Detectors for LAT

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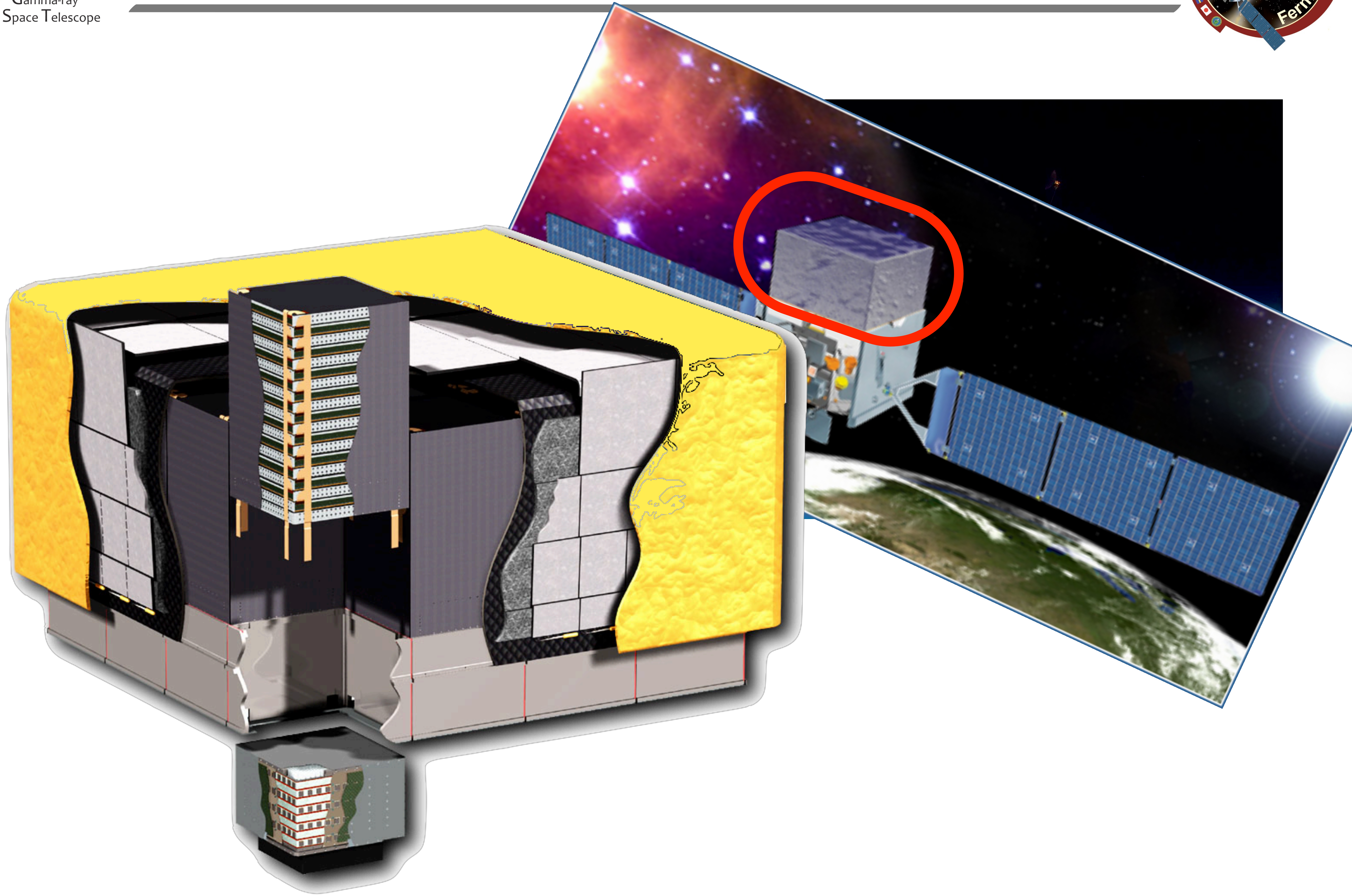
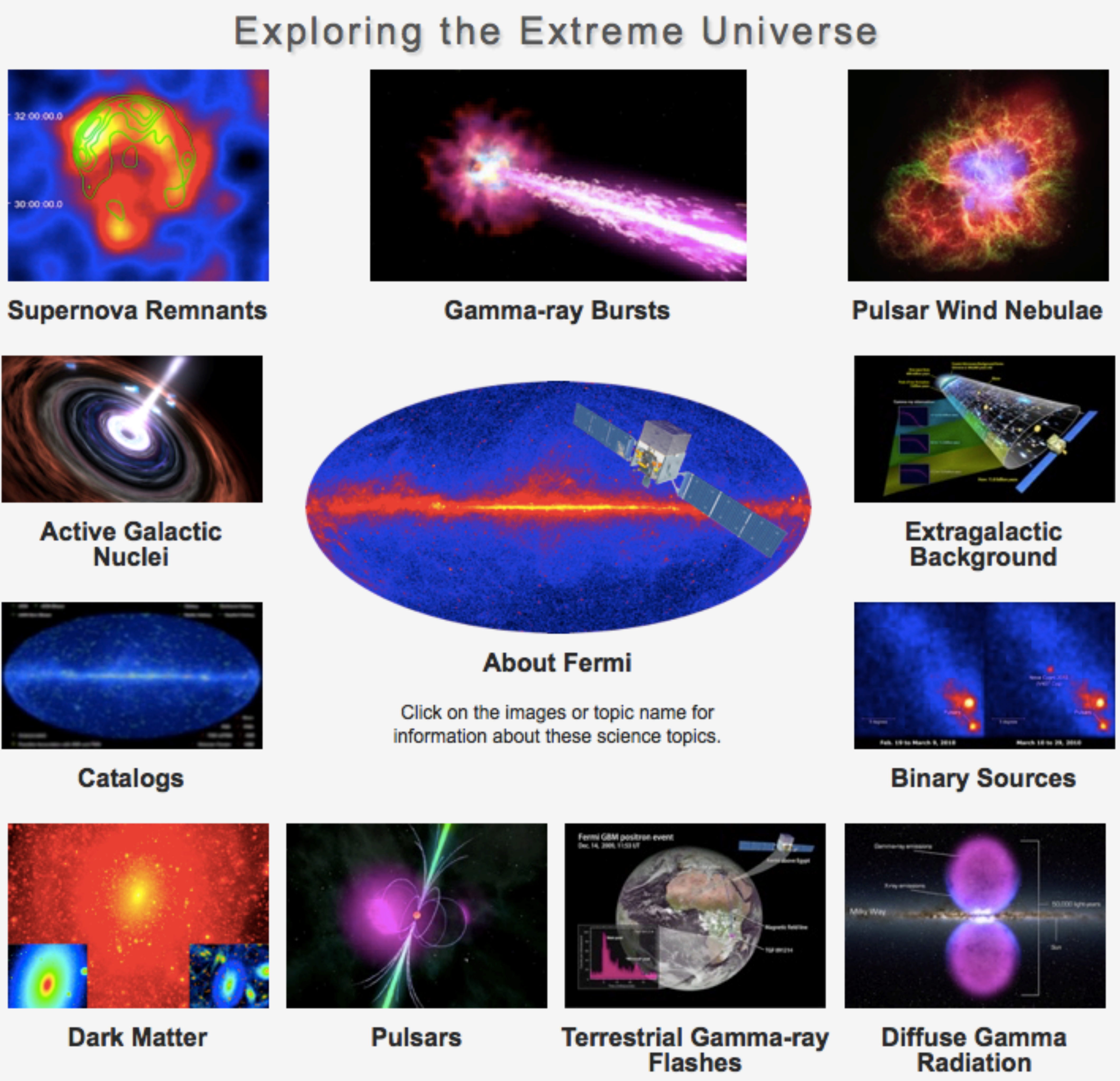
Fermi Large Area Telescope





Exploring the Extreme Universe

Supernova Remnants

Gamma-ray Bursts

Pulsar Wind Nebulae

Active Galactic Nuclei

Extragalactic Background

About Fermi

Click on the images or topic name for information about these science topics.

Catalogs

Binary Sources

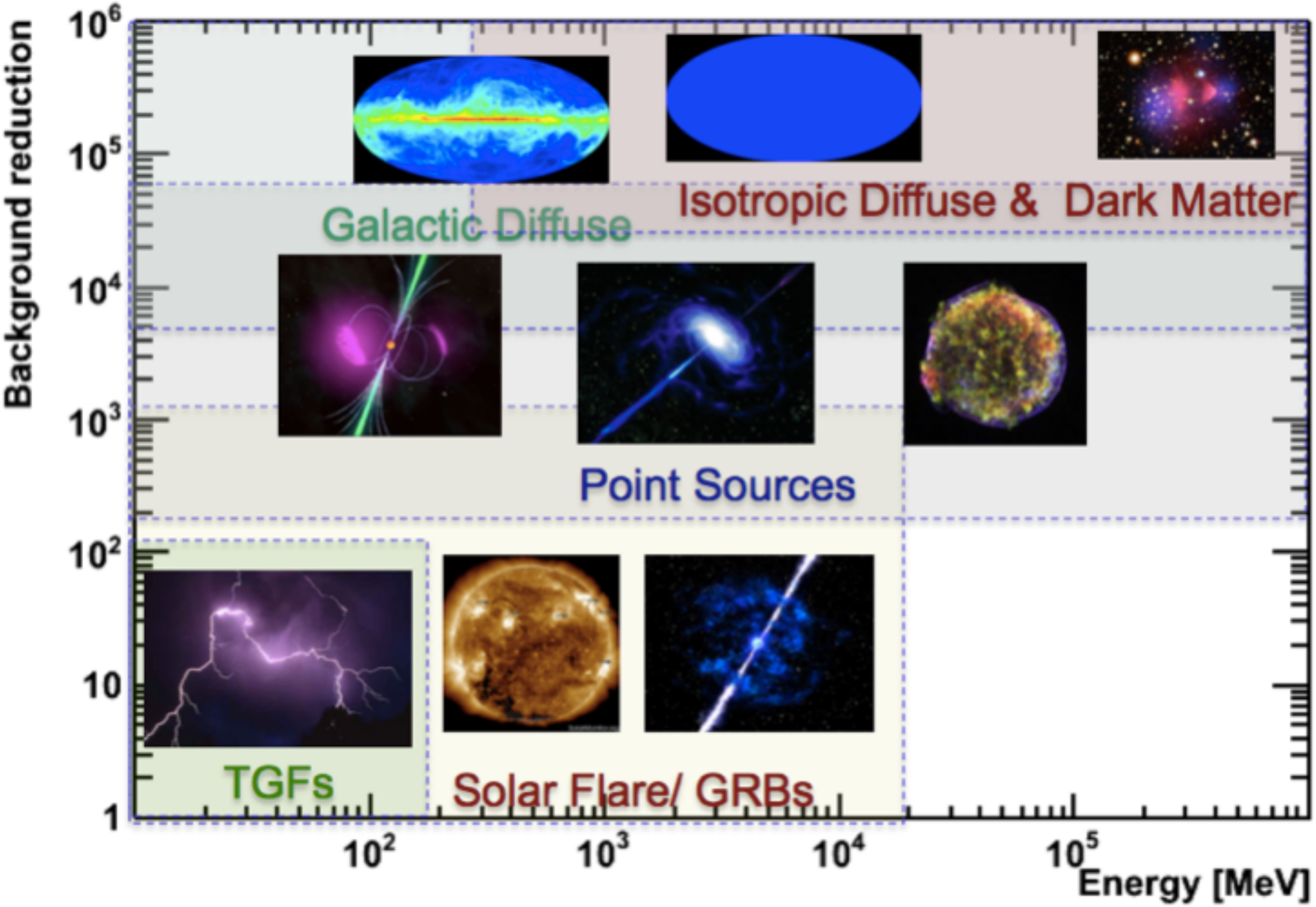
Dark Matter

Pulsars

Terrestrial Gamma-ray Flashes

Diffuse Gamma Radiation

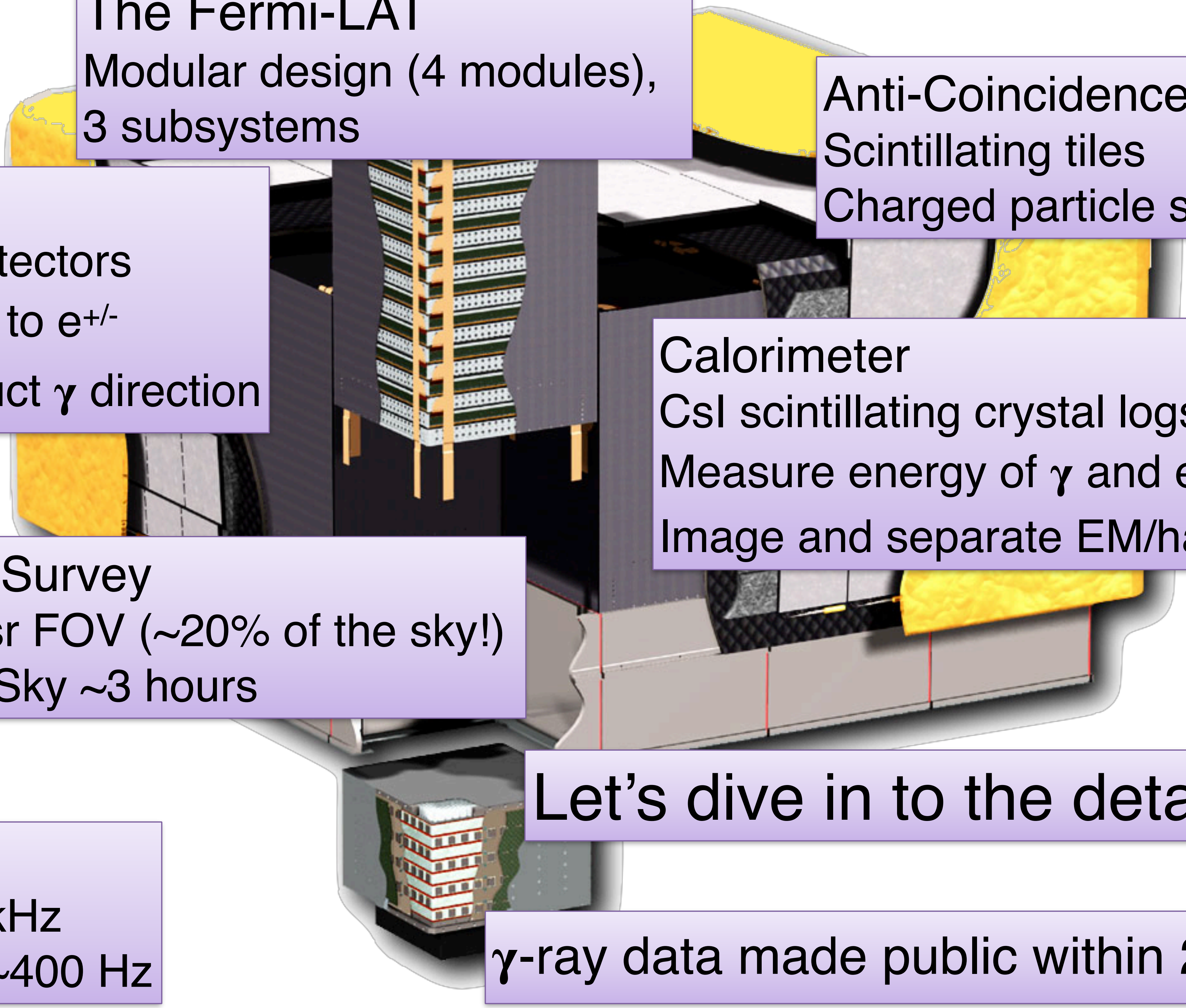
A Broad Range of Fermi-LAT Science



Develop event classes and event types specialized for each type of science

Getting to know you… what do you study?

Fermi Large Area Telescope



The Fermi-LAT
Modular design (4 modules),
3 subsystems

Anti-Coincidence Detector
Scintillating tiles
Charged particle separation

Tracker
Silicon detectors
Convert γ to $e^{+/-}$
Reconstruct γ direction

Calorimeter
CsI scintillating crystal logs
Measure energy of γ and $e^{+/-}$
Image and separate EM/had. showers

Sky Survey
2.5 sr FOV (~20% of the sky!)
Full Sky ~3 hours

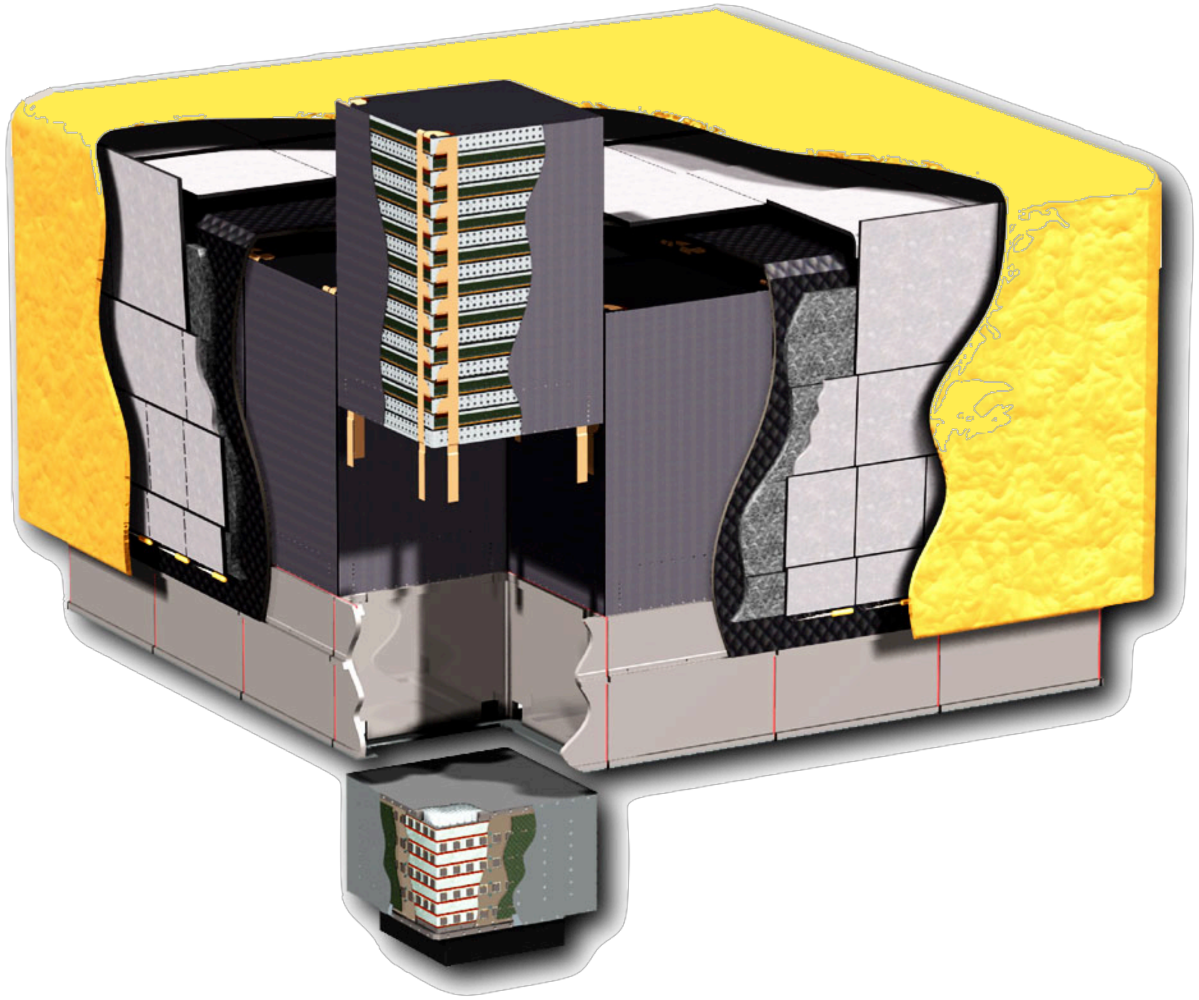
Let's dive in to the details!…

Trigger
rate: ~10 kHz
read out: ~400 Hz

γ-ray data made public within 24 hours

Why does the LAT look like this?

