

Detector Concepts in Low-Energy Neutrino Physics

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Neutrinos
Dark Matter
Messengers



TUM
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Outline

- Part 1 - **Principles of neutrino detection**

- Neutrino interactions
- Discovery of the neutrino
- Principles of particle detectors: heat, ionization, scintillation



Where we
stopped yesterday

- Part 2 – Neutrino Experiments

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

Measuring the recoiling particles

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



Ionization

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



e^+
nucleus

- O(meV)



Phonons/ Heat



Light

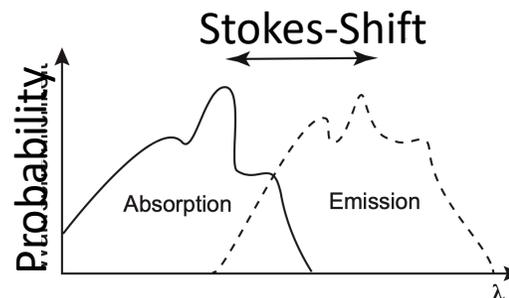
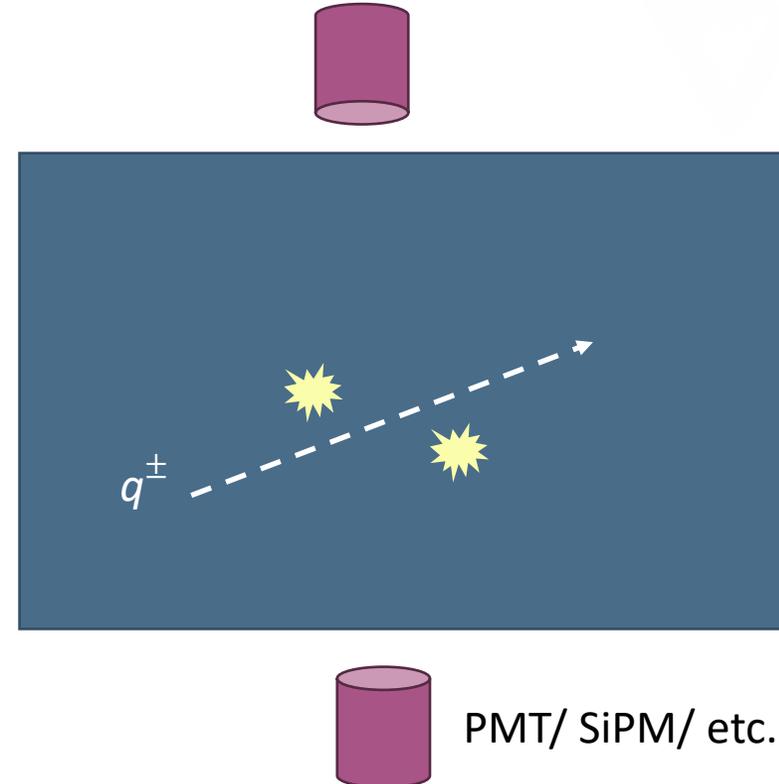
Scintillator:

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

Light/ Scintillation



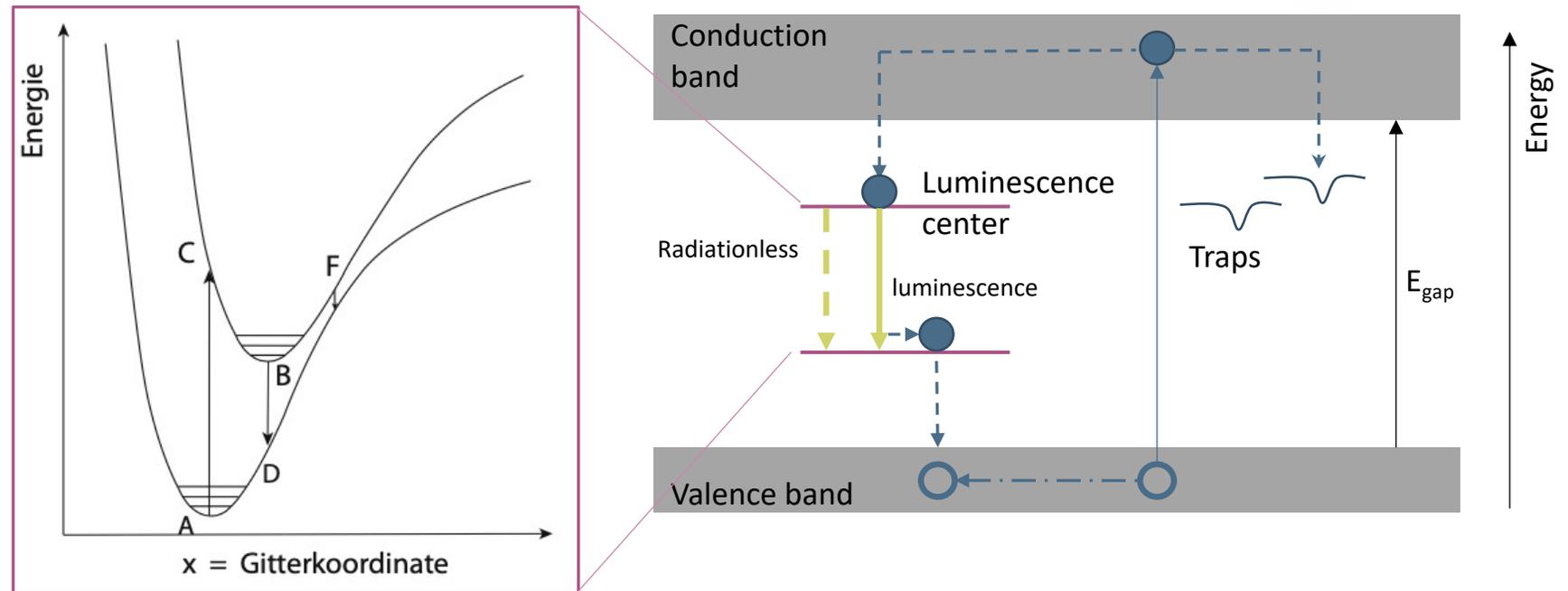
- Scintillation = creation of luminescence by absorption of ionization radiation
- Subsequent de-excitation releases scintillation photons
- Materials:
 - Inorganic crystals
 - Organic scintillators (liquid, plastic)
 - Noble gas liquids
- Typically only 1-10 % of recoil converted to light



Inorganic Scintillators



- Band structure of the lattice changed by activation centers

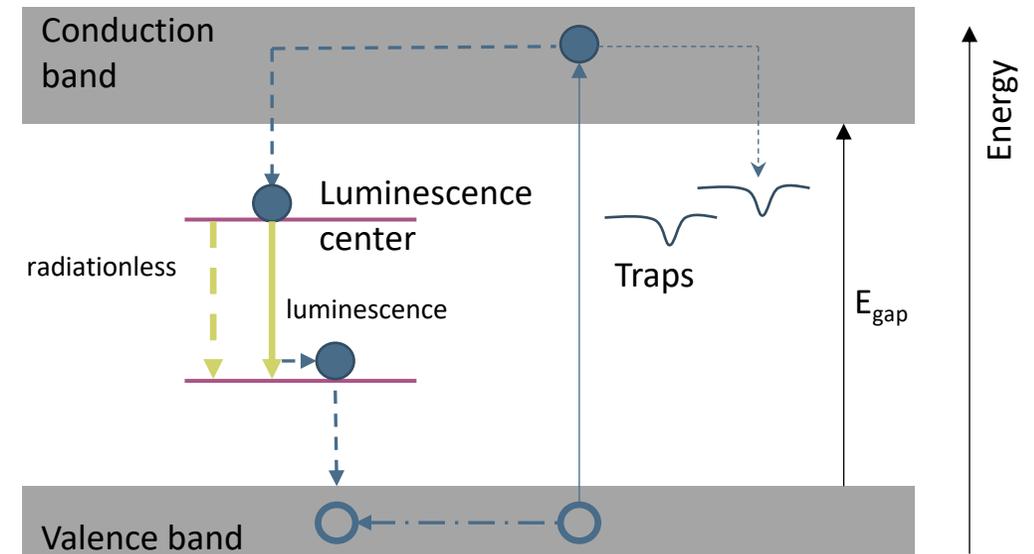


- AC: Absorption
- CB: thermalization
- BD: luminescence
- F: quenching (radiationless)

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 ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$)
- Typically 10% scintillation efficiency -> good energy resolution
- Crystals -> low mass
- Commercially available
- Detector response energy and particle dependent

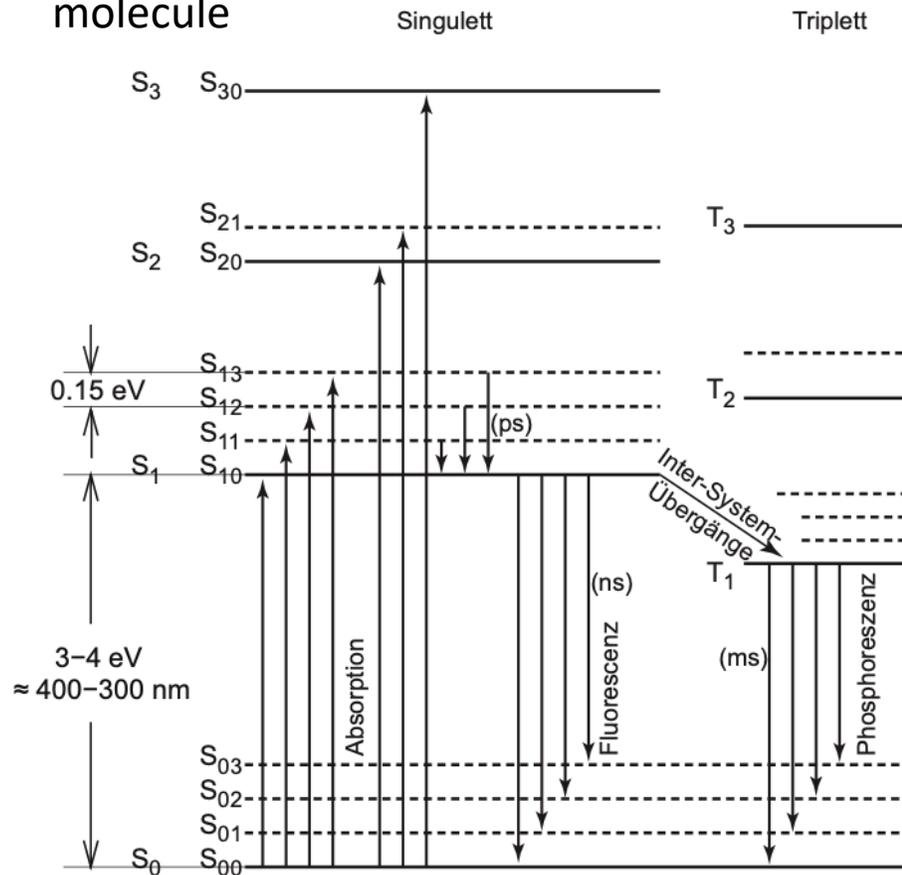


Organic Scintillators

aromatic hydrocarbon compounds, (C-H)



Energy levels of “free” valence electrons of the molecule



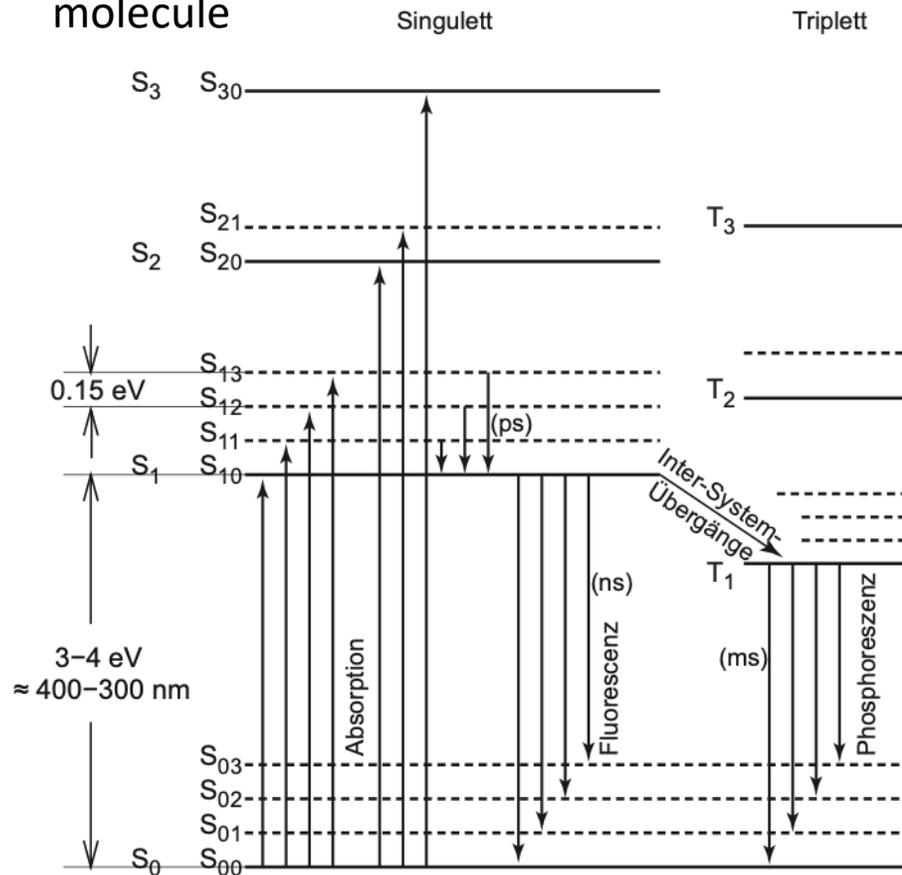
- Transition from T₁ to S₀ forbidden
 - Phosphorescence (ms)
 - Delayed fluorescence (μ s-ms)

Organic Scintillators

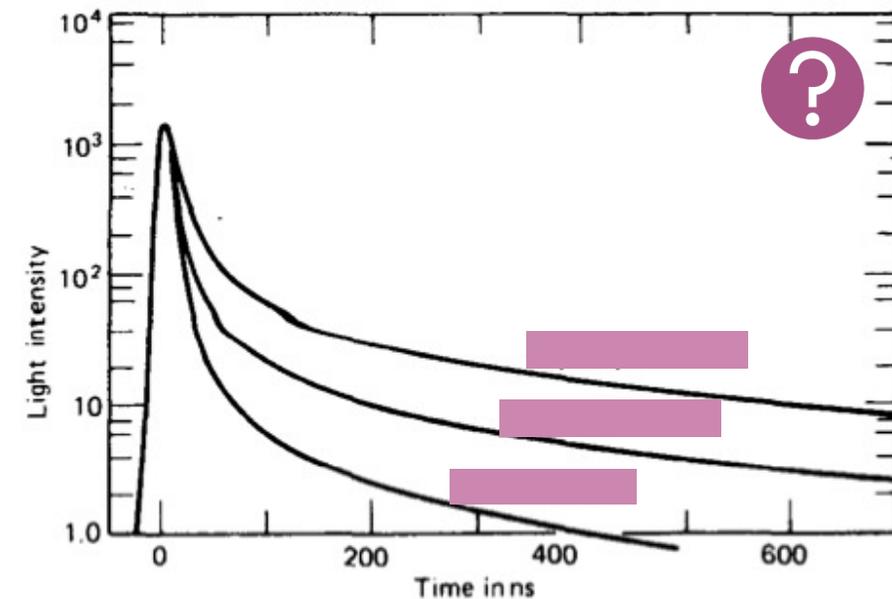
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Energy levels of “free” valence electrons of the molecule



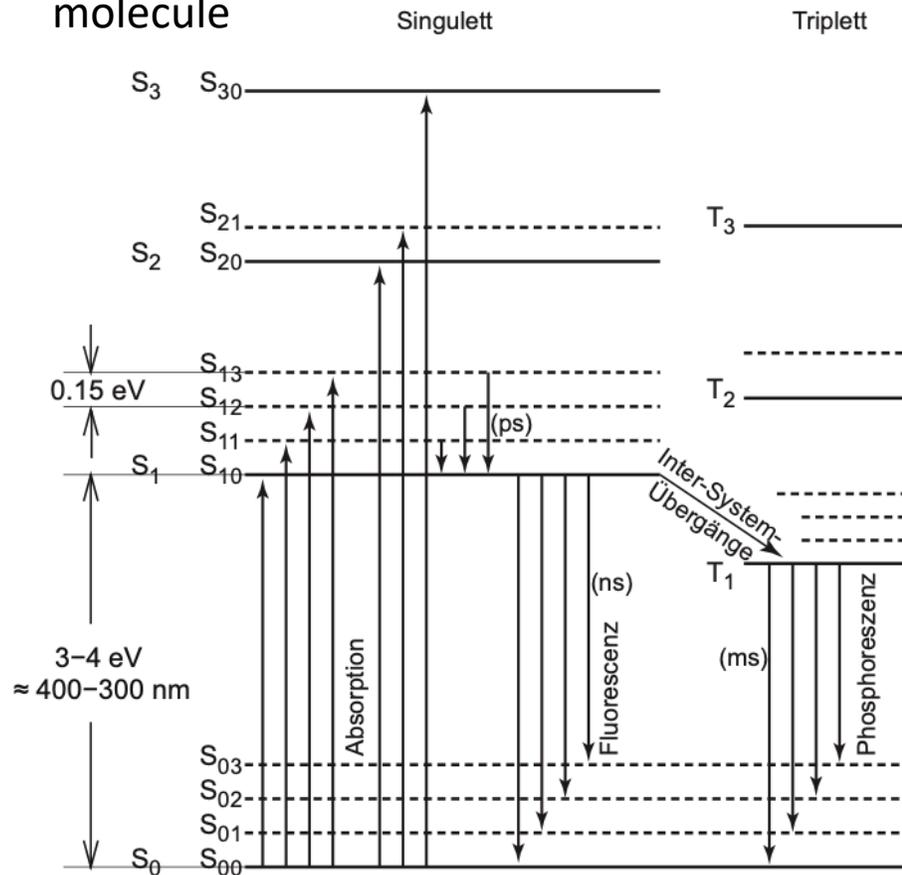
- Transition from T_1 to S_0 forbidden
 - Phosphorescence (ms)
 - Delayed fluorescence (μ s-ms)
- The population of S or T depends on dE/dX
 - > used for PSD



