Detector Concepts in Low-Energy Neutrino Physics

Magnificent-CEvNS-MONA School, March 27th, 2023

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SFB 1258 | Neutrinos Dark Matter Messengers

TECHNISCHE UNIVERSITÄT MÜNCHEN

Practical Information

- All material available on indico (https://indico.cern.ch/event/1215362/timetable/)
- Don't hesitate to contact me in case you have questions (Victoria.wagner@tum.de)

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Outline

- Part 1 - **Principles of neutrino detection**
  - Neutrino interactions
  - Discovery of the neutrino
  - Principles of particle detectors: heat, ionization, scintillation

- Part 2 – Neutrino Experiments
  - Neutrino Oscillations with JUNO – large mass scintillator experiment
  - CEvNS detection – COHERENT and NUCLEUS

Part I – Principles of Neutrino Detection

How do we detect neutrinos?

How was the neutrino discovered?

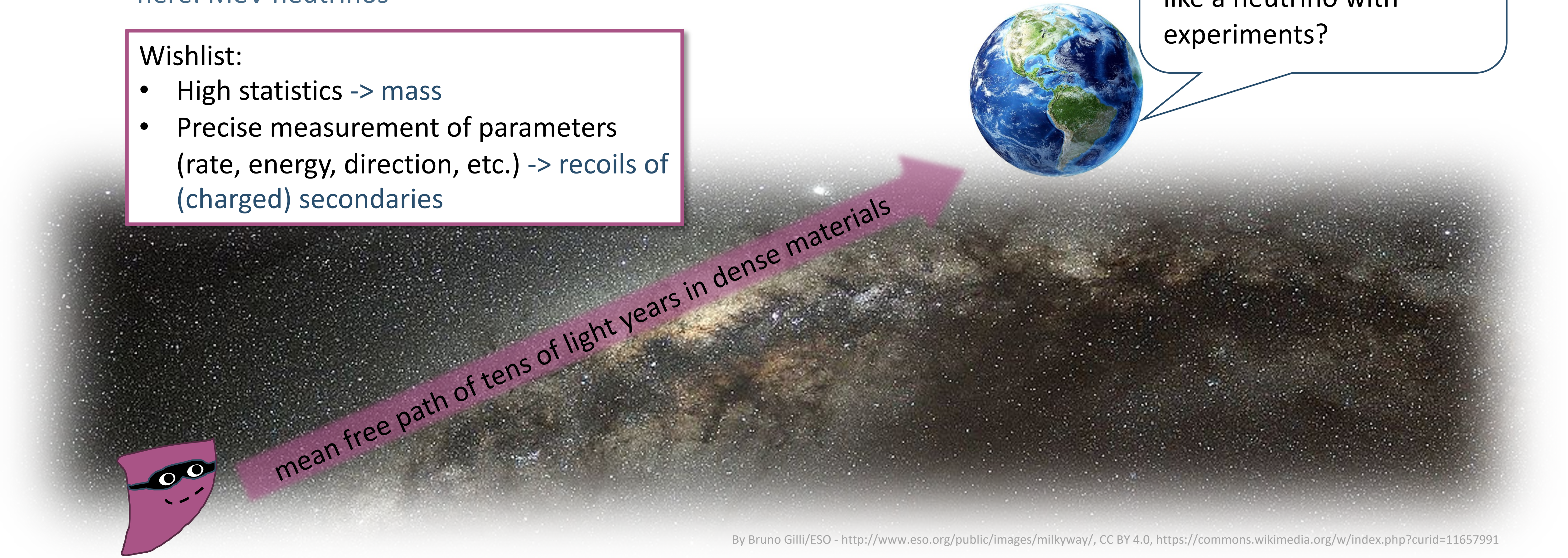
Which techniques are used to detect particles?

Low-energy* neutrino physics

* here: MeV neutrinos

Wishlist:
- High statistics -> mass
- Precise measurement of parameters (rate, energy, direction, etc.) -> recoils of (charged) secondaries

How can we detect such a weakly interacting particle like a neutrino with experiments?



Inverse Beta-decay (IBD)

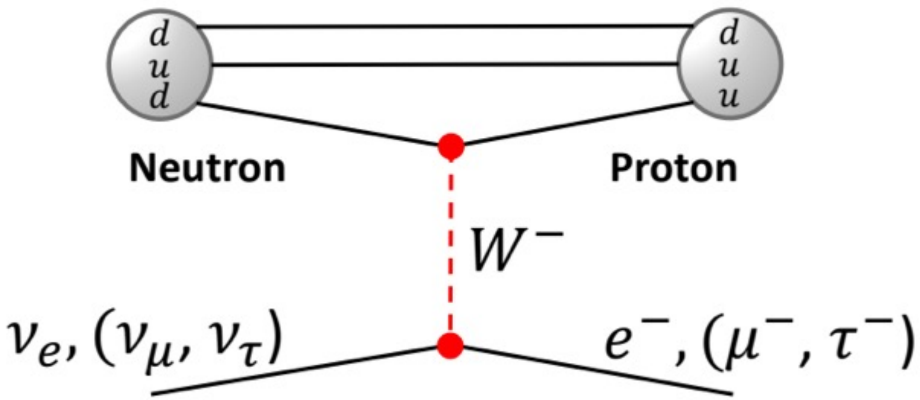
* quasi-elastic neutrino-nucleon scattering

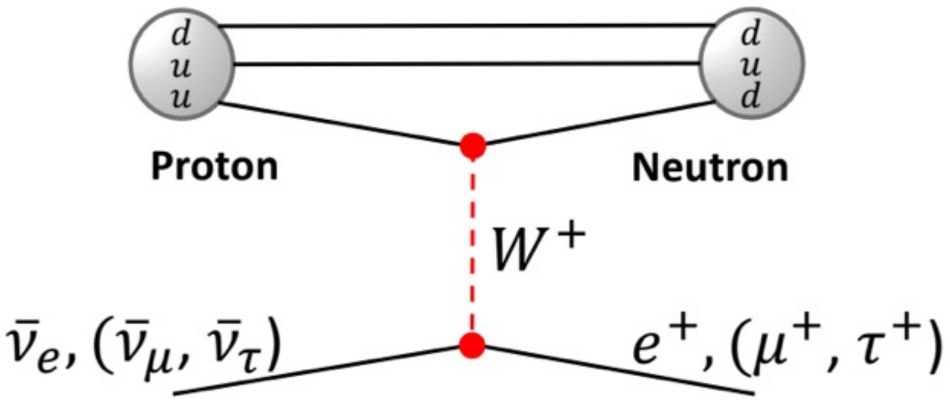
Inverse β^- decay

- Capture of electron neutrino
- Threshold for ν_μ (ν_τ) is 110 MeV (3.5 GeV)
- Used for e.g. for solar neutrino detection

Inverse β^+ decay

- Capture of electron anti-neutrino
- Threshold energy of 1.8 MeV for ν_e
- Most important channel for reactor neutrinos





adapted from S. Mertens

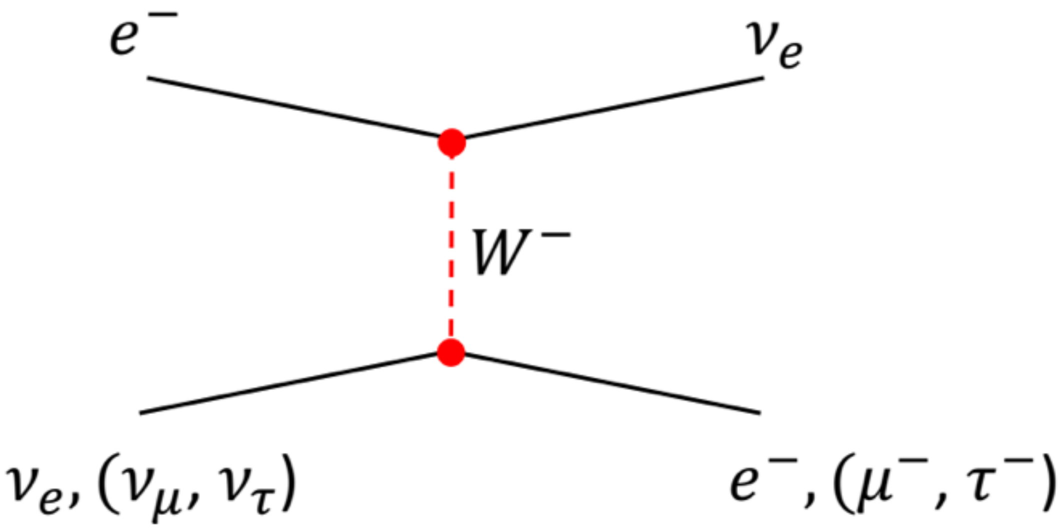
Elastic Scattering on Electrons

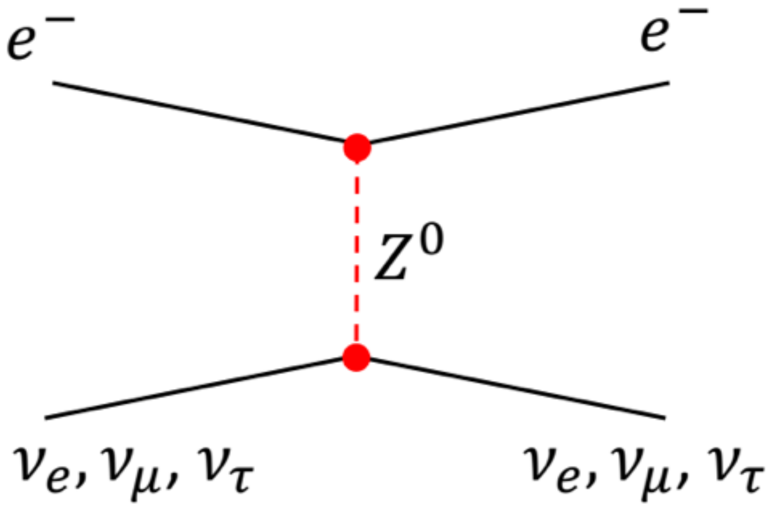
Charged – current

- Neutrino scattering via the exchange of W-boson
- Energy threshold for muon/ tau production

Neutral – current

- Neutrino scattering via the exchange of Z-boson
- Flavor-independent



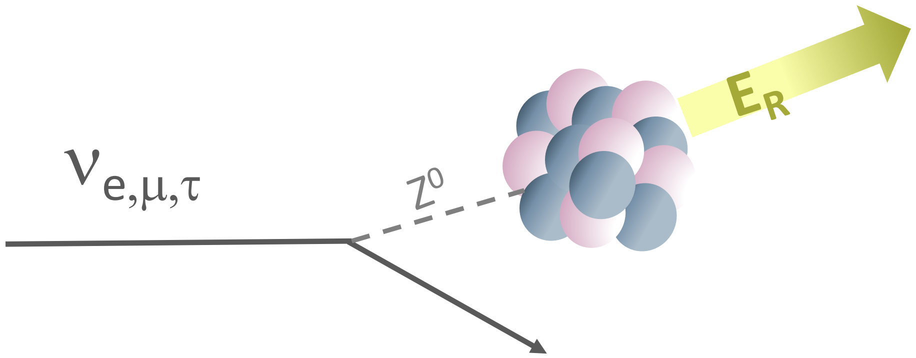


adapted from S. Mertens

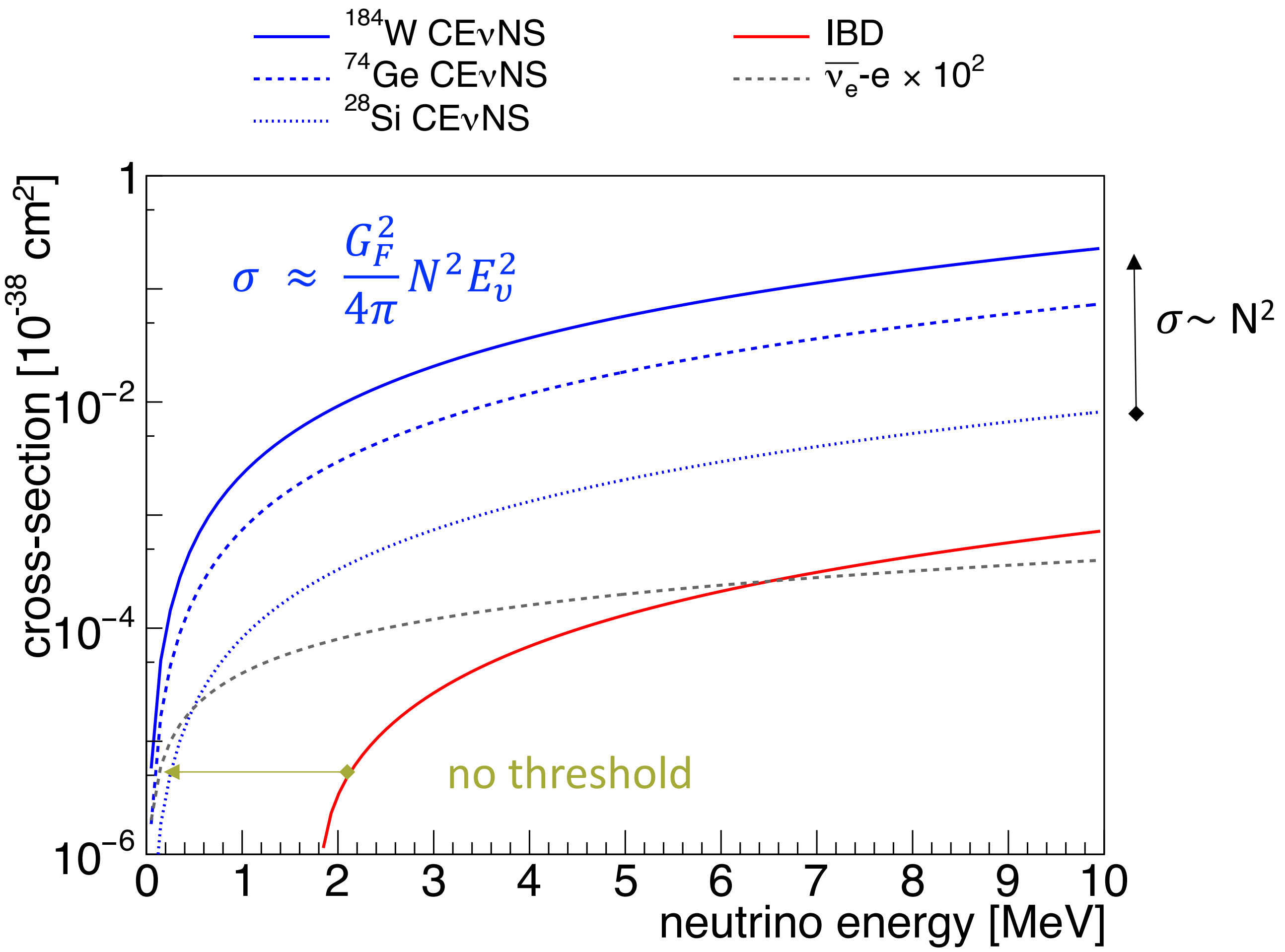
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

Dominant scattering process for E_ν < 50 MeV

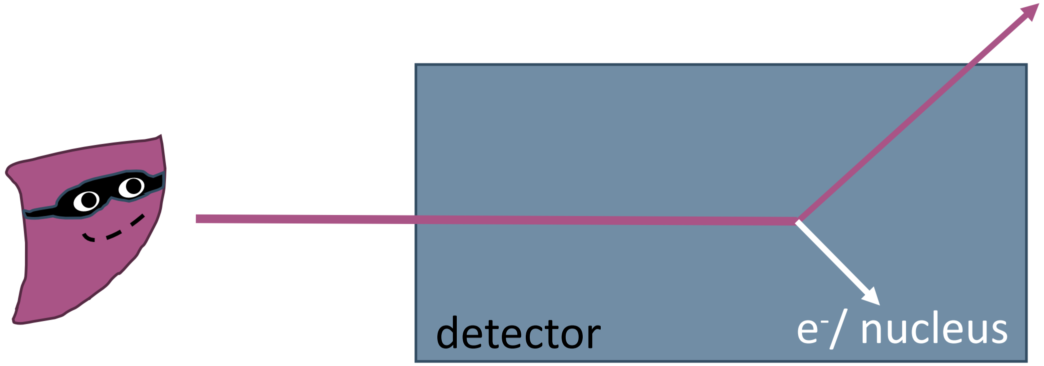
- Neutrino scattering via the exchange of Z-boson
- Flavor-independent
- No energy threshold
- Large cross-section: $\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\upsilon^2$



Neutrino Scattering in Matter

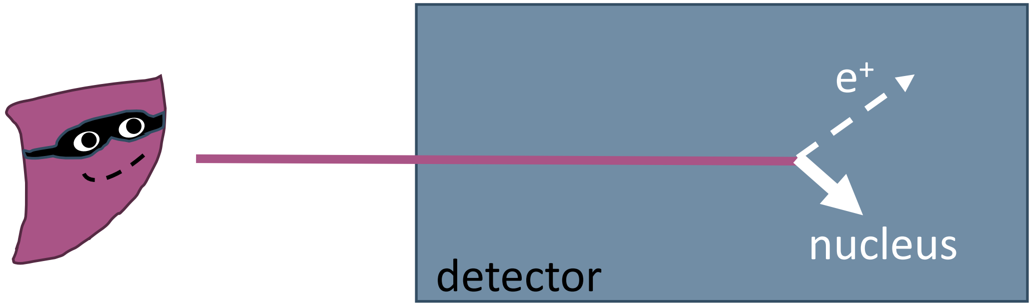


Neutrino Interaction in Matter



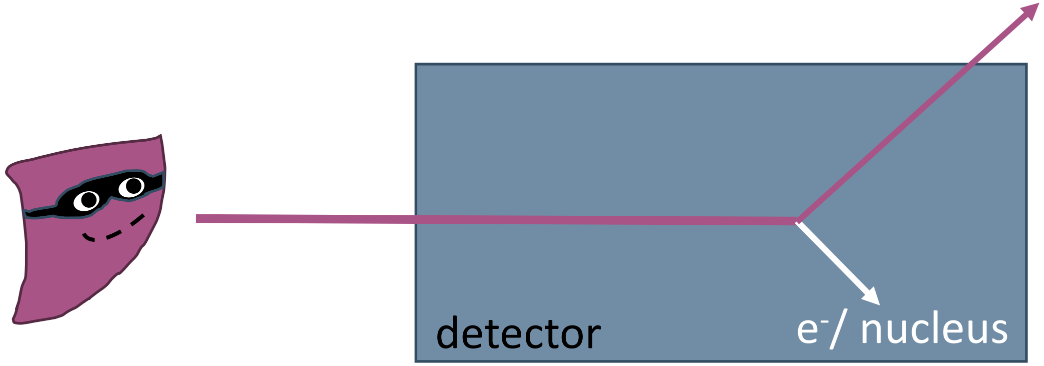
e^--ν_e & ν-nucleus - scattering

What are our observables?



