Karlsruhe Institute of Technology

Experimental High-Energy Astroparticle Physics

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Content:

1. **Introduction in HEAP**
   - **source-acceleration-transport**
   - **short history of cosmic ray research**
   - **extensive air showers**
2. **Ultra-High Energy Cosmic Rays**
   - **KASCADE, KASCADE-Grande and LOPES**
   - **Pierre Auger Observatory, JEM-EUSO**
3. **TeV-Gamma-rays & High-energy Neutrinos**
   - **TeV gamma rays**

     H.E.S.S., MAGIC, CTA
   - **high-energy neutrinos**

     IceCube and KM3Net

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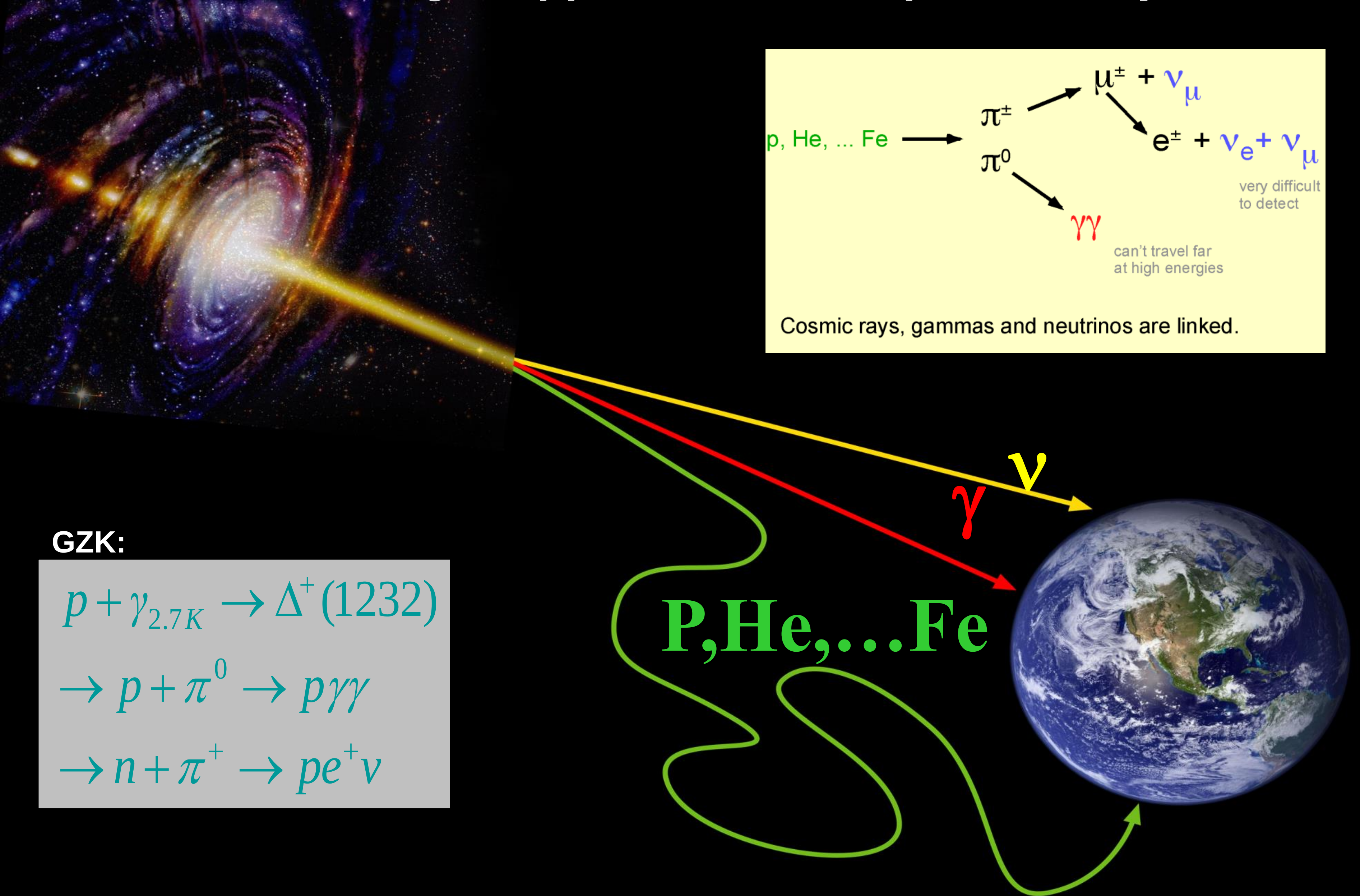
   - **TeV gamma rays**

     very short
   - **high-energy neutrinos**

     very very short

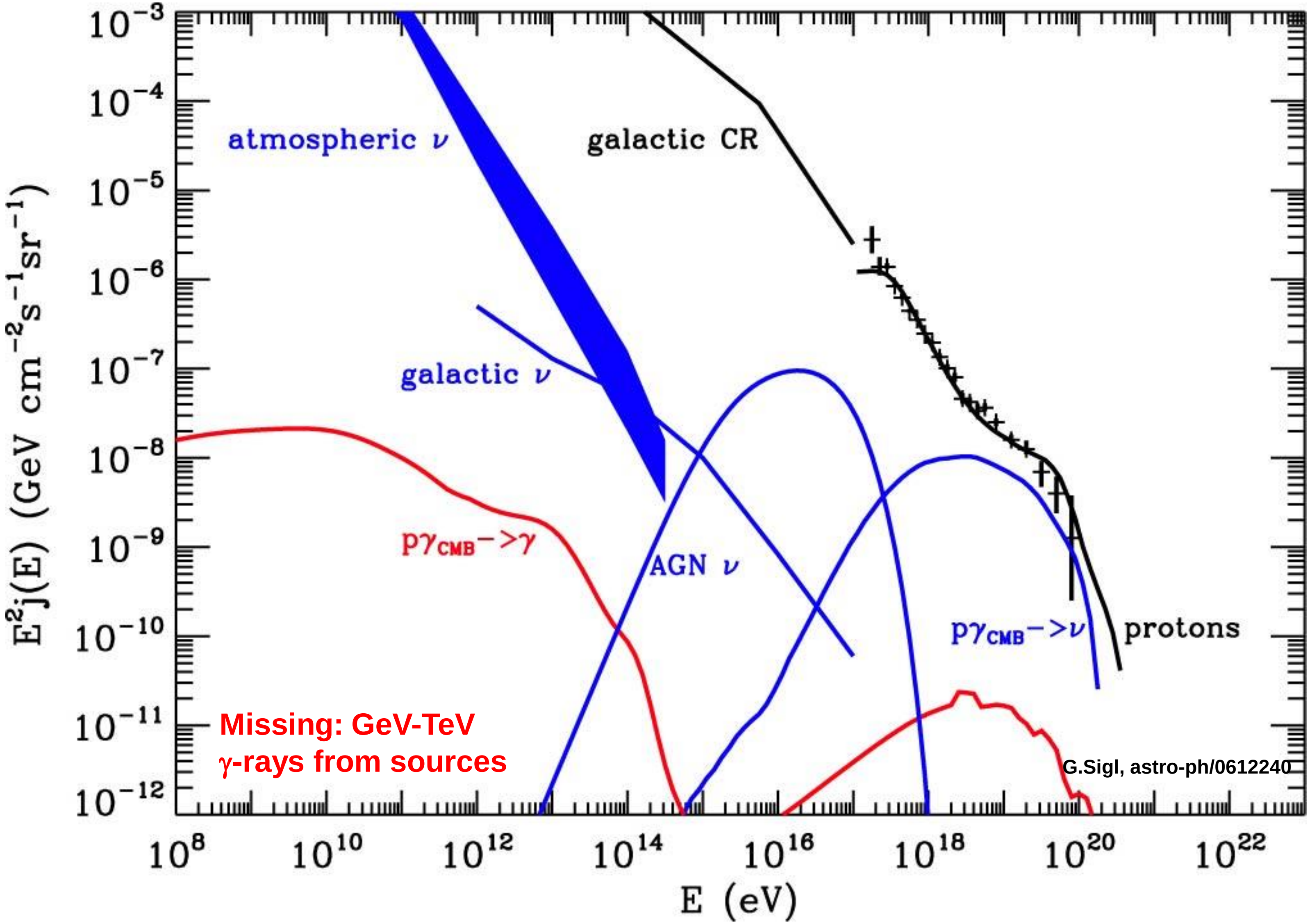
Multi-messenger Approach in Astroparticle Physics



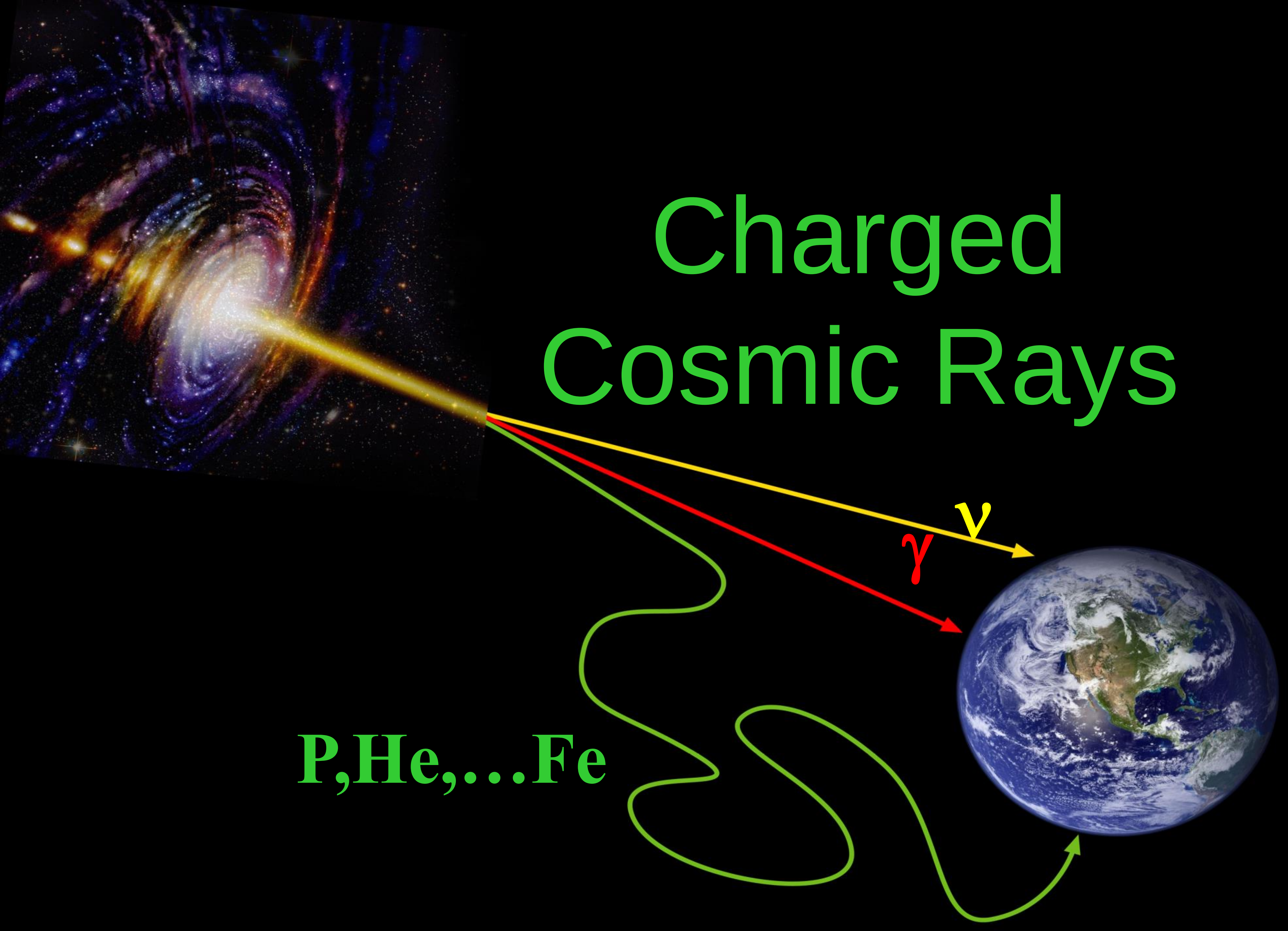
GZK:

$$p + \gamma_{2.7K} \rightarrow \Delta^{+}(1232)$$
$$\rightarrow p + \pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n + \pi^{+} \rightarrow pe^{+}\nu$$

High Energy Universe: nuclei, γ's, and ν's



Charged Cosmic Rays



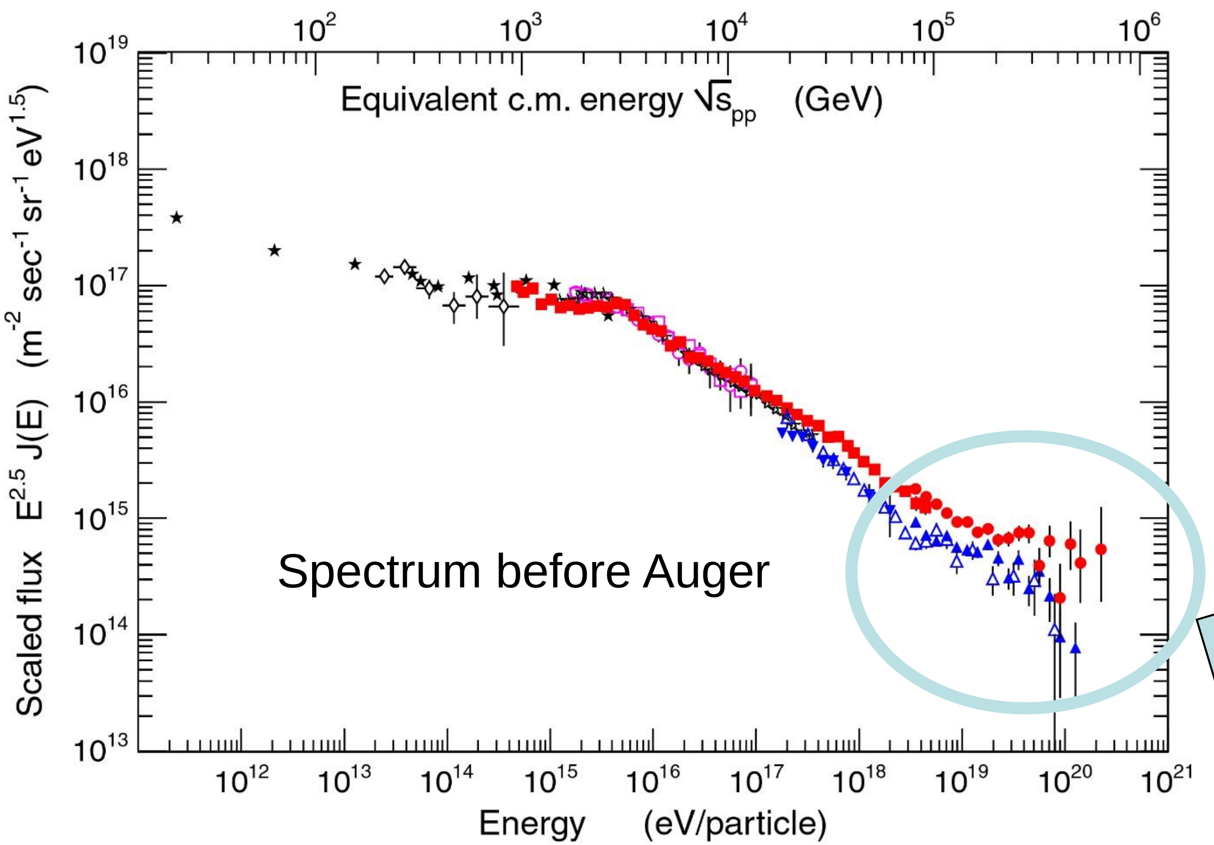
Cosmic Rays at highest energies before 2005

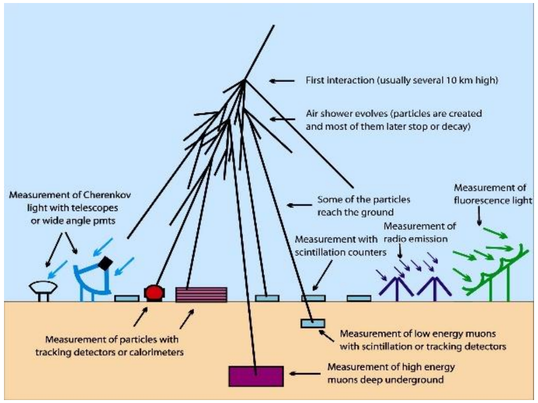
Source, acceleration, and mass of the particles unknown – but they exist !

Exists the cut-off? **(strong extragalactic processes which happens very close are necessary)**

Measurements by **large particle detector arrays (AGASA ➔ no cutoff)**

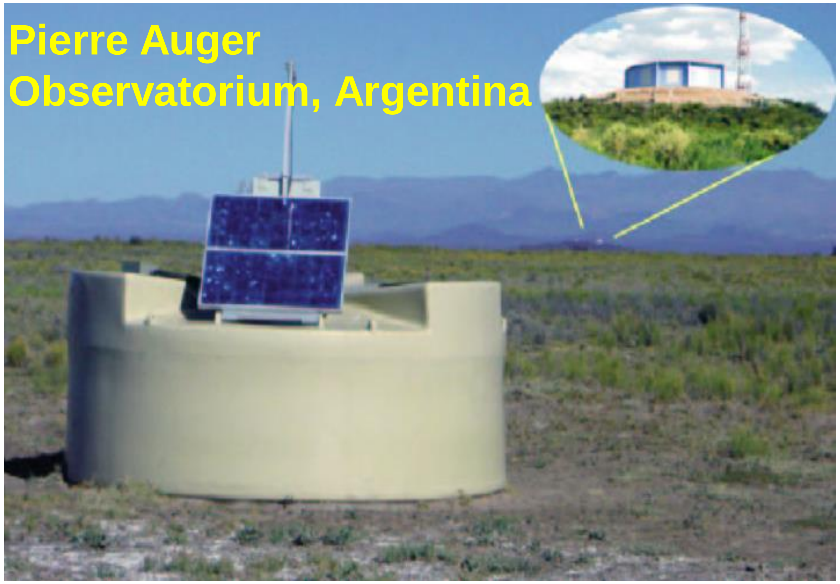
or **fluorescence telescopes (HiRes ➔ cutoff)**

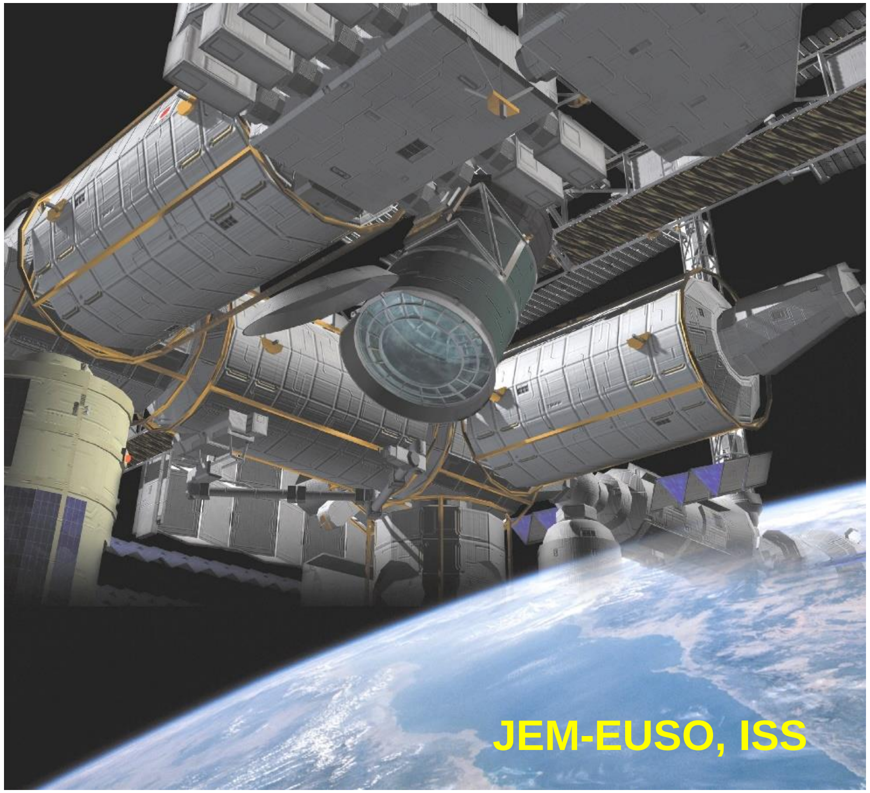




GZK-cutoff yes or no?

Cosmic Ray Experiments





The Pierre Auger Observatory:

Mission of the Pierre Auger Observatory:

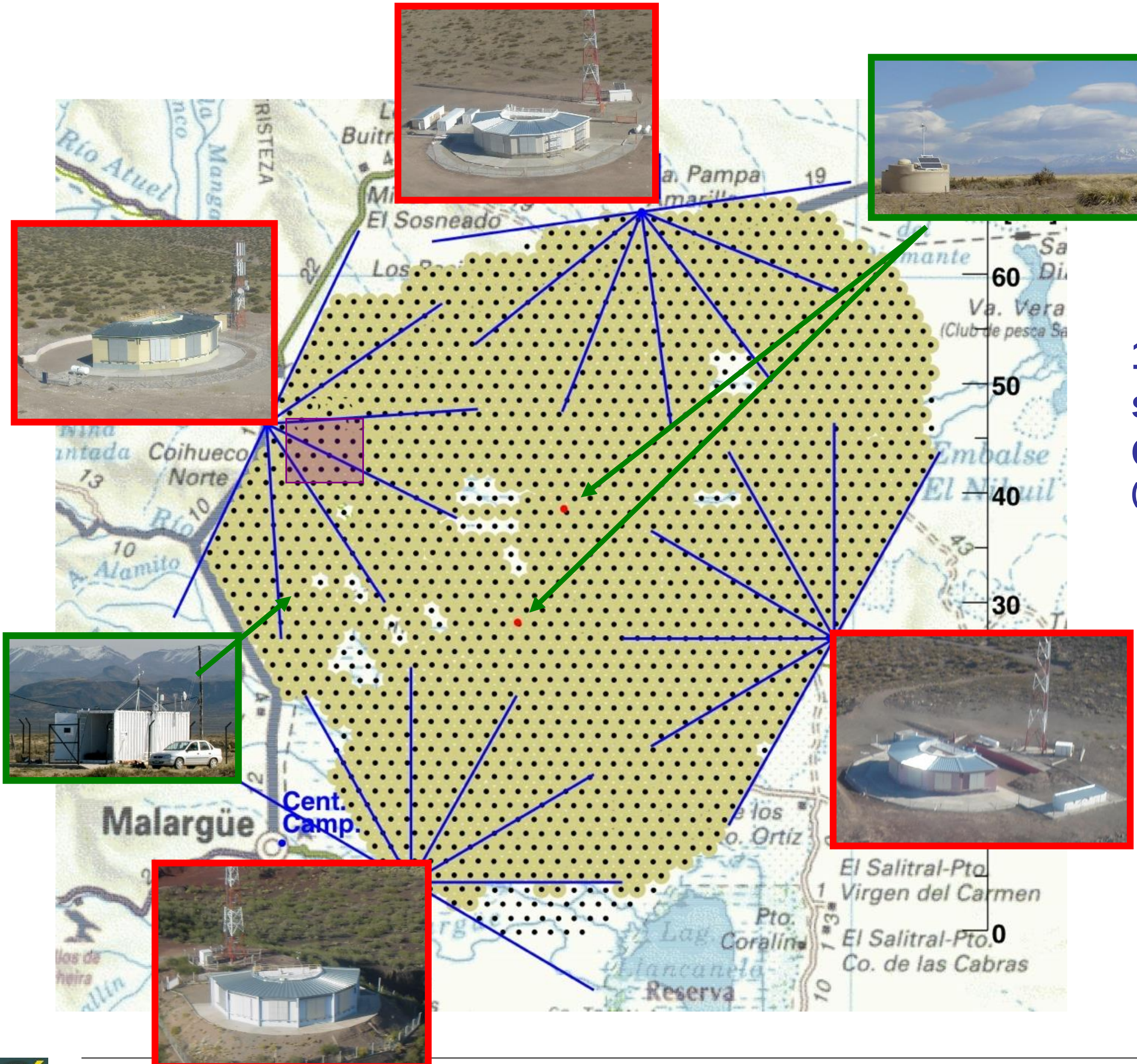
- assess the existence or absence of a spectral cut-off

- measure the anisotropy in the quest for the sources

- find out the nature of the primary cosmic rays

… with a hybrid detector to measure air showers

The Pierre Auger Observatory: completed July 2008



Area: 3000 km^2

1600 surface detector stations: water-Cherenkov tanks
(triangular grid of 1.5 km)

4 fluorescence detectors (24 telescopes in total)

2 laser stations
balloon station

~25 km^2 infill area
HEAT, AMIGA, AERA

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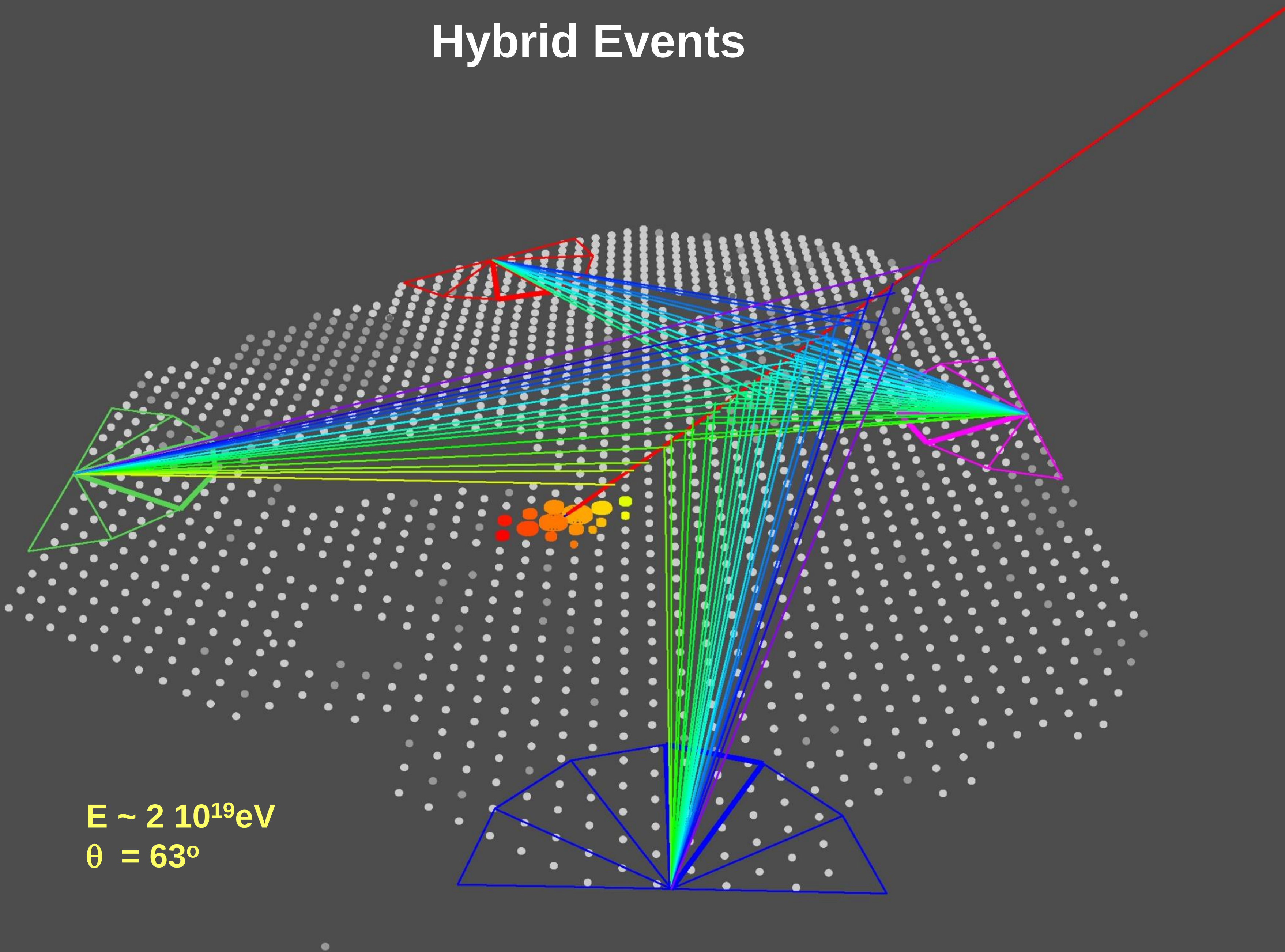
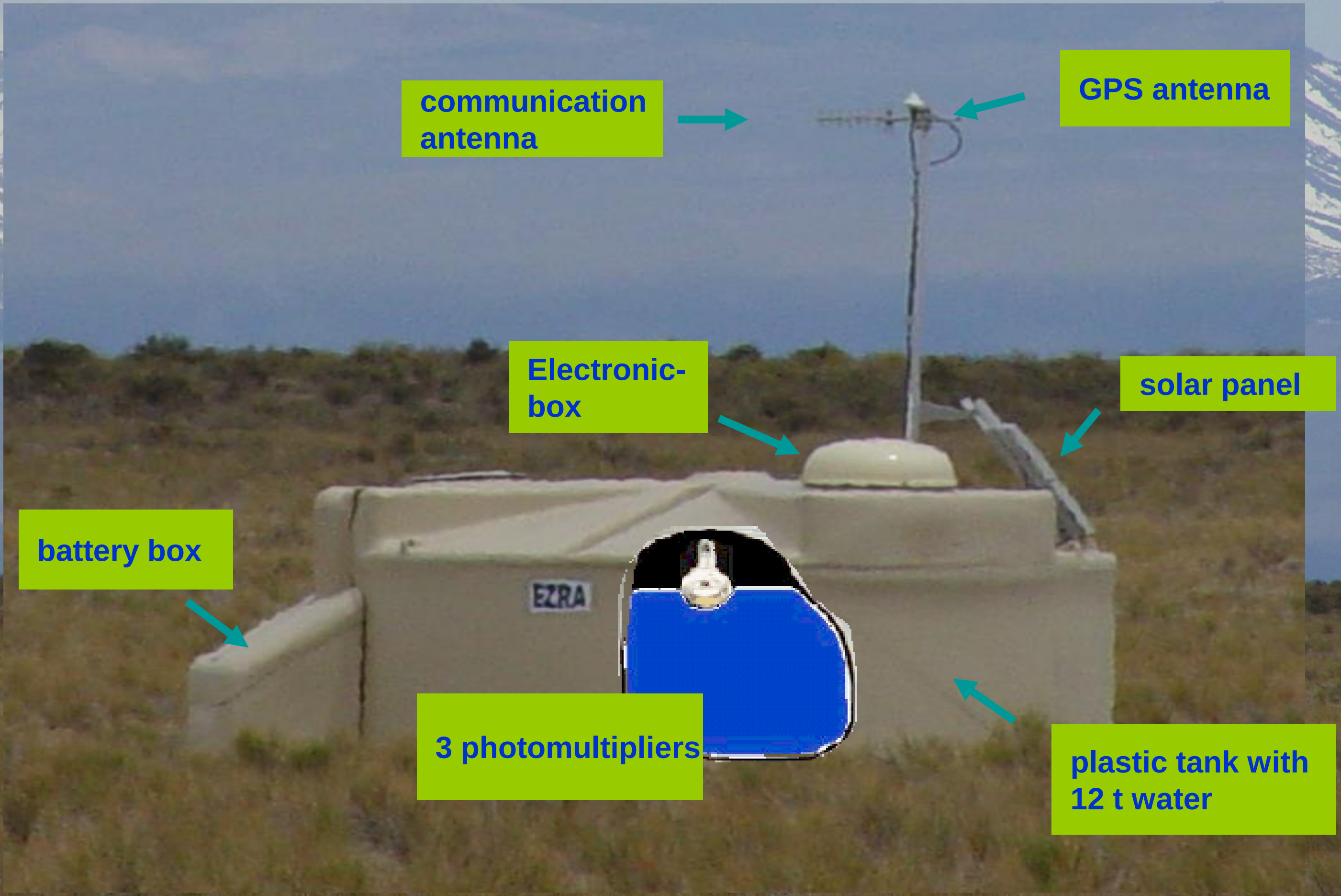
Hybrid Events



