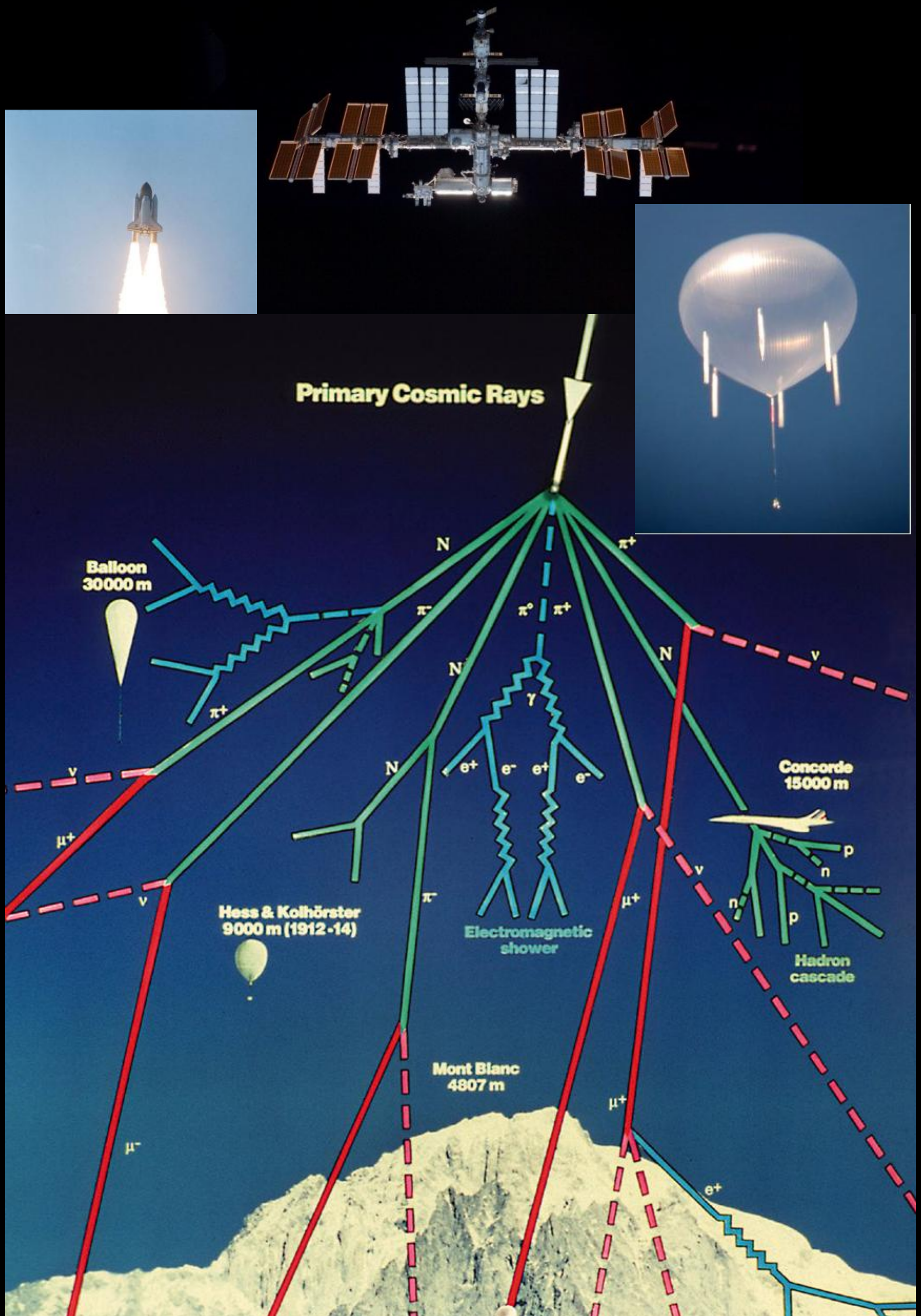
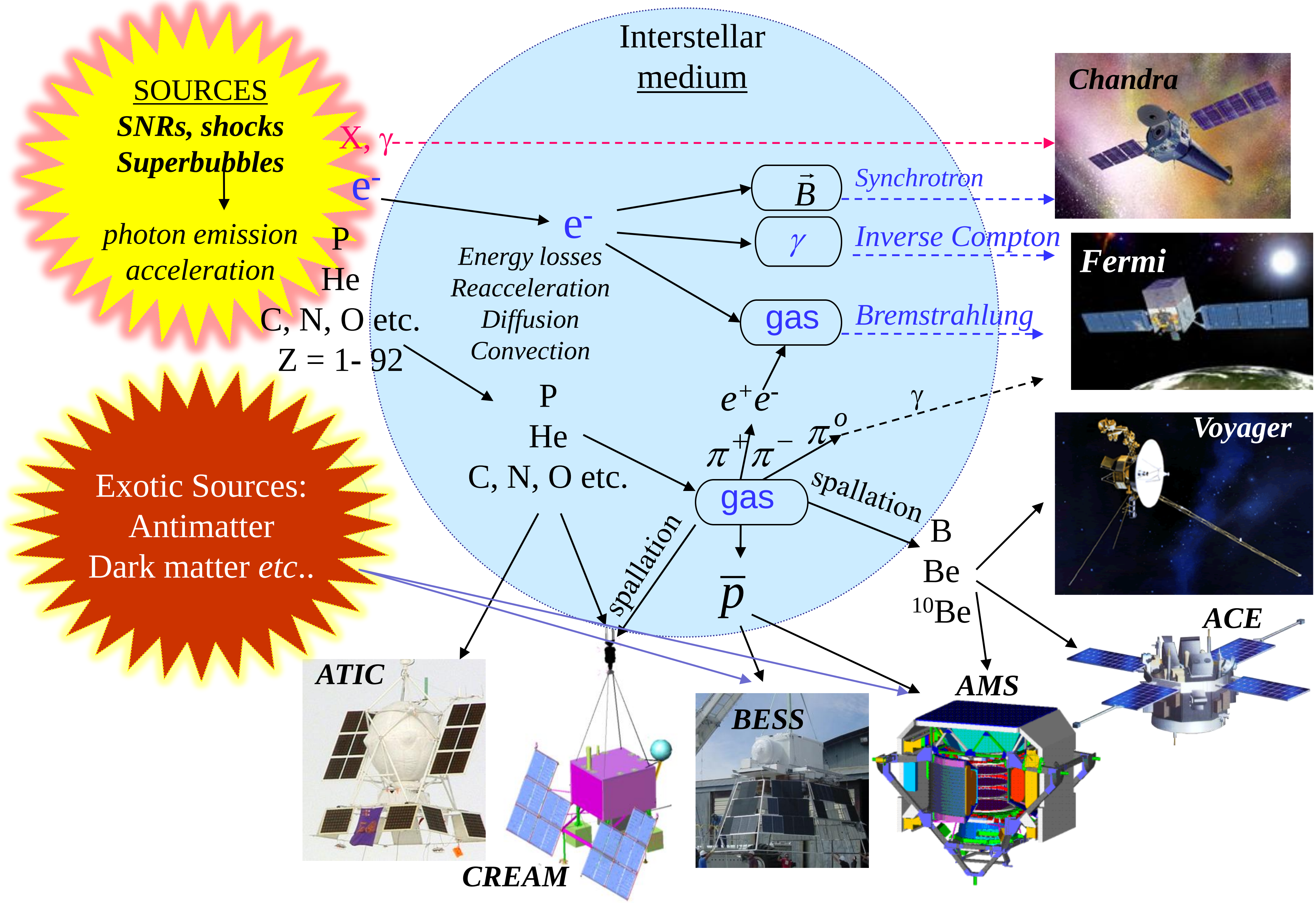


Balloon & Satellite Experiments: Non-magnet detectors

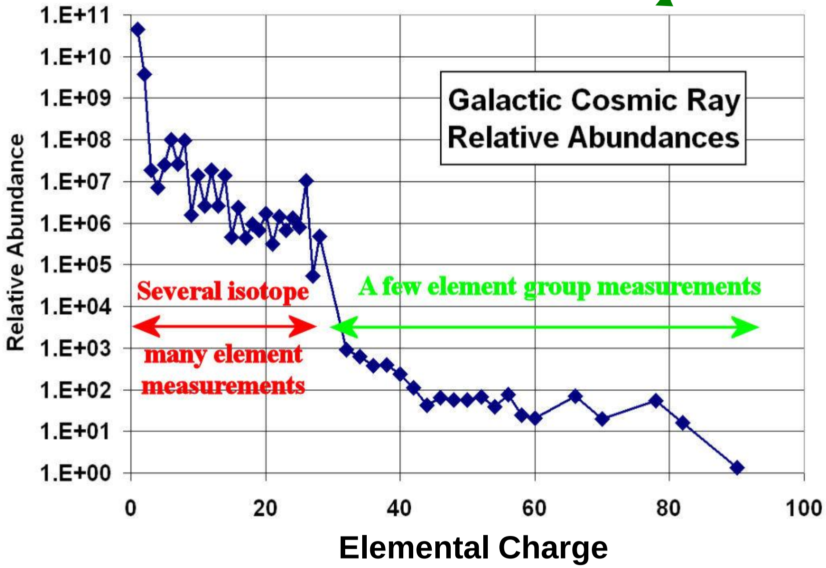
XVI International Symposium on
Very High Energy Cosmic Ray
Interactions (ISVHECRI 2010)
FNAL
6/28/10 – 7/2/10

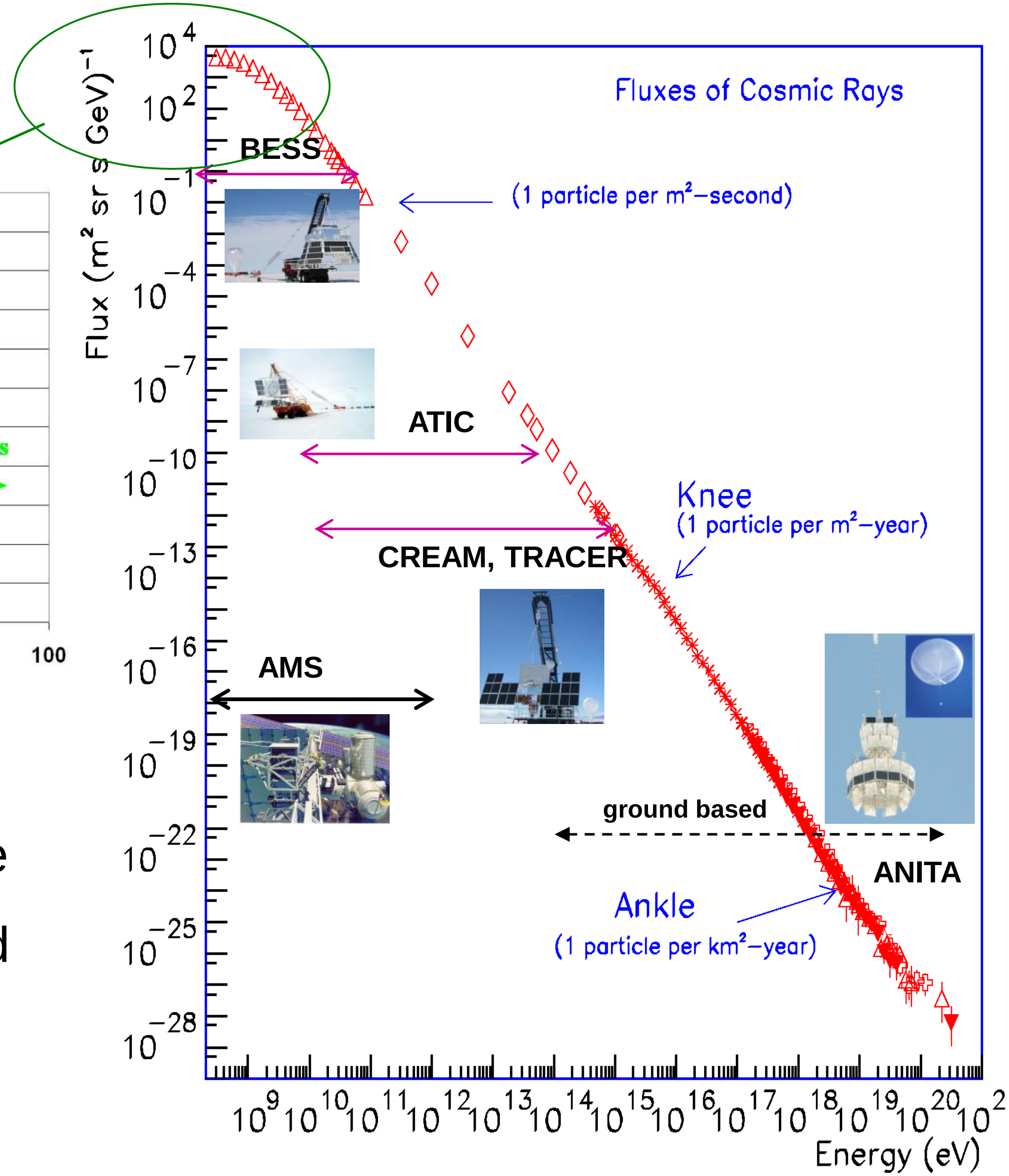
Eun-Suk Seo
Inst. for Phys. Sci. & Tech. and
Department of Physics
University of Maryland



SOURCES
SNRs, shocks
Superbubbles
photon emission
acceleration
X, γ
e⁻
P
He
C, N, O etc.
Z = 1- 92
Exotic Sources:
Antimatter
Dark matter etc..
Interstellar
medium
e⁻
Energy losses
Reacceleration
Diffusion
Convection
B⃗
γ
gas
Synchrotron
Inverse Compton
Bremstrahlung
e⁺e⁻
P
He
C, N, O etc.
π⁺π⁻
π⁰
γ
gas
spallation
spallation
p̄
B
Be
¹⁰Be
Chandra
Fermi
Voyager
ACE
AMS
BESS
ATIC
CREAM

How do cosmic accelerators work?