- Design choices
  - Tune for performance
    - Energy resolution
    - Localization accuracy
    - Sensitivity
- Technical limitations
  - Mass, cost
  - Power consumption
  - Data rates… etc



To make these decisions we first need to understand some things…

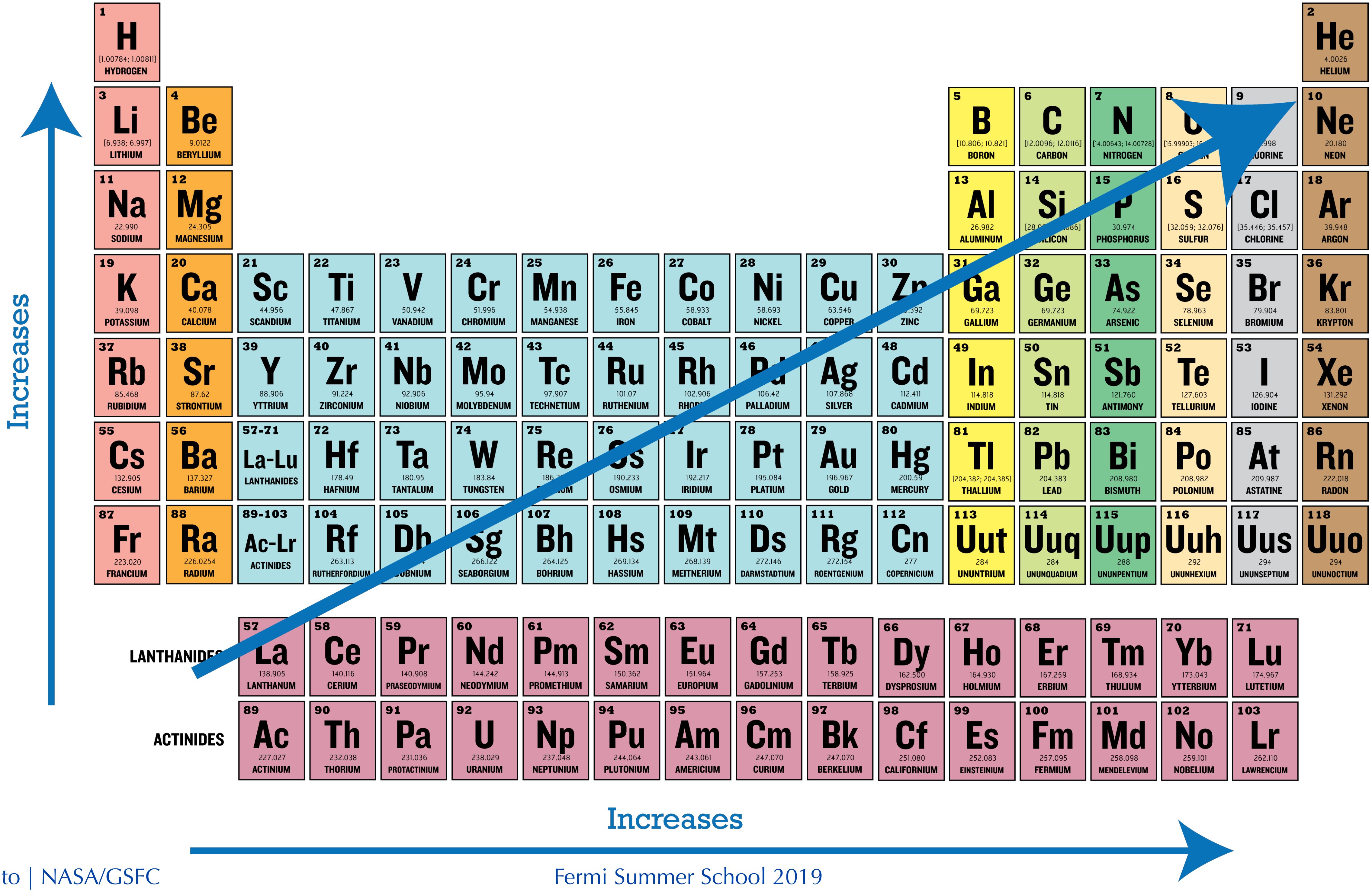
Why does the LAT look like this?

- **Particle interactions in matter**
  - **Detectors for different particles and interactions**
  - **Charged particles**
    - **Ionization, Bremsstrahlung, Scattering, Cherenkov**
  - **Photons Specifically**
    - **Photoelectric effect, Compton scattering, pair production**

- **Detecting those particles!**
  - **Tracking, Calorimeters**

Charged particle interactions in matter

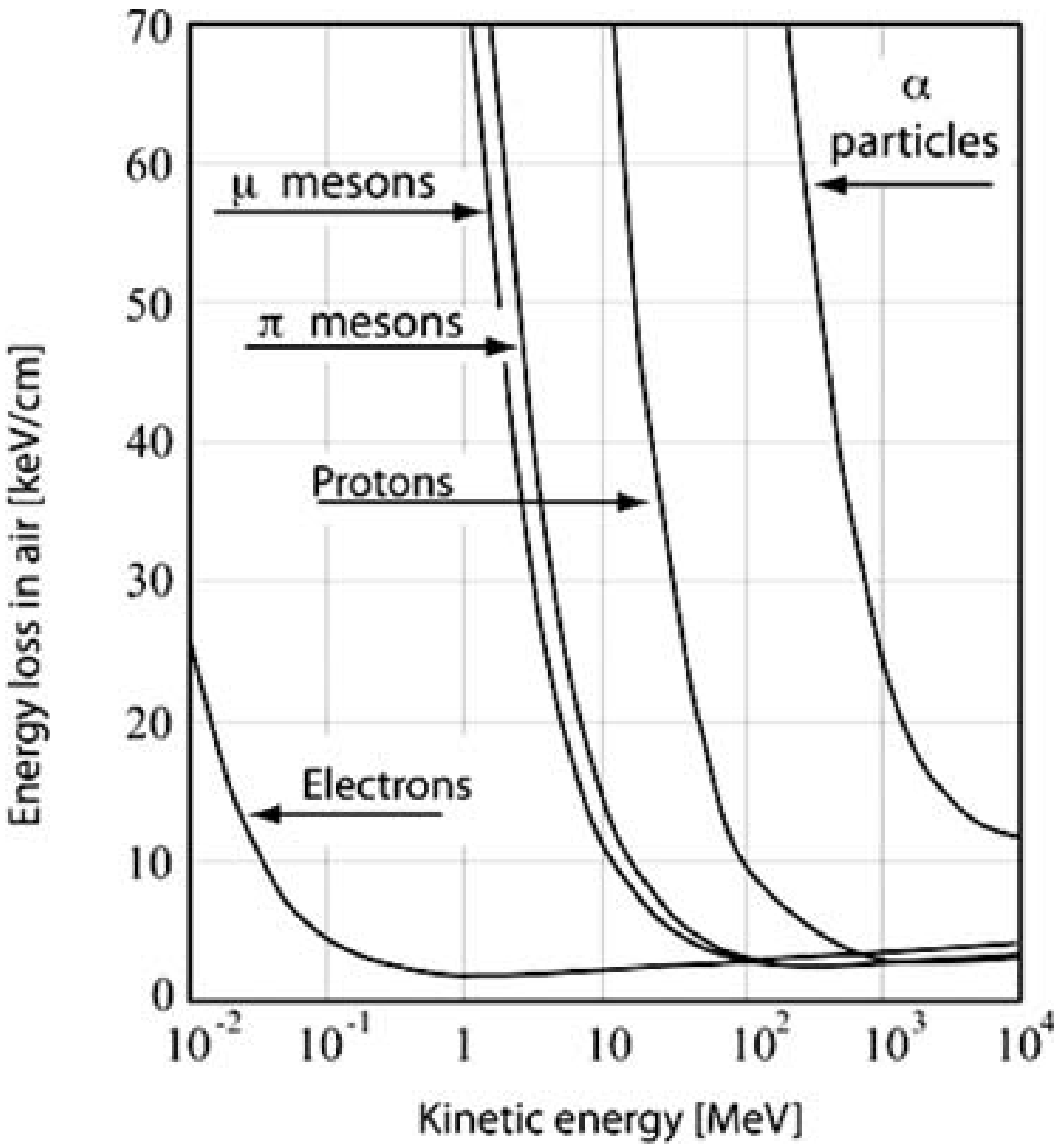
Ionization Energy: Energy required to remove outermost electron



1 H [1.00784; 1.00811] HYDROGEN																	2 He 4.0026 HELIUM
3 Li [6.938; 6.997] LITHIUM	4 Be 9.0122 BERYLLIUM											5 B [10.806; 10.821] BORON	6 C [12.0096; 12.0116] CARBON	7 N [14.00643; 14.00728] NITROGEN	8 [15.99903; 15	9 998 UORINE	10 Ne 20.180 NEON
11 Na 22.990 SODIUM	12 Mg 24.305 MAGNESIUM											13 Al 26.982 ALUMINUM	14 Si [28.0 086] LICON	15 P 30.974 PHOSPHORUS	16 S [32.059; 32.076] SULFUR	17 Cl [35.446; 35.457] CHLORINE	18 Ar 39.948 ARGON
19 K 39.098 POTASSIUM	20 Ca 40.078 CALCIUM	21 Sc 44.956 SCANDIUM	22 Ti 47.867 TITANIUM	23 V 50.942 VANADIUM	24 Cr 51.996 CHROMIUM	25 Mn 54.938 MANGANESE	26 Fe 55.845 IRON	27 Co 58.933 COBALT	28 Ni 58.693 NICKEL	29 Cu 63.546 COPPER	30 Zn .392 ZINC	31 Ga 69.723 GALLIUM	32 Ge 69.723 GERMANIUM	33 As 74.922 ARSENIC	34 Se 78.963 SELENIUM	35 Br 79.904 BROMIUM	36 Kr 83.801 KRYPTON
37 Rb 85.468 RUBIDIUM	38 Sr 87.62 STRONTIUM	39 Y 88.906 YTTRIUM	40 Zr 91.224 ZIRCONIUM	41 Nb 92.906 NIOBIUM	42 Mo 95.94 MOLYBDENUM	43 Tc 97.907 TECHNETIUM	44 Ru 101.07 RUTHENIUM	45 Rh 102.906 RHOD	46 Pd 106.42 PALLADIUM	Ag 107.868 SILVER	48 Cd 112.411 CADMIUM	49 In 114.818 INDIUM	50 Sn 114.818 TIN	51 Sb 121.760 ANTIMONY	52 Te 127.603 TELLURIUM	53 I 126.904 IODINE	54 Xe 131.292 XENON
55 Cs 132.905 CESIUM	56 Ba 137.327 BARIUM	57-71 La-Lu LANTHANIDES	72 Hf 178.49 HAFNIUM	73 Ta 180.95 TANTALUM	74 W 183.84 TUNGSTEN	75 Re 186.2 IUM	76 Os 190.233 OSMIUM	7 Ir 192.217 IRIDIUM	78 Pt 195.084 PLATINUM	79 Au 196.967 GOLD	80 Hg 200.59 MERCURY	81 Tl [204.382; 204.385] THALLIUM	82 Pb 204.383 LEAD	83 Bi 208.980 BISMUTH	84 Po 208.982 POLONIUM	85 At 209.987 ASTATINE	86 Rn 222.018 RADON
87 Fr 223.020 FRANCIUM	88 Ra 226.0254 RADIUM	89-103 Ac-Lr ACTINIDES	104 Rf 263.113 RUTHERFORDIUM	105 Db UBNIUM	106 Sg 266.122 SEABORGIUM	107 Bh 264.125 BOHRIUM	108 Hs 269.134 HASSIUM	109 Mt 268.139 MEITNERIUM	110 Ds 272.146 DARMSTADTIUM	111 Rg 272.154 ROENTGENIUM	112 Cn 277 COPERNICIUM	113 Uut 284 UNUNTRIUM	114 Uuq 284 UNUNQUADIUM	115 Uup 288 UNUNPENTIUM	116 Uuh 292 UNUNHEXIUM	117 Uus 294 UNUNSEPTIUM	118 Uuo 294 UNUNOCTIUM
	LANTHANIDES	57 La 138.905 LANTHANUM	58 Ce 140.116 CERIUM	59 Pr 140.908 PRASEODYMIUM	60 Nd 144.242 NEODYMIUM	61 Pm 144.913 PROMETHIUM	62 Sm 150.362 SAMARIUM	63 Eu 151.964 EUROPIUM	64 Gd 157.253 GADOLINIUM	65 Tb 158.925 TERBIUM	66 Dy 162.500 DYSPROSIUM	67 Ho 164.930 HOLMIUM	68 Er 167.259 ERBIUM	69 Tm 168.934 THULIUM	70 Yb 173.043 YTTERBIUM	71 Lu 174.967 LUTETIUM	
	ACTINIDES	89 Ac 227.027 ACTINIUM	90 Th 232.038 THORIUM	91 Pa 231.036 PROTACTINIUM	92 U 238.029 URANIUM	93 Np 237.048 NEPTUNIUM	94 Pu 244.064 PLUTONIUM	95 Am 243.061 AMERICIUM	96 Cm 247.070 CURIUM	97 Bk 247.070 BERKELIUM	98 Cf 251.080 CALIFORNIUM	99 Es 252.083 EINSTEINIUM	100 Fm 257.095 FERMIUM	101 Md 258.098 MENDELEVIUM	102 No 259.101 NOBELIUM	103 Lr 262.110 LAWRENCIUM	

Ionization

- What to keep in mind:
  - Energy of the incoming charged particle (β)
  - Charge of the incoming charged particle
  - Nuclear charge of the target material (Z)
  - Density of the target material (ρ)

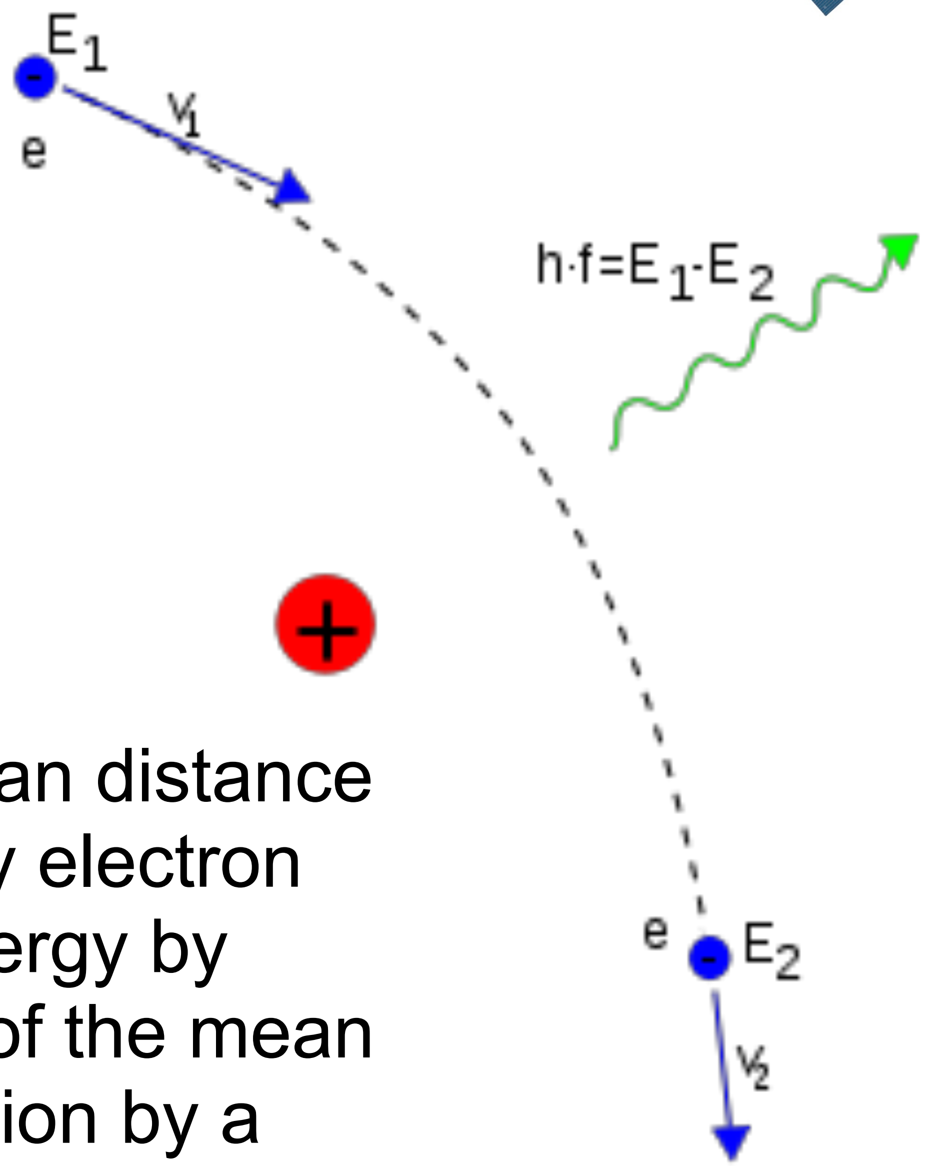


$$\frac{dE}{dx} \approx \rho\,(2\,\mathrm{MeV cm^2/g})\frac{Z^2}{\beta^2}$$

Bremsstrahlung

Bremsstrahlung is radiation due to hard Coulomb interactions of a particle with atomic nuclei (“braking radiation”)

High-energy electrons predominantly lose energy in matter by bremsstrahlung

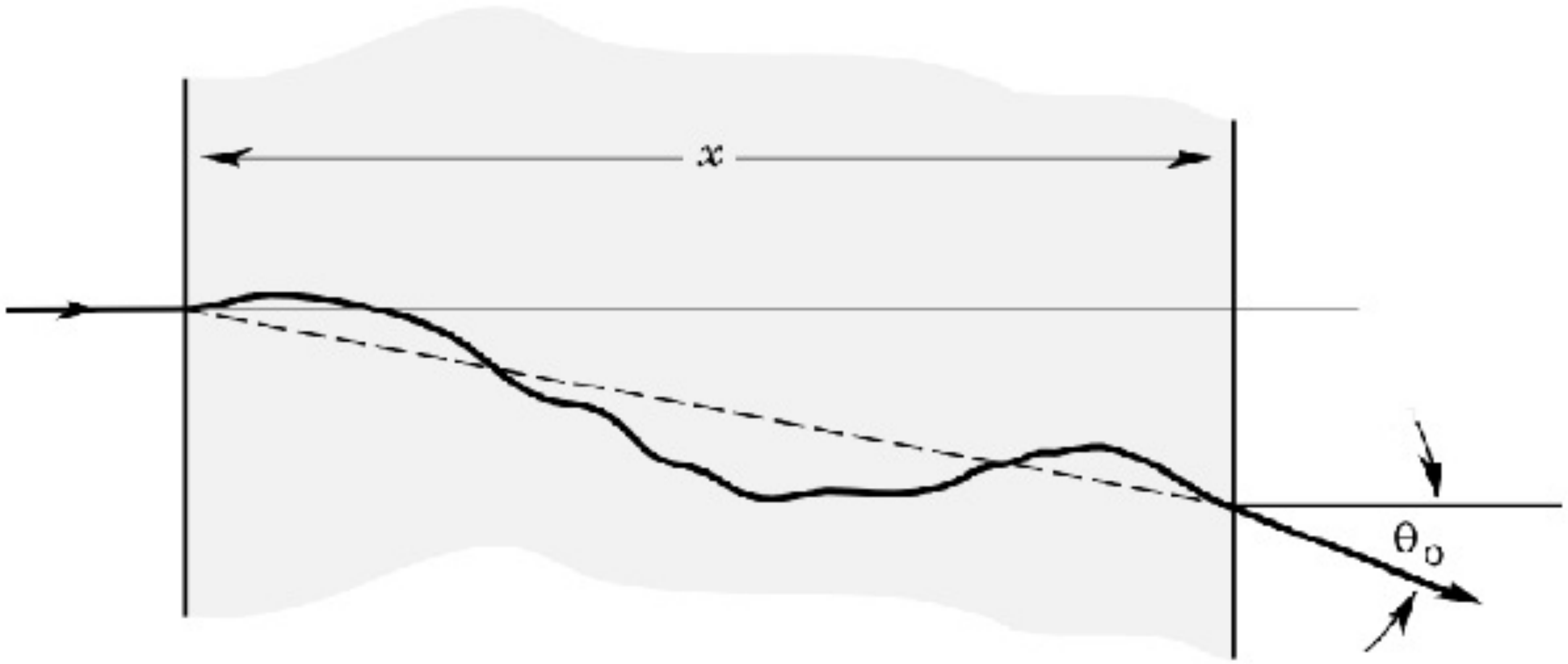


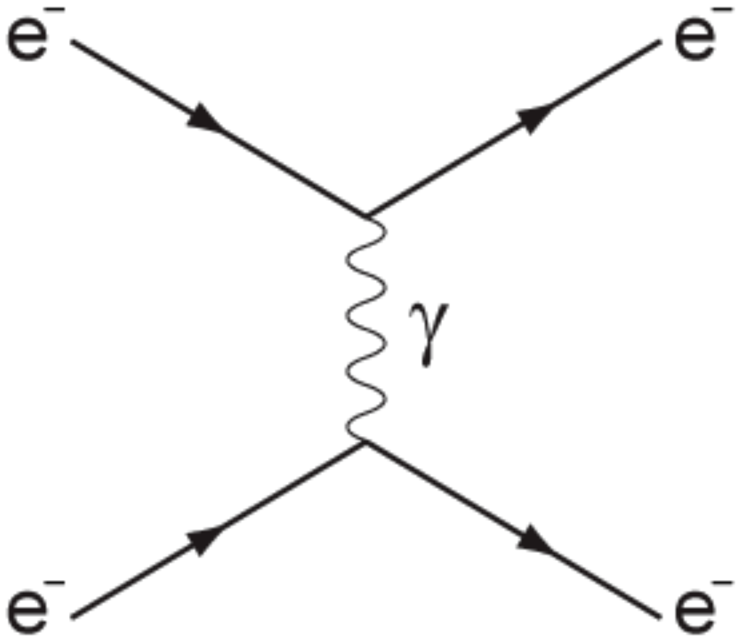
$$\frac{dE}{dx} = -\frac{E}{X_0}$$

Radiation length: the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung, and $^7/_9$ of the mean free path for pair production by a high-energy photon

$$X_0 = \frac{716.4\ \mathrm{g\ cm}^{-2}\ A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

