Physics of Neutrino detection

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Resume

- Last lecture, we discussed the main requirements for neutrino detection and the interplay with the cross-sections and neutrino sources.
- We also started to look into the passage of particles through matter: ionisation...

Cherenkov

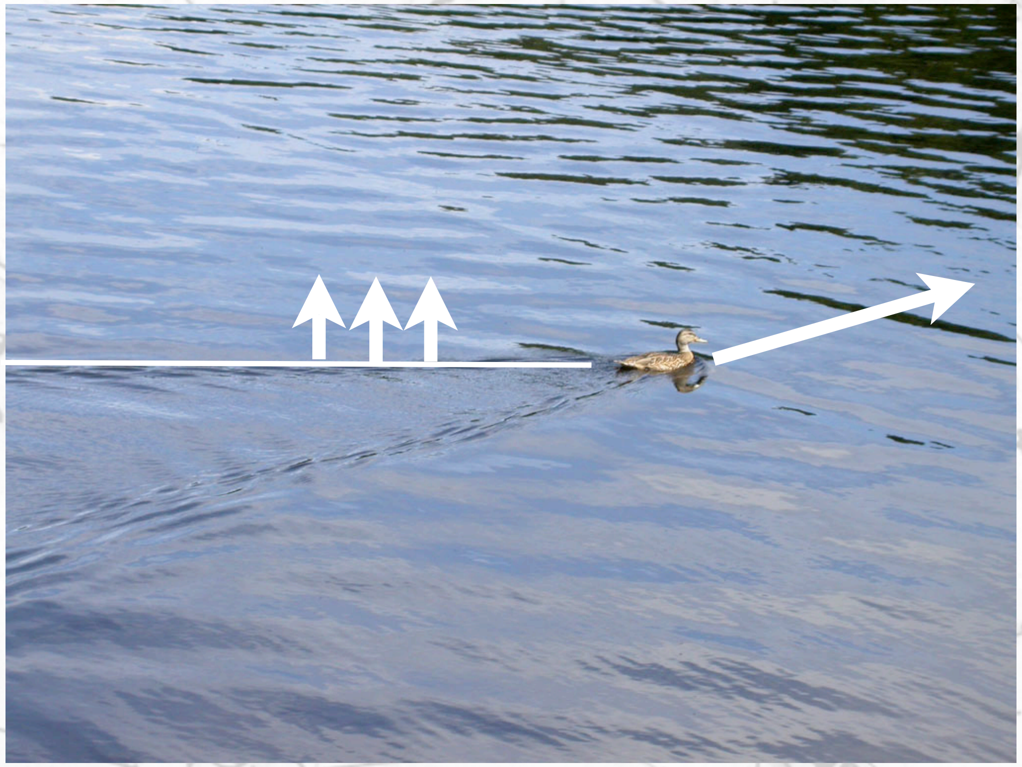
- A charged particle radiates if its velocity is greater than the local phase velocity of light (Cherenkov radiation) or if it crosses suddenly from one medium to another with different optical properties (transition radiation).

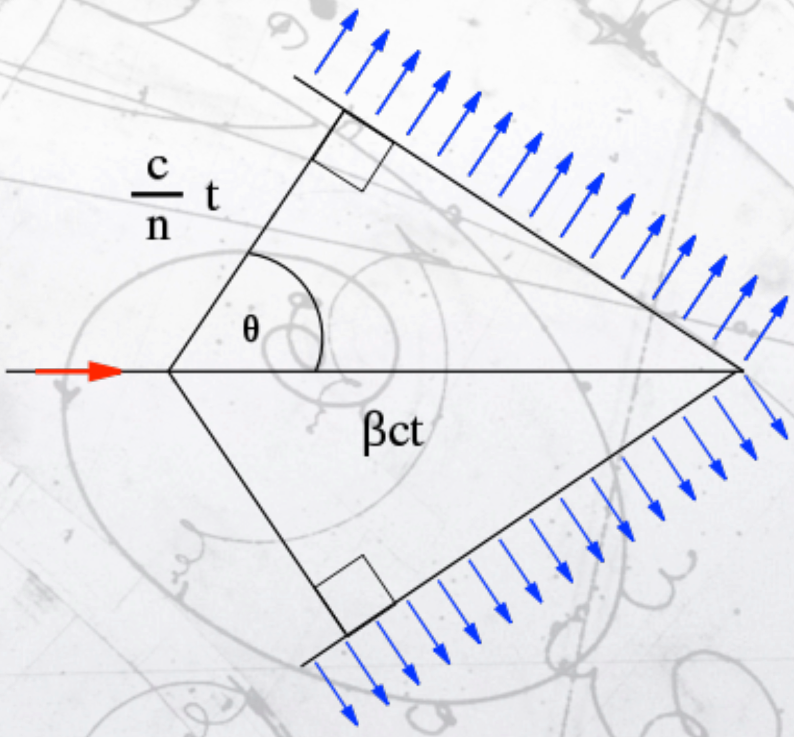
- This is a negligible energy loss but with interesting properties.

- Light is emitted in a light front with defined angle with respect to the particle direction (directionality):

$$\cos\theta = \frac{1}{n\beta}$$

n index of refraction
β particle velocity





- The threshold is $\beta > 1/n$, $\beta\gamma > 0.75$ in water. In momentum:

$$p \geq m\sqrt{\frac{1.}{(n^2-1)}}$$

Cherenkov

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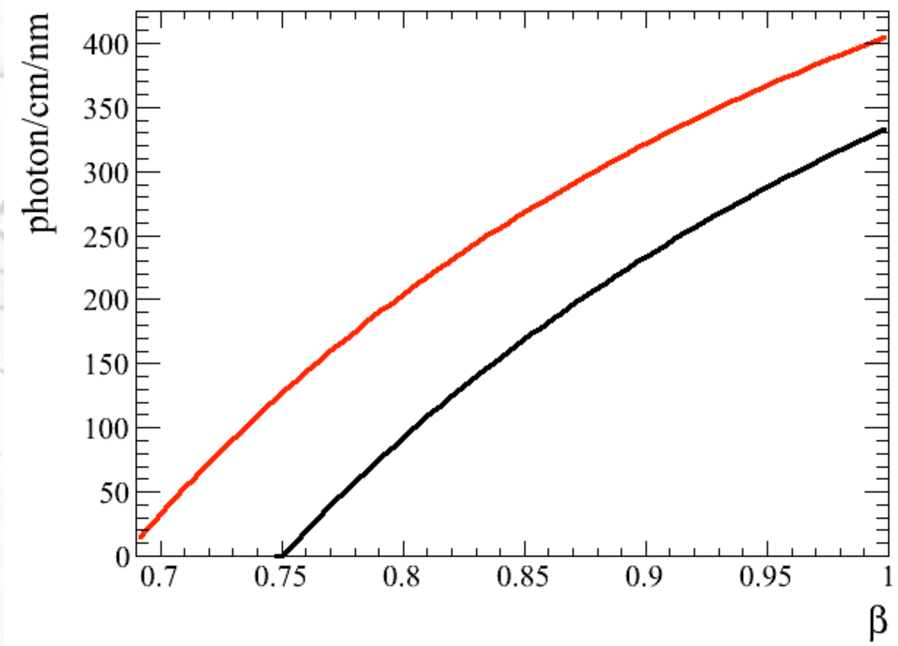
- In practise the number of photons is very limited at threshold so the real threshold is a bit larger.

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}(1-\frac{1}{\beta^2 n(\lambda)^2})$$

- This is 390 photons/cm for photons between 300nm and 700nm.



Wavelength	Water 20°
397 nm	1.3435 (+0.7%)
434 nm	1.3403 (+0.6%)
486 nm	1.3372 (+0.3%)
589 nm	1.333 (0.0%)
656 nm	1.3312 (-0.6%)

Particle	Water (n=1.33)	Oil (n=1.46)
electron	0.58 MeV/c	0.48 MeV/c
muon	121 MeV/c	99.0 MeV/c
proton	1070 MeV/c	880 MeV/c

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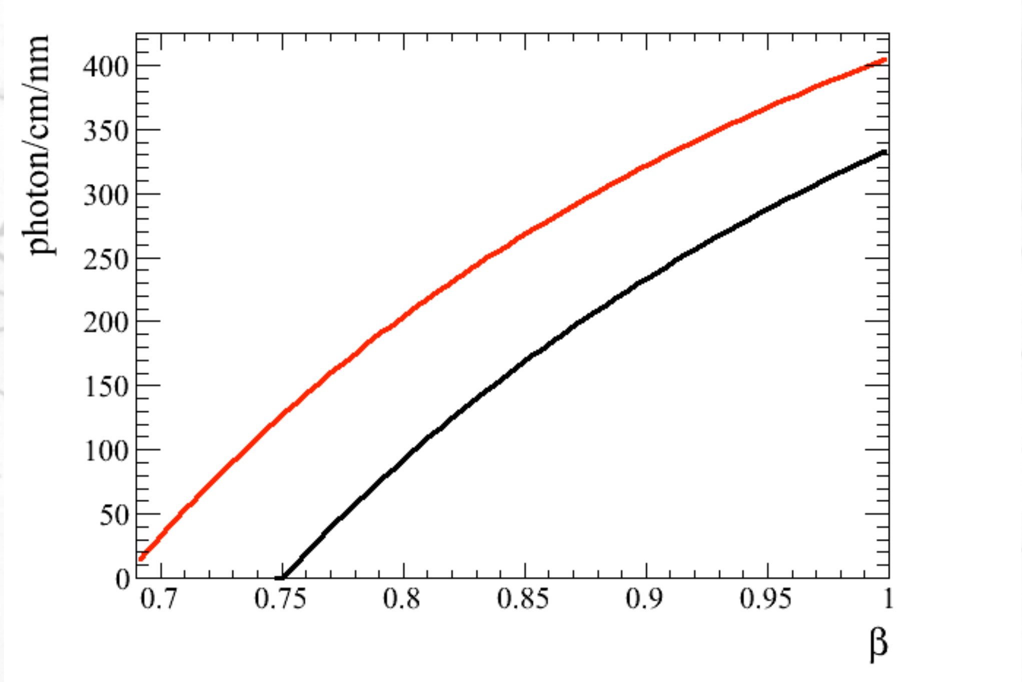

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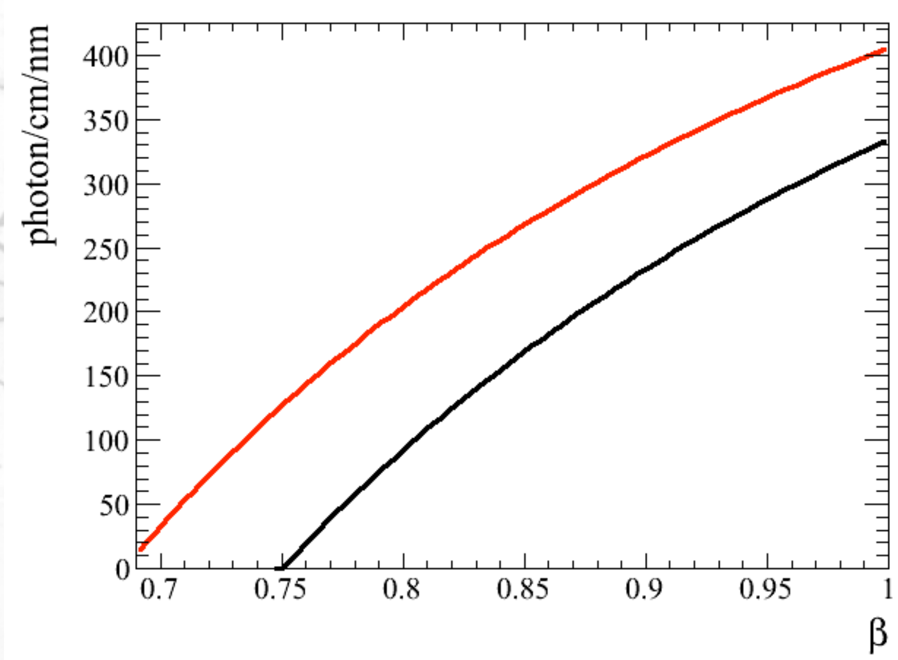

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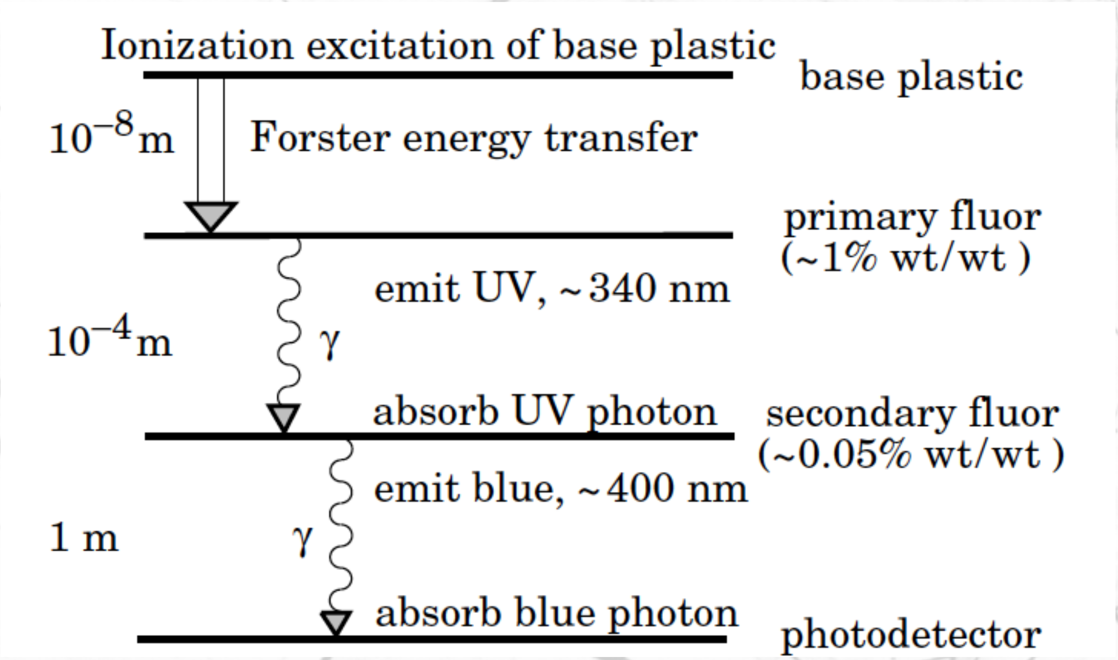
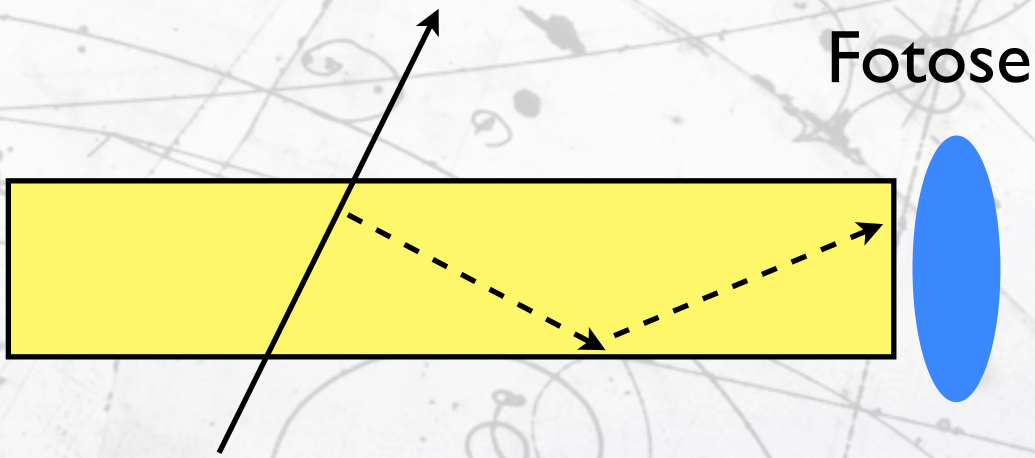
Change in angle emission is less than 1% between different wavelengths.

Scintillator

- Scintillators are materials that emit light (normally UV) shortly after it has been excited by the particle. This is ~3% of the cases.
- The decay time is of the order of 10 to few 100 ns and it has an exponential decay shape (decay probability).
- Some materials have several emission wavelengths and relaxation time. They can depend on the type of radiation.
- The UV needs to be shifted to other wavelengths to increase the path in the detector and the match to photo detectors.
- There might be non linear responses to the ionisation. Birk's constant (B) accounts for local saturation in high ionisation environments.

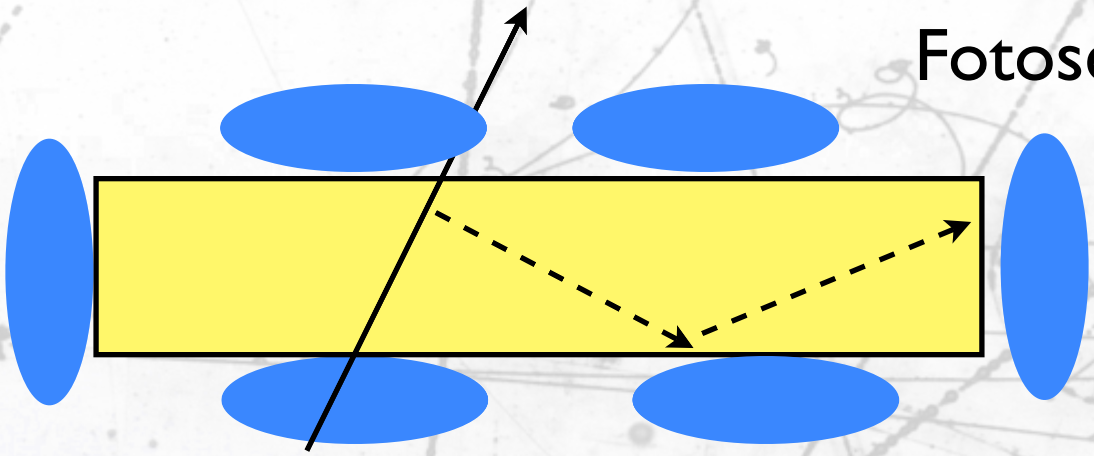




$$N_\gamma \propto \frac{E_{ionization}}{(1 + B \ E_{ionization})}$$

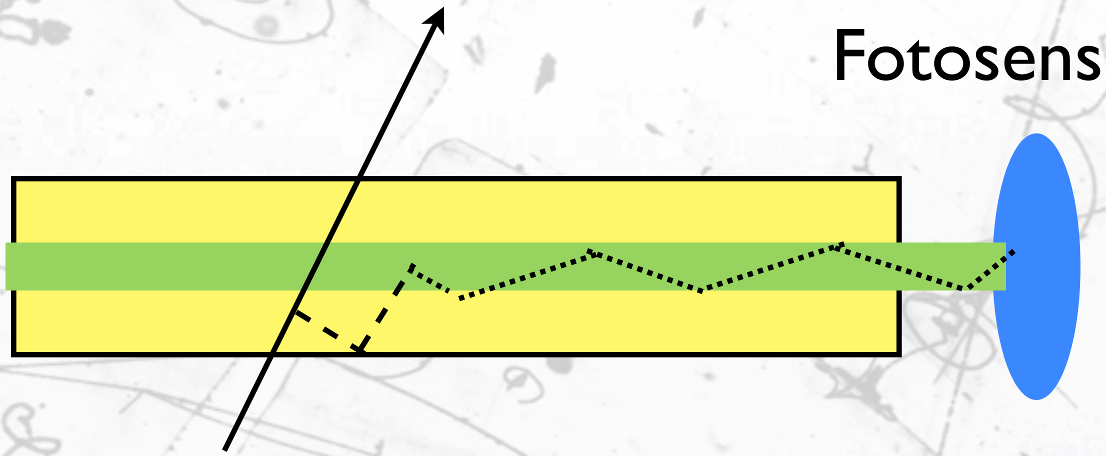
- Light collection can be done in two ways:

Direct attachment



- One or many photosensors are attached to the scintillator.
- The path from some light might be different and also the attenuation: non uniformities.
- Some liquid scintillator detectors use this technique.

WaveLength shifting fibers



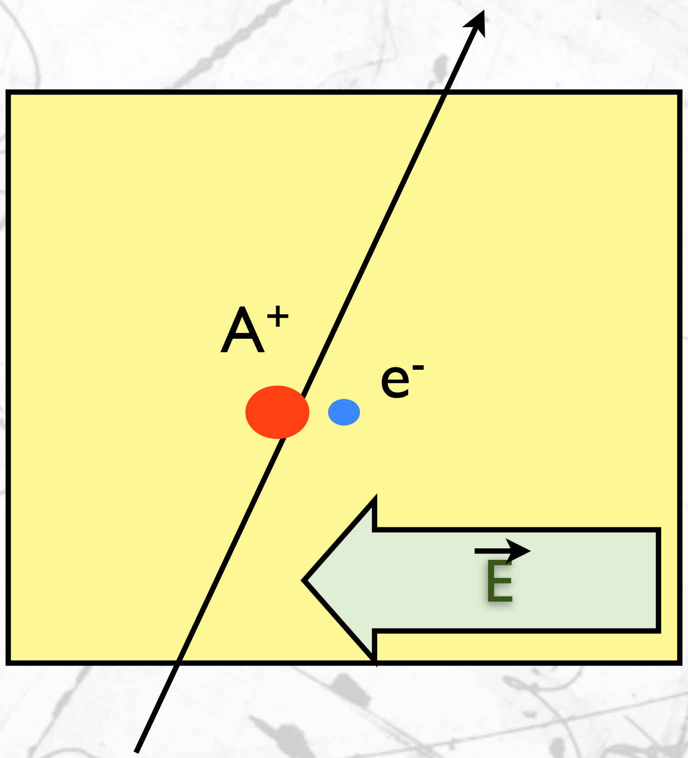
- Photosensors are attached to the WLS fiber.
  - The WLS fiber shifts the wavelength to one that propagates with small attachment in the fiber
- The light path is more uniform: uniform and with higher light collection efficiency.

Ionisation

- The passage of particles through a detector ionize atoms in the media.
- If we can separate the A^+ and e^- before they recombine, the number of electrons will be proportional to the energy deposited by the track.
  - To do that we need to apply strong electric field in the material.
- The number of electrons depends on the ionisation energy that is a property of the material:

$$N_{e^-} = \frac{dE/dx}{E_{ioni}}$$

- Based on this formula, the fluctuation of number of electrons will be 0.



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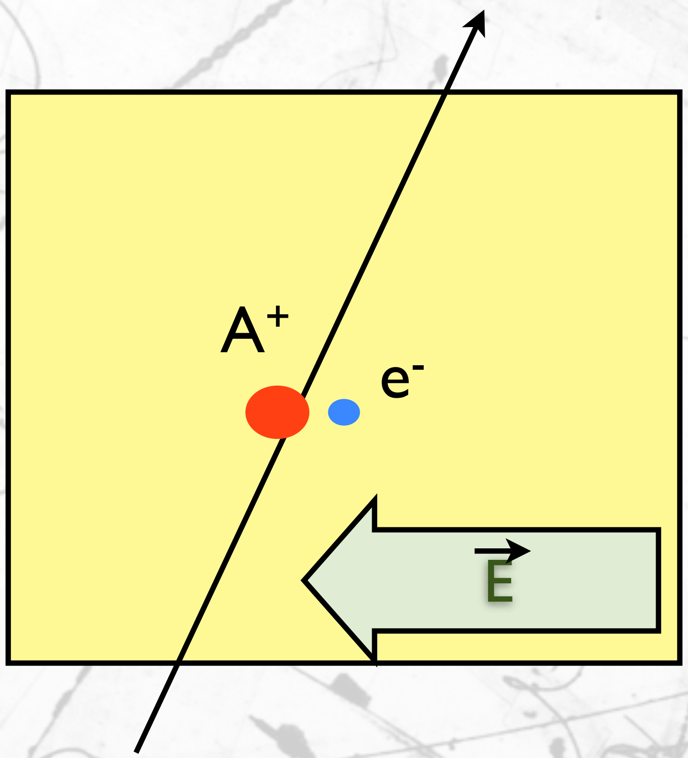

- The fluctuation is given by

$$\sigma_{N_{e-}} = \sqrt{F N_{e-}}$$

- where the Fano factor (F) takes into account:
  - that the total energy and momentum in each collision is conserved.
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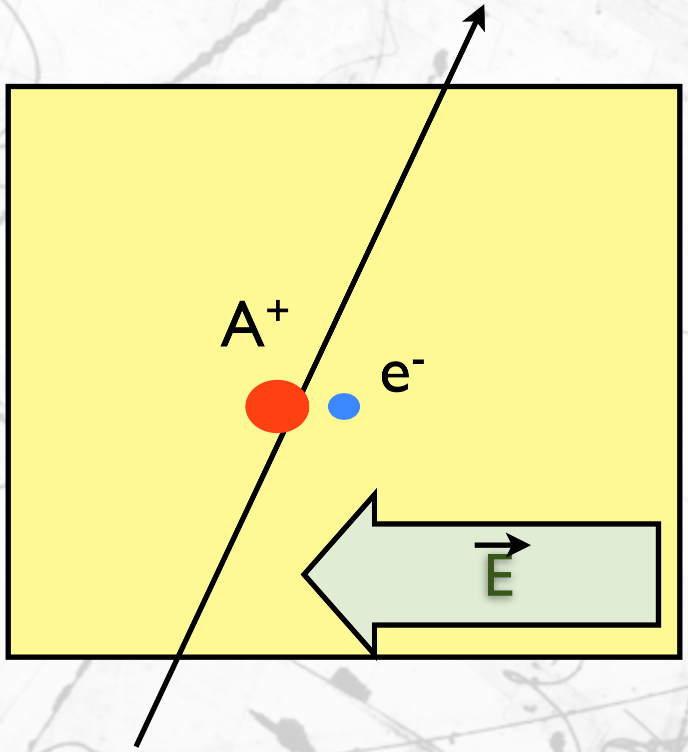

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Radiochemical:
a very special case

Radiochemical

- The method was first proposed by B.Pontecorvo (1946) to detect solar neutrinos.
- The idea profits from the charged current reaction:

$$\nu_e +^{37} Cl \rightarrow^{37} Ar + e^- \quad E_{thres} = 814.0\ KeV$$
$$\nu_e +^{71} Ga \rightarrow^{71} Ge + e^- \quad E_{thres} = 232.2\ KeV$$

- The detector was purged periodically to measure the amount of ^{71}Ge or ^{37}Ar produced.
  - $T^{1/2}$ (^{37}Ar) ~ 35 days $T^{1/2}$ (^{71}Ge) ~ 11.5 days

Extraction when equilibrium: Produced = decayed.

