ISAPP 2019 @ the Pierre Auger Observatory

UHECR: Summary, Open Questions & Perspectives

BERGISCHE UNIVERSITÄT WUPPERTAL

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Bundesministerium für Bildung und Forschung

Menu…

- **Primary goal of HE-Astroparticle Physics: Find Sources of UHECRs**
  - Which messenger is the best?
  - Photons?
  - Neutrinos?
  - or UHECR, or all together?

several lectures about this

- **Reminder: Unexpected surprises in UHECR observations**
  → **Seeing E_{max} of UHECR accelerators!**
- **What are the next logical steps** science wise**?**
- **How do we address the next (UHECR) challenges** experimental wise**?**
  - Taking shape: AugerPrime, TA*4
  - Go to space? POEMMA, EUSO…
  - Other dreams at ground

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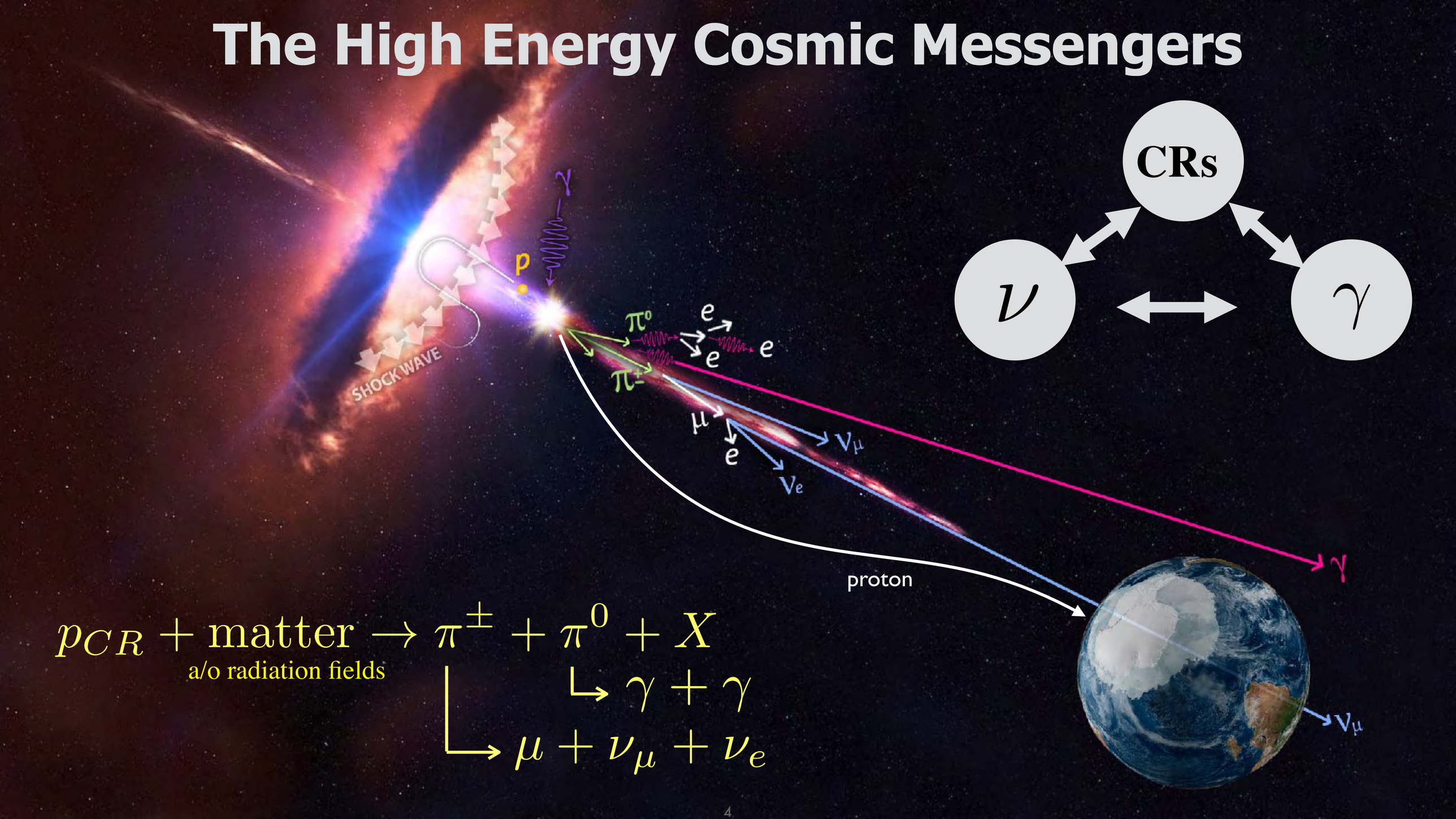
The High Energy Cosmic Messengers



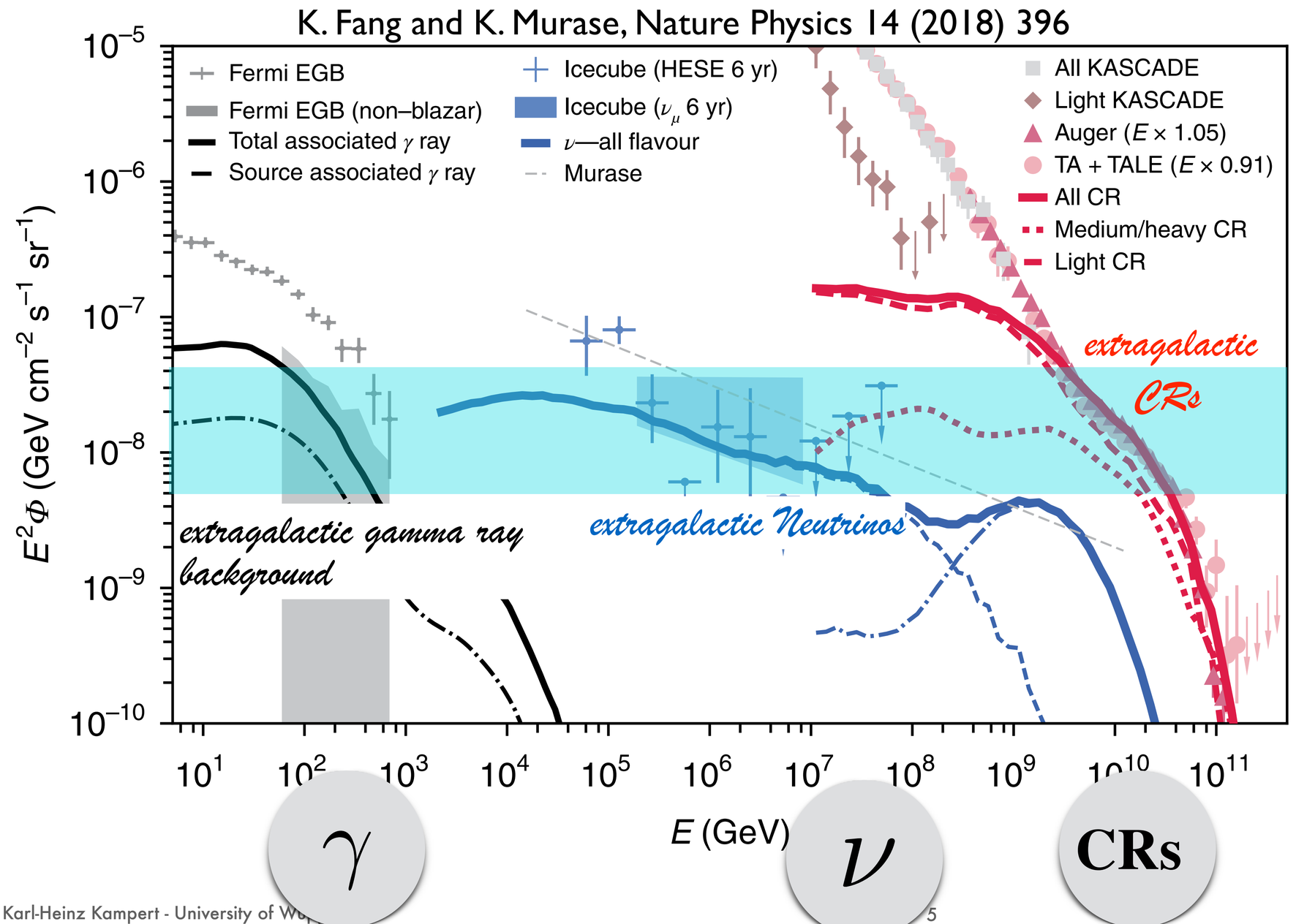
$$p_{CR} + \text{matter} \rightarrow \pi^{\pm} + \pi^{0} + X$$

a/o radiation fields

$$\pi^{0} \hookrightarrow \gamma + \gamma$$

$$\pi^{\pm} \hookrightarrow \mu + \nu_{\mu} + \nu_{e}$$

Cosmic Coincidence or Grand Unified Picture ?



10 orders of magnitude in energy, but

$E^2 \cdot \Phi$ is about the same

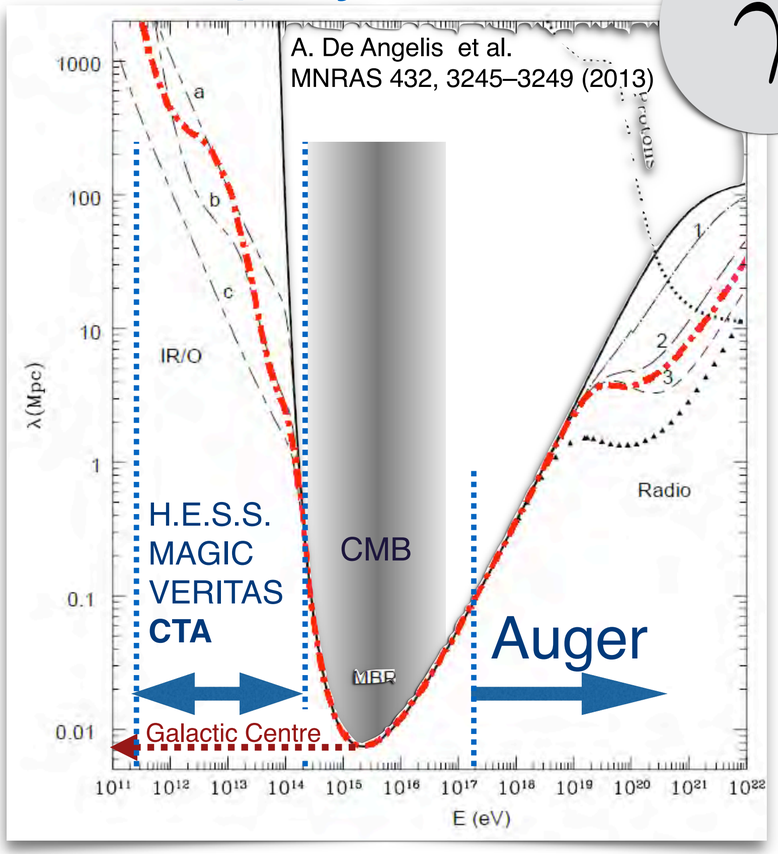
→ energy generation rates per decade in E are the same

Suggests again a common / related origin

but no guarantee !

A „Best" Messenger ??

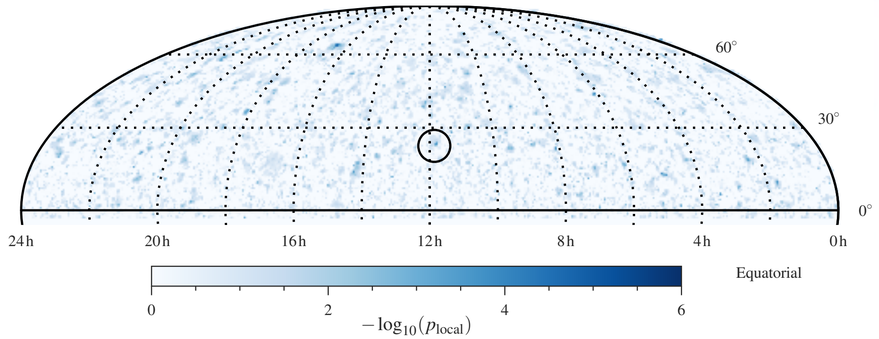
γ-ray horizon



⊕ straight lines
⊕ unexplored at >10^{17} eV
⊖ UHE Horizon < 10 Mpc
⊖ no clean probe of hadron acceleration

HE-Neutrino Sky

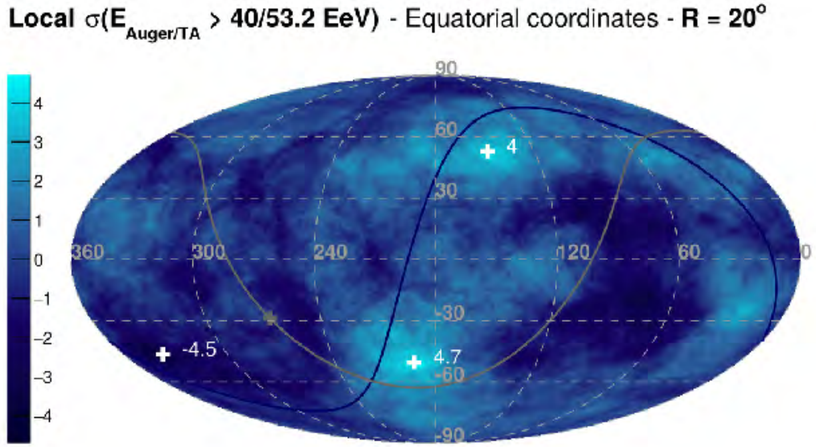
IceCube, EPJ 2019 (arXiv:1811.07979)



⊕ straight lines
⊕ clean hadronic probe
⊖ Horizon = Hubble ⇒ isotropic
⊖ point sources could be difficult, unless flaring sources

UHECR Sky
above 40 EeV

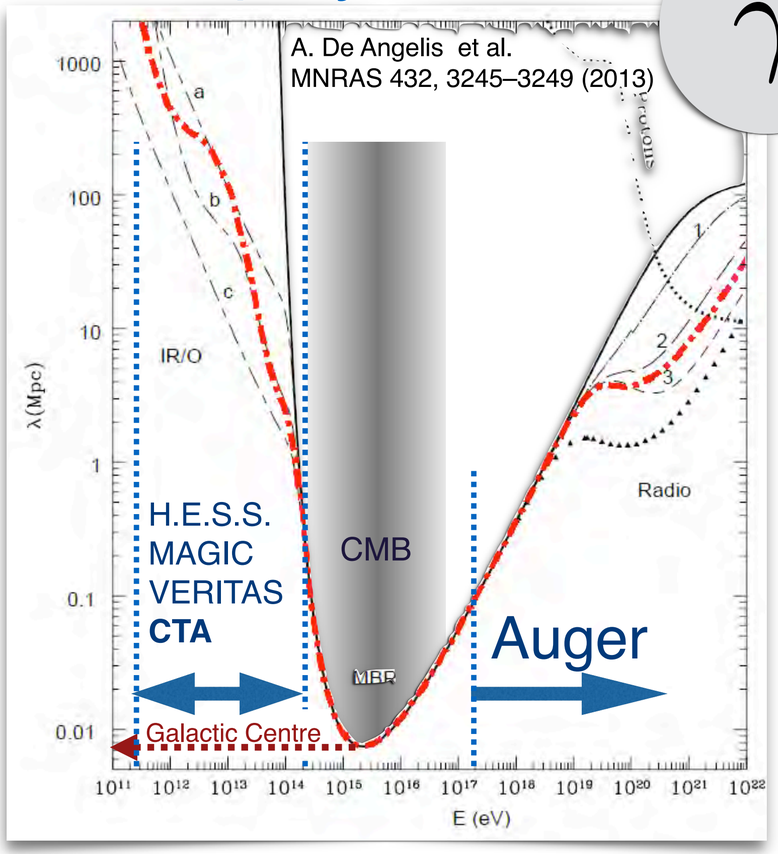
Auger & TA Working Group at UHECR2018



⊕ the only direct probe
⊕ probes extreme accelerator
⊕ chemical composition
⊕/⊖ Horizon some 100 Mpc
⊖ deflection in magnetic fields

A „Best" Messenger ??

γ-ray horizon



HE-Neutrino Sky

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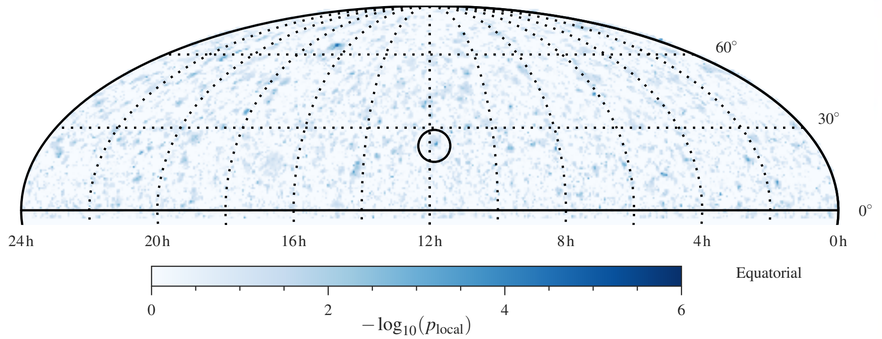

UHECR Sky
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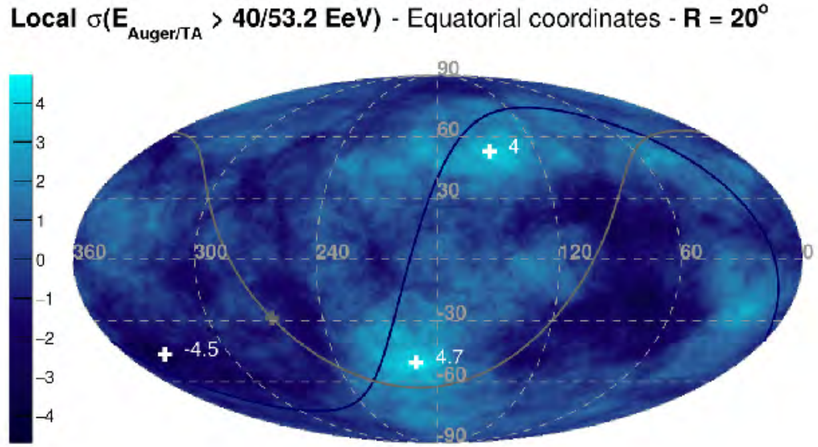

No clear winner: Competition and Multi-Messenger Cooperation

UHECR: unique probe of ZeVatrons !

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- **Reminder: Unexpected surprises in UHECR observations**
  (see Michael Ungers talk of yesterday)
- **What are the next logical steps** science wise**?**
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UHECR before Auger