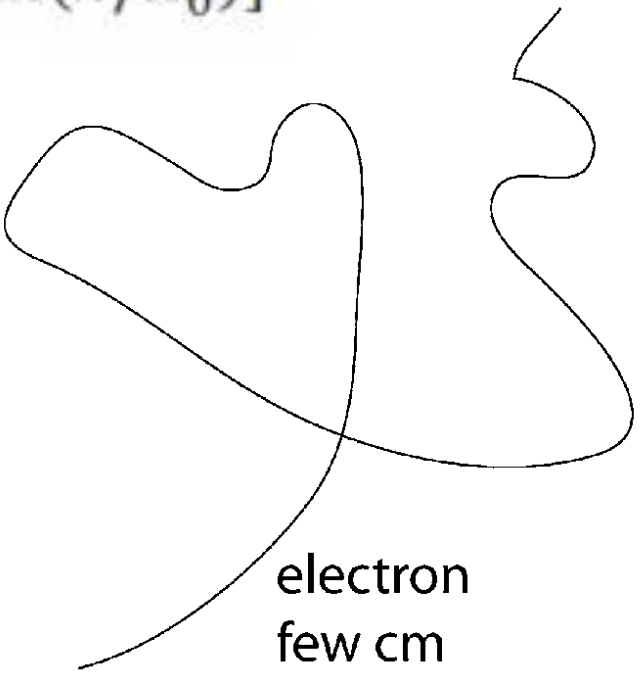
Multiple Scattering



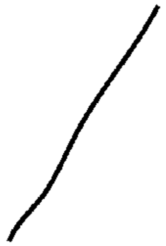


$$\theta_0 = \frac{13.6}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038 \ln(x/X_0)]$$

Same energy



electron
few cm

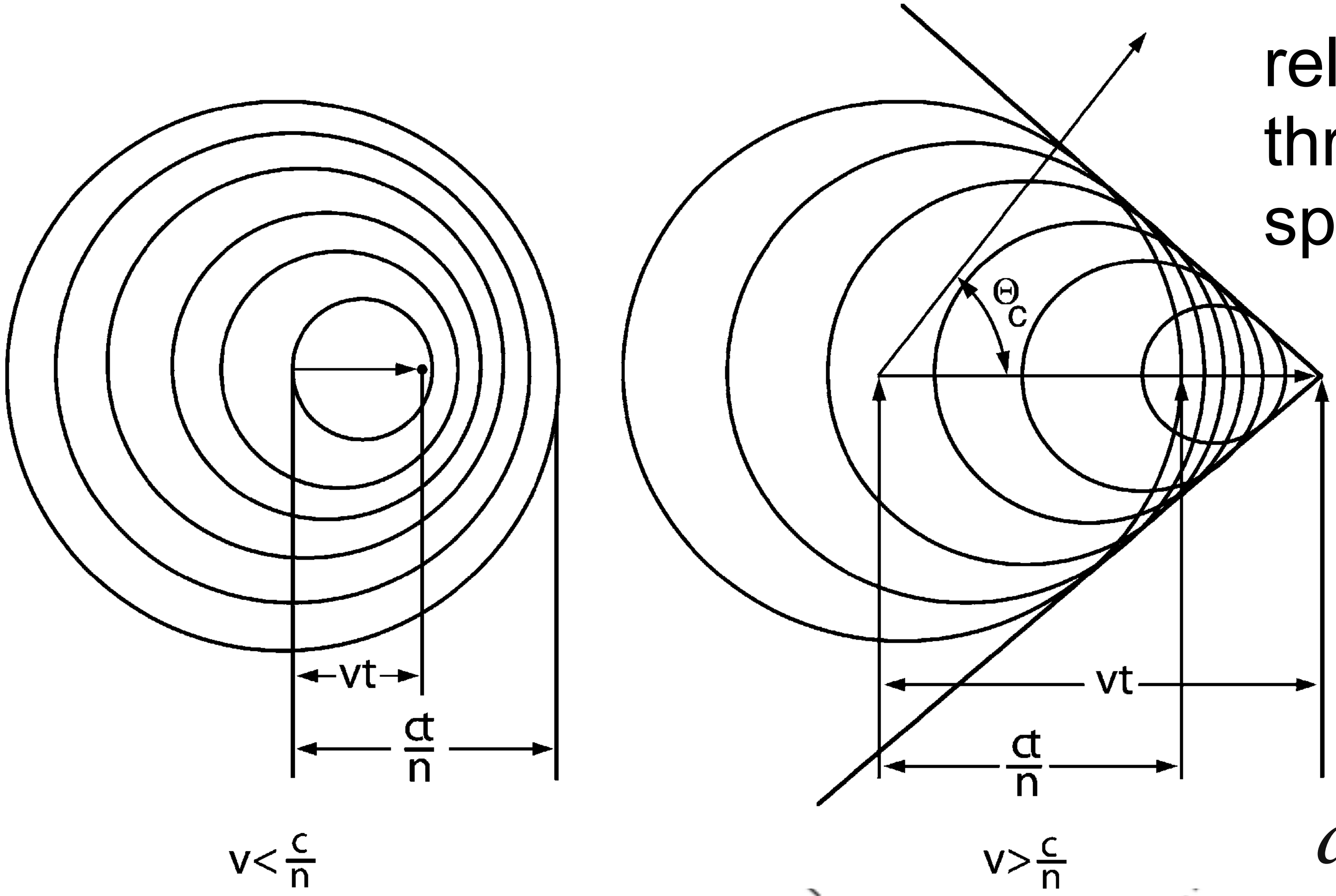


proton
0.8 mm

alpha particle
70 µm

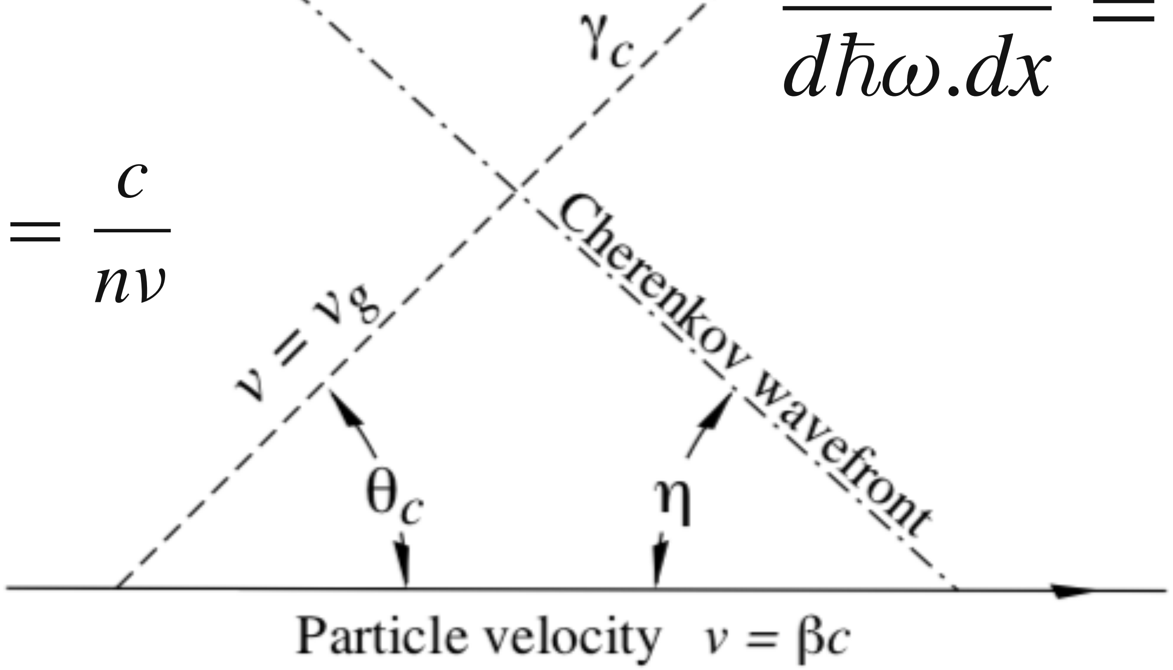
Cherenkov Radiation

relativistic charged particle travels through a medium faster than the speed of light in the medium (c/n)



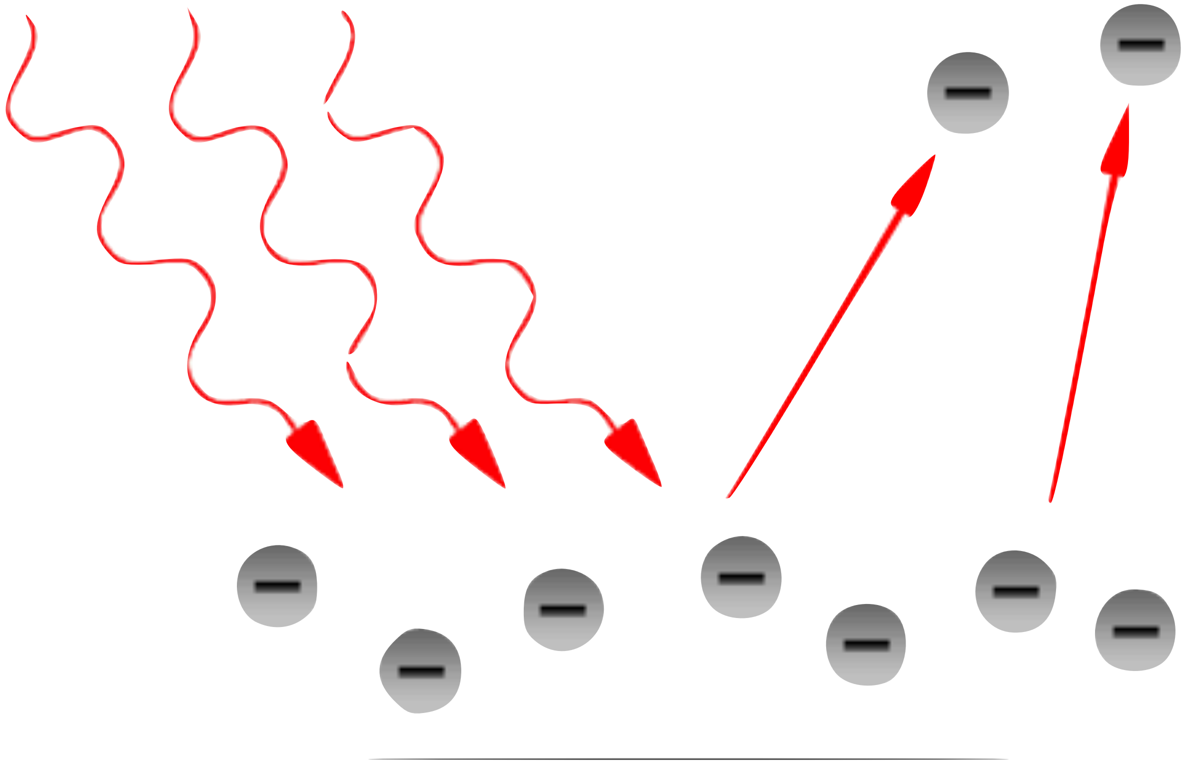
$$\frac{d^2E}{d\hbar\omega.dx} = \hbar\omega\,\frac{Z^2\alpha}{\hbar c}\left[1 - \frac{c^2}{n^2v^2}\right]$$

$$\cos\left(\theta_c\right) = \frac{(c/n)t}{v\,t} = \frac{c}{nv}$$



Back to business: Photons in Matter

Photons in Matter



Low Energy: Photoelectric Effect

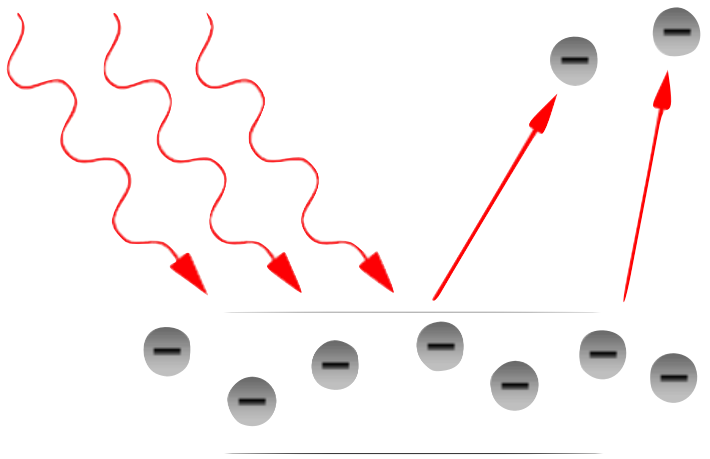
Medium Energy: Compton (Rayleigh/Thompson) Scattering

High Energy: Pair Production

Photoelectric Effect

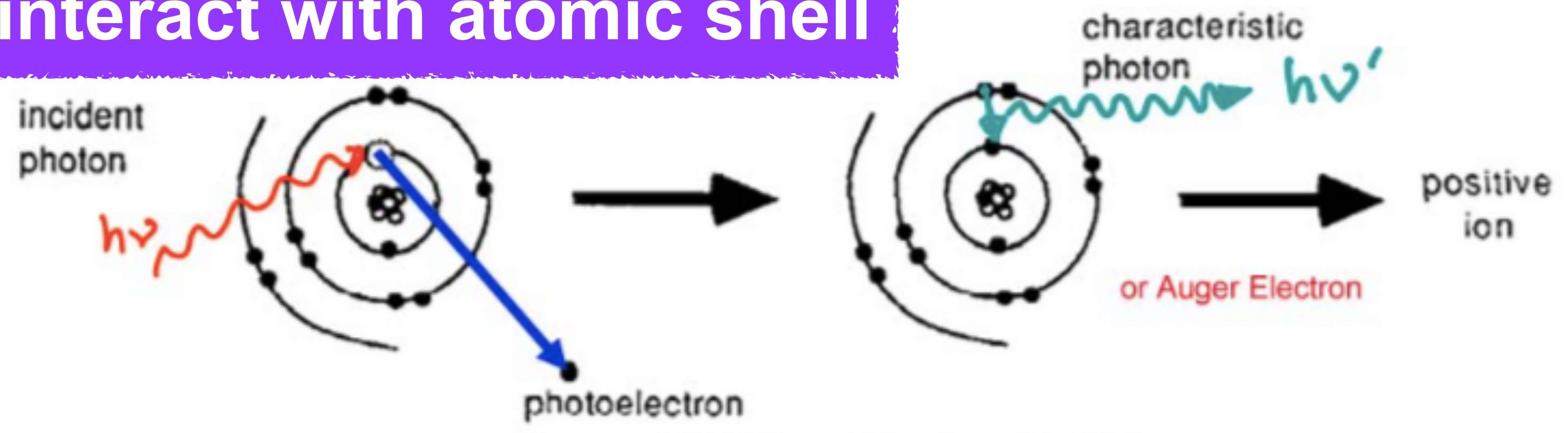
- **Photon absorbed by atom; electron excited or ejected**
  - **Photon energy > binding energy**

