NPAC
Noyaux
Particules
Astroparticules
Cosmologie
Master 2 Recherche

Detector physics – NPAC 2022-2023

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Plan

- Second lecture: intro, interaction of charged particles in matter
- Third lecture: interactions of photons in matter, scintillators
- Fourth lecture (this one):
  - Photodetectors
  - Interactions of other neutral particles in matter

Recap

The Bethe-Bloch Formula

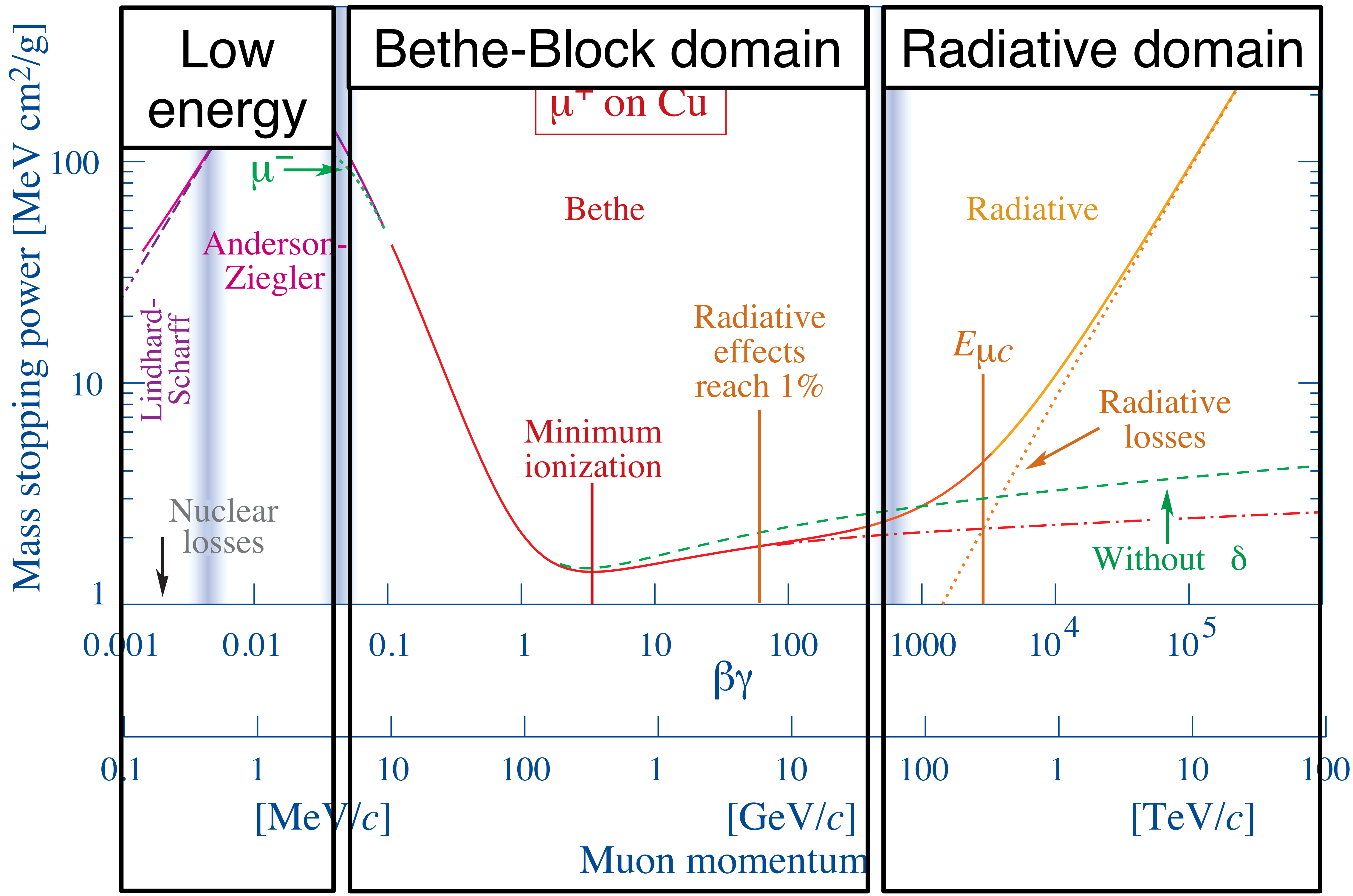
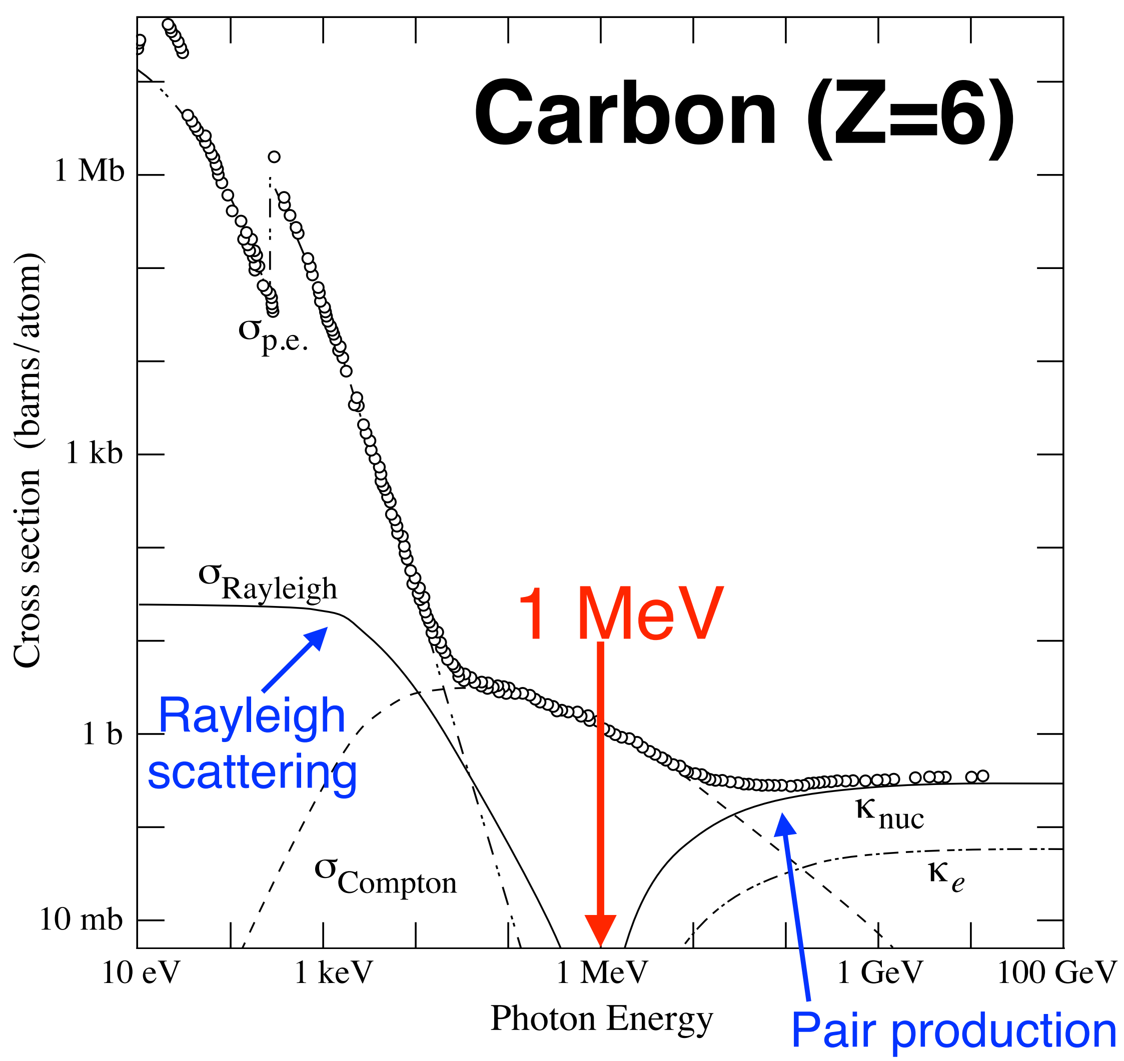
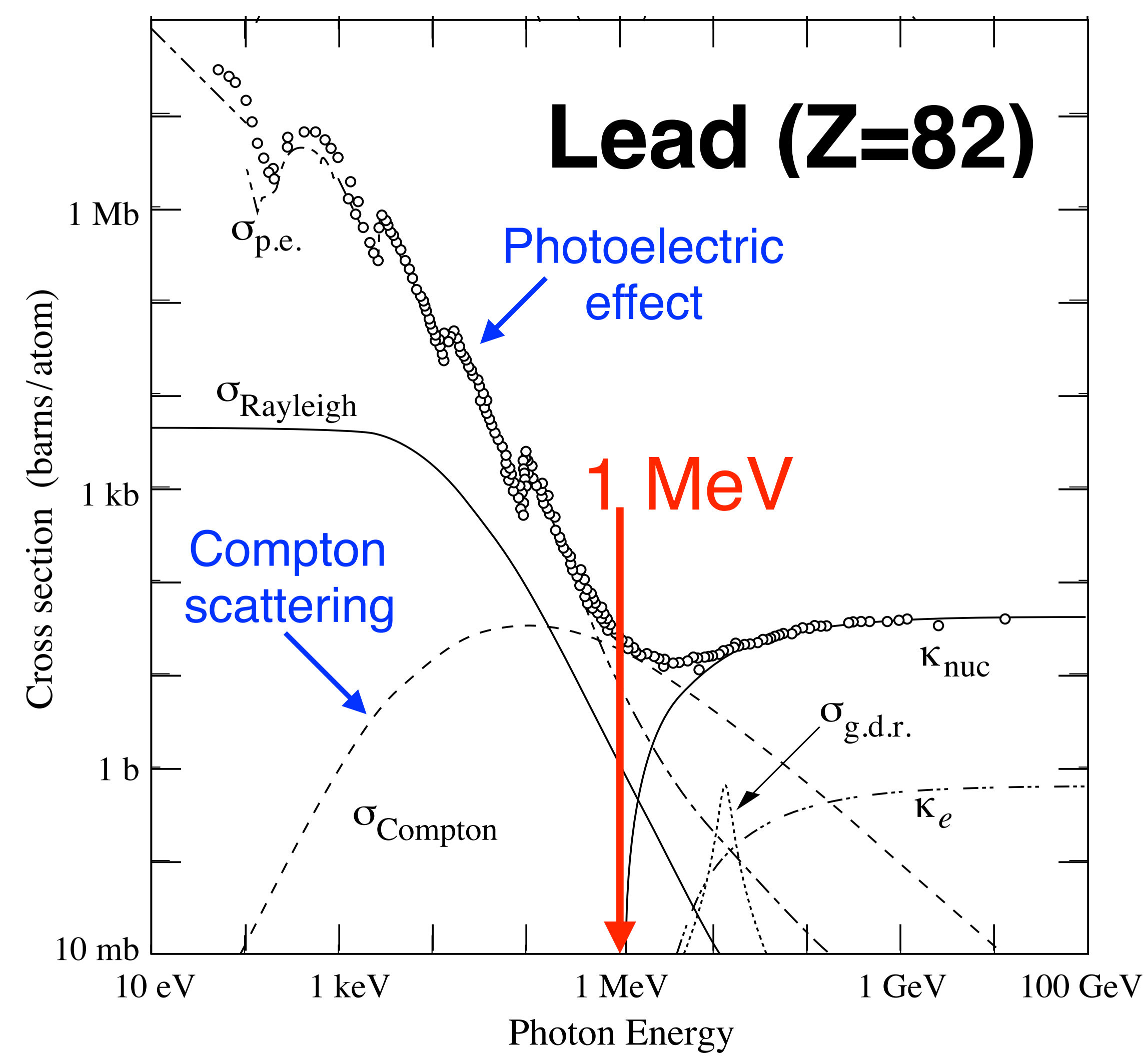


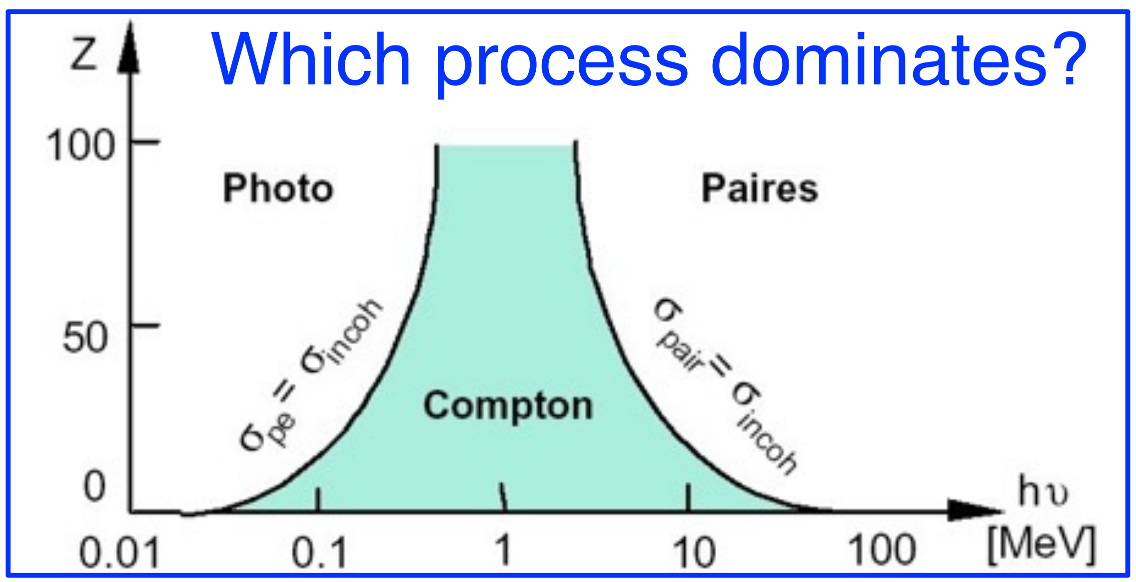
Figure from PDG

Recap

Photons & matter: Total photon x-sec

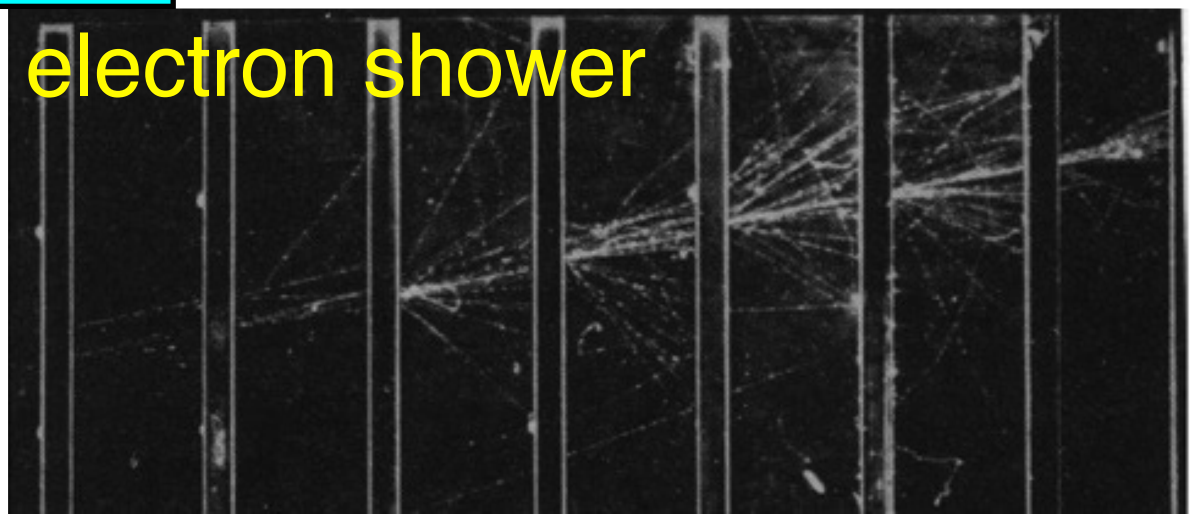






Recap

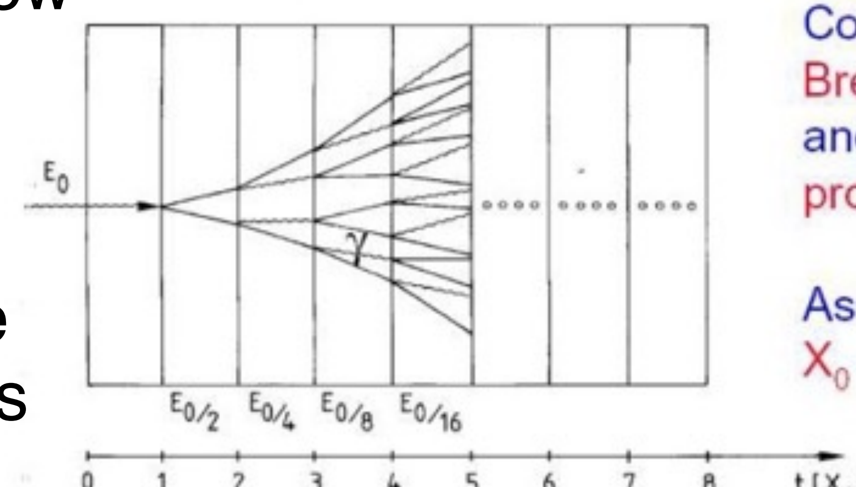
Electromagnetic showers



Electron shower in a cloud chamber with lead absorbers

For high energy γ and $e^\pm$ ($E \gg m_e c^2$), showers look very similar:

- An interaction happens (on average) once per radiation length, predominantly:
  - Bremsstrahlung ($e^\pm \to e^\pm \gamma$) or pair production ($\gamma \to e^+ e^-$) [quasi-spectator nucleon omitted]
- Both reactions are 1→2 for the EM shower particles ($\gamma/e^+/e^-$)
- So after t radiation lengths, $N(t) \sim 2^t$ particles, each of avg energy $E(t) \sim E_0/2^t$
- Shower stops at $t=t_{max}$, when E(t) falls below critical energy E_c needed to sustain it
  - $E(t_{max}) = E_0 / 2^{t_{max}} = E_c$
    => $t_{max} = \ln(E_0/E_c) / \ln(2) \propto \ln(E_0)$
  - $N(t_{max}) = 2^{t_{max}} = E_0/E_c \propto E_0$ -- and will be an ~ equal mix of e^+, e^-, γ => 1/3 photons



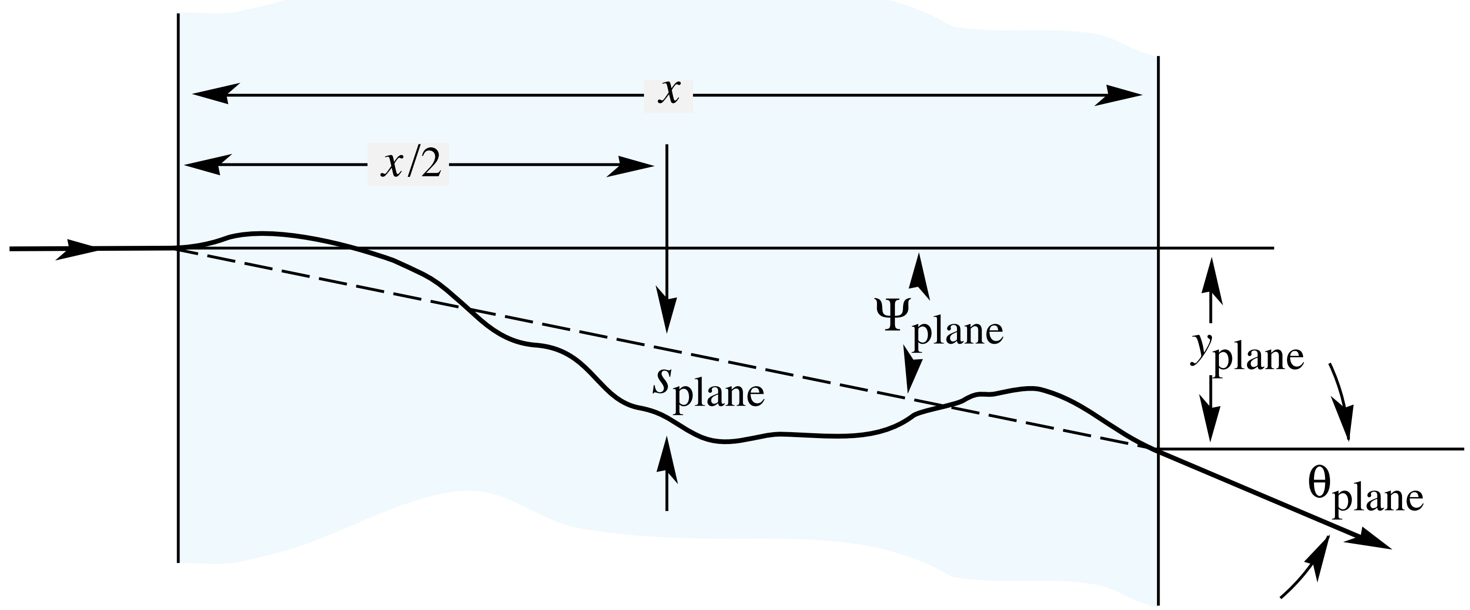
Consider only Bremsstrahlung and pair production.

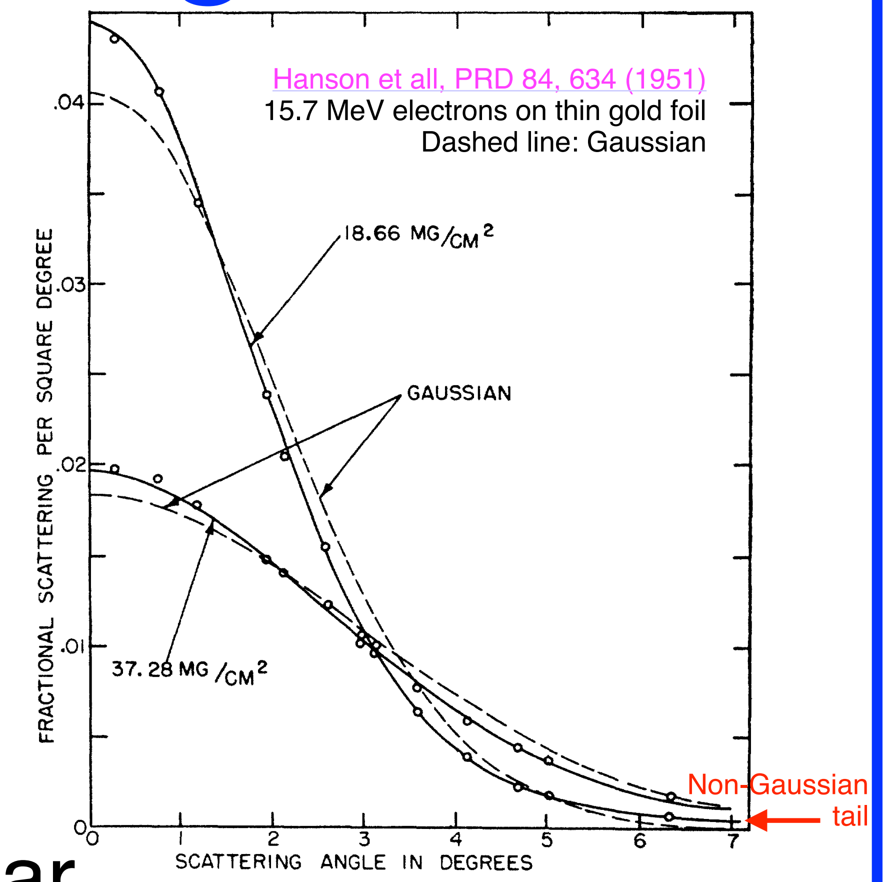
Assume: $X_0 = \lambda_{pair}$

Recap

Multiple scattering

Figure from PDG





- Finite width case is kind of a mess.
- For a thick absorber where many nuclear scatters expected, can model as Gaussian core (from many small-angle scatters) plus longer tails where angle is dominated by a single large-angle scatter.
- Track fitters need to allow for **correlated** fluctuations due to multiple scattering, e.g. using Kalman fitter.
  - Note that this is different from hit measurement resolution, i.e. independent random errors.

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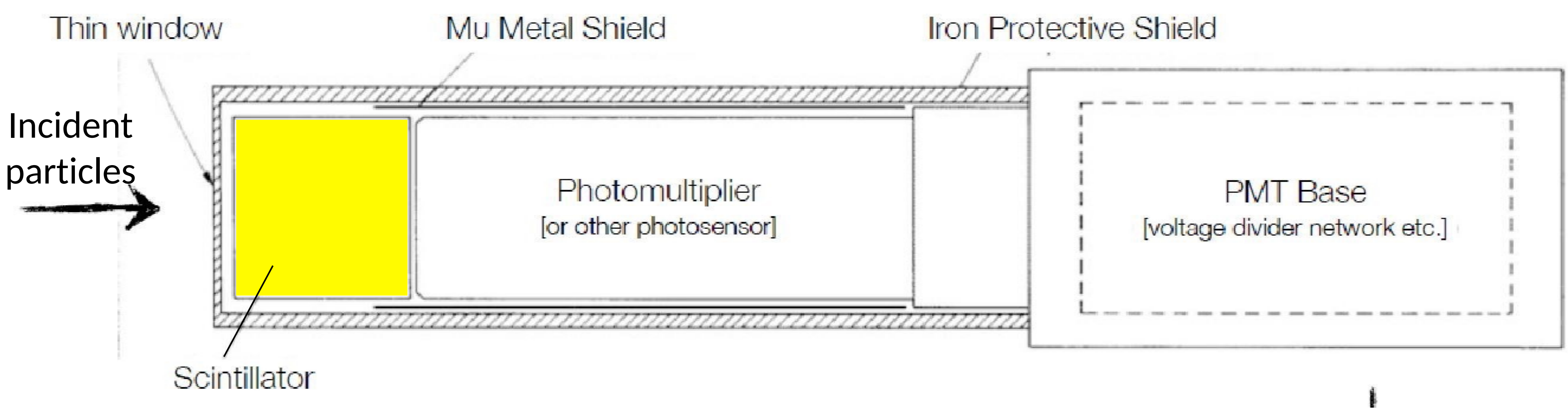
Remark: e± are susceptible to large-angle scatters on nuclei, can even backscatter out of the detector! Effect worse for heavy (large-A) materials.

