fermi
Gamma-ray
Space Telescope

Detectors for LAT

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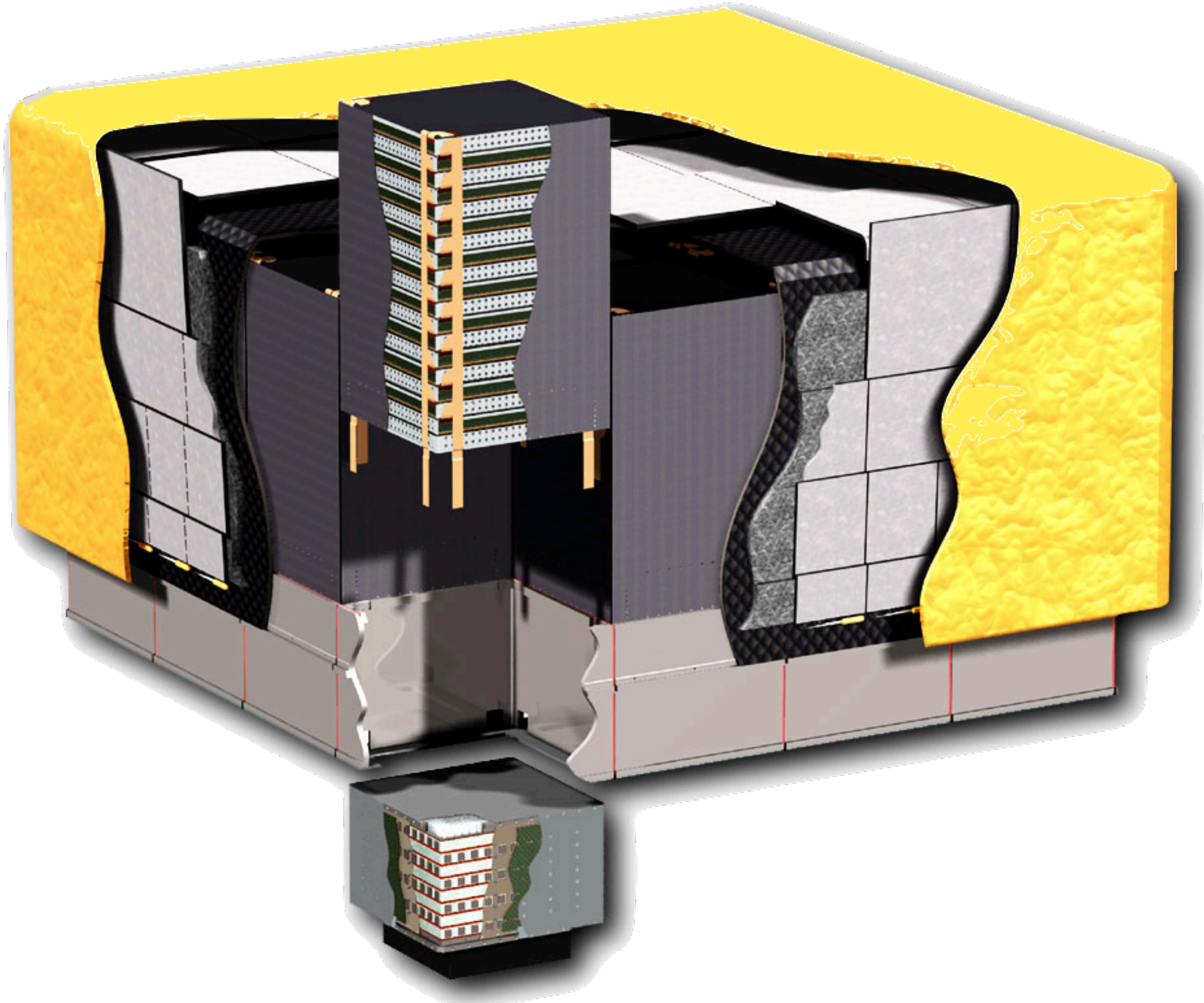
Fermi Summer School
Lewes, DE

May 31, 2018

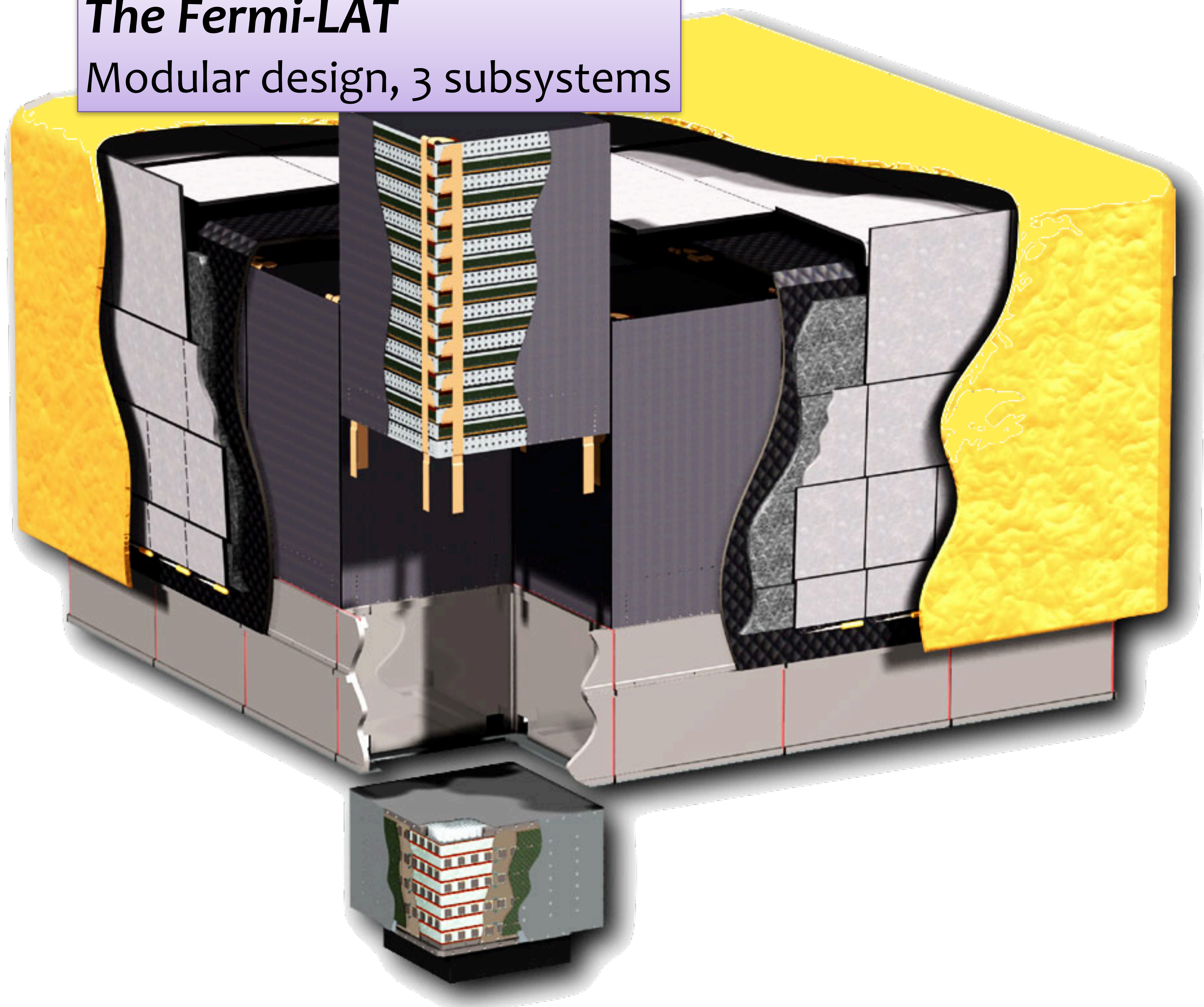
Fermi Large Area Telescope: Recap



Fermi Large Area Telescope: Recap

The Fermi-LAT

Modular design, 3 subsystems



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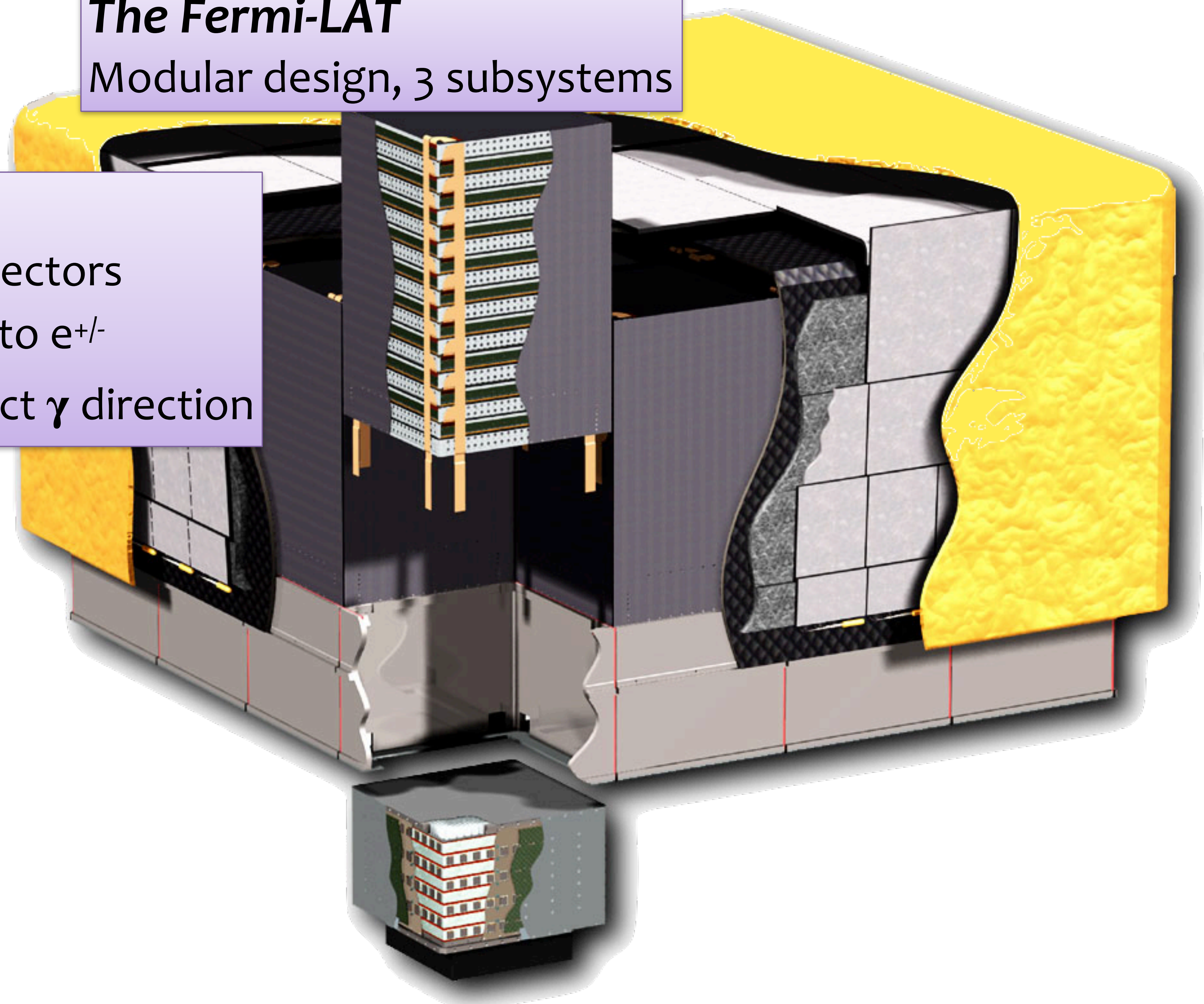
Tracker
Silicon detectors
Convert γ to $e^{+/-}$
Reconstruct γ direction



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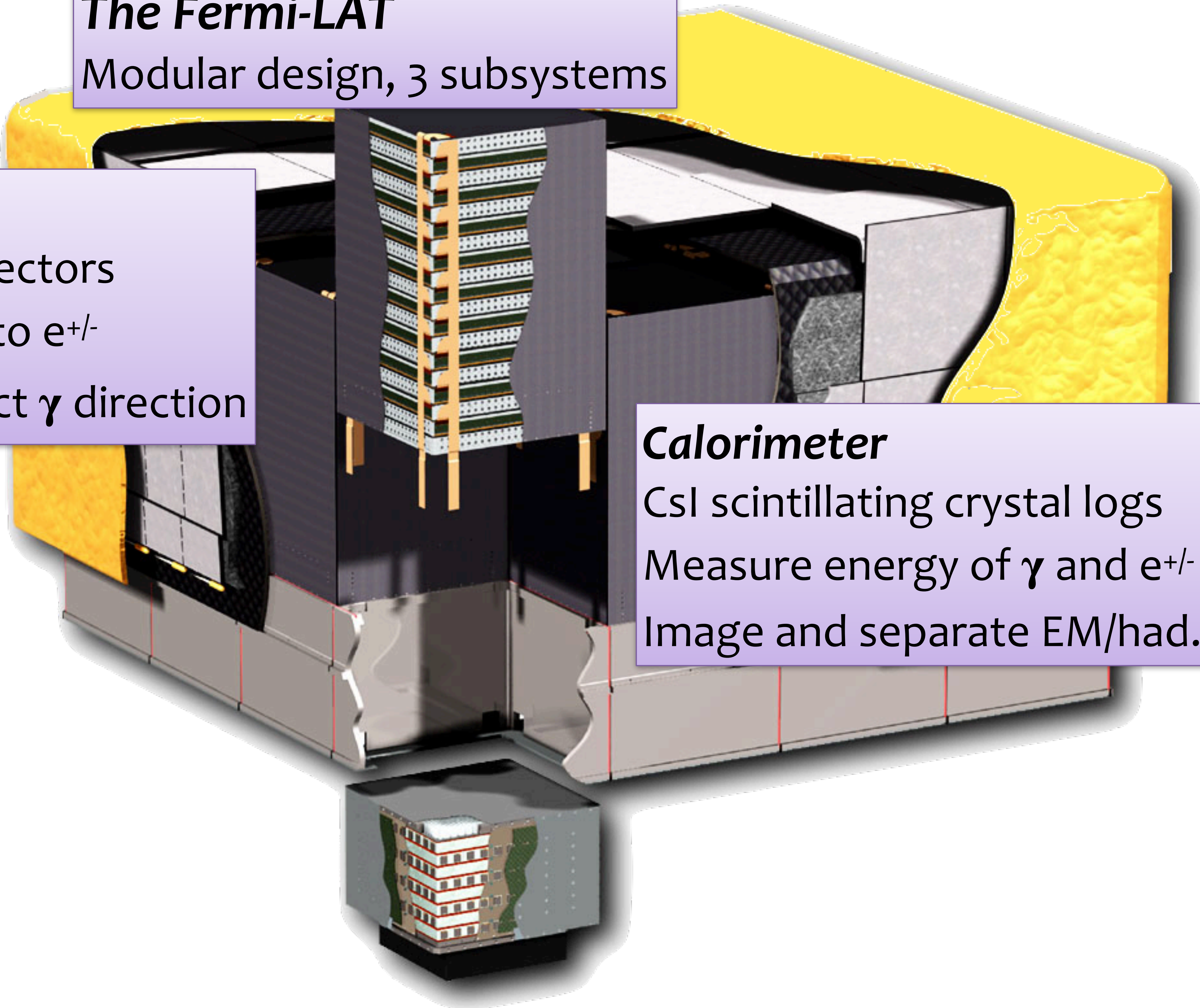

Calorimeter

CsI scintillating crystal logs

Measure energy of γ and $e^{+/-}$

Image and separate EM/had. showers

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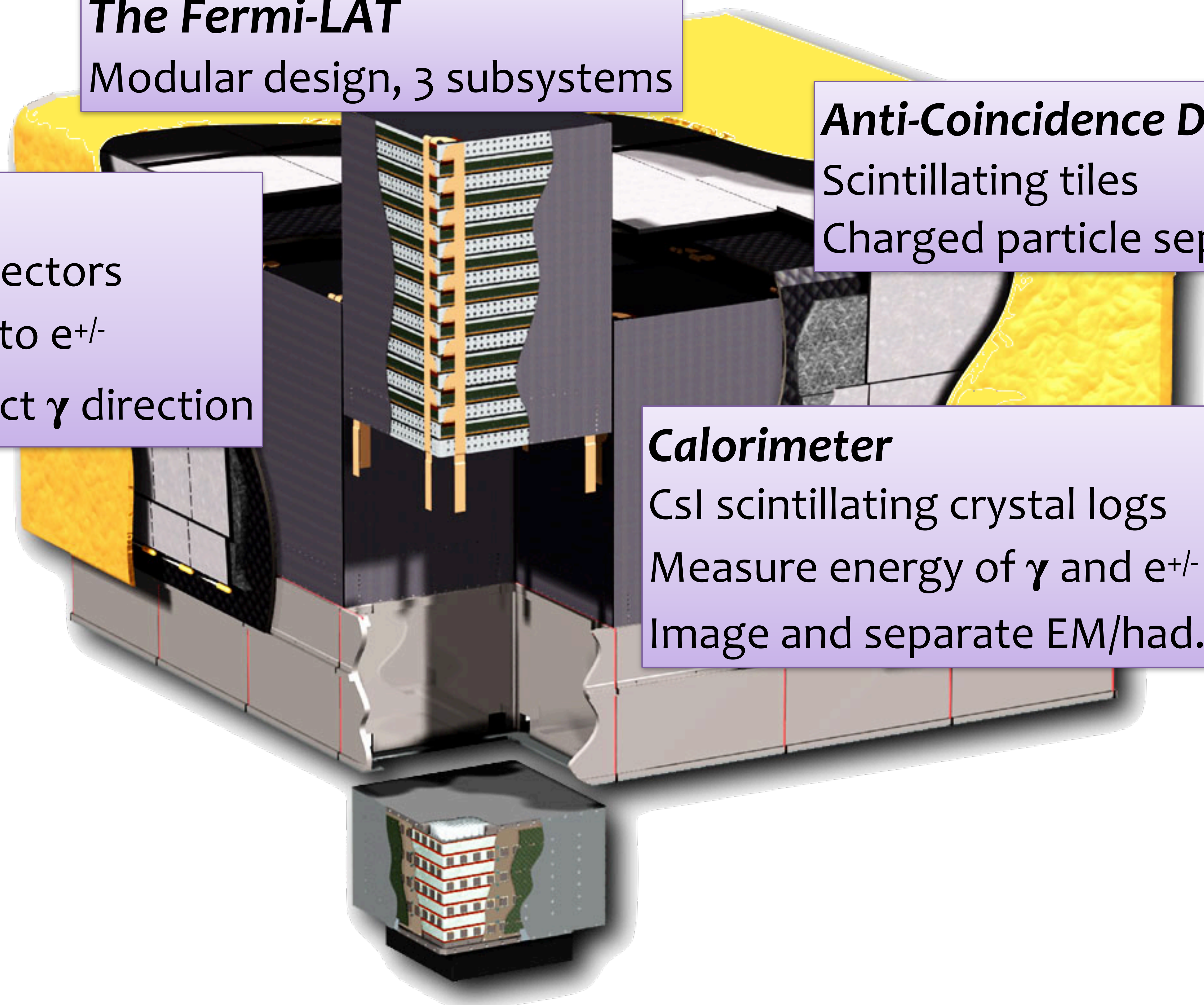

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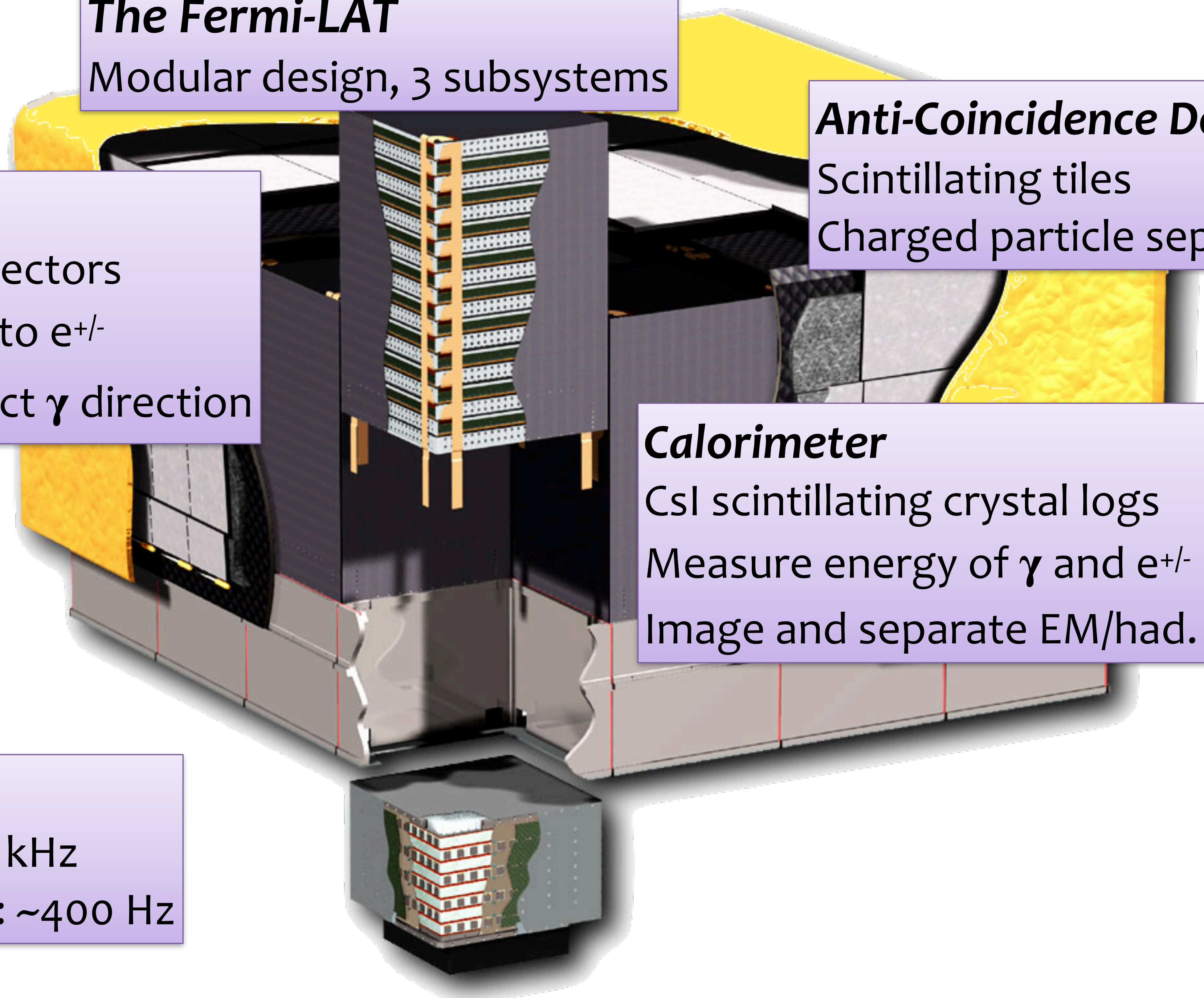

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rate: ~10 kHz

read out: ~400 Hz

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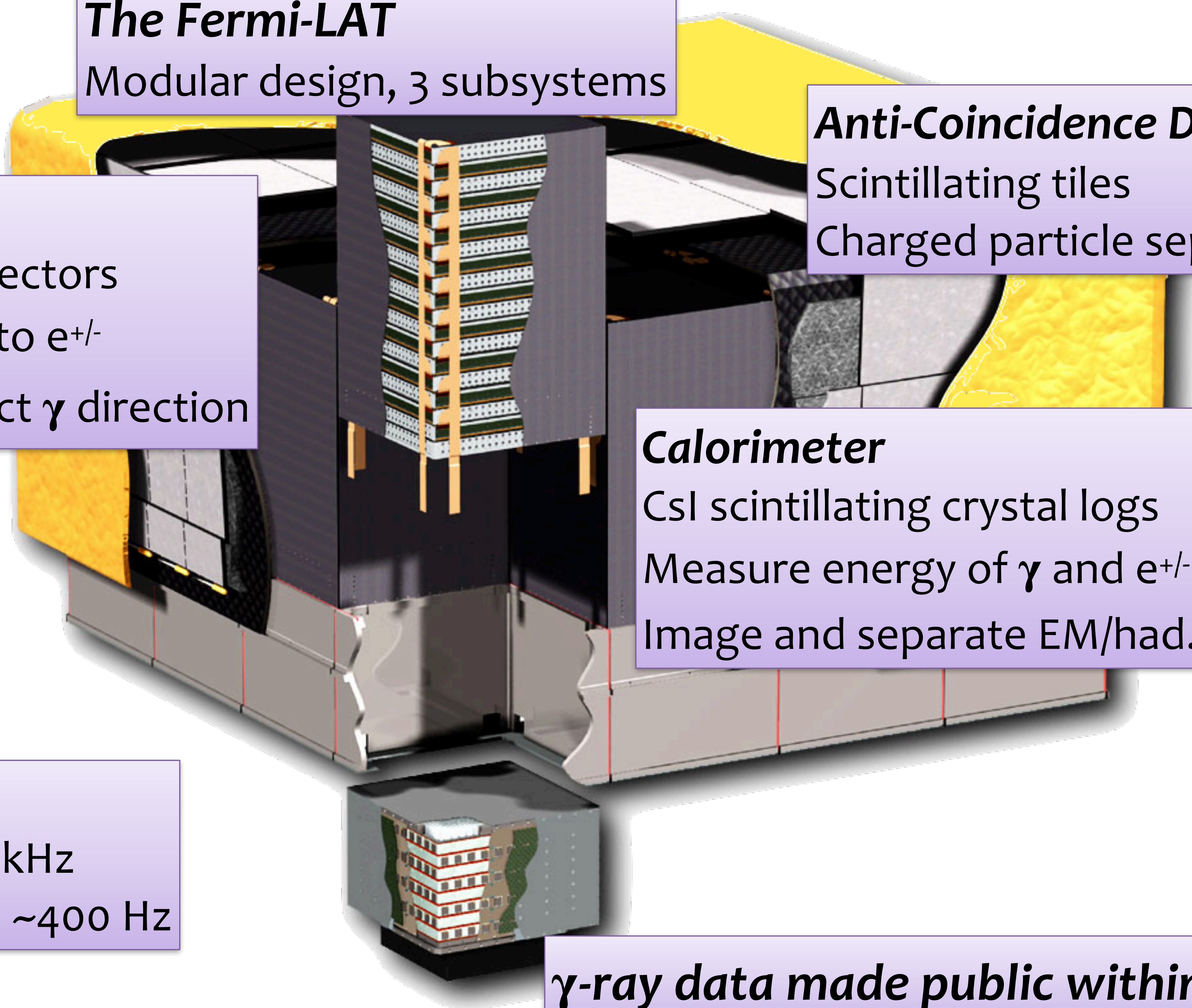

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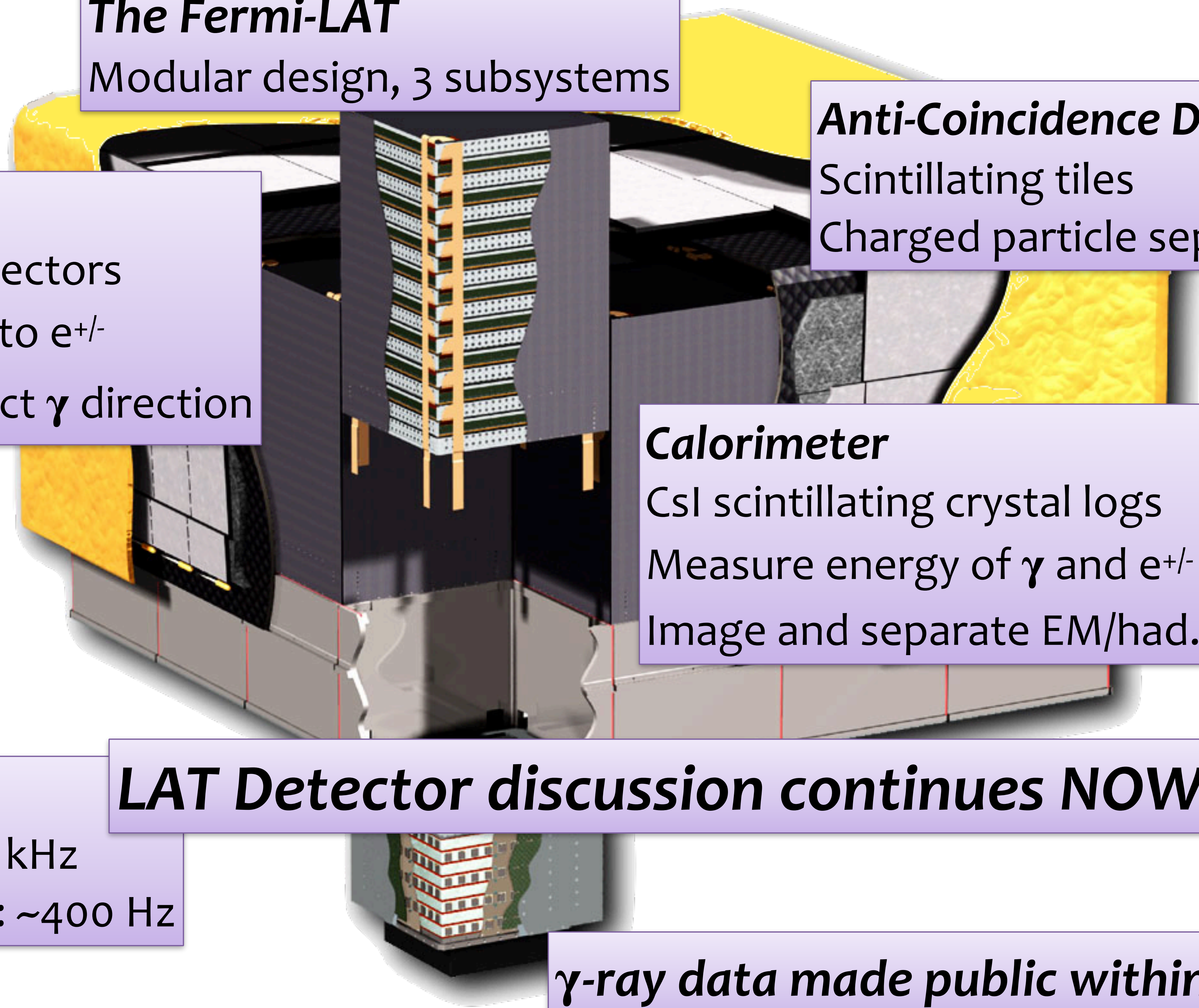

