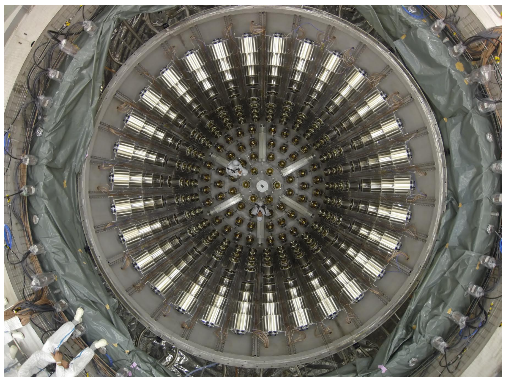
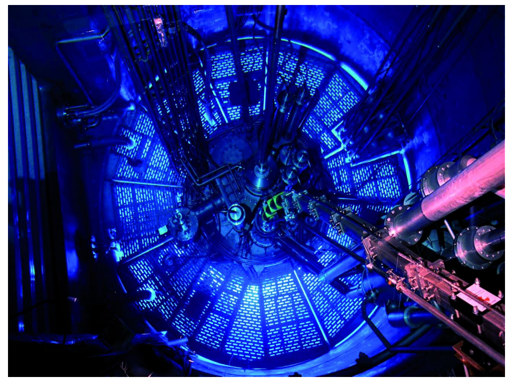
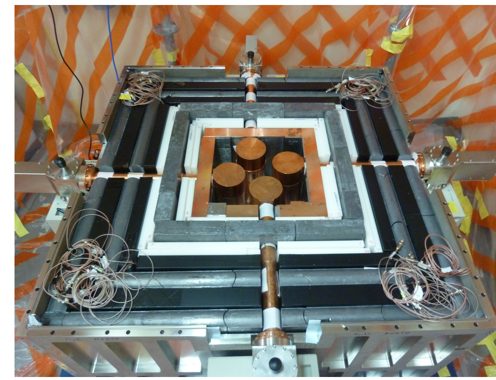
Neutrino detection at nuclear reactors







Christian Buck

MPIK Heidelberg

Gentner Kolloquium, Dec 20, 2023

DOUBLE CHOOZ

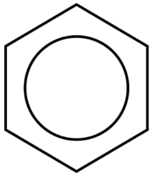
STEREO

CONUS

Outline

1. $\bar{\nu}_e$ detection in organic liquids

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



2. MPIK scintillators

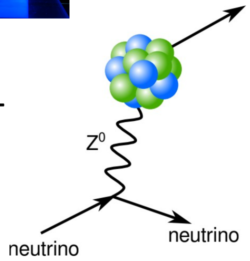
3. Performance in experiments

Mixing angle θ_{13}

Sterile neutrinos?

4. New developments

Coherent elastic ν-nucleus scattering



5. CONUS(+)

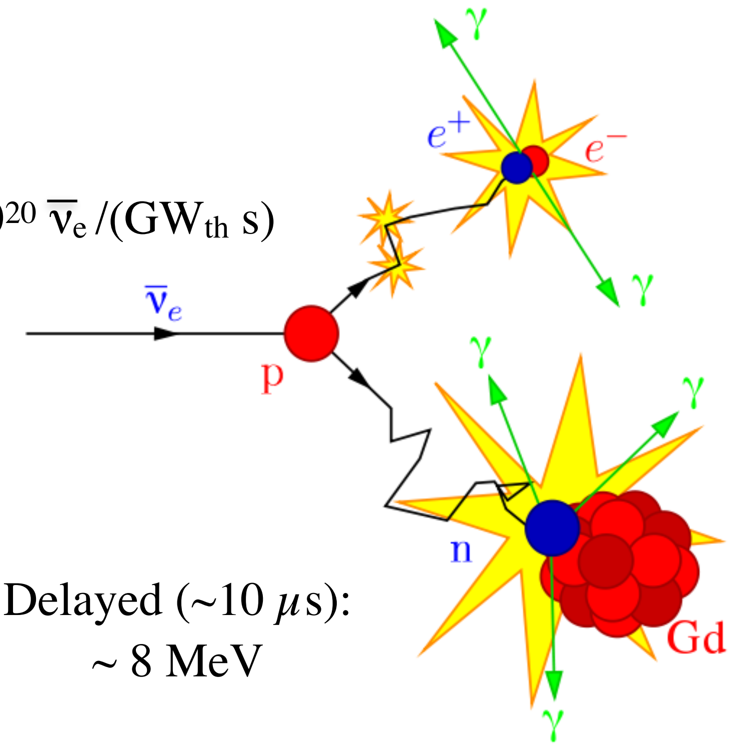
Inverse beta decay (IBD)

Nuclear reactors: strong and pure source of electron antineutrinos

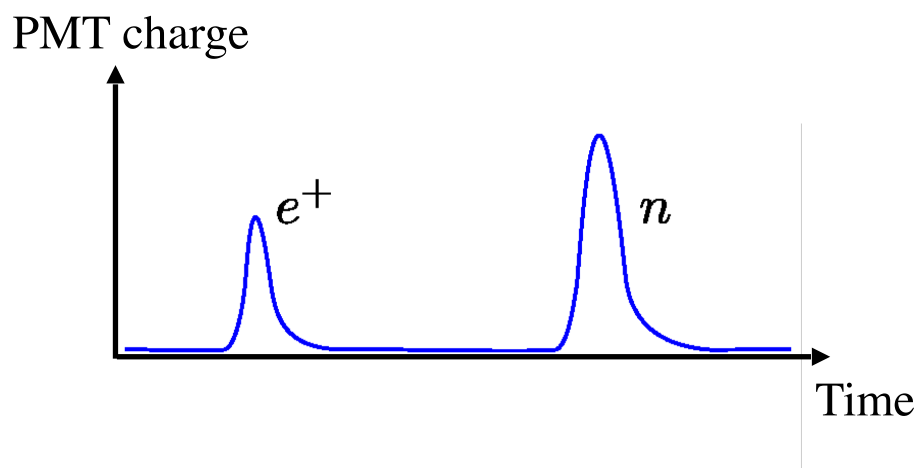
Prompt
(energy information)

$$\overline{\nu}_e + p \longrightarrow e^+ + n$$

$>10^{20}\ \overline{\nu}_e/(GW_{th}\ s)$

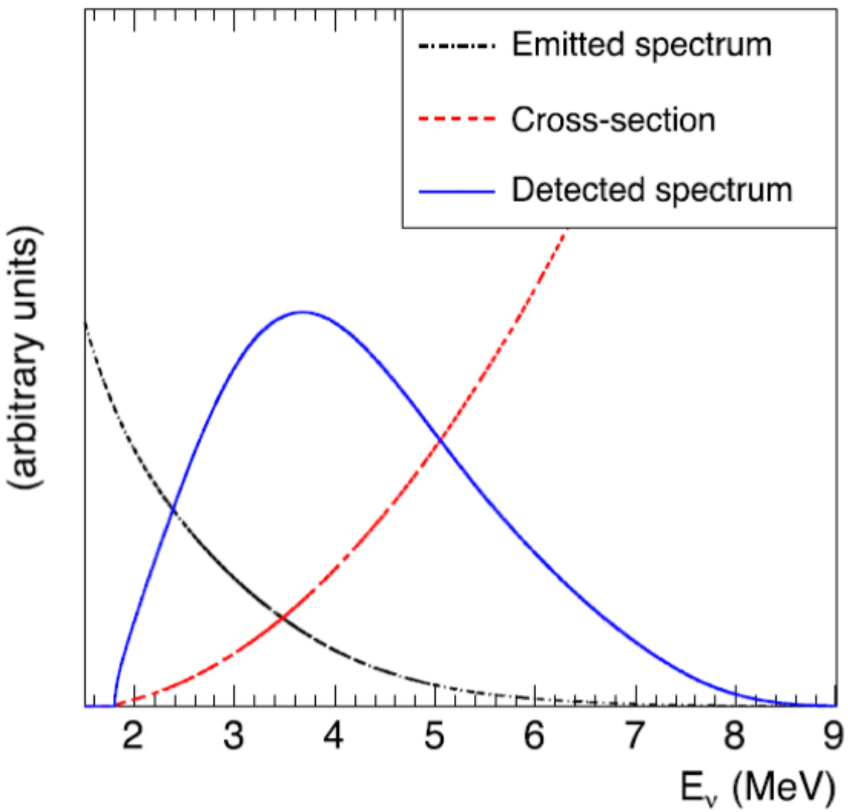


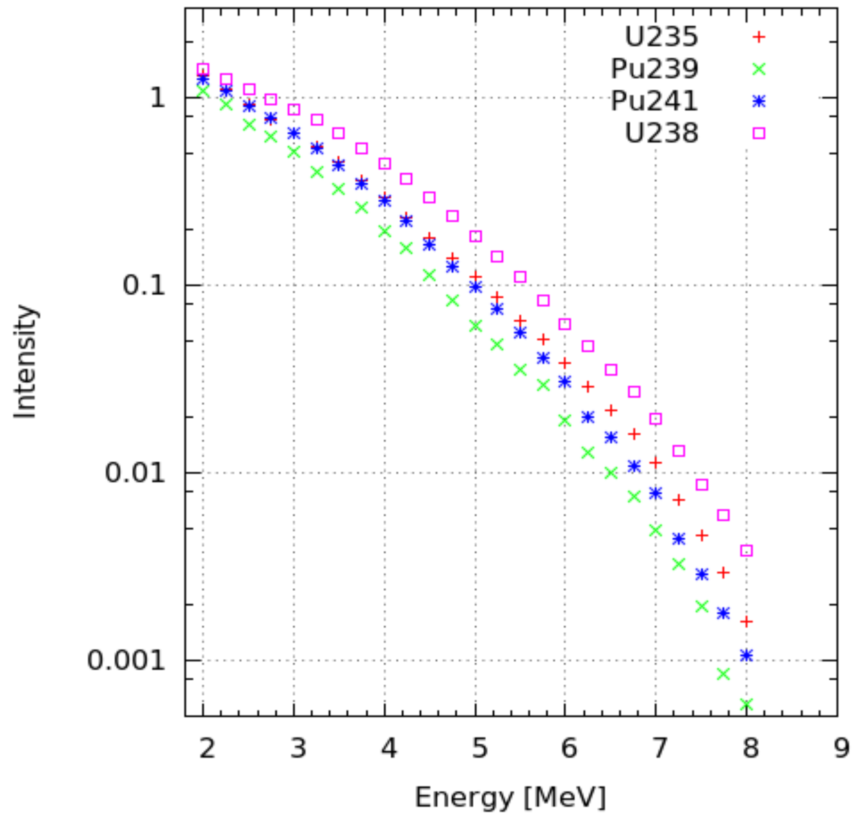
Delayed (~10 μs):
~ 8 MeV



Alternatives to Gd: Cd, ^{6}Li, ^{10}B,…

Reactor antineutrino spectrum

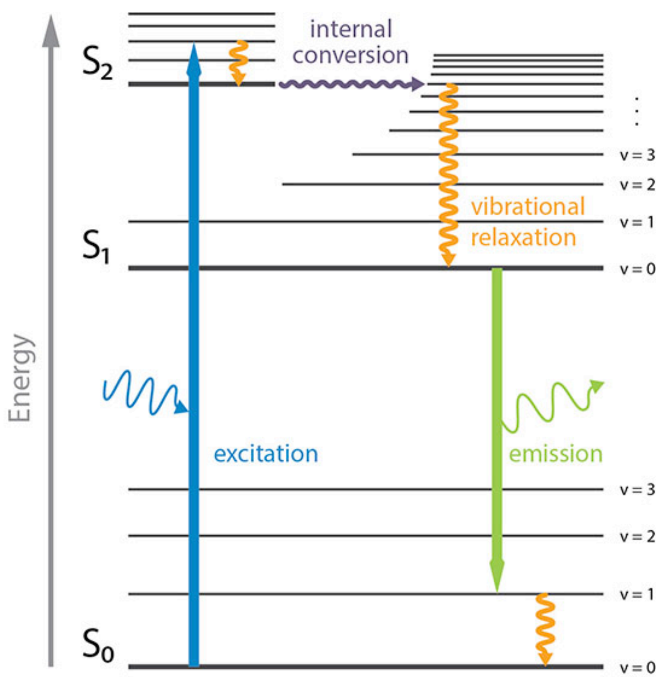


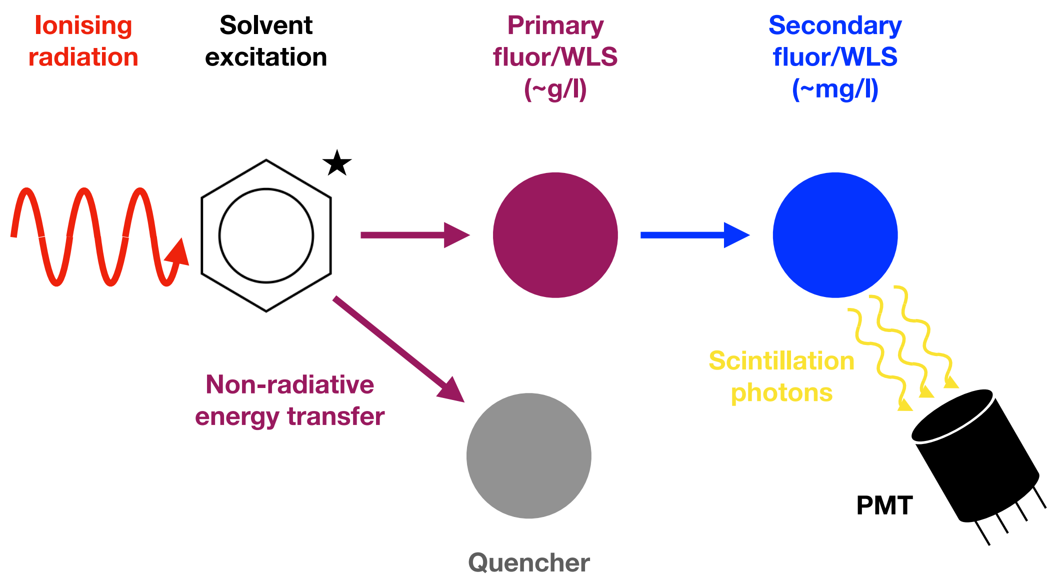


- IBD energy threshold: 1.8 MeV
- "Visible energy" in detector: $E_{vis} = E_{nu} - 0.78$ MeV

Organic liquid scintillators

Simplified Jablonski diagram

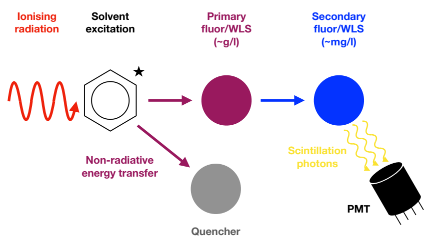




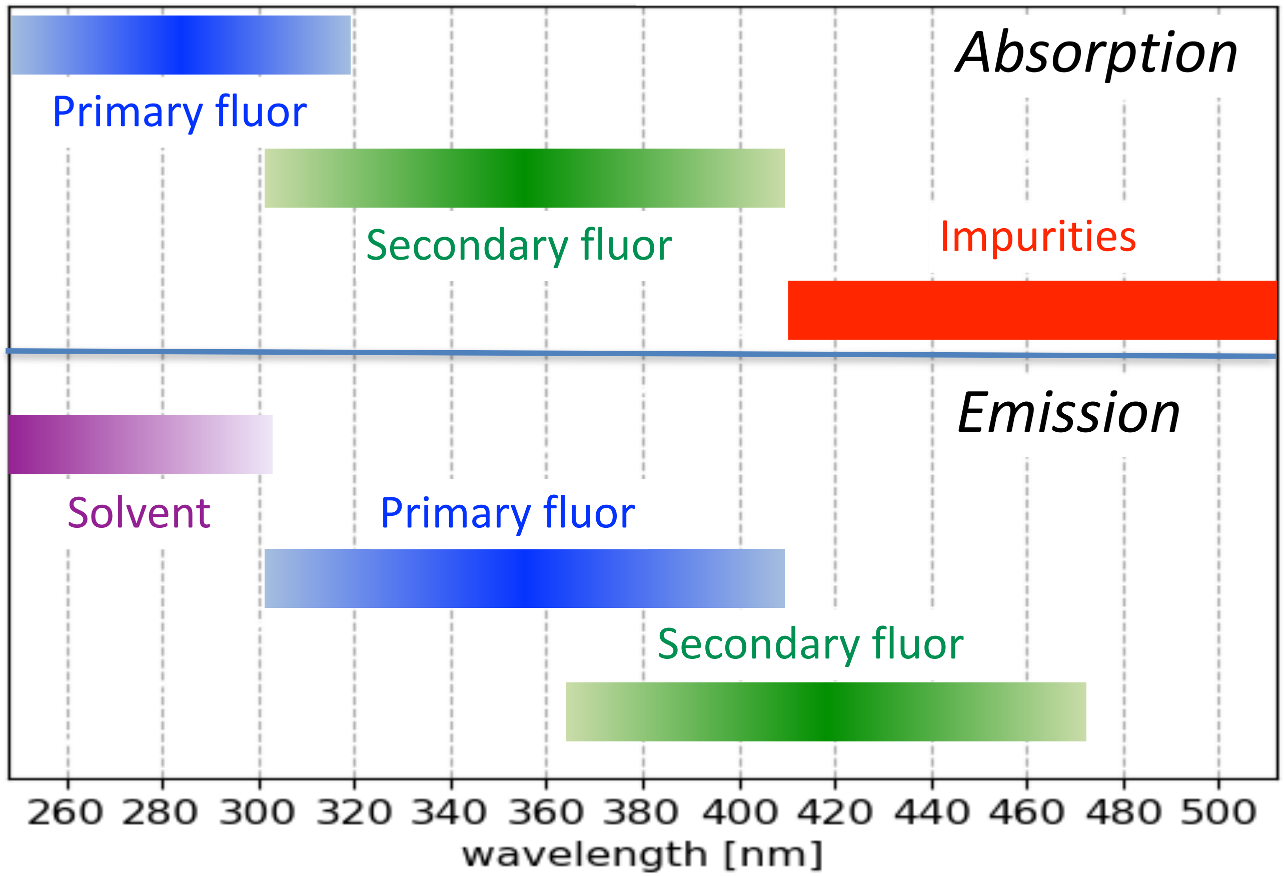
- Basis: fluorescent, aromatic molecules
- Composition: solvent, primary and secondary fluor (wavelength shifting agents, WLS)

Energy transfer in liquid scintillators

C. Buck, M. Yeh, J. Phys. G43 (2016) 093001



Stokes shift!