IBD

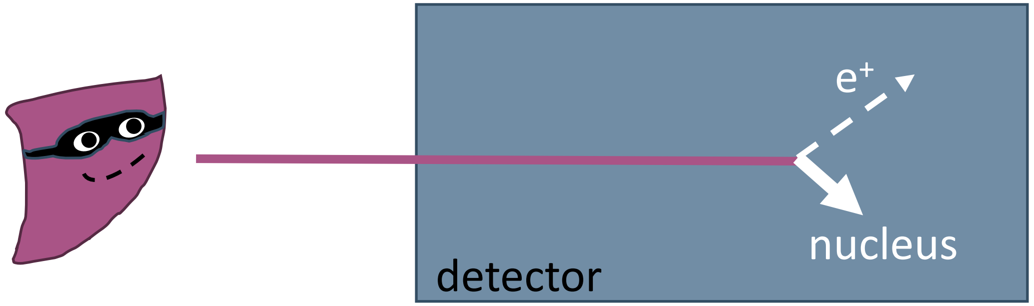
Neutrino Interaction in Matter



e^--ν_e & ν-nucleus - scattering

- Continuous recoil spectrum with $T_{max} = \dfrac{2E_\nu^2}{M + 2E_\nu}$

E_ν / T_{max}	e^- - ν_e	CEvNS (A = 100)
10 MeV	9.8 MeV	2.1 keV
1 MeV	0.8 MeV	0.02 keV

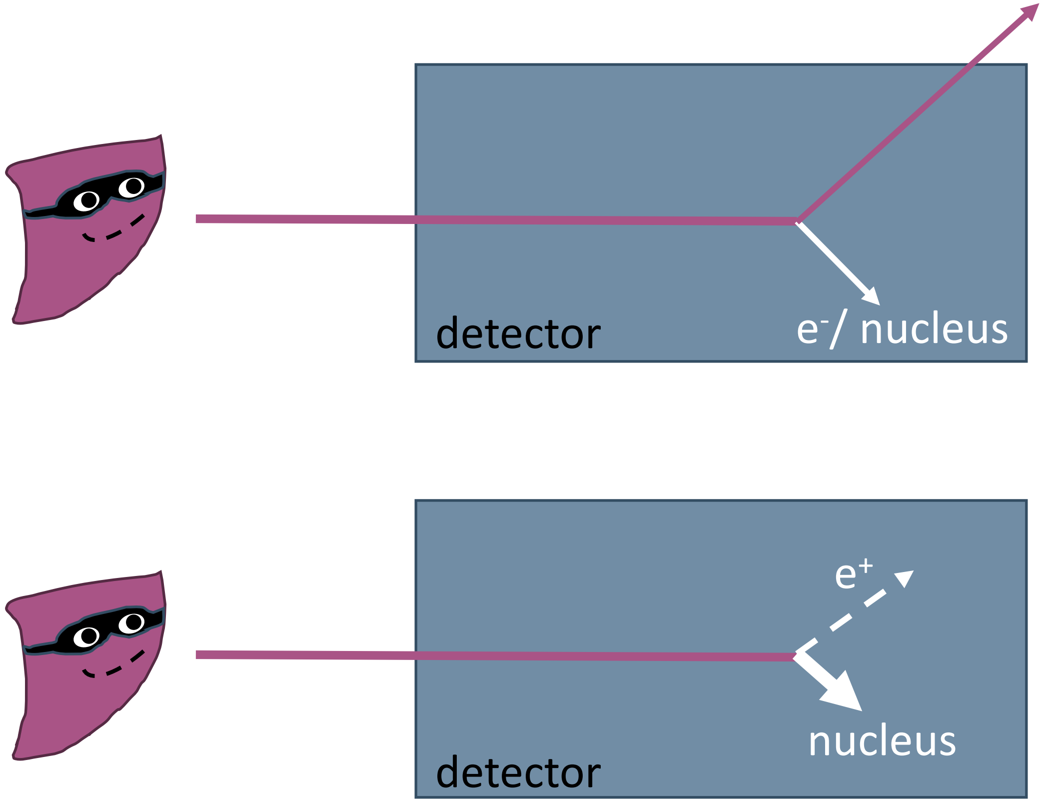


IBD

- Proton recoil small O(few keV) compared to the kinetic energy of positron (E_{kin})
- Reconstruction of neutrino energy

$$E_\nu = E_{e^+} + m_p - m_n = E_{kin,e} + 1.804\ \mathrm{MeV}$$

Neutrino Interaction in Matter



- Measure the recoiling particles produced in the ν-interaction with matter

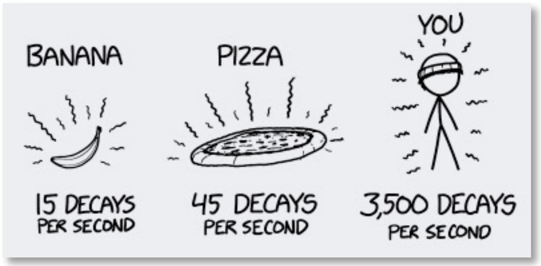
- Number of neutrino events:

$$N_\nu = N * \int \phi(E_\nu)\sigma(E_\nu)dE_\nu$$

Number of targets | Neutrino flux | Interaction cross-section

$\approx \mathbf{29 \frac{\nu}{day}}$ in a 1t water detector,

$\phi = 10^{12}\ cm^{-2}\ s^{-1}$, and $\sigma = 10^{-44}$ cm



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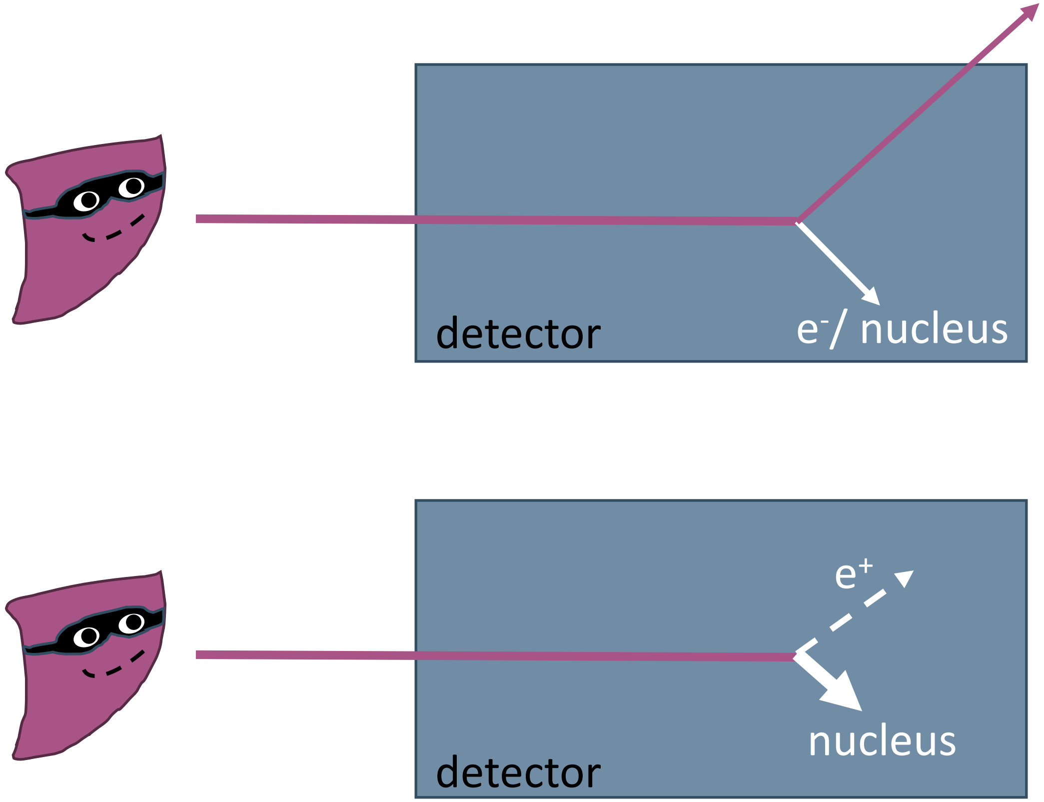


- Measure the recoiling particles produced in the ν-interaction with matter

- Distinguish ν-signal from background
- Study:
  - Rate ($\sigma_{interaction}$, E_{ν},)
  - Dynamics of interactions ($\sigma(E_{\nu}, E_{recoil}, \alpha_{scattering})$)

- Identification of charged leptons
- High energy/ directional resolution
- High mass

Part I – Principles of Neutrino Detection

How do we detect neutrinos?

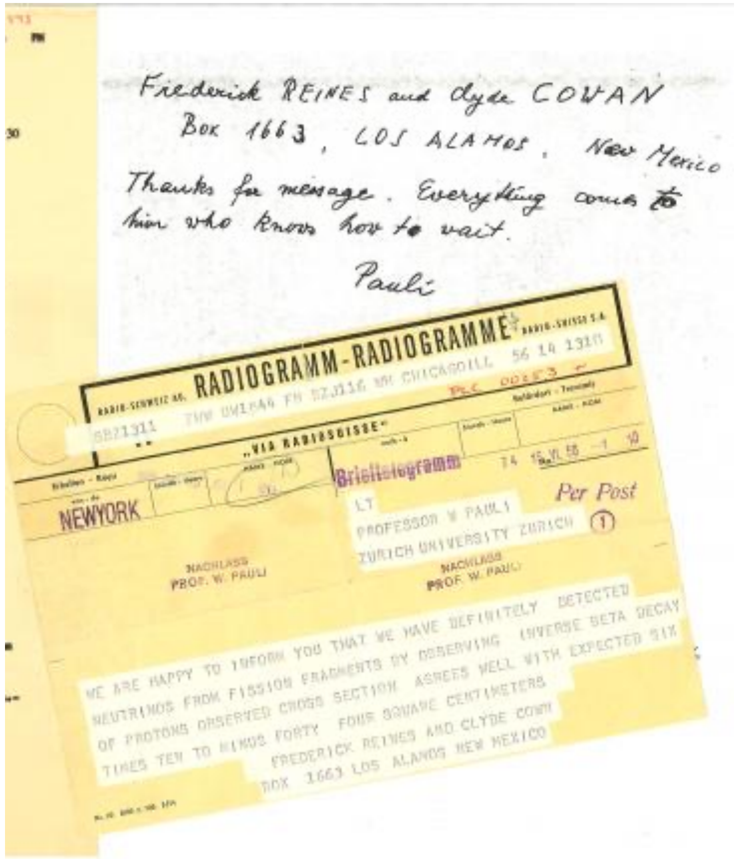
How was the neutrino discovered?

Which techniques are used to detect particles?

- Neutrinos interact via the weak force only
- We measure the (charged) particles produced in the neutrino interaction with matter
- Count the number of neutrino events given by $N_\upsilon = N * \int \phi(E_\upsilon)\sigma(E_\upsilon)dE_\upsilon$

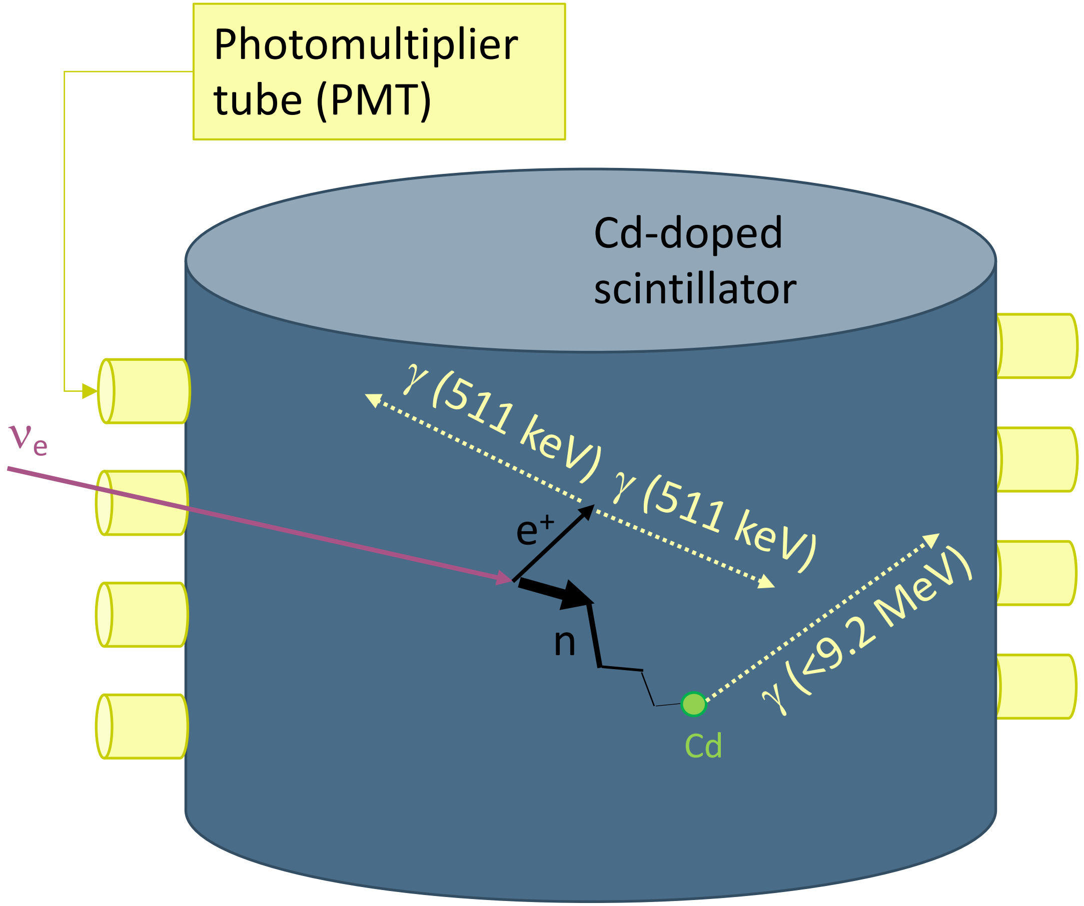
Project Poltergeist – the discovery of the neutrino

Nobel Prize (1995), Frederick Reines (Clyde Cowen died 1974)
“for pioneering experimental contributions to lepton physics […] **for the detection of the neutrino“**



- 1953: Hanford reactor site
- 1956: Savannah river reactor site

Project Poltergeist – IBD signature



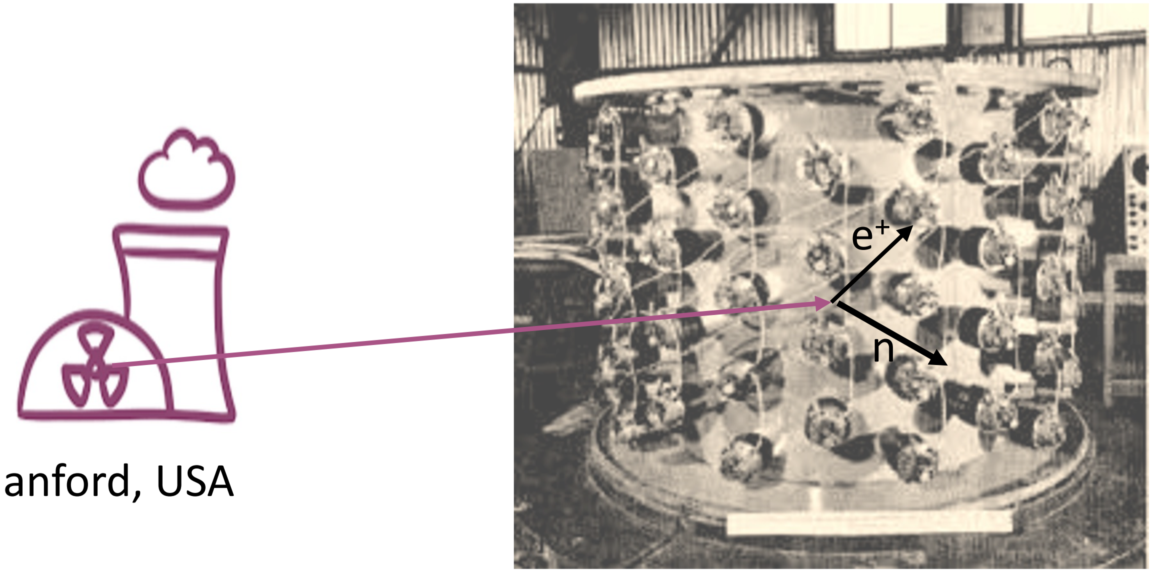
- $\bar{\nu}_e + p \rightarrow n + e^+$

$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$(N, Z) + n \rightarrow (N+1, Z) + \gamma$$

- Scintillation light detected by PMTs
- Scintillator acts as neutron moderator
- Moderation takes a few μsec (delayed-coincidence)
- Neutron captured on ^{113}Cd which has a cross-section 4 orders of magnitude larger than the one on H.

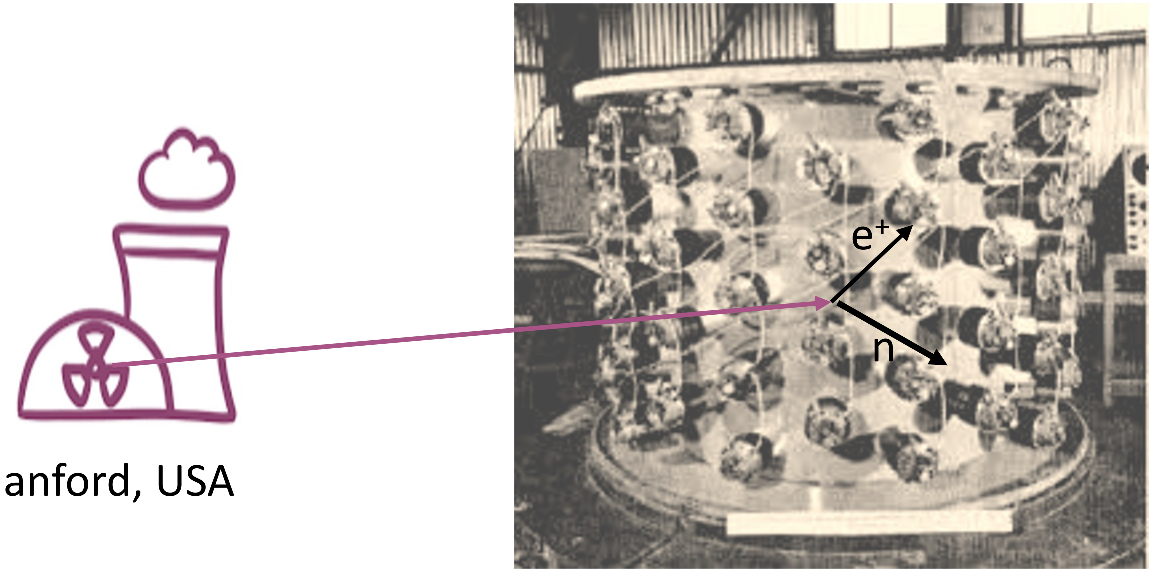
Herr Auge



Hanford, USA

- 300 l of scintillator
- 90 PMTs
- Boron-paraffin & lead to shield detector against reactor γ's and neutrons
- Expected rate of delayed coincidences 0.1-0.3 counts/ minute
- Measured: ~5 counts/ minute
- What could this be? ?

