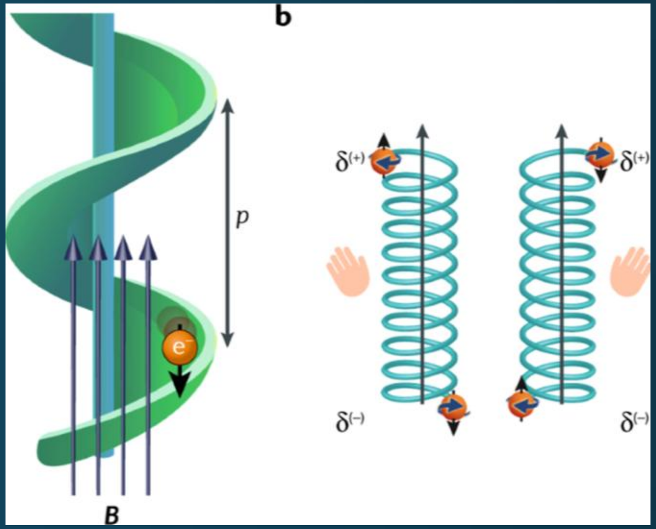
The Astroparticle Lens:

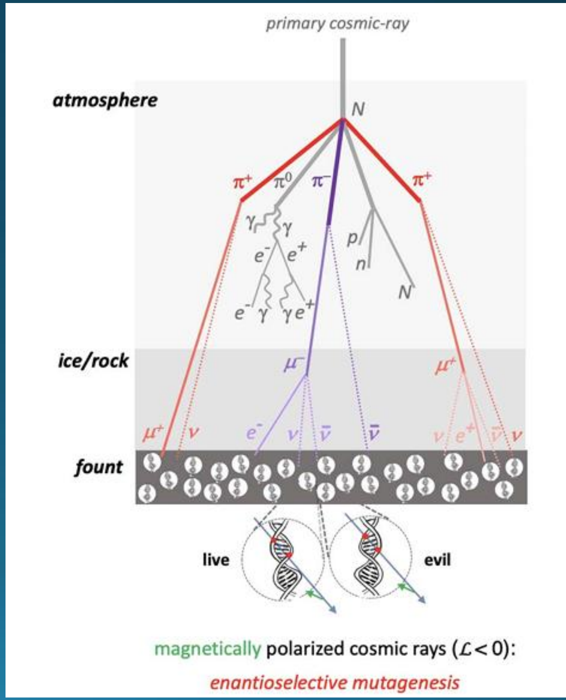
Using Particles From Space To Understand Our World

Cosmic ray isotopes that help us understand the Milky Way

Keith McBride-Compton Lecture 6

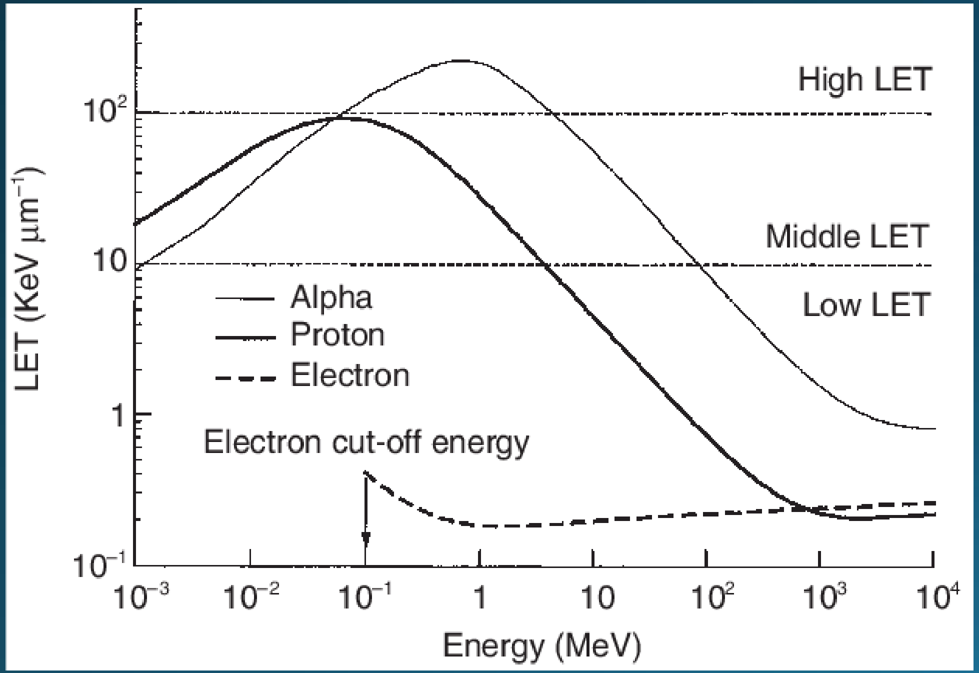


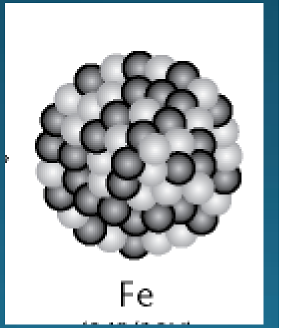
Last week, we discussed cosmic rays as damaging radiation

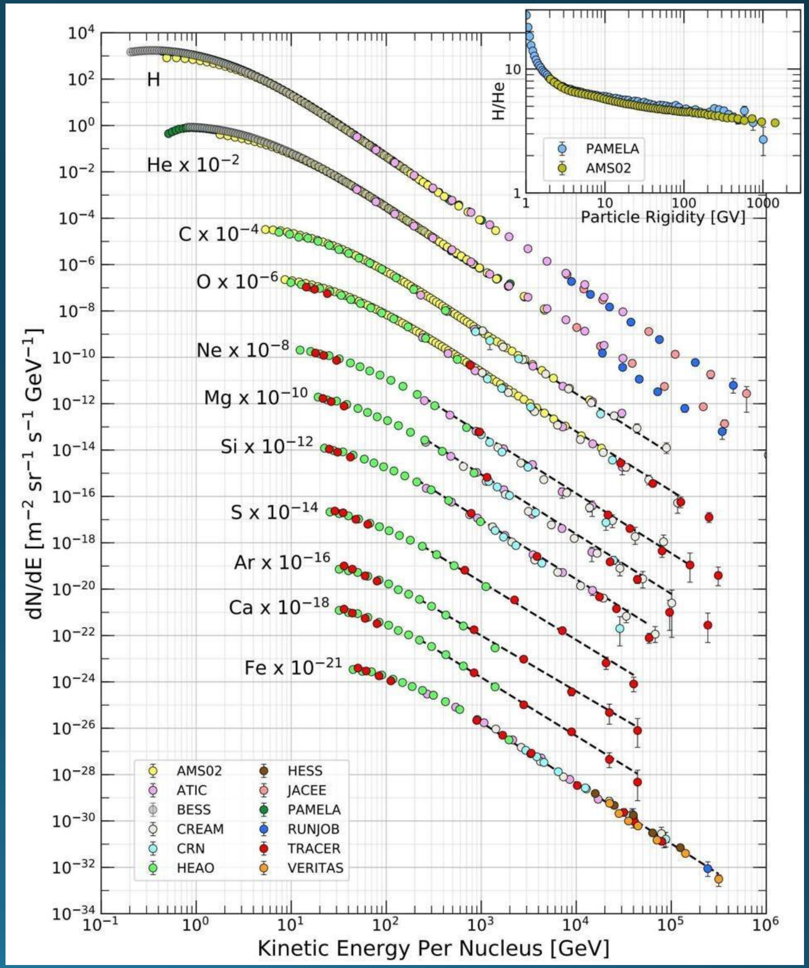


High-LET for higher charged particles

- Cosmic rays are not just protons 
  - ~90% are protons
  - But high-charge nuclei also, the other 10%



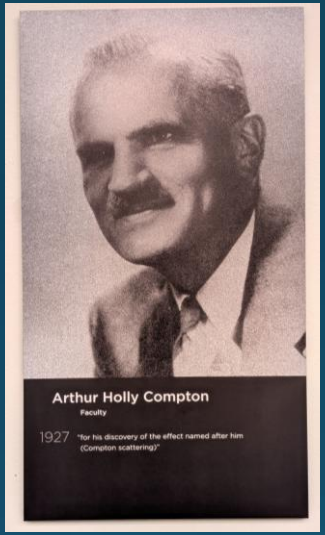




Discovery of cosmic radiation

Domenico Pacini

Victor Hess received the Nobel prize in 1936



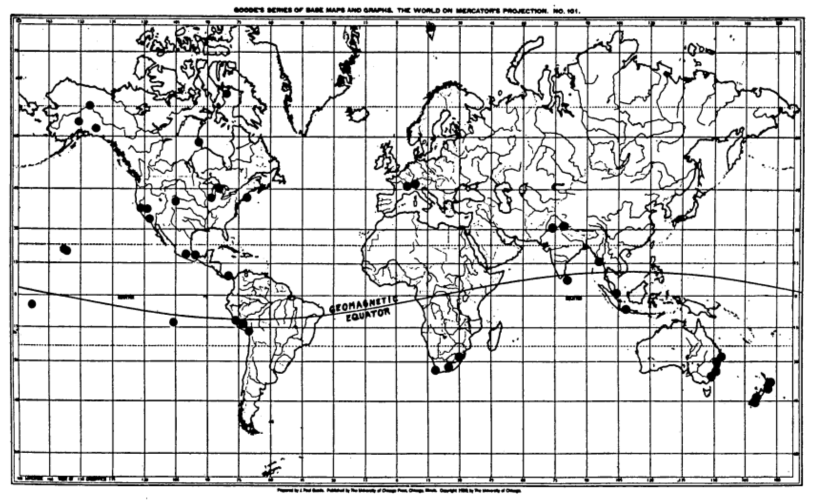
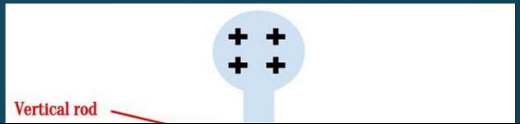


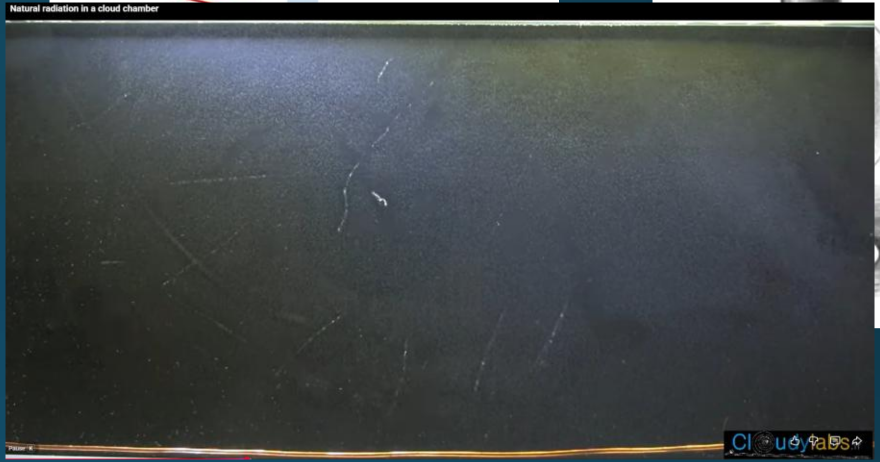
FIG. 4 Map with location of cosmic-ray measurements by Compton and his co-workers. *PR*, *43* (1933), 389.

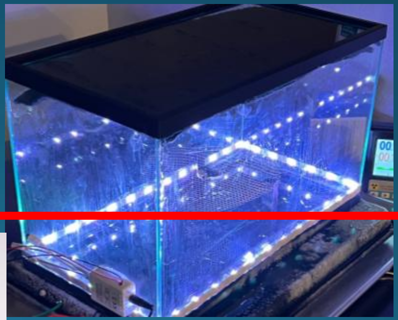
→This radiation is positively charged
Cosmic rays are protons

Built new detectors

- Electroscopes
- Cloud chambers
- Geiger-Muller counters
- Coincidence measurements with cameras

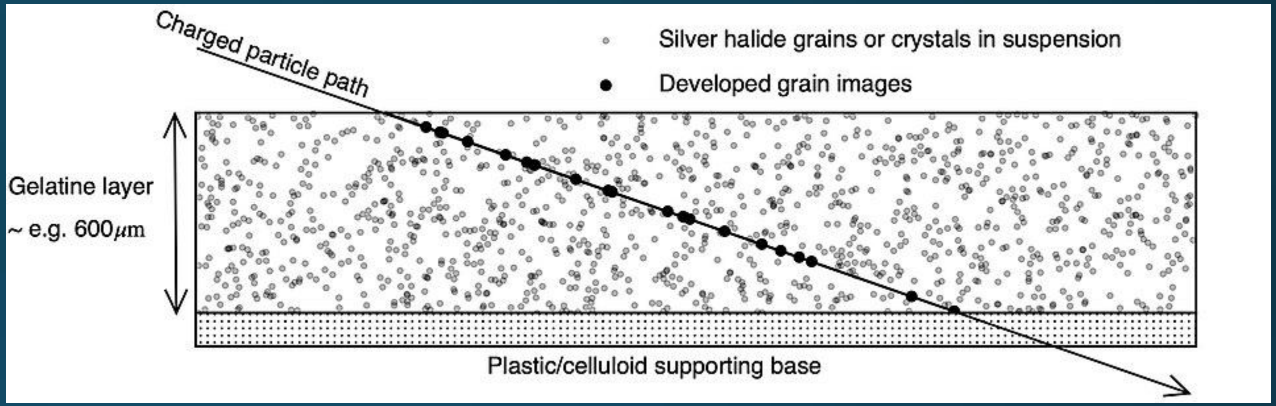


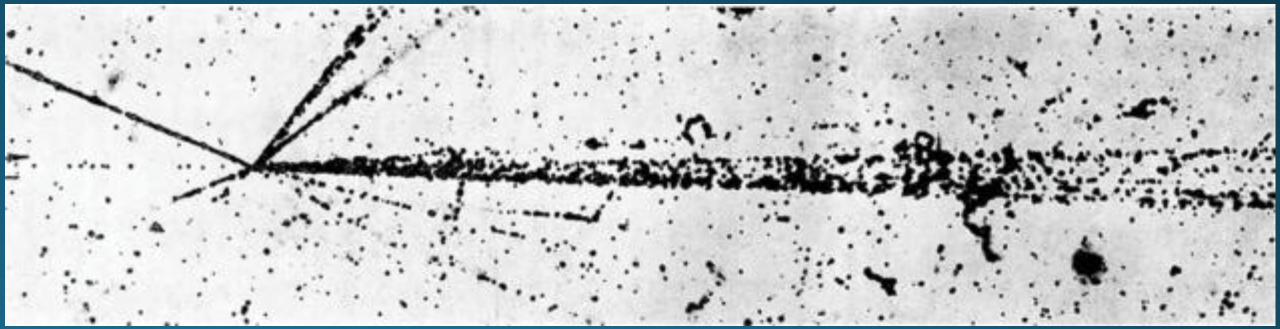



The shower of particles – new detectors!

- Nuclear emulsions
  - ~1947 on balloons
  - Lead to many particle physics discoveries
- Pions discovered
  - Bristol ballooning flights by Cecil Powell
- Direct observation of pion decay
  - Charged pions!





High charged cosmic ray nuclei

Phyllis Freier

Her expertise included

PHYSICAL REVIEW VOLUME 74, NUMBER 2 JULY 15, 1948

Evidence for Heavy Nuclei in the Primary Cosmic Radiation

PHYLLIS FREIER, E. J. LOFGREN, E. P. NEY, AND F. OPPENHEIMER
University of Minnesota, Minneapolis, Minnesota
AND
H. L. BRADT AND B. PETERS
University of Rochester, Rochester, New York

(Received June 8, 1948)

RECENT high altitude flights in free balloons have given evidence for the existence of nuclei of atomic number up to about 40 and

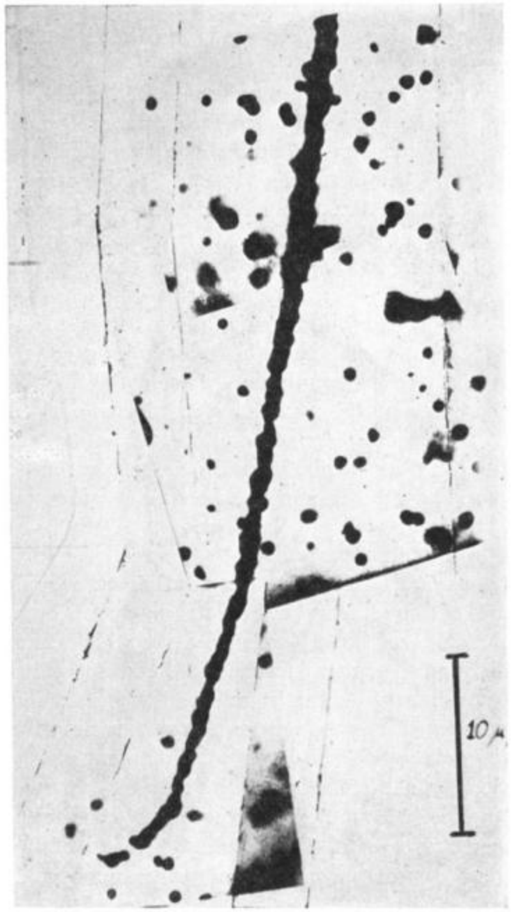
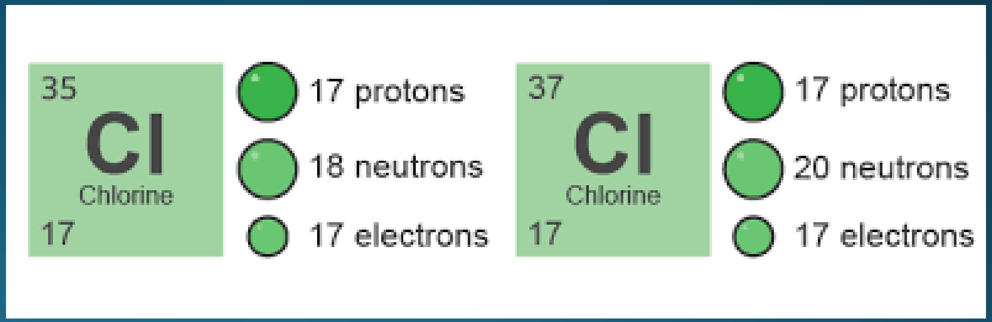


FIG. 3. A medium heavy track ($Z\sim10-15$) ending in the emulsion. The particle has a low velocity; δ-rays are almost entirely absent. Thinning of track towards the end of the range suggests gradual filling of electronic shells.

- Elements are identified by number of protons in the nucleus
  - Helium has Z=2 protons
  - Alphas are +2 charge
- Isotopes – identified by the number of neutrons and protons together
  - Some combinations are not stable

Neutrons and some nuclei decay!



A very interesting time for astrophysics

- Debates on the history of the universe
- In 1948 – George Gamow's famous Big Bang theory
  - "The Origin of Chemical Elements"
  - Protons and neutrons synthesize to make nuclei
- Meteorite samples
  - Just call up your geochemist friend, Victor Goldschmidt
- Problem: unstable nuclei of mass 5 and 8
  - Lithium-5 and Beryllium-8
  - How do you deal with the "mass gap"?

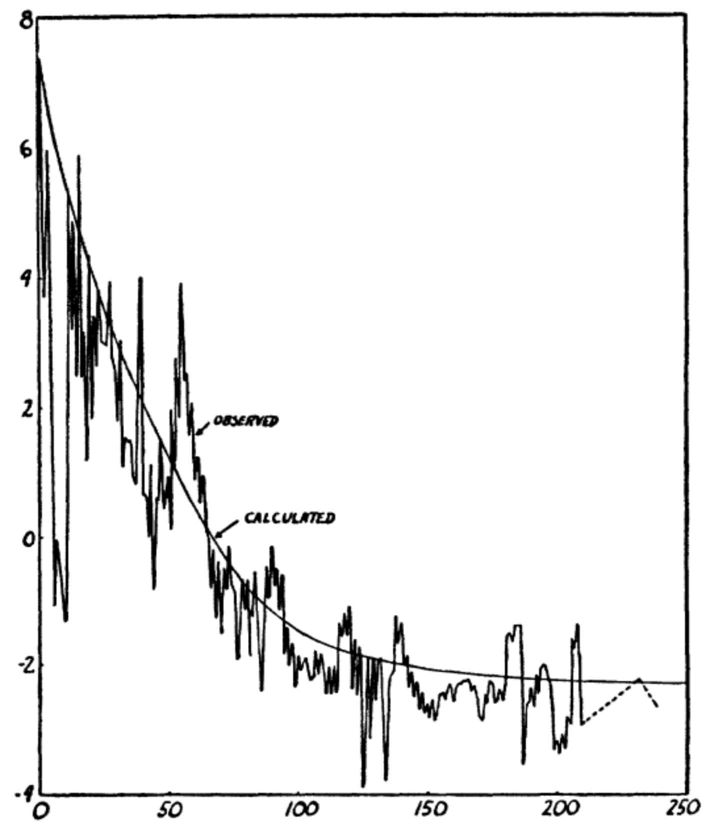


FIG. 1.

