# Neutrinos and Cosmic rays at the Highest Energies

Charles Timmermans and Sijbrand de Jong

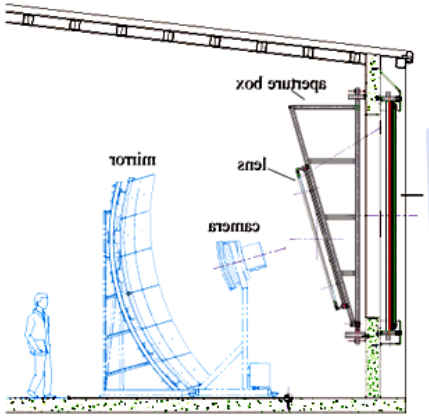
# Charged Cosmic Rays – The Basics

State-of-the-art: **FD**

Energy, direction & **particle type**

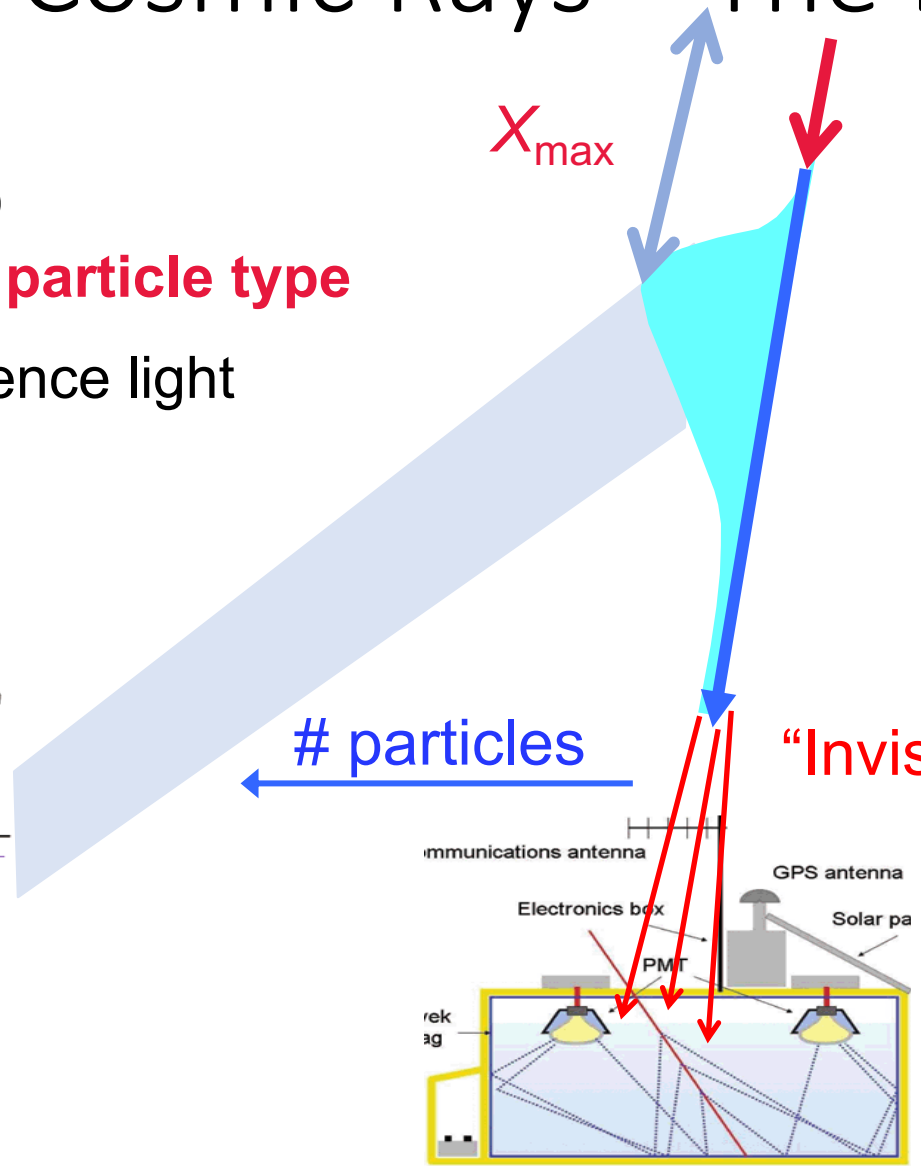
$X_{max}$ using fluorescence light

**$\sigma(X_{max})$ = 20 g/cm$^2$**



Only in dark nights

**10% duty cycle**



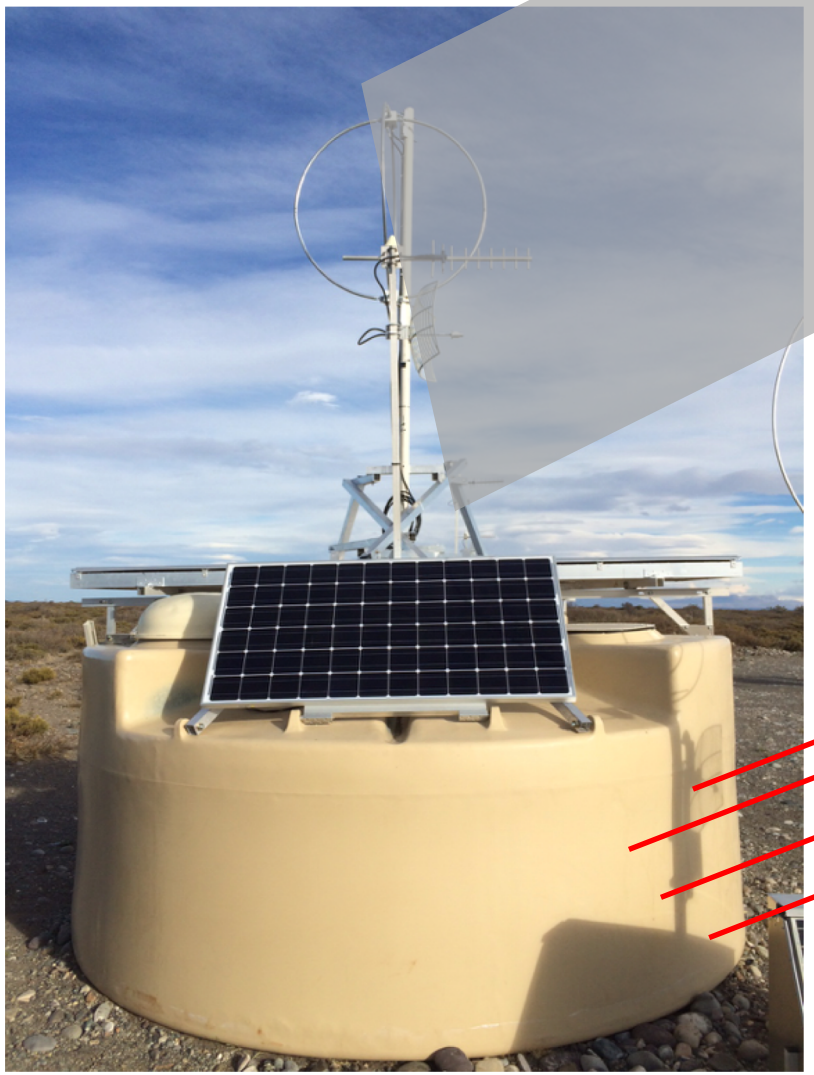

The FD measures the "visible" energy, ie energy converted in EM particles in the atmosphere.
The "invisible" energy is estimated from simulations

Particle type: $X_{max}$ = proportional to ln(A)
The fluctuations in $X_{max}$ provide an additional handle

Energy & direction

**100% duty cycle**

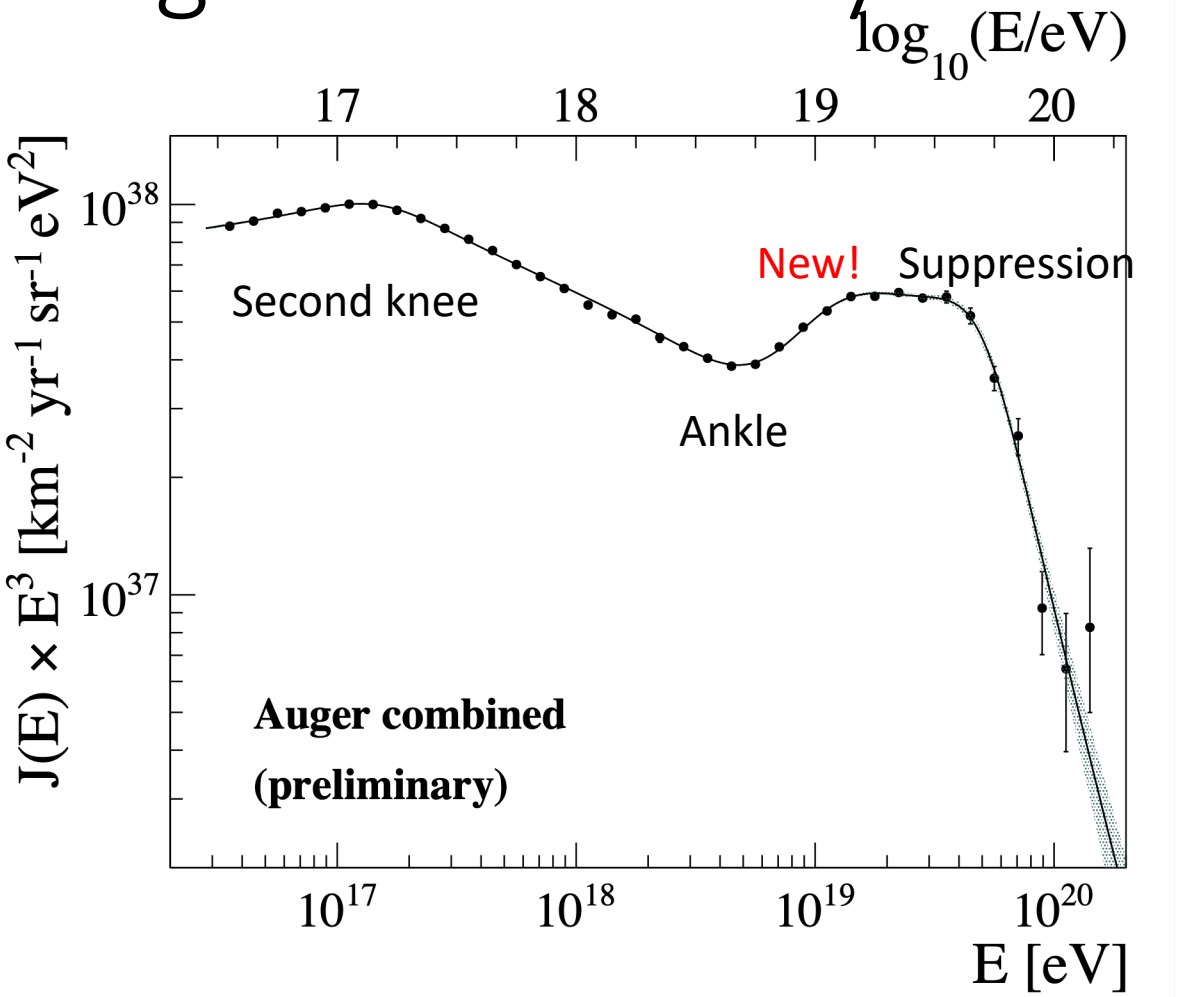
# Auger Upgrade – Radio Detection



Shower energy (EM particles)