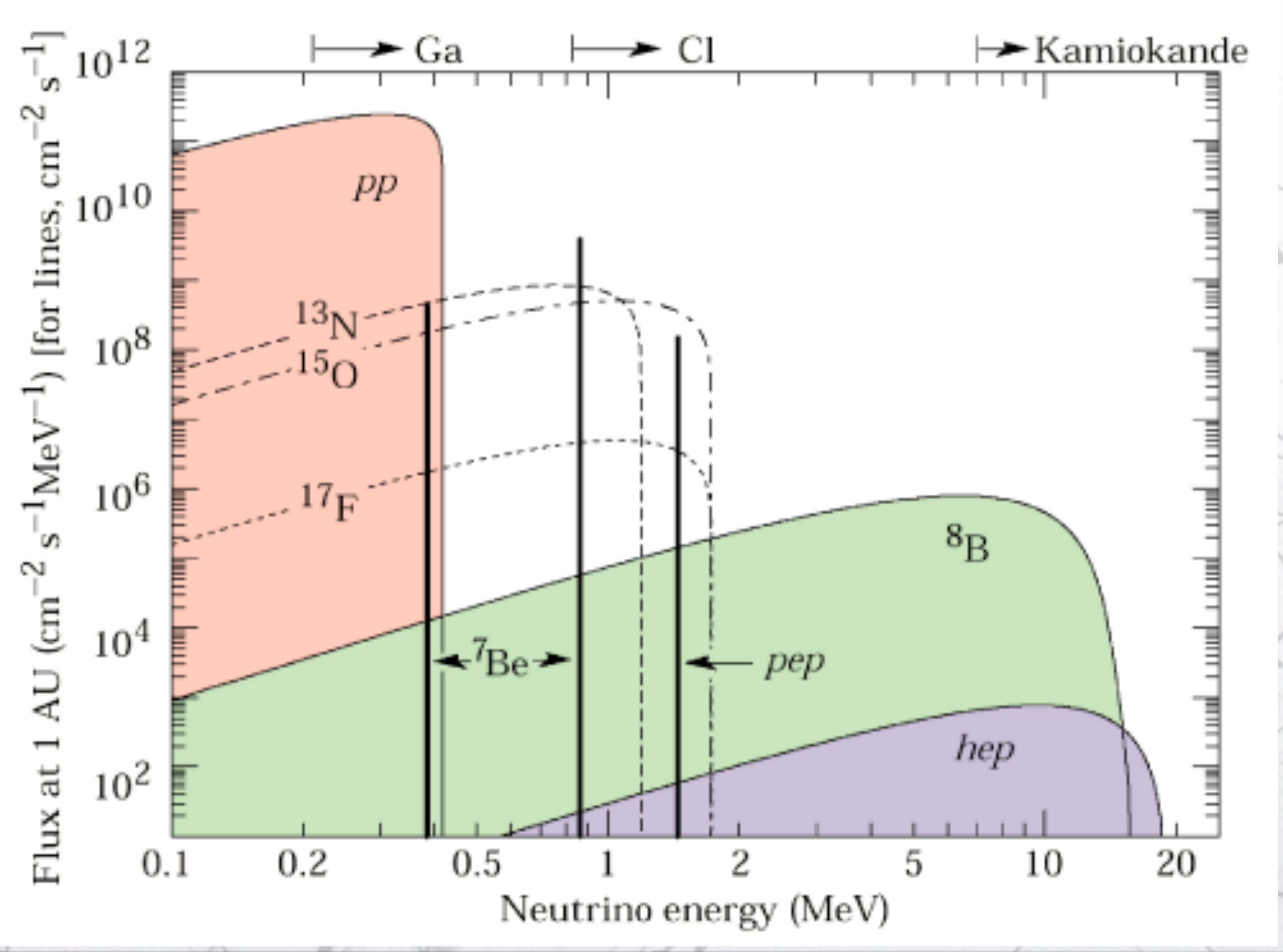
- The main advantages of this method was that the threshold was low and suitable for solar neutrino detection.

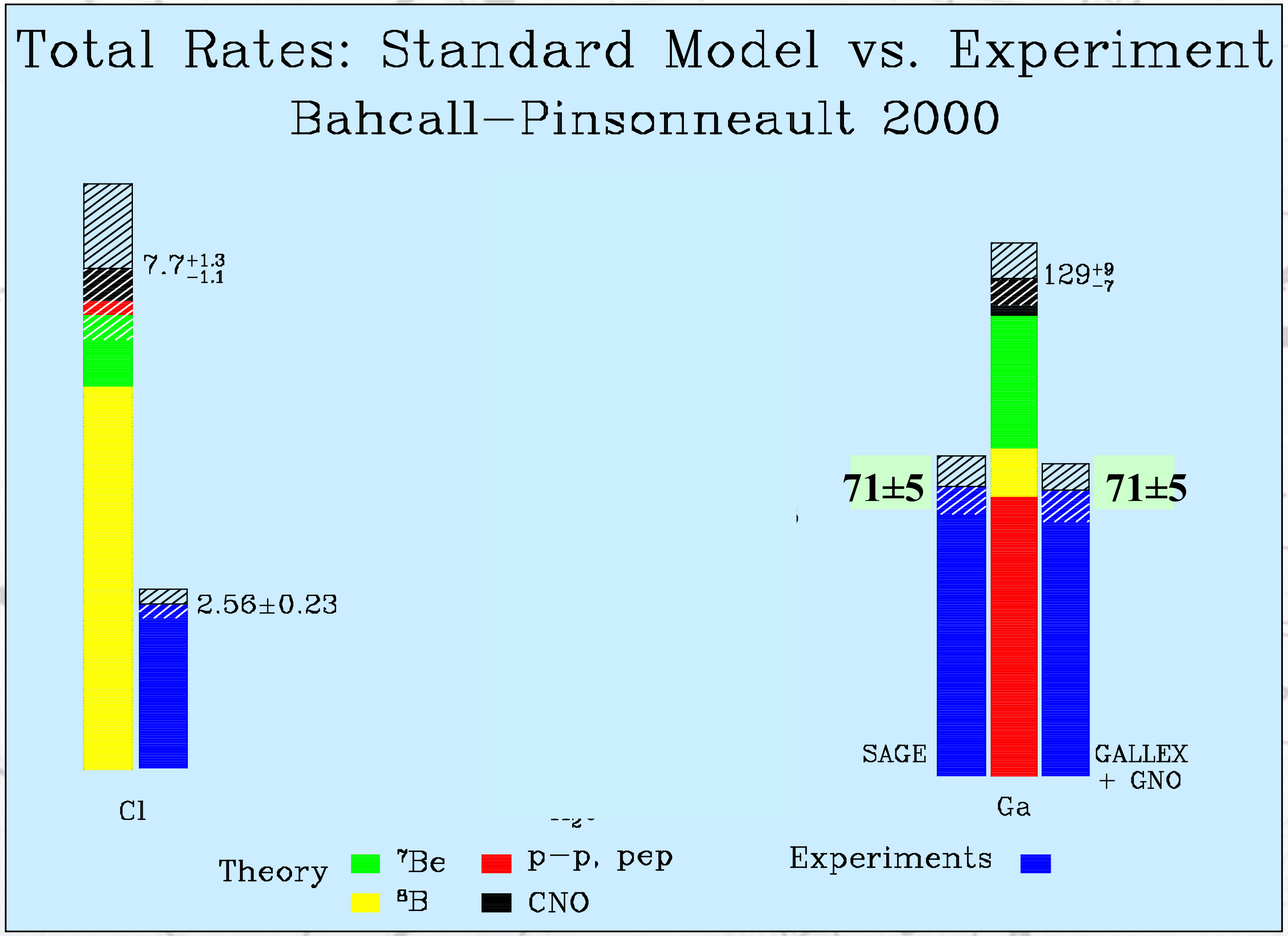
Radiochemical

- Why Radiochemical?:
  - Low energy threshold.
  - Small background.
  - Technically feasible in large mass.
- Process:
  - The ^{37}Ar and ^{71}Ge were extracted chemically by adding He or H to the target liquid.
  - Once extracted the activity of the ^{37}Ar and ^{71}Ge were measured and from there the total number of neutrino interactions.
- But!:
  - there are other reactions to produce ^{37}Ar and ^{71}Ge. Mainly neutron interactions.
  - Need to control all the efficiencies in the extraction and measurement of the ^{37}Ar and ^{71}Ge.

Radiochemical

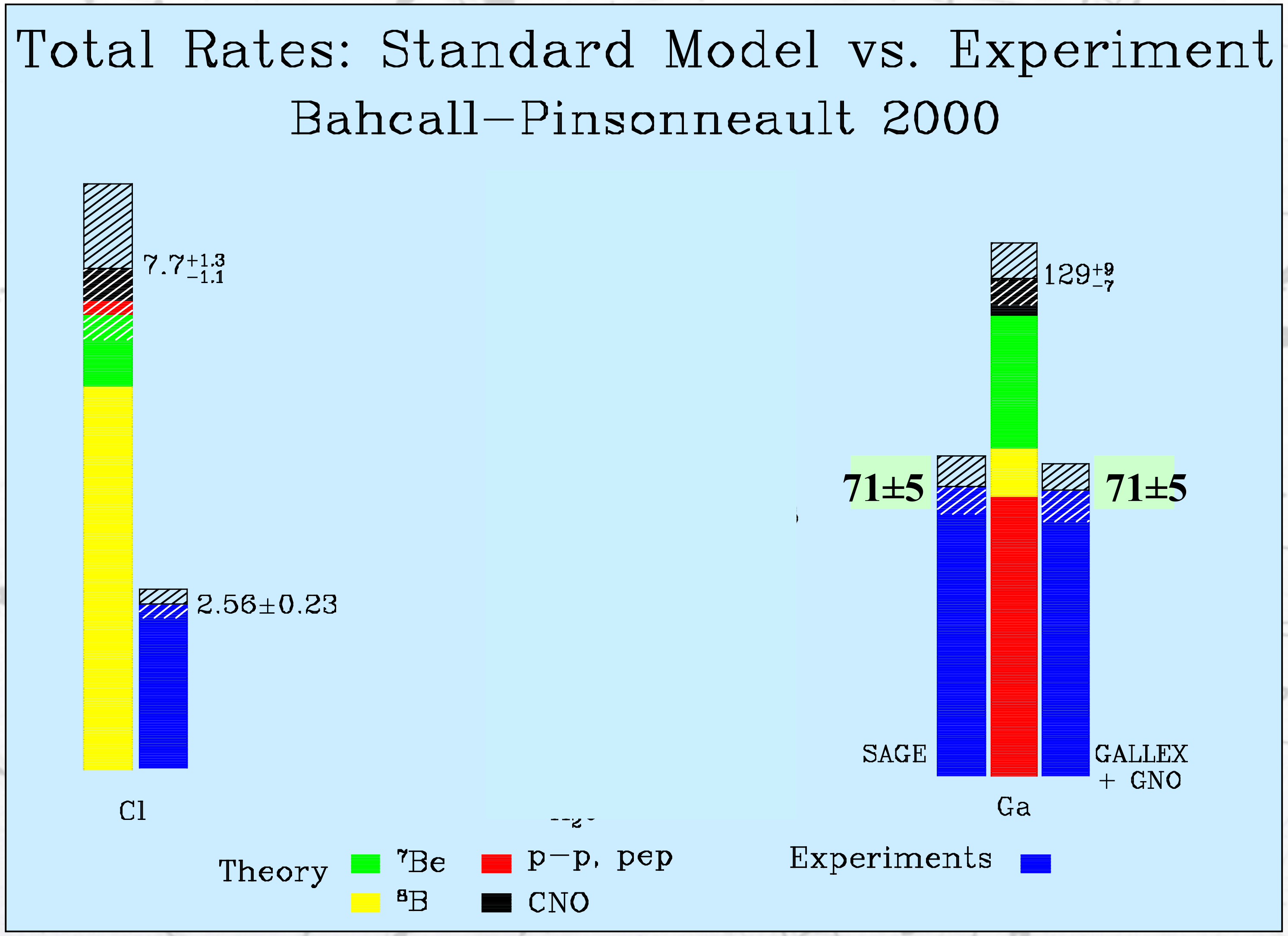
- The two different thresholds allow to make a kind of integrated spectrum measurement being sensitive to different parts of the solar neutrino spectra.





- Both techniques measured different rate than expected:
  - solar model?,
  - detector efficiencies?,
  - neutrino deficit through oscillations?,…
- This disagreement was called for years "the solar neutrino problem".

Nowadays the neutrino speed is another example.



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- For many years these experiments show the difference between the number of sigmas and the "confidence level".

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Low energy detectors

Calorimetric

Calorimetry

- It consists on the measurement of the energy of a particle on the total energy deposition in a detector. This can be done with any particle, including a muon.
- For this purpose the particle should be contained (or with minimal loses) in the detector to measure its energy:
    - It is easier to contain electrons and hadrons than muons in a detector, so it is normally used for these two:
        - electromagnetic calorimeters (electrons and photons)
        - hadron calorimeters (protons and pions).
        - muon range detectors (muons and pions).

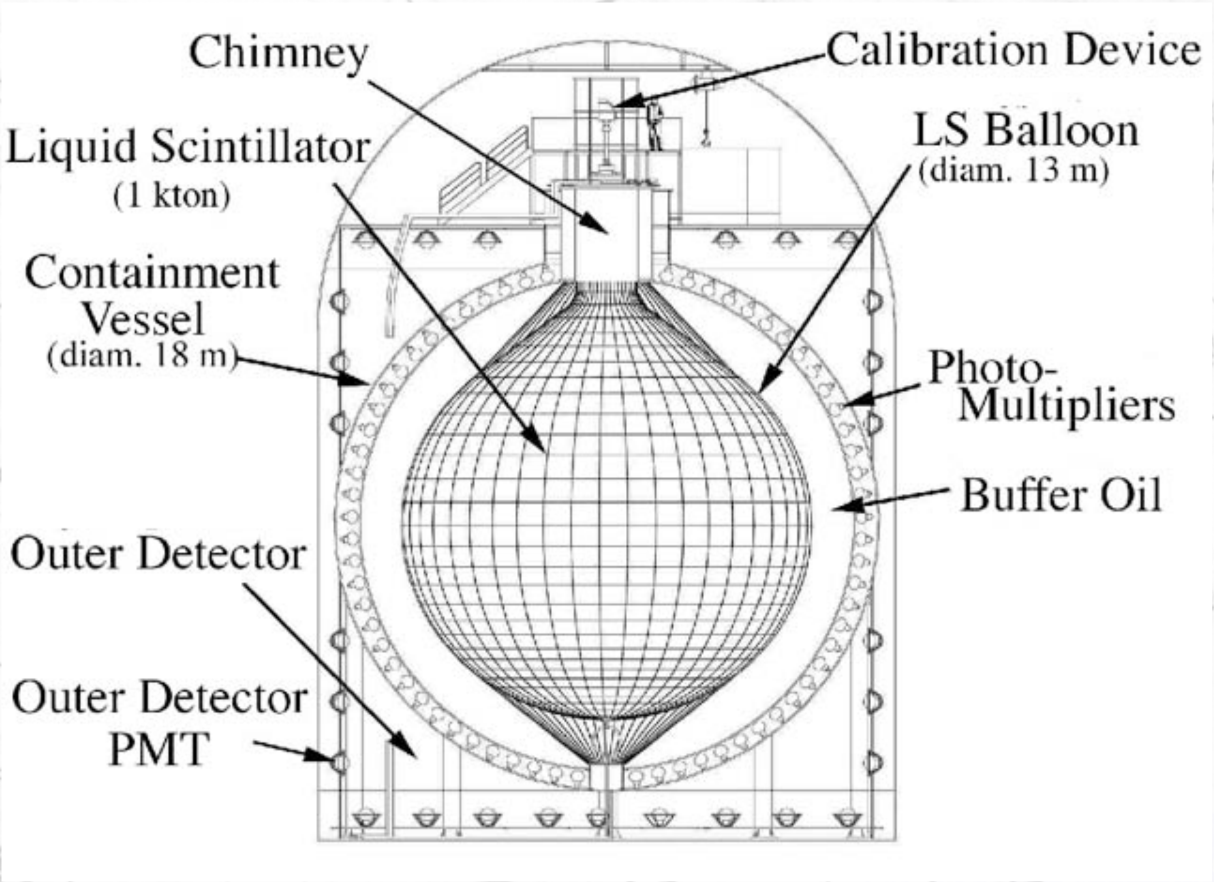
Scintillator detectors

- The main idea of this detectors is to measure all the energy deposited in the detector using scintillator. It requires large photo production: 200 photons/MeV.
- At low energies detectors are fully active to avoid fluctuations of the energy in the passive material.
- The detector can measure the energy, the time and the position of the deposition.
- Measuring low energy electron neutrinos and antineutrinos (~MeV) through CC and NC

$$\bar{\nu}_e p \rightarrow e^+ n$$

$$\nu_e n \rightarrow e^- p$$

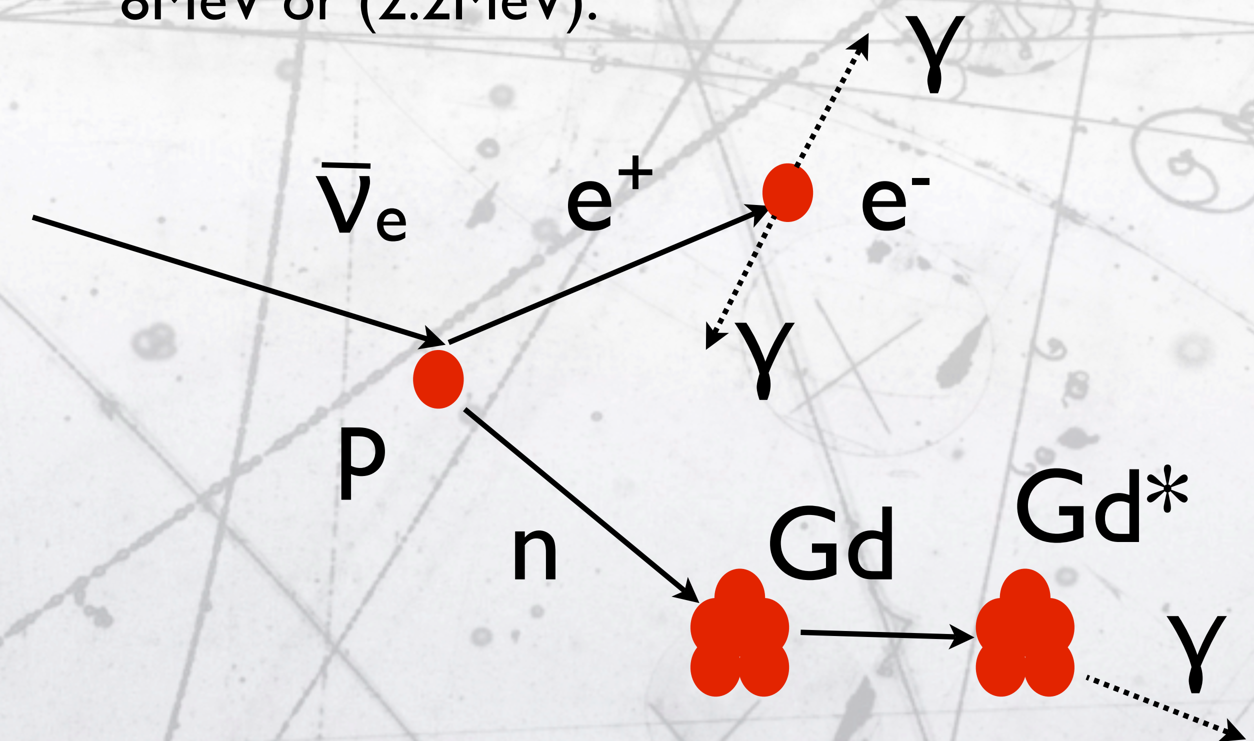
$$\nu_e e^- \rightarrow \nu_e e^-$$

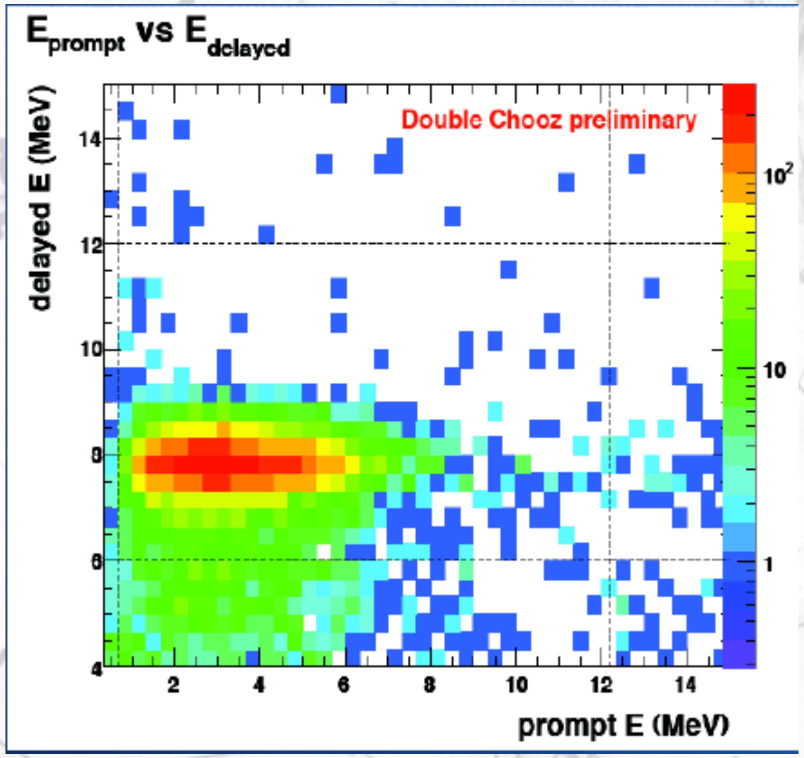


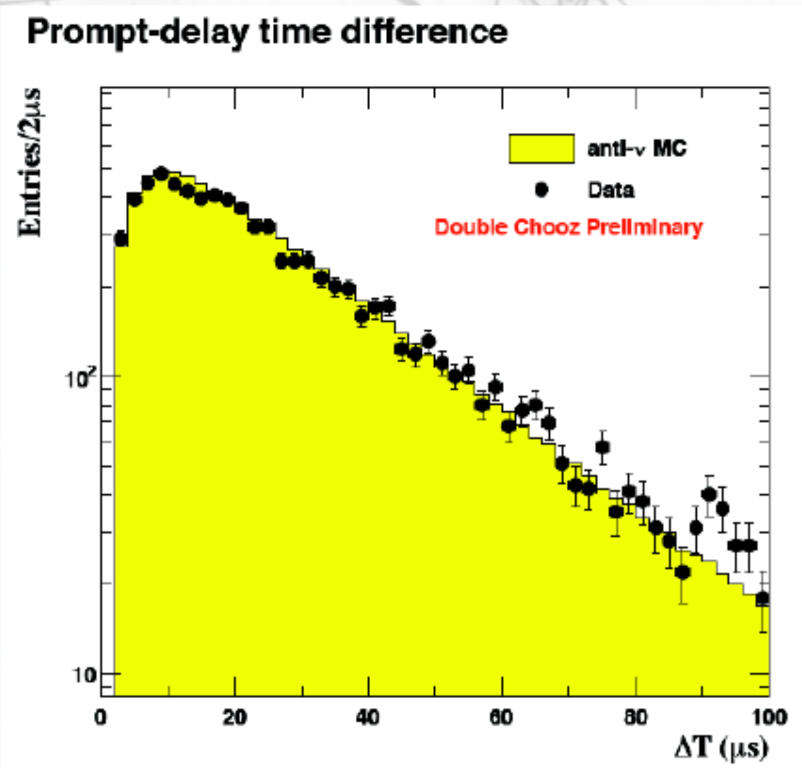
- The onion approach: layers of clean and active detectors to reduce radioactive background from outside.
- Dirty components (PMT) far from active area.
- Underground

Scintillator detectors

- For antineutrino detection, the reduction of background is achieved by a coincidence.
  - The prompt positron signal is detected with the energy.
  - The positron annihilates with electrons and produce two 511 KeV signals.
  - Neutrons produce in the reaction, moves in the detector and they are capture by Gd or Cd releasing a nuclear gamma of 8MeV or (2.2MeV).