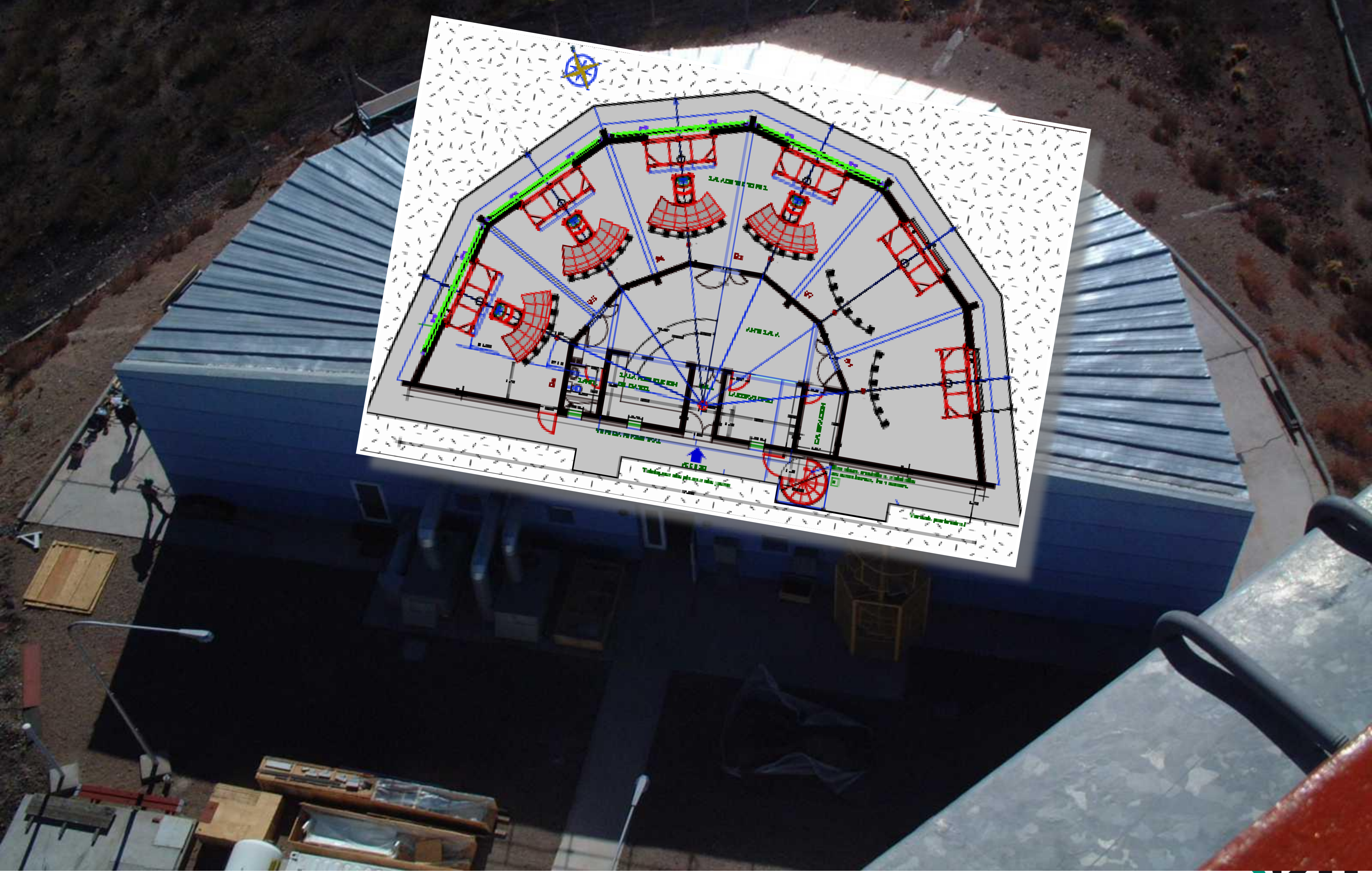
E ~ 2 10^{19}eV
θ = 63°

Surface detector array in the Argentinean Pampa

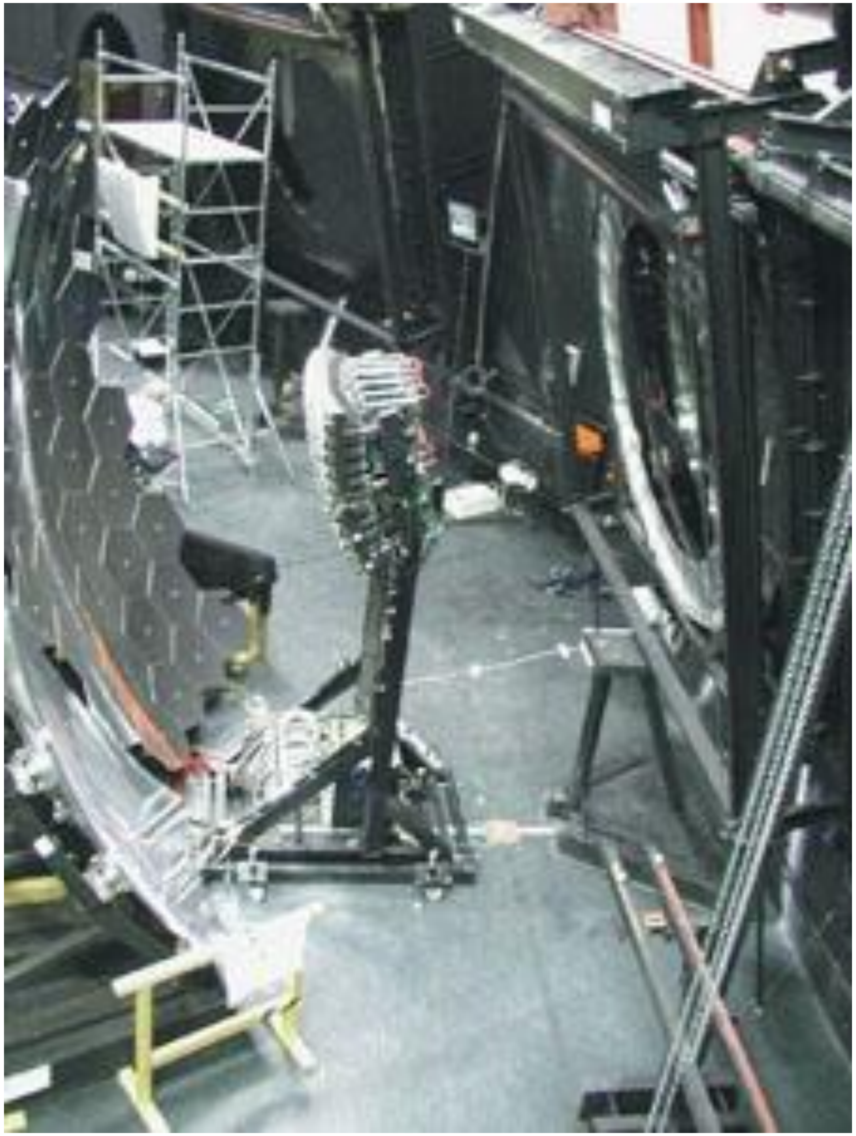


Fluorescence Telescopes

FD: six telescopes each viewing 30° by 30°



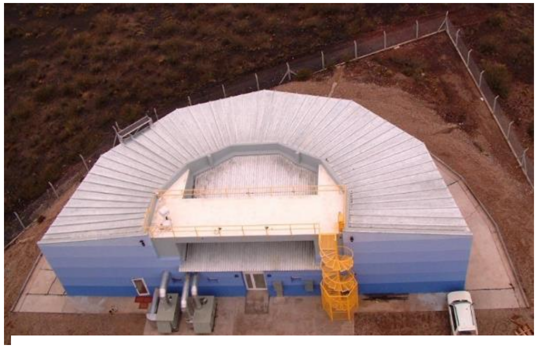
FD: six telescopes each viewing 30° by 30°



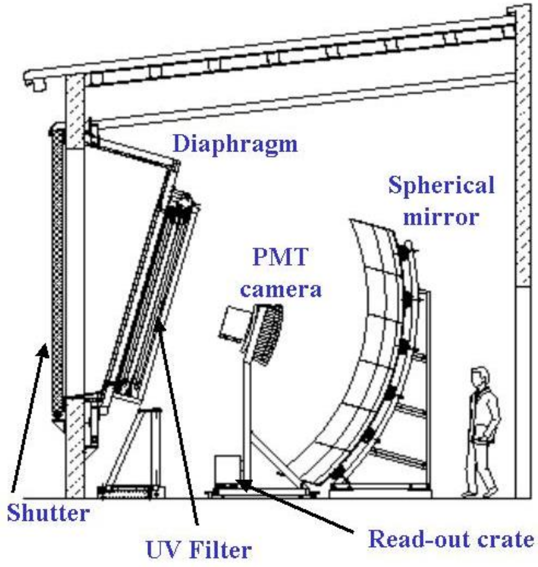
Aperture stop and optical filter

440 pixel camera

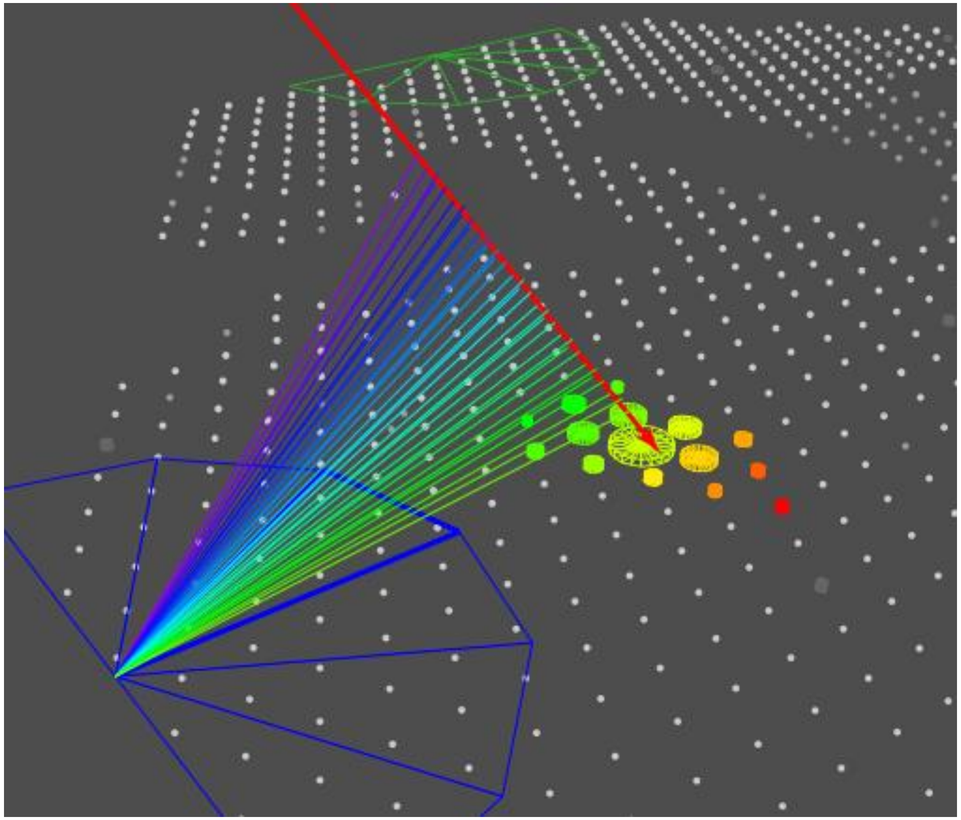
3.4 meter diameter segmented mirror

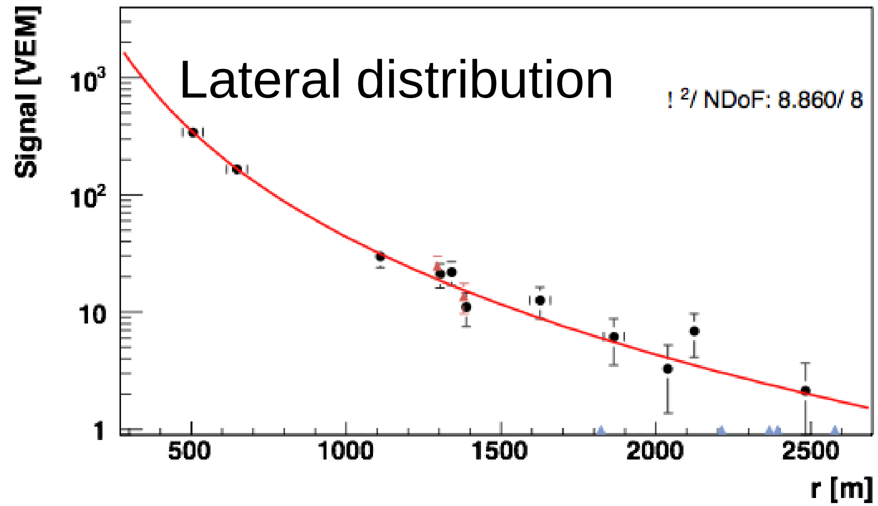


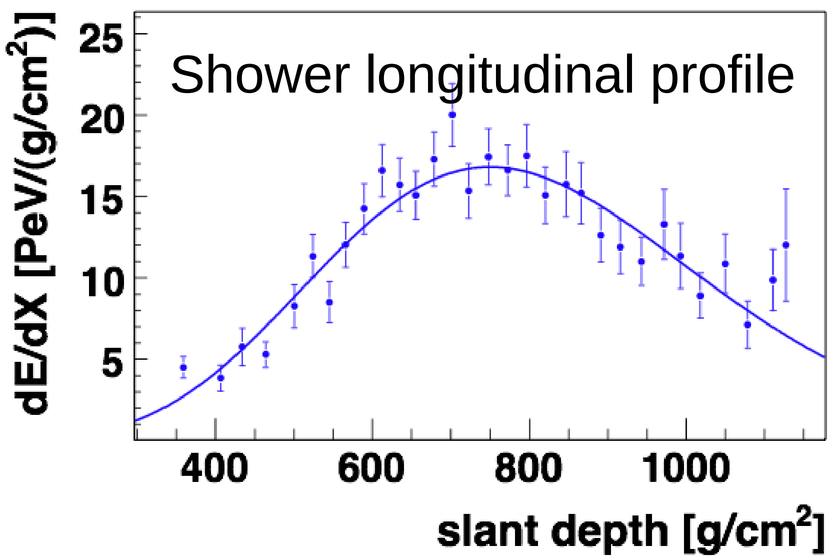
The FD telescope



Golden hybrid events

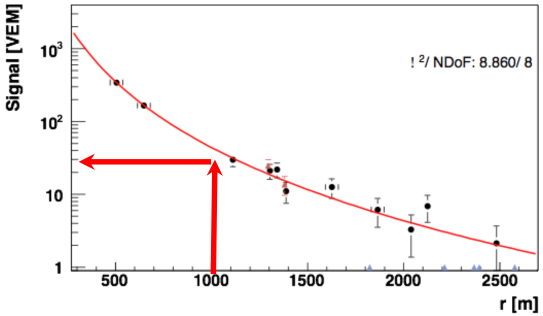


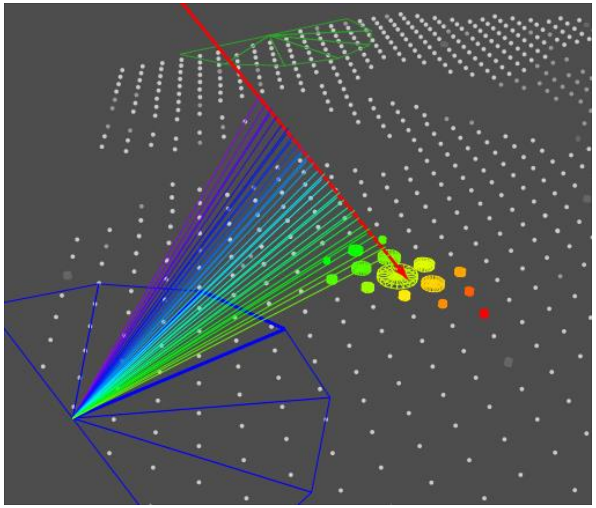


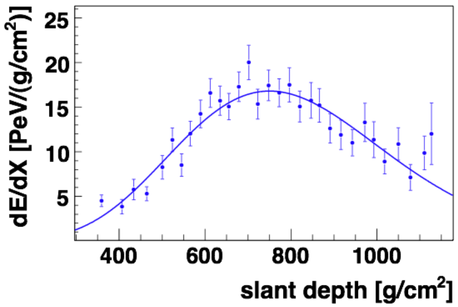


Hybrid events
Golden hybrid events

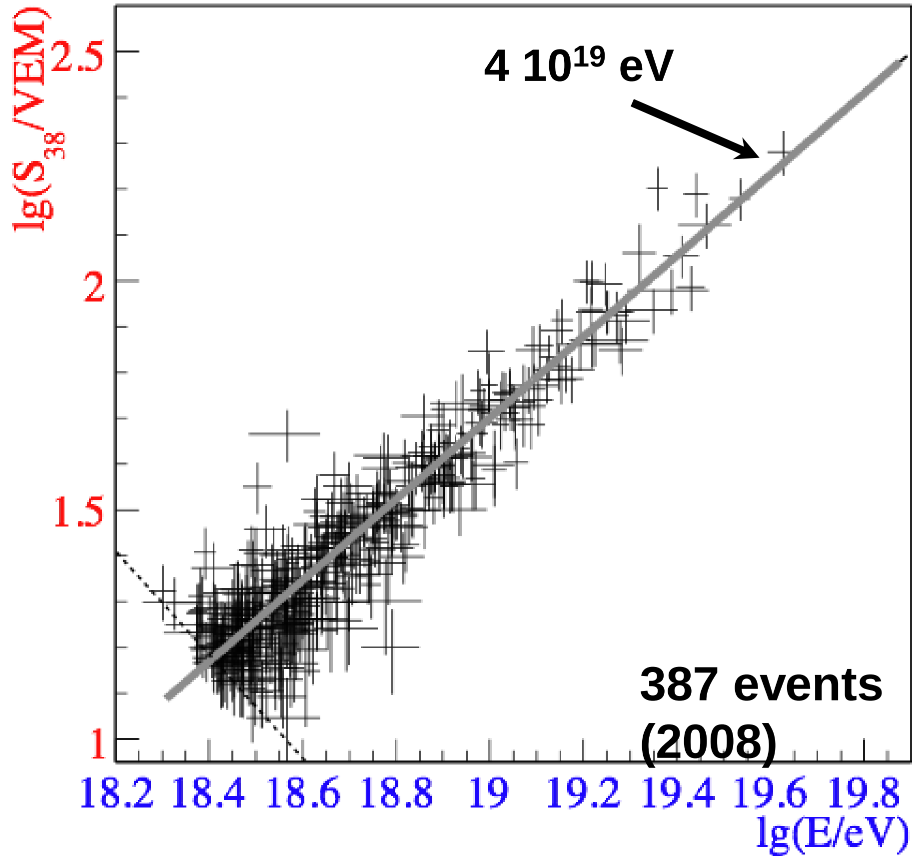
Energy calibration of surface detector by Hybrid events







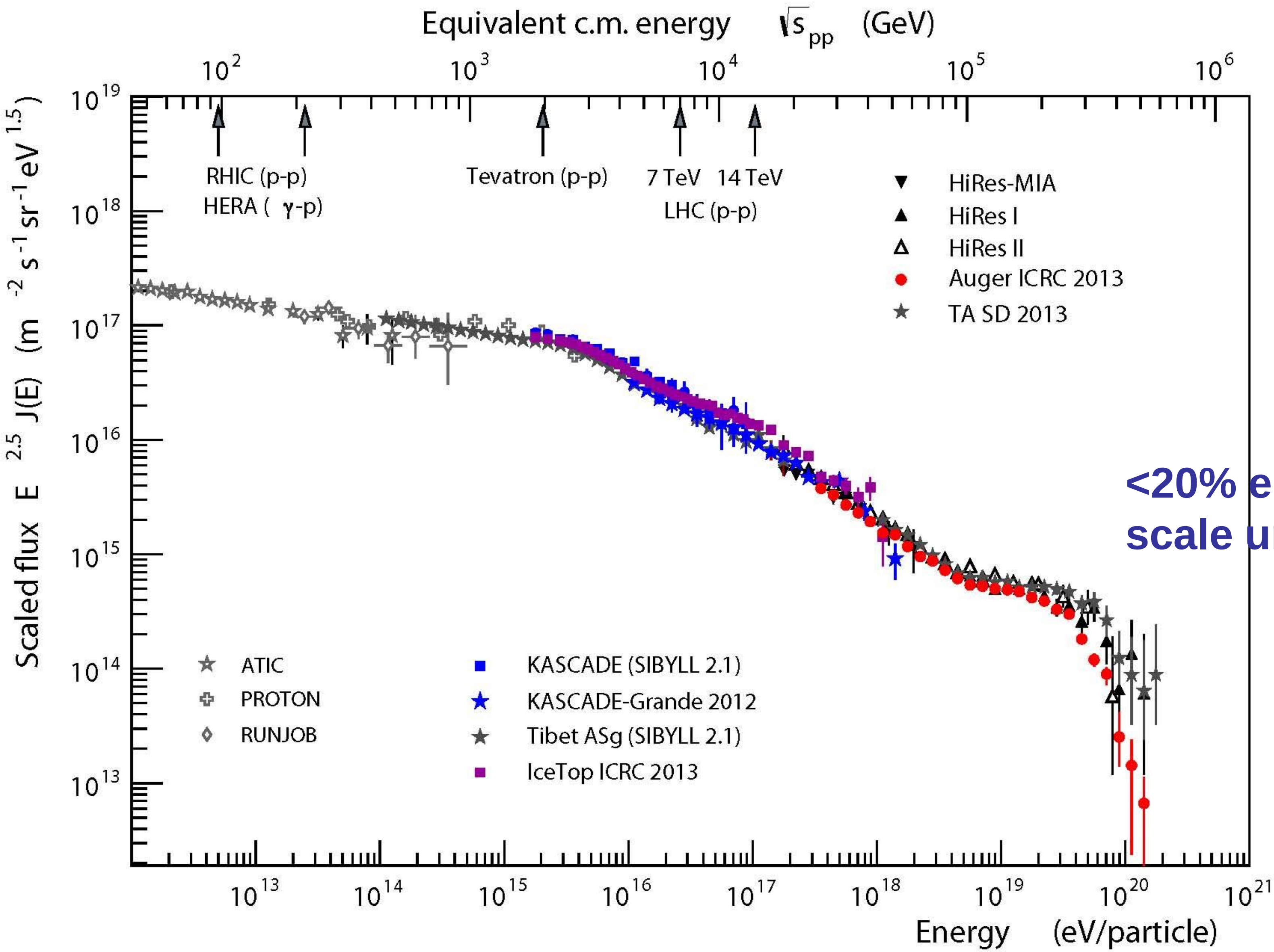
Shower size at 1000m and θ=38°



Fluorescence detector energy

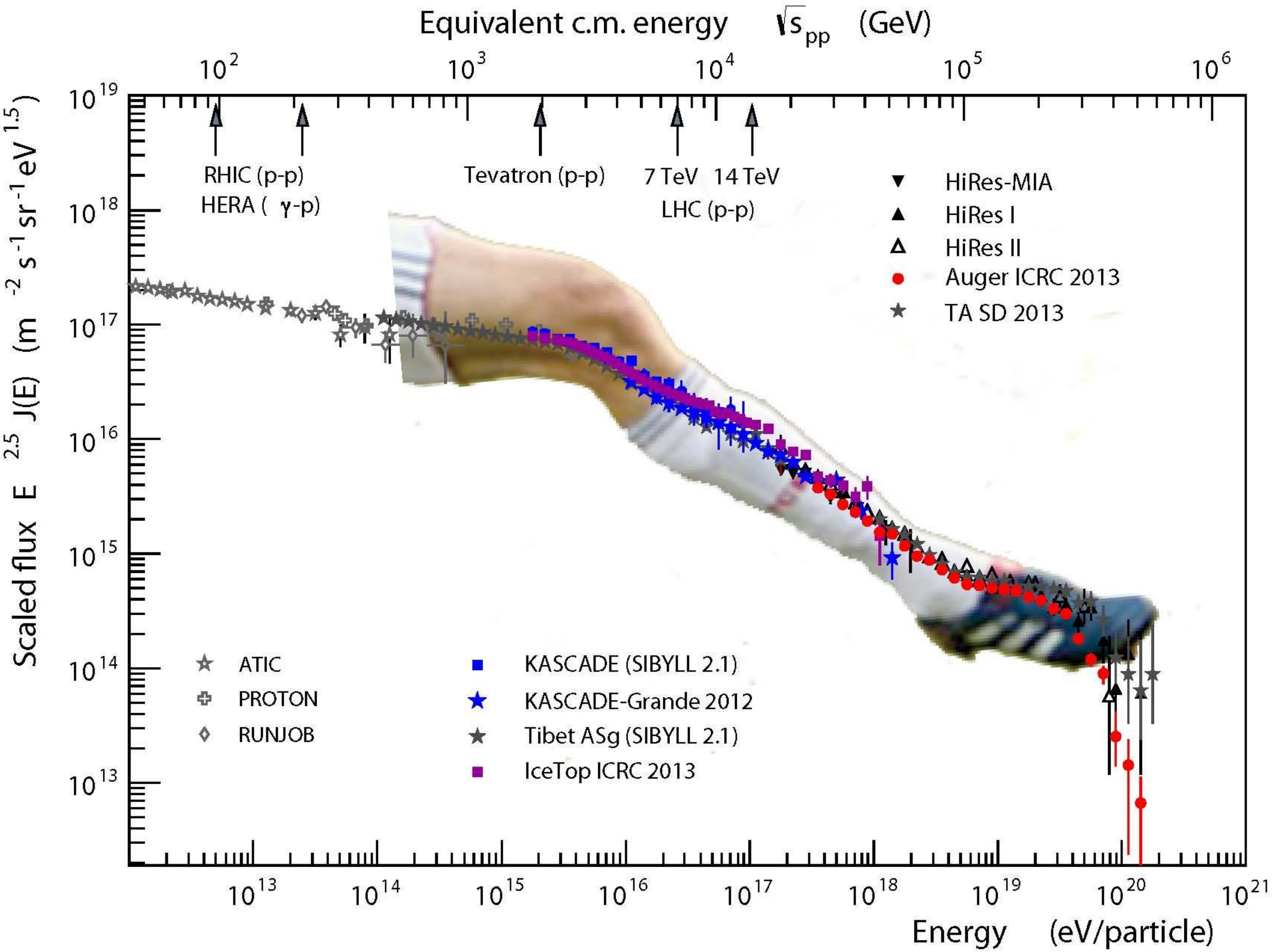
$$E_{\mathrm{prim}} = f_{\mathrm{corr}} \cdot \int \frac{\mathrm{d}E_{\mathrm{ion}}}{\mathrm{d}X}\,\mathrm{d}X$$

