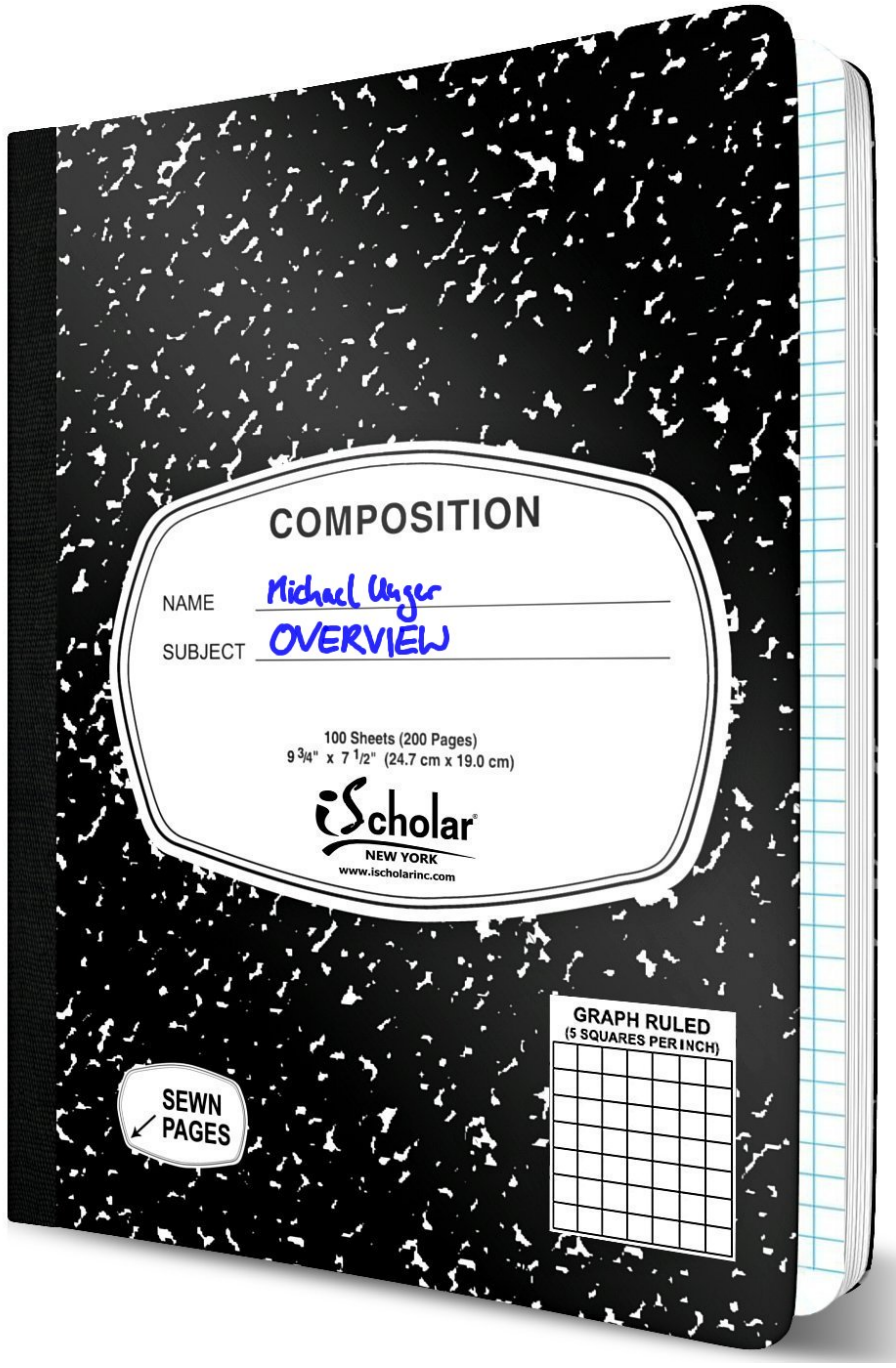
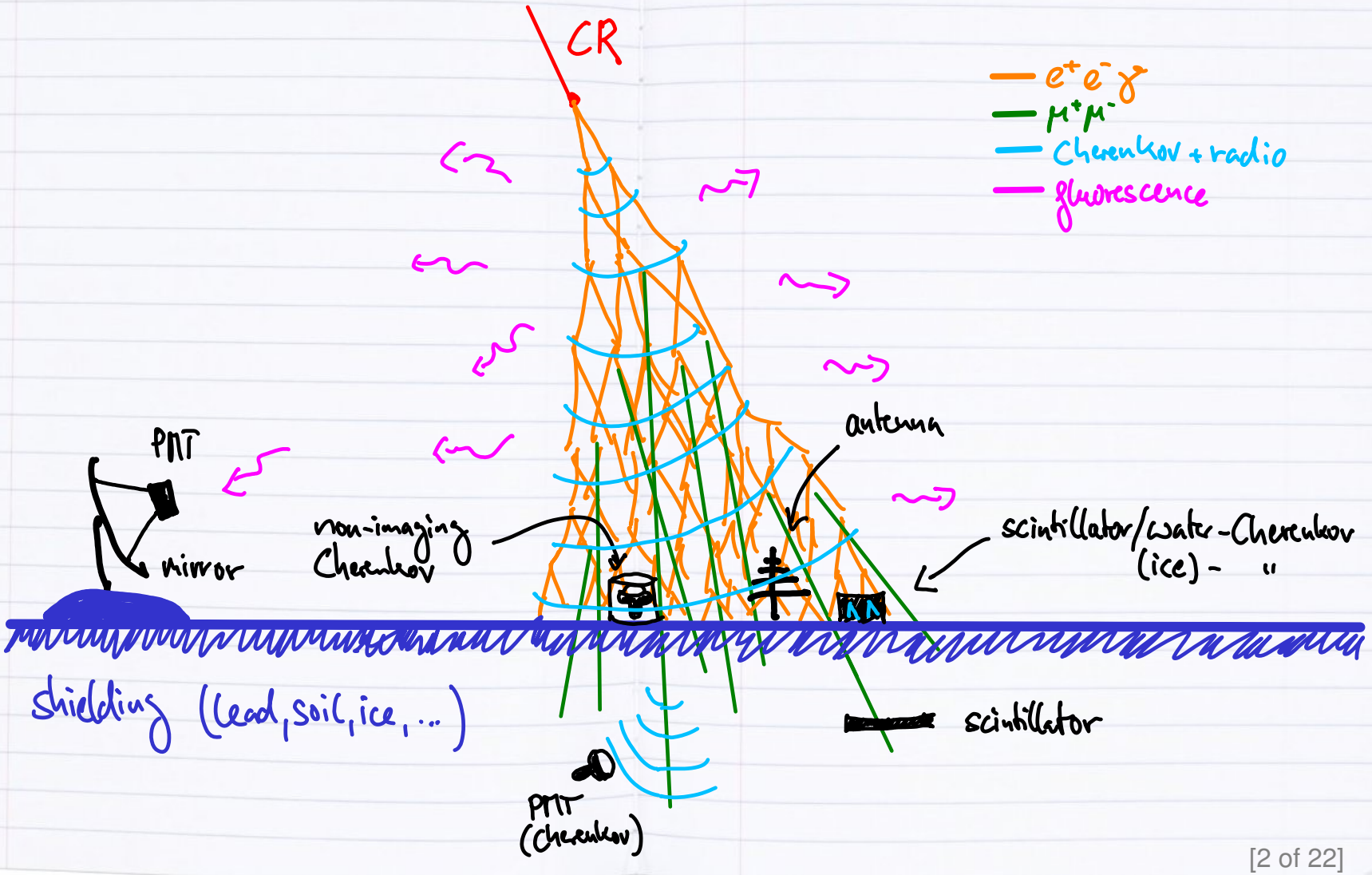


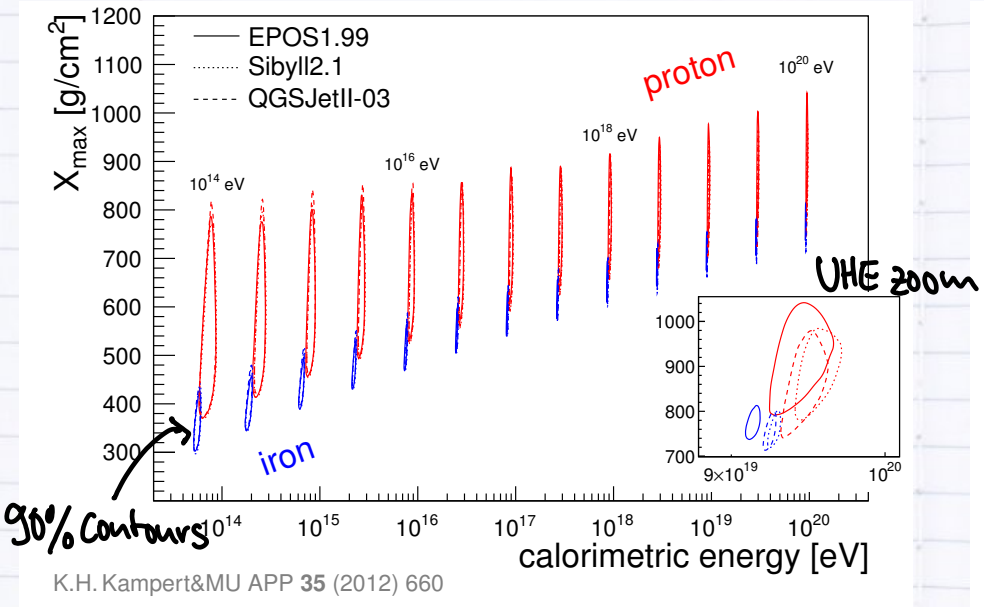
MARIE CURIE ACTIONS
Karlsruher Institut für Technologie

Air Shower Measurements



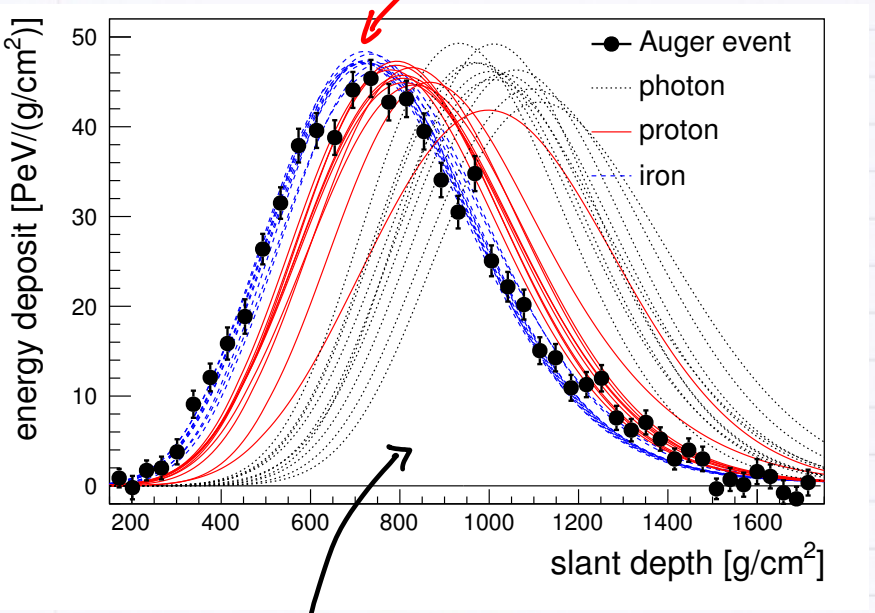
Mass Estimate: a) Xmax

(fluorescence detectors, non-imaging Č, radio)



K.H. Kampert&MU APP **35** (2012) 660

Longitudinal development:



area: calorimetric energy

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

mass

energy

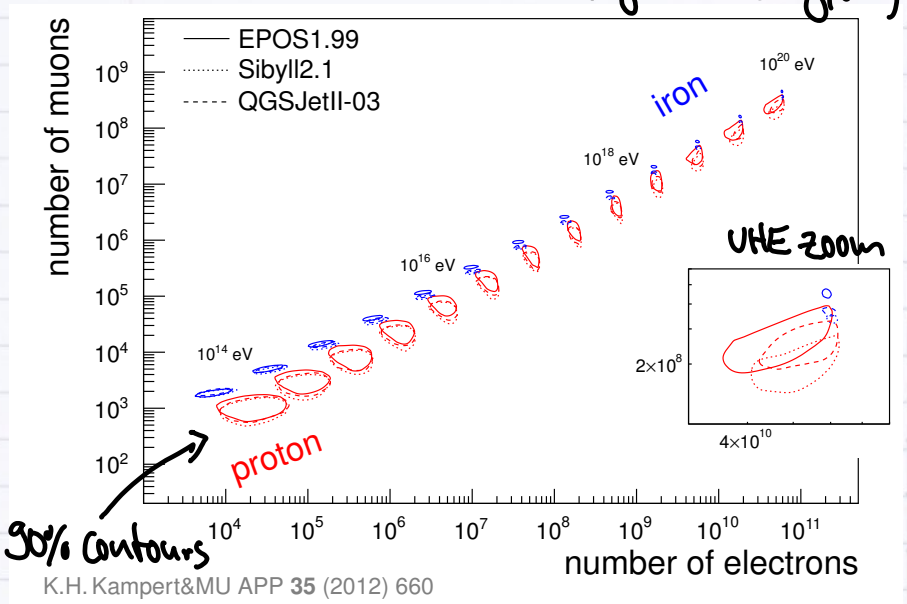
$$E_{cal} = \int dE/dX\, dX \gtrsim (0.85 \pm 0.05)\, E_{tot}$$

