ...
rescaling of σ_{p-air}
by a factor of 2
at 10^{19} eV!)

A Model-Independent Test of Composition

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

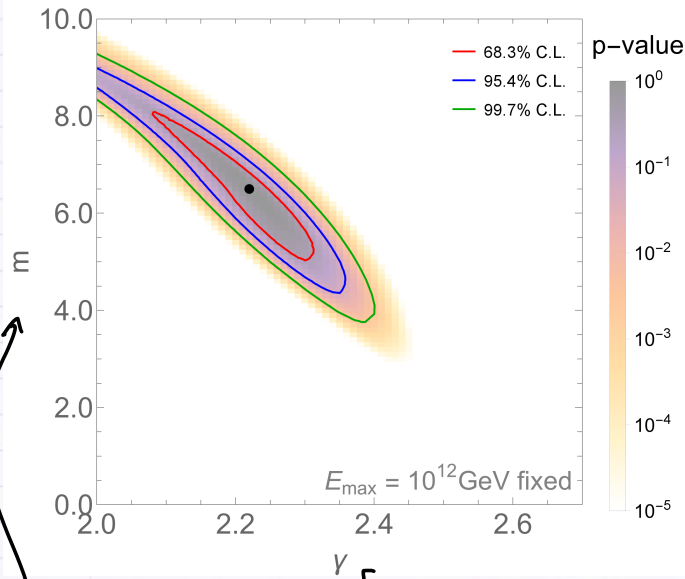


A. Yushkov [Pierre Auger Coll.] ICRC2015



⇒ data is mixed composition!