- Radiative and non-radiative energy transfer
- Strong overlap between donor emission and acceptor absorption bands

Scintillator requirements in neutrino detector

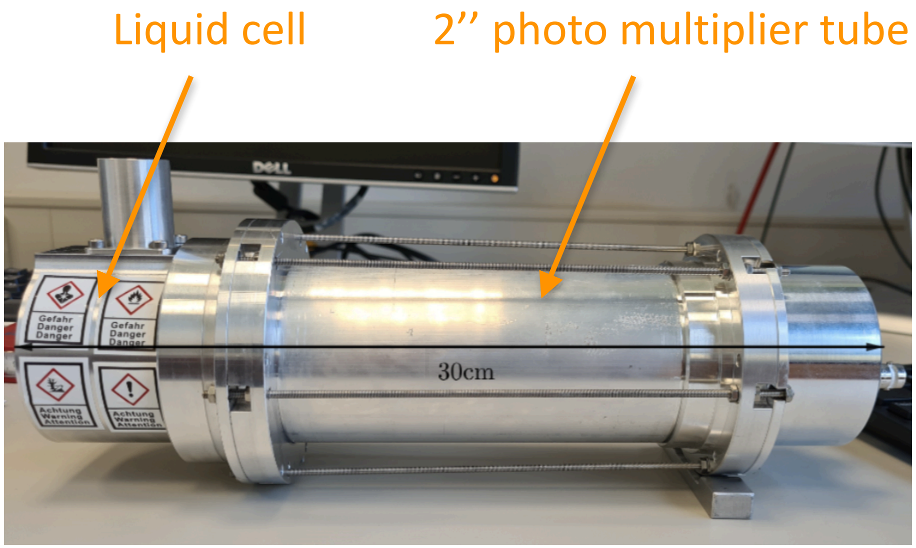
Background level
- Radiopurity (U, Th, K)
- Pulse shape discrimination

Detector response
- Light yield
- Transparency
- Stability
- Quantum yield
- Quenching
- Refractive index

Safety and detector integrity
- Flash point
- Toxicity
- Environmental "friendliness"
- Material compatibility

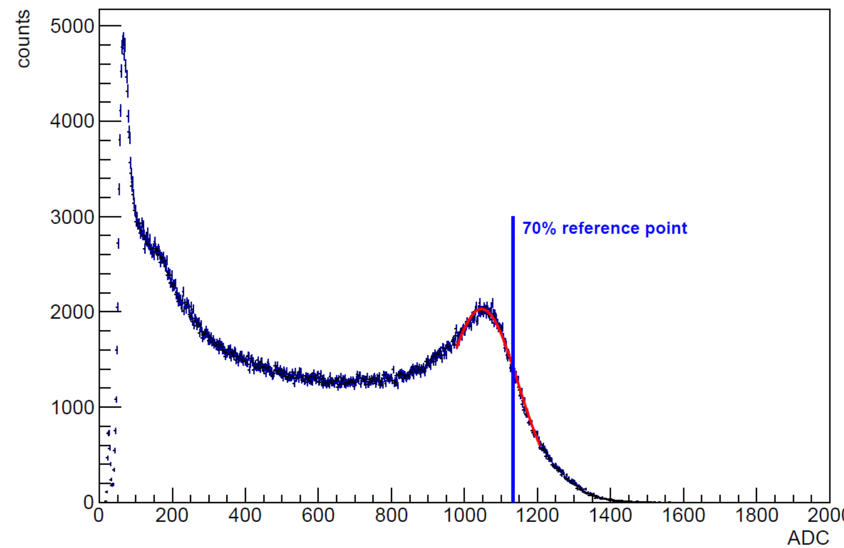
Statistics
- Proton fraction
- Density

Light yield



MPIK liquid scintillator modul

A. Bonhomme, C. Buck, B. Gramlich, M. Raab, JINST 17 (2022) P11025

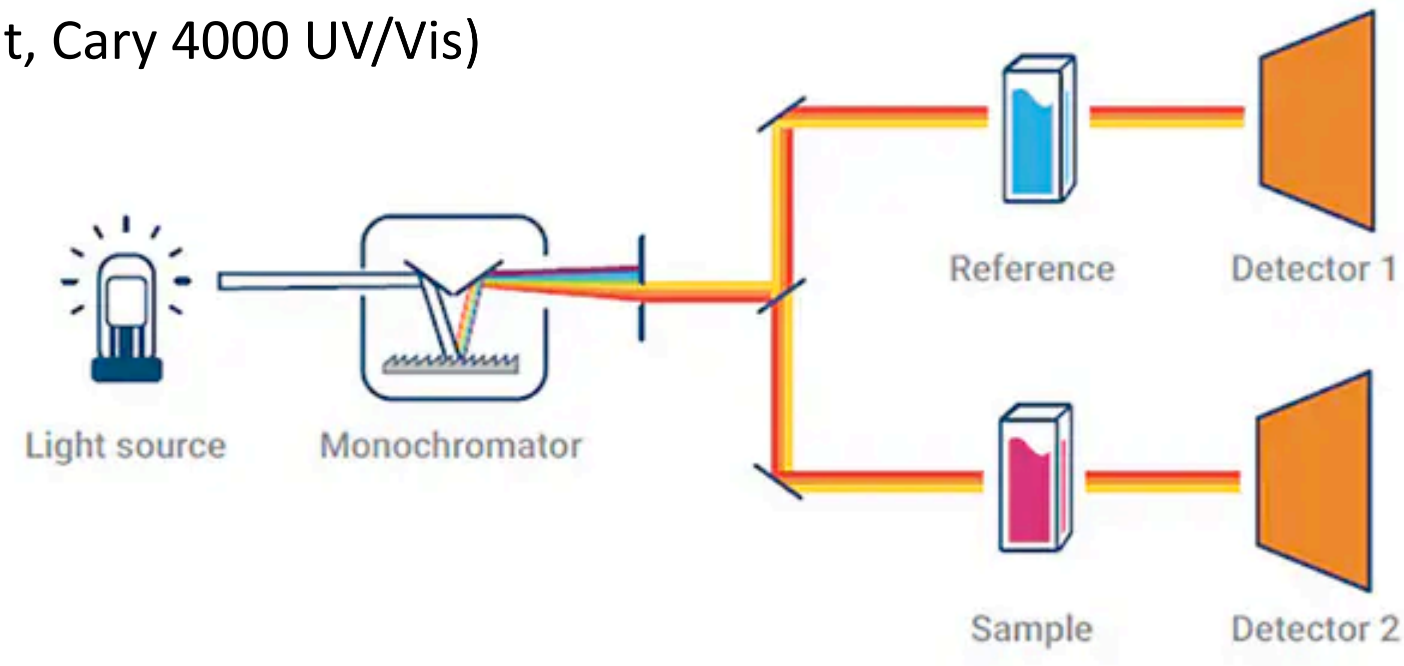


Compton spectrum with ^{137}Cs source

- Relevance: energy resolution and threshold
- Challenges: absolute light level, reference samples, control systematics
- Compton edge fitting vs Compton backscattering peak

Transparency

Double beam spectrophotometer
(Agilent, Cary 4000 UV/Vis)



https://www.agilent.com/en/support/molecular-spectroscopy/uv-vis-uv-vis-nir-spectroscopy/uv-vis-spectroscopy-spectrophotometer-basics

- Relevance: crucial in large scale detectors, energy reconstruction
- Challenges: light scattering, reflections, definition of zero absorbance
- Application of Beer-Lambert law? ($A= \varepsilon \cdot d \cdot c$)

Fluorescence quantum yield

$$\Phi(\lambda) = \frac{\text{photons emmited}}{\text{photons absorbed}}$$

Relative measurement (5% uncert.):

absorbed light (UV/Vis)

$$\Phi_x = \Phi_r \frac{B_r}{B_x} \frac{I_x}{I_r} \frac{n_x^2}{n_r^2}$$

emitted light (fluorimeter)

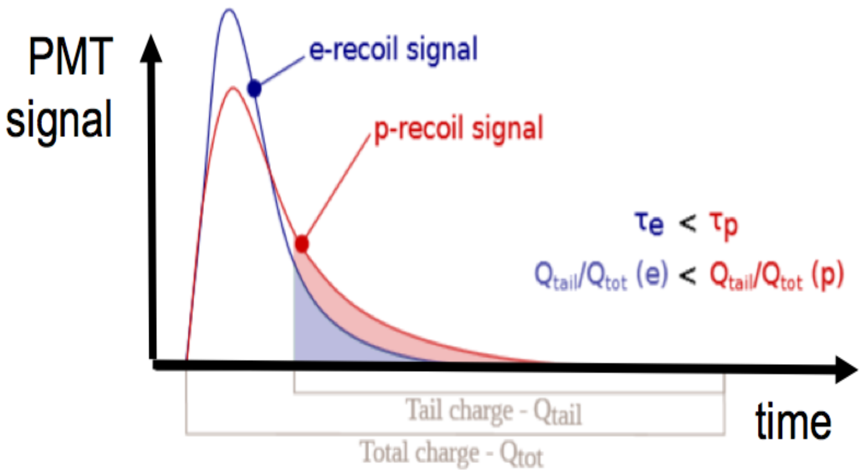
Fluor	Quantum yield
PPO	84 %
butyl-PBD	89 %
BPO	91 %
Bis-MSB	86 %
POPOP	90 %
DPA	91 %

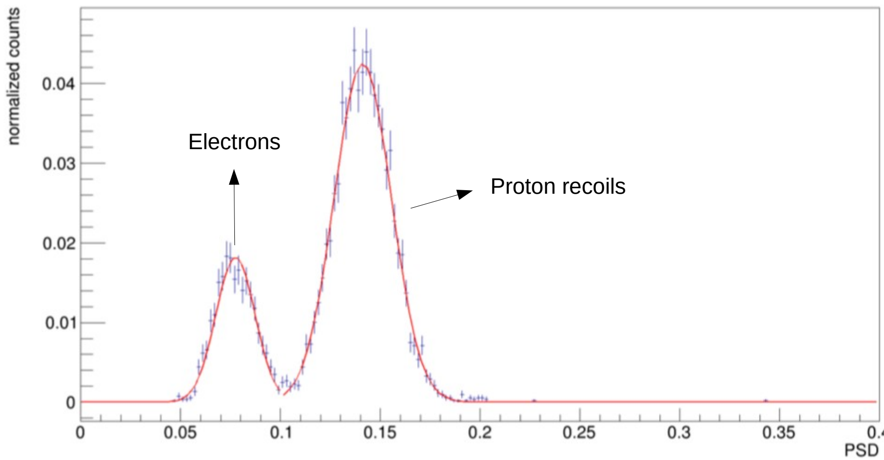
C. Buck, B. Gramlich, S. Wagner, JINST 10 (2015) P09007

- Relevance: light propagation and energy transfer
- Challenges: solvent, concentration and wavelength dependence
- Wide spread of values in literature

Pulse shape discrimination

Delayed fluorescence involving triplet states





$$\mathrm{PSD} := \frac{Q_{\mathrm{tail}}}{Q_{\mathrm{tot}}}$$

A. Bonhomme, C. Buck, B. Gramlich, M. Raab, JINST 17 (2022) P11025

- Relevance: background reduction
- Challenges: Energy dependence, define PSD parameter, reflections
- Light yield setup and AmBe source (ɣ+n); use “late light ratio” method

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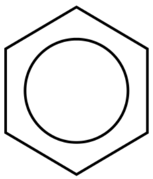
$\overline{\nu}_e + p \longrightarrow e^+ + n$



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Mixing angle θ_{13}

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Sterile neutrinos?

