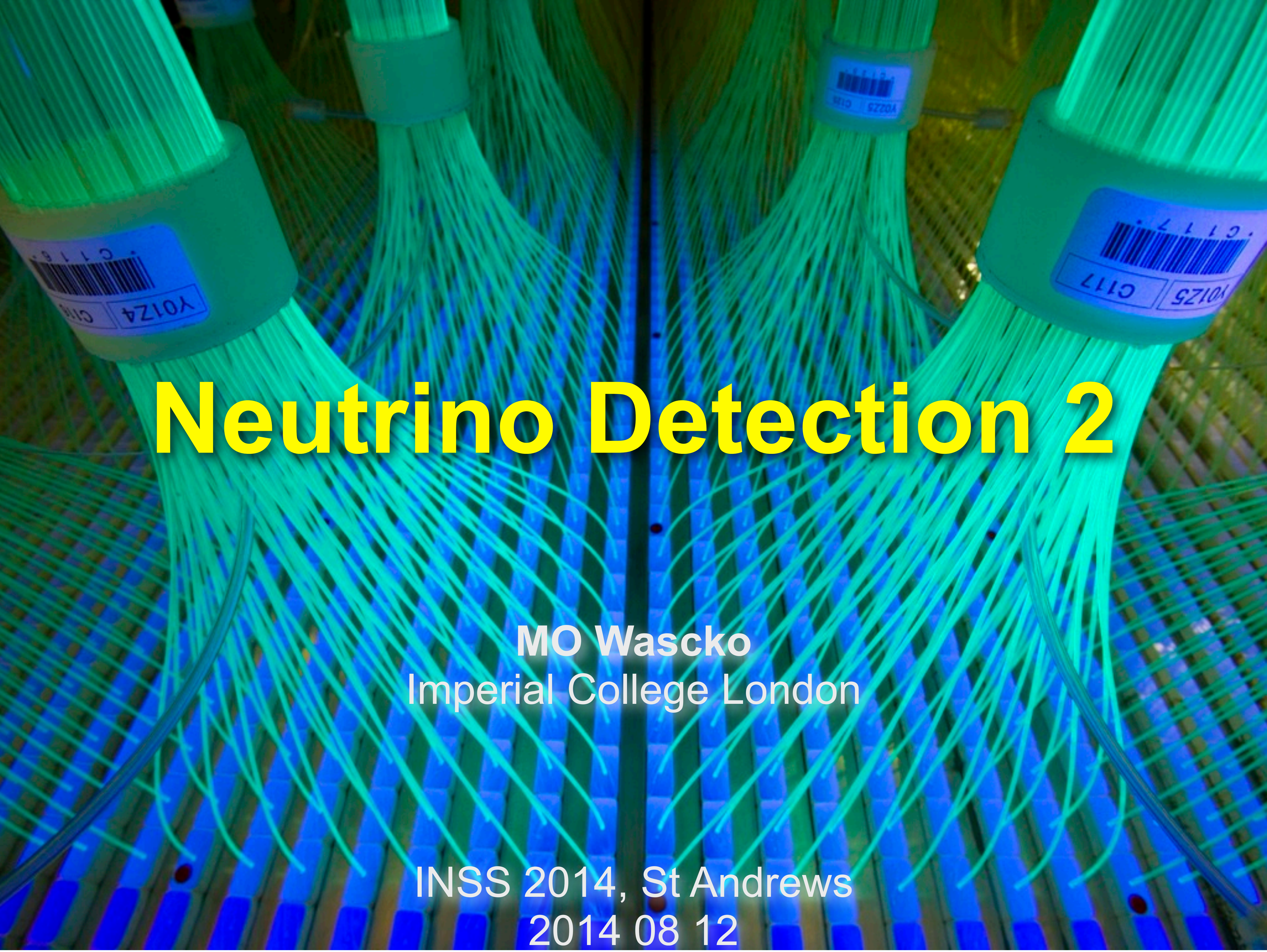


Neutrino Detection 2

MO Wascko
Imperial College London

INSS 2014, St Andrews
2014 08 12

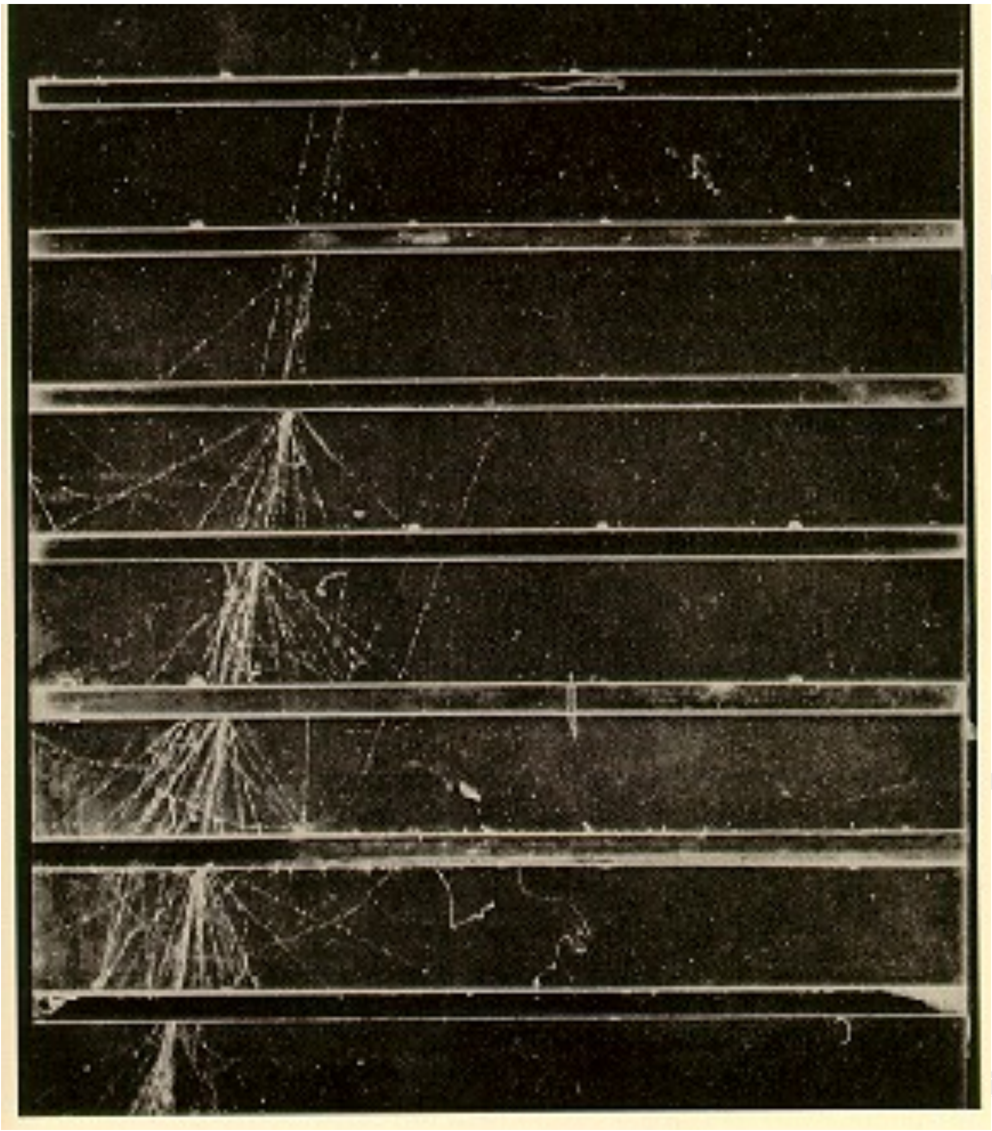
From last lecture

- Looked at signals and backgrounds of neutrino interactions
- Neutrino experiments span a wide range of energies
- In different energy regimes
    - Different configurations of secondary particles for signals
    - Different sources of backgrounds, different techniques needed to mitigate them

Particle Detection

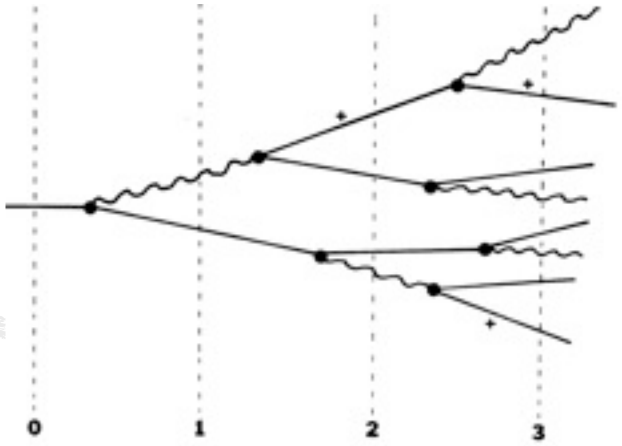
- *What happens as particles pass through matter?*
- *How can we use those processes to infer information about the signals and backgrounds of neutrino interactions?*
- List different particle processes
- Discuss detection techniques
    - Calorimetry
    - Cherenkov radiation
    - Scintillation
    - Ionisation
    - Radiochemical detection

Showers

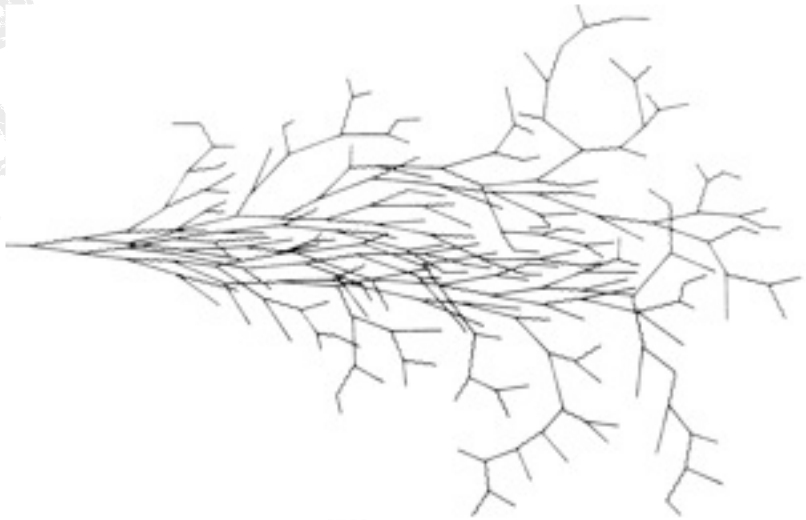


Lead plates

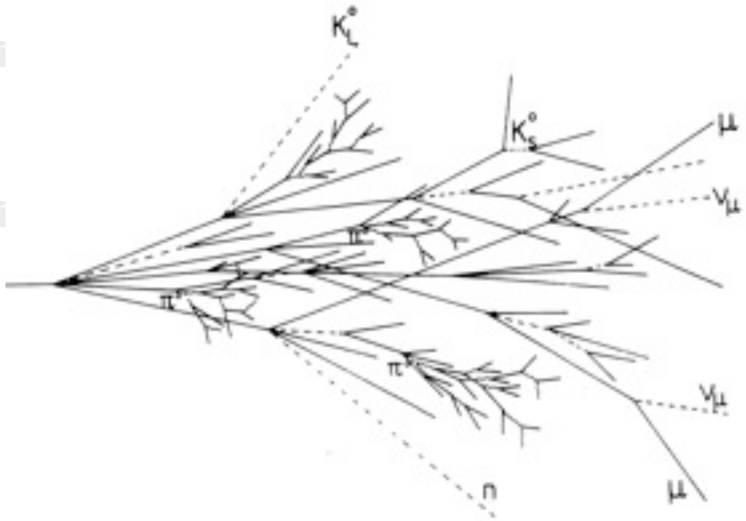
Cloud chamber photo of an electromagnetic shower.



$\#R_L$	$\#e^+ + e^-$	$\#\gamma$'s
0	1	0
0-1	1	1
1-2	3	1
2-3	5	3



EM shower



Hadronic shower

Calorimetry

- Measurement of a particles total energy deposition in a detector.
    - Usually involves showering particles
- Particle must be contained (or with minimal losses) 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).

Contributions to Photon Cross Section in Carbon and Lead

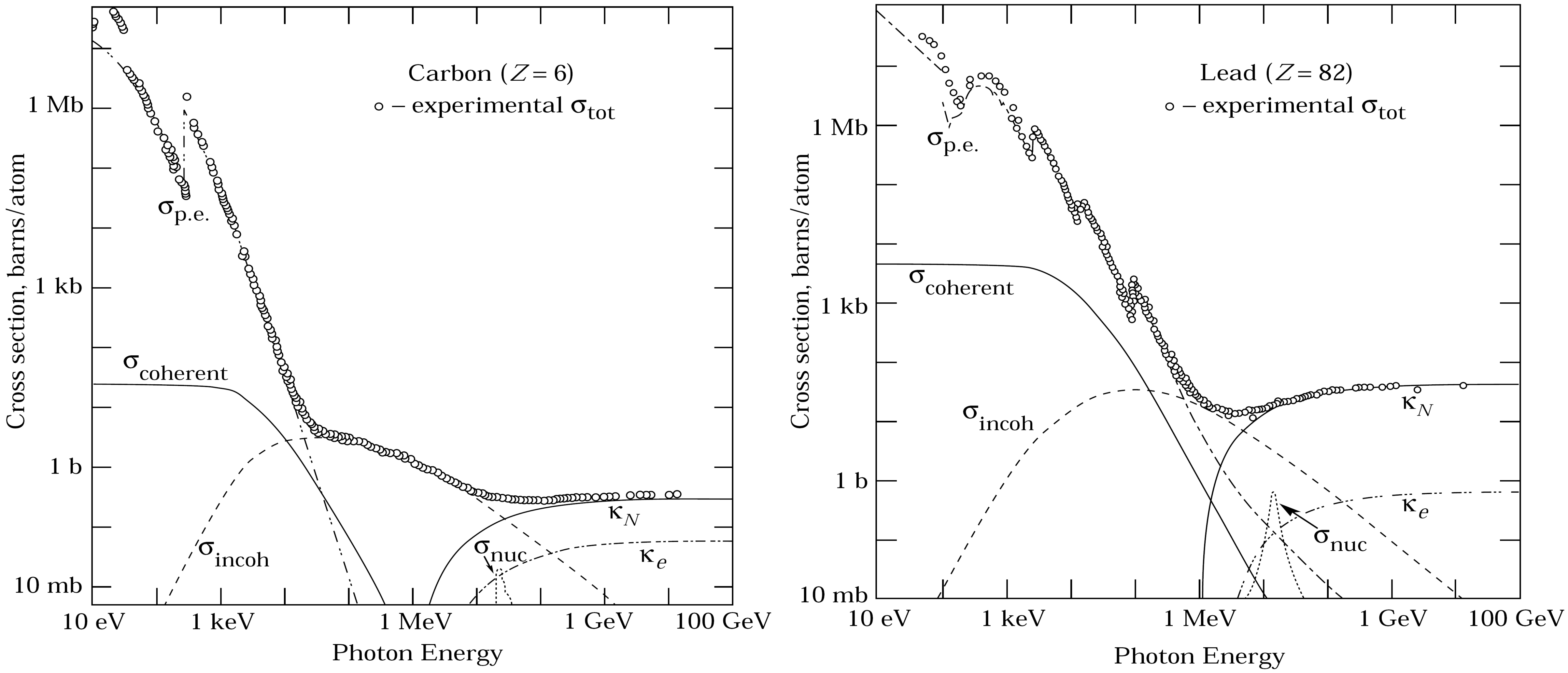
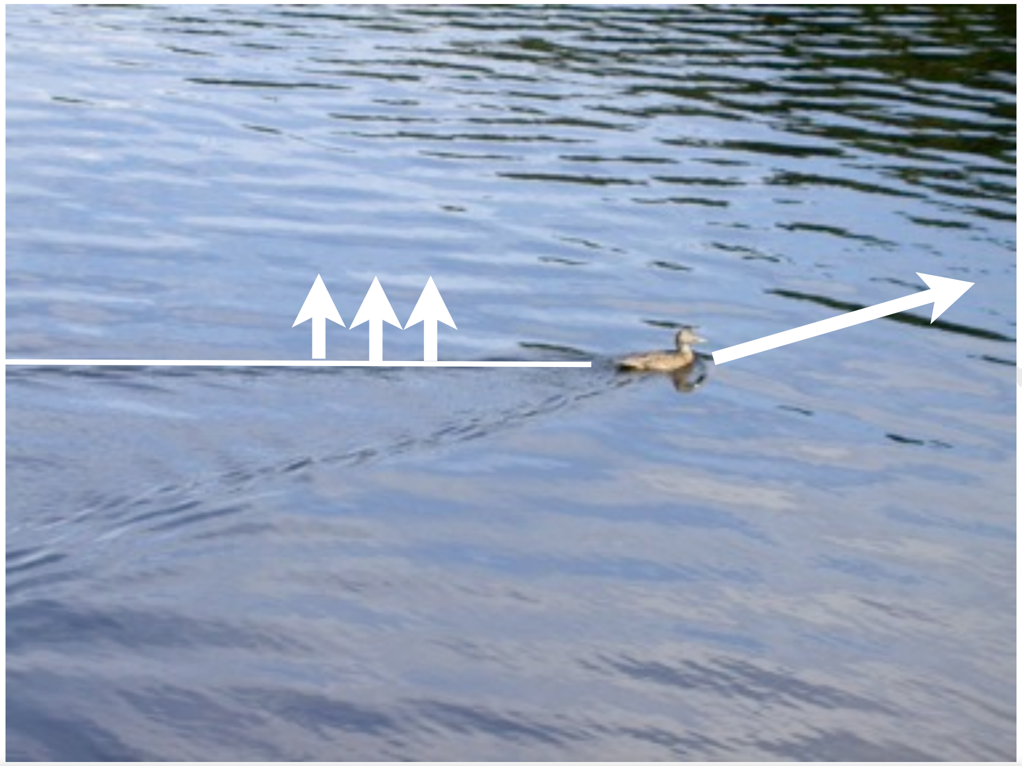


Figure 24.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes:

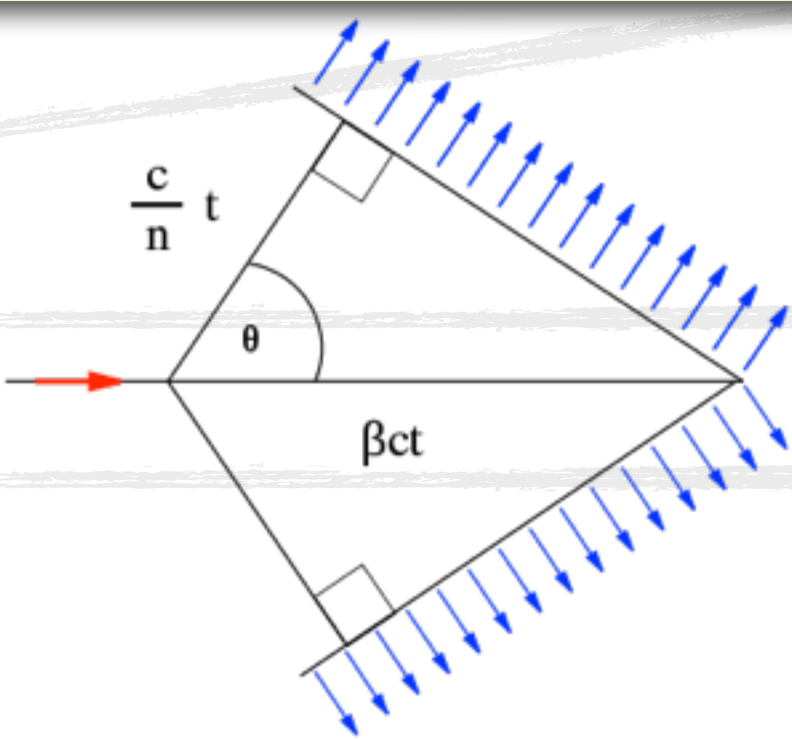
$\sigma_{\text{p.e.}}$ = Atomic photo-effect (electron ejection, photon absorption)
σ_{coherent} = Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)
$\sigma_{\text{incoherent}}$ = Incoherent scattering (Compton scattering off an electron)
κ_n = Pair production, nuclear field
κ_e = Pair production, electron field
σ_{nuc} = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). Data for these and other elements, compounds, and mixtures may be obtained from `http://physics.nist.gov/PhysRefData`. The photon total cross section is assumed approximately flat for at least two decades beyond the energy range shown. Figures courtesy J.H. Hubbell (NIST).

Cherenkov



n index of refraction, β particle velocity



Cherenkov threshold conditions

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

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

Cherenkov

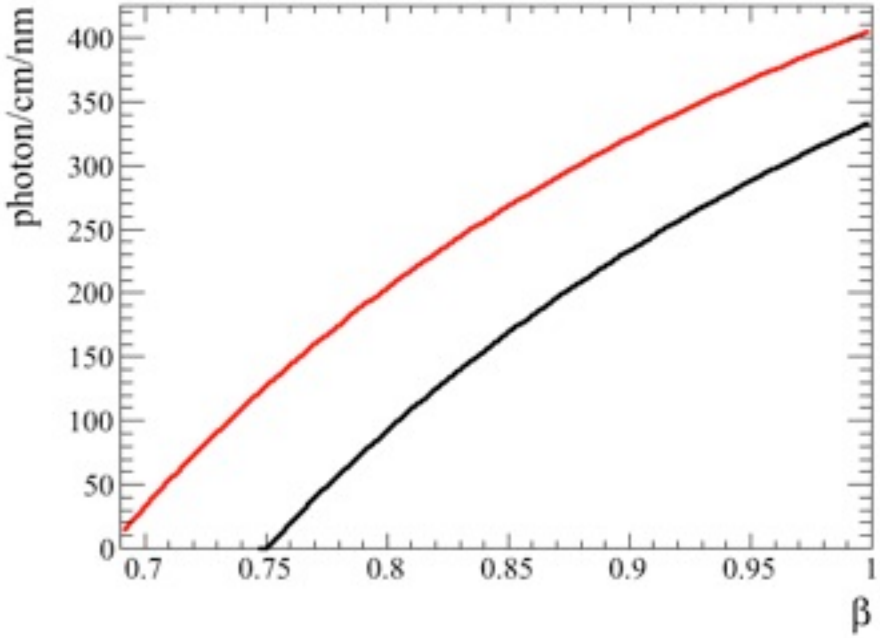
- The threshold is β > 1/n. In momentum:

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

- In practice 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.



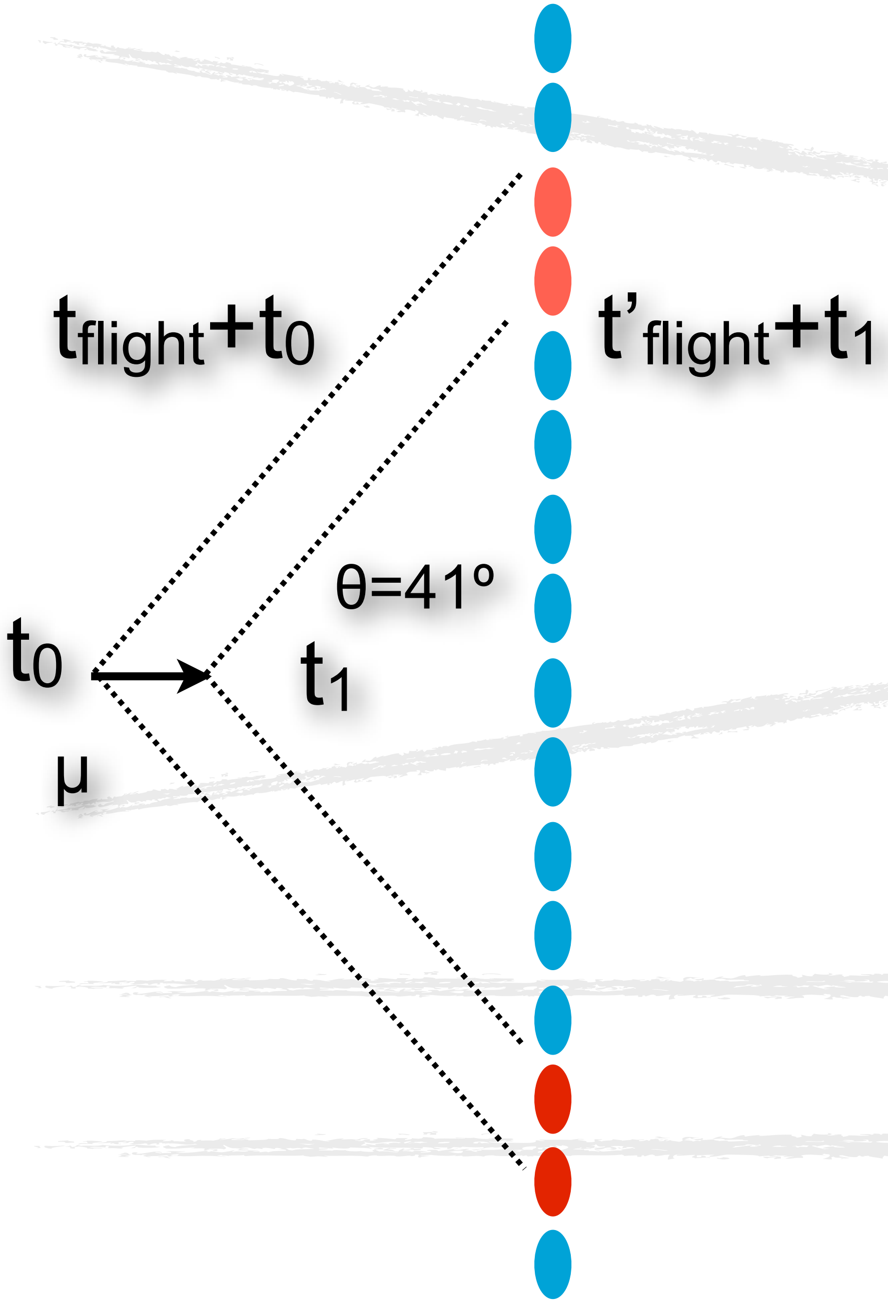
Wavelength	Water 20º
397 nm	1.3435 (+0.7%)
434 nm	1.3403 (+0.6%)
486 nm	1.3372 (+0.3%)
589 nm	1.333 (0.0%)
656 nm	1.3312 (-0.6%)

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

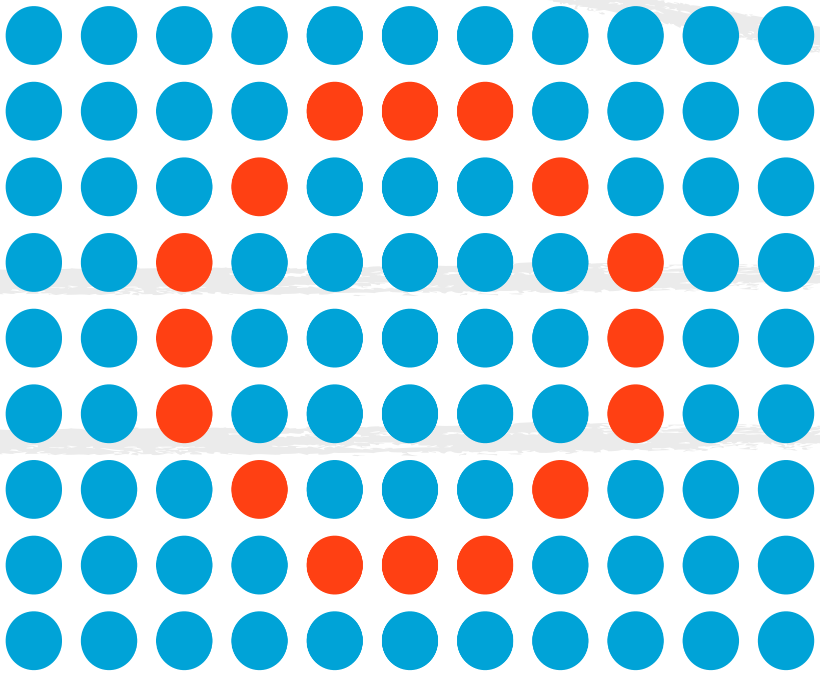
In principle there are more photons at low wavelength but they are absorbed in detector.

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

Cherenkov



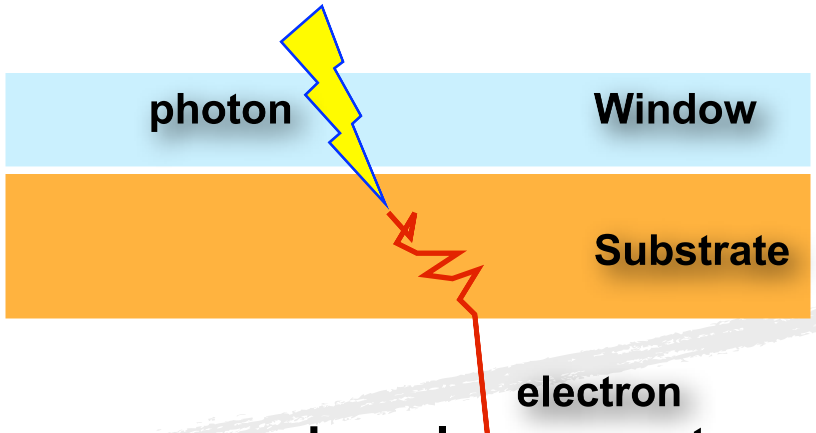
- The Cherenkov detector uses:
  - the directionality of the light emission.
  - the arrival time of photons.
  - the total light collected.
  - the light pattern in the detector
- Requires a segmented detector.