Dip Model vs. Secondaries

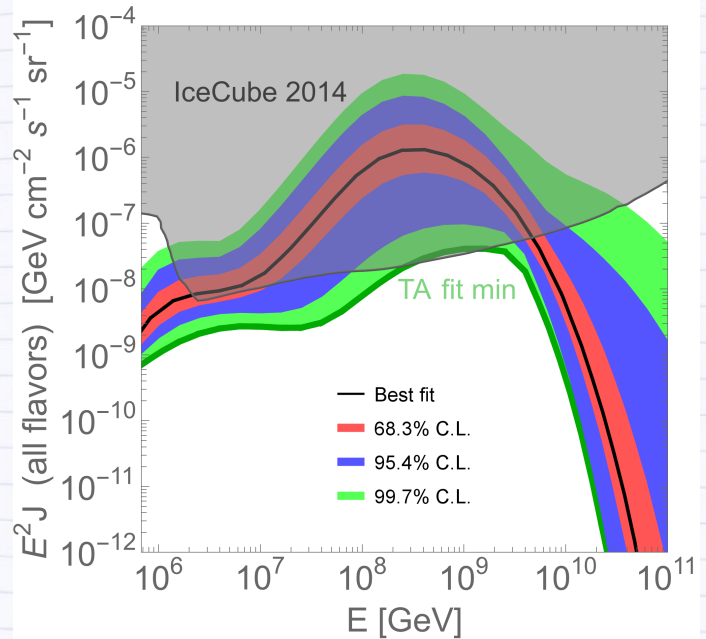


J. Heinze et al. ApJ 825 (2016) 122

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

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

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

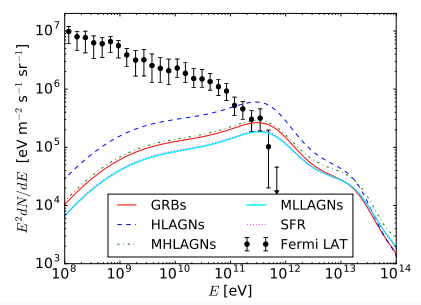
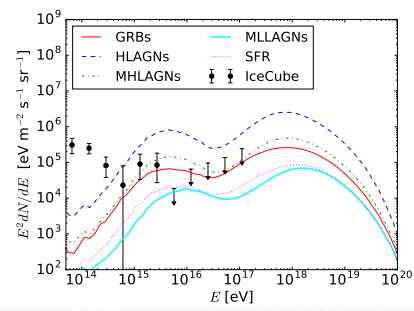
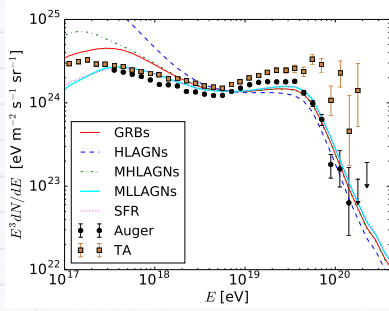
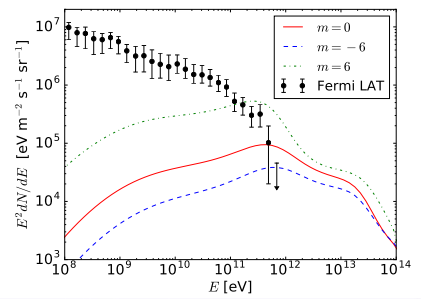
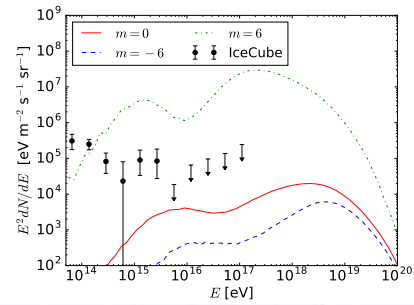
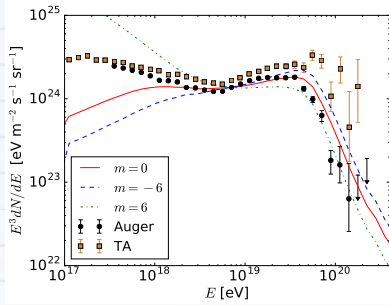


Dip Model vs. Secondaries

A. van Vliet, arXiv:1609.03336

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

↓
emaj. cascade

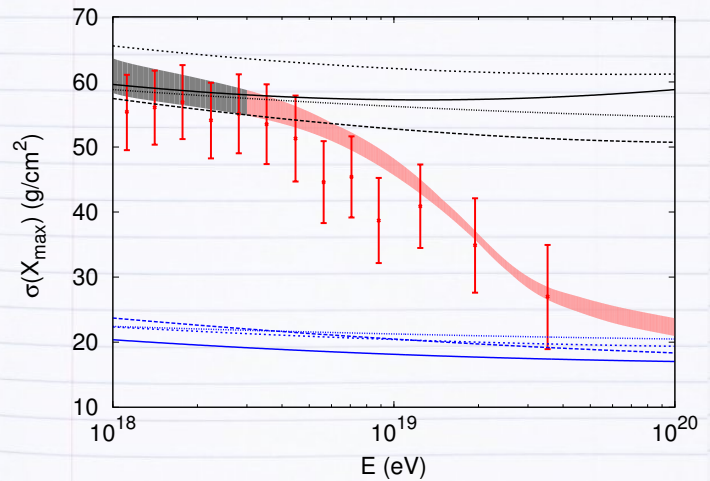
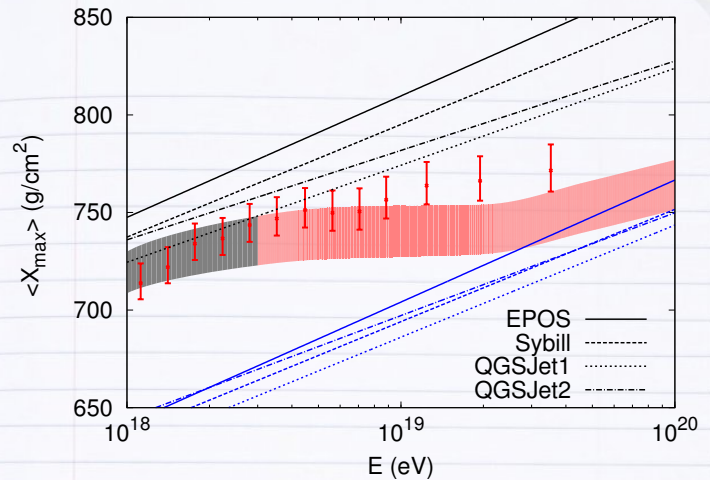
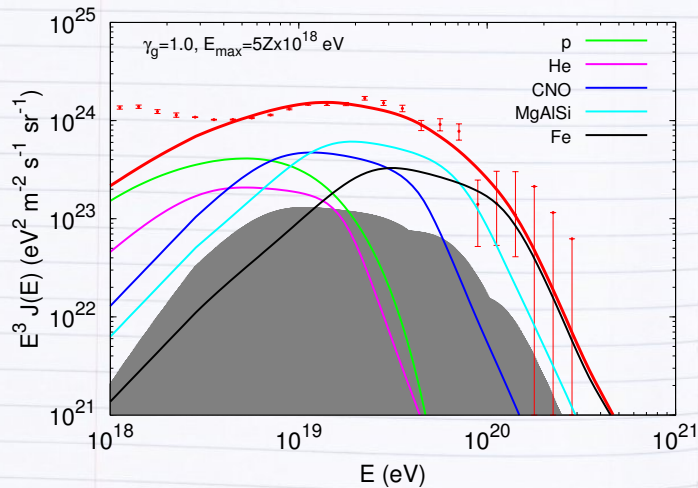