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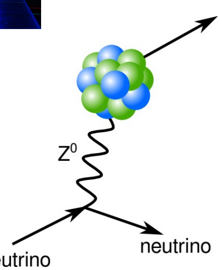
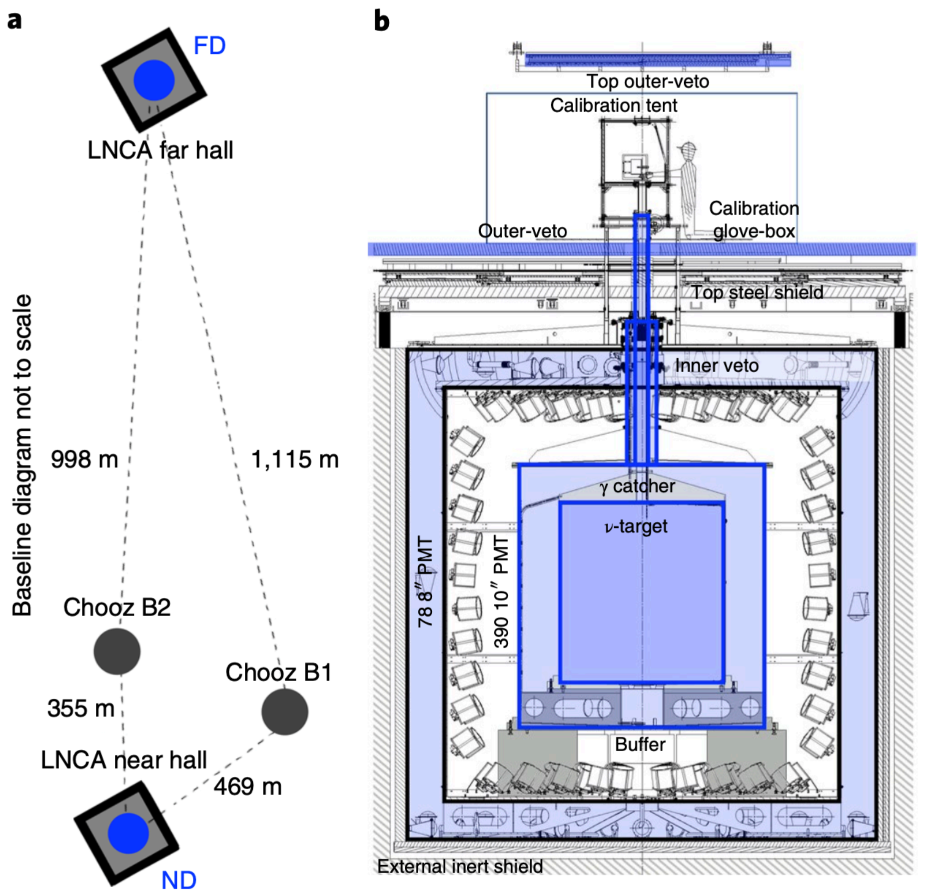


5. CONUS(+)

The Double Chooz detectors

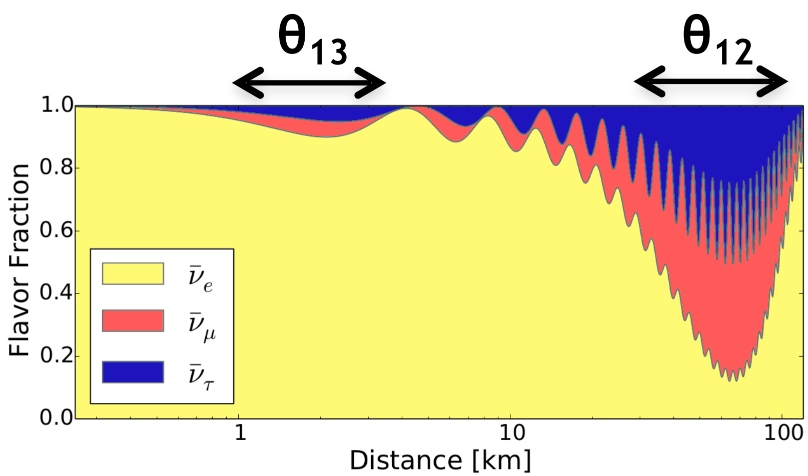
Neutrino oscillation experiment (θ_{13})



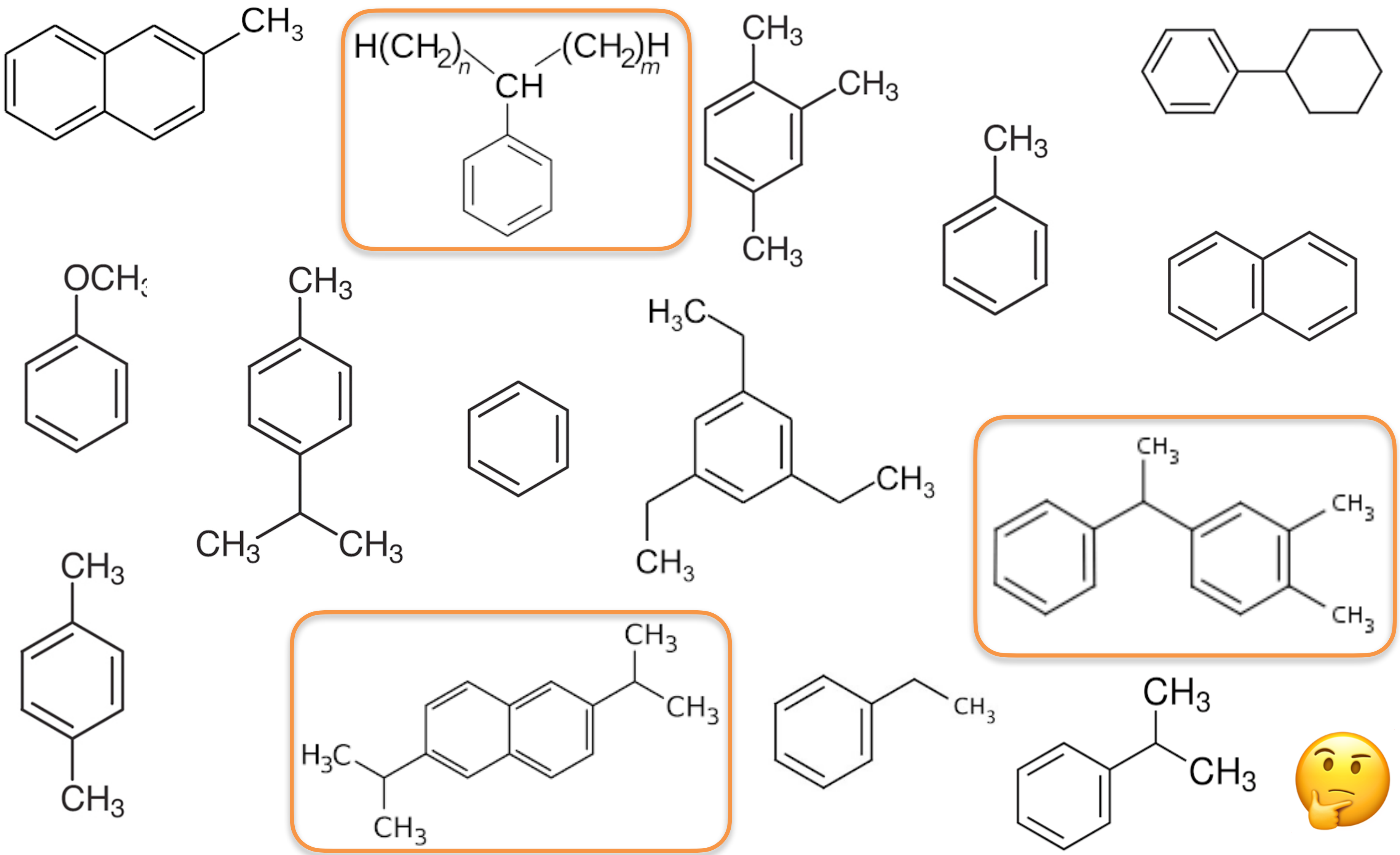
Double Chooz, Nature Physics 16 (2020) 558–564

Detector responsibilities

- Scintillators (~10 m^3 Gd-LS, ~20m^3 unloaded LS)
- Chemical region design
- Liquid and filling systems
- Nitrogen and vent systems
- Source calibration

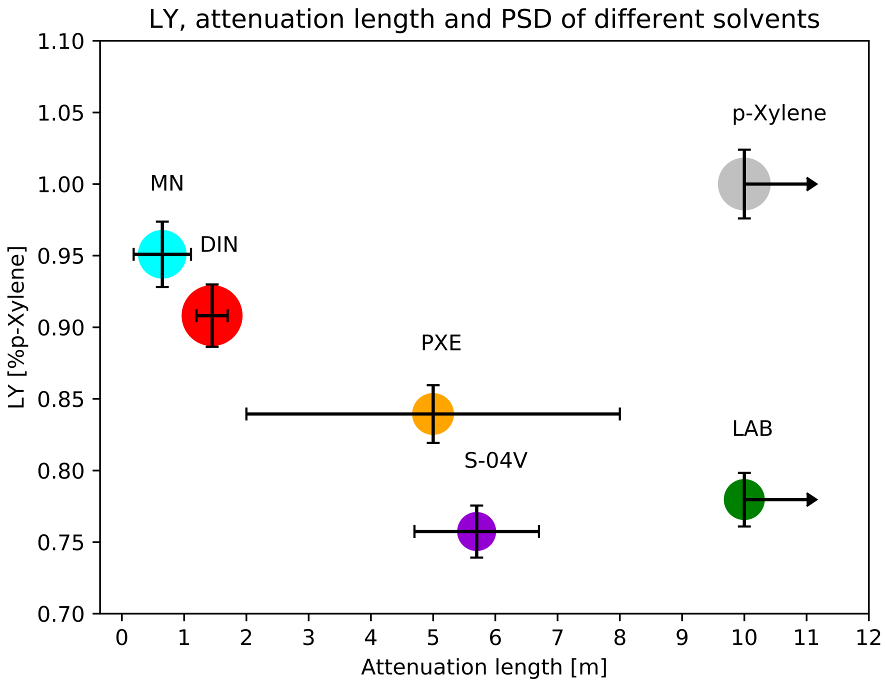


Which aromatic solvent?



Safe scintillators

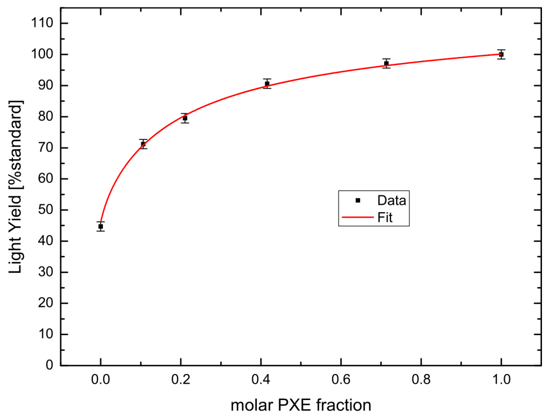
	FLASH POINT	VAPOR PRESSUR
XYLENE	27°C	900 Pa
METHYL-NAPHTALENE (MN)	82°C	200 Pa
LAB	140°C	1.3 Pa
DIN	140°C	0.5 Pa
PXE	167°C	0.1 Pa
POLYSILOXANE (S-04V)	230°C	~10^{-5} Pa



*A. Bonhomme, C. Buck, B. Gramlich, M. Raab, JINST **17** P11025 (2022)*

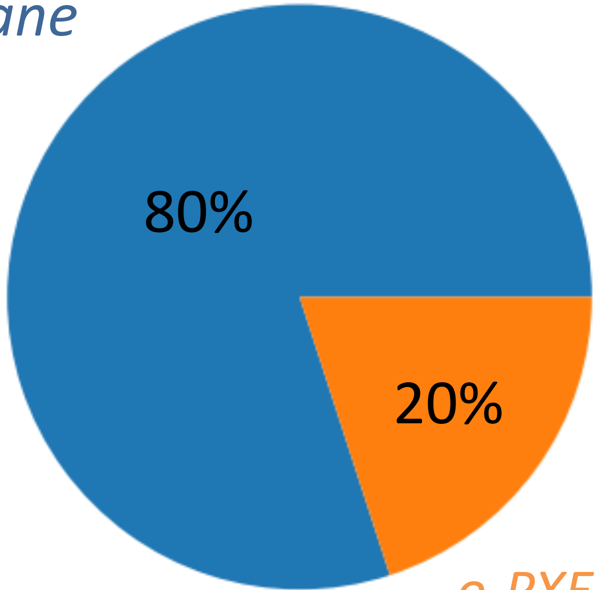
- Results vary with purity, storage conditions, sample prep., supplier,...
- Parameters can be tuned by solvent mixture

Double Chooz solvents



C. Aberle, C. Buck, F.X.Hartmann, S.Schönert, Chem. Phys. Lett. **516** (2011) 257

n-dodecane

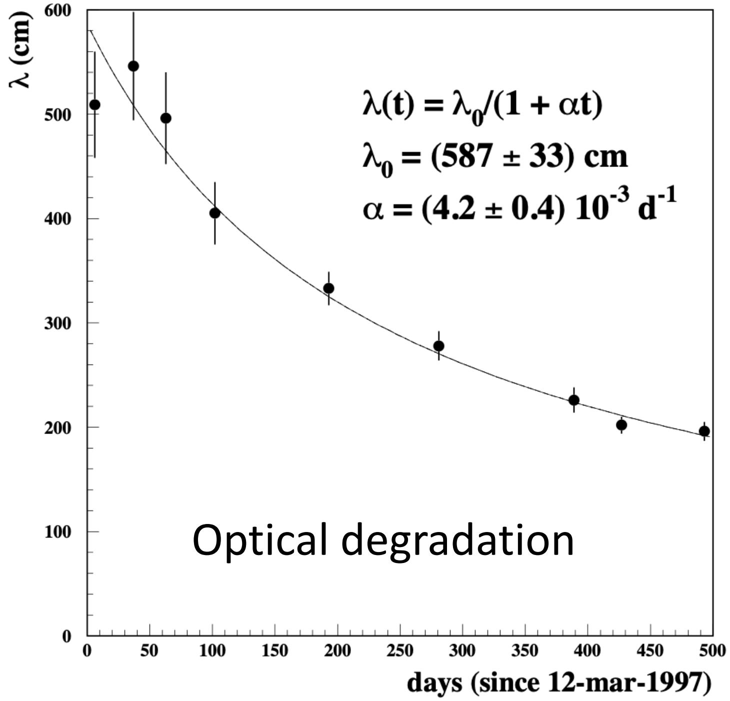


o-PXE (Purified!)

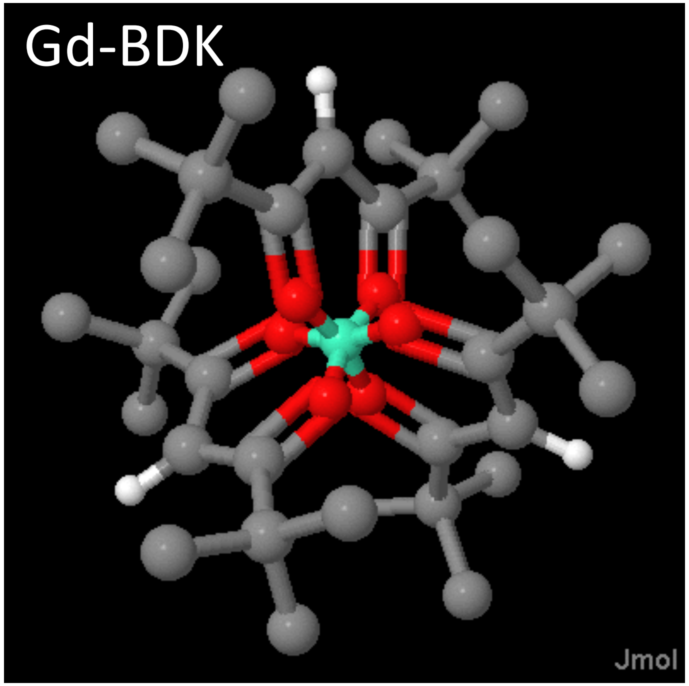
- Why not 100 % PXE? Material compatibility
- Why not LAB? Proton number uncertainty!
- Why n-dodecane? Radiopurity and transparency (KamLAND)

Metal loading

- Prepare and dissolve organometallic complex (1 g/l Gadolinium)
- Option 1: Carboxylate systems: favorable optics
- Option 2: Beta-diketone systems (BDK): radiopurity, **stability**



Goal:
Avoid this!

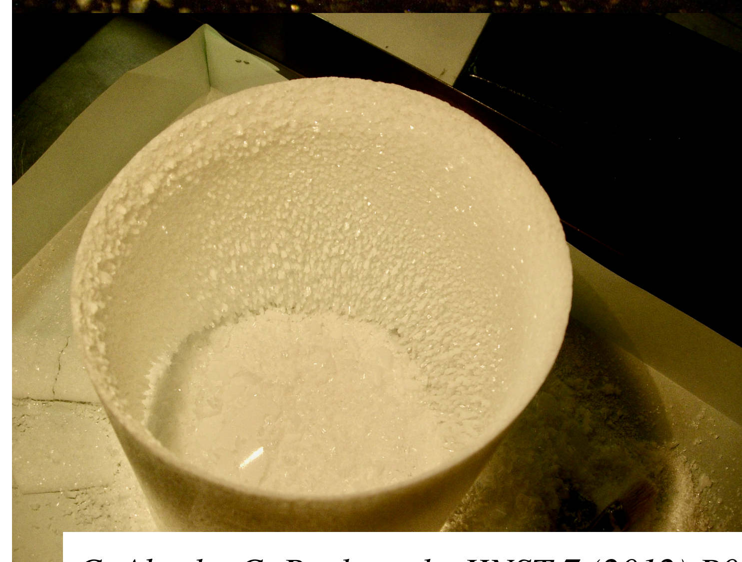


*M. Apollonio et al., EPJ C **27** (2003) 331*

C. Aberle, C. Buck et al., JINST 7 (2012) P06008

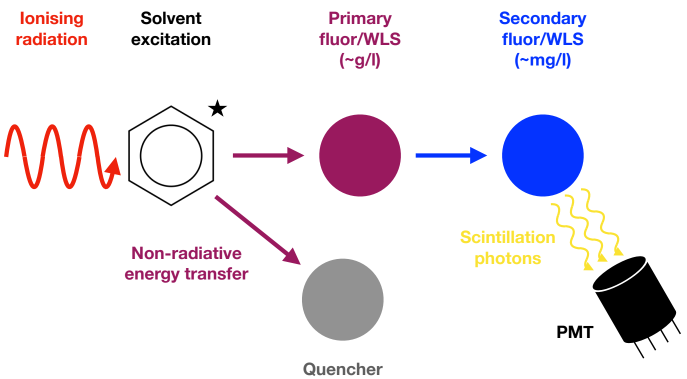
Sublimation of Gd-BDK molecules

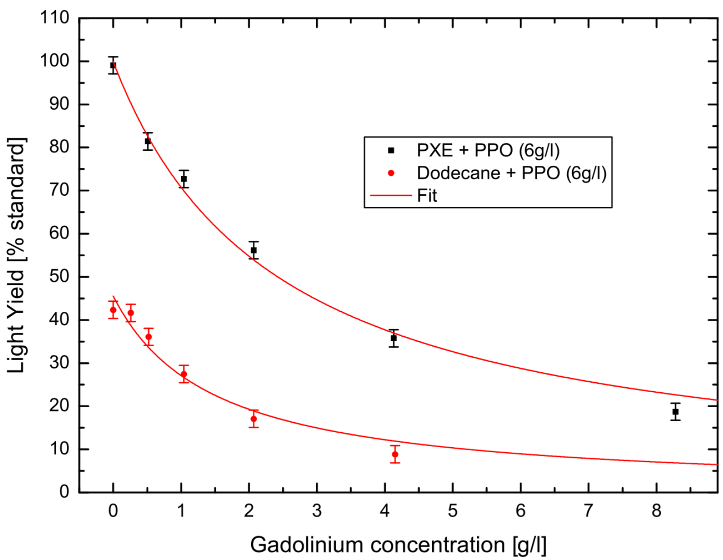
100 kg powder!