Energy spectrum

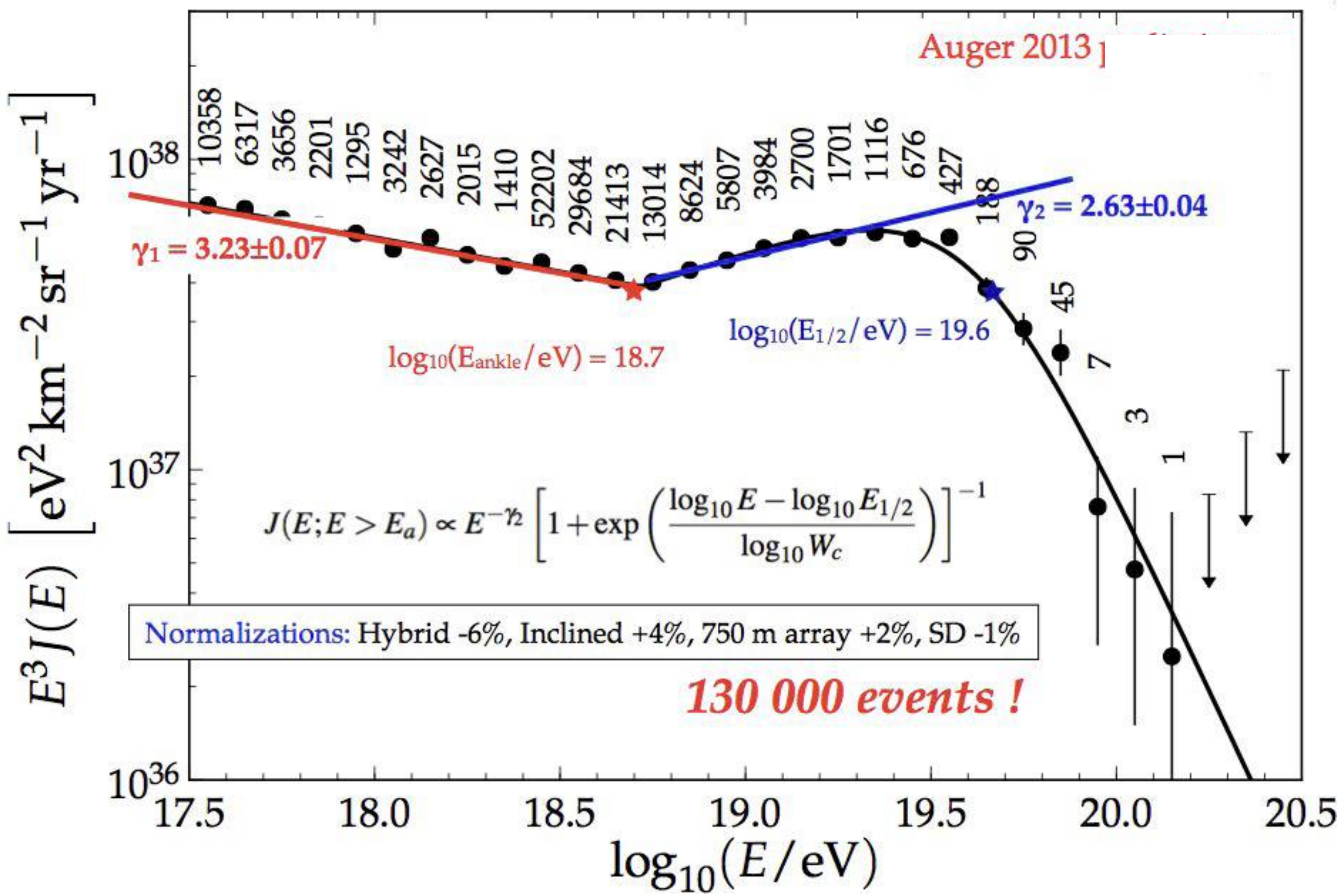


<20% energy scale uncertainty

Energy spectrum

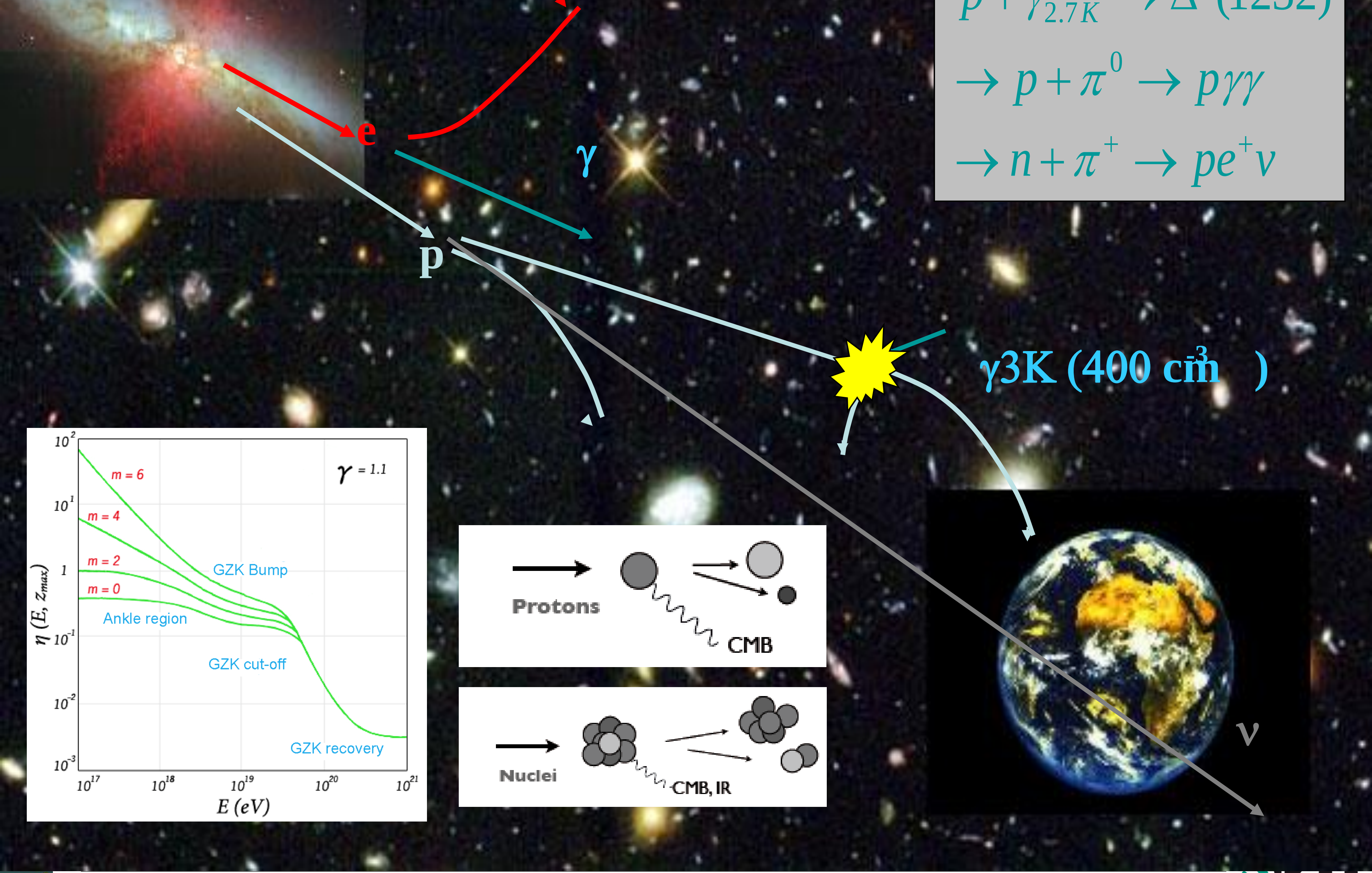


Energy spectrum

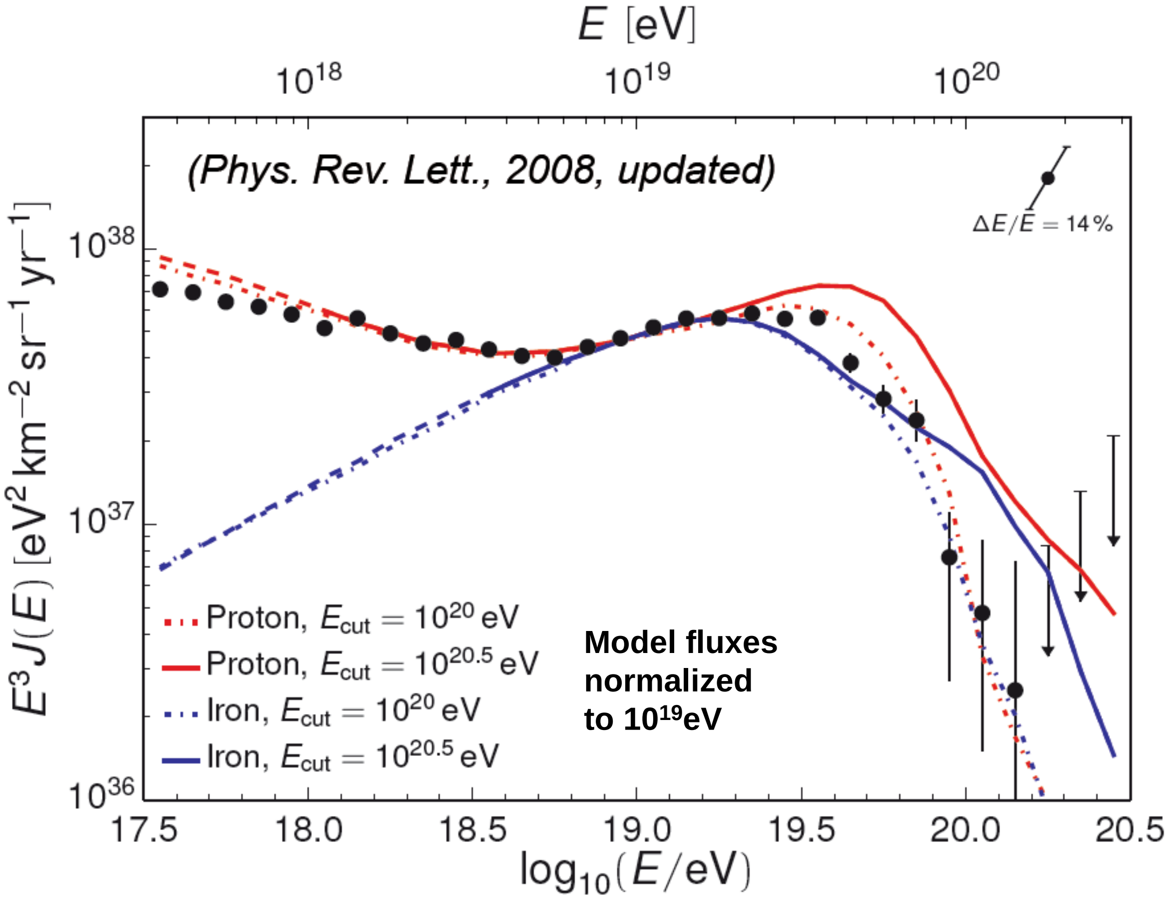


GZK-Cutoff

$$p+\gamma_{2.7K} \rightarrow \Delta^{+}(1232)$$
$$\rightarrow p+\pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n+\pi^{+} \rightarrow pe^{+}\nu$$

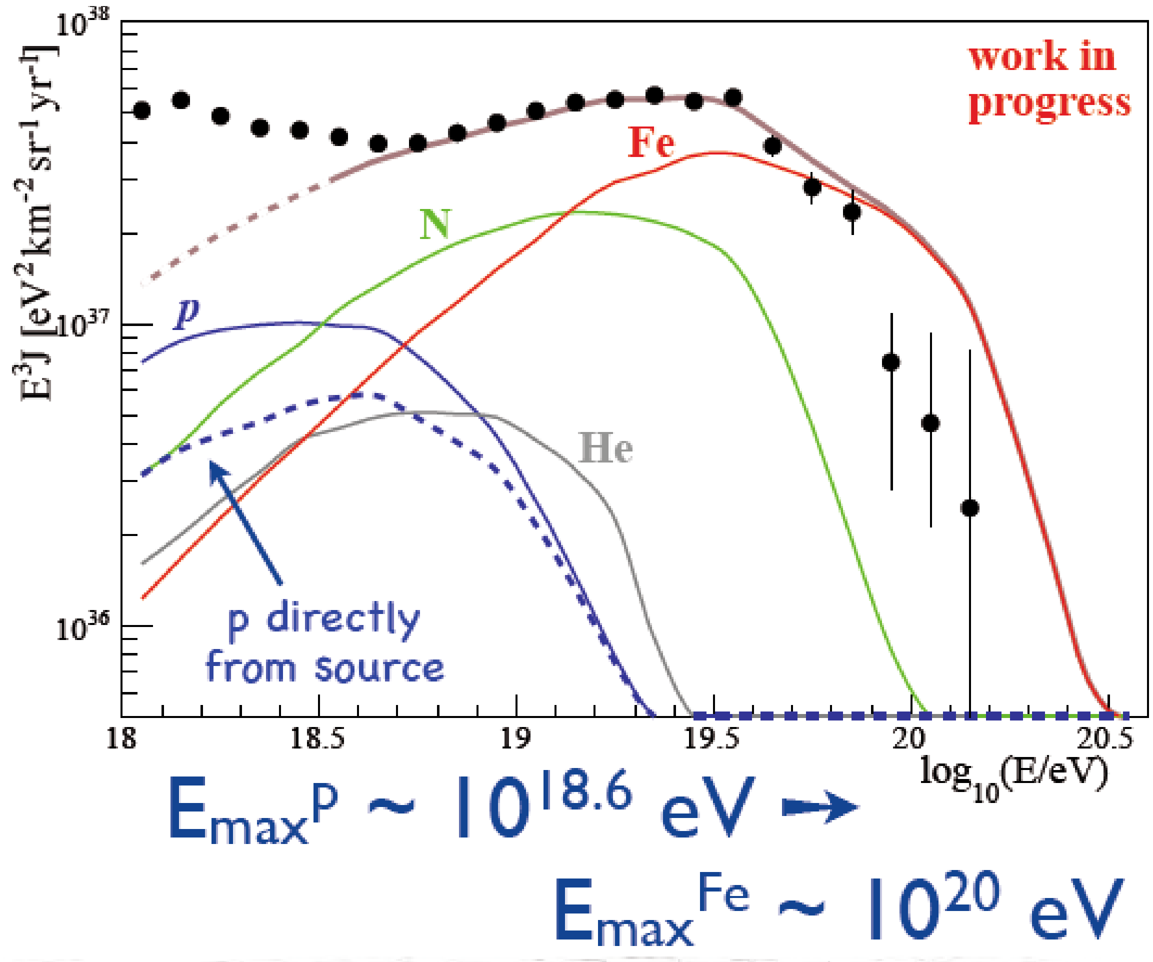


Energy spectrum – GZK suppression scenario



? Observed flux suppression is due entirely to GZK effect
? Observed flux suppression is signature of maximum acceleration energy
? Observed flux suppression is due to both source cutoff and GZK effect

Energy spectrum – maximum acceleration scenario



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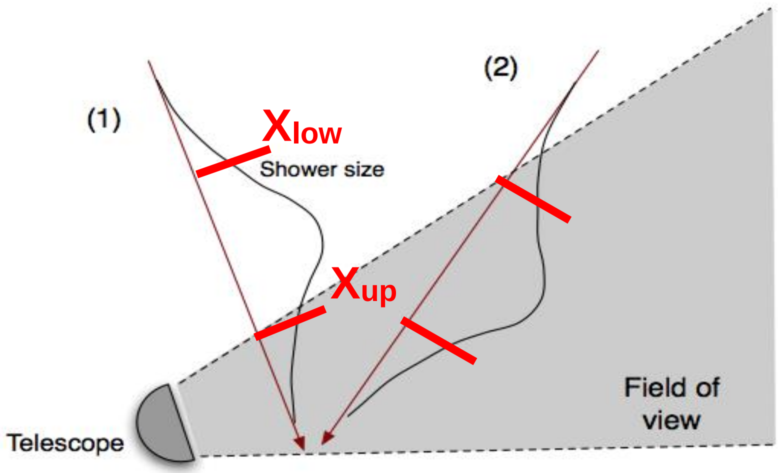
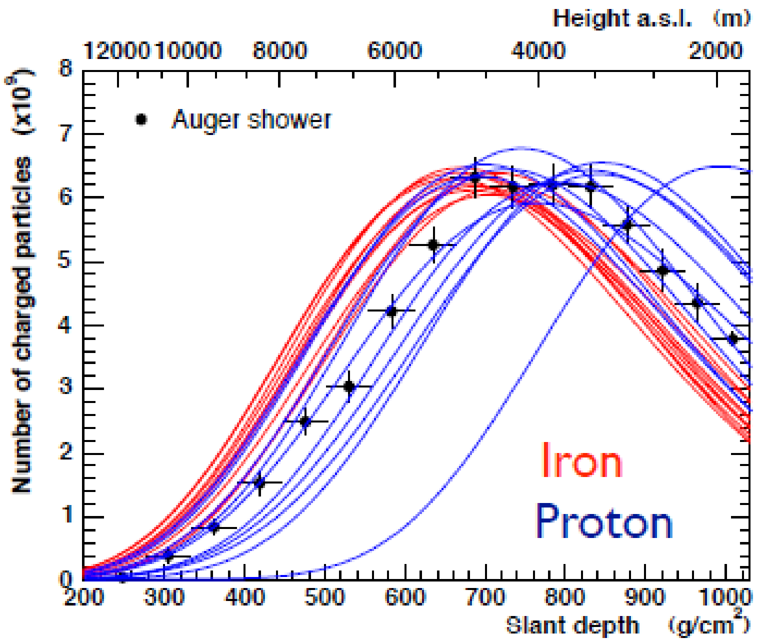
Composition: measurement of longitudinal profile

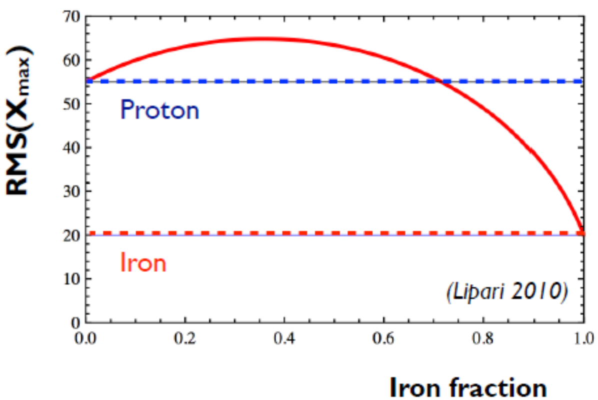




Field of view bias needs to be accounted for

X_{low}, X_{up} are determined from data, no simulation needed

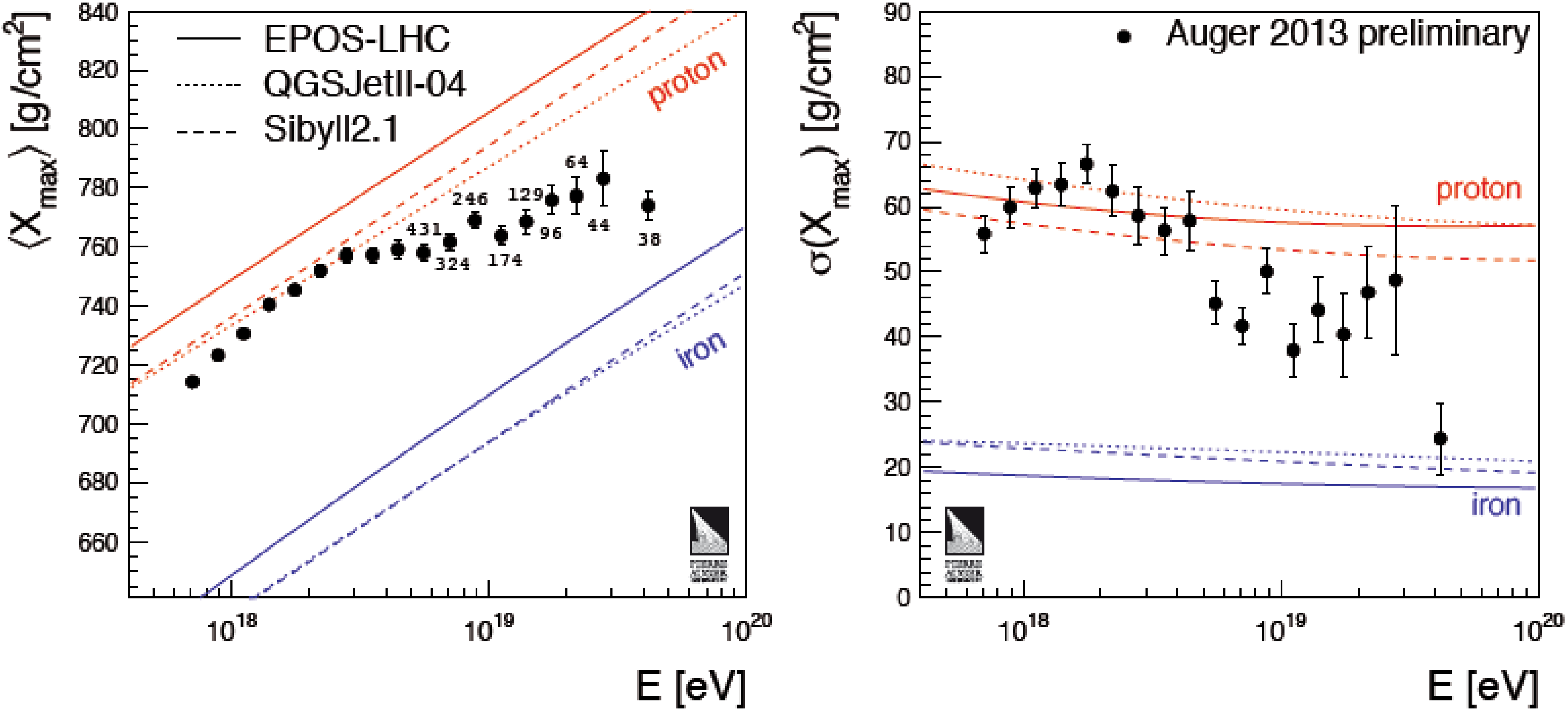
Fluctuations of depth of shower maximum



Mean depth of shower profiles and shower-to-shower fluctuations as measure of composition

(Unger et al., ICRC 2007)

Composition: mean depth and rms of shower maximum

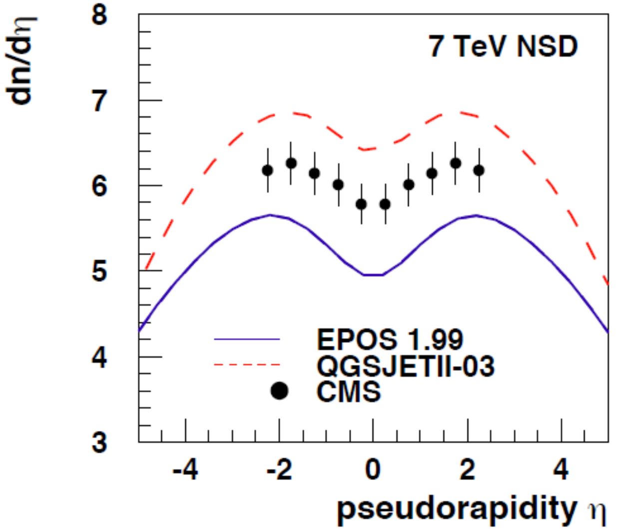


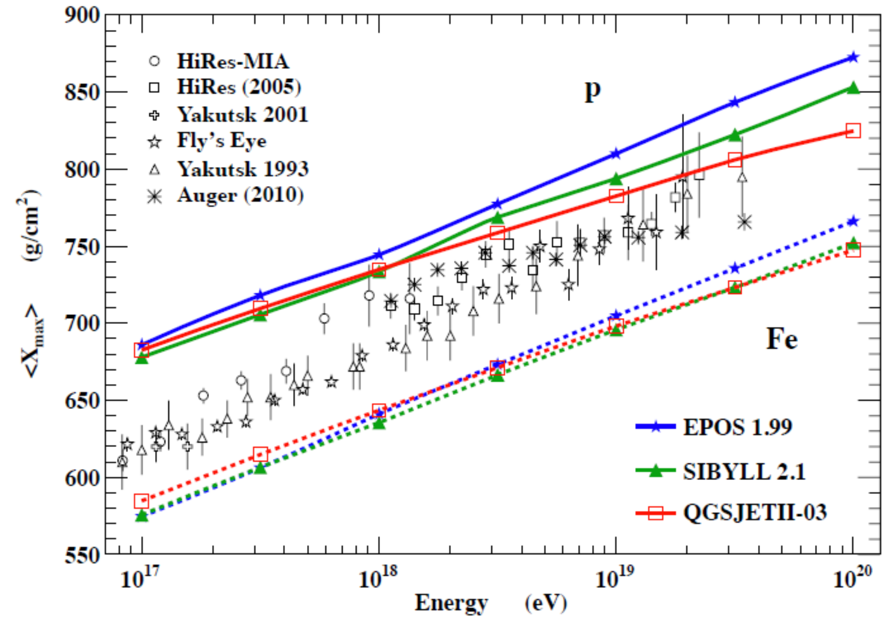
Composition is getting heavier with energy
Method only applicable up to 50EeV due to statistics

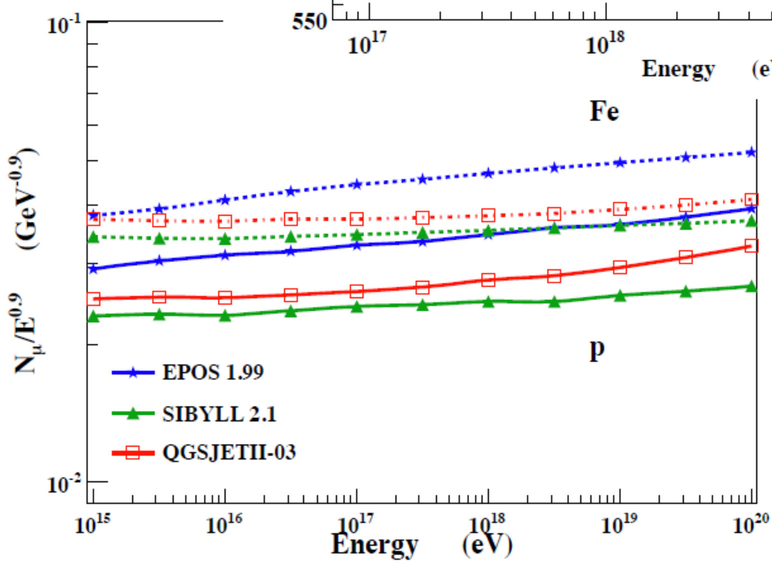
Auger Collaboration, ICRC13

Hadronic Interaction Models and LHC

Model predictions **before** LHC





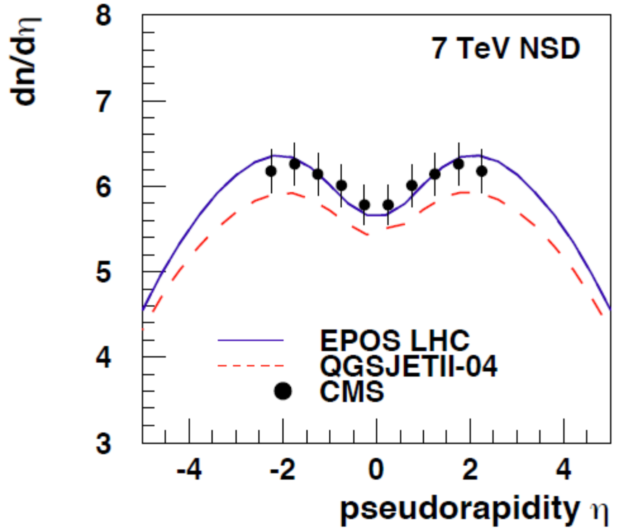


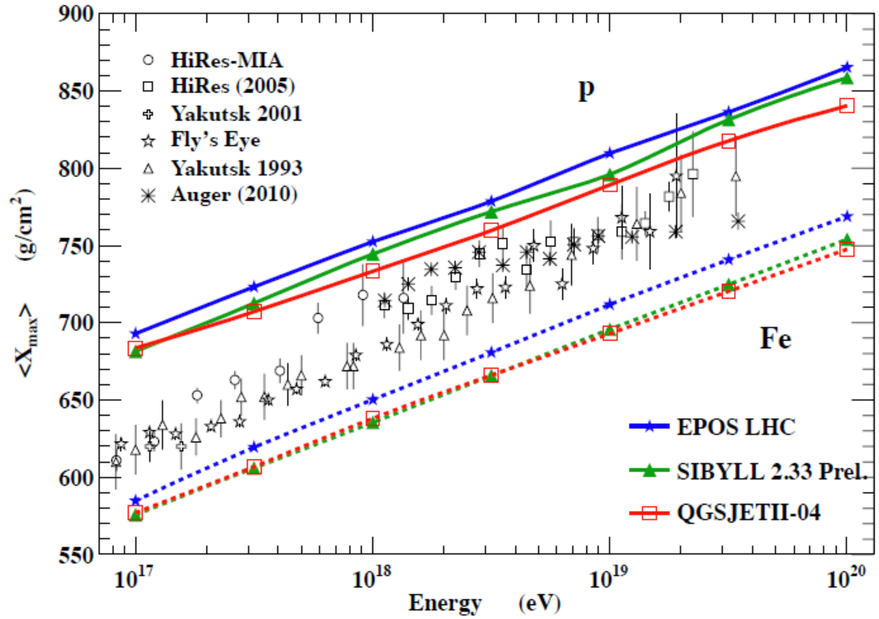
CORSIKA predictions

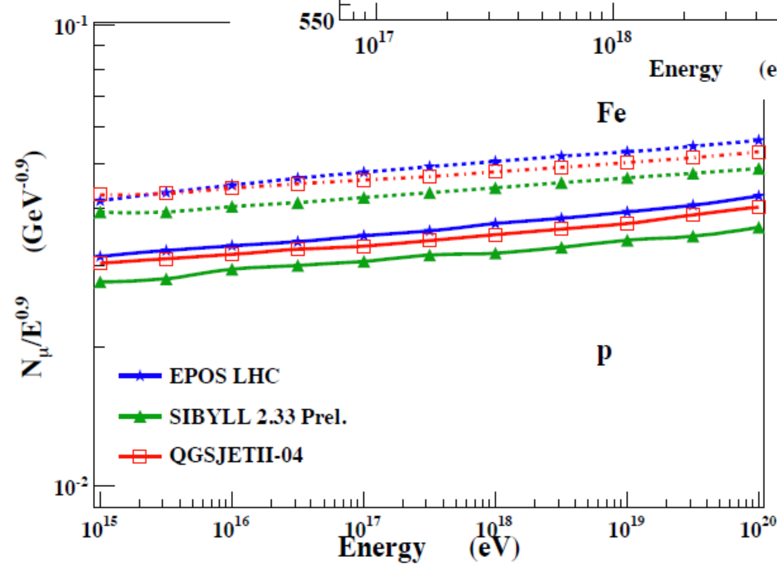
Number of muons

Hadronic Interaction Models and LHC

Model predictions **after** LHC







CORSIKA predictions

Number of muons

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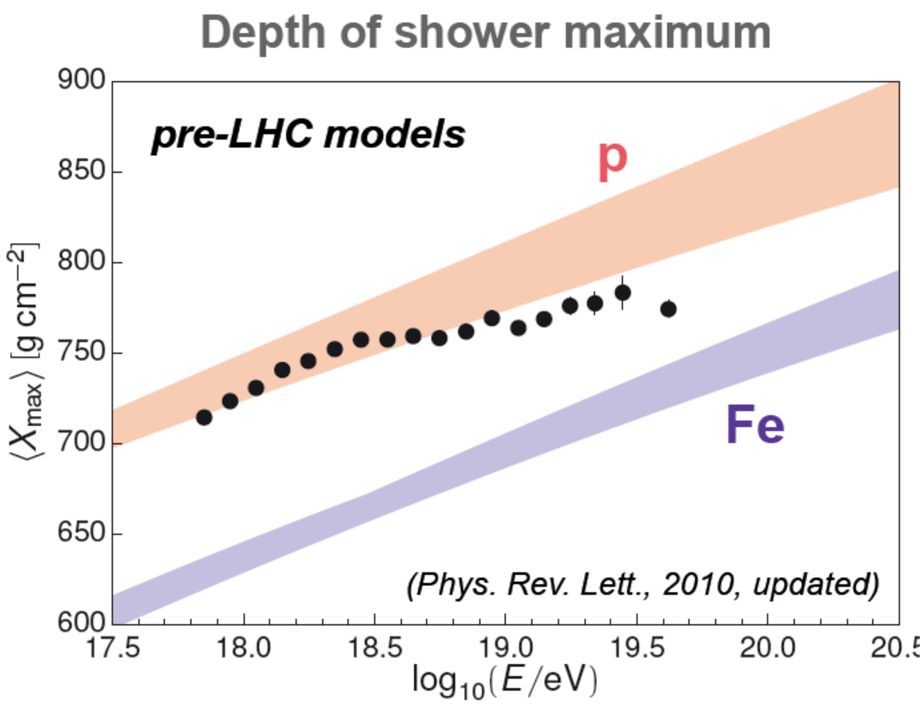
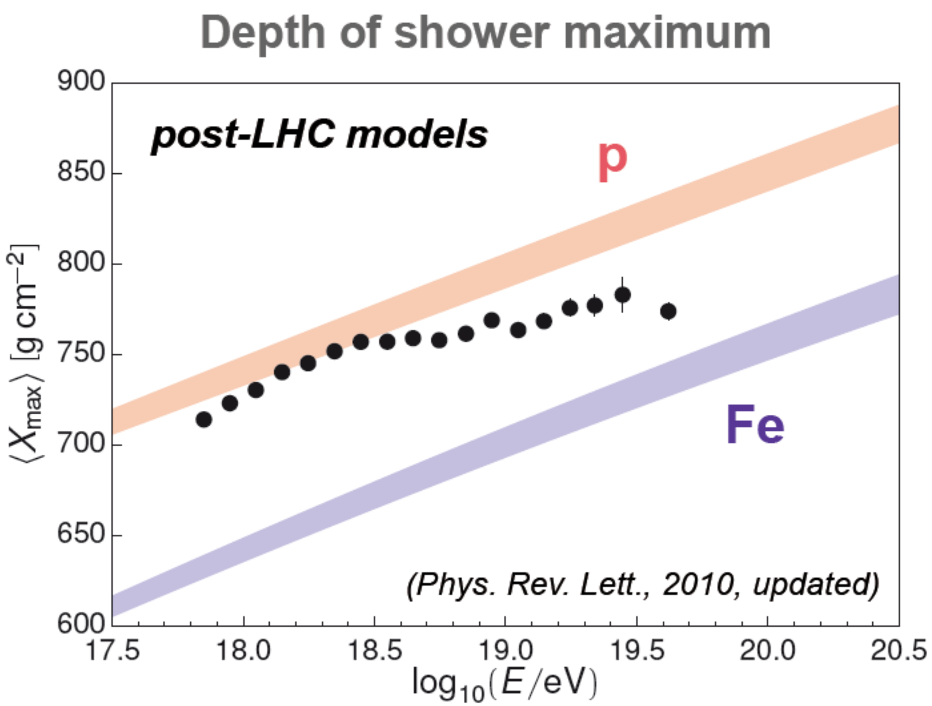
Mean depth of shower maximum
compared with old and new model predictions….