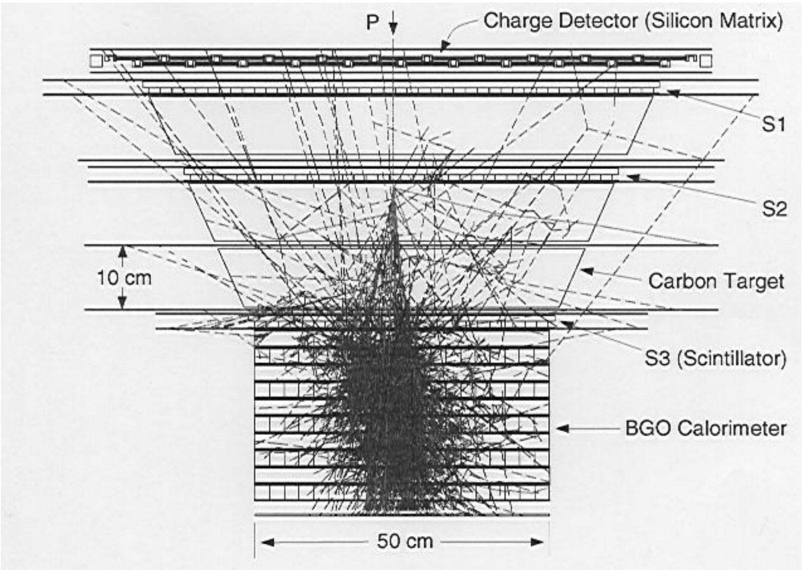


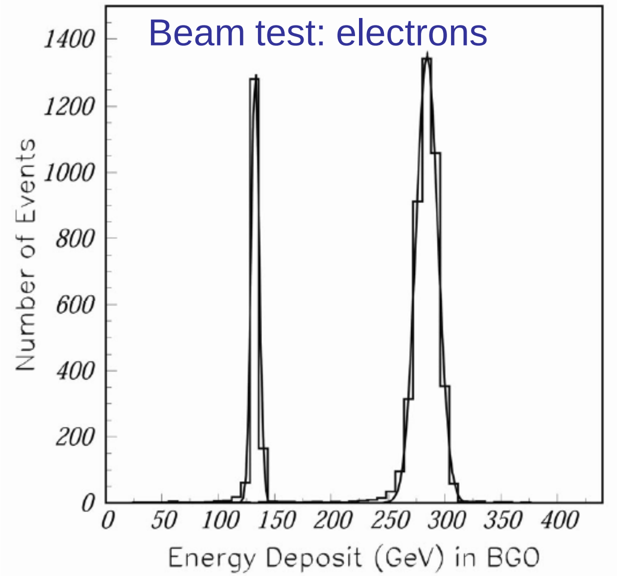


- Relative abundances range over 11 orders of magnitude
- Detailed composition limited to less than ~ 10 GeV/nucleon

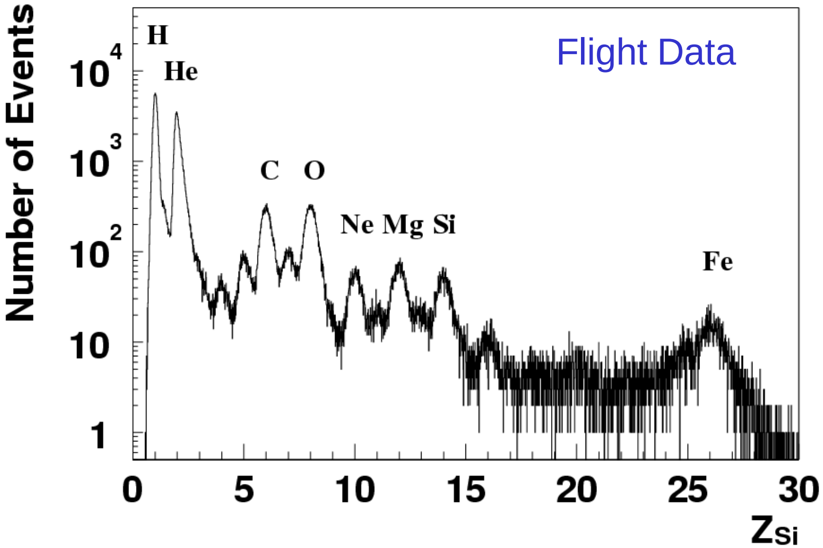
Advanced Thin Ionization Calorimeter (ATIC)

Seo et al. Adv. in Space Res., **19** (5), 711, 1997; Ganel et al. NIM A, **552**(3), 409, 2005





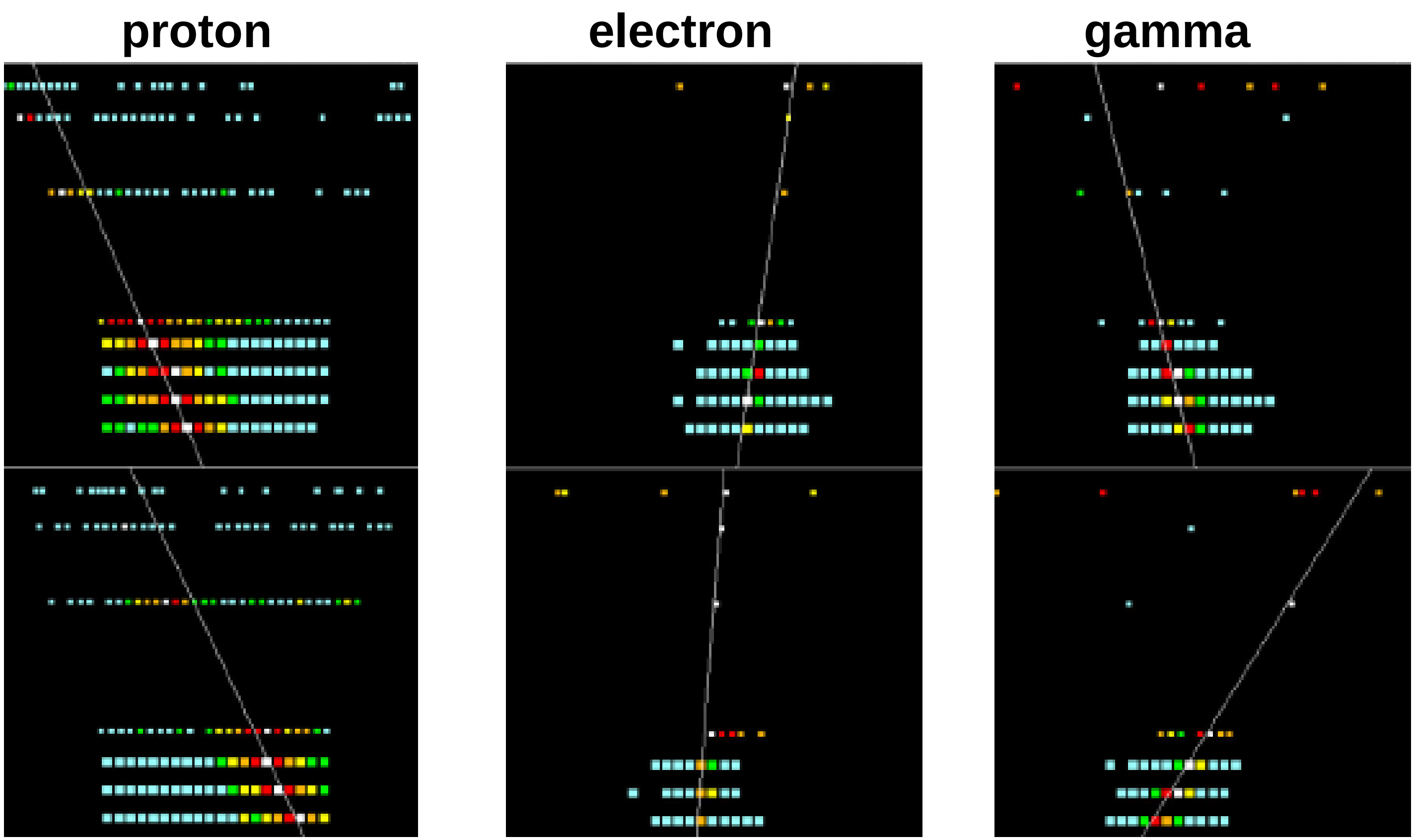
- Beam measurements for 150 GeV electrons show 91% containment of incident energy, with a resolution of 2% at 150 GeV
- Proton containment ~38%



Electron Selection

Reject all but 1 in 5000 protons while keeping 84% of the electrons

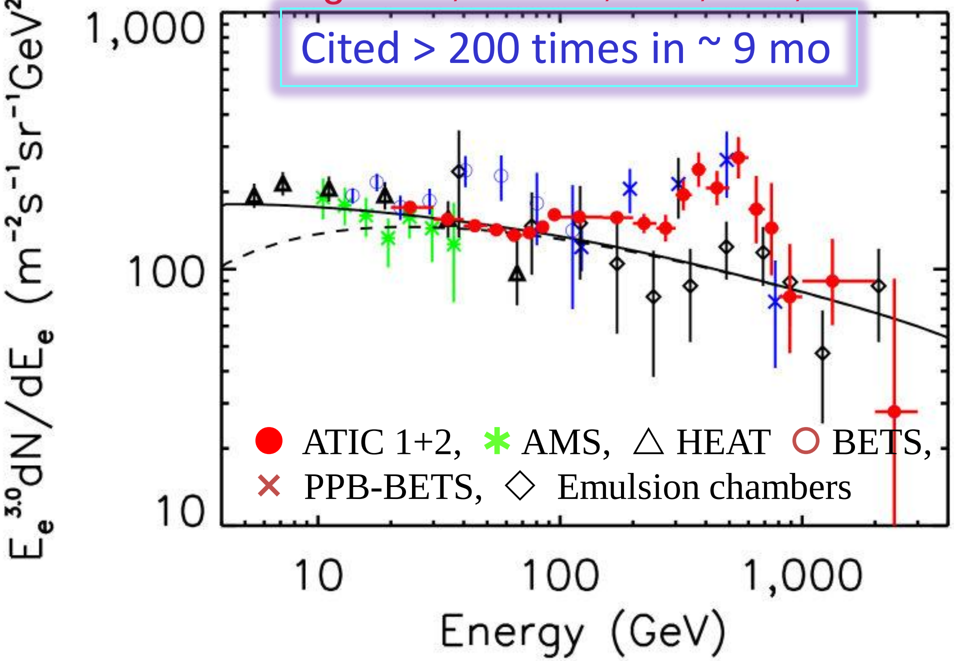
- Remove heavy ions with $Z_{Si} \geq 2$ and γ-ray with $Z_{Si} = 0$
- Separate e from p using shower profile in the calorimeter
  - Electron and gamma-ray showers are narrower than the proton showers



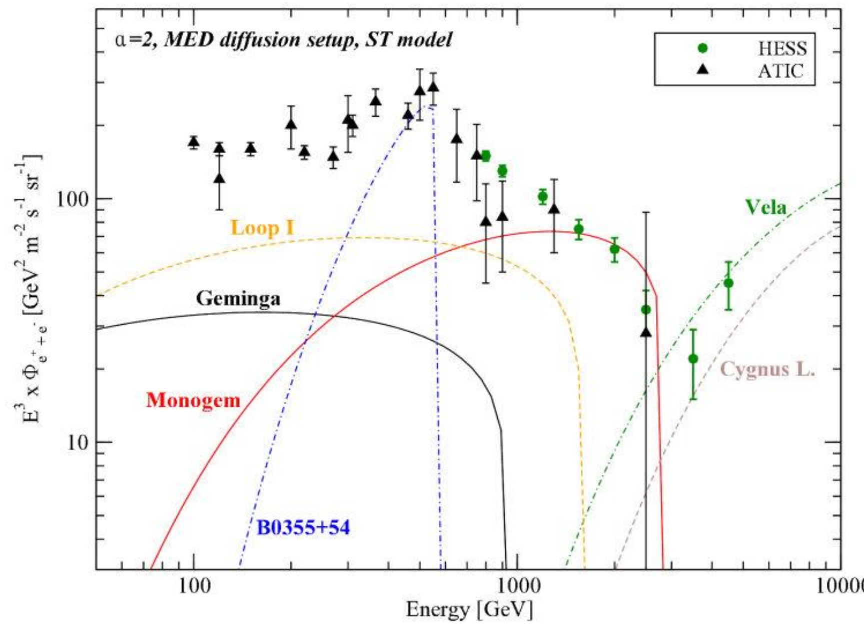
$E_d \sim 250$ GeV

The ATIC Electron Results Exhibits a "Feature"

Chang et al., Nature, **456**, 362, 2008



Profuma (arXiv: 0812.4457v1), 2008



- High energy electrons have a high energy loss rate ∝ E^2
  - Lifetime of ~10^5 years for >1 TeV electrons $(T \approx 2.5\times10^5 \times E[TeV]^{-1}\, years)$
- Transport of GCR through interstellar space is a diffusive process
  - Implies that source of electrons is < 1 kpc away $(R \approx 600/\sqrt{E[TeV]}\; pc)$
- **Possible candidate local sources would include supernova remnants (SNR), pulsar wind nebulae (PWN) and micro-quasars**

Or, a Message From the Dark Side?

"All the News That's Fit to Print"

The New York Times

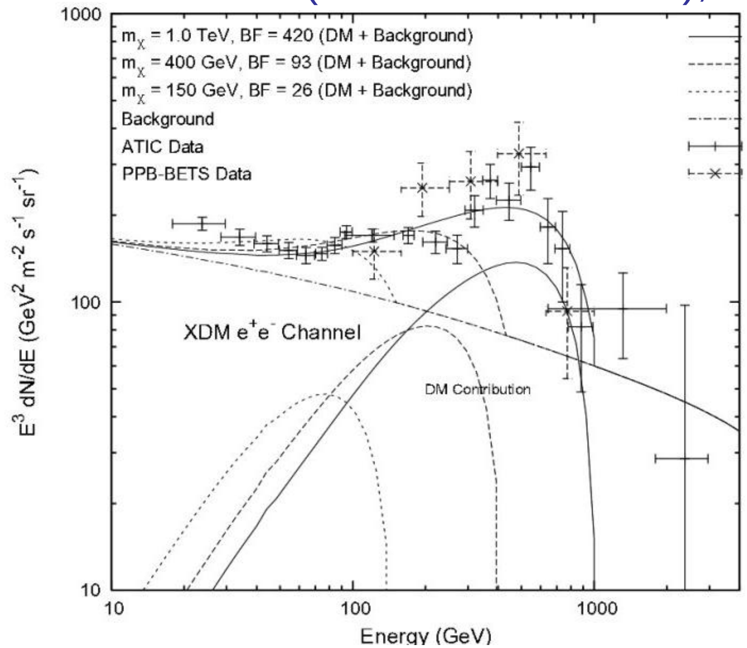
National Edition

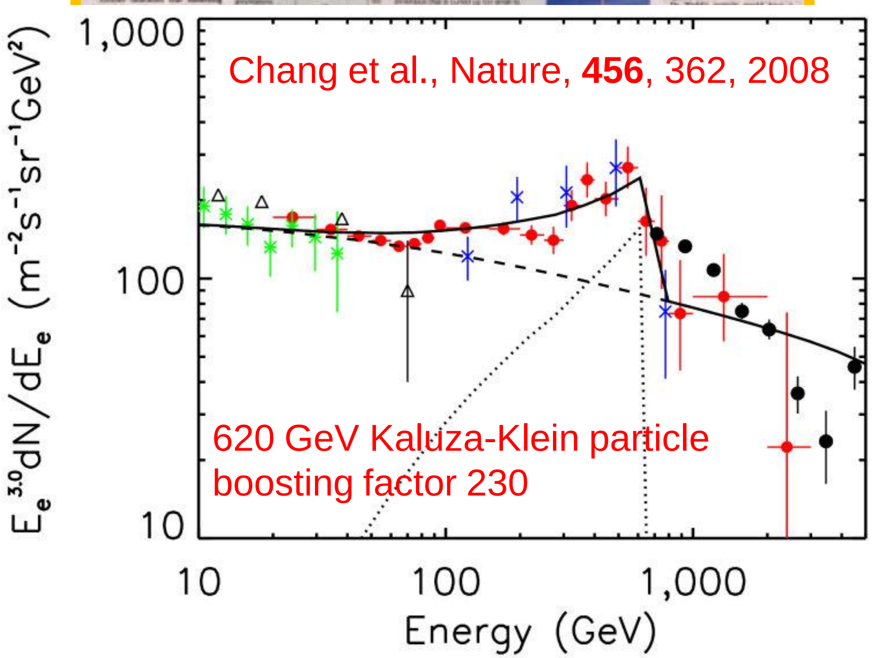
TUESDAY, NOVEMBER 25, 2008

Detecting a Whisper, Perhaps, From the Dark Side of the Universe

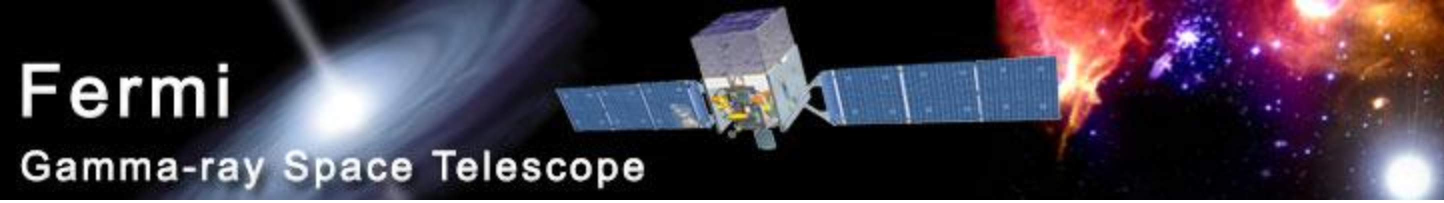
Searching for Dark Matter High Above the Antarctic