Log of relative abundance

Atomic weight

Heavy cosmic rays

- Feier – “I literally just saw some Lithium, George”
  - High-energy process for cosmic rays makes heavy elements? Maybe?
- Some mechanism accelerates and distributes these elements

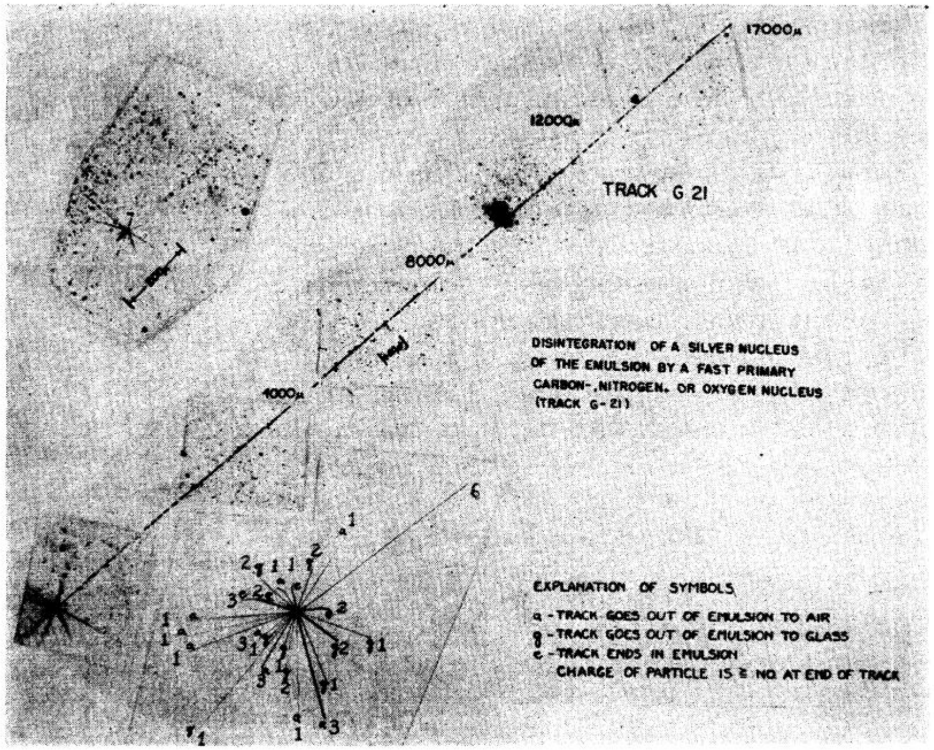
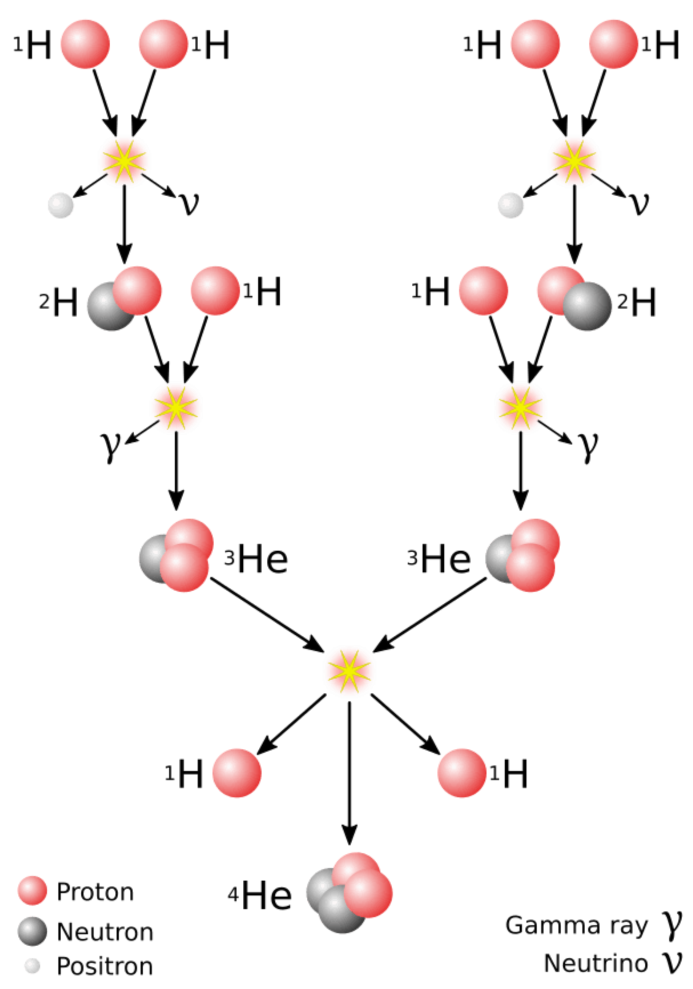


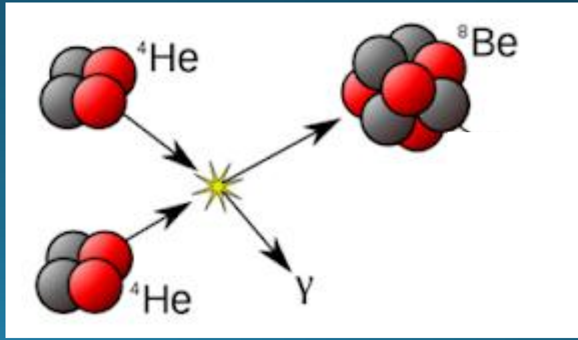
FIG. 2. Disintegration of a silver nucleus by a fast primary carbon, nitrogen, or oxygen nucleus (track G-21). The charge of the particle responsible for the 17,000μ long track G-21 has been determined to be $Z=6$, 7, or 8 from the specific energy loss $0.11<K<0.125$ Mev/(mg/cm²) and the δ-ray density

$$n=(2.8\pm0.5)(\delta\text{-rays}/100\mu).$$

Stellar Nucleosynthesis

- Proton-proton chain (nuclear fusion)
  - Produces Helium
    - Eddington (1920s)
  - Powers the sun and other stars
    - Eddington (1920s) and Hans Bethe(1939)
- But helium-fusion would produce Beryllium-8 (unstable)
  - Decays in 81.9 Attoseconds
  - Light can travel 3 Hydrogen atoms in ~1 Attosecond

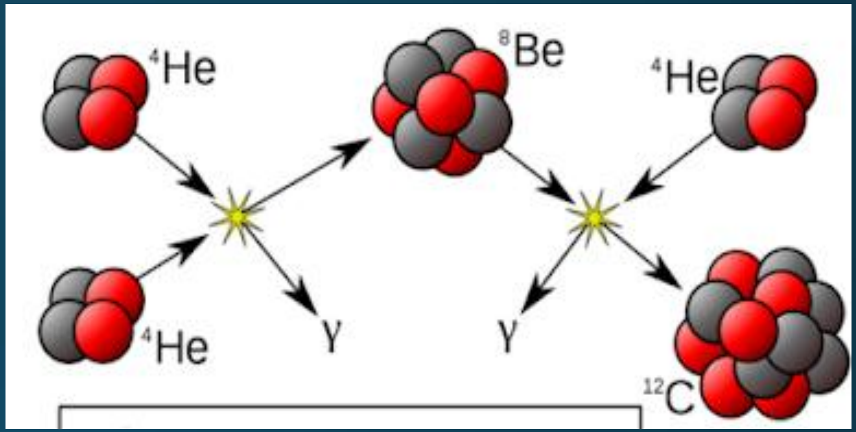


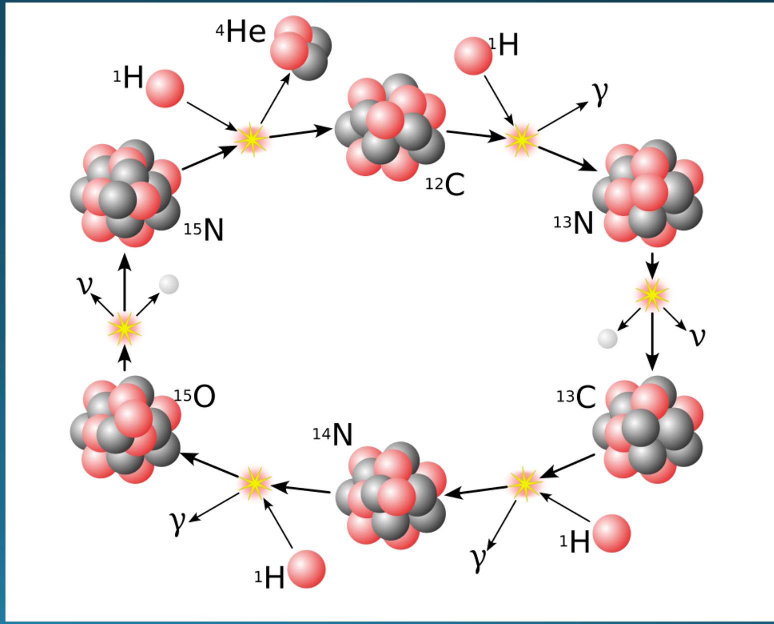


Stellar Nucleosynethesis

- Is cosmic radiation primordial?
  - Meaning from the Big Bang
- Or were heavy cosmic rays made in some other process?
- 1952 – Salpeter & Hoyle
  - Triple-alpha process:
  - Jump the mass gap issue
- CNO cycle in stars
  - Neutrinos detected in 2020 by Borexino

Heavier elements than hydrogen (and helium) are produced in stars





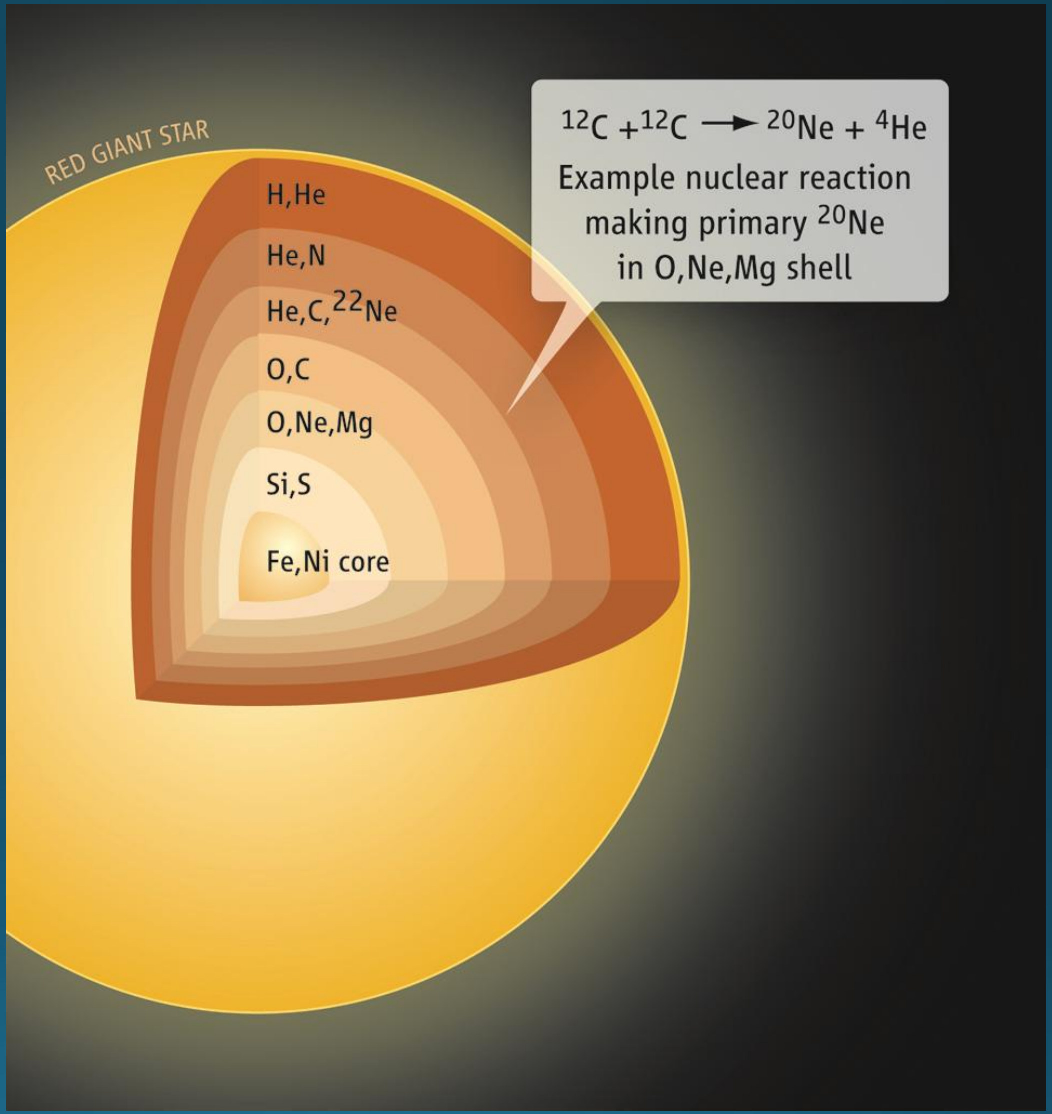
“The Origin of Chemical Elements”

Summary

1. Primordial hydrogen (and some helium)
2. Stellar evolution produces many other elements

*Entire research field

→So heavier elements are not from the Big Bang
Are cosmic rays born in stars?



Abundance comparison

Fig. 4.3: Comparison of cos
composition with the unive
(normalized to carbon)
(From Shapiro. M. M.. R.
Nucl. Sci. 20 (1970) 323)

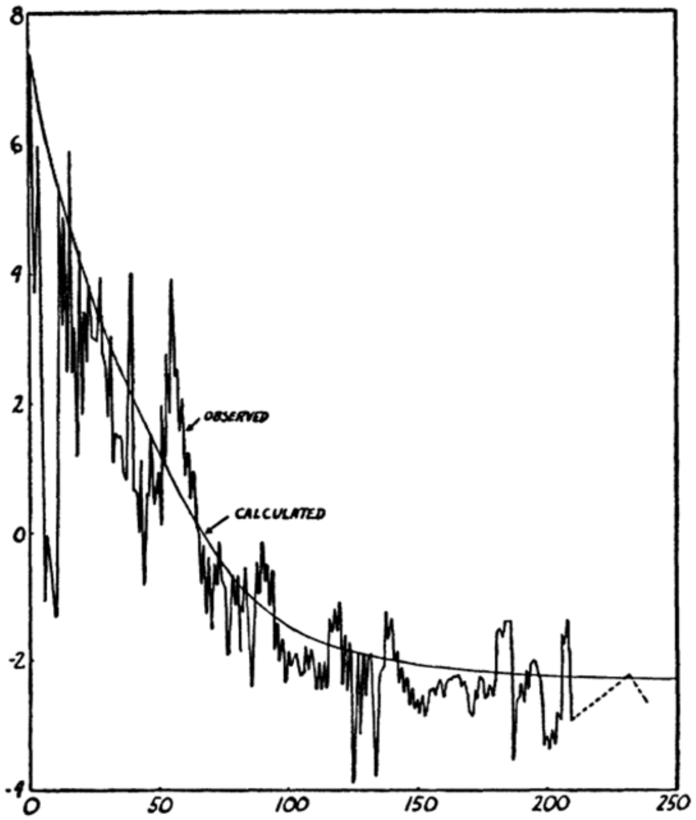
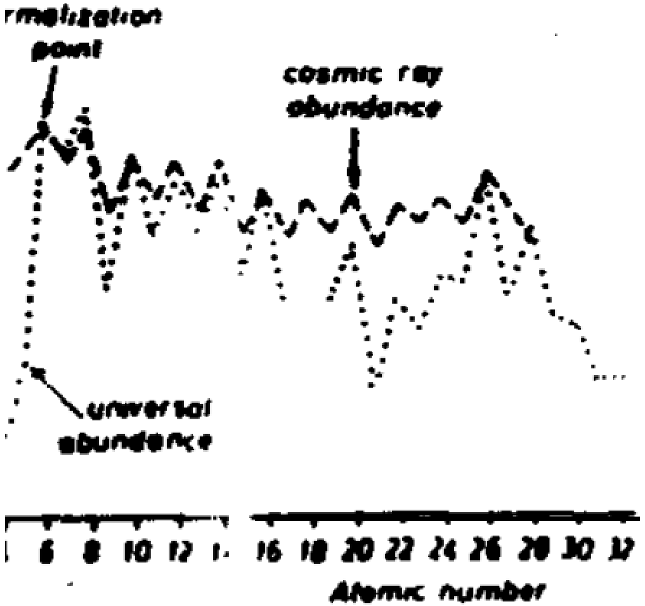


FIG. 1.
Log of relative abundance
Atomic weight



But stars ar ryllium, and
Bo ys

Stellar nucleosynthesis doesn't accelerate cosmic rays

- Although some scientists thought so until about ~1930
- Energy of stellar nuclear fusion is ~MeV
  - Mega electron volt
- But these cosmic ray protons and nuclei are GeV (x1000)
  - Or BeV (billions)
- Star collapse – Baade and Zwicky propose Supernovae in 1934

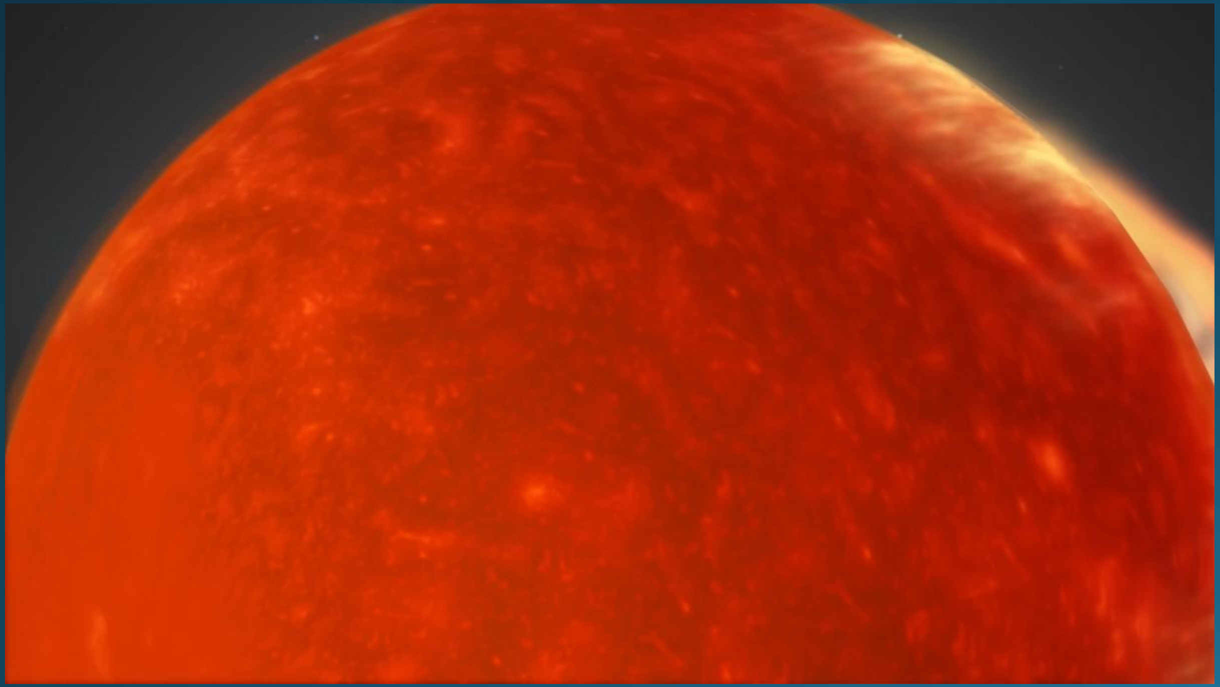
> Data on the energy spectrum of the total primary radiation have been obtained by observing total counting rates at the top of the atmosphere.[5] Since at any given latitude over 80 percent of the primary particles are protons, these investigations yield essentially the energy spectrum of the proton component in the range between 1 and 15 Bev. Some measurements on

What accelerates/produces cosmic rays?