Muons in the tail of the shower

# Charged Cosmic Rays – the Energy Spectrum

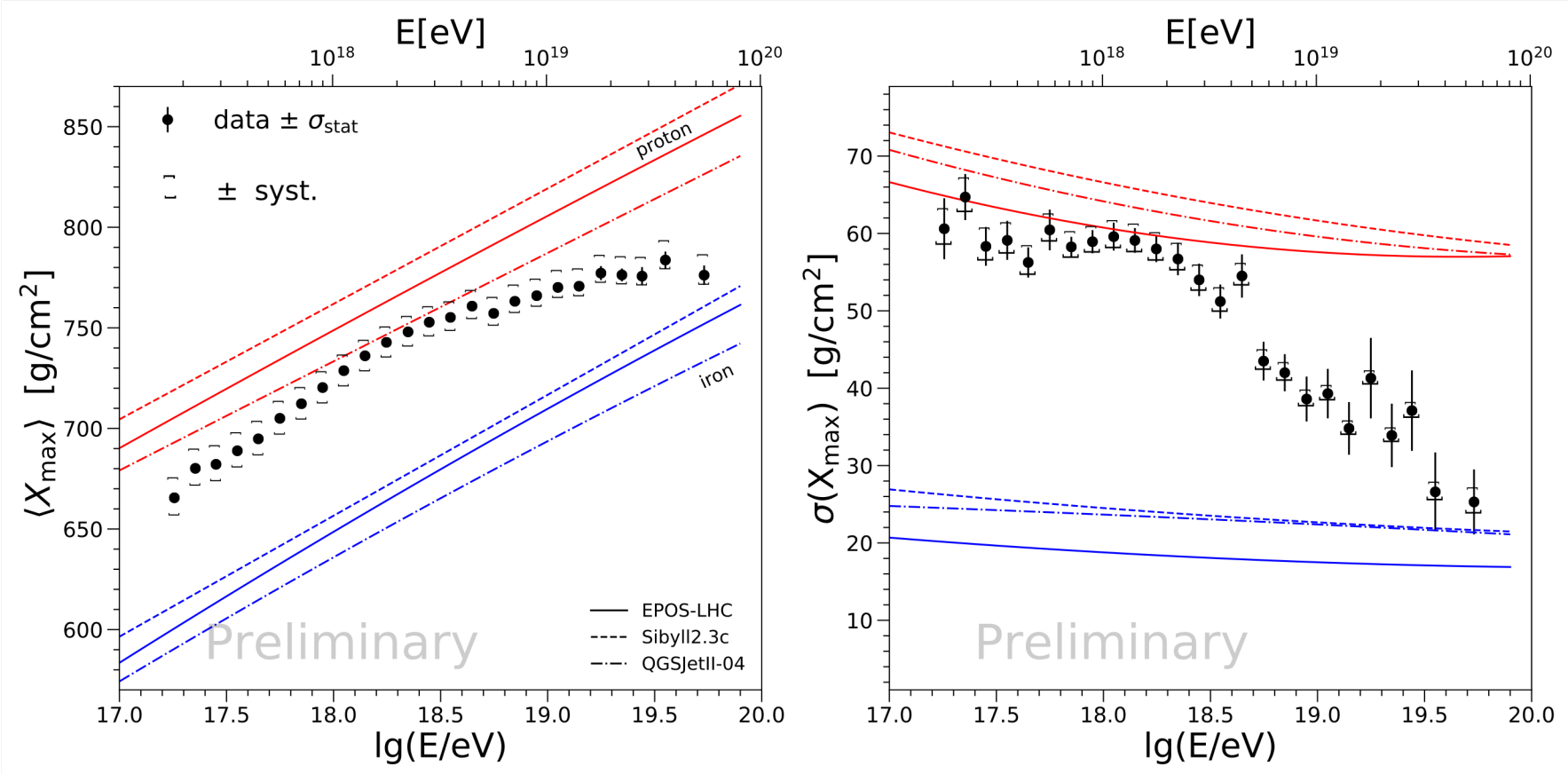



The energy spectrum is not simple!
More data required an elaborate description of the end of the spectrum.

$$J_{01234} \propto E^{-\gamma_0} \frac{1+(E/E_{01})^{\gamma_0}}{1+(E/E_{01})^{\gamma_1}} \frac{1+(E/E_{12})^{\gamma_1}}{1+(E/E_{12})^{\gamma_2}} \frac{1+(E/E_{23})^{\gamma_2}}{1+(E/E_{23})^{\gamma_3}} \frac{1+(E/E_{34})^{\gamma_3}}{1+(E/E_{34})^{\gamma_4}}$$

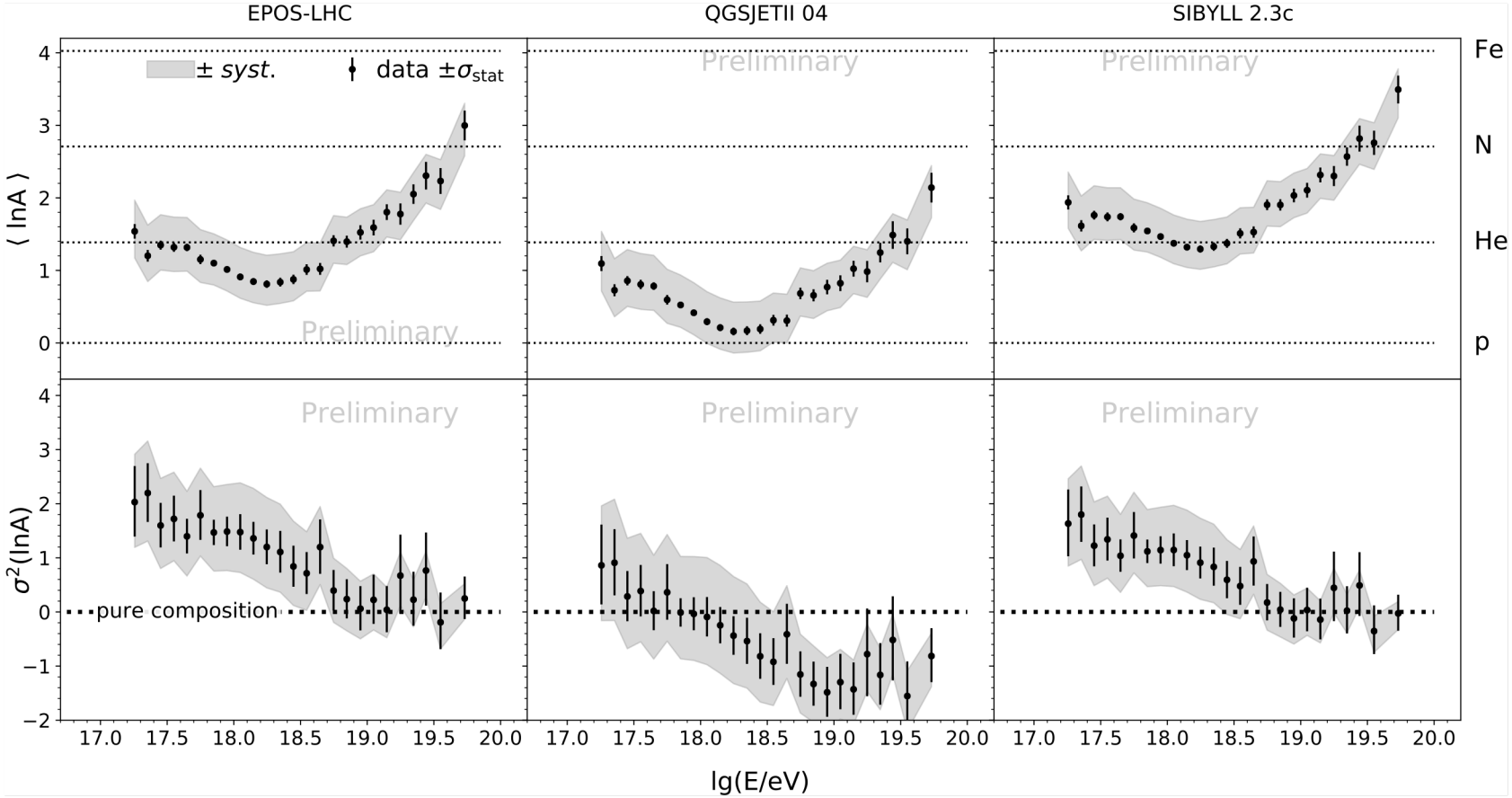
PoS(ICRC2019),450(2019)

# Charged Cosmic Rays – The Composition



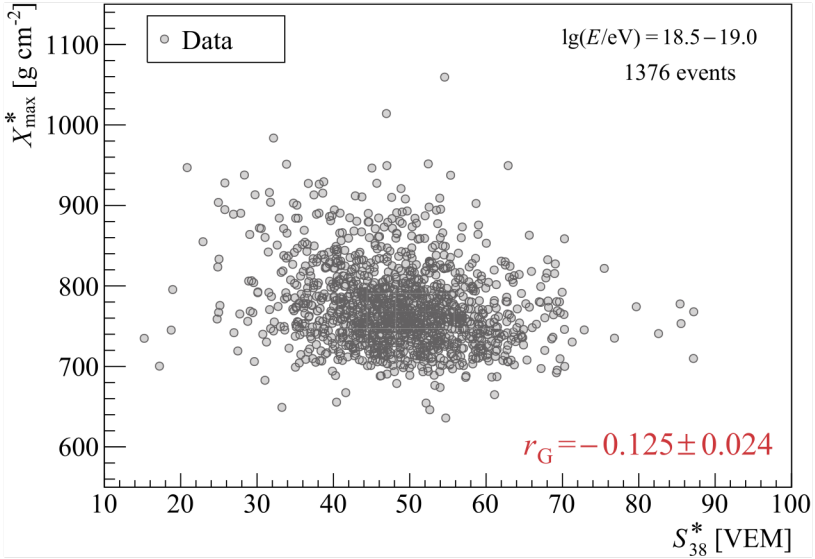

PoS(ICRC2019),482(2019)

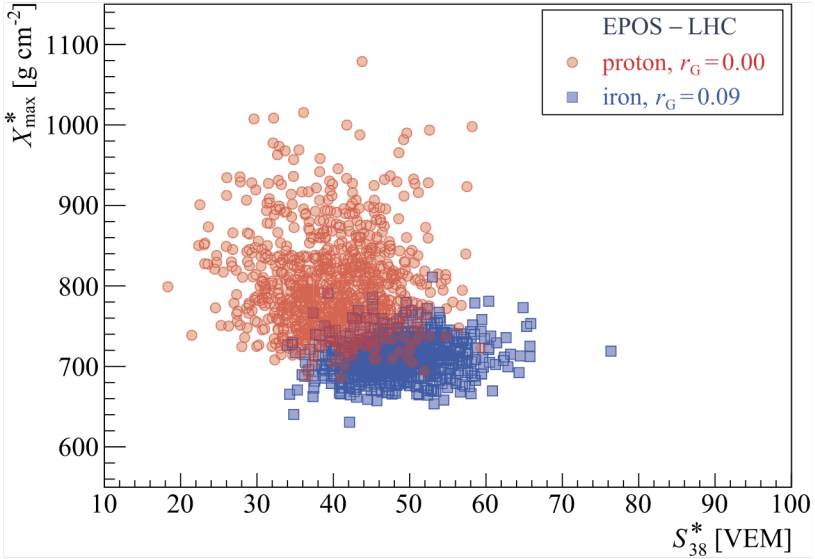
# Charged Cosmic Rays – The Composition

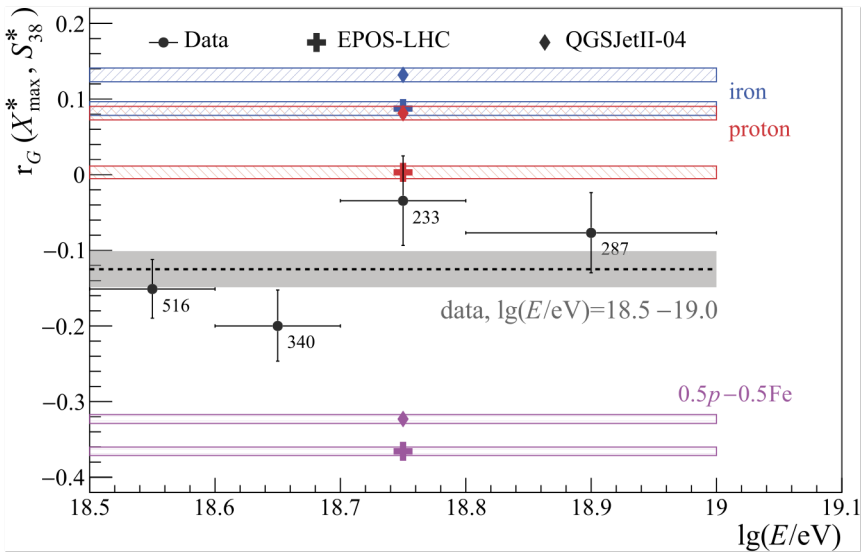



PoS(ICRC2019),482(2019)

# Charged Cosmic Rays – The Composition



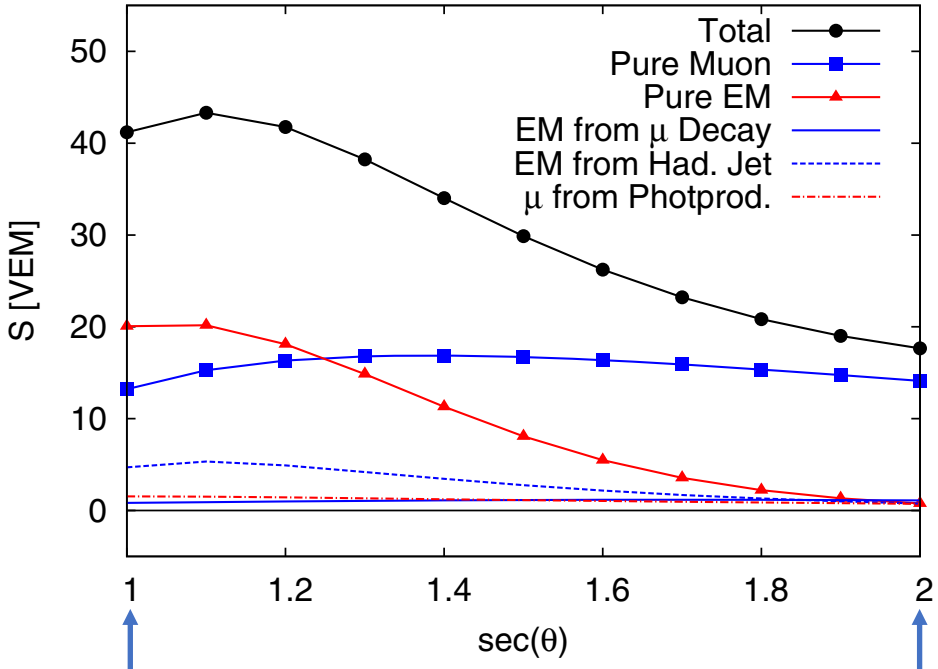




Note that in 2016 evidence was published that the composition is mixed in the range 18.5<lg(E)<19.0. This is evidence in which the muon content of showers is used.