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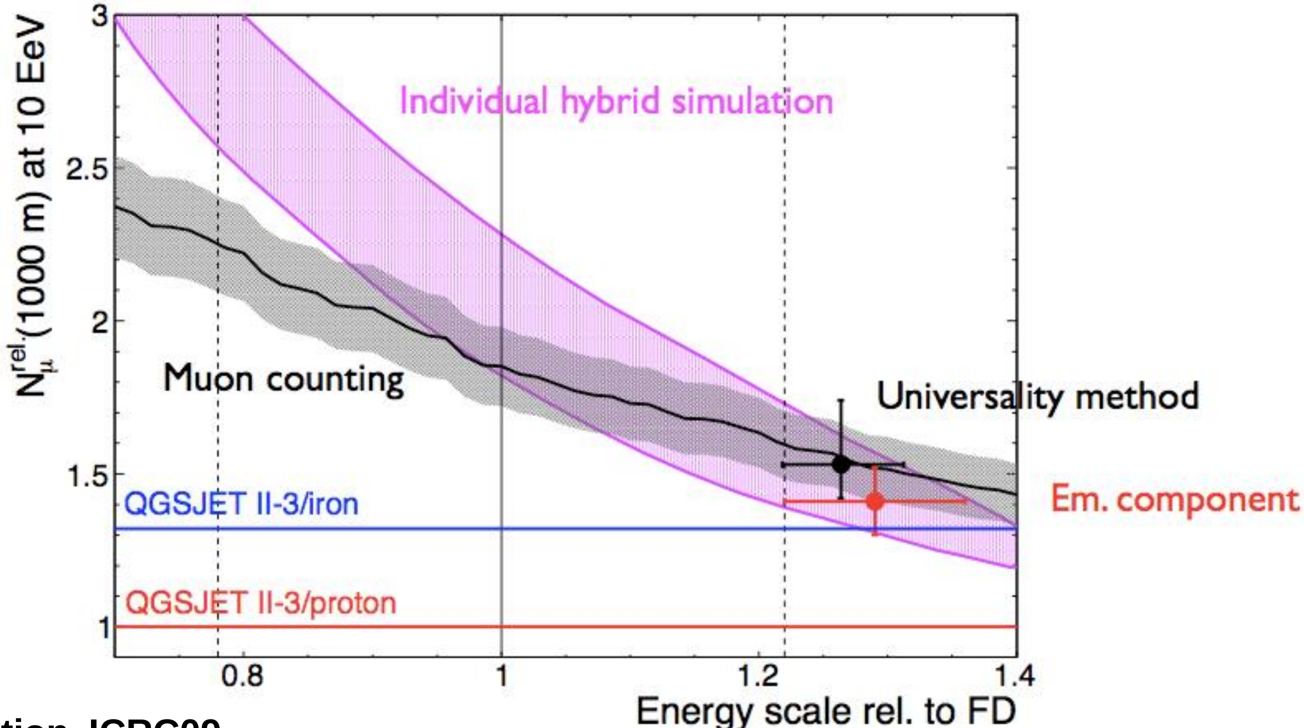
Validity of hadronic interaction models

A self consistent description of the Auger data is obtained only with a number of muons 1.3 to 1.7 times higher

than that predicted by QGSJET-II for protons at an energy 25-30% higher than that from FD calibration

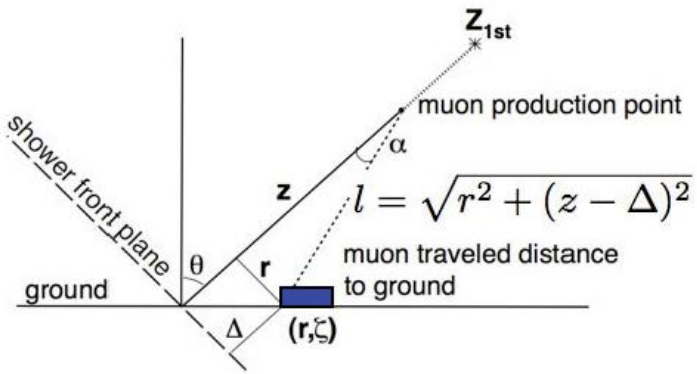
The results are marginally compatible with the predictions of QGSJET-II for iron primaries

Discrepancy: shower profile and muons at ground



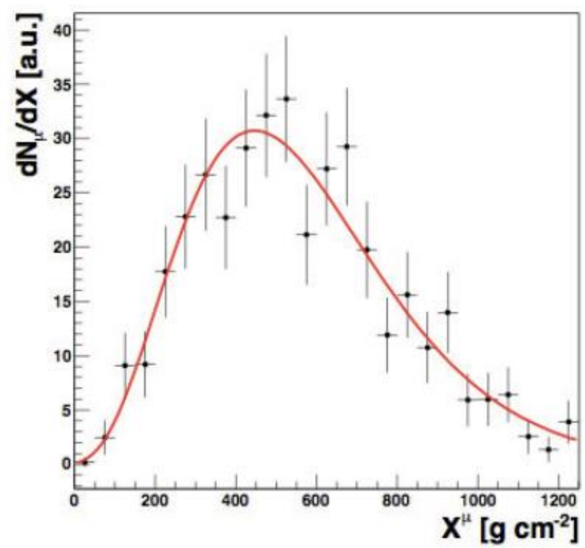
A.Castellina-Auger Collaboration, ICRC09

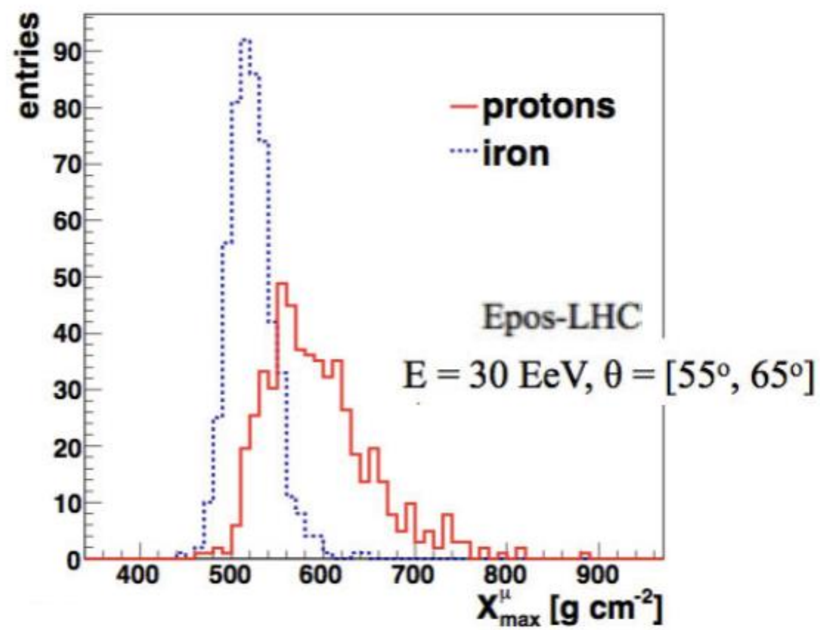
Composition studies with muons (SD measurements)



$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta \quad \rightarrow \quad X^{\mu} = \int_z^{\infty} \rho(z')dz'$$

$$t_g \simeq t - < t_\varepsilon >$$

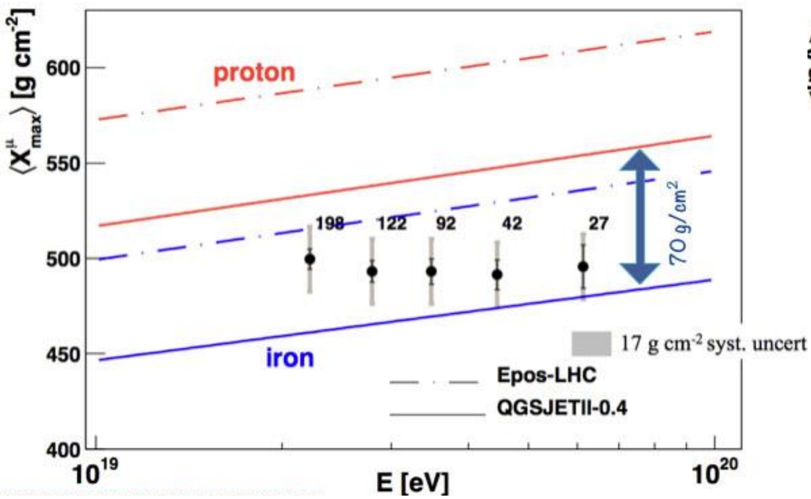


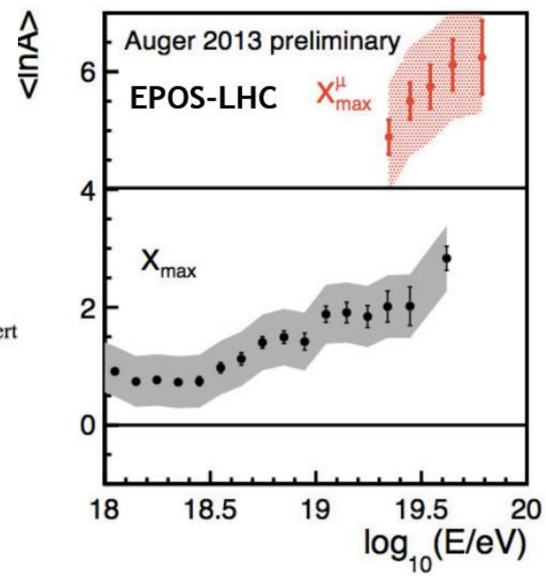


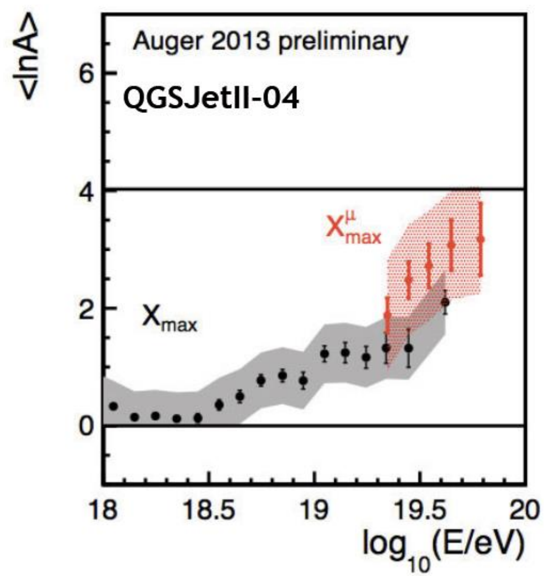
- **Muon production height is sensitive to the composition!**

Composition studies with muons (SD measurements)

$$\langle \ln A \rangle = \ln 56 \frac{X^{p}_{max} - \langle X_{max} \rangle}{X^{p}_{max} - X^{Fe}_{max}} \qquad \langle \ln A \rangle^{\mu} = \ln 56 \frac{X^{\mu p}_{max} - \langle X^{\mu}{}_{max} \rangle}{X^{\mu p}_{max} - X^{\mu Fe}_{max}}$$

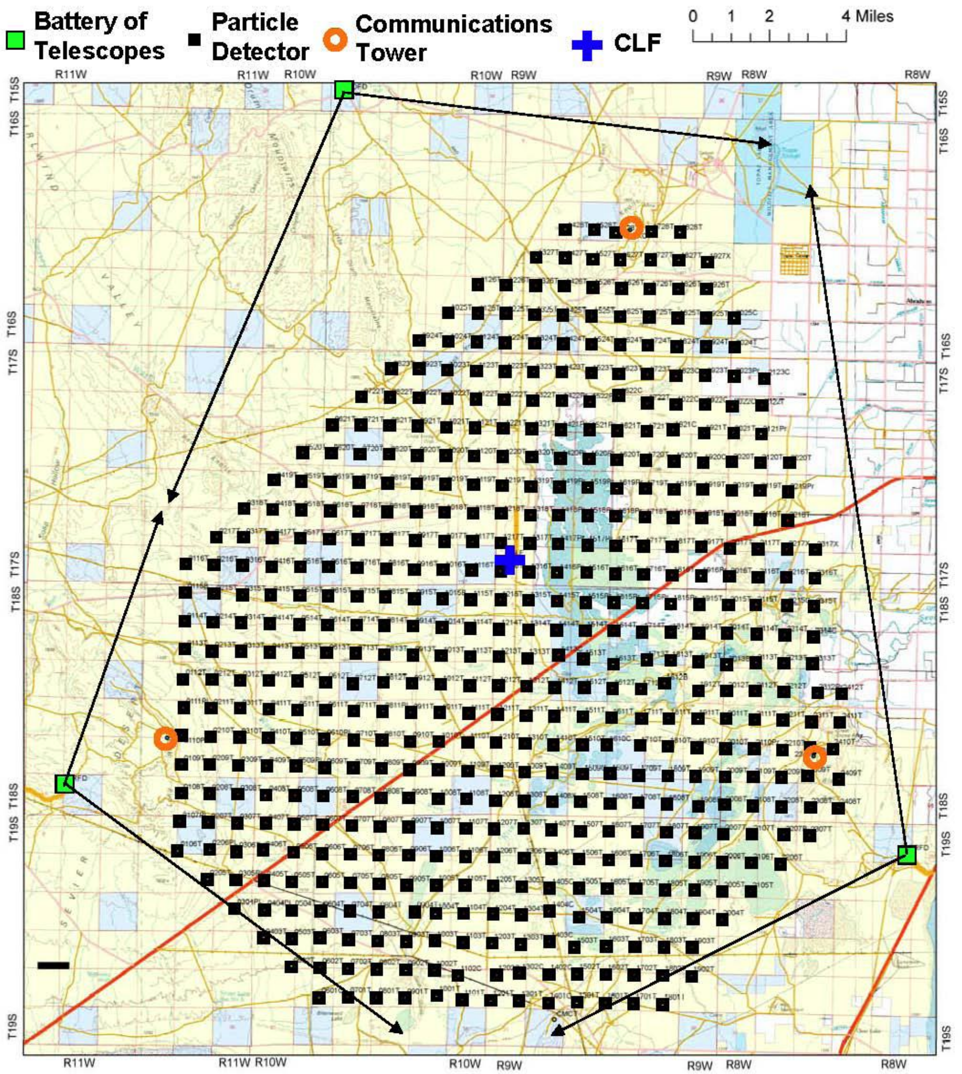




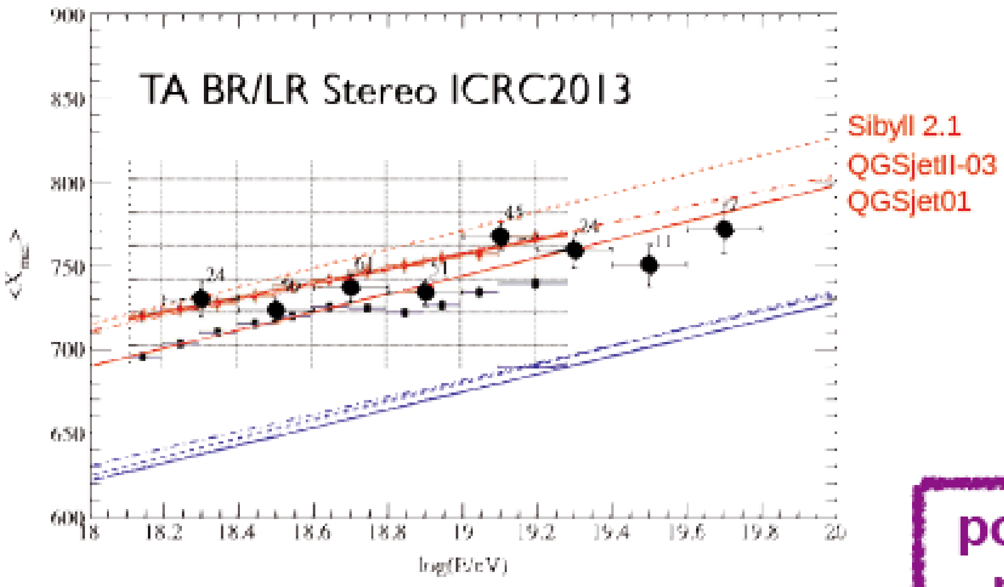


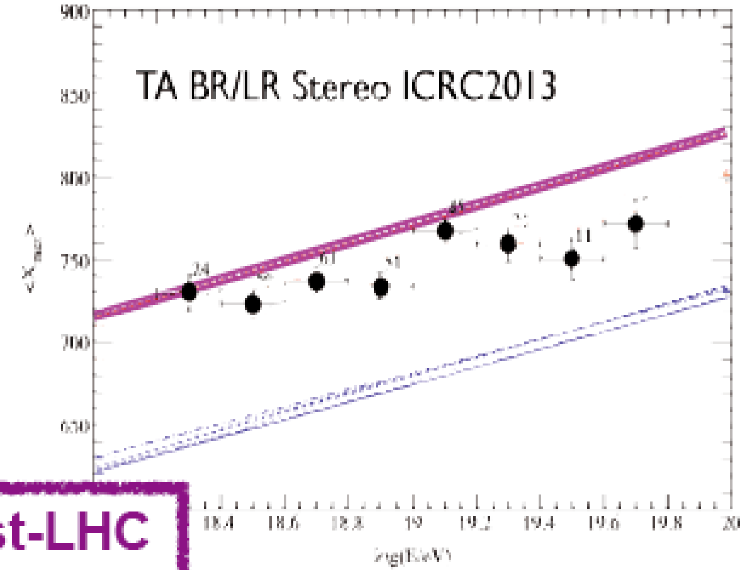
- approach to study the longitudinal EAS development
  selection: E>20 EeV, ϑ>55^0, only stations far from the core.
- in agreement with the conclusion from X_{max} (but large uncertainty)
- analysis should be extended to lower angles and energies and
  with smaller uncertainties (Auger upgrade)
- consistency between the two X_{max} helps to constrain
  hadronic interaction models

Telescope Array, Utah, US

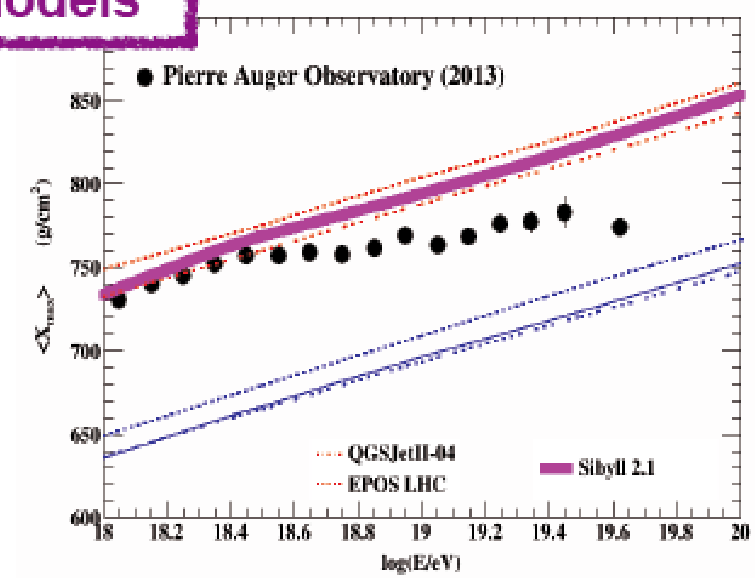


Composition Auger vs Telescope Array





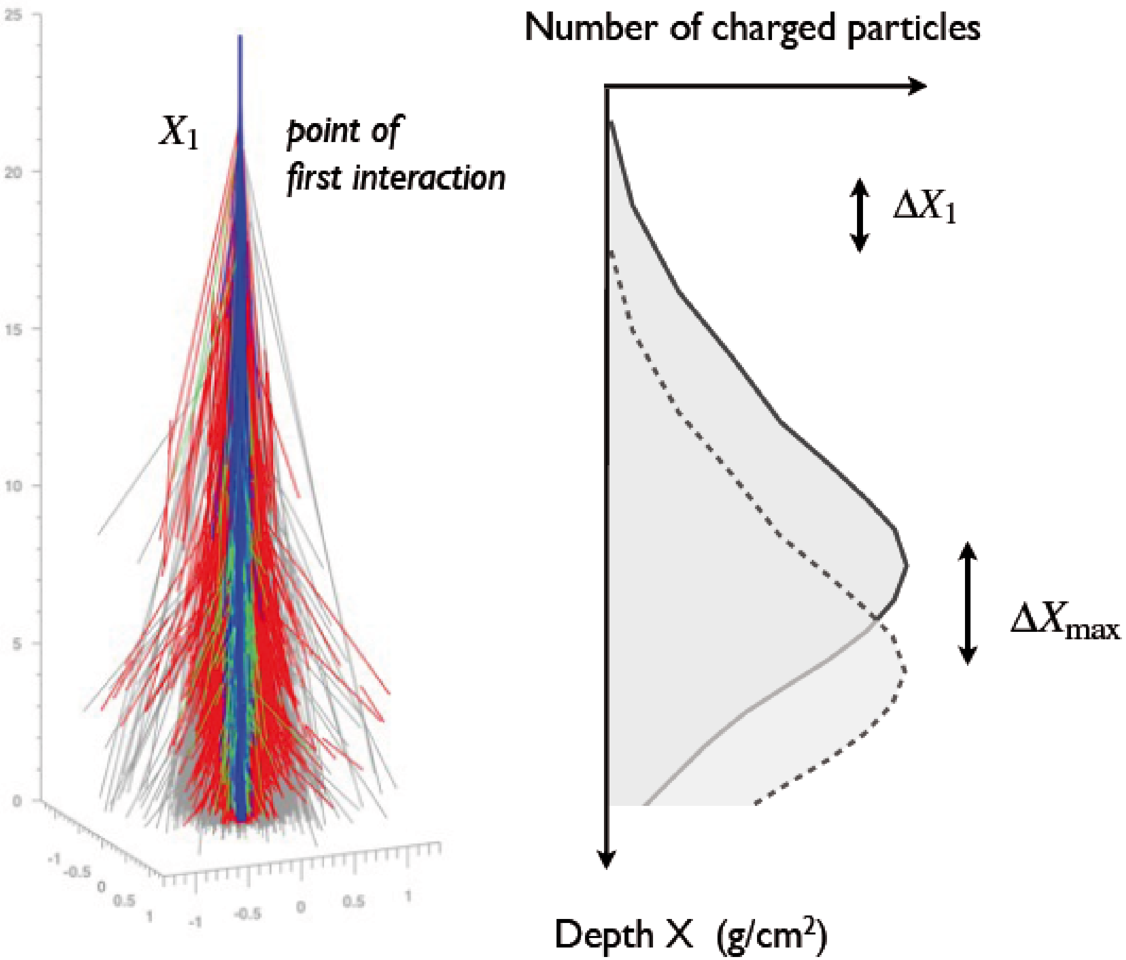
post-LHC models



Comparison (work in progress)

- Auger data acceptance-corrected
- TA data folded with acceptance
- Joint working group (ICRC 2013)

Particle Physics: Cross section



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

$$\mathrm{RMS}(X_1) = \lambda_{int}$$

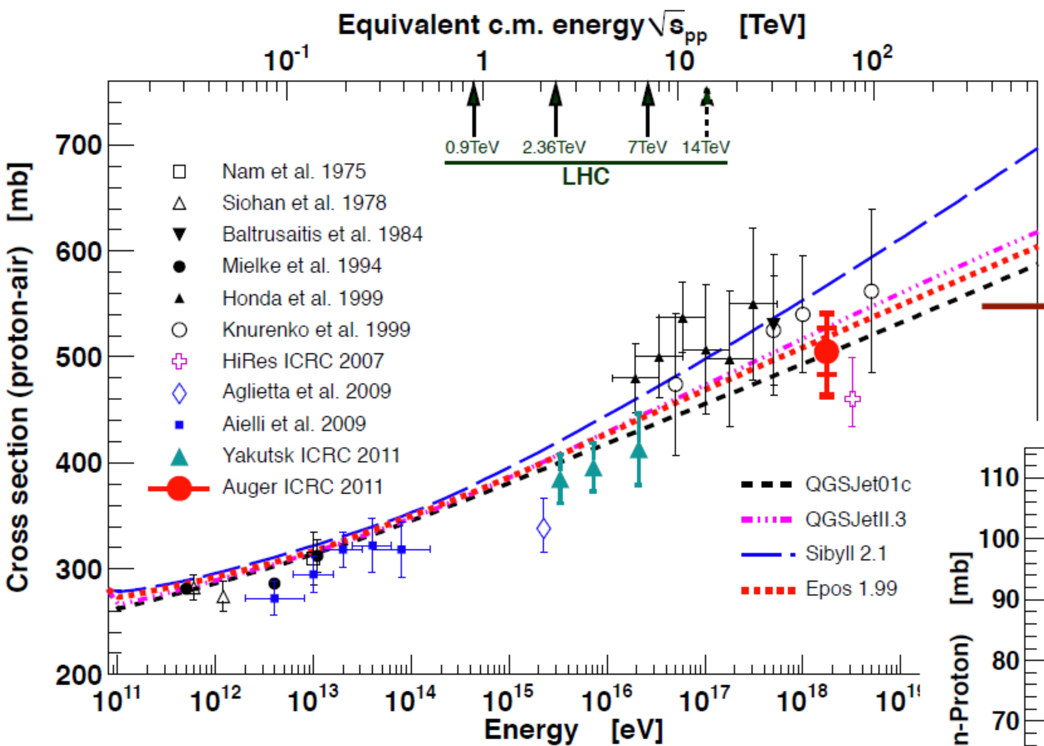
$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{int}}$$

Difficulties

- mass composition
- fluctuations in shower development (model needed for correction)
  $$\mathrm{RMS}(X_1) \sim \mathrm{RMS}(X_{max} - X_1)$$
- experimental resolution ~20 g/cm^2

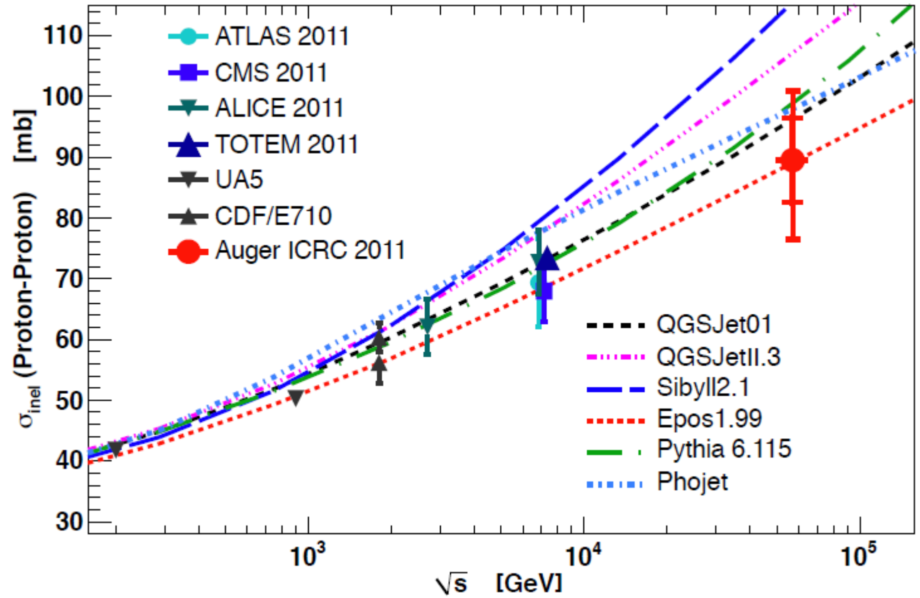
R. Ulrich et al. NJP 11 (2009) 065018

Cross section



Glauber model

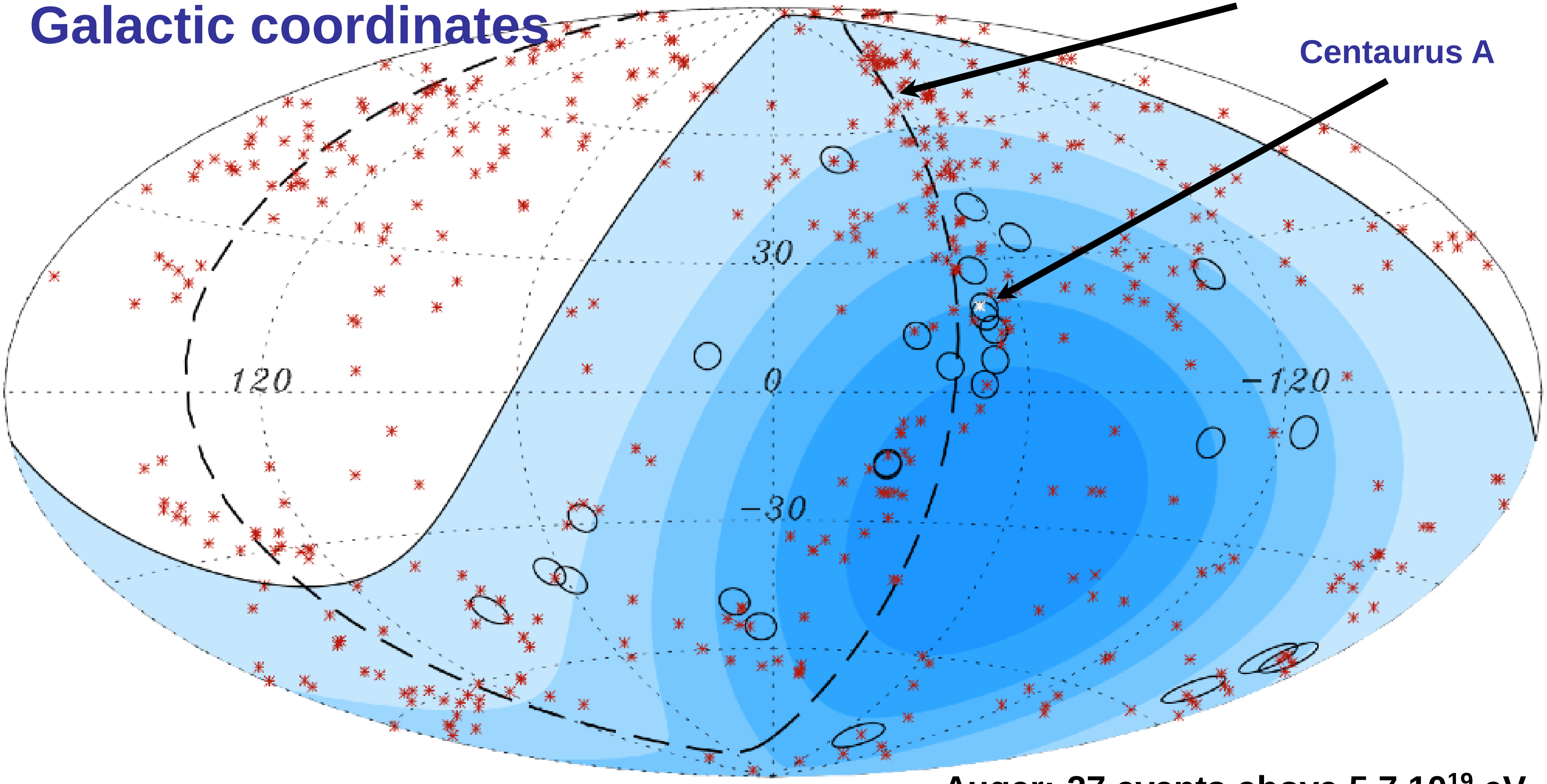
(Phys. Rev. Lett., 2012)



Measured p-air cross section
converted to p-p cross section

(Ulrich et al., Helmholtz YIG)

Anisotropy of ultra-high energy cosmic rays



Veron-Cetty: 472 AGN (z< 0.018, ~75 Mpc)
318 in field of view of Auger

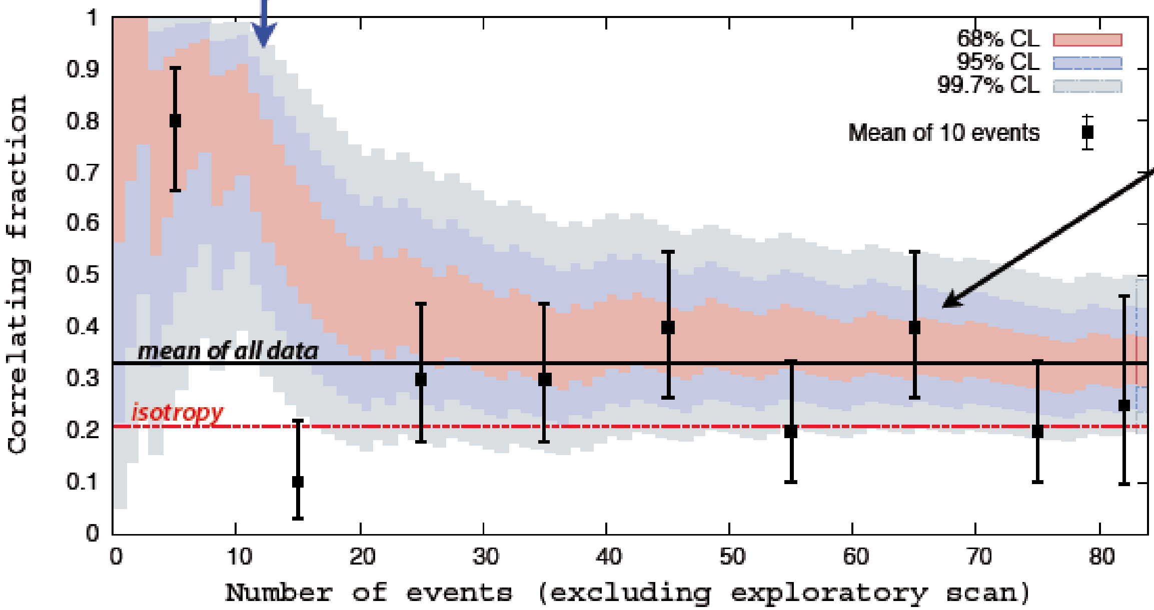
Auger: 27 events above 5.7 10^{19} eV,
20 correlated within 3.1°,
5.7 expected

Science 318 (2007) 939

Current status of correlation with AGNs

Auger Observatory (2011)

Science publication: 9/13 events ~69% correlated, expectation for isotropy 21%



Differential estimate every 10 events

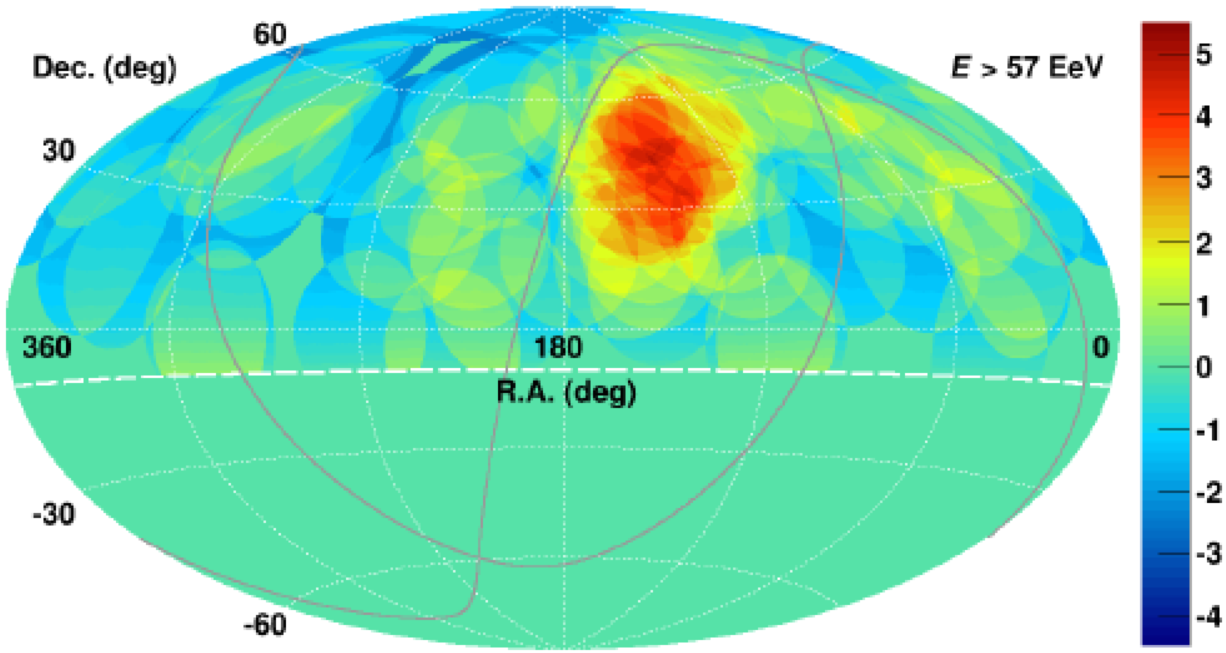
June 2011: 28 out of 84 correlated estimate now 33 ± 5% (P = 0.006)