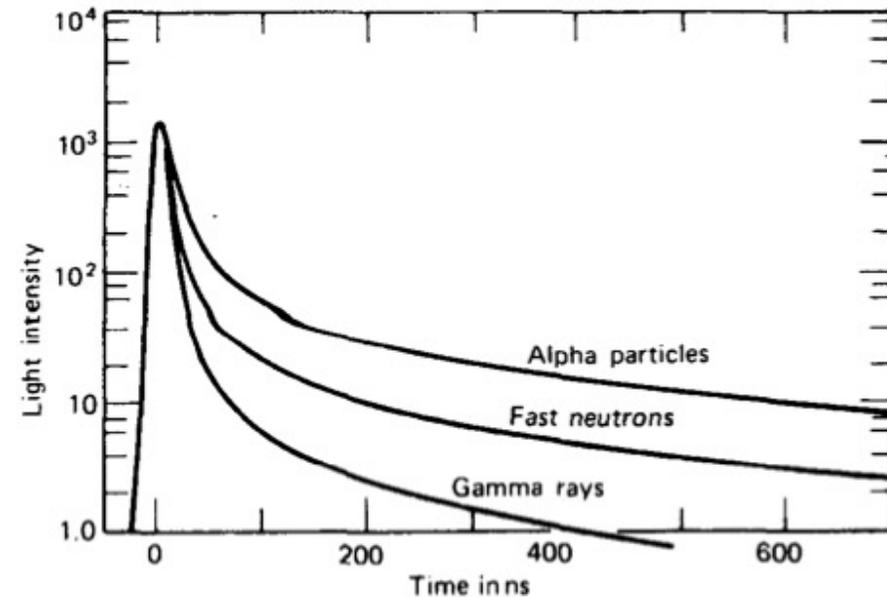
Organic Scintillators



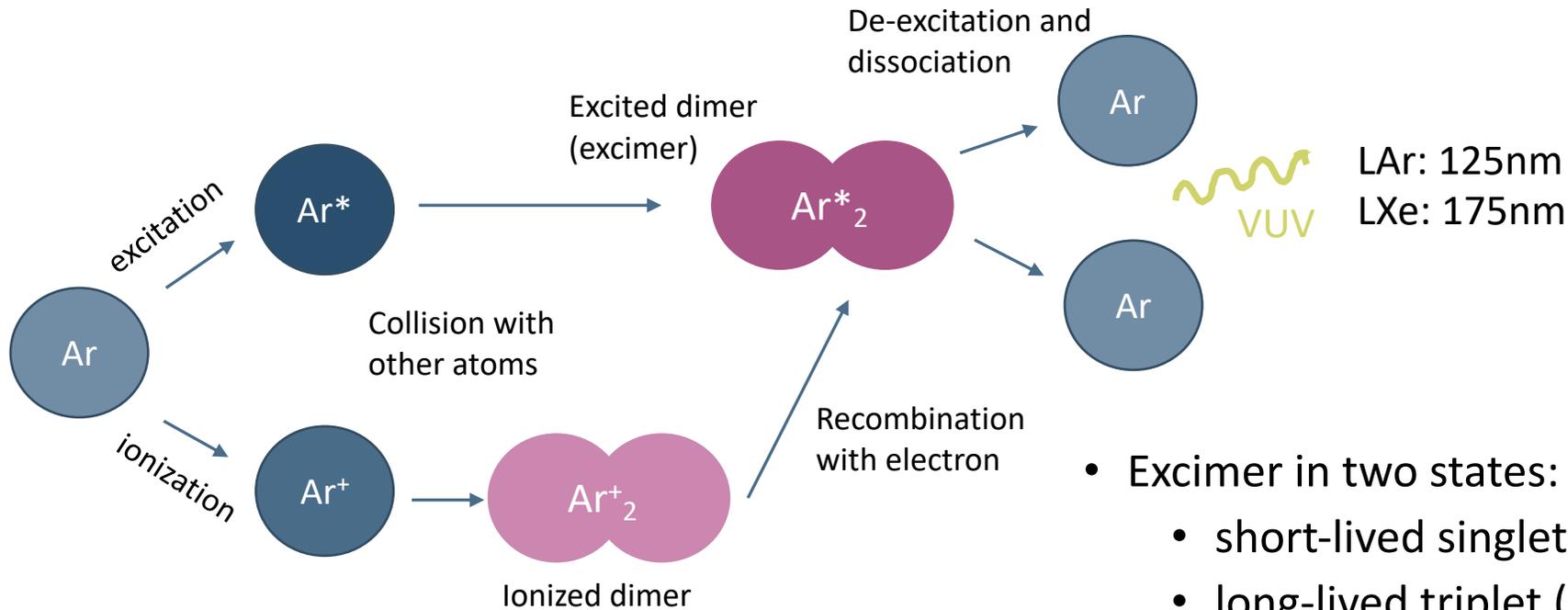
Energy levels of “free” valence electrons of the molecule



- 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



Liquid Noble Gases



- Excimer in two states:
 - short-lived singlet (τ_s)
 - long-lived triplet (τ_l)
- Population of states depends on $dE/dx \rightarrow$ PSD
- For LAr $\tau_s = 6\text{ns}$ and $\tau_l = 1.6\mu\text{s}$
- For LXe $\tau_s = 4\text{ns}$ and $\tau_l = 22\text{ns}$

Some Examples for Scintillators

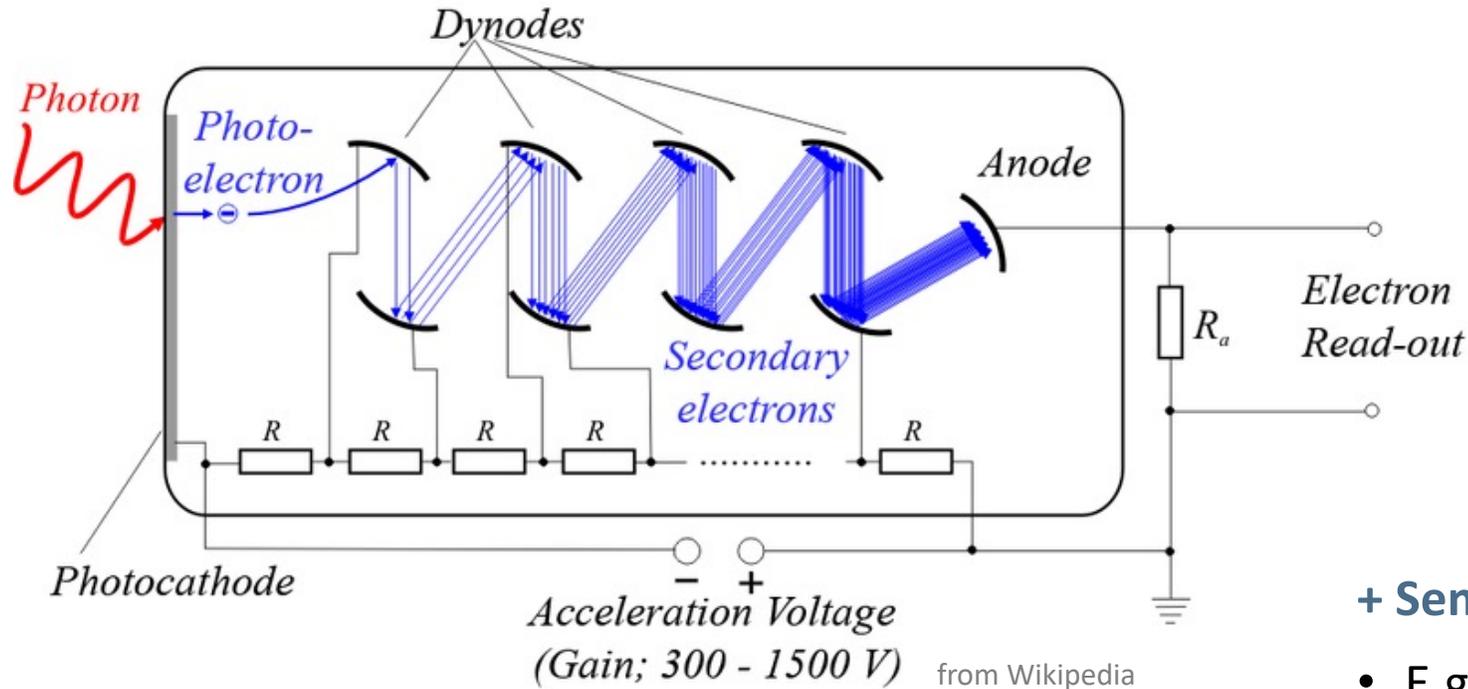
Wishlist:

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

	Organic Scintillators	Inorganic Crystals	Liquid Noble Gases
	BC-408	NaI(Tl)	LAr
Density	$\rho = 1 \text{ g/cm}^3$	$\rho = 3.7 \text{ g/cm}^3$	$\rho = 1.4 \text{ g/cm}^3$
Decay time	2.1 ns	0.25 μs	5 ns / 1.6 μs
Photons/ MeV	2×10^2	4×10^4	4×10^4
Wavelength maximum [nm]	423	410	125
Advantages	<ul style="list-style-type: none"> • Very fast • Easily shaped • PSD • Cheap 	<ul style="list-style-type: none"> • High light yield & good energy resolution • High density 	<ul style="list-style-type: none"> • High light yield • Fast • PSD (LAr)
Disadvantages	<ul style="list-style-type: none"> • Lower light yield 	<ul style="list-style-type: none"> • Crystals (expensive) • T-dependence 	<ul style="list-style-type: none"> • Expensive • LAr intrinsic background • VUV light

Photosensors in a Nutshell

Photomultiplier Tube (PMT)



Signal output:

- Quantum efficiency $O(25\%)$
- Coverage

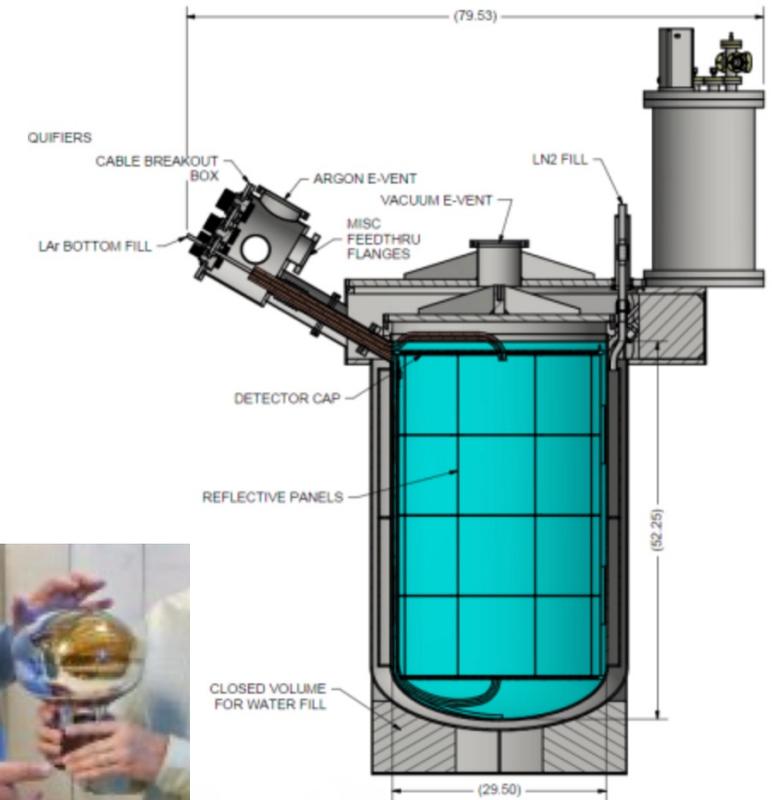
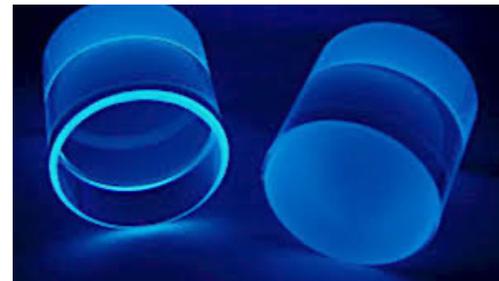
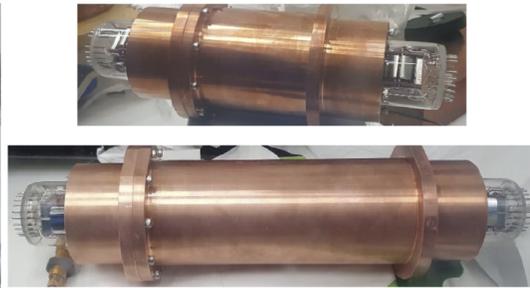
+ Semiconductor devices

- 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



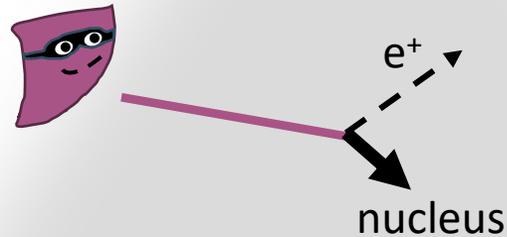
Ionization/ Charge

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

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



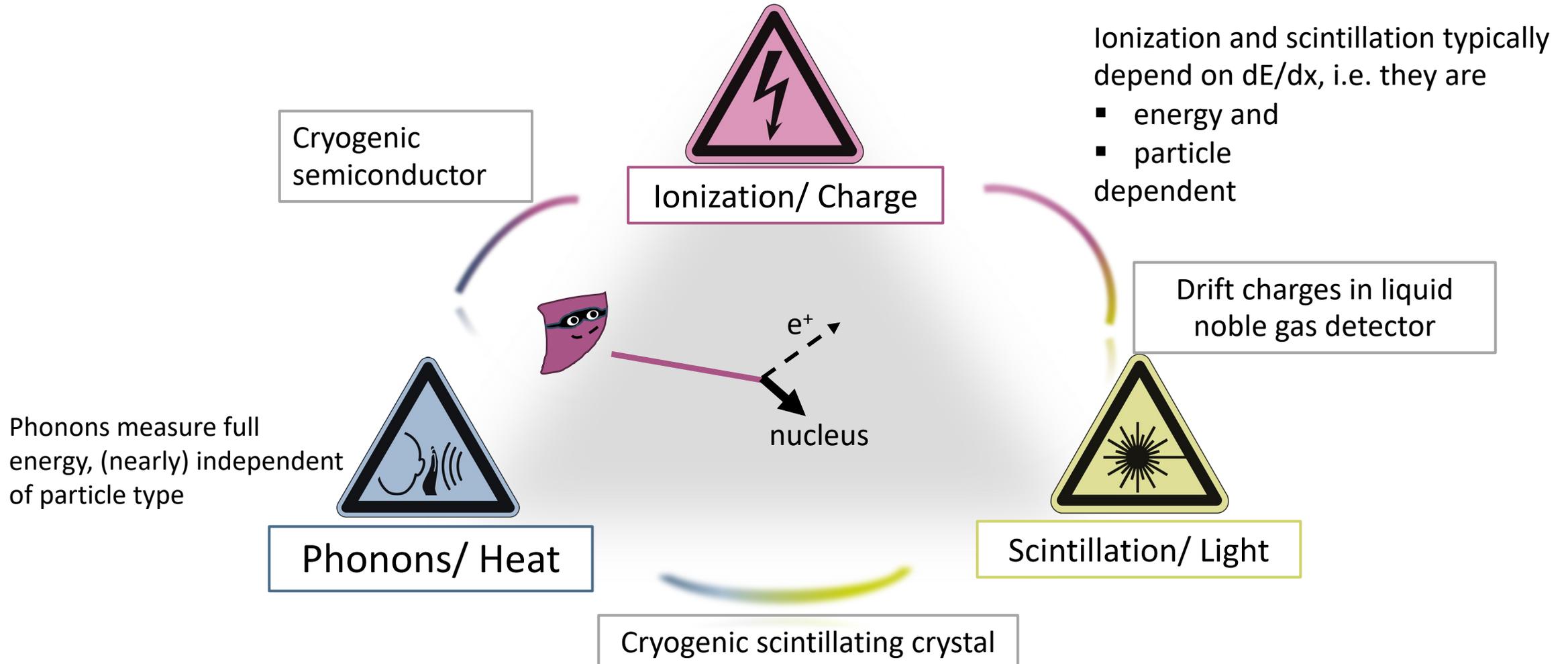
Phonons/ Heat



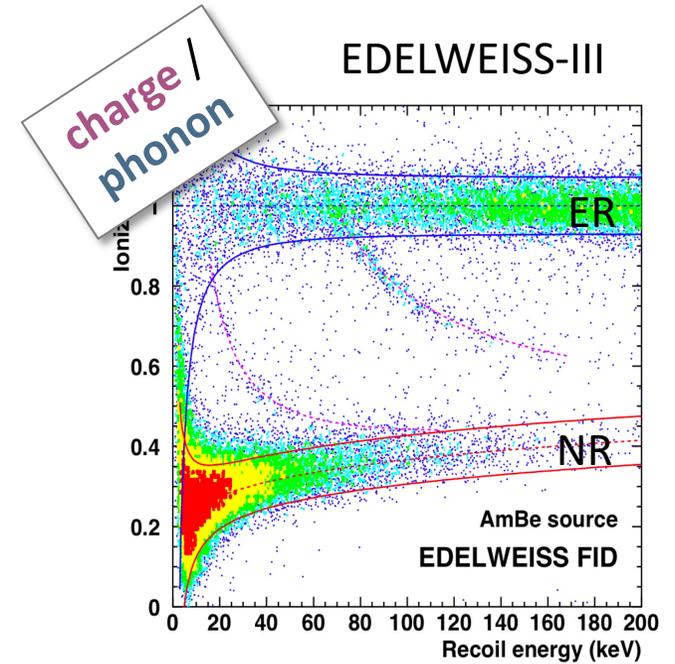
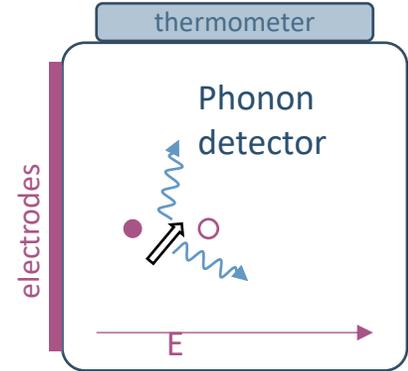
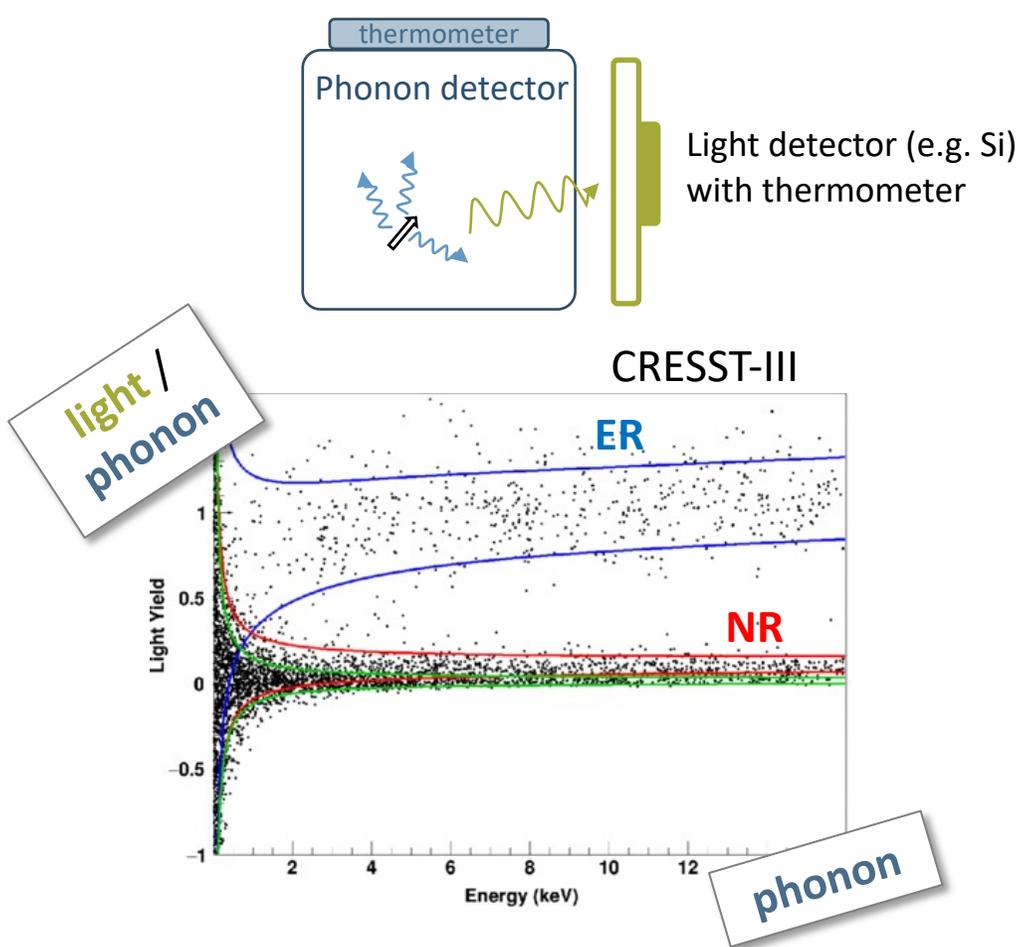
Scintillation/ Light

