Cosmic Ray Physics

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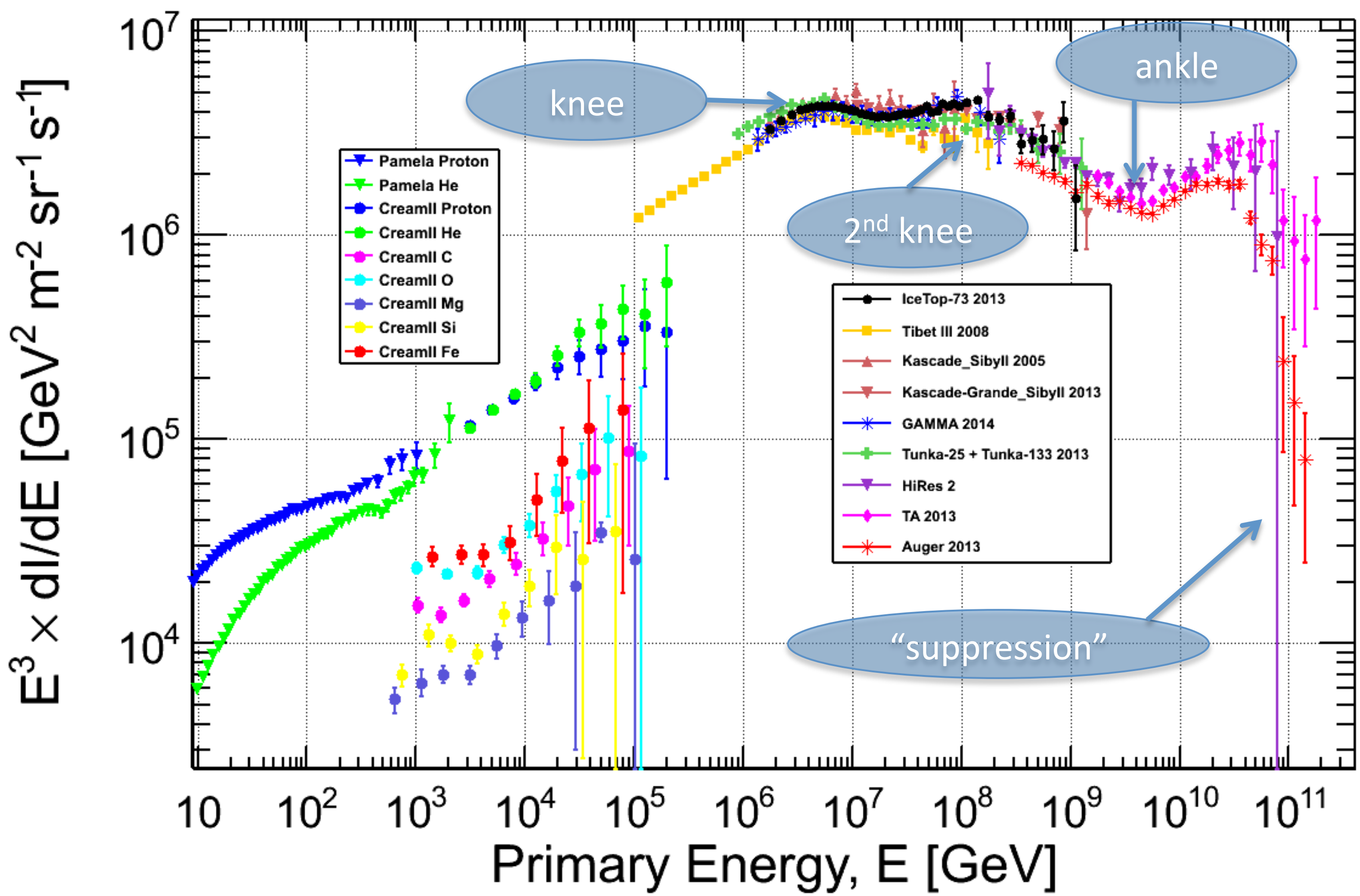
Outline

- Introduction & Motivations
- Direct Measurements
- Indirect Measurements
- Summary and Outlook

Why to study CRs

- ✓ Evidence of the most powerful astrophysical accelerators : multi-messenger astronomy
- ✓ Probe of cosmic environment through which they propagate
- ✓ Test of standard physical laws in extreme conditions
- ✓ Messengers of new physics or yet unknown particles

Cosmic Ray Spectrum



How to detect CR

Direct measurements:

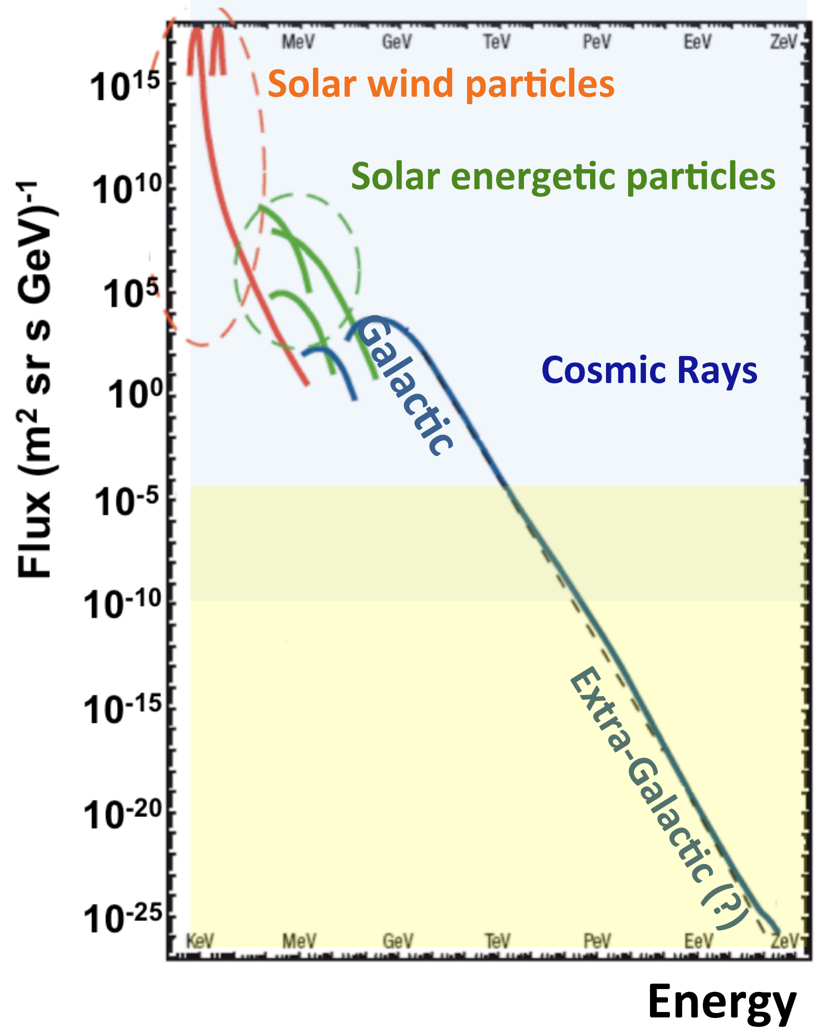
☺ Particle identification(Pid)/Energy calibration, anti-matter

☹ Space: Weight/Size constraints & limited energy range (< PeV)

Indirect measurements:

☺ Ground: Extended energy range (>PeV)

☹ Pid/Energy : dependence on modelling of atmospheric interactions



Physics Case

- **Origin**: where are they from?
- **Identity**: what are they?
- **Acceleration**: how do they get their energy?
- **Propagation**: what happens on their way?

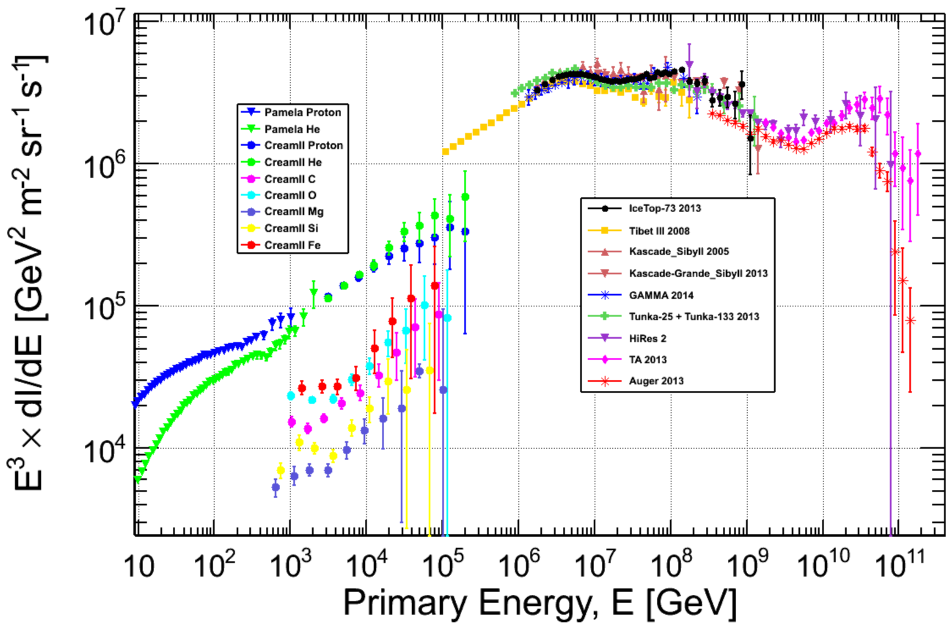
Energy spectrum | **Composition** | **Arrival direction**

- ✓ protons, helium and nuclei (B,C,O,....) spectrum
- ✓ ratio of components, like secondary over primary population, to understand propagation effects
- ✓ electron spectrum
- ✓ anti-matter components: e^+ fraction, e^+ spectrum, $\bar{p}/p$ ratio, $\bar{p}$ spectrum

Open Issues

- Detailed knowledge of particle abundances below the knee: is there any hint of new physics?
- Connection between direct and indirect observations

- Nature of CR spectrum features: knee, ankle…
- Galactic to Extragalactic transition
- The nature of the “End” of the spectrum



DIRECT DETECTION: BALLOON OR SPACE

Stratospheric Balloons: from few hrs to months

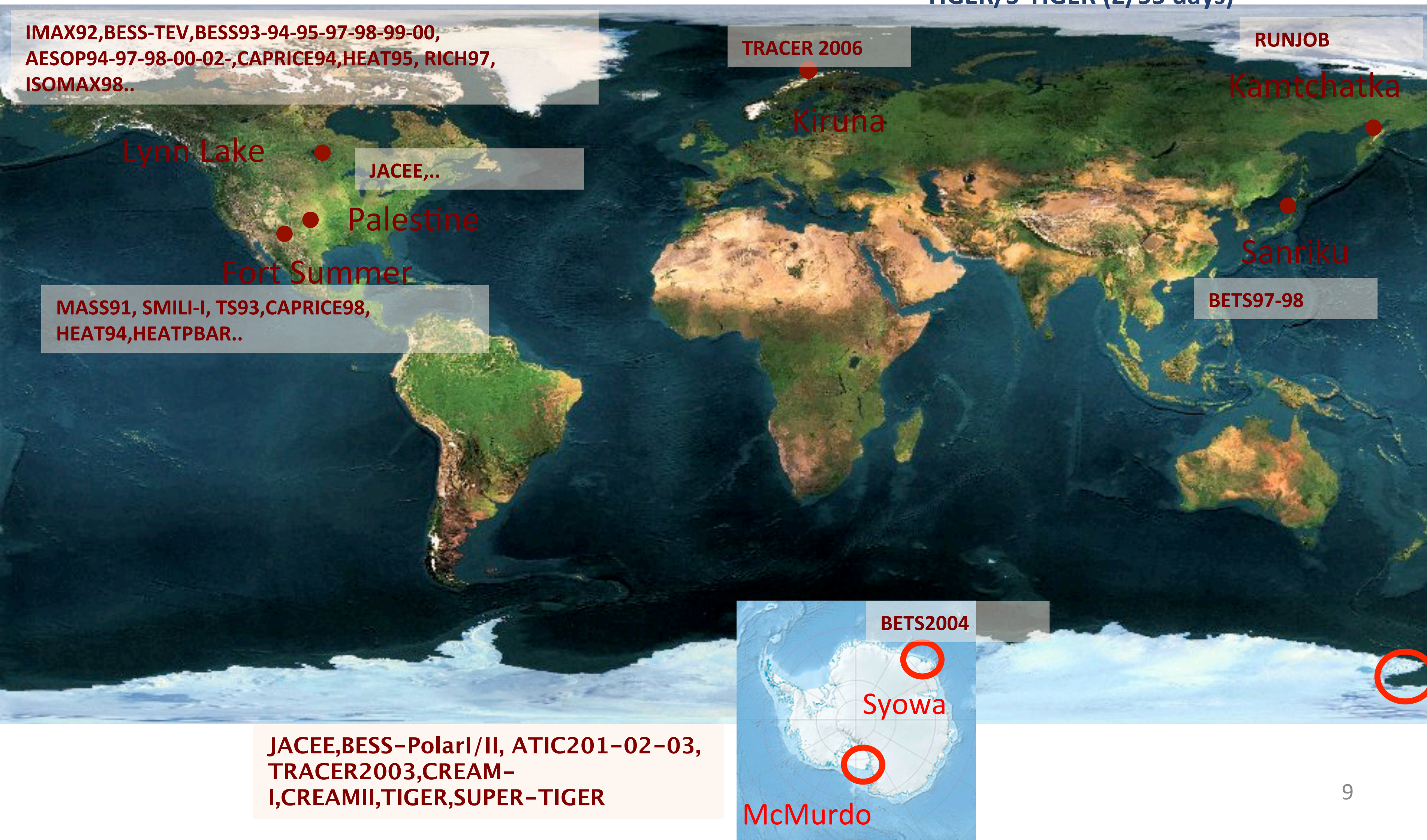
Direct Detection

Magnetic Spectrometers

...
BESS/POLAR/TEV (11 Flights)
WIZARD (6,Flights)
HEAT/PBAR (4,Flights)

Calorimetry, TRD +..

RUNJOB (62 day, 10 Flights)
TRACER (18 days, 3 Flights)
CREAM (161 days,6 Flights)
ATIC (53 days, 3 Flights)
TIGER/S-TIGER (2/55 days)



Space:

Long missions (years)
Small payloads
Low energies..

IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads

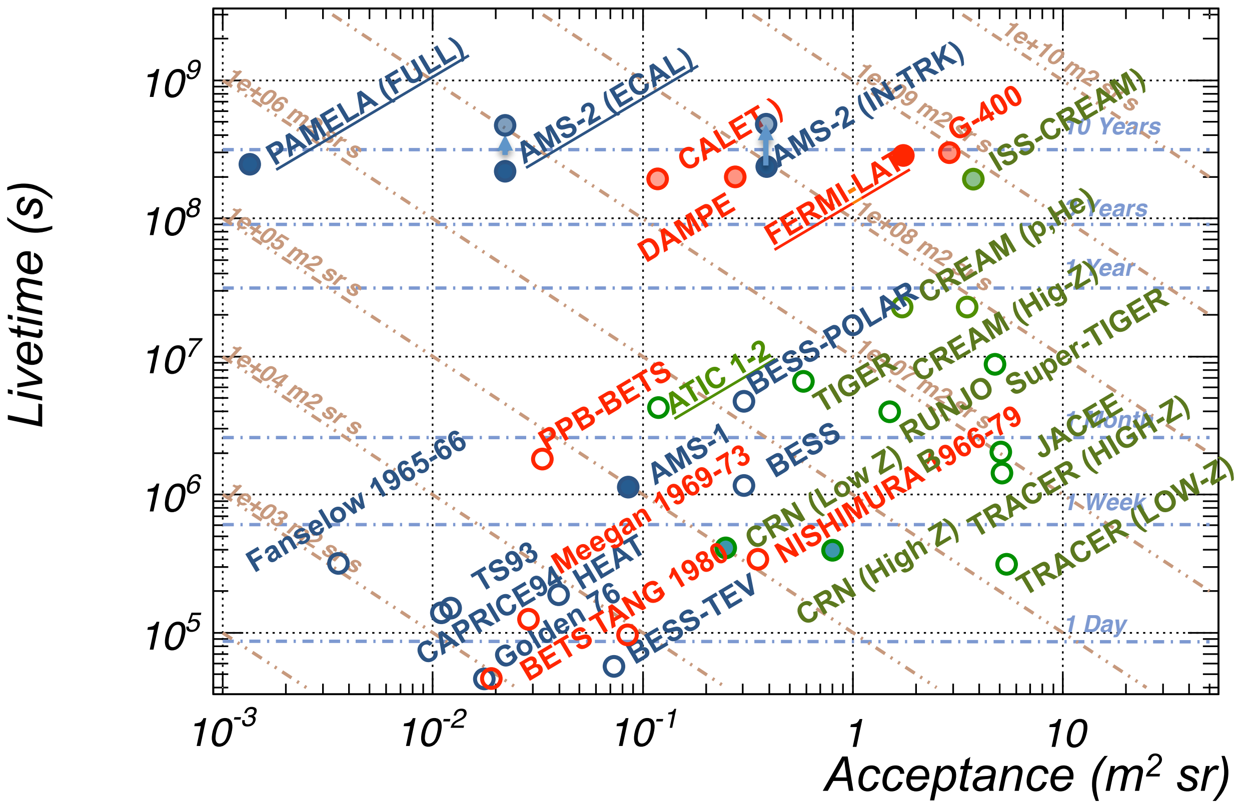
CRN on Challenger
(3.5 days 1985)

AMS-01 on Discovery
(8 days, 1998)

Long missions
Large payloads

Exposure Time vs Acceptance

Due to the statistics of particle flux, The sensitivity of the experiments are determined by the combination of detector livetime and acceptance



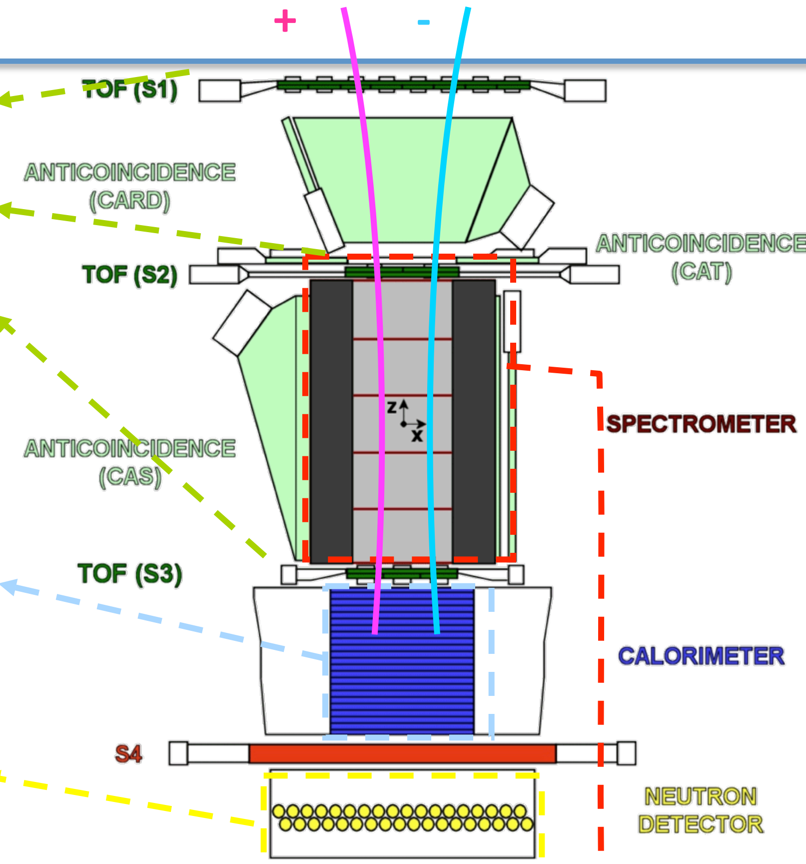
- No B field, different techniques with main focus on Z
- No B field, different techniques with main focus on e,γ
- Magnetic spectrometers

- Balloon
- Space
- Space (planned)

Recent results

- **P/He spectrum**
  - No updates from balloon experiments (CREAM,ATIC data sets..)
  - New published results from PAMELA @ “low” energy
  - Indirect measurement (?) from FERMI
  - Eagerly waiting AMS-02….
- **Chemical composition**
  - No updates from balloon experiments
  - New results from PAMELA
  - Eagerly waiting AMS-02…
- **Electrons and positrons**
  - **New results from AMS-02**

The PAMELA detector



Time-Of-Flight
6 layers (3 couples) of plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector
36 He^3 counters :
- High-energy e/h discrimination

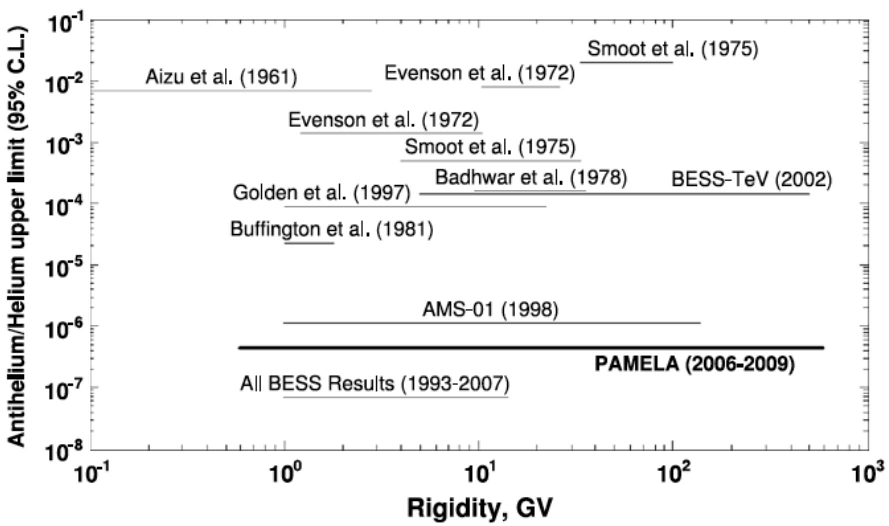
Spectrometer (6 double layer silicon detector planes)
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze MDR≈1(0.25) TV
- *Charge sign*
- *Charge value from dE/dx*

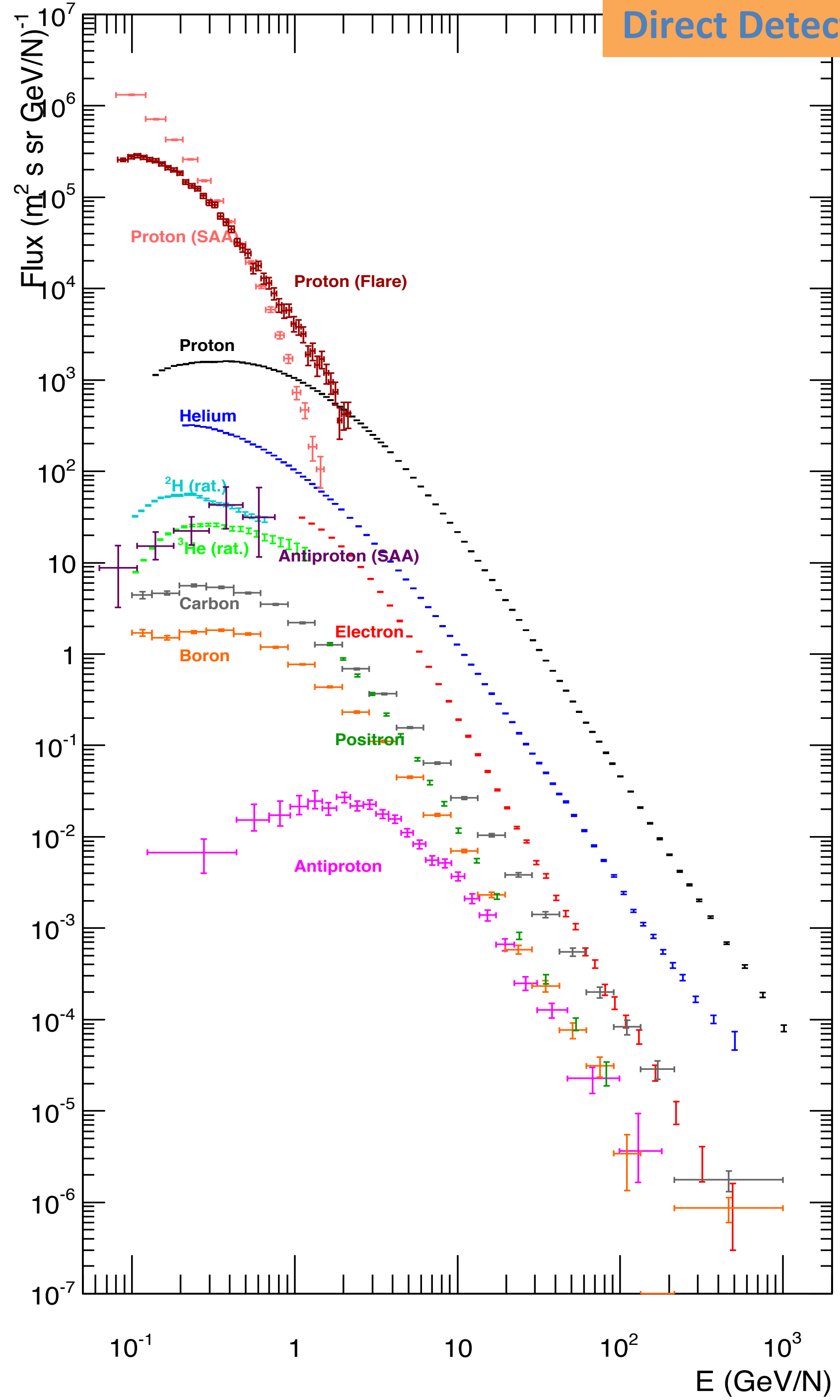
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

PAMELA: All particle results

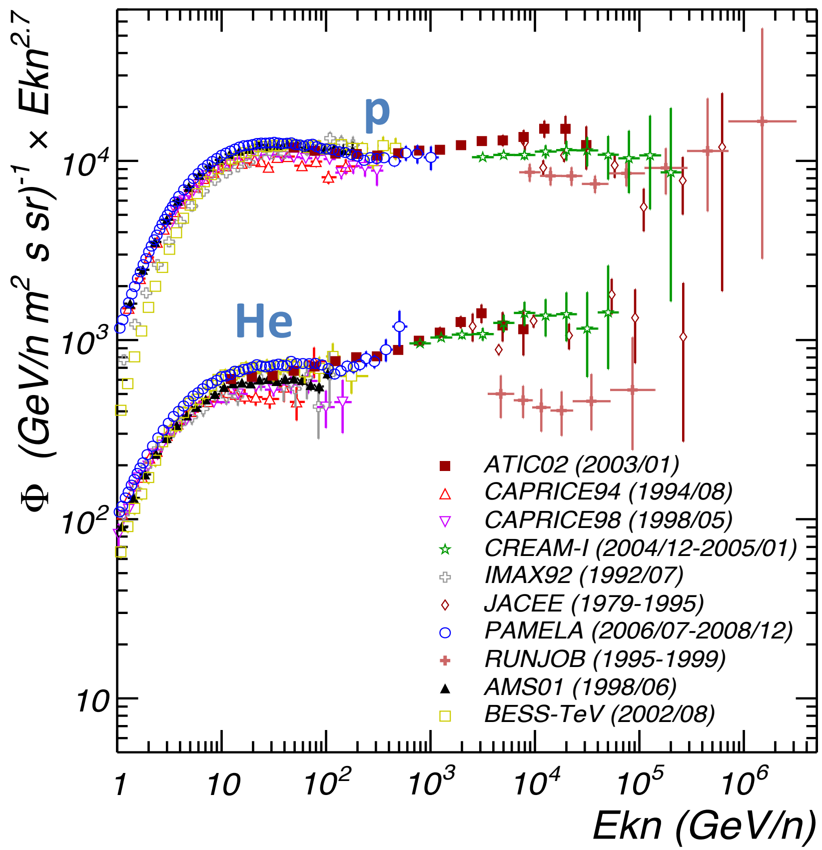
- → Antiparticles
- → Galactic CR
- → Solar Physics
- → Particles in Earth's magnetosphere

Article in press.
O. Adriani et al, Physics Reports (2014)
http://dx.doi.org/10.1016/j.physrep.2014.06.003



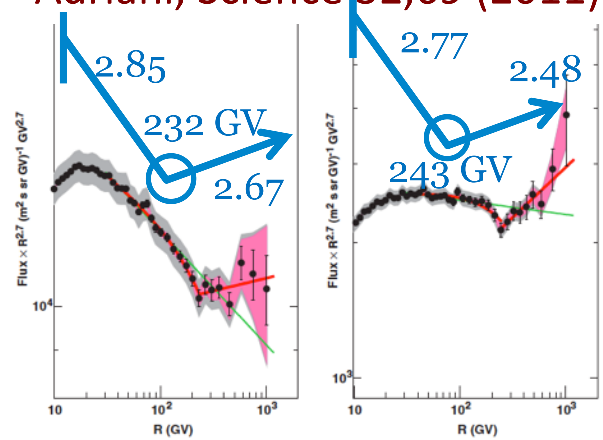


PAMELA: p/He spectra



Still waiting for full CREAM statistics
AMS-02 publication soon….(< 2015)

Adriani, Science 32,69 (2011)



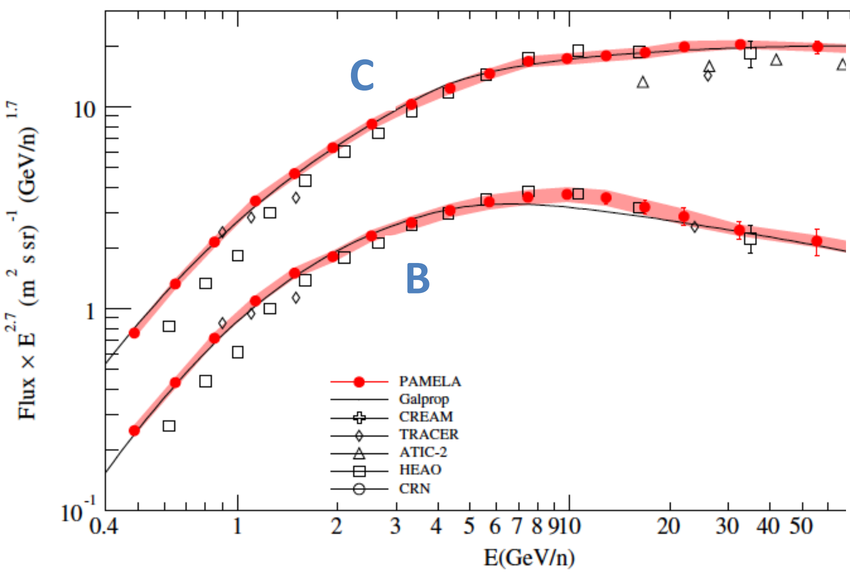
- No features were expected
- hint of a local CR source ?
- Is a new physical phenomenon is showing up in the propagation?

