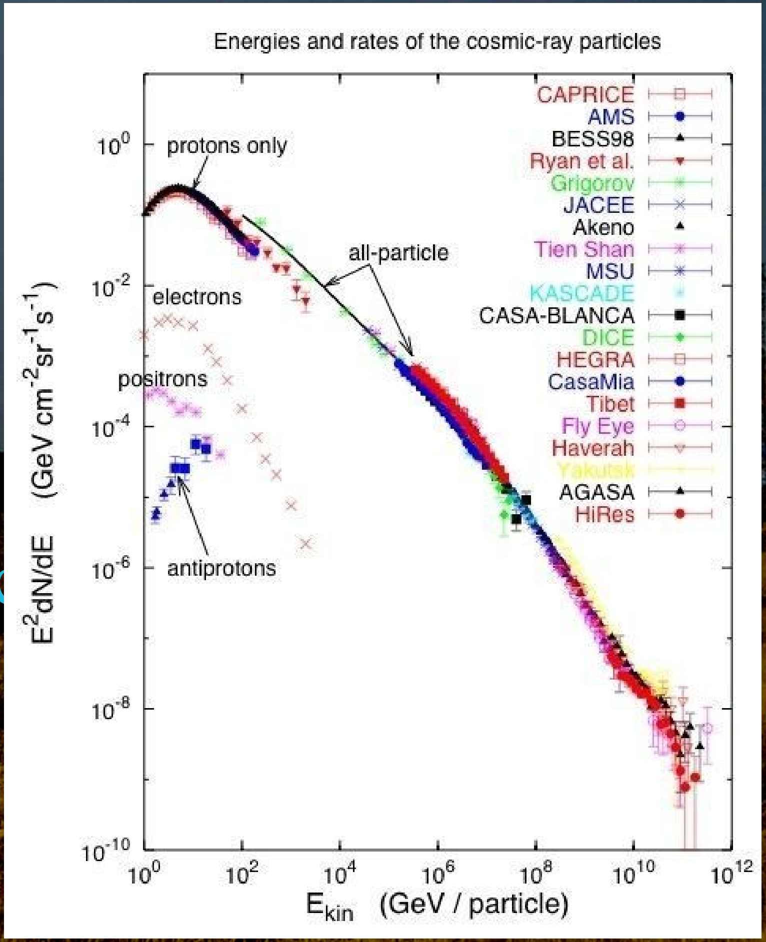
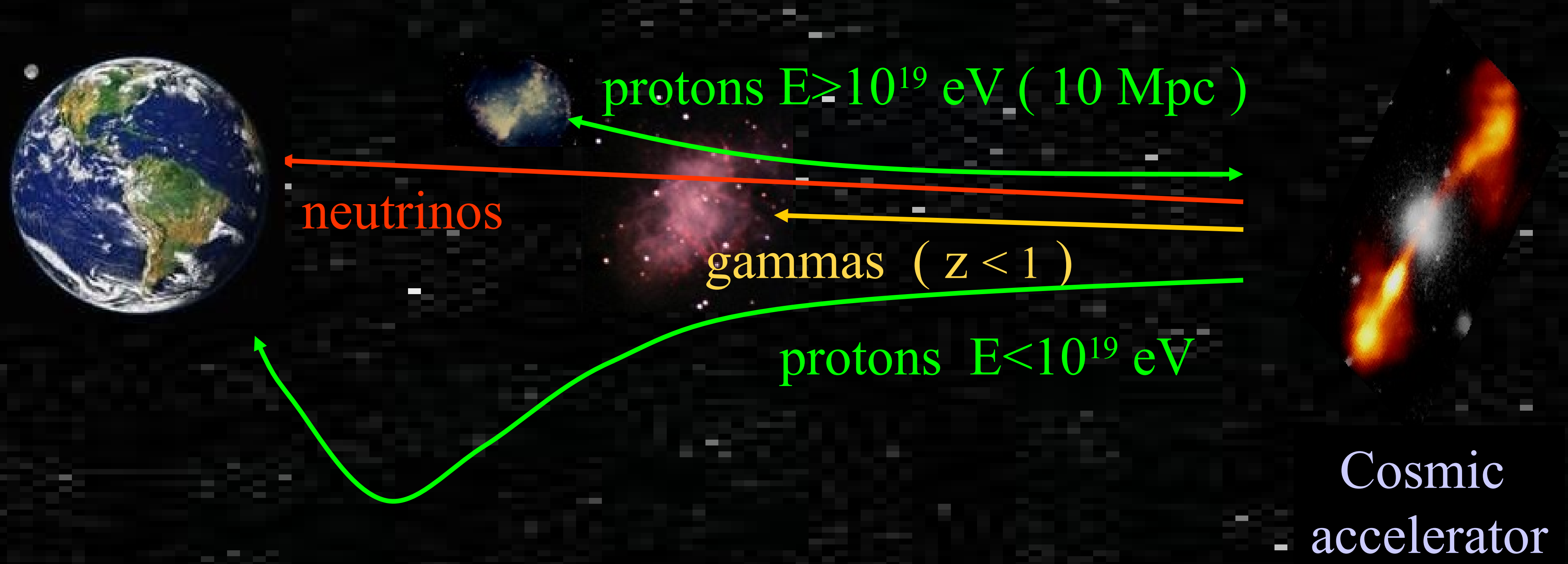
(Very/Ultra) High Energy Astrophysics
III – Charged Cosmic Rays

Mathieu de Naurois
LLR- *In2p3/CNRS – Ecole Polytechnique – France*
denauroi@in2p3.fr

- Charged Cosmic Rays from Space
- Hadronic Showers
- Very High- and Ultra High Energy



Multi-messenger observations of the Cosmos



photons: Absorbed by dust and radiation (pair creation on CMB)

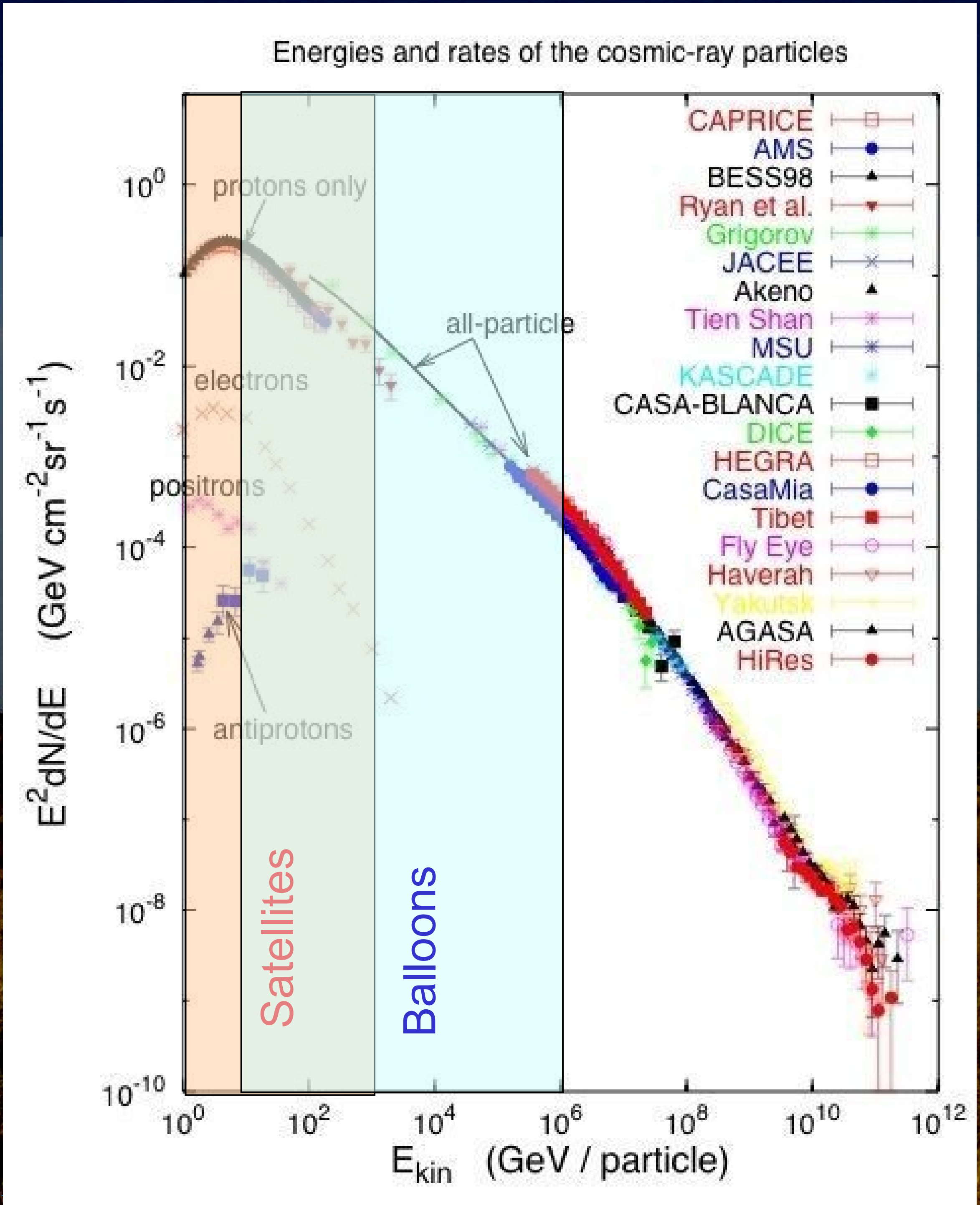
protons/nuclei: Deviated by B field, absorbed by CMB (GZK effect)

neutrinos: Difficult to detect

gravitational waves: Emerging

⇒ **Four "astronomies" possible...**

High Energy Charged Cosmic Rays ($E < 10^{15}$ eV)



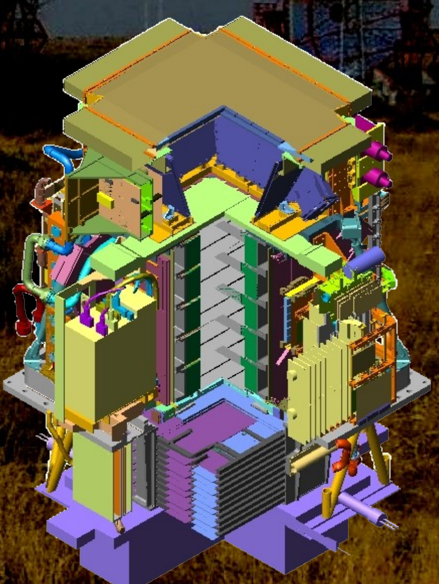
Mathieu de Naurois

Satellites & Balloons

- Short time scale: ~6 months
- Cost << satellite
- Supply recovery (emulsions, …)
- Remaining atmosphere
- Not very long exposure (~ months)

- “Clean” environment (above atmosphere)
- Long duration (~ years)
- Very expensive
- Long development cycle
- Automatic operation – no maintenance

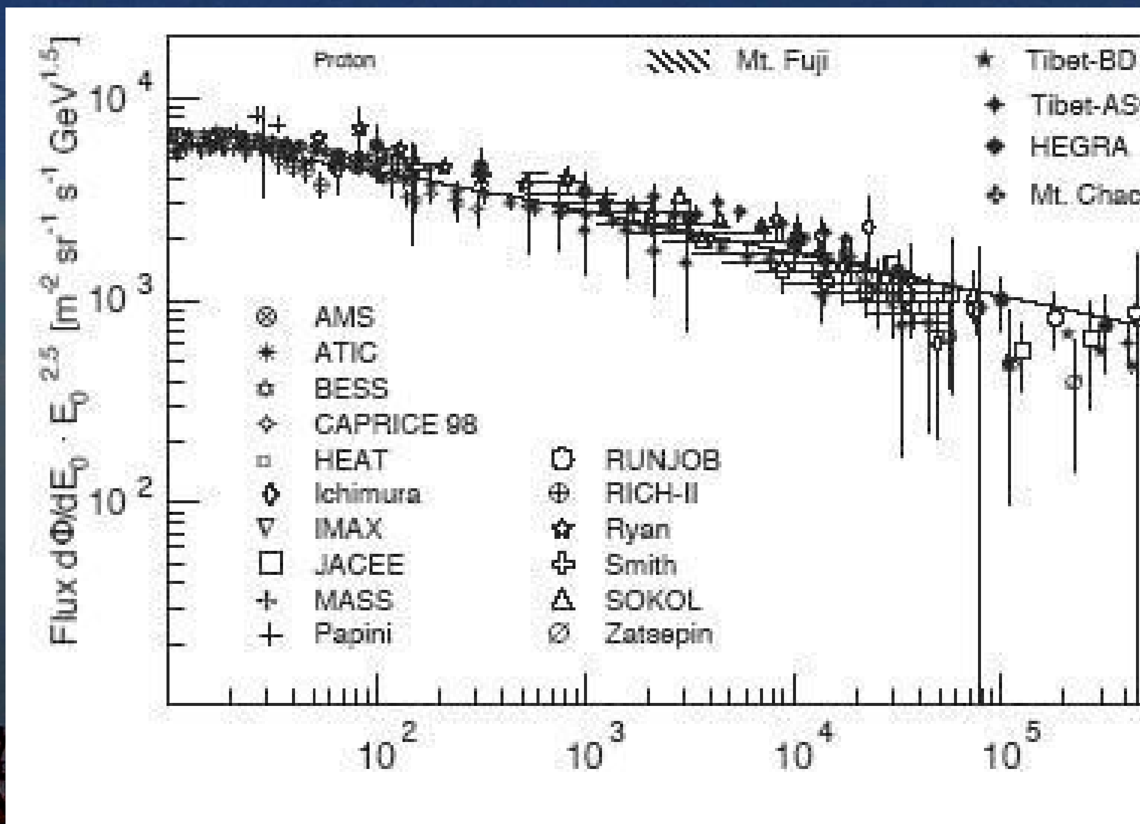


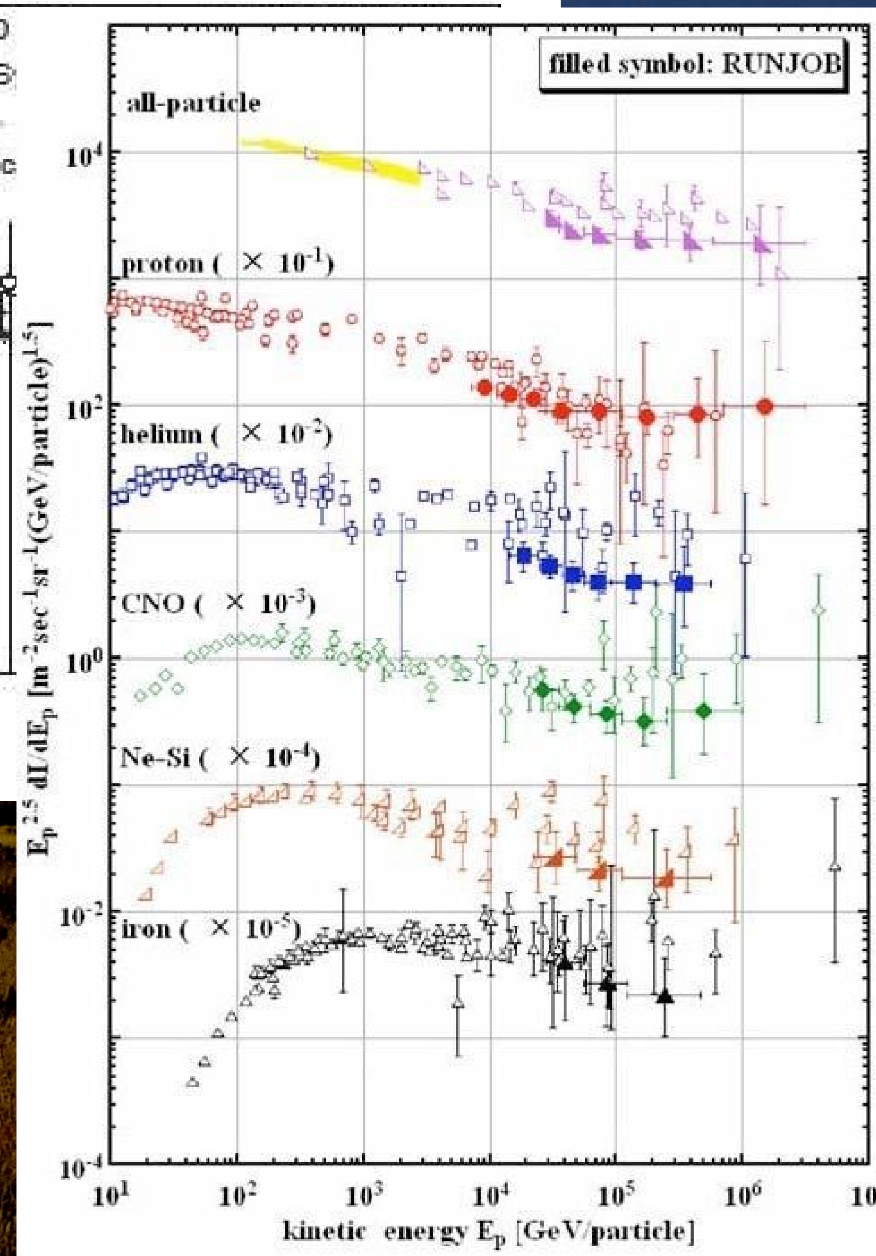



Easy detector recovery...

Or not…

Balloon experiment results

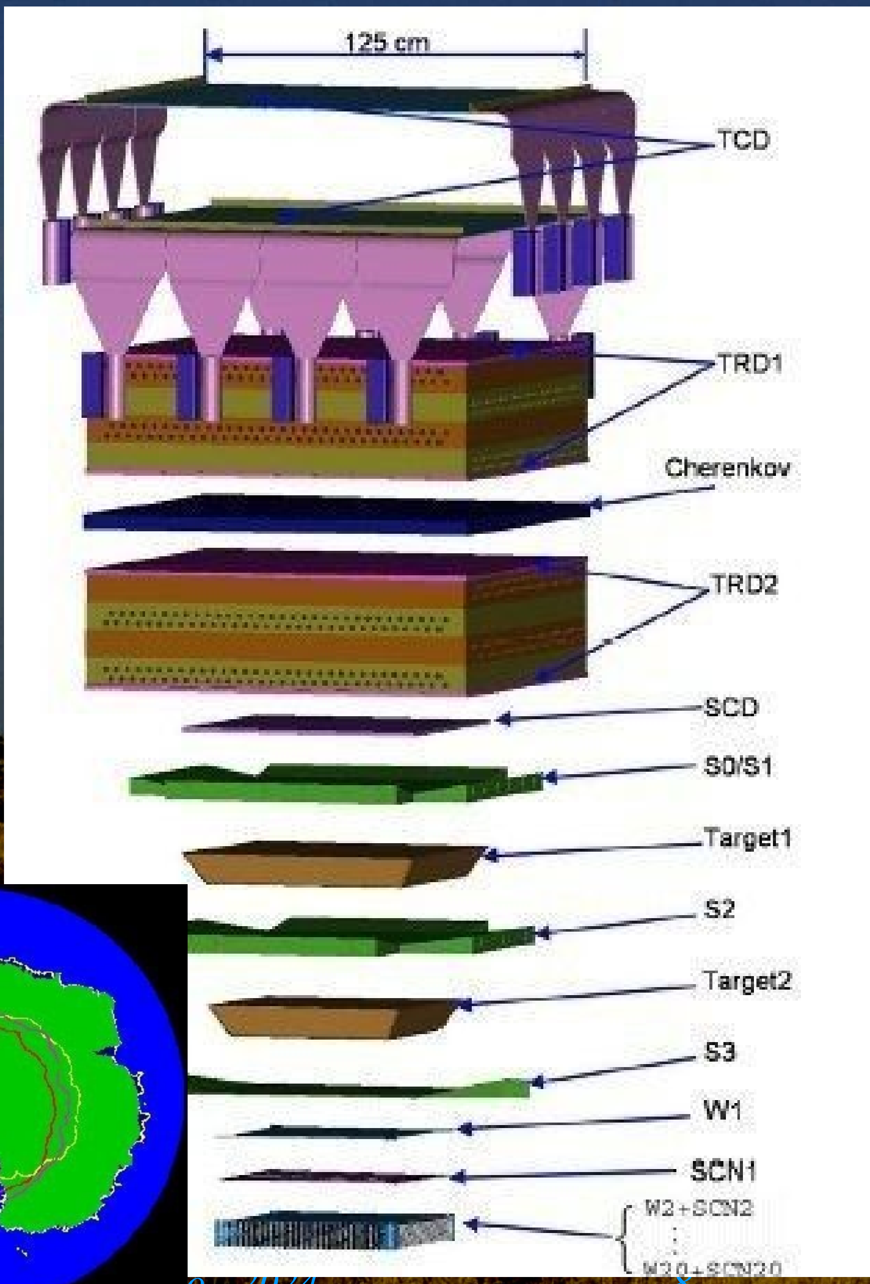


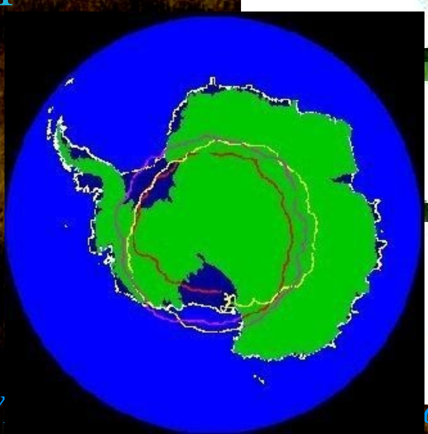


- Particle identification
- All particle spectra
- Composition resolved spectra

Structure of a Balloon Exp.