Supernovae Remnants do

- The powerful expansion of material around a star that exploded

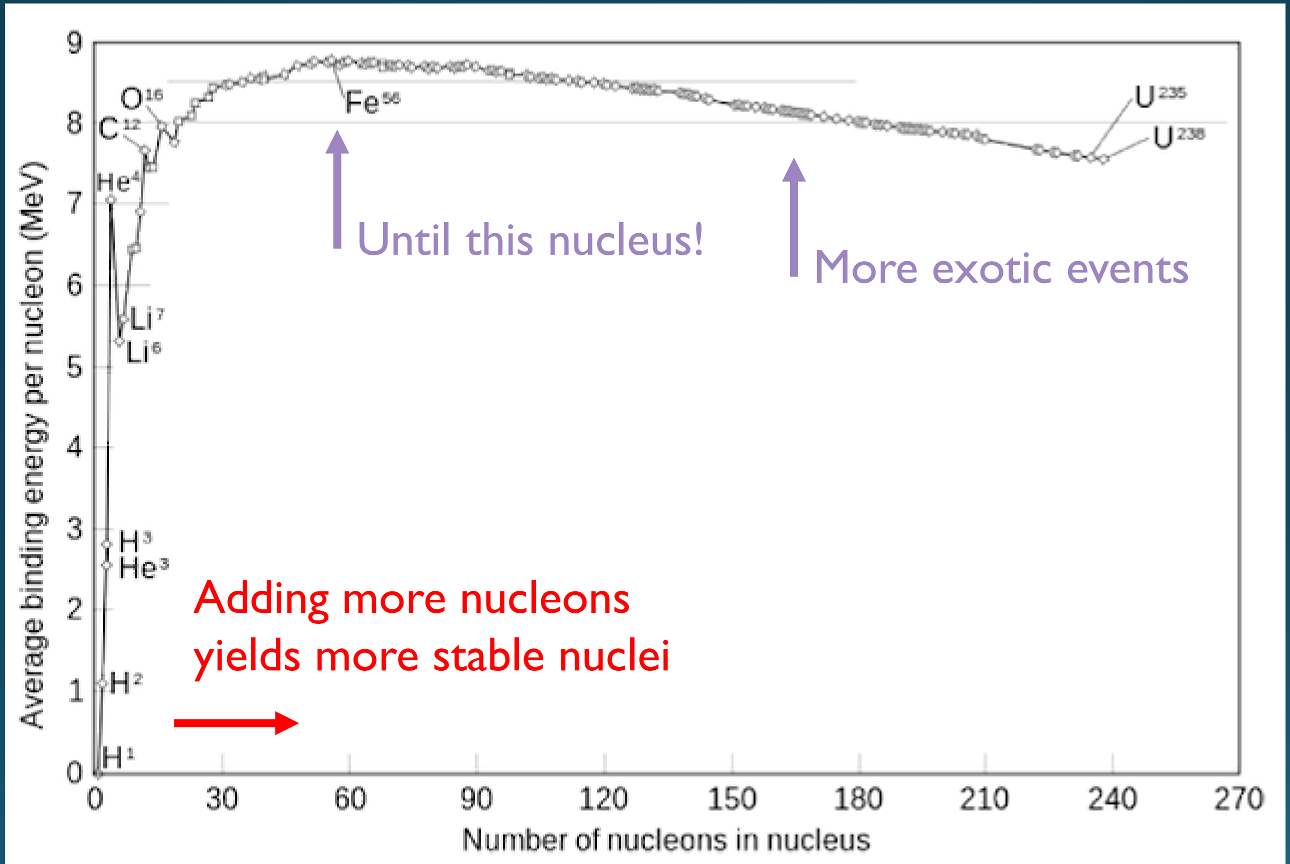
1. Supernova



2. Supernova Remnant

More nucleons isn't the answer

- It's like feeding your kid donuts (protons)
- They want 56 of them
- But then, eventually, they don't want another one



- The accumulation of iron nuclei at the center of the star
- Increased pressure that results in explosion
- Active area of research

Cosmic rays are accelerated in the Milky Way

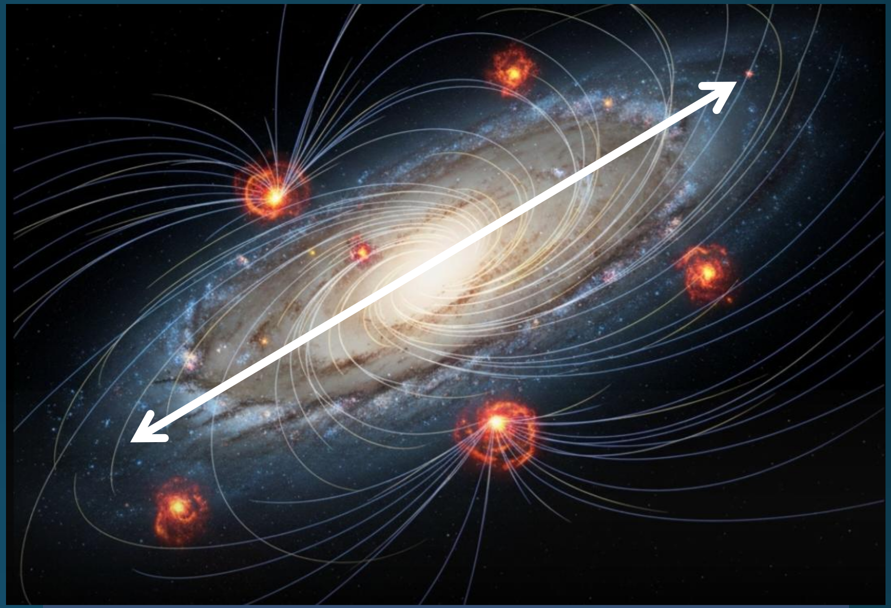
- Accelerate material around the SNR site
- Inject cosmic rays in bursts over the age of the Milky Way

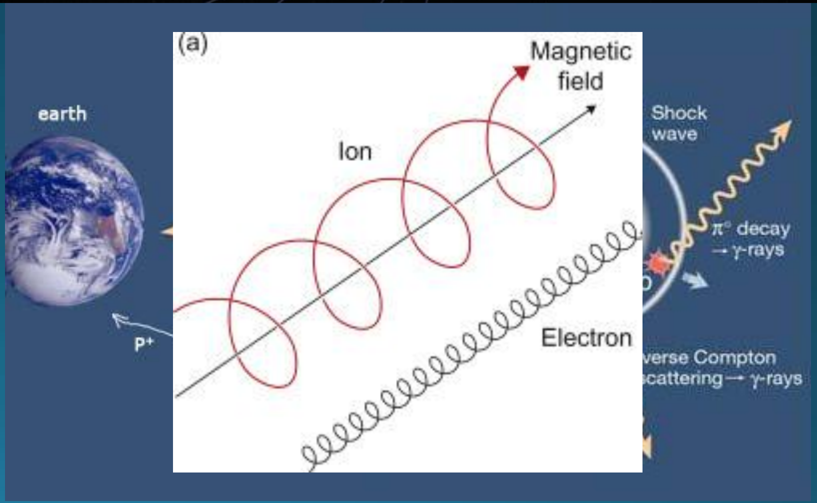
- Cosmic rays fill the Milky Way like a sea
- The Solar System is immersed in a sea of cosmic rays

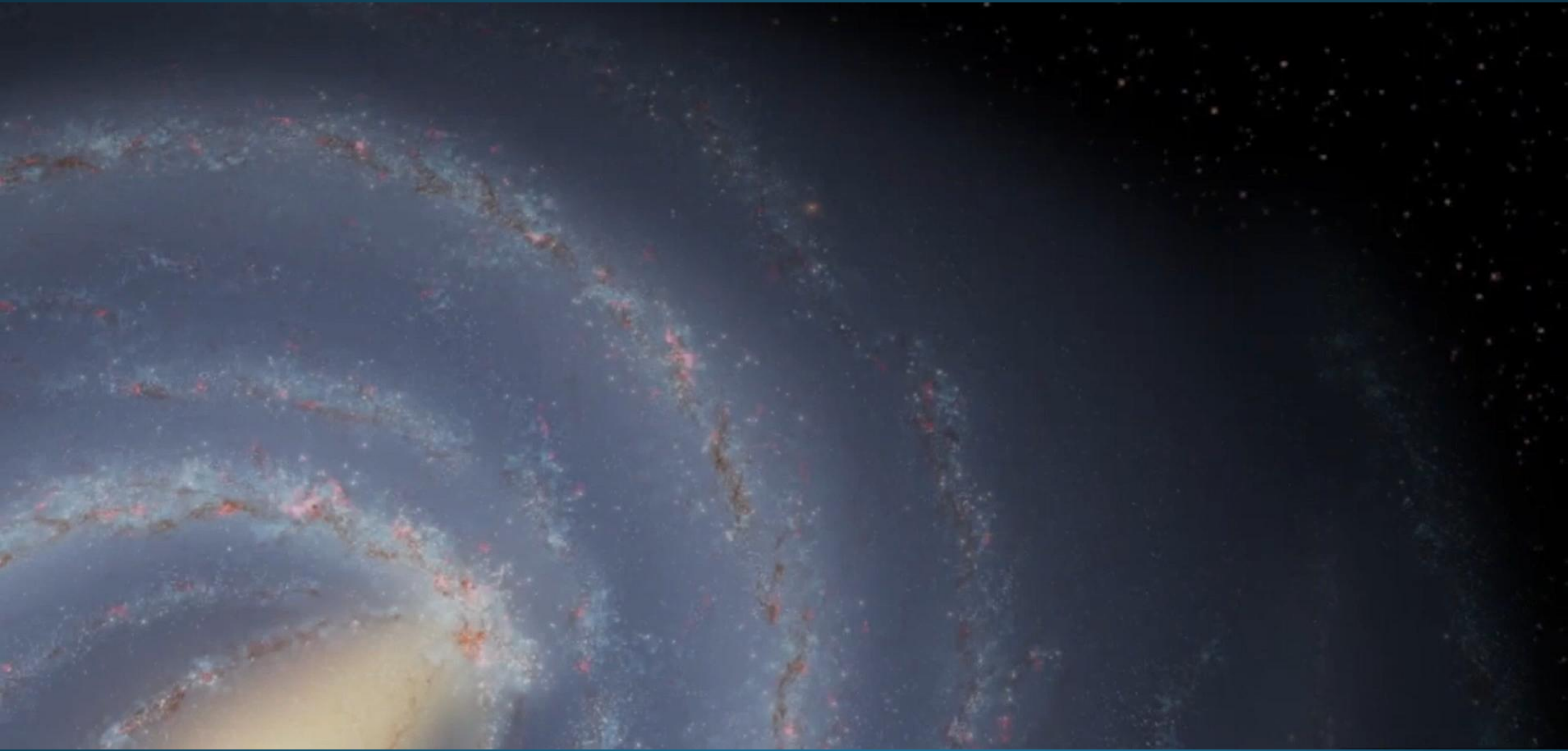
Cosmic rays are isotropic

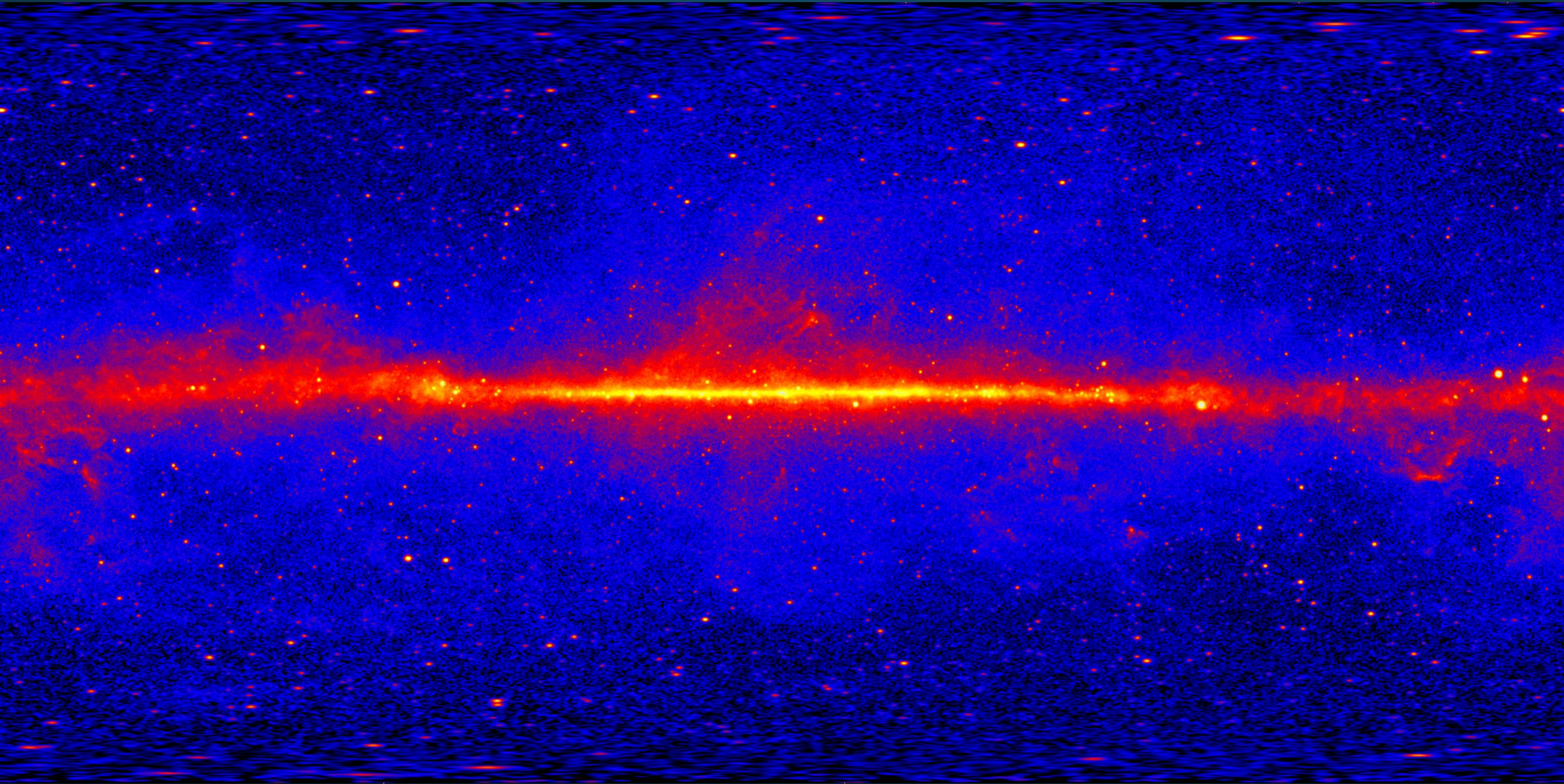
- Primary cosmic rays arrive from all directions about equally
  - Shouldn't they point back to the Supernovae Remnants?
- Fermi had the solution
  - Galactic magnetic fields
  - 1950s and 60's – first measurements (1-3 millionths of a Gauss)
  - 100,000 times weaker than fridge magnet
- Cosmic rays are sort of confined within the Milky Way
  - Unless they have enough energy
  - At 1 PeV, gyroradius is a light year