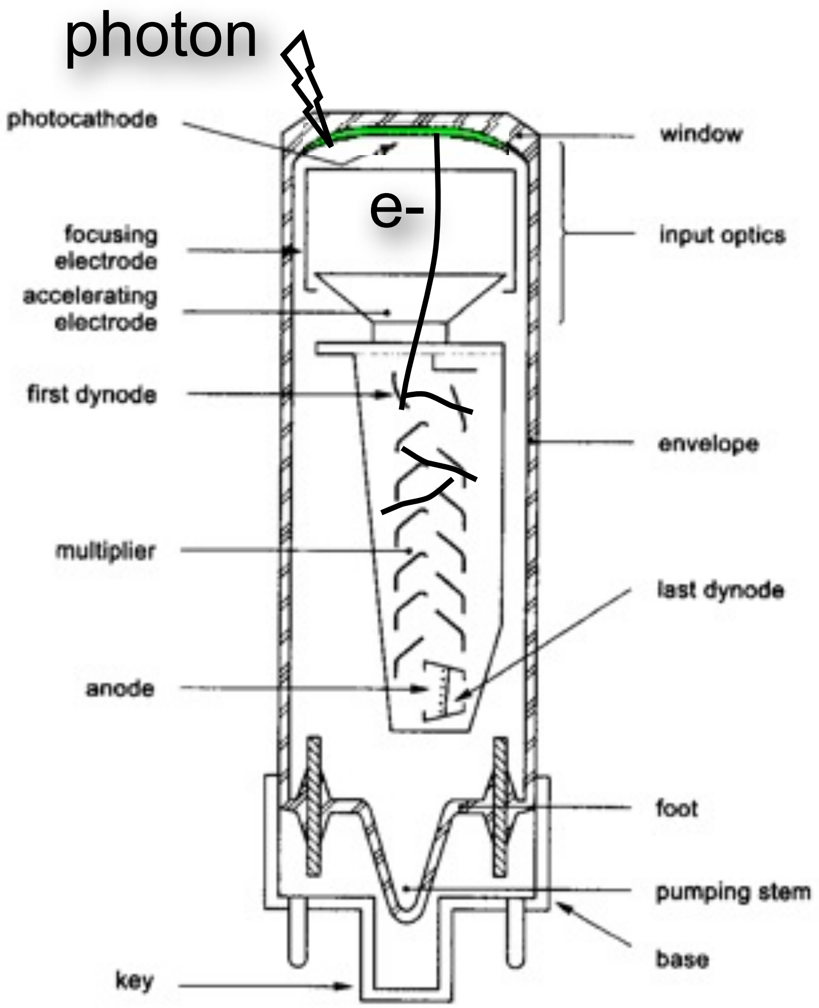


Providing

- vertex position
- range
- direction
- energy

Vacuum Based Photodetectors





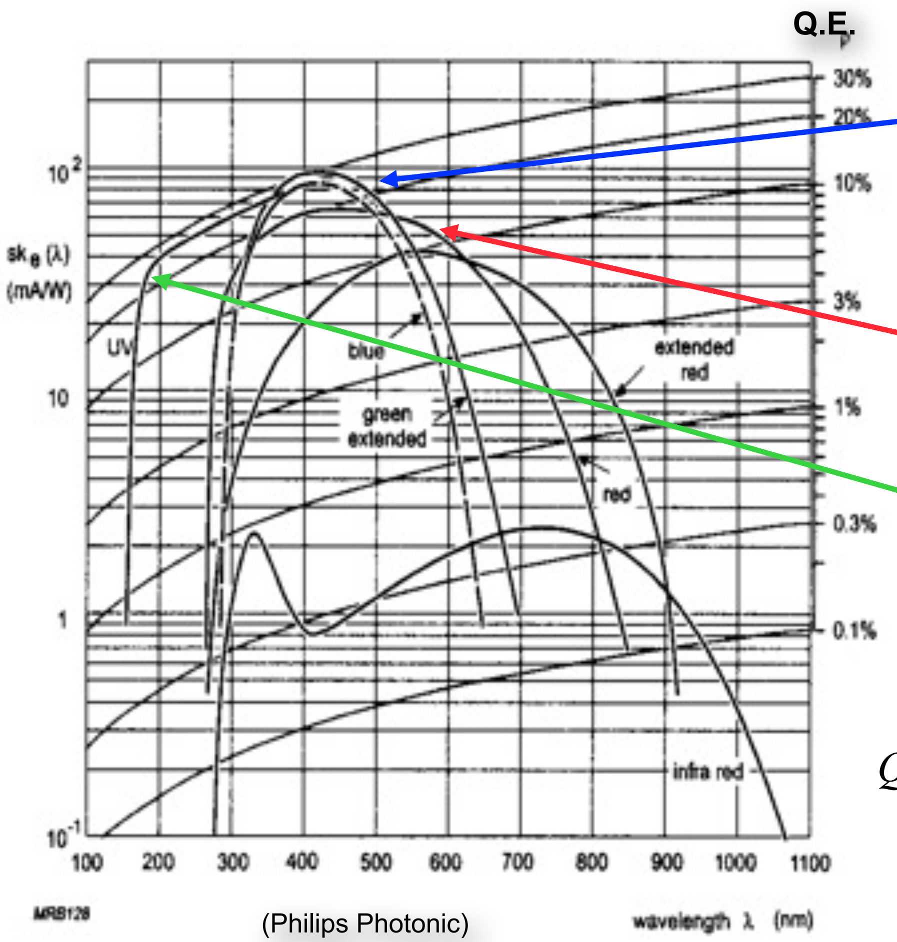
- A photo sensor simply counts photons, ignoring energy/wavelength.
  - Photo electric emission from photo cathode.
  - Secondary emission from dynodes.
    - Dynode gain: g_i = 3-50 depending on energy.

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

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

Photon detection

Quantum efficiencies of typical photo cathodes



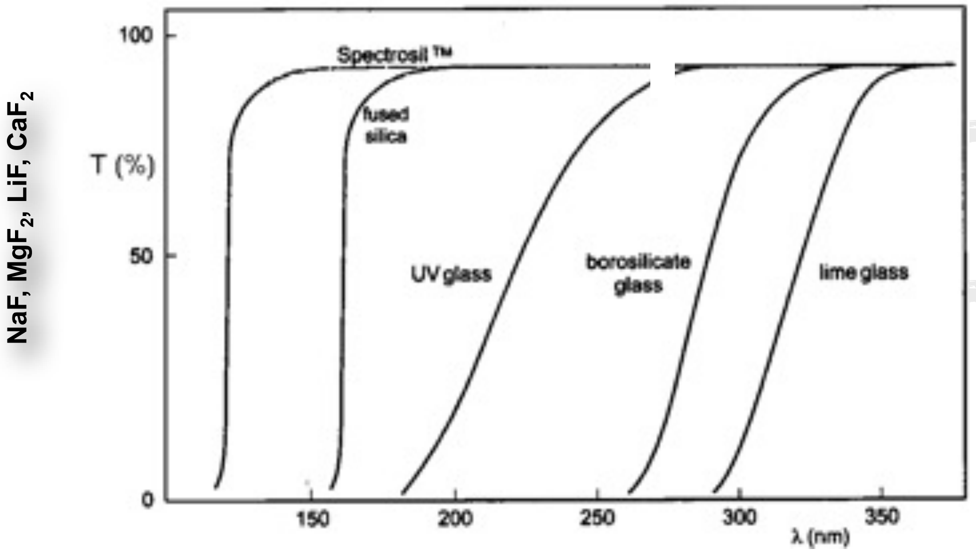
(Philips Photonic)

Bialkali
SbK_2Cs
SbRbCs

Multialkali
$SbNa_2KCs$

Solar blind
CsTe
(cut by quartz window)

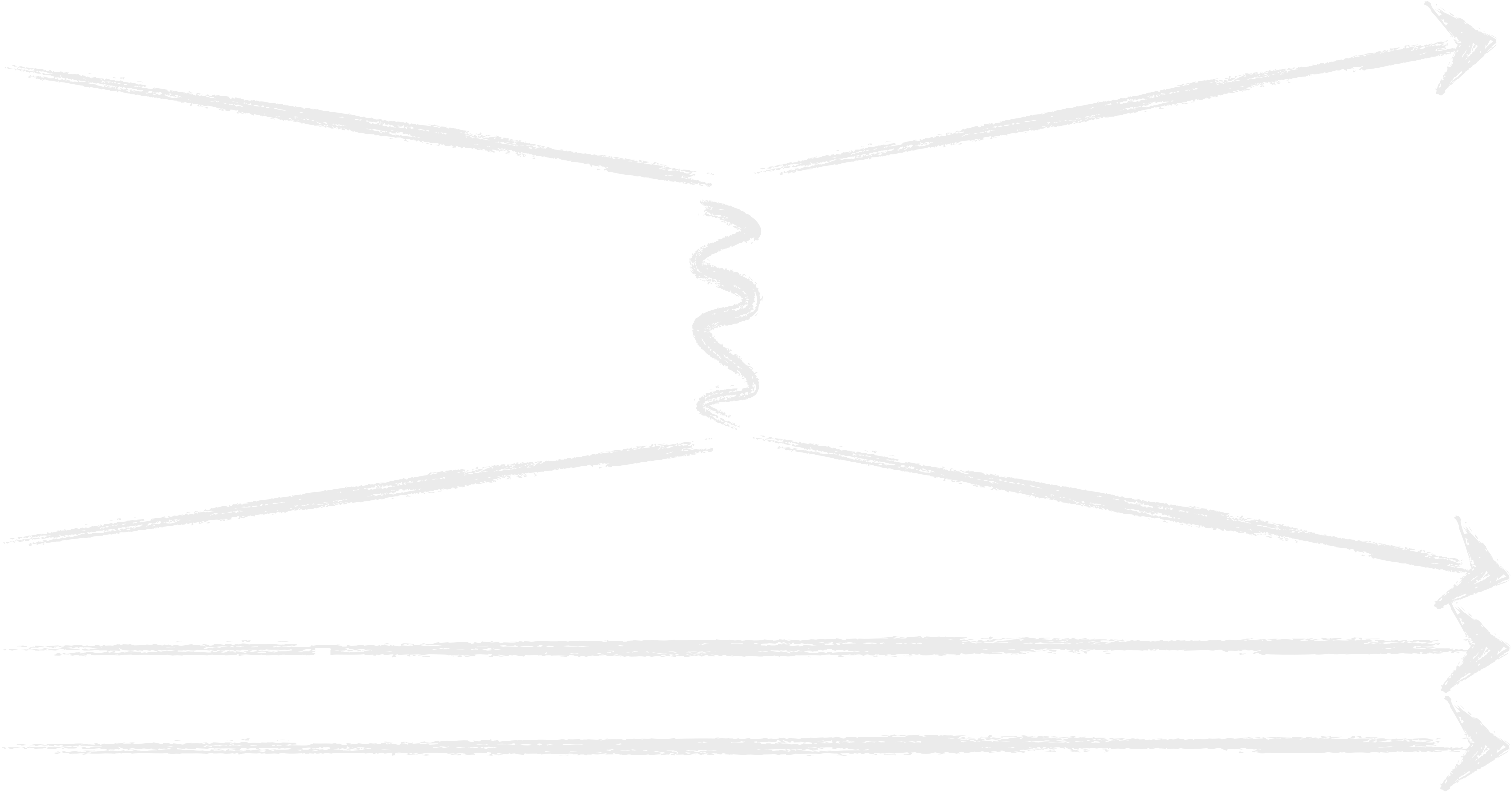
$$Q.E.(\%) \approx 124 \times \frac{sk_e(mA/W)}{\lambda(nm)}$$



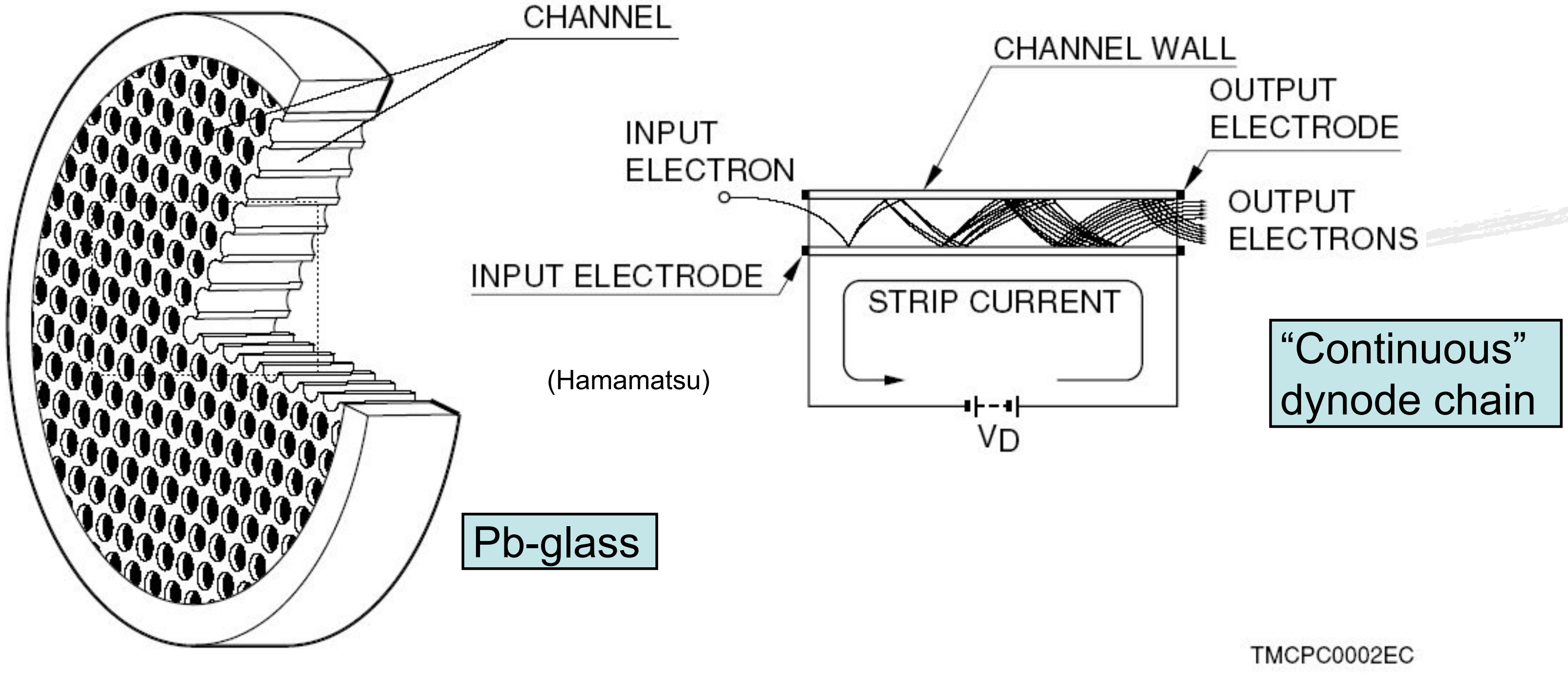
Transmission of various PM windows

- 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 dynode gain.

Other photo sensors



Other photo sensors

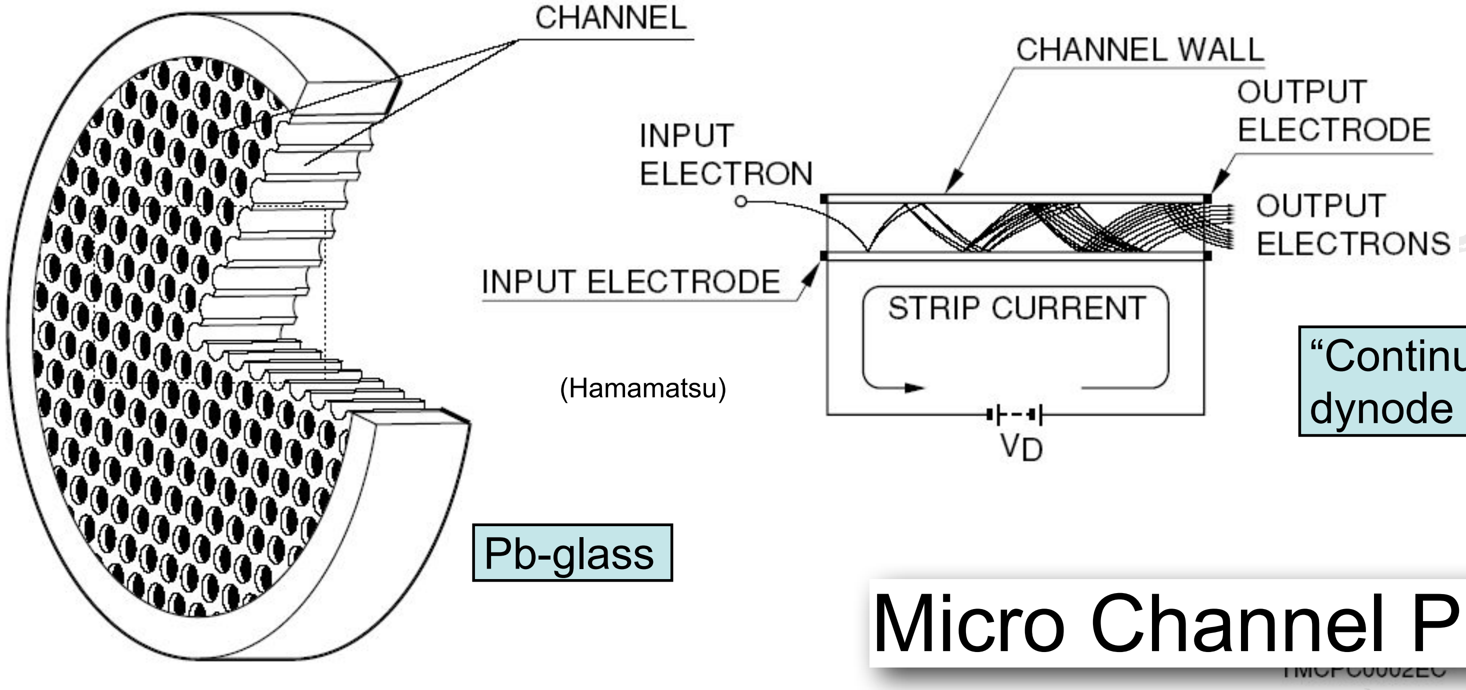


(Hamamatsu)

“Continuous” dynode chain

Pb-glass

Other photo sensors



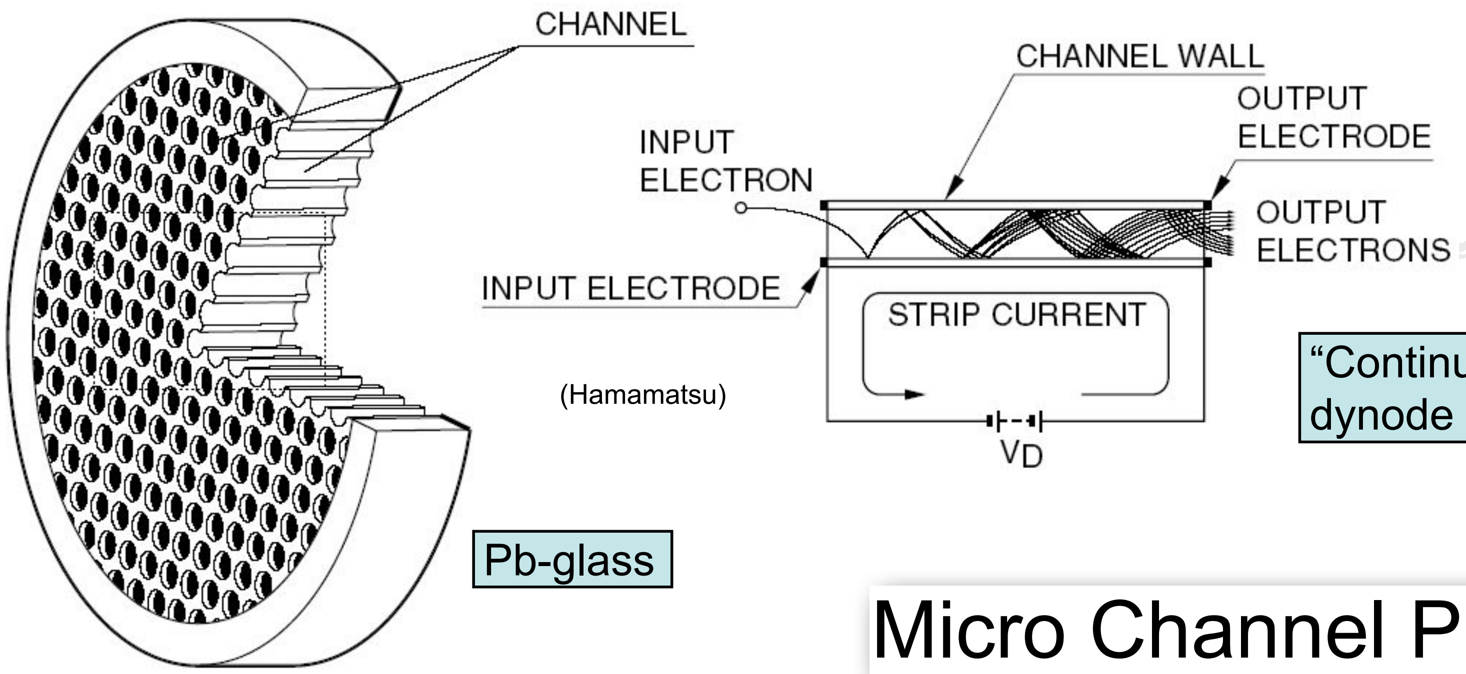
(Hamamatsu)

“Continuous” dynode chain

Pb-glass

Micro Channel Plate

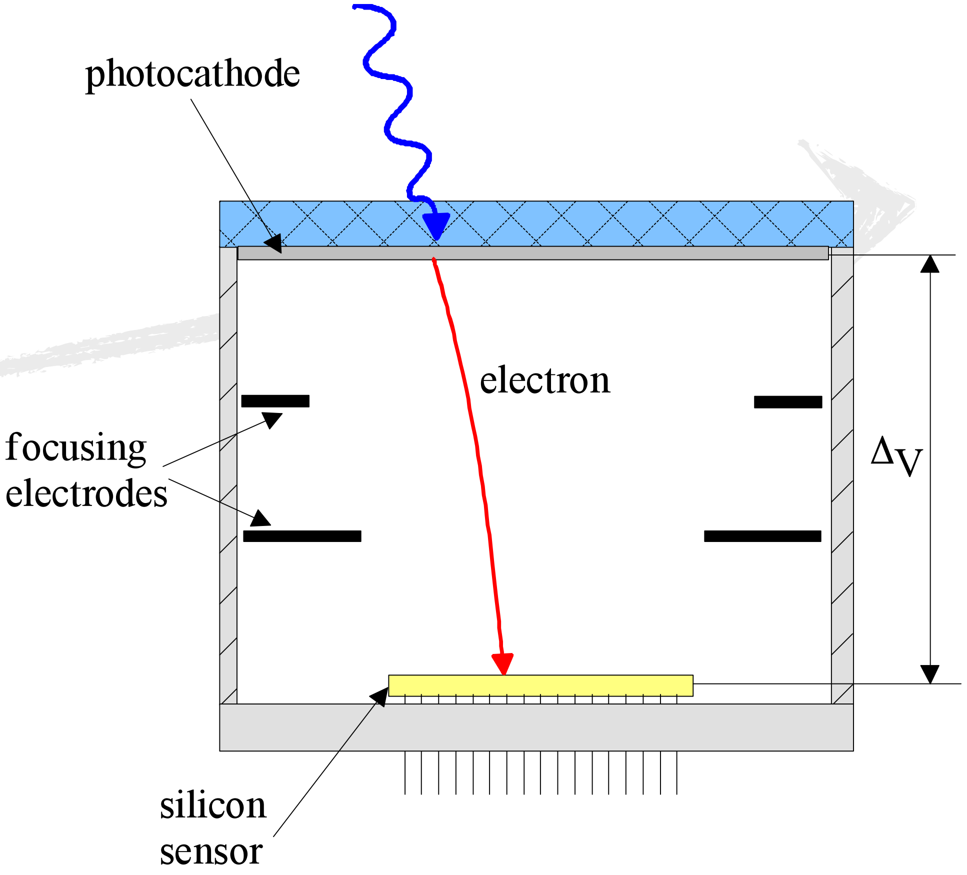
Other photo sensors



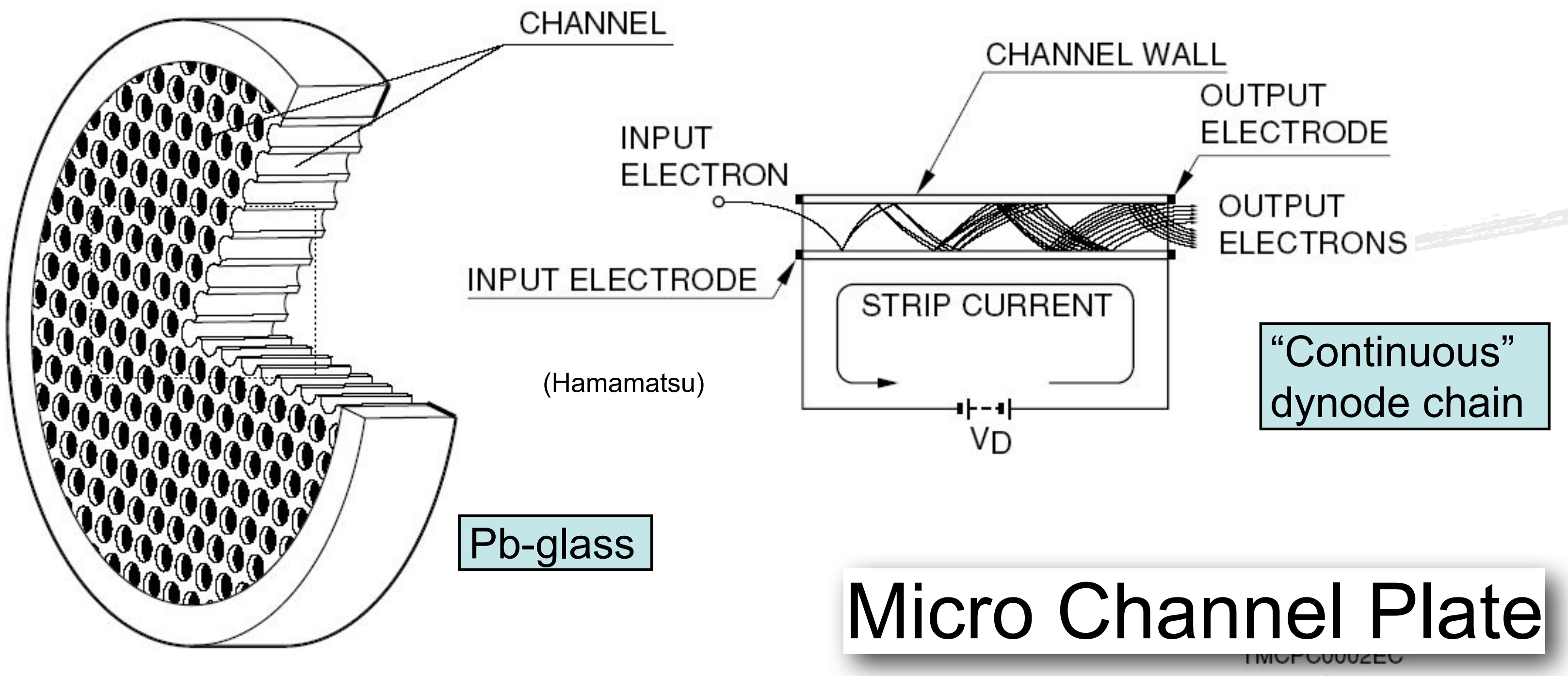
Pb-glass

"Continuous" dynode chain

Micro Channel Plate



Other photo sensors



(Hamamatsu)

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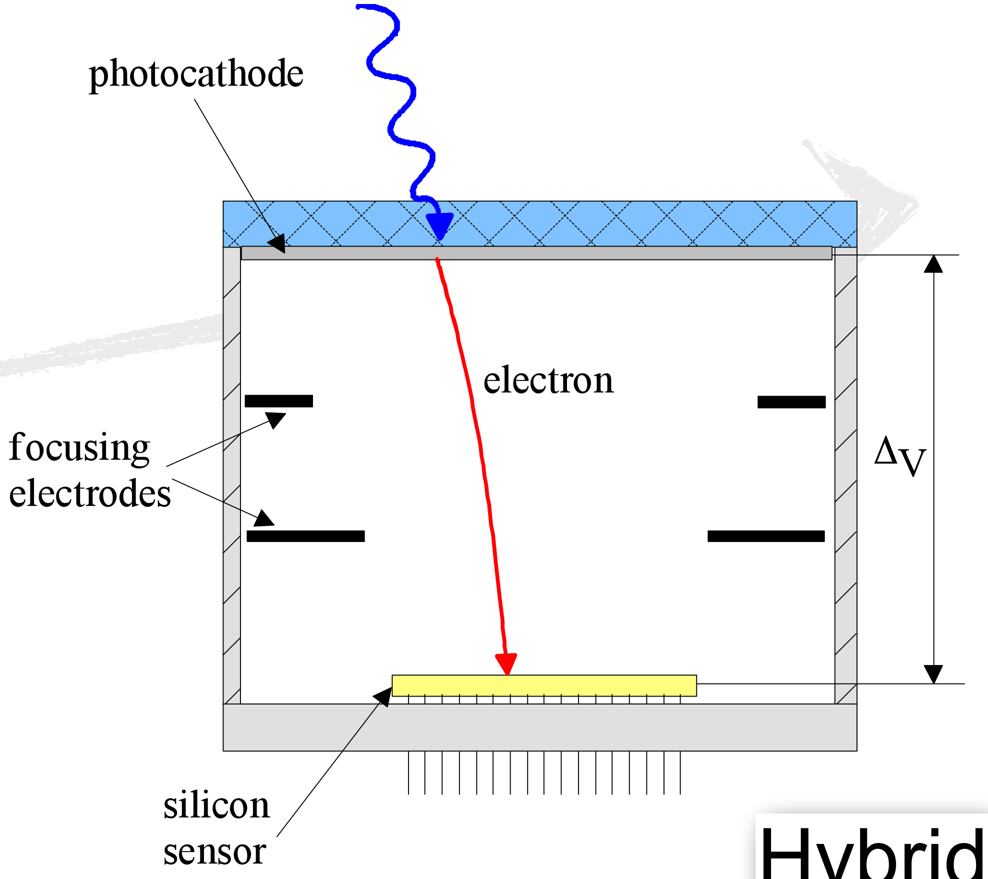
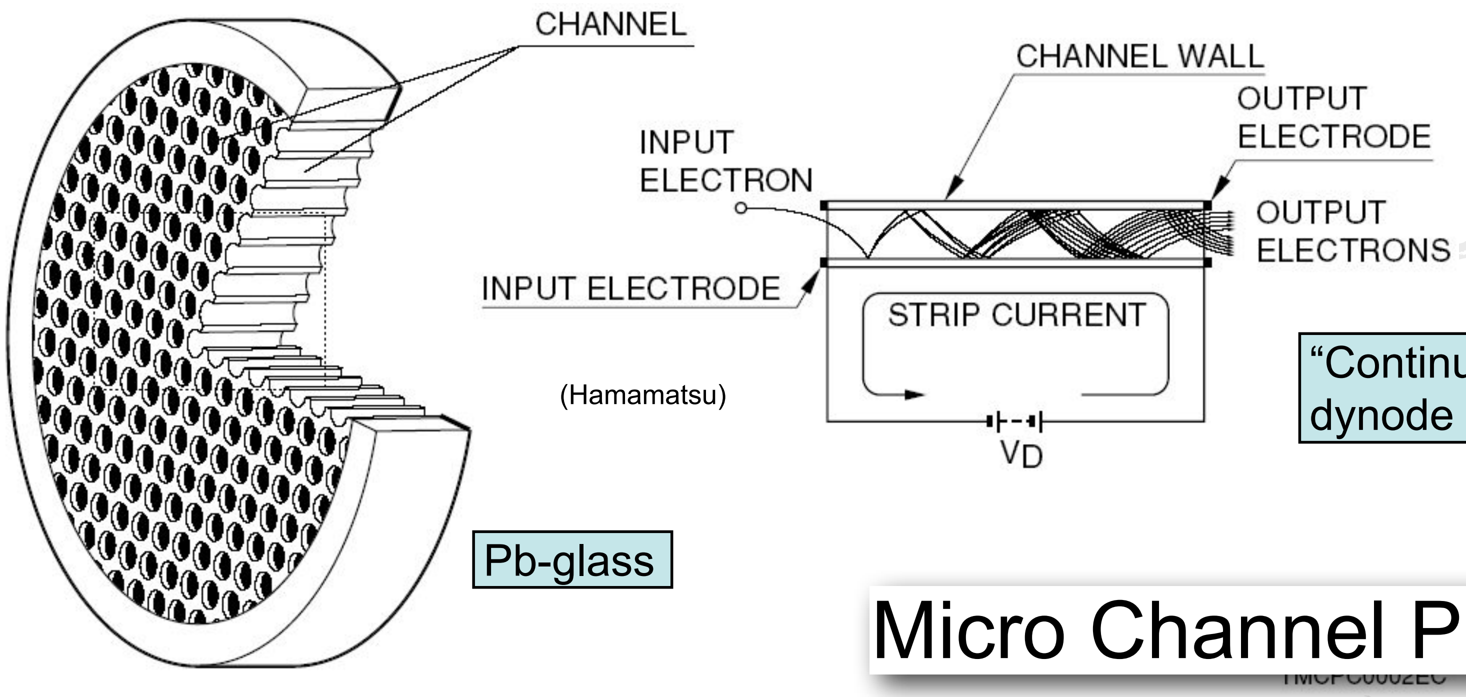