$\sigma=\text{const.}\times Z^n/E^3$



Note: photoelectric effect and Brems. must occur in the field of the nucleus

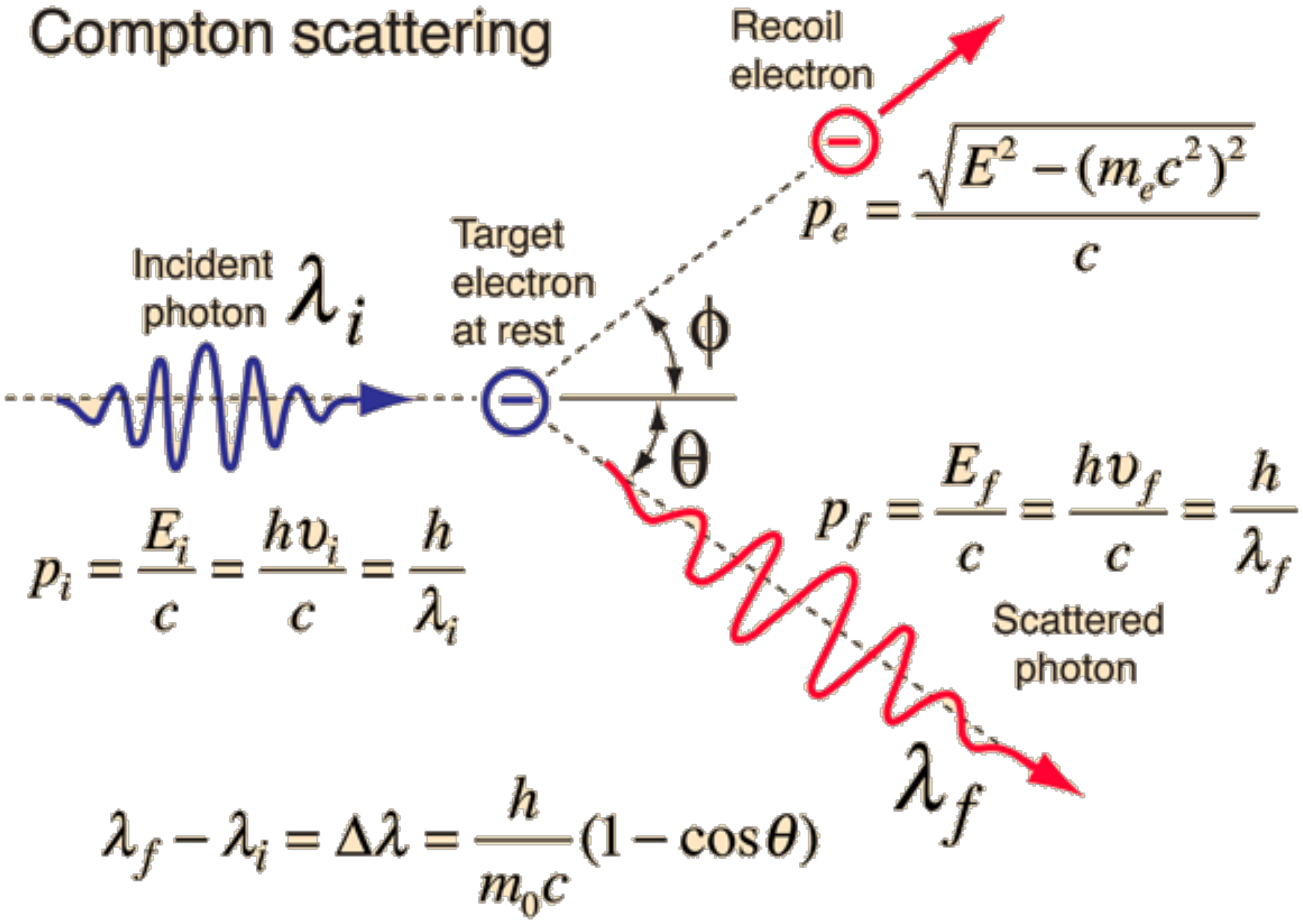
Photons interact with atomic shell



$KE = h\nu - BE$

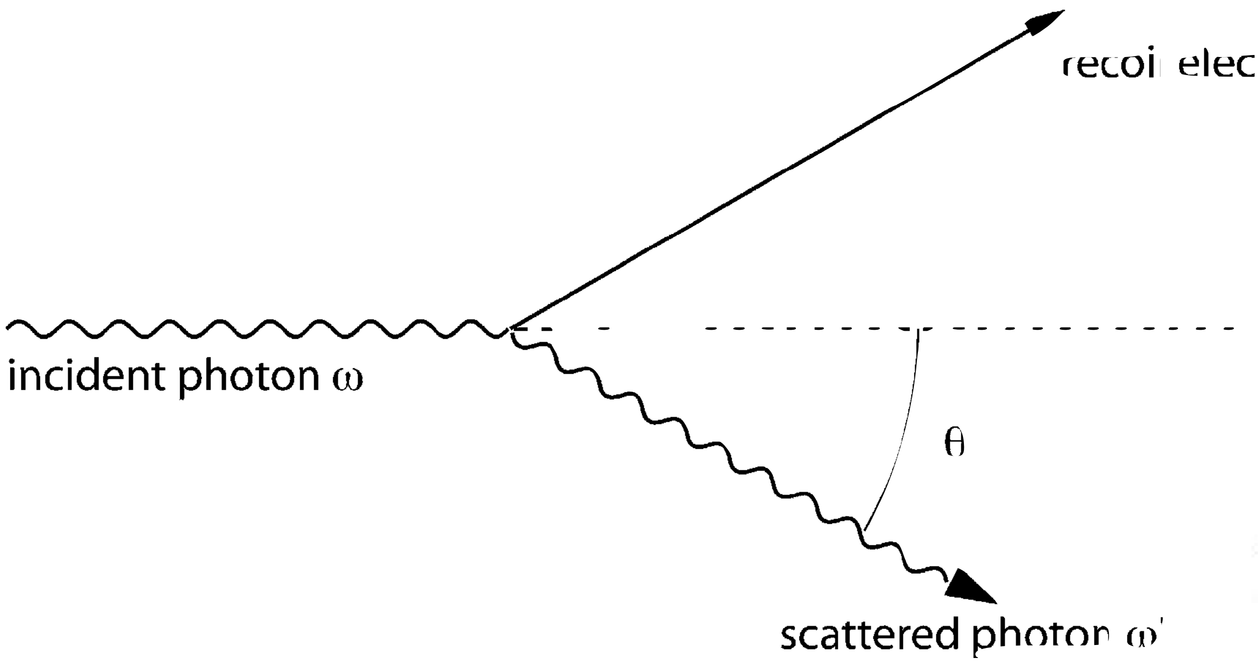
Compton Scattering

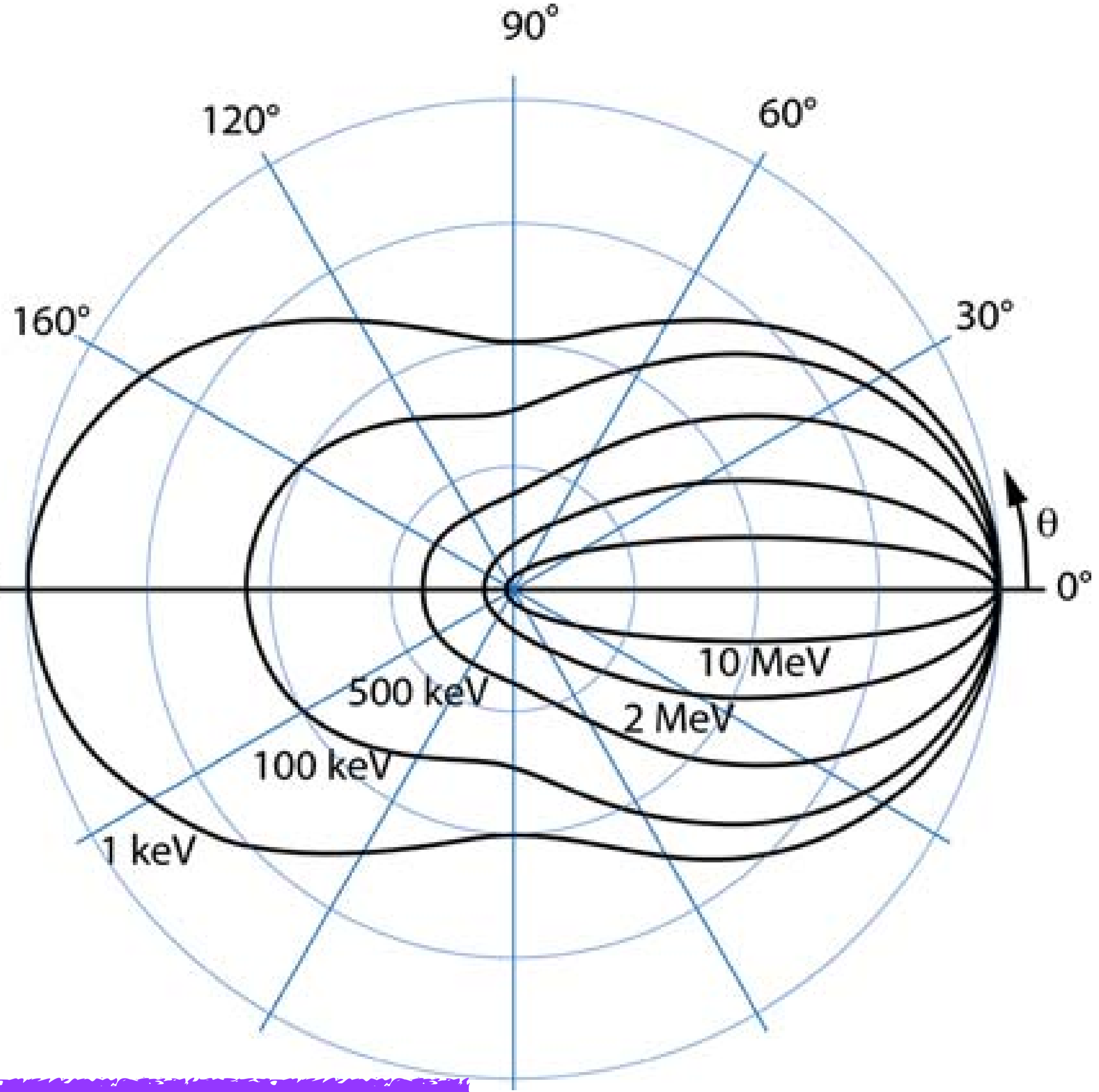
- Elastic scattering of photon and electron
  - Can be useful for photon detection
  - HOWEVER… changes photon direction



Low-energy limit is energy independent
–Scattering off single electrons: Thomson scattering
–Coherent scattering off bound electrons: Rayleigh scattering
—both elastic

Compton Scattering





The take home message: Scattering angle is energy dependent

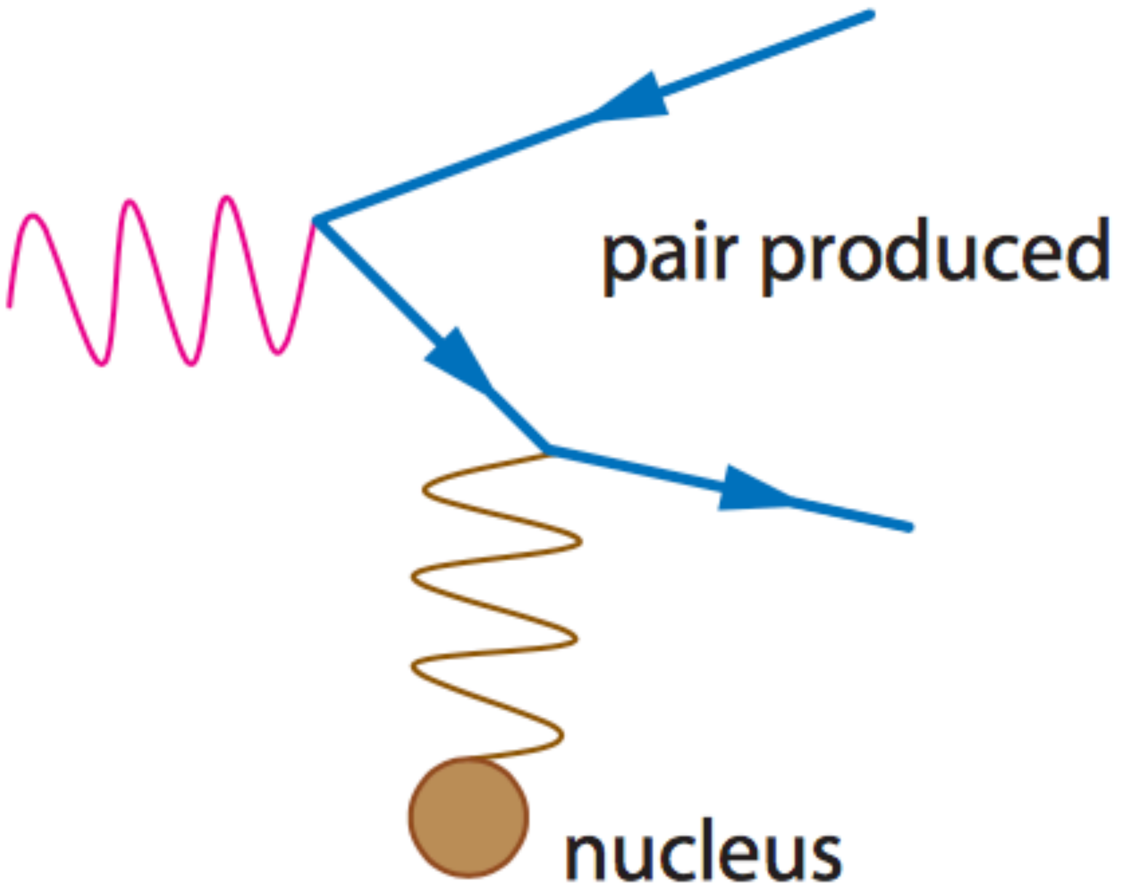
Photons interact with individual electrons

Pair Production

- Photon is converted to an electron-positron pair

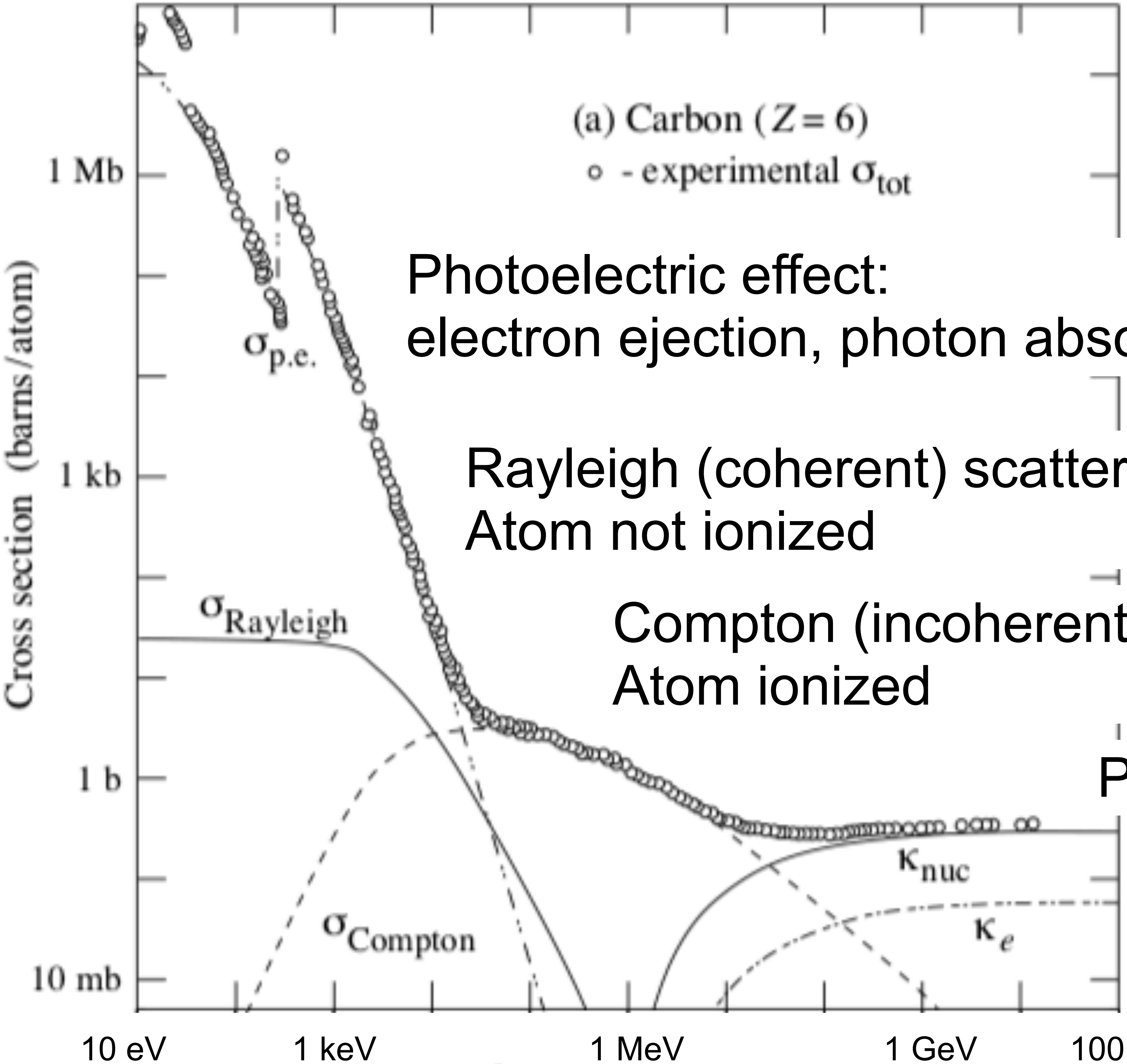
- Cross section rises quickly
- At high energy, mean free path for pair production is X_0*9/7

- Opening angle between electron and positron decreases with photon energy



Photons interact with nucleus

Photons in Matter: Summary



Photoelectric effect:
electron ejection, photon absorption

Rayleigh (coherent) scattering:
Atom not ionized

Compton (incoherent) scattering:
Atom ionized

Pair production

Photon Energy

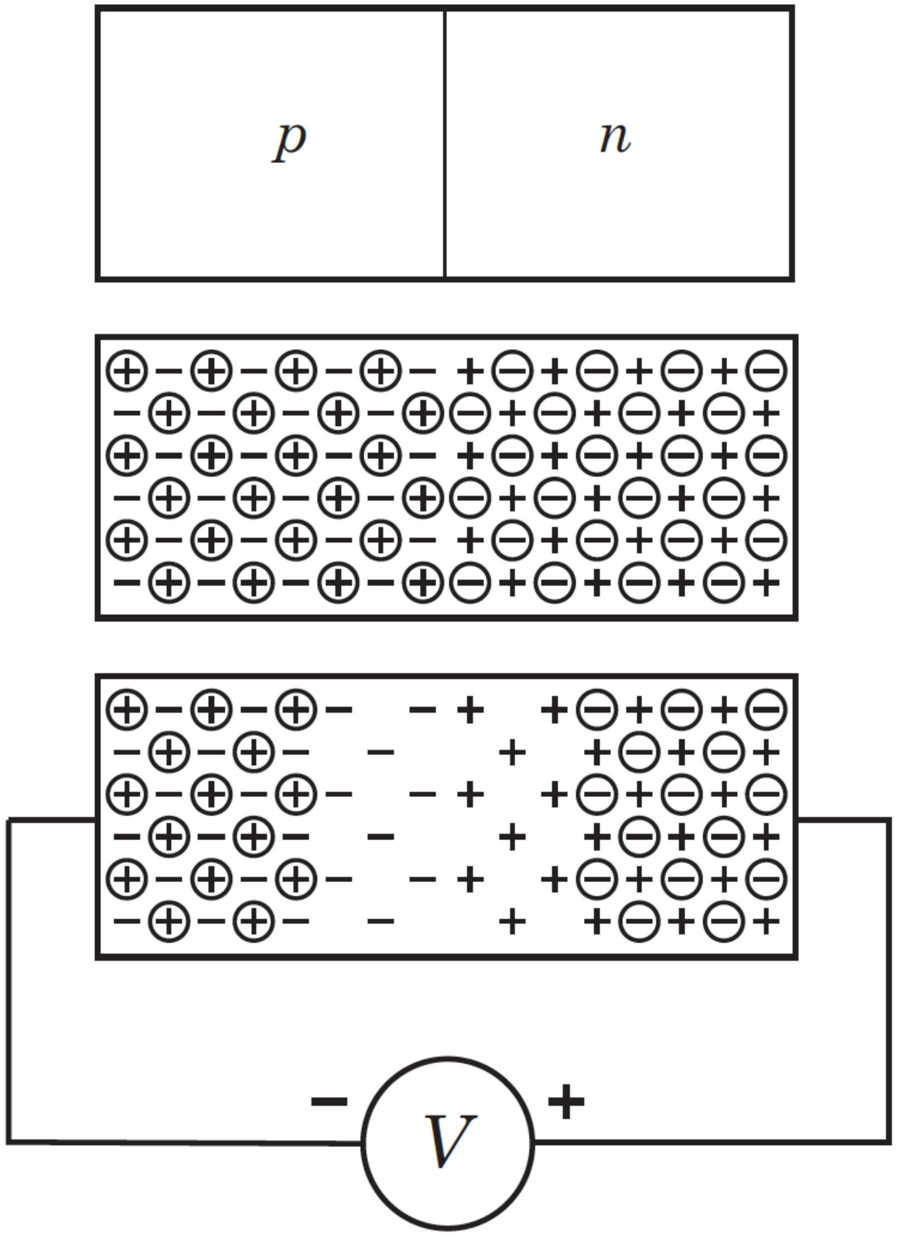
X-rays

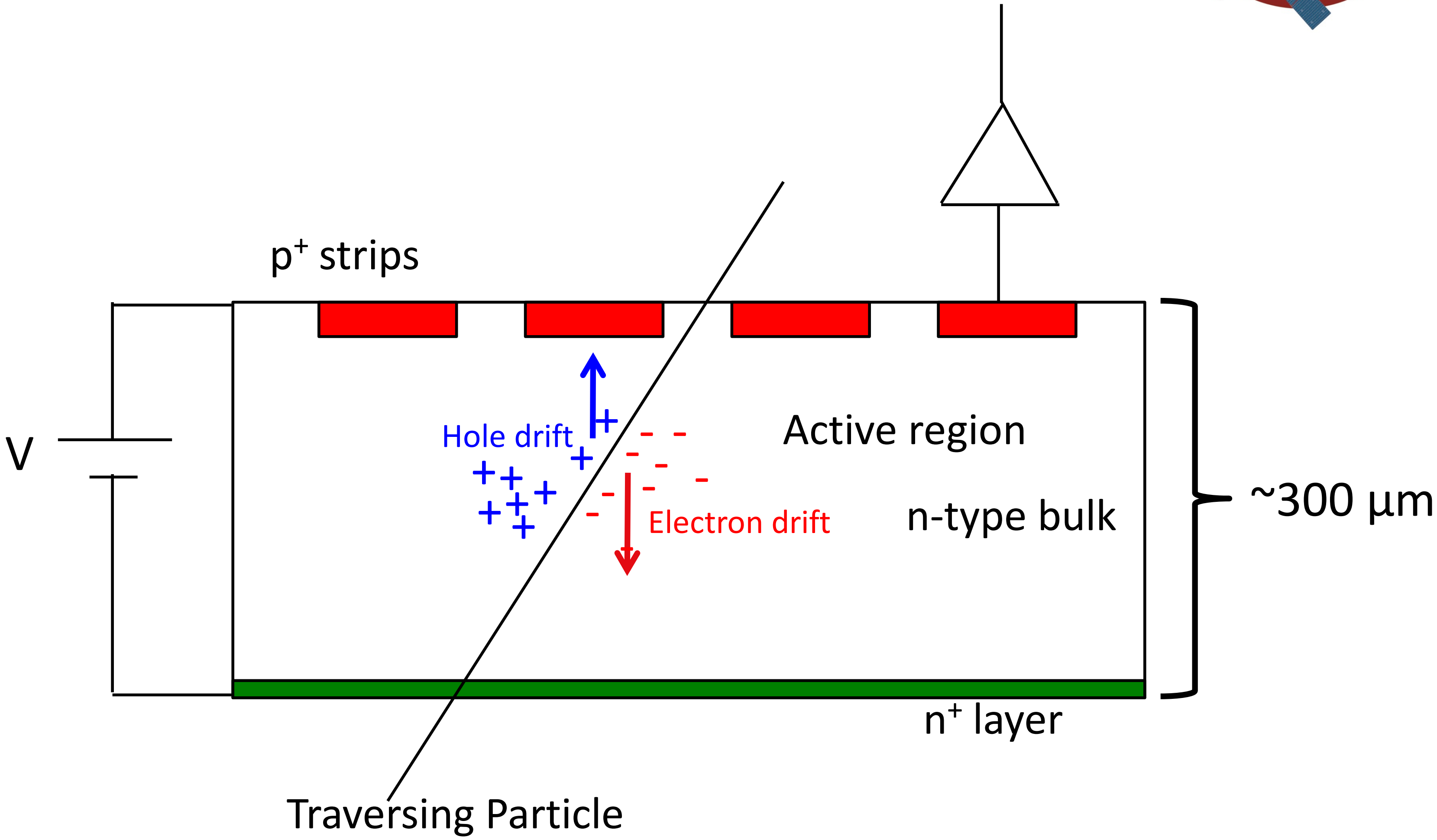
gamma-rays

Particle detectors

Detecting via Ionization

- **Tracking Detectors**





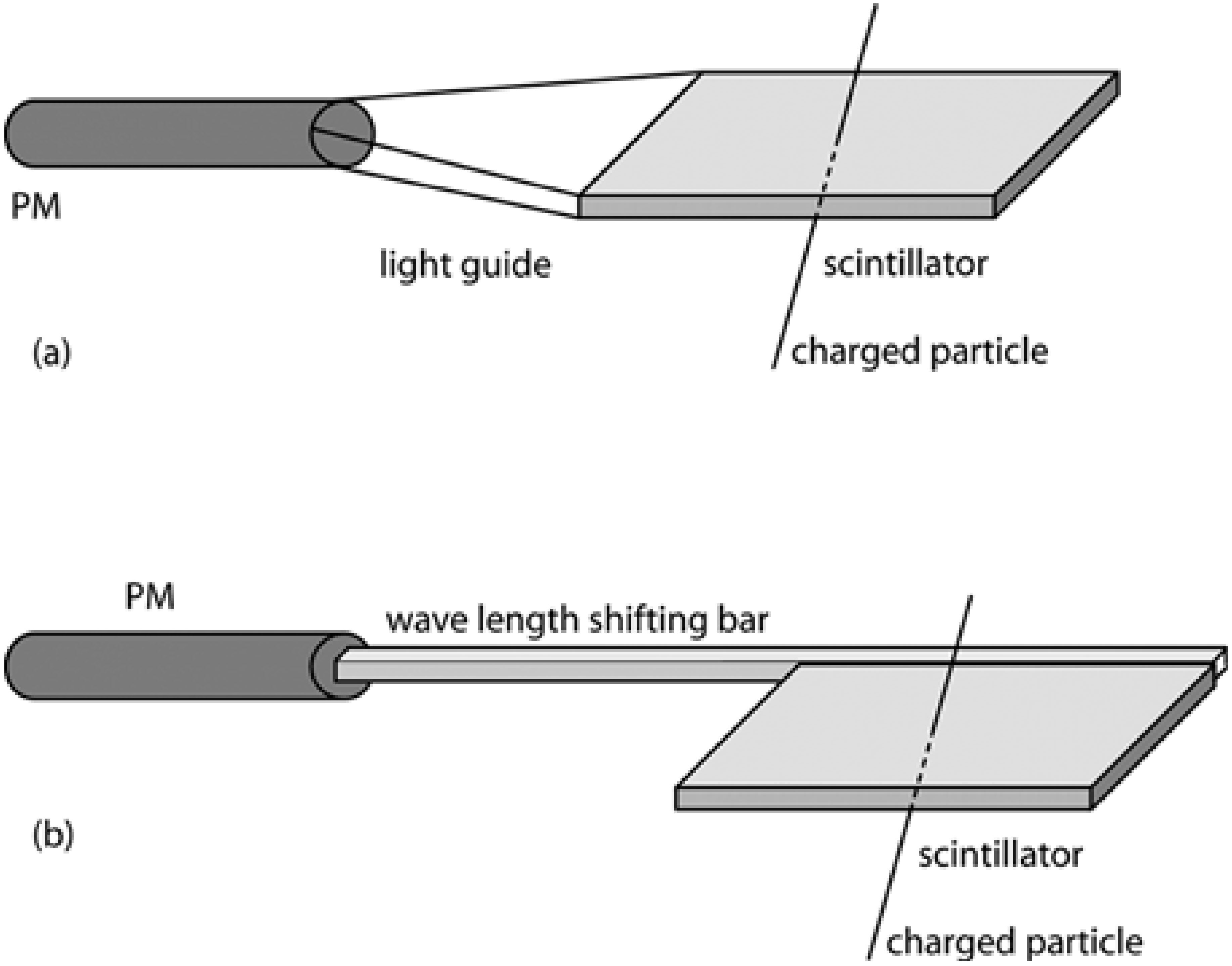
Basic Principle of a Silicon Sensor

- **Minimum Ionizing Particle (MIP)** creates electron hole pairs
  - drift to strip implants and backplane
  - signal is read out by Front-End electronics