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LAT Detector discussion continues NOW…

γ-ray data made public within 24 hours

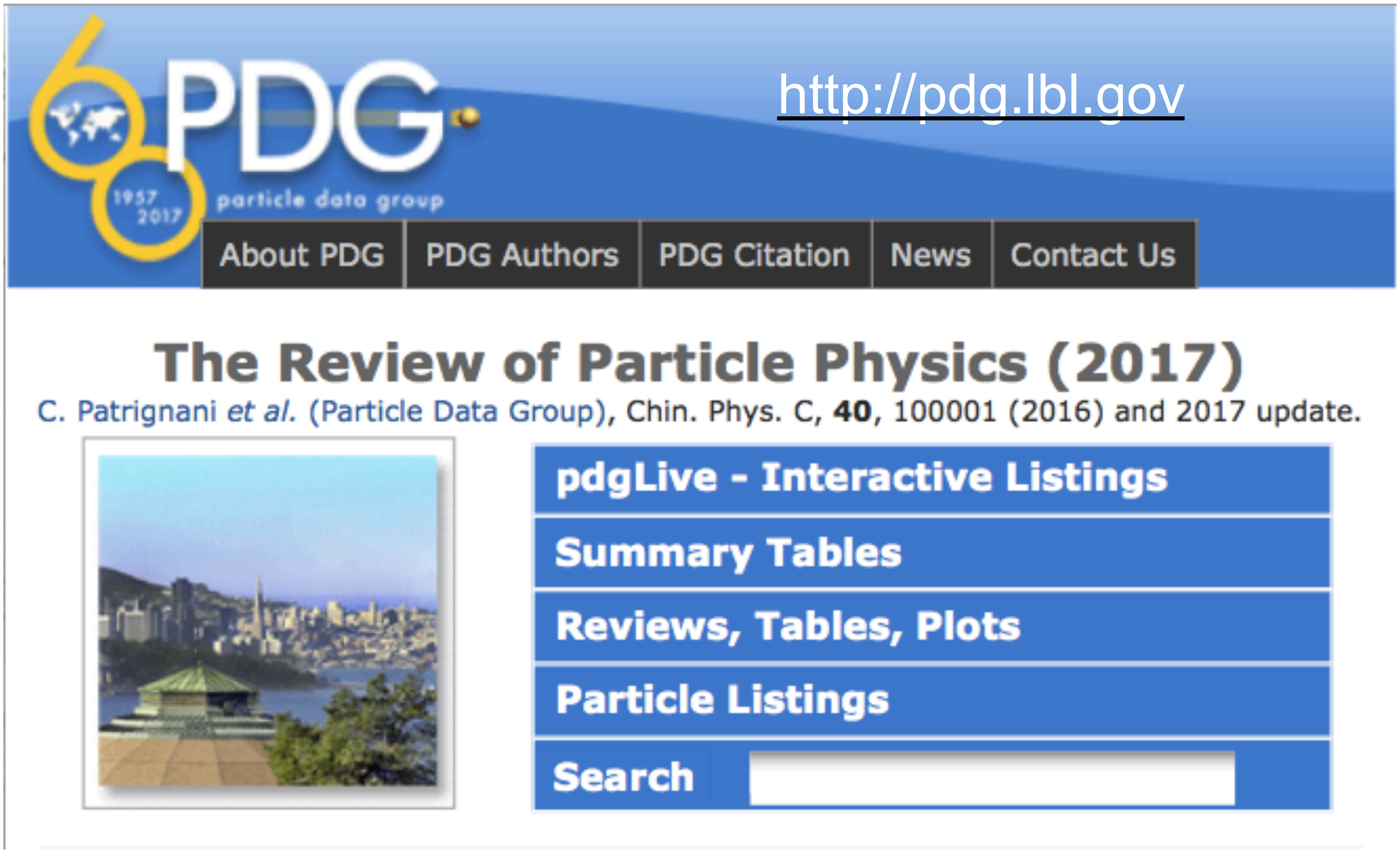
Outline

- Particle interactions in general
  - The Standard Model

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

- Detectors!
  - Tracking, Calorimeters

A Valuable Resource



Covers particle properties, particle physics, astrophysics, statistics… *everything*

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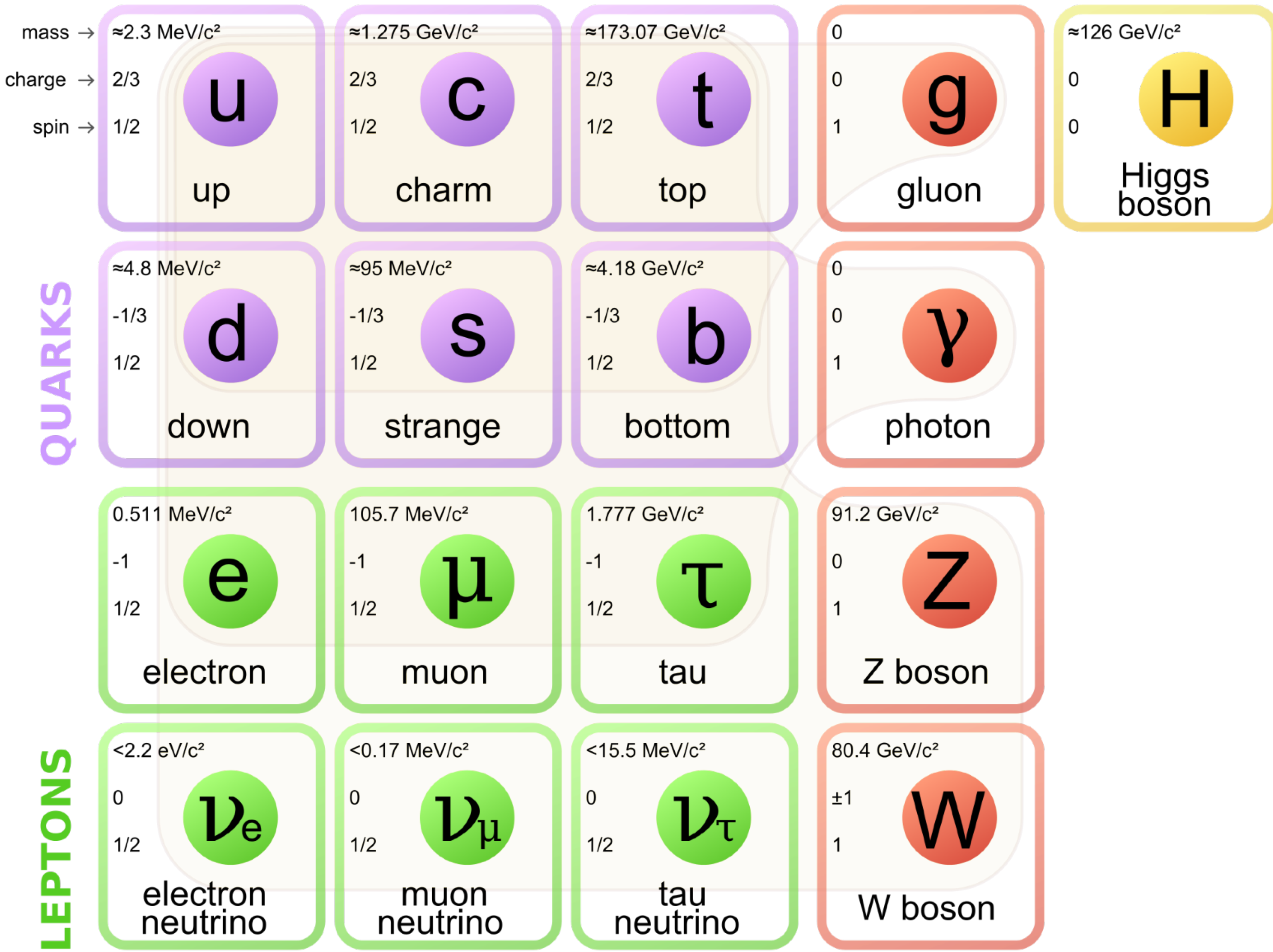
Covers particle properties, particle physics, astrophysics, statistics… *everything*

Standard Model of Particle Physics



Standard Model of Particle Physics

Protons/Neutrons/Pions

mass →
charge →
spin →

QUARKS	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
LEPTONS	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

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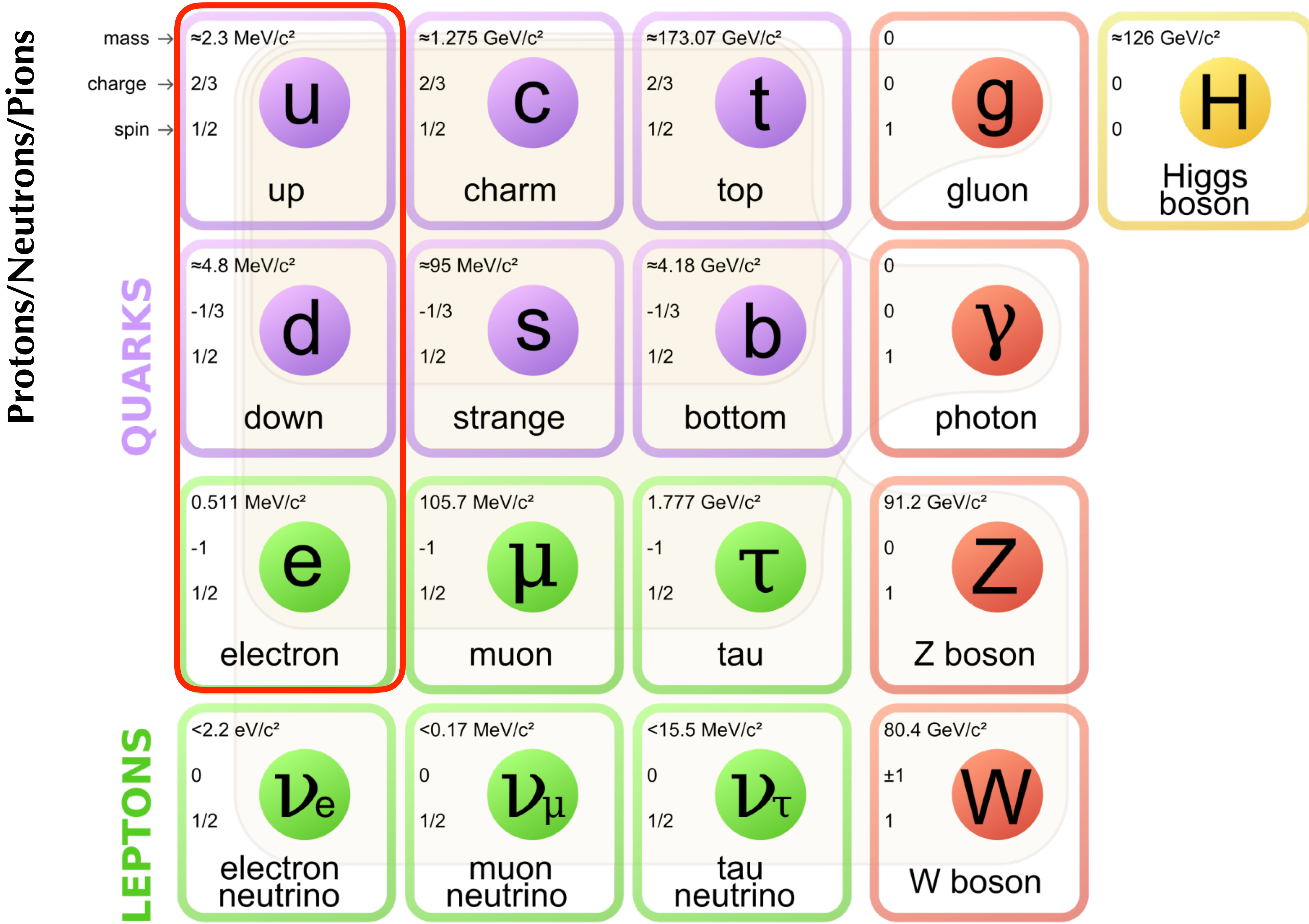

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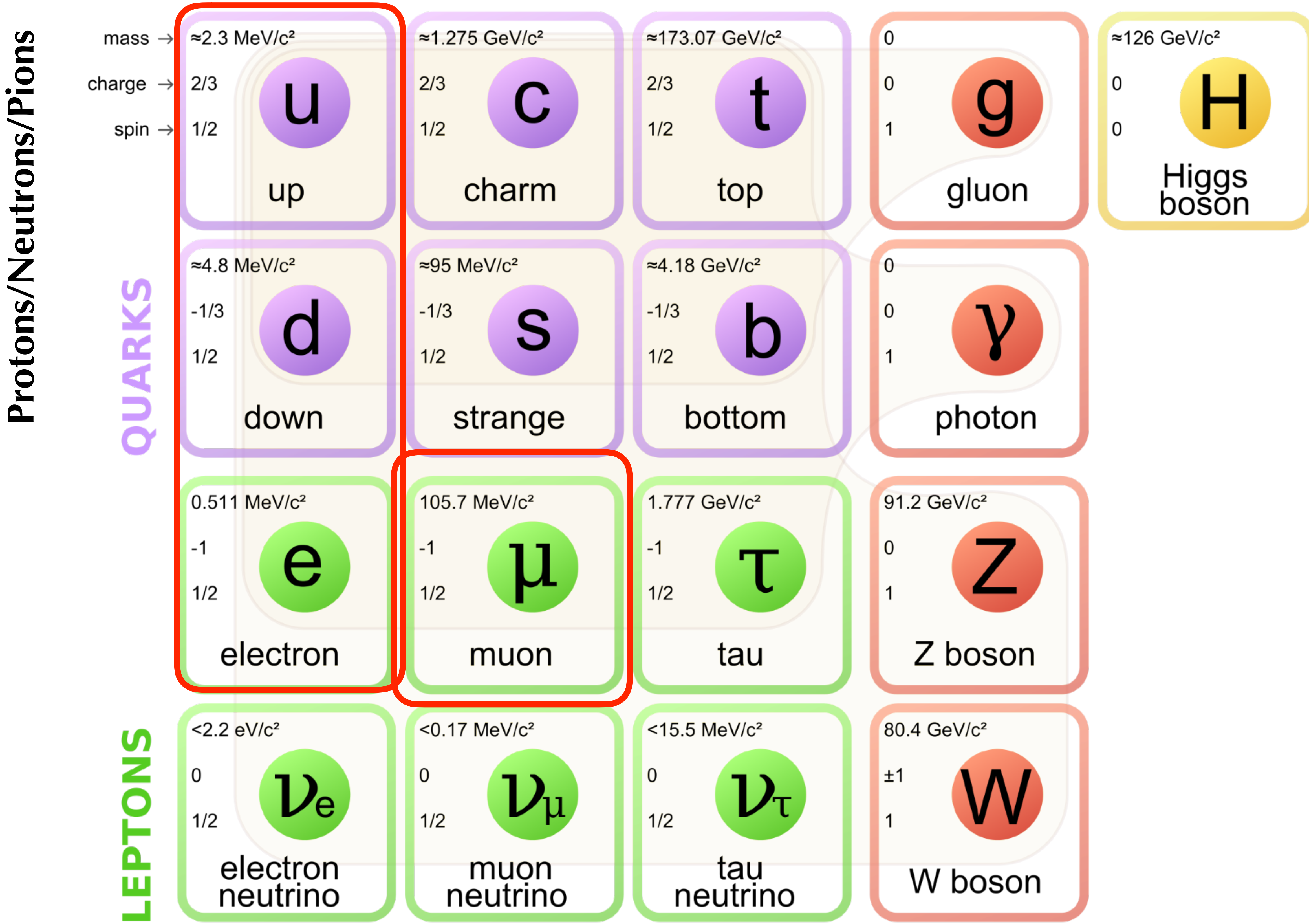

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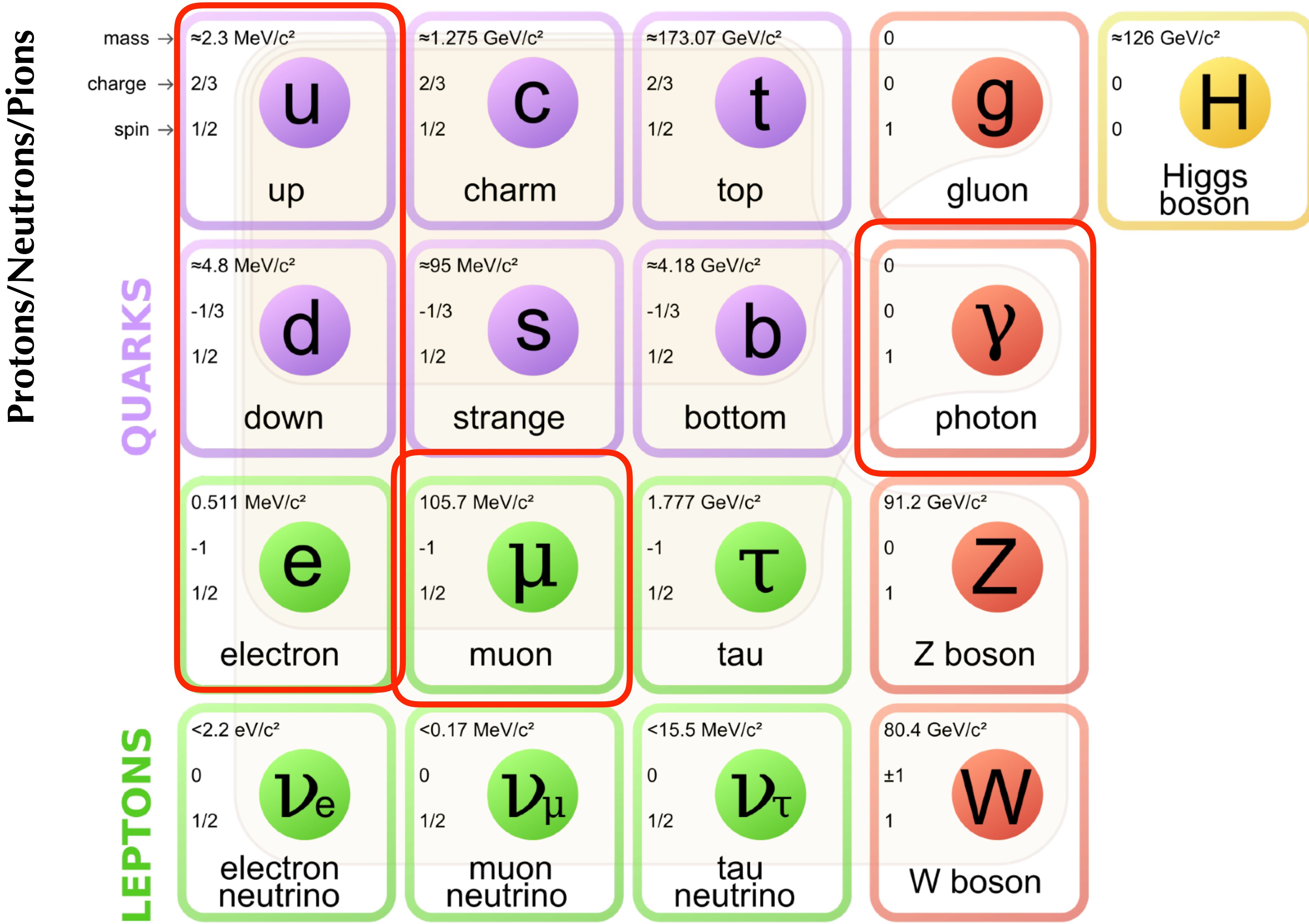

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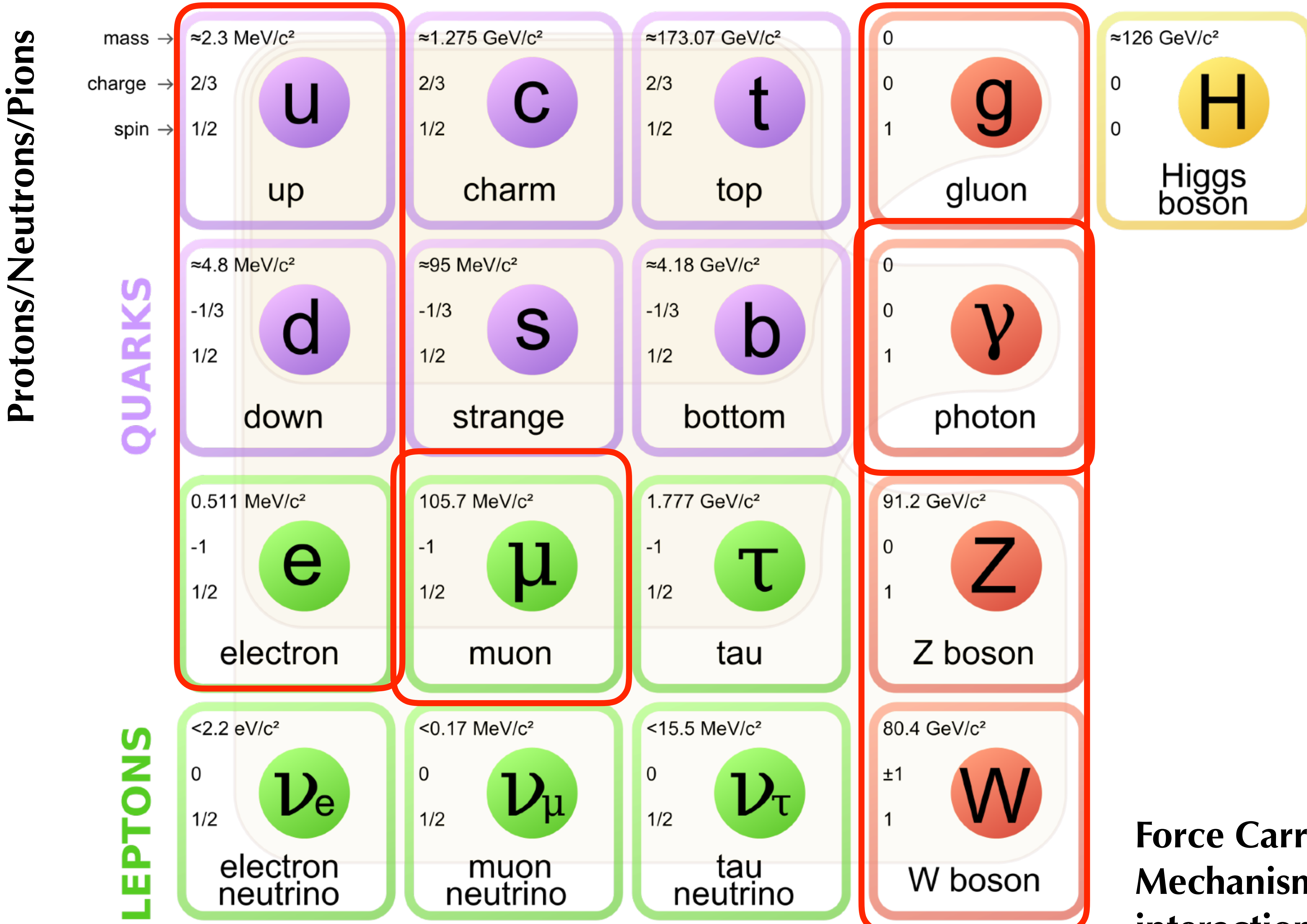

Force Carriers: Mechanisms for interactions

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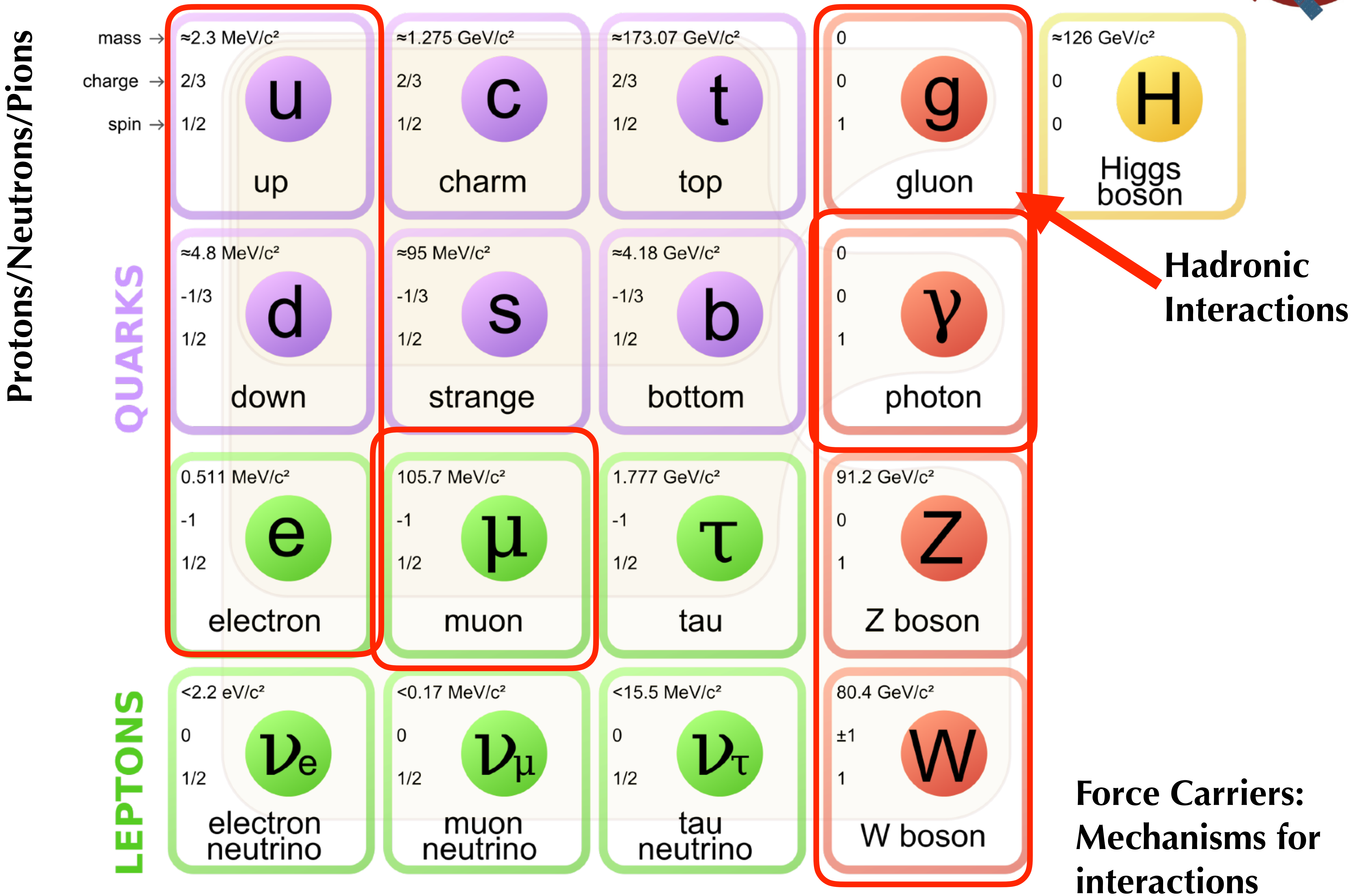

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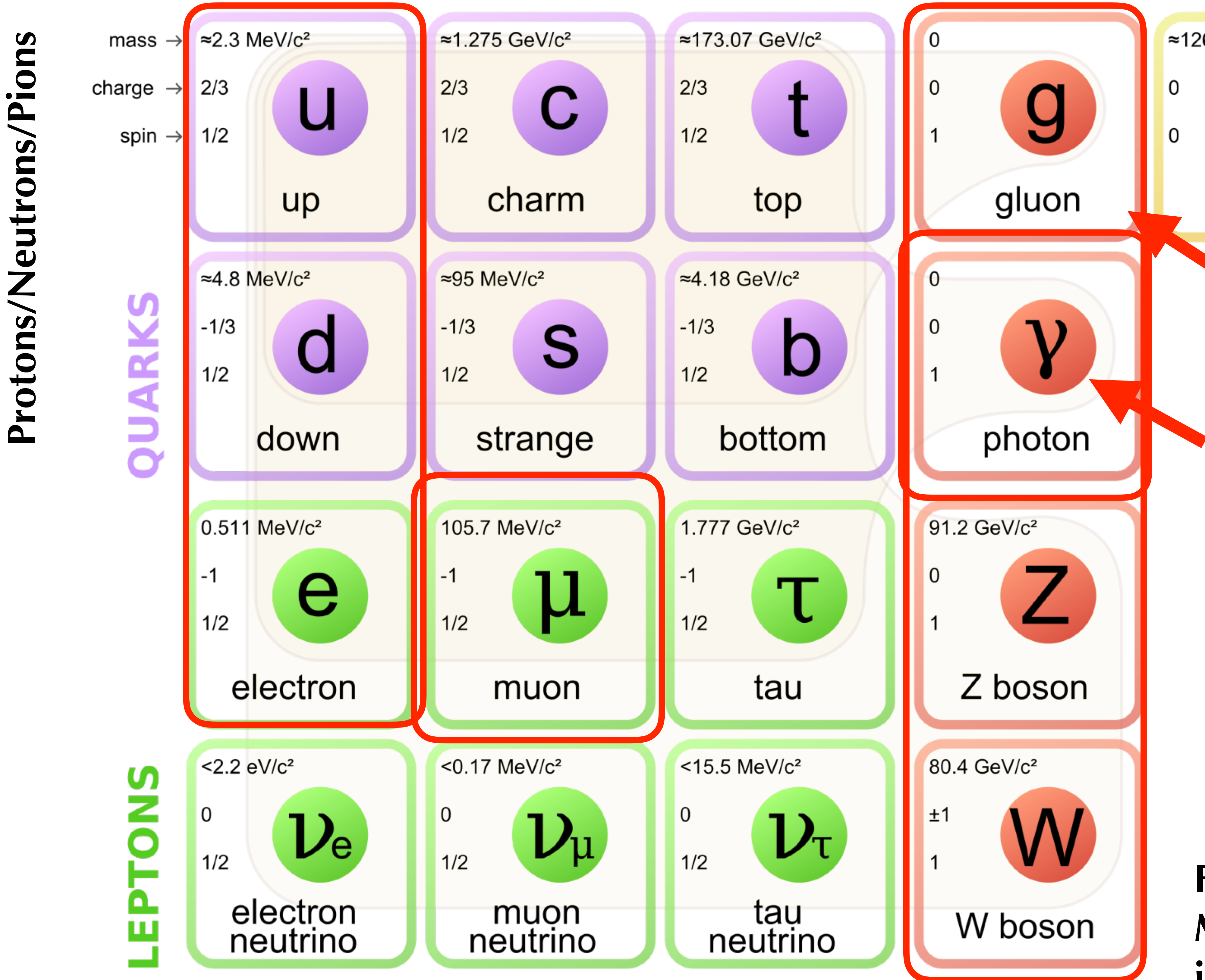