Hybrid PMT

Other photo sensors

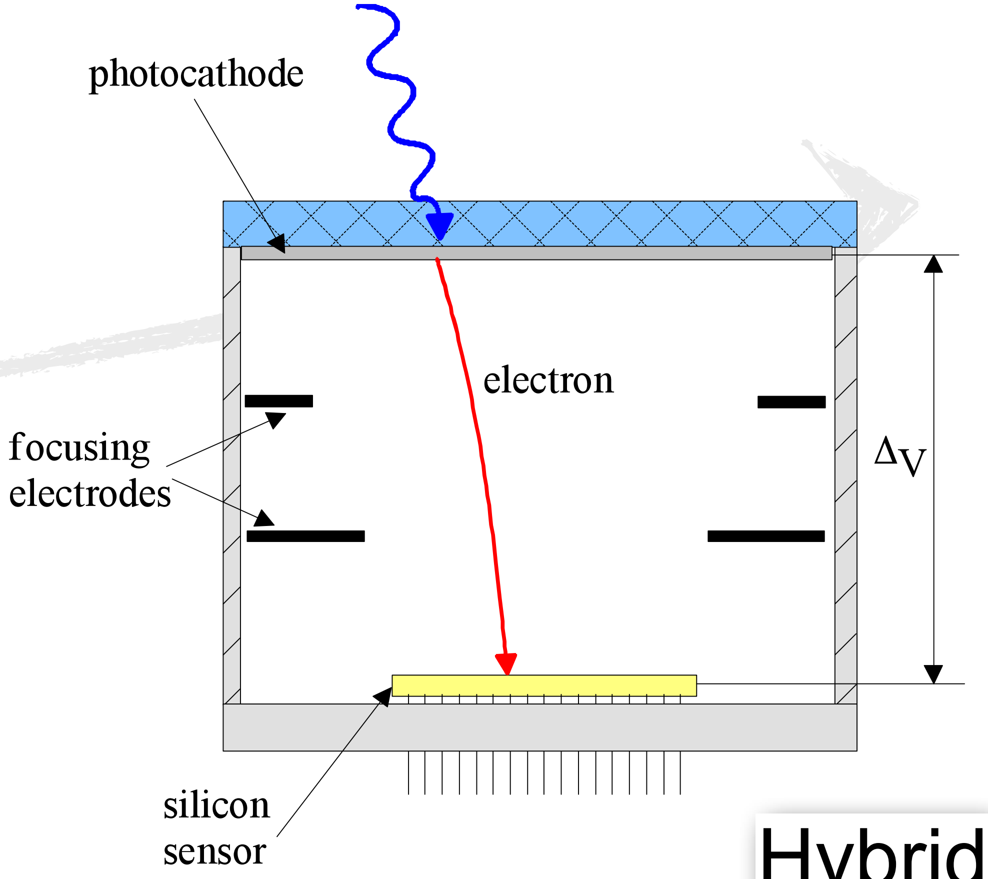


(Hamamatsu)

Pb-glass

"Continuous" dynode chain

Micro Channel Plate



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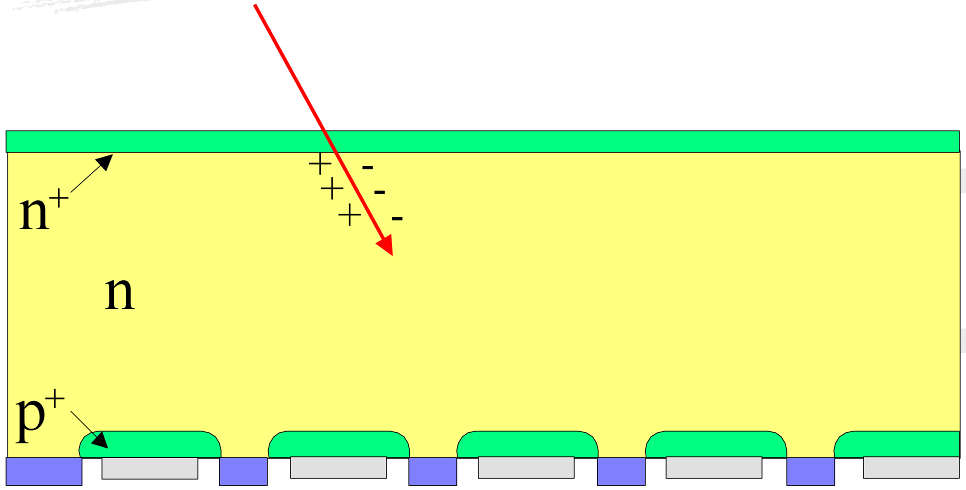
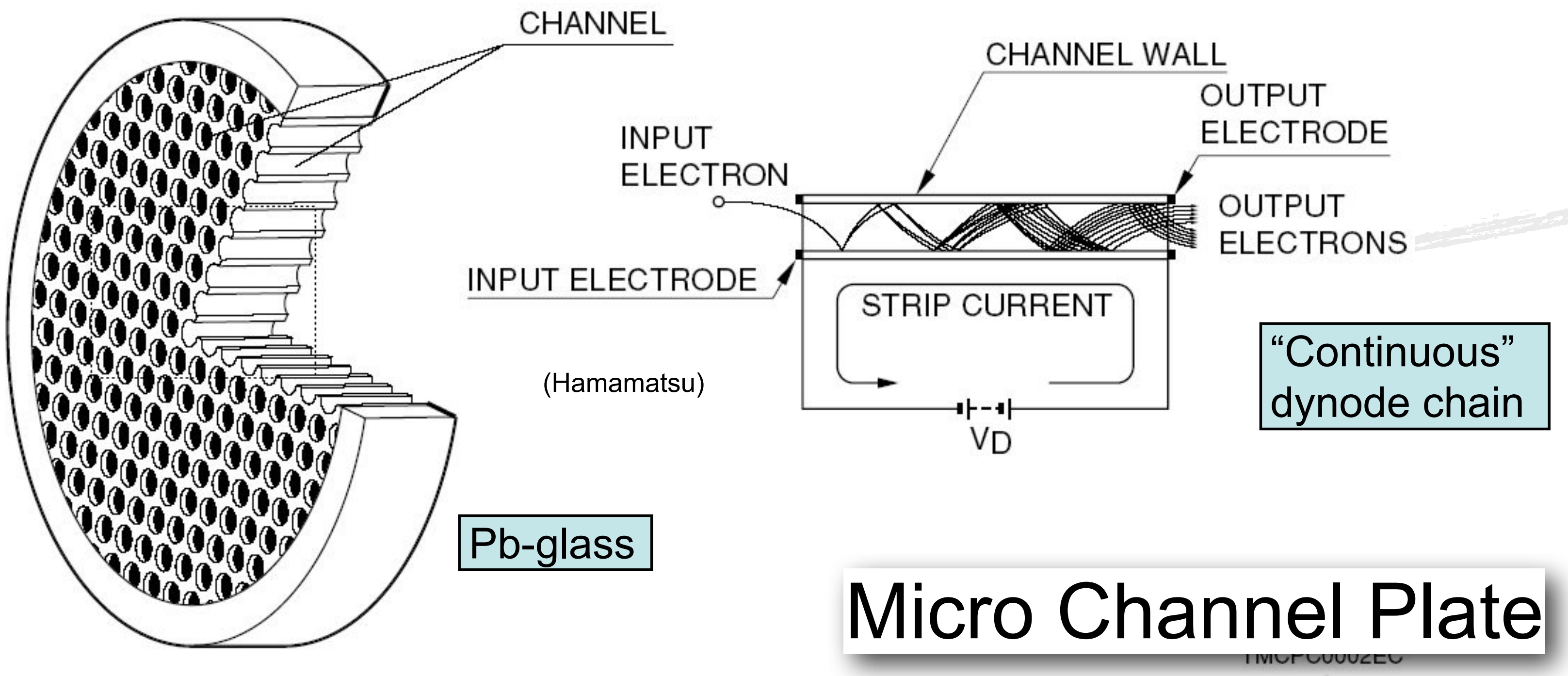


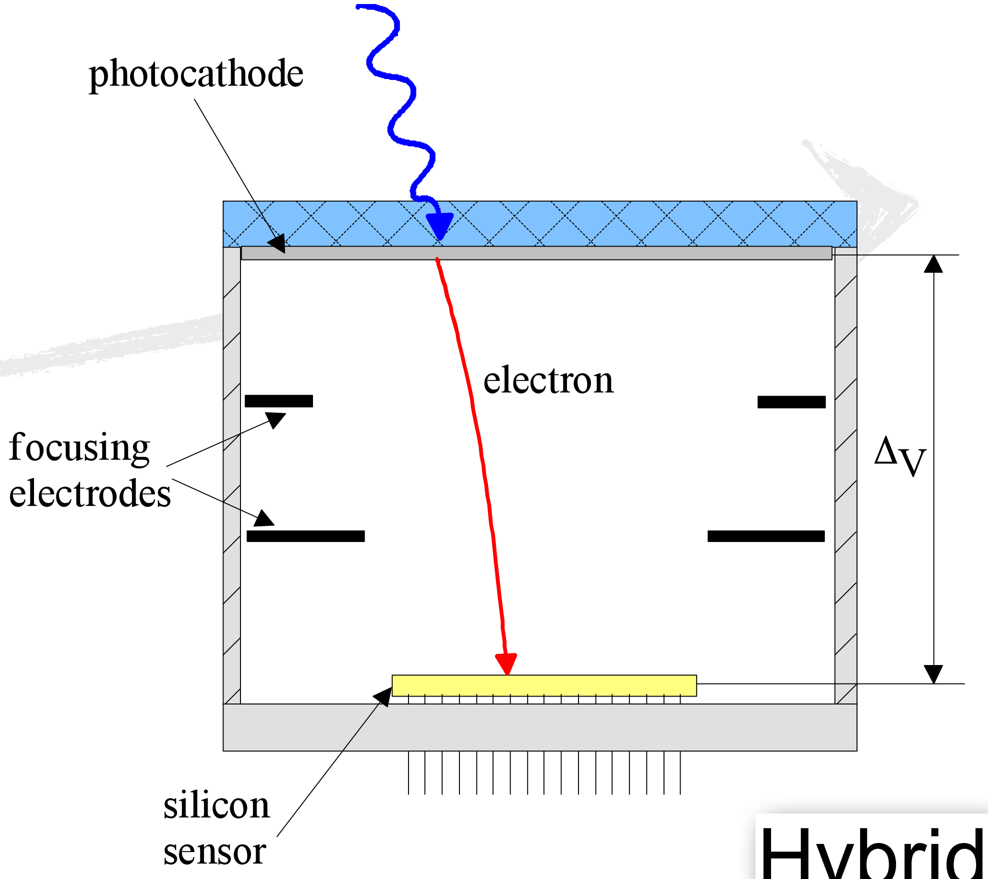
Other photo sensors



"Continuous" dynode chain

Pb-glass

Micro Channel Plate



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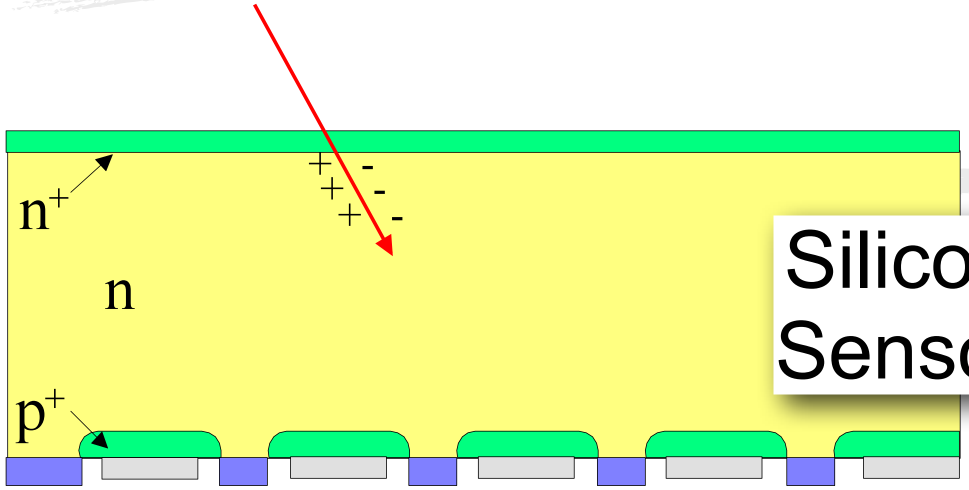
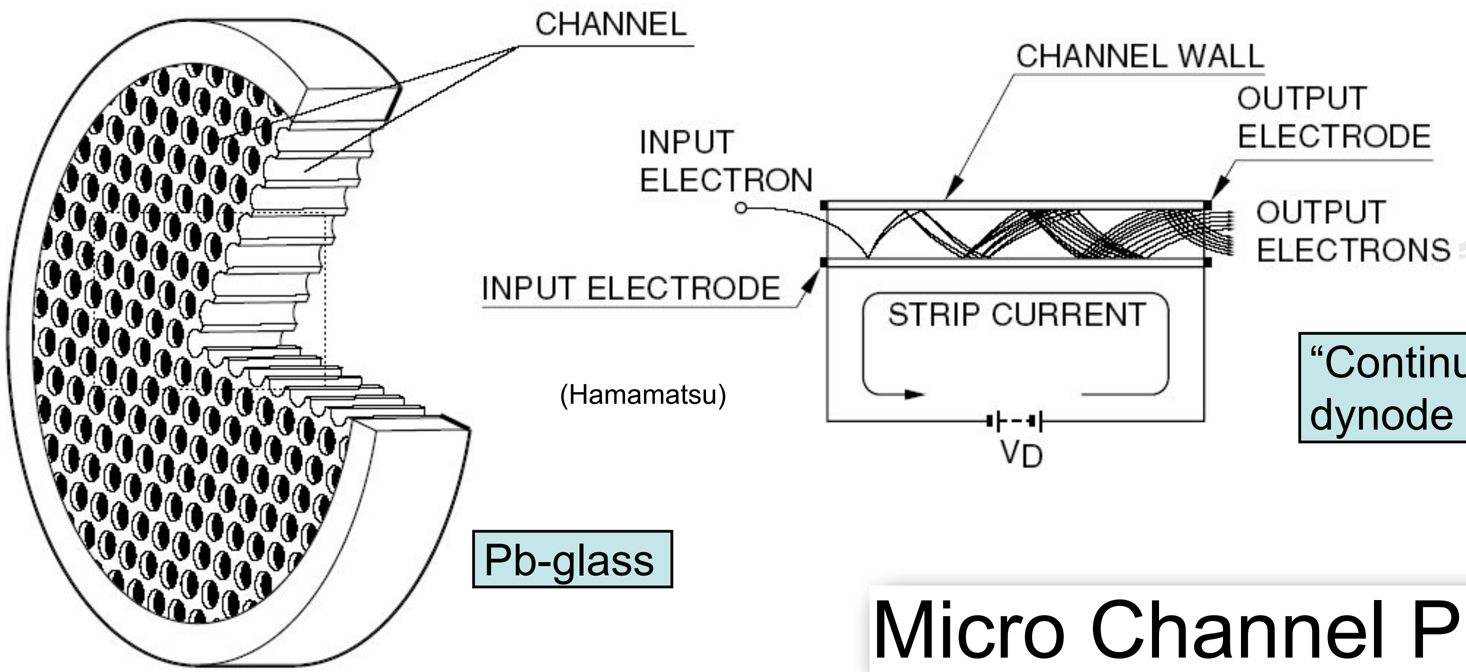


Silicon Sensor

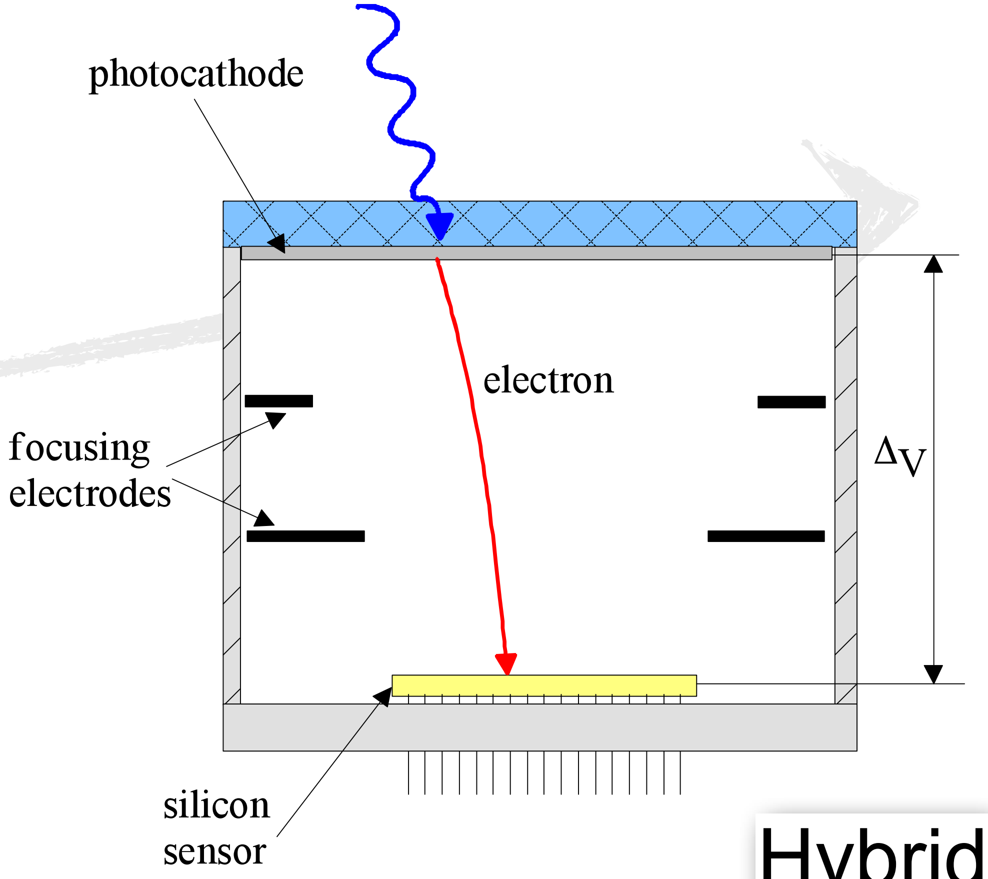
Other photo sensors



Pb-glass

"Continuous" dynode chain

Micro Channel Plate



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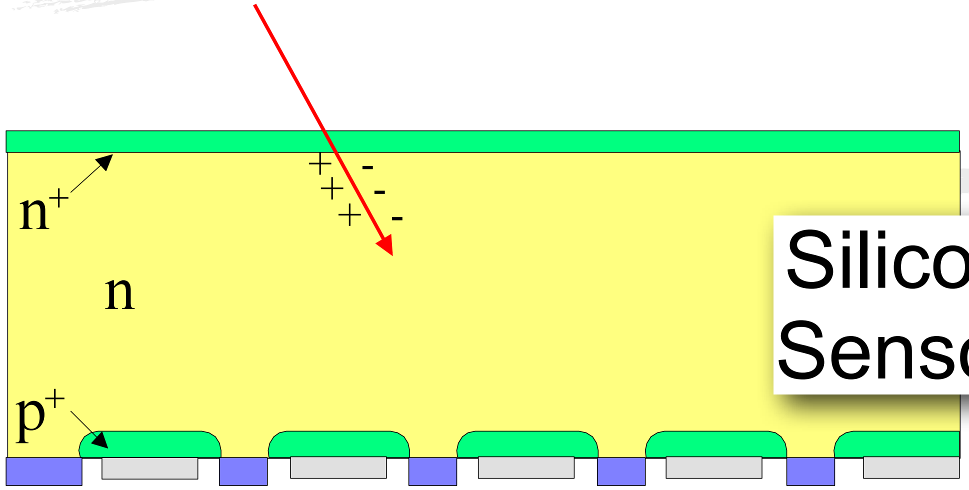
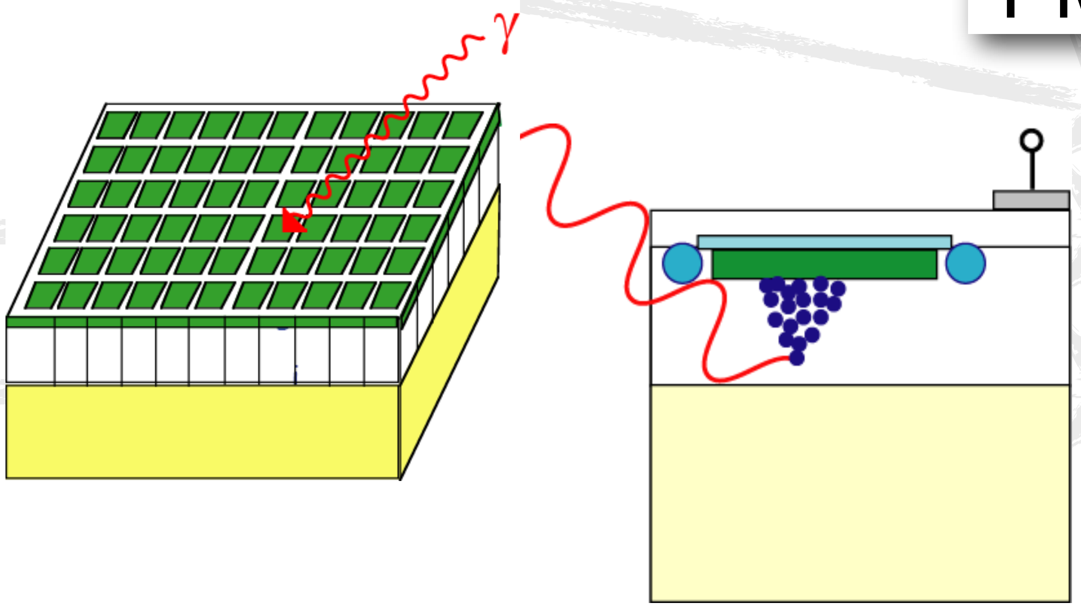
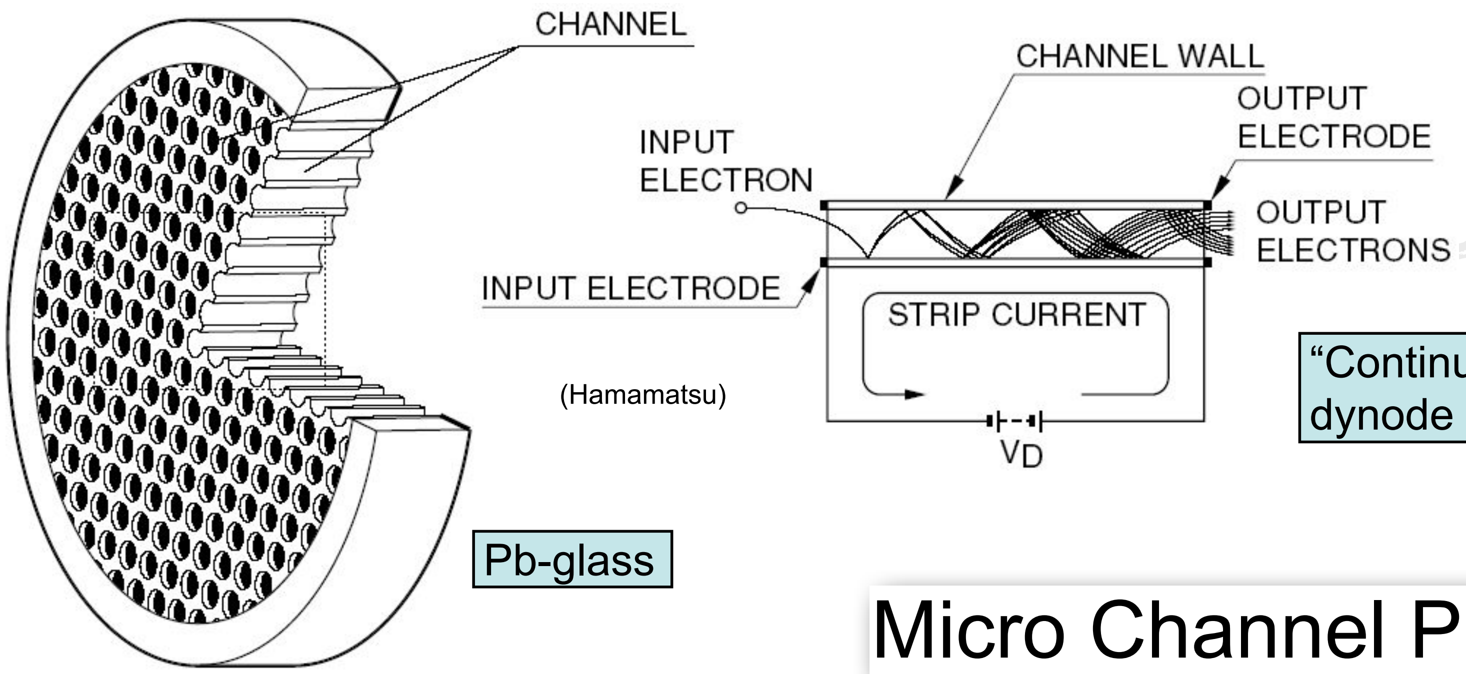