20,000 light years

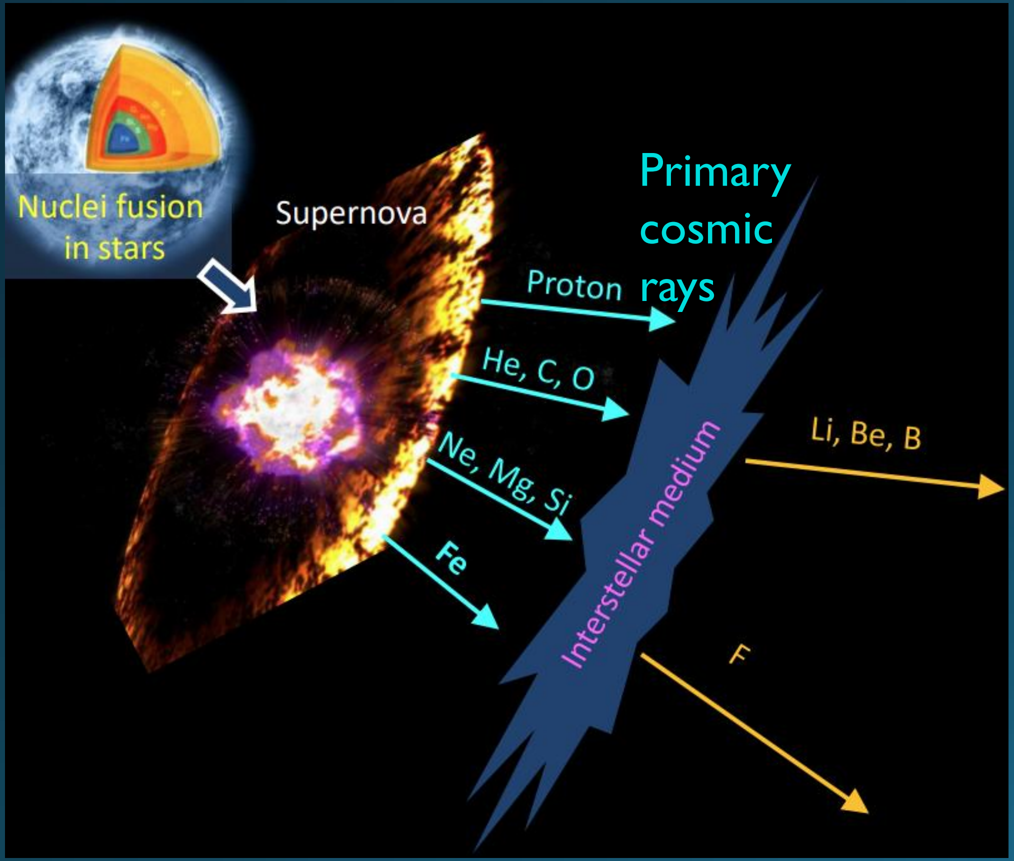


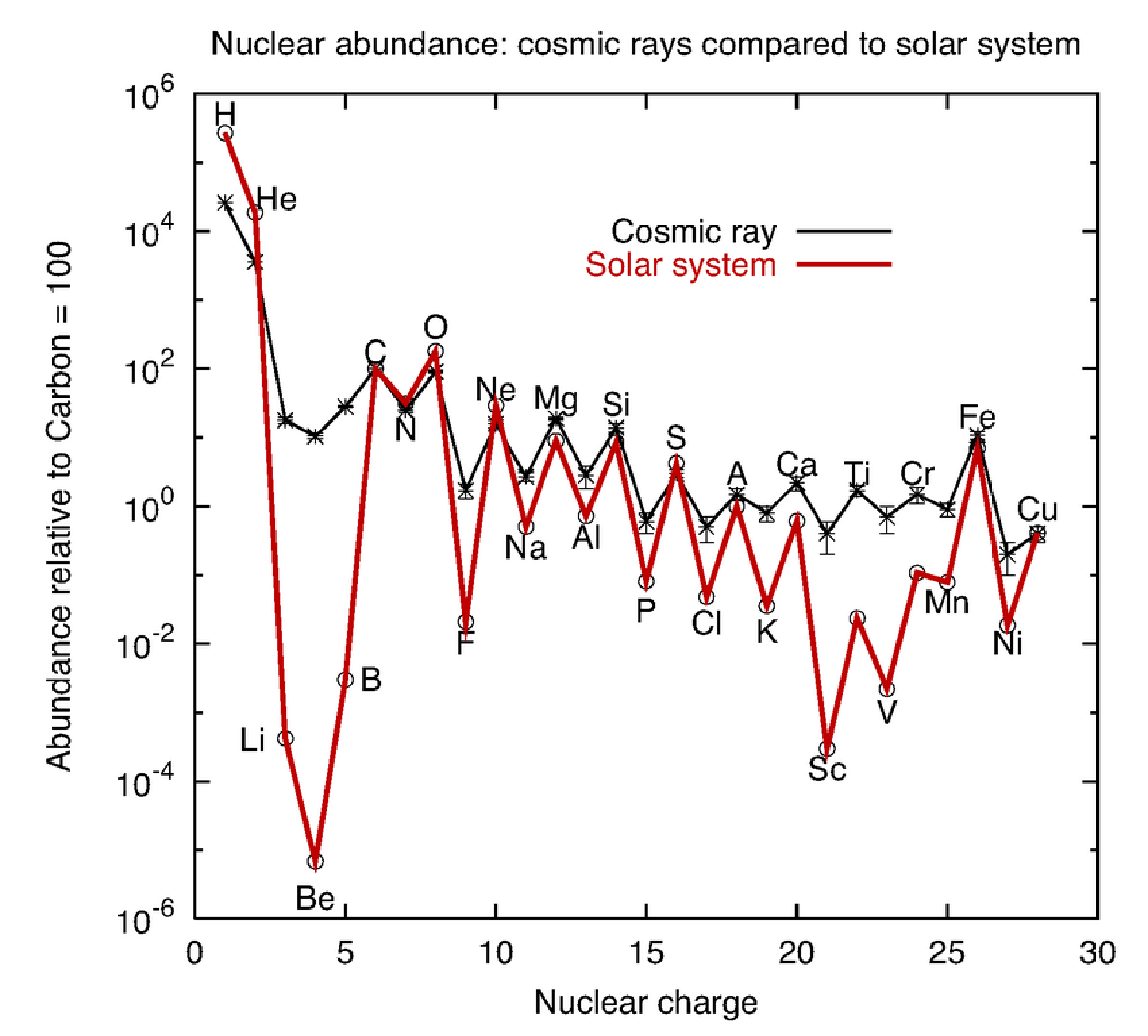






Overabundance of light elements



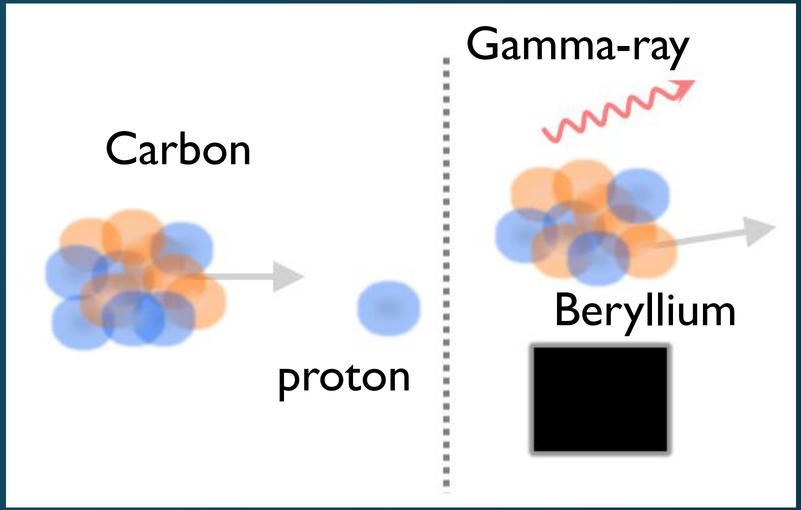


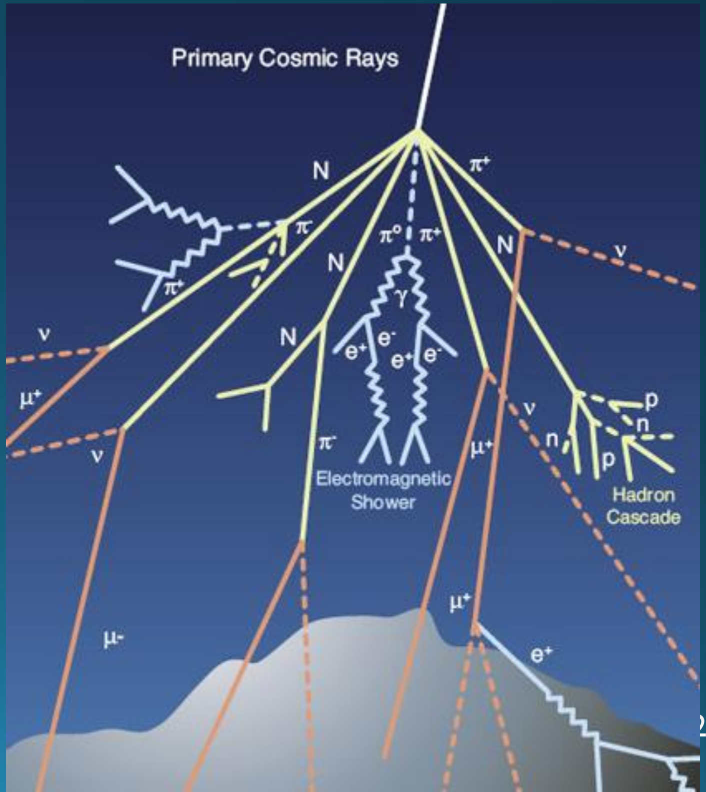
ary
rays

The A

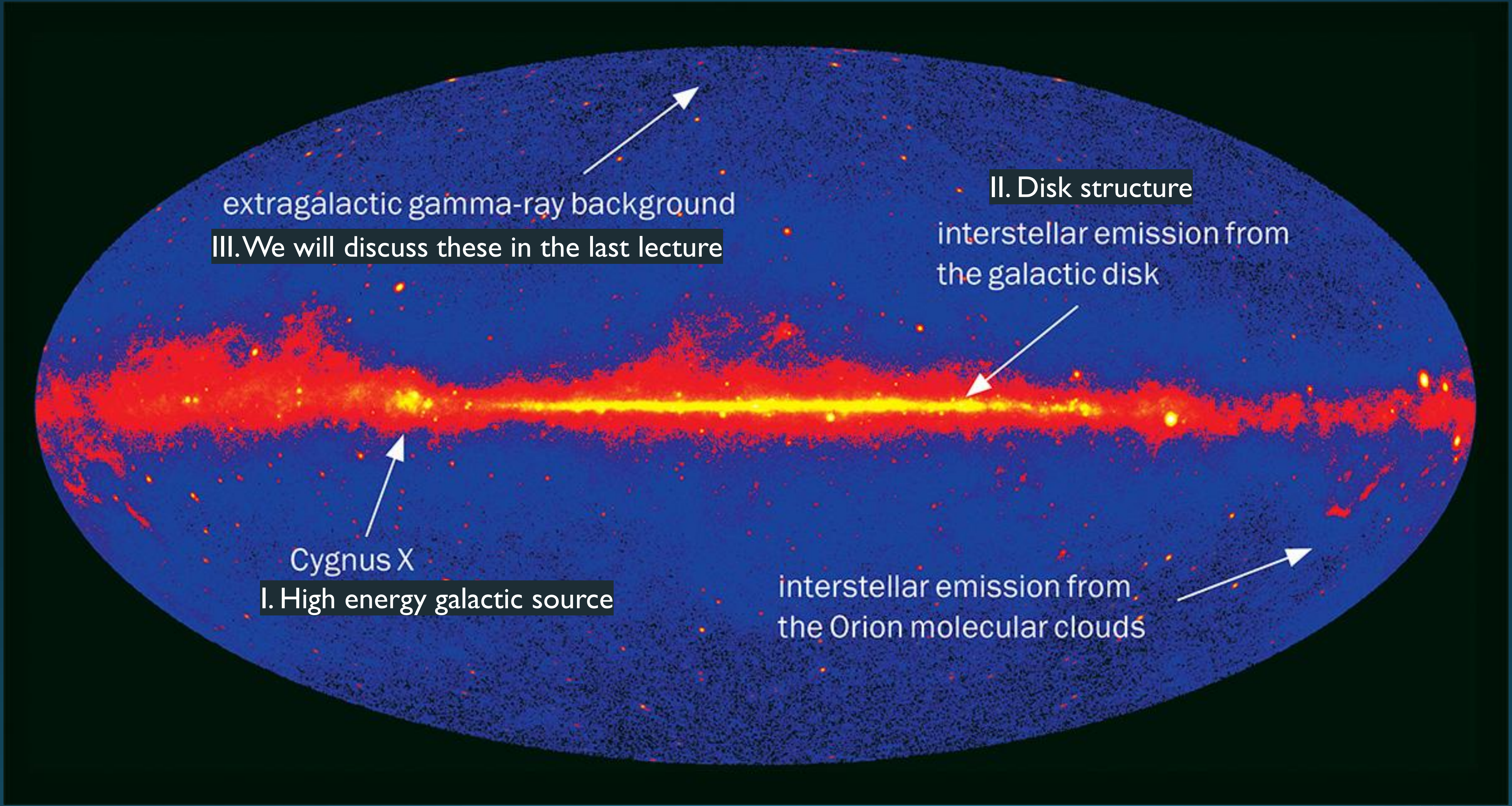
Cosmic ray spallation

- Primary cosmic rays are accelerated as a sample of stellar material
  - Example, Carbon-12
    - 6 protons and 6 neutrons
- Interstellar medium
  - Hydrogen/proton
  - Also molecular clouds
- Interaction produces secondary cosmic rays
  - Example, Beryllium-10
  - 4 protons, 6 neutrons
- Also, extra stuff (black box)
  - Gamma rays



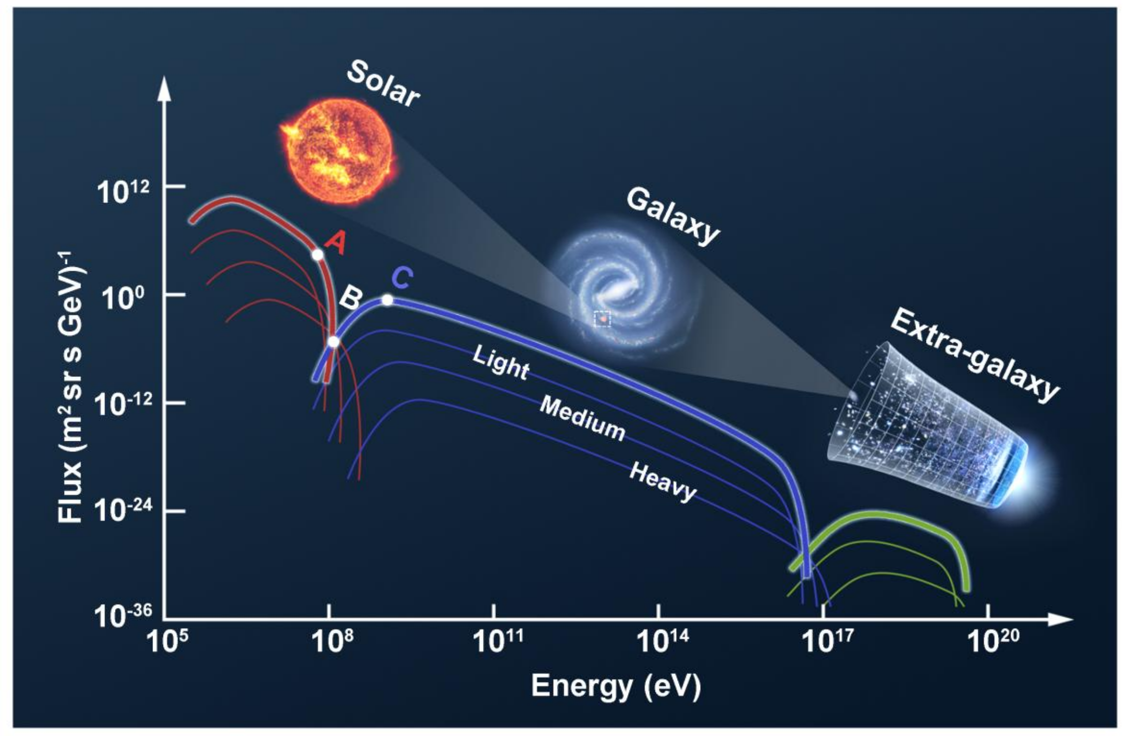


Similar to collisions of cosmic rays with atmosphere

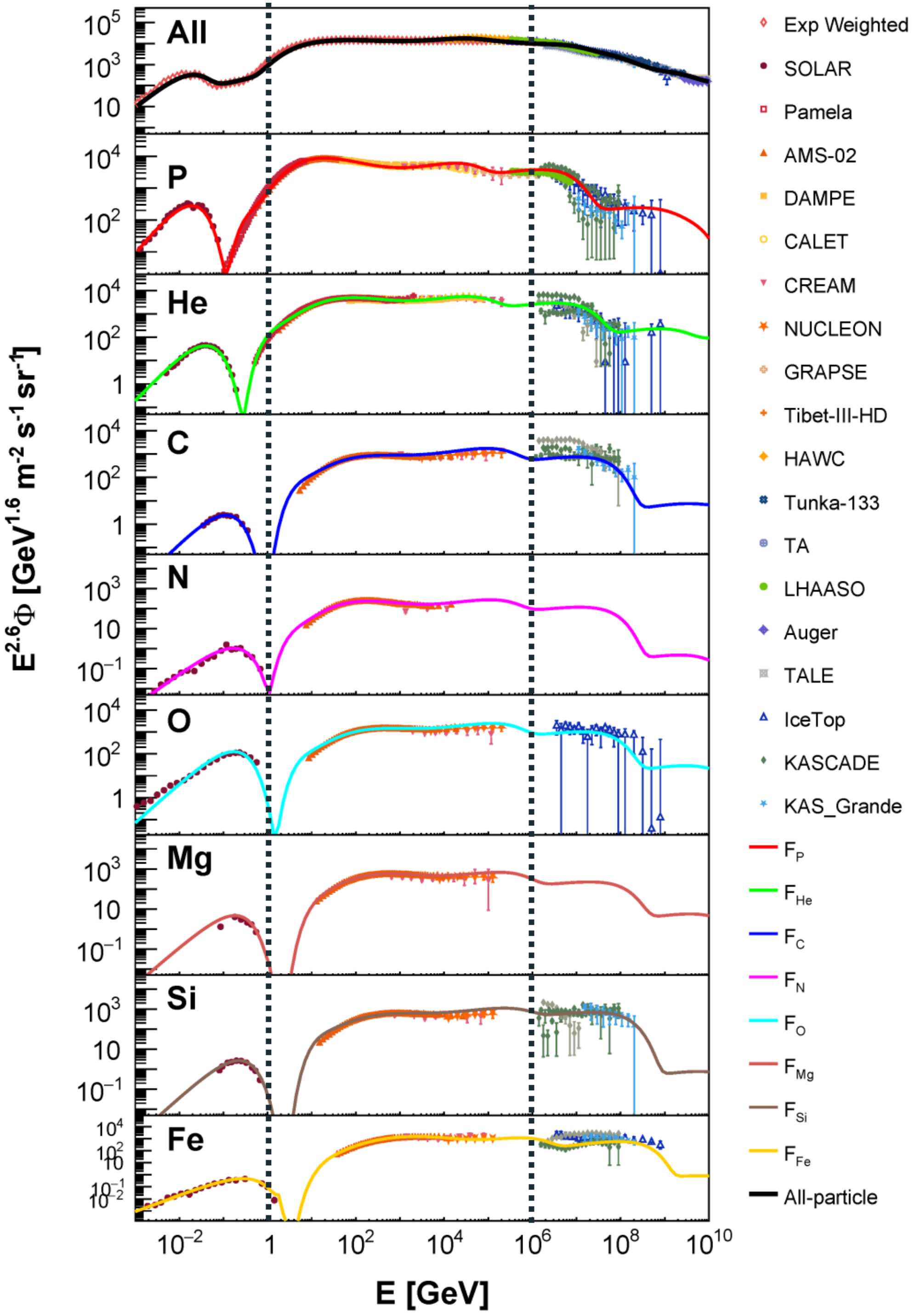

extragalactic gamma-ray background
III. We will discuss these in the last lecture
II. Disk structure
interstellar emission from the galactic disk
Cygnus X
I. High energy galactic source
interstellar emission from the Orion molecular clouds

Not just Supernovae Remnants (SNR)

- SNRs can't seem to accelerate cosmic rays to PeV energies
  - 1,000,000 GeV
- There might be other sources in the Milky Way

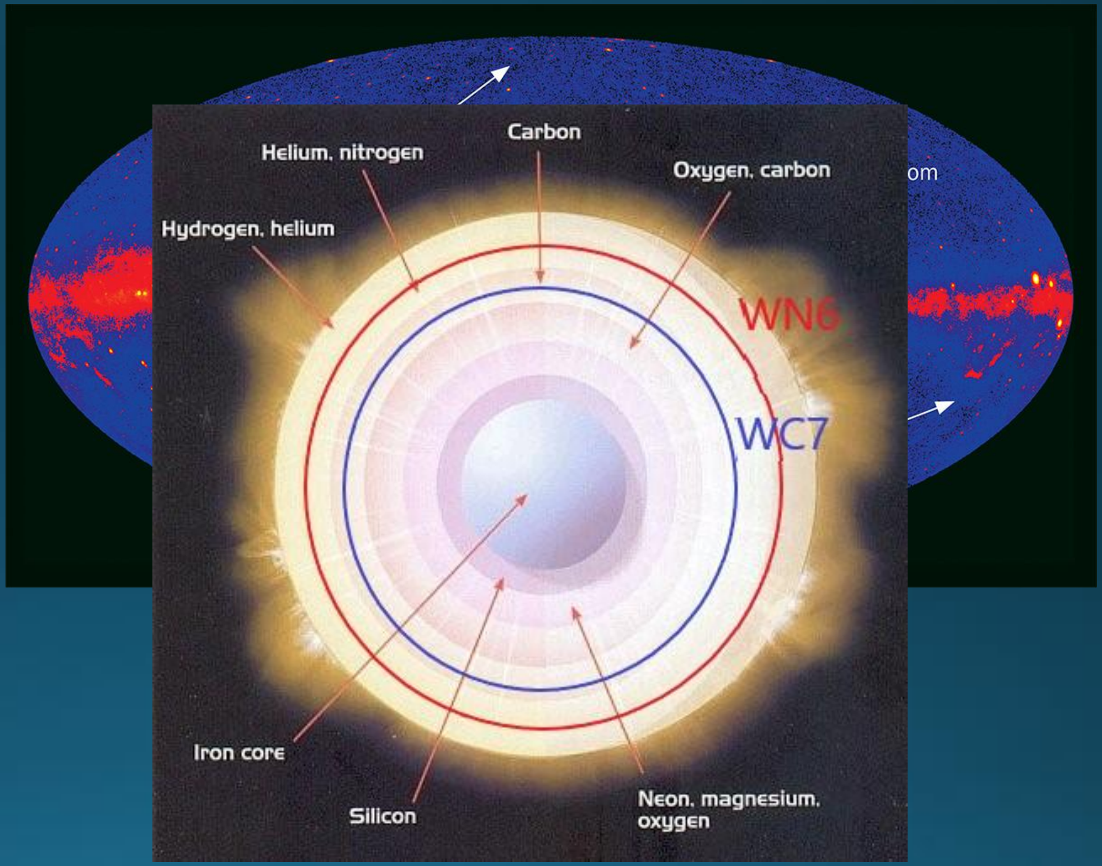


- Flux of different cosmic ray nuclei
- Change in behavior depends on the composition
- Low energies, solar modulation
- High energy limit of galactic accelerators



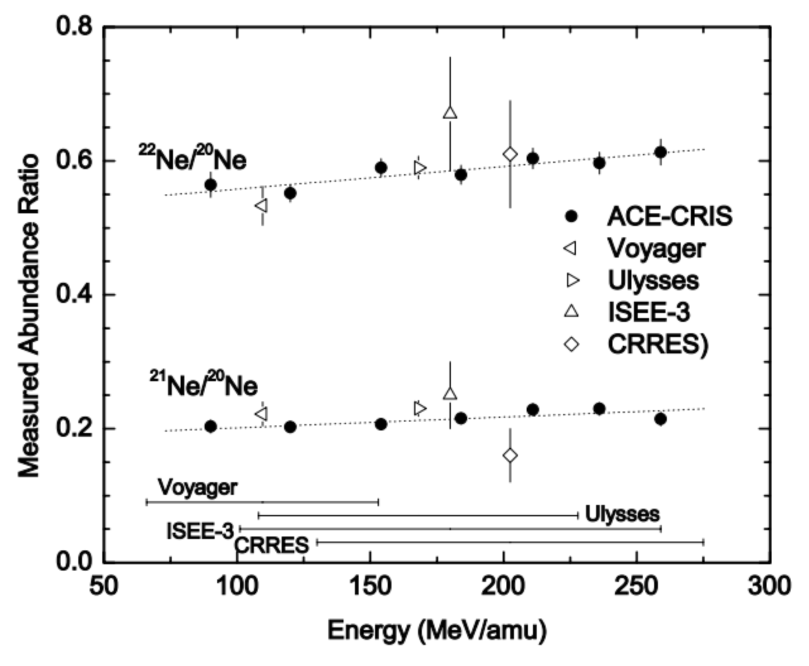
Other Galactic accelerators

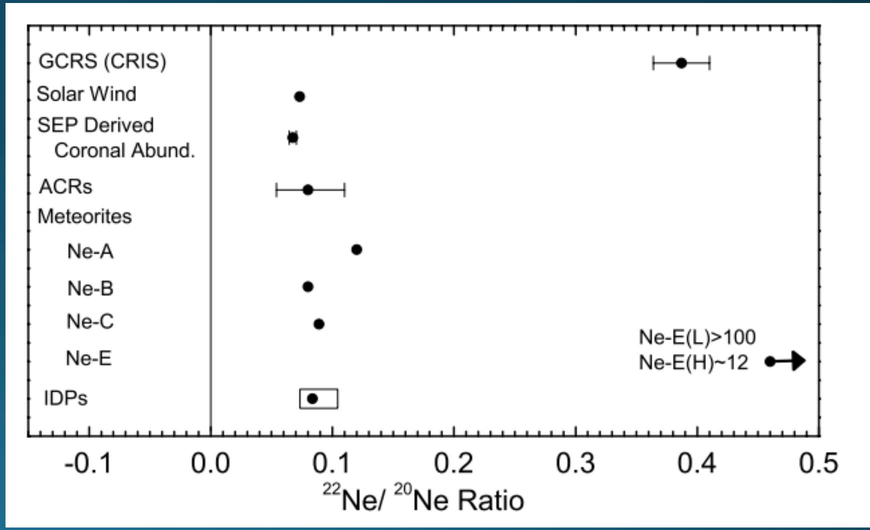
- Center of the Milky Way
  - Supermassive black hole (4 million suns)
- Star clusters
- Wolf-Rayet stars
  - Stellar winds have gamma ray emission
  - Inside of Cygnus X
  - Mass loss of hot outer shells