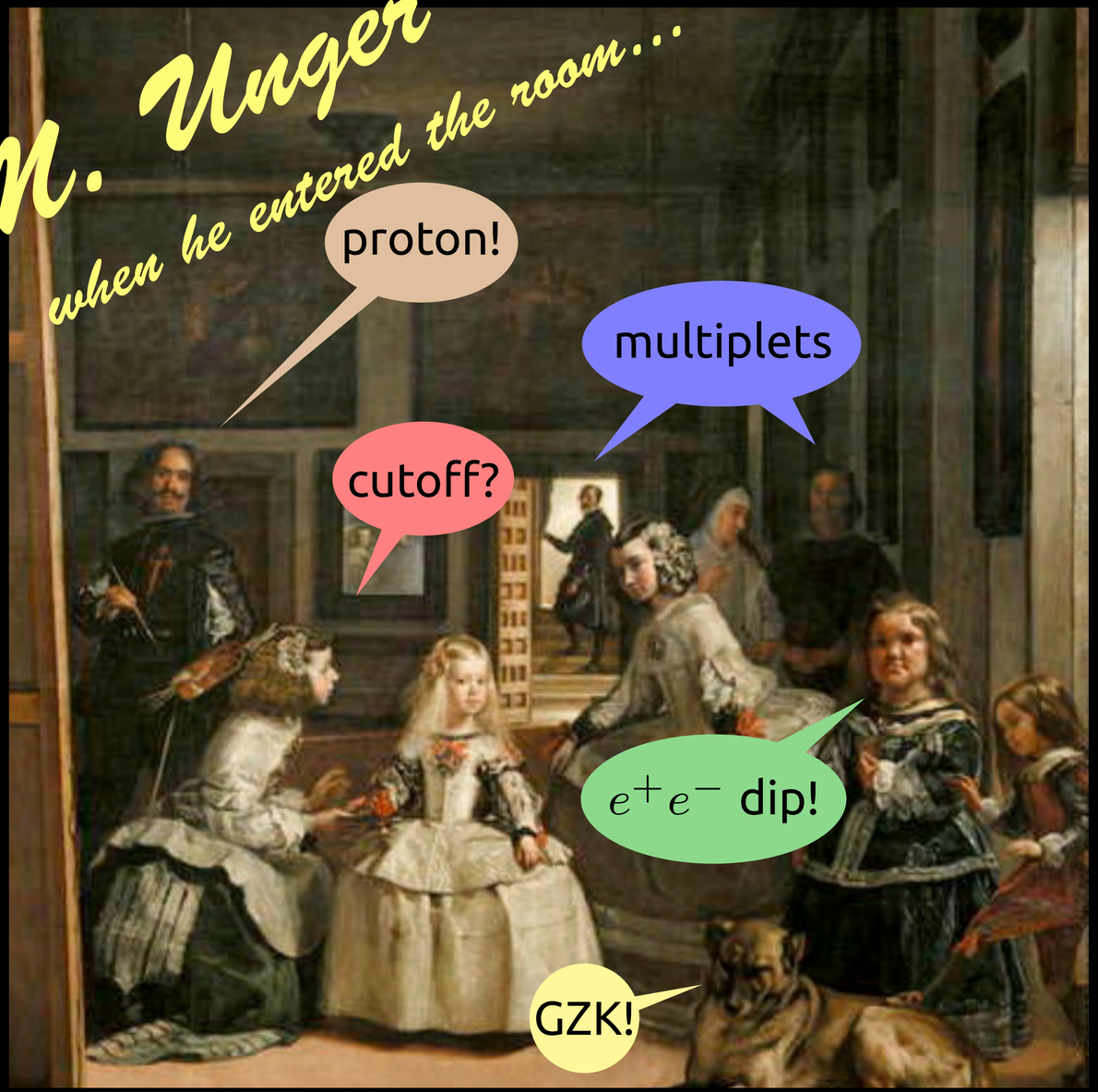
UHECR in 2019

M. Unger

Las Meninas by Diego Velazquez 1656

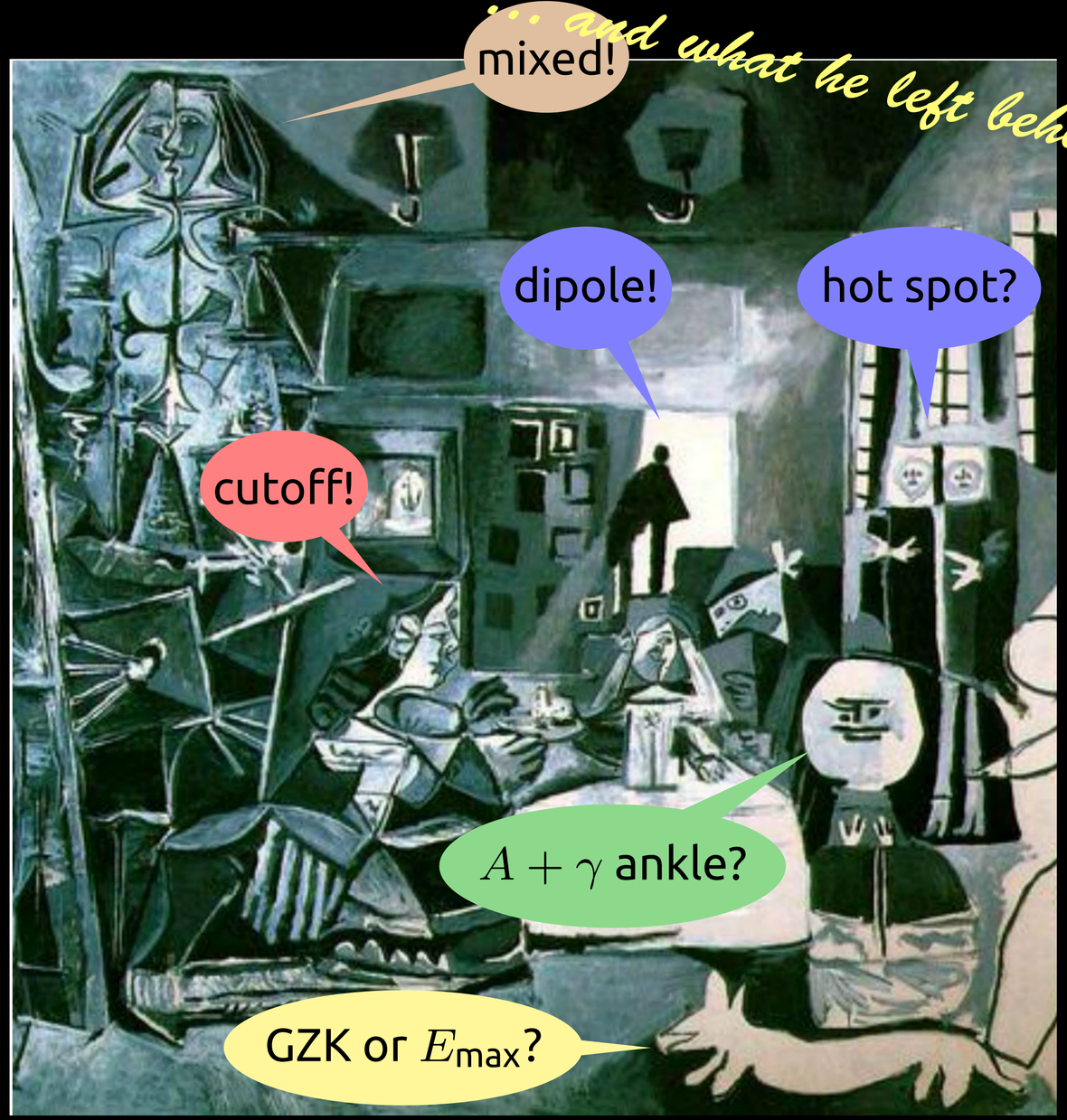
Las Meninas by Pablo Picasso 1957

UHECR before Auger



Las Meninas by Diego Velazquez 1656

UHECR in 2019

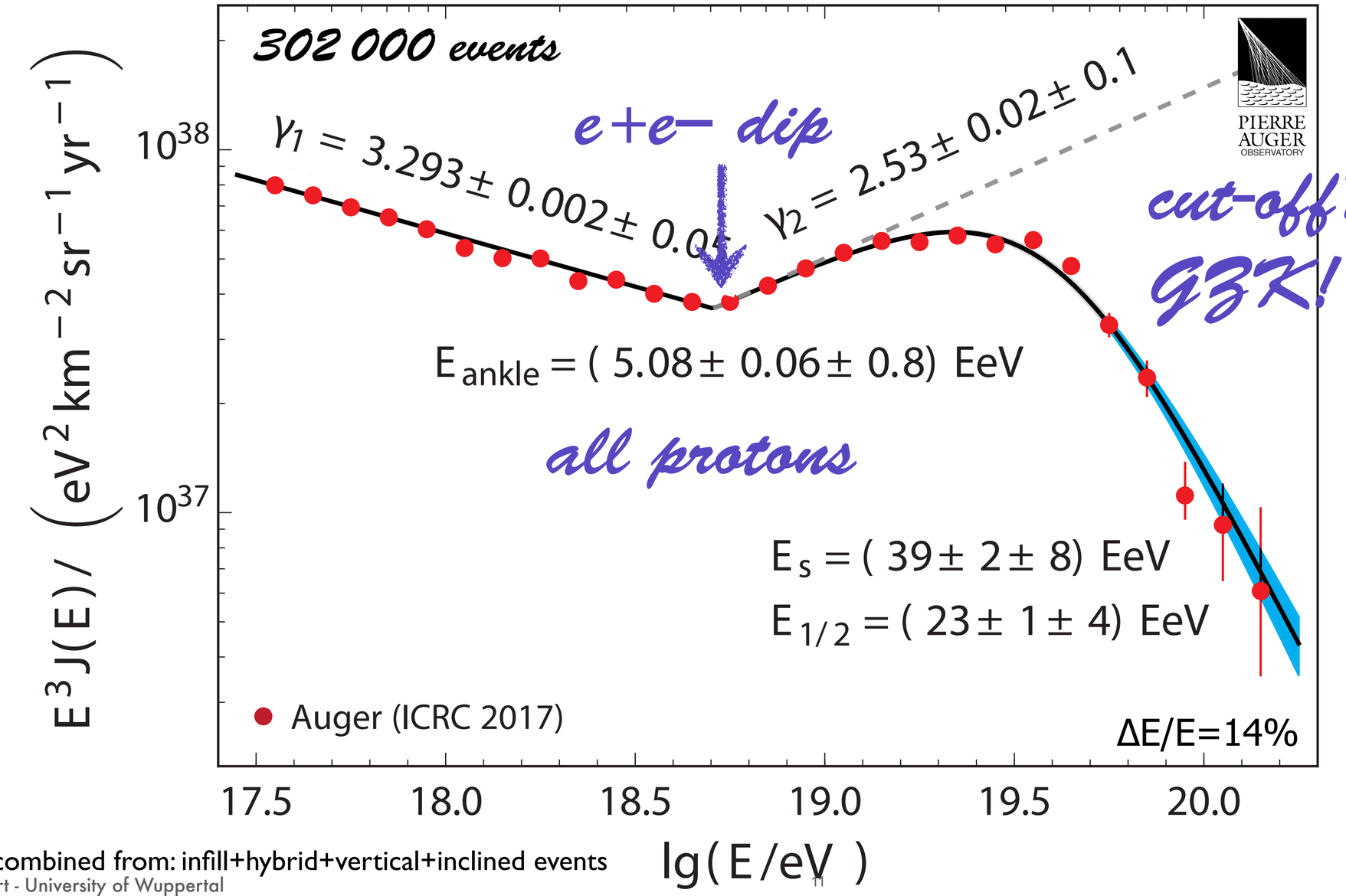


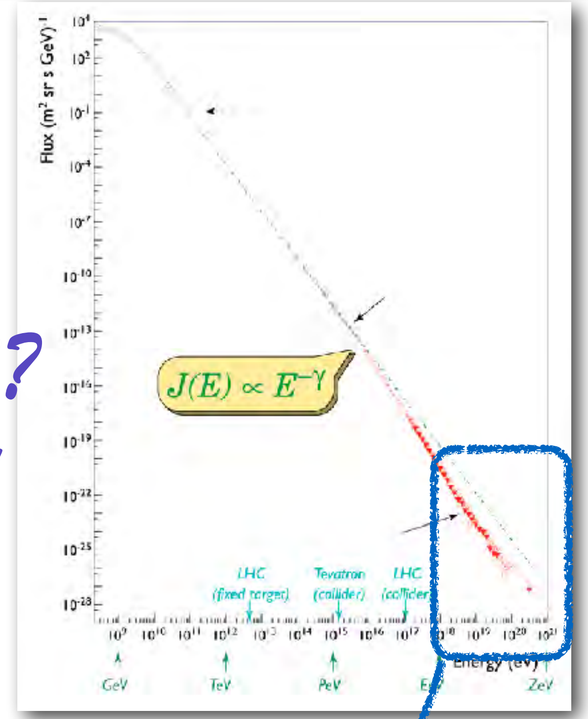
Las Meninas by Pablo Picasso 1957

End of the CR-Spectrum (0°-80°)

arXiv:1708.06592
Update from: PRL 101, 061101 (2008), Physics Letters B 685 (2010) 239

Before Auger…





combined from: infill+hybrid+vertical+inclined events

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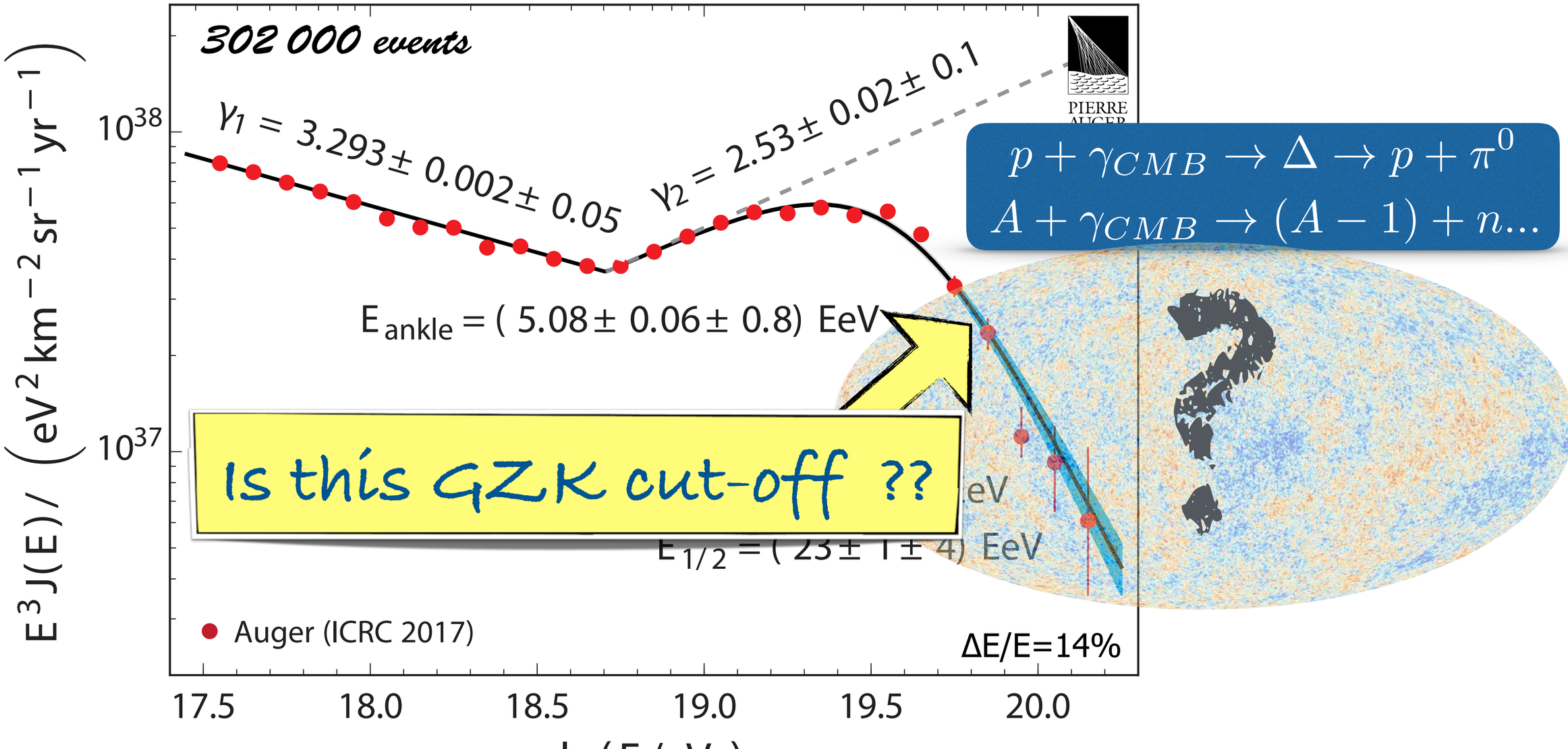
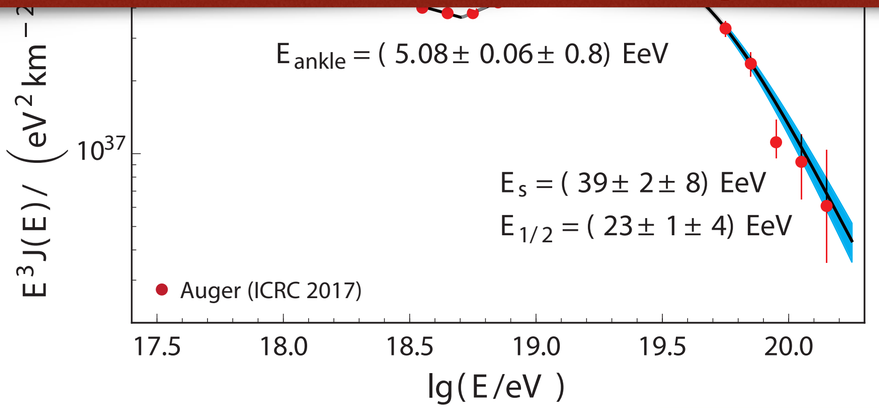


$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0$$
$$A + \gamma_{CMB} \rightarrow (A-1) + n...$$

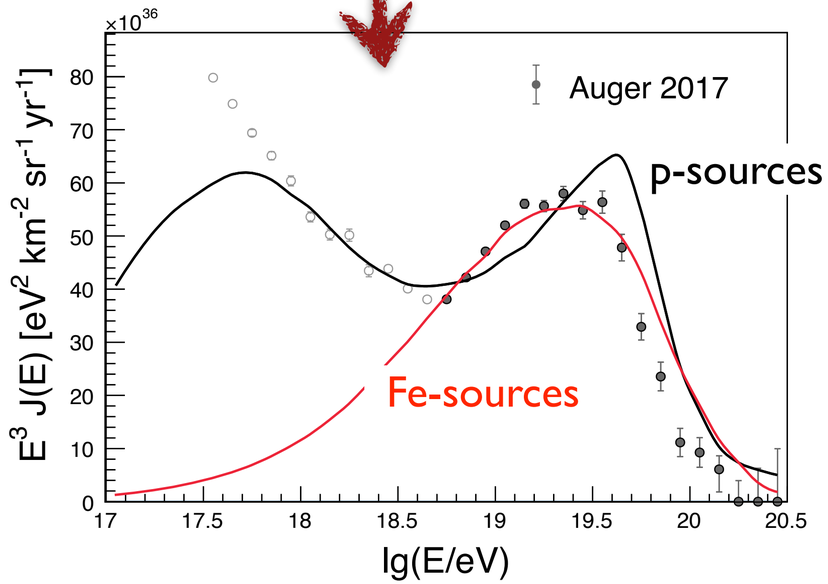
combined from: infill+hybrid+vertical+inclined events

GZK-effect or Sources running at their limits?

Energy spectrum alone cannot tell origin of the cut-off, need mass composition in addition

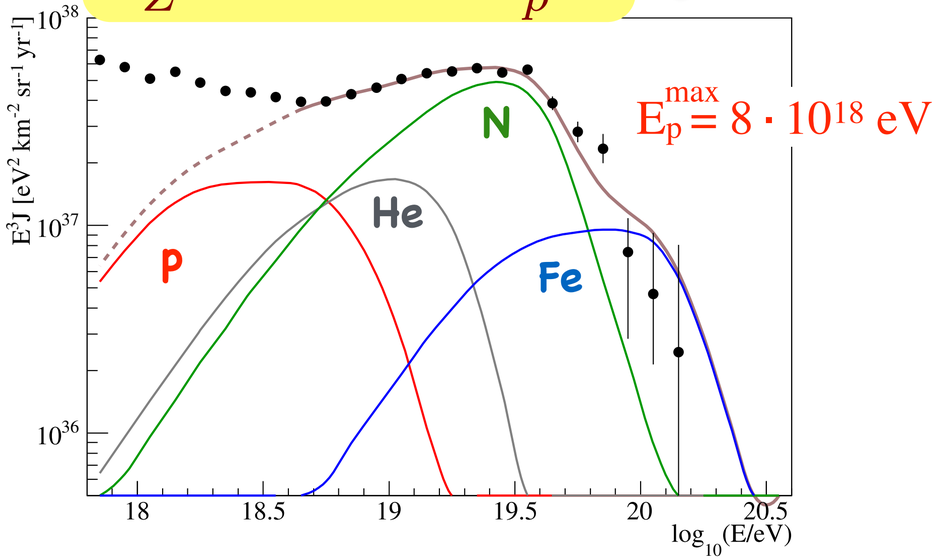


GZK-effect



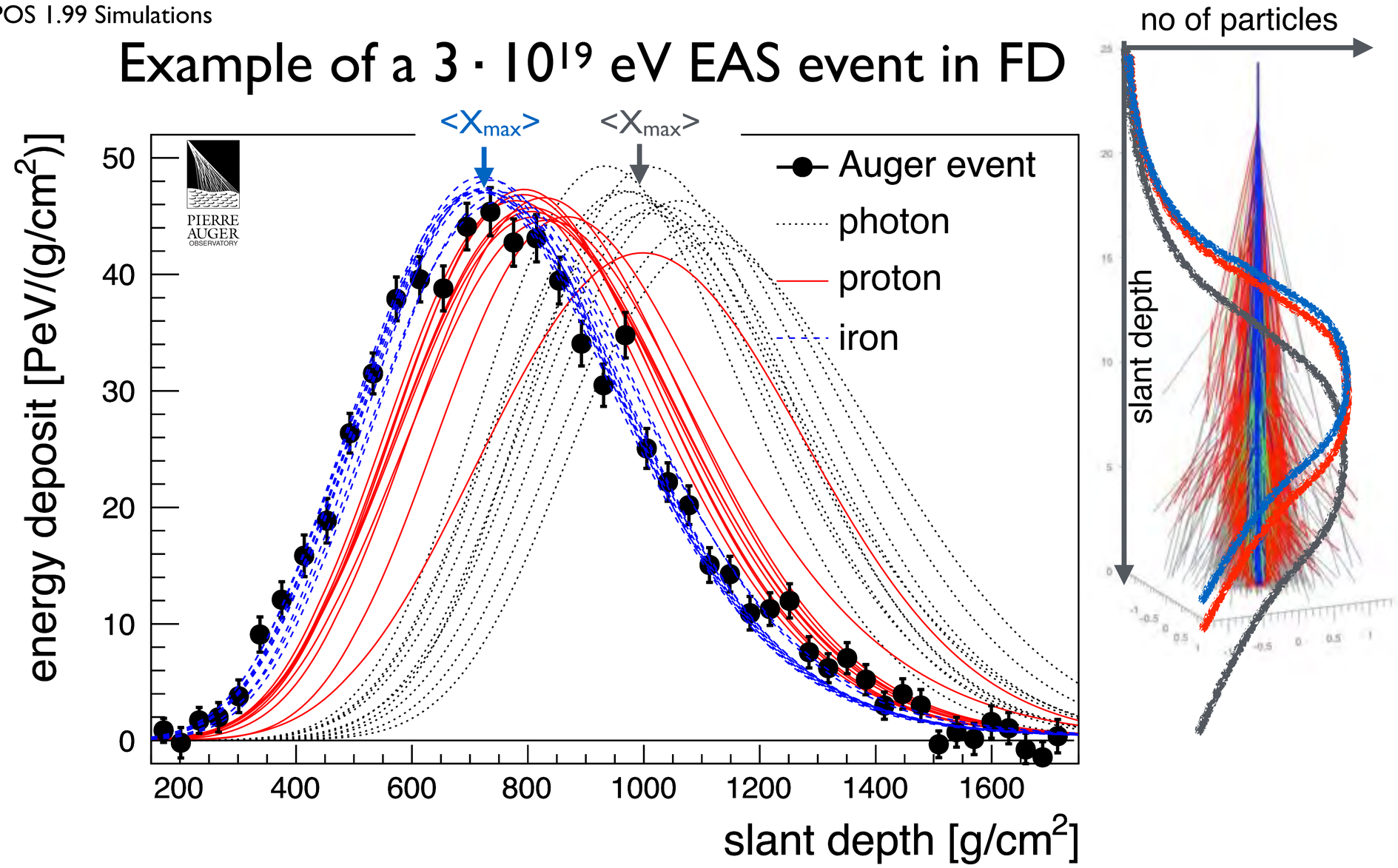
limited UHECR acc. energy

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

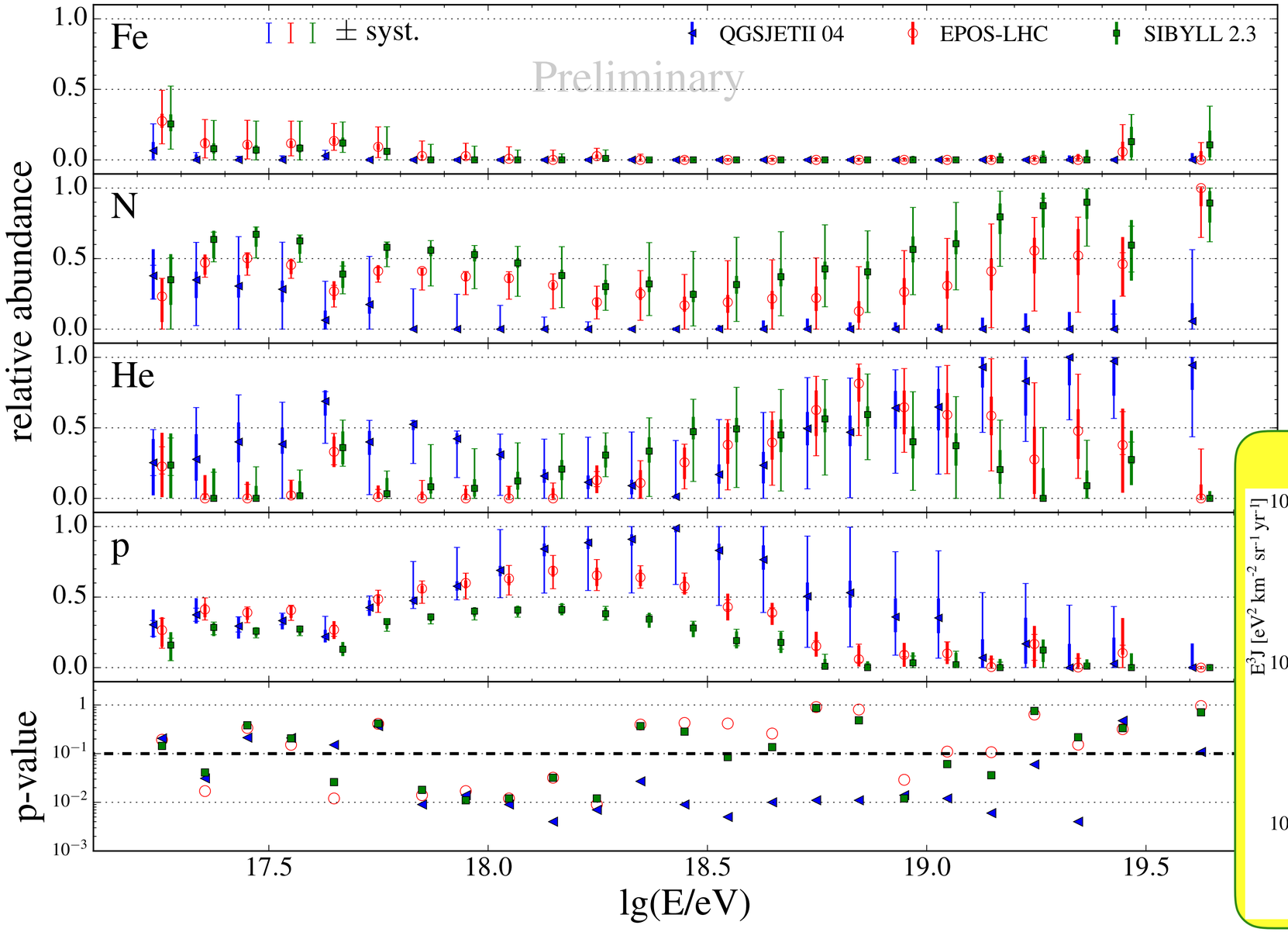


Longitudinal Shower Development → Primary Mass

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

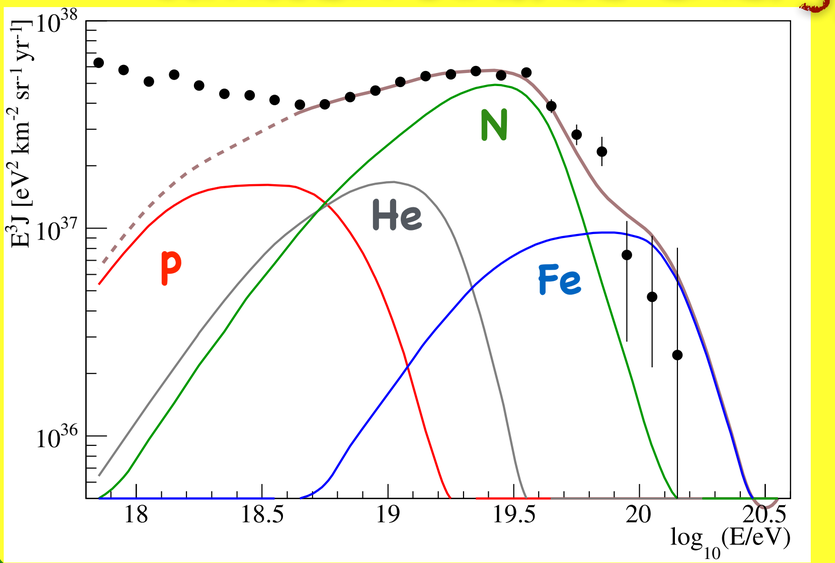


Mass Fractions



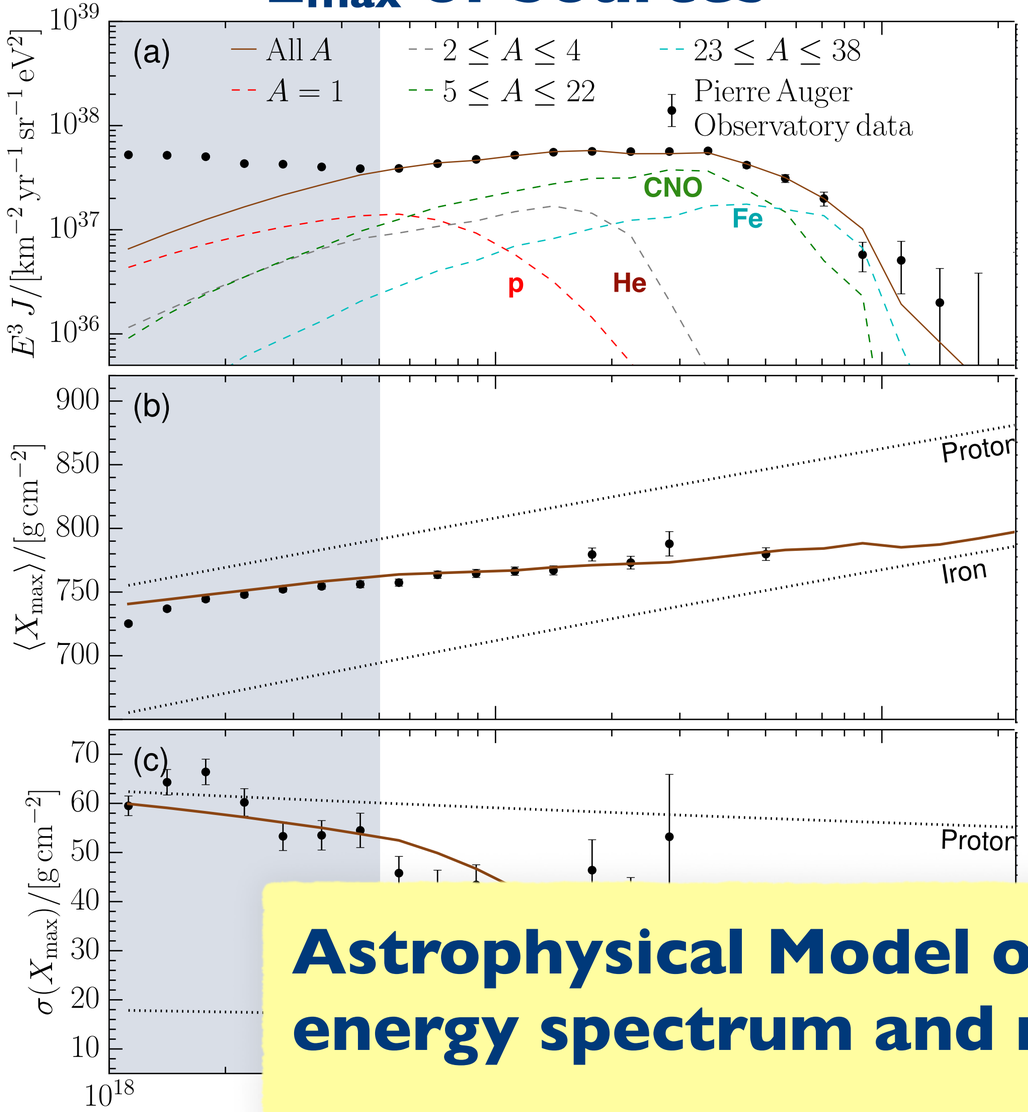
Bellido (Auger)
@ ICRC2017
arXiv:1708.06592

remember....
limited source energy ?