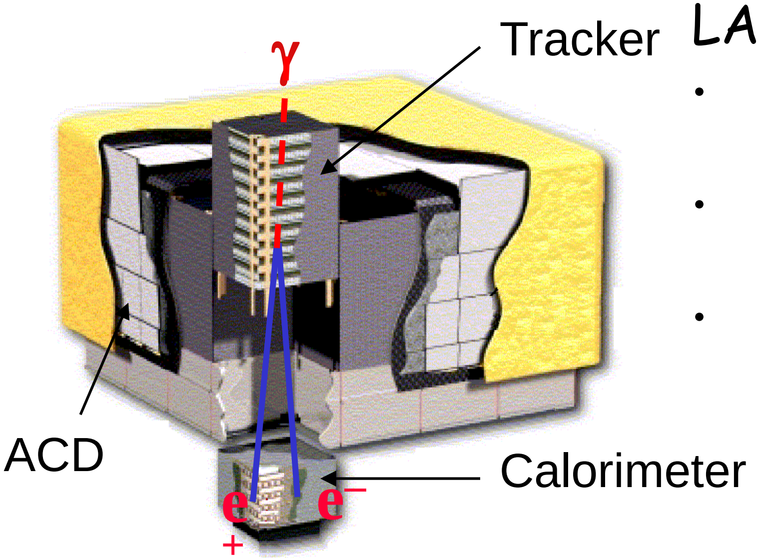
Cholis et al. (arXiv: 0811.3641v1), 2008





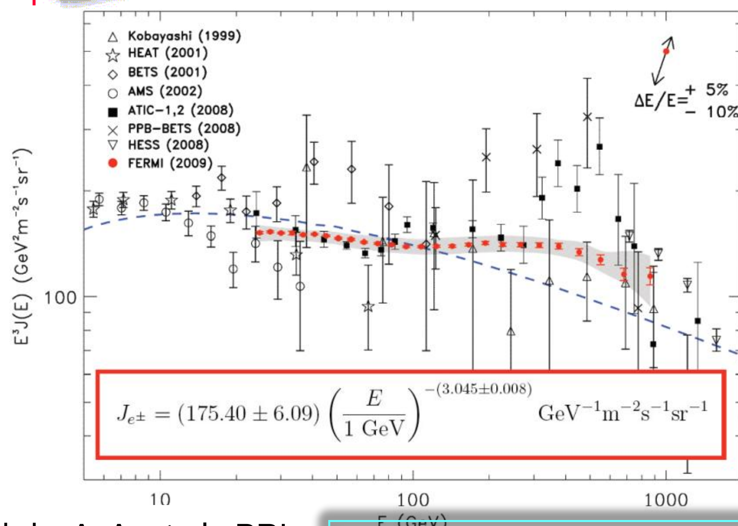
- DM annihilation to light boson → e^+e^-
- *An intermediate light boson represses production of anti-protons.*
- *Reasonable fit to PAMELA, ATIC & WMAP with particle mass of ~1 TeV and similar "boost factors".*
- *Also predicts enhancement of GC gammas*

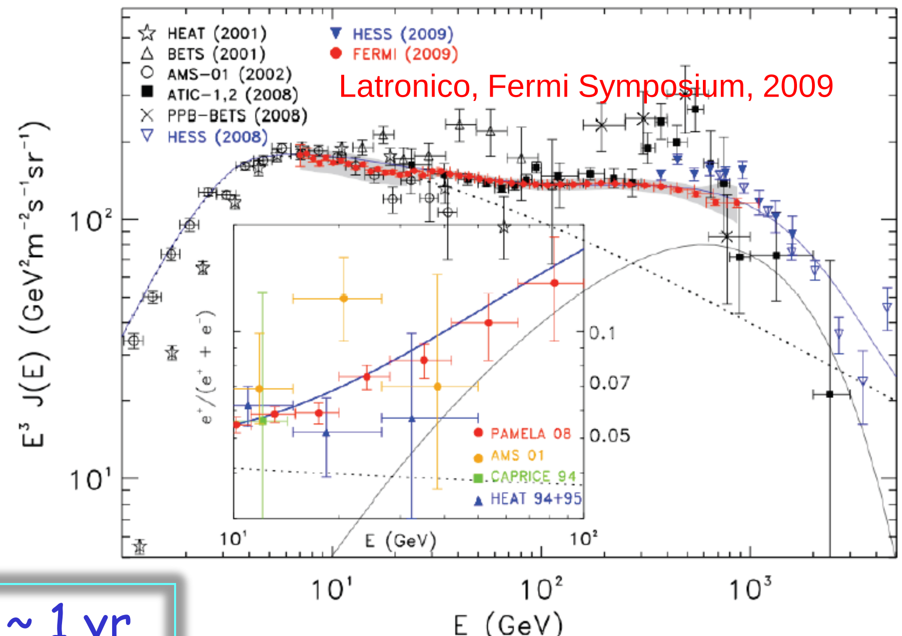




LAT

- Highly granular multi-layer Si stripTracker (1.5 X_0)
- Finely segmented fully active CsI Calorimeter (8.6 X_0)
- Highly efficient hermetic Anti-Coincidence Detector (ACD)



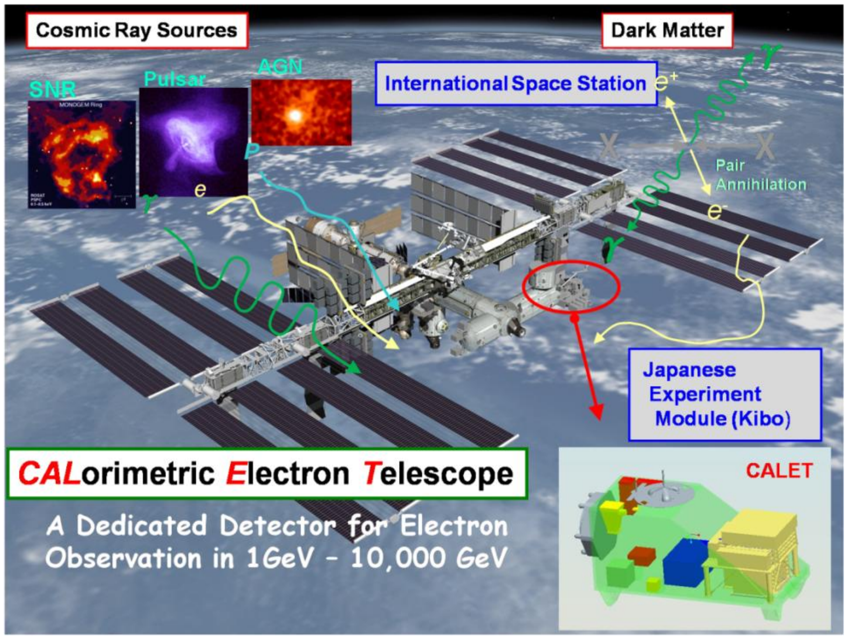


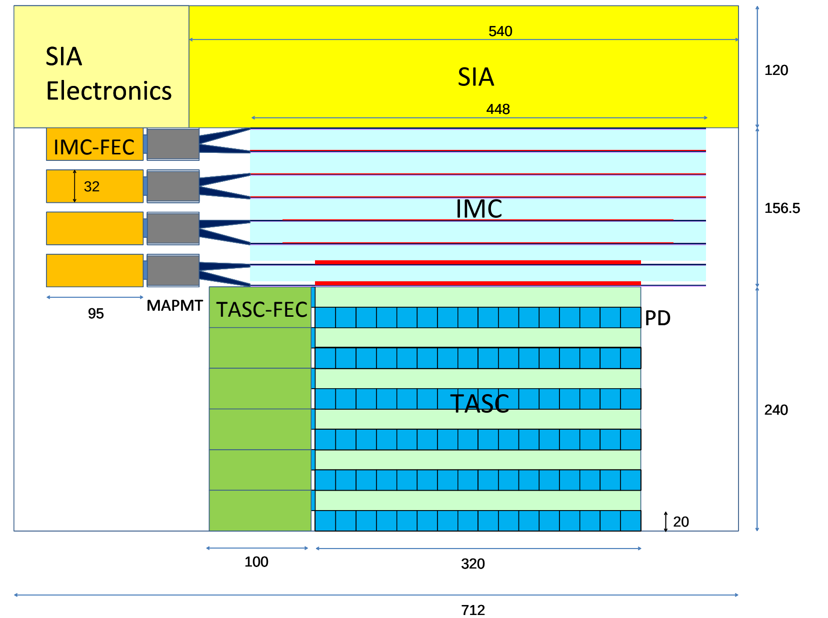
Abdo, A. A. et al., PRL **102, 181101, 2009**

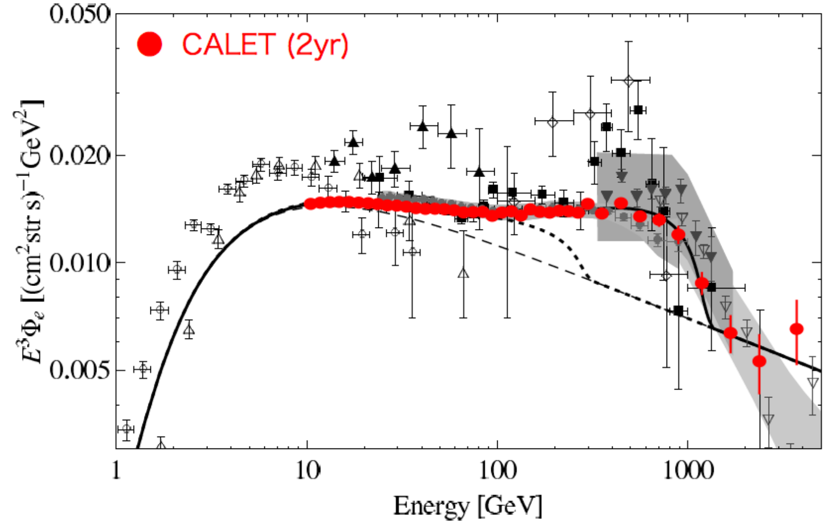
Cited > 150 times in ~ 1 yr

Calorimetric Electron Telescope (CALET)

Approved for Phase B: launch target summer, 2013







Silicon Pixel Array (Charge Z=1-35)

Silicon Pixel 11.25 mm x 11.25 mm x 0.5mm

2 Layers with a coverage of 54 x 54 cm^2

Imaging Calorimeter (Particle ID, Direction)

Total Thickness of Tungsten (W) : 3 X_0

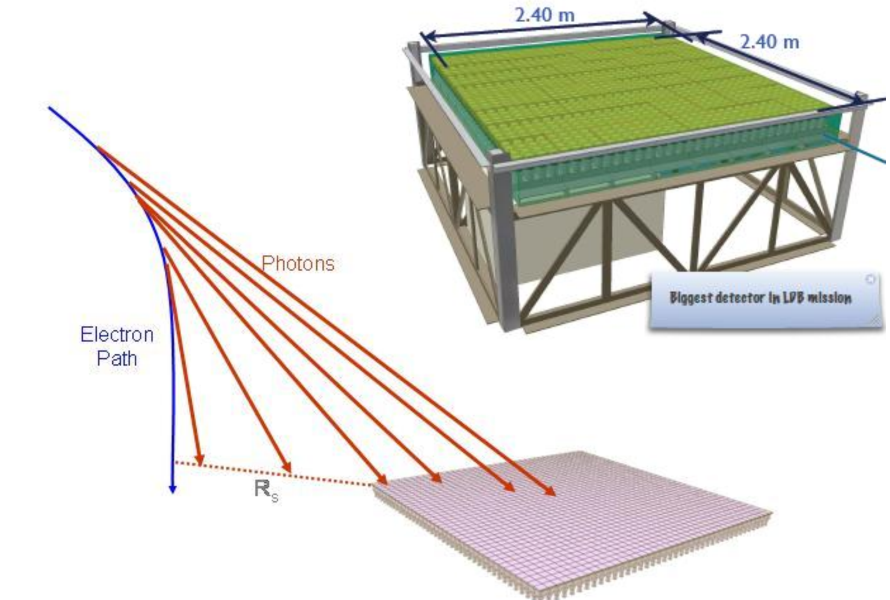
Layer Number of Scifi Belts : 8 Layers ×2(X,Y)

Total Absorption Calorimeter (Energy Measurement, Particle ID)

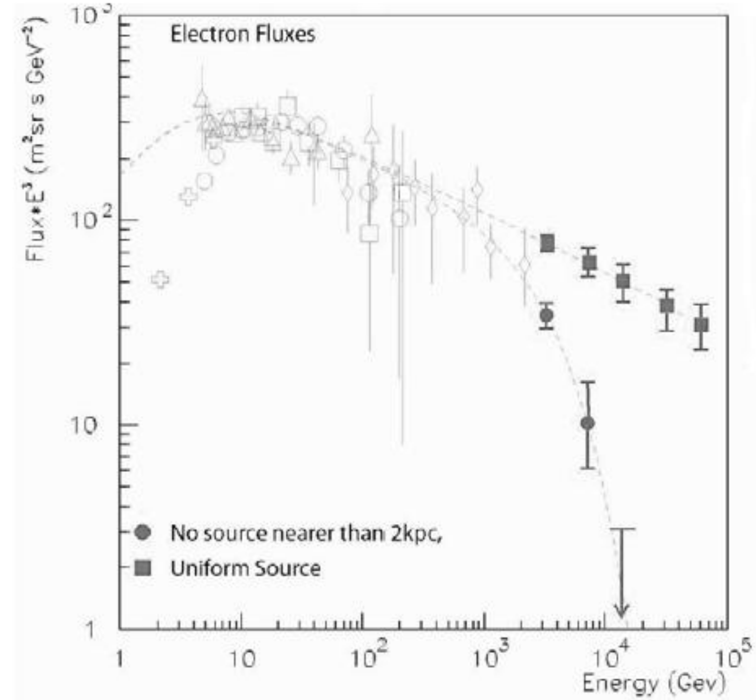
PWO 20 mm x 20 mm x 320 mm

Total Depth of PWO : 27 X_0 (24 cm)

Cosmic Ray Electron-Synchrotron Telescope (CREST)



CREST Detector – A 2 x 2 m array of 1600 1” diameter BF_2 crystals.

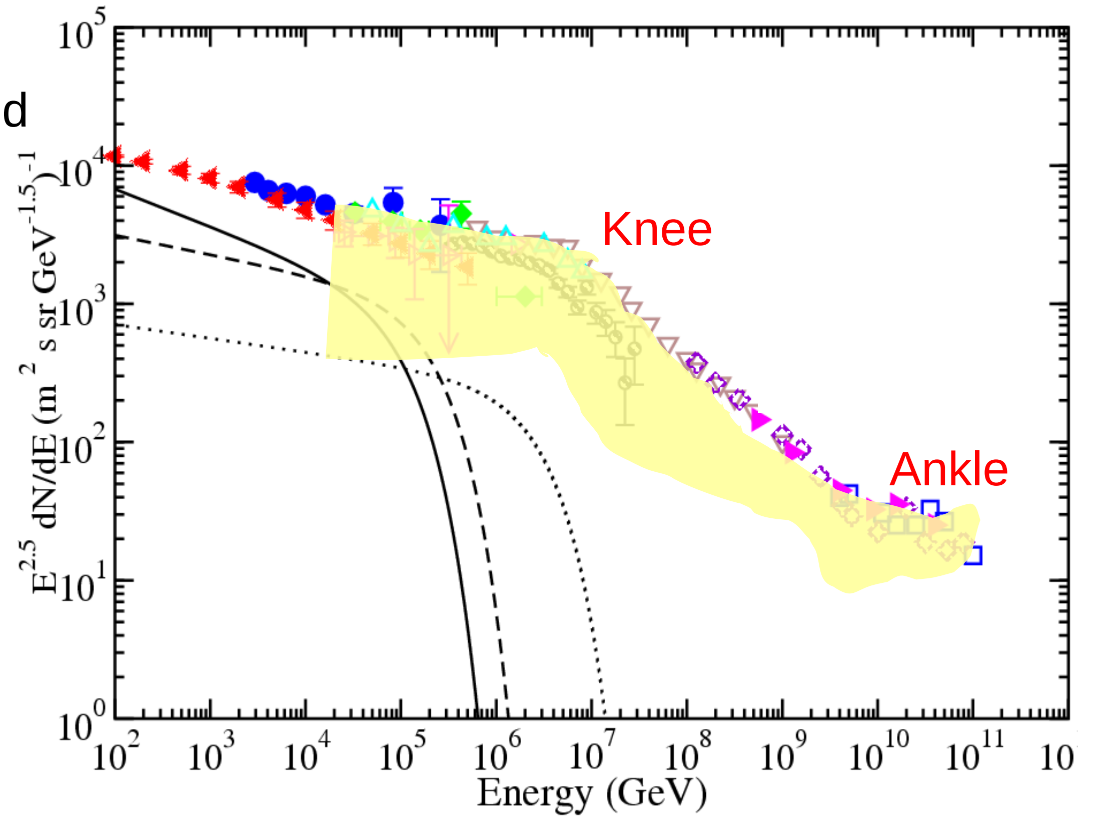


Expected result: 100-day CREST exposure

- CREST identifies UHE electrons by observing the characteristic linear trail of synchrotron gamma rays generated as the electron passes through the Earth’s magnetic field
  - This results in effective detector area much larger than the physical instrument size
- CREST expected to fly as Antarctic LDB payload in the 2010-2011 season
- Upgrade of CREST for ULDB operation would be straightforward

Is the "knee" due to a limit in SNR acceleration?

