Cosmic Ray Instrumentation & Scientific Ballooning

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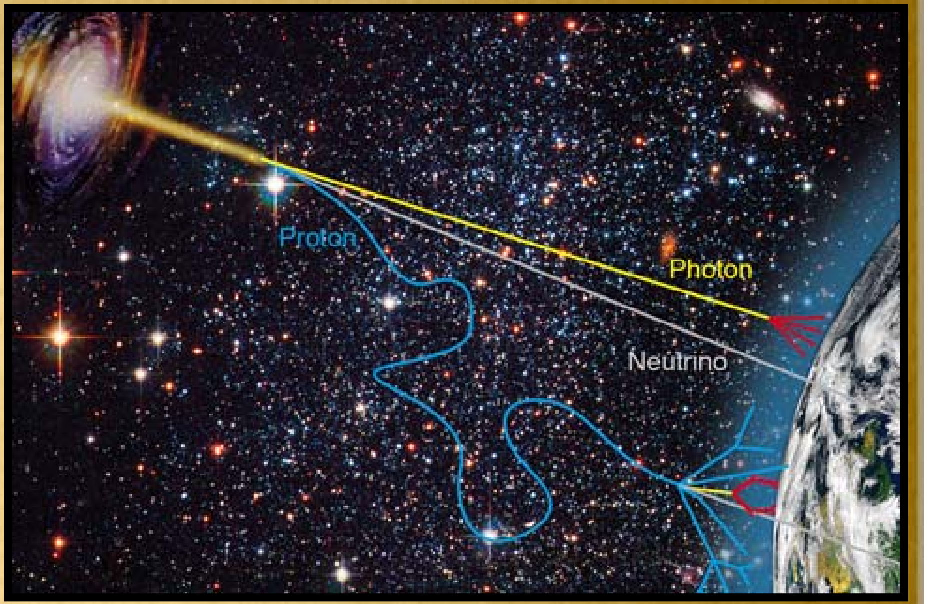
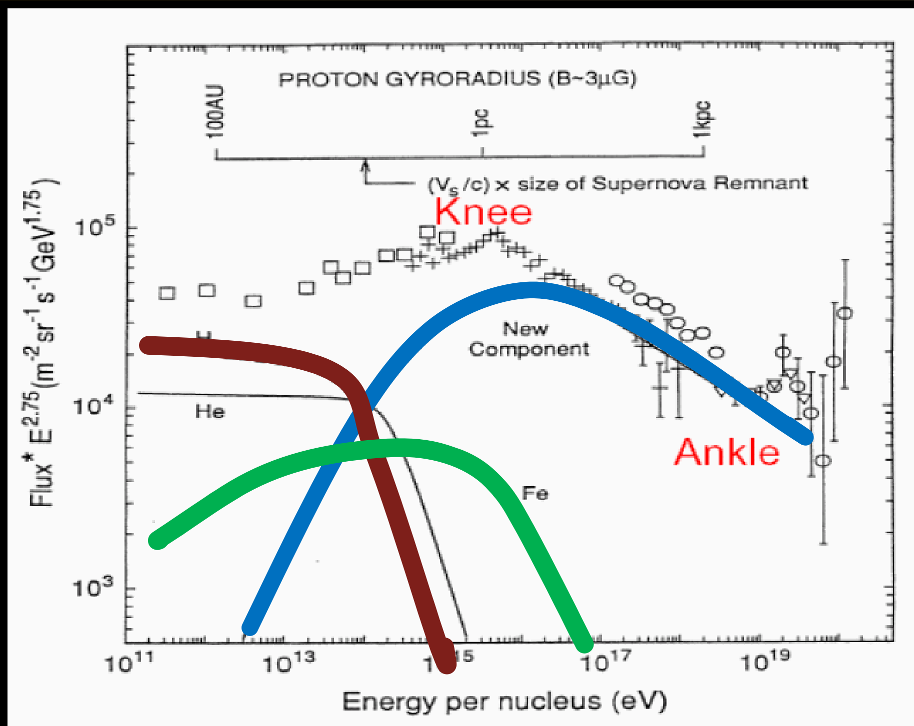
Goals?

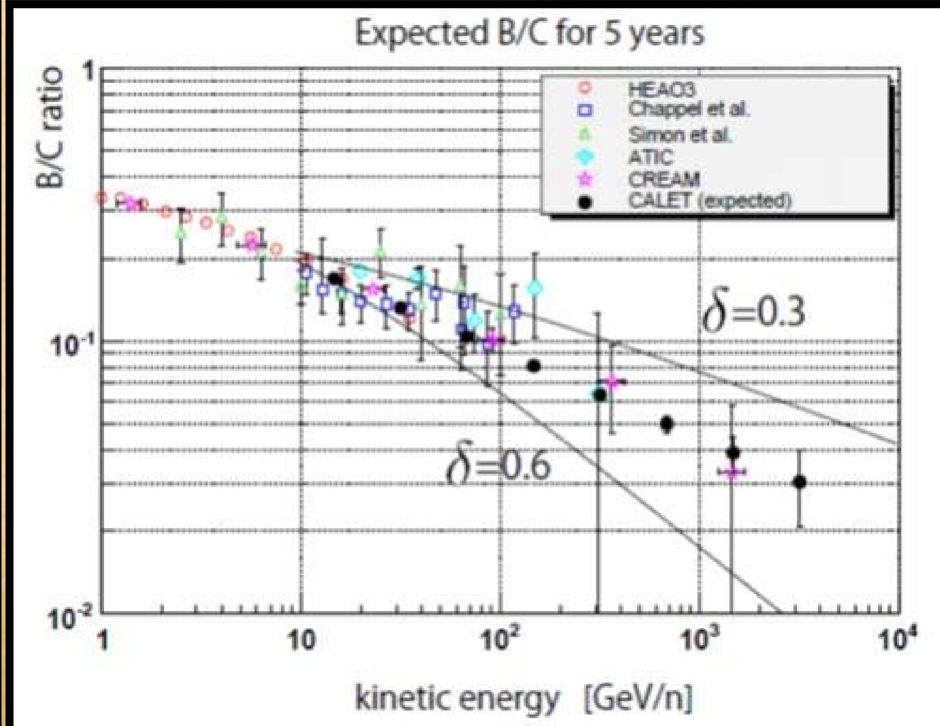
- In the absence of pointing, rely entirely on other measurements:
  - Overall composition and how it changes with energy
    - Atomic Mass, A
      - Or, as a proxy, the atomic charge, Z
    - Particle Energy, E



Goals?

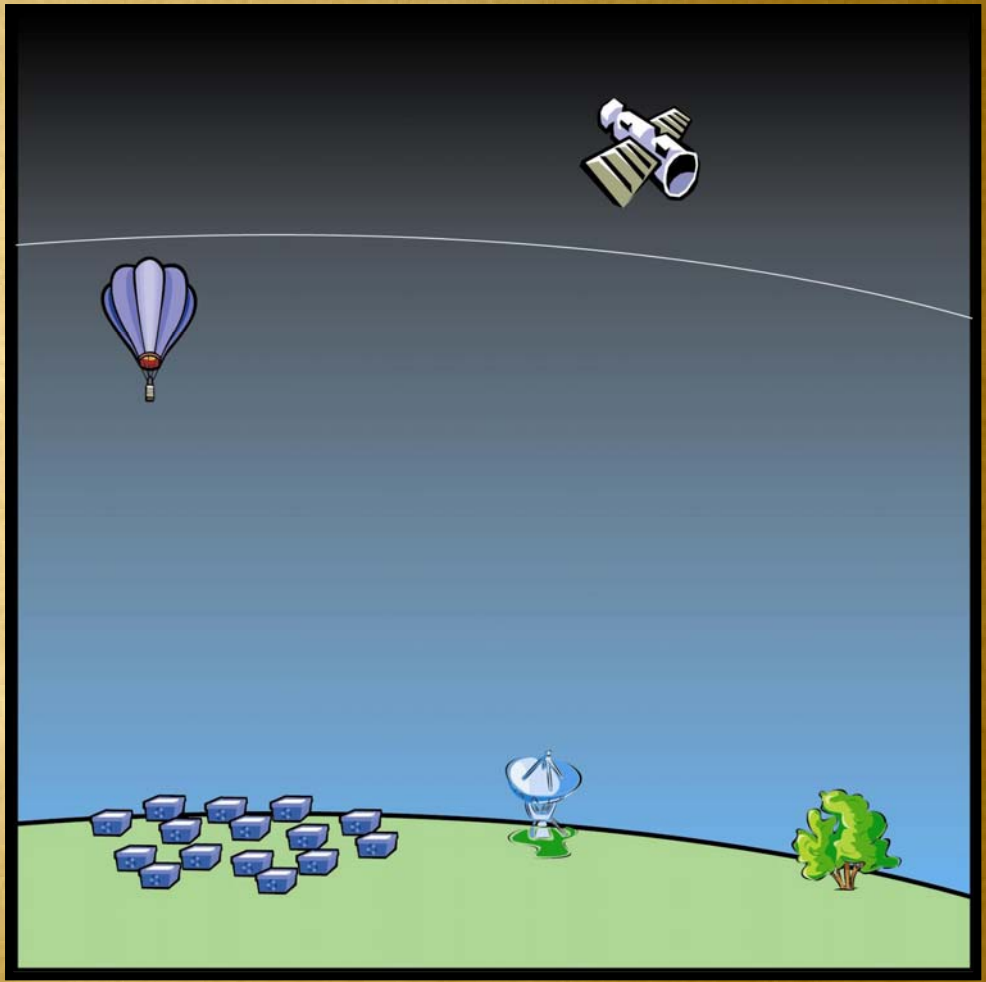
- Variation in primary components
- Secondary to Primary Ratios





Challenges

- Above a few GeV – fluxes are quite low: need big detectors.
- But, can't do it from the ground: need to get above atmosphere.
  - Some options available at higher energy, but precision is much worse
    - Except Direct Cherenkov
- Achieving BOTH is difficult



Why Ballooning?

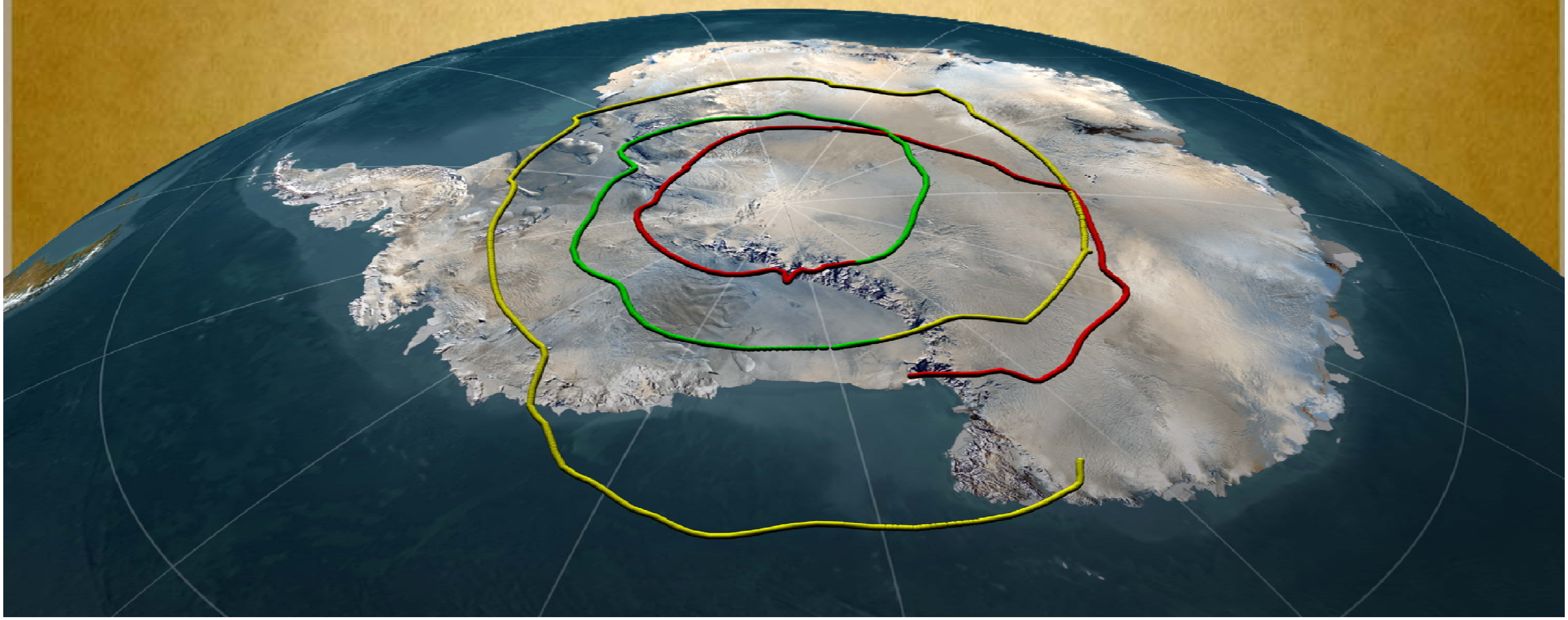
- Quick Turnaround
  - Can hope to do more than 1 per career
  - Often used as satellite pathfinders (e.g., GFEM in 2001)
- Cost
  - Standard Space Launch
    - Shuttle: >$450M
    - Space-X Dragon: $55M
  - Entire NASA BPO Budget for FY13: ~$35M
    - 10-15 launches per year (domestic & foreign)
- Drawbacks:
  - Short exposures
  - Still have a residual 0.5% of atmosphere overburden

Ballooning

- **Ultra-long duration balloon program (NASA/CSBF)**
  - Up to 40 million ft^3 | He-filled
  - Altitudes > 40km
  - Payloads up to 8000lbs
  - Yearly domestic and Antarctic campaigns (sometimes others)

Why Antarctica?