Hadronic Interactions

Electromagnetic Interactions

Force Carriers: Mechanisms for interactions

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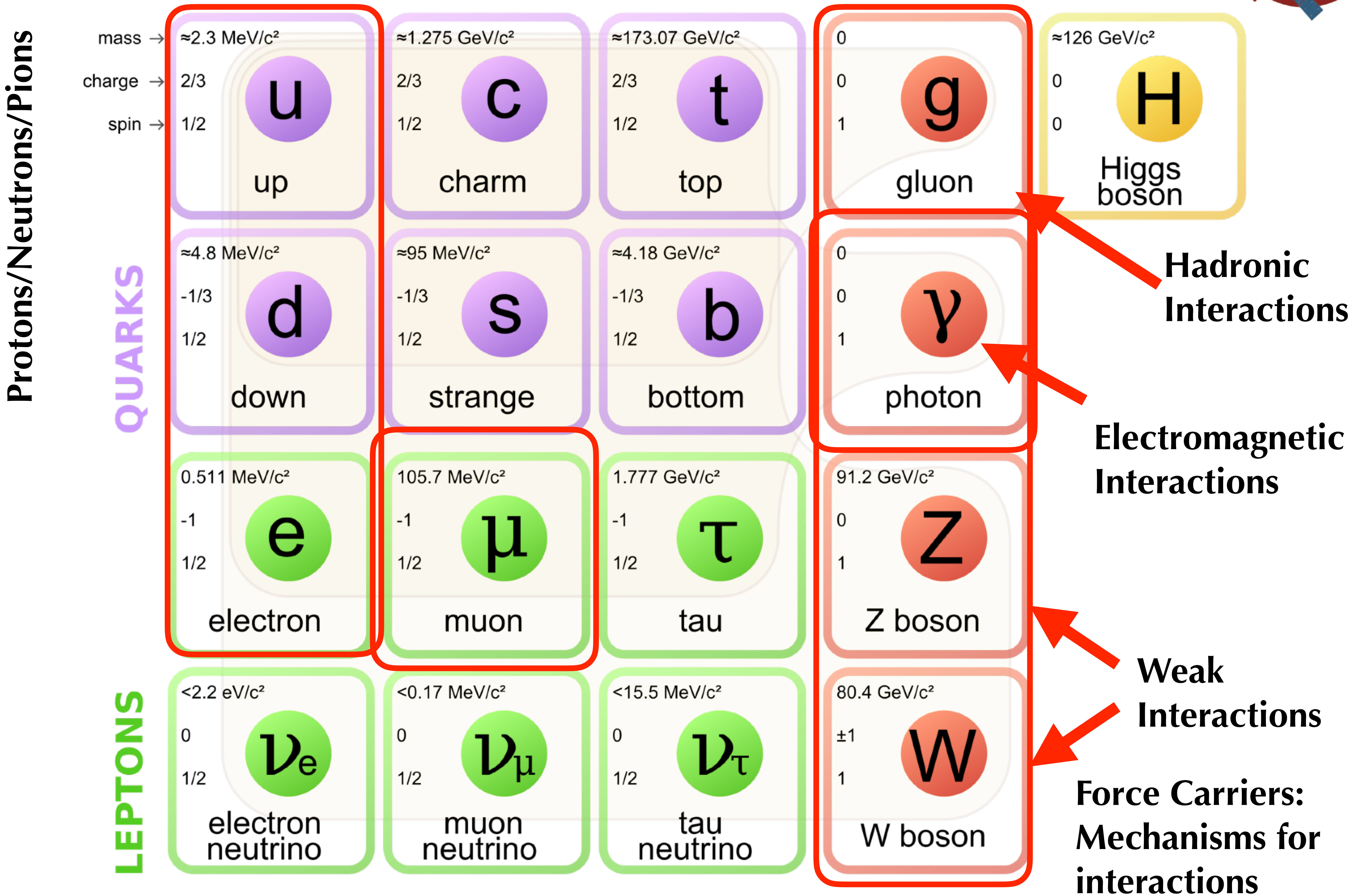
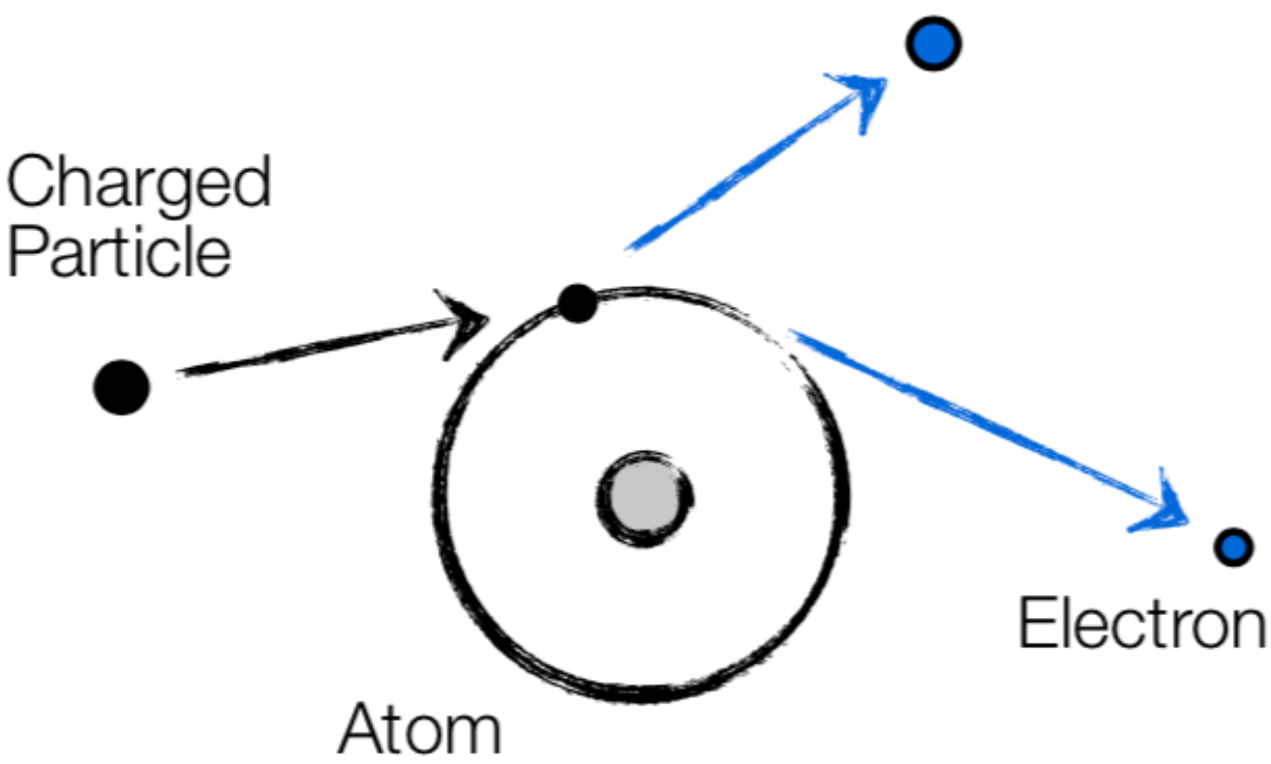


From Particle interactions in theory to Particle interactions in practice

- Goal: design detectors to utilize the way these particles interact via these forces…

- A few notes (Feynman diagram cheat sheet)

Ionization



What happens

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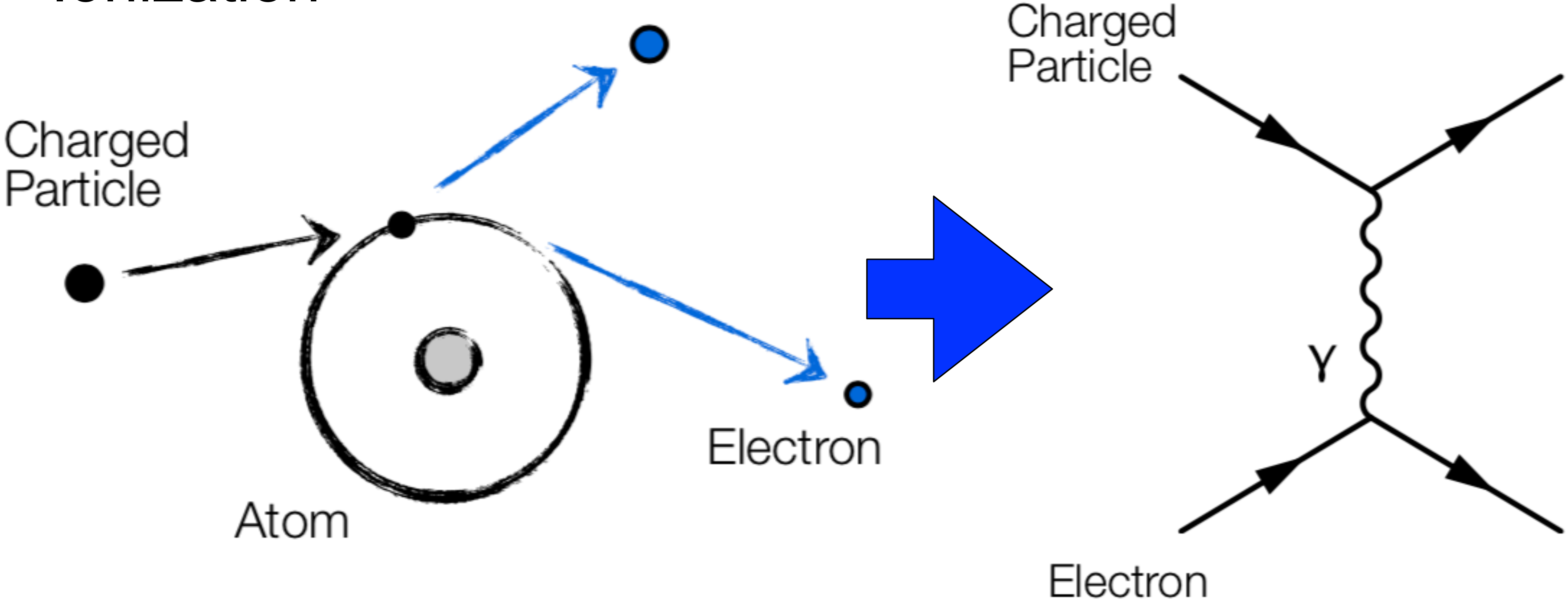

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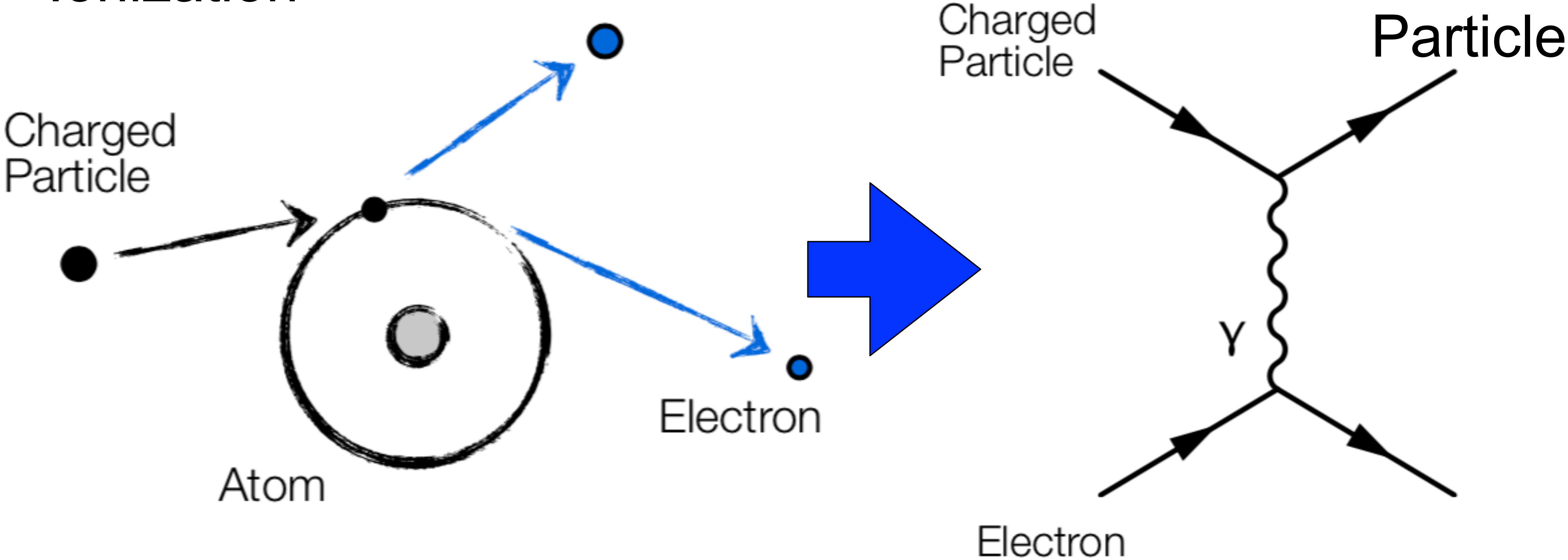

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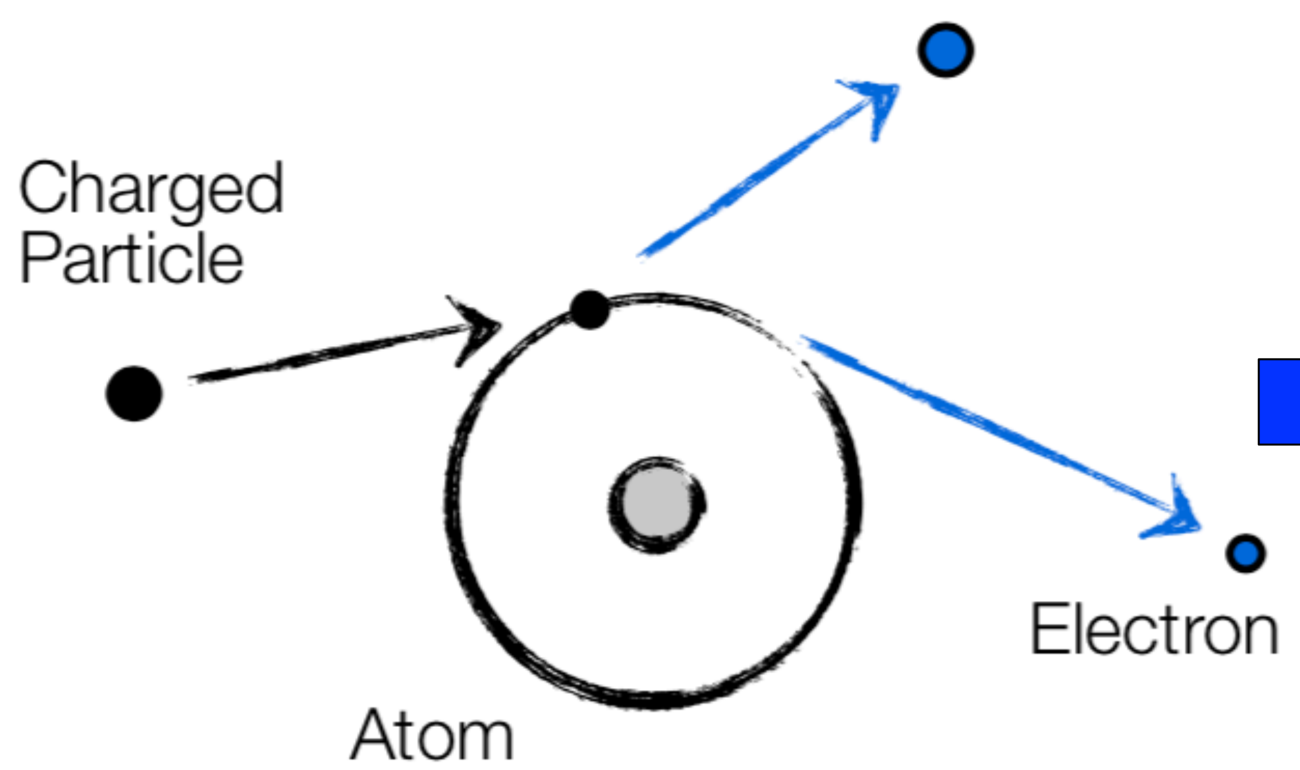

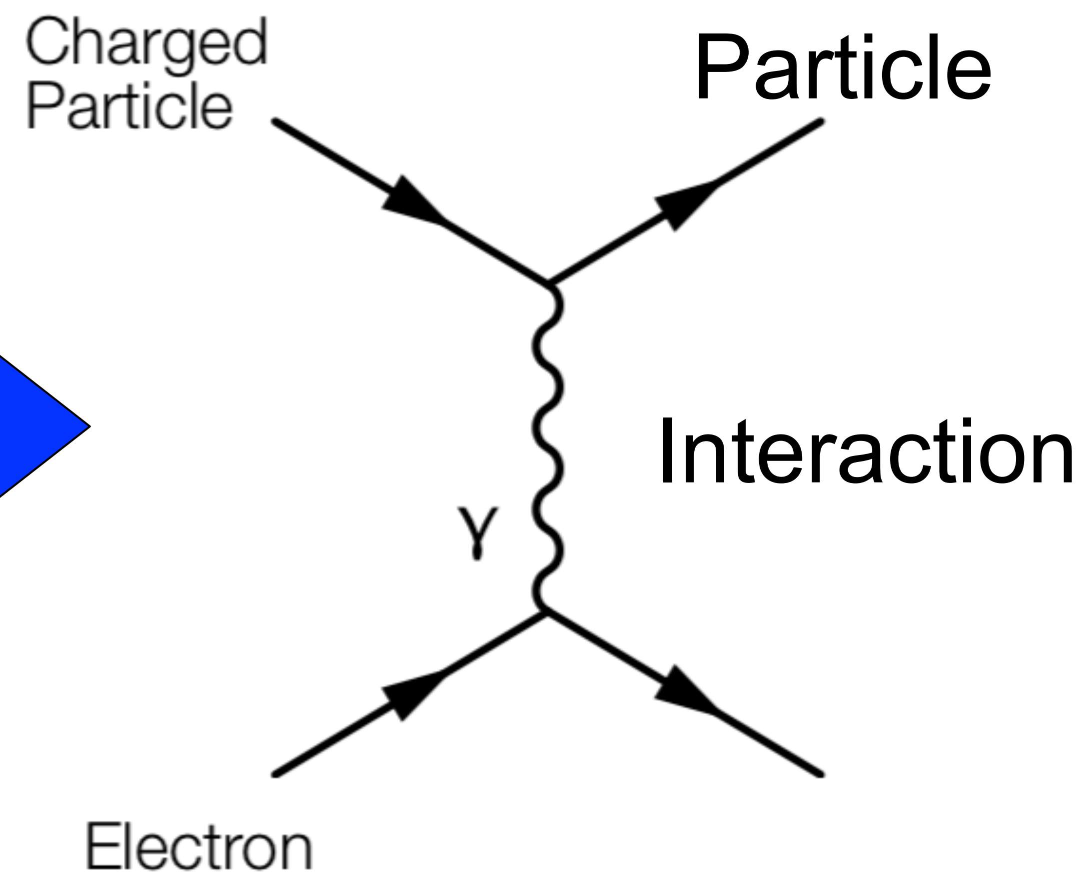

What happens

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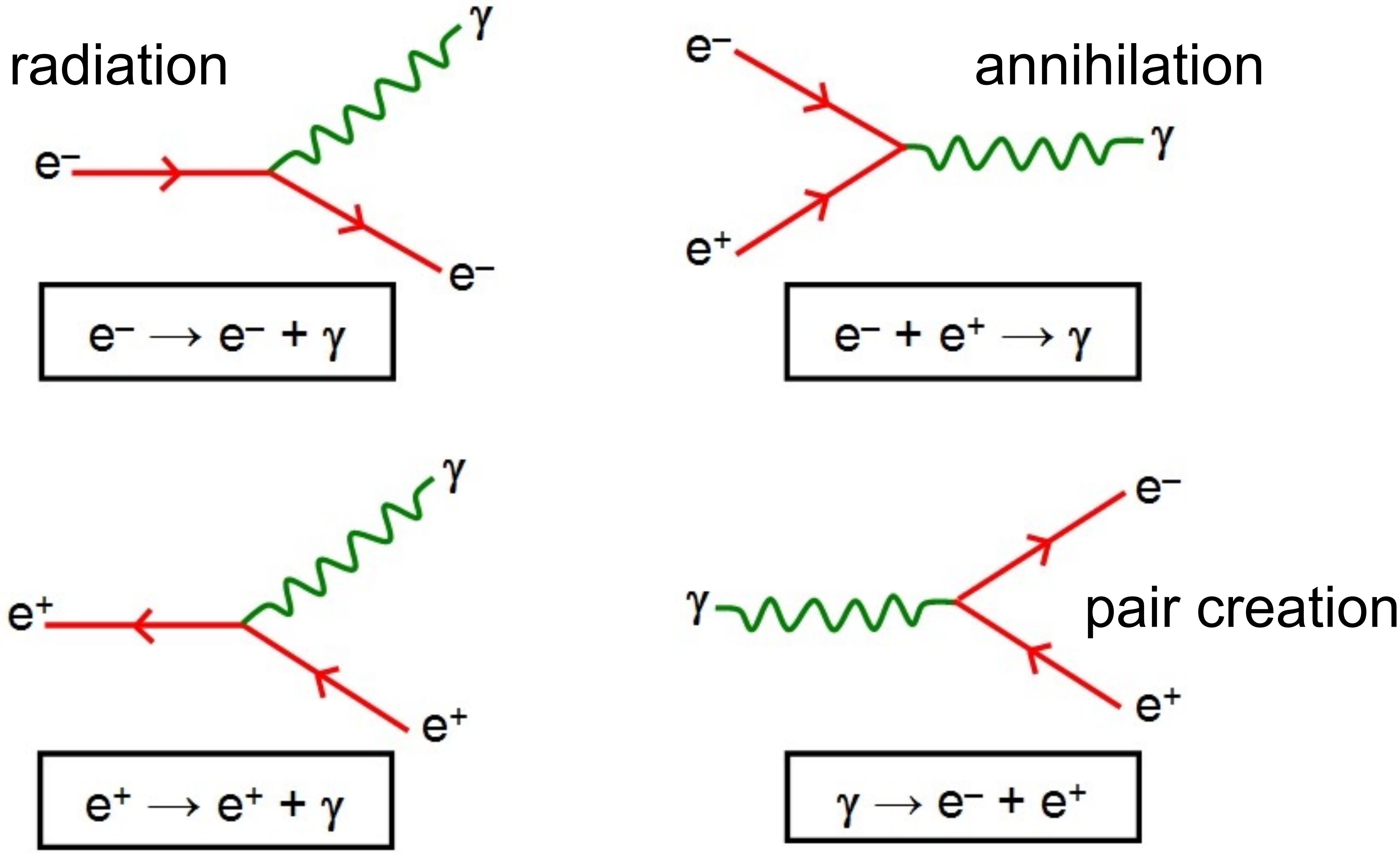
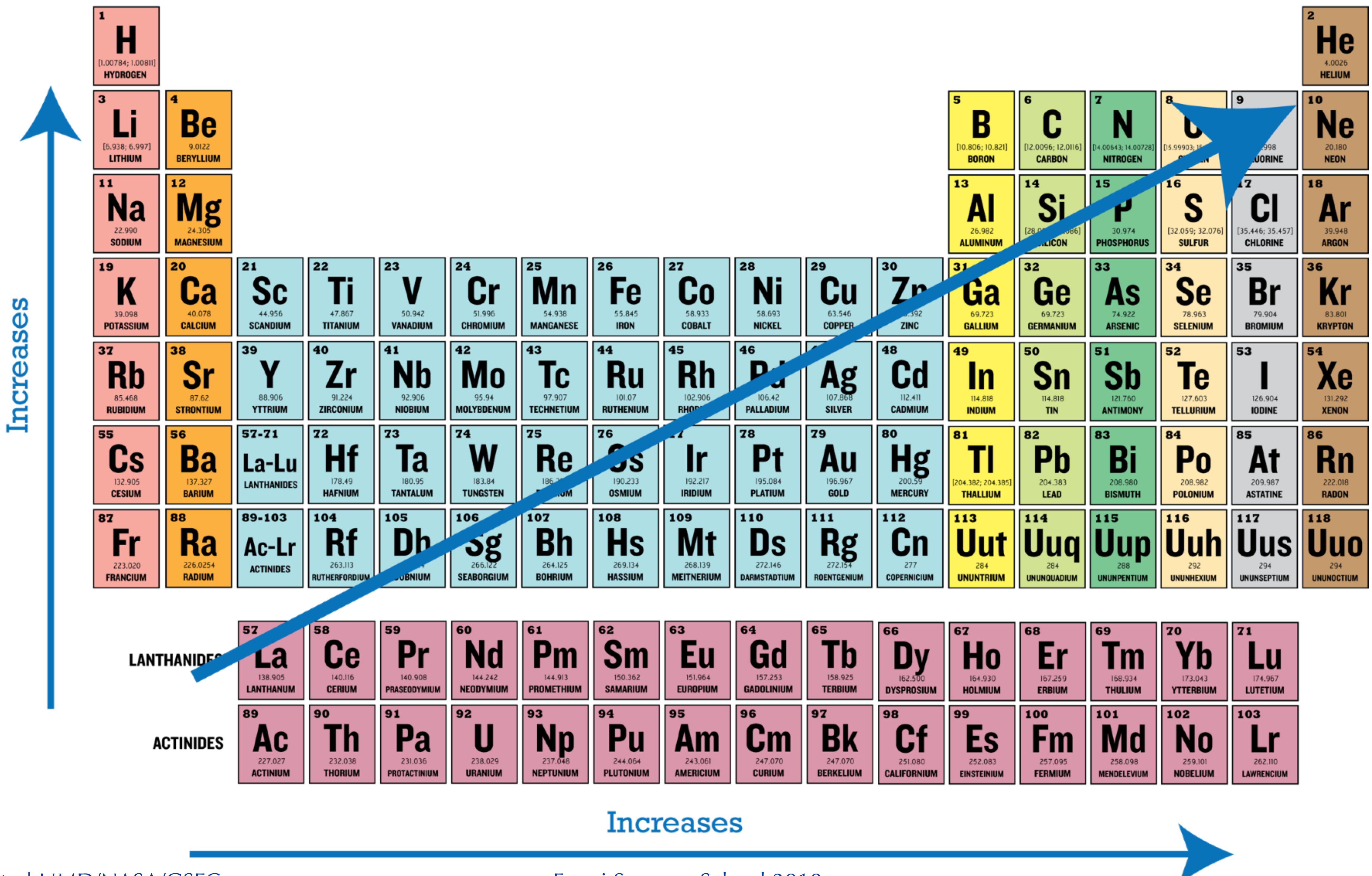
Electromagnetic interactions



https://physics.stackexchange.com/questions/66309/do-excited-electrons-drop-back-to-same-quantum-state