Events correlating with near-by AGNs of all events above 5×10^{19} eV

Indications for weak anisotropy

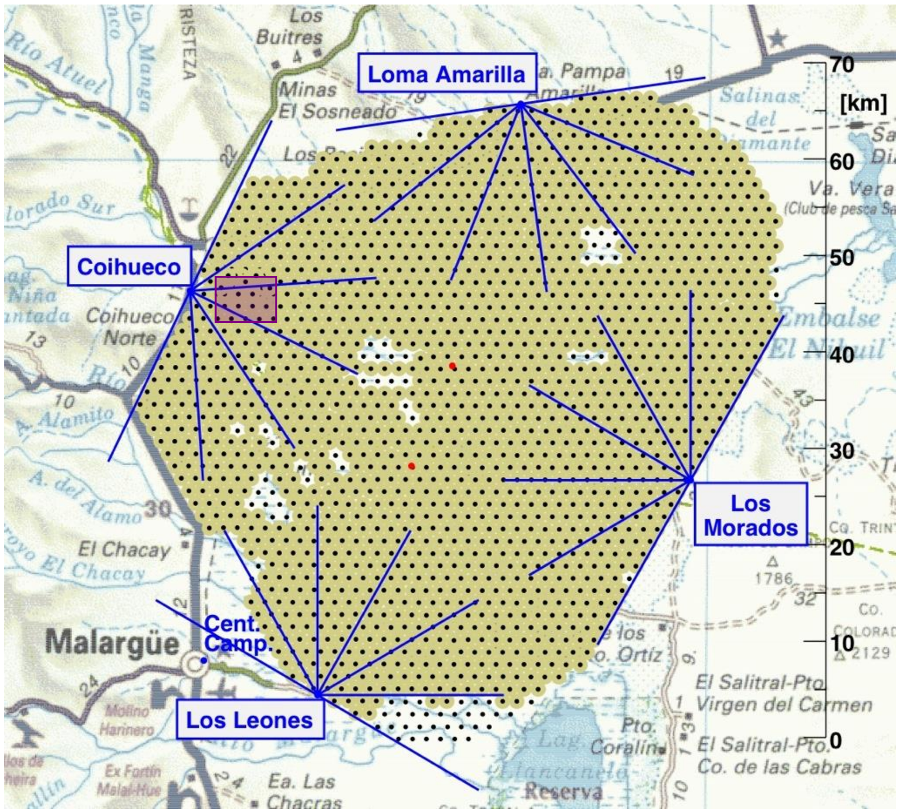
Anisotropy: TA "Hotspot"

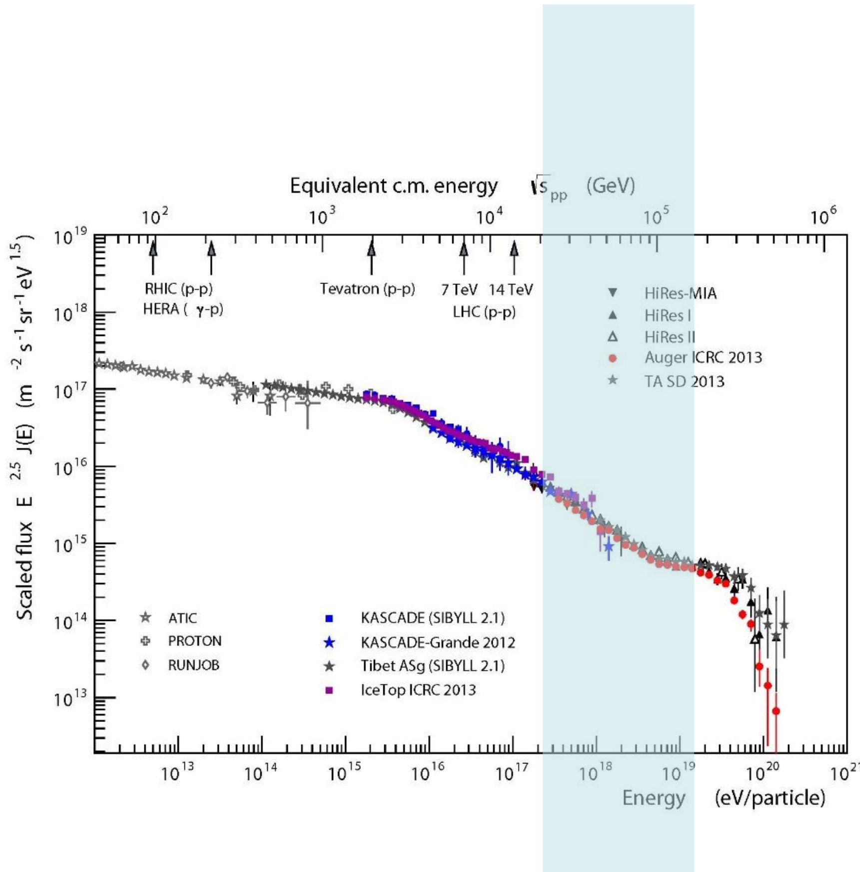
- There is a cluster of just south of the supergalactic plane, "the hotspot". Plot uses oversampling, r = 20°.
- **5-year SD data:** 72 ev. > 57 EeV, 19 corr. (expect 4.5)
- 26% of events in 6% of sky.
- Li-Ma significance = 5.1σ
- Chance probability = 3.6σ (3.4σ with correction)



Ap.J. **790**, L21 (2014)

Auger Enhancements: investigating the ankle

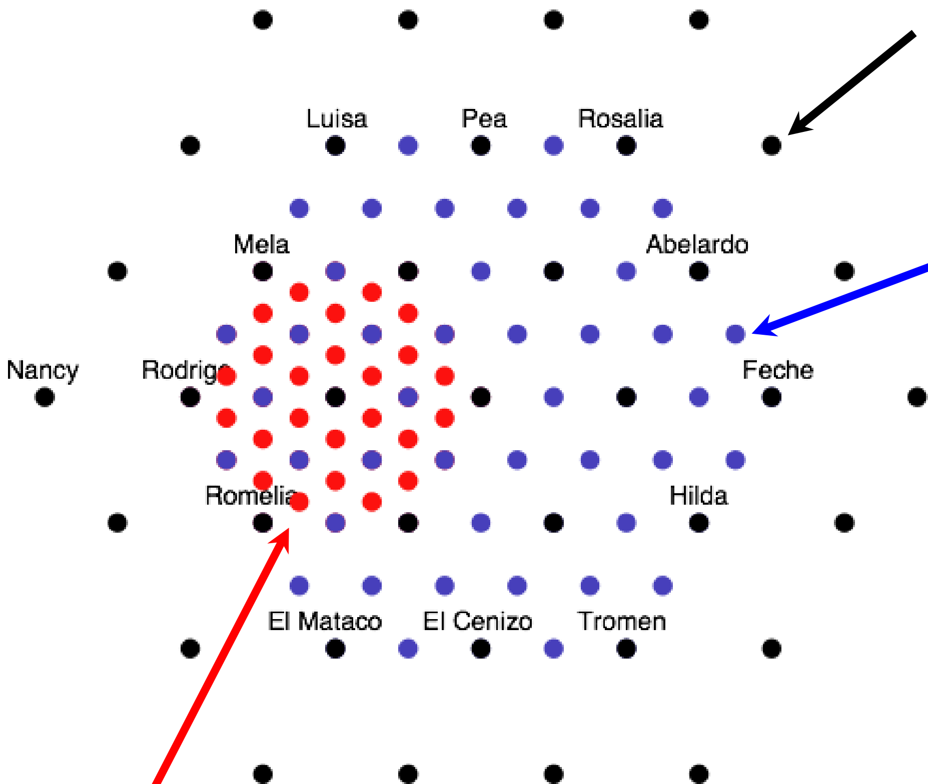




AMIGA
HEAT
AERA

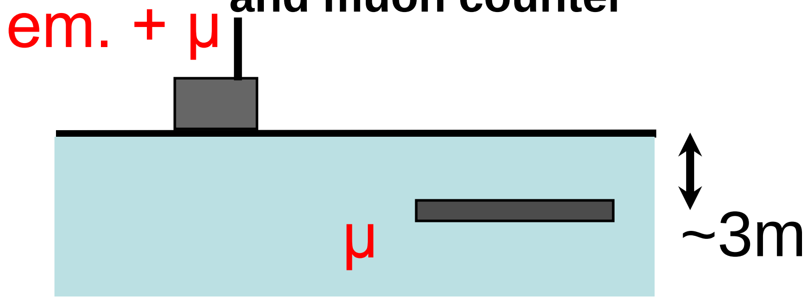
AMIGA: Auger Muons and Infill for the Ground Array

Existing tank array 1500m



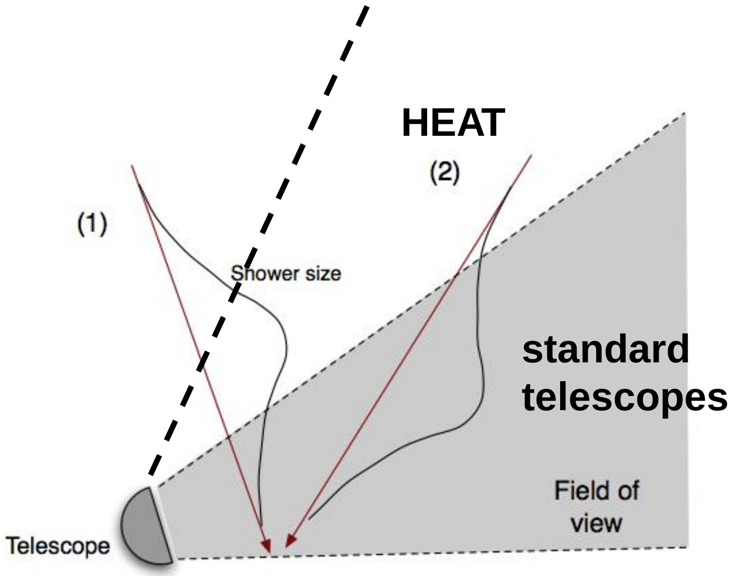
Infill array 750m
42 additional detectors
Area ~ 23.5 km^2
(first spectrum will be published soon)

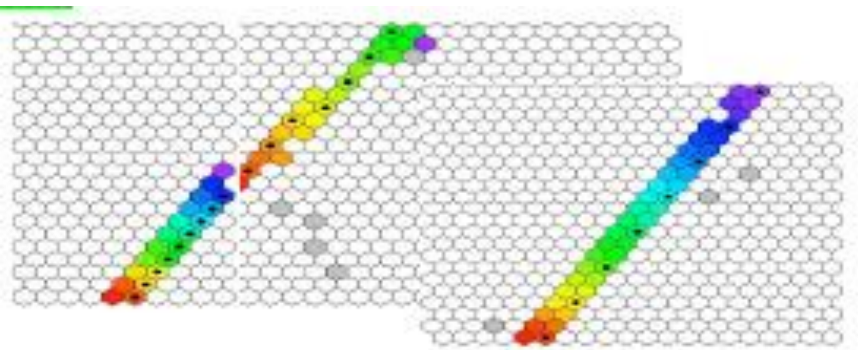
Each of the 85 detectors:
pair of Cherenkov tank and muon counter



Infill array 433m
24 additional detectors
Area ~ 5.9 km^2

HEAT: High Elevation Auger Telescopes



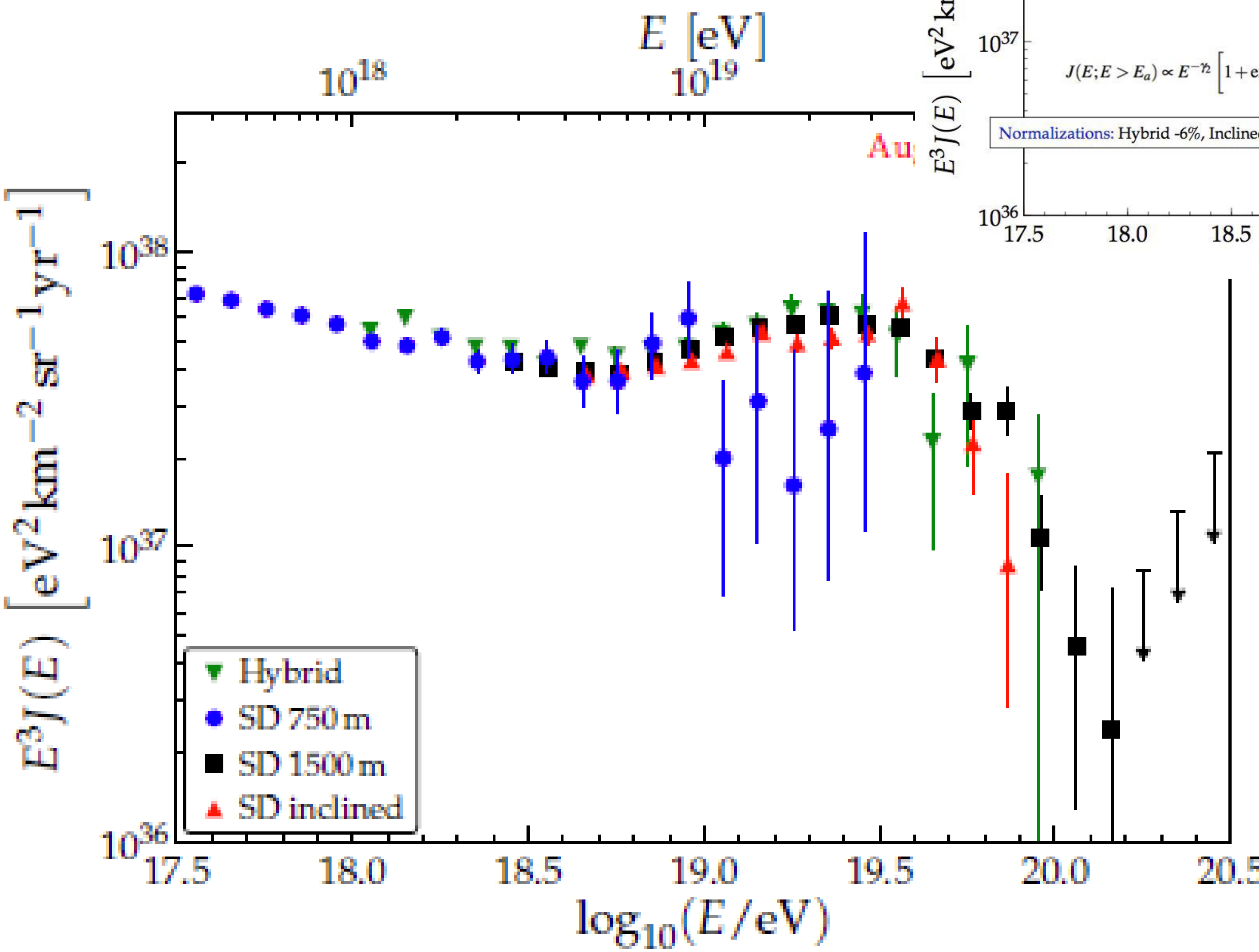


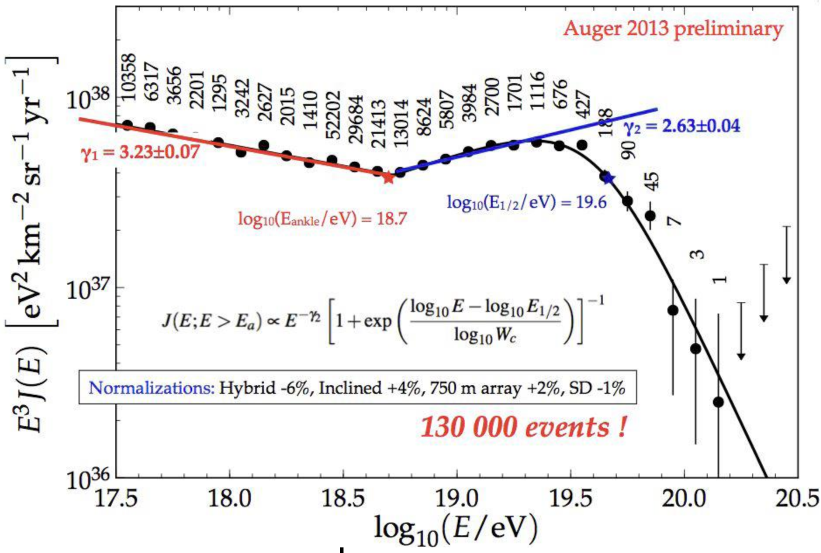
- **3 ``standard´´ Auger telescopes tilted to cover 30 - 60° elevation**
- **Custom-made metal enclosures**
- **Also prototype study for next generation experiment**

Telescopes in operation!
(Spectrum/composition will be published soon)

Karlsruhe Institute of Technology

Combined spectrum: first result from Enhancements





AERA: Auger Engineering Radio Array

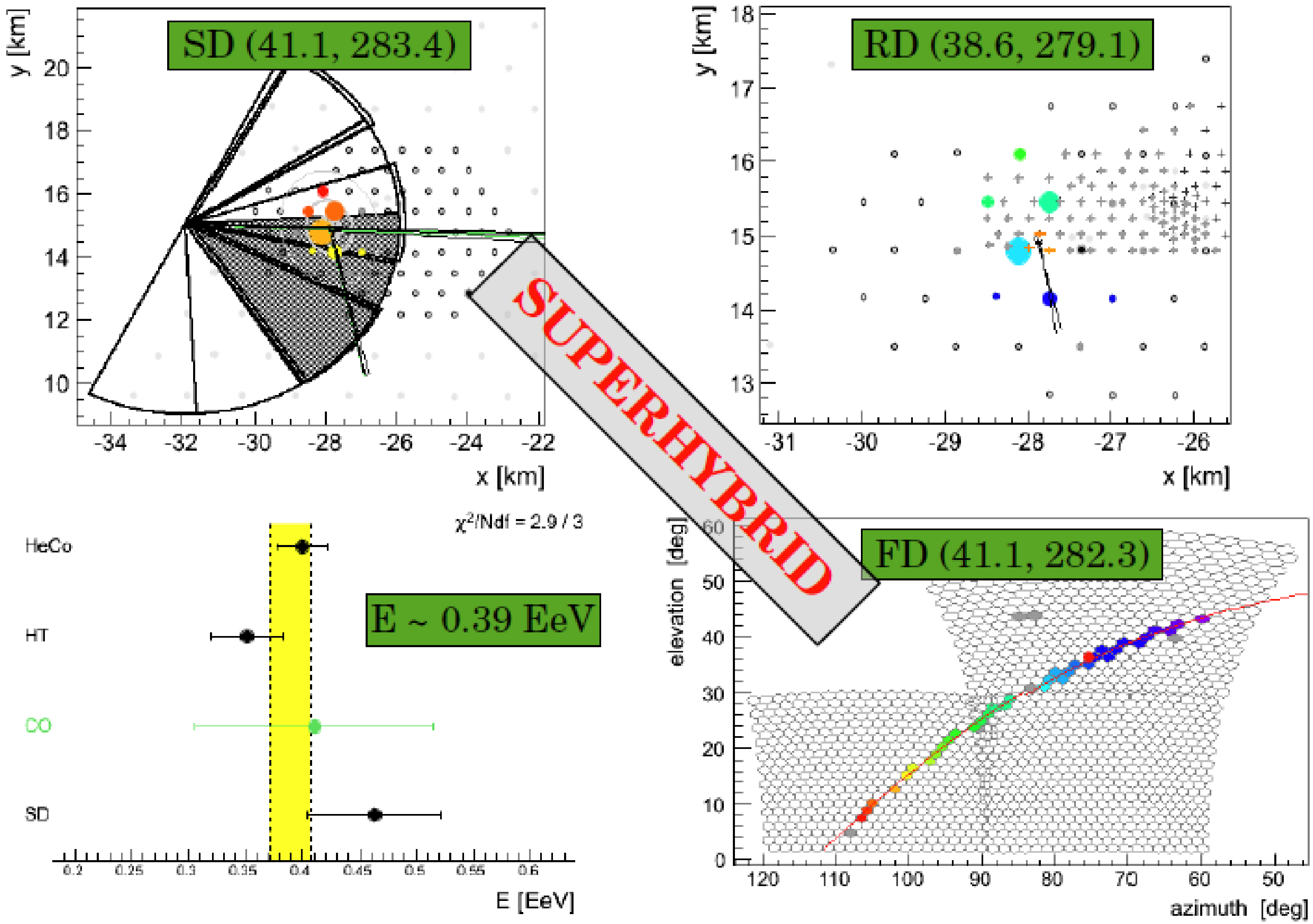
Aims:

- **Establish radio detection technique**
- **Establish test self-trigger concepts for $E > 5 \times 10^{17}$ eV**
- **Calibrate radio signal**
- **Investigation of transition from galactic to extragalactic CR**

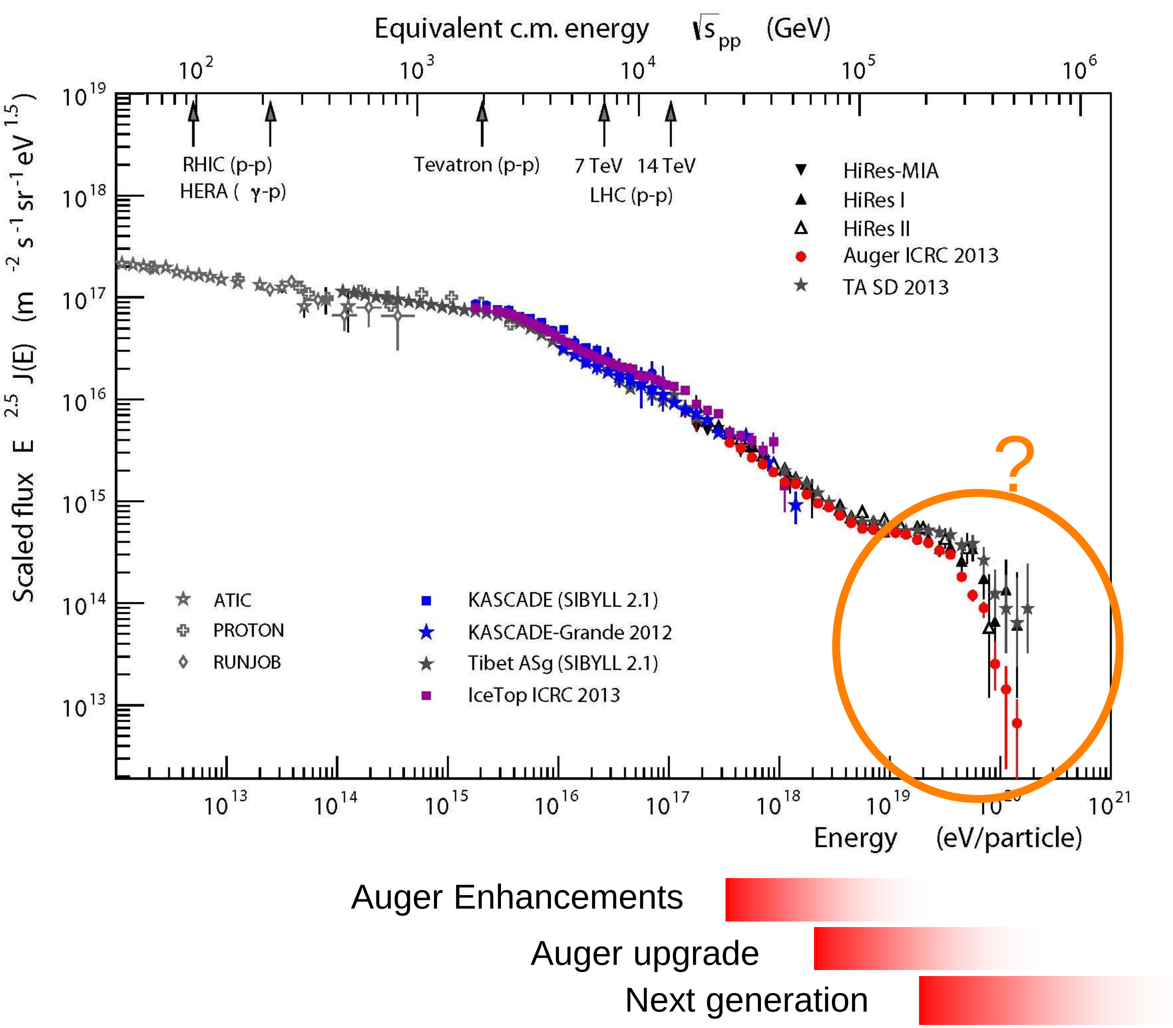
Plan:

- **Array of >10 km^2**
- **30 - 80 MHz**
- **200 Ms/s**
- **25 antennas since spring 2010**
- **100 antennas early 2013**
- **25 antennas early 2015**

AERA: Auger Engineering Radio Array
"Superhybrid events"



Go for highest energies
with larger statistics and better mass sensitivity



Auger results

- **Suppression of flux (like GZK effect)**
- **Anisotropy E > 6x10^{19} eV**
- **Mixed cosmic ray composition at lower energy**
- **Trend to heavy composition >10^{19}eV**
- **Problems with hadronic interaction models**
- **Photon fraction small**
- **Neutrino flux low**

Auger upgrade - rational

Enhancing the surface detector array for better em/mu separation will boost the science of Auger

- ➙ factor of ~10 in statistics for composition measurements
- ➙ GZK vs maximum energy
- ➙ allow p-astronomy (composition enhanced anisotropy)
- ➙ learn about global features of hadronic interactions at $\sqrt{s} > 70$ TeV
- ➙ decisive prediction of UHE (cosmogenic) ν-fluxes
- ➙ decisive for next generation UHECR Experiments

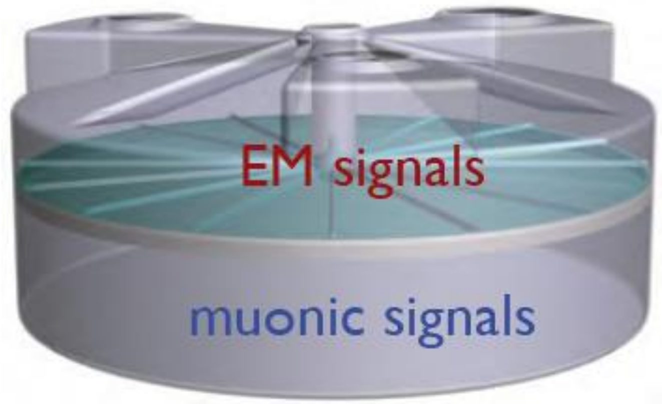
Auger is the only experiment in place to address all these questions for at least the next decade

Karl-Heinz Kampert, spokesperson of the Pierre Auger Observatory

Auger beyond 2015 (the upgrade) to improve mass sensitivity above 10^{19} eV

1) New Electronics for Surface Detector (design ready)
2) Enhanced Muon Detection in Surface Detector Array

Different realizations under test in the field.



Selection will be done end 2014
based on performance, reliability, readiness, cost, risk

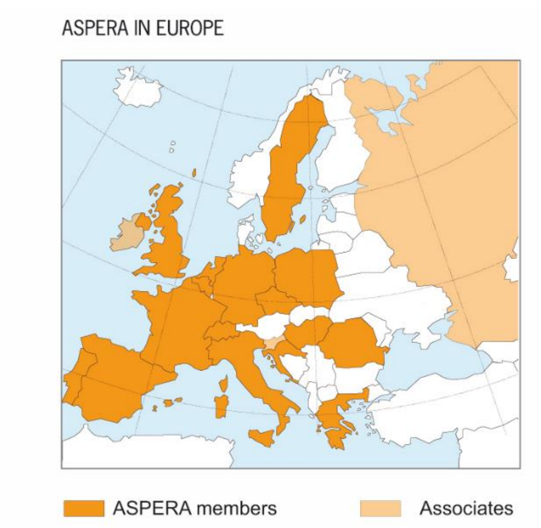
ASPERA

www.aspera-eu.org

AStroParticle ERAnet

ASPERA is a network of national government agencies responsible for Astroparticle Physics

- BMBF, DESY/PT
- CNRS, CEA
- FRS-FNRS, FWO
- HRZZ
- MEYS, FZU
- DEMOKRITOS
- INFN
- FOM
- NCBiR
- FCT
- IFIN-HH
- MICINN
- VR
- SNF
- STFC
- NIH
- CERN
- ARRS
- RIA
- RFBR



The ASPERA calls:

- Targeted R&D and design studies in view of the realization of future Astroparticle infrastructures

- 2nd call was targeted towards future high energy cosmic rays and neutrino mass experiments. (first call: high energy gamma rays and dark matter)

➔ **AugerNext**
Innovative Research Studies for the Next Generation Ground-Based Ultra-High Energy Cosmic-Ray Experiment

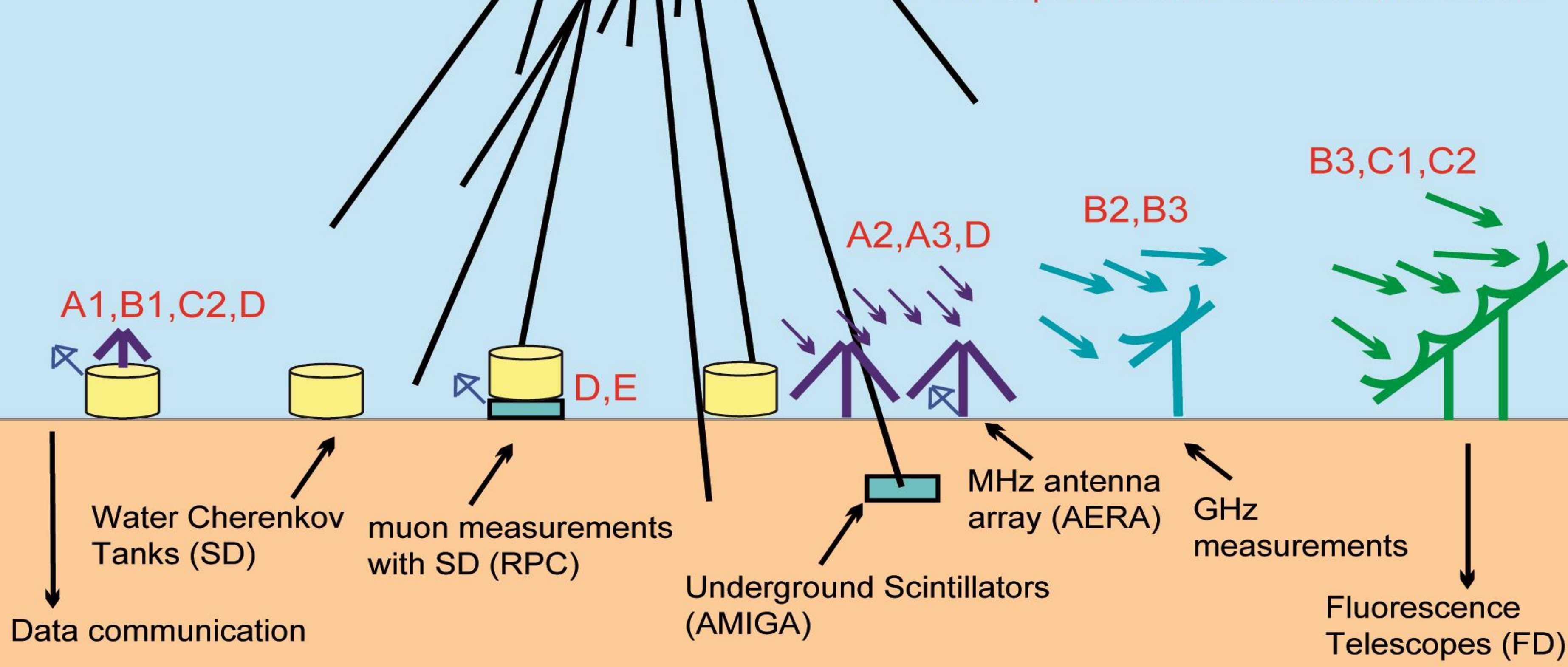
Proposal of the ASPERA Pierre-Auger-Consortium:

Project Coordinator:
Andreas Haungs, KIT– Helmholtz Sector, IK, Karlsruhe, Germany
Co-applicants:
Johannes Blümer, KIT–University Sector, IEKP, Karlsruhe, Germany
Martin Erdmann, RWTH Aachen, Germany
Karl-Heinz Kampert, University of Wuppertal, Germany
Ad van den Berg, KVI Groningen, The Netherlands
Zbigniew Szadkowski, University of Lodz, Poland
Henryk Wilczynski, INP PAN, Cracow, Poland
Antoine Letessier-Selvon, IN2P3/CNRS , France
Mario Pimenta, LIP-LIsabon, Portugal
Enrique Zas, Univ Santiago de Compostela - USC, Spain
Valerio Verzi, INFN Roma Tor Vergata, Italy
Iliana Brancus, IFIN-HH Bucharest, Romania
Associated Partners:
Masahiro Teshima, MPI Physik, München, Germany
Martina Bohacova, FZU, Prague, Czech Republic

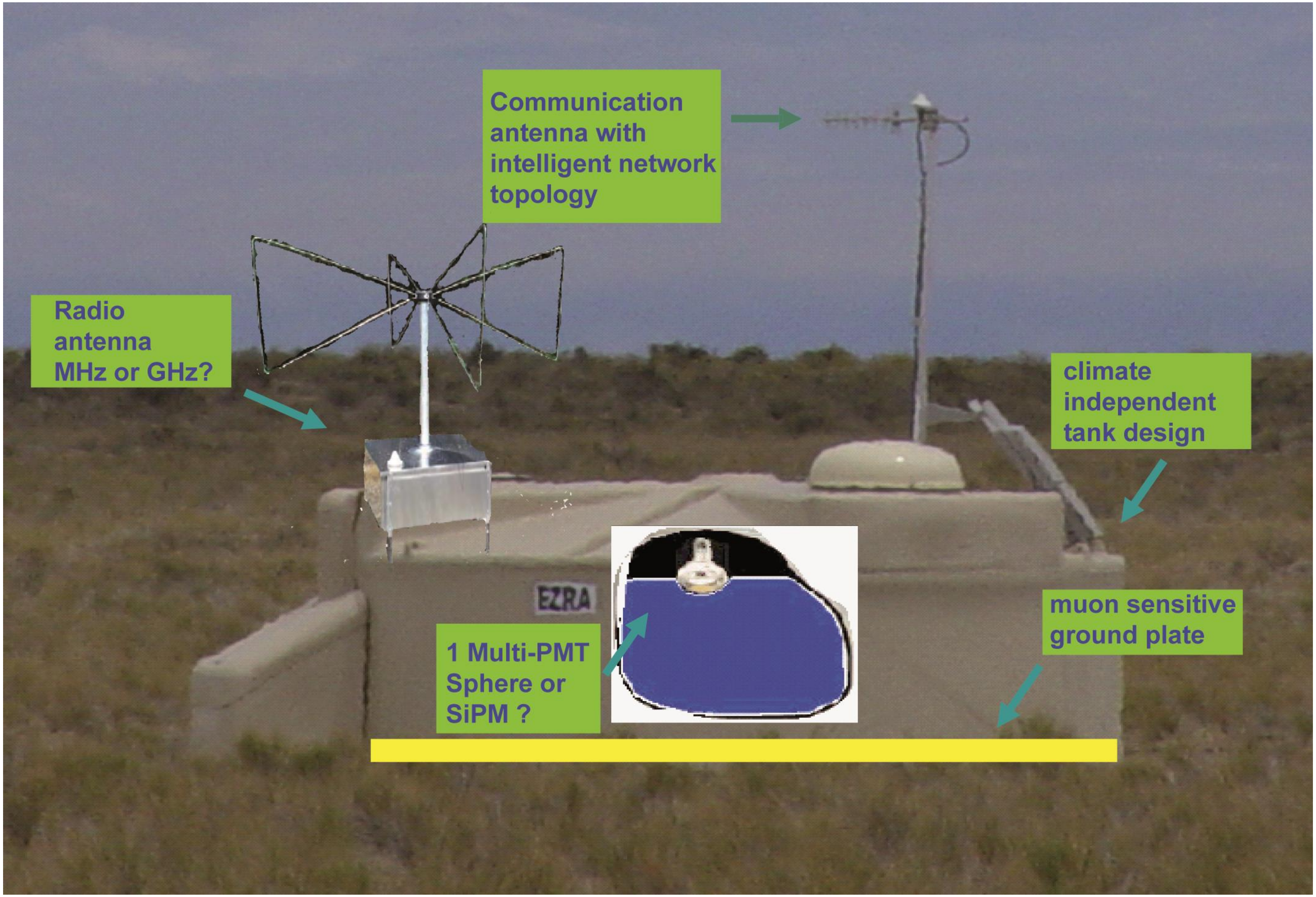
The work packages:

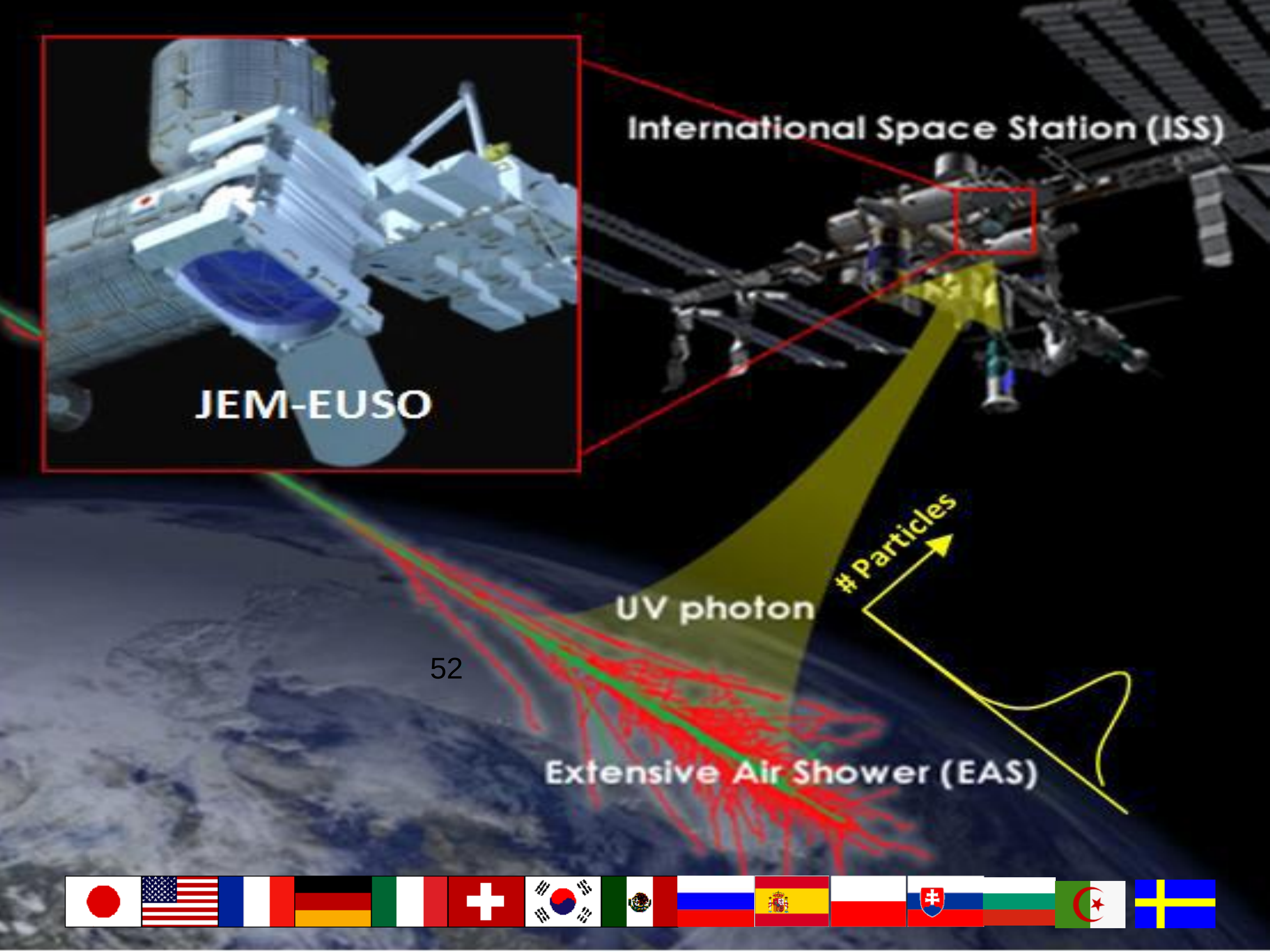
Tasks in ASPERA:

A: Improvement of MHz measurements
B: Measurement of GHz emission
C: Improvement of Photodetection
D: Improvement of data communication
E: Improvement of muon measurements

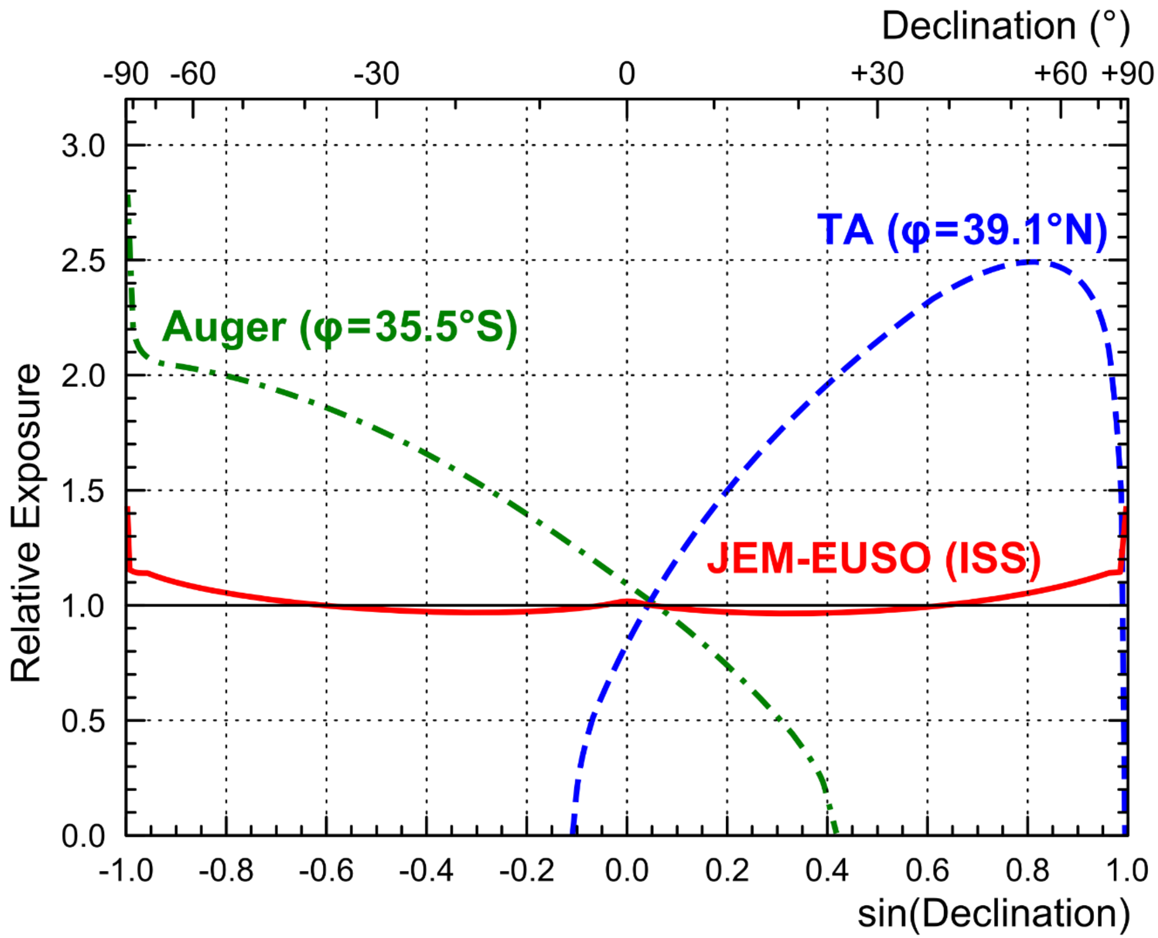


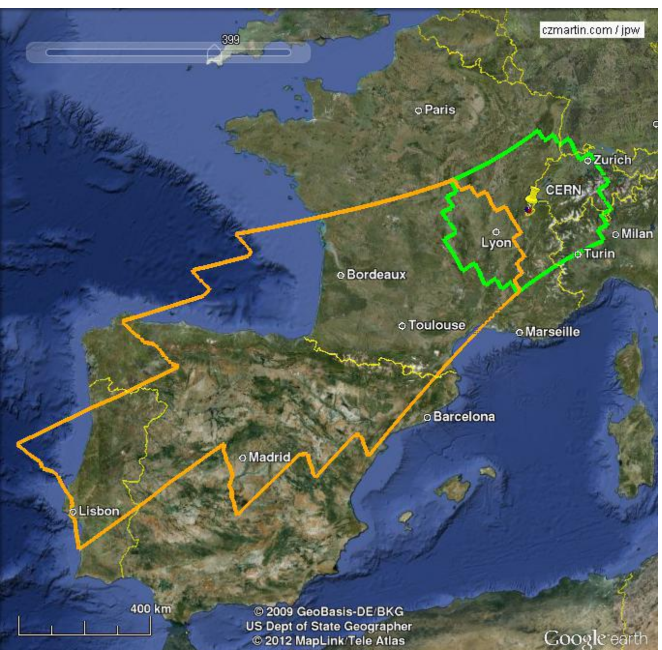
Future (next generation) surface detector:




International Space Station (ISS)
JEM-EUSO
#Particles
UV photon
Extensive Air Shower (EAS)

JEM-EUSO: aperture





- **Uniform coverage of both hemispheres!**

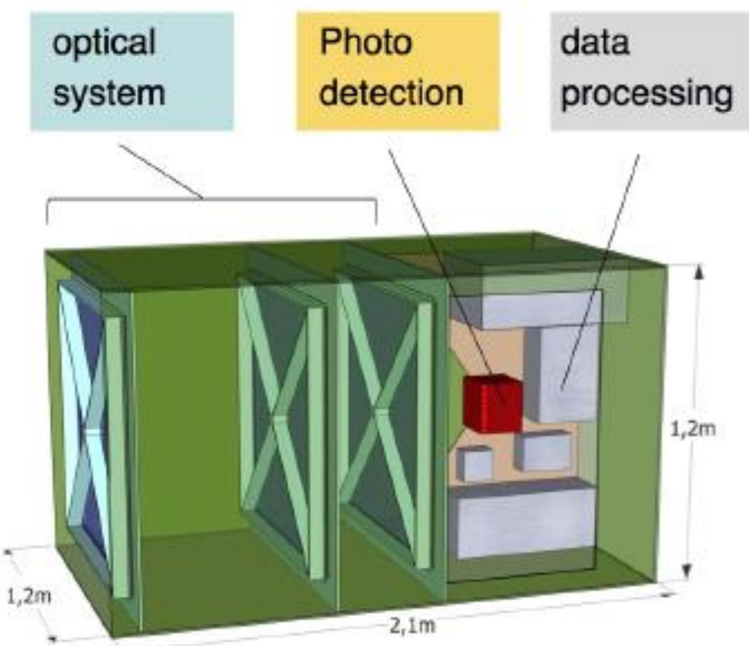
EUSO-Balloon
JEM-EUSO prototype at 40km altitude

Main purpose: Background measurements and engineering tests

- **Engineering test**
- **UV-Background measurement**
- **Air shower observations from 40 km altitude**

CENTRE NATIONAL D'ETUDES SPATIALES

First flight: 2014!

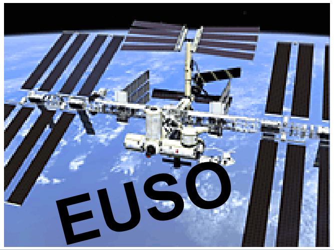


EUSO-Balloon

First flight Timmins, Canada: 25th August 2014

- **c. 5h data available**
- **incl. IR camera and laser (helicopter)**

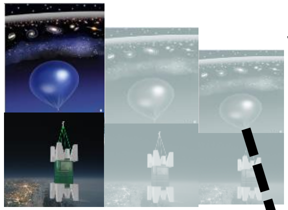
Air Shower Observations from Space



2014 2017 2024

2020 2024

TA-EUSO



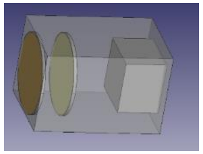
EUSO-Balloon

JEM-EUSO

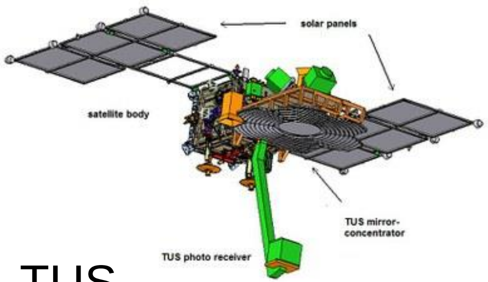
AO from NASA in 2014?

SiPM-PDM?

M4 mission
Free flyer?

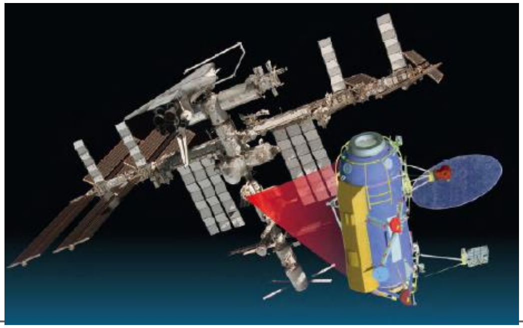


Mini-EUSO



TUS

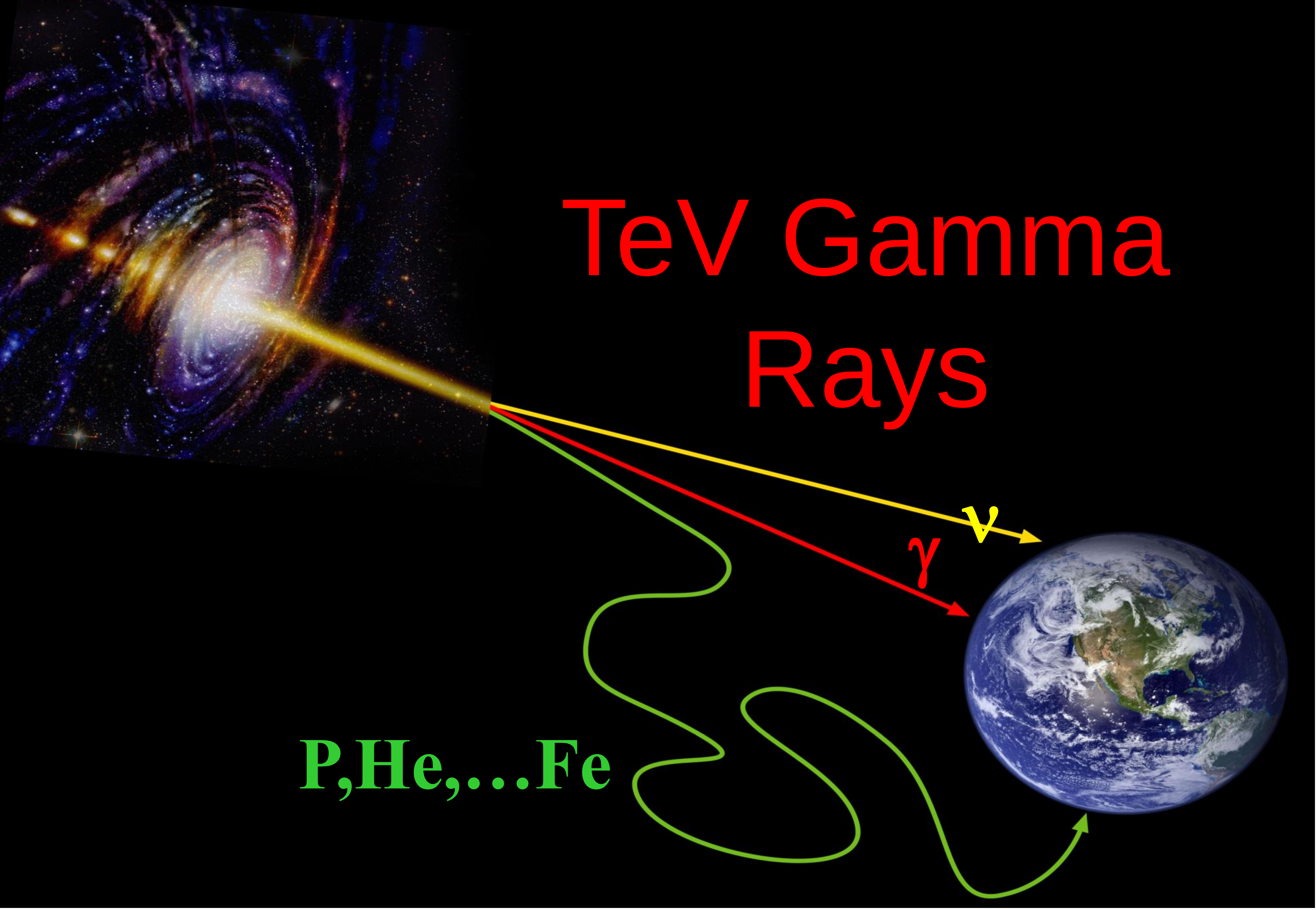
Collaboration with a Russian project, KLYPVE



“K-EUSO”

Karlsruhe Institute of Technology

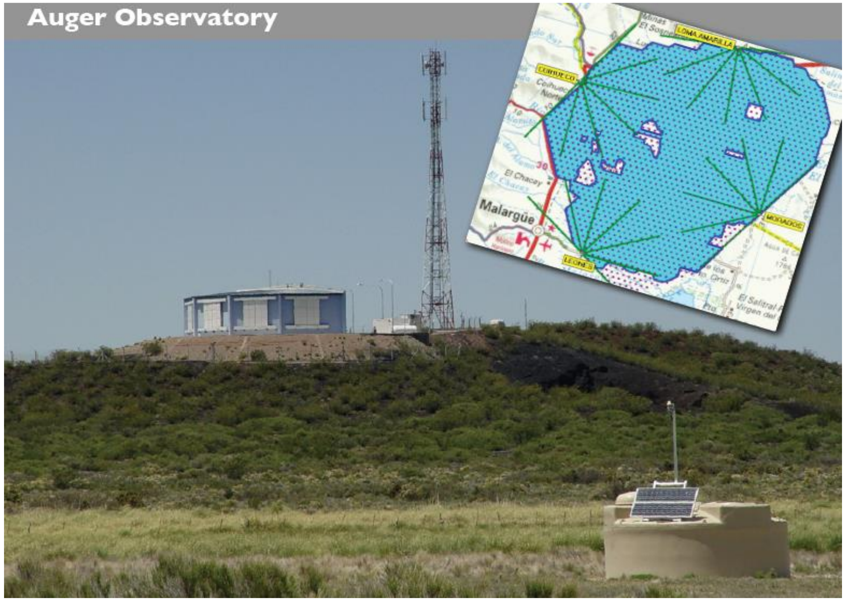
TeV Gamma Rays

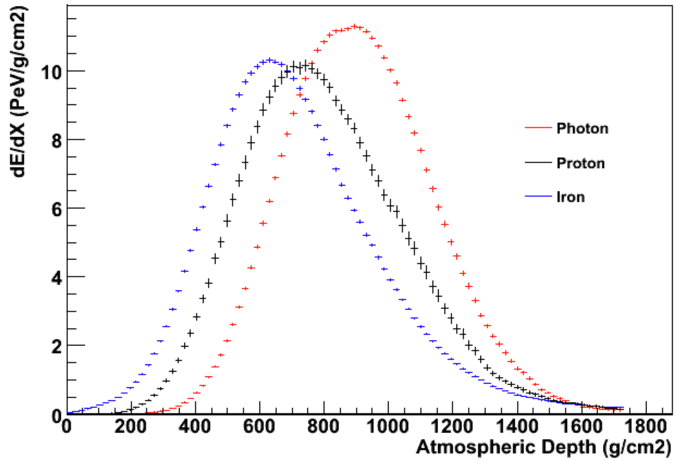


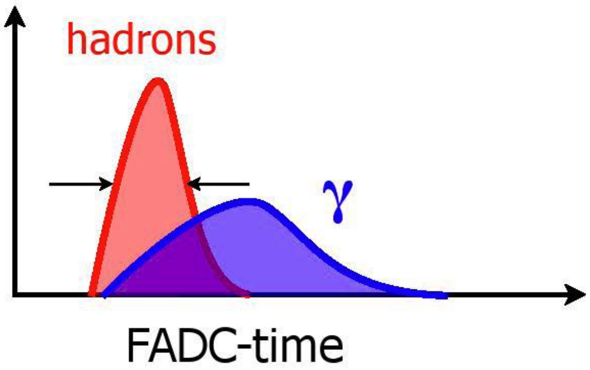
Photon search at the Pierre Auger Observatory
$E_\gamma = 10^{18}$-10^{20}eV

Photon inititated showers penetrate deeper in the atmosphere
➔higher X_{max} (FD)

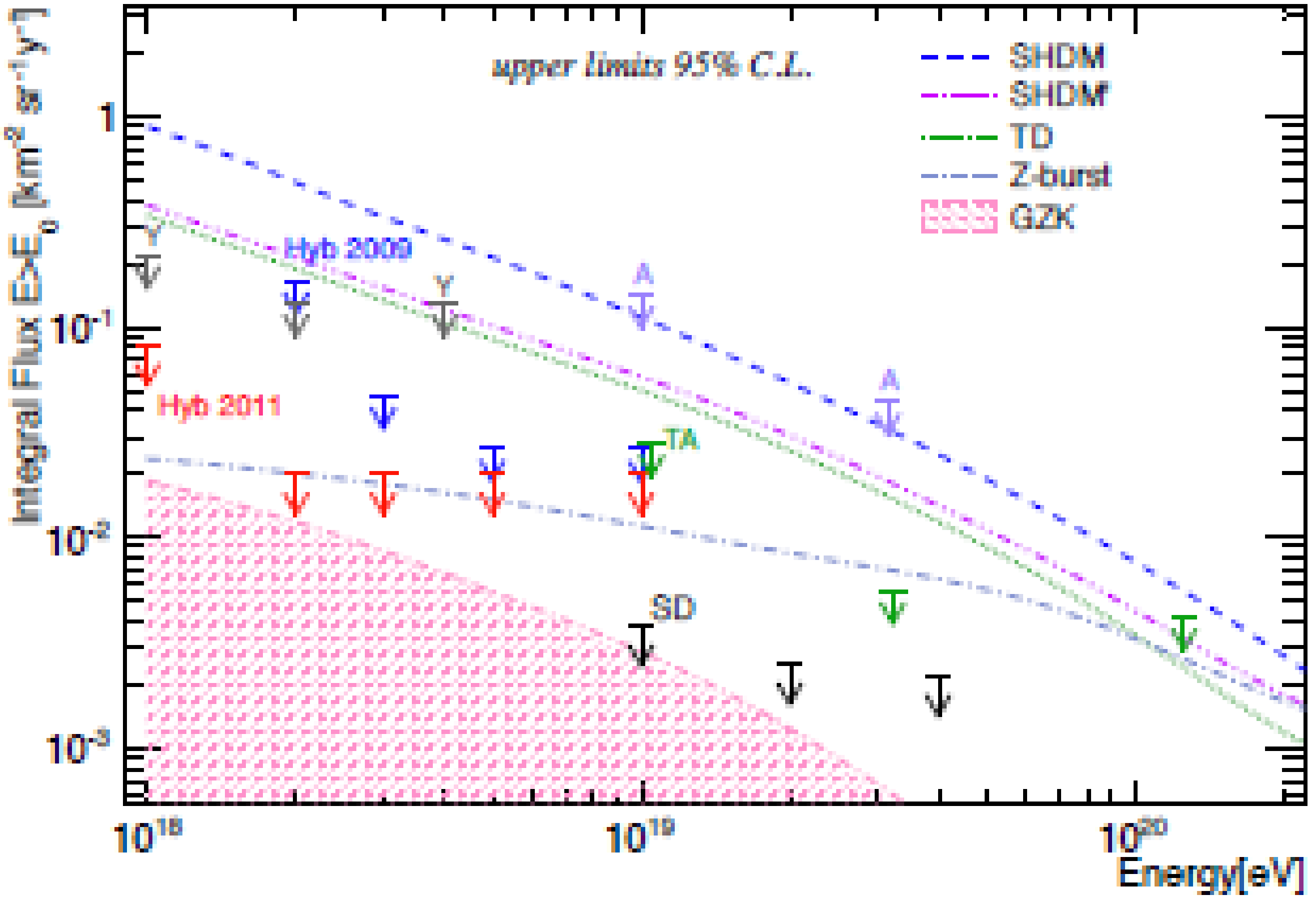
Photon inititated showers are pure electromagnetic EAS
➔less muons, different signal
➔shape in particle detector (SD)







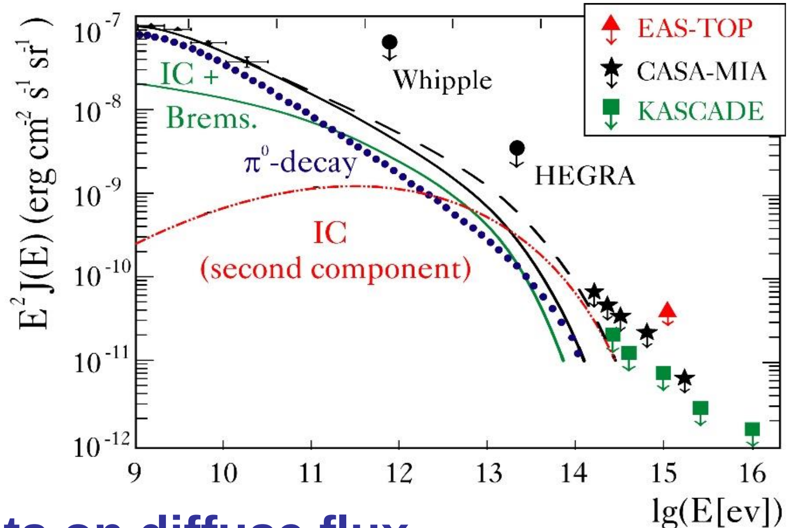
Limit on fraction of photons in UHECR flux



Astropart. Phys. 29 (2008) 243
Astropart. Phys. (2009) in press, arxiv 0903-1127

Many exotic source scenarios excluded

Photon-shower detection: Tibet AS\g – Argo – Grapes - …
$E_\gamma = 10^{13}$-10^{16}eV



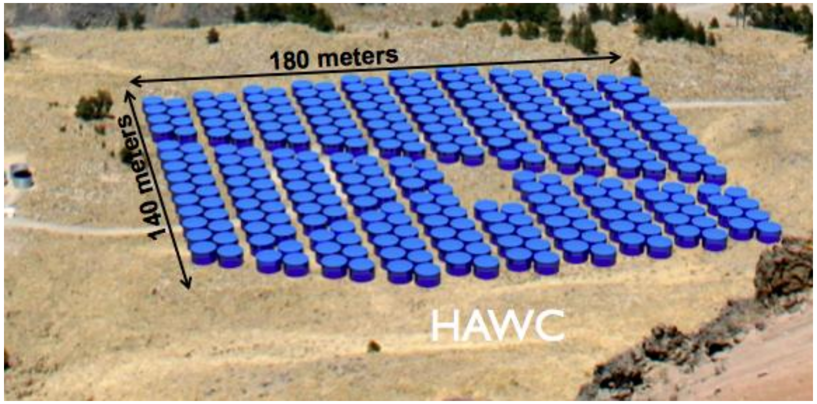
Limits on diffuse flux

Some point sources at low energies

shower detection: Milagro ➔ HAWC
$E_\gamma = 10^{12}$-10^{14}eV

Milagro was a first generation wide-field gamma-ray telescope:

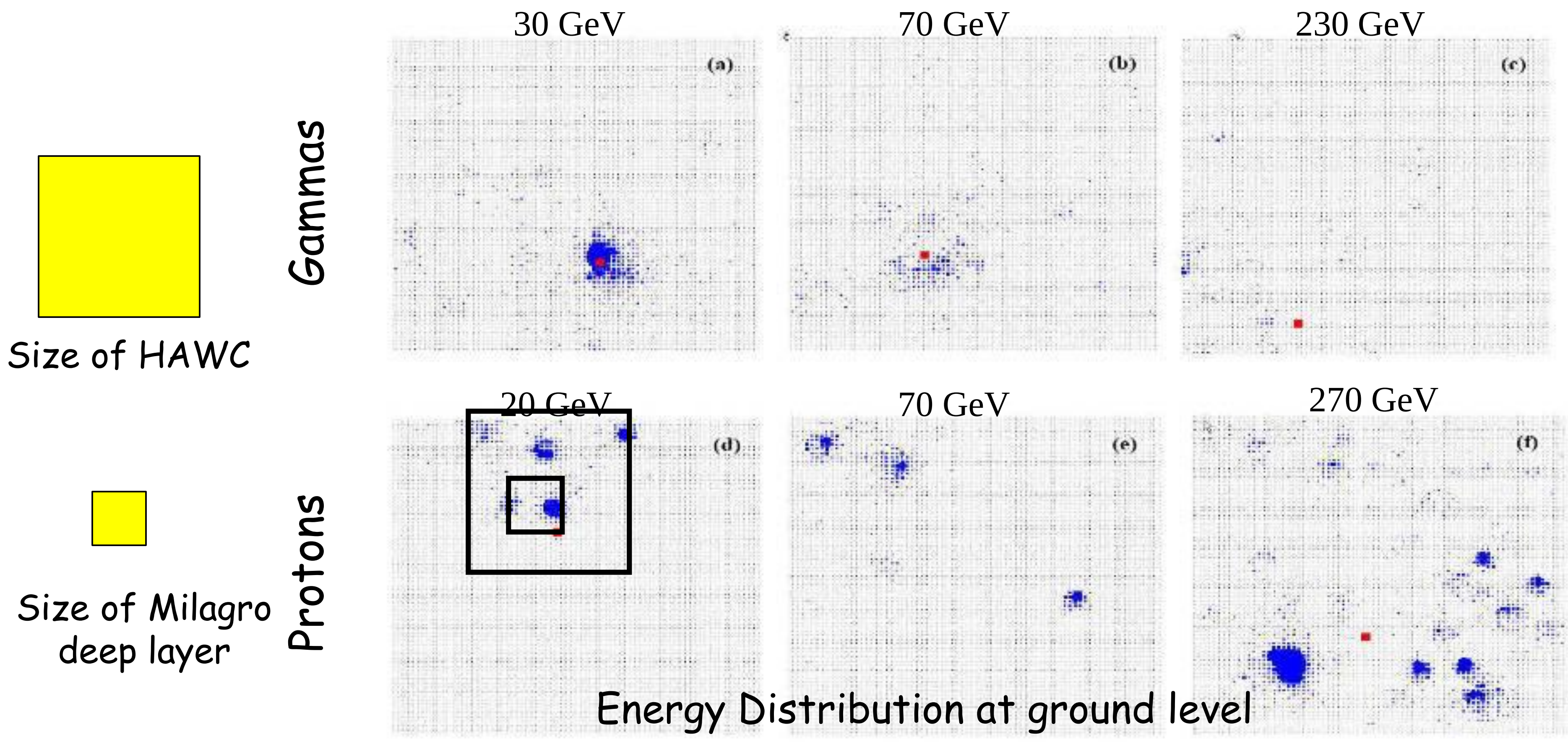
Discovered:
- more than a dozen TeV sources
- diffuse TeV emission from the Galactic plane
- a surprising directional excess of cosmic rays



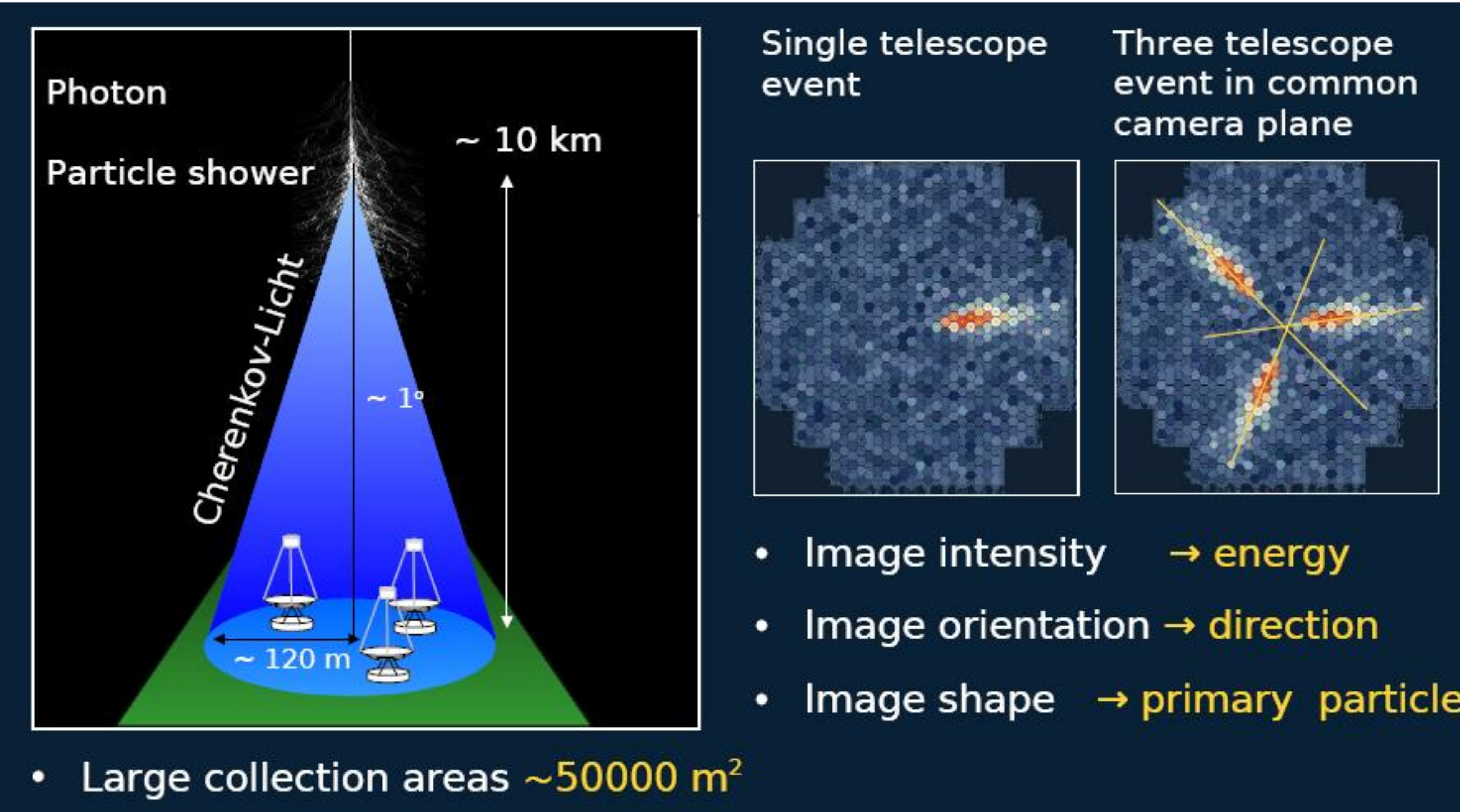
HAWC will use what we have learned from Milagro

HAWC will:
- extend the reach of IACTs to ~100 TeV
- point to the sources of cosmic rays
- be the best instrument to study short GRBs and prompt emission at 100s of GeV

Gamma/Hadron Separation



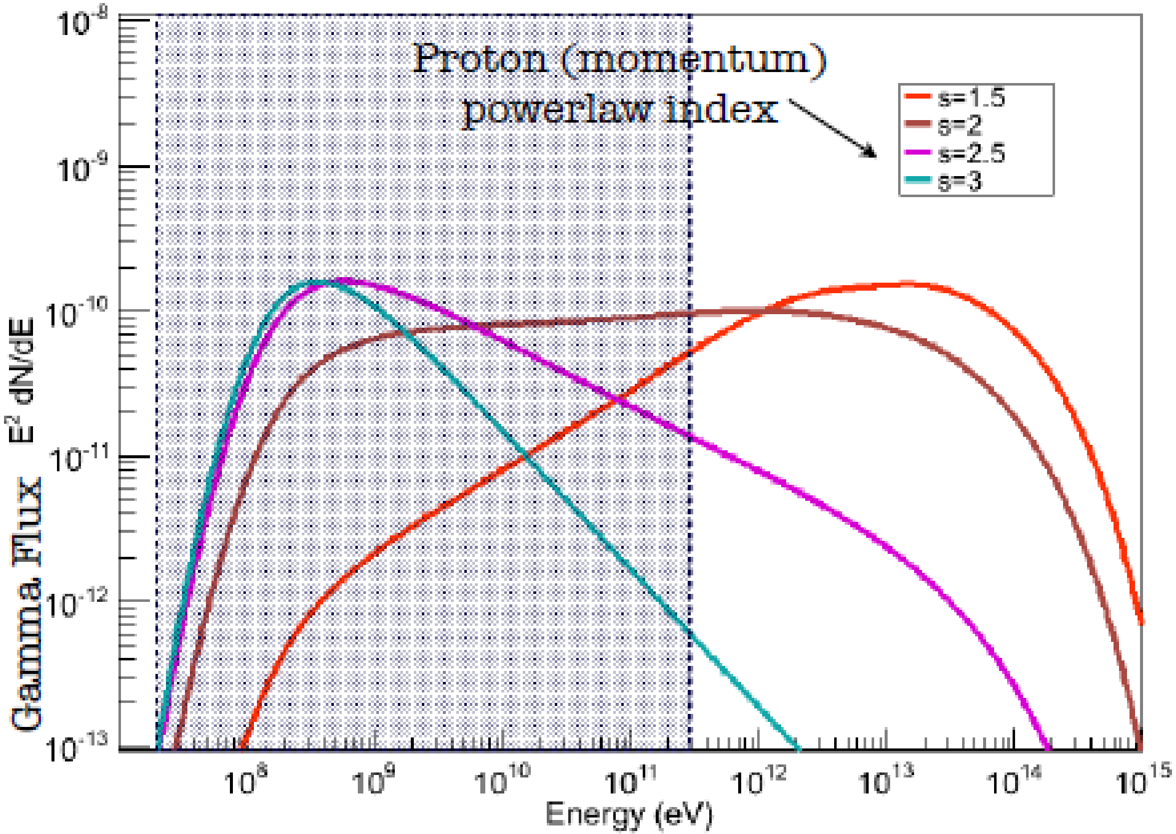
TeV – γ-rays: detection principle of Imaging Air-Cherenkov Telescopes



TeV – γ-ray astronomy
nowadays telescopes

Synergy of Cosmic-rays - Gamma-rays

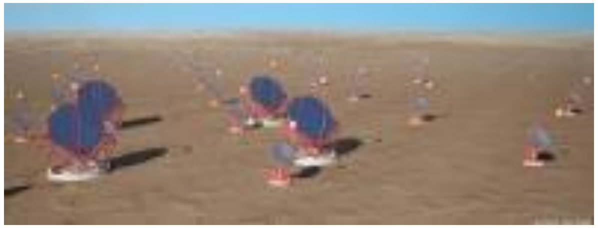
- **Do shell-type SNR accelerate protons? (via π^0-decay!)**
- **To which energy? (up to 10^{15}eV?)**
- **Distinguishable from electron acceleration?**



Stefan Funk, TAUP 2013, Asilomar, CA, US

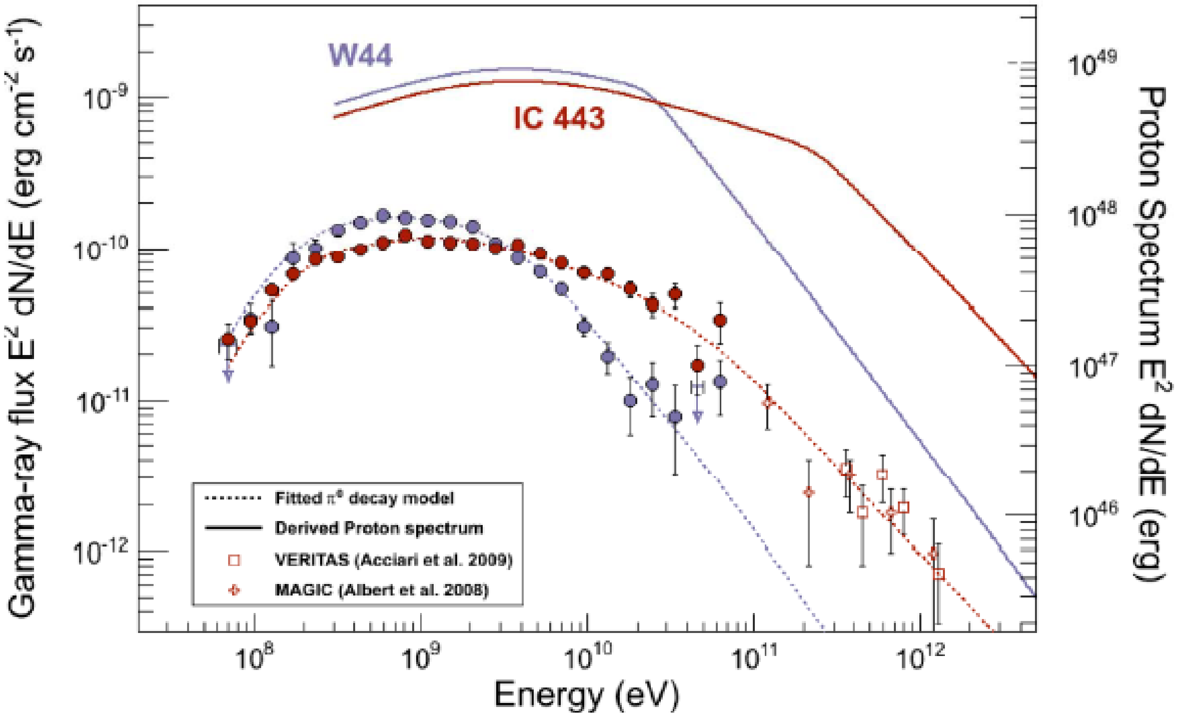
Expected gamma flux (π^0 –bump) for different proton injections

- **Fermi-Lat**
- **TeV γ-ray Cherenkov**



Gamma-ray astronomy: Fermi

- IC 443 and W44 are the two brightest SNRs in the Fermi-LAT range



Measured gamma-rays and calculated proton spectrum

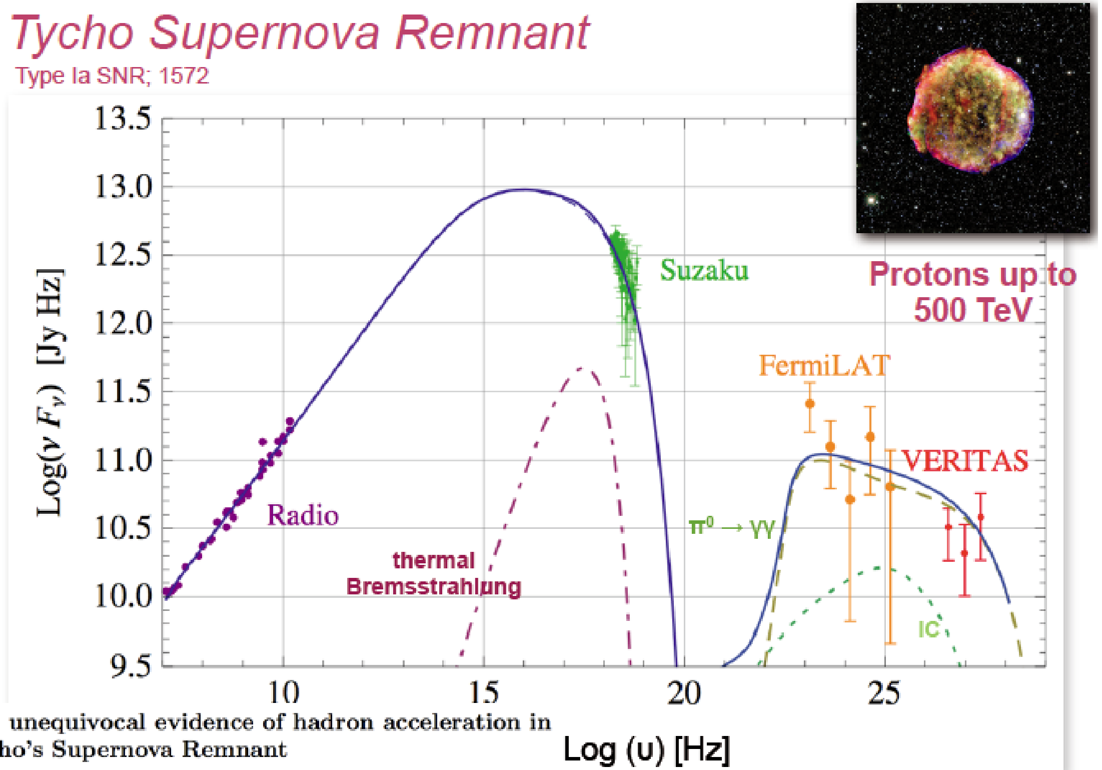
Proton acceleration yes
but only up to TeV?
🡐 Dependent on age of SNR?

Stefan Funk, TAUP 2013, Asilomar, CA, US

Gamma-ray astronomy: IACT

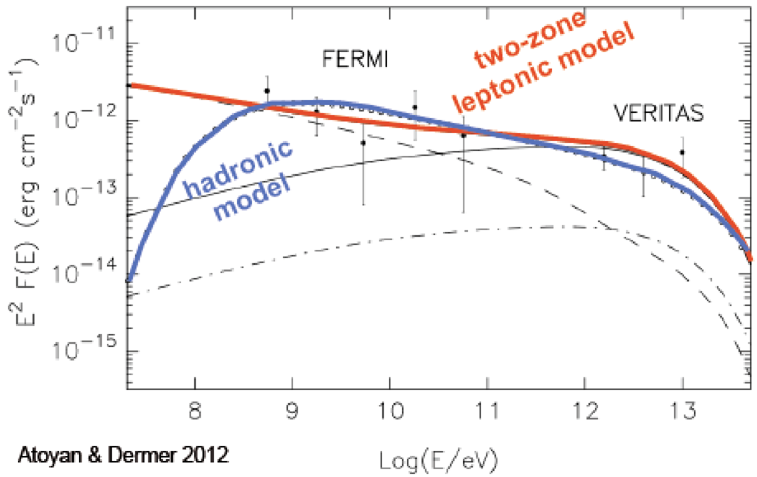
-problems: gas density for hadronic
magnetic fields for leptonic

Measurement also explainable by hadronic and leptonic models



The unequivocal evidence of hadron acceleration in Tycho's Supernova Remnant

G. Morlino[1*], D. Caprioli[1]†,
[1] INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5, 50125, Firenze, Italy

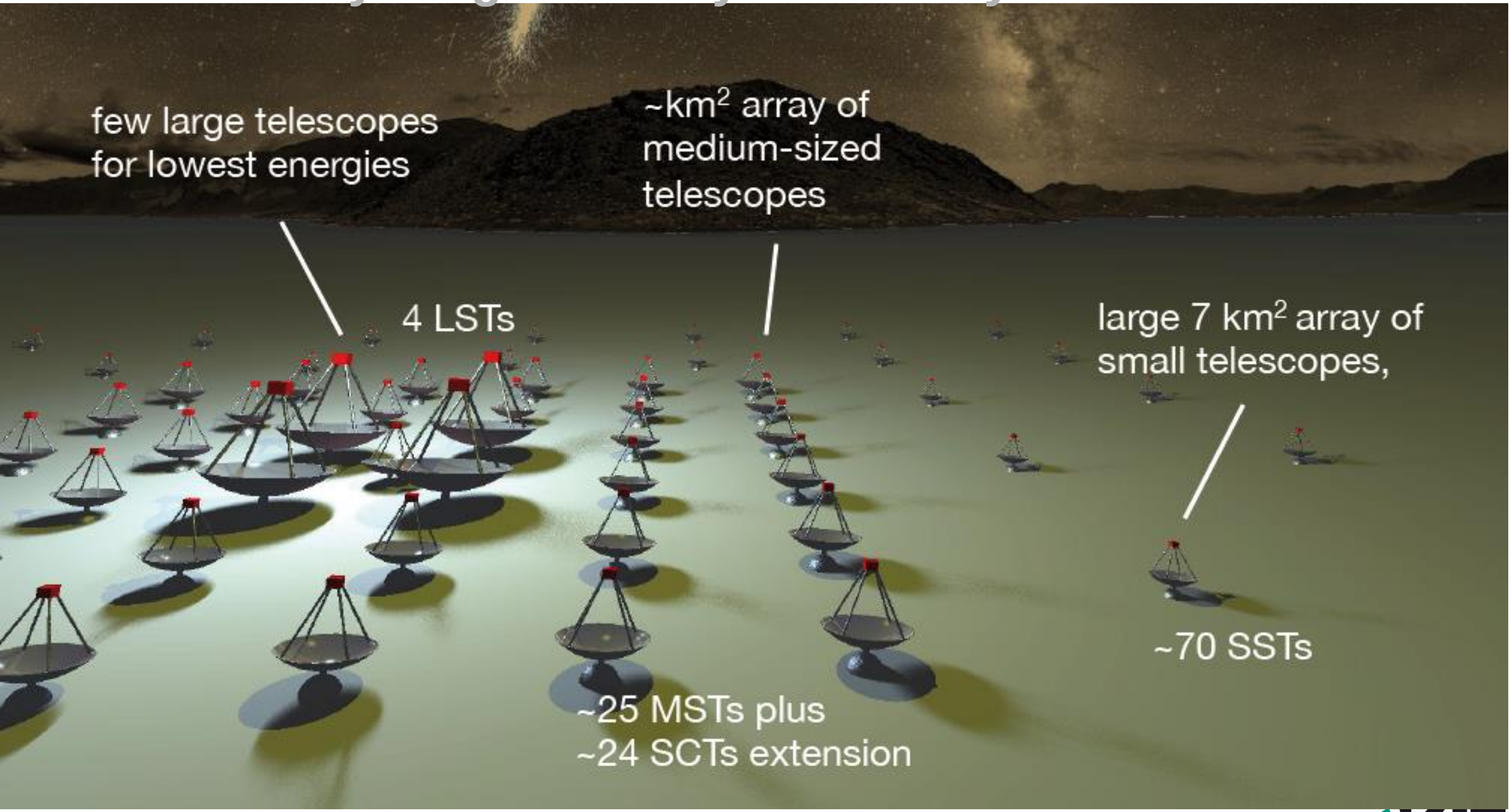


← Still no proof that SNR accelerate protons up to the knee, but also no exclusion….

Gernot Maier, TAUP 2013, Asilomar, CA, US

Cherenkov Telescope Array

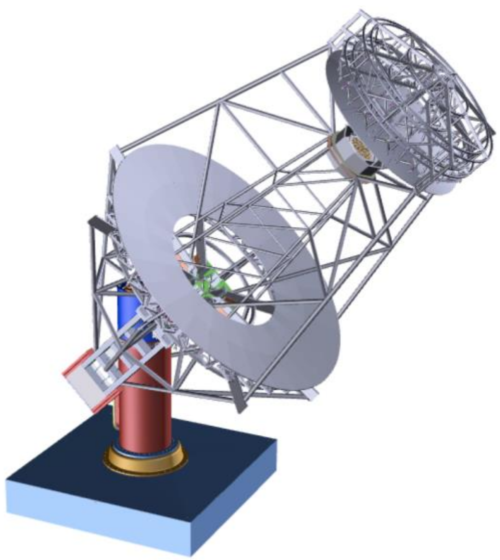
an observatory for gamma-ray astronomy in the next decade

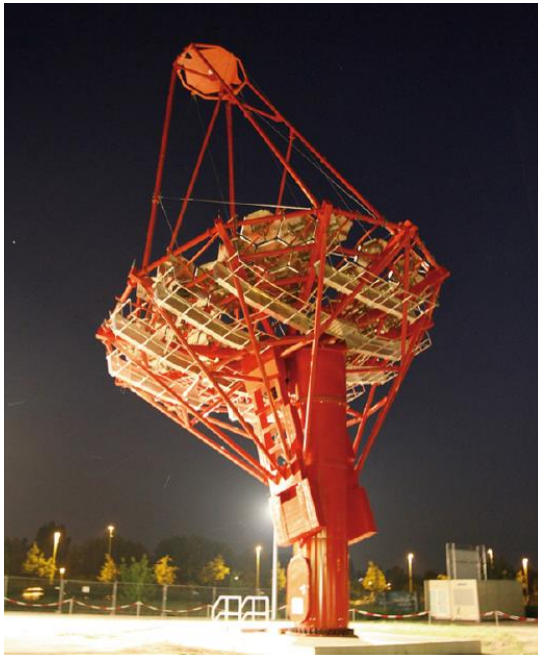


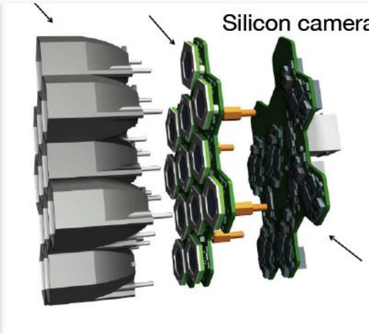
TeV – γ-ray astronomy: The future: CTA prototypes are existing; start of operation 2016-17?

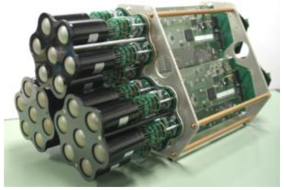
-- Larger sensitivity (x10)
– Lower threshold (few 10 GeV)
– Larger energy range (>PeV)
– Larger field of view
– Improved angular resolution
– Larger detection rates

- more sources
- Pulsars, distant AGN, source mechanisms
- Cut-off of galactic sources
- extended sources, surveys
- structure of extended sources
- transient phenomena

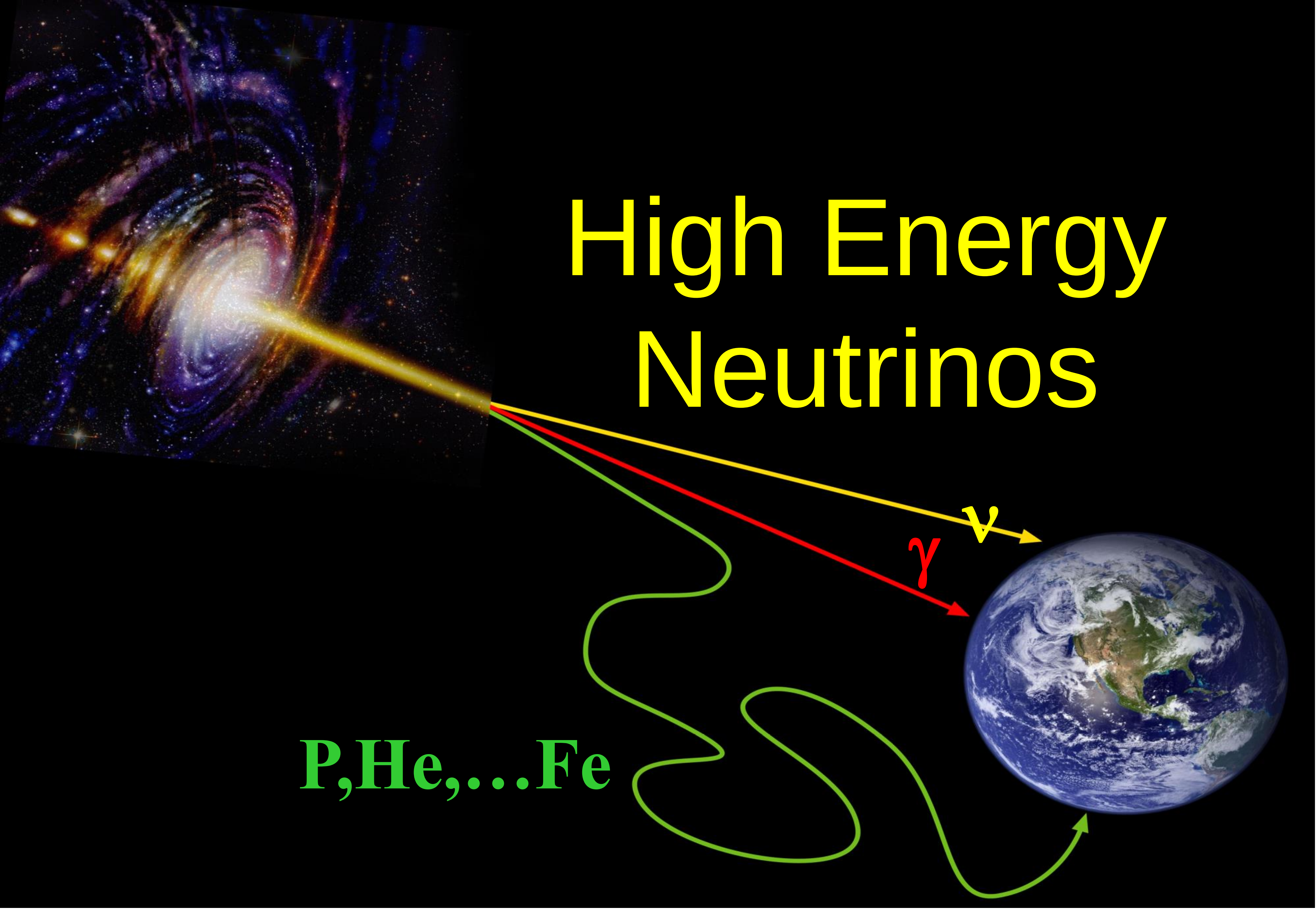




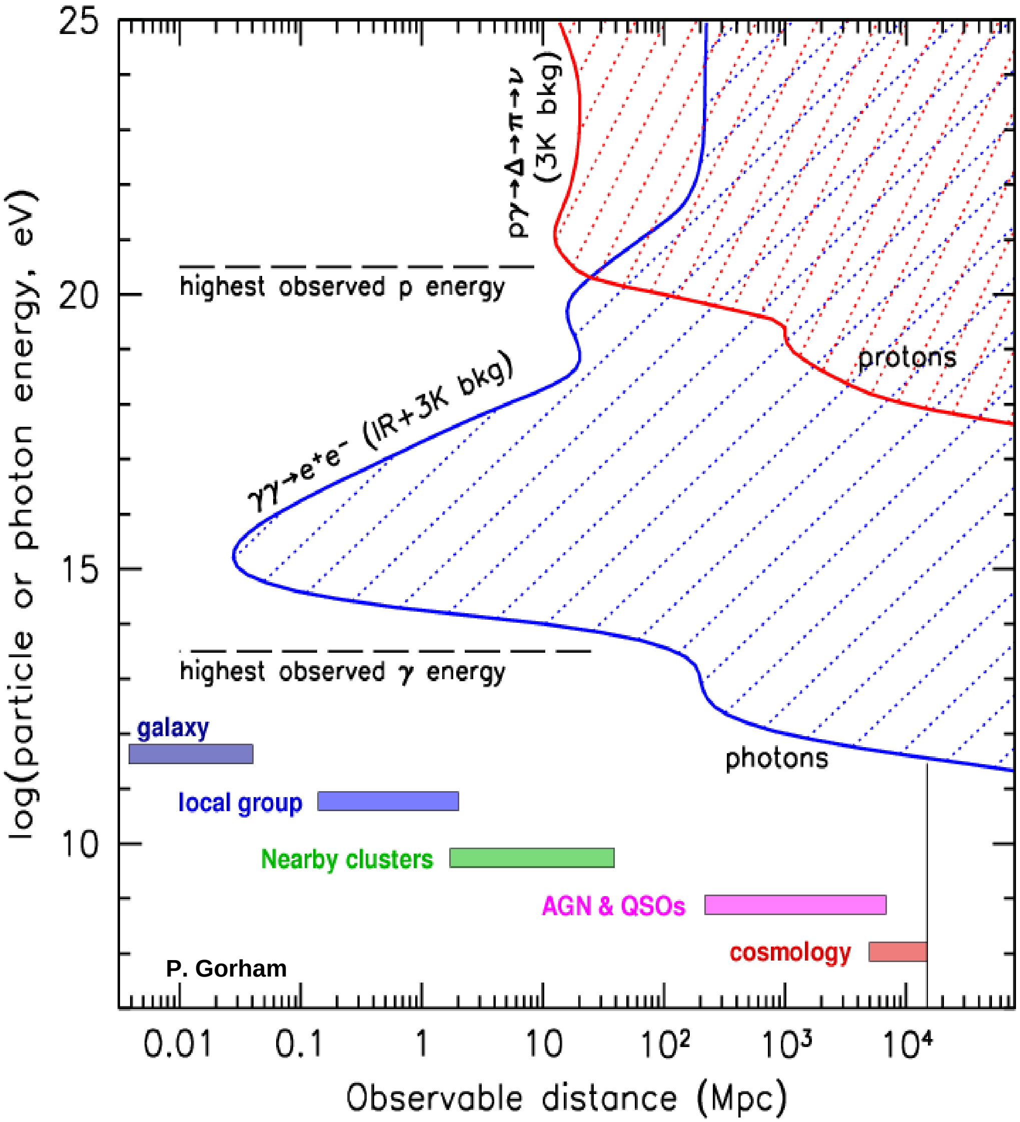




High Energy Neutrinos



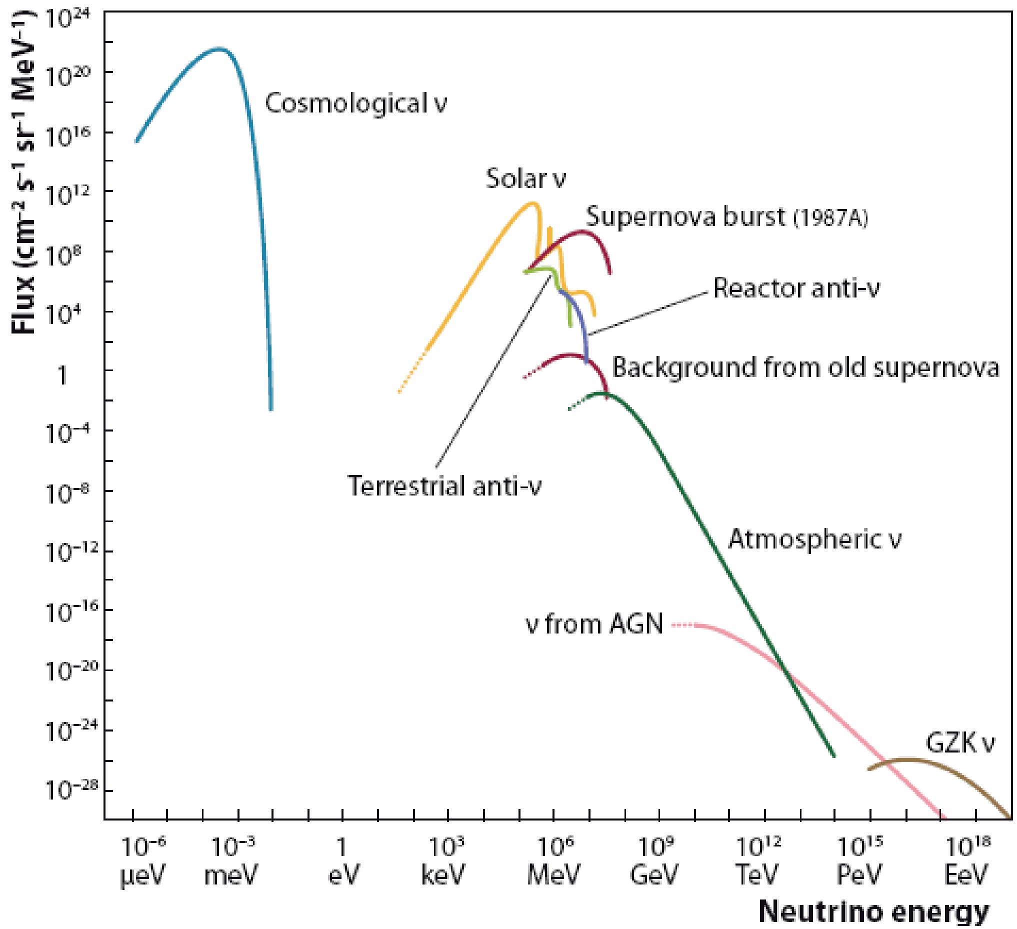
Motivation for the ν - approach



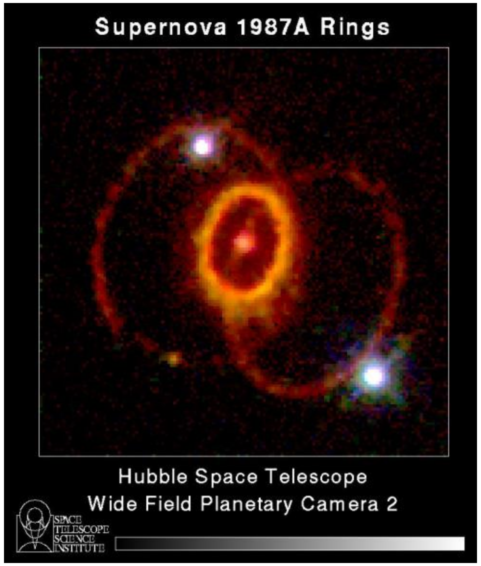
- **Gammas:**
  >30 TeV interaction with IR background
- **Charged particles:**
  - **Low energies: deflection in magnetic fields**
  - **High energies: GZK effect with CMB**
- **Neutrinos:**
  straight tracks from source
  But: needs huge detector volumes due to low cross-sections