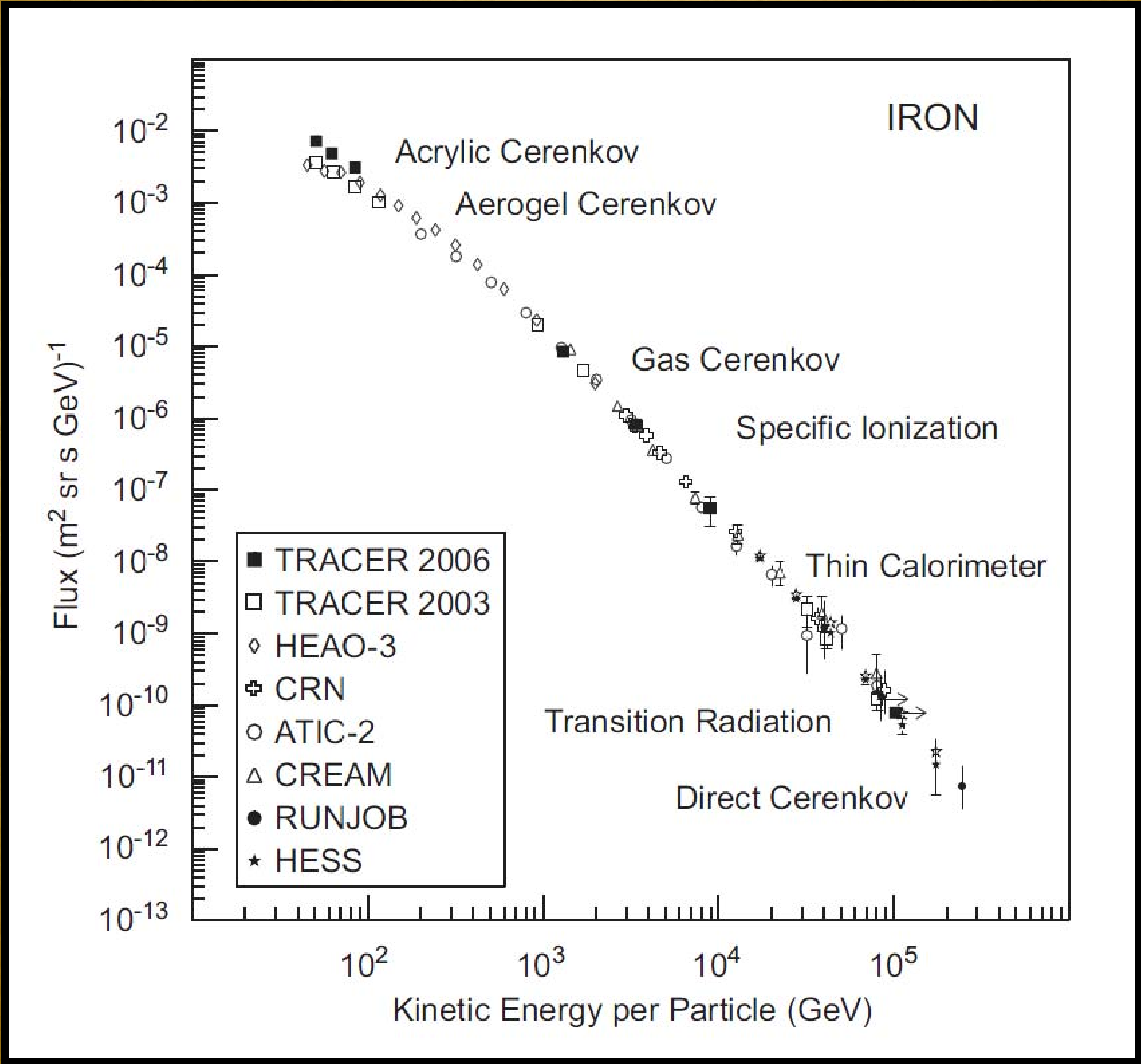
- Because the Sun never sets during Antarctic summer: power & fluctuations
- Stratospheric wind pattern is circular around pole.



Measurements

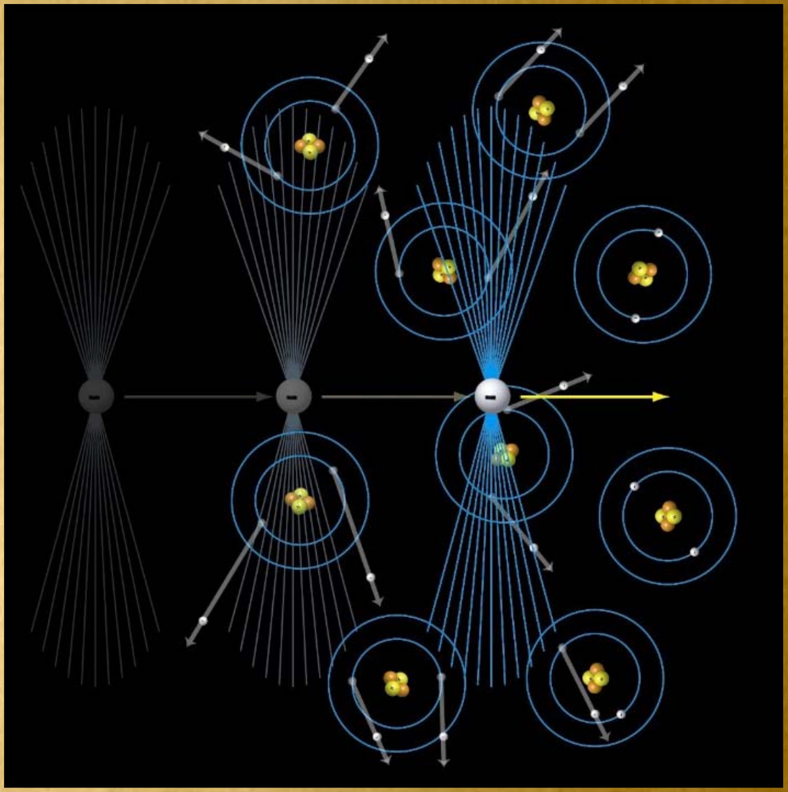
- **To determine particle characteristics, we leverage our knowledge of how particles interact in matter and fields, and how those materials respond.**
  - Example Interaction Processes:
    - Ionization
    - Cherenkov Radiation
    - Transition Radiation
    - Lorentz Forces
    - Nuclear Interactions
  - Often have to use more than one of these to extract single particle properties
  - Also have to apply different methods for different energy regions

7 Approaches to Iron Nuclei



Particle Charge

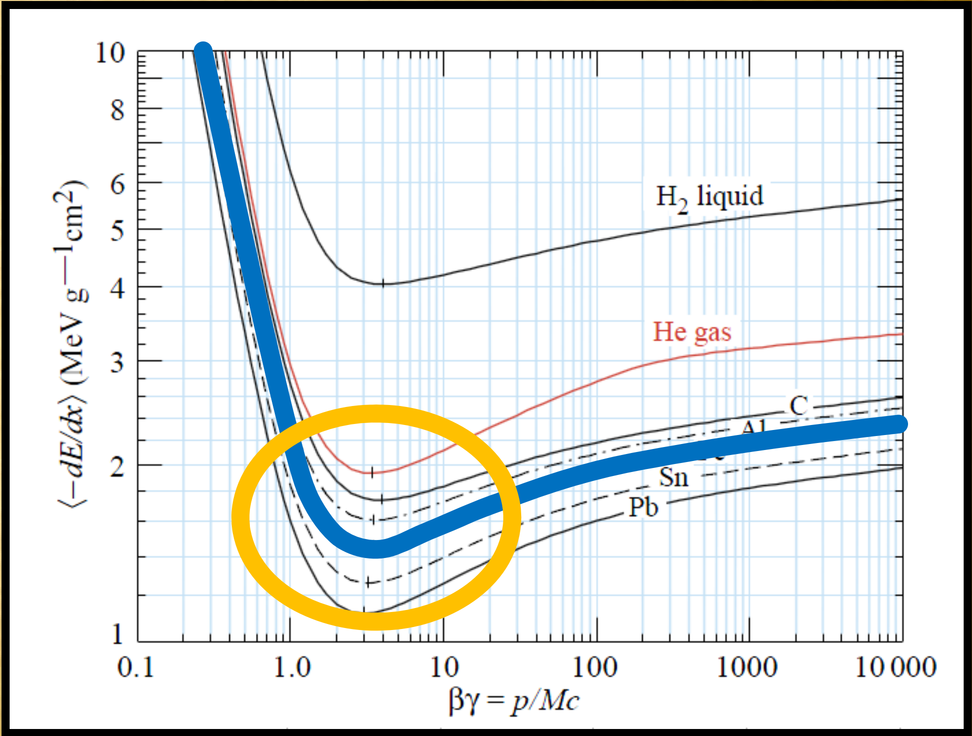
- **A common way to determine particle charge is to utilize ionization**
  - When a charged particle enters a volume of material, its electric field can strip some electrons from atoms
  - In some materials this can be used to infer some properties of the incoming particle



Bethe Formula (ions)

$$-\frac{dE}{dX} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right] \quad [\text{MeV}/(\text{g/cm}^2)]$$

- **Some points:**
  - ∝ Incoming particle z^2
    - Can't tell sign!
  - Low-energy: $\propto 1/\beta^2$
  - Minimum energy loss occurs at $\beta\gamma \sim 3$ [MIPs - Minimum Ionizing Particles]
    - dE/dX ~ 2 MeV/(g/cm2) for most materials



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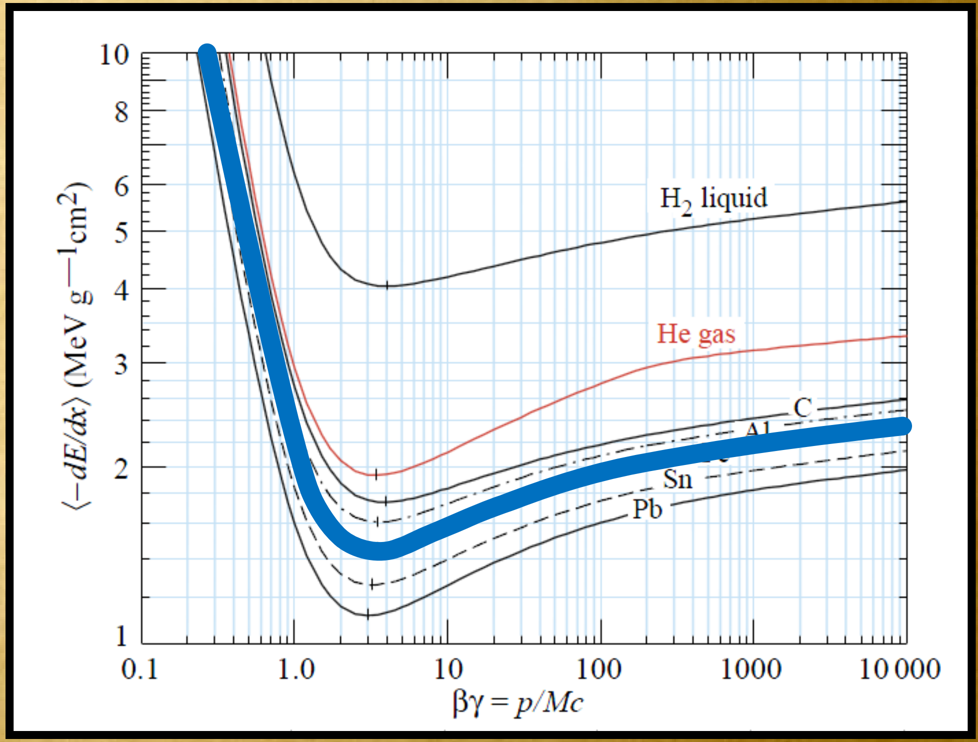
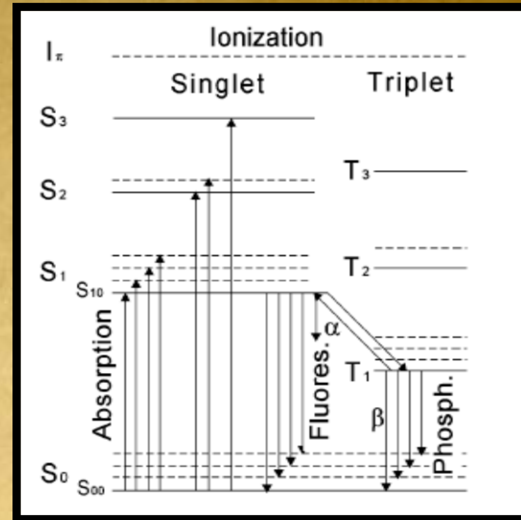
- **Some points:**
  - At higher energy: dE/dX $\propto \ln(\beta\gamma)^2$
    - Slow "Relativistic Rise" due to enhancement of the transverse E field
    - Eventually saturates in the "plateau" region
      - Varies with material
    - NB! Lost energy does not always equal deposited energy