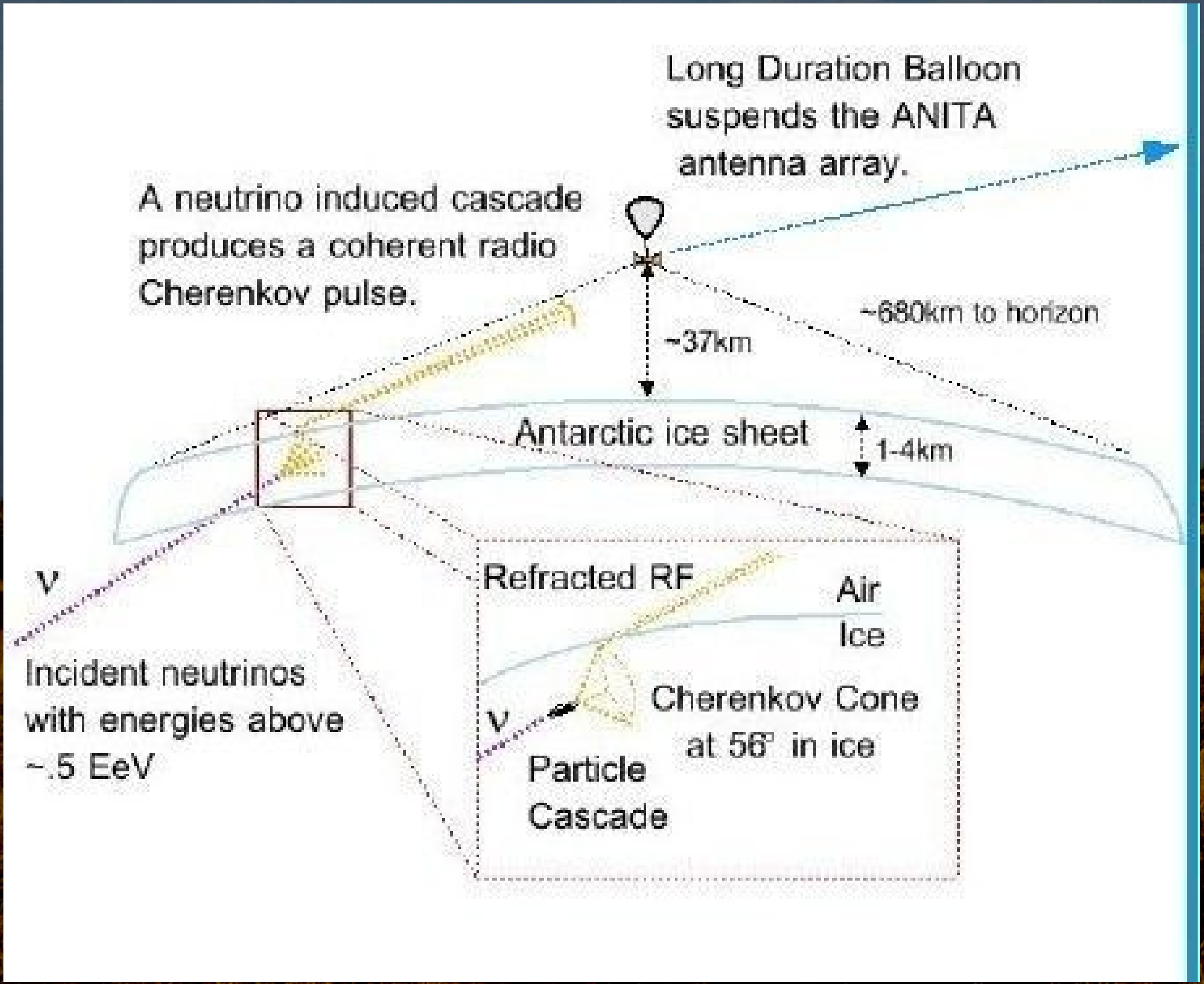
- Here CREAM as example:
- Composition and spectrum of high energy cosmic rays (TeV to ~500 TeV)
- Acceptance : 2,2 m^2 sr
- Energy measurement :
  - Thick calorimeter 20 X_0 (W + fibres)
  - Transition radiation detectors
- Identification :
  - Transition radiation detectors
  - Ring Imaging Cherenkov « CHERCAM » similar to AMS-2
- Flight up to 2 months above south pole
- Flight V: 12/01/2009 ⇒ 01/06/2010
- Now on ISS



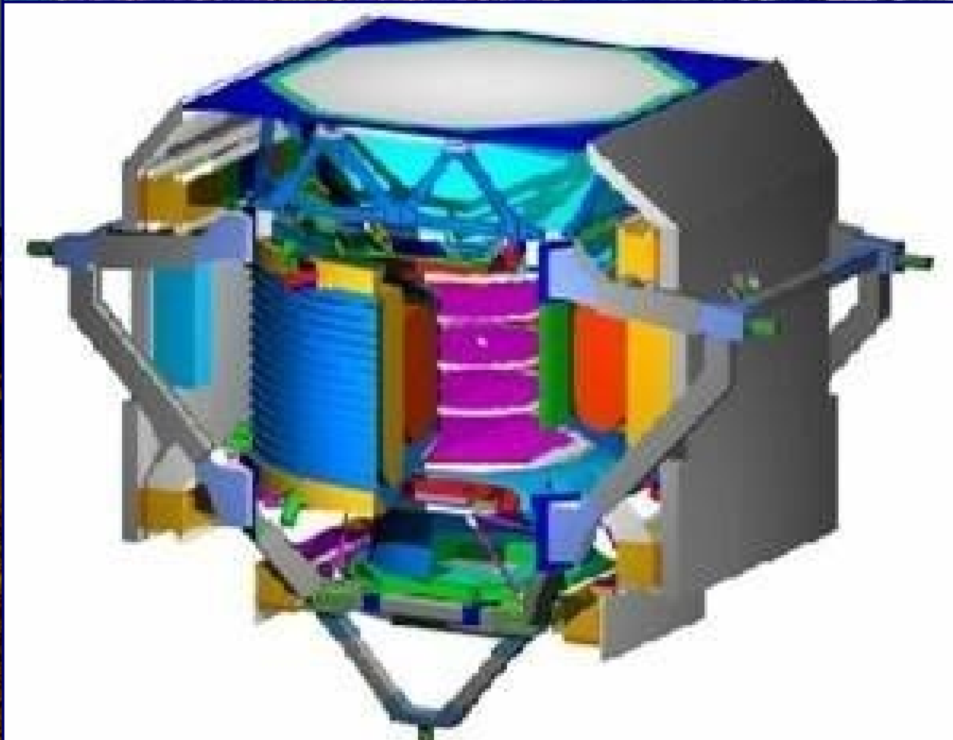


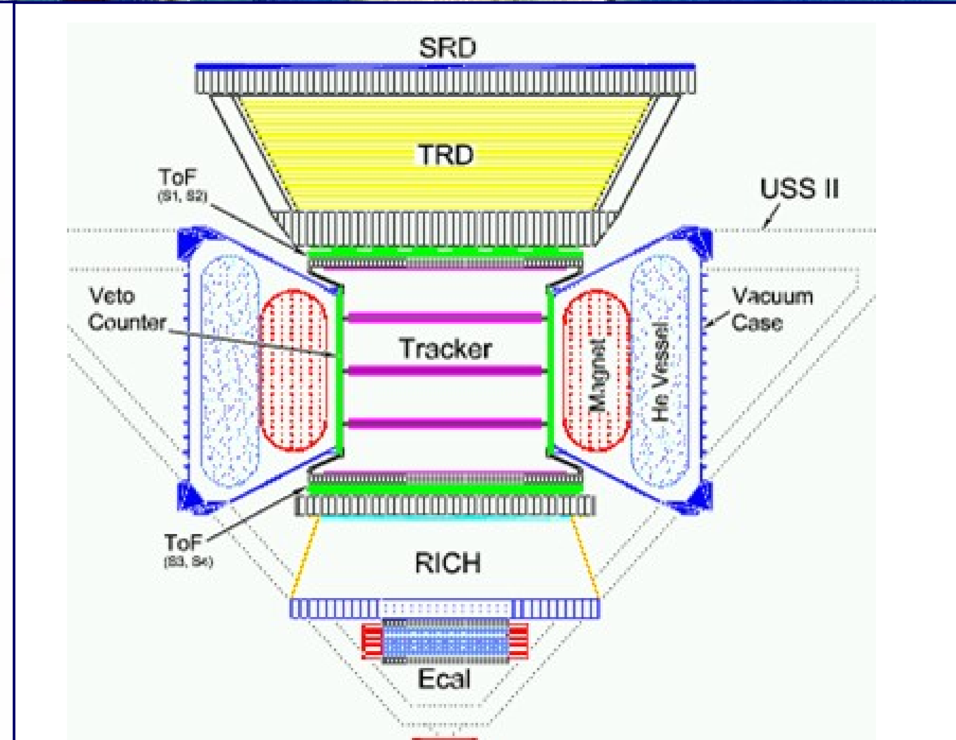
Testing Fancy ideas – ANITA

- Radio detection of earth skimming neutrinos...



Space – AMS – Alpha Magnetic Spectrometer

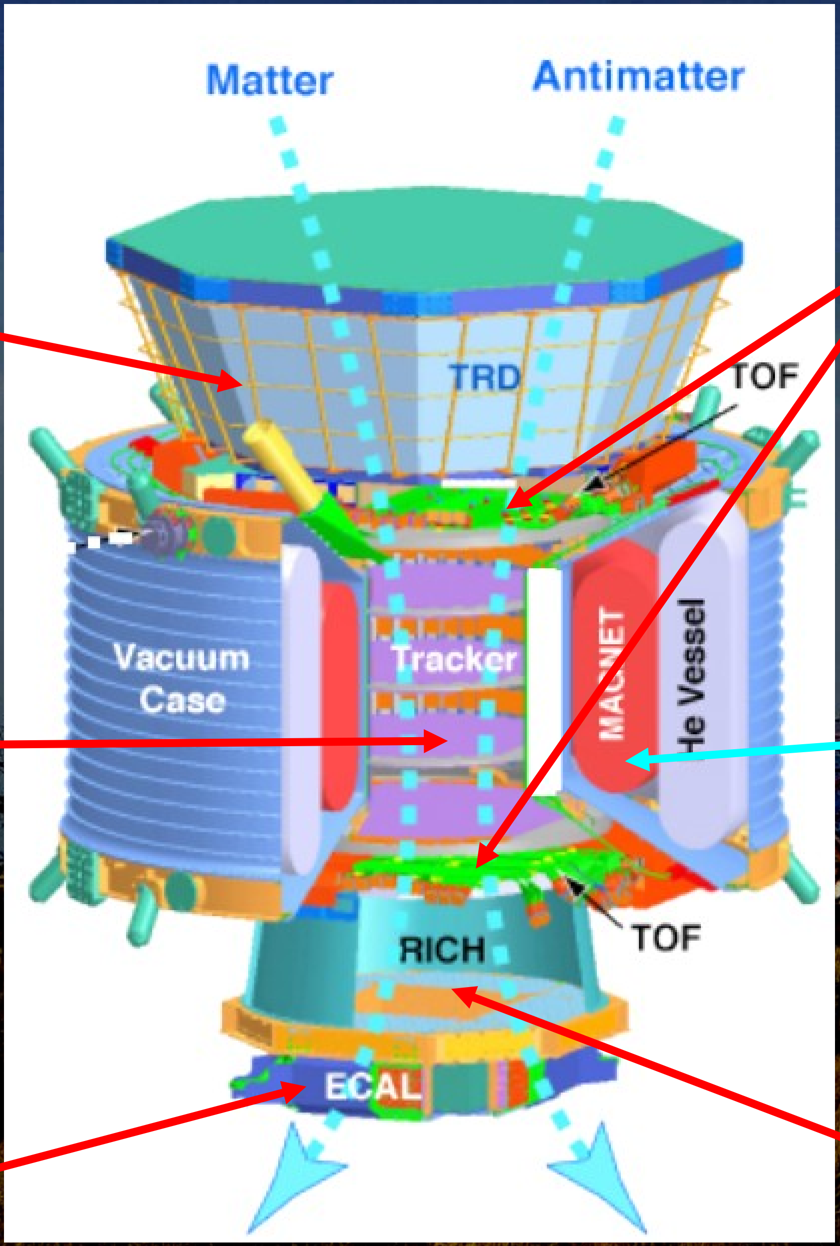




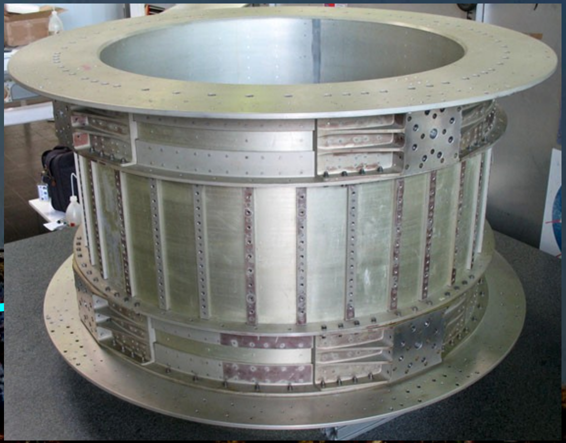
AMS detector

TRD
Discrimination e/p

Time of flight
β, Z



Permanent Magnet



Tracker
Z,R

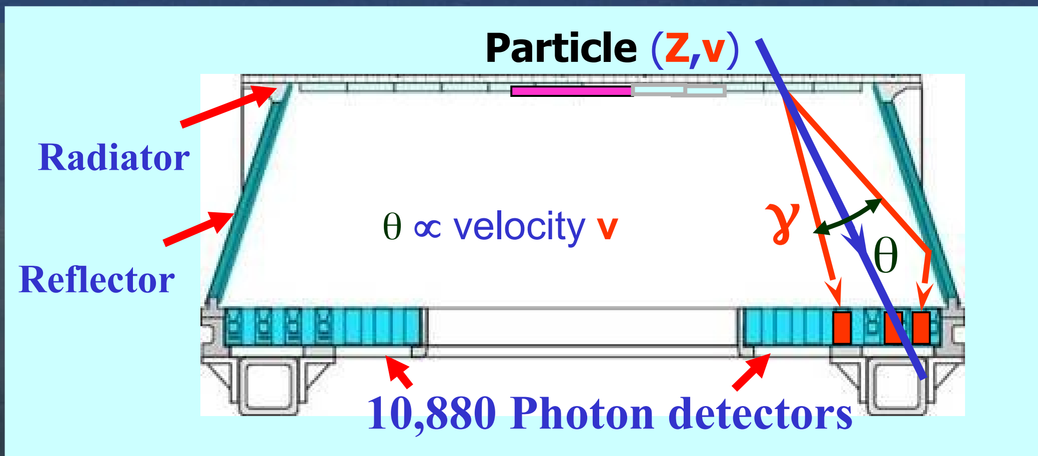
Electromagnetic Calorimeter
Discrimination e/p , E

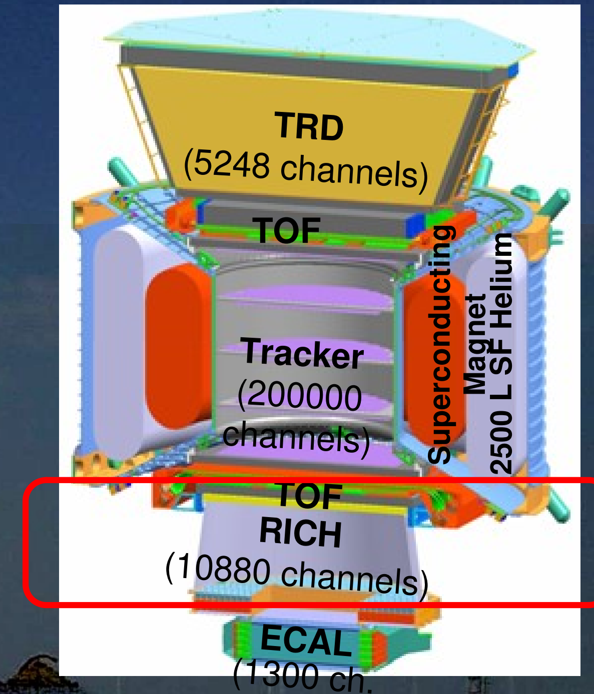
RICH
β, Z

Size: 3m x 3m x 3m
Weight: 7 tons

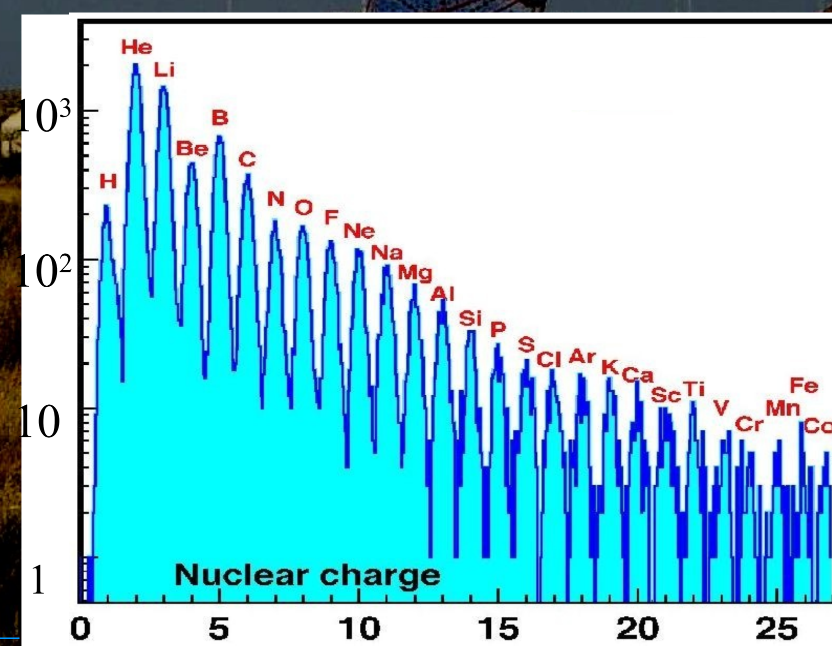
Cerenkov Imaging (RICH)

- Charge measurement ($\sigma(Z) = 0.3$) from photon density

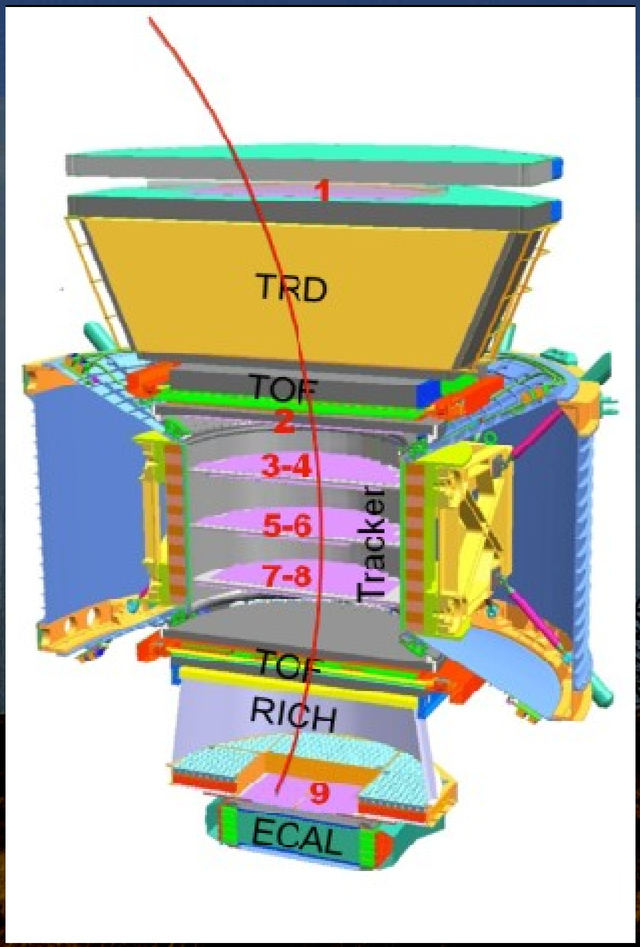




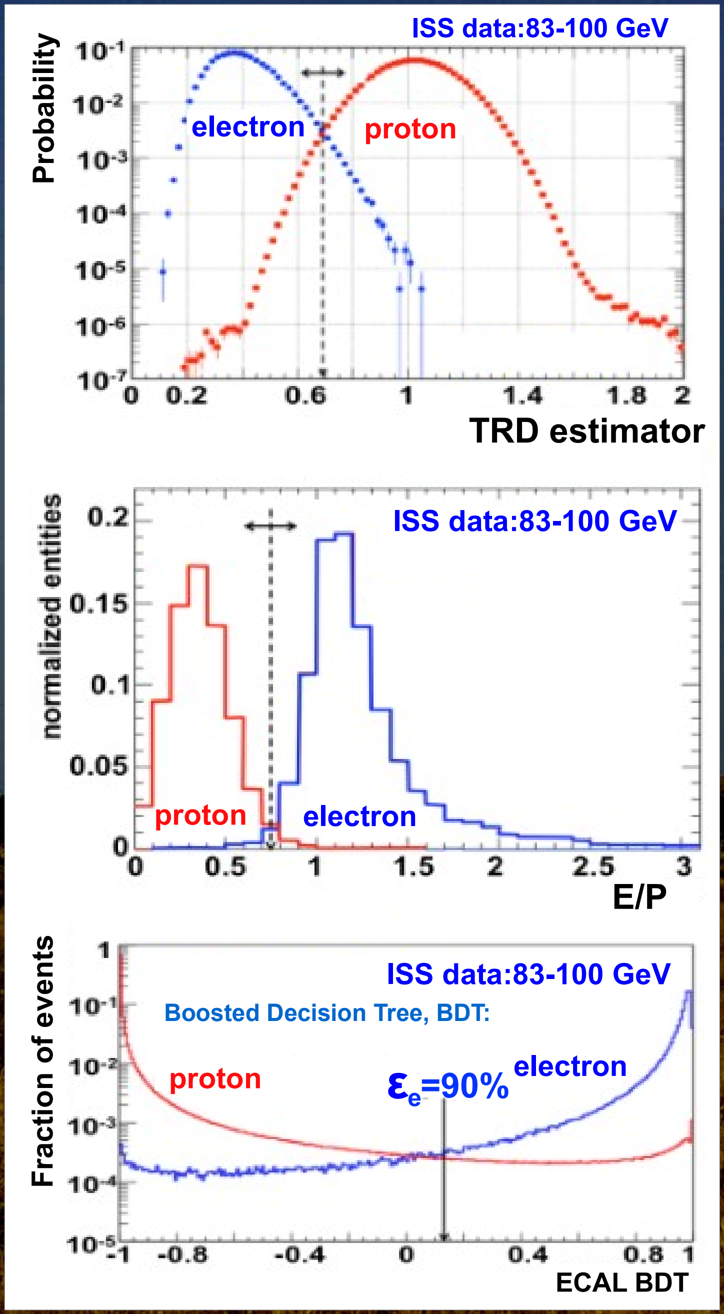
Tests @ 158 GeV/n



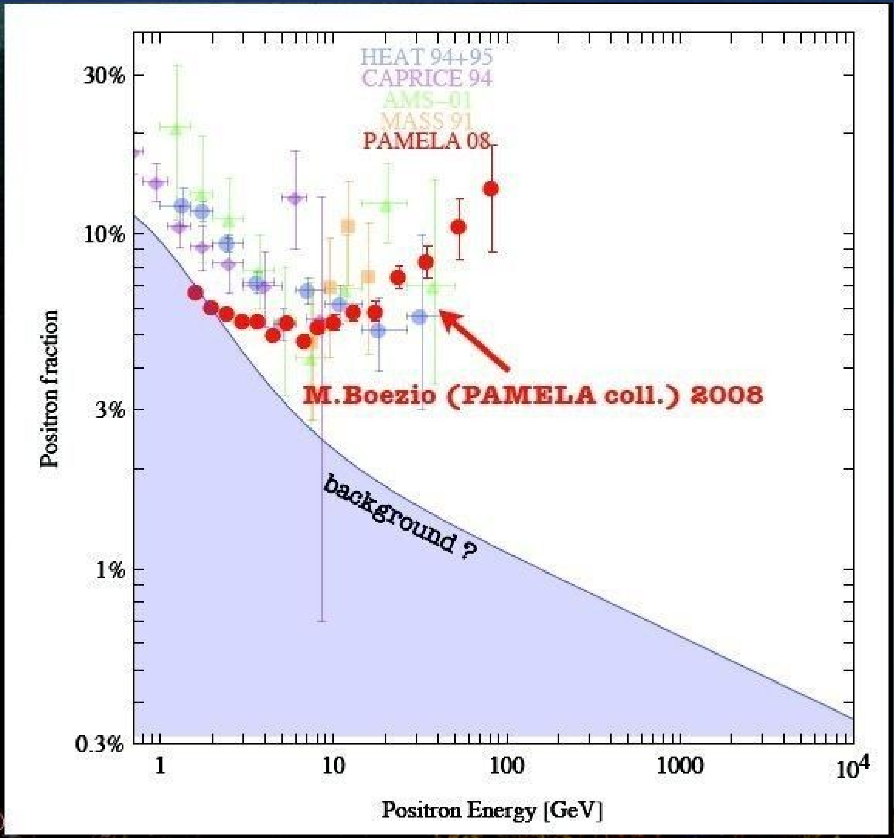
Particle identification & redundancy

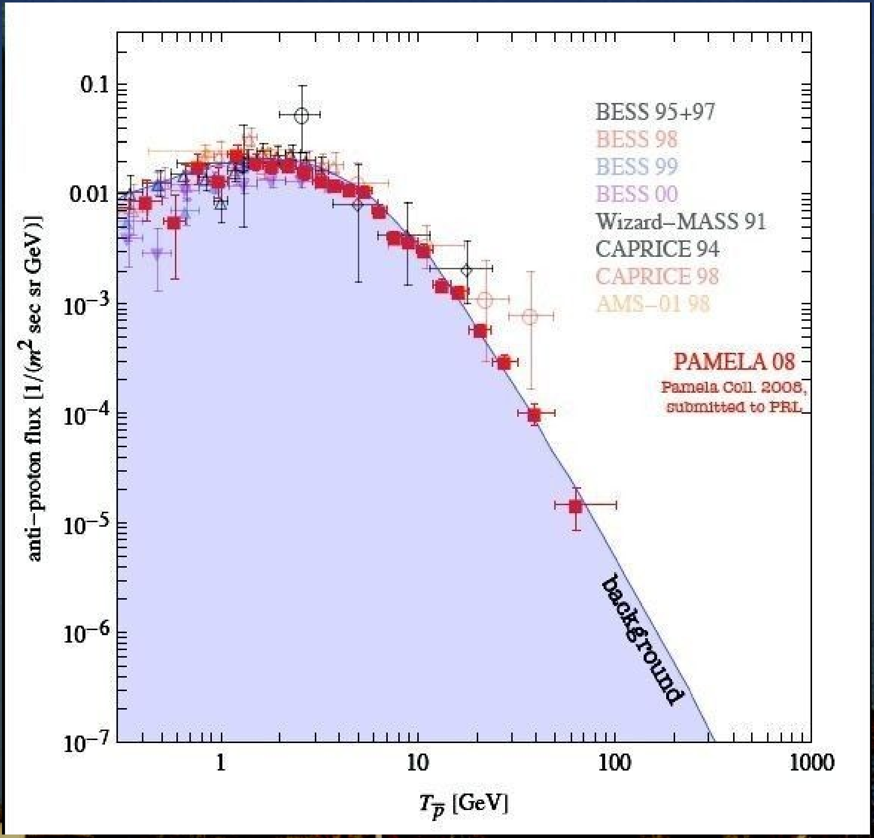


- TRD: identifies $e^{\pm}$
- Tracker: measures p
- ECAL: measures E
  - $e^{\pm}$: $E = Pc$
  - Protons: $E < pc$
- Hodoscopic ECAL measures shape of shower



