CLOUD

The first reactor antineutrino experiment using the novel LiquidO detection technology

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On behalf of the CLOUD collaboration

20 July 2024

ICHEP 2024 PRAGUE

ichep2024.org

42nd International Conference on High Energy Physics

18-24 July · 2024 · Prague · Czech Republic

C L U D

Ciemat

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

cfp

CIEMAT

física de partículas

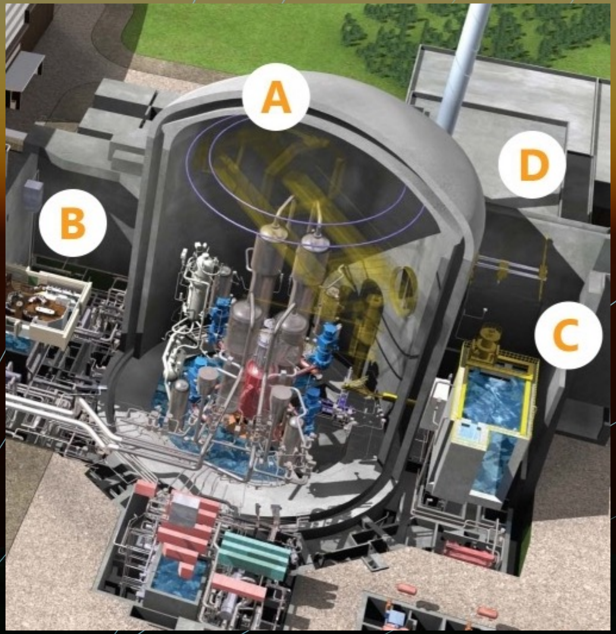
Welcome back to Chooz…


eDF
Baseline: ≥30 m (Ultra Near Detector site @ Chooz)

