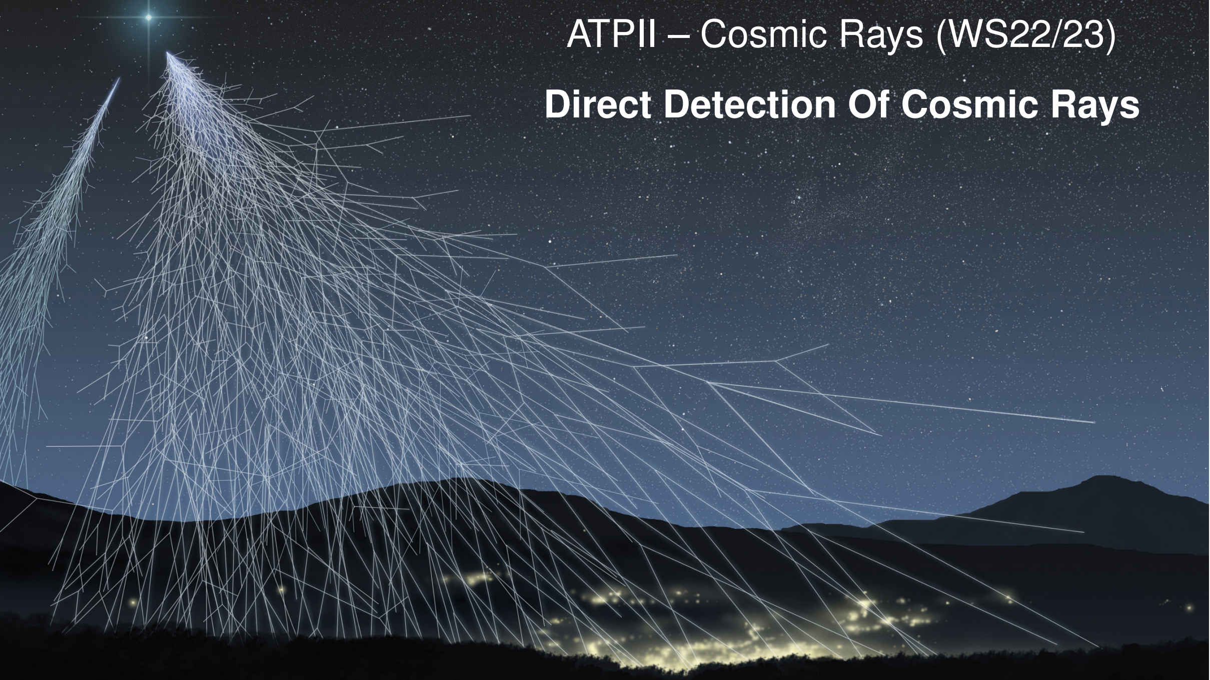
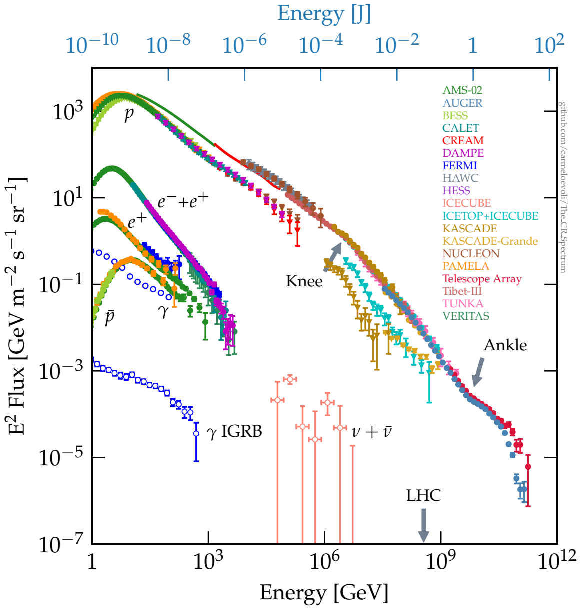
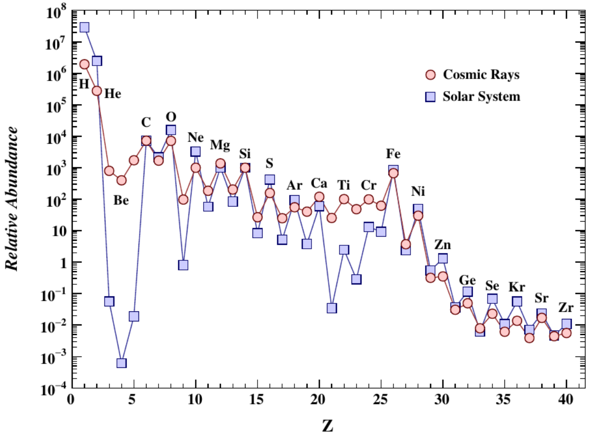
ATPII – Cosmic Rays (WS22/23)