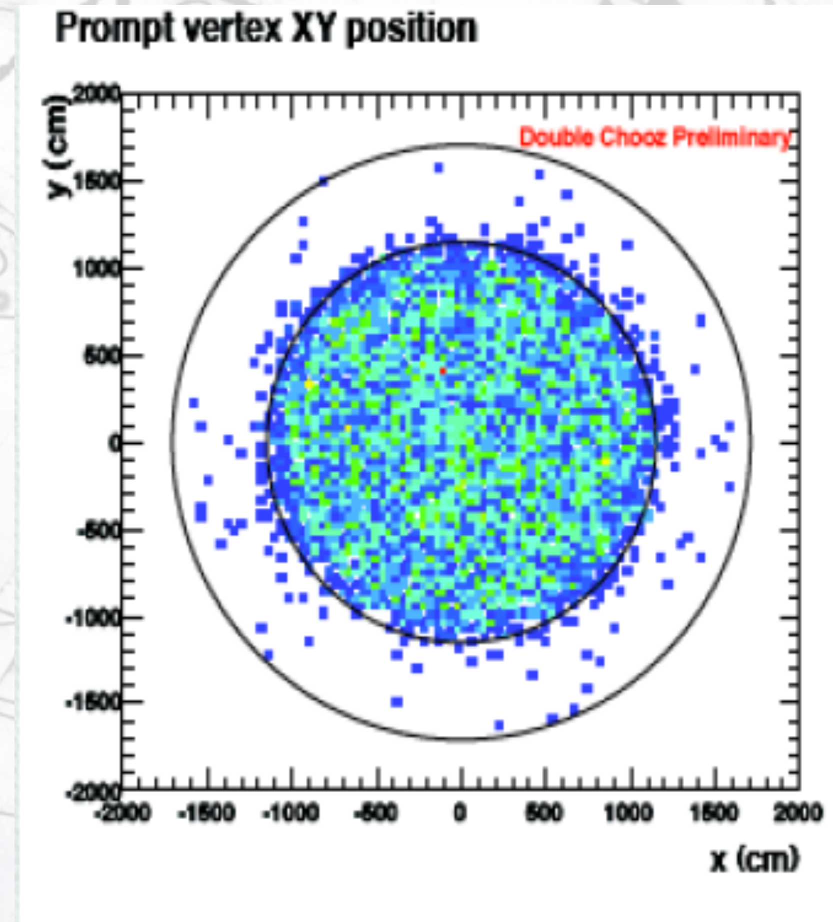






Scintillator detectors

- The position of the interaction can be computed using the time and light density of photons in the detector.

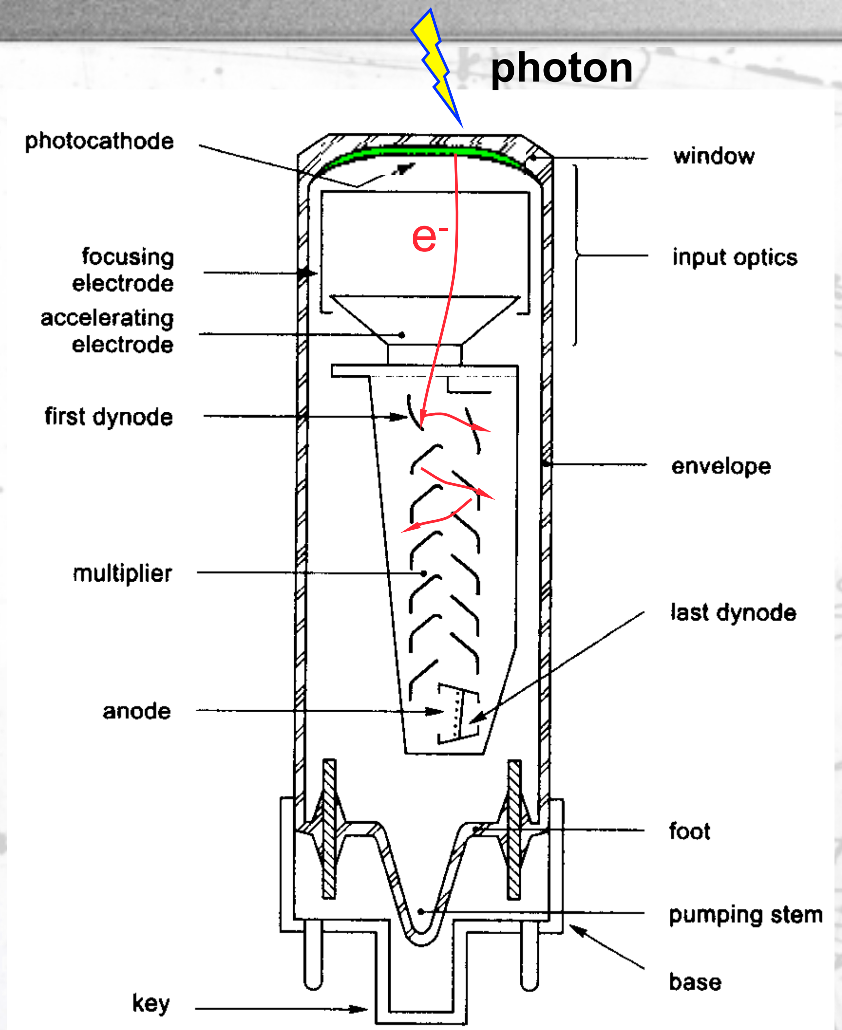


$(N_\gamma/cm)_{far} < (N_\gamma/cm)_{near}$ if $r \neq 0$

$(N_\gamma/cm)_{far} \sim (N_\gamma/cm)_{near}$ if $r = 0$

- If there is absorption in the detector, the position is needed to correct for light collection.

Photo detection



- The photo sensors basically count photons, ignoring the energy or wavelength of it.
- Main phenomena:
  - Photo electric emission from photo cathode.
  - Secondary emission from dynodes.
    - Dynode gain: gi = 3-50 depending on energy.

$$M = \prod_{i=1}^{N} g_i$$

    - 10 dynodes with g = 4, $M = 4^{10} = 10^6$
  - Transient time ~200ps (time is critical in some applications)

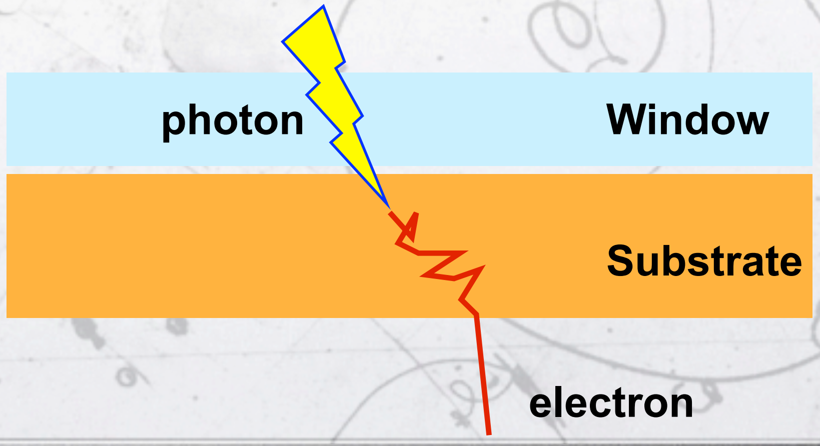
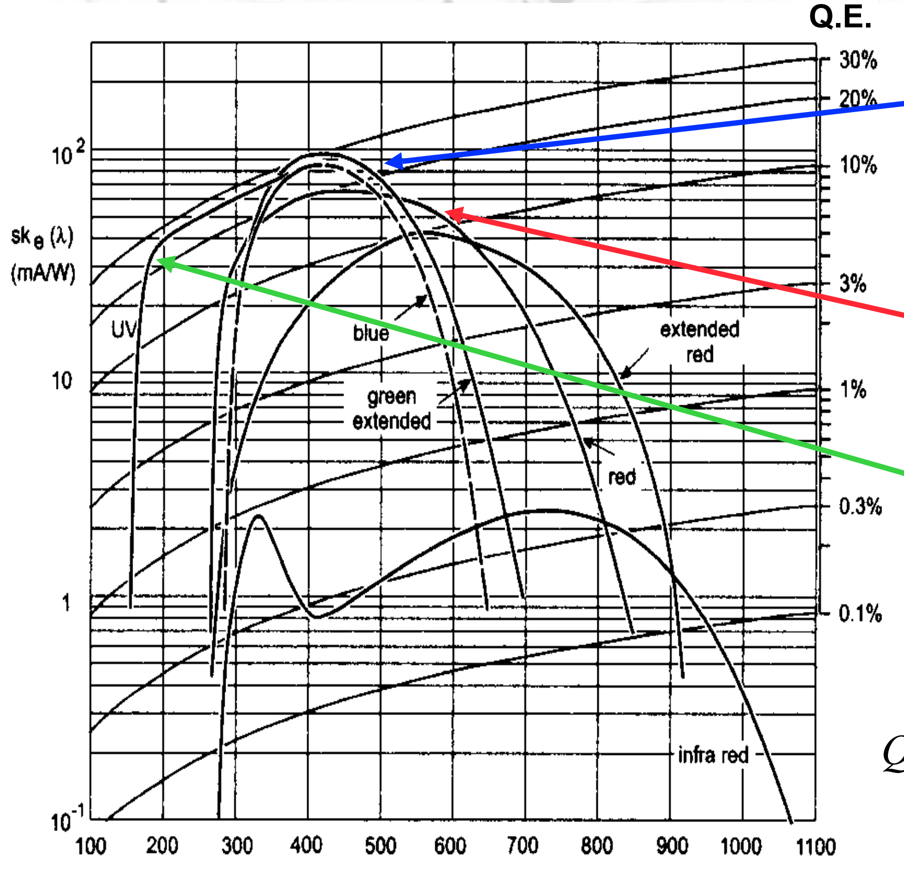


Photo detection

Quantum efficiencies of typical photo cathodes



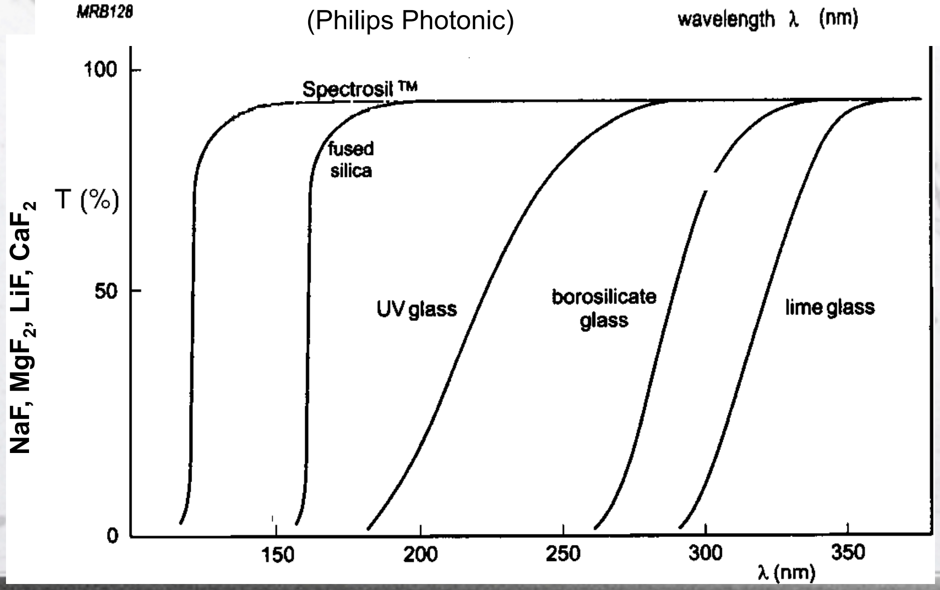
(Philips Photonic)

Bialkali
SbK_2Cs
SbRbCs

Multialkali
$SbNa_2KCs$

Solar blind
CsTe
(cut by quartz window)

$$Q.E.(\%) \approx 124 \times \frac{sk_e(mA/W)}{\lambda(nm)}$$

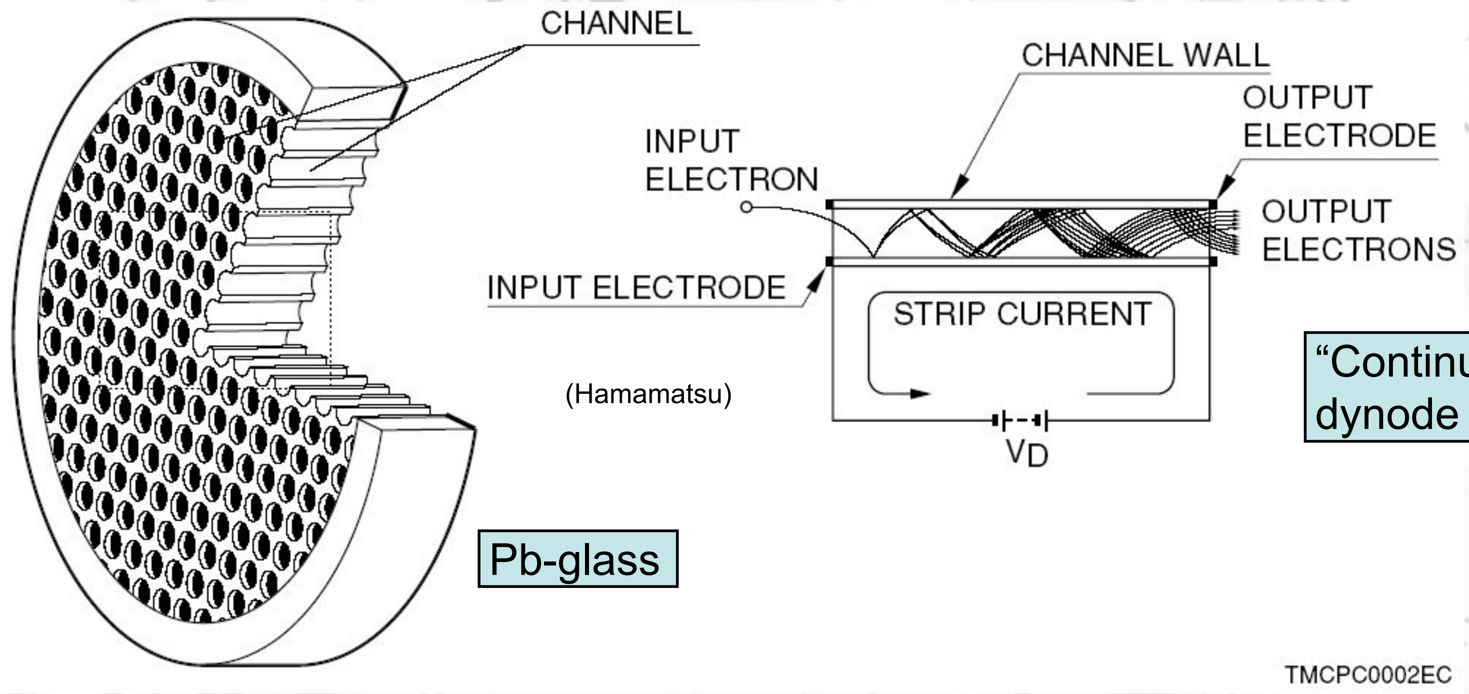


Transmission of various PM windows

- The response of the PMT depends on:
  - quantum efficiency of the substrate (<~30%)
  - window transparency (~100%)
  - efficiency collection of first dynode.
- Energy resolution depends (mainly) upon the first dyode gain.

Other photo sensors

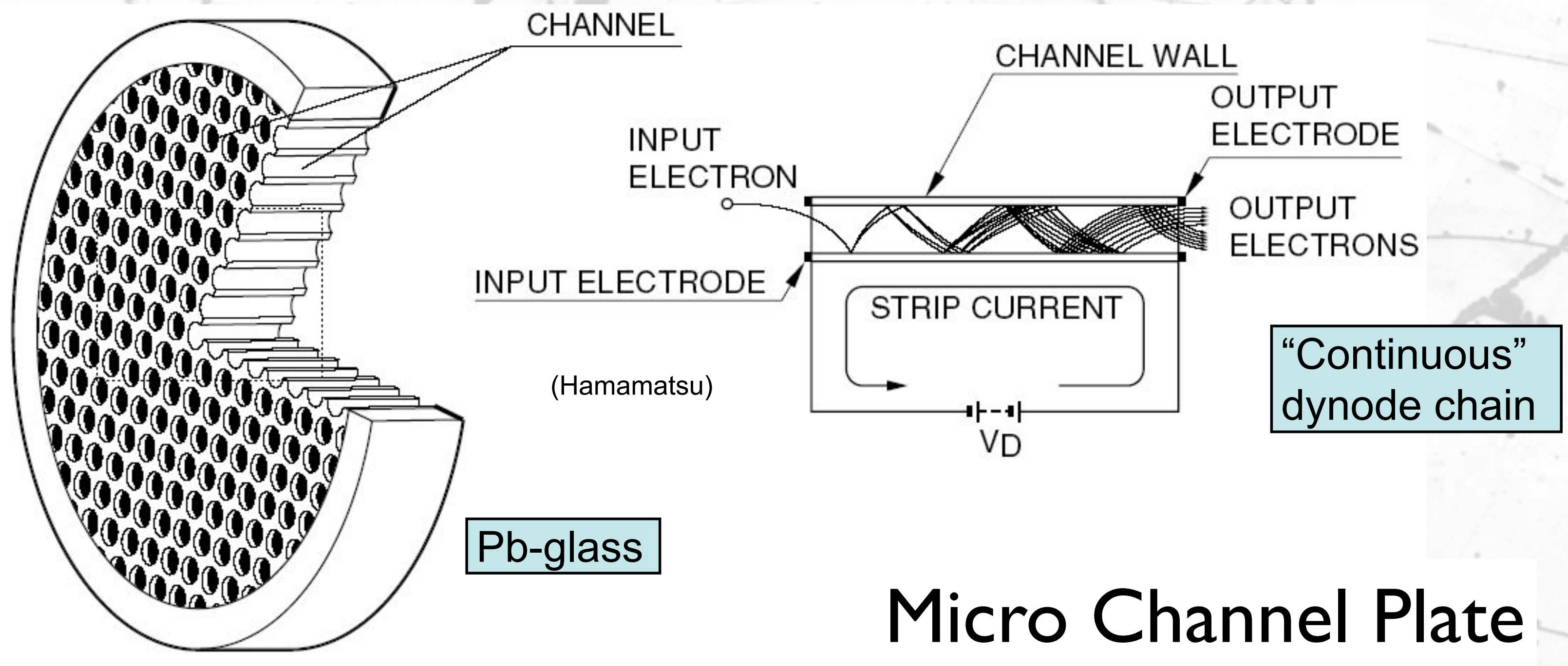
Other photo sensors



“Continuous” dynode chain

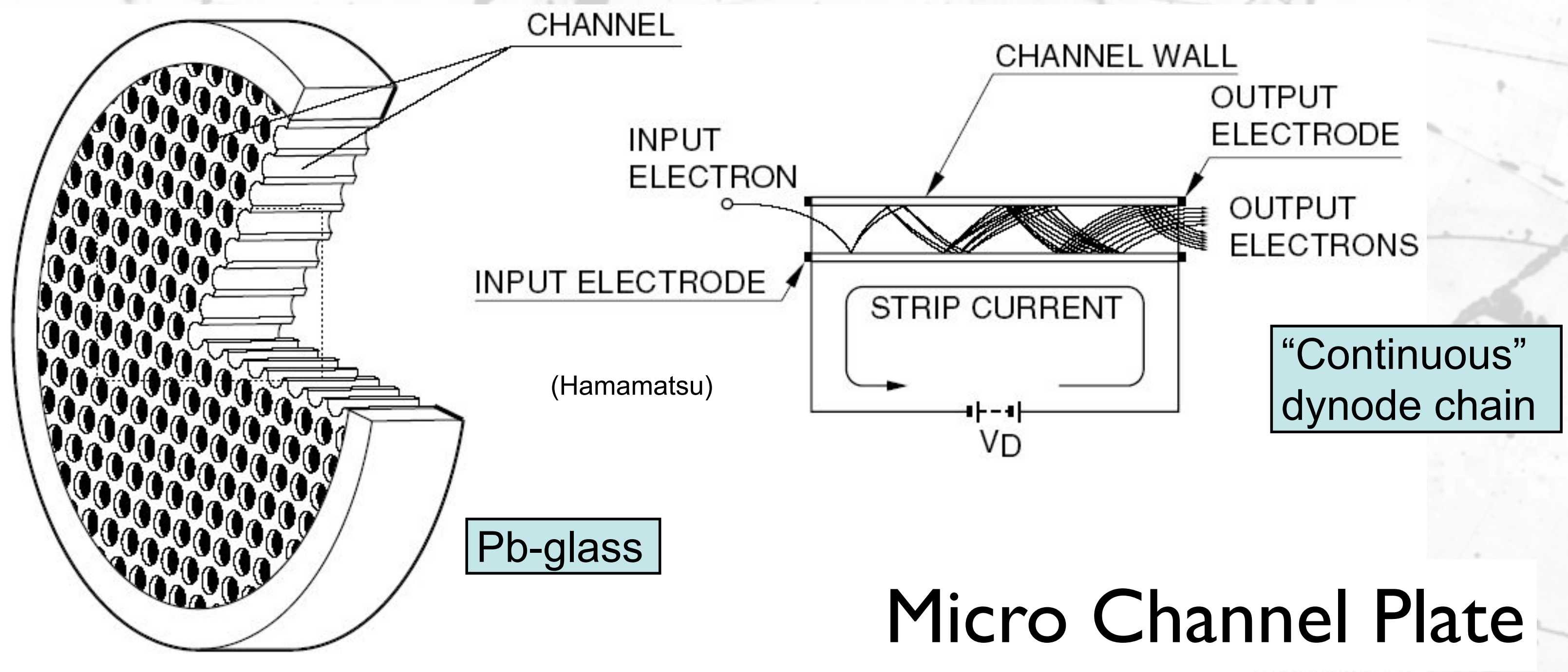
Pb-glass

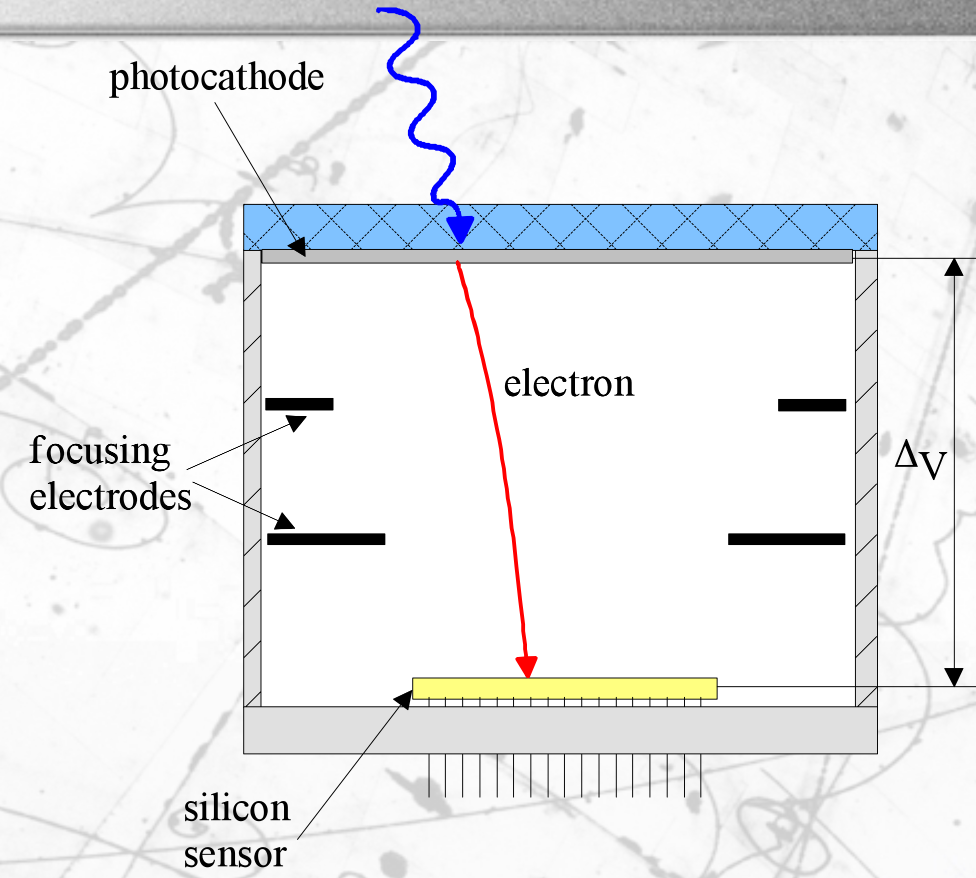
Other photo sensors



Micro Channel Plate

Other photo sensors





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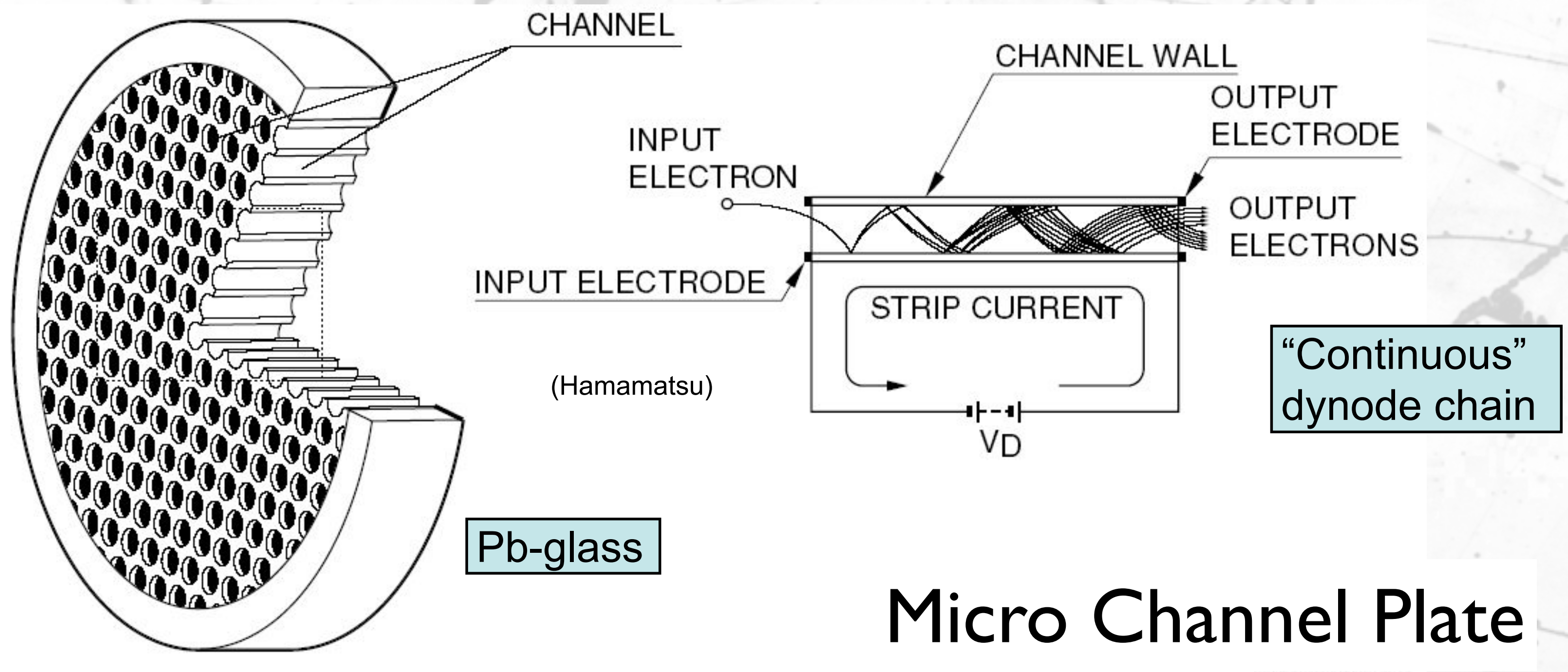

