Exploring the Universe at the highest energies with the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

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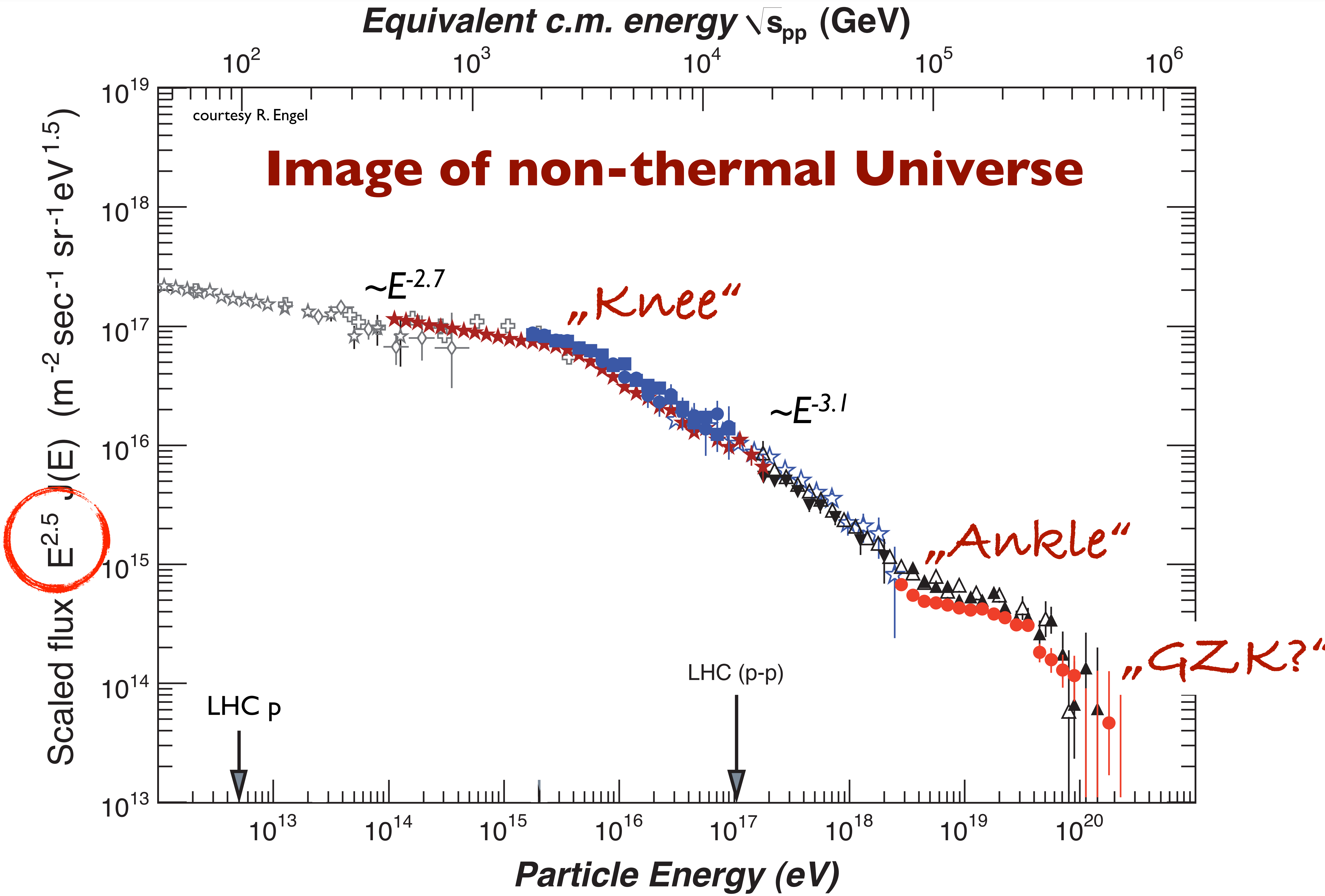
University Wuppertal

BERGISCHE UNIVERSITÄT WUPPERTAL

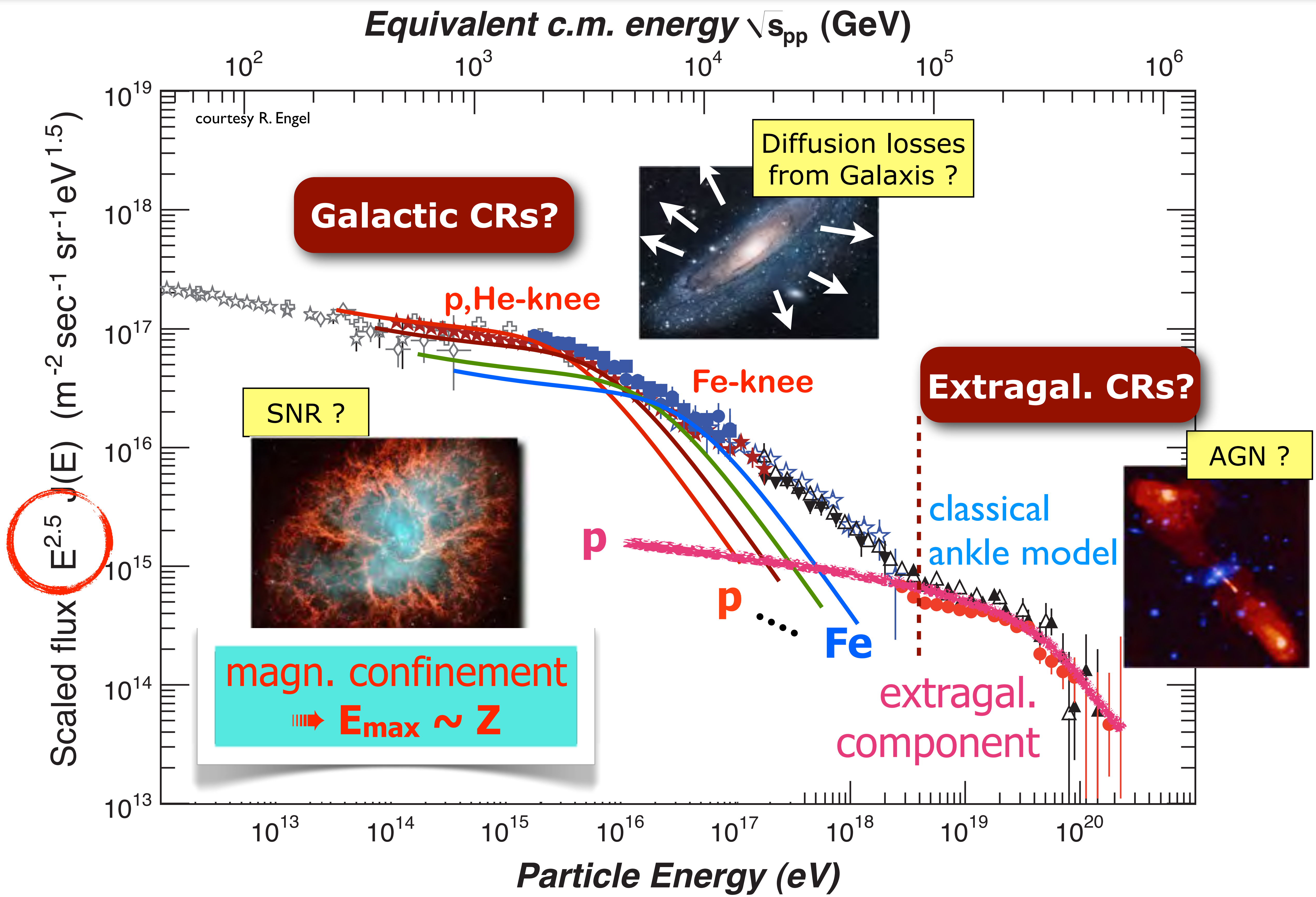
Colloquium DESY-Hamburg/Zeuthen, June 24/25, 2014

Photo by Steven Saffi

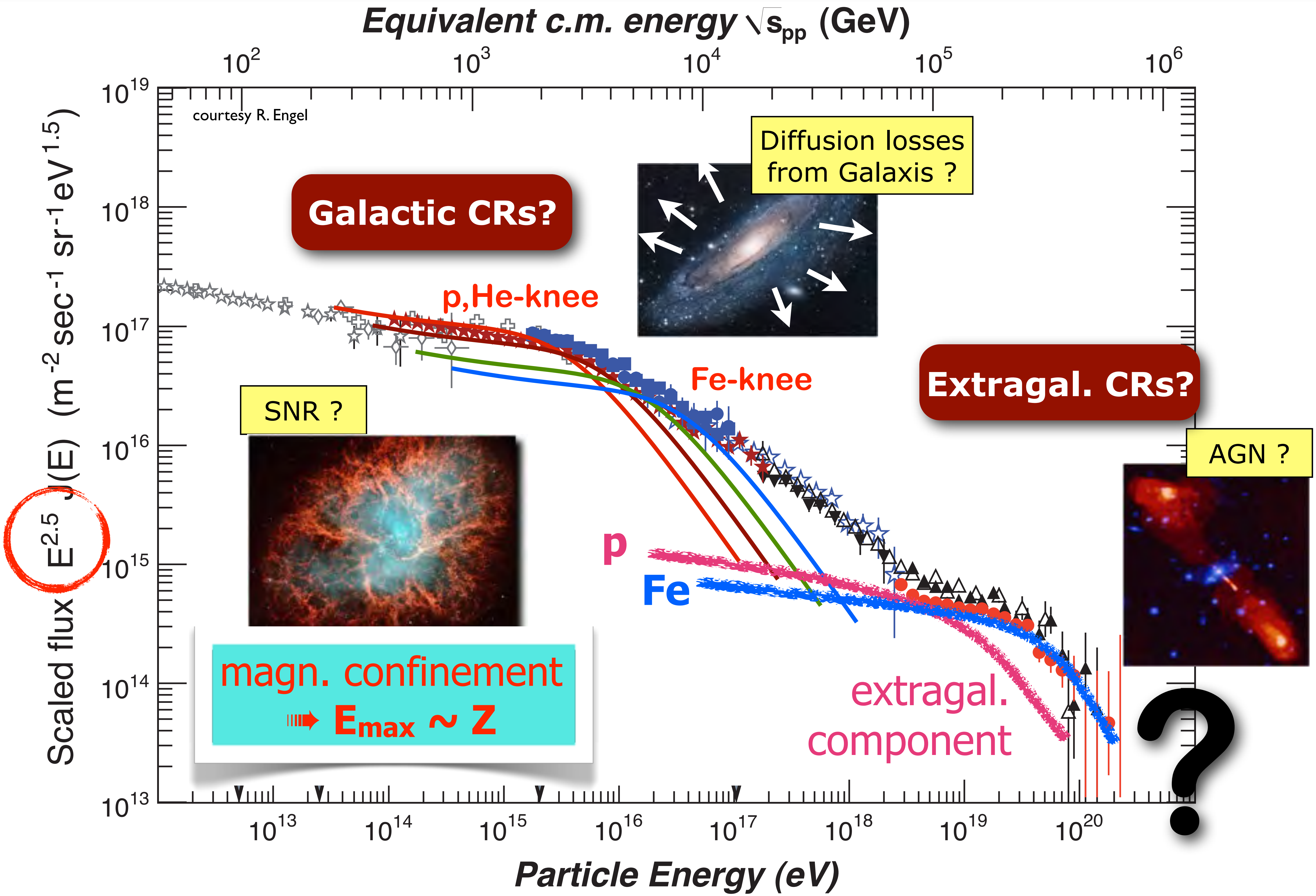
Features of CR spectrum



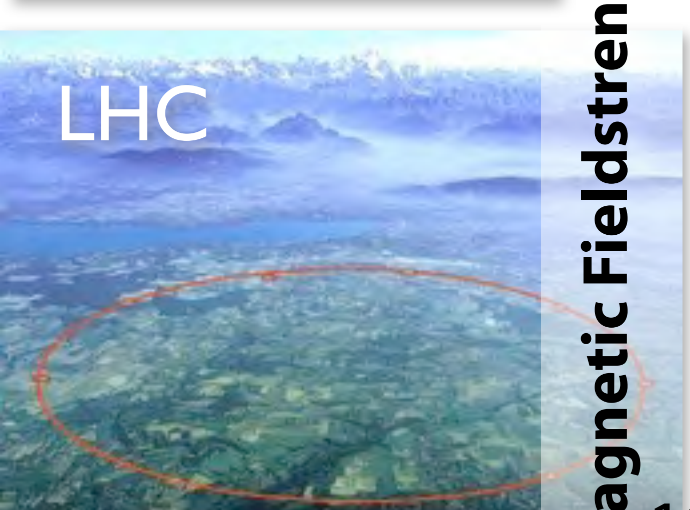
Features of CR spectrum

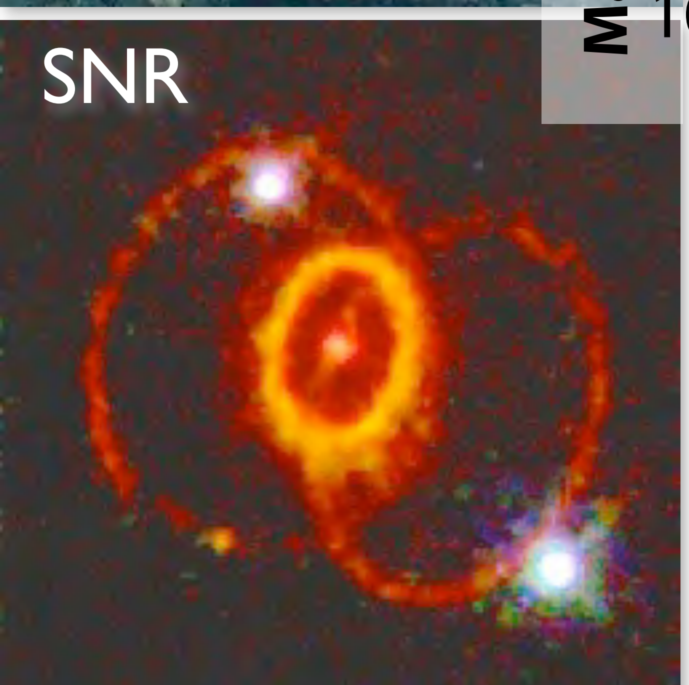


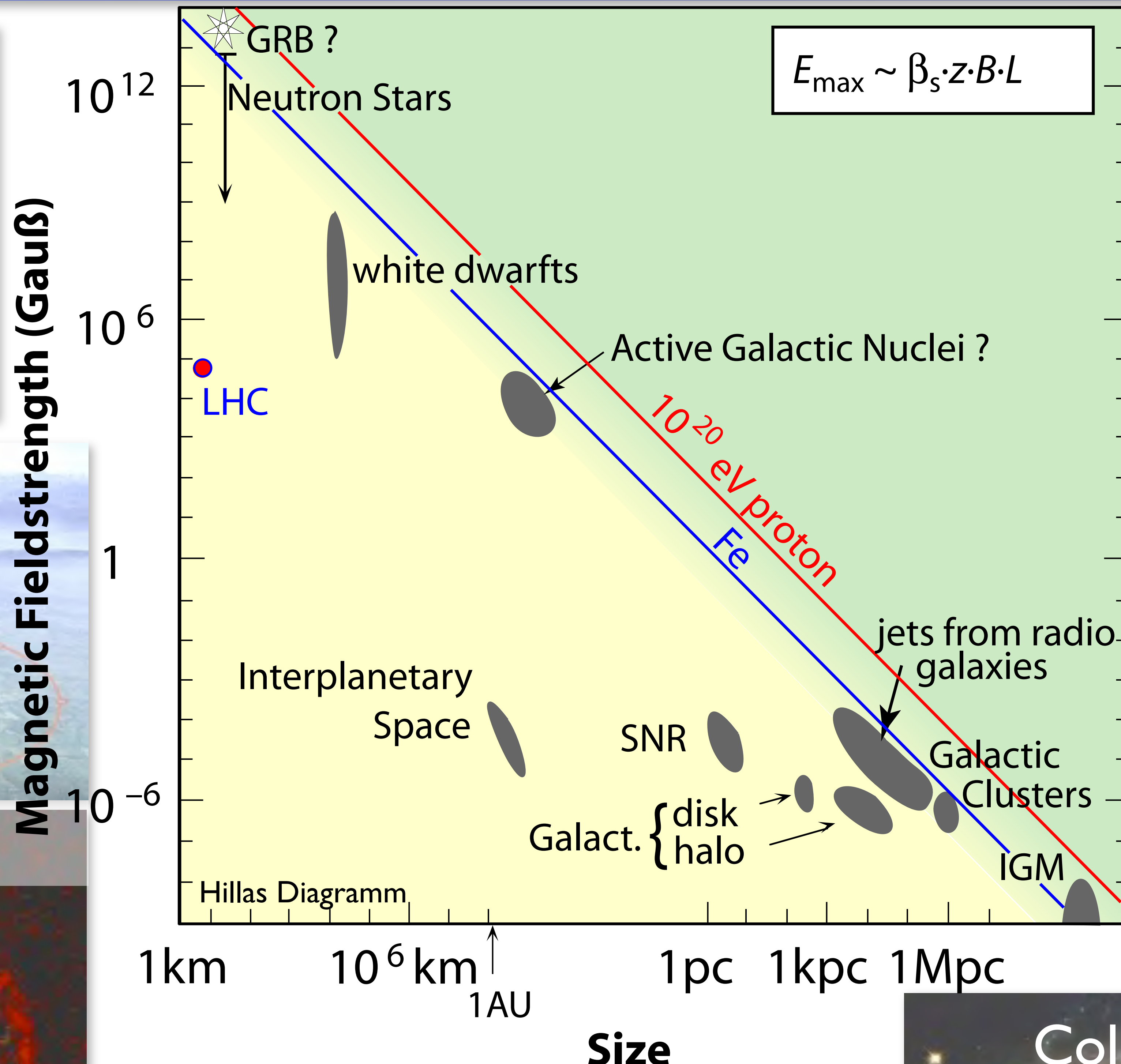
Features of CR spectrum



Potential Sources of 10^{20} eV particles

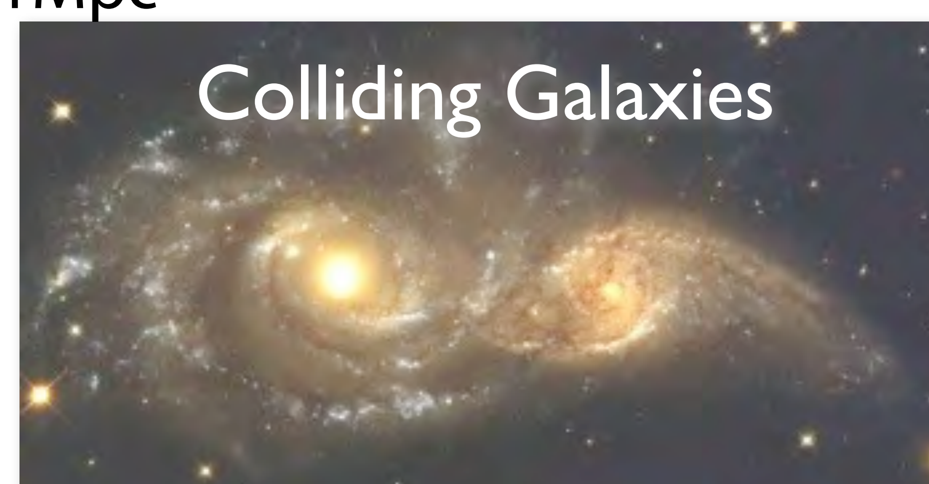






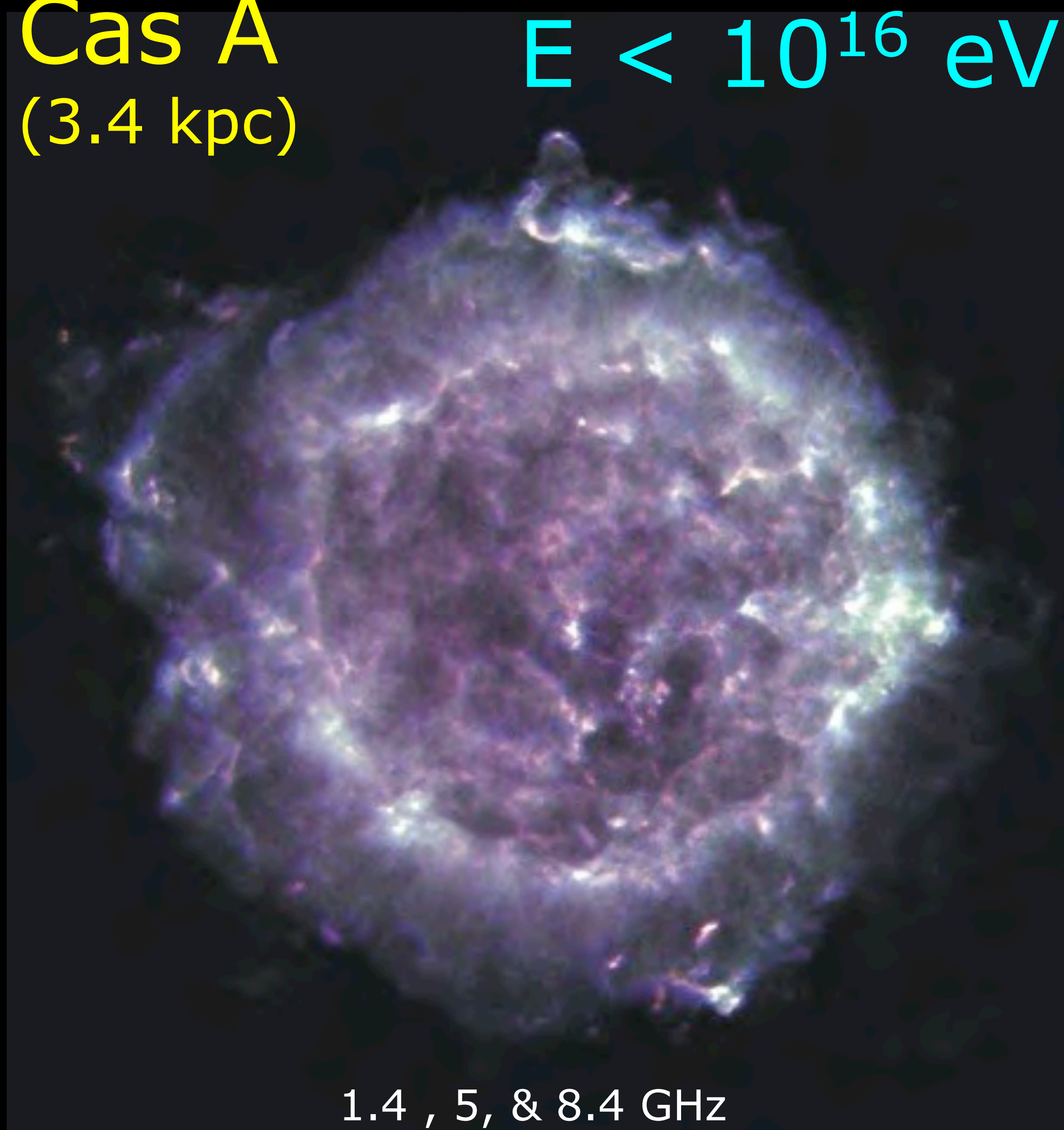
Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