Silicon Sensor



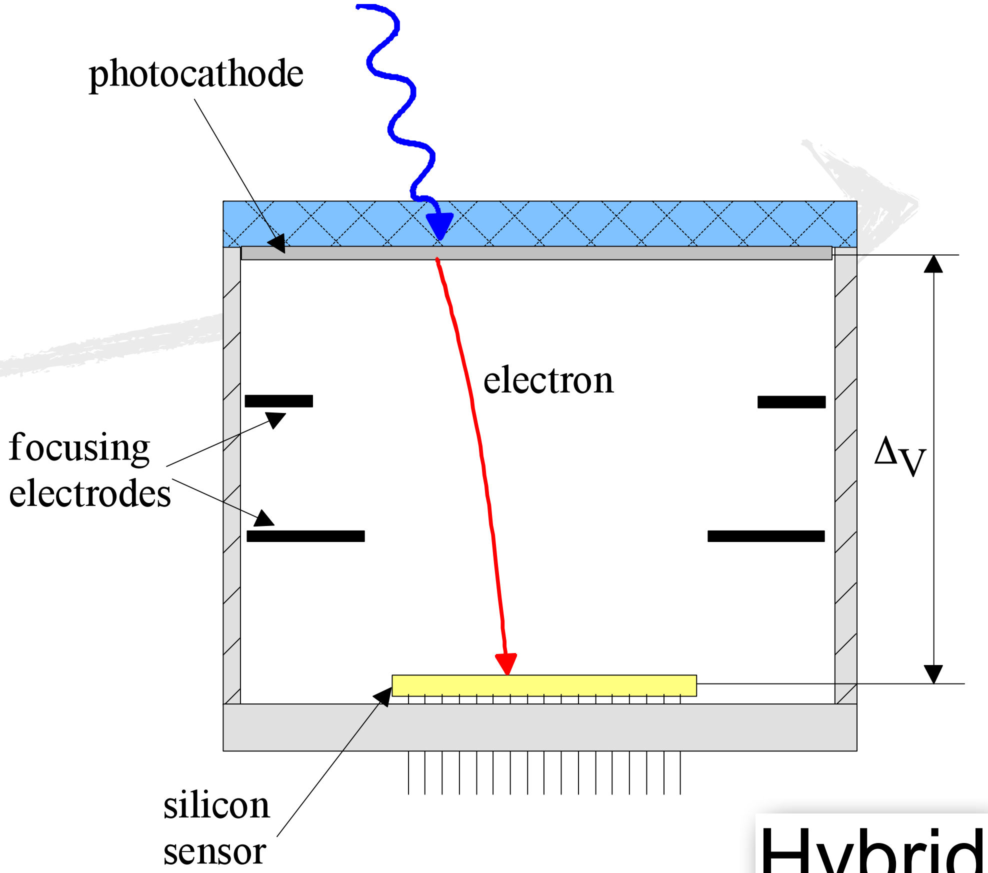
Other photo sensors



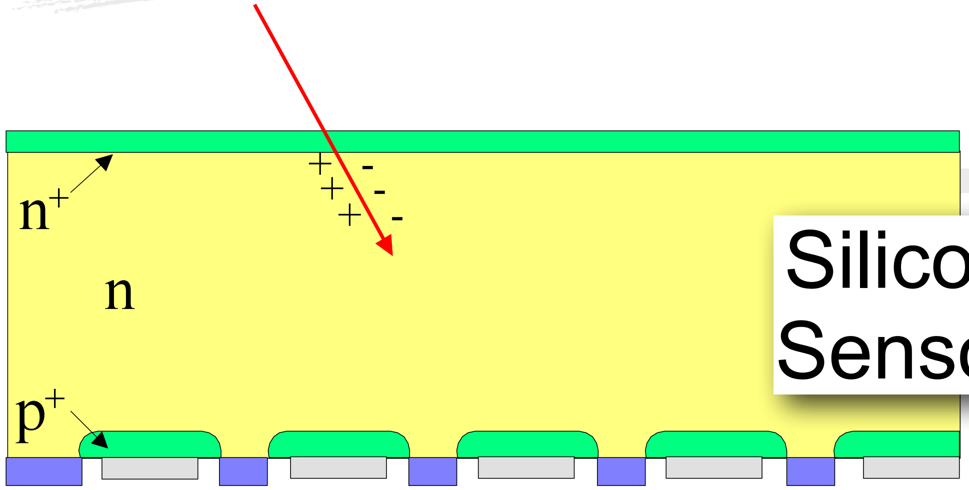
Pb-glass

"Continuous" dynode chain

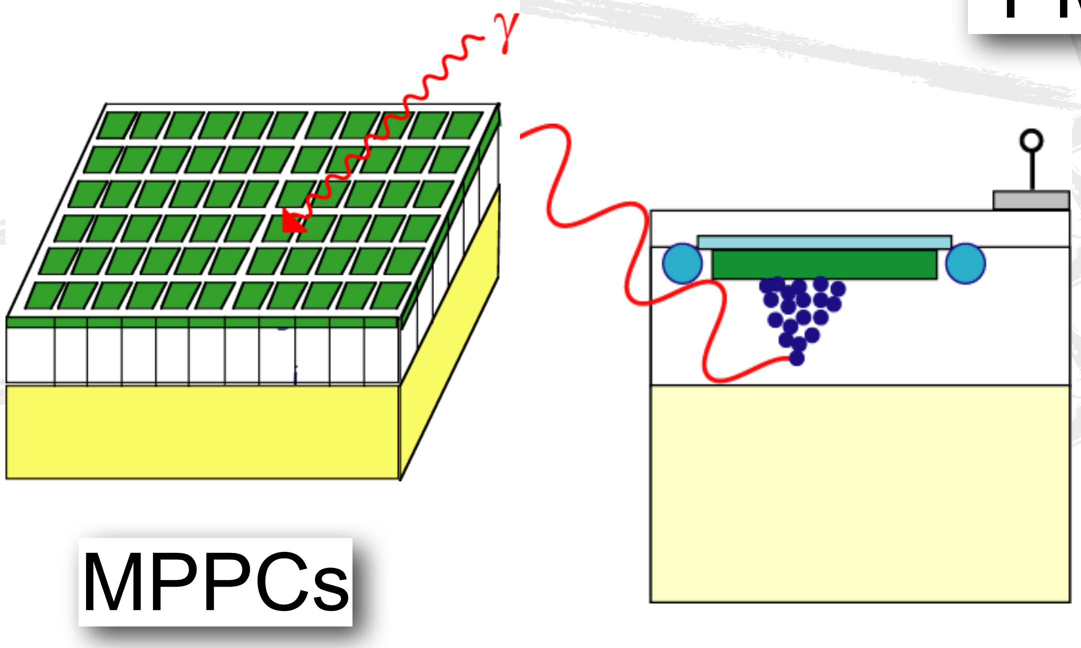
Micro Channel Plate



Hybrid PMT



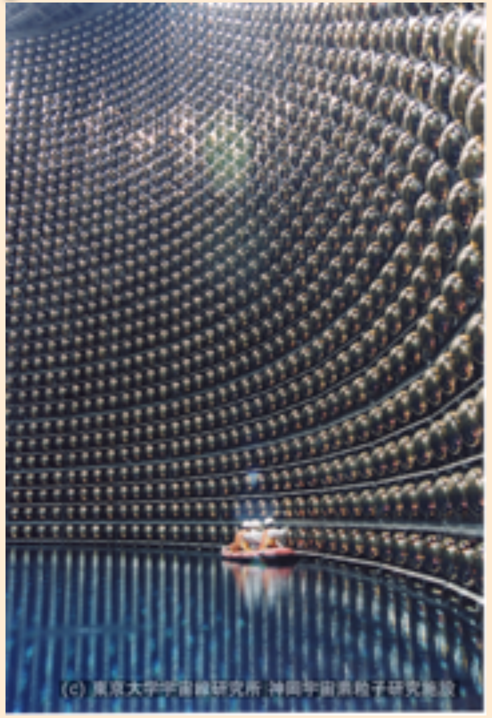
Silicon Sensor



MPPCs

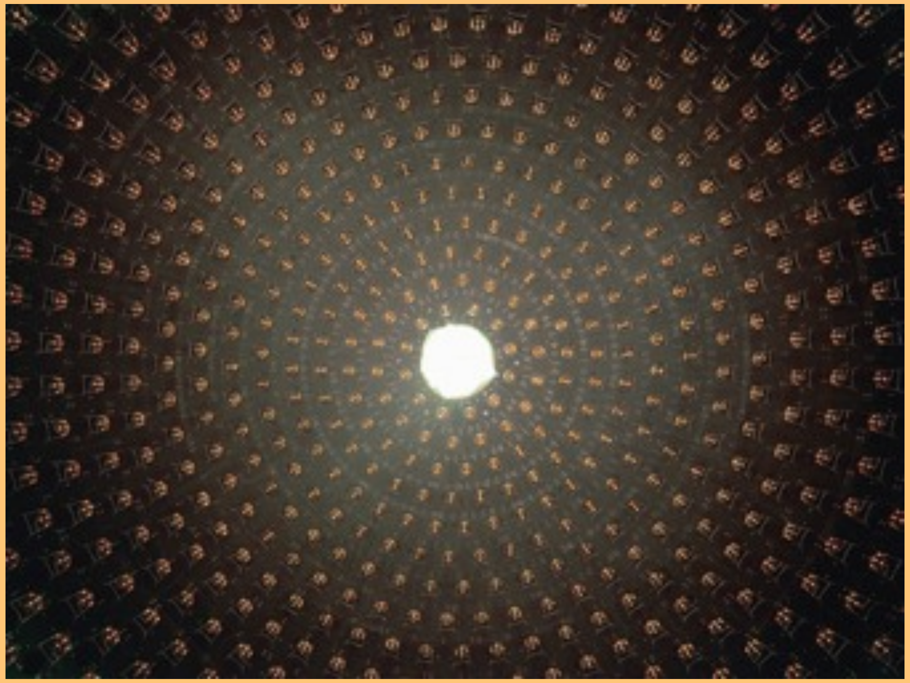
Experiments

SuperKamiokande



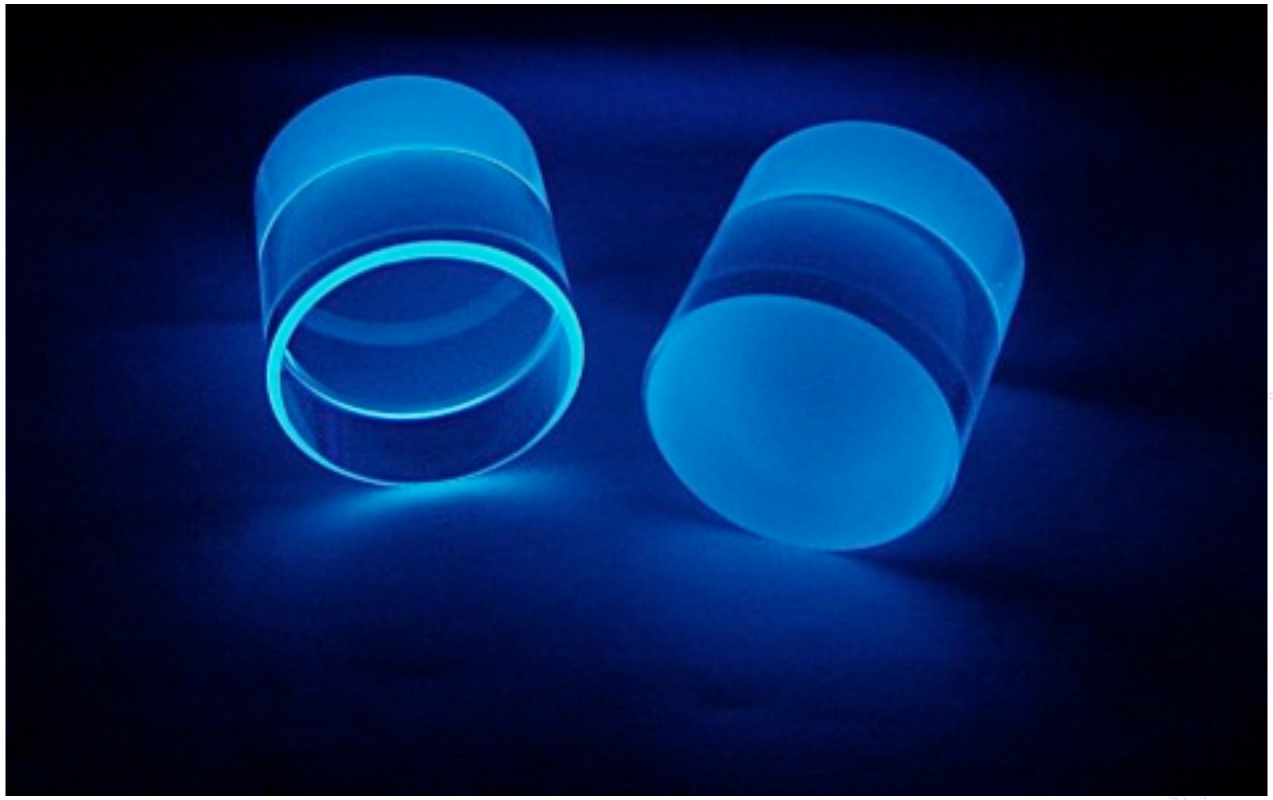
SNO

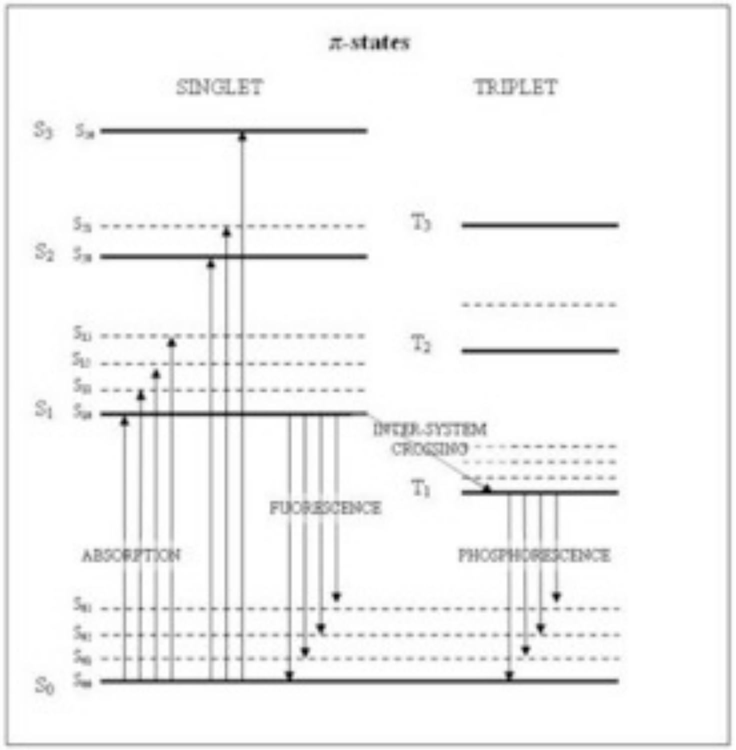
MiniBooNE



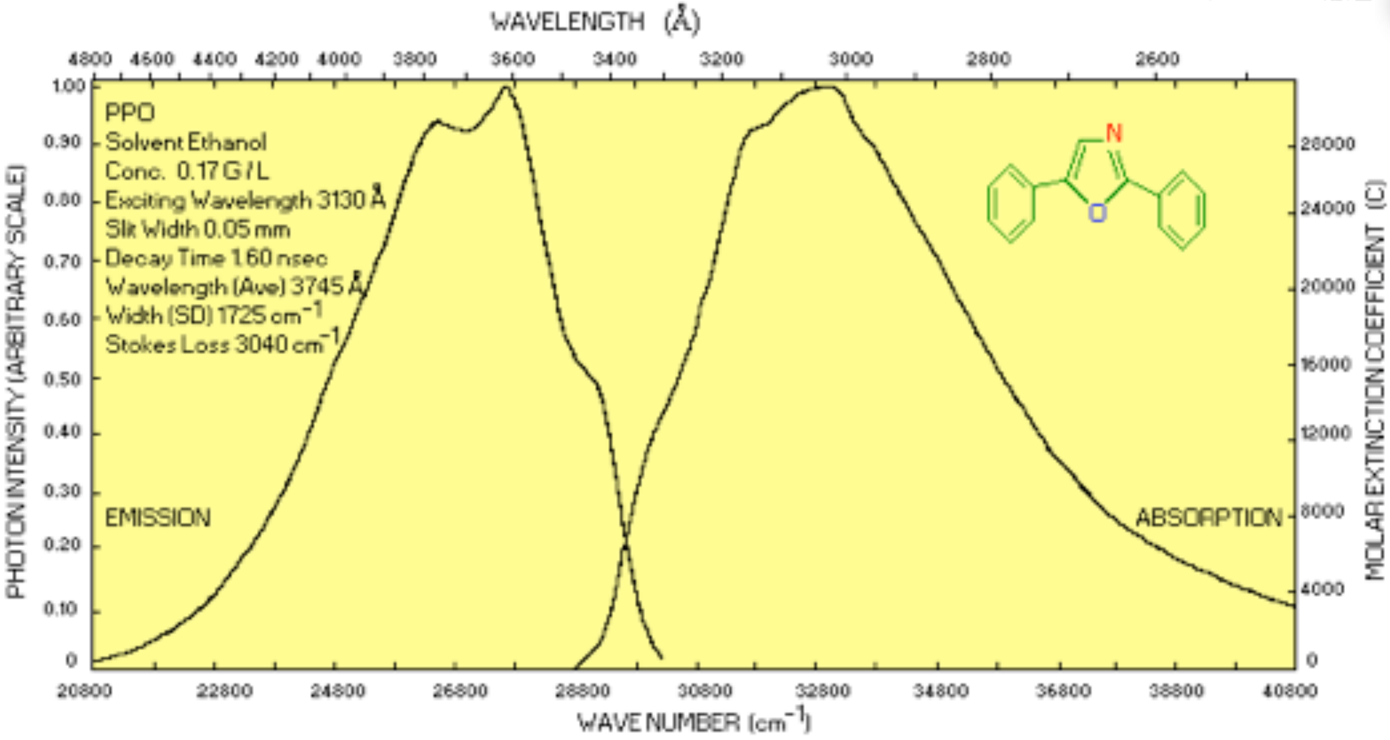
IMB

Scintillation





electron energy levels of organic scintillator



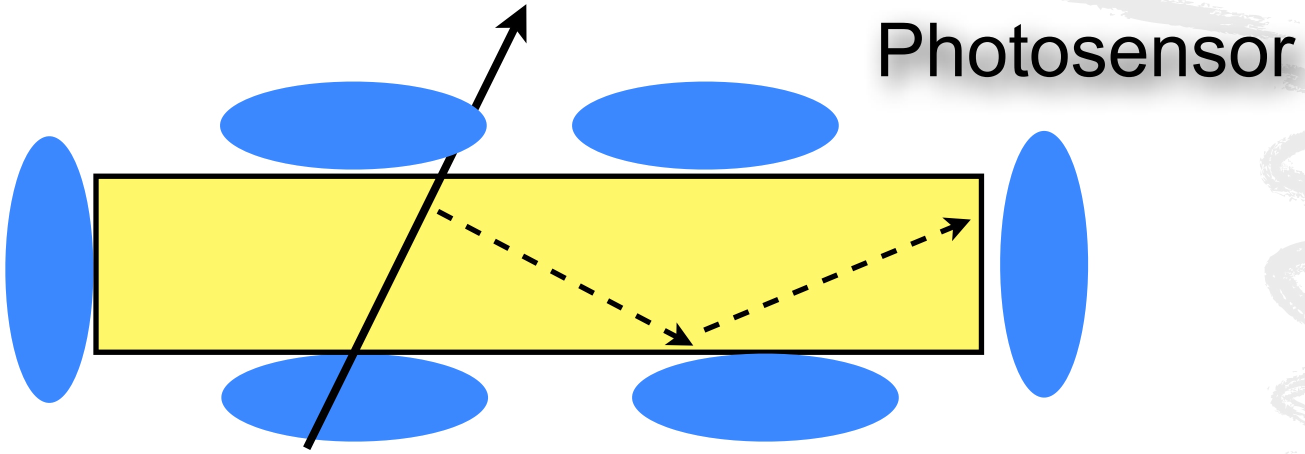
Birk's Law

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

Scintillation

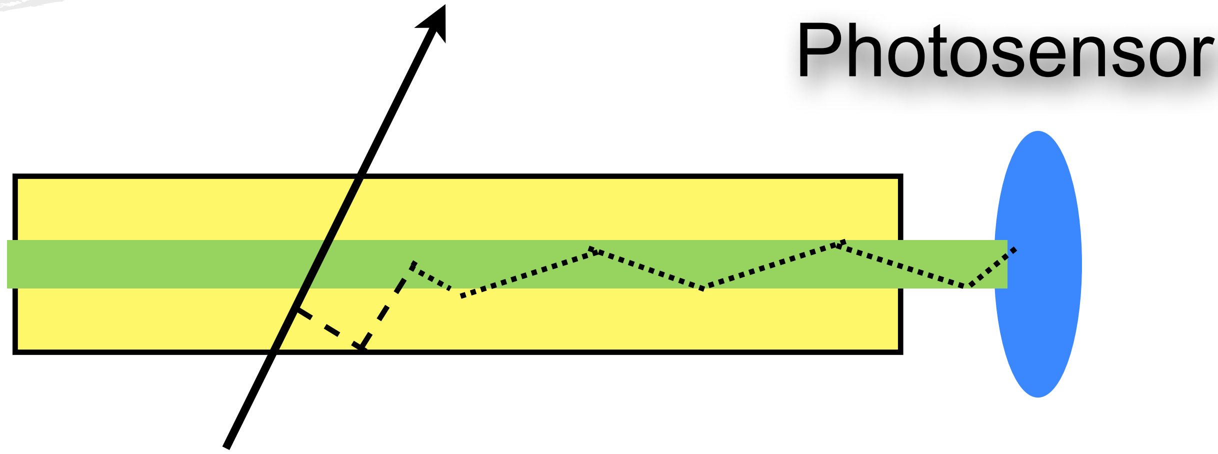
- Light collection can be done in two ways:

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.

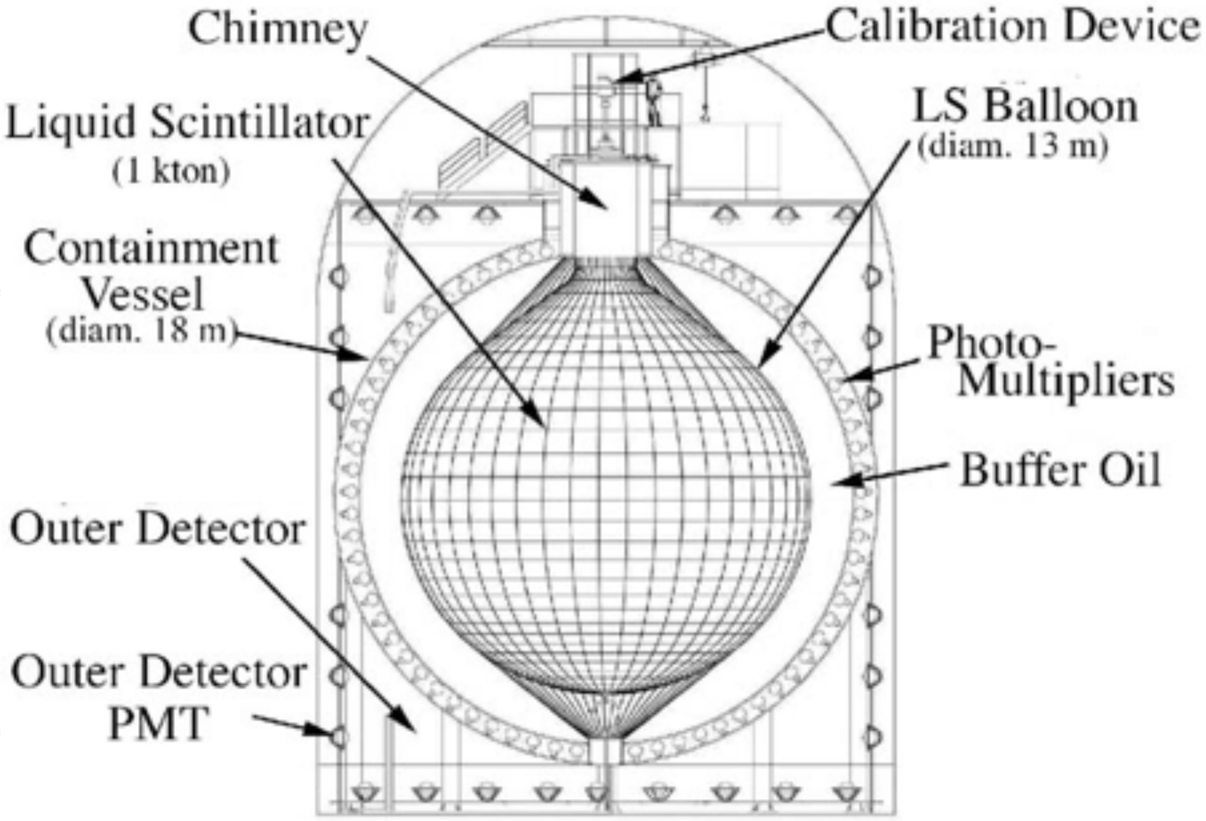
Scintillator detectors

- 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

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

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

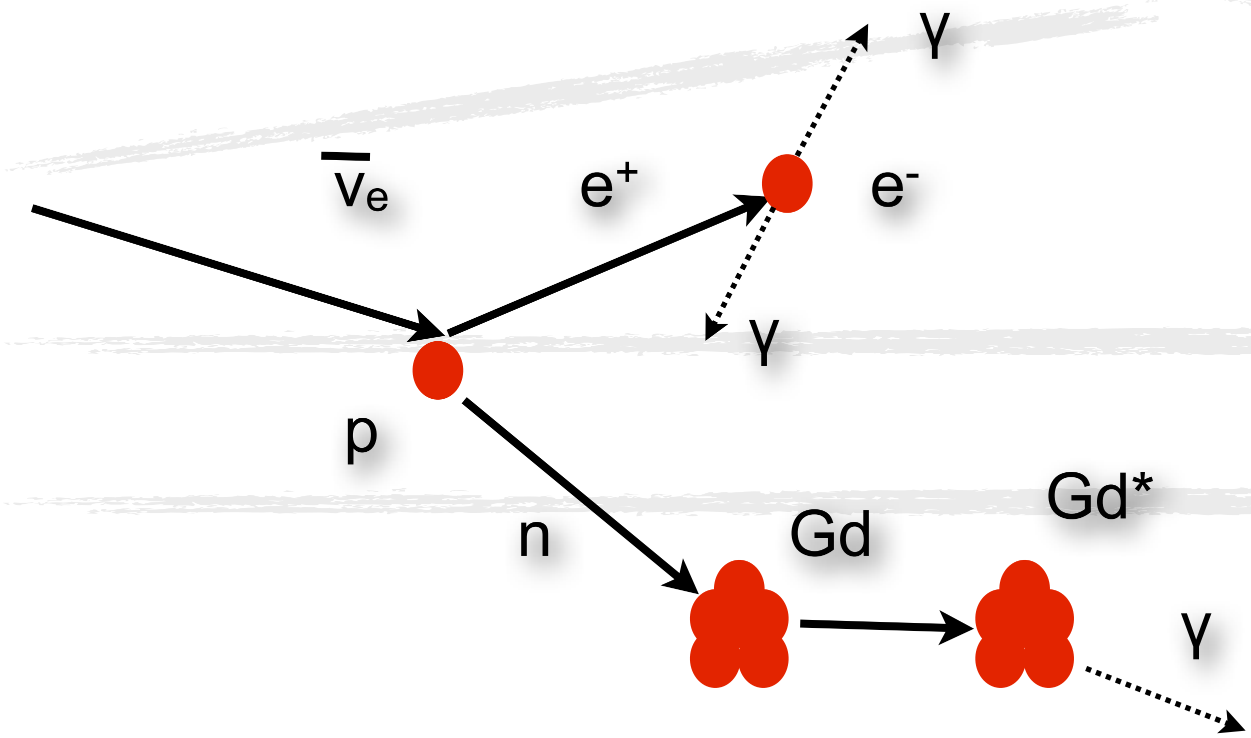
$$\nu_e e^- \rightarrow \nu_e e^-$$

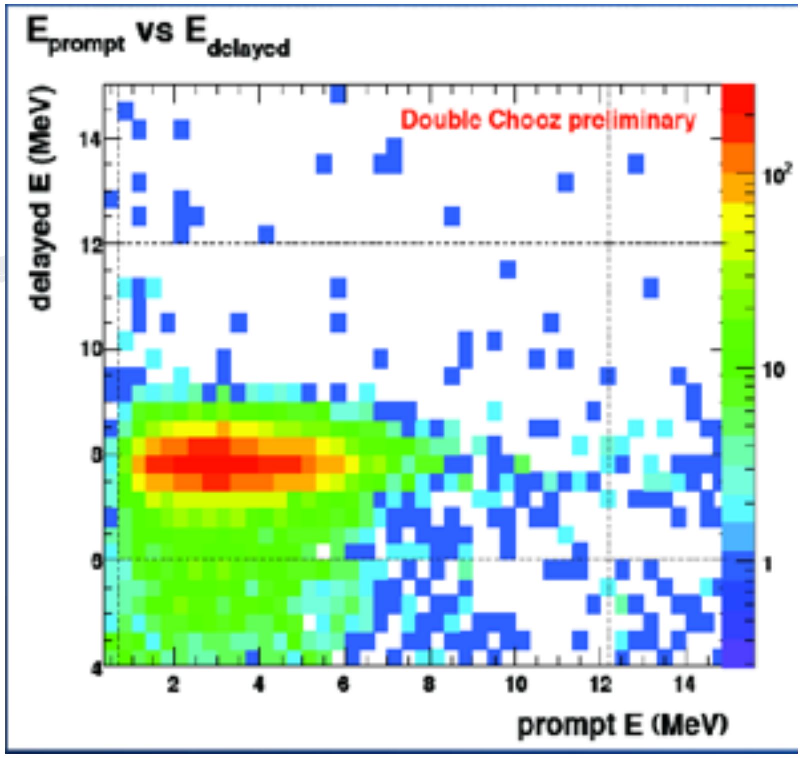


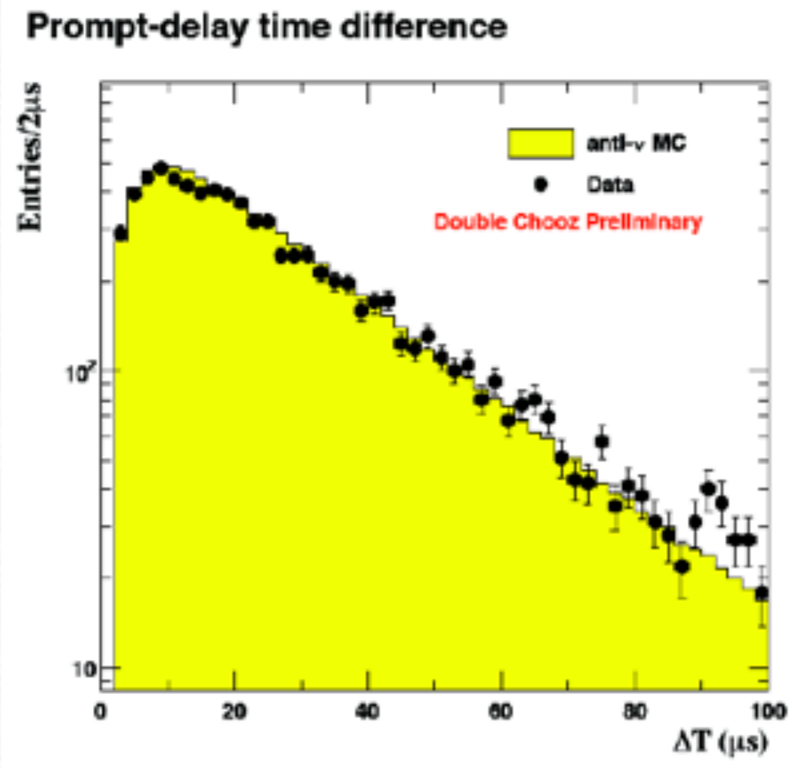
- The onion approach: layers of clean and active detectors to reduce radioactive background from outside.
- Dirty components (PMT) far from active area.
- Underground

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).





