Cosmic Rays from an Observational Perspective

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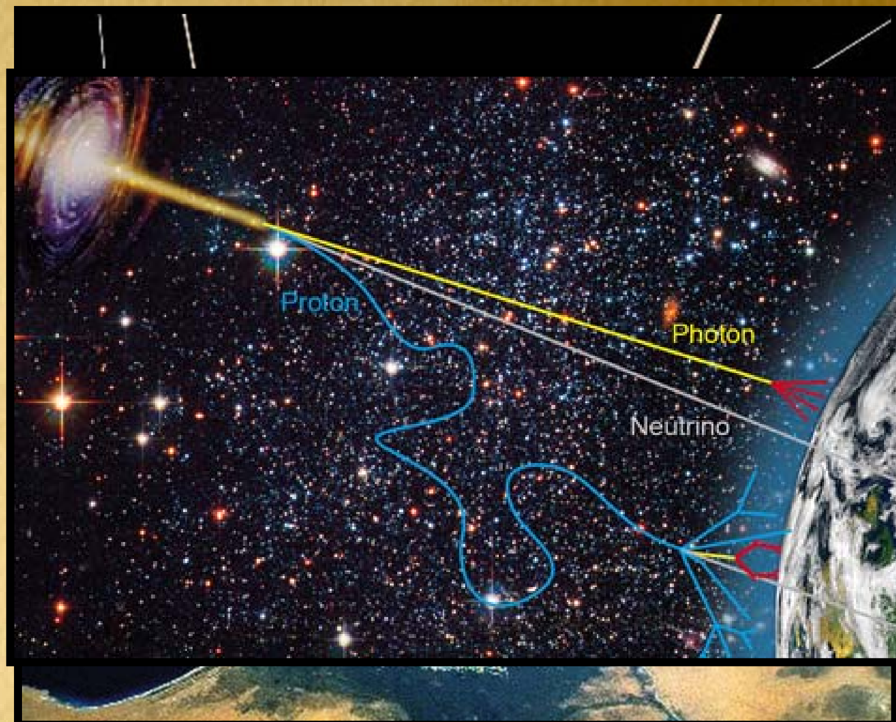
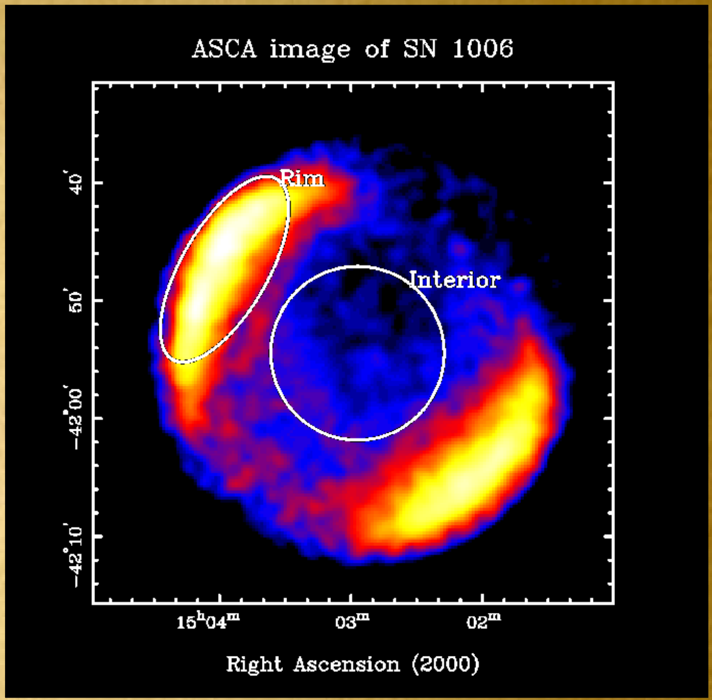
Cosmic Rays

- **A steady flux of extra-terrestrial high-energy charged particles** [primarily protons]
  - Constantly impinging on the upper atmosphere of the Earth
  - The flux is large (thousands per $m^2 s$)
  - The flux is largely isotropic
    - CR don't point!
  - They fill our Galaxy with an energy density of ~1 eV/cm^3
    - But not the whole universe!



Cosmic Rays

- Definitive answers remain elusive, but a `Standard Notion' has emerged.
  - Most CR are produced in and around (isolated?) supernova remnants (SNRs). Three common arguments:
    - A viable acceleration mechanism (DSA)
      - Smooth power laws
    - Power requirements
    - Existence of very-high-energy electrons in SNR, as revealed by synchrotron radiation



Adding to this a motivation for gamma-ray astronomy. (Gamma rays point!)

Discovery

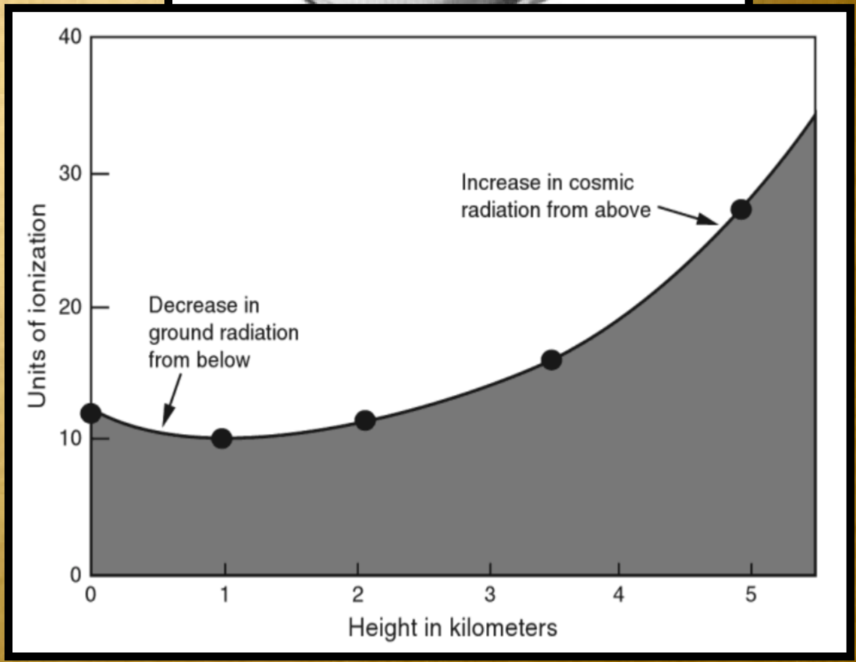
- Credited to Victor Hess, who in 1912, carried instruments on a series of balloon flights, reaching ~5.5km on August 7 with a hydrogen-filled balloon.
  - No oxygen tanks

- Won the Nobel Prize for this in 1936 (along with Carl Anderson – for discovering the positron)

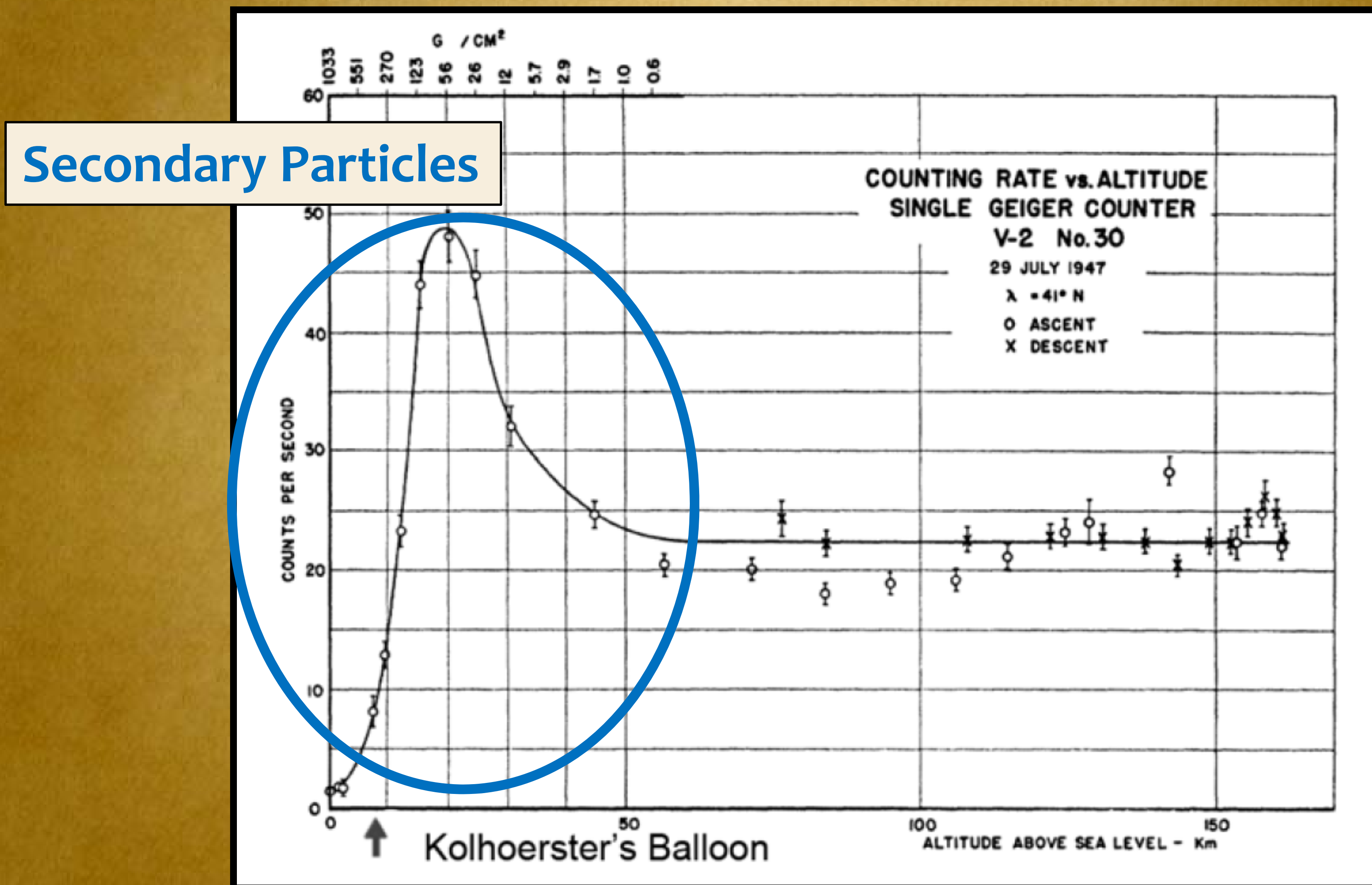
Discovery

- Attempting to solve a ~10-year mystery: what was responsible for the discharge of electroscopes?
  - Knew it was penetrating radiation, but from where?
    - From Earth's crust?
    - Extraterrestrial?