$(E \geq 10^{18}\,\text{eV})$

Mass Estimate: b) N_e / N_μ

(particle detectors)

($X_{ground} = 800$ g/cm²)



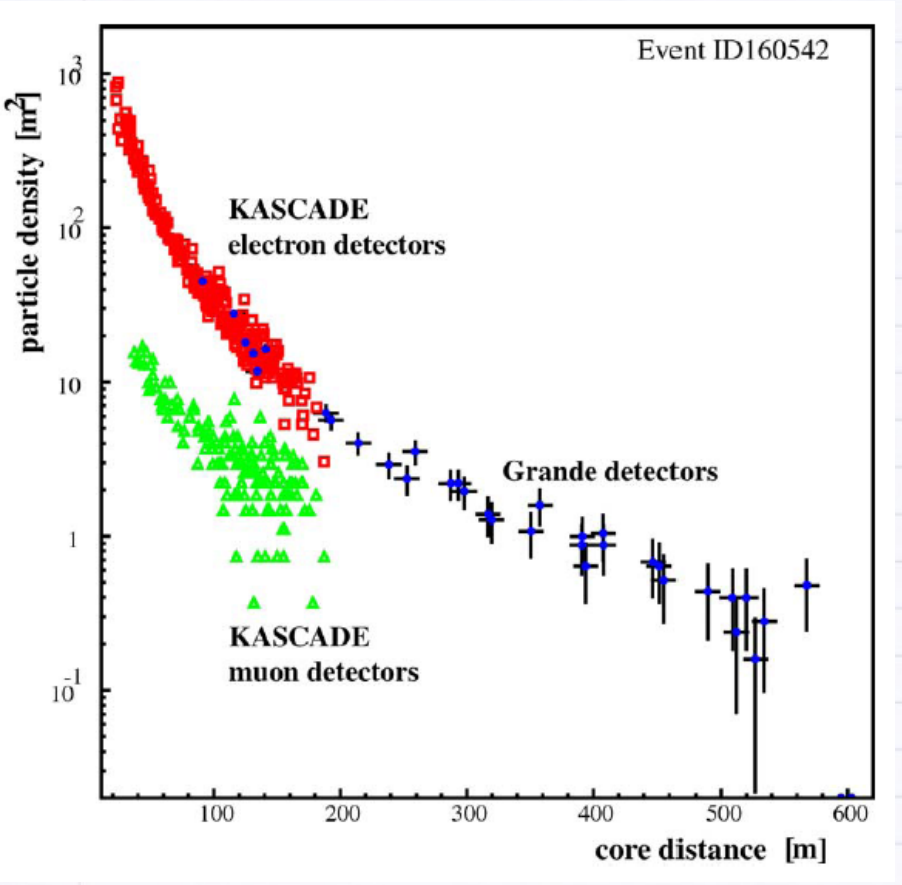
K.H. Kampert&MU APP **35** (2012) 660

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

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

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

Lateral distribution:



integral → total number of particles: N

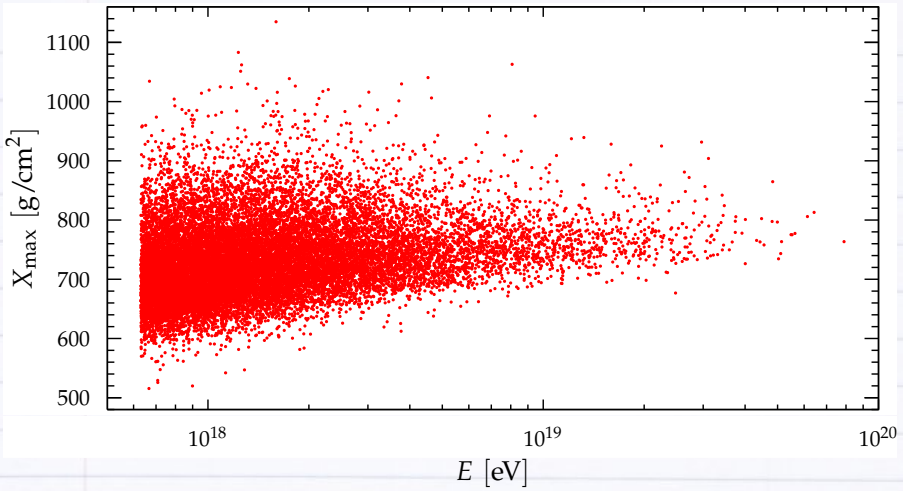
or

shower size at certain distance: Sr

Examples

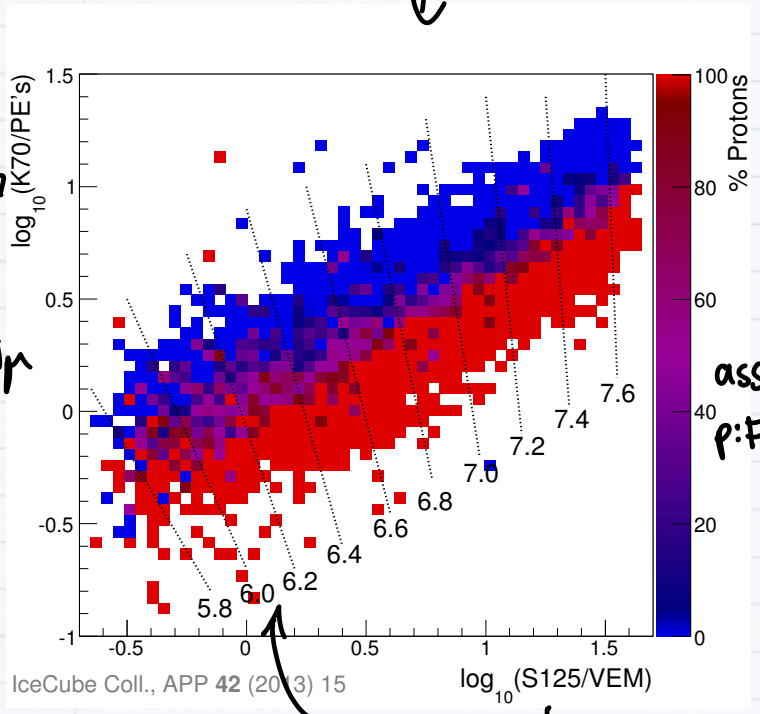
Auger fluorescence →

Pierre Auger Coll., PRD **90** (2014) 122005



IceCube surface detector vs. in-ice

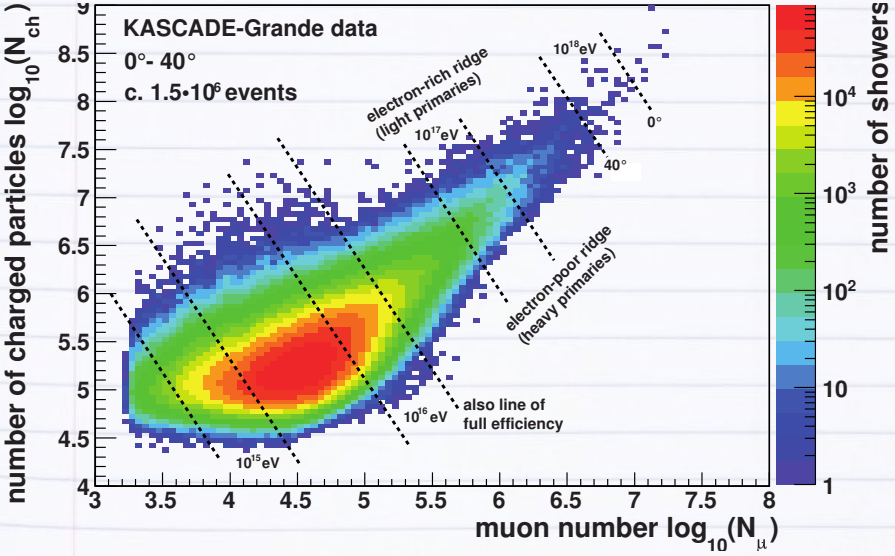
↓



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

KASCADE-Grande ↓

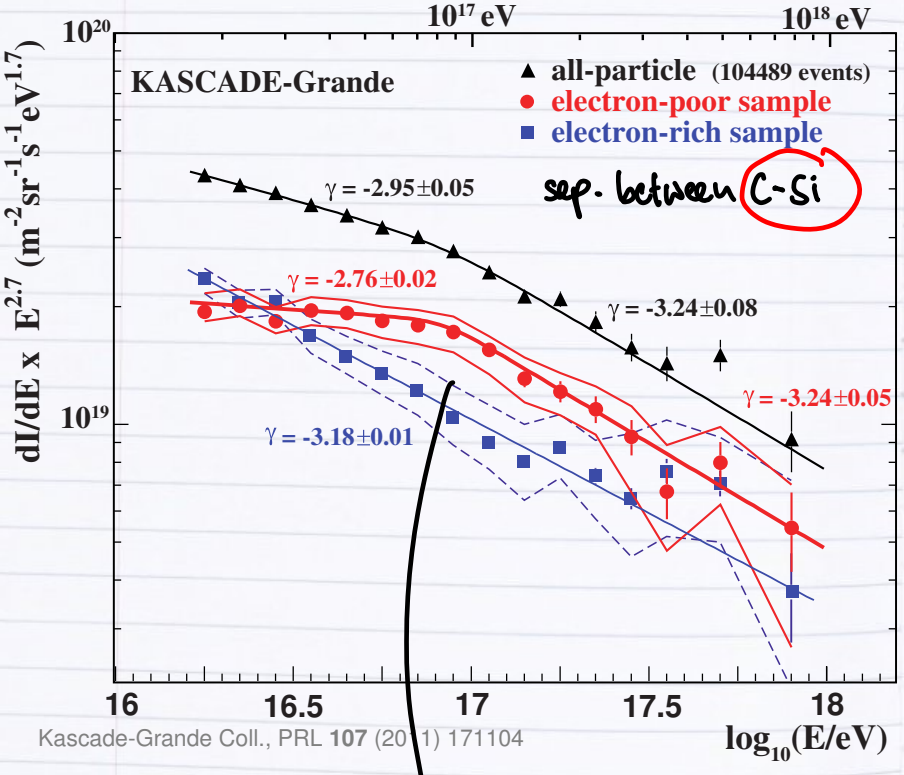
Kascade-Grande Coll., PRL **107** (2011) 171104



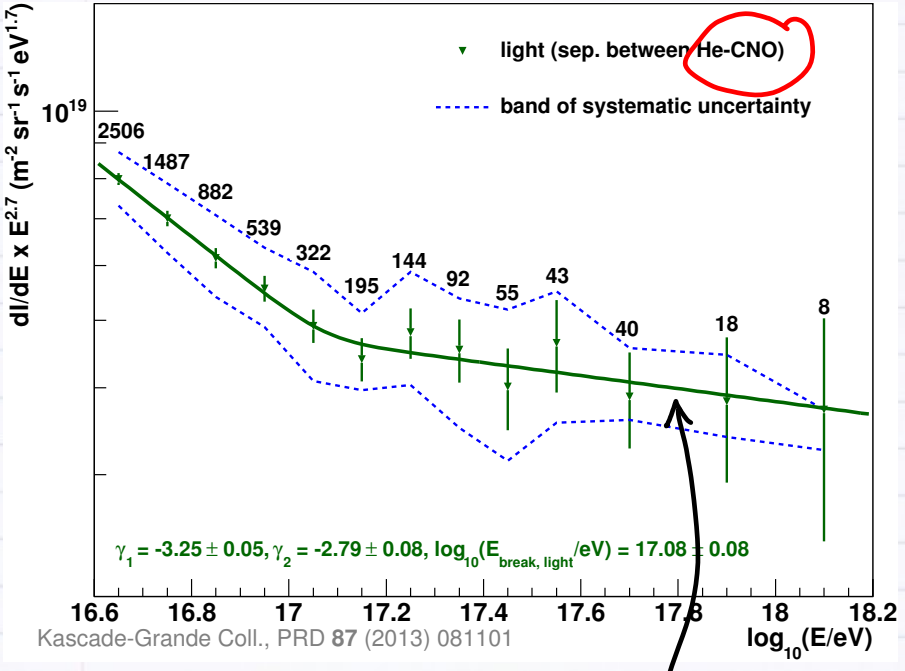
"Iron knee" and "proton ankle" (KASCADE-Grande)