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

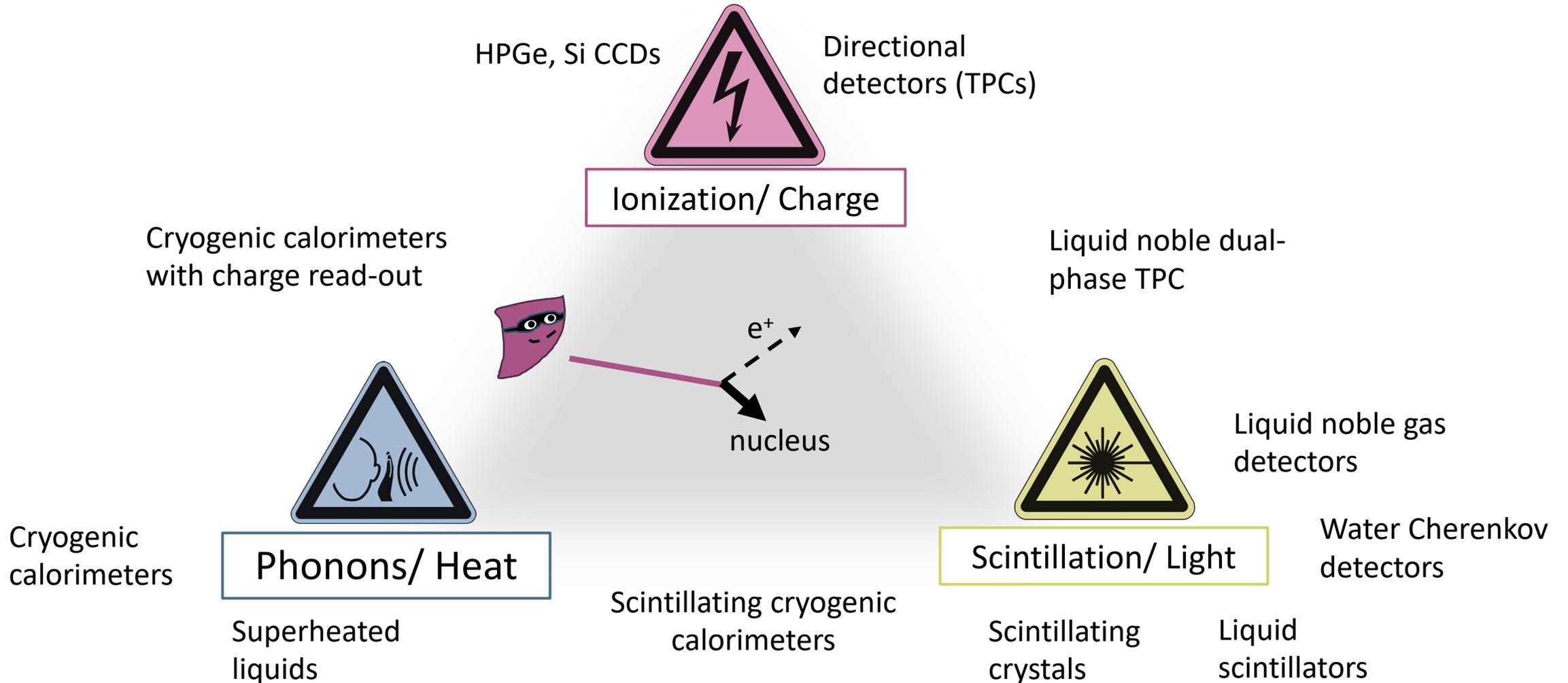
Combing channels yields background discrimination



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

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

Part II - Neutrino Detectors

How to measure neutrino and mass hierarchy oscillations?



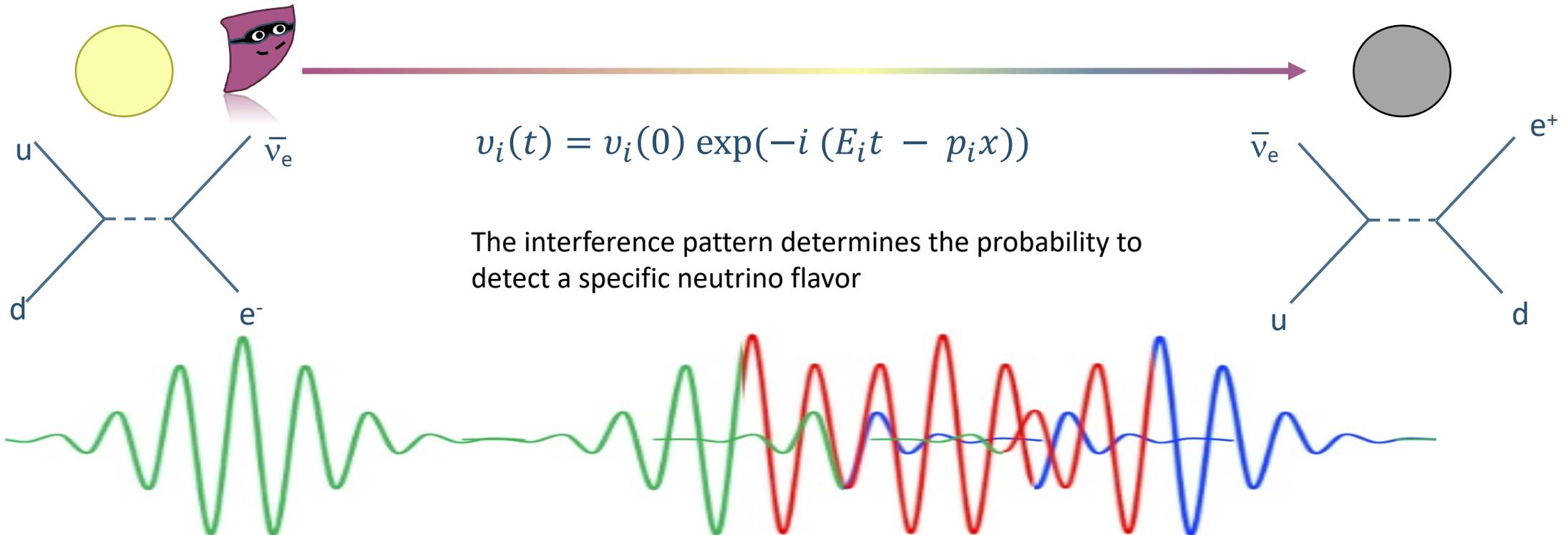
How to study coherent elastic neutrino-nucleus scattering (CEvNS)?



Neutrino Oscillation

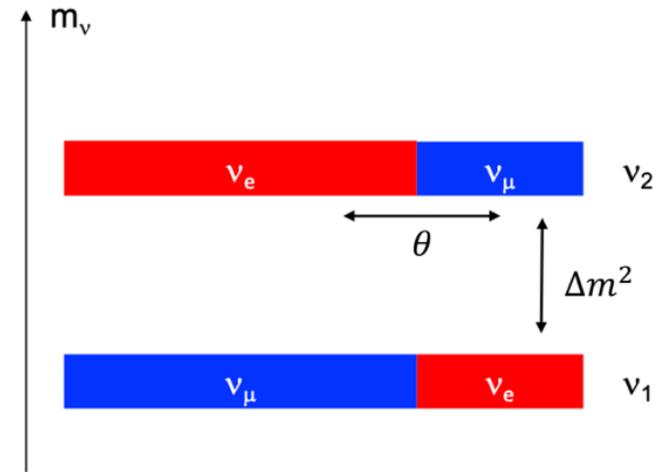
Neutrino source

Neutrino detector

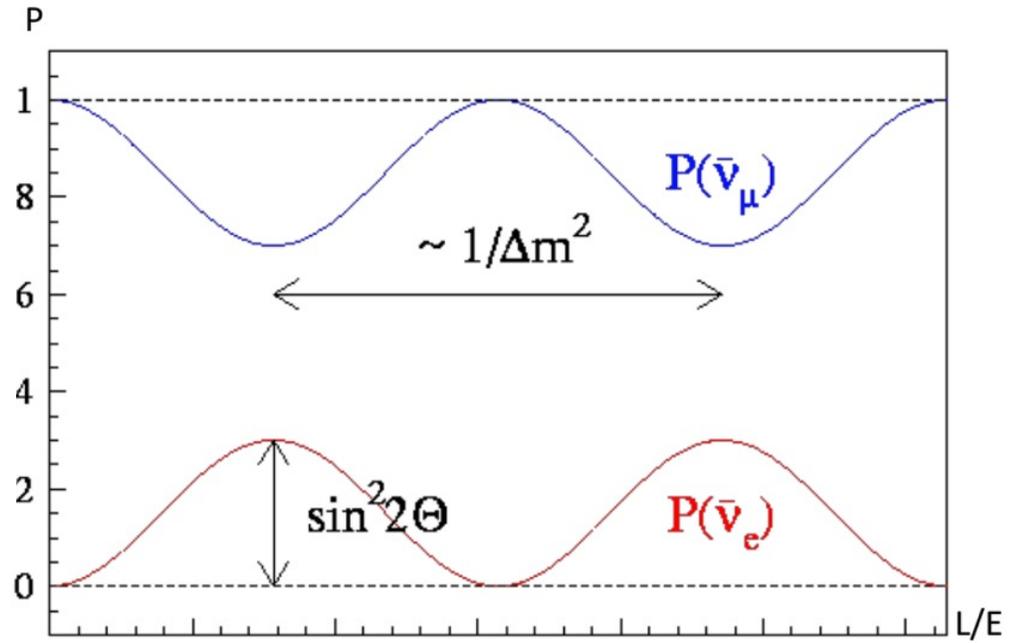


Two-flavor Picture

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2 \left(\frac{\Delta m^2 \cdot L_\nu}{E_\nu} \right)$$



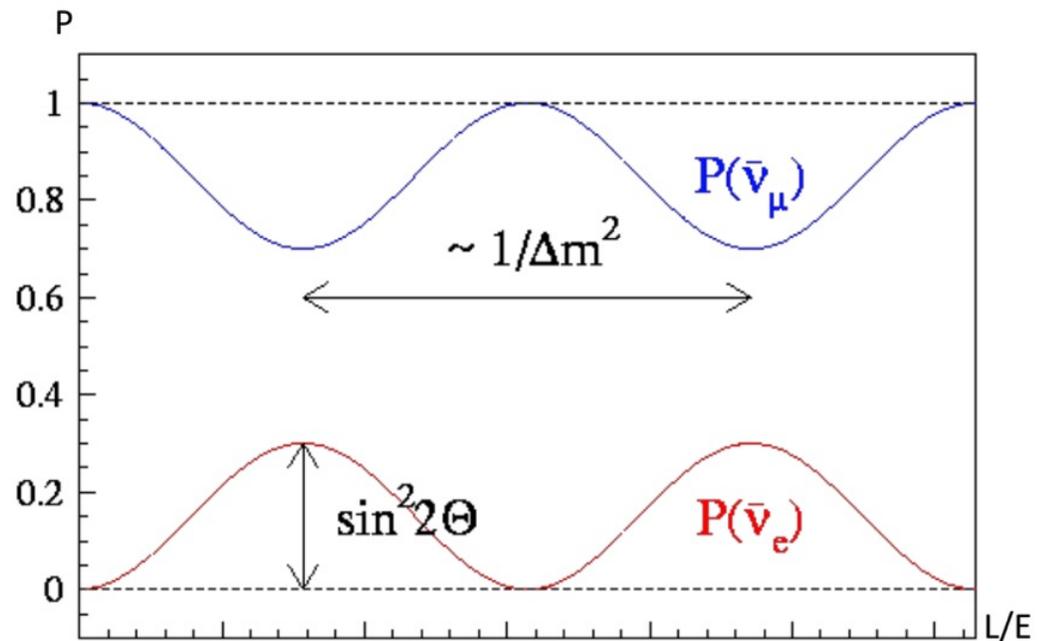
- θ : mixing angle
→ amplitude of oscillation
- $\Delta m^2 = m_2^2 - m_1^2$: mass difference square
→ frequency of oscillation
- L_ν : distance travelled from source
- E_ν : neutrino energy



slide adopted from S. Mertens

Two-flavor Picture

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2 \left(\frac{\Delta m^2 \cdot L_\nu}{E_\nu} \right)$$



3 scenarios:

- $L/E \ll 1/\Delta m^2$: detector too close to source, oscillations not yet developed
- $L/E \approx 1/\Delta m^2$: most sensitive region
- $L/E \gg 1/\Delta m^2$: oscillations on a scale which cannot be resolved by the detector

Neutrino Oscillation Parameters

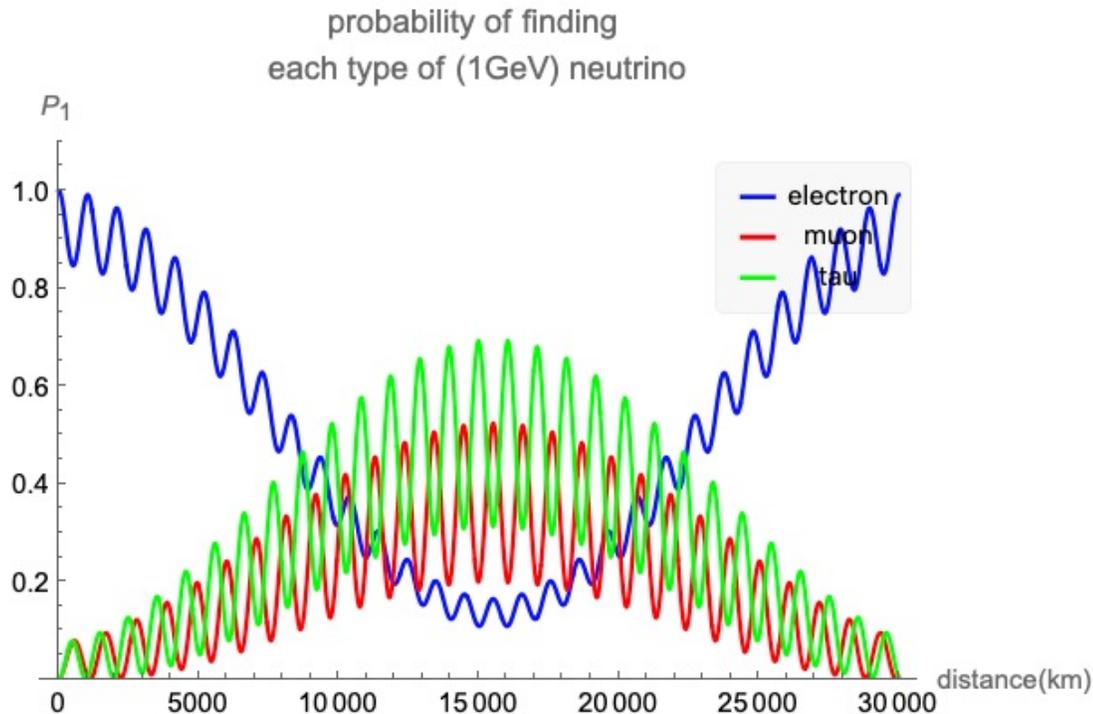
- Oscillation probability $P_{\alpha\beta}(t, \mathbf{x}) = \left| \sum_i U_{\alpha i} U_{i\beta}^* e^{-i\left(\frac{m_i^2 t}{2p}\right)} \right|^2$
- PMNS Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric mixing}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{reactor mixing}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar mixing}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Mixing angles $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$ determine the amplitude
- Mass differences and energy determine the oscillation length

Measuring Neutrino Oscillations

<https://demonstrations.wolfram.com/NeutrinoOscillations/>



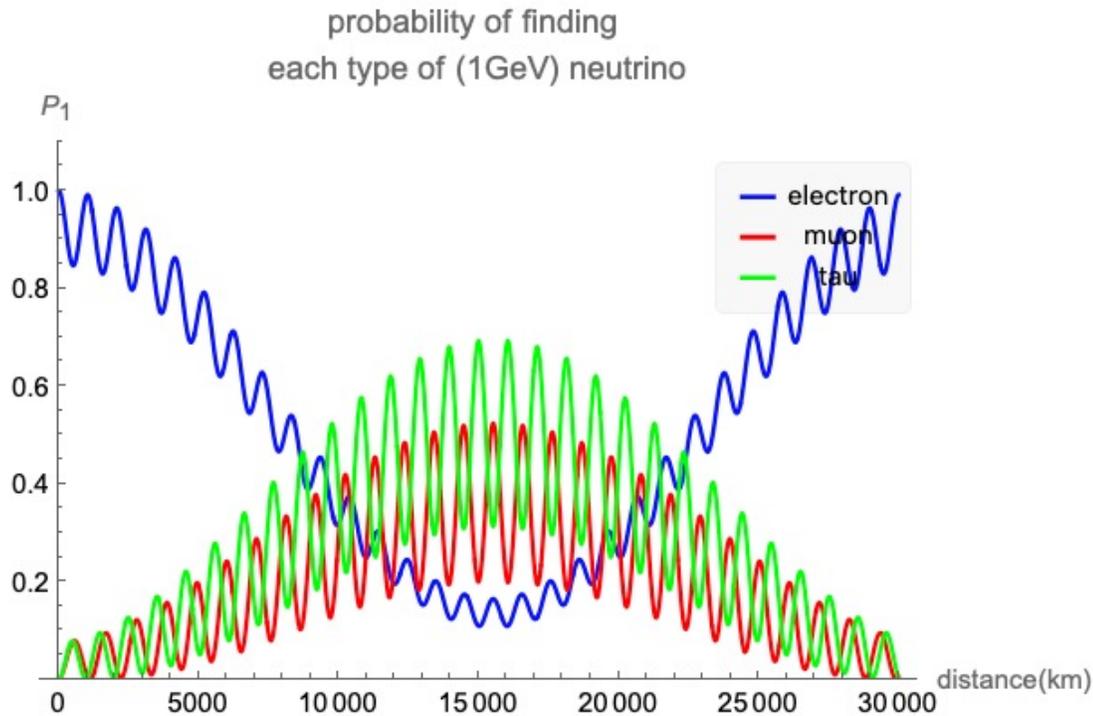
- **Appearance:** search for new flavors which are not produced in the neutrino source
- **Disappearance:** search for reduction of the expected (total) neutrino flux and/or change of spectral shape

What are the typical neutrino experiments/ sources used here?