  - Balloon flights could answer
    - If discharge increased with height, would point to 'cosmic' [extra-terrestrial] origins
    - It did - verified quickly by Kolhörster



Rate vs Altitude

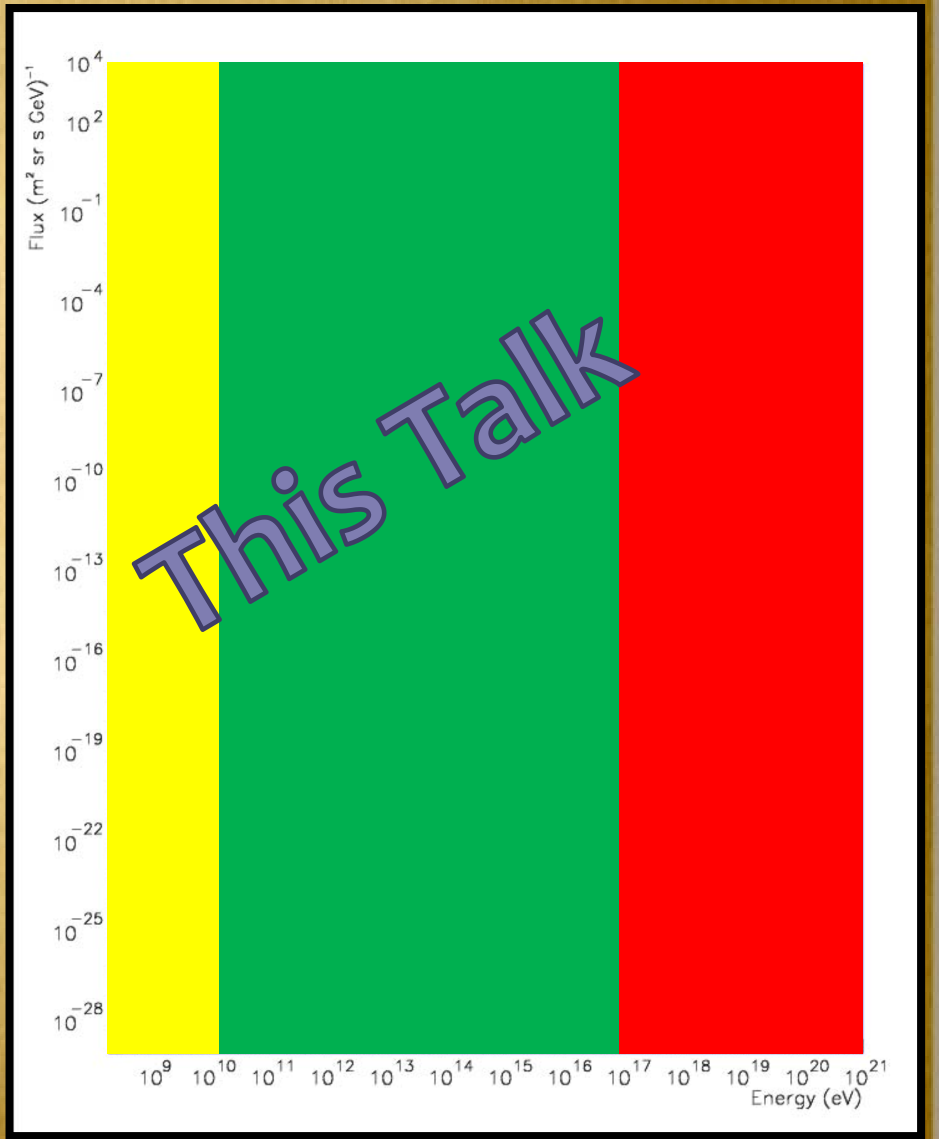


van Allen (1948)

Energy Spectrum

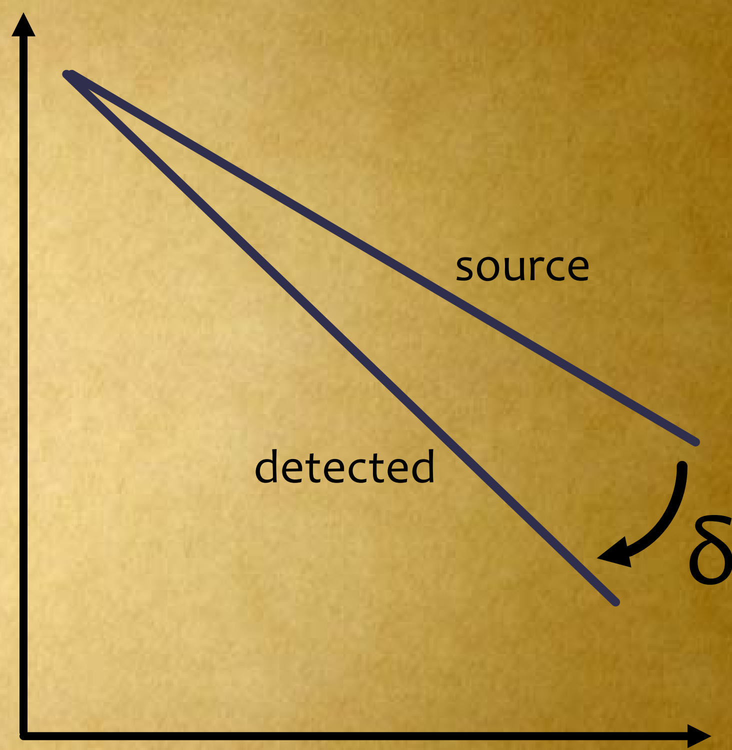
Energy Spectrum

- "All-Particle Spectrum": a vast span in energy and differential flux
  - 12+ orders in energy
  - 30+ orders in flux
- Roughly distributed over this range according to a power-law in energy: ~E^{-3}
  - Two commonly referred-to features:
    - A 'knee' at ~$10^{15.5}$ eV
    - An 'ankle' at ~$10^{18.5}$ eV
- A few regions of interest:
  - Low-energy end – influence from the sun
  - Middle range – 'Galactic' Cosmic Rays
  - Upper end – 'Extra-galactic' Cosmic Rays

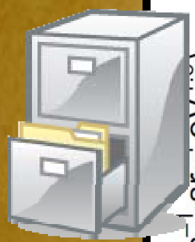


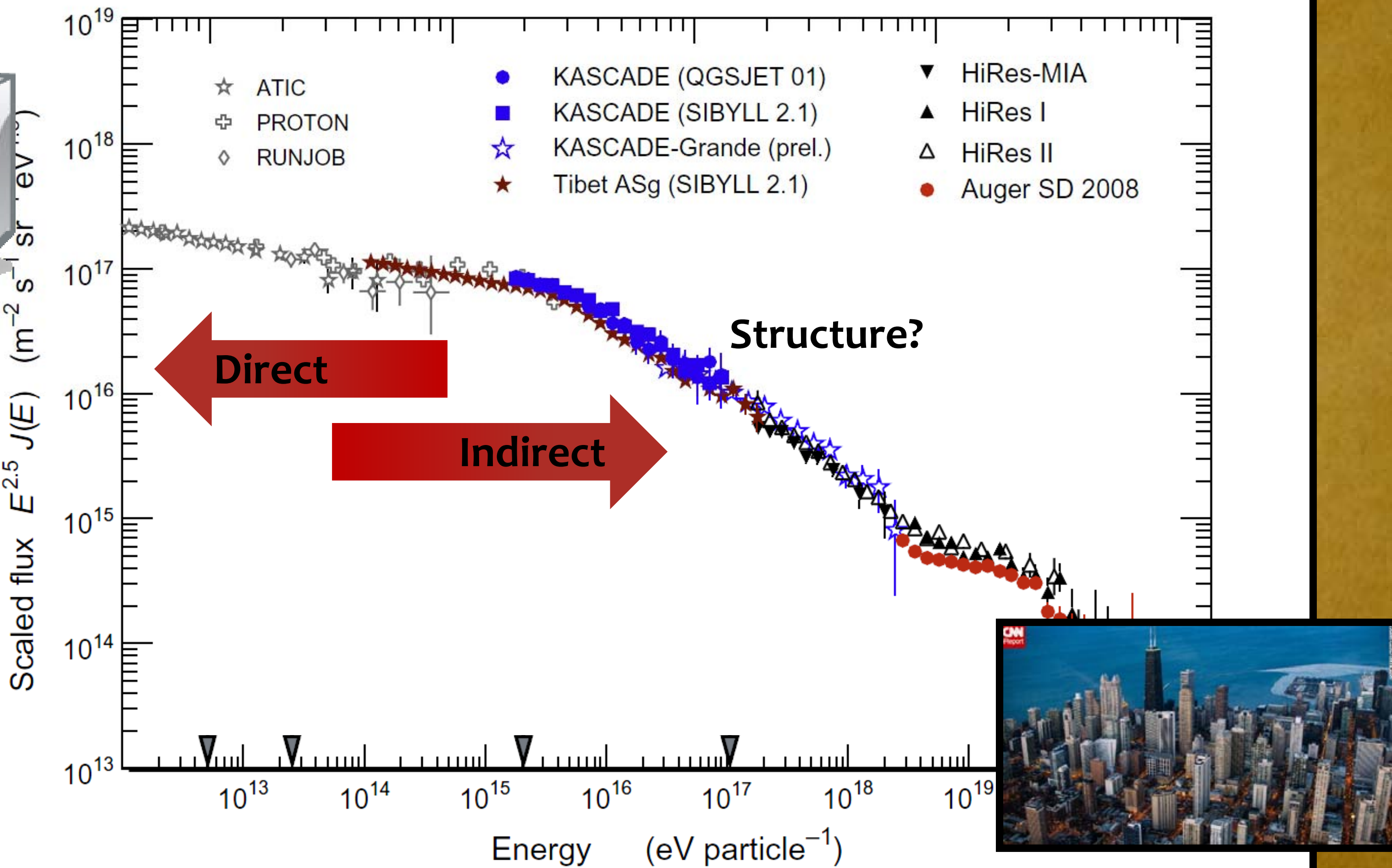
Propagation Effects

- **The spectrum we see at earth is not the source spectrum!**
  - As CR propagate from the sources to earth, they are affected by energy-dependent phenomena
    - One of which is escape from the galaxy
  - These processes modify the spectrum, steepening the index by δ
    - The value of δ has implications for global propagation physics, inferred source properties, CR power requirements, CR anisotropies, etc.



Scaled Energy Spectrum

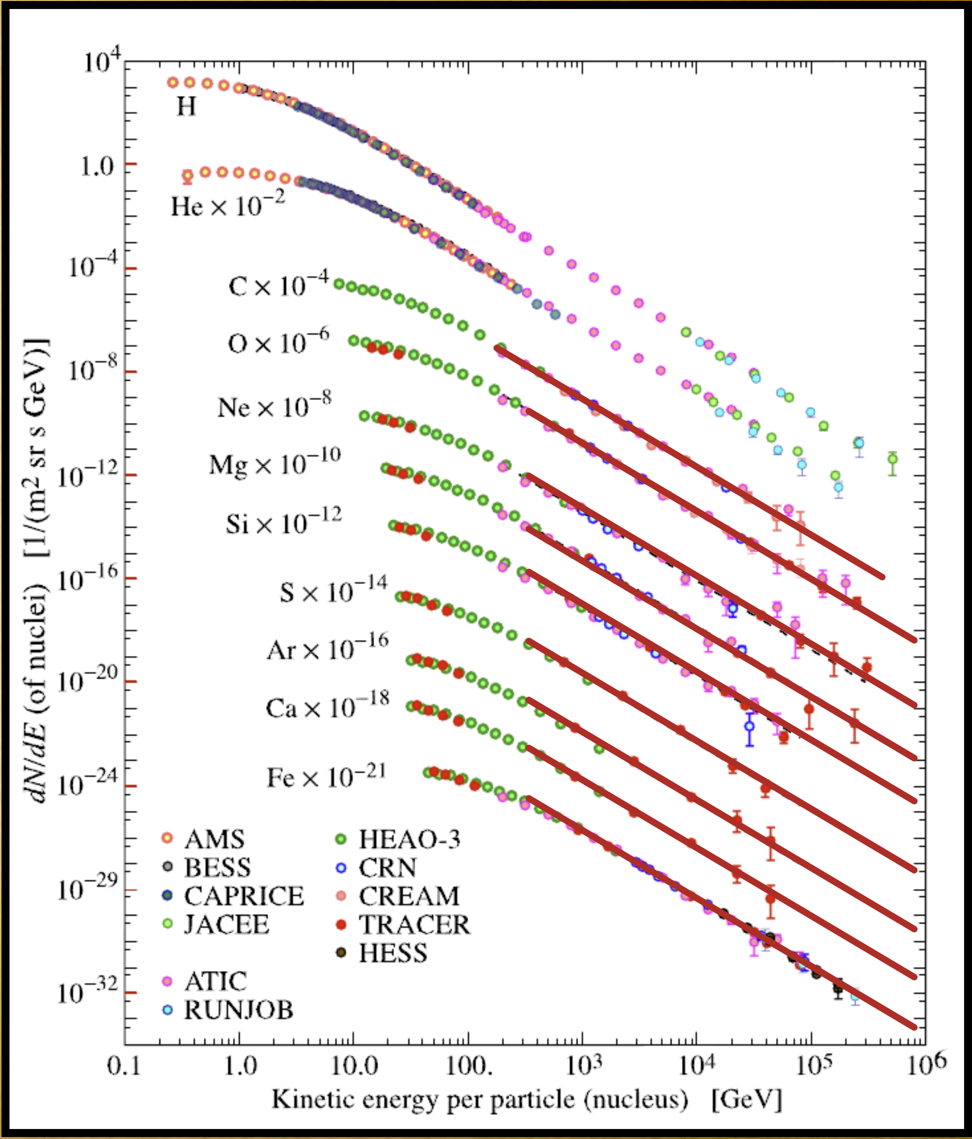




Auger Collab

Energy Spectra

- **Breaking down by elements:**
  - Spectral slopes aren't grossly different for a variety of elements
    - Here a $E^{-2.65}$ spectrum is fit to all the Z>2 elements
  - There may be something else going on with H&He

