PIERRE AUGER OBSERVATORY

Rhein-Ruhr RRAPP

Inauguration Conference
Bochum, Sept. 21-23, 2016

Ultra-High Energy Cosmic Ray Observations

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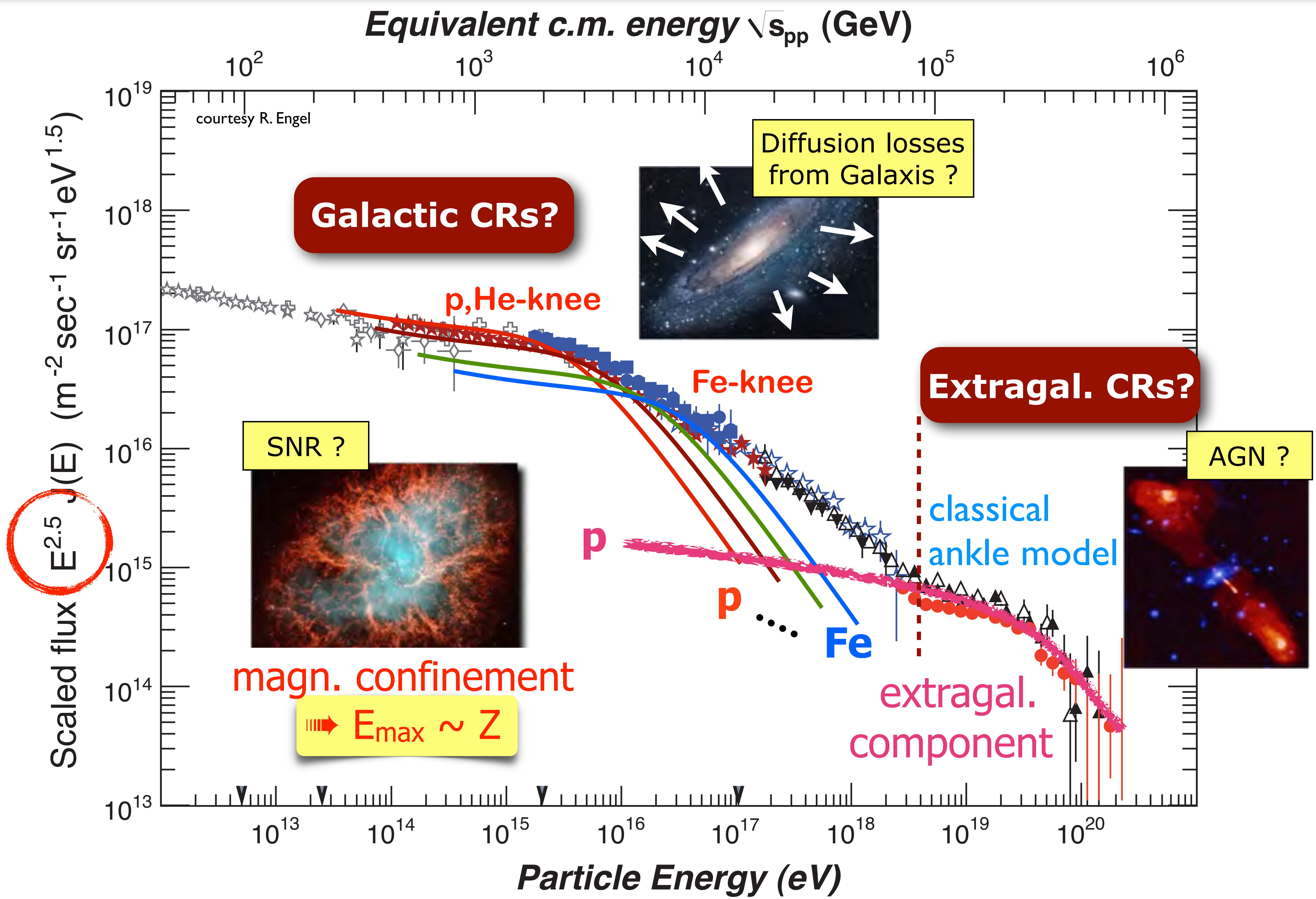
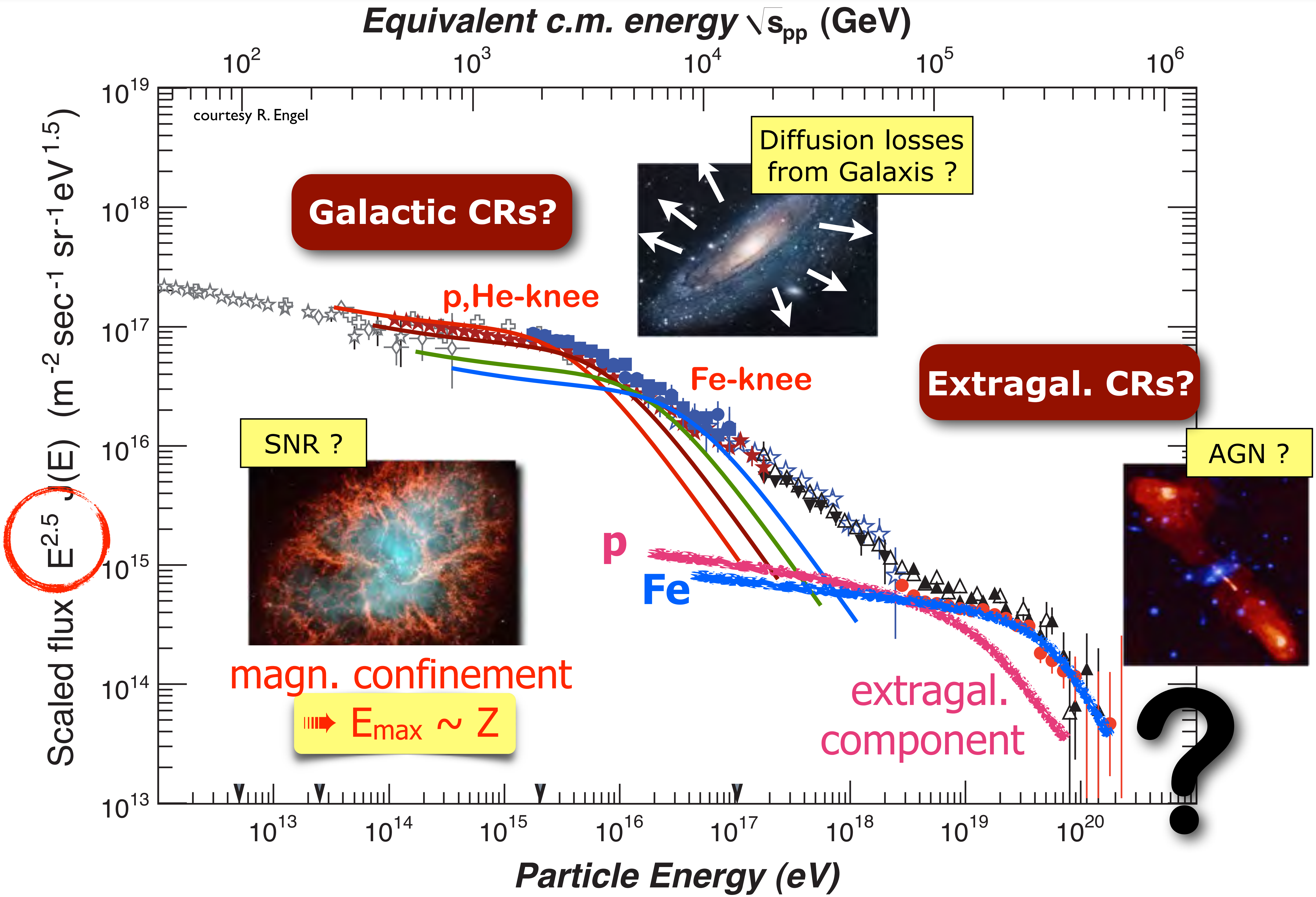
BERGISCHE UNIVERSITÄT WUPPERTAL

bmb+f
Großgeräte der physikalischen Grundlagenforschung

Features of CR spectrum

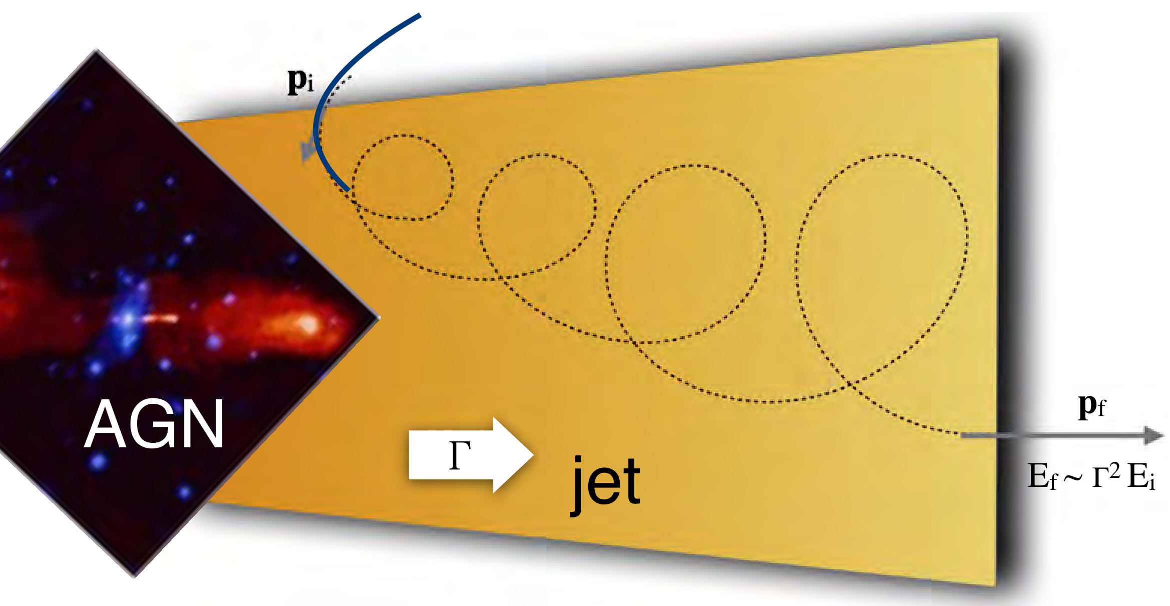


Features of CR spectrum



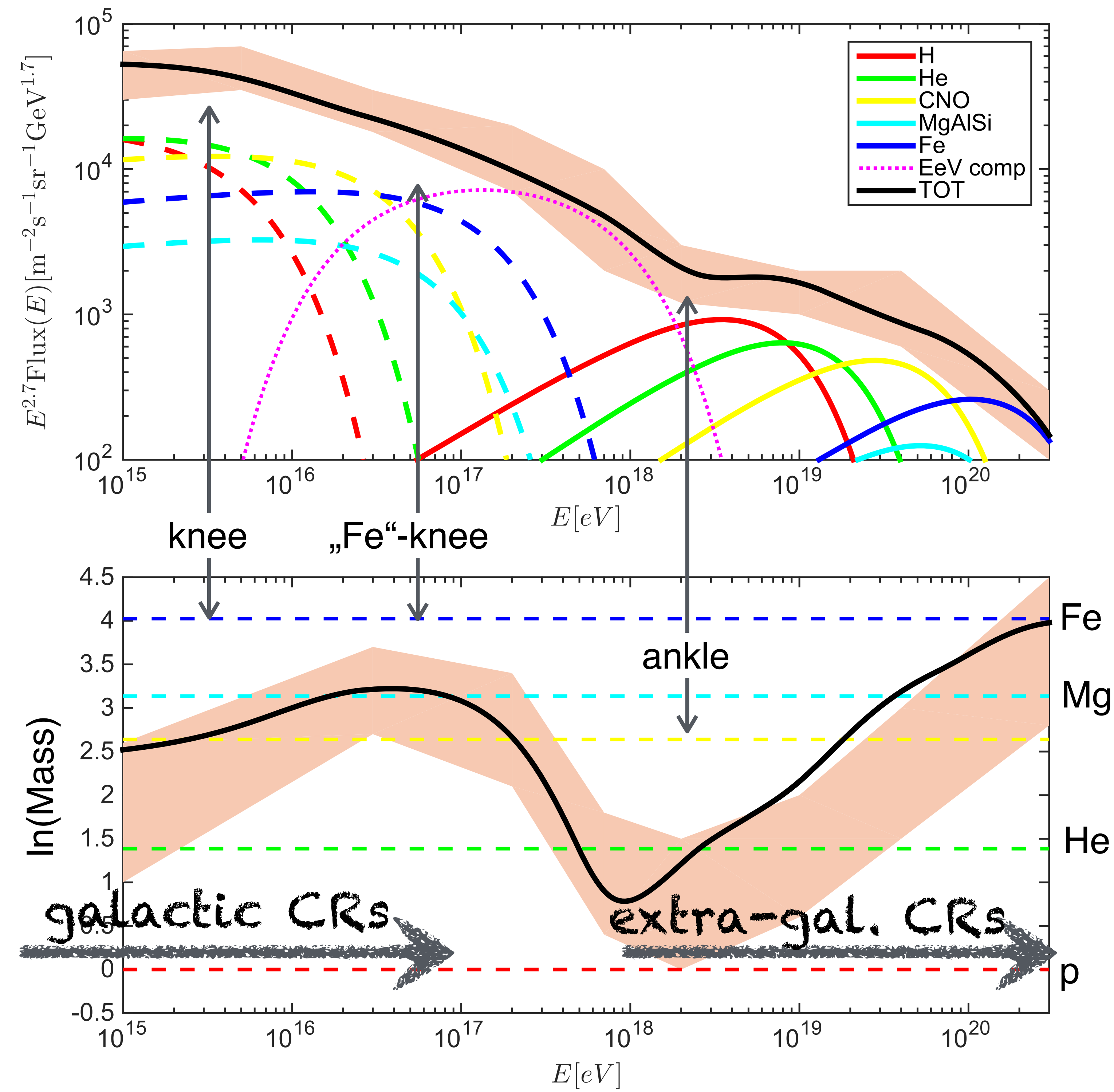
„Espresso“ Acceleration

Galactic CRs as seed



$\Gamma > 30$ derived from Blazars
CRs get boost by Γ^2 in one shot
$\Rightarrow E > 10^{20}$ eV possible

The Astrophysical Journal Letters, 811:L38 (5pp), 2015 October 1

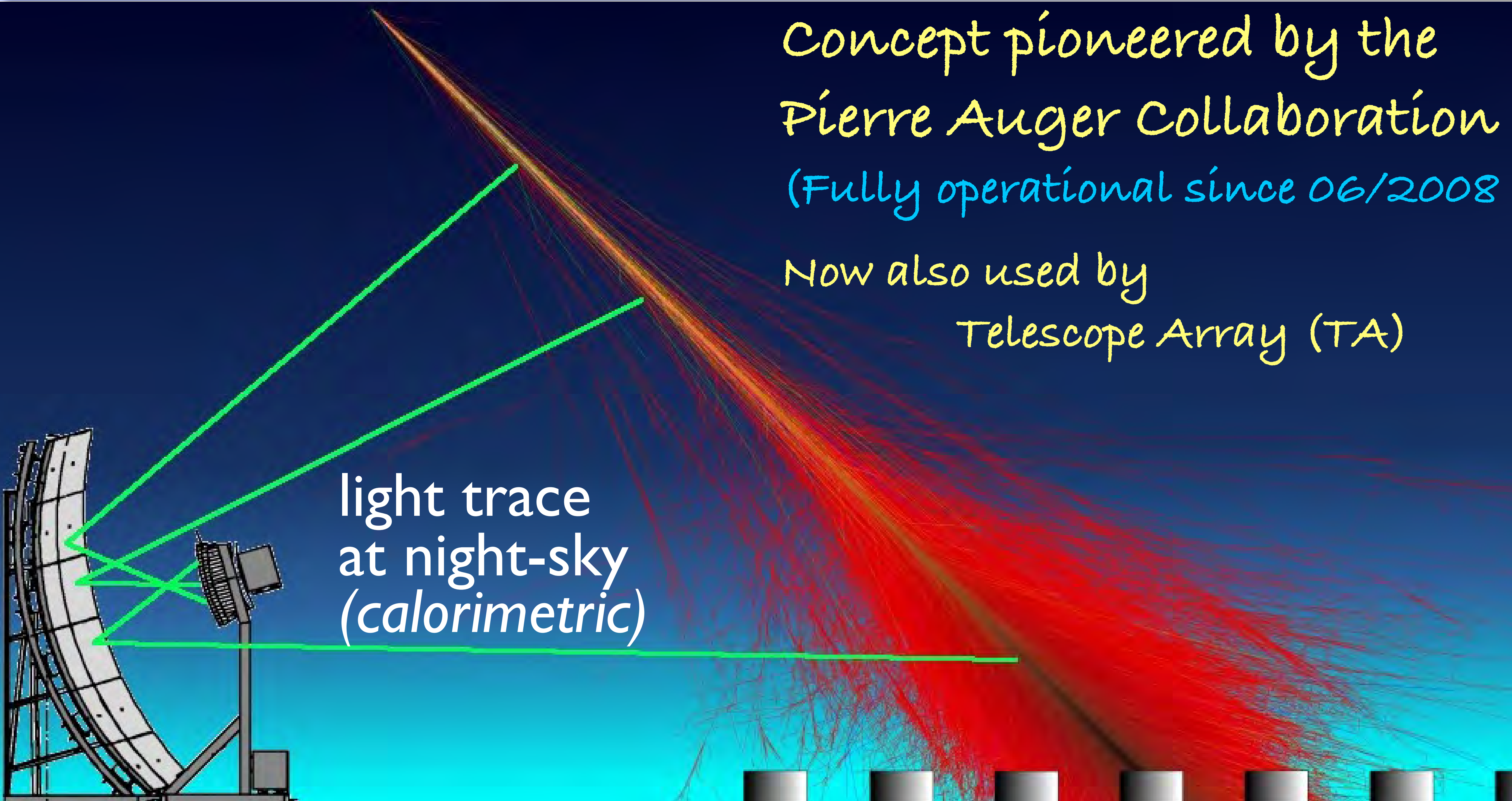


D. Caprioli, ApJ 811 (2015) L38
Similarly:
S. Wykes et al. A&A 558, A19 (2013)
P. Biermann, et al. ApJ 746:72 (2012)
…

Contents

- **Experimental: Hybrid Observation of CRs**
- **The End of the Energy Spectrum:**
  GZK-effect or Exhaustion of Sources?
- **Mass Composition: getting heavier**
- **Arrival Directions: surprisingly isotropic**
- **Multi-Messenger: UHECR - neutrino link**
- **Future: Upgrades of Auger and TA**