E_{max} of Sources vs GZK-Energy losses

E_{max} of Sources

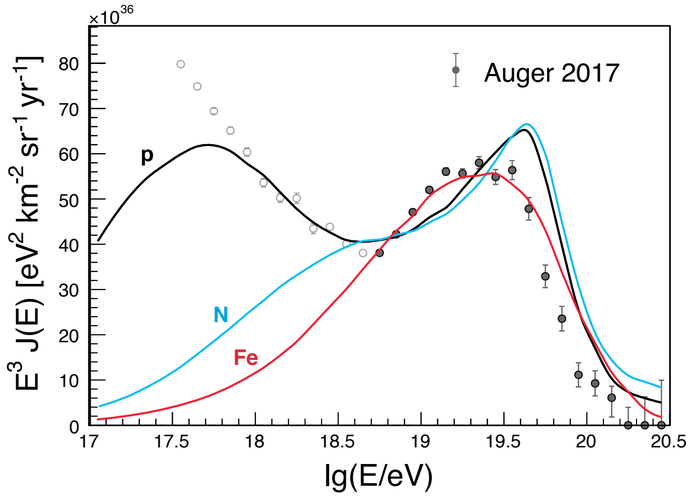


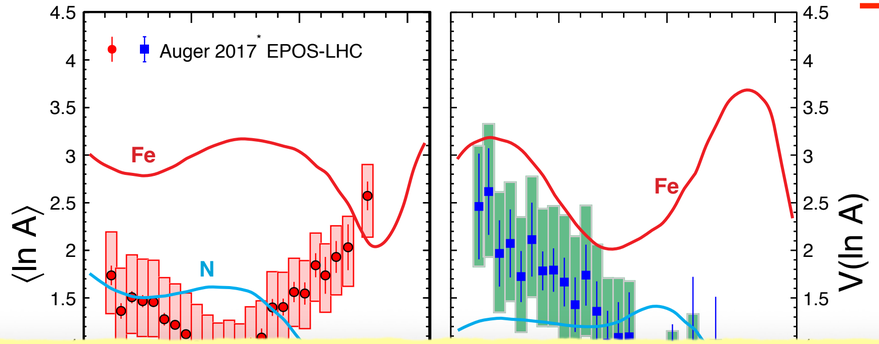
✔

✔

✔

GZK-effect





😑

☹️

— p-sources
— N-sources
— Fe-sources

Astrophysical Model of maximum source rigidity describes energy spectrum and mass composition…

… and the observed anisotropies!

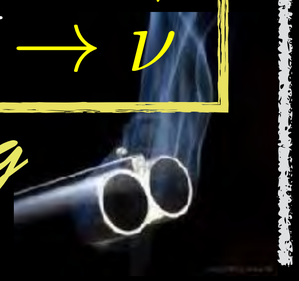
Independent test of seeing E_{max} of sources vs GZK suppression

Flux suppression above 5.10^{19} eV due to...

- GZK-effect

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0 \rightarrow \gamma$$
$$\rightarrow n + \pi^+ \rightarrow \nu$$

smoking gun...



- E_{max} of sources

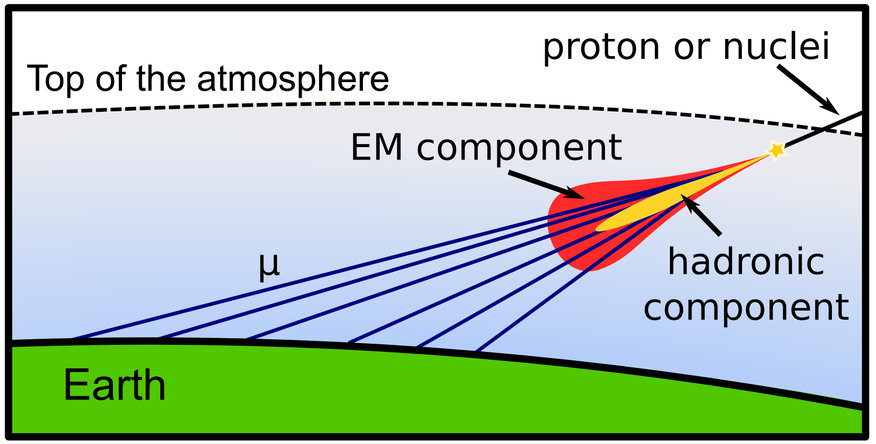
no cosmogenic neutrinos or photons

⇒ cosmogenic neutrino & photon fluxes sensitive to origin of flux suppression

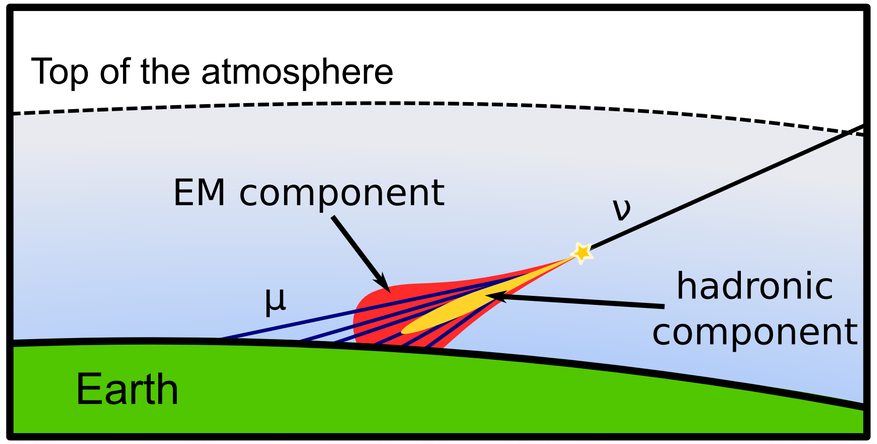
EeV Neutrinos detectable in inclined air showers

- 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



hadronic induced shower
at large zenith angles
→ no em-component („old“ shower)



neutrino induced shower
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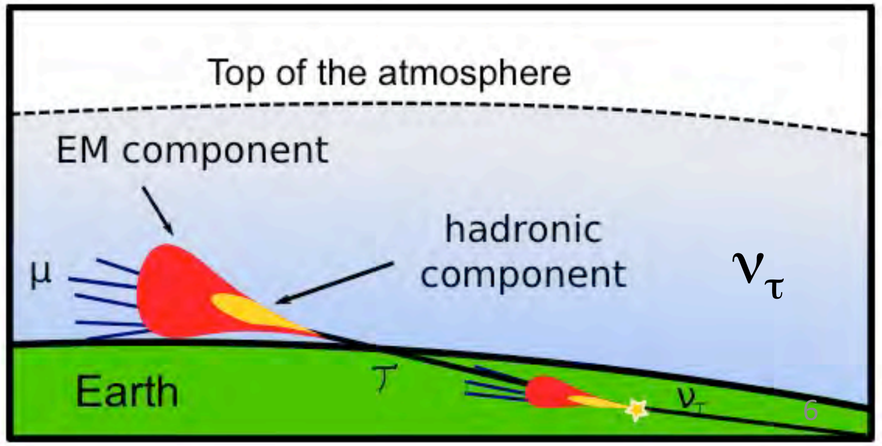

tau-neutrino in Earth skimming event
produces
up-going young shower

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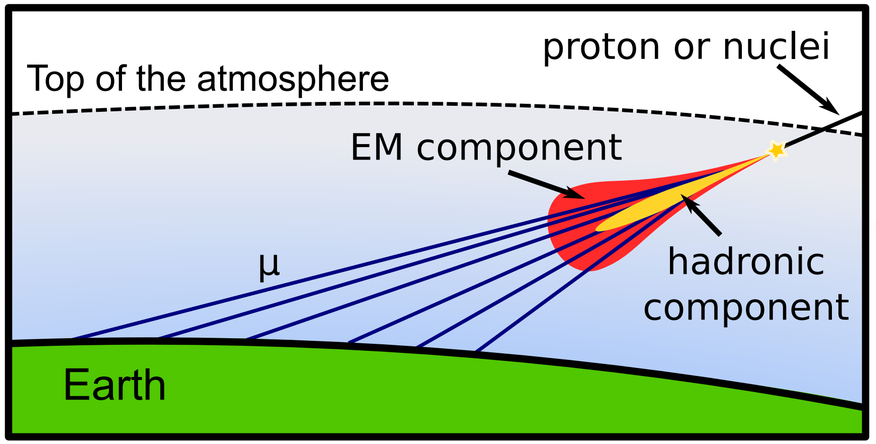
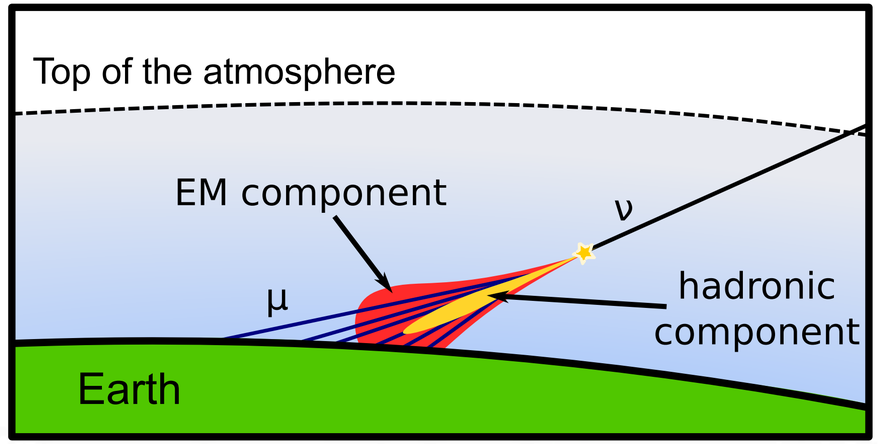
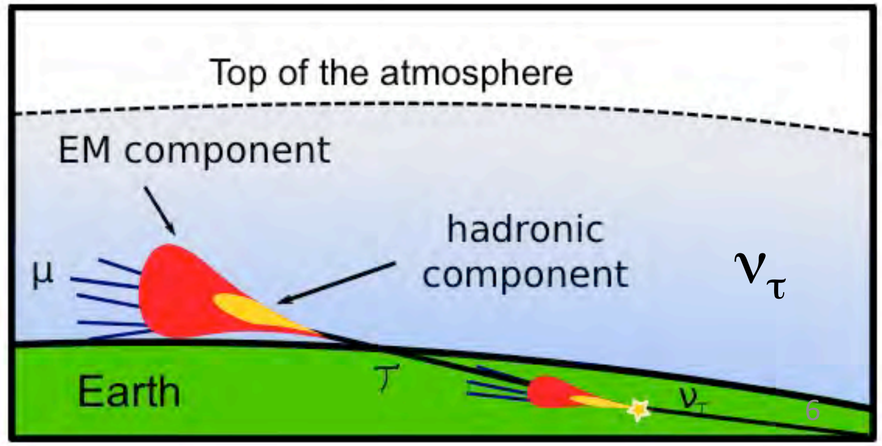
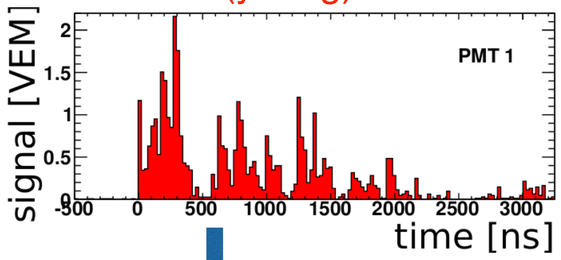




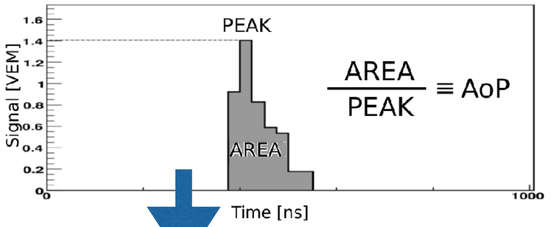


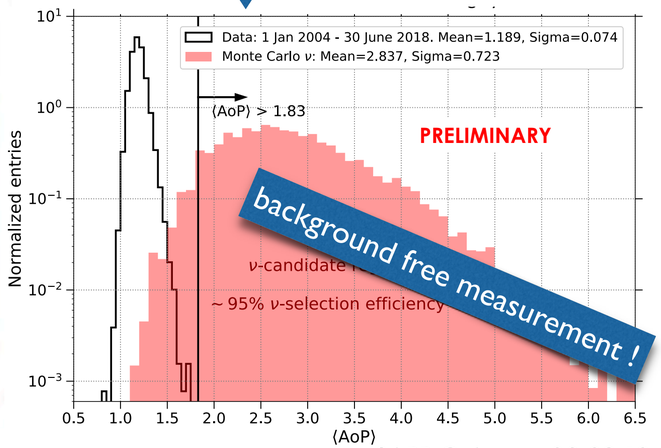
young / old showers identified by signal trace in water Ch-detectors

Typical signal trace of an em-rich (young) shower



Define Area-over-Peak (AoP)

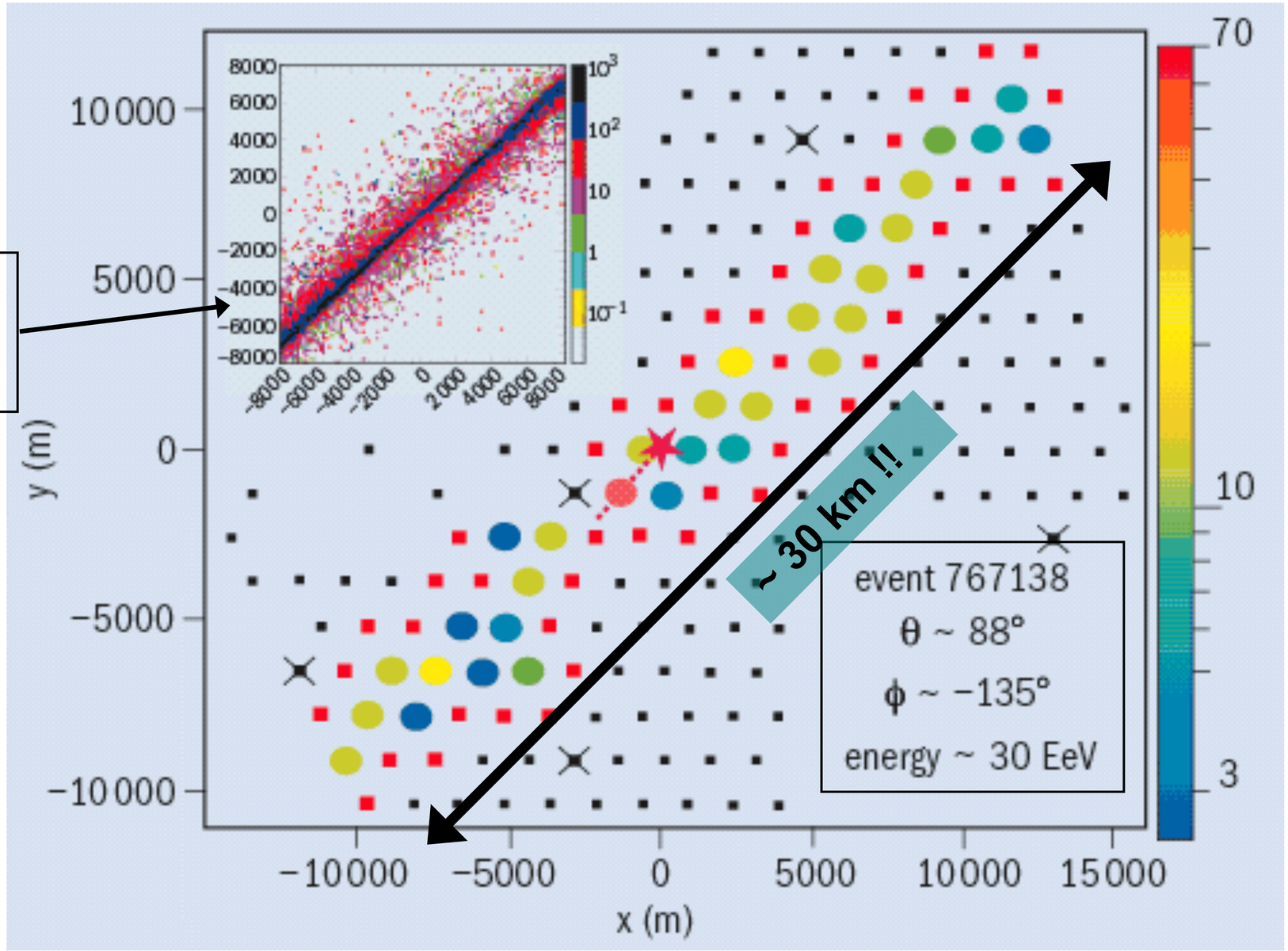




Example of an inclined event seen in Auger

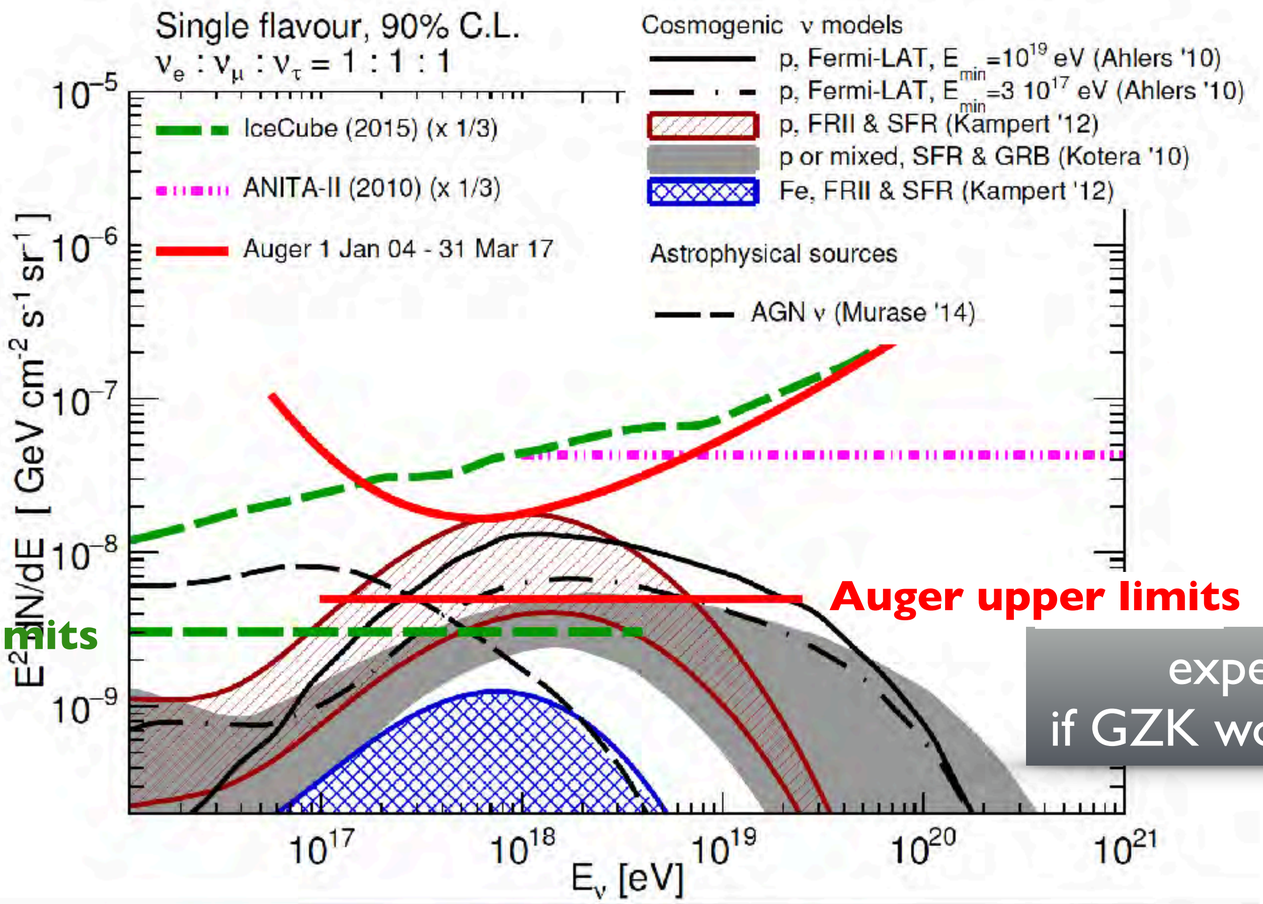
CERN Courier
July 25 2006

MC simulation of an event with the same angle and energy.