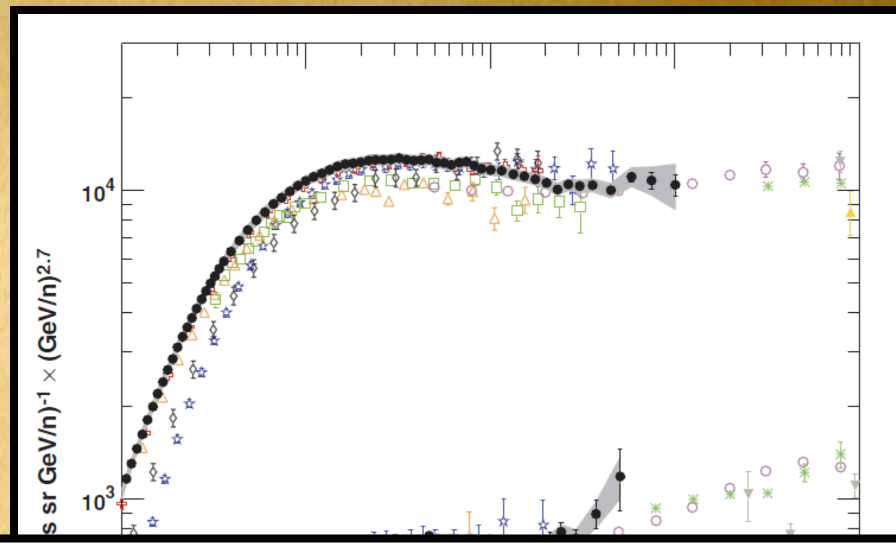


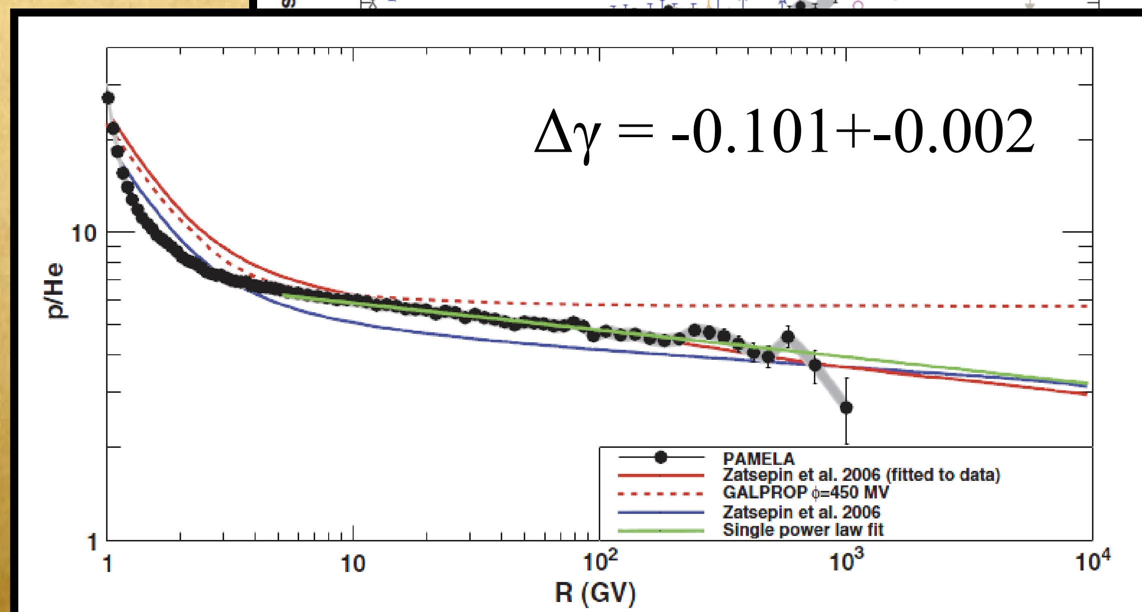
PDG

H & He

- **Best published data set is from the PAMELA space experiment**
  - Main conclusion #1: The H & He spectra do not have the same shape
    - Helium is flatter by a small, but significant amount

NB: Rigidity Spectra

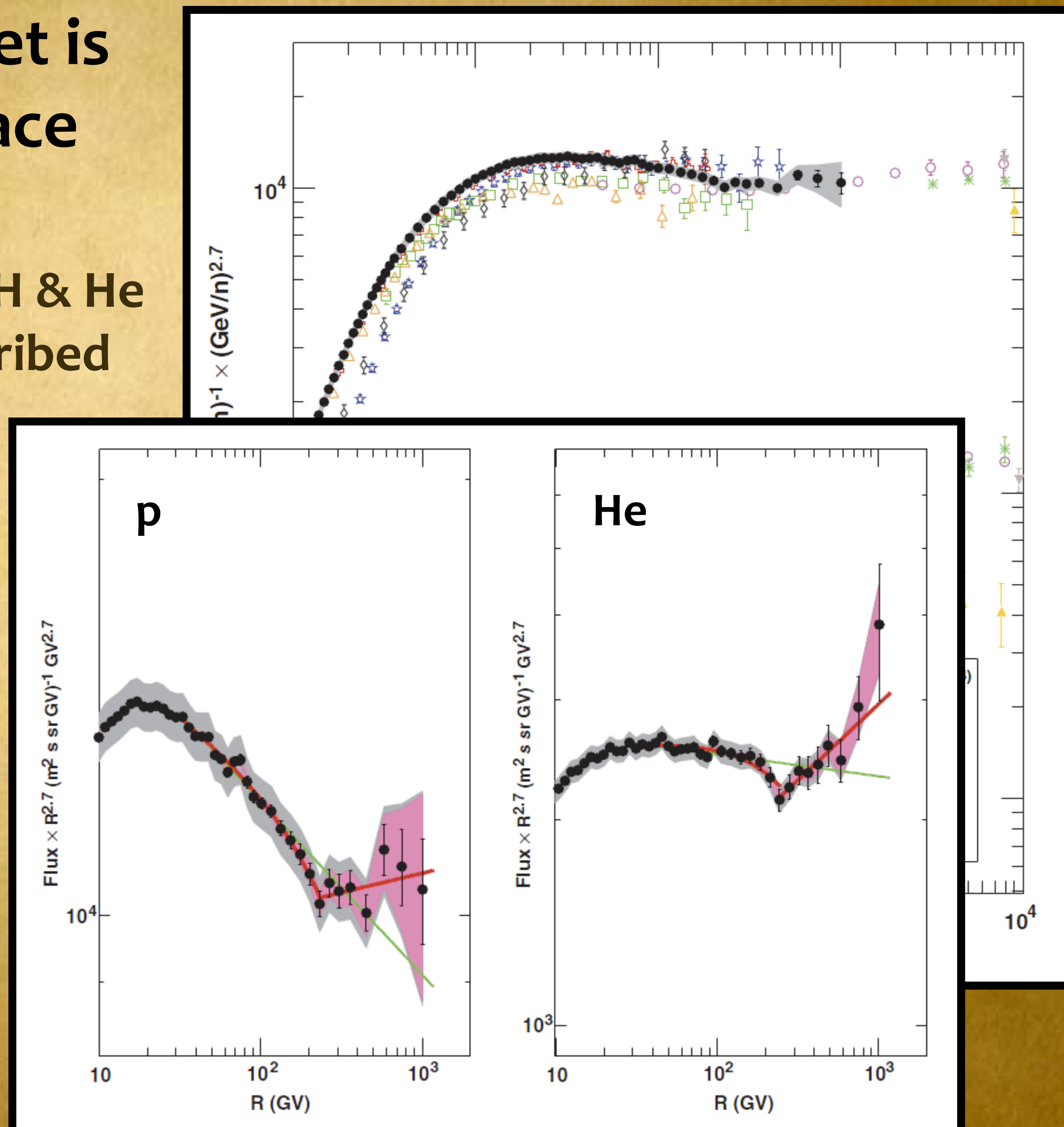




H & He

- Best published data set is from the PAMELA space experiment
  - Main conclusion #2: The H & He spectra are not well-described by single power-laws
    - Breaks at ~200 GV

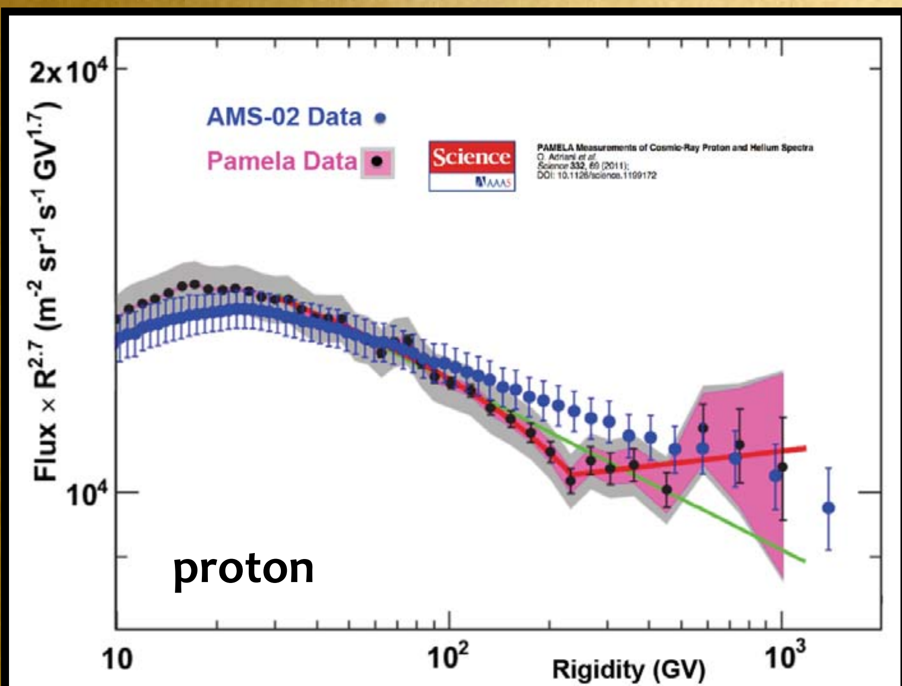
NB: Rigidity Spectra

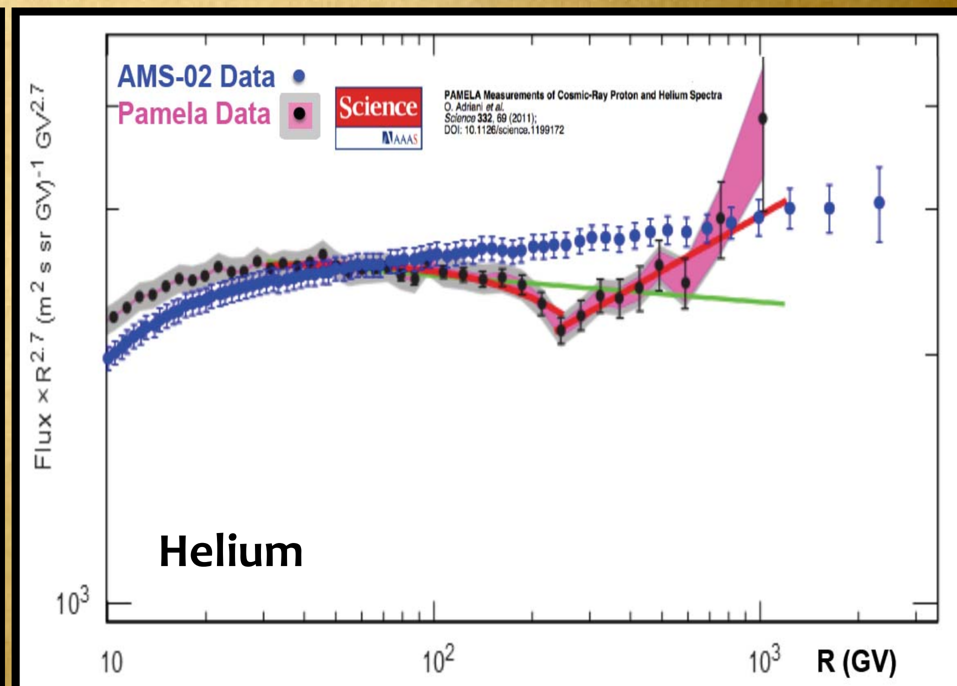


Neither of these features fit into the classical picture of cosmic ray physics

H & He

- The most recent (but still unpublished) high-statistics results come from the AMS-02 space experiment.
  - Spectral features do not seem to be confirmed
  - p/He differences seem confirmed