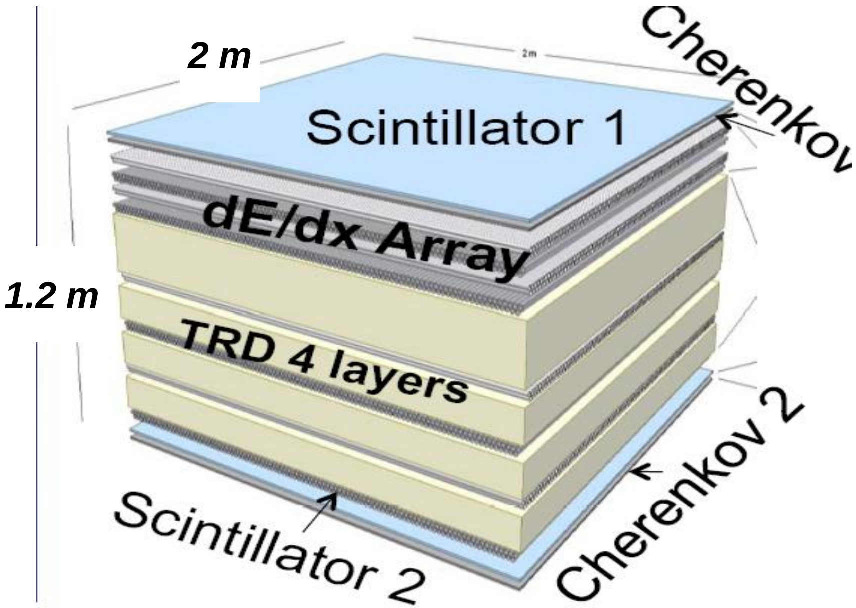
- The all particle spectrum extends several orders of magnitude beyond the highest energies thought possible for supernova shocks
- And, there is a "knee" (index change) above 10^{15} eV
- Acceleration limit signature: Characteristic elemental composition change over two decades in energy below and approaching the knee
- Direct measurements of individual elemental spectra can test the supernova acceleration model

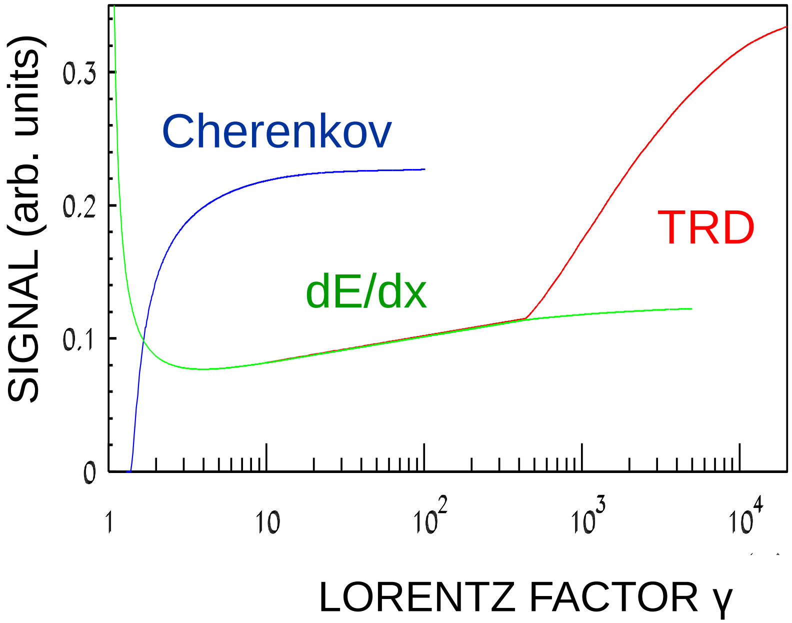


SNR acceleration limit:

$$E_{\max} \sim \frac{v}{c} ZeBVT \sim \underline{Z \times 100 TeV}$$

Transition Radiation Array for Cosmic Energetic Radiation (TRACER)





ENERGY RESPONSE:

Acrylic Cherenkov Counter ***(γ < 10)***

Specific Ionization in Gas ***(4 < γ < 1000)***

Transition Radiation Detector ***(γ > 400)***

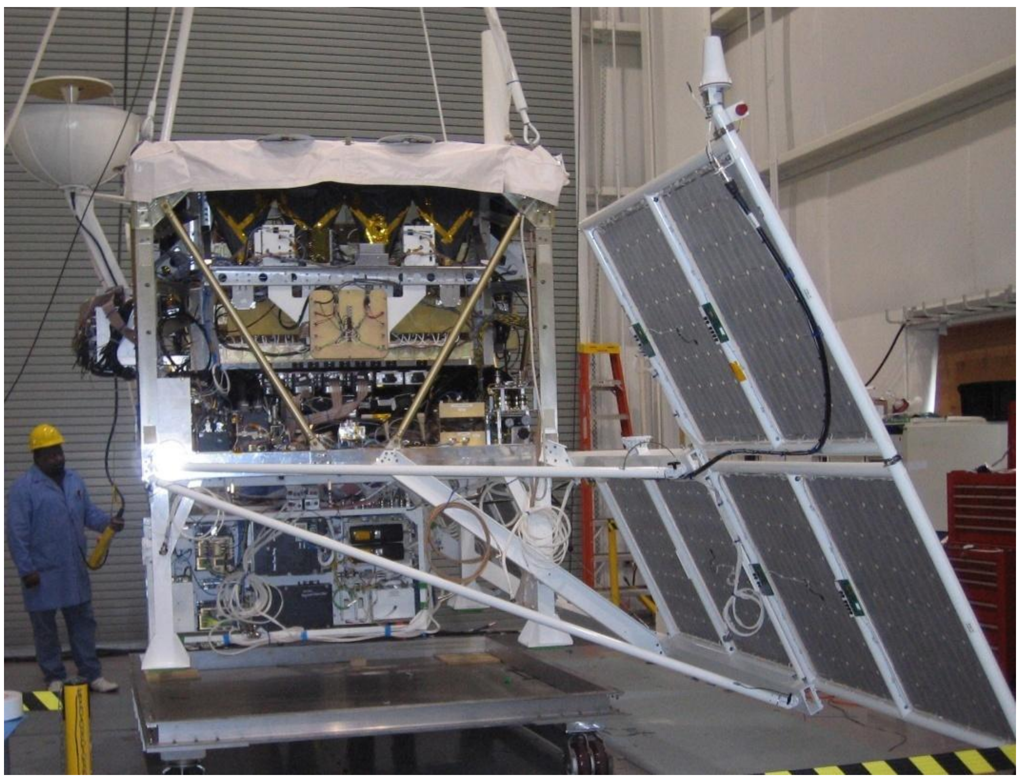
- ***2003*** ANTARCTICA *14 days*
  OXYGEN (Z=8) to IRON (Z=26)
- ***2006*** SWEDEN→CANADA *4.5 days*
  BORON (Z=5) to IRON (Z=26)

Eun-Suk Seo

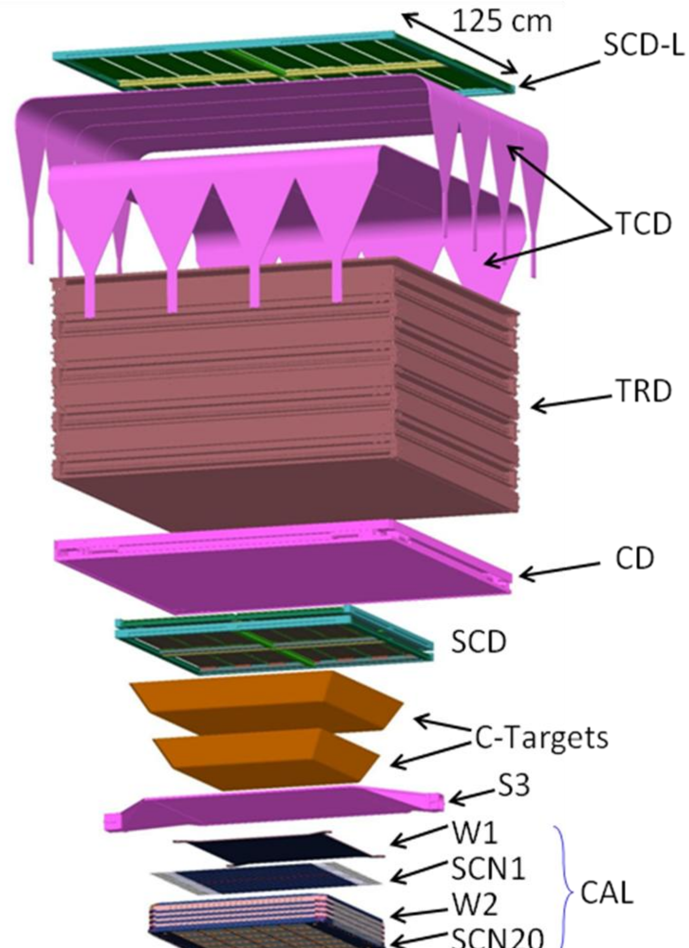
Cosmic Ray Energetics And Mass (CREAM)

Seo et al. Adv. in Space Res., **33** (10), *1777*, 2004; Ahn et al., NIM A, **579**, 1034, 2007

- Transition Radiation Detector (TRD) **and** Tungsten Scintillating Fiber Calorimeter
  - In-flight cross-calibration of energy scales for Z > He
- Complementary Charge Measurements
  - Timing-Based Charge Detector
  - Cherenkov Counter
  - Pixelated Silicon Charge Detector

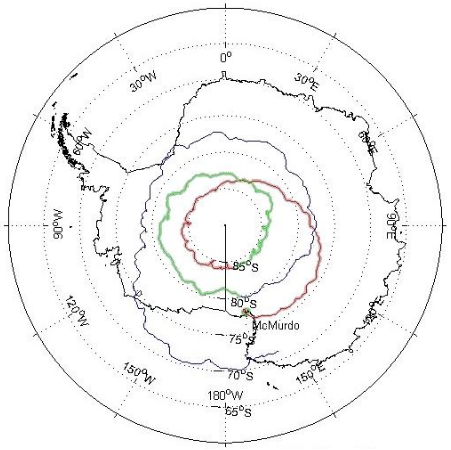


- **CREAM uses two designs**
  - With and without the TRD
- This exploded view shows the “With TRD” design
- The “Without TRD” design uses Cherenkov Camera

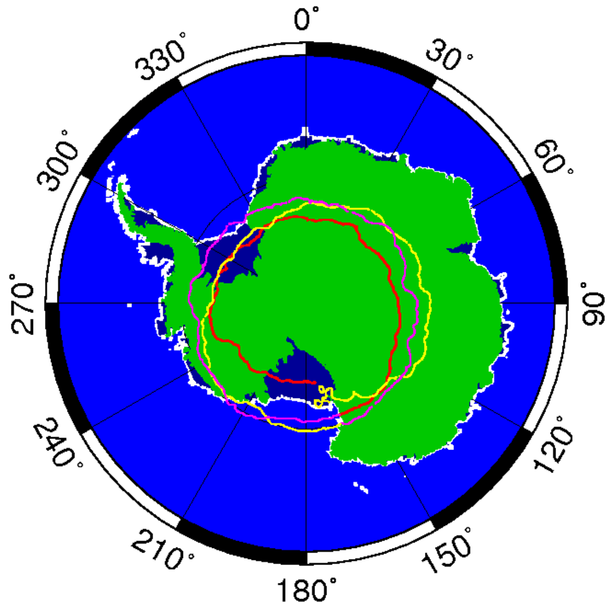


Five successful Flights: ~ 156 days cumulative exposure

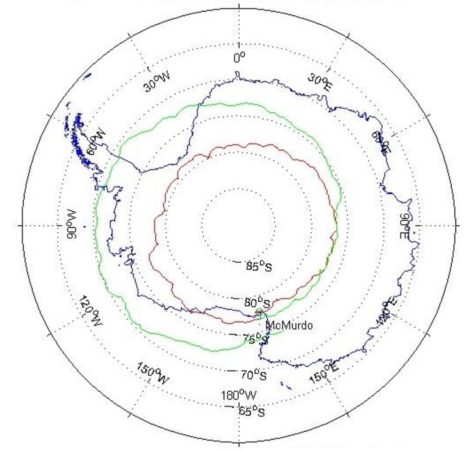
Many thanks to CSBF, WFF, NSF & RPSC for a great campaign!