Hybrid Observation of EAS



Concept pioneered by the Pierre Auger Collaboration

(Fully operational since 06/2008

Now also used by
Telescope Array (TA)

Fluorescence light

Particle-density and
-composition at ground

Also:
Detection of Radio- & Microwave-Signals

Pierre Auger Observatory

1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

153 radio antennas over 17 km^2

Province Mendoza, Argentina

Auger Hybrid Observatory

3000 km^2 area, Argentina
27 fluorescence telescopes plus
...1660 Water Cherenkov tanks

Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

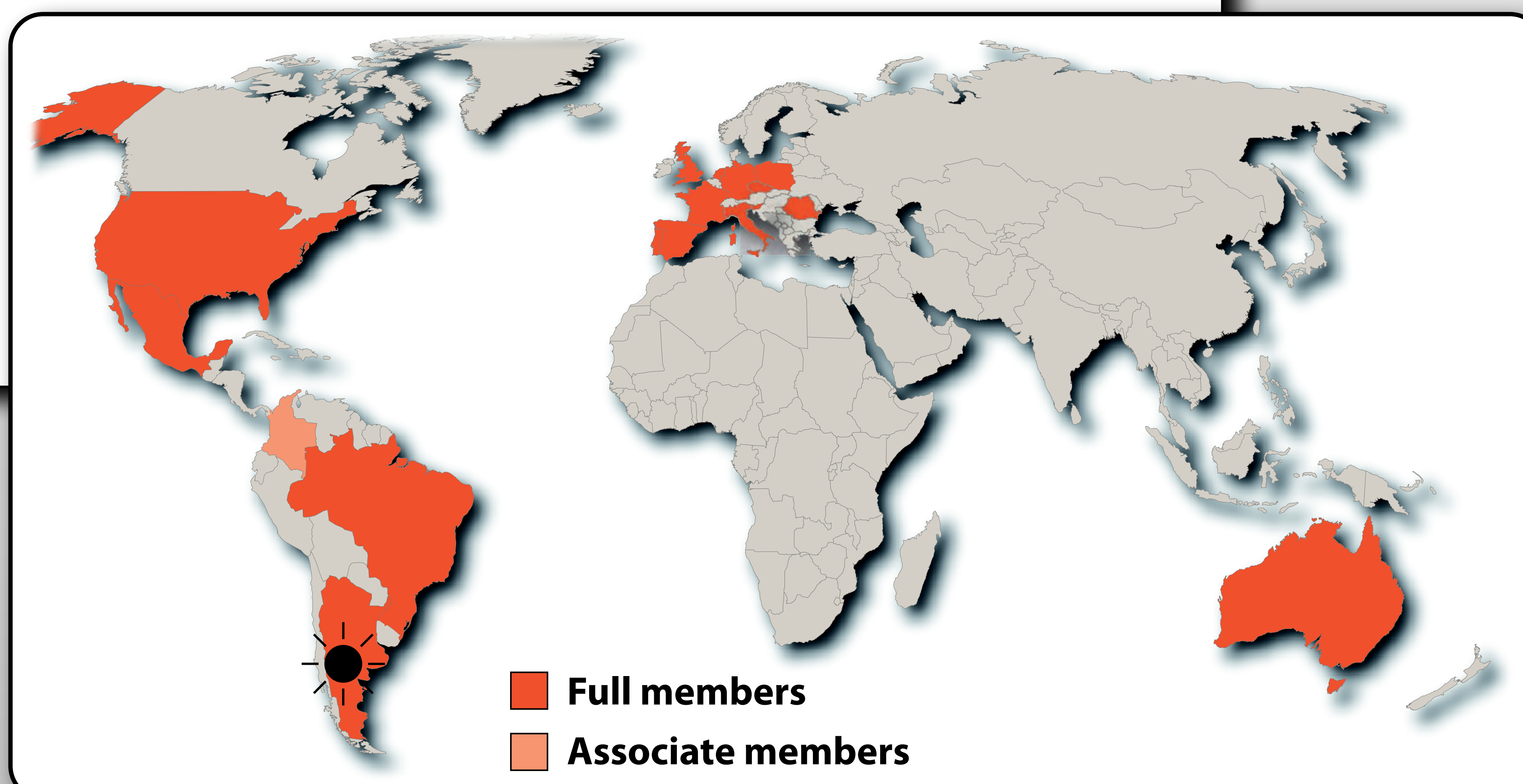
~450 Collaborators; 92 Institutions, 18 Countries:

Argentina
Australia
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
UK
USA

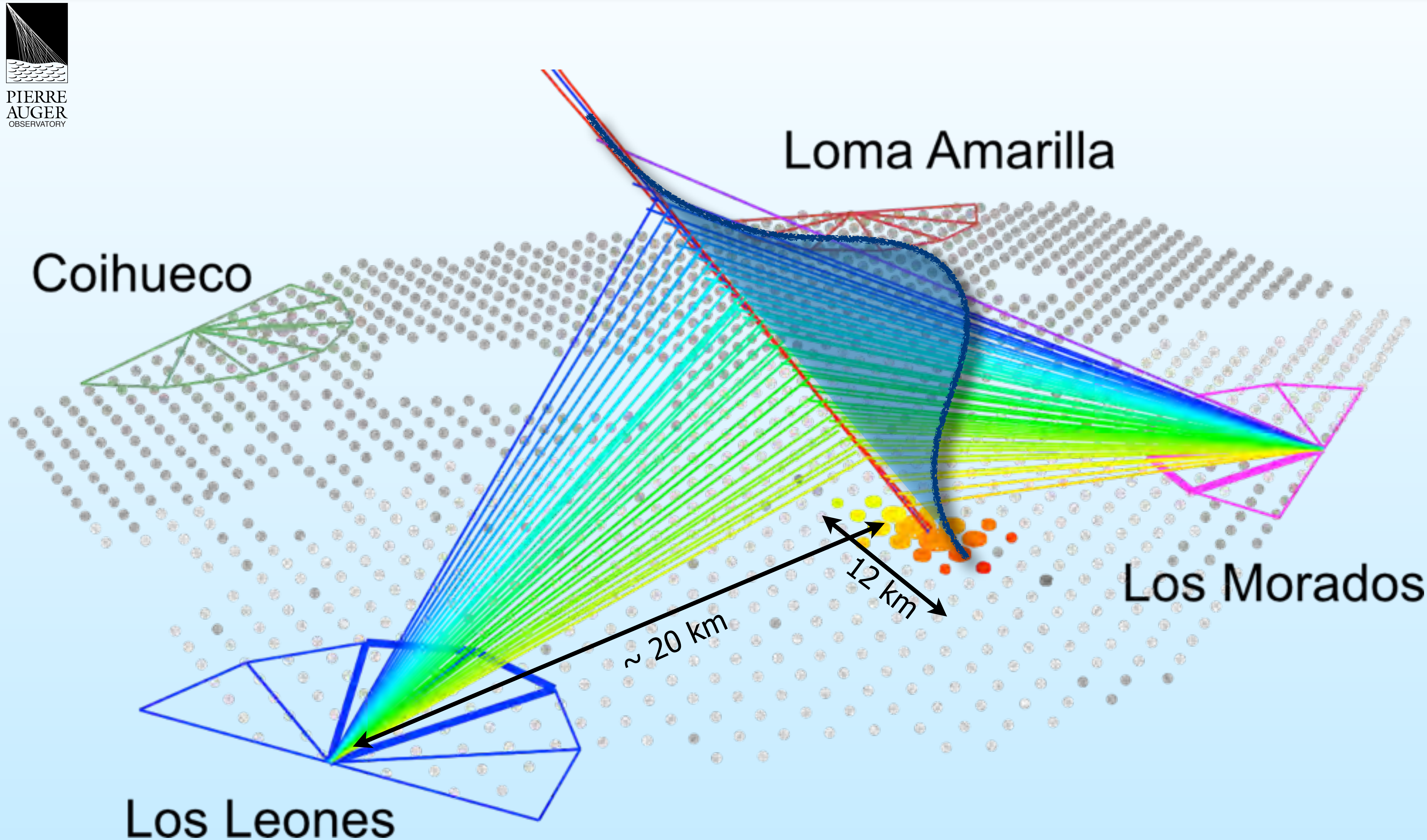
Colombia
Belgium
Associated

Peru
Bolivia
EoI

New members are welcome!

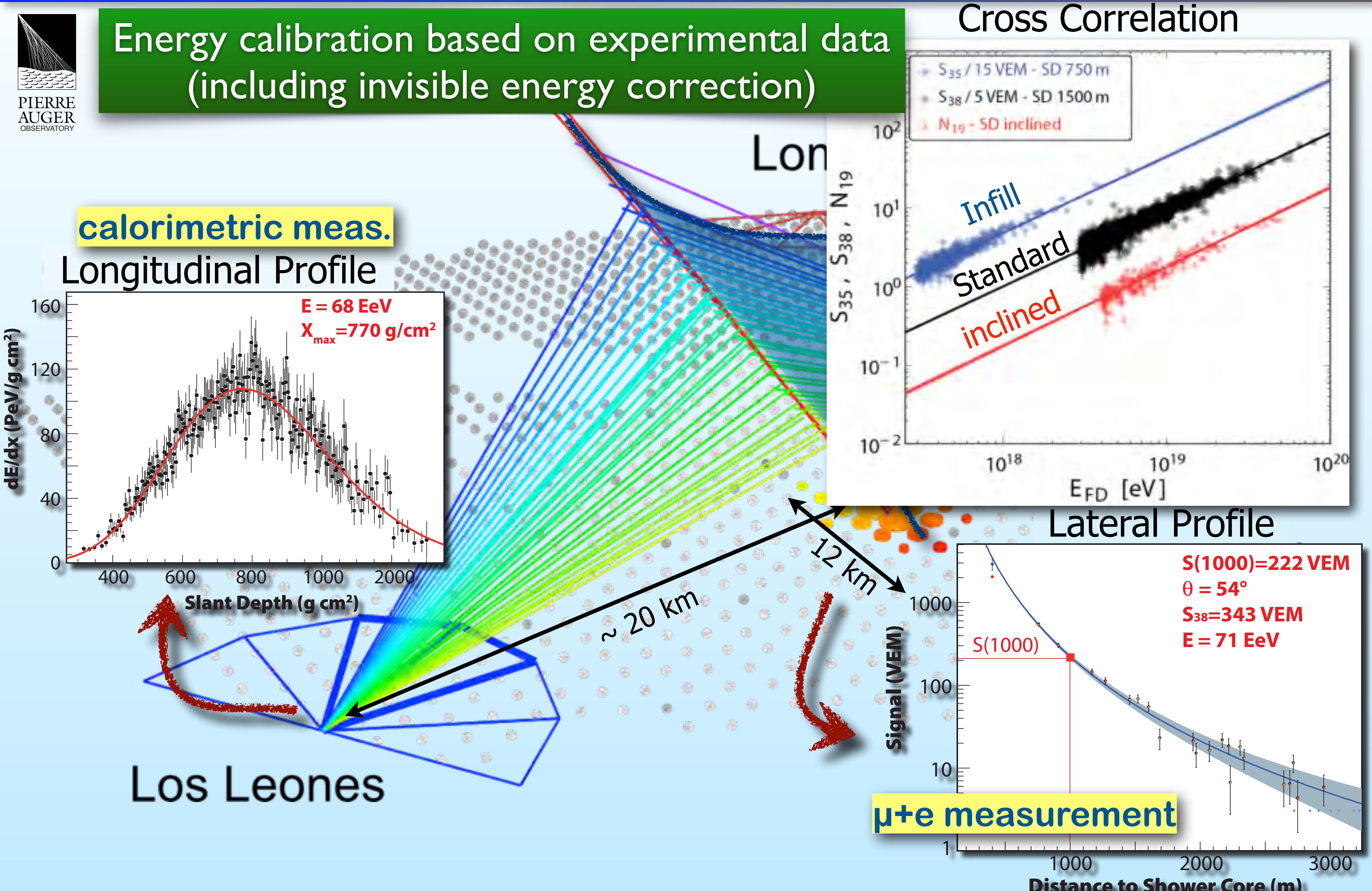


Event Example in Auger Observatory



Event Example in Auger Observatory

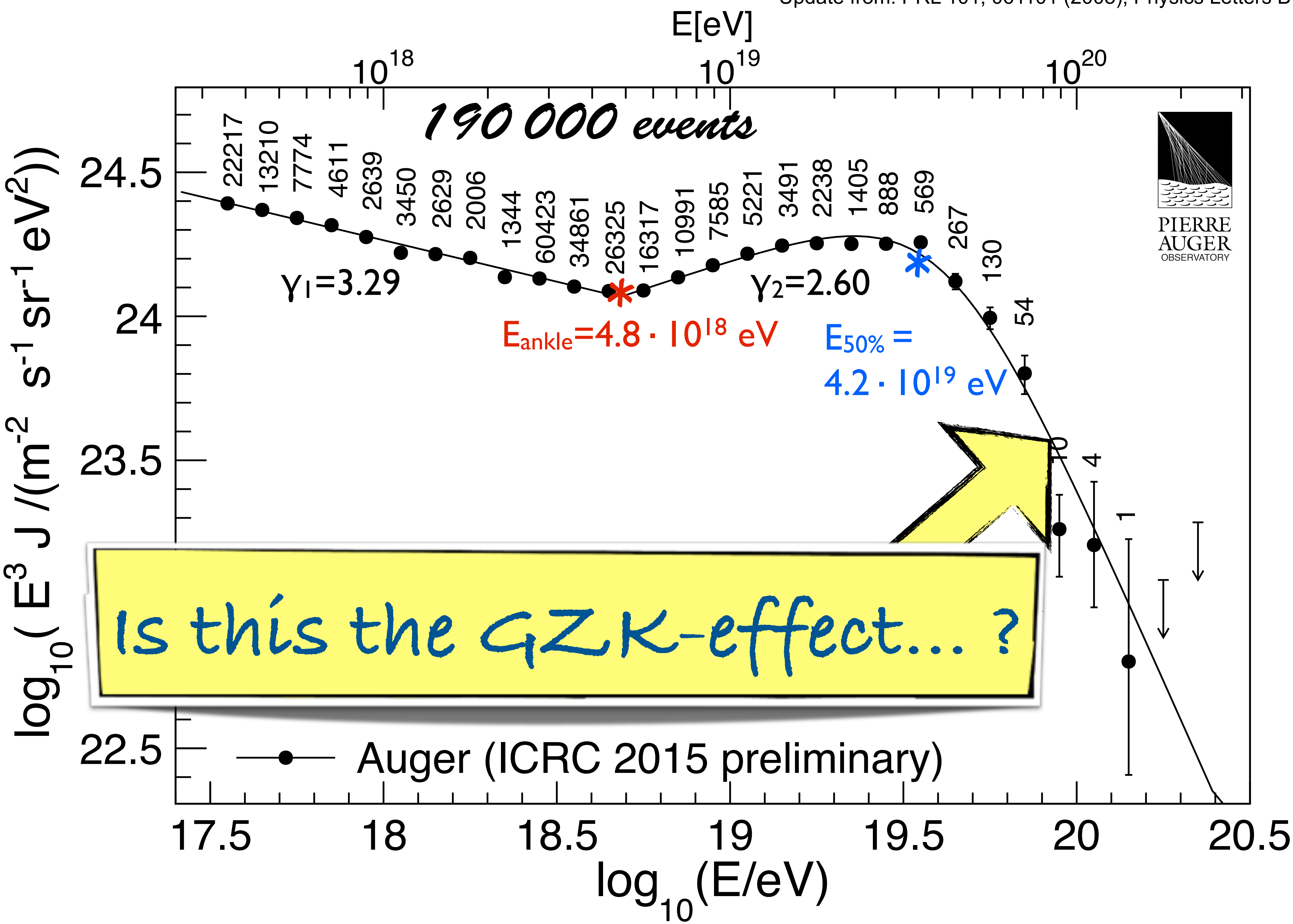
Energy calibration based on experimental data (including invisible energy correction)