"K-parameter" method: a) "rotate" Nch-Nμ diagram to E-κ ($\kappa \sim \log N_{ch}/N_\mu \sim \log A$)

b) measure flux for different cuts in κ



Kascade-Grande Coll., PRL **107** (2011) 171104



Kascade-Grande Coll., PRD **87** (2013) 081101

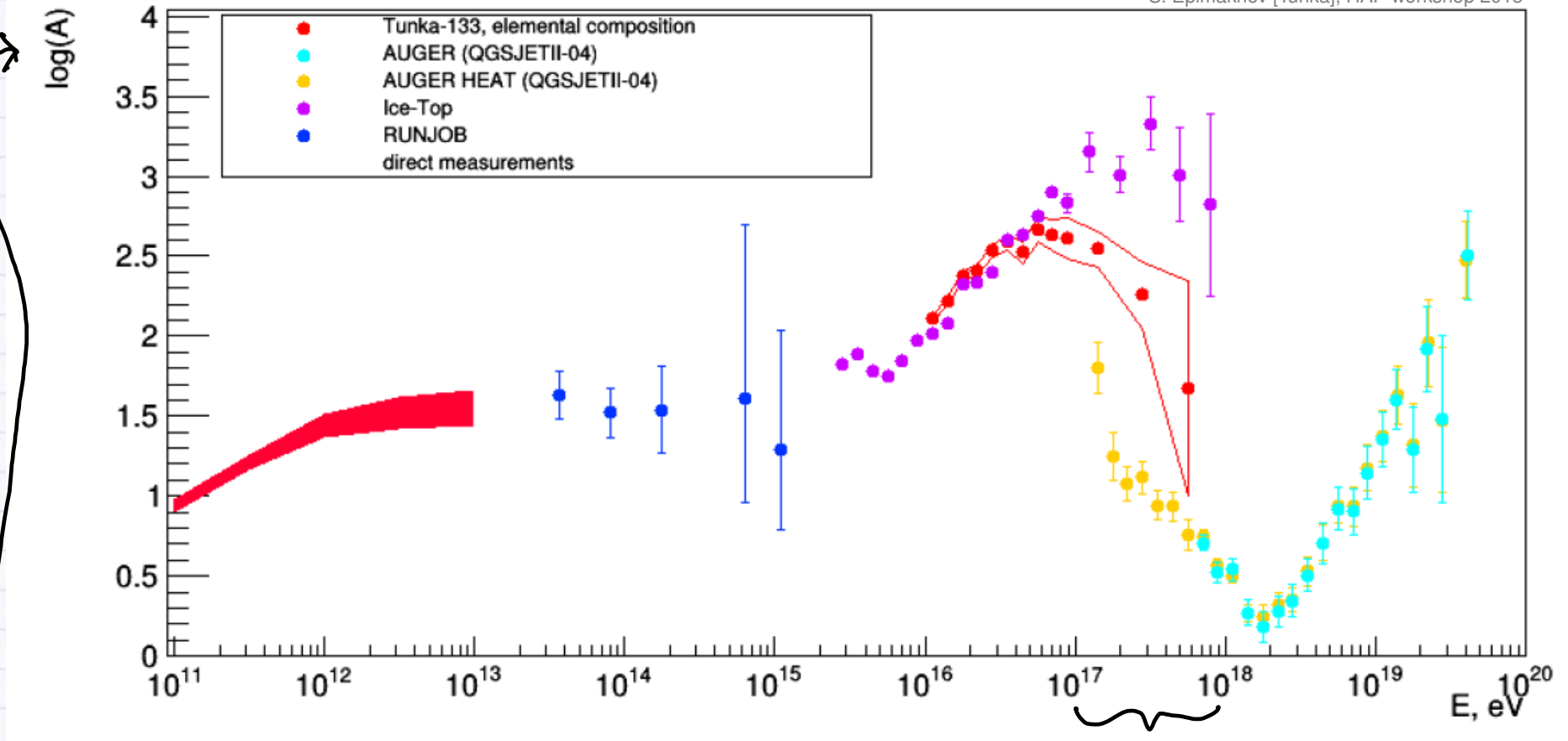
$E_{break} \sim 10^{16.9}$ eV $\leftrightarrow$ $E^p_{max} \approx E_{break}/26 = 3 \cdot 10^{15}$ eV ?!

transition to light, extragal. component?

Overview of recent "low-energy" results

(new LOFAR data is between Auger + Tunka)

S. Epimakhov [Tunka], HAP workshop 2015



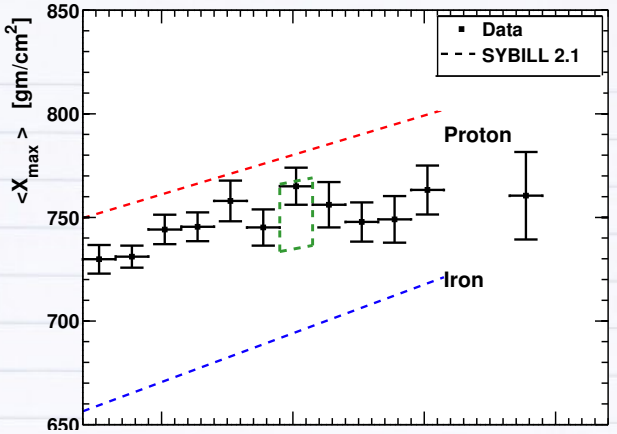
$\ln A = \sum f_i \ln A_i \sim \langle X_{max} \rangle$

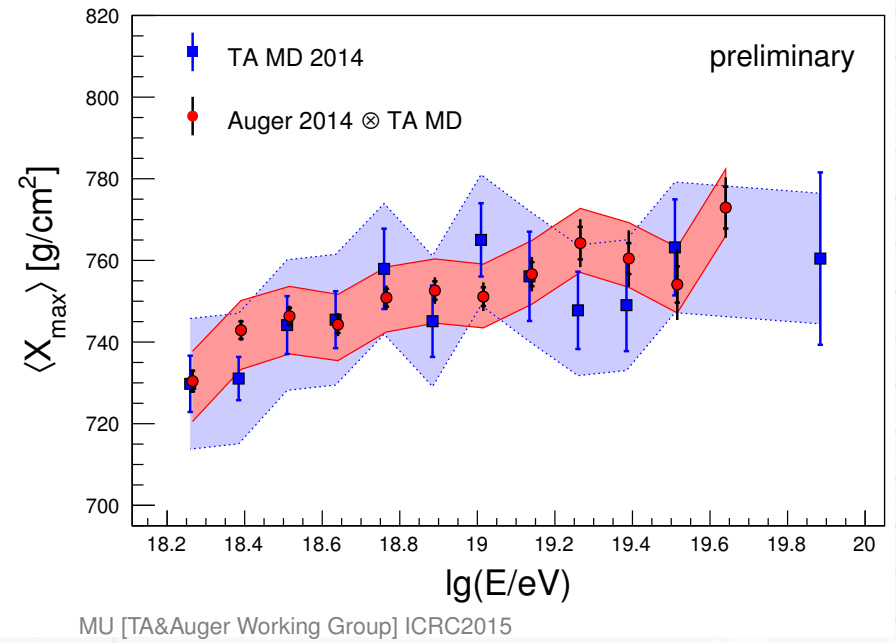
large discrepancies in presumed region of gal. to egal. CRs ☹

Composition at Ultrahigh Energies

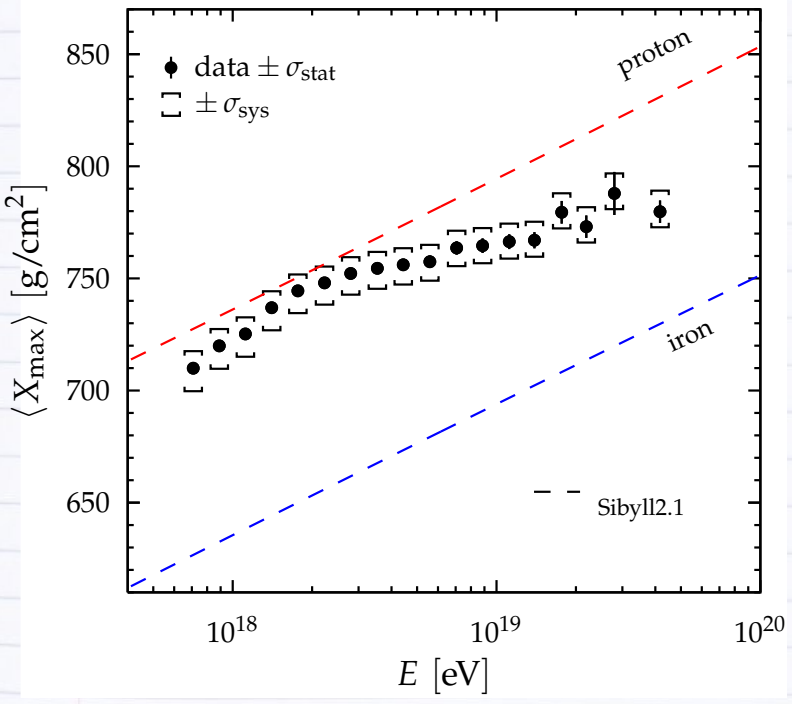
(fluorescence detector results)

TA Coll., APP **64** (2014) 49





MU [TA&Auger Working Group] ICRC2015



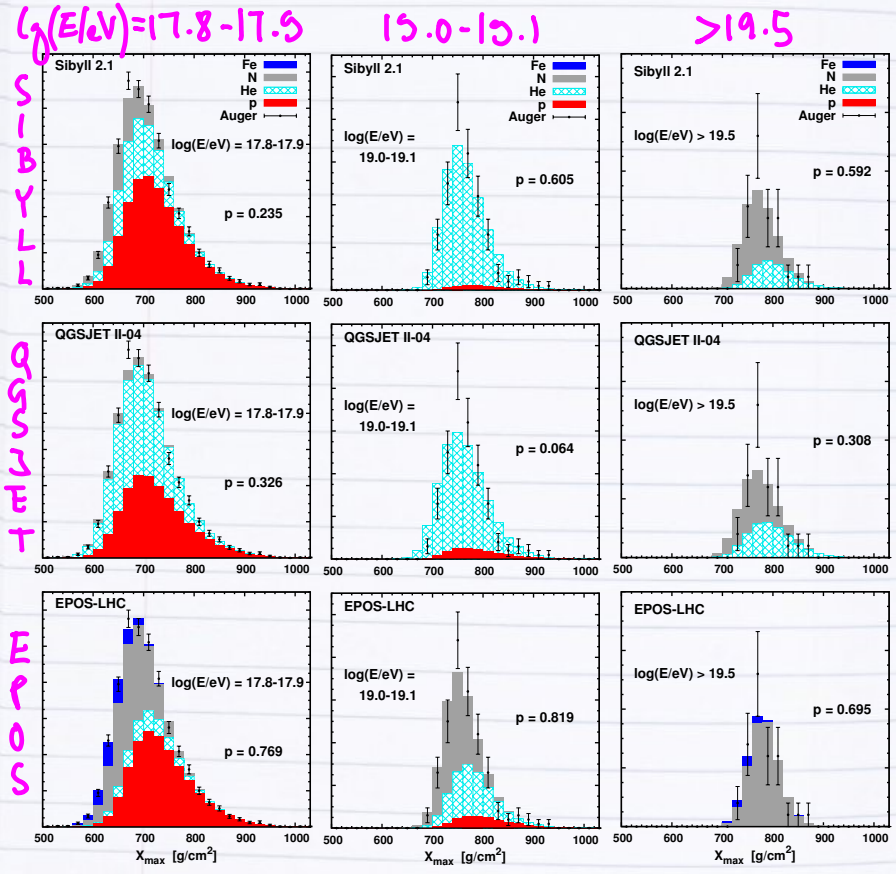
Pierre Auger Coll., PRD **90** (2014) 122005

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

⇒ ok! ☺

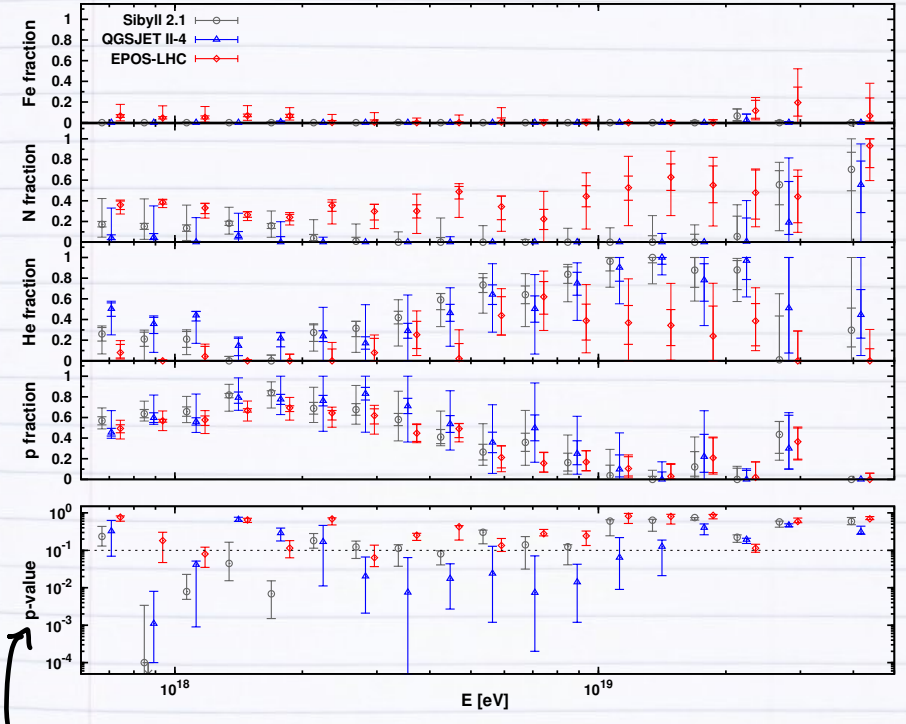
Interpretation of Xmax Distributions

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



fitted fractions:

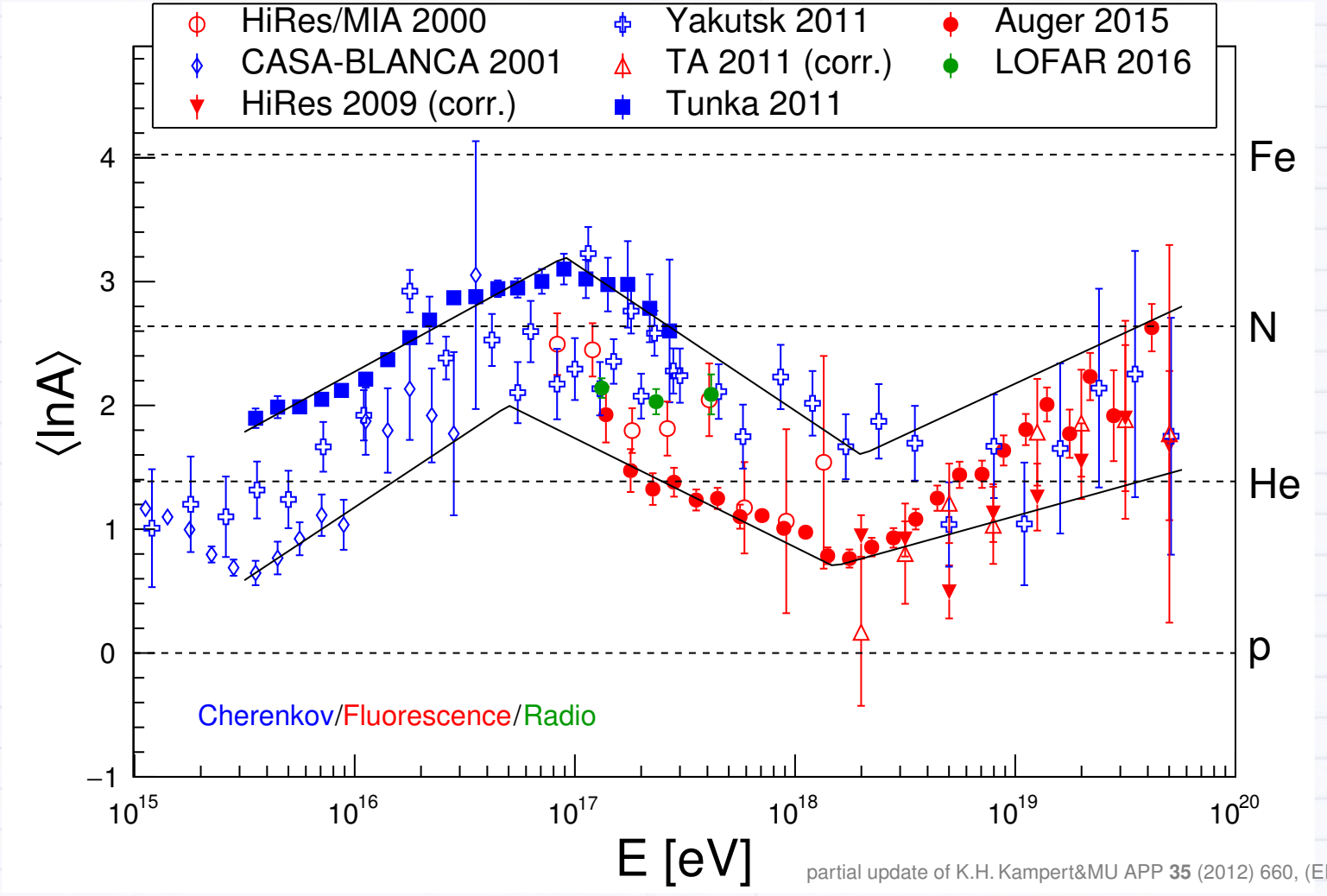
Pierre Auger Coll., PRD **90** (2014) 12, 122006



fit probability (bad fits with QGSJetII-04)

Zig-Zag Plot

(only Xmax measurements)



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

exp. syst. typically $\geq \pm 10\,g/cm^2 \leftrightarrow \pm 0.4$ in $\langle \ln A \rangle$

End of galactic Component?

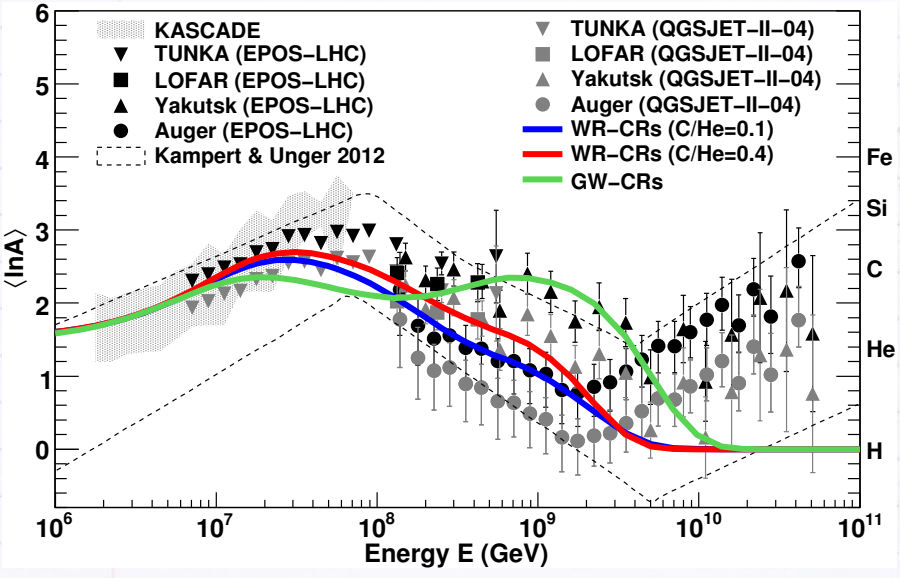
→ SNR E_{max} = few $Z \cdot 10^{15}$ eV ?

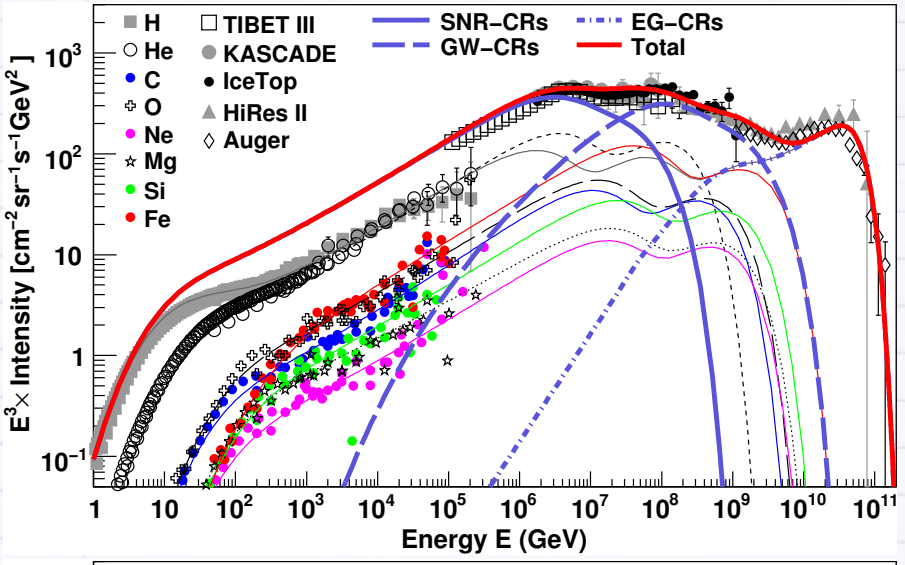
→ additional galactic component ?

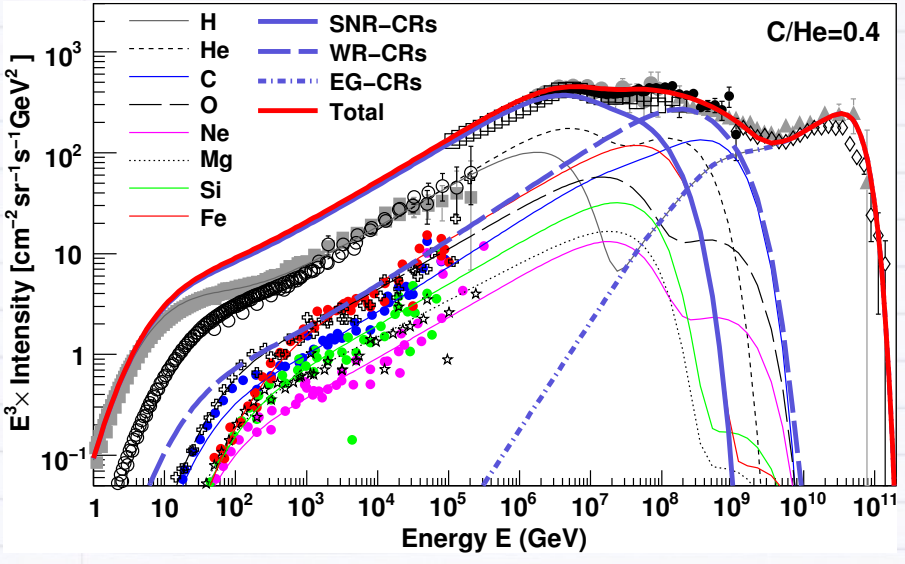
→ Wolf-Rayet stars ?

→ re-acceleration at Gal. wind termination shock ?

→ ... ?



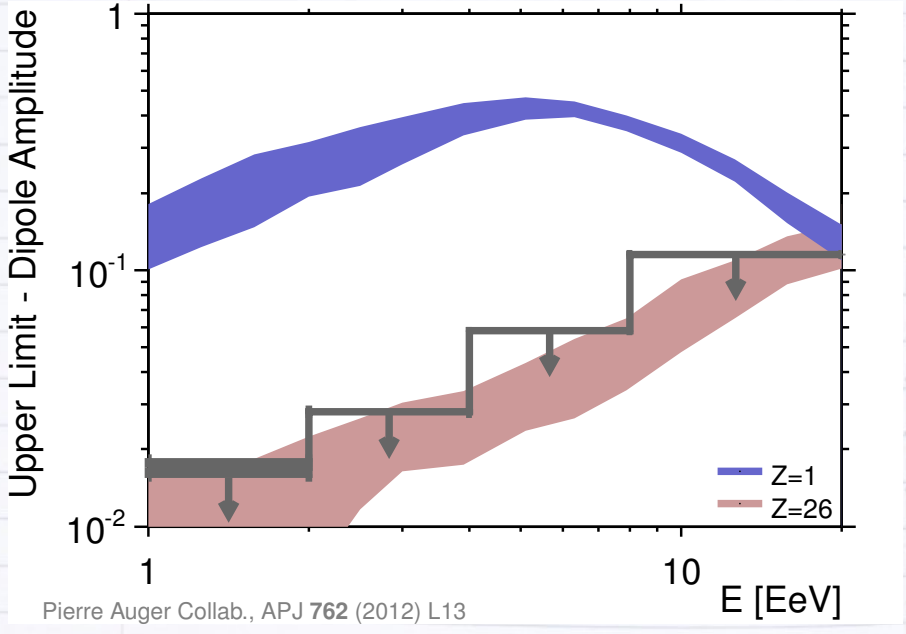




S. Thoudam et al. arXiv:1605.03111

Low-Mass Galactic CRs at EeV?

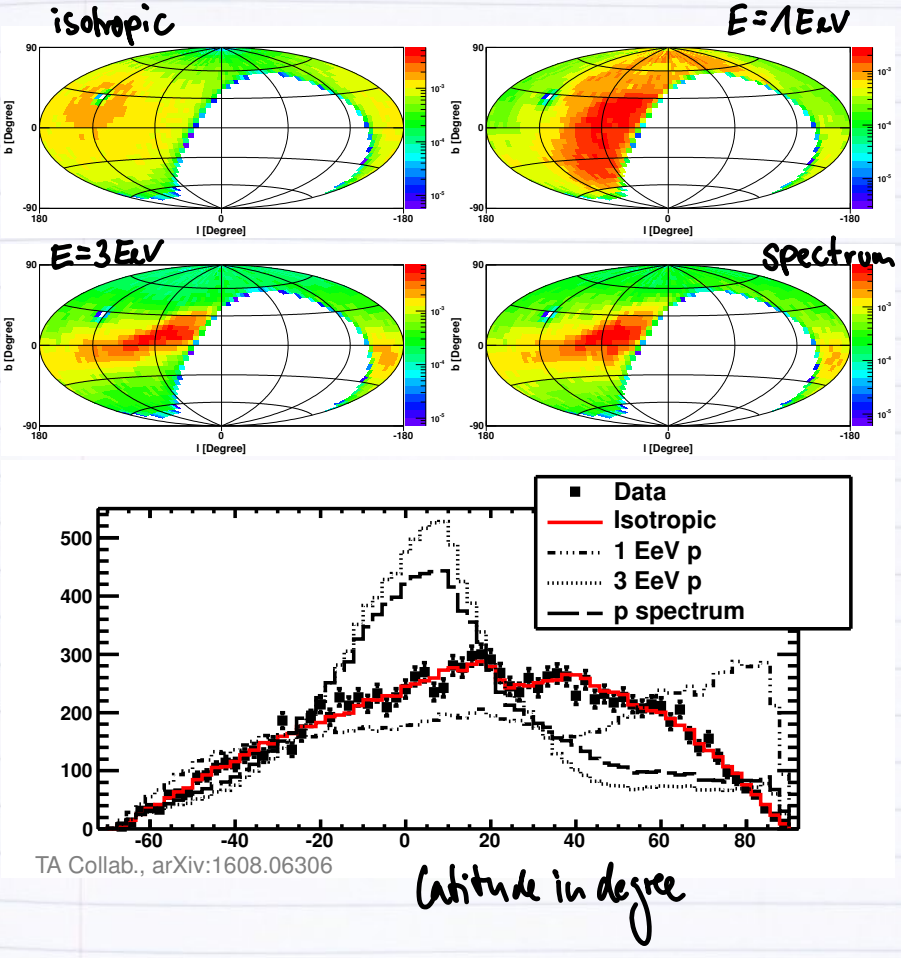
Auger dipole amplitude limits:



Pierre Auger Collab., APJ **762** (2012) L13

answer: No! → if light, then extragalactic!