Herr Auge



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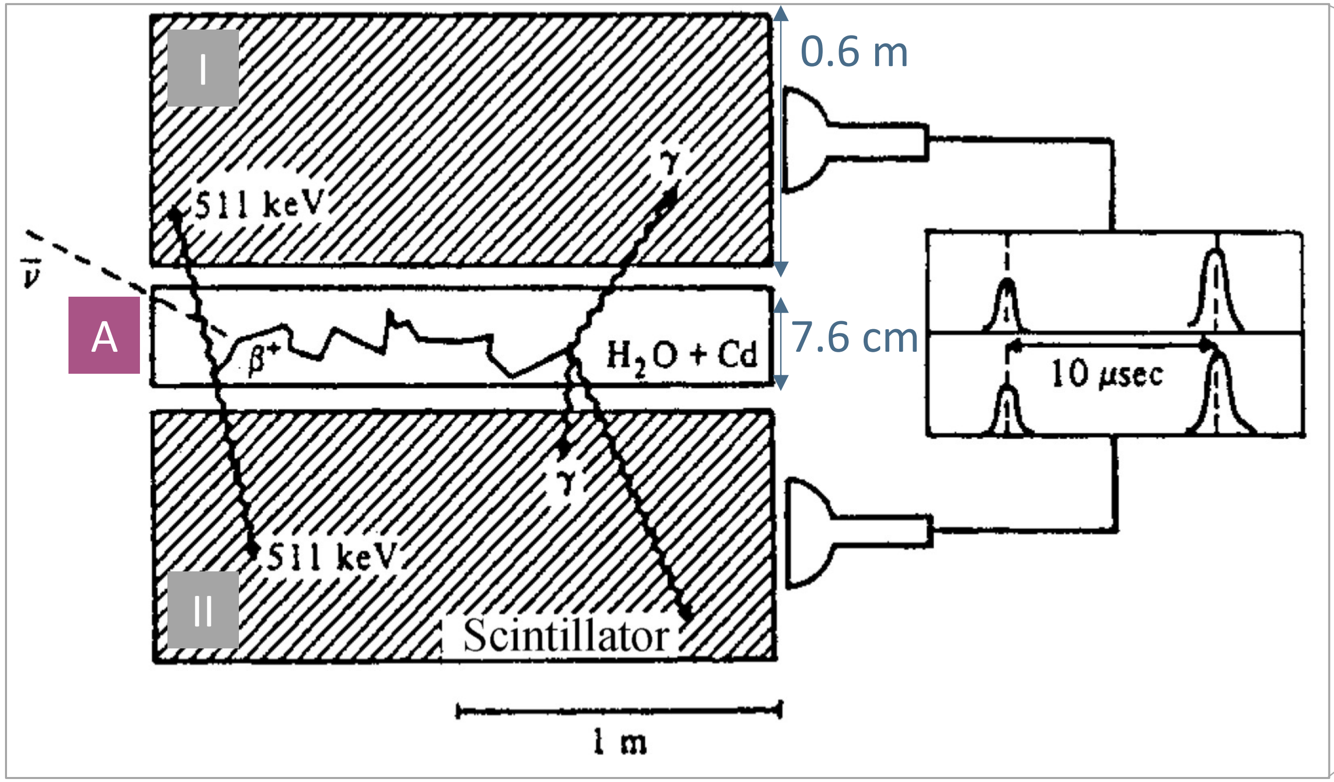
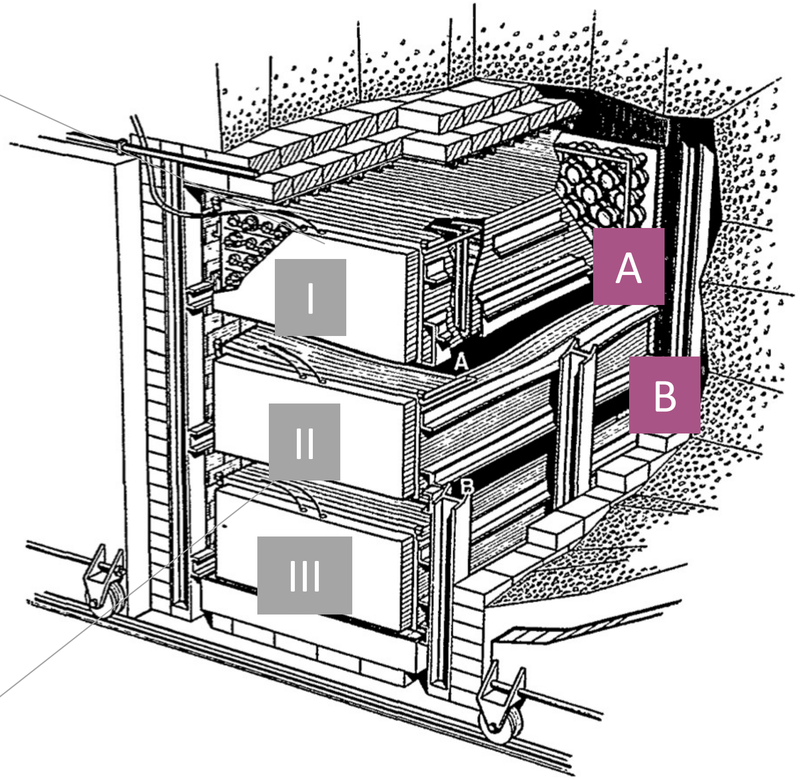
- 90 PMTs
- Boron-paraffin & lead to shield detector against reactor γ's and neutrons
- Expected rate of delayed coincidences 0.1-0.3 counts/ minute
- Measured: ~5 counts/ minute
- Identified cosmic rays as the dominant background

Improved Design – The Savannah River Experiment

- More powerful reactor
- 2 x 200 l Cd-doped water target & 3 x 1400 l liquid scintillator detector with 110 PMTs
- Add energy and spatial information of signals

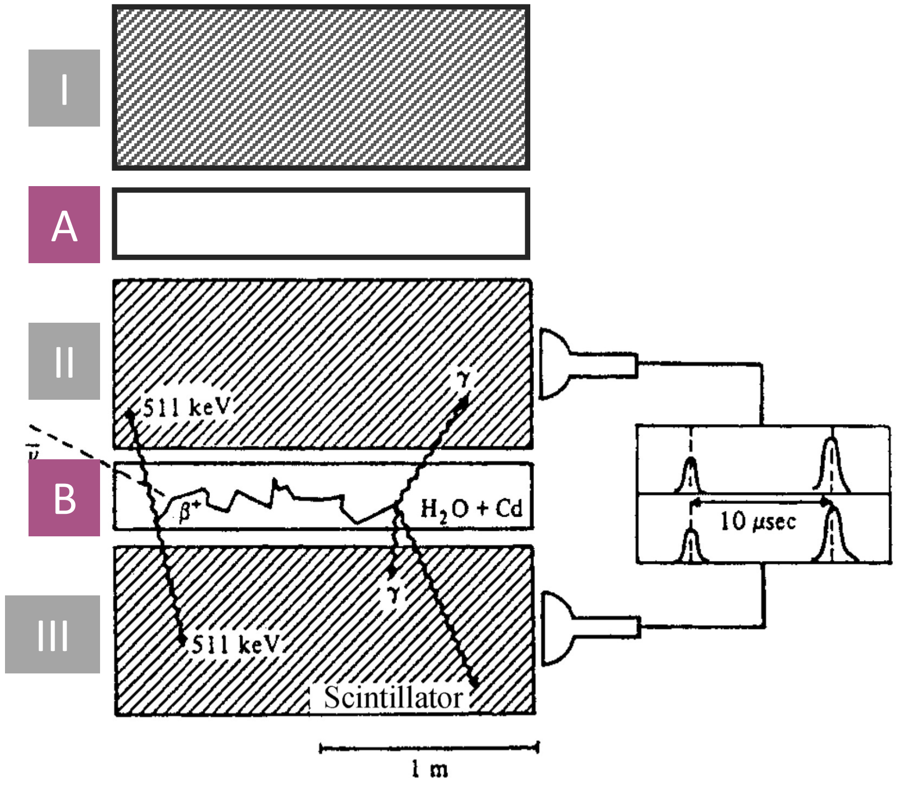




Neutrino Signals

- Positron:
  - Energy deposition in I/II or II/III
  - No energy deposition in third detector
  - Energy cut: 0.2 < E < 0.6 MeV
  - Prompt coincidence (200 ns)

- Neutron:
  - Energy deposition in I/II or II/III
  - No energy deposition in third detector
  - E > 0.2 MeV with 3 < Etot < 11 MeV
  - Delayed coincidence with positron signal (<30 μsec)



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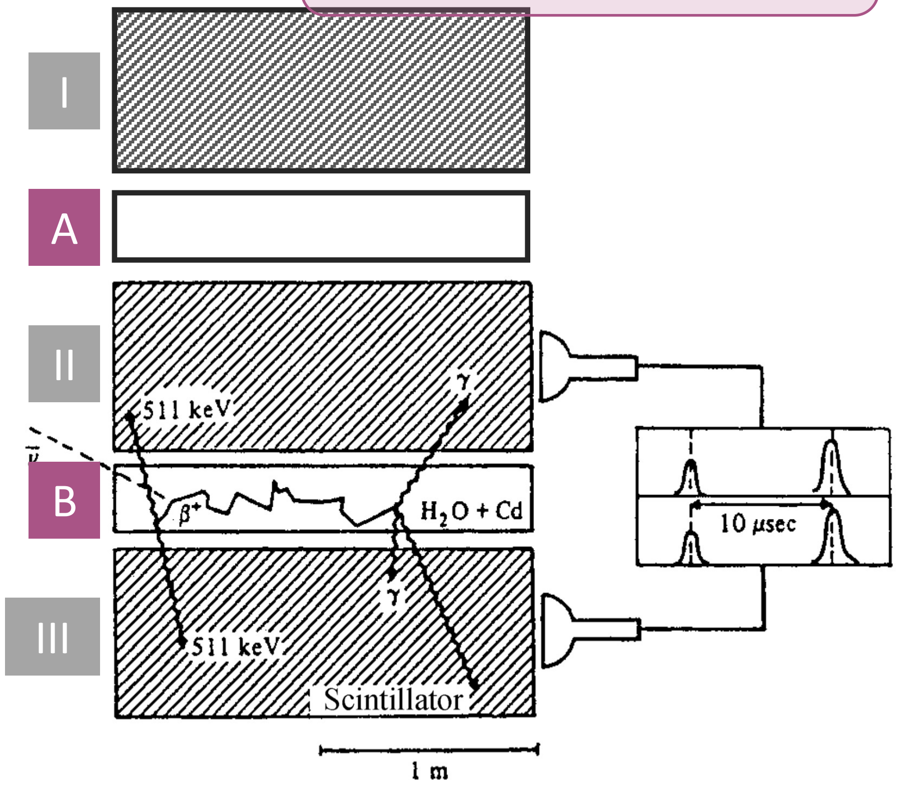
What would a muon signature look like?



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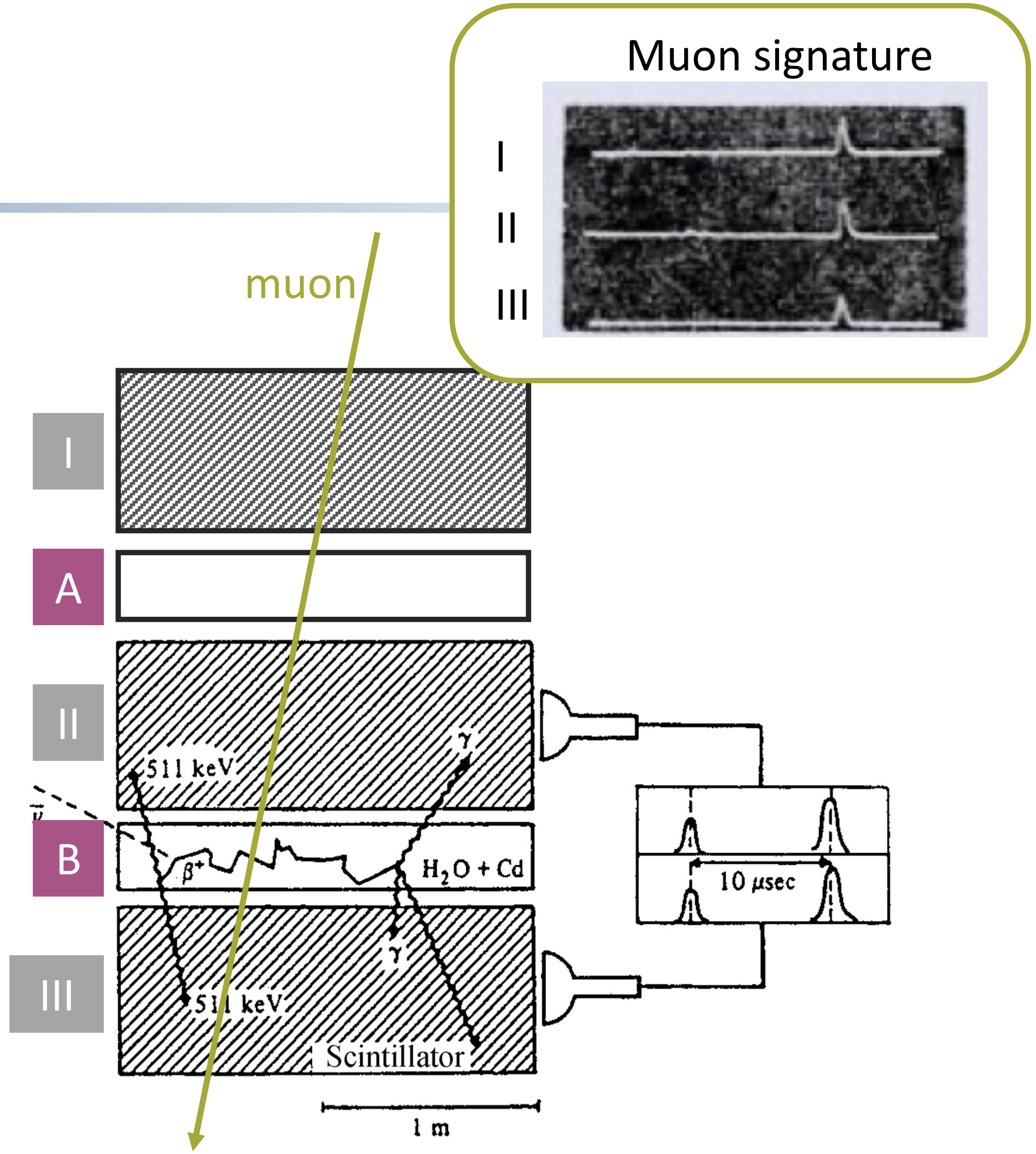


Part I – Principles of Neutrino Detection

How do we detect neutrinos?

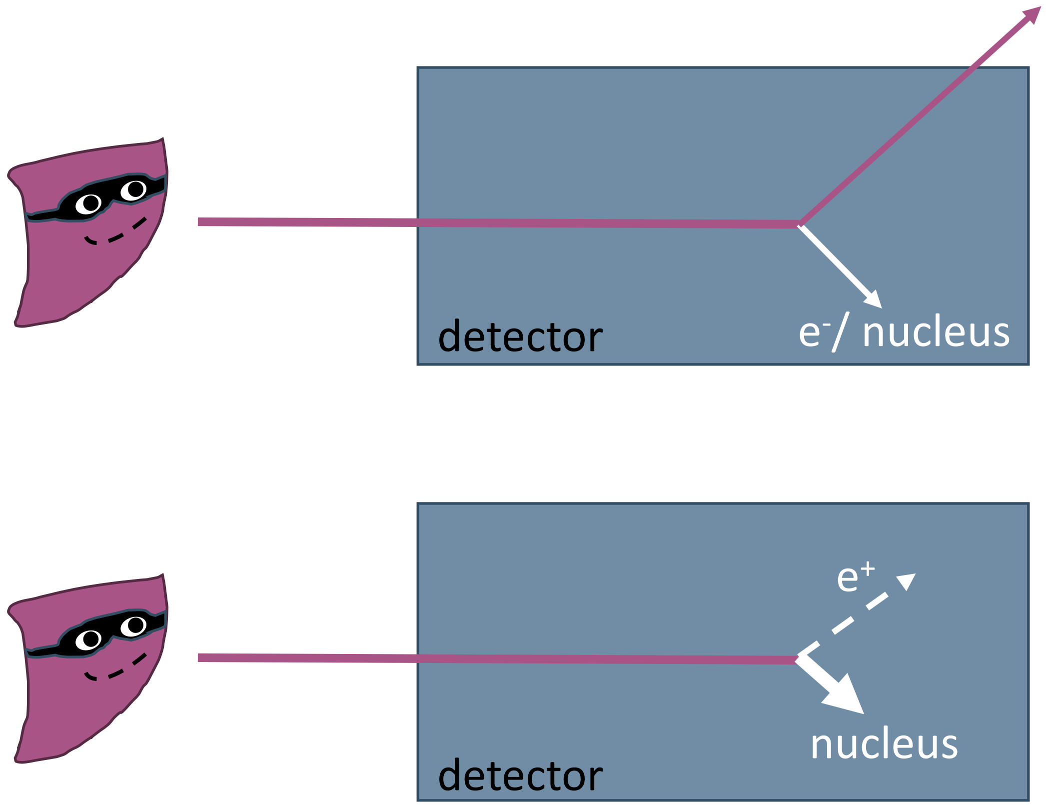
- Neutrinos interact via the weak force only
- We measure the (charged) particles produced in the neutrino interaction with matter
- Count the number of neutrino events given by $N_\upsilon = N * \int \phi(E_\upsilon)\sigma(E_\upsilon)dE_\upsilon$

How was the neutrino discovered?

