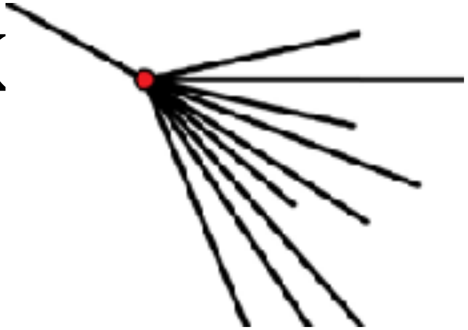
21st ISCRA
August 2018

High Energy Cosmic Rays II

Cosmic Rays above 10^{18} eV

Alan Watson
University of Leeds, UK
a.a.watson@leeds.ac.uk



1953: Bassi, Clark and Rossi – scintillators and fast timing

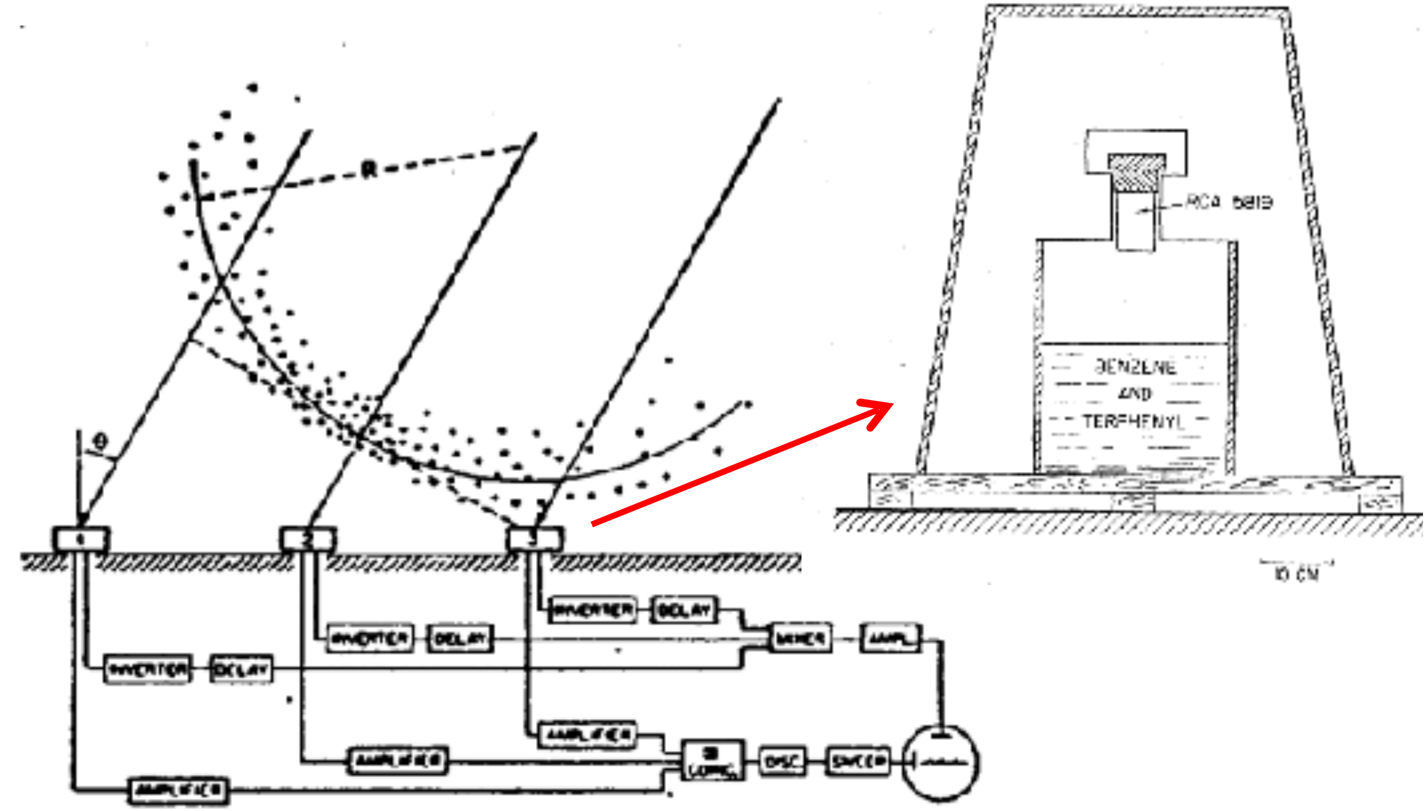


FIG. 2. Block diagram of the apparatus with a schematic representation of an air shower about to strike the counters. The counters are in arrangement II.

Directional uncertainty ~ 7°

Thickness of electron disc and fact that electrons lead muons close to the axis: inferences about energy of nucleons

2388

J. LINSLEY AND L. SCARSI

Phys Rev 1962

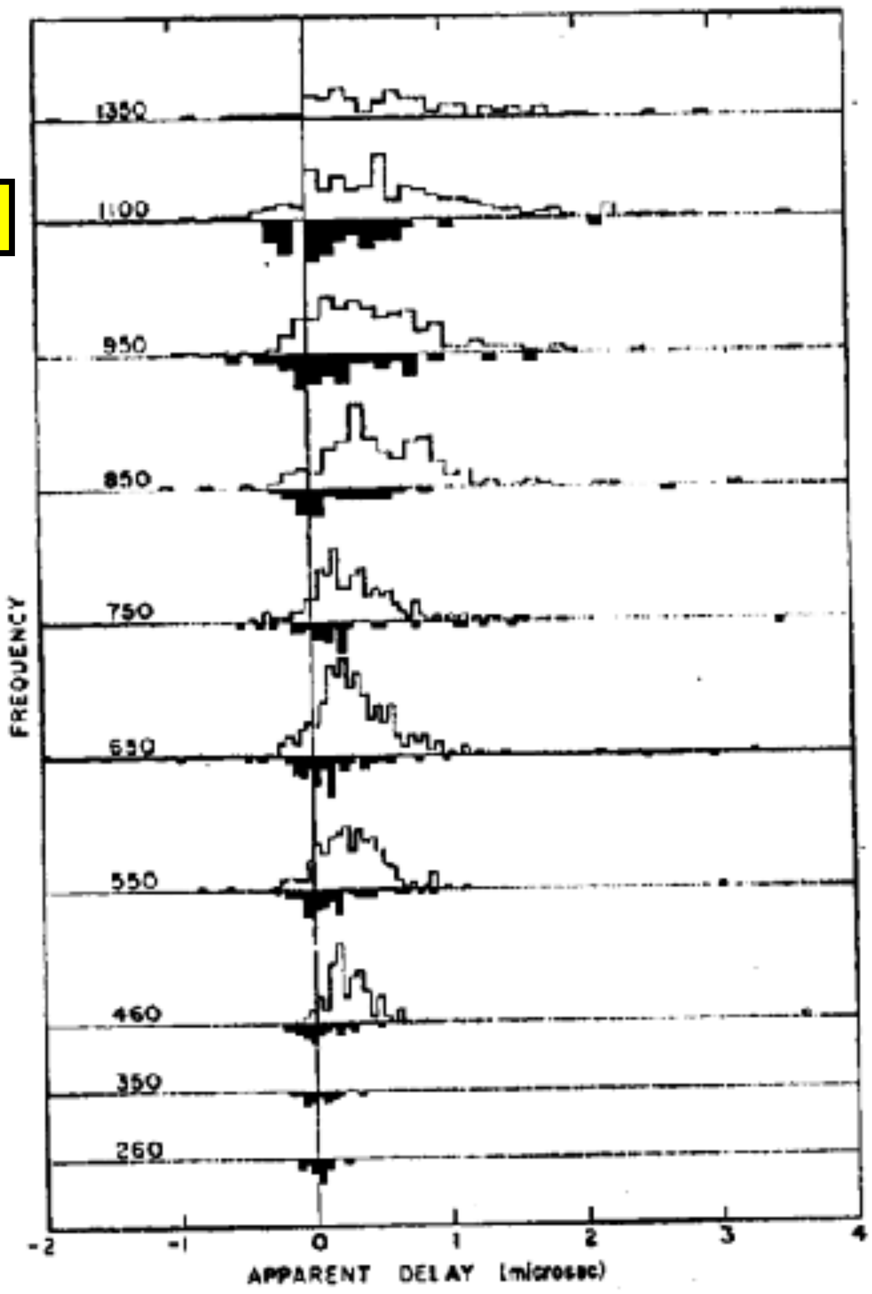


TABLE I. Single-particle
tangent plane, for vari

Distance (m)	Shielded detecto Mean	Medi
260	0.03 ±0.02	0.04 ±
350	0.04 ±0.03	0.03 ±
460	0.05 ±0.04	0.02 ±
550	0.14 ±0.05	0.07 ±
650	0.14 ±0.03	0.13 ±
750	0.26 ±0.10	0.14 ±
850	0.20 ±0.04	0.10 ±
950	0.30 ±0.06	0.18 ±
1100	0.38 ±0.07	0.20 ±
1350	···	··

the result for several c
est to the largest that

I

The large pulses w
plane, so as to minin
investigate the fluctu
the smallest pulses,
Measurements of t_{obs}
distance from the s
interval we plotted t
apparent delays. We
median of each distri
for pulses from the
the shielded detecto
the data were also se
to the zenith angle of
of frequency distribu

Homework:

- Bassi, Clark and Rossi found that the electrons arrived **EARLIER** than the muons
- Linsley and Scarsi found that electrons arrived **LATER** than the muons

Why? What about the photons?

Why is there LESS invisible energy at high energies?

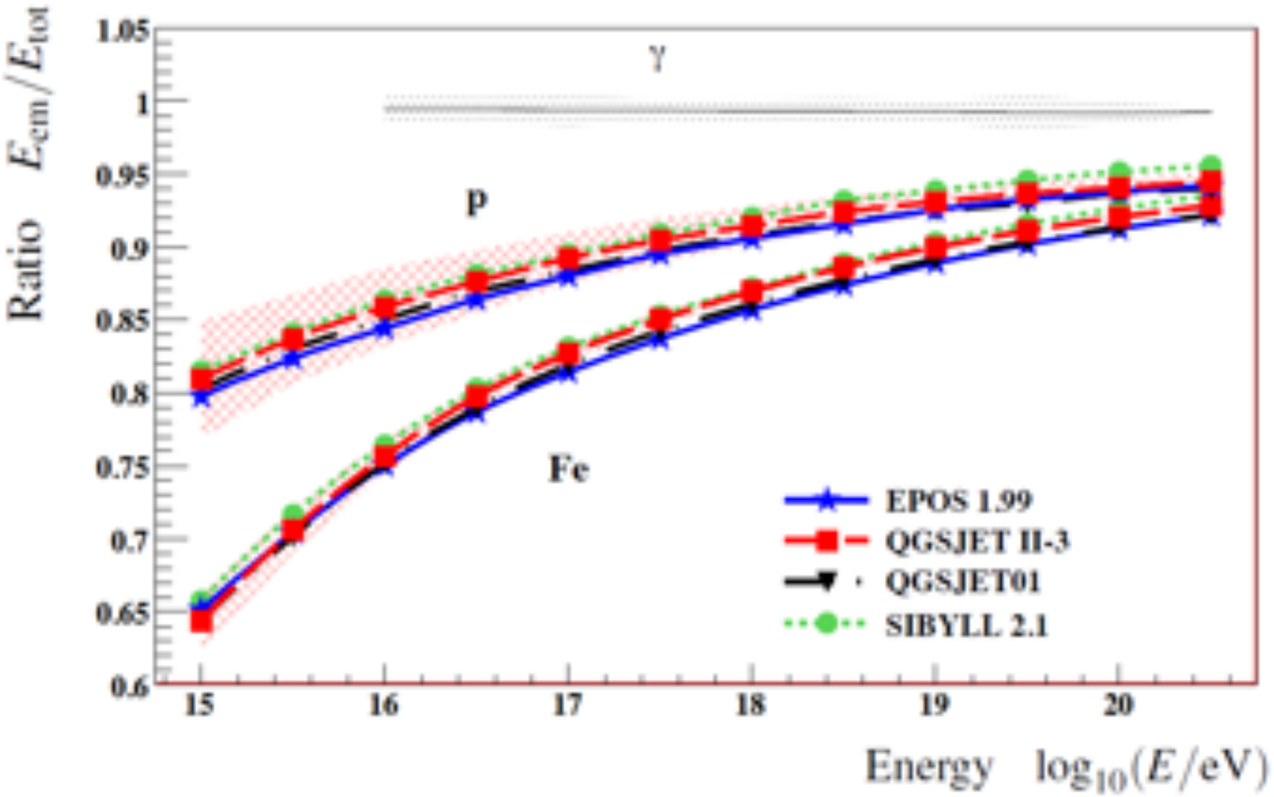
A proton typically makes ~ 10 – 12 interactions as it comes through the atmosphere

At low energies, the electromagnetic cascades from the π^0s will die out quite quickly so that at sea-level you see only the electrons of electromagnetic cascade from last proton interaction

The muons come from all of the interactions but are not as fast as the protons and so arrive after the electrons

At higher energies, far from the core, the electrons are from energetic cascades high in the atmosphere and will suffer scattering and so be delayed relative to the muons

Photons arrive contemporaneously with the electrons
Essentially they are in equilibrium with them



Invisible Energy

This is the energy carried into the ground by muons and neutrinos. Not measured by the fluorescence detectors

Reason that this is relatively more of a correction at low energies is because at the higher energies pions tend to interact, not producing muons or neutrinos. Also explains difference between p and Fe (think energy per nucleon)

Outline

- **Measuring the properties of Extensive Air Showers**
- **The energy spectrum**
- **Arrival Directions**
- **The mass - the problem of hadronic interactions**
- **Neutrinos – Diffuse and Multi-messenger**
- **Plans for the future**

Questions to answer:

(i) Are there excesses from some regions of sky?

Deflections in magnetic fields:

at ~ 10^{19} eV: still ~ 10° for proton in Galactic magnetic field

(ii) Steepening of spectrum above 5 x 10^{19} eV as predicted?

Greisen-Zatsepin-Kuz'min – GZK effect (1966)

$$\gamma_{2.7\,K} + p \rightarrow \quad \Delta^+ \quad \rightarrow \quad n + \pi^+ \ \text{or} \ p + \pi^o$$

and

$$\gamma_{IR/2.7\,K} + A \rightarrow \quad (A - 1) + n$$

Sources must lie within about 100 Mpc

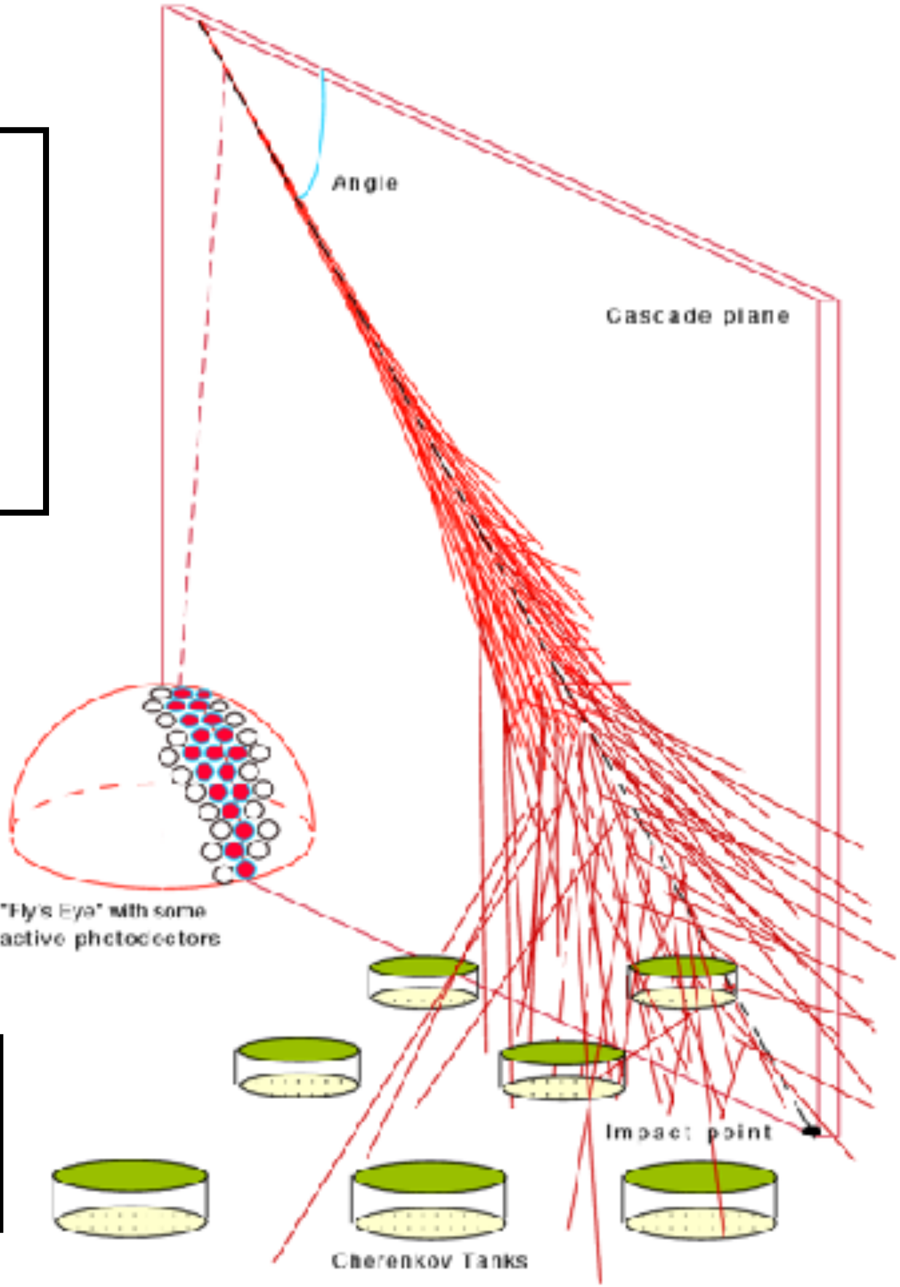
(iii) Mass Composition – nuclei, neutrons and photons?

Results from all three observations are needed to infer the origin(s)

The Auger Schematic Design

The design of the Pierre Auger Observatory marries two well-established techniques

→ the 'HYBRID' technique

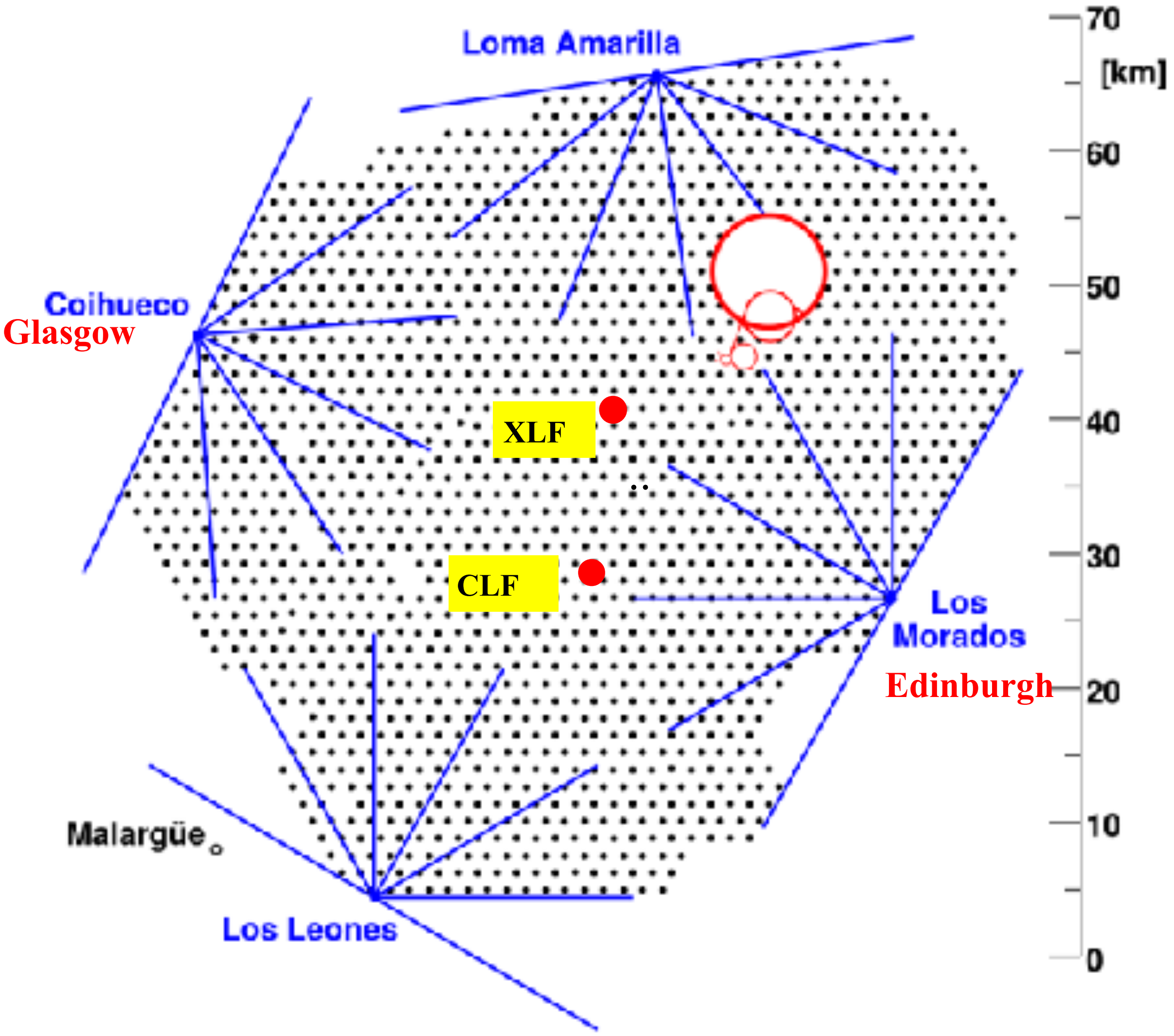


Fluorescence →

AND

Arrays of water-Cherenkov detectors →

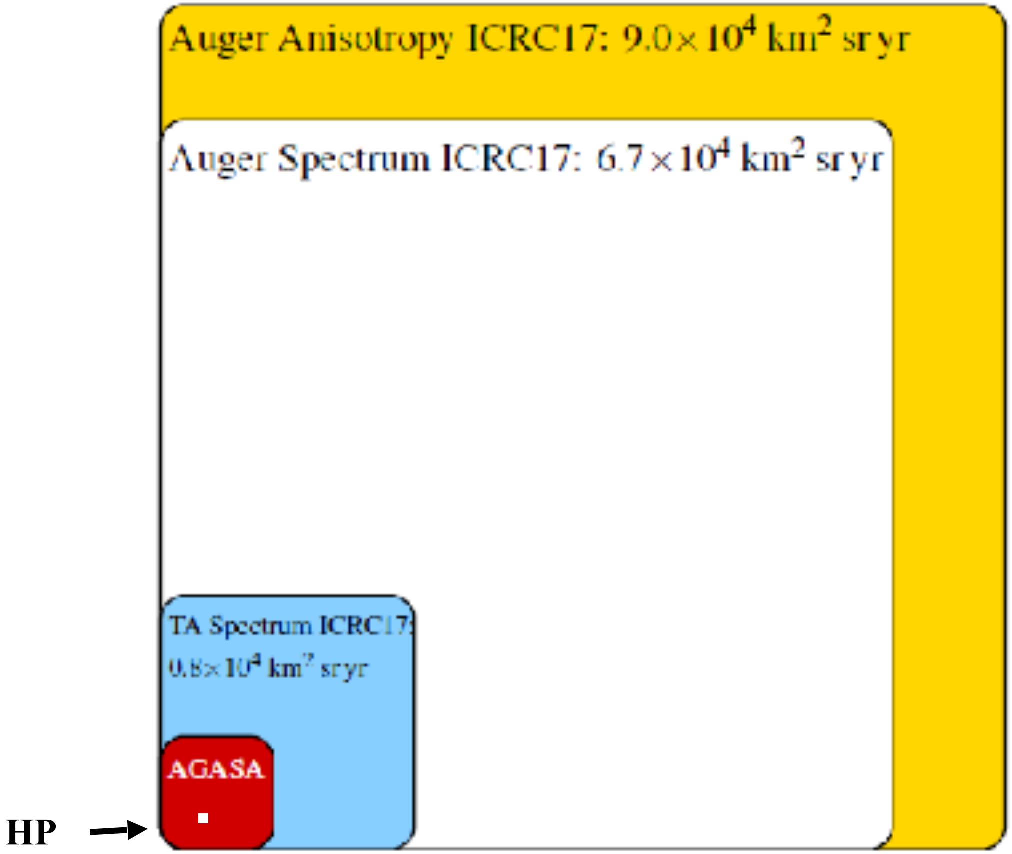
The Pierre Auger Observatory: Malargüe, Argentina



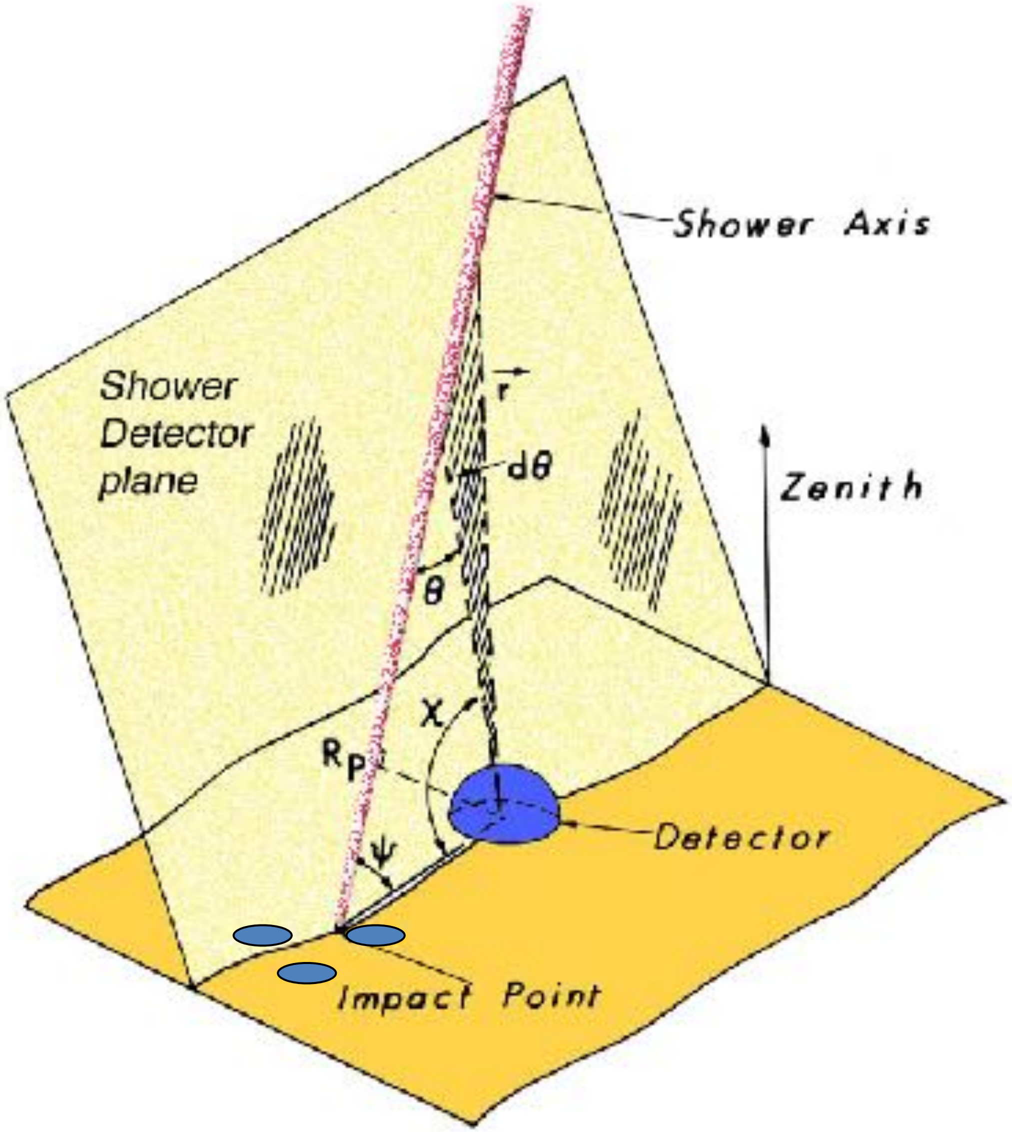
- 1600 water-Cherenkov detectors: 10 m² x 1.2 m
- 3000 km²
- Fluorescence detectors at 4 locations
- Two laser facilities for monitoring atmosphere and checking reconstruction
- Lidars at each FD site
- Capital cost ~$50M
- About 1/8th the area of Sicily