UHECR
Energy Spectrum

End of the CR-Spectrum (0°-80°)

arXiv:1509.03732
Update from: PRL 101, 061101 (2008), Physics Letters B 685 (2010) 239



combined from: infill+hybrid+vertical+inclined events

GZK-Effect: Energy losses in CMB

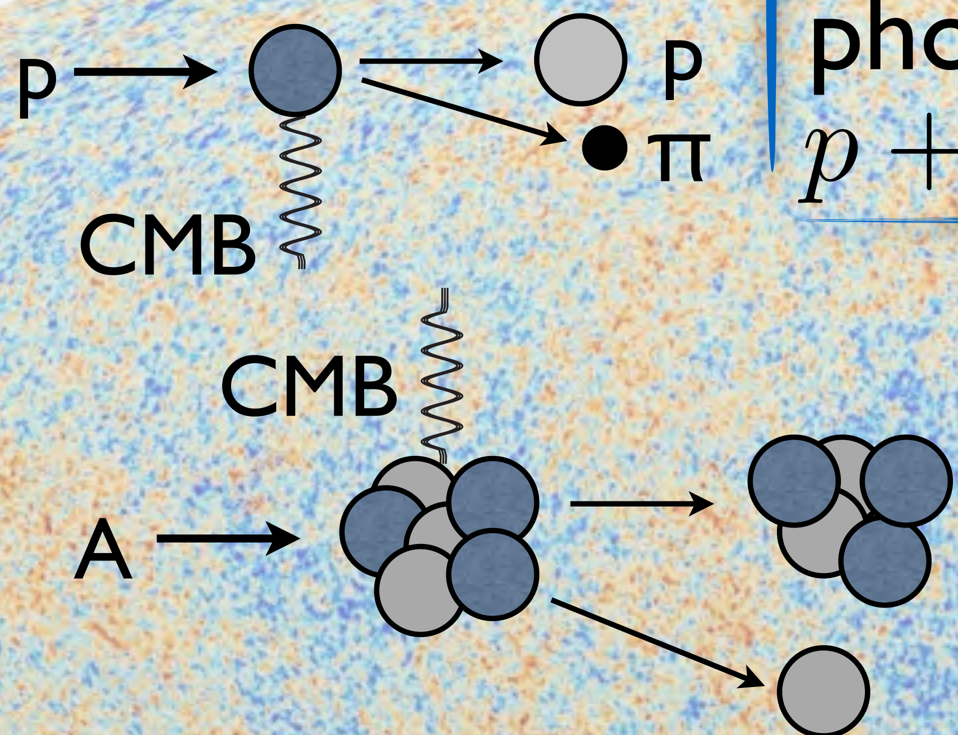
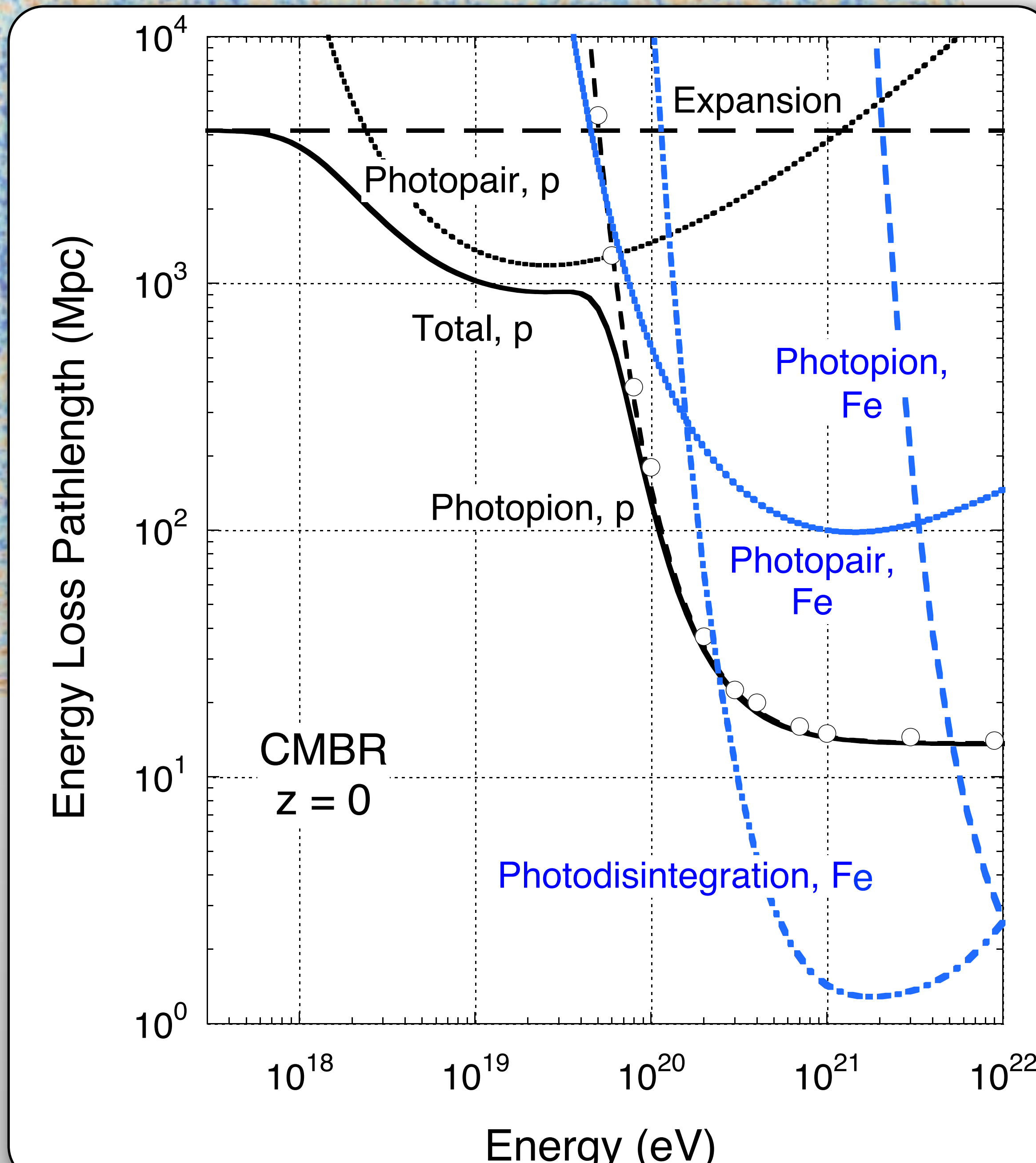


photo-pion production

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow p + \pi^0$$

photo disintegration

$$A + \gamma_{\mathrm{CMB}} \rightarrow (A-1) + n \ldots$$



Greisen-**Z**atsepin-**K**uz'min (1966)

threshold: $E_p E_\gamma > (m_\Delta^2 - m_p^2)$

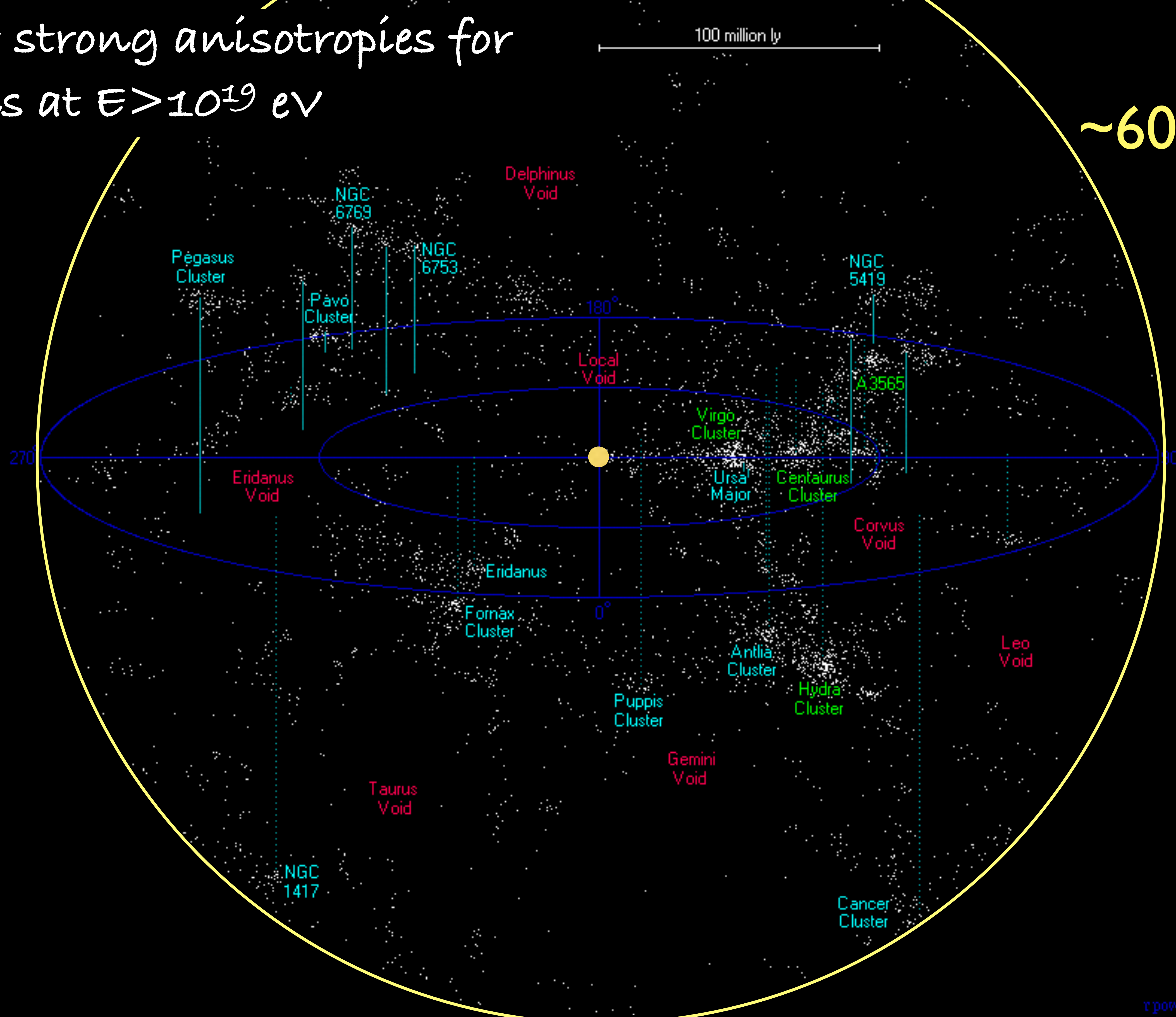
$\Rightarrow E_{\mathrm{GZK}} \approx 6 \cdot 10^{19}$ eV

➙ **GZK-Horizon ~ 60 Mpc**

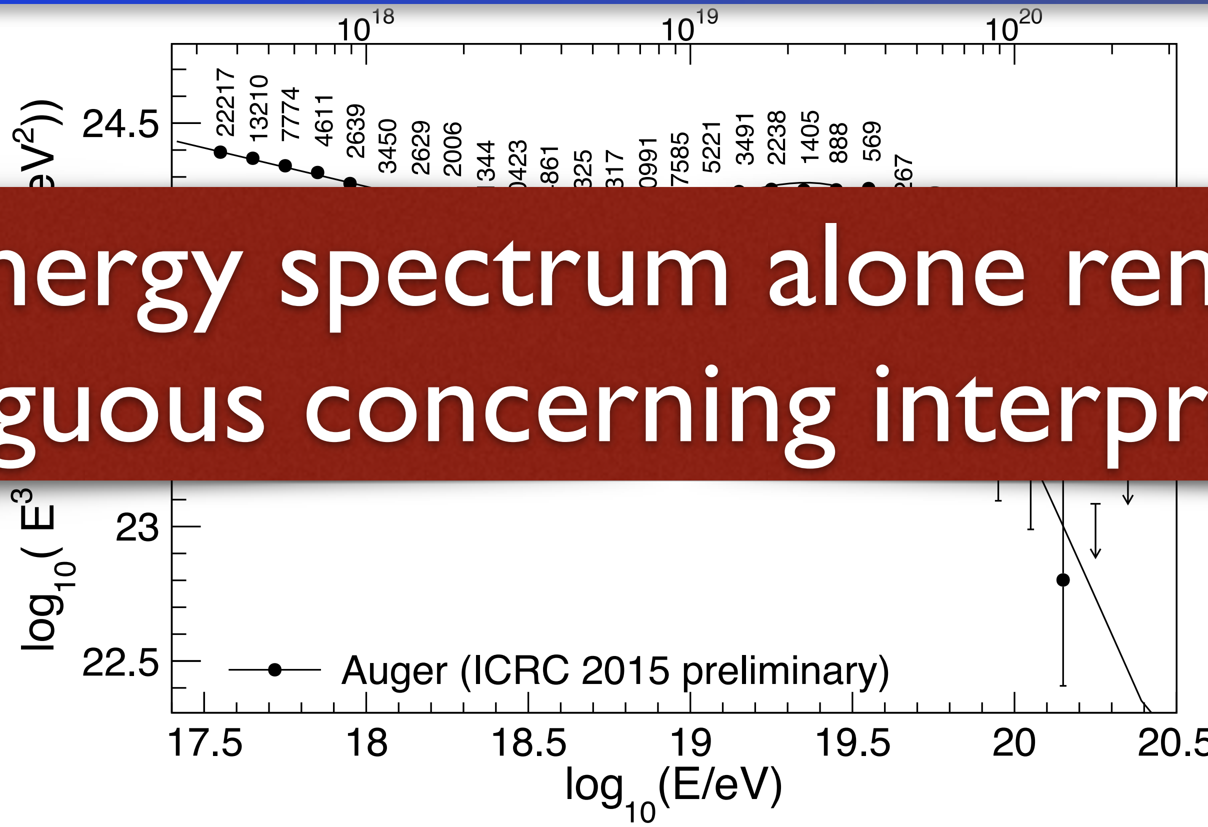
The GZK - Horizon

Expect strong anisotropies for protons at $E>10^{19}$ eV

~60 Mpc



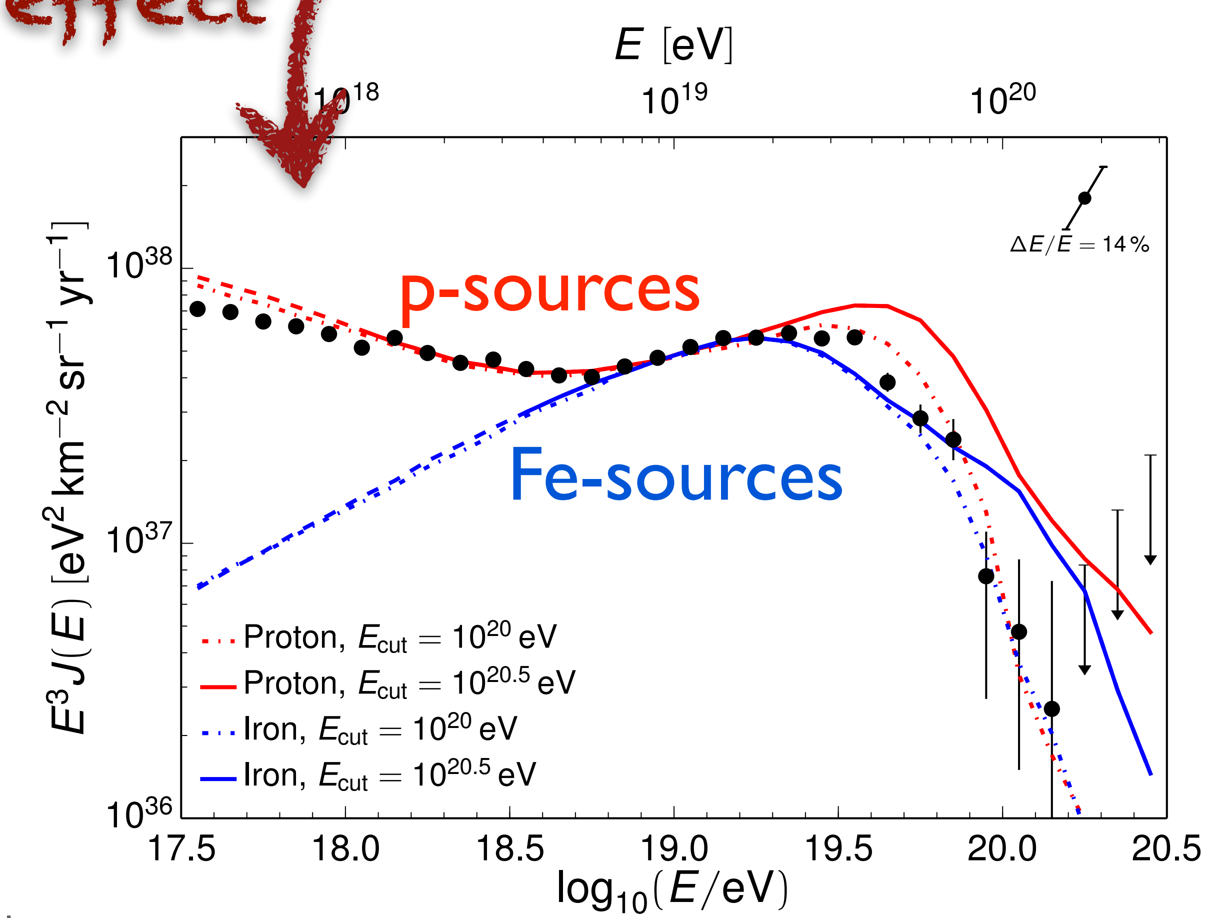
GZK-Effect or Exhausted Sources?



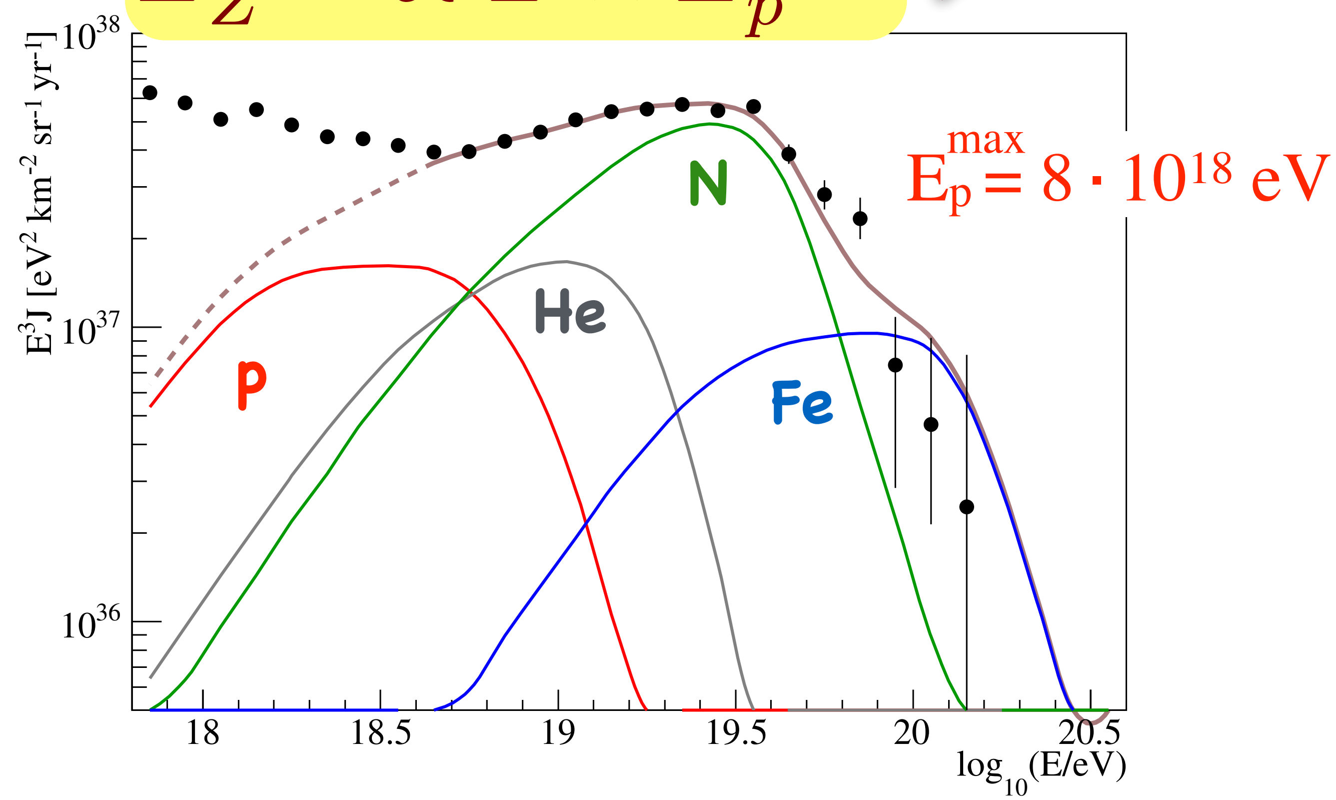
Energy spectrum alone remains ambiguous concerning interpretations