Recap Scintillators: Basic design



- Scintillator types:
  - Inorganic crystals
  - Organic scintillators
  - Gases
  - ... or even liquids (e.g. liquid Argon)
- Photodetectors:
  - Photomultipliers (PMTs)
  - Microchannel plates (MCPs)
  - Hybrid photodiodes (HPDs)
  - Silicon photomultipliers

Excitation/ionization → light → photo-sensor → electric signal

Photodetectors

Photon detection

- Goal: convert light into a detectable electronic signal
- Visible or near-visible light (not γ or very soft photons)

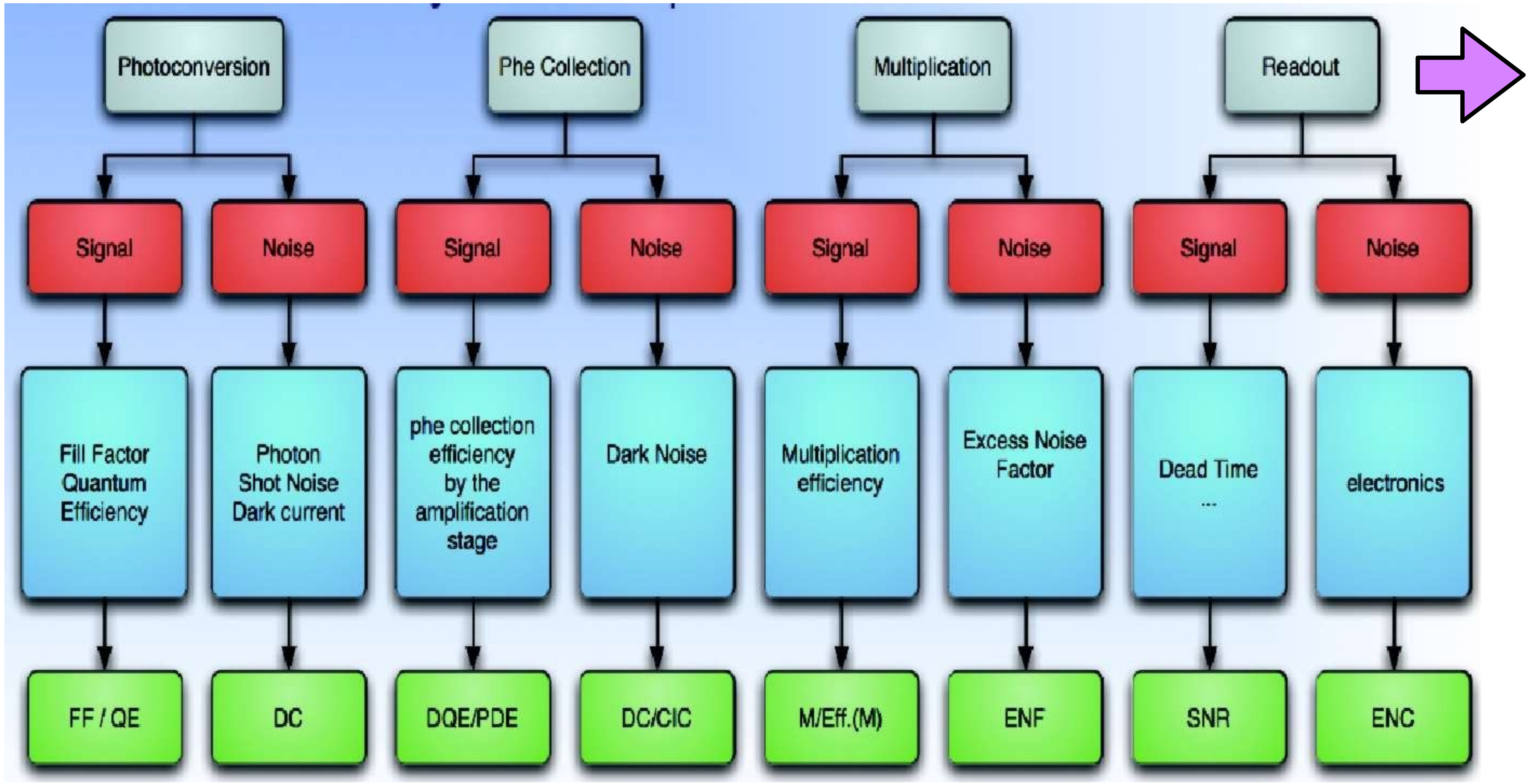
- We have ways to detect visible light in everyday life (e.g. film cameras, CCD cameras, photoresistors and photodiodes, eyeballs)...
- ... but HEP experiments are more demanding.
We often want many or all of:
  - electronic readout
  - rapid response, little deadtime
  - linear response to many photons
  - good time resolution
  - good single-photon detection efficiency (for good overall energy resolution of scintillator+photodetector system)
  - decent granularity, spatial resolution
  - moderate cost per unit area instrumented

- How do we get there?

Considering only detection of visible photon spectrum

Photon detection

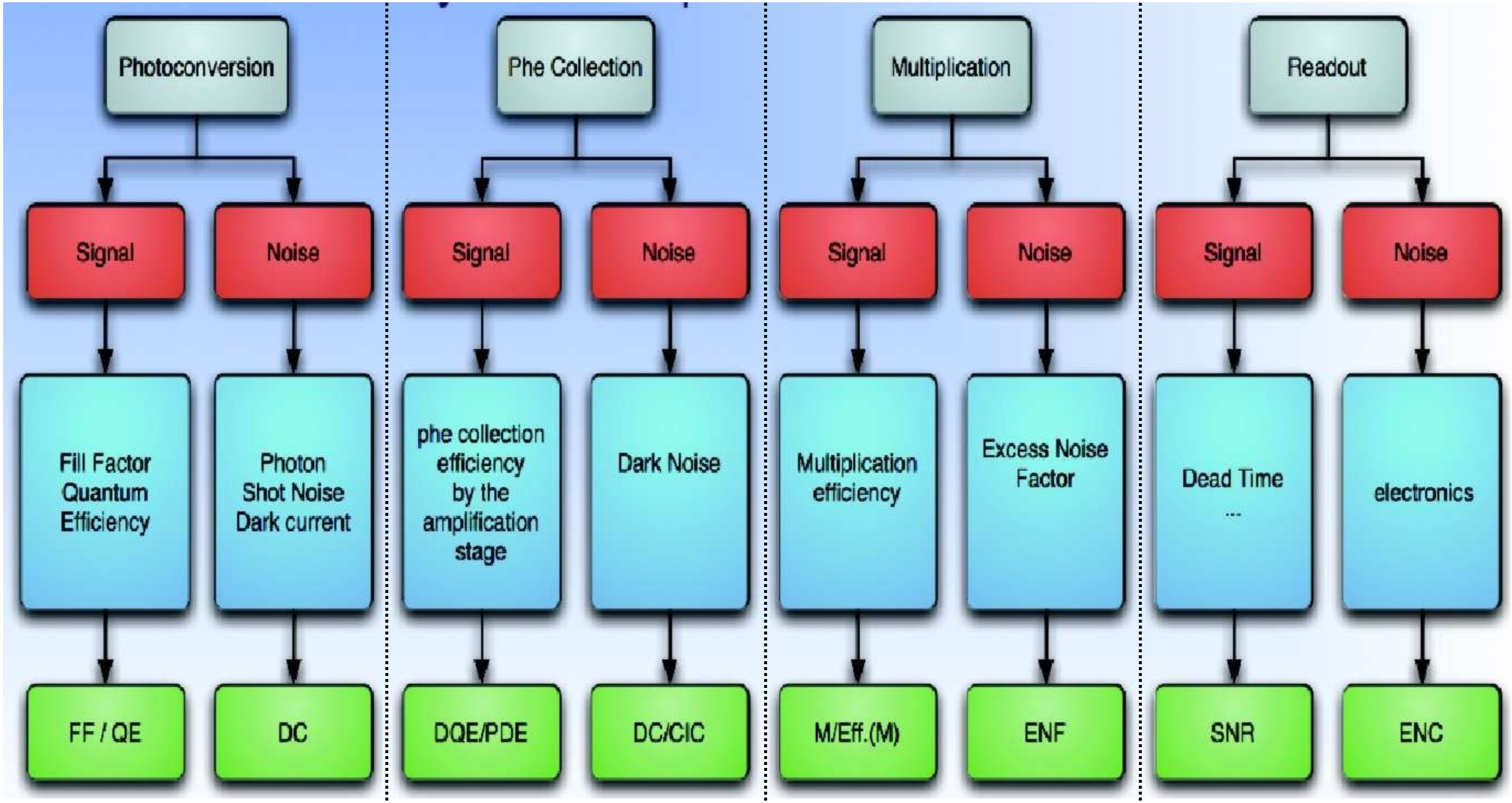
- Goal: convert light into a detectable electronic signal
- Principle: Use photoelectric effect to convert photons to photoelectrons
- The four steps of the process:
  - The primary charge carrier (pe, e/h) is produced
  - The primary charge carrier is collected
  - The primary charge carrier is multiplied/amplified or not (CMOS/CCD/PD)
  - The secondary (or primary) charges are collected and read out
- Each process is modified by noise sources:



Considering only detection of visible photon spectrum

Photon detection

Produce primary charge carriers	**Collect** primary charge carriers	**Amplify** charge carriers	Collect & **read out** amplified charge carriers



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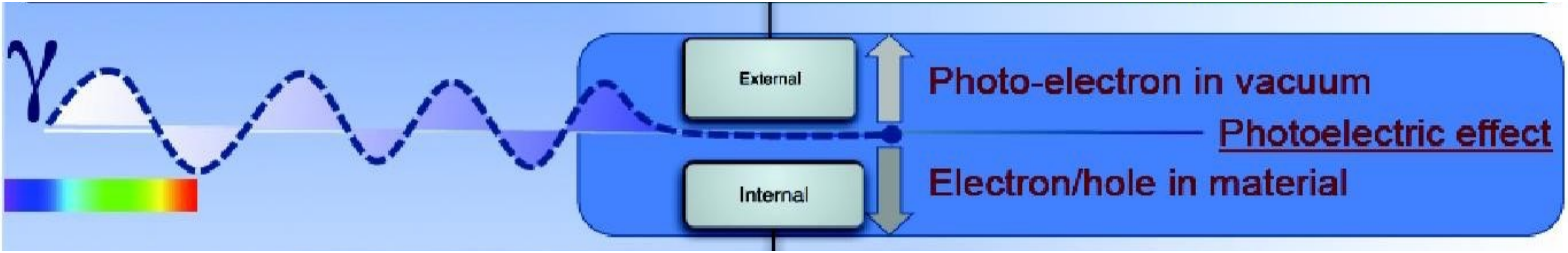
Photosensors: Key parameters

- **Fill Factor** (FF), aka geometrical efficiency (ε_{geom}): ratio between the sensitive surface area and the detector surface area
- **Quantum efficiency** (QE): #(photoelectrons) / #(photons)
- **Collection Efficiency*** (CE): probability to transfer the primary photoelectron (or charge carrier) to the amplification stage or readout channel.
- **Multiplication Efficiency** (ME): probability that amplification gives a detectable signal. Should be high.
- **Photon Detection Efficiency** (PDE), aka **Detectable Quantum Efficiency** (DQE): overall probability that a single photon gives a detectable output pulse

$$DQE = PDE = (FF).(QE).(CE).(ME)$$

* Sometimes CCE: "charge collection efficiency"

Photosensors: Different types



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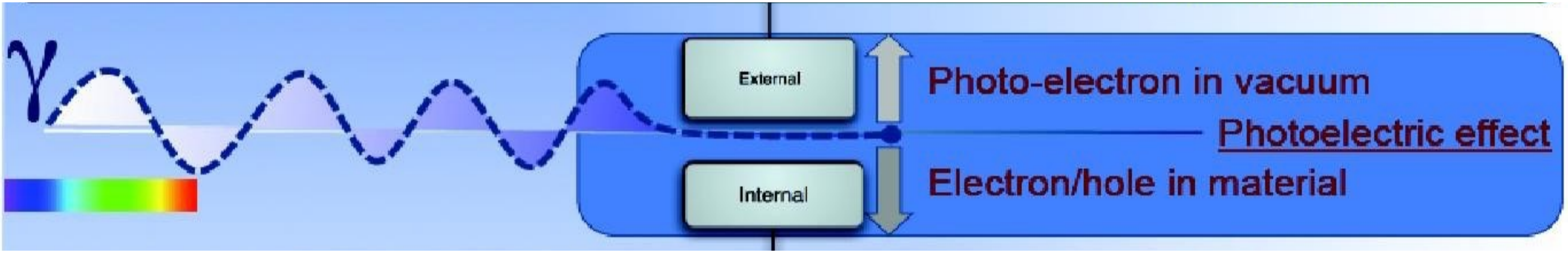
Photosensors: Different types

Today: detectors where the photon produces a photoelectron in a vacuum (e.g. via a thin foil), and the electron is then accelerated by an electric field and detected.



... or use a solid-state detector: the photon ionises an electron inside solid material. See semiconductor detectors lecture.

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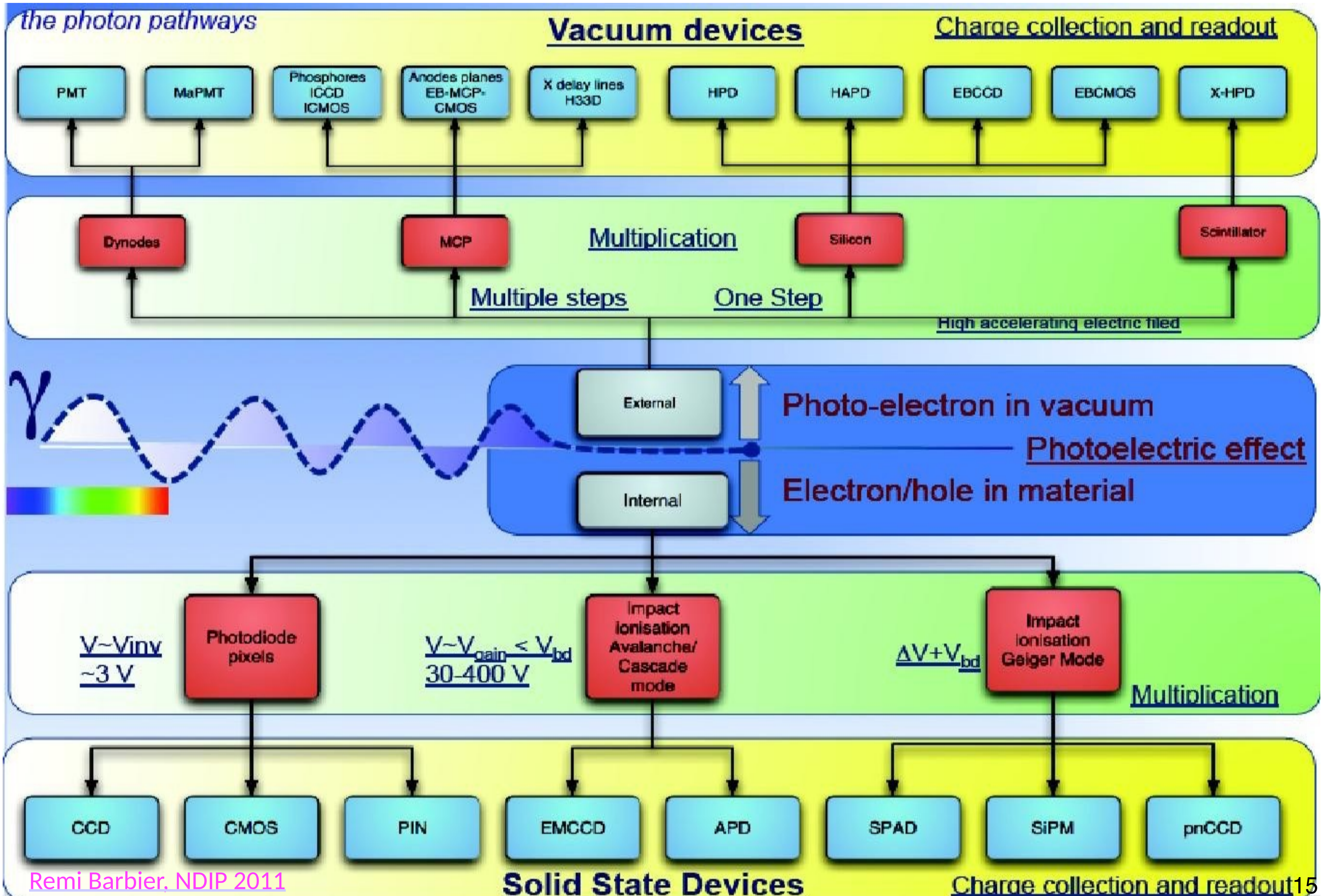
Photosensors: Different types



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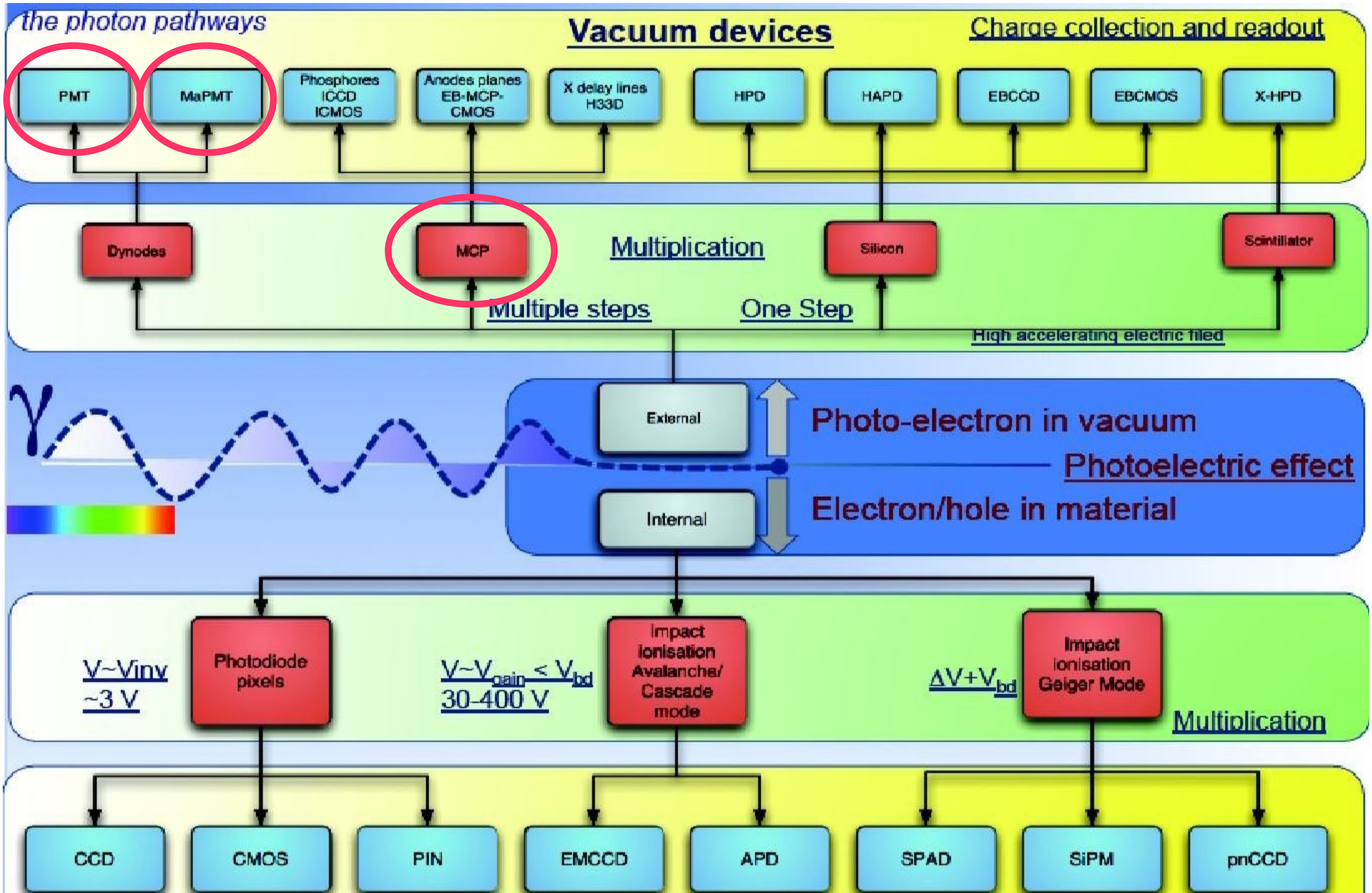
Photosensors: Different types



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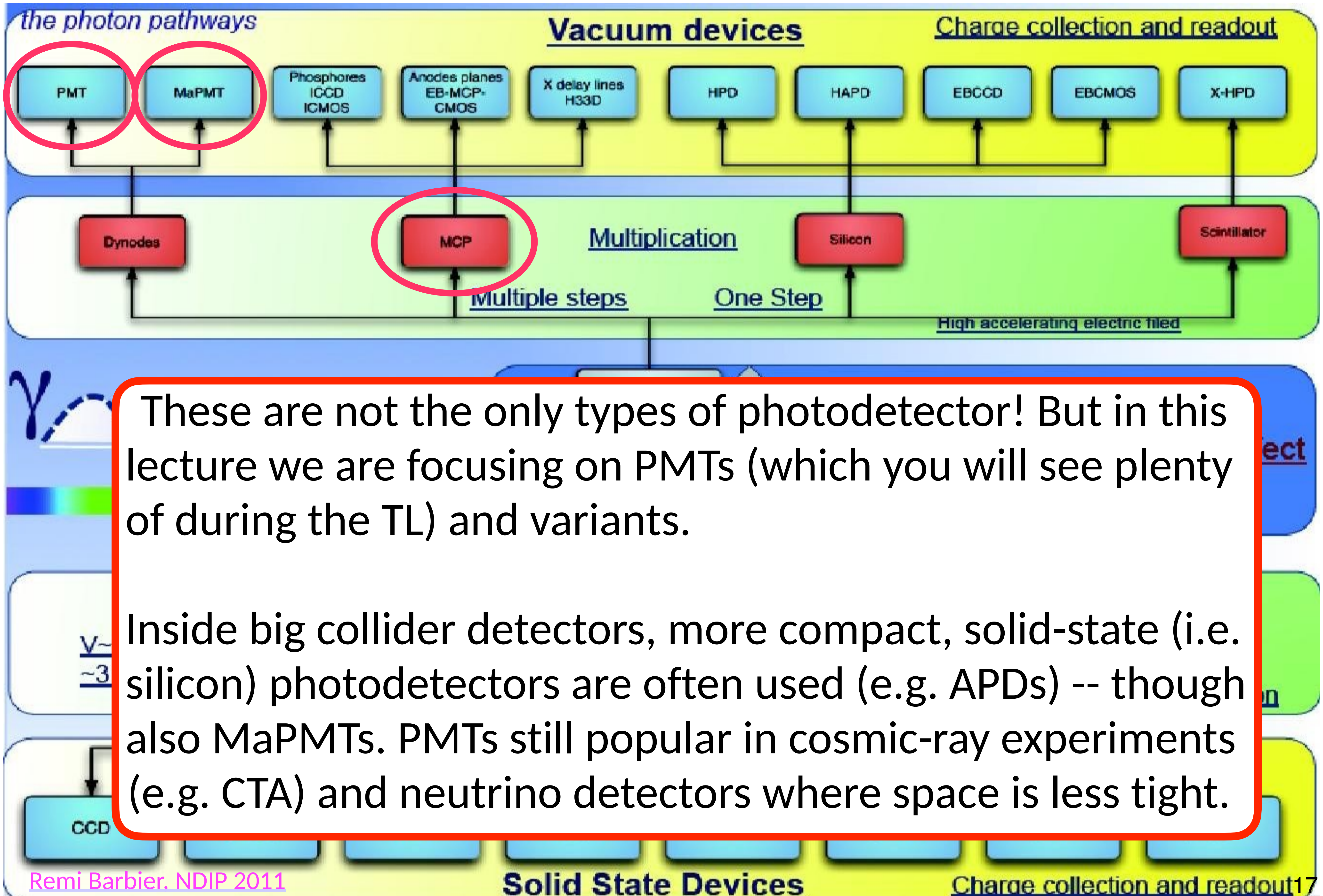
Photosensors: Different types



These are not the only types of photodetector! But in this lecture we are focusing on PMTs (which you will see plenty of during the TL) and variants.

Inside big collider detectors, more compact, solid-state (i.e. silicon) photodetectors are often used (e.g. APDs) -- though also MaPMTs. PMTs still popular in cosmic-ray experiments (e.g. CTA) and neutrino detectors where space is less tight.

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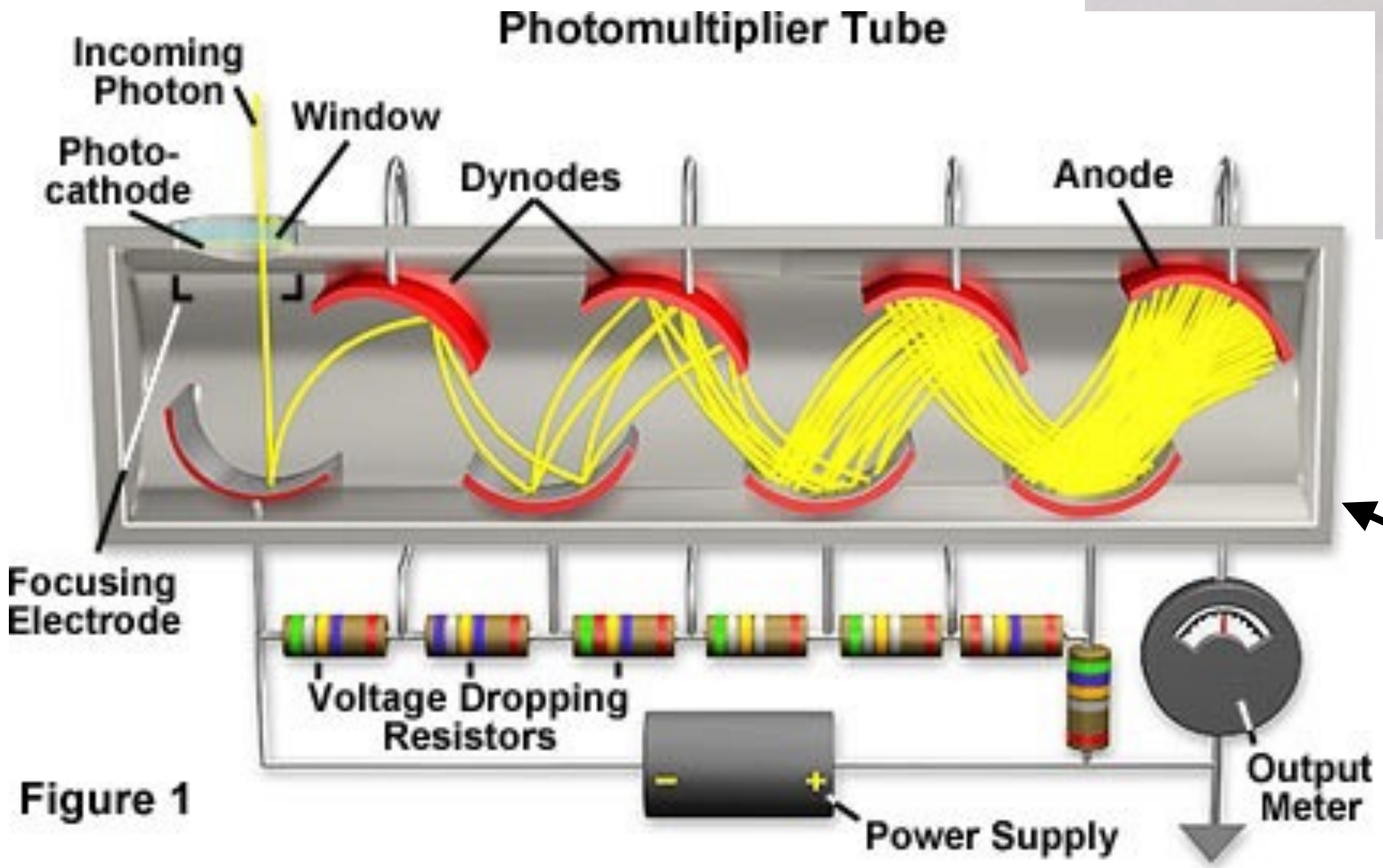
Photosensors: Photomultipliers (PM/PMT)

Principle:

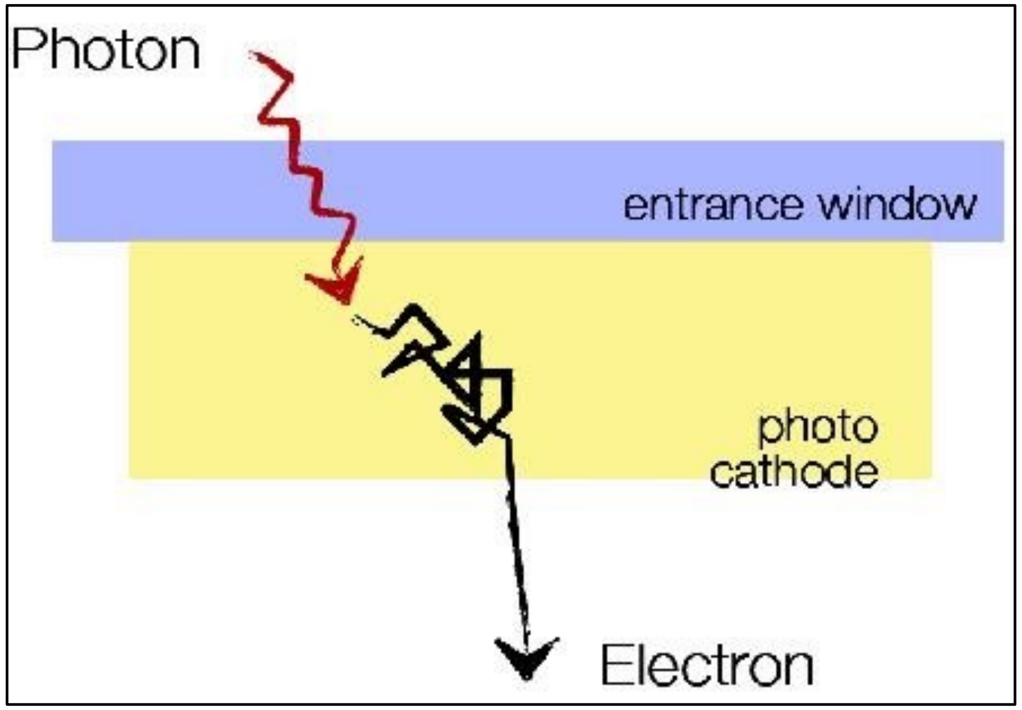
- Electron emission from photocathode
- Secondary emission by multiplication from dynodes