2004: Data taking started with about 200 water-Cherenkov detectors and two fluorescence telescopes - 13 years after first discussions

Soon surpassed the exposure at Haverah Park accrued in 20 years – now over 67,000 km² sr years



After Michael Unger 2017



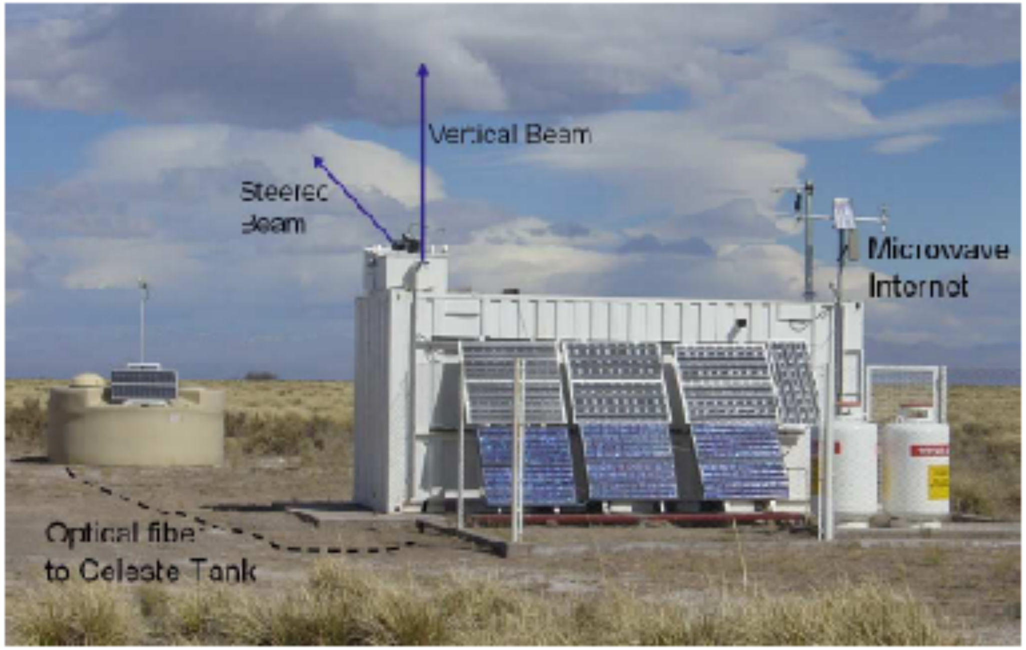
Important feature of the hybrid approach

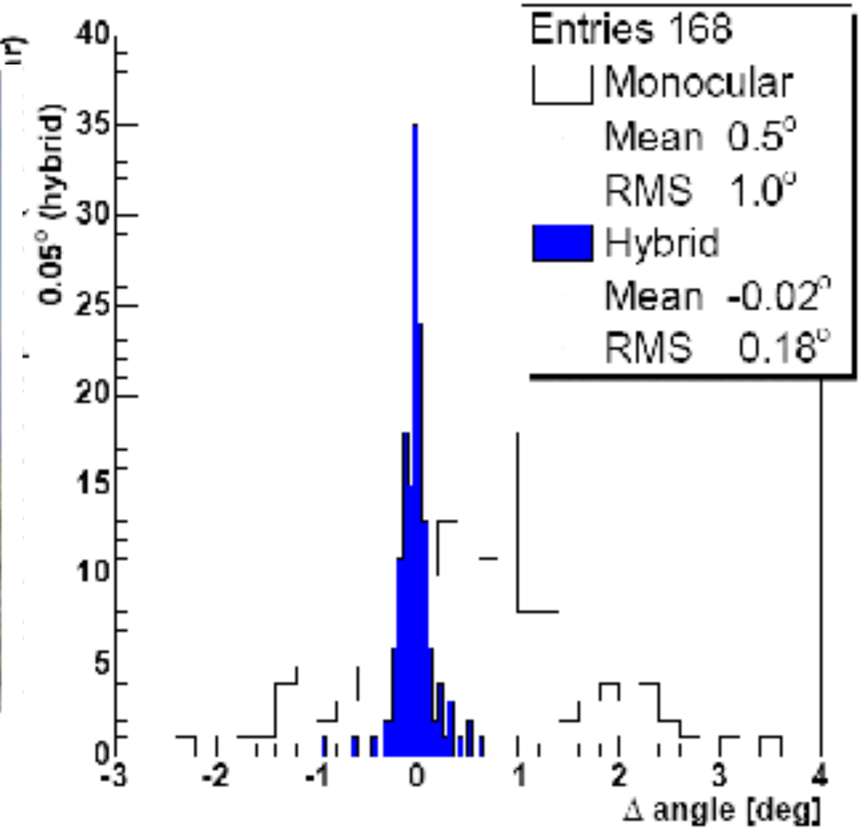
Precise shower geometry from degeneracy given by SD timing

Essential step towards high quality energy and X_{max} resolution

Times at angles, χ , are key to finding R_p

Angular Resolution from Central Laser Facility

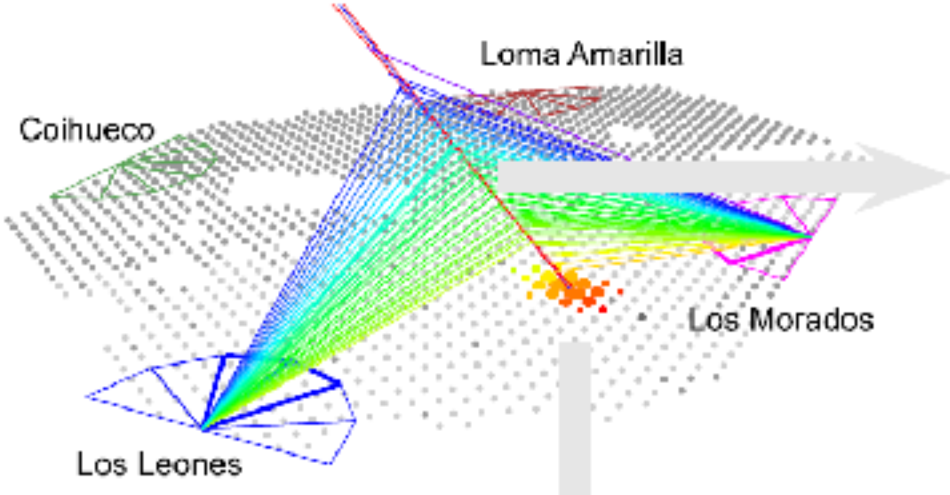


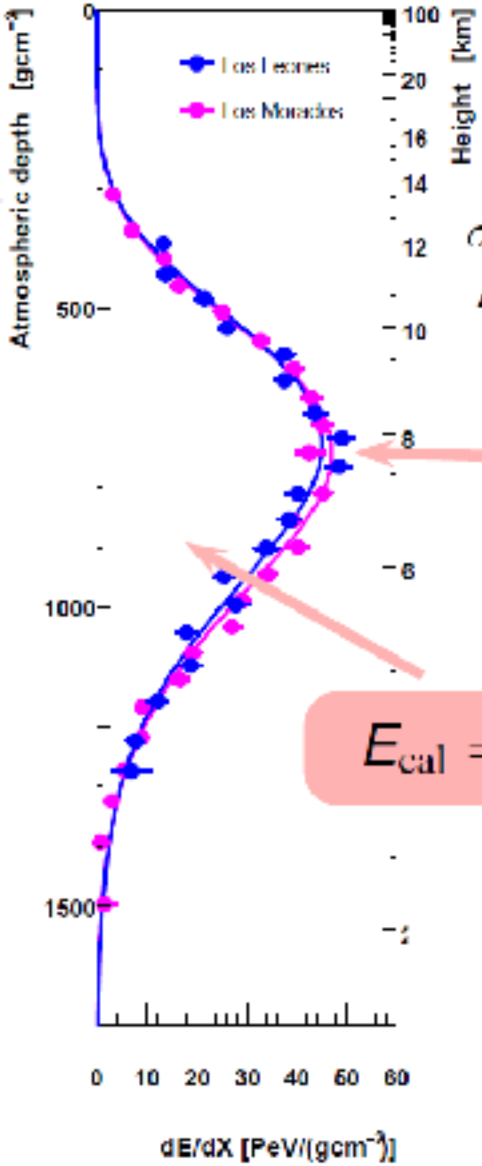


355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy

Mono/hybrid rms 1.0°/0.18°

Hybrid Detection of Air Showers



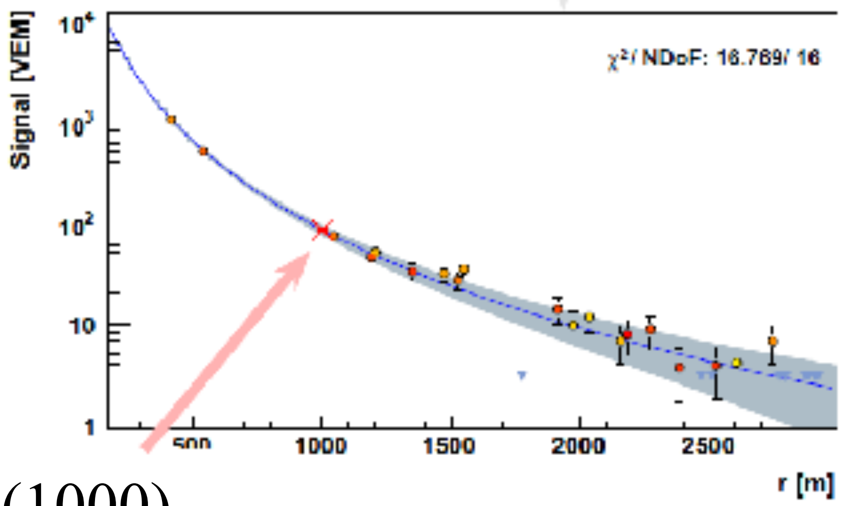


$\sigma X_{\mathrm{max}} \lesssim 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \lesssim 10\,\mathrm{g/cm^2}$

X_{max}

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

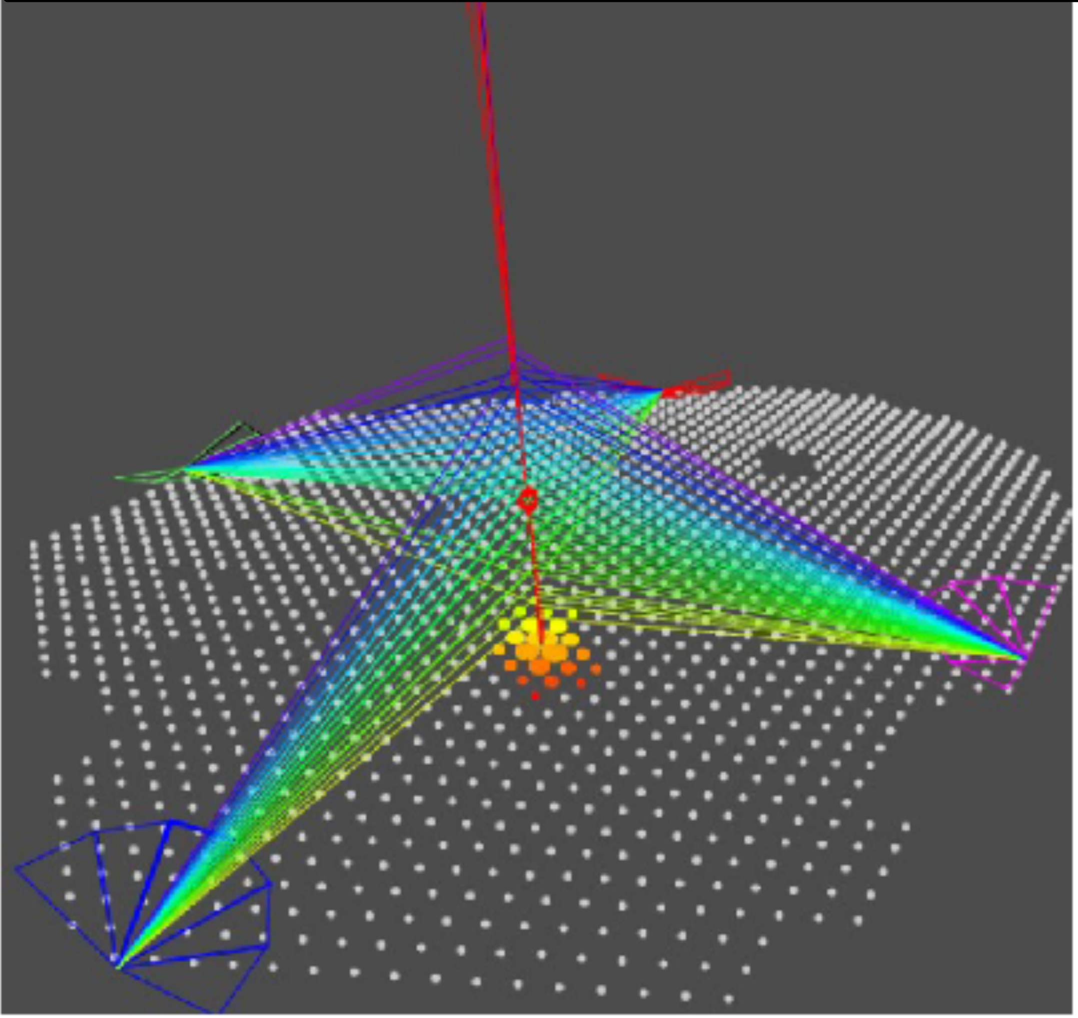
$\sigma_E / E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

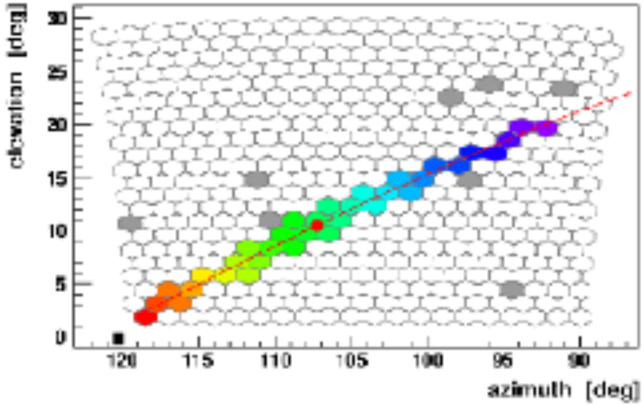


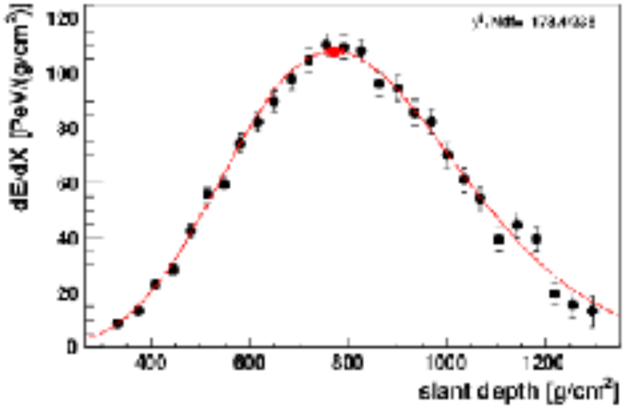
S(1000)

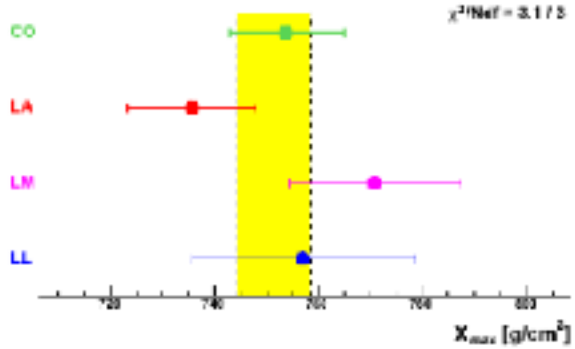
$E_{\mathrm{surface}} = f(S_{1000}, \theta)$

Precision of energy and X_{max} measurements

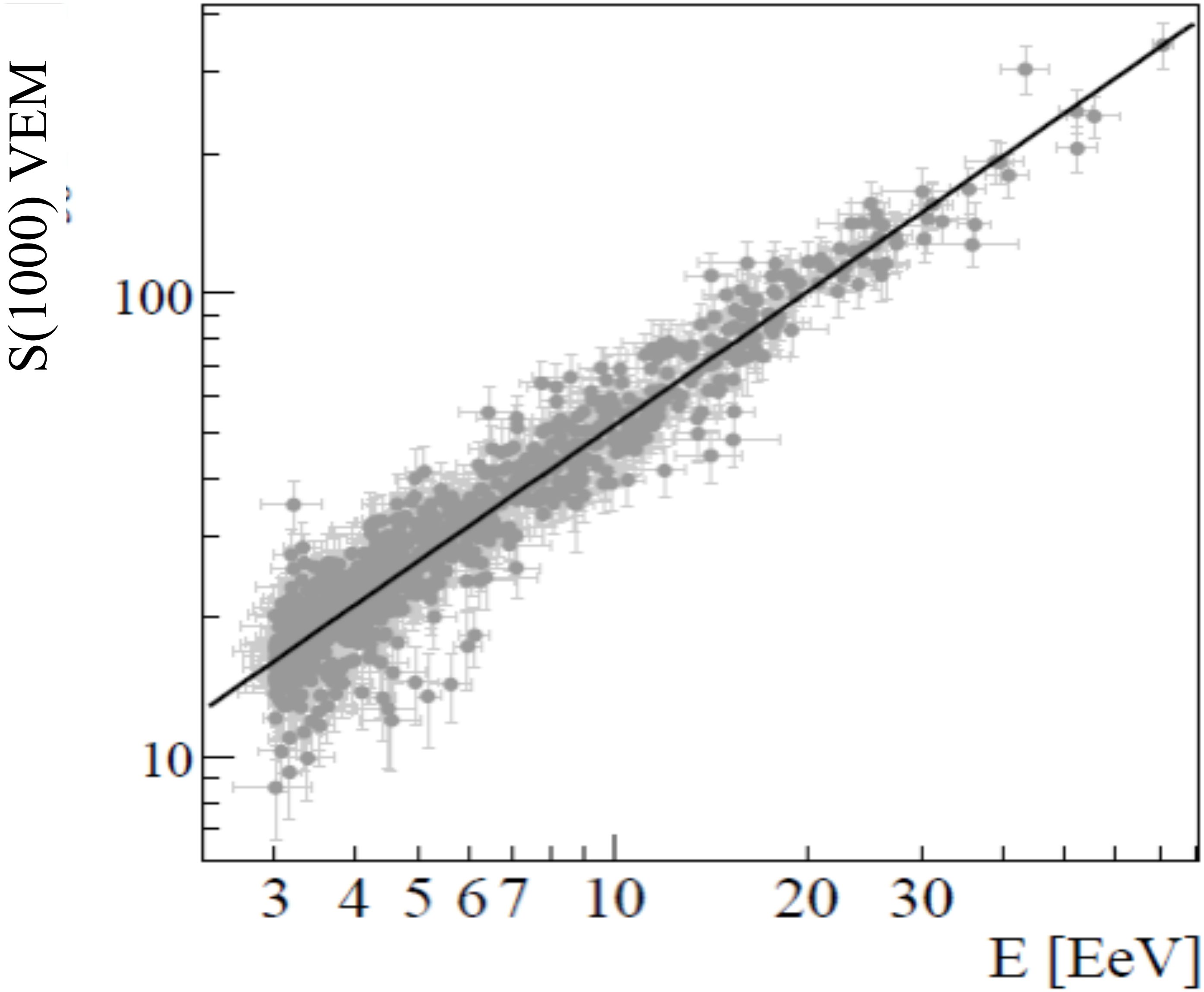








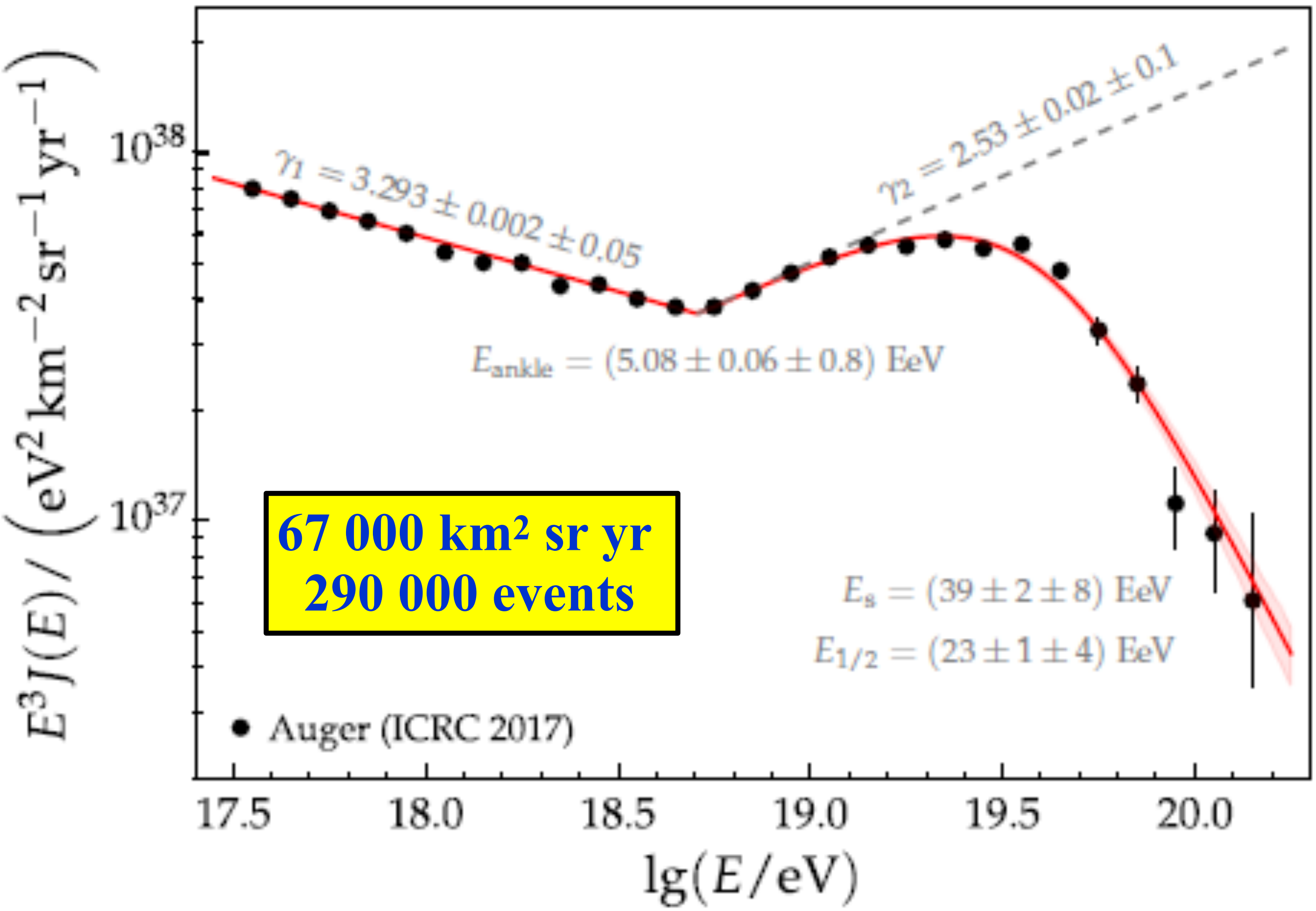
E = 7.1± 0.2 10^{19} eV - X_{max} = 752 ± 7 g/cm²



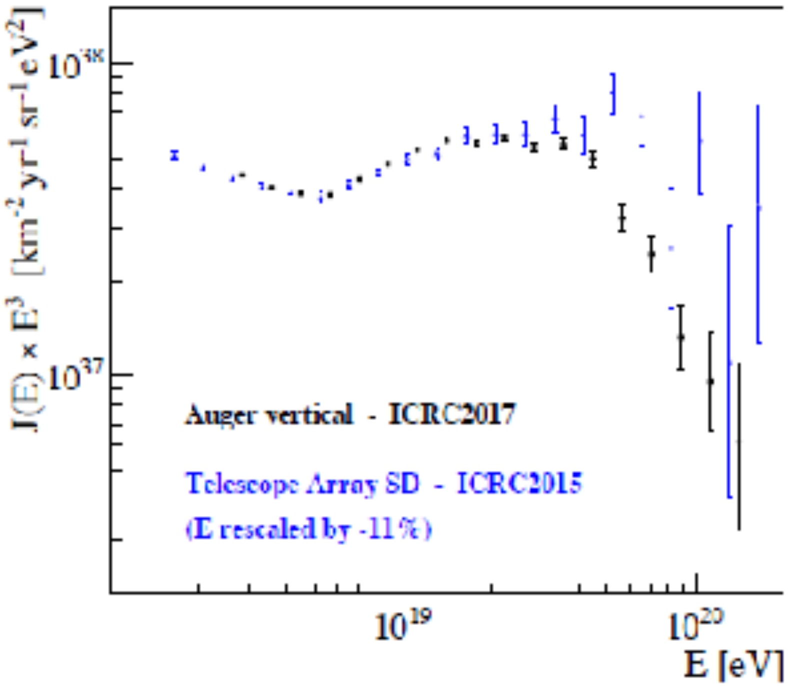
839 events

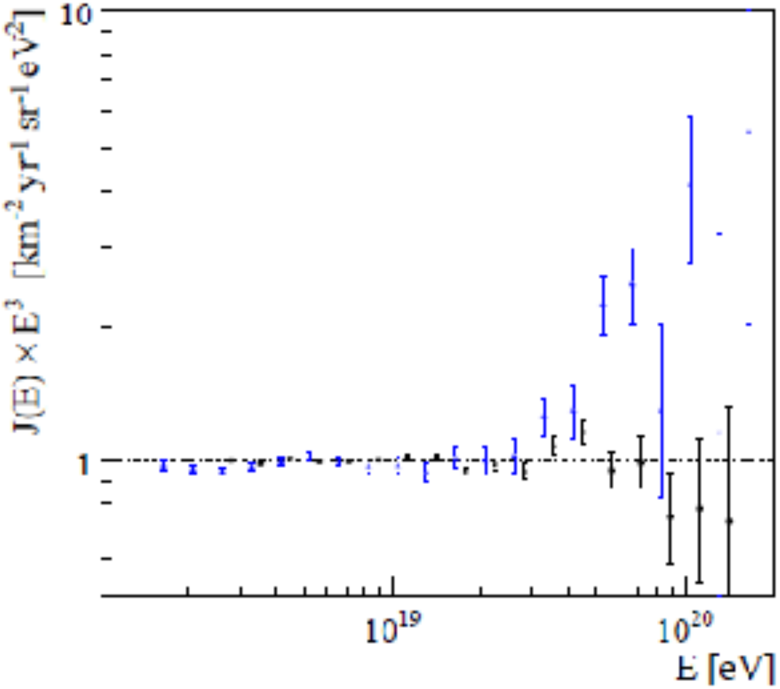
7.5 x 10^{19} eV

Auger Energy Calibration



67 000 km² sr yr
290 000 events


J(E) × E^3 [km^-2 yr^-1 sr^-1 eV^2]
10^38
10^37
10^19
10^20
E [eV]
Auger vertical - ICRC2017
Telescope Array SD - ICRC2015
(E rescaled by -11%)


J(E) × E^3 [km^-2 yr^-1 sr^-1 eV^2]
10
1
10^19
10^20
E [eV]