Phys. Lett. B762,288(2016)

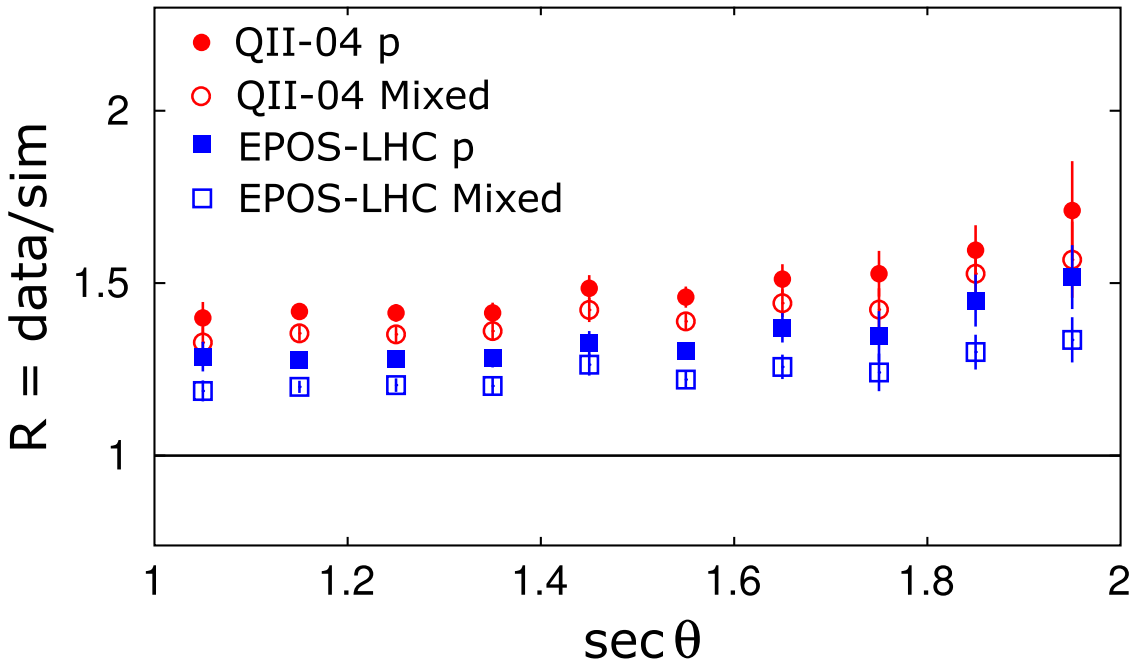
# Charged Cosmic Rays – Muon Deficit

QGSJet II-04 simulations,
10 EeV Proton-Air
1 km from shower core



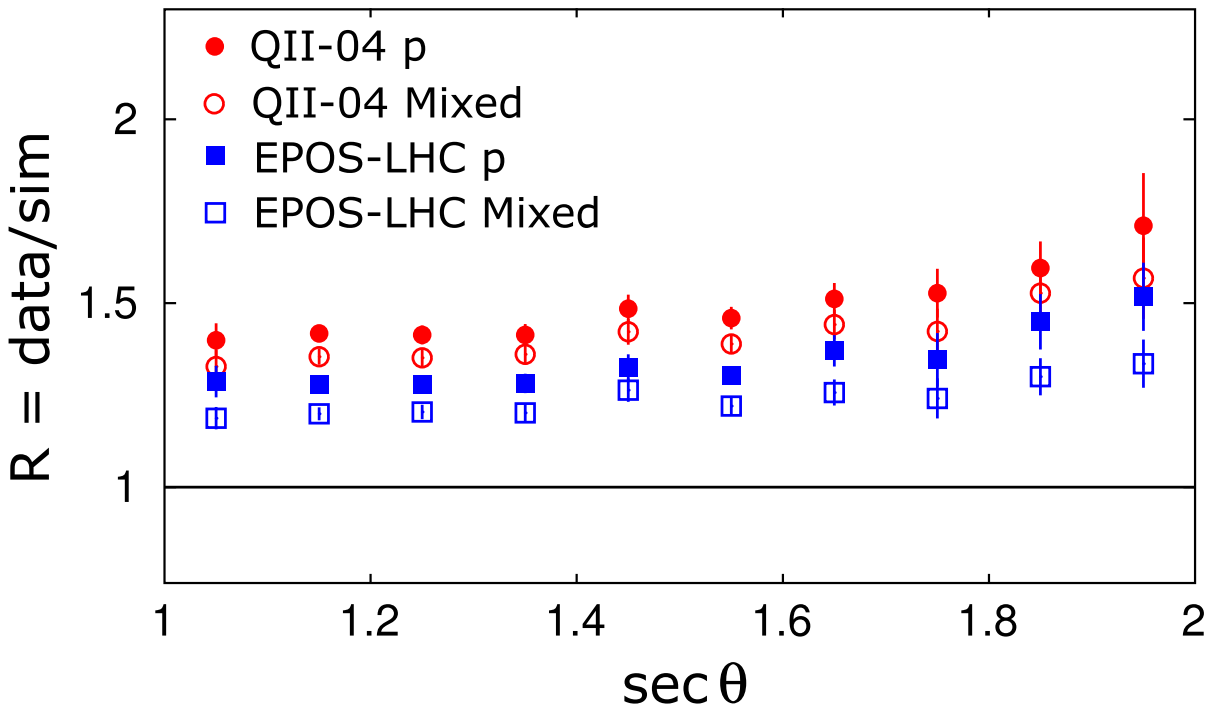

Vertical

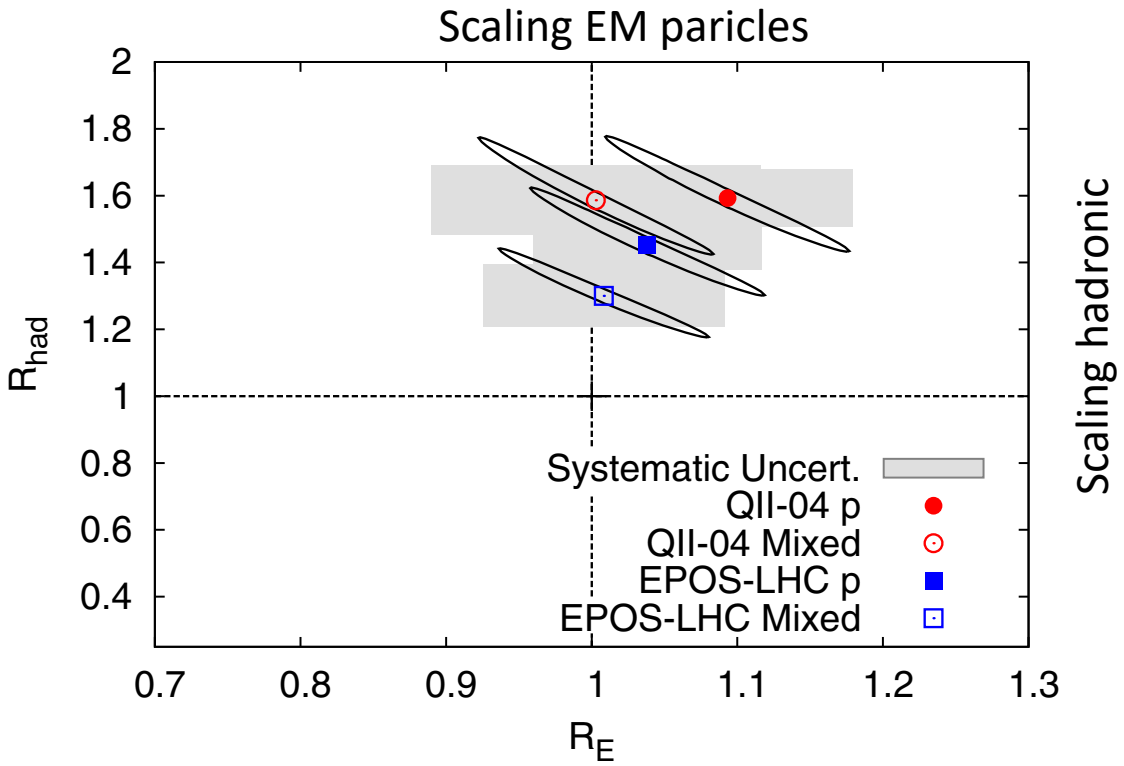
60 degrees
Muon dominated




PRL 117, 192001 (2016)

# Charged Cosmic Rays – Muon Deficit




PRL 117, 192001 (2016)