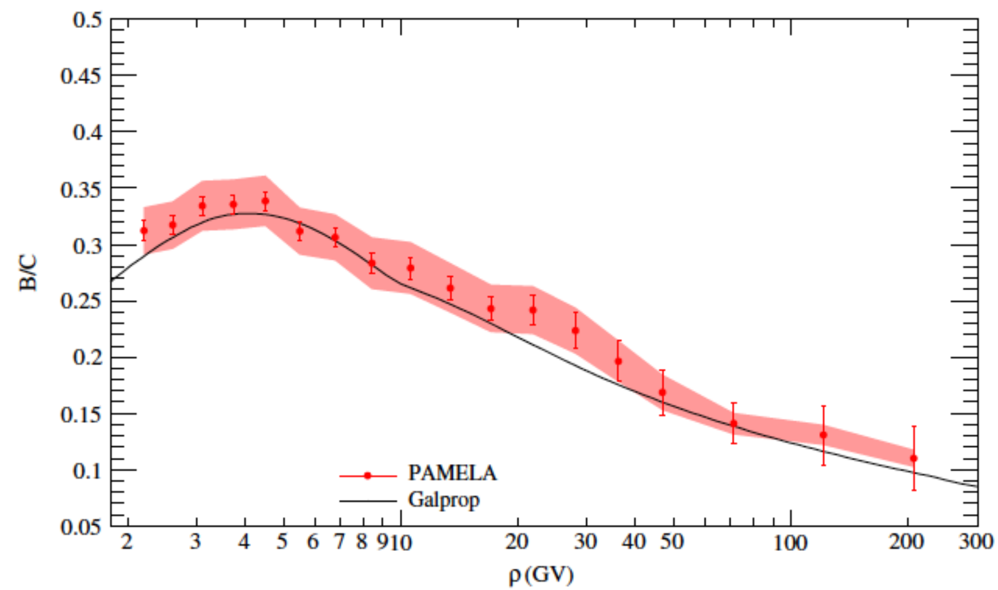
PAMELA: B,C

Primary CR such as C or O may interact with inter stellar material to produce secondary fragments like Li, Be, B.
B purely a secondary and mainly produced by C and O
B/C is the ratio less affected by systematics or solar modulation (similar charge)

B/C as probe for propagation model

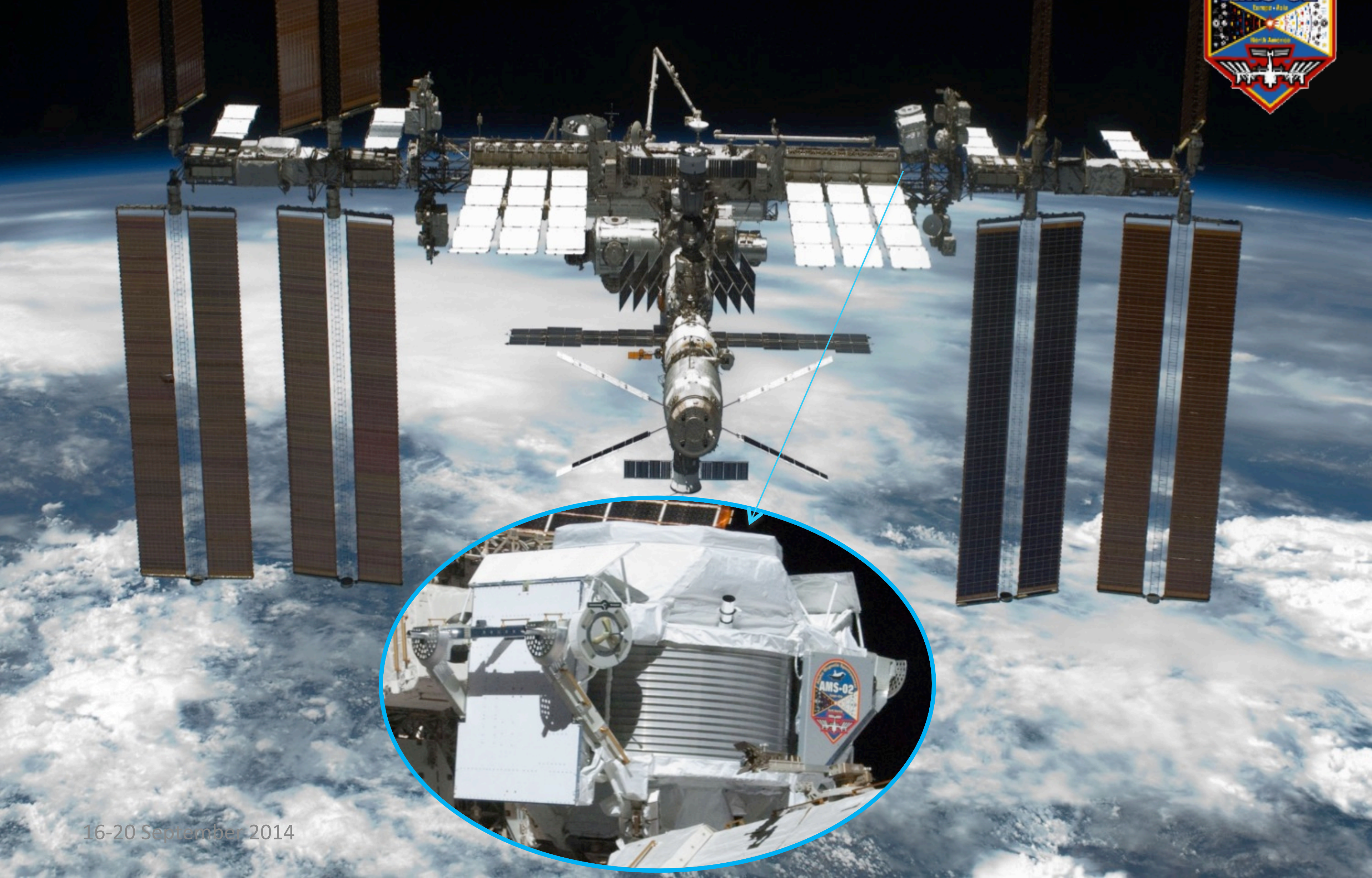
Not enough to constraint the slope of the diffusion coefficient…





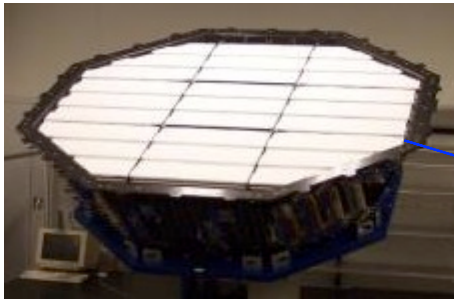
Adriani et al., ApJ 791 (2014), 93

The Alpha Magnetic Spectrometer (AMS) on the International Space Station

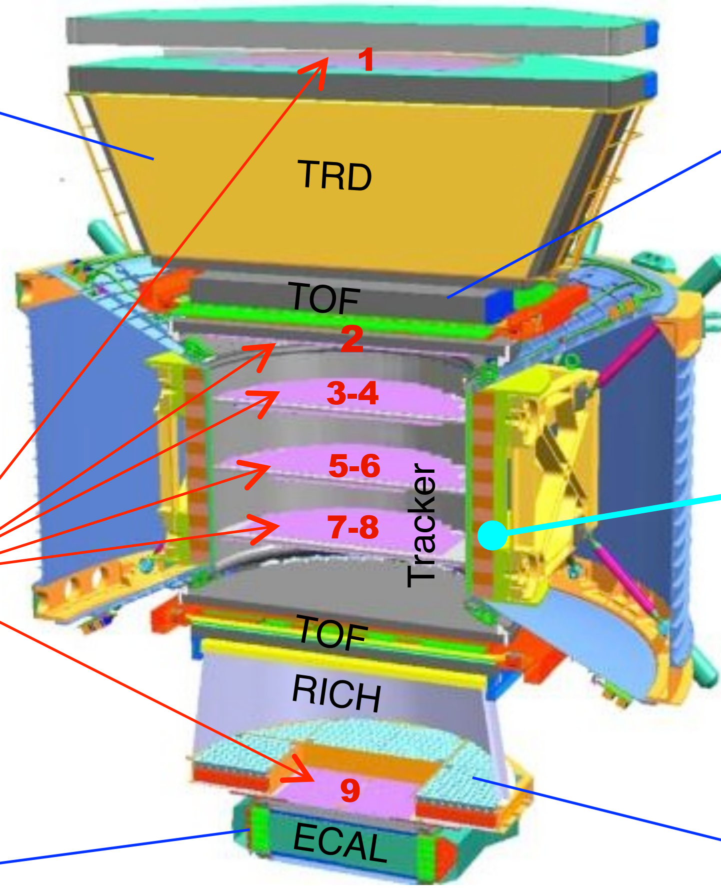


AMS : A TeV precision, multipurpose spectrometer

Transition Radiation Detector
Identify electrons

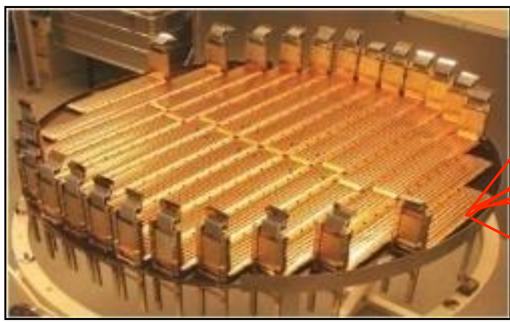


Particles are defined by their charge (Z) and energy (E) or momentum (P)

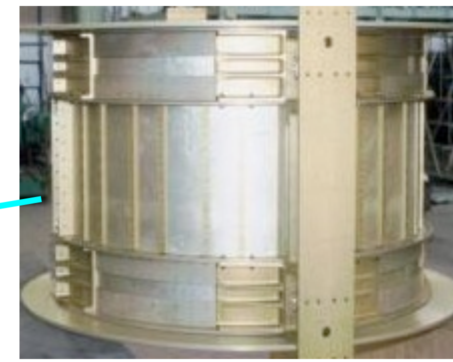


Time of Flight
Z, E

Silicon Tracker
Z, P



Magnet
±Z



Electromagnetic Calorimeter
E of electrons

Ring Imaging Cherenkov
Z, E

The Charge and Energy (momentum) are measured independently by many detectors

AMS Measurements and Future Plans

Cosmic rays

Proton spectrum

Helium spectrum

Electron Spectrum

Light Nuclei Spectrum

(B,C,B/C,O,....)

Dark Matter

Positron Fraction

Anisotropy

Positron Spectrum

Antiproton/Proton Ratio

Antiproton Spectrum

Future Plans

→ DM measurement

→ Light Nuclei Spectrum

→ Heavy Nuclei

Photons

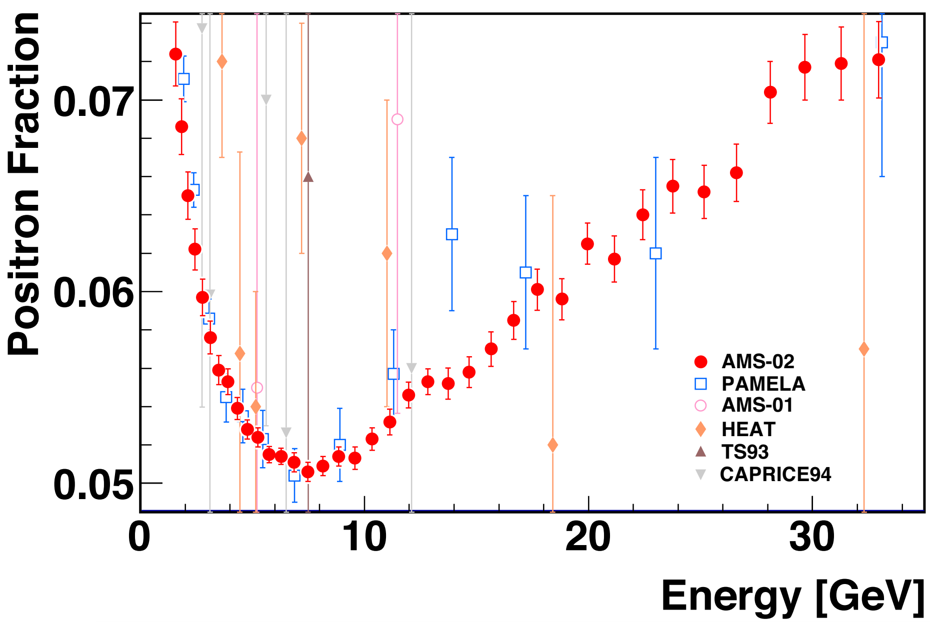
Antimatter Search

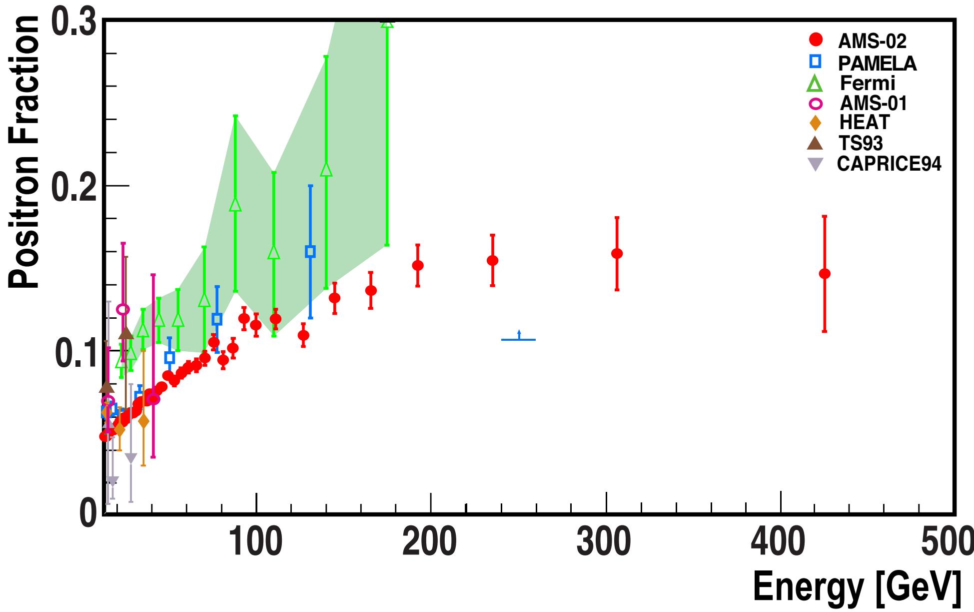
Strangelets Search

AMS-02: Positron Fraction

- Rapid decrease from 1-8 GeV, as expected from diffuse positron production.
- A steadily increasing from 10 to ~200 GeV, **no longer increasing above 200 GeV**
- Upper limit on dipole anisotropy amplitude δ≤0.030@95%CL (E>16 GeV)
- "End" of positron spectrum crucial to understand the nature of the excess