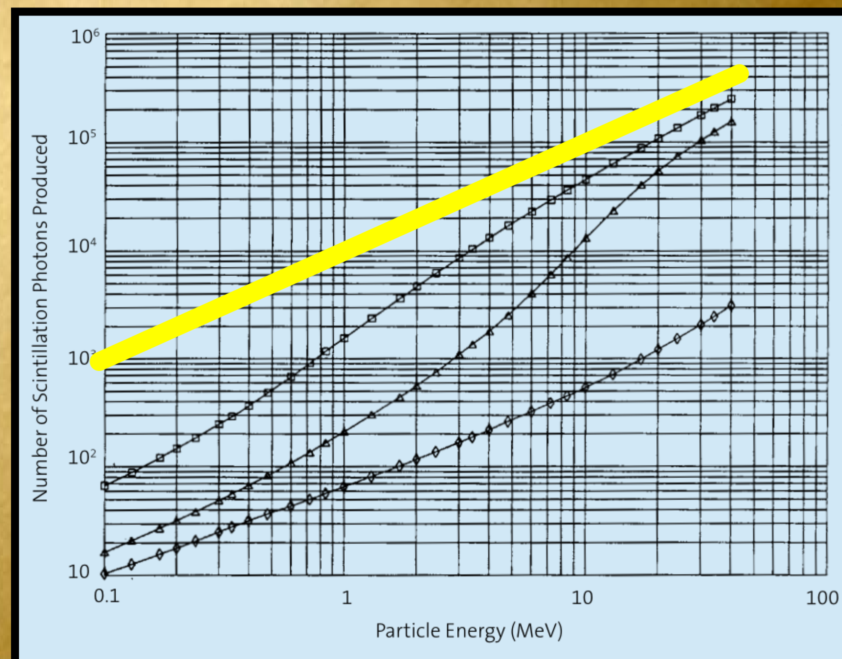


Similar (not identical) results apply for electrons

Scintillators

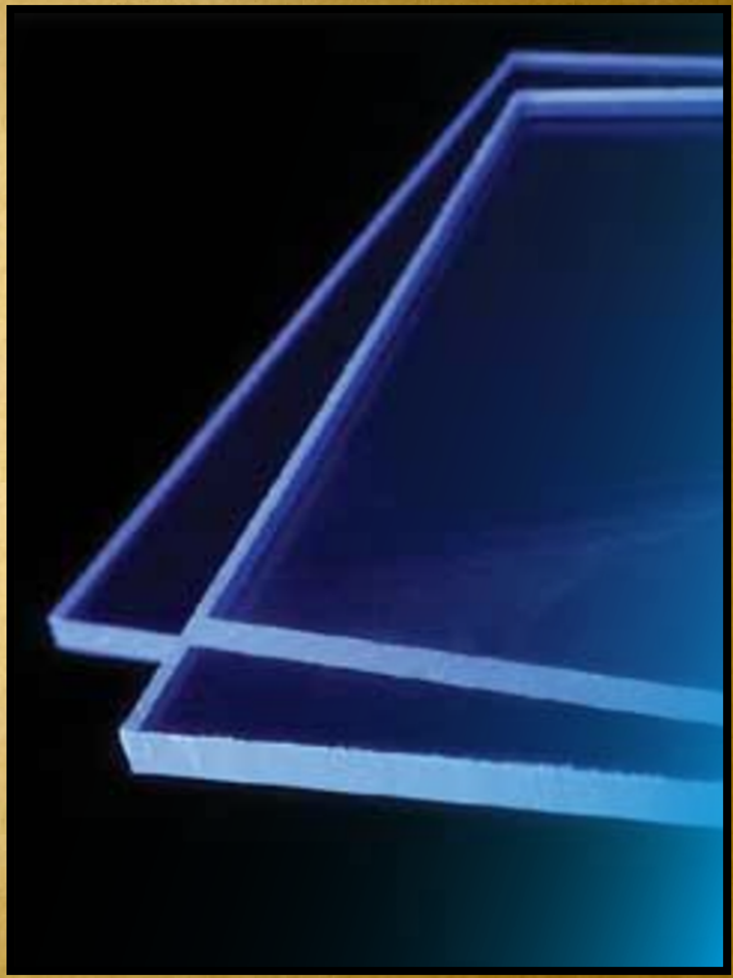
- Some materials respond to ionization energy deposits by emitting light
  - Excitation of molecules to elevated energy levels, and subsequent rapid (~ns) decay with the release of photons
  - For a large range of deposited energy (i.e., before saturation), the light level will vary linearly (or can be linearized) with the energy deposit
    - Hence: light level tells you Z^2





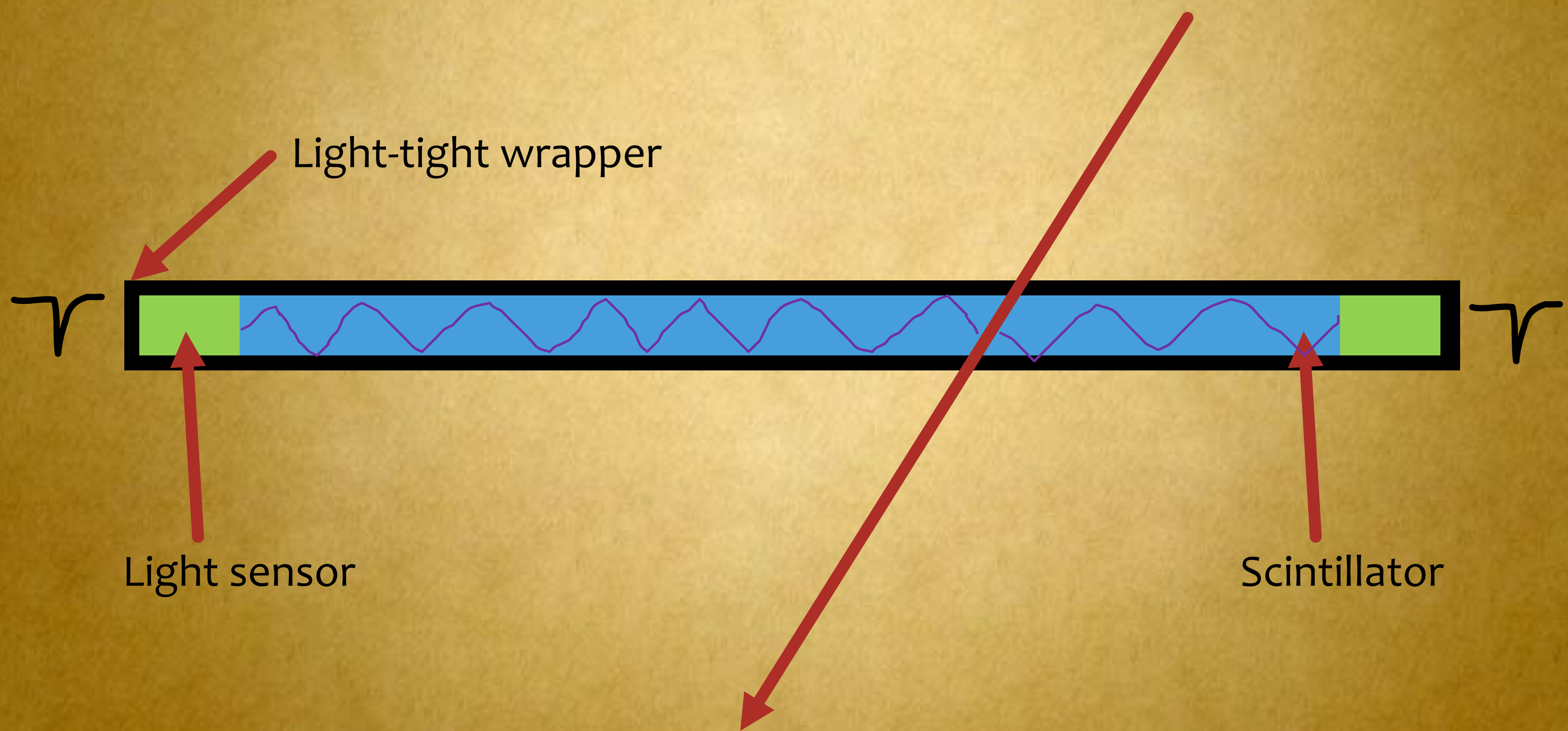
Scintillators

- **The standard scintillator used in CR detectors is thin (~cm) slabs of plastic with organic scintillator dissolved in it**
  - Cheap, Lightweight
  - Good light response (~10,000 photons for a 1 MeV electron)
  - Fast (~2 ns)
    - Requires a fast detector
    - Can employ this as an instrument trigger



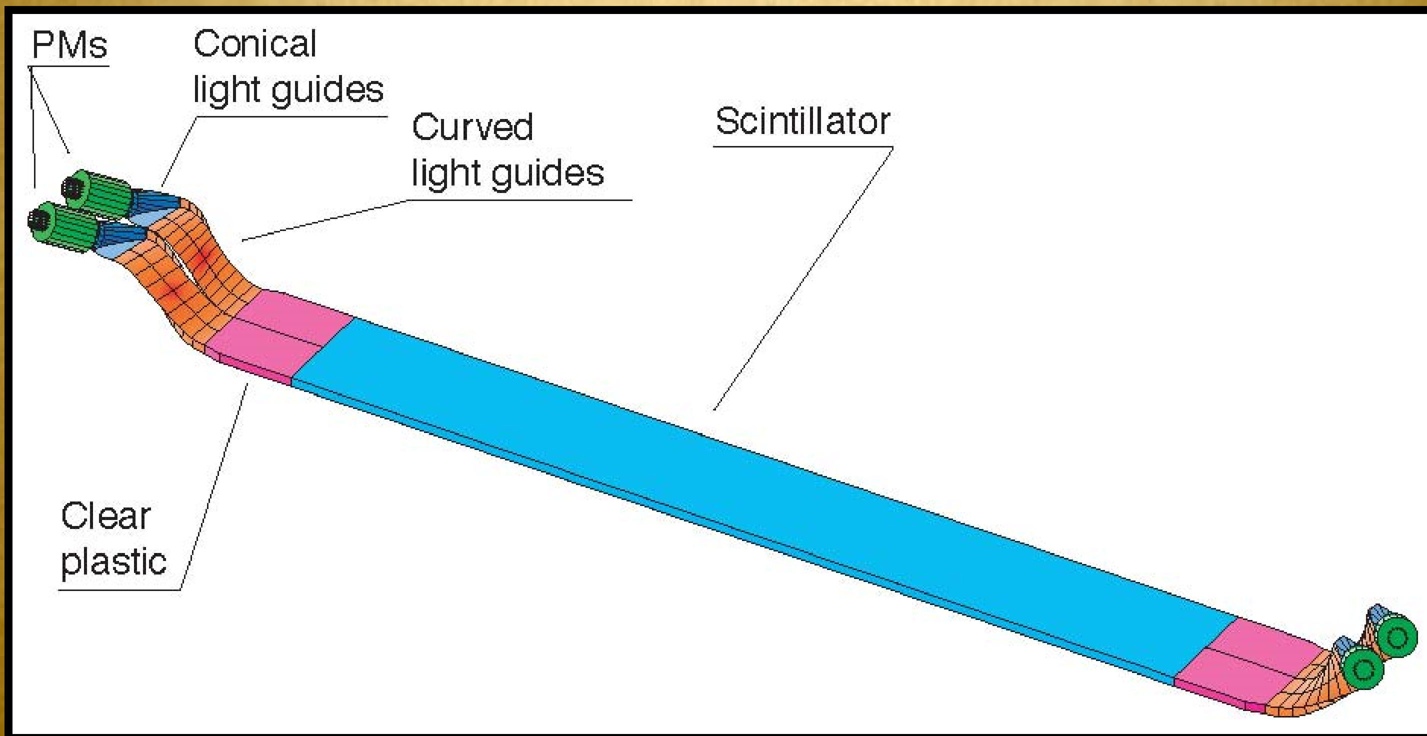
Scintillators

- **Cartoon 'Paddle' Setup:**
  - Amplitude and timing can both be used



Scintillators

- Real Designs more complex
  - May employ 'light guides' to better map scintillator faces to photodetectors