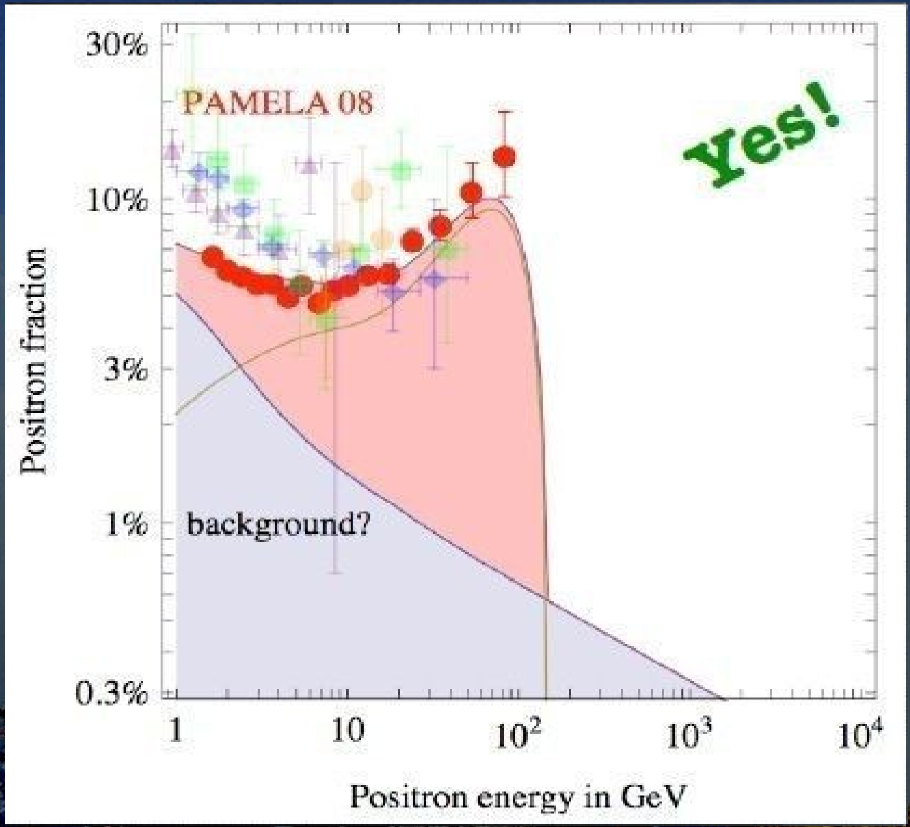
Positrons & Antiprotons

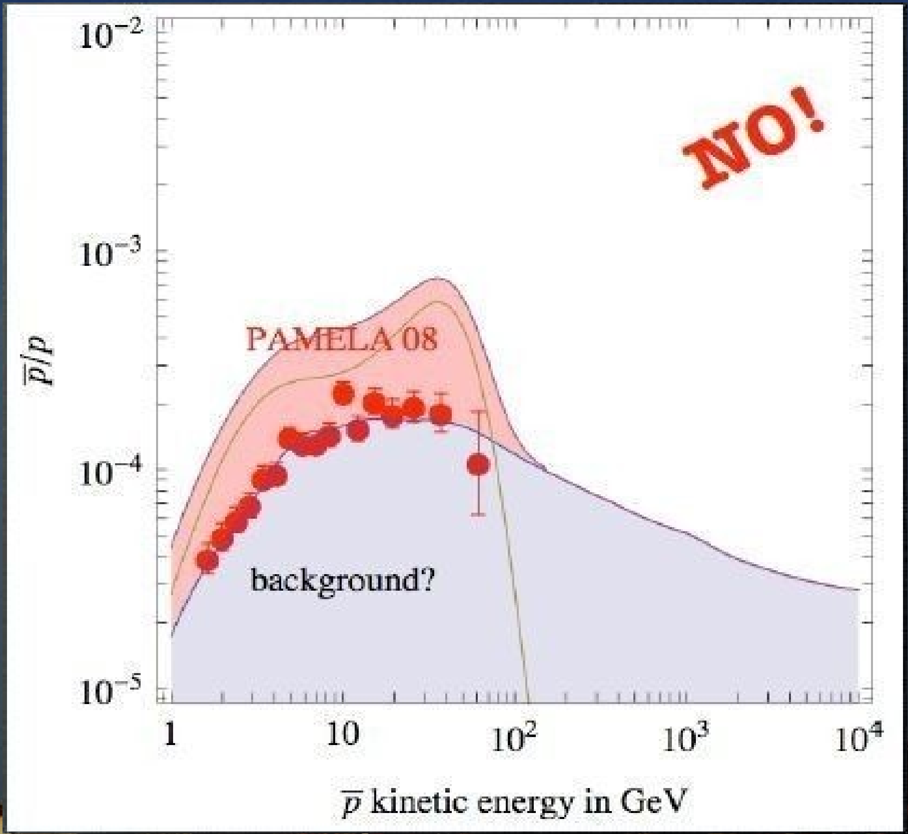




- Antiprotons & positrons are produced during propagation in the galaxy
  - Unvaluable information on interstellar medium, But fraction is very low
- Antiprotons flux compatible with propagation model
- Positron fraction is not, rising quickly above 10 GeV – why??

Dark Matter ?

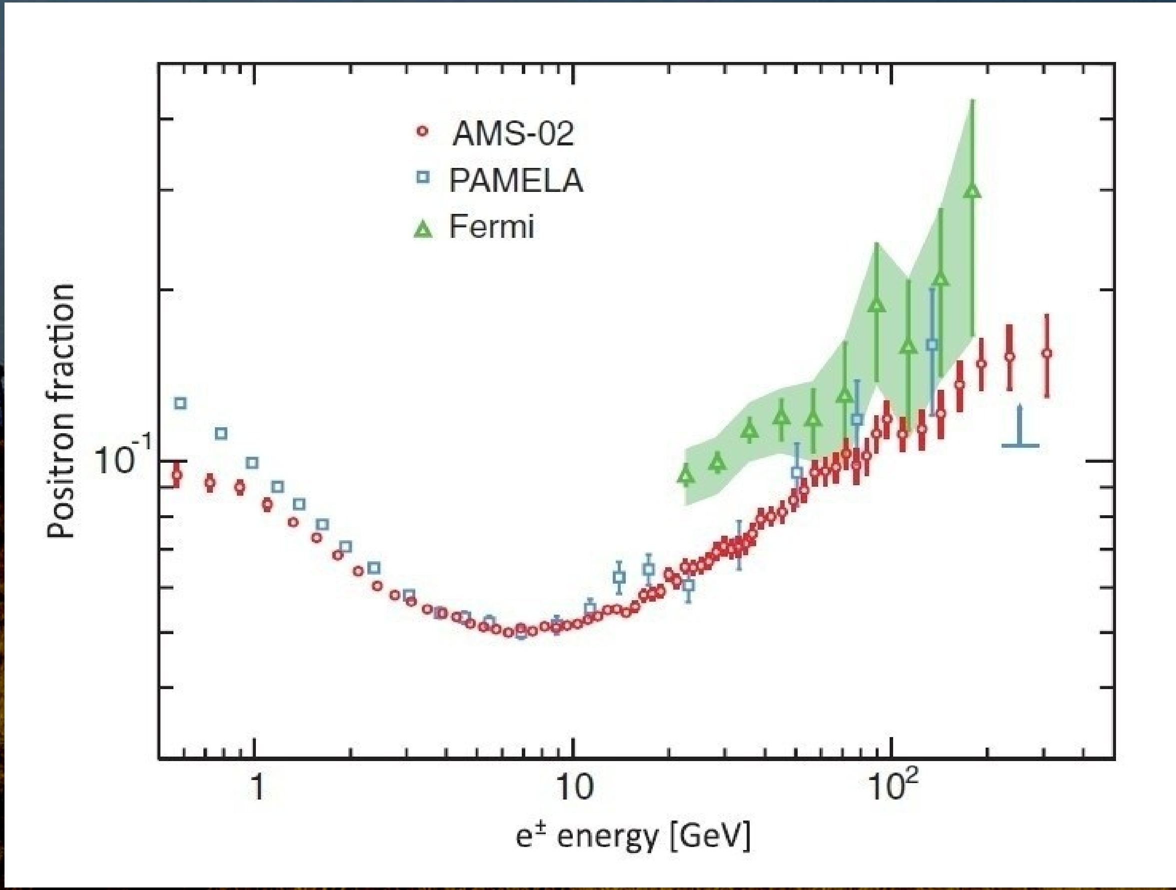




- Positron excess compared to diffusion models, antiprotons shows no excess
- A wino ($\omega\ \omega \rightarrow W^+ W^-$) at 150 GeV is consistent with positrons excess, but not with anti-protons
- A much higher mass (10 TeV) could fit the data, but conflicts with relic density (factor 1000)
- Possible exotic solution: annihilation into leptons ($\mu^+ \mu^-$), ... many papers

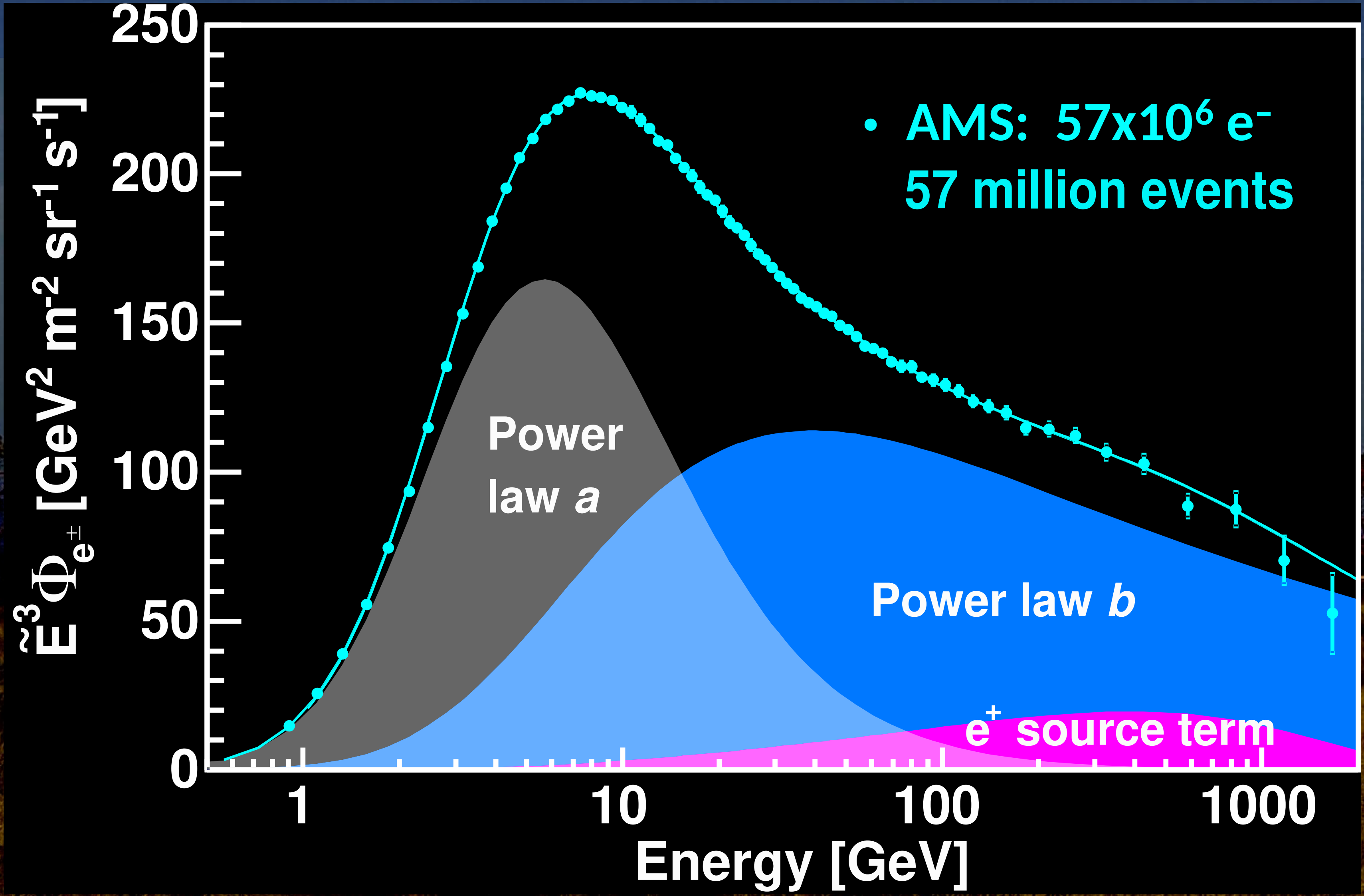
First Results (summer 2013)

- 6.8 million e^+, e^- events
- Positron fraction rising up to 250 GeV, slope decreasing above 20 GeV (PRL, April 2013)
- No structure
- Isotropic (dipole < 0,036)
- Interpretation:
  - Diffuse component
  - Single nearby source of e+/e- (1%)



Electron Spectrum – Summer 2023

- Well reproduced by 2 power laws + a source term like e^+

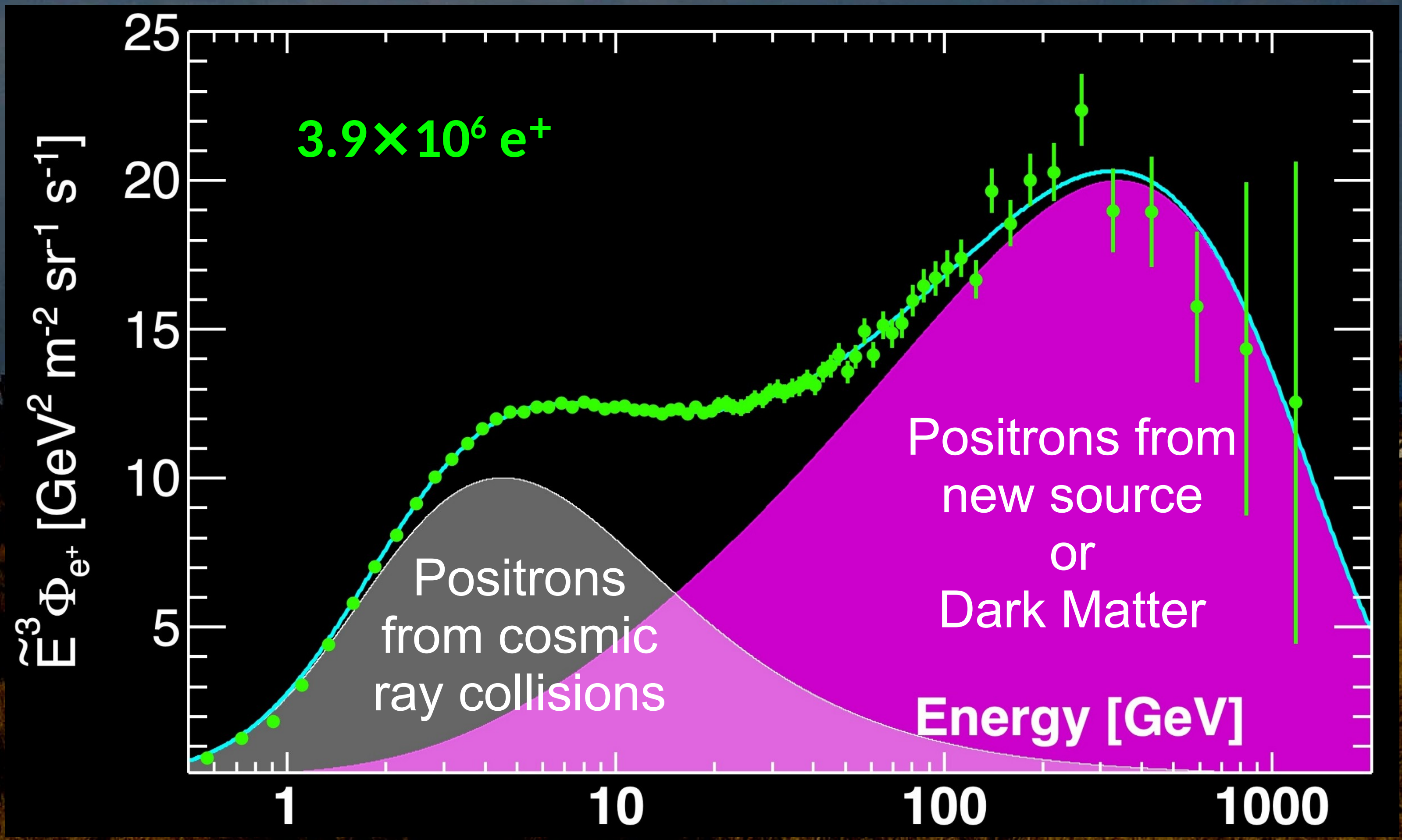


Positron Spectrum – Summer 2023

- Sum of two component:
  - Secondaries (propagation)
  - Source (pulsar and/or dark matter) with cutoff at 749 GeV

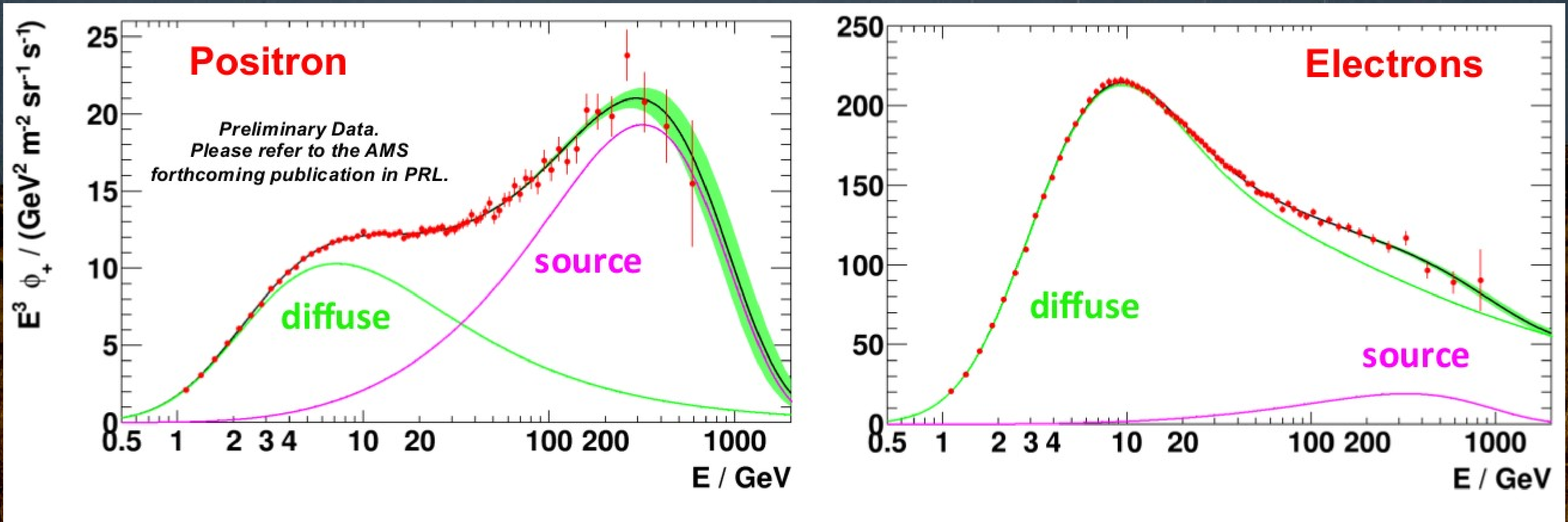
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

Solar Collisions Pulsars or Dark Matter

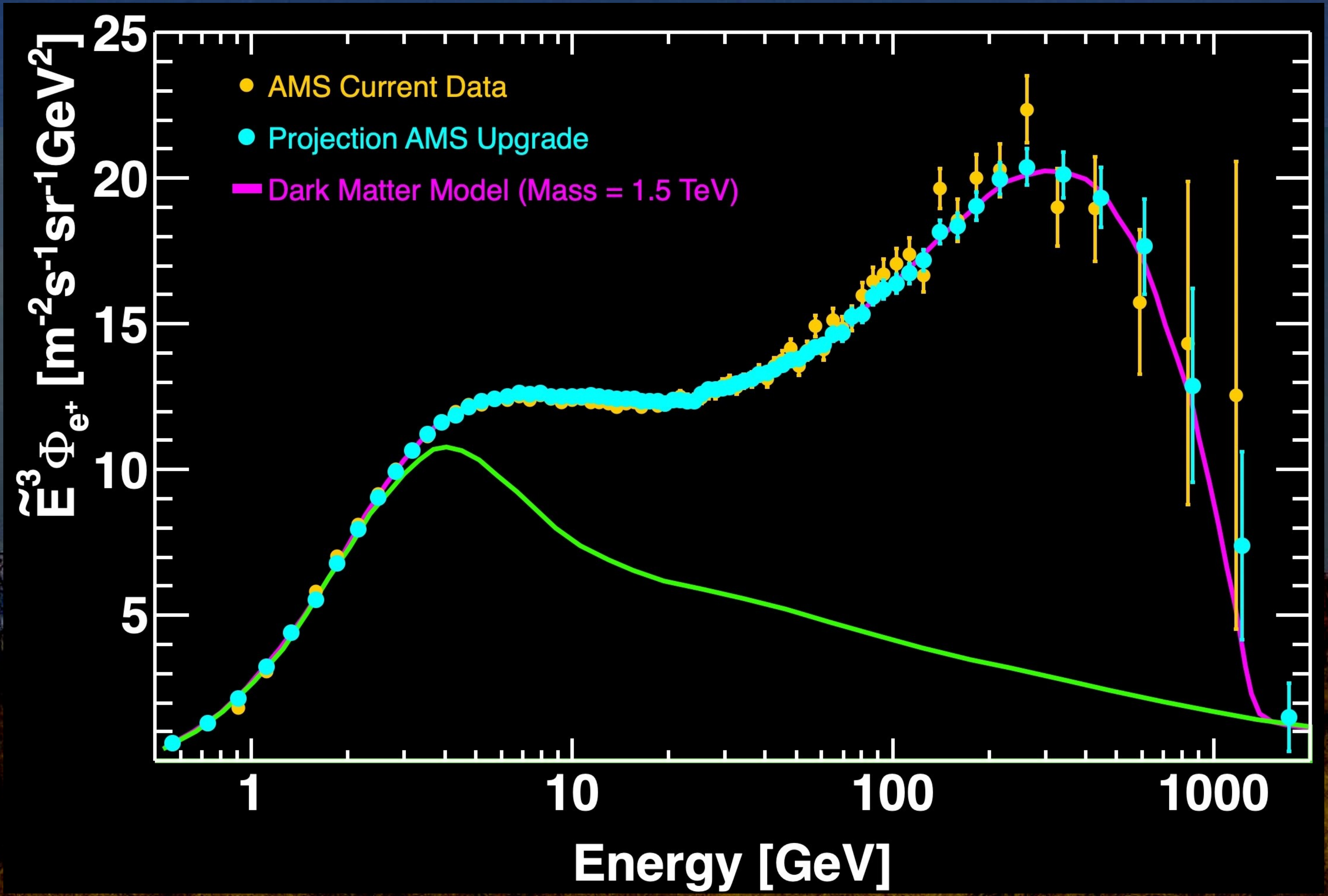


Minimal model

- Spectral shape can be well reproduced with a minimal model (5 parameters) including diffuse power spectra (different for e^+ and e^-) + contribution of a single common source of $e^\pm$ with power law γ_S
- Dark matter not needed here, astrophysics is good enough!