Measuring Neutrino Oscillations

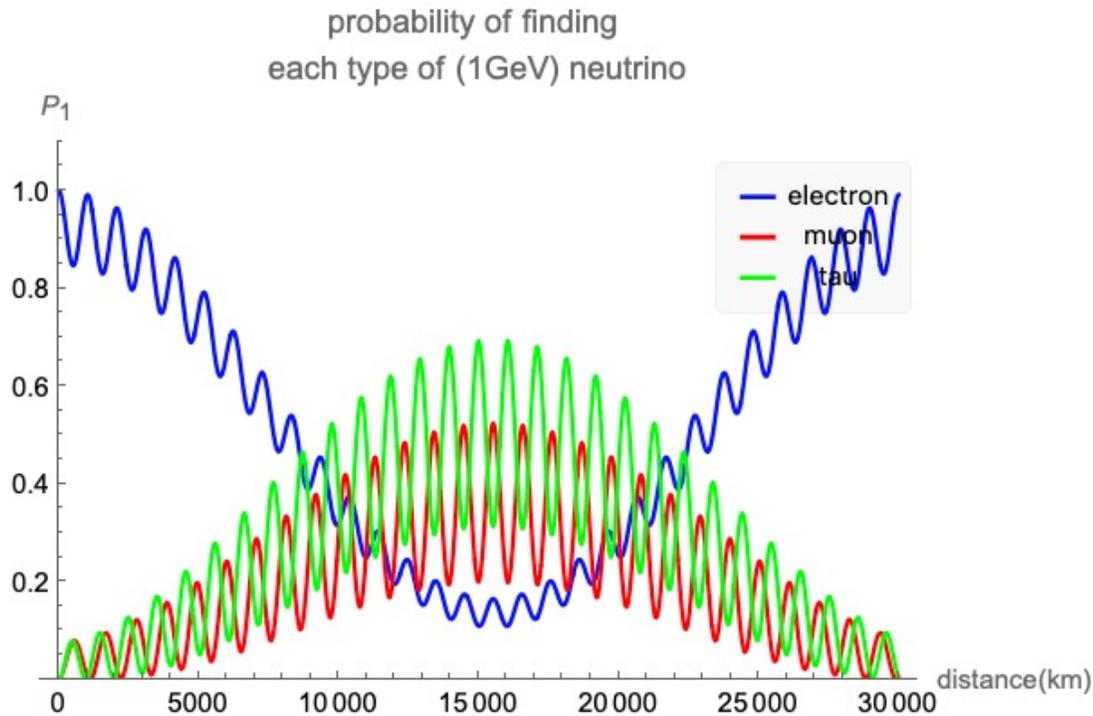
<https://demonstrations.wolfram.com/NeutrinoOscillations/>



- **Appearance:** search for new flavors which are not produced in the neutrino source
 - Accelerator neutrinos since energies high enough to produce charged leptons
- **Disappearance:** search for reduction of the expected (total) neutrino flux and/or change of spectral shape
 - Solar and reactor neutrinos of MeV energies since energy not sufficient to produce muon or tau leptons in detector

Neutrino Oscillations

<https://demonstrations.wolfram.com/NeutrinoOscillations/>



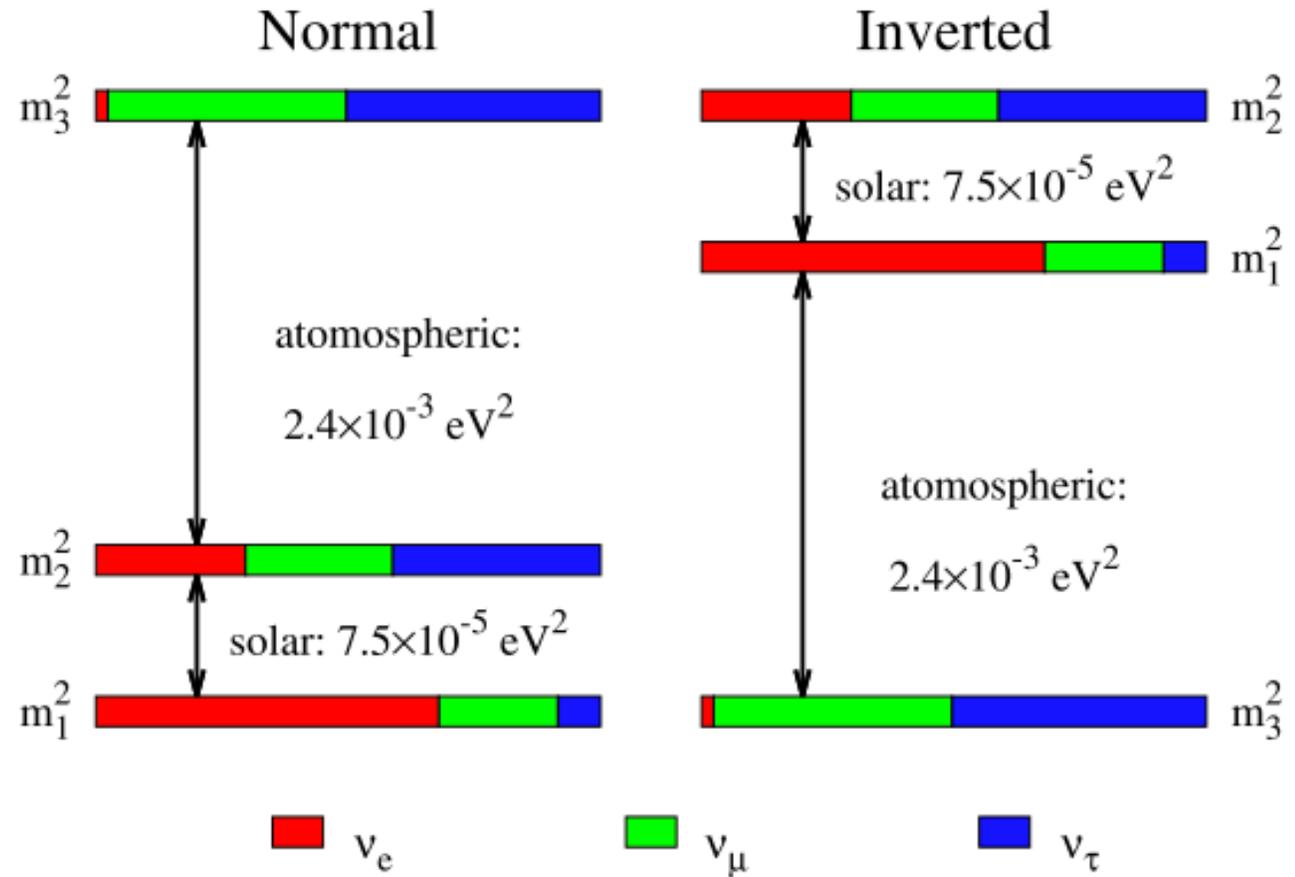
*With smart choice of neutrino
source (energy) and distance*

- Amplitude
 - $\theta_{12} \approx 33^\circ$ (large $e \rightarrow \mu$)
 - $\theta_{23} \approx 48^\circ$ (large $\mu \rightarrow \tau$)
 - $\theta_{13} \approx 9^\circ$ (small oscillation)
- Oscillation frequency
 - $\Delta m^2_{\text{atm}} = \Delta m^2_{23} \approx \Delta m^2_{13} \approx 3 \cdot 10^{-3} \text{ eV}^2$ (high)
 - $\Delta m^2_{\text{sol}} = \Delta m^2_{21} \approx 8 \cdot 10^{-5} \text{ eV}^2$ (small)

Mass Hierarchy – one of the Unknowns

- **Mass hierarchy**

Sign of Δm^2_{atm}



How to measure neutrino mass ordering?

- Survival probability of reactor electron anti-neutrinos

$$P_{ee} = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\Delta_{21} \quad \rightarrow$$

Oscillations not yet developed at 1-2 km to reactors

$$P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\Delta_{31}$$

$$P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\Delta_{32}$$

So far: reactor neutrinos
assume $\Delta m^2_{13} \approx \Delta m^2_{23}$

$$\Delta_{ij} = \frac{|m_i^2 - m_j^2|}{L/E}$$

How to measure neutrino mass ordering?

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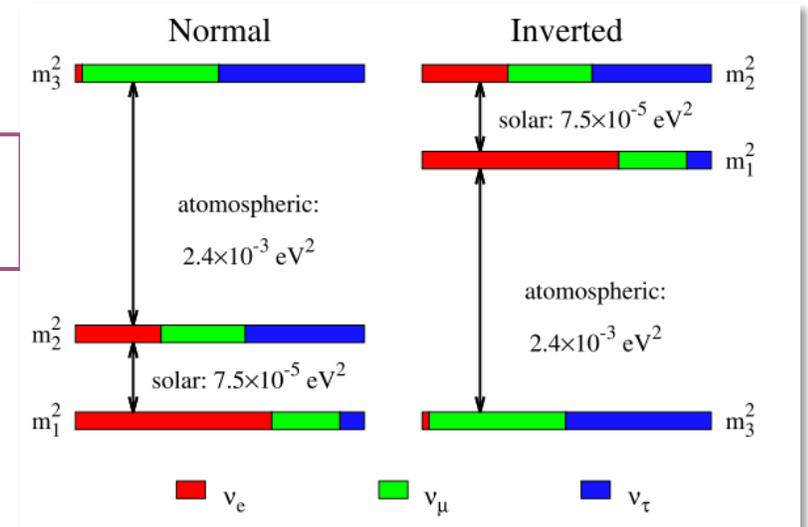
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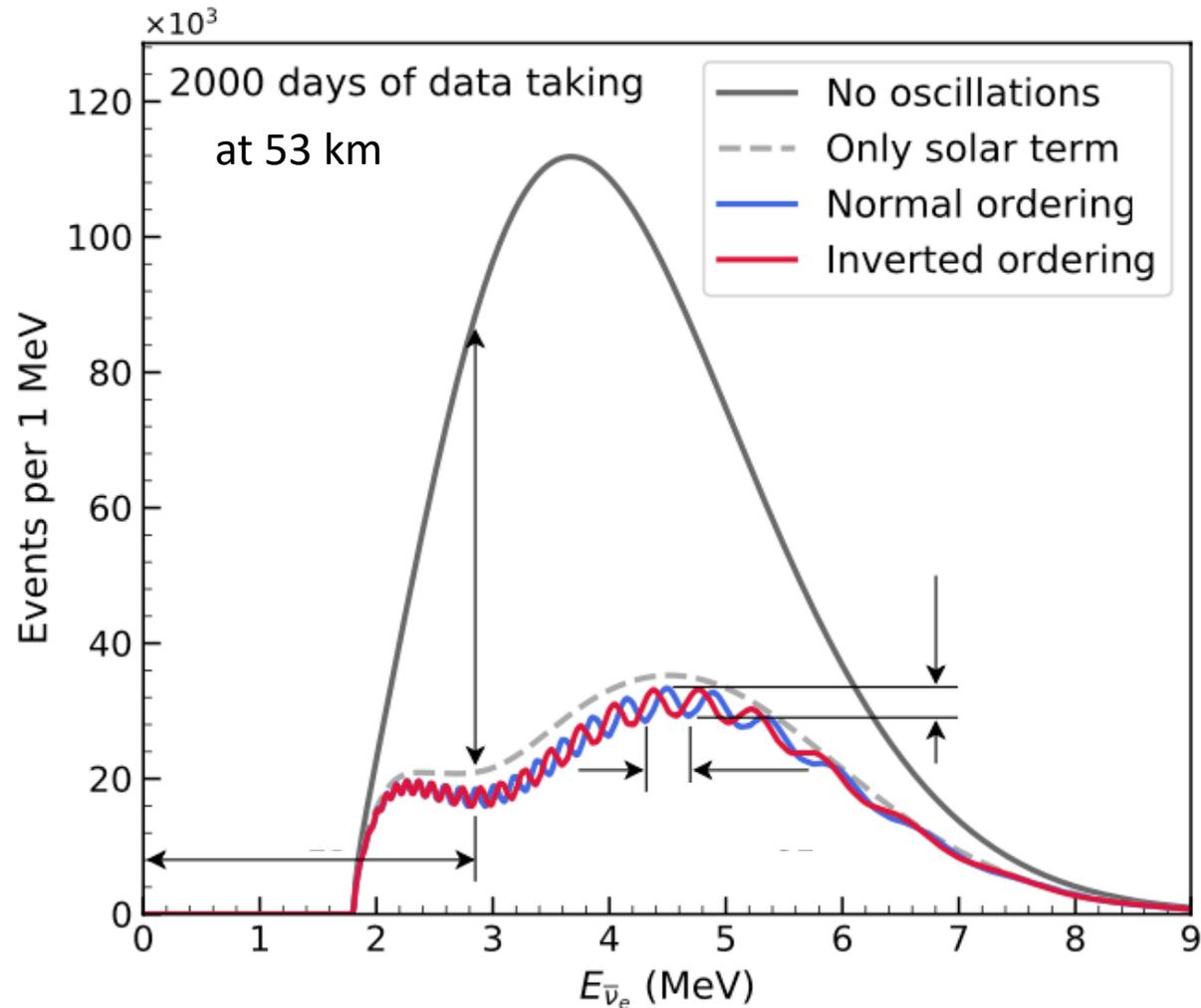
At ~60 km

Dominant term

Ordering of $\Delta m^2_{13} \gtrless \Delta m^2_{23}$



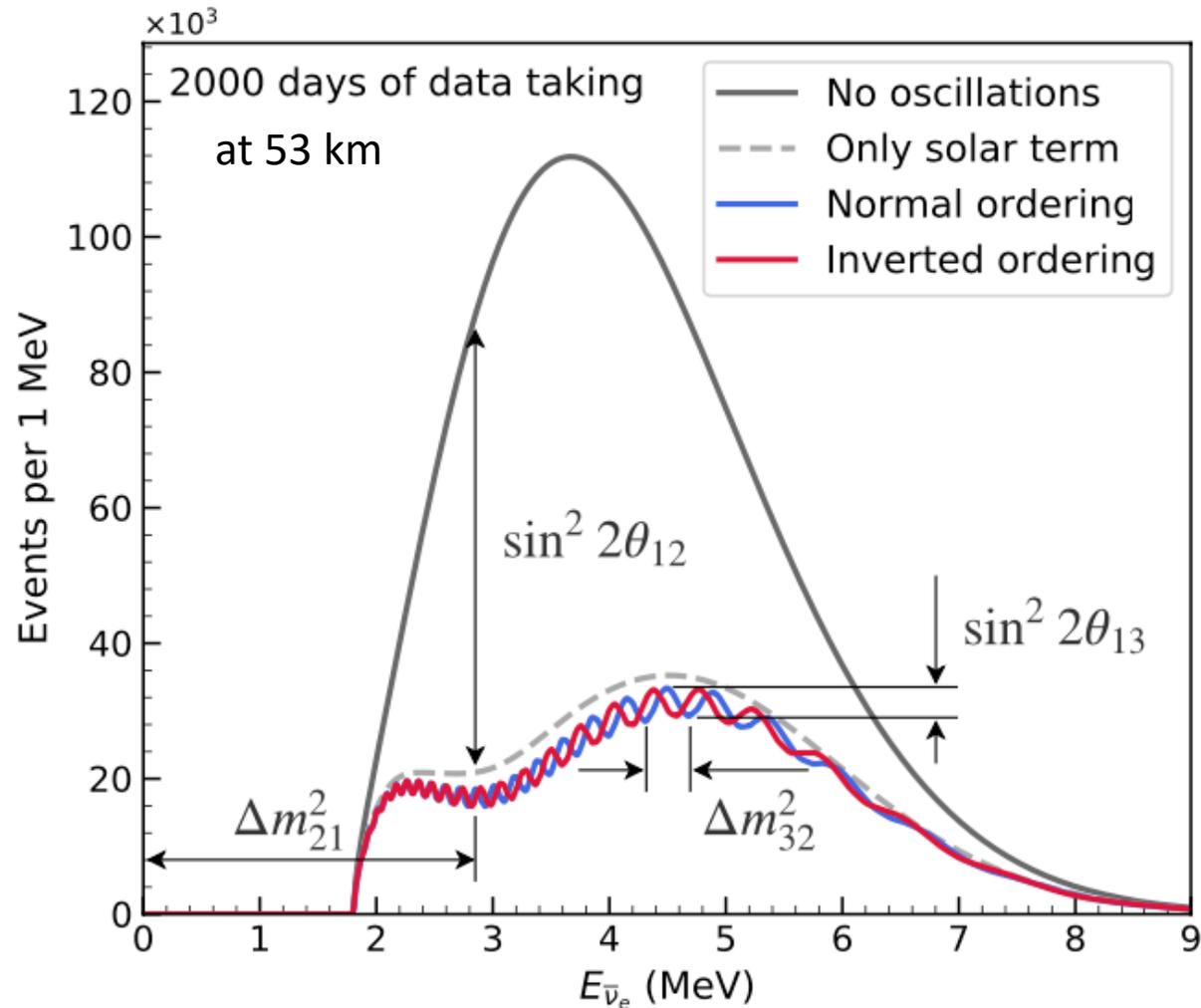
Determining the mass hierarchy with JUNO



Which parameters do we measure?
What are the requirements for our neutrino detector?