TA latitude distribution:

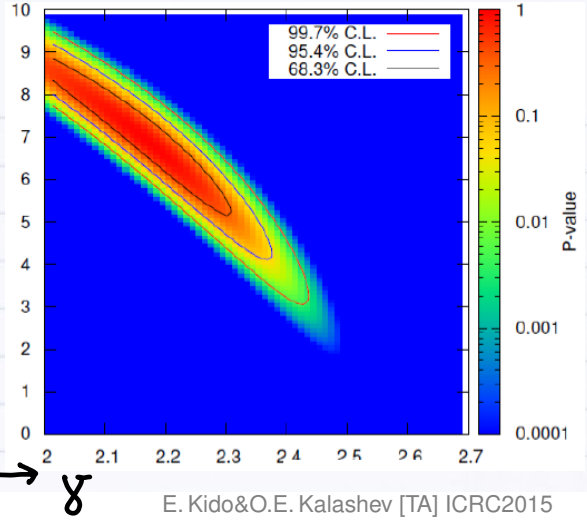


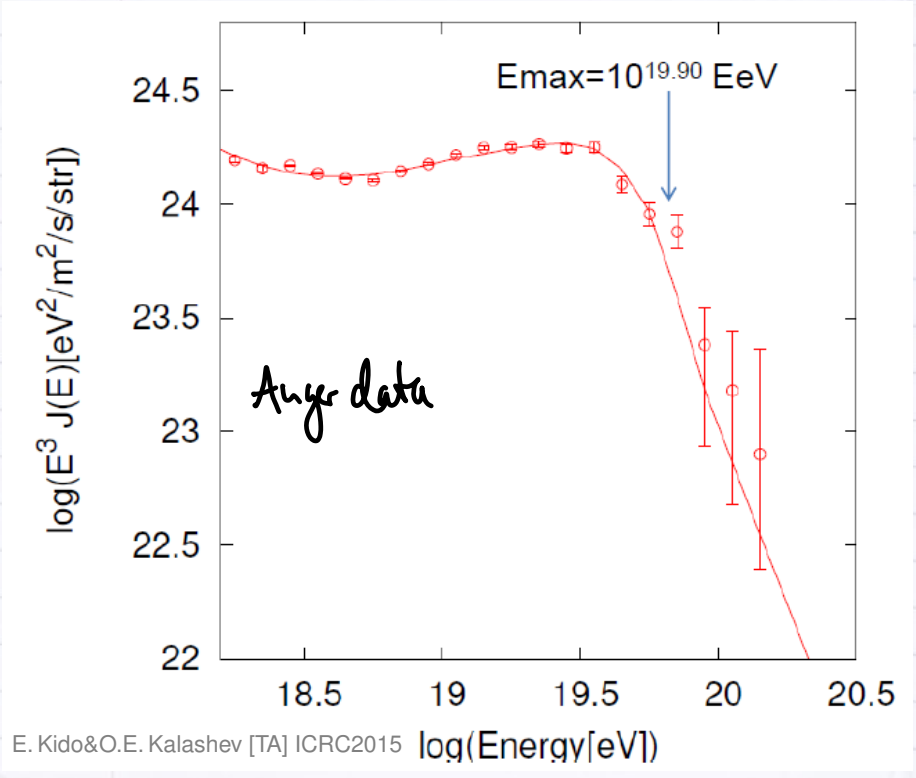
TA Collab., arXiv:1608.06306

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

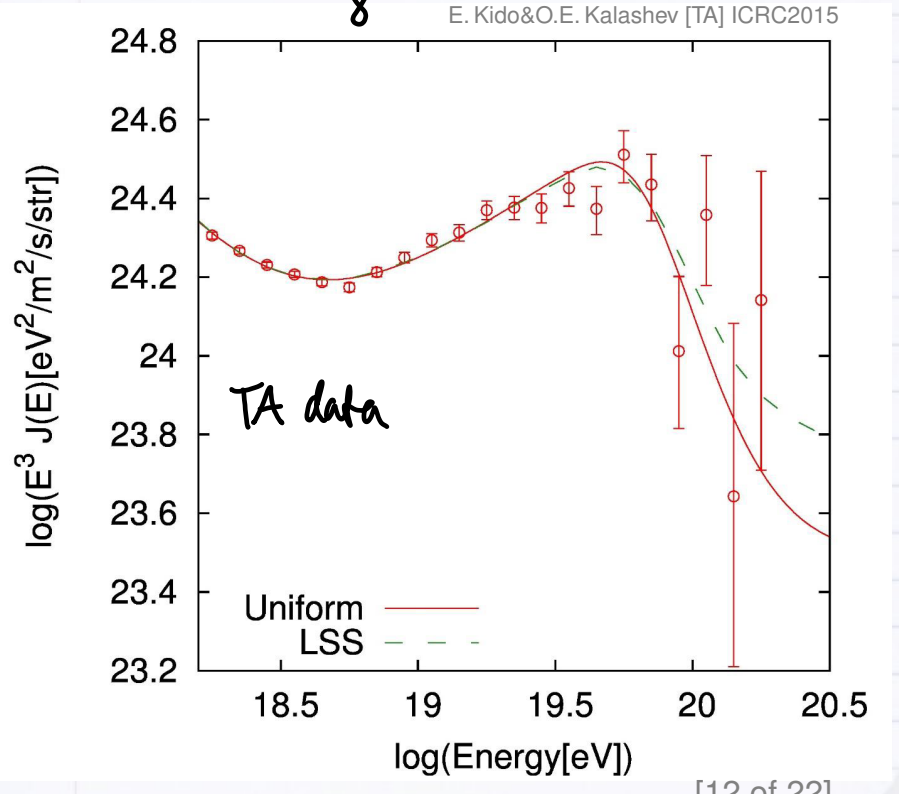
origin of ankle: $p + \gamma_{CMB} \rightarrow p + e^+ + e^-$

parameters:
- source evolution e.g. $\sim (1+z)^m$ → m
- spectrum at injection $\sim E^{-\gamma}$ → γ
- if needed: E_{max}





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

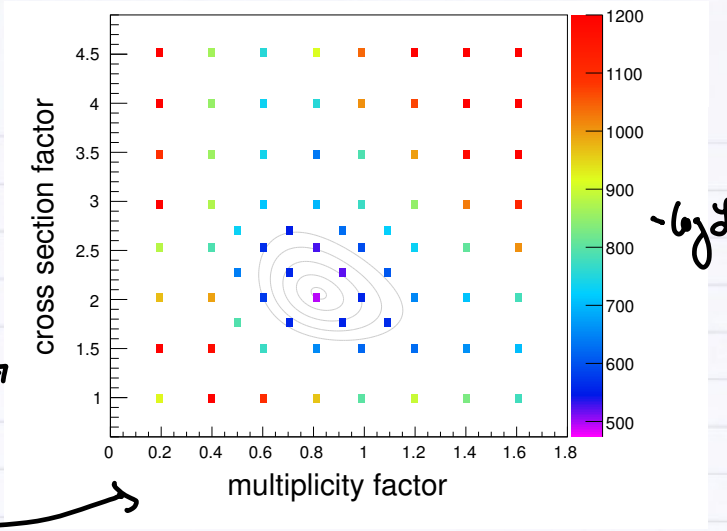


E. Kido&O.E. Kalashev [TA] ICRC2015

How to reconcile with Xmax ?

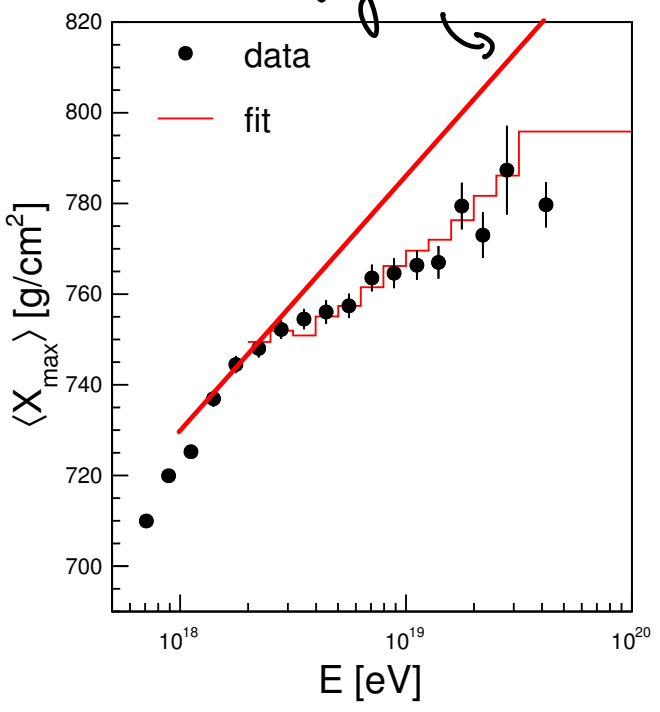
→ exotic hadronic interactions?

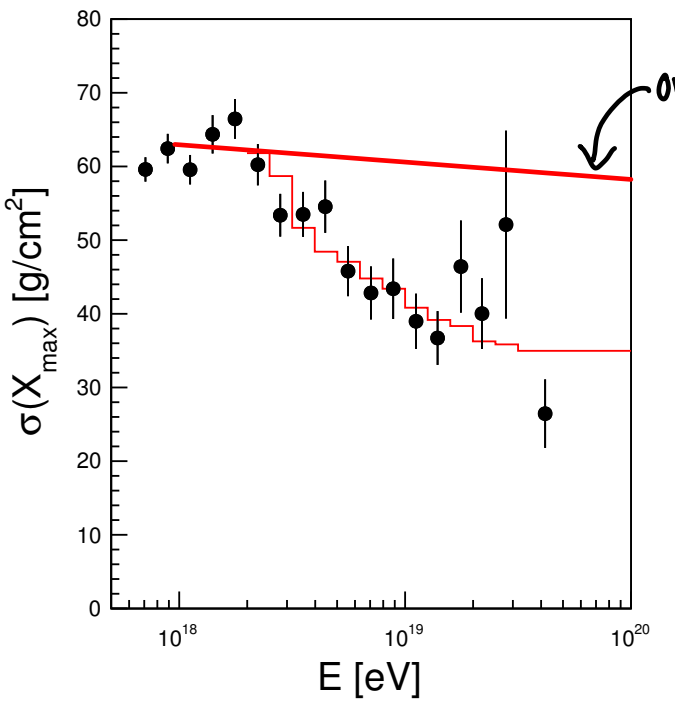
e.g. linear rescaling of cross section and multiplicity above $10^{18.3}$ eV (QGSJetII-04)



rescaling at 10^{19} eV

original model





original model

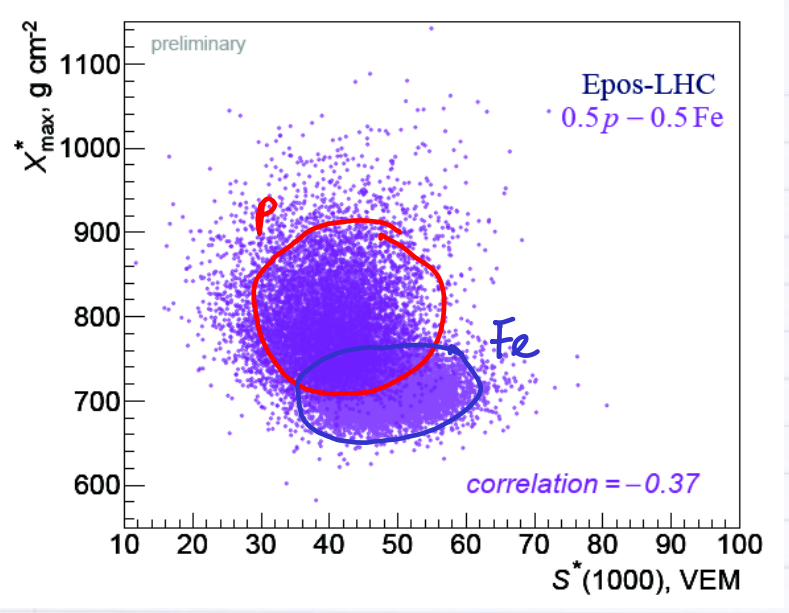
⇒ works!!