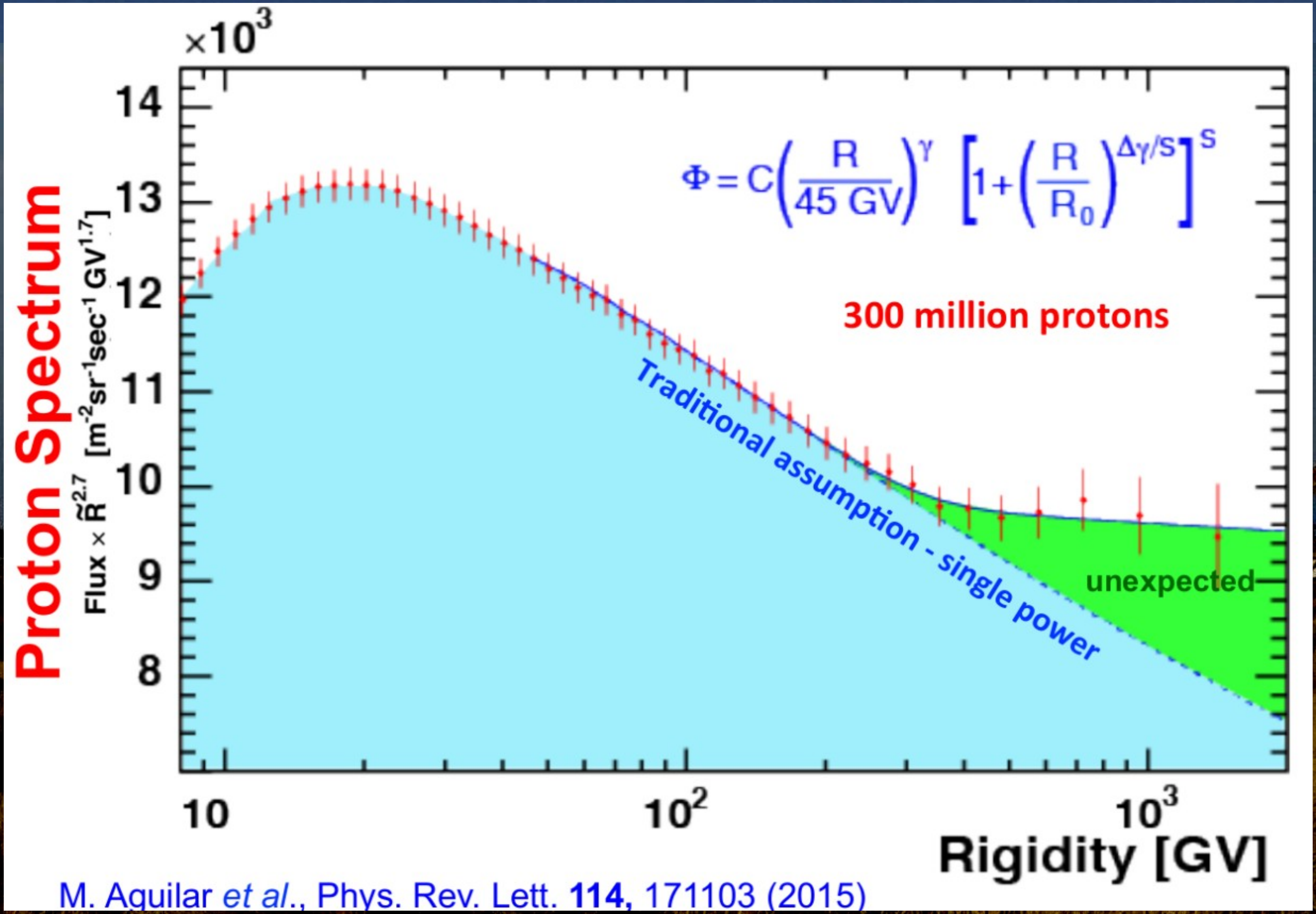
Future: increase of statistics (2030)



- Results on positrons up to ~ 1 TeV expected in ~ 7 years

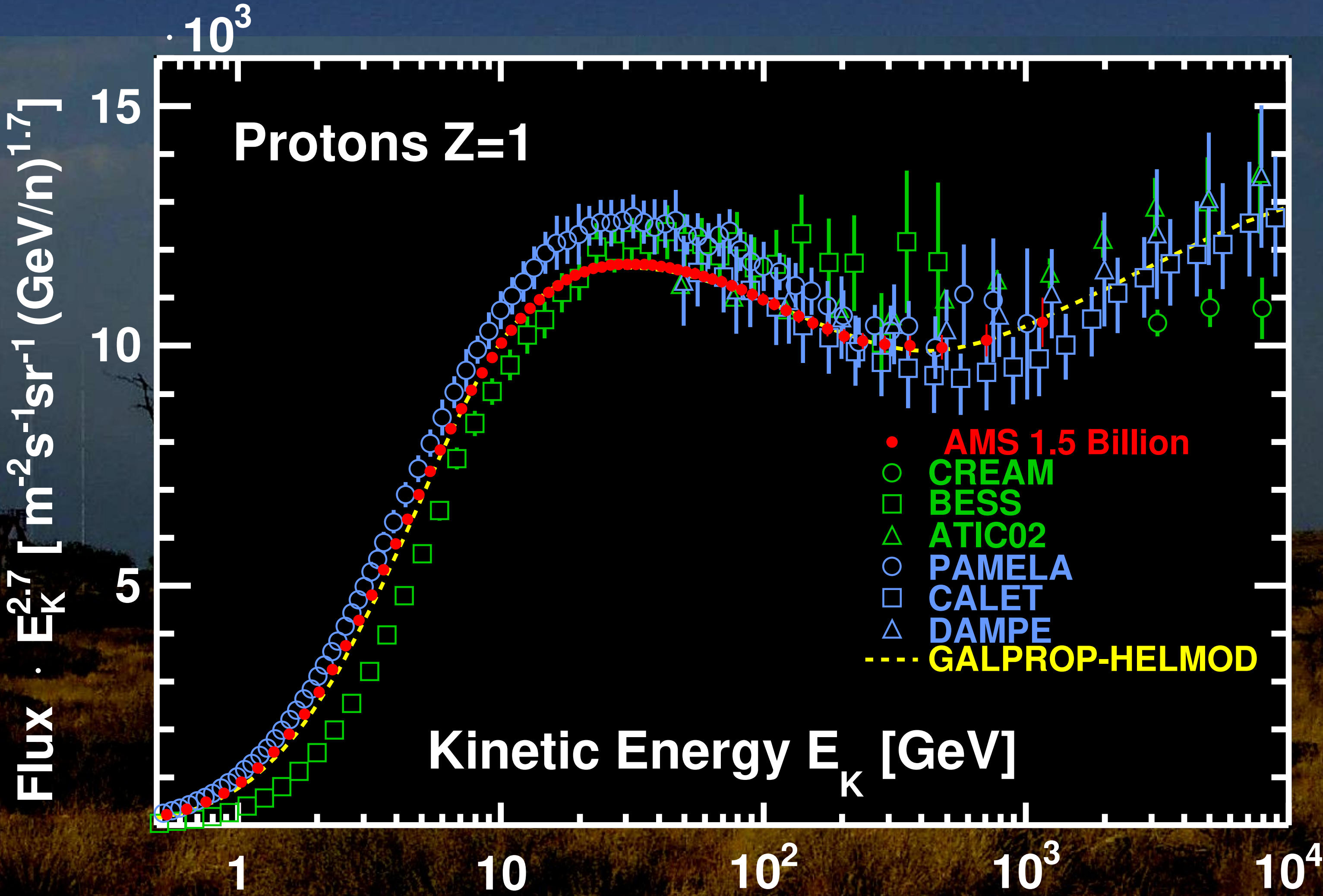
Proton Spectrum – 2017

- Unexpected hardening of the spectrum at a rigidity of ~ 300 GV



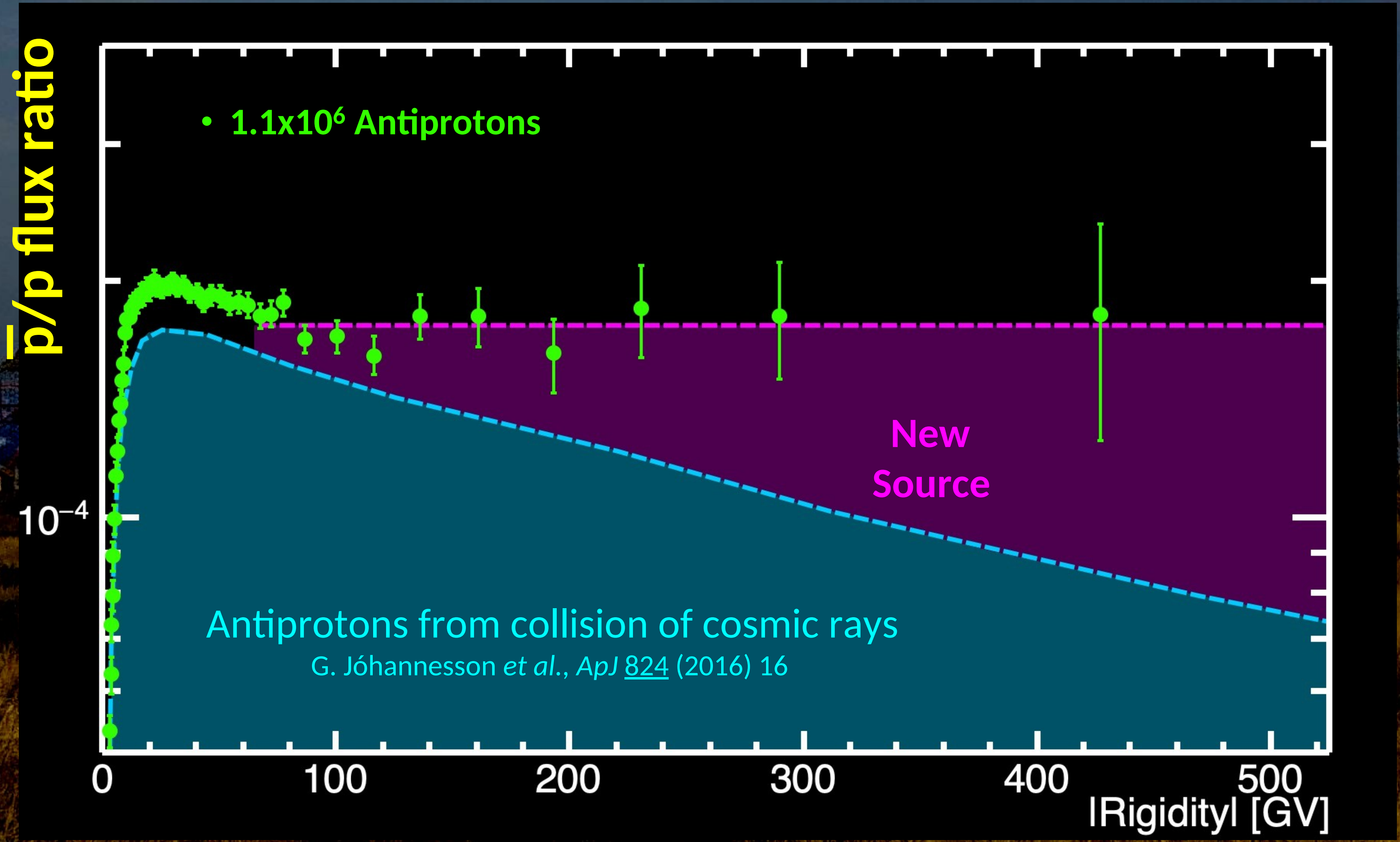
Proton Spectrum – 2023 update

- Hardening confirmed at ~ 200 GV

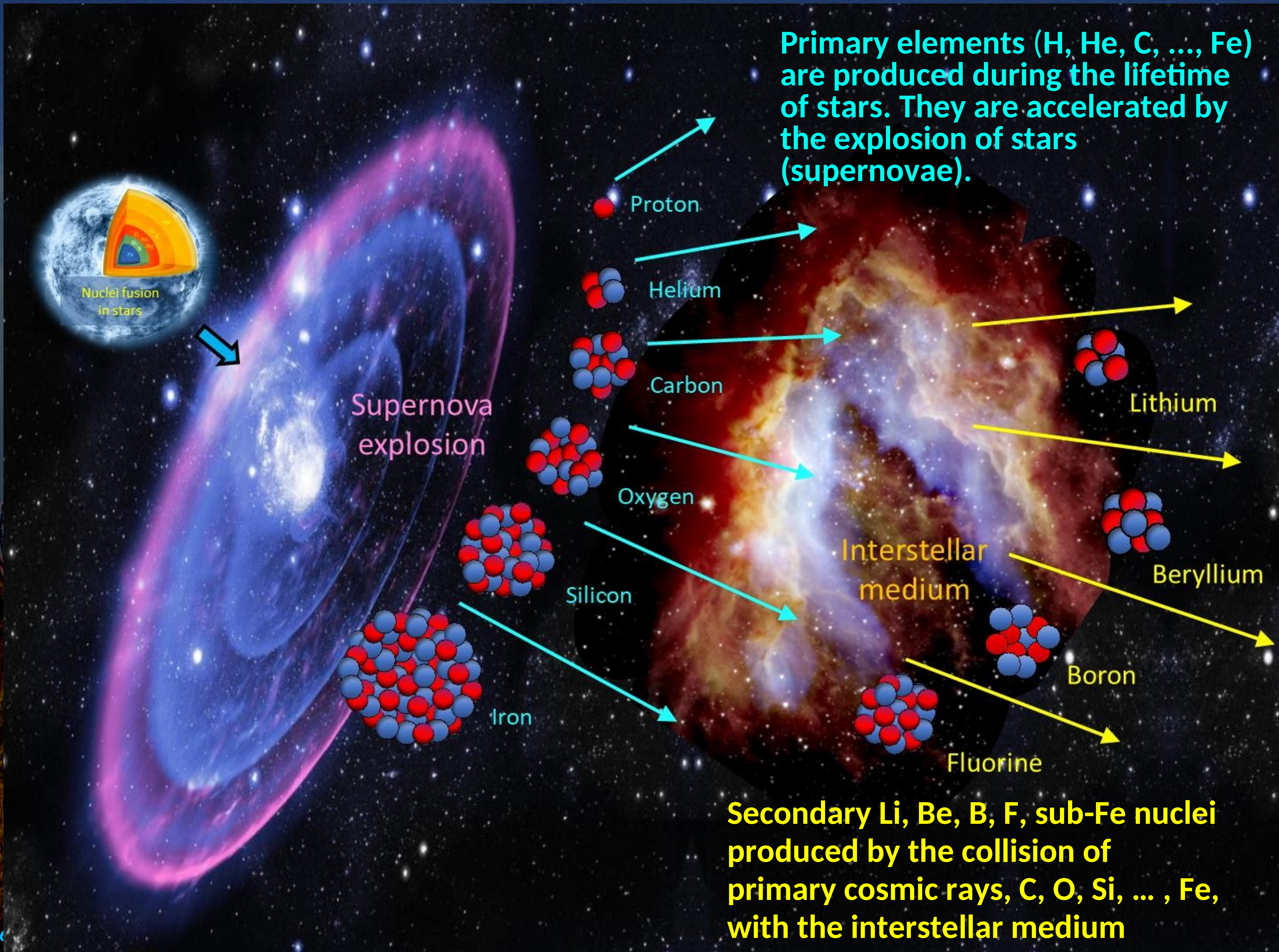


Antiprotons/Protons ratio – 2023

- Ratio almost constant above ~ 60 GeV
- Unexpected as antiprotons are secondaries!

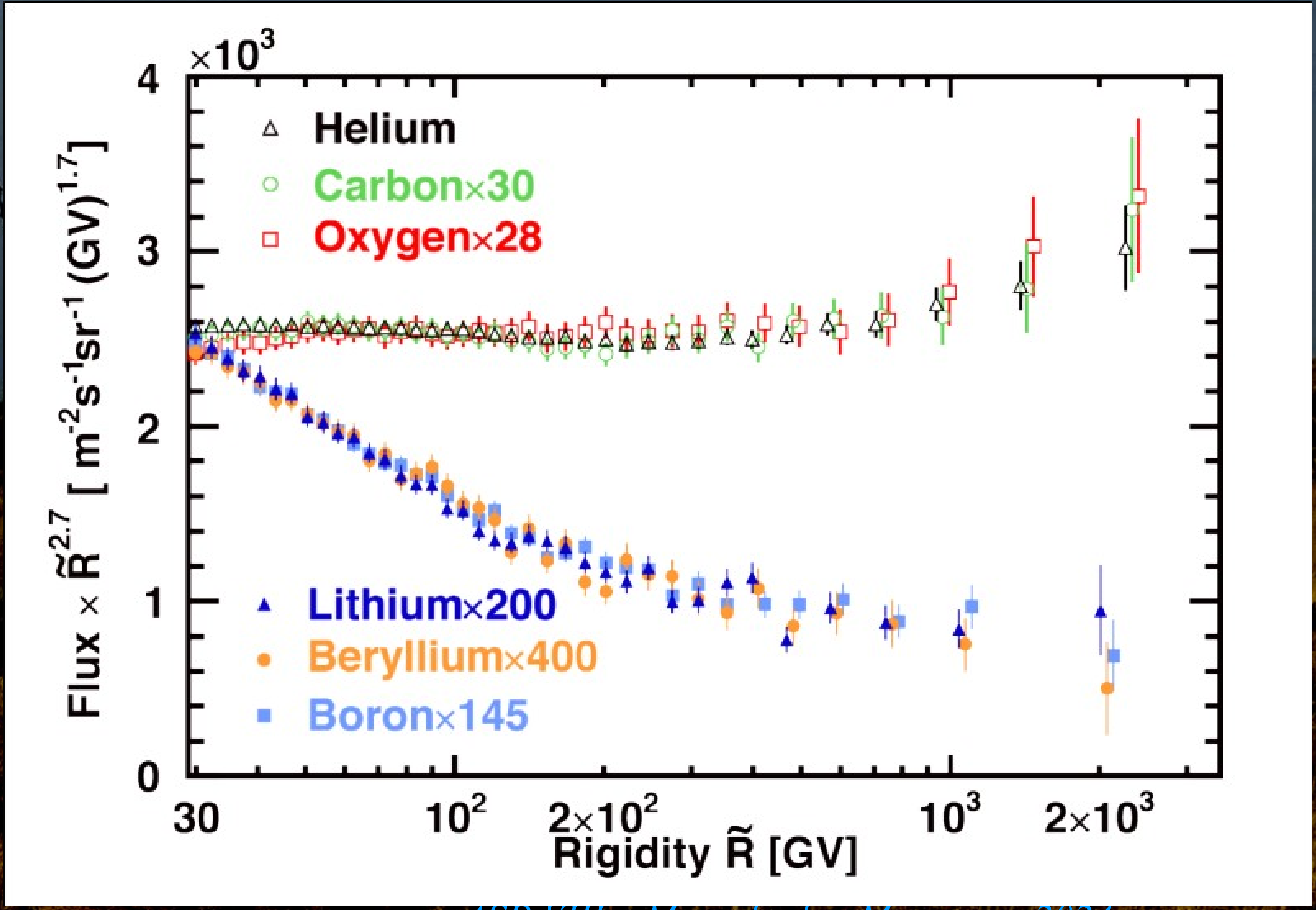


Primary and Secondaries



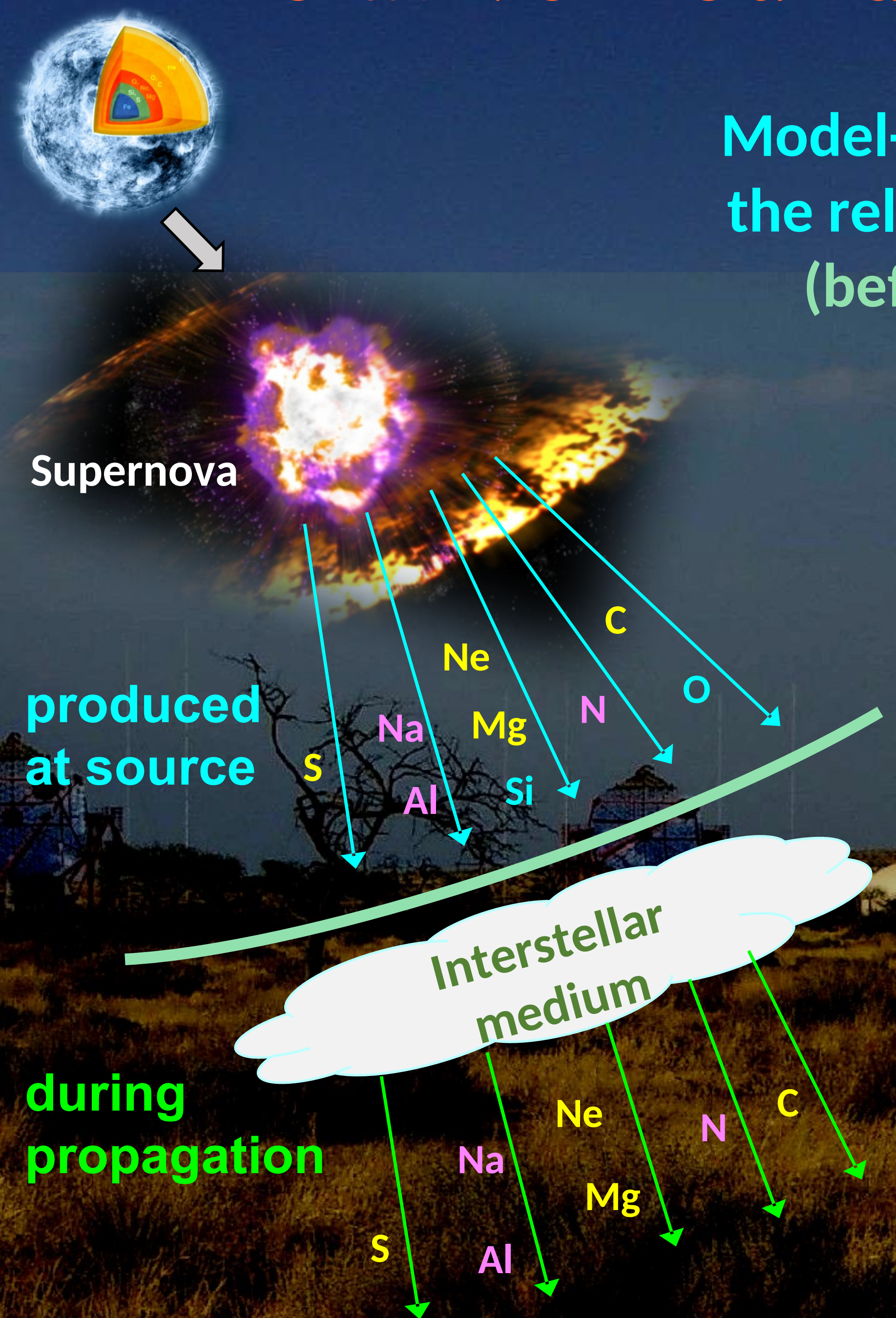
Primaries & Secondaries – 2021

- 2 groups of identical spectral shapes
- Steeper spectra for secondaries caused by propagation
- All spectra exhibit a break at ~ 200 GV
- Break 2 × more pronounced in secondaries ⇒ propagation effect?