Determining the mass hierarchy with high JUNO



Key parameters:

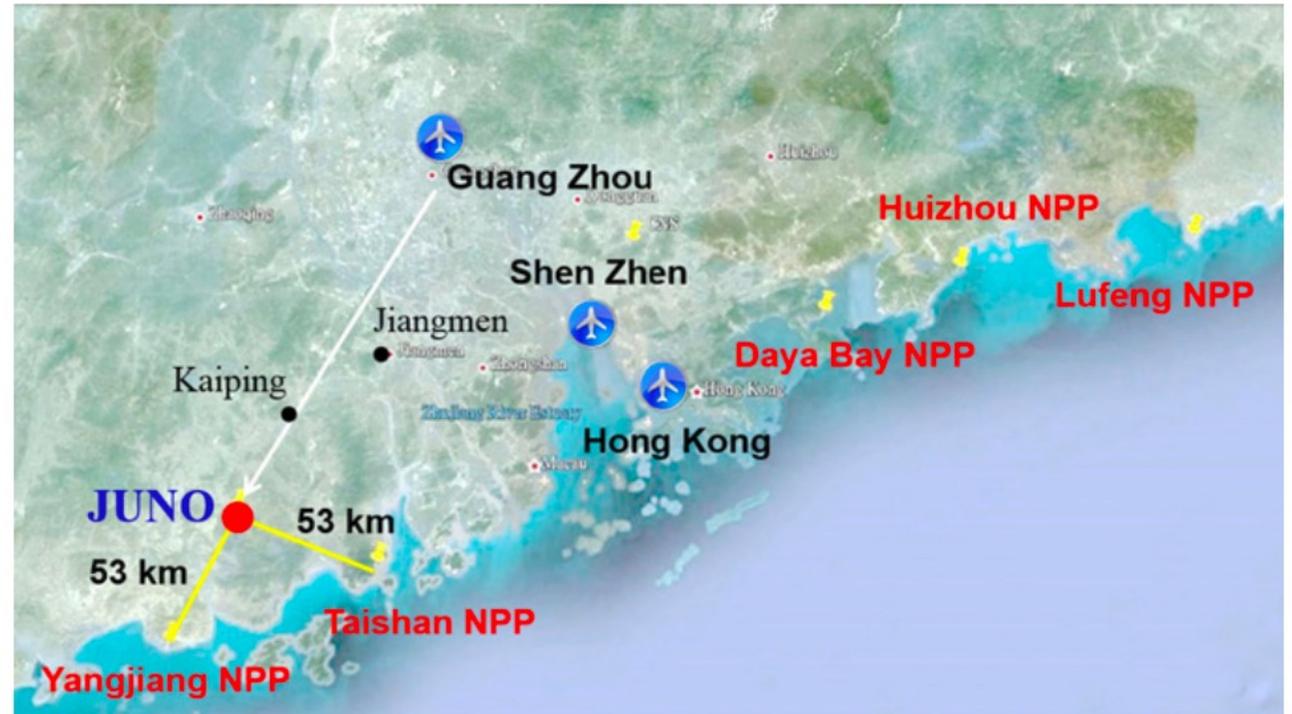
- High statistics \rightarrow mass
- High energy resolution



Scintillation
detector

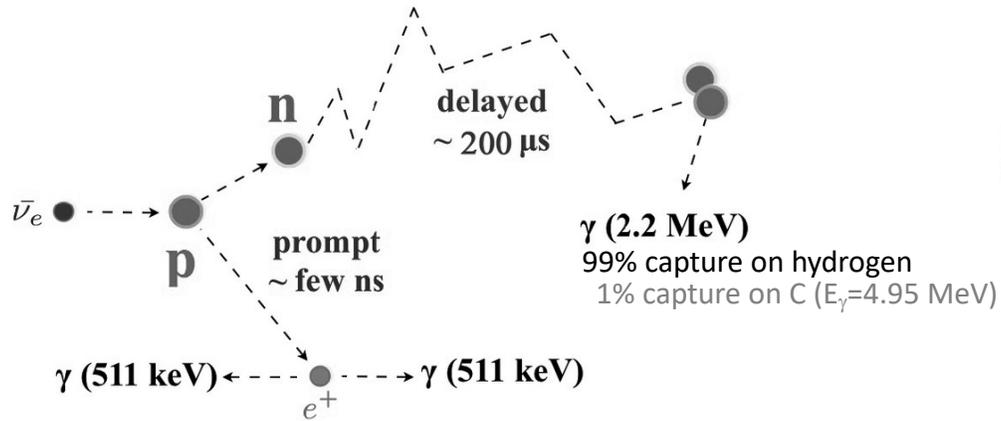
JUNO Experiment

- Jiangmen Underground Neutrino Observatory
- Located in China
- New underground lab with 1800 m.w.e.
- 20 kt liquid scintillator detector
- Required energy resolution:
3% at 1 MeV (1σ)

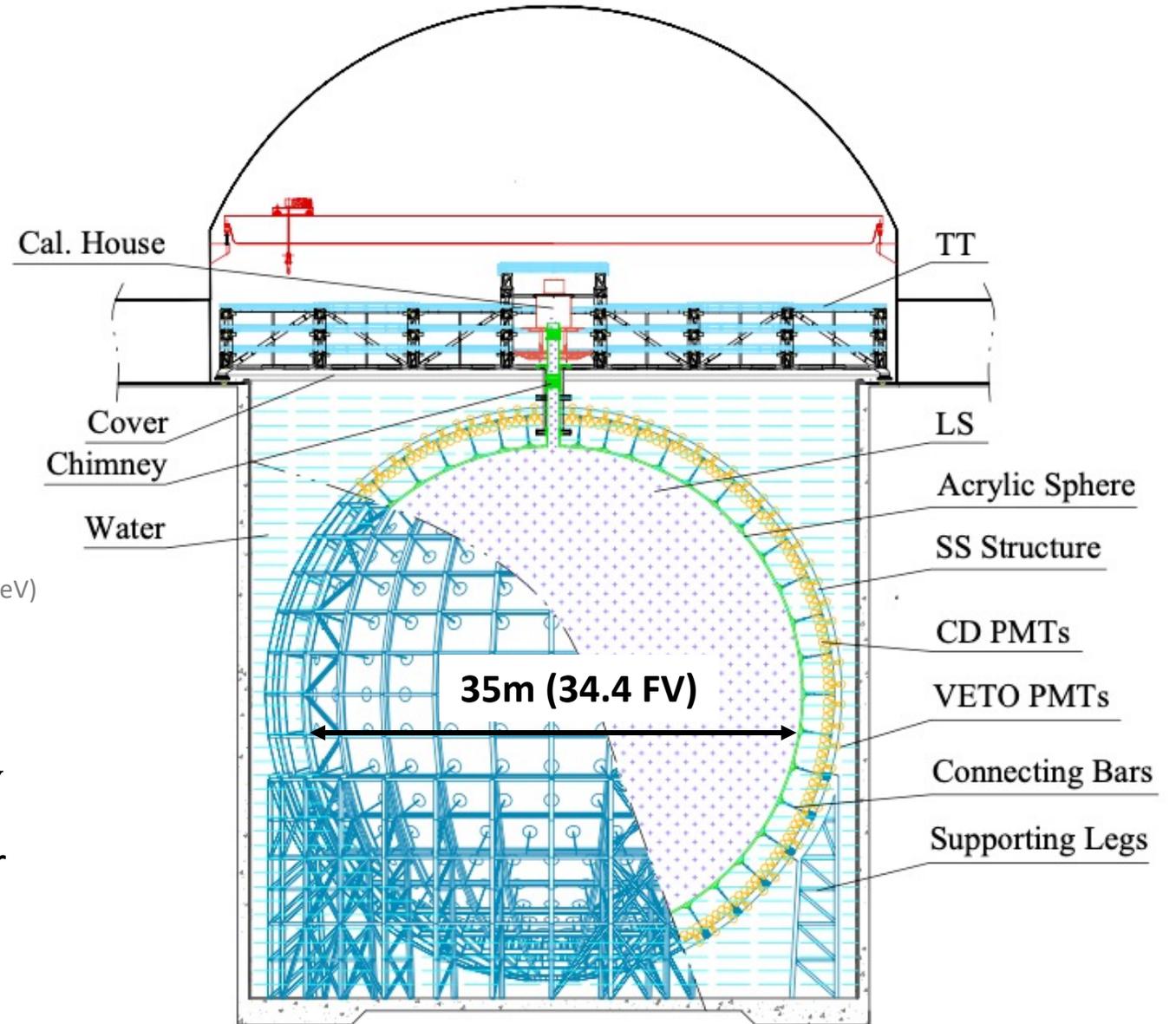


The JUNO Detector

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



- Prompt signal: $E_\nu \sim E_p(e^+) + 0.8$ MeV
- Expected signal rate: 60 IBD/days (after cuts)

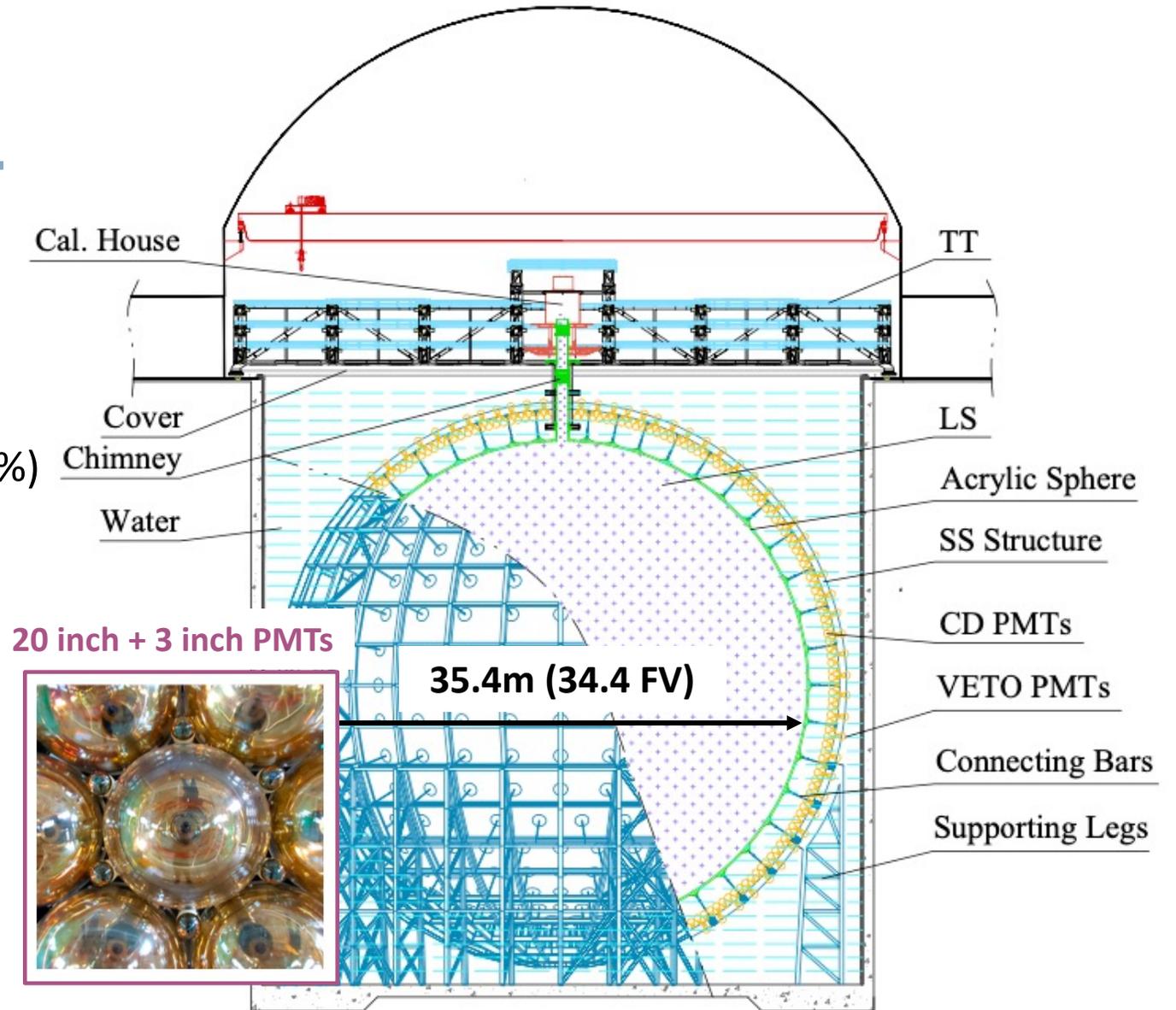


The JUNO Detector

Central detector (CD): 20kt liquid scintillator

Most critical: Light yield 1235 p.e./MeV

- High PMT photocathode coverage (78%)
- High PMT photocathode quantum efficiency (>24%)
- Large attenuation length of the LS (>20m)

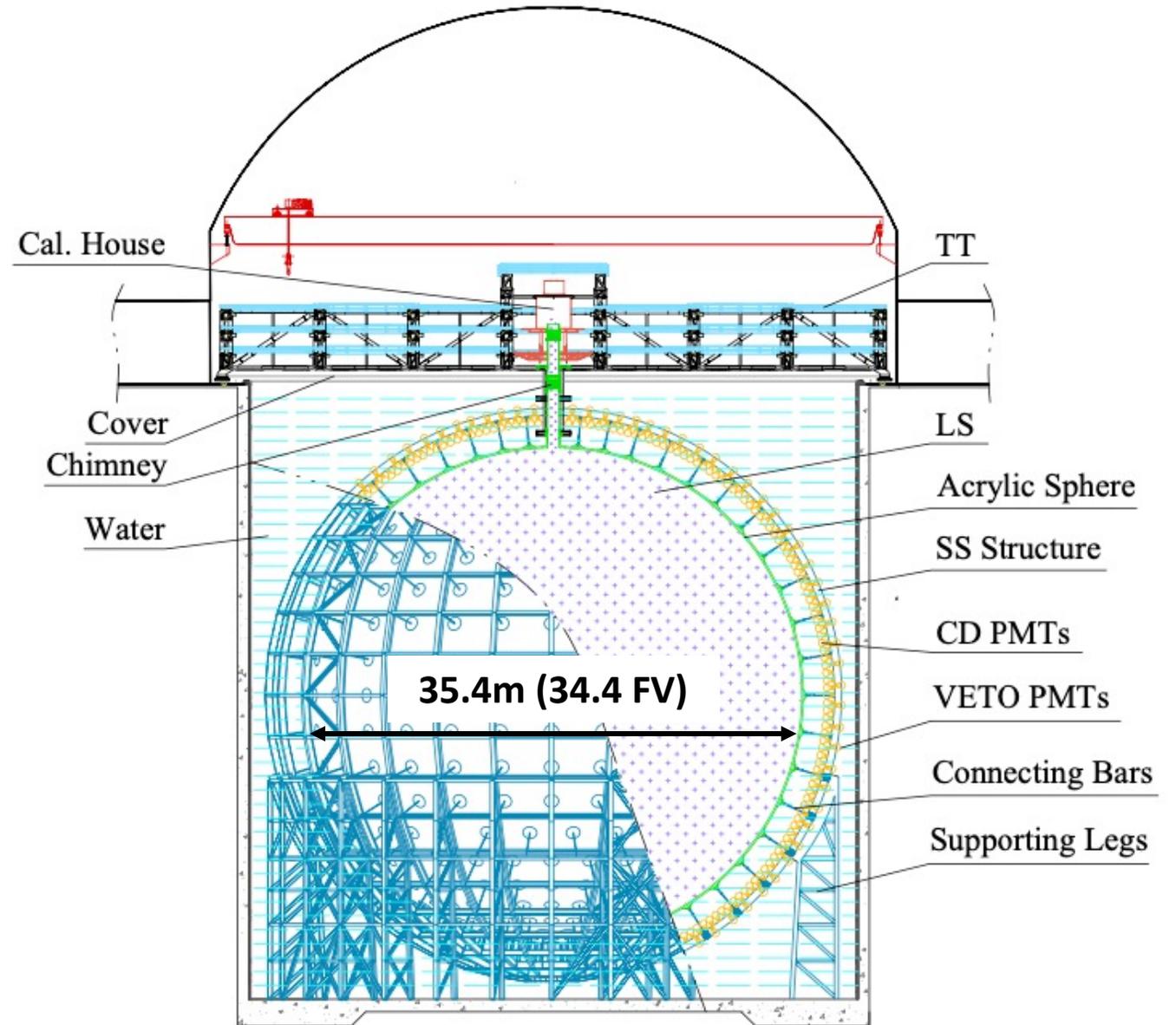


The JUNO Detector

Calibration to obtain 1% non-linearity and effective 3% resolution

Background mitigation

- Material screening
- Water buffer between LS & PMTs
- Muon veto:
 - Water Cherenkov detector with 20 inch PMTs
 - Plastic scintillator panels (TT) covering chimney



Part II - Neutrino Detectors

How to measure neutrino and mass hierarchy oscillations?



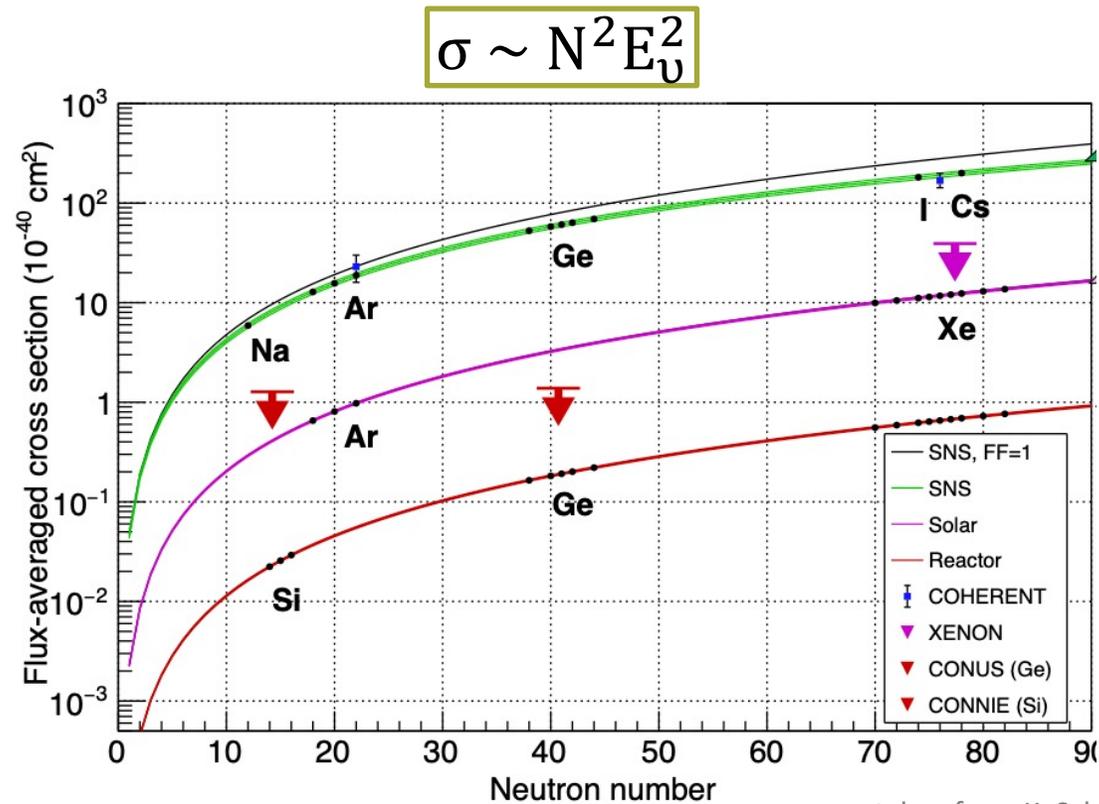
How to study Coherent elastic neutrino-nucleus scattering (CEvNS)?