- In 1956 by Cowen and Reines, Project Poltergeist
- The neutrino was detected via inverse beta decay
- Unique signature: coincident signal of positron and neutron capture

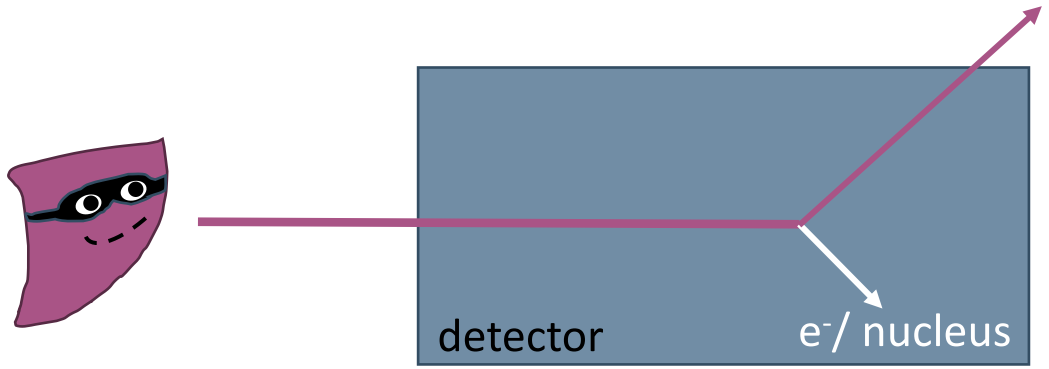
Which techniques are used to detect particles?

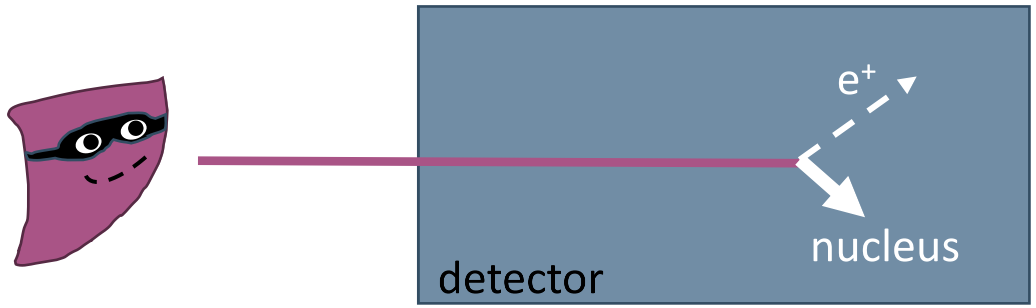
Challenges for Neutrino Detectors



- What makes a good neutrino detector?

Challenges for Neutrino Detectors





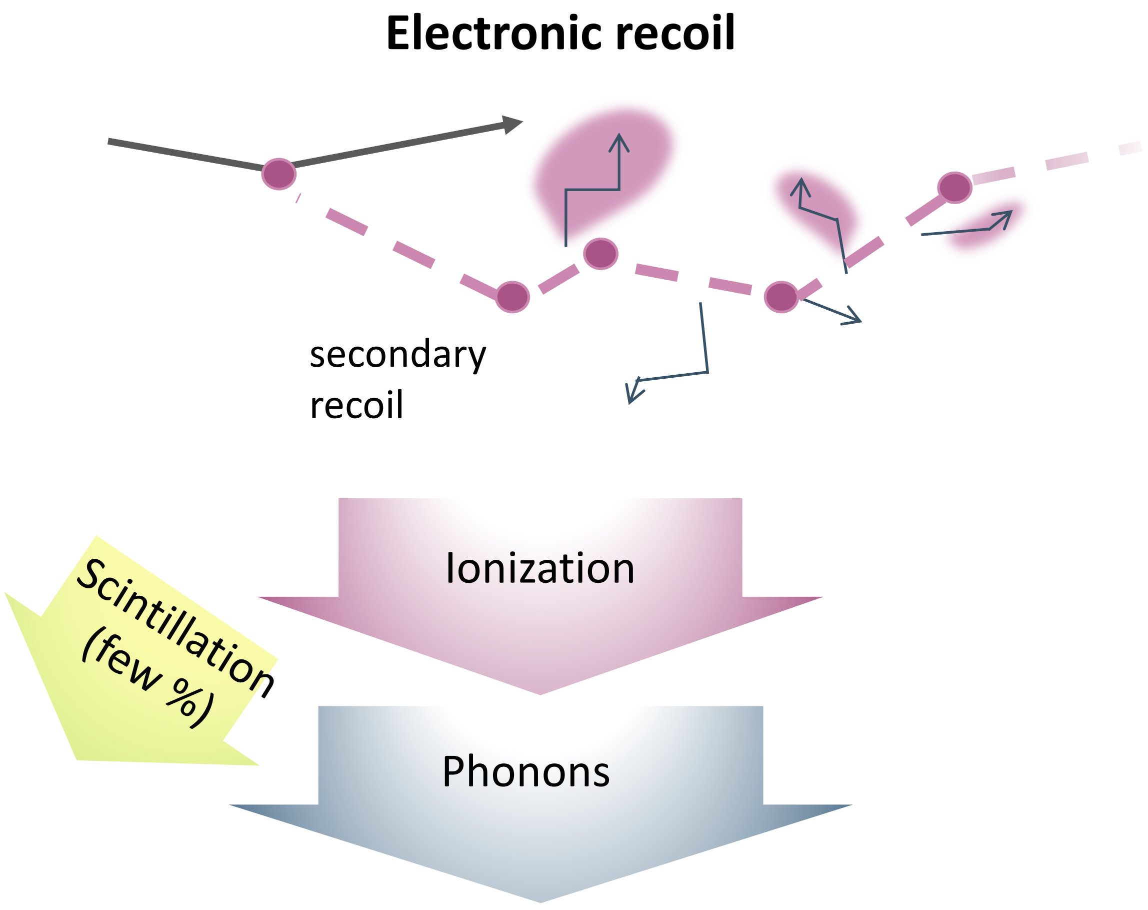
- Large detector mass – scalability
- Stable performance of O(years)

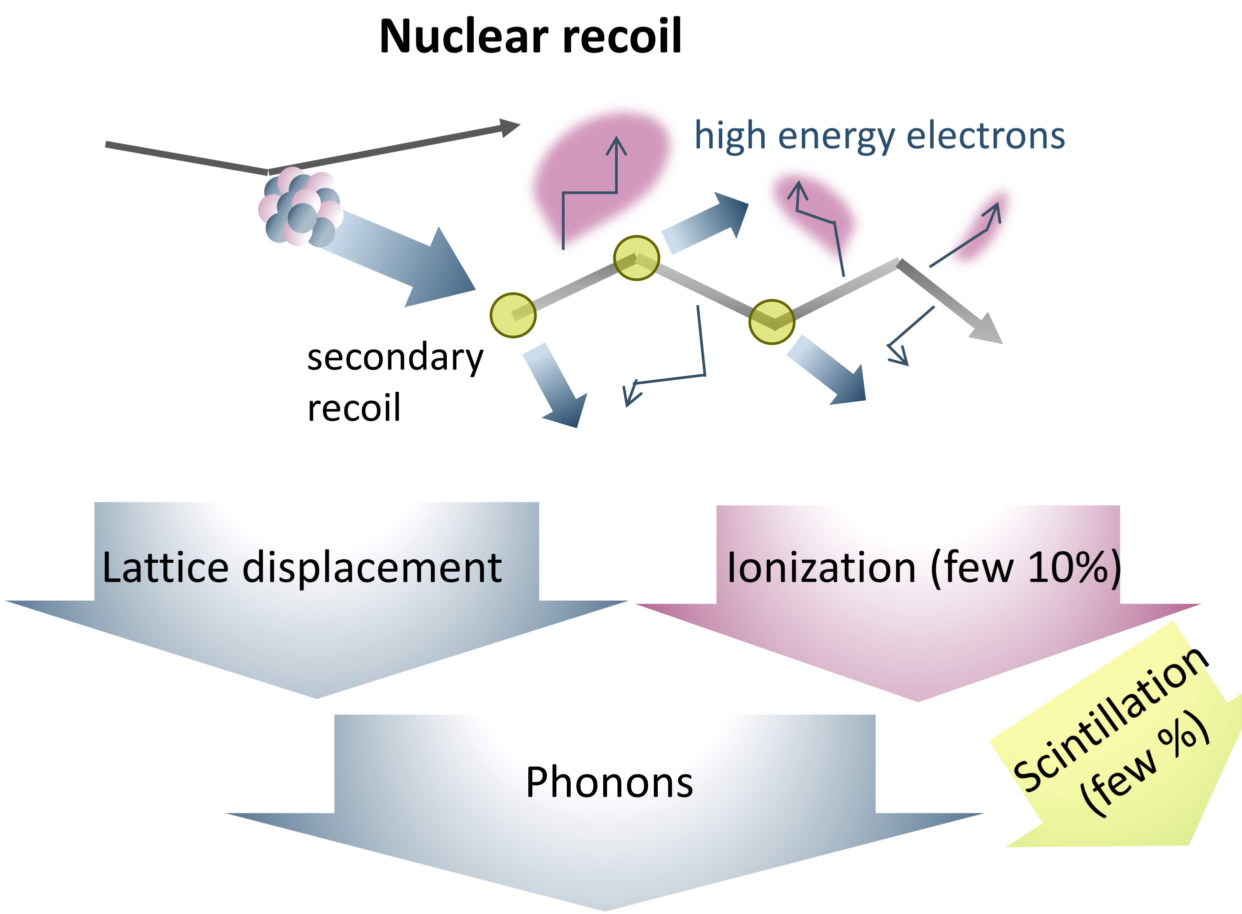
} exposure

- Low background
- High energy resolution & low threshold
- Understanding of detector response
- Particle identification
- Use of different target materials

-> How well can we measure the recoil of the secondary particles?

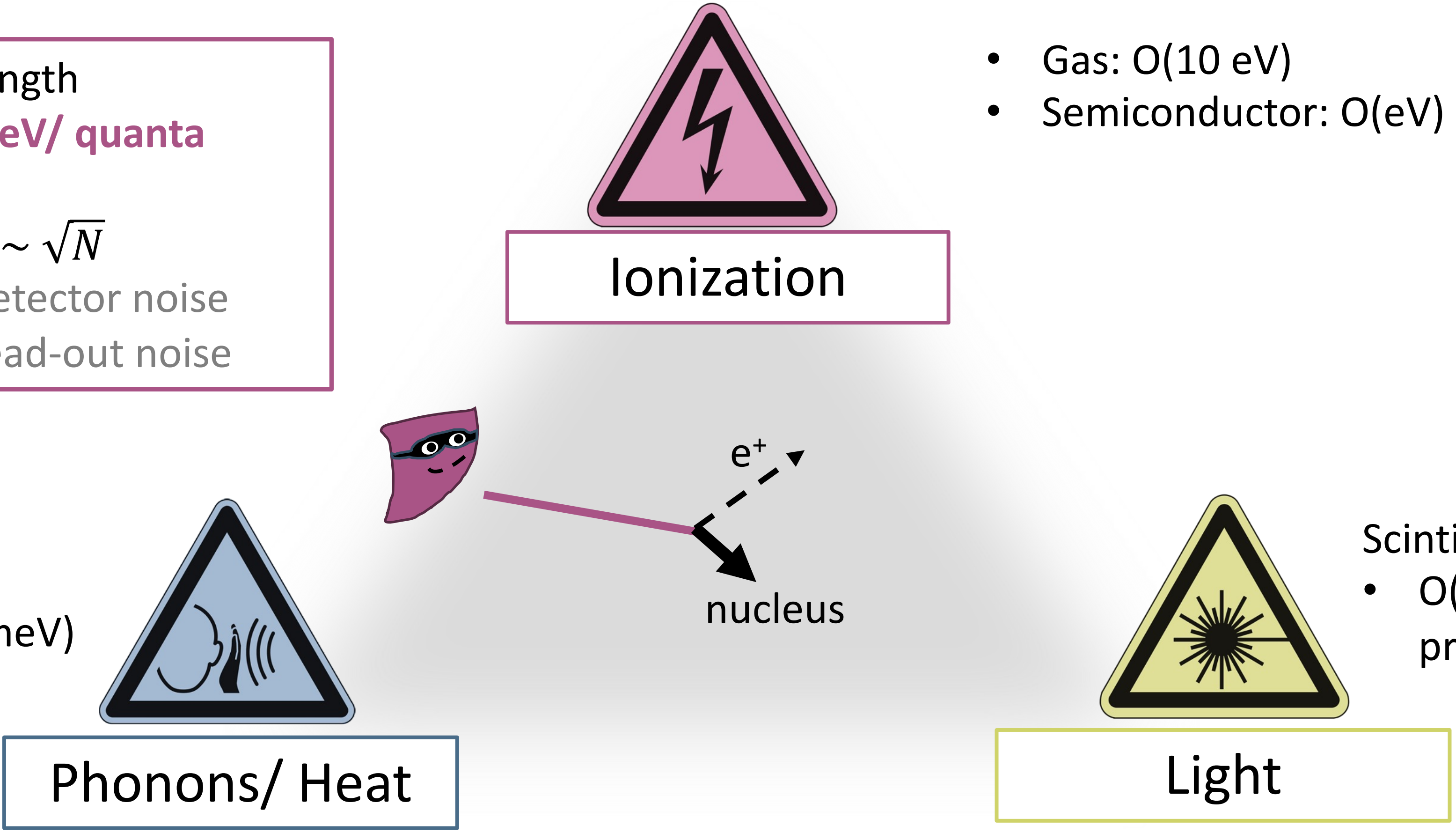
Energy Dissipation in Detectors





Measuring the recoiling particles

- Signal strength
  ϵ : eV/ quanta
- Resolution
  $\Delta E \sim \sqrt{N}$
  + detector noise
  + read-out noise



- Gas: O(10 eV)
- Semiconductor: O(eV)

- O(meV)

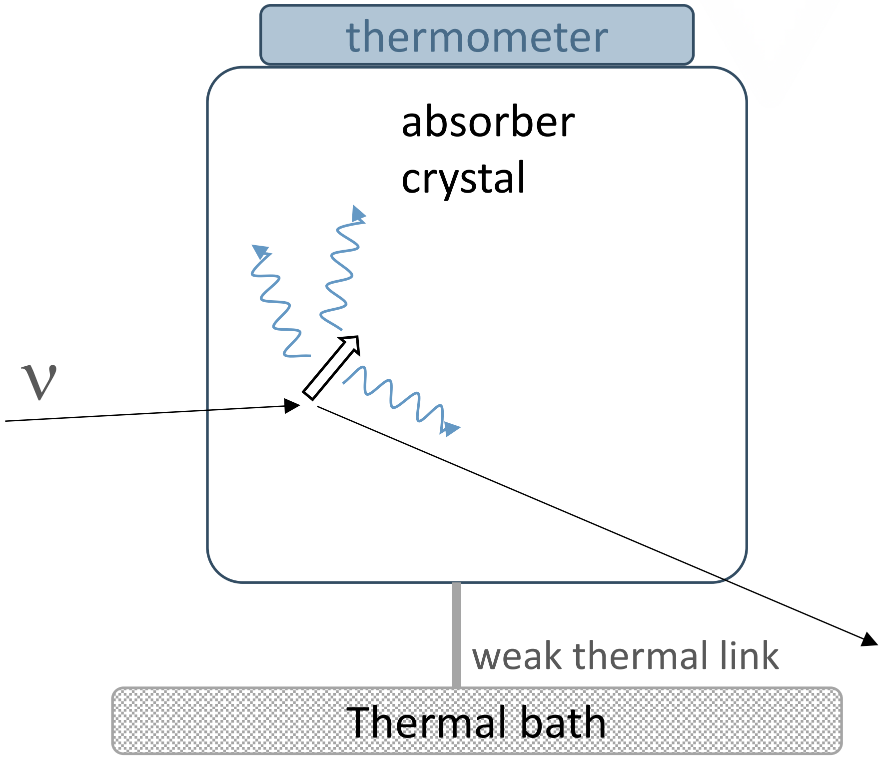
Scintillator:
- O(100 eV) need to produce O(eV) photon

Phonon Signals

- Measure $\Delta T = \Delta E/C$
- C: heat capacity $C \sim T^3$ (dielectric)

  $C \sim T$ (metal)
- Temperatures of O(<100 mK)
- Example (24 g Al_2O_3)

  $\Delta T/\Delta E \sim 120\ \mu K/\ keV$



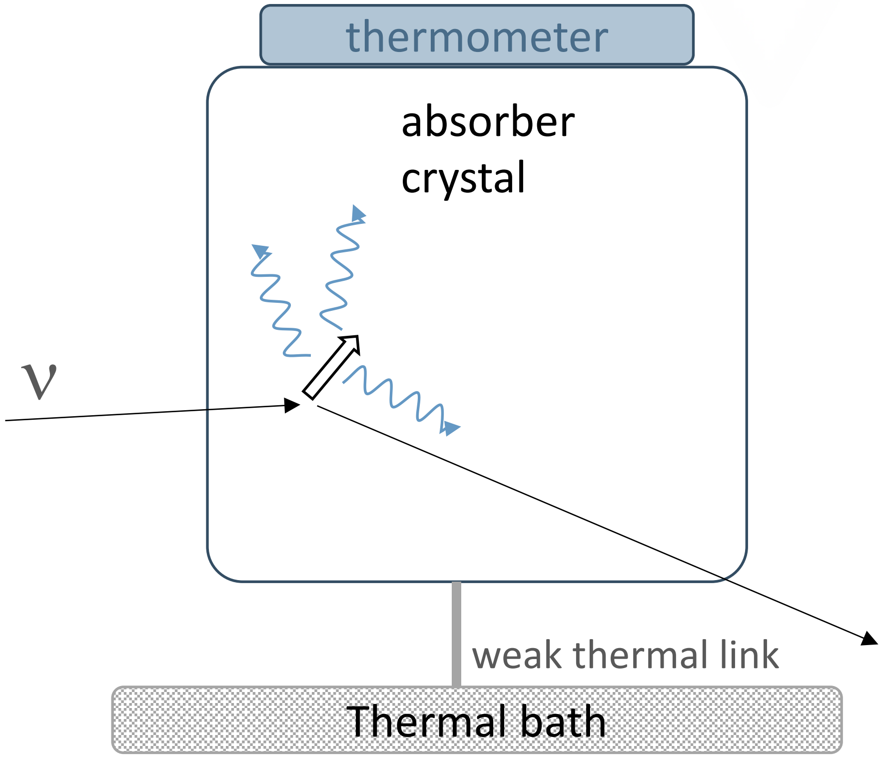
Phonon Signals

Particle interaction:

ns

ms

- High-frequency optical phonons
- Decay to acoustic phonons
- Phonons decay ~ω^5
- Ballistic streaming of phonons
- Thermalization via inelastic scattering at the surface