(see also IceCube Coll. arXiv:1607.05886; R.-Y. Liu et al., PRD **94** (2016) 043008; V. Berezhinsky et al, APP **84** (2016) 52; A.D. Supanitsky PRD **94** (2016) 063002; E. Gavish, D. Eichler ApJ **822** (2016) 56, ...)

⇒ sources of UHECR p strongly constrained!

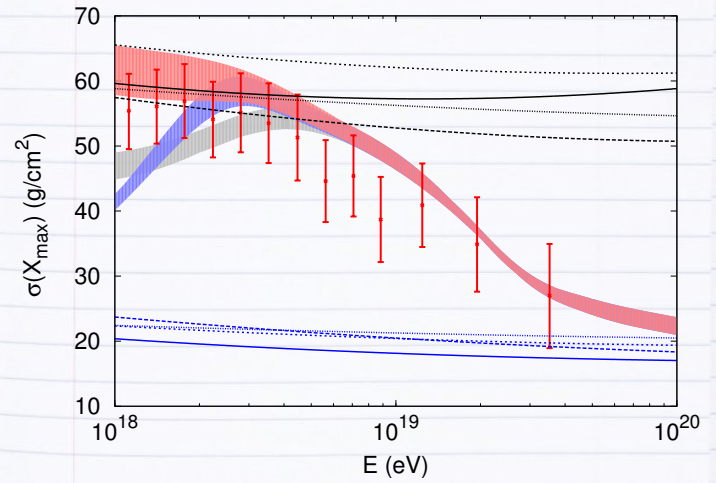
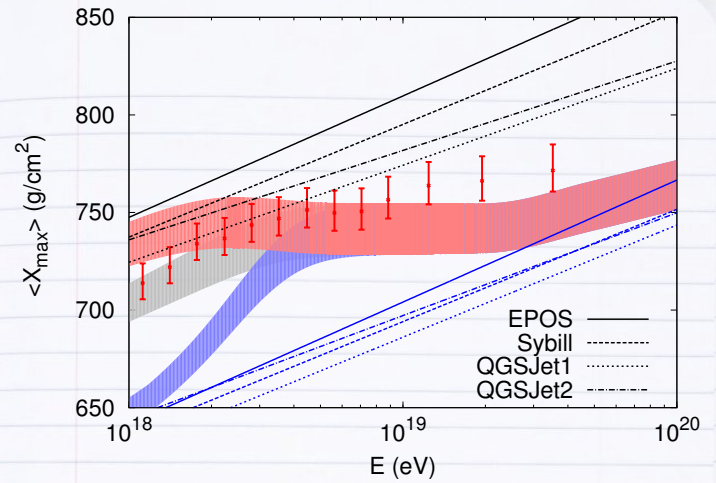
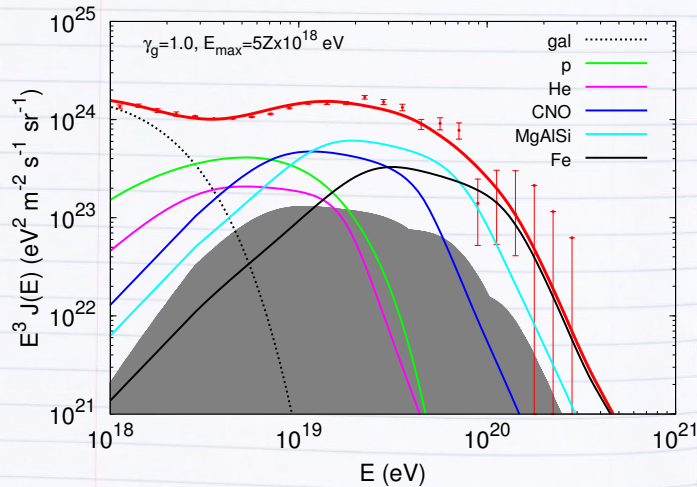
Mixed Composition Model