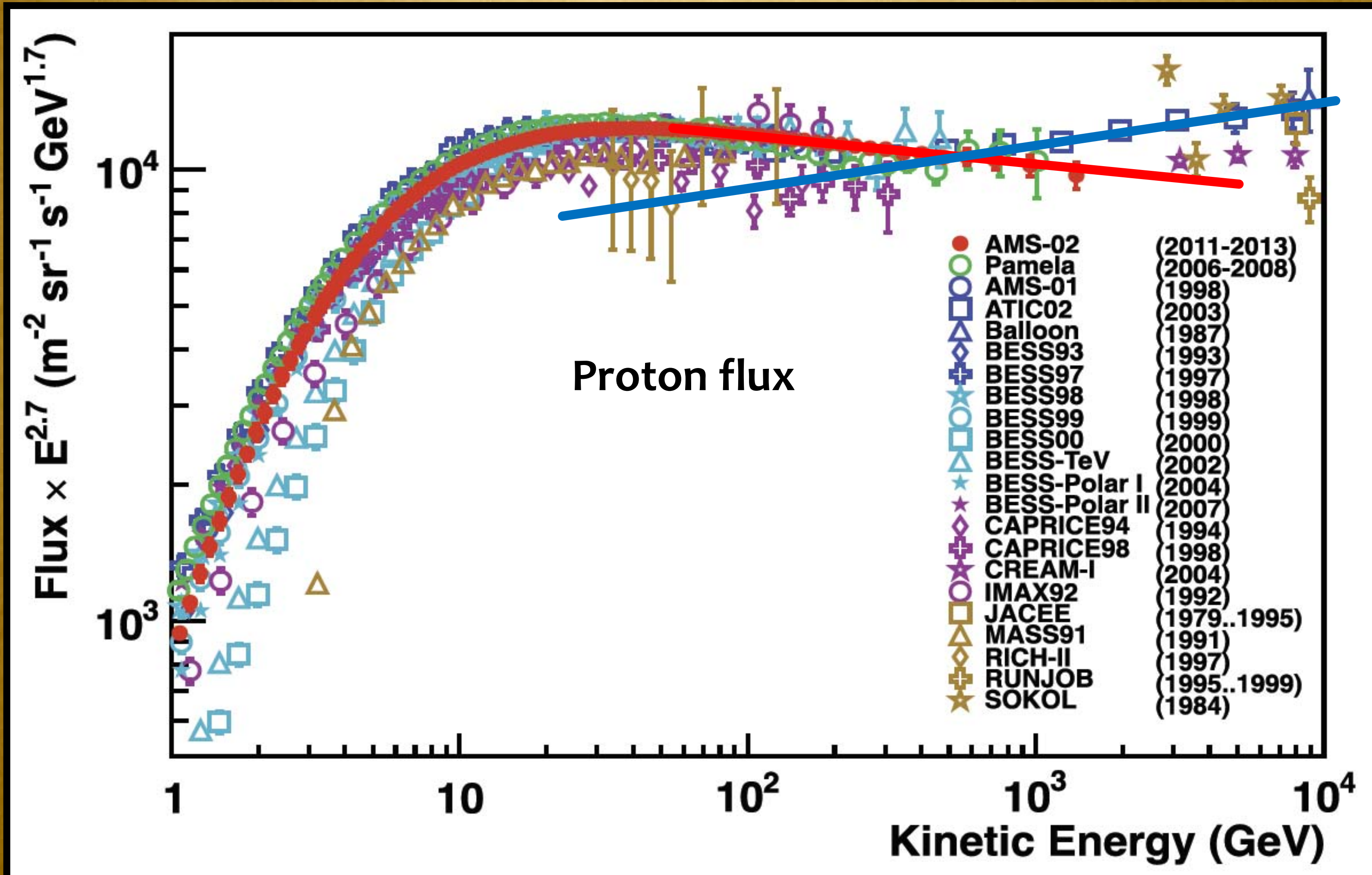




Ting (2013)

H & He

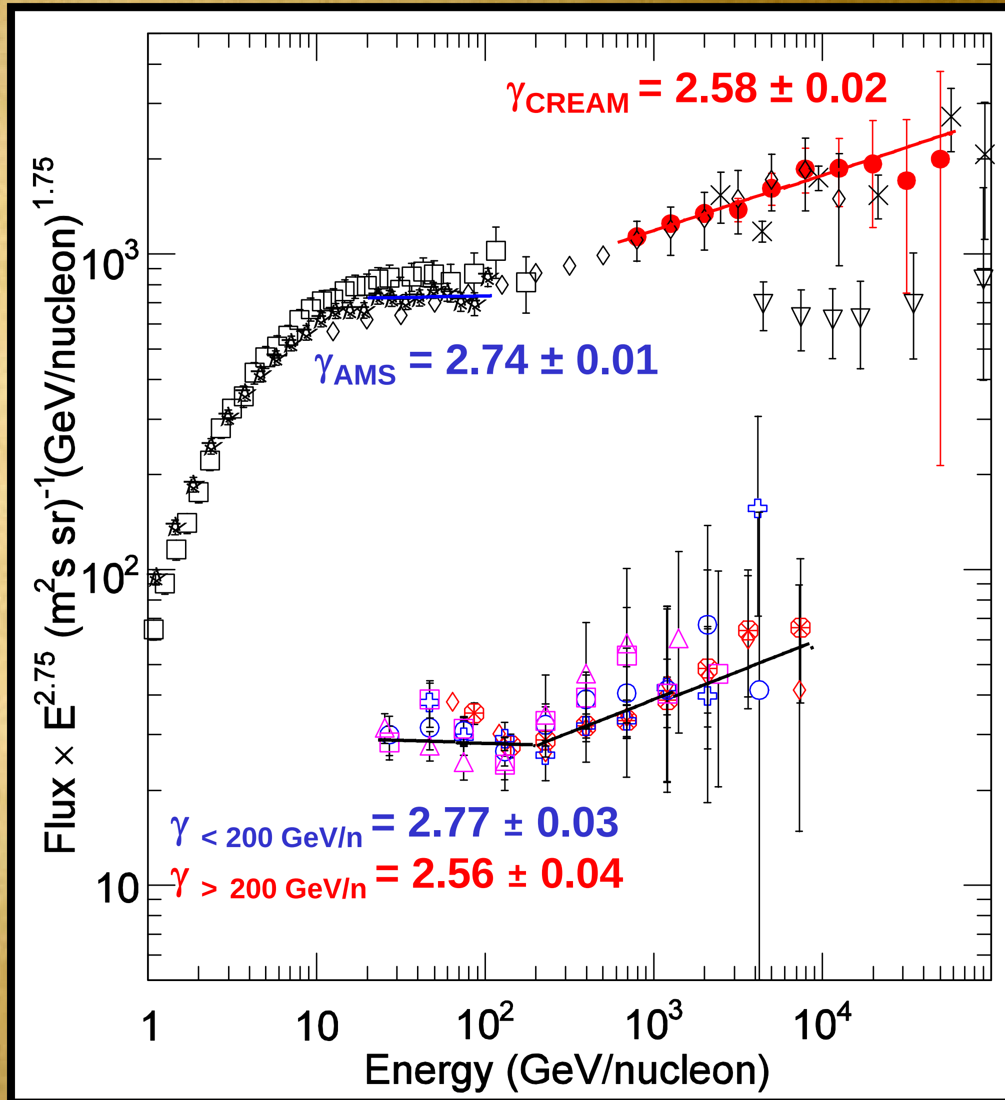
- This may lead to troubles at higher energy though



Heavier Nuclei

- Similar claims have been made for heavier nuclei. So-called 'discrepant hardening':
  - He: AMS-01 spectra vs CREAM Data
  - CNO: CREAM low-E data vs CREAM high-E data

- These results (if true) are difficult to explain with traditional CR models



CREAM Collaboration

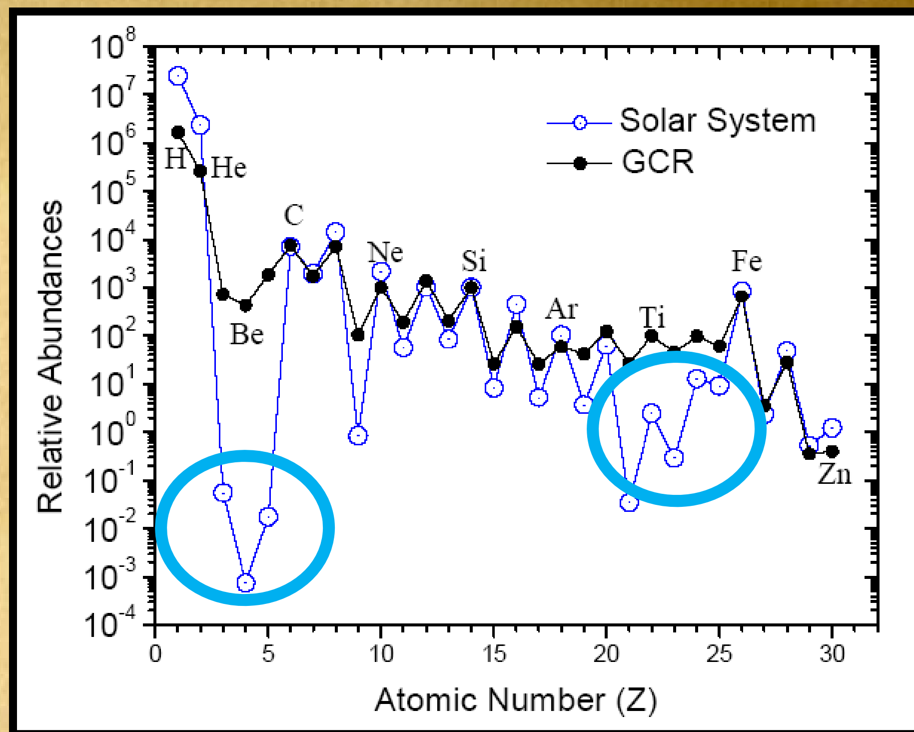
Elemental Composition

- **The CR flux is mostly protons (90%) and Helium nuclei (9%), with small amounts of all the other elements (beyond even Uranium)**
  - Also includes electrons and even some antimatter (positrons and antiprotons)

- **Overall - remarkably similar to the abundances in our solar system, except for a few anomalies**

Elemental Composition

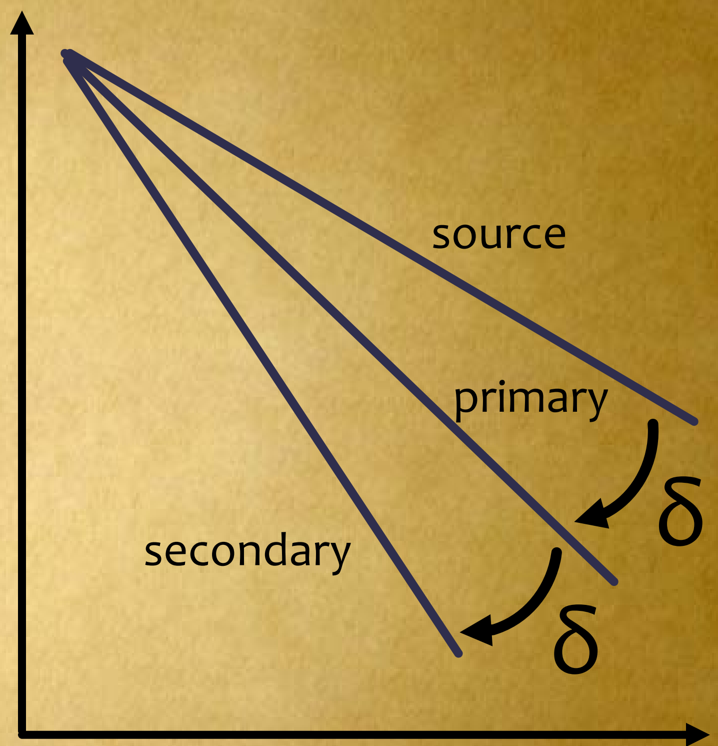
- **The most conspicuous differences:**
  - Surplus of CR just below CNO and Fe
    - Due to spallation of parents during propagation
    - "Secondary" Cosmic Rays
      - Can be used to infer the amount of material traversed by the primaries and more