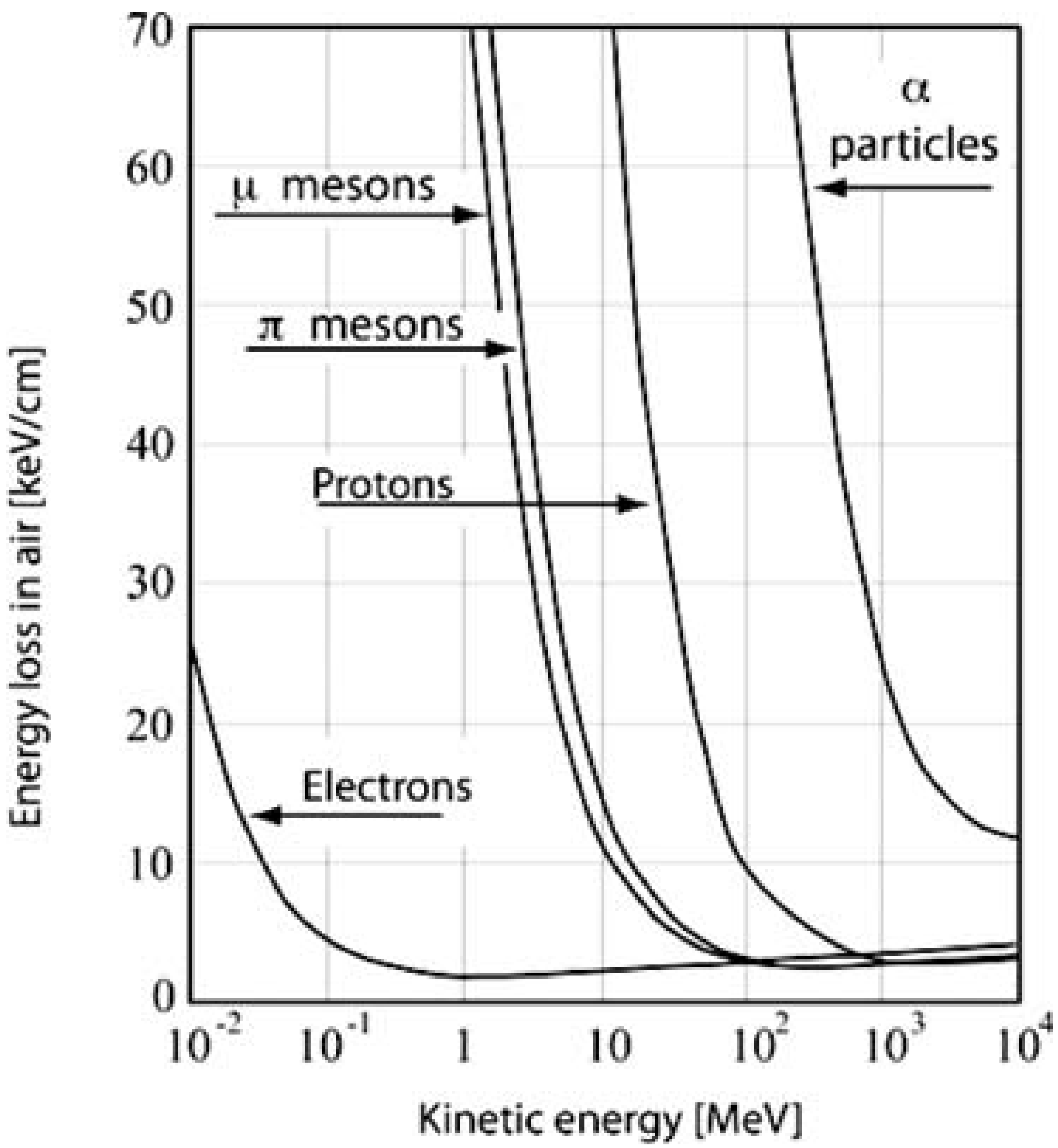
Charged particle interactions in matter

Ionization Energy: Energy required to remove outermost electron



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)**



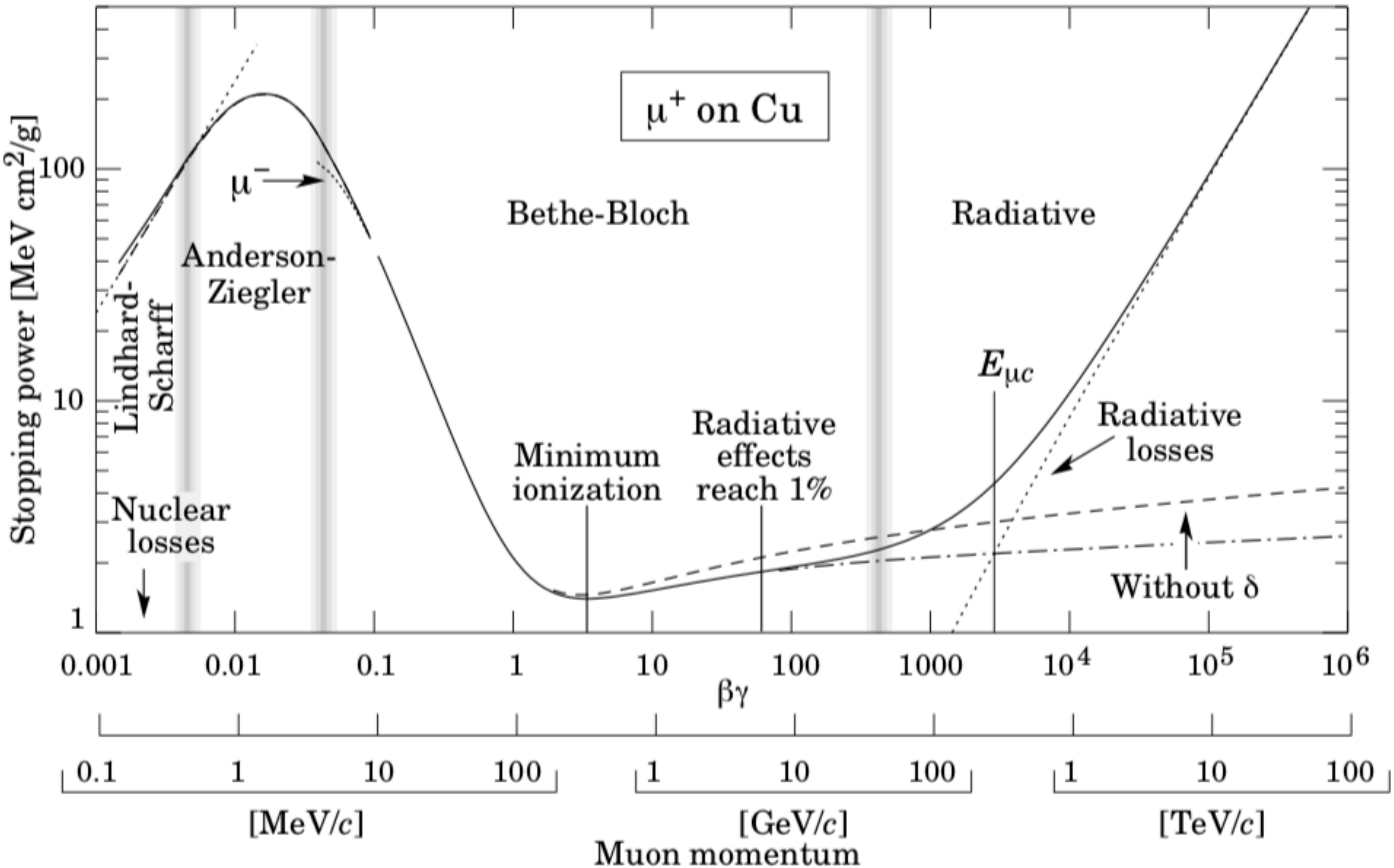
$$\frac{dE}{dx} \approx \rho\,(2\,\mathrm{MeV cm^2/g})\frac{Z^2}{\beta^2}$$

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

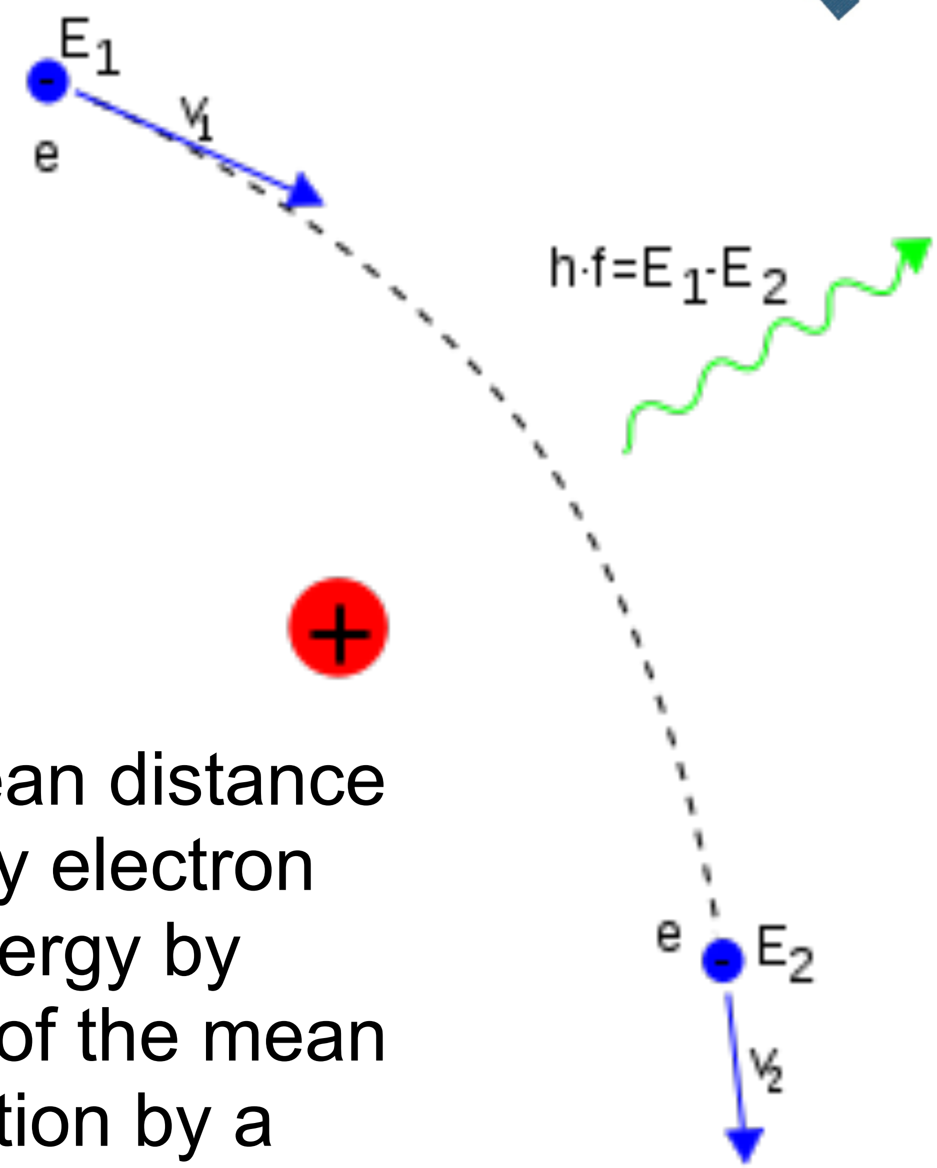
Bethe-Bloch in action: Muons in Copper



Bremsstrahlung

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

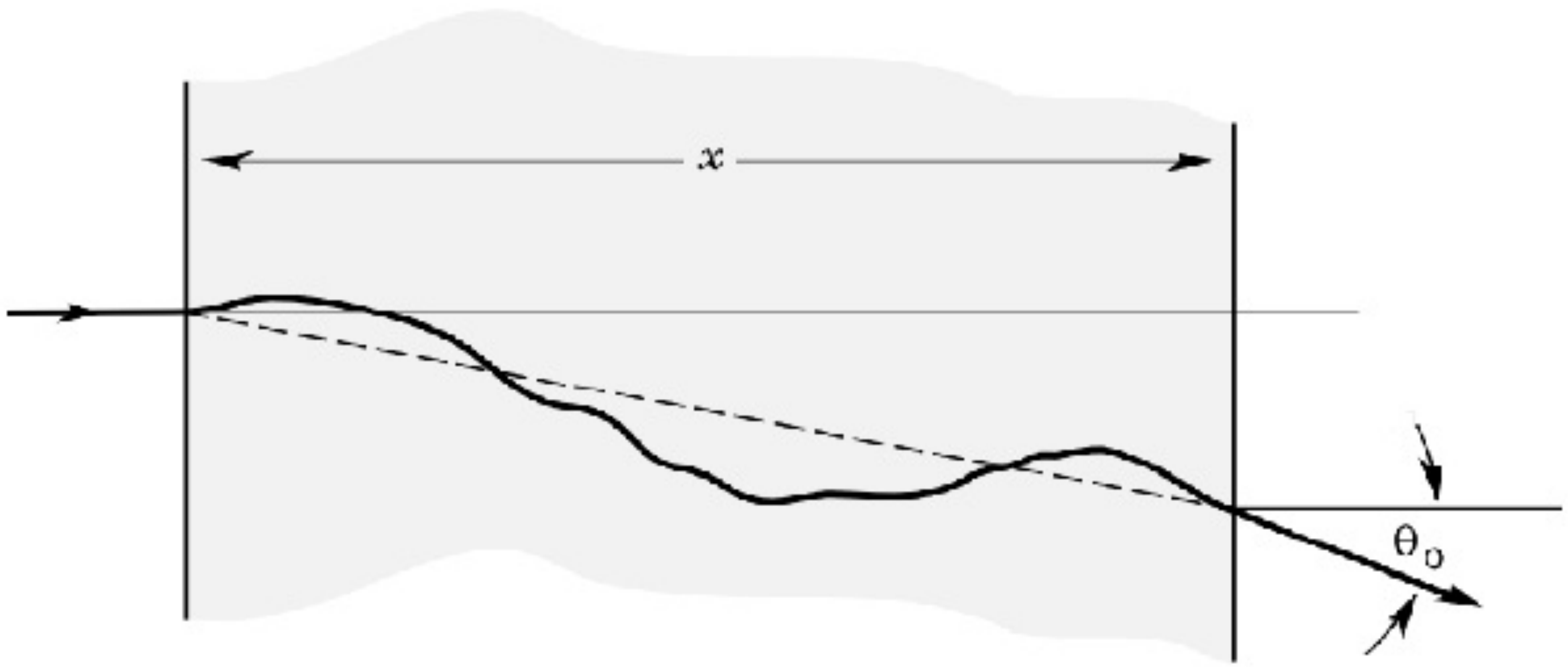


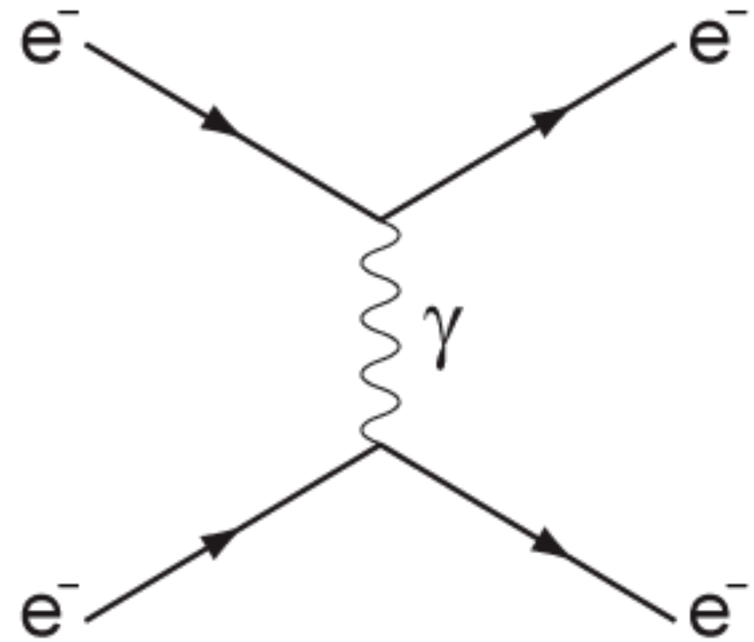
$$\frac{dE}{dx} = -\frac{E}{X_0}$$

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

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

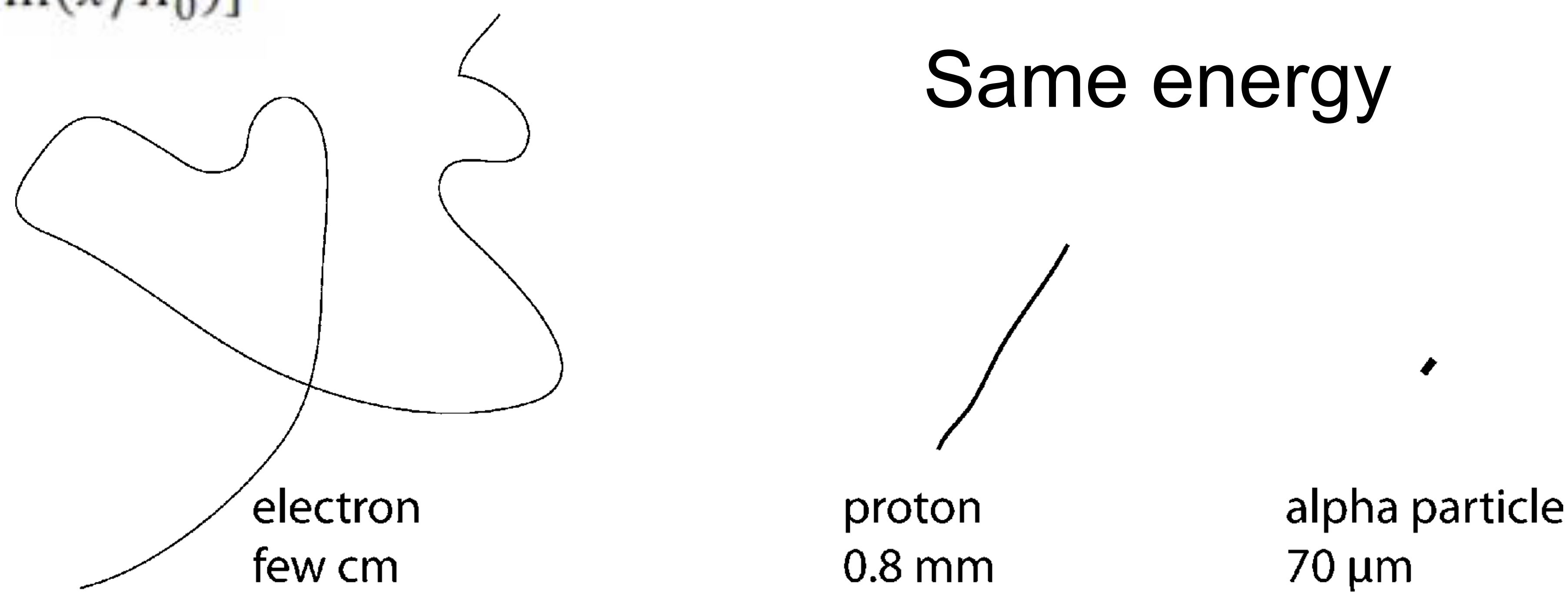
Multiple Scattering



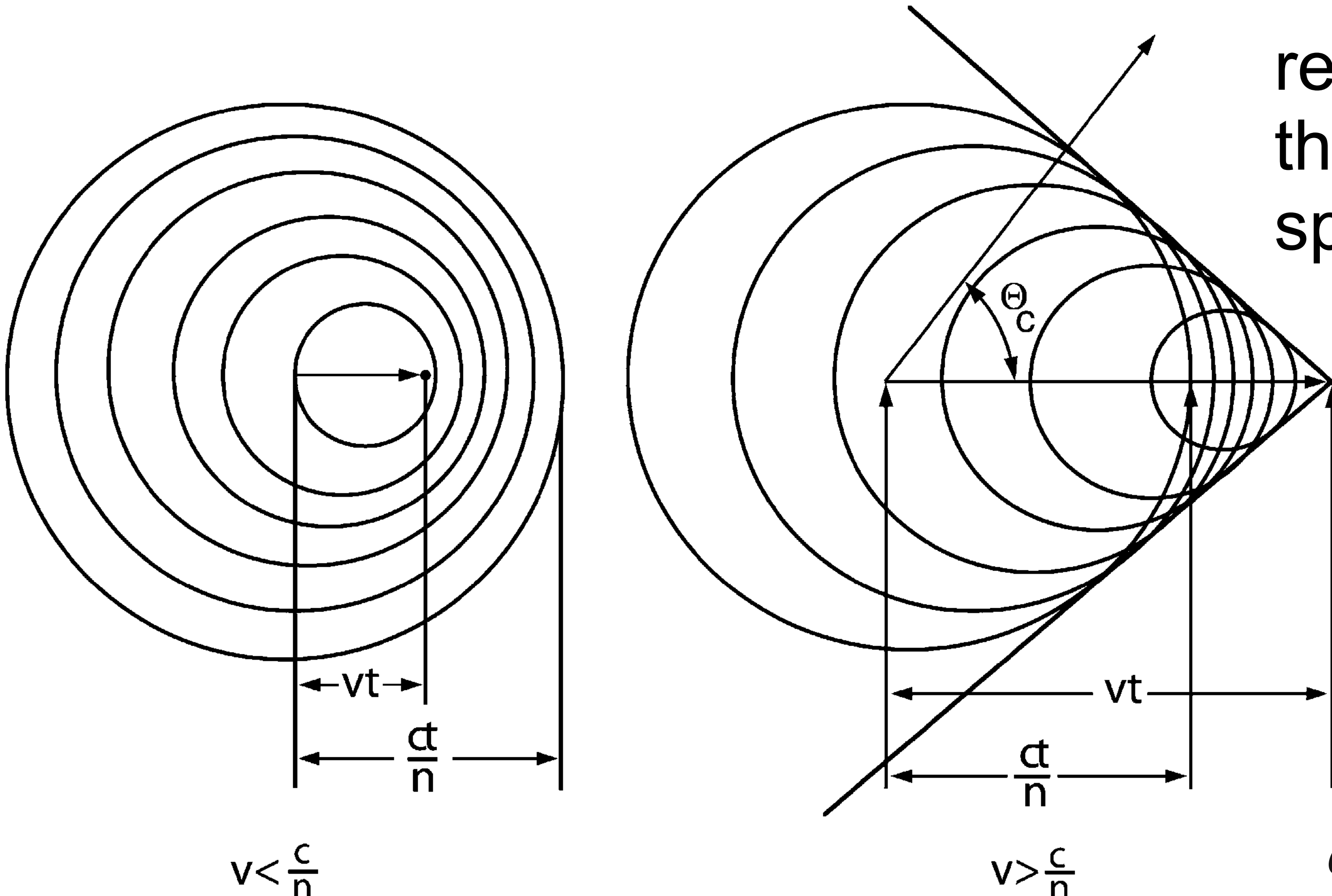


$$\theta_0 = \frac{13.6}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038 \ln(x/X_0)]$$

Same energy



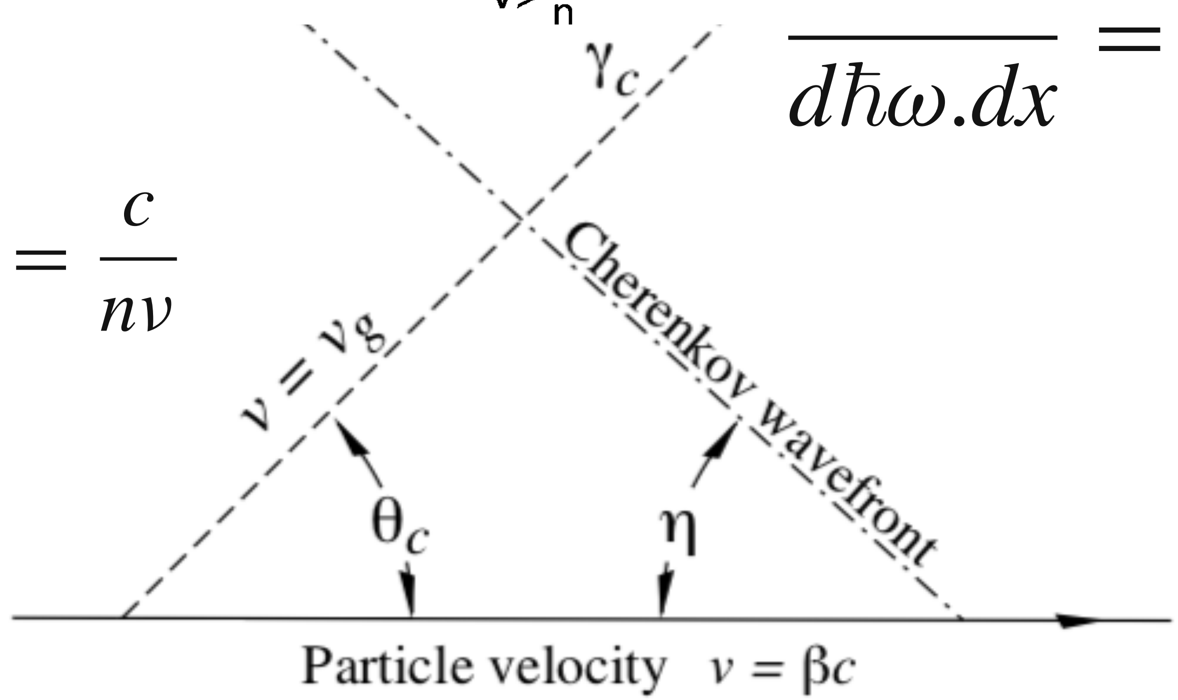
Cherenkov Radiation



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

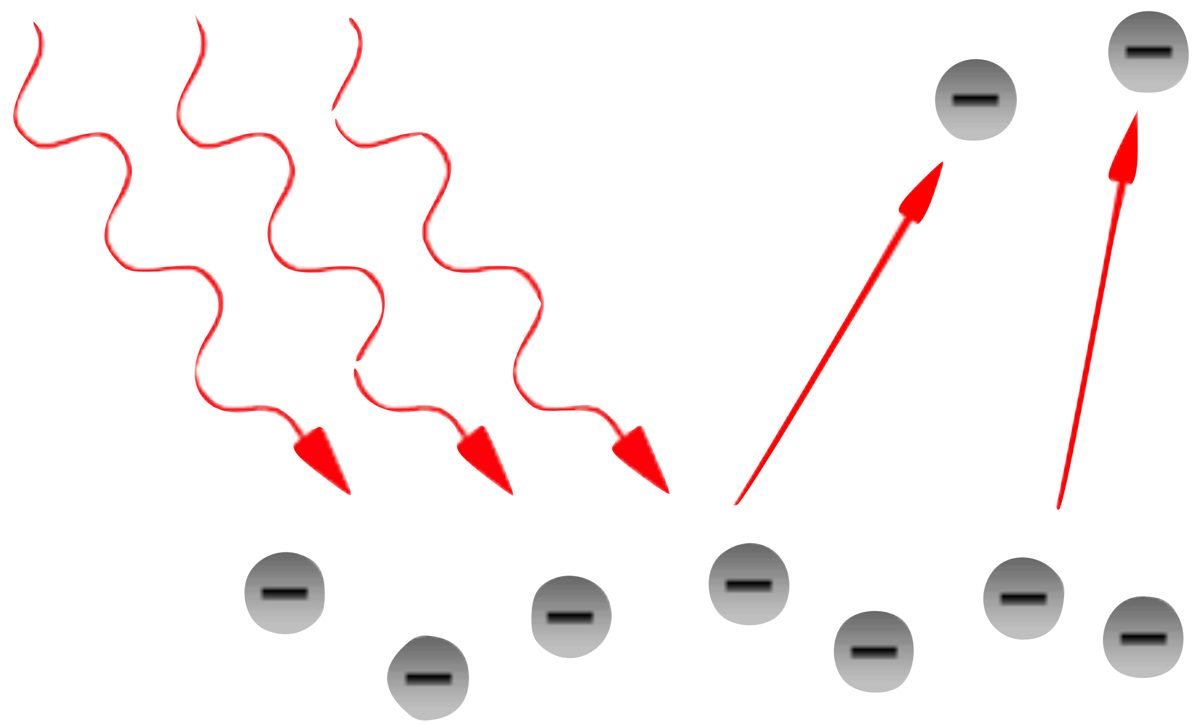
$$\frac{d^2E}{d\hbar\omega.dx} = \hbar\omega \frac{Z^2\alpha}{\hbar c}\left[1 - \frac{c^2}{n^2v^2}\right]$$

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



Back to business: Photons in Matter

Photons in Matter



Low Energy: Photoelectric Effect

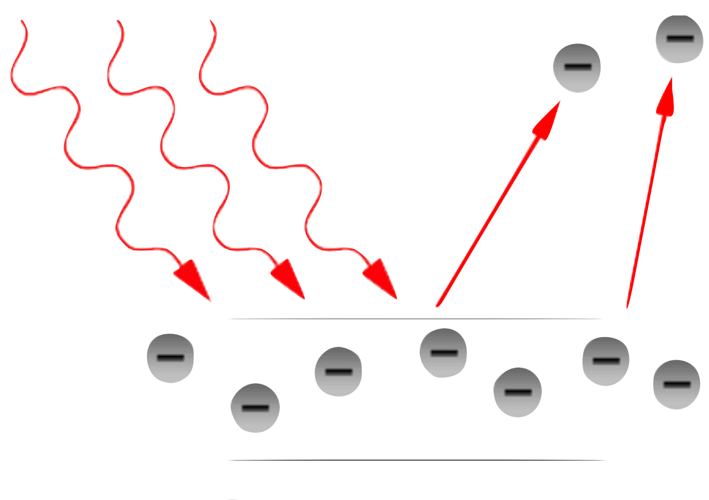
Medium Energy: Compton (Rayleigh/Thompson) Scattering

High Energy: Pair Production

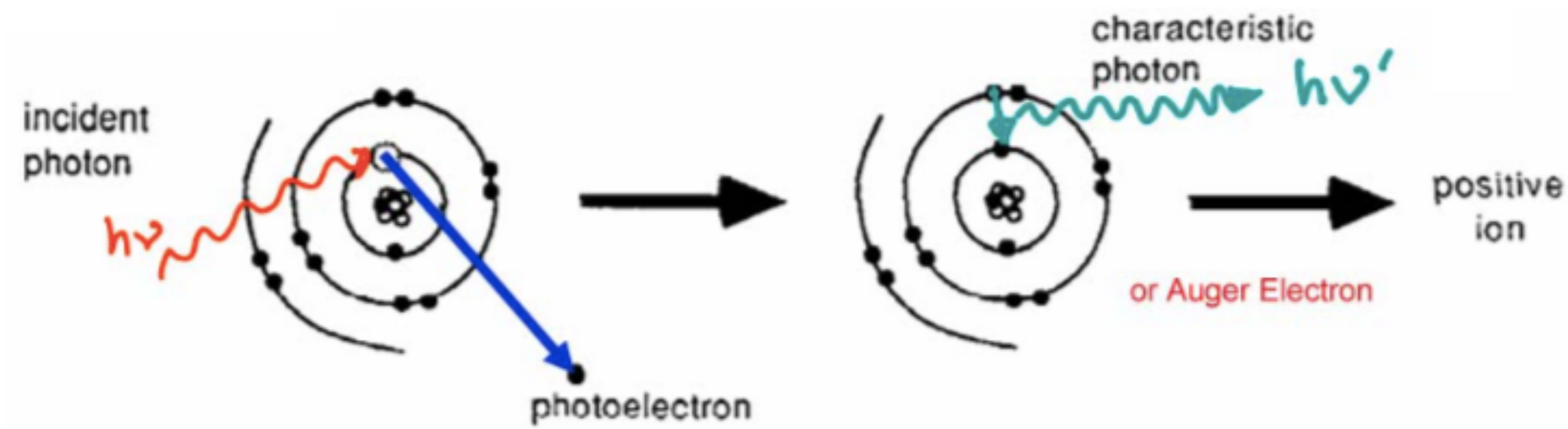
Photoelectric Effect

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

σ=const.×Z^n/E^3



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



$KE = h\nu - BE$

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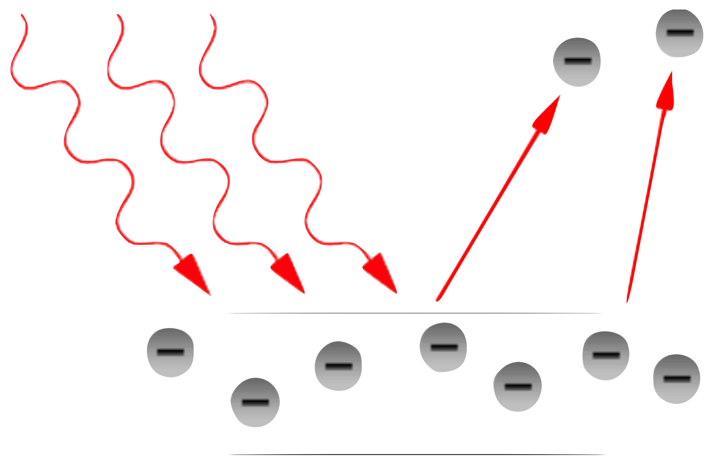