C. Aberle, C. Buck et al., JINST 7 (2012) P06008

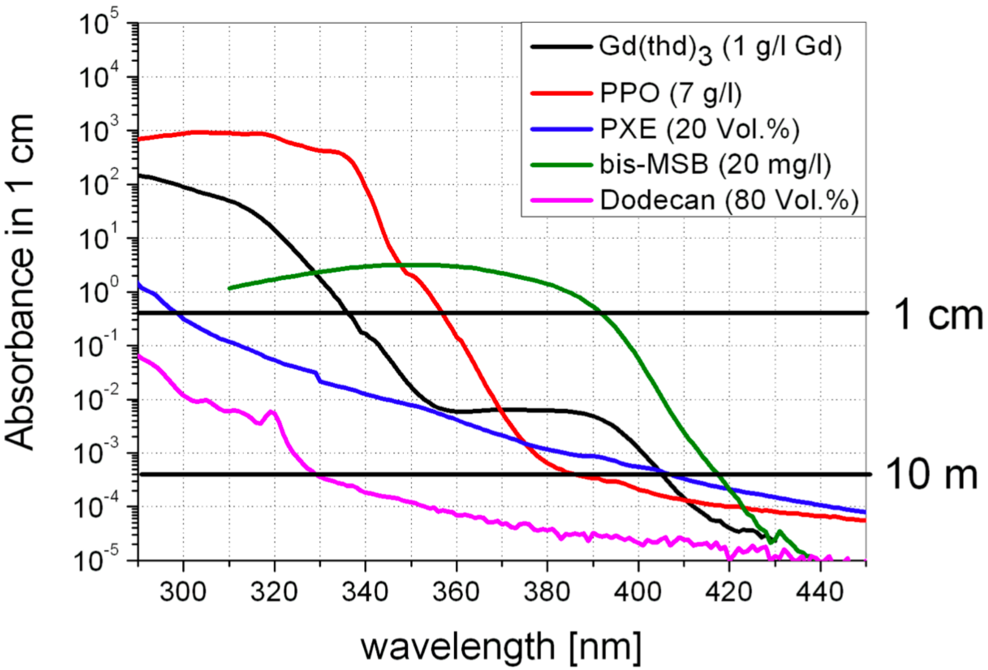
Light quenching





C. Aberle, C. Buck, F.X.Hartmann, S.Schönert, Chem. Phys. Lett. ***516*** *(2011) 257*

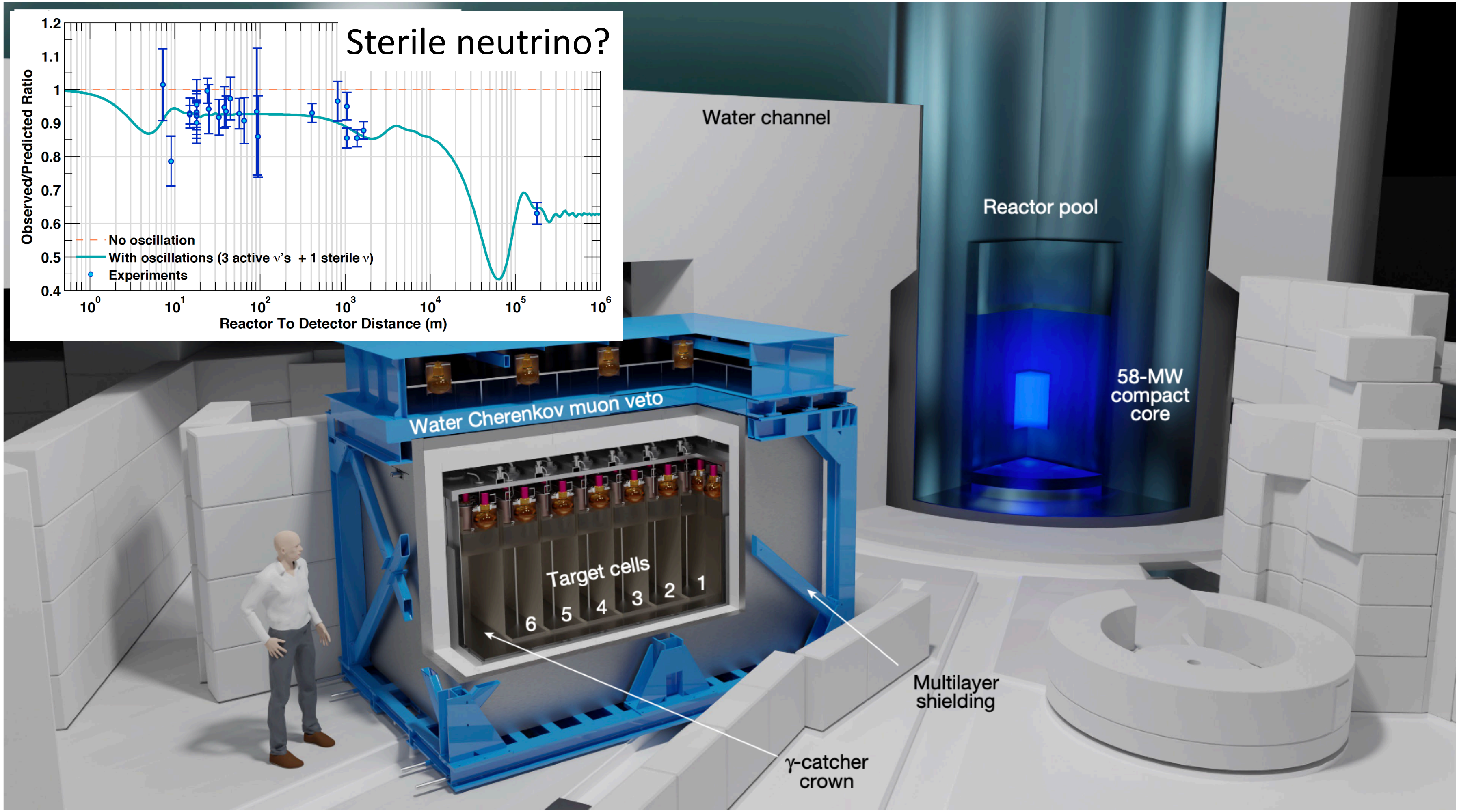
Compensate light loss by increase of primary fluor (PPO) concentration



C. Aberle, C. Buck et al., JINST 7 (2012) P06008

Secondary fluor dominates ~400 nm

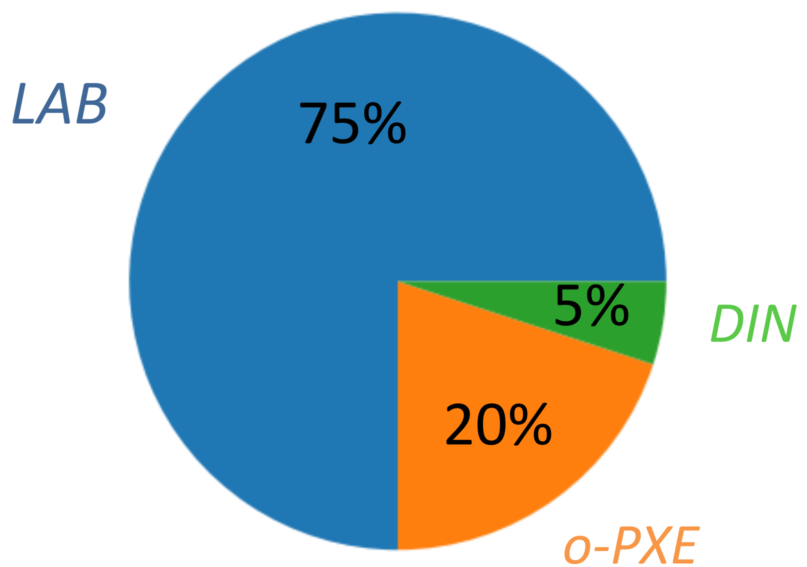
Stereo experiment



Stereo, Nature 613 (2023) 257

Stereo scintillator

- Use same loading technique as in Double Chooz (about 2 t Target)
- Different needs: higher Gd-loading, pulse shape discrimination
- Solvent tuning (light yield, PSD, transparency)



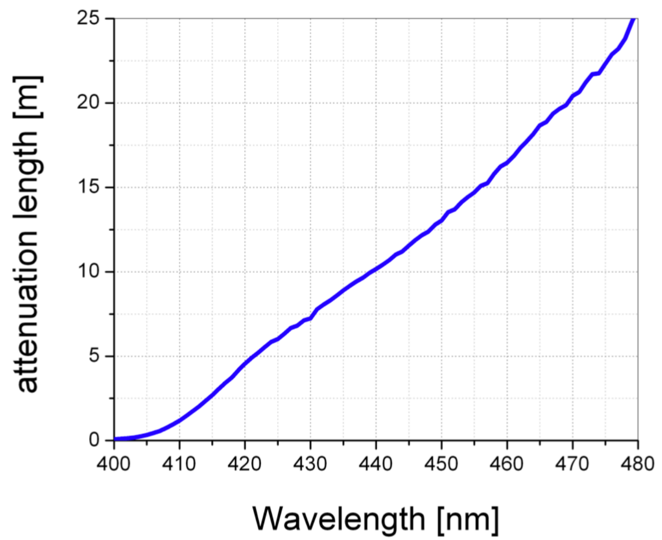
0.2% Gd

Column purification

Transparency of Stereo scintillator

$$\Lambda_i = k \times \frac{M_i}{\epsilon_i c_i}$$

$$\frac{1}{\Lambda_i} = \frac{1}{\Lambda_{LAB}} + \frac{1}{\Lambda_{PXE}} + \frac{1}{\Lambda_{DIN}} + \frac{1}{\Lambda_{PPO}} + \frac{1}{\Lambda_{bis-MSB}} + \frac{1}{\Lambda_{Gd}}$$



Values calculated/measured at 430 nm

Component	LAB	PXE	DIN	PPO	bis-MSB	$Gd(thd)_3$	total
$\Lambda_{Gd-loaded}$ (m)	23	35	33	41	176	94	7.0
$\Lambda_{unloaded}$ (m)	23	35	33	95	176		8.4

Scattering length ~ 25 m

Measured (±10 %): Gd-LS: 6.9 m
GC: 9.7 m

C.Buck, B.Gramlich, M.Lindner, C.Roca, S.Schoppmann, JINST 14 (2019) 01, P01027

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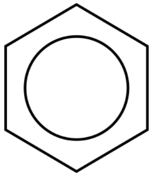

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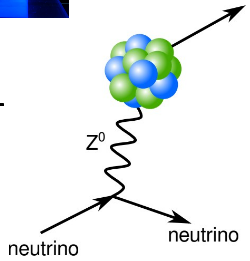
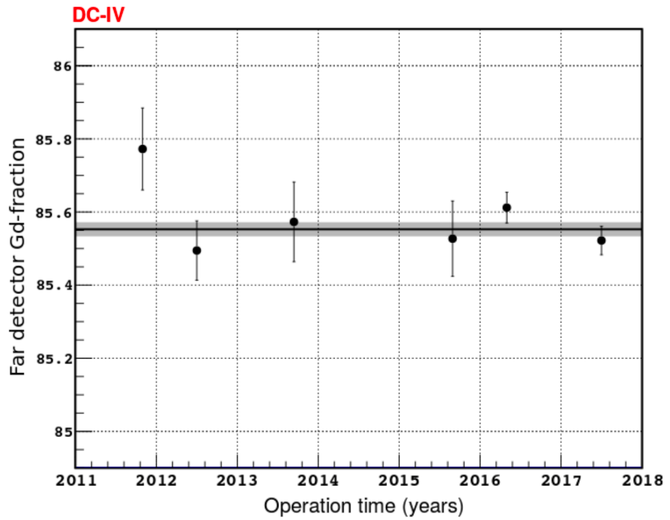
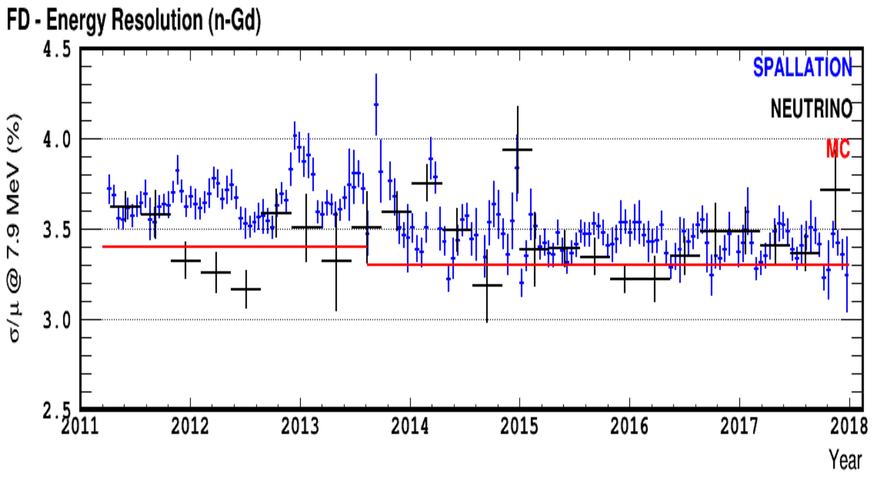


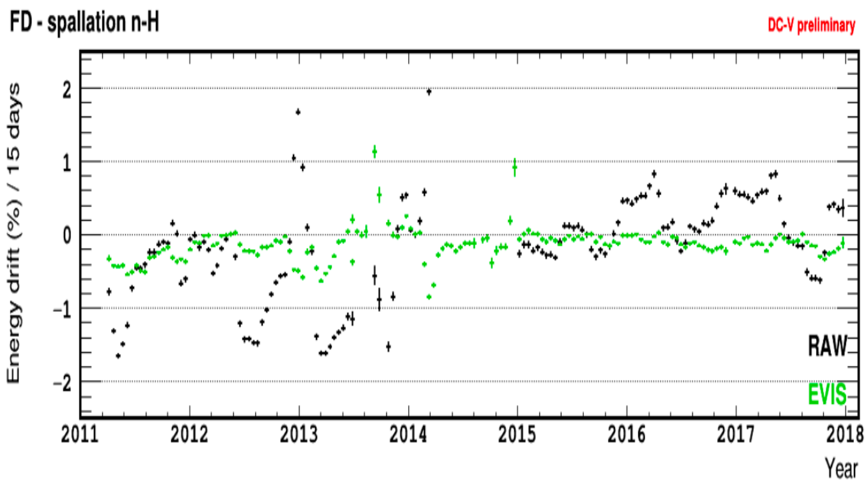
5. CONUS(+)