GZK-effect

exhausted sources



$$E_Z^{\max} \propto Z \times E_p^{\max}$$



Need

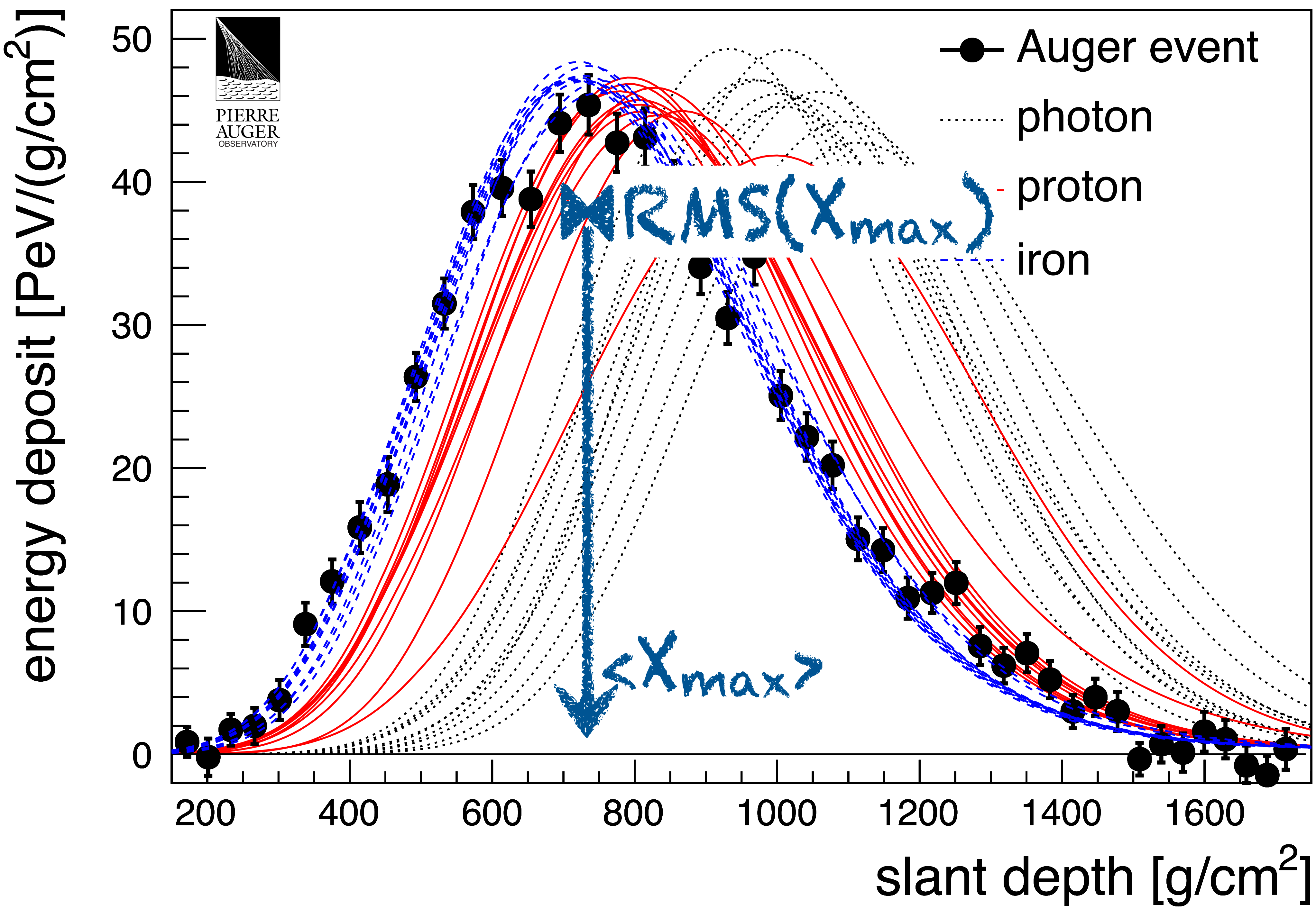
Mass Composition

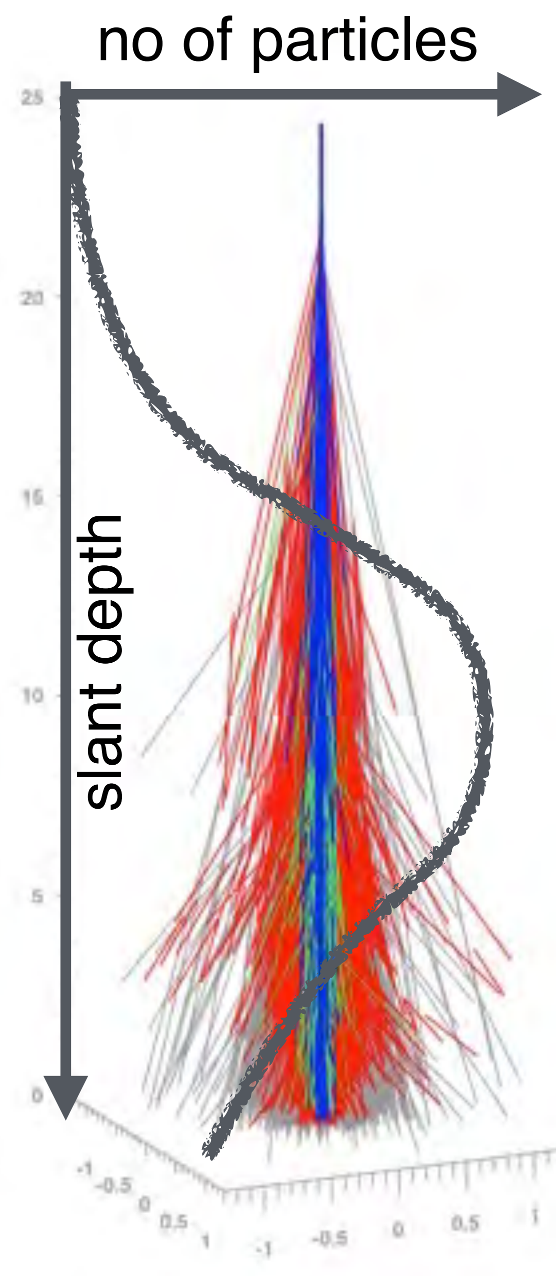
to disentangle GZK-suppression from maximum energy scenario

Longitudinal Shower Development → Primary Mass

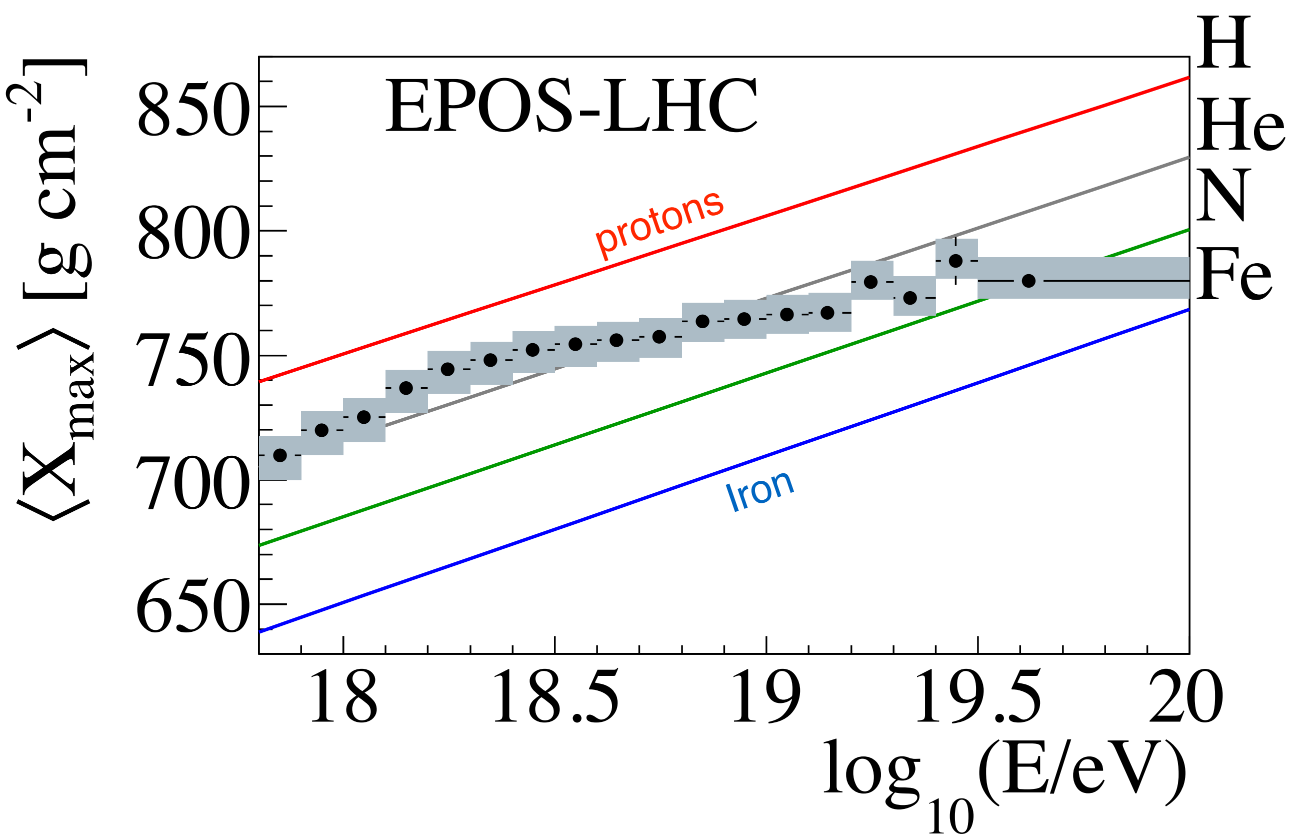
KHK, Unger, APP 35 (2012)
EPOS 1.99 Simulations

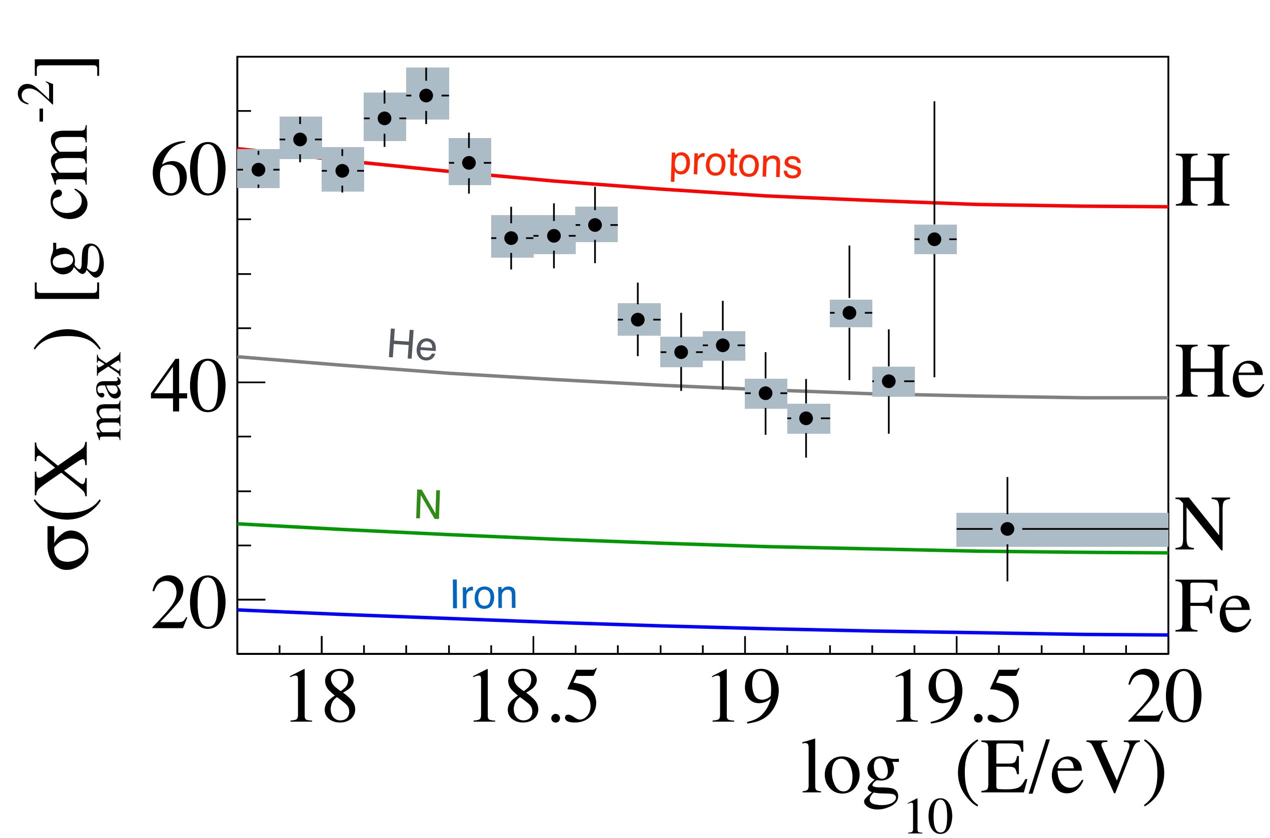
Example of a $3 \cdot 10^{19}$ eV EAS event in FD