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

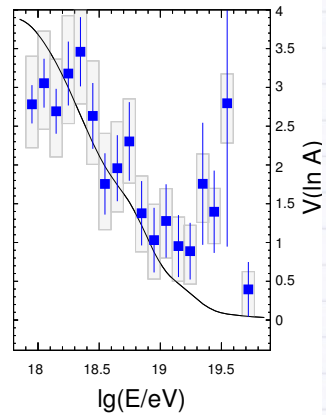
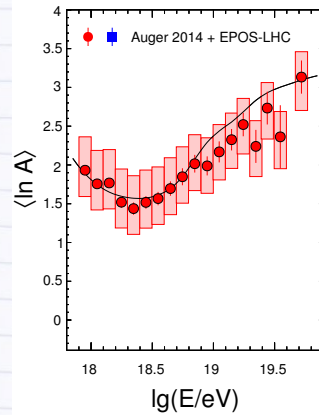
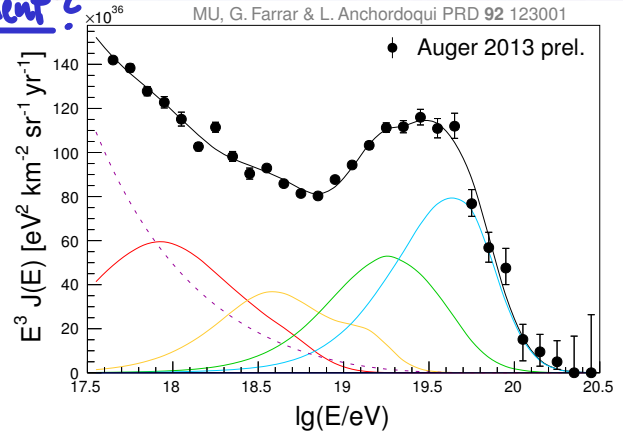
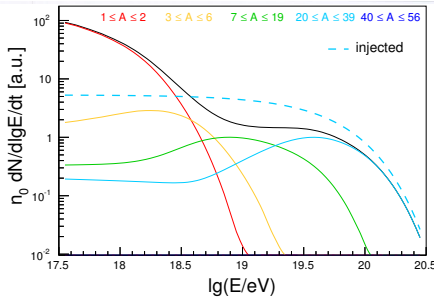
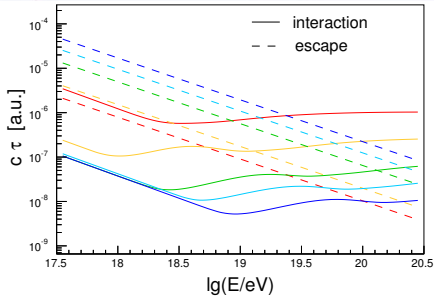
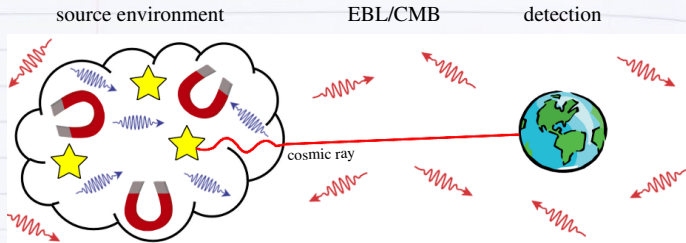