WR stars & Neon-22

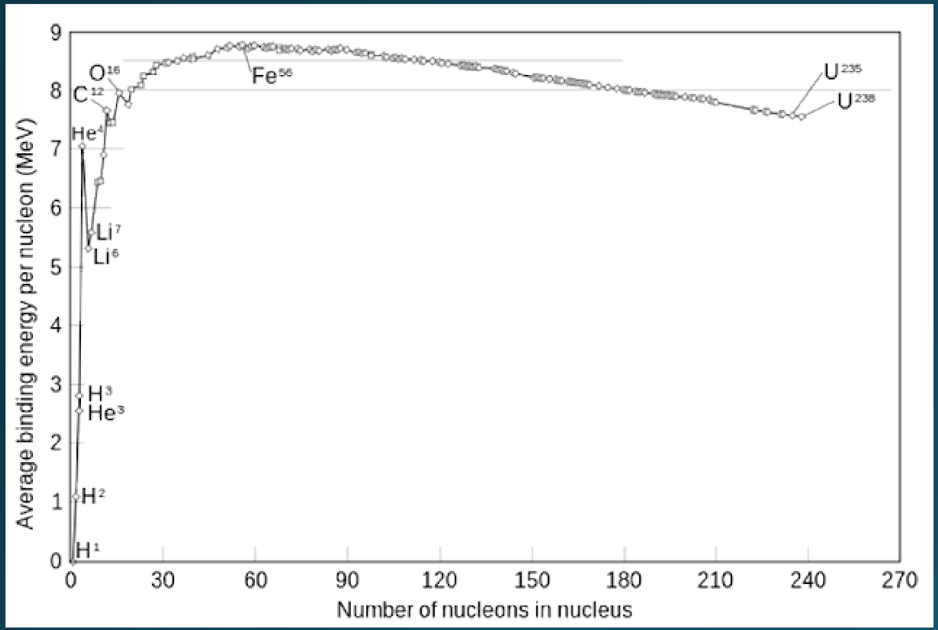
- Mass loss - enriched material in Neon
- Measured excess in Galactic cosmic rays (GCRs)

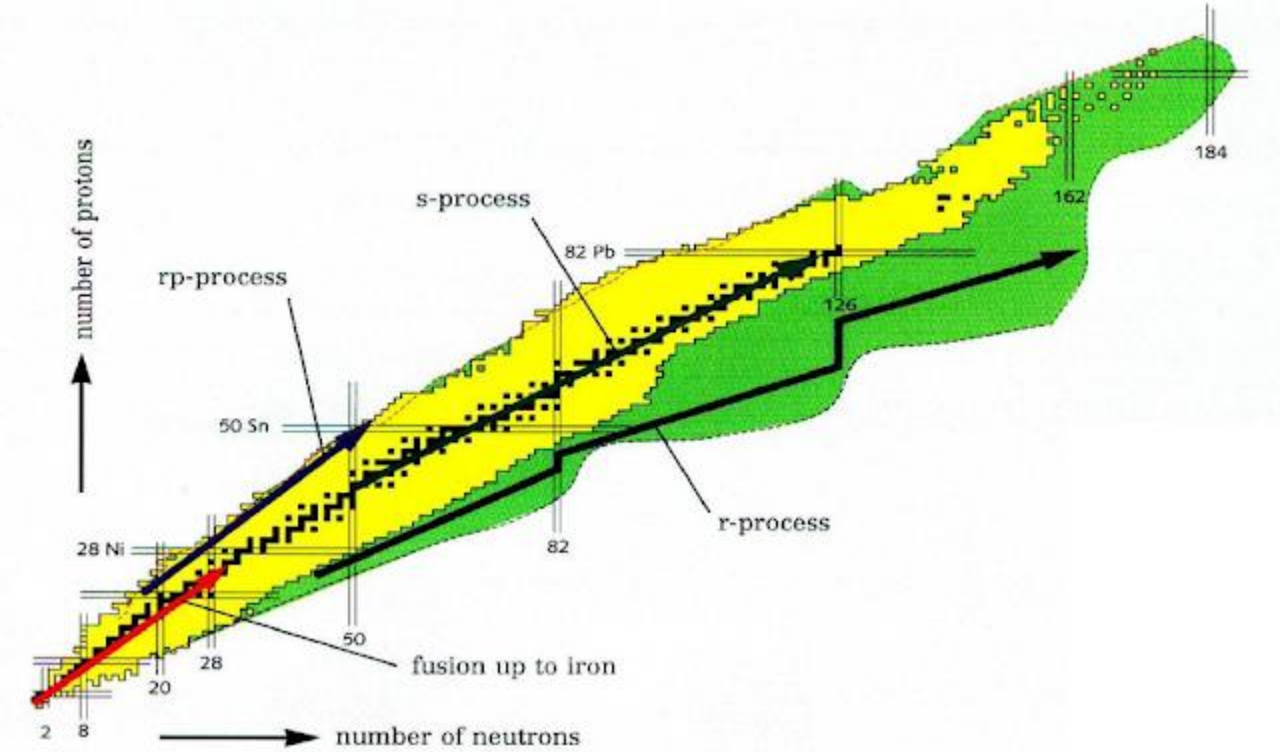




*Active area of research

Heavier elements than Iron

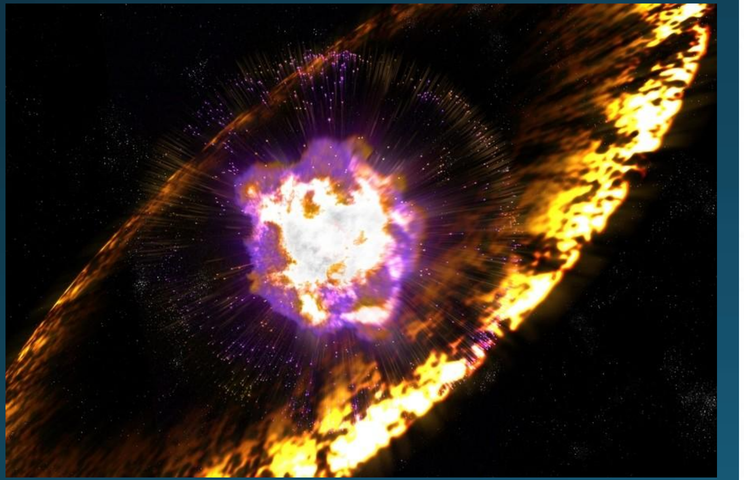




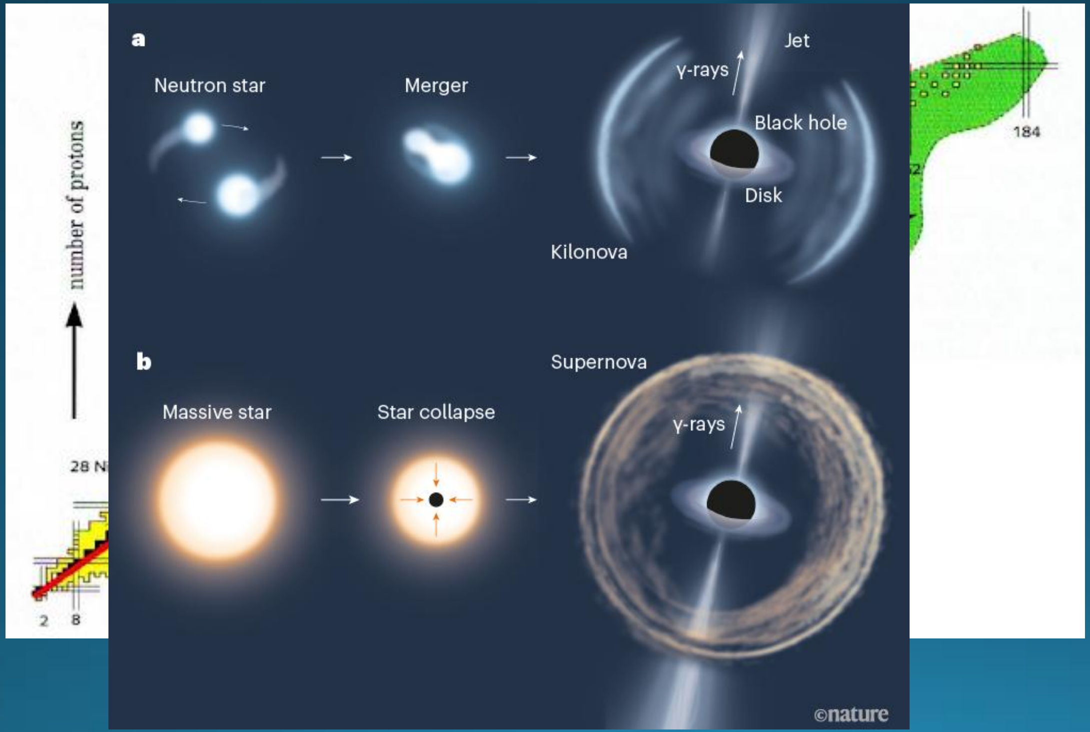
1. Z~ 34 - supernovae seem capable of producing them
2. Z~50 - some supernovae can produce them
3. Z~78-82 (gold, platinum, lead) - supernovae cannot make these

SNe vs NSM

- Do Supernovae (SNe) make all the elements heavier than Iron?
- Neutron-star mergers (NSM) also make heavy elements
  - And are enriched in neutrons…
  - Gravitational wave measurements in 2017 (Kilonova)



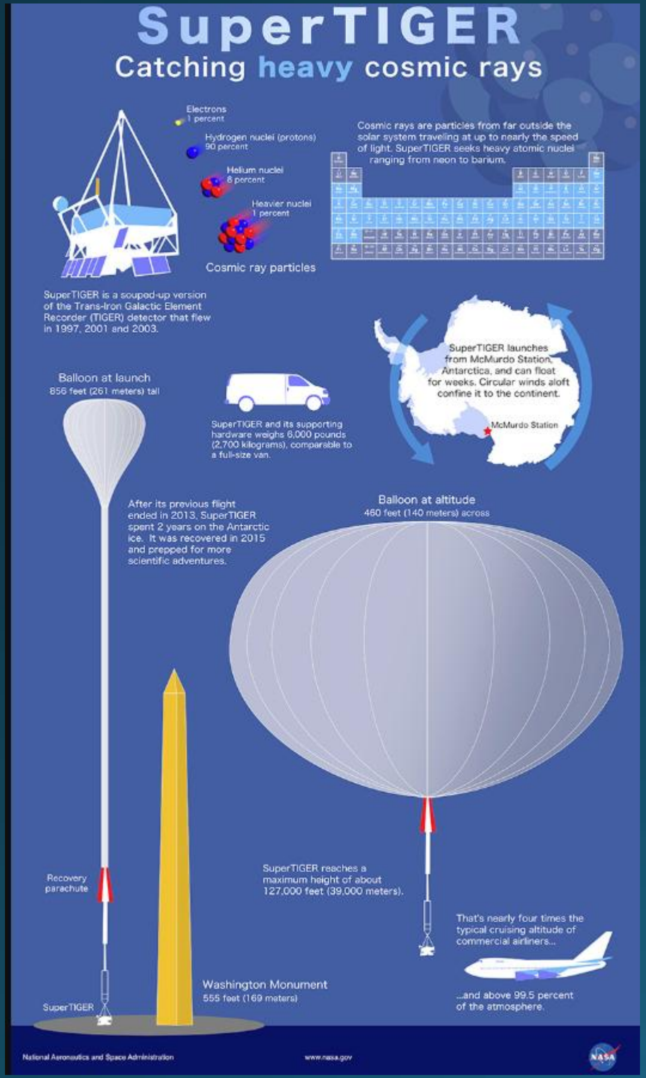
SNe



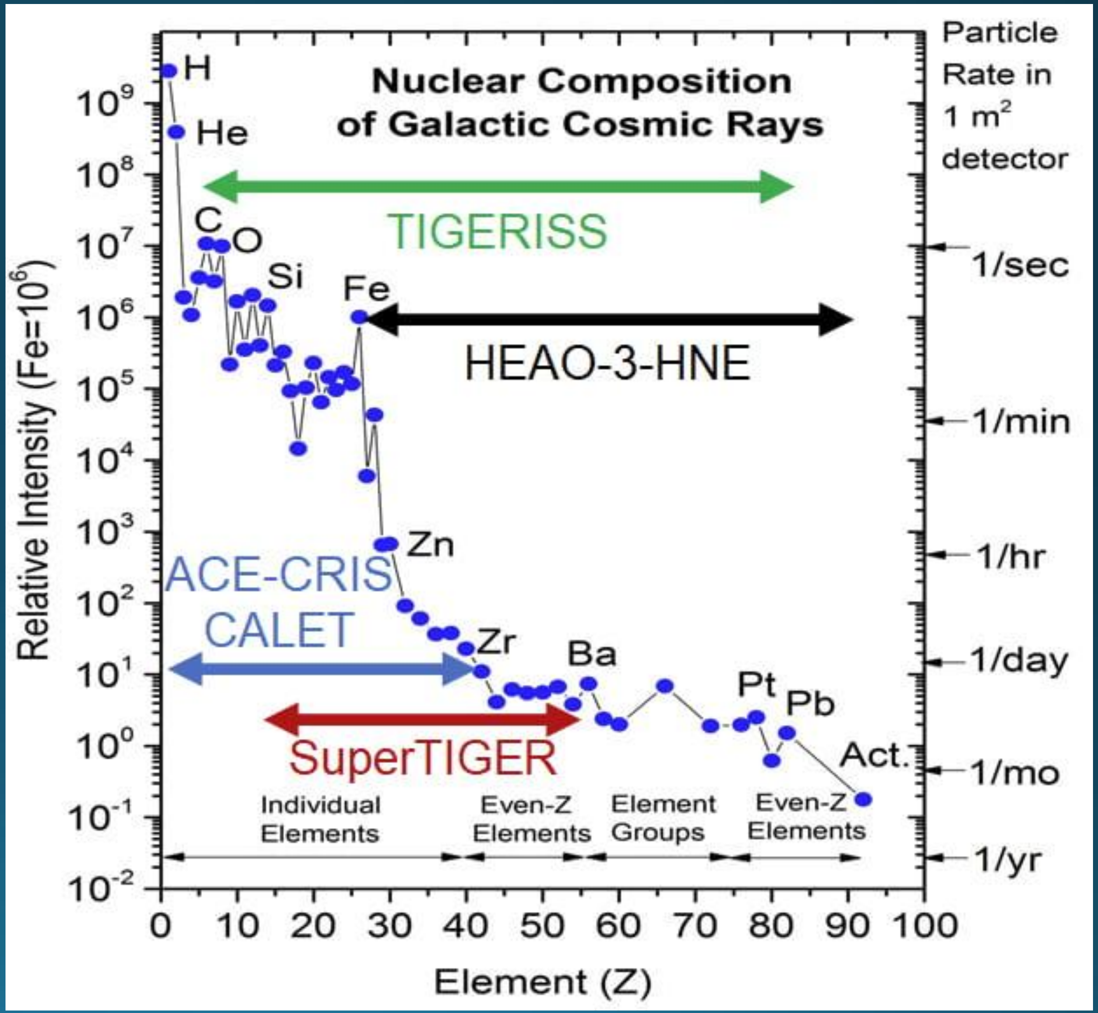
NSM

Ultra heavies (Z~78) in cosmic rays

(TIGER) Trans-Iron Galactic Element Recorder



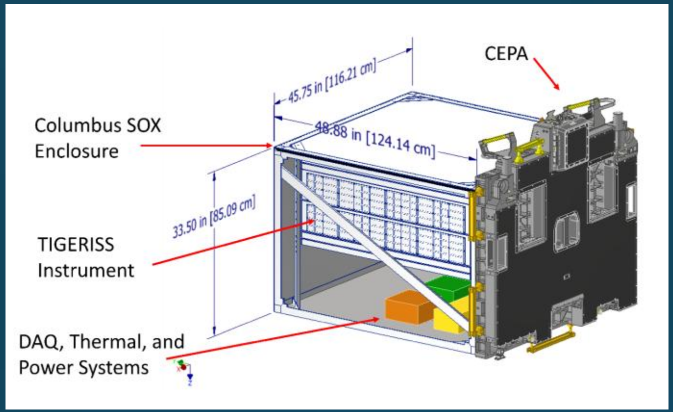
- 3 TIGER flights 1997-2003
- 2 Super TIGER flights
  - 2012 & 19



TIGERISS

Trans-Iron Galactic Element Recorder for the International Space Station

- Improvements on detectors from Super TIGER flights
- In space is better
  - Residual atmosphere leads to larger uncertainties for heavy elements than at ISS



SuperTIGER-2 instrument

*Stay tuned for installation in ~2027

Cosmic ray detectors in space

- ACE/CRIS
  - Launched in 1997
- Measured Iron-60 isotope in cosmic rays
  - Unstable – half-life of 2.6 million years
- Voyager also has cosmic ray detectors
  - Interstellar medium measurements of excess Iron

→Recent (2-3 Million years ago) supernova activity nearby?

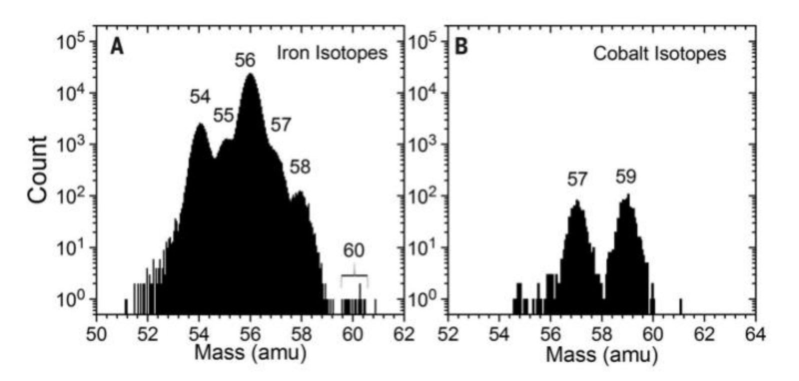
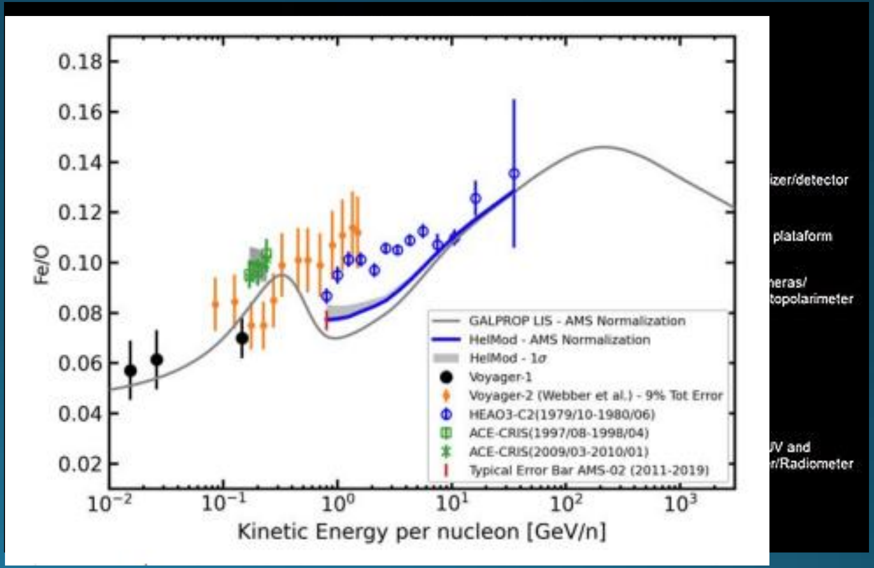
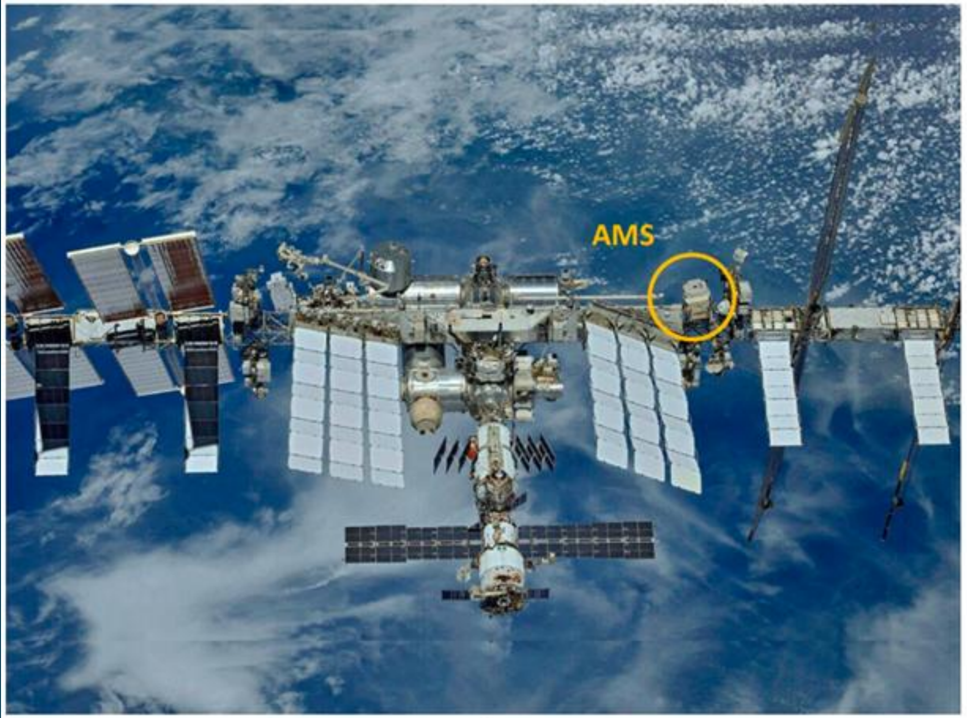