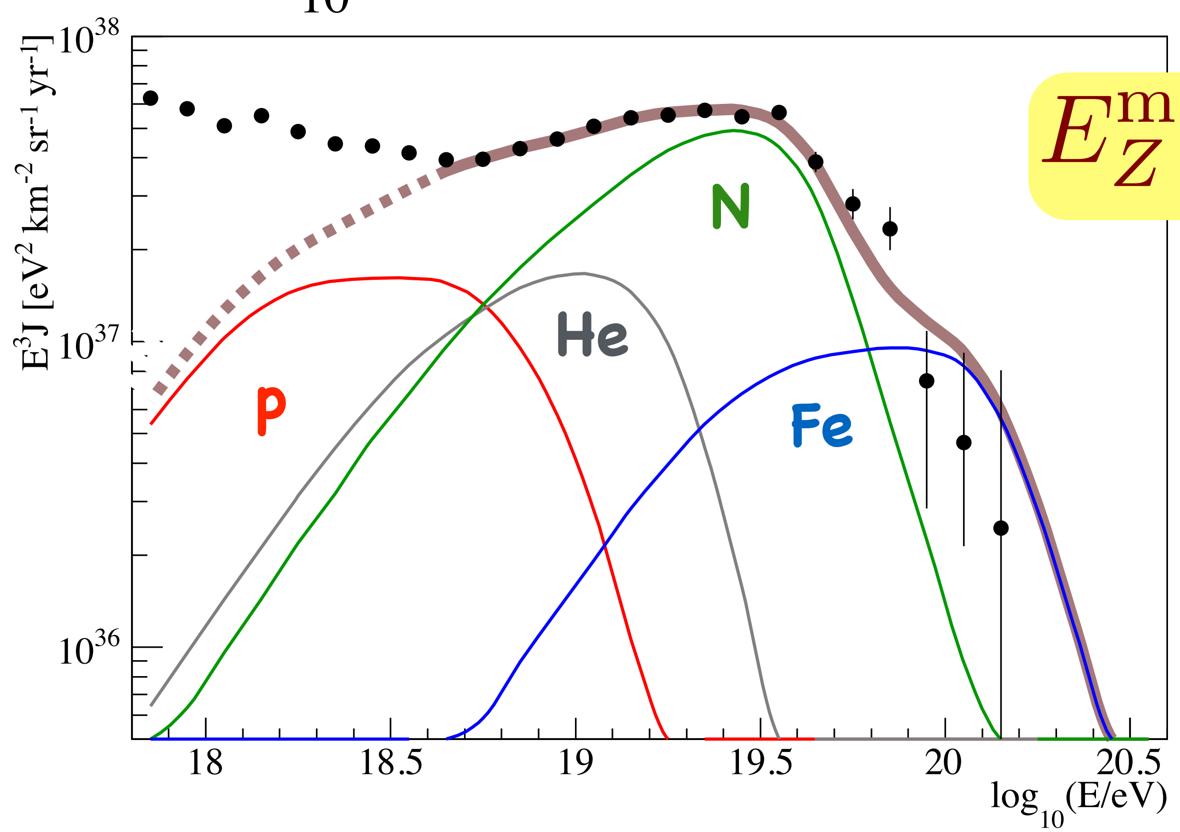




Smooth trend to heavier composition



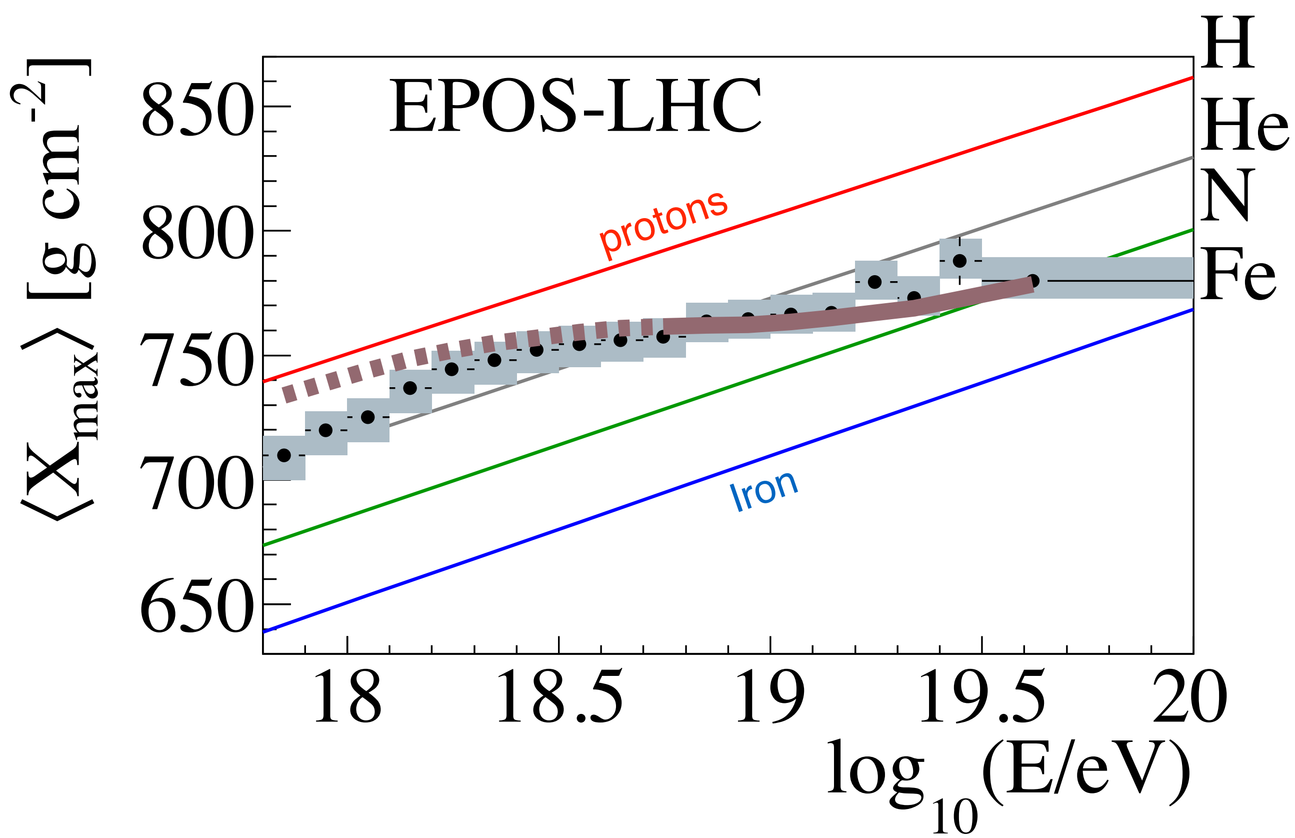


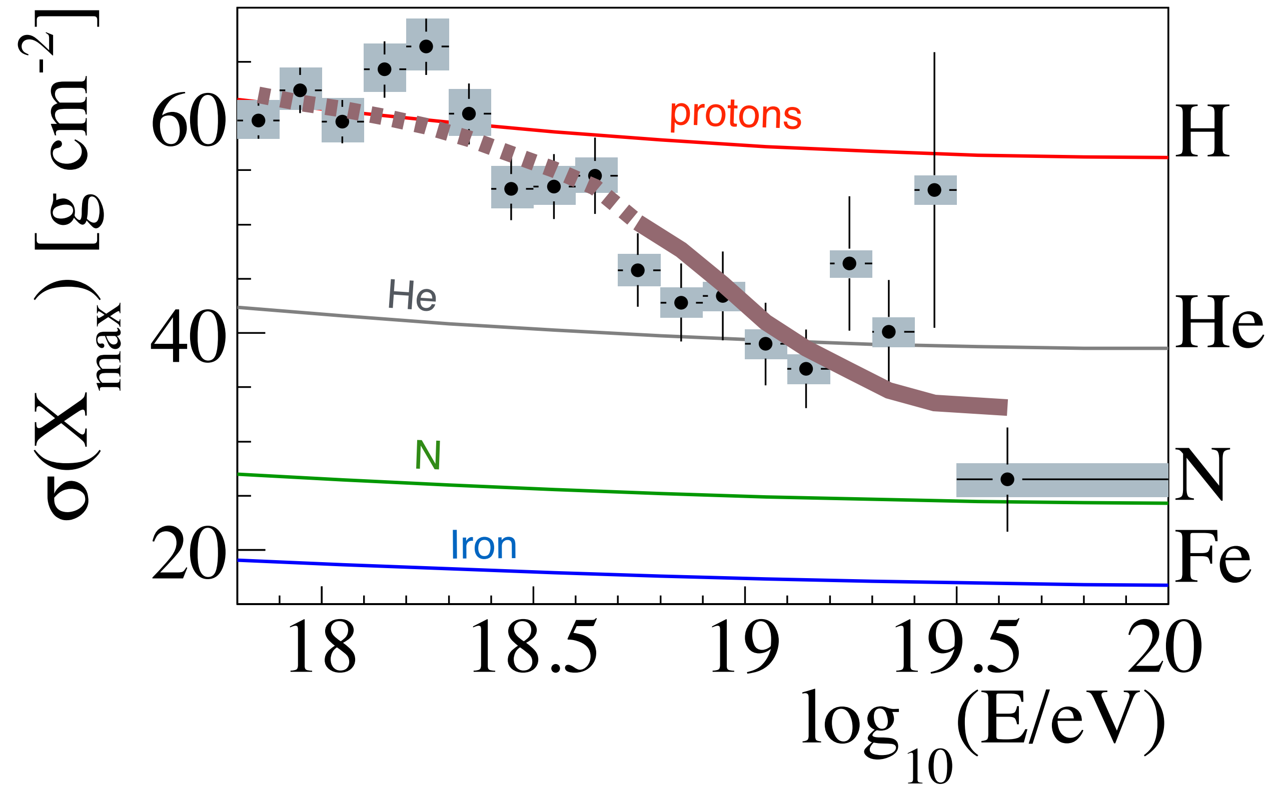


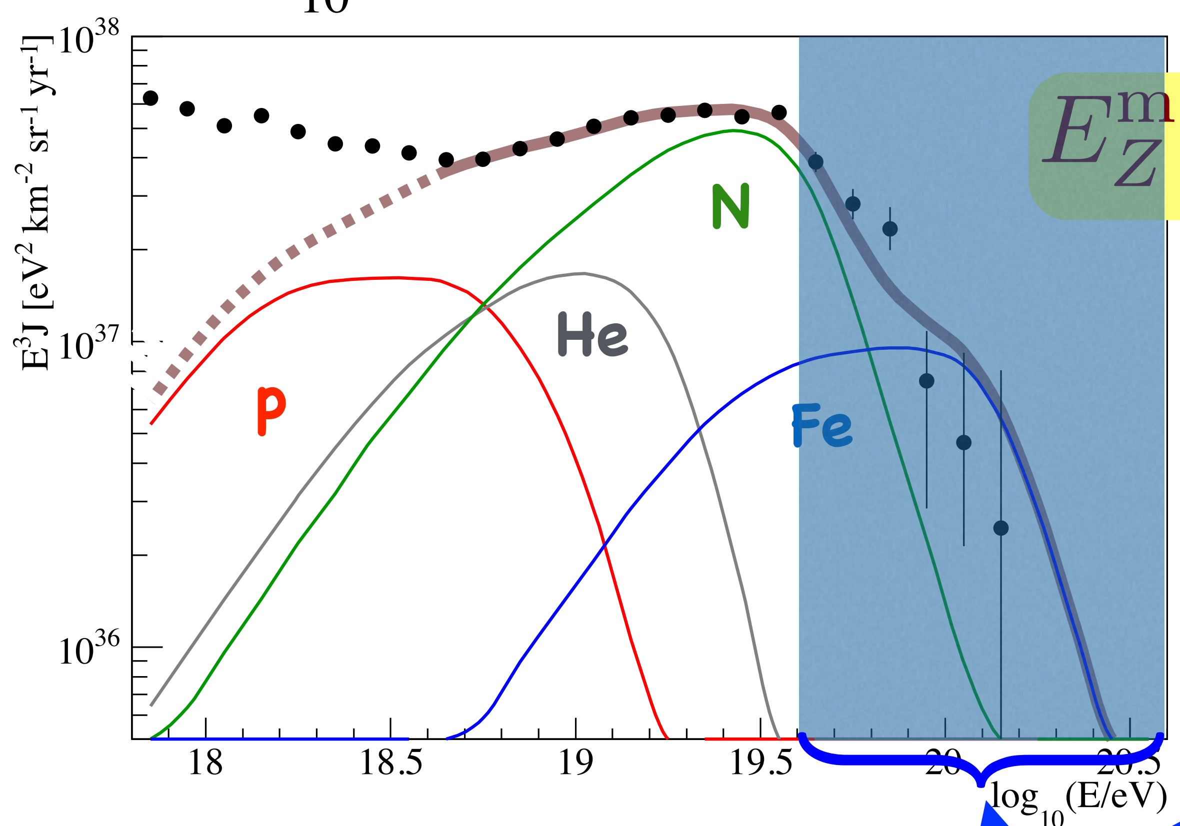
$$E_Z^{max} \propto Z \times E_p^{max}$$

$E_p^{max} = 8 \cdot 10^{18}$ eV

Data well Described by Exhausted Sources







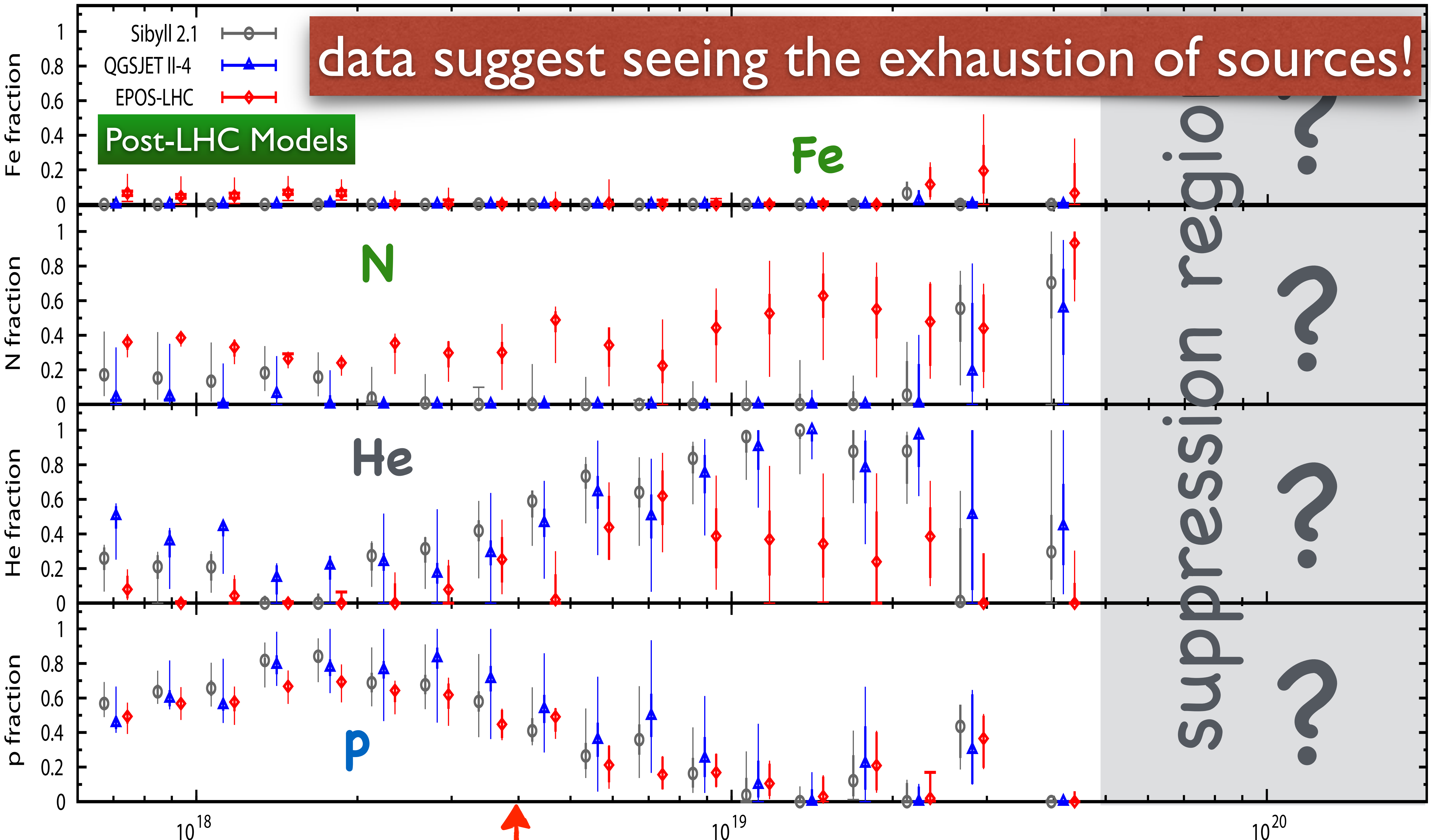
$$E_Z^{\max} \propto Z \times E_p^{\max}$$

$E_p^{\max} = 8 \cdot 10^{18}$ eV

no composition data available in the region of the flux suppression !

Decomposition of X_{max}-Distributions

Auger collaboration, Phys. Rev. D 90, 122006 (2014)



no pure beam at ankle!

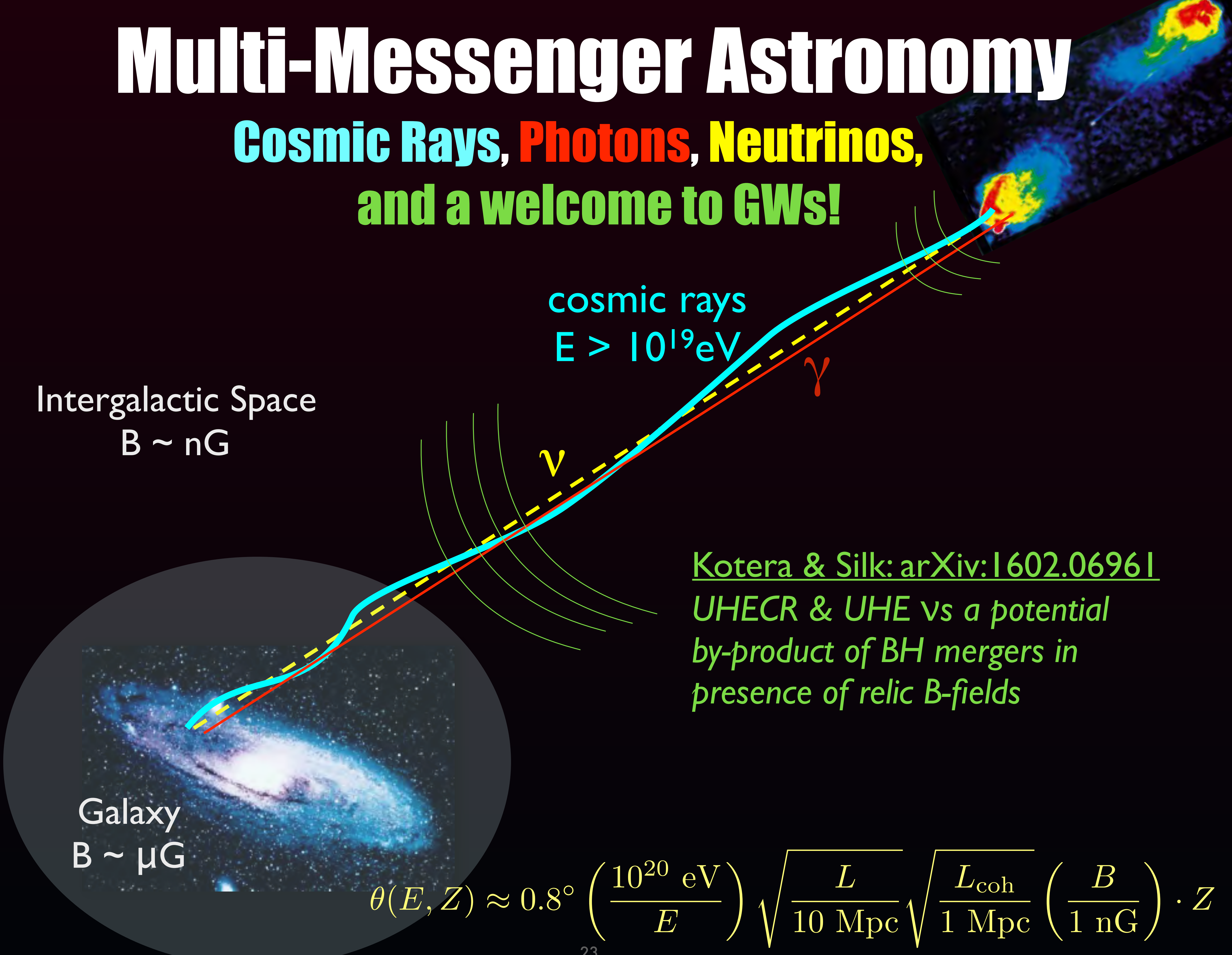
See also: Yushkov @ ICRC2015

Anisotropies

may tell us more

Multi-Messenger Astronomy

Cosmic Rays, Photons, Neutrinos, and a welcome to GWs!