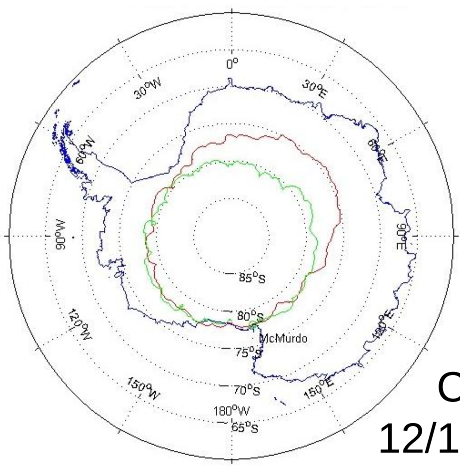
CREAM-I
12/16/04 – 1/27/05
42 days



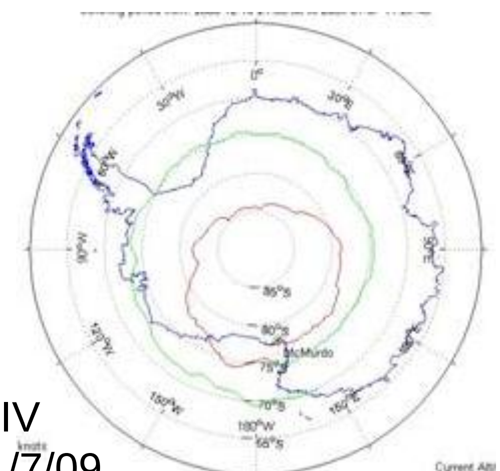
CREAM-V
12/1/09 – 1/8/10
37 days 10 hrs



CREAM-II
12/16/05-1/13/06
28 days

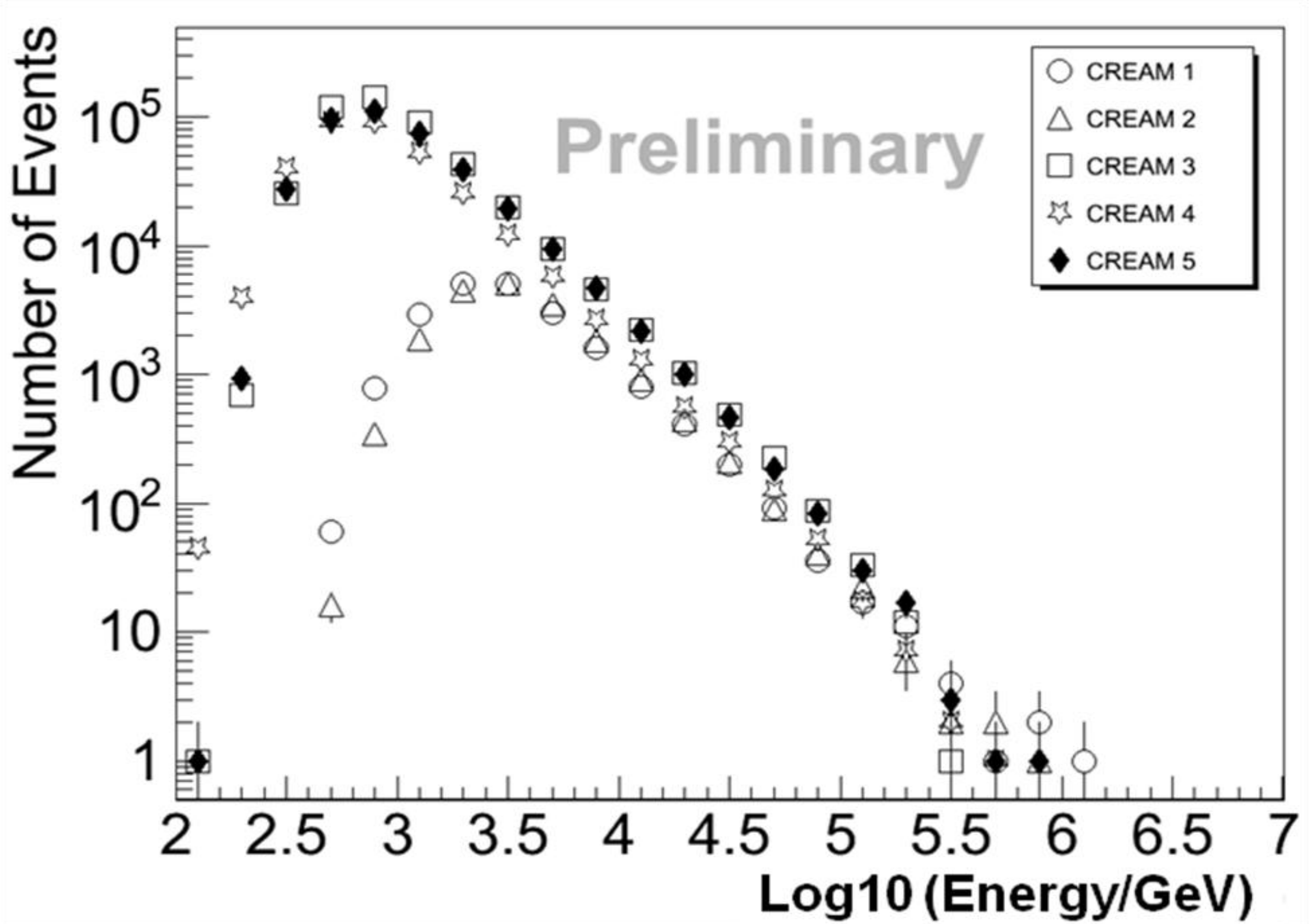


CREAM-III
12/19/07-1/17/08
29 days

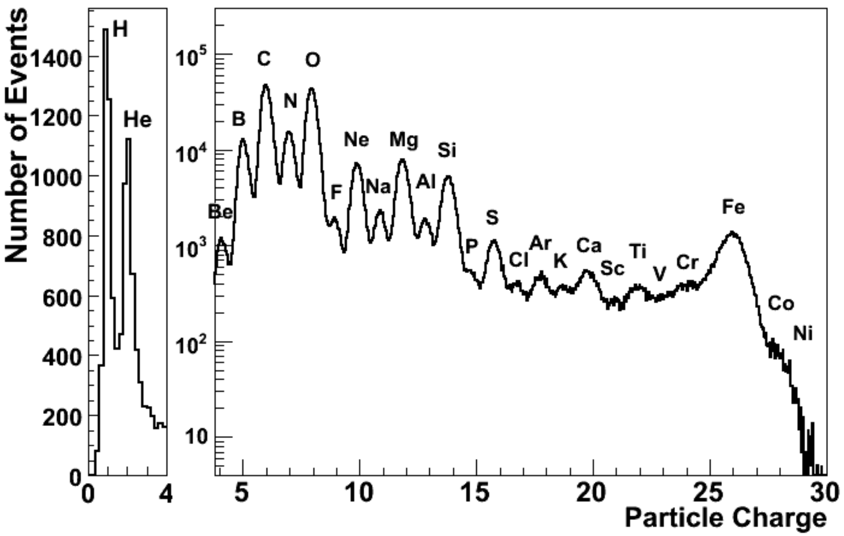


CREAM-IV
12/19/08 – 1/7/09
19 days 13 hrs

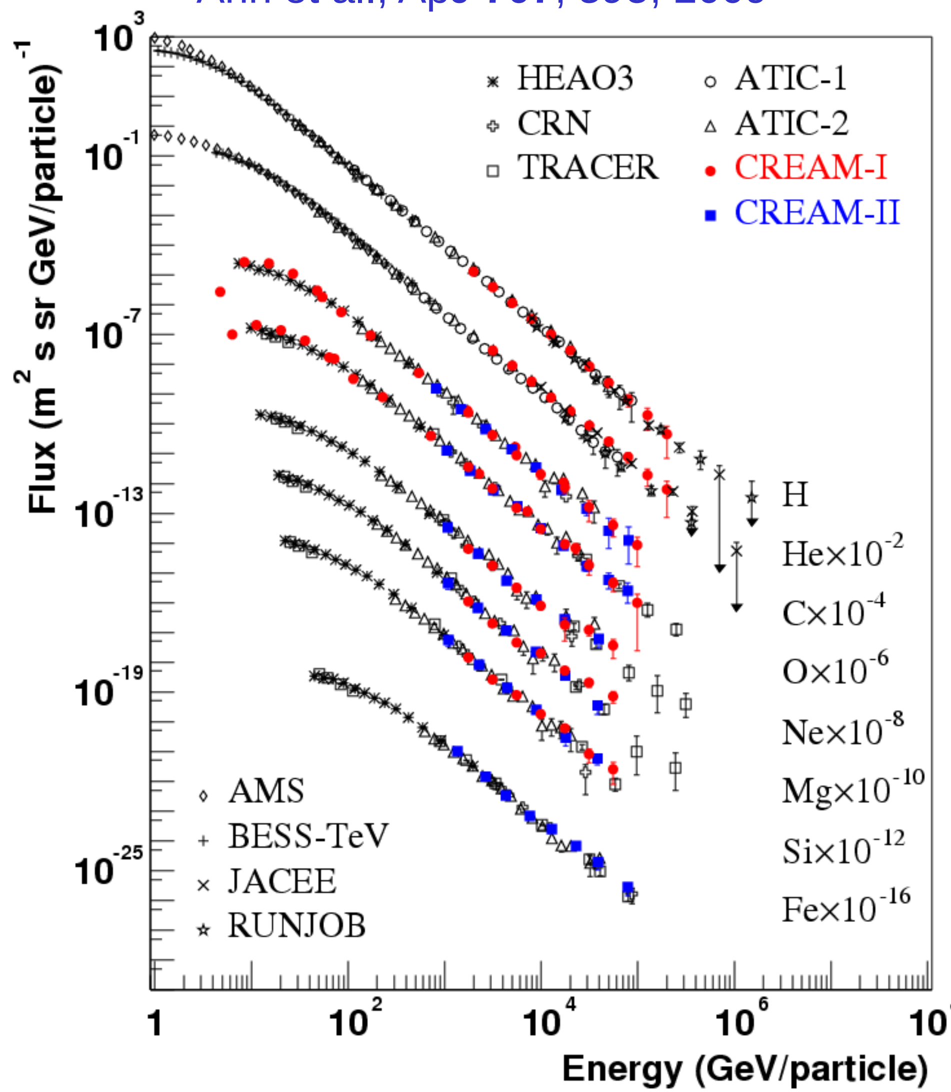
CREAM flight data: all particle counts



Elemental Spectra over 4 decades in energy



Ahn et al., ApJ **707**, *593*, 2009



Cosmic Ray Propagation

Consider propagation of CR in the interstellar medium with random hydromagnetic waves.

Steady State Transport Eq.:

$$\partial \frac{\partial}{\partial z} D_j \frac{\partial f_j}{\partial z} + \frac{\rho}{m} v \sigma f_j + \frac{1}{p^2}\frac{\partial}{\partial p} p^2 K_j \frac{\partial f_j}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \left(\frac{dp}{dt}\right)_{j,ion} f_j \right] = q_j + \sum_{k<j} S_{jk}$$

The momentum distribution function f is normalized as $N = \int dp\, p^2 f$

where N is CR number density, D: spatial diffusion coefficient, σ: cross section…

$$\frac{I_j}{X_e} + \frac{\sigma_j}{m} I_j + \alpha\{\ldots\} + \frac{d}{dE}\left[\left(\frac{dE}{dx}\right)_{j,ion} I_j \right] = \frac{Q_j}{\rho_0} + \sum_{k<j} \frac{\sigma_{jk}}{m} I_k$$

Cosmic ray intensity $I_j(E) = A_j p^2 f_{0j}(p)$

Escape length Xe

Reacceleration parameter α

E. S. Seo and V. S. Ptuskin, Astrophys. J., **431**, *705-714*, 1994.

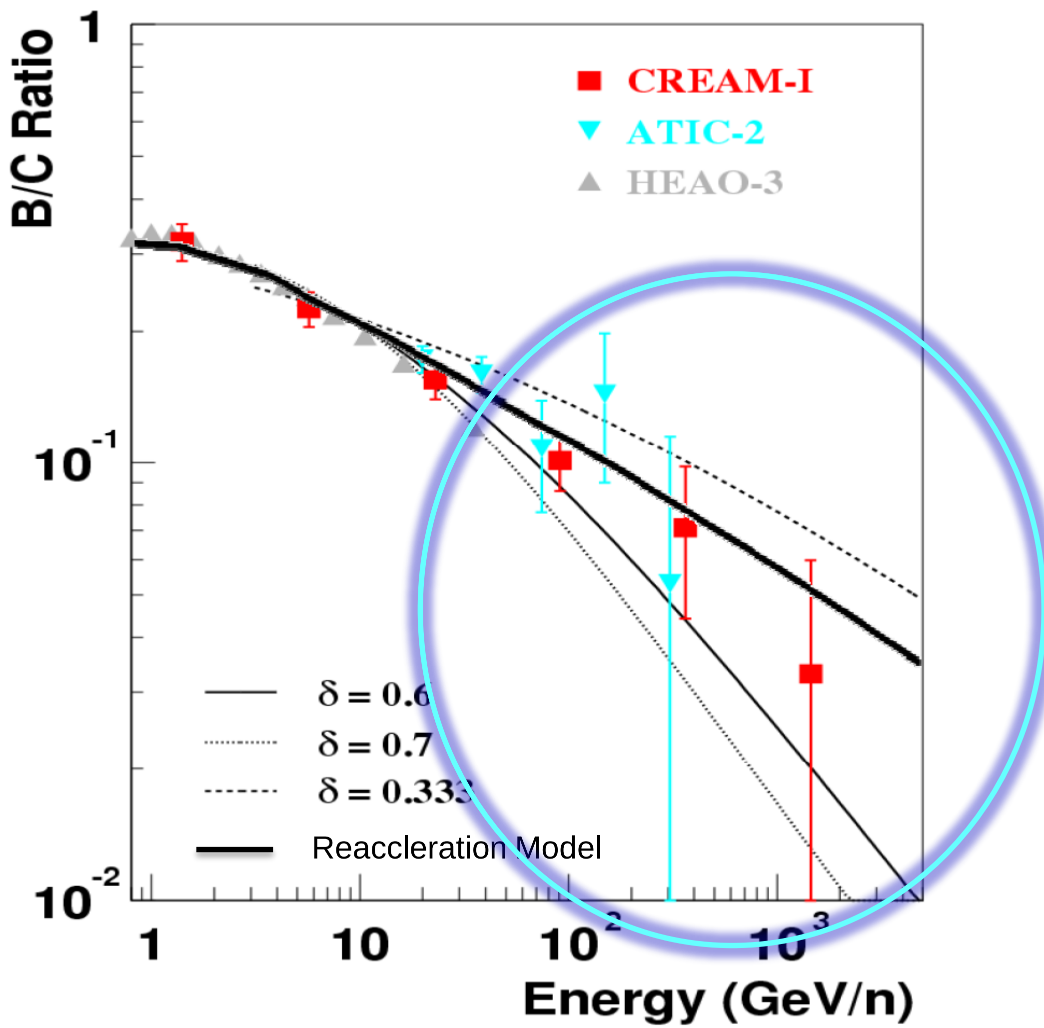
What is the history of cosmic rays in the Galaxy?

Ahn et al. (CREAM collaboration) Astropart. Phys., 30/3, 133-141, 2008

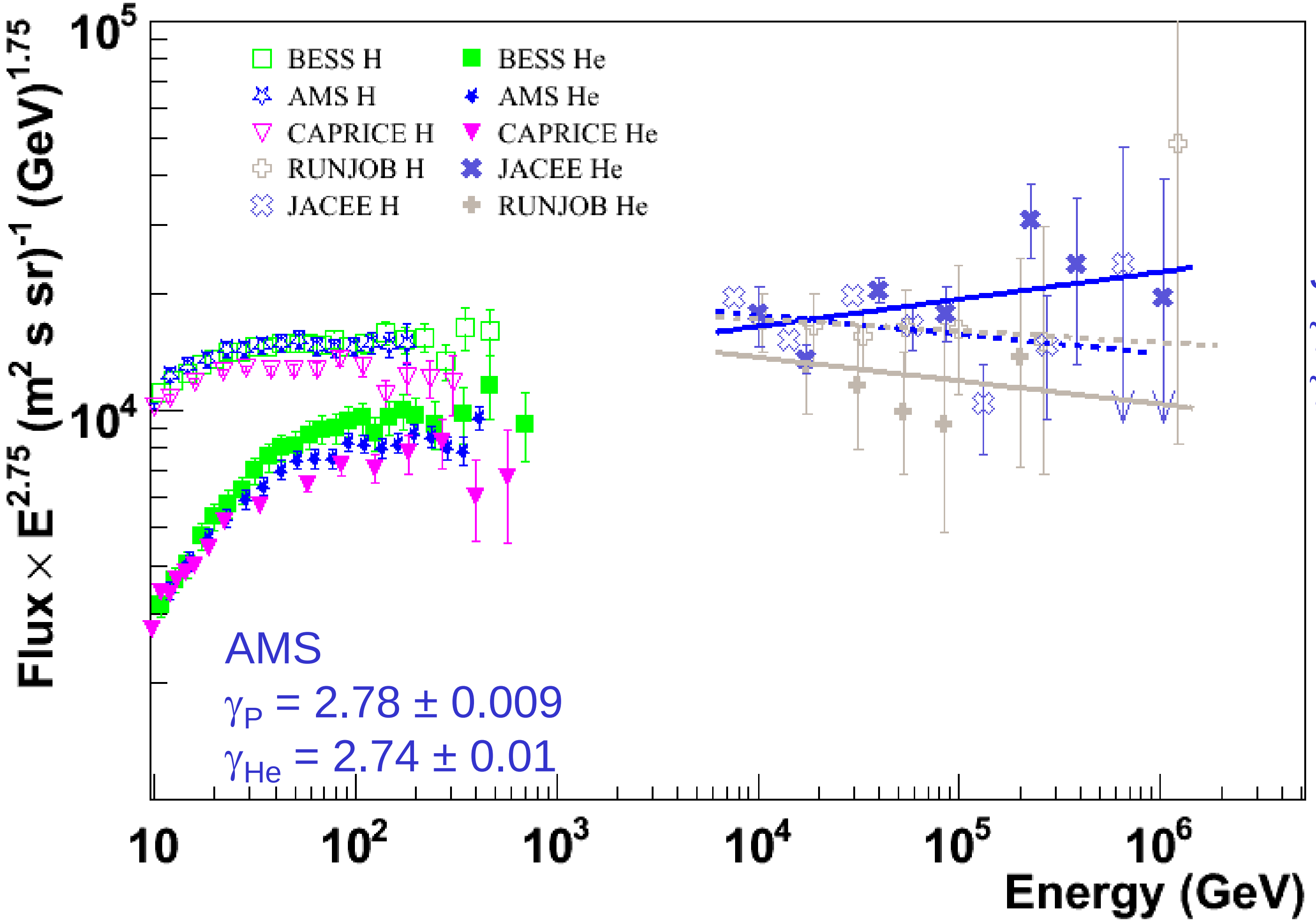
- Measurements of the relative abundances of secondary cosmic rays (e.g., B/C) in addition to the energy spectra of primary nuclei will allow determination of cosmic-ray source spectra at energies where measurements are not currently available