Detecting via Scintillation (special type of ionization)

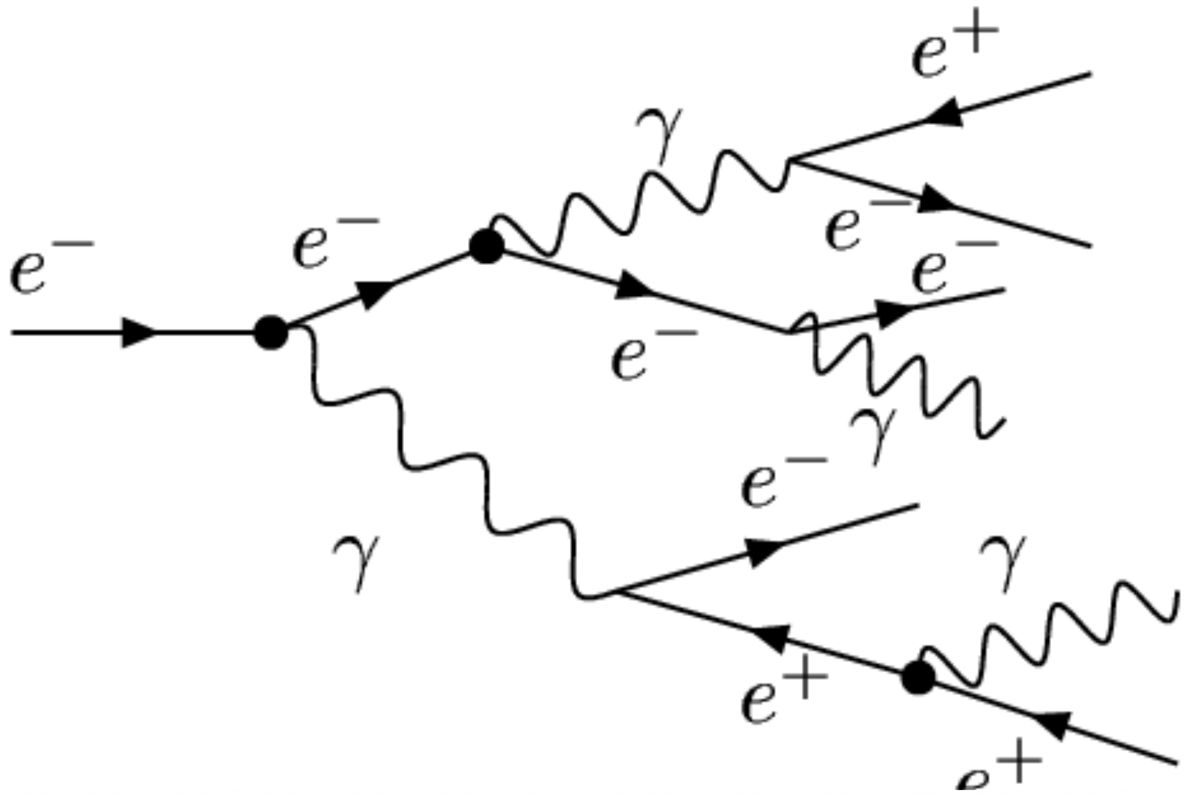
- While collection of ionization is difficult in solids and liquids, scintillation light can be used instead as a proxy for charge collection
- Scintillators have metastable excited states
  - Isotropic emission, lots of photons
  - Emitted at one or more spectral lines, not continuum
- Depending on material, amount of light is roughly linear with deposited energy in ionization
- Large index of refraction (~1.5) promotes total internal reflection
- Scintillators useful: calorimetry, tracking, vetos
  - Can be made of plastics, inorganic solids, liquid, air

Detecting via Scintillation (special type of ionization)

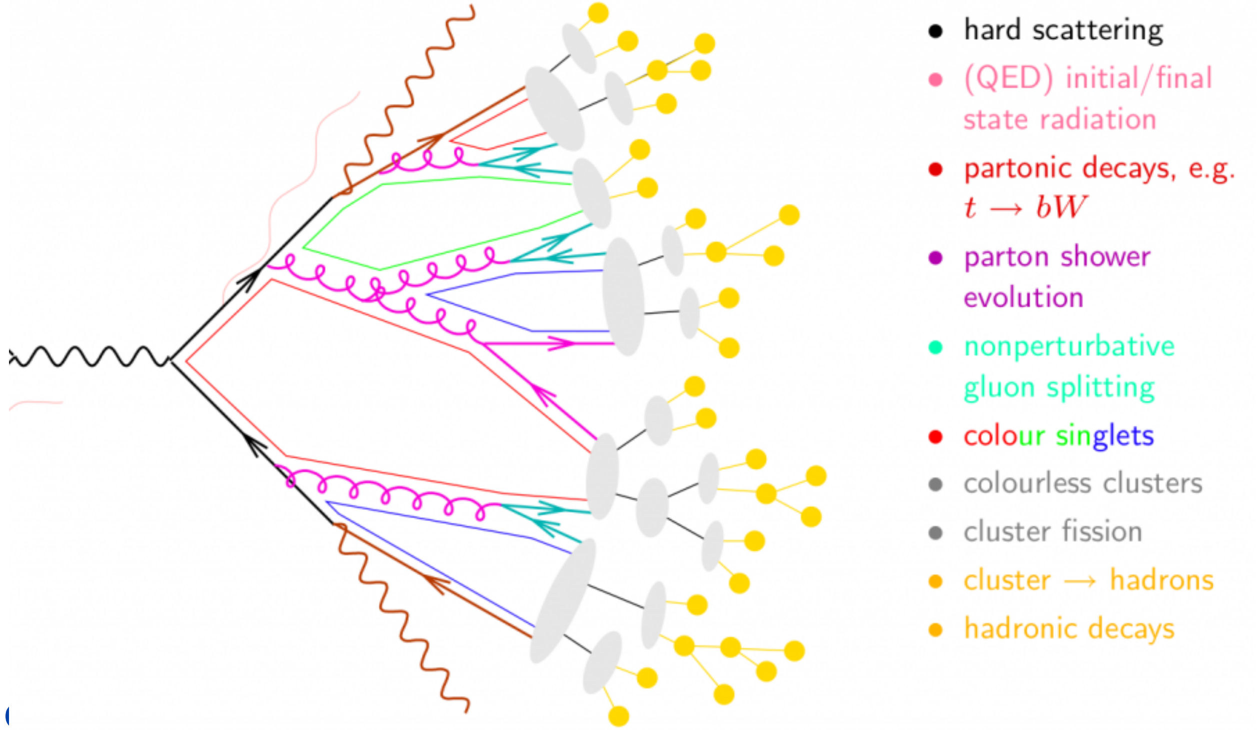


Detecting via Bremsstrahlung/Pair Production

- **Calorimeters (electromagnetic and hadronic)**



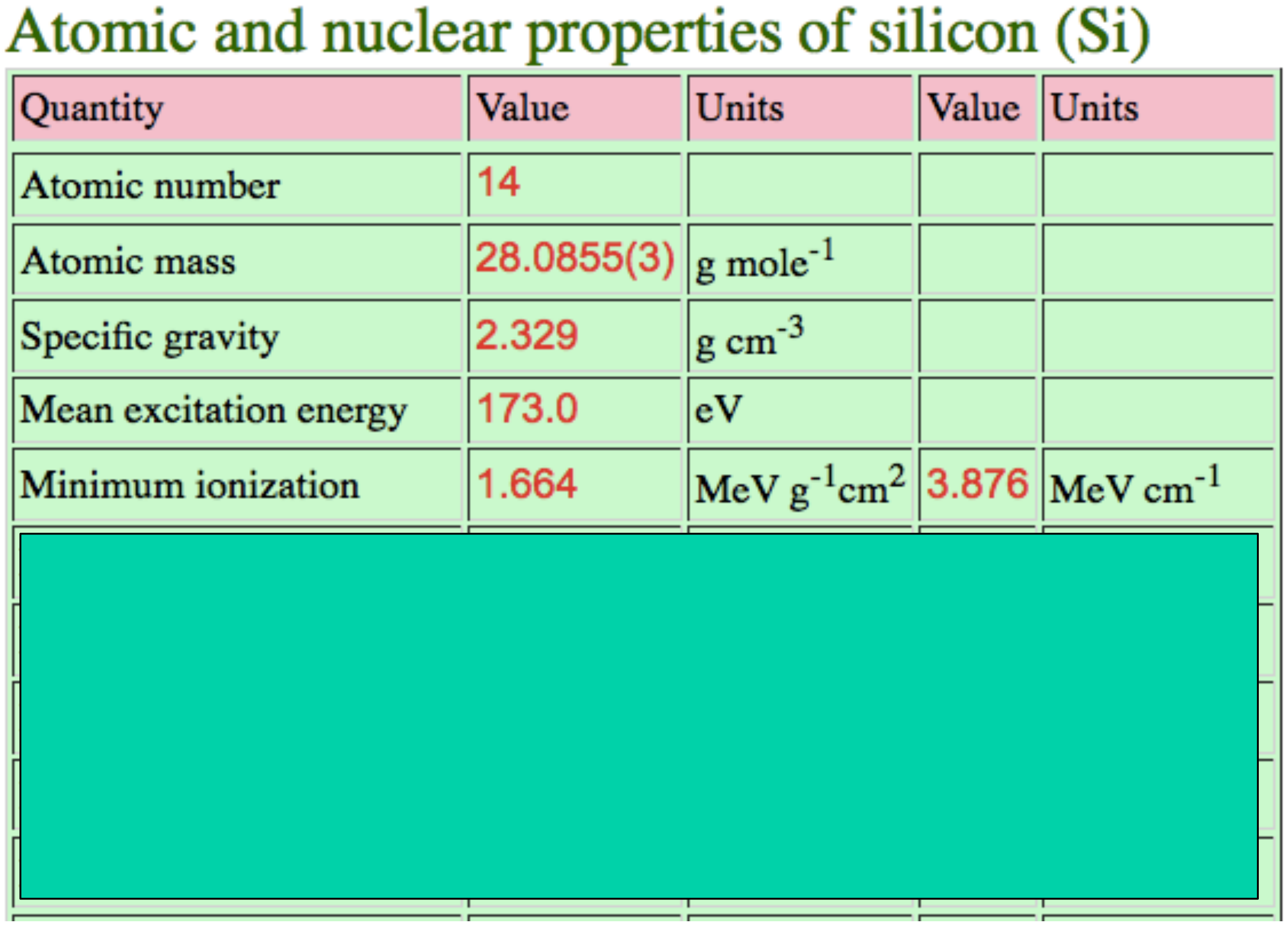
γ or $e^\pm$: pair production (occurs near nucleus) and bremsstrahlung alternating (interaction near nucleus)



p/n, $\pi^\pm$: pair production (occurs near nucleus) and bremsstrahlung alternating (interaction near nucleus), color charge GLUONS!

Detecting via Bremsstrahlung/Pair Production

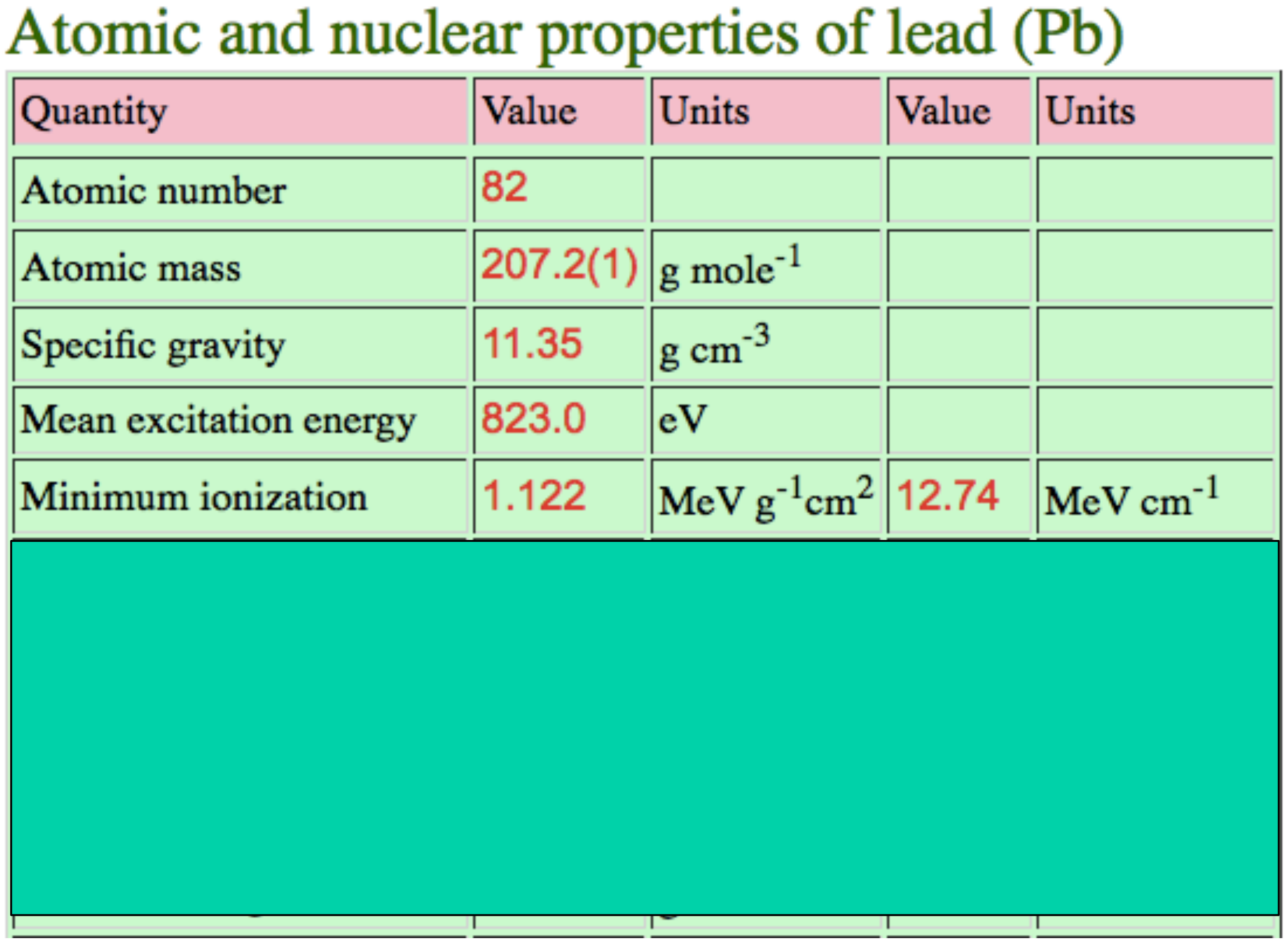
- **Calorimeters (electromagnetic and hadronic)**



Atomic and nuclear properties of silicon (Si)

Quantity	Value	Units	Value	Units
Atomic number	14			
Atomic mass	28.0855(3)	g mole^{-1}		
Specific gravity	2.329	g cm^{-3}		
Mean excitation energy	173.0	eV		
Minimum ionization	1.664	MeV g^{-1}cm^{2}	3.876	MeV cm^{-1}

[redacted]



Atomic and nuclear properties of lead (Pb)

Quantity	Value	Units	Value	Units
Atomic number	82			
Atomic mass	207.2(1)	g mole^{-1}		
Specific gravity	11.35	g cm^{-3}		
Mean excitation energy	823.0	eV		
Minimum ionization	1.122	MeV g^{-1}cm^{2}	12.74	MeV cm^{-1}

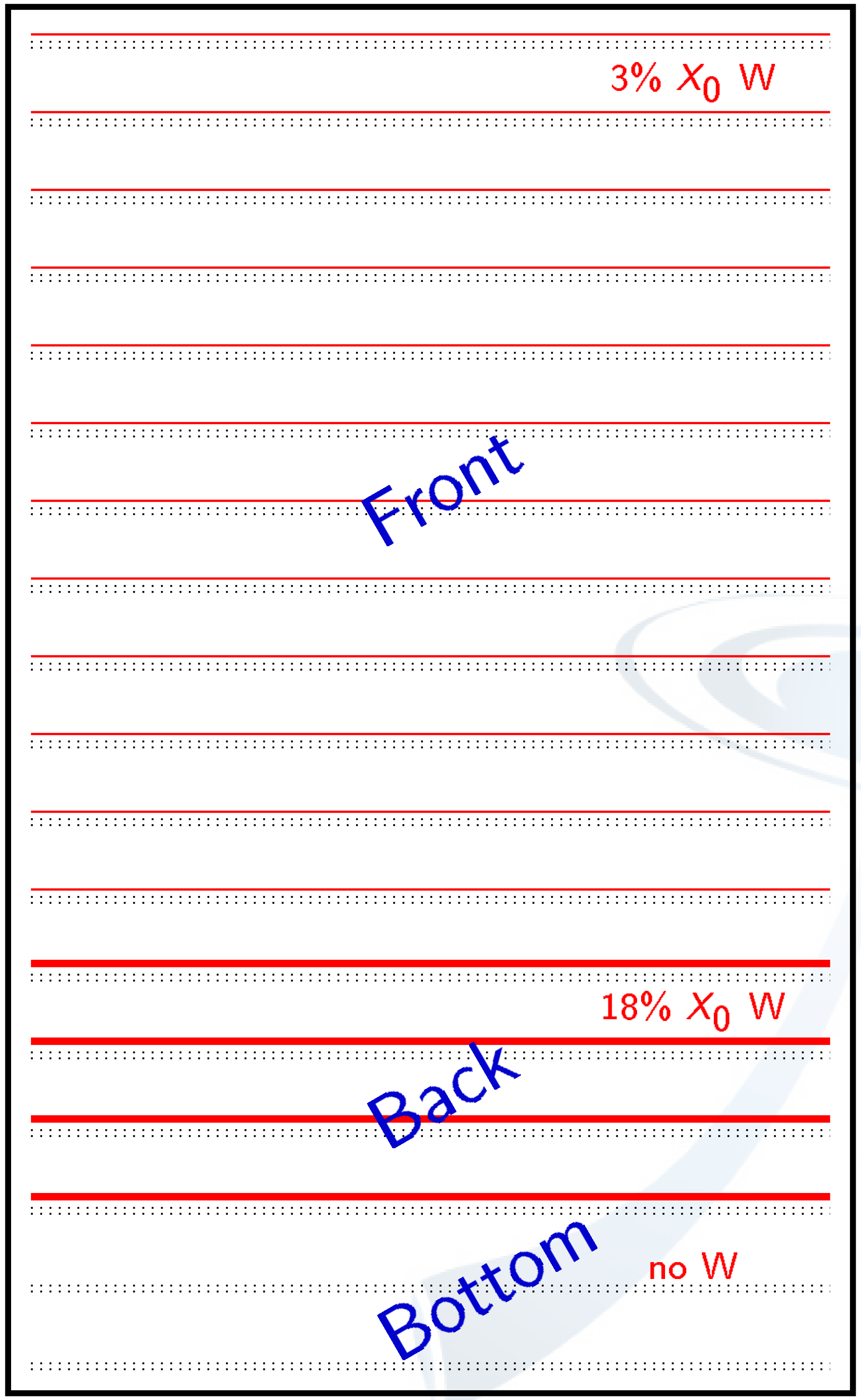
[redacted]

Different materials are better at different things…

http://pdg.lbl.gov/2017/AtomicNuclearProperties/

Which detectors make up the LAT?