EeV Neutrino Limits challenge protons suffering GZK-losses

Auger Collaboration, PRD 91, 092008 (2015); update ICRC2017



IceCube upper limits

Auger upper limits

expected cosmogenic fluxes
if GZK would cause cut-off in spectrum

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

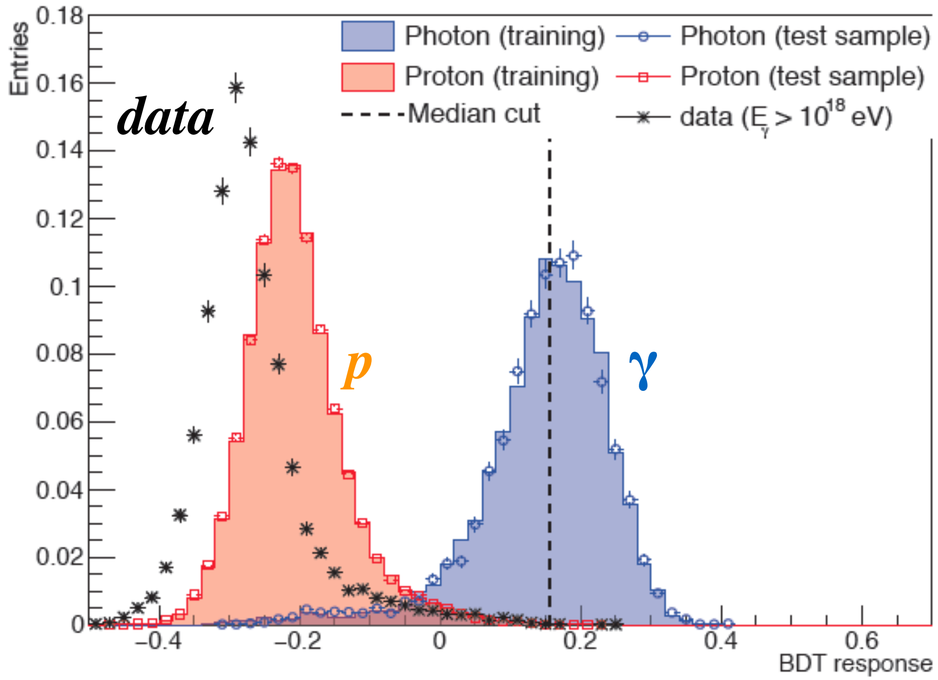
Neutrino upper limits start to constrain
cosmogenic neutrino fluxes of p-sources

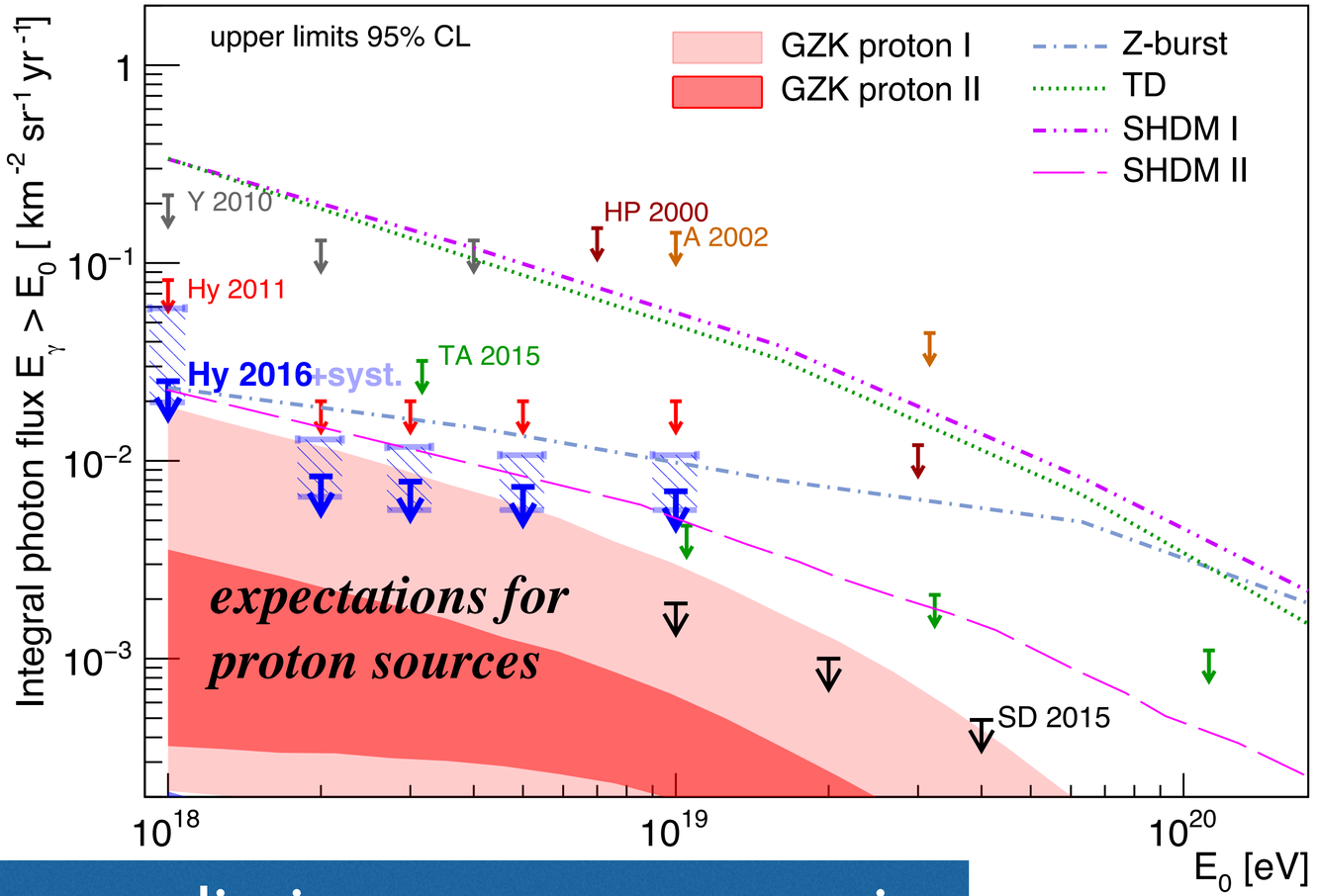
EeV Photon Limits challenge protons suffering GZK-losses

Auger Collaboration, JCAP04 (2017) 009

M. Niechciol (Uni Siegen), Diss. N. Krohm / P. Papenbreer (BUW)

Photons can be identified by deep X_{max} and low muon number





Similarly, photon upper limits start to constrain cosmogenic photon fluxes of p-sources

E_{max} of Sources
Consequences to Neutrinos

... yet, no observation of cosmogenic neutrinos and photons

...but not all of parameter space tested, yet

...could be a guaranteed source of UHE neutrinos for doing particle physics

→ wish to improve sensitivities even further (more later)

E_{max} of Sources
Consequences to particle physics

... 10^{20} eV proton beam is at least subdominant

...cms-energies for doing particle physics is limited

... still, there are some indications for a small fraction O(10%-20%) of protons at the highest energies

→ wish to identify those event-by event

E_{max} of Sources
Consequences to UHECR astronomy

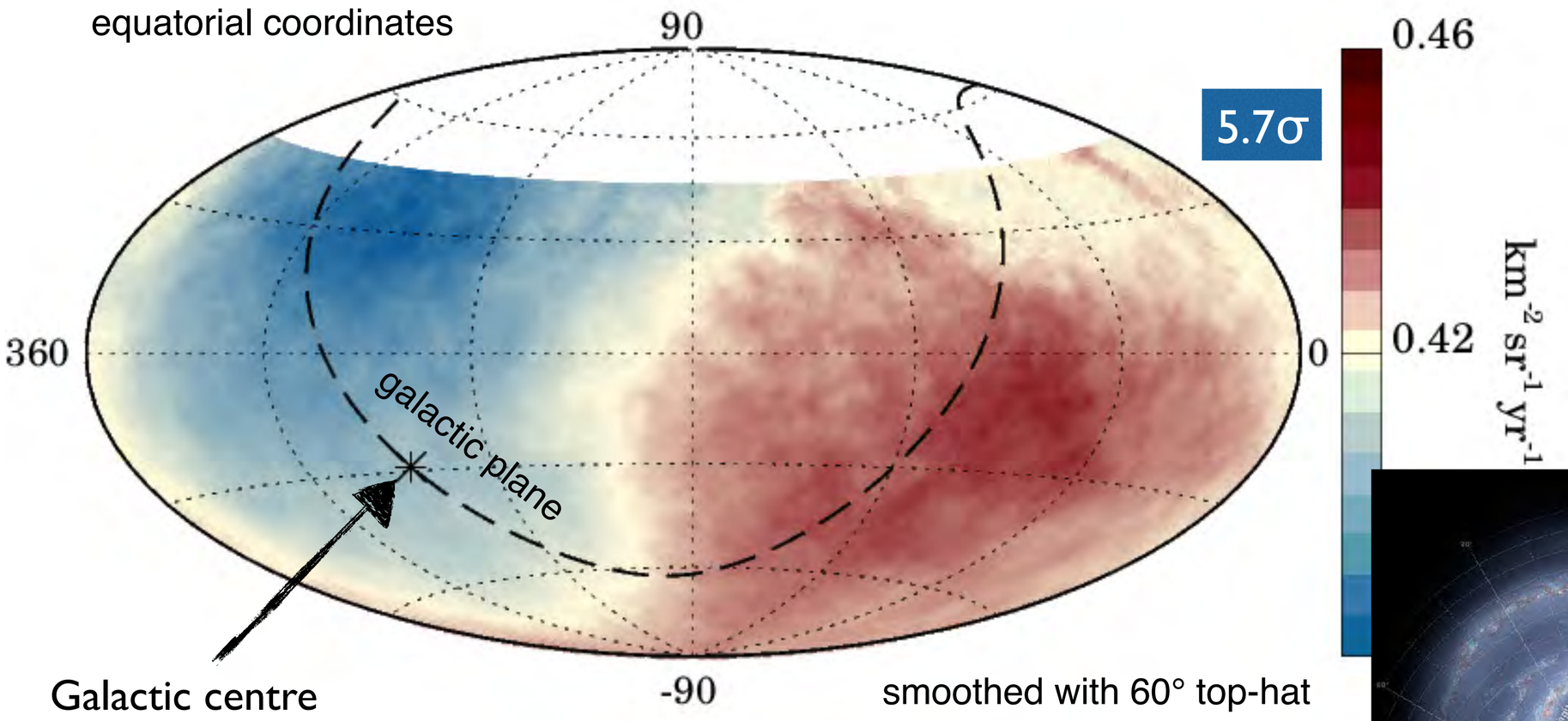
... seeing the sources of UHECR is more difficult than we had hoped

...more source candidates possible because of relaxed constraints at sources

→ if light primaries could be selected at highest energies, proton-astronomy still possible

All-Particle Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266



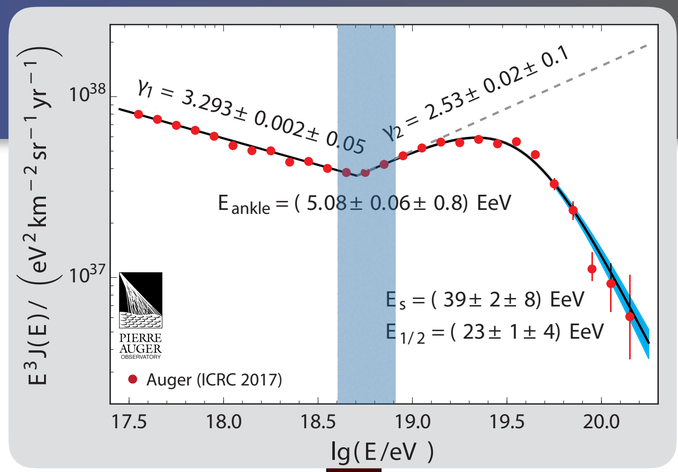
$$\mathcal{A} = 6.5^{+1.3}_{-0.9}\,\% \;\; ; \;\; \alpha_d = (100 \pm 10)^\circ \;\; ; \;\; \delta_d = (-24^{+12}_{-13})^\circ$$

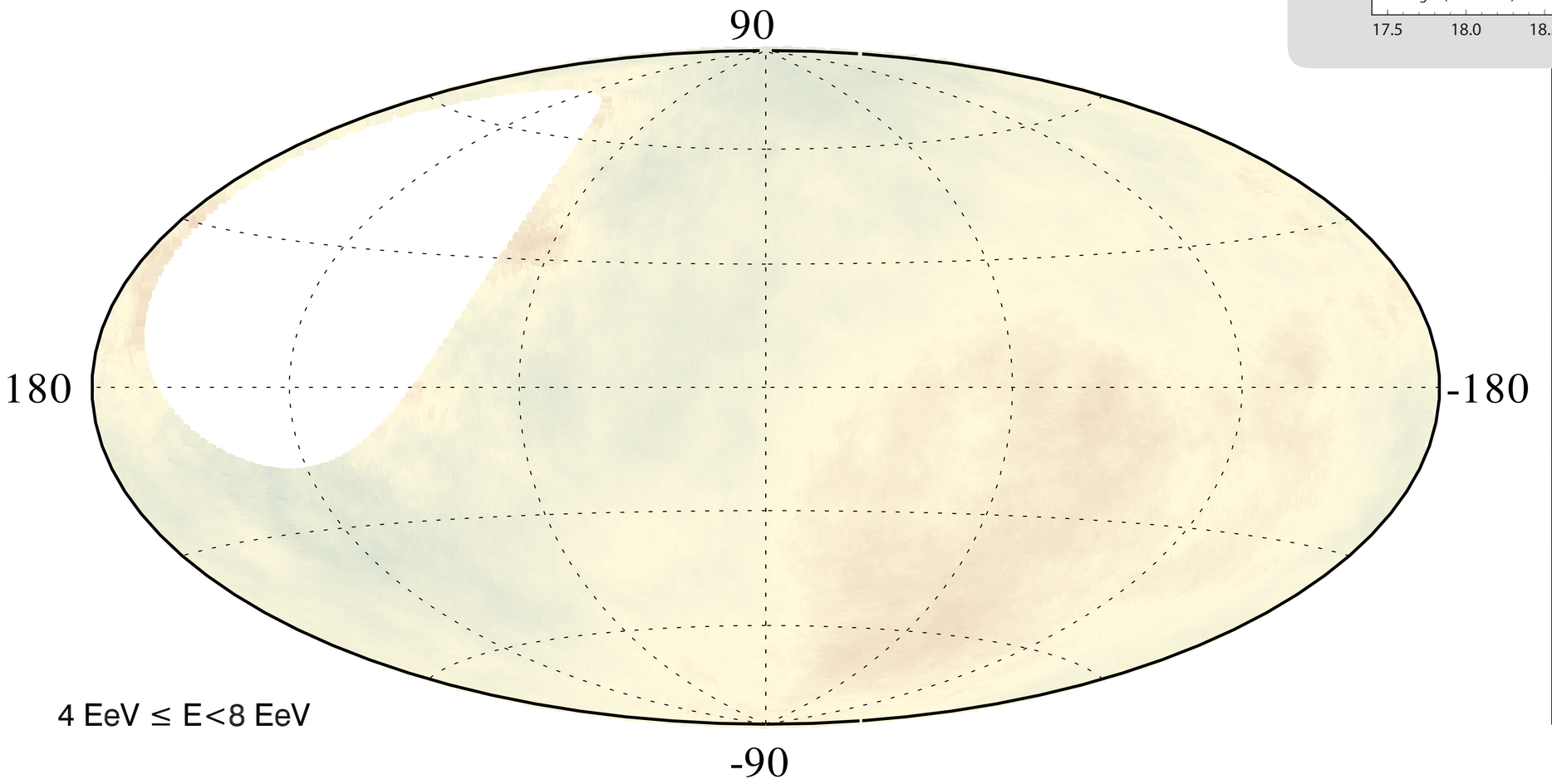
Evolution with Energy: 4-8 EeV

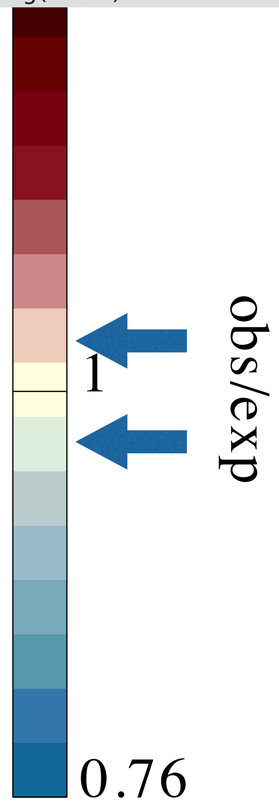
Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale







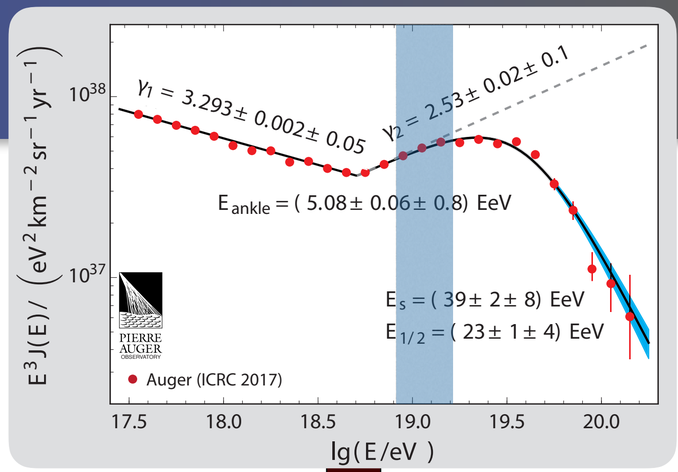
4 EeV ≤ E<8 EeV

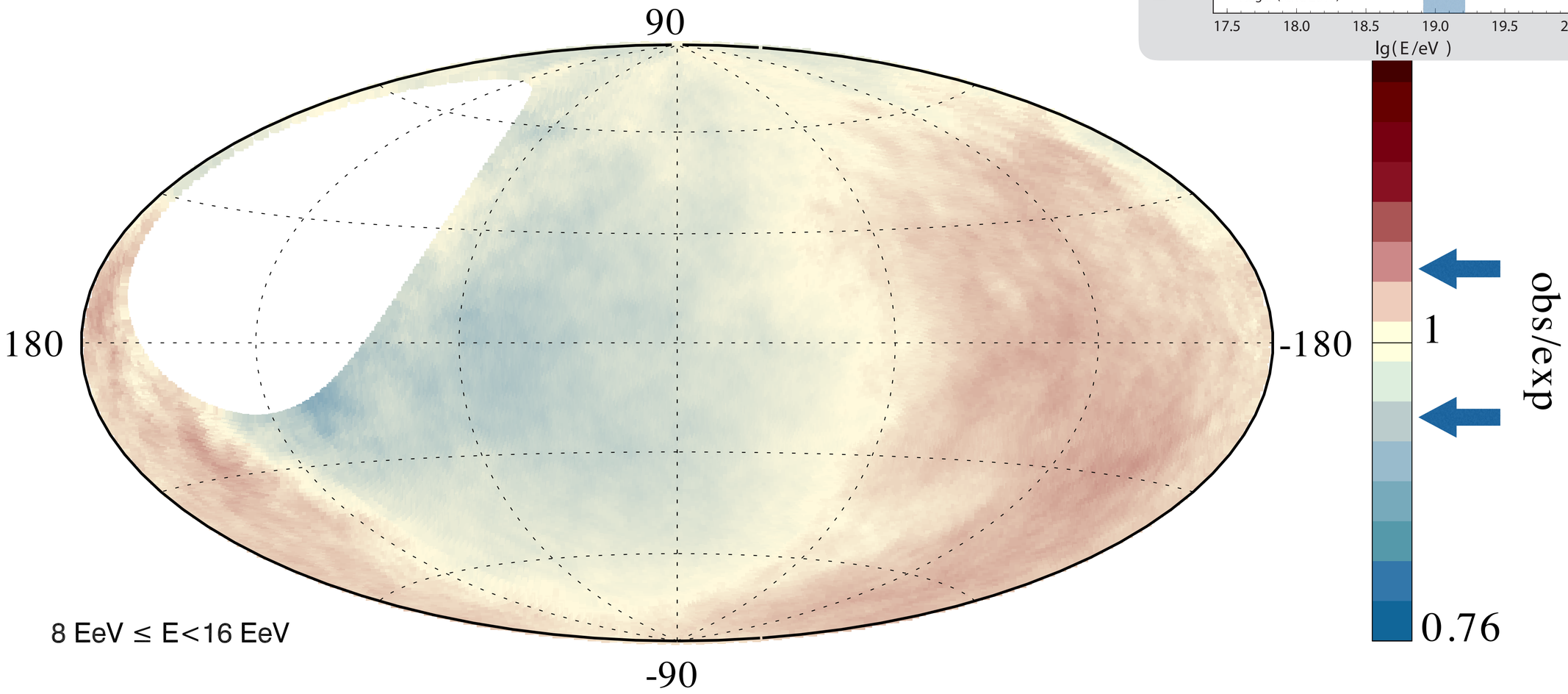
Evolution with Energy: 8-16 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



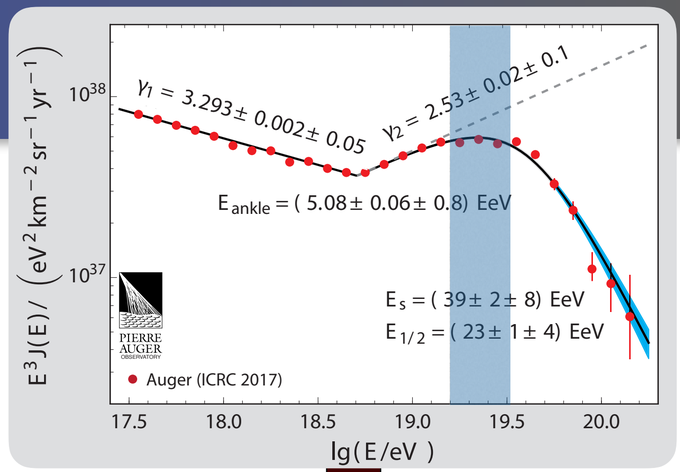


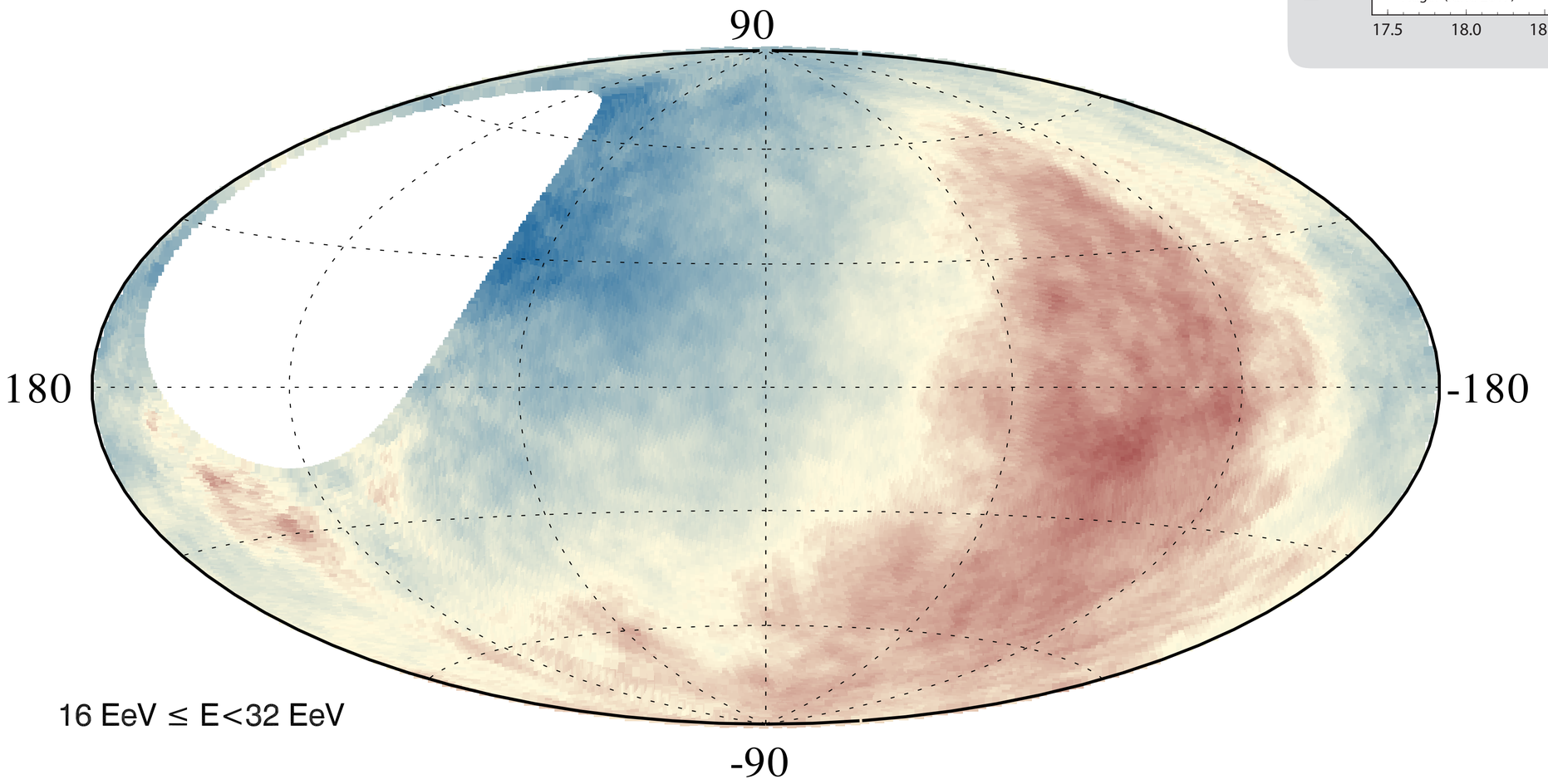
Evolution with Energy: 16-32 EeV

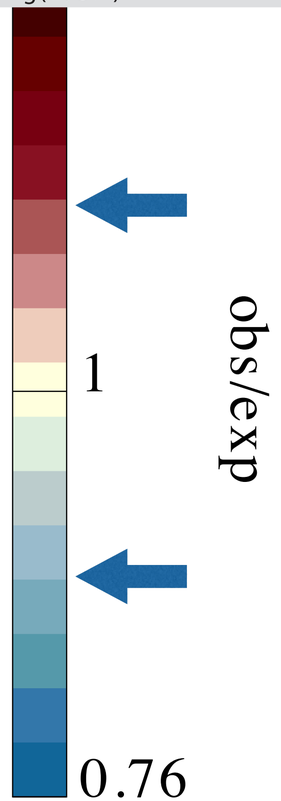
Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale





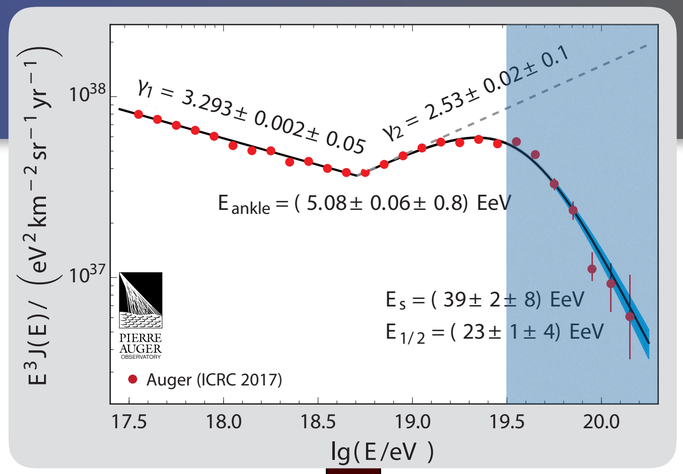


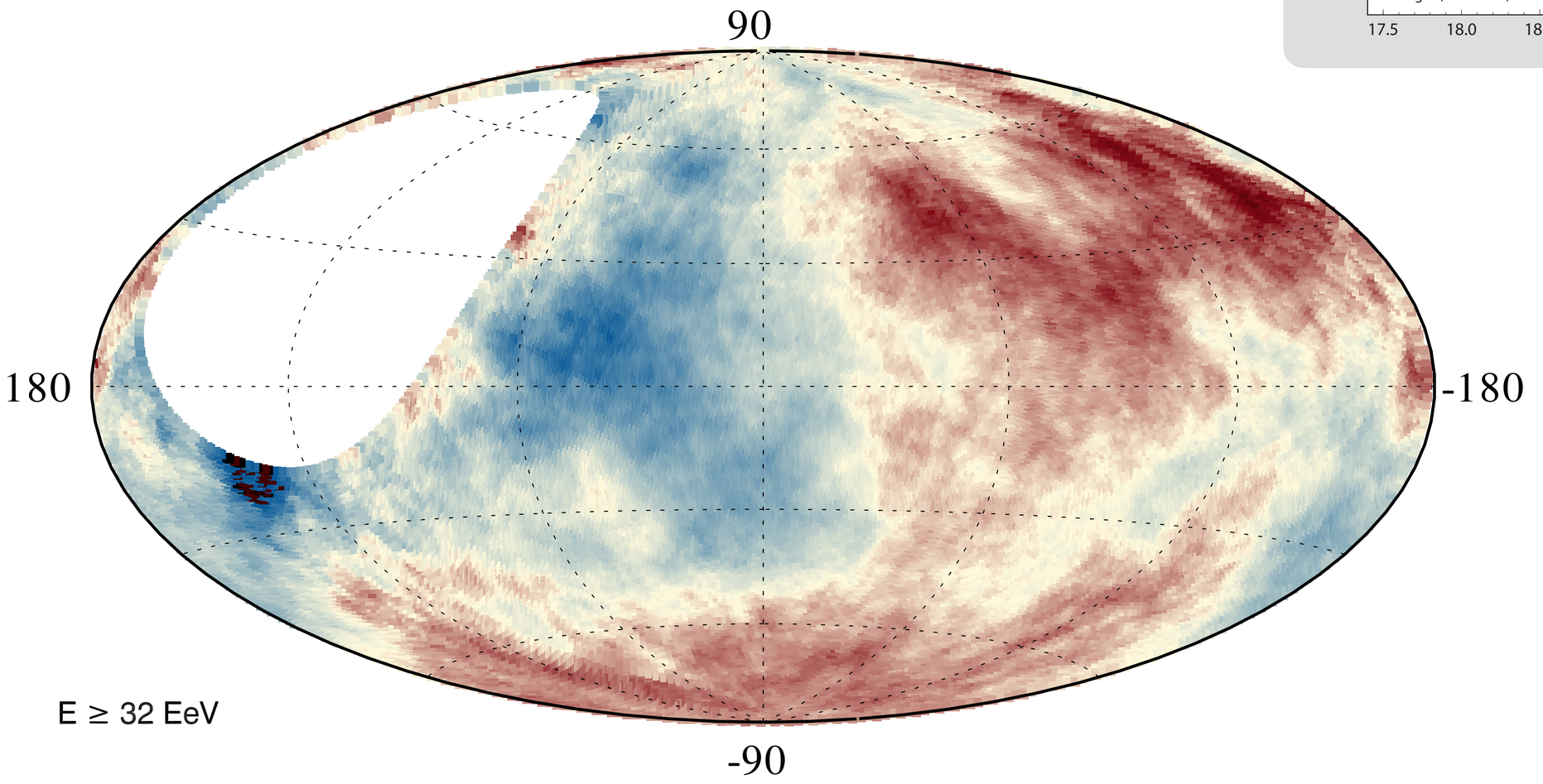
Evolution with Energy: >32 EeV

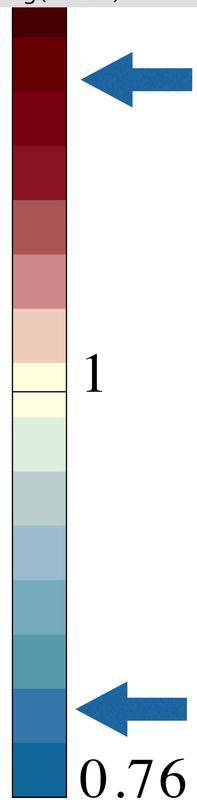
Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



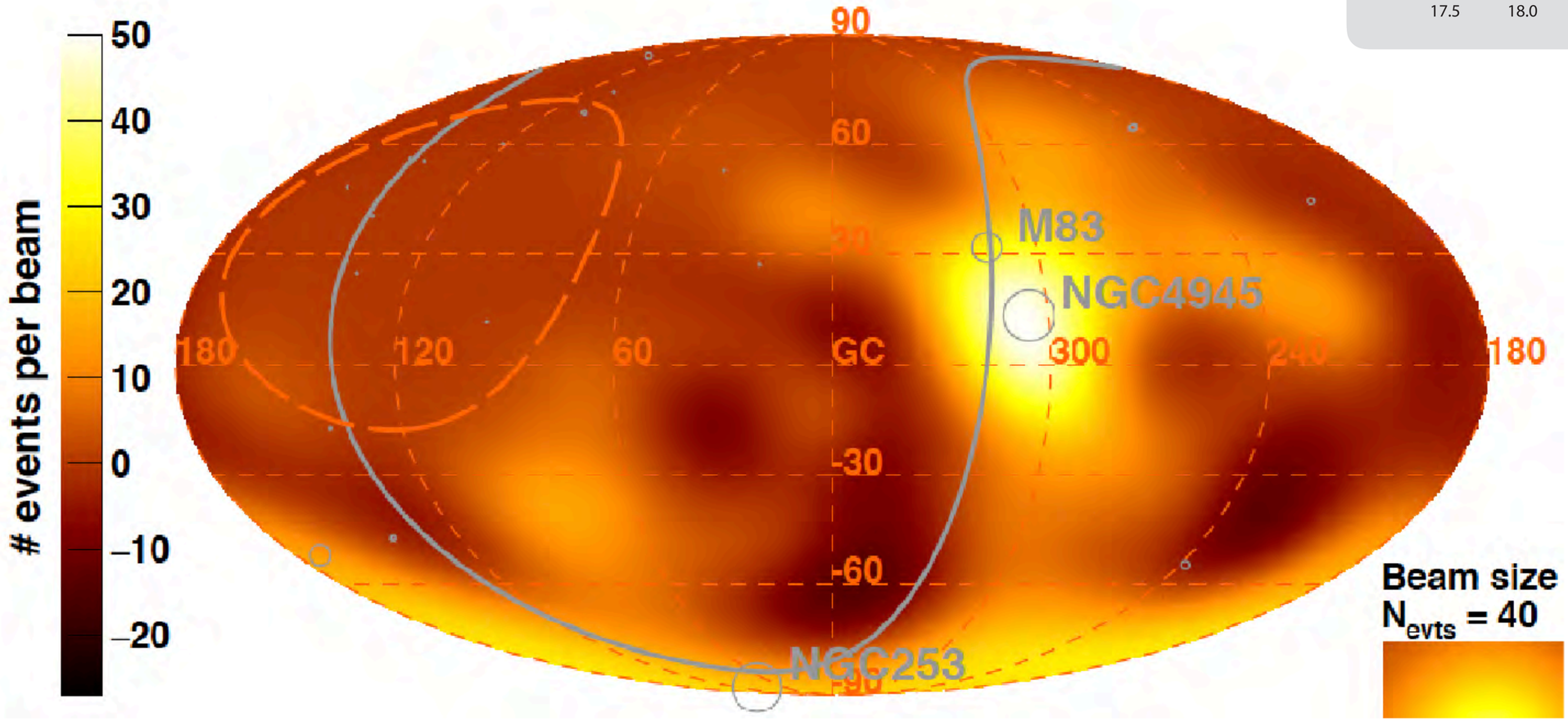


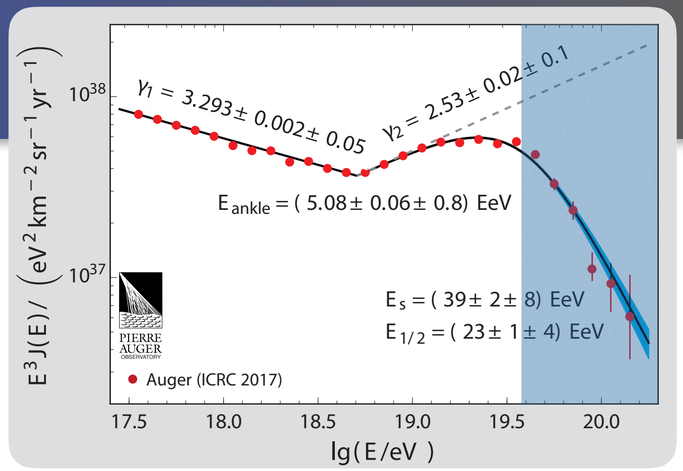


Evolution with Energy: >39 EeV

Auger: ApJL 853:L29 (2018)

map smoothed with 15° top-hat
Galactic coordinates

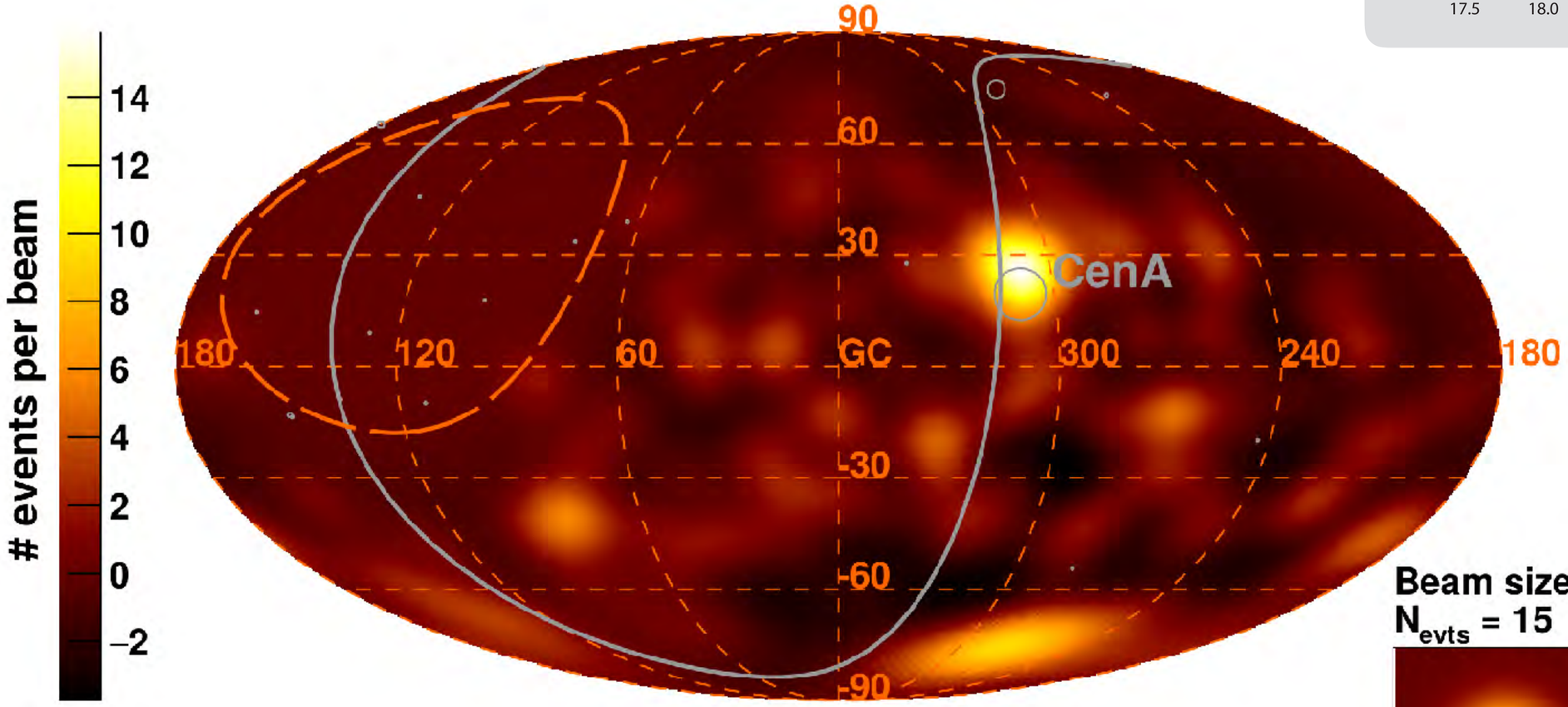


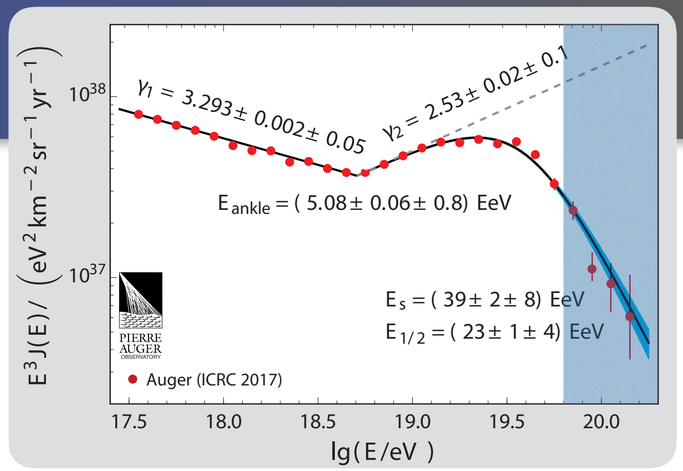


Evolution with Energy: >60 EeV

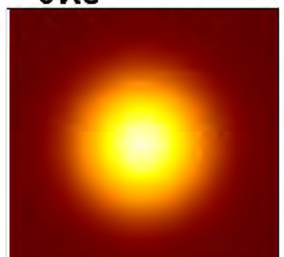
Auger: ApJL 853:L29 (2018)

map smoothed with 7° top-hat
Galactic coordinates



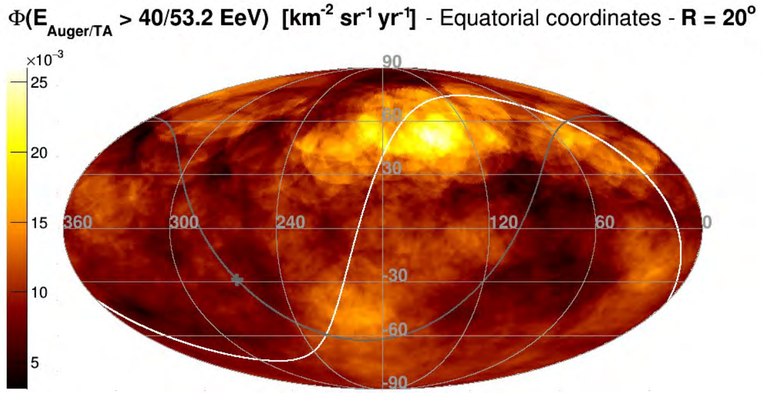


Beam size
$N_{evts} = 15$



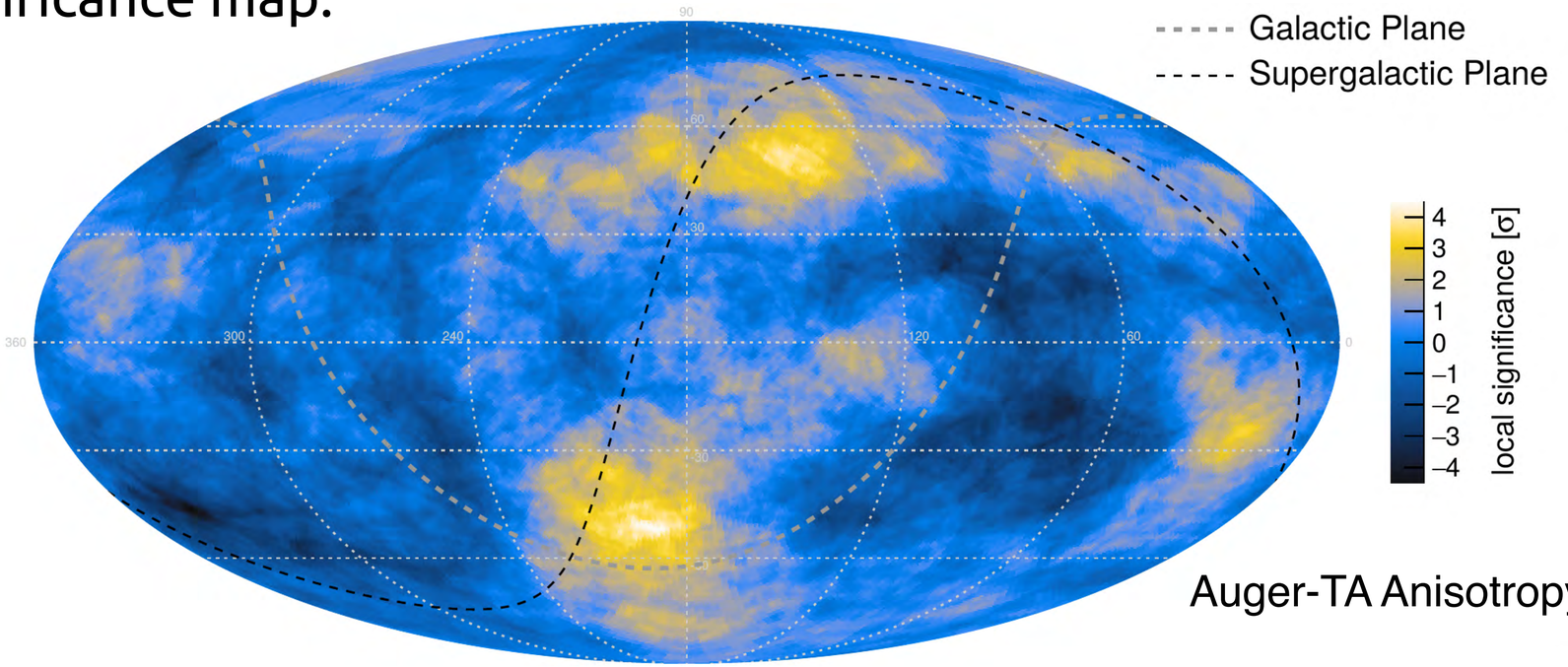
Full-Sky picture of TA and Auger

flux map:



- two “warm spots” with 4.7/4.2 σ local significance
- post-trial 2.2/1.3 σ
- aligned along super-galactic plane?

significance map:



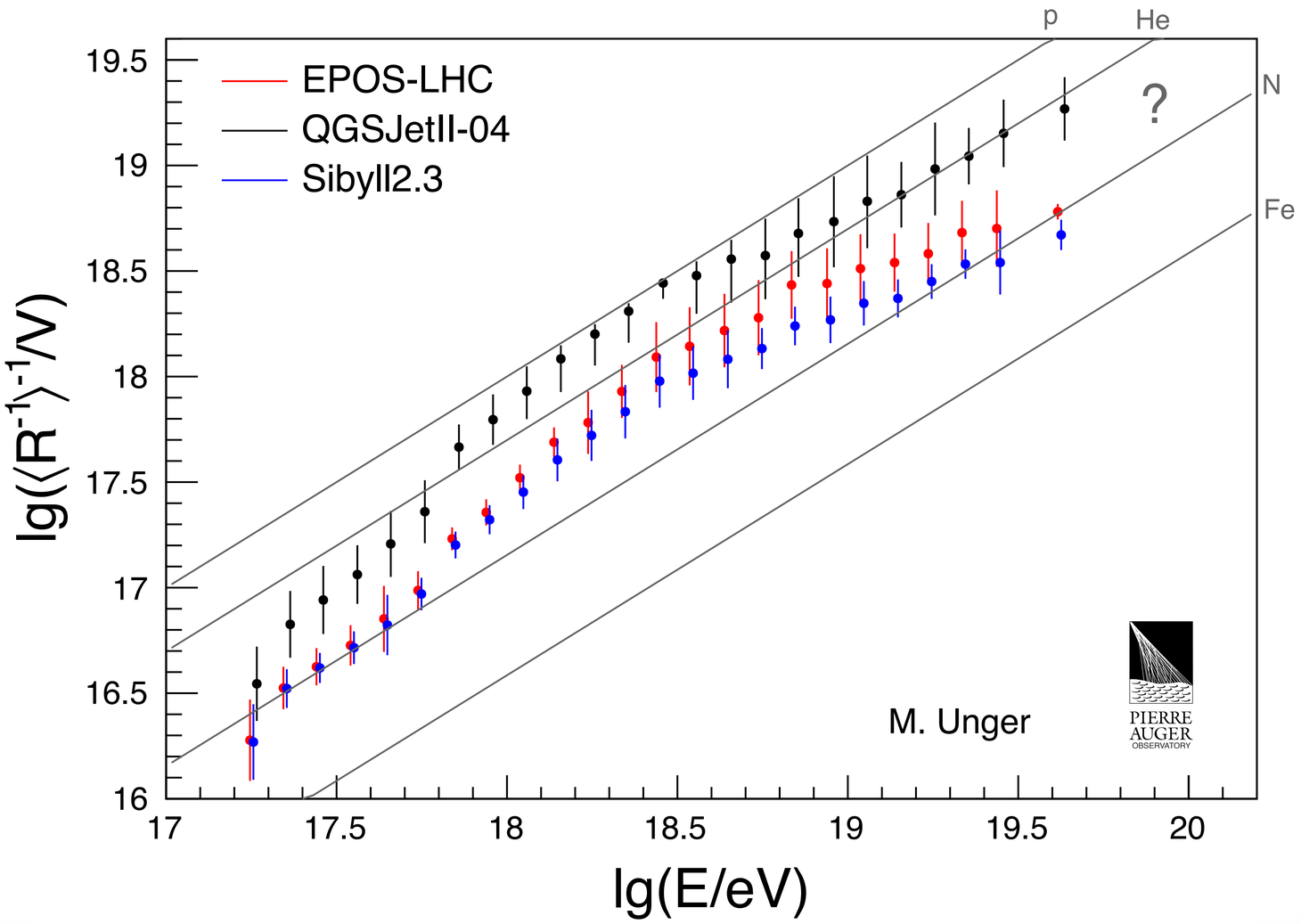
Auger-TA Anisotropy Working Group

What can we conclude from seeing increasingly more structures towards higher energies ??

Remember: $\text{deflection} \propto \frac{Z \cdot B}{E}$

... apparently E grows faster than Z !

Mean Rigidity vs Primary Energy



Rigidity ≃ E/Z continues to increase with energy despite increasing mass

Menu…

- **Primary goal of HE-Astroparticle Physics: Find Sources of UHECRs**
  - Which messenger is the best?
  - Photons?
  - Neutrinos?
  - or UHECR, or all together?
- **Reminder: Unexpected surprises in UHECR observations**
  (see Michael Ungers talk of yesterday)
- **What are the next logical steps** science wise **?**
- **How do we address the next (UHECR) challenges** experimental wise **?**
  - Taking shape: AugerPrime, TA*4
  - Go to space? POEMMA, EUSO…
  - Other dreams at ground

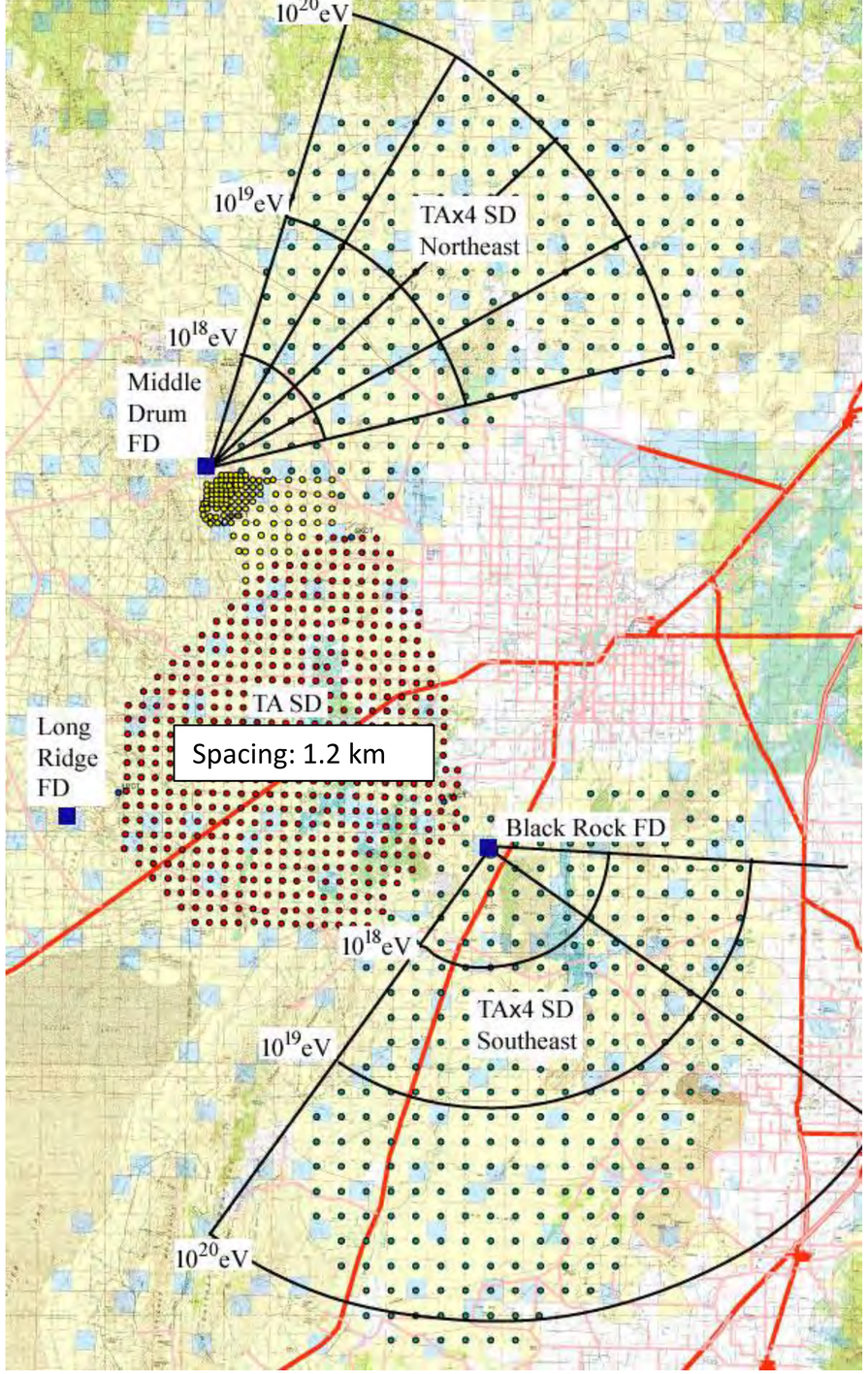
Just improve statistics...?