Direct Detection Of Cosmic Rays



Reminder: Cosmic-Ray Spectrum and Composition





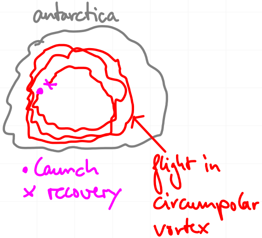
Direct Detection of Cosmic Rays

- atmosphere: $\int_0^\infty \rho(h)\,dh \approx 1000\ g/cm^2$ $\leftrightarrow$ had/em interaction length (tens of g/cm^2)

$\Rightarrow$ space experiments (AMS, DAMPE, Voyager...)

$\Rightarrow$ long duration balloon flights (eg. SuperTIGER 55 days!)

$h \approx 40\,km \leftrightarrow \int_h^\infty \rho(h)\,dh \lesssim 5\ g/cm^2$

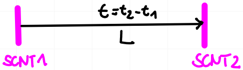


$\Rightarrow$ particle identification

$\Rightarrow$ particle energy or momentum

Particle Identification (mass and/or charge)

- **time of flight** $\Rightarrow \beta$
  $+ p/E \Rightarrow m$



$$v = \frac{L}{t}, \quad \beta = \frac{L}{t \cdot c} = \frac{p}{E} = \frac{p}{\sqrt{p^2+m^2}}$$

$$\Rightarrow \quad m^2 = p^2\left(\frac{1}{\beta^2} - 1\right) = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

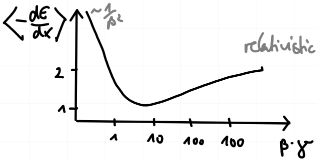
- **energy loss/deposit** $\Rightarrow z^2$ (some knowledge of p/E needed)

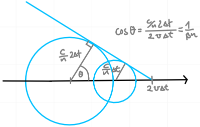
ionization: $\left\langle -\frac{dE}{dx}\right\rangle \sim z^2 \, \rho \; \mathrm{MeV/g/cm^2}$

z^2: particle charge
ρ: density of medium

Bethe(-Bloch) equation

minimum ionizing particle / MIP : $\beta\gamma = 4$





- **Cherenkov light** $\Rightarrow \beta$
  $+ p/E \Rightarrow m$

$v > c \cdot n$ — refractive index

→ threshold $\beta_T = \frac{1}{n}$

→ emission angle $\cos\theta = \frac{1}{\beta n}$

and: $\frac{dN}{dx} \sim z^2$!

slow particle in dielectric medium

fast particle in dielectric medium

Particle Momentum (Spectrometer)

relativistic charge in magnetic field

Lorentz force

equation of motion: $\frac{d\vec{p}}{dt} = \vec{F} \leftrightarrow \frac{d}{dt}(\gamma m \vec{v}) = z \cdot e \cdot (\vec{v} \times \vec{B})$

$\dot{\vec{v}} \perp \vec{v} \Rightarrow \dot{\gamma} = 0$ $\qquad \gamma m \dot{\vec{v}} = z \cdot e (\vec{v} \times \vec{B})$

for $\vec{B} \perp \vec{v}$ $\qquad \dot{v}_x = \frac{z \cdot e}{\gamma m} v_y B \qquad \dot{v}_y = -\frac{z \cdot e}{\gamma m} v_x B$

solution $\qquad v_x = v \sin\left(\frac{zeB}{\gamma m} t\right) \qquad v_y = v \cos\left(\frac{zeB}{\gamma m} t\right)$

$$x = -\frac{v\gamma m}{zeB} \cos\left(\frac{zeB}{\gamma m} t\right) \qquad y = \frac{v\gamma m}{zeB} \sin\left(\frac{zeB}{\gamma m} t\right)$$