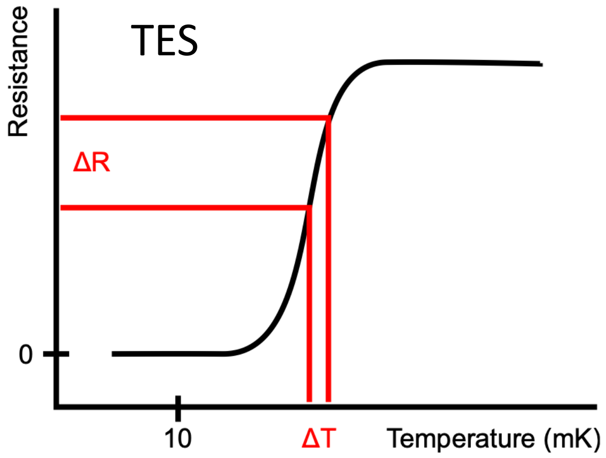


Phonon Signals

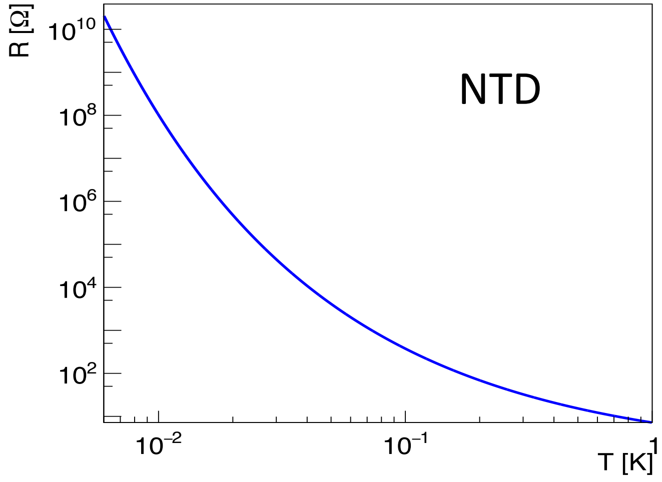
R = R(T)
M = M(T)

Thermometer: ΔT -> electrical signal

- Transition edge sensor (TES)
  - Fast O(μs-ms) response
  - Limited dynamic range
  - SQUID read-out
- Neutron transmutation doped (NTD)
  - Slow response (ms) - thermal measurement
  - Wide dynamic range
  - Simple read-out
- Magnetic Calorimeter (MMC)
- Microwave kinetic inductance detectors (MKIDs)

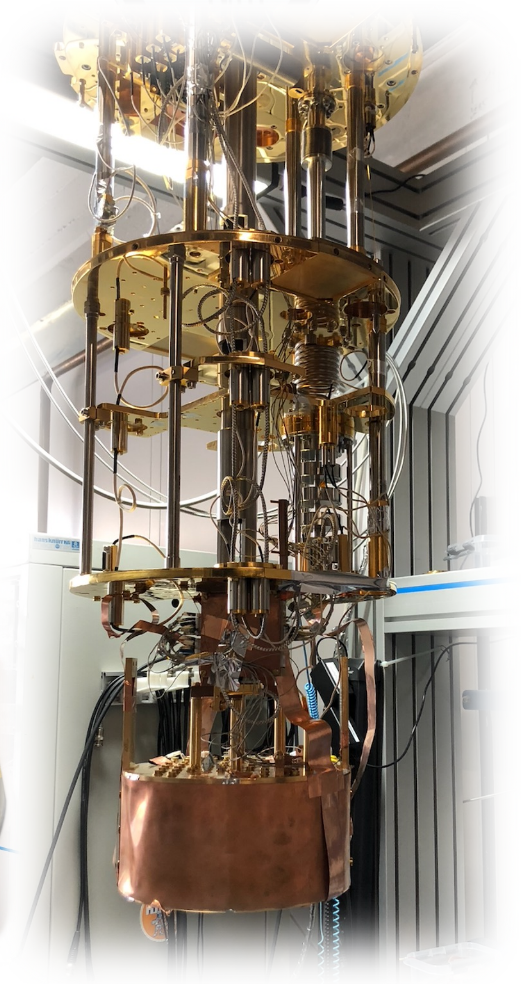


$\Delta T = O(100\ \mu K)$ → **$\Delta R = O(100\ m\Omega)$**



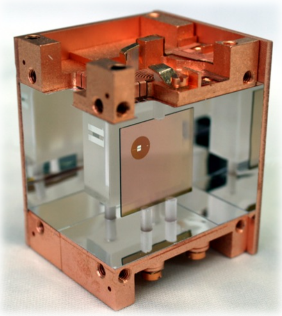
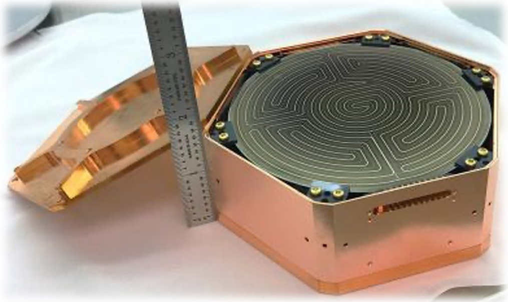
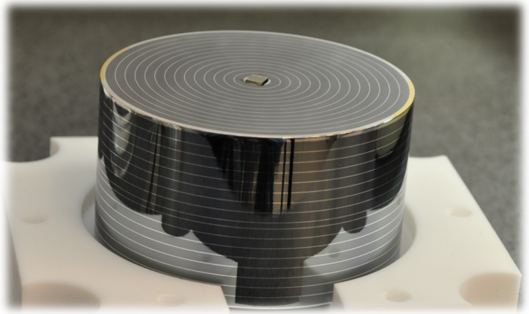
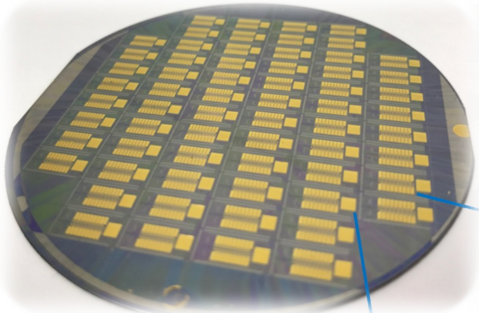
$\Delta T = O(100\ \mu K)$ → **$\Delta R = O(8\ M\Omega)$**

Phonon Detectors



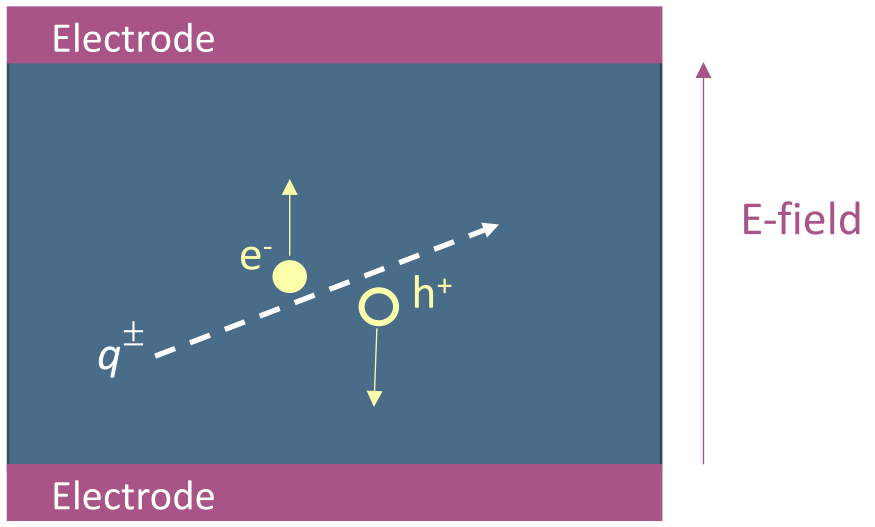
- ✓ Can reach eV energy thresholds & resolution $\Delta E \approx \sqrt{k_B T^2 C(T)}$
- ✓ Measure full energy, independent of particle type
- ✓ Wide range of target materials
- ✓ Large synergy of CEvNS and light Dark Matter

- ! Limited in mass (<kg)
- ! Multiplexing of channel read-out

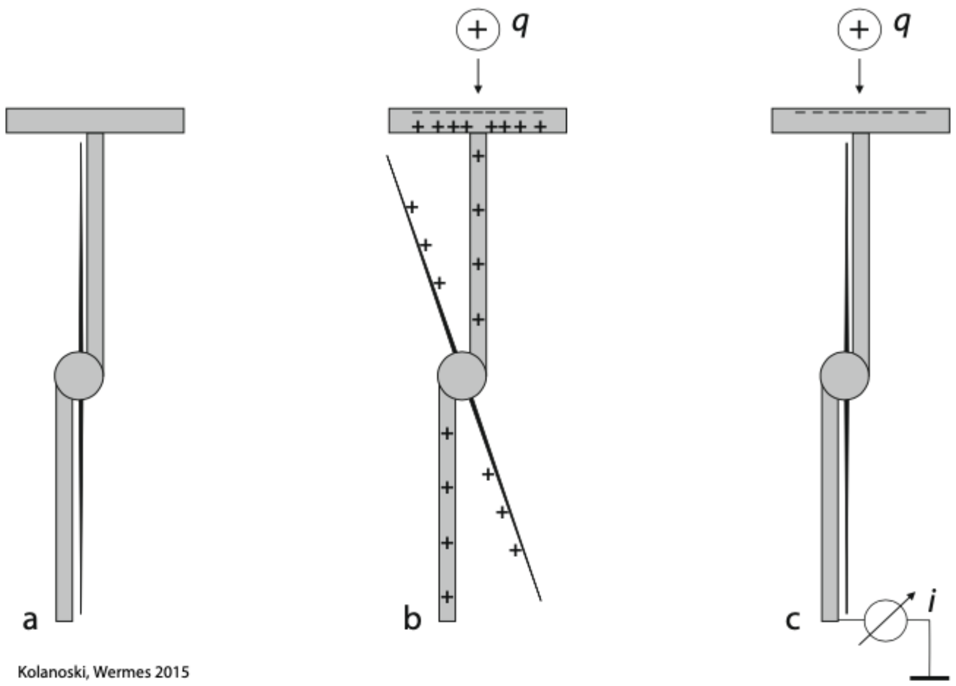





Ionization/ Charge Read-Out

- Ionization produces charges
  - e^-/h^+ pairs in semiconductors
  - e^-/ion pairs in gases
- Apply E-field to separate charges
- Signal: induce charges/ current on electrodes
- **The signal produced by the motion of charges in the detector medium**



Signal produced by moving charges

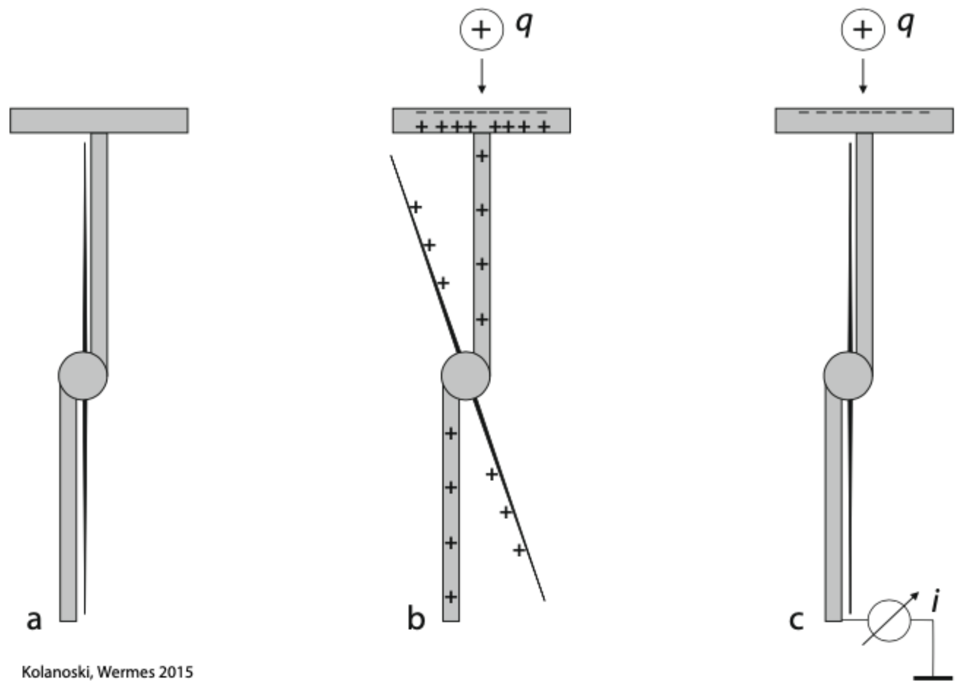


a) A positive charge *q* approaches an isolated electroscope

b) The closer *q* gets, the more charges are induced

c) What happens if we ground the electroscope?

Signal produced by moving charges



a) A positive charge *q* approaches an isolated electroscope

b) The closer *q* gets, the more charges are induced

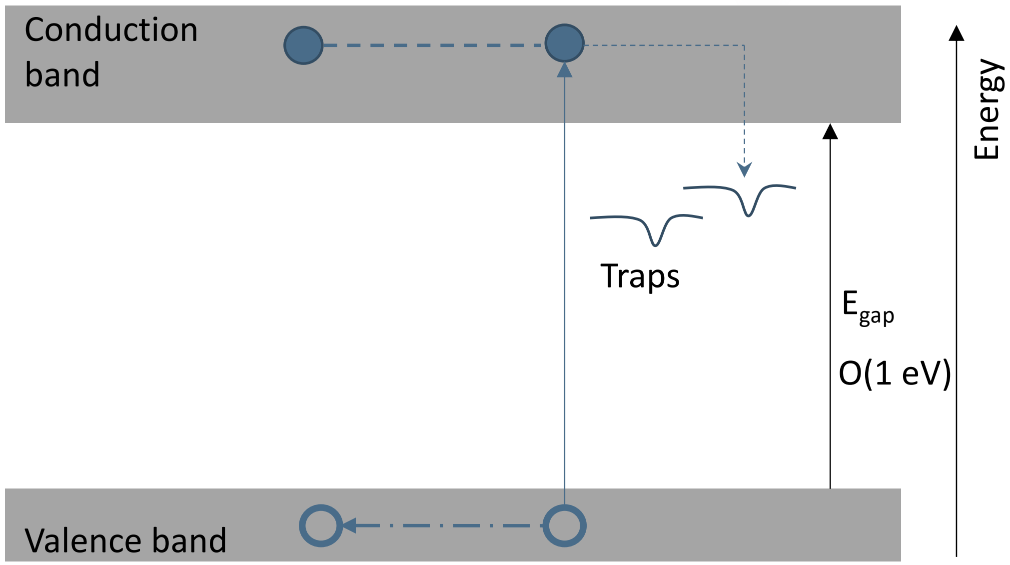
c) If the electroscope is grounded a current flows which continues as long as *q* keeps moving

Semiconductor (HPGe)

- Only a fraction of energy converted to ionization

Element	E_{gap} [eV]	$E_{e/h}$ [eV]	F
Si	1.12	3.65	0.115
Ge	0.66	2.96	0.13

- Need to be operated at low temperatures (LN)



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Element	E_{gap} [eV]	$E_{e/h}$ [eV]	F
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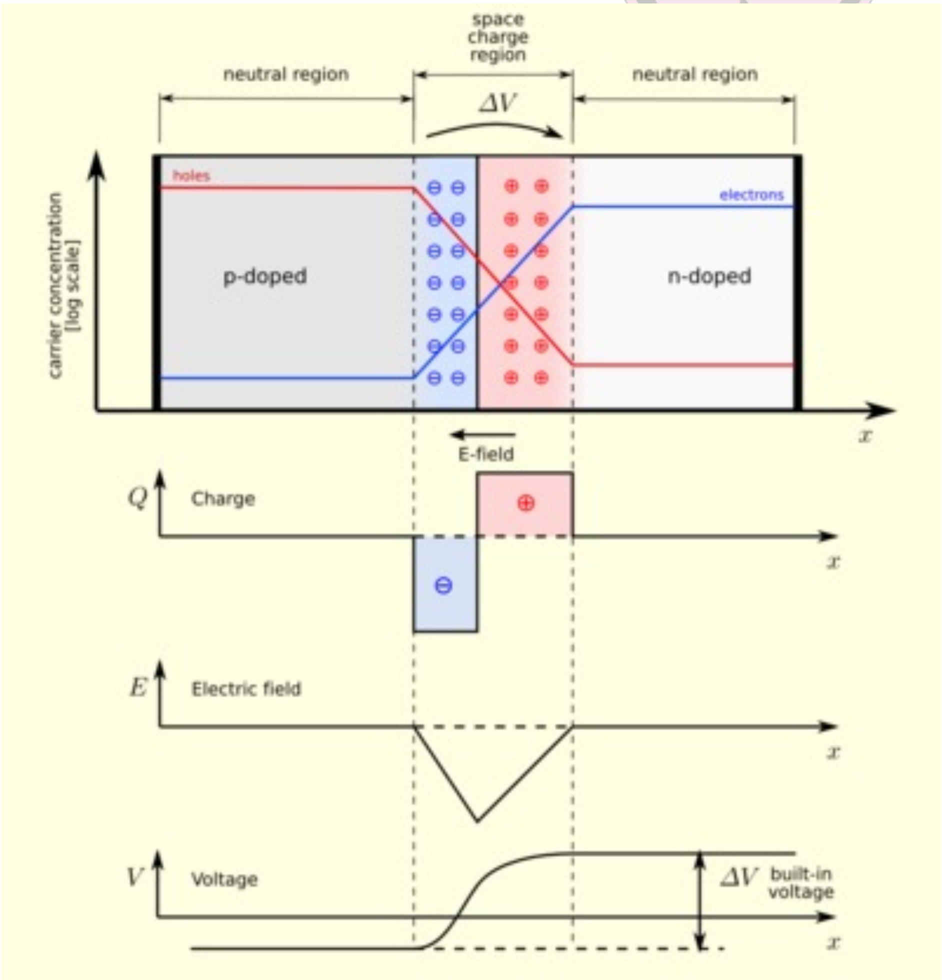
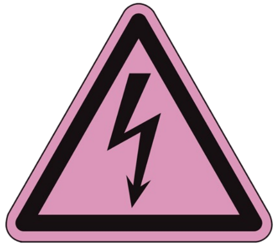
- Need to be operated at low temperatures (LN)
- Detectors based on p-n junction to deplete sensitive volume from free charges
- Reverse bias to increase depletion zone:

$$d \sim \left(\frac{V}{eN}\right)^{1/2}$$

- High-purity germanium (HPGe) with N $O(10^{10}$ atoms/cm$^3)$



Charge Detectors



✓ Excellent energy resolution $\Delta E \approx \sqrt{F\, \epsilon\, E}$

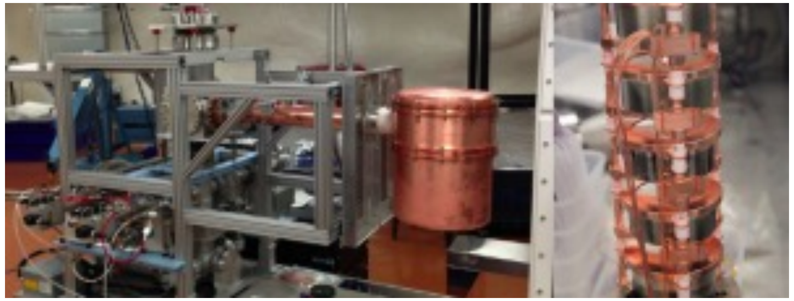
✓ Position sensitive

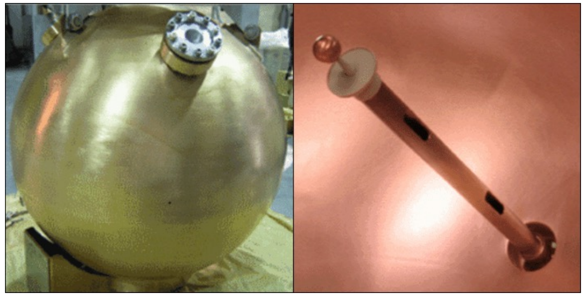
✓ Directionality for gas detectors

! Low mass/ low density

! Response particle type dependent (dE/dx)