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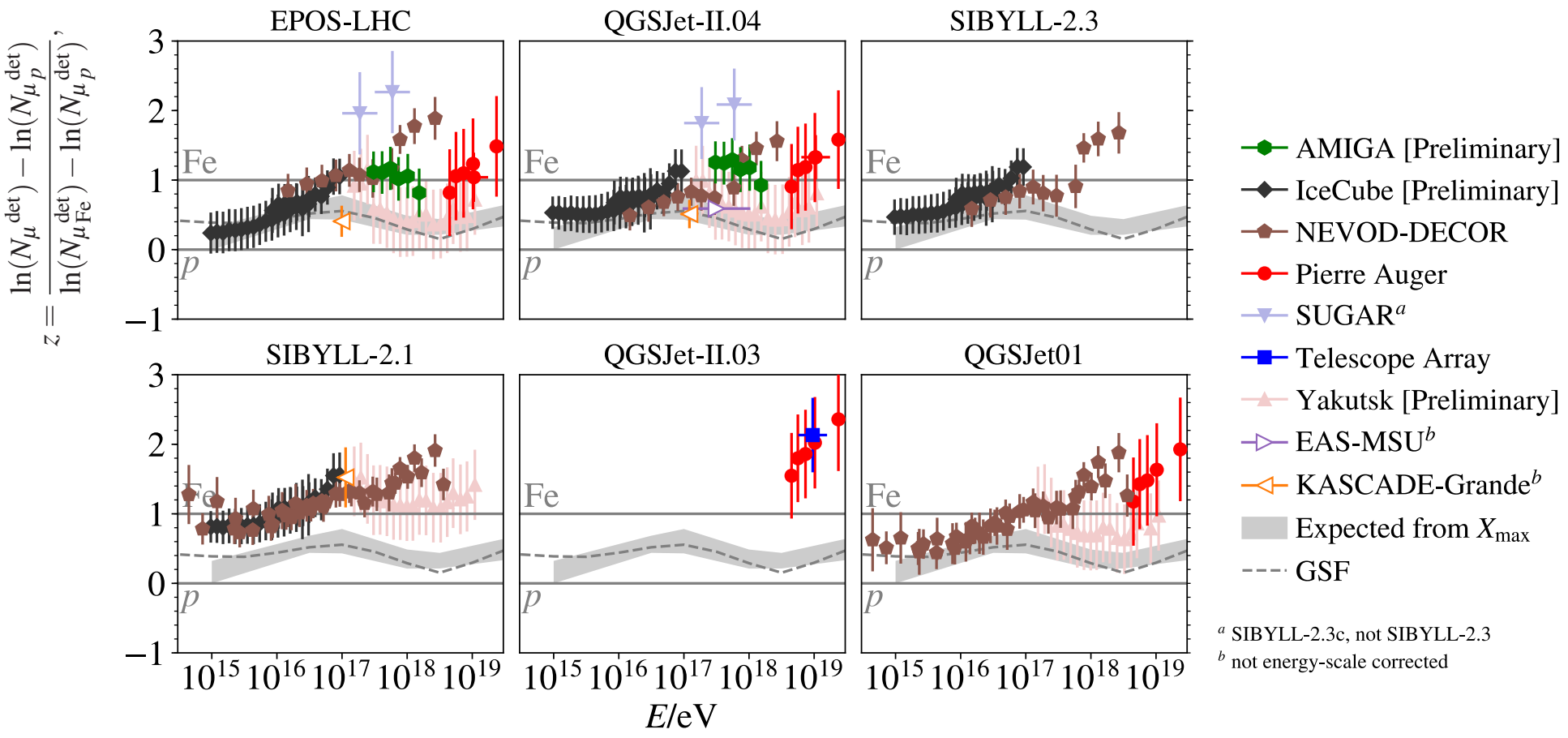
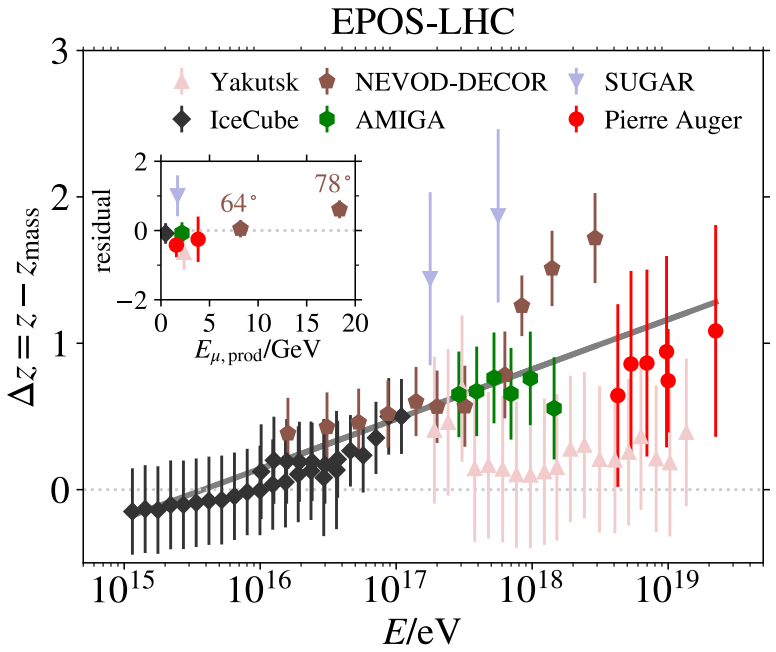
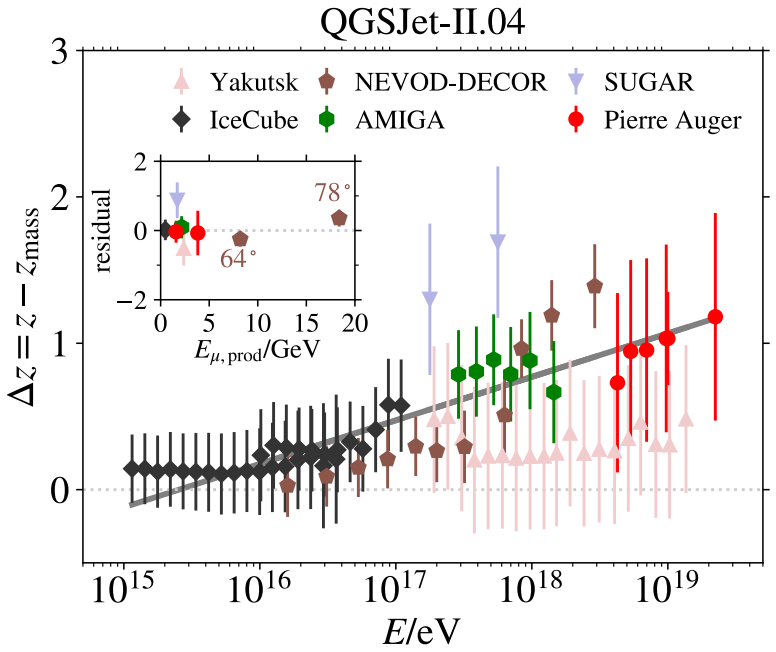



PoS(ICRC2019),214(2019)

# Charged Cosmic Rays – Muon Deficit




Slope = 0.34±0.04



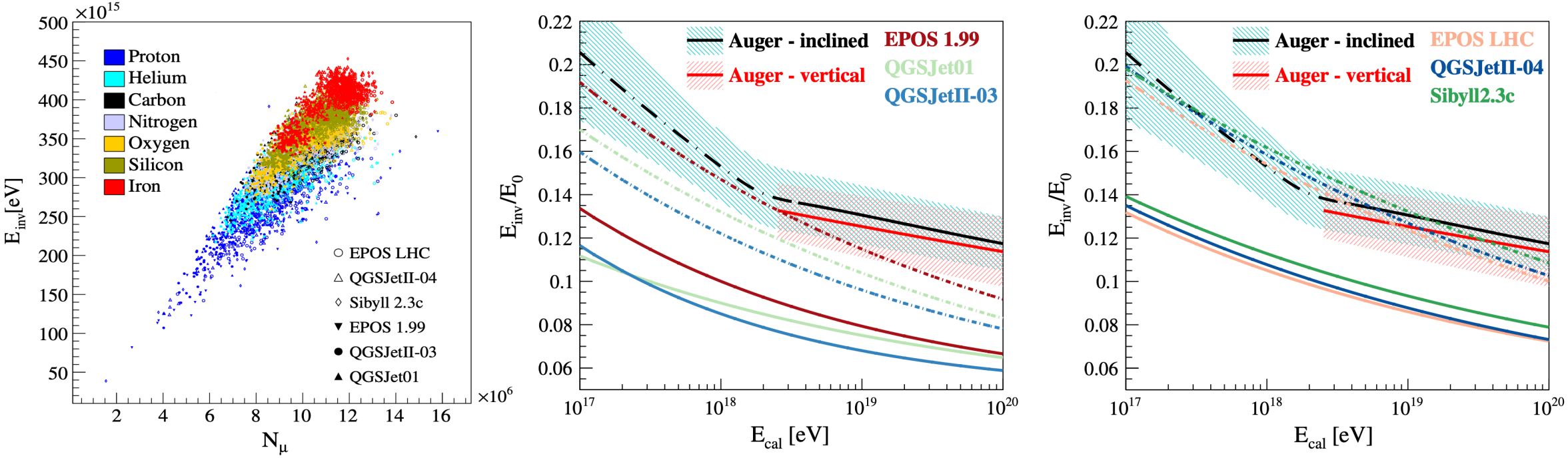

Slope = 0.30±0.03

$$z = \frac{\ln({N_\mu}^{\mathrm{det}}) - \ln({N_\mu}_p^{\mathrm{det}})}{\ln({N_\mu}_{\mathrm{Fe}}^{\mathrm{det}}) - \ln({N_\mu}_p^{\mathrm{det}})},$$

Different experiments, very different methods and a very consistent picture.
Deviations start at an energy of about $10^{16}$ eV

PoS(ICRC2019),214(2019)

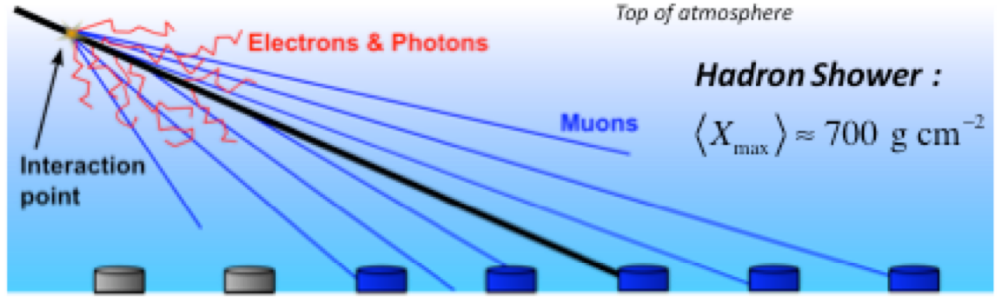
# Charged Cosmic Rays – Muon Deficit



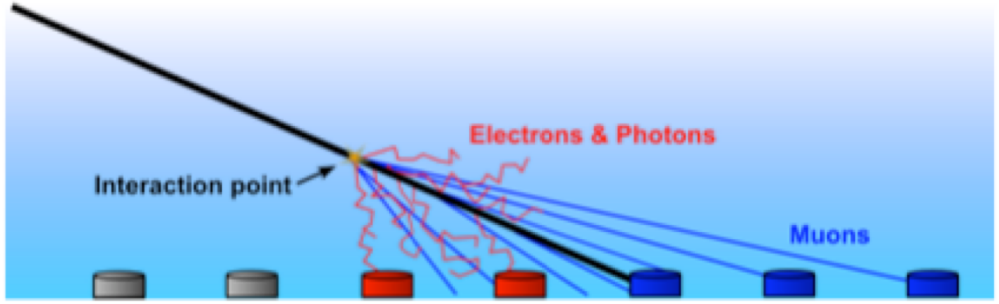

Another way to look at the muon deficit is a look at the amount of invisible energy. Auger uses a data driven approach, which depends on the number of muons, to estimate this

Phys. Rev. D. 100,082003(2019)

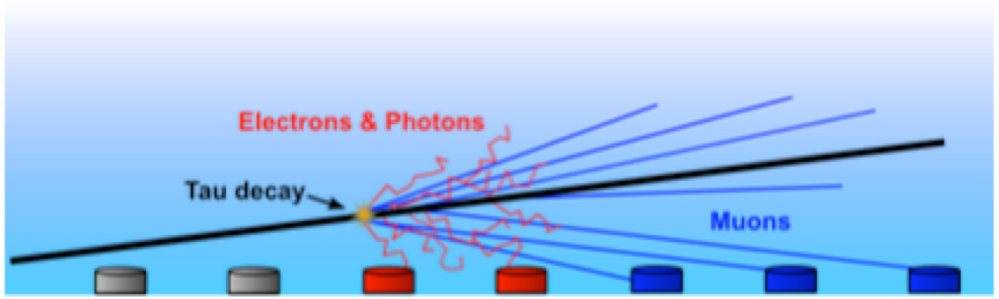
# Neutrinos - Auger




"normal" inclined shower:
only muons left

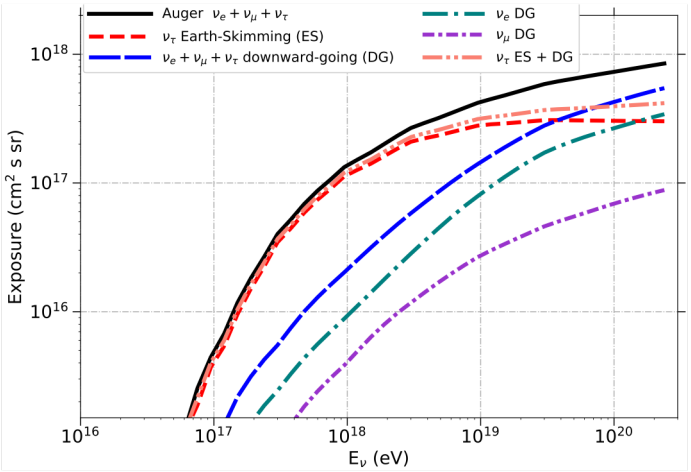



neutrino-induced shower:
young EM component
(broad signals in tanks)