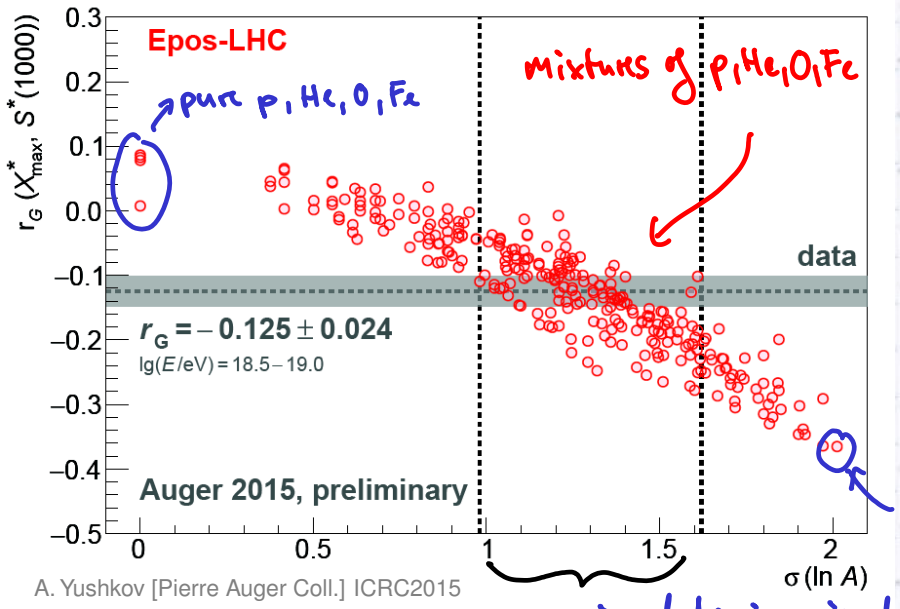
(but very exotic ... rescaling of $\sigma_{p\text{-air}}$ by a factor of 2 at 10^{19} eV!)

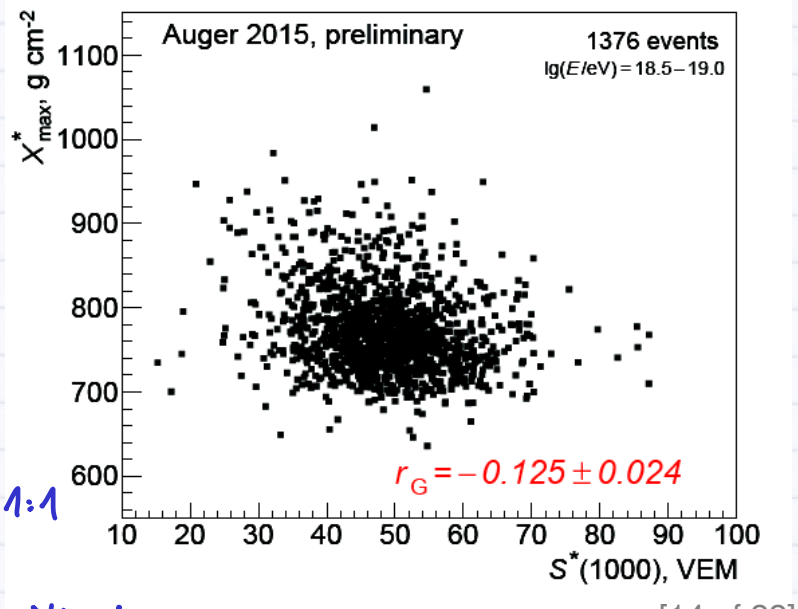
MU, R. Ulrich, R. Engel (unpublished); see also J.D. Allen and G.R. Farrar ICRC13 arXiv:1307.2322

A Model-Independent Test of Composition

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



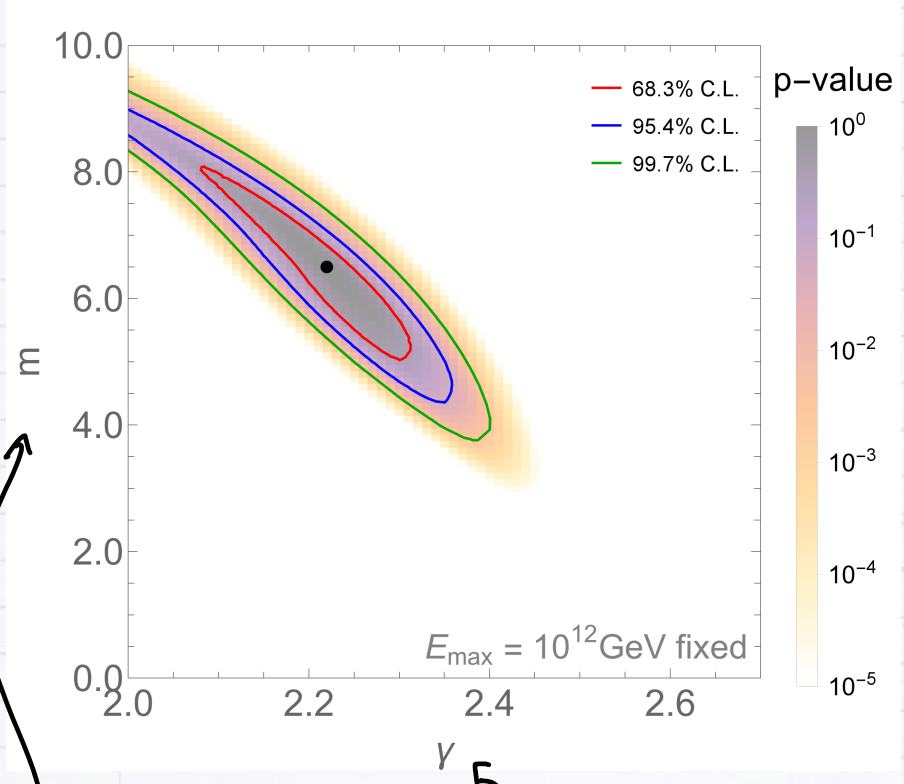




A. Yushkov [Pierre Auger Coll.] ICRC2015

⇒ data is mixed composition!

Dip Model vs. Secondaries

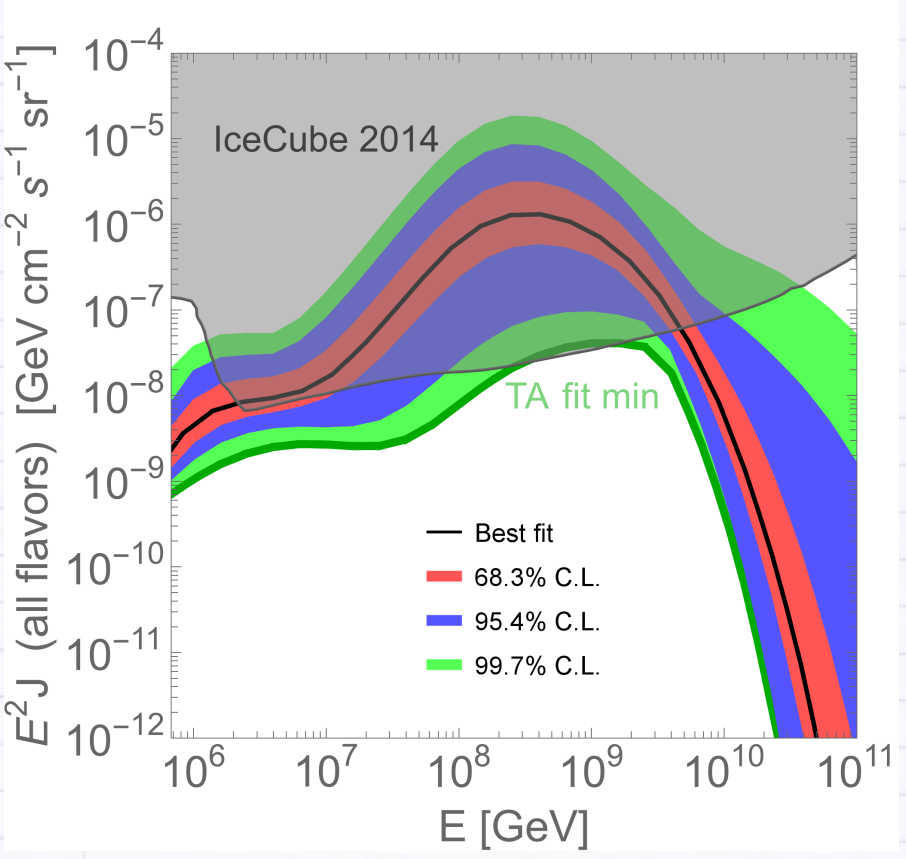


J. Heinze et al. ApJ **825** (2016) 122

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

⇒ very strong source evolution needed to fit spectrum ⇒ too many neutrinos

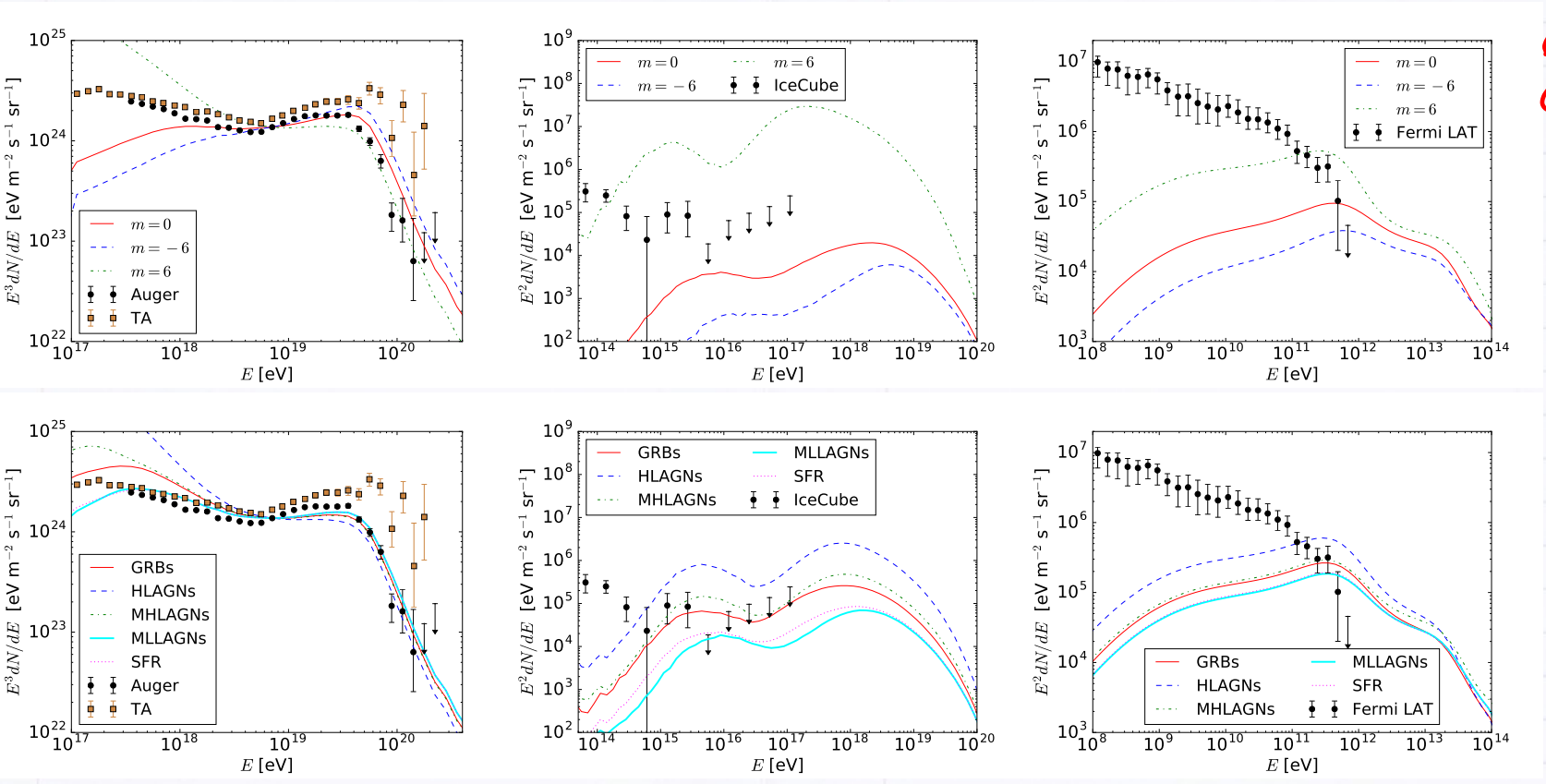
a) neutrinos from photopion production (ν_{GZK})



Dip Model vs. Secondaries

b) ν_{GZK} and photons from $p + \gamma_{CMB} \rightarrow p + e^+ + e^-$ ↓ emg. cascade