Fig. 2. Mass histograms of the observed iron and cobalt nuclei. (**A**) The mass histogram of iron



Cosmic ray detectors in space – AMS



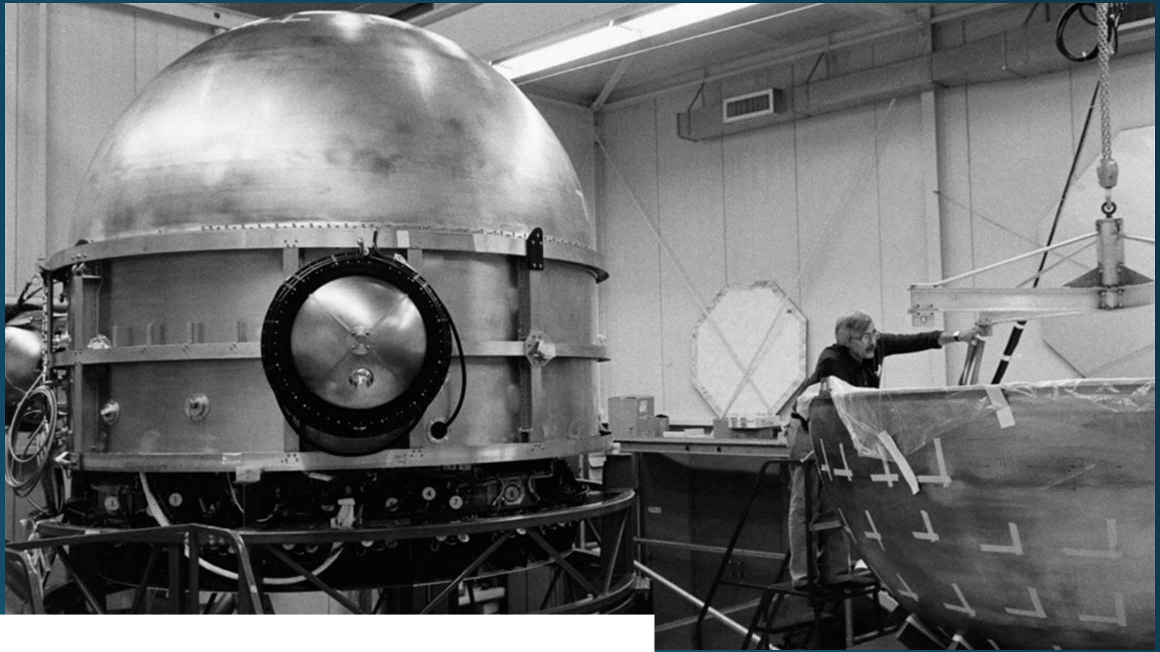
Alpha Magnetic Spectrometer (AMS) on the International Space Station.

Cosmic ray detectors in space

"Chicago Egg"

Flew on Mission: STS-51-F on Challenger

- launched July 29, 1985



ENERGY SPECTRA AND COMPOSITION OF PRIMARY COSMIC RAYS

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Received 1990 August 16; accepted 1990 December 3

ABSTRACT

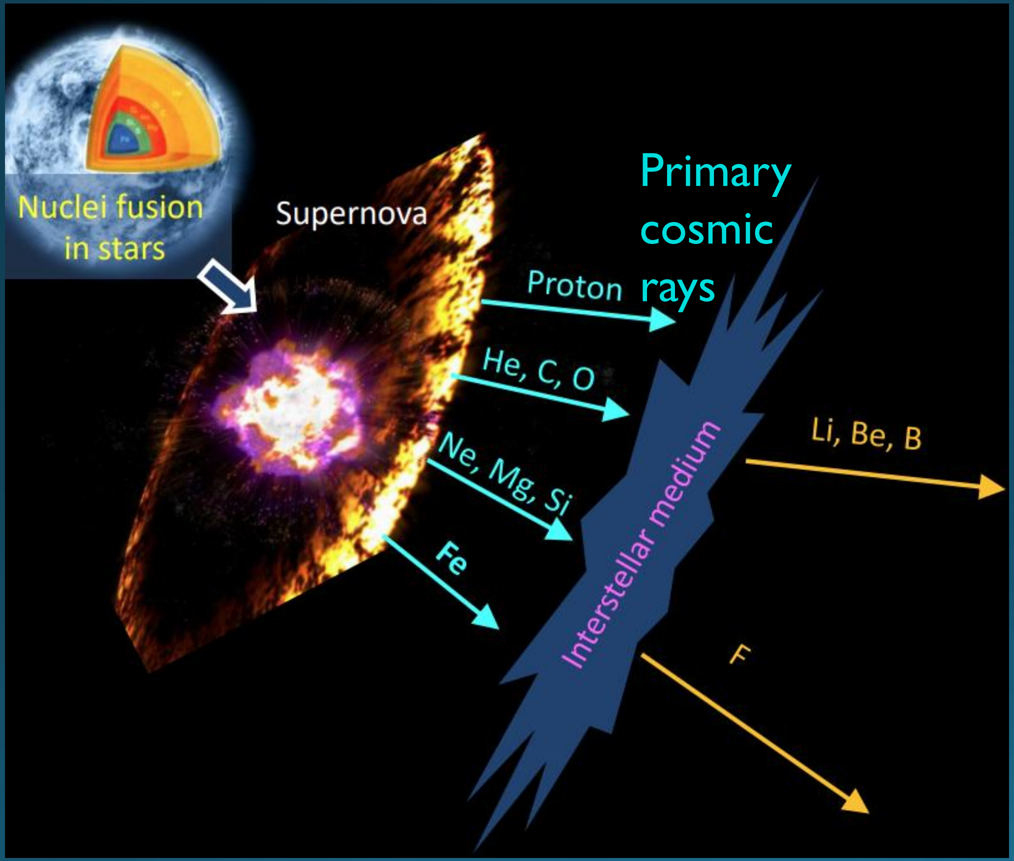
We describe new results on the energy spectra and relative abundances of primary cosmic ray nuclei from carbon to iron. The measurement was performed on the Spacelab-2 mission of the Space Shuttle *Challenger* in 1985, and extends to energies beyond 1 TeV per amu. The data indicate that the cosmic ray flux arriving near Earth becomes enriched with heavier nuclei, most notably iron, as energy increases. Extrapolating to the source, with a simple leaky box model of galactic propagation with rigidity-dependent containment time, we obtain relative abundances of the elements that are quite similar to those reported at lower energy. In particu-

Chicago Egg results - ratios

Secondary to primary ratios

1. **Carbon** is a primary
2. **Boron is a secondary**

→The more Boron measured, the more interactions occurred



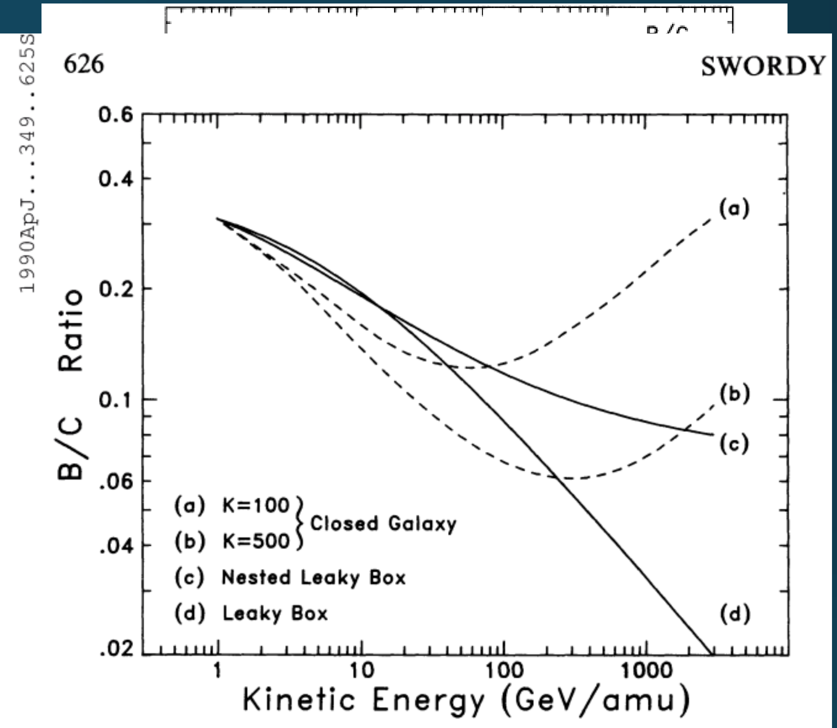
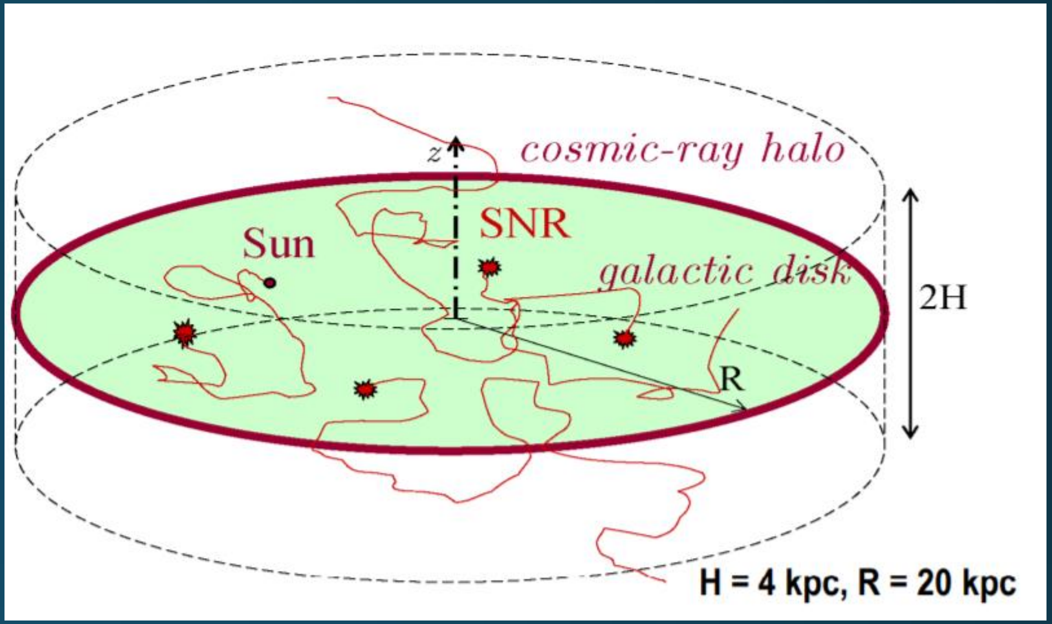
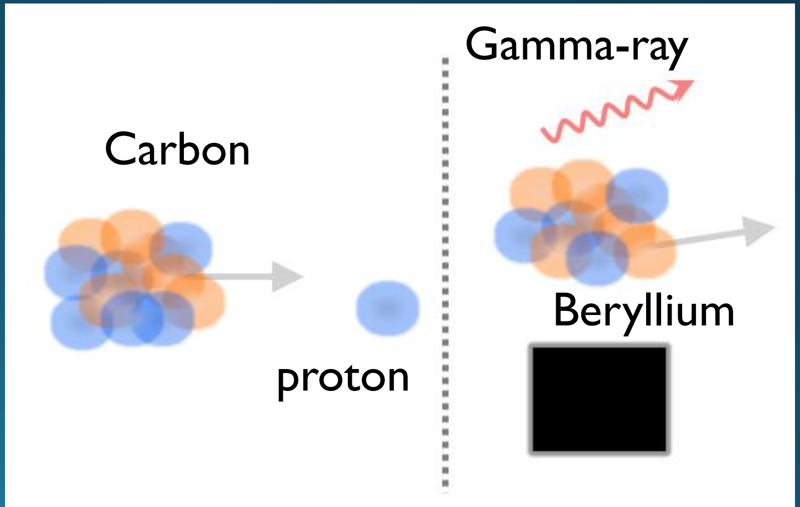


FIG. 1.—The energy dependence of the B/C ratio as predicted by different propagation models: (*a*) The "closed galaxy" model with *K*, the ratio of the mass in the galaxy to the mass in the spiral arms, as $K = 100$, (*b*) "closed galaxy" model with $K = 500$. (*c*) The "nested leaky box model" with a rigidity-dependent escape $\propto R^{-0.5}$ and residual path length of 1 gm cm^{-2}. (*d*) The homogeneous "leaky box" model with a rigidity-dependent escape

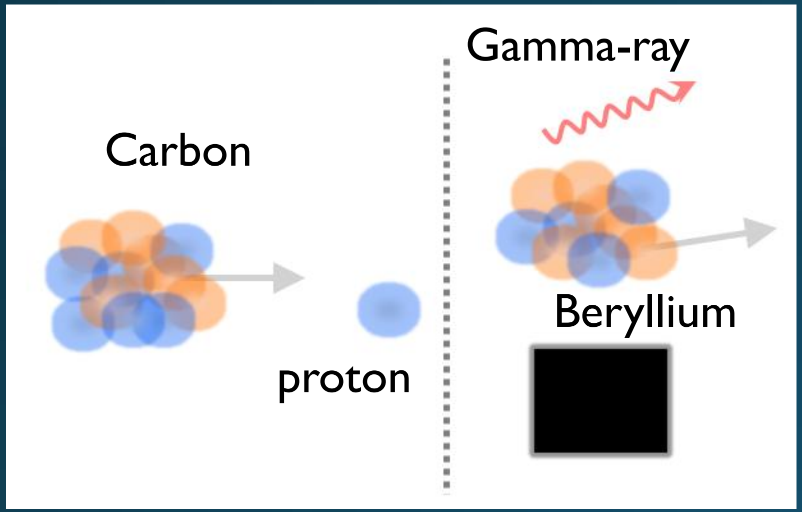
Summary – 1990s

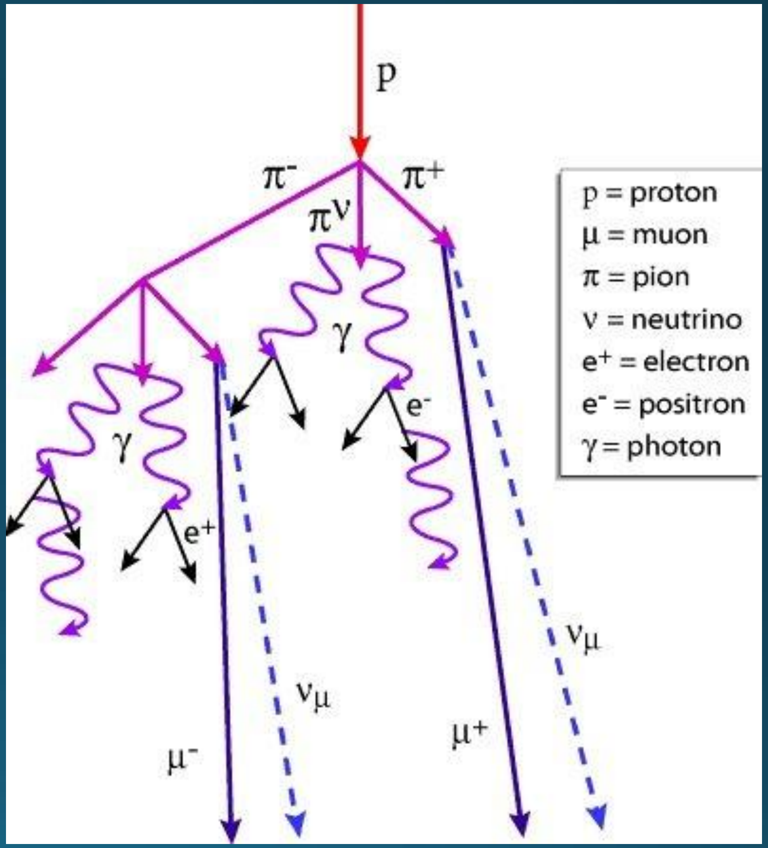
- Cosmic rays in the Milky Way are probably produced by SNR
  - But (nowadays) maybe also WR stars, NSM, clusters of stars, etc
- *Primary* cosmic rays are accelerated at those sites and deflect via magnetic fields
  - Composition reflects the sites:
    - Protons, Helium, Carbon, Nitrogen
- Propagation/spallation of primaries into secondaries
  - Lithium, Beryllium, Boron





Cosmic ray spallation revisited





What about the electrons, positrons, and ~~muons~~?
~~And the neutrinos?~~

→Muons decay

The High-Energy Antimatter Telescope (HEAT): An instrument for the study of cosmic-ray positrons

S.W. Barwick[a,*], J.J. Beatty[b], C.R. Bower[c], C. Chaput[d], S. Coutu[d], G. de Nolfo[e], D. Ellithorpe[f], D. Ficenec[e], J. Knapp[g], D.M. Lowder[h], S. McKee[d], D. Müller[f], J.A. Musser[c], S.L. Nutter[i], E. Schneider[a], S.P. Swordy[f], K.K. Tang[f], G. Tarlé[d], A.D. Tomasch[d], E. Torbet[f]

- Balloon-borne cosmic ray detector
  - positron and antiproton detector, 1994 flight
- Superconducting magnet
  - Separate negative and positive charges
- Found hints of excess in positrons
  - Maybe its effects of atmosphere

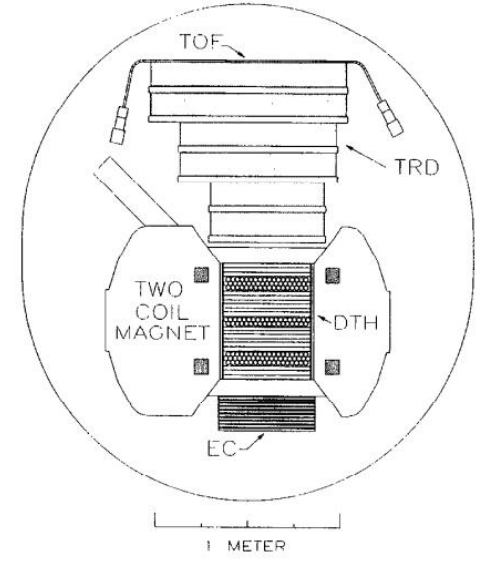


Fig. 1. Cross section drawing of the HEAT instrument.