Phys. Rep. 894 (2021) 1-116

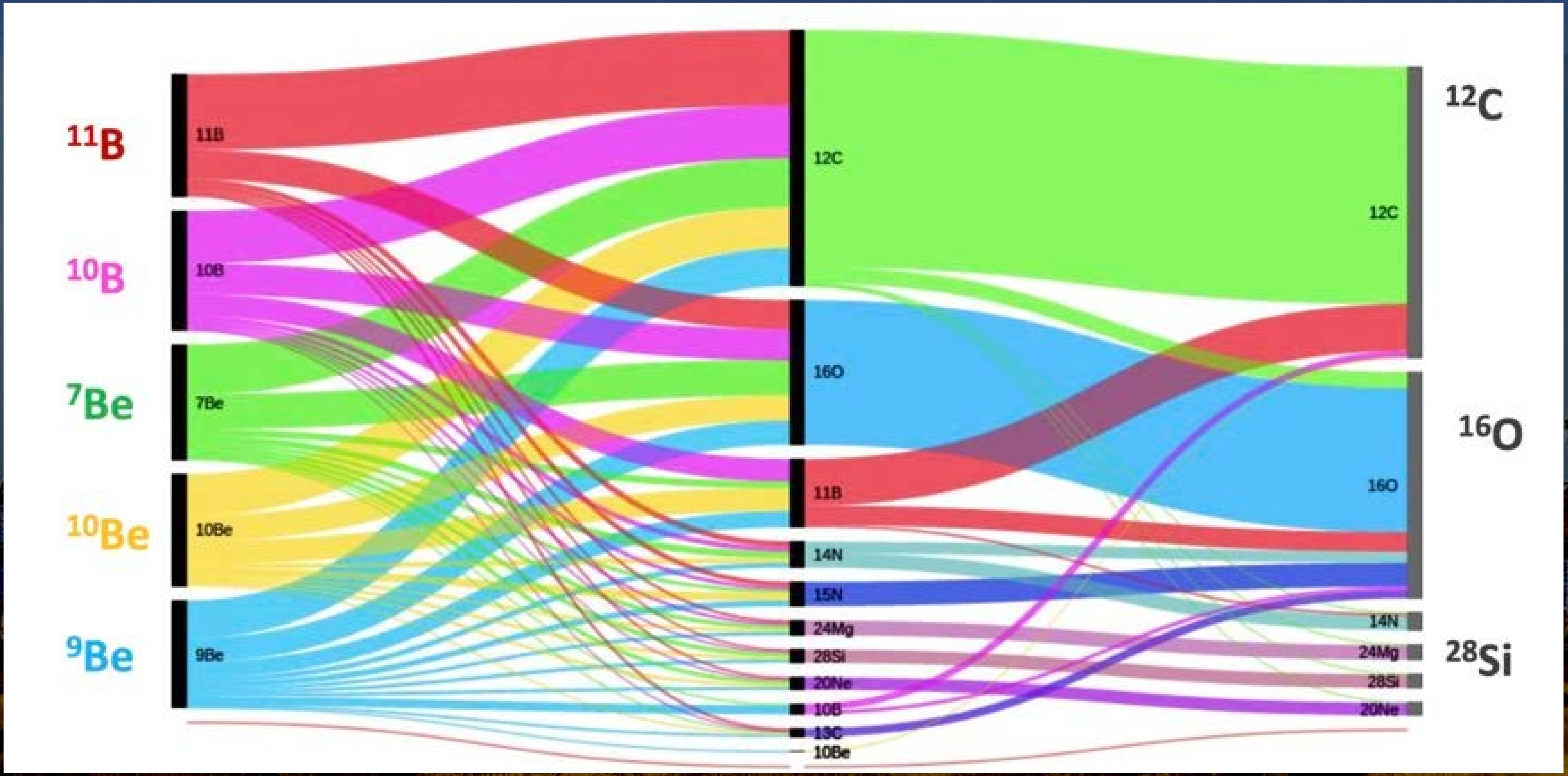
Relative Abundances – 2023



Model-independent measurements of the relative abundances at the source (before cosmic ray propagation)

Abundance Ratio	Value at the Source
C/O	0.836 ± 0.025
Ne/Si	0.833 ± 0.025
Mg/Si	0.994 ± 0.029
S /Si	0.167 ± 0.006
N/O	0.092 ± 0.002
Na/Si	0.036 ± 0.003
Al/Si	0.103 ± 0.004

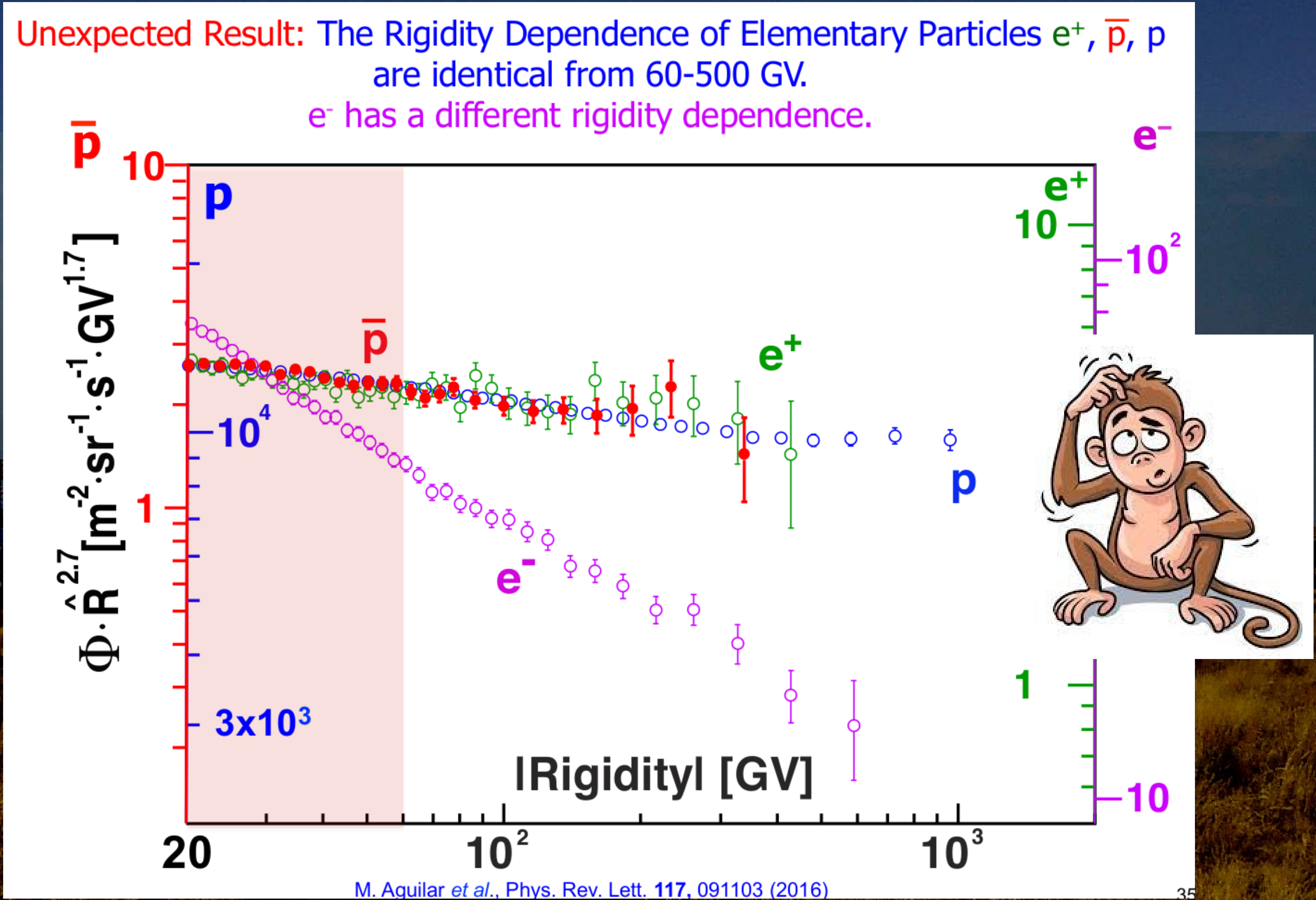
Complicated – Spallation scenario



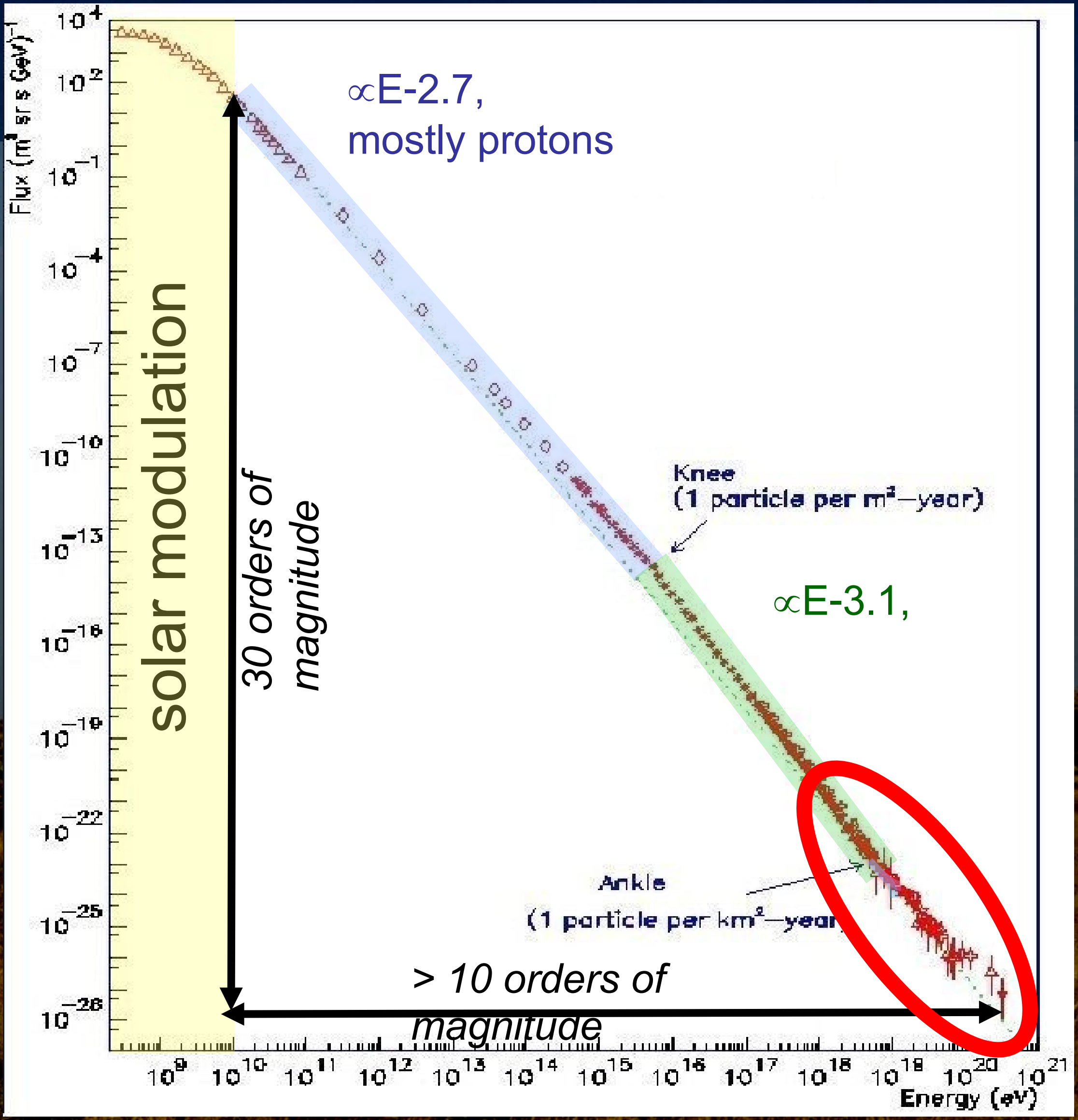
Secondary Intermediate, long lived Primary

Nicola Tomassett, 2017

Summary of AMS results

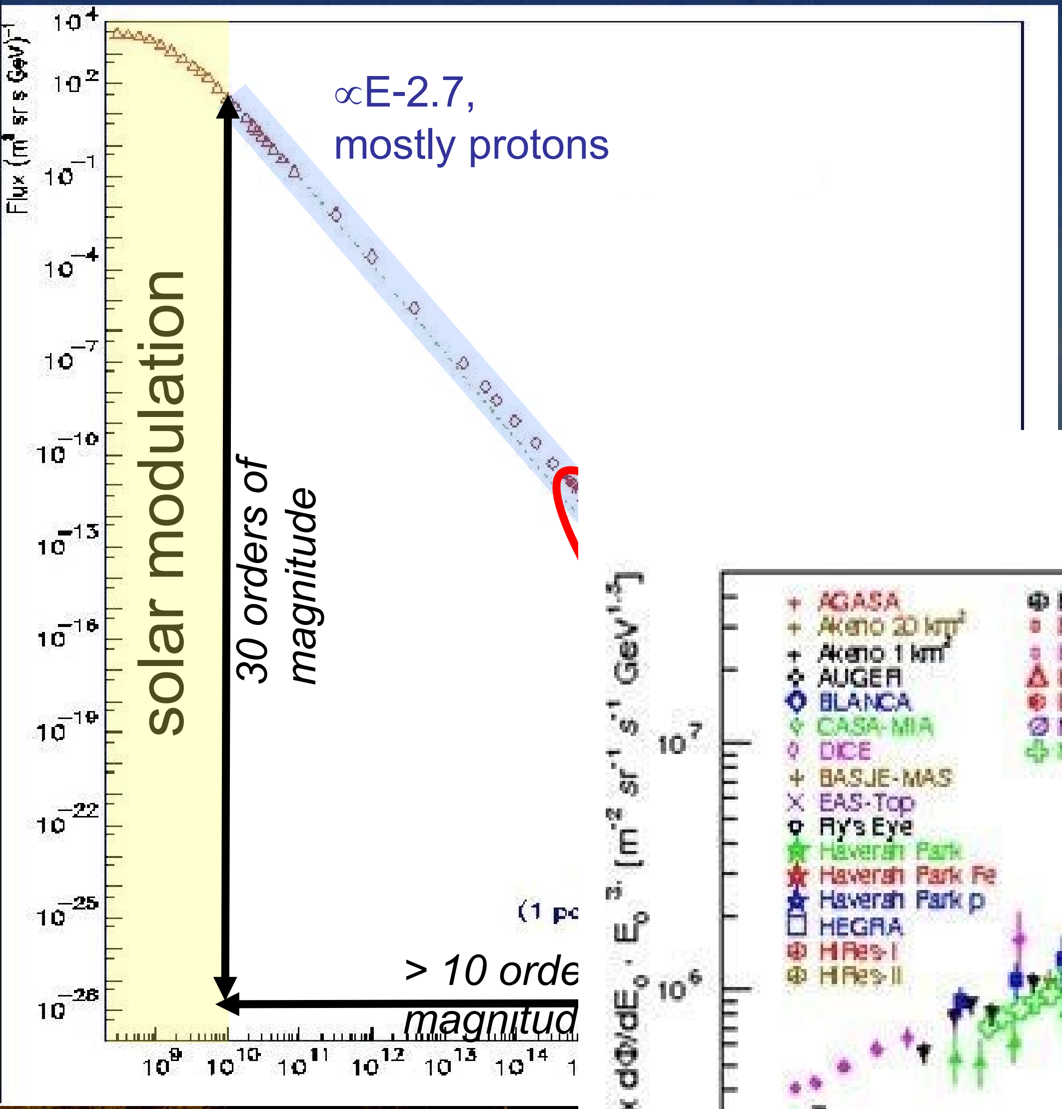


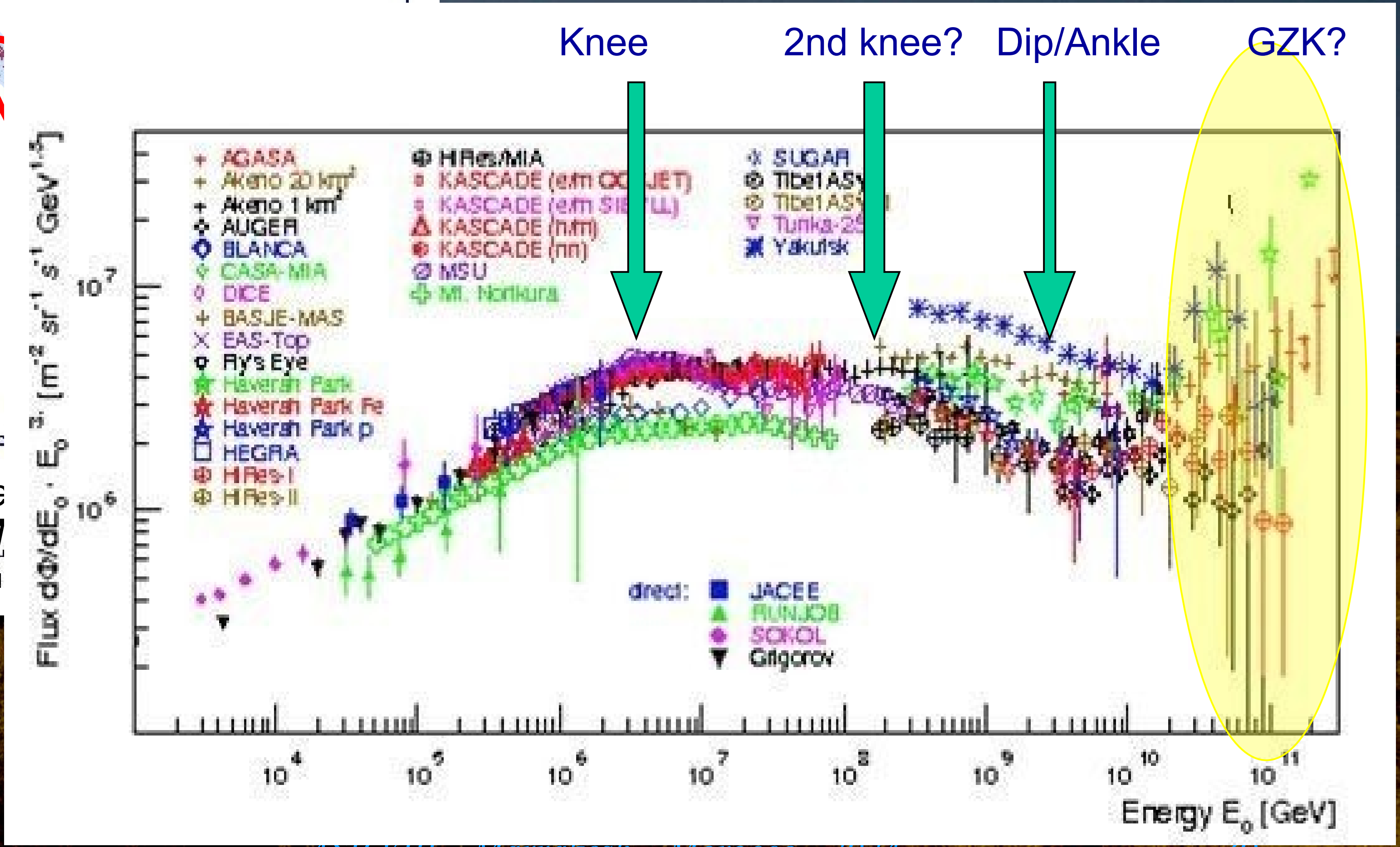
Ultra High Energy Cosmic Rays (UHECR)



Structures in the CR spectrum

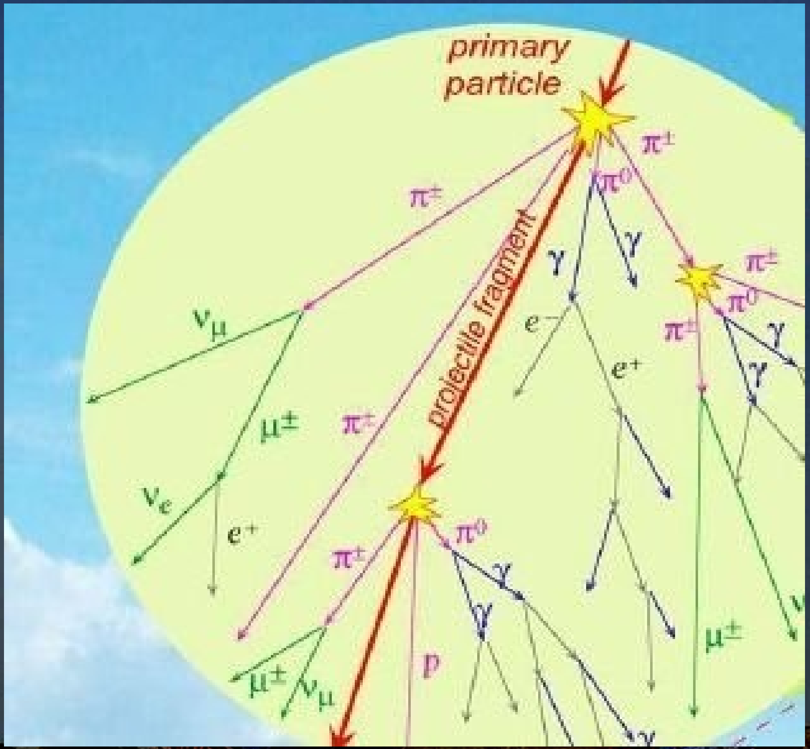
- Somewhat messy picture
- Different experiments/techniques
- Many things to understand!





Hadronic Showers

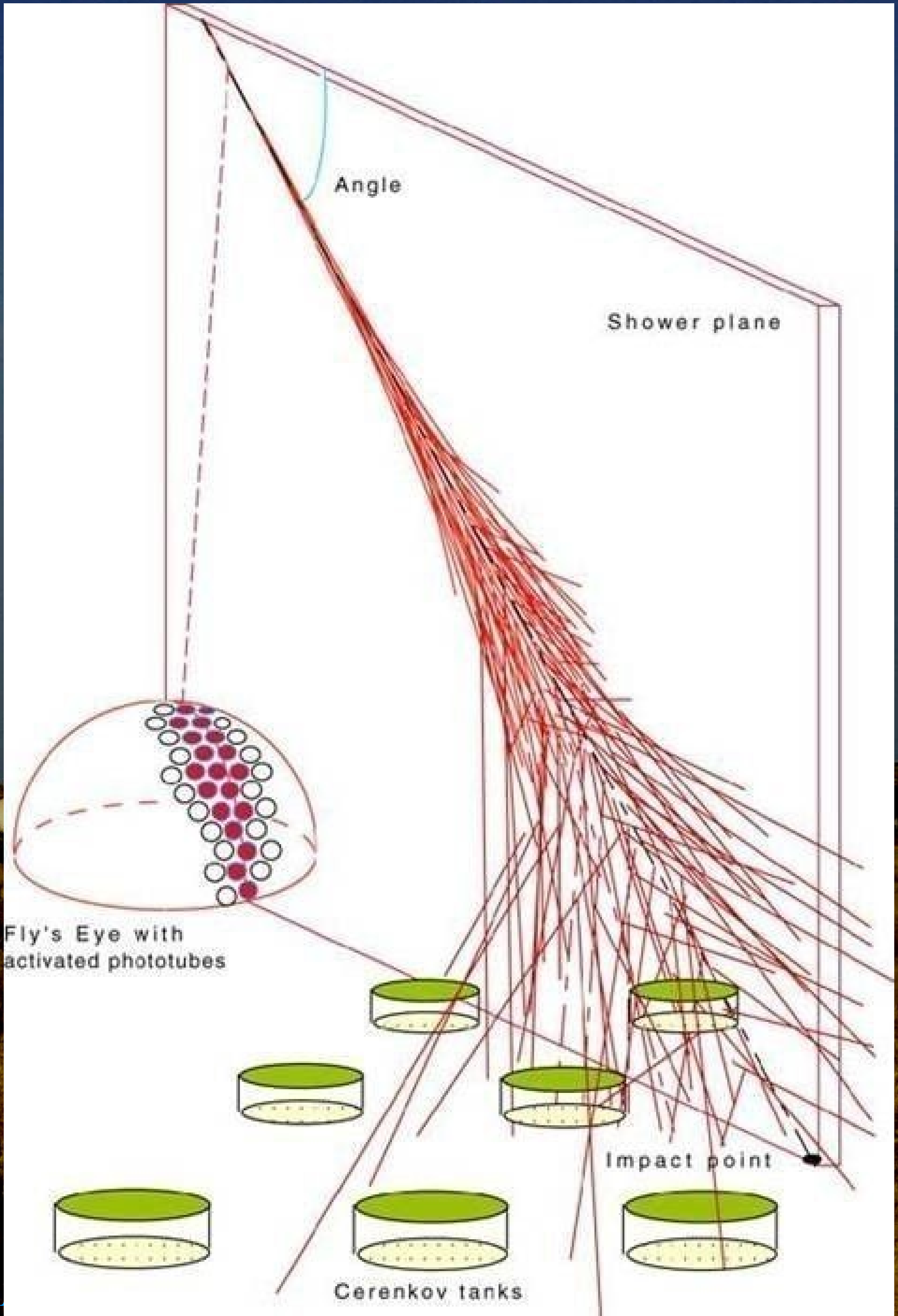
- **Hadronic component** : nuclear fragments, nucleons, π & K mesons, etc.
- **Electromagnetic component** : from $\pi^0 \longrightarrow \gamma\gamma$ and other radiative decays
- **Muonic component** : from decay of charged mesons ($\pi^\pm$ & $K^\pm$)
- **Atmospheric neutrinos** from decay of $\pi^\pm$, $K^\pm$ & $\mu^\pm$



Detection of extended shower

3 complementary techniques

- ❑ Detection of charged particles on the ground
  - ☑ 24h/24h duty cycle
  - ☒ Degraded information (shower tails)
- ❑ Detection of nitrogen fluorescence
  - ☑ Direct measure of shower development profile
  - ☒ 10% duty cycle (dark nights)
- ❑ Radio emission from showers