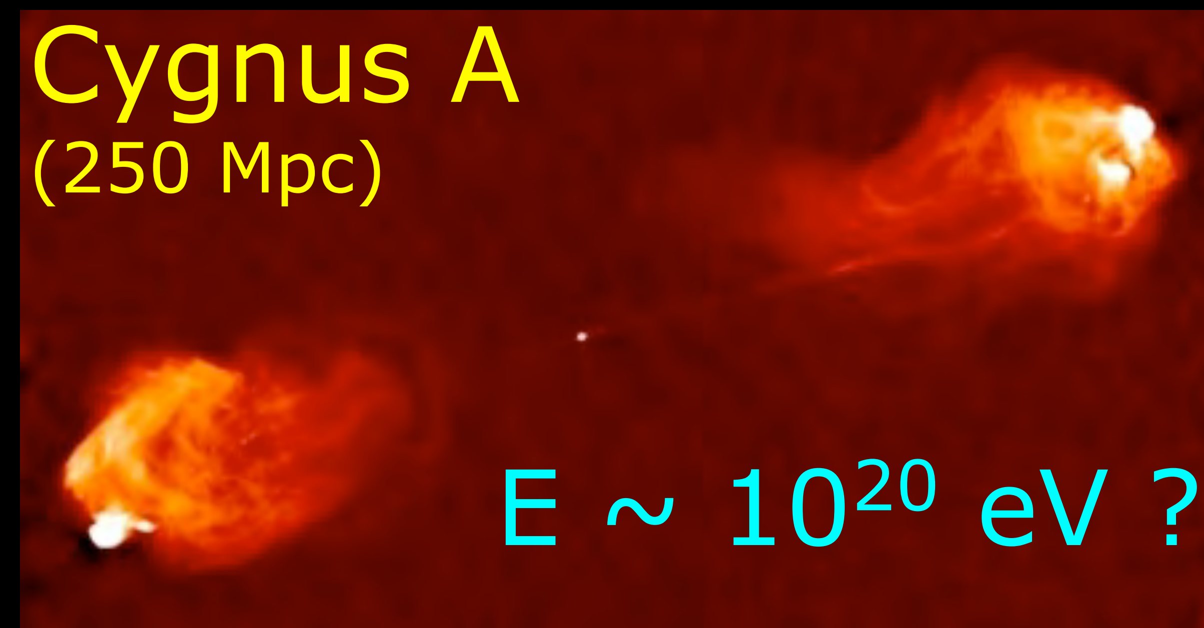


Radio Images of Cosmic Accelerators

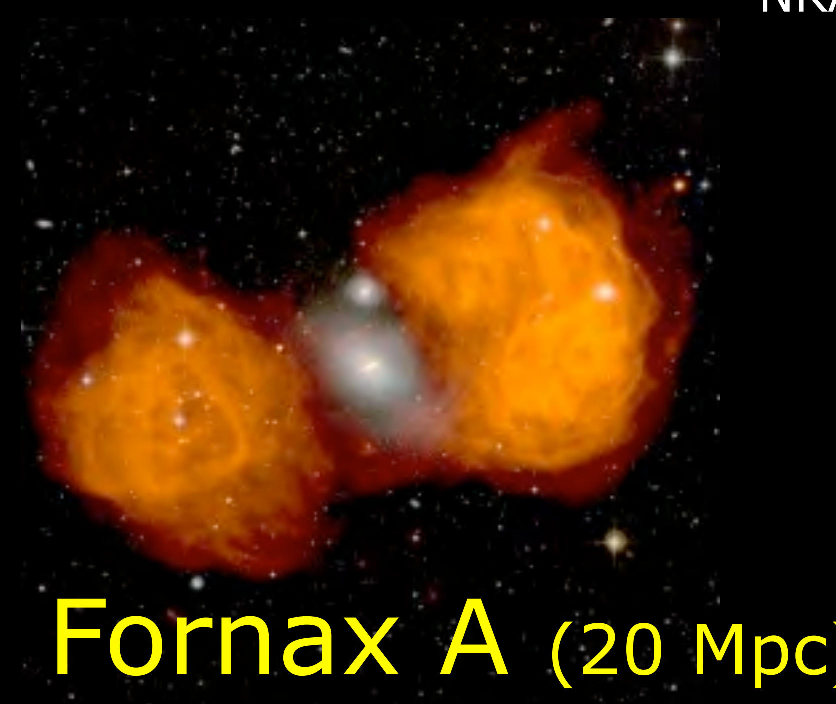
Supernova Remnants



Accreting Supermassive Black Holes



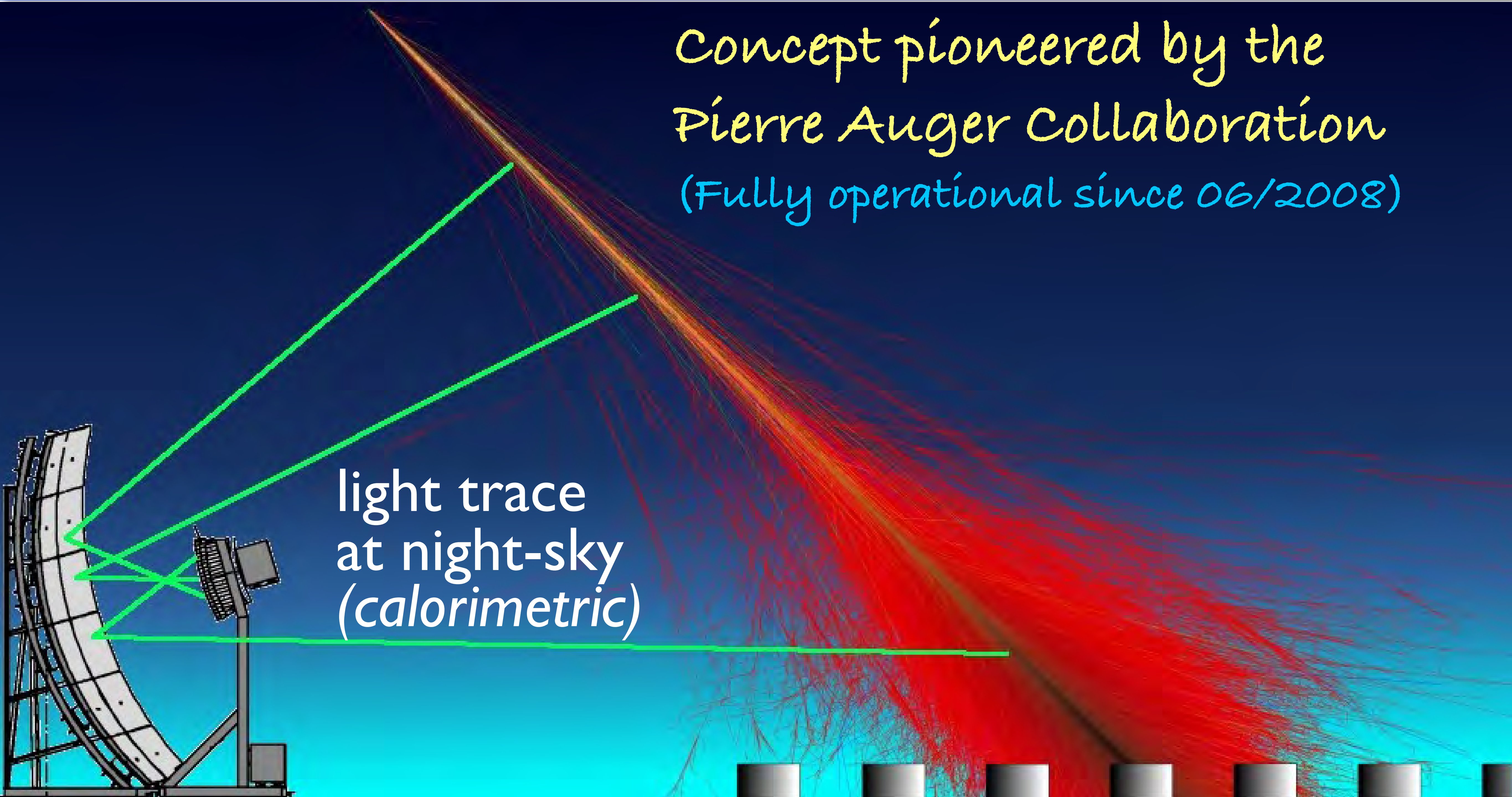
NRAO/AUI



Key Questions about Ultra High-Energy Cosmic Rays

- **Where do they come from?**
- **What are they made of ?**
- **How do their accelerators work?**
- **Is there a maximum limit to their energy ?**
- **What can can they tell us about fundamental and particle physics?**

Hybrid Observation of Extensive Air Showers



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

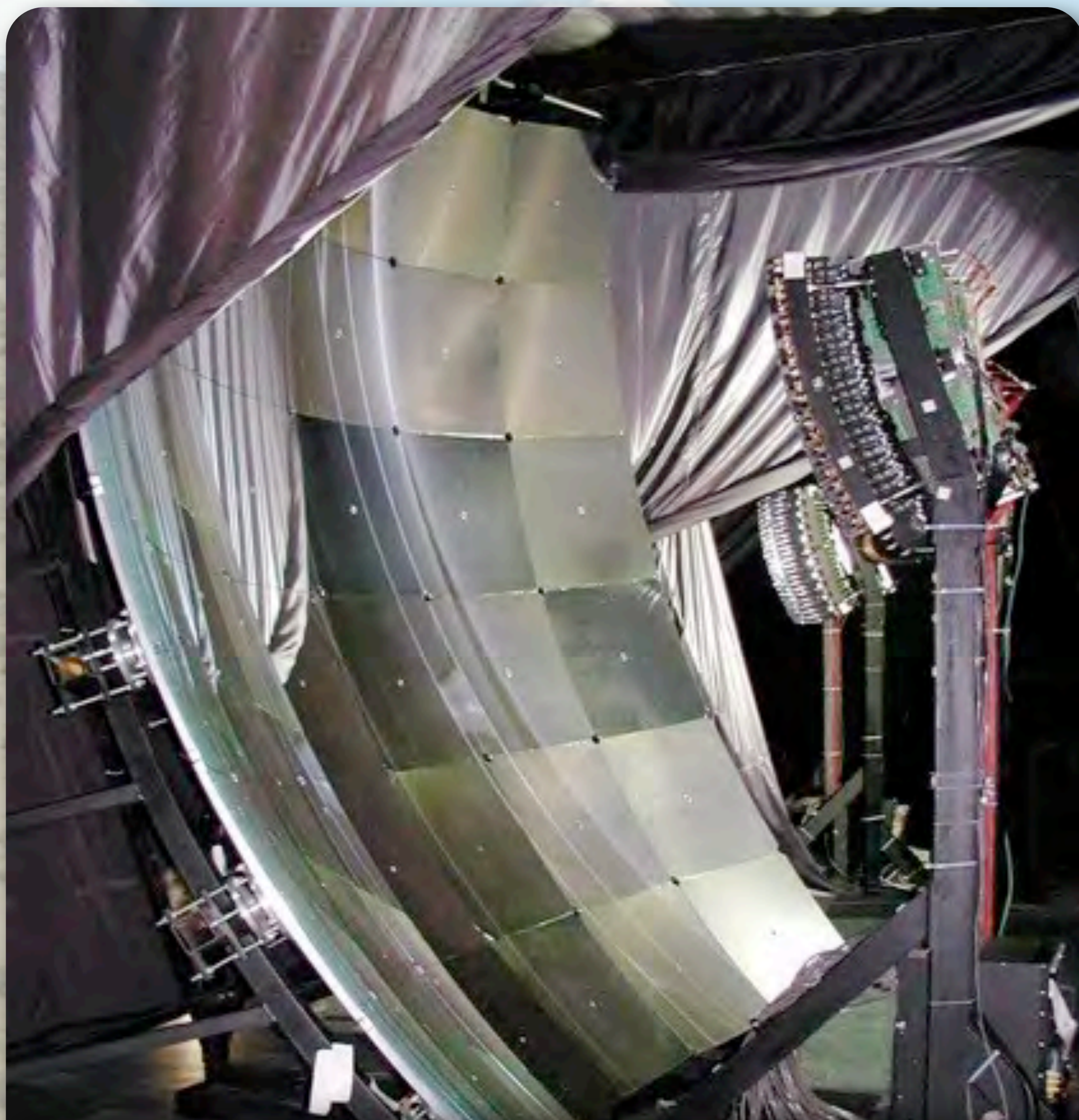
130 radio antennas

Province Mendoza, Argentina

ARGENTINA
Laguna Mar Chiquita
Córdoba
Mercedario
Aconcagua
Mendoza
Tupungato
SANTIAGO
Chile
Plata
Lanín
Lago Nahuel Huapi
Oranienburg
Basdorf
Oberkrämer
Karte
Neuendorf
Bernau bei Berlin
Hennigsdorf
Tegel
Bezirk Pankow
Strausberg
Bezirk Spandau
Berlin
Hellersdorf
Rehfelde
Dahlwitz-Hoppegarten
Bezirk Treptow-Köpenick
Zehlendorf
Grünheide (Mark)
Potsdam
Teltow
Schönefeld
Blankenfelde-Mahlow
Spreenhagen
Ludwigsfelde
Königs Wusterhausen
Storkow (Mark)
Beelitz
Bestensee
Trebbin
Zossen
Naturpark Dahme-Heideseen
Wünsdorf
Teupitz

Auger Hybrid Observatory

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

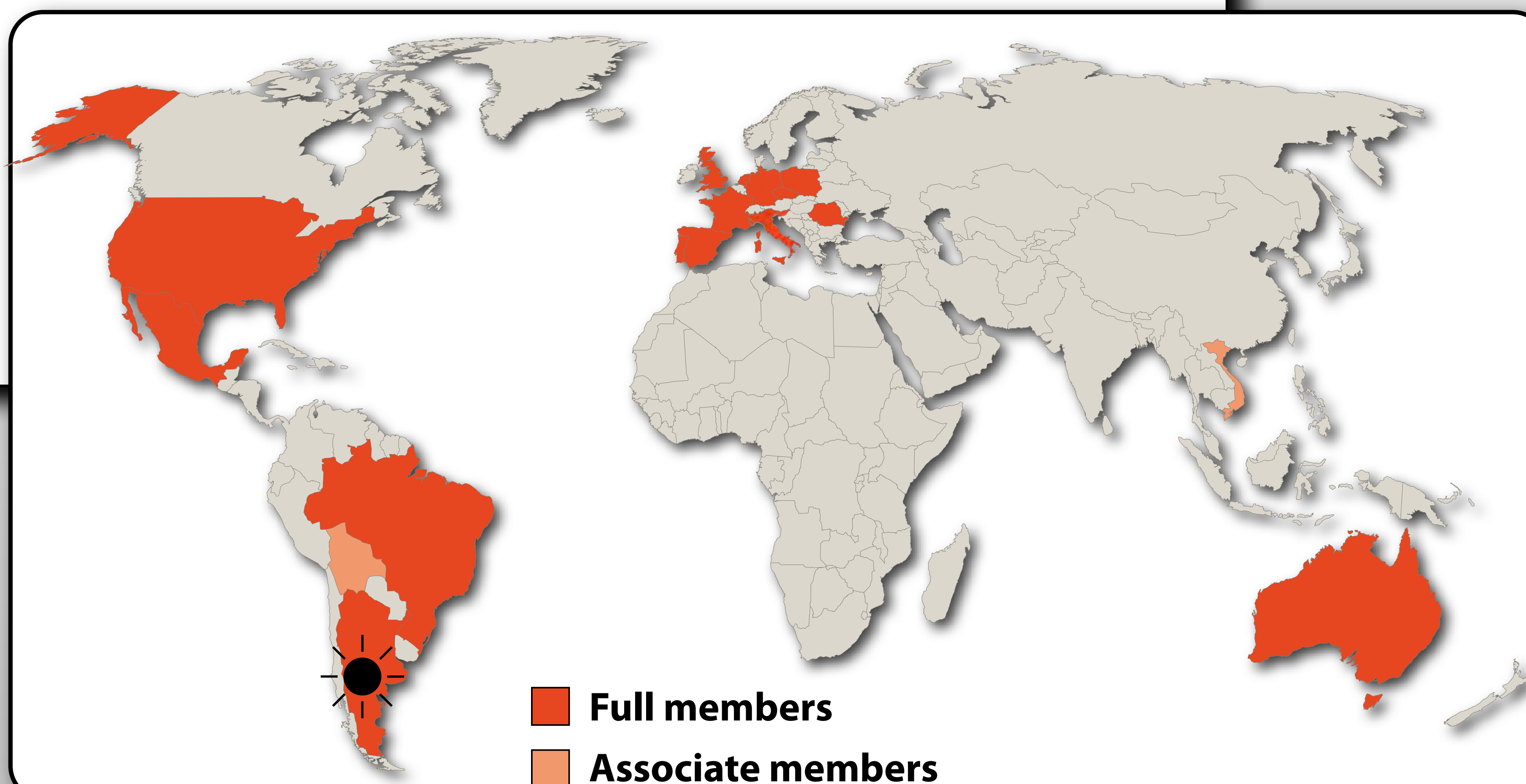


Pierre Auger Collaboration

~500 Collaborators; 90 Institutions, 18 Countries:

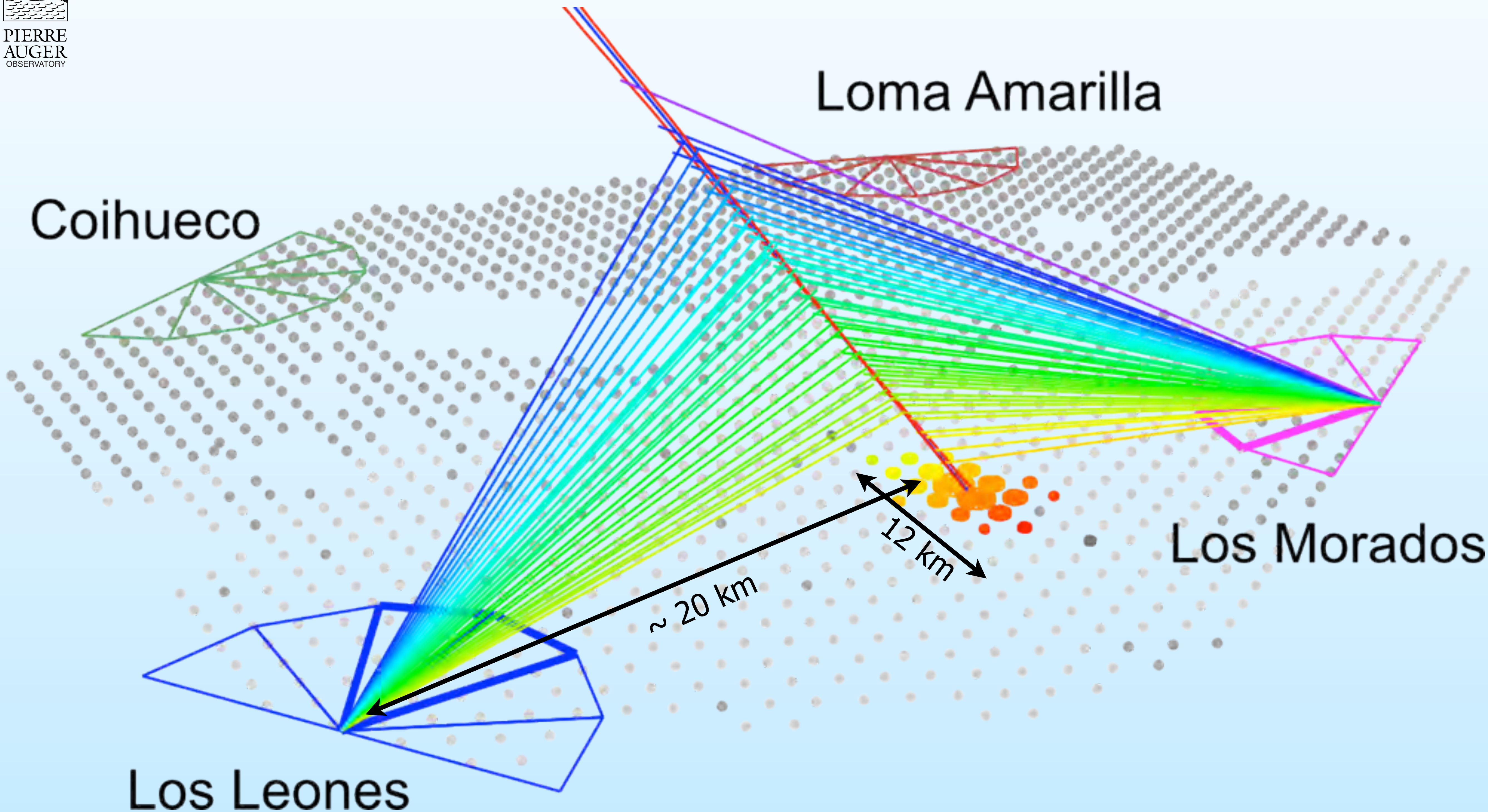
Argentina
Australia
Brasil
Czech Republic
France
Germany — Aachen, Bonn MPfR, Hamburg, Karlsruhe, Siegen, Wuppertal
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
UK
USA
Bolivia*
Vietnam*