- Appearance of new flavor
- Disappearance of neutrinos -> rate & spectral distortion measurement
- JUNO: 20kt liquid scintillator
- At 53 km oscillation of reactor neutrino sensitive to mass ordering

Study CEvNS energy & N^2 dependence

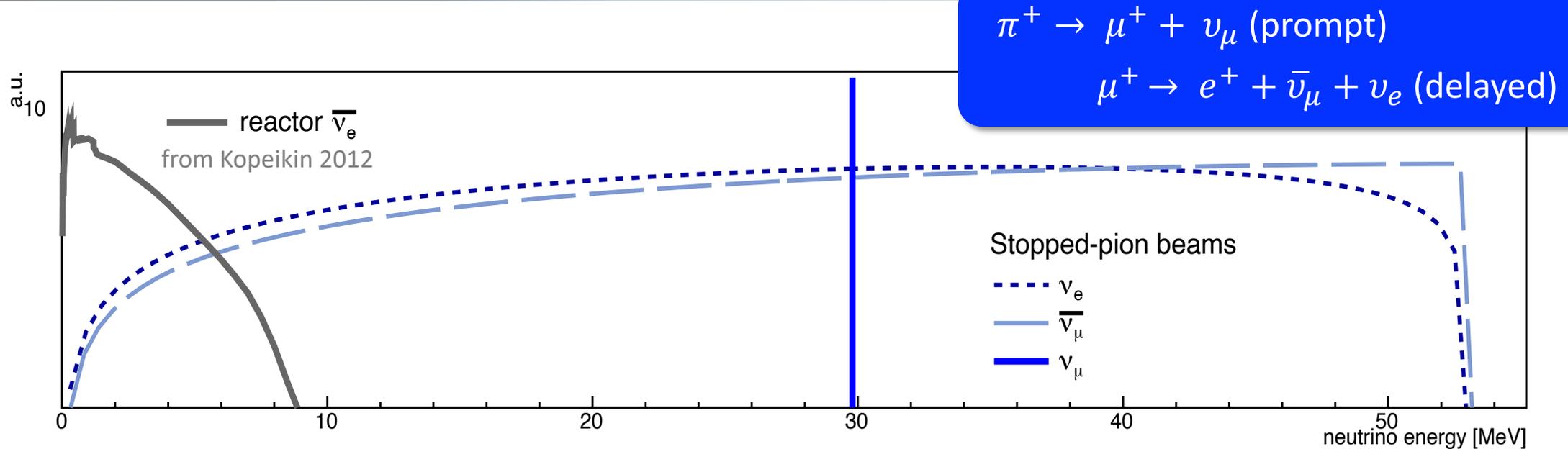
→ large variety of neutrino experiments



taken from K. Scholberg, talk at PANIC 2021

Source	Publication
Stopped π -DAR source	<i>Phys.Rev.Lett.</i> 129 (2022) 8, 081801 (Csl) <i>Phys.Rev.Lett.</i> 126 (2021) 1, 012002 (Ar)
^8B solar neutrinos	<i>Phys.Rev.Lett.</i> 126 (2021) 091301 (XENON)
Reactor neutrinos	<i>Phys. Rev. Lett.</i> 126 , 041804 (CONUS) <i>Phys.Rev.D</i> 106 (2022) 5, L051101 (vGen) 2202.09672 [hep-ex] (DRESDEN) <i>JHEP</i> 04 (2020) 054 (CONNIE)

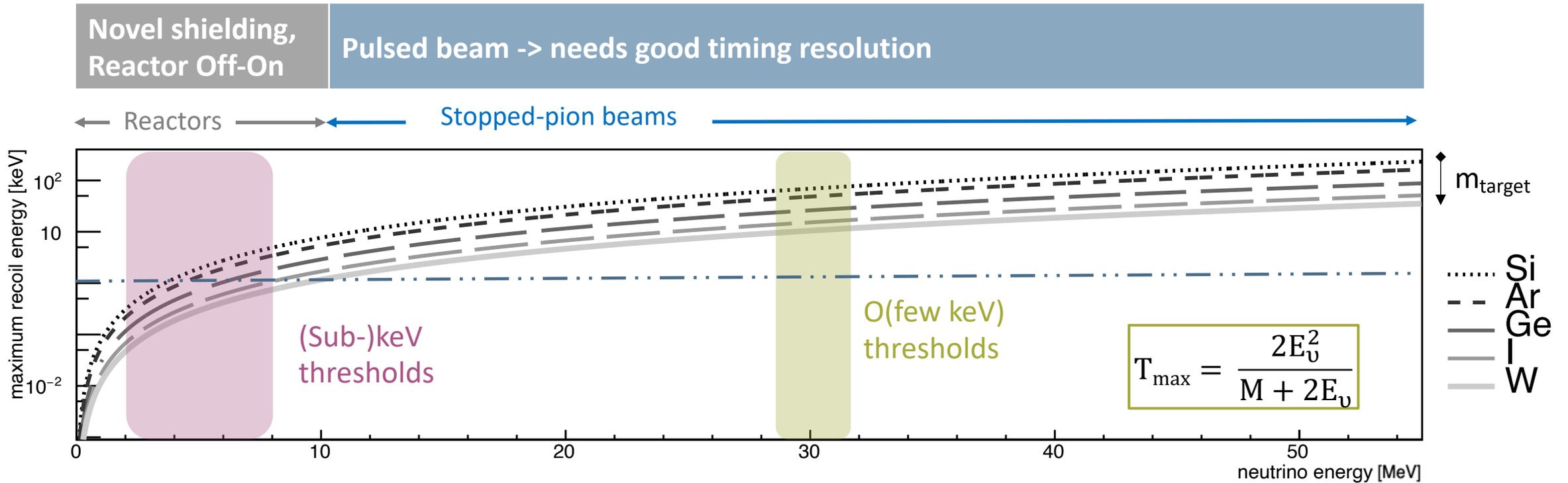
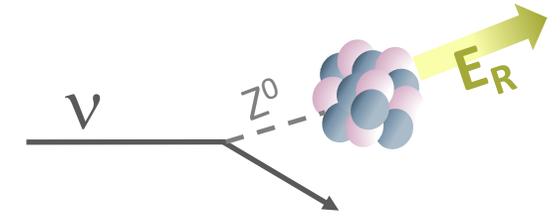
Reminder: Neutrino Sources for CEvNS



- **High flux:** $O(10^{20} \text{ v/s})$ @ power reactors
- Low neutrino energy: **coherency**

- Flux at SNS in Oakridge (US): $4.3 \times 10^7 \text{ v}/(\text{cm}^2 \text{ s})$
- High neutrino energy: start of incoherence

Energy Threshold for CEvNS



- Measurement of (sub-)keV nuclear recoil signals: **Low energy threshold**

Overlap with DM searches

What we measure in CEvNS

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} [Z(1 - 4\sin^2\theta_w) - N]^2 \left(1 - \frac{MT}{2E_\nu^2}\right) F_w^2(q^2)$$

weak charge ->
target nucleus

weak form factor ->
v-source

kinematics -> detection
threshold & v-source

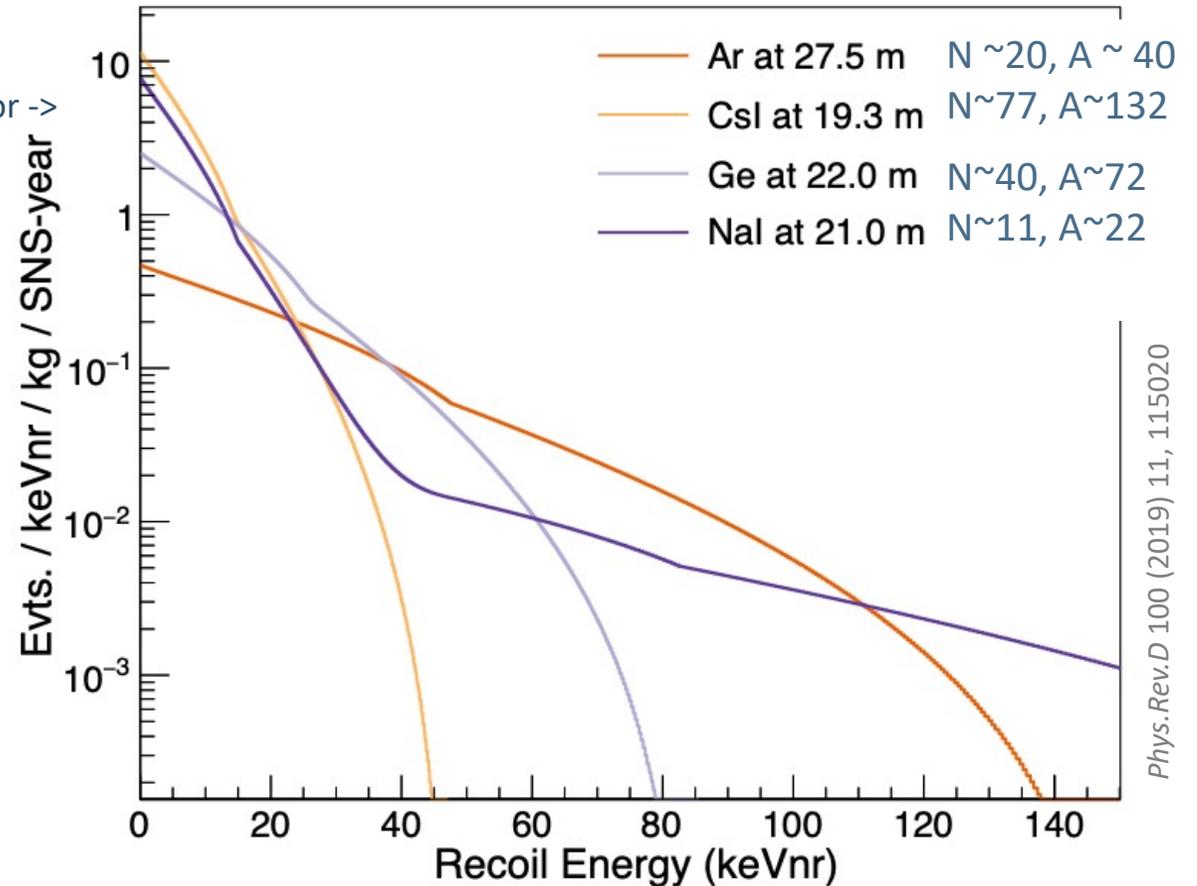
Trade-off between

$$\sigma \sim N^2 E_\nu^2$$

$$E_{\text{recoil}} \sim \frac{E_\nu^2}{m_n(N + Z)}$$

$$Q < 1/R$$

Nuclear recoil energy spectra from CEvNS for the SNS neutrino



Phys.Rev.D 100 (2019) 11, 115020

What we measure in CEvNS

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weak form factor ->
v-source

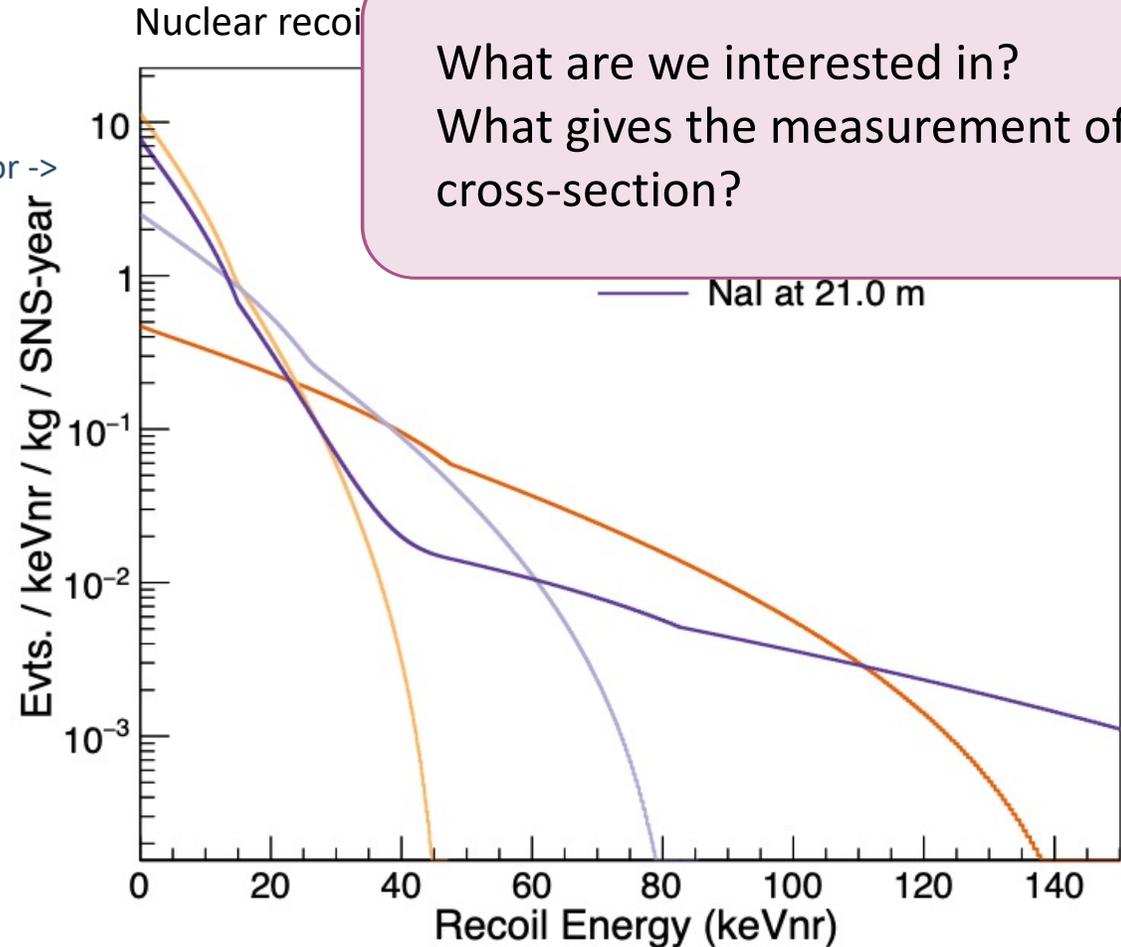
kinematics -> detection
threshold & v-source

Trade-off between

$$\sigma \sim N^2 E_\nu^2$$

$$E_{\text{recoil}} \sim \frac{E_\nu^2}{m_n(N + Z)}$$

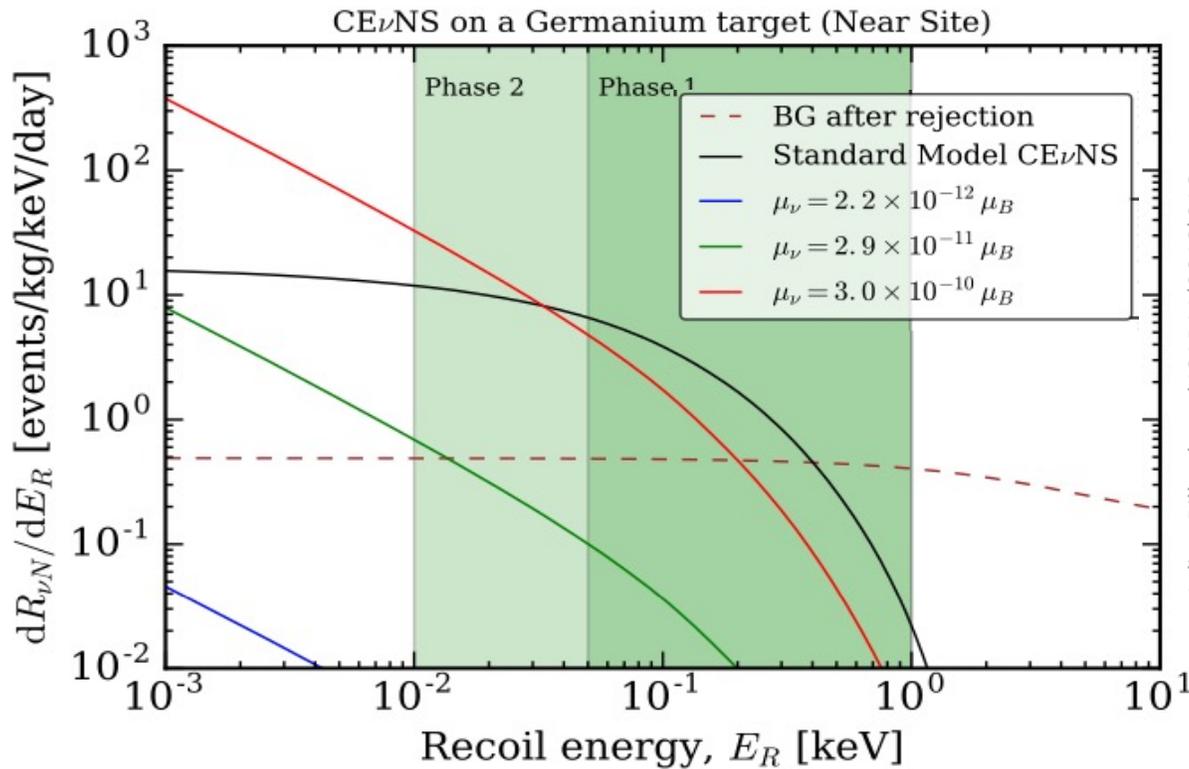
$$Q < 1/R$$



What are we interested in?
What gives the measurement of the cross-section?

Phys.Rev.D 100 (2019) 11, 115020

What we measure in CEvNS



- Normalization measurement:

$$\sigma \sim \left[Z \left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV} \right) + N \left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV} \right) \right]^2$$

$$g_V^p = +\frac{1}{2} - 2 \sin^2 \theta_W$$
- Shape measurement for neutrino magnetic moments (μ_ν), new mediators, etc.

We are looking for neutrinos!