Double Chooz stability

- First 4 years with one detector only
- No optical degradation in 7 years (stable energy resolution and scale)
- No stratification or plate-out observed (stable efficiency)

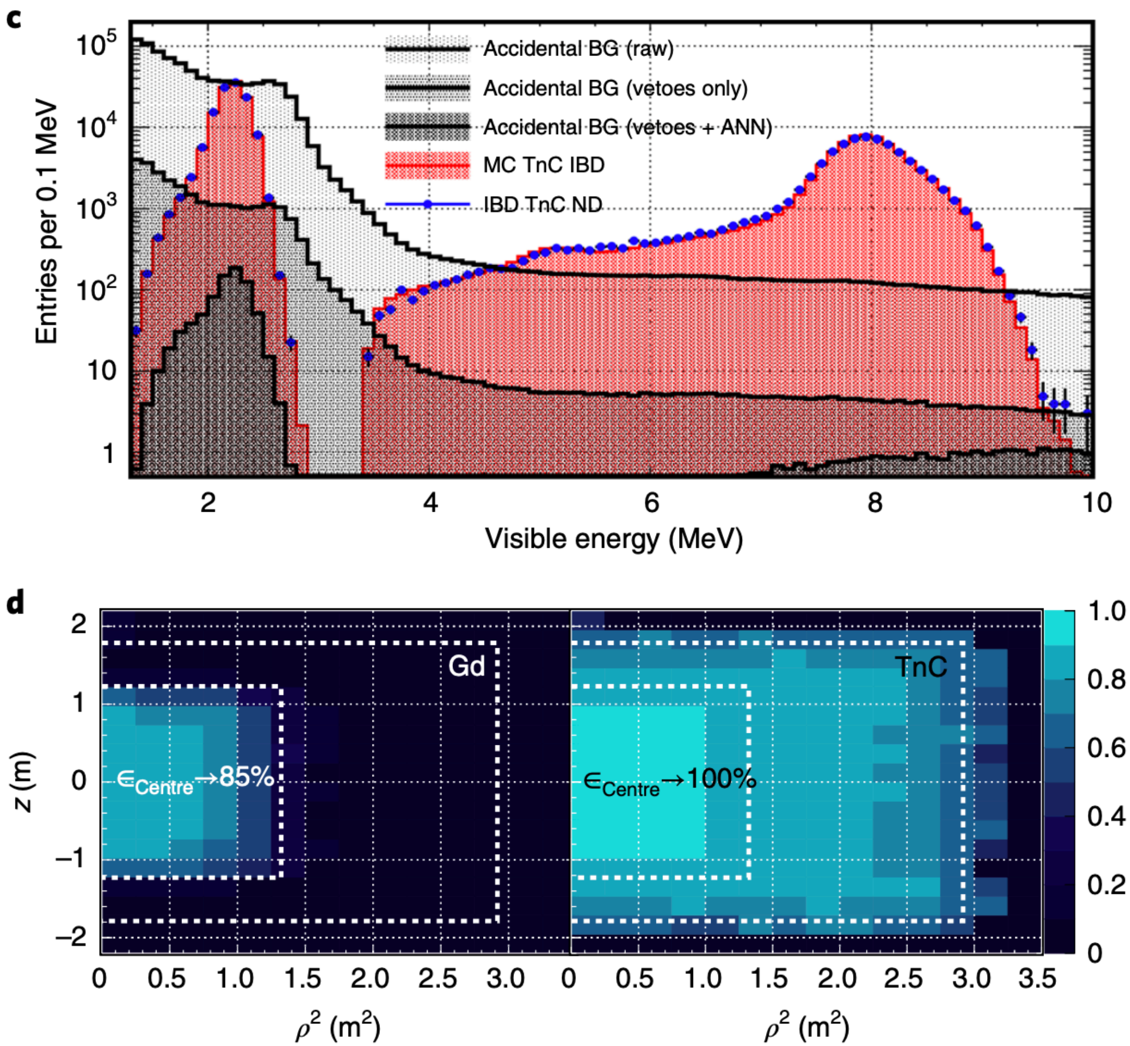






Double Chooz, EPJ C 82 (2022) 9, 804

Radiopurity and TnC technique



Target scintillator

$< 10^{-14}$ g/g U

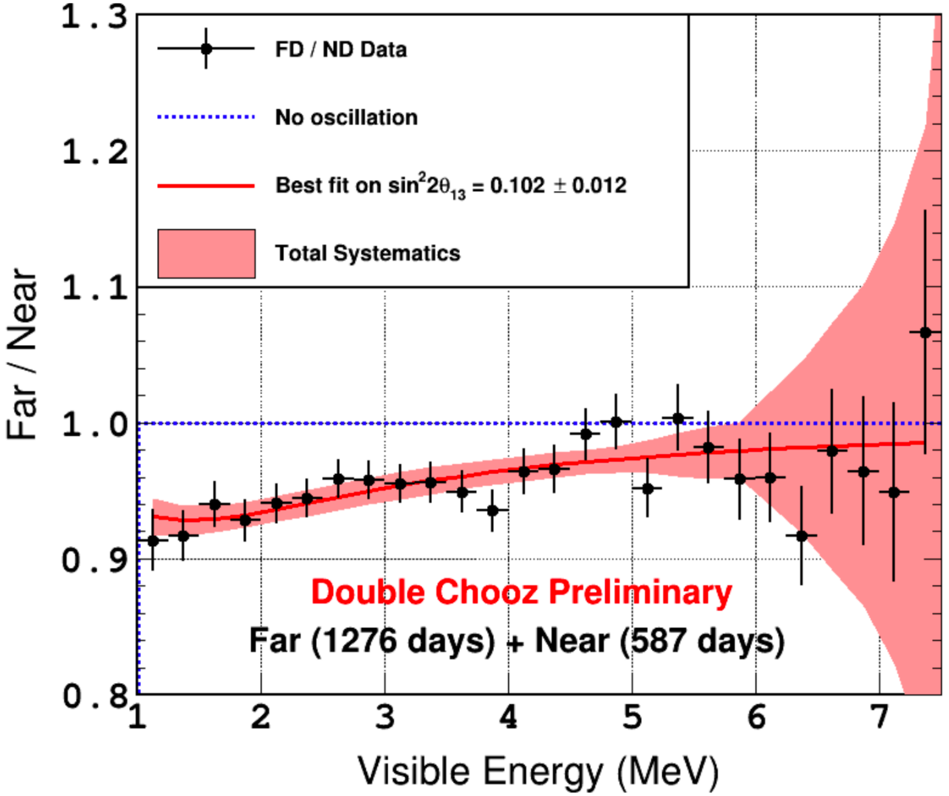
$< 10^{-12}$ g/g Th

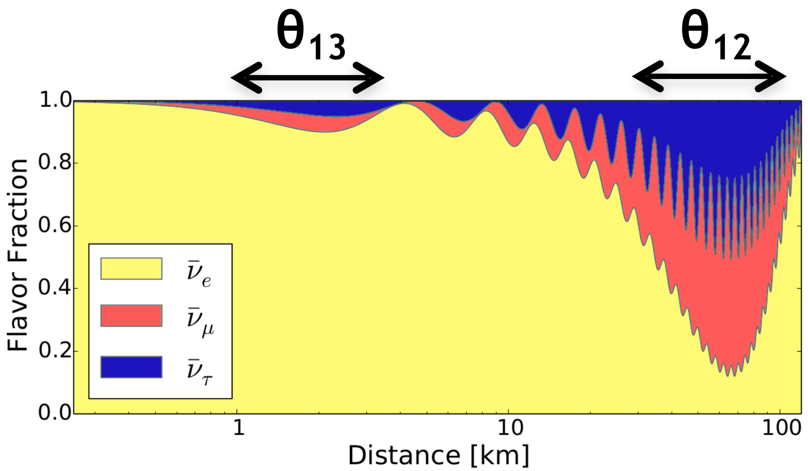
- n-H analysis
- Increase detector volume by factor ~3
- Insensitive to small leaks (near detector)

Double Chooz, Nature Physics 16 (2020) 558–564

Double Chooz oscillation result

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267\, \Delta m^2_{ee}\, L/E_{\overline{\nu}_e})$$





Daya Bay (2023):
$\sin^2(2\theta_{13}) = 0.0851 \pm 0.0024$
RENO (2018):
$\sin^2(2\theta_{13}) = 0.090 \pm 0.007$
Double Chooz (2020):
$\sin^2(2\theta_{13}) = 0.102 \pm 0.012$

Rate + shape analysis

From the least to the best known mixing angle…

Energy scale and "5 MeV bump"

$$E_{vis} = N_{PE} \times f_{MeV} \times f_u(\rho, z) \times f_s(t) \times f_{nl}(E)$$

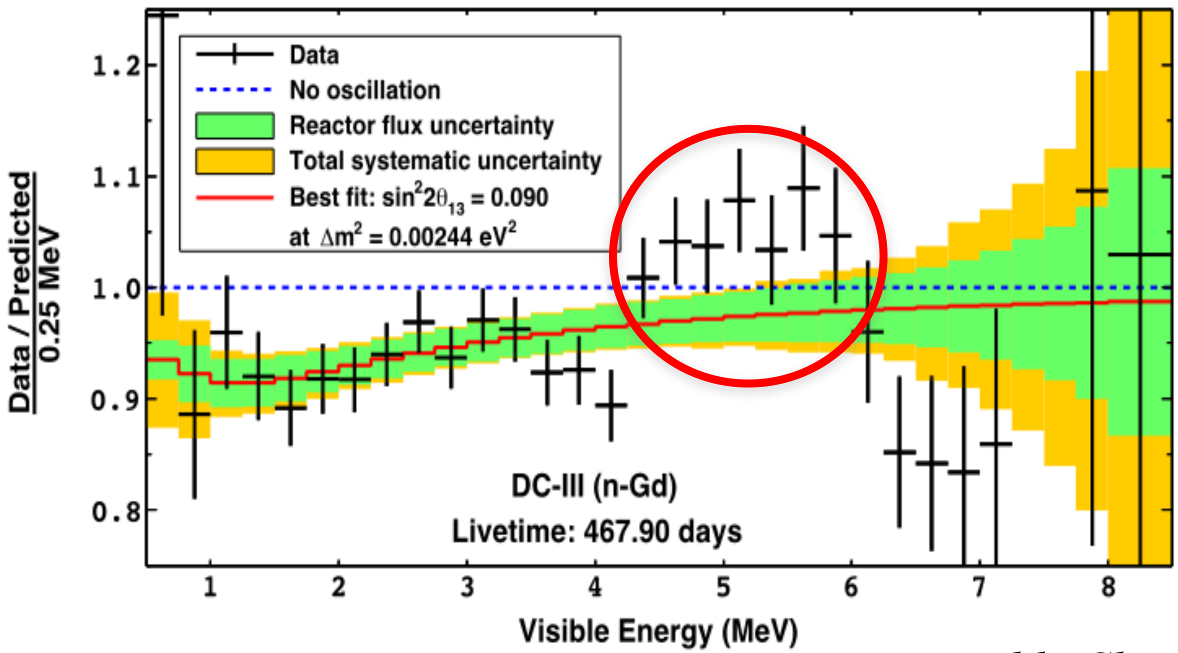
Light yield

n-H from Cf (2.2 MeV)

Uniformity (transparency!)

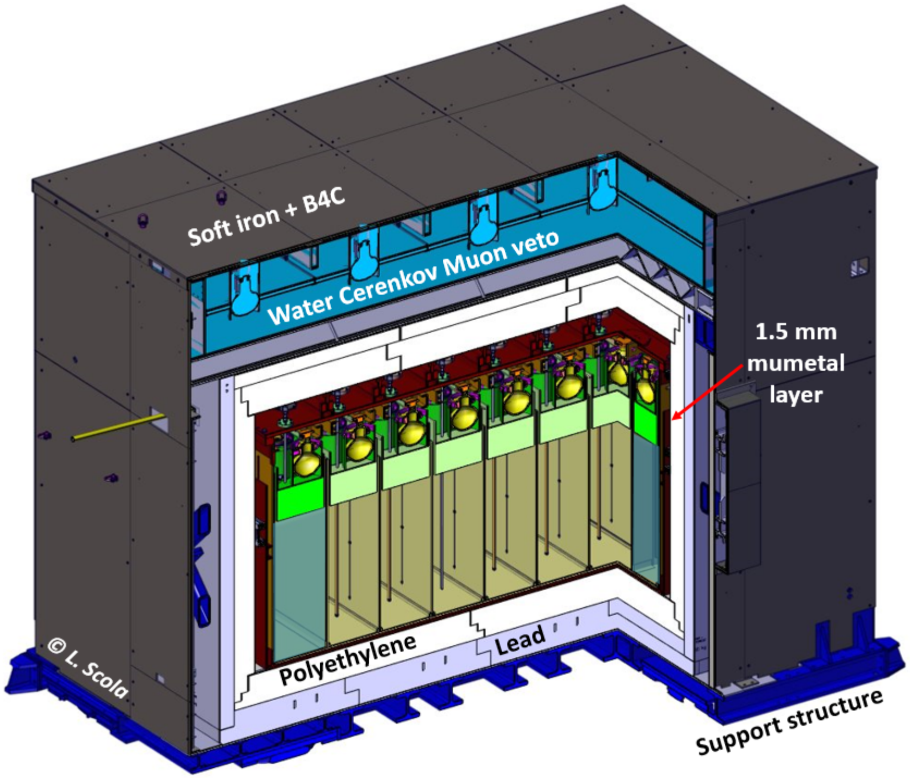
Stability (e.g. PMT gain)

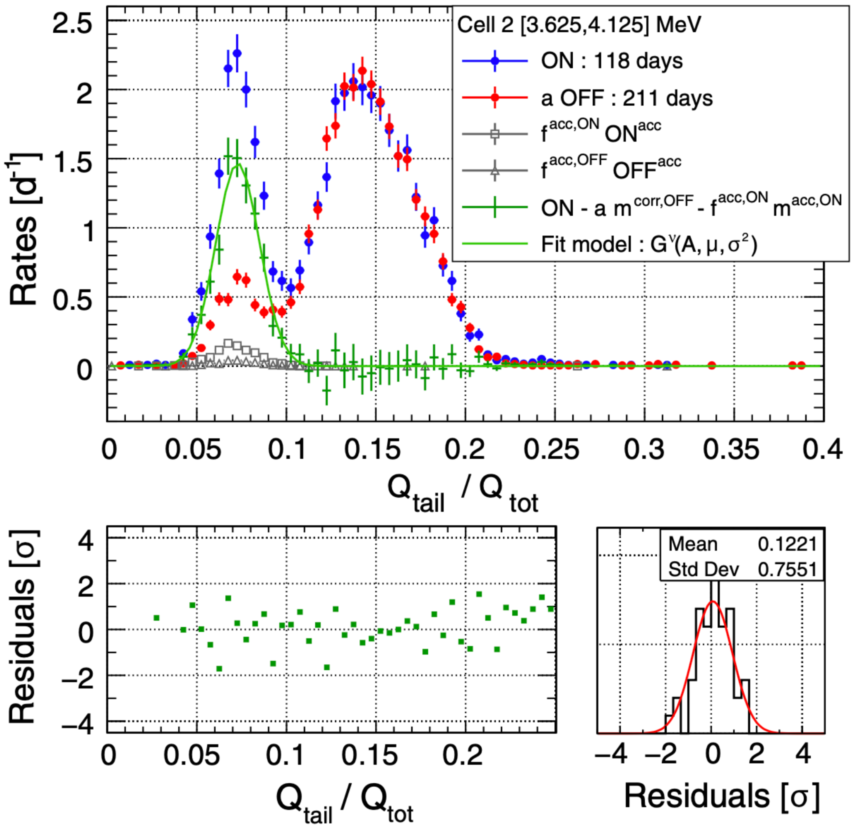
Non-linearity (low E quenching)



Double Chooz, JHEP10 (2014)