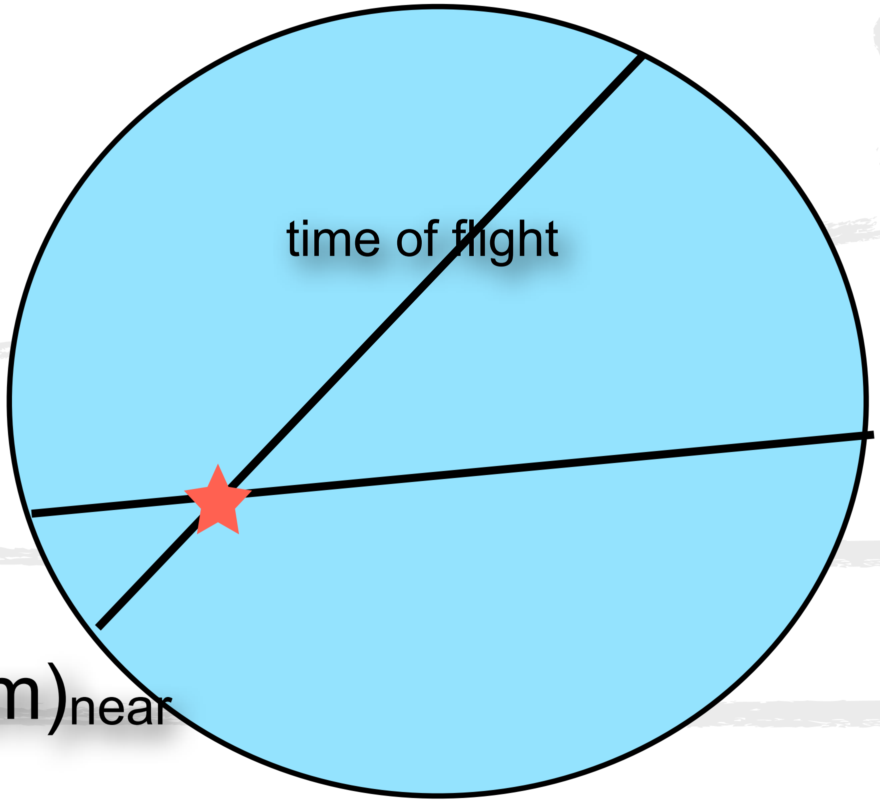


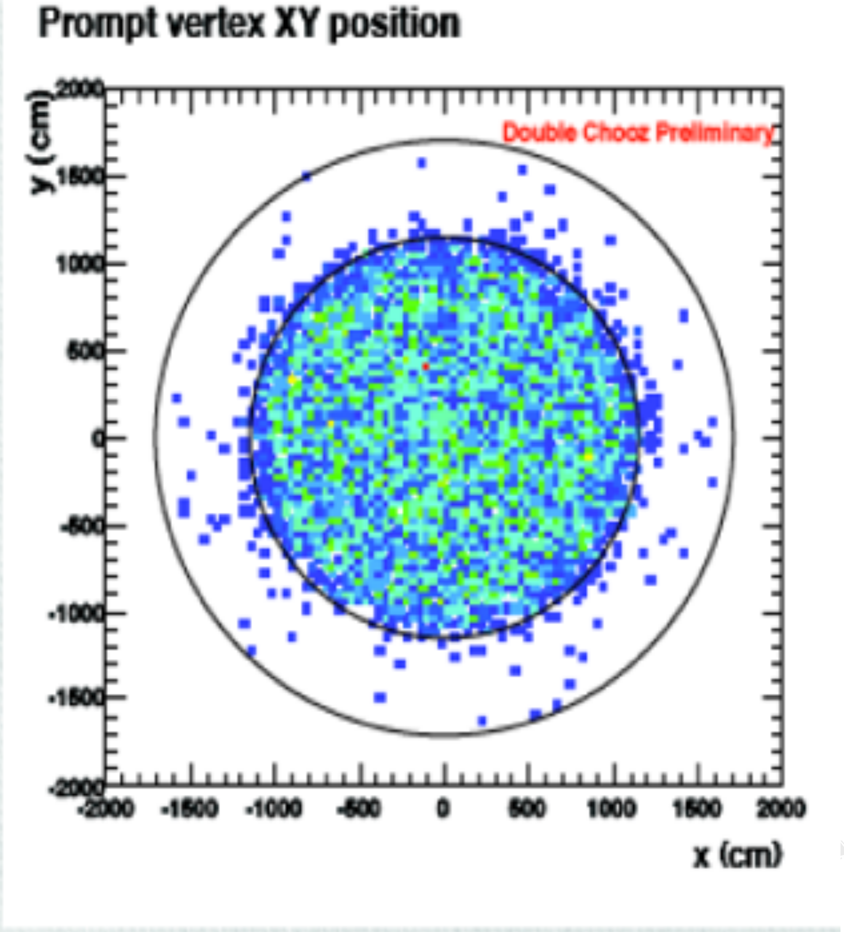
Scintillator detectors

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

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

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

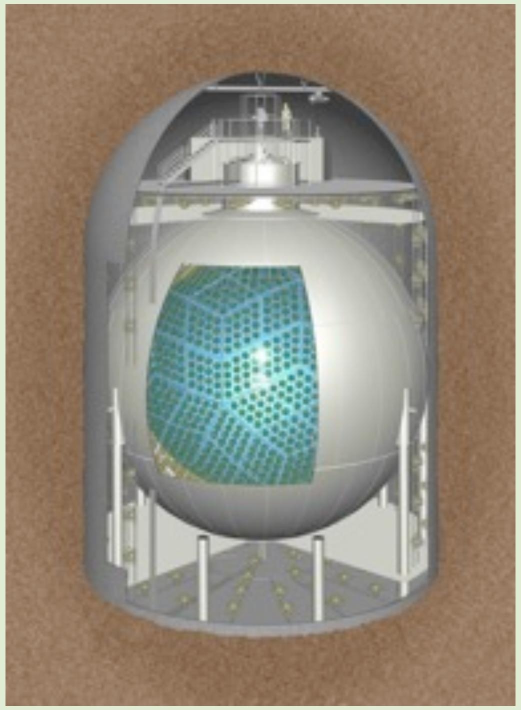




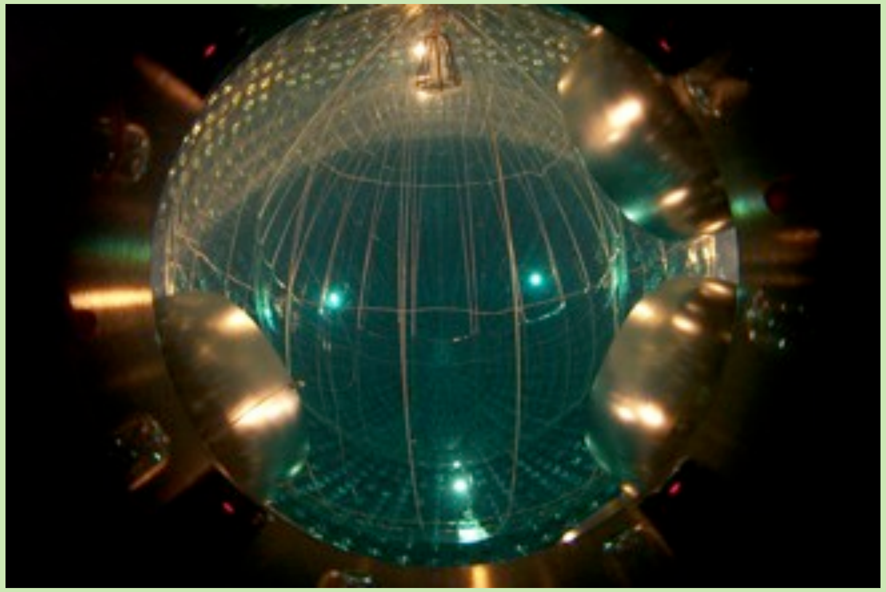
- If there is absorption in the detector, the position is needed to correct for light collection.

Experiments

Kamland



Borexino



LSND

Daya Bay

Ionisation

- The number of electrons depends on ionisation energy, a property of the material:
    - Based on this formula, the fluctuation of number of electrons will be 0.
    - 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.
    - There is a competition between ionisation and scintillation

Ionisation

- The number of electrons depends on ionisation energy, 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.

- The fluctuation is given by

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

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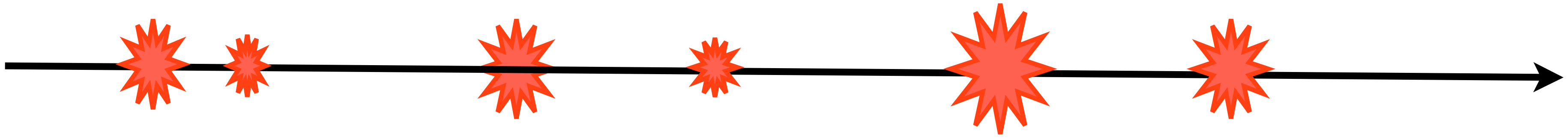
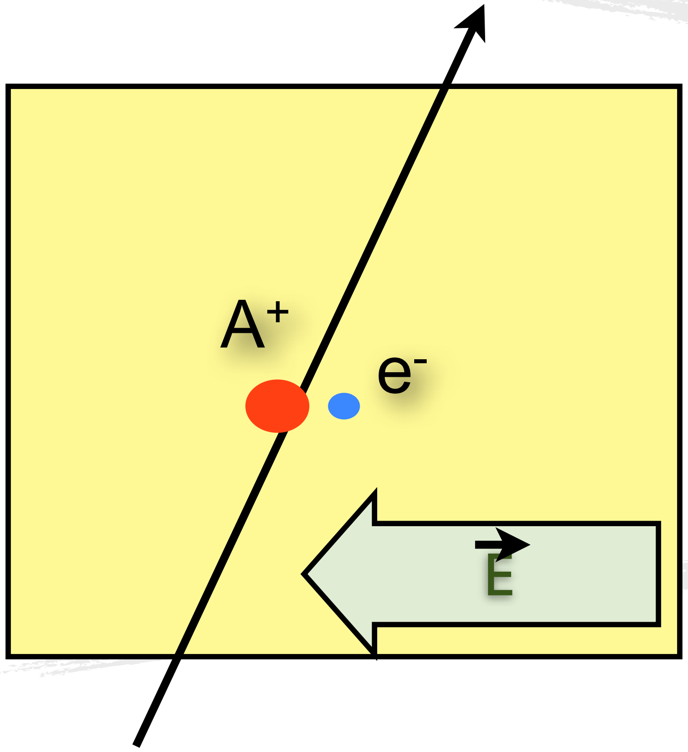
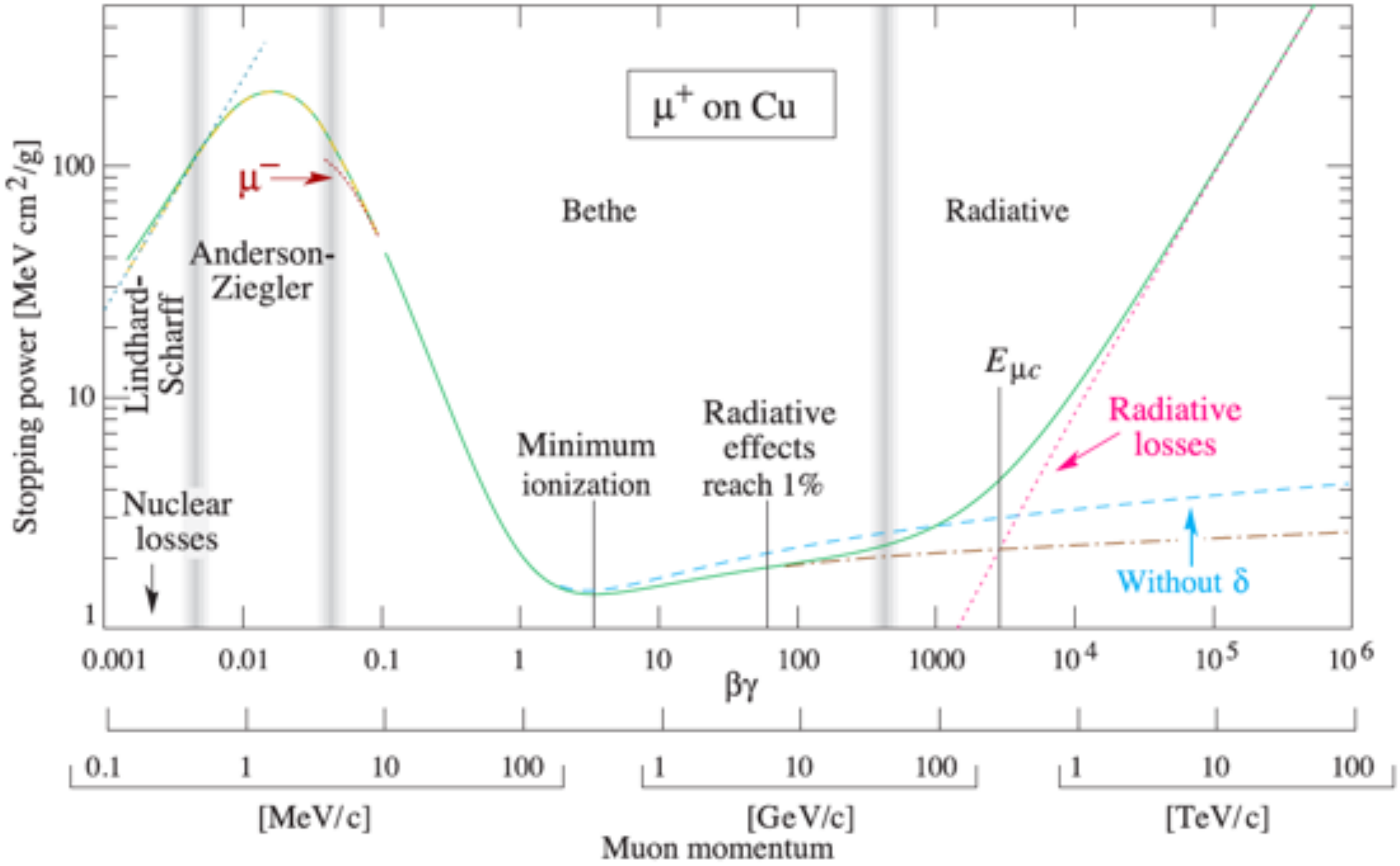
Ionisation





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



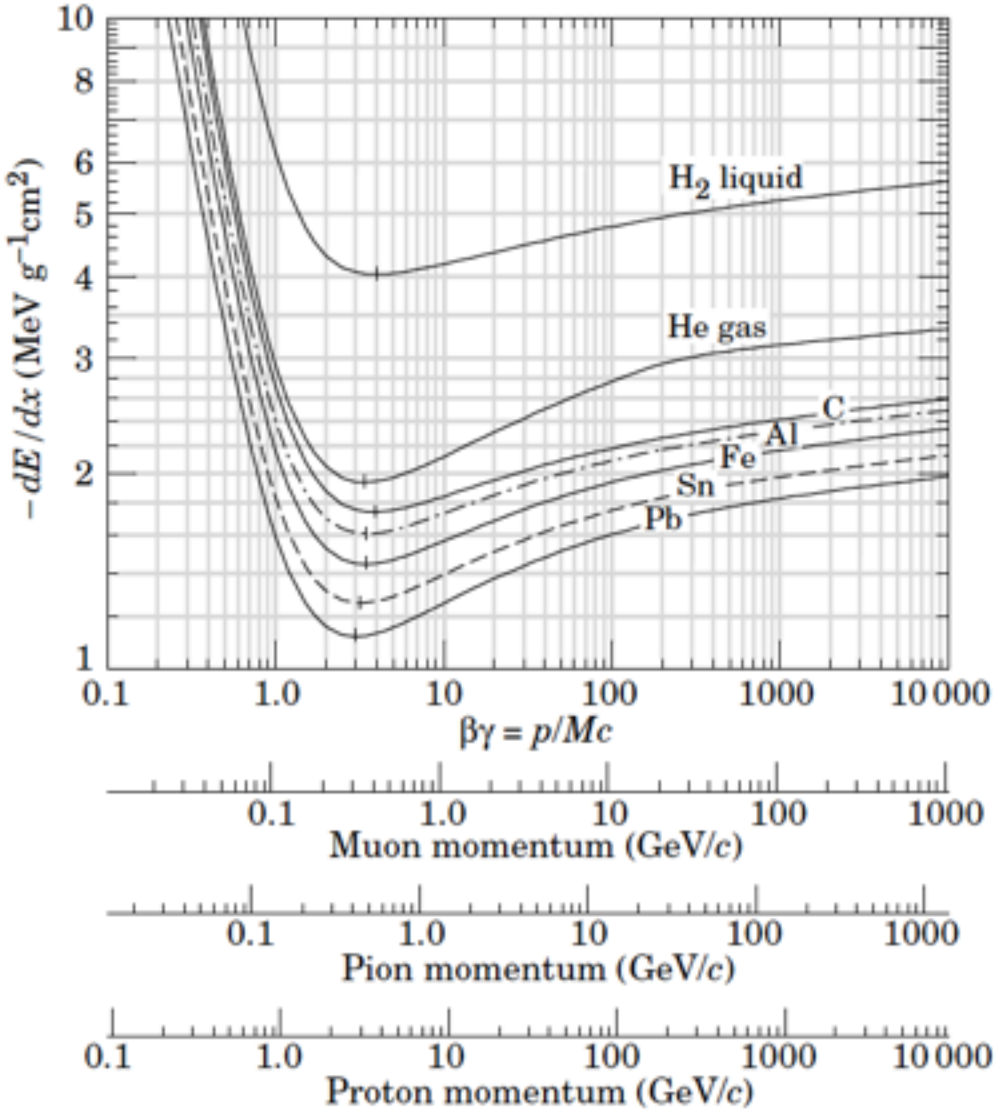
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Bethe-Block approach is valid in a large range of βγ

$0.1 < \beta\gamma < 1000$

Ionisation

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



- The energy loss depends on βγ, so it is different for different particle masses.
- Measuring both the dE/dx and the momentum of the particle we can compute its mass: identify the particle.
- This will be the same with the particle range, because the kinetic energy of a particle is:

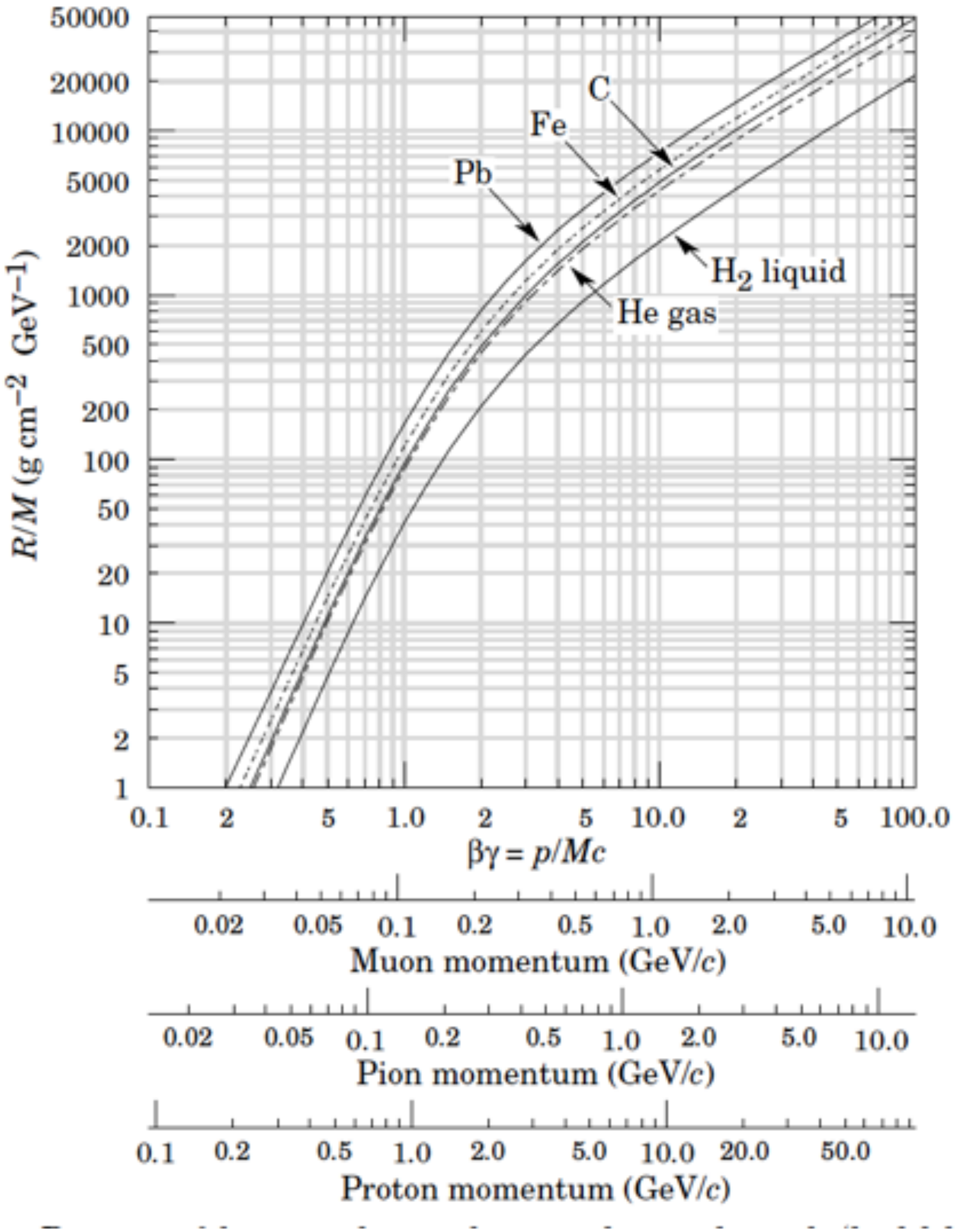
$$E_{kin} = \sqrt{p*p+m*m} - m = m(\sqrt{(\beta\gamma)^2+1} - 1)$$

  - measuring range and energy deposit also identifies the particle.

Ionisation

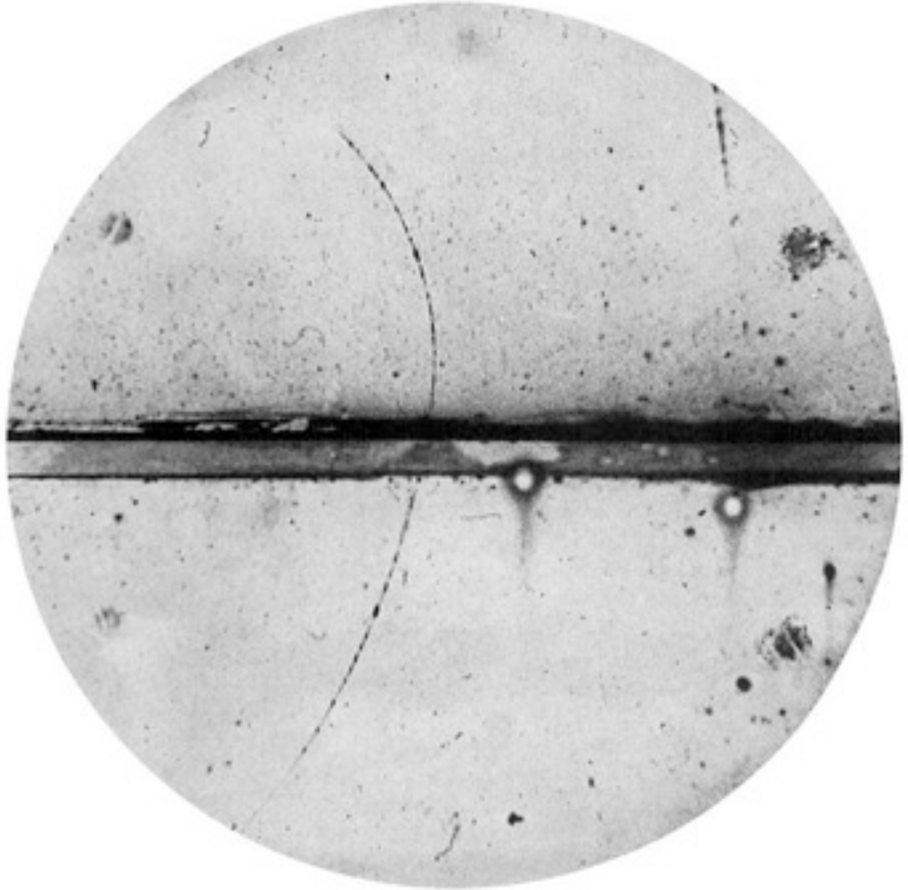
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-passage-particles-matter.pdf

- Particles crossing thick detectors can lose all kinetic energy and come to rest → “range”.
- The range depends on βγ so it will be different for every particle type and initial momentum.
- Through the range, we could compute the initial βγ, and then compute the momentum and energy of the particle if identified.
- Range/Mass has almost a power law dependence for $\beta\gamma > 5$ and $\beta\gamma < 1$
    - for $\beta\gamma > 5$: $R/M = \alpha\, p^1 + \beta$



Cloud chamber

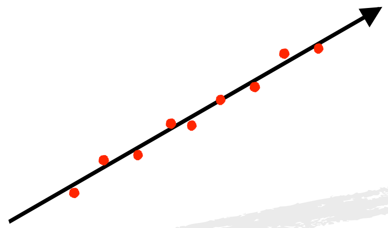
e$^+$ discovery



- The cloud chamber is the simplest ionising detector one could build.
- It is a supersaturated environment of alcohol. The particle ionise ions and the alcohol saturates around the ions leaving visible traces.

Gas Ionisation

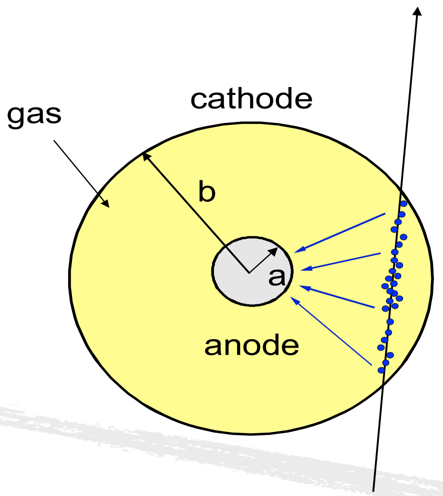
- Charged particles ionise the atoms of a gas.
- If the A^+ and the e^- are not separated, they recombine → apply E field to drift them apart.
- In 1cm of gas ~100 e- are produced. We need to increase the number of electrons.
- We can accelerate the electrons in an intense electric field (narrow wire).
- The electrons can ionise 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.