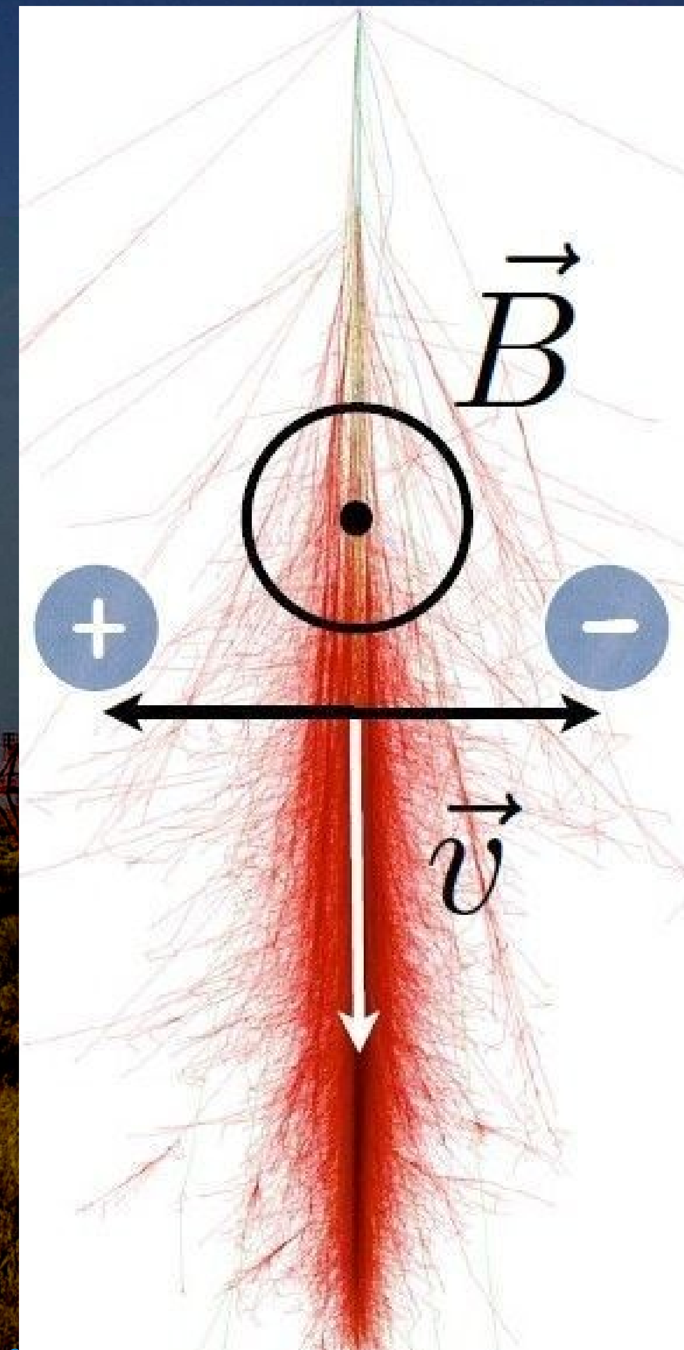
Radio Emission

- Positron Annihilation & Compton scattering create a small (~10%) asymmetry between e^+/e^- in showers

  ⇒ Vertical current (seed for lightnings)
- Earth magnetic fields separates e^+/e^- apart

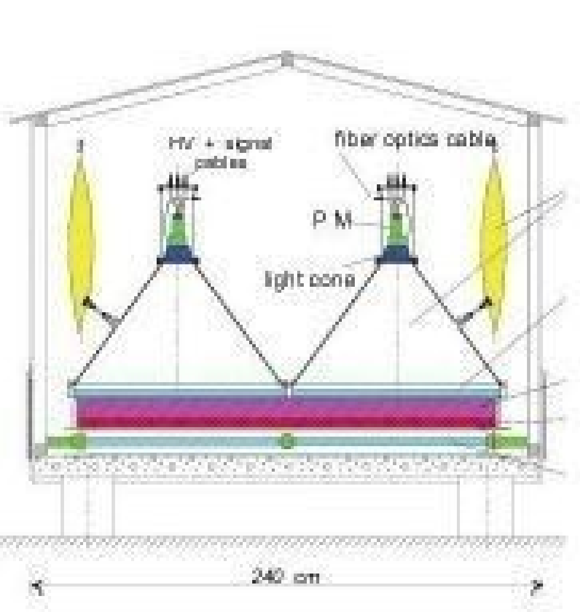
  ⇒ Dipole in relativistic motion...
- Synchrotron emission of e^+/e^-

- Radio signal in [1-200] MHz
- Lots of human emission in this band
  ⇒ difficult to detect
- Calorimetric measurement



Surface Detector

- Charged particles in shower tail ($e^{\pm}$ & $\mu^{\pm}$)
  - Water Cherenkov tanks ($e^{\pm}$ & $\mu^{\pm}$) : AUGER
  - Scintillator arrays. Absorber (20 X_0) can be used to separately measure $e^{\pm}/\mu^{\pm}$ components



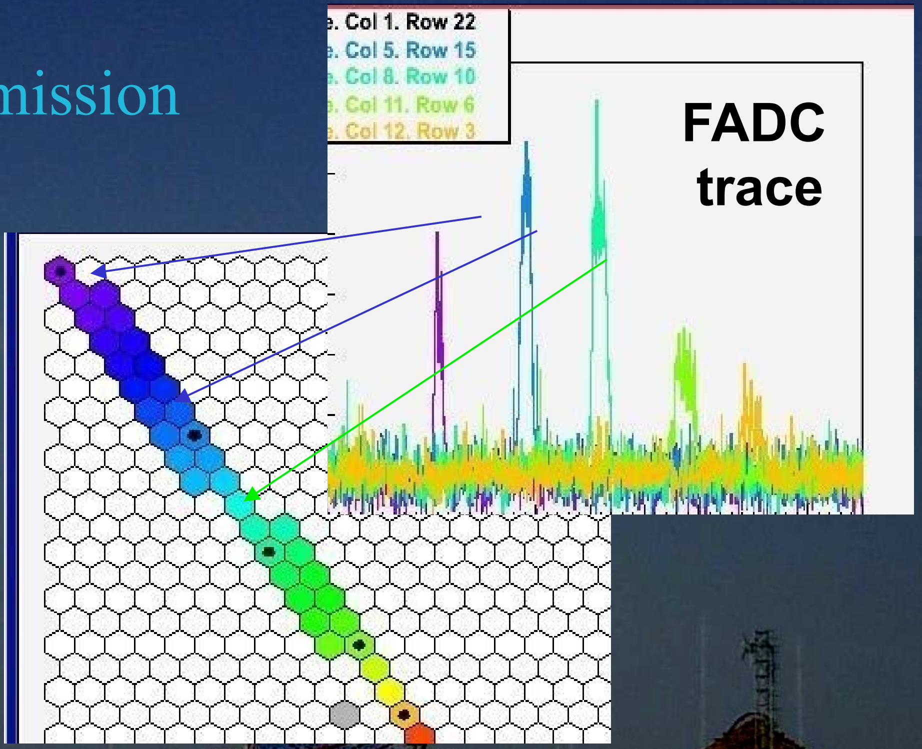
- Reconstruction relies on simulation
  - Hadronic Models
  - Detector geometry

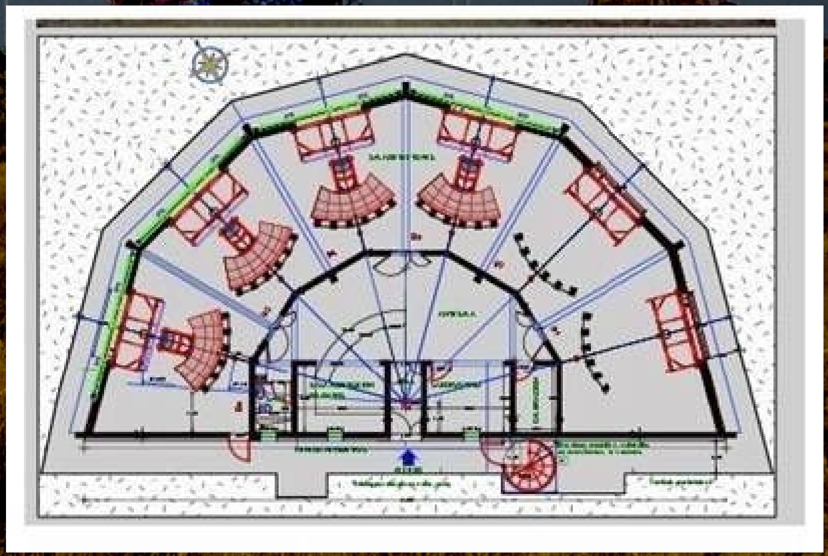
⇒ Poorly controlled systematics

Fluorescence Detector

- Nitrogen excitation, Molecular lines emission proportional to ionization
- Isotropic emission (310-400 nm)
  ⇒ can be detected up to several 10 km
- Direct calorimetric measure
  ⇒ Longitudinal profile

- Stereoscopy ⇒ simple geometric reconstruction. Time sequence also usable
- Problems:
  - Fluorescence light yield poorly known. Depends on composition, humidity, …
  - Atmospheric transparency
  - Need to subtract forward Cherenkov

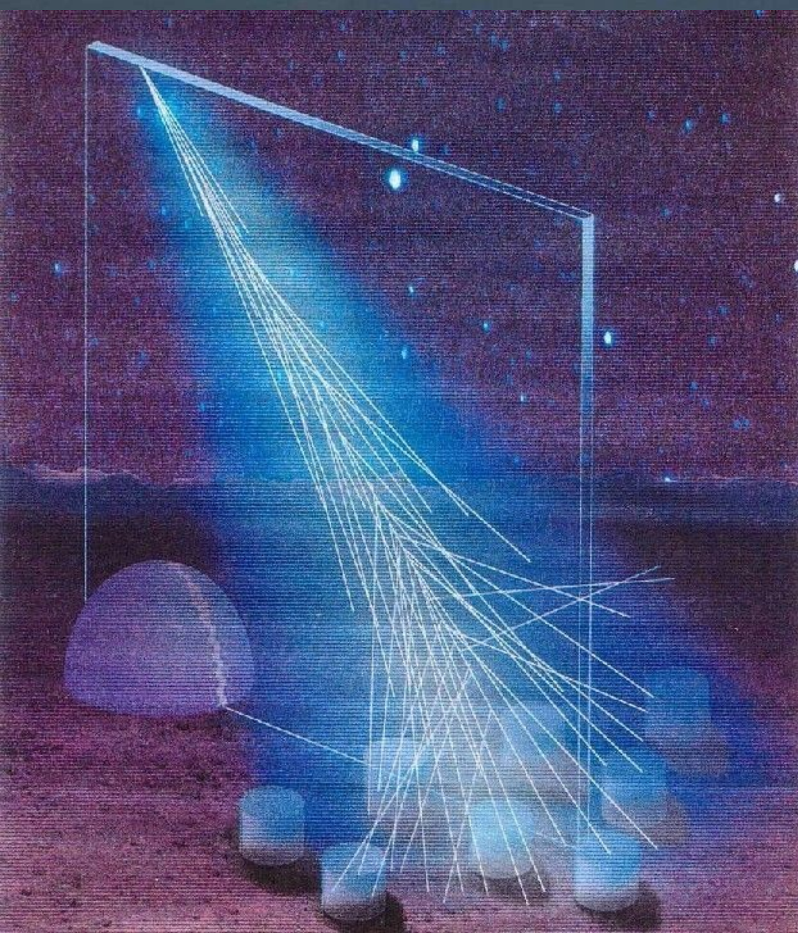


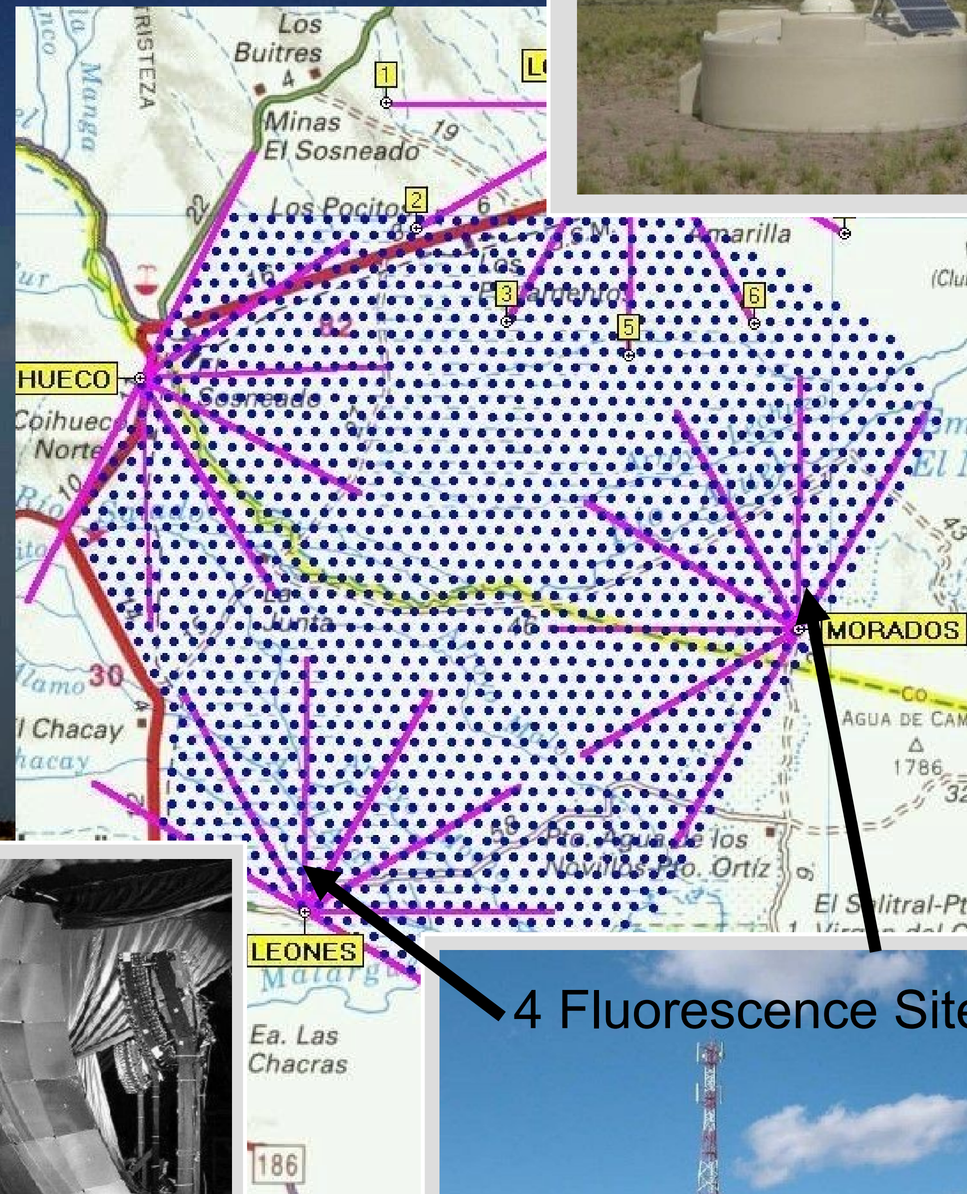


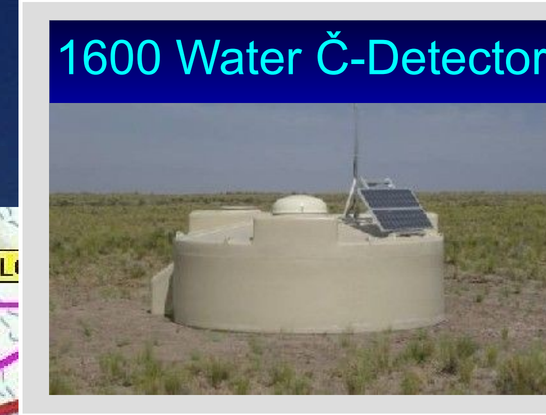
Experiments

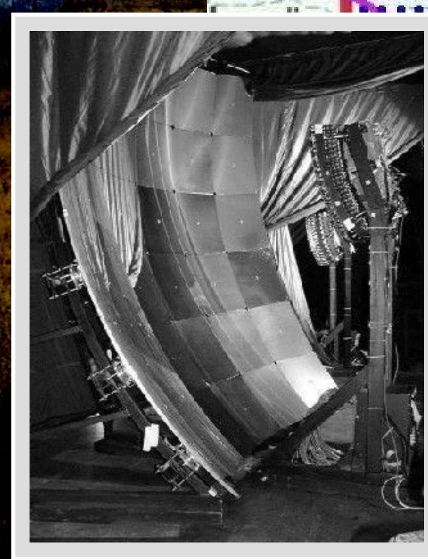
Auger @ Argentina

- Hybrid detector
  - 1600 tanks over 1000 km^2
  - 4 fluorescence detectors with 6 telescopes each



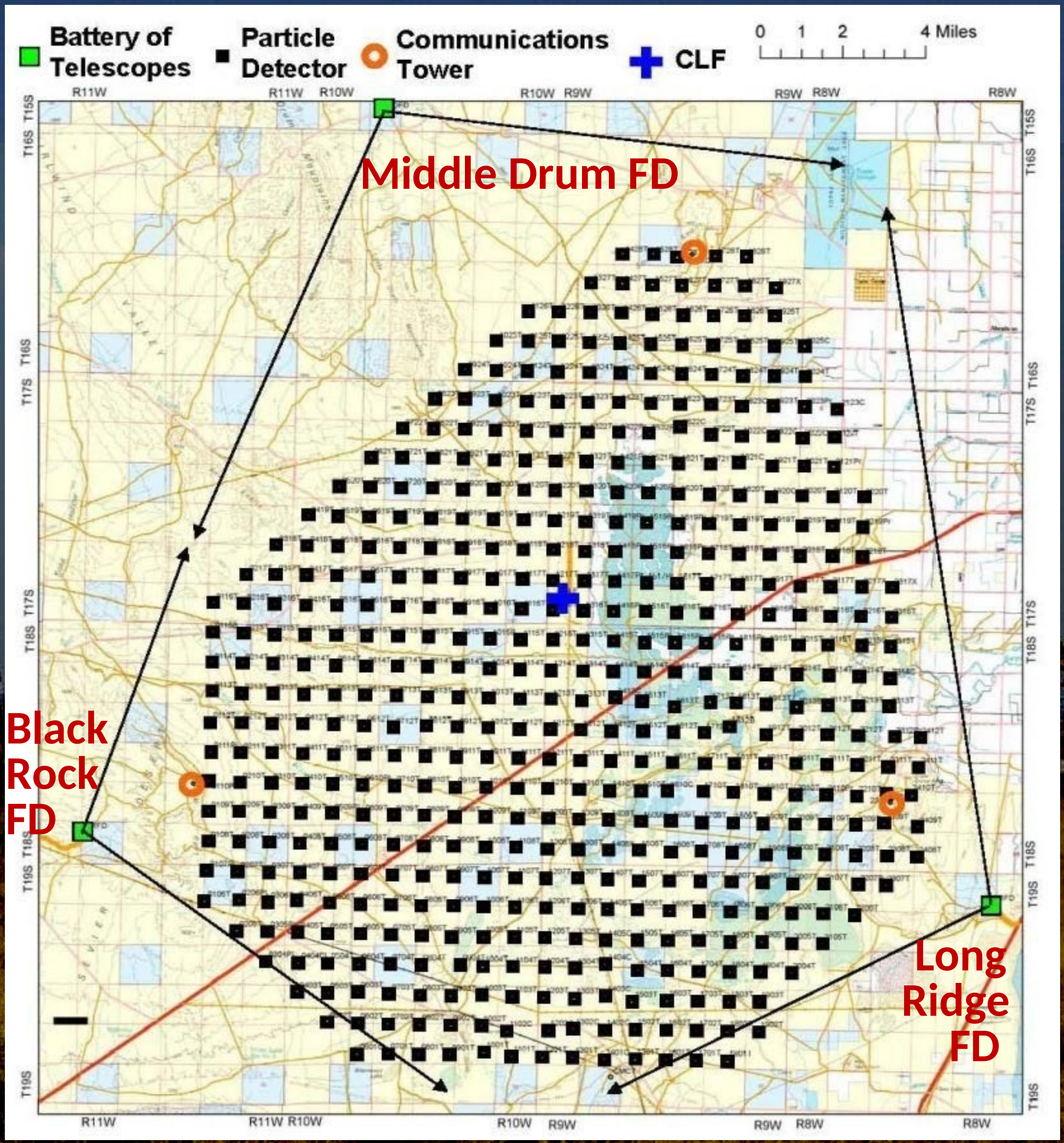




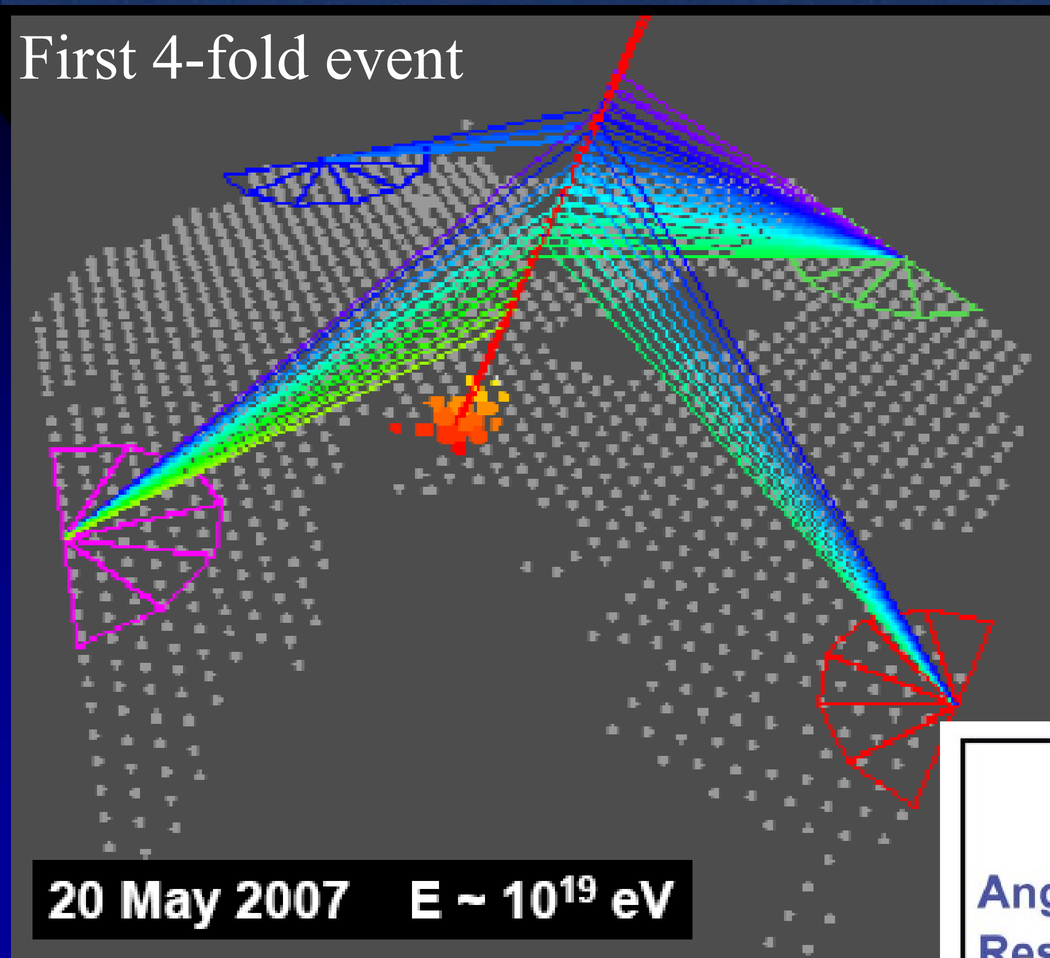


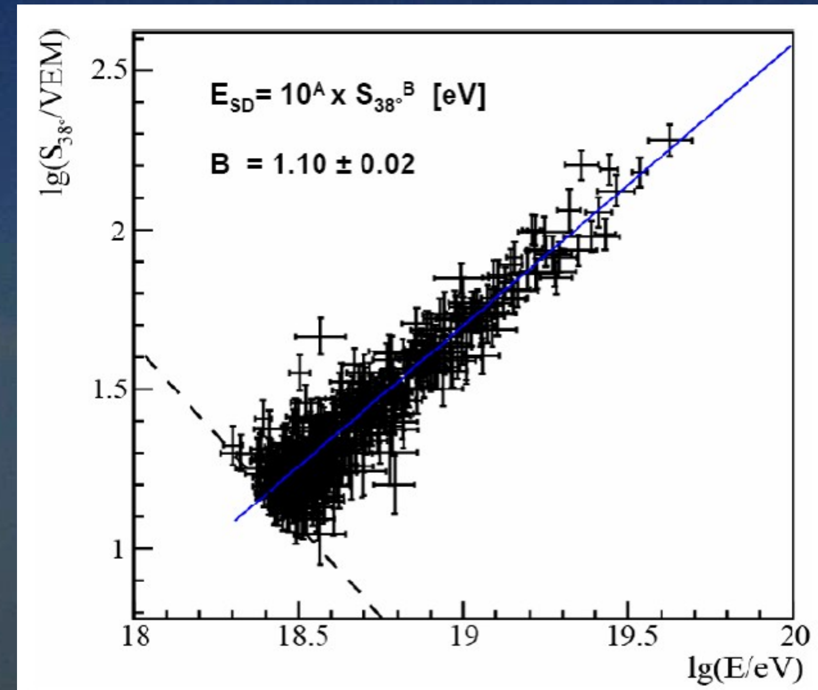
Telescope Array @ USA

- 507 scintillation counters surface detector (SD)
  - Area: ~700 km^2
- 3 fluorescence detector (FD) stations
  - Located at the "corners" of the SD array
  - + Low energy extension (TALE)
- In operation since March 2008