TA Spectrum: Abbasi et al. arXiv: 1801.07820

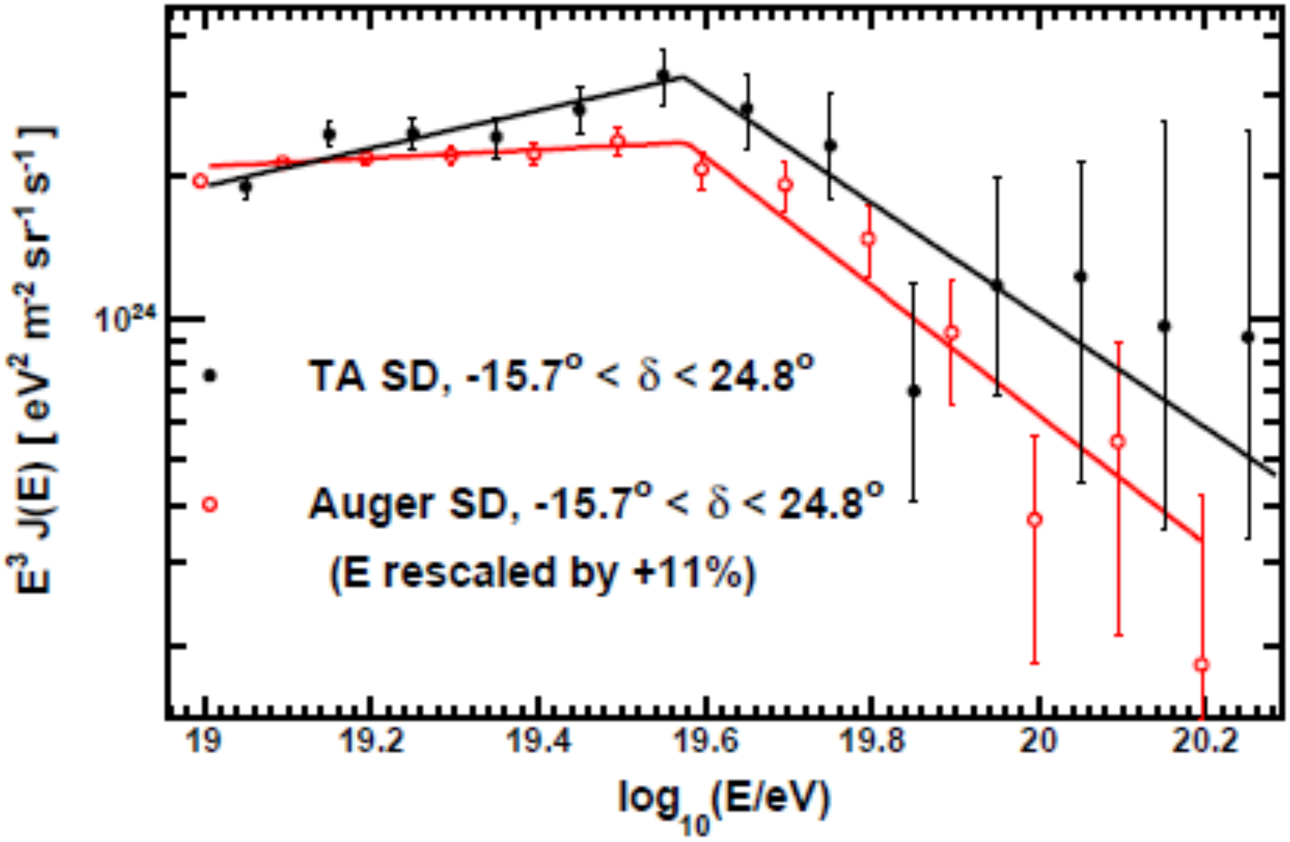
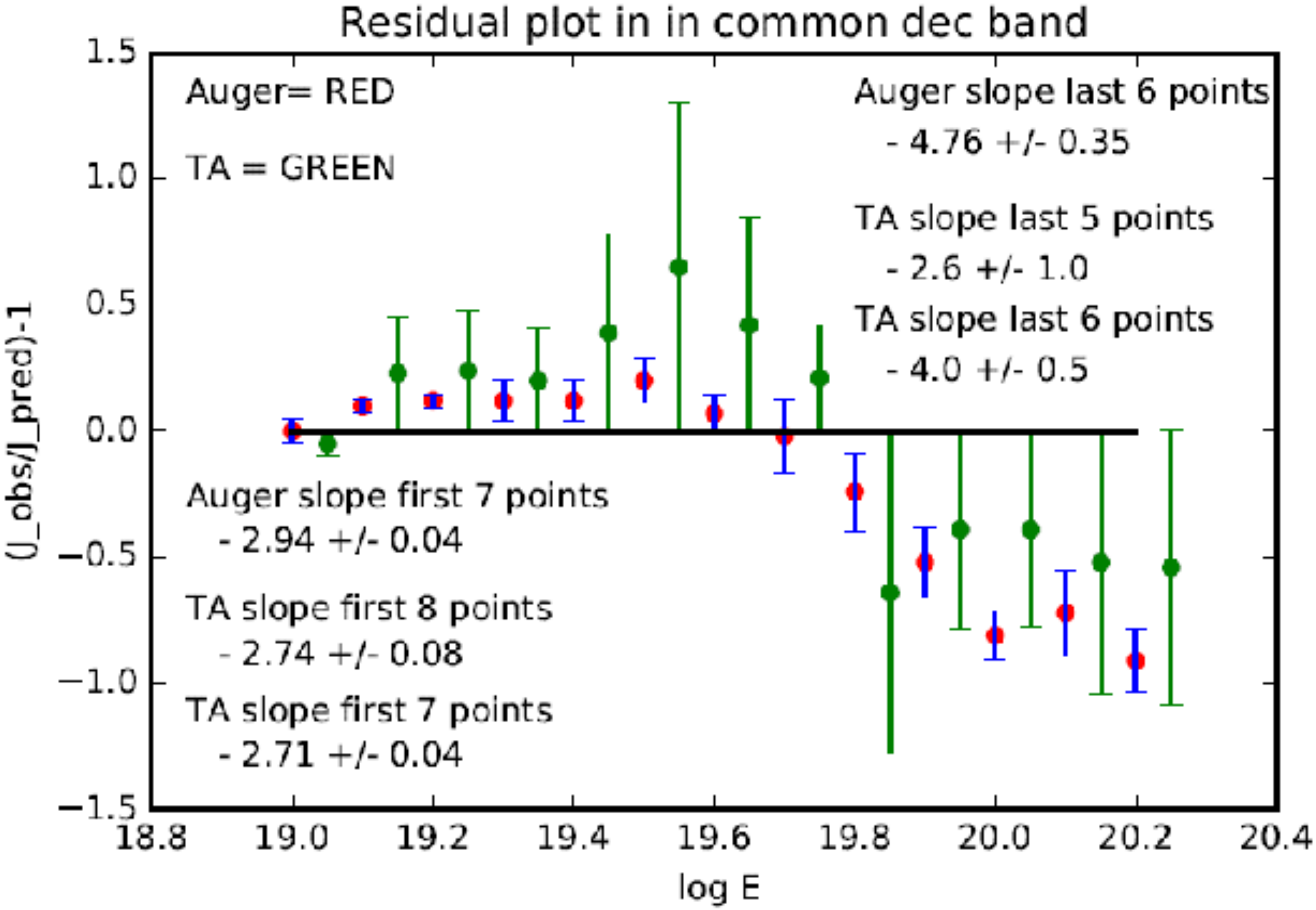


Figure 3: Energy spectra of TA and Auger in the common declination band.

That cut-off energies agree within 1 sigma taken as evidence of agreement between two measurements



One or both measurements are in error

The steepening itself is INSUFFICIENT for us to claim that we have seen the Greisen-Zatsepin-Kuz'min effect

It might simply be that the sources cannot raise particles to energies as high as 10^{20}eV – Nature could be teasing us!

probably is!

Energy densities of CMB, galactic magnetic field, cosmic rays and starlight are very similar – this may be another coincidence

- **Are there anisotropies in the arrival direction distributions?**

- **Knowing the mass composition would be useful – but for this we need to extrapolate key features of hadronic interactions to high energies**

- cross-section, multiplicity, inelasticity, pion collisions…

Arrival Direction studies

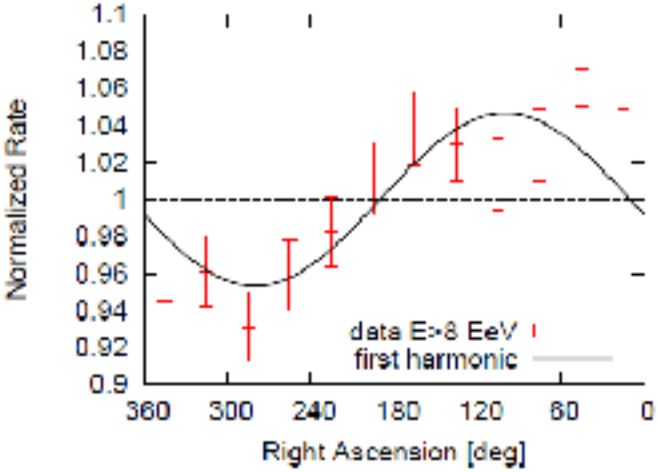
- The cosmic-ray sky is remarkably isotropic, even at the very highest energies
- This surely reflects the high charge of the particles and magnetic fields that lie between us and the sources – or there could be a huge number of sources
- There may be hot-spots in the sky at the highest energies
- There is now very strong evidence for a dipole anisotropy 8 EeV

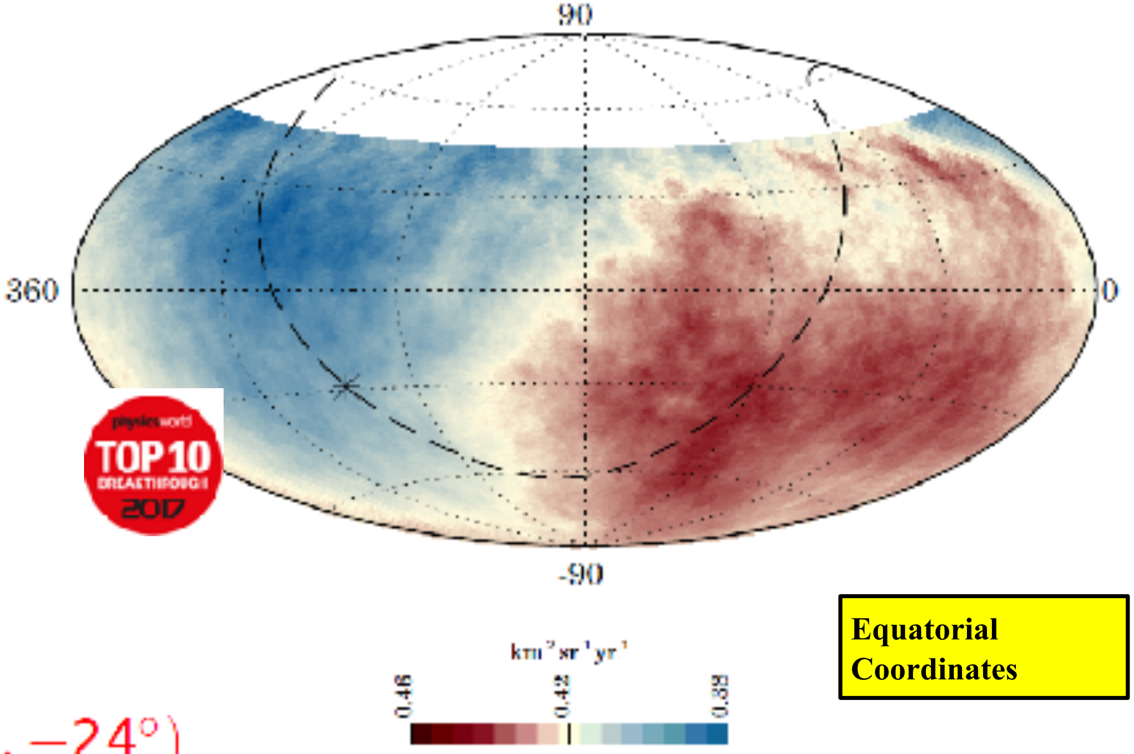
Observation of Dipolar anisotropy above 8 EeV

Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2 σ (5.6σ before penalization for energy bins explored)



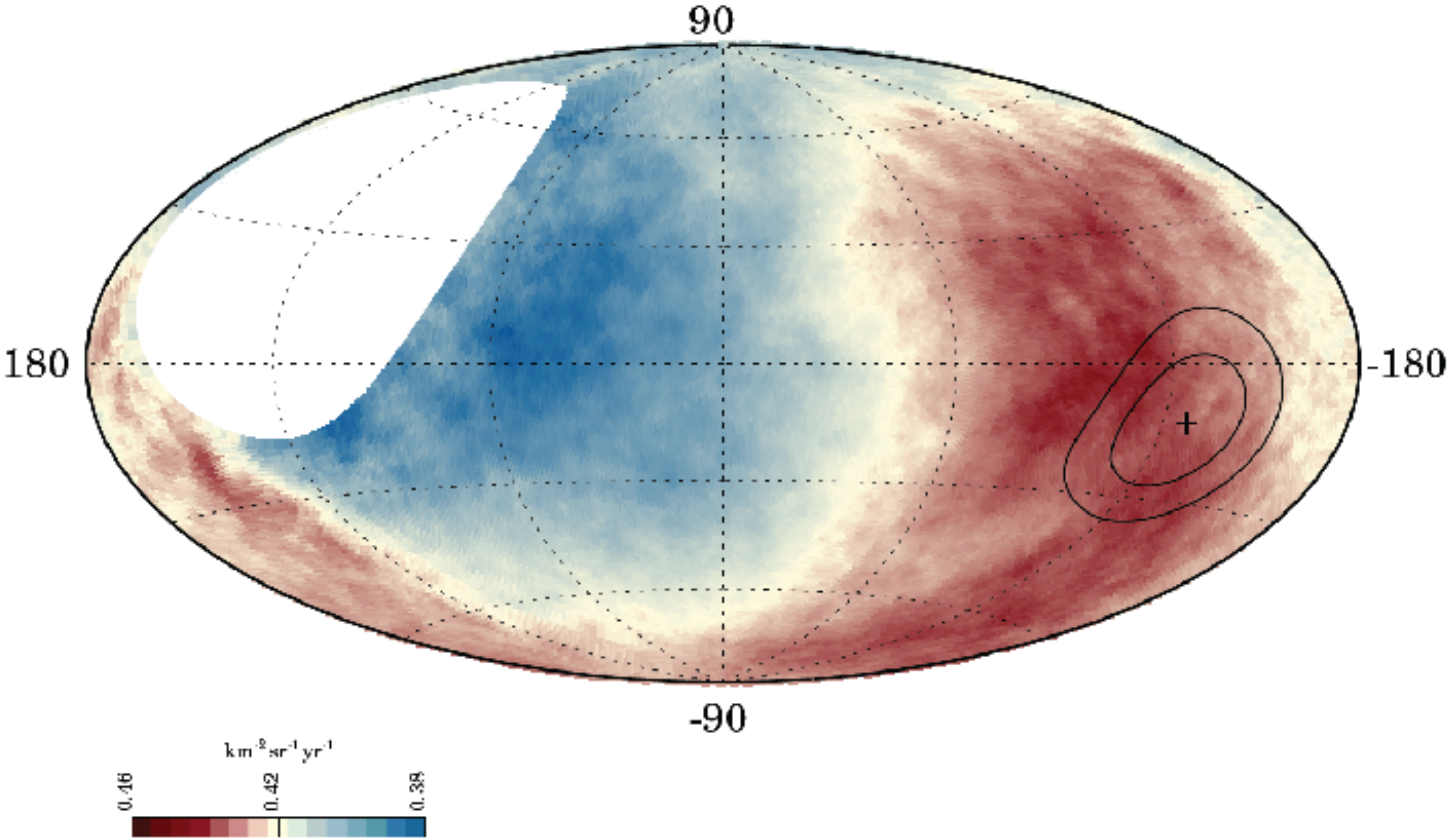


Equatorial Coordinates

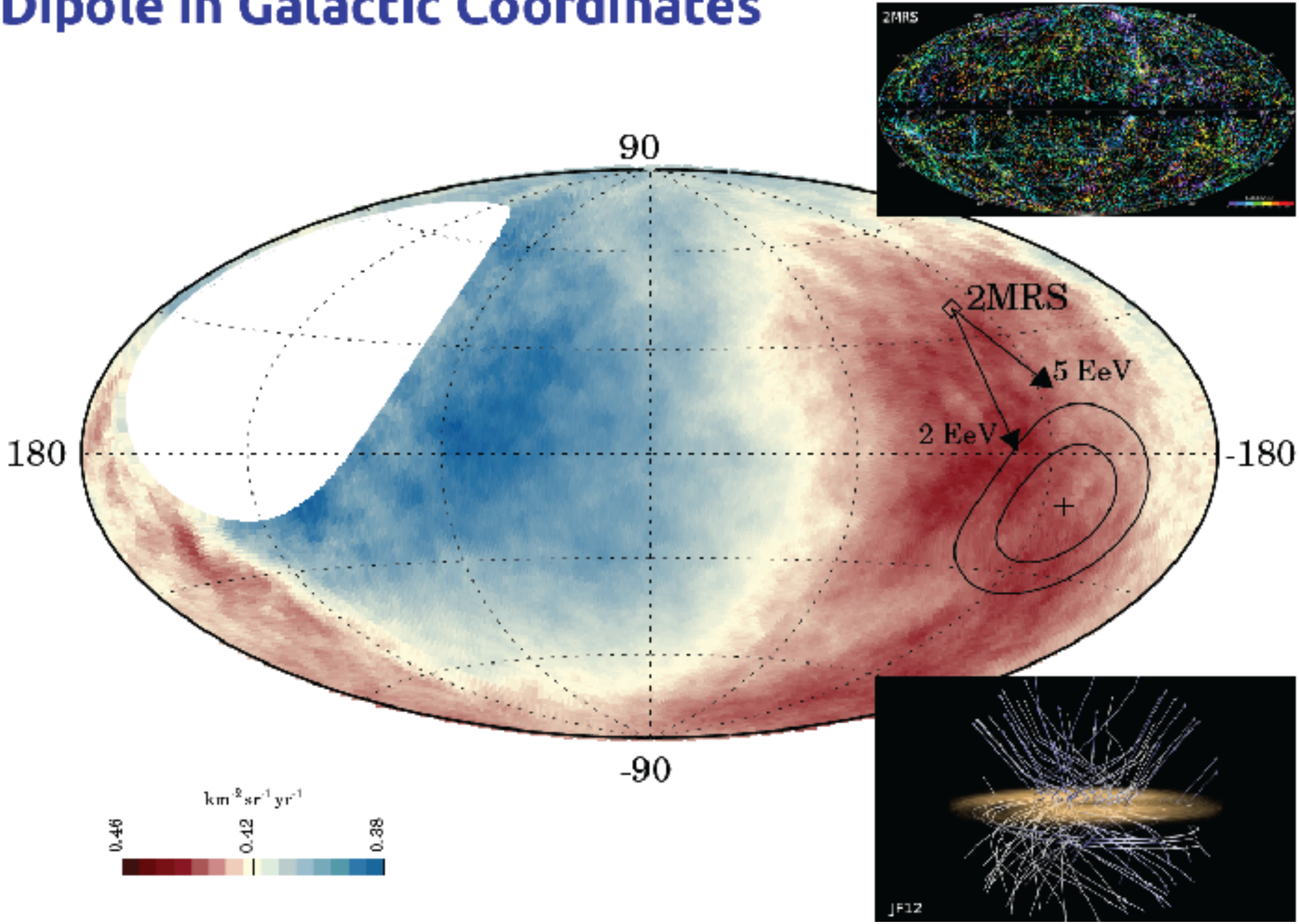
3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

Dipole in Galactic Coordinates



Dipole in Galactic Coordinates



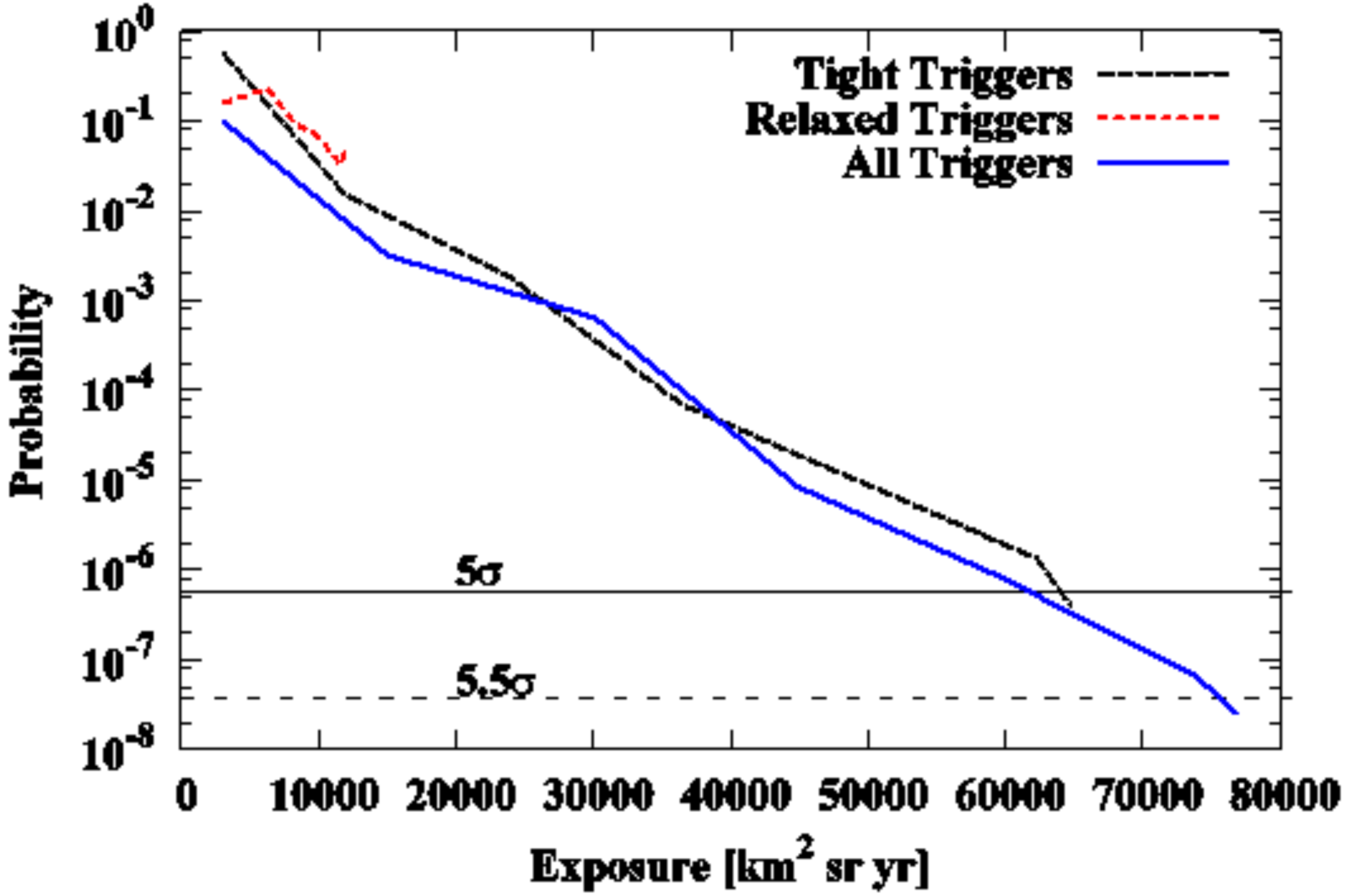


Fig. S3. Evolution of the probability that the signal arises by chance as a function of

Sur la piste des rayons cosmiques dans la pampa argentine

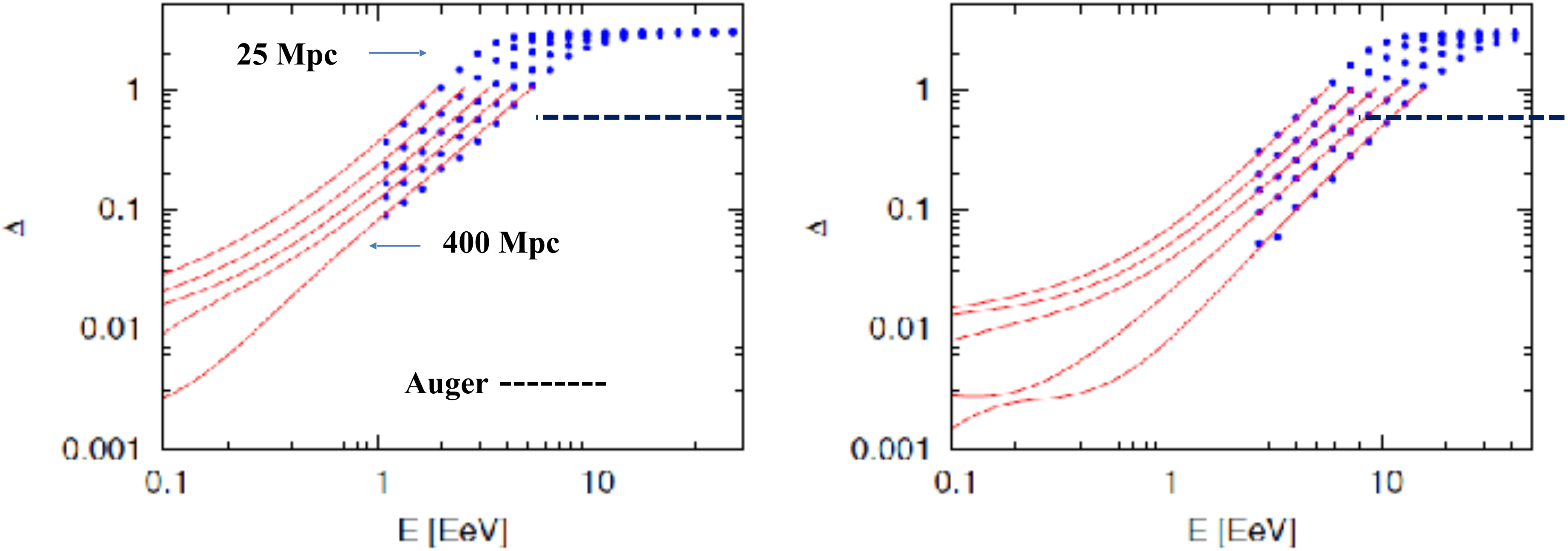
Quelle est l'origine des **rayons cosmiques** *? C'est pour résoudre cette* **énigme** *que des chercheurs ont investi la pampa argentine. Là, ils ont installé* **le plus grand détecteur** *du monde qui, jour et nuit, traque les* **flux de particules** *venues du* **cosmos**. *Une* **quête** *dont les physiciens espèrent beaucoup.*

Cette cuve perdue dans la pampa [illegible] la trace des rayons cosmiques.

Par Claire Martin. Photos : Rodrigo Gomez Rovira/Vu

Harari, Mollerach and Roulet PRD 89 123001 2014

Single Source Model



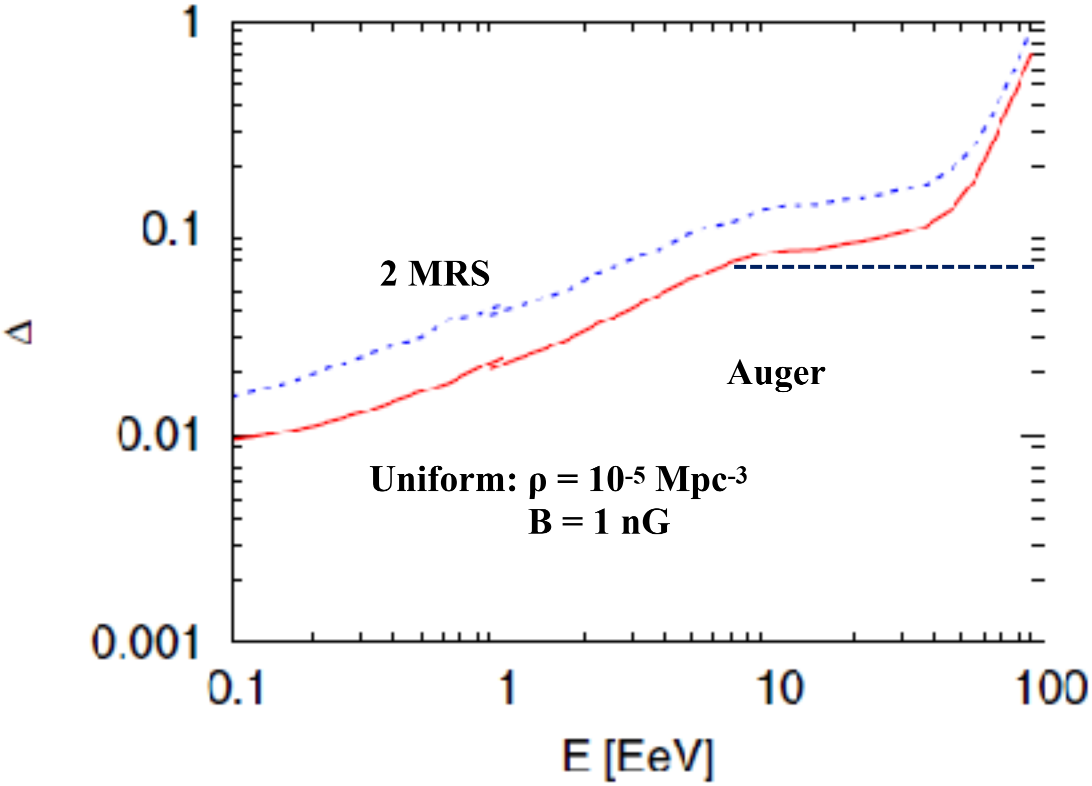
Coherence length = 1 Mpc.