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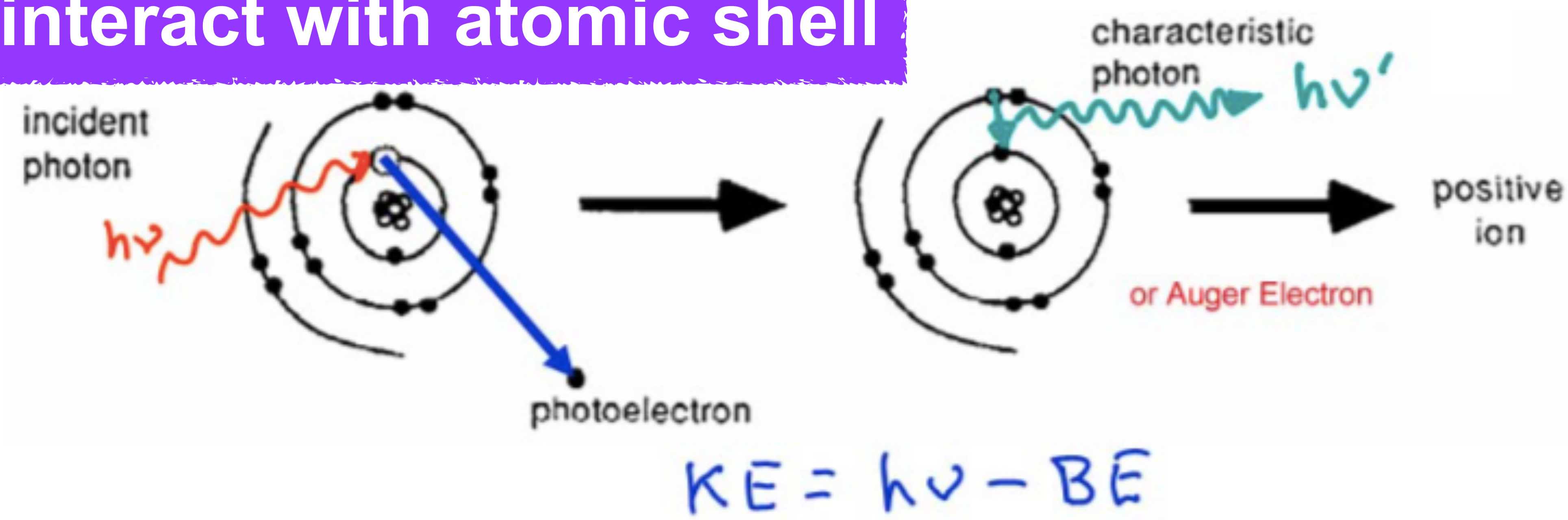
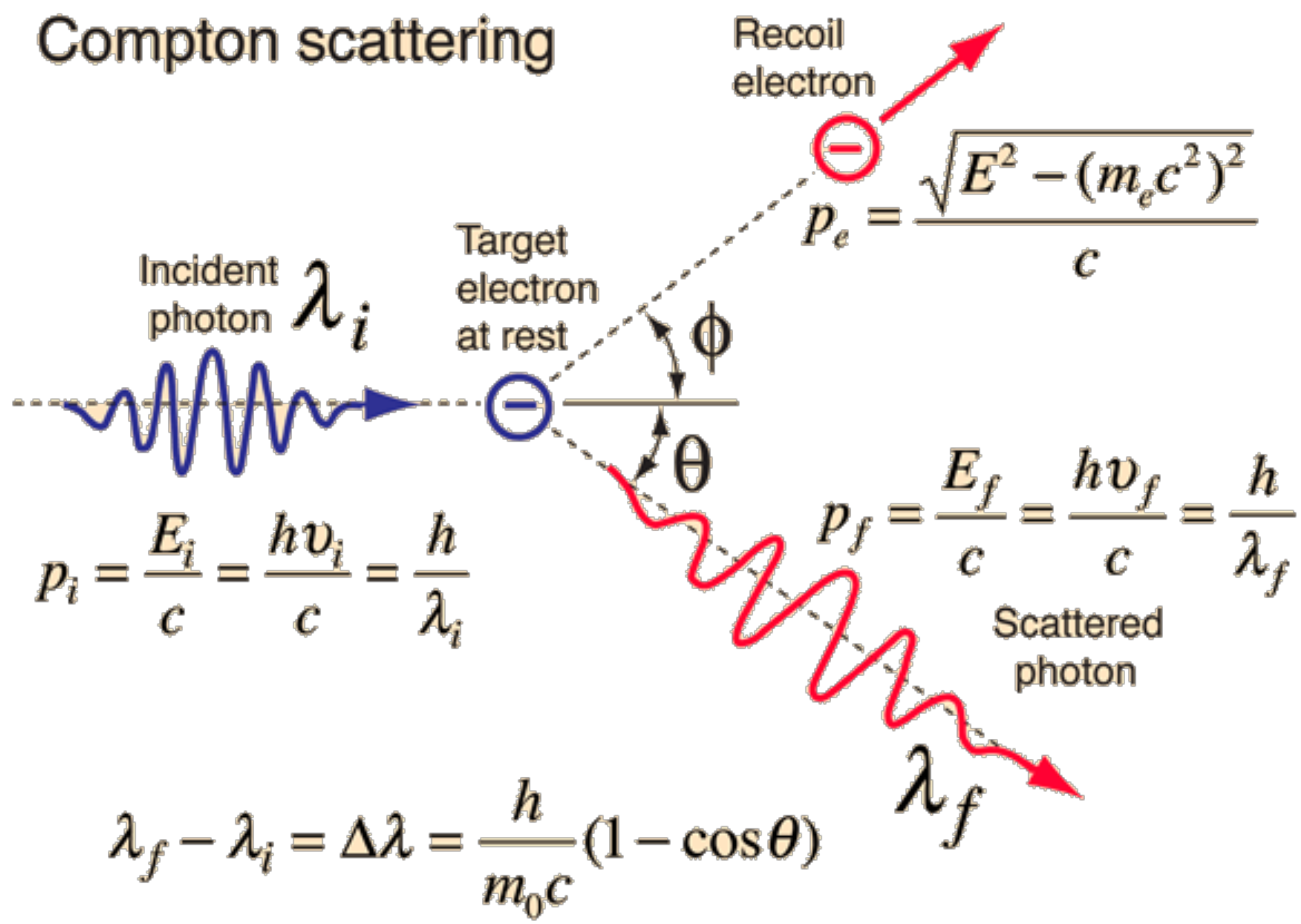
Photons interact with atomic shell



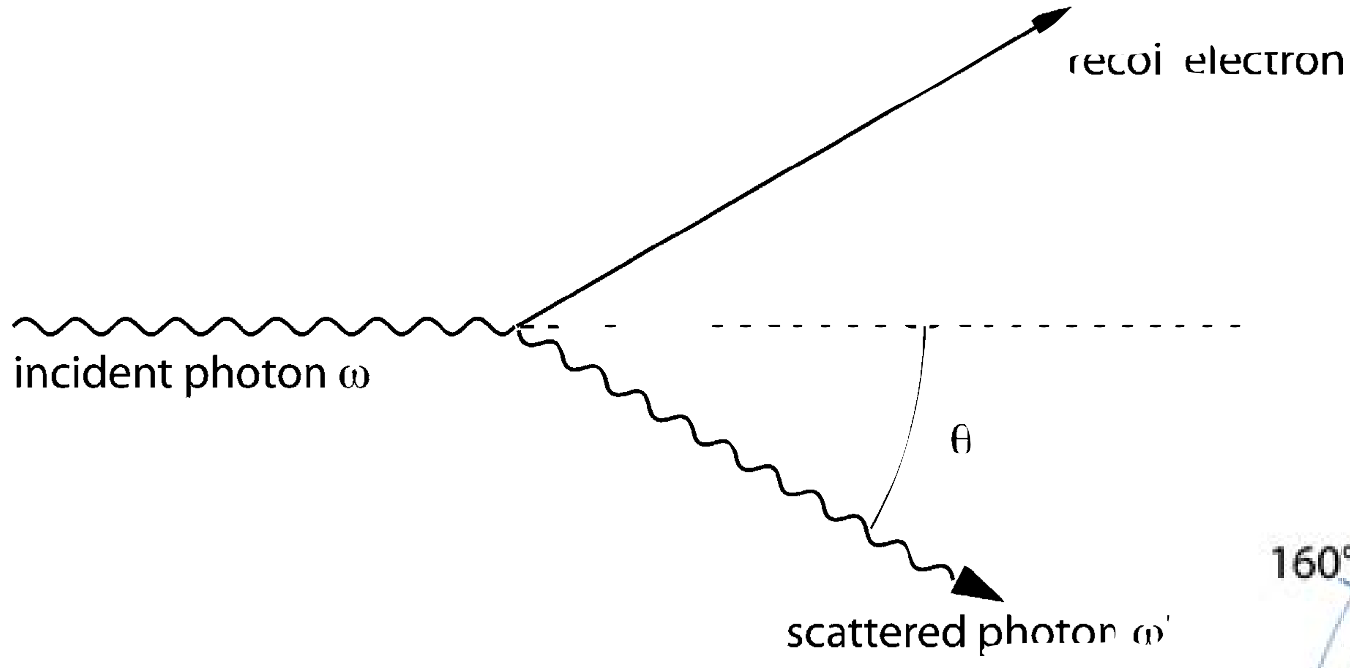
Compton Scattering

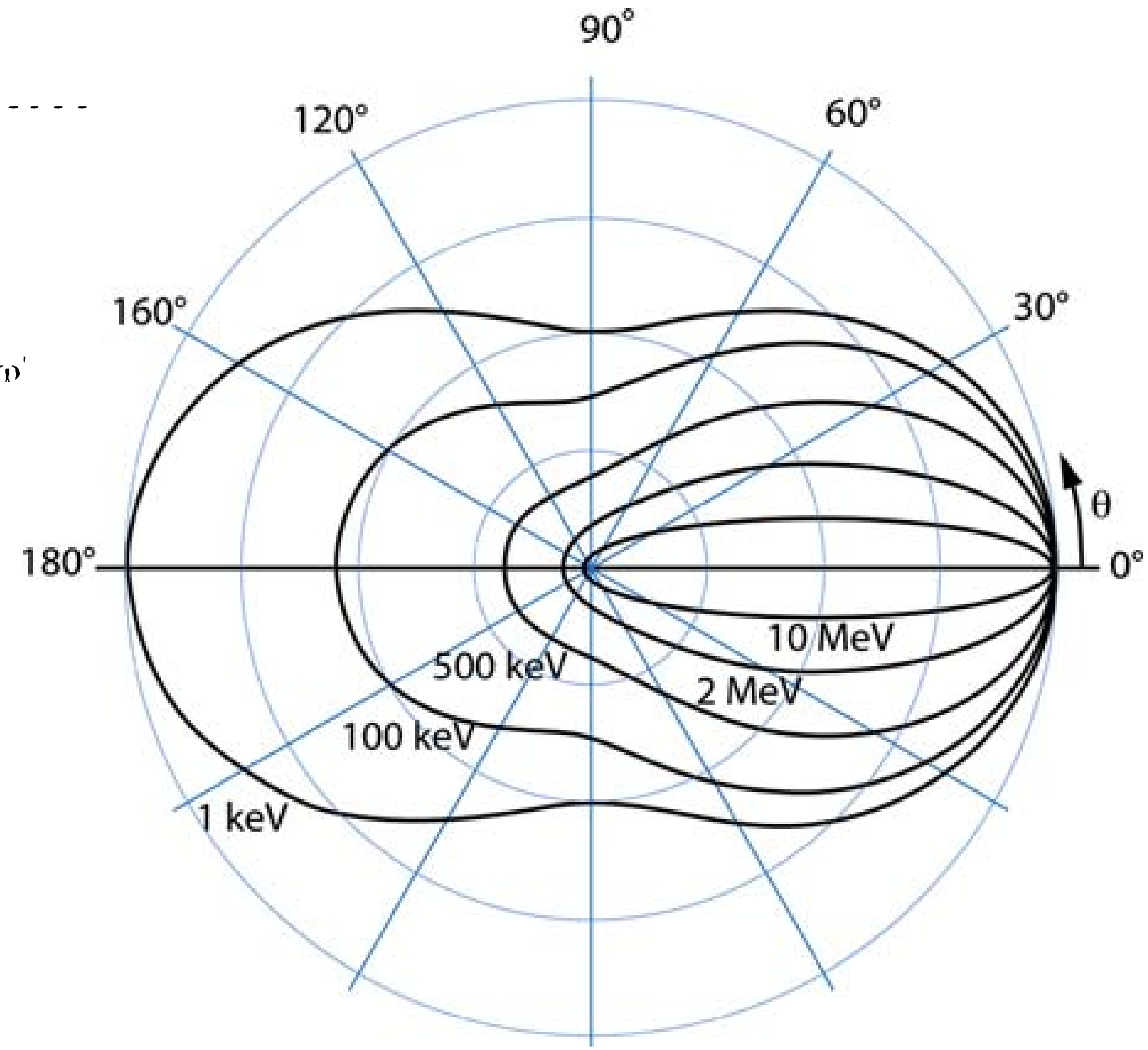
- Elastic scattering of photon and electron
  - Can be useful for photon detection
  - HOWEVER… changes photon direction



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

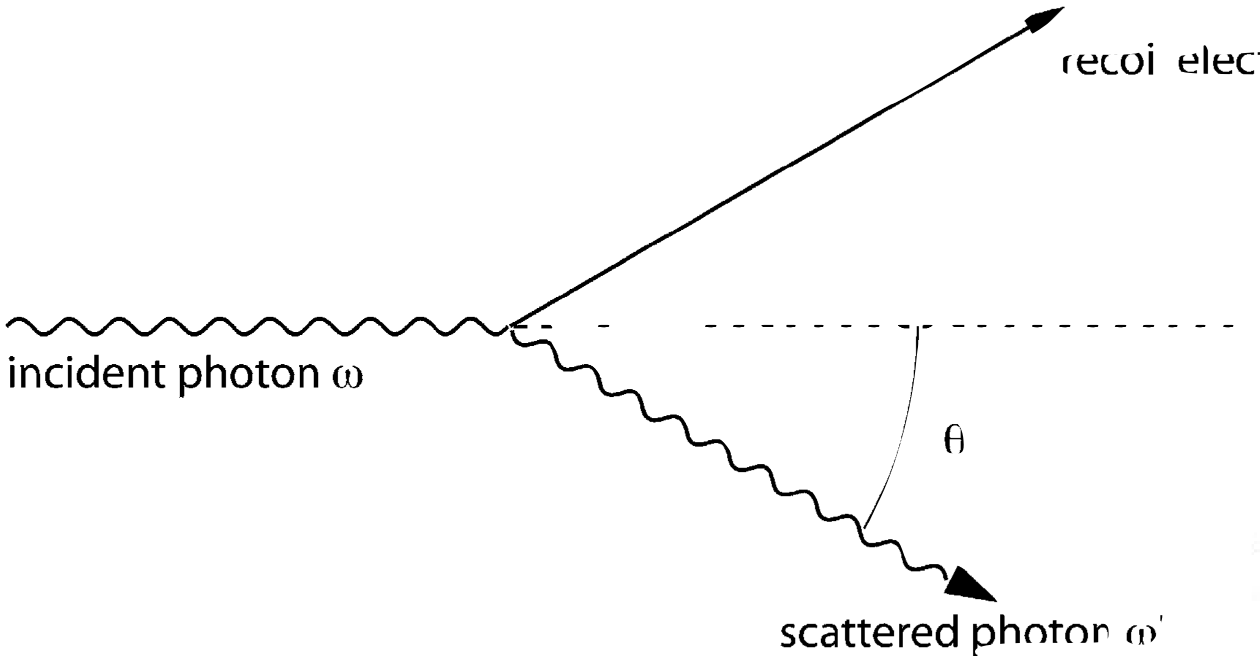
Compton Scattering

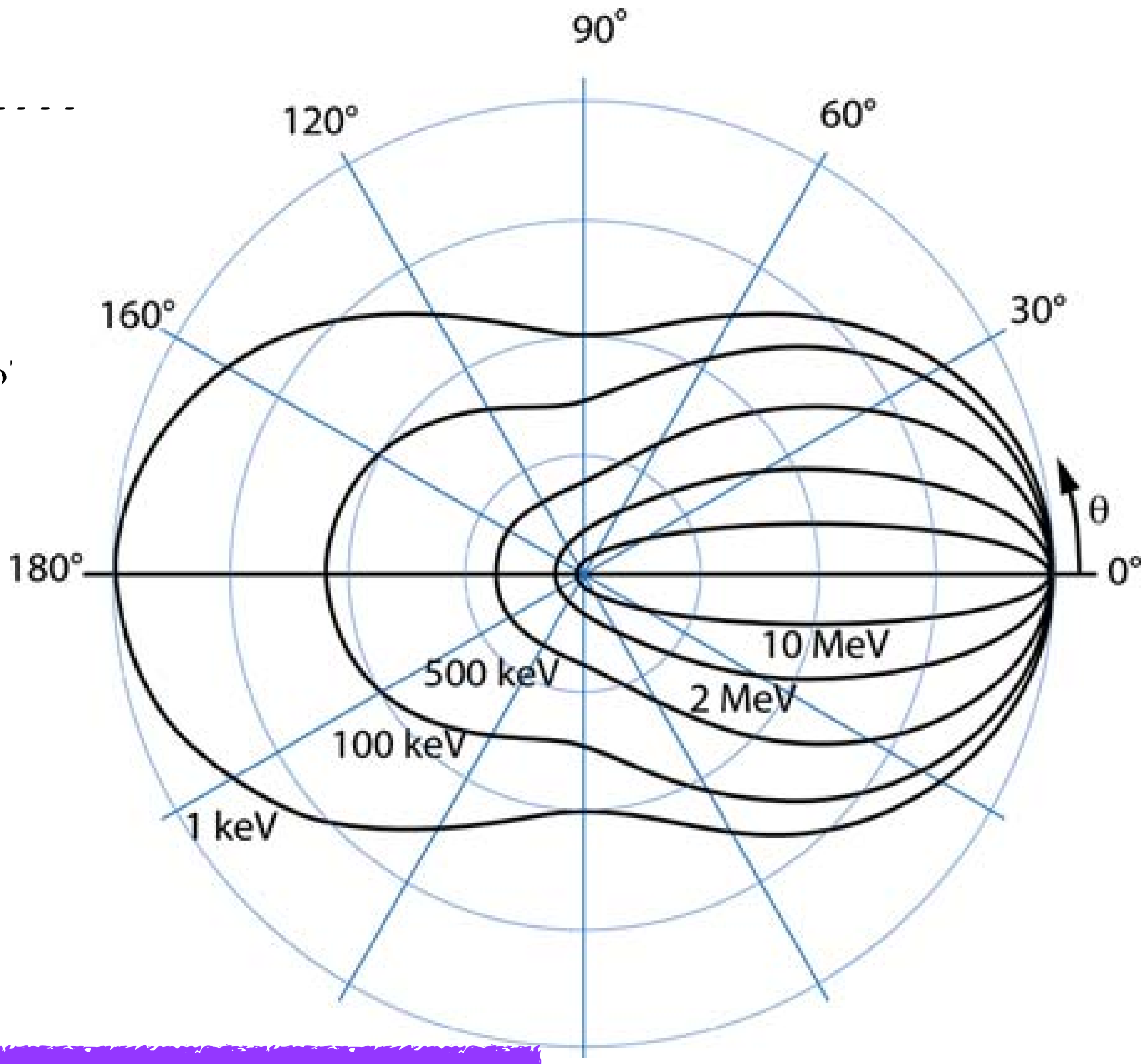




The take home message: Scattering angle is energy dependent

Compton Scattering





The take home message: Scattering angle is energy dependent

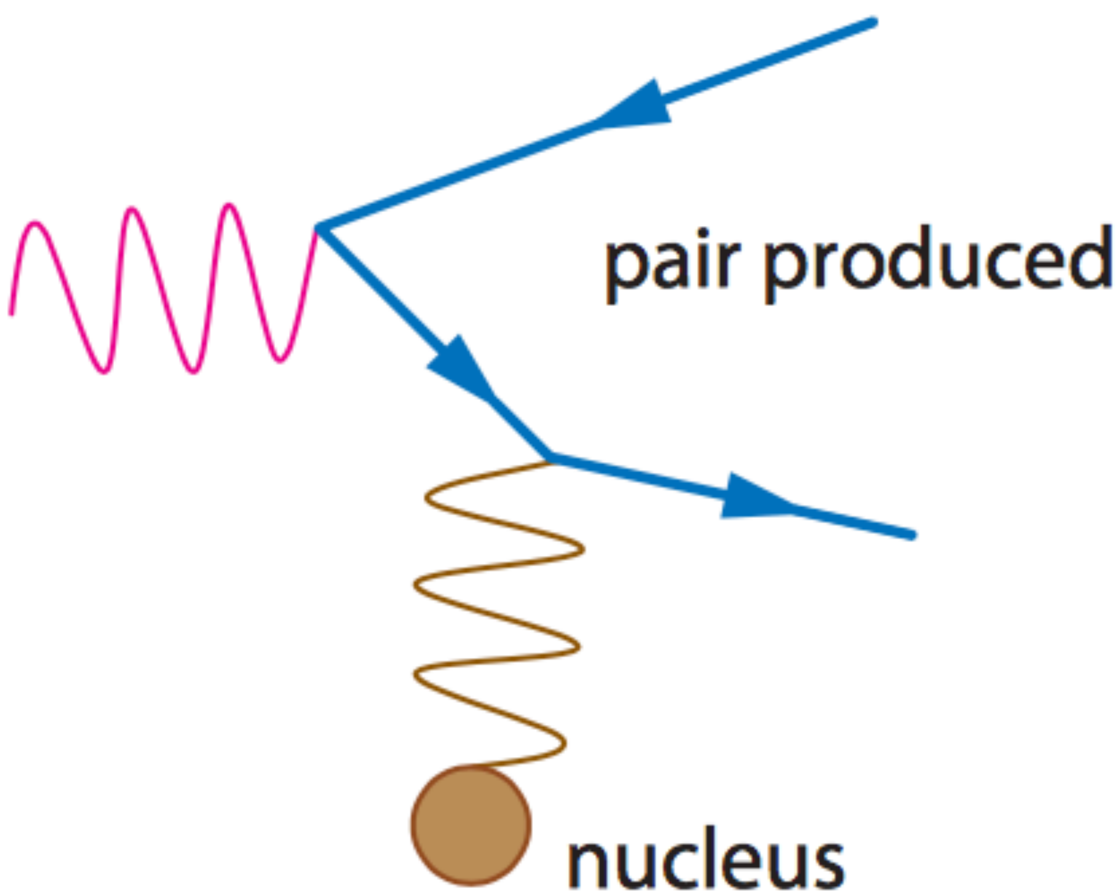
Photons interact with individual electrons

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**



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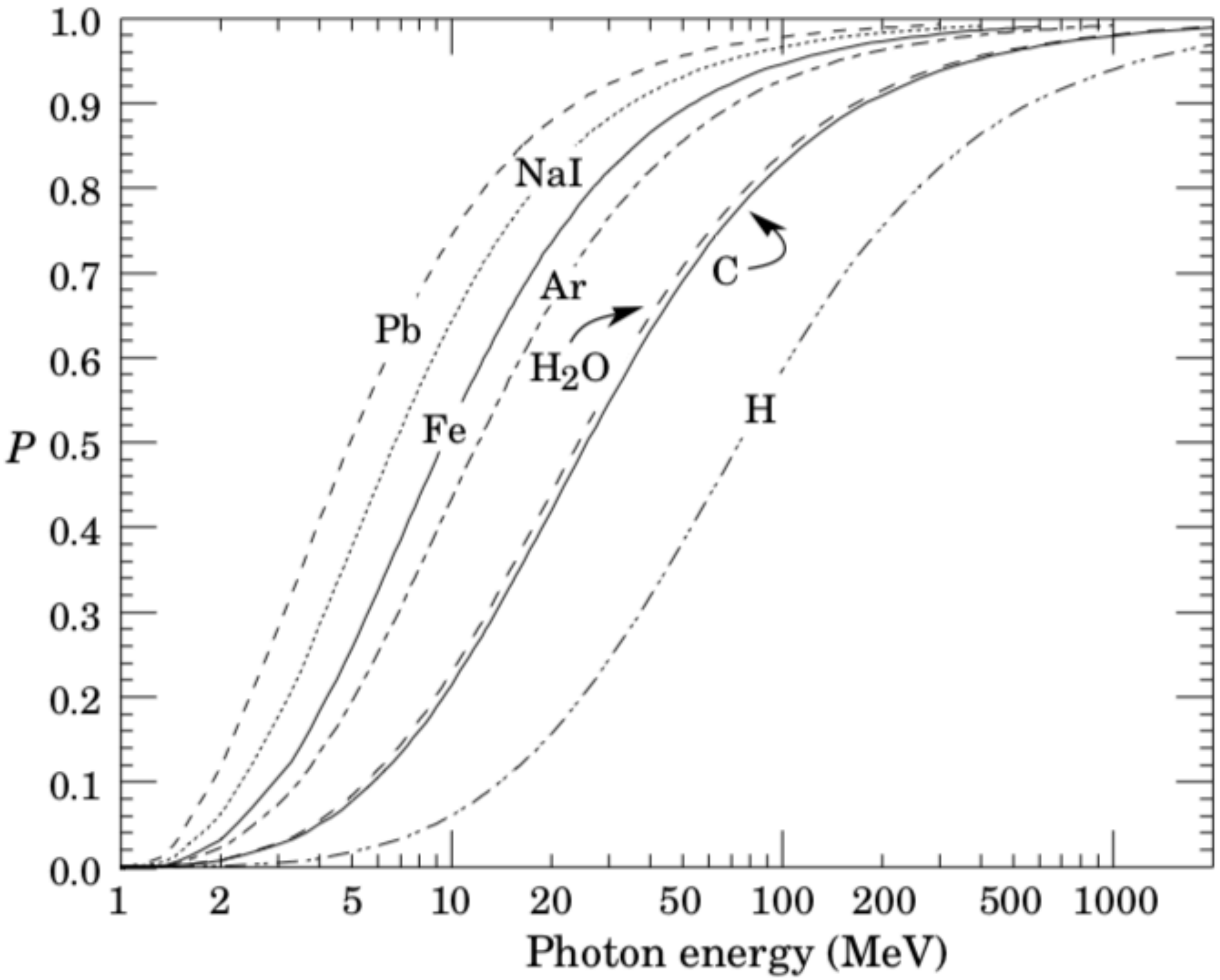

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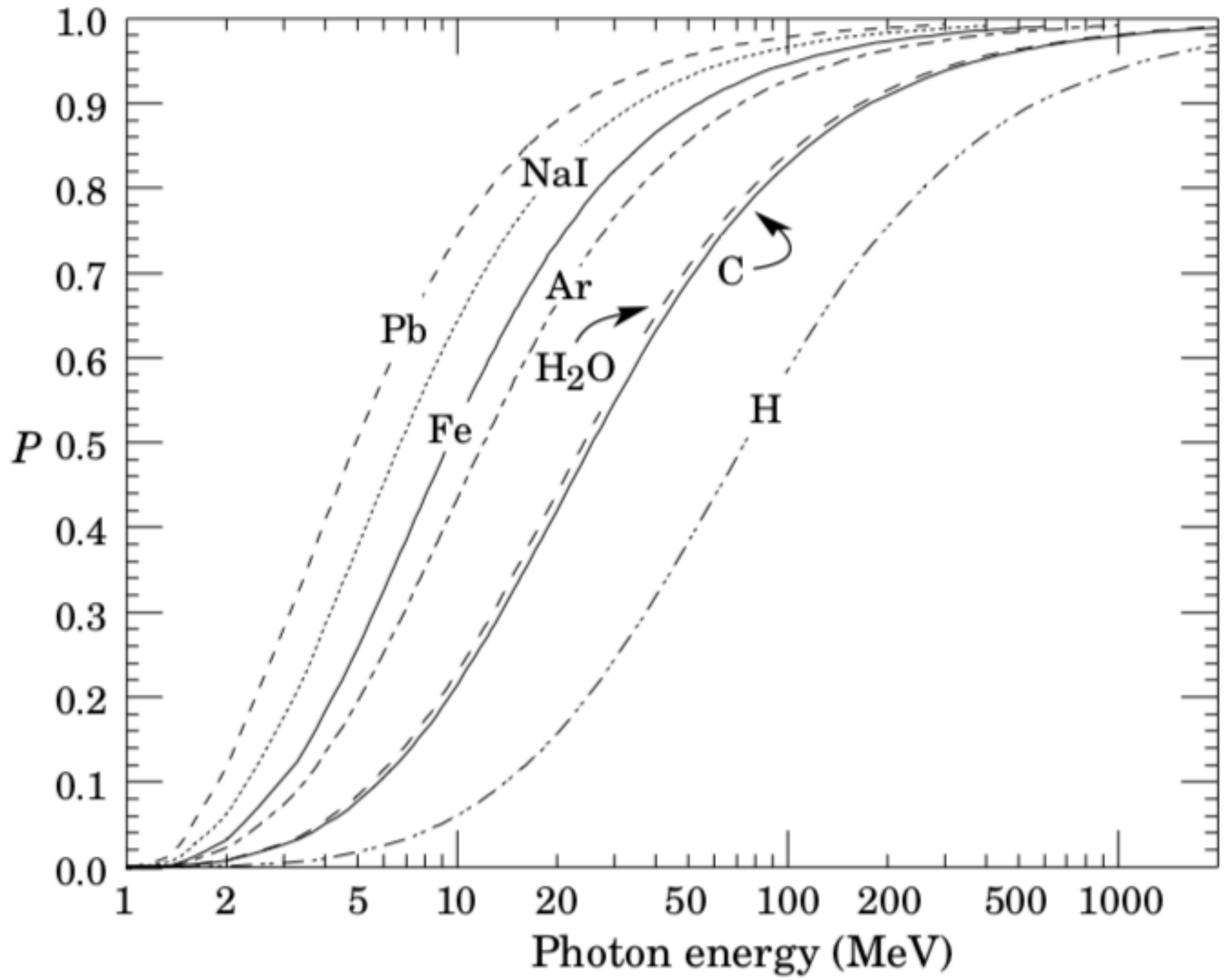
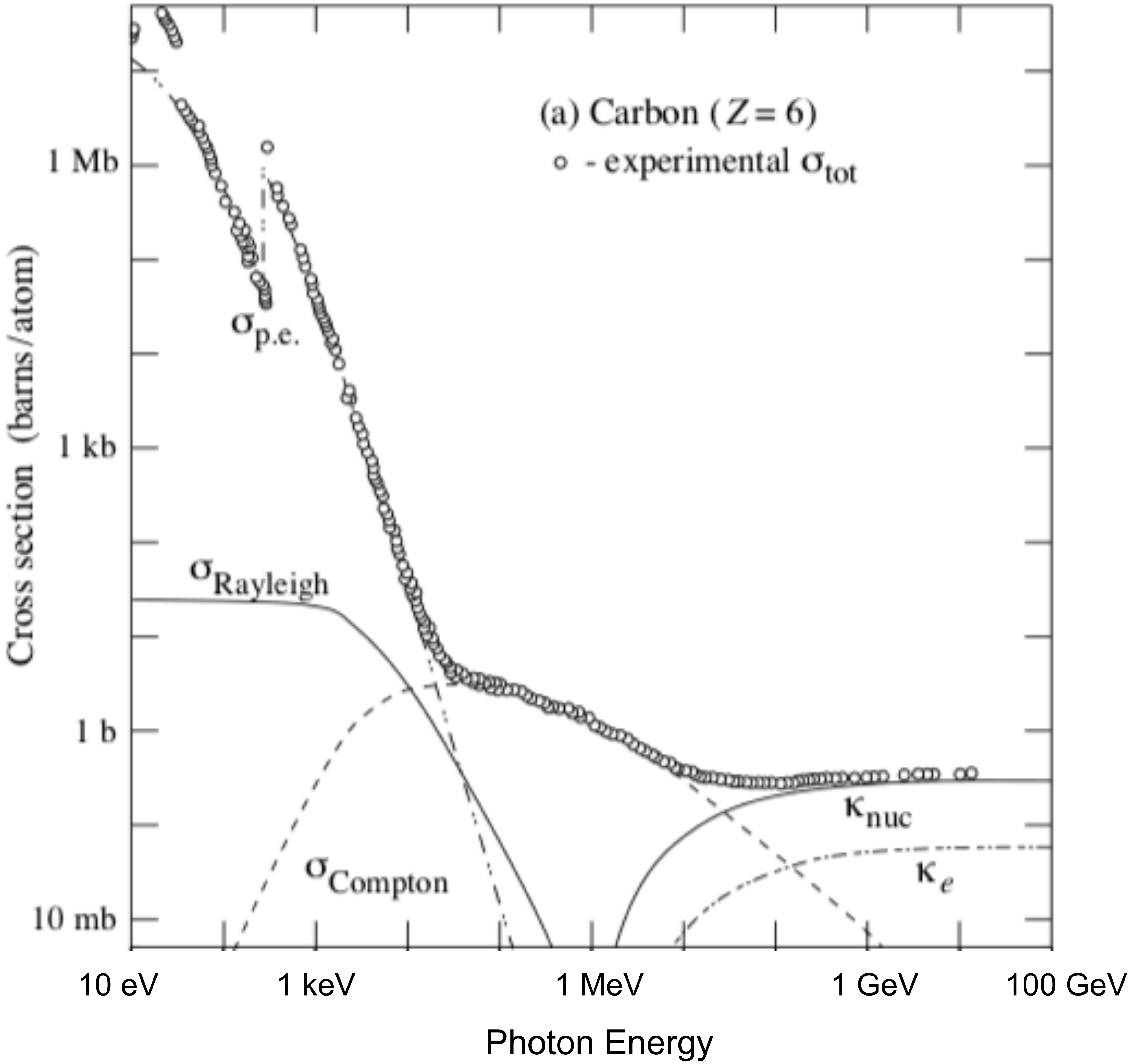