*Associated

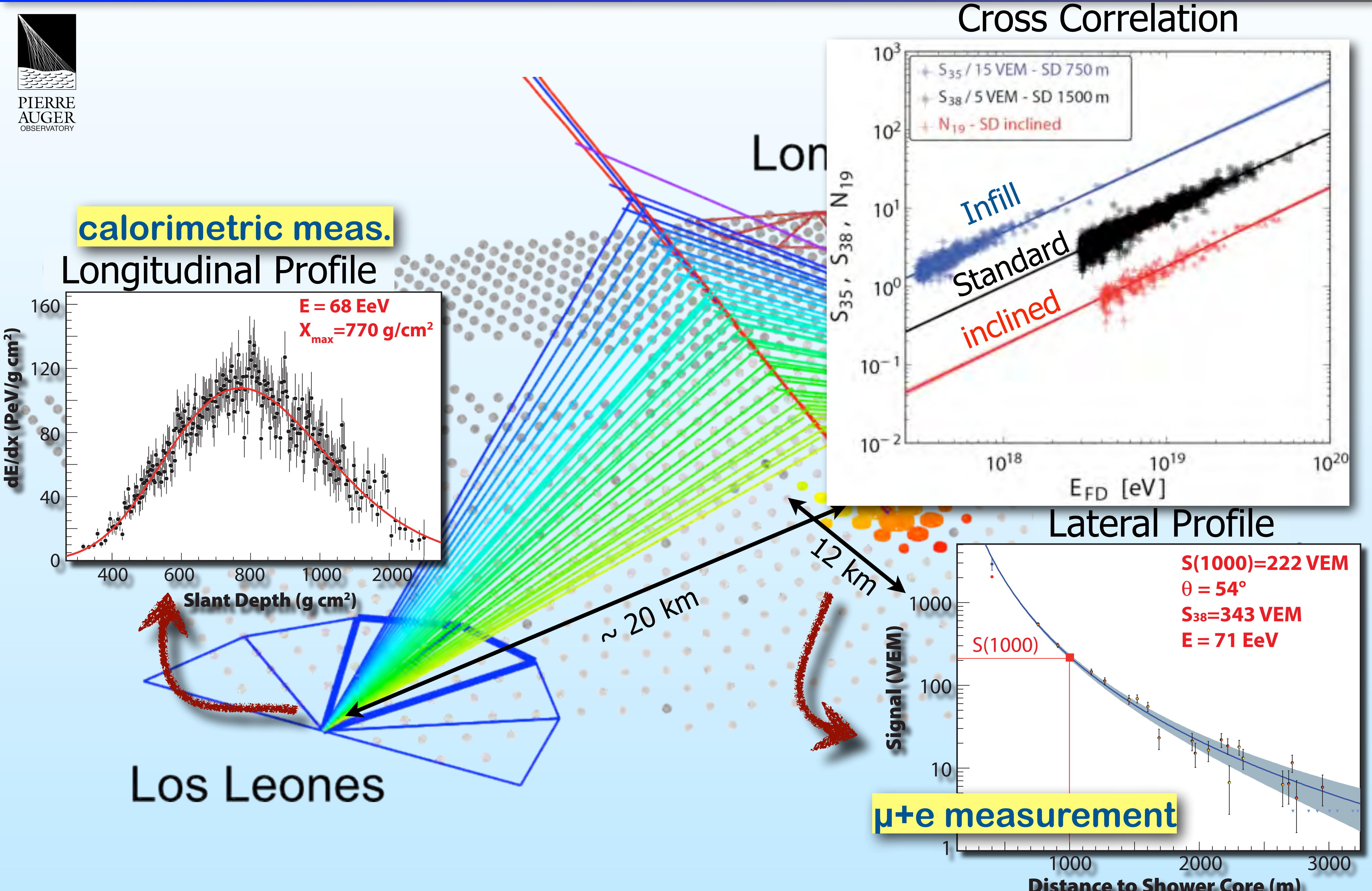


PIERRE AUGER OBSERVATORY

Event Example in Auger Observatory



Event Example in Auger Observatory



Systematics of Energy Scale

paper t.b.subm. soon

Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere - sec. 3)	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration - sec. 4)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec. - sec. 5)	**6.5% ÷5.6%**
Invisible energy (sec. 6)	**3%÷1.5%**
Stat. error of the SD calib. fit (sec. 7)	**0.7%÷1.8%**
Stability of the energy scale (sec. 7)	**5%**
Total	**14%**

Based on AirFly data

Based on Atmosph. Monitoring data

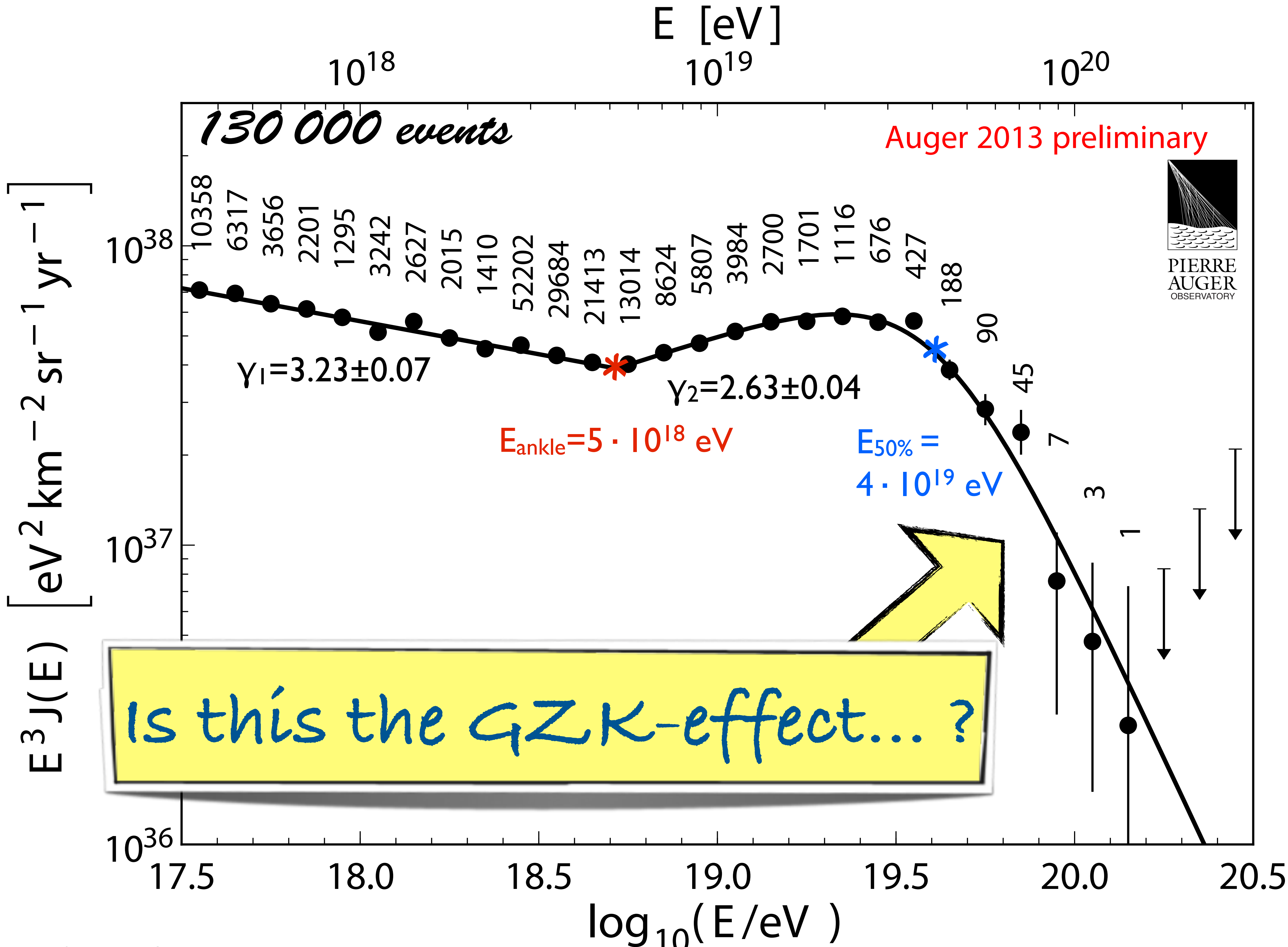
Better optical tools

Better understanding of FD data

Based on golden hybrid

down from 22% before

End of the CR-Spectrum



combined from: infill+hybrid+vertical+inclined events

GZK-Effect: Energy losses in CMB

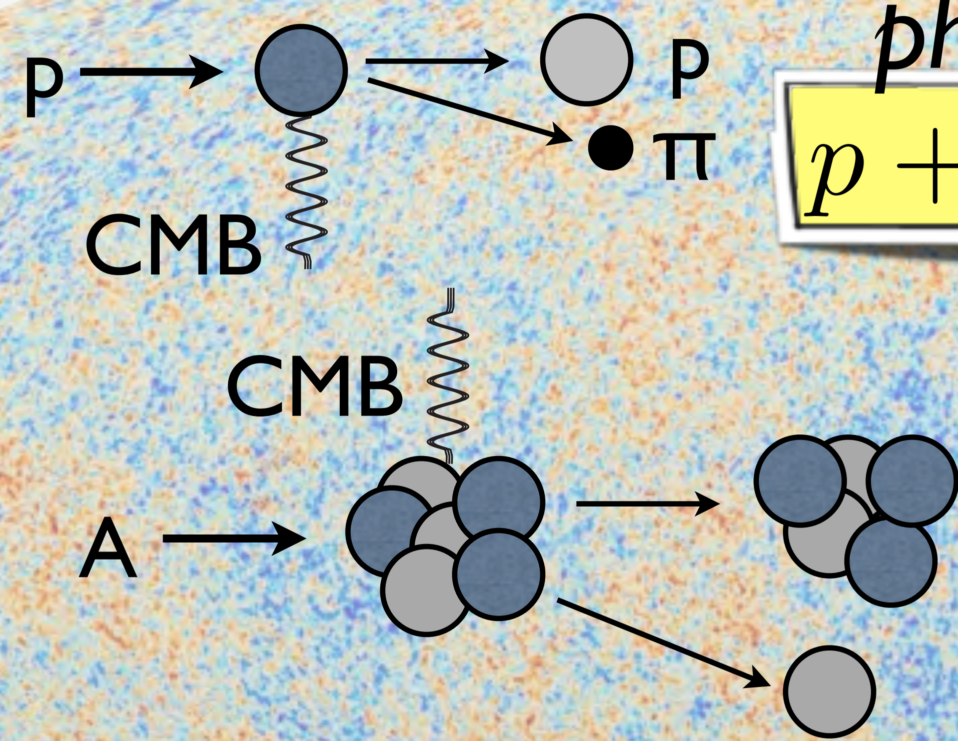


photo-pion production

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

photo disintegration

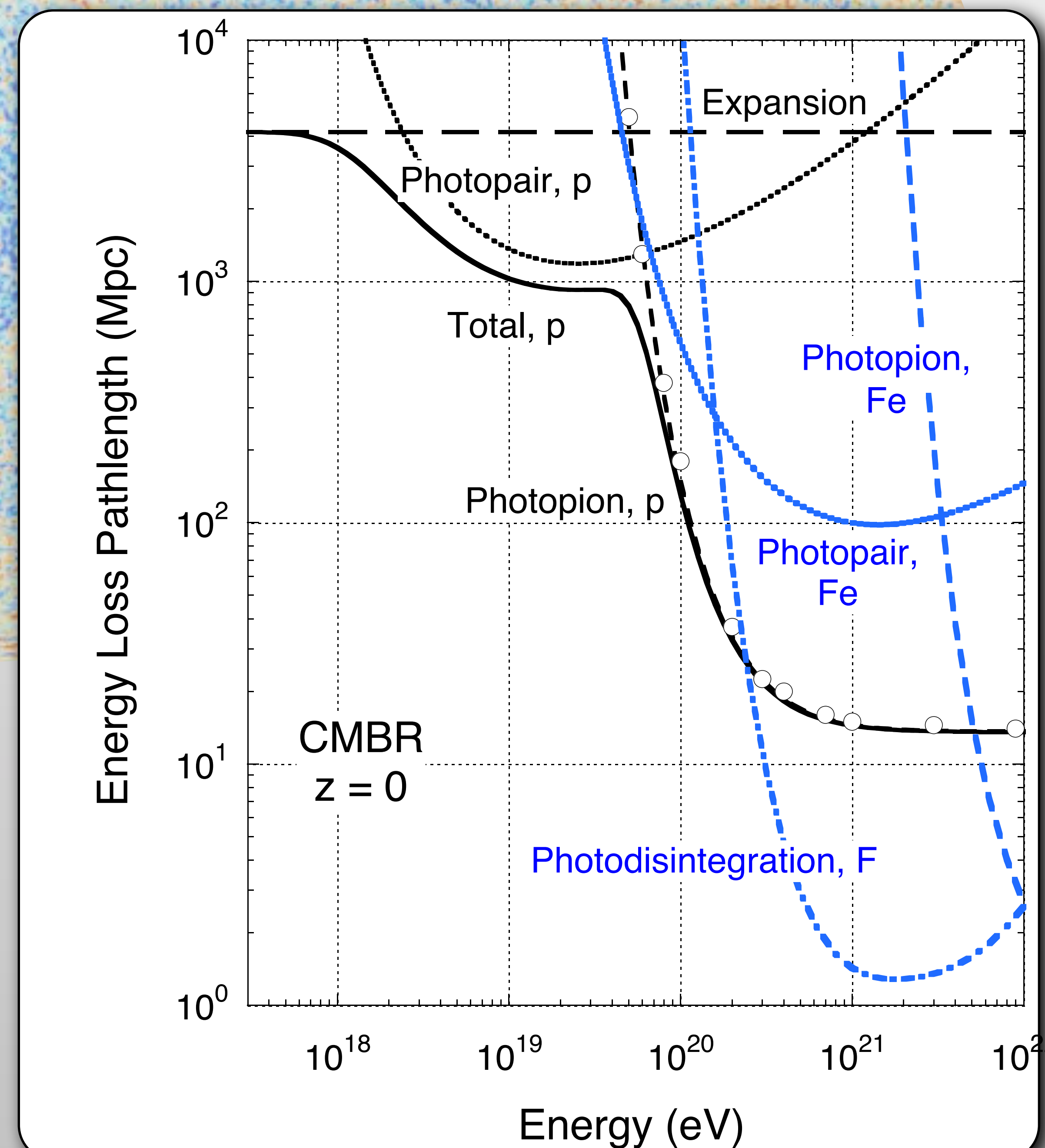
$$A + \gamma_{\mathrm{CMB}} \rightarrow (A-1) + n \ldots$$

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

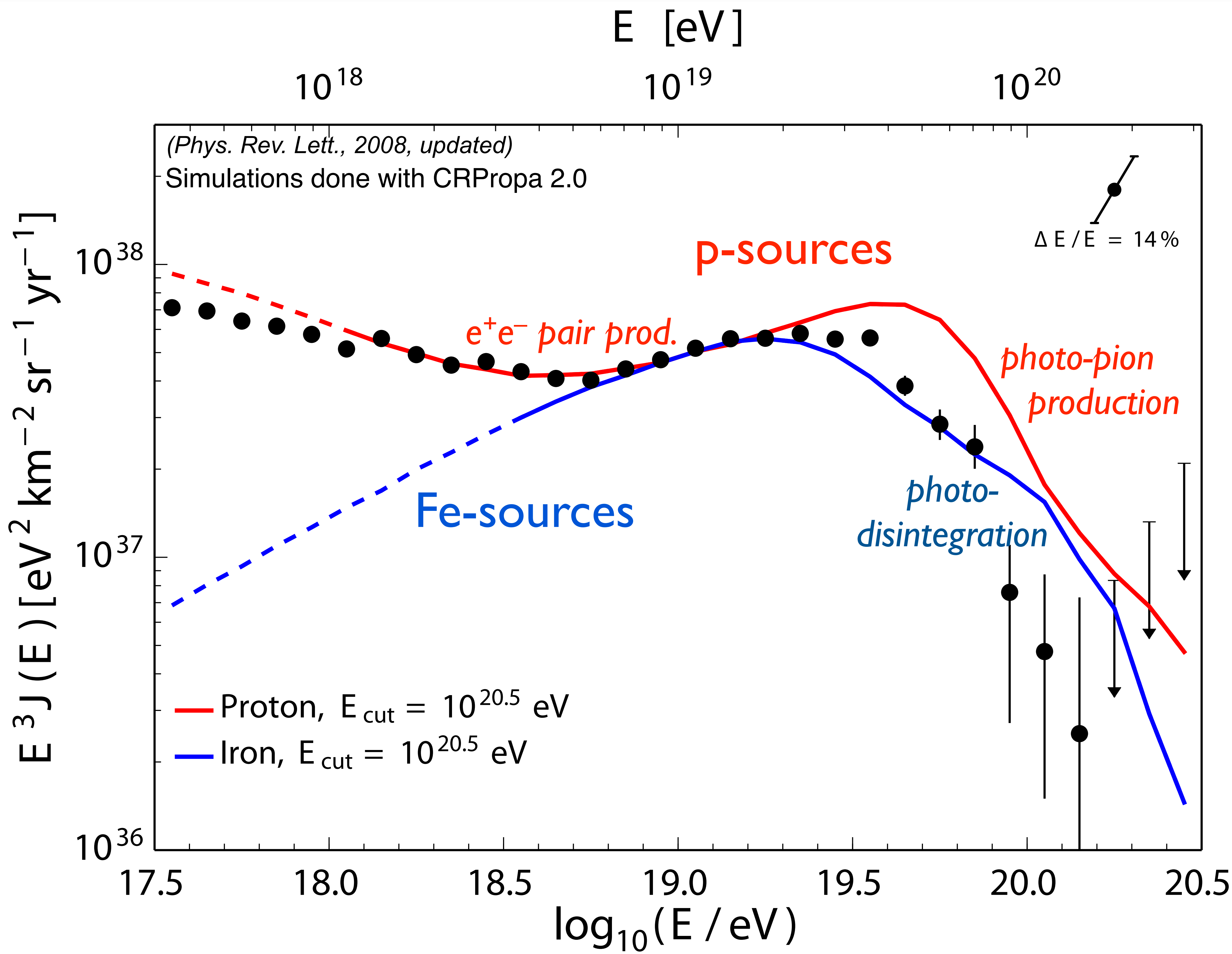
threshold: $E_p E_\gamma > (m_\Delta{}^2 - m_p{}^2)$

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

➙ **GZK-Horizon ~ 60 Mpc**



Data compared to GZK-effect

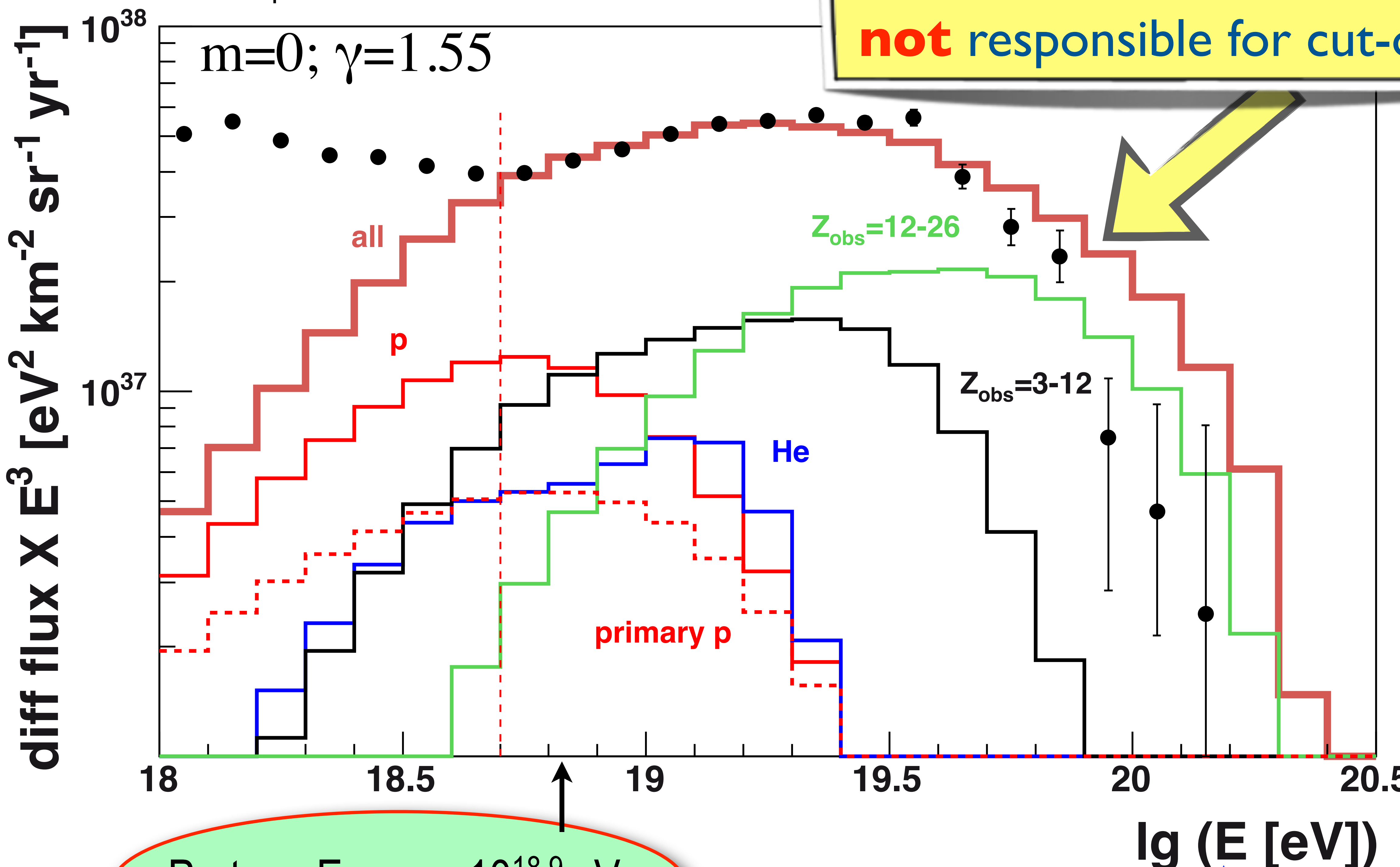


Limiting Energy of Sources (E_{max}~Z) + GZK

Model inspired by Allard, Astropart. Phys. 39-40, 2012

Simulations done with CRPropa 2.0

In this case GZK-effect is **not** responsible for cut-off!