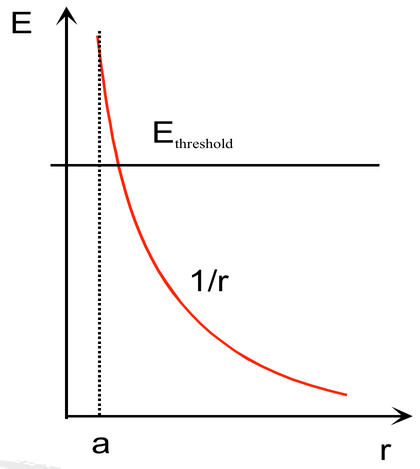


Primary ionisation

10 - 40 pairs/cm

ΔE/pair ~ 20 - 40 eV



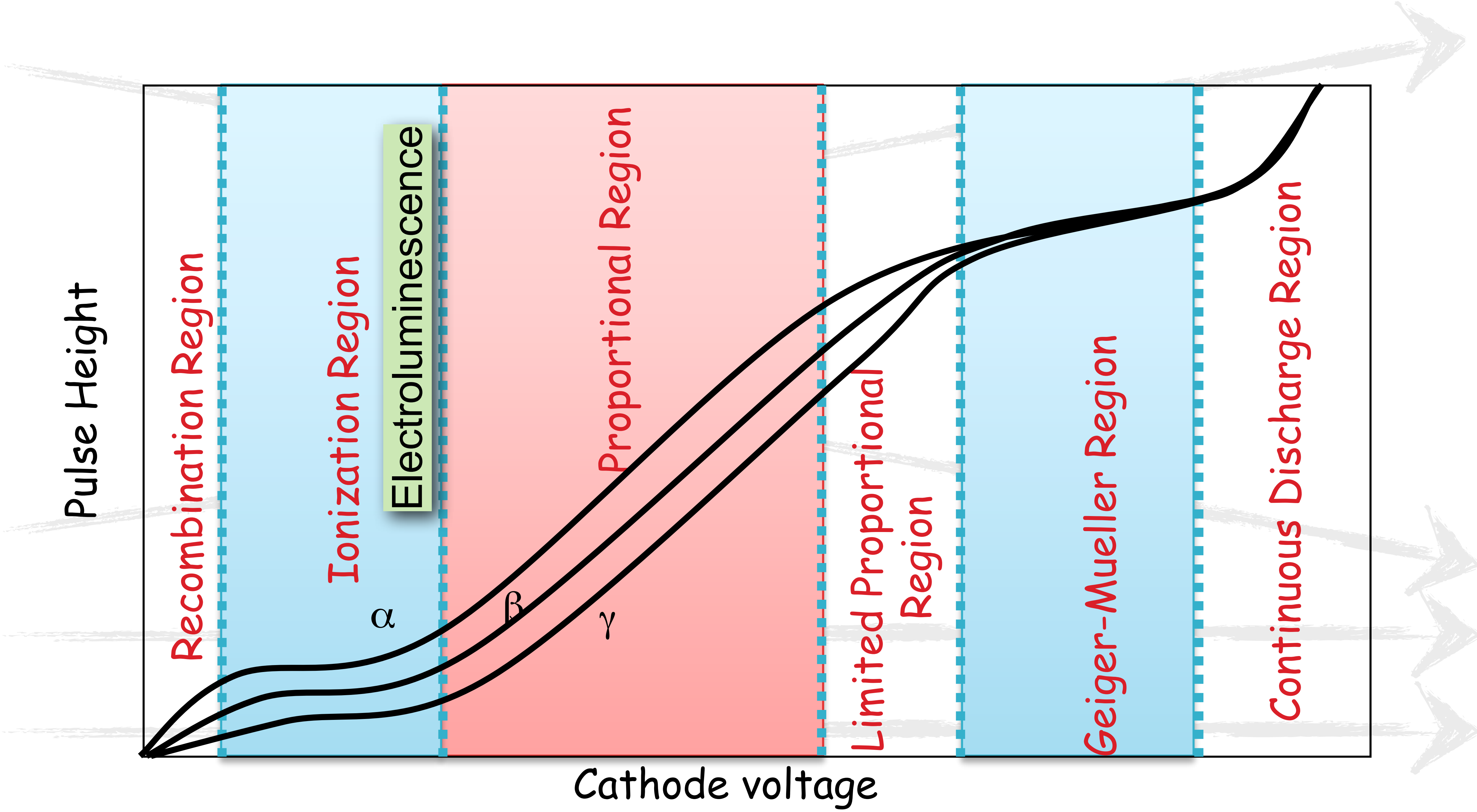


$$M = \frac{n}{n_0} = \exp\left[\int_a^{r_C} \alpha(r)\,dr\right]$$

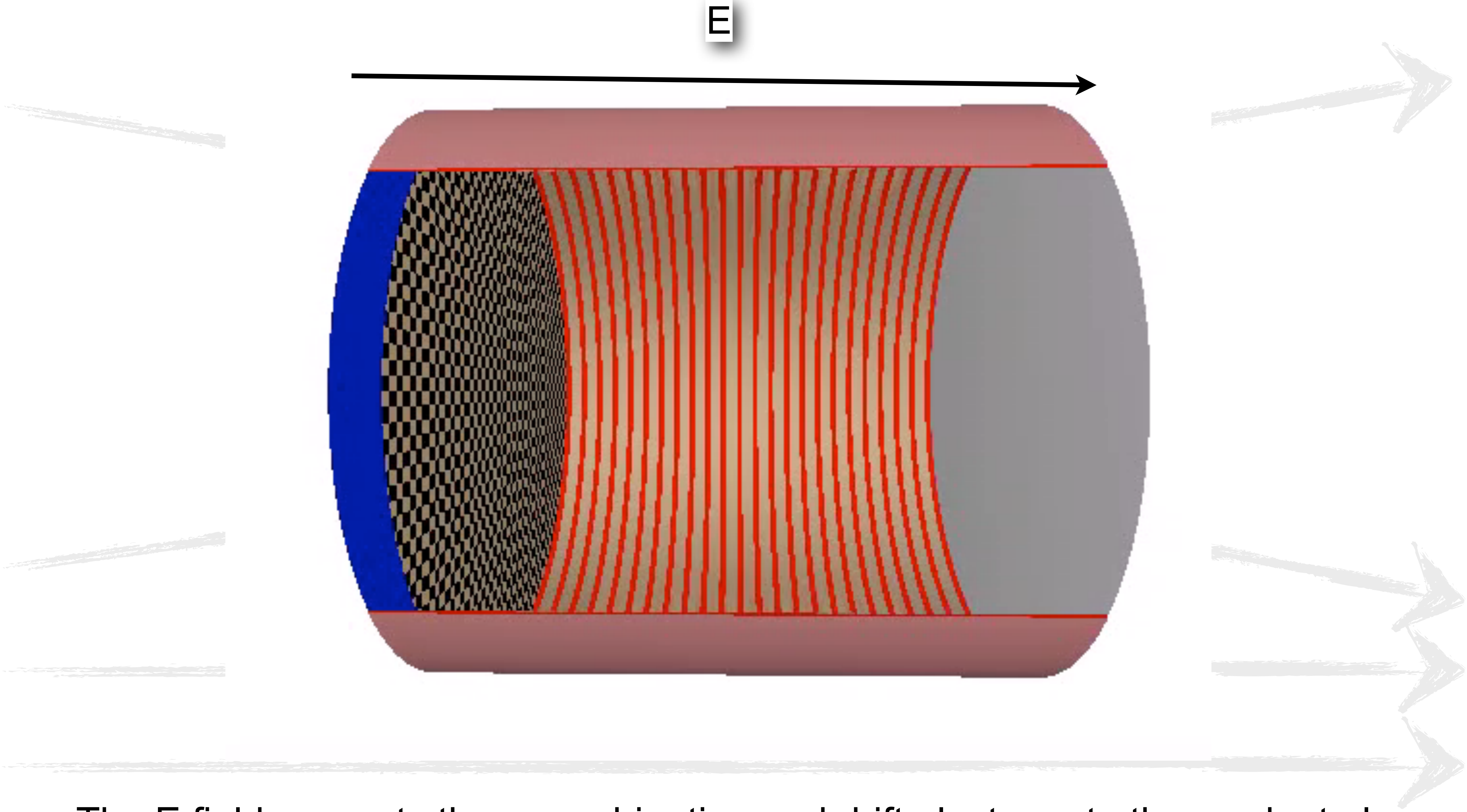
$$\alpha = \frac{1}{\lambda}$$

λ = mean free path

Readout techniques

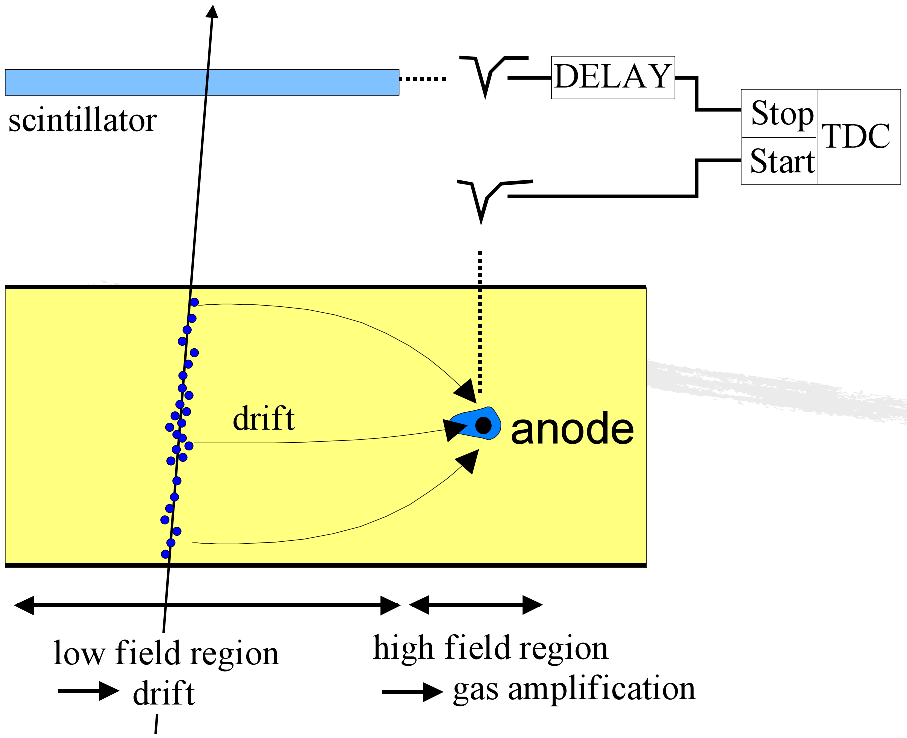


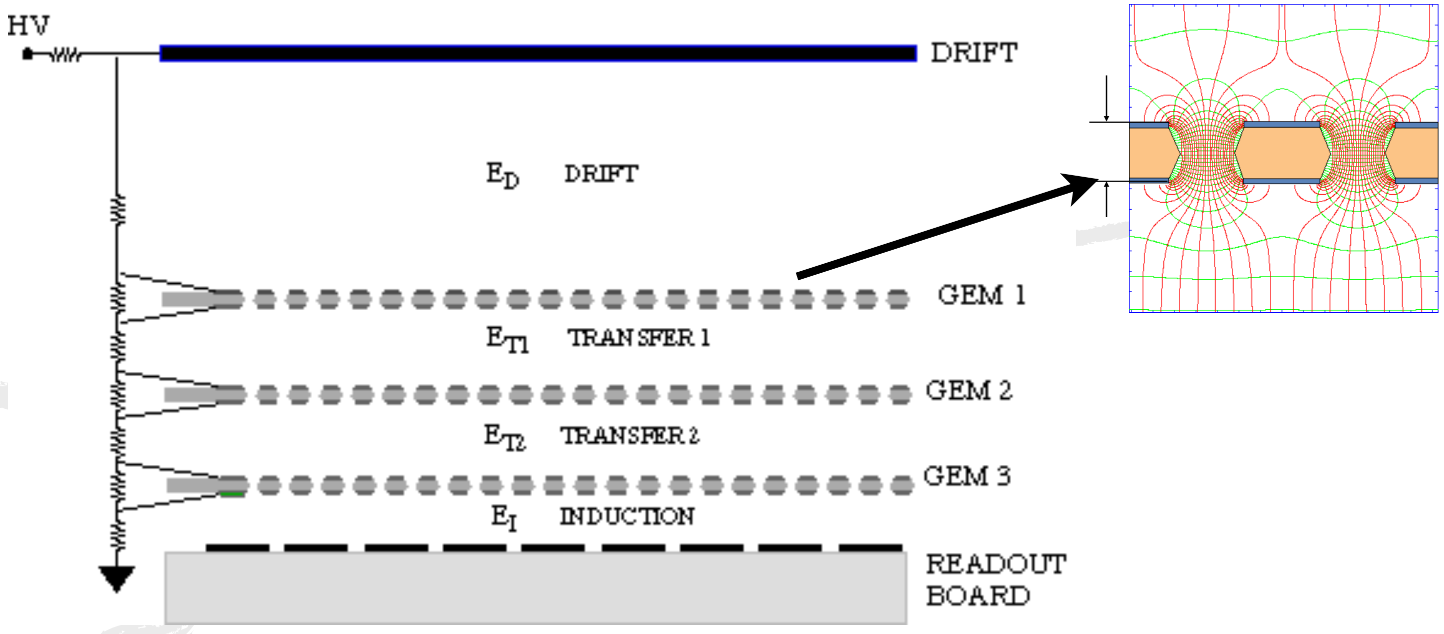
Time Projection Chamber

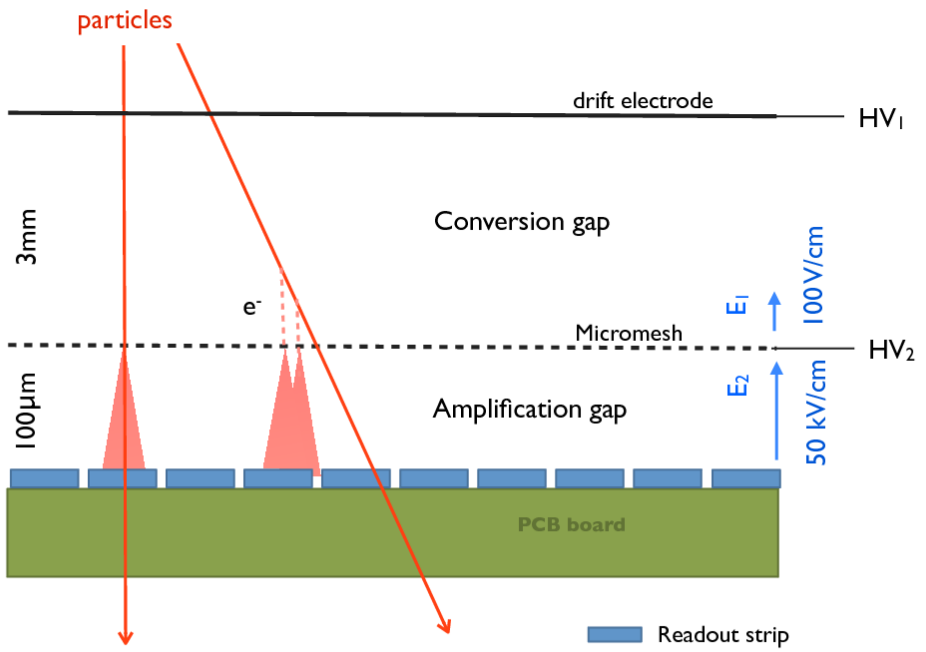


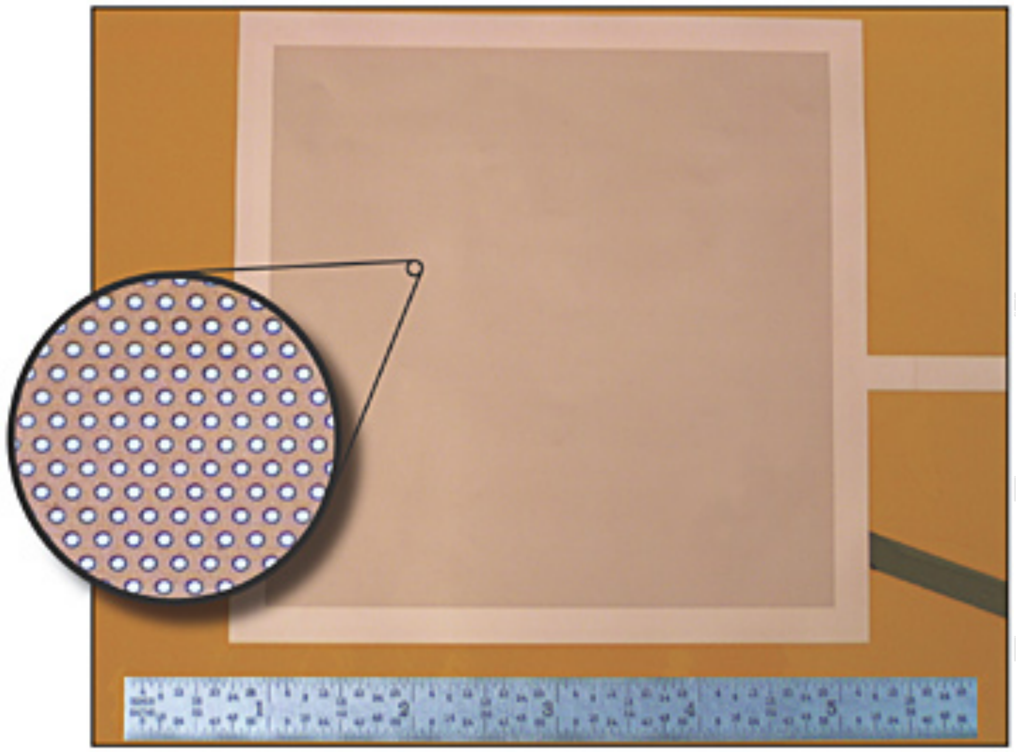
- The E field prevents the recombination and drift electrons to the readout planes.

Readout techniques

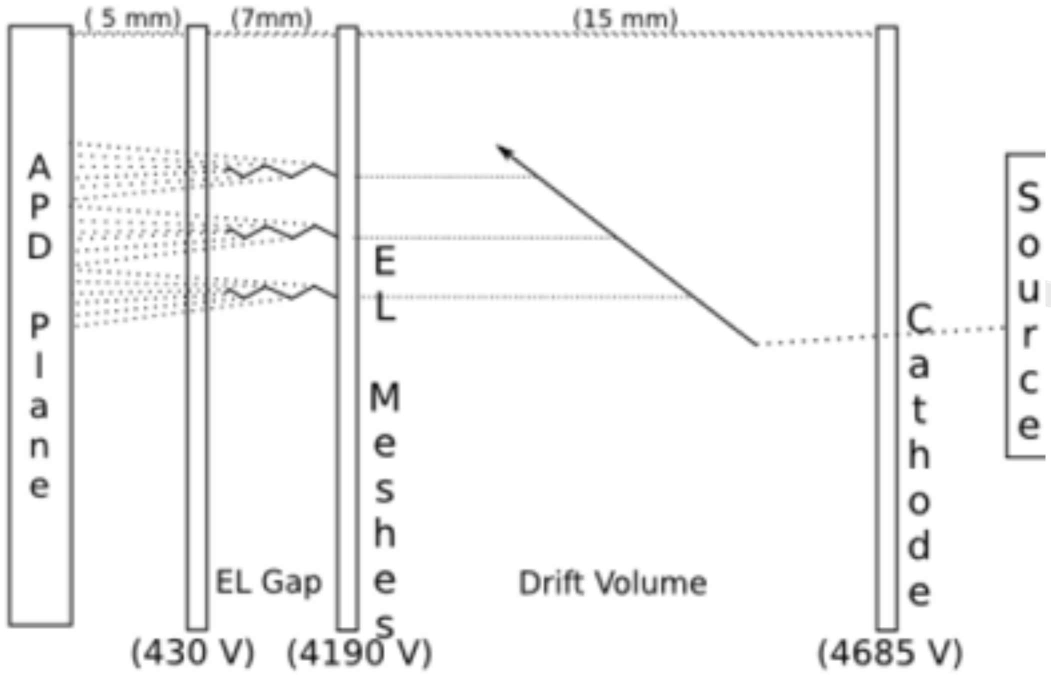


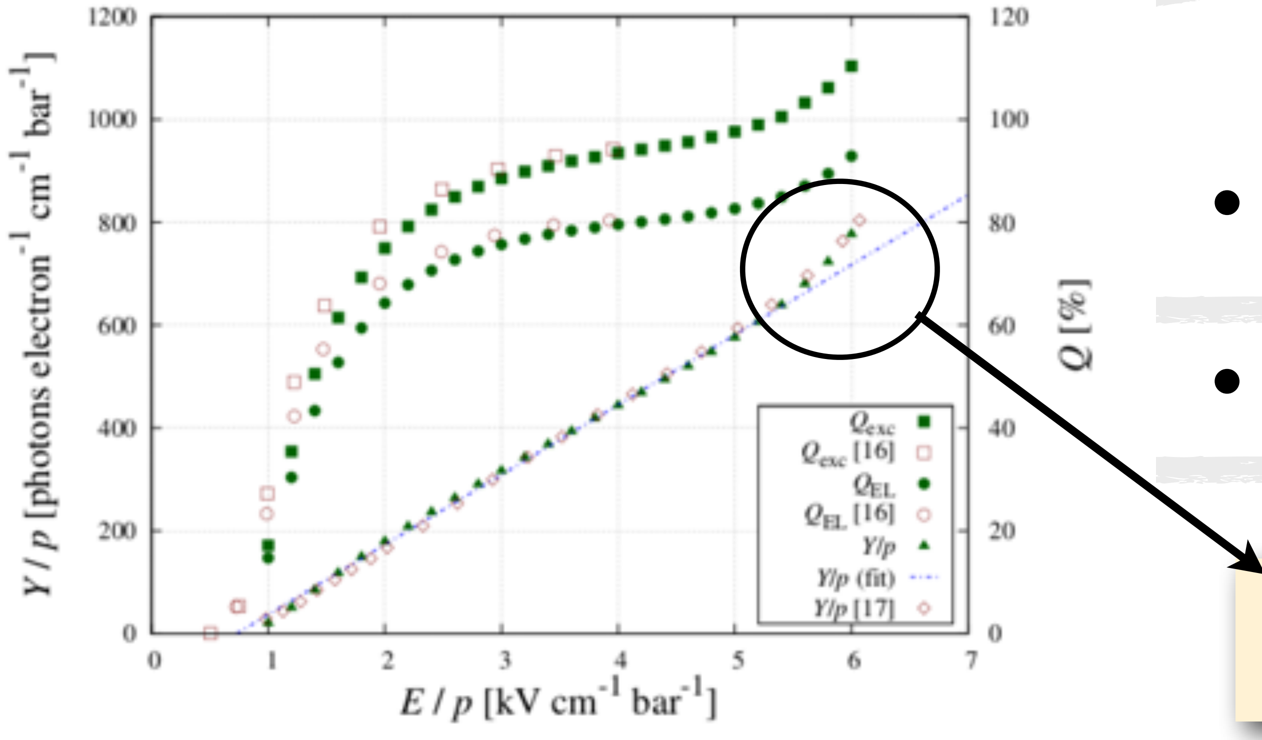






Electroluminescense



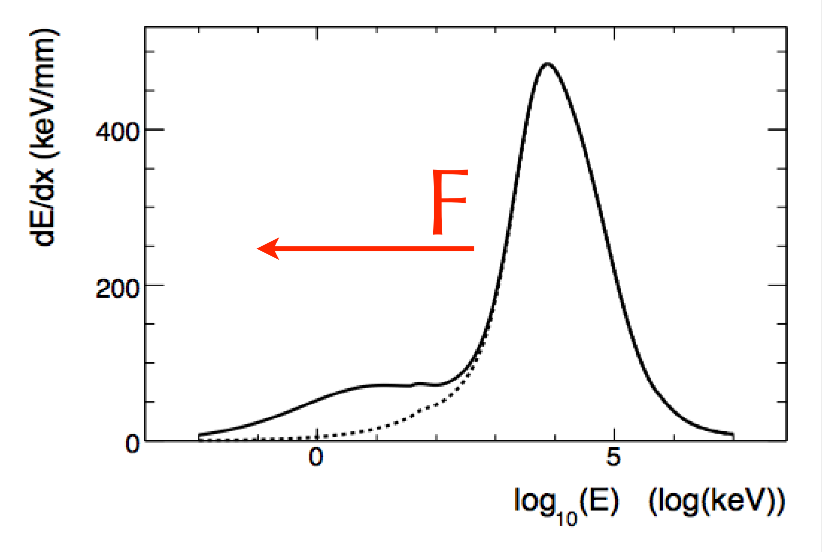


- Electroluminescence is a way to make a linear amplification of primary electrons.
- At fixed P and voltage the number of photons produced by an electron is proportional to the gap.
- Poisson photon statistics, not exponential like in charge amplification. This is important when energy resolution is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

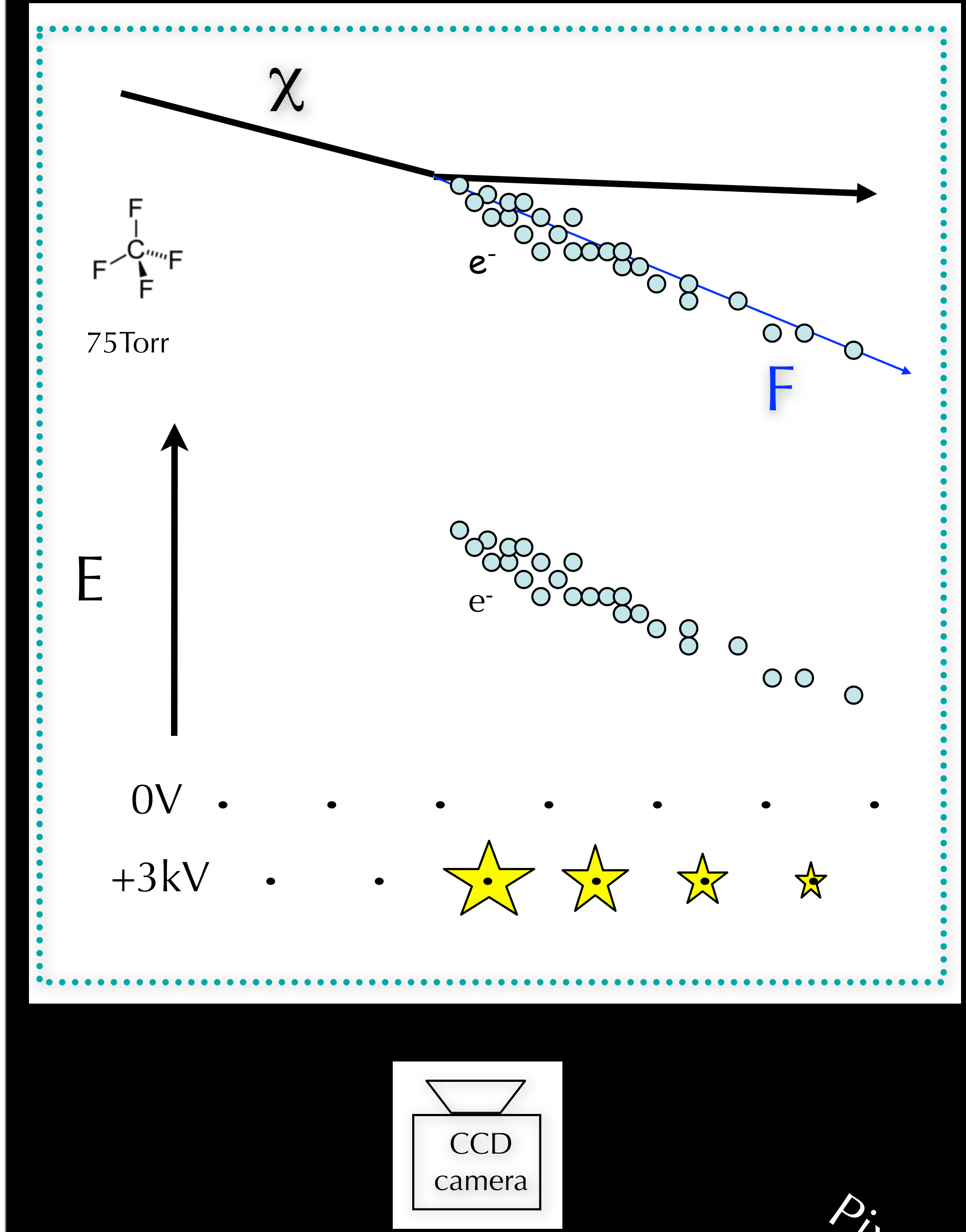
The deviation from linear dependency is an indication of charge amplification.

DMTPC Principle

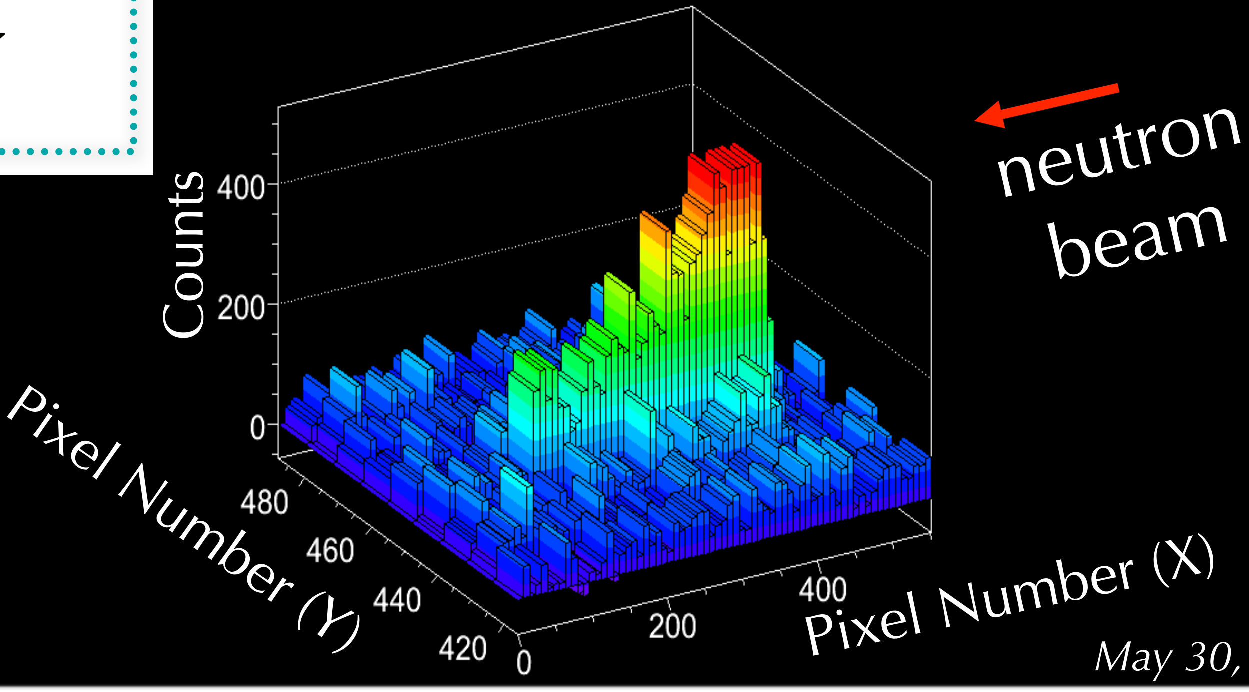
1. primary ionization encodes track direction via dE/dx profile



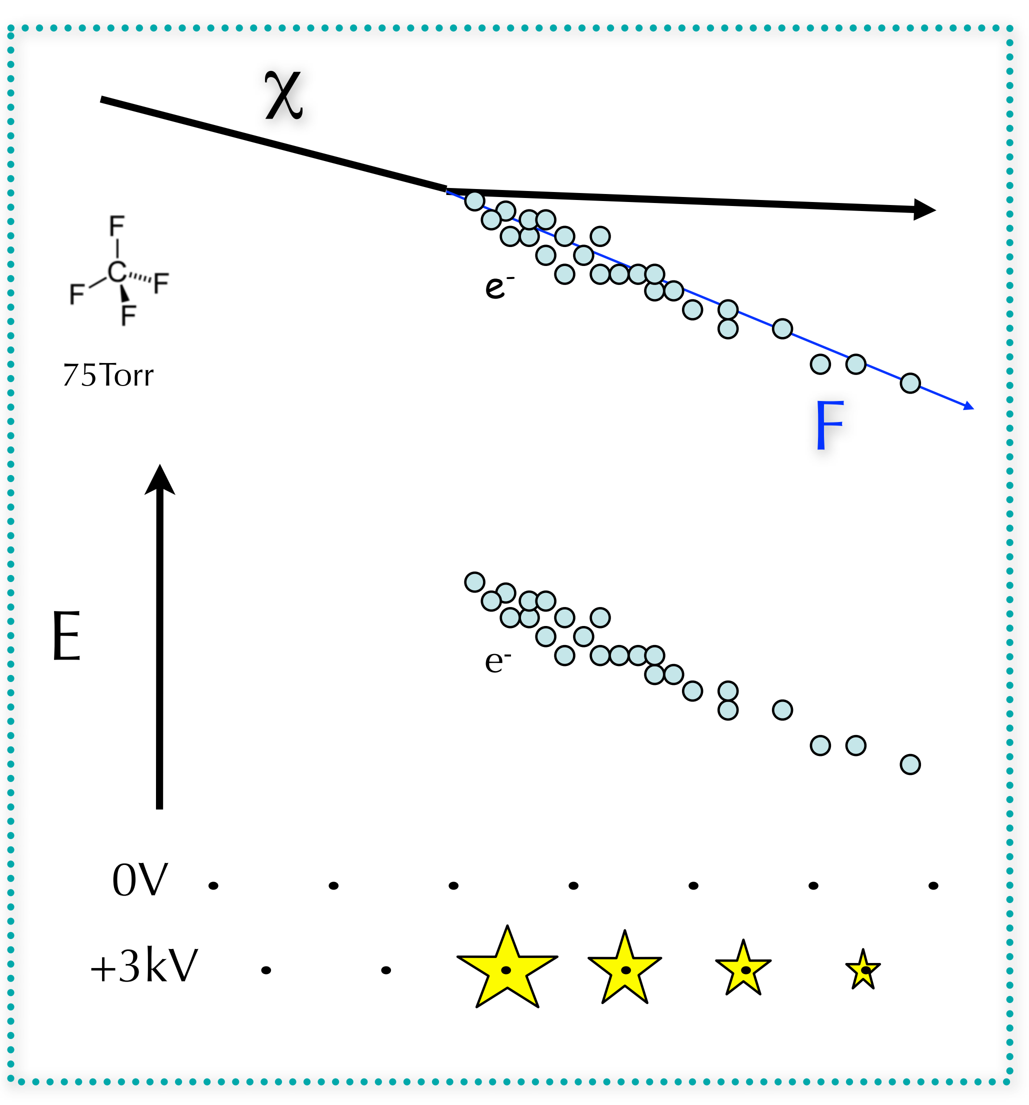
2. drifting electrons preserve dE/dx profile if diffusion is small
3. multiplication in amplification region produces e- + scintillation g



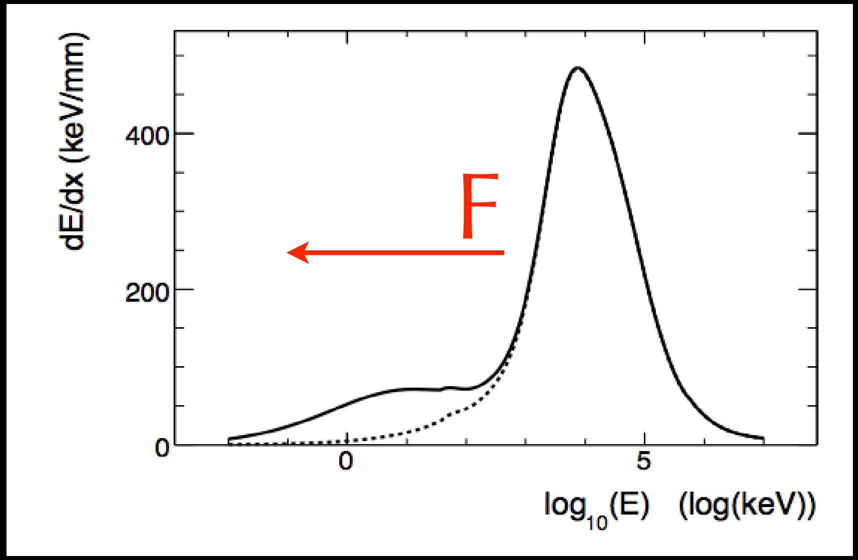
D. Dujmic, JM, et al., NIMA 584:337 (2008)