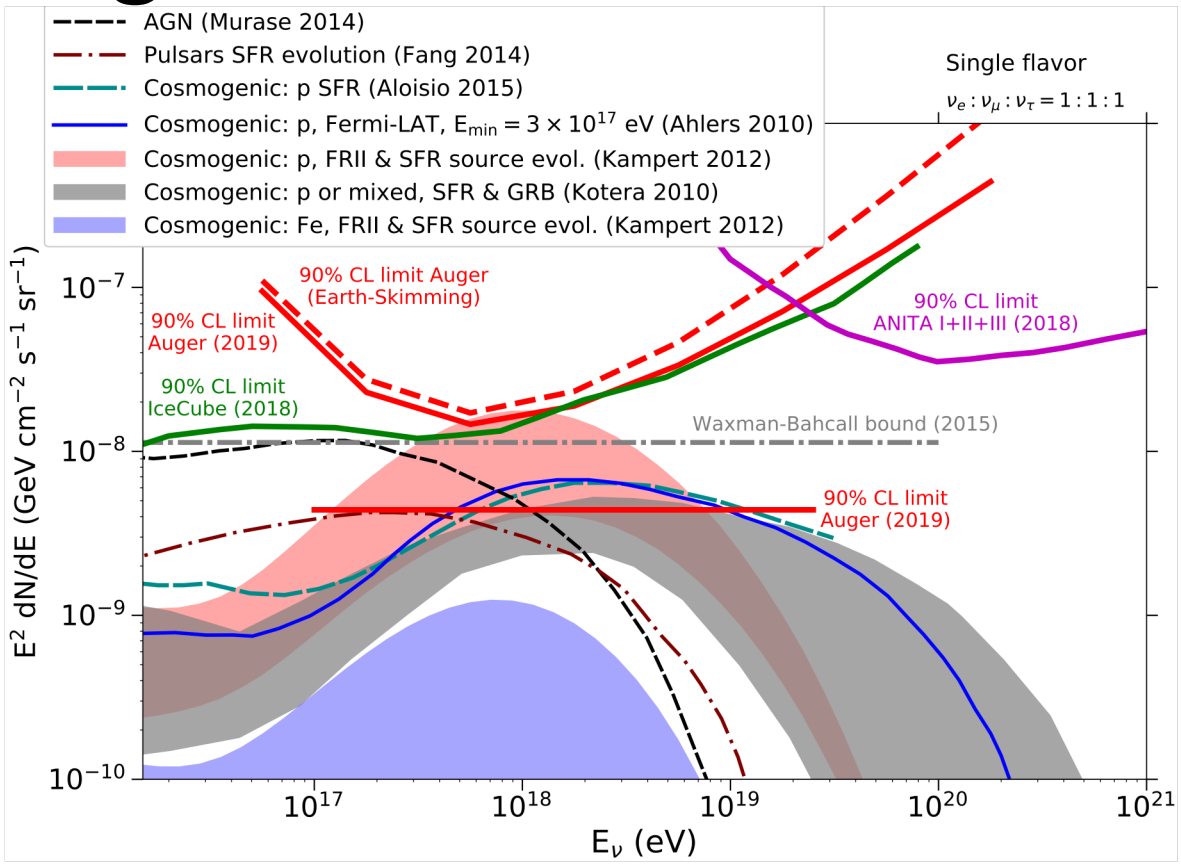



tau decay from Earth-skimming $\nu_\tau$:
dense target, but only one flavor

# Diffuse Neutrinos - Auger



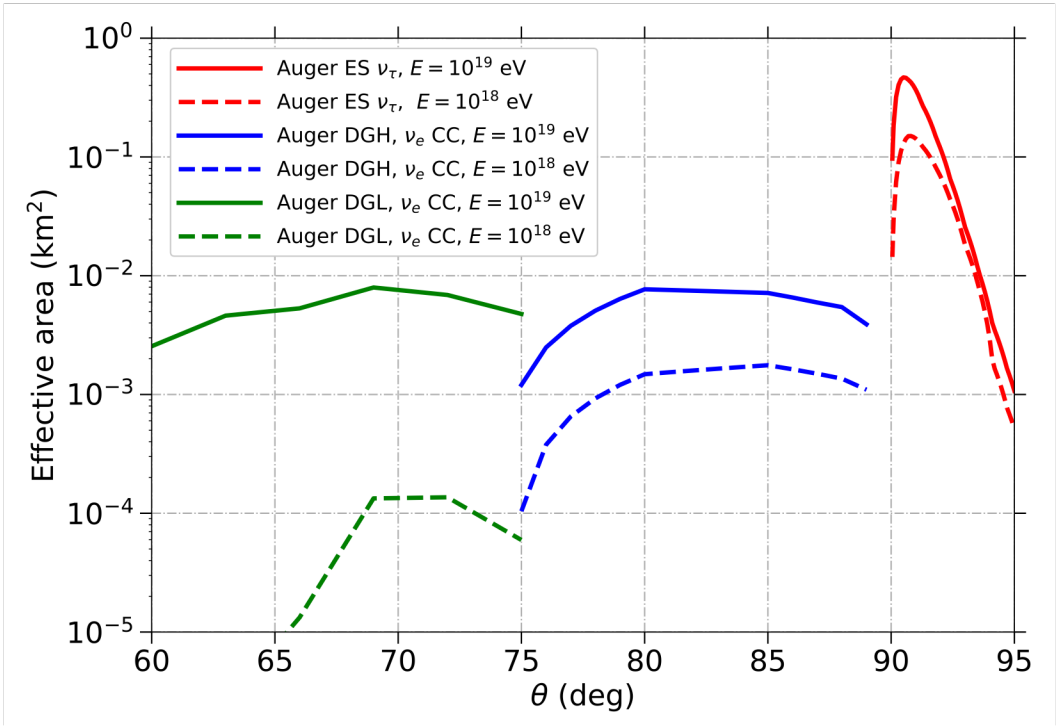

| Neutrino Model (Diffuse flux) | Expected number of $\nu$ events | Probability of observing 0 |
|---|---|---|
| Cosmogenic | | |
| (Kampert et al. [61]) | | |
| proton, FRII | $\sim 5.9$ | $\sim 2.7 \times 10^{-3}$ |
| proton, SFR | $\sim 1.4$ | $\sim 0.25$ |
| iron, FRII | $\sim 0.4$ | $\sim 0.67$ |
| (Aloisio et al. [62]) | | |
| proton, SFR | $\sim 2.3$ | $\sim 0.10$ |
| (Ahlers et al. [60]) | | |
| proton, $E_{\rm min} = 10^{19}$ eV | $\sim 4.6$ | $\sim 1.0 \times 10^{-2}$ |
| proton, $E_{\rm min} = 10^{17.5}$ eV | $\sim 2.4$ | $\sim 9.0 \times 10^{-2}$ |
| (Kotera et al. [20]) | | |
| p or mixed, SFR & GRB | $\sim 0.8$–$2.0$ | $\sim 0.45$–$0.13$ |
| Astrophysical | | |
| (Murase et al. [69]) | | |
| Radio-loud AGN | $\sim 2.9$ | $\sim 5.5 \times 10^{-2}$ |
| (Fang et al. [70]) | | |
| Pulsars — SFR | $\sim 1.5$ | $\sim 0.22$ |

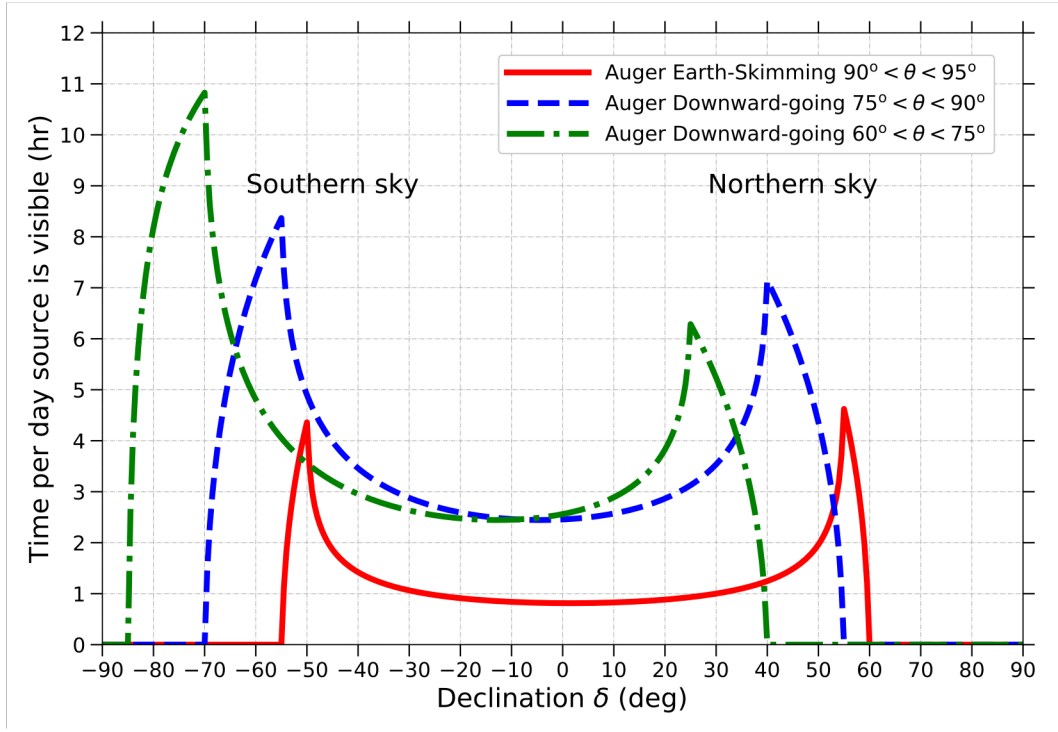



Note: Auger is mostly sensitive to Tau-neutrinos
Expected number of neutrinos depends on the CR composition

JCAP 10,022(2019)