Photons interact with nucleus

Photons in Matter: Summary



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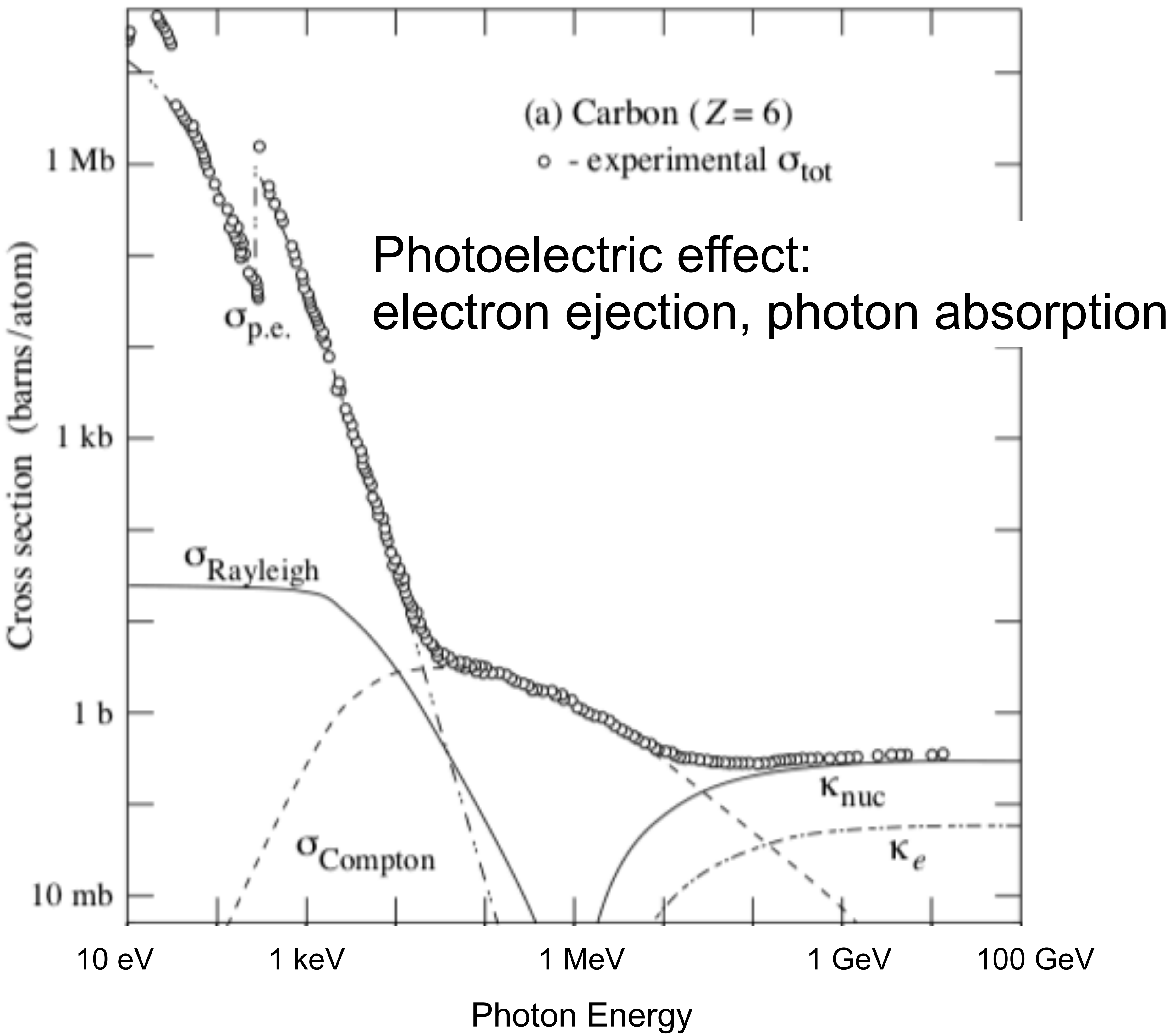

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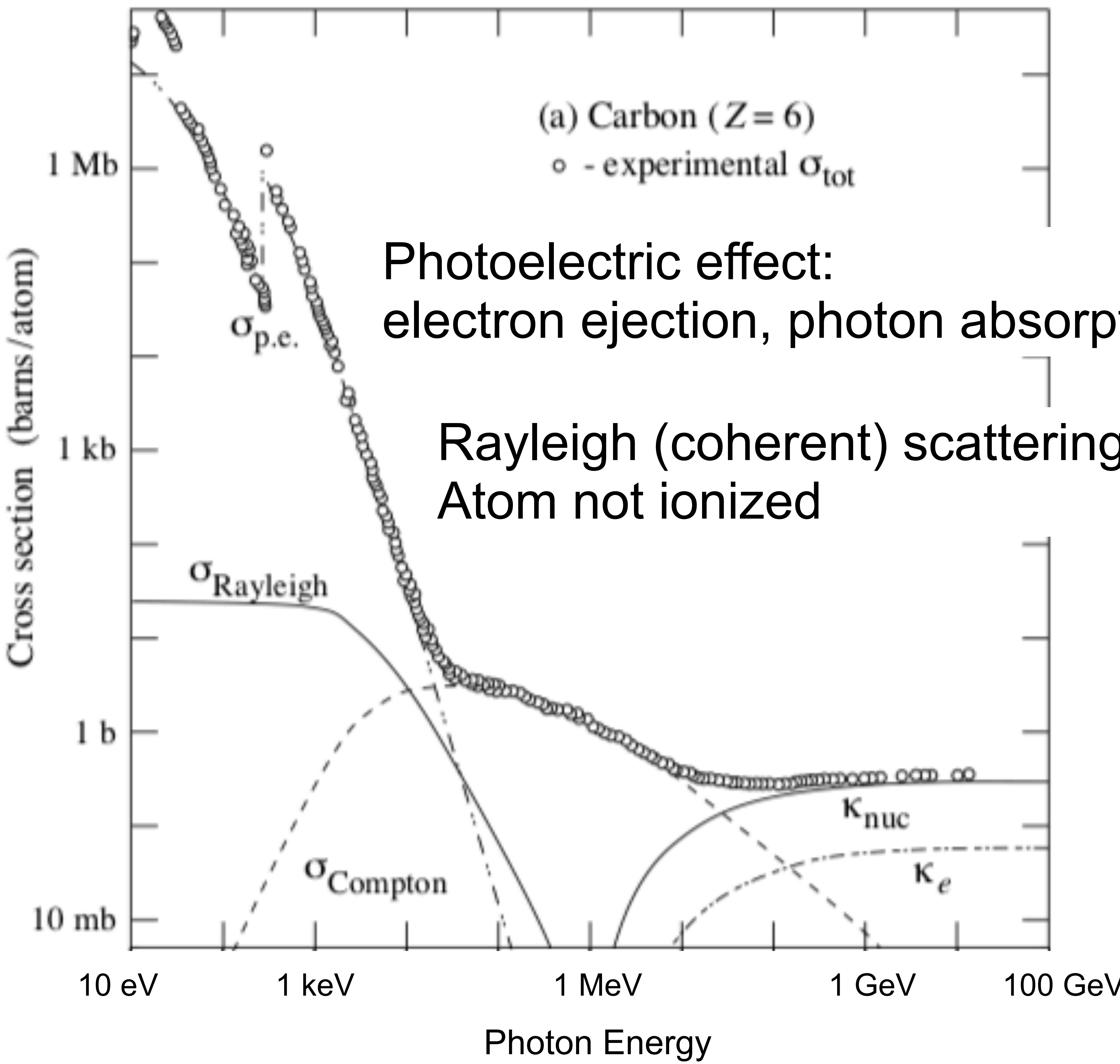

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Rayleigh (coherent) scattering:
Atom not ionized

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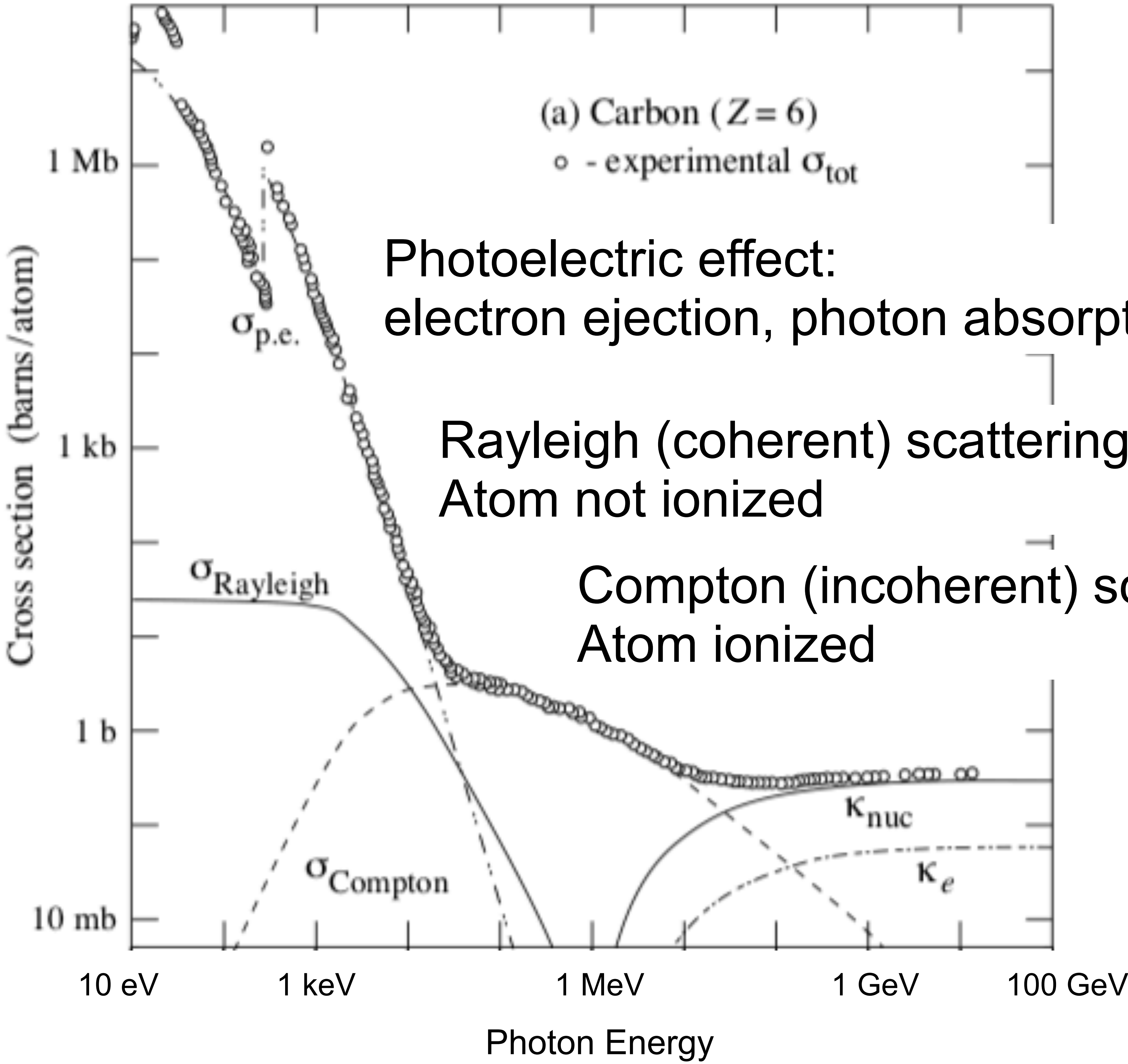

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Compton (incoherent) scattering:
Atom ionized

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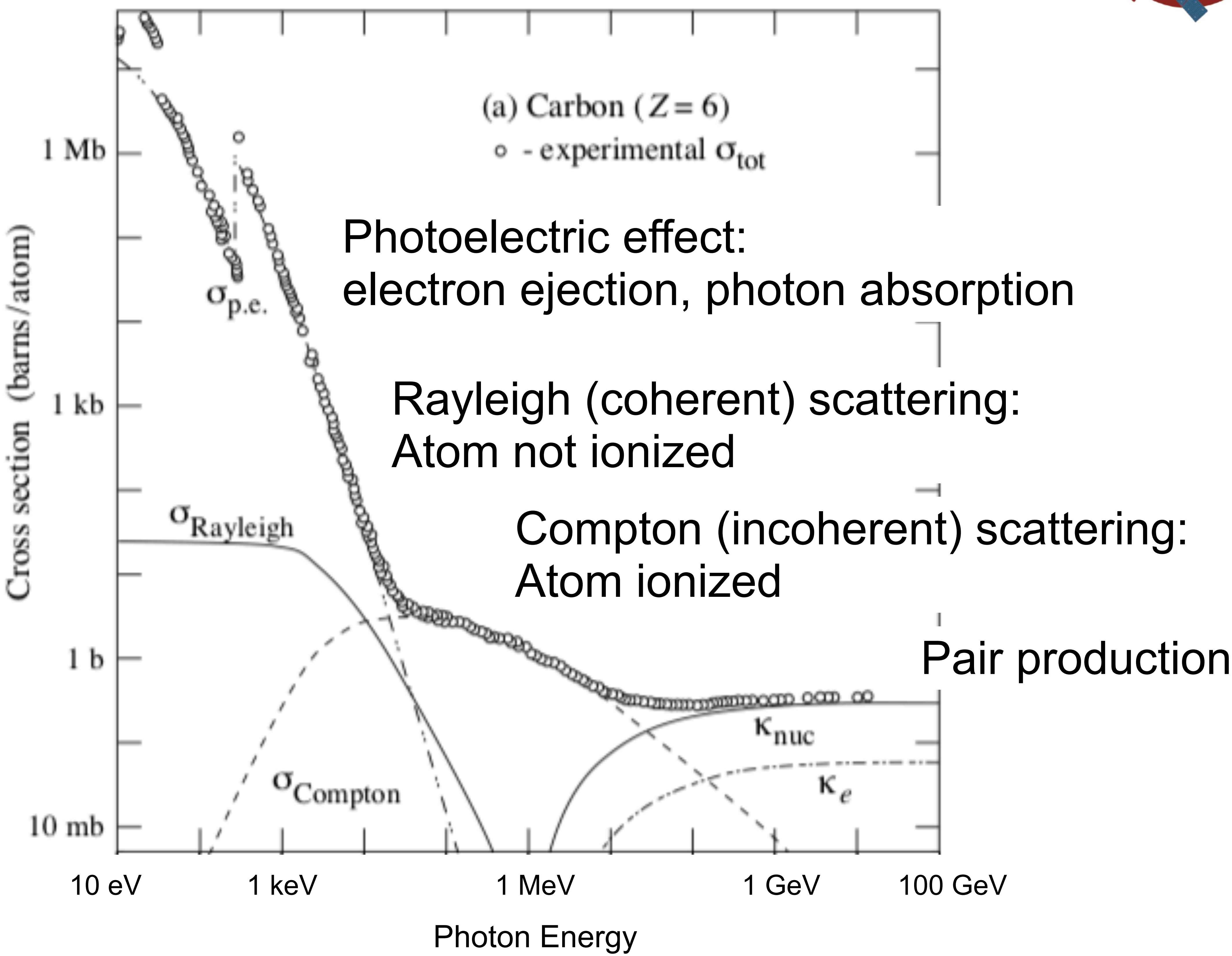

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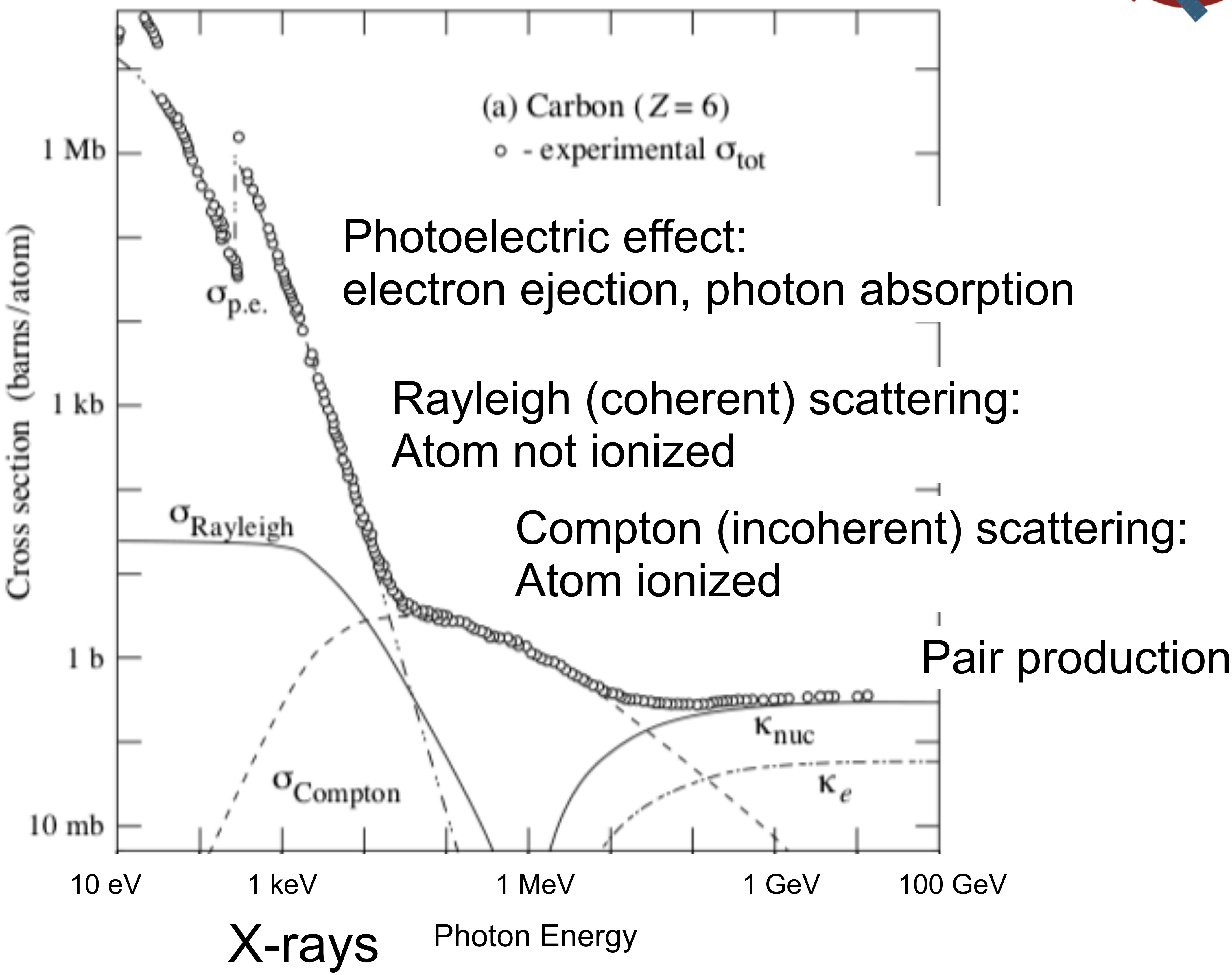
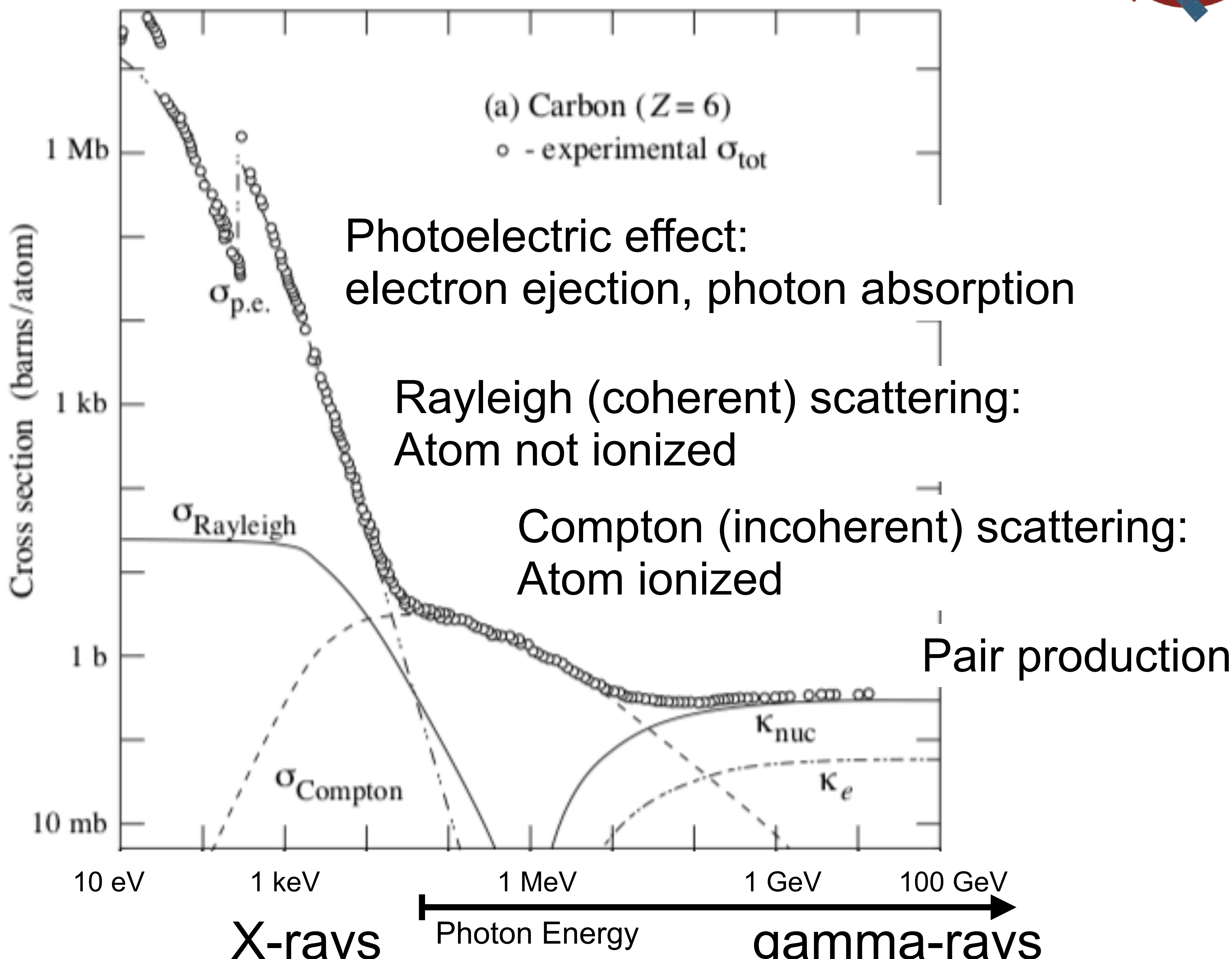
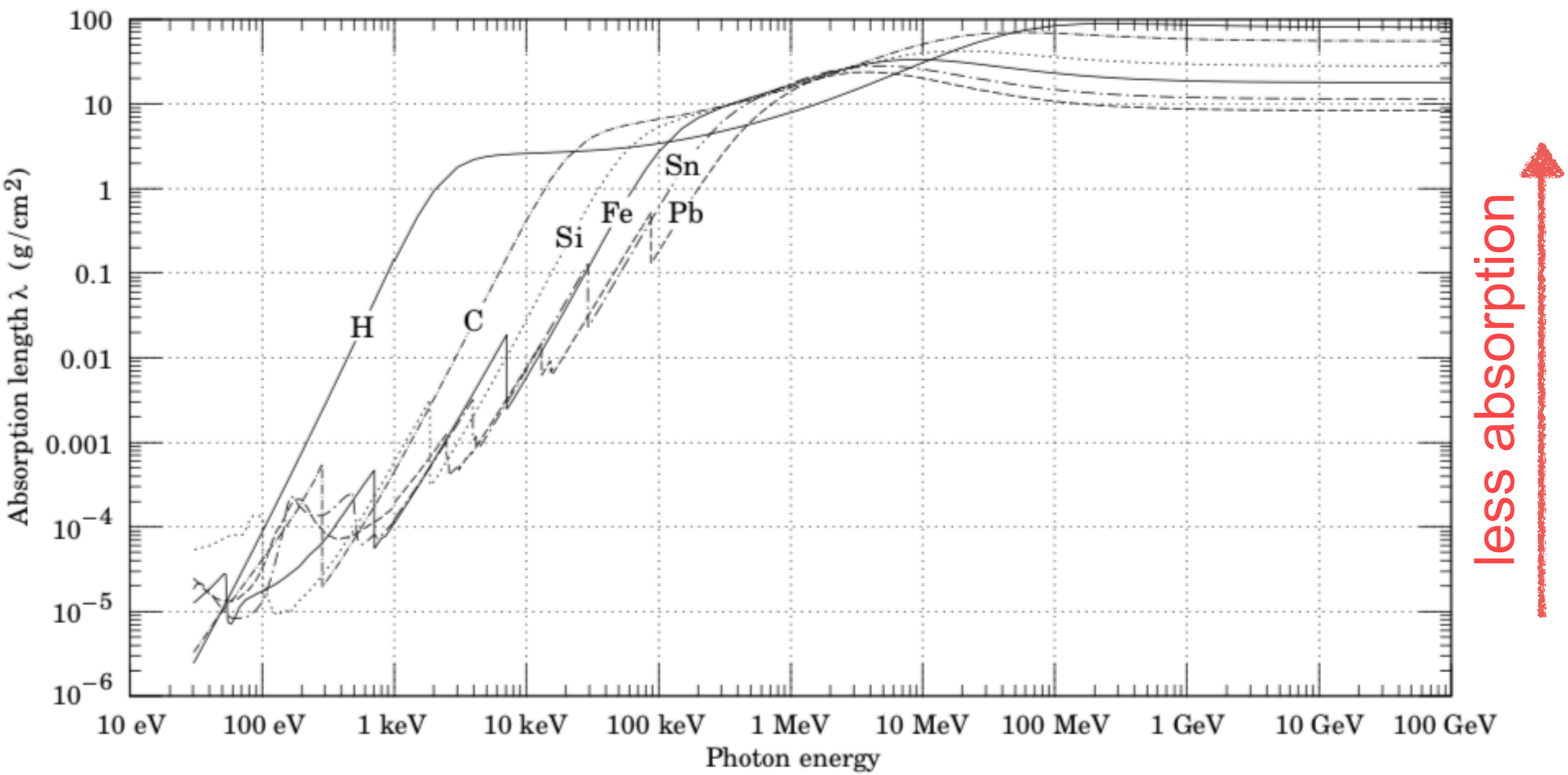