Vacuum chamber

Photosensors: PMT photocathode

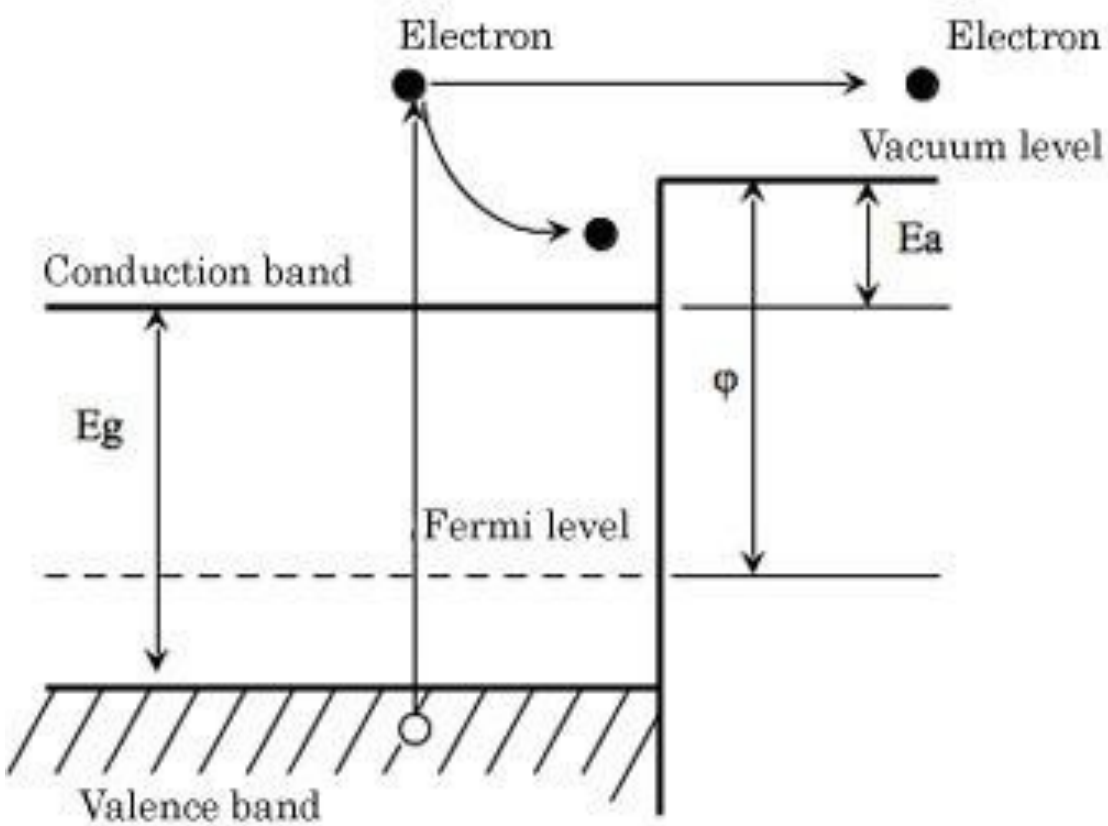
Conversion via photoelectric effect:



Photocathode: thin deposit of material on the entry window

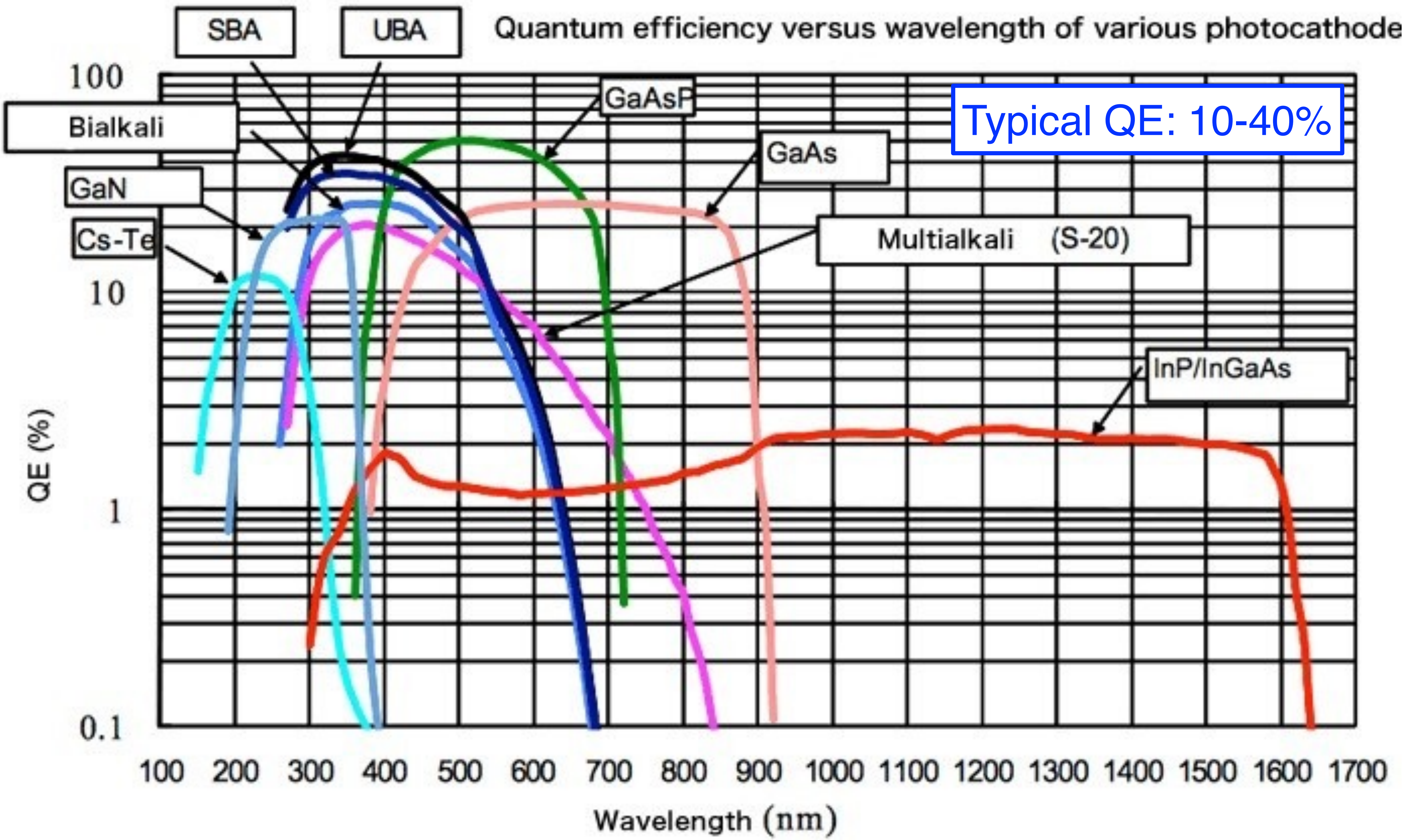
3-step process:

- e⁻ generation by **photoelectric effect**
- Propagation/migration toward surface
- Escape of electron into the vacuum device (low work-function)



Band model for alkali photocathode

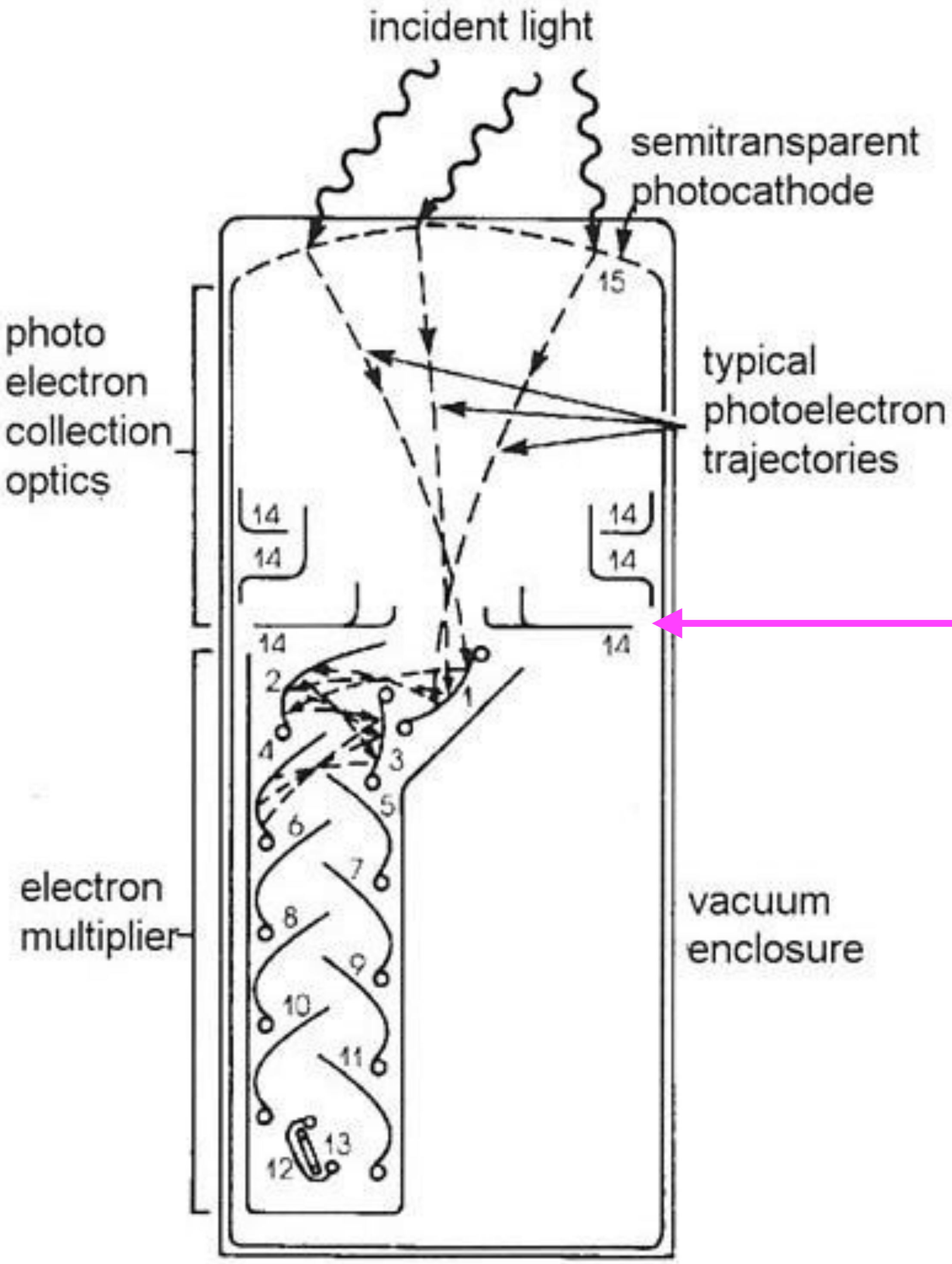
Photocathode quantum efficiency

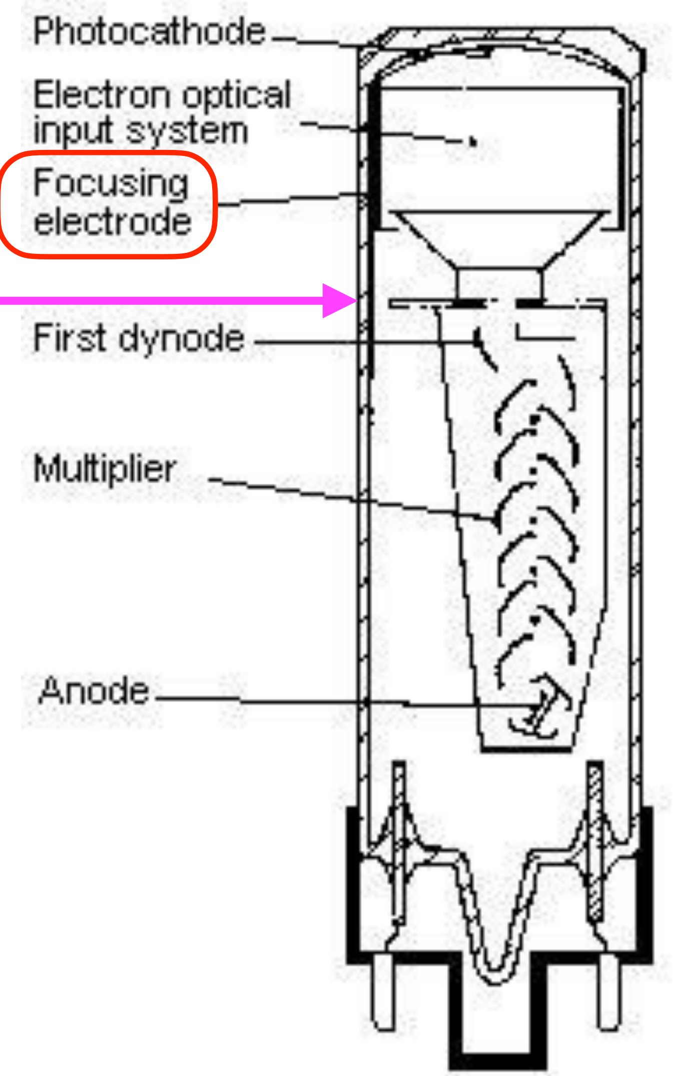


DQE = PDE = (FF).(**QE**).(CE).(ME)

Remember: works by photoelectric effect, so there is a minimum energy needed, and cross-section drops rapidly with energy.

Photocathode collection efficiency





Focusing electrode focuses the emitted electrons onto the first dynode.

Accelerating electrode (between the photocathode and the first dynode) looks like a wall with a small gate.

Typical CE: ~90%

(but that may not be the whole story, e.g. time alignment/TTS spread)

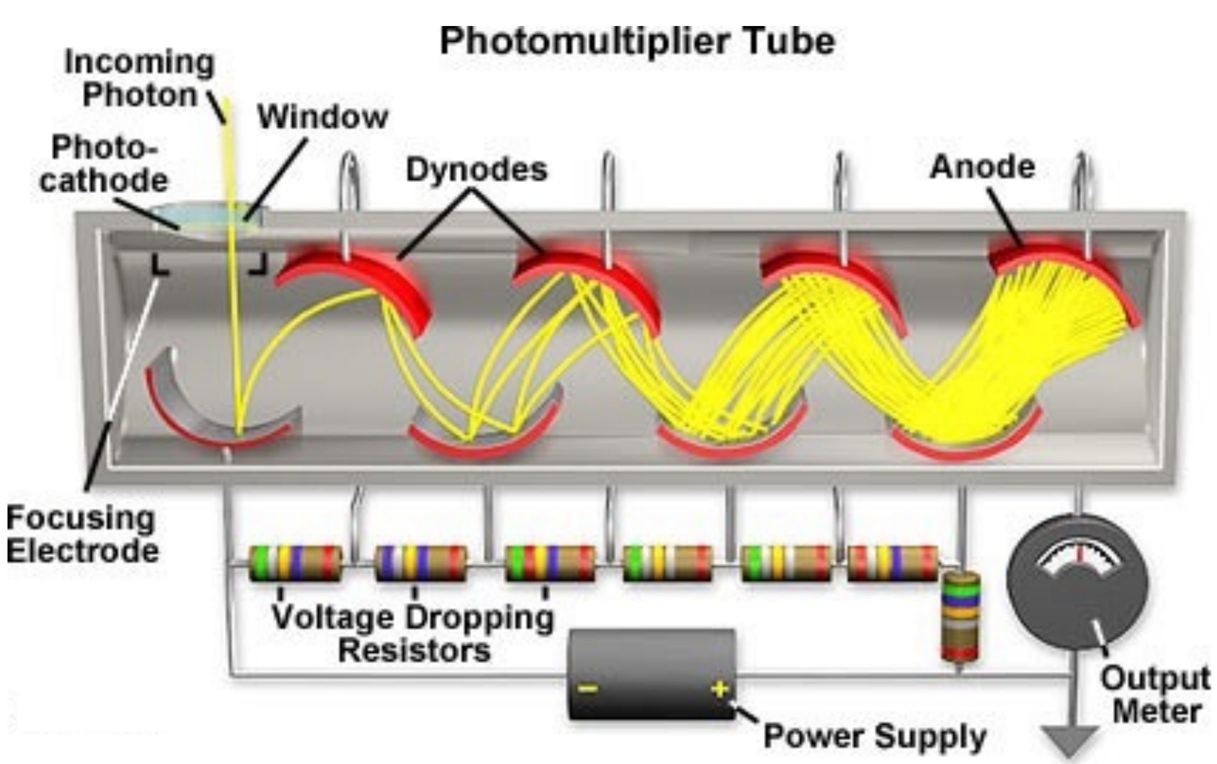
DQE = PDE = (FF).(QE).(**CE**).(ME)

PMT: Dynode chain

Goal: multiply up a single incoming electron* into a measurable signal.

Want gain to be **large** and **stable**.

- Large: typically 10^6-10^8, to measure the signal easily and precisely
- Stable: for energy measurement (roughly, counting # photoelectrons)



* Or other charge carrier

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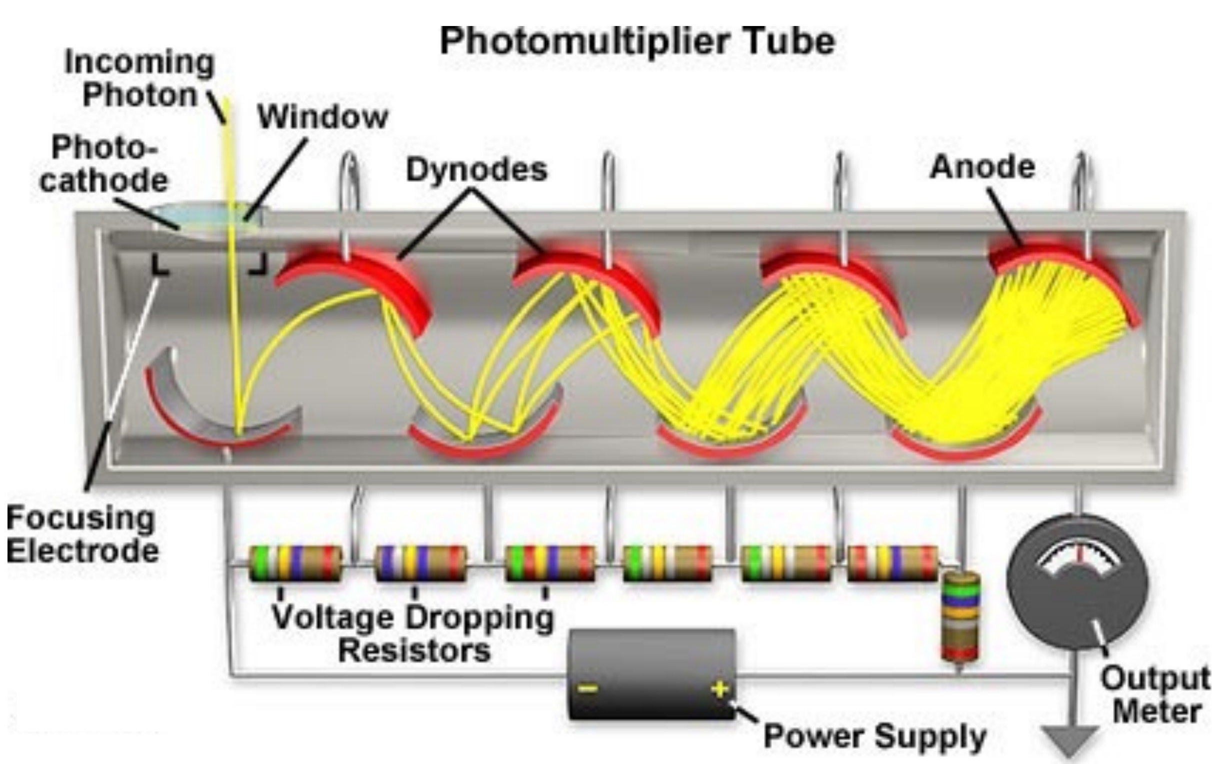


Dynodes made of semiconductors and insulators, deposited on a conducting material to ensure a constant E-field to accelerate electrons.

Three important material characteristics:

- High secondary emission factor (δ)
- Secondary emission stable under high currents
- Low thermal emission, i.e. low noise

* Or other charge carrier

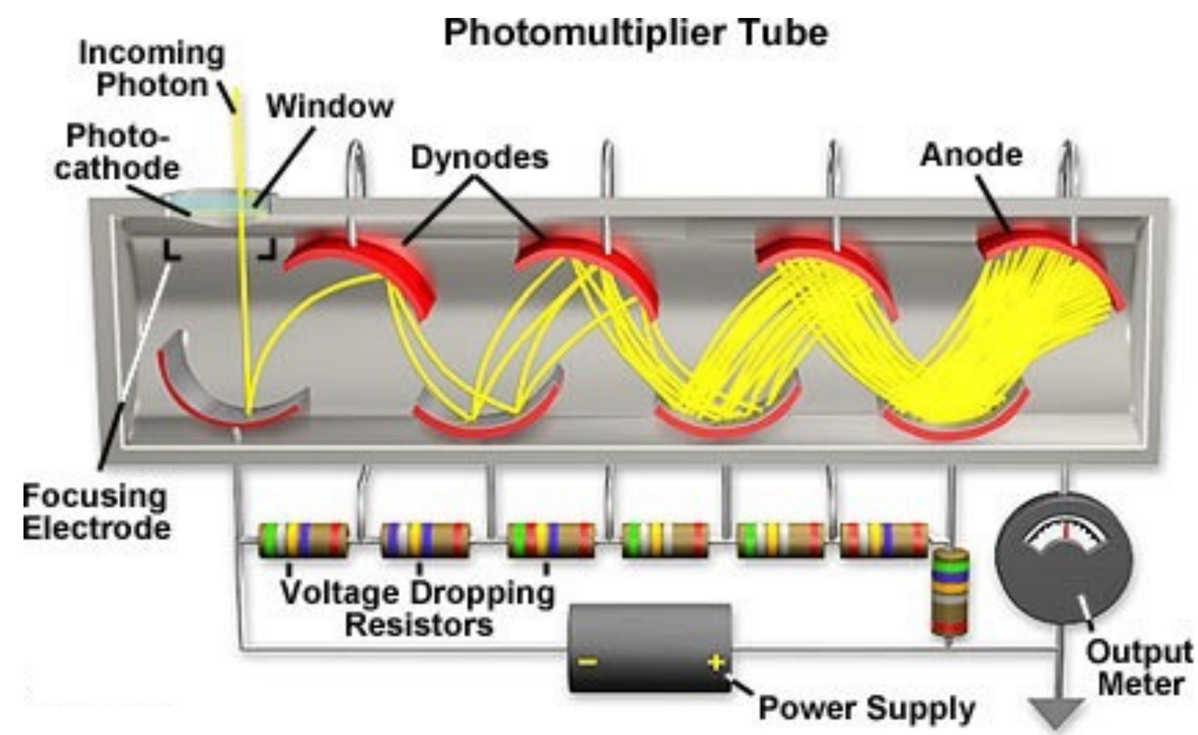
PMT: Dynode chain

At each stage i in chain of n dynodes:

- N_i incoming electrons are all accelerated towards next dynode.
- They strike the next dynode, each producing on average ($\delta-1$) more electrons, where $\delta \propto V^k$ (for k ~ 0.7-0.8)
- => $N_{i+1} = \delta N_i$ => $N_i \sim \delta^i$

Typical values: $\delta \sim 2\text{-}10$; $n \sim 6\text{-}15$

=> Gain $M = \delta^n \sim 10^6\text{-}10^8$



Statistical fluctuations in output for one PE driven by first step*:

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{N_{\text{produced at } i=1}}} = \frac{1}{\sqrt{\delta - 1}}$$

Express same concept as Excess Noise Factor (ENF):

$$\text{ENF} = 1 + \frac{\sigma_M^2}{M^2} = 1 + \frac{1}{\delta_1} + \frac{1}{\delta_1 \delta_2} + \frac{1}{\delta_1 \delta_2 \delta_3} + \ldots \approx \frac{\delta}{\delta - 1}$$

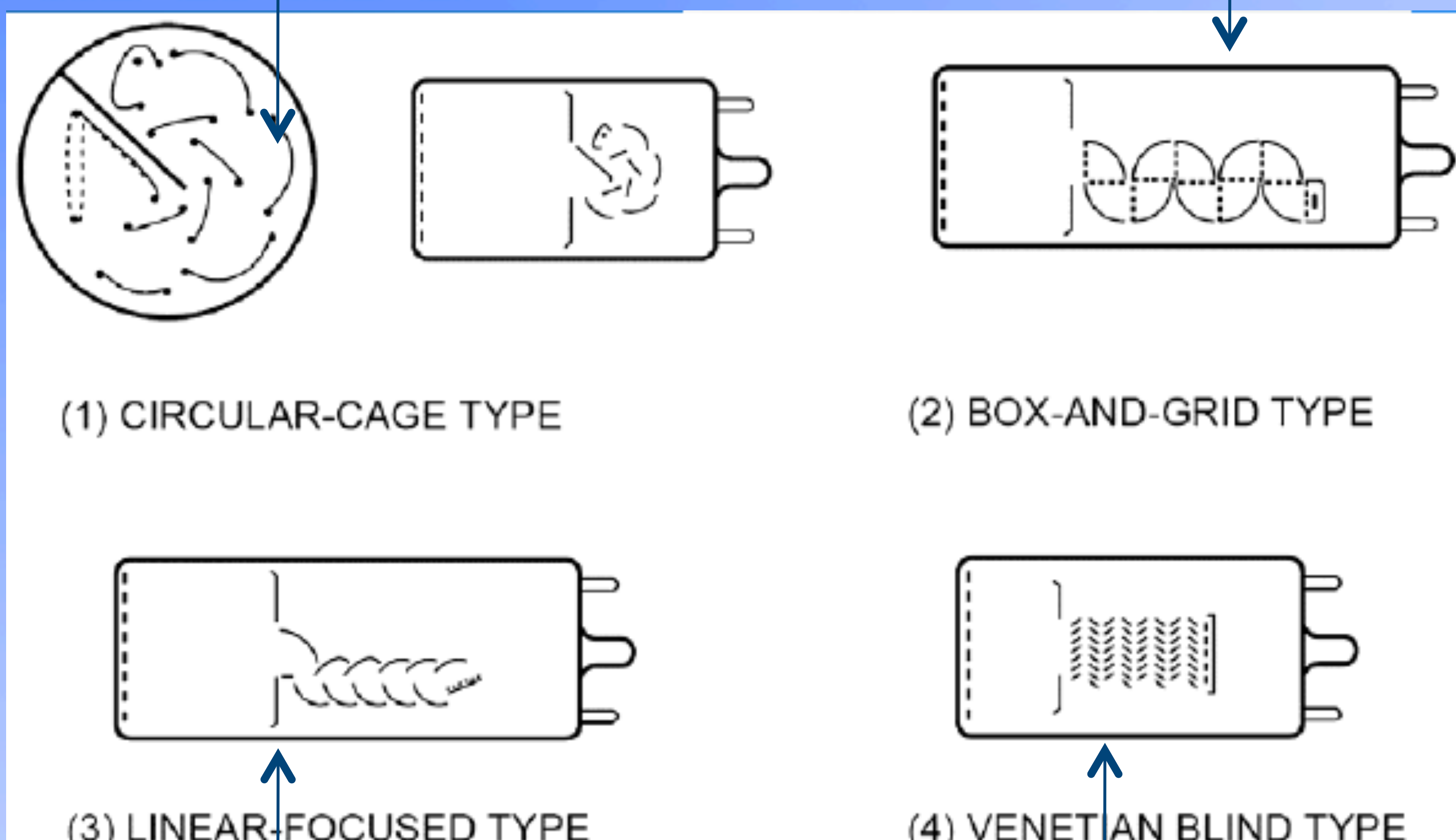
* Simplifying a bit, but this is what dominates.

PMT: Dynode chain designs

Numerous designs, such as:

Circular-cage:
very compact

Box-and-Grid:
Good CE
Slow



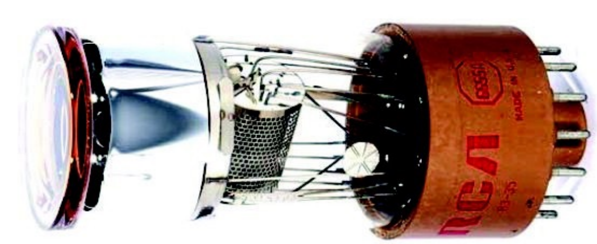
Linear-focused:
Small TTS, fast,
Sensitive to magnetic field

Venetian-blind:
Good CE, Gain stability,
Slow

HAMAMATSU

PMTs are sensitive to magnetic fields (even Earth's ambient B-field, let alone high fields from detector magnets)

=> Magnetic shielding required.