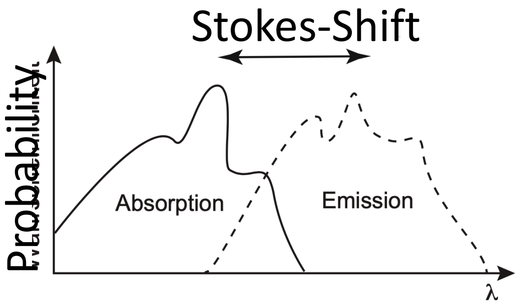
Element	E_{gap} [eV]	$E_{e/h}$ [eV]	F
Si	1.12	3.65	0.115
Ge	0.66	2.96	0.13

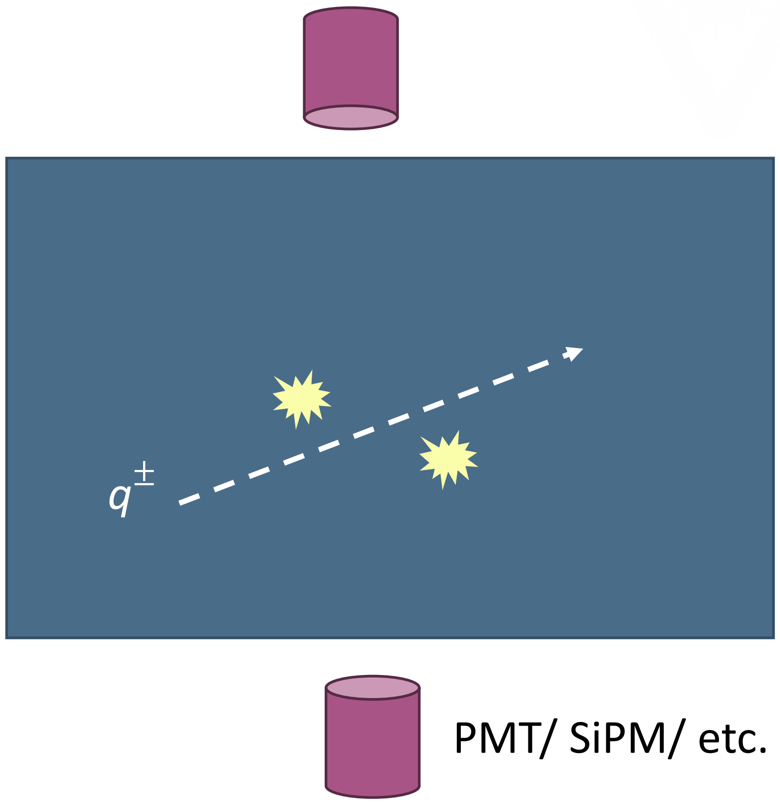




Light/ Scintillation

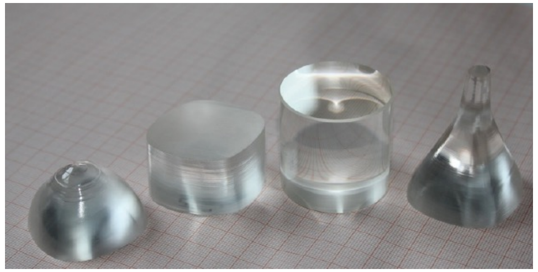
- Scintillation = creation of luminescence by absorption of ionization radiation
- Subsequent de-excitation releases scintillation photons
- Materials:
    - Inorganic crystals
    - Organic scintillators (liquid, plastic)
    - Noble gas liquids
- Typically only 1-10 % of recoil converted to light

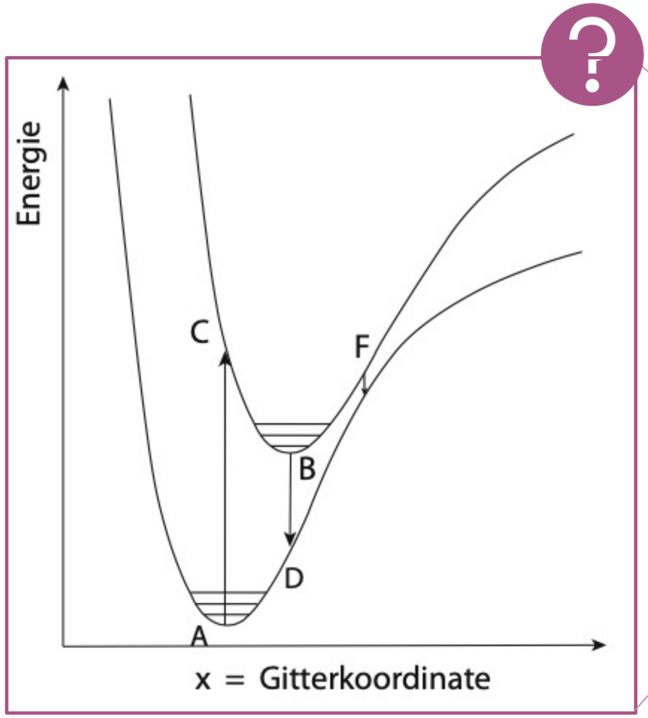


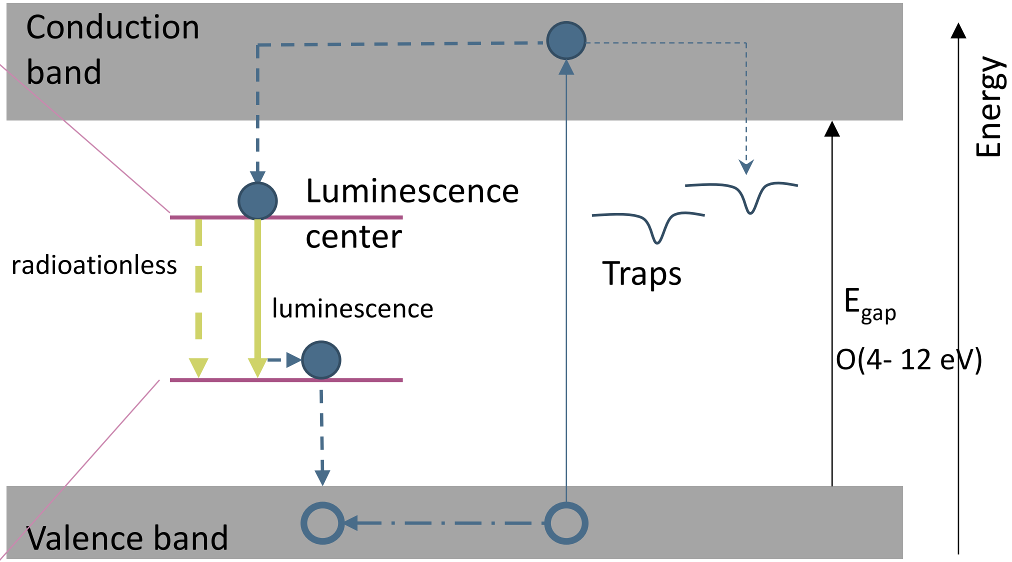


Inorganic Scintillators

- Band structure of the lattice changed by activation centers

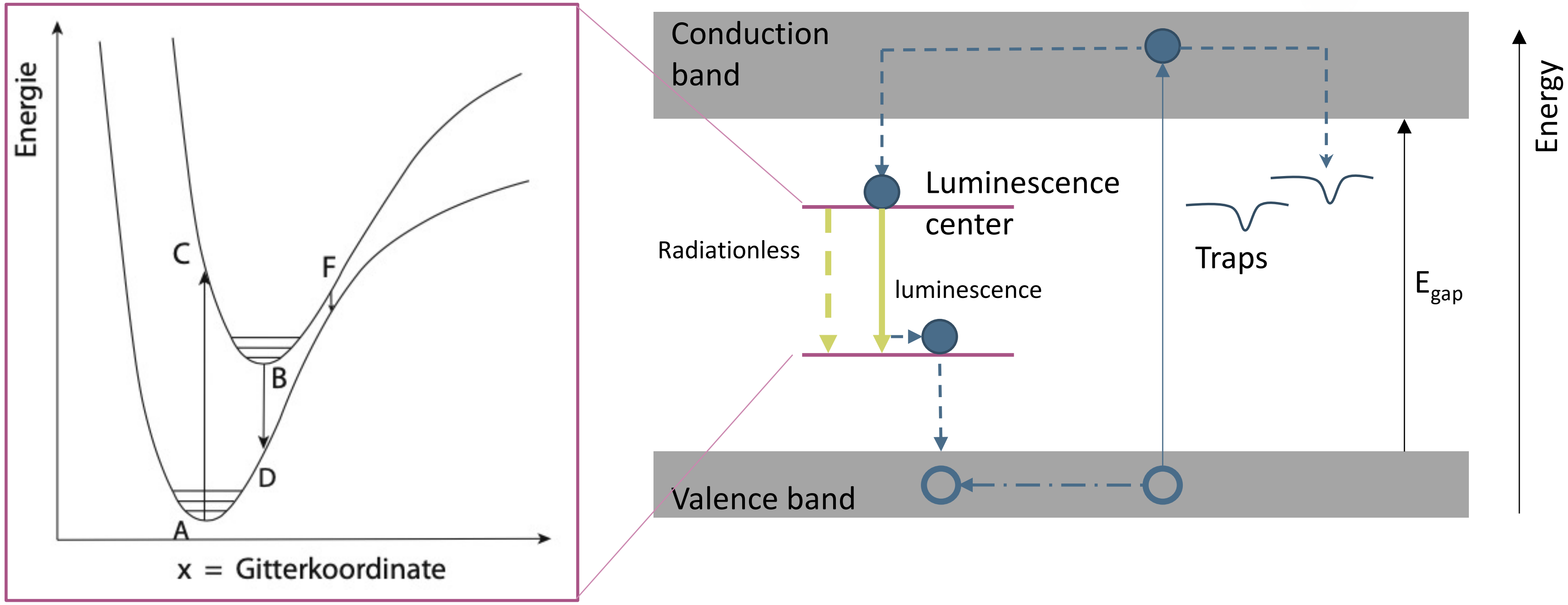






Inorganic Scintillators

- Band structure of the lattice changed by activation centers

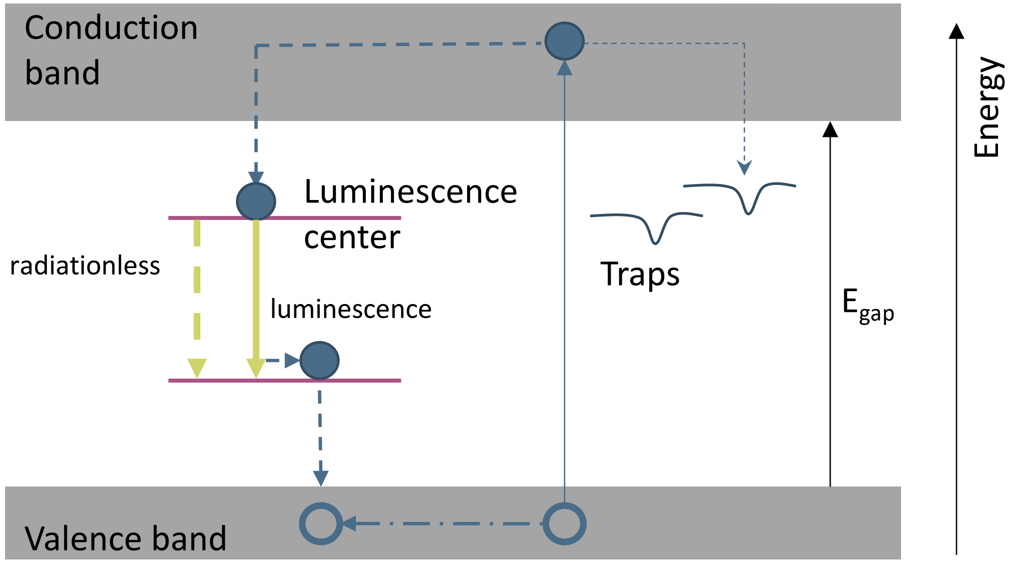


- AC: Absorption
- CB: thermalization
- BD: luminescence
- F: quenching (radiationless)

Inorganic Scintillators

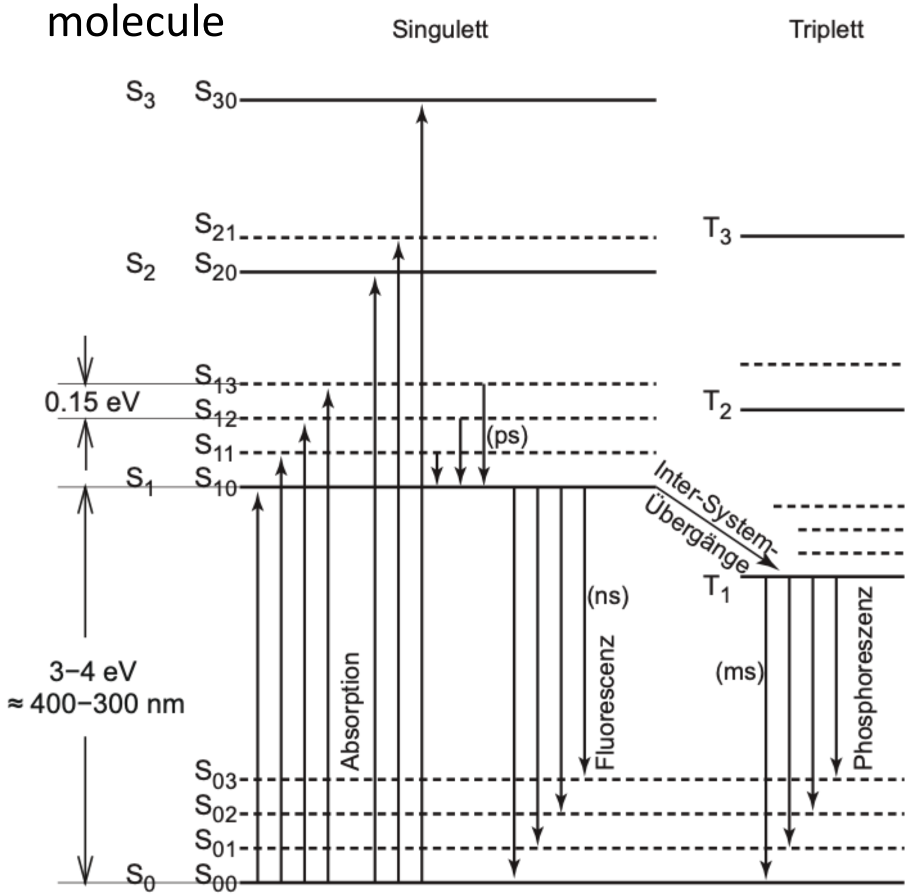
- Band structure of the lattice changed by activation centers

- Materials (examples):
  - Doped alkali metal halides: NaI(Tl) and CsI(Tl)
  - Oxides: $CaWO_4$ or BGO ($Bi_4Ge_3O_{12}$)
- Typically 10% scintillation efficiency -> good energy resolution
- Crystals -> low mass
- Commercially available
- Detector response energy and particle dependent



Organic Scintillators aromatic hydrocarbon compounds, (C-H)

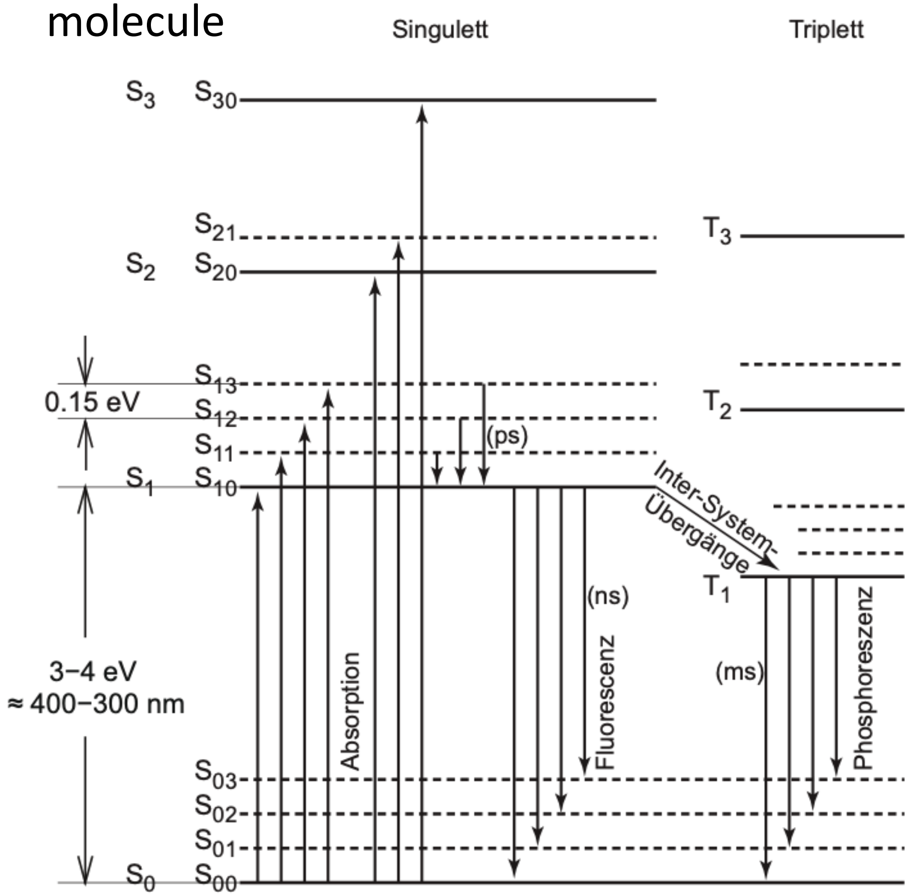
Energy levels of “free” valence electrons of the molecule