... more statistics is always nice :-)
in fact, TA suffers most from statistics → TA*4

... combine improved statistics with improved performance → AugerPrime

→ we can gain a lot by composition enhanced anisotropy studies

TA*4



SD: 700 ➔ **2800 km²**

- 500 new SD stations on 2.08 km spacing
- 2 new FD stations
- Optimized for UHECR above cutoff (fully efficient above ~60 EeV)

→ hot spot verification ☜ *prime goal*

GO FOR SIZE

First stations are now being deployed

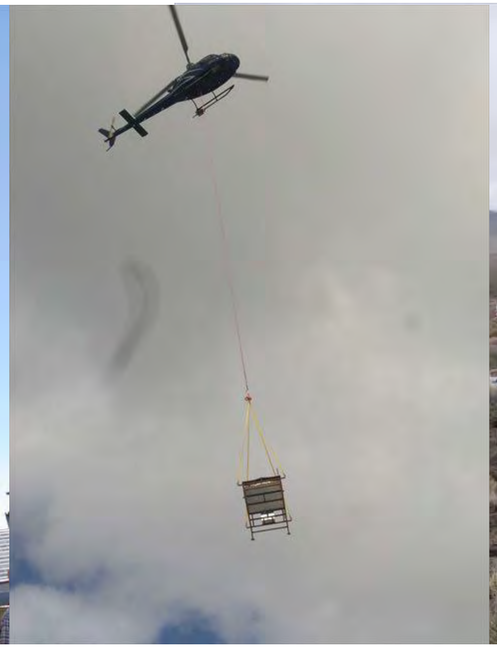
This is not a picture from an end-time movie

TA*4 Deployment

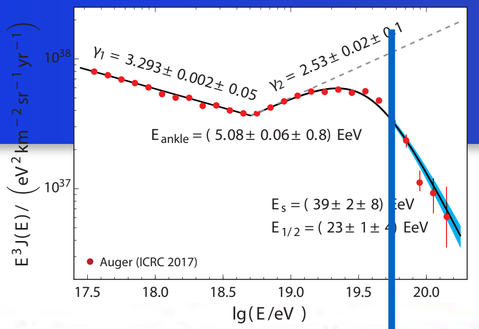
- Deploy SDs with helicopters.
- Communication towers will be constructed.
- Communication b/w SDs and comm. tower will be tuned.

→ start DAQ from SDs!

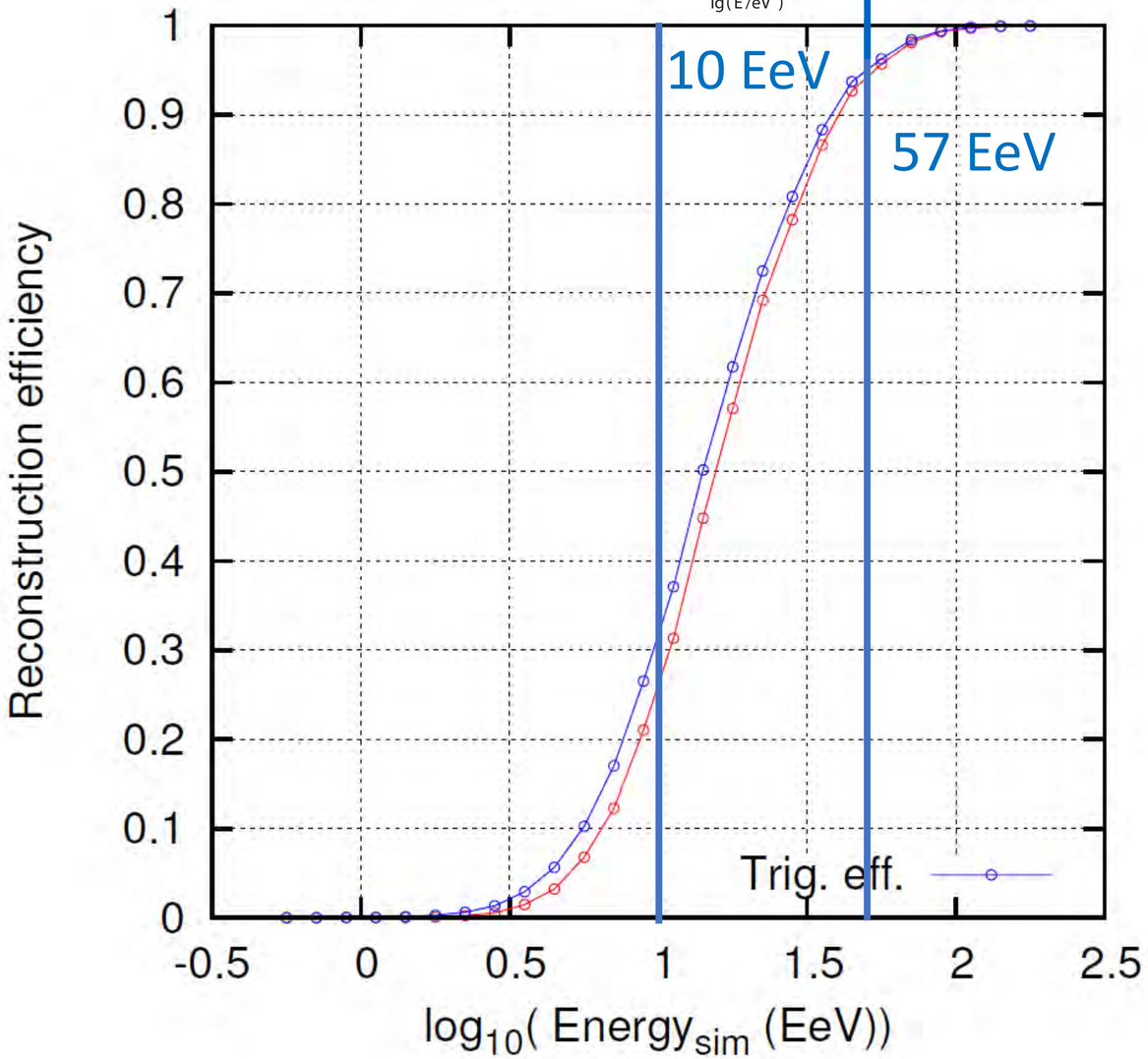
Pictures below: deployment of TALE SDs last year.

TA*4 Energy Threshold



Issue: Threshold in cut-off region!



SD array: square grid with 2.08 km spacing

E > 57 EeV:

- Reconstruction efficiency > 95%
- Angular resolution: 2.2°
- Energy resolution: ~25%

Science Goals of AugerPrime

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 $\sqrt{s}$=70 TeV**
   - particle physics beyond man-made accelerators
   - derivation of constraints on new physics phenomena

Key Elements of AugerPrime

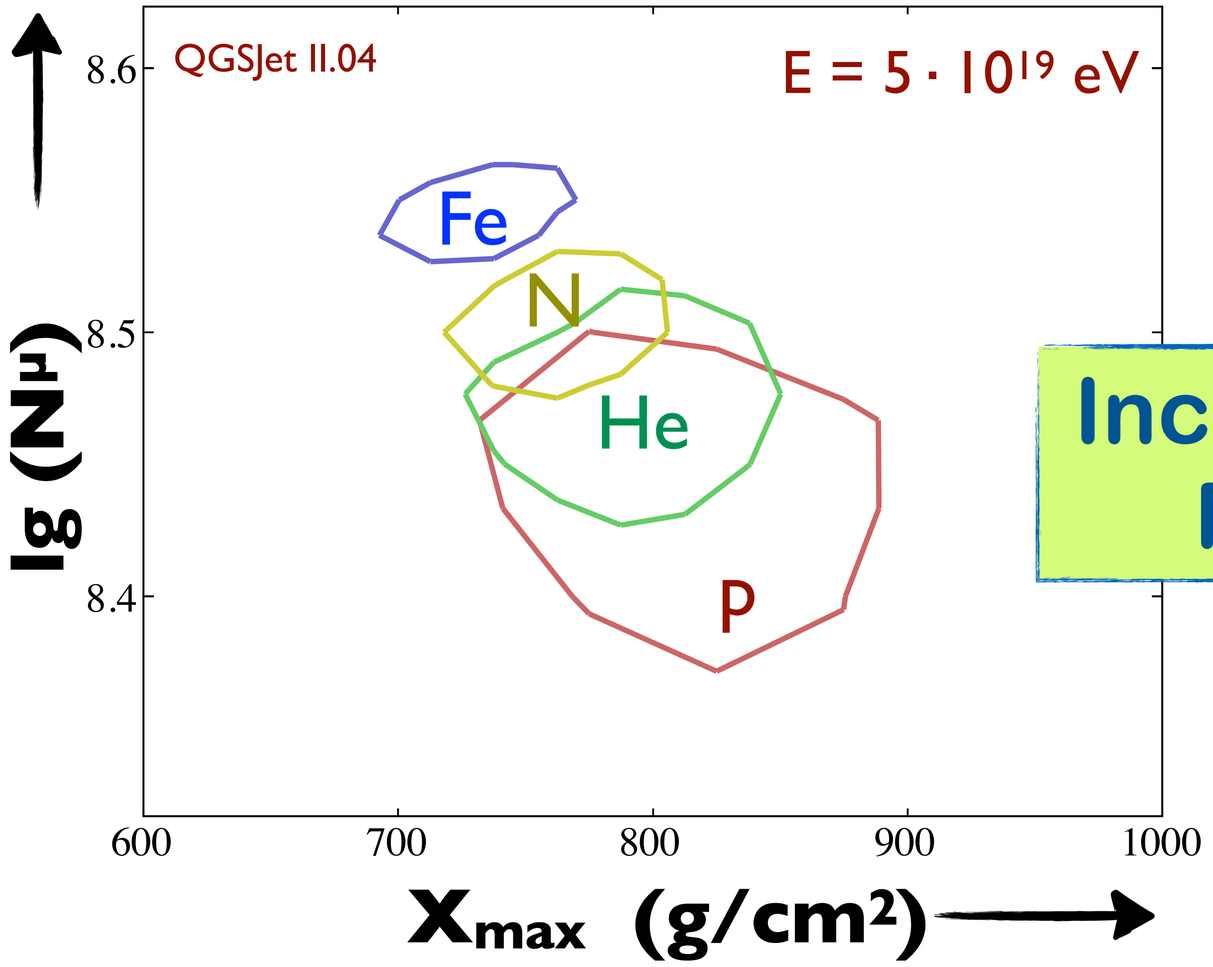
Measure primary mass with 10 times better statistics

- 3.8 m^2 scintillators (SSD) on each 1500 m array stations improve e/μ discr.
- upgrade of station electronics
- additional small PMT to increase dynamic range
- buried muon counters in 750 m array (AMIGA)
- increased FD uptime

Scintillators on top of each Water Cherenkov Tank

(non invasive, fast to install, robust technology, relatively inexpensive)

N^{μ}_{max} vs X_{max}



Increasing Mass

→ **Increasing μ-number**

→ **Shallower X_{max}**

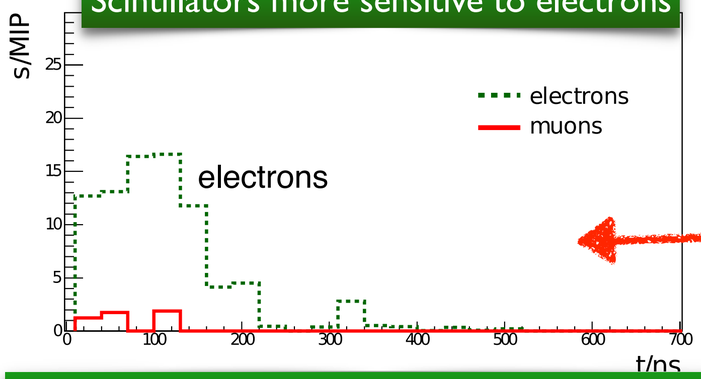
Muons measurements may even outperform X_{max} at highest energies !

Technical Realisation

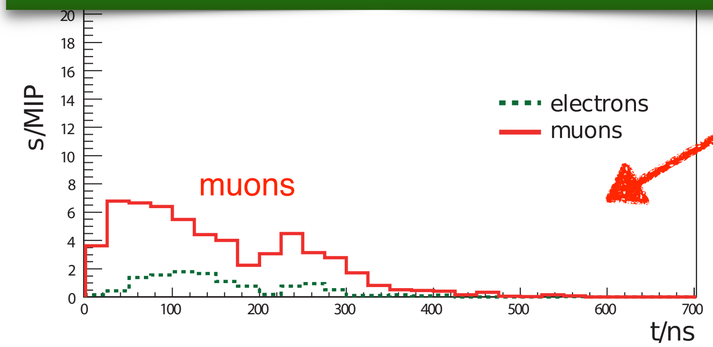
100% duty cycle

15% duty cycle

Scintillators more sensitive to electrons



Water Cherenk. Detect. more sensitive to muons



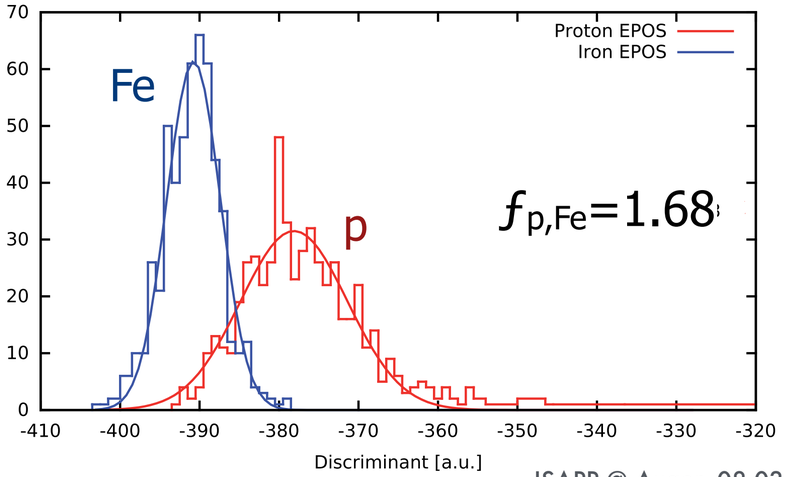
Linear system of equations:

$$\begin{pmatrix} S_{\mathrm{top}} \\ S_{\mathrm{bot}} \end{pmatrix} = \begin{pmatrix} a_{\mathrm{em}} & a_{\mu} \\ 1-a_{\mathrm{em}} & 1-a_{\mu} \end{pmatrix} \begin{pmatrix} S_{\mathrm{em}} \\ S_{\mu} \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} S_{\mathrm{em}} \\ S_{\mu} \end{pmatrix} = \begin{pmatrix} a_{\mathrm{em}} & a_{\mu} \\ 1-a_{\mathrm{em}} & 1-a_{\mu} \end{pmatrix}^{-1} \begin{pmatrix} S_{\mathrm{top}} \\ S_{\mathrm{bot}} \end{pmatrix}$$

figure of merit:

$$f_{\mathrm{p,Fe}} = \frac{|\langle S_{\mathrm{Fe}} \rangle - \langle S_{\mathrm{p}} \rangle|}{\sqrt{\sigma(S_{\mathrm{Fe}})^2 + \sigma(S_{\mathrm{p}})^2}}$$



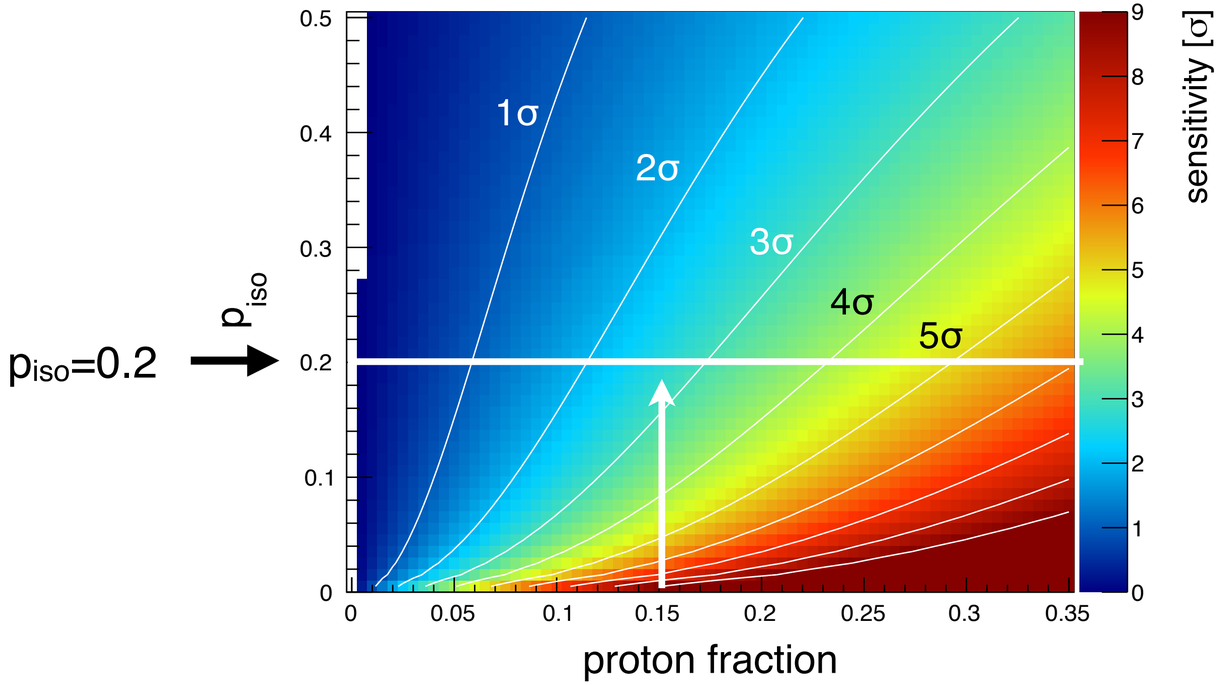
Proton Astronomy

Assume 155 events above energy threshold (e.g. 55 EeV) with f_p proton and (1-f_p) iron fraction

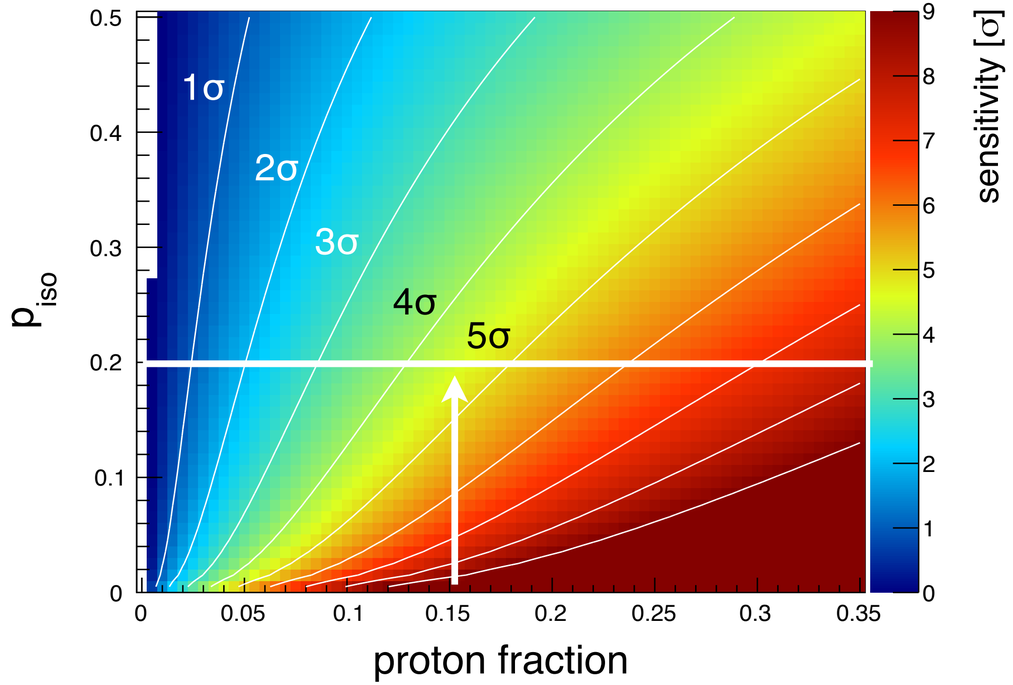
assume 75% of all protons correlate to source (quite realistic), no Fe correlates

and assume that 20% of all events correlate to sources by chance (quite realistic)

Merit factor = 0 ; (Auger)



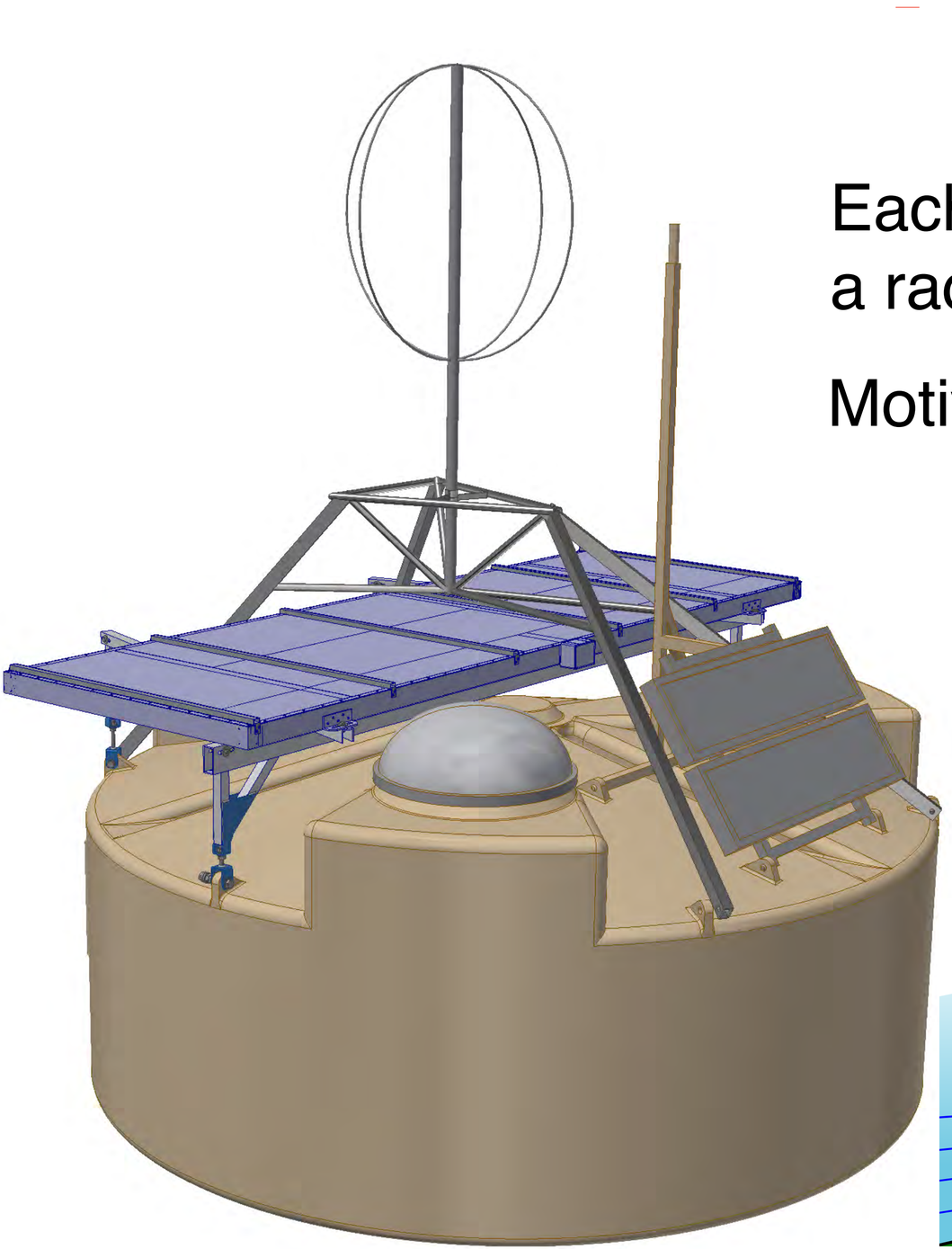
Merit factor = 1.5 ; (AugerPrime)



e.g. for f_p=15% proton fraction above 55 EeV correlation improves to 4.5 σ significance

⇒ 2.6 σ correlation significance

Can we get you a little more?