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PMT: Energy resolution

Energy resolution influenced by:

- **Number of photoelectrons** (Poisson statistics):

$$P(n_{\rm obs}, n_{\rm exp}) = \frac{(n_{\rm exp})^{n_{\rm obs}}\, e^{-n_{\rm exp}}}{(n_{\rm obs})!}$$

$$\sigma = \sqrt{n_{\rm exp}}$$

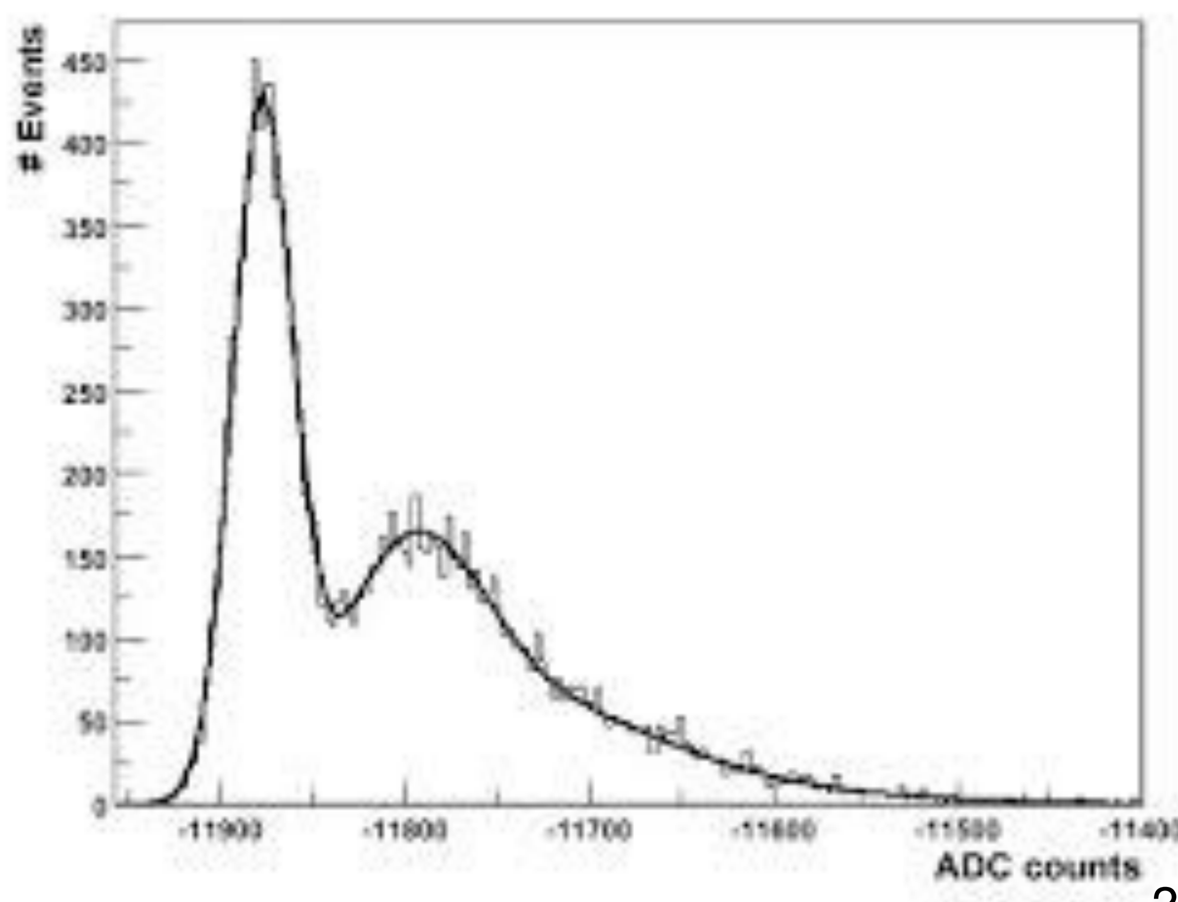
- **PMT linearity:** at high dynode current possible saturation by space charge effect $I_A \propto N_{pe}$ (3 orders of magnitude possible)

Ideal case:

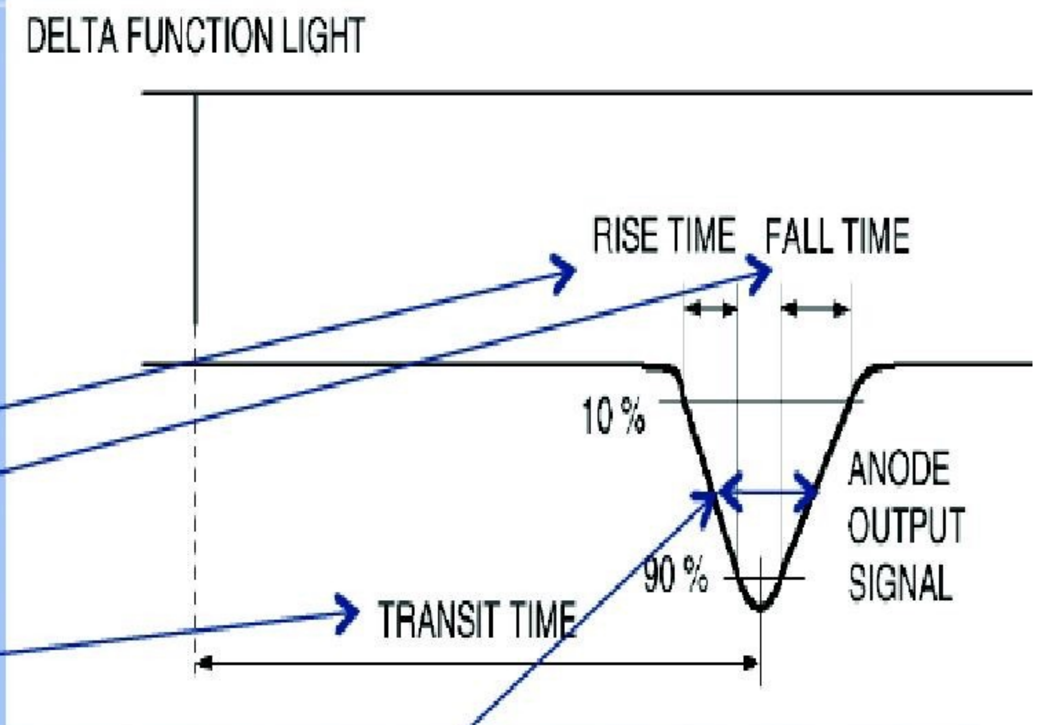
$$\frac{\sigma}{E} = \frac{\sqrt{N_\gamma}}{N_\gamma} = \sqrt{\frac{1}{N_\gamma}}$$

For one photoelectron, related to ENF (excess noise factor) defined earlier:

$$\left(\frac{\sigma}{E}\right)_{1\,\rm pe} = \sqrt{\mathrm{ENF}_{\rm pe} - 1}$$



PMT: Time resolution



Definitions:

- Rise Time (10% to 90%)
- Fall Time
- Electron Transit Time
- Transit Time Spread : FWHM of the distrib. of the TT (TTS) or Transit Time jitter

Unit : ns

Dynode Type	Rise Time	Fall Time	Pulse Width (FWHM)	Electron Transit Time	TTS
Linear-focused	0.7 to 3	1 to 10	1.3 to 5	16 to 50	0.37 to 1.1
Circular-cage	3.4	10	7	31	3.6
Box-and-grid	to 7	25	13 to 20	57 to 70	Less than 10
Venetian blind	to 7	25	25	60	Less than 10
Fine mesh	2.5 to 2.7	4 to 6	5	15	Less than 0.45
Metal channel	0.65 to 1.5	1 to 3	1.5 to 3	4.7 to 8.8	0.4

Table 4-3: Typical time characteristics (2-inch dia. photomultiplier tubes)

PMT: Some sources of noise & distortion

- **Photon shot noise** (Poisson fluctuations in photoelectrons)
  - An electric current is the movement of discrete electric charges (Shot noise). Photoemission and secondary emission lead to statistical fluctuations* => $(\sigma_{noise})^2 = 2\ e\ i_{pk}\ \Delta v$. Noise from secondary emission (dynodes) is negligible.
- **Dark current** (electron shot noise)
  - Even if no signal photons arrive, thermal excitation => electrons are occasionally generated at the cathode or one of the dynodes. They are accelerated and generate a current pulse too.
  - This current is O(30 Hz per square centimetre of cathode area). Small stats => Poisson fluctuations.
- **Johnson Noise** (Electric Resistor Noise)
  - Any resistor just sitting on the table generates a noise voltage across its terminals, which arises from the random thermal motion of electrons within it.
  - $(V_J)^2 = 4\ kB\ R\ T\ \Delta v$, for V_J = RMS magnitude of the noise signal, T = temperature
- **Afterpulses**
  - Residual gas/ions ejected from dynodes could follow electric field to photocathode or a dynode => **afterpulse**, typically 0.1 to 10 μs after the physical pulse.
- **Stability** (PMT ageing)
  - Typically, the gain reduced by factor of 2 after delivered charge of ~300 Coulomb.

* where e is electron charge, i_{pk} is DC current flowing, Δv is bandwidth in Hz over which the noise is considered.

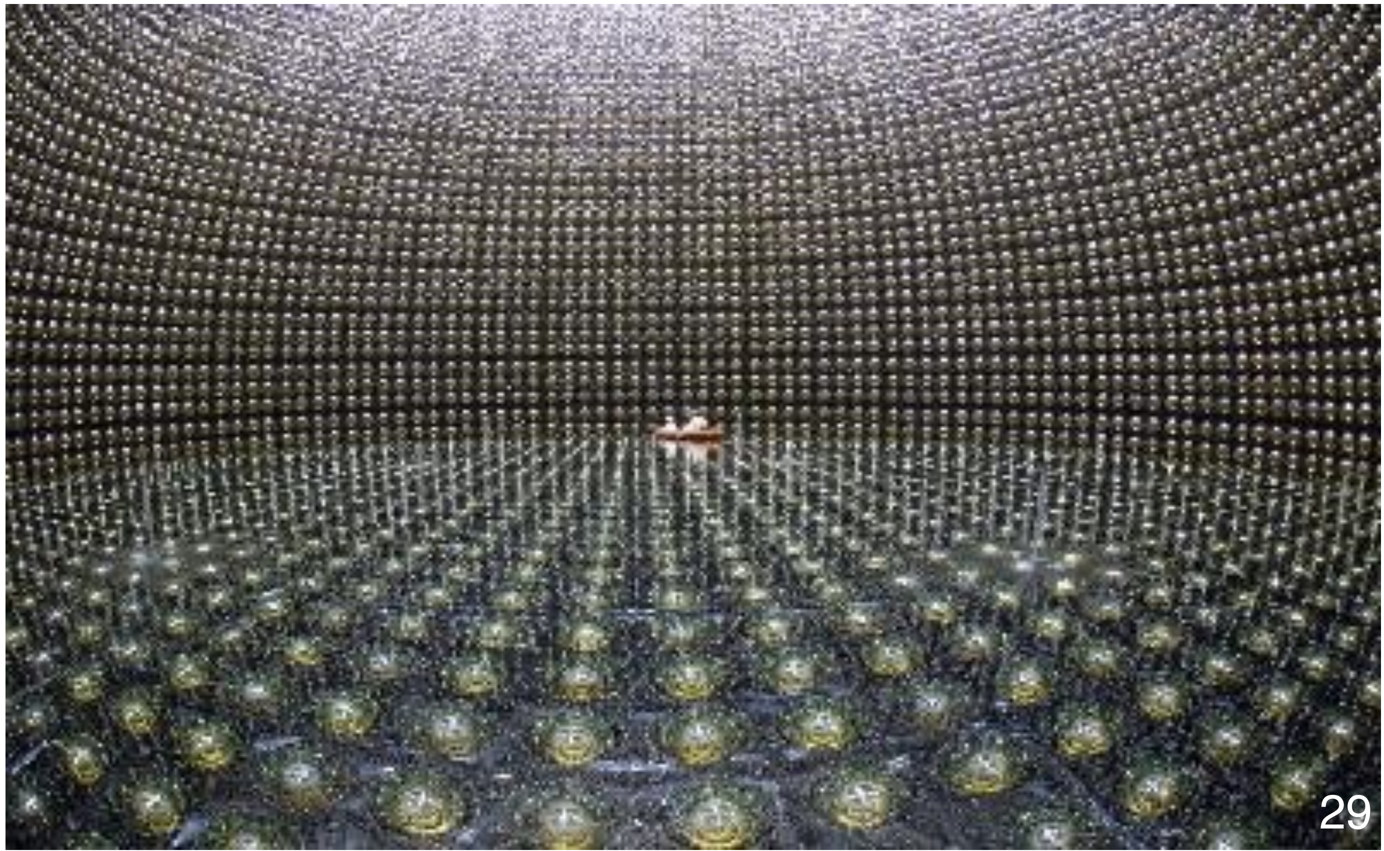
PMT: Summary

Advantages

- Linearity
- Fast
- Sensitive
- Internal amplification
- Low noise
- Price
- Simple to use
- ...

Disadvantages

- Spatial resolution
- Energy resolution
- Quantum efficiency
- Sensitive to magnetic fields
- Size
- ...



Some other examples of photodetectors

See also the semiconductor lectures for silicon-based photodetectors

- CCDs (charge-coupled devices)
- APDs (avalanche photodiodes)
- SiPMs (silicon photomultipliers)

Multi-Anode PMT (MAPMT)

MAPMT: large photomultiplier with complex dynode structure and segmented anode (multi-anode) at the base, usually in a grid.

Many readout channels.

Allows much finer position resolution (~ mm).

Caution:

- photons arriving at an angle.
- magnetic field

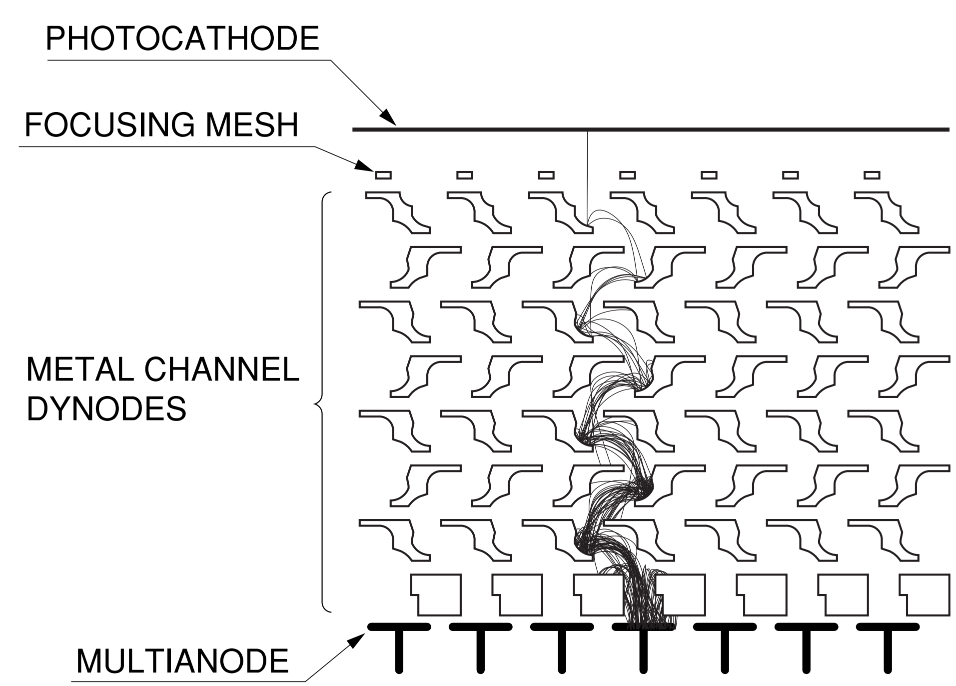
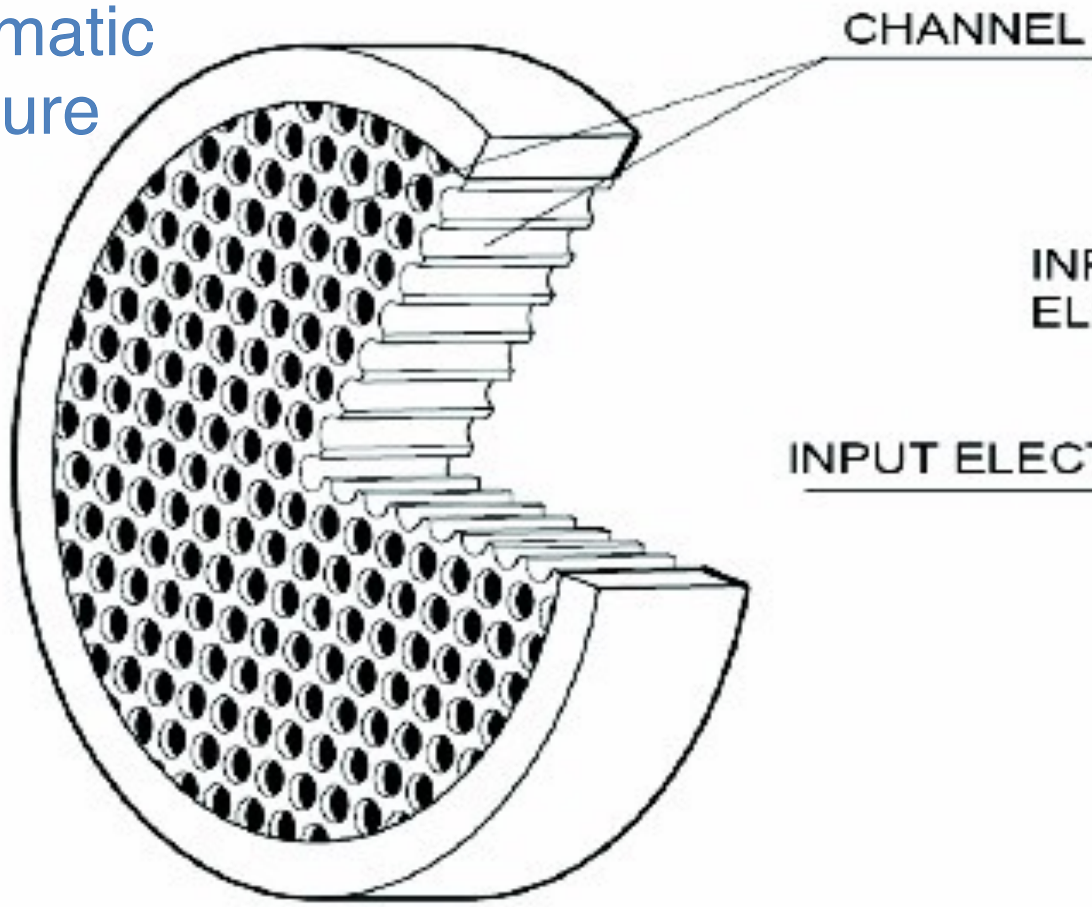


Figure 9-2: Electrode structure and electron trajectories

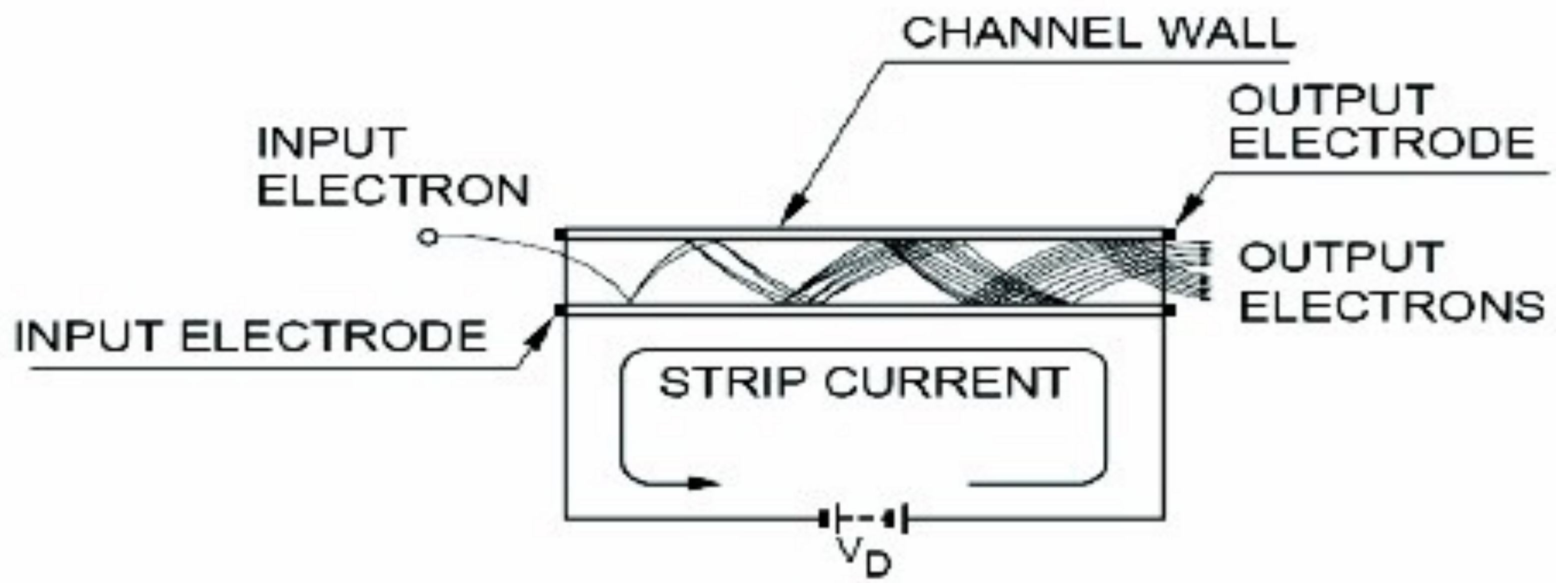
Image: Hamamatsu Photonics

MultiChannel Plates (MCPPMT)

Schematic structure

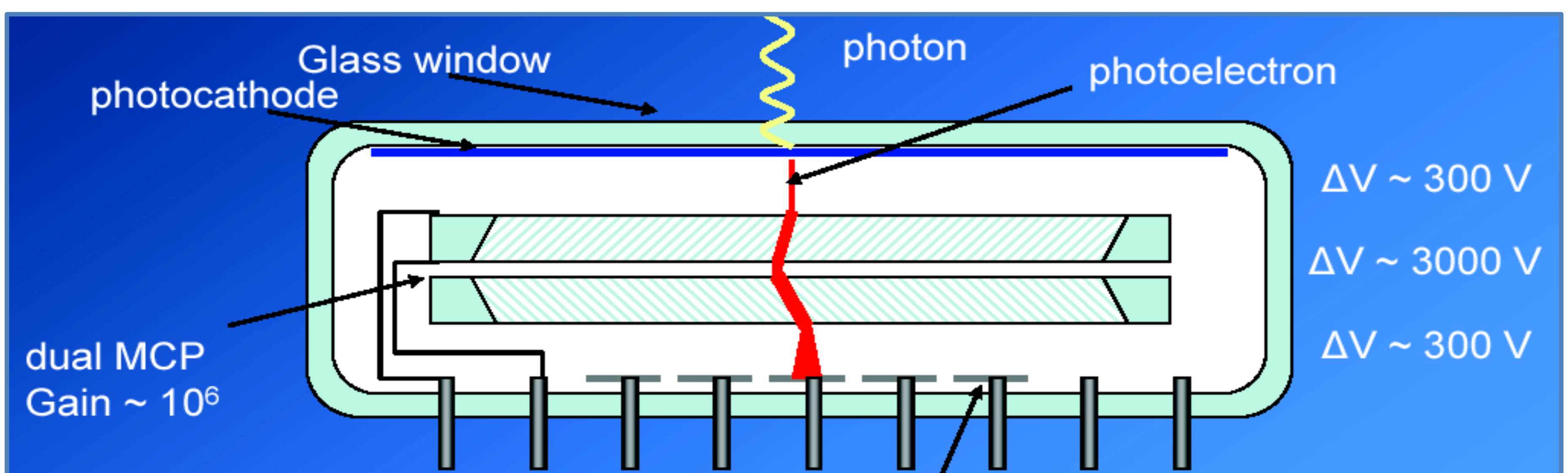


Principle of multiplication



Planacon XP85012 Photonis

- 8x8 (64) anodes
- Pixel size 5.9x5.9 mm²
- Pitch : 6.05 mm
- Effective area = 49x49 mm square
- FF = 80%
- G = 6. 10⁶
- 2 MCP chevron 25 micron pore 40:1 L:D ratio
- PC: Bialkali 24% @ 420 nm
- Pulse Width = 1.8 ns
- Rise Time = 0.6 ns



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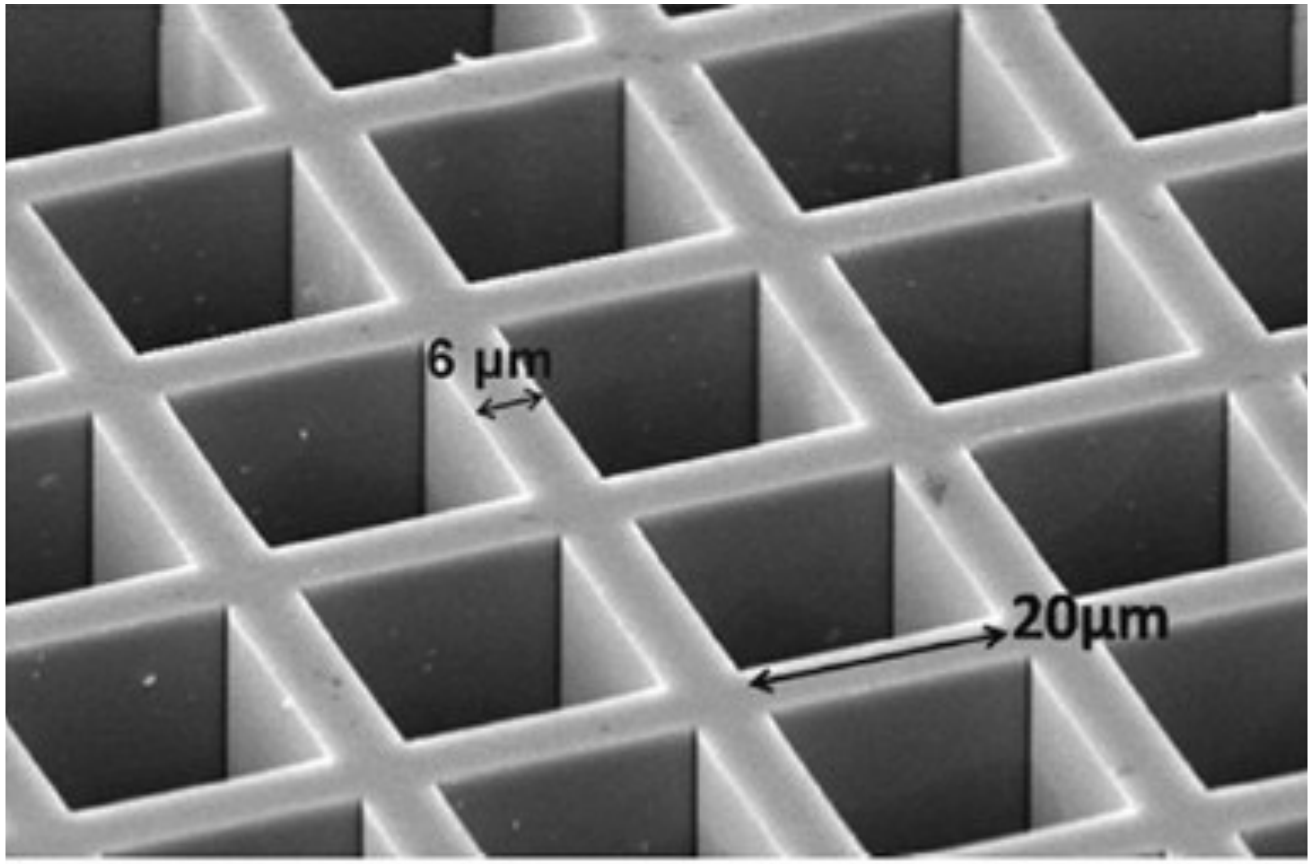
MultiChannel Plates (MCPPMT)

- Gain:
  - Single stage: G ~ 10^3 to 10^4
  - Dual MCP: G ~ 10^6 to 10^7
- Temporal resolution:
  - Ultrafast devices
  - Low transient time ~ 1ns
  - Transient Time Spread ~ 50 ps
  - Sub-ns rise and fall time
  - Example: 30 ps resolution (Hamamatsu R3809)
  - But: needs several kV.