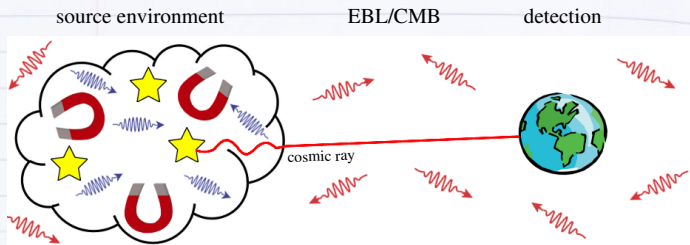
Mixed Composition Model

- $E_{\max} \sim Z$ 😊
- ad hoc composition fractions 😞
- hard injection spectrum 851 😞
- ad hoc low-E light component 😞

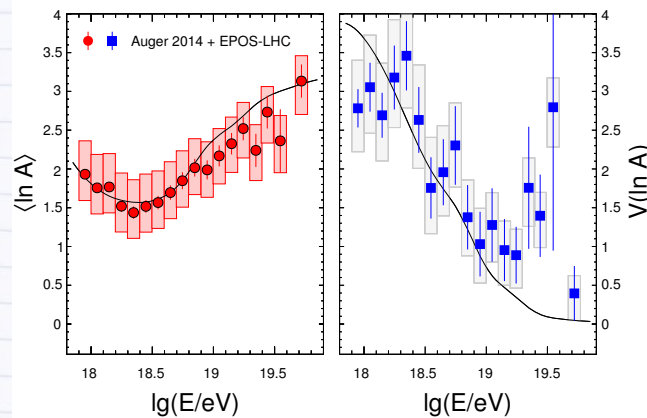
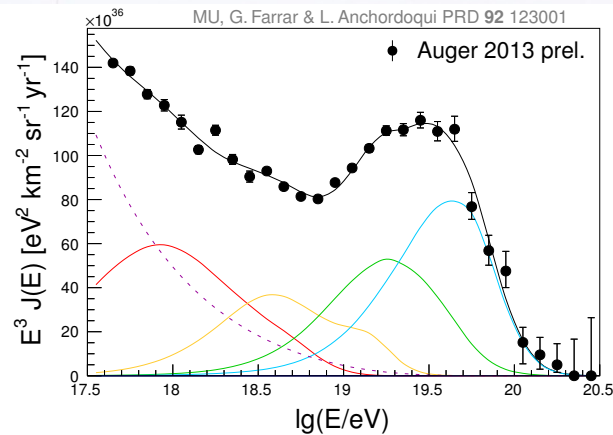


Photoneuclear Interactions in Source Environment?