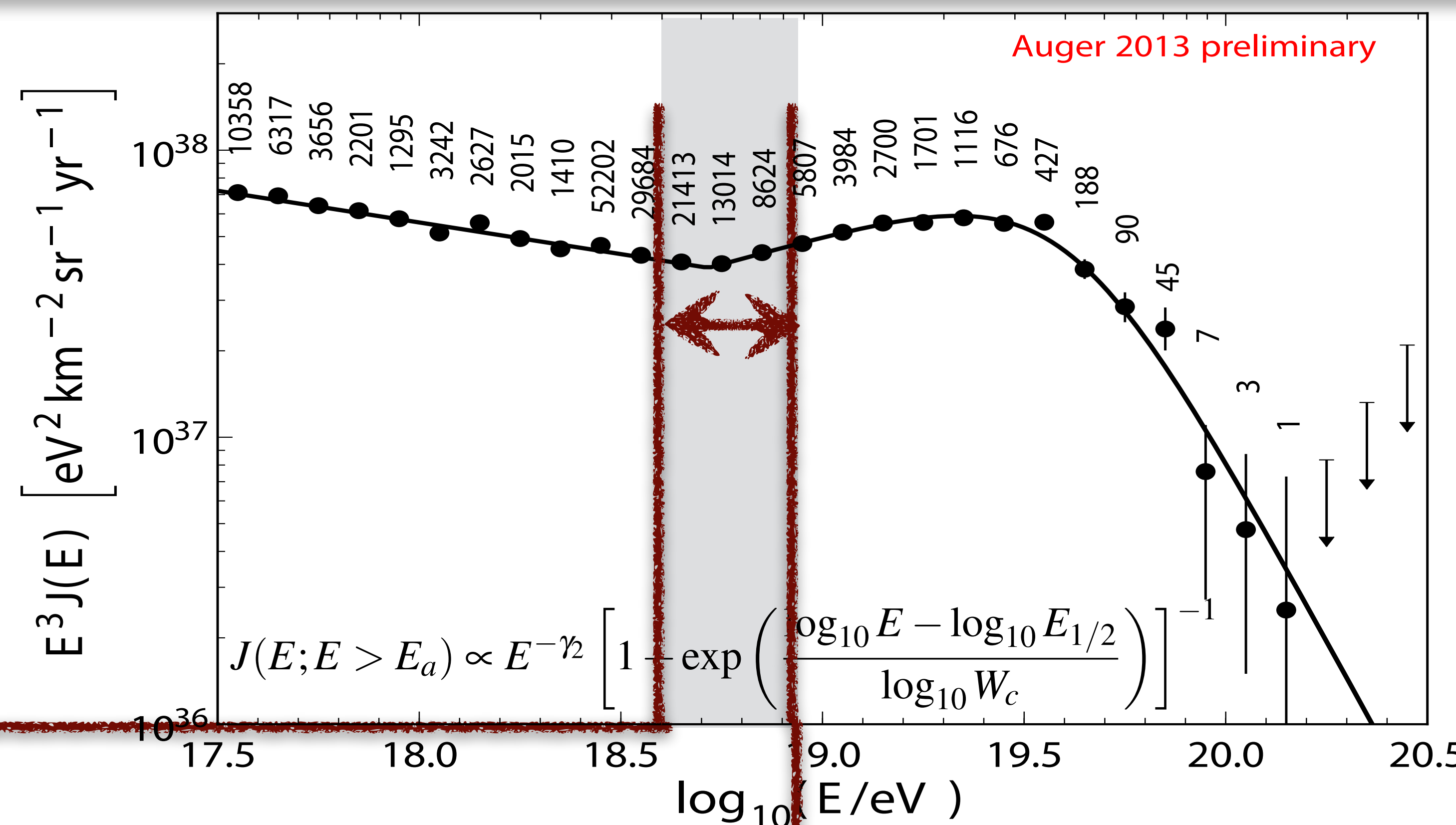


Kotera & Silk: arXiv:1602.06961

UHECR & UHE νs a potential by-product of BH mergers in presence of relic B-fields

$$\theta(E,Z) \approx 0.8^\circ \left(\frac{10^{20}\ \mathrm{eV}}{E}\right)\sqrt{\frac{L}{10\ \mathrm{Mpc}}}\sqrt{\frac{L_{\mathrm{coh}}}{1\ \mathrm{Mpc}}}\left(\frac{B}{1\ \mathrm{nG}}\right)\cdot Z$$

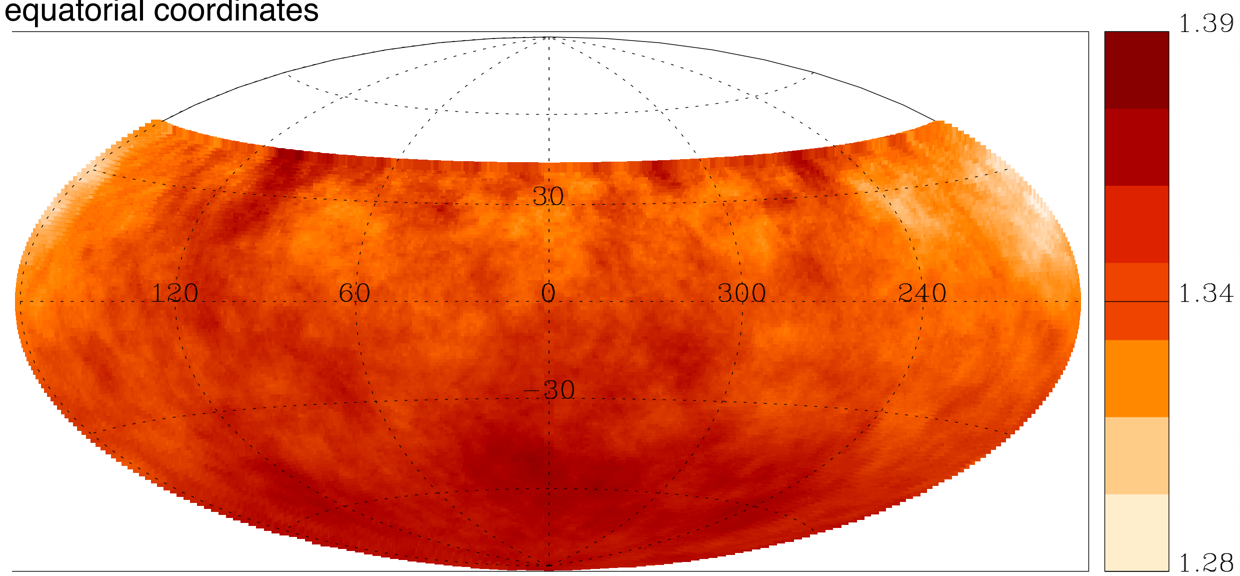
UHECR Sky surprisingly isotropic



isotropic distribution

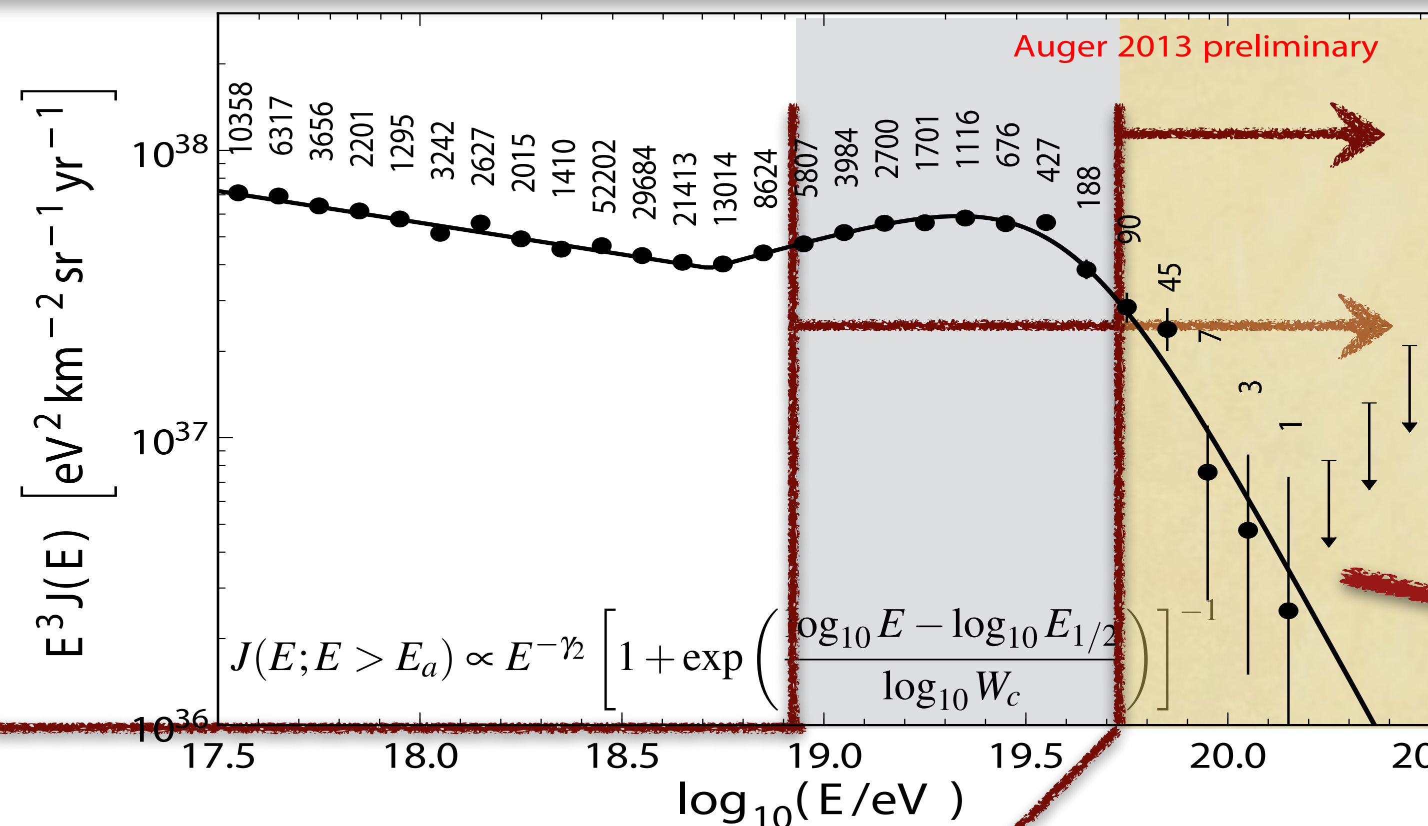
E=4-8 EeV

equatorial coordinates



Auger Collaboration ApJ 802:111 (2015)

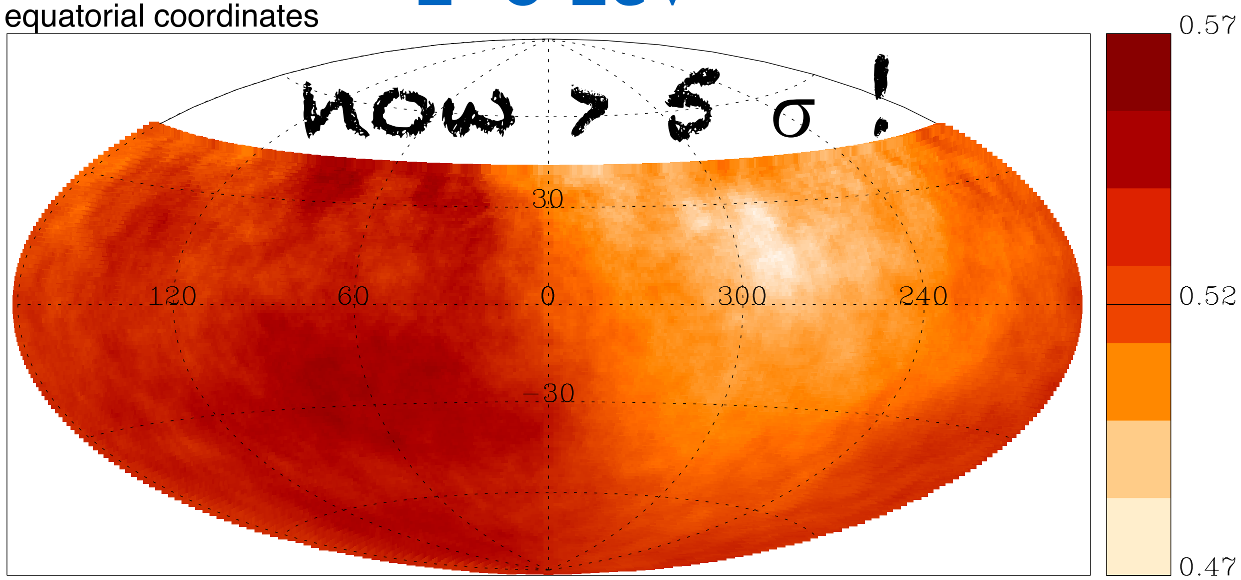
UHECR Sky surprisingly isotropic



hot/warm spot

dipole like anisotropy

E>8 EeV

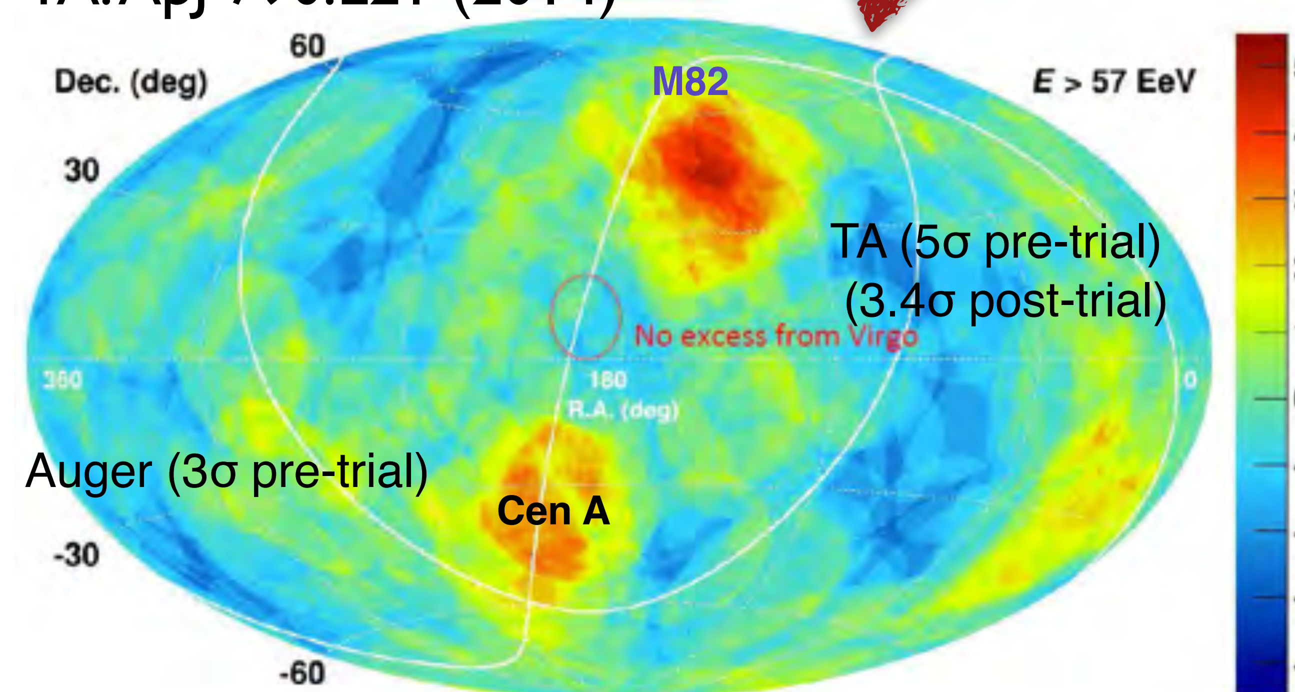


Auger Collaboration ApJ 802:111 (2015)

Amplitude: (4.4±1.0)%; p=6.4 · 10^{-5}

E>57 EeV

TA: ApJ 790:L21 (2014)

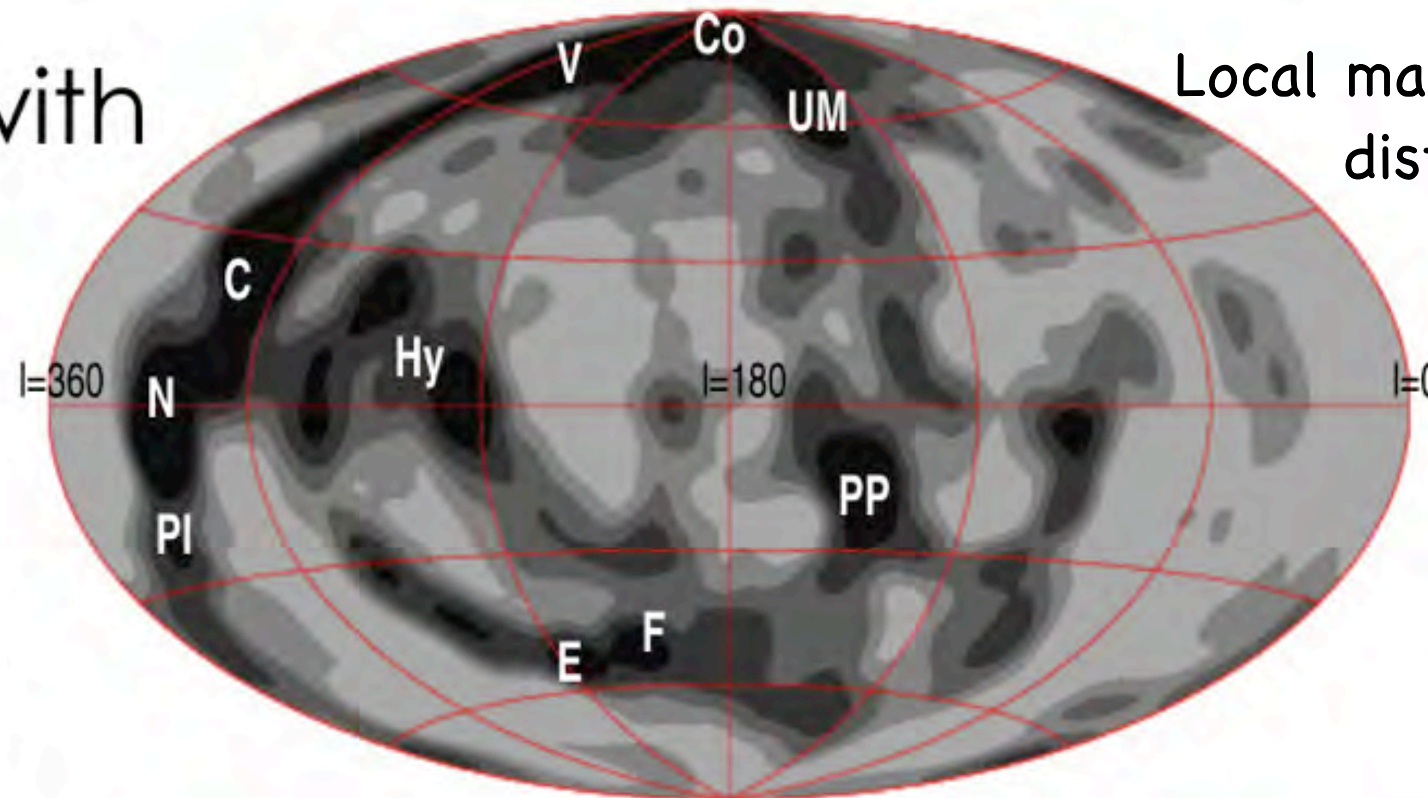


Auger: APP 34(2010) 314

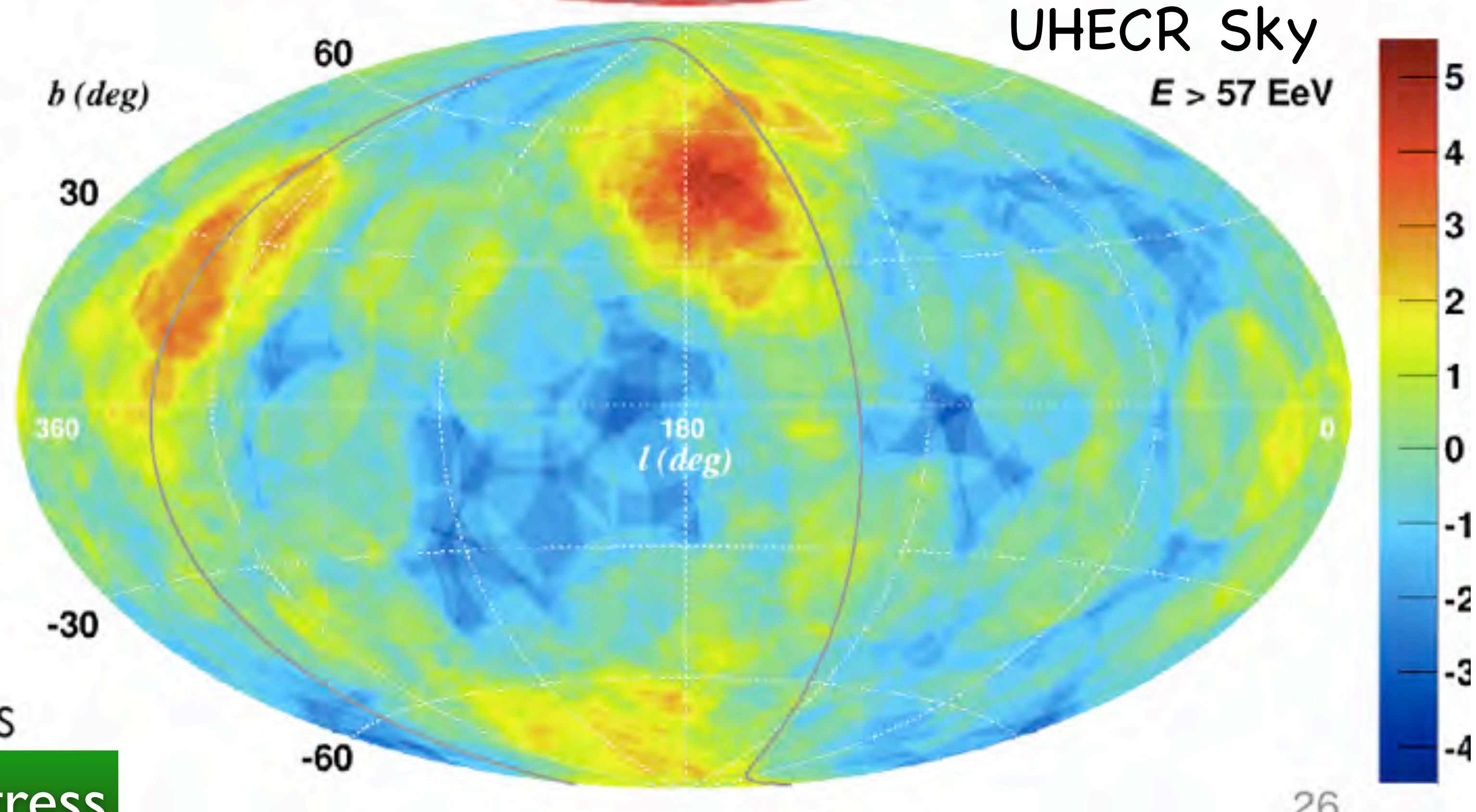
Auger/TA: small/intermediate-scales

Comparison with Large-Scale Structure

Local matter distribution



UHECR Sky



very blurry UHECR sky and no clear point sources, yet:
⇒ surprisingly strong* B-fields a/o UHECR dominated by Z>1