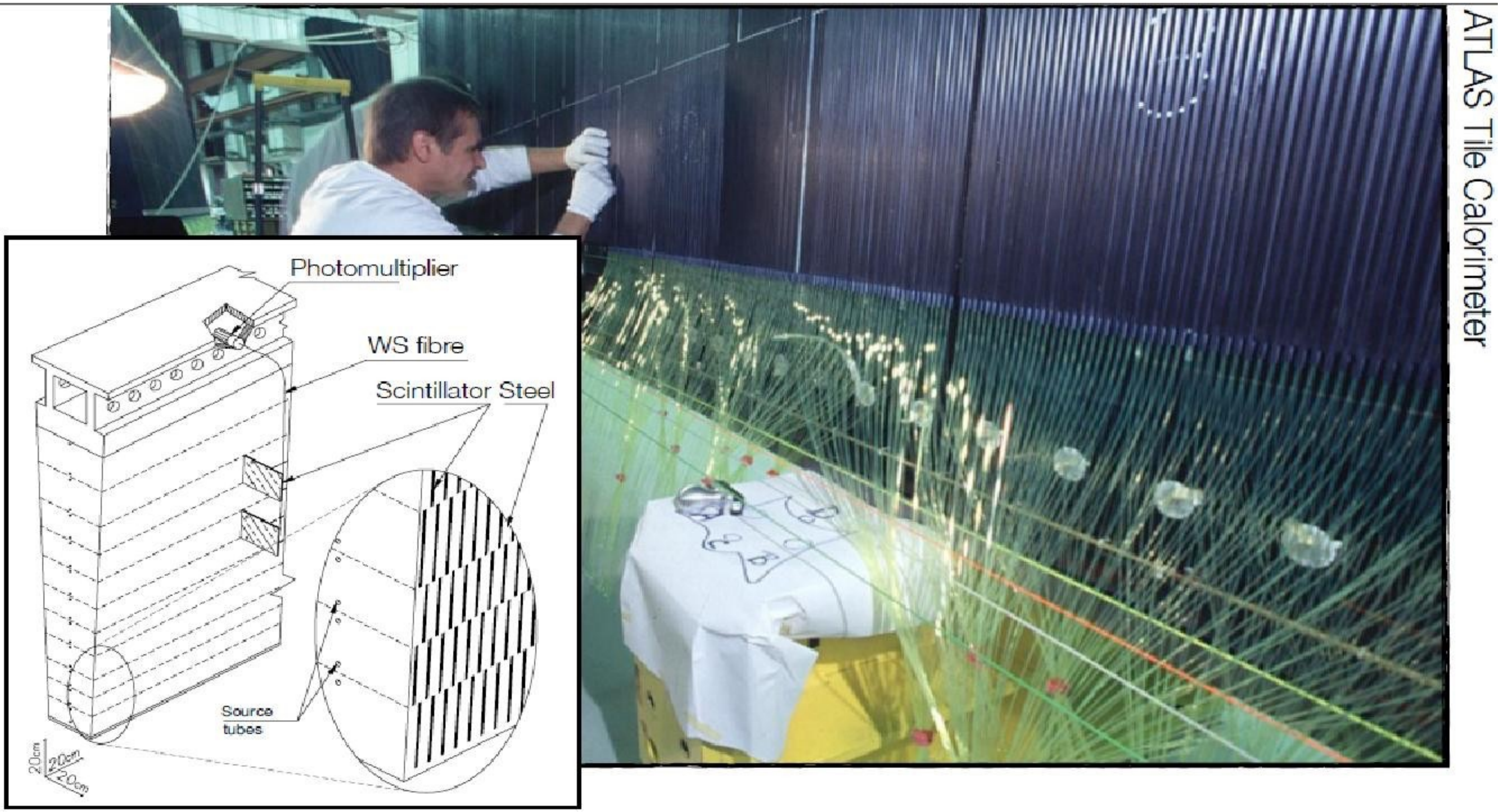


PMTs vs some silicon photomultipliers

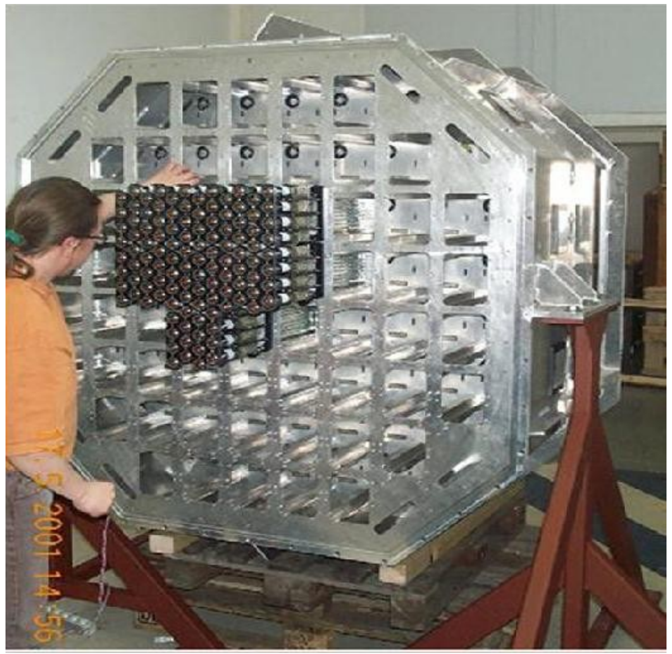
	PIN	APD	PMT	SPM
Gain	1	10^2	10^6	10^6
Operational Bias	Low	High	High	Low**
Temp. Sensitivity	Low	High	Low	Low
Mechanical Robustness	High	Medium	Low	High
Ambient light exposure?	OK	OK	NO	OK
Spectral range	Red	Red	Blue/UV	Green
Readout / Electronics	Complex	Complex	Simple	Simple
Form factor	Compact	Compact	Bulky	Compact
Large area available?	No	No	Yes	Yes
Sensitive to magnetic fields?	Yes*	Yes*	Yes	No
Noise	Low	Medium	Low	High
Rise time	Medium	Slow	Fast	Fast

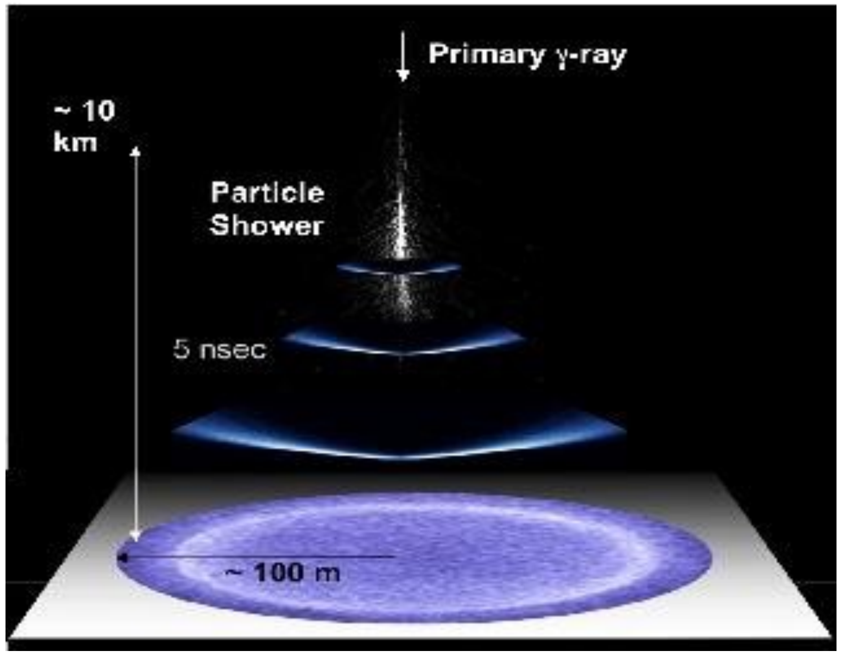
Just for reference -- don't worry about the details now. This will make more sense after the semiconductor detectors lecture.

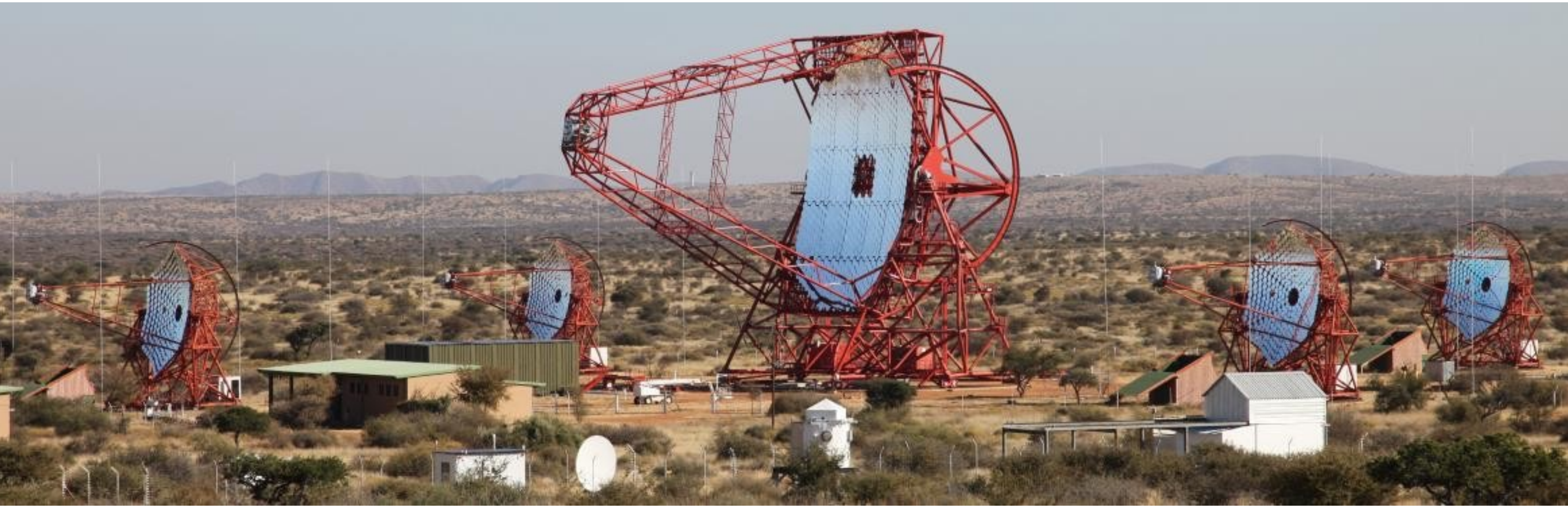
Example: ATLAS tile calorimeter



Example: HESS







Other applications

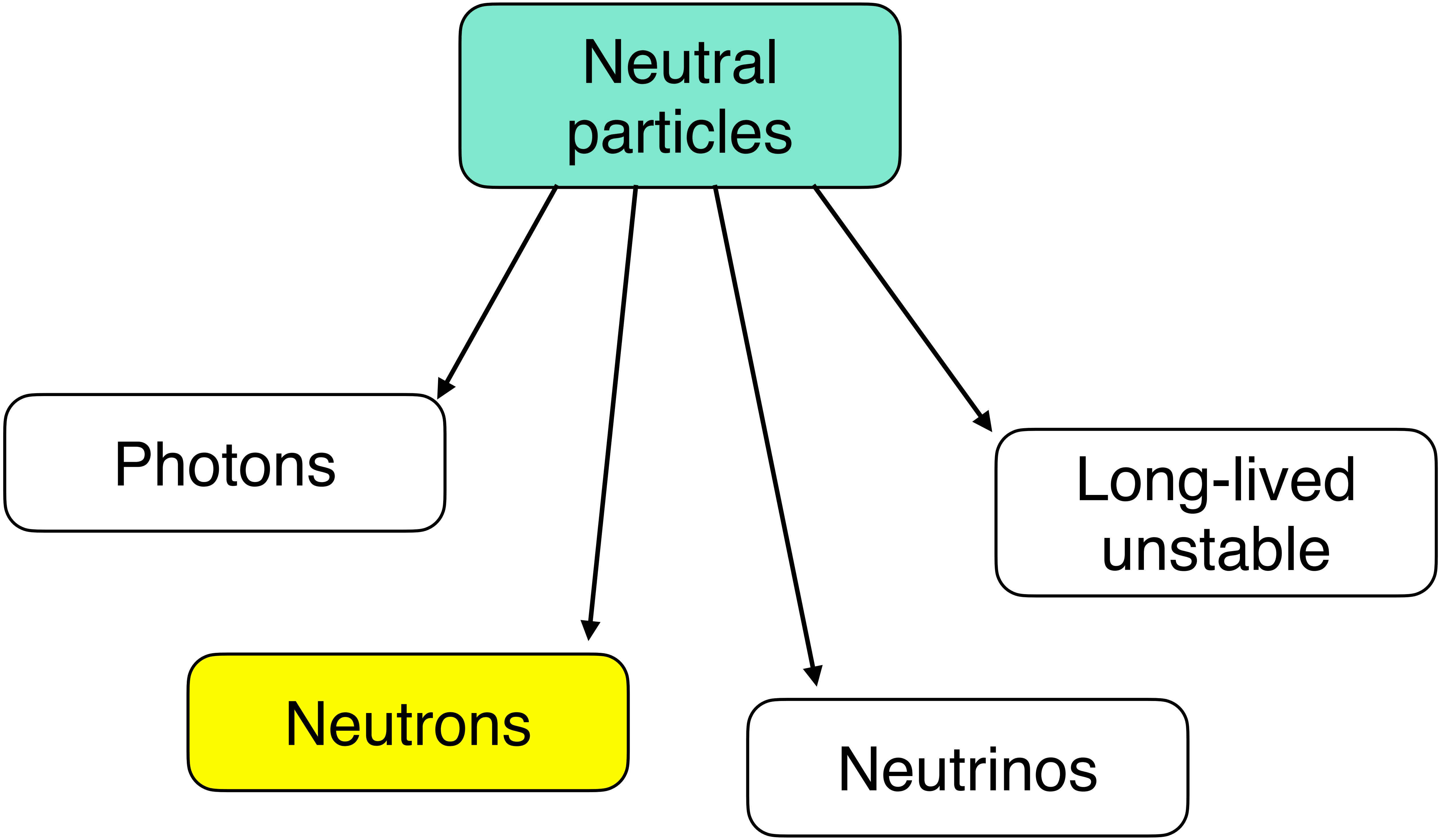
- We've talked about photodetectors for scintillators.
- But there are other HEP use cases for detecting optical photons, especially for:

- Cherenkov detectors (esp. RICH):
  - You'll hear more about these in a later lecture
  - Spatial resolution very important for RICH
  - Time-of-flight detectors need great time resolution

- Cherenkov telescopes

- Optical telescopes & cosmology

Interaction of particles with matter:
Other neutral particles


Neutral particles
Photons
Neutrons
Neutrinos
Long-lived unstable

Neutrons in matter

- Neutrons are neutral (no Coulomb interactions).
  - No pair production either ($n \nrightarrow e^+e^-$, baryon # conservation)
  - Technically some EM interactions via magnetic moment possible, but these are normally negligible.
  - Weak interactions with matter negligible -- see neutrinos!
- What's left? Strong interactions with nucleus.
- Several kinds of strong interaction possible, as we'll see, with cross-sections depending on the energy.
- At particle physics energies where neutrons are relativistic (E_n ~ hundreds of MeV or into the GeV range), a neutron looks basically like any other high-energy hadron and will produce a hadronic shower (see calorimetry lectures).
- Last point: remember that an unbound neutron is slightly unstable and will eventually decay weakly (mean life ~ 15 min)

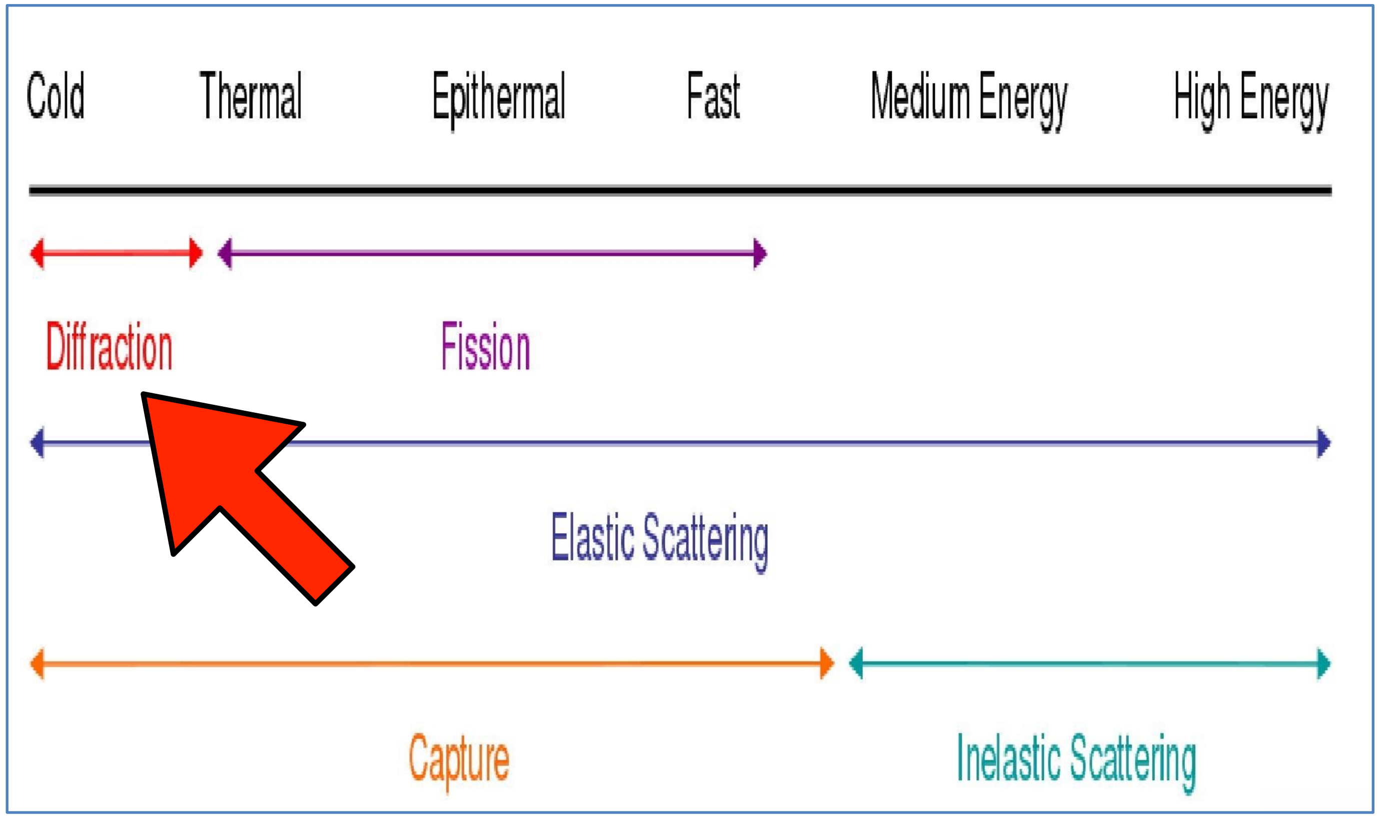
Neutrons in matter

- Useful concept: thermal neutrons have E ~ kT (for T ~ 300K), i.e. in thermal equilibrium with matter (E ~ 0.025 eV).
- Then build up an energy scale in relation to that:
  - Cold/ultracold neutrons (e.g. E < 1 meV) behave quantum mechanically, scatter through diffraction.
  - Thermal neutrons (E ~ 0.025 eV)
  - Epithermal neutrons (roughly 10^{-1} eV to 10^{2} keV)
  - Fast neutrons (roughly 10^{2} keV to 10^{1} MeV)
  - High energy (> 10^{2} MeV)

Caution: ranges not exact

- What kinds of processes are these undergoing?
  - Elastic scattering with nucleus -- at any energy
  - Inelastic scatters in which the neutron transfers energy to nucleus and puts it in an excited state -- typically needs O(MeV) or more
  - Nuclear-capture-based reactions [radiative neutron capture, capture followed by charged particle emission, fission, …] -- cross-sections generally go like 1/v, thermal neutrons favoured.
    - Some of these may proceed via resonances.

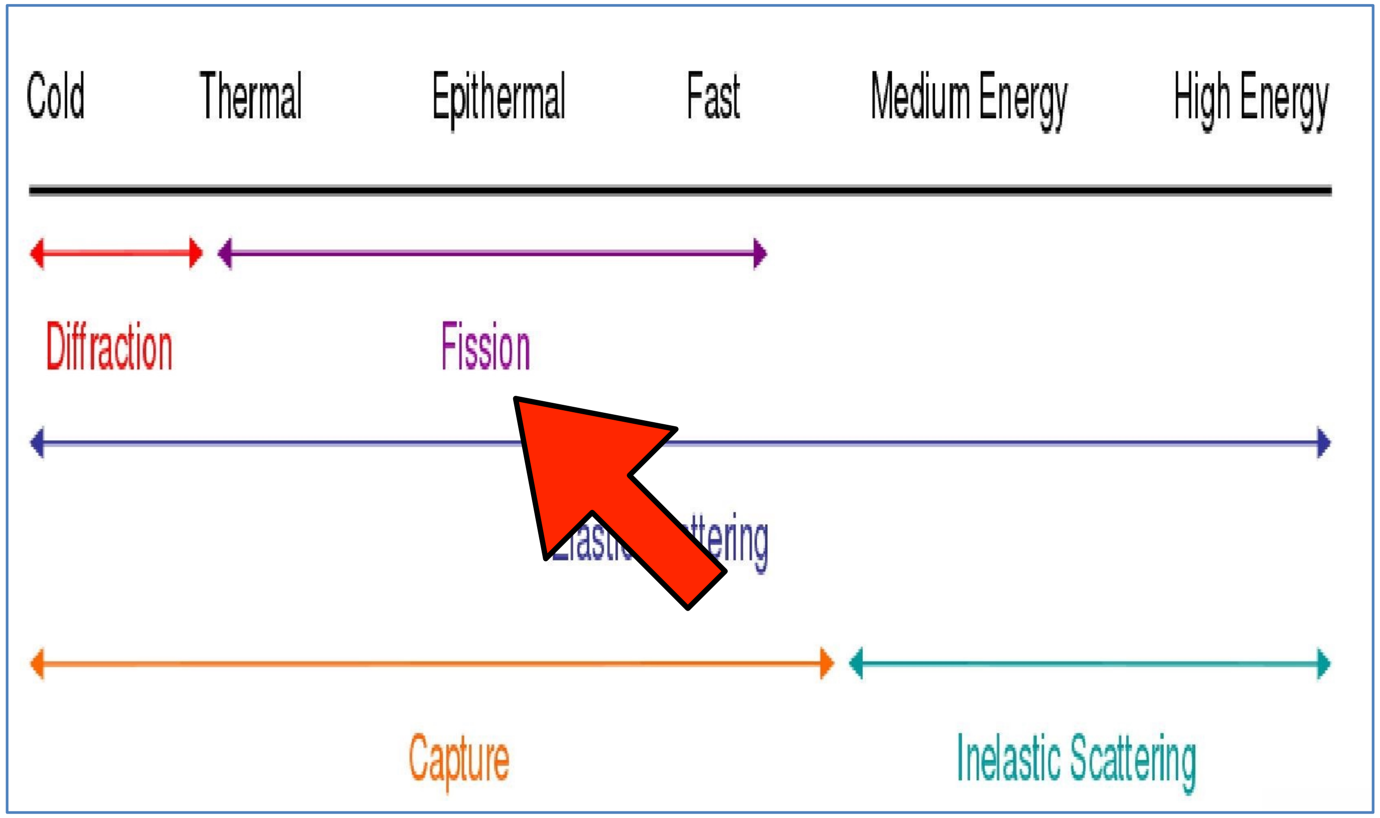
Interaction of neutrons with matter



Diffraction:

Thermal/cold neutrons have wavelengths on the order of crystal lattice spacing, so neutrons could be used as a wave-like probes of matter. They are sensitive to magnetic distributions, not charge distributions

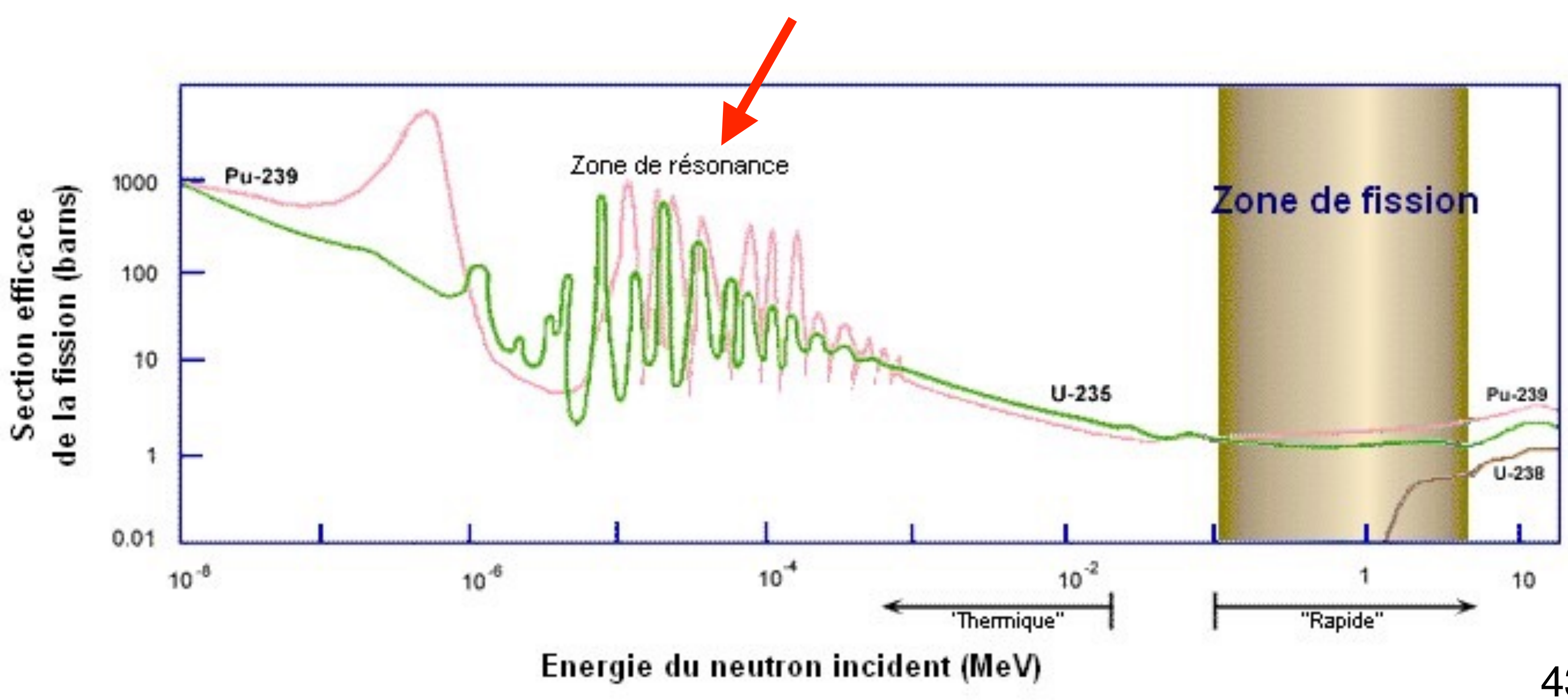
Interaction of neutrons with matter



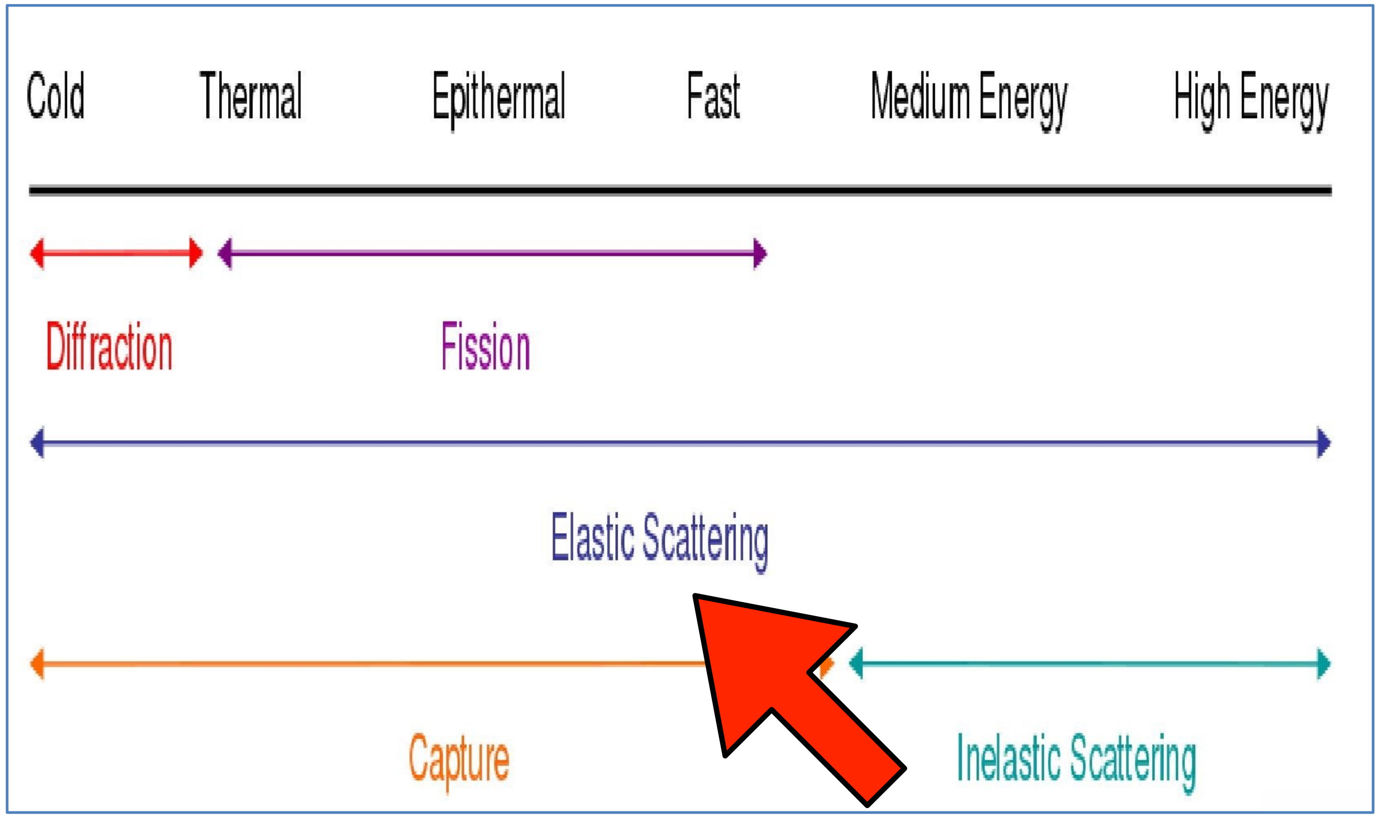
Fission:

- Very strong & rapid energy dependence for neutron-nucleus fission cross-section.
- Strongly affected by (nuclide-specific) resonances.
- Makes calculations of propagation ("transport") of neutrons very difficult

Many heavy nuclei are fissionable but Uranium, Plutonium and Thorium are the most important fissile nuclei in the nuclear fuel cycle. By-products of fission include neutrons, photons and other types of radiation. This leads to the concepts of neutron multiplication and chain reactions.