- First B/C ratio at these high energies to distinguish among the propagation models

$$X_e \propto R^{-\delta}$$



P & He: prior to CREAM

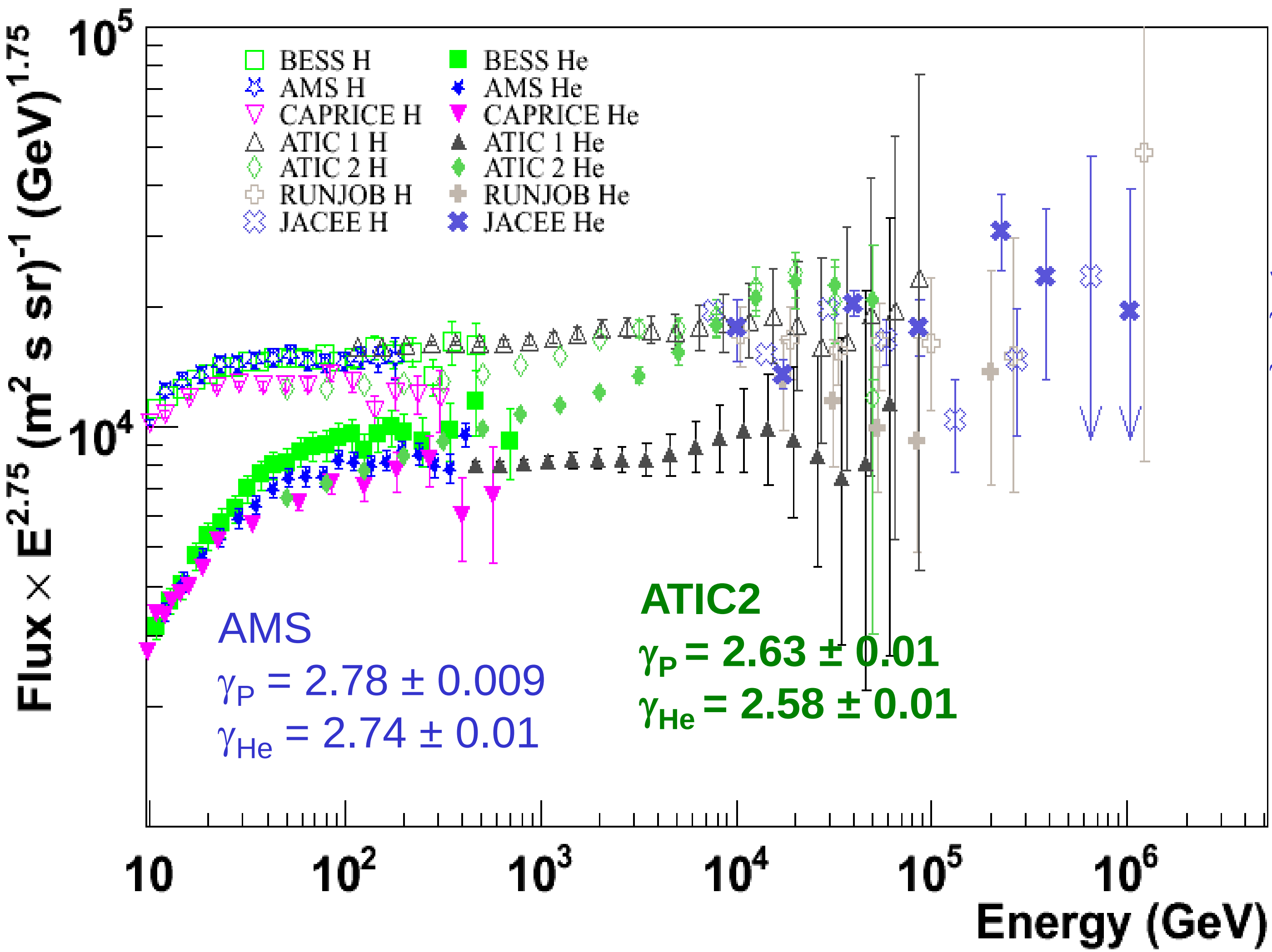


$$I_j \propto E^{-\gamma}$$

JACEE
$\gamma_P = 2.80 \pm 0.04$
$\gamma_{He} = 2.68{+}0.04{-}0.06$

RUNJOB
$\gamma_P = 2.78 \pm 0.05$
(2.74 ± 0.08)
$\gamma_{He} = 2.81 \pm 0.06$
(2.78 ± 0.2)

P & He: prior to CREAM

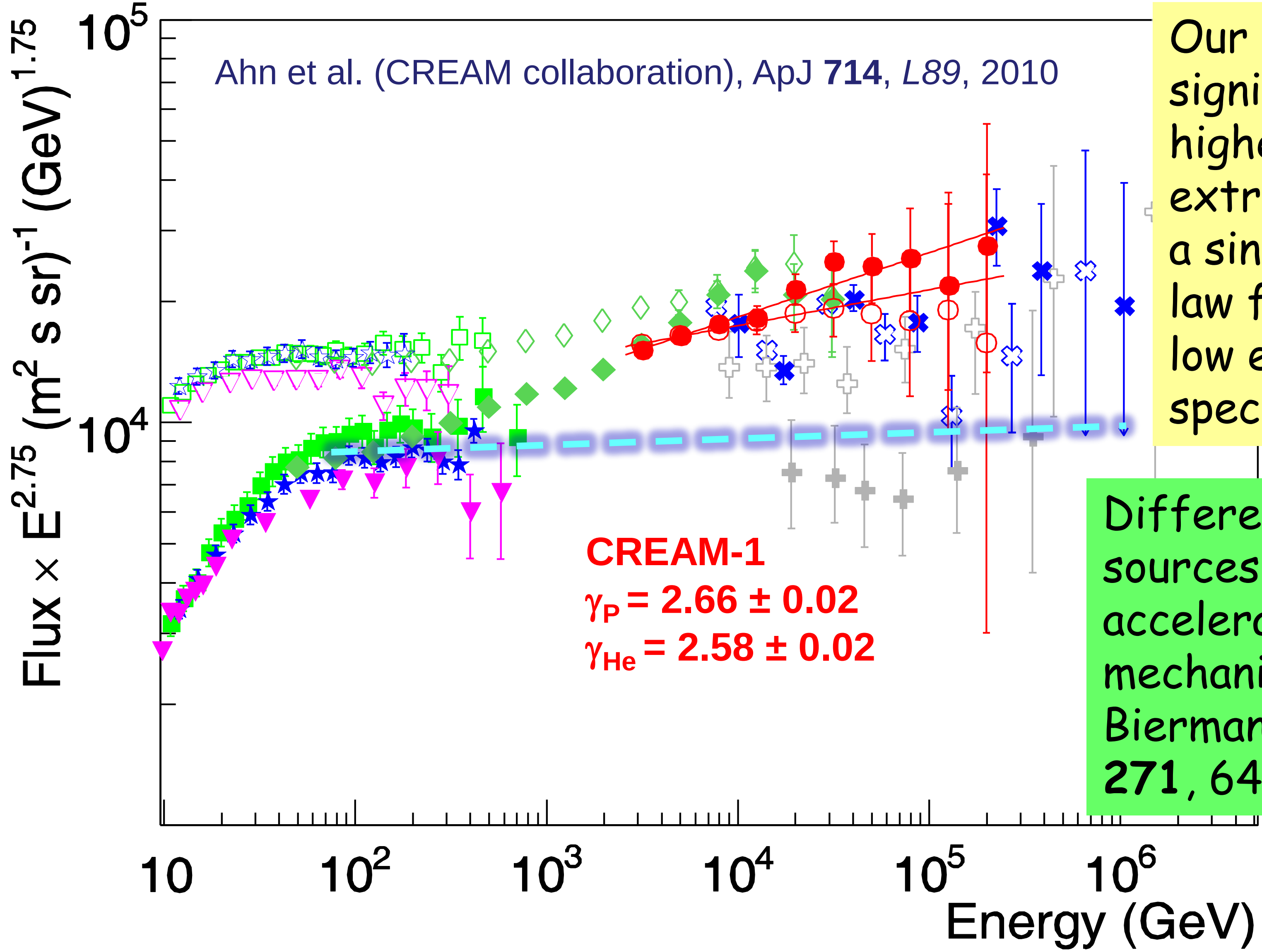


$I_j \propto E^{-\gamma}$

JACEE
γ_P = 2.80 ± 0.04
γ_{He} = 2.68+0.04-0.06

RUNJOB
γ_P = 2.78 ± 0.05
(2.74 ± 0.08)
γ_{He} = 2.81 ± 0.06
(2.78 ± 0.2)

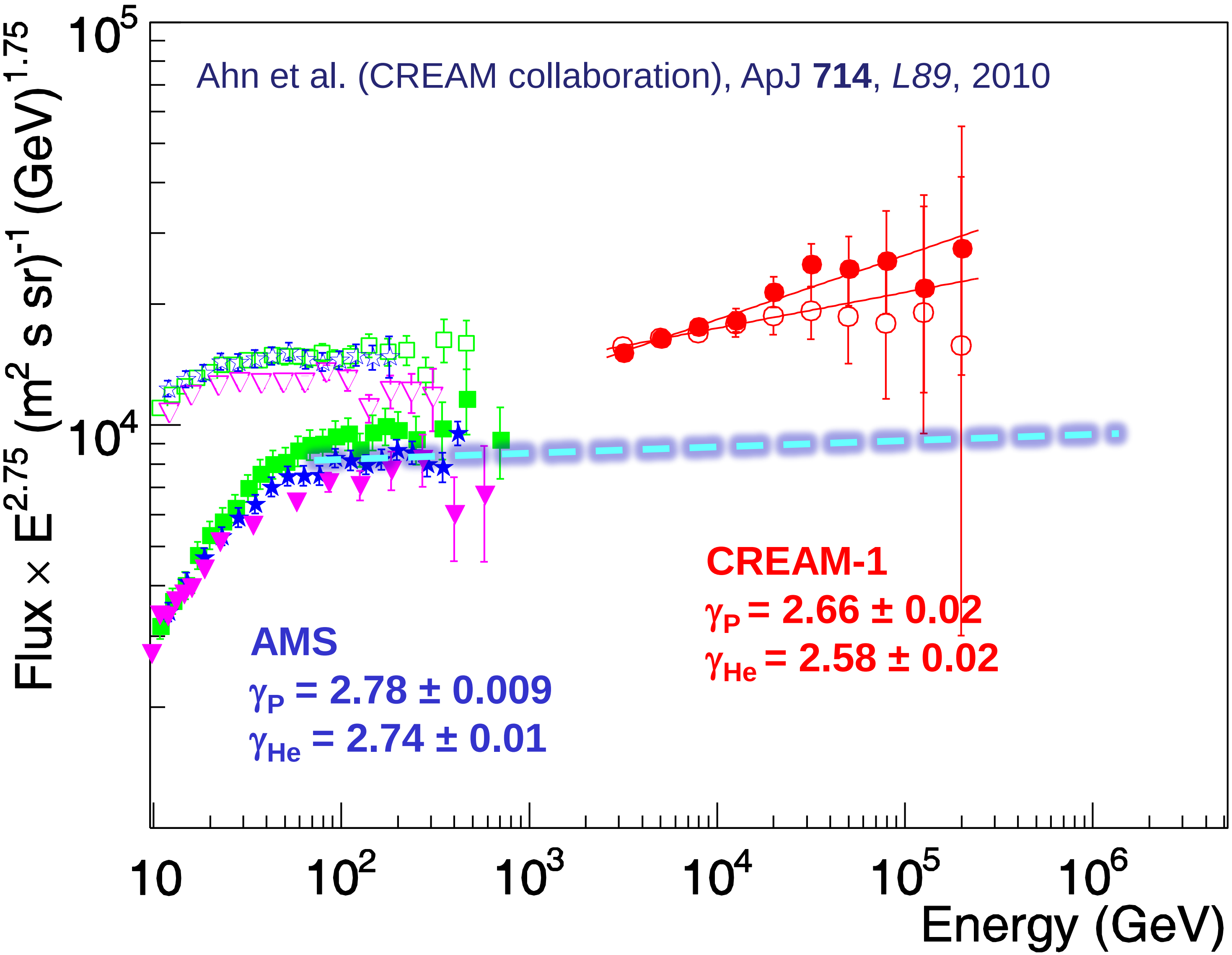
CREAM: p & He spectra are not the same



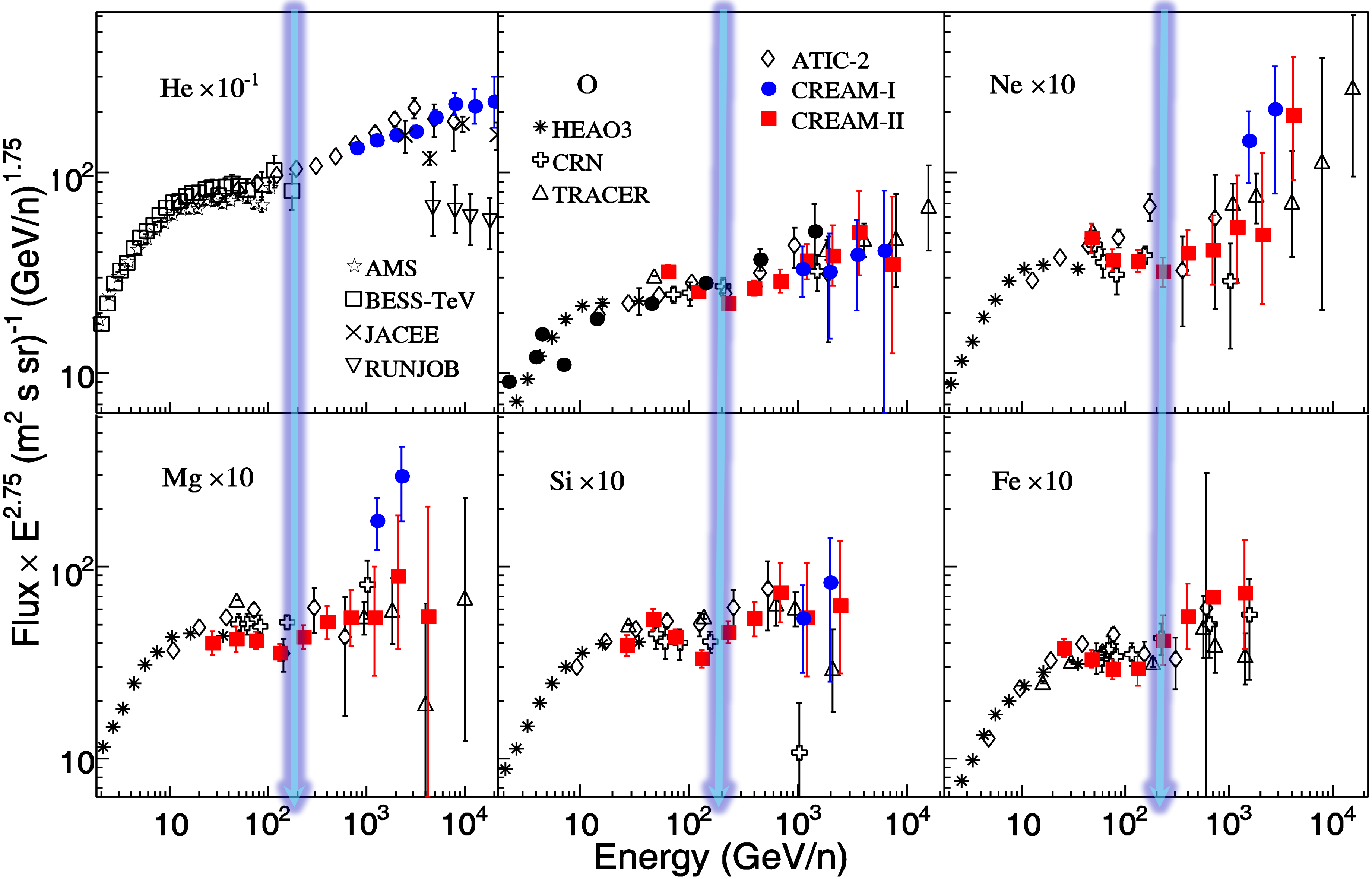
Our fluxes are significantly higher than the extrapolation of a single-power law fit to the low energy spectra