LH B= 1 nG; RH B= 3 nG

-proton primaries are assumed

Harari, Mollerach and Roulet PRD 89 123001 2014

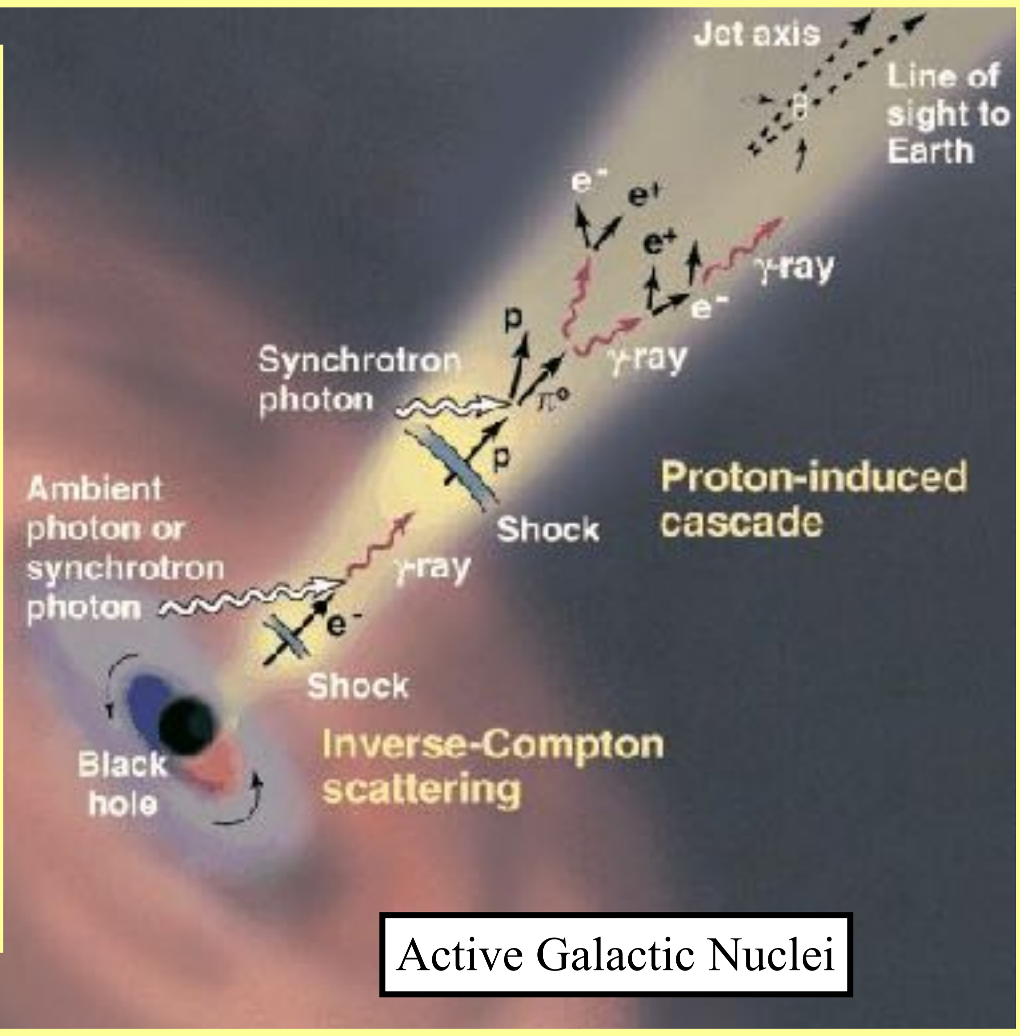
Multiple sources



Soon: Results on amplitudes and phases above 8 EeV as function of energy

Testing for correlations

image of M87 with Hubble Space Telescope



Active Galactic Nuclei

Production in Starburst Galaxies ApJ Letters (Jan 2018)

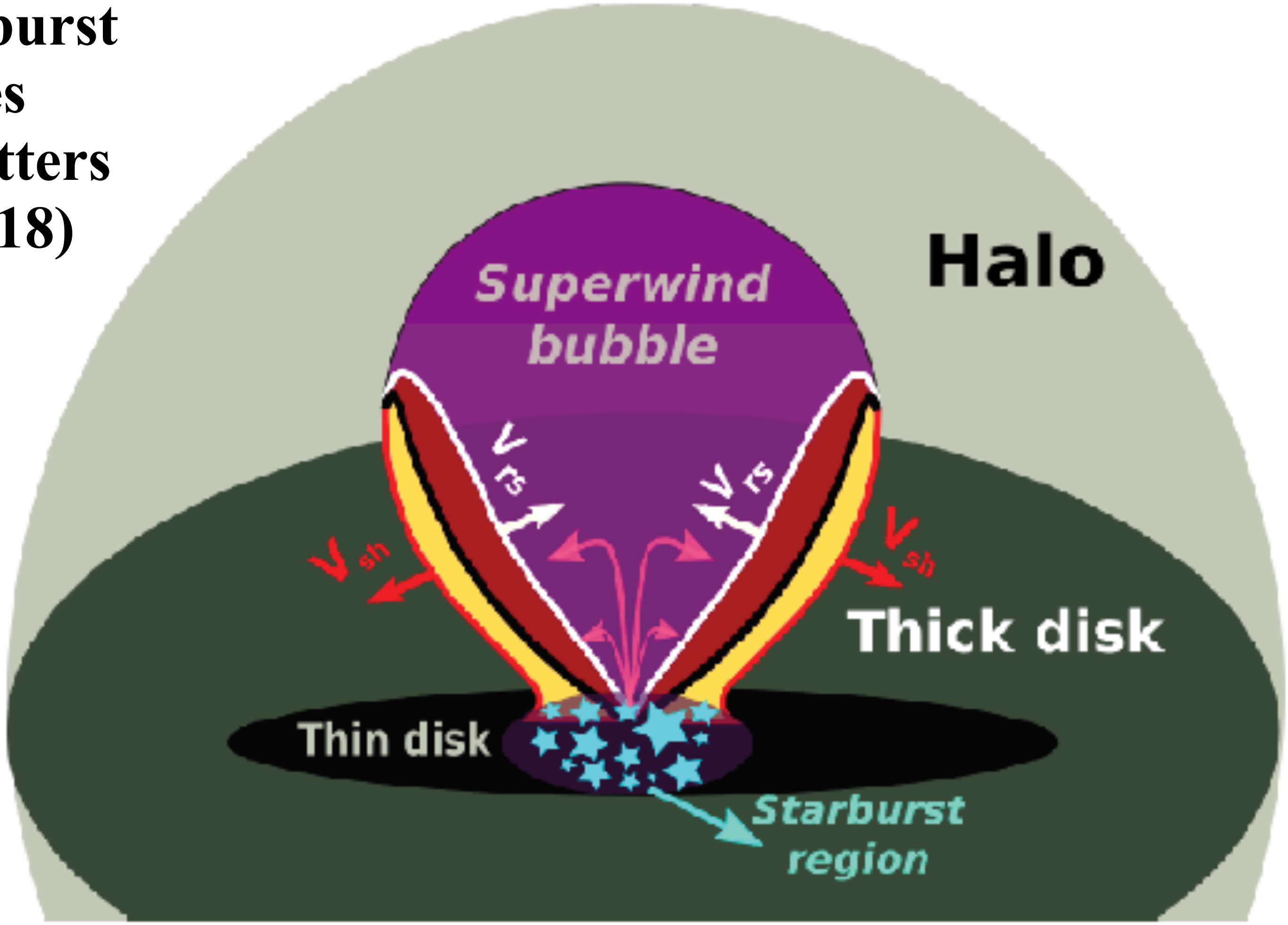
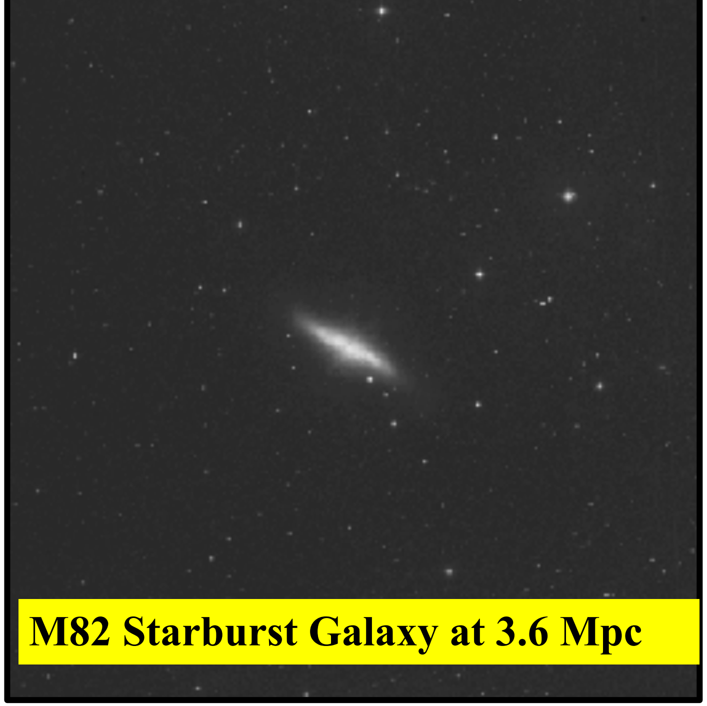
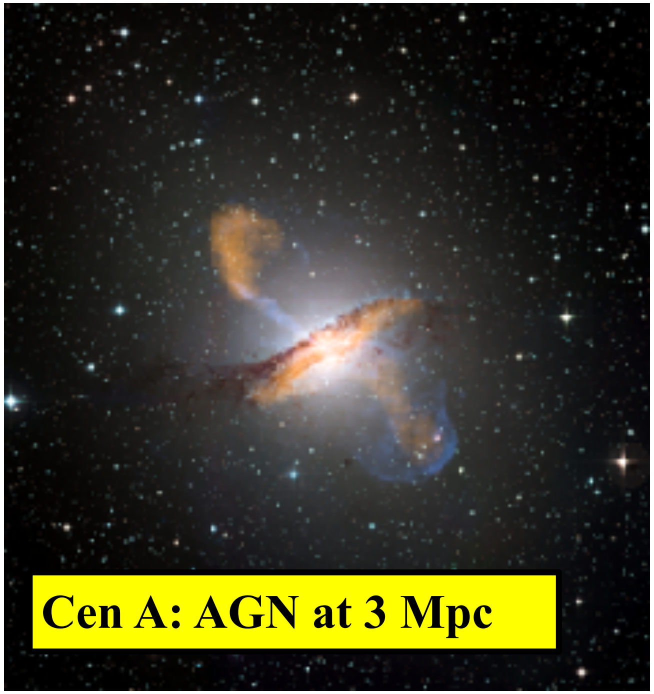


Fig. 1. Scheme of the physical scenario considered in this work. Not to scale. Adapted from Strickland et al. (2002).


M82 Starburst Galaxy at 3.6 Mpc


NGC 253: Sculptor Galaxy at 3.5 Mpc


NGC 4945 at 3.6 Mpc


Cen A: AGN at 3 Mpc

UHECR come from Starburst Galaxies and from AG: ApJ Letters January 2018

Search for Intermediate-scale Anisotropies

Analysis Strategy:

- arrival directions of data, D
- sky model from source candidates, M_i

$M_i =$ (flux model) × (attenuation model) × (angular smearing) × (exposure)

- null hypothesis: isotropy M_0
- single population signal model:

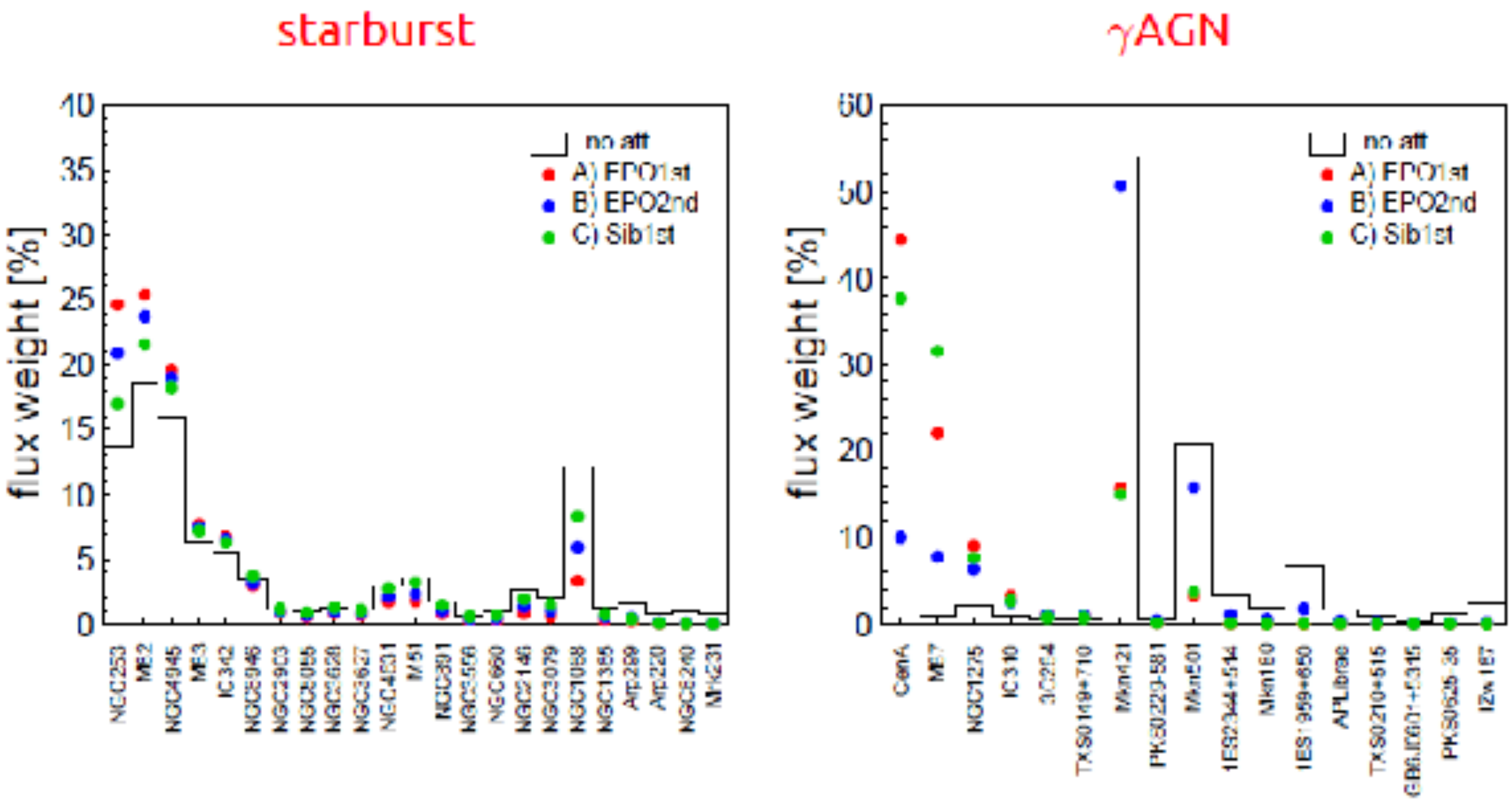
$$M \quad (1-\alpha)\,M_0 + \alpha\,M_i$$

- test statistics:
  - ratio of likelihoods of model-data comparison

    $\mathrm{TS} - 2\log(P(D|M)/P(D|M_0))$

    think $\Delta\chi^2$ of (isotropy + signal) vs. isotropy
  - p-value from Wilk's theorem: $p(\mathrm{TS}) \quad p_{\chi^2}(\mathrm{TS}, \Delta\mathrm{ndf})$
  - of large TS
    - M describes D much better than M_0
    - M_0 excluded at p (**not:** M "proven" at p)

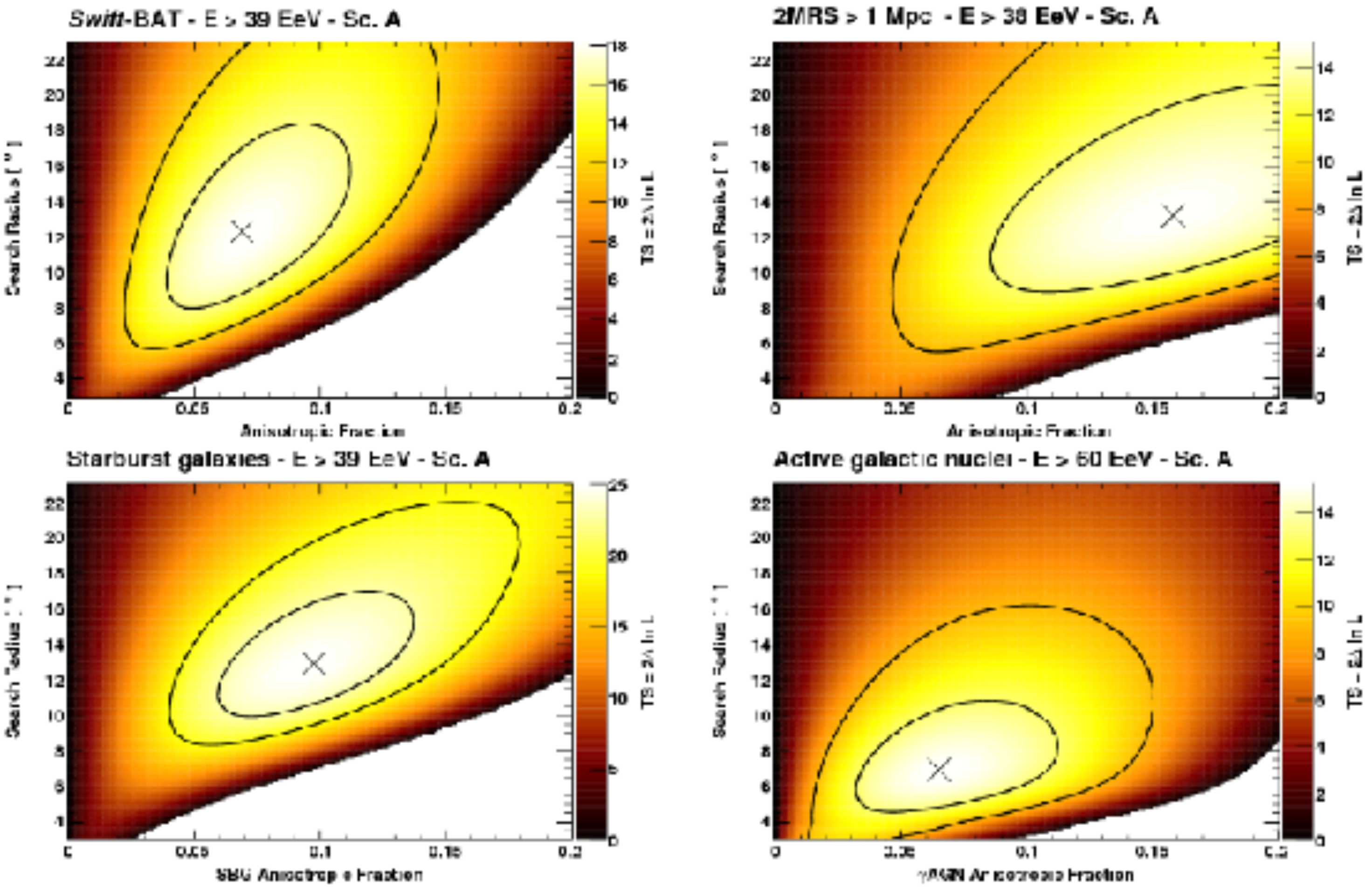
Flux Attenuation (top: SBG, bottom: γAGN)



composition scenarios from Pierre Auger Coll., JCAP 1704 (2017) 038 + CRPropa3

name	$\lg(R_{\max}/V)$	f_p	f_{He}	f_N	f_{Si}	γ
EPO1st	18.68	0.000	0.673	0.281	0.046	0.96
EPO2nd	19.88	0.000	0.000	0.798	0.202	2.04
Sib1st	18.28	0.702	0.295	0.003	0.000	1.50

Optimization: Signal Fraction and Angular Smearing



Swift-BAT - E > 39 EeV - Sc. A

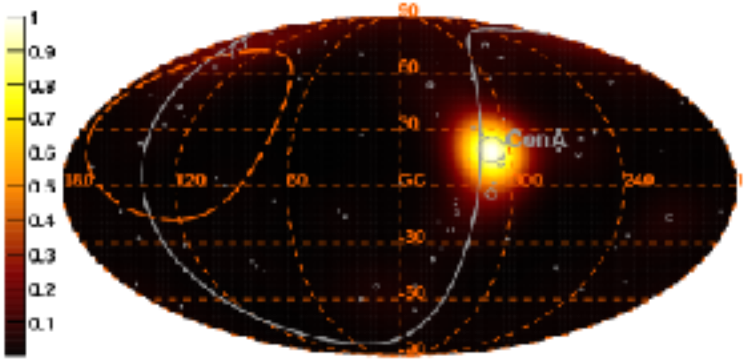
2MRS > 1 Mpc - E > 38 EeV - Sc. A

Starburst galaxies - E > 39 EeV - Sc. A

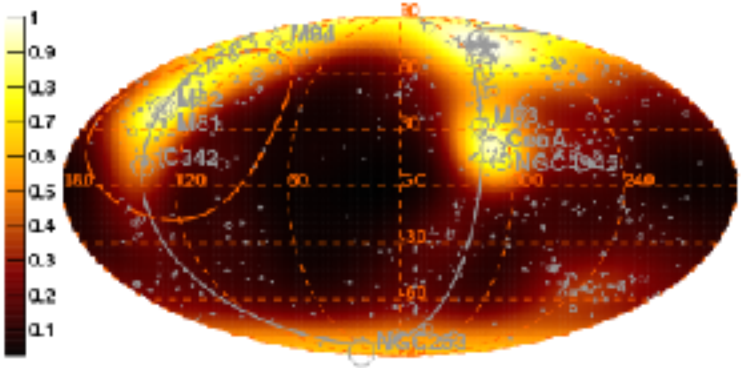
Active galactic nuclei - E > 60 EeV - Sc. A

Sky Model (flux) × (attenuation model)$_A$ × (angular smearing), gal. coord.

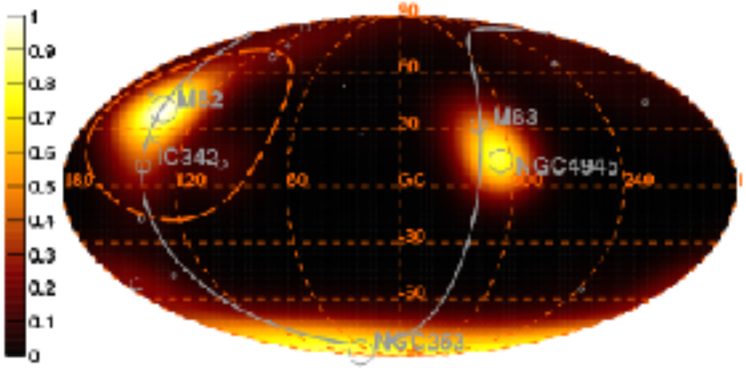
Model Flux Map - *Swift*-BAT - E > 39 EeV - Sc. A



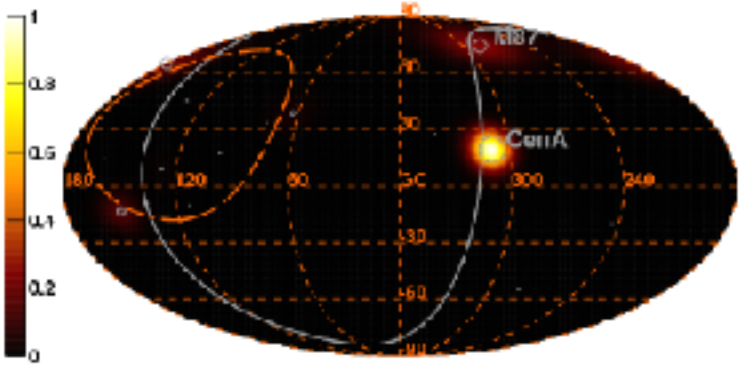
Model Flux Map - 2MRS > 1 Mpc - E > 38 EeV - Sc. A



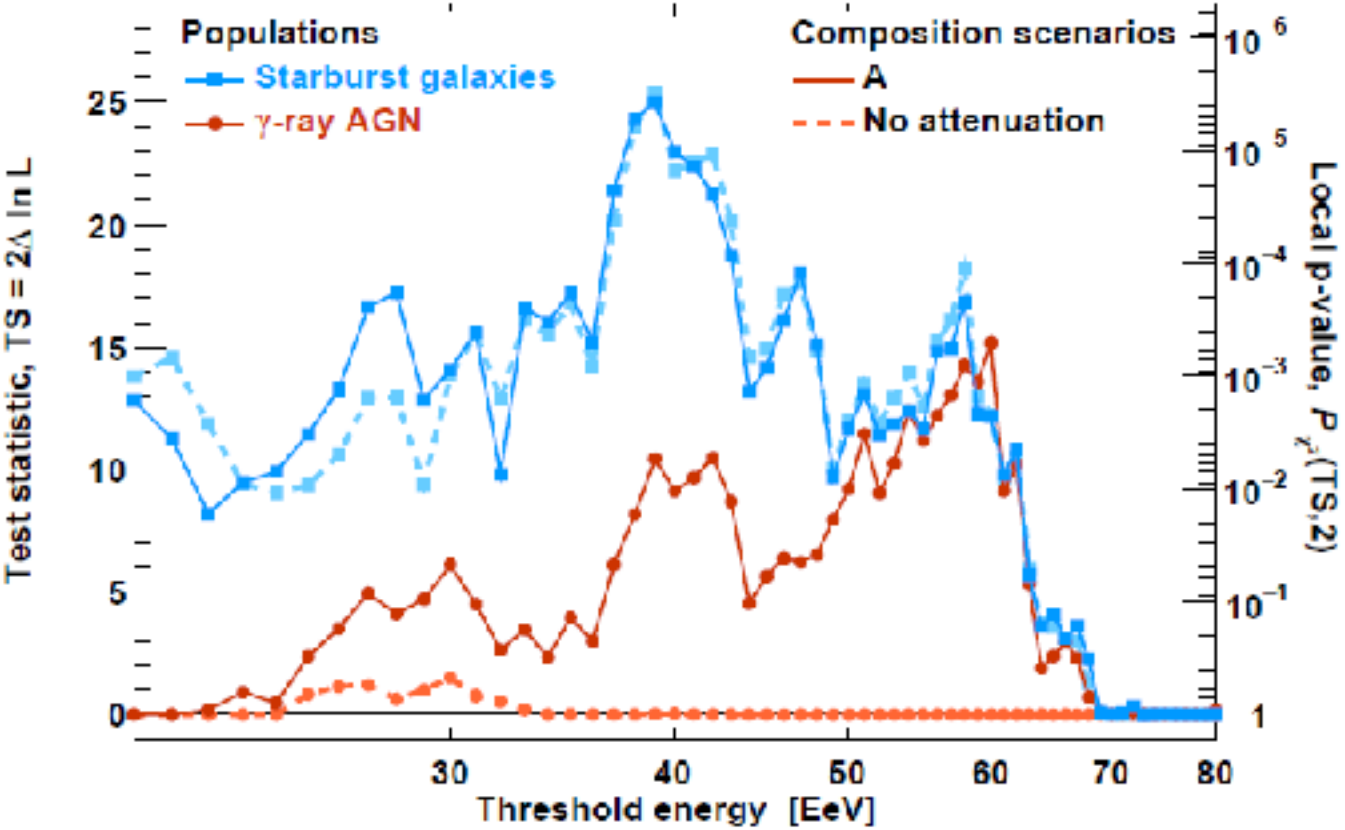
Model Flux Map - Starburst galaxies - E > 39 EeV - Sc. A



Model Flux Map - Active galactic nuclei - E > 60 EeV - Sc. A

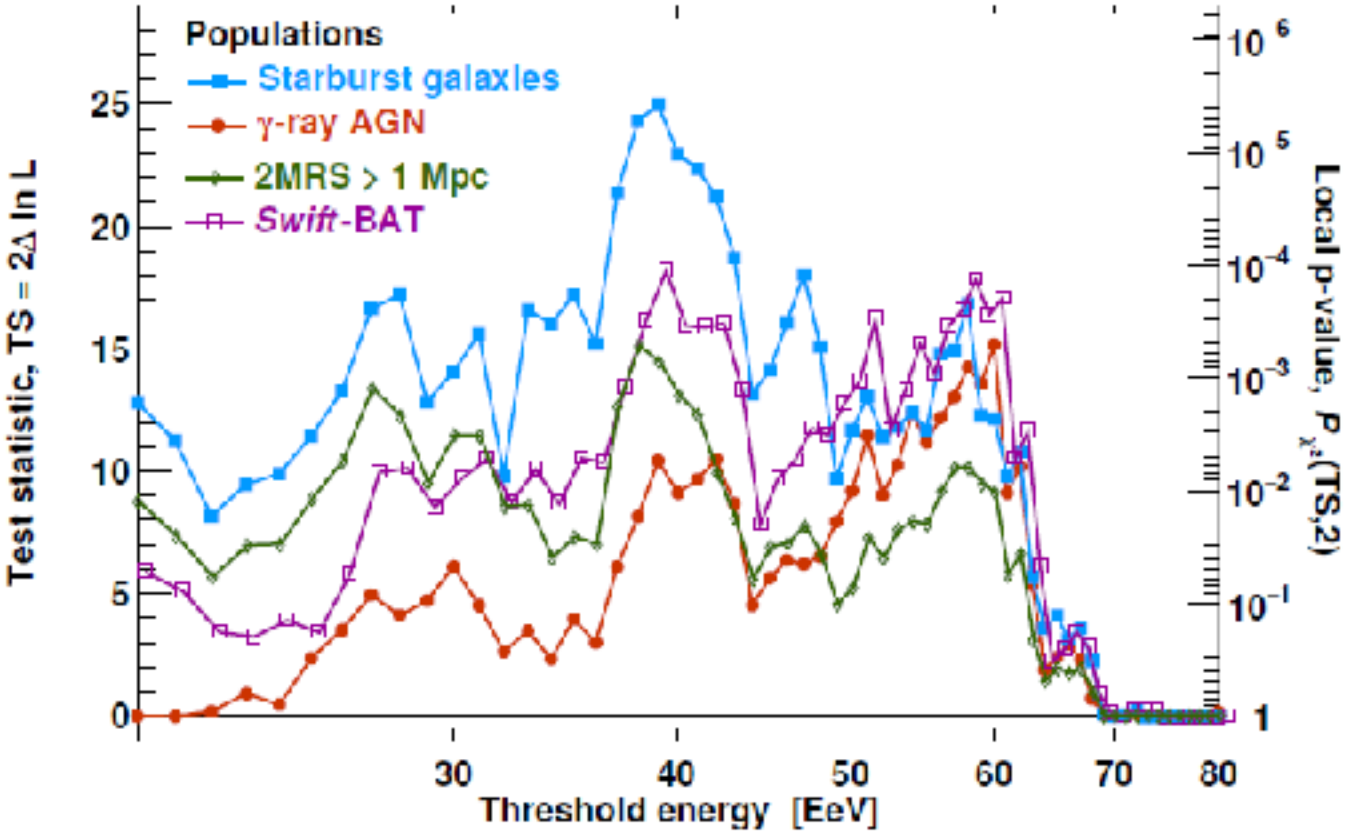


Test Statistics vs. Energy



starburst model fits data better than isotropy, significance of 4 σ^*.