Interaction of neutrons with matter



Elastic Neutron Nucleus Scattering A(n,n)A:

- Energy and direction of neutron altered per collisions
- Dominant energy loss process at intermediate to high (nuclear) energies
- Process responsible for neutron moderation (slowing down)
- Energy loss depends strongly on A (next slide...)

Neutron energy loss by elastic scattering

- At nonrelativistic energies (e.g. few MeV and below), neutron-nucleus scatter becomes a simple classical two-body problem.
- Can further simplify problem by taking m(nucleus) ≈ A × m(neutron)
- See Leo 2.8.1 for derivation, but key points are:
- Post-scatter neutron energy E falls into a limited range:

  $$\left(\frac{A-1}{A+1}\right)^2 E_0 < E < E_0$$

  ... so the lighter the nucleus, the more energy the neutron can lose (limiting case: all of its energy for *pn* scatter, A=1)
  ... and the neutron energy distribution in this range is uniform.
- Consequence: **on average,** E is reduced by a factor after each collision and that factor is constant, independent of energy and depending only on A.

  [obviously applies only to neutrons with energy > thermal]

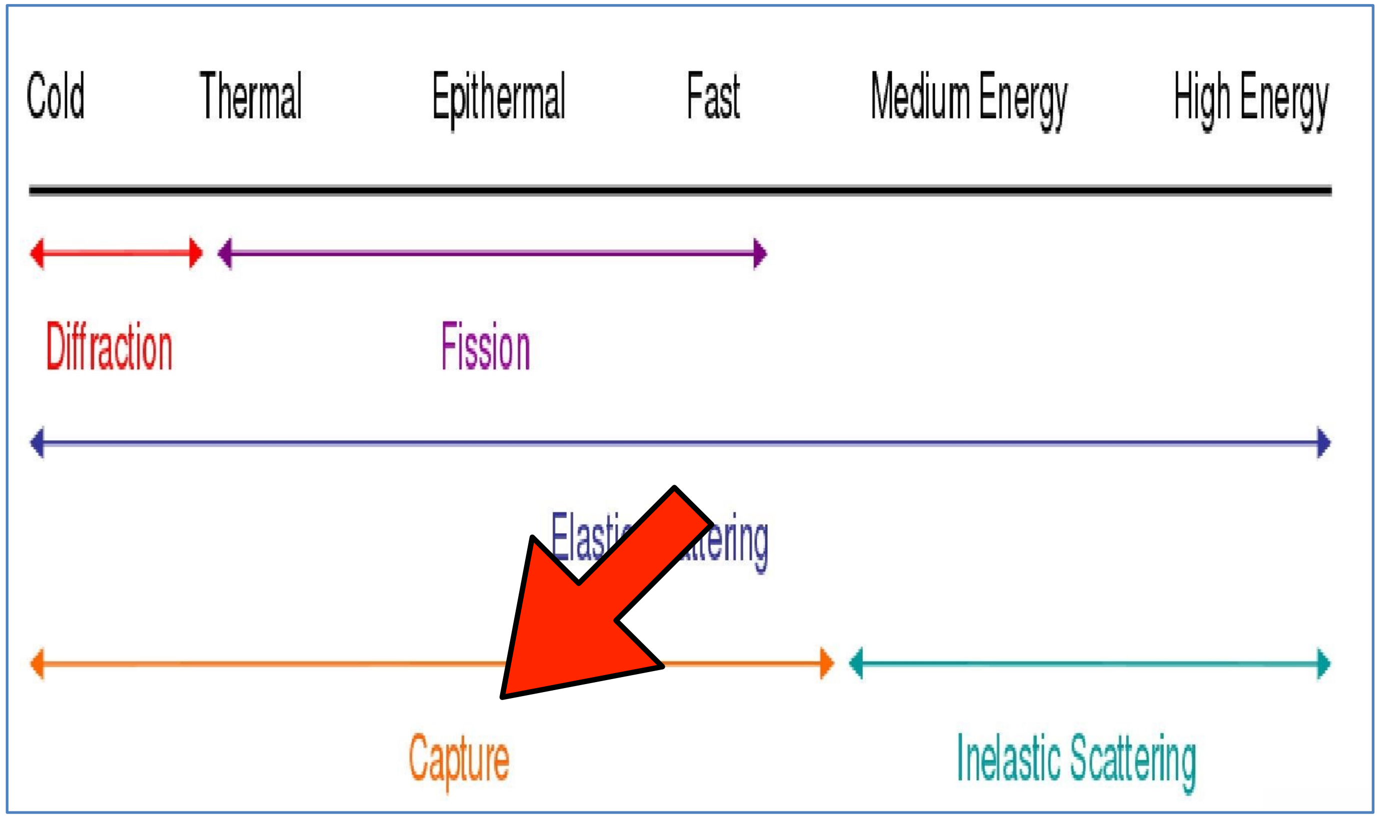
Neutron energy loss by elastic scattering

- Since energy loses a set factor [on average] after each collision, useful to work with $\ln(E_0/E)$, which will step up by a constant [on average] after each collision -- jargon: "lethargy".
- This constant (for a single collision) looks like

$$\xi = \left\langle \ln\left(\frac{E_0}{E}\right) \right\rangle = 1 + \frac{(A-1)^2}{2A} \ln\left(\frac{A-1}{A+1}\right)$$

- Again, note that it depends on A but not on energy -- and that energy drops by a bigger factor for low-A material.
- So a neutron will take an average of $\ln(E_0/E)/\xi$ collisions to reduce its energy from E_0 to E.
  - Neutrons thermalise faster in material with lots of light nuclei, e.g. water or paraffin, than in heavy material like lead.
- Example (Leo): to thermalise a 1 MeV neutron down to 0.025 eV takes on average 111 collisions in C-12:
  - $\xi(A=12) = 0.158$; $\ln(E_0/E) = \ln(1\text{ MeV} / 0.025\text{ eV}) = 17.5$
  - number of collisions = $\ln(E_0/E)/\xi = 17.5 / 0.158 \sim 111$

Interaction of neutrons with matter



Radiative capture $A(n,\gamma)A^*$:

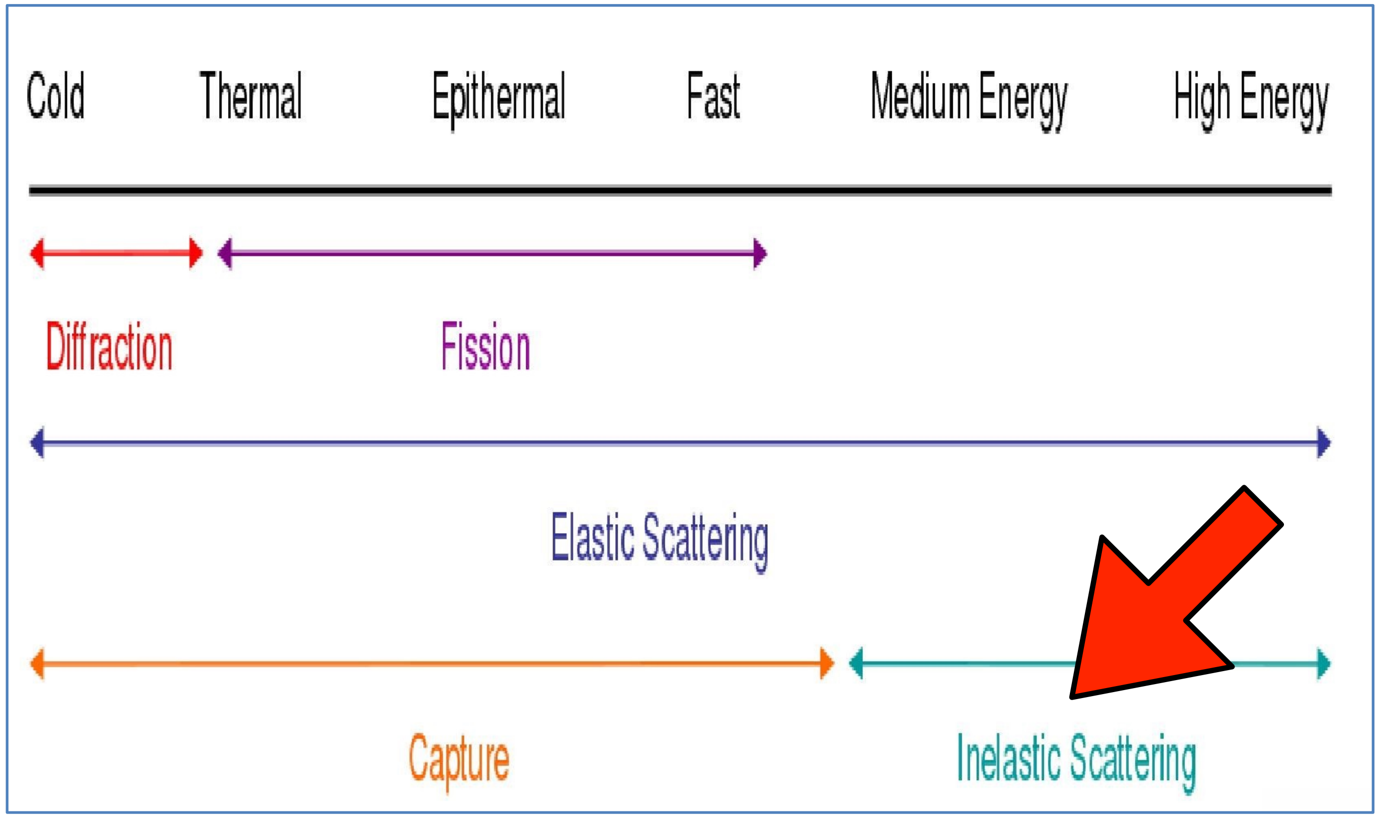
Nucleus absorbs the neutron, finds itself in an excited state. Emits a photon promptly to get to a stable/metastable state. New isotope might itself decay later by beta emission.

Very important in radiation protection and reactor physics: certain nuclei have very large capture cross sections (resonances) at low energies. So neutron shielding usually includes (1) a material to slow down neutrons, and (2) a material to absorb the slow neutrons.

Important capture nuclei include Boron, Cadmium and Gadolinium.

Other neutron capture processes exist, such as with proton or alpha emission.

Interaction of neutrons with matter



Inelastic scattering A(n,n')A*:

The neutron scatters off the nucleus, bumping it up into an excited state when then decays by emitting additional particle(s). Only significant for neutrons with $\gtrsim$ 1 MeV of energy.

The scattered neutrons typically lose a large fraction of their initial energy.

Interaction of neutrons with matter: Summary

Small EM couplings => neutrons interact much less frequently than charged particles, photons.

Interactions dominated by collisions with nuclei: scattering, capture, or fission.

Calculation/modelling of neutron interactions in matter is complicated.

Shielding for neutrons: also complicated!

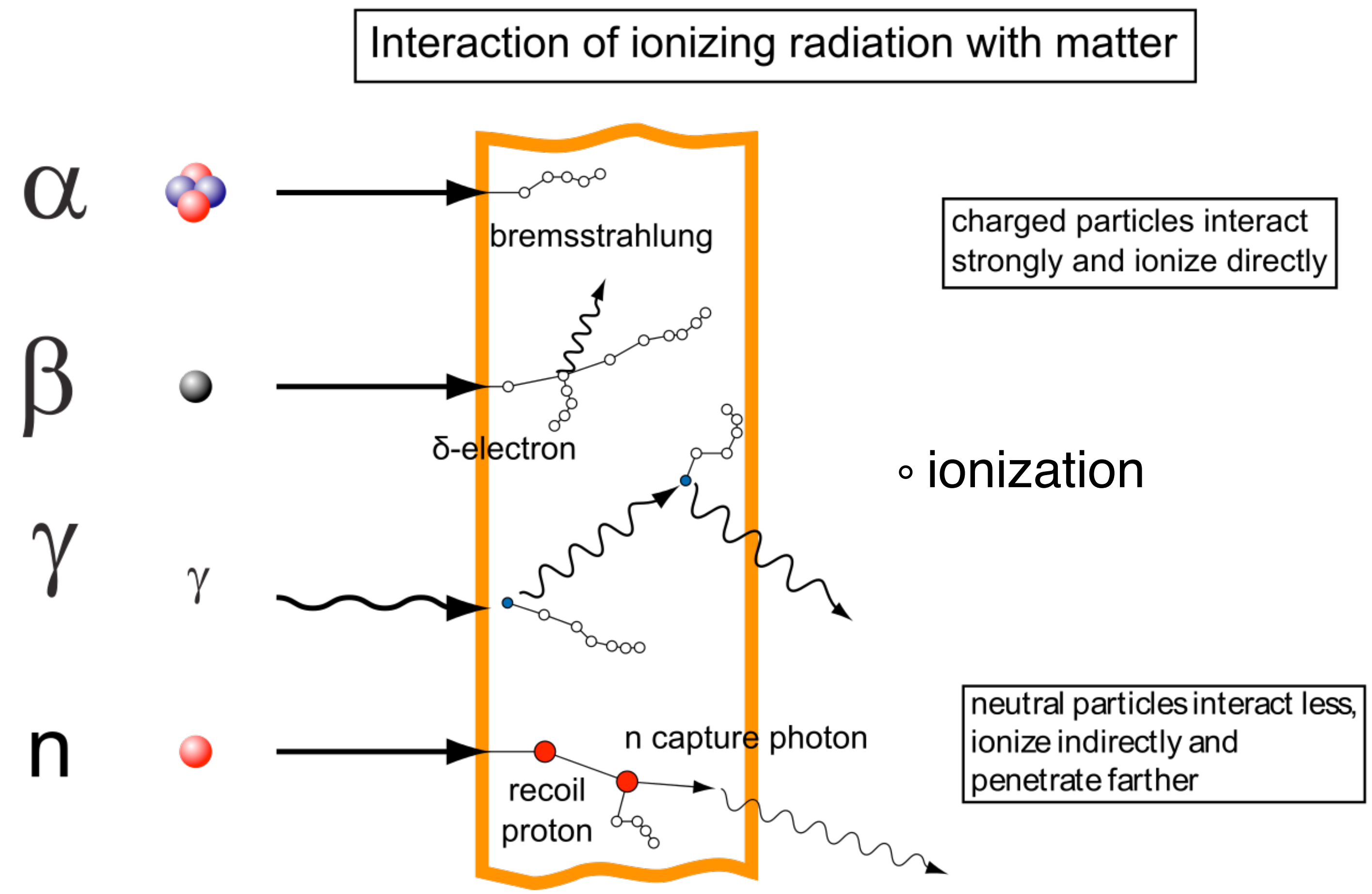
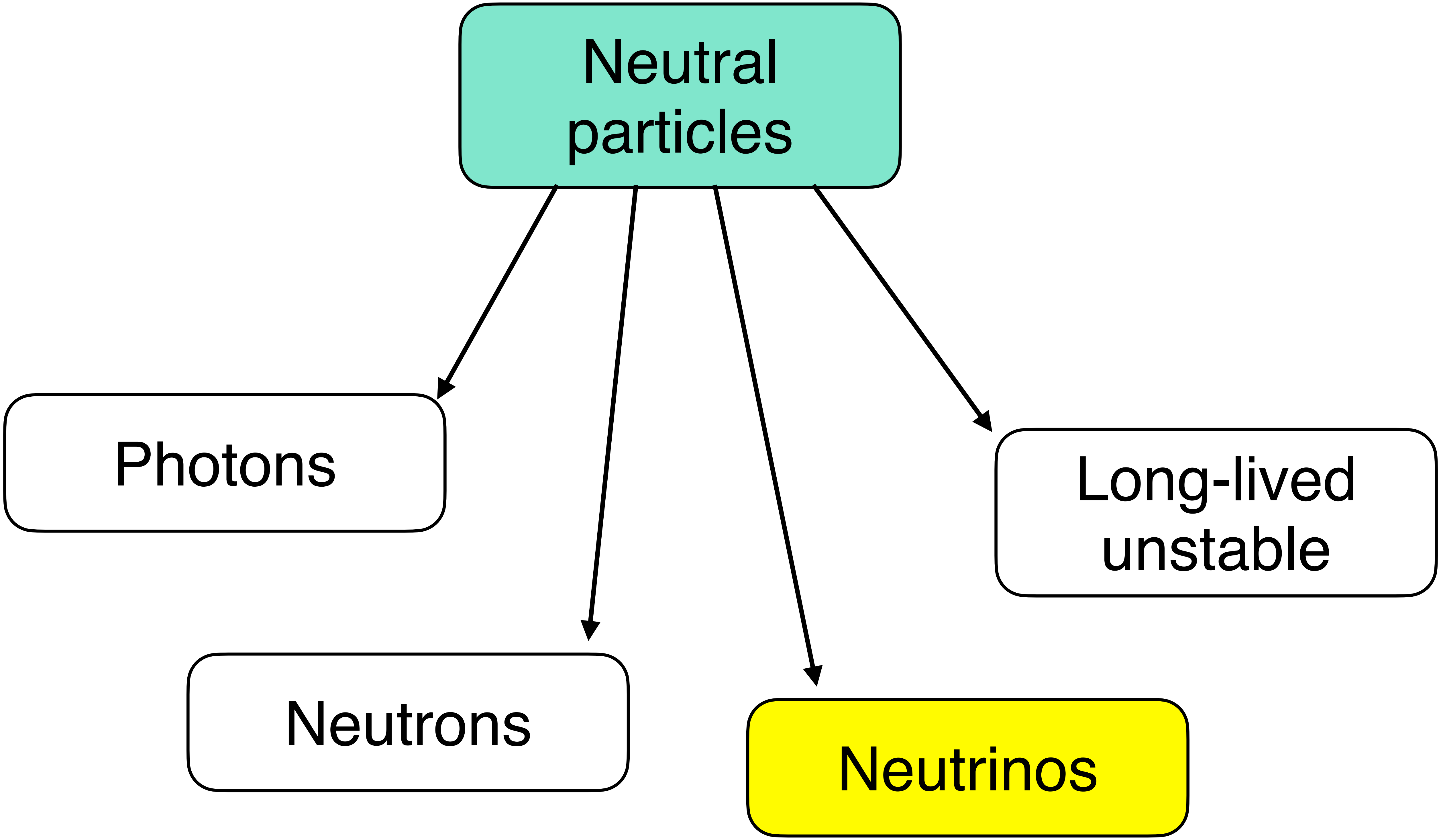


Image source: Wikipedia

Aside: qualitatively similar for long-lived neutral hadrons, e.g. K_L ($c\tau$=15m), though with fewer interaction mechanisms possible.

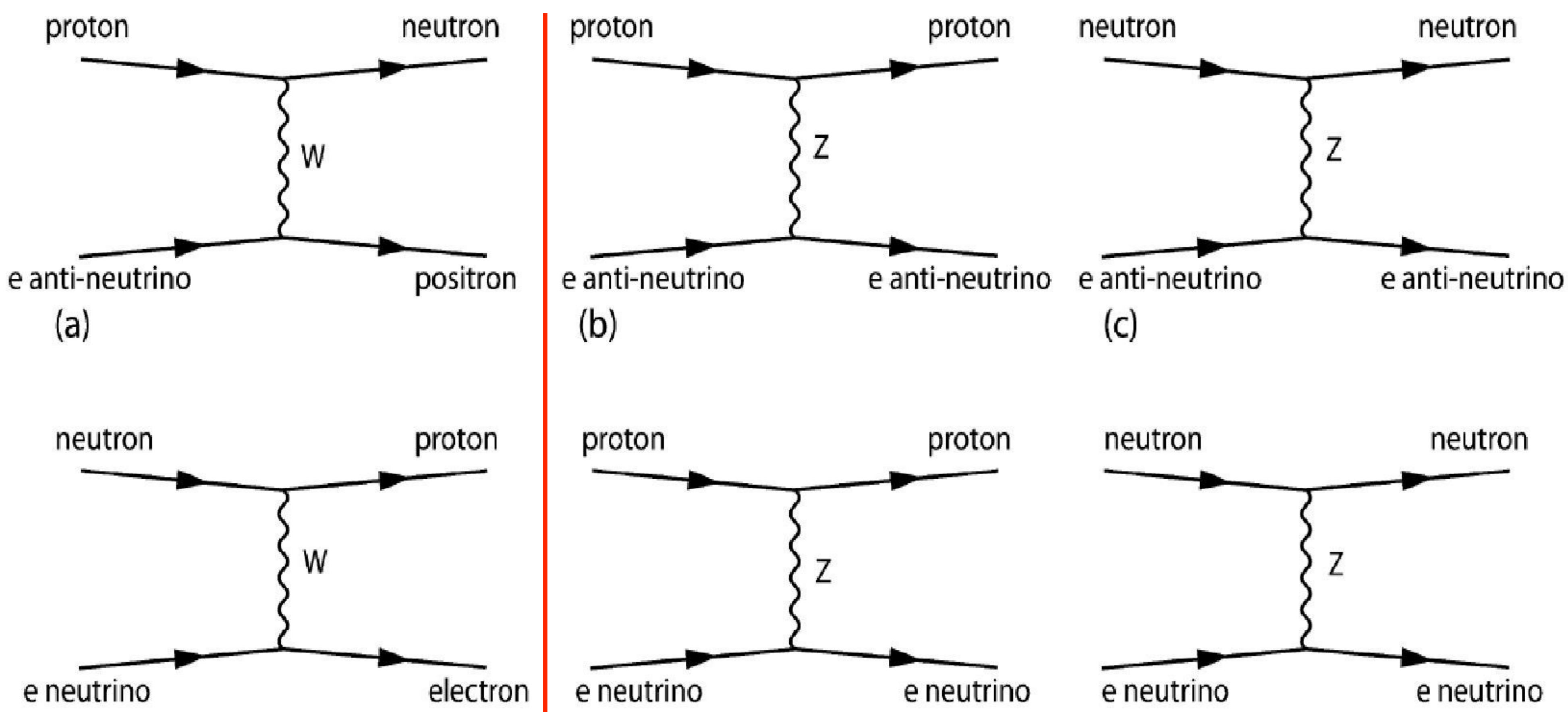

Neutral particles
Photons
Neutrons
Neutrinos
Long-lived unstable

Interaction of neutrinos

- Neither EM nor strong charge, only weak => very low x-sec, O(10^{-40} cm^2)
- Corresponds to mean free path in normal matter ~ several thousand km!
- e.g. interaction x-sec with a proton when well above energy threshold:

$$\sigma(\nu p) = E_v \times \left(6.7 \times 10^{-42}\ \mathrm{cm}^2\,\mathrm{MeV}^{-1}\right)$$

- Different interactions possible according to neutrino flavour (e/μ/τ; $\nu/\bar{\nu}$)
- Must distinguish from backgrounds [typically more abundant] (cosmic rays, radiation from outside & inside detector)

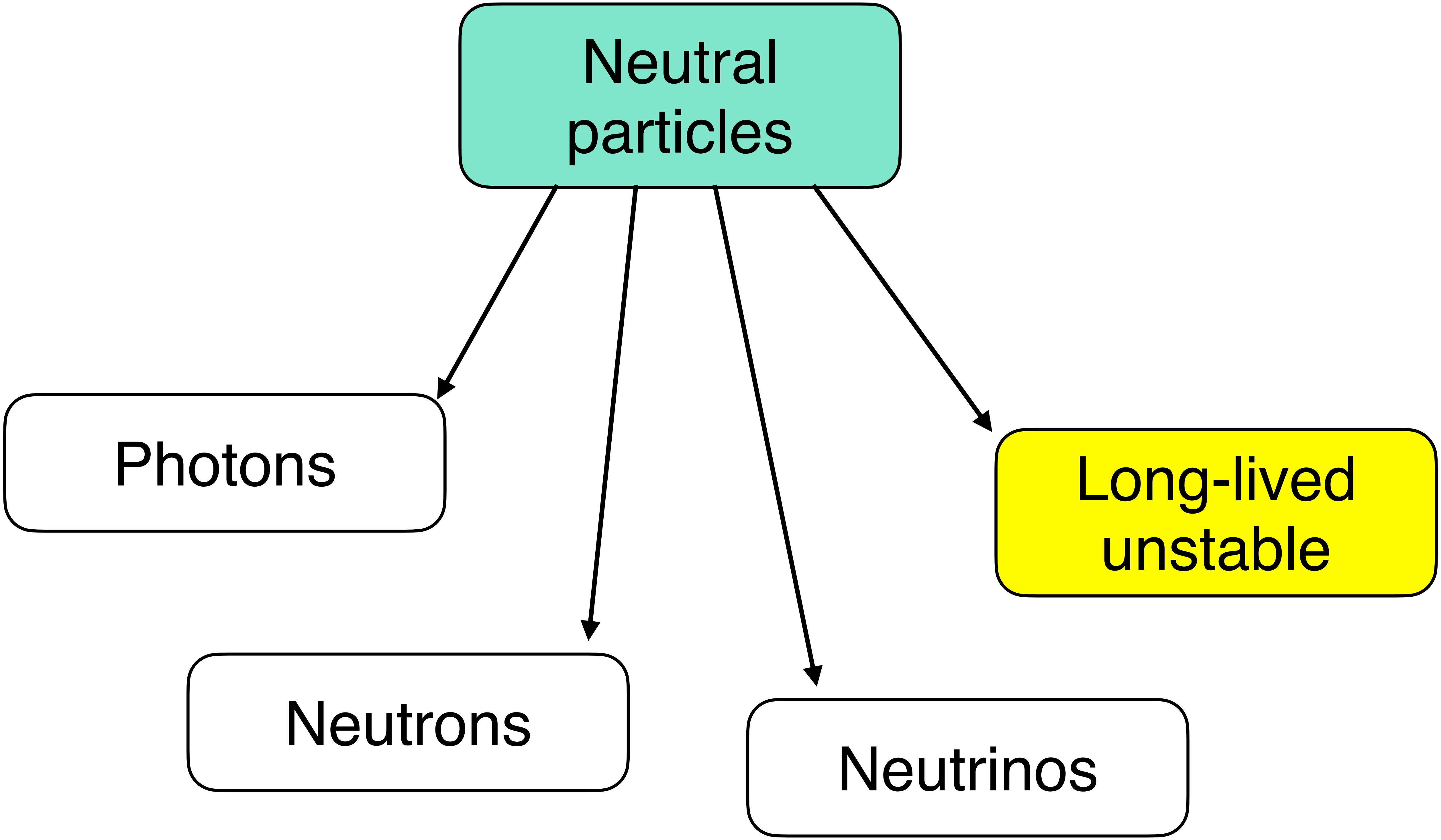


Charged Current (CC) | Neutral Current (CC)

Interaction of neutrinos

- Note that neutral-current interactions are universal (same for all flavours of neutrino and anti-neutrino), but charged-current interactions are not.
  - W-exchange with nucleon: must have enough energy to produce on-shell e/mu/tau
  - W-exchange with electron: same, and only valid for ν (not $\bar{\nu}$)
  - W-annihilation with electron: only valid for $\bar{\nu}_e$

- Neutrino oscillations in matter also important (and a very active subject of research), but way out of scope for detector physics lectures!