Different types of sources or acceleration mechanisms? (e.g., Biermann, P. L. *A&A* **271**, 649,1993)

TeV spectra are harder than spectra < 200 GeV/n

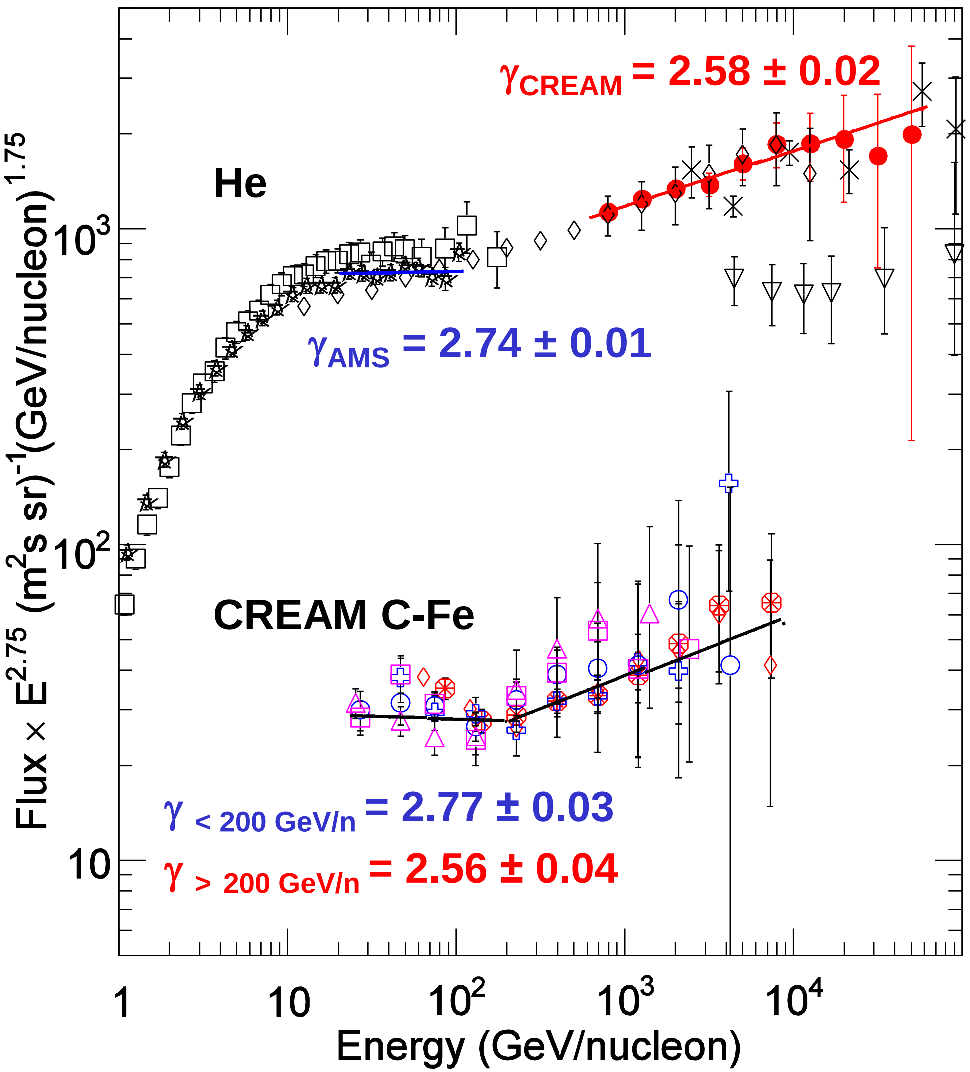


Discrepant hardening



Not a single power law

Ahn et al. ApJ **714**, *L89*, 2010



- Effect of a non-uniform distribution of sources? (Erlykin & Wolfendale *A&A* **350**, L1,1999)
  - Younger sources would dominate the high-energy spectra (Taillet et al. *ApJ* **609**, 173, 2004)
- Effect of distributed acceleration by multiple remnants? (Medina-Tanco & Opher *ApJ* 411, 690, 1993)
  - Superbubbles? (Butt & Bykov, *ApJ* 677, L21, 2008)
- Departure from a single power law caused by cosmic ray interactions with the shock? (e.g., Ellison et al. *ApJ* **540**, 292, 2000)

Results & Implications

Spectral difference between p and He

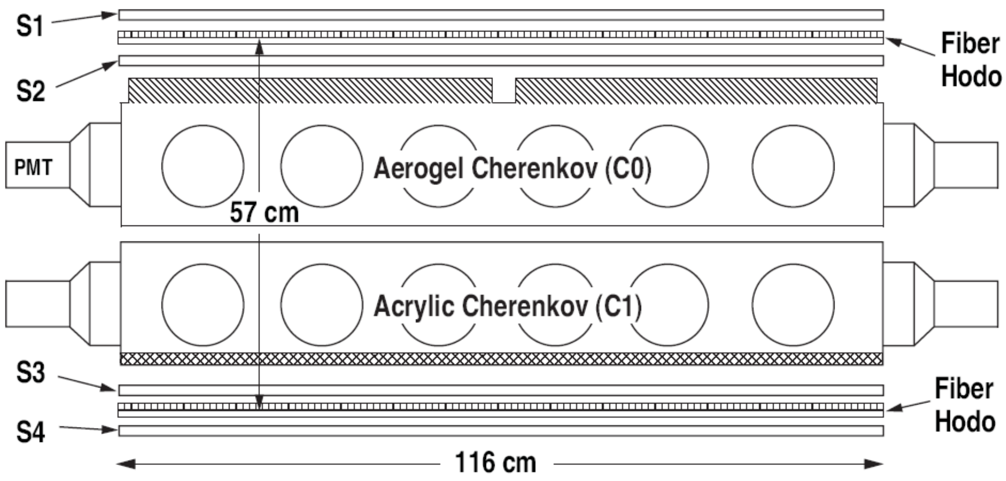
- Are there different types of sources or acceleration mechanisms? (Biermann, *A&A* **271**, *649*,1993; Biermann et al. PRL **103**, *061101*, 2009; ApJ **710**, *L53*, 2010)

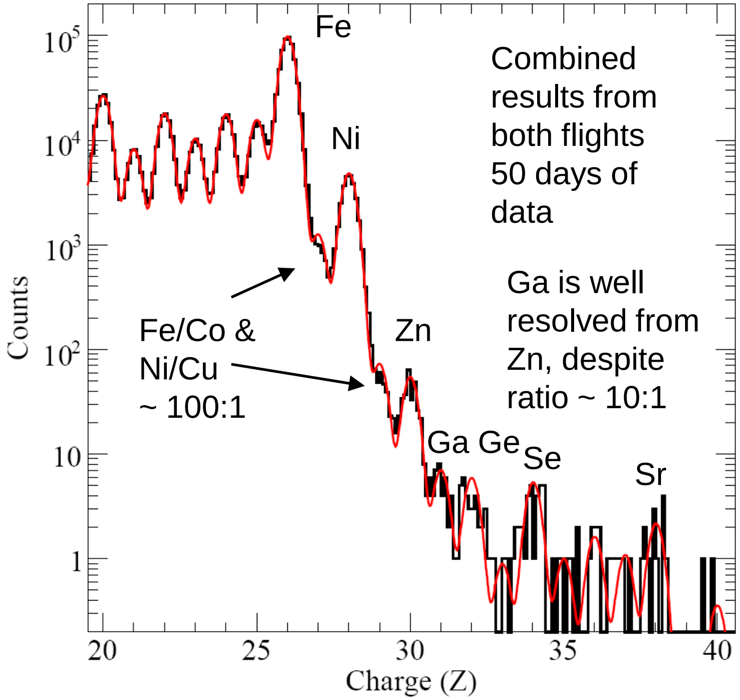
Flattening of elemental spectra at high energies

- Are the source spectra harder than previously thought, based on the low energy data?
- Evidence for concavity due to cosmic ray interactions with the shock? (Ellison et al. *ApJ* **540**, 292,2000; Allen et al. *ApJ* **683**/2,773, 2008).
- If not an effect of acceleration or propagation, and if the conventional model is valid, are we seeing a local source of hadrons?
- Effect of a non-uniform distribution of sources? (Erlykin & Wolfendale *A&A* **350**, L1,1999;Taillet et al. *ApJ* **609**, 173, 2004)
- Effect of distributed acceleration by multiple remnants (Medina-Tanco & Opher *ApJ* 411, 690, 1993)
  - ➢ Superbubbles? (Butt & Bykov, *ApJ* 677, L21, 2008)
- Related to 10 TeV anisotropy reported by Milagro? (Abdo et al. *PRL*, 101, 221101, 2008)

Trans-Iron Galactic Element Recorder (TIGER)

Ultra heavy nuclei, clues to nucleosynthesis and origin of galactic CRs

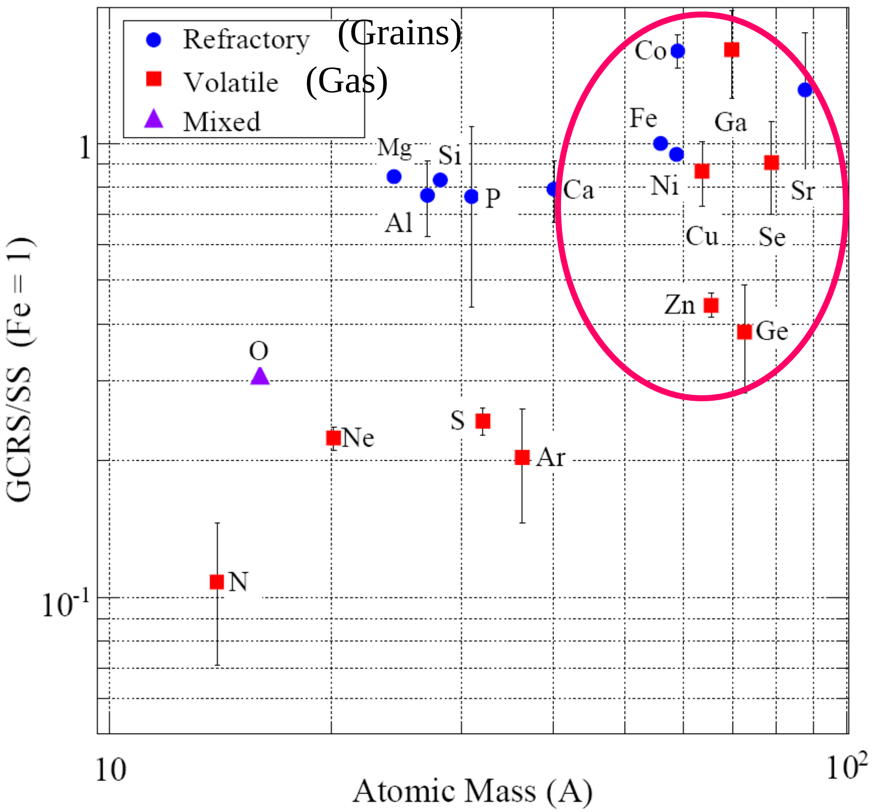


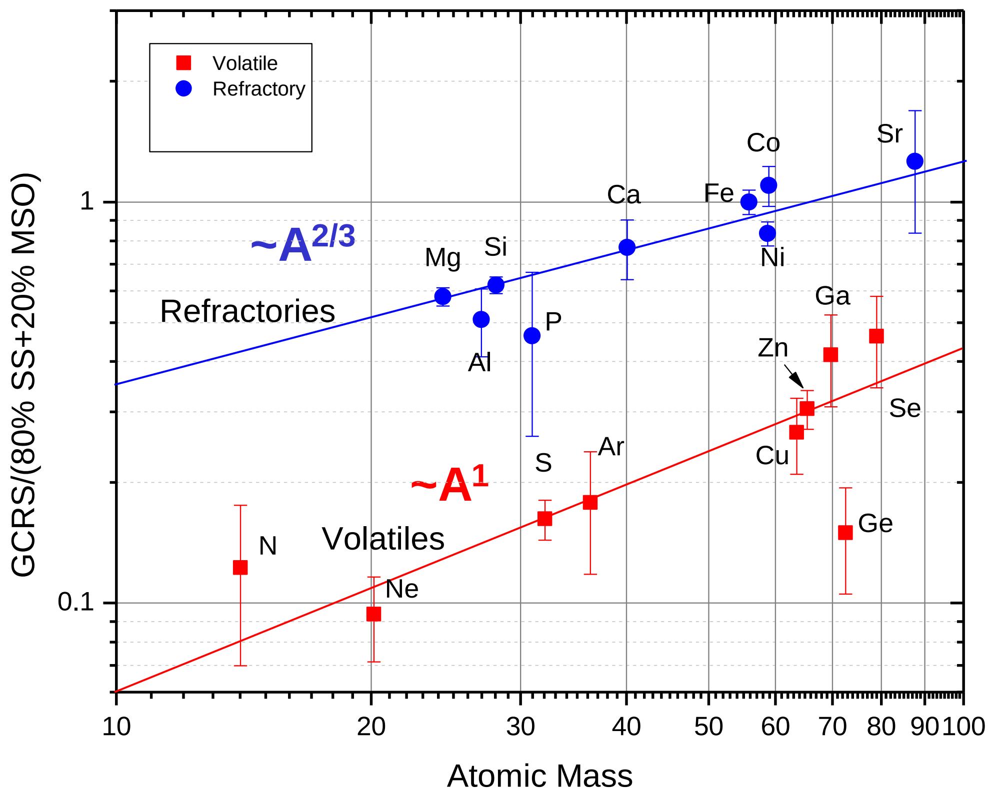


- TIGER was a 1 m^2 electronic instrument to measure the elemental composition of the rare galactic cosmic rays heavier than iron
  - Obtained best measurement to date of abundances of $_{31}$Ga, $_{32}$Ge, & $_{34}$Se.
- Two balloon flights over Antarctica totaling 50 days at float
  - Dec. 2001 – Jan. 2002, 32 day flight; Dec. 2003 – Jan. 2004, 18 day flight
  - TIGER data recovered, but instrument only partially recovered in Jan. 2006