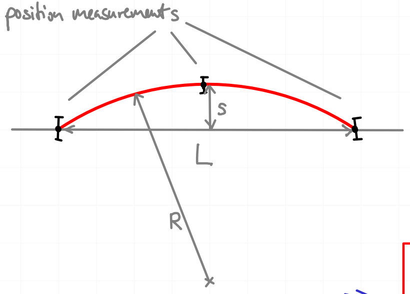
circular motion with radius $\qquad r = \sqrt{x^2 + y^2} = \frac{v\gamma m}{zeB} \underset{v \approx c}{\approx} \frac{c\gamma m}{zeB} \equiv \frac{R}{B}$

$$\boxed{r = 3.3\,\mathrm{m}\, \frac{p/\mathrm{GeV}}{z \cdot (B/\mathrm{T})}}$$

"rigidity" R

$[R] = \mathrm{V}$ (GV, TV etc)

Particle Momentum (Spectrometer)



"sagitta" $s \approx \frac{L^2}{8r}$ ($s \ll L$)

uncertainty $\sigma_s \approx \frac{\sigma_{pos}}{\sqrt{N}}$

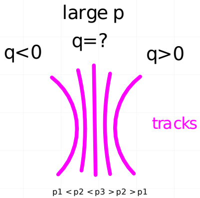
→ uncert. of position measurement

→ number of position measurements

$$\Rightarrow \boxed{\frac{\sigma(p)}{p} \sim \frac{\sigma_{pos}}{\sqrt{N}\, L^2 B}\, p} \quad (z=1)$$

"maximum detectable momentum" MDM $\Leftrightarrow$ $\frac{\sigma(p)}{p} = 1$

also: "maximum detectable rigidity" MDR



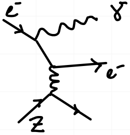
Energy (Calorimeter)

electromagnetic (see later for hadronic showers)

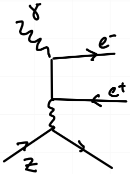
$$\left\langle -\frac{dE}{dx} \right\rangle_{\text{brems, pair}} = \frac{E}{X_0} \quad \leftrightarrow \quad E(x) = E_0 e^{-x/X_0}$$

radiation length $\quad X_0 \sim \Big(\underbrace{\frac{1}{m^2}}_{\text{projectile}} \overbrace{\frac{Z^2}{A} \rho}^{\text{material}} \Big)^{-1}$

interactions with nuclei of material (Z)



bremsstrahlung



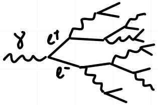
pair production

$\left\langle -\frac{dE}{dx} \right\rangle_{\text{brems}} \sim E$

$\left\langle -\frac{dE}{dx} \right\rangle_{\text{ion}} \sim \text{const}$

E_{crit} when $\left\langle -\frac{dE}{dx} \right\rangle_{\text{brems}} = \left\langle -\frac{dE}{dx} \right\rangle_{\text{ion}}$

electromagnetic shower: cascade of $e^+ e^- \gamma$



splitting length $\quad d = \ln 2 \cdot X_0$

proceeds until $E(n) = E_0 / N = E_{crit}$

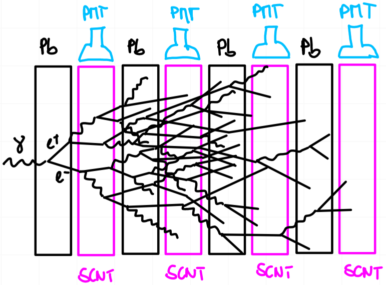
number of particles after n splittings: $\quad N = 2^n$

$$n_{max} = \frac{\ln(E_0/E_{crit})}{\ln 2} \qquad \boxed{N_{max} = \frac{E_0}{E_{crit}}}$$