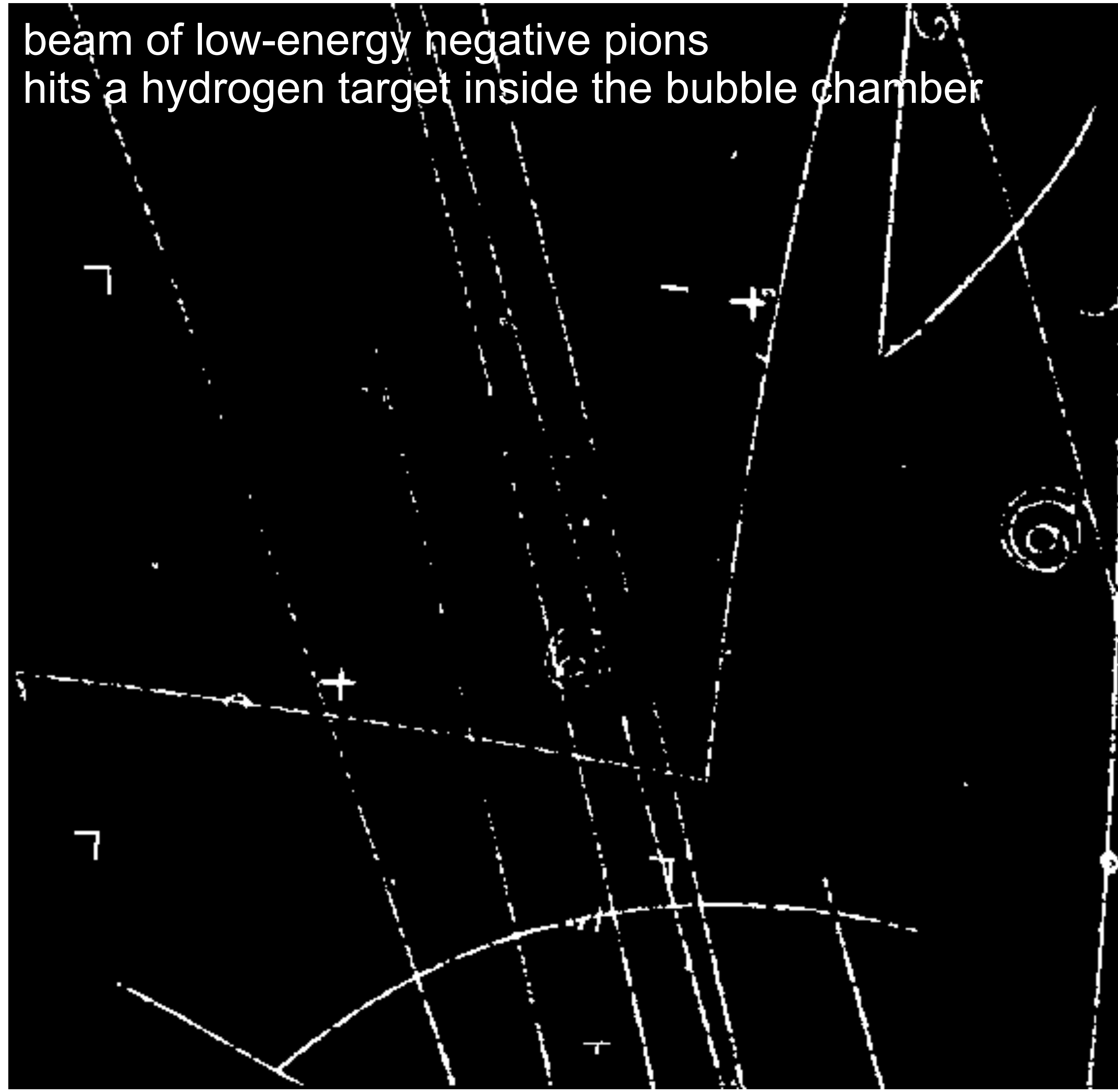

Neutral particles
Photons
Neutrons
Neutrinos
Long-lived unstable

Long-lived unstable

... i.e. things like K_S, Λ^0 with lifetimes long enough to fly through part of the tracker, but short enough to decay inside the detector.

No track (since they don't ionize) -- we don't detect them directly, but instead look for their decay products (vertex reconstruction, track identification)

Might interact with detector material and/or live long enough to reach calorimeter.



Long-lived unstable

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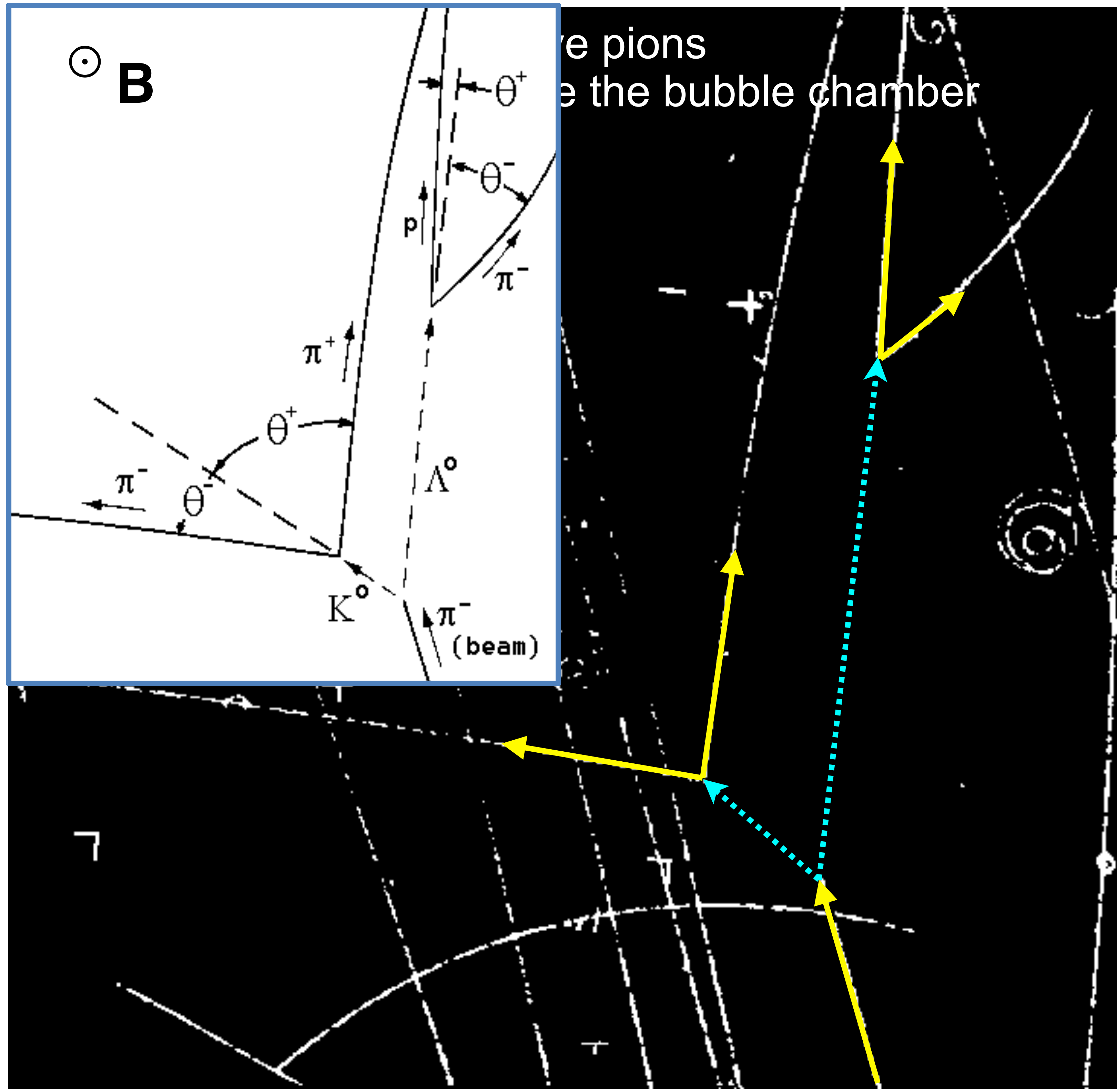
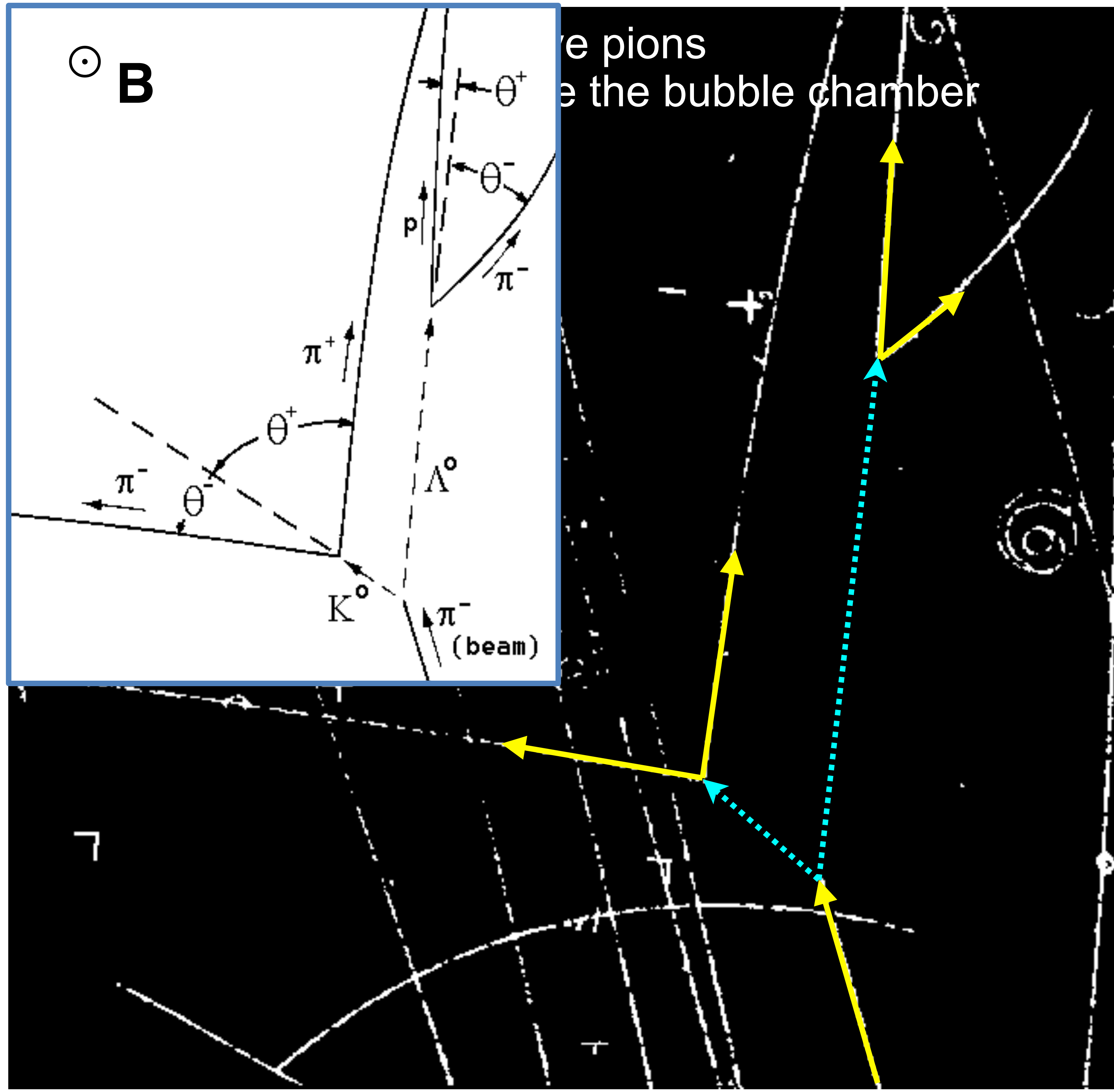
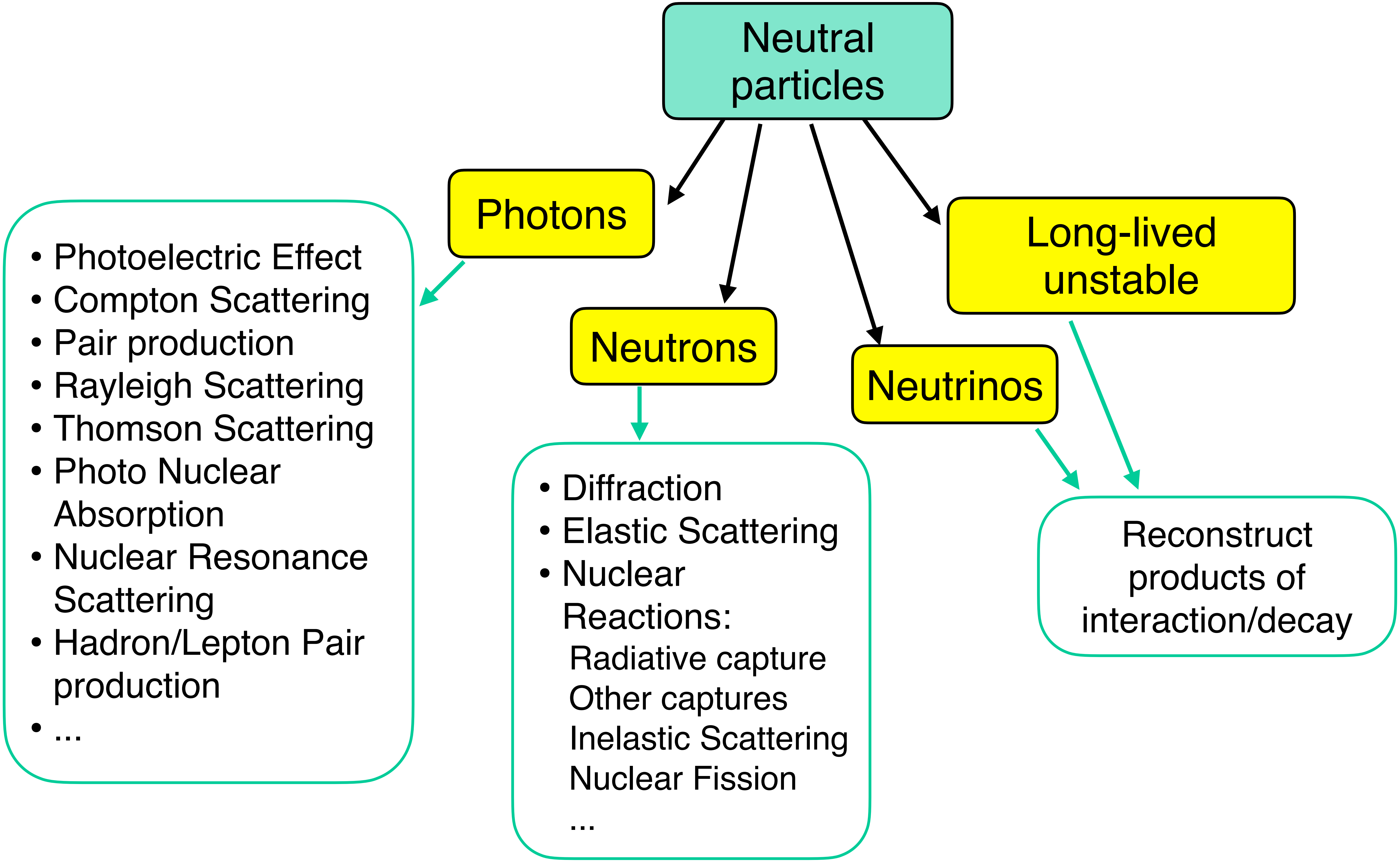


Long-lived unstable

Discussion point: Which quantities do you need to reconstruct the Λ^0 and K^0 masses?

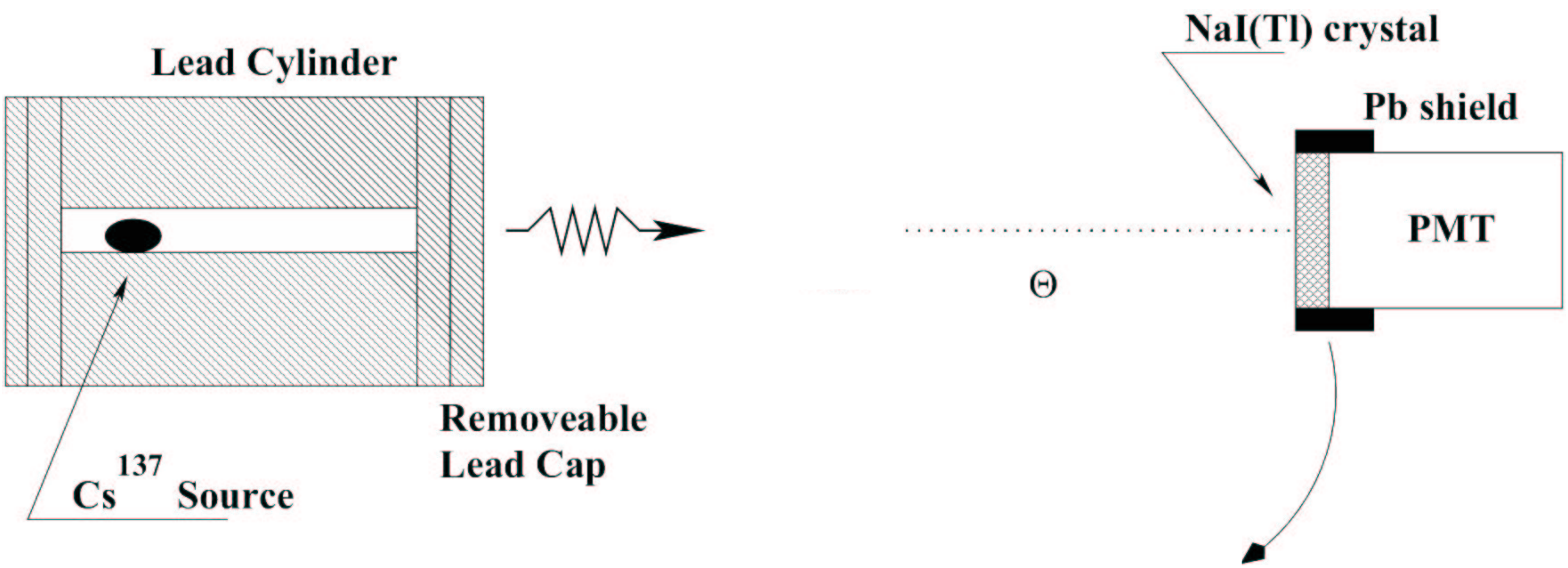


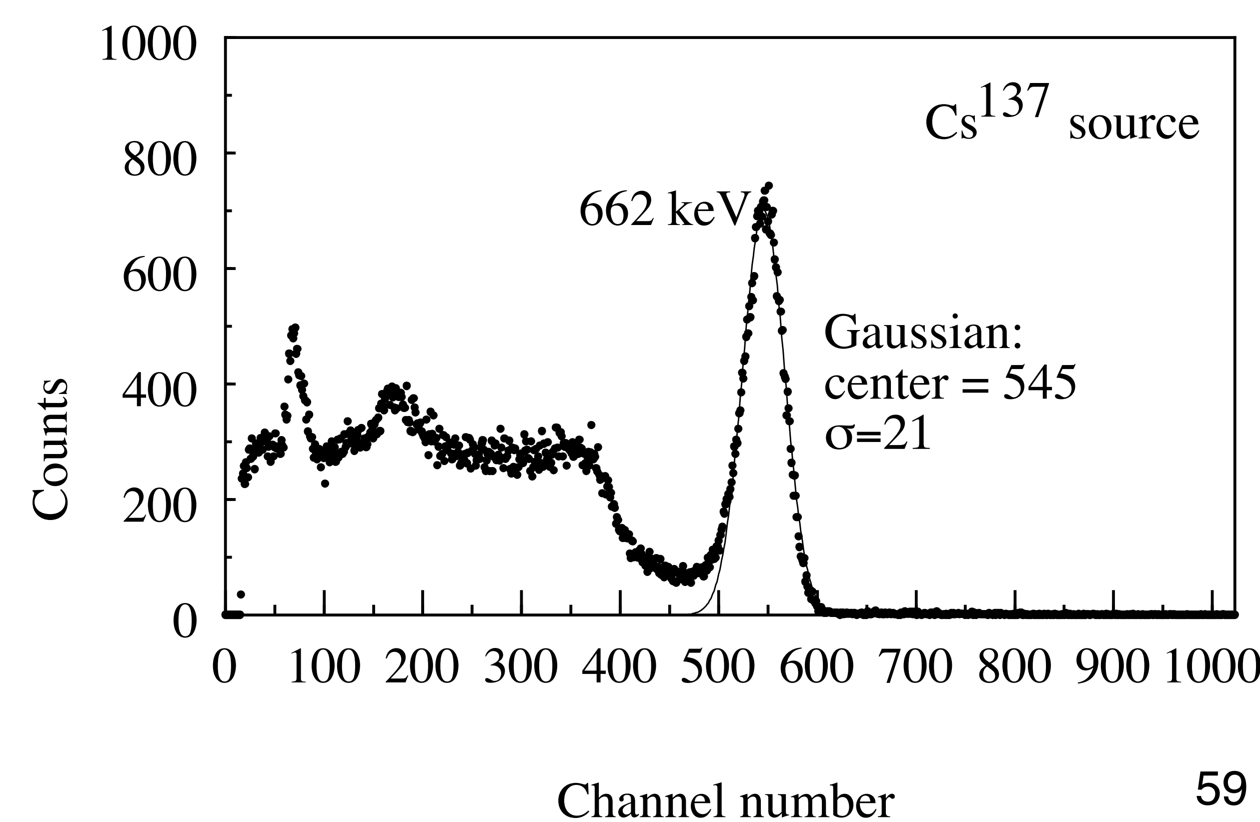

Neutral particles
Photons
Neutrons
Neutrinos
Long-lived unstable
• Photoelectric Effect
• Compton Scattering
• Pair production
• Rayleigh Scattering
• Thomson Scattering
• Photo Nuclear Absorption
• Nuclear Resonance Scattering
• Hadron/Lepton Pair production
• ...
• Diffraction
• Elastic Scattering
• Nuclear Reactions:
Radiative capture
Other captures
Inelastic Scattering
Nuclear Fission
...
Reconstruct products of interaction/decay

Some exercises

Exercise 0

Here is an example experimental set-up and energy spectrum [images from a U. Wisconsin TP, slightly modified]





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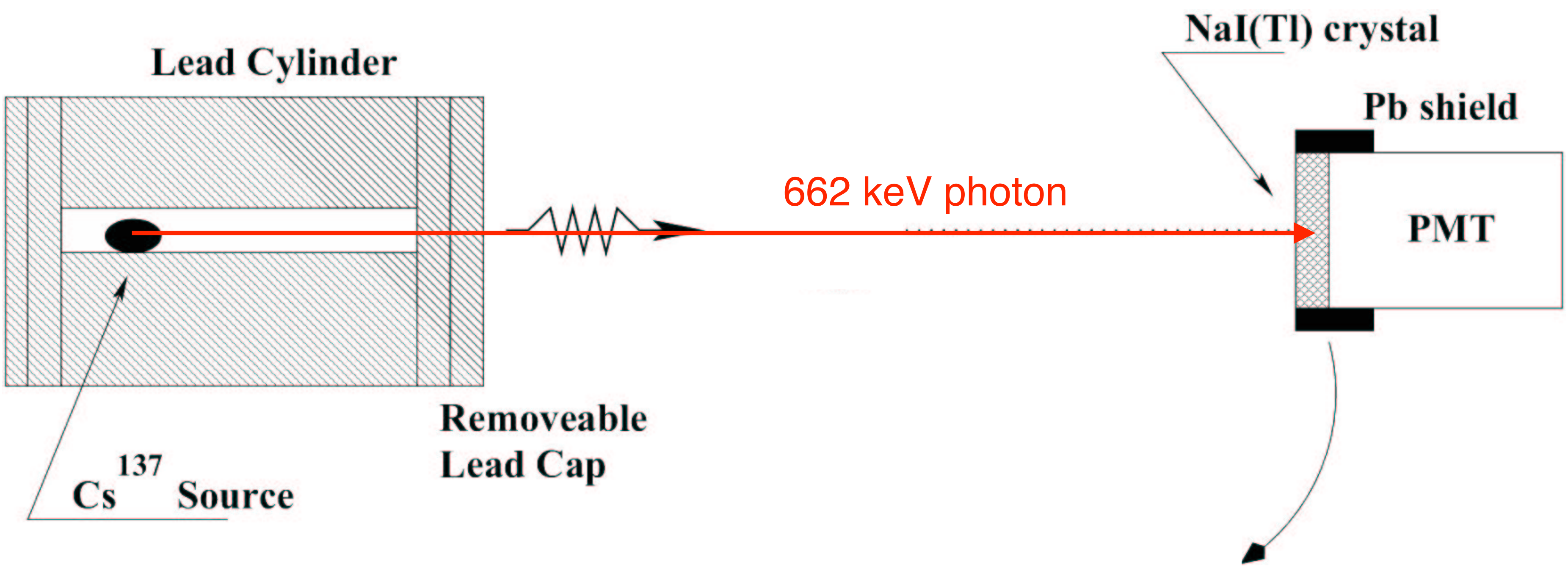