Silicon Tracker: Direction Reconstruction



- Tracker is 1.5 radiation lengths total on axis (63% conversion efficiency)

- 18 xy silicon planes alternating with passive tungsten converter layers
  Front: 12 planes with 95 μm (0.03 X_0) converter
  Back: 4 planes with 720 μm (0.18 X_0) converter

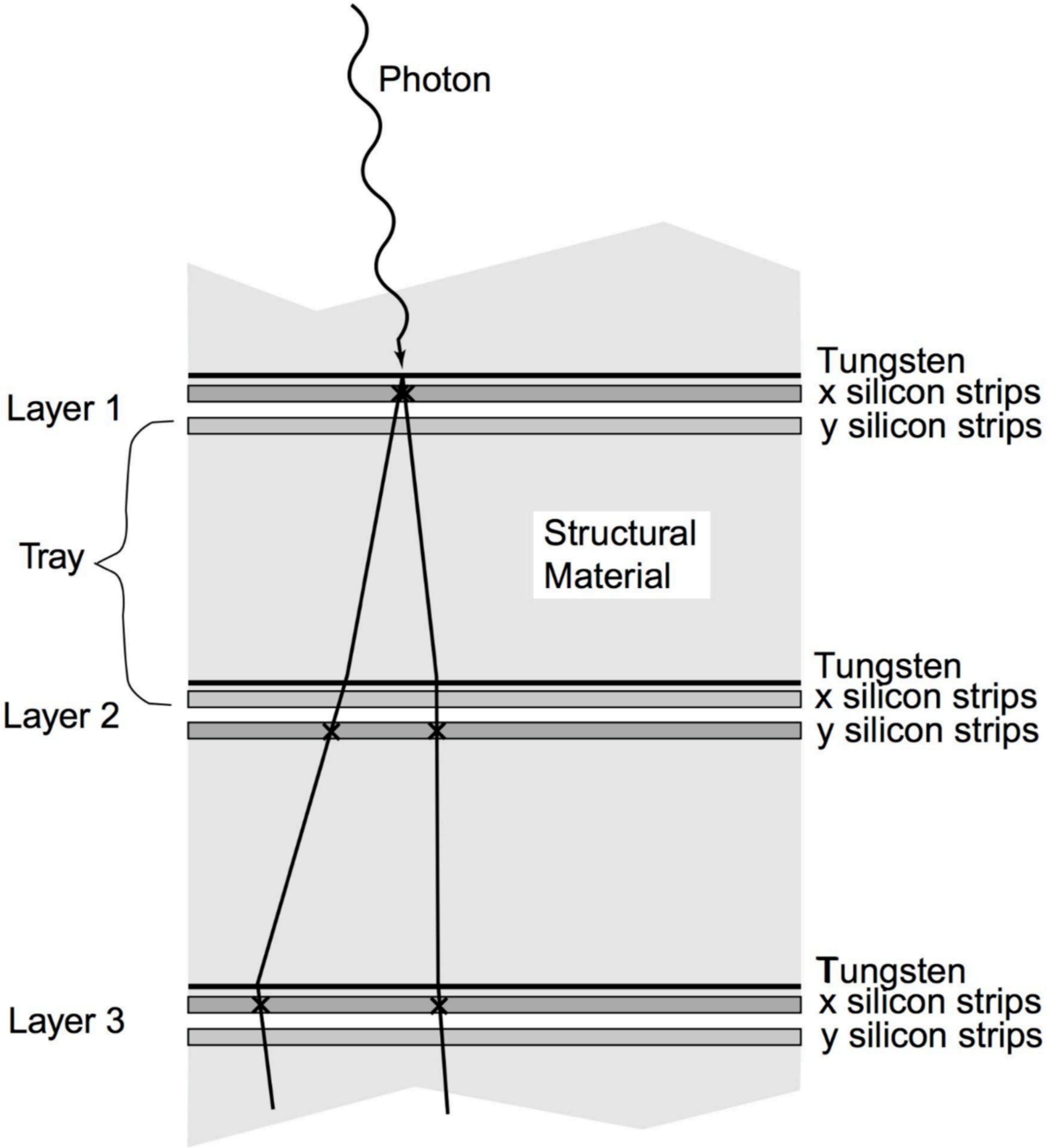
- 160 W power consumption (of 650 W total), compared to 1100 watt toaster
- ~1 M readout channels

Silicon Tracker: Direction Reconstruction

- Probability of gamma-ray conversion within the detector is proportional to material radiation length (X_0) – most ɣ rays convert in tungsten foils (which have high X_0 relative to other components of the LAT)

- The e^+/e^- pair produces hits in X/Y SSDs below each converter which can be used to reconstruct a 3-D coordinate (cluster) for that particle

- SSDs in the LAT tracker are extremely efficient (~99.9%) and have very low noise (~10^{-6} noise occupancy)

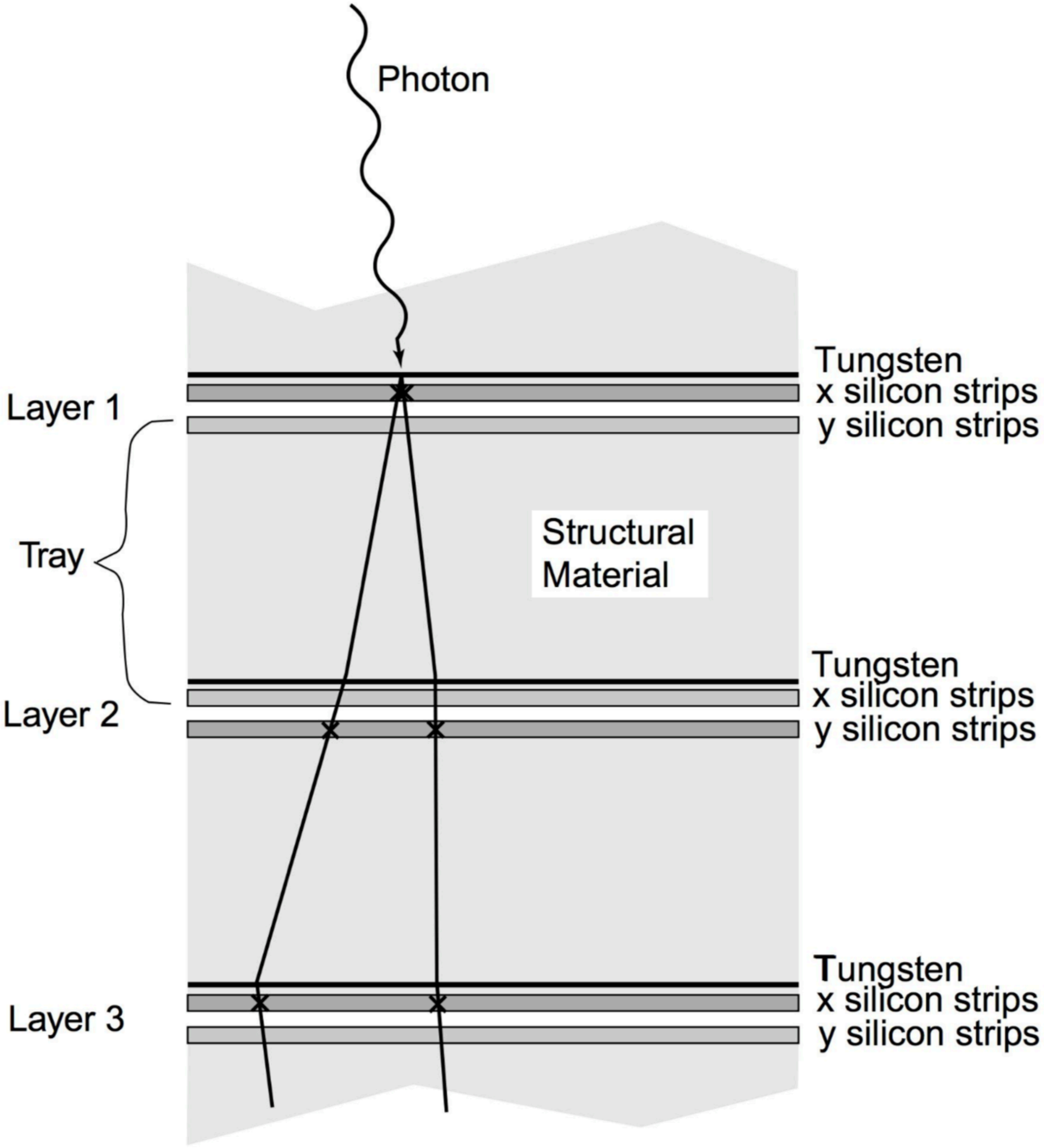


Silicon Tracker: Direction Reconstruction

- Tracker angular resolution is limited by multiple scattering at low energies and strip pitch at high energies

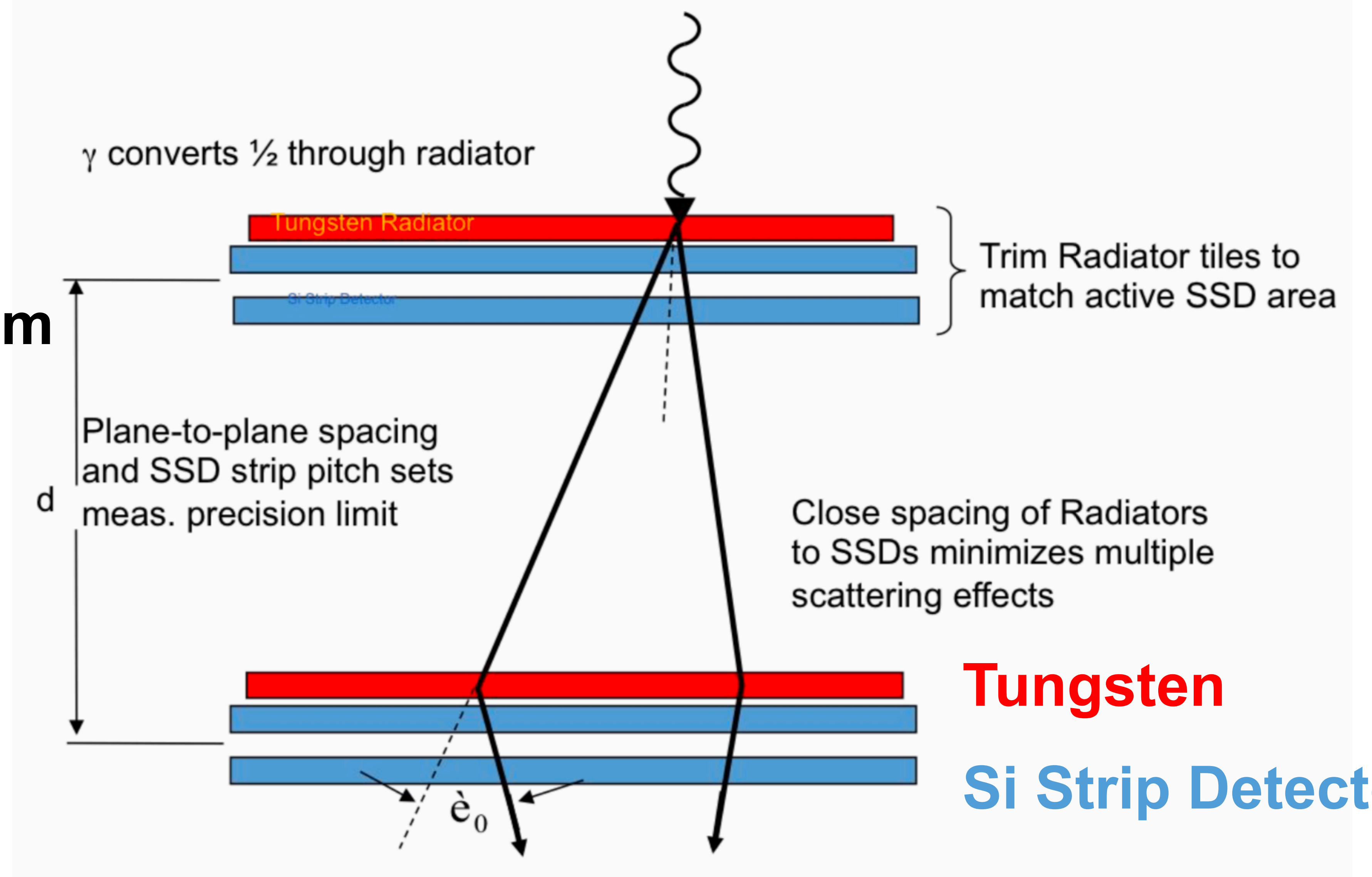
- Tracker design is a tradeoff between FoV, PSF, and effective area
  - Large X_0 provides high conversion efficiency (effective area) but worse PSF
  - Larger spacing between tracker planes improves PSF but decreases FoV

- Front and Back sections provide a balance between conversion efficiency and good PSF



Silicon Tracker: Direction Reconstruction

Pitch = 288μm
d = 32.9 mm



Tungsten

Si Strip Detector (SSD)

Position Resolution (σ_{ssd}) = pitch/√(12)

LAT tracker: $\theta_{det} = \sqrt{(2)}*\sigma_{ssd}/d = \sqrt{(2)}*288\mu m/(\sqrt{(12)}*32.9mm)$
$= 2.8$ mrad $= 0.16°$

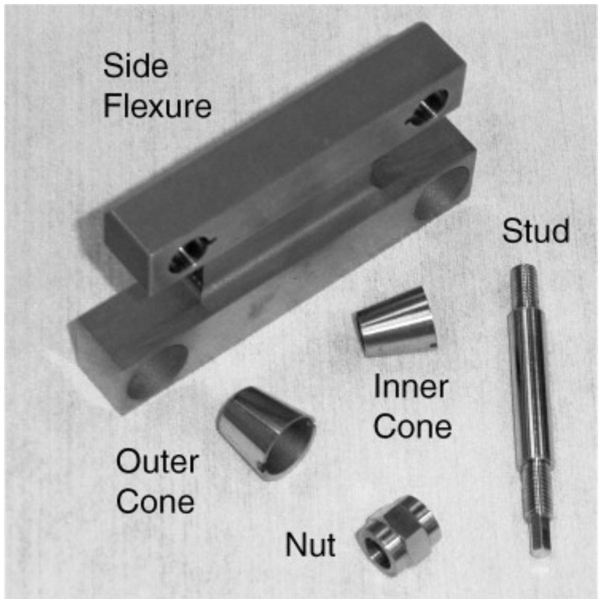
***best resolution for these 2 layers**

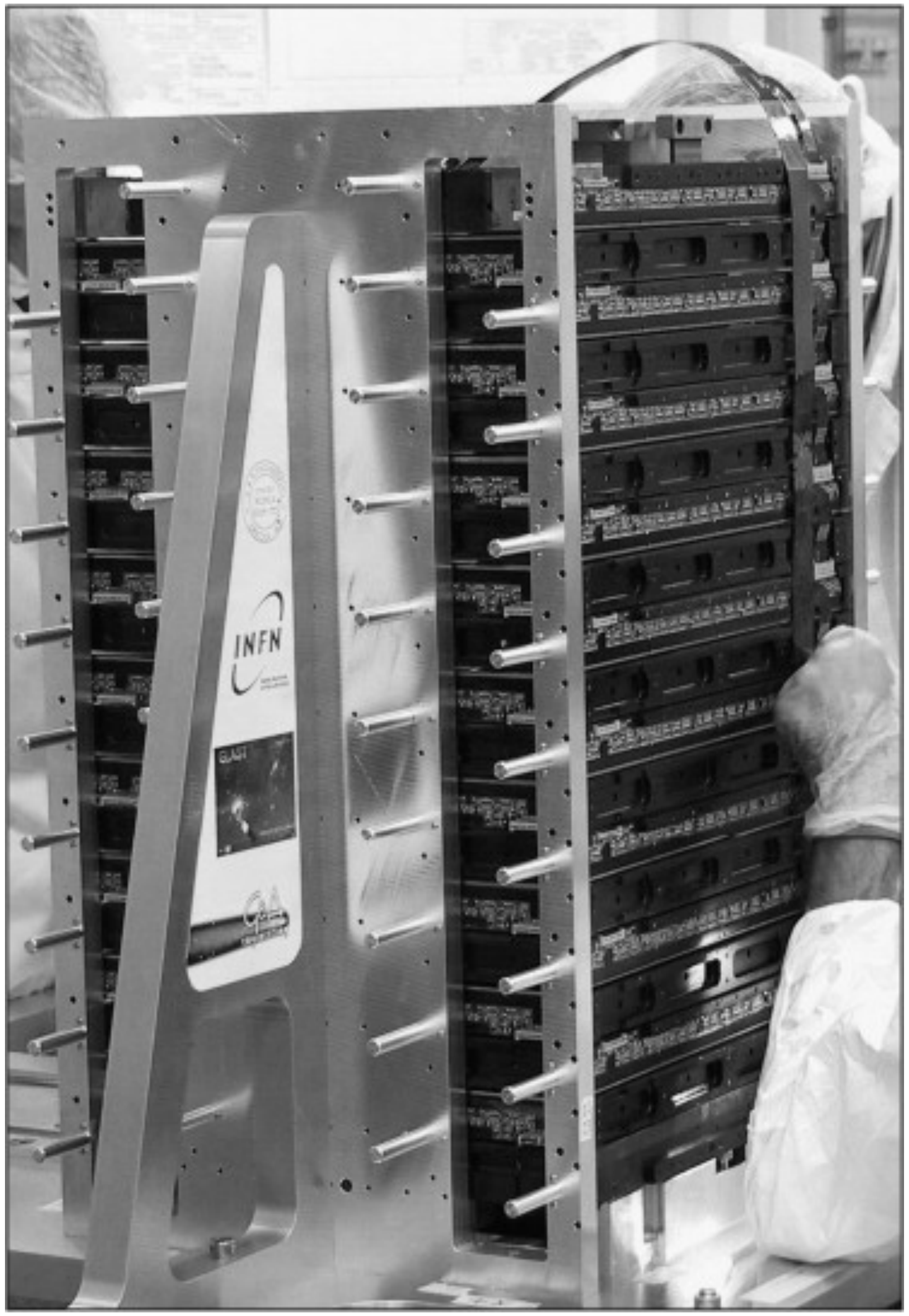
Silicon Tracker: Direction Reconstruction

Table 1
Summary of Tracker performance metrics

Metric	Measurement
Active area at normal incidence	1.96 m^2
Gamma-ray conversion probability	63%
Active area fraction within a Tracker module	95.5%
Overall Tracker active area fraction	89.4%
Single-plane hit efficiency in active area	>99.4%
Dead channel fraction	0.2%
Noisy channel fraction	0.06%
Noise occupancy	$<5 \times 10^{-7}$
SSD strip spacing	0.228 mm
Power consumption per channel	180 μW
Tower-module mass	32.5–33.0 kg
Maximum misalignment at top of module	0.59 mm
Maximum misalignment at bottom of module	0.29 mm

Photo Noir



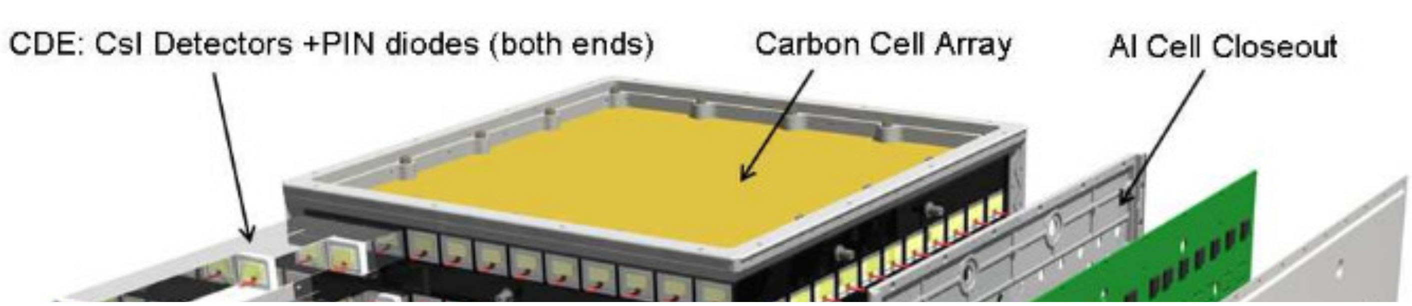


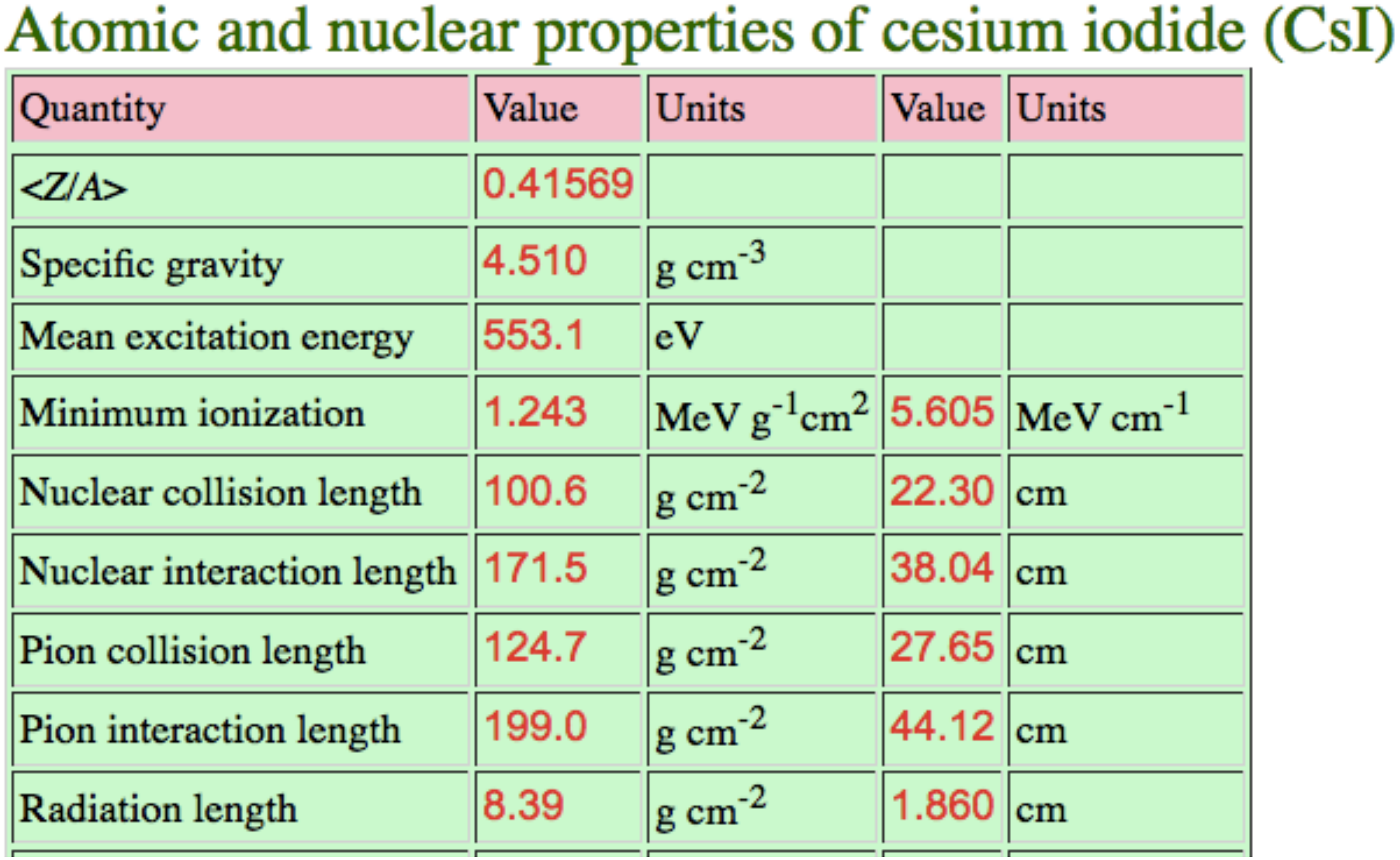
Now to the Calorimeter…

https://www.sciencedirect.com/science/article/pii/S0927650507001302

Calorimeter: Energy Reconstruction

- Measures energy deposition - contains particle shower





Atomic and nuclear properties of cesium iodide (CsI)