L. Accardo et al. (AMS Collaboration) Phys. Rev. Lett. 113, 121101 (2014)

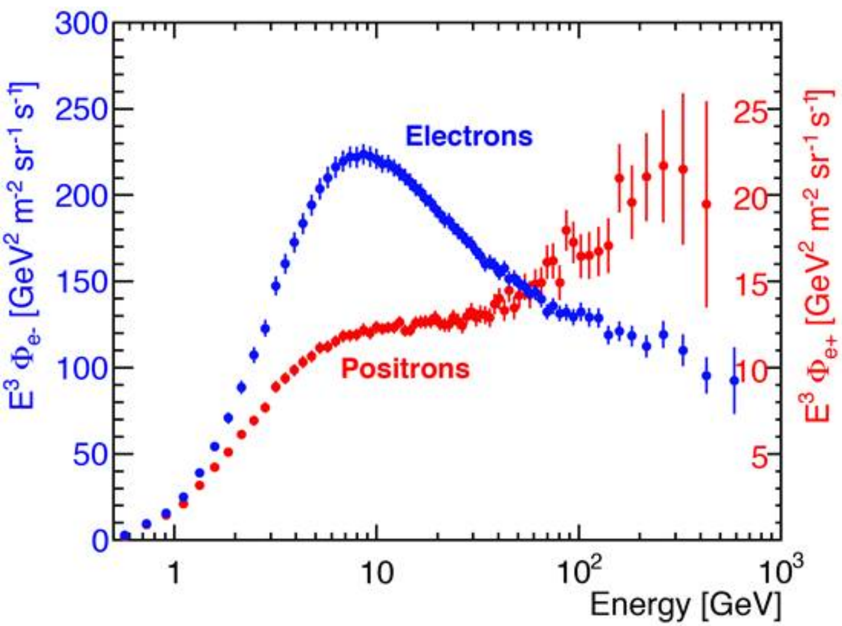


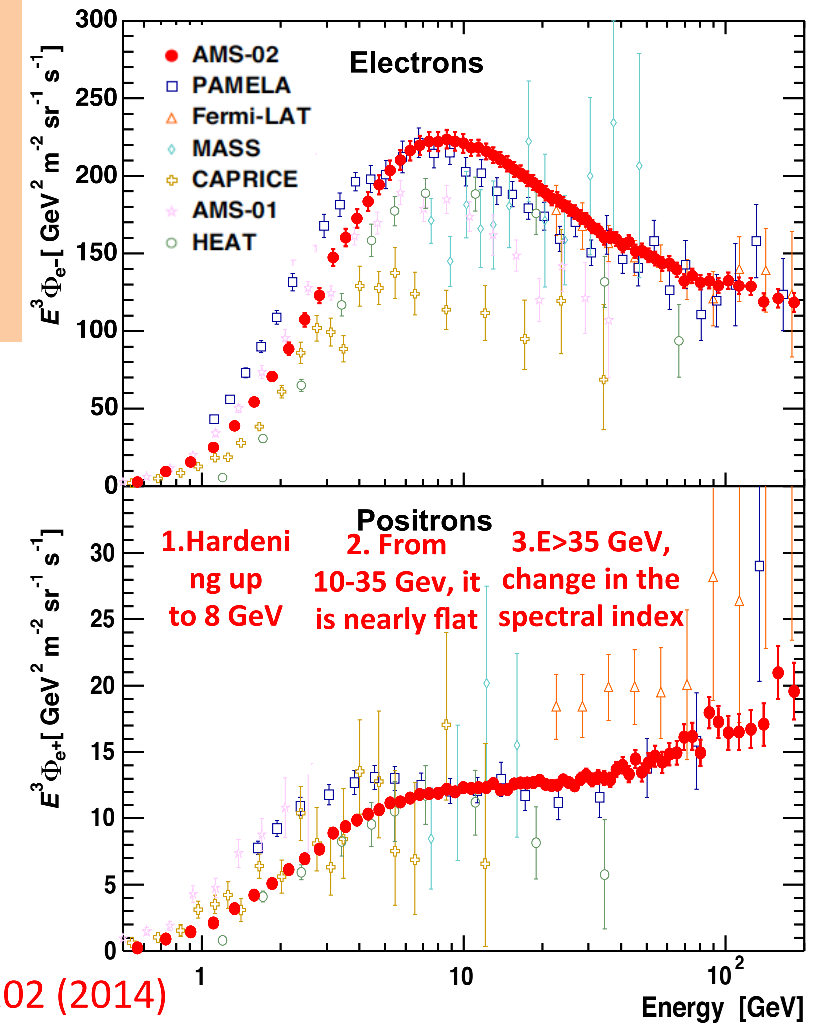


AMS-02: Positron Electron Fluxes

(GeV)	e+	e-
En. Range	0.5-500	0.5-700
Ev. Sample	0.58×10^6	10.5×10^6
γ(15.1-31.8)	2.97±0.03	3.28±0.03
γ(49.3-198)	2.75±0.05	3.15±0.04

- Not a single power law
- From 20 to 200 GeV **e^-** flux decreases more rapidly then **e^+** one: not consistent with a pure positron secondary production scenario
- Above 20 GeV, spectral indices (γ_{e-} and γ_{e+}) are significantly different



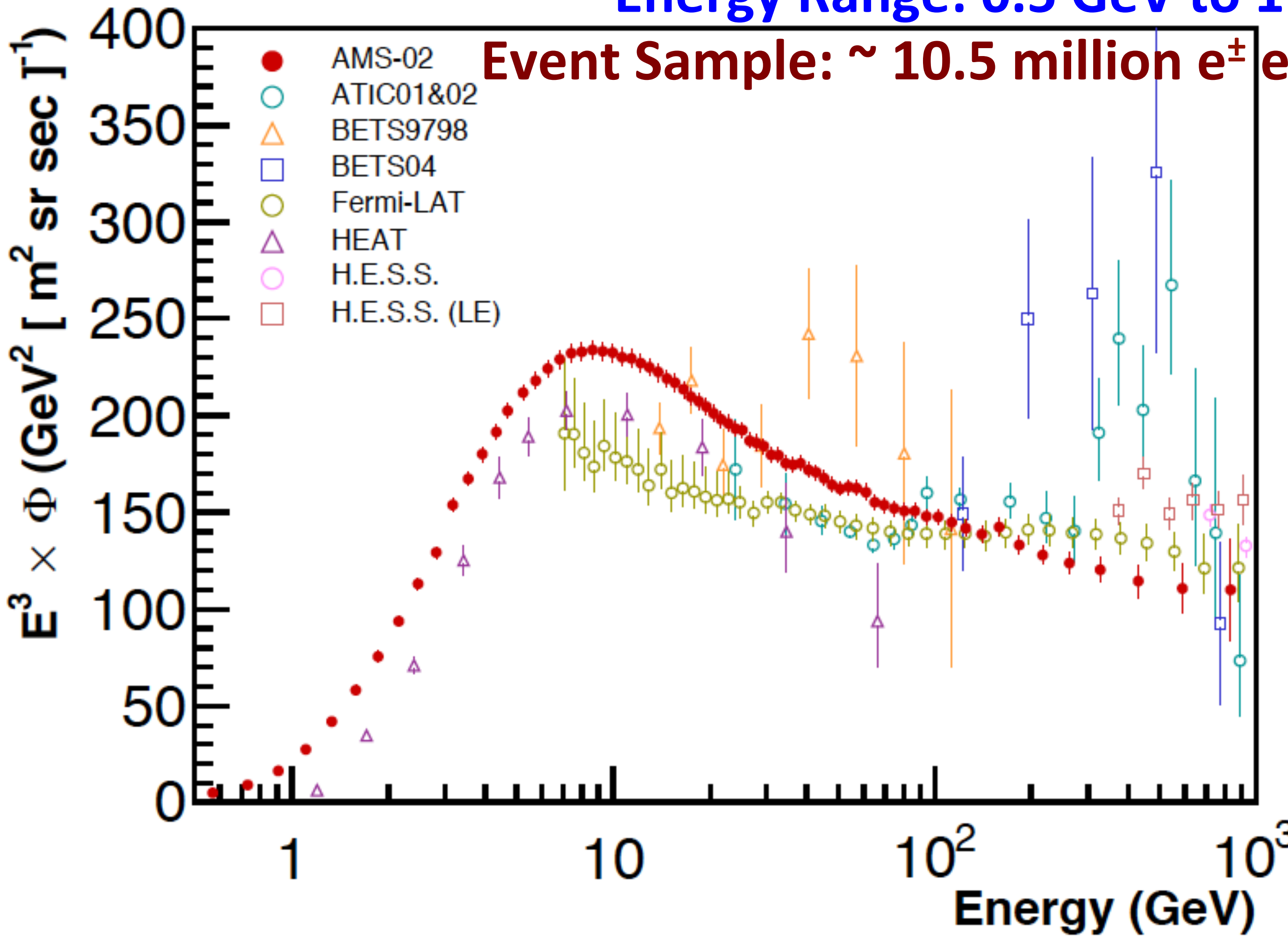


M. Aguilar et al. (AMS Collaboration) Phys. Rev. Lett. 113, 121102 (2014)

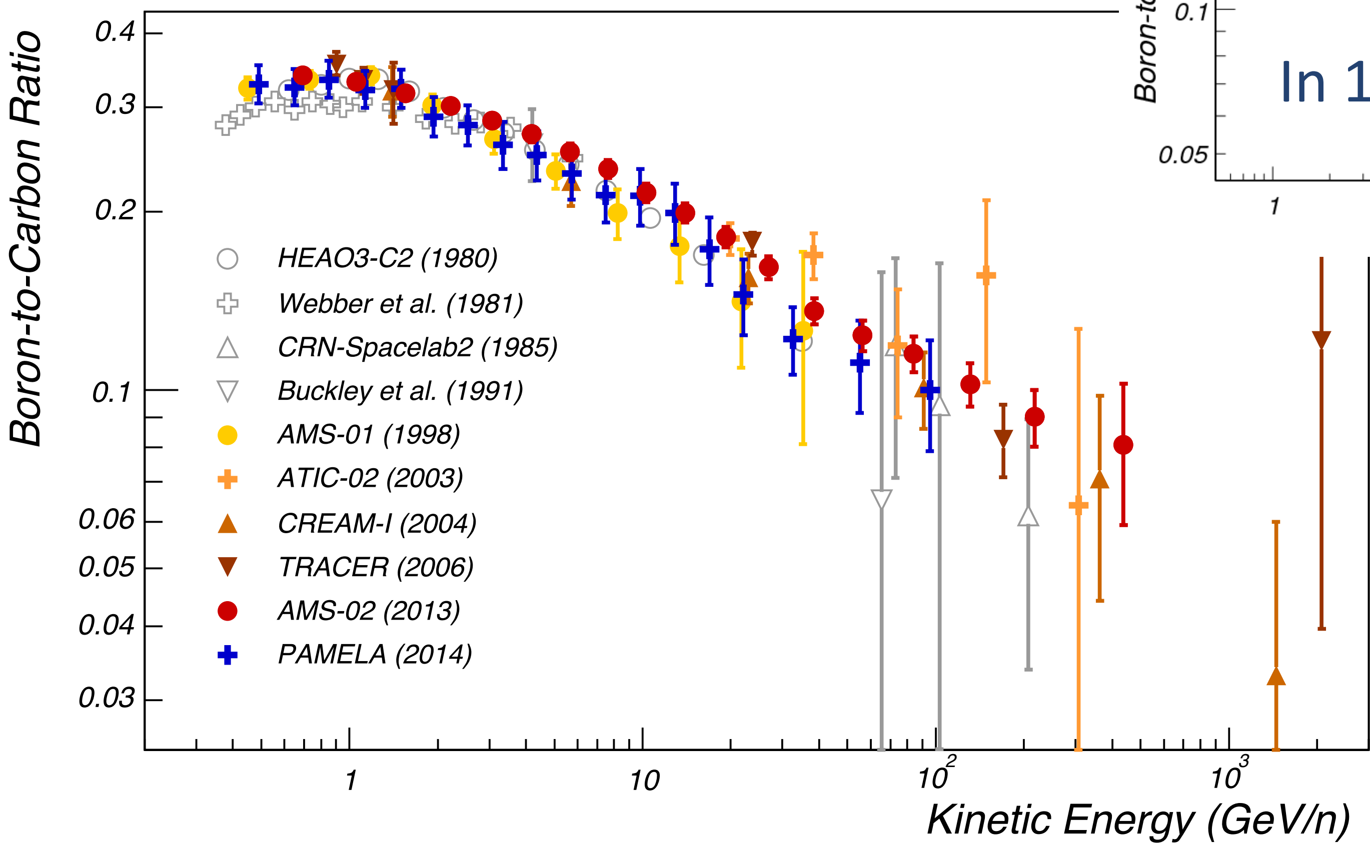
AMS-02: $e^+ + e^-$ Flux

Energy Range: 0.5 GeV to 1 TeV

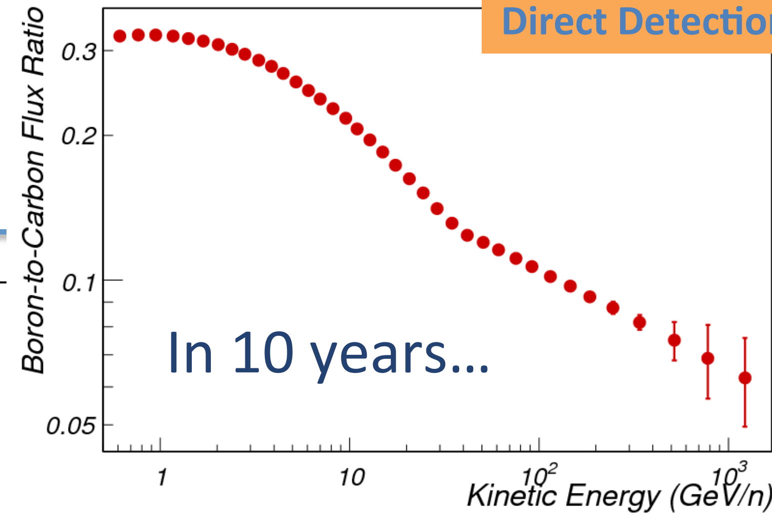
Event Sample: ~ 10.5 million $e^\pm$ events