ACE/CRIS

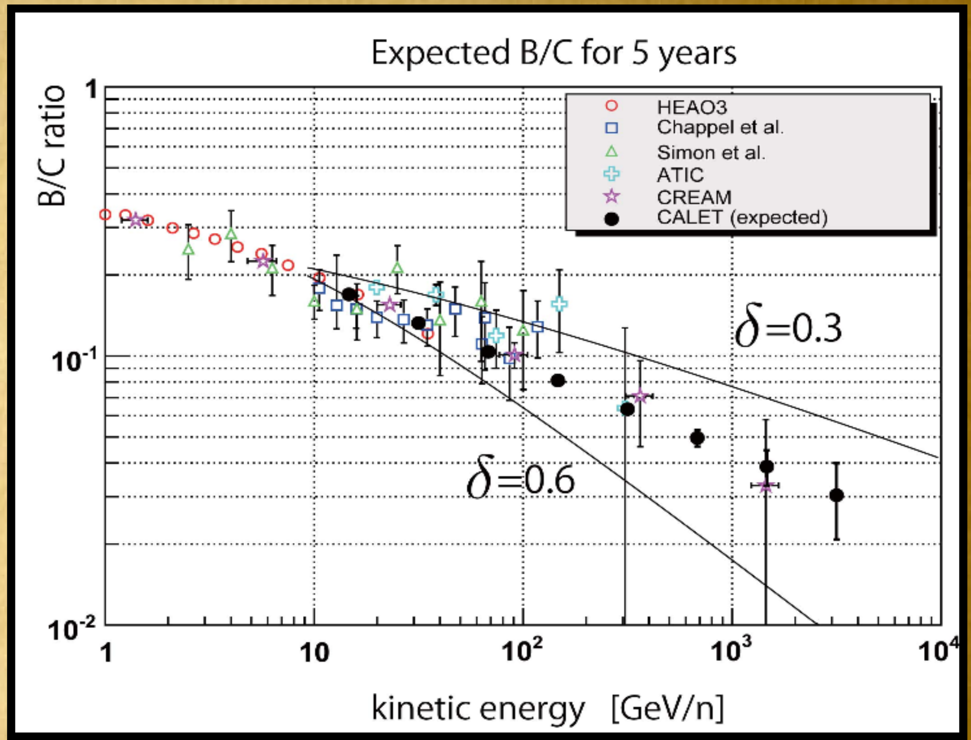
Secondary to Primary

- **As seen earlier, propagation modifies CR spectra in an energy-dependent fashion**
  - Without a sample of source CR, though – how to determine δ?
    - Look at a sample of CR which 'propagate twice' – secondaries!
  - Secondary spectra are modified by 2δ, so S/P ratios can be used to reveal δ without access to source material



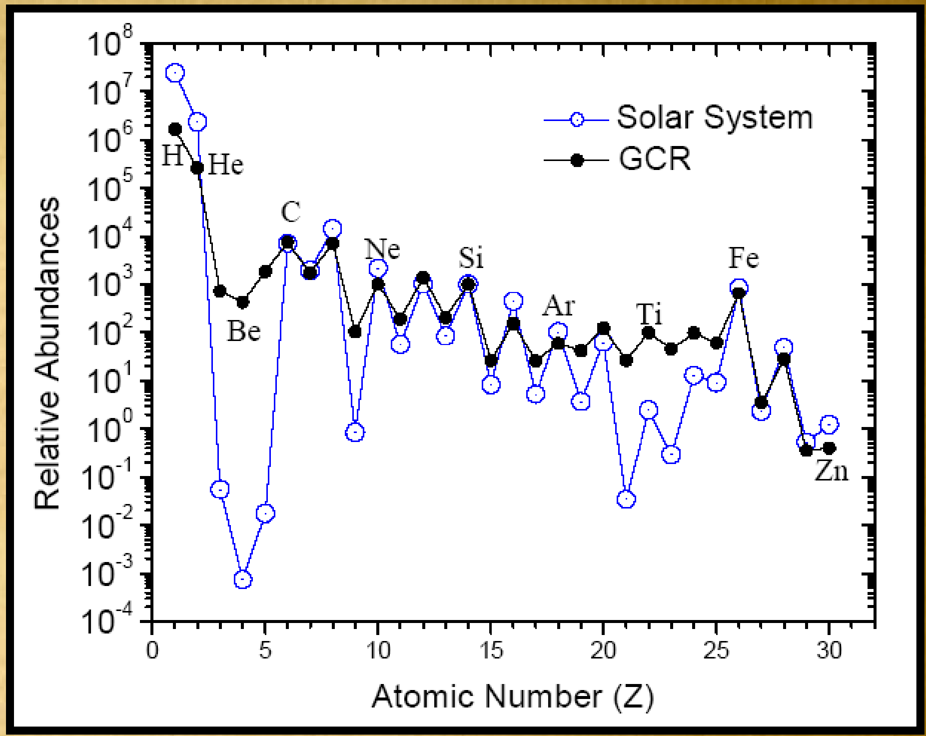
Secondary to Primary

- **The best-measured such ratio is the Boron-to-Carbon ratio**
  - Measurements now extend past 1000 GeV/n
  - Data favor δ~0.5, but error bars are large
  - New data coming soon from CALET.
- **Can also look at the so-called sub-Iron to Iron and others**



Elemental Composition

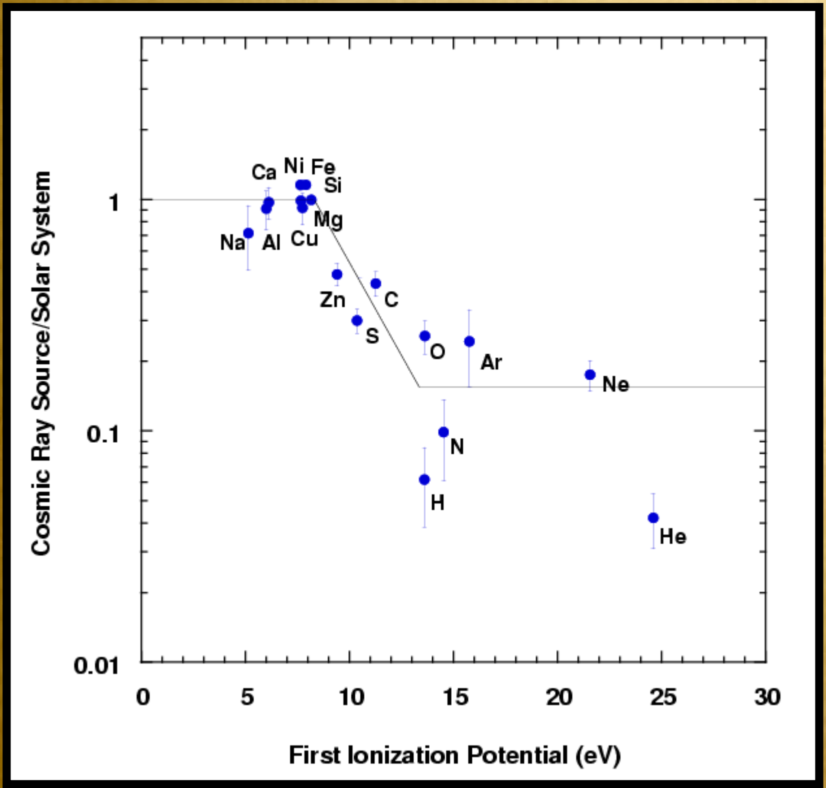
- Some other subtle differences can also be seen on this plot:
  - Under-abundance of H & He
    - Also: O, Ne, S, Ar, …

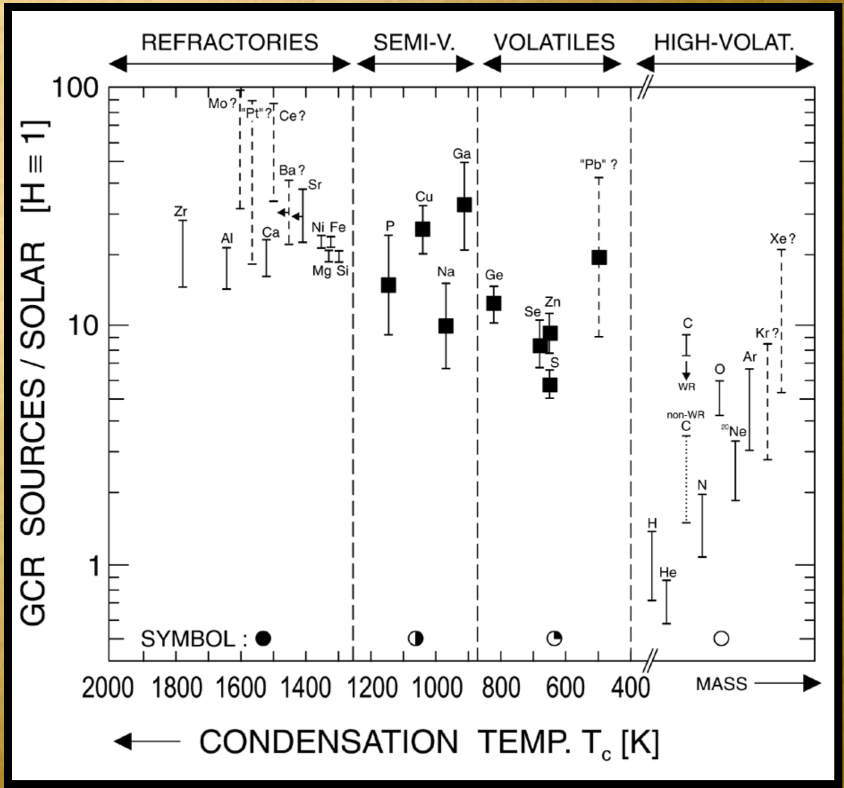


ACE/CRIS

FIP vs Volatility

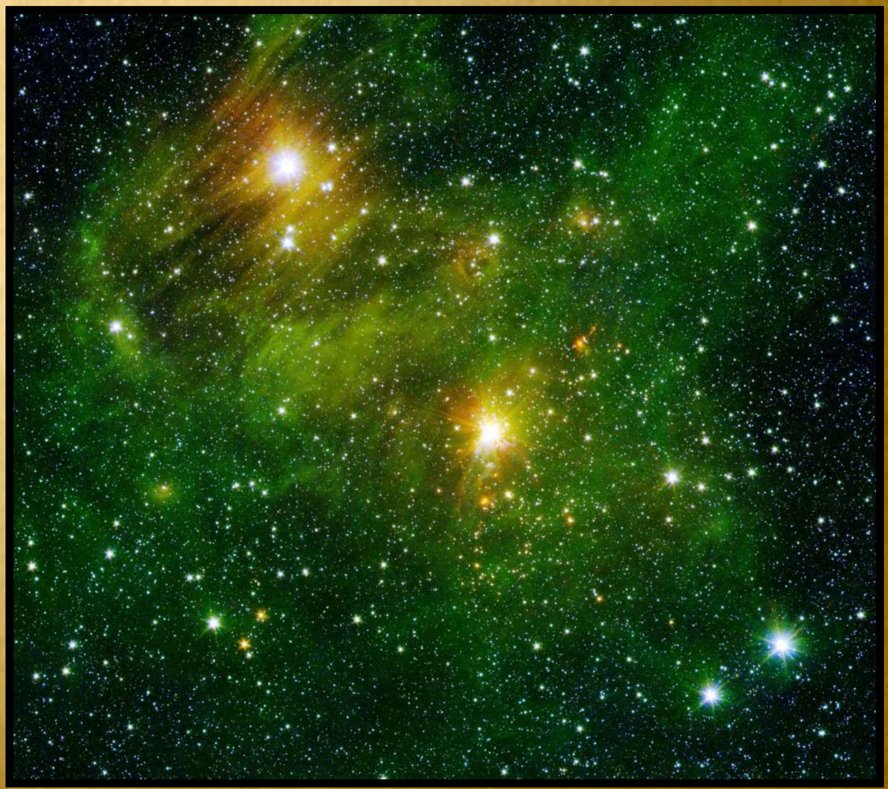
- These discrepancies seem to be correlated with the atomic properties of the elements.
  - Atoms which are hard to ionize (high-FIP) seem under-abundant
  - However, these atoms also tend to be ‘volatile’, which means they like to stay in a gas phase, rather than forming dust grains
    - Difficult to unravel because only a few elements break the FIP/volatility correlation