Photon Detection

- **Need something to convert those light pulses (back) into electronic pulses for readout**
  - The standard for the last >50 years has been the photomultiplier tube (PMT)
    - Basically consists of a photon-to-electron conversion device (photocathode), plus an amplification device (electron multiplier)

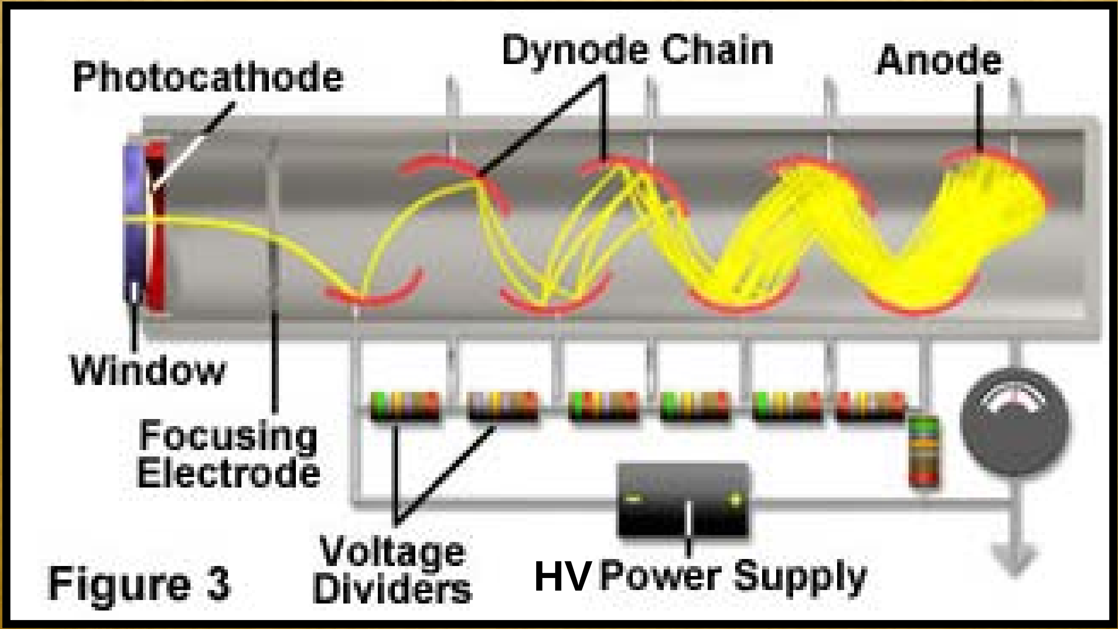
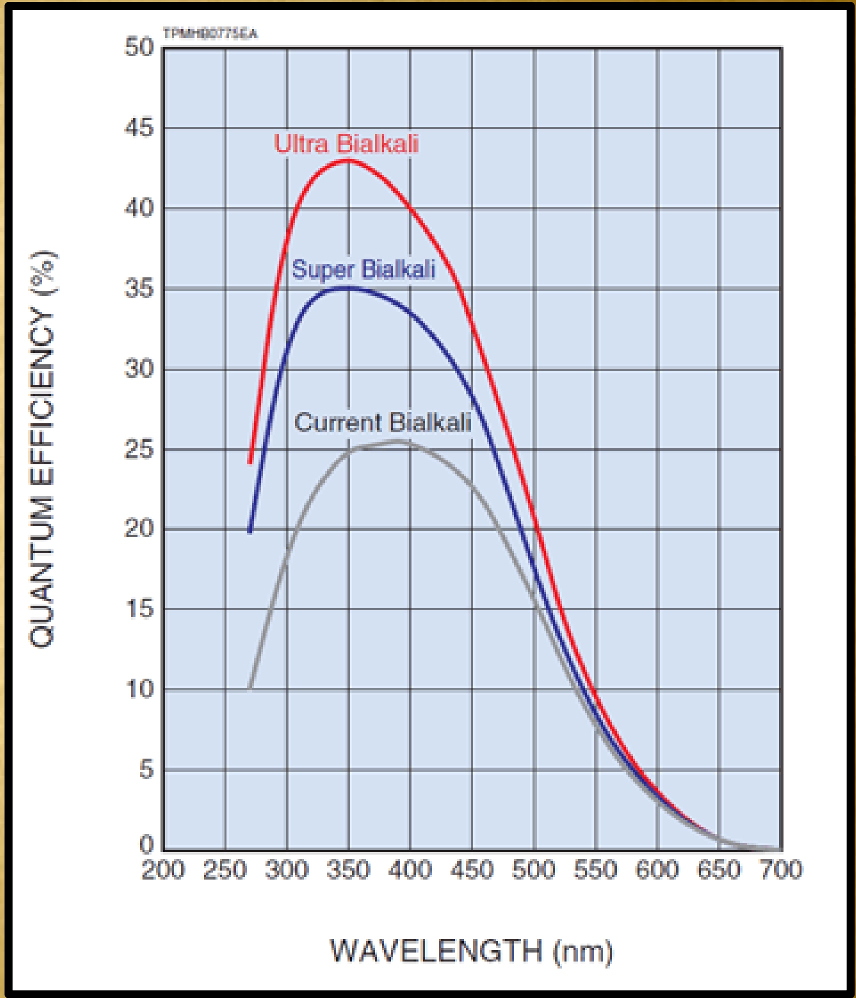


Figure 3

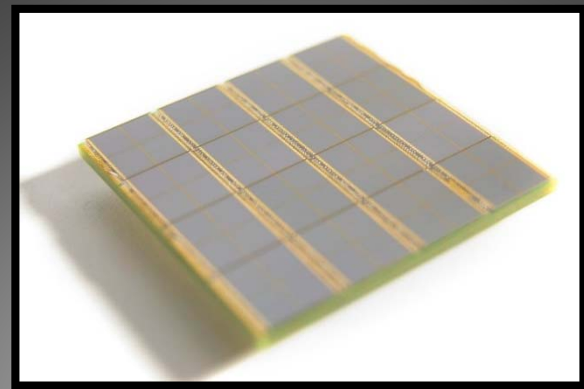
PMT Sensitivity

- "Quantum Efficiency" (QE) describes the sensitivity
  - #PEs Emitted/#Photons Incident
    - A (wavelength-dependent) property of the photocathode
    - Want to match this to the emission spectrum of your scintillator
  - PMT QE has not historically been great, but improvements are now appearing



PMT Characteristics

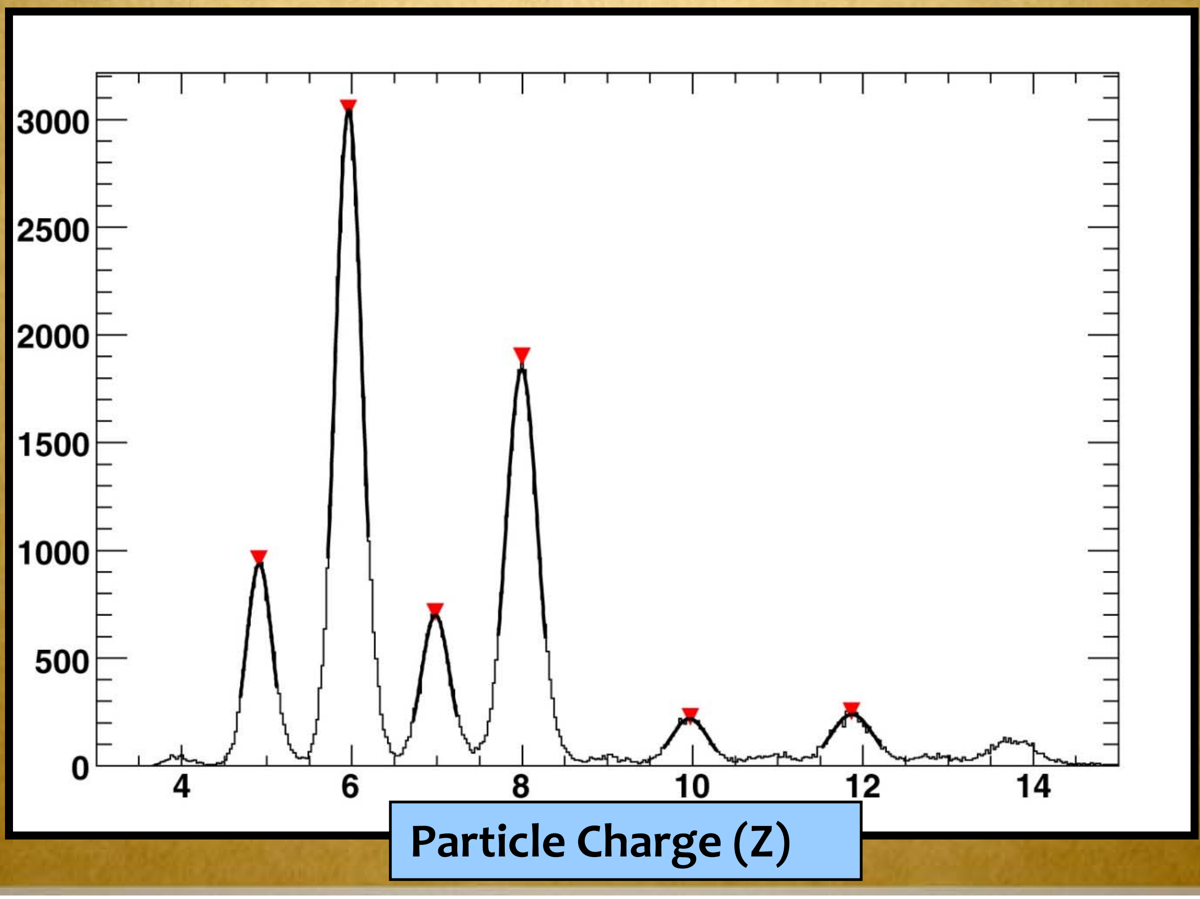
- **Pros:**
  - Good Gain
  - Fast Operation
  - Relatively quiet
- **Cons:**
  - Expensive (per unit)
  - Fragile (evacuated glass tubes)
  - Requires High Voltage
  - Sensitive to magnetic fields



- New solid-state devices (SiPM) now starting to become an option
  - Cheap
  - High resolution
  - No High Voltage
  - Still very noisy

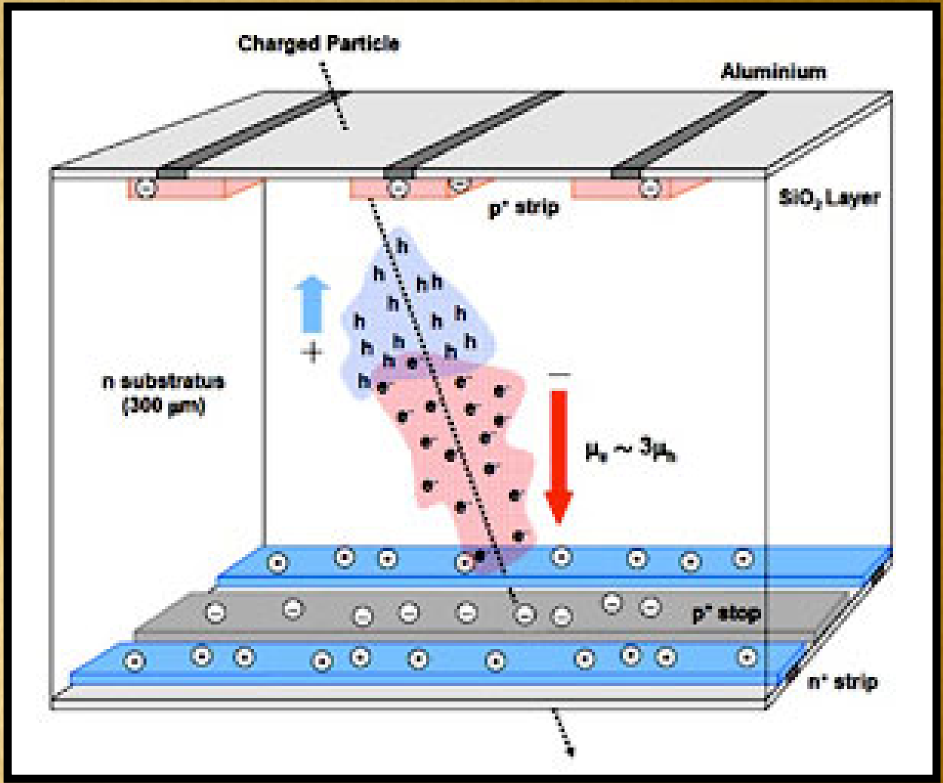
Charge Spectrum

- The kind of cosmic ray data you get from such a scintillator system looks like this:
  - (Some massaging required to achieve this!)