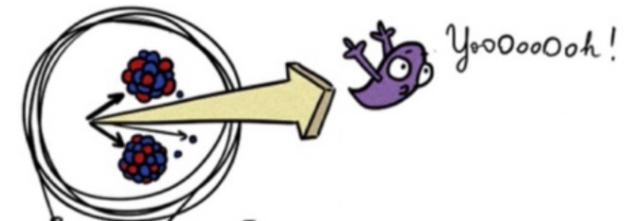


Chloé Goupy (chloe.goupy@cea.fr), CEA Saclay, 2022

The COHERENT Experiment

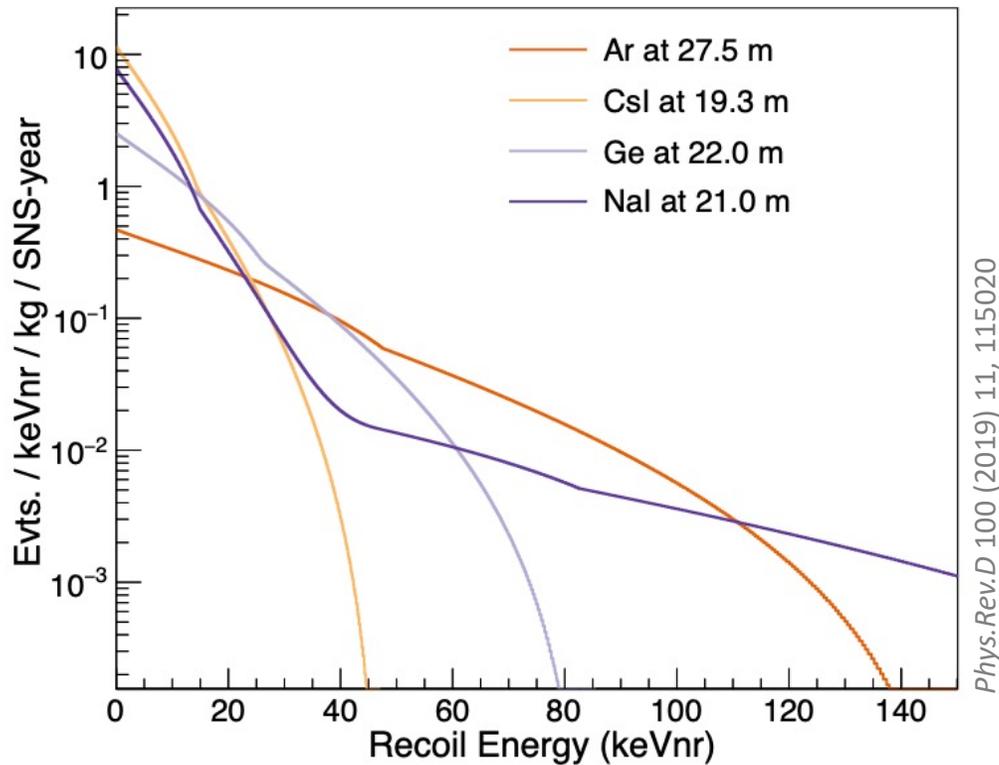
CEvNS discovery

Multi-detector experiment



The COHERENT Experiment

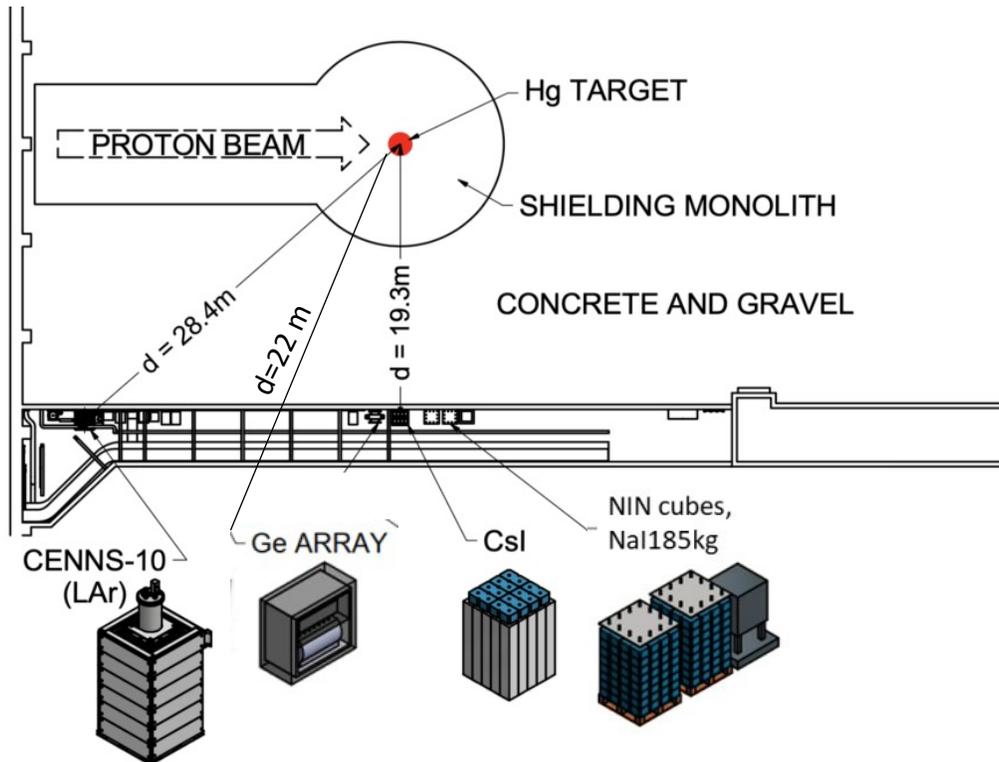
@Spallation Neutron Source (SNS) at Oakridge National Laboratory



Target	technology	Mass [kg]	Threshold [keV _{nr}]	Status
CsI[Na]	Scintillation	14.6	6.5	Decommissioned
Ar	Scintillation Single phase LAr	24/ 610	20	Running Update 2024
Ge	Ionization HPGe PPC	18	< 5	Commissioning in 2022
NaI[Tl]	Scintillation	3388	13	Commissioning in 2022

The COHERENT Experiment

modified from <https://coherent.ornl.gov/the-coherent-detector-suite/>

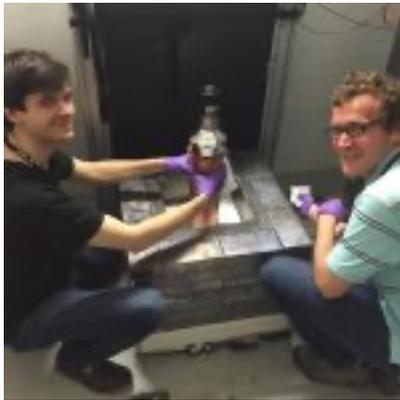


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COHERENT – CsI Detector

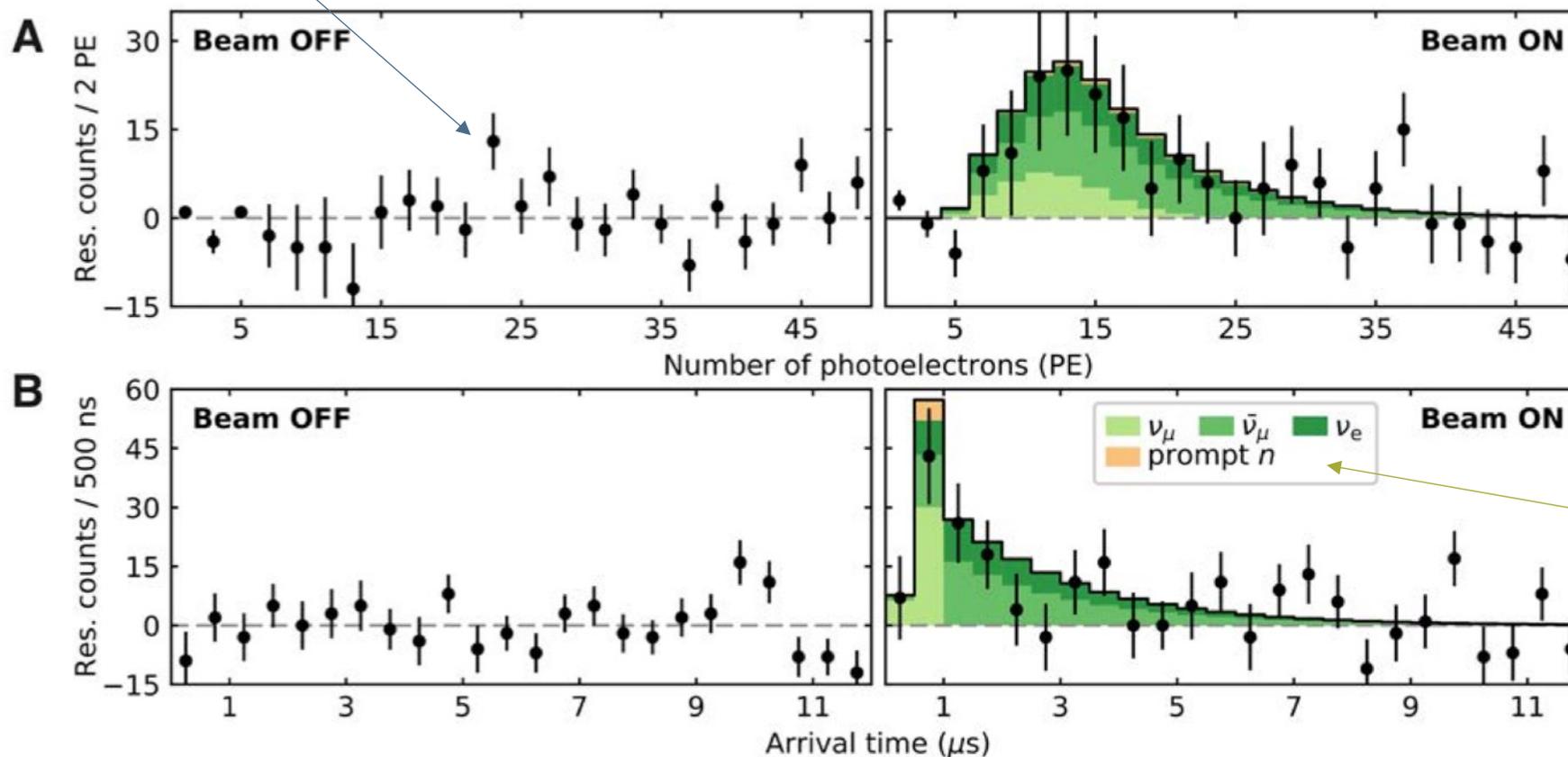
- 14.6 kg NaI[Tl]
- SNS source with ν flux of $4.3 \times 10^7 \nu/\text{cm}^2/\text{s}$ @20m
- > 3 years of data
- **Final result:** CEvNS observation on CsI at 11.6σ
flux averaged cross section of $\langle \sigma \rangle_{\phi} = (165^{+30}_{-25}) \times 10^{-40} \text{cm}^2$
- Consistent within 1σ with the SM prediction





COHERENT – CEvNS Discovery

12 μ s after POT trigger
12 μ s before POT trigger



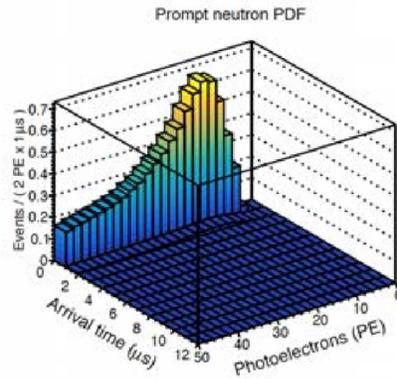
Calibration:
1.17 PE/ keV

SM predictions

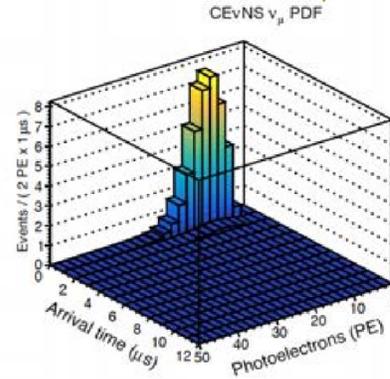
COHERENT – CEvNS Discovery



background

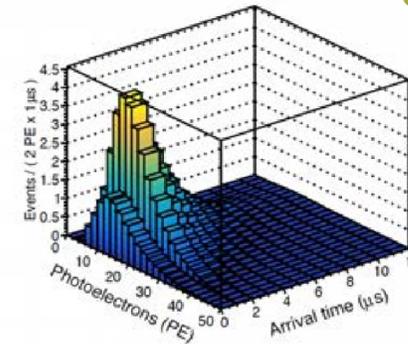


prompt ν_μ



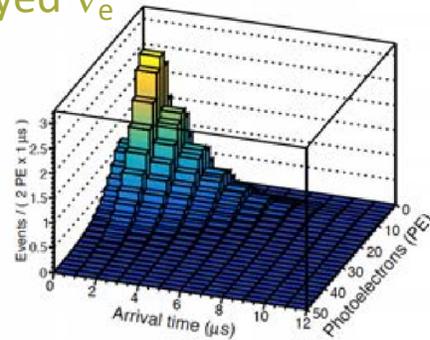
CEvNS $\bar{\nu}_\mu$ PDF

delayed ν_μ

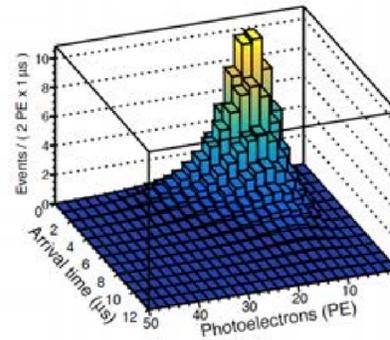


delayed ν_e

CEvNS ν_e PDF

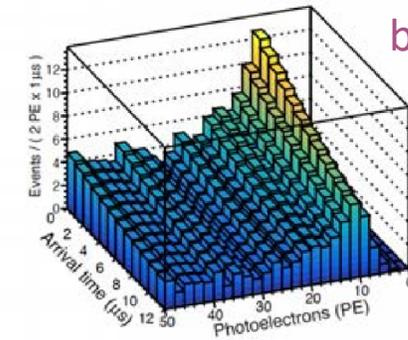


Summed CEvNS PDF

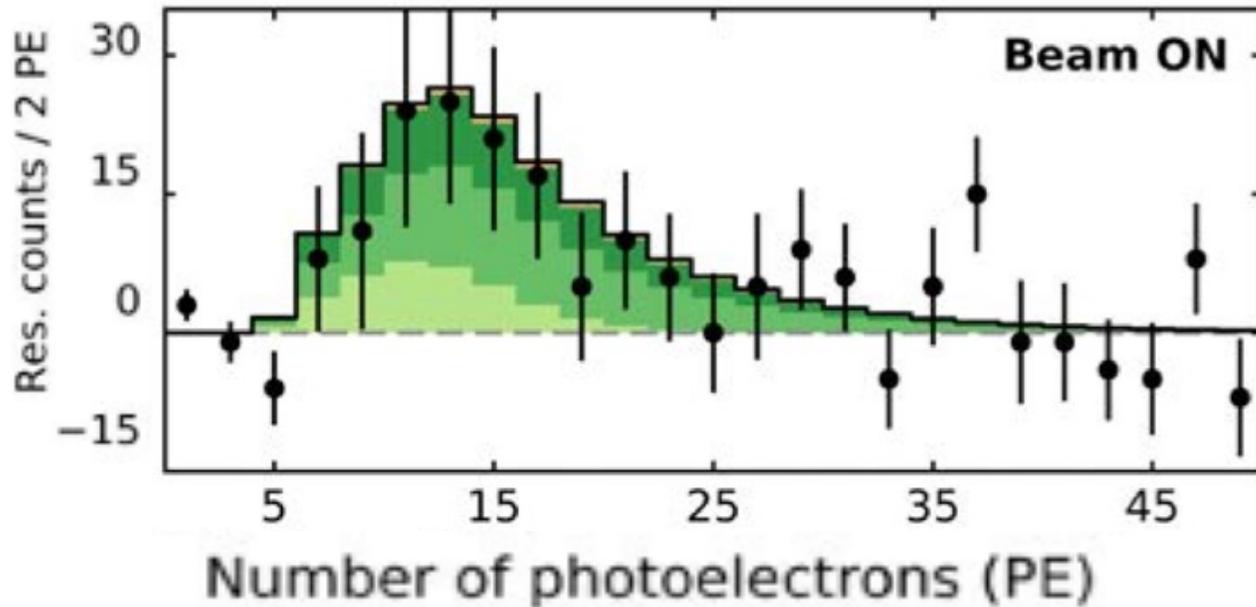


Steady-state background PDF

background



COHERENT – CEvNS Discovery

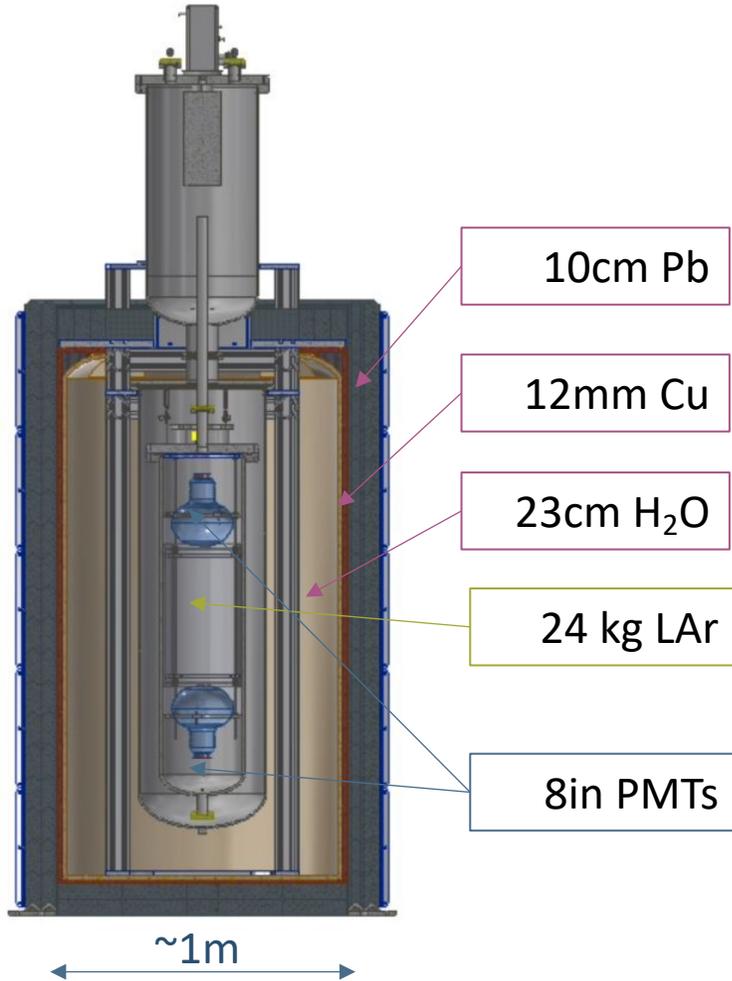


Main systematics:

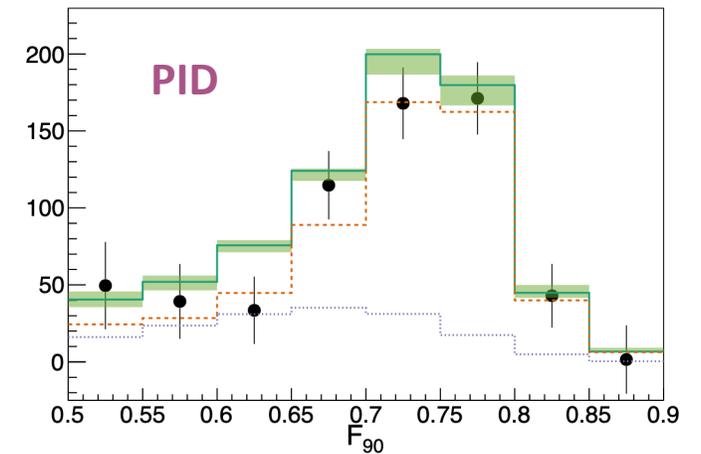
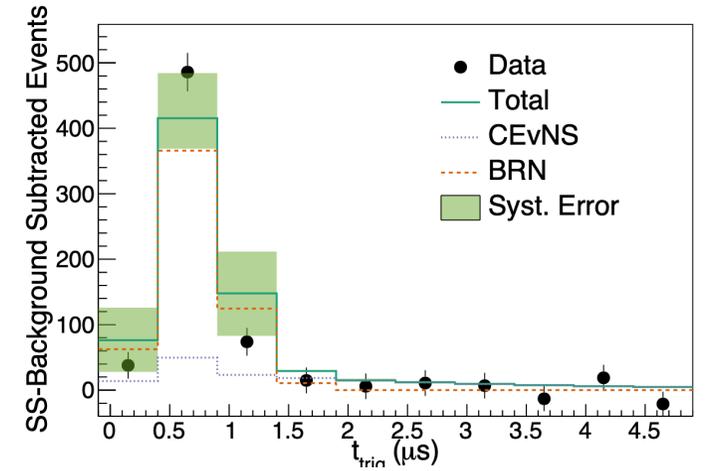
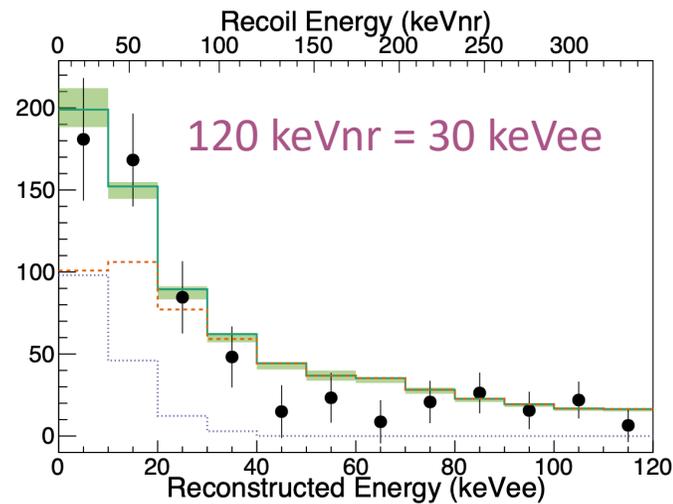
- 10% neutrino flux
- 25% quenching factor