DMTPC Principle



1. primary ionization encodes track direction via dE/dx profile



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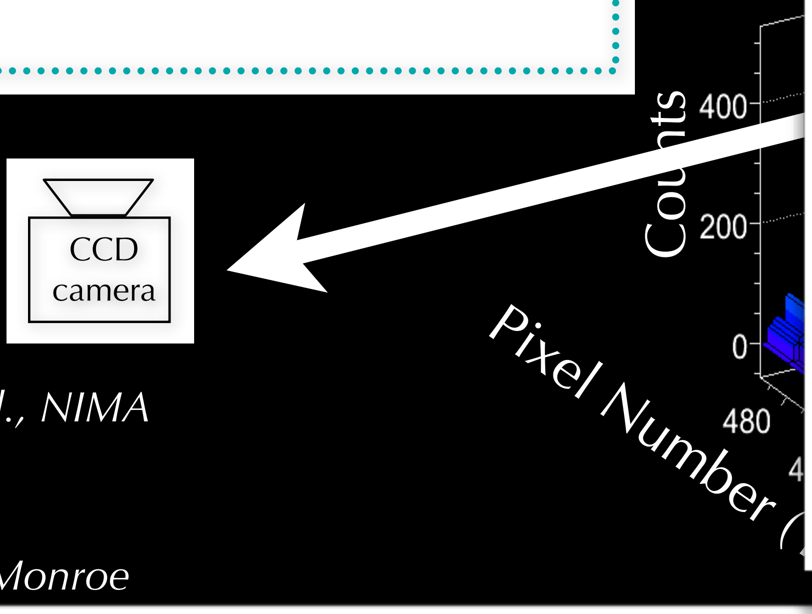


Adding fast optical readout
(for example MCP-PMT)
can restore time-projection capability by allowing track reconstruction in the drift direction

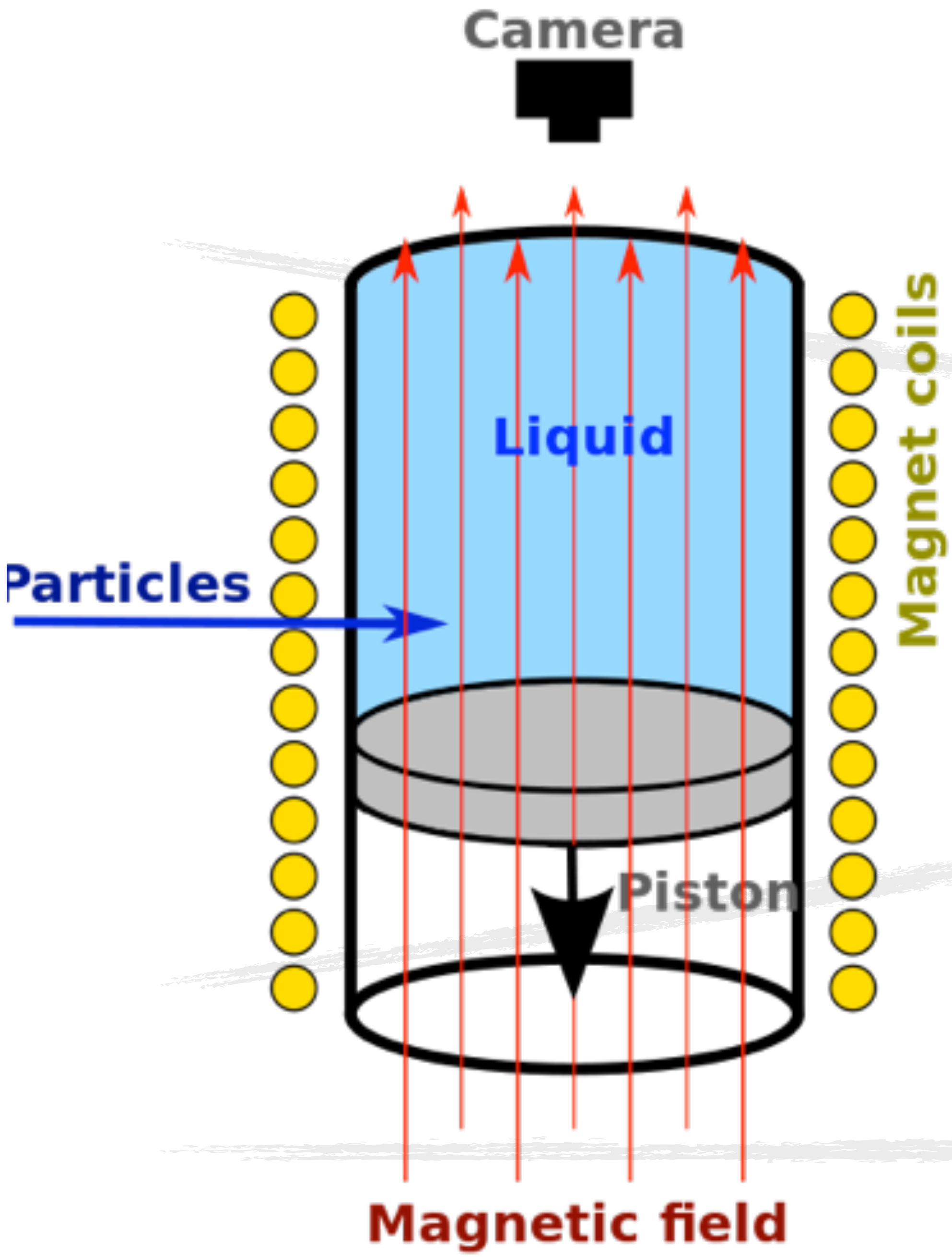
Imperial/RHUL/Bristol working on this concept

D. Dujmic, JM, et al., NIMA 584:337 (2008)

RHUL *Jocelyn Monroe*

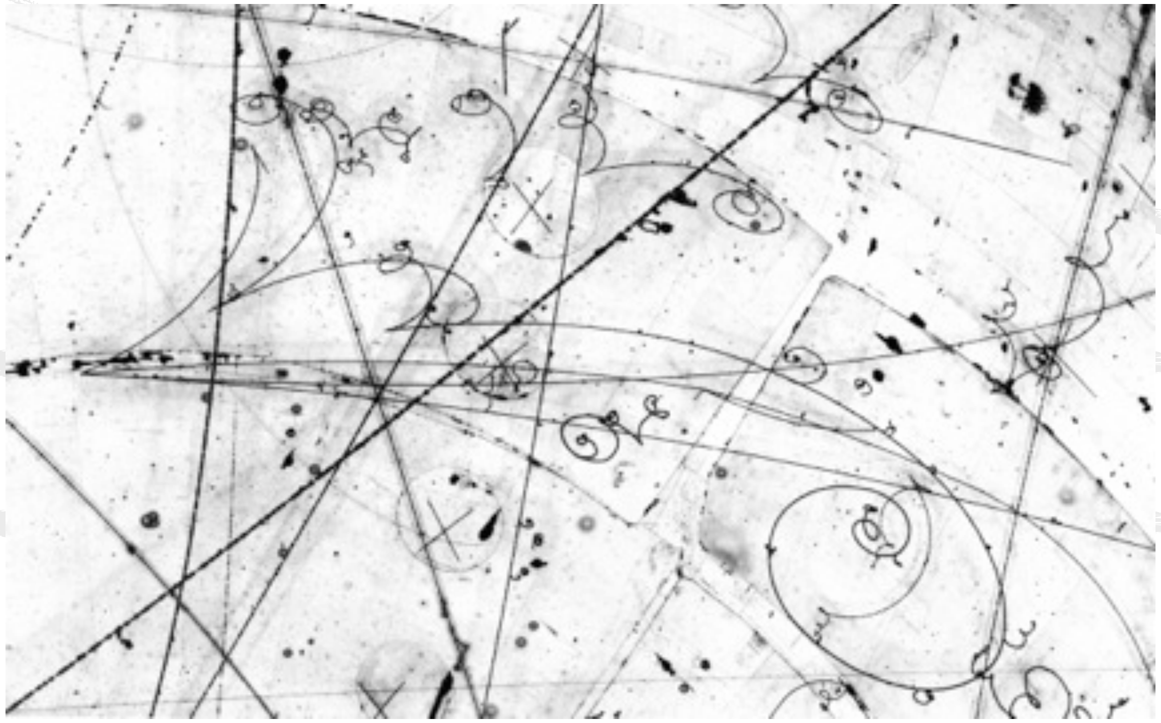
May 30, 2014

Bubble chamber

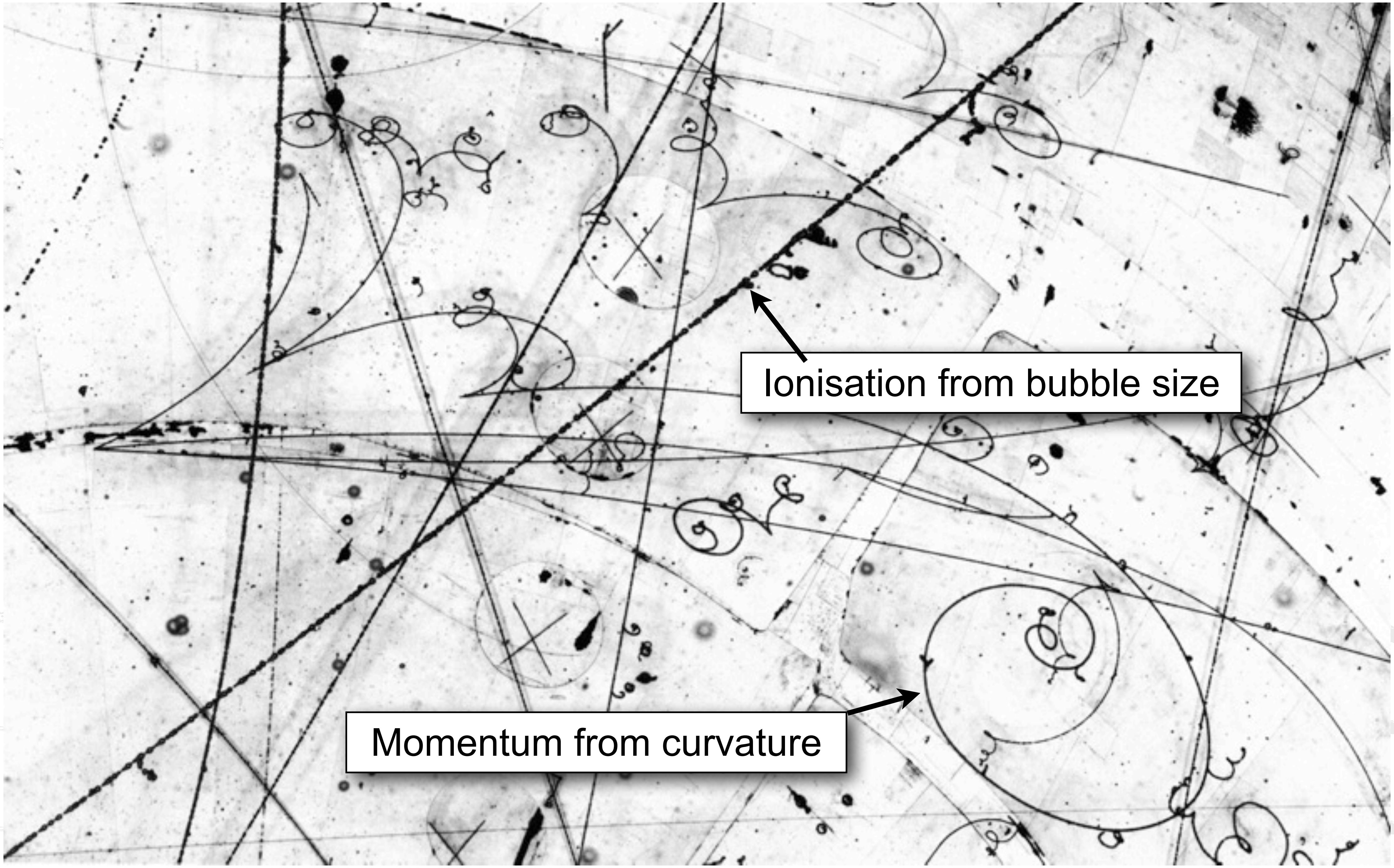


1952, D.A.Glaser

- 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.
- Ionising particles breaks the state and produce micro bubbles that expand.
- The image is taken as a photograph.



Bubble chamber



Ionisation from bubble size

Momentum from curvature

The reconstruction principle is the same of modern tracking detectors,

Bubble chamber

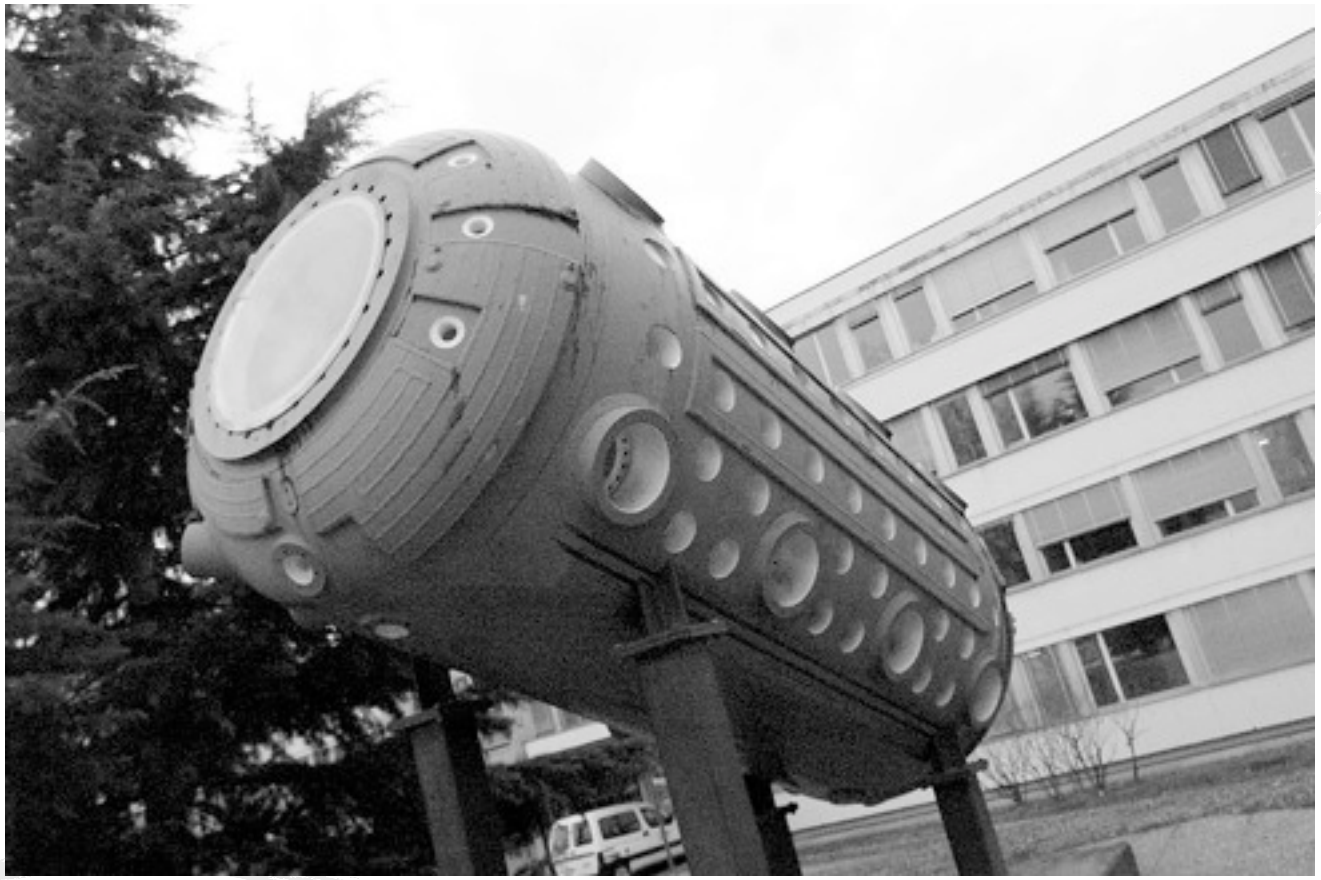
Pro's

- 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 digitised.

- 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?

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$_{Ar\ gas}$→8.2 x 8.2 x 8.2 m^3 but 1 ton$_{plastic}$→1 x 1 x 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.

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
- 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.

Thank you for your attention!

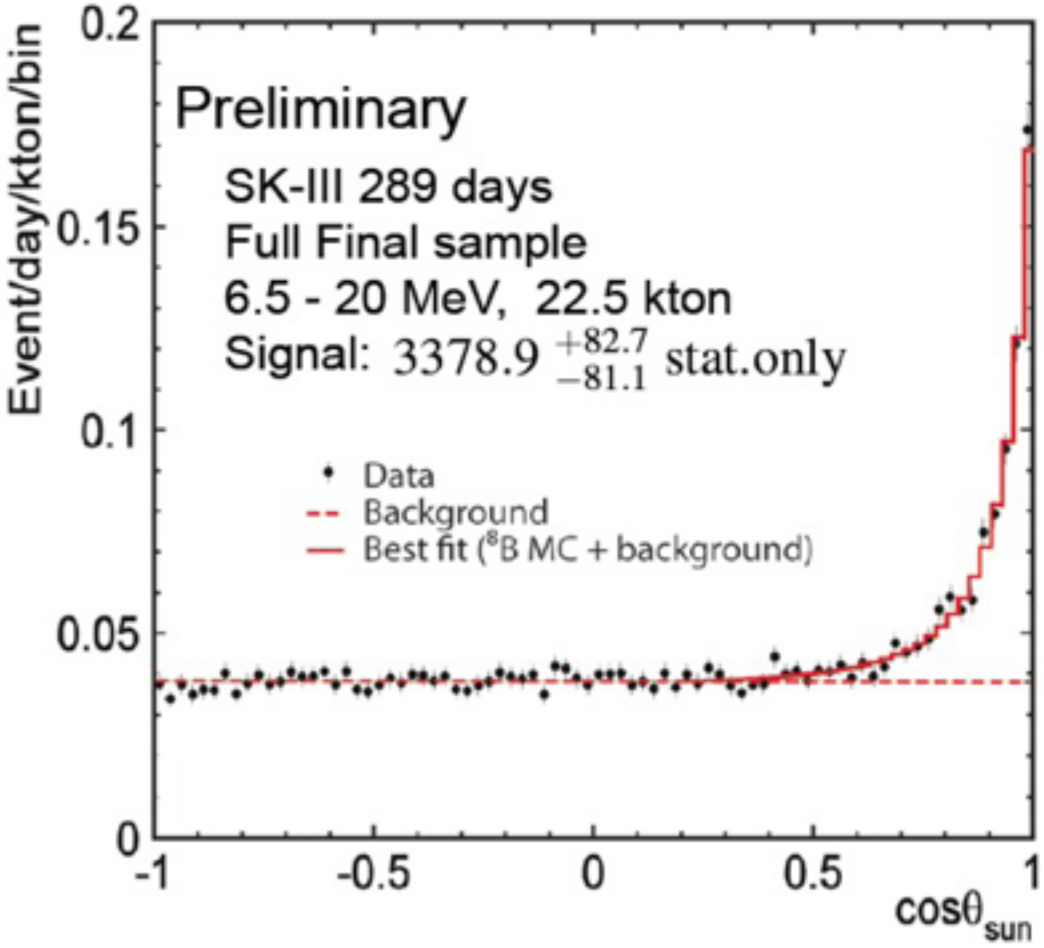
ご清聴ありがとうございました

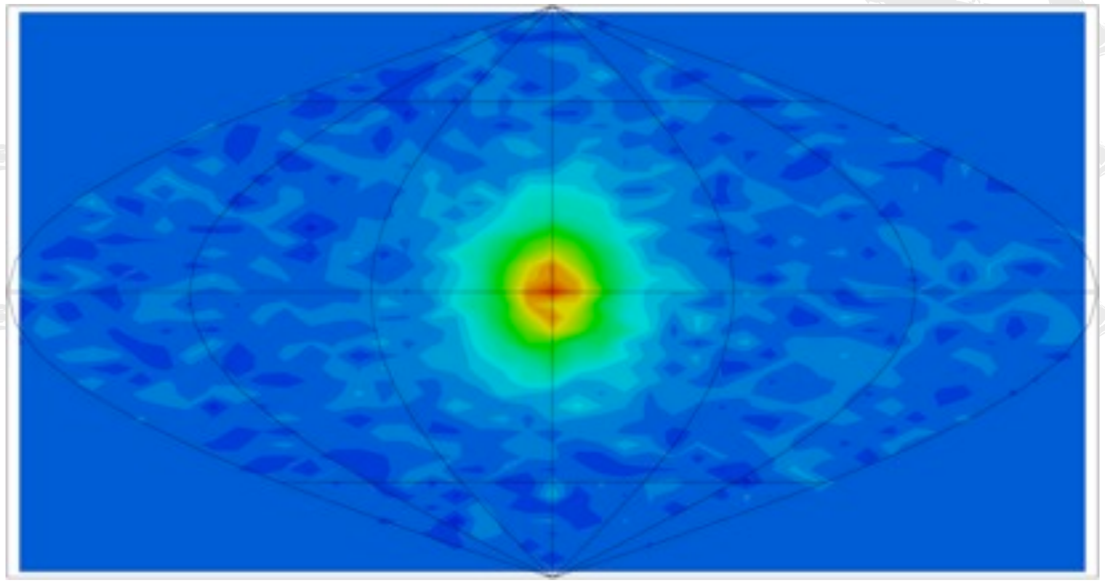
水戸の梅の花

Many thanks to:
P Hamilton, F di Lodovico, J Monroe, F Sanchez, T Stainer, for valuable input

Cherenkov

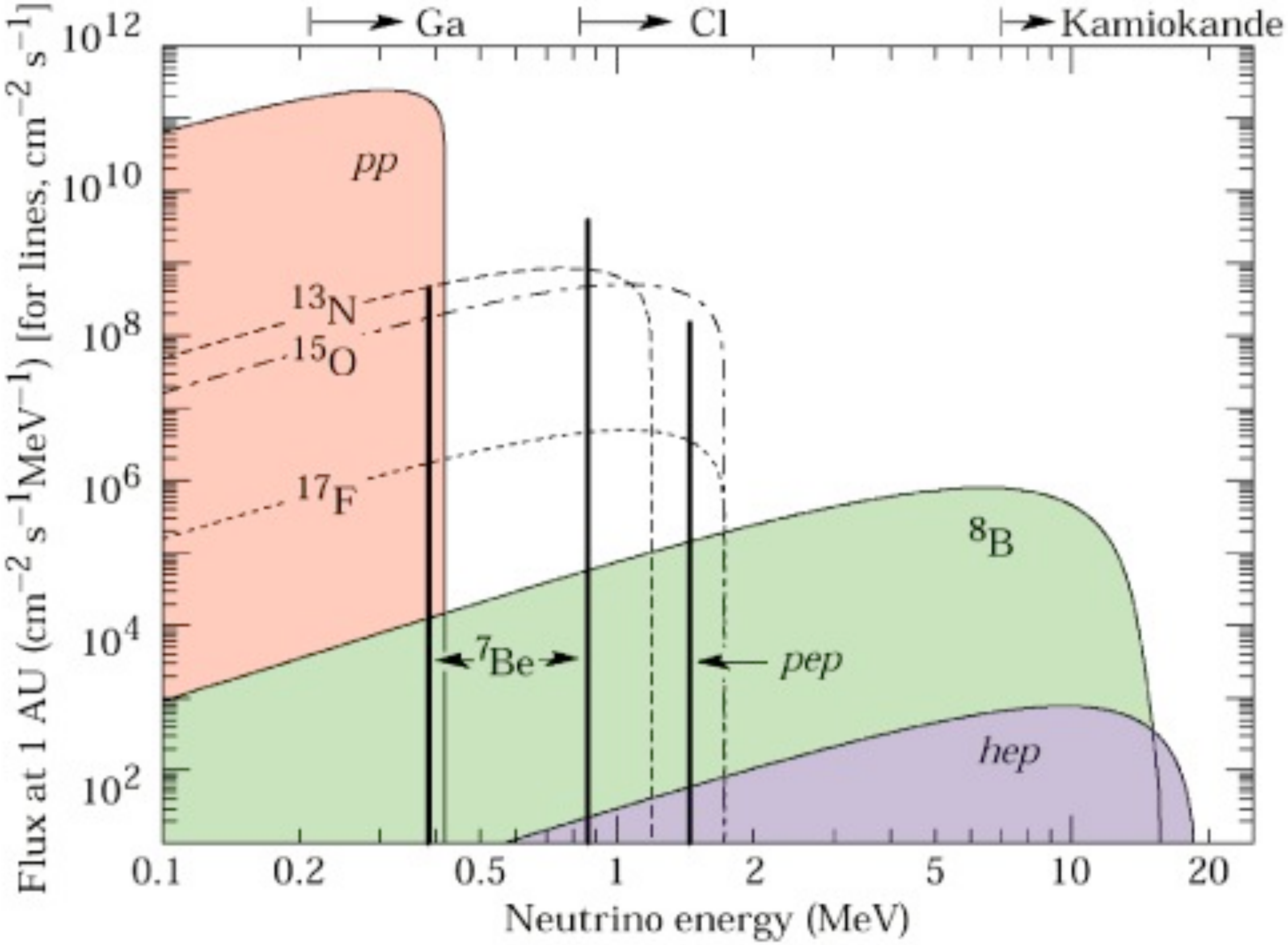
- Utility at low energies (MeV) is the determination of the neutrino direction.
- To use this, one must:
    - have neutrino reactions which remember the neutrino direction ($\nu_e e^- \rightarrow \nu_e e^-$).
    - have a point like source so we can have a reference neutrino direction from the source. 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.



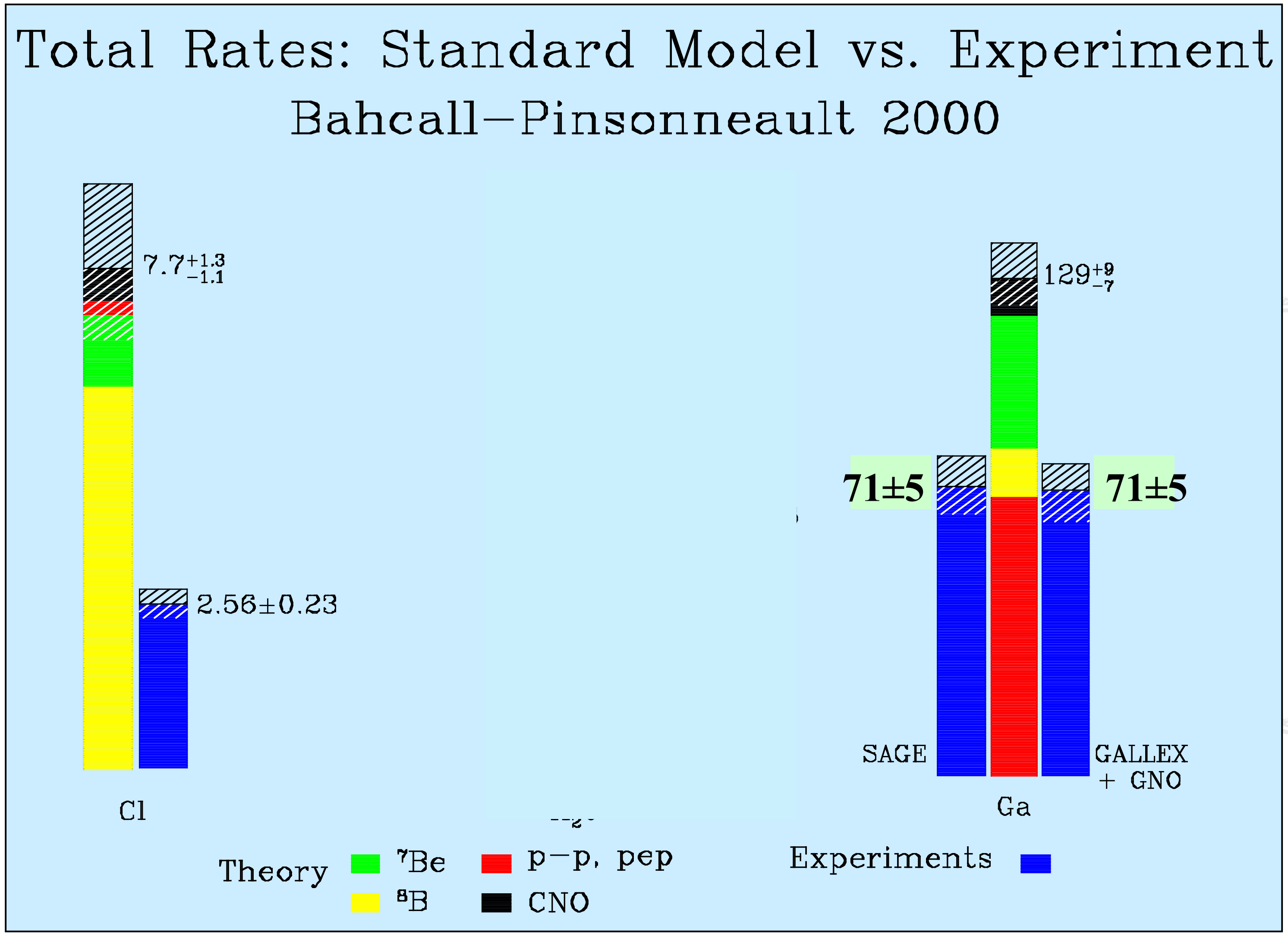


Radiochemical

- The two different thresholds allow an integrated spectrum measurement, sensitive to different parts of the solar neutrino spectra.