Quantity	Value	Units	Value	Units
<Z/A>	0.41569			
Specific gravity	4.510	g cm^{-3}		
Mean excitation energy	553.1	eV		
Minimum ionization	1.243	MeV $\text{g}^{-1}\text{cm}^{2}$	5.605	MeV cm^{-1}
Nuclear collision length	100.6	g cm^{-2}	22.30	cm
Nuclear interaction length	171.5	g cm^{-2}	38.04	cm
Pion collision length	124.7	g cm^{-2}	27.65	cm
Pion interaction length	199.0	g cm^{-2}	44.12	cm
Radiation length	8.39	g cm^{-2}	1.860	cm

Each calorimeter tower: 8 layers of 12 CsI bars hodoscopic arrangement
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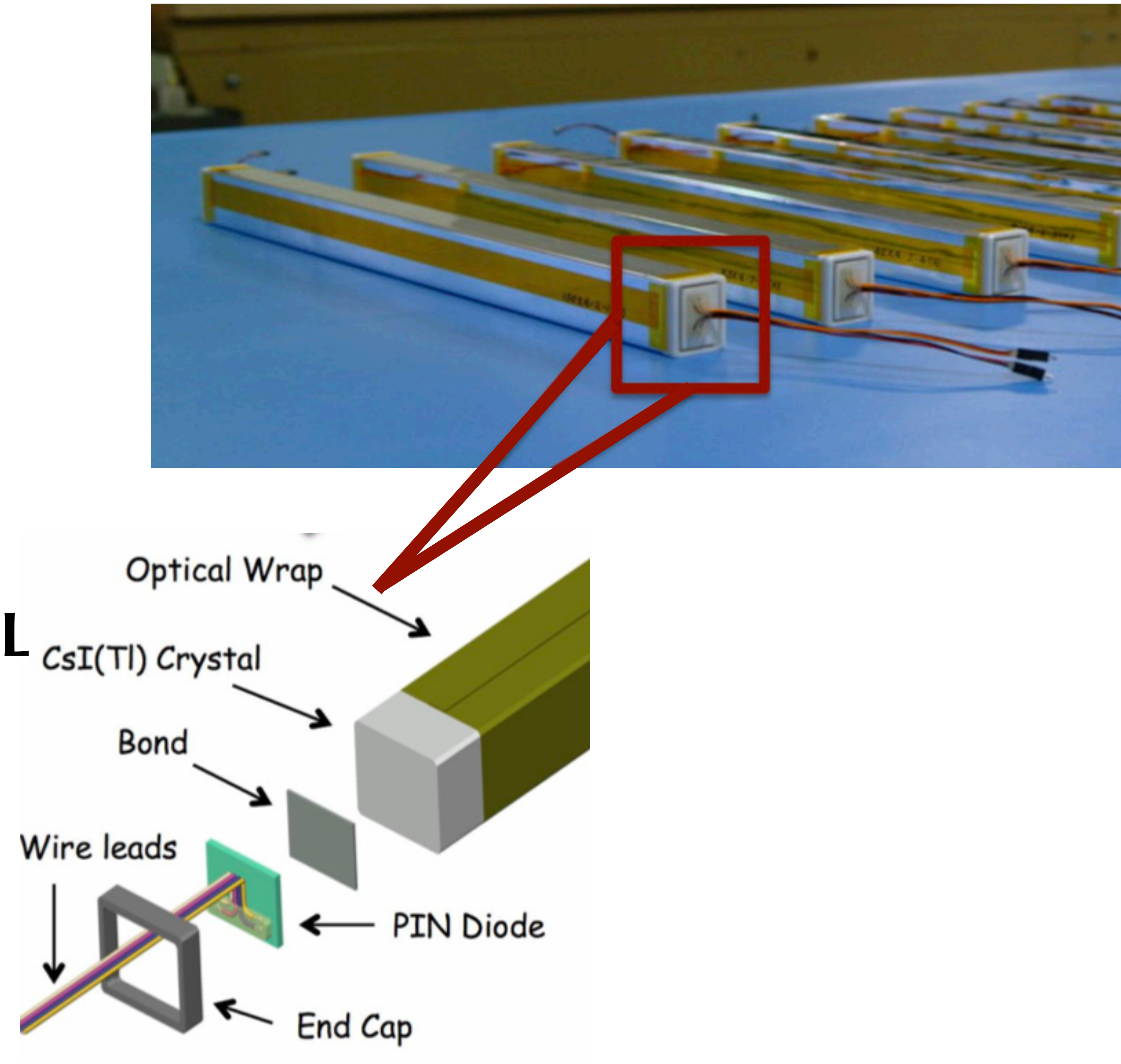
Calorimeter: Energy Reconstruction

- Total radiation length of 8.6 X_0 on-axis (vs 1.5 X_0 for tracker)

Many radiation lengths needed to induce an electromagnetic shower

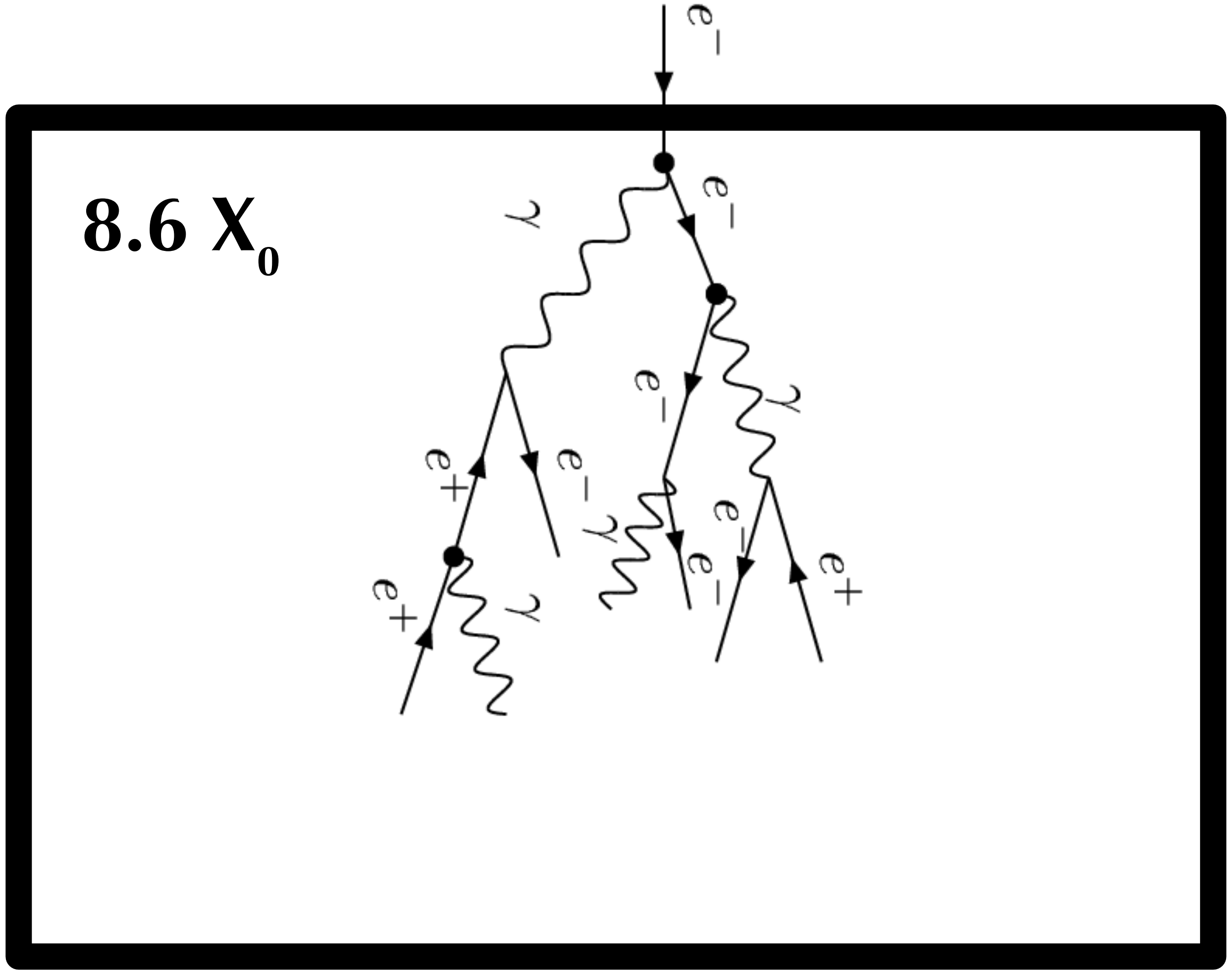
Each CAL module is composed of segmented CsI crystals arranged in orthogonal layers

Relativistic charged particles produce scintillation light in the CAL crystals which is collected by PIN diodes at either end

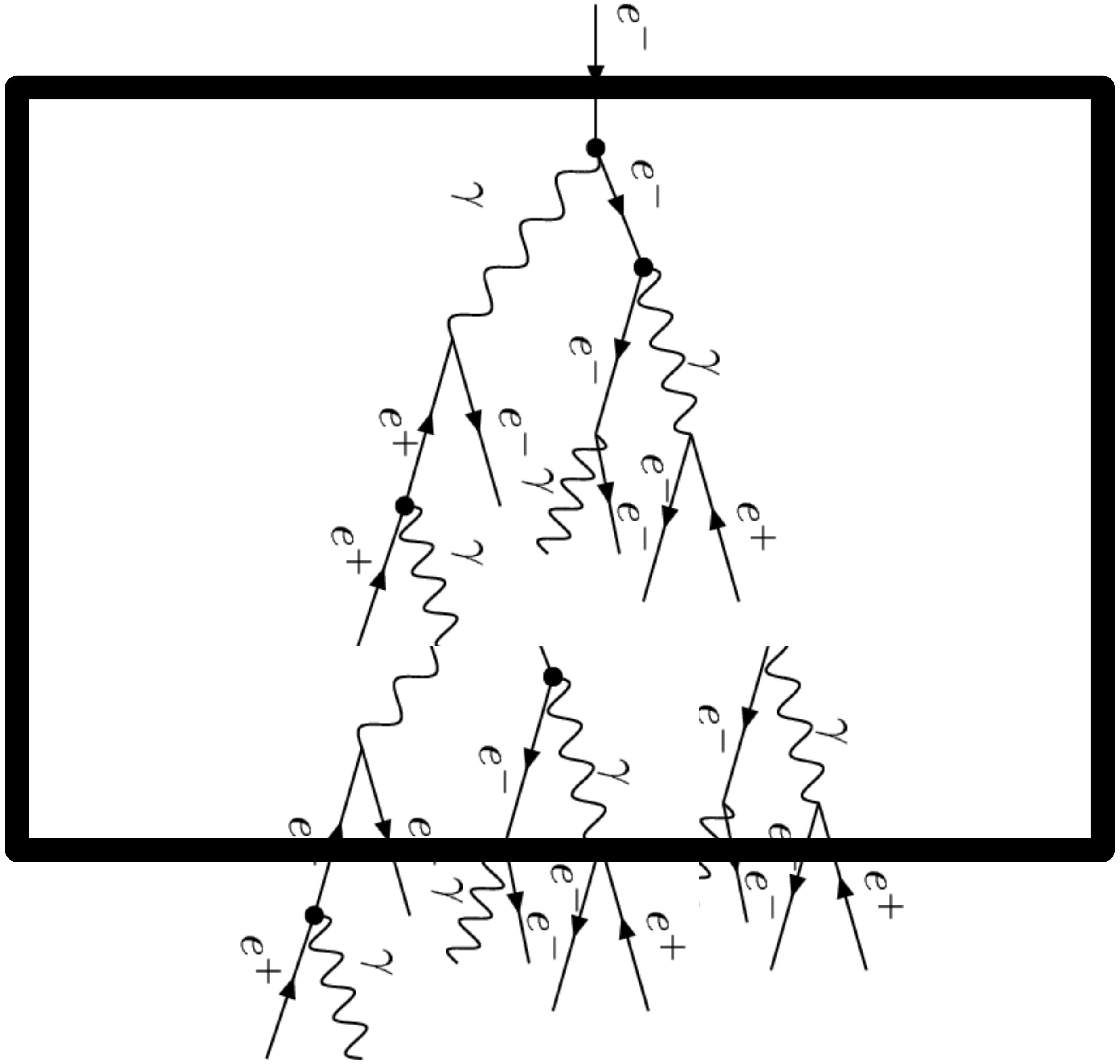


Calorimeter: Energy Reconstruction

~1 GeV electron



~100 GeV electron

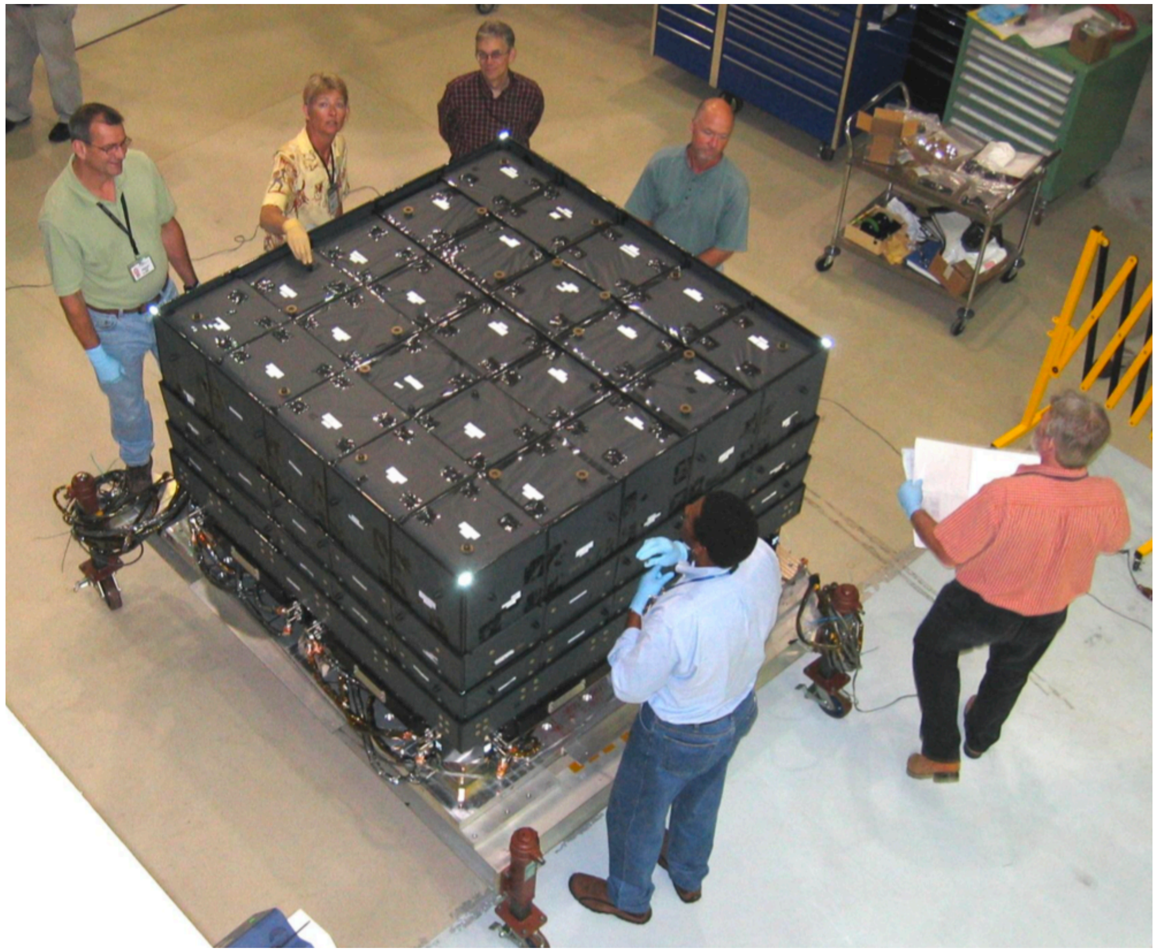


https://ieeexplore.ieee.org/document/672494

Now to the ACD…

AntiCoincidence Detector (ACD)

- Primary subsystem for rejection of charged cosmic rays
    - Veto at hardware-level for trigger and onboard filter
    - ACD information also used in offline reconstruction to identify CR events
- Cosmic-ray shield around the four sides and top of the LAT
    - 89 plastic scintillating tiles, 8 ribbons to cover remaining gaps
    - Segmented design minimizes self-veto effect -- shower backsplash from the CAL can be distinguished from genuine cosmic-ray events



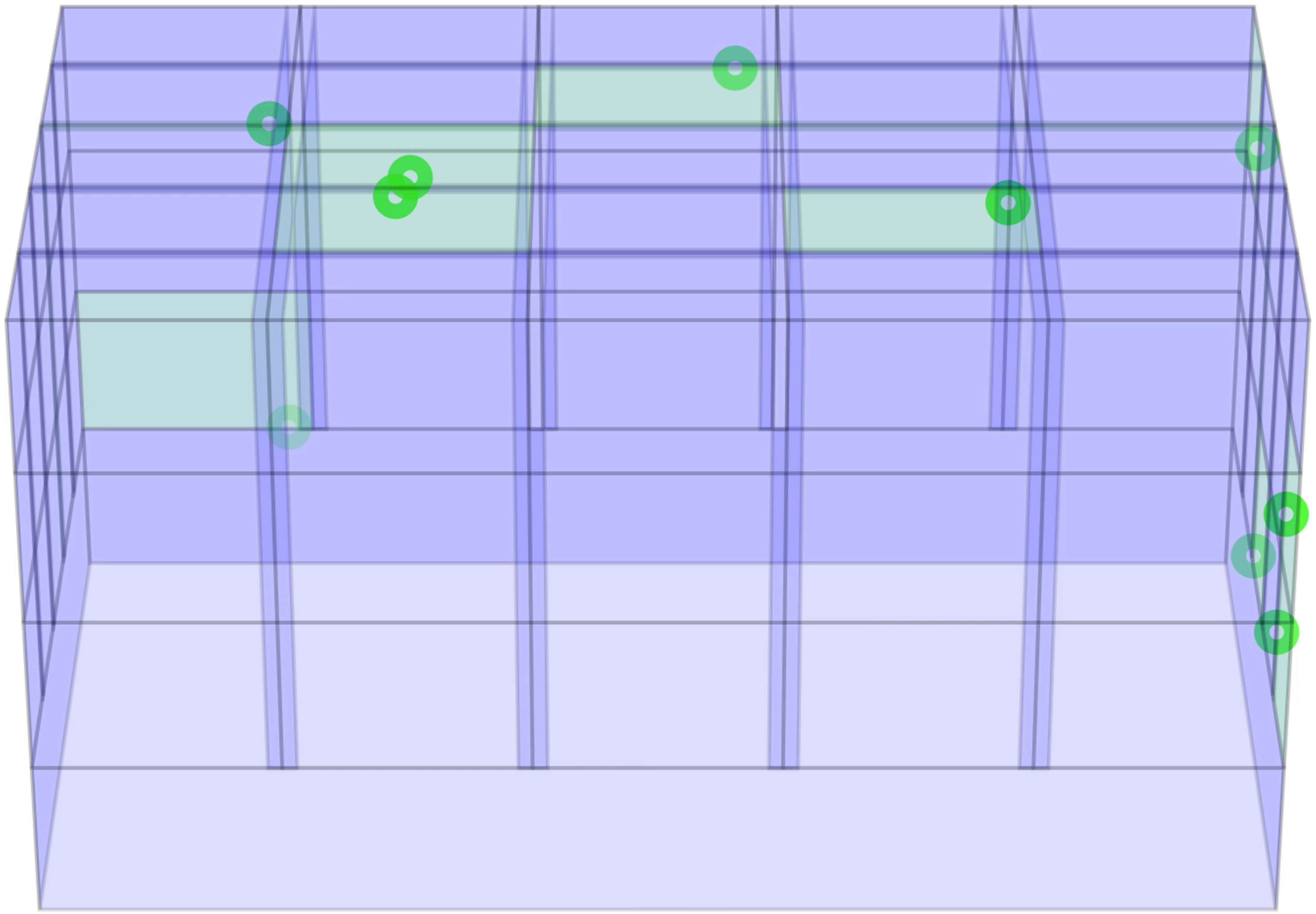
AntiCoincidence Detector (ACD)

Elapsed Time : 0.00s

No. of Gamma-rays : 0

No. of Proton CRs : 1

No. of Electron CRs : 0



https://www.sciencedirect.com/science/article/pii/S0927650506001885

Now what?