Observed CEvNS events: 134 ± 22 counts
Predicted CEvNS events: 173 ± 48 counts
Presence of SM-CEvNS at 6.7σ

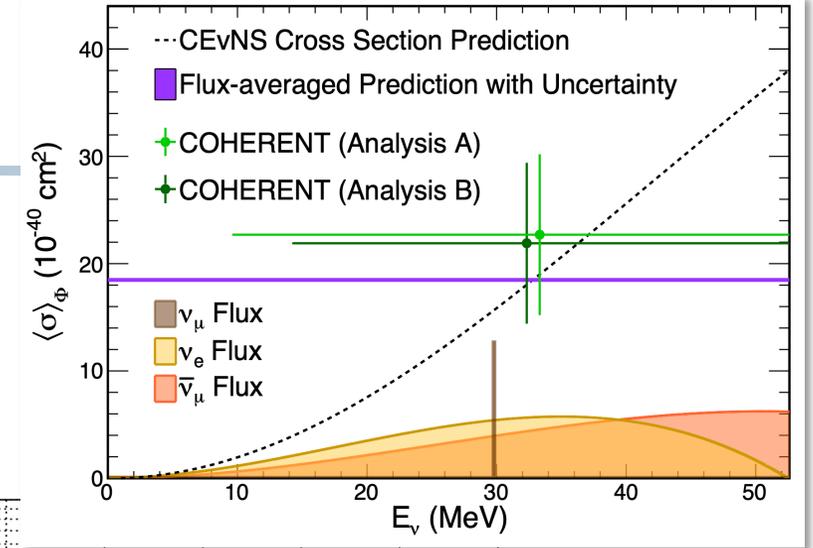
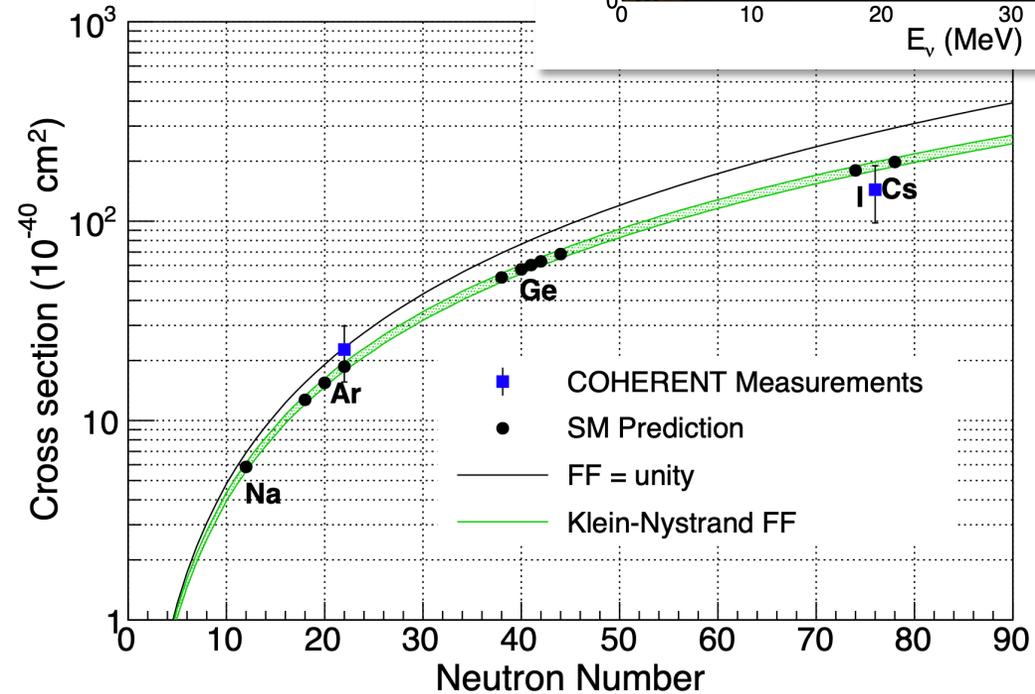
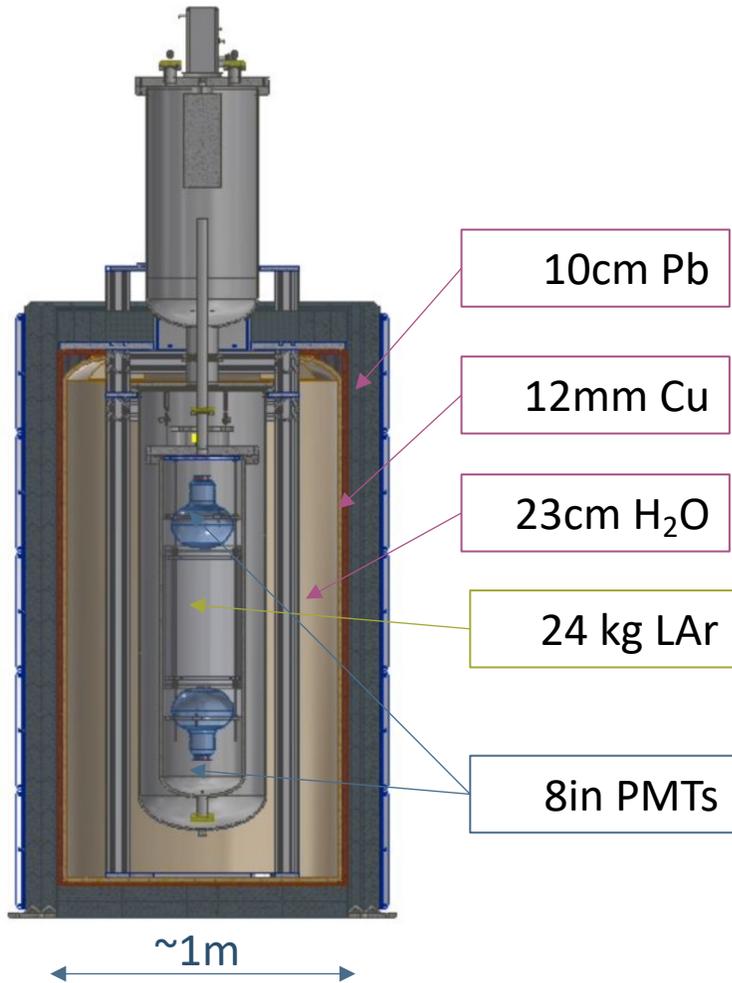
COHERENT - Argon



- Dominant background from Ar-39, b-decay with $Q=565$ keV

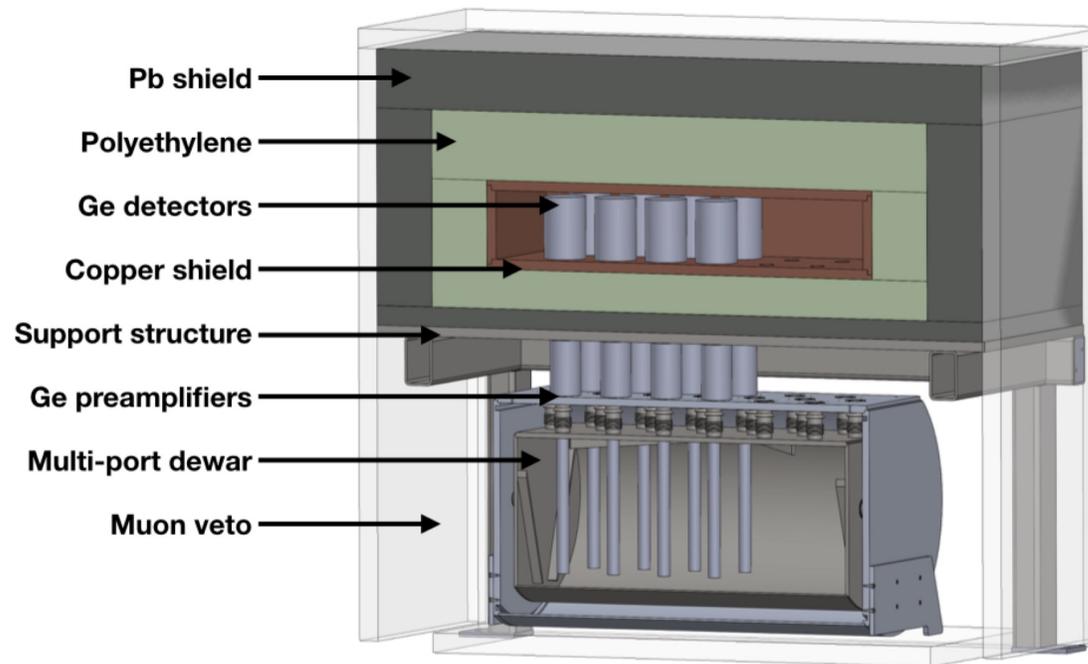
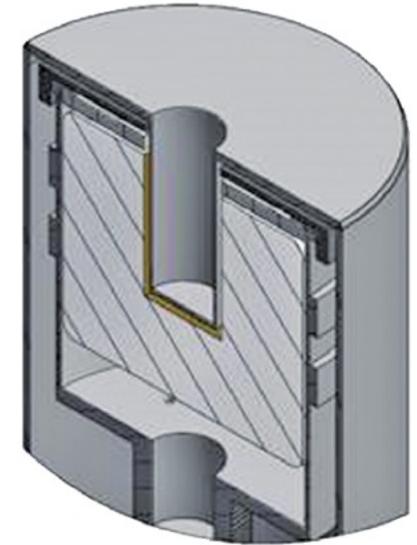


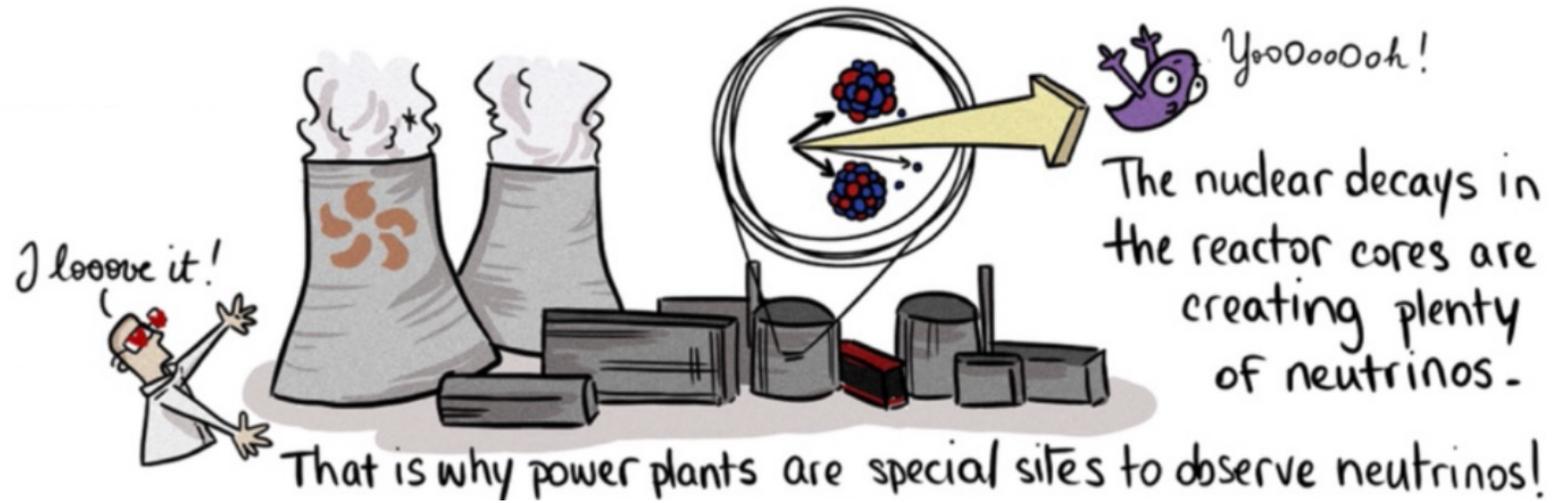
COHERENT - Argon



COHERENT – Ge

- 10 kg array of p-type point contact detectors
- Lowest energy threshold
- Intermediate mass





Chloé Goupy (chloe.goupy@cea.fr), CEA Saclay, 2022

CEvNS at reactors

Very briefly ...

Ge at reactors

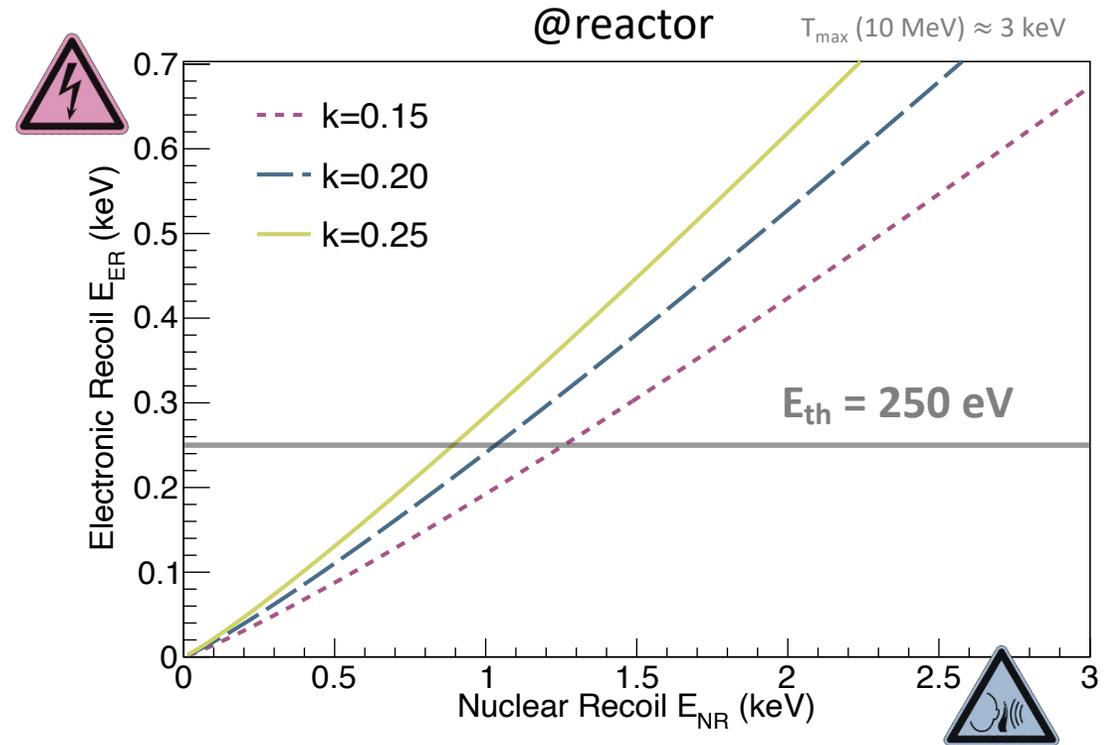
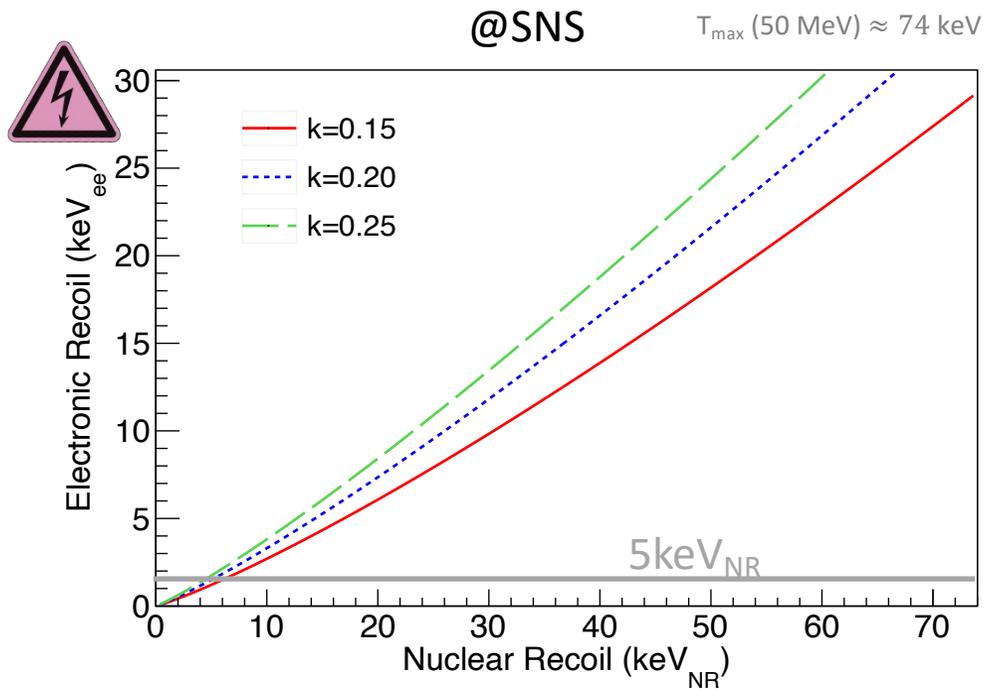
Lindhard model

$$E_{ER} = QF(E_{NR}) \cdot E_{NR} = \frac{k \cdot g(\epsilon)}{1 + k \cdot g(\epsilon)} E_{NR}$$

$$\epsilon = 11.5 Z^{-7/3} E_{NR}$$

$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

CONUS $k = 0.162$



Part II - Neutrino Detectors

How to measure neutrino and mass hierarchy oscillations?



- Appearance of new flavor
- Disappearance of neutrinos -> rate & spectral distortion measurement
- JUNO: 20kt liquid scintillator
- At 53 km oscillation of reactor neutrino sensitive to mass ordering

How to study Coherent elastic neutrino-nucleus scattering (CEvNS)?



- Normalization and shape of recoil spectrum
- Study N^2 -dependence of cross-section
- π -DAR sources explore time dependence of CEvNS signal and have keV threshold
- Reactor-CEvNS experiments need (sub-)keV thresholds
- Phonon-detectors overcome quenching of nuclear recoils