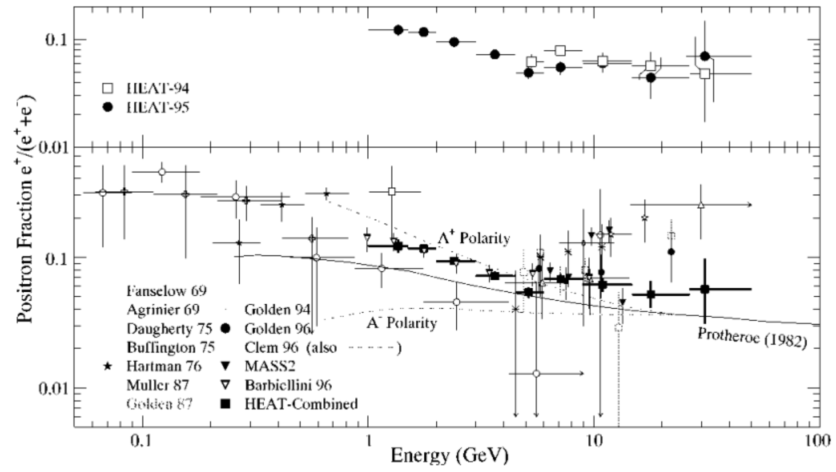
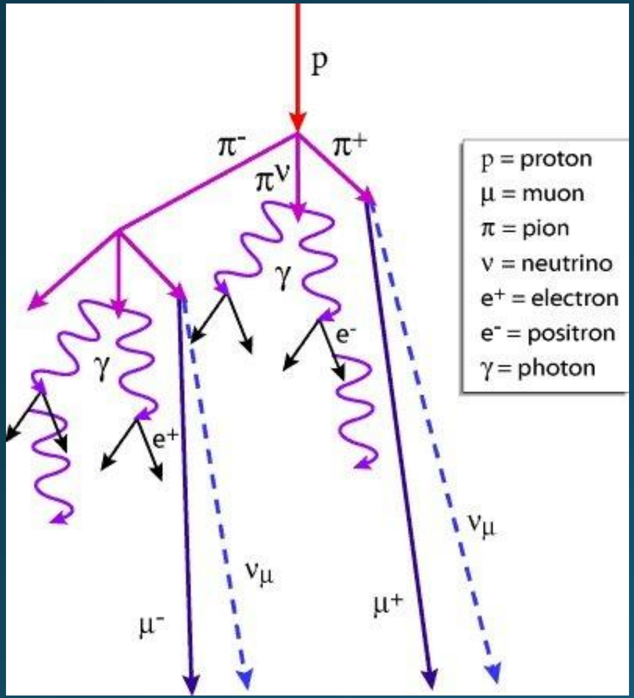


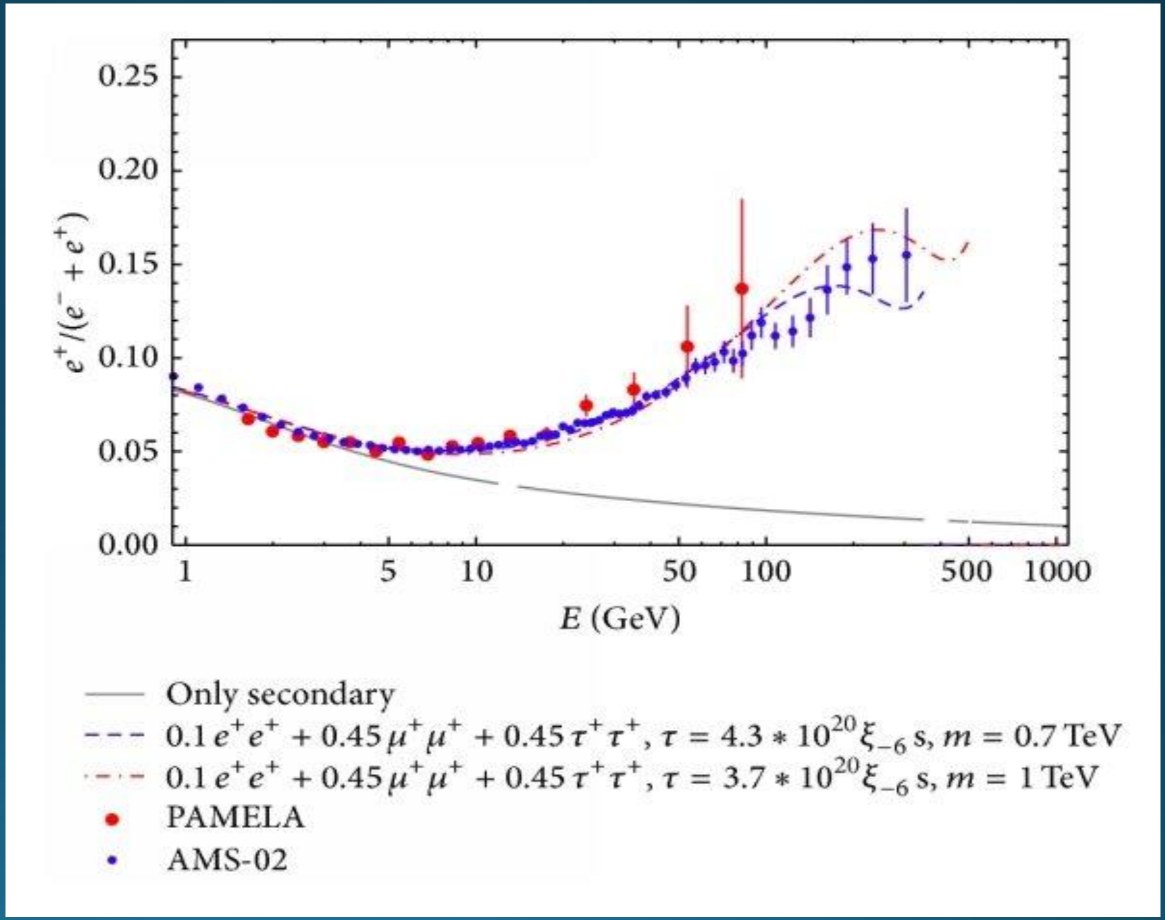
FIG. 2.—Positron fraction as a function of energy obtained from the two data sets. The error bars applied to the HEAT data points represent statistical errors only. The curve labeled "Protheroe (1982)" is calculated for a purely secondary positron origin, assuming the leaky-box approximation for Galactic propagation. Points for MASS2 are from Hof et al. (1995).

HEAT hints → PAMELA and AMS in space

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA)

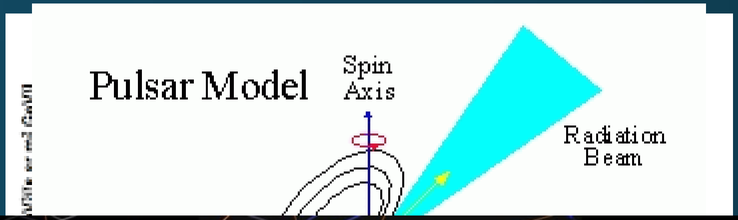


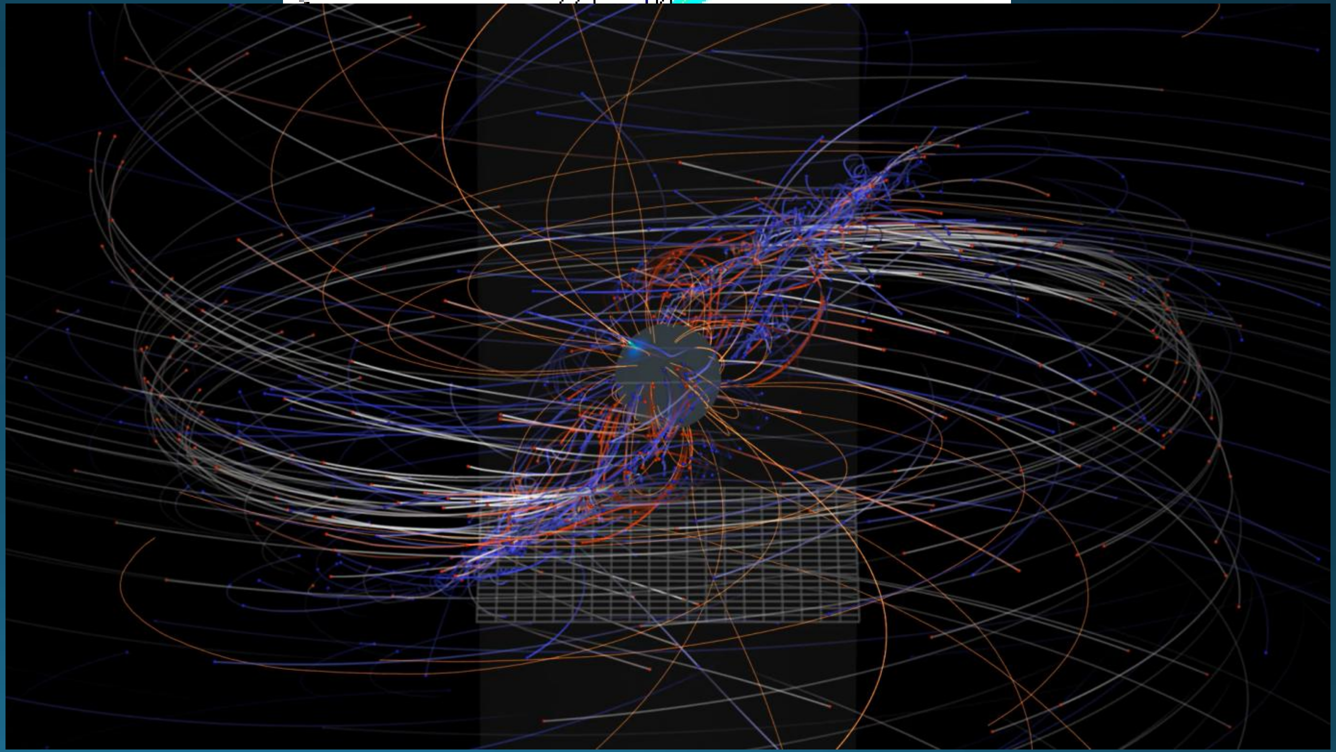
positrons were supposed to be only secondary from spallation



What is producing extra positrons?

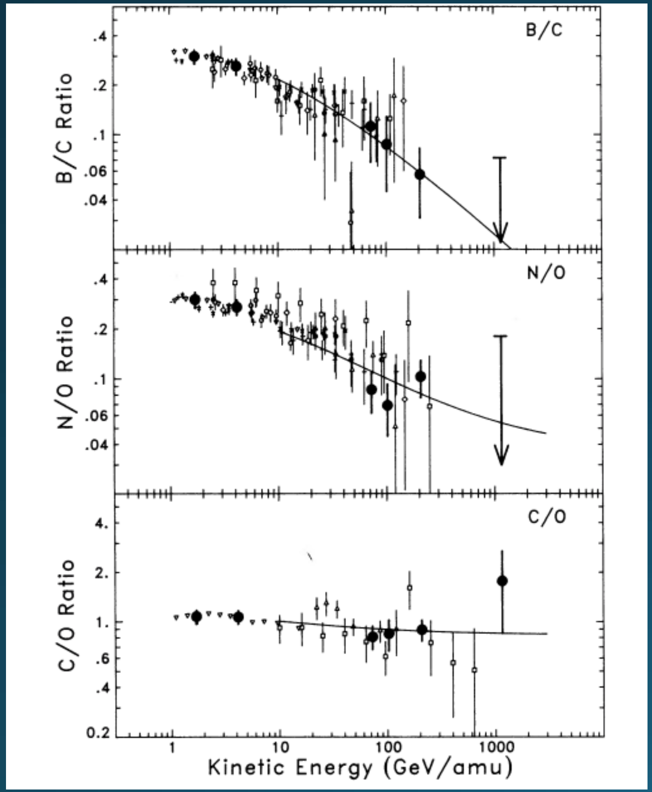
- Dark Matter?
  - Many theories
- Pulsars?
  - Known to have mostly electrons and positrons in surrounding medium
- Our lack of understanding of the spallation or propagation?

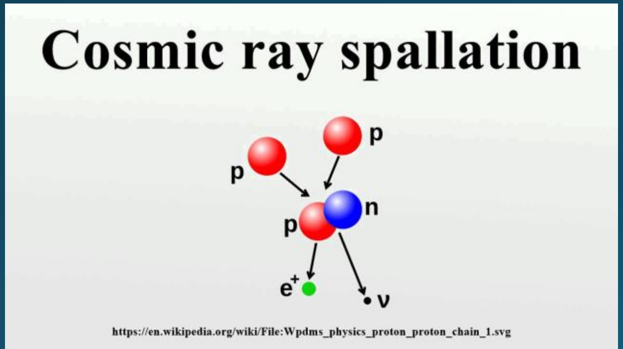


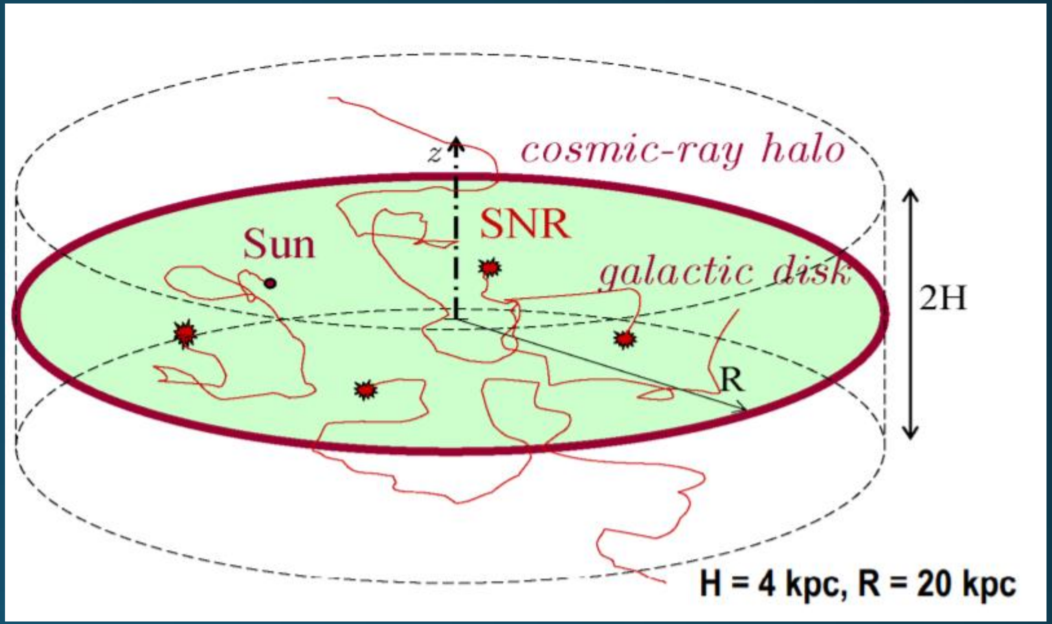


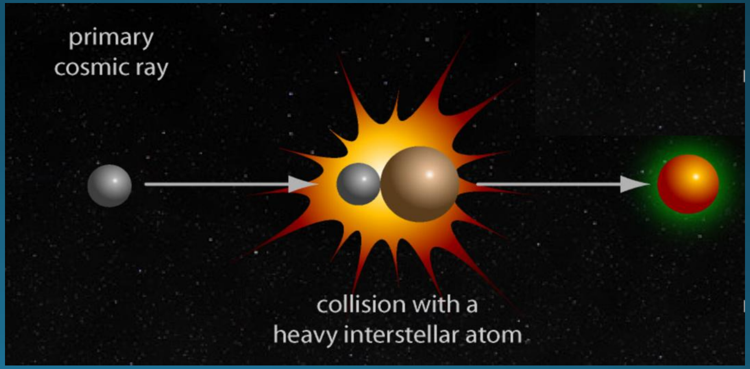
Composition to improve understanding

Secondary-primary ratios show how much material cosmic rays propagate through







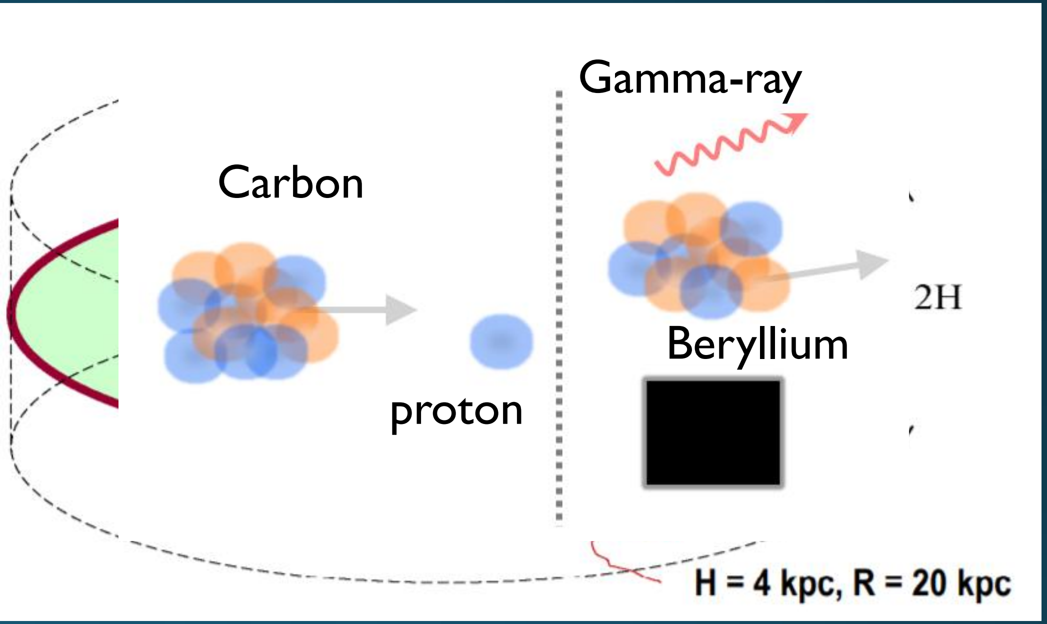


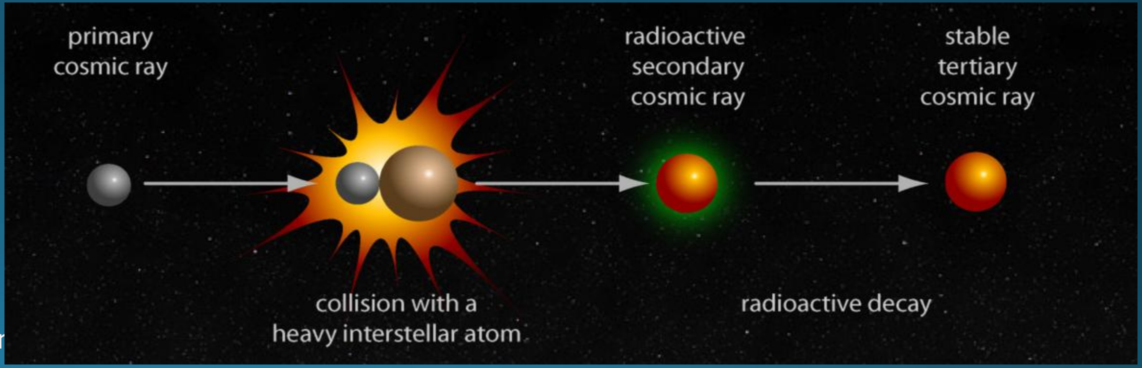
Secondary cosmic rays

Radioactive dating of the propagation

How long have cosmic rays been contained/propagating/producing secondaries within the Milky Way?