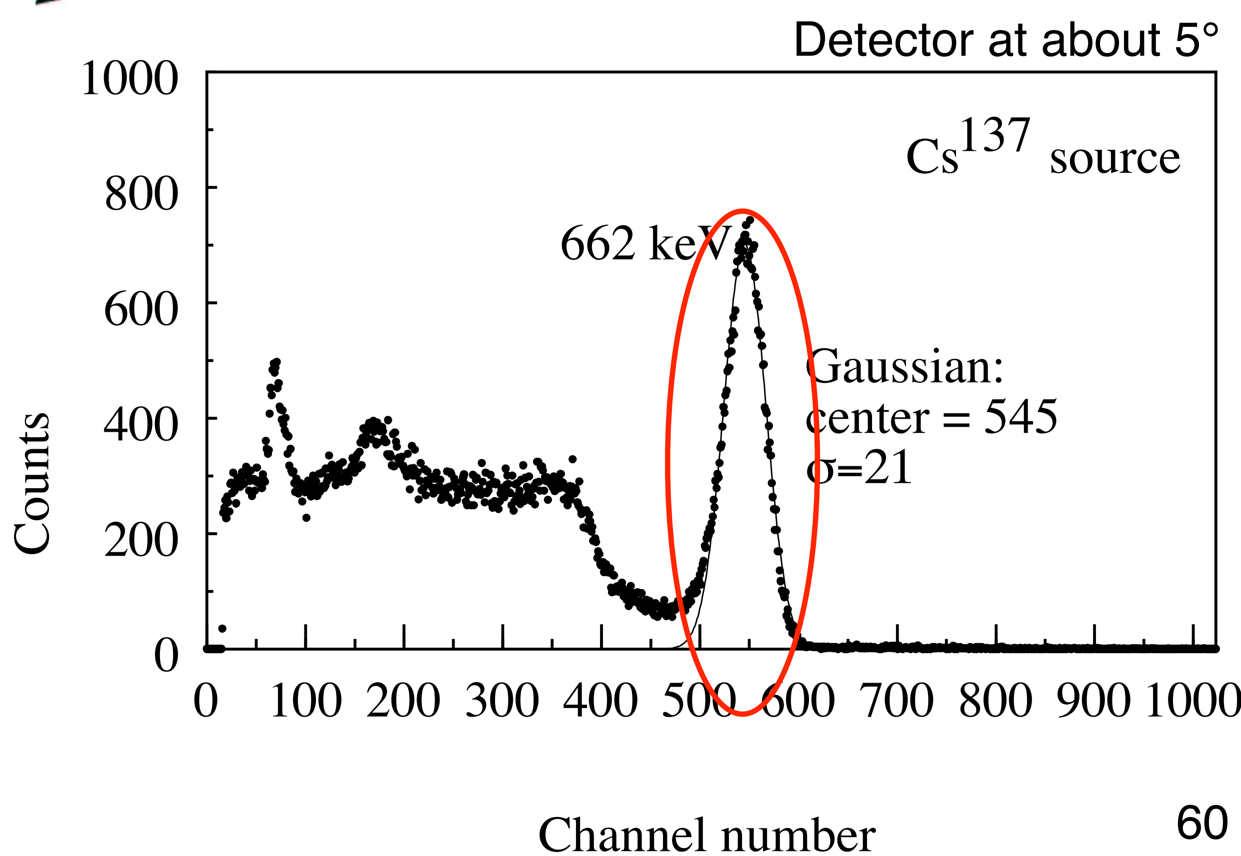

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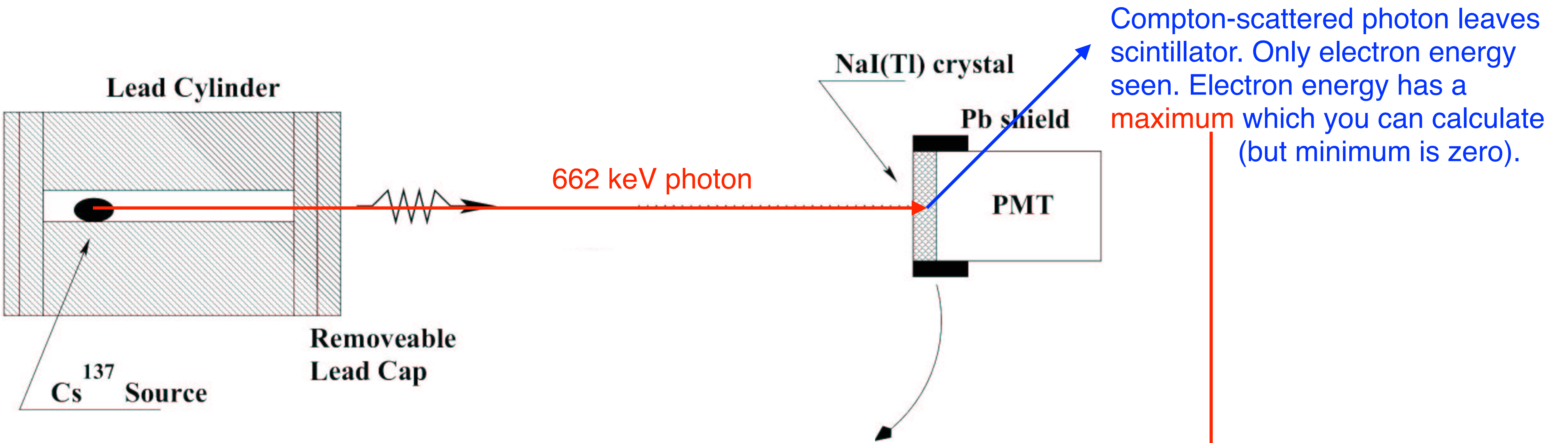

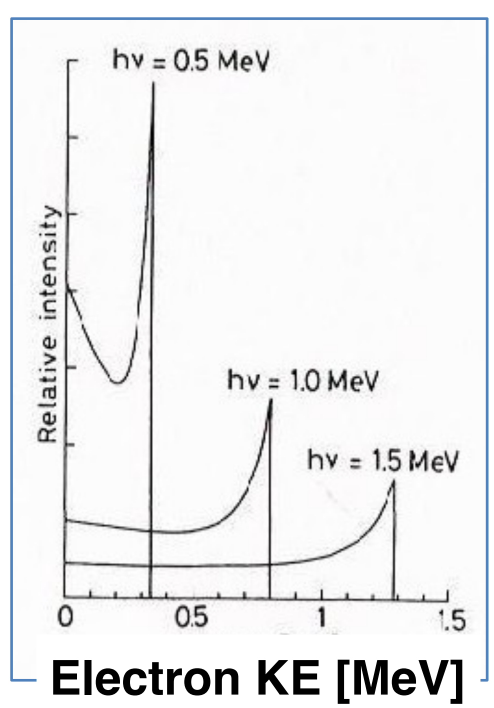

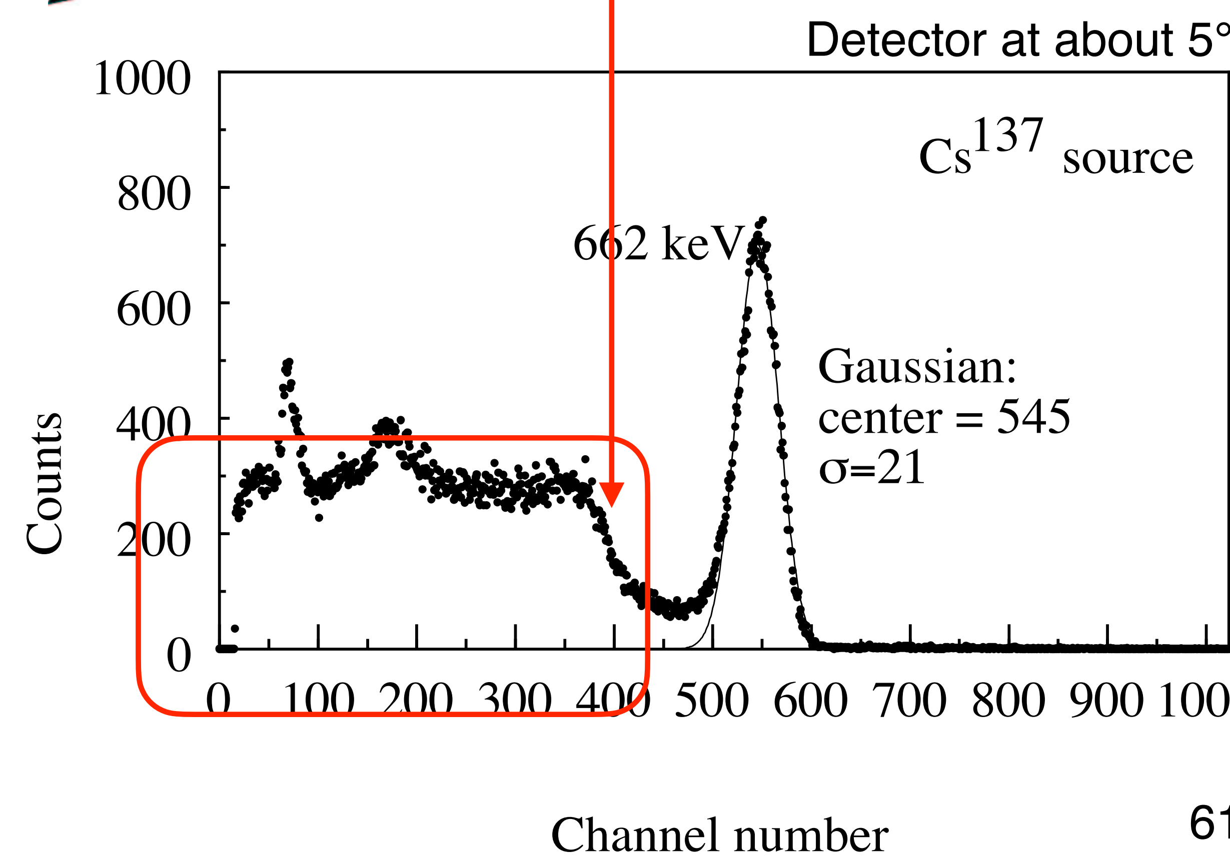

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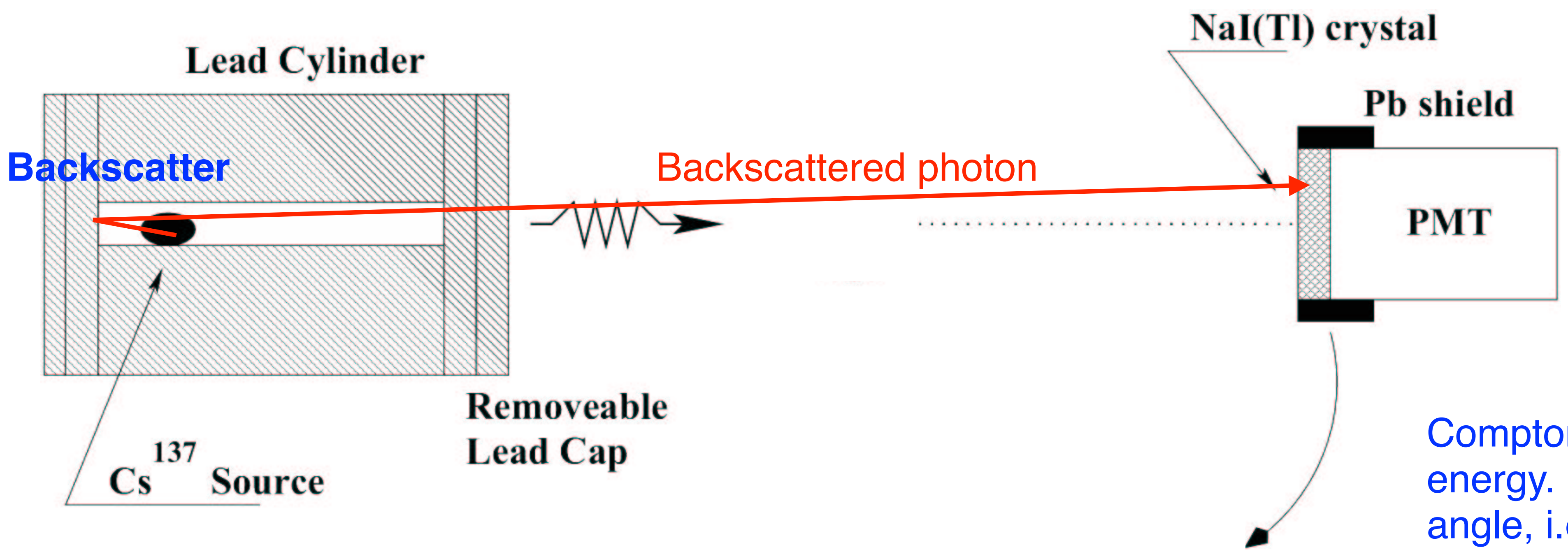
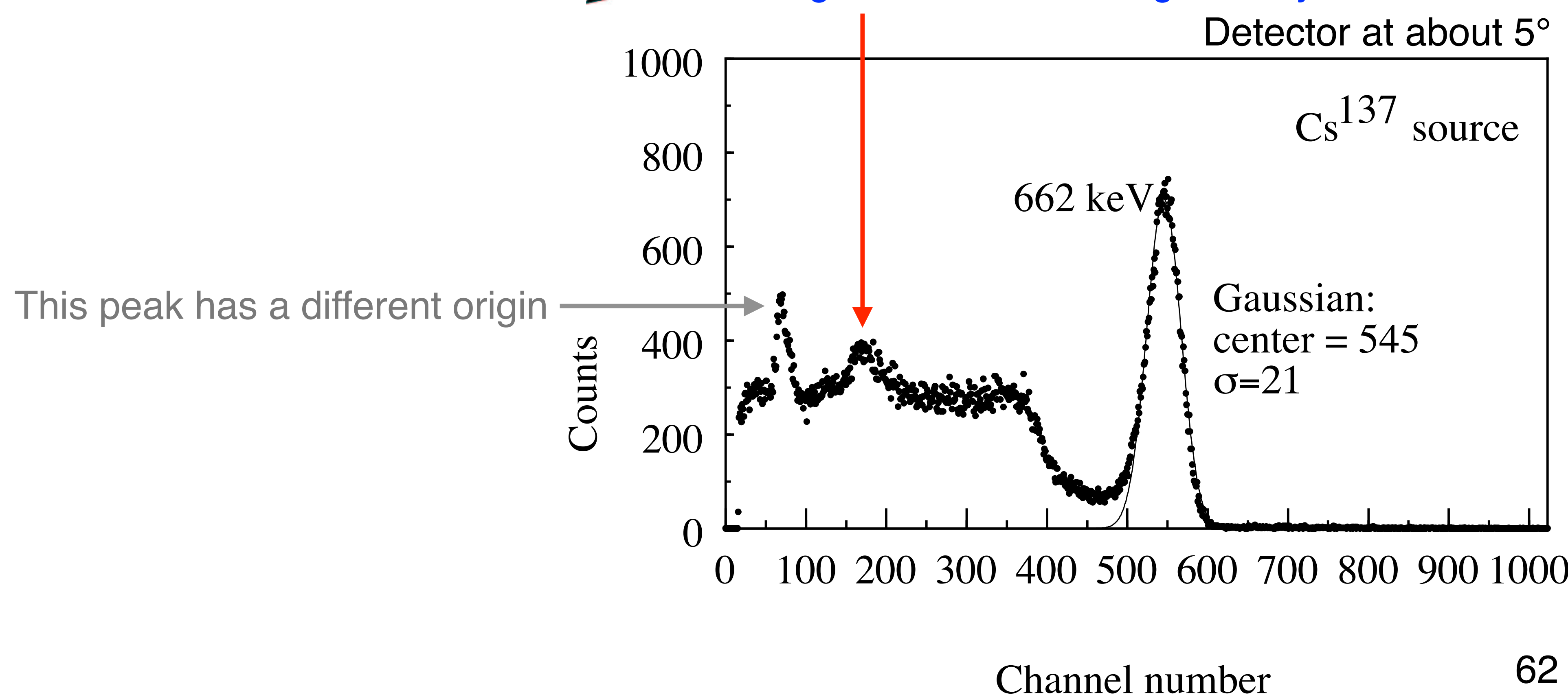


Compton backscatter reduces photon energy. Energy and shape depend on angle, i.e. on detector geometry.



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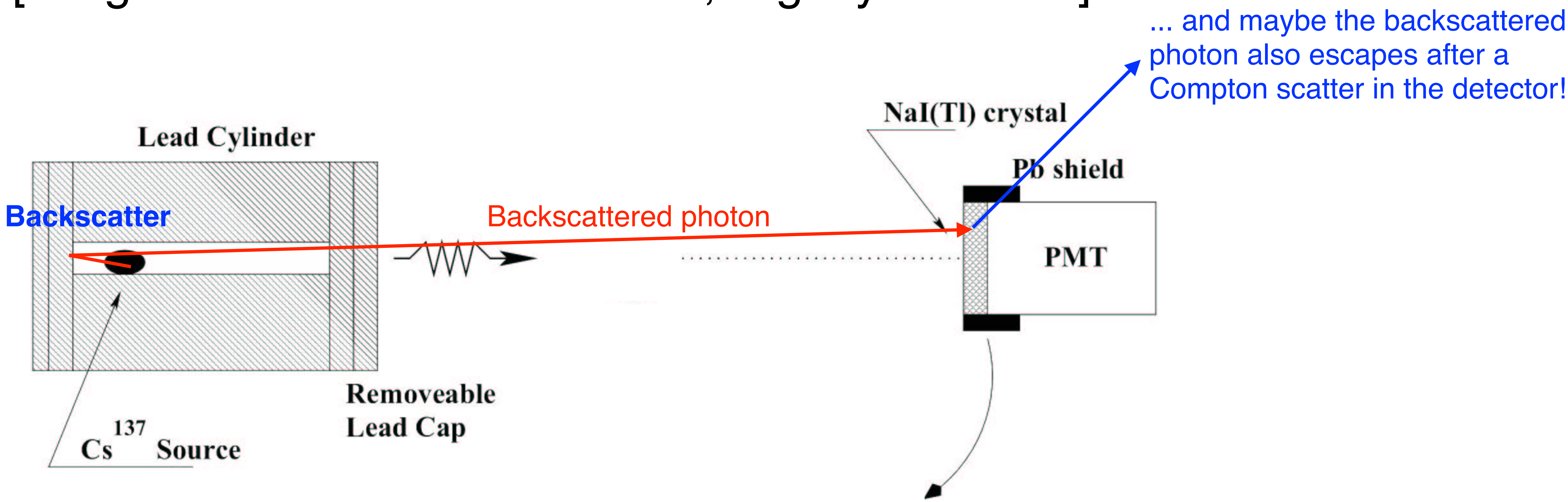

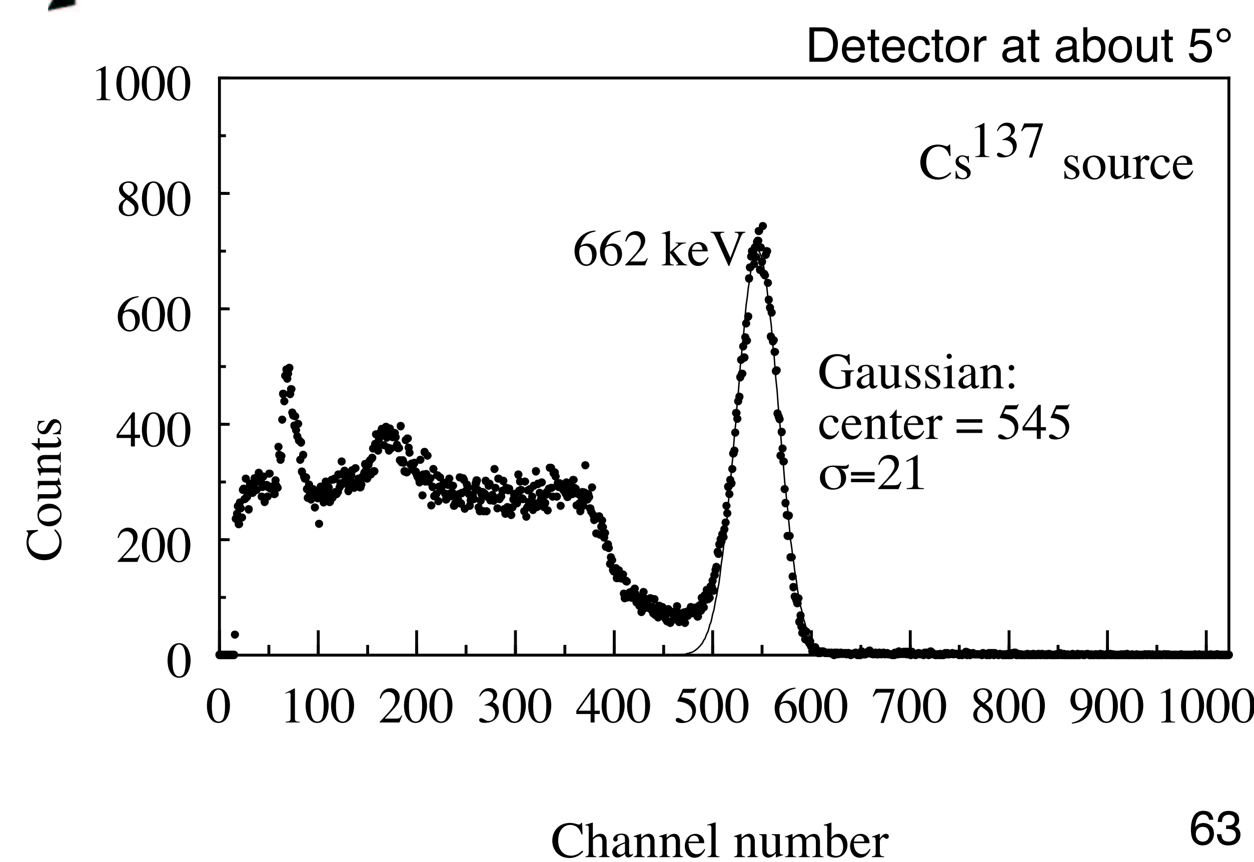

Exercise A

The quantum efficiency of a Photomultiplier Tube is 15%. If 8 photons hit the photocathode, what are the probabilities of emitting

(a) no electrons?
(b) exactly one electron?
(c) at least one electron?

Hint: The binomial coefficients for n=8 are (1, 8, 28, 56, 70, 56, 28, 8, 1)

The PMT is used to detect the light from an organic scintillator (whose density $\rho=1.1$ g/cm^3 and in which particles emit about 10^4 photons in the visible spectrum per MeV of energy loss). Due to absorption in the scintillator and light-guide, scintillation photons have only a 5% probability of reaching the photomultiplier. How thick must the scintillator slab be, so that a minimum-ionizing particle will be detected with an efficiency of at least 99%?

Exercise A

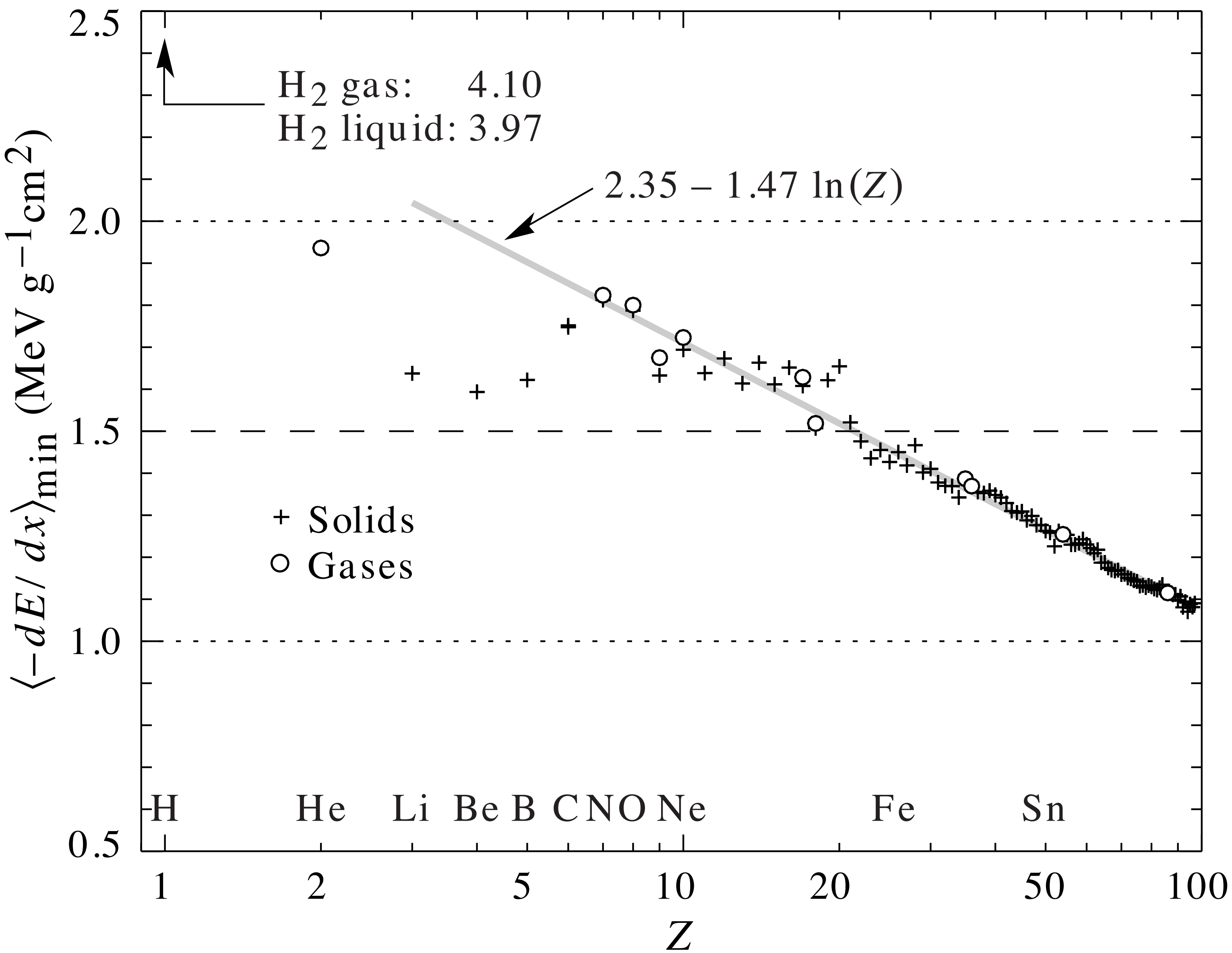

Figure 27.2: Stopping power at minimum ionization for the chemical elements. The straight line is fitted for $Z > 6$. A simple functional dependence on Z is not to be expected, since $\langle -dE/dx \rangle$ also depends on other variables.

Figure from PDG: K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update

Exercise B

Scintillators, gaseous and silicon detectors can be used to measure the energy lost by a particle. The key parameter is the energy required to create a photon (or e/ion pair, or e/hole pair). Consider three cases:

1) A scintillator, where one photon is emitted for every 100 eV of deposited energy, only 6% of the photons reach the photomultiplier, and the PMT has a quantum efficiency of 30%.
2) A silicon detector, where 3.6 eV is required to create one electron-hole pair (more detail in the next lecture)
3) A gaseous detector, where one electron-ion pair is created for every 20 eV of energy deposited (more detail in later lectures)

What is the relative precision with which energy losses of (a) 100 keV, (b) 5 MeV, and (c) 20 MeV can be measured in the three detectors?

Exercise C

Suppose that you are designing the electromagnetic calorimeter for a particle physics detector working at a centre-of-mass energy of E (for the cases E = 10 GeV, E = 200 GeV, E = 10 TeV). What design would you use, and why? What type of detector technology would you use? Could other technologies be used instead? Does your answer work for both e^+e^- and hadron colliders?

[Note that there is no unique answer here. You might compare your answer to what previous experiments have used. For a real detector, practical constraints like budgets and readout bandwidth are also important.]

Example exam questions from previous years

Note: The exam format has changed over time, and the syllabus has also evolved somewhat. The point is not to give you the exact style or content of this year's questions, but to help you prepare.

Exam questions

From 2016:

A photomultiplier tube contains N dynodes. The potential difference between the photocathode and the anode is V. In passing from dynode i to dynode $i+1$, each electron is accelerated through a potential difference ΔV and liberates $[a(\Delta V/V_0)^k - 1]$ additional electrons at dynode $i+1$. Assuming that ΔV is the same at each step, find an expression for the total gain G. If $N = 10$, $V_0 = 1$ volt, $k = 0.7$, and $a = 0.15$, what gain would we expect for the following voltages V? (a) 200 volts; (b) 1000 volts; (c) 3000 volts. What practical limitations keep us from increasing V indefinitely?

Exam questions

From 2017:

Consider a detector consisting of a block of scintillator and a photomultiplier tube. The scintillator has a light yield of 13%, and produces scintillation photons with $\lambda = 410\,\text{nm}$. Estimate the energy resolution (in units of keV) of the detector for photons of energy $E_\gamma \approx 0.5\,\text{MeV}$, stating any assumptions.

Suggest another detector technology that could be used if a significantly better energy resolution is needed.

$[\hbar c = 197.3\,\text{MeV fm}]$

Exam questions

From 2021:

Q4 (approx. 20 min)

We wish to detect photons with energy $E_\gamma = 1\,\text{MeV}$.

(a) Suggest a suitable scintillator material, giving an approximate value for its light yield in %. Roughly how many scintillation photons will be produced? (Order-of-magnitude estimates are fine.)

(b) We use a photomultiplier tube to detect the scintillation photons. Sketch a simple PMT design, noting the key physical processes that occur in the detection of a scintillation photon. Explain **briefly** the meaning of the terms "quantum efficiency", "collection efficiency", and "multiplication efficiency".

[$\hbar c = 197.3\,\text{MeV fm}$]