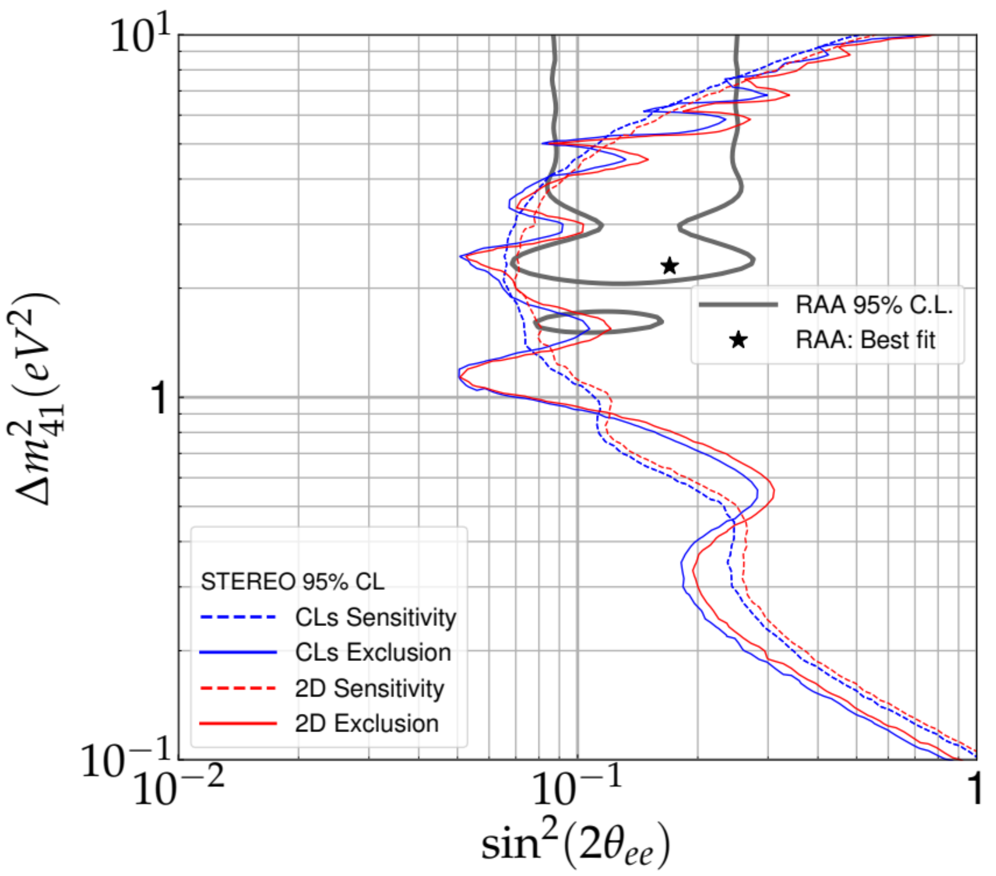
Stereo: signal extraction applying pulse shape discrimination



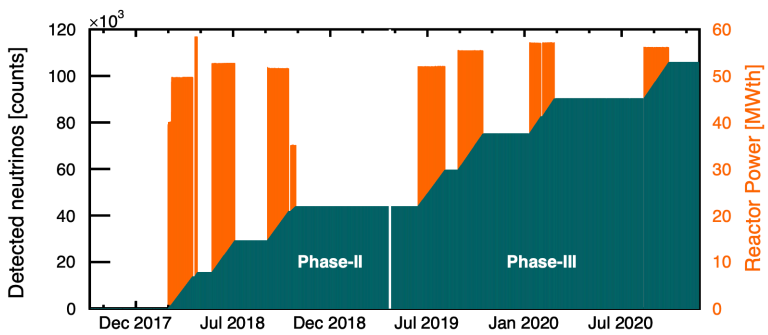


Stereo, PRD 102 (2020) 5, 052002

Oscillation analysis in Stereo

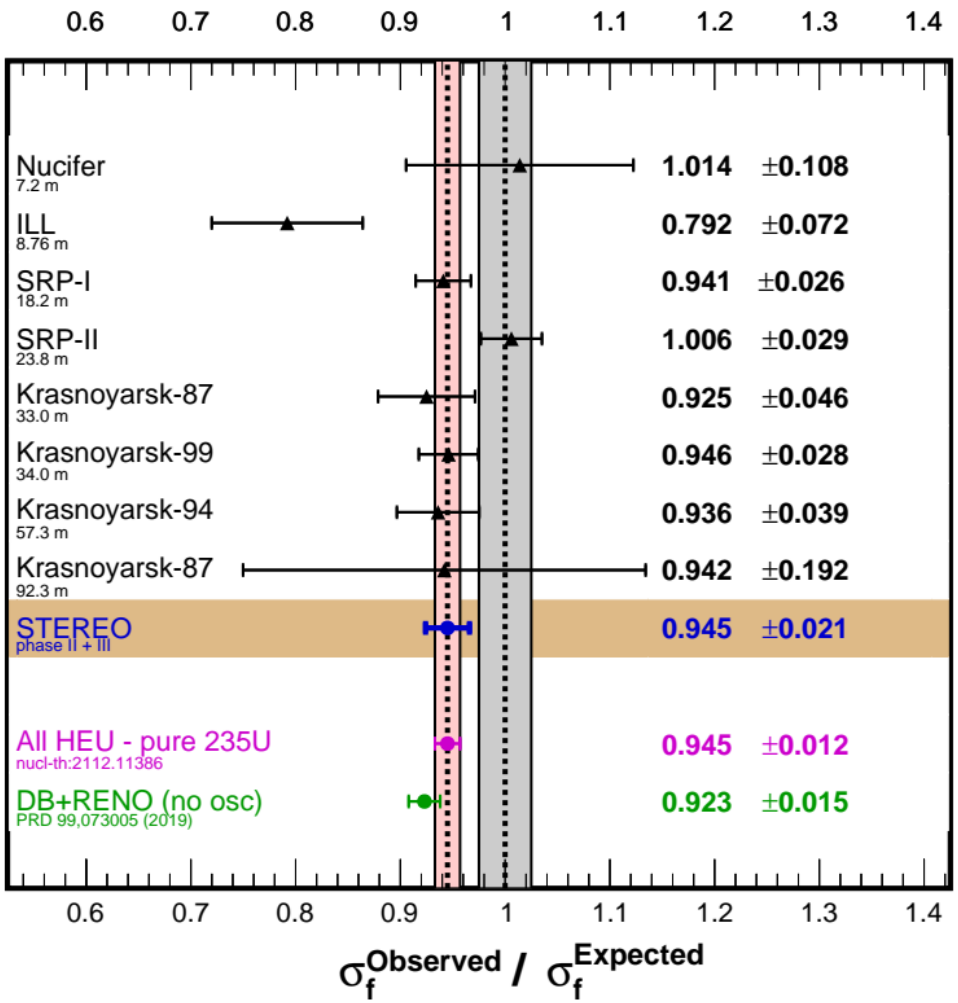


- Data taking 2017 - 2020
- ~400 neutrino interactions per day (total > 100 000!)
- 273 days reactor ON
- 520 days reactor OFF
- Data compatible with no-oscillation hypothesis!



Stereo, Nature 613 (2023) 257 / Stereo, PRD 102 (2020) 5, 052002

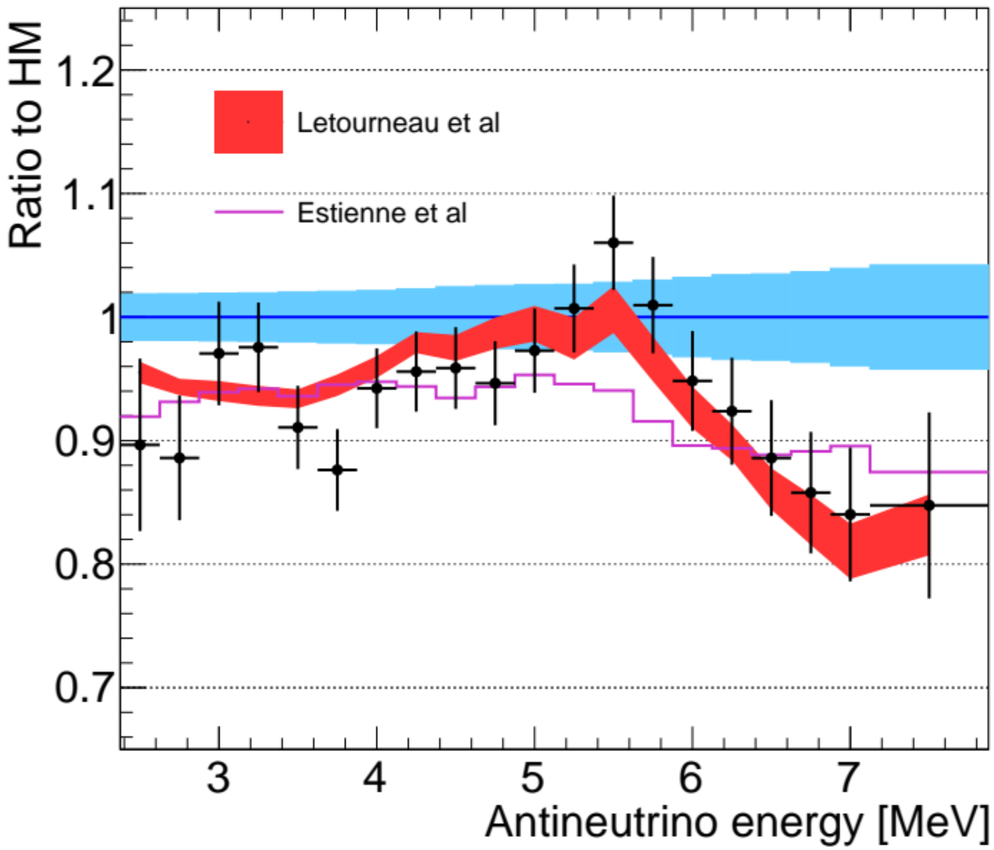
Flux normalisation and efficiency



- Precise **absolute** knowledge on neutron detection efficiency —> scintillator understanding
- Confirmed deficit: 5.5±2.1% reduction
- Relevant contribution of ^{235}U to RAA
- Most precise result for highly enriched uranium reactors (HEU)

Stereo, Nature 613 (2023) 257 / Stereo, PRL 125 (2020) 20, 201801

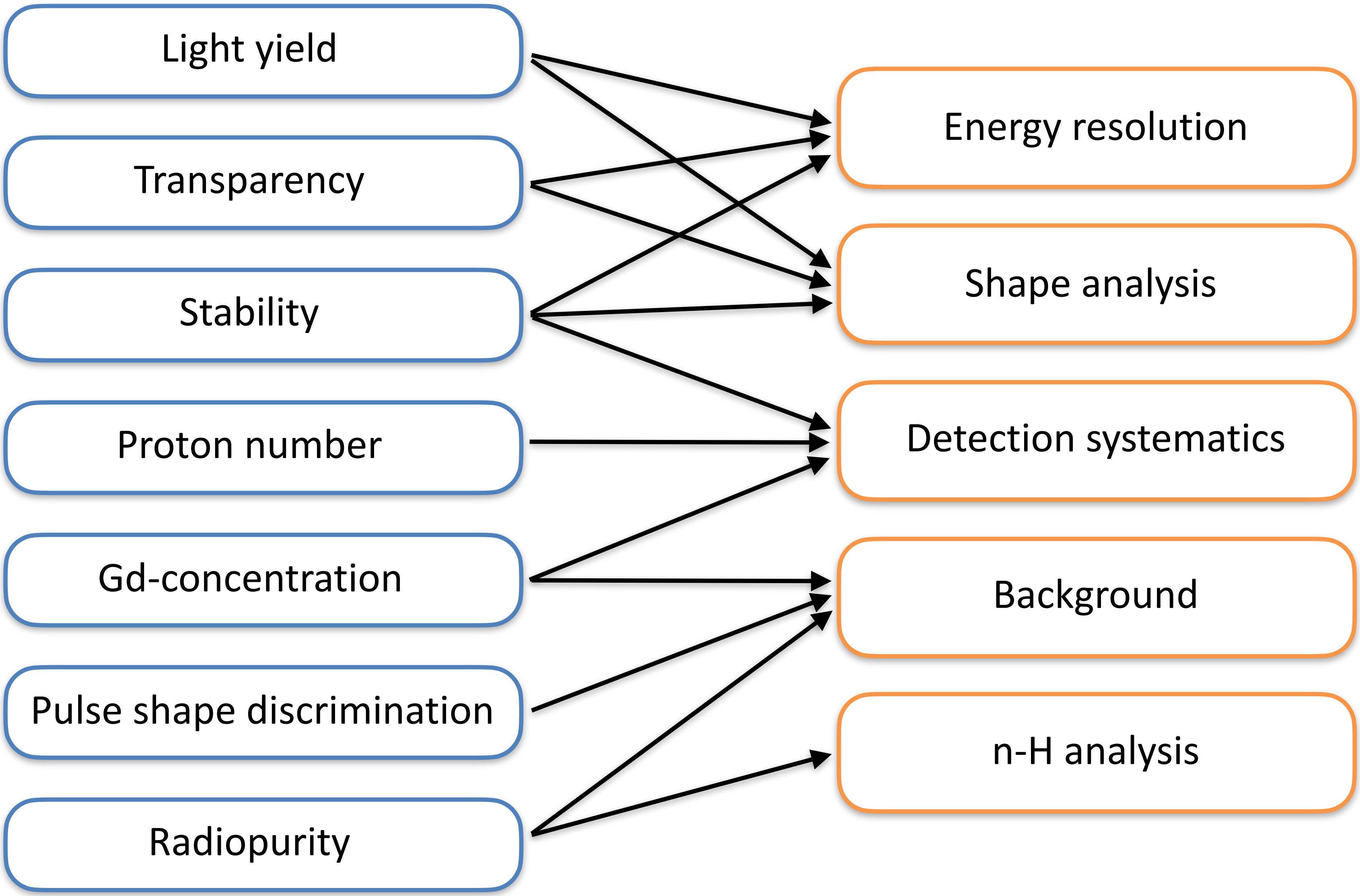
Spectral distortion in Stereo



- Combine cell spectra
- Compare to different model predictions (Huber/Mueller)
- 5 MeV bump confirmed
- Joint analysis with Prospect
- Global picture: anomalies from biases in nuclear data/ measured beta spectrum ^{235}U
- Precision era: use neutrino to validate nuclear data

Stereo, Nature 613 (2023) 257 / Stereo, J.Phys.G 48 (2021) 7, 075107

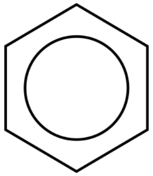
Relevance of some scintillator properties



Outline

1. $\bar{\nu}_e$ detection in organic liquids

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



2. MPIK scintillators

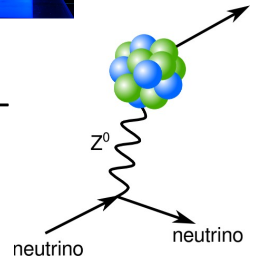
Mixing angle θ_{13}

3. Performance in experiments

Sterile neutrinos?