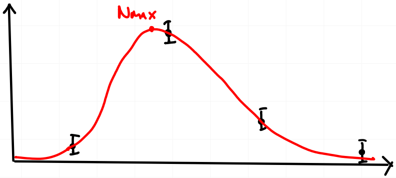
$\Rightarrow$ energy from number of particles at shower maximum

Energy (Calorimeter)

"sandwich calorimeter"



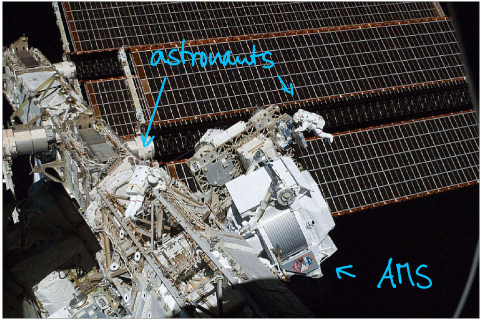
PMT signal $\sim \left(\frac{dE}{dx}\right)_{e^+e^-} \cdot N_{e^+e^-}$

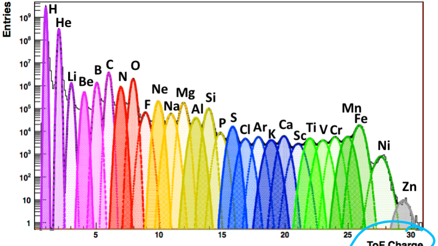


typical resolution $\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E/GeV}}$ $\left(\sim \frac{1}{\sqrt{N_{max}}}!\right)$

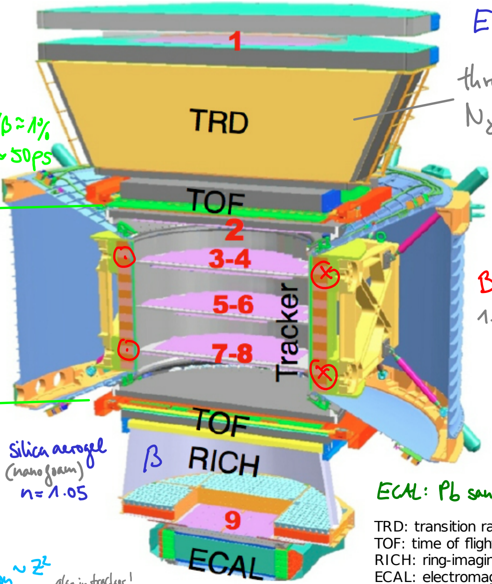
Alpha Magnetic Spectrometer (AMS) on the ISS

since 2011, $A = 0.5\,\mathrm{m^2 sr}$ (aperture)
$E \approx$ GeV to TeV





$\langle -\frac{dE}{dx} \rangle_{\text{ion}} \sim Z^2$ also in tracker!