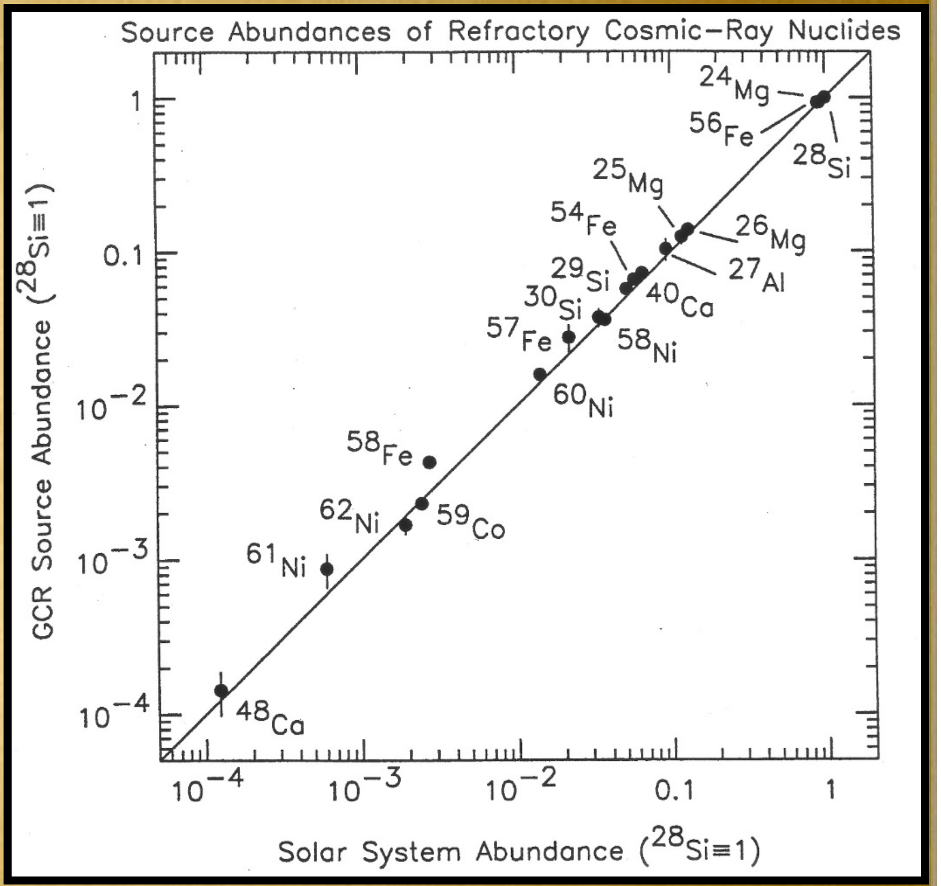
FIP vs Volatility

- **Since the same FIP correlation is seen in solar energetic particle releases and in the photosphere, while grain formation is associated with an undisturbed interstellar medium, this 'origins' question is sometimes framed as:**
  - **Hot Stellar Ejecta vs Cold ISM**



Isotopic Composition

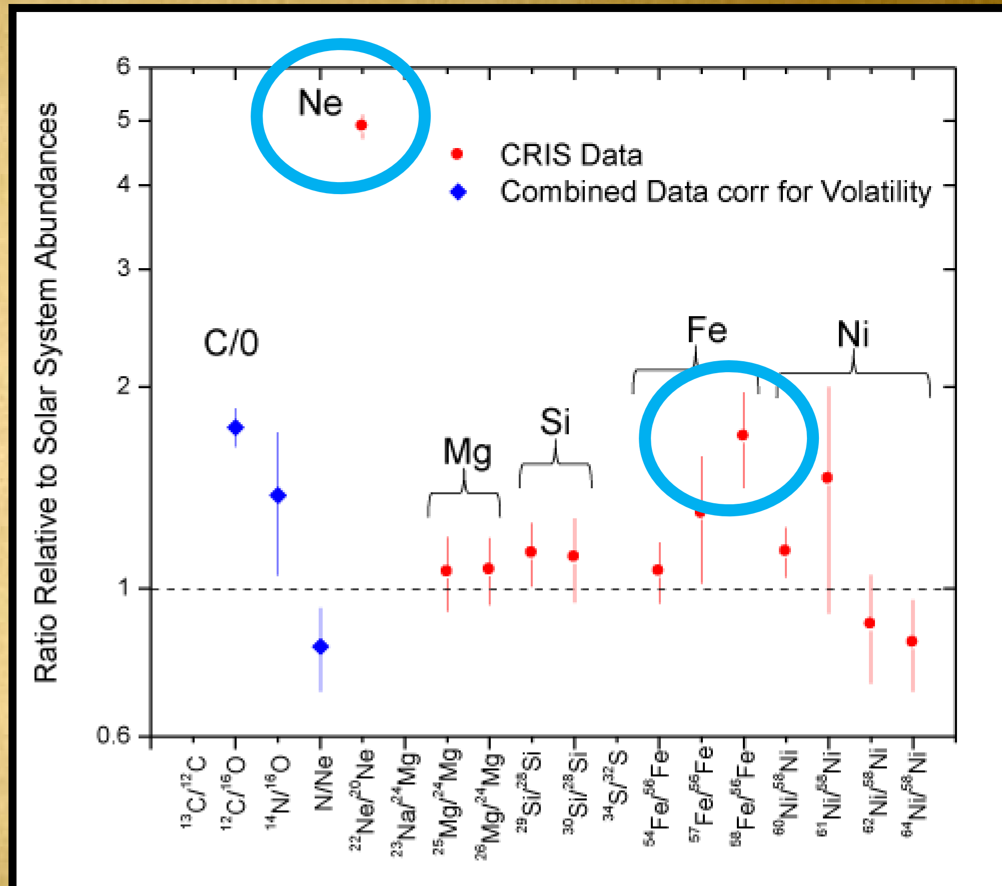
- **With the proper instrumentation, isotopic information can be obtained in addition to elemental composition**
  - These measurements are very difficult to obtain, but they have given us profound insights into cosmic-ray origins
- **The best measurements have come (at low energy) from the ACE/CRIS mission.**
  - Again - for the most part, the isotopic abundances are similar to solar, with a few exceptions



Wiedenbeck et al., 2003

Isotopic Composition

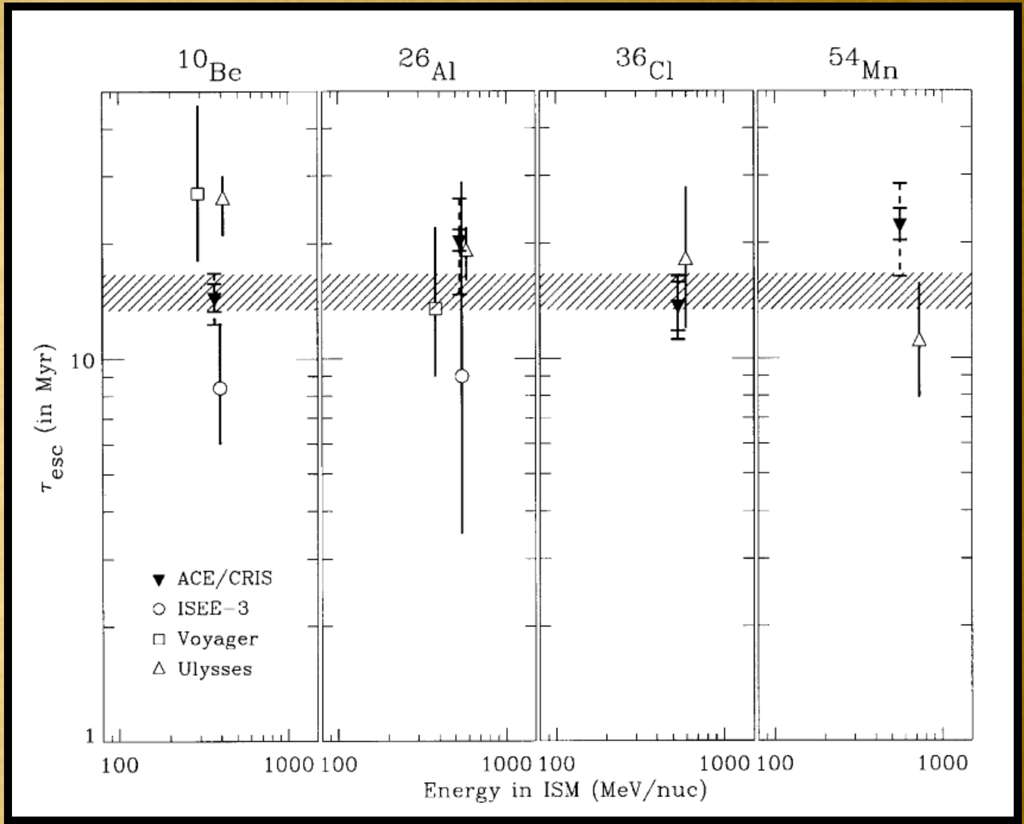
- **The biggest differences are found 2 isotope ratios:**
  - Ratio of 22Ne/20Ne
    - About x5 higher in CR
  - Ratio of 58Fe/56Fe
    - About x1.8 higher
- **Provides clues into source regions..**
  - Models of Wolf-Rayet stars, for example, predict large enhancements of 22Ne and smaller enhancements of 58Fe



Binns et al (2005)

Radioactive Clocks

- Some isotopes produced at sources or during propagation are radioactive
  - Observing the relative abundance of such an isotope vs a chemically identical one provides a 'stopwatch'
- The most famous such isotope is 10Be
  - A 'pure secondary', produced only by the spallation of heavier CR, it decays (beta-decay) with a half-life of 1.39Myr. Hence, measuring the ratio 10Be/9Be can provide information on how long CR have been propagating
    - Multiple clocks suggest 15 Myr



Origins...

OB Associations/Superbubbles

- OB Associations are clusters of O(100) hot massive O & B stars contained in a small (~30pc) volume

- Multiple supernovae taking place in an OBA leads to the production of a superbubble: a large hot SN/wind-blown cavity within the ISM

N44 Superbubble

Higdon & Lingenfelter 2005

OB Associations/Superbubbles

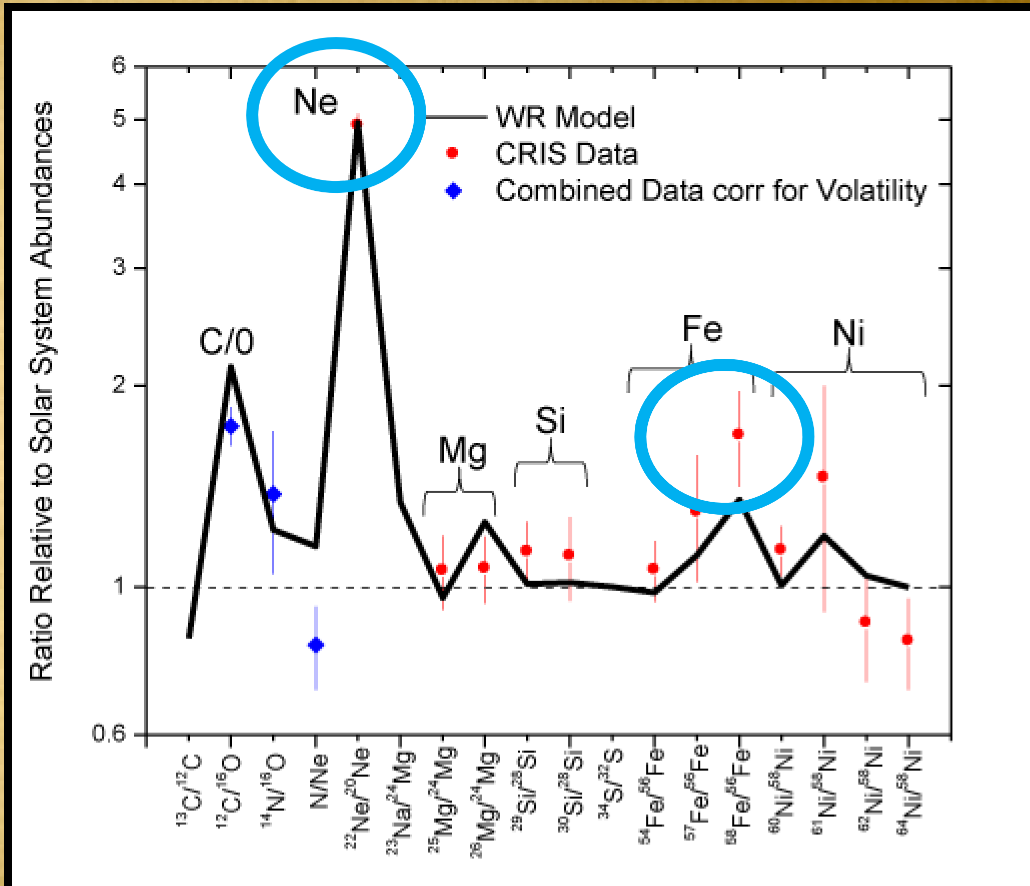
- ~75% of Galactic supernovae occur in such Superbubbles
- The majority of W-R stars occur in such OB associations
- Can signatures be found in the CR data?