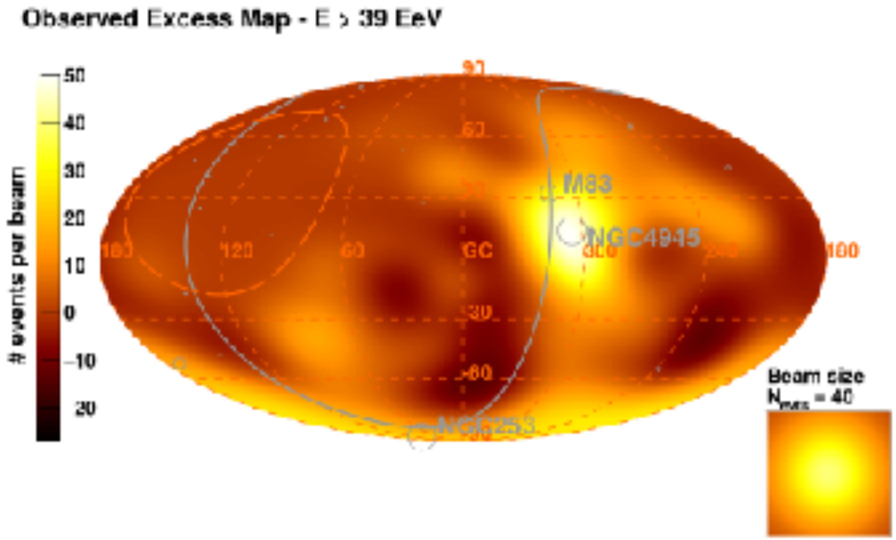
Test Statistics vs. Energy

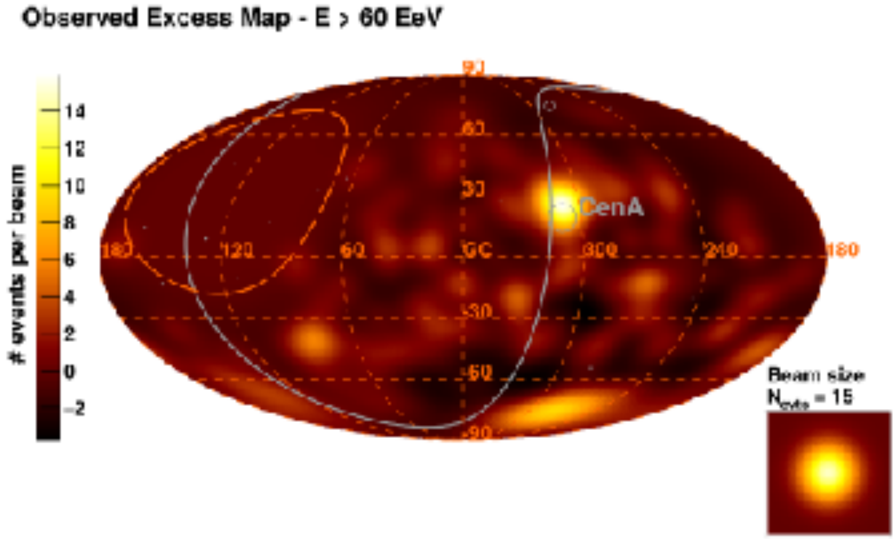


starburst model fits data better than isotropy, significance of 4 σ^*.

* P_{χ^2} (TS, 2) penalized for energy scan

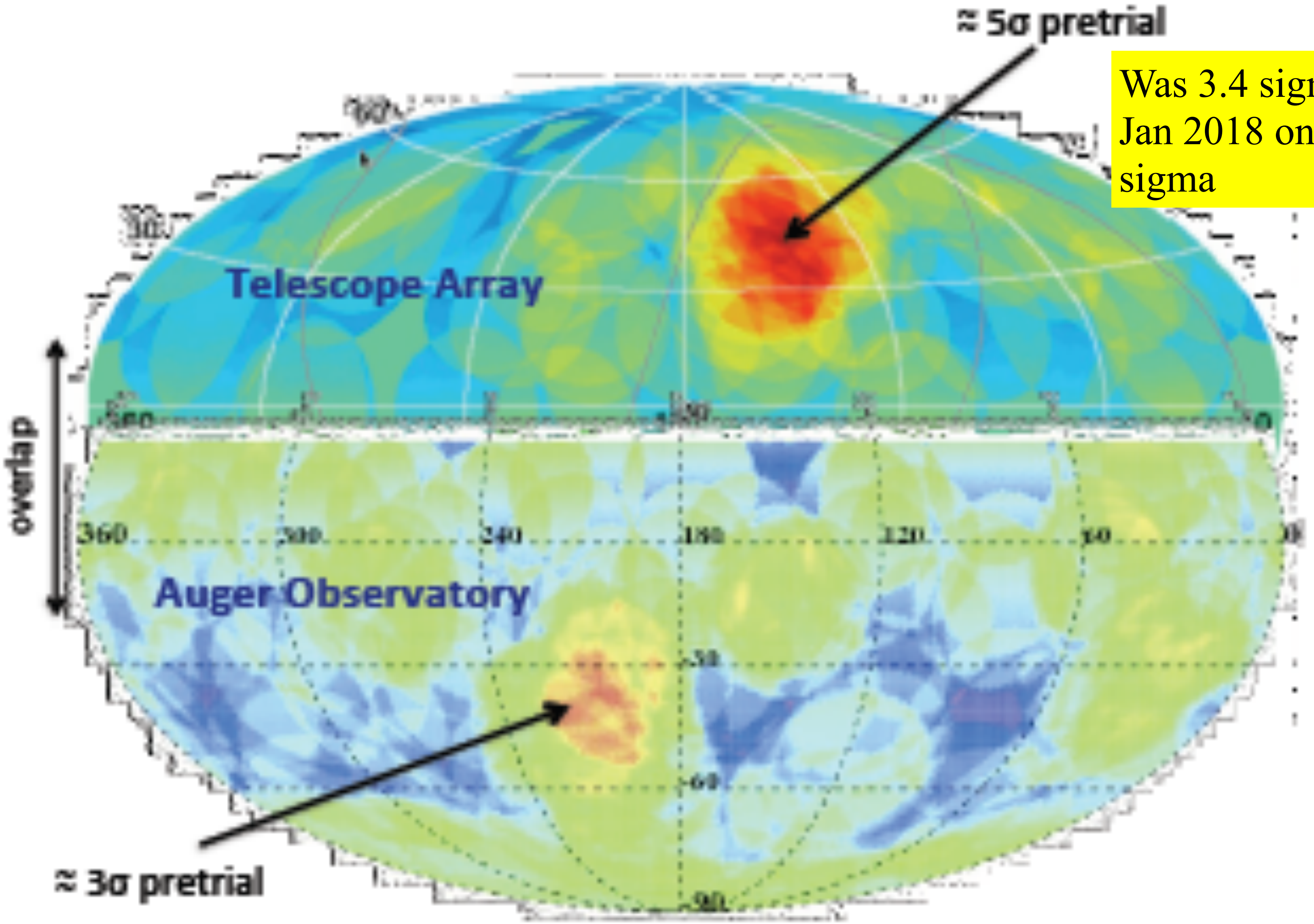
top: starburst galaxies





bottom: γAGN

Auger and Telescope Array Hot-Spots



Was 3.4 sigma
Jan 2018 only 3
sigma

< 2 sigma

It would be enormously useful to know the mass composition

Uncovering the mass composition is extremely difficult

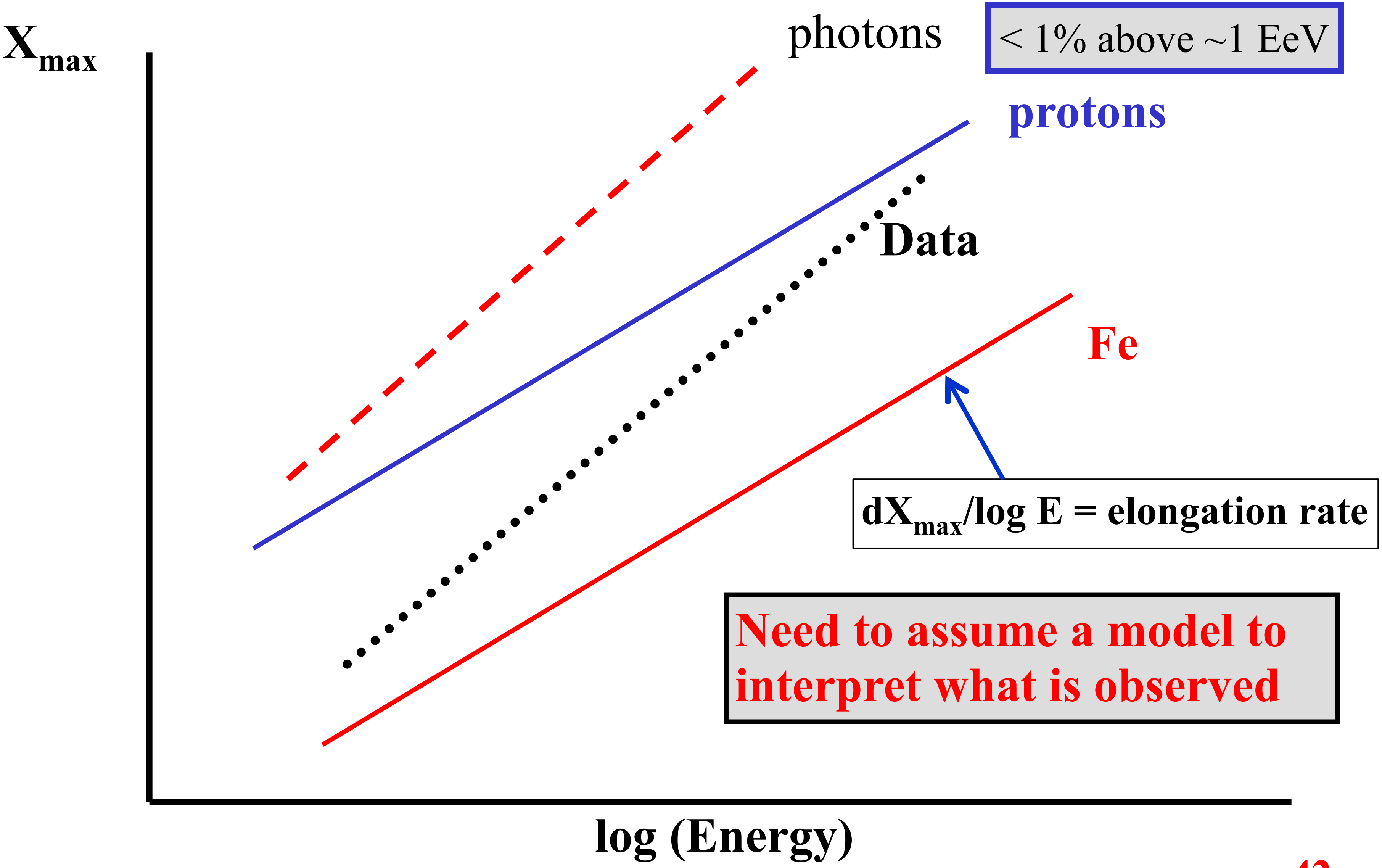
In absence of a strong point-like anisotropy (protons?), one must rely on extrapolations of hadronic physics from accelerators to help interpret the data

Eventually, we will find a hadronic model that fits all of the data

It will give a unique mass composition – but we are not there yet!

Will also benefit from using galactic magnetic field as a magnetic spectrometer

One method to try to infer the variation of mass with energy



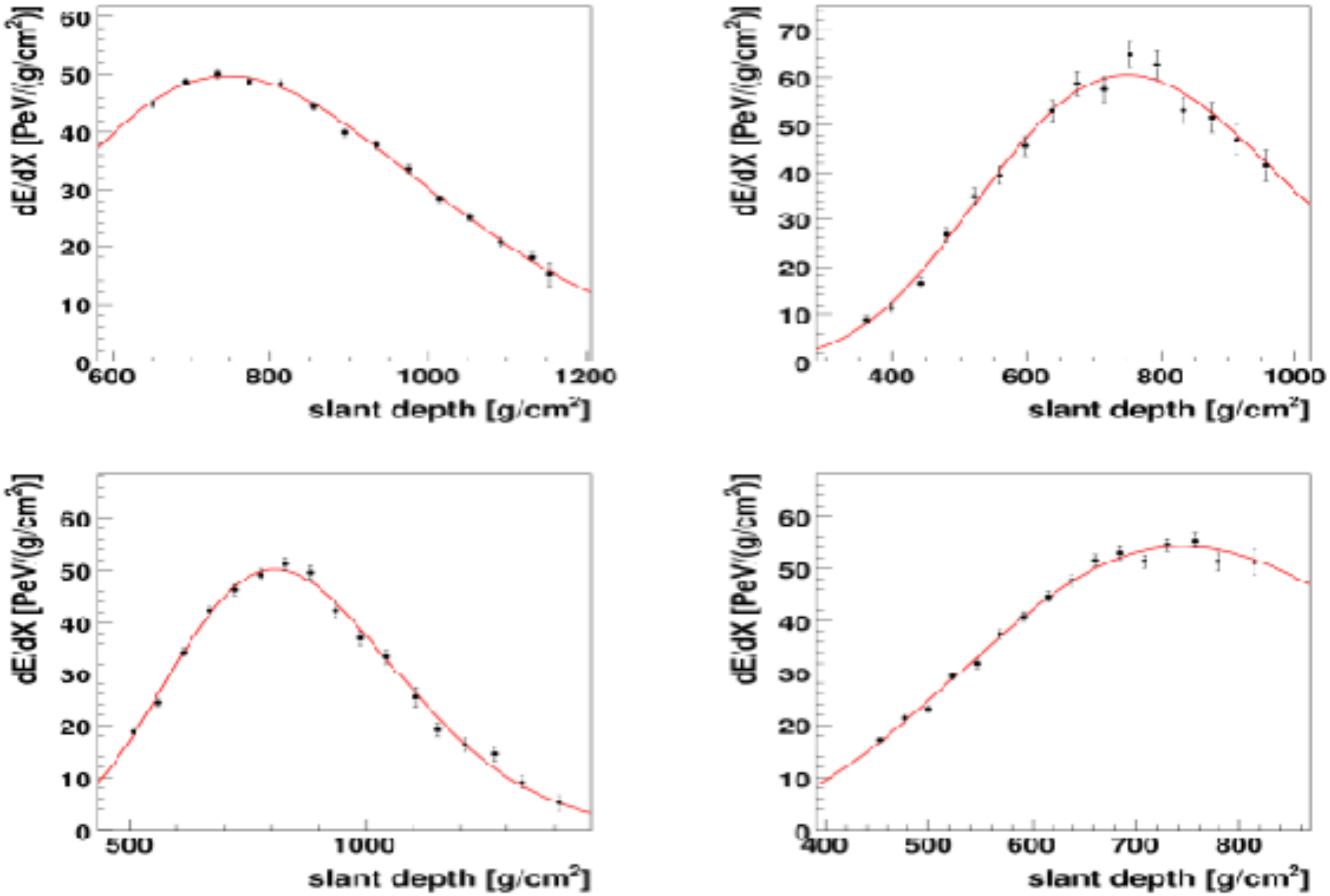
< 1% above ~1 EeV

$dX_{max}/\log E$ = elongation rate

Need to assume a model to interpret what is observed

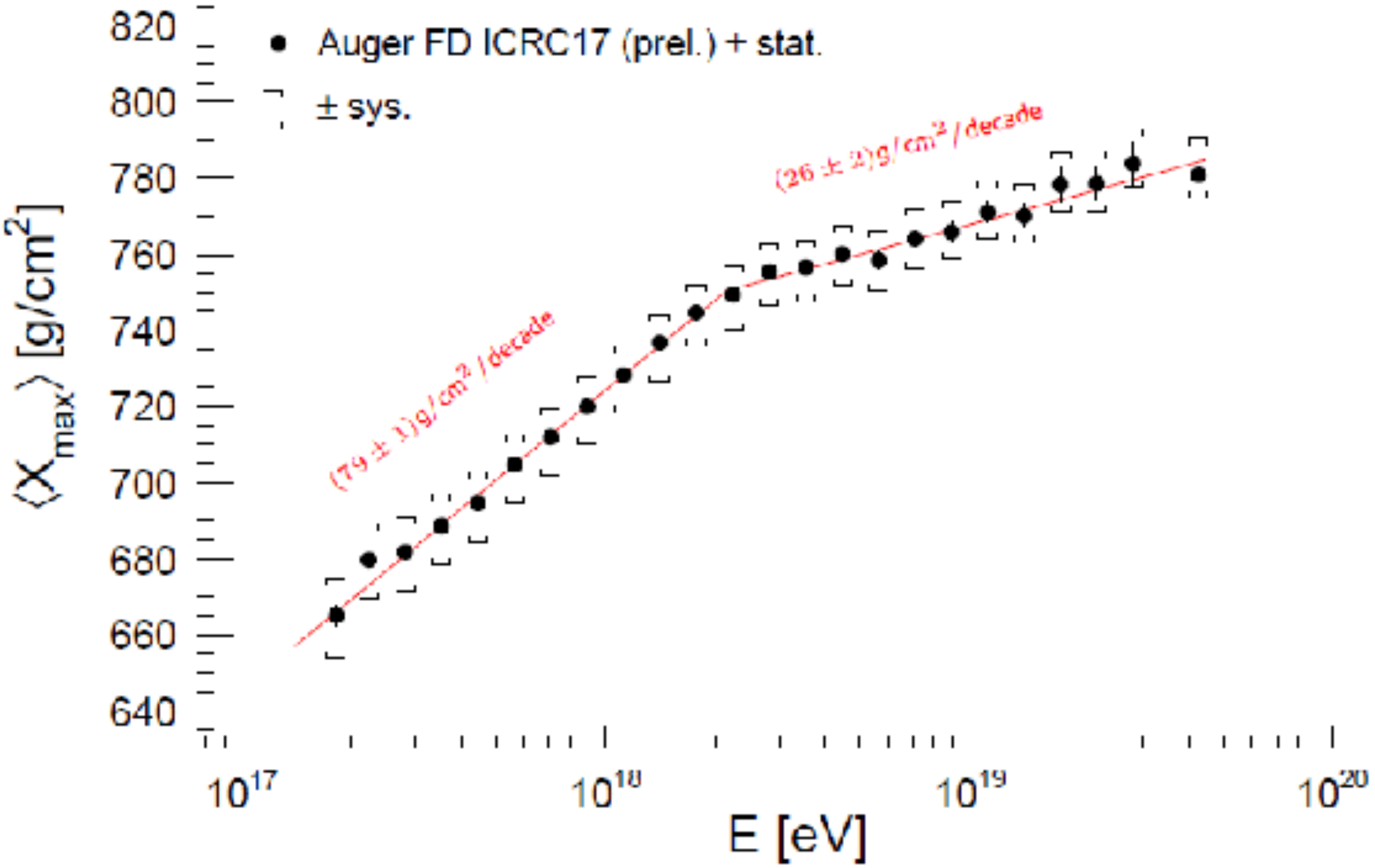
Some Longitudinal Profiles measured with Auger

1000 g cm^{-2} = 1 Atmosphere ~ 1000 mb

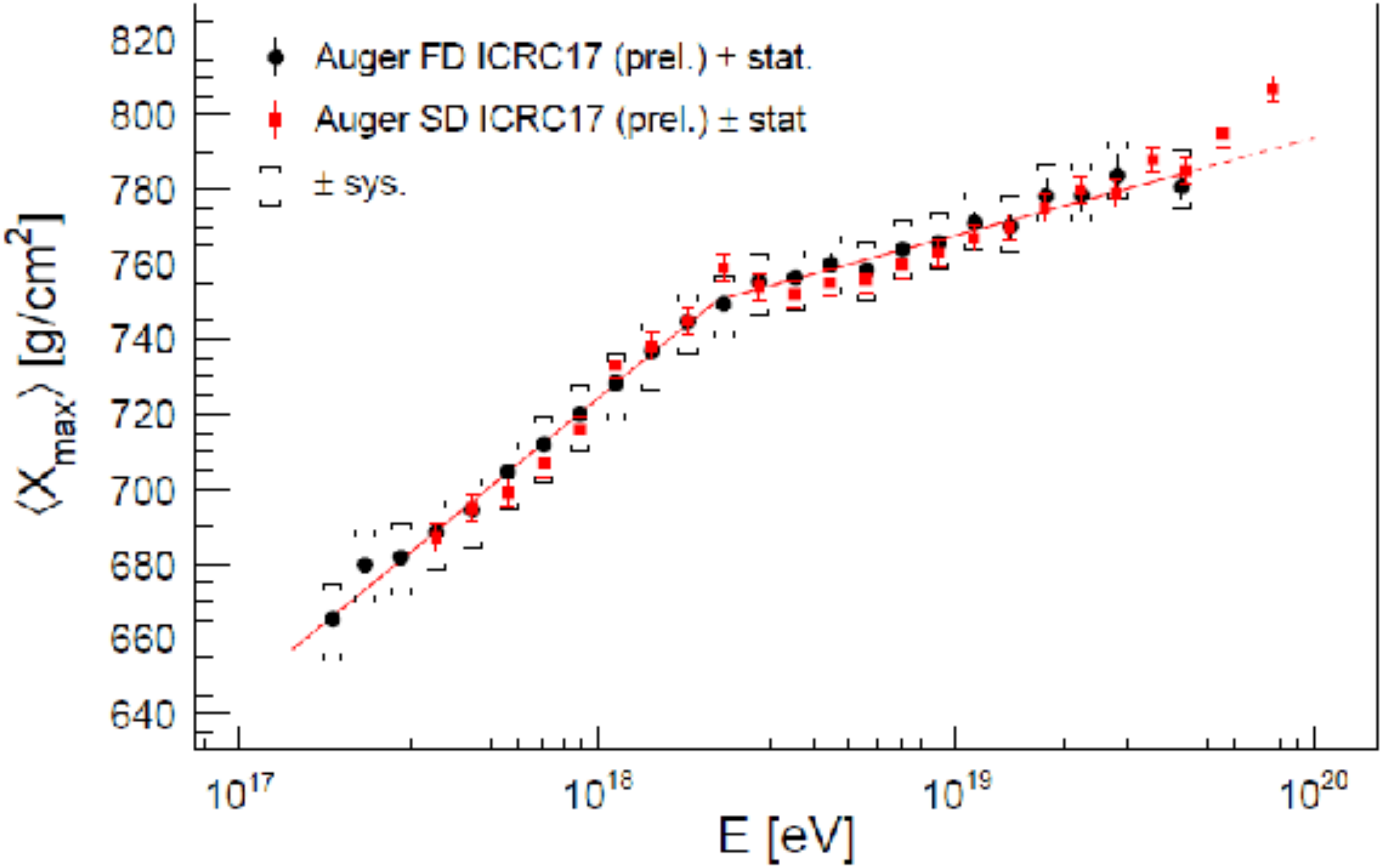


rms uncertainty in X$_{max}$ < 20 g cm^{-2} from stereo-measurements

Average X_{max} **Fluorescence Detector**



Average X_{max} Fluorescence and Surface Detector



Results on mass from depth of maximum with fluorescence detectors

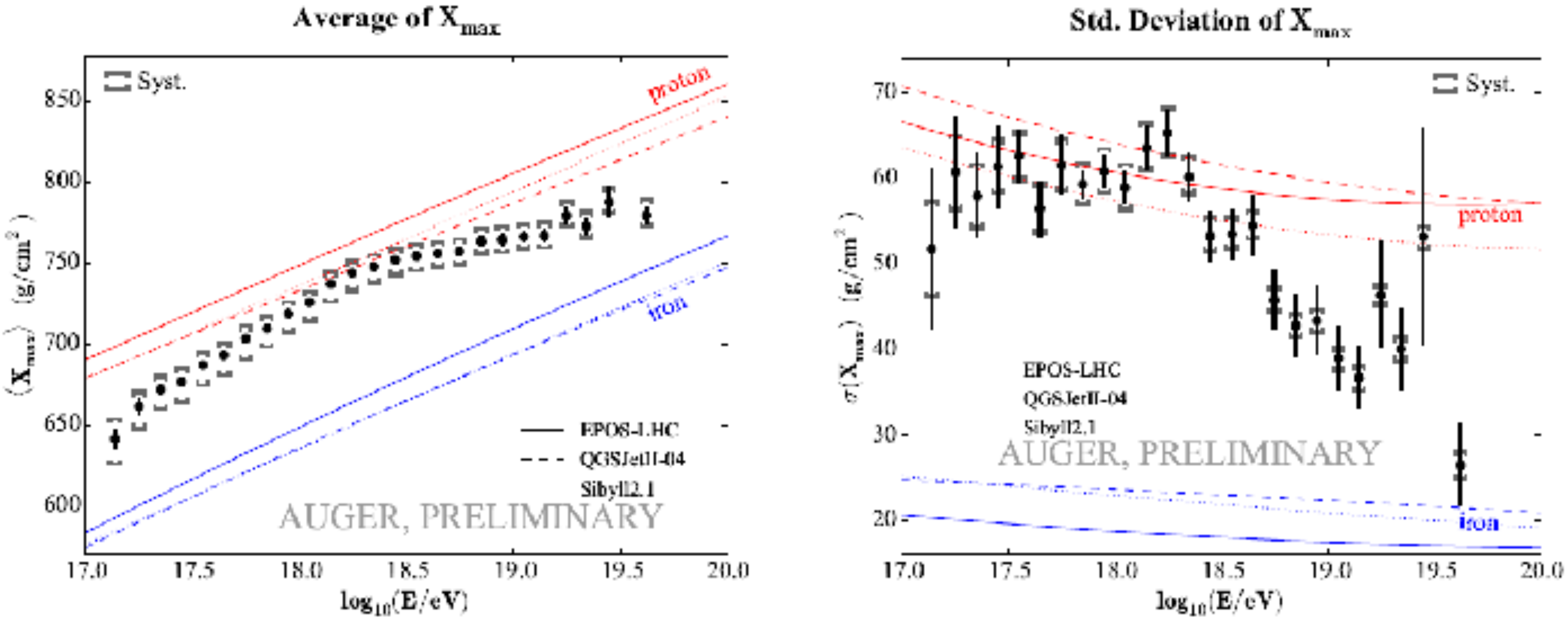
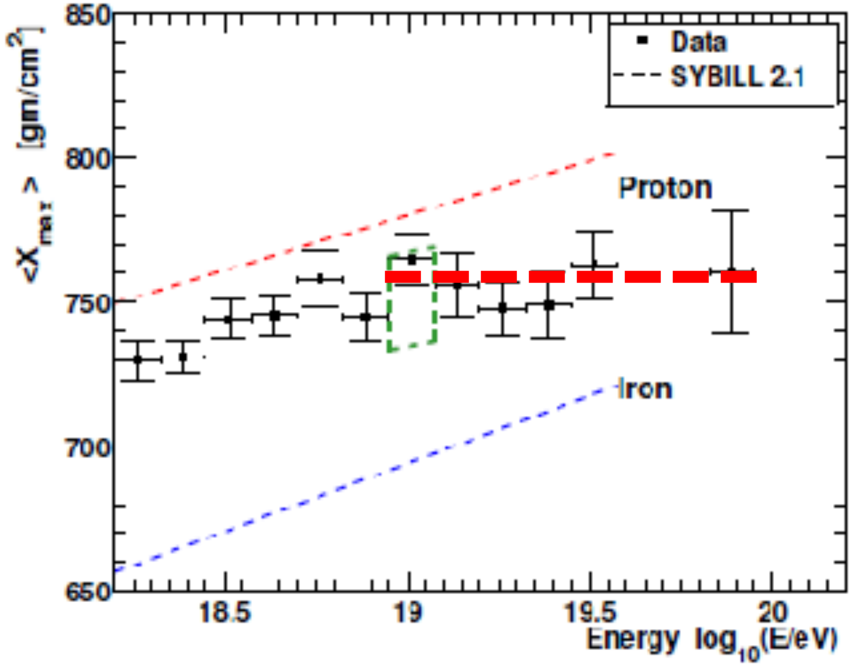


Figure 3: The mean (left) and the standard deviation (right) of the measured X_{max} distributions as a function of energy compared to air-shower simulations for proton and iron primaries.