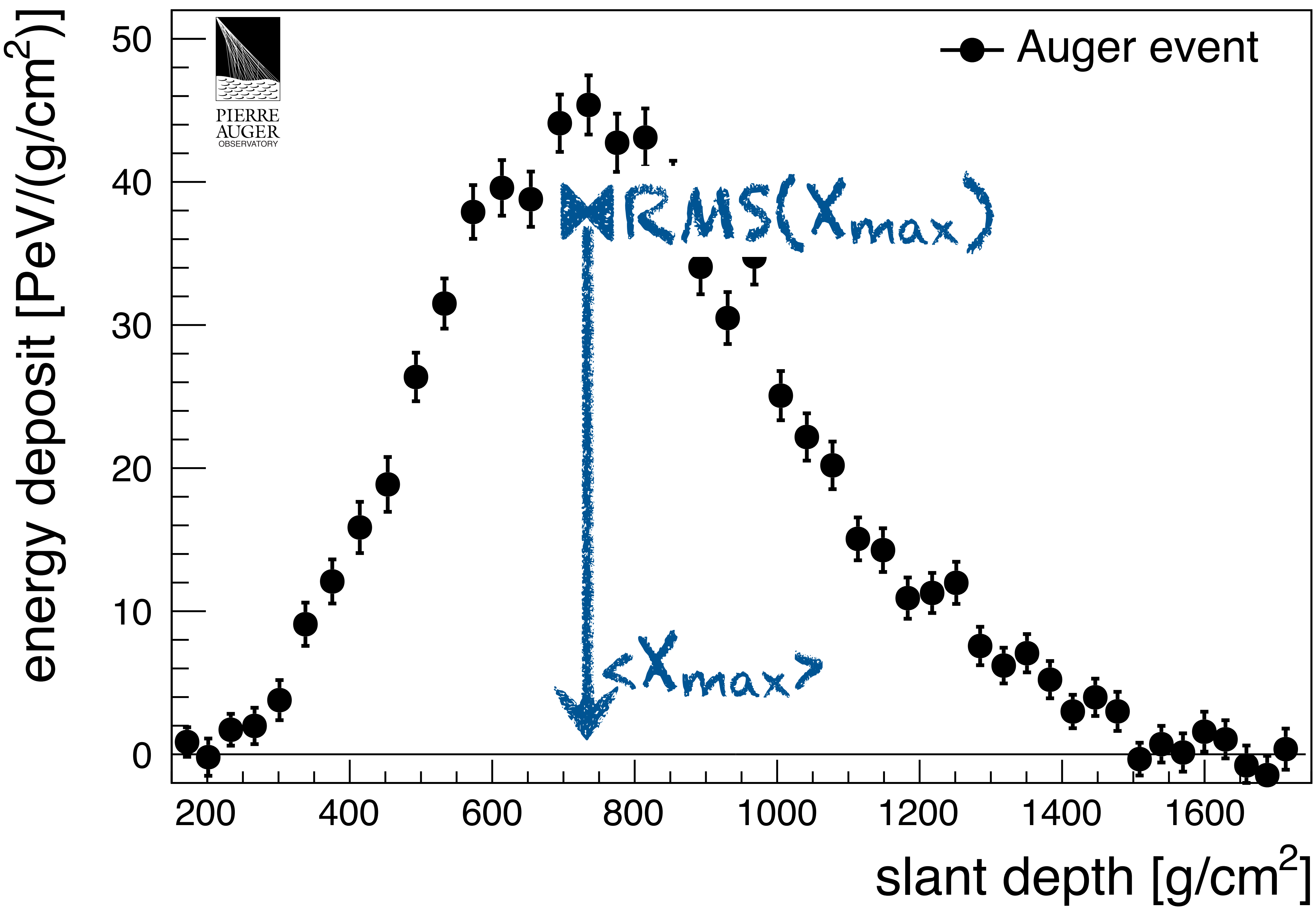
Protons $E_{max,p} = 10^{18.9}$ eV

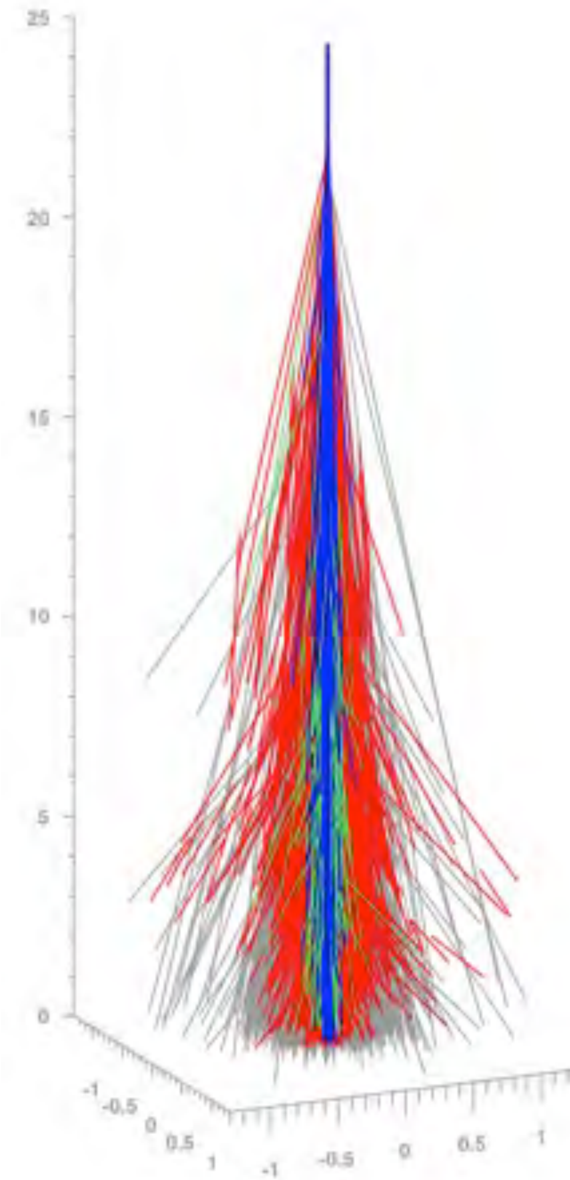
Iron $E_{max, Fe} = 26\ E_{max,p} = 10^{20.3}$ eV

Longitudinal Shower Development → Primary Mass

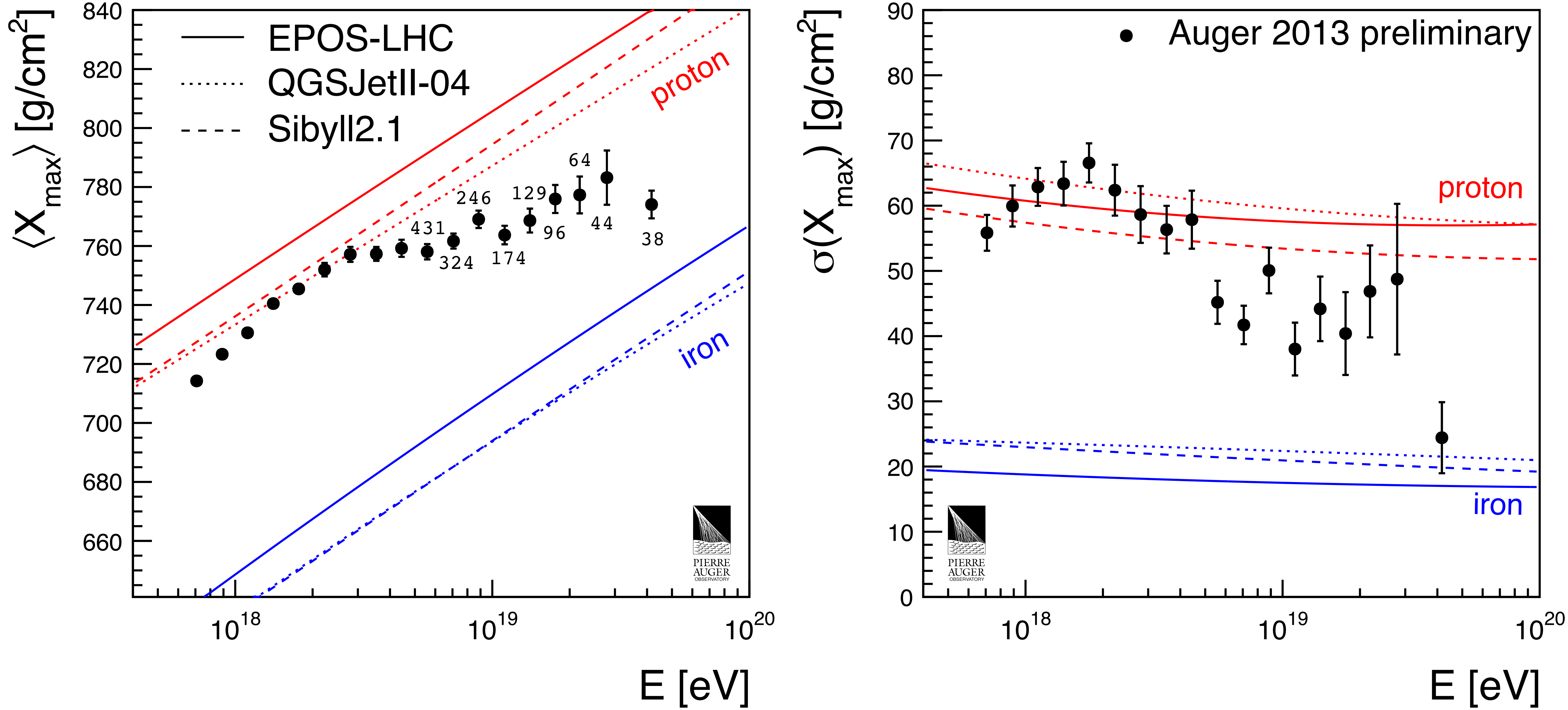
KHK, Unger, APP 35 (2012)
EPOS 1.99 Simulations

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





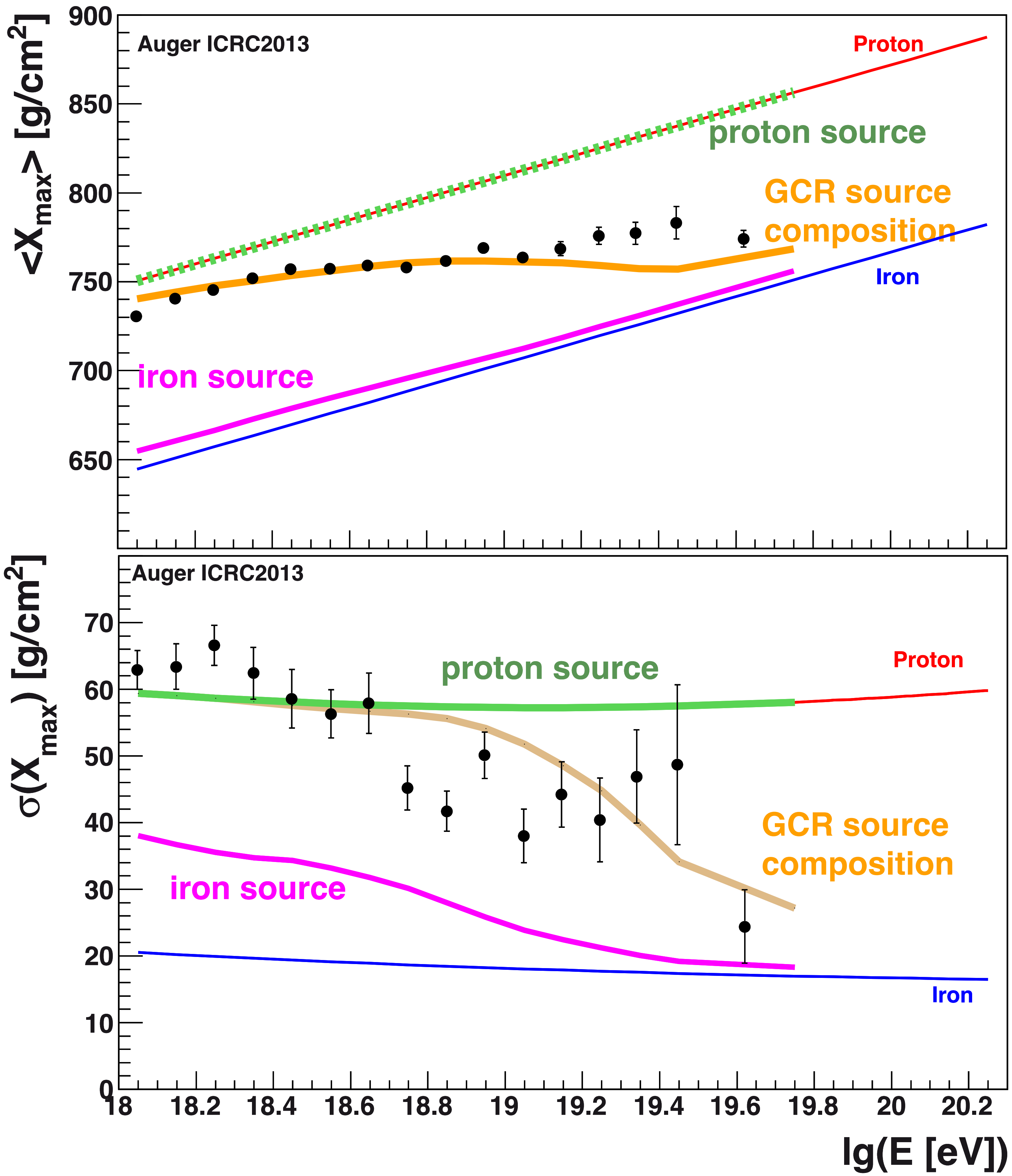
X_{max} and RMS(X_{max}) as a fct of E

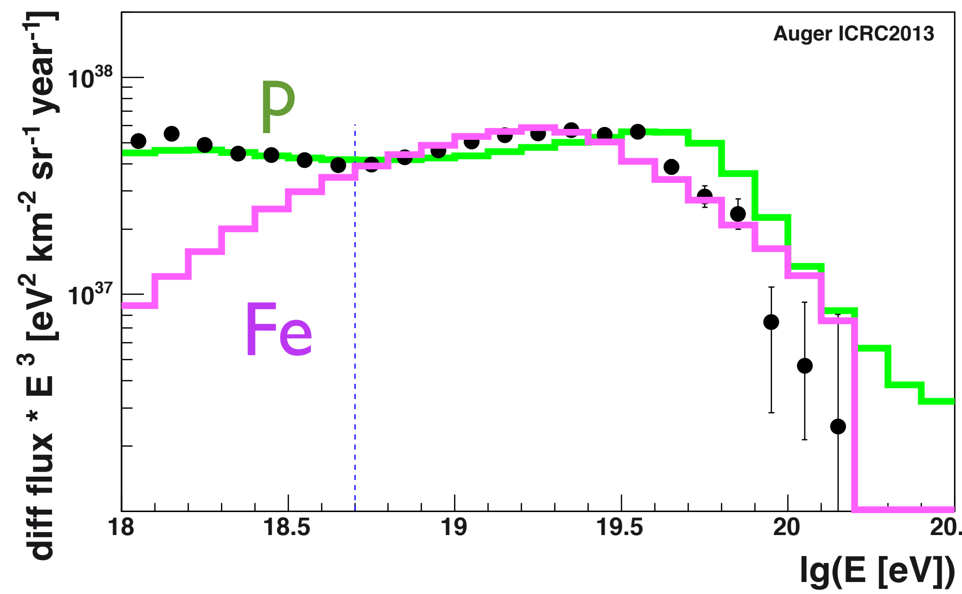


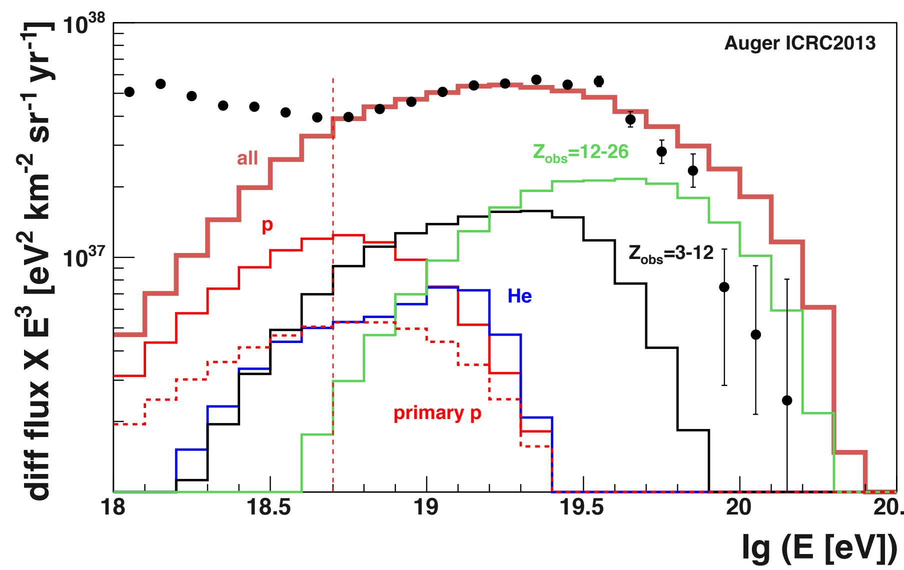
using post LHC interaction models:

Auger data show a smooth change to a heavier composition above 5 EeV

Composition compared with astrophys. scenarios







Limiting energy of sources combined with GZK describes composition data best

Implications of a heavy composition

Astroparticle Physics 39-40 (2012) 33-43
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart

ELSEVIER

Extragalactic propagation of ultrahigh energy cosmic-rays ☆

Denis Allard

Laboratoire Astroparticule et Cosmologie (APC), Université Paris 7/CNRS, 10 rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France

Astroparticle Physics 54, 48 (2014)
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart

ELSEVIER

UHECR composition models

Andrew M. Taylor *

ELSEV

On the

Dan Ho

uclei

...and many more papers of this type

all require very **hard injection spectra** unless a **nearby source** (population) is assumed

Frontiers

December 2013, volume 8, Issue 6, pp 748-758

Cosmic ray energy spectrum from measurements of air showers

T. K. Gaisser, T. Stanev, S. Tilav

cosmic rays:
implications of Auger data for source spectra and chemical composition