N44 Superbubble

Higdon & Lingenfelter 2005

OB Associations/Superbubbles

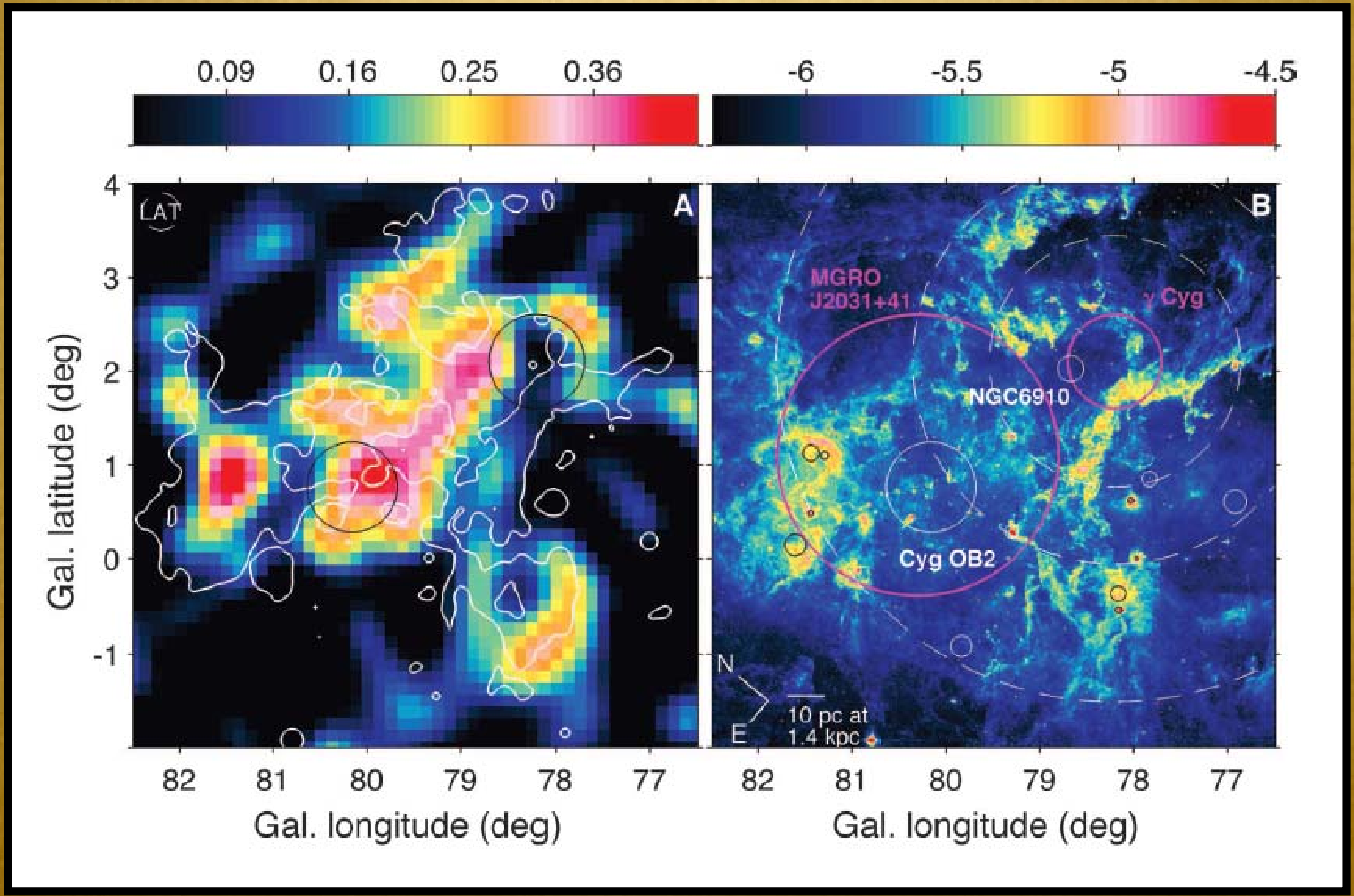
- **Yes. A mix of ~20% superbubble-type material with 80% standard ISM seems to match the isotopic data well**
  - And elemental data at low and high mass too
- **However, other work comes to a different result**
  - DSA in superbubbles?



Binns et al (2005)
Prantzos (2012)

Fermi/LAT Superbubble

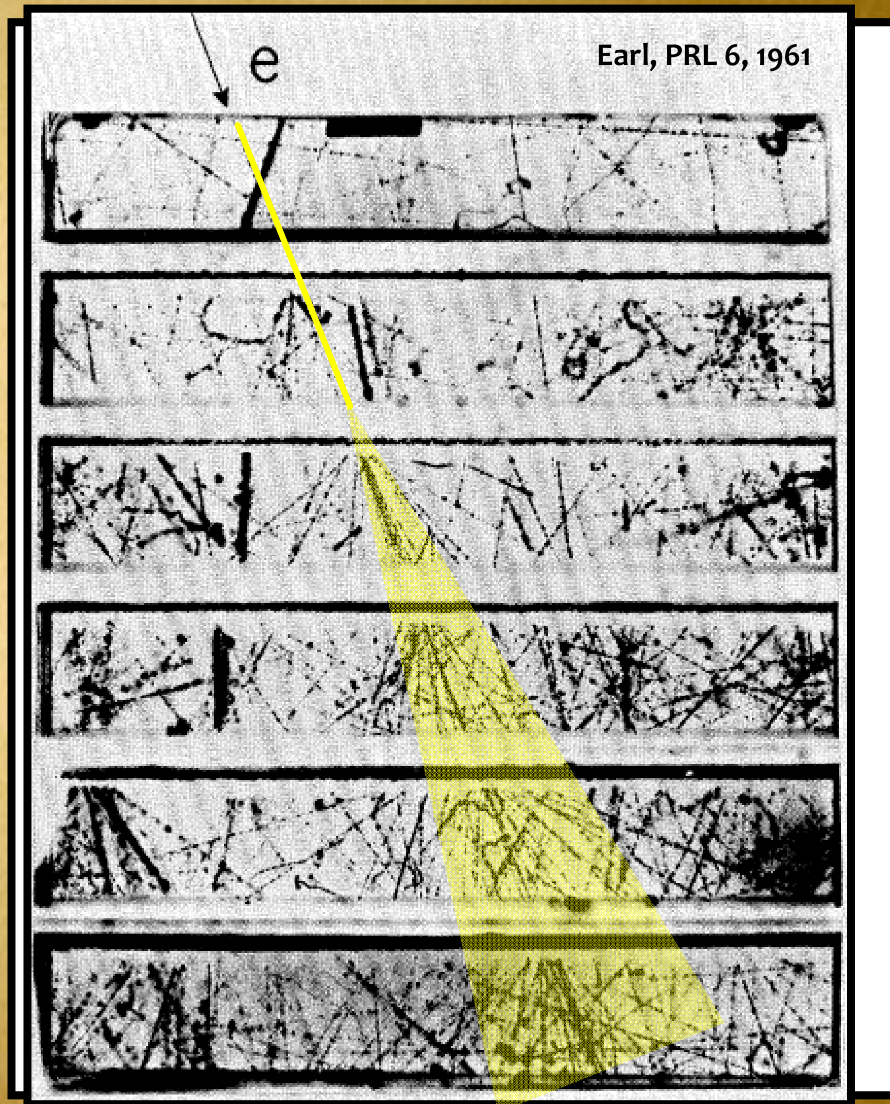
- **Cygnus Superbubble, as imaged by LAT**



Fermi/LAT Team - 2011

Cosmic Electrons

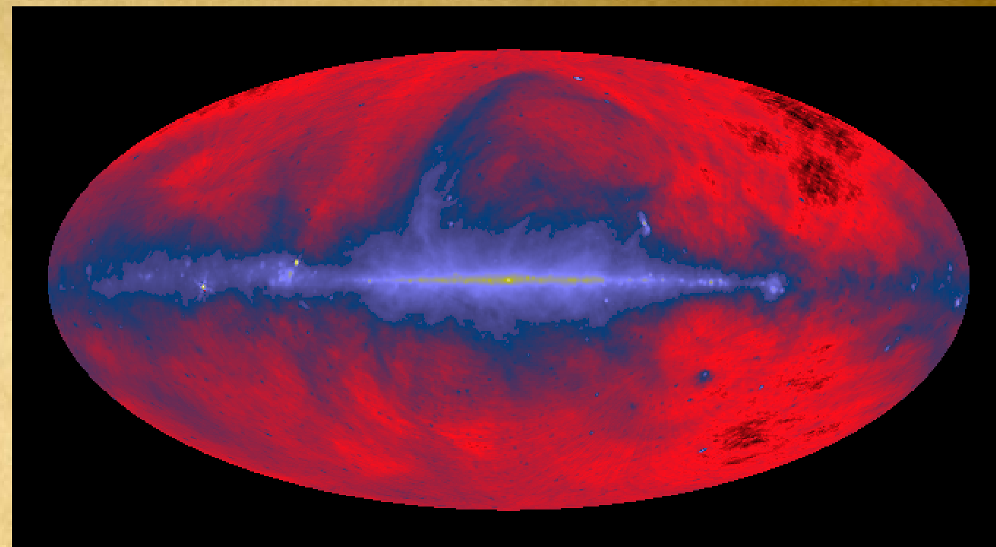
- Cosmic-ray electrons were discovered with balloon instrumentation in 1961
  - Took 50 years!
- Modern measurements put the cosmic ray electron flux at ~1% of the overall flux
  - Dropping even faster than the CR proton flux

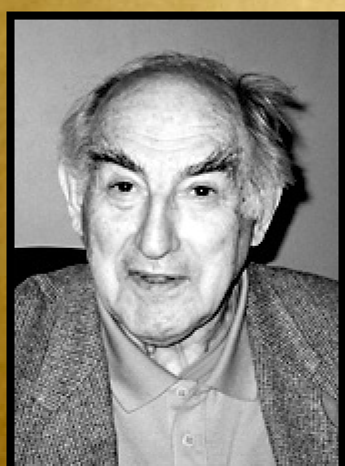


Yoshida – Adv. Sp. Res. 42, 477 (2008)