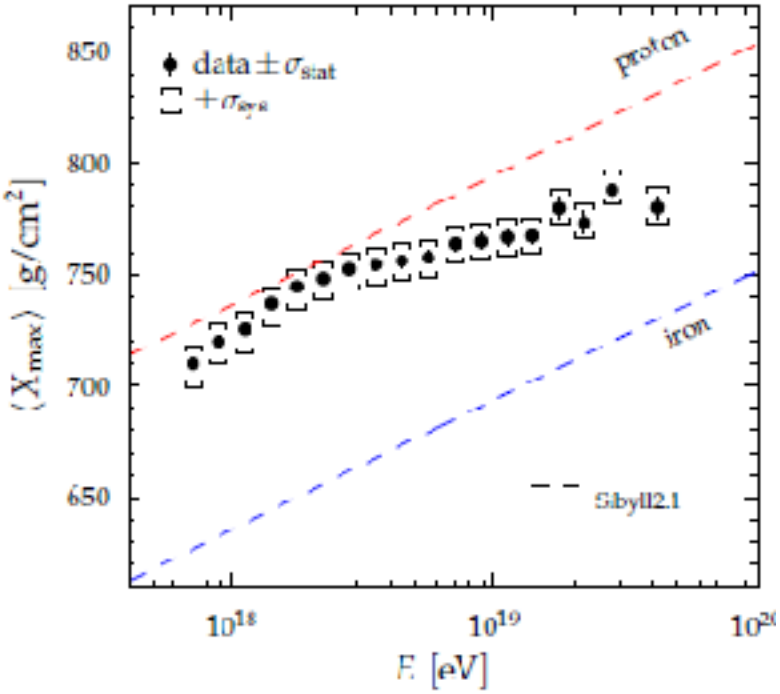
Predictions from Sibyl model lie between those with QGSjet and EPOS-LHC

Comparison of TA and Auger results against a single model

— Michael Unger



Telescope Array Collaboration, APP 64 (2014) 49

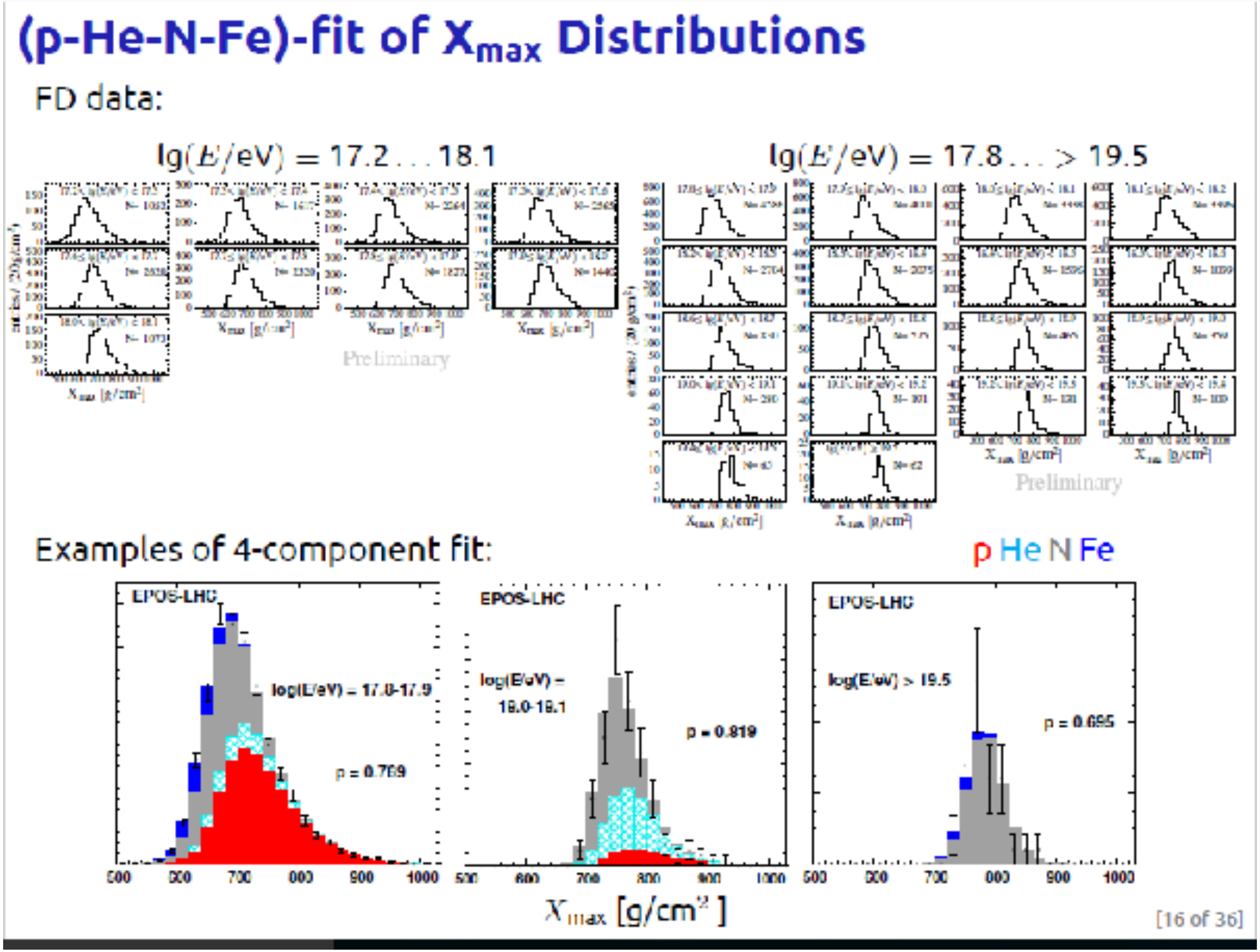


Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

- **New Sybil model moves depth of maximum DEEPER into atmosphere and thus *pure proton claims become harder to sustain***

  This is a key issue for neutrino searches

- **Change of elongation rate seen in BOTH data sets**



(p-He-N-Fe)-fit of X_{max} Distributions

FD data:

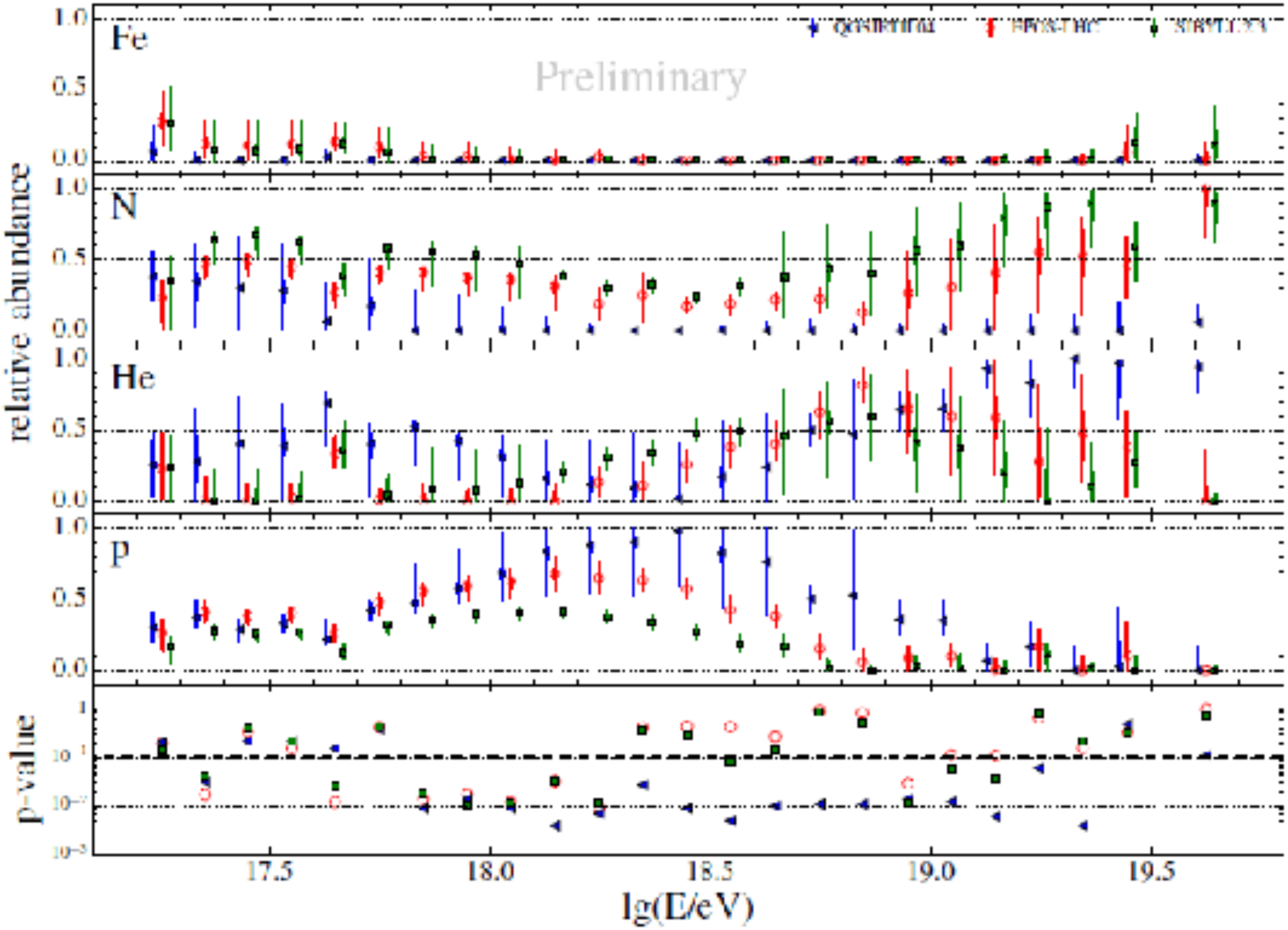
$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$

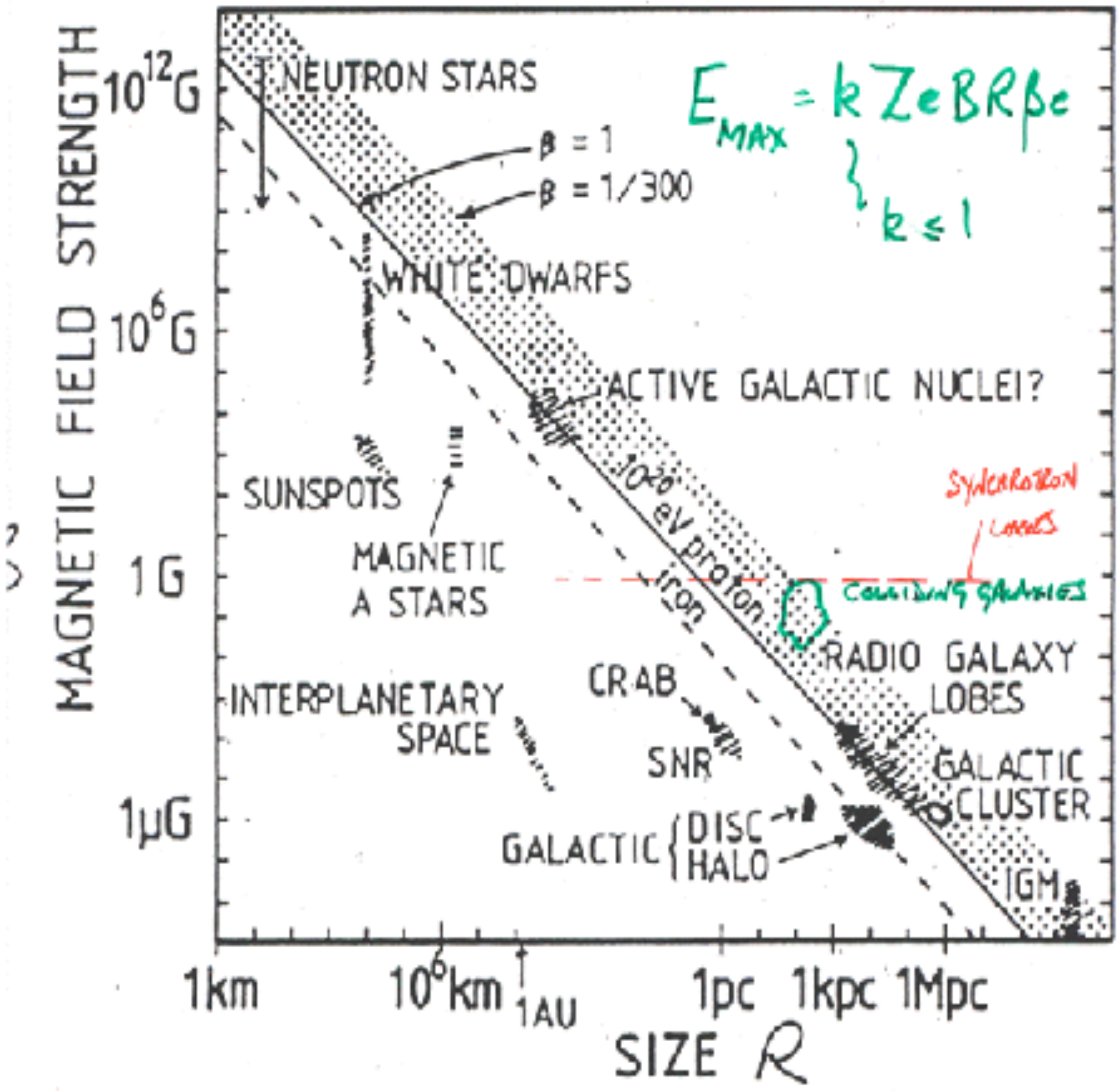
$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$

Examples of 4-component fit:

p He N Fe

Composition Fractions





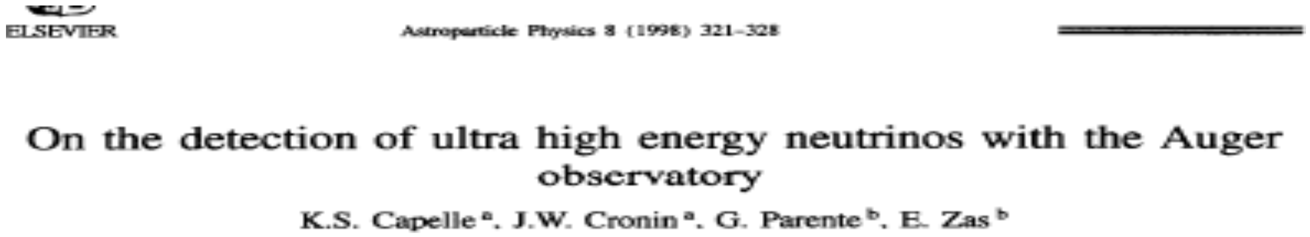
Hillas 1984
ARA&A
B vs R

Magnetars?

GRBs X

High-Z nuclei easier to accelerate

Search for UHE neutrinos at the Auger Observatory



ELSEVIER Astroparticle Physics 8 (1998) 321–328

On the detection of ultra high energy neutrinos with the Auger observatory

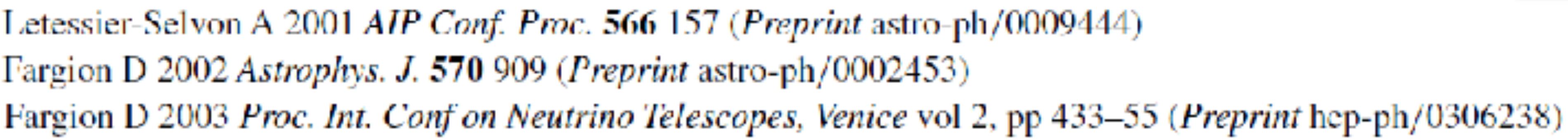
K.S. Capelle[a], J.W. Cronin[a], G. Parente[b], E. Zas[b]

Parente and Zas: Venice Meeting 1996, arXiv 960609

τ at EeV may decay before reaching the ground

→ Secondary shower (Double Bang event)

Also interactions in mountains or upward-going in earth

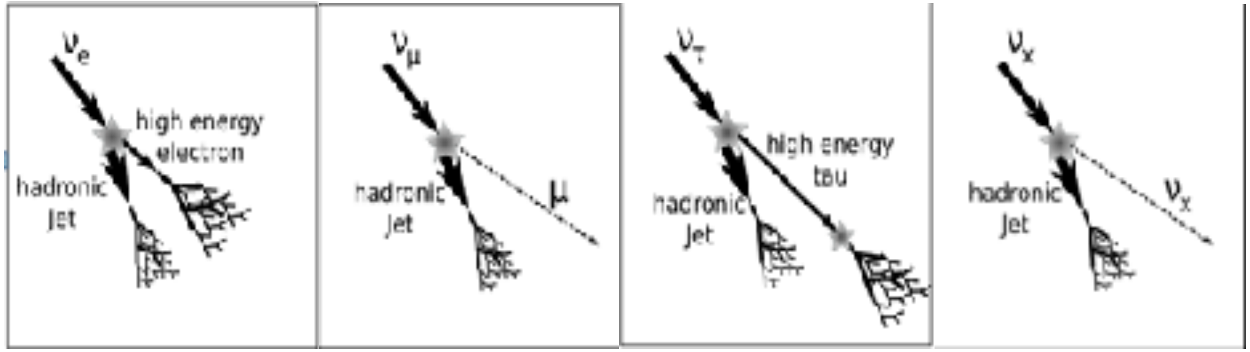


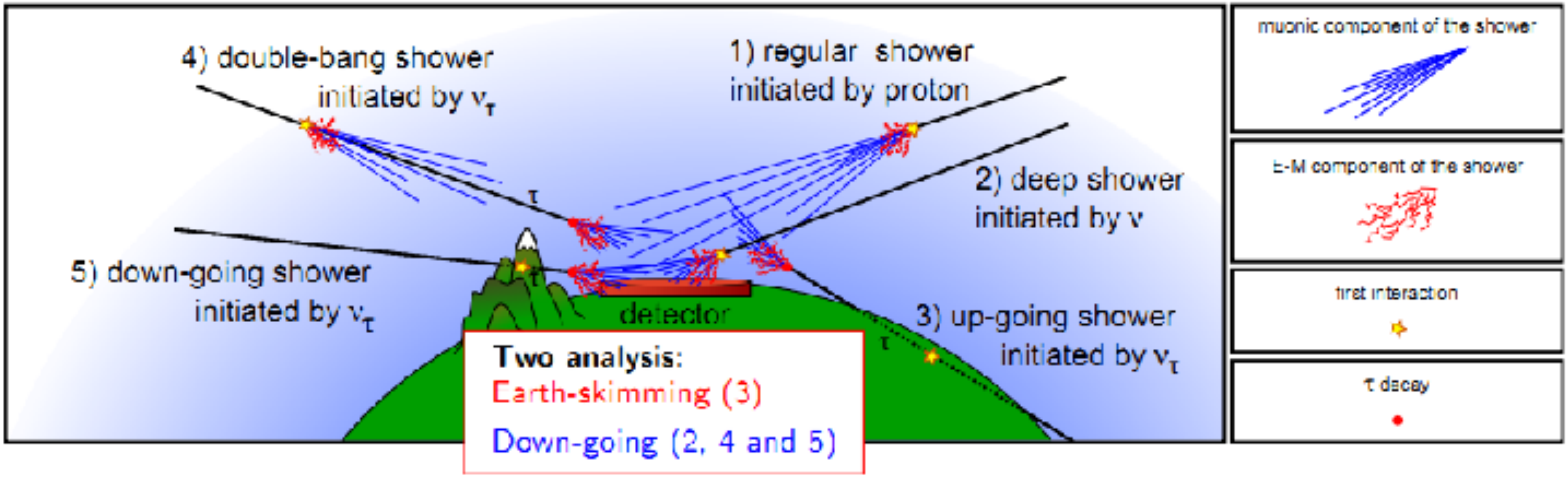
Letessier-Selvon A 2001 *AIP Conf. Proc.* **566** 157 (*Preprint* astro-ph/0009444)

Fargion D 2002 *Astrophys. J.* **570** 909 (*Preprint* astro-ph/0002453)

Fargion D 2003 *Proc. Int. Conf on Neutrino Telescopes, Venice* vol 2, pp 433–55 (*Preprint* hep-ph/0306238)

$$p + \gamma_{CMB} \longrightarrow \pi \longrightarrow \nu$$

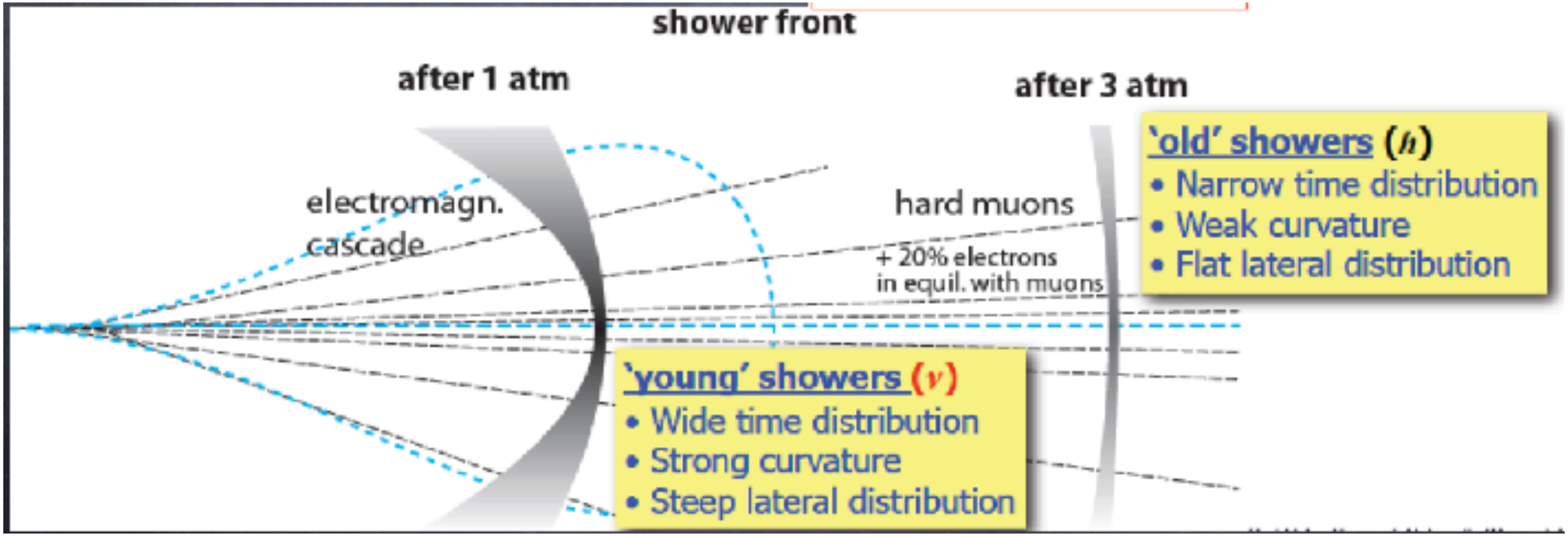




Two analysis:
Earth-skimming (3)
Down-going (2, 4 and 5)

Search Method for neutrinos

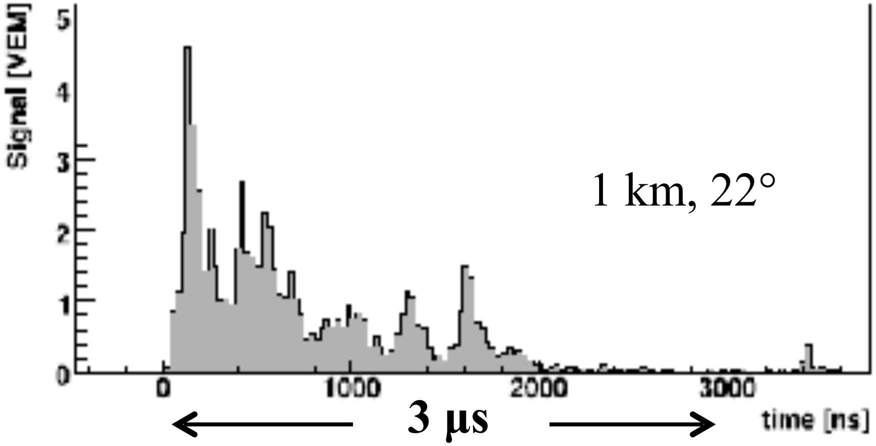
Look for inclined, BUT young, showers



'old' showers (h)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

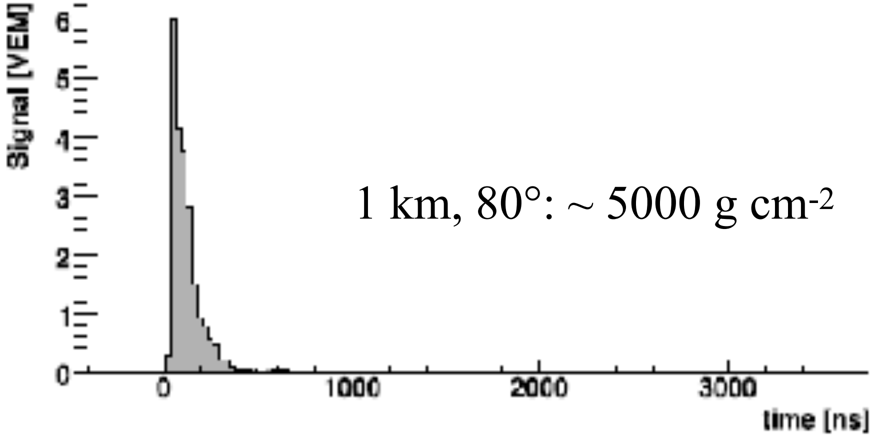
'young' showers (ν)
- Wide time distribution
- Strong curvature
- Steep lateral distribution