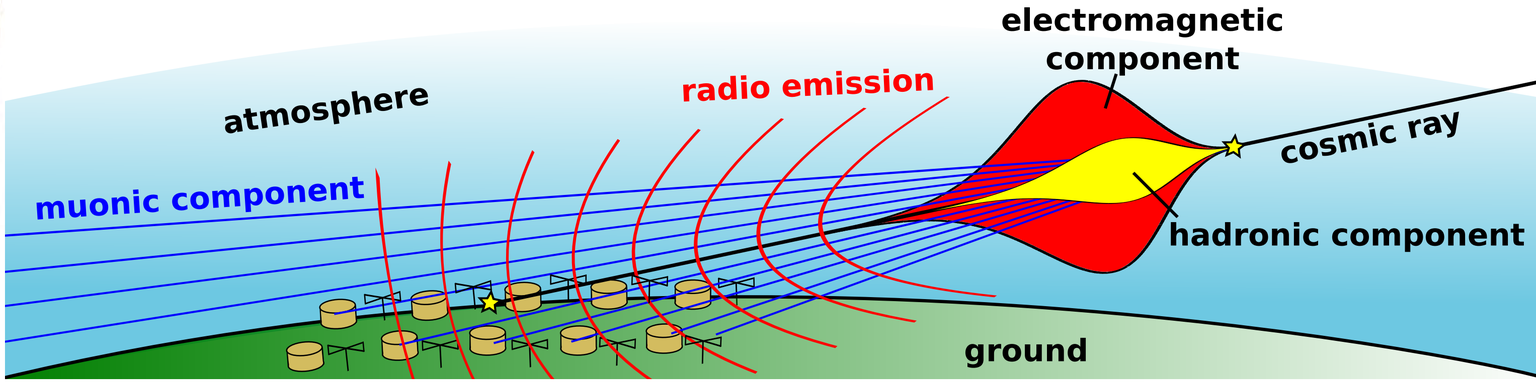


Each SD Station will be complemented with a radio antenna

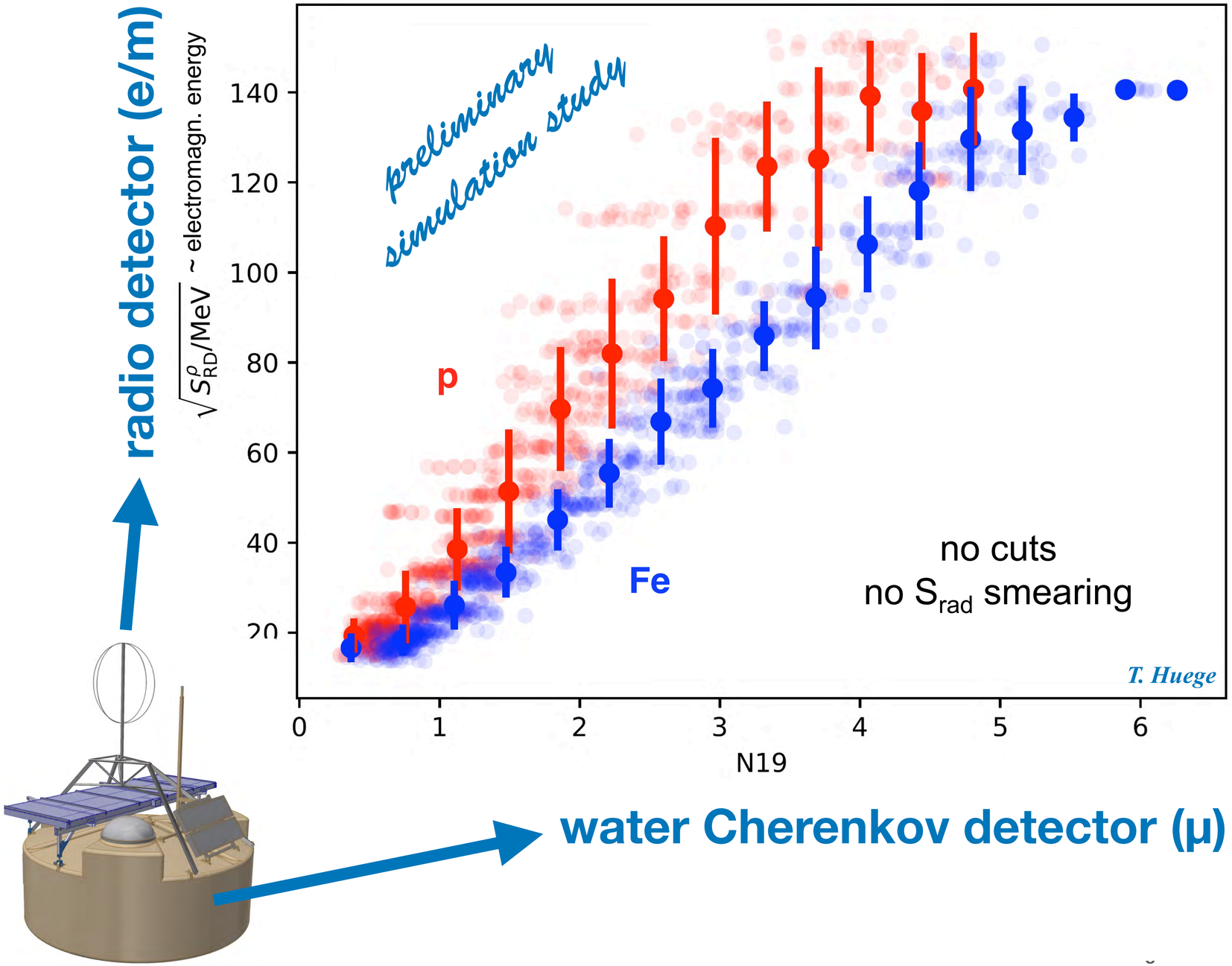
Motivation: extend composition enhanced anisotropy studies to inclined showers

Note: scintillators offer little X-section to inclined showers

radio antennas will see em-part and water Cherenkov detectors will see μ-part of inclined showers



Preliminary performance study



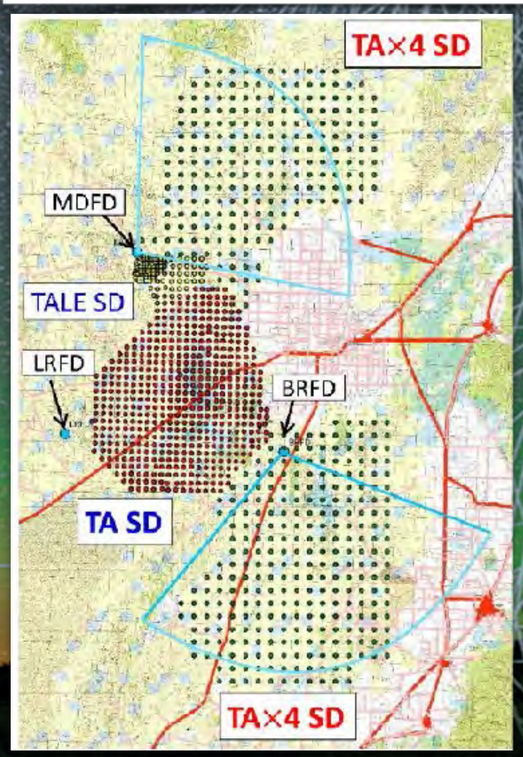
J. Hörandel @ UHECR2018

Science Expections by 2030

- Origin of the flux suppression will be known
- Simple astrophysical scenarios will be discriminated
- If proton fraction > 15%, it will be noted, and …
- if > 20%, realistic prospects for point source identification
- TA Hot Spot will either be proven or falsified
- UHECR source classes and source candidates will be identified
- Neutrino and photon limits will be improved only by factor 2-3
- Basic particle physics at √140 TeV will have been done
- LIV and BSM parameters will be improved significantly

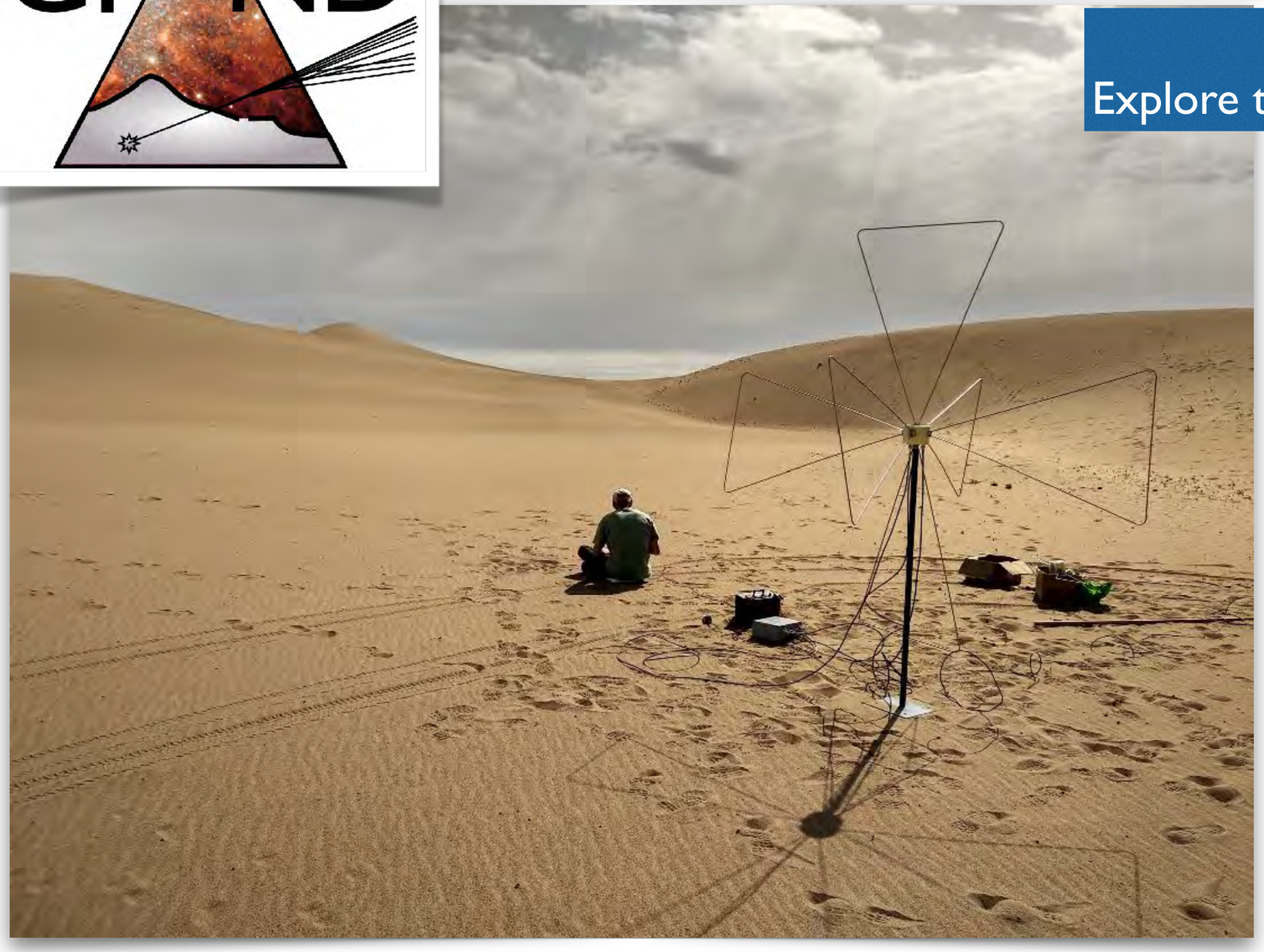
Looking more ahead to the Future

POEMMA

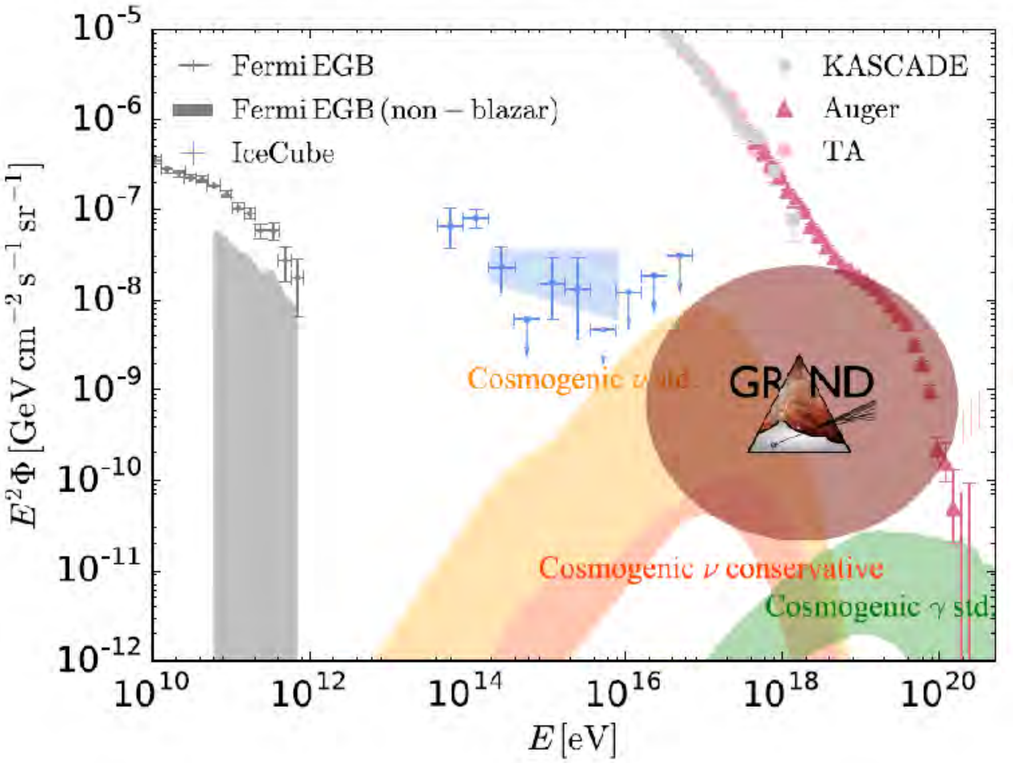


GRAND

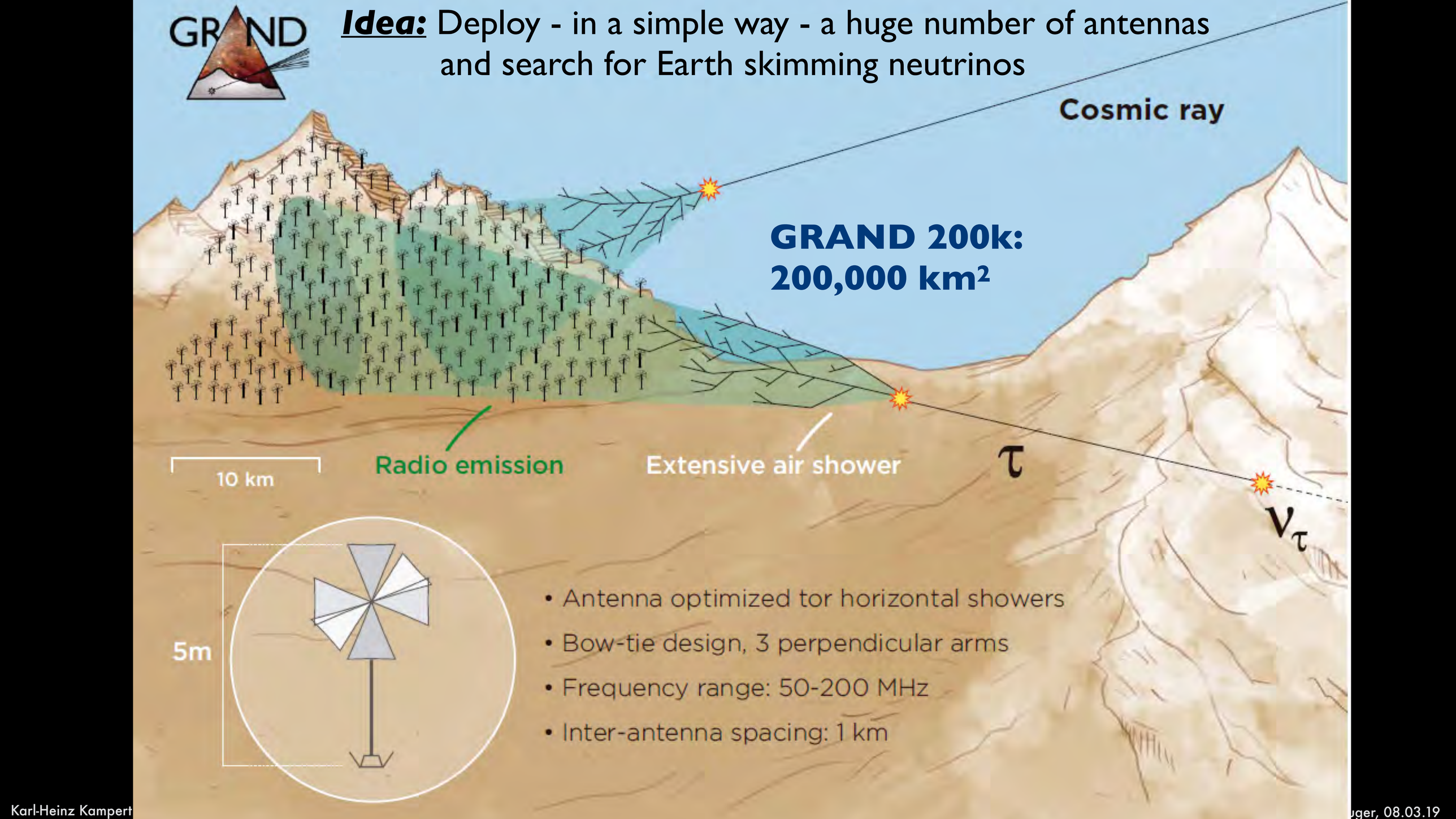
GRAND: The Giant Radio Array for Neutrino Detection



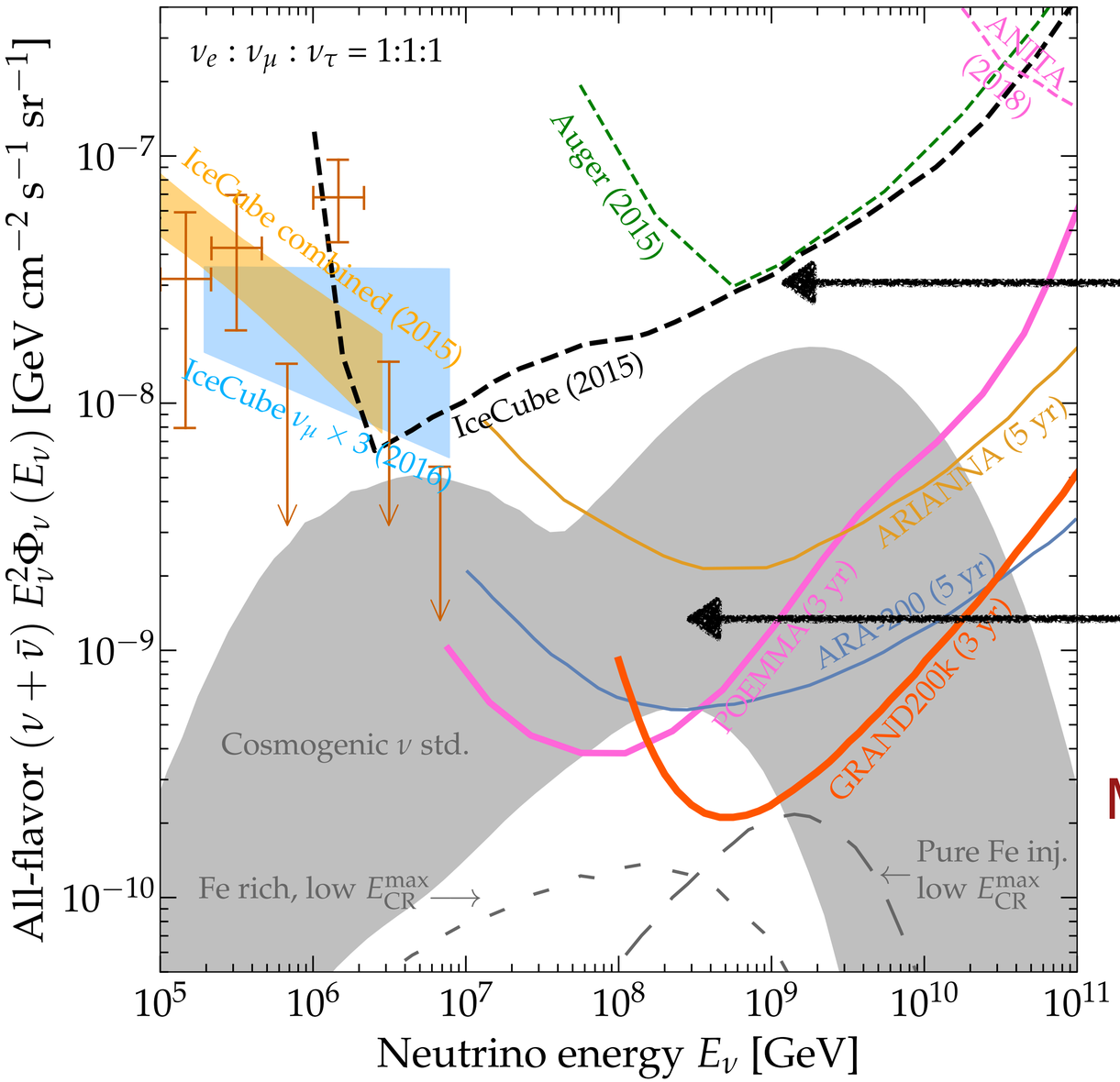
Goal:
Explore the E>10^{17}eV neutrinos is uncharted territory



could also do some UHECR physics


GRAND
Idea: Deploy - in a simple way - a huge number of antennas and search for Earth skimming neutrinos
Cosmic ray
GRAND 200k:
200,000 km²
10 km
Radio emission
Extensive air shower
τ
ν_τ
5m
• Antenna optimized tor horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km

Planned Sensitivities for cosmogenic neutrinos



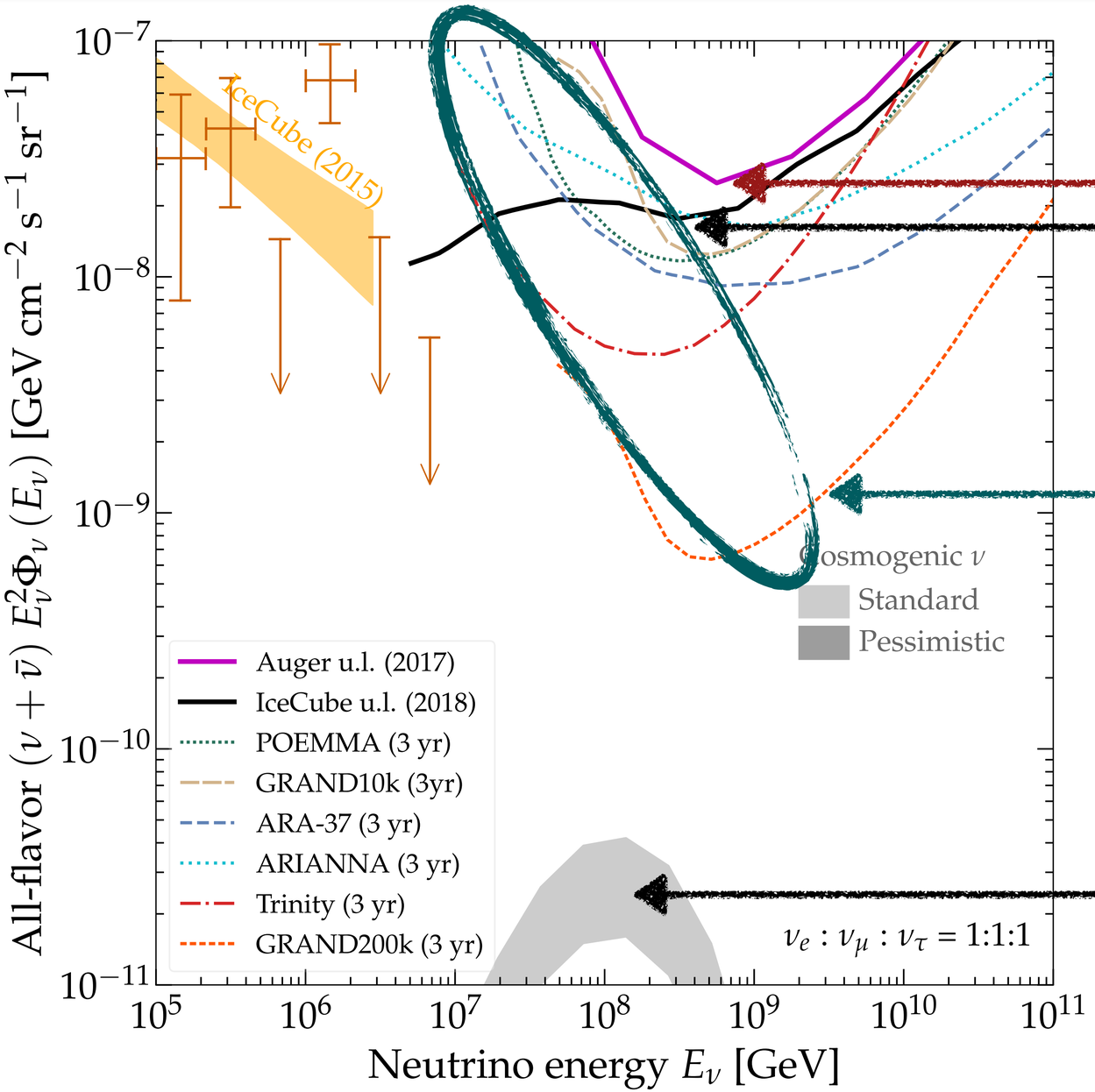
present limits from Auger and IceCube

GZK-Flux range from p-sources

Most of that parameter range could be tested

But....