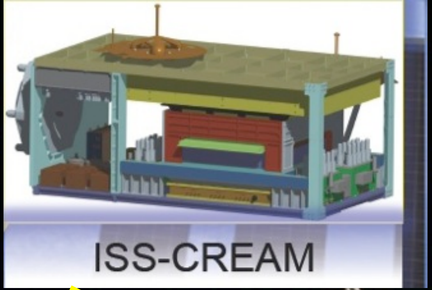
AMS-02: B,C

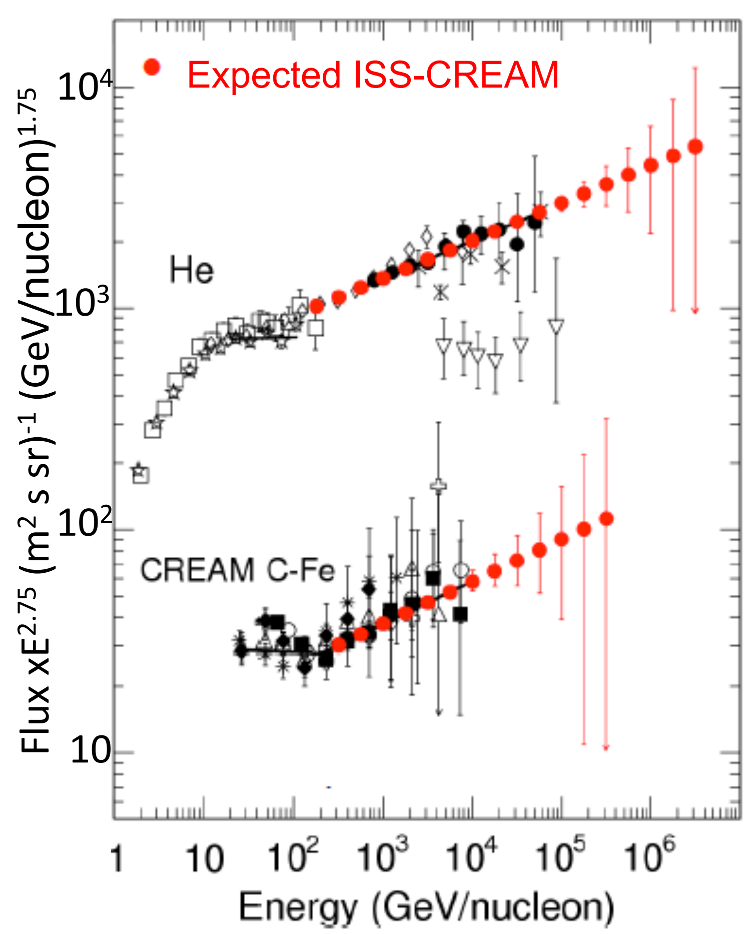


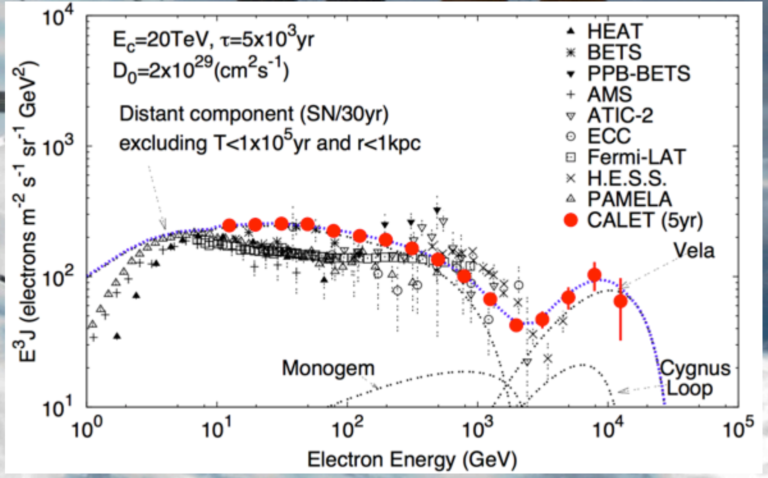
Direct Detection



PAMELA new result up to 100 GeV/n
AMS-02 (ICRC-2003) → incoming pub up to 1 TeV



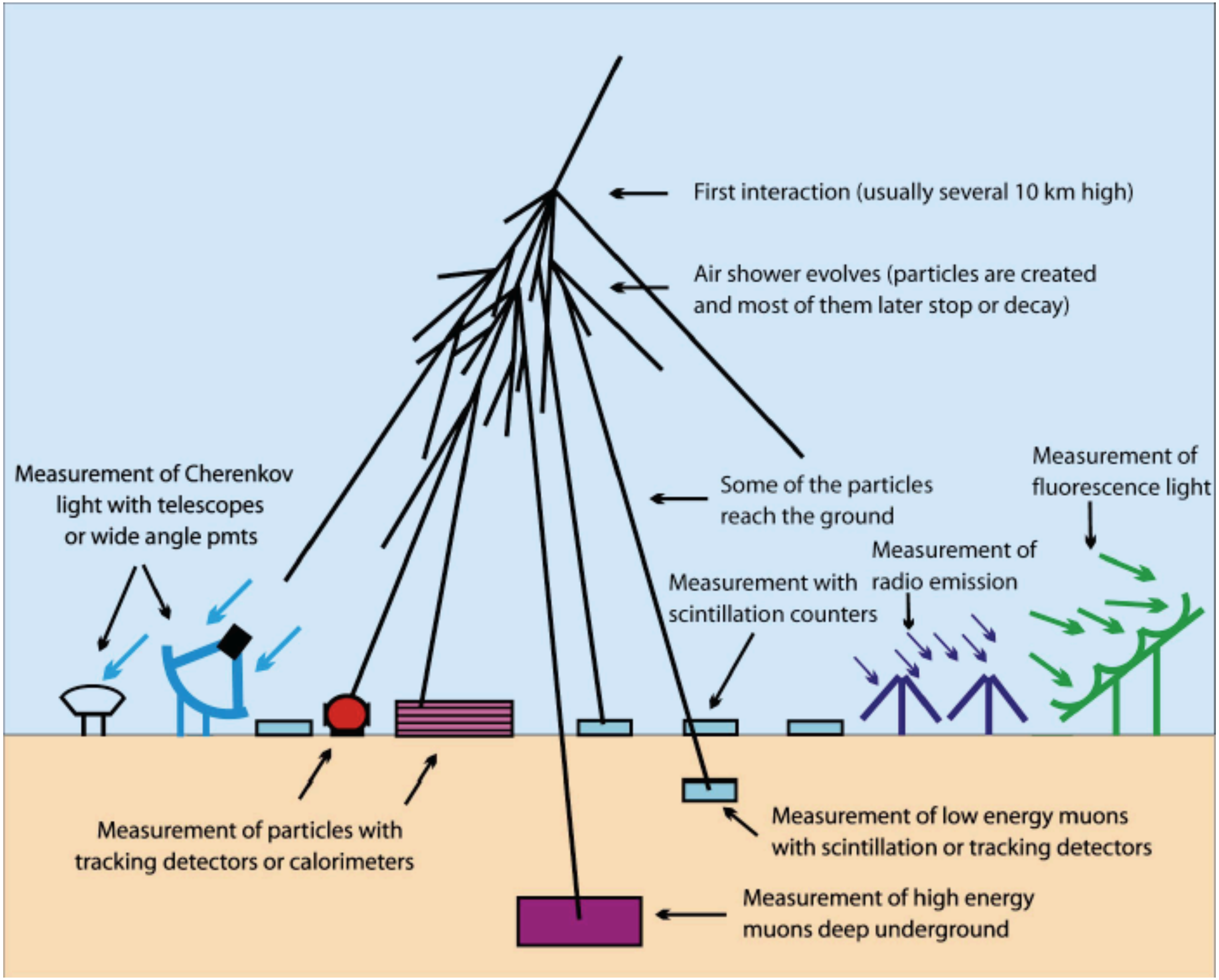




- **Approved Calorimetric experiments:**
  Focused on γ, electron and high Z particles

INDIRECT DETECTION

Extensive Air-Shower (EAS)



EAS Observables

- Particles at ground
  - ✓ electrons
  - ✓ muons
  - ✓ hadrons
- Cherenkov light
- Fluorescence light
- Radio signals (recently proven)
- Acoustic signals (maybe in the future)
- Infrared signals (under test)
- ….

Particles at ground: $E>10^{14}$ eV

Cherenkov light: $10^{14} < E < 10^{16}$ eV

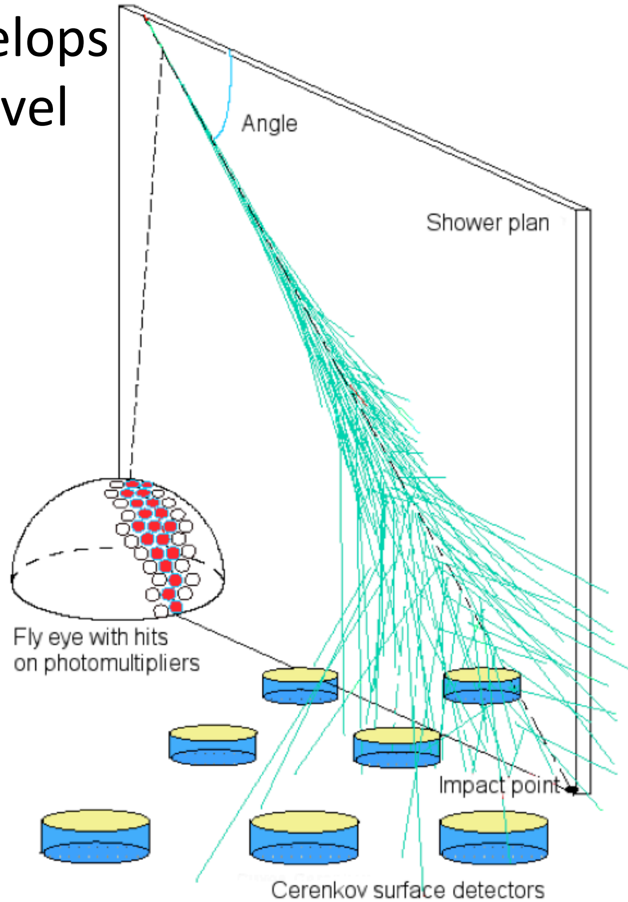
Fluorescence light, Radio signals: $E>10^{17}$ eV

Recent results

- **Energy spectrum**
  - ✓ new measurements in the knee region
  - ✓ updates of Auger and TA data in the “GZK”region (ICRC2013)
- **Mass Composition**
  - ✓ updates of mass estimate in the UHE region from Auger and TA
  - ✓ photon and neutrino limits
- **Anisotropy**
  - ✓ updates from Auger and TA of event arrival distributions above 57 EeV
- **Interconnection with Particle Physics**
  - ✓ Proton-Air Cross Section estimate (2012)

UHE Cosmic Rays – Hybrid Detection

Nitrogen fluorescence detected as shower develops
Particles detected as they reach the detector level

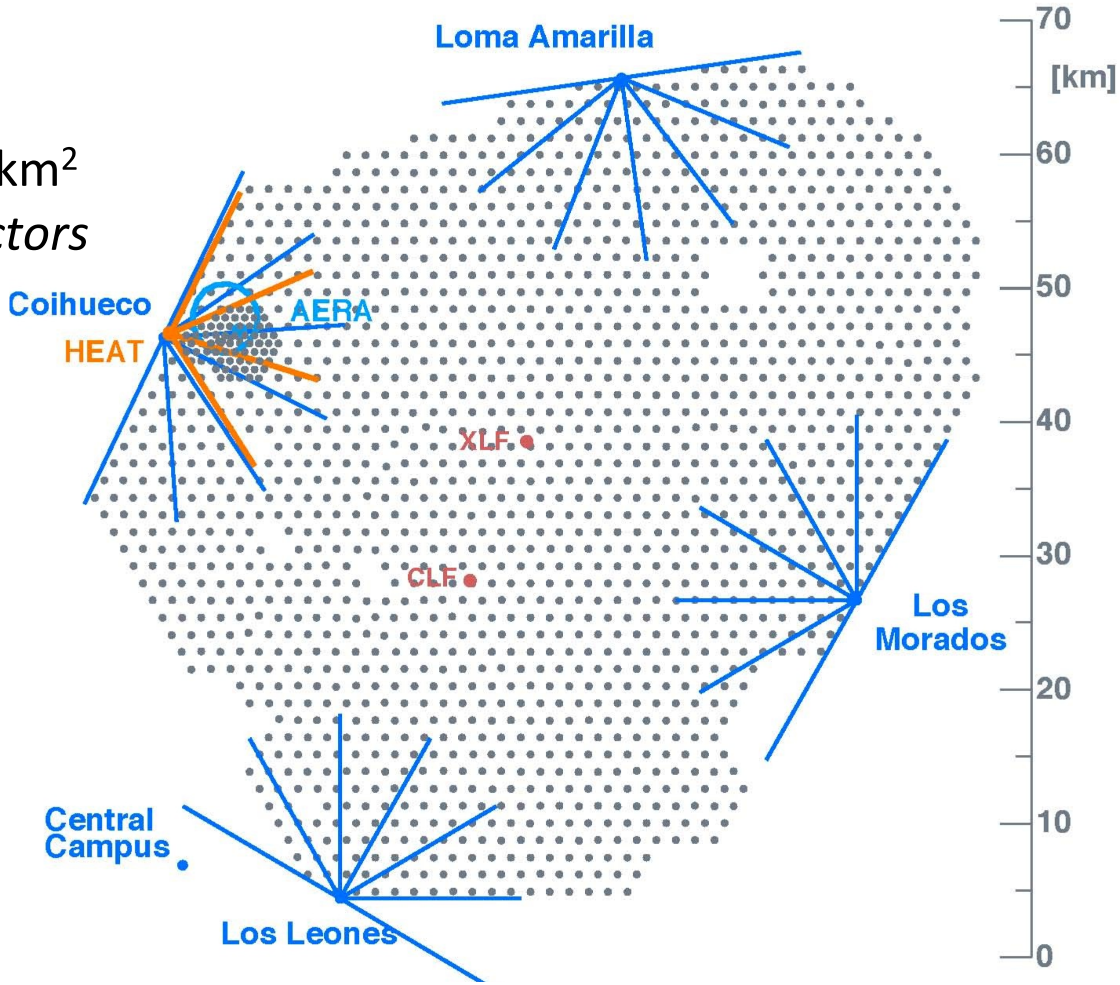


- Fluorescence detector
  - + nearly calorimetric measurement
  - + direct view of shower evolution
  - – ~15% of duty cycle
  - – acceptance depends on energy and atmosphere conditions
- Surface detector
  - + 100% of duty cycle
  - + Acceptance flat above threshold
  - – estimation of primary energy and mass based on simulation studies

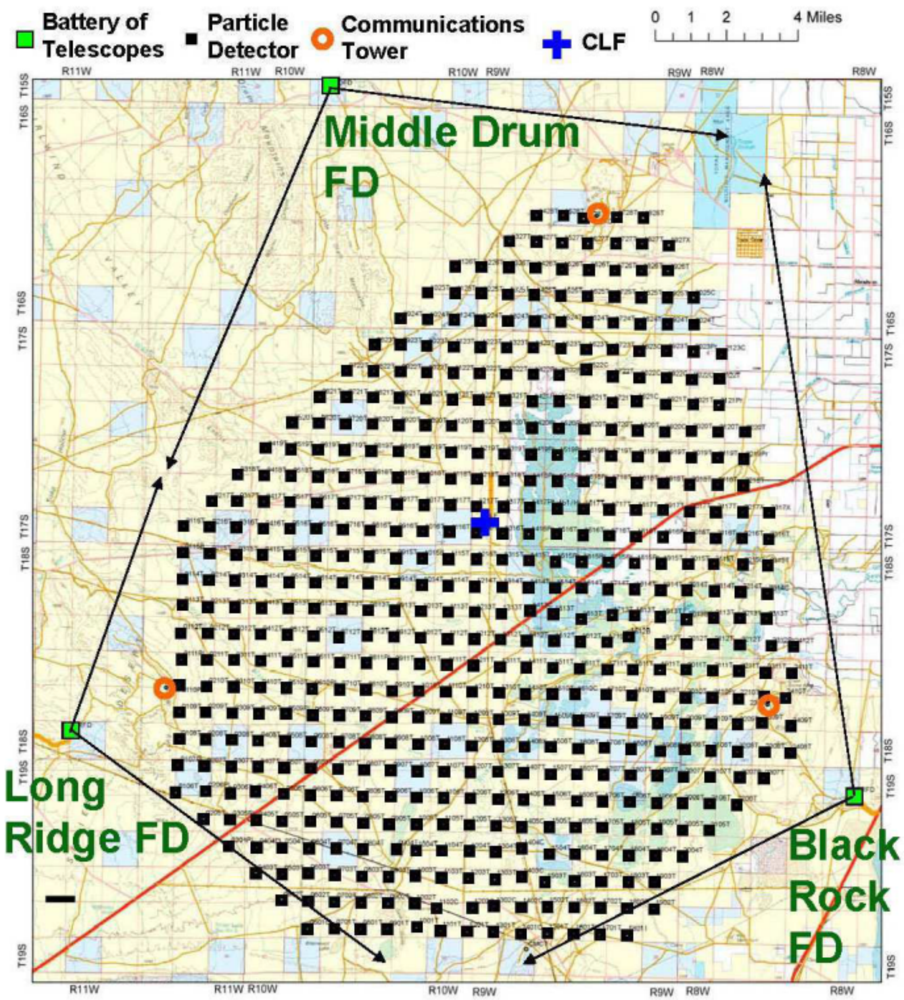
Pierre Auger Observatory

Fluorescence: 4 "Eyes"