Hybrid Era



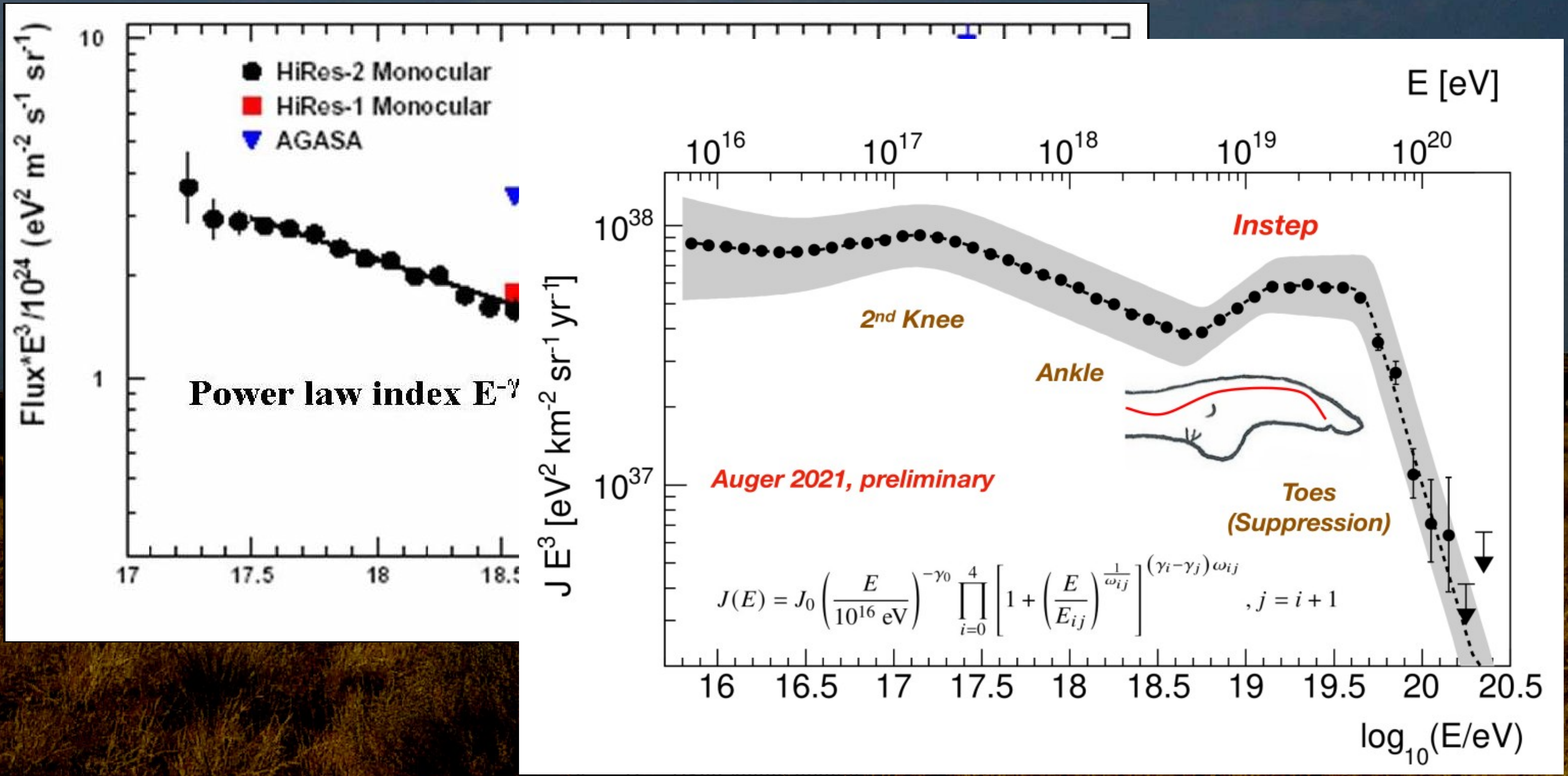


- Cross-calibration SD-FD
- Improved resolutions
- Less model dependency
- Control on systematics

	Hybrid	SD-only	FD-only mono (stereo – low N)
Angular Resolution	~ 0.2°	~ 1 - 2°	~ 3 - 5°
Aperture	Flat with energy AND mass and model (M) free		E, A, spectral slope and M dependent
Energy	A and M free	A and M dependent	A and M free

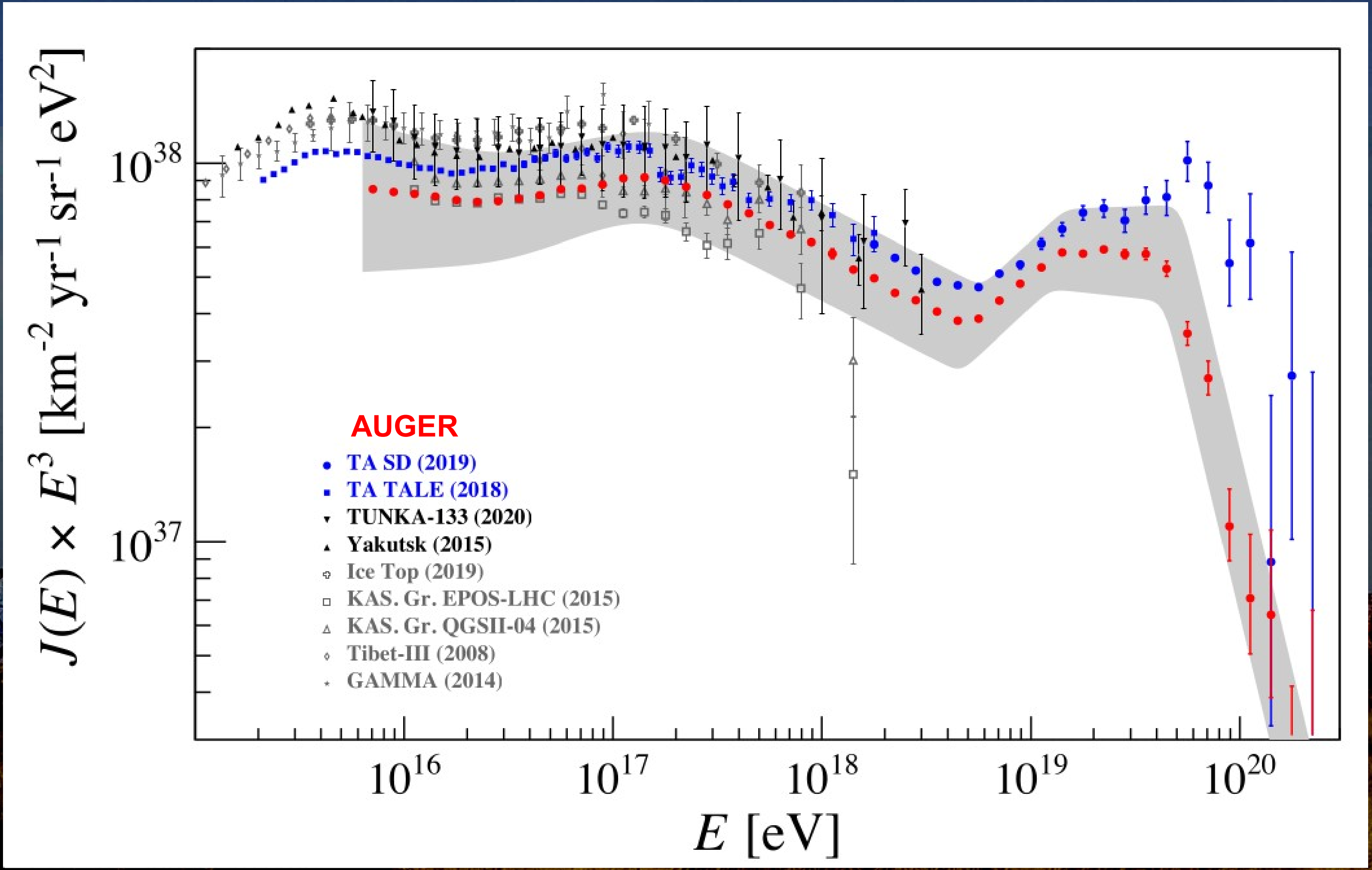
Energy Spectrum

- Situation before Auger unclear
- FD / SD intercalibration on hybrid events
- Confirmation of a cutoff @ $10^{19.7}$ eV (20 σ effect)



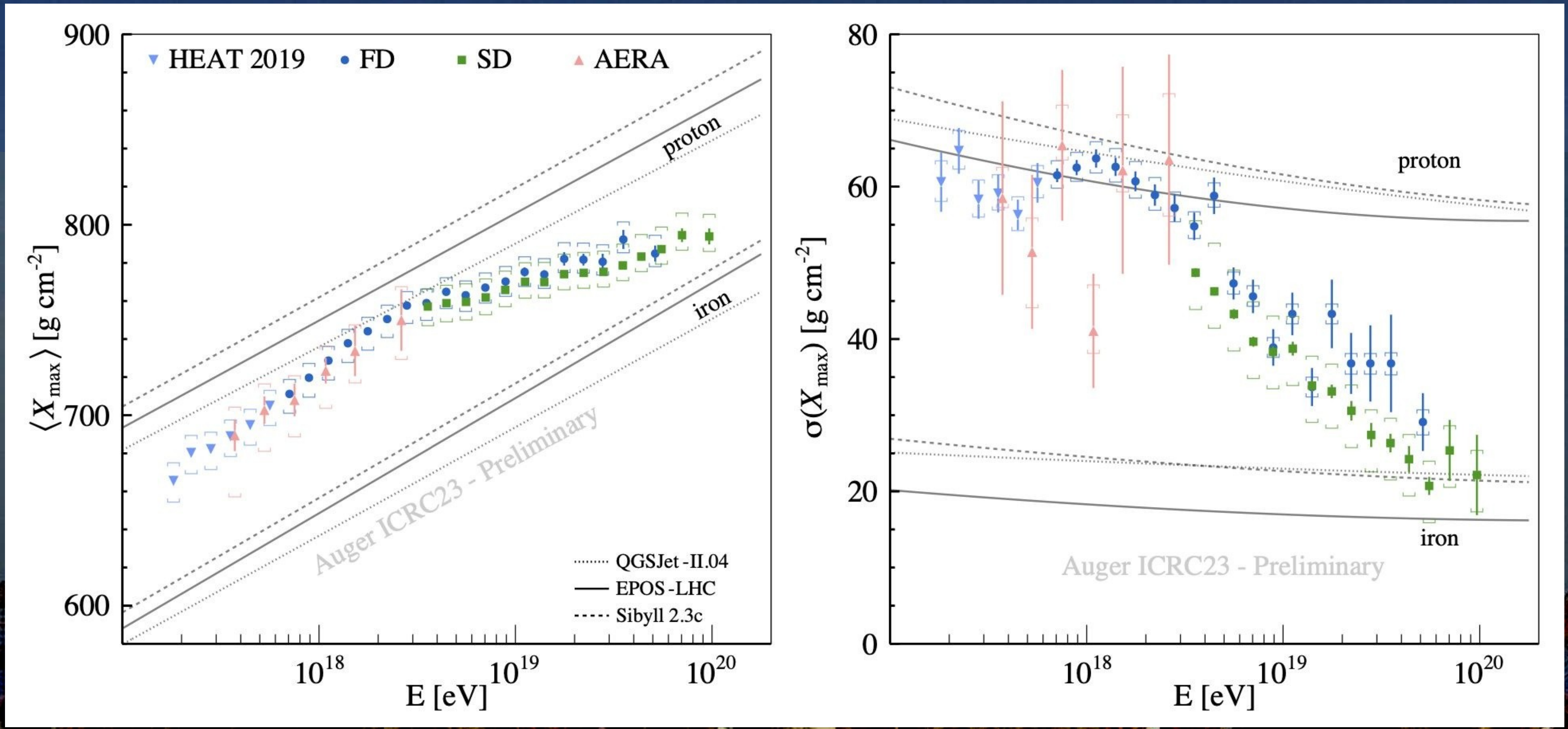
$$J(E) = J_0 \left(\frac{E}{10^{16}\,\mathrm{eV}}\right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\,\omega_{ij}}, \; j = i+1$$

Energy Spectrum – Comparison



- Overall shape agreement
- Need ~10% energy rescale for complete agreement

Composition – 2023

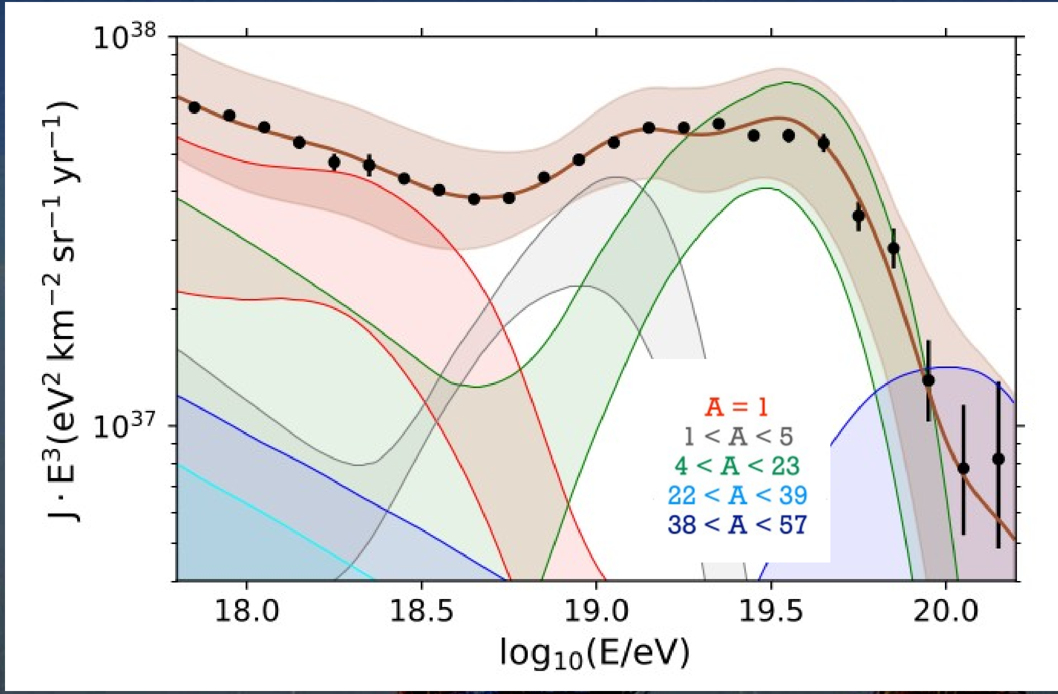


- 4 different measurements
- <Xmax>: composition becoming lighter up to 2×10^{18}eV (clear break) and heavier again as the energy increases
- □(Xmax) shows that composition is more mixed below 2×10^{18} eV and more pure at higher energies.

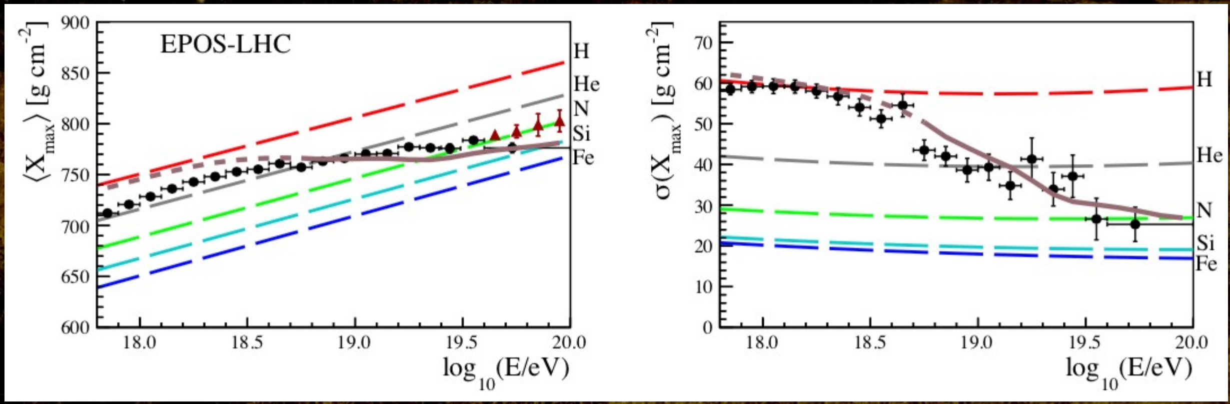
Astrophysical Scenario

- Homogeneous distribution of identical sources of p, He, N and Fe nuclei
- Power-law spectrum with rigidity-dependent broken exponential cut-off

  $R_{cut} \sim 1.5\times10^{18}$ V

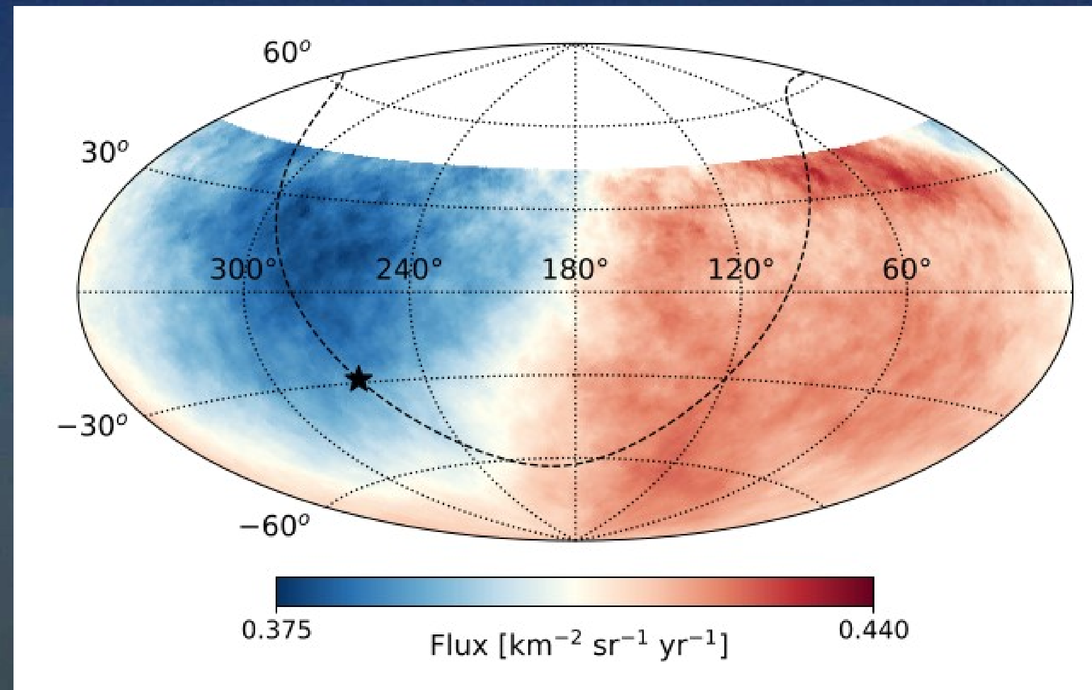


- Cut-off well explained by source max. energy + propagation losses

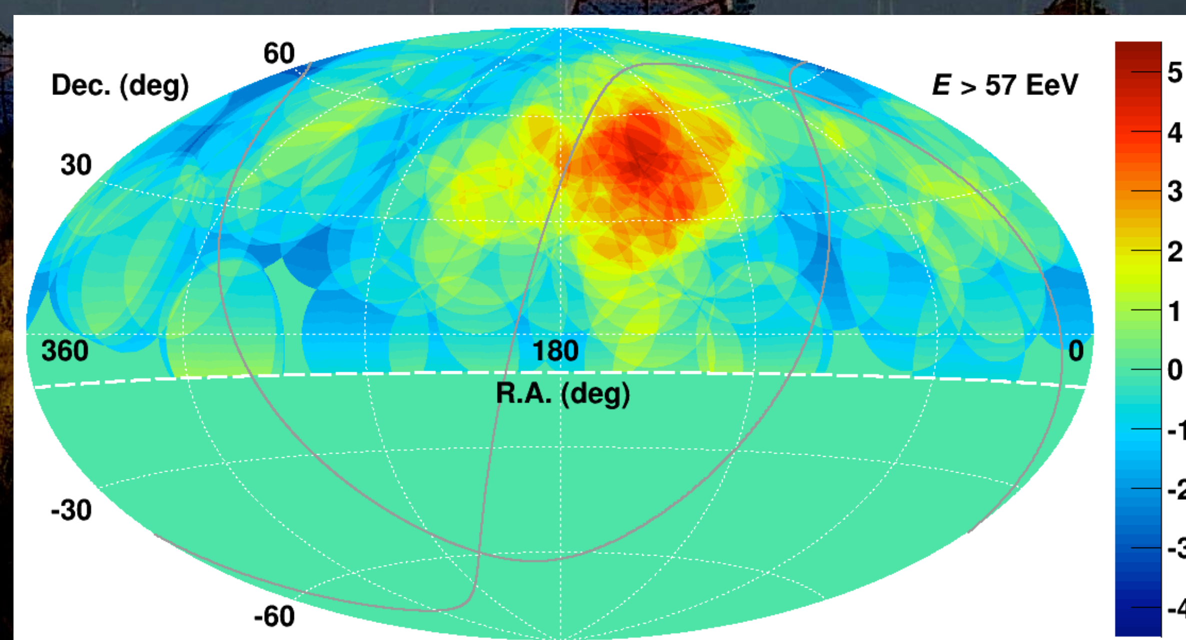


Sources ?

- Dipolar anisotropy observed > 8 EeV → Extragalactic Origin



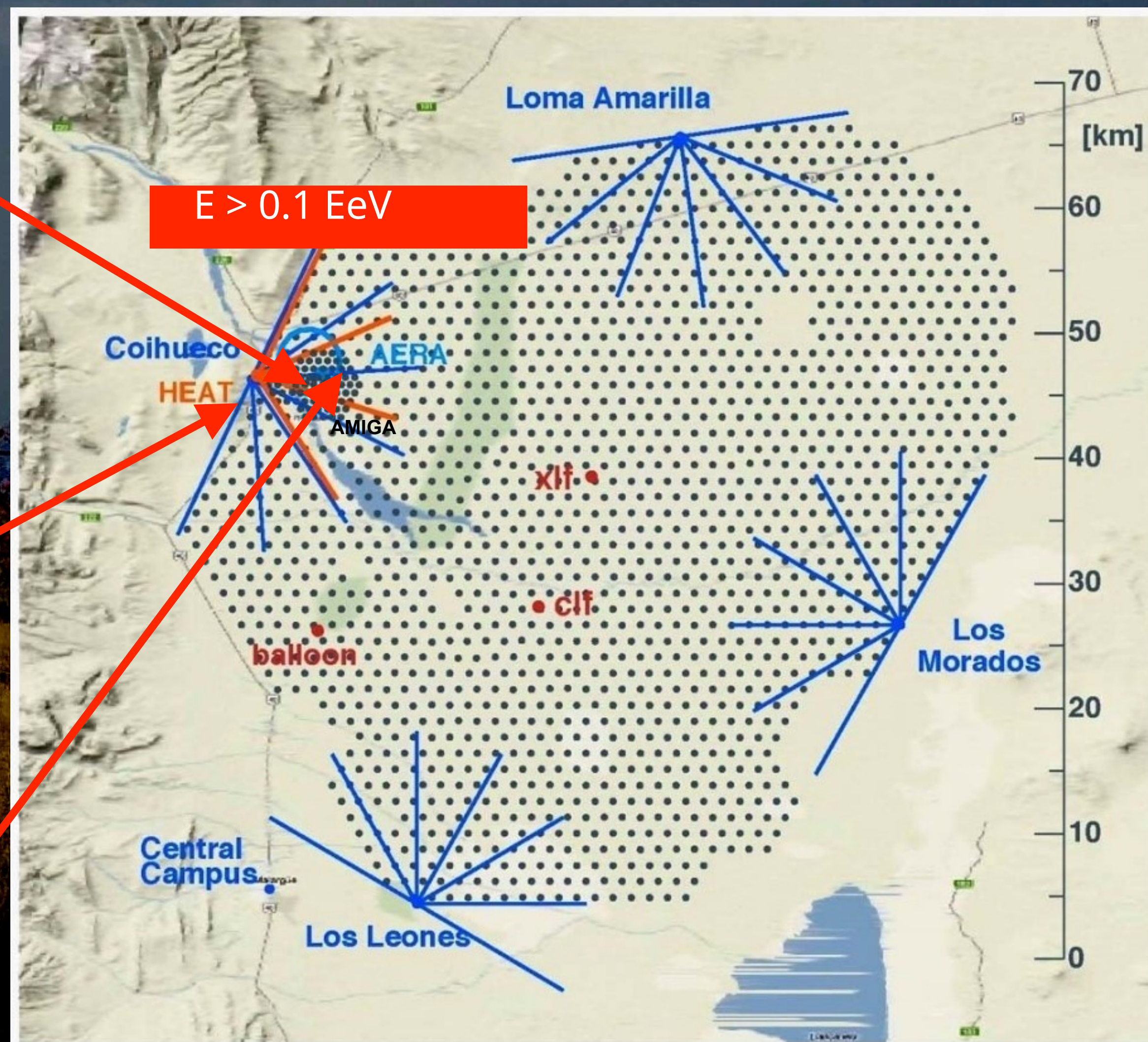
- Telescope Array (on the North) reported a 3.4 σ in the direction of Ursa Major



- To be followed!