A. van Vliet, arXiv:1609:03336

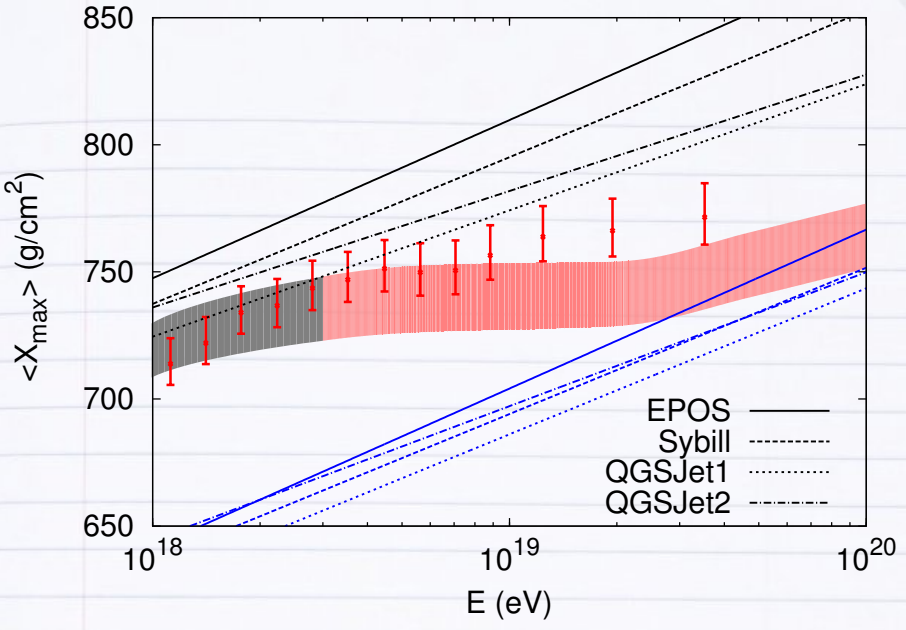


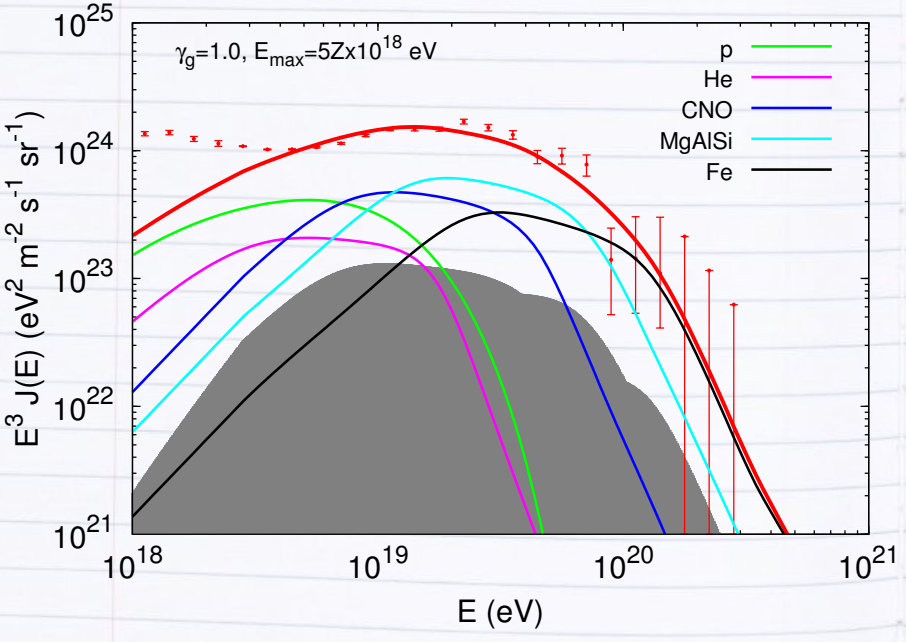
(see also IceCube Coll. arXiv:1607.05886; R.-Y. Liu et al., PRD **94** (2016) 043008; V. Berezinsky et al, APP **84** (2016) 52; A.D. Supanitsky PRD **94** (2016) 063002; E. Gavish, D. Eichler ApJ **822** (2016) 56, ...)

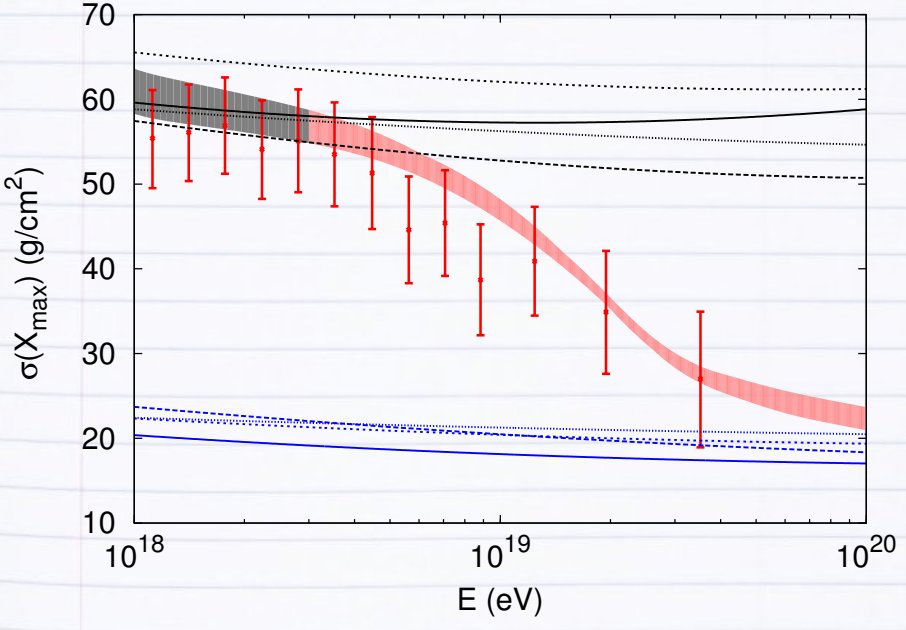
⇒ sources of UHECR p strongly constrained!

Mixed Composition Model

- $E_{max} \sim Z$ ☺
- ad hoc composition fractions ☹
- hard injection spectrum $\gamma \approx 1$ 😐



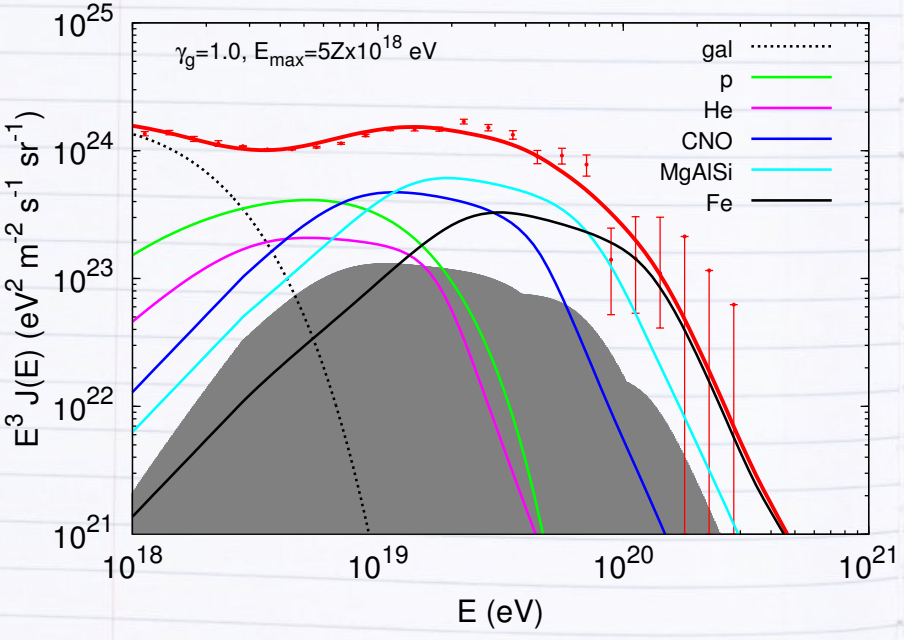


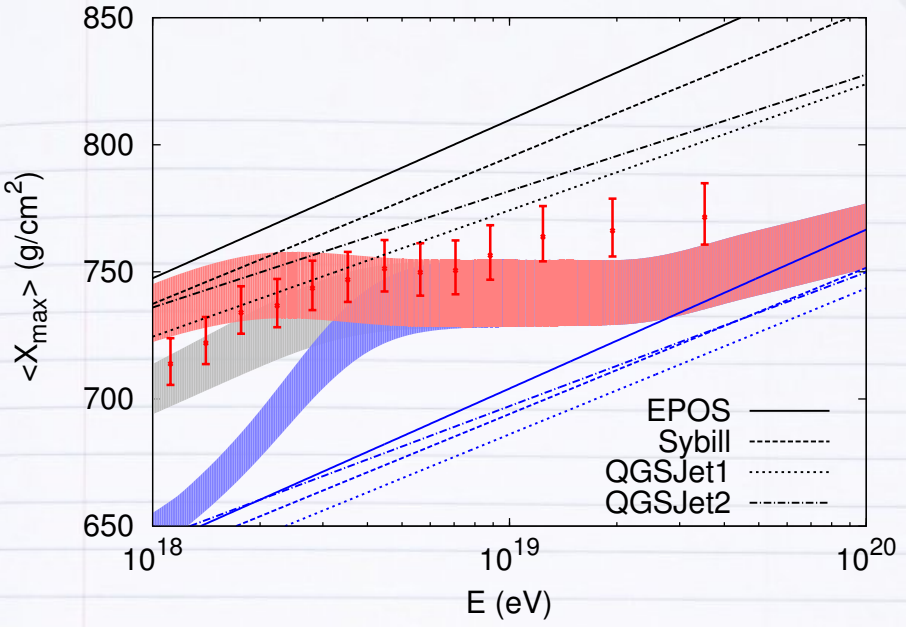


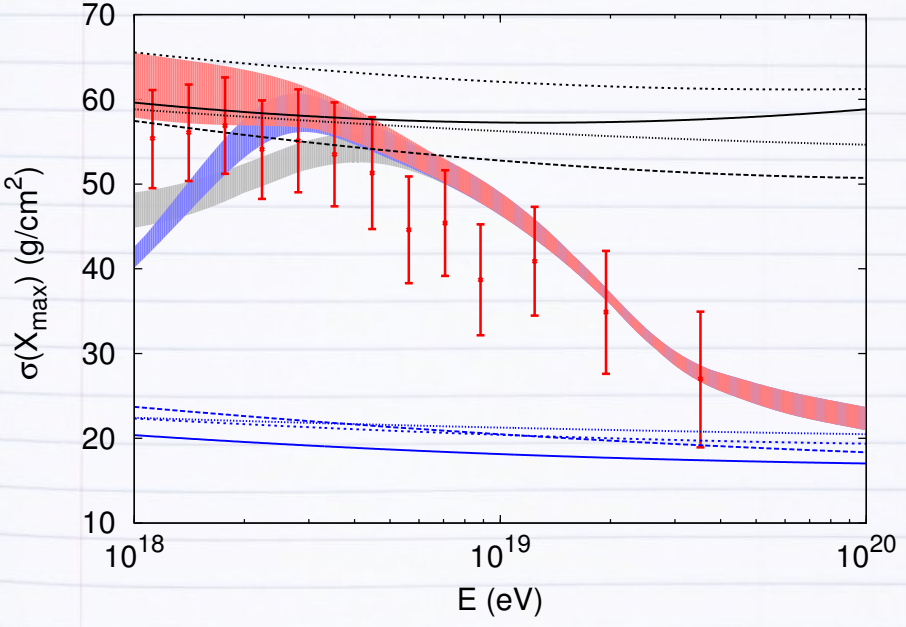
R. Aloisio, V. Berezinsky&P. Blasi JCAP **1410** (2014) 020; see also D. Allard, arXiv:1111.3290 and A. Di Matteo [Pierre Auger Coll.] ICRC2015

Mixed Composition Model

- $E_{max} \sim Z$ ☺
- ad hoc composition fractions ☹
- hard injection spectrum $\gamma \approx 1$ 😐
- ad hoc low-E light component ☹

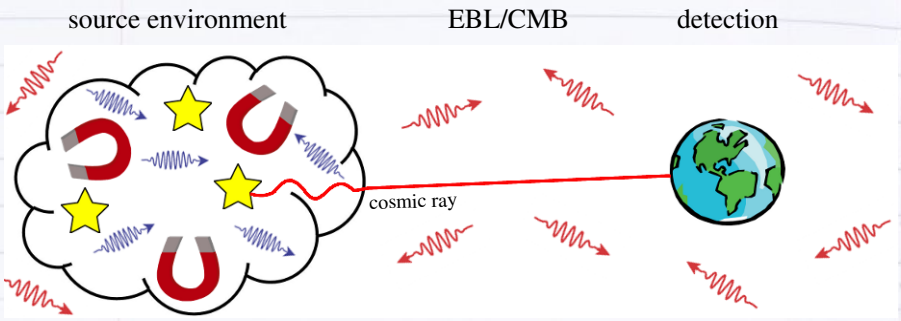


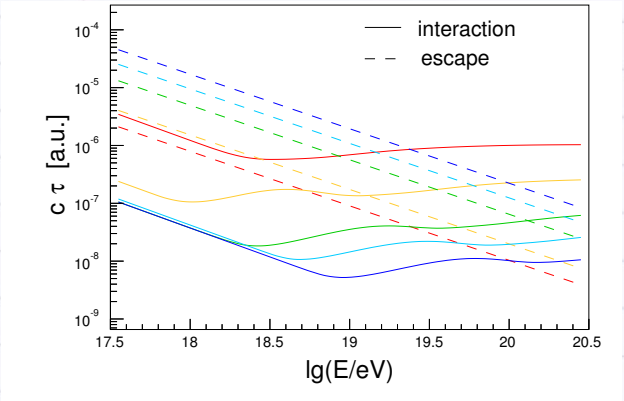


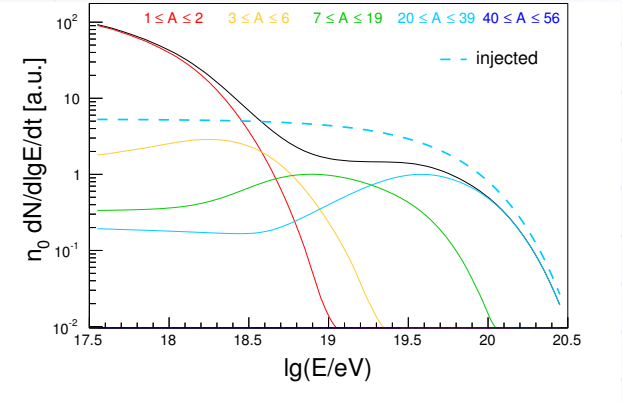


R. Aloisio, V. Berezinsky&P. Blasi JCAP **1410** (2014) 020; see also D. Allard, arXiv:1111.3290 and A. Di Matteo [Pierre Auger Coll.] ICRC2015

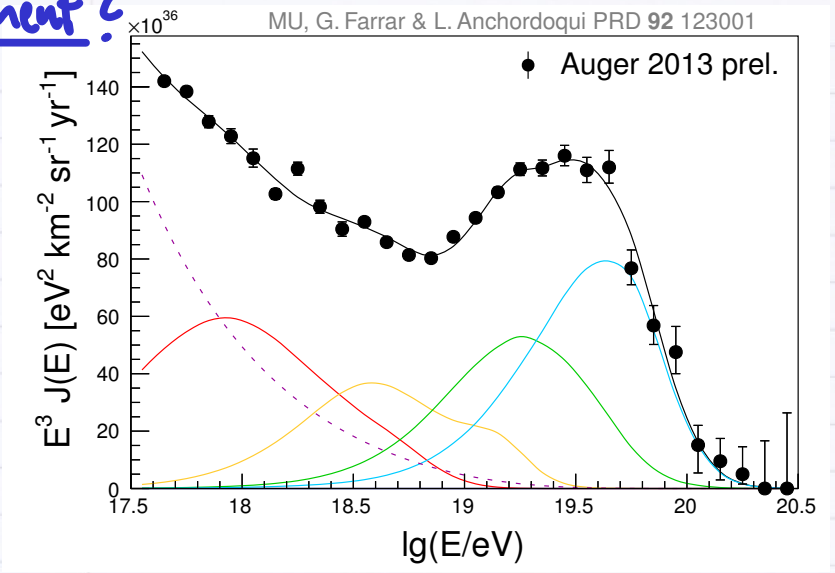
Photonuclear Interactions in Source Environment ?