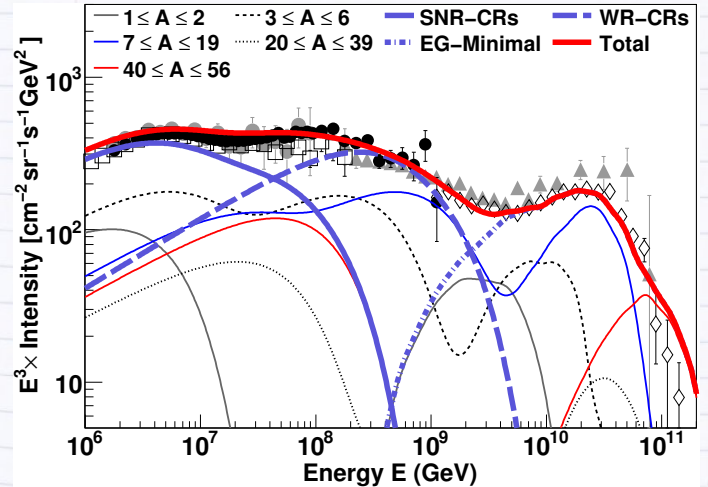
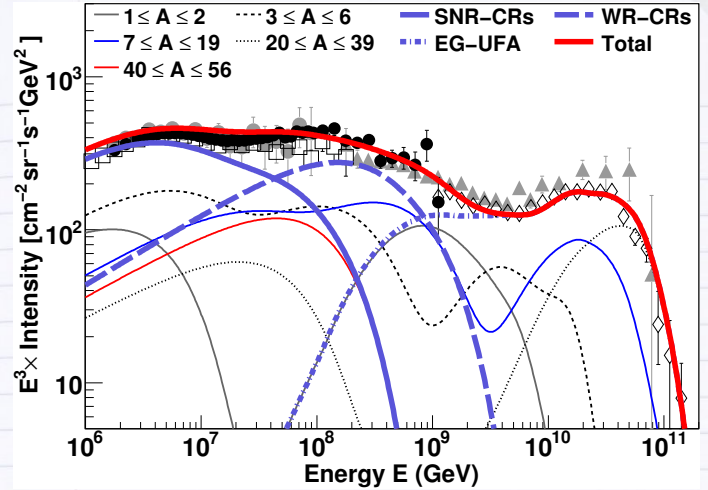
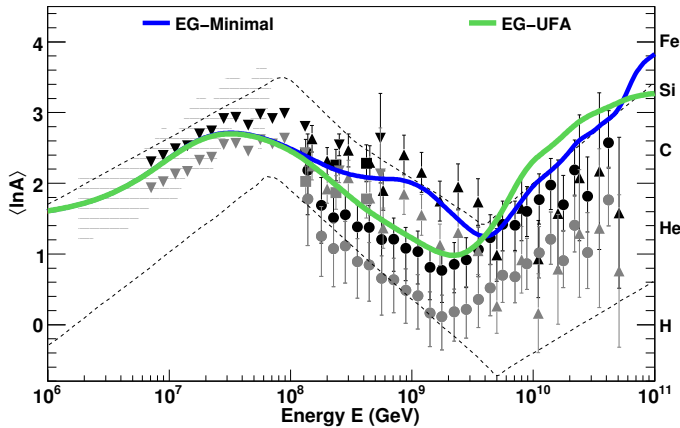


- $E_{\max} \sim Z$ 😊
- Composition: heavy or Gal. mix 😊
- hard injection spectrum $g \approx 1$ 😊
- low-E light component for free 😊
- next-gen ν observatories can probe model + parameters 😊
- additional degrees of freedom (escape + interaction lengths) 😊



Conclusions

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





→ Cherenkov - fluorescence discrepancy?
- NICHE at TALE!
- HiScore at Auger?
→ currently no statistics above $\sim 10^{13.5}$ eV
→ AugerPrime!!
→ will ART+ARIANNA 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
> 10^{16} eV further into the GRX range?
→ how to control model uncertainties
for surface-detector-based composition
studies ("muon discrepancy")?
→ how important are p=0 data from UCC?