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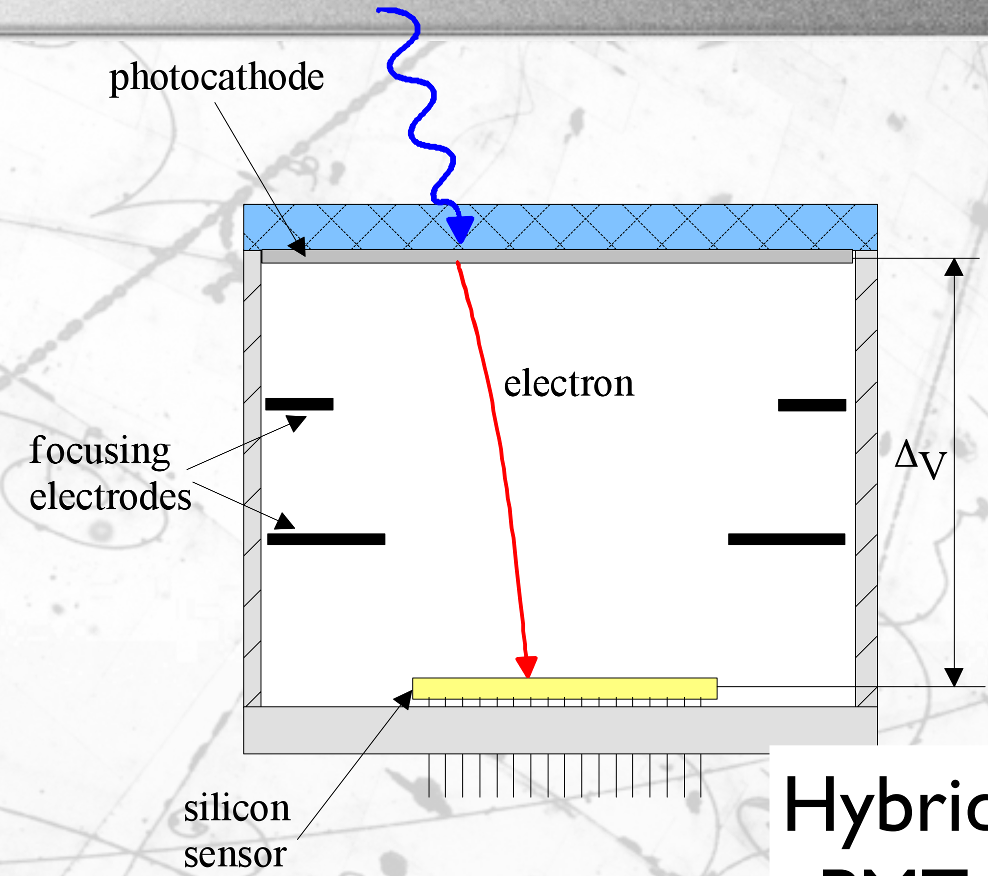
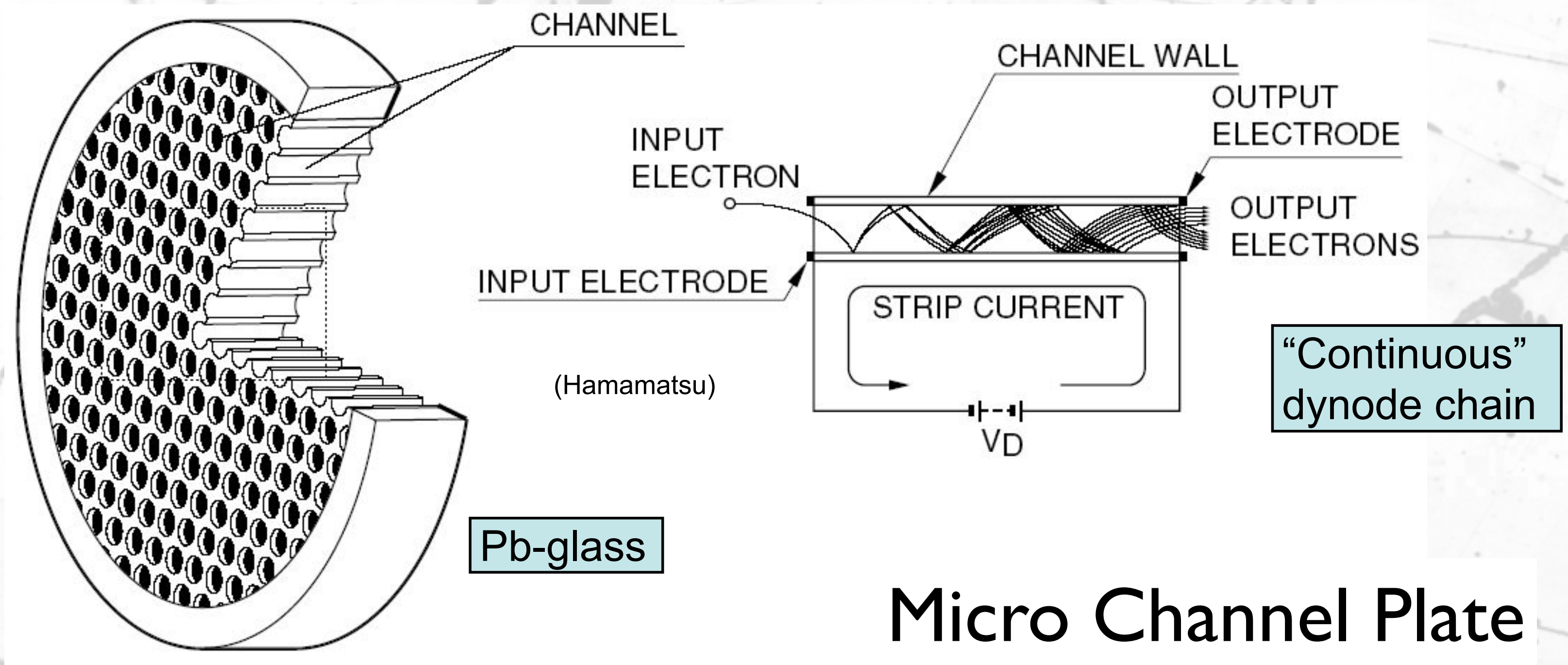


Hybrid PMT

Other photo sensors



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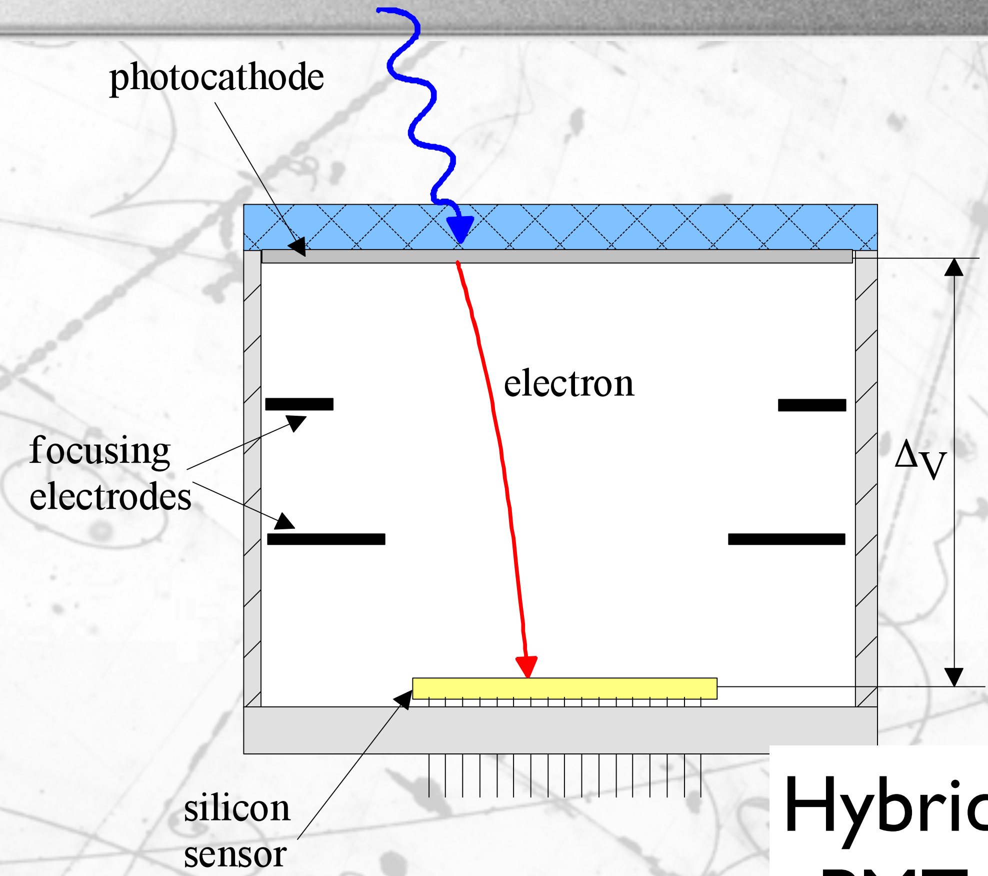

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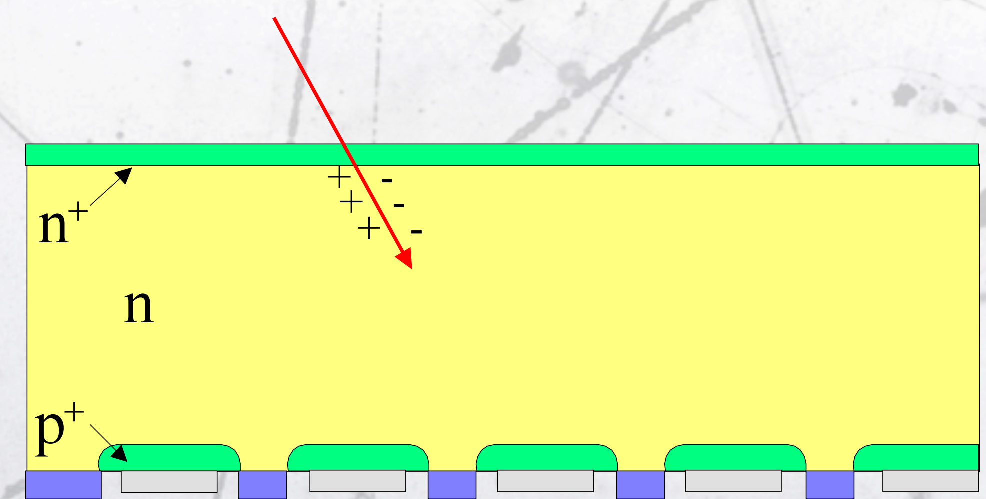

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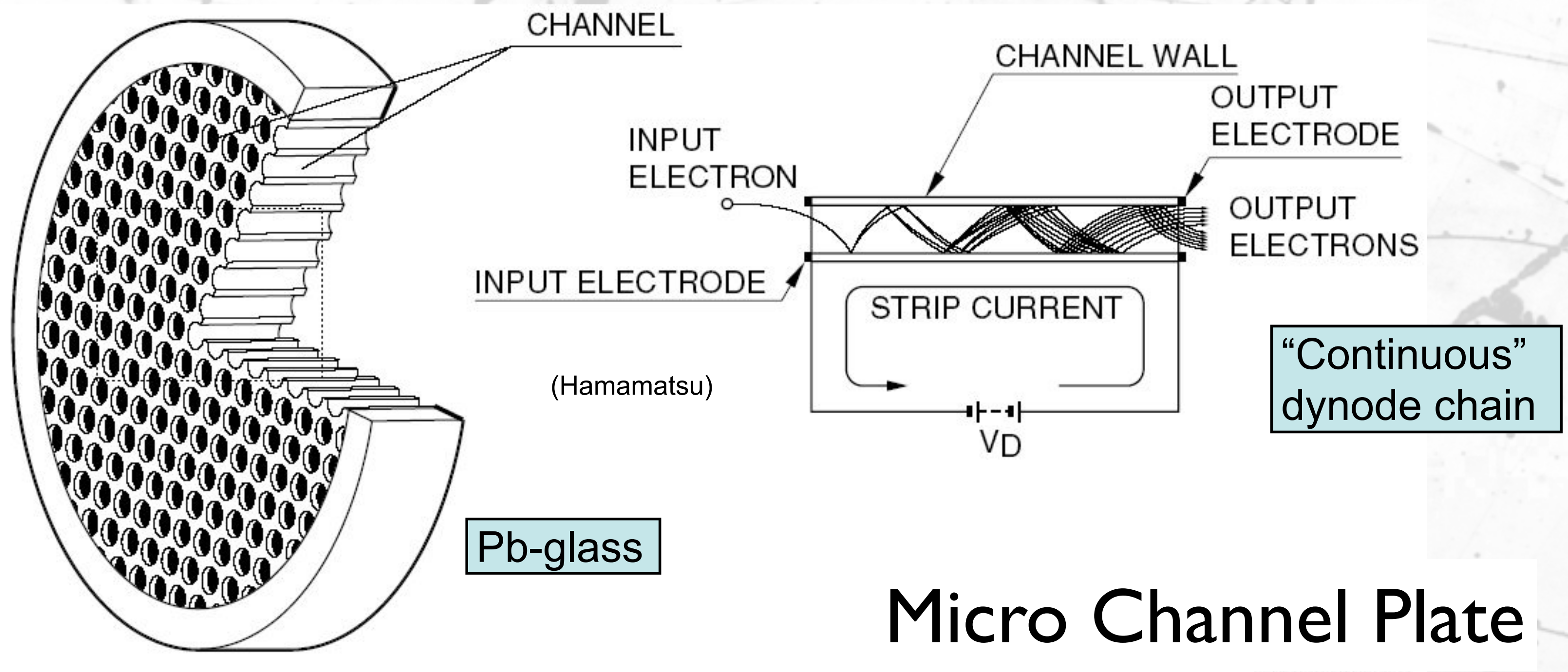

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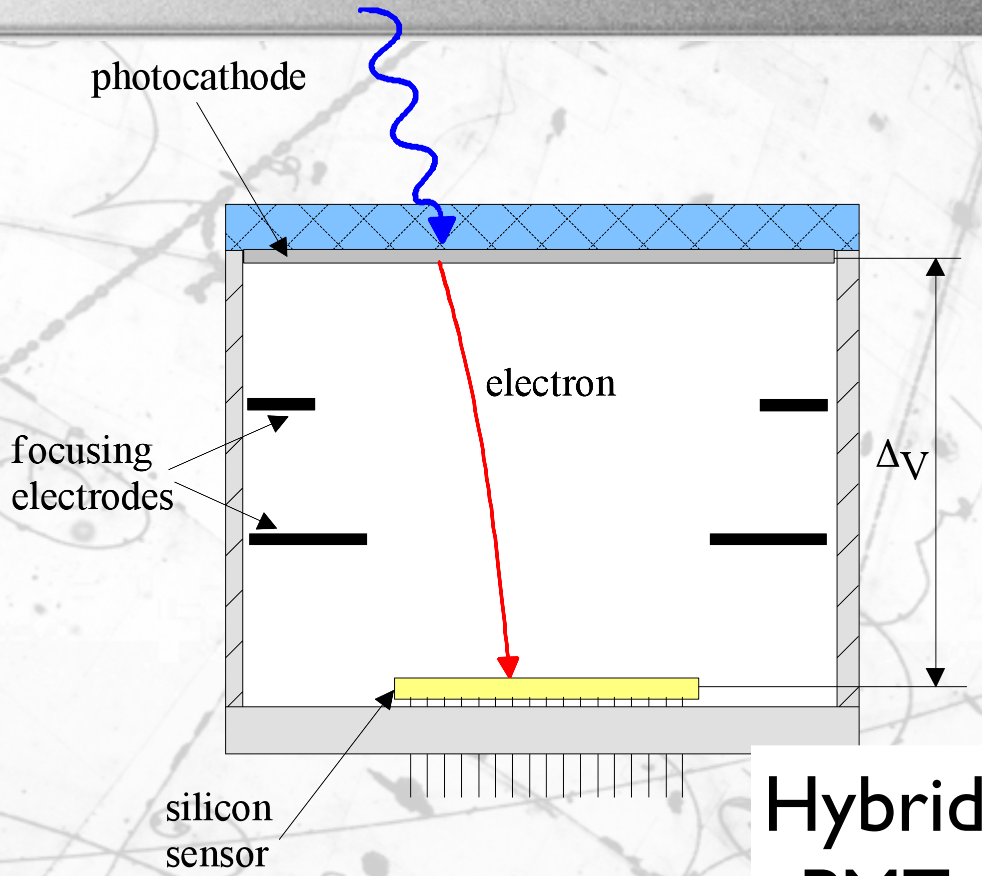

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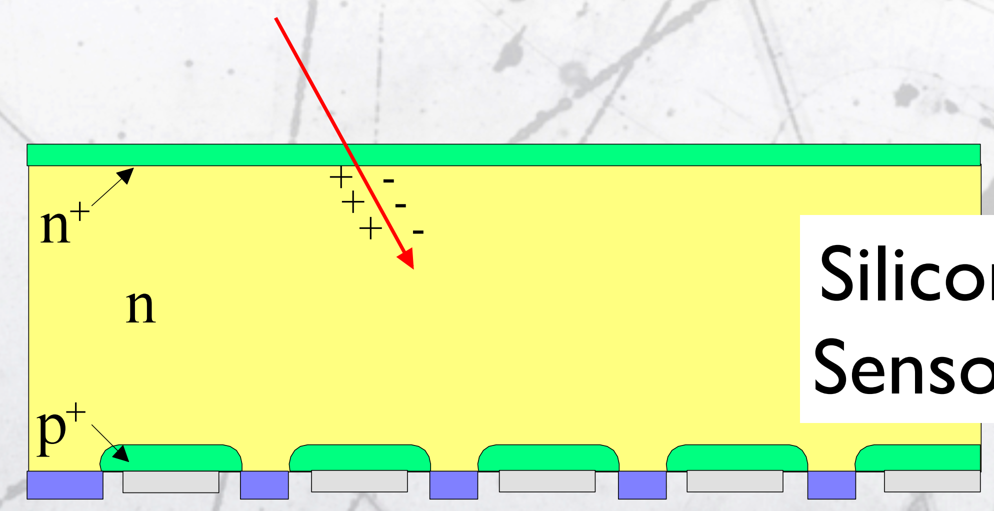
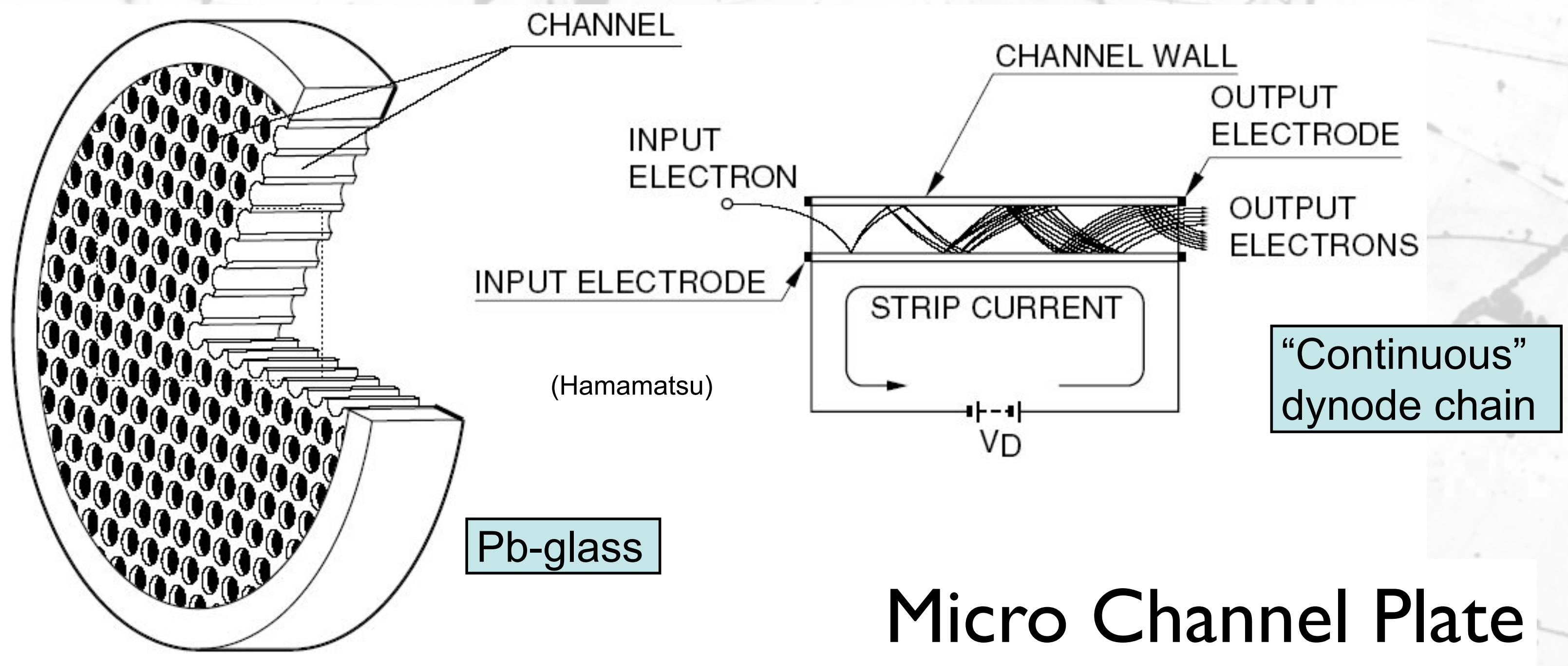


Silicon Sensor

Other photo sensors



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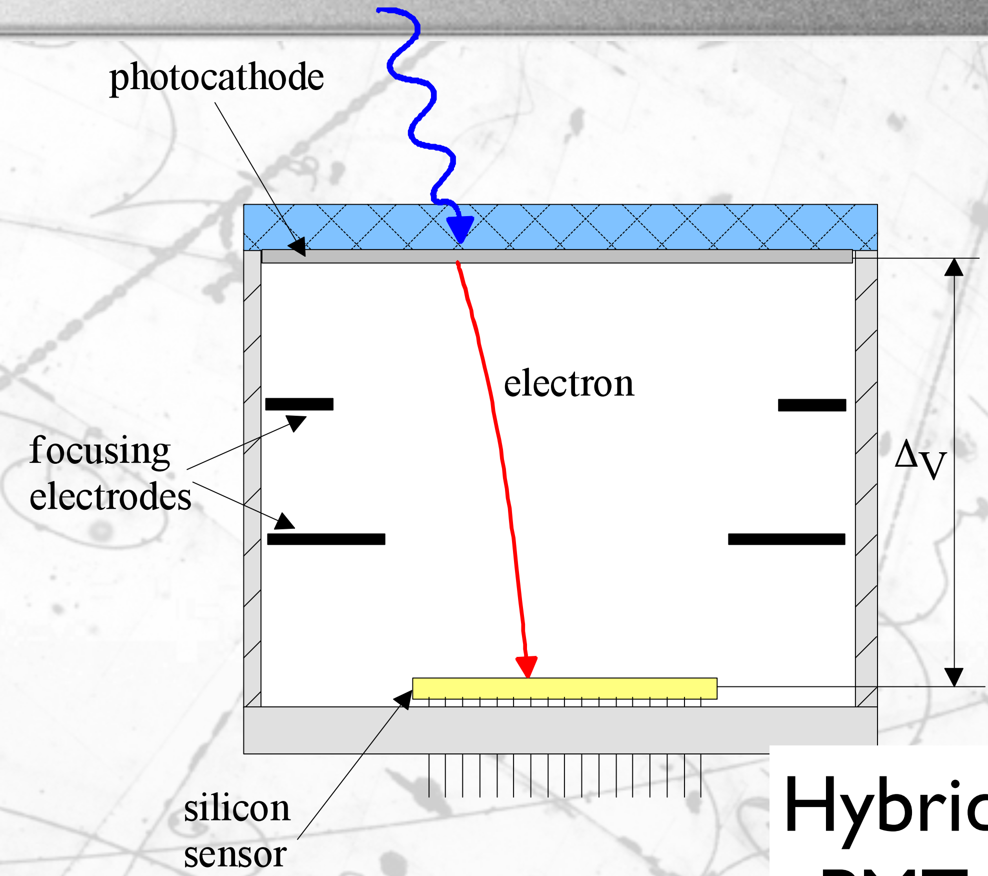