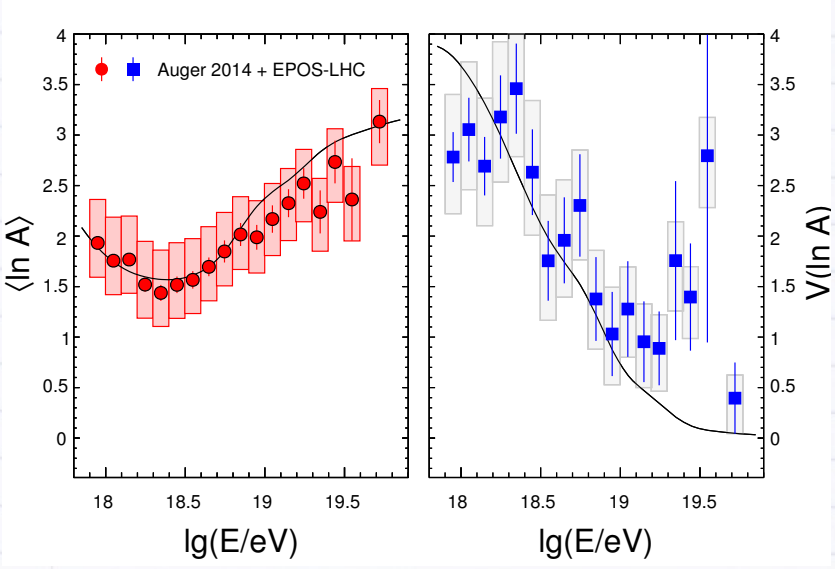


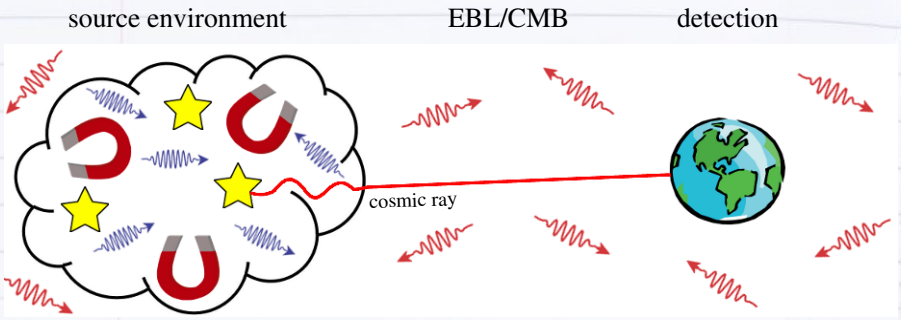




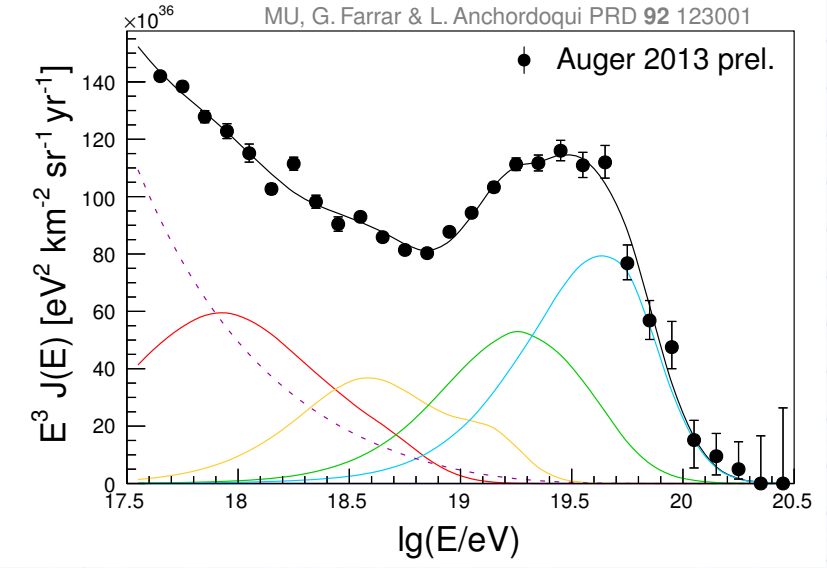
MU, G. Farrar & L. Anchordoqui PRD **92** 123001

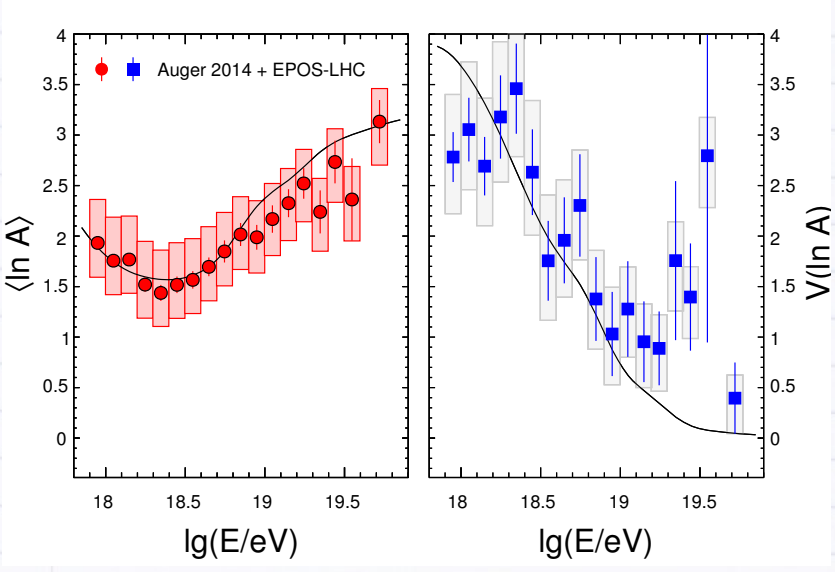






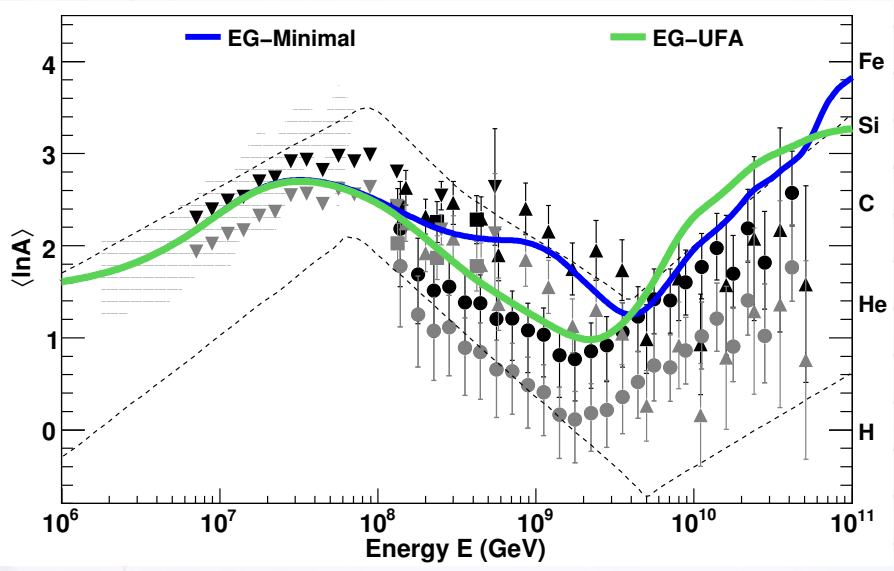
- $E_{max} \propto Z$ ☺
- Composition: heavy or Gal. mix ☺
- hard injection spectrum $\gamma \approx 1$ 😐
- low-E light component for free ☺
- next-gen ν observatories can probe model + parameters ☺
- additional degrees of freedom (escape + interaction lengths) 😐

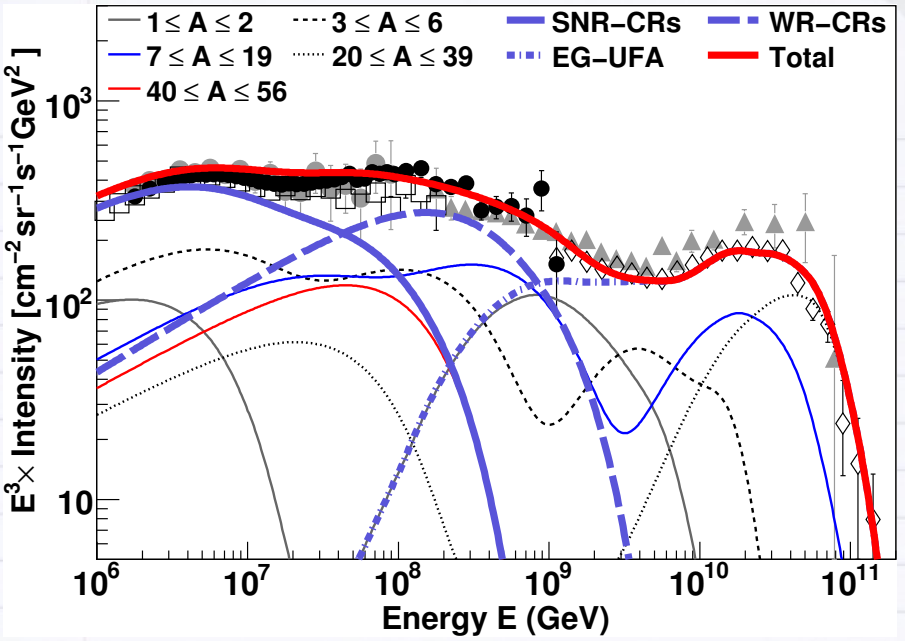


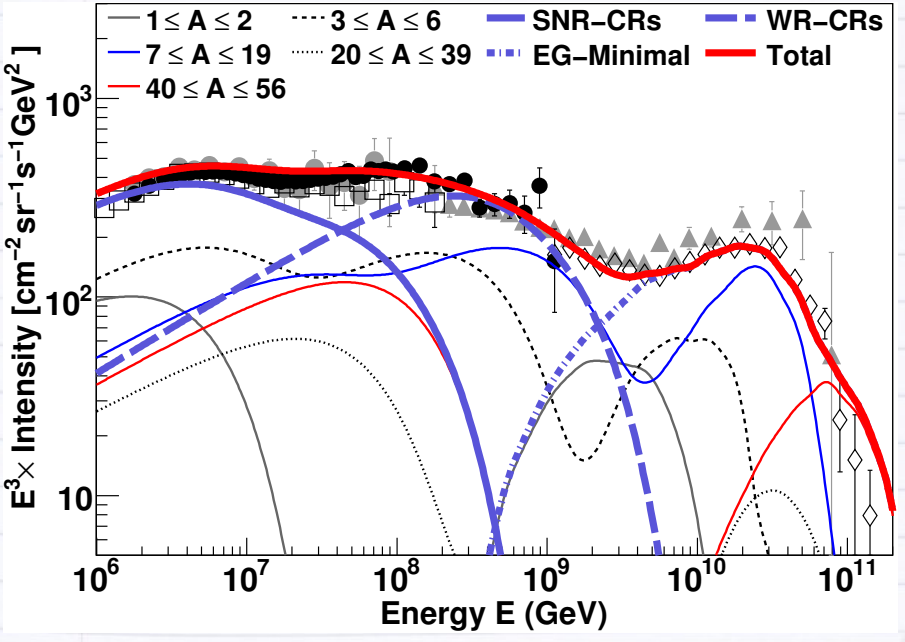


Conclusions

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







S. Thoudam et al. arXiv:1605.03111

→ Cherenkov – fluorescence discrepancy?
– NICHE at TALE!
– HiSCORE at Auger?

→ currently no statistics above ~ $10^{19.5}$ eV
→ Auger Prime !!

→ will ARA & 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 $> 10^{18}$ eV further into the GZK range?

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

→ how important are p+O data from LHC?