AUGER Extensions

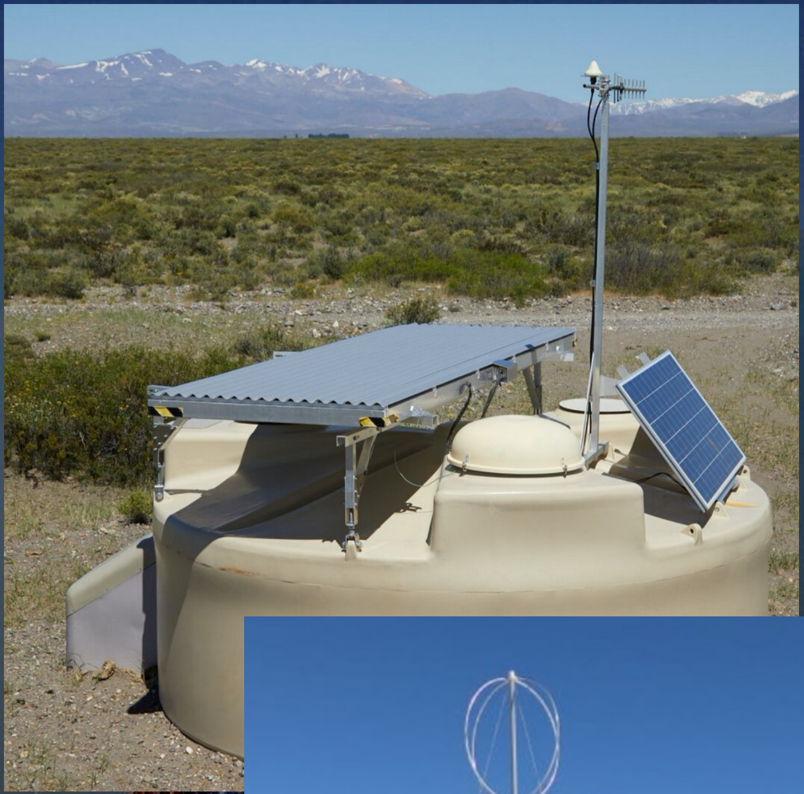
- Main goals:
  - extension towards lower energy
  - inclusion of radio detection



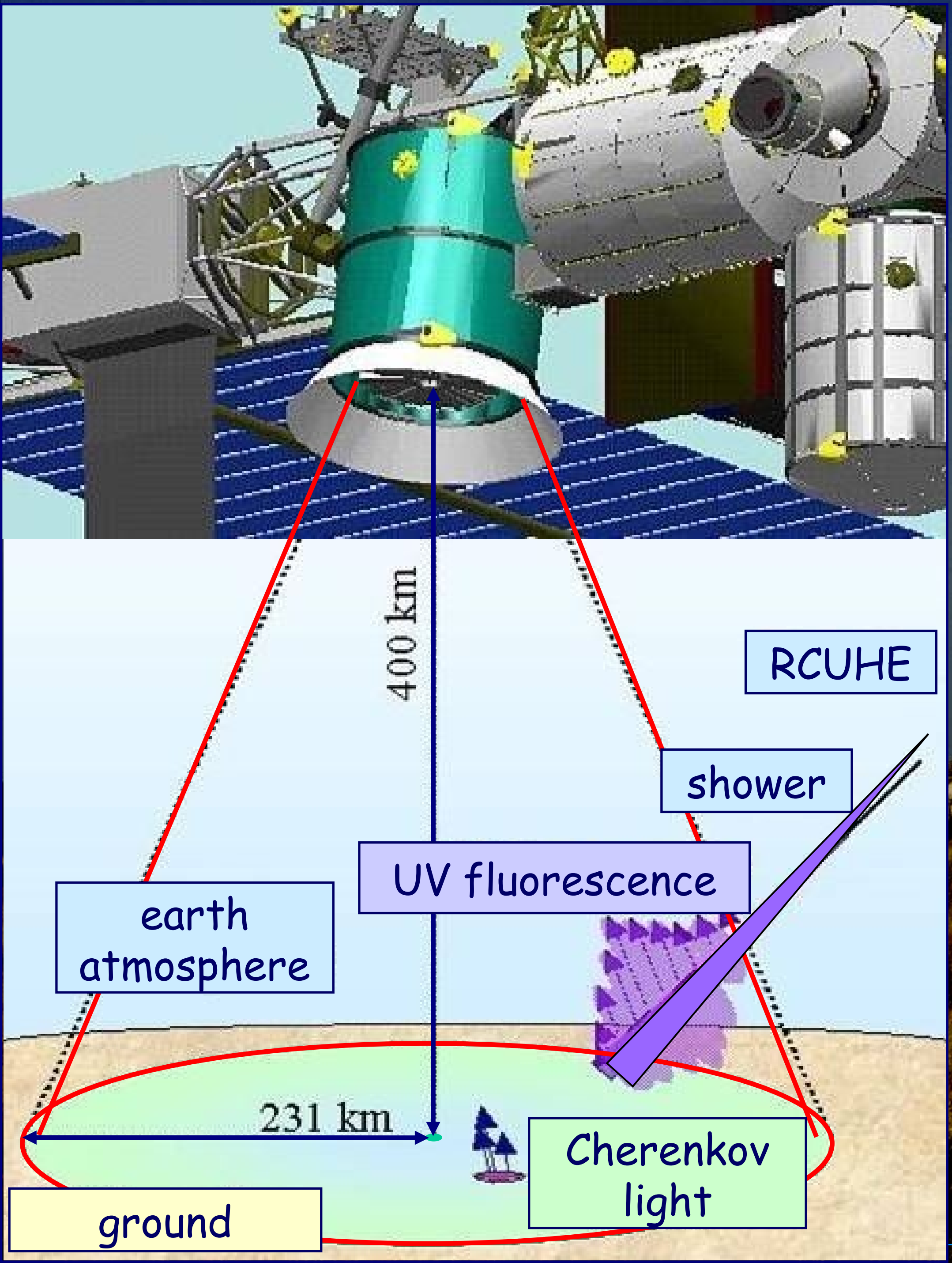
Mathieu

Ongoing Upgrades: Auger Prime

- Aim :Improve the knowledge on mass composition
  - Equip each SD tank with a 4 m^2 (1 cm thick) scintillator layer on top (SSD - Scintillators sensitive to the electromagnetic content of the shower)
  - Radio antenna
  - Upgraded and faster electronics
  - Some underground muon detector (UMD)



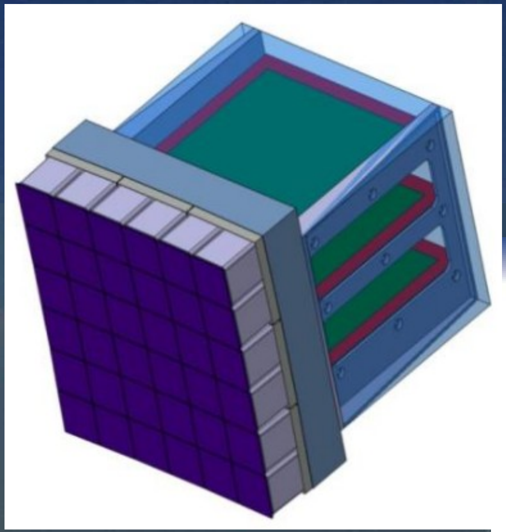
JEM - EUSO

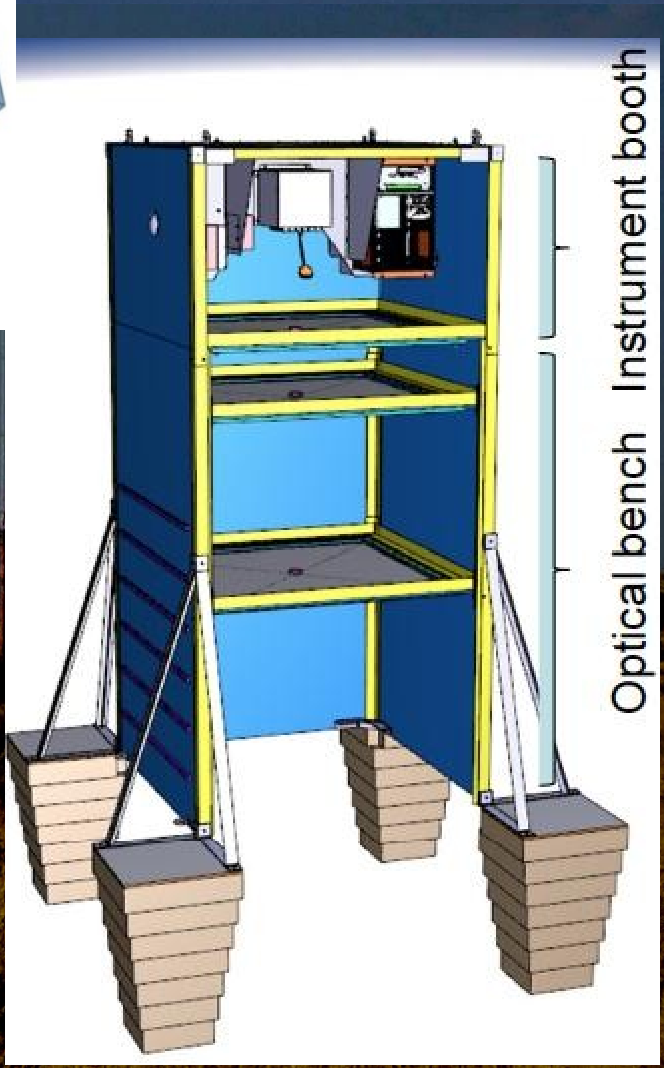


- Acceptance : 10^6 km^2 sr
- Target air mass : 10^{13} T
- Full sky coverage in one year
- 1000 events per year with E>10^{20} eV
- Balloon flight in 2014
- Launch foreseen in 2024 ?

PathFinder – EUSO BALLOON

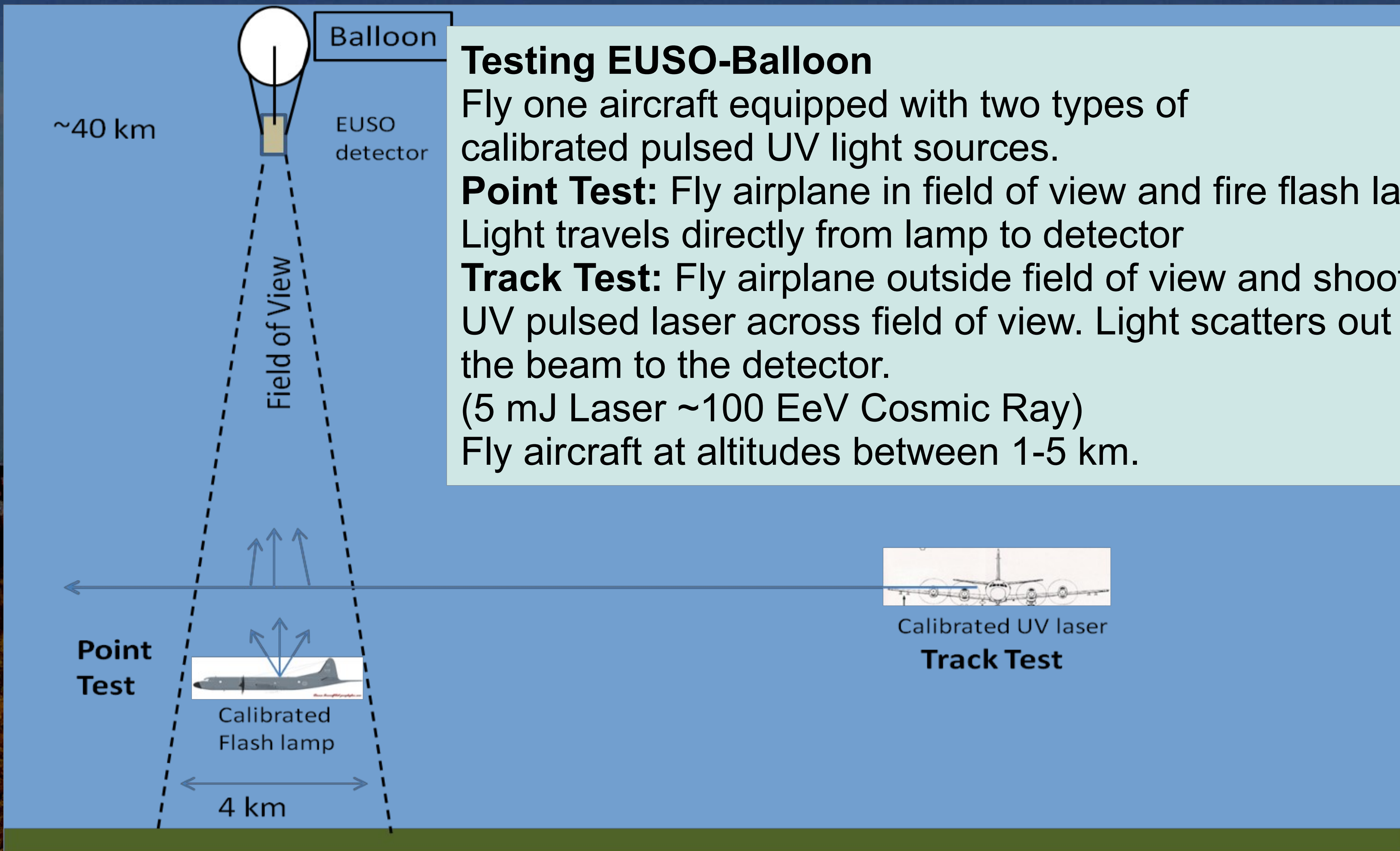
- Prototype with
  - 1 Optical system (3 flat-type lenses)
  - 1 Photodetector module (2304 pixels)
  - 1 Data Processor
  - 1 Telescope structure





EUSO Balloon tests

- First flight: august 2014



Testing EUSO-Balloon
Fly one aircraft equipped with two types of calibrated pulsed UV light sources.
Point Test: Fly airplane in field of view and fire flash lamp. Light travels directly from lamp to detector
Track Test: Fly airplane outside field of view and shoot a UV pulsed laser across field of view. Light scatters out of the beam to the detector.
(5 mJ Laser ~100 EeV Cosmic Ray)
Fly aircraft at altitudes between 1-5 km.

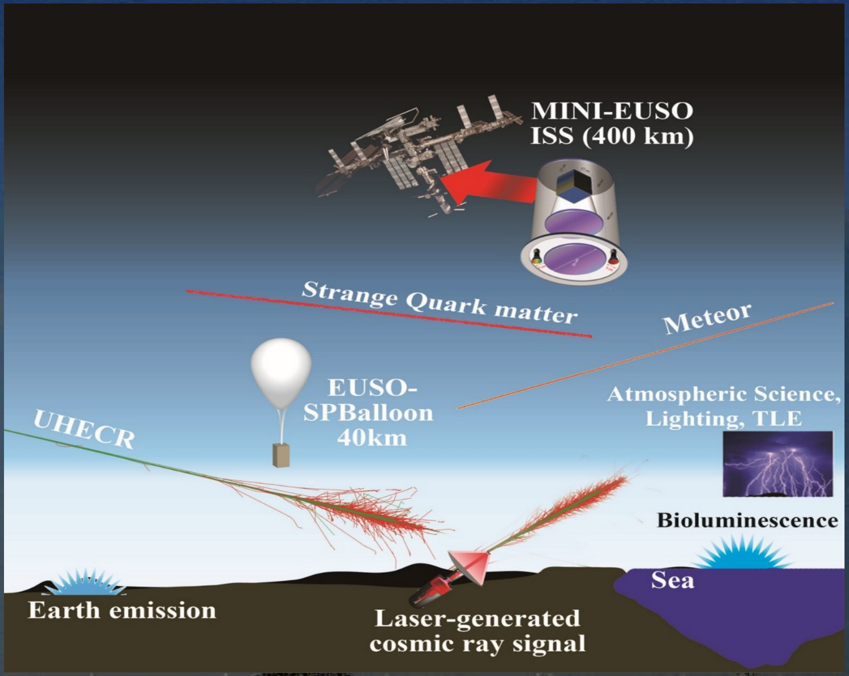
First Flight: august 24th 2014

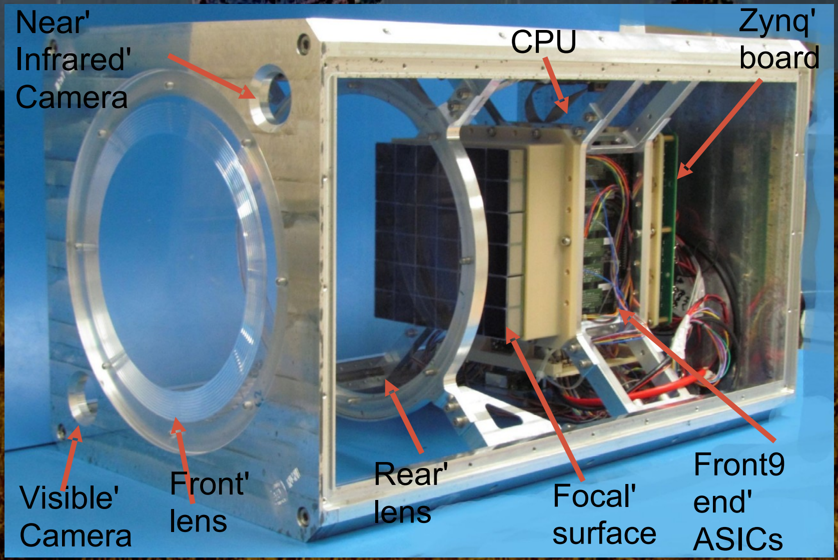
Landing...

- Waterproof instrument!

Mini-EUSO

- Send to ISS August 22nd, 2019
- Small scale full demonstrator



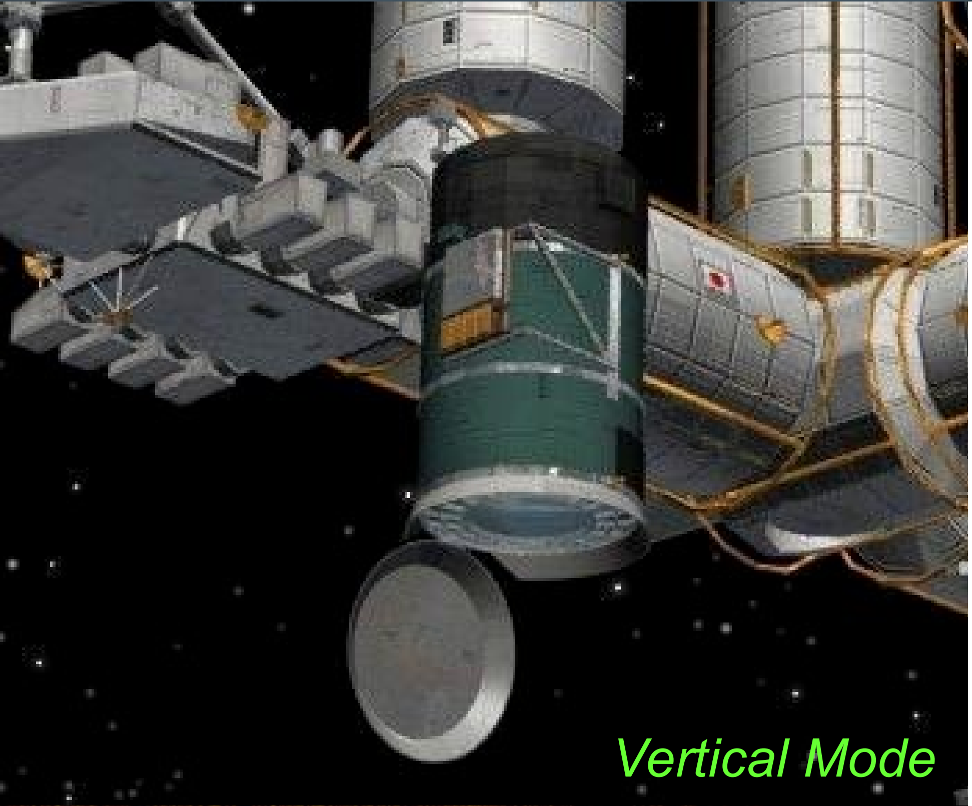


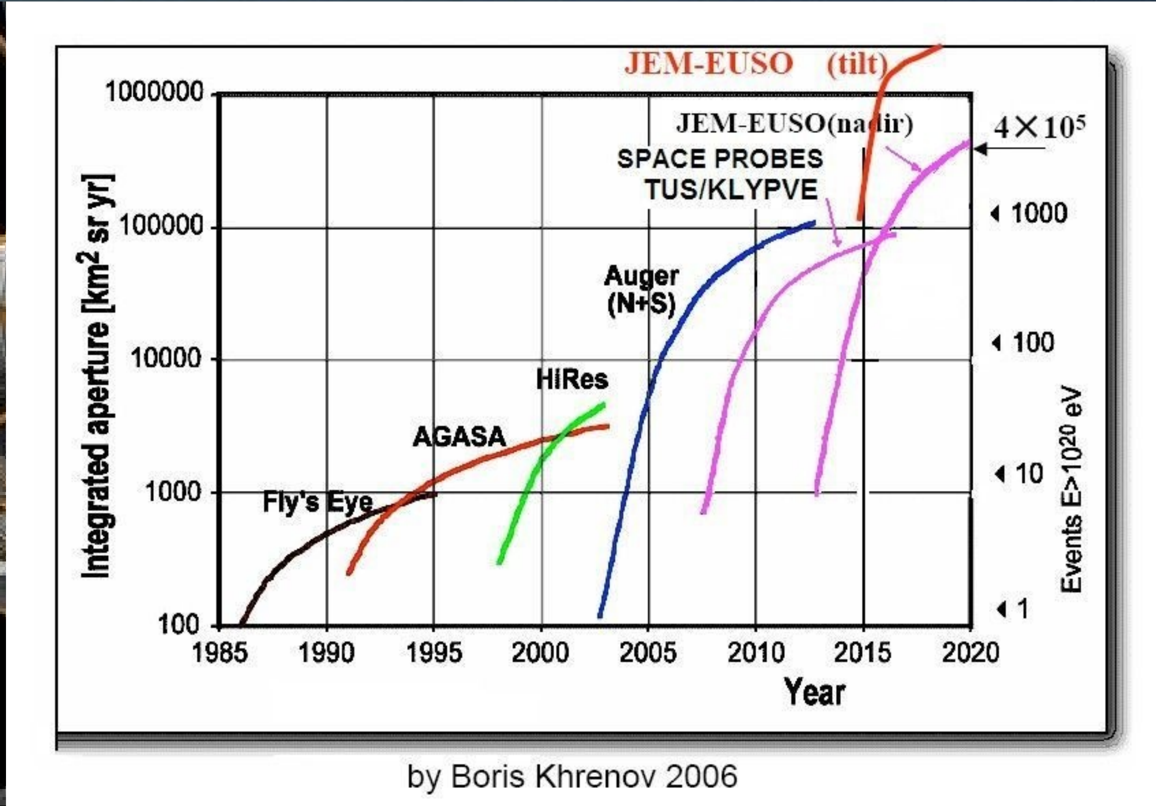
Summary

- ❑ Lots of excellent data acquired in the last decade
- ❑ But a situation that remains puzzling:
  - ☑ Primary (resp. secondary) nuclei exhibit similar spectra (expected by acceleration + diffusion theory)
  - ☑ Break in all spectra at similar rigidity points toward a change of diffusion regime, ☒ of unknown origin
  - ☒ Spectra of p, $\bar{p}$ and e^+ look similar and differ a lot from the e^- spectrum
  - ☑ e^- and e^+ spectra (and e^+ excess) can be explained by conventional astrophysics (nearby leptonic source), no need for dark matter
  - ☒ Dark matter remains elusive!
  - ☑ Trend toward heavier composition at the highest energy points toward accelerators reaching their maximal energy
  - ☒ … but why exactly where GZK is expected? Conspiracy?
  - ☒ No actual source of VHE / UHE Cosmic Ray identified so far

Perspectives

- Larger network for investigating the highest energies: Auger North + JEM-EUSO Telescope on ISS
- Upgrade of existing networks (HEAT, AMIGA…)
- Low energy extensions toward the knee (Tel. Array)
- A lot of R&D in other detection techniques (Radio!)





by Boris Khrenov 2006

Universality?