Other Options

- **Another solid state device which can replace the entire scintillator/PMT chain: silicon strip/silicon pixel detectors**
  - Thin (300-400μm) layers of silicon material with readout
  - Direct collection of ionization electrons freed by the passage of charged particles.
    - About 3.6 fC/Z^2 for MIPs in a 300um layer



Silicon Charge Detectors

- **Can use this to collect charge information, AND, due to small pixels/strips – tracking info**
  - Optimizations needed (dynamic range, channel counts, etc) for tracking vs for charge collection
- **Pros:**
  - Good resolution
  - Comes with free tracking information
- **Cons:**
  - Expensive!
  - High to very high channel count
    - CREAM: 3000 channels vs <50 channels (TCD)

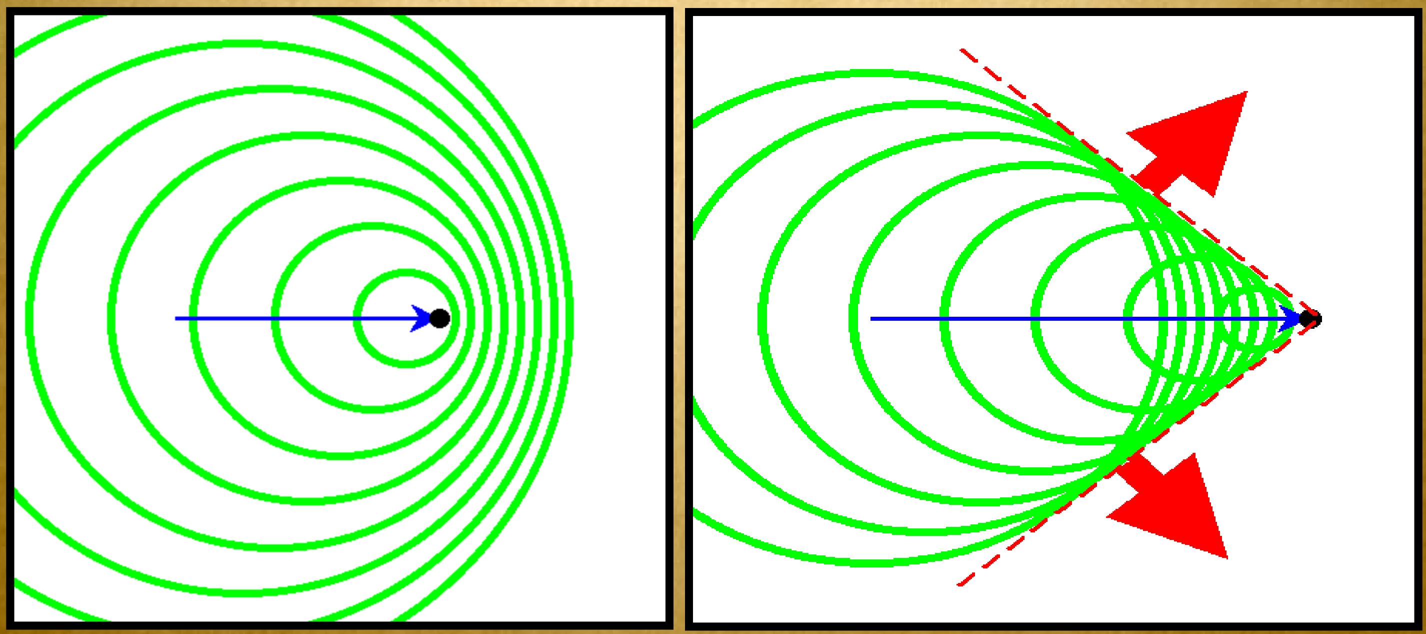
What Next?

- **Now that you know what your particles are made of, you need to figure out their energy:**
  - **You have a few options:**
    - **Get velocity and determine energy:** $E = mc^2/\sqrt{1 - v^2/c^2}$
      - **Cherenkov Detector**
    - **Measure energy directly:**
      - **Calorimetry**
    - **Measure Lorentz Factor and determine energy:** $E = \gamma mc^2$
      - **Transition Radiation Detector**

Cherenkov Detectors

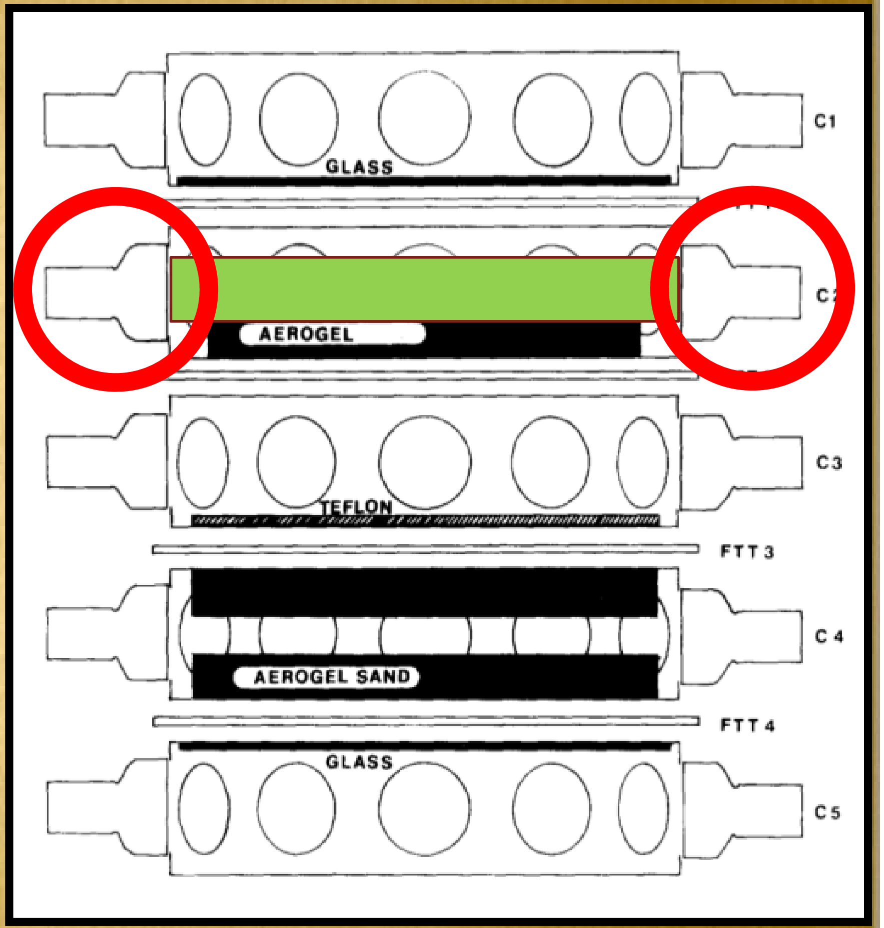
- **Photon emission from charged particles exceeding the local speed of light**
  - Photon yield varies with Z^2 and velocity (β) of the particle

$$\frac{dN}{dEdx} \approx 370\ Z^2[1 - \frac{1}{\beta^2 n^2}]$$



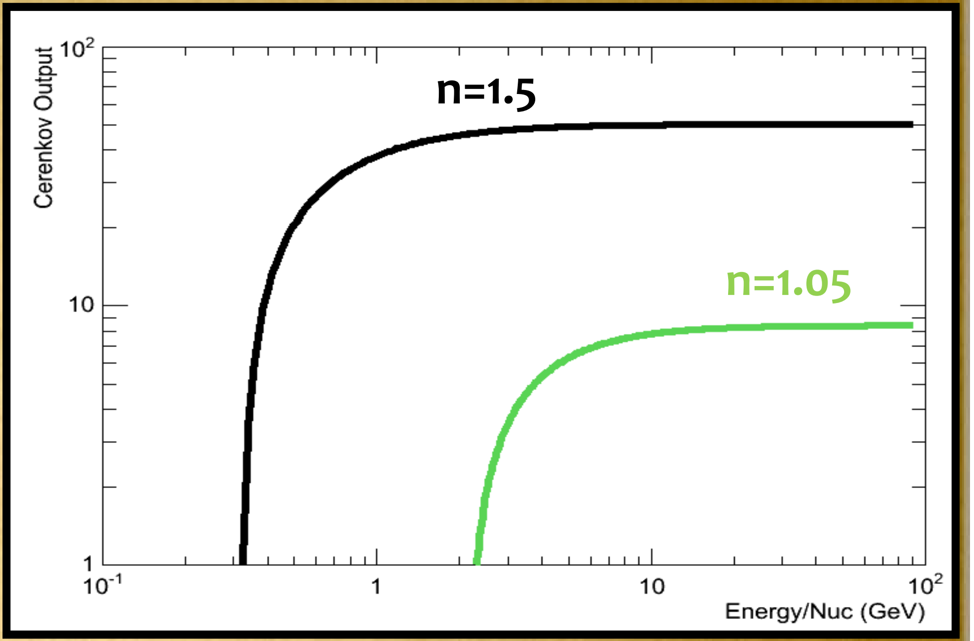
Cherenkov Detectors

- Cosmic ray CER detectors generally take the form of integrating volumes of radiator material read out with photomultipliers
  - (In some cases) structure is similar to a scintillator system
  - Typical 'radiator' materials: acrylic, aerogel, gas



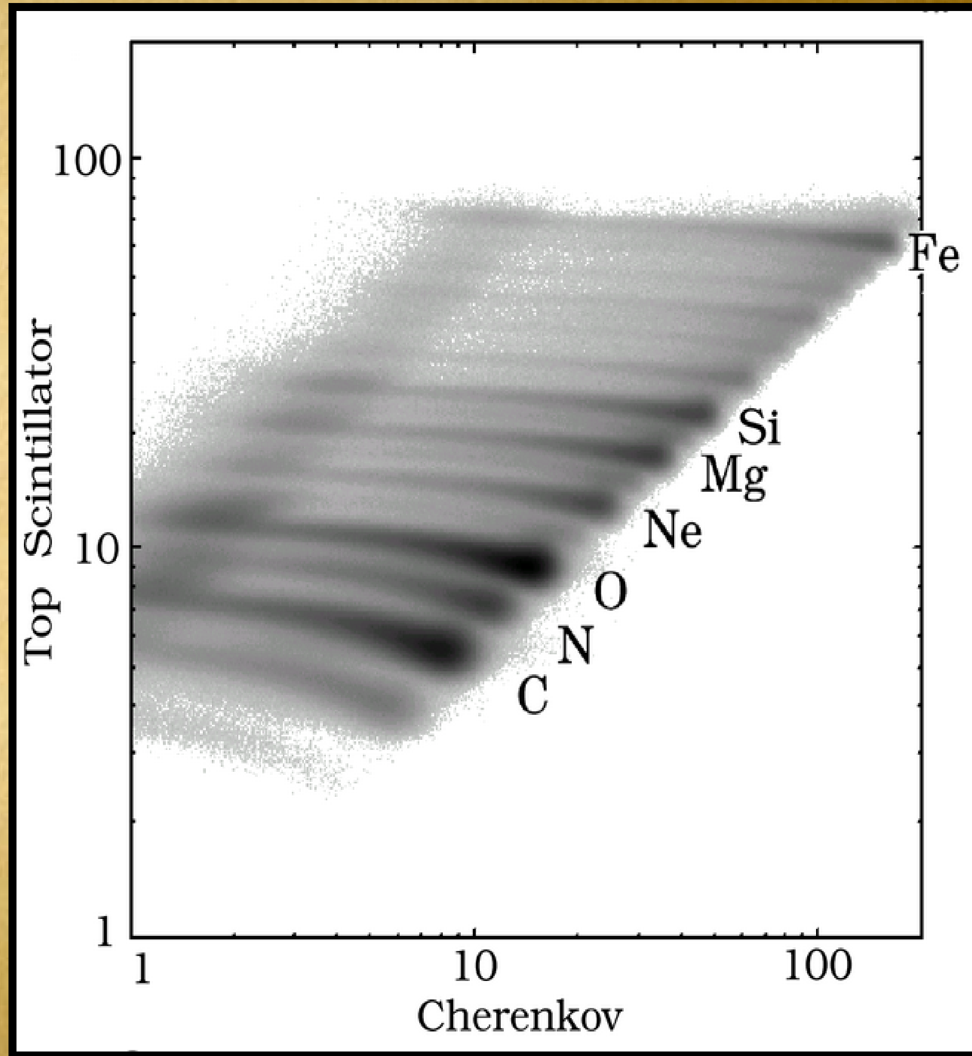
Cherenkov Detectors

- Yield saturates relatively quickly after threshold ($\beta > 1/n$), so multiple radiators allow to extend the energy reach
  - Examples: HEAO, TIGER
- But prior to saturation – a measure of β can be obtained, and hence Lorentz Factor, and thus energy