- Use the detector subsystems to reconstruct events!

- Look for:
  - a conversion in the tracker
  - energy deposition in the calorimeter
  - NO signal in the ACD

- Then apply Instrument Response functions (IRFs)
  - More on this later this afternoon *yay!* and on Saturday

Can you tell if an event is signal or background?

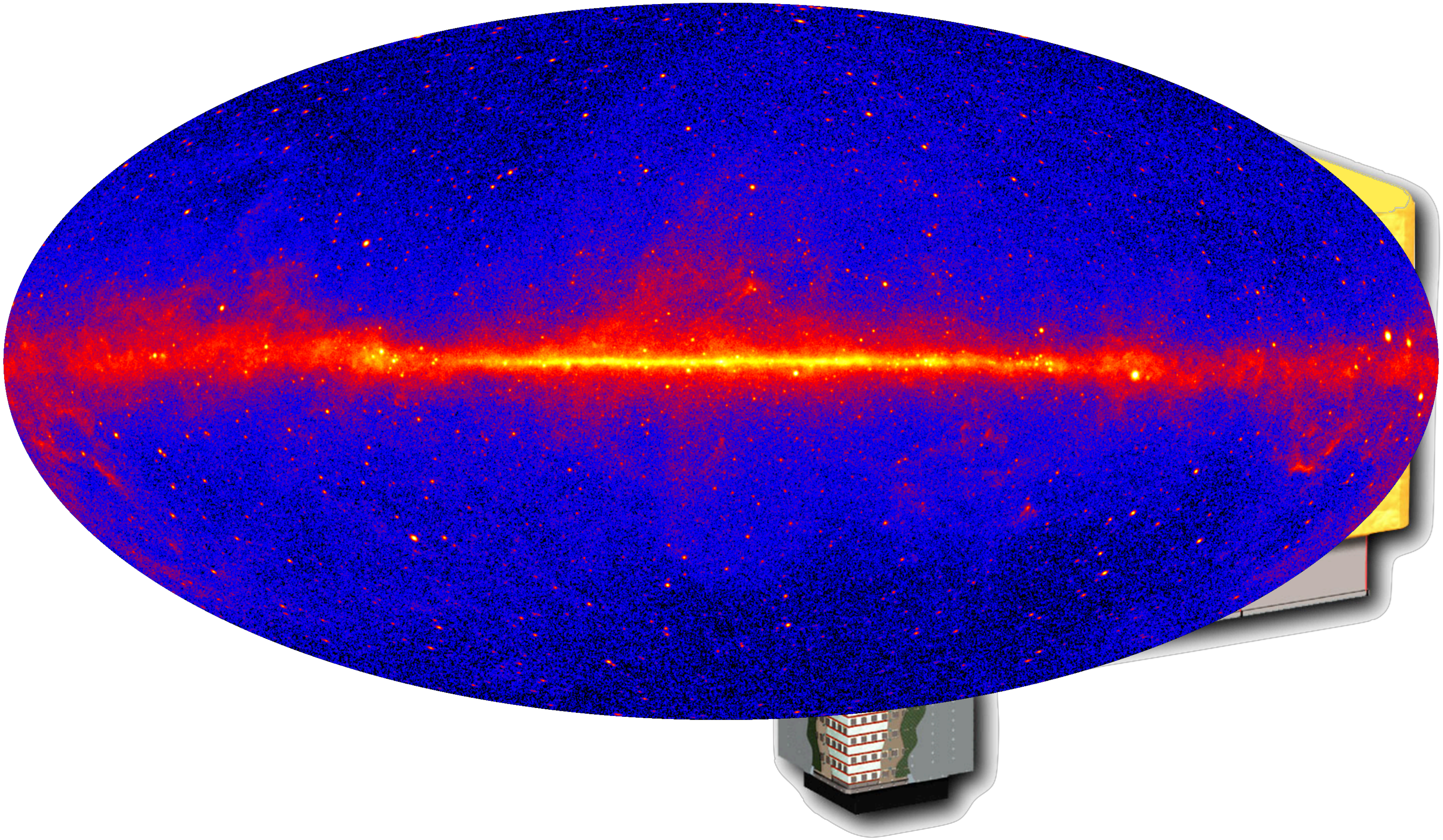
Event Displays

POP QUIZ!!!

Go to: kahoot.it

51154

And… that's the LAT



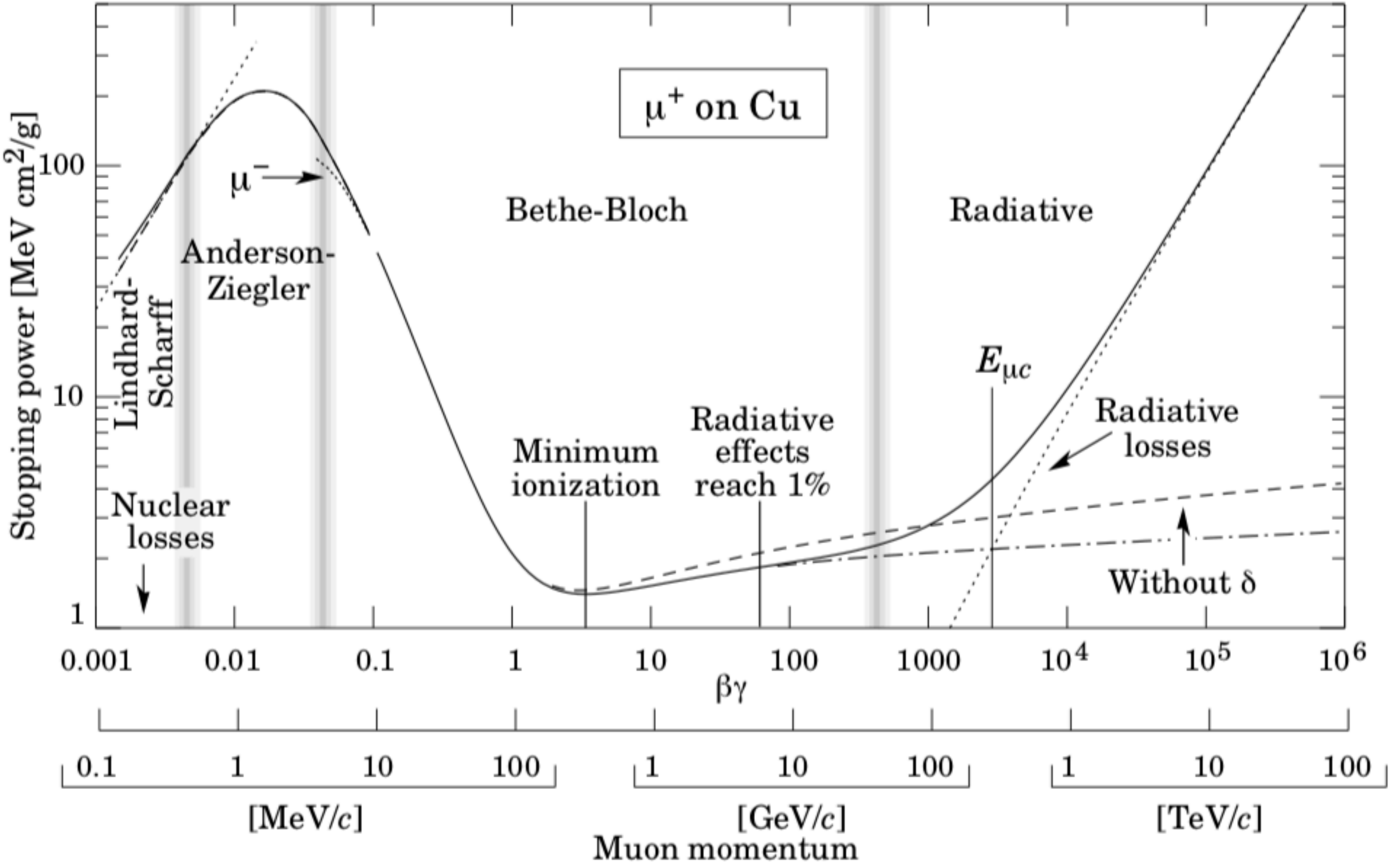
Backups

Bethe-Bloch equation

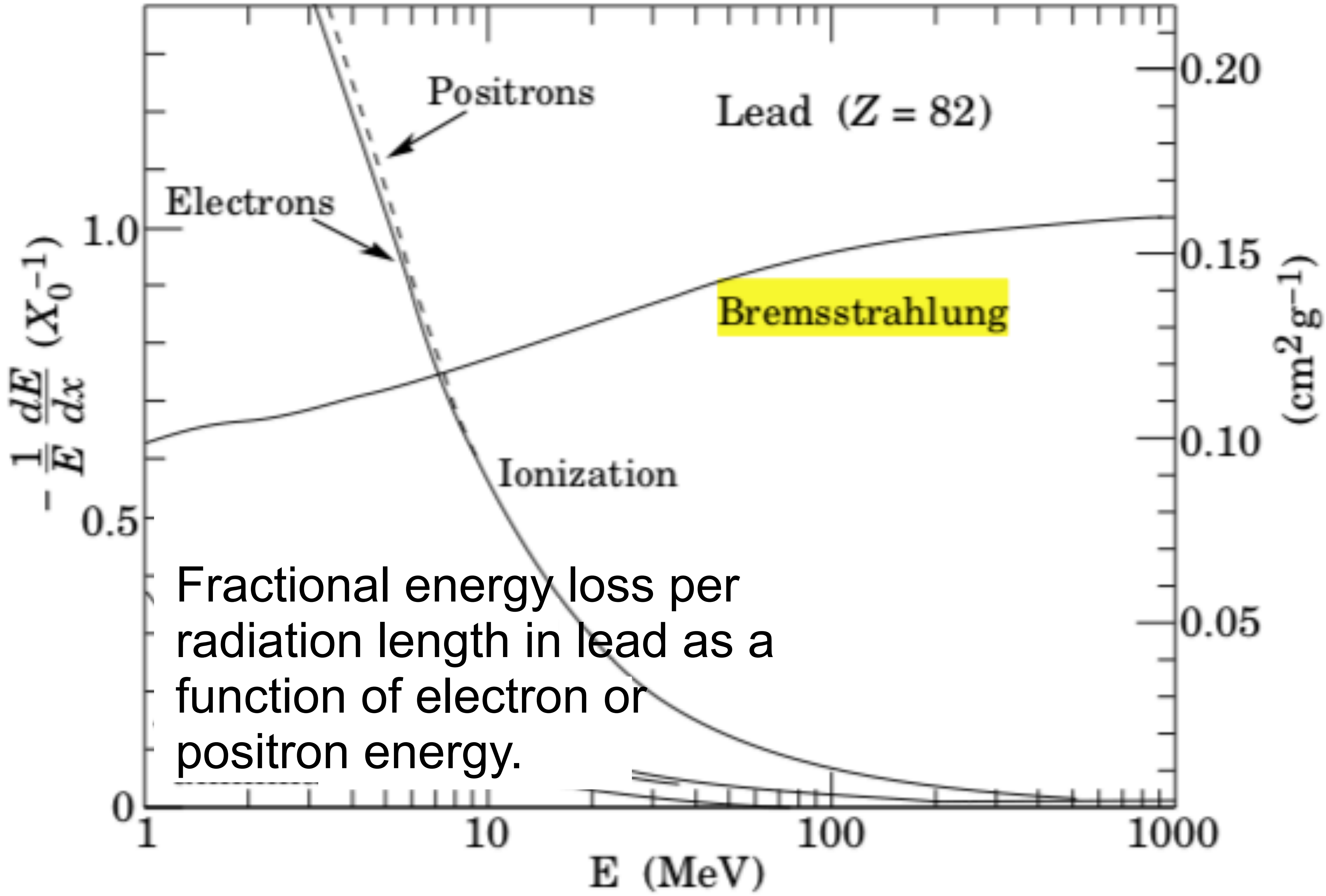
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Z: Atomic Number of target material
A: Atomic Mass of target material
I: Mean excitation Energy
z: charge of incident particle
T_{max}: is the maximum kinetic energy which can be imparted to a free electron in a single collision

Bethe-Bloch in action: Muons in Copper

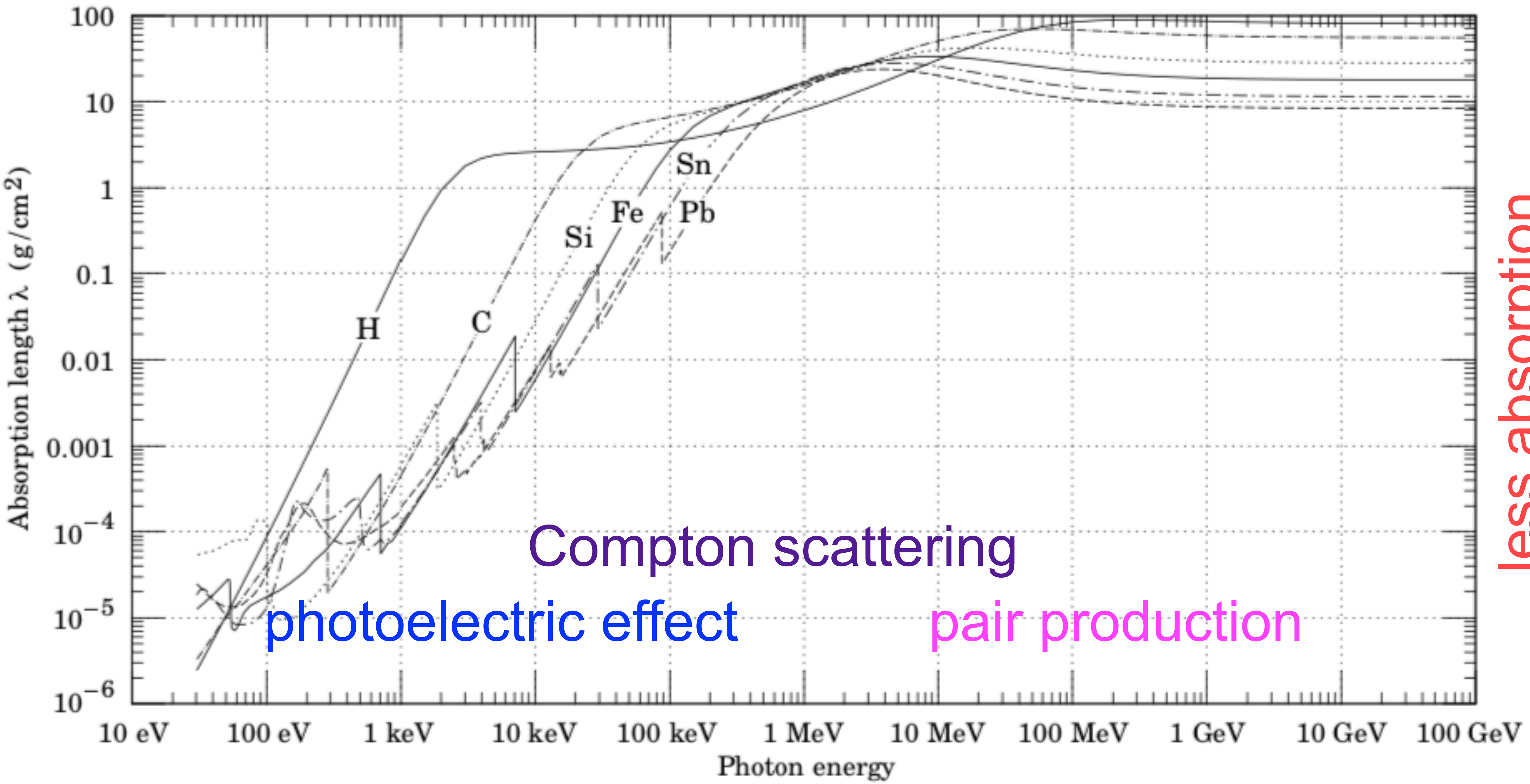


Bremsstrahlung



Fractional energy loss per radiation length in lead as a function of electron or positron energy.

Photon Mass attenuation Length



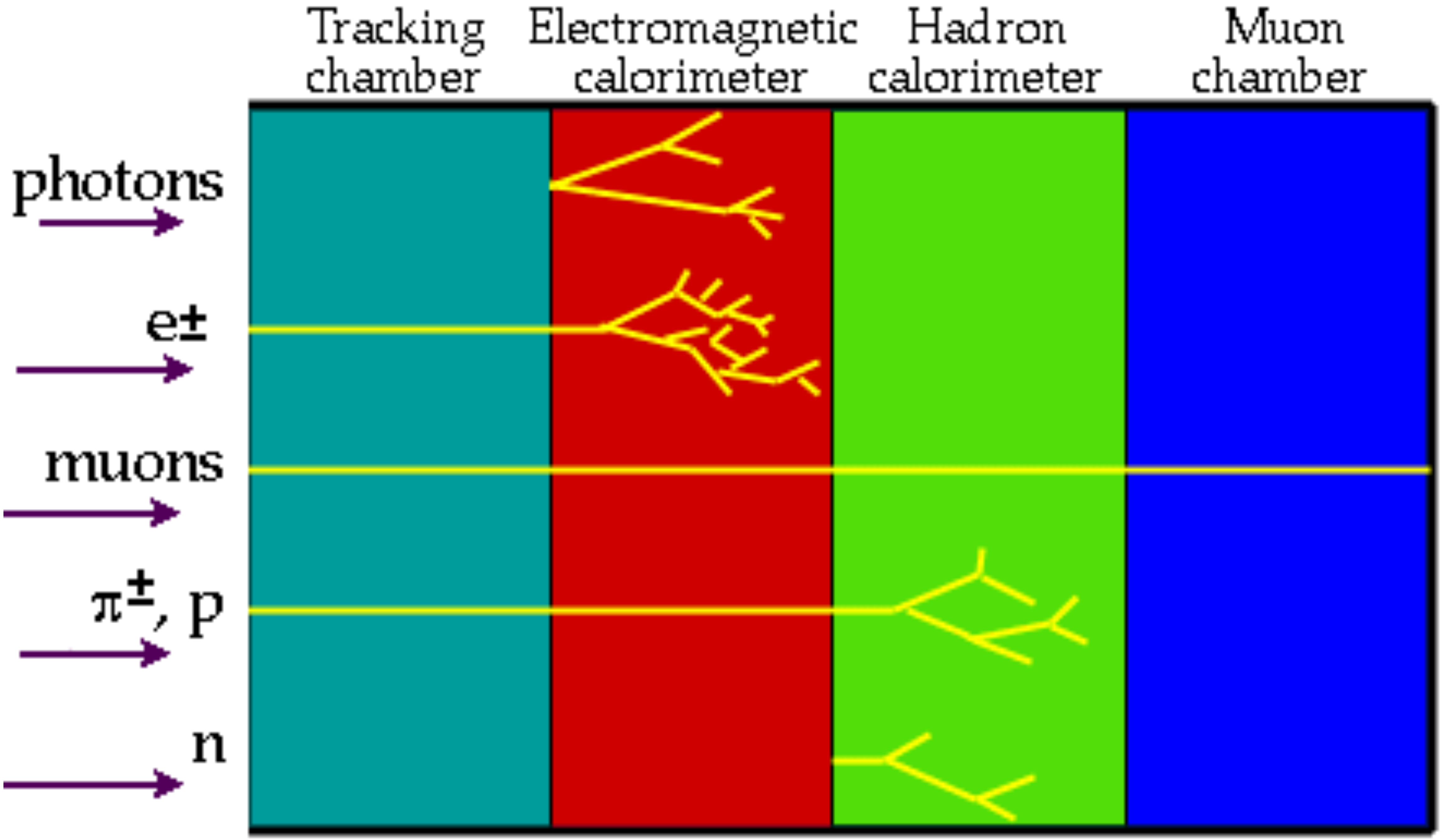
Compton scattering

photoelectric effect

pair production

less absorption

Overview of particle interactions



Interactions with the electron shell nucleus electron shell

http://www.quantumdiaries.org/wp-content/uploads/2009/04/decay_chart1.gif