Cosmic Electrons

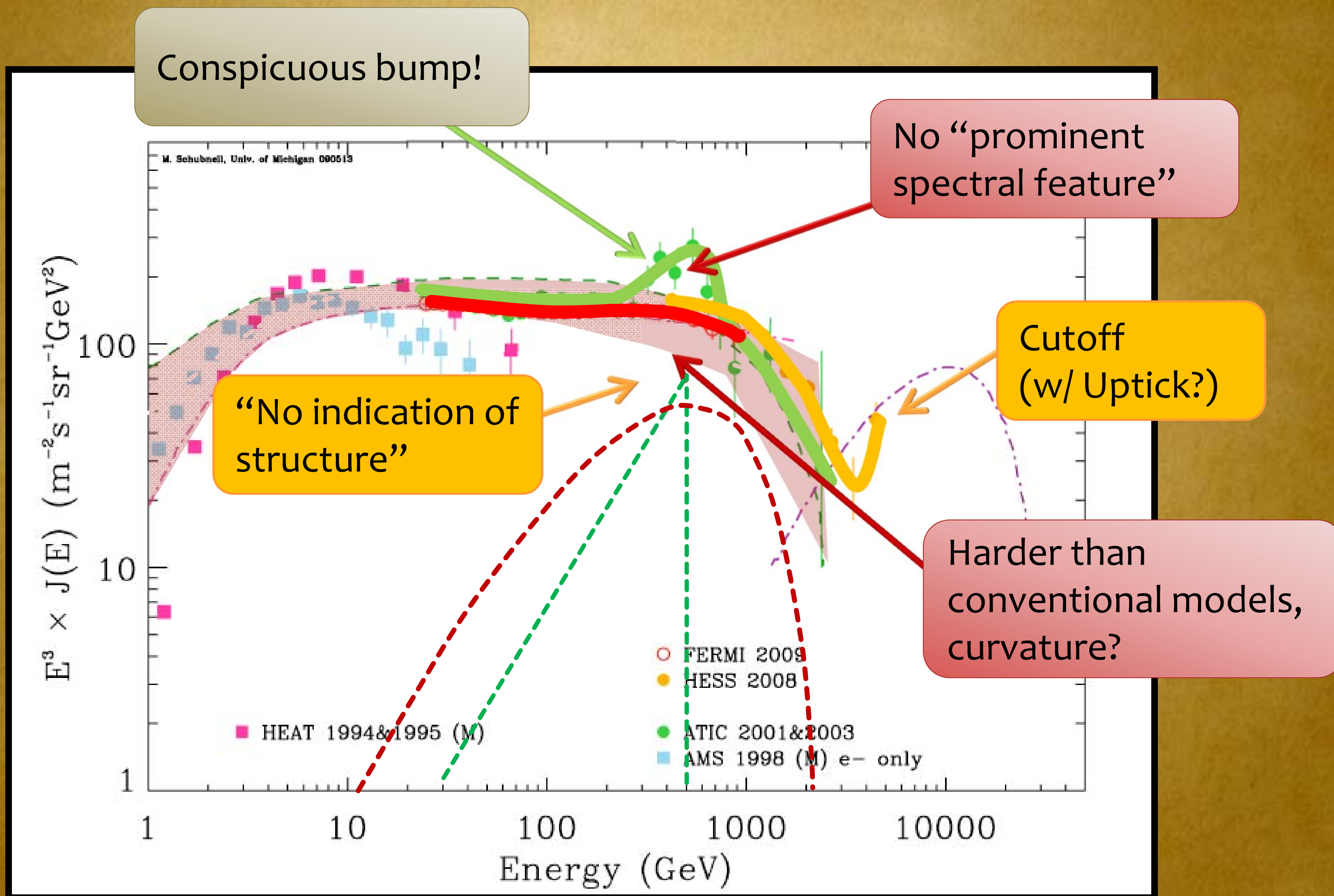
- Interesting aside: these cosmic-ray electrons were predicted by V. Ginzburg in 1950s to explain Galactic radio emissions.





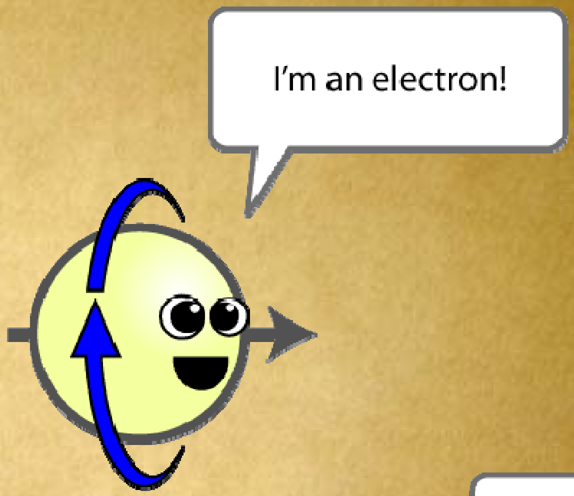
→ Synchrotron Radiation

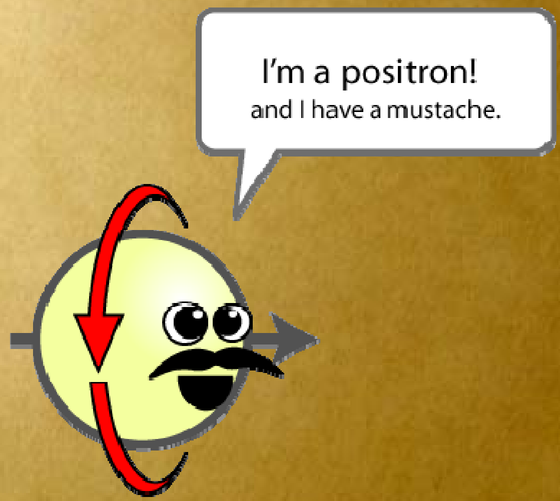
Cosmic Electrons



Antimatter

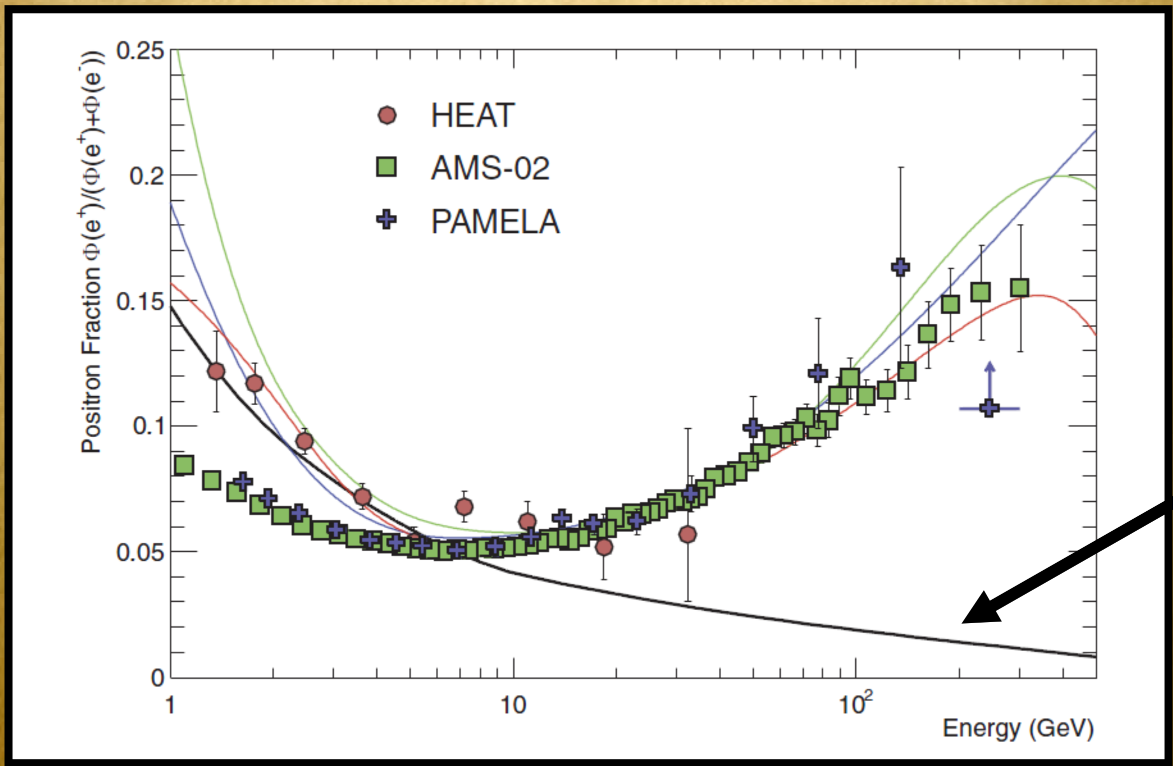
- **Antimatter is also found in the cosmic rays, the most plentiful component being positrons**
  - Even in the absence of SOURCES of positrons, you expect some level of secondary positrons, due to interactions of CR as they propagate
    - There have long been predictions for what level this flux should be at.





Positron Measurements

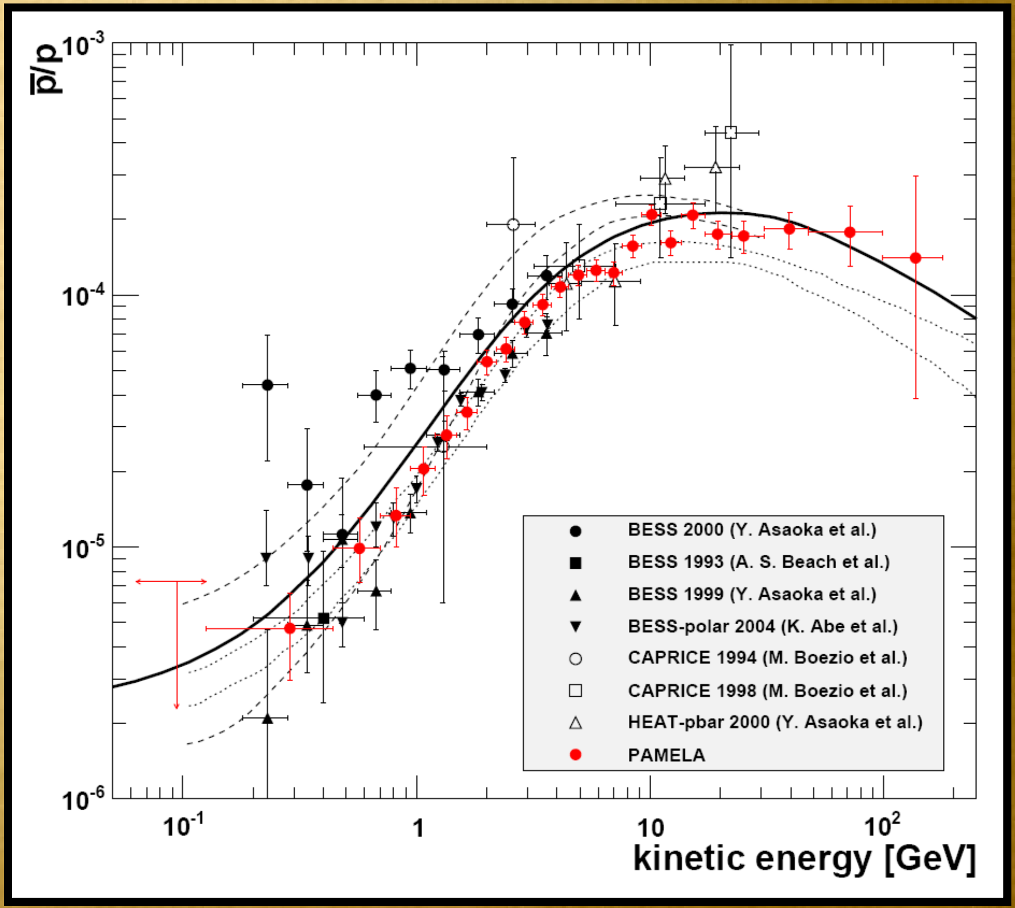
- Hints appeared in the 90s (and before) that there were more positrons than expected at >10 GeV
  - Recent data confirm a large surplus in the positron fraction
    - Pick a model! Pulsars (e- too!), propagation physics, dark matter…



Secondary Prediction

Antiprotons too!

- Critics of dark matter models point out that the antiproton (p-bar) level, which is also measured, is remarkably boring
  - This means that some of the more natural dark matter models won't work, since they predict extra p-bars too.



Summary

- **A few conclusions:**
  - Cosmic rays are an important energy component in the galaxy
  - With a few important (telling) differences, they have a composition relatively similar to the solar system
  - A relatively simple standard model has emerged
    - But better measurements are starting to stress the limits of this
    - Some promising recent ideas have been shown to explain some of the patterns in the data
      - But the jury is still out
      - And more measurements are needed!
  - Lepton measurements show that surprises are still to be found in the cosmic ray flux, as we open up new windows in energy and precision

Summary

- **I had to omit a huge amount of 'observational' material!**
  - Anisotropy
  - Ultra-heavy nuclei
  - Measurements above the knee
  - Other isotope ratios
  - Gamma-ray luminosity of the Galaxy (+other galaxies, +SFR)
  - Cross sections

- **Related subjects:**
  - Propagation models
  - Acceleration mechanisms
  - Detector physics (next talk)