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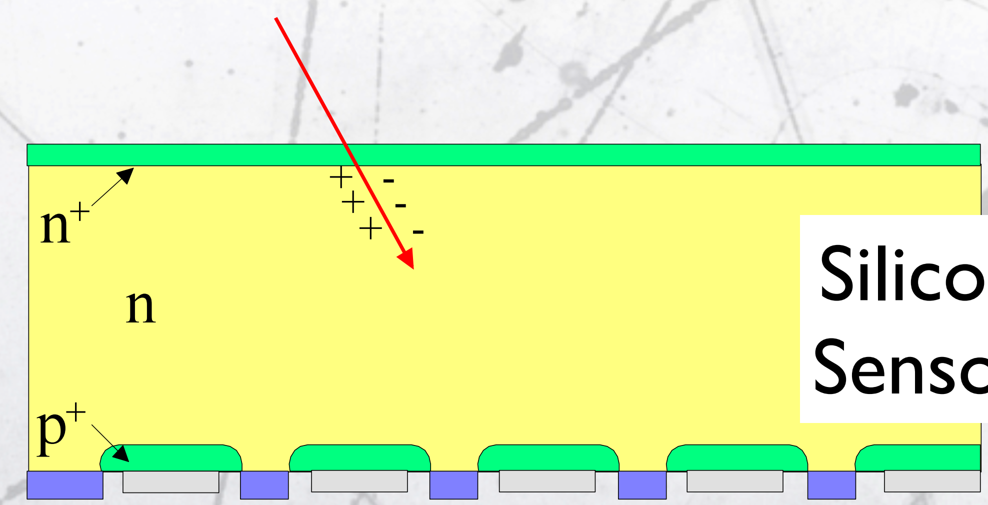

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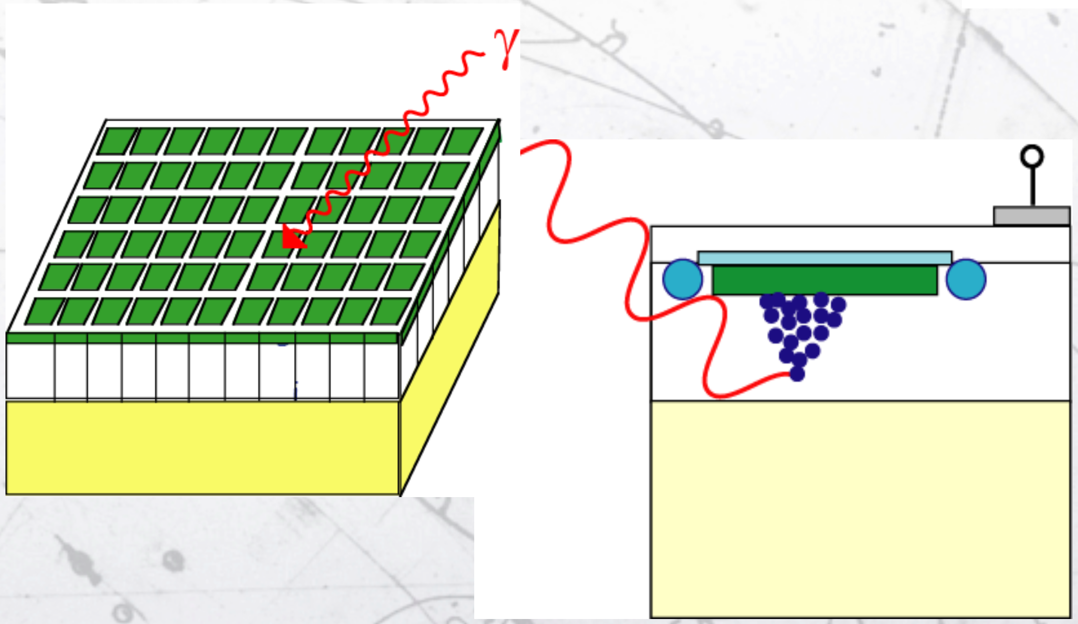

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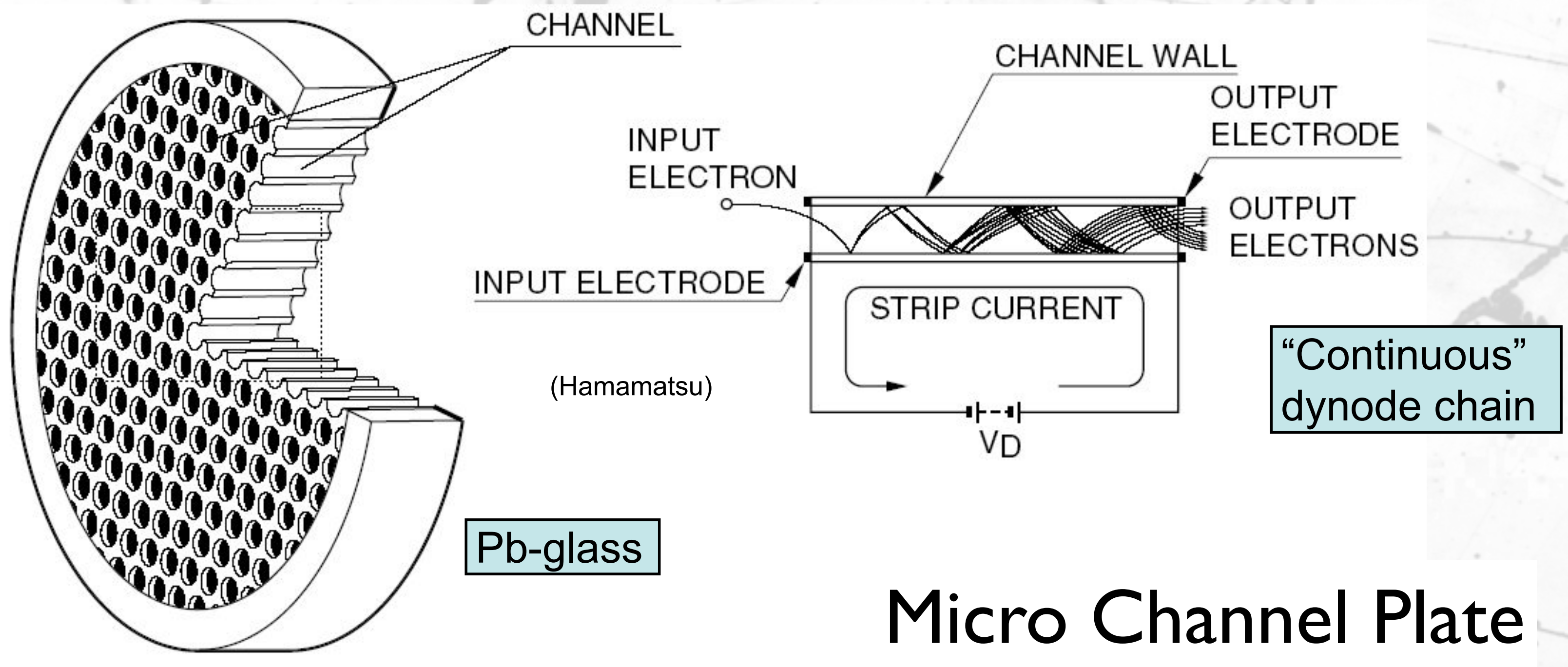

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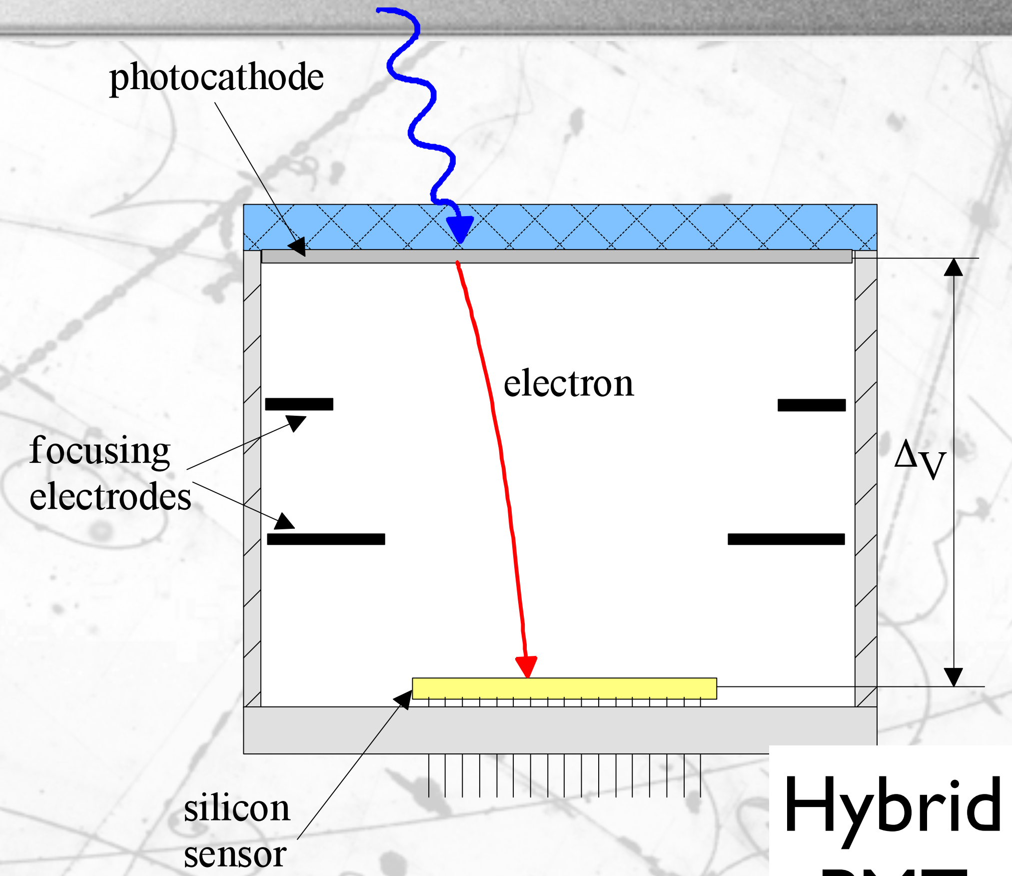

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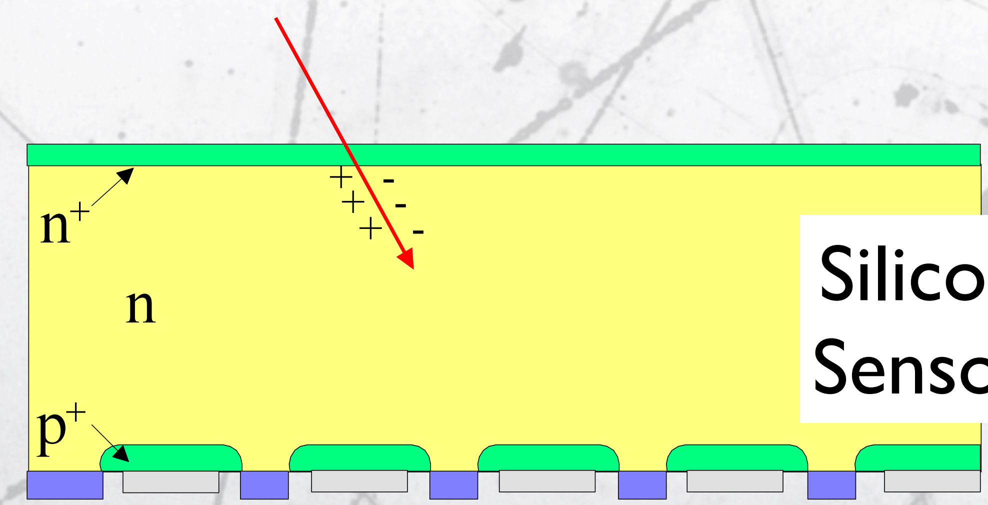

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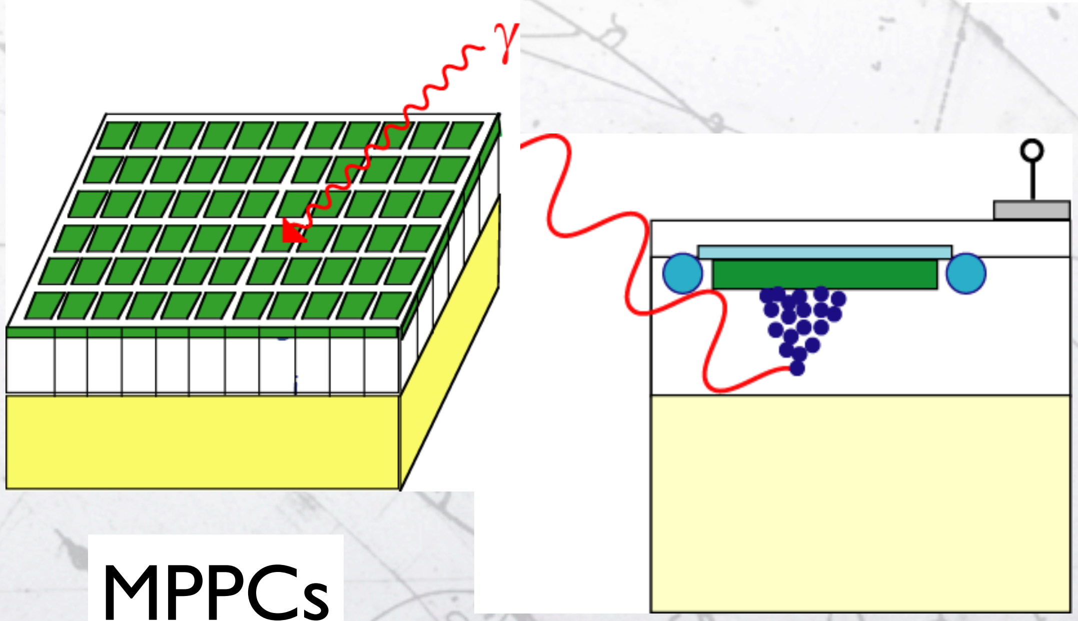
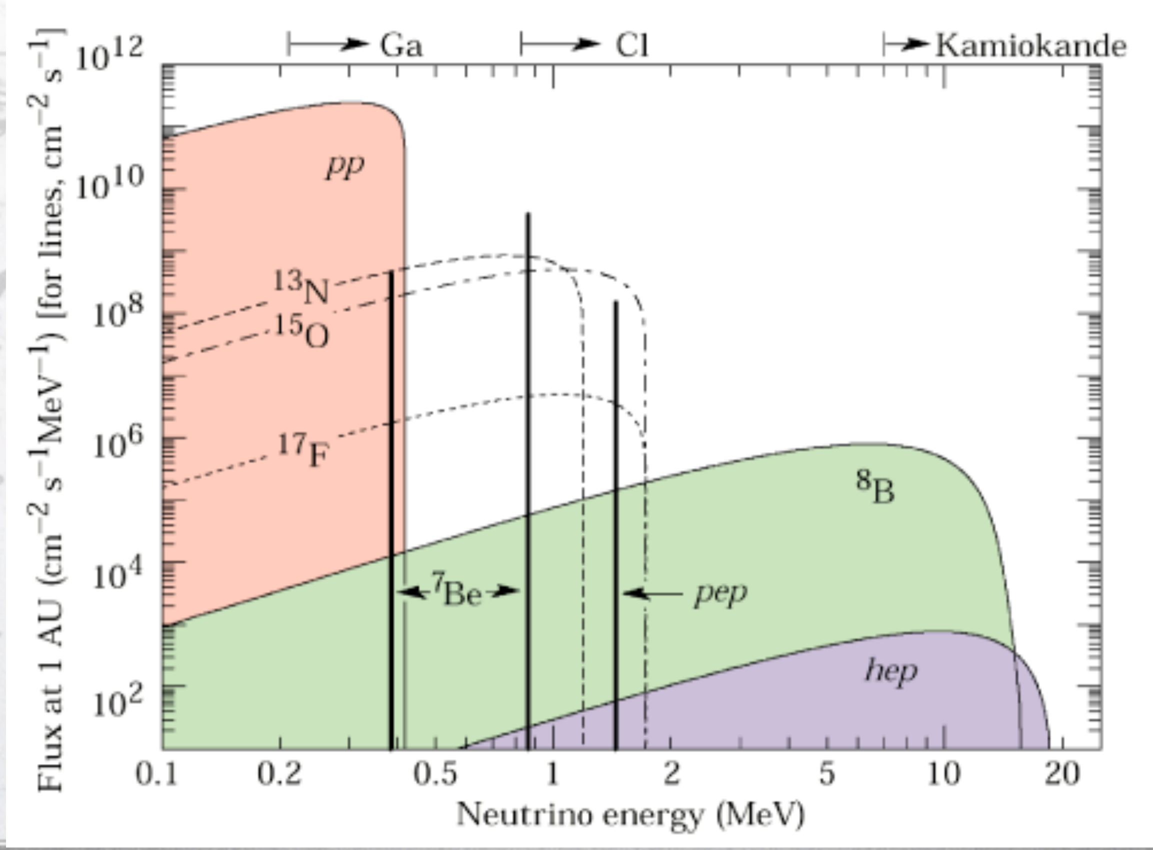


MPPCs

Scintillator

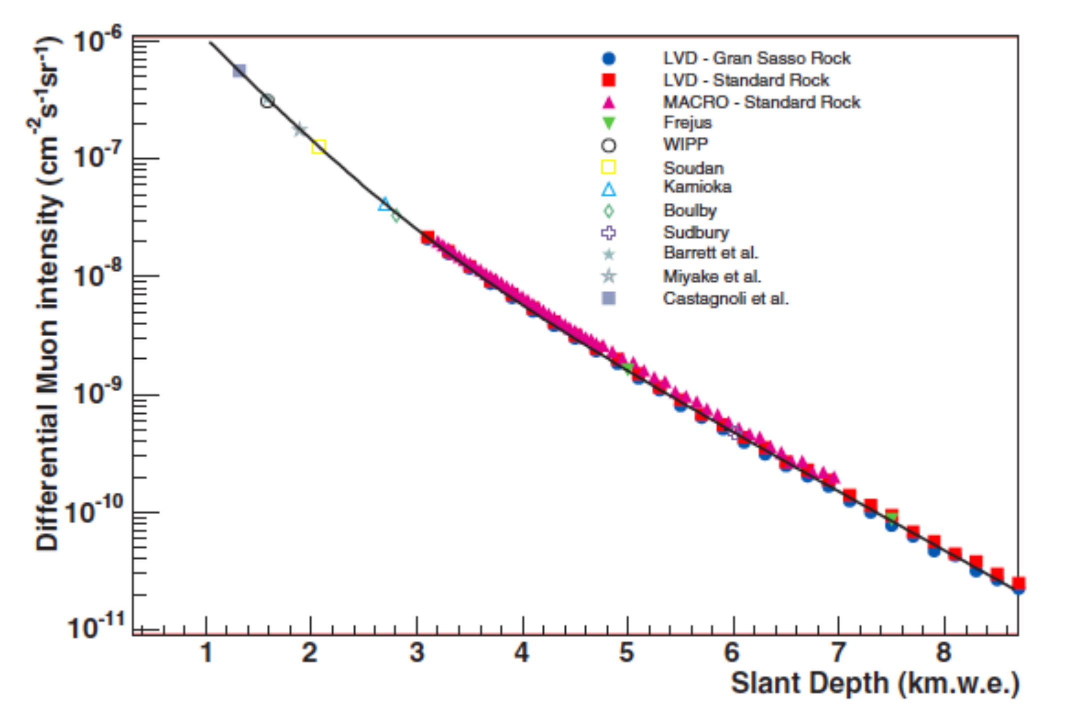
- Imaging you want to look at low energy solar neutrinos (neutrinos, no anti-neutrinos!).
  - You can't use the inverse beta decay with neutron tagging.
  - You can enrich neutrons in matter by using deuterium target (SNO) but thresholds are high (2MeV).
  - The only option is the very low threshold electron scattering: $\nu\ e^- \rightarrow \nu\ e^-$



Scintillator detectors

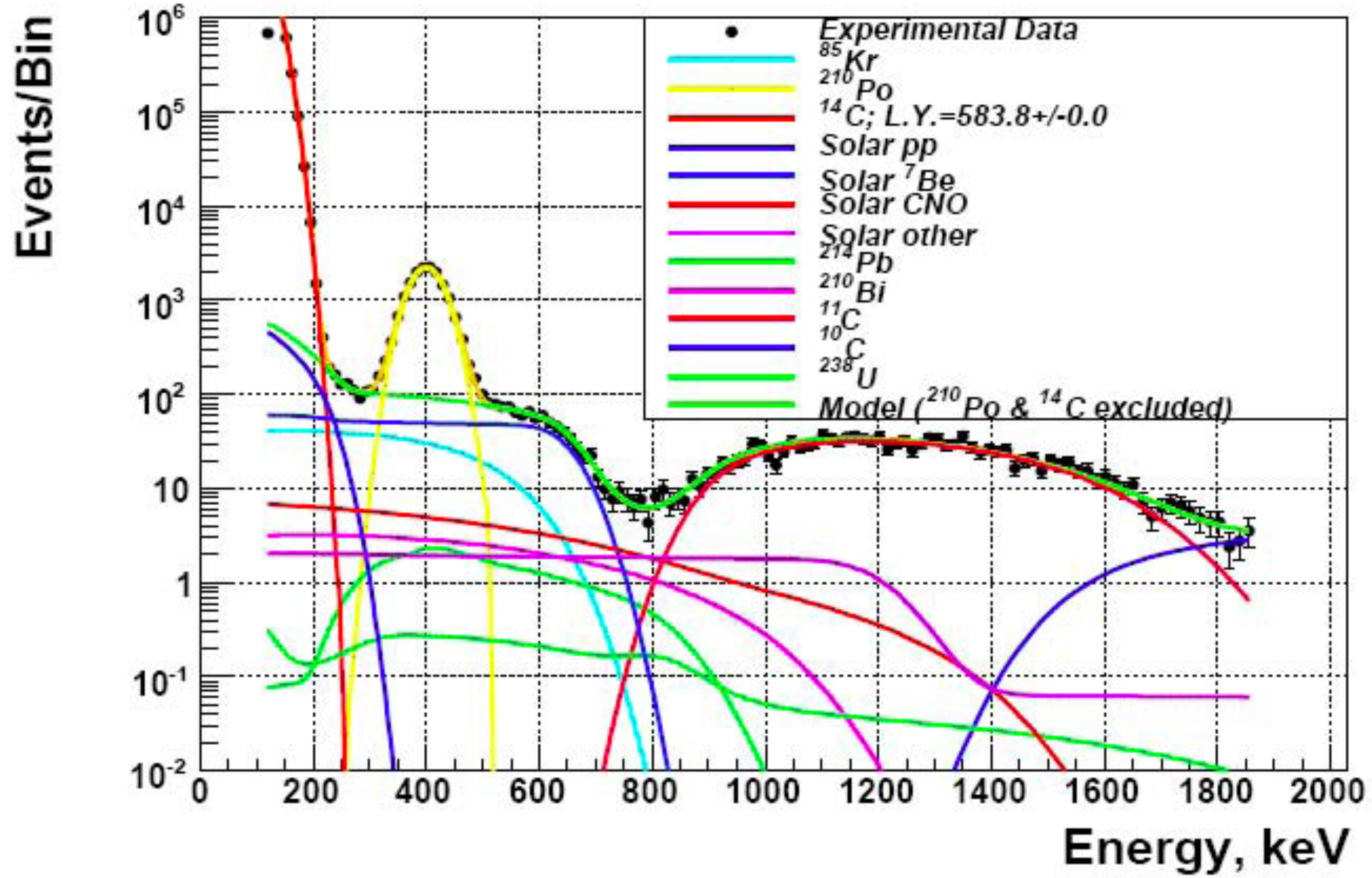
- The electron signal is very similar to β (also α and γ) decay signature!.
  - No background reduction from coincidence.
  - No pointing capability to reduce 4π background (we will see this in SK)
- The only option is a clean detector in a clean environment:
  - Borexino manage backgrounds of the order of 2 10^{-18} g/g → ~10^{8} atoms/kg
- Cosmogenic stands for radioactivity induced by cosmic rays. That means it is produced constantly. This is dramatically reduced by going underground.