Cross Correlations

- **The power of multiple detectors**
  - Cherenkov Signal vs Scintillator signals – allows you to separate high-Z, high-E particles from low-Z, low-E particles



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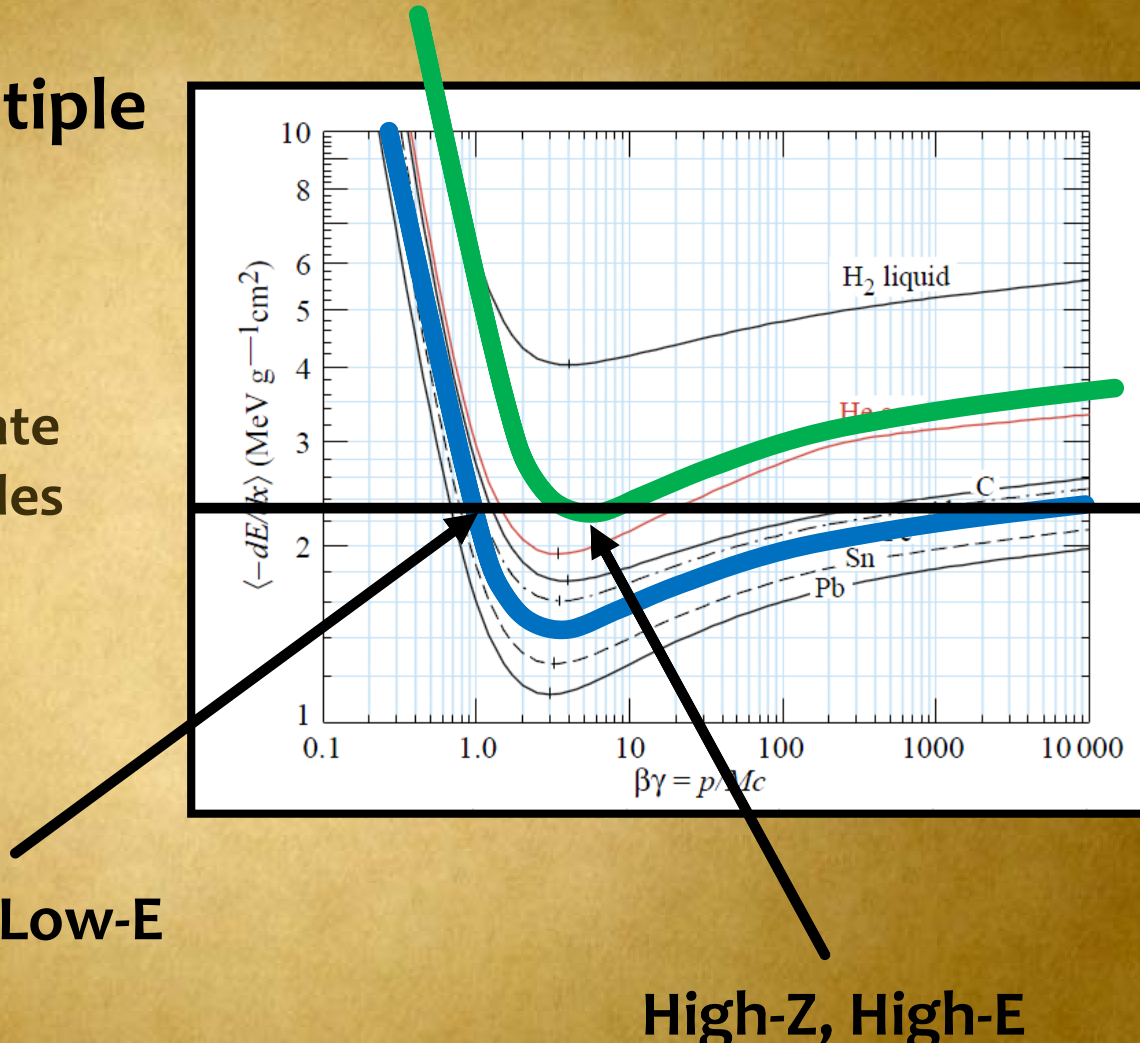
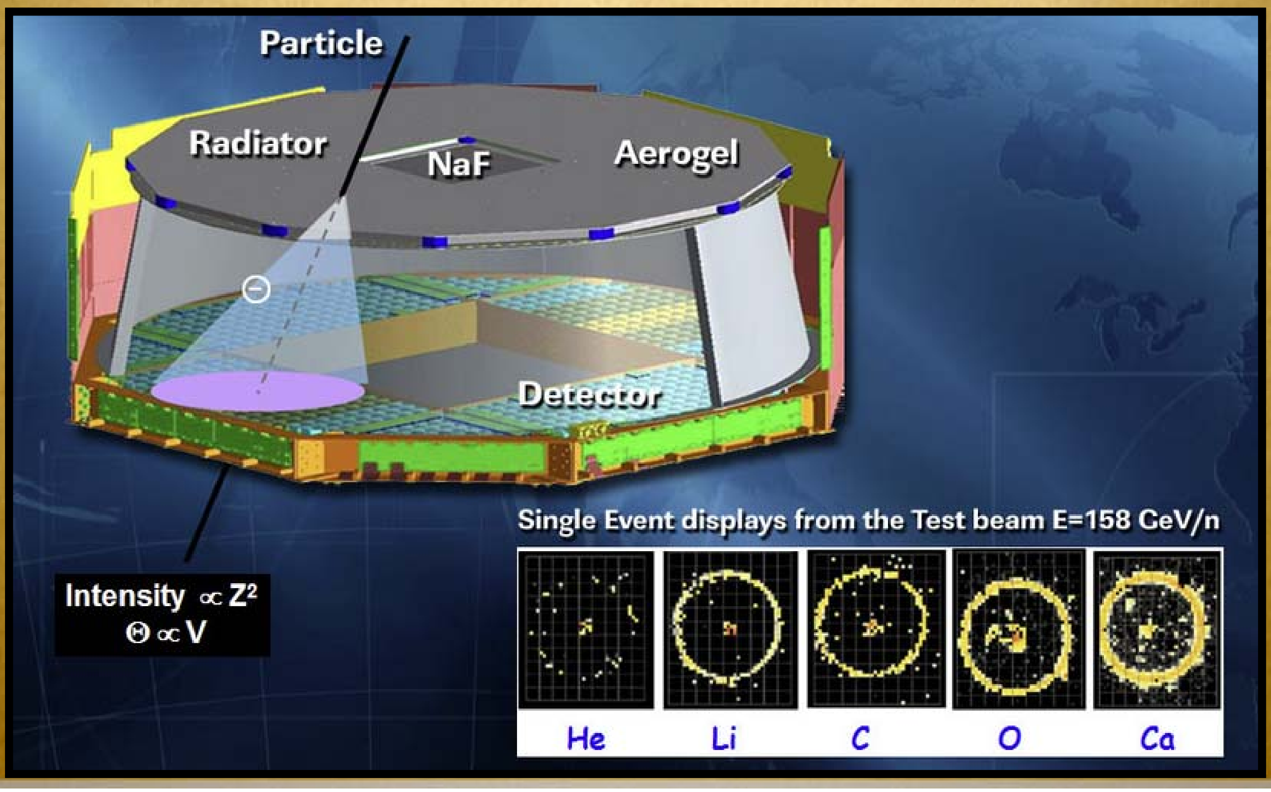


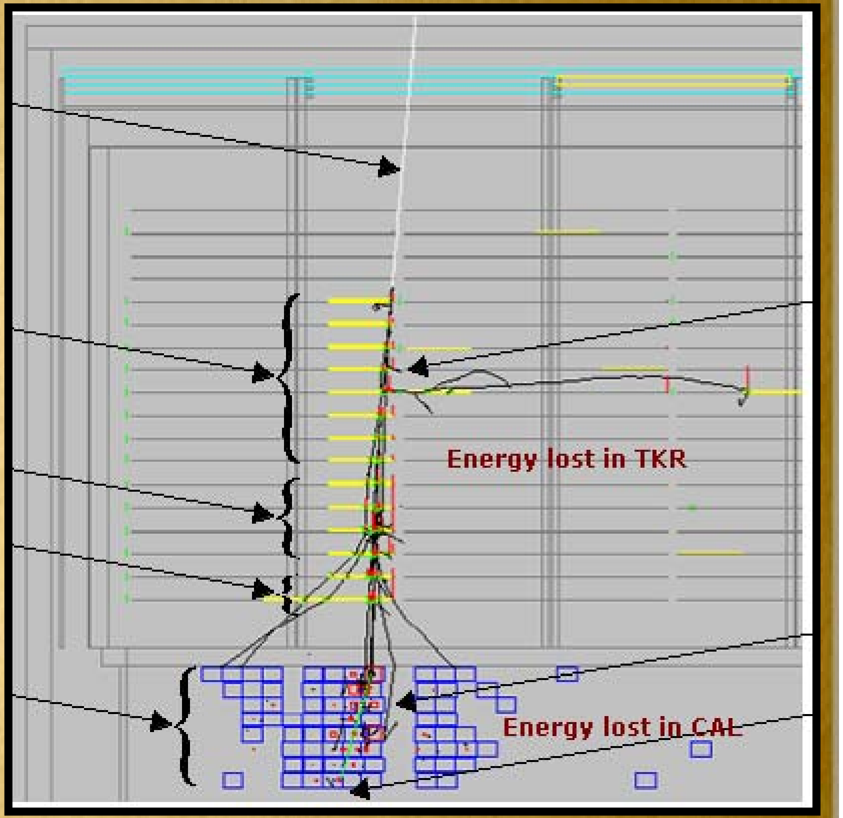
Ring Imaging CHerenkov

- **RICH detectors improve resolution (Δv/v) and energy range by also using angular information**
  - Requires an imaging detector plane
  - Used on UC-RICH/CAPRICE, AMS experiments



Calorimeters

- Generally work by having the particle smash in, initiating an EM cascade, and then absorbing the energy of daughter particles in a series of subsequent detectors
  - A stack of scintillators and photo-detectors (LAT), or solid state ionization detectors (CRIS), etc.



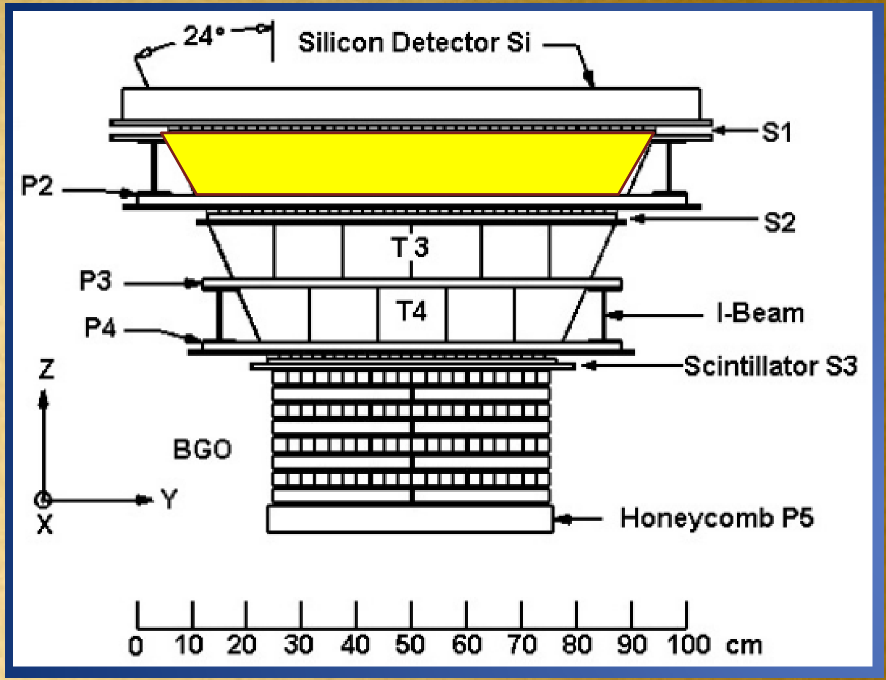
Nuclear Calorimeters

- **Calorimeters are trickier to use with nuclei vs electrons & photons**
  - Nuclear Interaction lengths tend to be much longer than radiation lengths in most materials
    - LAT, e.g., is 8.6 X_0 deep, but only 0.43 λ_{int} deep

material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

Nuclear Calorimeters

- This has led to the introduction of "target" or "thin" calorimeters for CR studies.
  - These basically take an EM calorimeter and stick a non-instrumented high-λ_{int} target in front to 'jumpstart' hadronic cascades and allow shorter (lighter) detectors
  - Examples: ATIC, CREAM