# Point Source Neutrinos - Auger

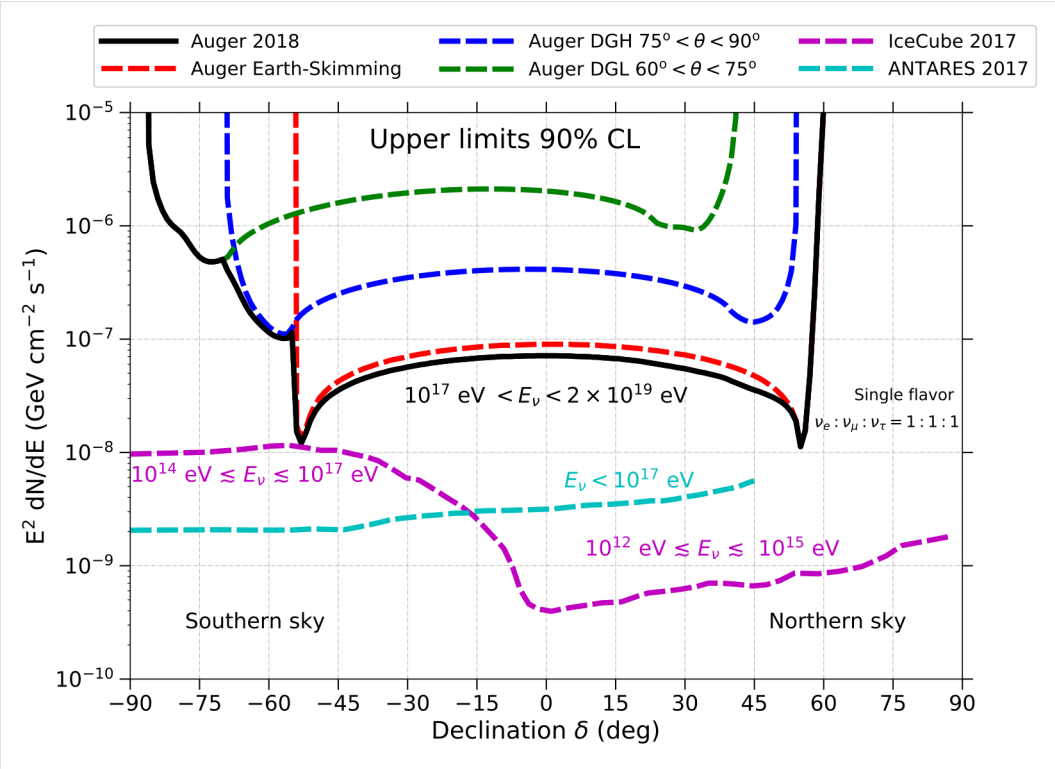


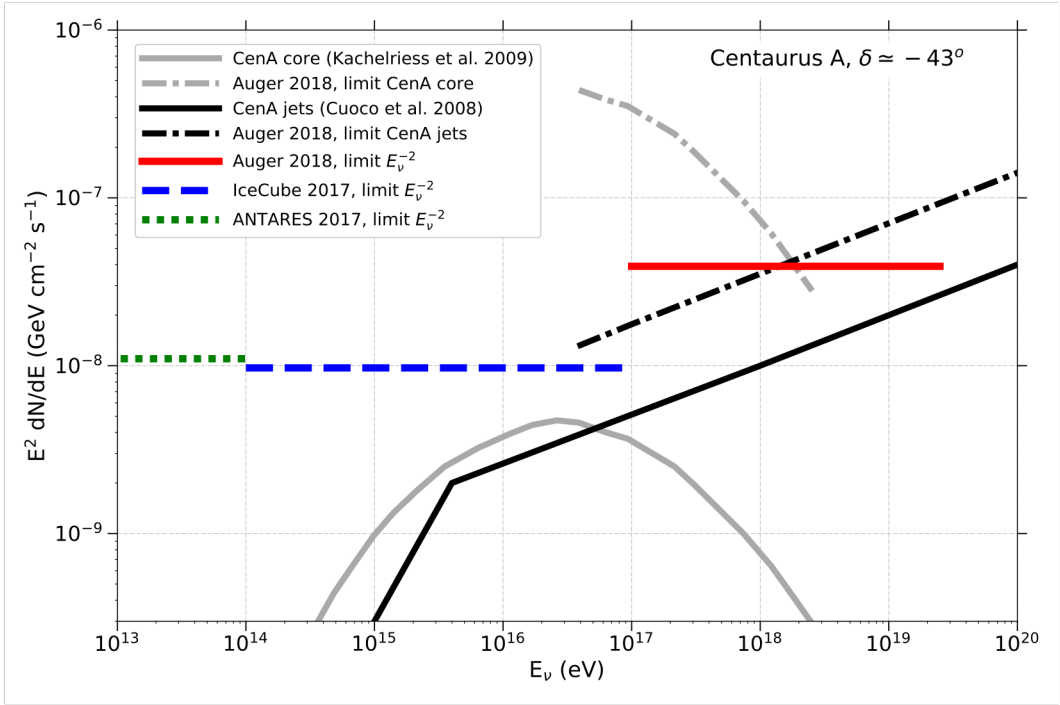




Note that there is a big difference between transient sources (you have to be very lucky to be visible) and continuous sources

JCAP 11,004(2019)

# Point Source Neutrinos - Auger

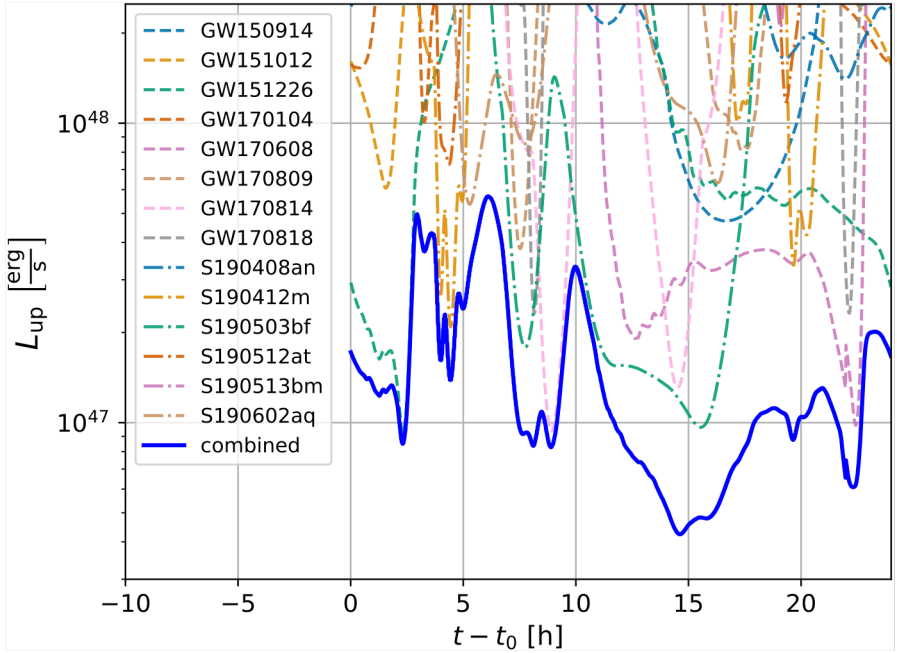


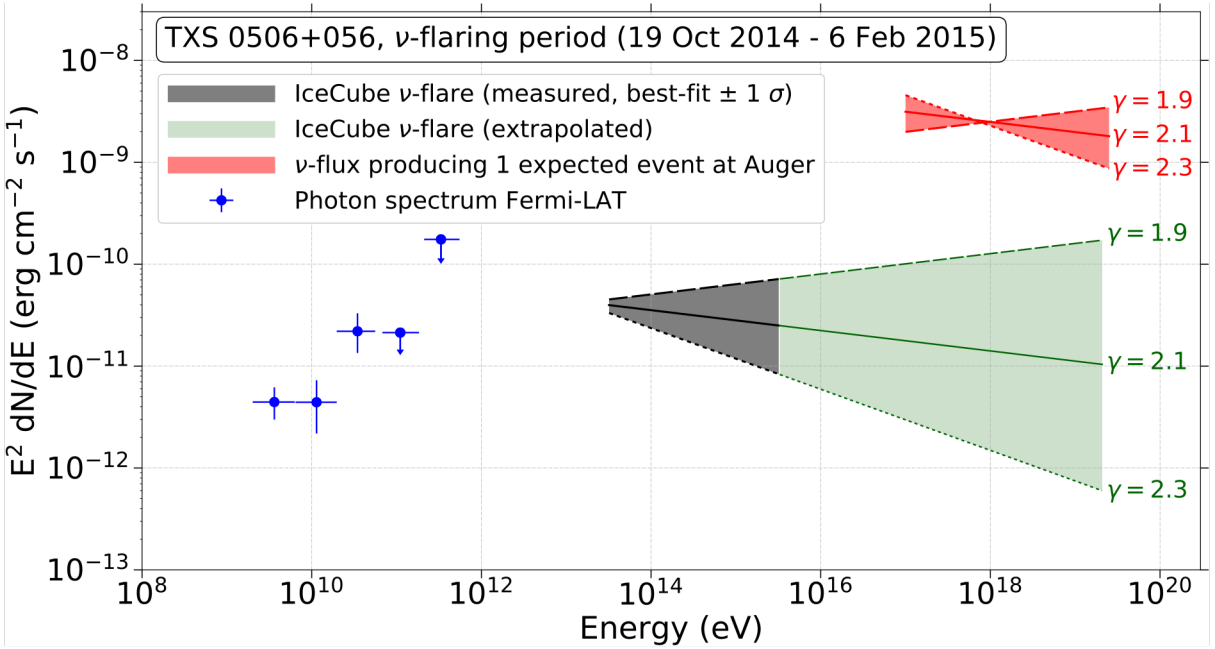




Limits on steady sources, example: CEN-A including the IceCube and ANTARES limits

JCAP 11,004(2019)

# Point Source Neutrinos - Auger

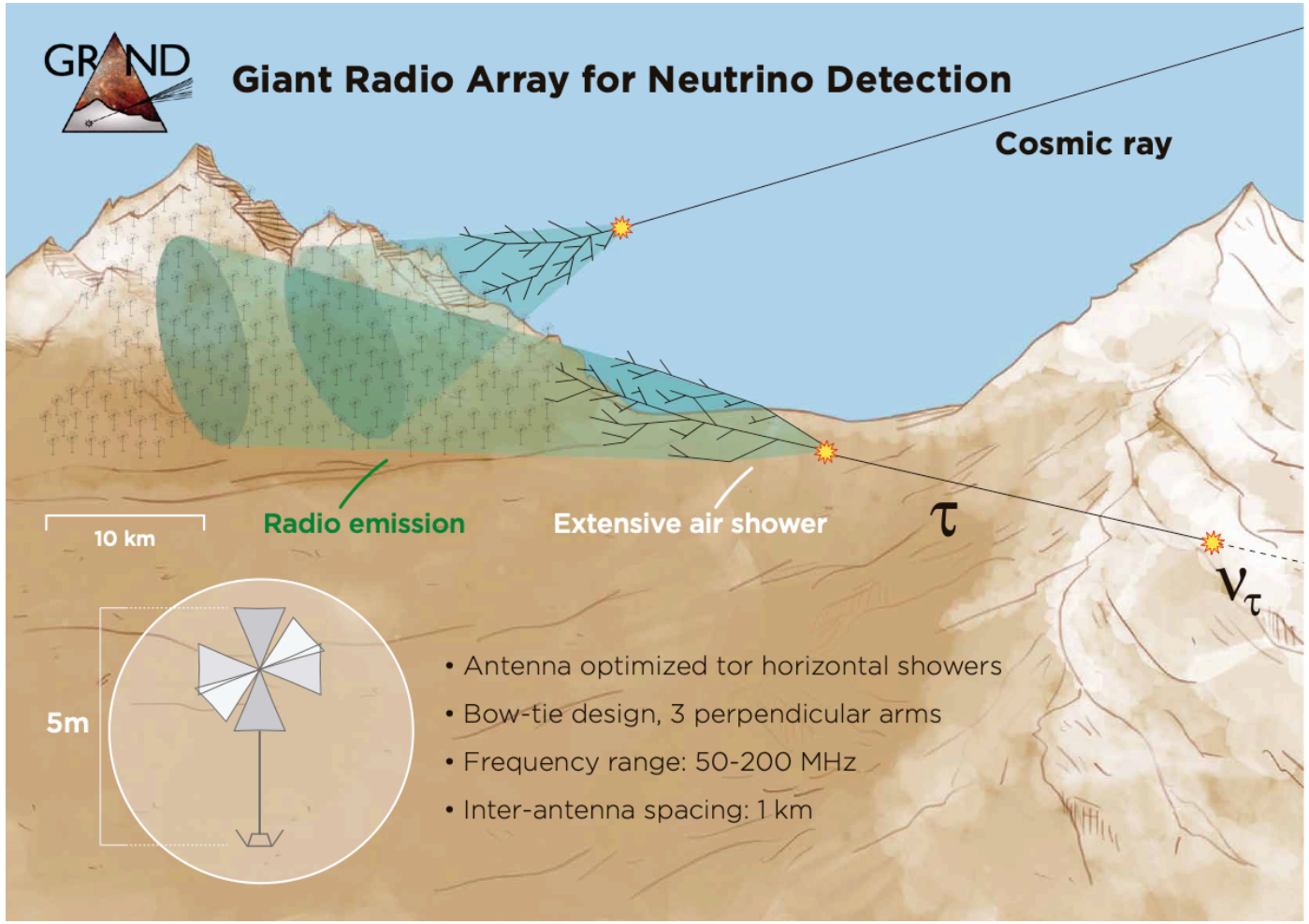



Examples of transient sources: Follow up on GW events and Blazar TXS 0506-056. In no case were UHE neutrinos observed.