* S. Hackstein et al., arXiv:1607.08872
⇒ B ~ 1 nG

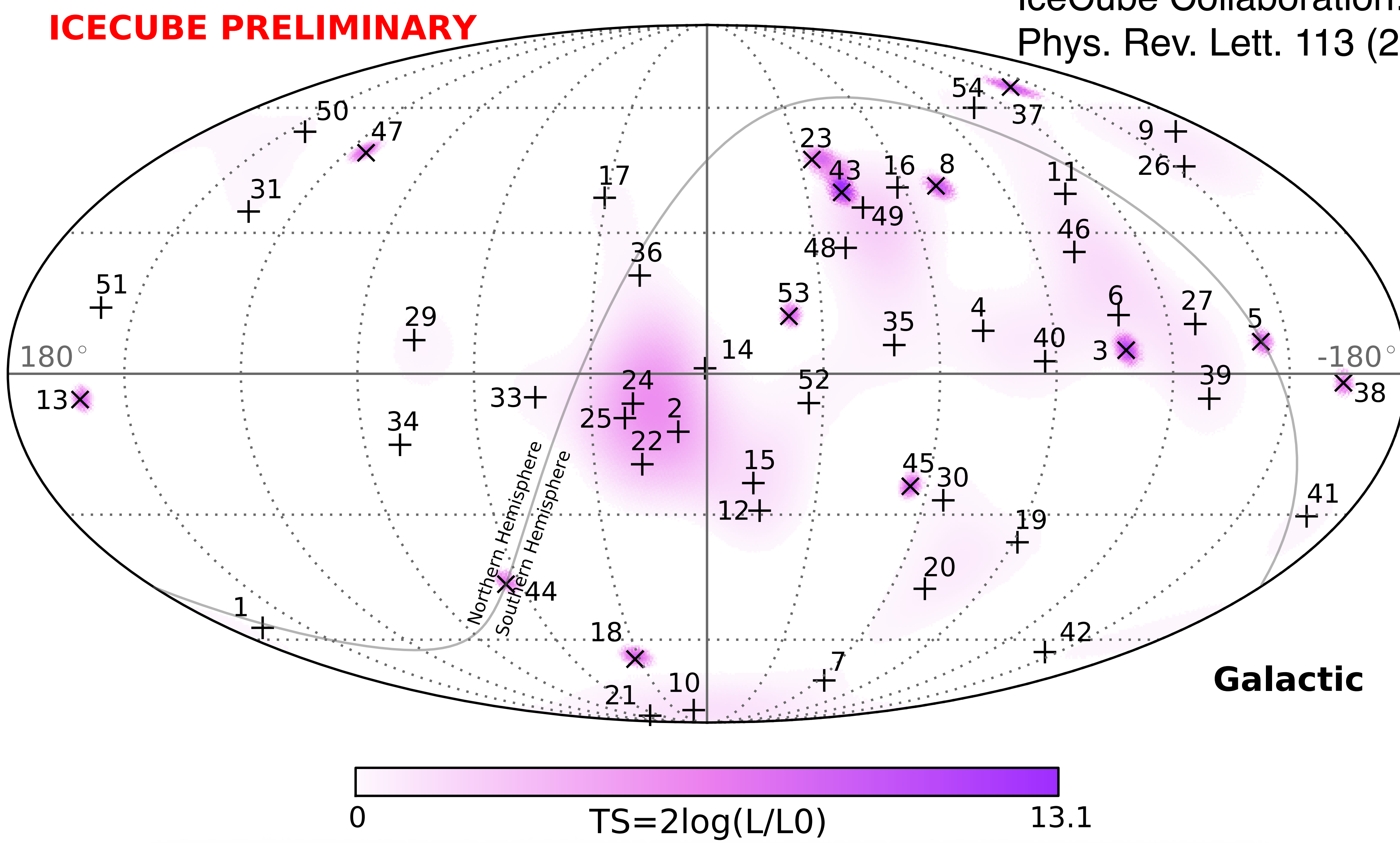
TA 7 years + PAO 10 years

Joint analysis with TA in progress

Astrophysical Neutrinos

A look to the PeV Neutrino Sky

IceCube Collaboration: update from Phys. Rev. Lett. 113 (2014) 101101

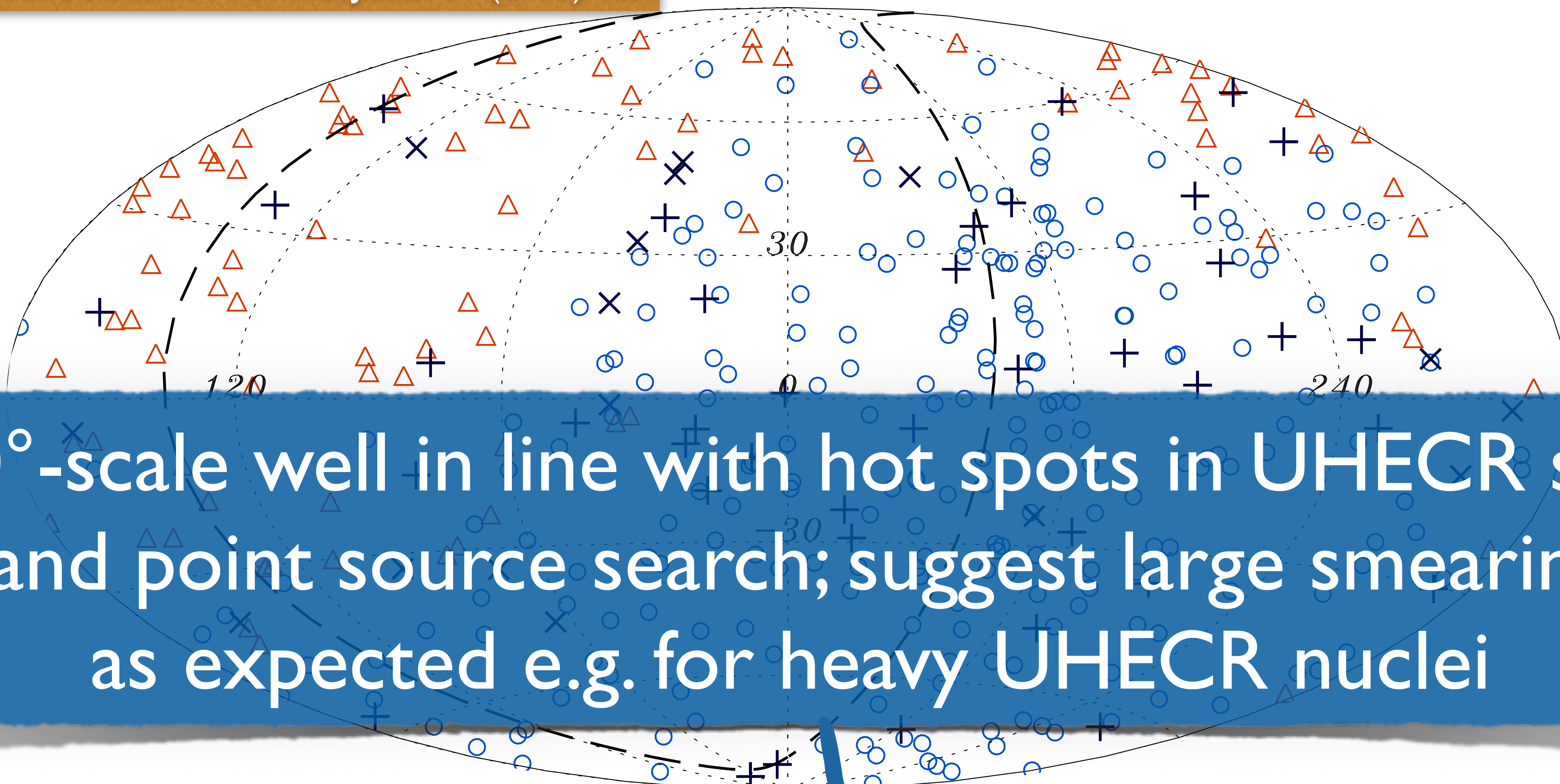


No significant clustering seen (p=84%)

cross correlations to catalogs or HESS sources ⇛ no signal yet

UHECR-Neutrino correlations?

IC+ Auger+TA-Coll., arXiv:1511.09408; JCAP 01 (2016) 037



20°-scale well in line with hot spots in UHECR sky and point source search; suggest large smearing as expected e.g. for heavy UHECR nuclei

△ TA >57EeV ; ○ Auger >52EeV; × IceCube cascades ; + IceCube tracks

- cross correlation and stacking analysis done
- 3°, 6°, 9° UHECR angular smearing at 100 EeV around neutrino direction

cascade events: smallest pre-trial value for 22°: 575 pairs observed, 490 expected
⇒ **post-trial p-value of $5 \cdot 10^{-4}$** ($8.5 \cdot 10^{-3}$) **assuming isotropic CRs** (ν's)

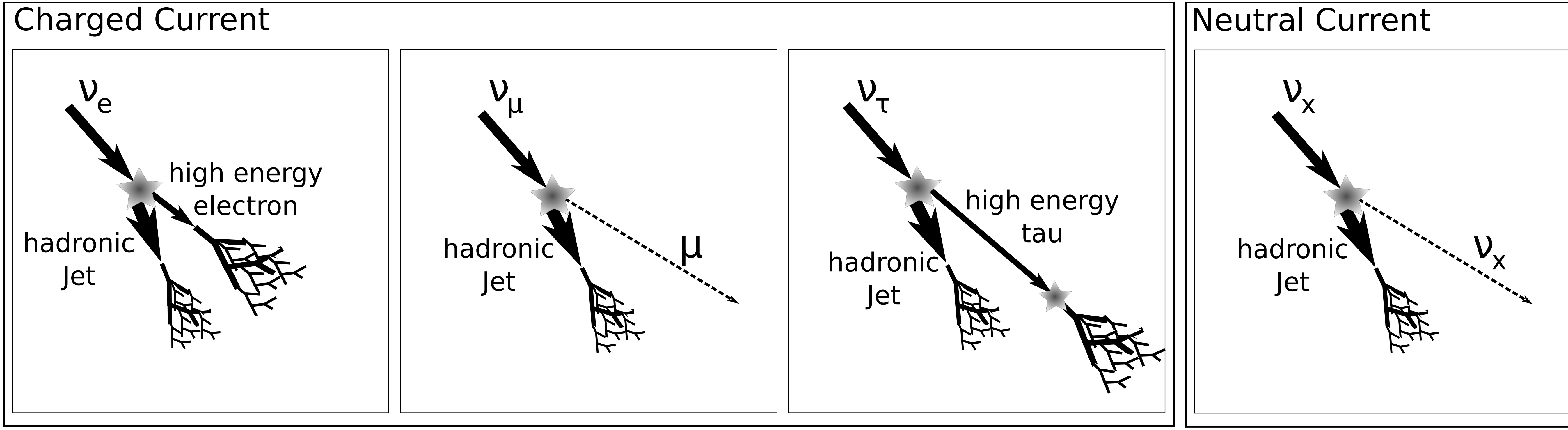
Potentially interesting, will be monitored

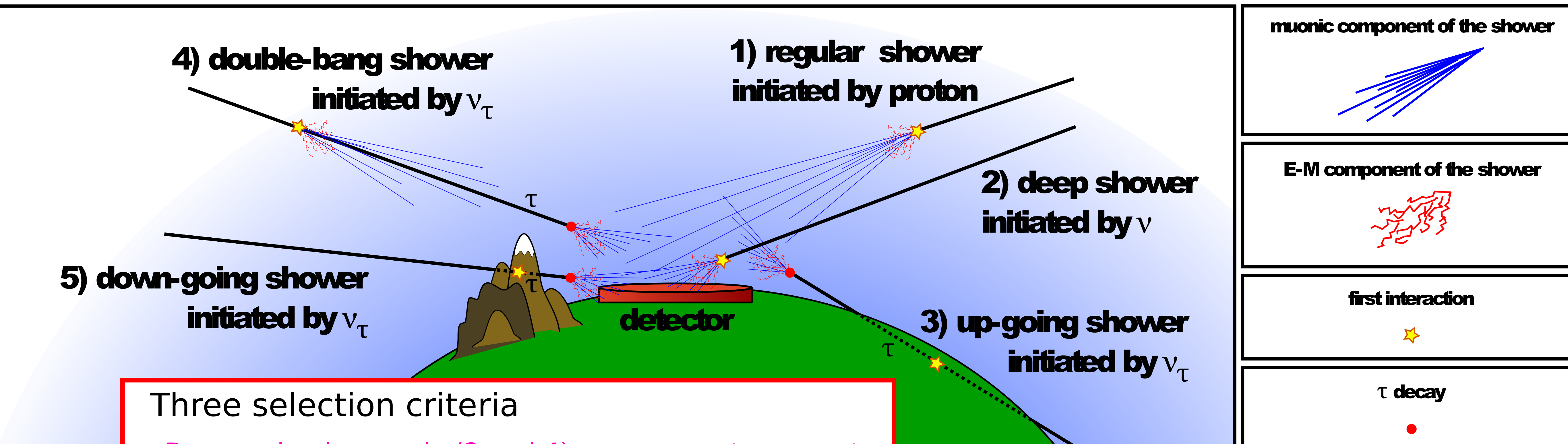
Cosmogenic Neutrinos

Recall:

- If flux suppression above $5 \cdot 10^{19}$ eV is due to GZK-effect: expect cosmogenic neutrinos & photons
- If due to source exhaustion: neutrinos & photons strongly suppressed

EAS are sensitive to all ν flavors and channels





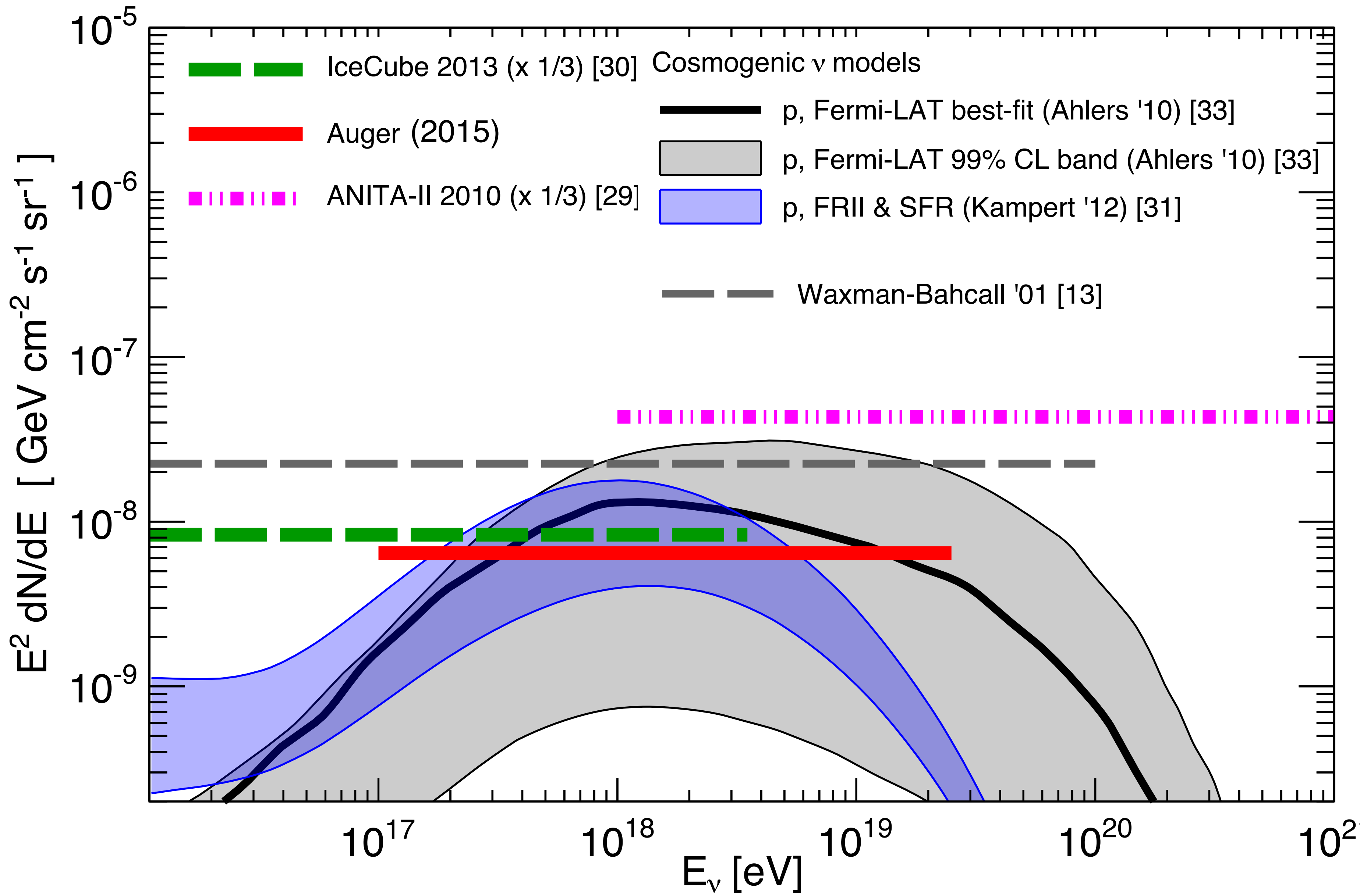
Three selection criteria

Down-going low angle (2 and 4) ⟶ DGL (60º - 75º)
Down-going high angle (2, 4 and 5) ⟶ DGH (75º - 90º)
Earth-skimming (3) ⟶ ES (90º - 95º)

EeV Neutrino Limits

Single flavour, 90% C.L.