Background	Typical abundance (source)	Borexino goals	Borexino measured
$^{14}C/^{12}C$	10^{-12} (cosmogenic) g/g	10^{-18} g/g	~ 2 10^{-18} g/g
^{238}U (by ^{214}Bi-^{214}Po)	2 10^{-5} (dust) g/g	10^{-16} g/g	(1.6±0.1) 10^{-17} g/g
^{232}Th (by ^{212}Bi-^{212}Po)	2 10^{-5} (dust) g/g	10^{-16} g/g	(5±1) 10^{-18} g/g
^{222}Rn (by ^{214}Bi-^{214}Po)	100 atoms/cm^3 (air) emanation from materials	10^{-16} g/g	~ 10^{-17} g/g (~1 cpd/100t)
^{210}Po	Surface contamination	~1 c/d/t	May 07 : 70 c/d/t Sep08 : 7 c/d/t
^{40}K	2 10^{-6} (dust) g/g	~ 10^{-18} g/g	< 3 10^{-18} (90%) g/g
^{85}Kr	1 Bq/m^3 (air)	~1 c/d/100t	(28±7) c/d/100t (fast coinc.)
^{39}Ar	17 mBq/m^3 (air)	~1 c/d/100t	<< ^{85}Kr



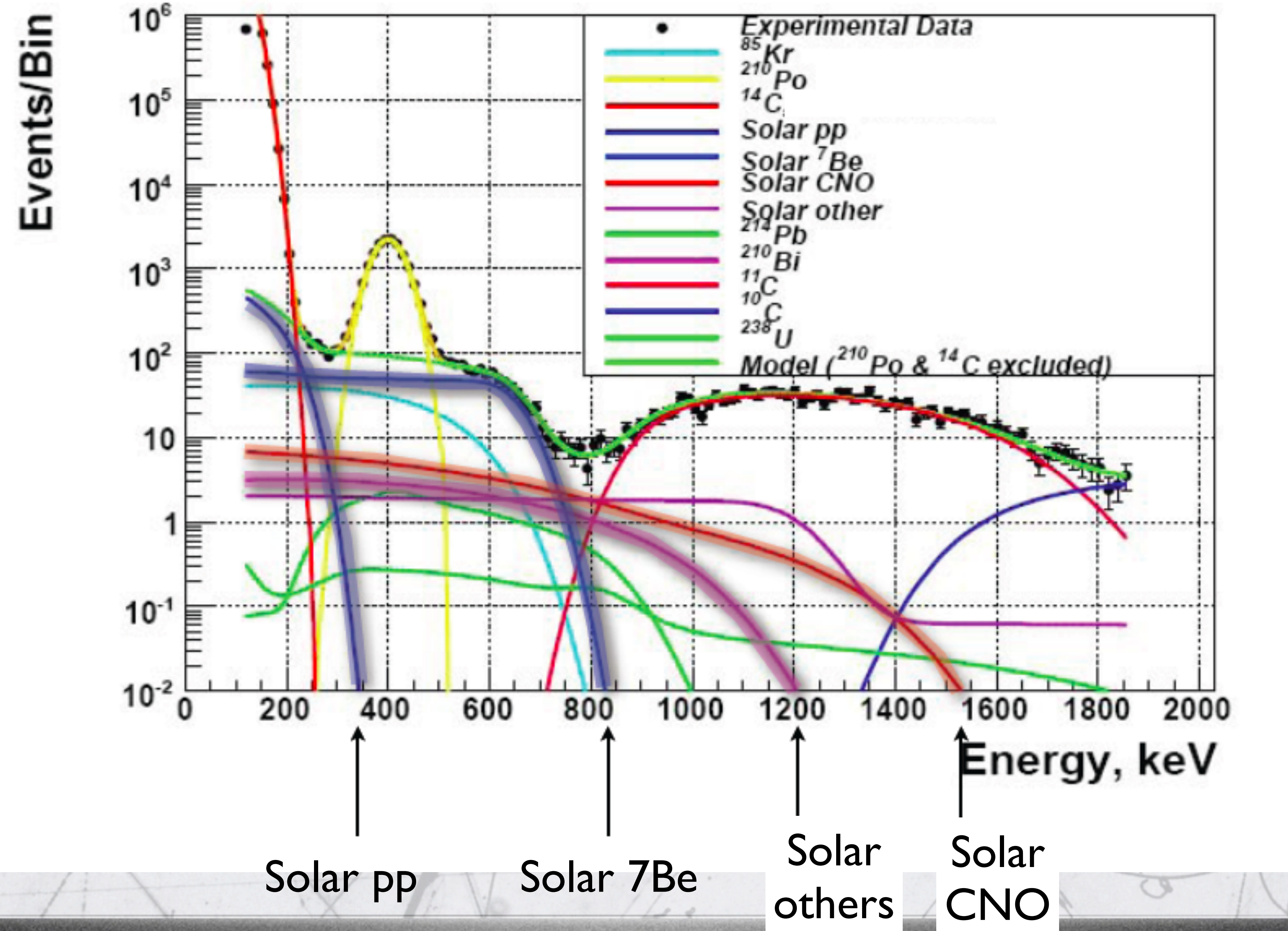
Scintillator detectors

But, this level is not enough. Background has to be measured….



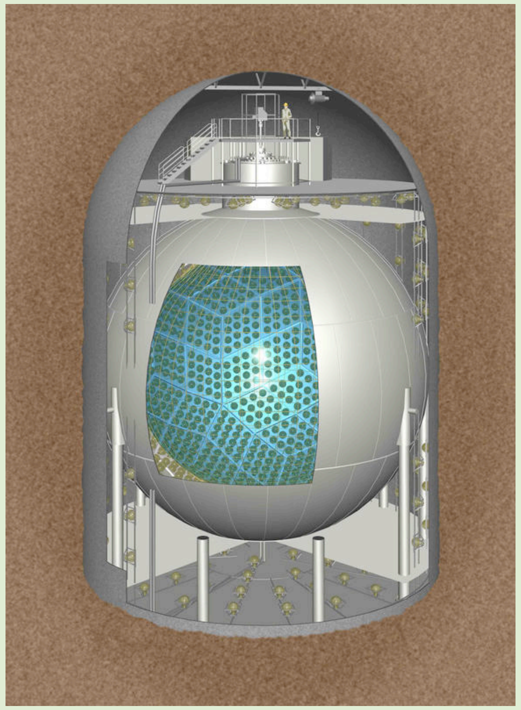
Scintillator detectors

to extract the signal...

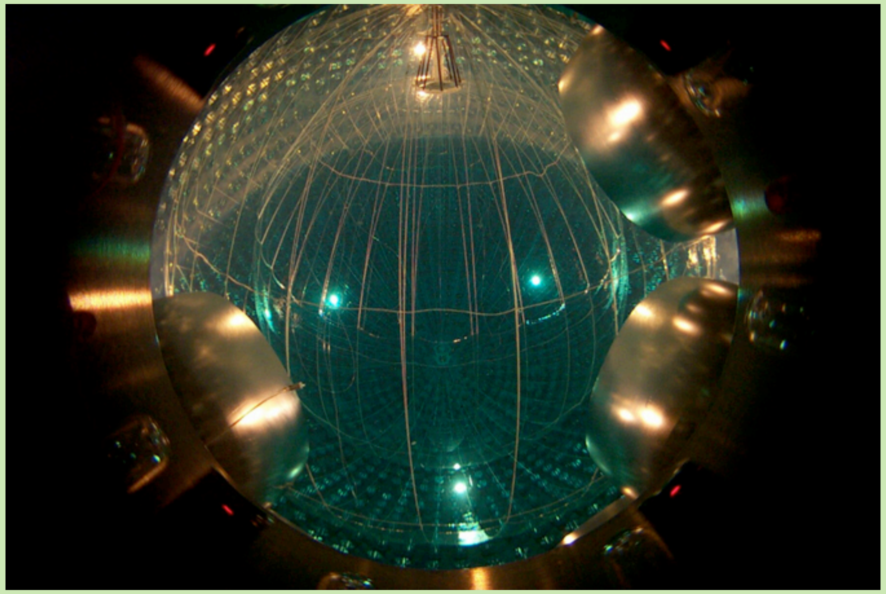


Experiments

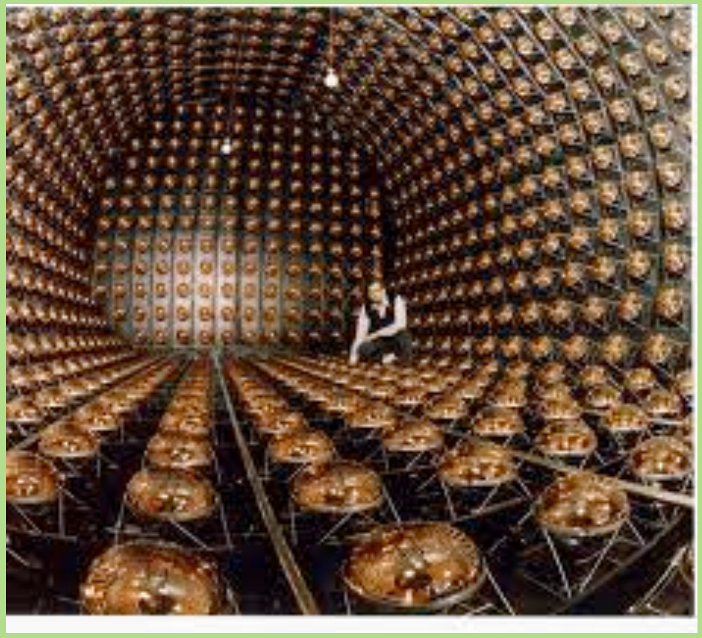
Kamland



Borexino



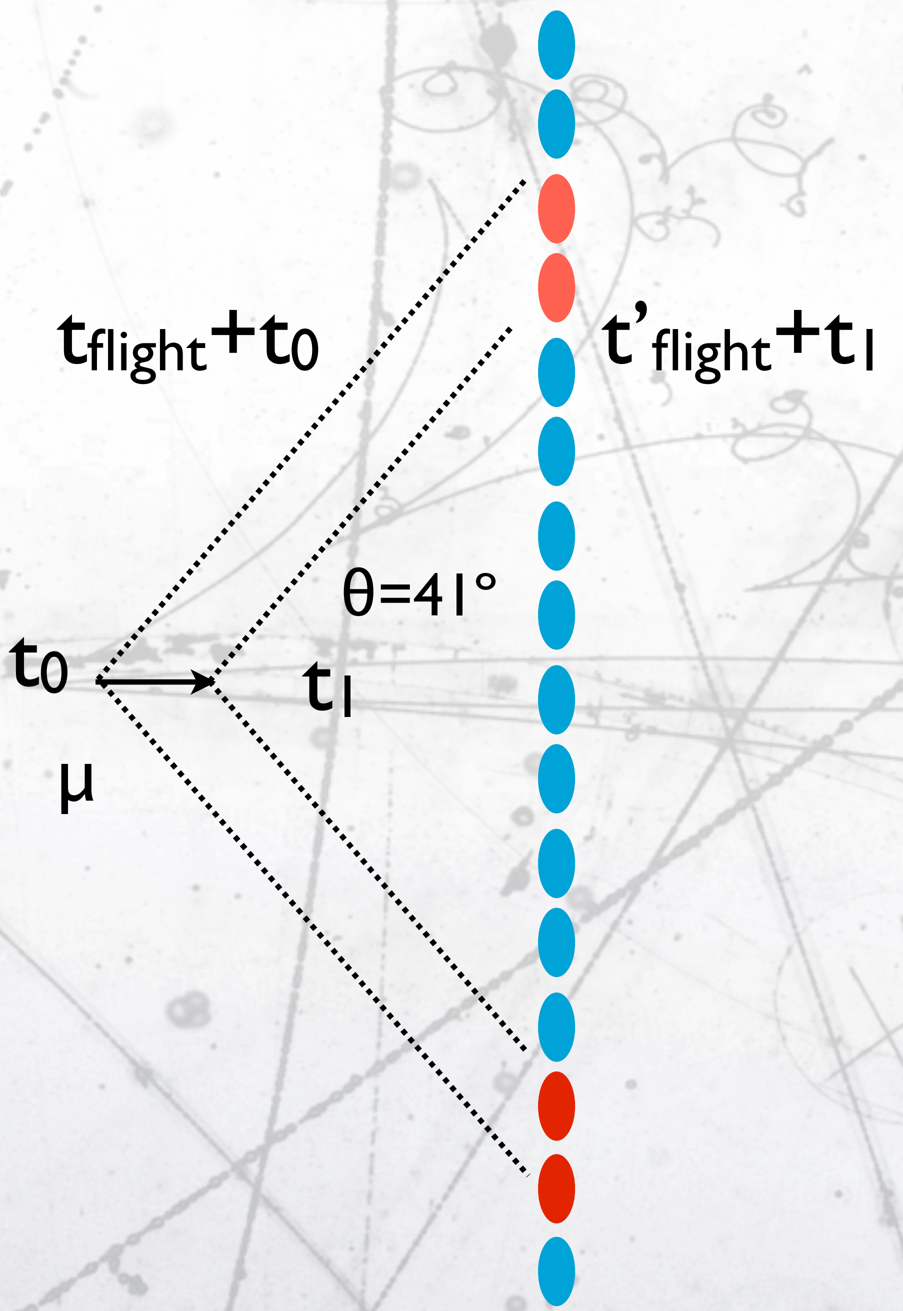
LSND



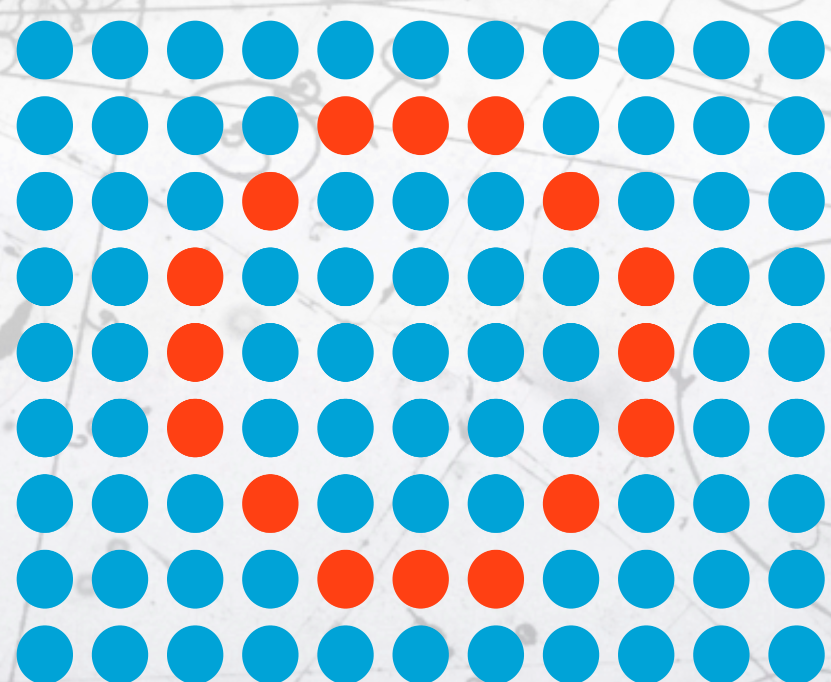
Daya Bay

Cherenkov

Cherenkov



- The Cherenkov detector uses:
    - the directionality of the light emission.
    - the time arrival of photons.
    - the total light collected.
    - the light pattern in the detector
- Requires a segmented detector.

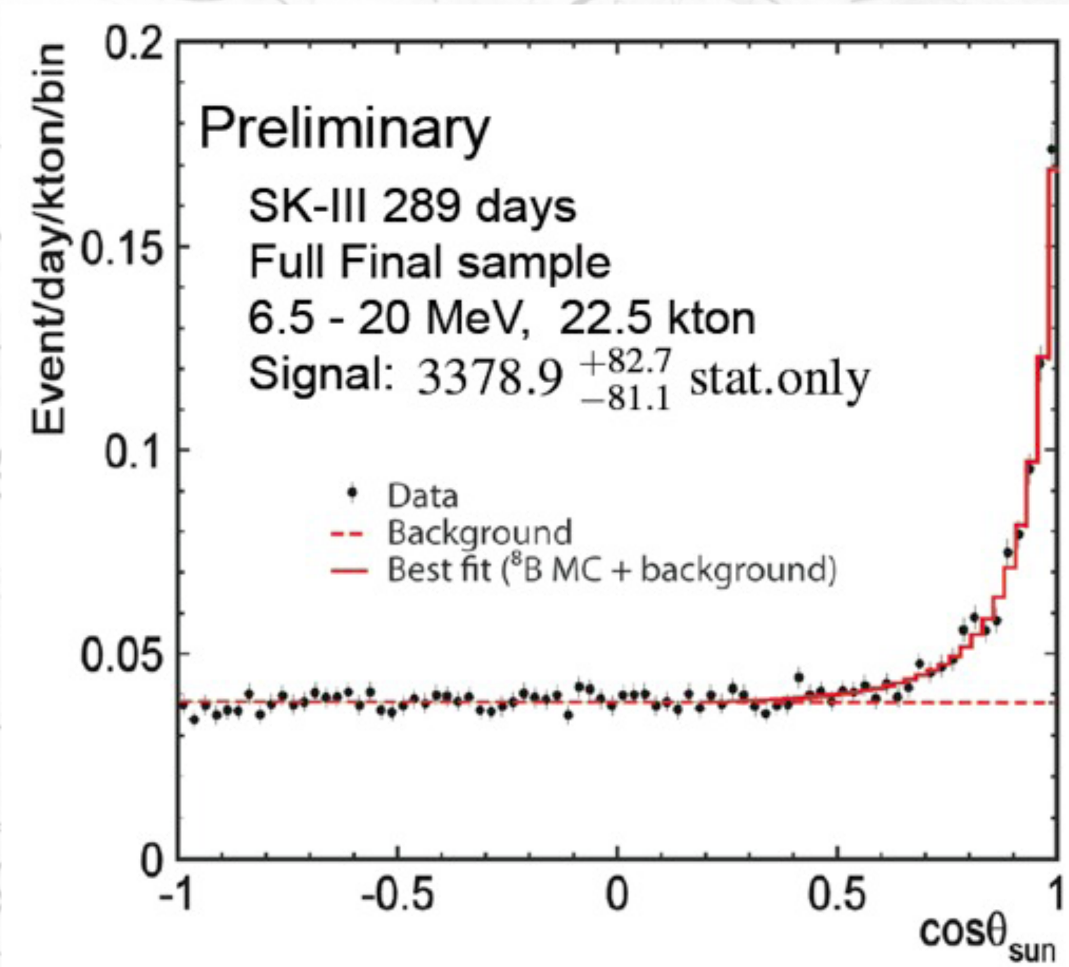


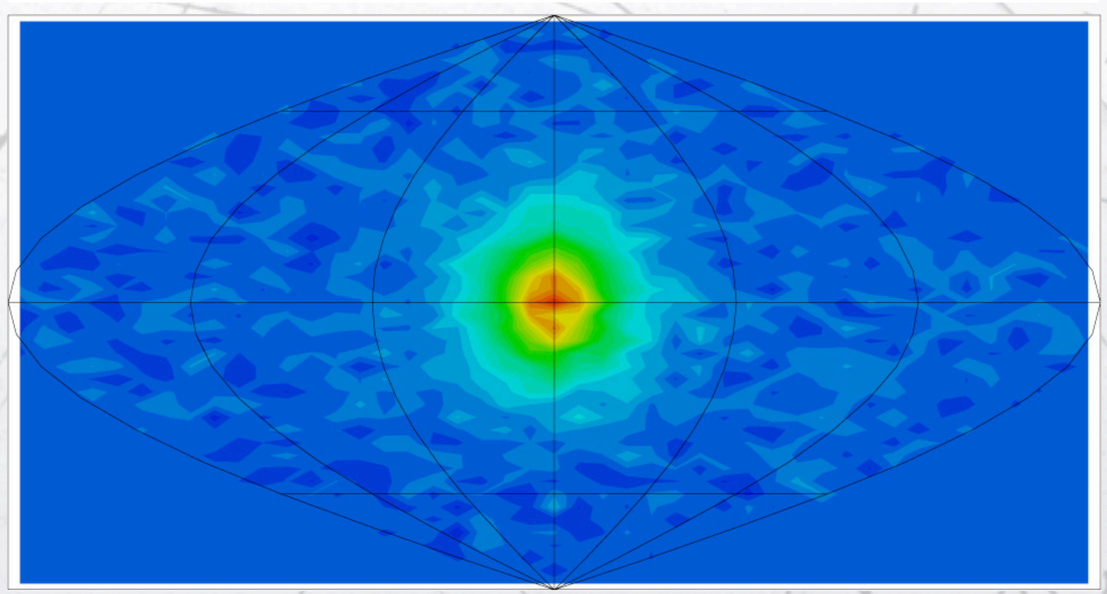
Providing

- vertex position
- range
- direction
- energy

Cherenkov

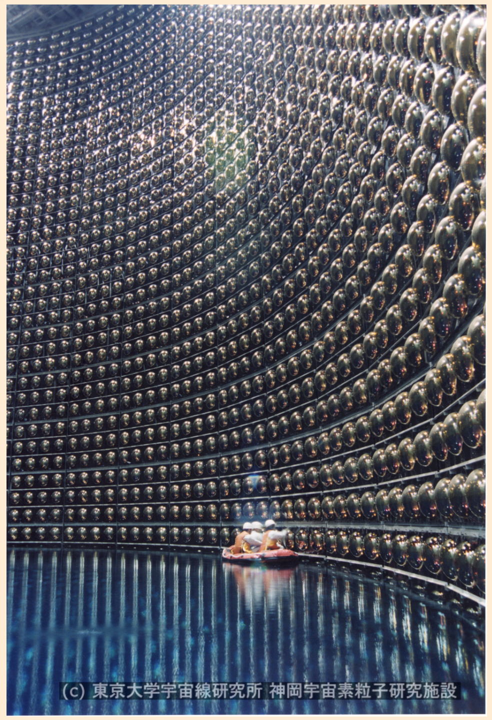
- The main advantage at low energies (MeV) to calorimetric approach is the determination of the neutrino direction.
- To profit from this, we need to:
  - have neutrino reactions which remember the neutrino direction ($\nu_e e^- \rightarrow \nu_e e^-$).
  - have a point like source so we can have a reference neutrino direction from the source. If it is moving with respect to the detector (i.e. the sun) we need to track the position at the time of the event.
- We can reduce the background by cutting (0.5 in figure) and have an estimation of the background by extrapolation.



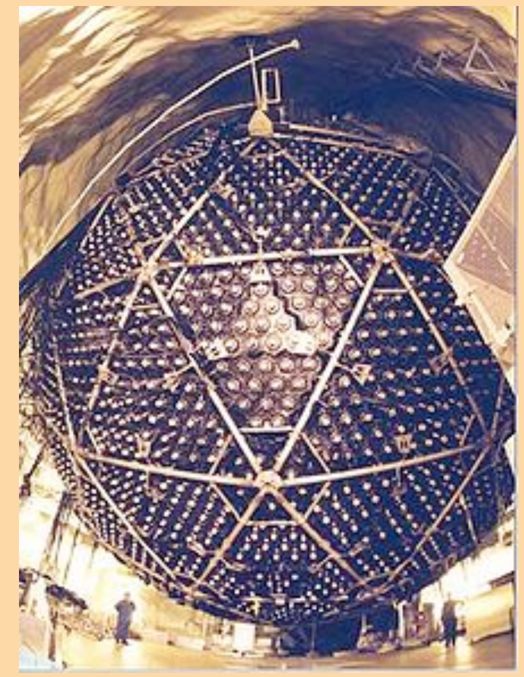


Experiments

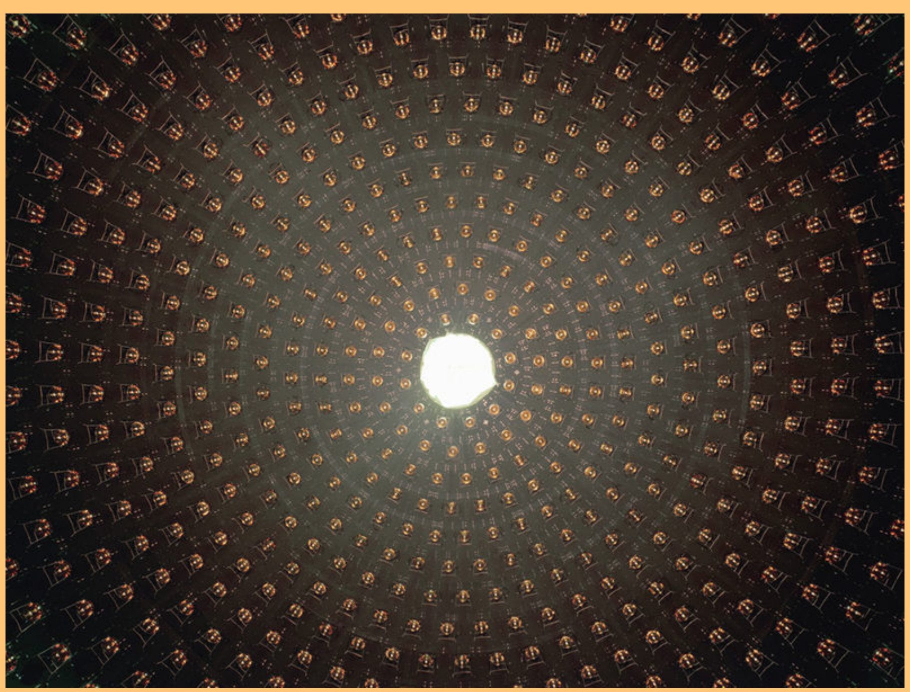
SuperKamiokande



SNO



MiniBoone



IMB

High energy detectors

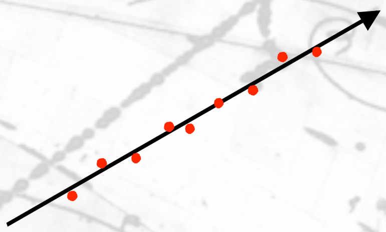
High Energy

- When going to high energies the detection gets more complicated:
  - There is energy to produce heavier leptons in CC. Particle identification starts to be crucial.
  - The particles are not contained in the detector: $E_{ionization} \neq E_{particle}$
  - The neutrino interactions are dominated by nuclear interactions:
    - interaction channel and hadron identification are important.
  - The particles are energetic enough to shower in the detector:
    - + Particle id.
    - - Energy reconstruction.