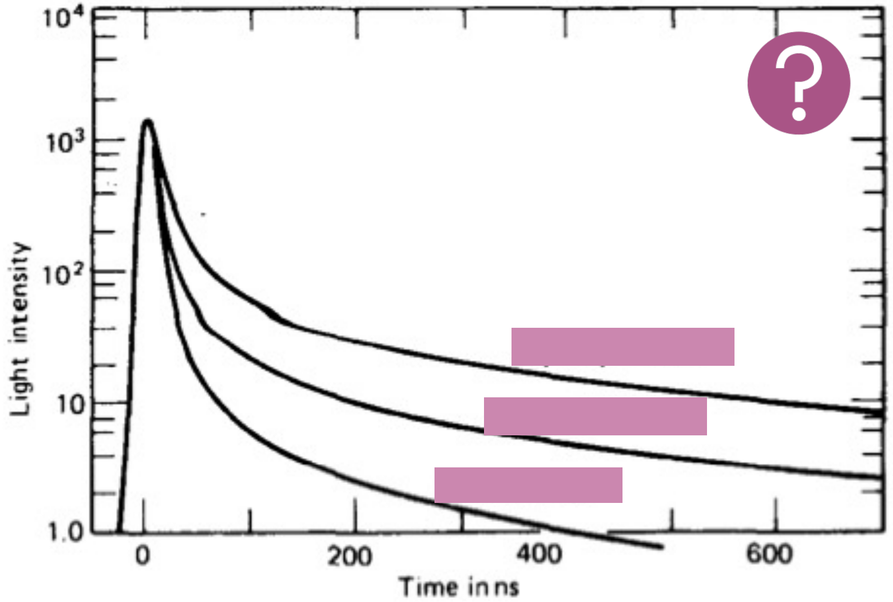
- Transition from T_1 to S_0 forbidden
  - Phosphorescence (ms)
  - Delayed fluorescence (μs-ms)

Organic Scintillators aromatic hydrocarbon compounds, (C-H)

Energy levels of “free” valence electrons of the molecule

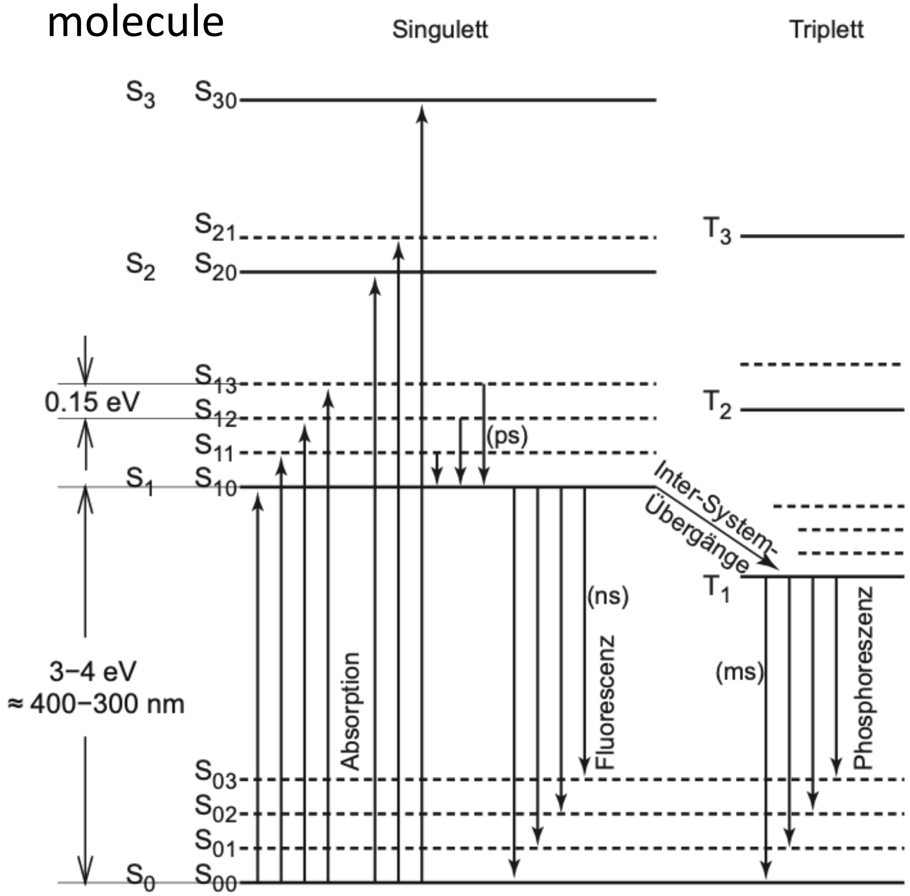


- Transition from T_1 to S_0 forbidden
  - Phosphorescence (ms)
  - Delayed fluorescence (μs-ms)
- The population of S or T depends on dE/dX -> used for PSD



Organic Scintillators

Energy levels of “free” valence electrons of the molecule



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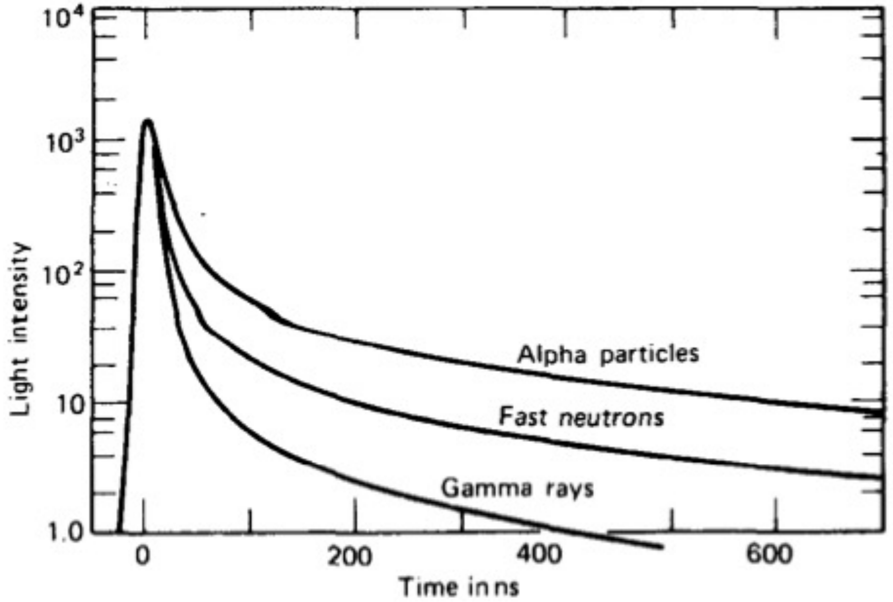
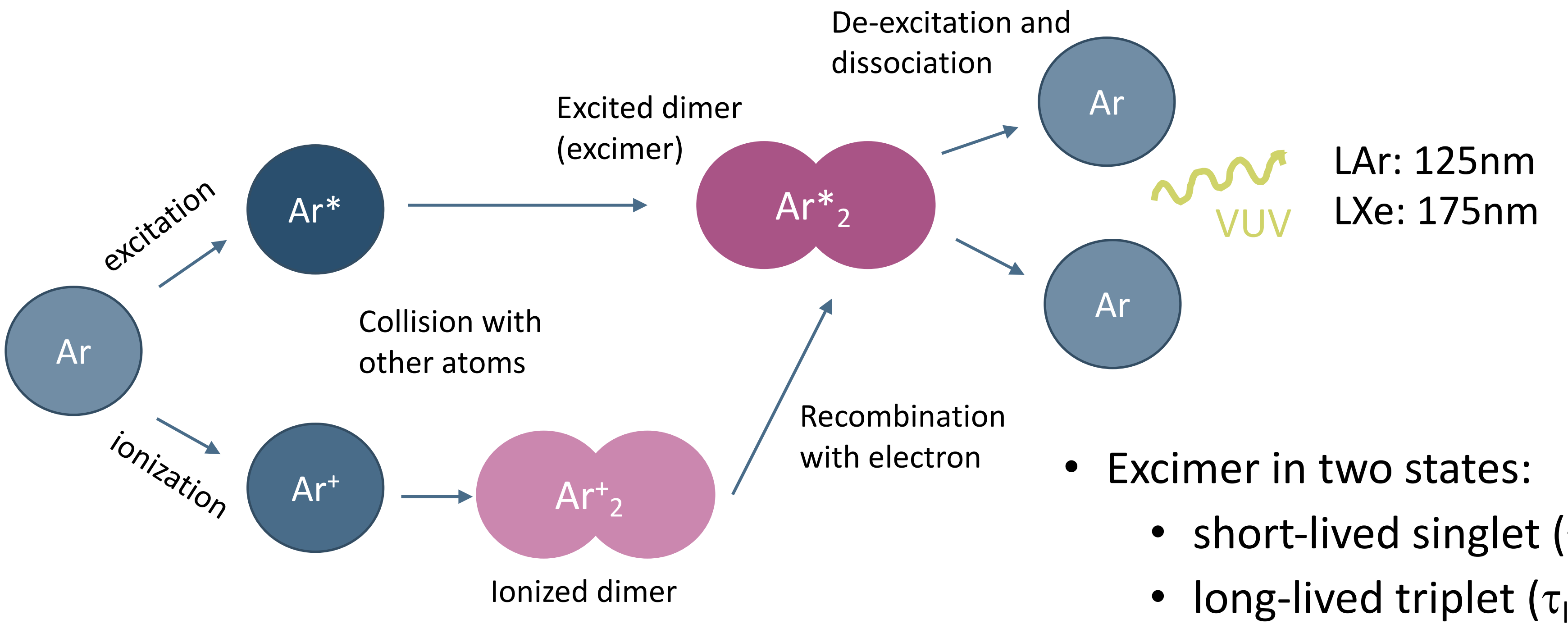


Liquid Noble Gases



- Excimer in two states:
  - short-lived singlet (τ_s)
  - long-lived triplet (τ_l)
- Population of states depends on dE/dx -> PSD
- For LAr τ_s = 6ns and τ_l = 1.6μs
- For LXe τ_s = 4ns and τ_l = 22ns

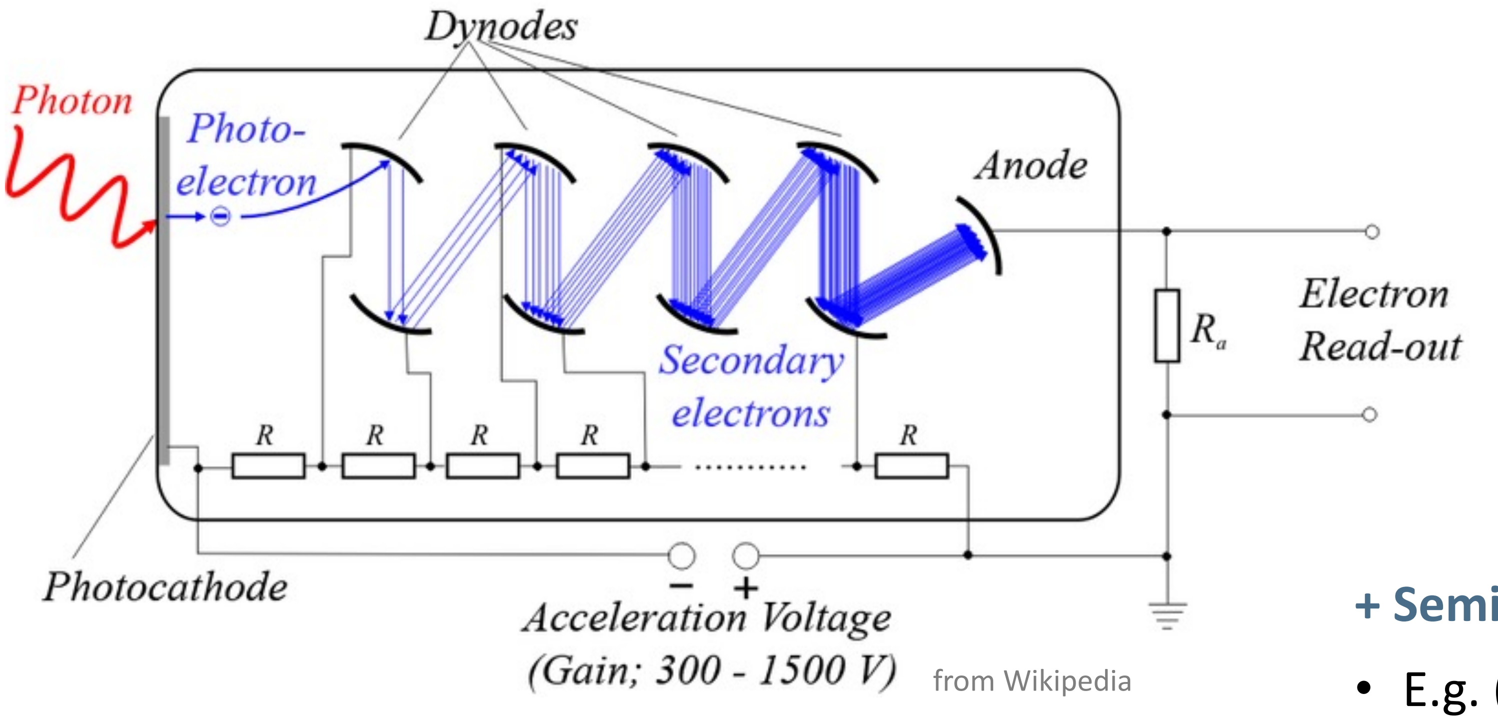
Wishlist:
- High efficiency
- Transparency
- Emission in spectral range of PMTs
- Fast response

Some Examples for Scintillators

	Organic Scintillators	Inorganic Crystals	Liquid Noble Gases
	BC-408	NaI(Tl)	LAr
Density	ρ = 1 g/cm^3	ρ = 3.7 g/cm^3	ρ = 1.4 g/cm^3
Decay time	2.1 ns	0.25 μs	5 ns / 1.6 μs
Photons/ MeV	2 x 10^2	4 x 10^4	4 x 10^4
Wavelength maximum [nm]	423	410	125
Advantages	• Very fast • Easily shaped • PSD • Cheap	• High light yield & good energy resolution • High density	• High light yield • Fast • PSD (LAr)
Disadvantages	• Lower light yield	• Crystals (expensive) • T-dependence	• Expensive • LAr intrinsic background • VUV light

Photosensors in a Nutshell

Photomultiplier Tube (PMT)



from Wikipedia

Signal output:

- Quantum efficiency O(25%)
- Coverage

+ Semiconductor devices

- E.g. (Avalanche) photodiodes, SiPMs

Light-Based Detectors

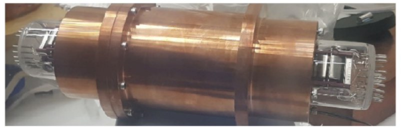
✓ Scalability for liquids

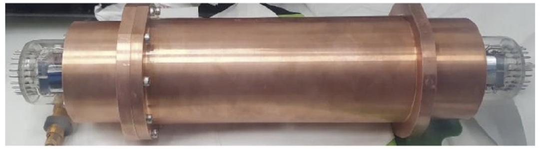
✓ Prize (some)