Surface Array: covers 3000 km^2
1650 water-Cherenkov detectors
(10 m^2 , 1.5 km separation)



Telescope Array



Fluorescence: 3 "Eyes"

Surface Array: covers 700 km^2

507 scintillator stations (3 m^2, 1.2 km separation)

The "GZK Cutoff"

The proton energy threshold for pion photoproduction on the CMB is a **few x 10^{19} eV**. E.g.,

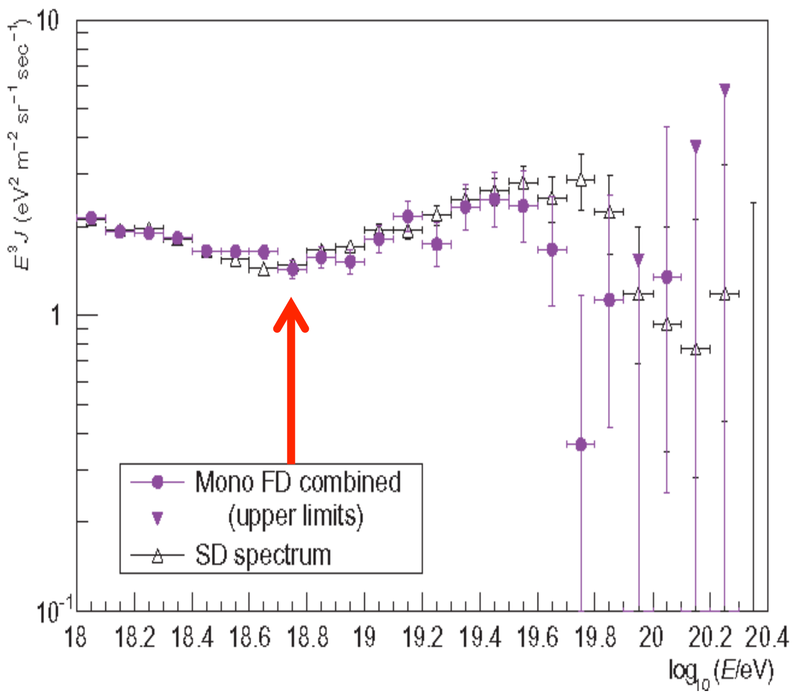
$p + \gamma\,(2.7^{o}K) \rightarrow \Delta^{+} \rightarrow p + \pi^{o}\ ,\ n + \pi^{+}\ , \ldots$

1. Any observed CR proton **above this energy** must have originated "nearby" (within ~ 100 Mpc)

2. Similar thresholds, distances for nuclear photodisintegration.

3. Spectrum **suppressed** if non-local sources

Energy Spectrum



TA

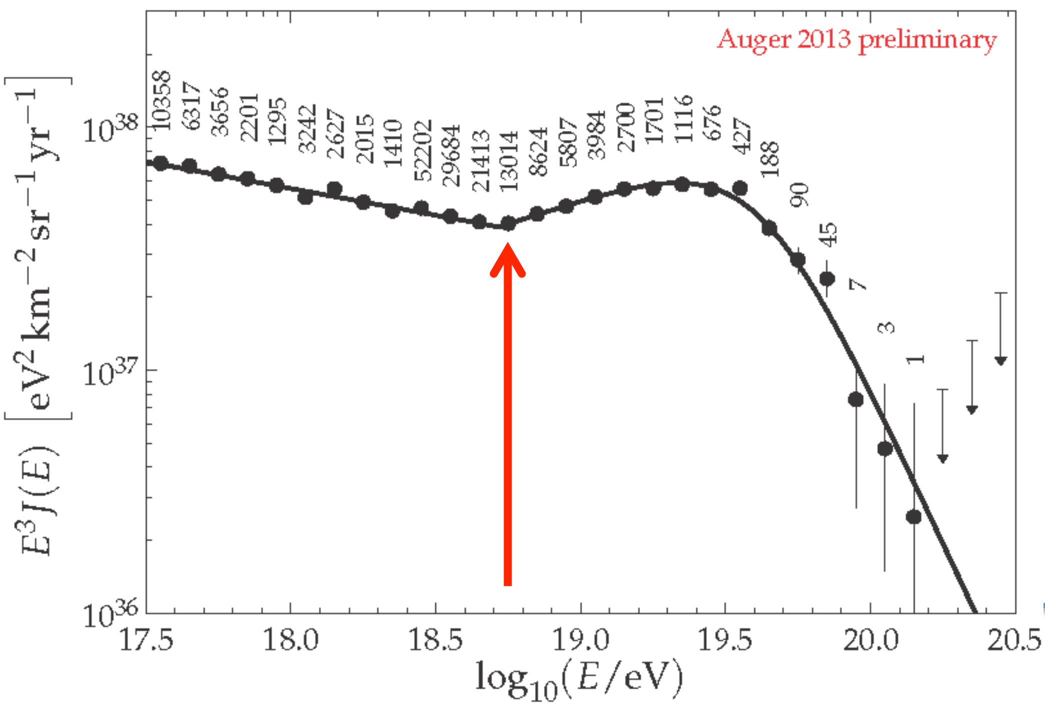
*Astropart. Phys. **48** (2013) 16*

Both experiments see spectral structure:

Flux **suppression** (GZK?)
Interaction or source scenario?

The **"ankle"**

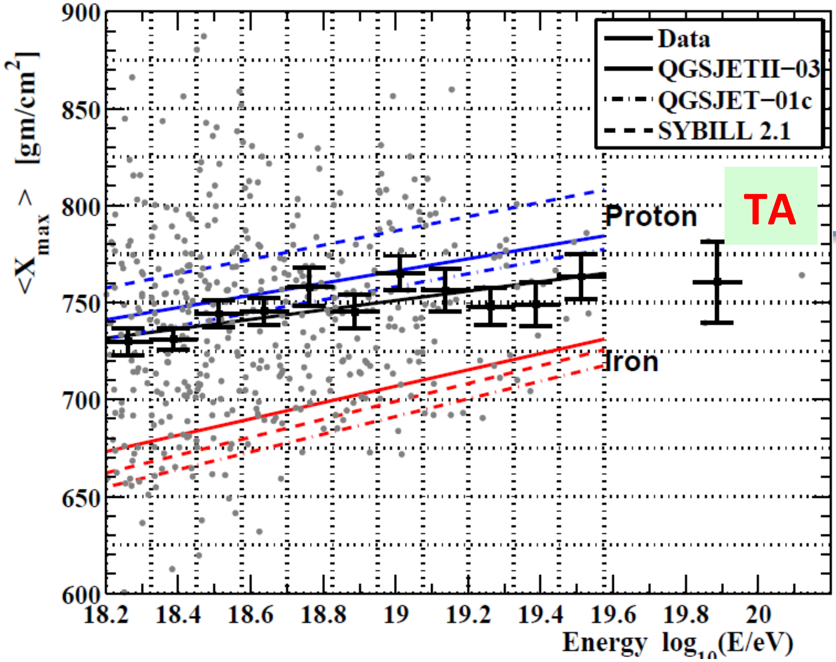
(structures in the same place)

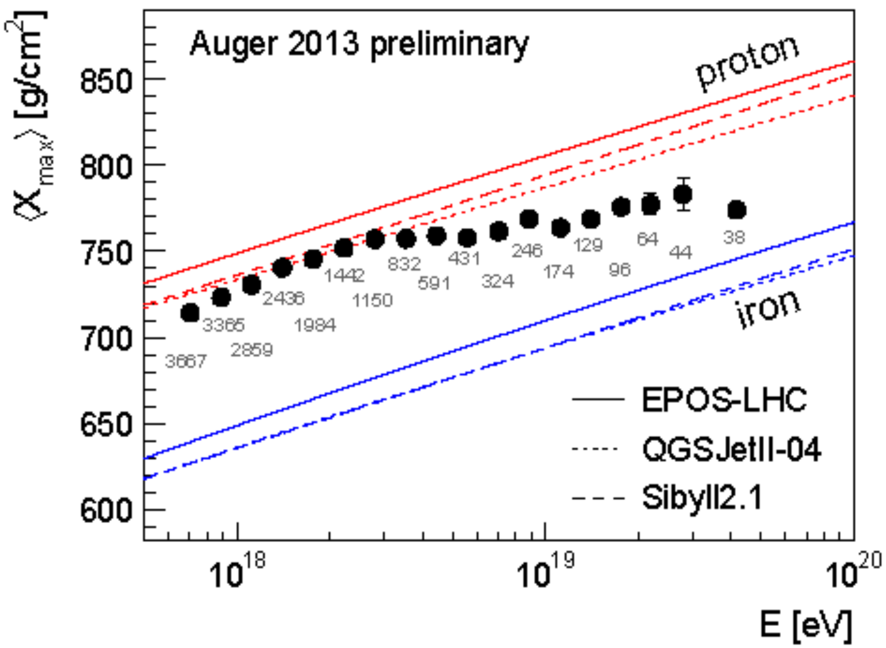


Auger

ICRC 2013

Composition





TA and Auger apparently differ:

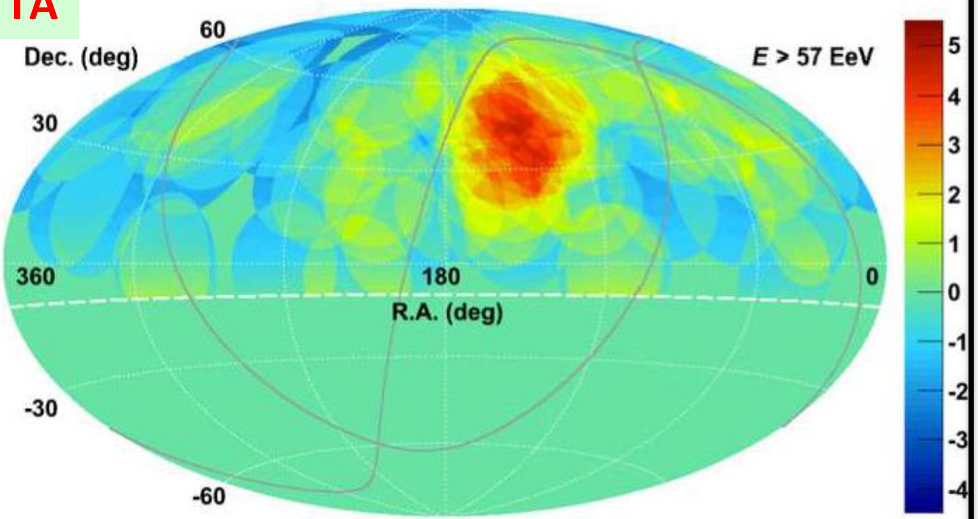
- **GZK scenario, flux suppression from particle energy losses during propagation**
- **source scenario, suppression determined from limit of power of acceleration site**

Observable: **Mean depth of shower maximum X_{max}** as a function of the energy, elongation rate, closely related to interaction length of primary.

Abbasi et al. arXiv:1408.1726v1
Letessier-Selvon et al. arXiv:1310.4620

Anisotropy: TA vs Auger

TA



10^6 total events over 6 years

87 events > 57 EeV , < 60°

Shown: events within 20° of each point

Hot Spot at RA= **148.4°** and dec= **+44.5°**

(*Mrk 421 is in the vicinity …)*

4.3 σ significance compared to isotropic fluctuation

R. Abbasi et al., Ap. J (Lett) **790** (2014) L21; arXiv:1404.5890 [astro-ph.HE]

Auger

Events > 55 EeV

Excess from directions "near" (~20°) **Cen-A**

P. Abreu et al. , Astropart. Phys. **34** (2010) 314.

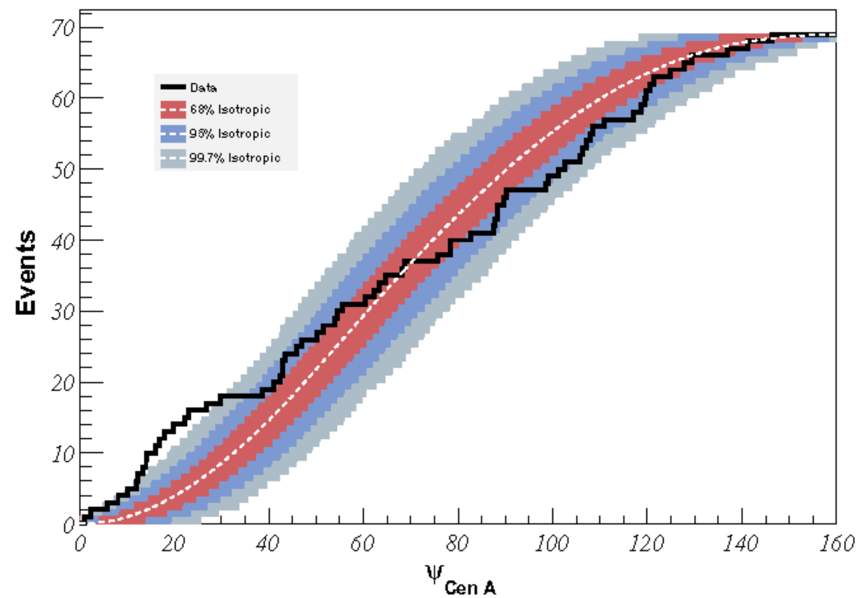
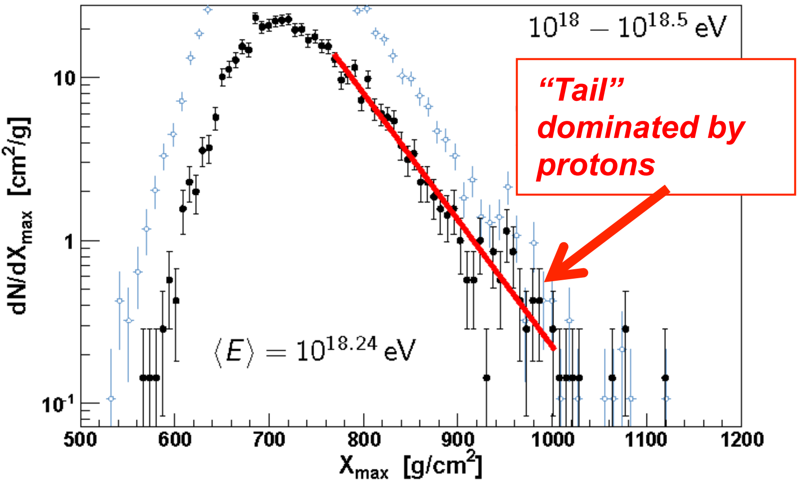
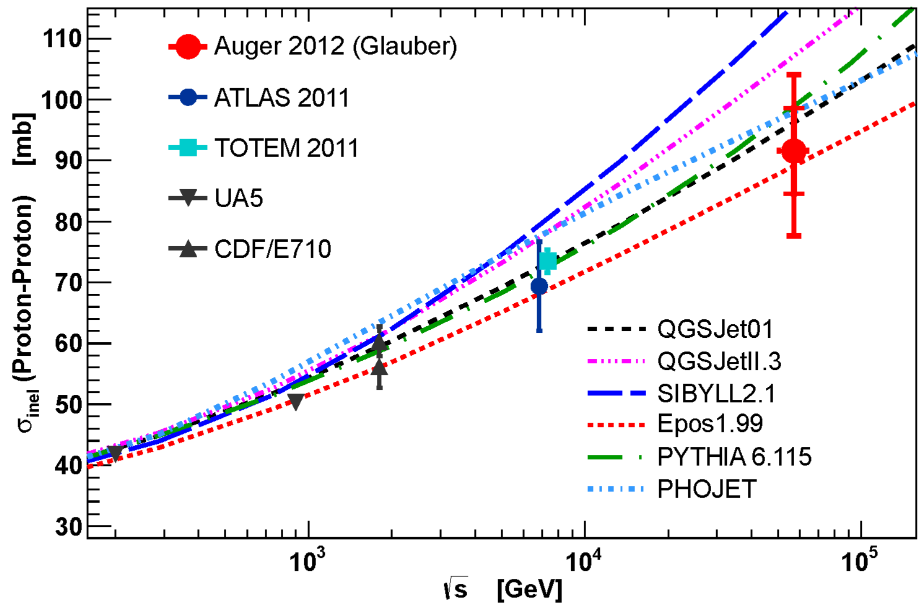


Fig. 9. Cumulative number of events with $E \geqslant 55$ EeV as a function of angular distance from the direction of Cen A. The bands correspond to the 68%, 95% and 99.7% dispersion expected for an isotropic flux.