Cosmogenic fluxes may be of reach



Auger upper limit

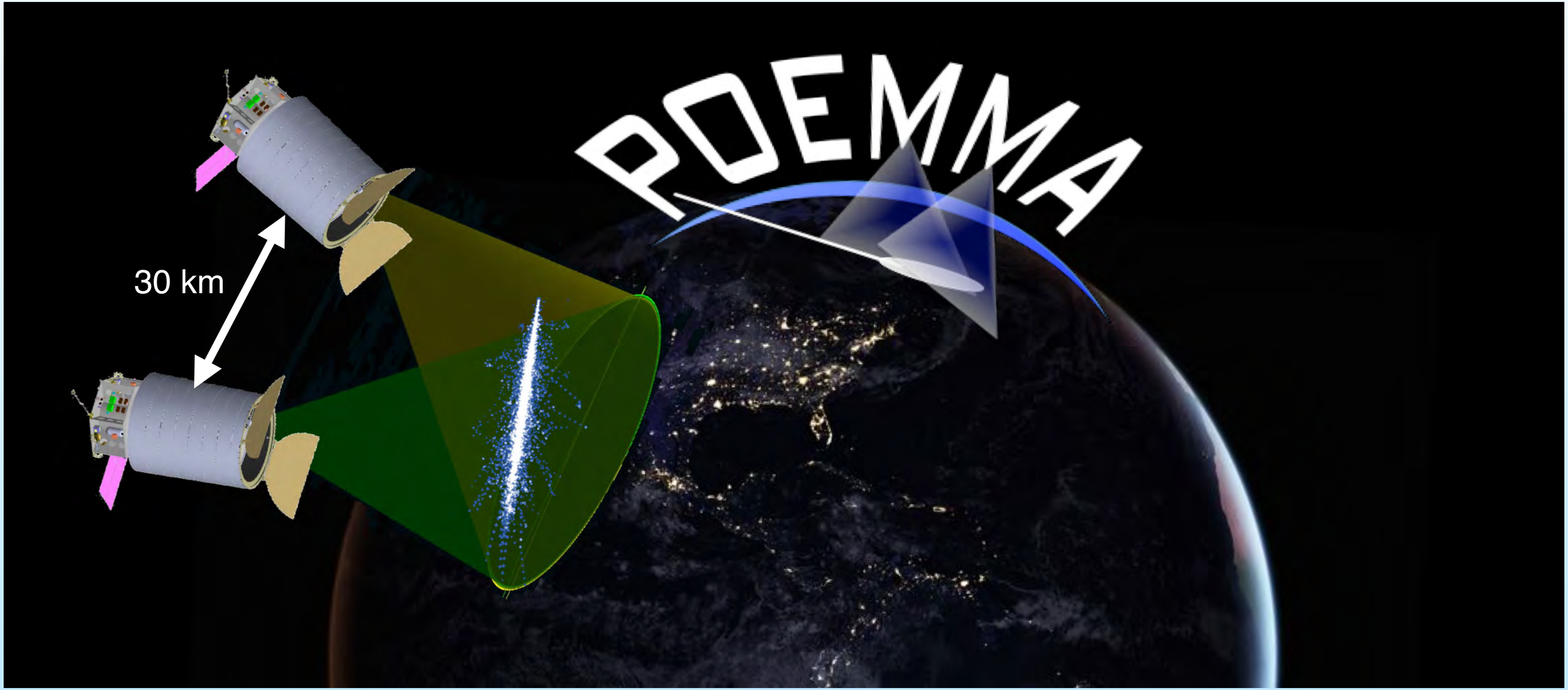
IceCube upper limit

All these lines represent expected sensitivities

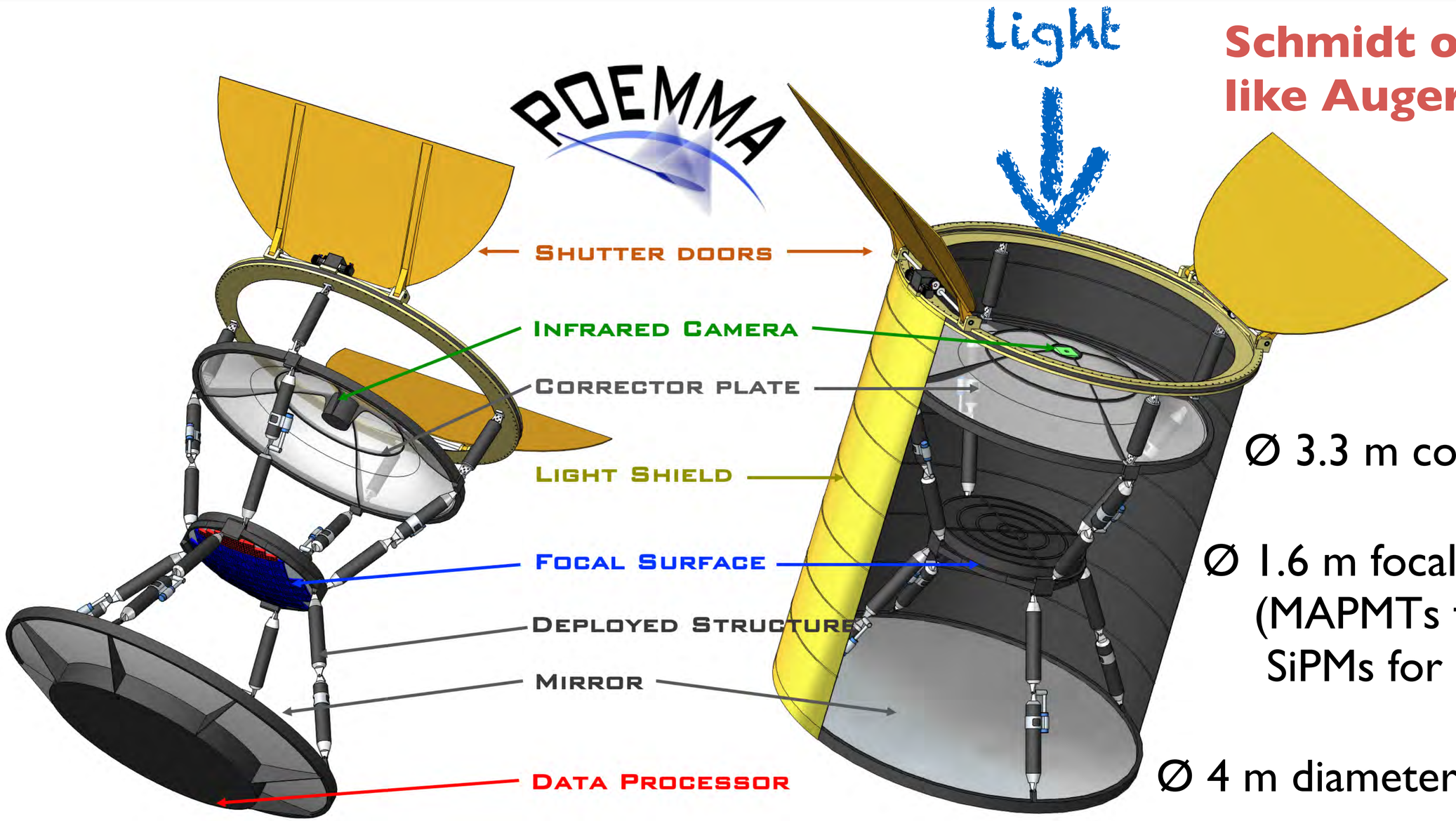
Flux may be as low as this in case we see E_{max} of sources

POEMMA: Probe of Extreme Multi-Messenger Astrophysics

Stereoscopic Observations from Space



POEMMA Camera



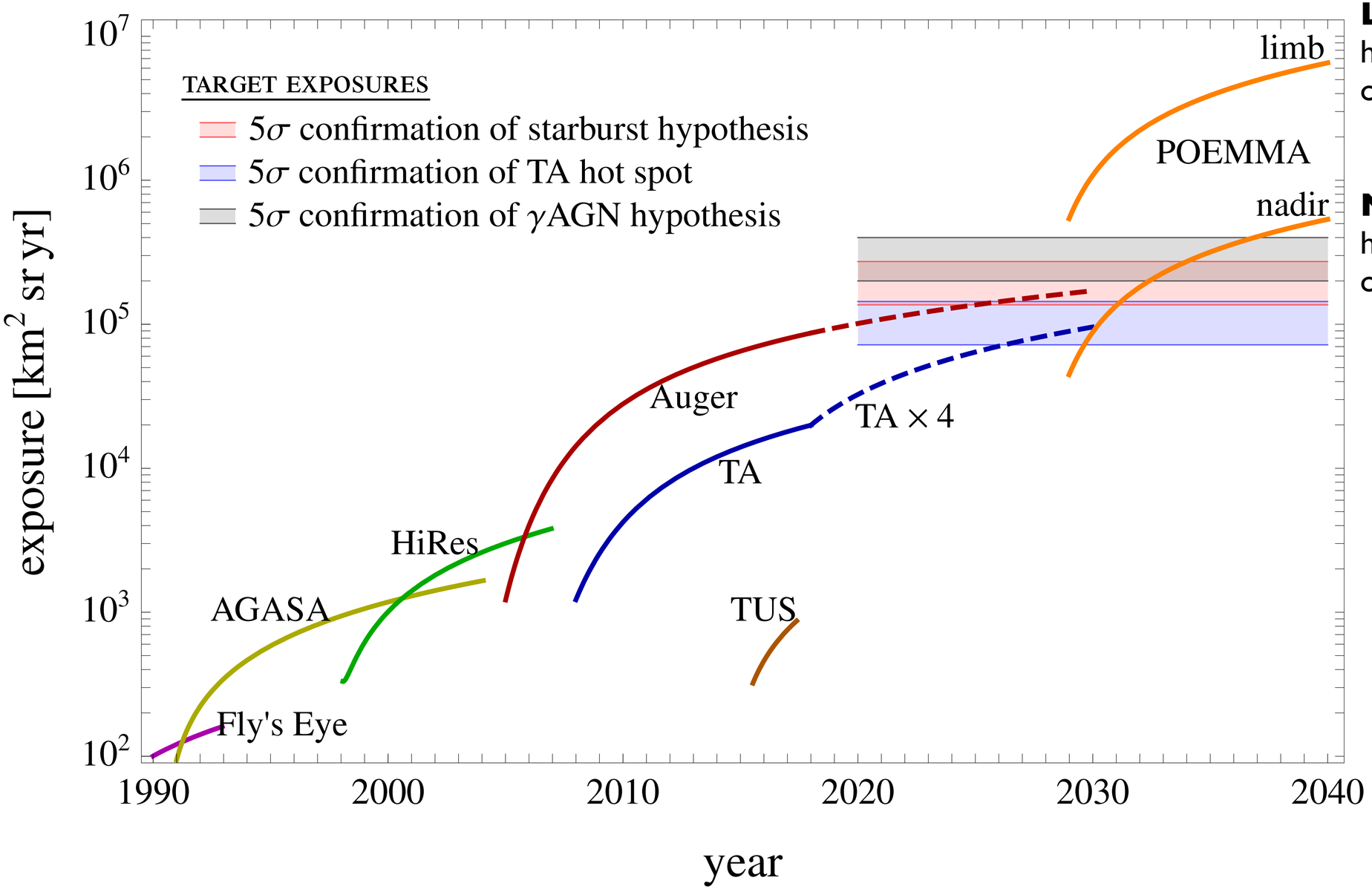
Schmidt optics 45° fov, like Auger telescopes

Ø 3.3 m corrector lens

Ø 1.6 m focal area
(MAPMTs for fluorescence
SiPMs for Cherenkov)

Ø 4 m diameter mirror

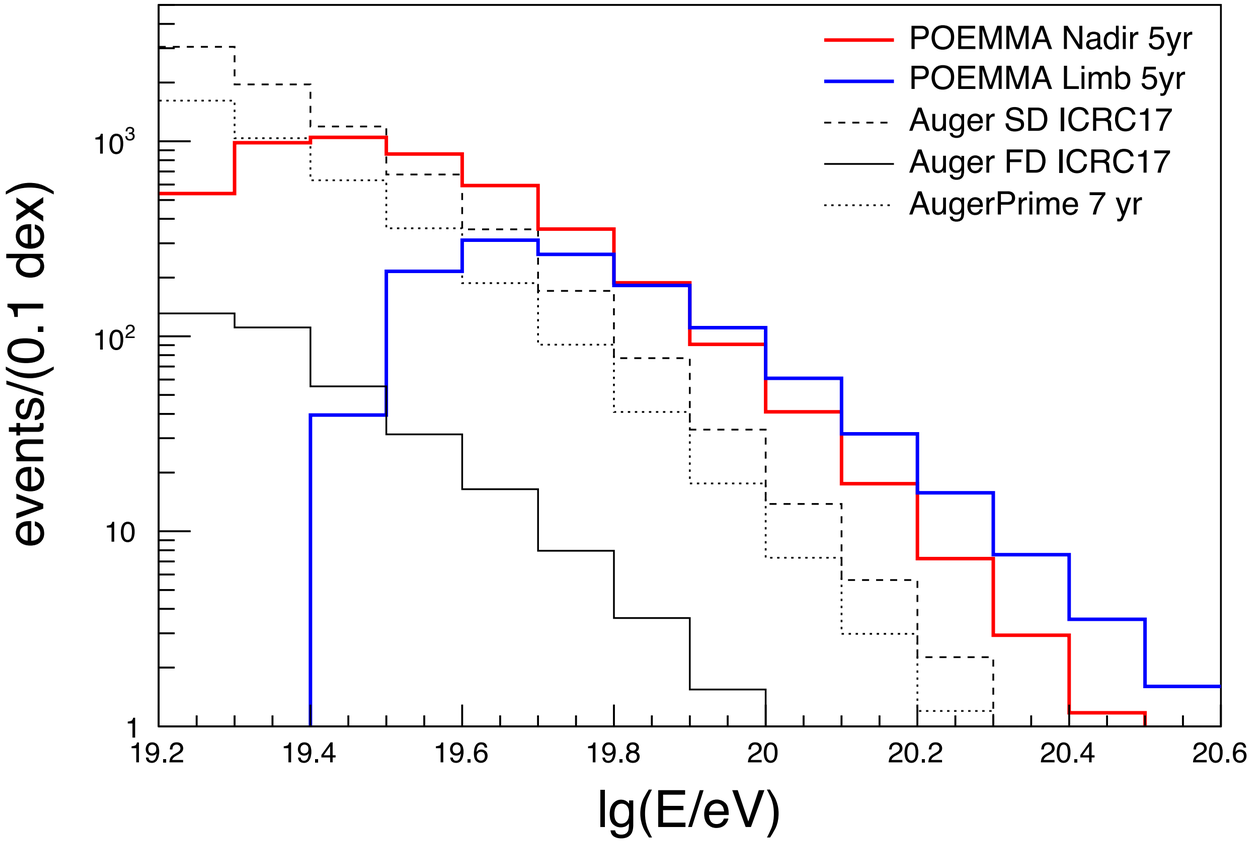
Exposures by 2030 and beyond....

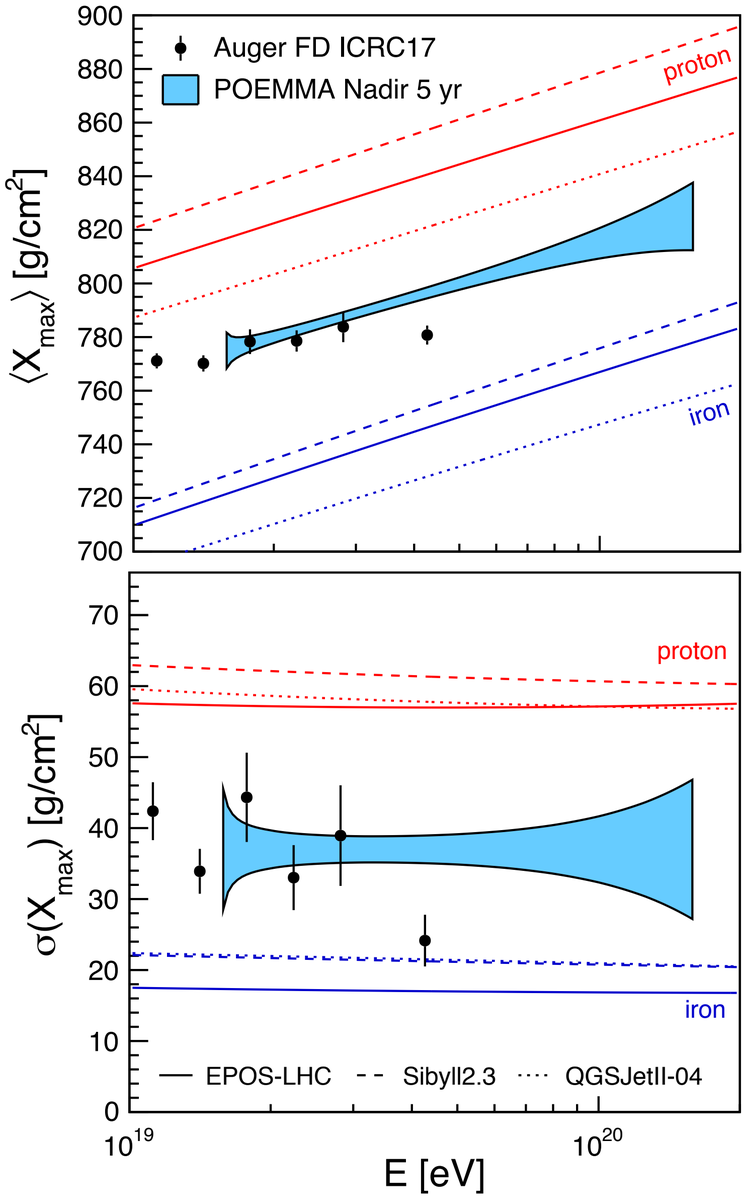


Limb observations:
high-resolution fluorescence, optimised for stereo

Nadir observations:
high-resolution fluorescence, optimised for stereo

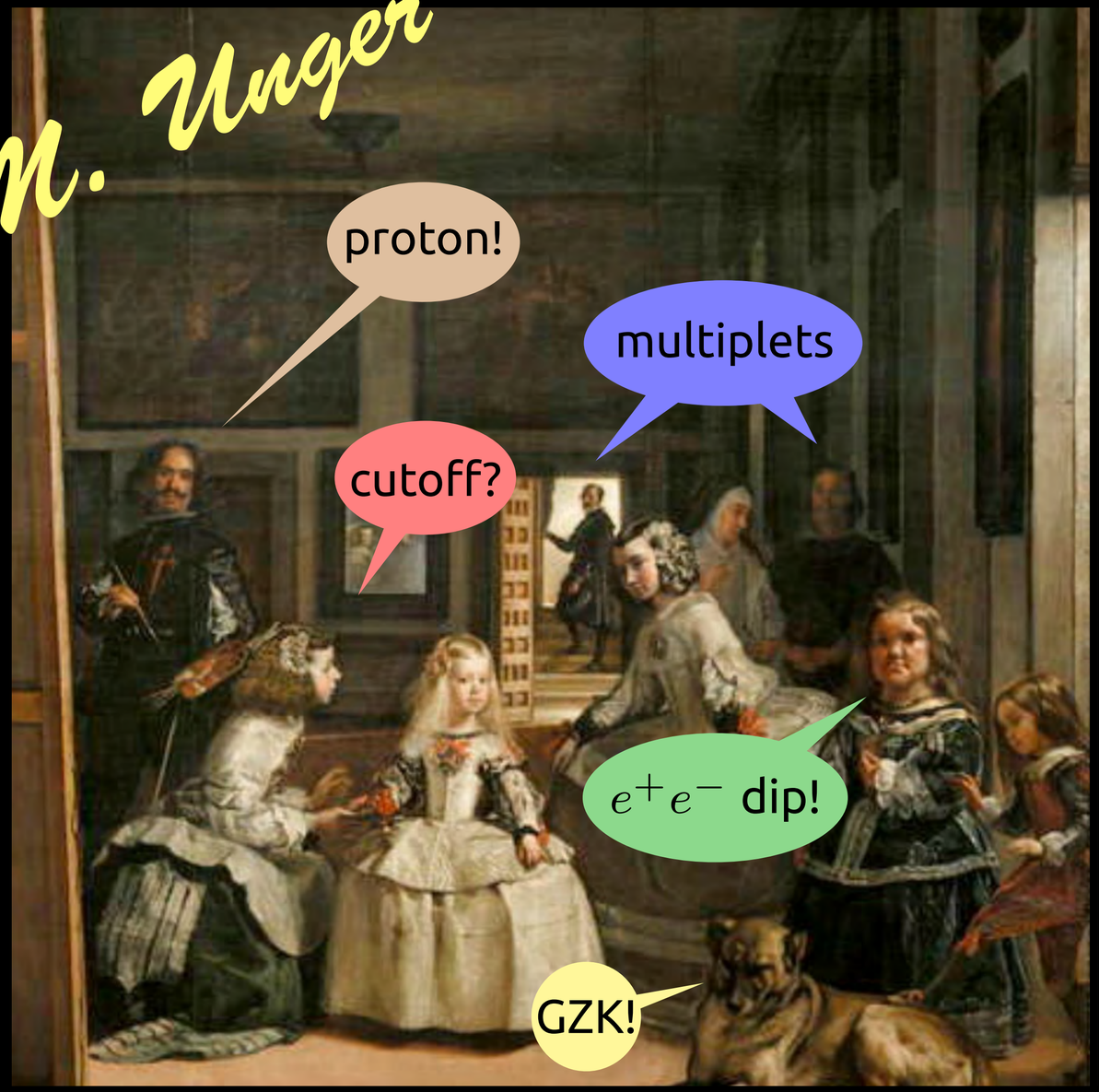
POEMMA: expected statistics & X_{max}-resolution





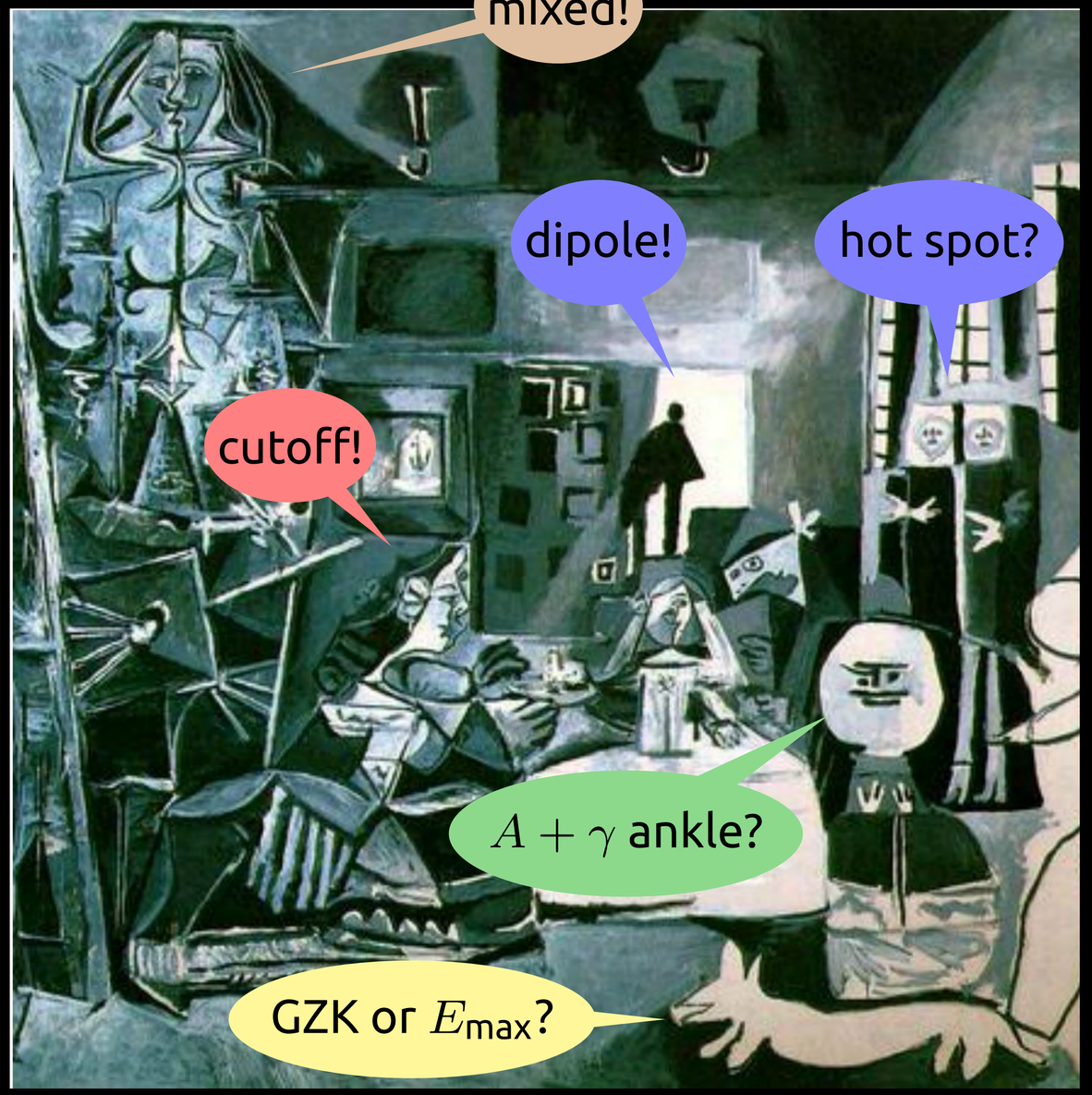
- Present Auger-FD statistics will be enlarged by factor 20
- Present Auger-SD statistics will be enlarged by factor 1.5
- X_{max} resolution not much worse than that of Auger

UHECR before Auger



Las Meninas by Diego Velazquez 1656

UHECR in 2019



Las Meninas by Pablo Picasso 1957

UHECR in 2019

Las Meninas by Pablo Picasso 1957

UHECR in 2030

a shining source will be identified

Sandro Boticelli: The Birth of Venus (1494-1486)

UHECR in 2019

Las Meninas by Pablo Picasso 1957

UHECR in 2030+

source hunting season has been opened

Domenichino: Diana and her Nymphs (1616)

Thank you for your attention!

Photo by Steven Saffi