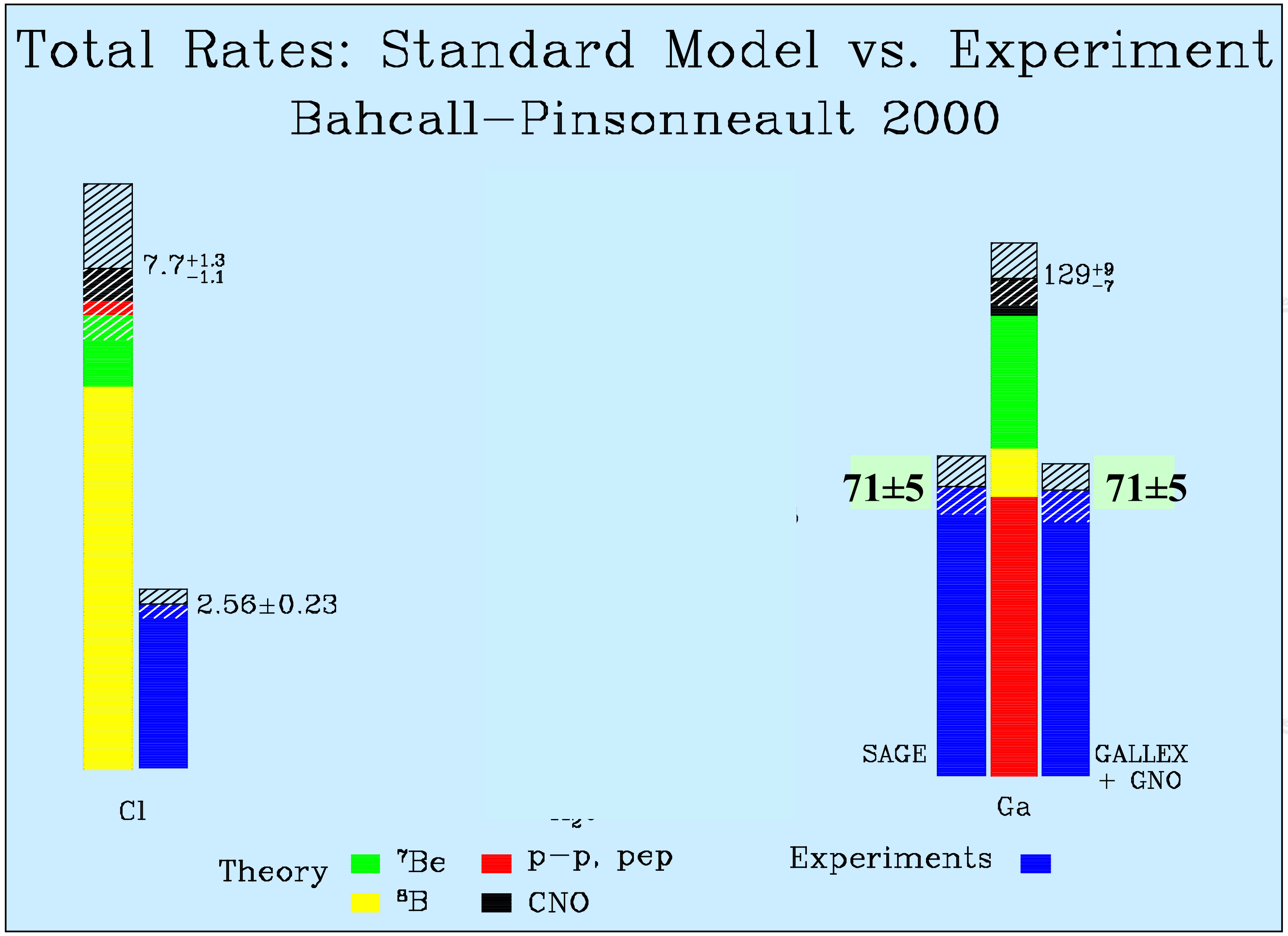
Comparison



- 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.

Comparison

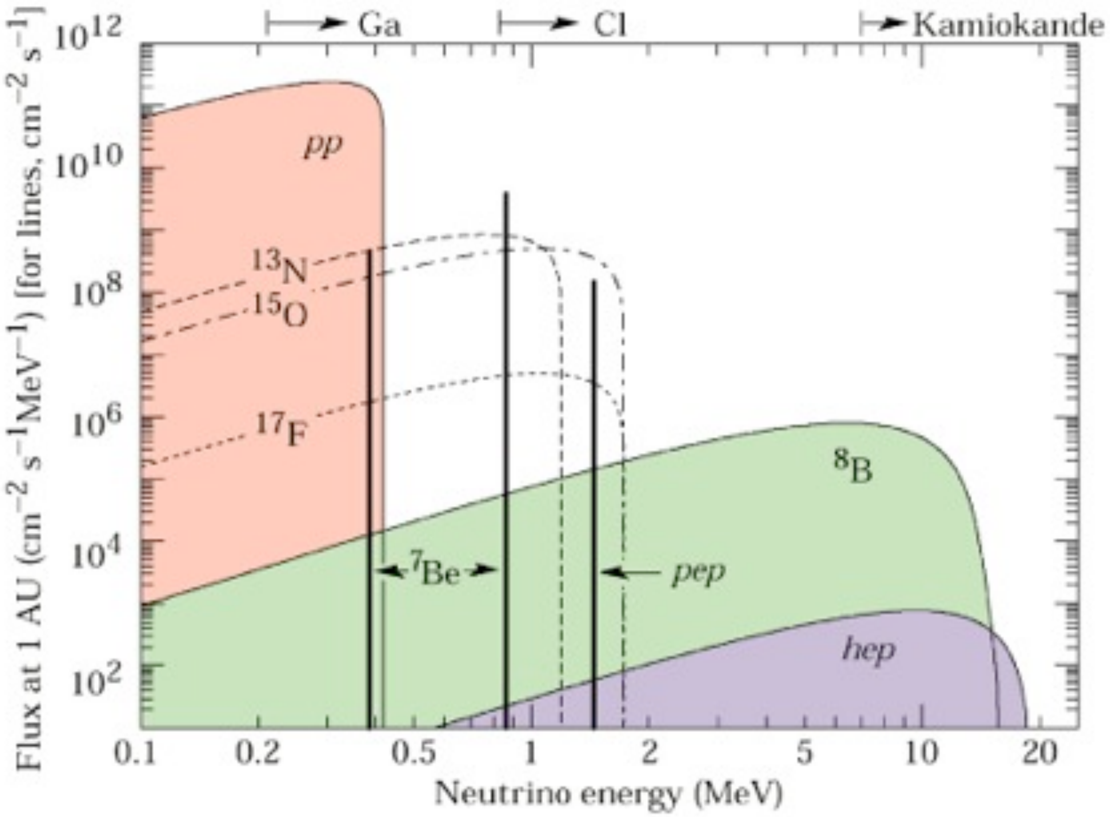


- Both techniques measured different rate than expected:
  - solar model?,
  - detector efficiencies?,
  - neutrino deficit through oscillations?,…
- This disagreement was called for years “the solar neutrino problem”.
- For many years these experiments show the difference between the number of sigmas and the “confidence level”.

Nowadays the neutrino speed is another example.

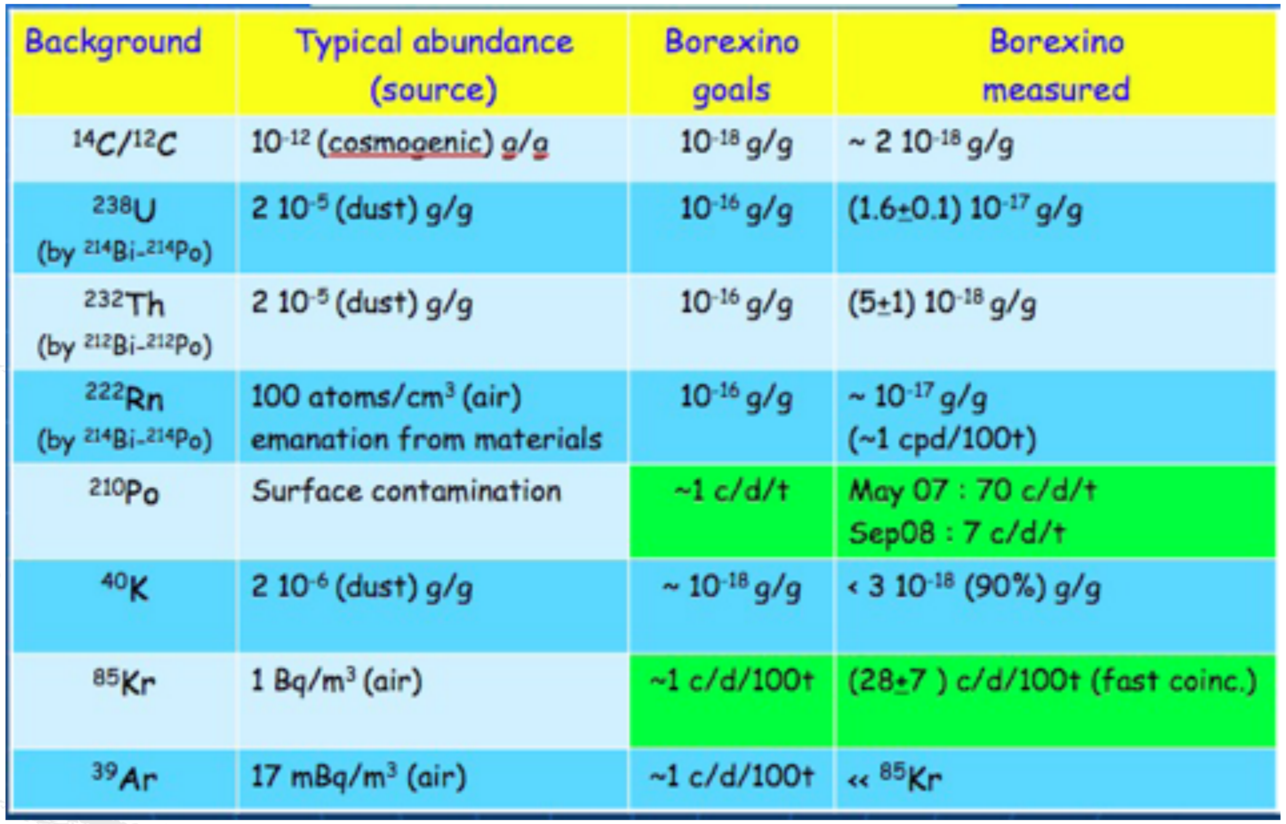
Scintillator

- 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: ν e- → ν e-
  -



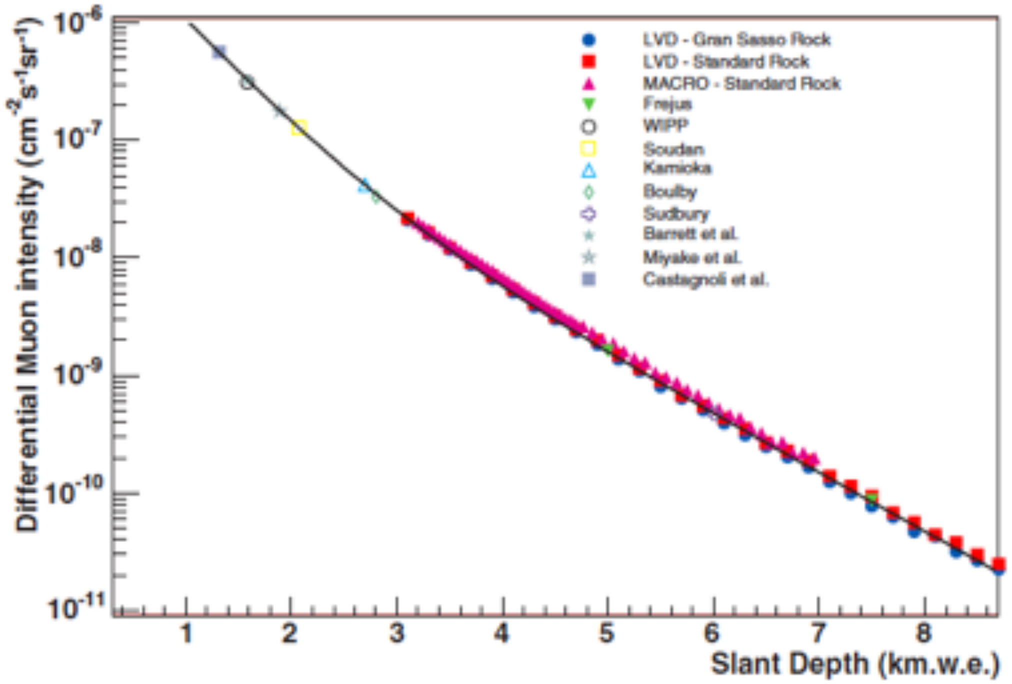
Scintillator detectors

- 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



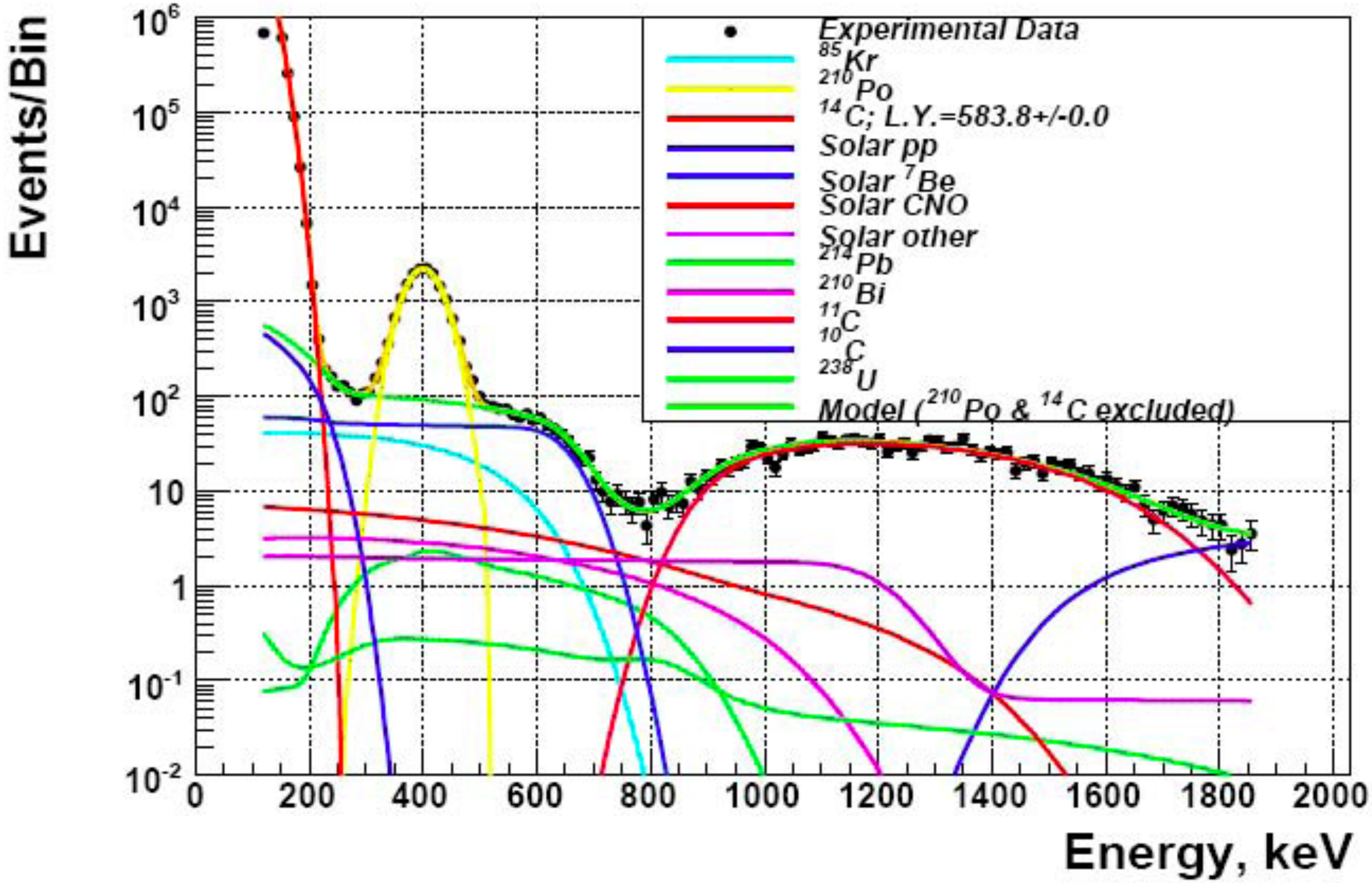
Background	Typical abundance (source)	Borexino goals	Borexino measured
$^{14}C/^{12}C$	10^{-12} (cosmogenic) g/g	10^{-18} g/g	~ 2 10^{-18} g/g
^{238}U (by ^{214}Bi-^{214}Po)	2 10^{-5} (dust) g/g	10^{-16} g/g	(1.6±0.1) 10^{-17} g/g
^{232}Th (by ^{212}Bi-^{212}Po)	2 10^{-5} (dust) g/g	10^{-16} g/g	(5±1) 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

- Cosmogenic stands for radioactivity induced by cosmic rays. That means it is produced constantly. This is dramatically reduced by going underground.



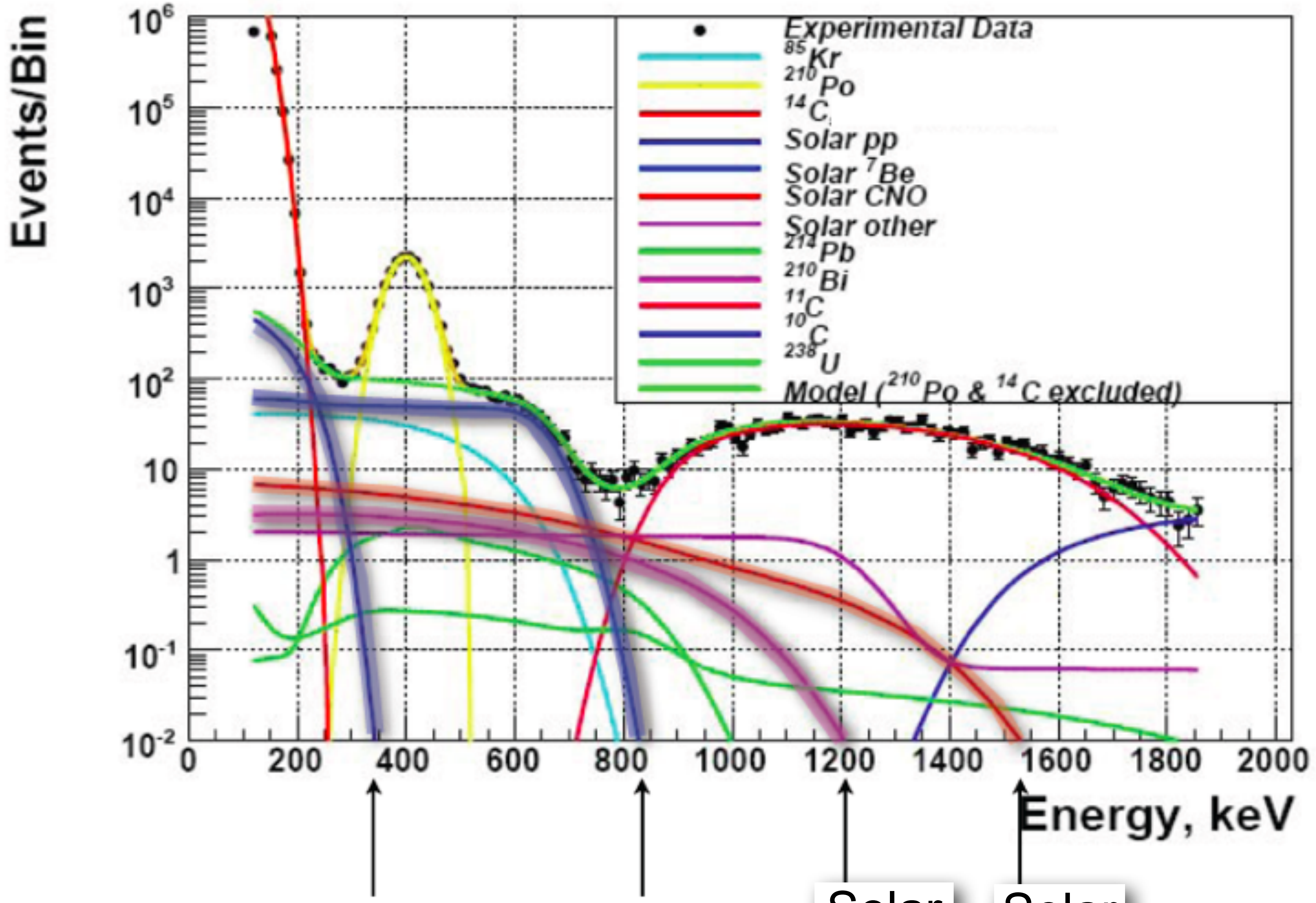
Scintillator detectors

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



Scintillator detectors

to extract the signal...



Solar pp

Solar 7Be

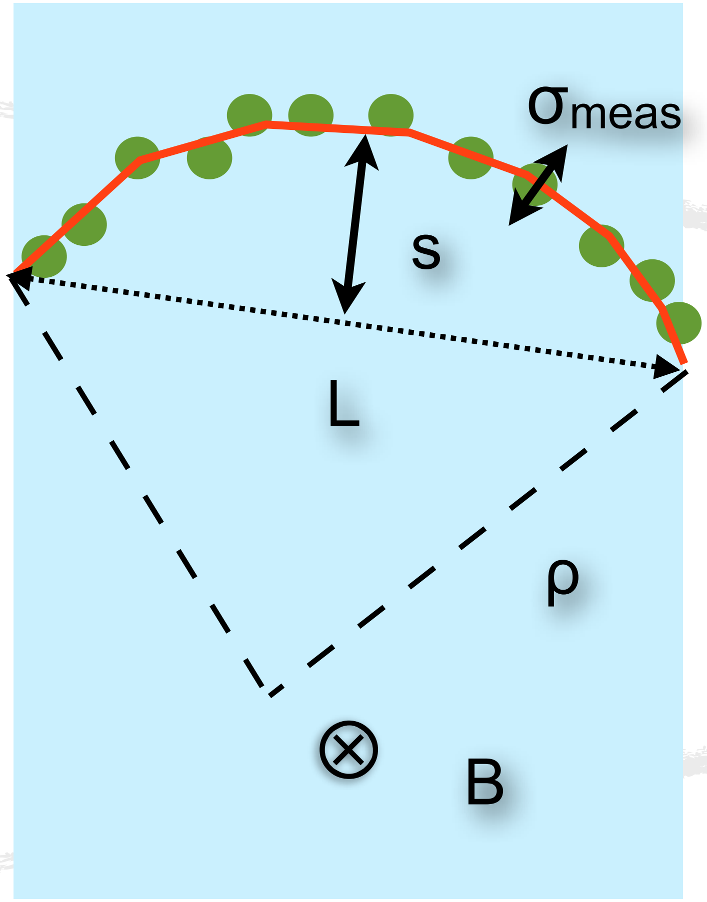
Solar others

Solar CNO

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.

Momentum by curvature



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

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

B in Tesla
ρ in m
p in GeV

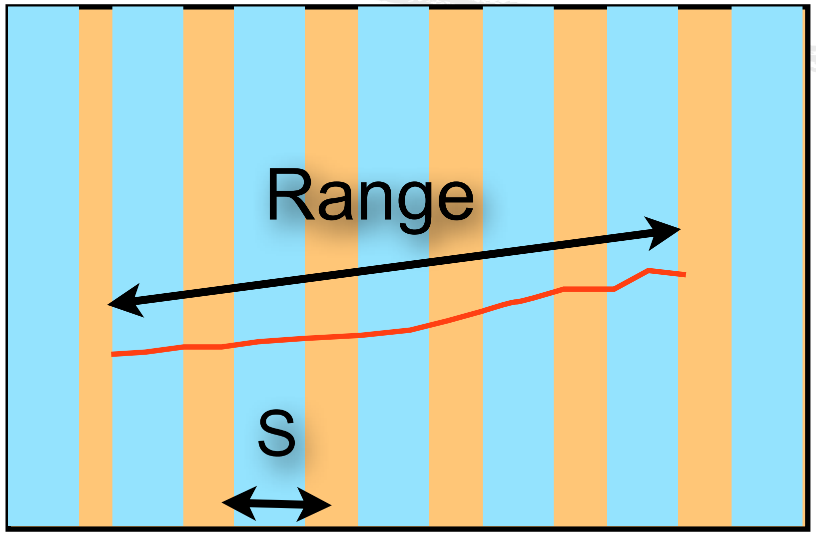
- The resolution in momentum depends on the detector resolution (δ_{res}) and the multiple scattering (δ_{ms}).
- The detector contribution can be parametrized as:

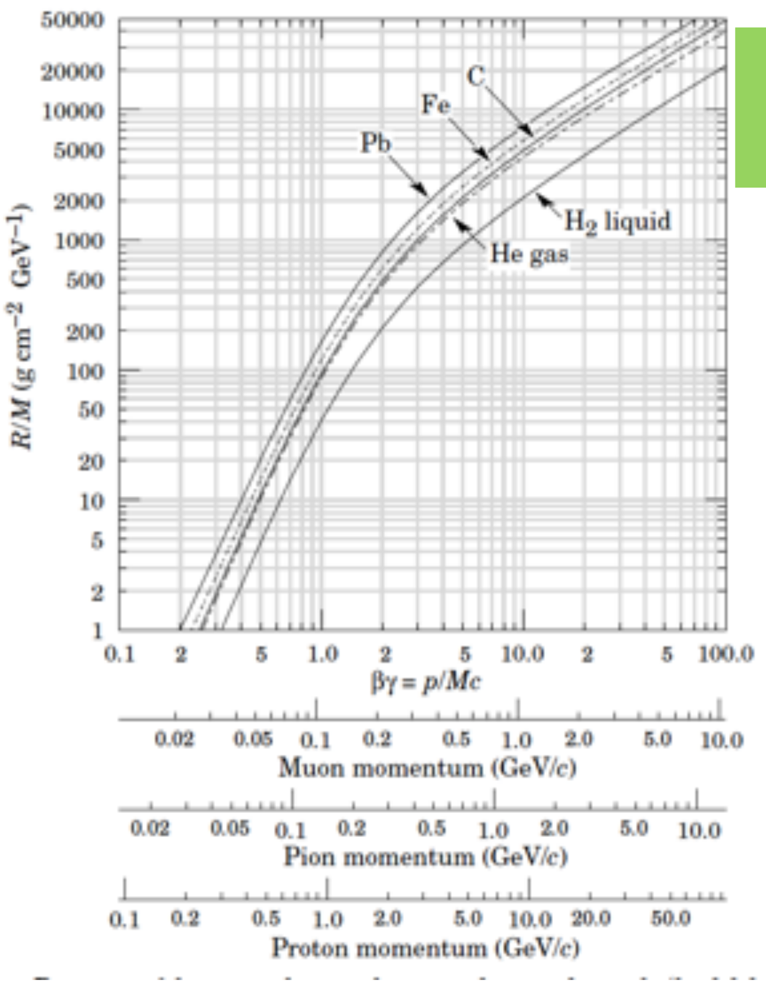
$$\delta_{res} \approx \frac{\sigma_{meas}}{L^2}\sqrt{\frac{720.}{N+4}}$$

In order of importance:
L > σ_{meas} > N

Momentum by Range

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





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

$$\beta\gamma > 5$$

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

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

- 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

Multiple scattering

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

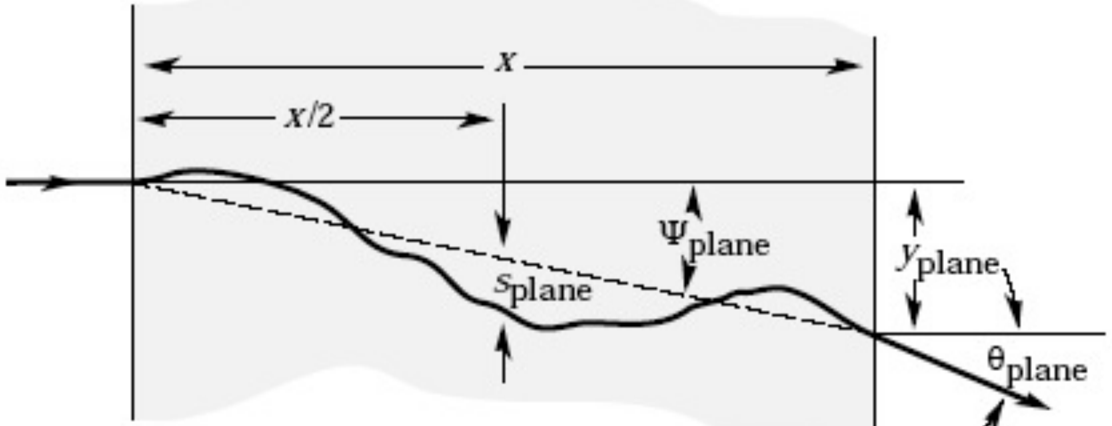


Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

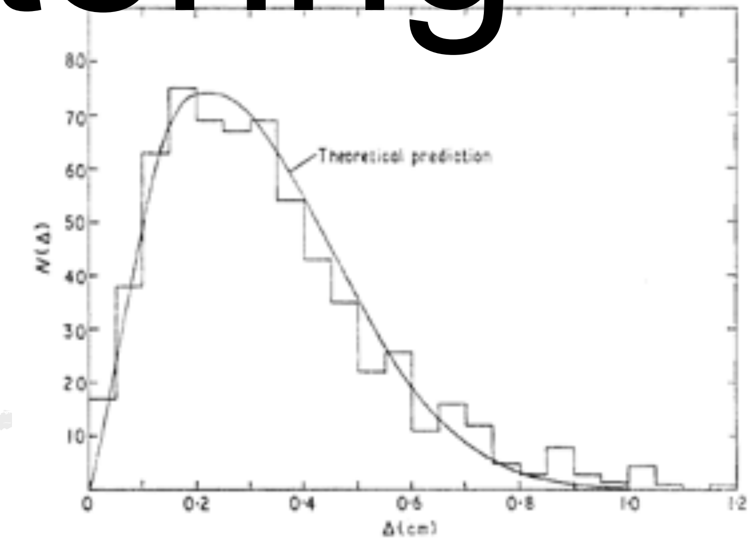


Figure 1. Comparison of observed and expected Δ distributions for incident muons in the momentum range 20–25 GeV/*c*.

- 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

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

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

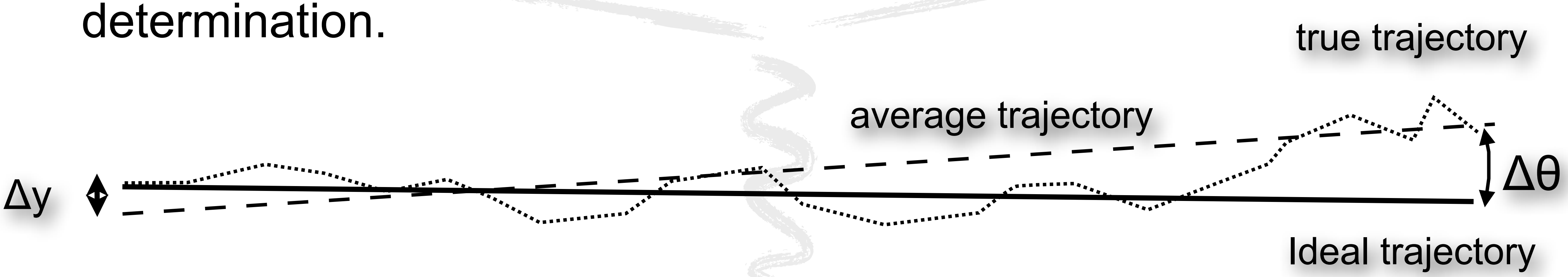
p,β = particle momentum (MeV) & velocity

z = particle chargex = 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: Δy, Δθ.
- 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↓