Interconnection with HEP:p-air cross section





$$\Lambda_\eta = [55.8 \pm 2.3_{\rm stat} \pm 1.6_{\rm sys}]\ {\rm g/cm^2}$$

$$\sigma_{pp}^{\rm inel} = [92 \pm 7({\rm stat})^{+9}_{-11}({\rm syst}) \pm 7({\rm Glauber})]\ {\rm mb},$$

$$\sigma_{pp}^{\rm tot} = [133 \pm 13({\rm stat})^{+17}_{-20}({\rm syst}) \pm 16({\rm Glauber})]\ {\rm mb}.$$

P.Abreu et al., Phys. Rev. Lett. 109.062002 (2012)

Summary and Outlook

Direct Detection:

- Important results from space based CR direct detection experiments
  - ✓ Accurate measurements of e^+ fraction and e^+ and e^- fluxes:
    - above 200 GeV e^+ fraction is no longer increasing with energy
    - separated fluxes cannot be described by a single power law
    - positron fraction excess due to the hardening of positron flux
  - ✓ p/He energy spectra (AMS results by the end of 2014)
  - ✓ B/C constraints on propagation models
- New Space based calorimetric experiments will extend the energy range of direct measurements of galactic CR (Cosmic Ray Observatory on ISS): connection of direct and indirect observations

Summary and Outlook

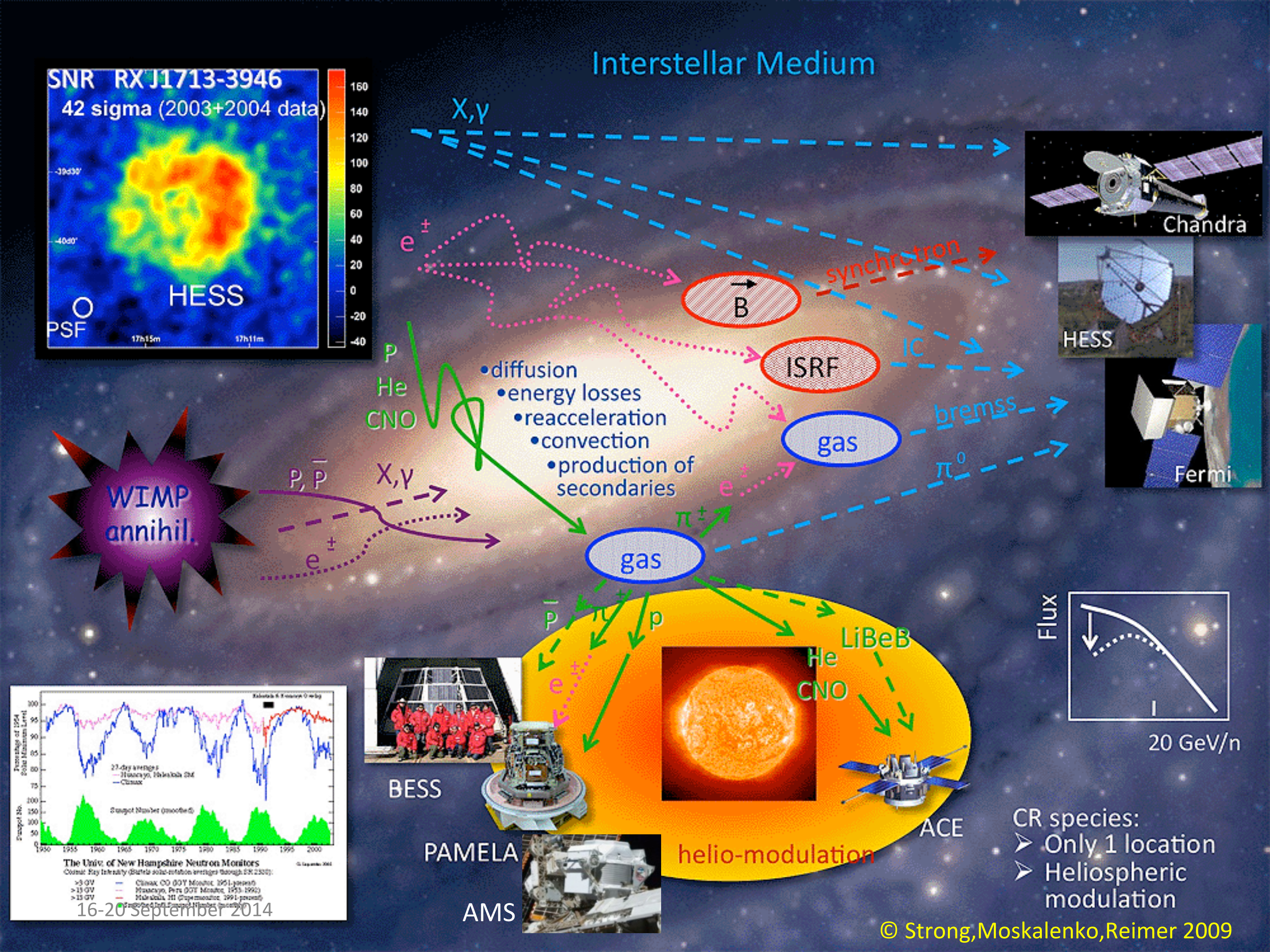
Indirect Detection

- "End" of the spectrum, GZK or source limit to be understood
- Mass composition: UHECR composition still an open issue
- Future Plans & Goals:
  - TA and Auger each have enhancements underway:Radar, Radio, "Infill" arrays, Lower thresholds
    - Expand TA to 3000 km^2
    - Expand Auger muon coverage
  - Determine origin of the flux suppression
  - Search a proton flux contribution at the highest energies
  - Improve hadron interaction models from EAS studies and cross section measurements, reducing systematics from energy scale and proton selection

BACKUP SLIDES

What we know

- Most CRs are supposed to originate from sources in the local galaxy
- Their diffusion depends on energy
- CR accelerated by expanding supernova remnants to energies higher then 10 TeV
- "knee" associated with the escaping of a particle species accelerated by galactic sources
- Highest energy particles from extragalactic sources


Interstellar Medium
SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
X,γ
e±
B
synchrotron
ISRF
IC
gas
bremss
π0
P
He
CNO
•diffusion
•energy losses
•reacceleration
•convection
•production of secondaries
WIMP annihil.
P, P̄
X,γ
e±
π±
gas
P̄
π±
p
e±
LiBeB
He
CNO
Chandra
HESS
Fermi
Flux
20 GeV/n
BESS
PAMELA
AMS
ACE
helio-modulation
CR species:
➢ Only 1 location
➢ Heliospheric modulation
The Univ. of New Hampshire Neutron Monitors
Sunspot Number (smoothed)
27-day averages

The experimental challenge

No atmosphere: Stratospheric Balloons
Space

⇩ Limits on size and time

Detector design focused on specific measurements

p,He,e^-,anti-matter

⇩

Magnetic spectrometers
Energy reach limited by MDR

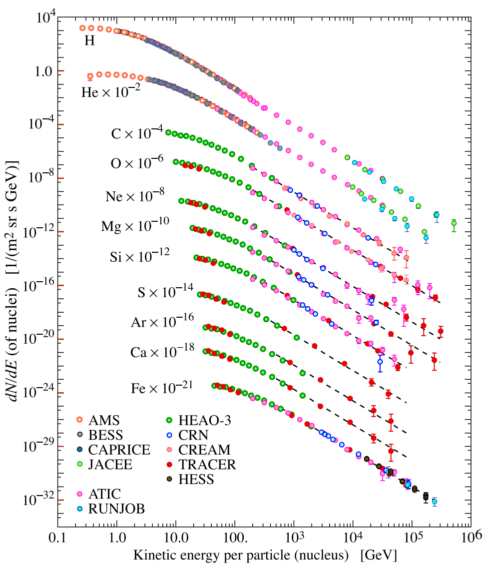
Primary spectra, Nuclei

⇩

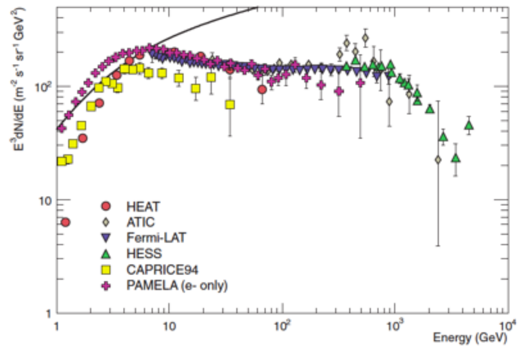
Calorimetry, TRD, +..
Energy reach limited by Statistics

Direct Detection : detailed view …

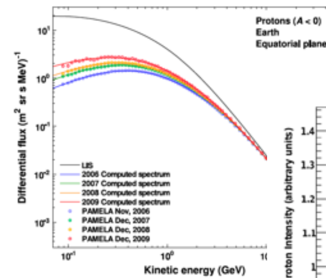
Chemical composition

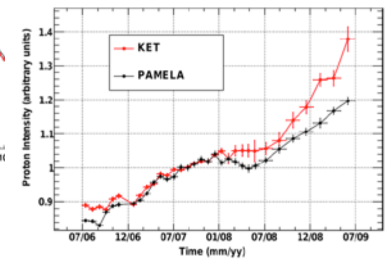


The electron component



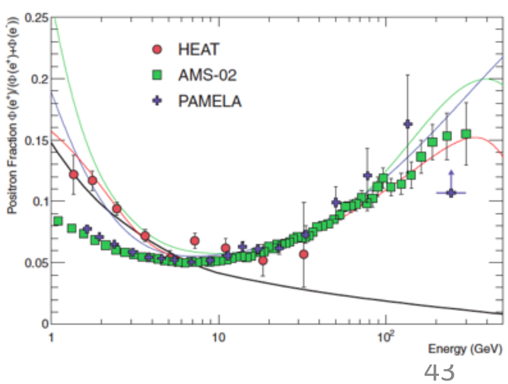
Earth & Sun

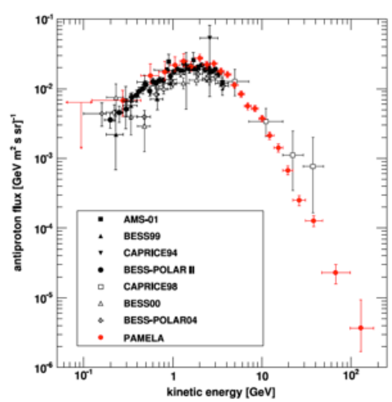


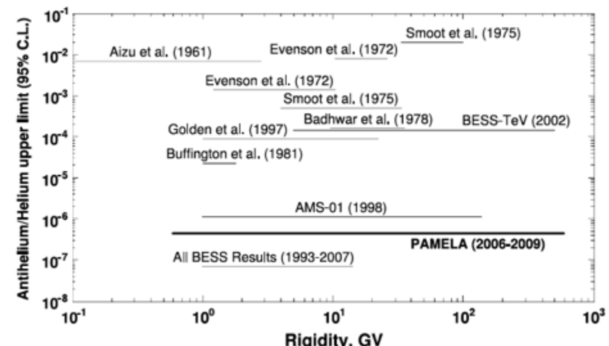


Sources | **Propagation**

ISM | **New Physics?**



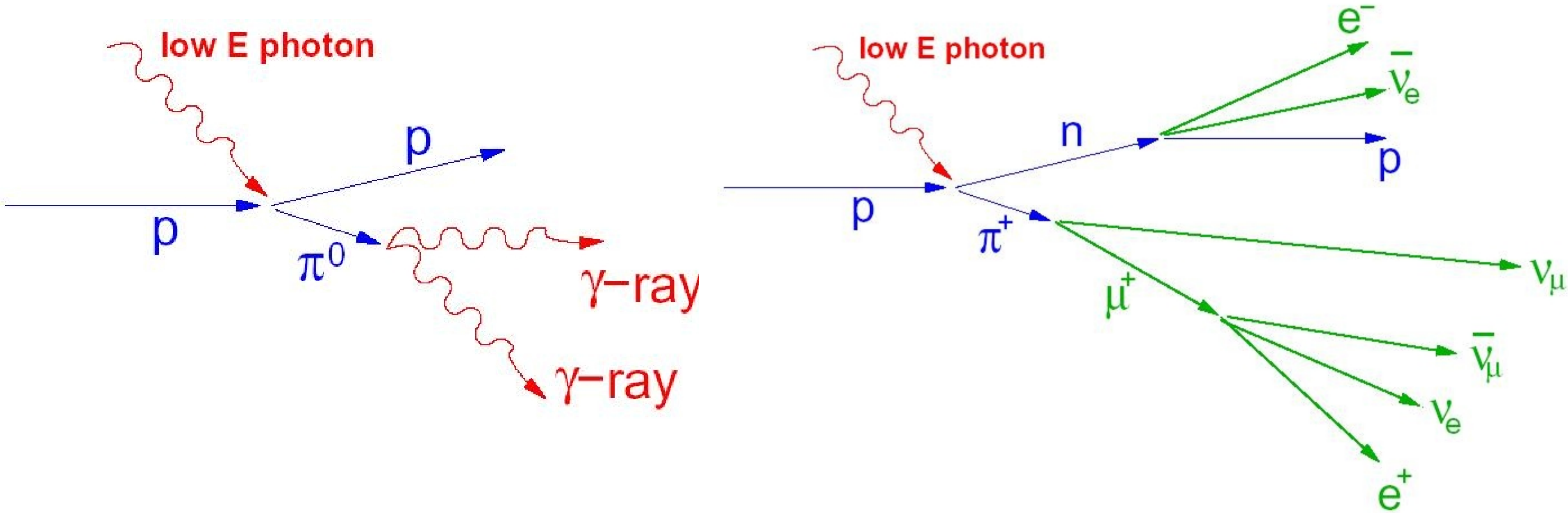




Anti-matter

GZK process

p + γ (2.7°K) → Δ⁺ → p + π° , n + π⁺ , ...