PoS(ICRC2019),415(2019)

# Neutrinos - GRAND




Focus: Tau neutrinos

Similar to Auger, also sensitivity to other neutrino types

We will measure the energy of the air shower induced by the Tau lepton (to be more precise: the EM part thereof)

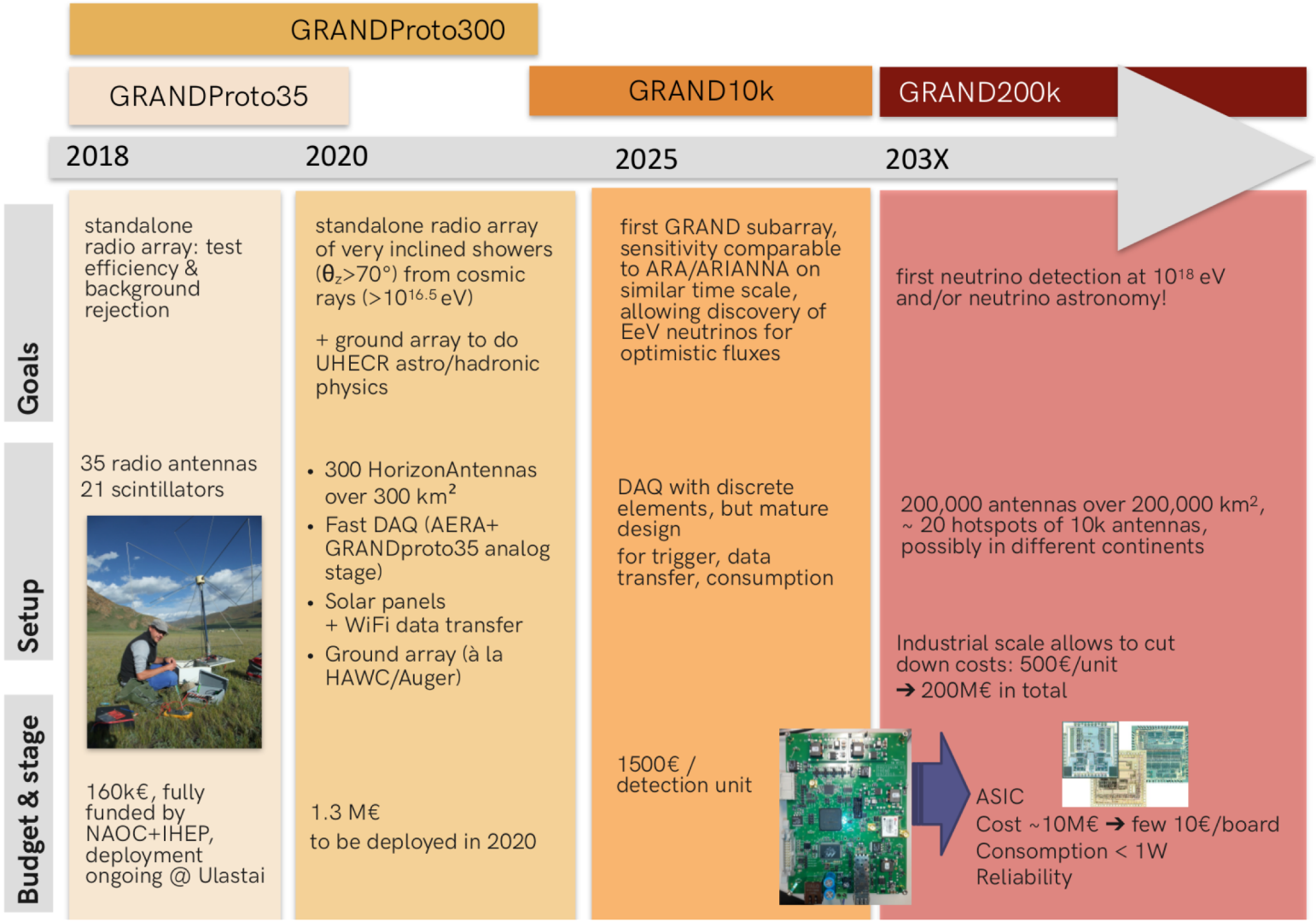
Difference with Auger:
Auger infers this energy from the particle footprint of the shower. The addition of Auger RD improves this situation drastically.

# Neutrinos - GRAND

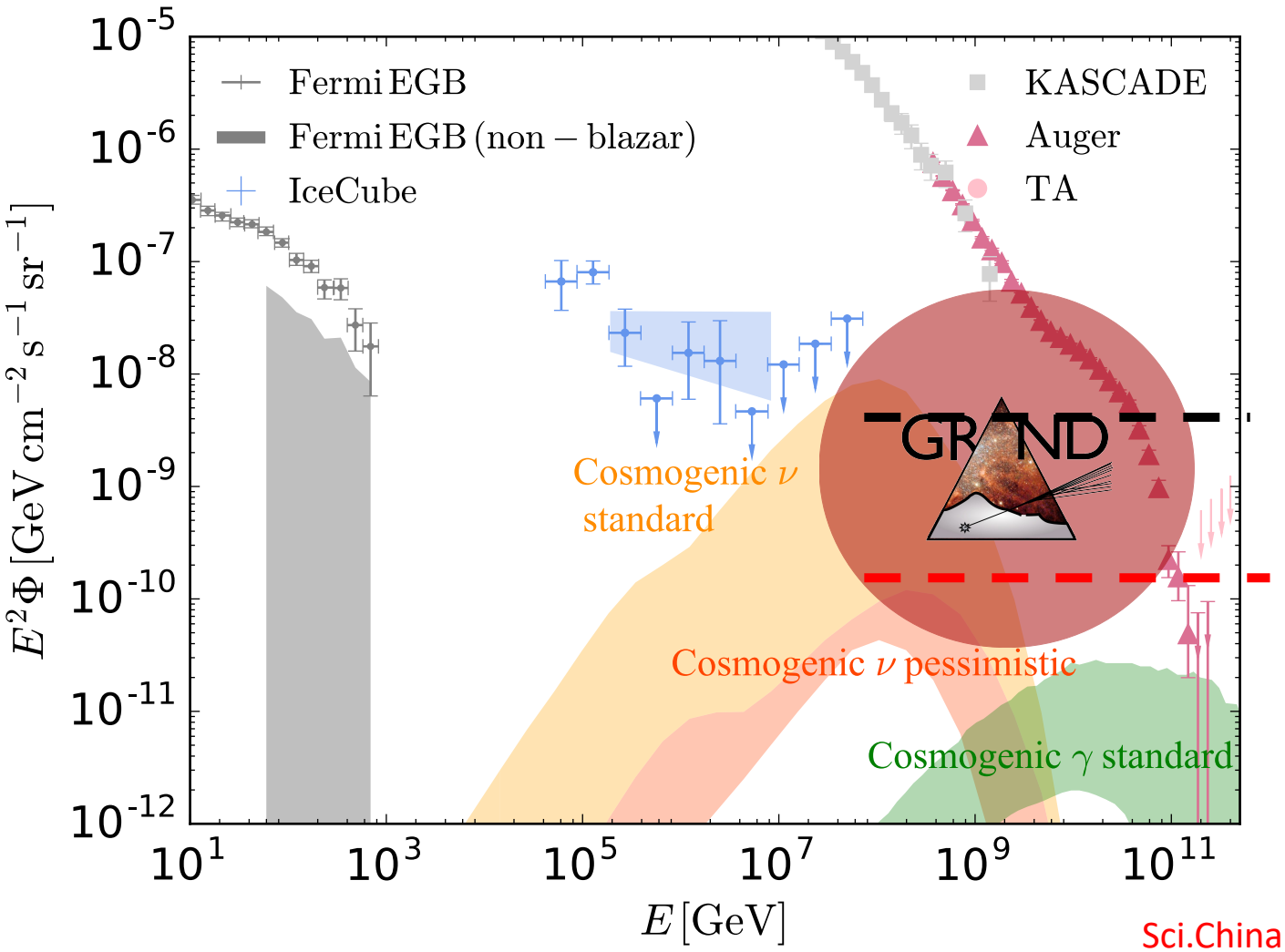
GRAND is not going to be there tomorrow.

There is an aggressive timeline in which GRAND is completed in about 15 years.

However: Physics (CR and neutrino) will start in initial stages already.



# Neutrinos - GRAND

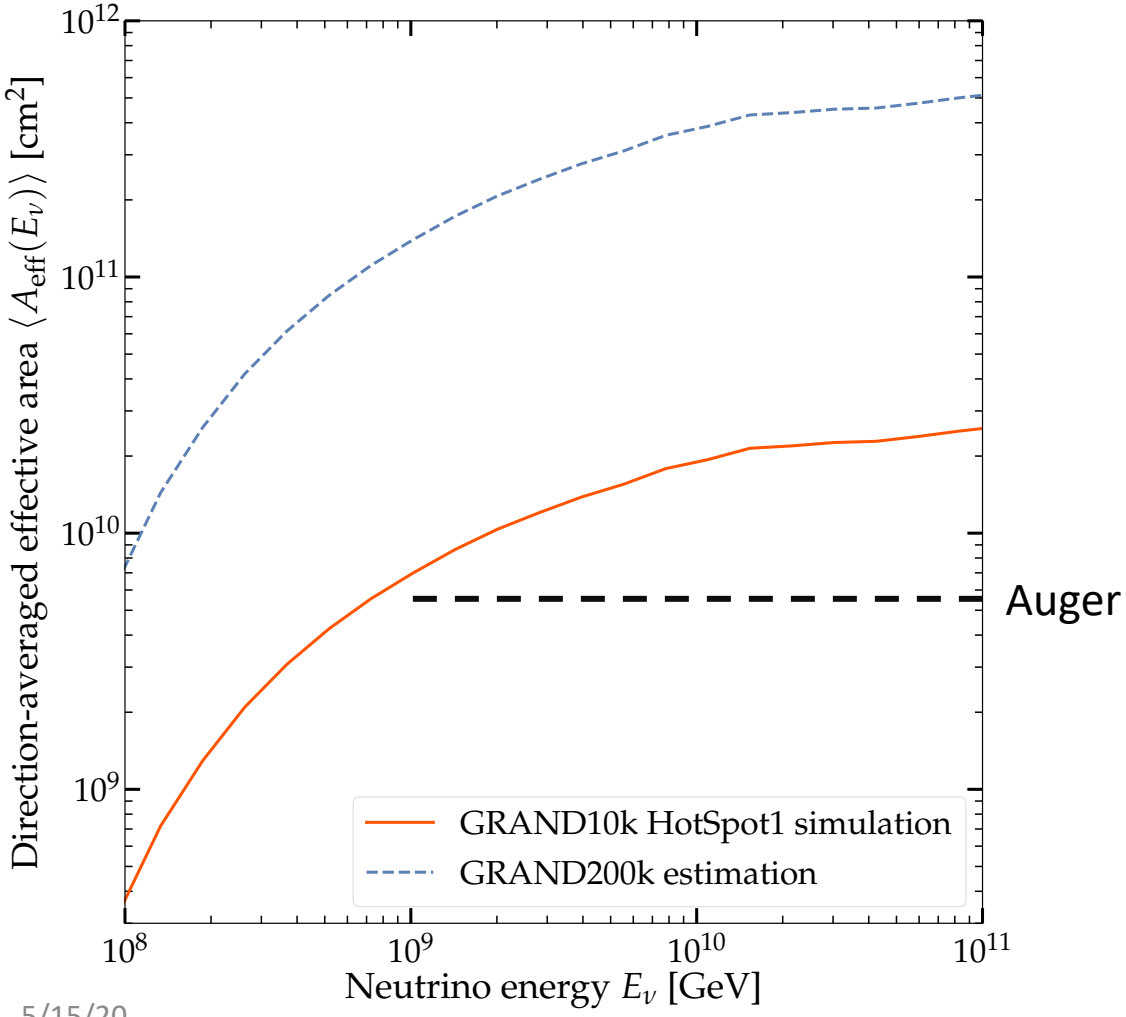


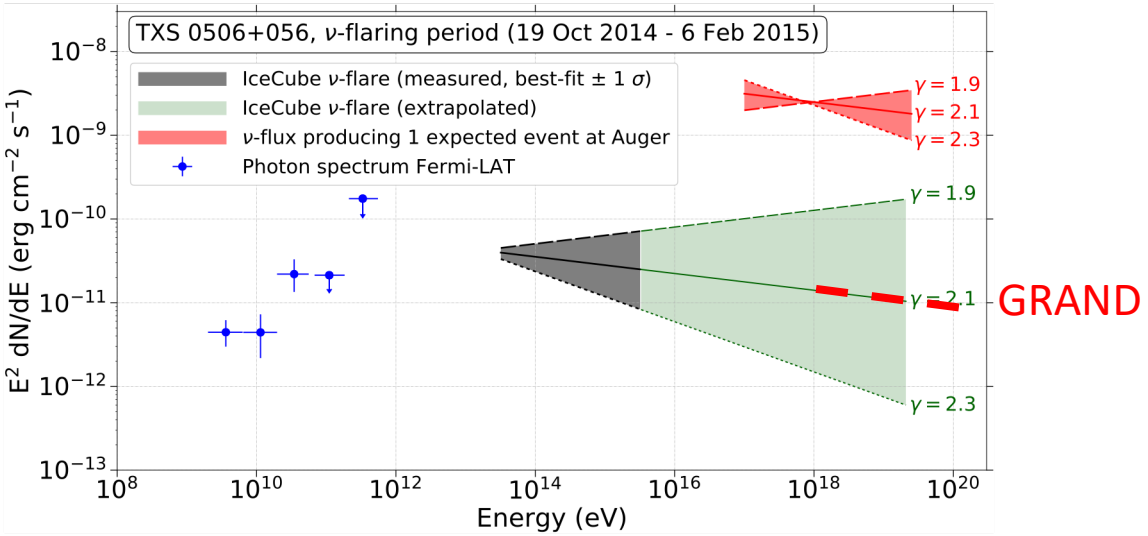

Auger 90% integrated diffuse neutrino limit

GRAND 90% integrated diffuse neutrino limit after 10 years running

Sci.China Phys.Mech.Astron. 63 (2020)