Origin of Cosmic Rays

Rauch et al., ApJ 697, 2083, 2009



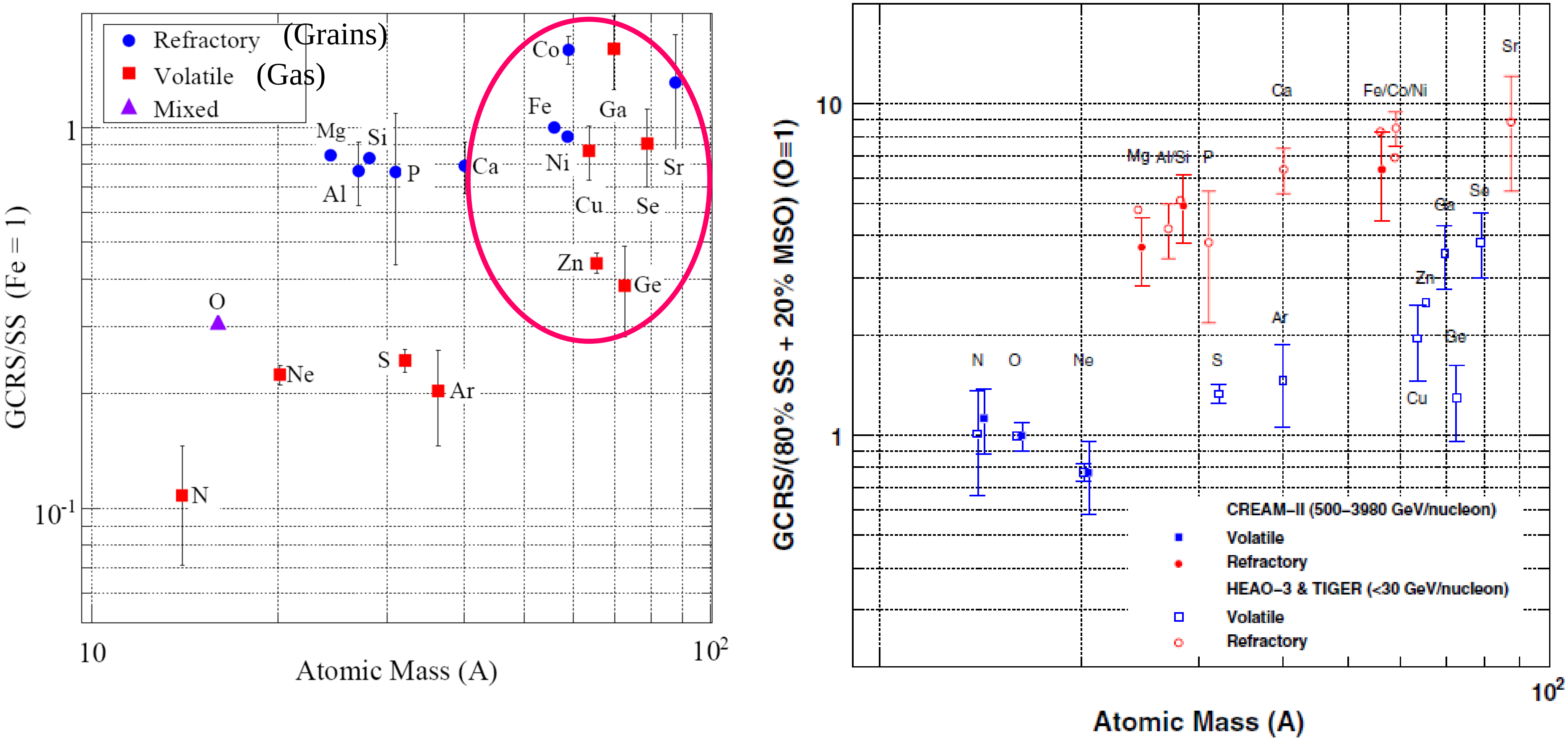


- Elements present in interstellar grains are accelerated preferentially compared with those found in interstellar gas
- Data are consistent with the idea of CR origin in OB associations

Origin of Cosmic Rays

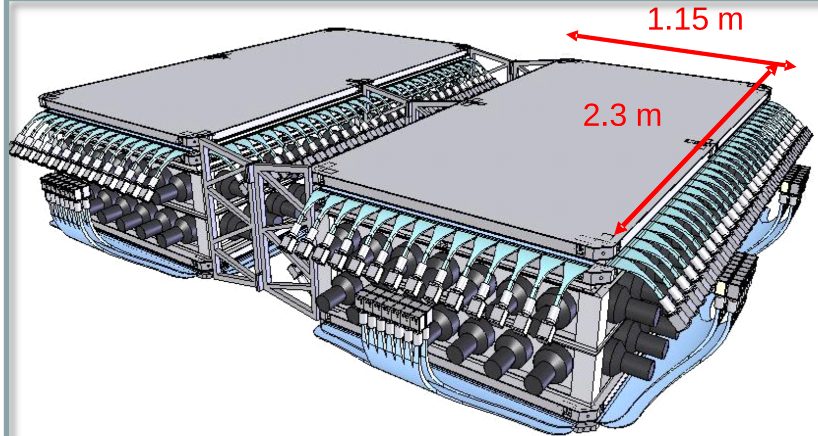
Rauch et al., ApJ 697, 2083, 2009

Ahn et al., ApJ, 715, 1400, 2010



- Elements present in interstellar grains are accelerated preferentially compared with those found in interstellar gas
- Data are consistent with the idea of CR origin in OB associations

Super-TIGER balloon mission & OASIS study

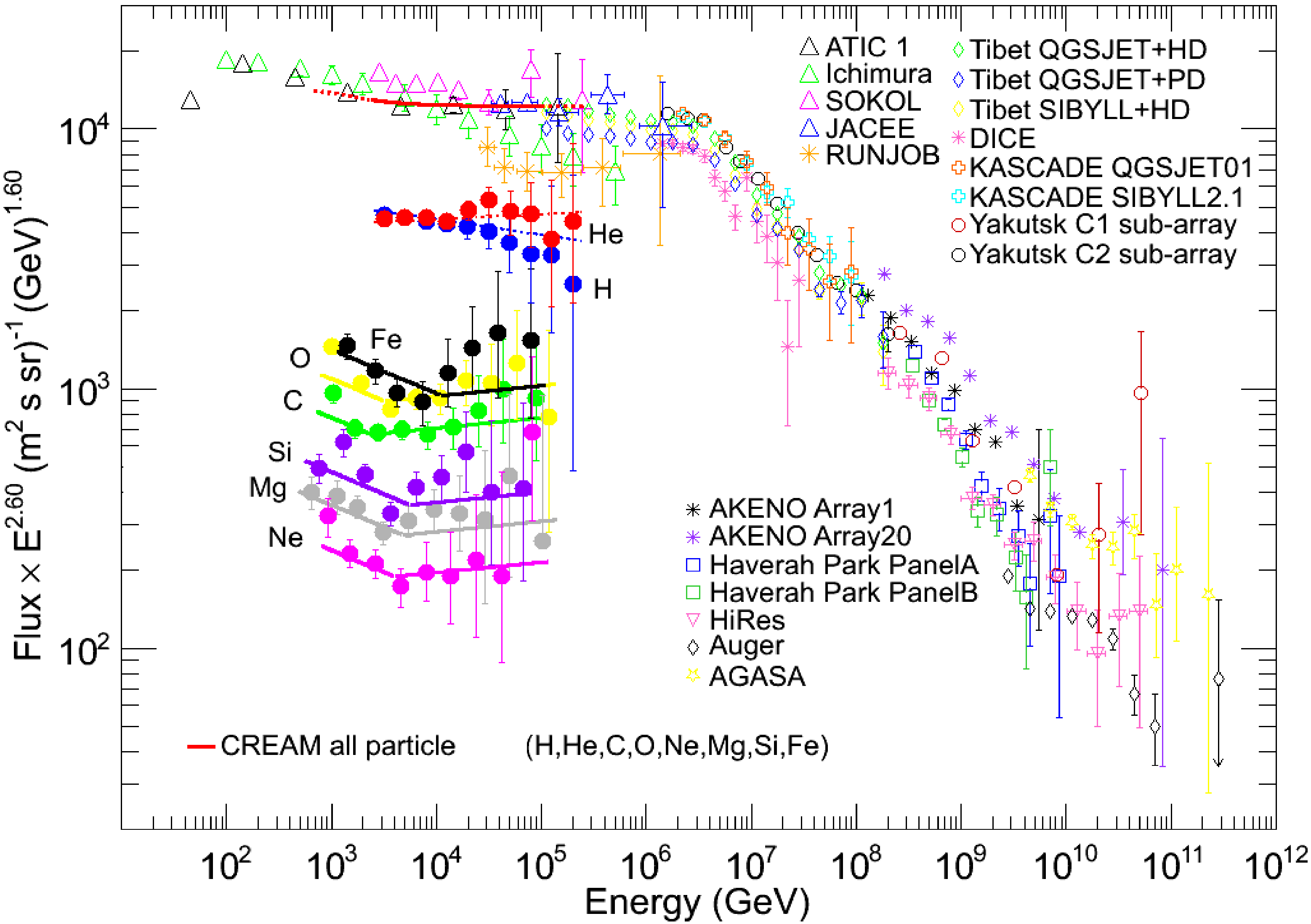


First LDB flight planned for December 2012.

ULDB Super-TIGER mission: measure individual element abundances up to Barium (Z=56) with high precision, even Pt to Pb with ~20% precision

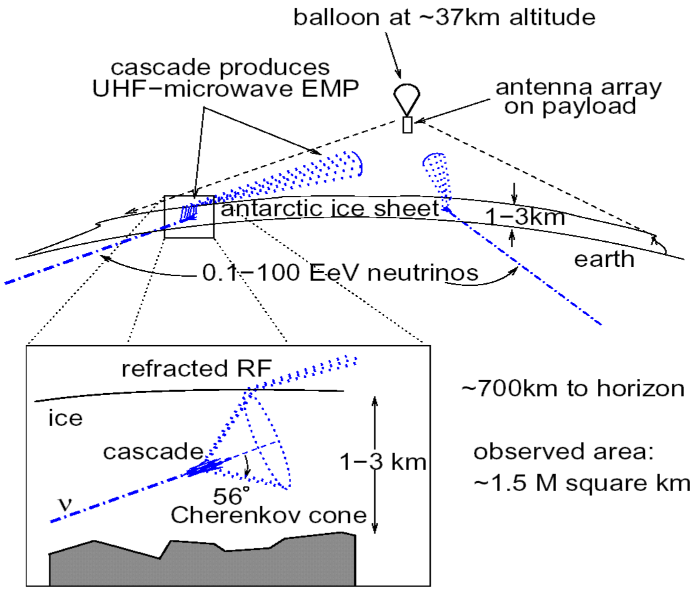
- OASIS: Being studied as a medium class NASA Astrophysics Strategic Mission in the US
  - ENTICE: With three years in polar orbit would detect at least 100 cosmic-ray actinides.

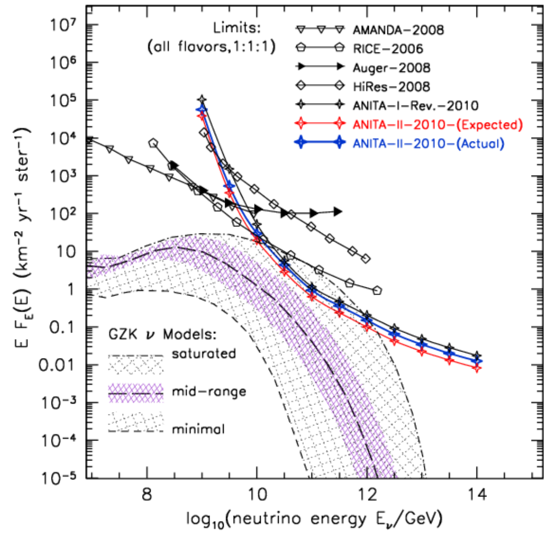
All Particle Spectrum



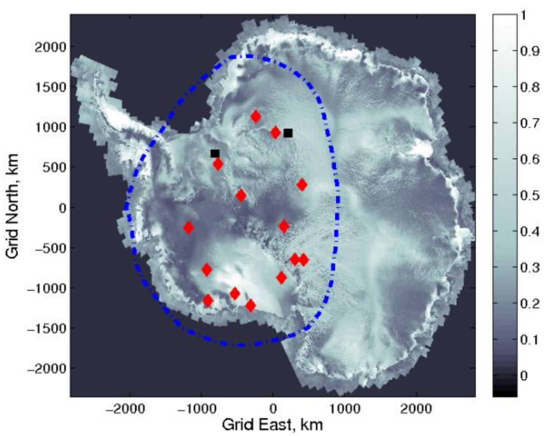
Antarctic Impulsive Transient Antenna (ANITA)

Ultra-High Energy Particle Astrophysics





ANITA-2 (2008-2009) limits 2010: currently world's best in UHE range; several mainstream cosmogenic neutrino models are now eliminated at >90%CL; **several models predict 2-3 events.**



ANITA-1 (2006-2007) detected UHECRs via geosynchrotron radio impulse detection

arXiv:1005.0035v2 [astro-ph.HE]

ANITA-3 plans:

- **Improve sensitivity by x3 with better hardware trigger, more antennas**
- **Optimize for both UHECRs & neutrinos**
  - **~350-500 UHECR events expected**
- **Try for up to 60 days of flight exposure, 5-10 neutrino events?**

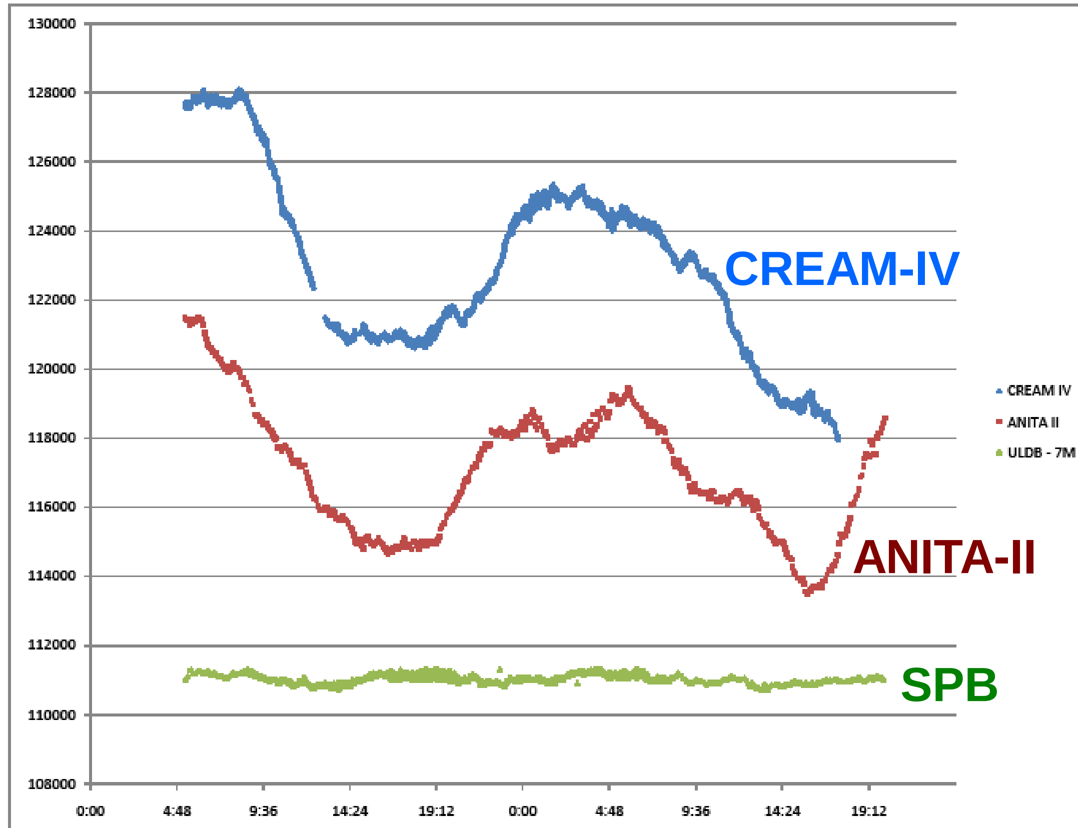
A step closer to ULDB

Successful SPB Test Flight

7 MCF At Float

54 days (12/28/08 – 2/20/09)

The super pressure balloon's altitude stability



Acknowledgment