Gas ionisation

Gas Ionisation

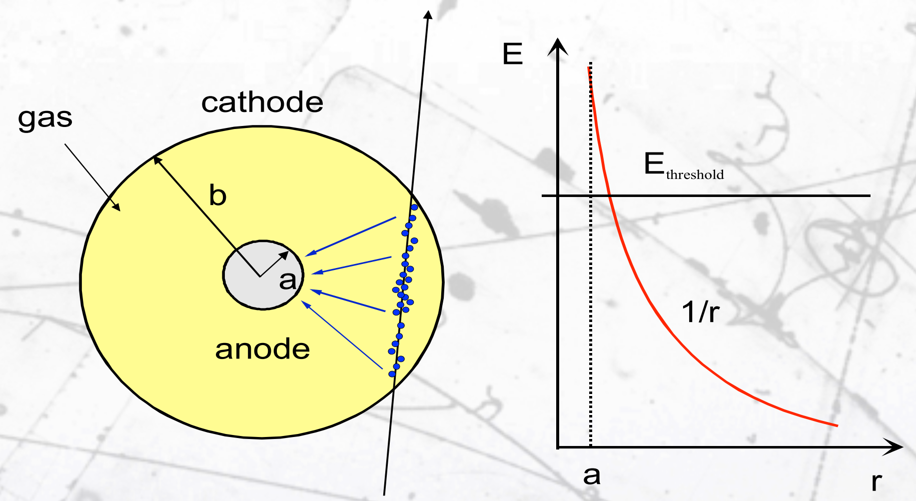
- Charged particles ionize the atoms of a gas.
- If the A^+ and the e^- are not separated, they recombine → apply E field to drift them appart.
- In 1cm of gas ~100 e- are produced. We need to increase the number of electrons.
- We can accelerate the electrons in an intense electric field (narrow wire).
- The electrons can ionize the media and produce more electrons that are accelerated and produce more electrons in an avalanche.
  - The gain is more or less exponential:
    - Large gain.
    - Poor energy resolution.



Primary ionization

10 - 40 pairs/cm

ΔE/pair ~ 20 - 40 eV

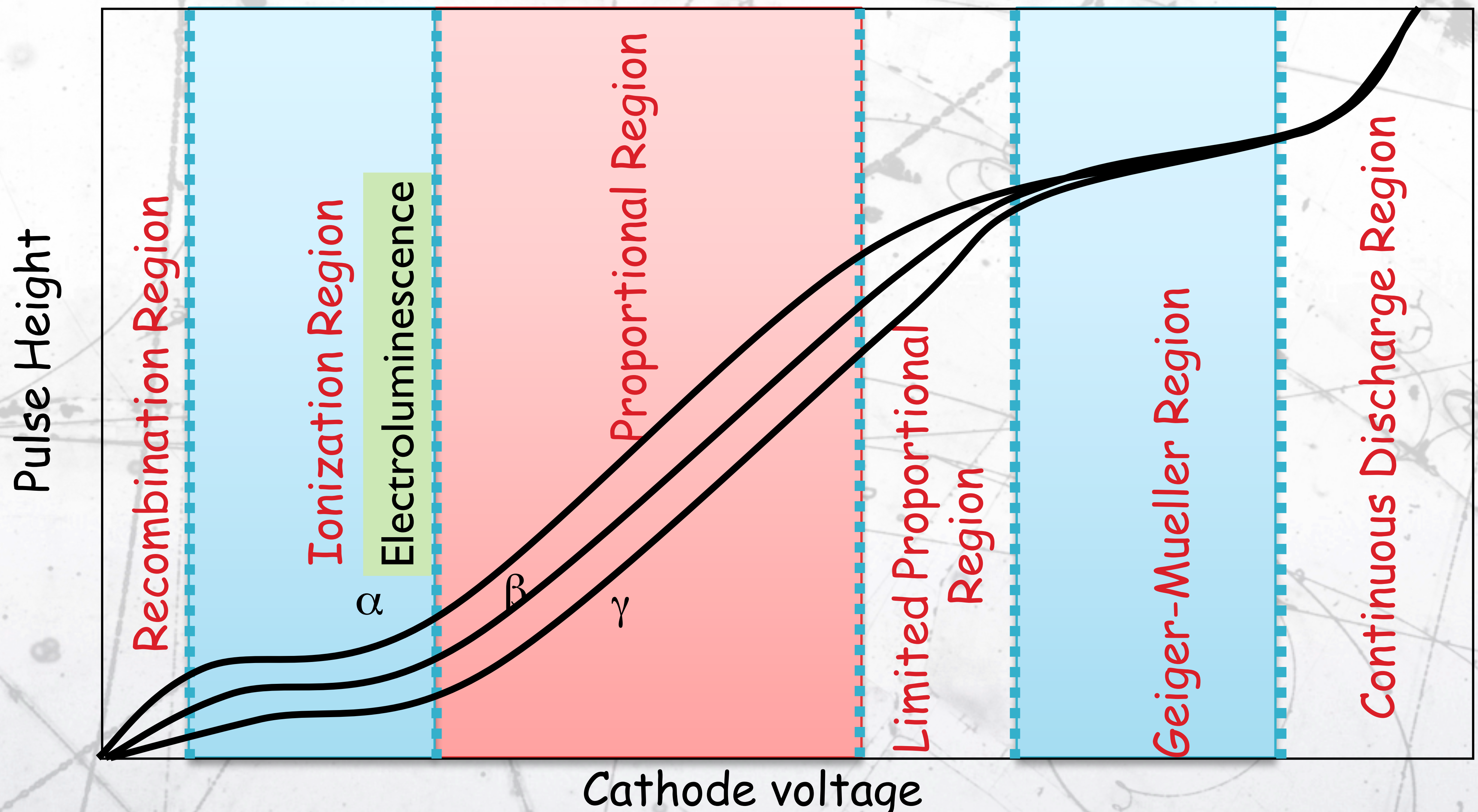


$$M = \frac{n}{n_0} = \exp\left[\int_a^{r_C} \alpha(r)\,dr\right]$$

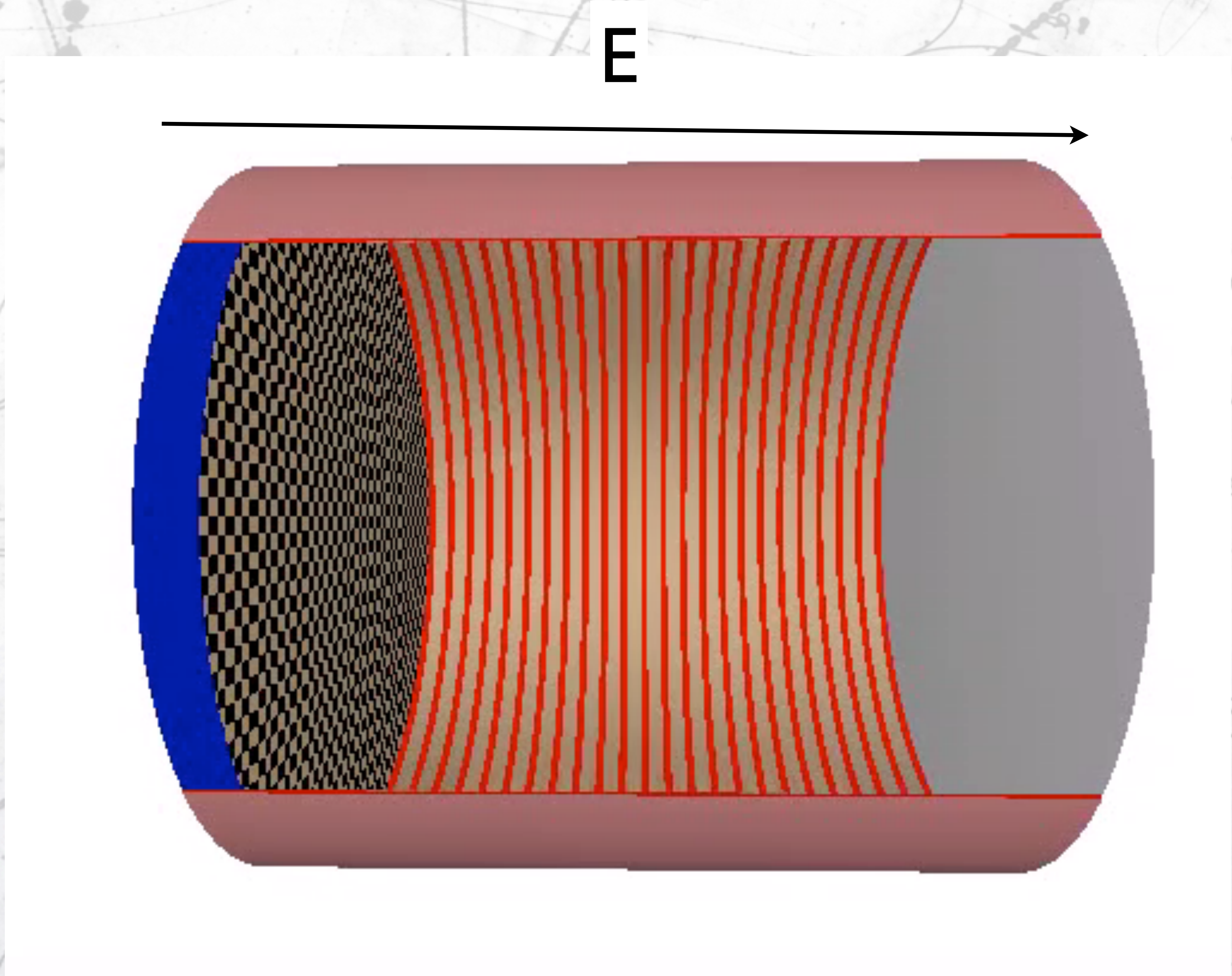
$$\alpha = \frac{1}{\lambda}$$

λ = mean free path

Readout techniques

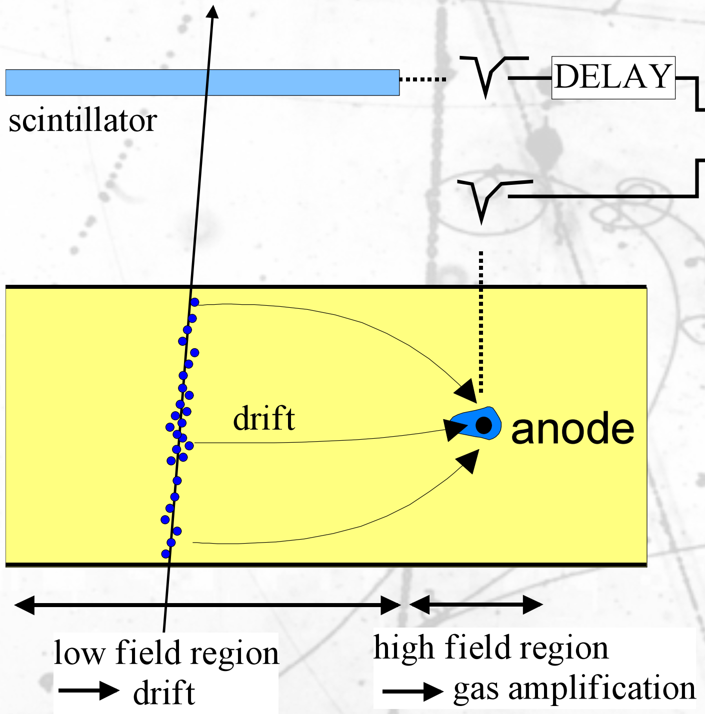


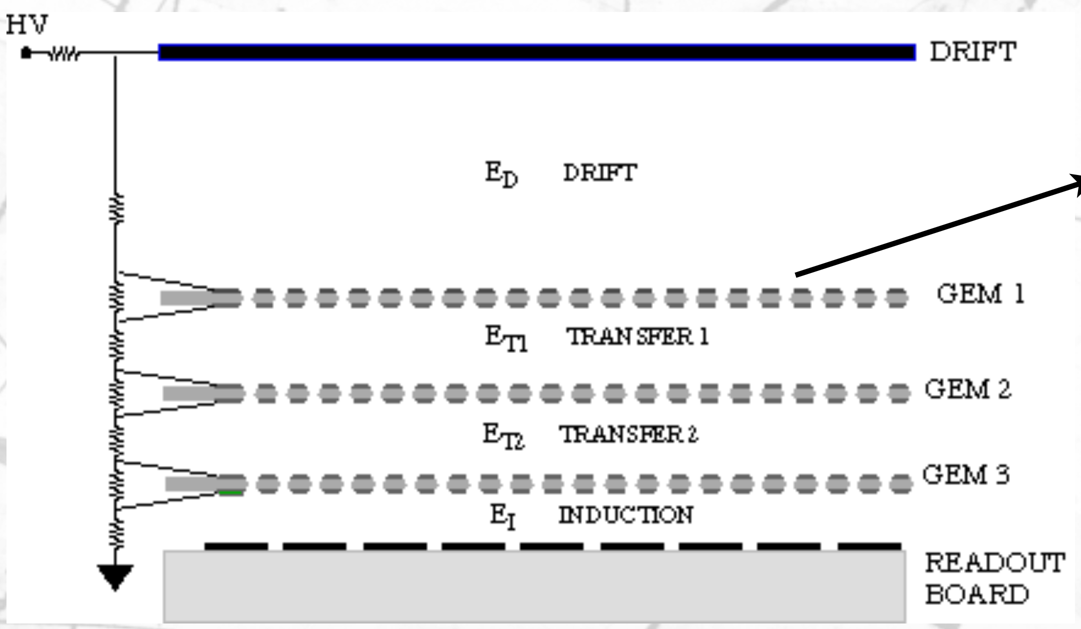
Time Projection Chamber

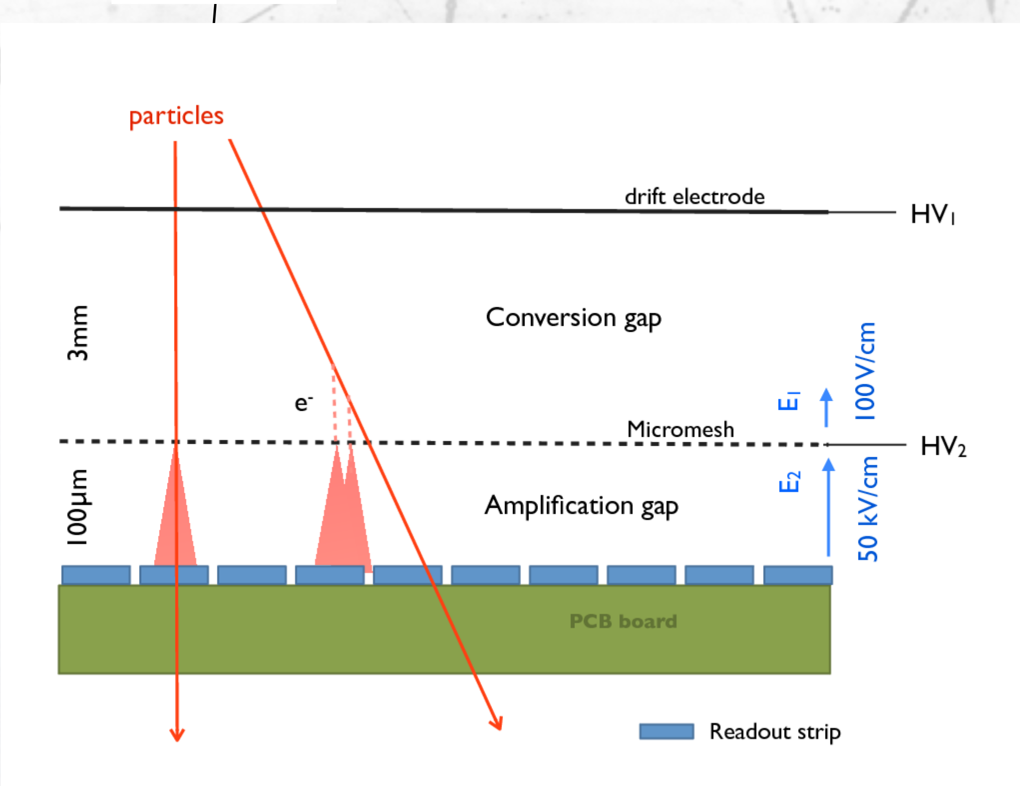


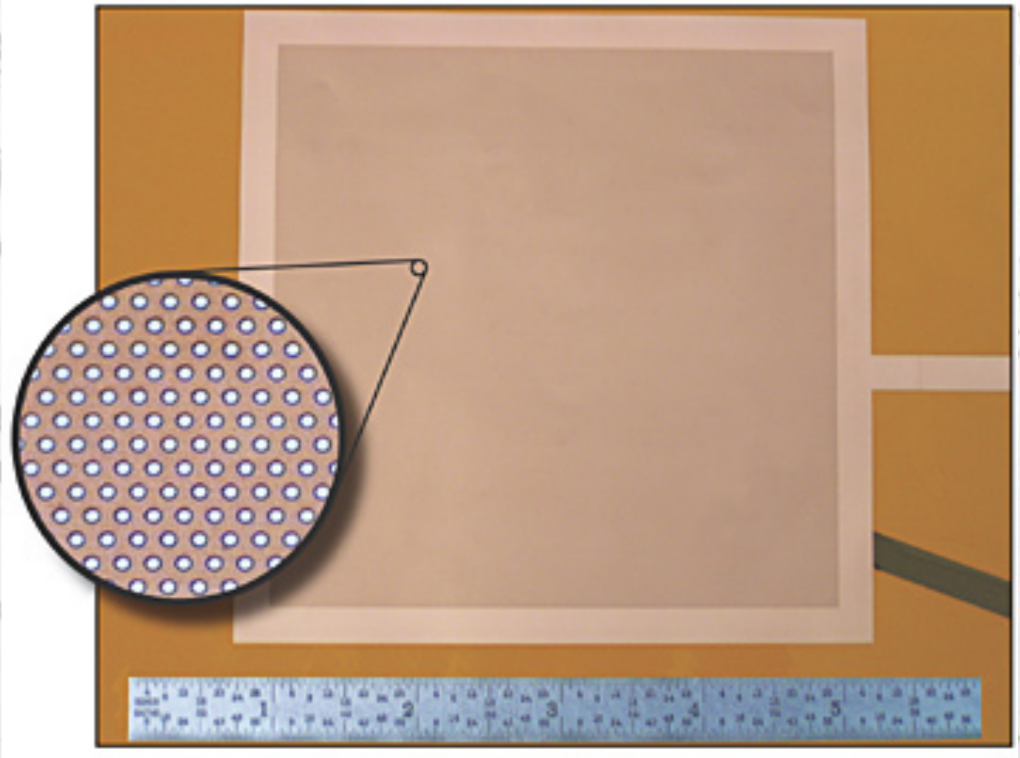
- The E field prevents the recombination and drift electrons to the readout planes.

Readout techniques

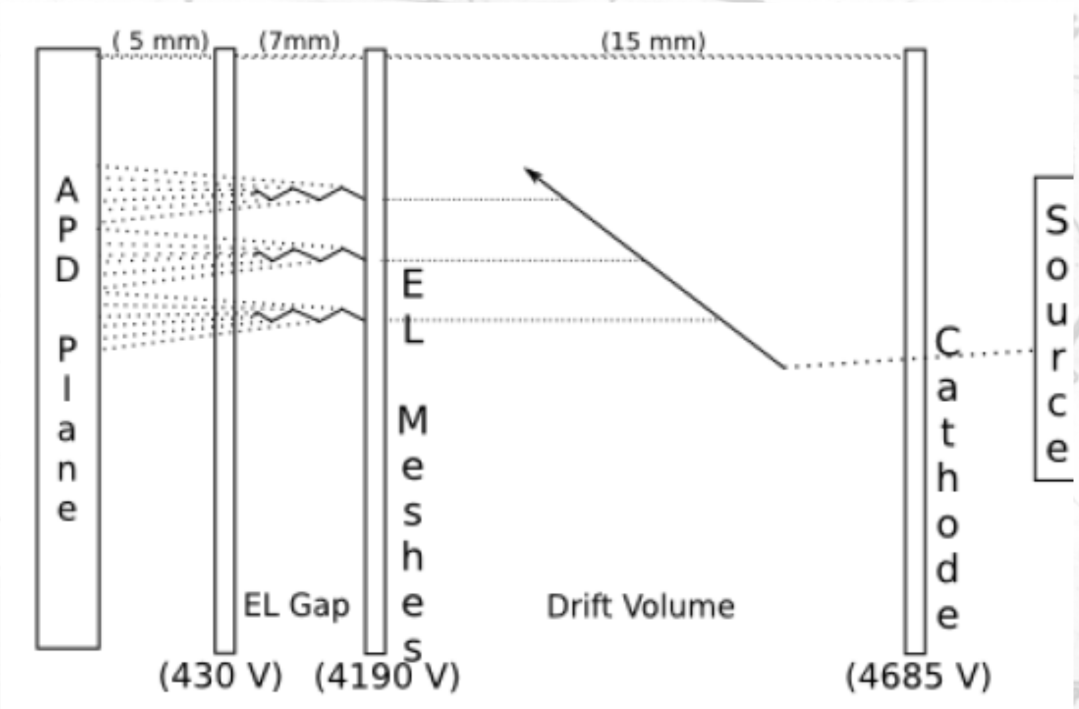


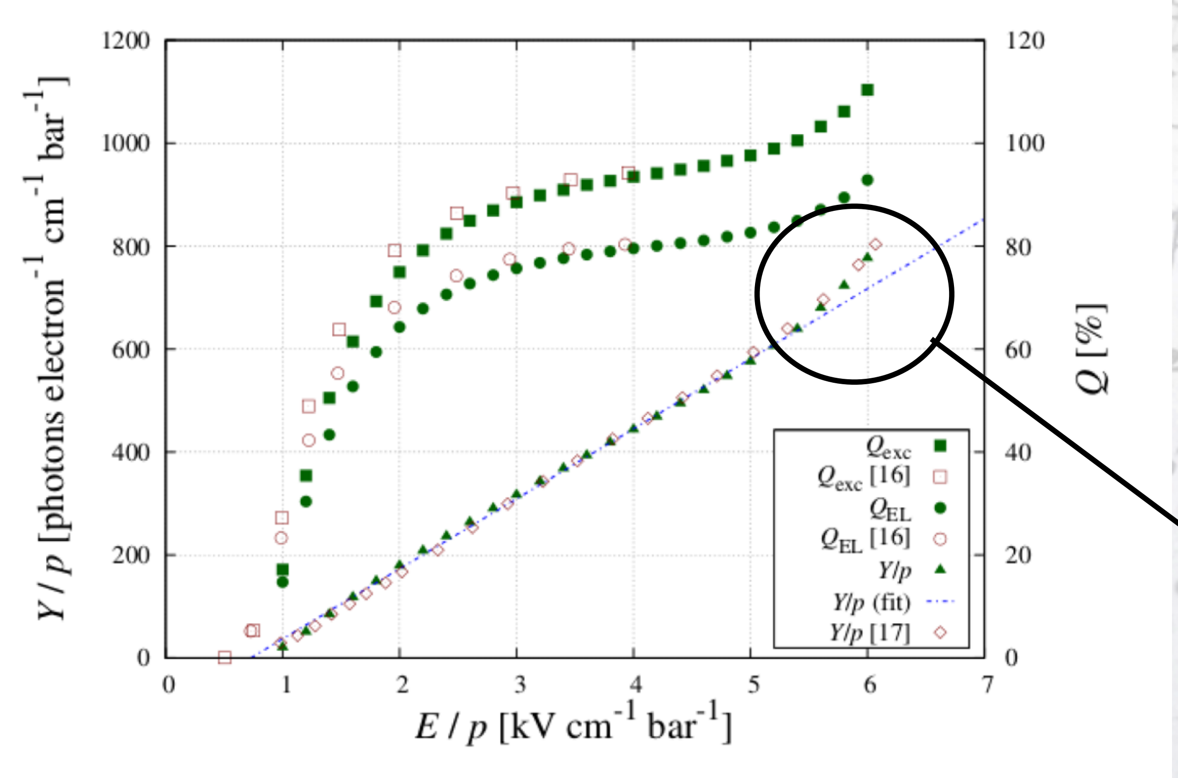






Electroluminiscense

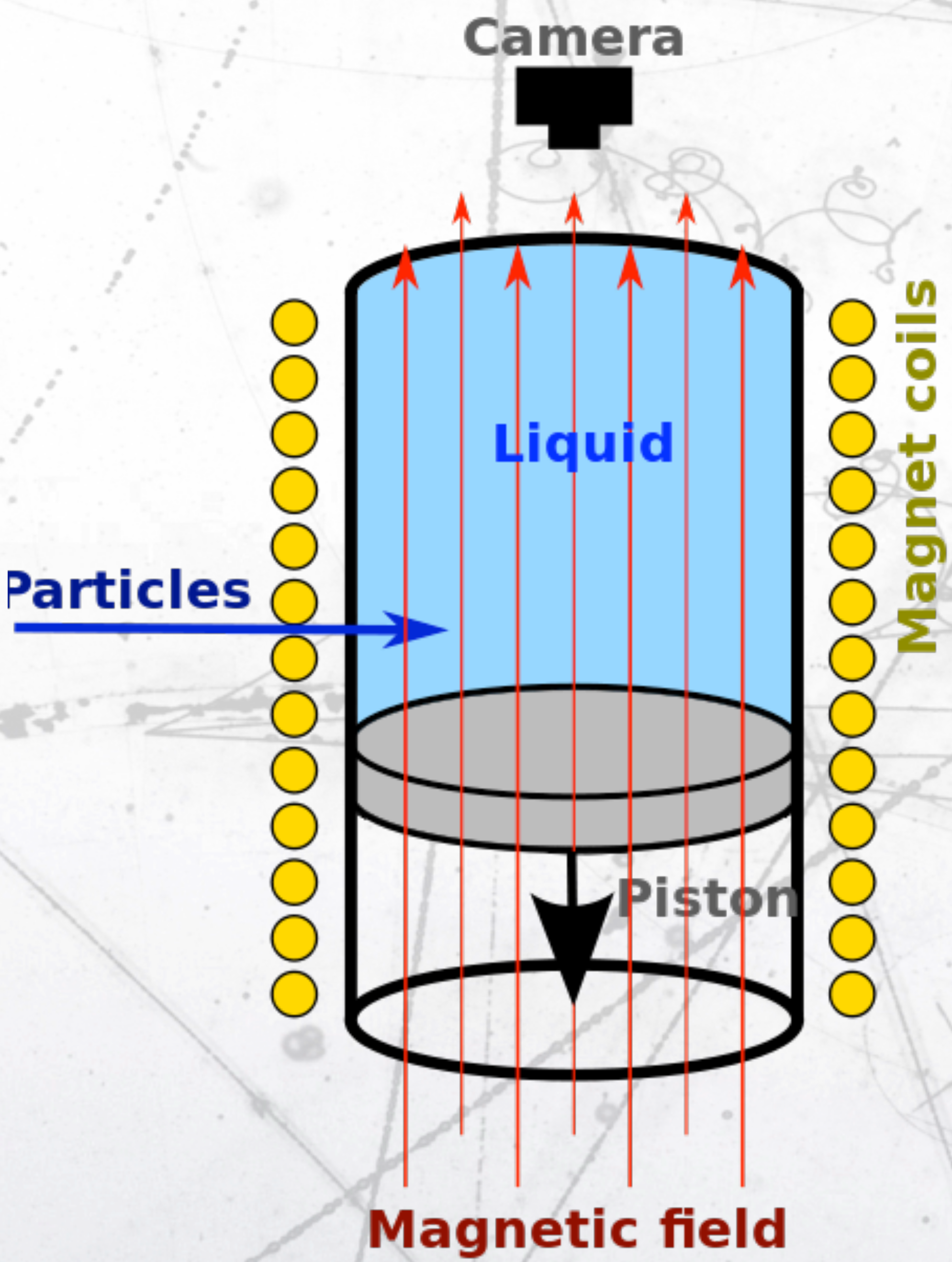




- Electroluminiscence is a way to make a linear amplification of primary electrons.
- At fixed P and voltage the number of photons produced by an electron is proportional to the gap.
- The photon statistic is Poisson and not exponential like in charge amplification. This is important when energy resolution is critical.
  - With EL amplification is possible to obtain the nominal resolution due to primary electron fluctuation $\simeq\sqrt{F\,N_e}$
- This process happens always above a certain E field (depending on gas and P).
- A pure EL amplification happend when the E is not enough to produce charge amplification.