# Point Source Neutrinos - GRAND



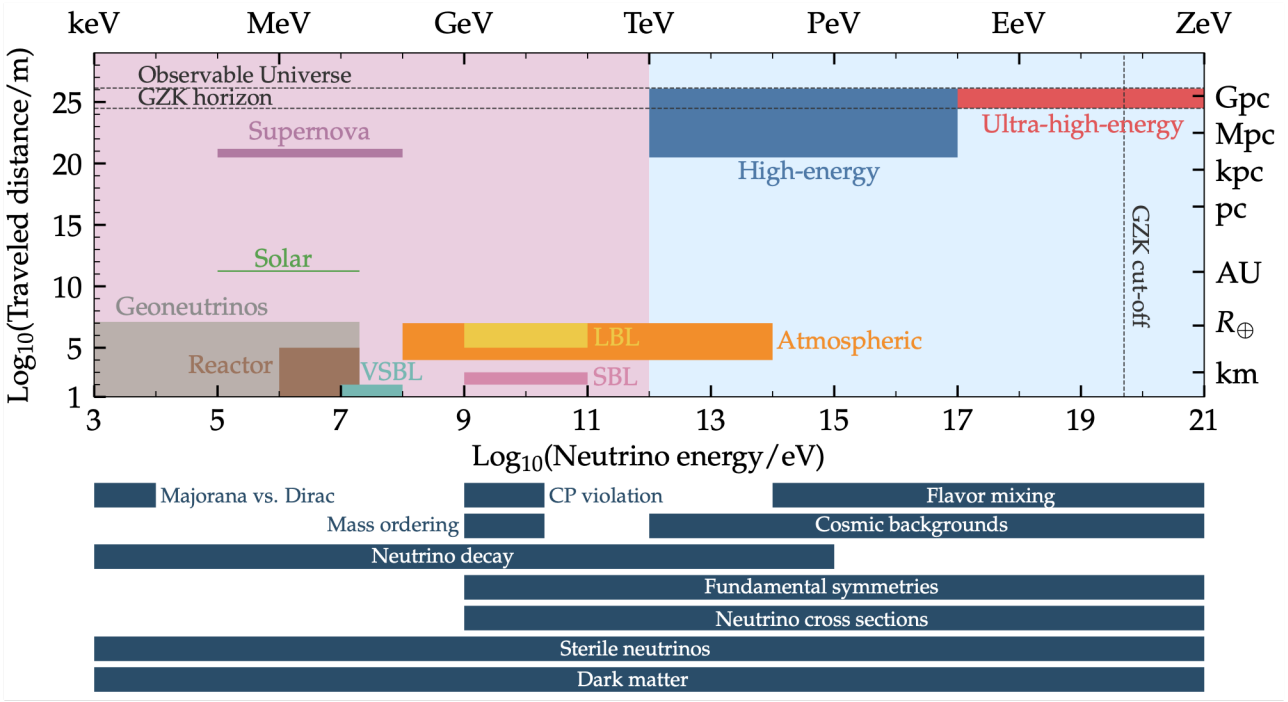



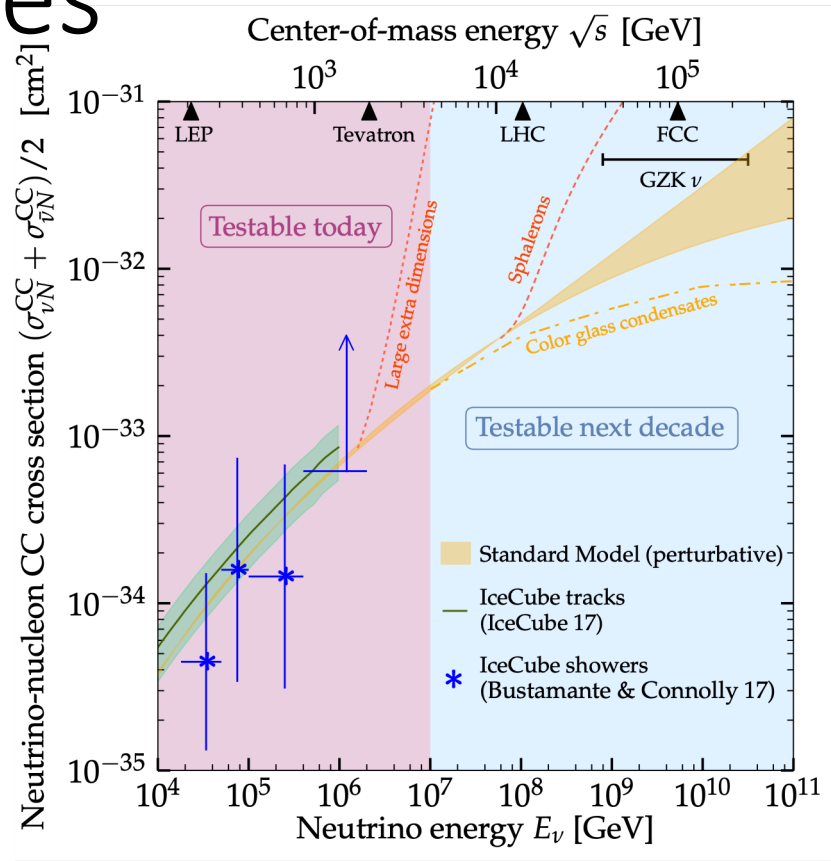

The additional sensitivity can greatly help for individual transient events, eg TXS 0506+056

Similar for stacking analyses of GW events (certainly in combination with ET and/or CE)

Sci.China Phys.Mech.Astron. 63 (2020)

# Fundamental neutrino properties



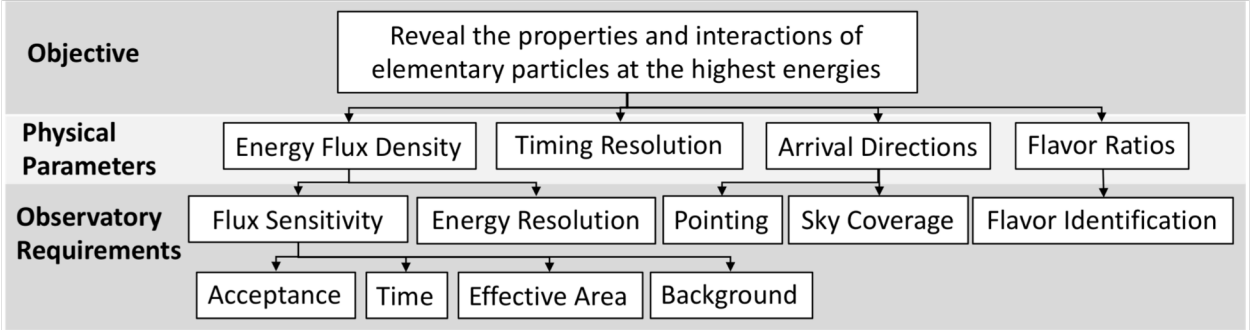



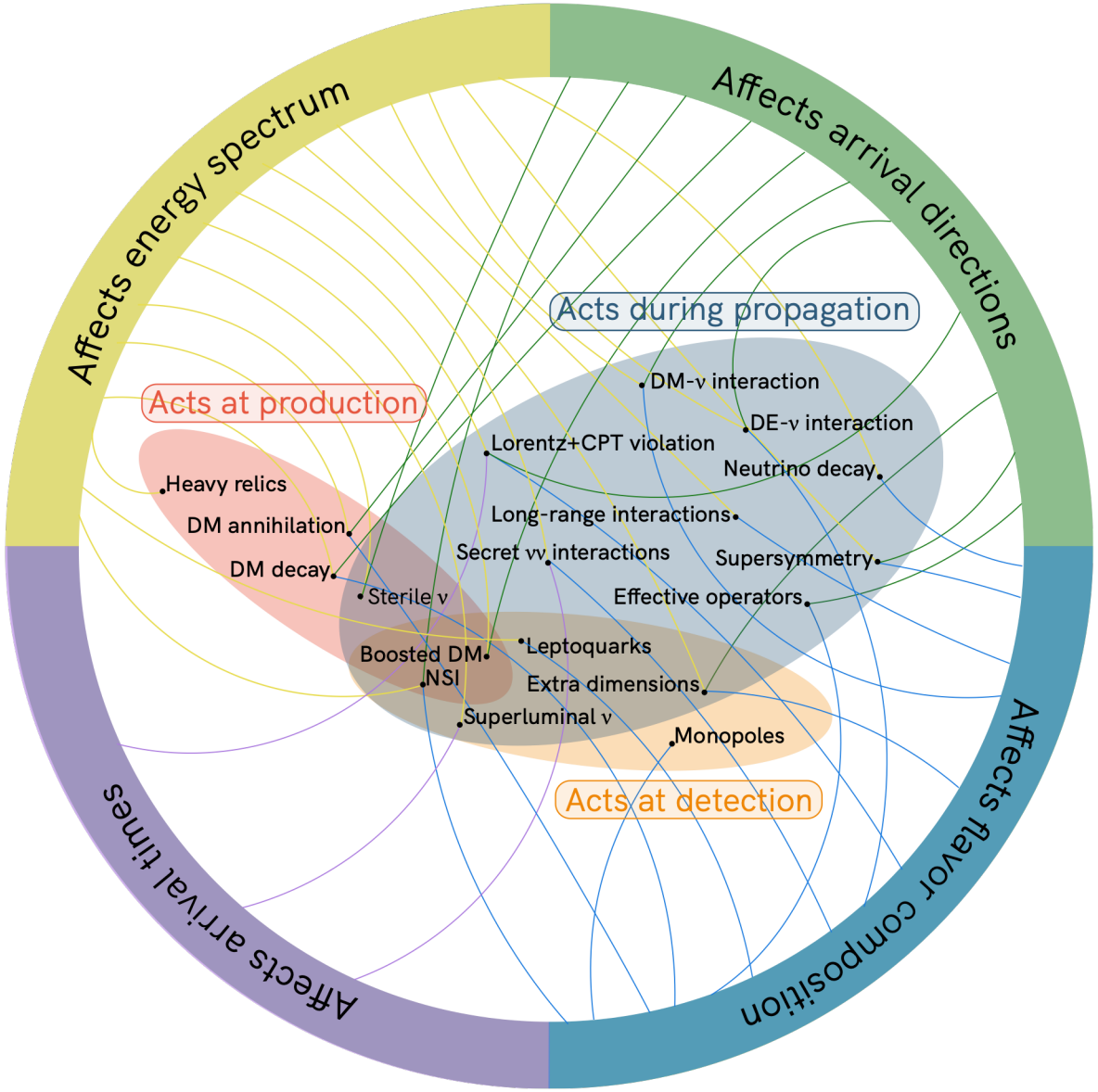

Figure 4: Observatory requirements to test fundamental physics with cosmic neutrinos.

The GRAND design is taking these requirements into account

Astro 2020 white paper

ArXiv 1903.04333

# BSM Searches with Neutrinos




There are nice compilations of different BSM effects, however we could use guidance into what observables we need to construct in order to perform meaningful tests.

ArXiv 1907.08690

# GRAND Fundamental Parameters

- Angular Resolution <0.05 degrees
- $X_{MAX}$ 20-40 g/cm$^2$
- Shower Energy ~15%
- Neutrinos sensitivity 4 $10^{-10}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
- Fully efficient for UHECR and gamma rays above $10^{10}$ GeV for zenith angles beyond 65$^o$

- What aspect to improve would be worth investing in from a theoretical perspective?

# Wish list from an experimentalist point of view

- Theoretical understanding of the muon deficit.
  - What parameters could help theoretical understanding of this phenomenon?
- MC neutrino interaction cross section
  - What is included (eg coherent neutrino-nucleus interaction)
  - What about new physics effects and how to observe this?
- Neutrino mixing at the highest energies
  - Sensitivity to BSM, LIV
- Possible effects of LIV in different models of space-time
- Dark matter
  - Heavy dark matter annihilation
  - Neutrino-Dark matter interactions in halo galaxy/ other galaxies
- UHE gamma rays
  - Not discussed at all, but extremely interesting physics (LPM effect, ..)