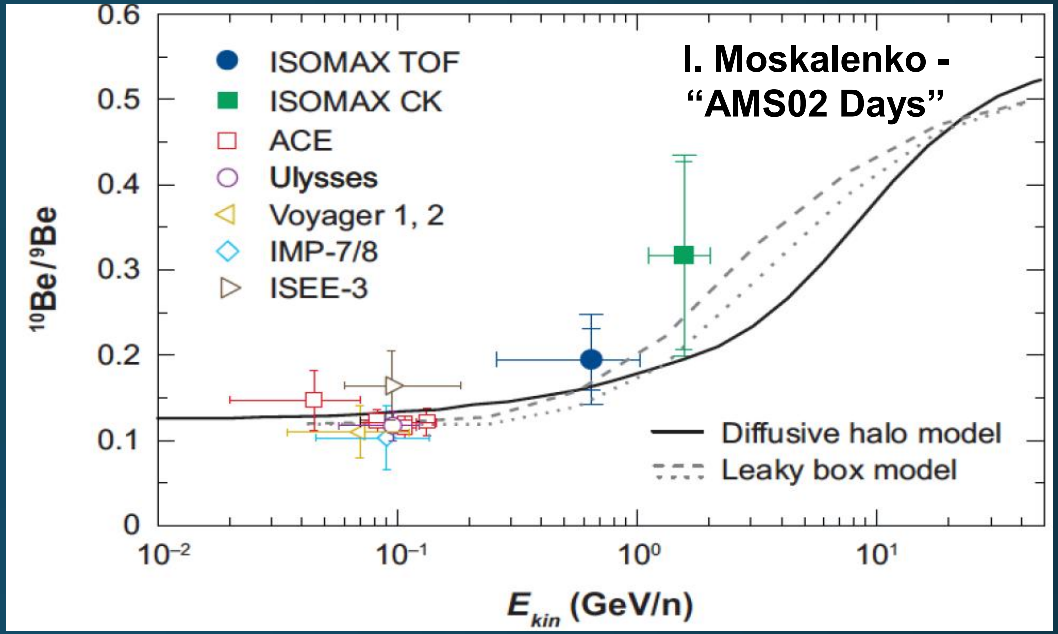
- Beryllium is useful in this regard
  - Secondary - produced from spallation
- Be-10 is a long-lived isotope
  - Be-10 beta-decays with a half-life of 1.4 Million years
- If we measure very little Be-10, cosmic rays are old enough for it to decay away

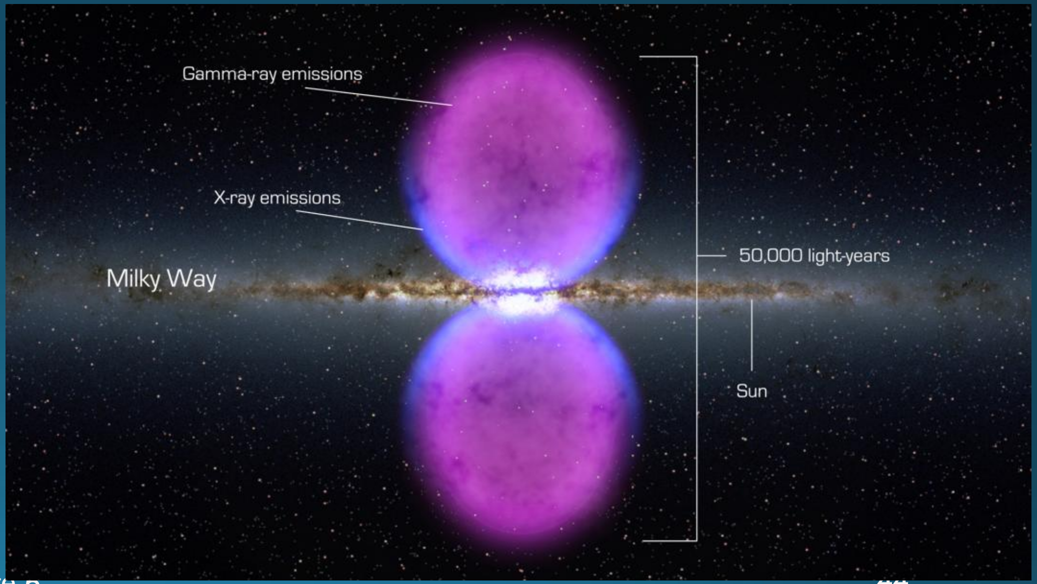




Beryllium isotope ratio

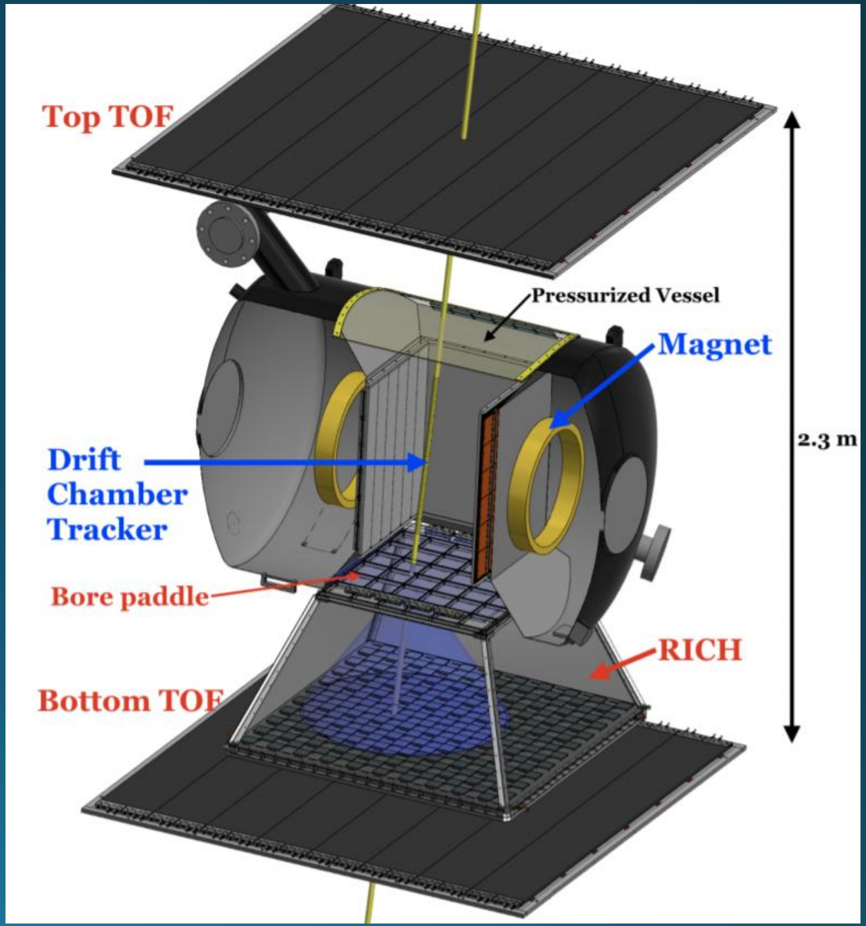
- Be-9 is stable and Be-10 is unstable
- Ratio is <u>sensitive to time</u> of GCR propagation
  - Larger cosmic ray halo, H, longer timescale for diffusion/propagation into the halo.
- Lower energy, decay
- Higher-energy, time dilation kicks in and Be-10 lives longer
  - Ratio increases





The High Energy Light Isotope eXperiment (HELIX)

- We designed a balloon-borne magnet spectrometer
  - Similar to HEAT
  - Uses the same magnet
- Utilizes the coincidence method
- Detect cosmic rays and measures:
  - Charge (Z), velocity (v), and momentum (p)
- Calculate the mass and determine the isotope of the cosmic ray nuclei
  - $m = \frac{p}{v}$

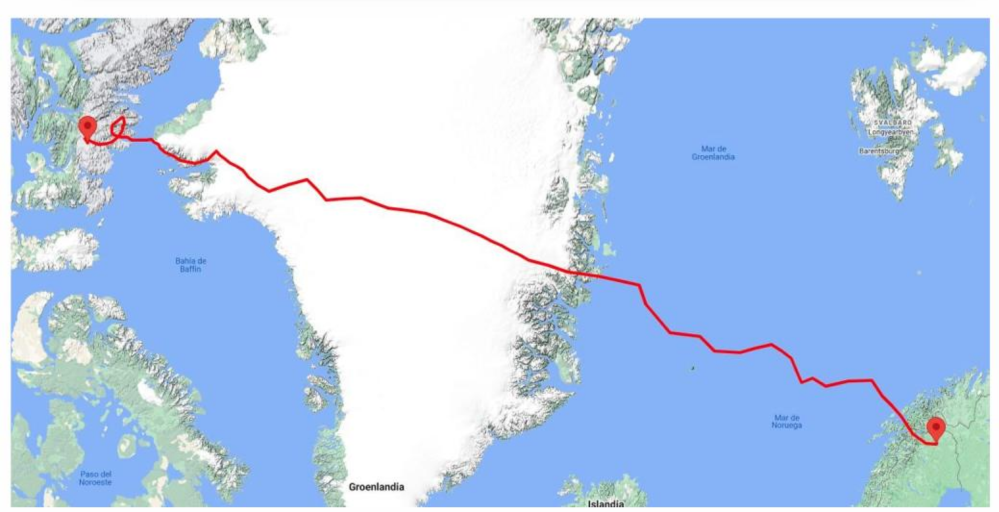


HELIX instrument

- Solar panels for power
- Antennas for telemetry
- Crane for the balloon launch
- First flight was from Esrange, Sweden in May 2024


HELIX 2024 Flight Trajectory
Day 6
Day 5
Landing
Day 4
Day 3
Day 2
Day 1
Launch
80°N
75°N
70°N
65°N
60°N
55°N
50°N
90°W
60°W
30°W
0°
30°E

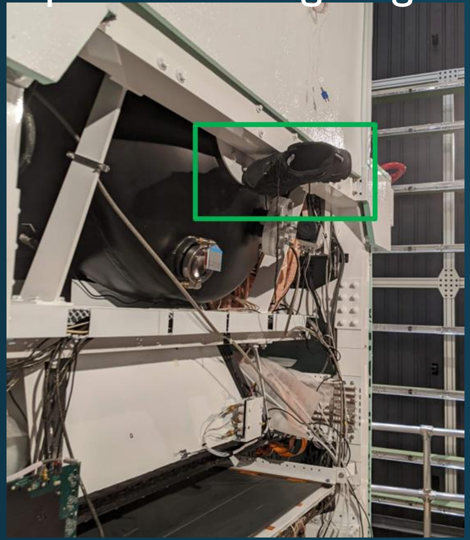
Recovery on Ellesmere Island



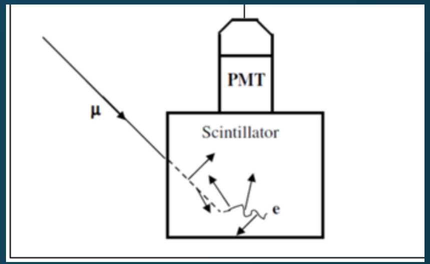
Analyze the data &
refurbish for next flight!

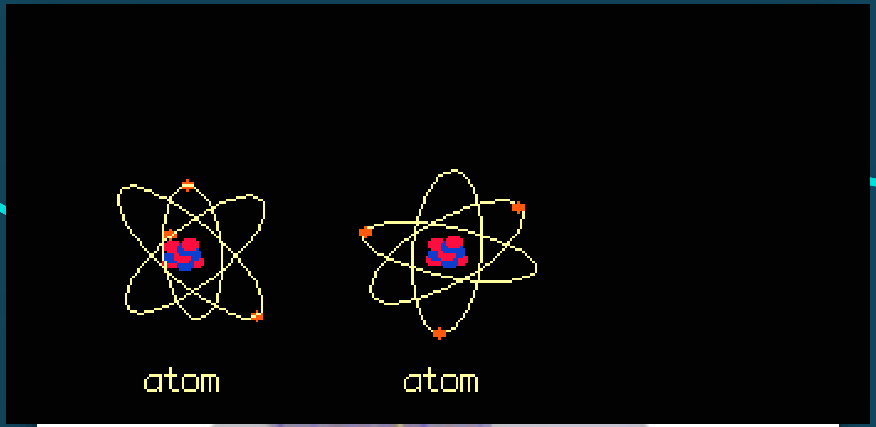
HELIX event

Superconducting magnet



Time of Flight

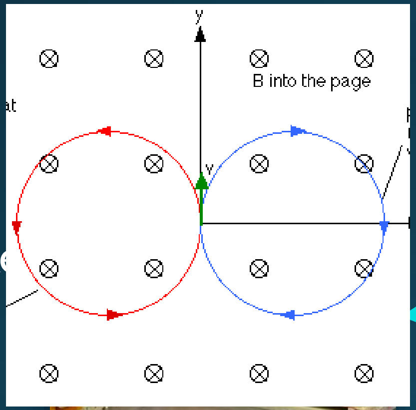


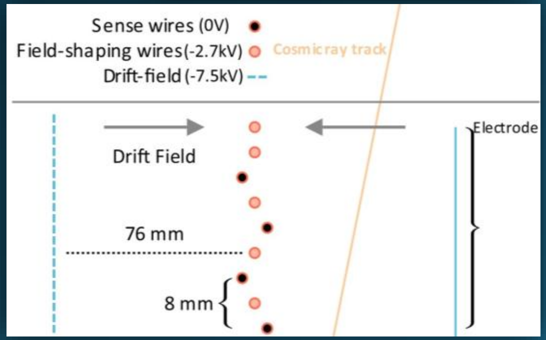


Measure momentum (p)

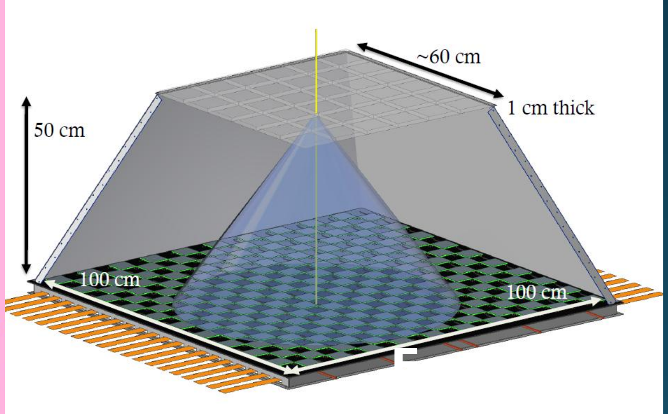
Measure velocity (v) and charge (Z)

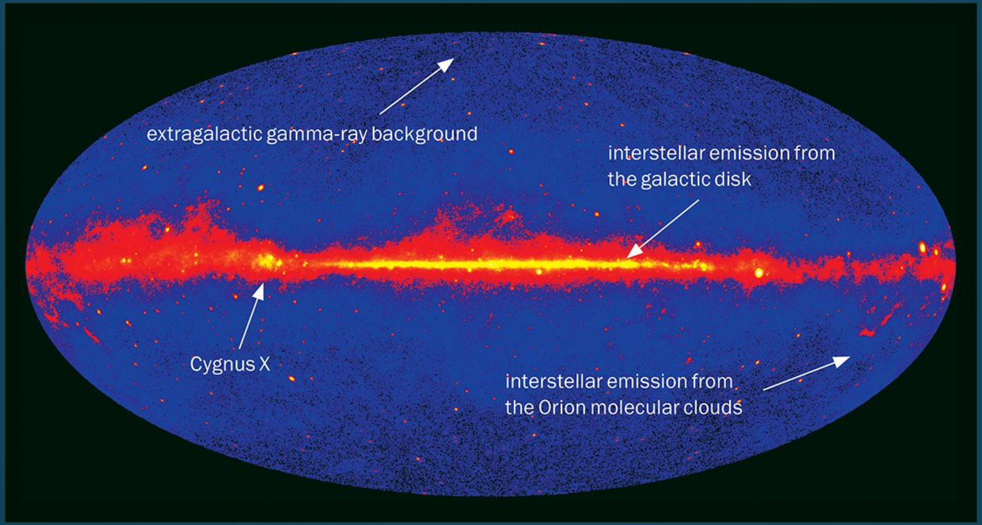
Tracker

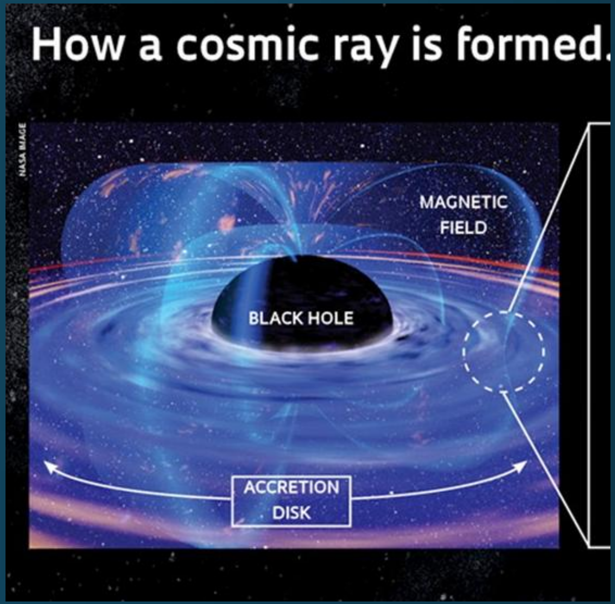




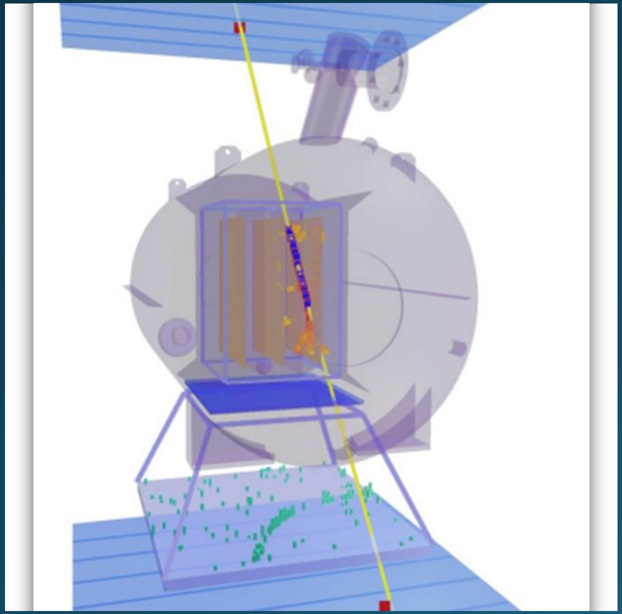
Cherenkov imaging

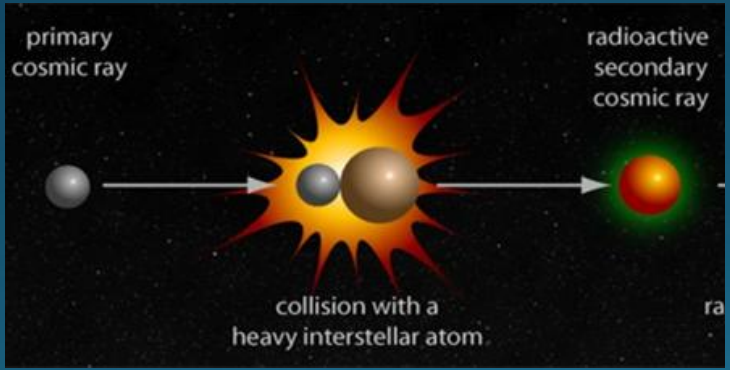


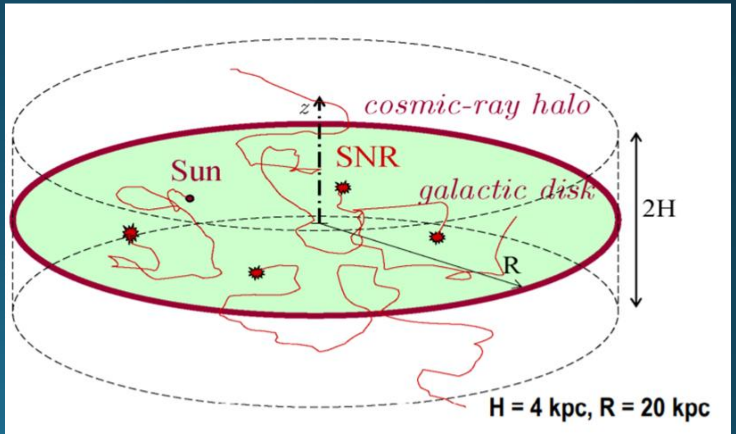


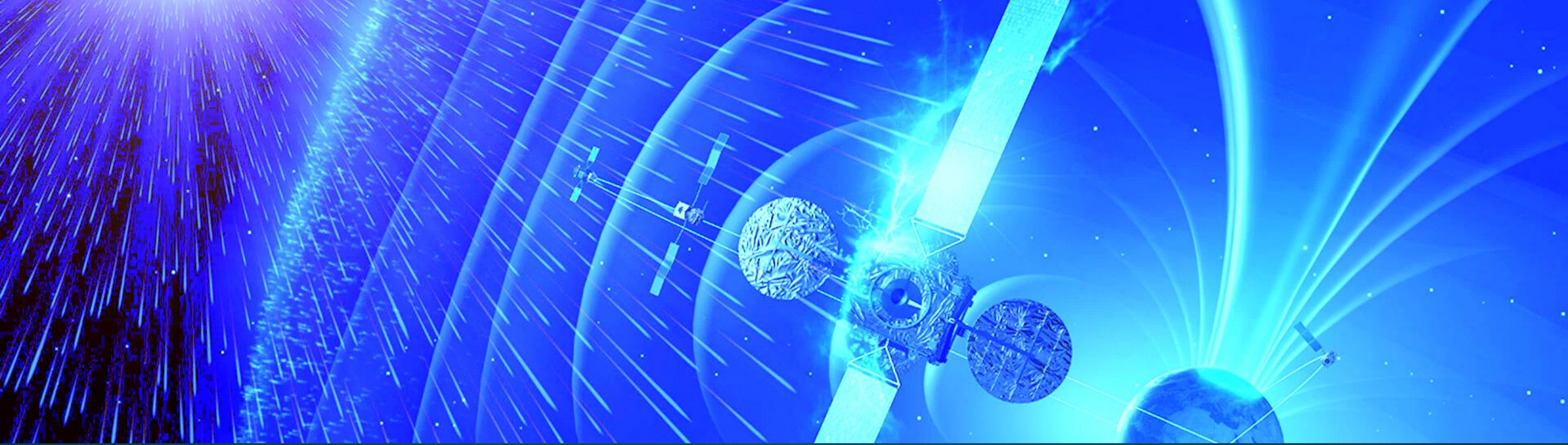


Through the astroparticle lens, we learn about the Milky Way and its high energy sources









Next week: Payton Linton, PhD candidate at Ohio State, giving guest lecture on cosmic rays and the Moon.

Thank you!