Using inclined showers to look for neutrinos

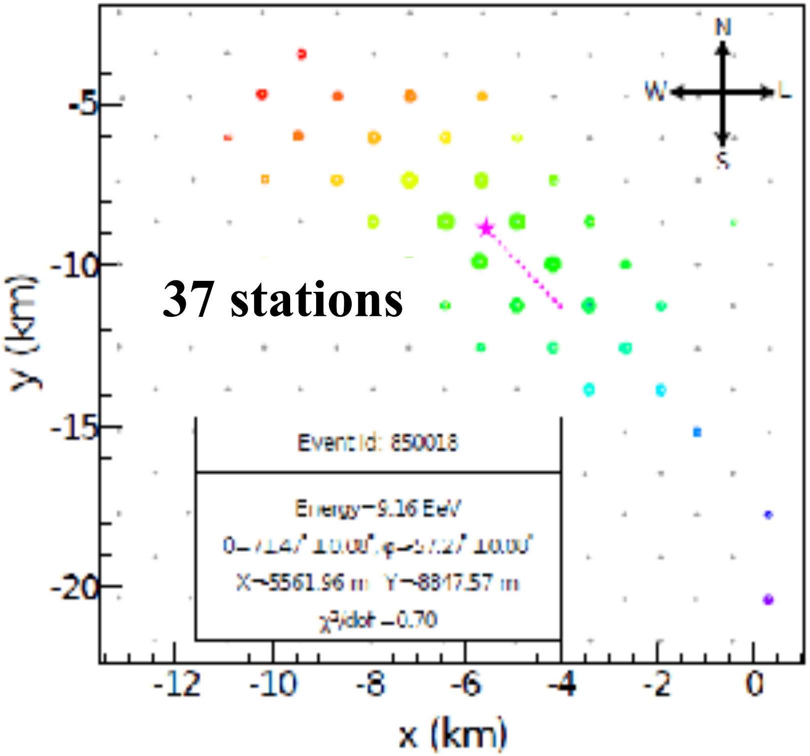


1 km, 22°

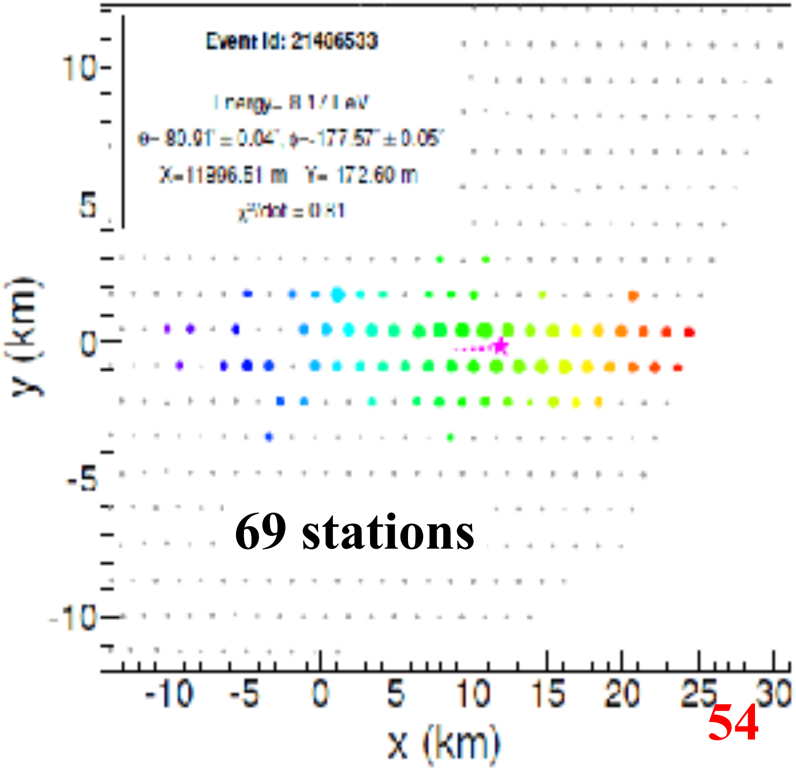
3 µs



1 km, 80°: ~ 5000 g cm^{-2}



37 stations



69 stations

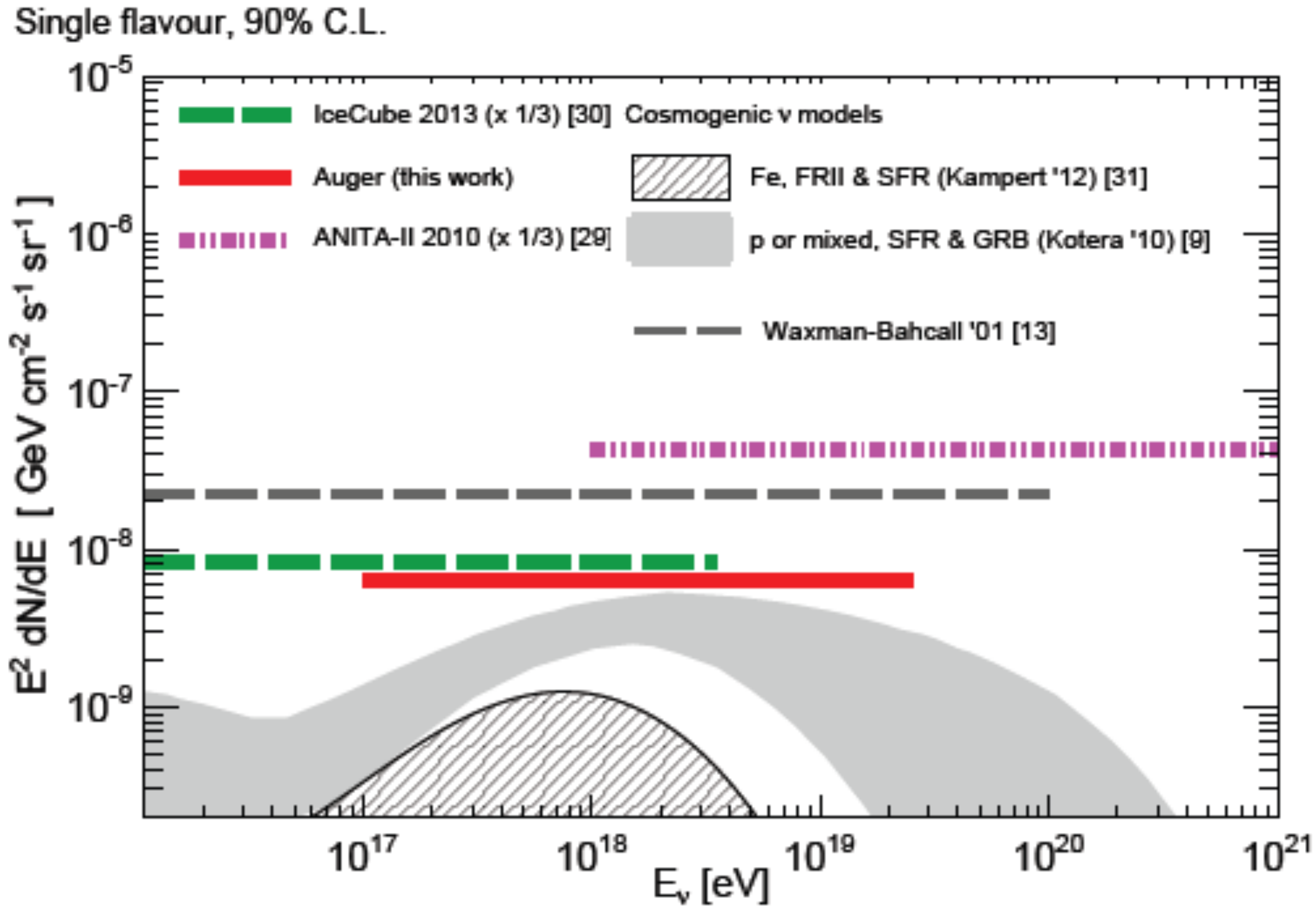
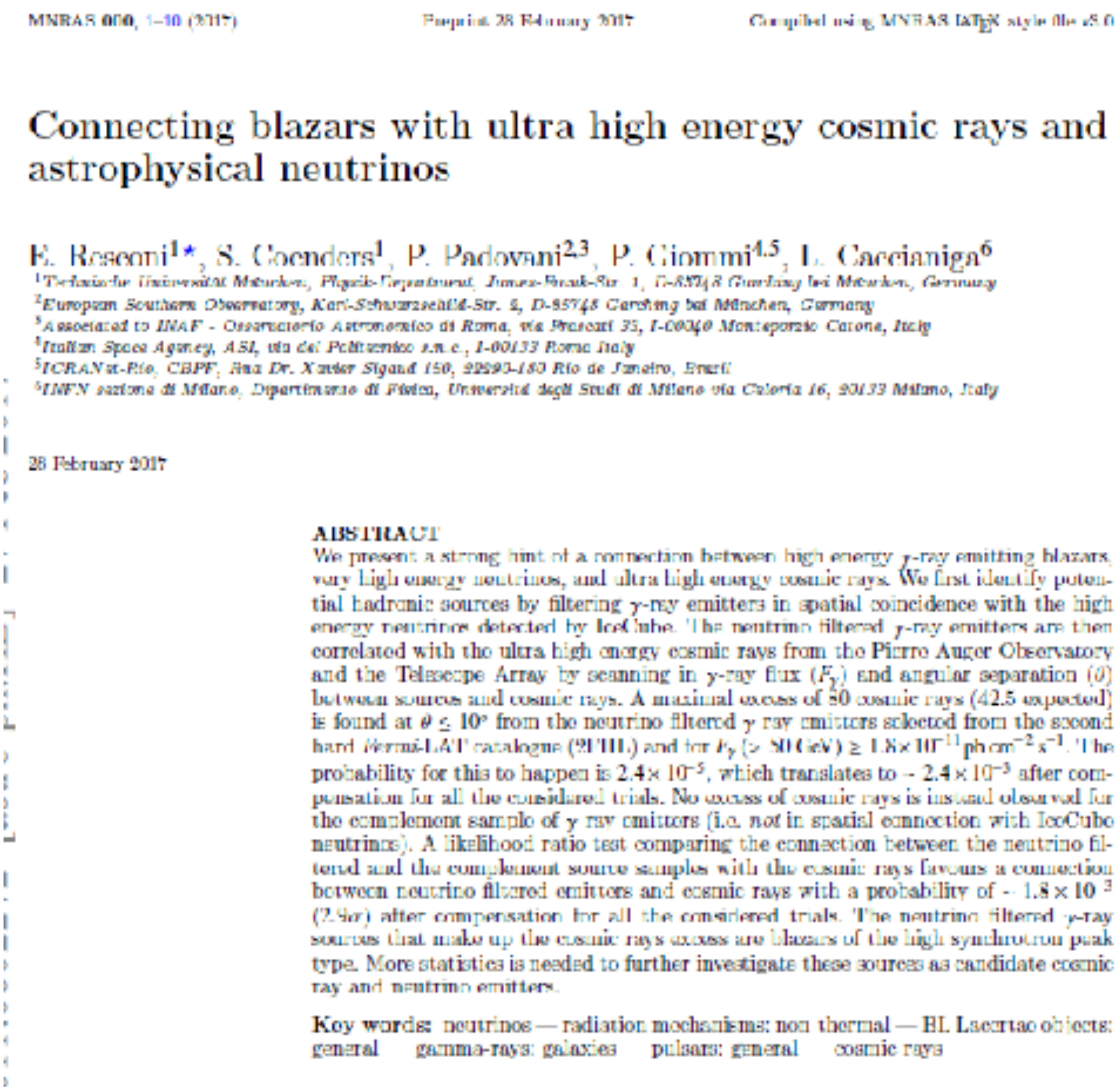


Figure 4. Top panel: Upper limit (at 90% C.L.) to the normalization of the diffuse flux of UHE neutrinos as given in Eqs. (2) and (3), from the Pierre Auger Observatory. We

Searching neutrinos in coincidence with other ‘happenings’

1. **GW170817 Superbly positioned for Auger neutrino searches**
   -but only upper limits – joint paper with ~7000 others!

2. **TXS0506+056**
   Again no neutrinos seen. Joint paper with IceCube, ANTARES and Auger



MNRAS 000, 1–10 (2017) Preprint 28 February 2017 Compiled using MNRAS LaTeX style file v3.0

Connecting blazars with ultra high energy cosmic rays and astrophysical neutrinos

E. Resconi[1]*, S. Coenders[1], P. Padovani[2,3], P. Giommi[4,5], L. Caccianiga[6]
[1]*Technische Universität München, Physik-Department, James-Franck-Str. 1, D-85748 Garching bei München, Germany*
[2]*European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany*
[3]*Associated to INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy*
[4]*Italian Space Agency, ASI, via del Politecnico s.n.c., I-00133 Roma Italy*
[5]*ICRANet-Rio, CBPF, Rua Dr. Xavier Sigaud 150, 22290-180 Rio de Janeiro, Brazil*
[6]*INFN sezione di Milano, Dipartimento di Fisica, Università degli Studi di Milano via Celoria 16, 20133 Milano, Italy*

28 February 2017

ABSTRACT
We present a strong hint of a connection between high energy γ-ray emitting blazars, very high energy neutrinos, and ultra high energy cosmic rays. We first identify potential hadronic sources by filtering γ-ray emitters in spatial coincidence with the high energy neutrinos detected by IceCube. The neutrino filtered γ-ray emitters are then correlated with the ultra high energy cosmic rays from the Pierre Auger Observatory and the Telescope Array by scanning in γ-ray flux (F_γ) and angular separation (θ) between sources and cosmic rays. A maximal excess of 80 cosmic rays (42.5 expected) is found at $\theta \leq 10^\circ$ from the neutrino filtered γ-ray emitters selected from the second hard *Fermi*-LAT catalogue (2FHL) and for $F_\gamma(> 50\,\mathrm{GeV}) \geq 1.8 \times 10^{-11}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$. The probability for this to happen is 2.4×10^{-5}, which translates to $\sim 2.4 \times 10^{-3}$ after compensation for all the considered trials. No excess of cosmic rays is instead observed for the complement sample of γ-ray emitters (i.e. *not* in spatial connection with IceCube neutrinos). A likelihood ratio test comparing the connection between the neutrino filtered and the complement source samples with the cosmic rays favours a connection between neutrino filtered emitters and cosmic rays with a probability of $\sim 1.8 \times 10^{-3}$ (2.9σ) after compensation for all the considered trials. The neutrino filtered γ-ray sources that make up the cosmic rays excess are blazars of the high synchrotron peak type. More statistics is needed to further investigate these sources as candidate cosmic ray and neutrino emitters.

Key words: neutrinos — radiation mechanisms: non-thermal — BL Lacertae objects: general — gamma-rays: galaxies — pulsars: general — cosmic rays

Astrophysical Models

There are many and the data are not very constraining

John von Neumann famously said

> With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.

By this he meant that one should not be impressed when a complex model fits a data set well. With enough parameters, you can fit any data set.

Truth ... is much too complicated to allow anything but approximations.

Next steps:

On the ground

TA x4:

this will increase area of TA to that of Auger. Operational in next year or so. Fully Sensitive above ~ 30 EeV. Main aim is to increase Statistics on Hot Spot

Auger to Auger Prime:

4 m^2 of scintillator to allow muon separation: event by event mass at highest energies

Radio antenna on every tank

(ii) 4 m^2 Scintillators above Water-Cherenkov detectors

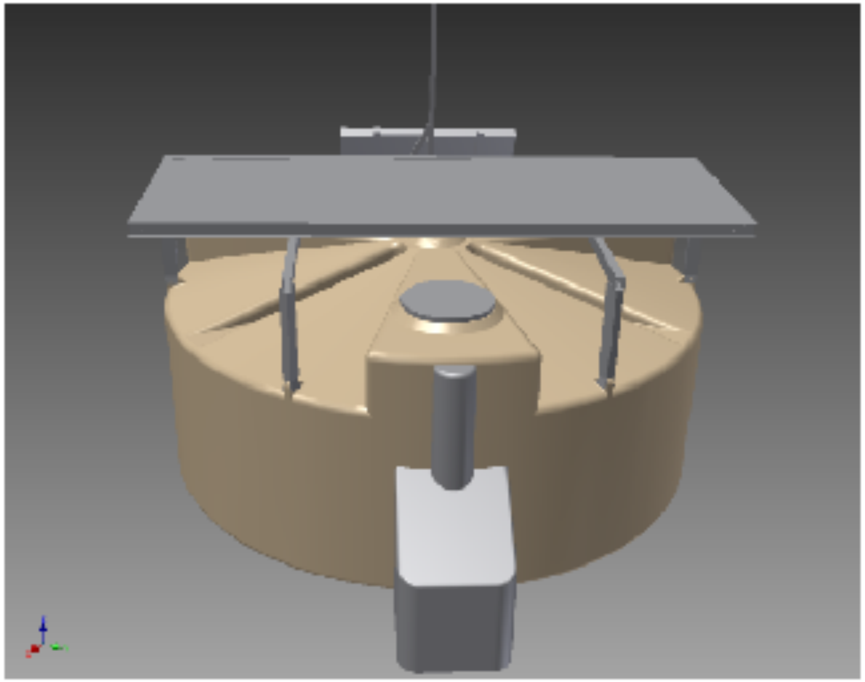
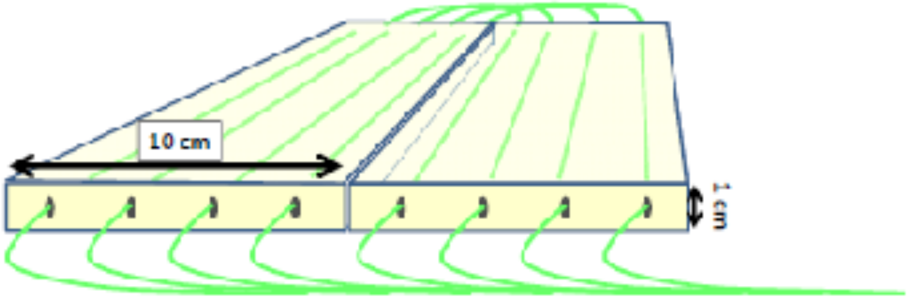


Figure 4.1: 3D view of a water-Cherenkov detector with a scintillator unit on top.

Scintillators respond to muons and electromagnetic component

Water-Cherenkov detectors absorb all of the em component and are fully sensitive to muons

It has been demonstrated with simulations that techniques exist to separate out the muon component



(iii) Buried Muon Detectors (1.3 m below surface)

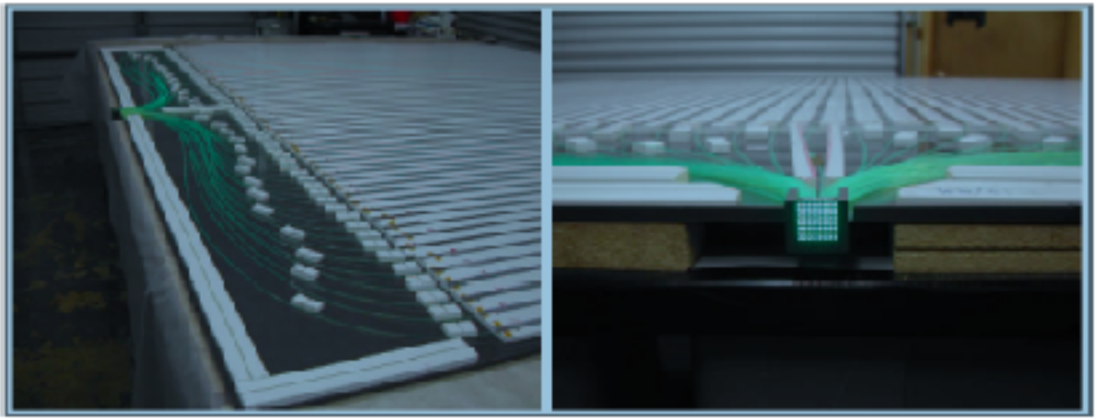


Figure 5.1: Scintillators stripes: left: general mounting in the PVC housing, right: detail of the 64-pixel optical connectors.

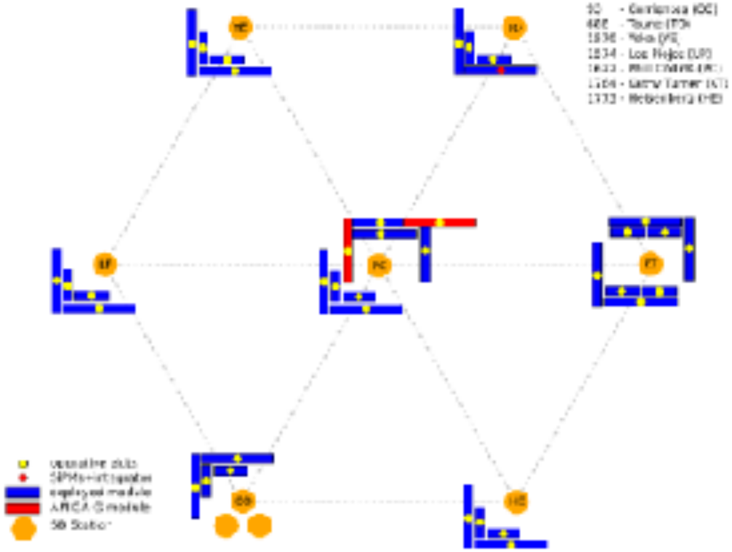


Figure 5.2: AMIGA unitary cell.

60 x 20 m²

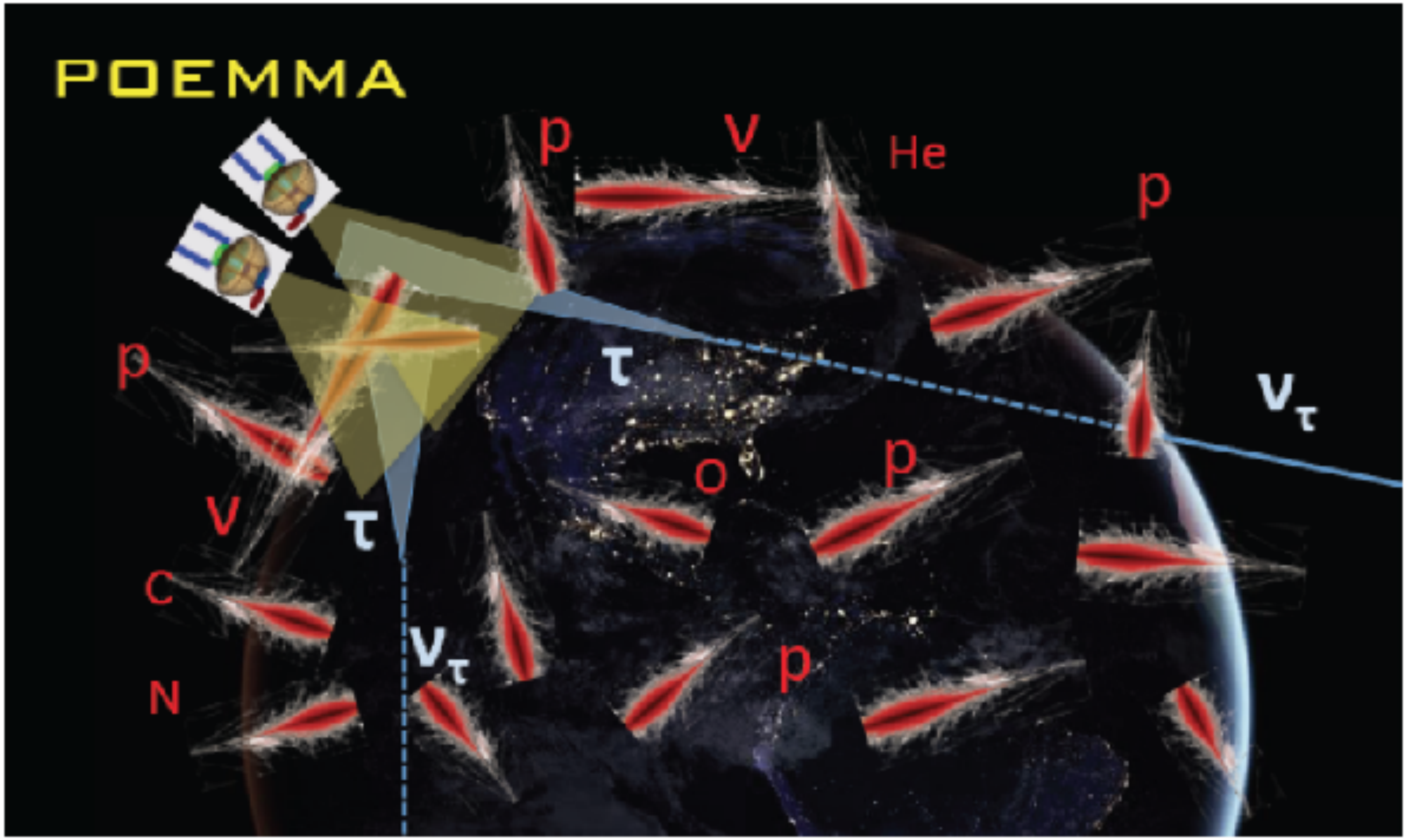
Linsley proposed (1979) that a fluorescence detector should be put into space
Eventually led to EUSO (ESA phase A (with Livio Scarsi))