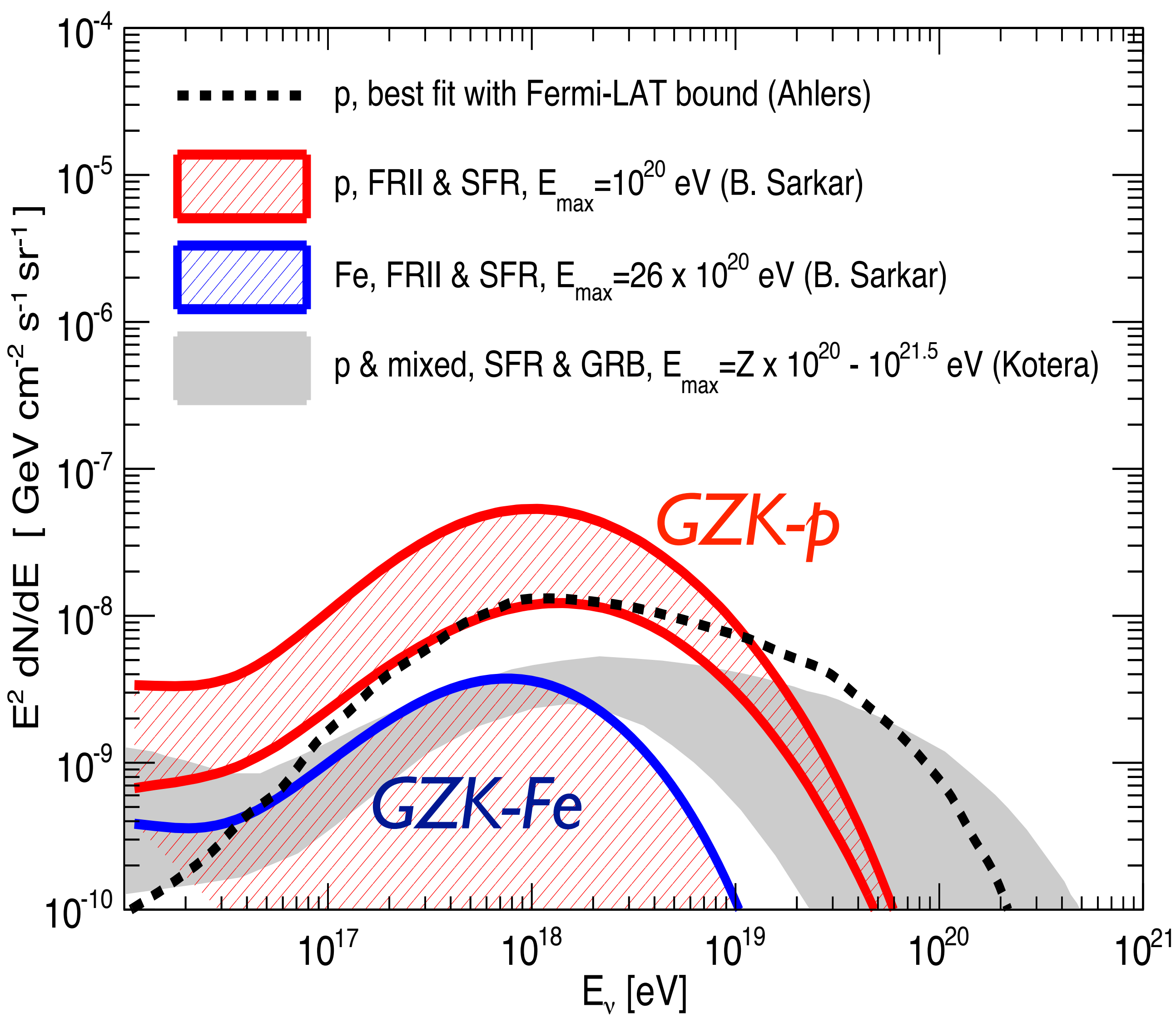
Subm. to JCAP 2013

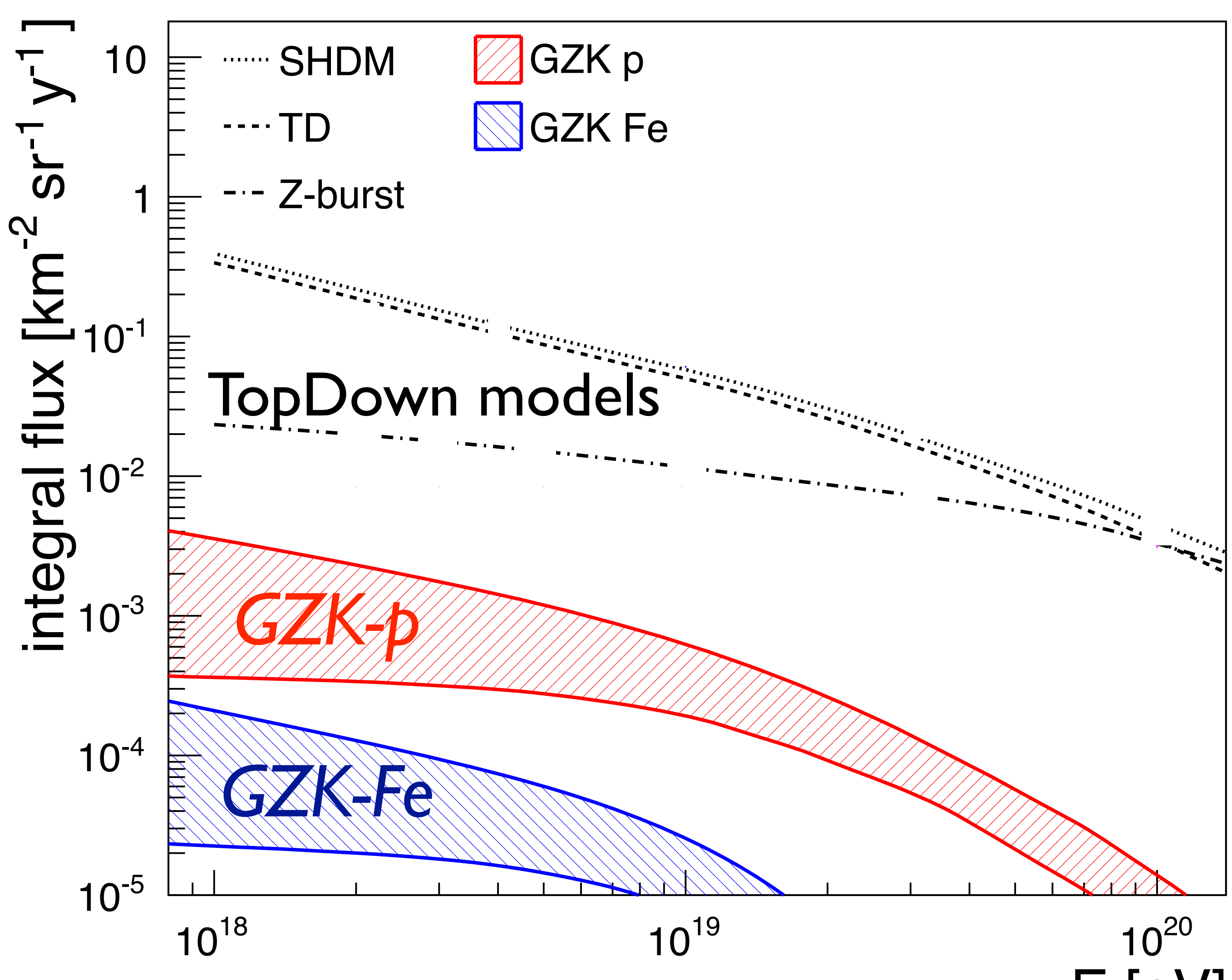
R. Aloisio[1,2], V. Berezinsky[2,3] and P. Blasi[1,2]

Cosmogenic Neutrinos and Photons
– a guaranteed signal in presence of GZK –

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow$$

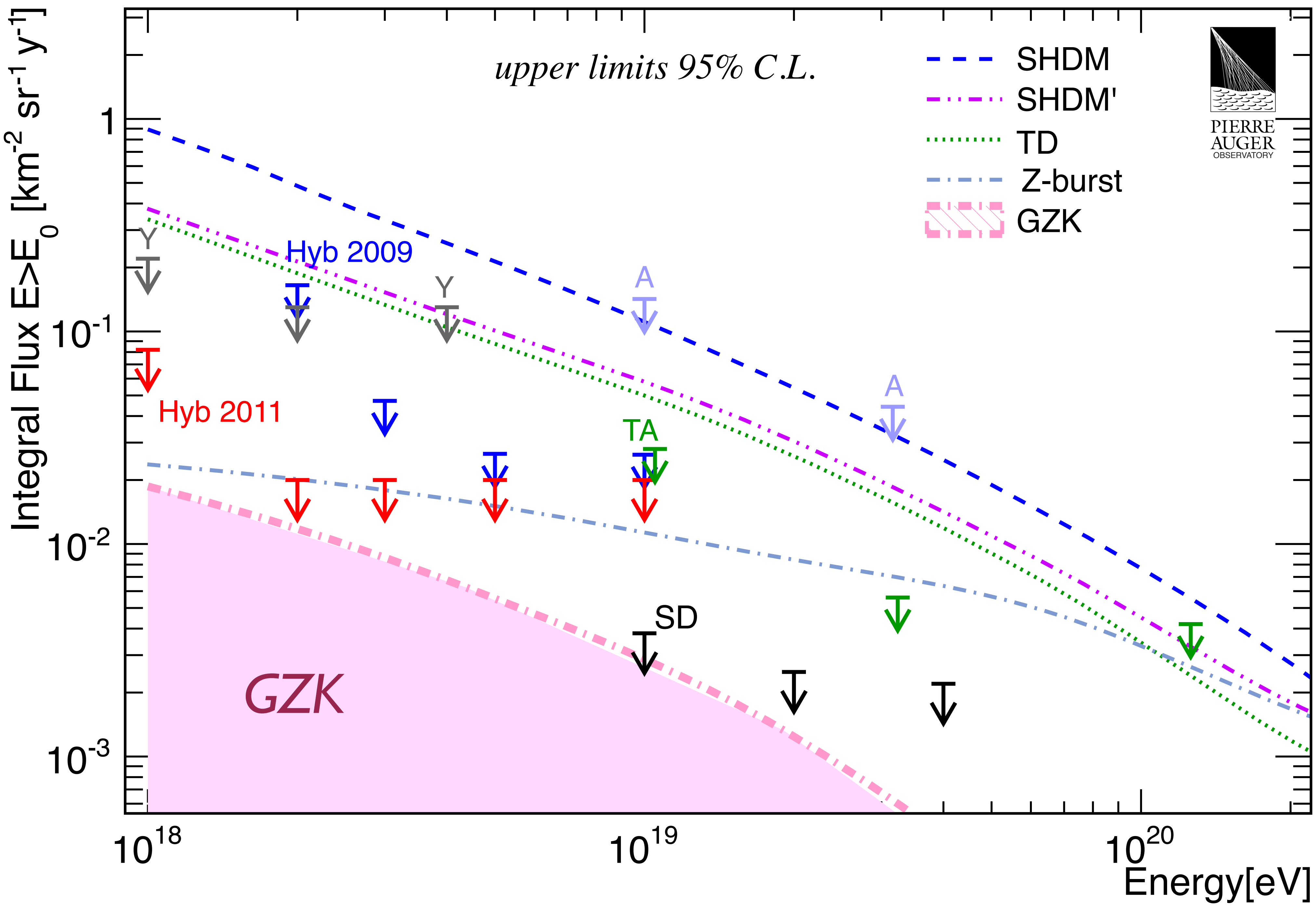
$$\rightarrow n + \pi^+ \rightarrow \nu_{\mathrm{EeV}} \qquad \rightarrow p + \pi^0 \rightarrow \gamma_{\mathrm{EeV}}$$





KHK, Unger, APP 35 (2012)

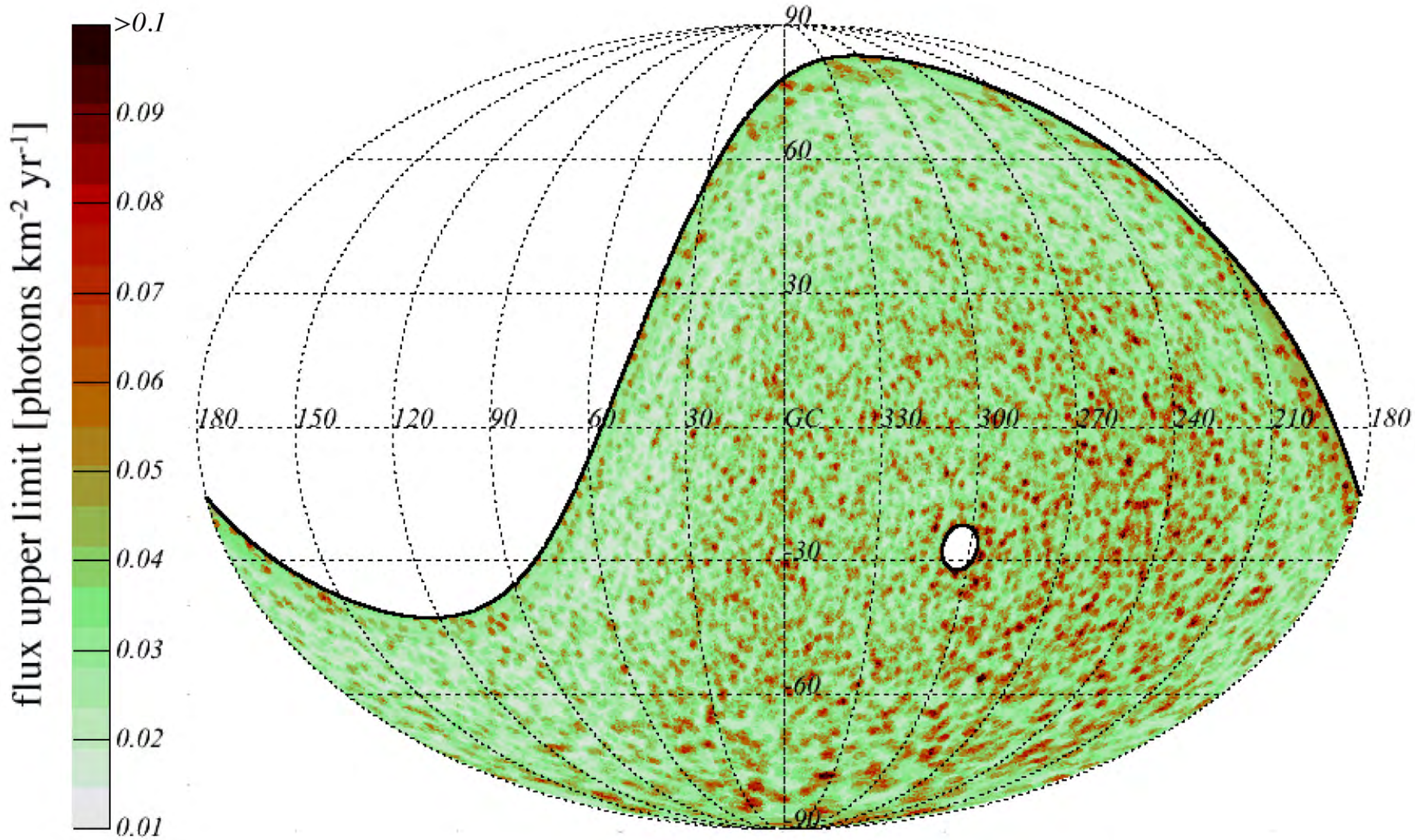
Diffuse Photon Limits

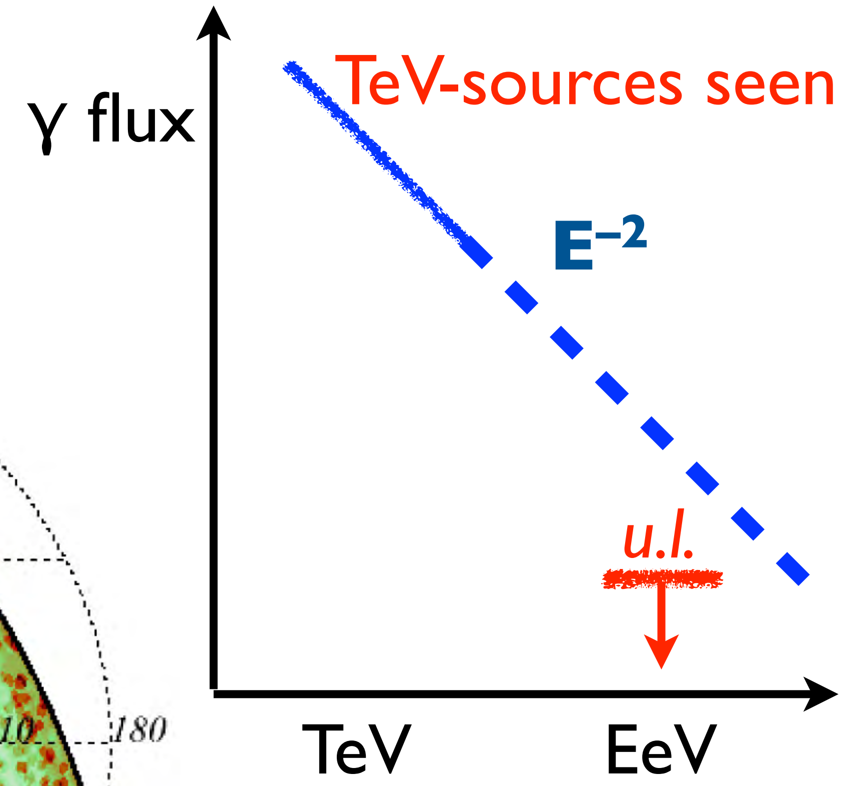


Photon upper limits rule out Top-Down Models and get close to expected GZK-fluxes

Directional Limits of EeV Photons

A&A in press

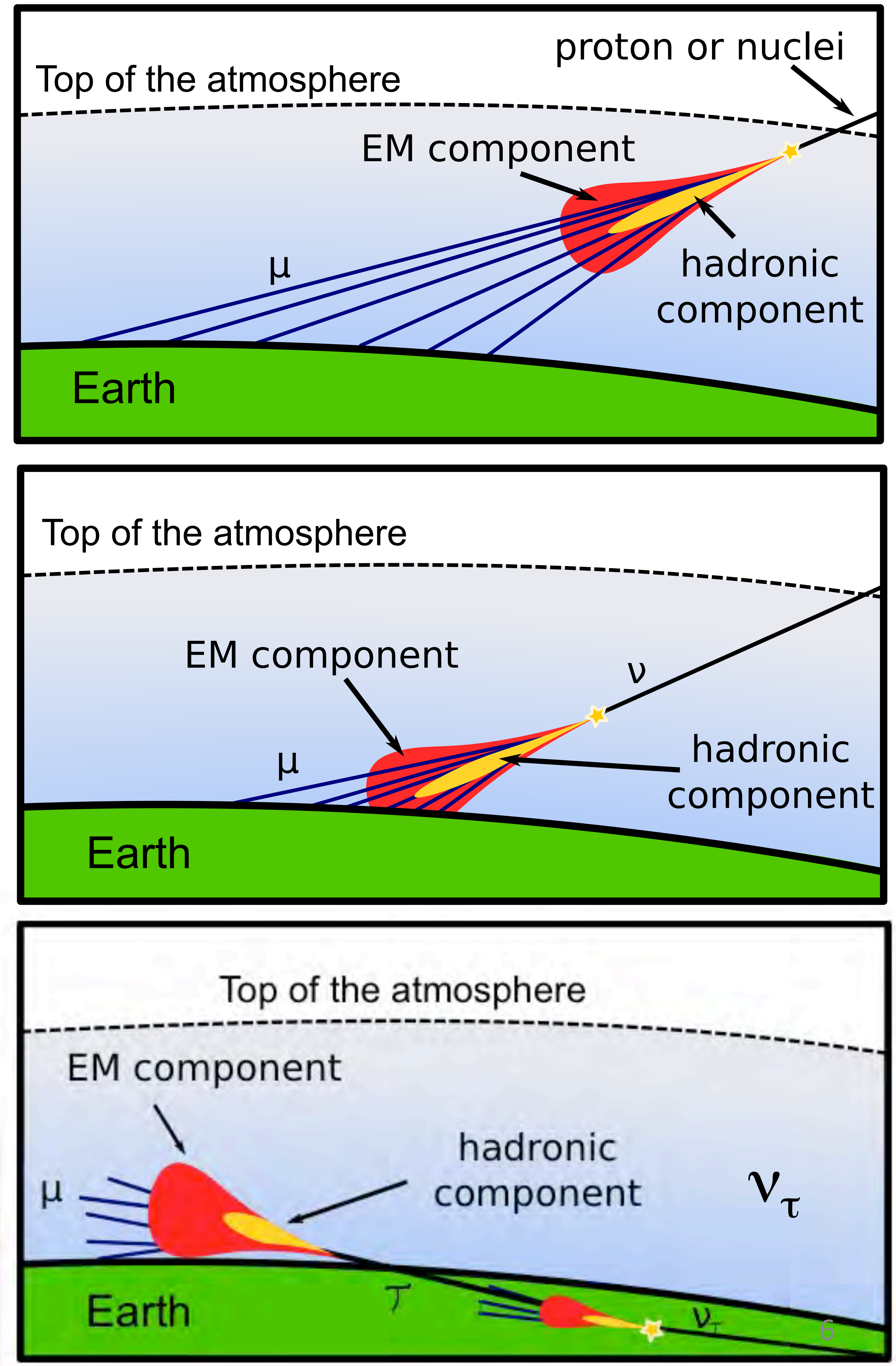




Energy flux of 0.25 eV/cm^{2}s would yield a 5σ excess (assuming E^{-2} spectr.)
Note, some Galactic TeV sources exceed 1 eV/cm^{2}s !

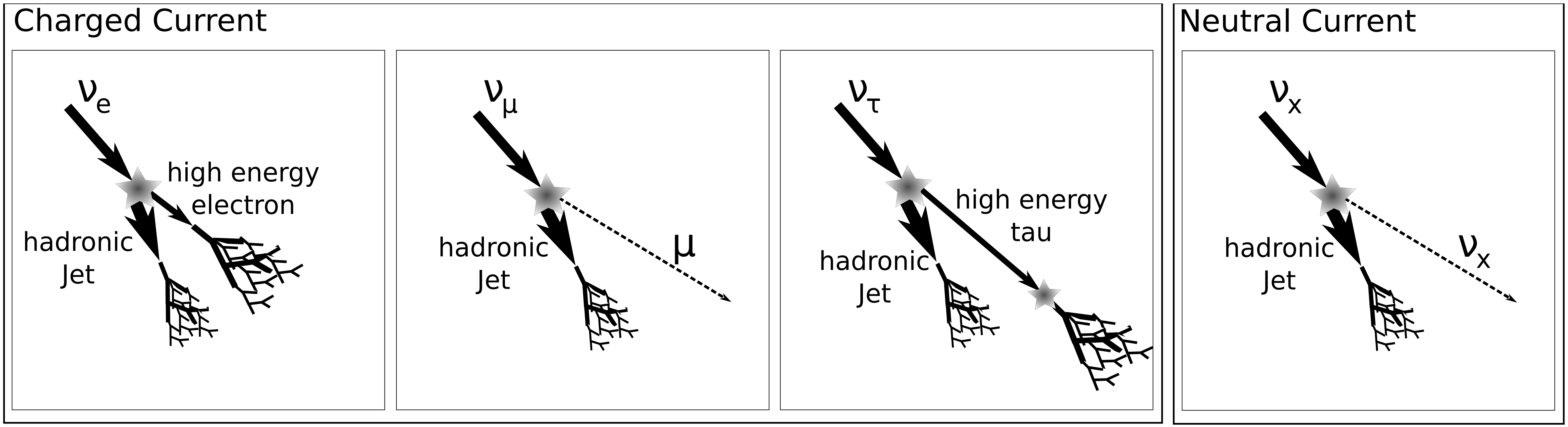
Inclined showers & UHE neutrinos

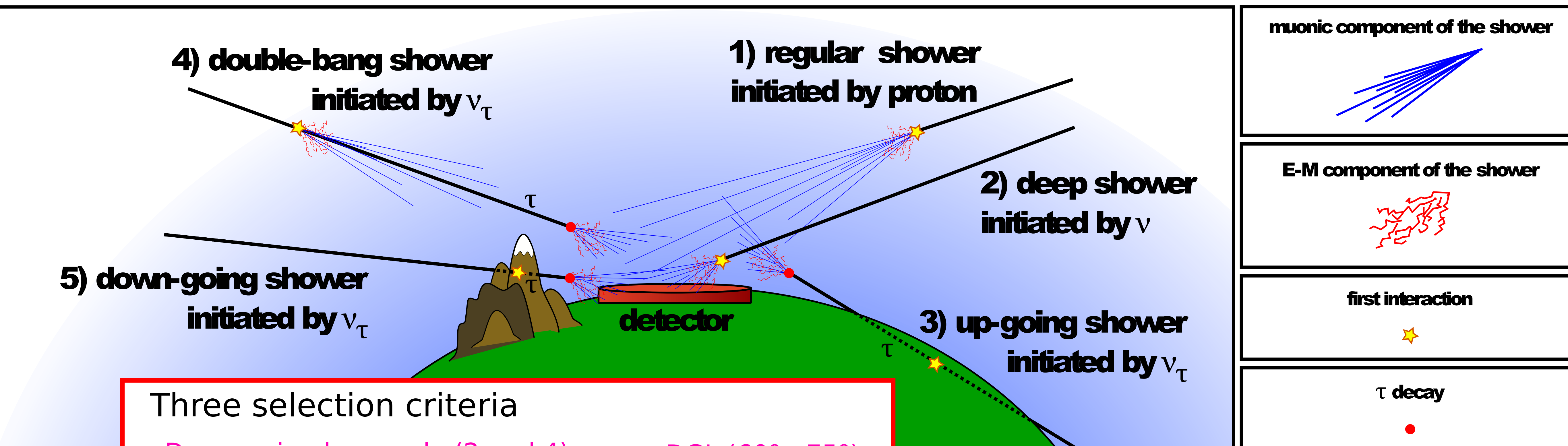
- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate “deep” showers close to ground.
  - Shower front at ground: electromagnetic + muonic components



Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

Sensitivity to all ν flavors and channels

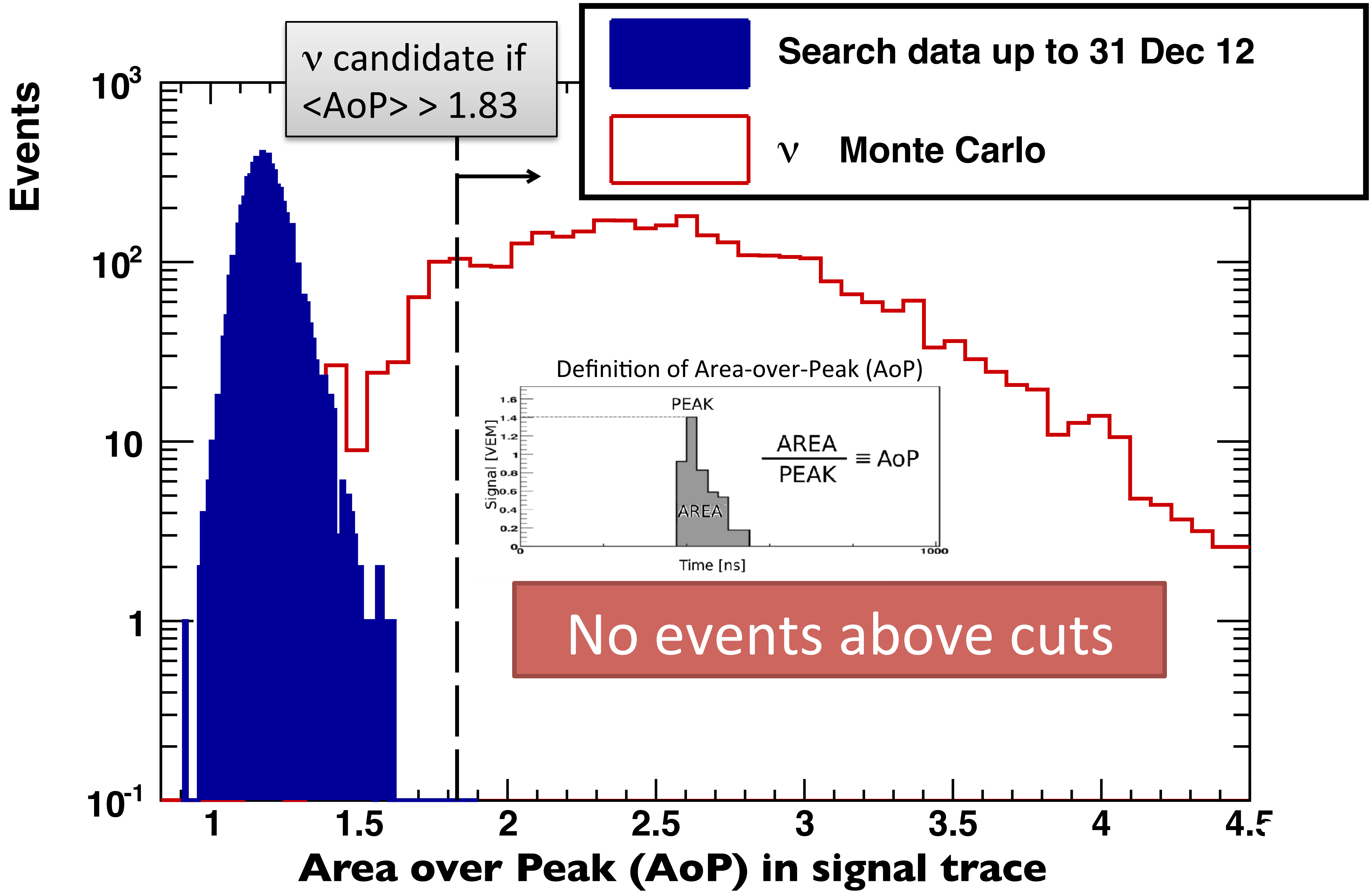




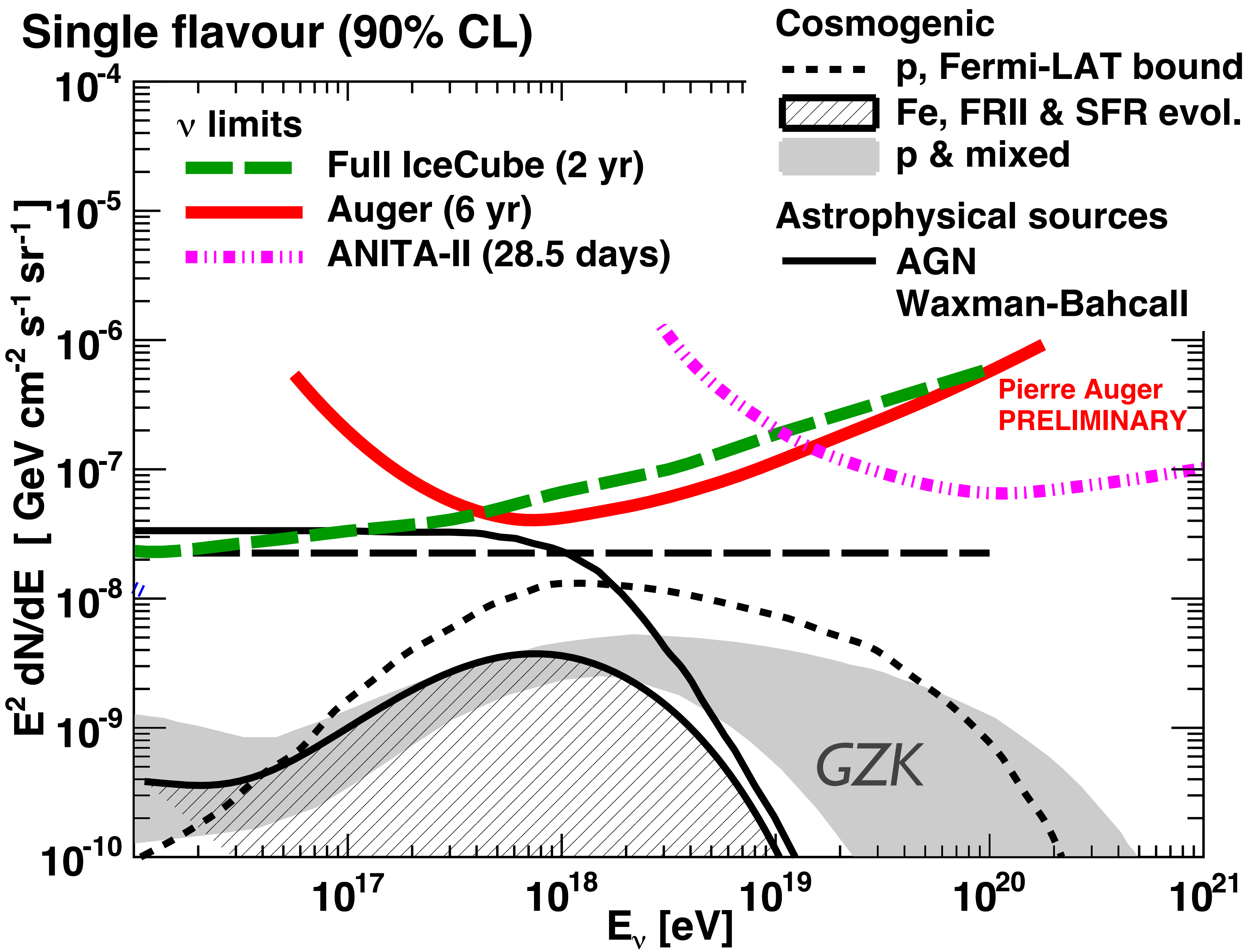
Three selection criteria

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)

ν identification: Earth Skimming



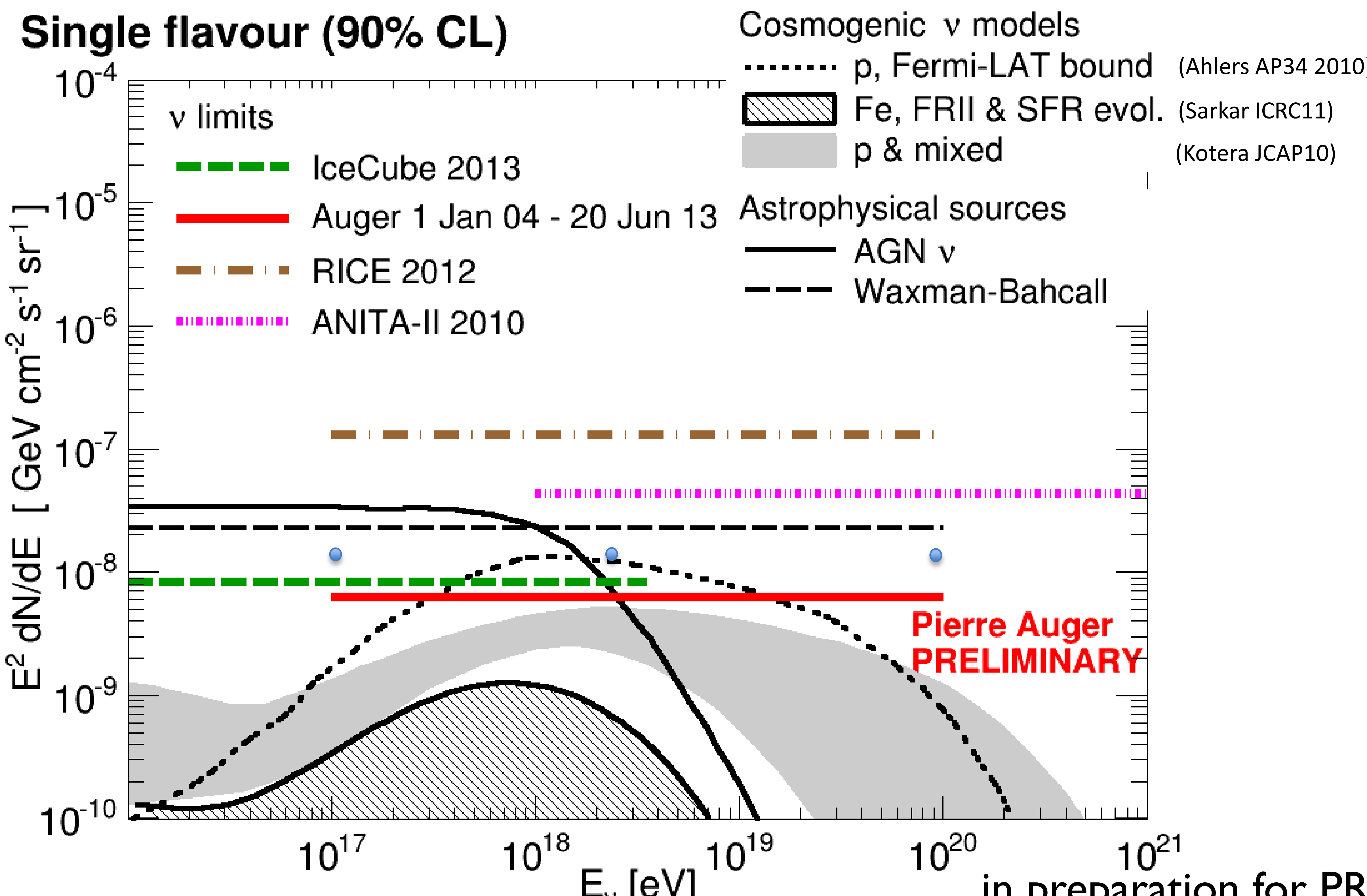
Differential diffuse ν flux limits



All limits converted to single flavour and given per half a decade of energy

in preparation for PRD

Integral diffuse ν flux limits

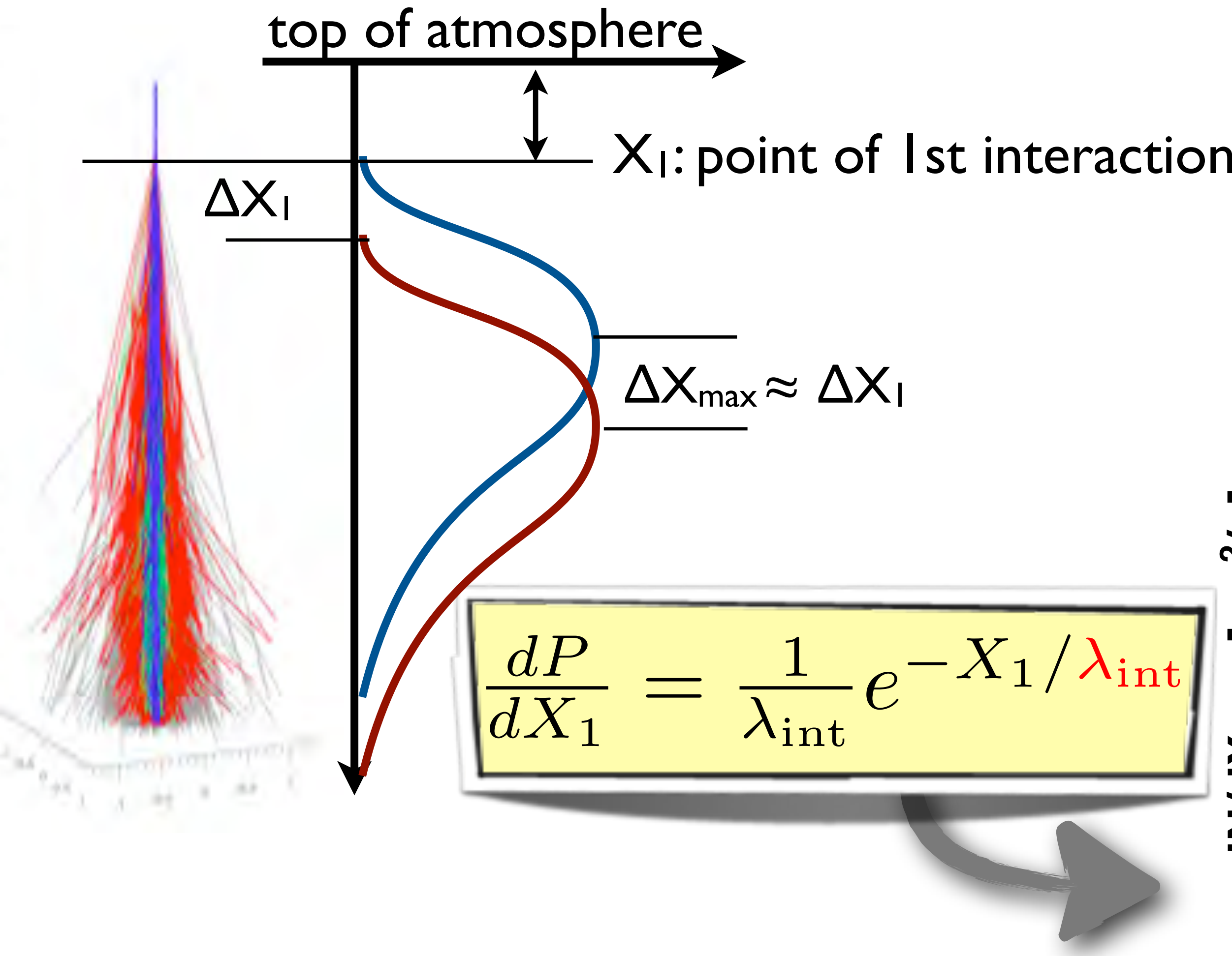


in preparation for PRD

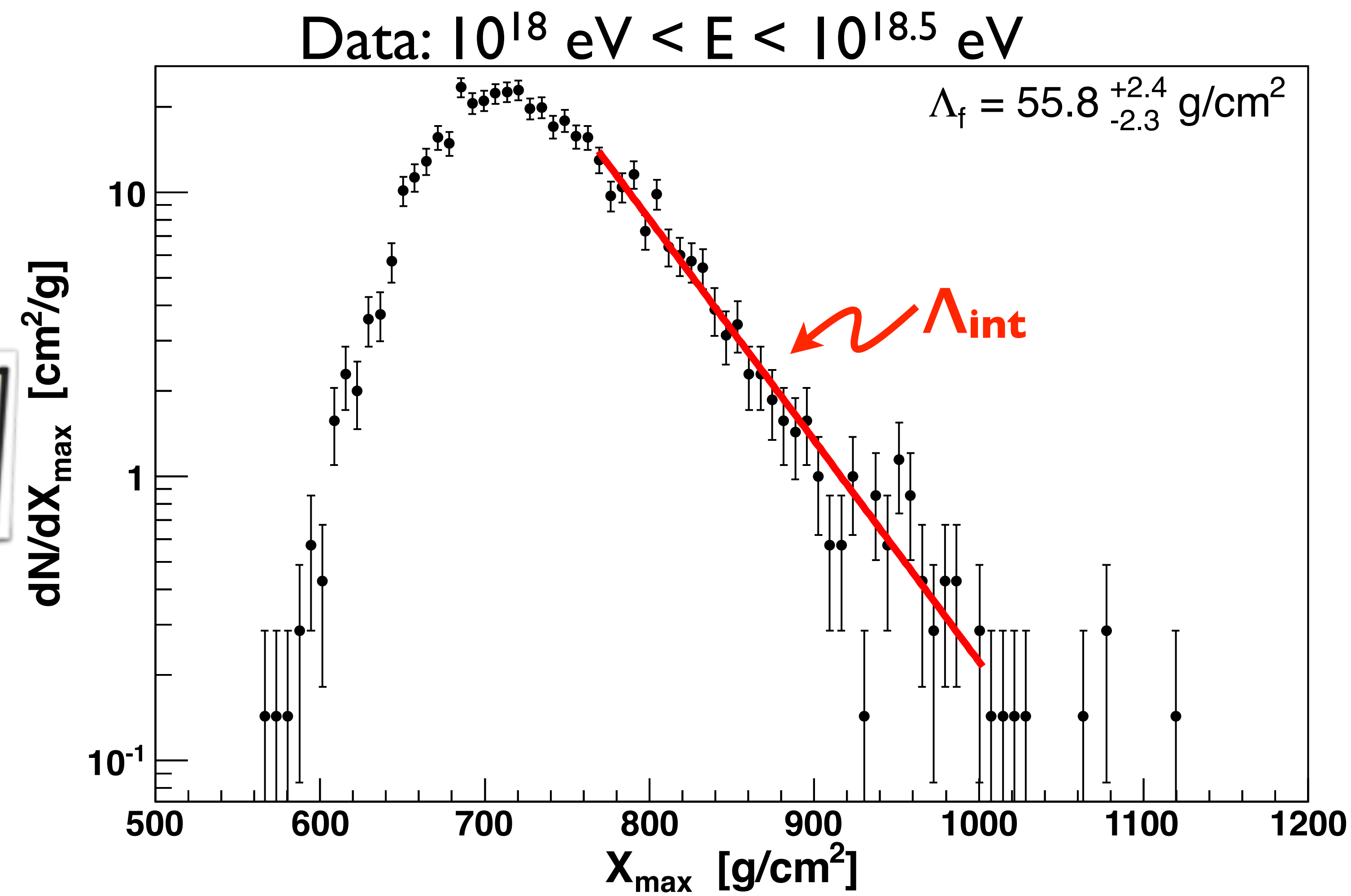
$dN/dE = k\,E^{-2} \longrightarrow k^{90} < 6.3 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} @ 90% C.L. [10^{17} eV < E < 10^{20} eV]

Testing Hadronic Interactions...

p-Air Cross-Section from X_{max} distribution



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$



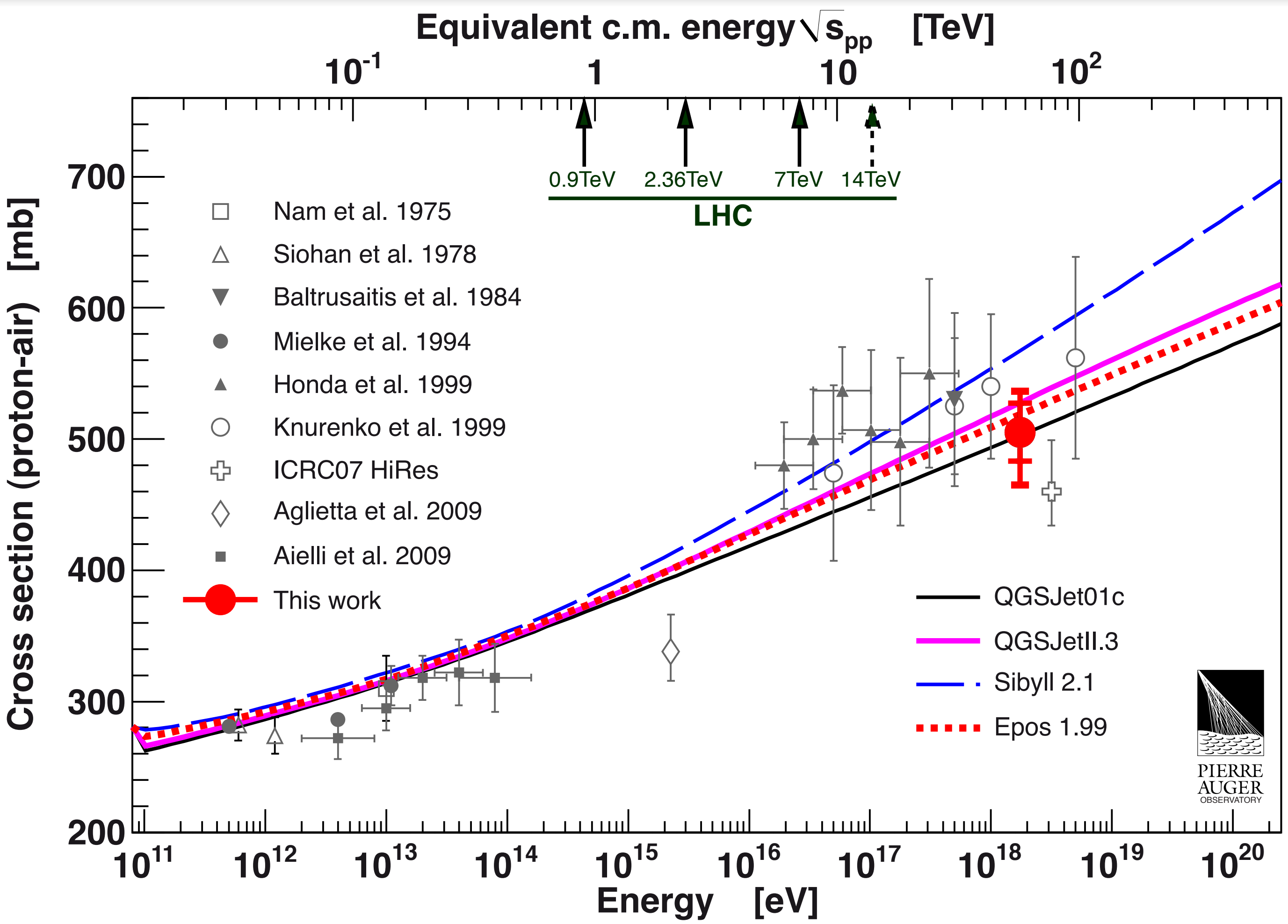
Difficulties:

- mass composition can alter Λ
- fluctuations in X_{max}
- experimental resolution ~ 20 g/cm²

$$\sigma_{p-Air} = \frac{\langle m_{Air} \rangle}{\lambda_{int}}$$

In practice: $\sigma_{p\text{-}Air}$ by tuning models to describe Λ seen in data

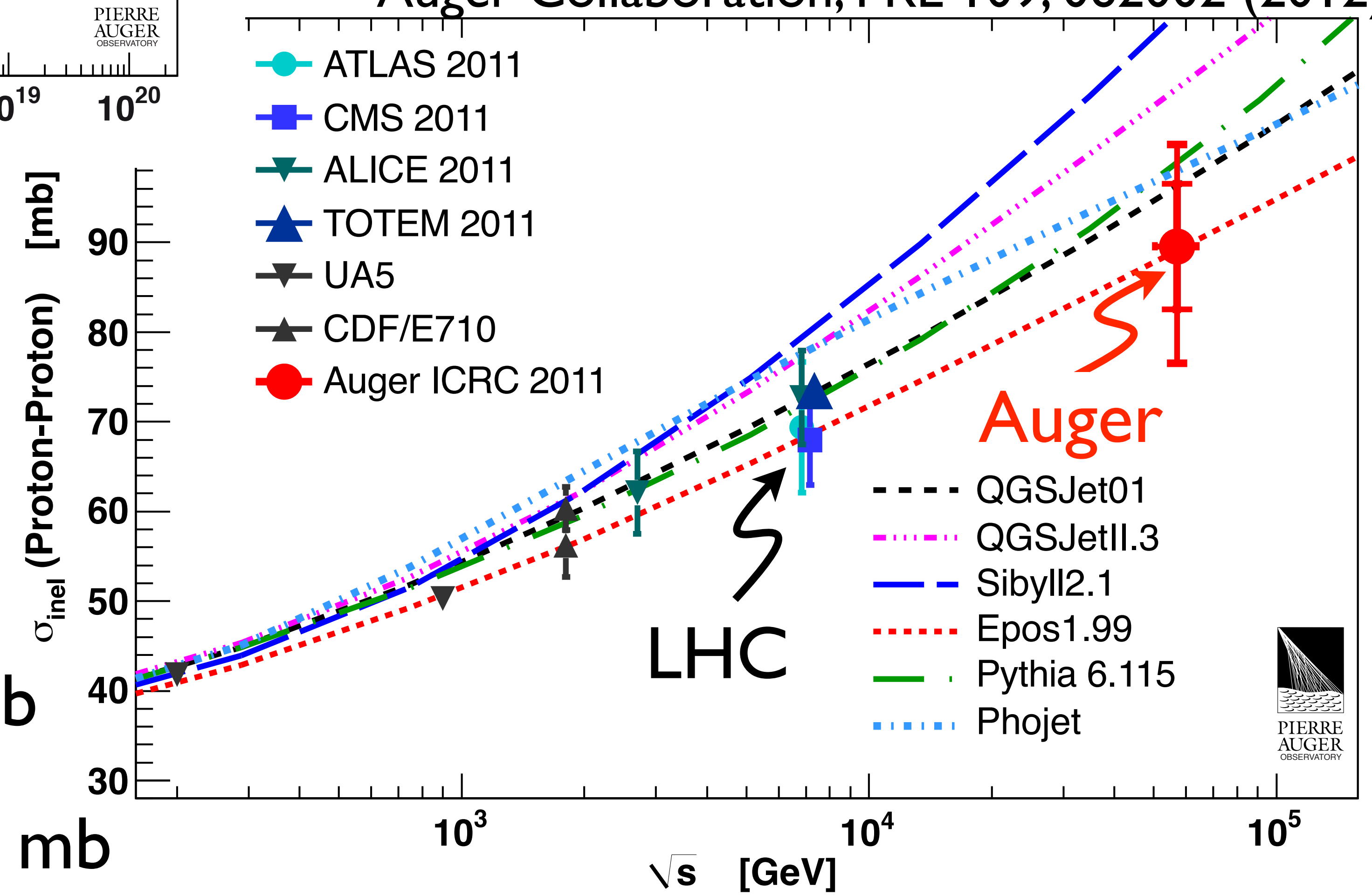
p-Air and pp Cross section @ √s=57 TeV



Conversion from p-air to p-p cross section by Glauber-approach

$$\sigma^{prod}_{p\text{-}Air} = (505 \pm 22_{stat}\, (^{+26}_{-34})_{sys}\,)\ \text{mb}$$

Auger Collaboration, PRL 109, 062002 (2012)



$$\sigma^{inel}_{pp} = [92 \pm 7_{stat}\, (^{+9}_{-11})_{sys} \pm 7.0_{Glauber}]\ \text{mb}$$

$$\sigma^{tot}_{pp} = [133 \pm 13_{stat}\, (^{+17}_{-20})_{sys} \pm 16_{Glauber}]\ \text{mb}$$

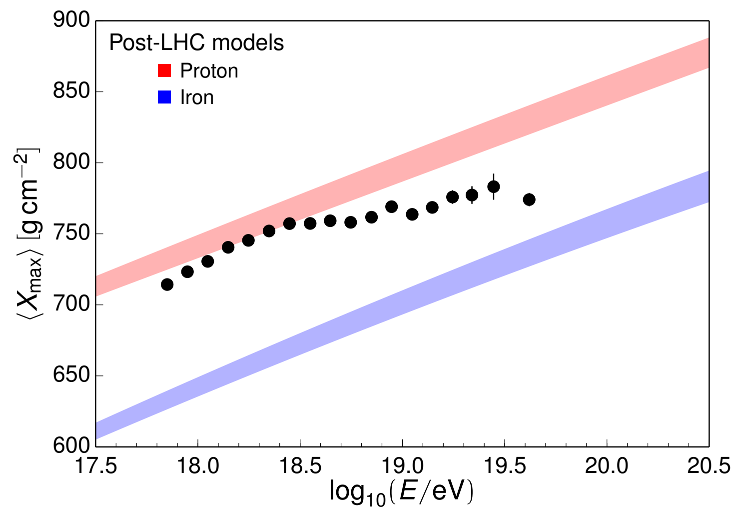
Some Speculation...

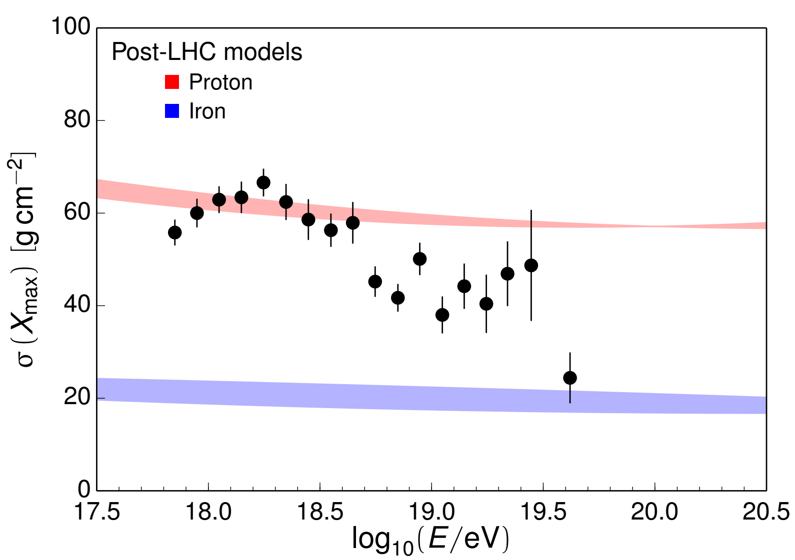
Could protons dominate up to the highest energy ?

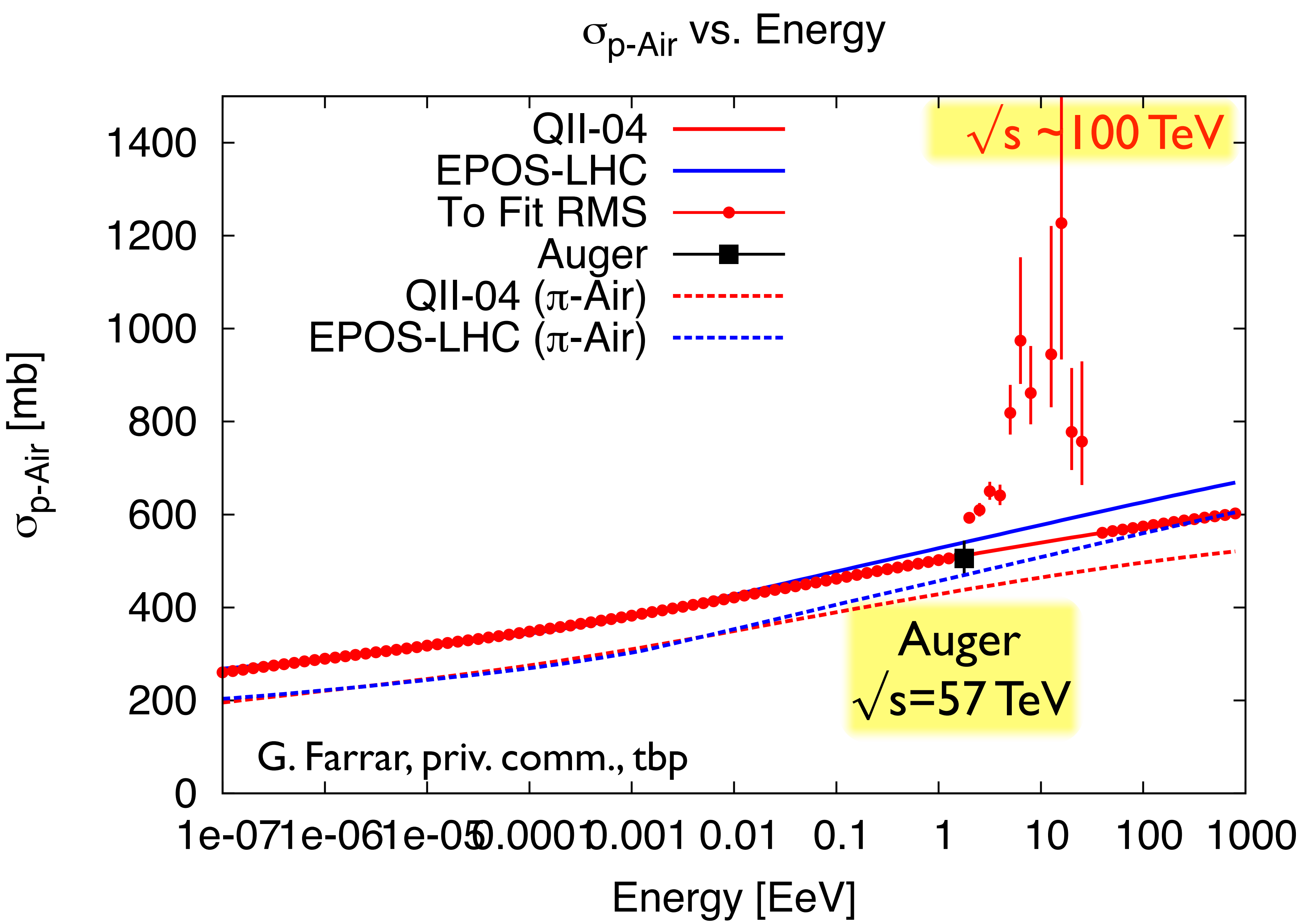
⇩

Something would need to be wrong with the hadronic interaction models ....

X_{max} and RMS(X_{max}) could be described by protons with a rapidly rising cross section above $\sqrt{s}$~60 TeV

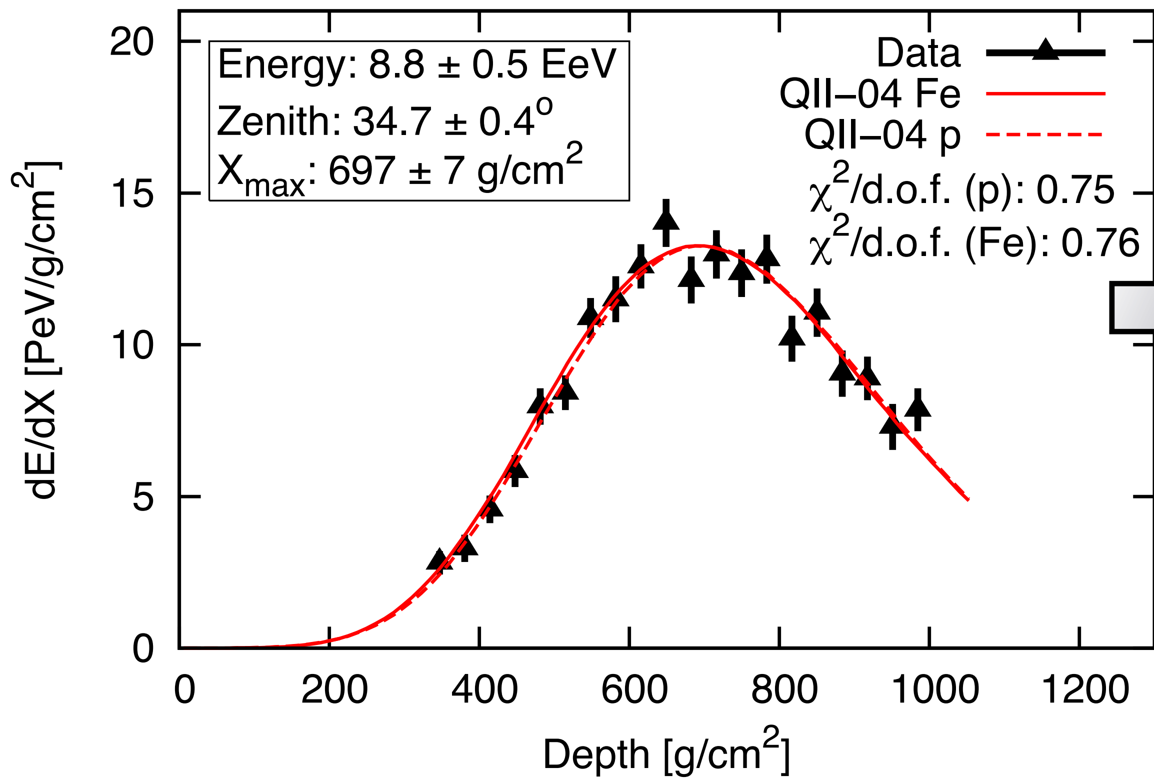






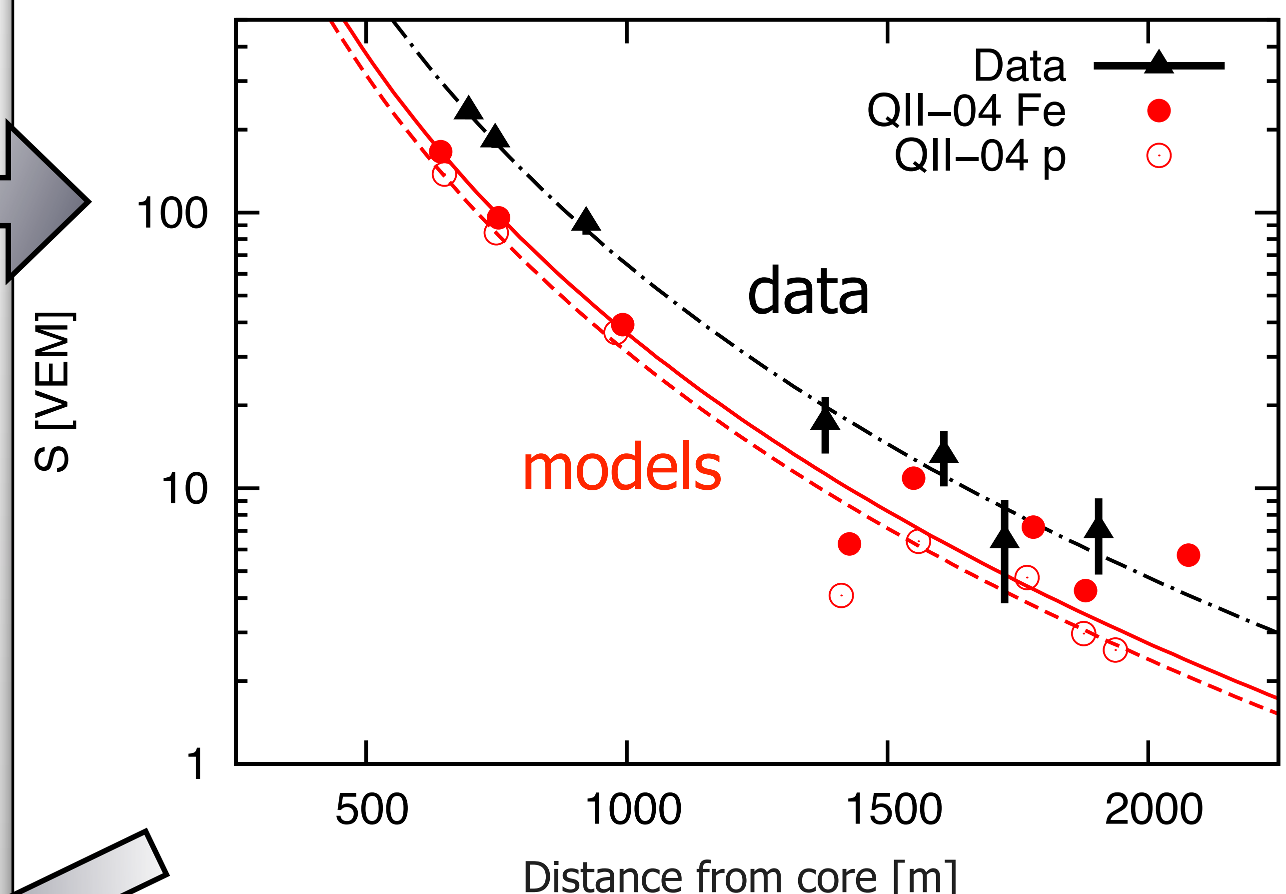
Interaction Models underestimate Muon-numbers

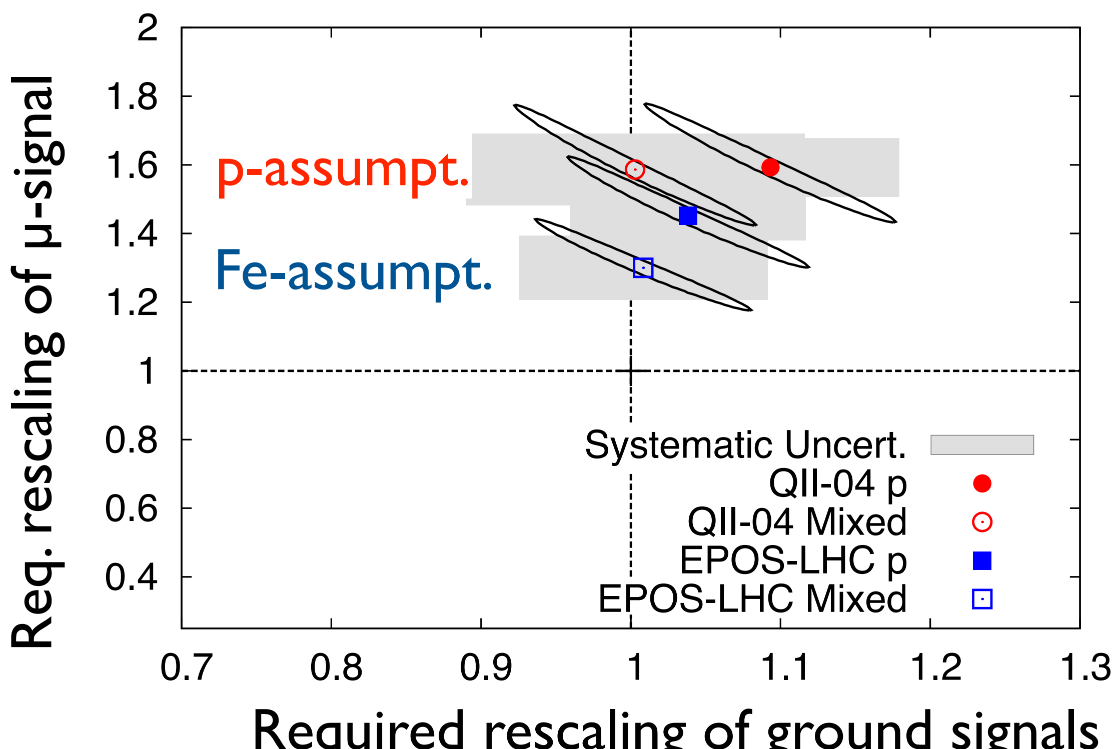
Measured event
with **matching p and Fe-simulations**



2 papers submitted to PRD

Same measured Event
with **predicted signals for p and Fe**





Models underestimate μ-content of EAS by 30-60%

independent tests e.g. using shower universality yield the same results

Major Achievements in the first 6 years of operation

- Clear observation of flux suppression
- Strongest existing bounds on EeV ν and γ
- Strongest existing bounds on large scale anisotropies
- First hints on directional correlations to nearby matter
- Increasingly heavier composition above ankle
- pp cross section at ~10*E_{LHC}, LIV-bounds, ...
- muon deficit in models at highest energies
- geophysics (elves, solar physics, aerosols...)