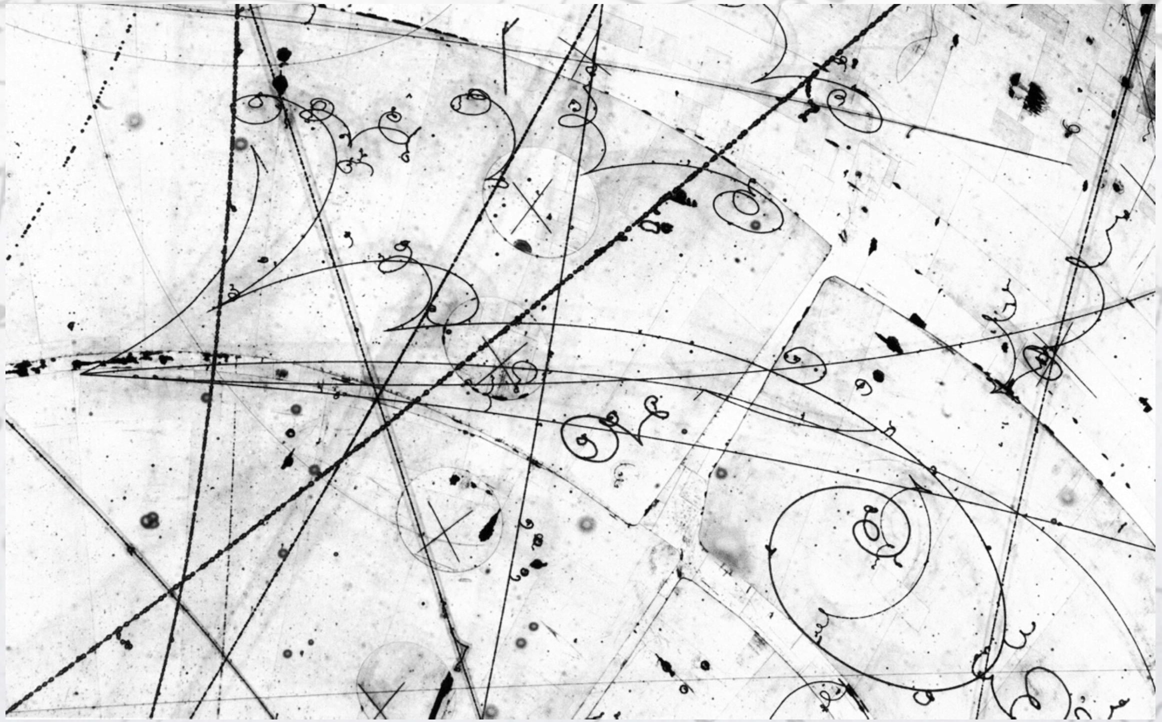
The deviation from linear dependency is an indication of charge amplification.

Bubble chamber

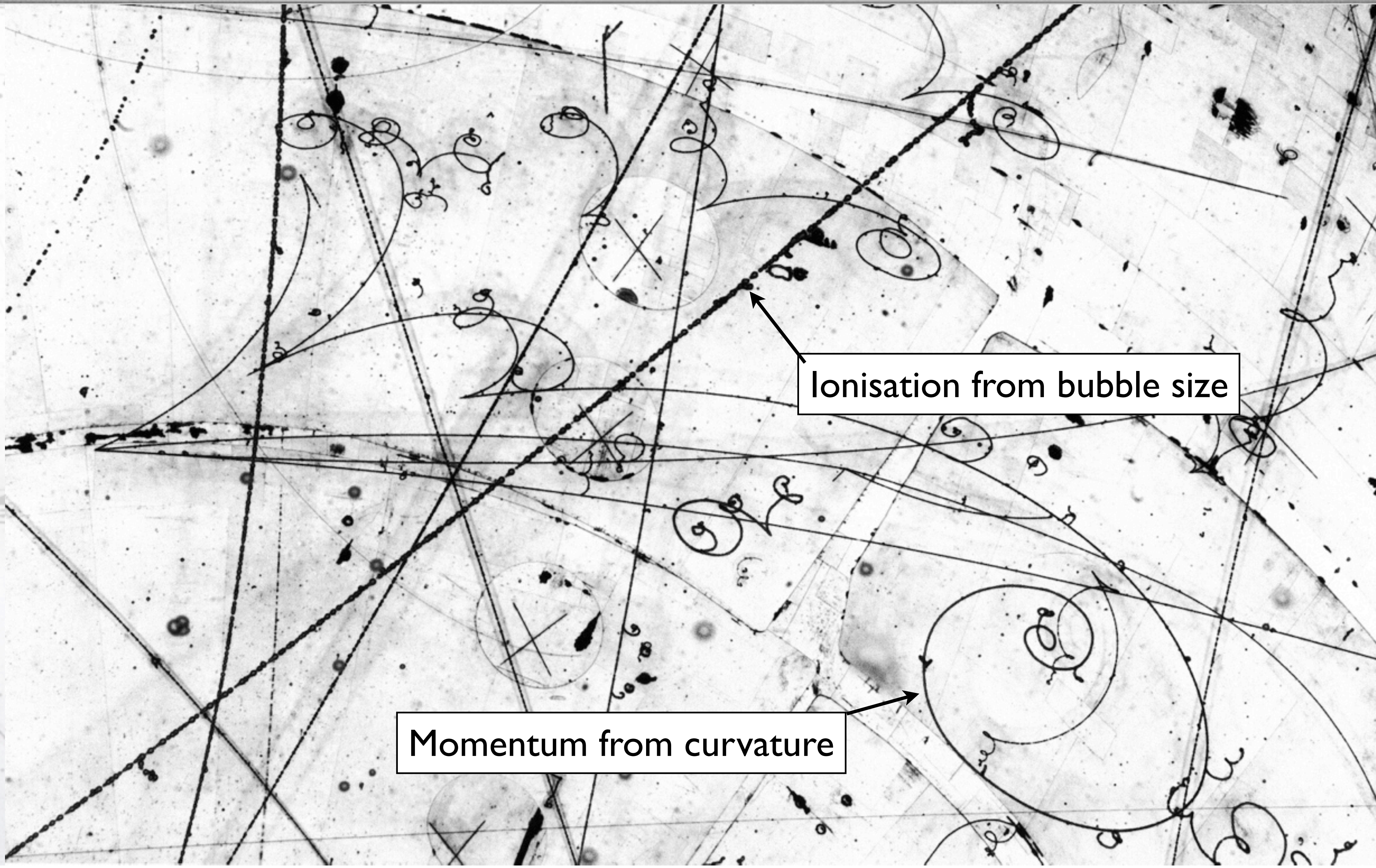


1952, D.A.Glaser

- The liquid is at a boiling temperature and high pressure.
- At the moment the particles enter the detector, the piston is released leaving the liquid in a metastable state.
- Ionizing particles breaks the state and produce micro bubbles that expand.
- The image is taken as a photograph.



Bubble chamber



The reconstruction principle is the same of modern tracking detectors,

Bubble chamber

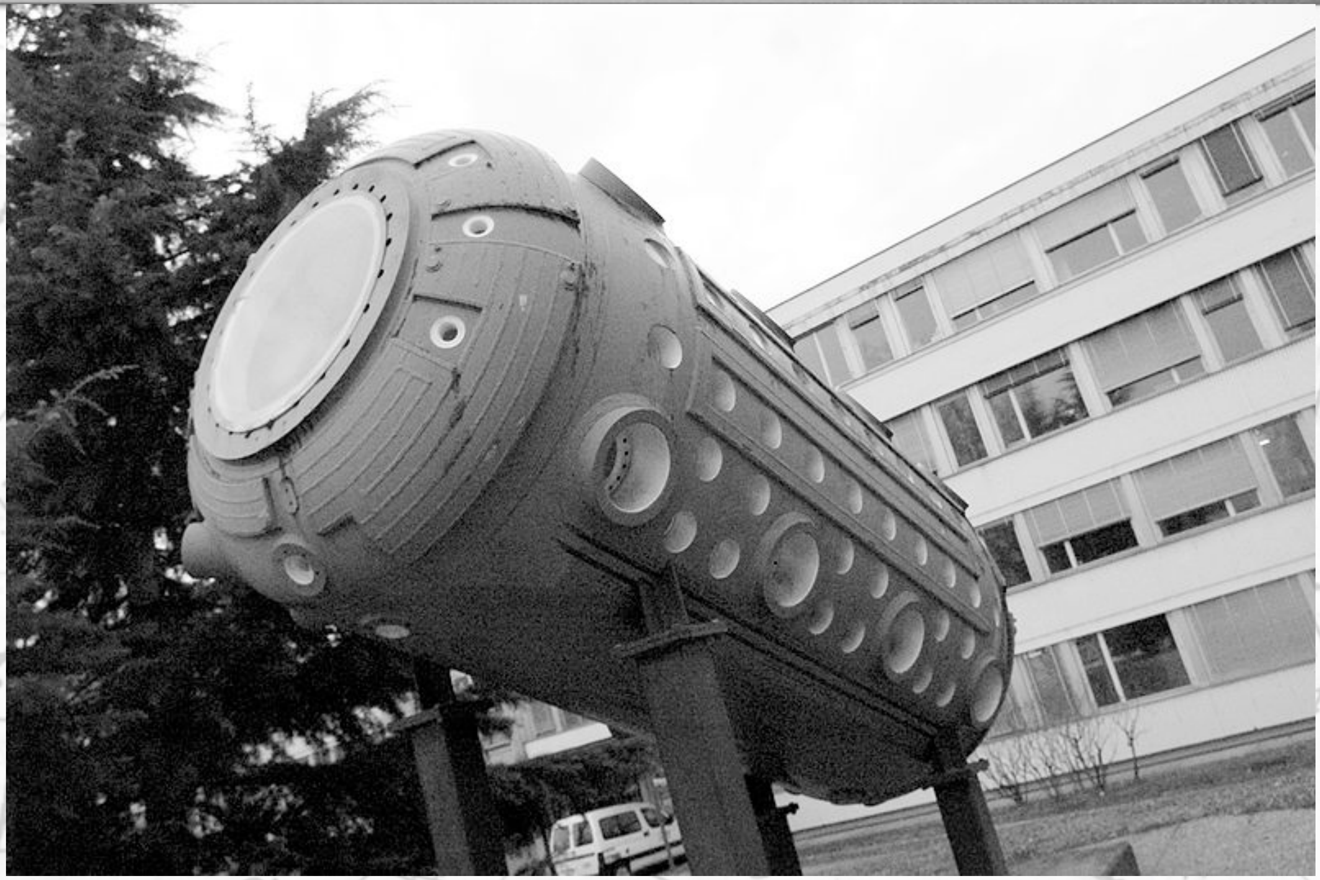
Pro's

- Can have almost any target material.
- Excellent point, momentum resolution and track separation.

Con's

- Slow (mechanical piston), but OK for neutrinos.
- Needs to analyse pictures: nowadays digitilized.

- Gargamelle discovered the Neutral Currents at CERN with this technology in 1973.



- Bubble chambers are the perfect example of excellent neutrino interactions:
  - large mass
  - high resolution.
  - Target = detector to avoid low energy loses.

What is the new bubble chamber?

Momentum measurement

Multiple scattering

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-passage-particles-matter.pdf

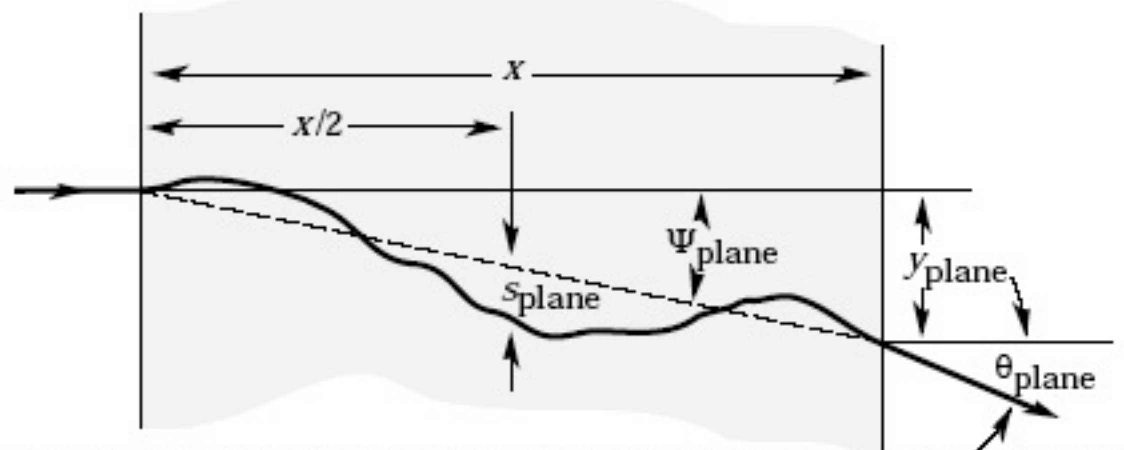


Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

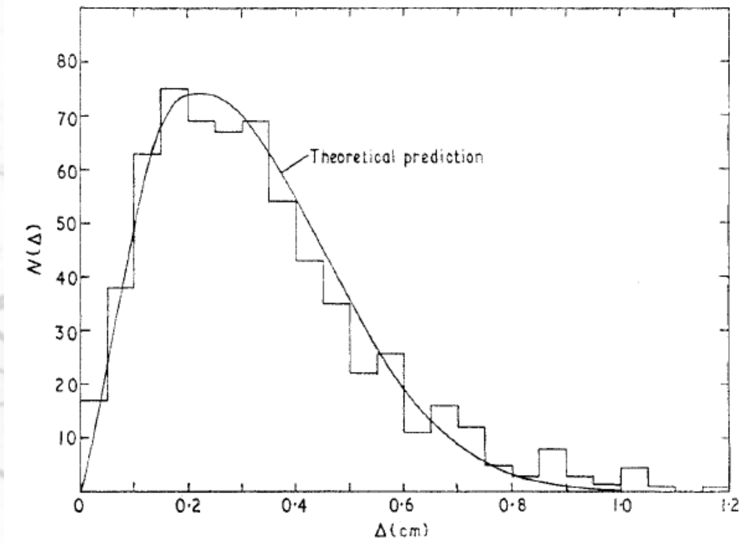


Figure 1. Comparison of observed and expected Δ distributions for incident muons in the momentum range 20–25 GeV/c.

- Particles traversing any media suffers rutherford scattering.
- This produces (correlated) changes in angle and position.
- First approximation for think materials (central limit theorem) , it can be described by a gaussian

$$P(\theta) \propto \exp^{\frac{-\theta^2}{2.\theta_0^2}}$$

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

p,β = particle momentum & velocity

z = particle charge x = particle path length

X_0 = material radiation length

Multiple scattering

- Multiple scattering is relevant for several detection techniques.
- The trajectory determination is affected in several ways: $\Delta y, \Delta\theta$.
- It also affects the measurement of the track curvature and the charge determination.

- The parameter to tune is the radiation length. "the largest X0 the better"
- Radiation length defines the characteristic amount of matter traversed by a photon before producing a pair e^+e^-

$$X_0 = \frac{716.4A}{Z(Z+1)ln(\frac{287}{\sqrt{z}})\rho}(cm^{-1})$$

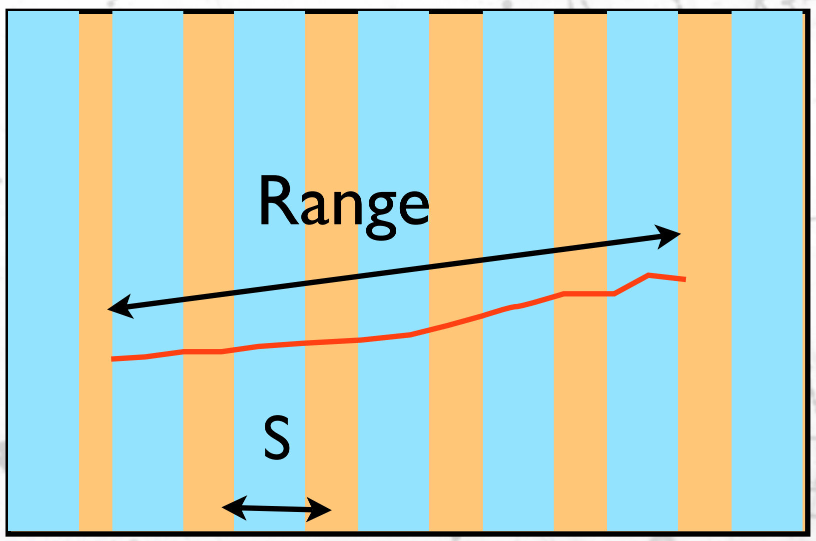
Z,A atomic and mass numbers of nucleus

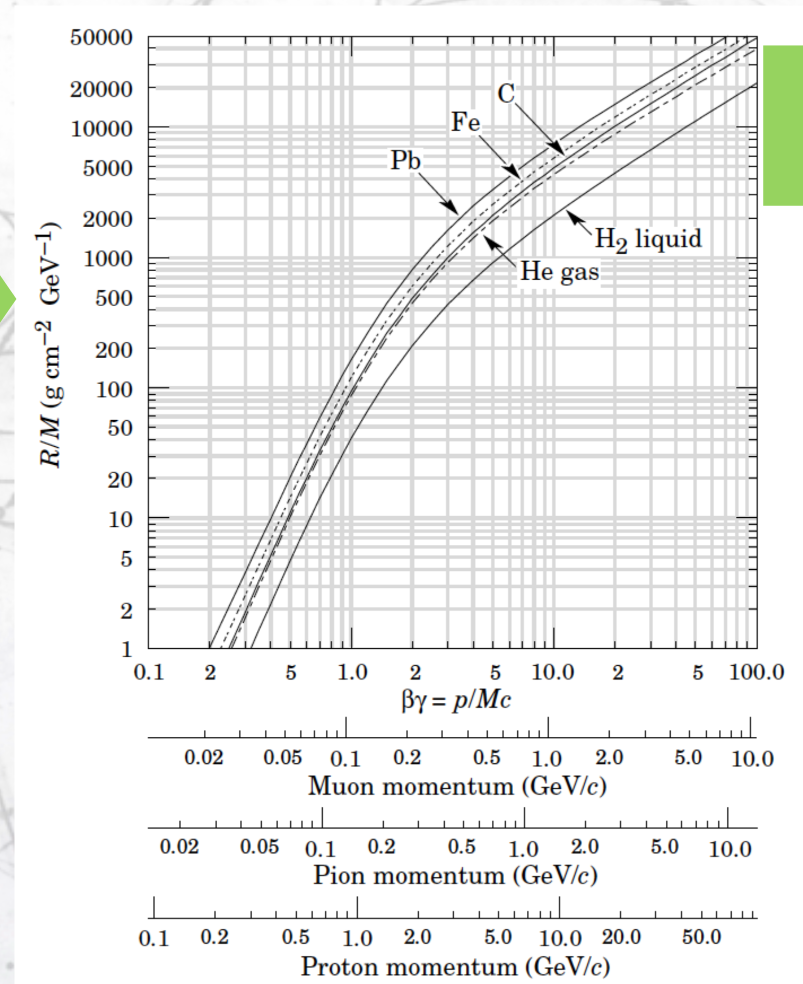
ρ material density

Best material

A↑
Z↓
ρ↓

- When a detector is long enough we can compute the momentum of a particle by measuring the range.





$$\frac{\sigma_p}{p} \simeq \frac{1}{2}\sqrt{\frac{M_{electron}}{M_{particle}}} = 3.5\%|_{\mu^-}$$

$$\beta\gamma > 5$$

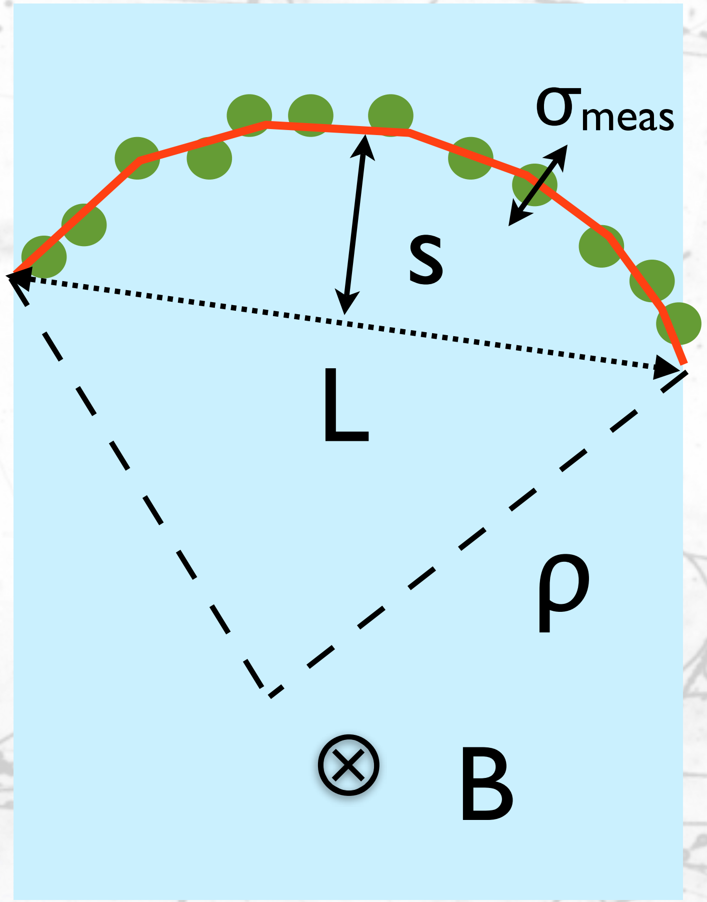
$$p > 500MeV/c|_{\mu^-}$$

- The detector sampling determines the range precision measurement:
- σ^2_{Range} ~ $S^2/12$

- The momentum error do not have a momentum dependency except for the detector sampling precision.

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-passage-particles-matter.pdf

Momentum by curvature



- The presence of a magnetic field curves the track according to momentum and track charge.

$$p \cos\delta \approx 0.3 z B \rho$$

- The resolution in momentum depends on the detector resolution (δ_{res}) and the multiple scattering (δ_{ms}).
- The detector contribution can be parametrized as:

$$\delta_{res} \approx \frac{\sigma_{meas}}{L^2}\sqrt{\frac{720.}{N+4}}$$

In order of importance:
$L > \sigma_{meas} > N$

Neutrinos and Gas

- Normally the gas detectors are too light for neutrino detection.
  - In intense neutrino beams like T2K we have ~50000 neutrino events/ton
  - 1 ton detector made of gas is a box of :
    - ρ_{Ar} = 1.8 kg/m^3
    - 1 $ton_{Ar\ gas} \rightarrow 8.2 \times 8.2 \times 8.2$ m^3 but 1 $ton_{plastic} \rightarrow 1 \times 1 \times 1$ m^3
  - On the other hand gas detectors have nice properties to preserve:
    - fine resolution.
    - fully active.
    - dE/dx

Options

- High pressure TPC:
  - a 10 bar detector reduces the size of the detector by a factor of ~2.2 per side.
  - Good for near detector.
- Liquid noble gases:
  - The density is 1.7 times the scintillator or water.
  - Similar good properties to gas detectors.
  - Good as far detector.