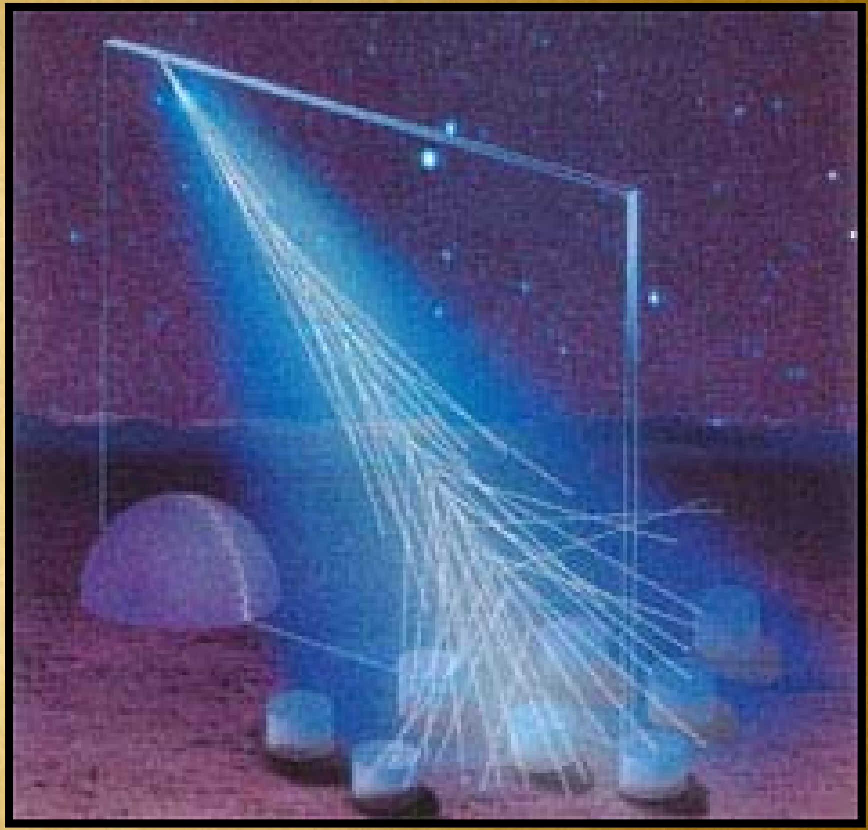


Calorimeters

- **General operational mode is simple:**
  - Count up all the deposited energy in your active components and this is the particle energy (or a value related to the particle energy)
- **Pros**
  - Good energy resolution
  - Simple?
- **Cons**
  - Can't calibrate for all energies/particles
  - Heavy! Generally have to be small

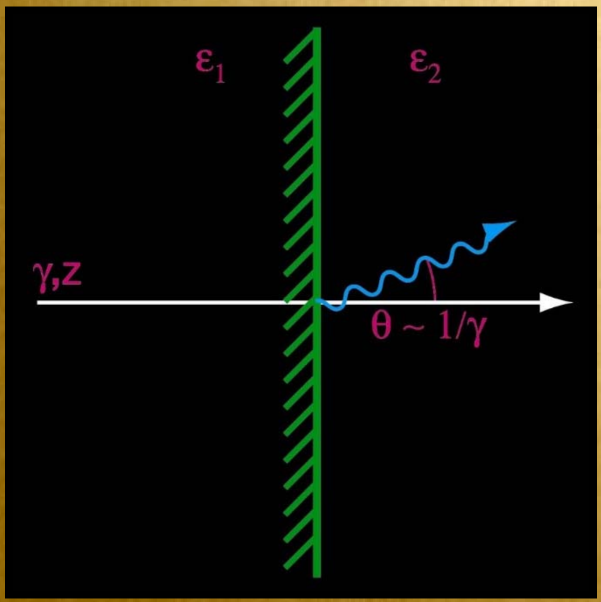
Calorimeters

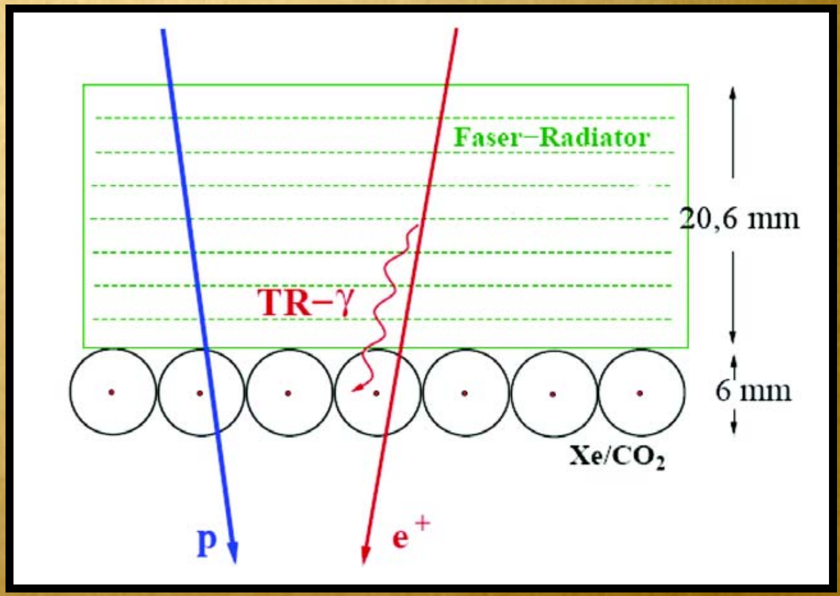
- Probably worth mentioning that air shower arrays and ground-based gamma-ray instruments are calorimeters – use the atmosphere as absorber



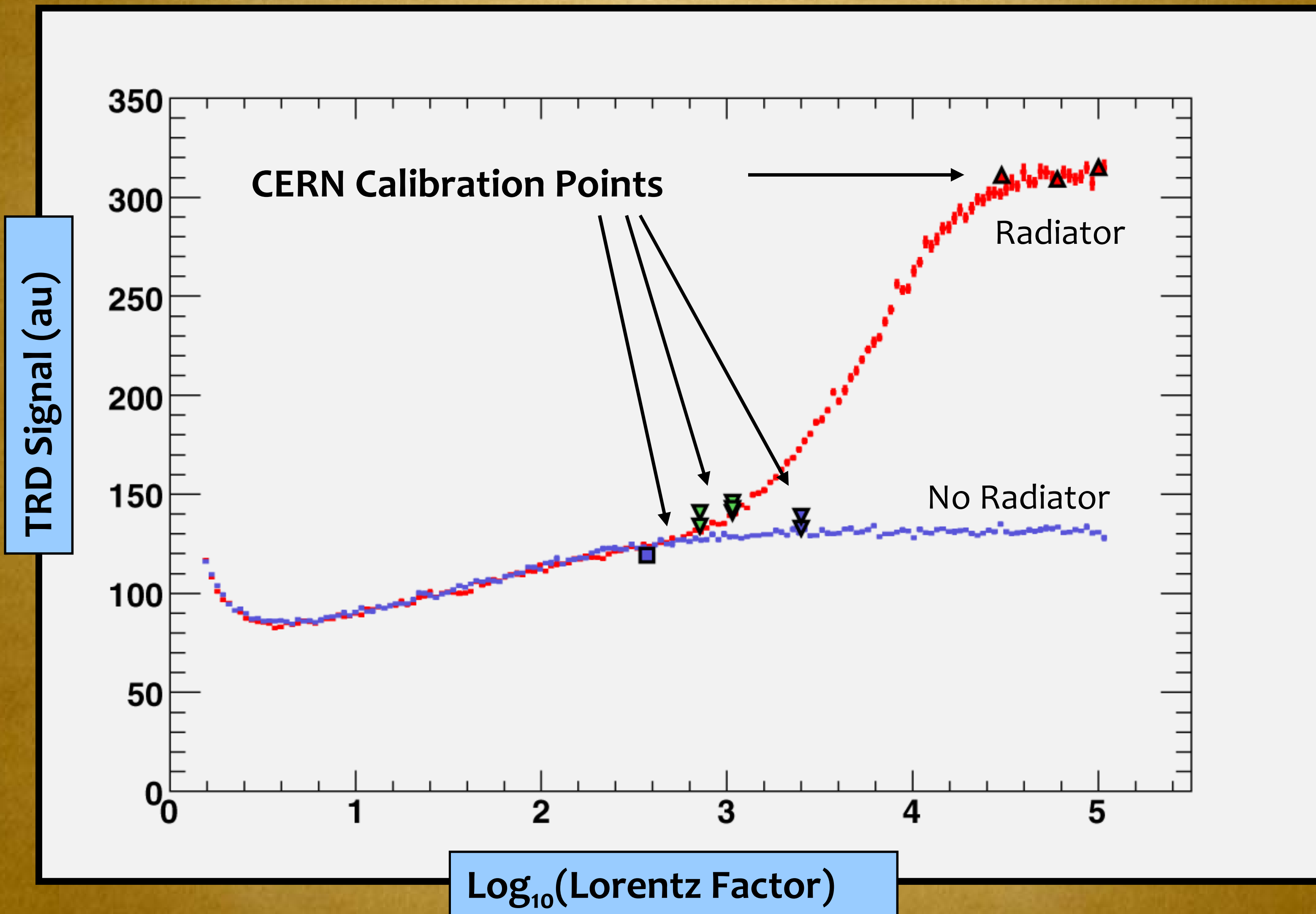
Transition Radiation

- X-ray radiation from dielectric transitions
  - Varies with Lorentz Factor (γ) and charge Z^2
  - Electron and proton at same energy have much different γ
- Detectors require multiple interfaces + thin gas detectors
- Important points:
  - Process not destructive to the particle
  - Can be calibrated at beamlines [cf calorimeters]