Science Goals of Auger Upgrade

1. **Elucidate the origin of the flux suppression, i.e. GZK vs. maximum energy scenario**
   - fundamental constraints on UHECR sources
   - galactic vs extragalactic origin
   - reliable prediction of GZK ν- and -γ fluxes

2. **Search for a flux contribution of protons up to the highest energies at a level of ~ 10%**
   - proton astronomy up to highest energies
   - prospects of future UHECR experiments

3. **Study of extensive air showers and hadronic multiparticle production above √s=70 TeV**
   - particle physics beyond man-made accelerators
   - derivation of constraints on new physics phenomena

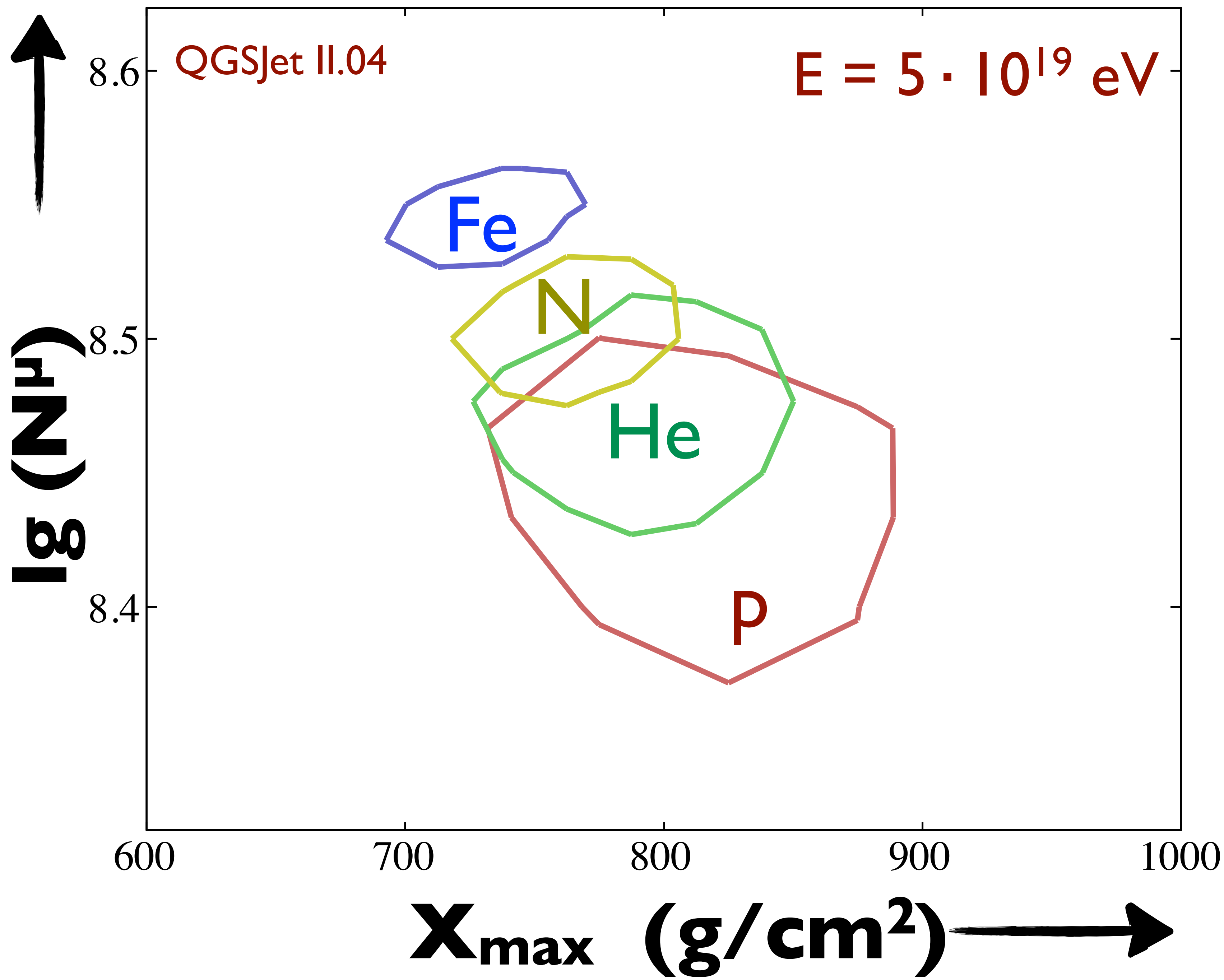
measure composition into flux suppression region...

... and do so event-by-event → composition enhanced anisotropies

do good muon counting

improve muon counting in surface detector array:
factor of 10 in event statistics

N^{μ}_{max} vs X_{max}



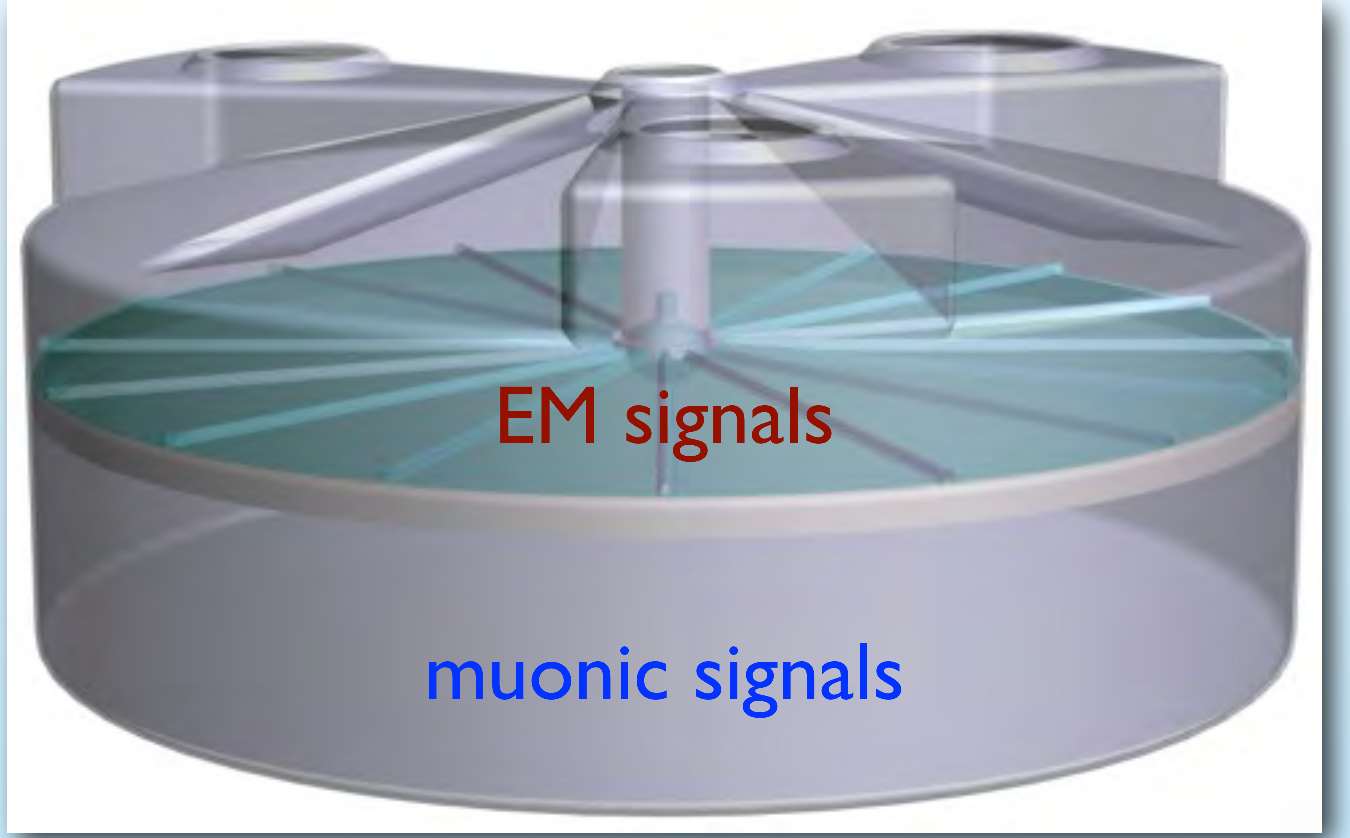
Muons may even outperform X_{max} at highest energies !

Two Upgrade Options under Study

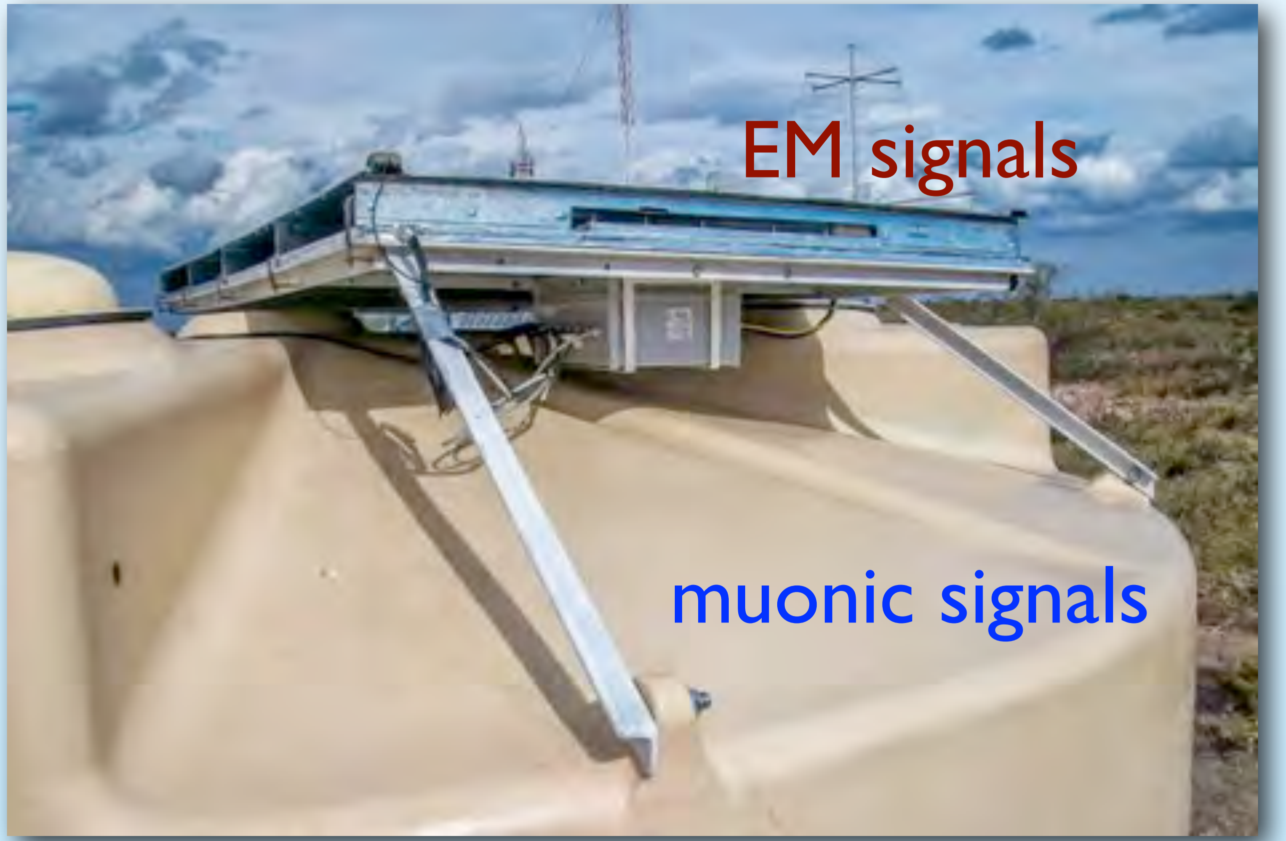
Improve on em/mu separation in EAS over full Array

Two different realisations for a full array upgrade under test in the field

- segmented tank

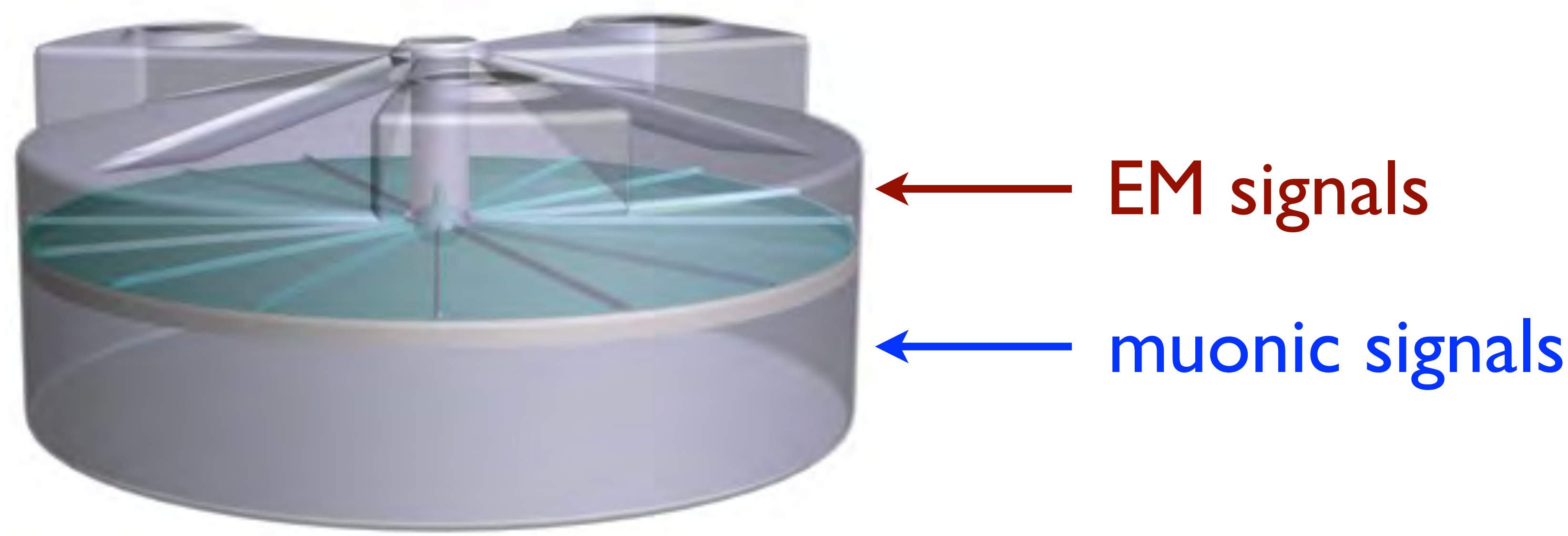


- scintillators on top

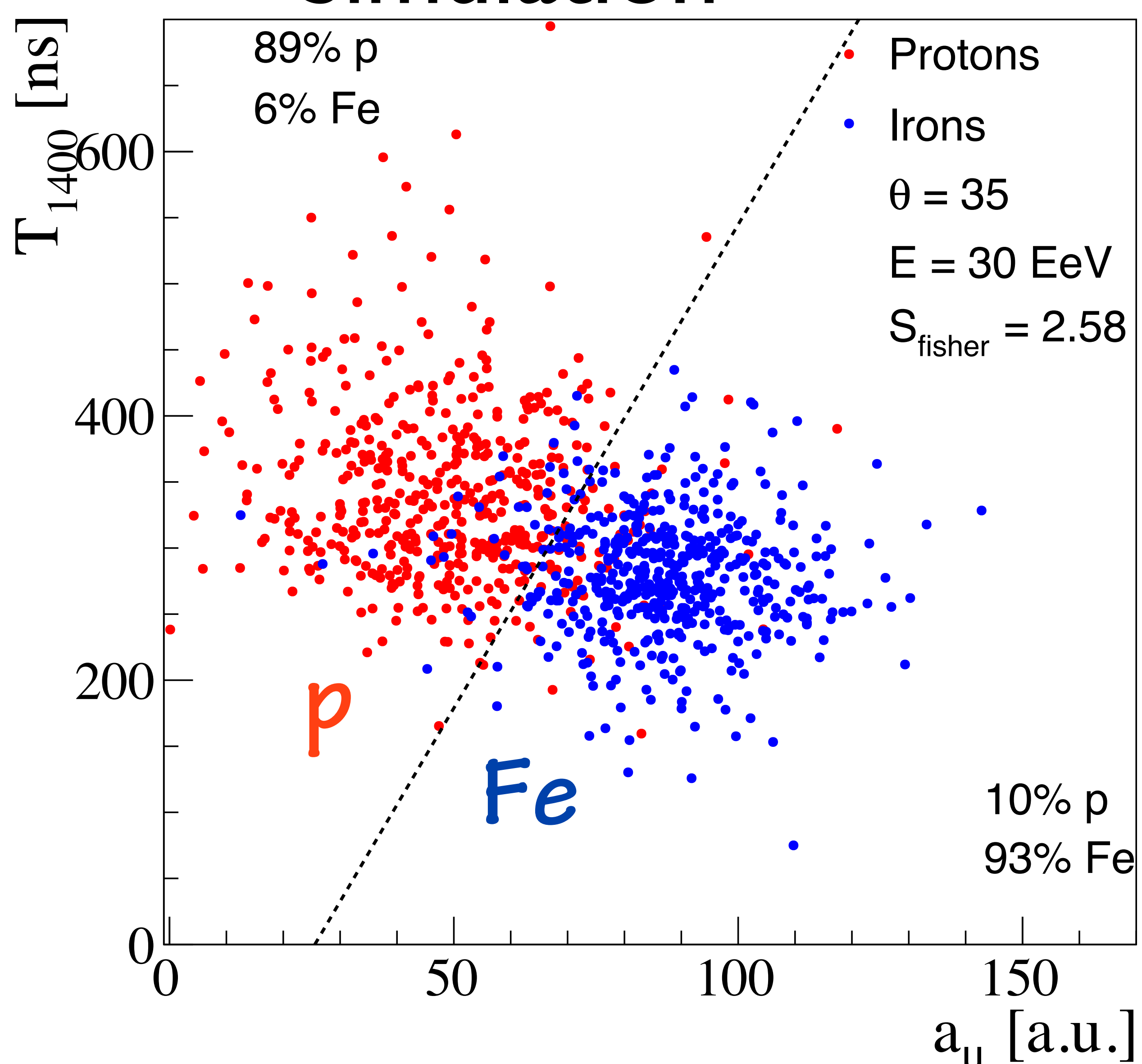


Final Selection will be done in November based on performance, reliability, readiness, cost, risk

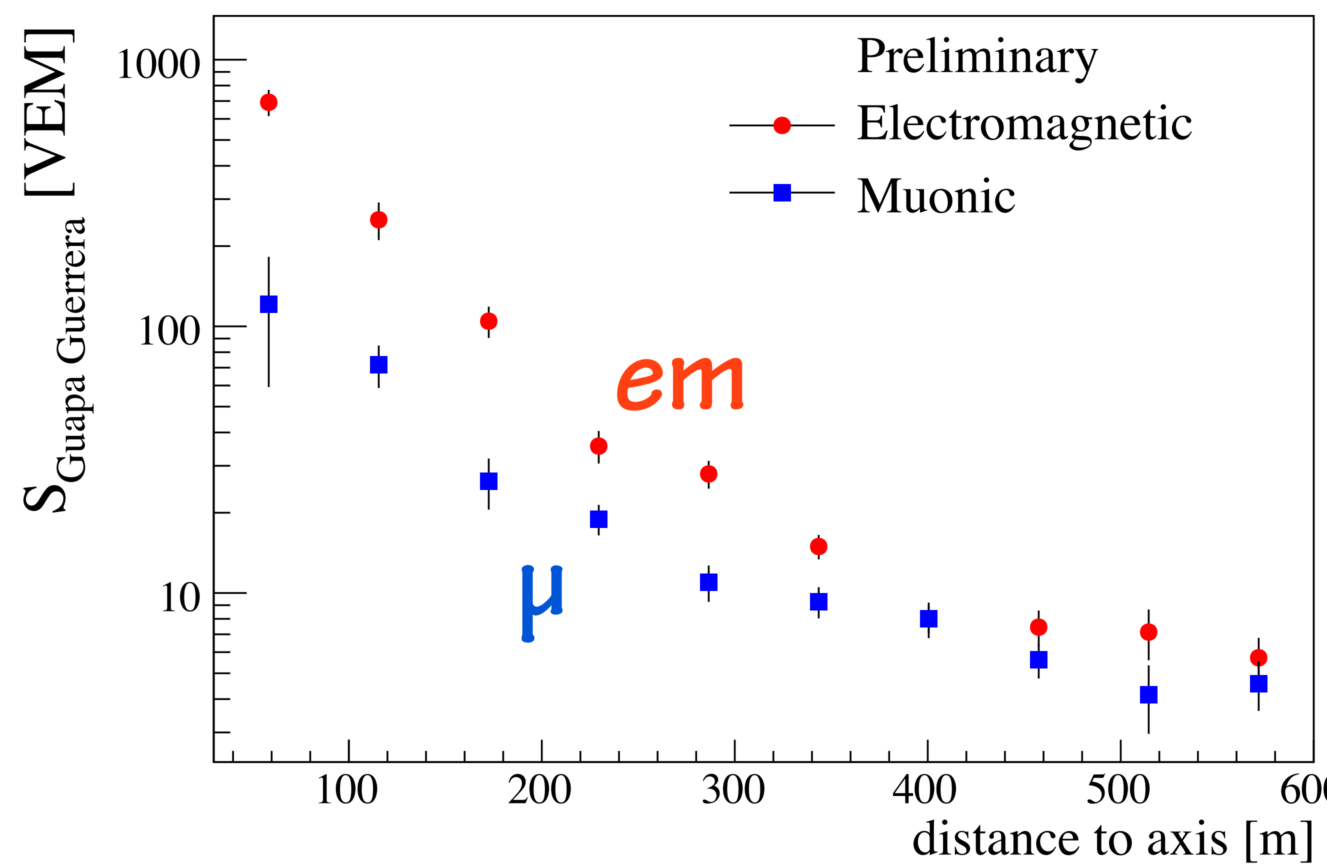
LSD (segmented tanks)



Simulation



Data from prototype



UHECR

Boost in understanding UHECRs

Auger data ➙ change of paradigm at GZK energies:
seem to see maximum energy of cosmic accelerator(s)

Precise data and modelling required!

UHECR ⇔ LHC: mutual benefits

The True High-Energy Frontier of Physics

most stringent tests on LIV, Space-Time Structure...

Upgrades of present observatories
and
Preparation for Next Generation Observatories in Space and at Ground