4. New developments

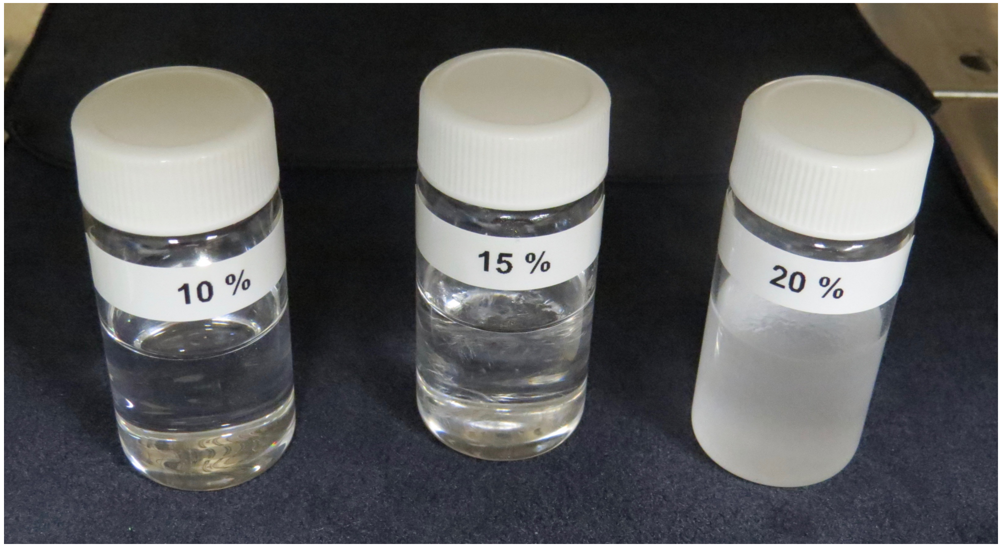
Coherent elastic ν-nucleus scattering

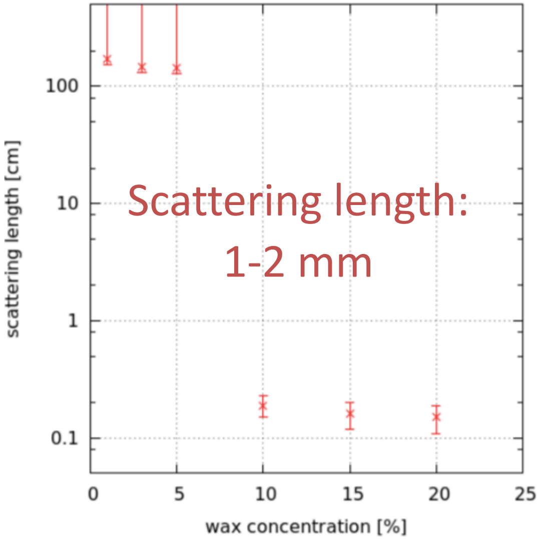


5. CONUS(+)

Opaque scintillators

- Light collection at origin using fibers + fast readout
- Highly improved vertex resolution by light confinement
- Wax based scintillator (NoWaSH)
- High metal loading possible (up to 10%), suspensions
- Potential applications: reactor, geo, 0νββ, solar,…

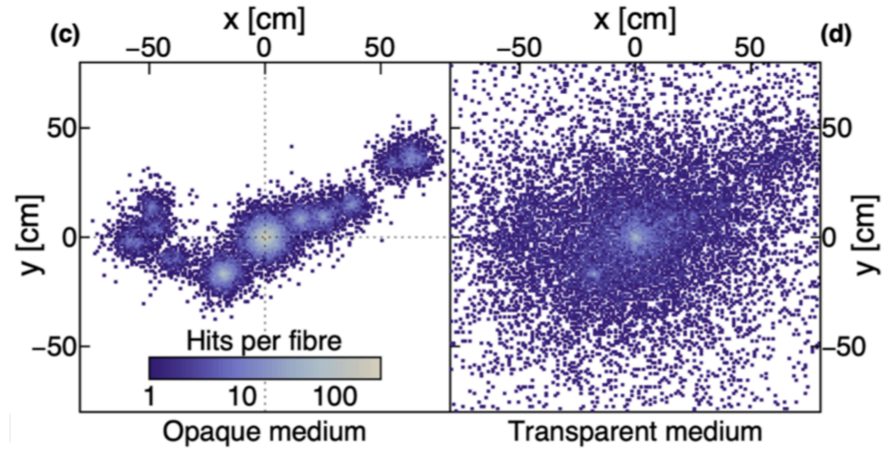


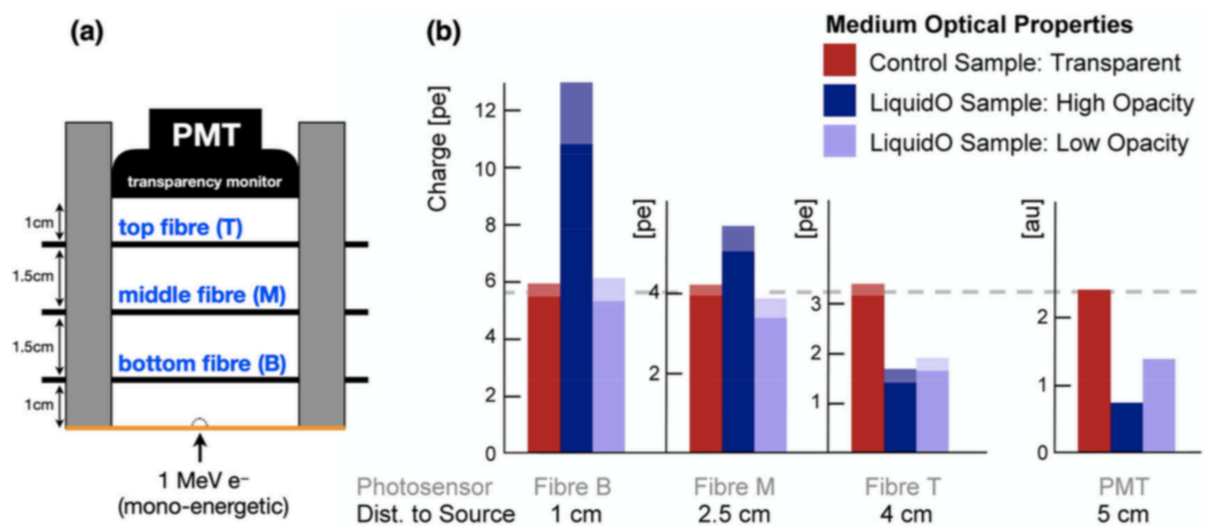


C. Buck, B. Gramlich, S. Schoppmann, JINST ***14*** *P11007 (2019)*

Proof of principle

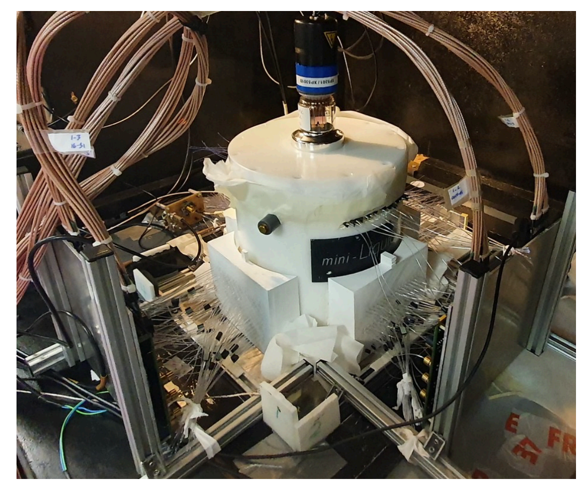
Micro-LiquidO with NoWaSH:
- 0.25 liter prototype
- Point-like e⁻ source (1 MeV)
- ~ mm instead of ~10 cm resolution
- New: Mini-LiquidO (64 fibres)





A. Cabrera et al., Commun.Phys. 4 (2021) 273

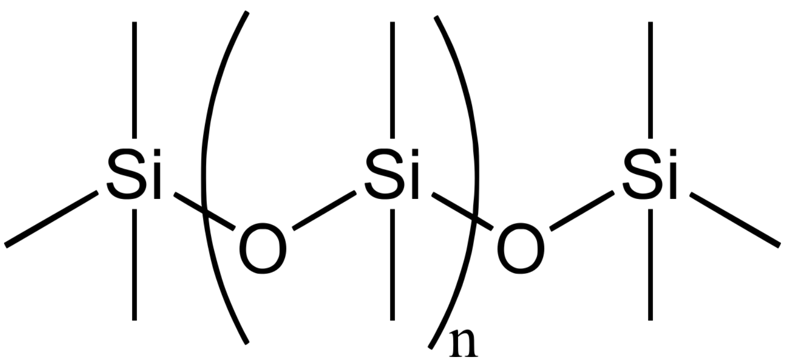
10 liter scale



D. Navas, Rencontres de Moriond 2023

Gel-like scintillators (silicon oils)

- Pros
  - Safety
  - High density, higher Z
  - Less sensitive to leaks
  - Stability
- Cons
  - Costs
  - Purity?



- Si-O backbone (strong!)
- Side chains: methyl and phenyl groups

Other approaches: quantum dots, water based liquid scintillators

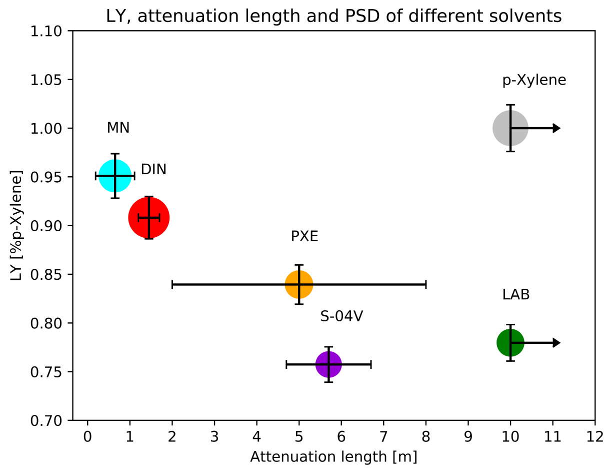
Which scintillator for which experiment?

First define your primary goals, main requirements

High LY, PSD: DIN

↓

Fast neutron detector (particle identification)



Transparency: LAB

↓

Large detector (e.g. JUNO)

Safety: Polysiloxane

↓

Special environment, Veto

Background: Opaque

↓

Shallow depth

Other factors: costs, density, H fraction, material compatibility,…

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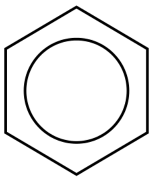

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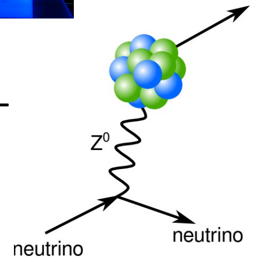
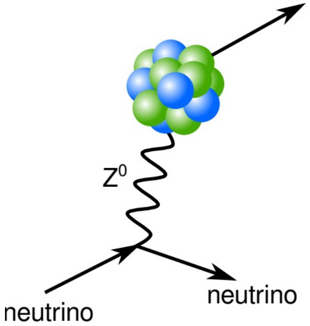


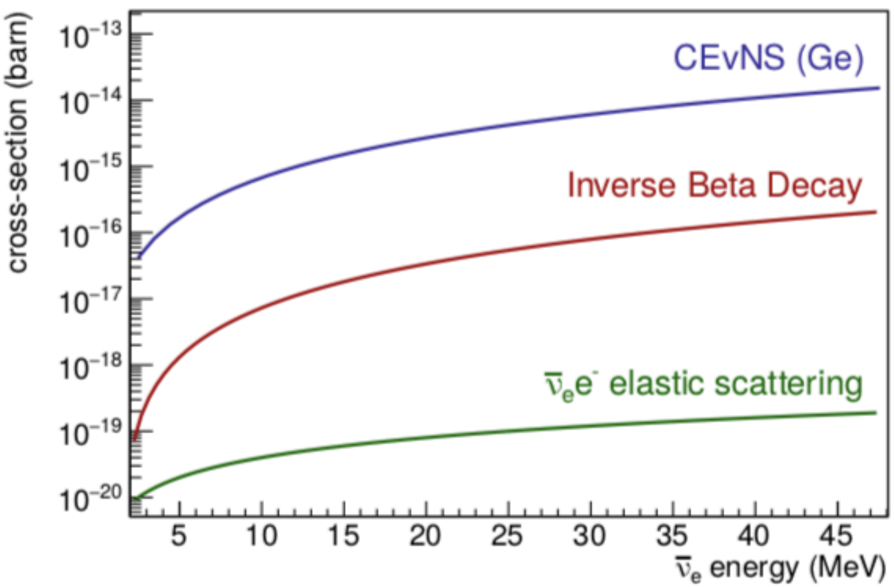
5. CONUS(+)

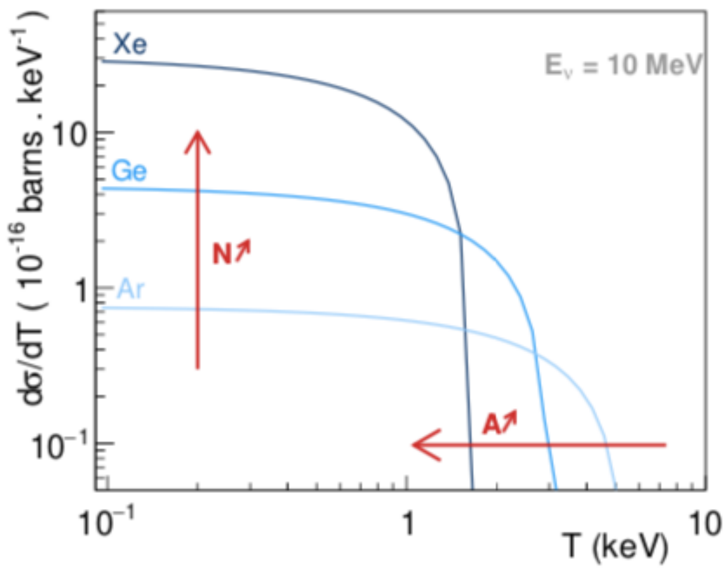
Coherent elastic neutrino nucleus scattering (CEvNS)



$$\frac{d\sigma}{d\Omega} = (\frac{G_F}{4\pi})^2 (N - Z(1-\sin^2\theta_W))^2 \cdot E_\nu^2 \cdot (1+\cos\theta) \cdot F^2(Q^2)$$

$$\rightarrow \sigma_{tot} \propto N^2$$

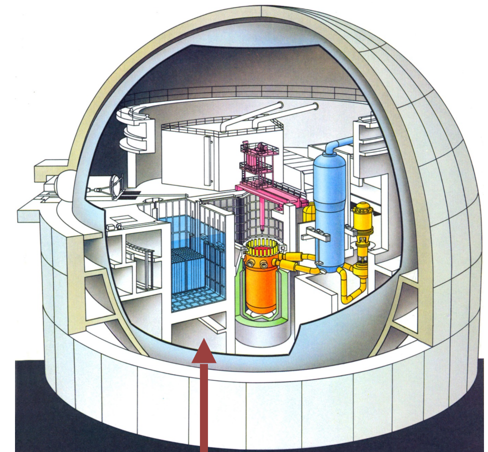




Predicted in 1974, first detected at pion decay-at-rest source 2017

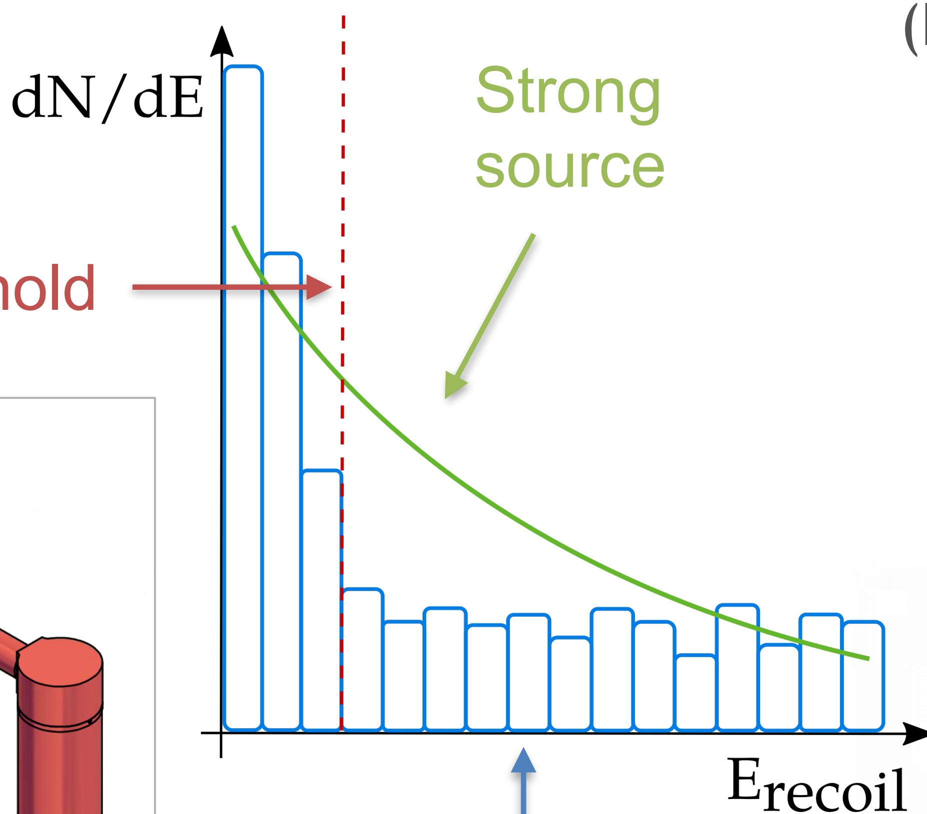
CONUS concept

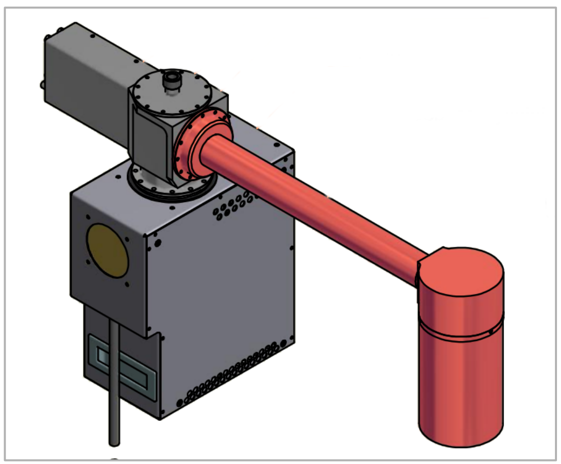
Nuclear power plant (Brokdorf, KBR, 17m)