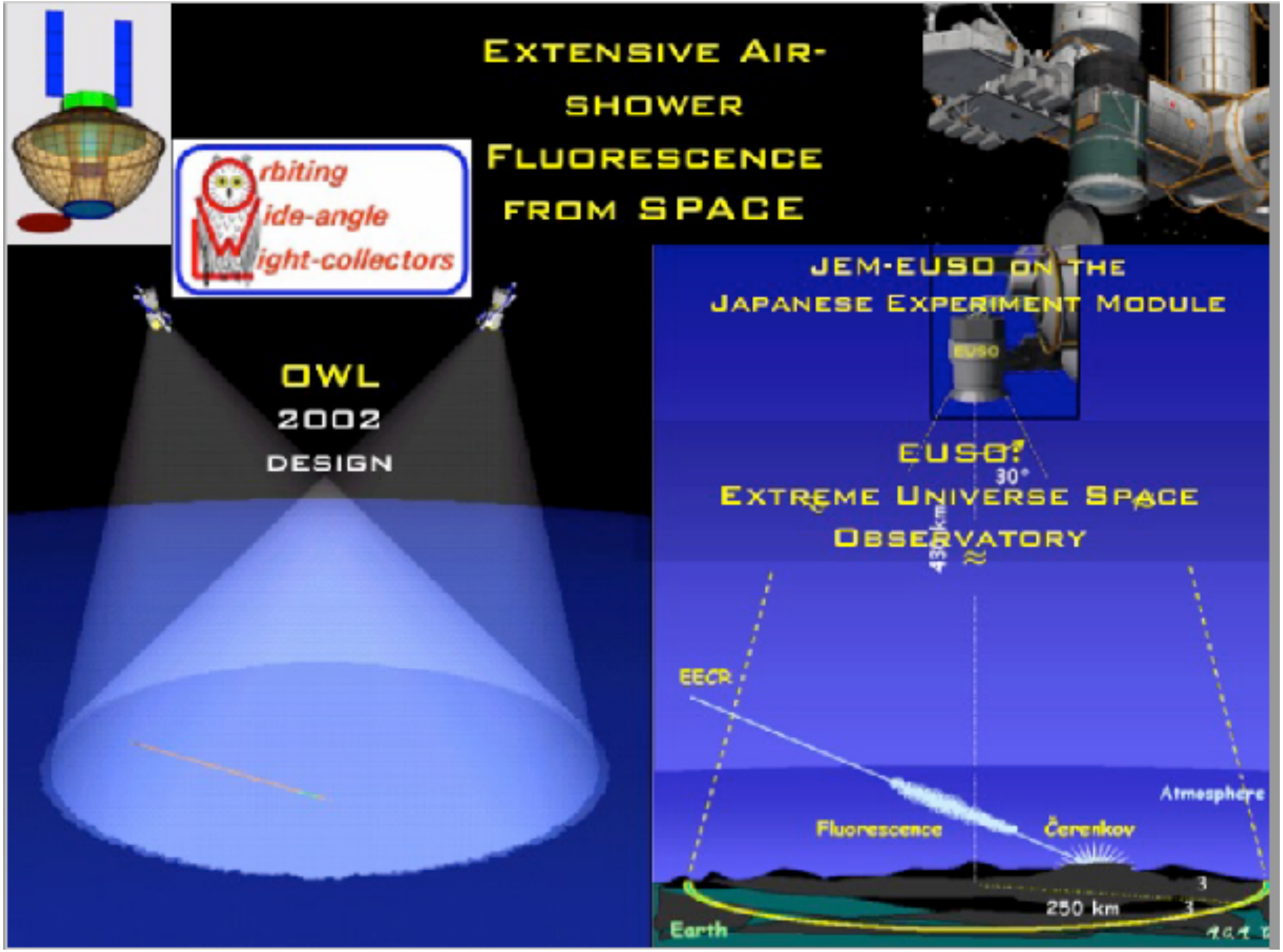
and then to JEM-EUSO

Currently module at TA and super-pressure balloon test flights

ISS flight

Twin satellites:
POEMMA: Probe of Extreme Multi-Messenger Astrophysics


POEMMA
p
ν
He
p
p
τ
ν$_\tau$
p
o
p
ν
τ
C
ν$_\tau$
N
p



EXTENSIVE AIR-SHOWER FLUORESCENCE FROM SPACE

Orbiting Wide-angle Light-collectors

OWL
2002
DESIGN

JEM-EUSO ON THE JAPANESE EXPERIMENT MODULE

EUSO: EXTREME UNIVERSE SPACE OBSERVATORY

ISS, SUBORBITAL, GROUND EXPERIENCE

MINI-EUSO – LAUNCH END OF 2018 INSIDE ISS

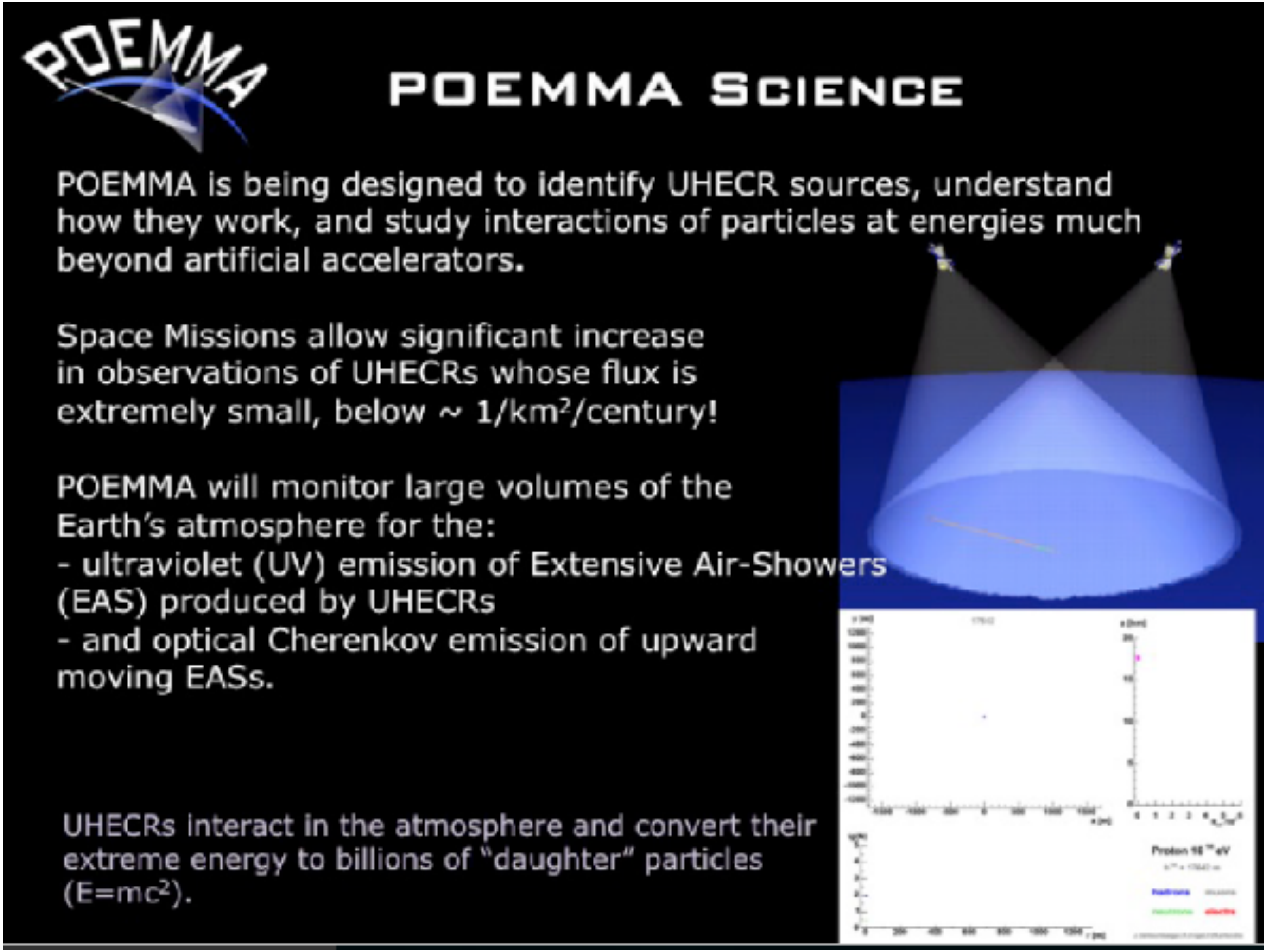
EUSO-SPB: FLIGHT APRIL/MAY 2017

EXTREME UNIVERSE SPACE OBSERVATORY ON A SUPER PRESSURE BALLOON

EUSO-TA – SINCE 2015

PIERRE AUGER OBSERVATORY – SINCE 2004

TELESCOPE ARRAY – SINCE 2008



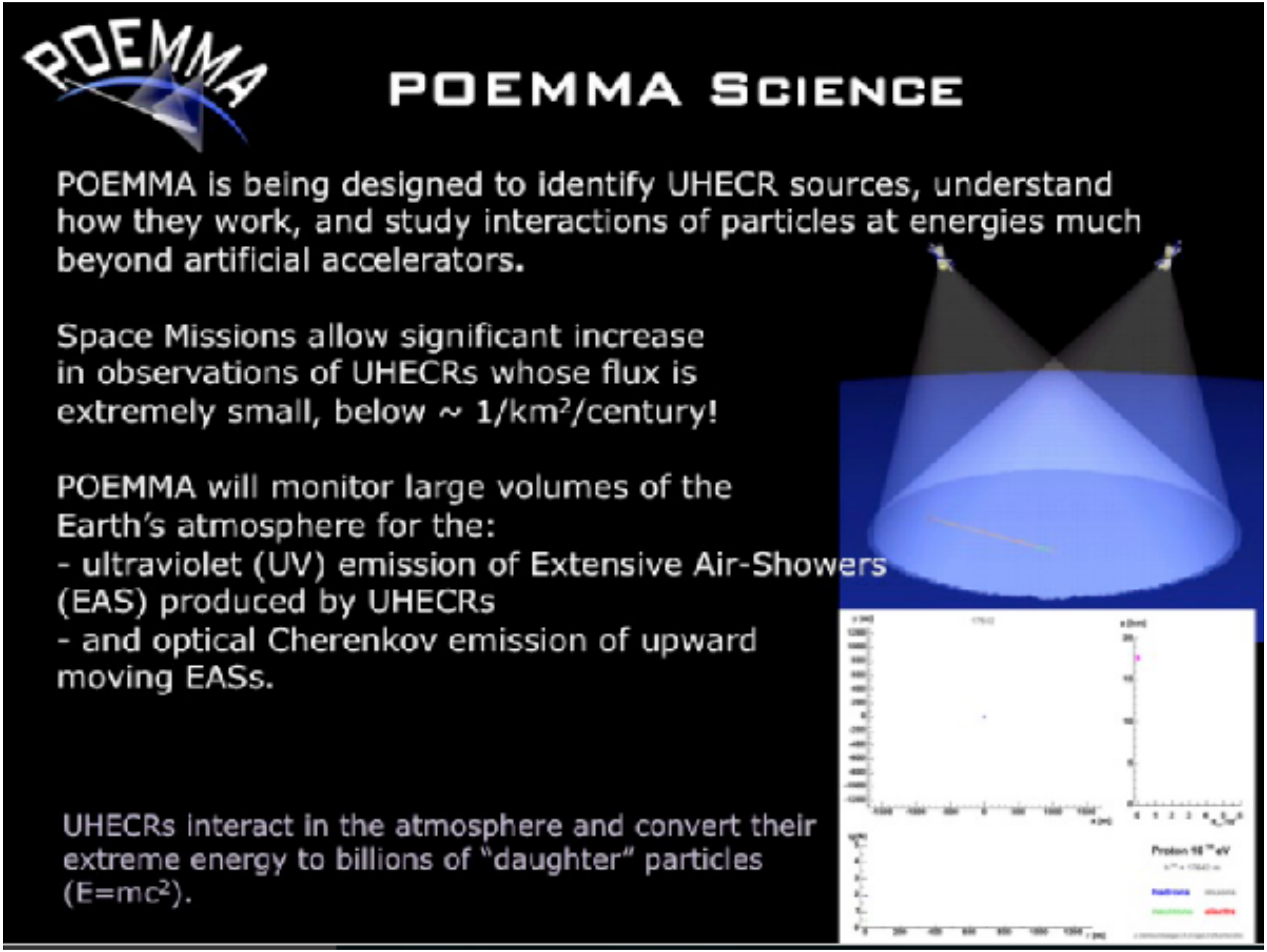
POEMMA SCIENCE

POEMMA is being designed to identify UHECR sources, understand how they work, and study interactions of particles at energies much beyond artificial accelerators.

Space Missions allow significant increase in observations of UHECRs whose flux is extremely small, below ~ 1/km²/century!

POEMMA will monitor large volumes of the Earth's atmosphere for the:
- ultraviolet (UV) emission of Extensive Air-Showers (EAS) produced by UHECRs
- and optical Cherenkov emission of upward moving EASs.

UHECRs interact in the atmosphere and convert their extreme energy to billions of "daughter" particles ($E=mc^2$).



POEMMA SCIENCE

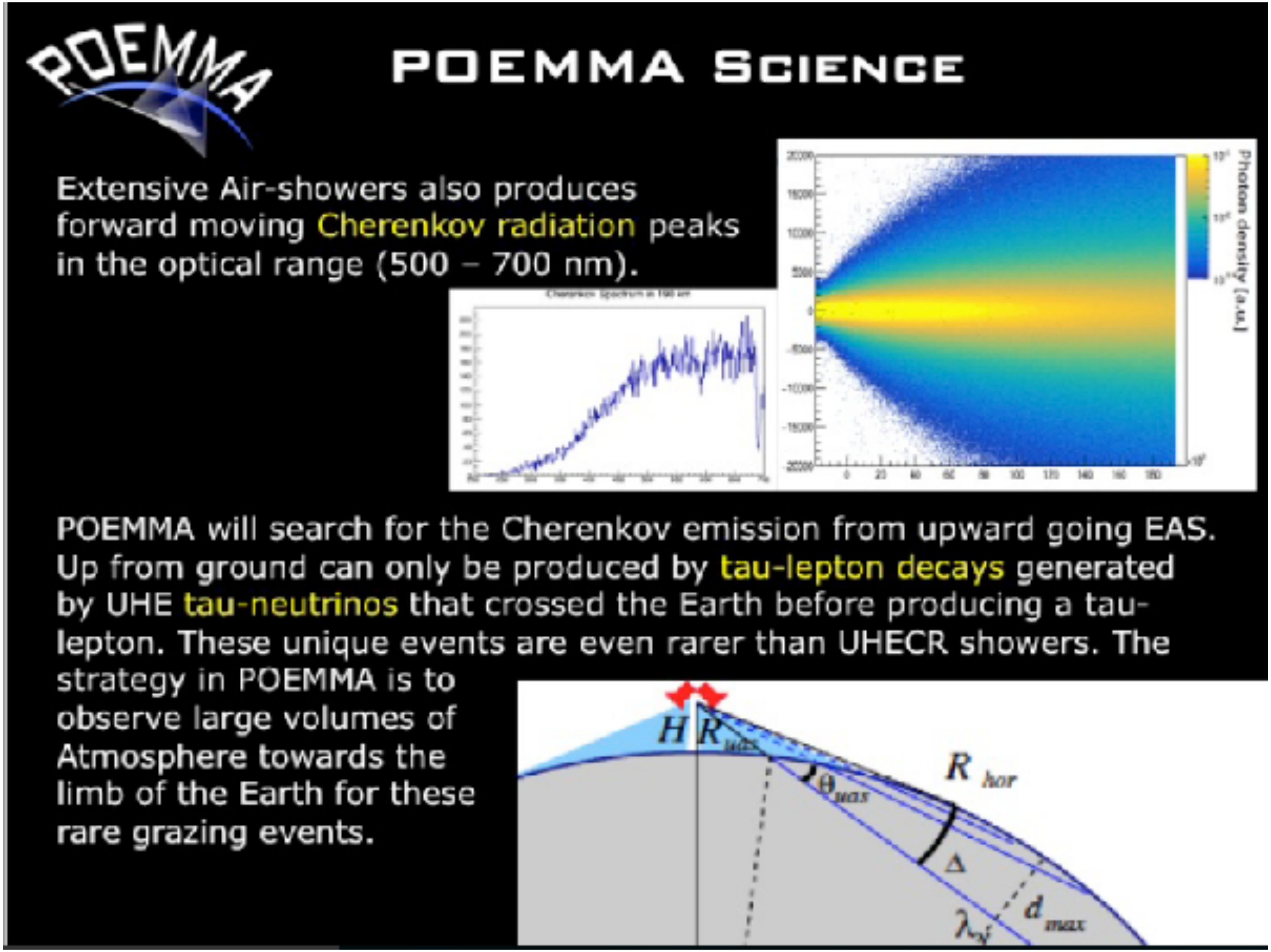
POEMMA is being designed to identify UHECR sources, understand how they work, and study interactions of particles at energies much beyond artificial accelerators.

Space Missions allow significant increase in observations of UHECRs whose flux is extremely small, below ~ 1/km²/century!

POEMMA will monitor large volumes of the Earth's atmosphere for the:

- ultraviolet (UV) emission of Extensive Air-Showers (EAS) produced by UHECRs
- and optical Cherenkov emission of upward moving EASs.

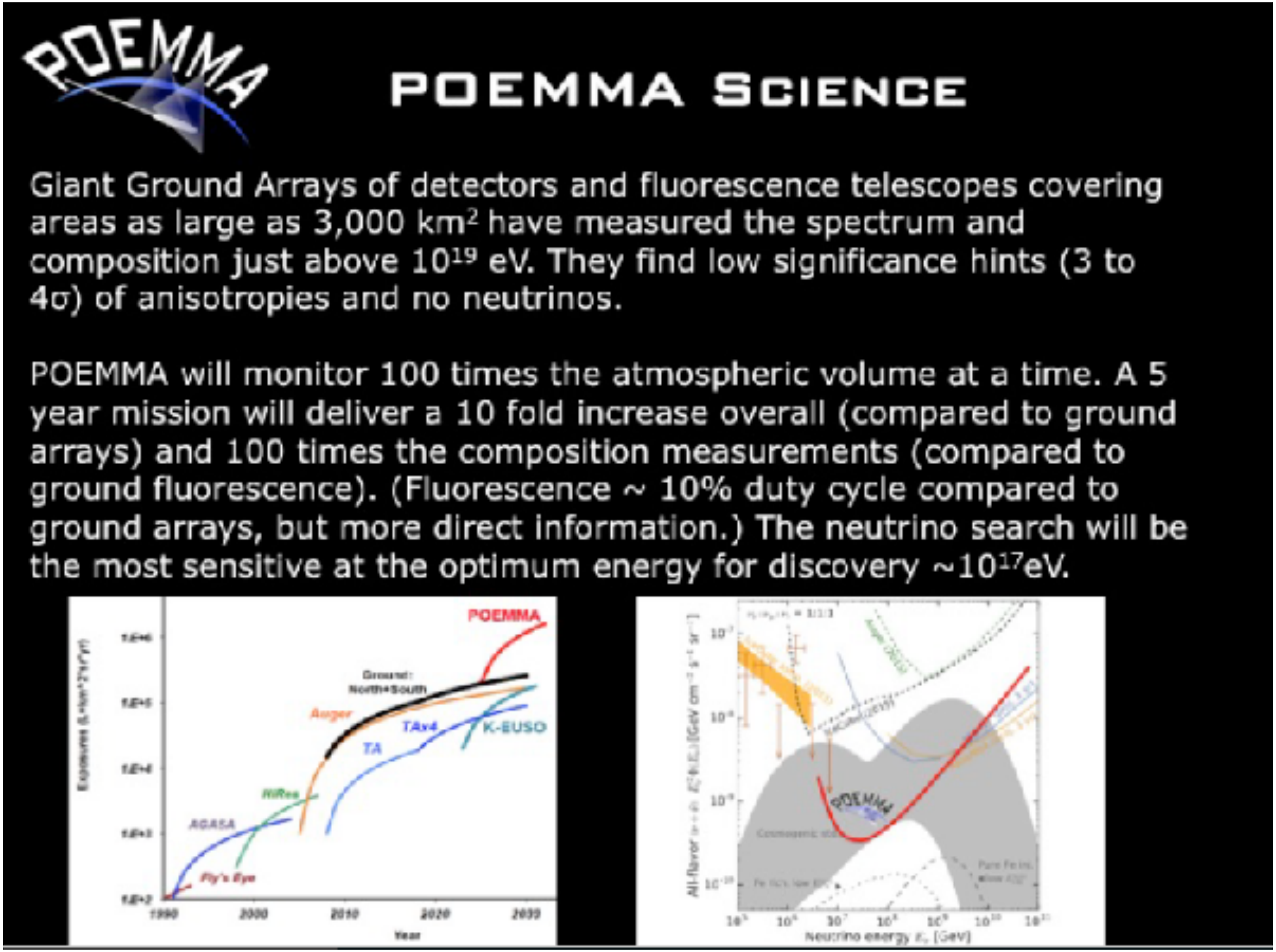
UHECRs interact in the atmosphere and convert their extreme energy to billions of "daughter" particles ($E=mc^2$).



POEMMA SCIENCE

Extensive Air-showers also produces forward moving Cherenkov radiation peaks in the optical range (500 – 700 nm).

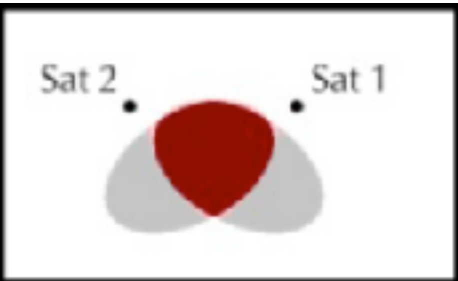
POEMMA will search for the Cherenkov emission from upward going EAS. Up from ground can only be produced by tau-lepton decays generated by UHE tau-neutrinos that crossed the Earth before producing a tau-lepton. These unique events are even rarer than UHECR showers. The strategy in POEMMA is to observe large volumes of Atmosphere towards the limb of the Earth for these rare grazing events.



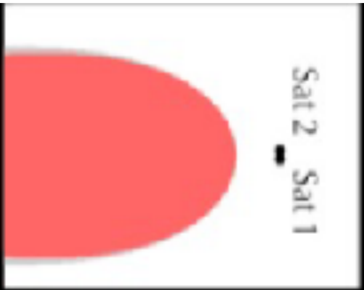
POEMMA Science

Giant Ground Arrays of detectors and fluorescence telescopes covering areas as large as 3,000 km^2 have measured the spectrum and composition just above 10^{19} eV. They find low significance hints (3 to 4σ) of anisotropies and no neutrinos.

POEMMA will monitor 100 times the atmospheric volume at a time. A 5 year mission will deliver a 10 fold increase overall (compared to ground arrays) and 100 times the composition measurements (compared to ground fluorescence). (Fluorescence ~ 10% duty cycle compared to ground arrays, but more direct information.) The neutrino search will be the most sensitive at the optimum energy for discovery ~10^{17}eV.

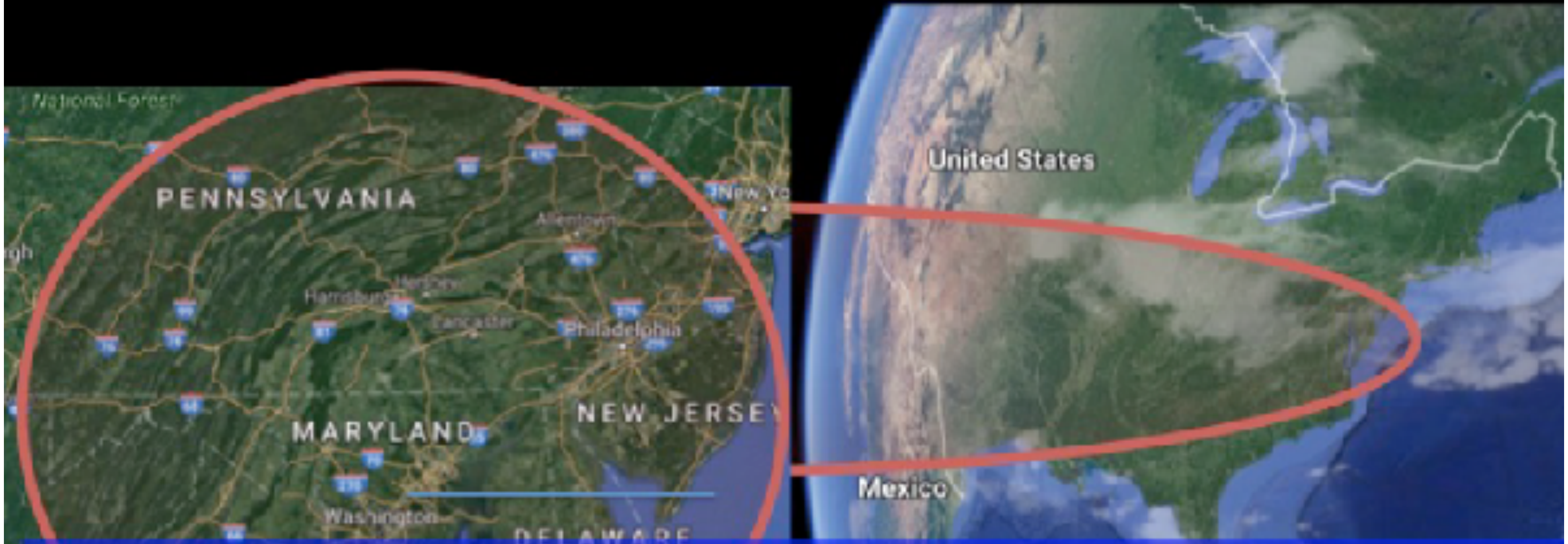


POEMMA

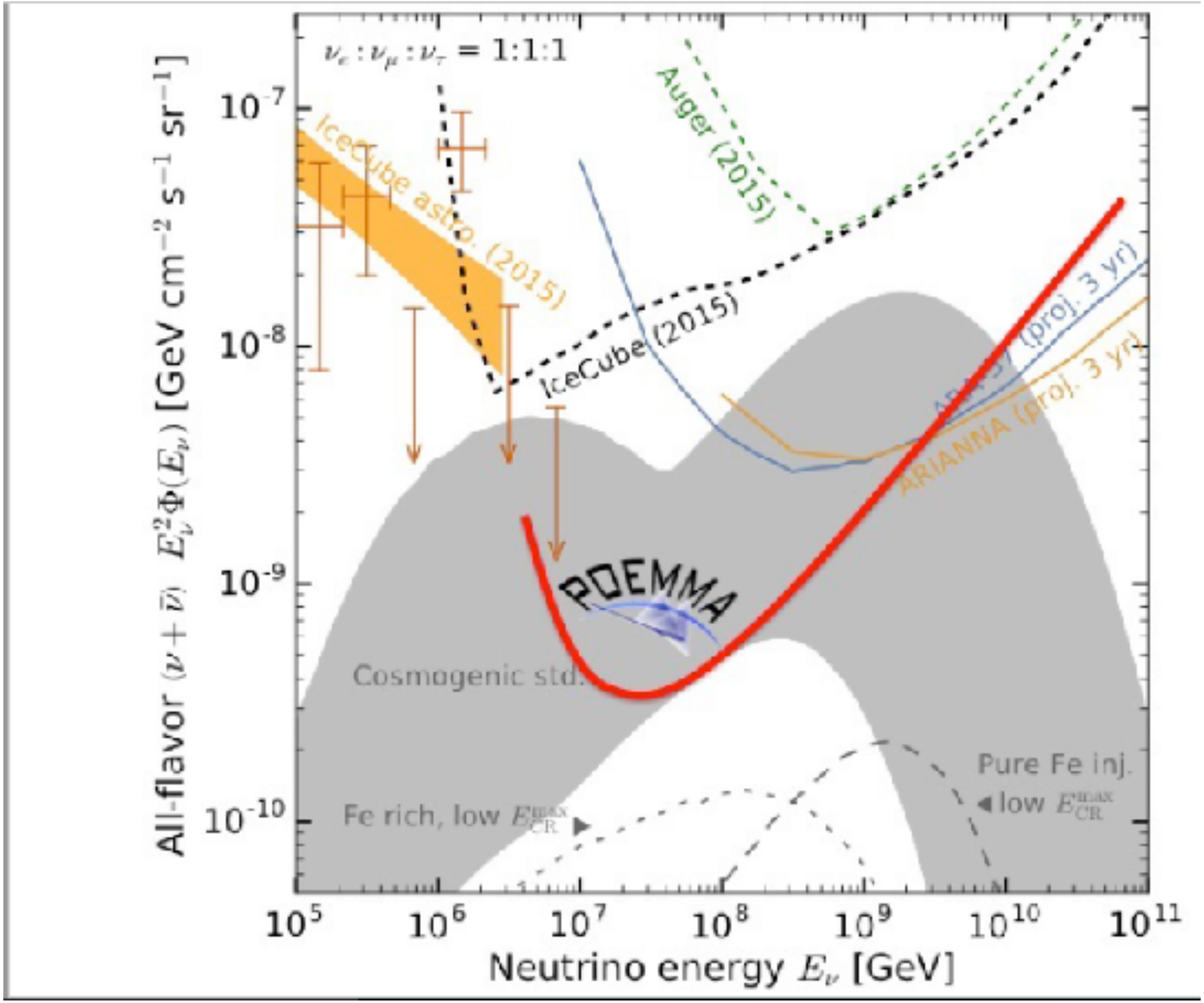


NADIR FOR UHECR:
RADIUS 200-400 KM

LIMB FOR NEUTRINOS:
RADIUS 2.6-3.7 10^3 KM



POEMMA will measure the UHECR spectrum and composition at the highest energies (to understand the source mechanisms), find significant anisotropies (to identify the sources), and discover the highest energy neutrinos, called cosmogenic neutrinos (to begin a new era of astroparticle physics).


$\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1
IceCube astro. (2015)
Auger (2015)
IceCube (2015)
ARA-37 (proj. 3 yr)
ARIANNA (proj. 3 yr)
POEMMA
Cosmogenic std.
Fe rich, low E_{CR}^{max} ▶
Pure Fe inj.
◀ low E_{CR}^{max}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
All-flavor $(\nu + \bar{\nu})$ $E_\nu^2 \Phi(E_\nu)$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]

Summary of experimental data discussed above

- **Ankle at ~ 4 EeV and steepening at ~ 50 EeV clearly established**
- **Strong evidence for dipole anisotropy in Auger data above 8 EeV**
- **Weaker evidences (~4 sigma) for coincidence with starburst galaxies above 39 EeV and some evidence (~2.5 sigma) for γAGNs above 60 EeV**
- **Mass composition getting heavier above the ankle (still some dispute)**
- **No diffuse neutrinos seen (at level similar to IceCube) nor any from specific events (GW170817 or TX0506+56)**

Remains a fascinating field with very exciting prospects!