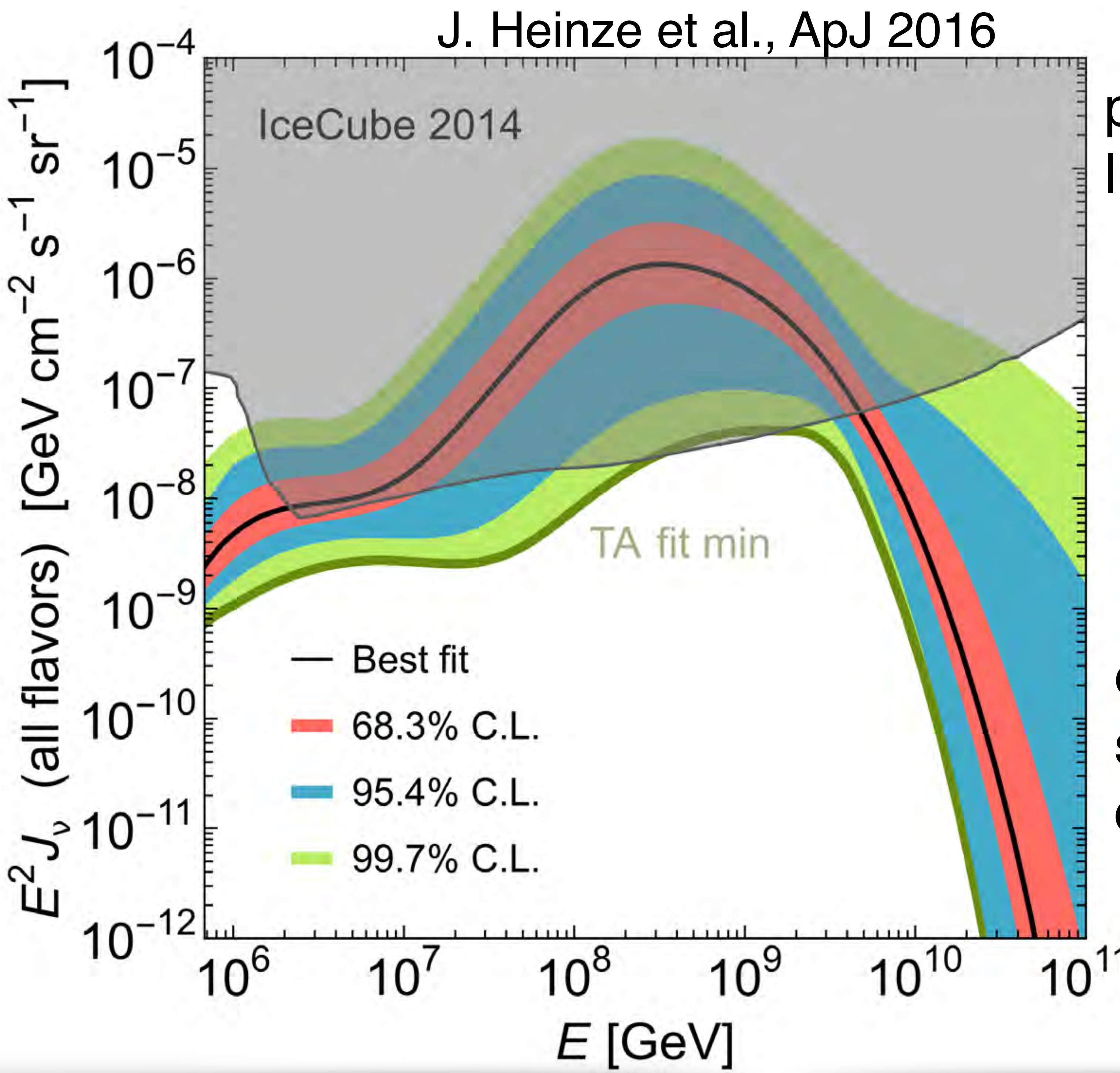
Auger Collaboration, PRD 91, 092008 (2015)



Would have expected to see 1-7 GZK neutrinos (for different models), have seen none

Neutrino upper limits start to constrain cosmogenic neutrino fluxes of p-sources

EeV Neutrino Limits Challenge GZK



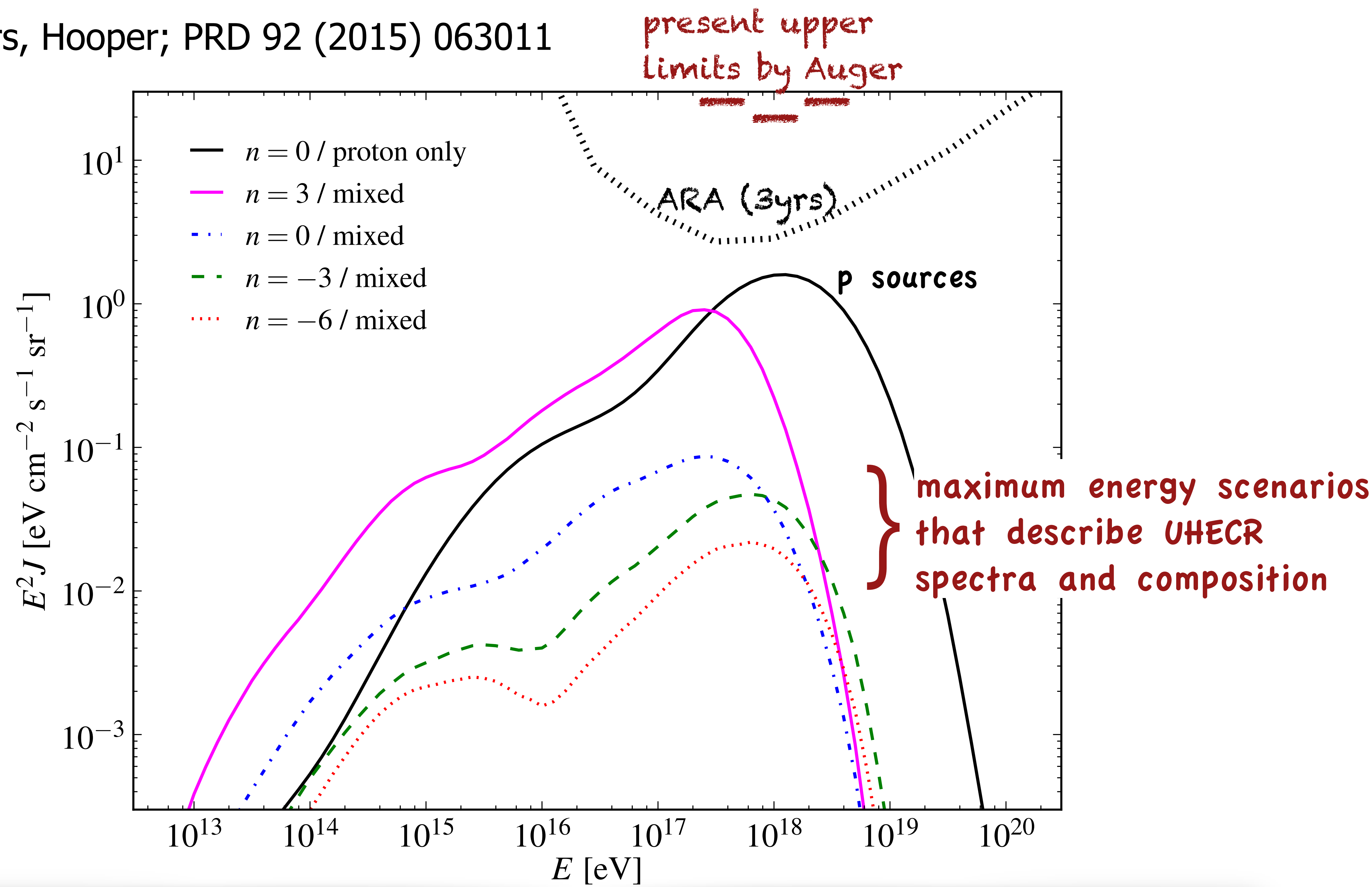
preliminary exclusion limits from IceCube

expected ν-fluxes if flux suppression of TA is due to GZK-effect

Pure proton with GZK suppression challenged by upper limits to neutrino fluxes

Exhausted UHECR Sources

Taylor, Ahlers, Hooper; PRD 92 (2015) 063011



Cosmogenic neutrino fluxes may be down by ~2-3 orders of magnitudes for exhausted sources !!

What did we learn? Where to go?

- UHECR Flux suppression clearly established
  … but what is the cause of it?
- Composition increasingly heavier above the ankle
  … unexpected astrophysics or exotic particle physics?
- UHECR sky surprisingly isotropic, only dipole LSA >5σ
  … much stronger B-fields or heavy nuclei ?
- Cosmogenic neutrino & photon fluxes constrain GZK interpr.

Single key observation is needed to answer all the questions:

composition measurement into flux suppression region

⇒ composition enhanced anisotropy

⇒ attempt for proton astronomy

⇒ study particle physics features at cms-energies > 100 TeV

How to measure composition with large statistics

Up to know, composition based solely on Fluorescence Telescopes, duty cycle ~10-15%
(different operation modus planned to yield factor ~2)

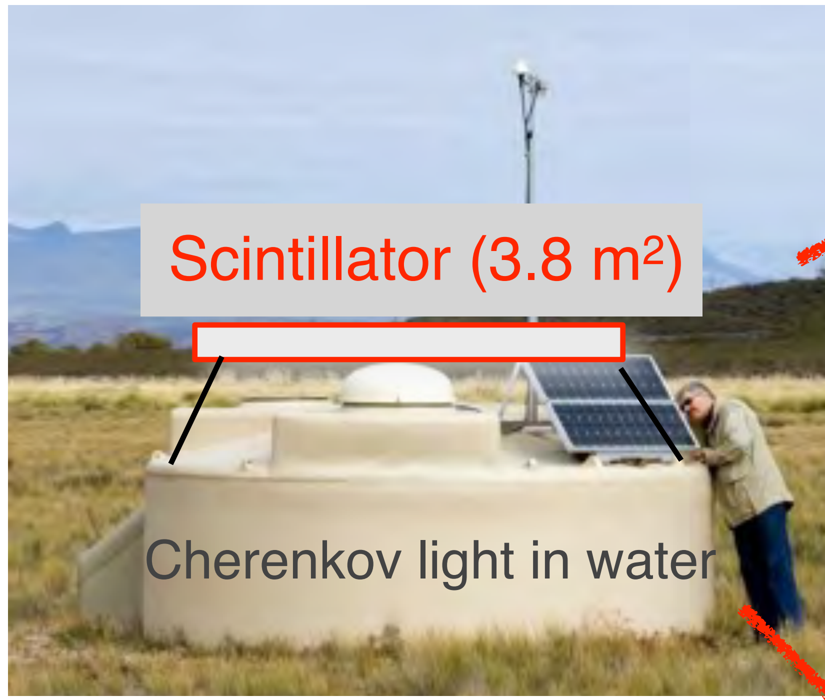
➙ most effectively achieved by upgrade of surface detectors (duty cycle 100%)
➙ immediate boost in statistics by a factor of ~10 !

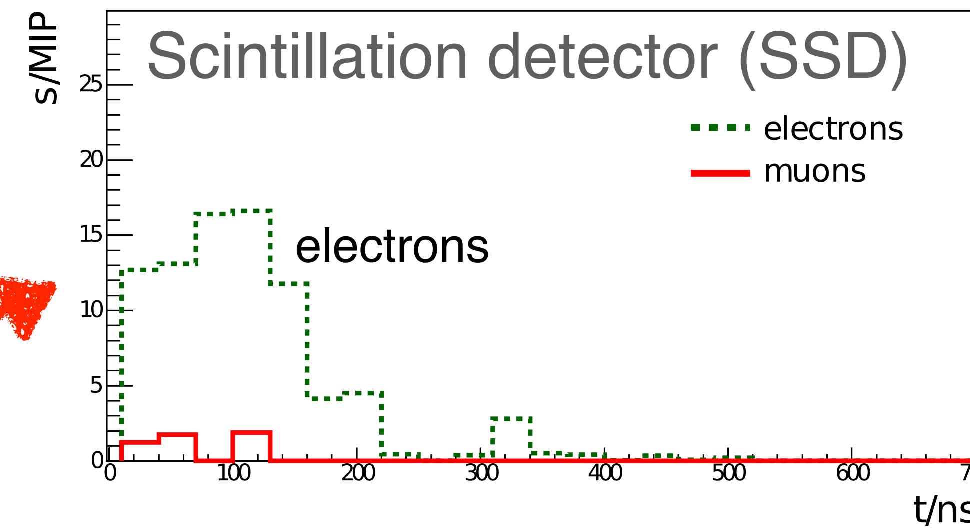
classical approach:
enhance electromagnetic/muonic separation of stations

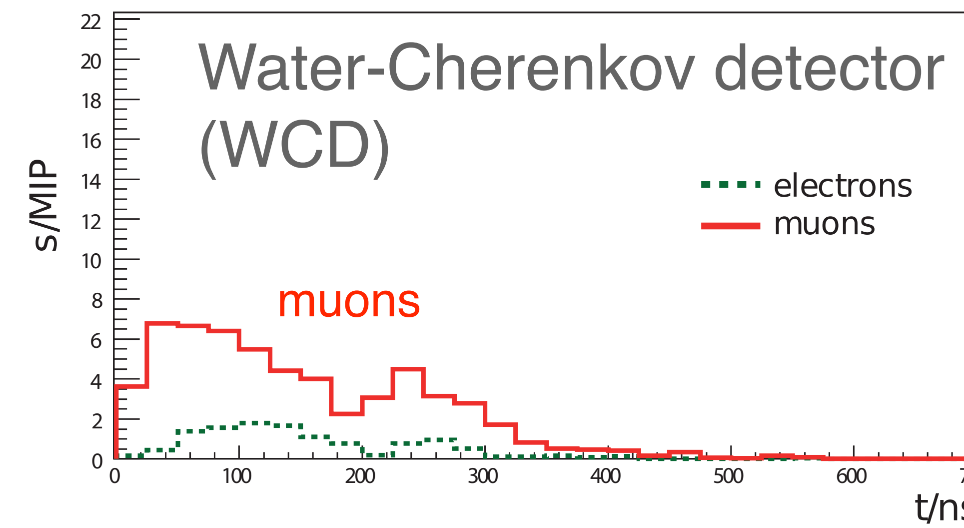
Technical Realisation

100% duty cycle

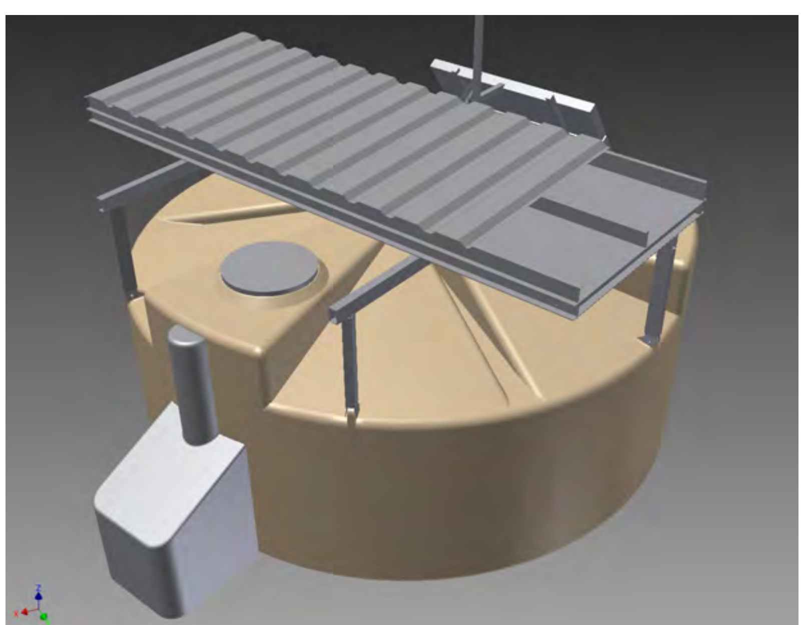
15% duty cycle







$$\boxed{S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}}$$



AugerPrime featured in current Cern Courier

- positively evaluated by International Advisory Committee
- endorsed by International Finance Board
- engineering array 08/2016
- construction 03/2017 - 2018
- data taking into 2025
- costs: 12.5 M€
- ~60% of required funds already collected

- ☑ do composition enhanced anisotropy
- ☑ p-astronomy: proof of principle
- ☑ particle physics beyond LHC
- ☑ ....

The road to a better understanding of the sources and origin of UHECRs passes through the joint study of the three fundamental observables:

energy spectrum, composition and arrival directions

Only AugerPrime can do this!

Multi-Messenger is becoming Reality !

RAPP

RAPP is perfectly in place at the right time !

Thank you for your attention!

Photo by Steven Saffi