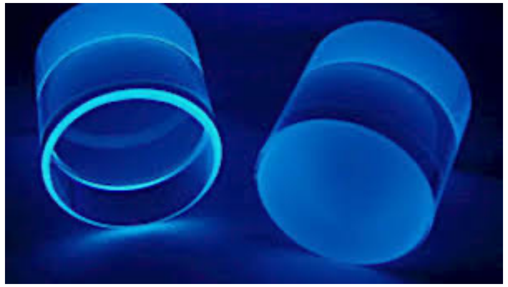
✓ Particle ID

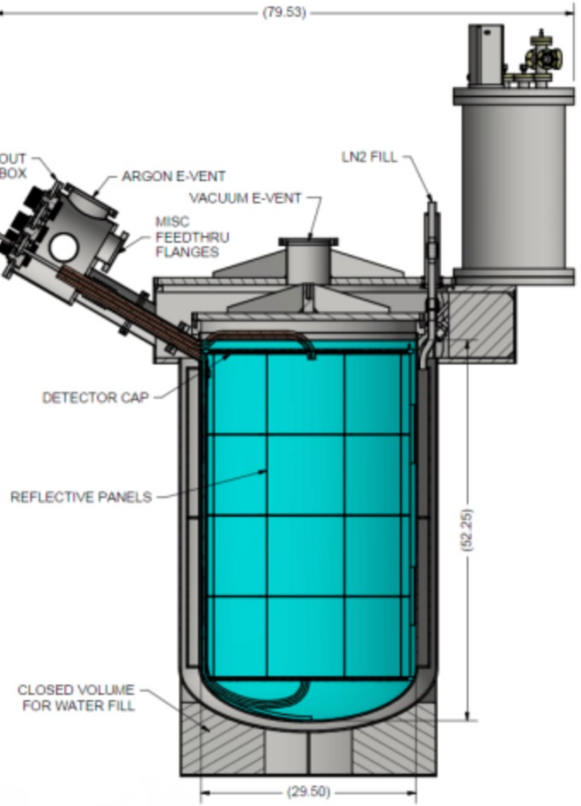
❗ Response particle dependent

❗ Energy resolution: light yield low

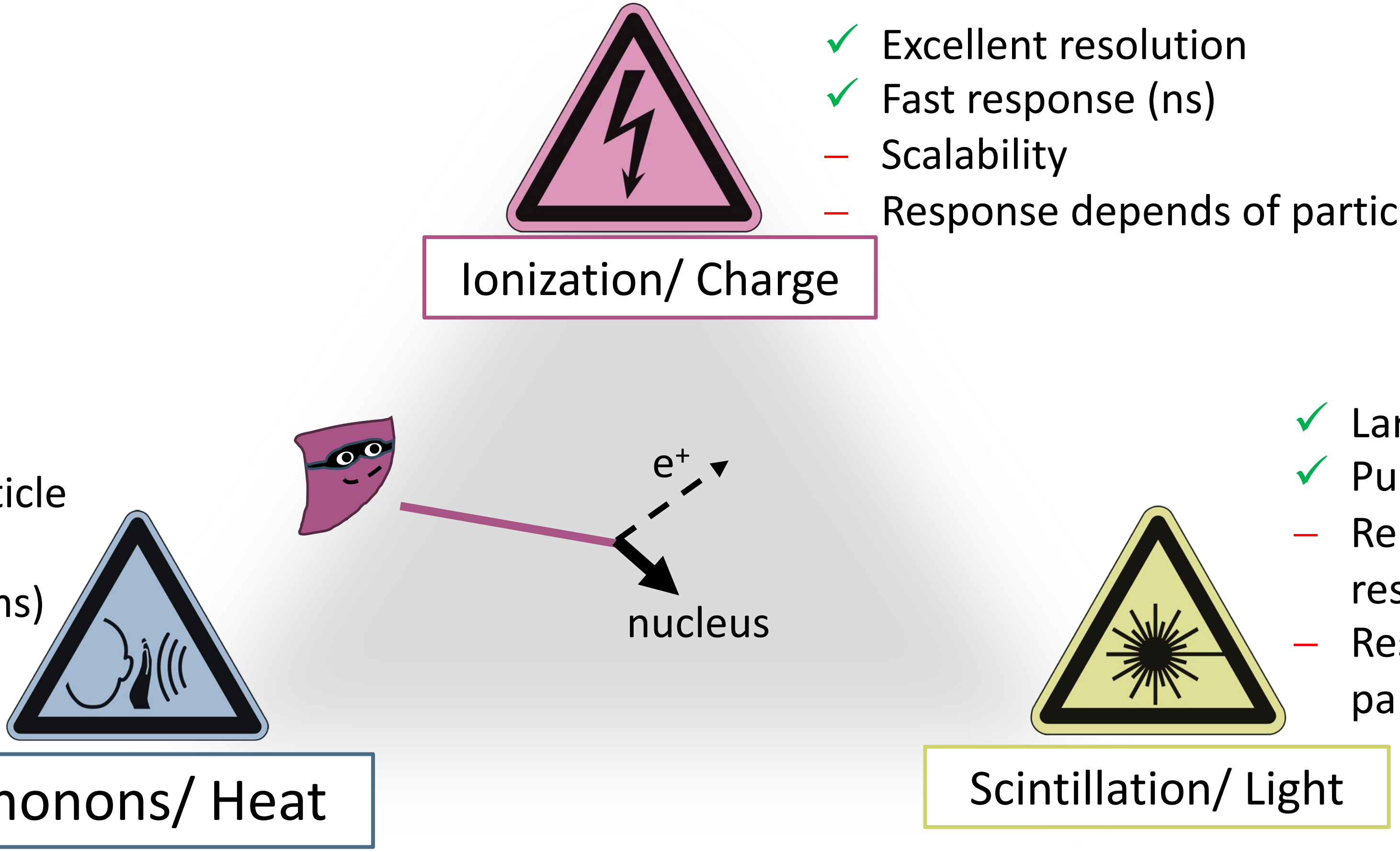








The Observables – (some) Pro's and Con's



Ionization/ Charge

- ✓ Excellent resolution
- ✓ Fast response (ns)
- – Scalability
- – Response depends of particle type

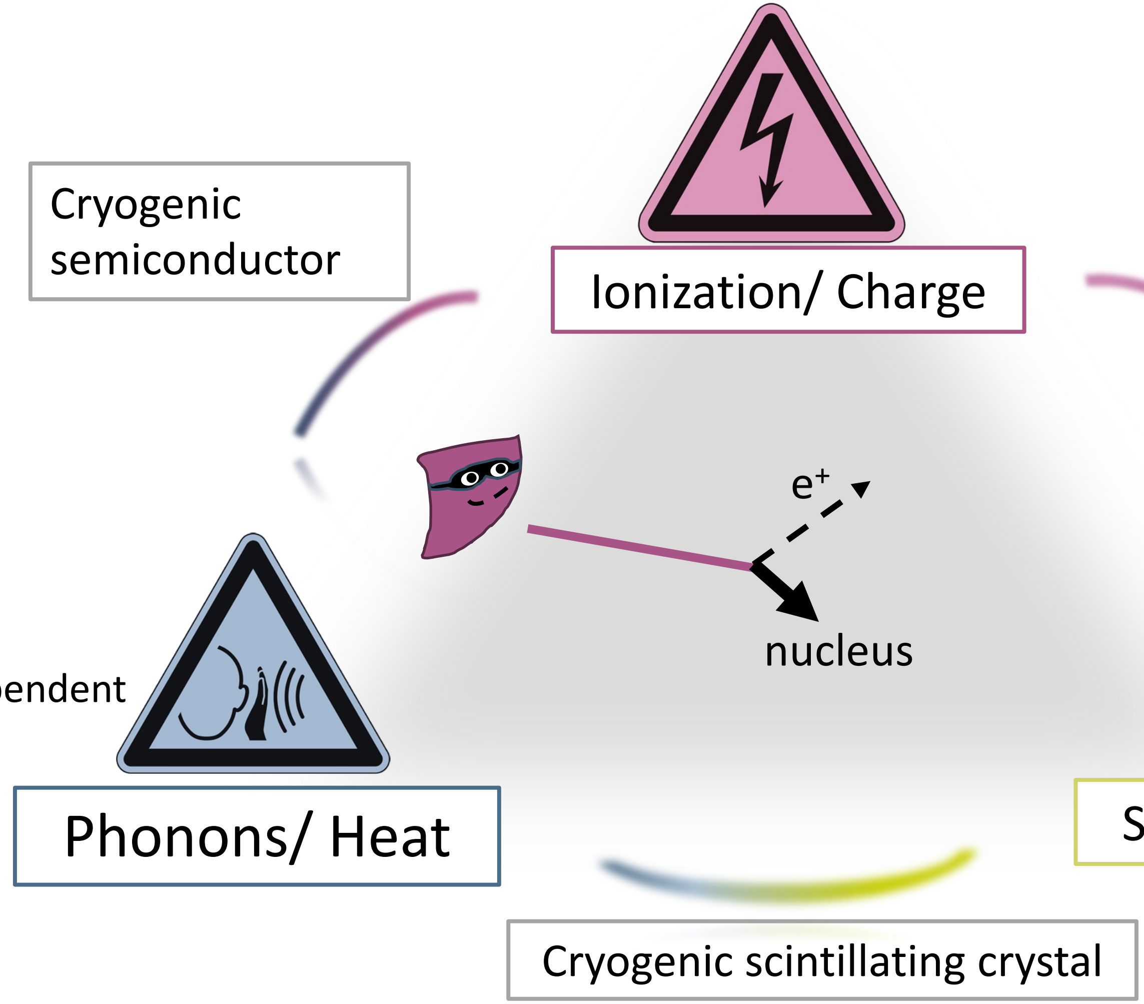
Phonons/ Heat

- ✓ Excellent resolution
- ✓ Response (nearly) independent of particle type
- – Slow response (us-ms)
- – Scalability

Scintillation/ Light

- ✓ Large masses possible
- ✓ Pulse shape discrimination
- – Relatively poor energy resolution
- – Response depends on particle type

Combing channels yields background discrimination



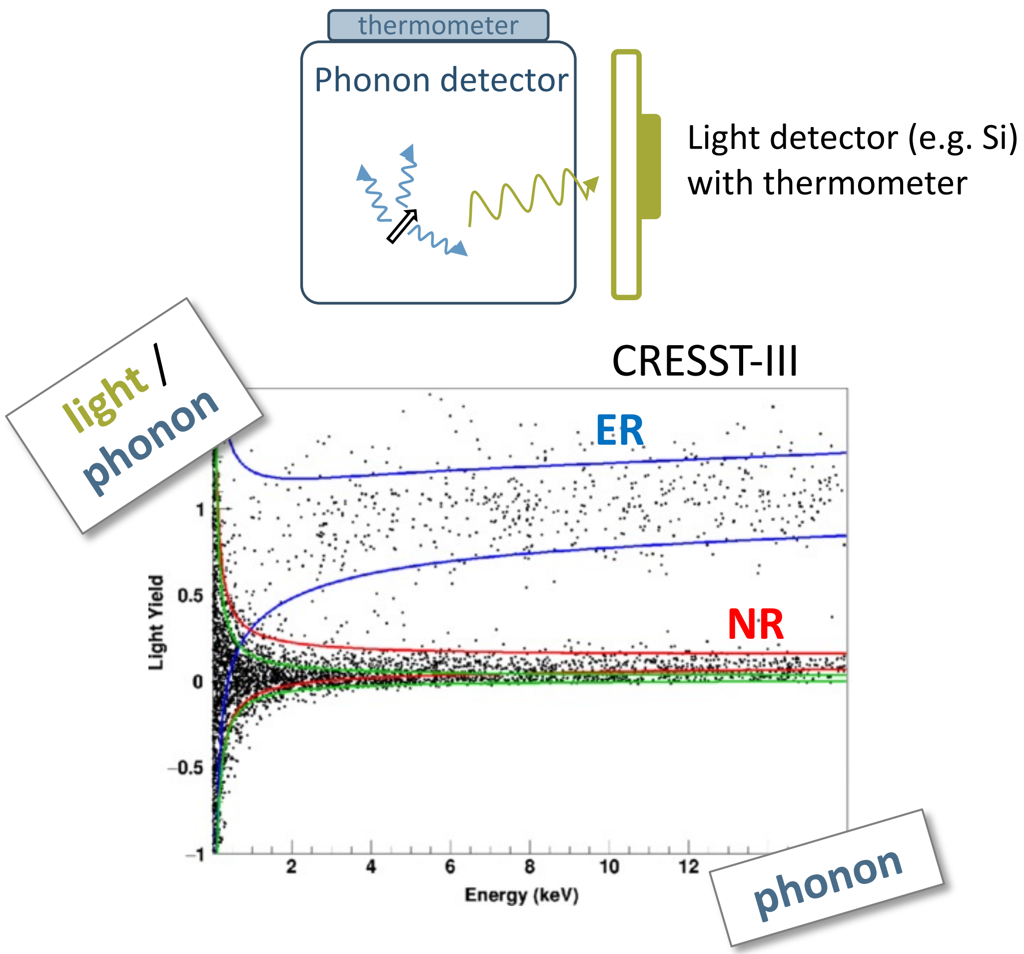
Ionization and scintillation typically depend on dE/dx, i.e. they are

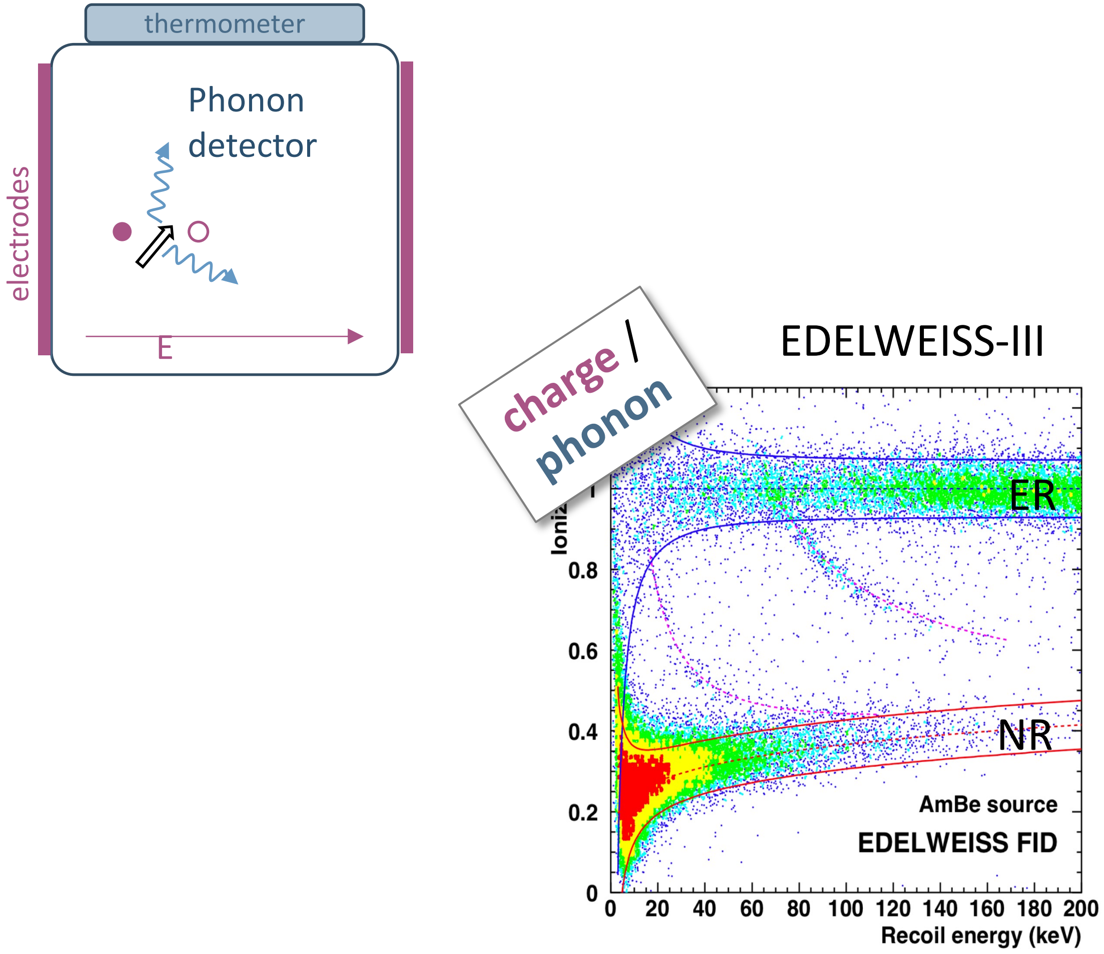
- energy and
- particle

dependent

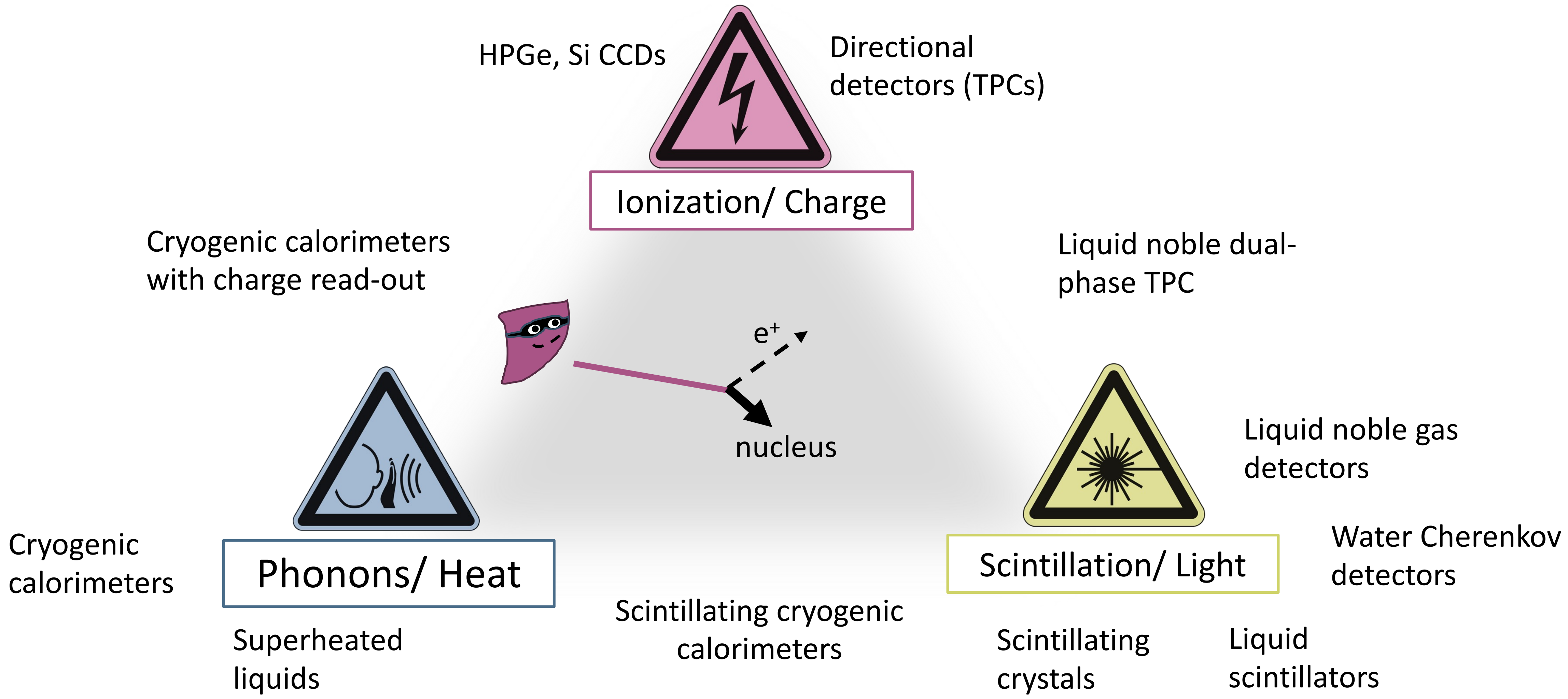
Phonons measure full energy, (nearly) independent of particle type

Combing channels yields background discrimination





Different Detector Types



Part I – Principles of Neutrino Detection

How do we detect neutrinos?

- Neutrinos interact via the weak force only
- We measure the (charged) particles produced in the neutrino interaction with matter
- Count the number of neutrino events given by $N_{\upsilon} = N * \int \phi(E_{\upsilon})\sigma(E_{\upsilon})dE_{\upsilon}$

How was the neutrino discovered?

- In 1956 by Cowen and Reines, Project Poltergeist
- The neutrino was detected via inverse beta decay
- Unique signature: coincident signal of positron and neutron capture

Which techniques are used to detect particles?

- Heat/phonon measure full recoil energy with excellent energy resolution/ threshold
- Ionization gives very good energy resolution
- Liquid scintillation detectors build large neutrino detectors
- Combination of channels provides background discrimination

Outline

- Part 1 - Principles of neutrino detection
  - Neutrino interactions
  - Detection of charged particles
  - Discovery of the neutrino
  - Principles of particle detectors: heat, ionization, scintillation

- **Part 2 – Neutrino Experiments**
  - Neutrino Oscillations with JUNO – large mass scintillator experiment
  - CEvNS detection – COHERENT and NUCLEUS