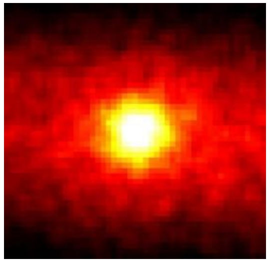
- **UHE neutrinos and HE photons are by-products of GZK and hadronic acceleration**

Cosmic Neutrinos



5 - 40MeV





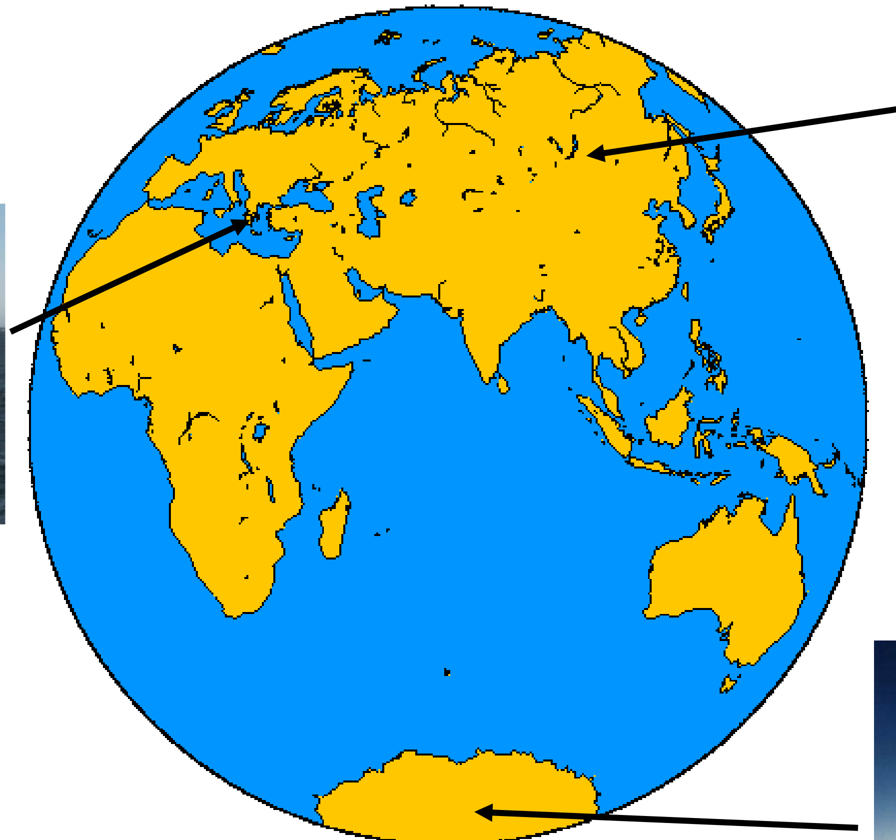
> 1 GeV

Seen so far: atmospheric ν from EAS….

…..and more (IceCube) !!!

High-Energy Neutrinos: Nowadays Experiments
$E_\nu = 10^{12}\text{-}10^{17}$eV

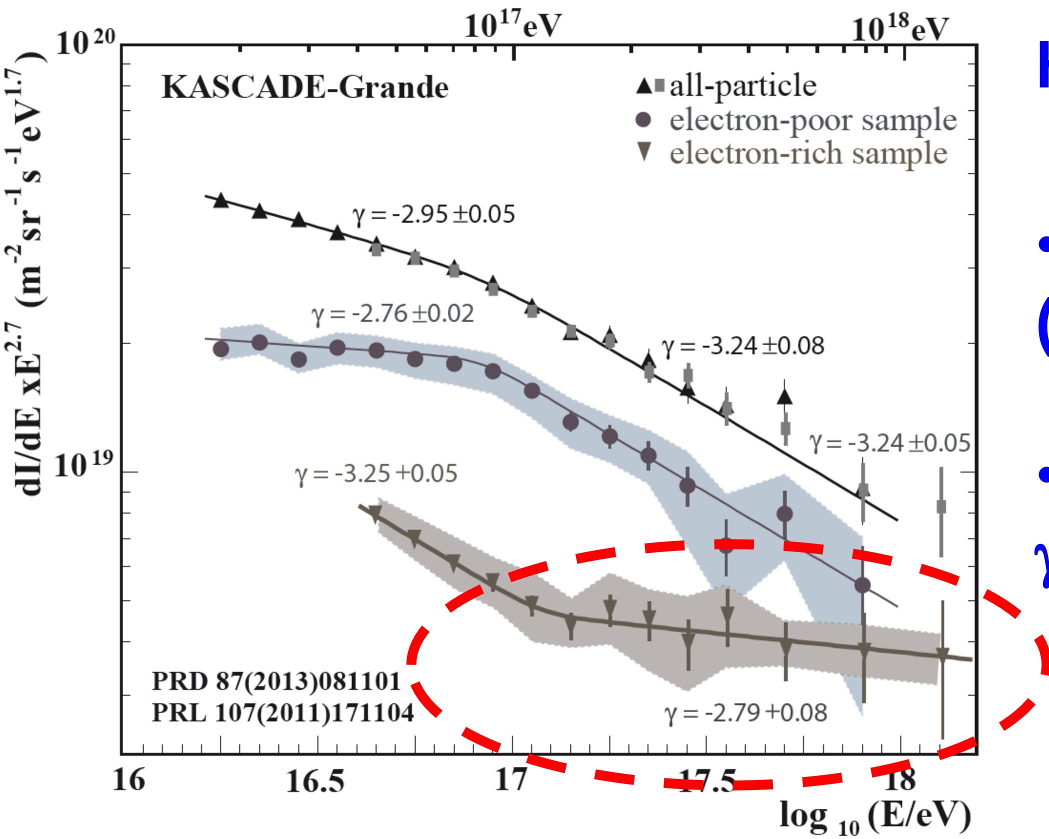
Mediterranean:
ANTARES, France
NESTOR, Greece
NEMO, Italy



BAIKAL, Sibiria

AMANDA & IceCube, South pole

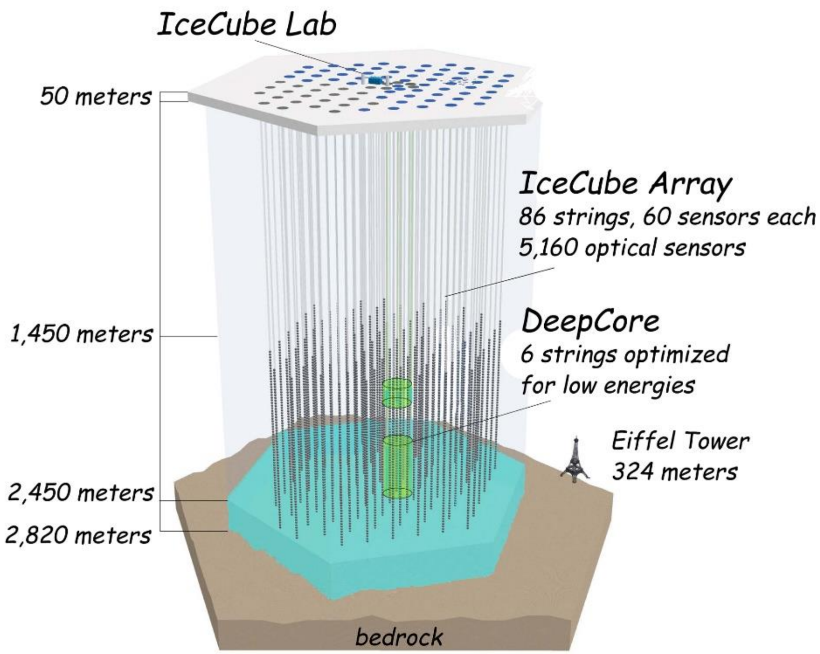
KASCADE-Grande
energy spectra of mass groups



- **steepening due to heavy primaries (3.5σ)**
- **hardening at $10^{17.08}$ eV (5.8σ) in light spectrum**
- **slope change from $\gamma = -3.25$ to $\gamma = -2.79$!**

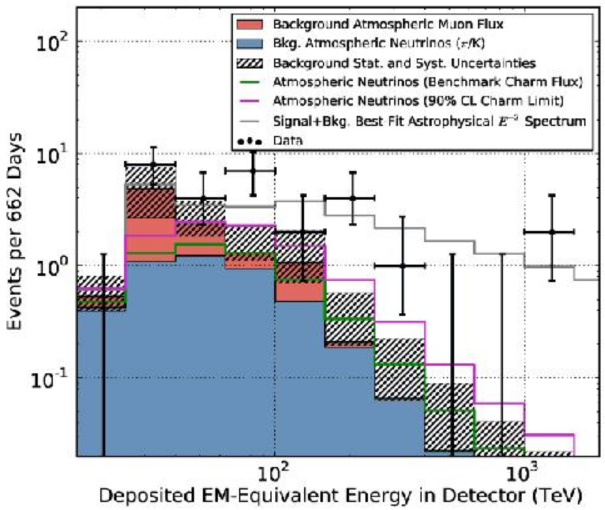
Phys.Rev.Lett. 107 (2011) 171104
Phys.Rev.D (R) 87 (2013) 081101

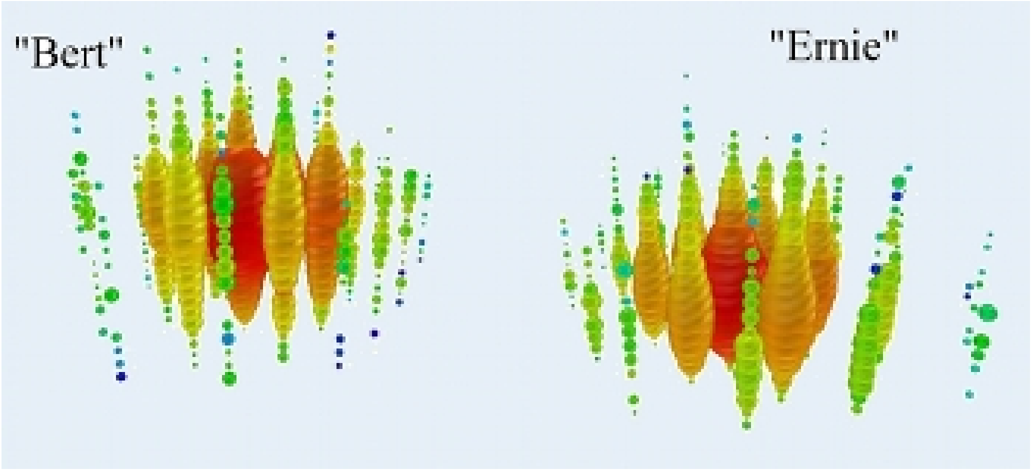
Synergy of Neutrino astronomy with KASCADE(?)



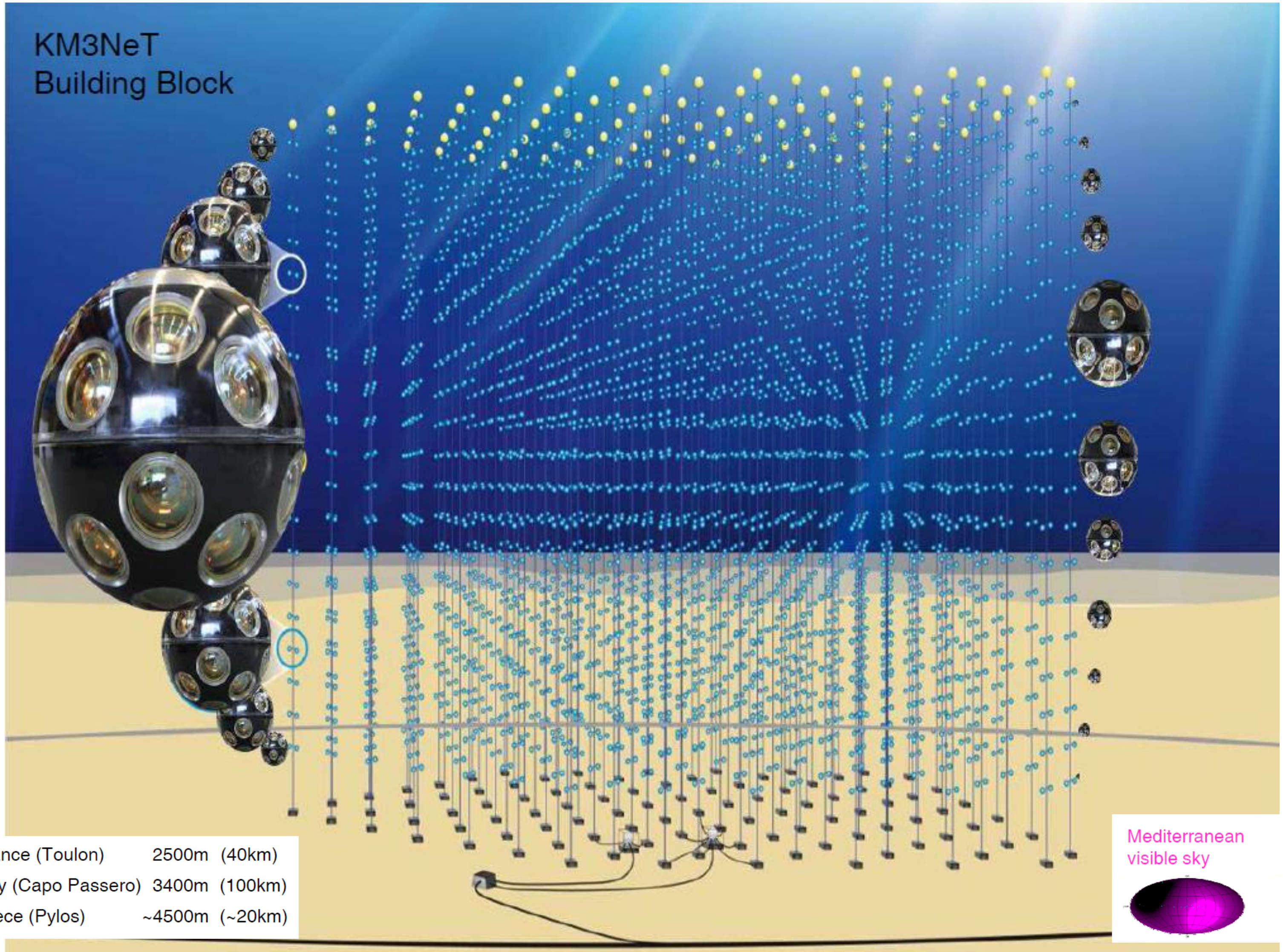
- **cosmic neutrinos from IceCube correspond to 10^{17}eV protons**
  🡸 galactic or extragalactic source?

Measured PeV-neutrinos by IceCube



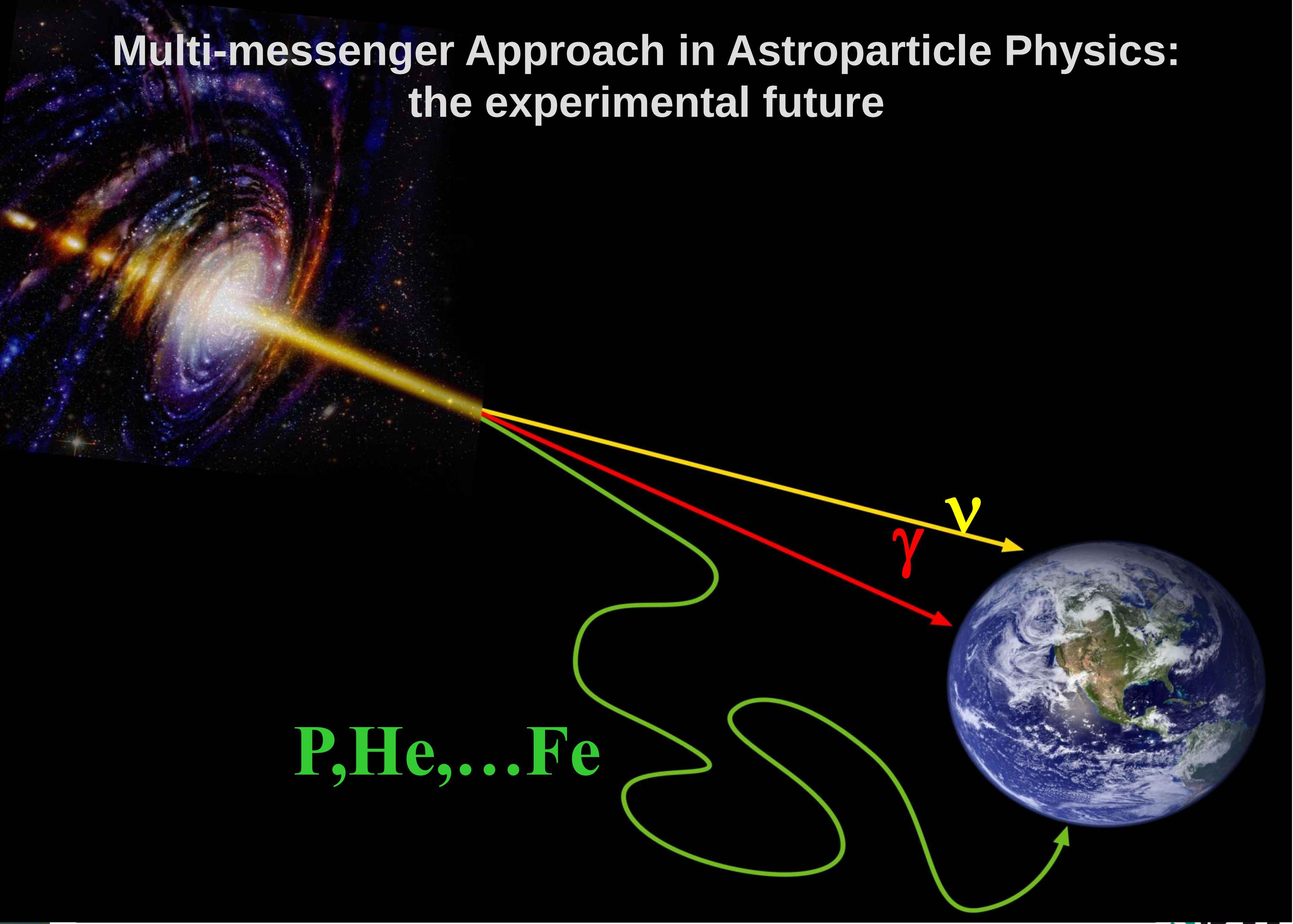


The future: KM3Net and/or IceCube++
➔ high-energy neutrino astronomy



- KM3NeT-France (Toulon) 2500m (40km)
- KM3NeT-Italy (Capo Passero) 3400m (100km)
- KMNeT-Greece (Pylos) ~4500m (~20km)

Multi-messenger Approach in Astroparticle Physics: the experimental future



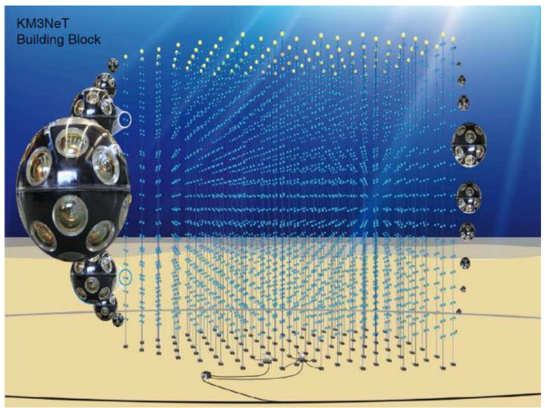
The High Energy Universe

- **Gamma Rays**
  CTA
- **Neutrinos**
  IceCube++ + KM3NeT
- **Charged Cosmic Rays**
  Auger upgrade + JEM-EUSO

The next phase in Astroparticle Physics:
(European) Roadmap Priorities: High-Energy Universe

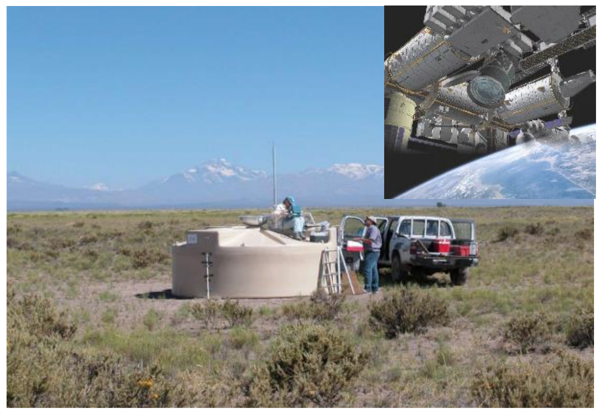
Neutrinos:

KM3Net + IceCube++

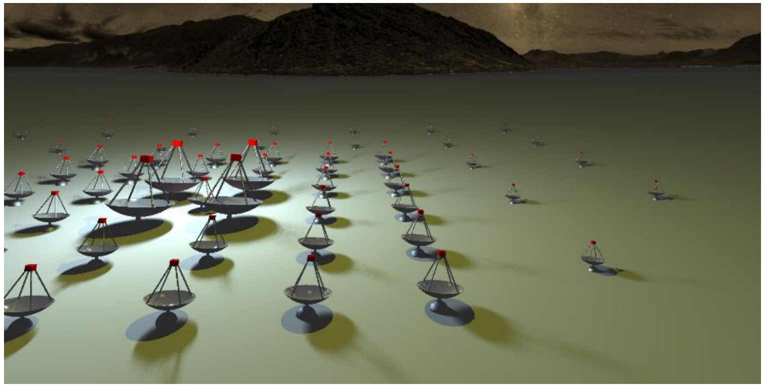


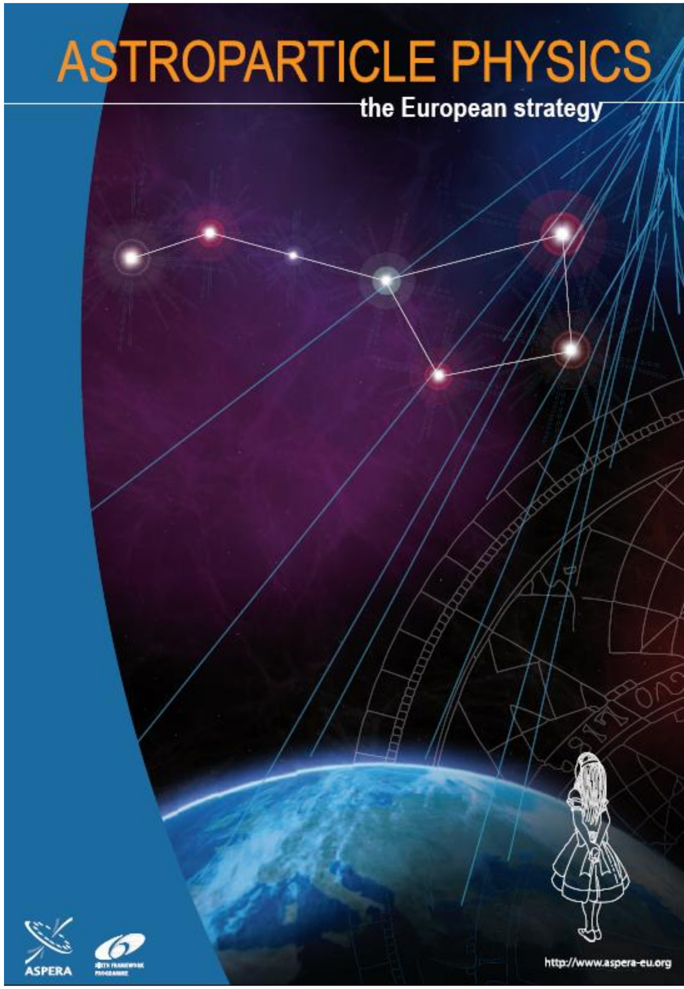
Charged Cosmic Rays:

Auger Upgrade + JEM-EUSO



Gamma Rays: CTA

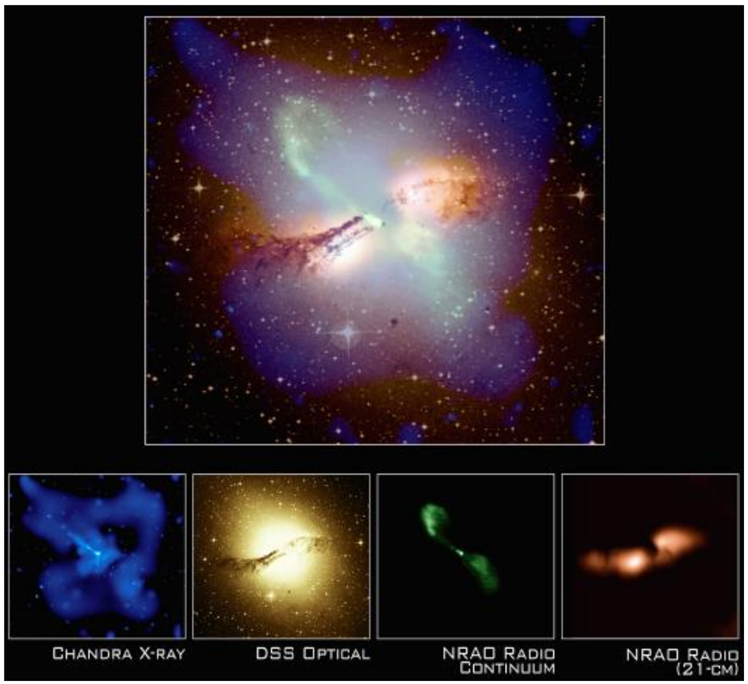


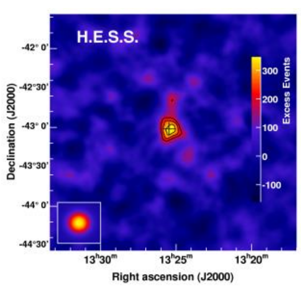


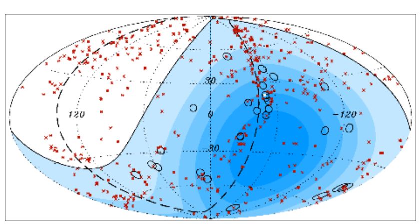
Roadmap from scientists for Funding Agencies!

Can we do Particle Astronomy?

i.e. multi-messenger observations of individual sources?
example: Centaurus A (NGC 5128, Cen A)







- closest radio-loud (d ~ 3.4Mpc) AGN
- one of the best studied active galaxies
- observed at many frequencies: from radio to X-ray

- **<u>Gamma-rays</u>**

70's: Narrabri [Grindlay et al., 1975]
90's: EGRET [Sreekumar et al., 1999]
Feb. 2009: Fermi-LAT [Abdo et al., 2009]
March 2009: H.E.S.S. [Aharonian et al, 2009]

- **<u>UHECRs</u>**

2007: PAO [Abraham et al., 2007]
possible, but no agreement [Lemoine, 2008]
2014: Hotspot TA [Abassi et al.2014]
Cen A in hotspot region

- **<u>neutrinos</u>**

no observation ... yet
➔ detailed calculations and predictions!

Can we do Particle Astronomy?

i.e. multi-messenger observations of individual sources?

Discussion / Question / Exercise

- **how to distinguish GZK-suppression from max. acceleration?**

- **what JEM-EUSO could be do better than Auger?**

- **why TeV-Gamma-ray physics is already astronomy?**

Discussion / Question / Exercise

- how to distinguish GZK-suppression from max. acceleration?
  - anisotropy
  - composition
  - photon and neutrinos
- what JEM-EUSO could be do better than Auger?
  -
  -
  -
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  -
  -
  -

Discussion / Question / Exercise

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  - energy spectrum north and south hemisphere
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  -
  -
  -

Discussion / Question / Exercise

- **how to distinguish GZK-suppression from max. acceleration?**
  - **anisotropy**
  - **composition**
  - **photon and neutrinos**
- **what JEM-EUSO could be do better than Auger?**
  - **statistics**
  - **energy spectrum north and south hemisphere**
  - **interdisciplinary physics**
- **why TeV-Gamma-ray physics is already astronomy?**
  - **source morphology**
  - **source classes**
  - **used to model astrophysical processes**