Strong source

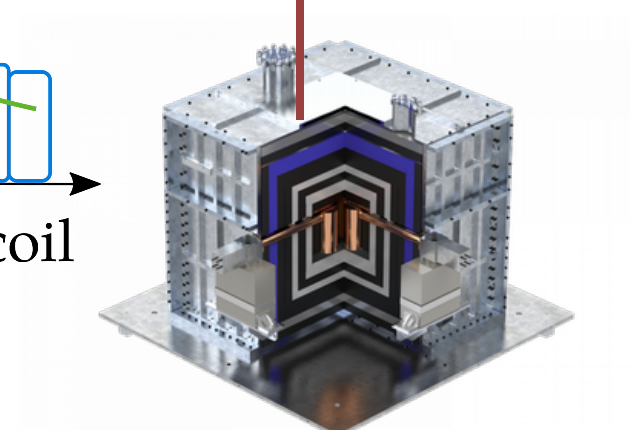
Low threshold





4 x 1 kg point contact HPGe spectrometer

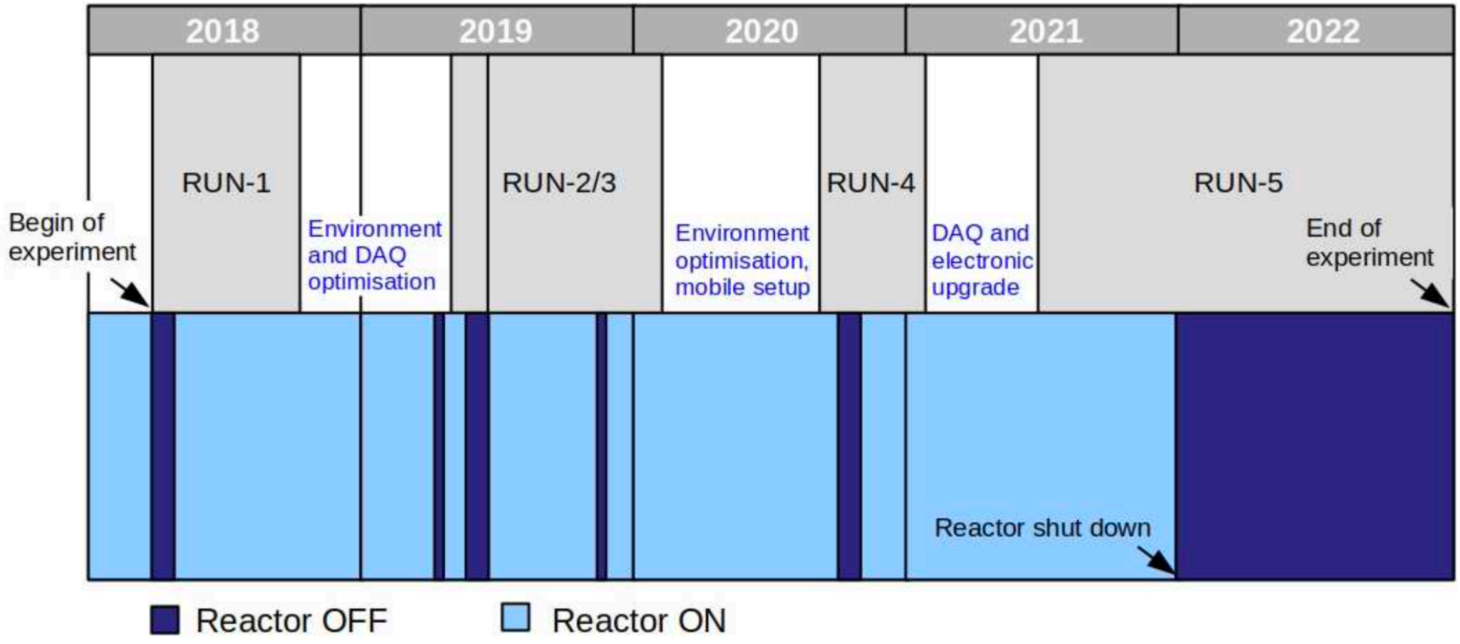
Low background



Shield (11 t, 1.6 m³)

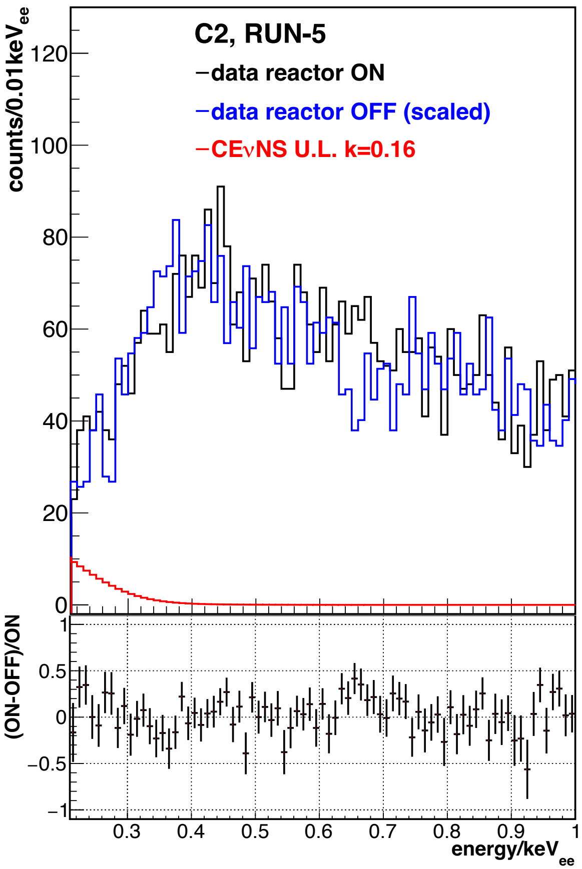
Run-5: improved analysis

Detectors	ON [kg d]	OFF [kg d]	E threshold [eV]
C1, C2, C4	~450	~300	210



- Improvements: stability, DAQ, E threshold, PSD, reactor OFF…
- Background level: ~10/(keV d kg)

New result

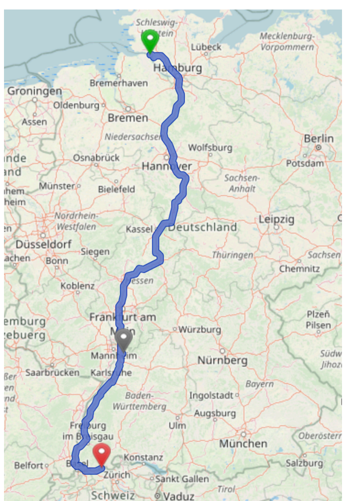


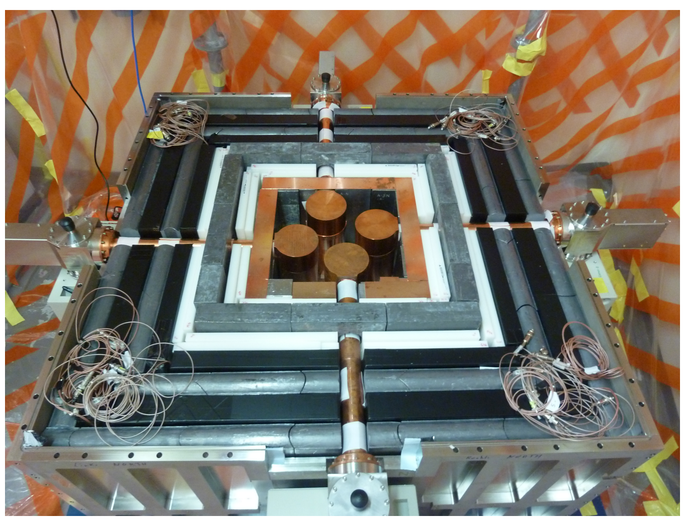
Detector	Signal prediction	Fit constraint (90% C.L.)
C1	42±8	< 59
C2	26±5	< 75
C4	24±4	< 90
All	92±10	< 163

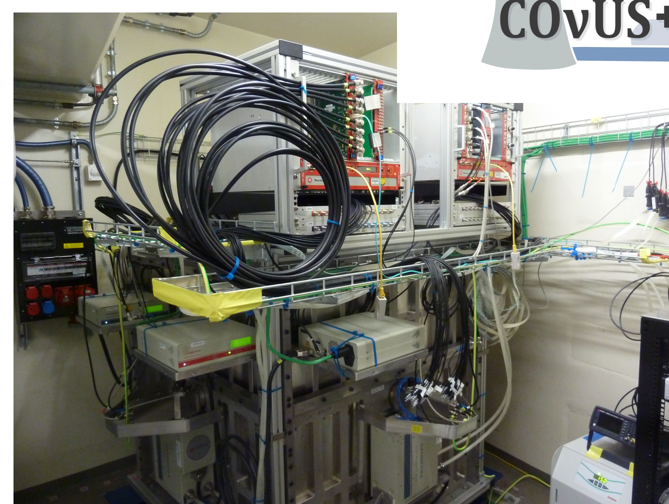
- Limit factor ~2 above predicted SM value (strongest limit at reactor)
- ~ 1 order of magnitude improvement as compared to Run-1+2!

CONUS+

- Site characterisation (d=20.7 m): gamma, neutron and muon flux
- Further improve energy resolution, detector thresholds, trigger efficiency and muon veto performance
- Improved CONUS setup installed this Summer at KKL Leibstadt, CH
- Start of Run-1: 09 Nov 2023 (< 1 y from data taking at KBR to KKL)

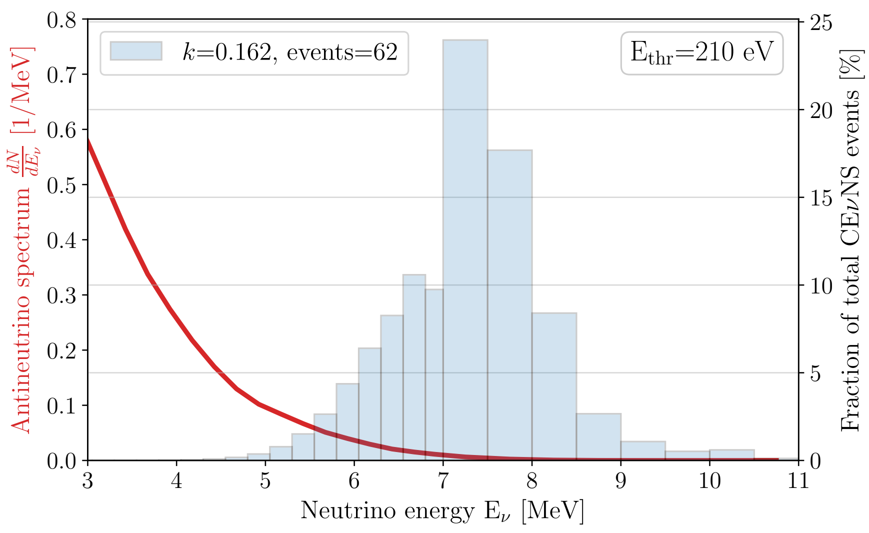


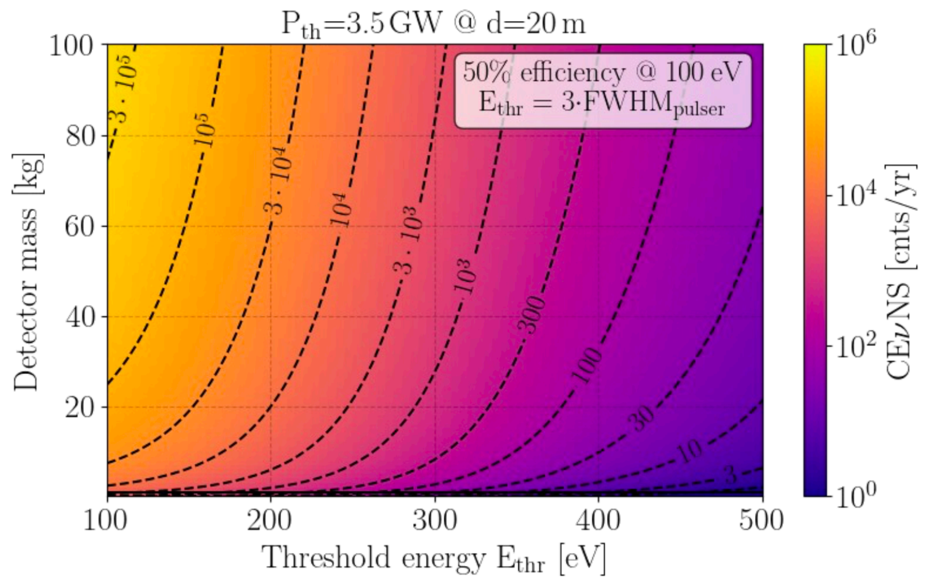




Signal rate expectation

- Low threshold key for high statistics (noise and efficiency)
- Compensate slightly longer distance by improved detectors

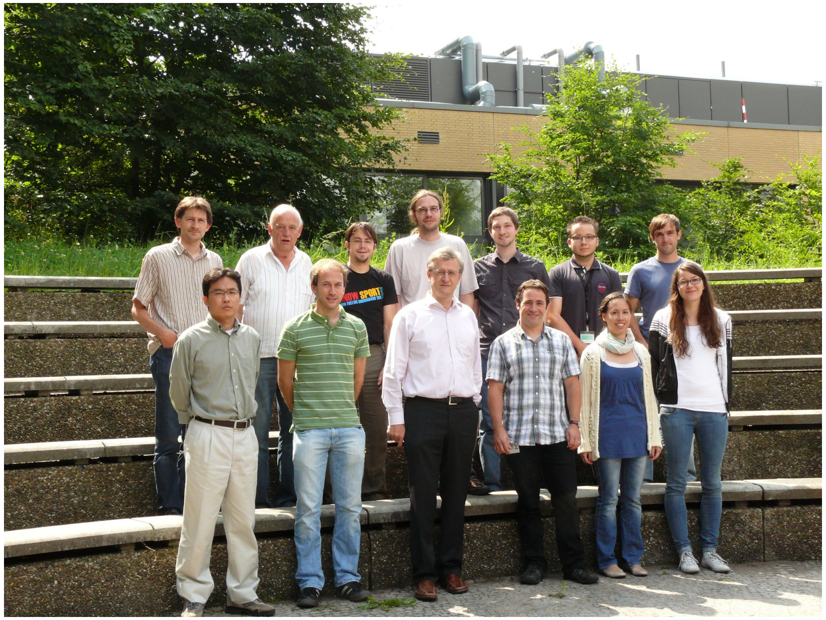




Most relevant contributions (personal bias)

- Double Chooz:
  - Unique stability of Gd-scintillator
  - Unblock situations during "DC crises" when things seemed stuck
- Stereo:
  - Scintillator design: good compromise between light yield, PSD and transparency found with 3 solvent mixture
  - Design of liquid and gas systems
- CONUS:
  - Achieving stable conditions in reactor ON and OFF phases
  - Smooth movement of setup from KBR to KKL control zone
- Working with many talented master, PhD and PostDocs. Thank you!

Double Chooz MPIK group



Stereo MPIK group

CONUS group (including 2 external collaboration members)