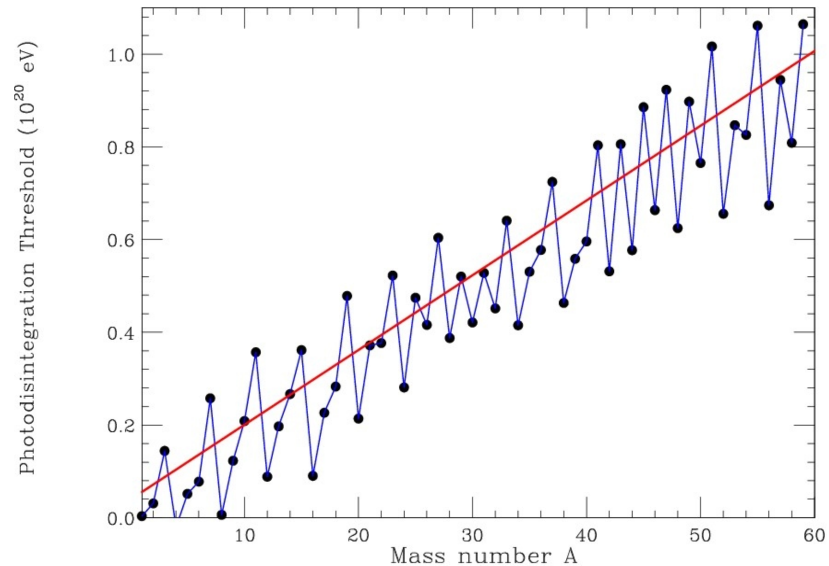
$$E^{\pi}_{\rm th} \sim \frac{m_\pi \; m_p}{10 \; T_\gamma} \simeq 6 \times 10^{19} \; {\rm eV}$$

Photo-disintegration of nuclei

$$A + \gamma \to (A-1) + N$$

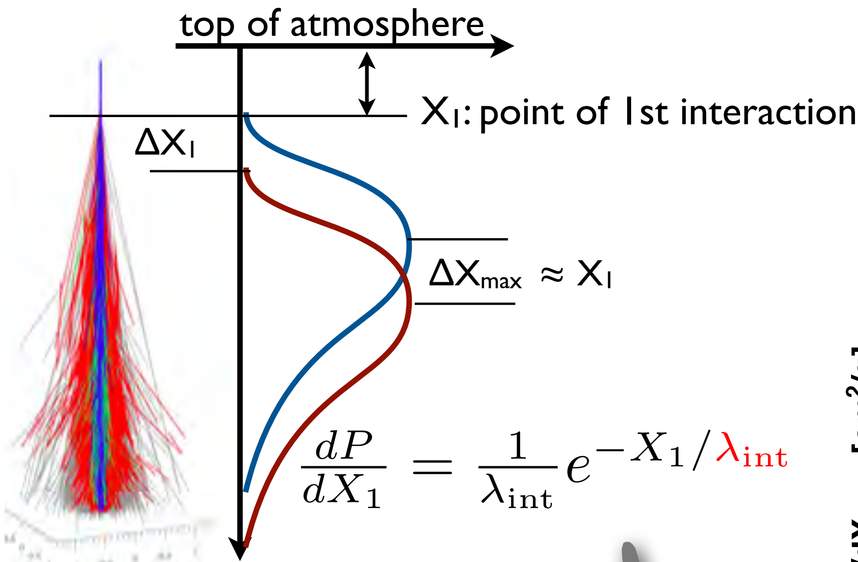
$$E_A \geq \frac{(m_{A-1} + m_N)^2 - m_A^2}{2\,\varepsilon_\gamma\,(1-\cos\theta_{p\gamma})}$$

$$m_A \simeq A\ \,(m_N - \epsilon_B)$$

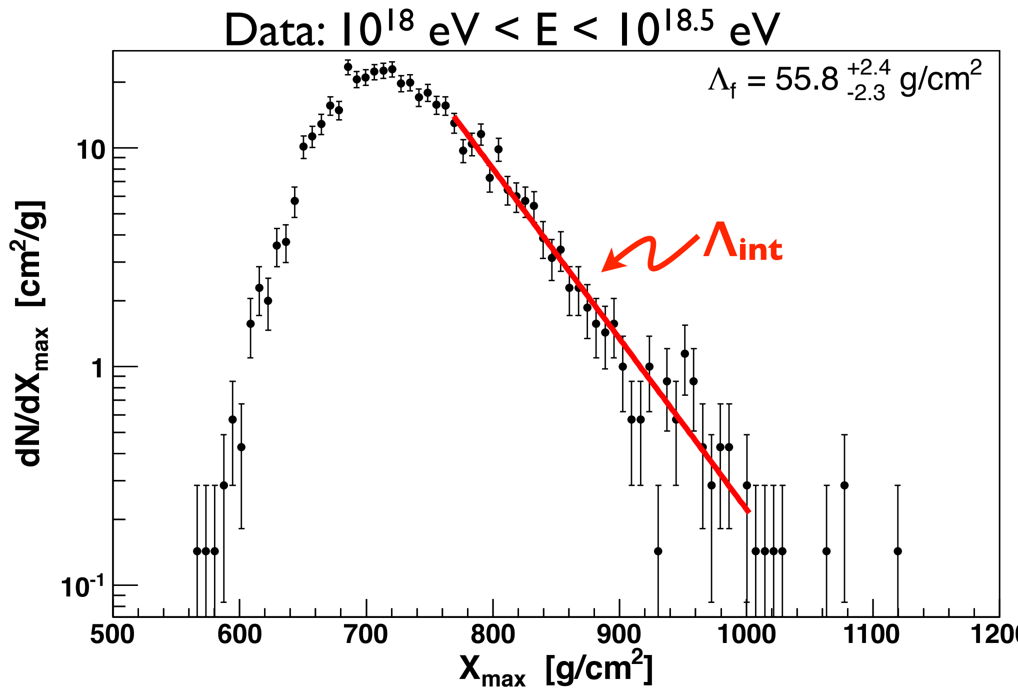


$$E_A \gtrsim \frac{A\,m_N\epsilon_B}{2\,\varepsilon_\gamma\,(1-\cos\theta_{p\gamma})} \simeq \frac{A}{56} \times 10^{20}\ \text{eV}$$

p-Air cross section



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



Difficulties:

- mass composition can alter Λ
- fluctuations in X_{max}
- experimental resolution ~ 20 g/cm^2

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

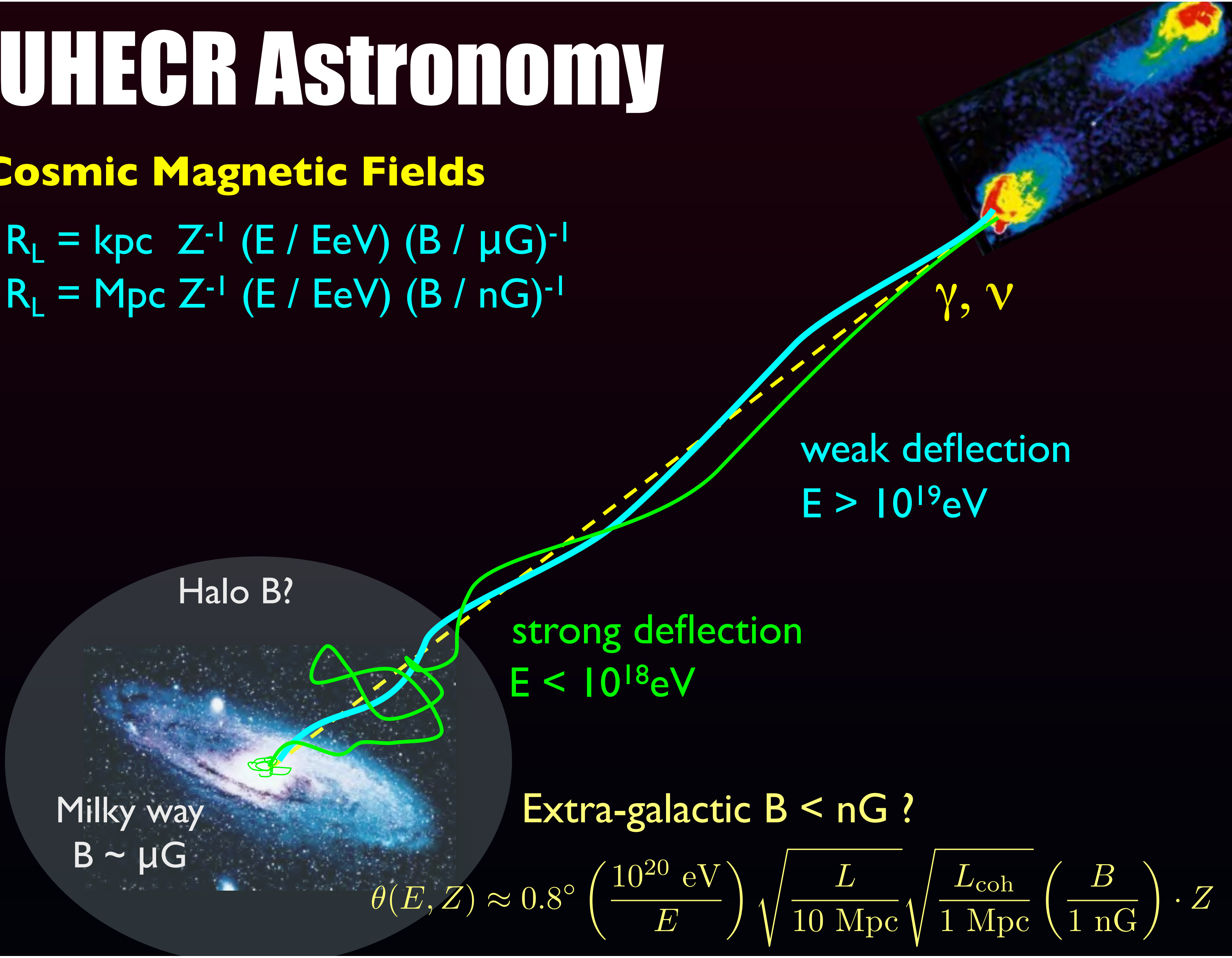
In practice: $\sigma_{\text{p-Air}}$ by tuning models to describe Λ seen in data

UHECR Astronomy

Cosmic Magnetic Fields

R_L = kpc Z^{-1} (E / EeV) (B / μG)$^{-1}$

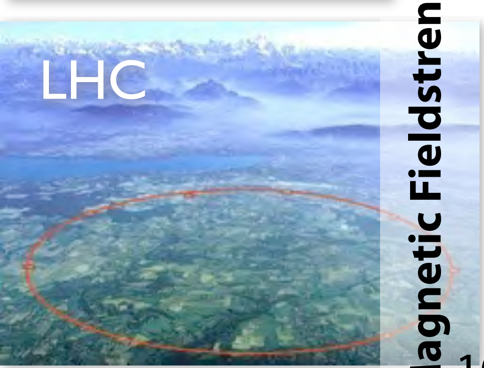
R_L = Mpc Z^{-1} (E / EeV) (B / nG)$^{-1}$

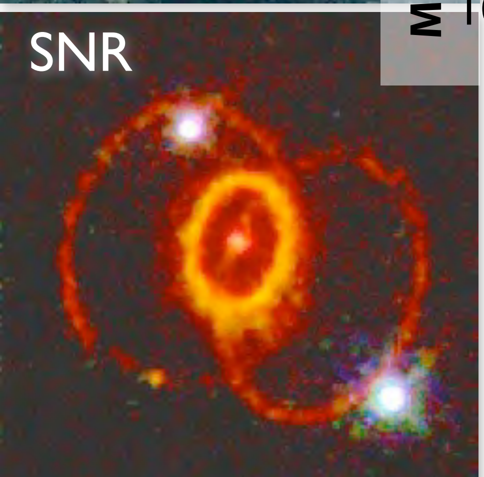


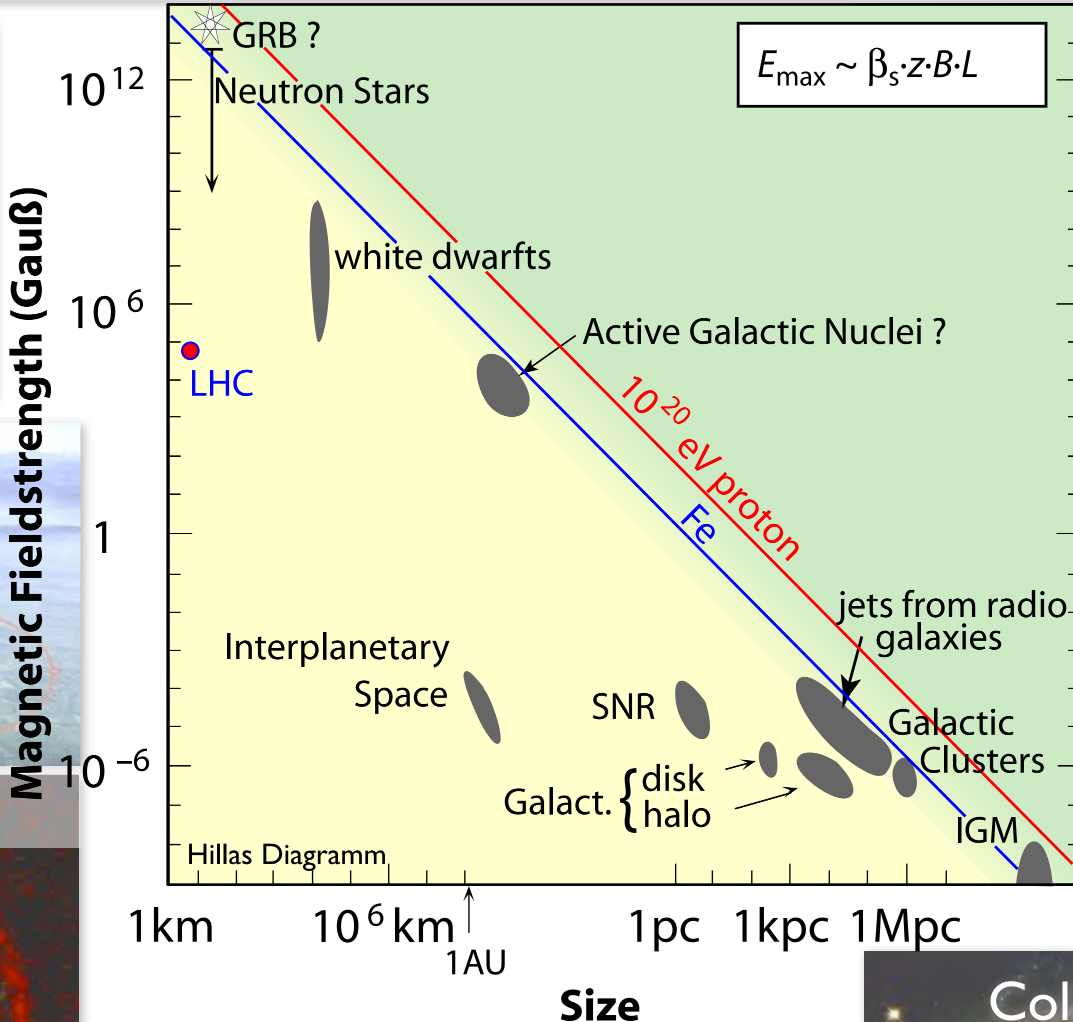
Extra-galactic B < nG ?

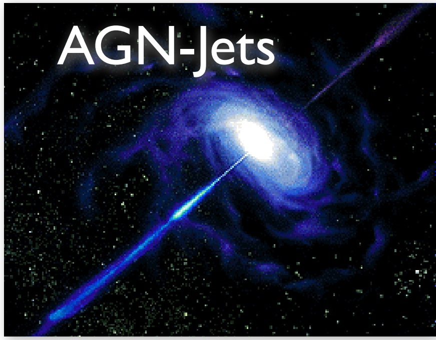
$$\theta(E,Z) \approx 0.8^\circ \left(\frac{10^{20}\ \mathrm{eV}}{E}\right)\sqrt{\frac{L}{10\ \mathrm{Mpc}}}\sqrt{\frac{L_{\mathrm{coh}}}{1\ \mathrm{Mpc}}}\left(\frac{B}{1\ \mathrm{nG}}\right)\cdot Z$$

Potential sources









Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region