Photons in Matter: Summary



Photon Mass attenuation Length



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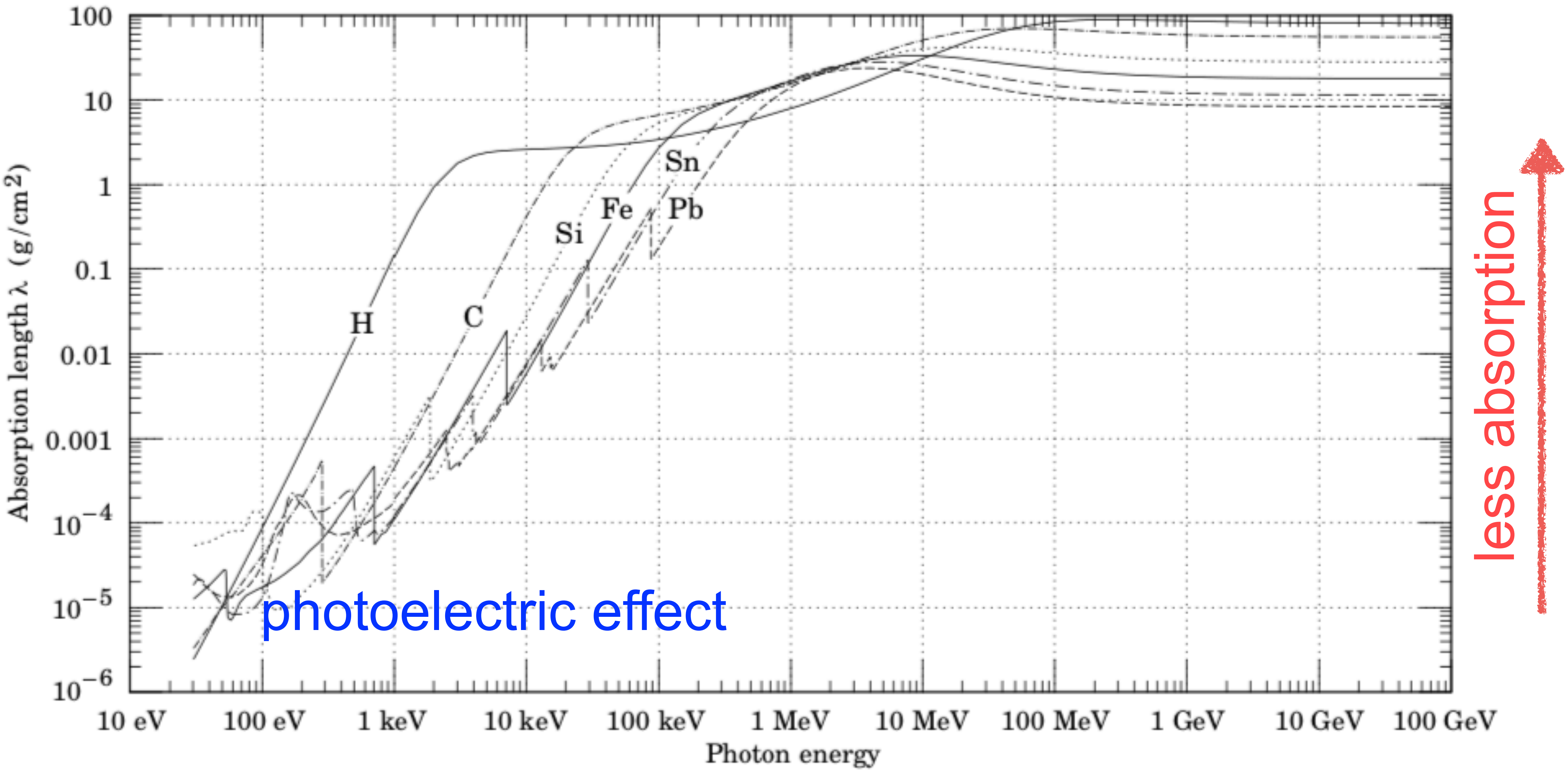

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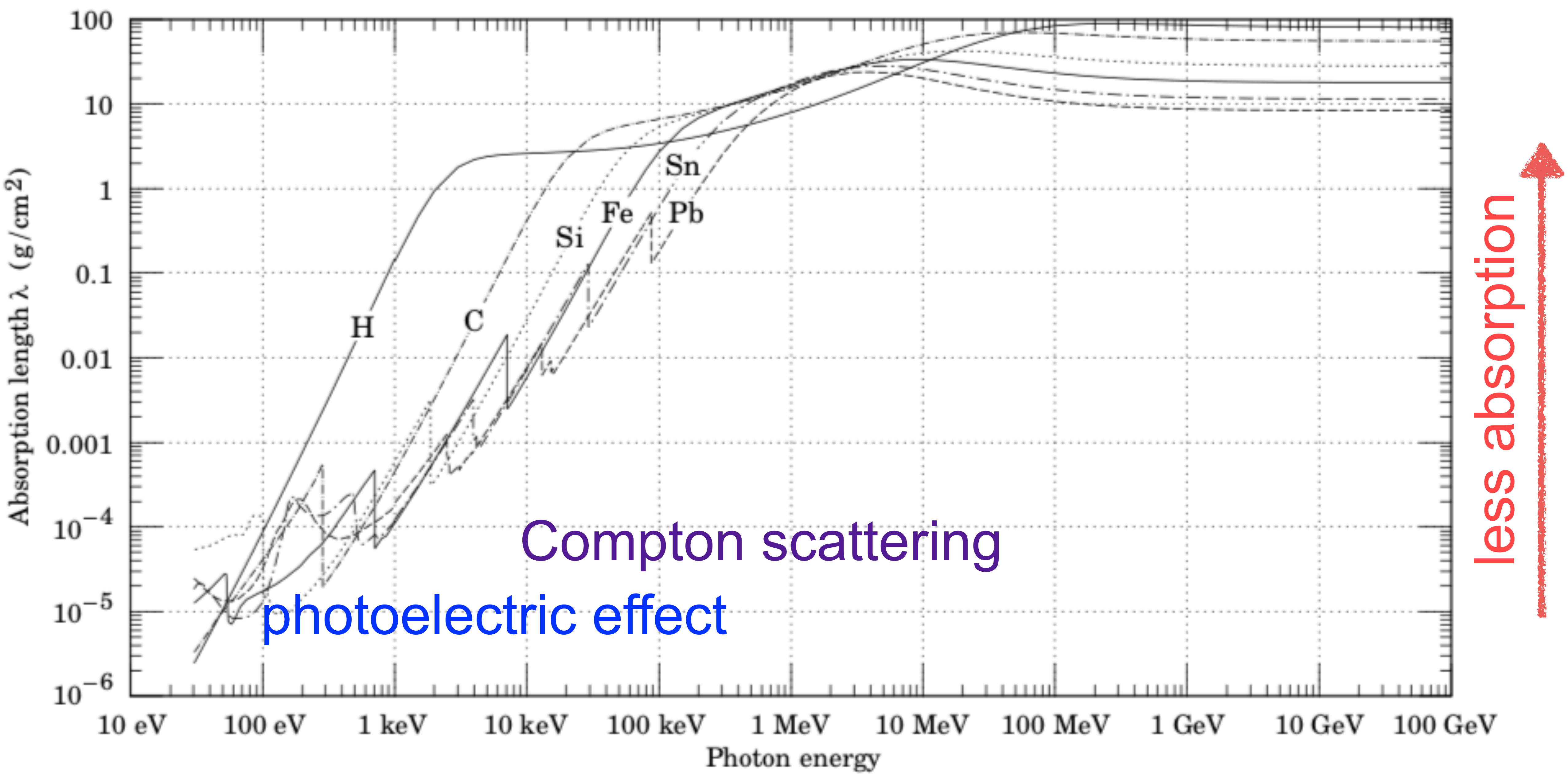

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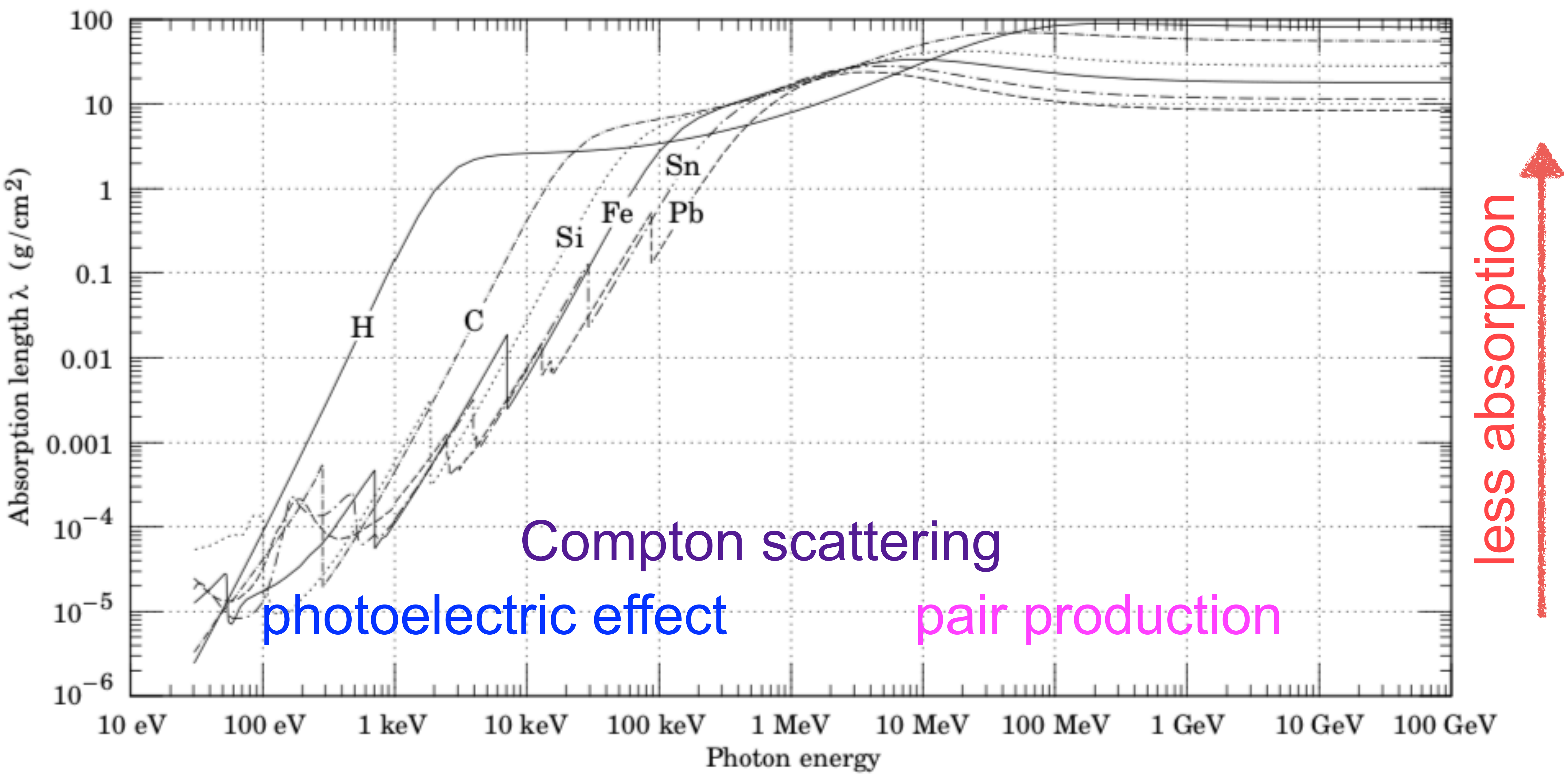
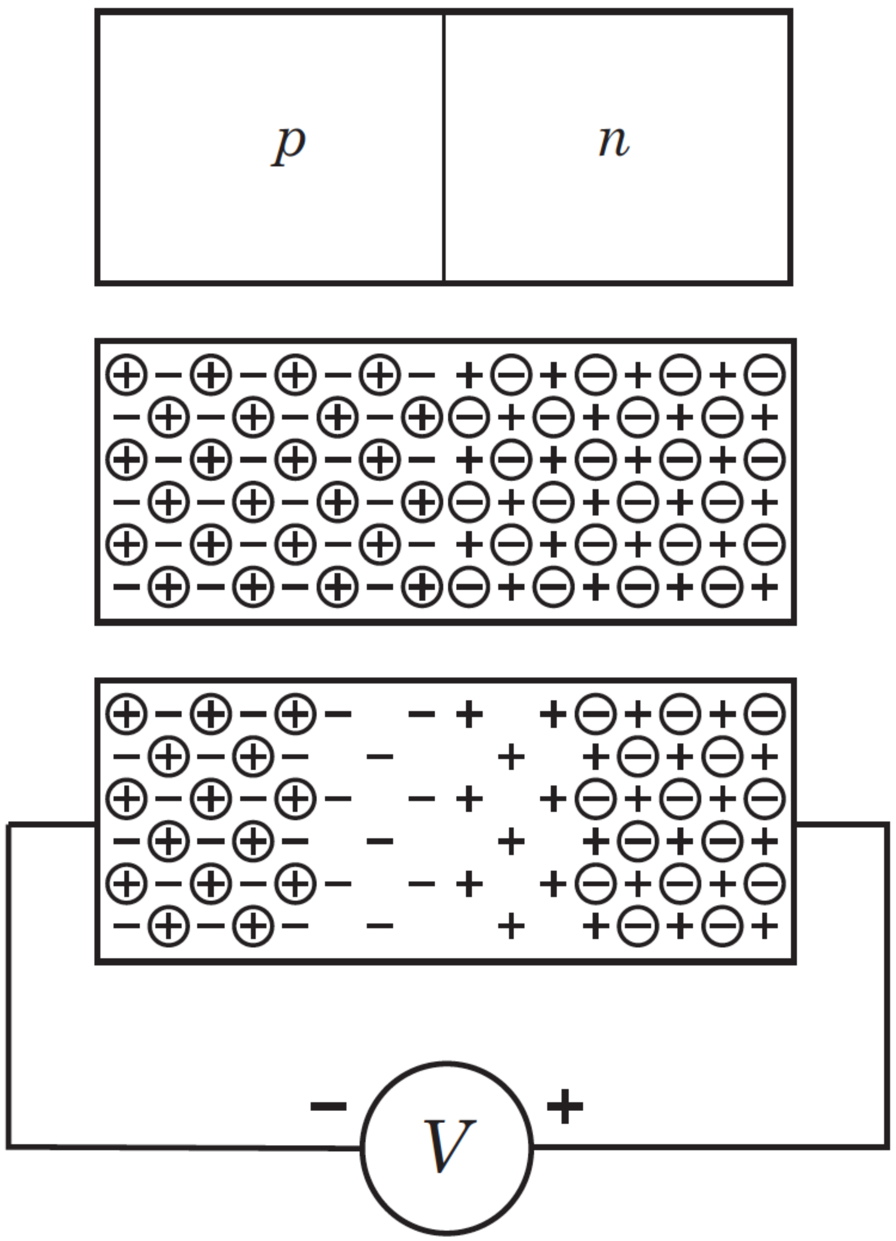
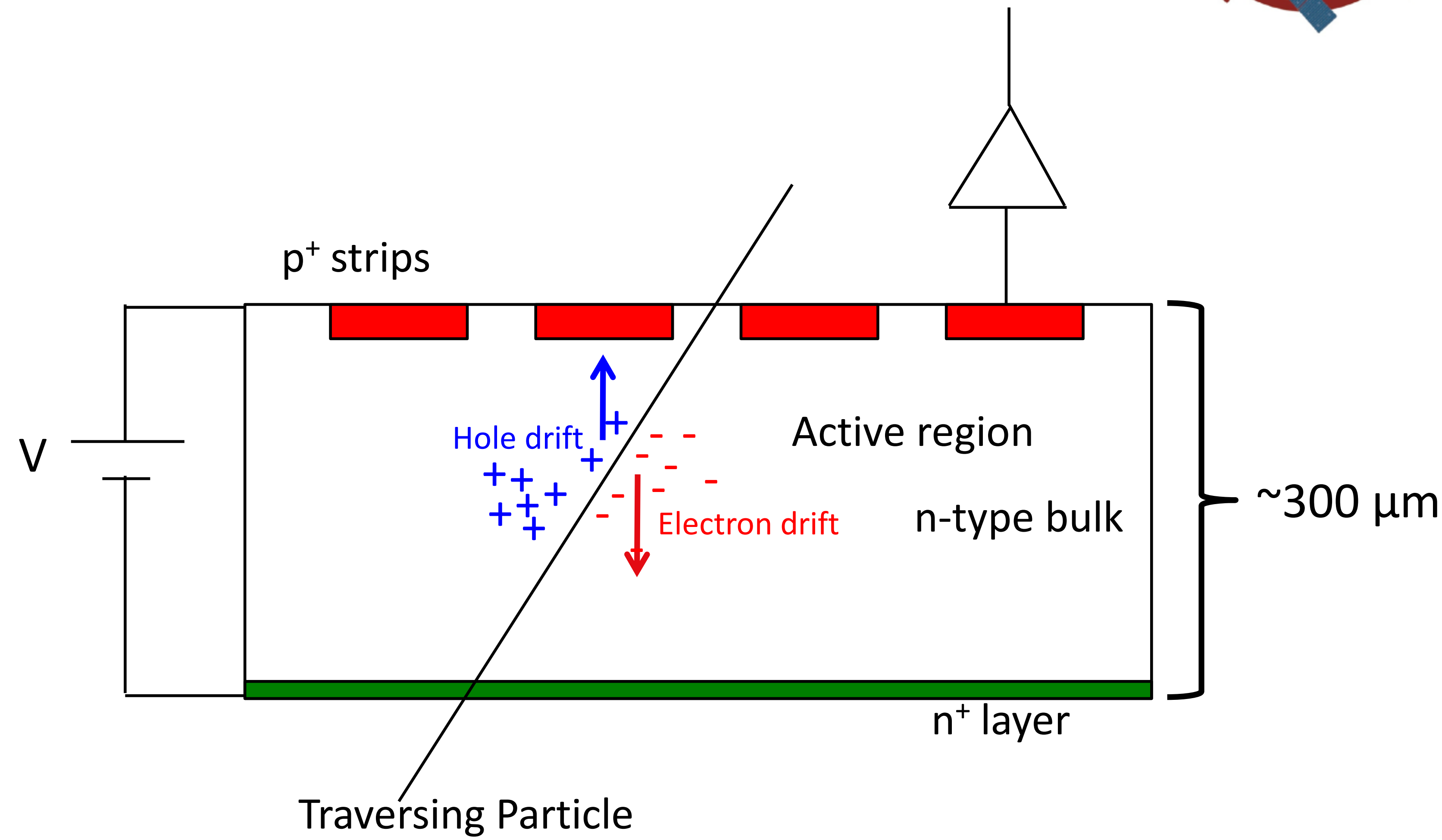


Particle detectors

Detecting via Ionization

- **Tracking Detectors**





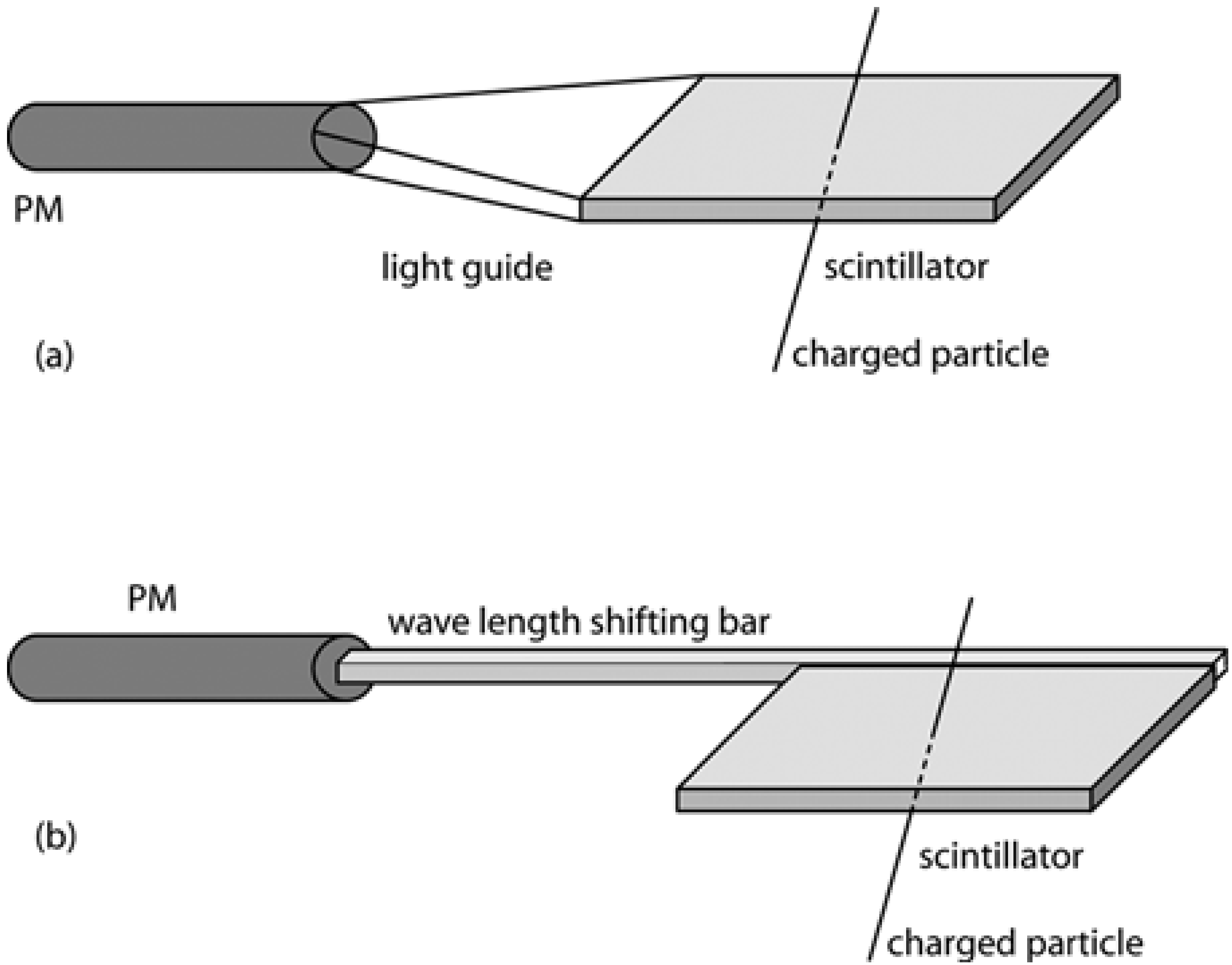
Basic Principle of a Silicon Sensor

- **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)

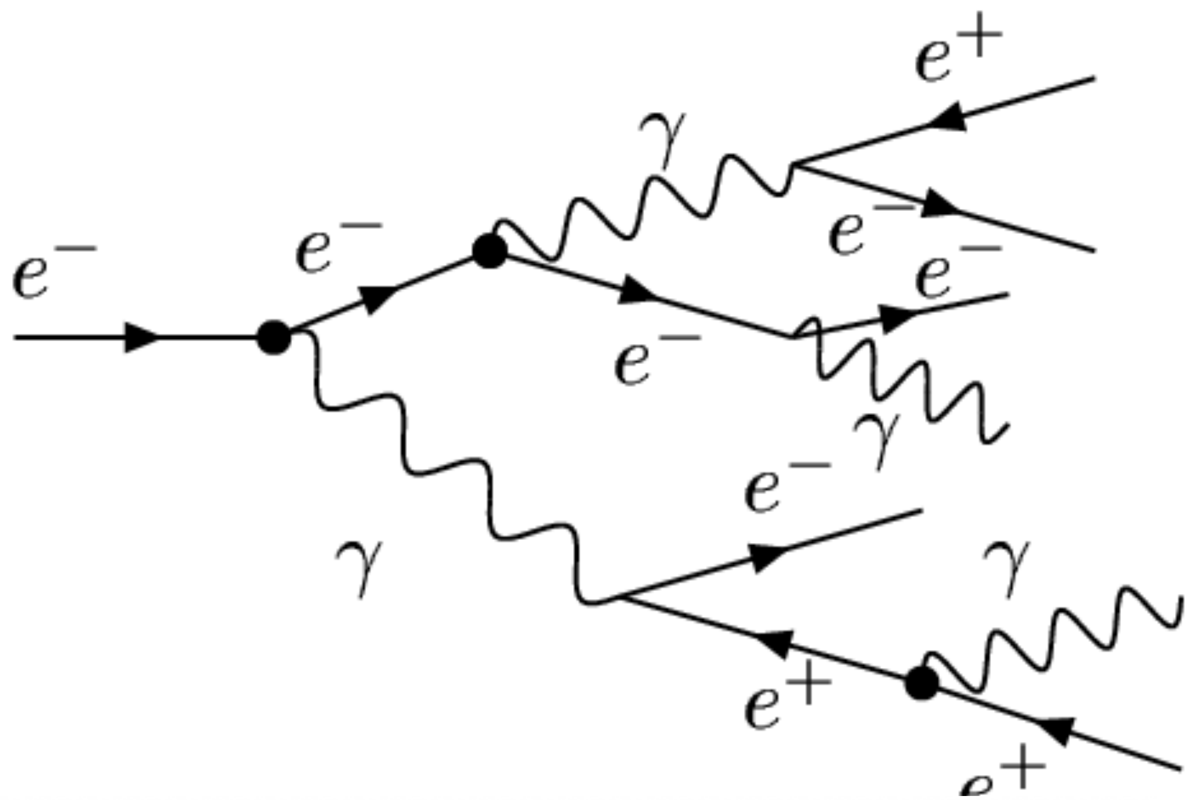
- While collection of ionization is difficult in solids and liquids, scintillation light can be used instead as a proxy for charge collection
- Scintillators have metastable excited states
  - Isotropic emission, lots of photons
  - Emitted at one or more spectral lines, not continuum
- Depending on 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)

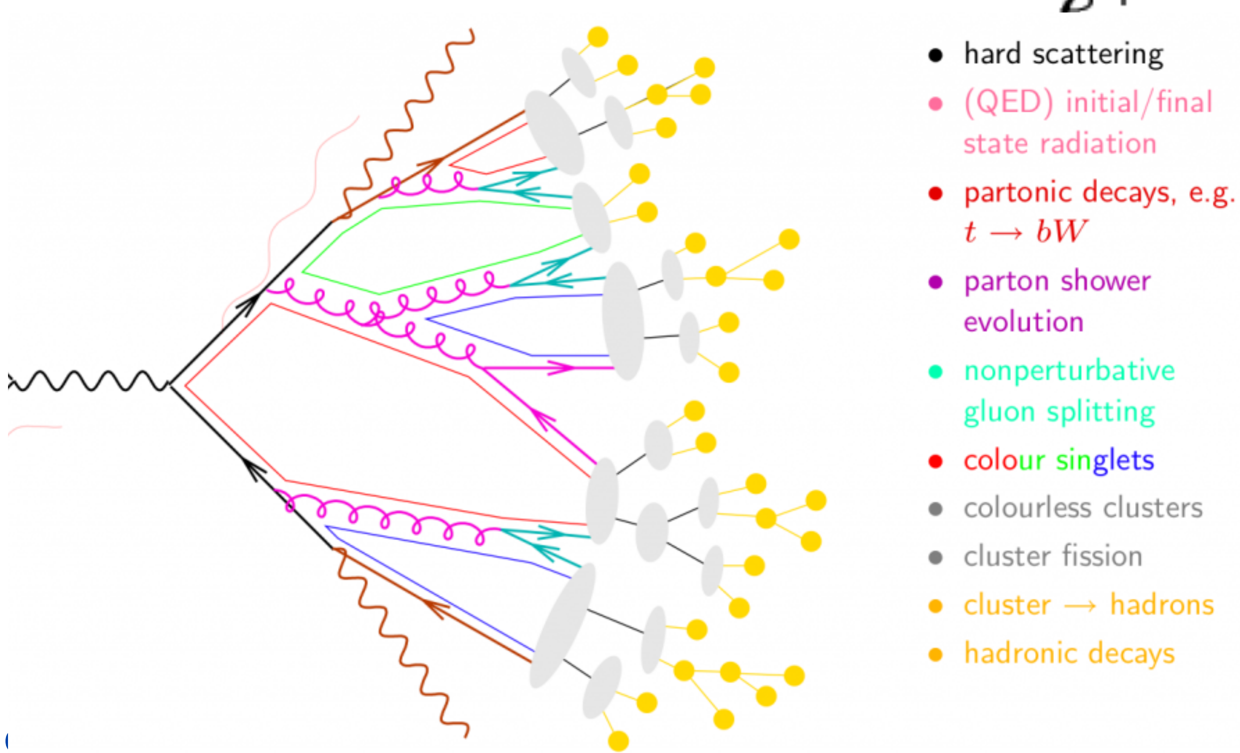


Detecting via Bremsstrahlung/Pair Production

- **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}

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}

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

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Nuclear collision length	70.2	g cm^{-2}	30.16	cm
Nuclear interaction length	108.4	g cm^{-2}	46.52	cm
Pion collision length	96.2	g cm^{-2}	41.29	cm
Pion interaction length	137.7	g cm^{-2}	59.14	cm
Radiation length	21.82	g cm^{-2}	9.370	cm

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Nuclear collision length	114.1	g cm^{-2}	10.05	cm
Nuclear interaction length	199.6	g cm^{-2}	17.59	cm
Pion collision length	137.3	g cm^{-2}	12.10	cm
Pion interaction length	226.2	g cm^{-2}	19.93	cm
Radiation length	6.37	g cm^{-2}	0.5612	cm

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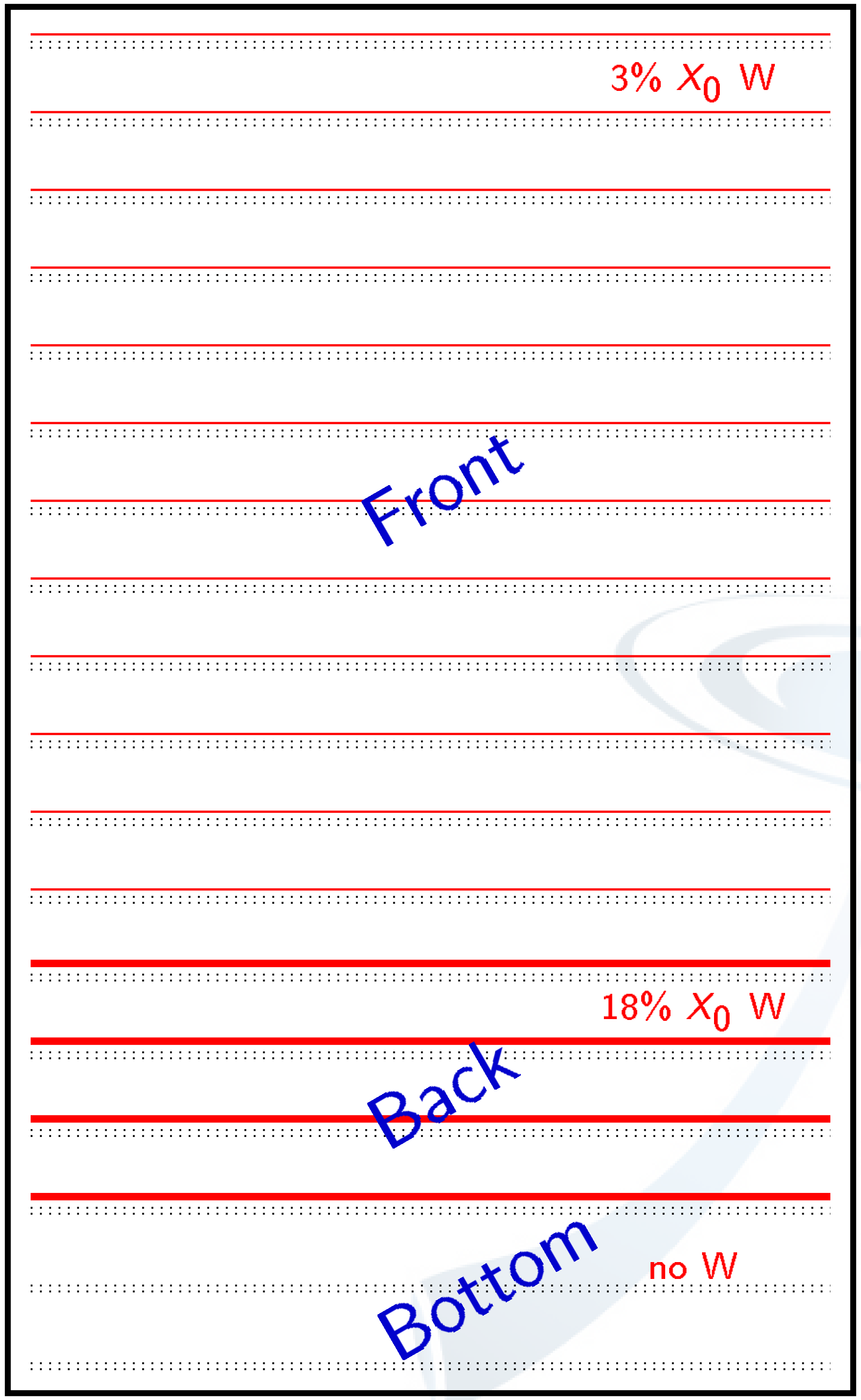
Different materials are better at different things…

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

Which detectors make up the LAT?