TOF: $\sigma(\beta)/\beta \approx 1\%$
$\sigma(t) \sim 50\,\mathrm{ps}$

β

threshold $\sim \gamma$
$N_\gamma \sim \gamma$

$B = 0.15\,\mathrm{T}$
1.2t neodymium

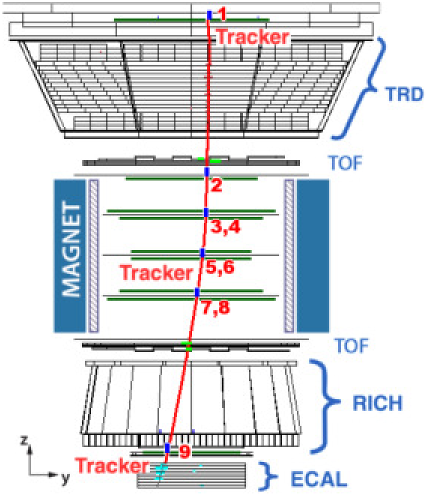
Silica aerogel (nanofoam) $n = 1.05$

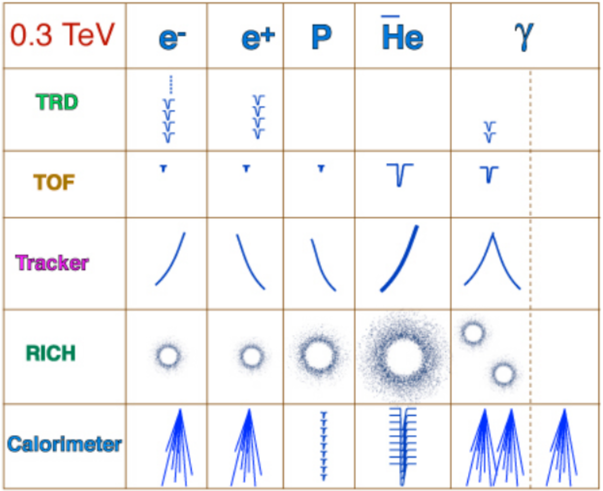
β

ECAL: Pb sandwich, $17 X_0$

TRD: transition radiation detector
TOF: time of flight
RICH: ring-imaging Cherenkov
ECAL: electromagnetic calorimeter

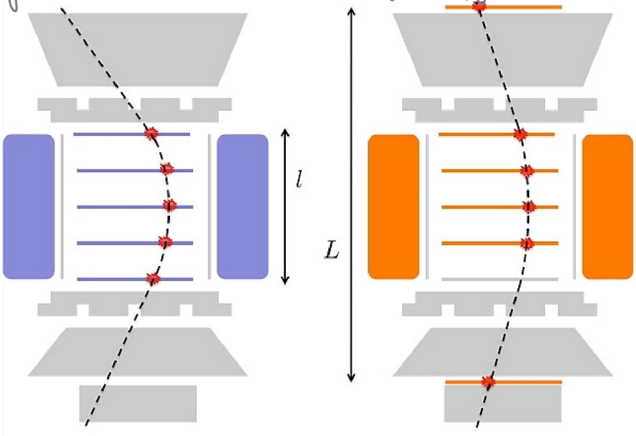
Alpha Magnetic Spectrometer (AMS) on the ISS





Alpha Magnetic Spectrometer (AMS) on the ISS

original plan (end ISS 2015) final configuration (→2028)



Superconducting Magnet Scenario Permanent Magnet Scenario

$B_{SCM} \sim 5\, B_{PM}$

$l \sim 1\,m \quad L \sim 3\,m$

but: smaller aperture ↔ exposure??

⇒ see problem set 1!

Dark Matter Particle Explorer (DAMPE) Satellite

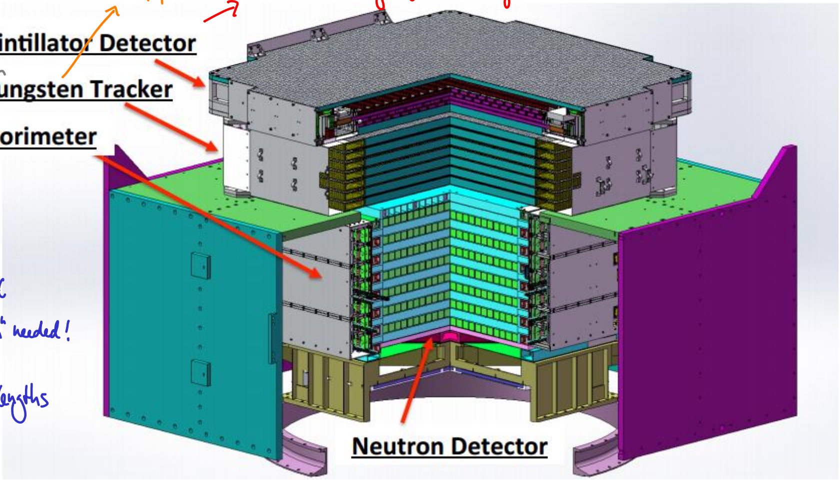
since 2015, $A = 0.2\,m^2 sr$

$E \approx$ GeV to $\gtrsim 10$ TeV

detector

Z=74

anti-coincidence for γ-id, Z^2 for nuclei



$Bi_4 Ge_3 O_{12}$

Z = 83 32 8

scintillating crystal

$\Rightarrow$ no "sandwich" needed!

31 radiation lengths

boron-doped plastic scintillator

high neutron cross section

$\Rightarrow \gamma/e$-hadron separation

Dark Matter Particle Explorer (DAMPE) Satellite