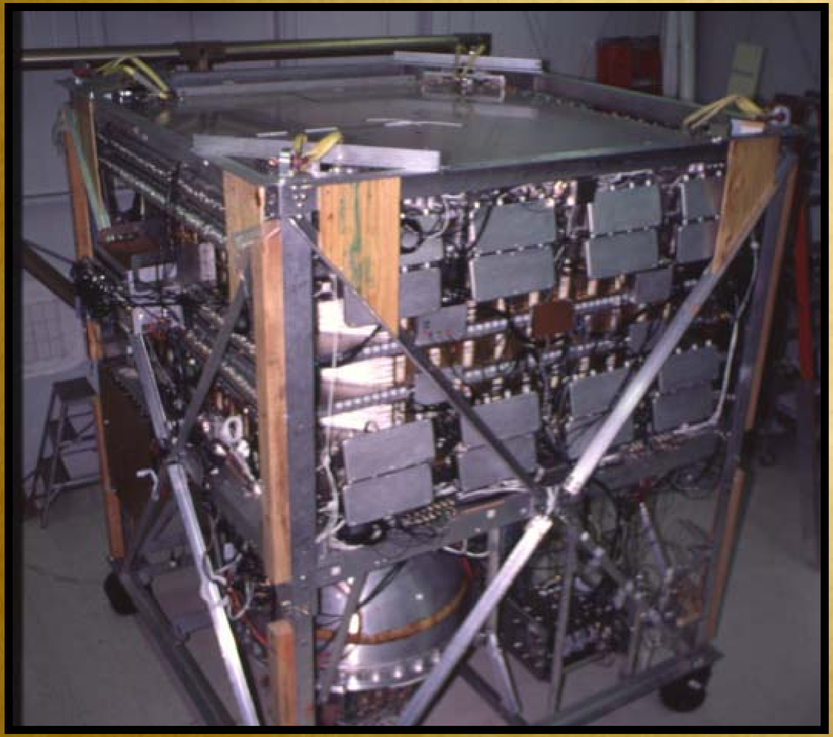
Simulations vs CERN Calibration



Modified GEANT 4.7.1.p01

CR Detectors

- Examples: TRACER & CREAM



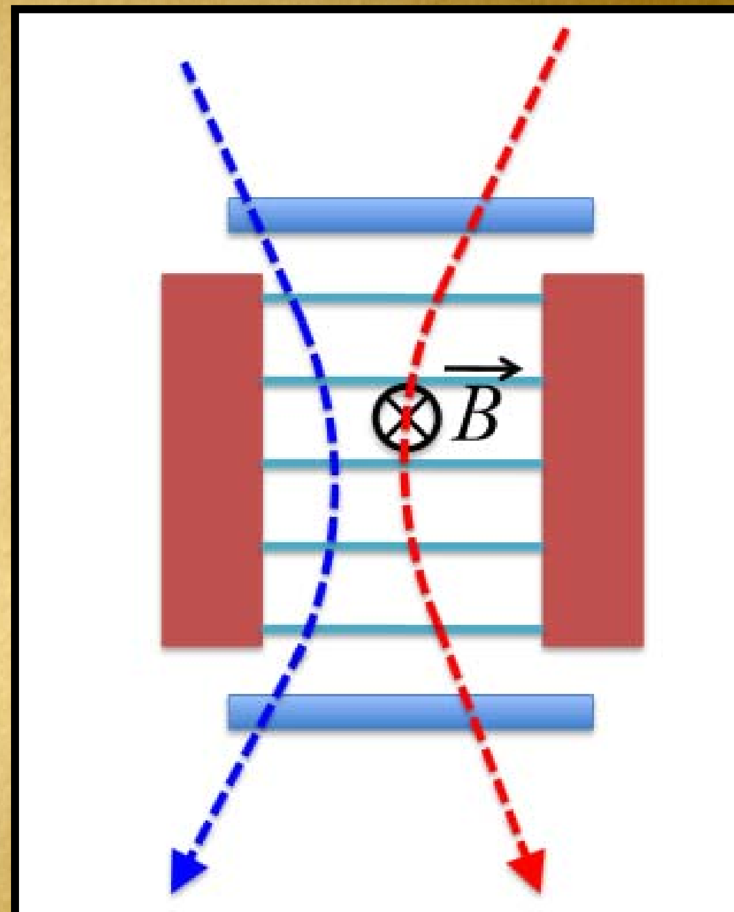
Magnet Spectrometry

- **If you really want to measure the mass of the primary particles (e.g., isotope measurements), then using Z as a proxy for A will not be sufficient**
- **But how to make a detector which responds to mass?**
  - **Magnet spectrometers achieve this by measuring multiple particle properties and inferring the mass.**
    - **For instance, a simultaneous measure of momentum and velocity will give you the mass: $p = \beta\gamma mc$**

$$m = p\left(\frac{\sqrt{1-\beta^2}}{\beta}\right)$$

Magnet Spectrometry

- **In practice, you do this by measuring how the particle bends in a magnetic field, obtaining the rigidity (R = pc/Ze)**
  - Use tracking detectors like silicon strips or gas detectors
- **Then use, e.g., scintillators to tell you the charge, which gives you momentum, p**



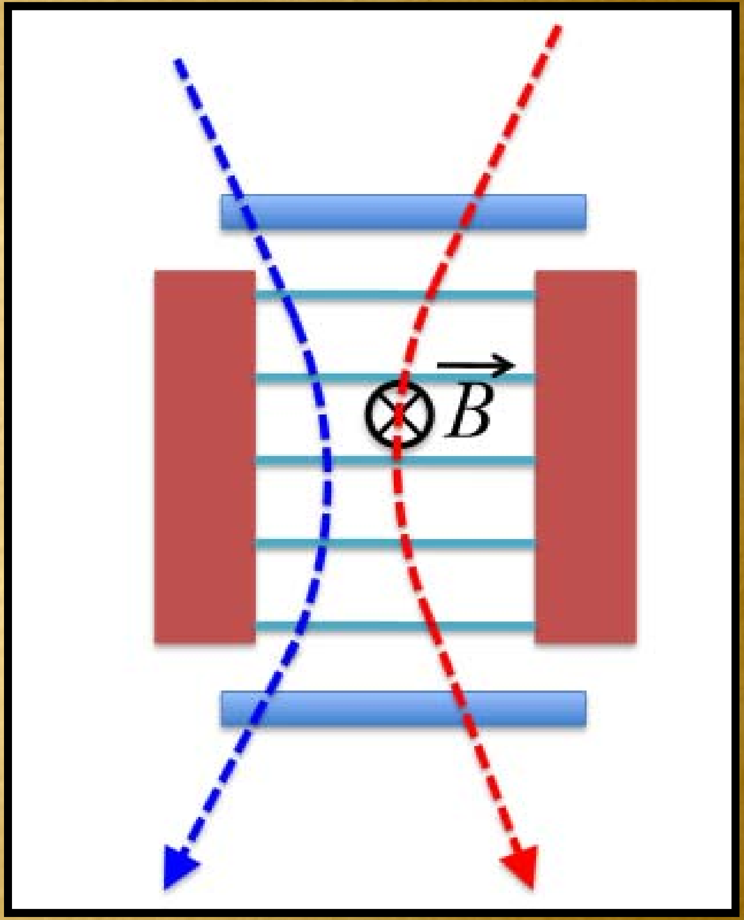
Magnet Spectrometry

- Then you can use time-of-flight or Cherenkov detectors to give you β (and thus γ)

- Error Formula:

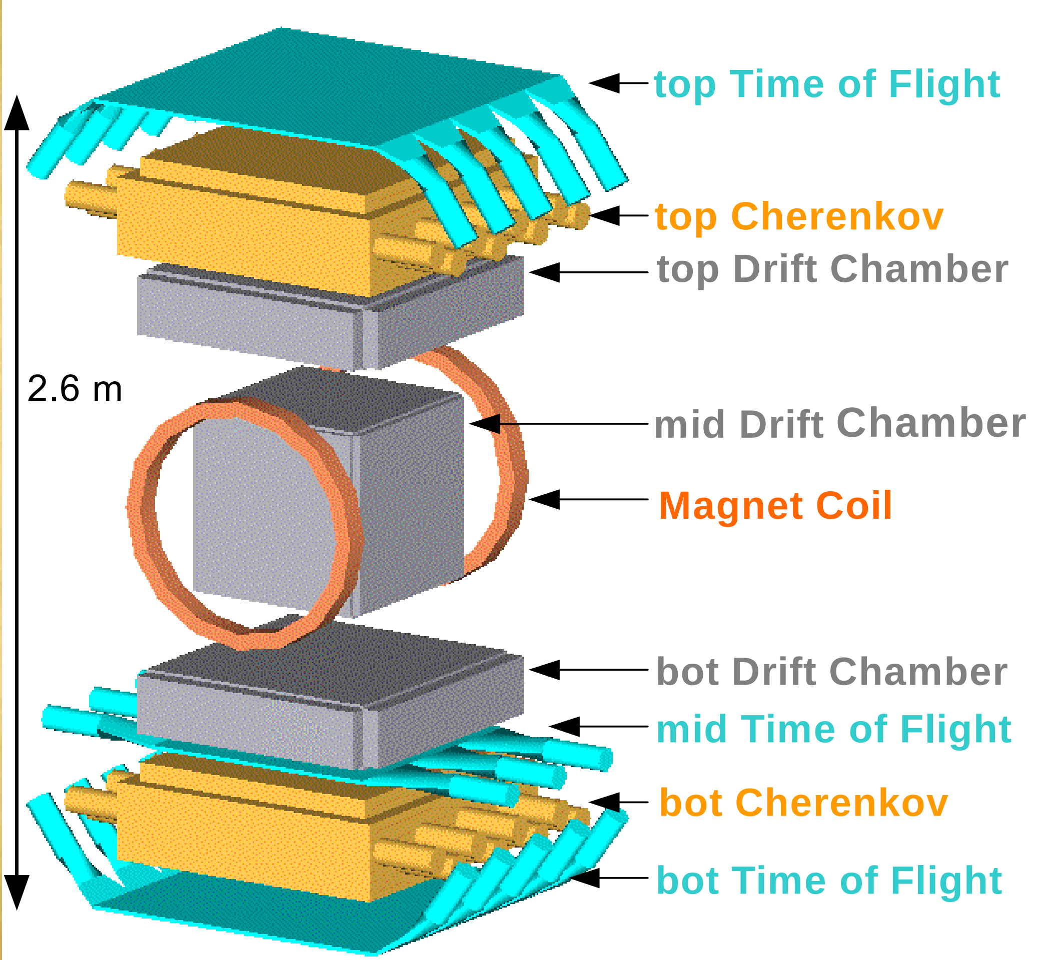
$$\left(\frac{\sigma_M}{M}\right)^2 = \left(\frac{\sigma_P}{P}\right)^2 + \left(\gamma^2 \frac{\sigma_\beta}{\beta}\right)^2$$

This term severely impacts energy reach



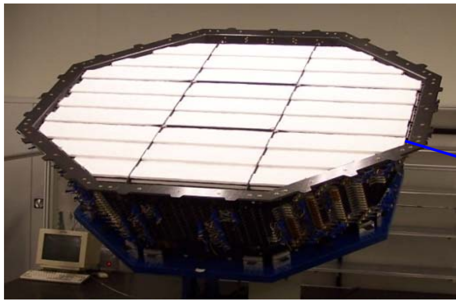
ISOMAX

- Most successful detector for high-energy isotope measurements was ISOMAX
  - Multiple charge detectors
  - Multiple Cherenkov detectors
  - Gas ionization tracking chambers
  - 0.8T B-field

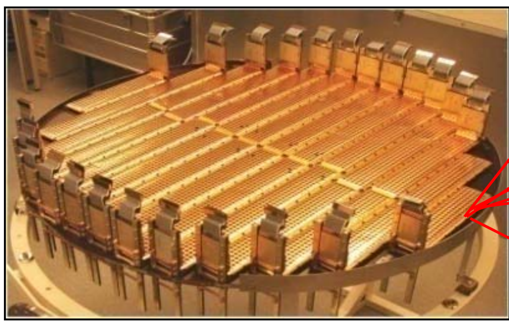


AMS: A TeV precision, multipurpose spectrometer

TRD
Identify e+, e-

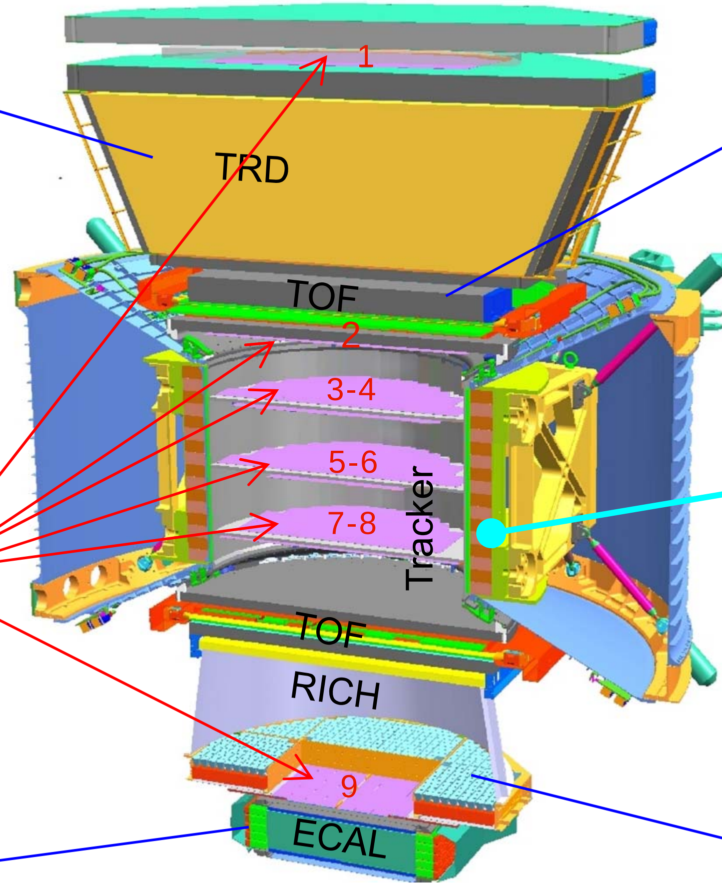


Silicon Tracker
Z, P



ECAL
E of e+, e-, γ

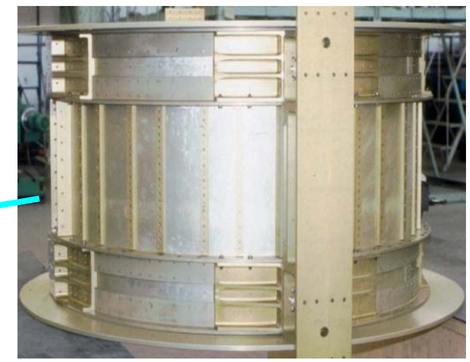
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)



Z, P are measured independently from Tracker, RICH, TOF and ECAL

TOF
Z, E

Magnet
±Z



RICH
Z, E

Summary

- To measure particle properties over a large range of particle types and energies, multiple techniques are required
  - Need to understand how particles interact with matter to do this.

- Other resources:
  - Particle Data Booklet
  - The Particle Detector BriefBook
  - Longair's Book(s)
  - Knoll's Book