Silicon Tracker



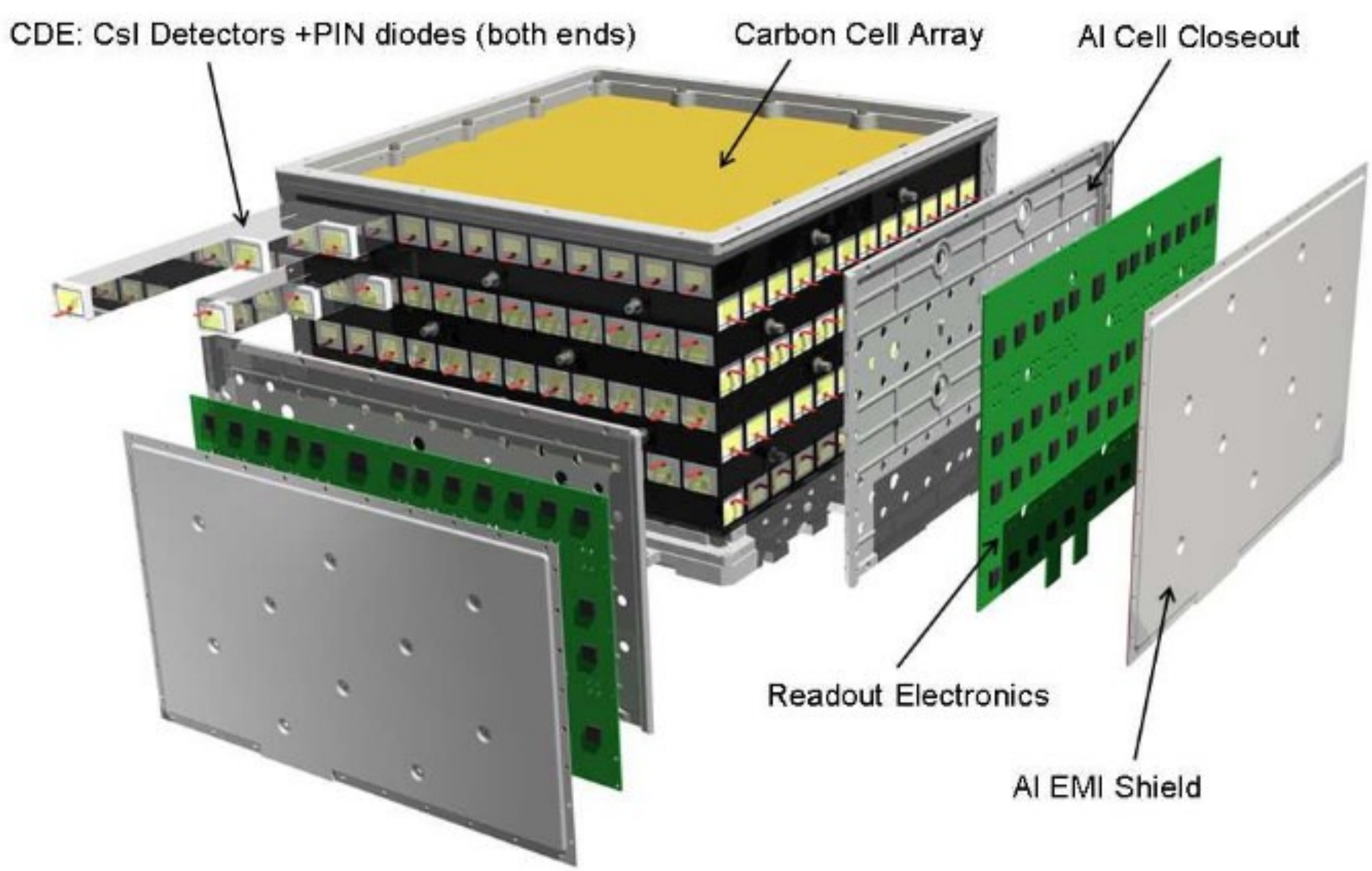
- Tracker is 1.5 radiation lengths total on axis (63% conversion efficiency)

- 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

Calorimeter

- **Measures energy deposition - contains particle shower**



Each calorimeter tower: 8 layers of 12 CsI bars hodoscopic arrangement read out by photodiodes
10 X_0
can measure the three-dimensional profiles of showers
permits corrections for energy leakage and capability to discriminate hadronic cosmic rays

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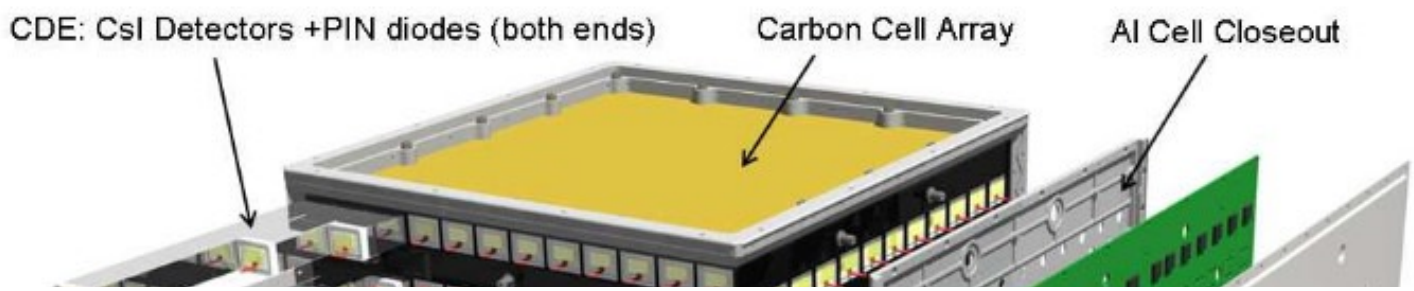

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ıasure the three-
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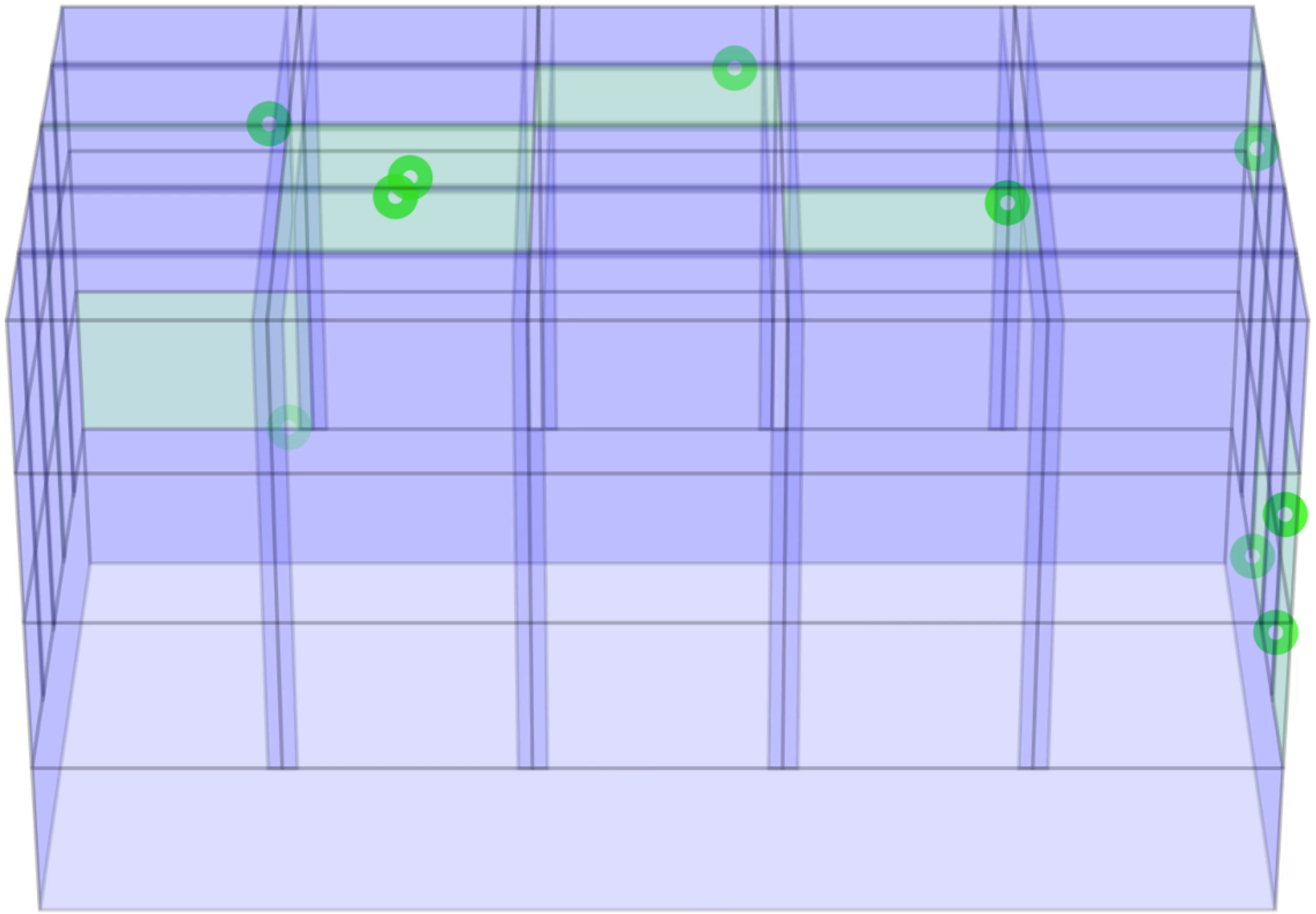
Atomic and nuclear properties of cesium iodide (CsI)

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	$MeV\ g^{-1}cm^{2}$	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

AntiCoincidence Detector (ACD)

covers the array of towers,
employs segmented tiles of scintillator,
read out by wavelength-shifting fibers and miniature phototubes.

Elapsed Time : 0.00s
No. of Gamma-rays : 0
No. of Proton CRs : 1
No. of Electron CRs : 0



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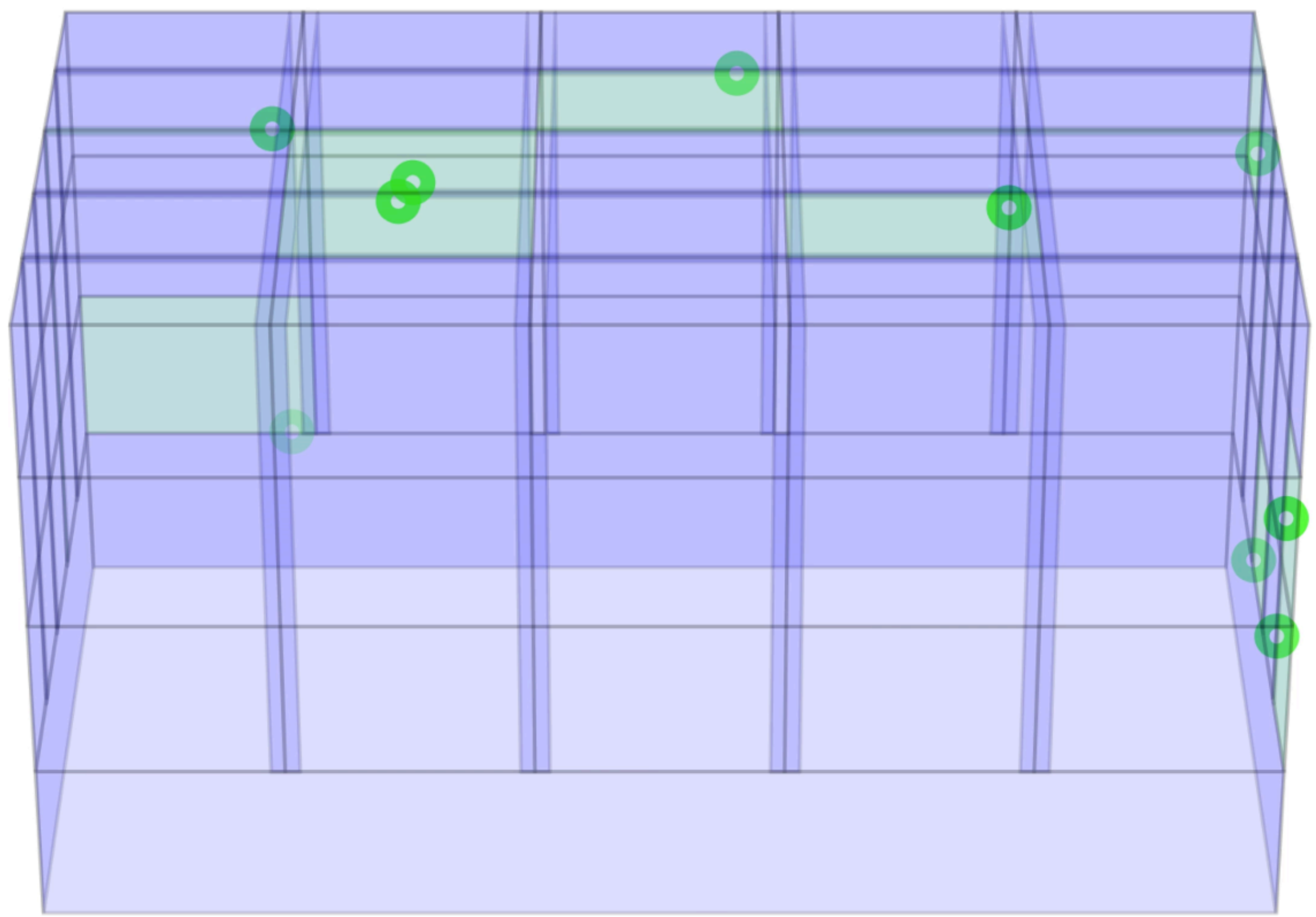
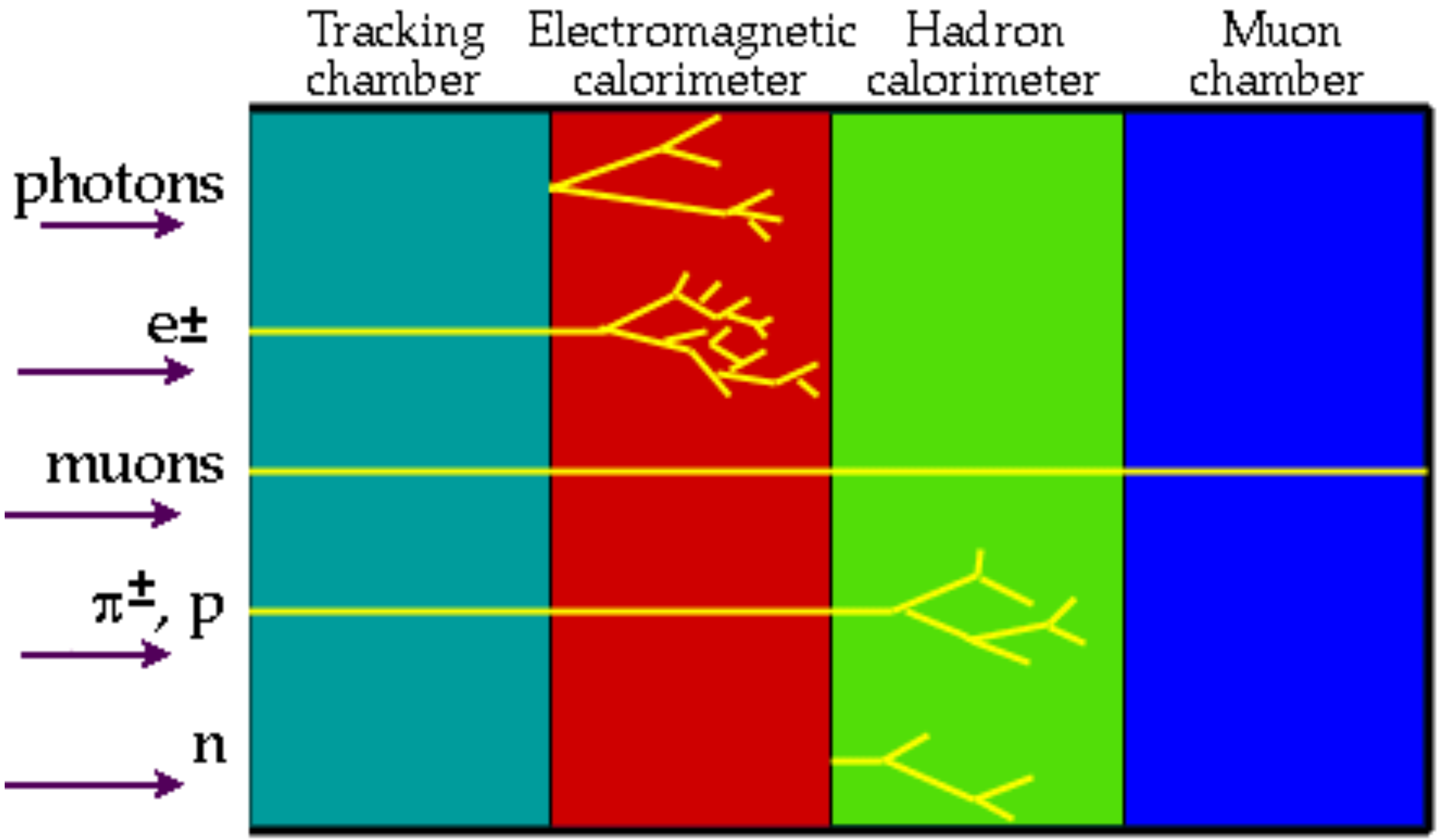


Overview of particle interactions



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

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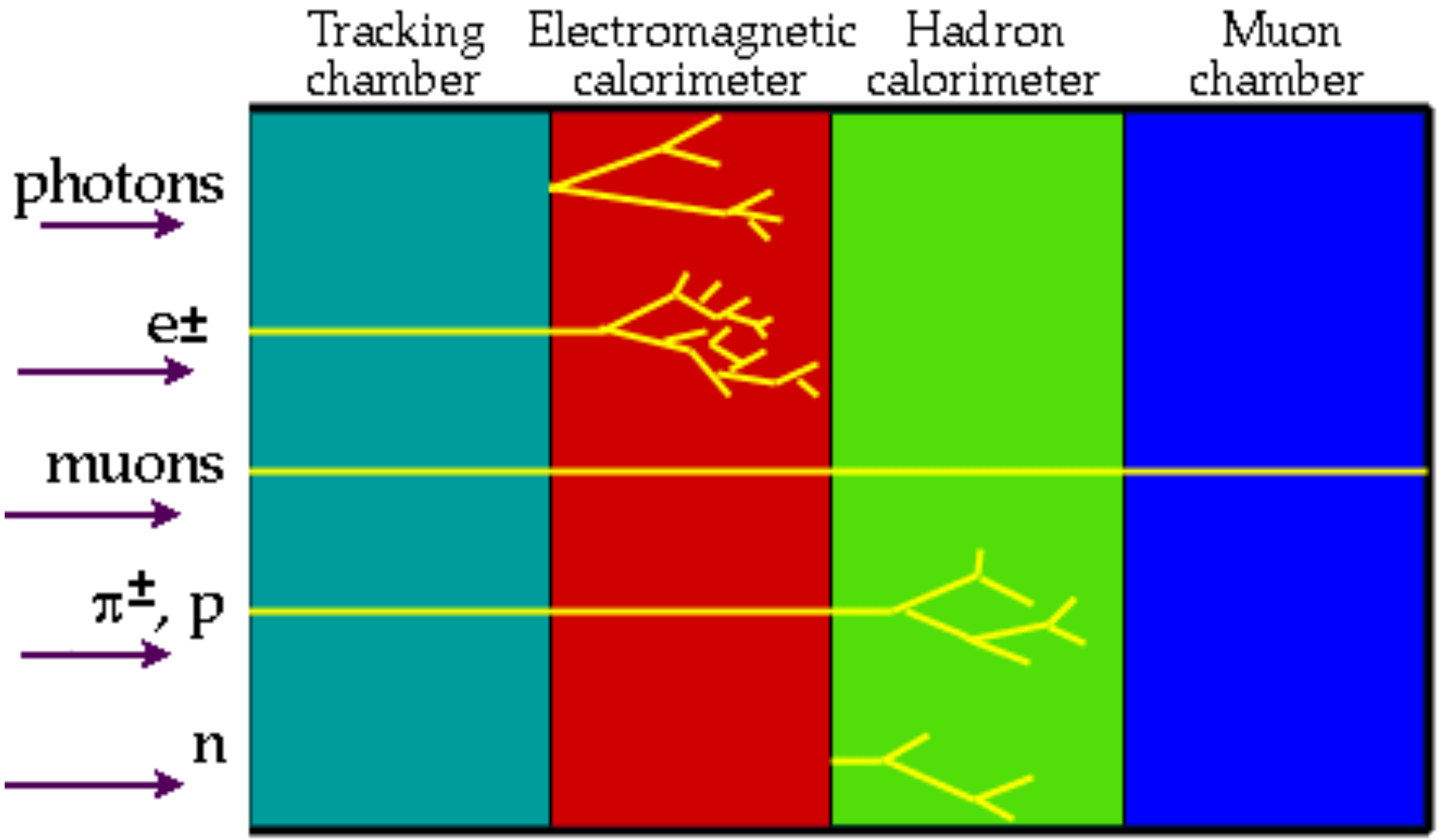

Interactions with the electron shell

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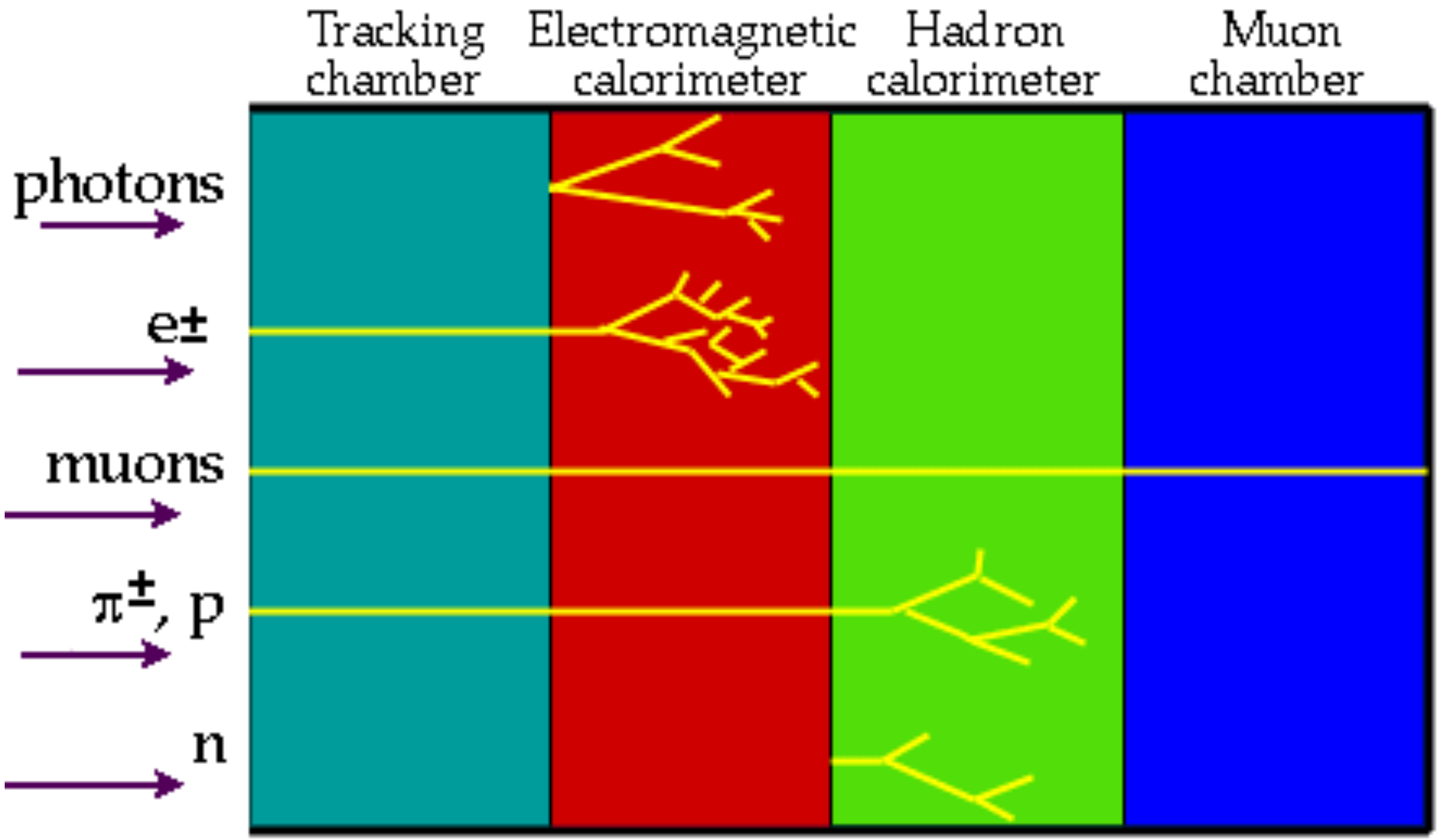
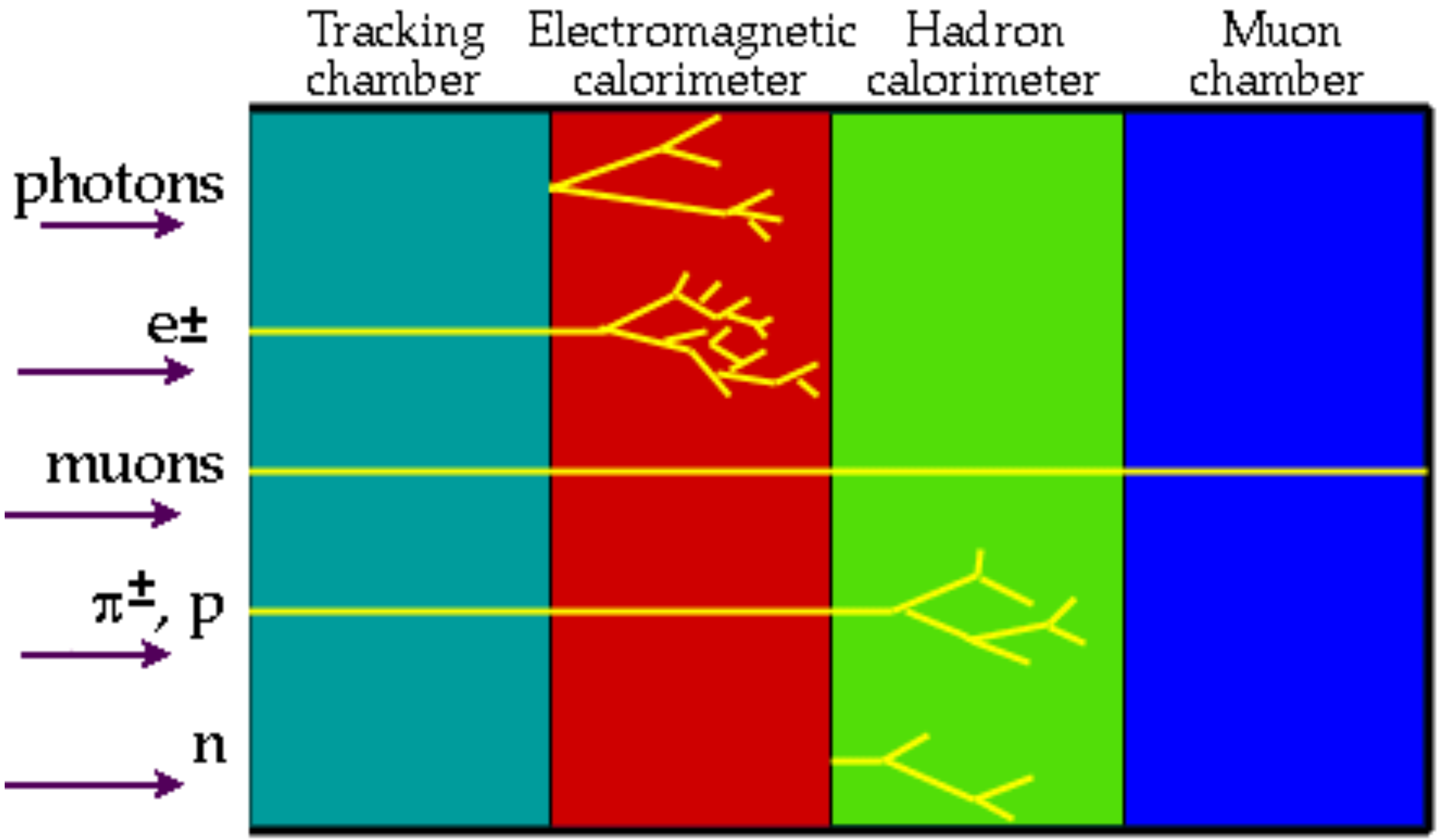


Interactions with the electron shell   nucleus

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

Overview of particle interactions



Interactions with the electron shell nucleus electron shell

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BREAKING NEWS!!!

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- Need to build a muon telescope!

- What do we build?

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Building the LAT

Backups

Bremsstrahlung