AntiMatter Tech

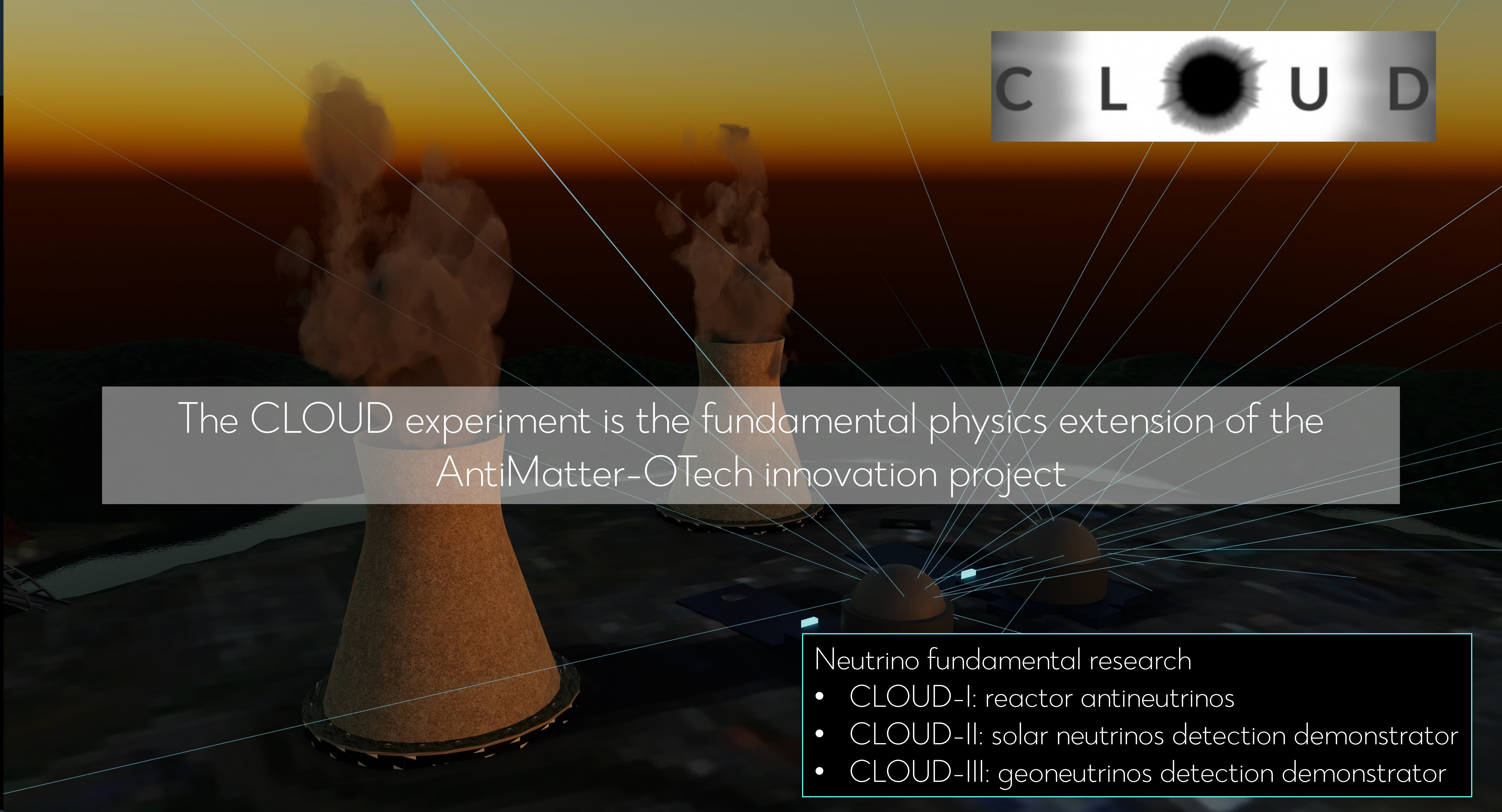
European Innovation Council

UK Research and Innovation



Monitor nuclear reactors with neutrinos

Not covered in this talk



The CLOUD experiment is the fundamental physics extension of the AntiMatter-OTech innovation project

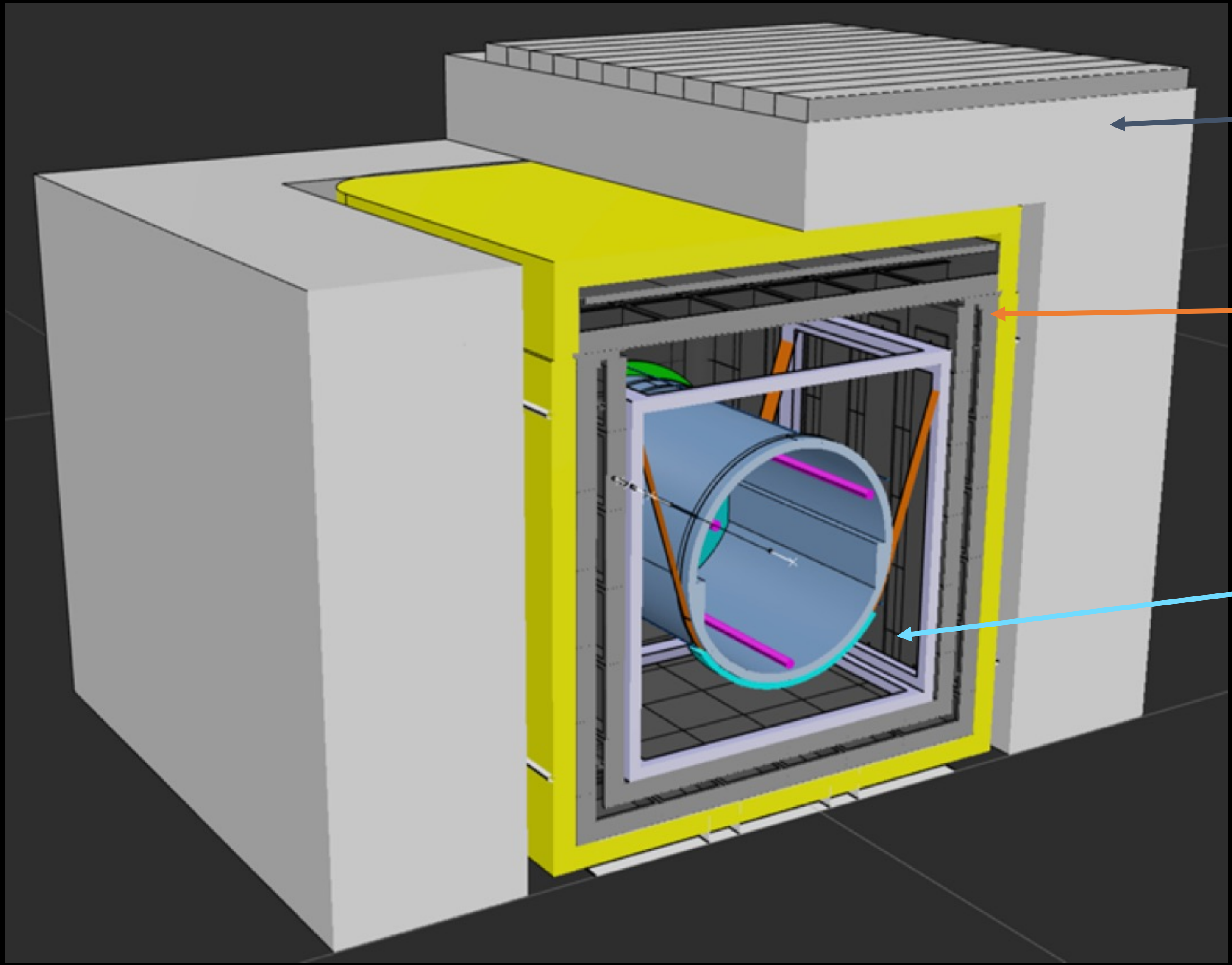
Neutrino fundamental research
- CLOUD-I: reactor antineutrinos
- CLOUD-II: solar neutrinos detection demonstrator
- CLOUD-III: geoneutrinos detection demonstrator

Nuclear power plant site

UND
Ultra Near Detector
~ 35 m from reactor core

- ★ Operate on surface
- ★ Minimum shielding: detector as compact as possible
  - Goal S/BG>100? -> to be demonstated

The detector

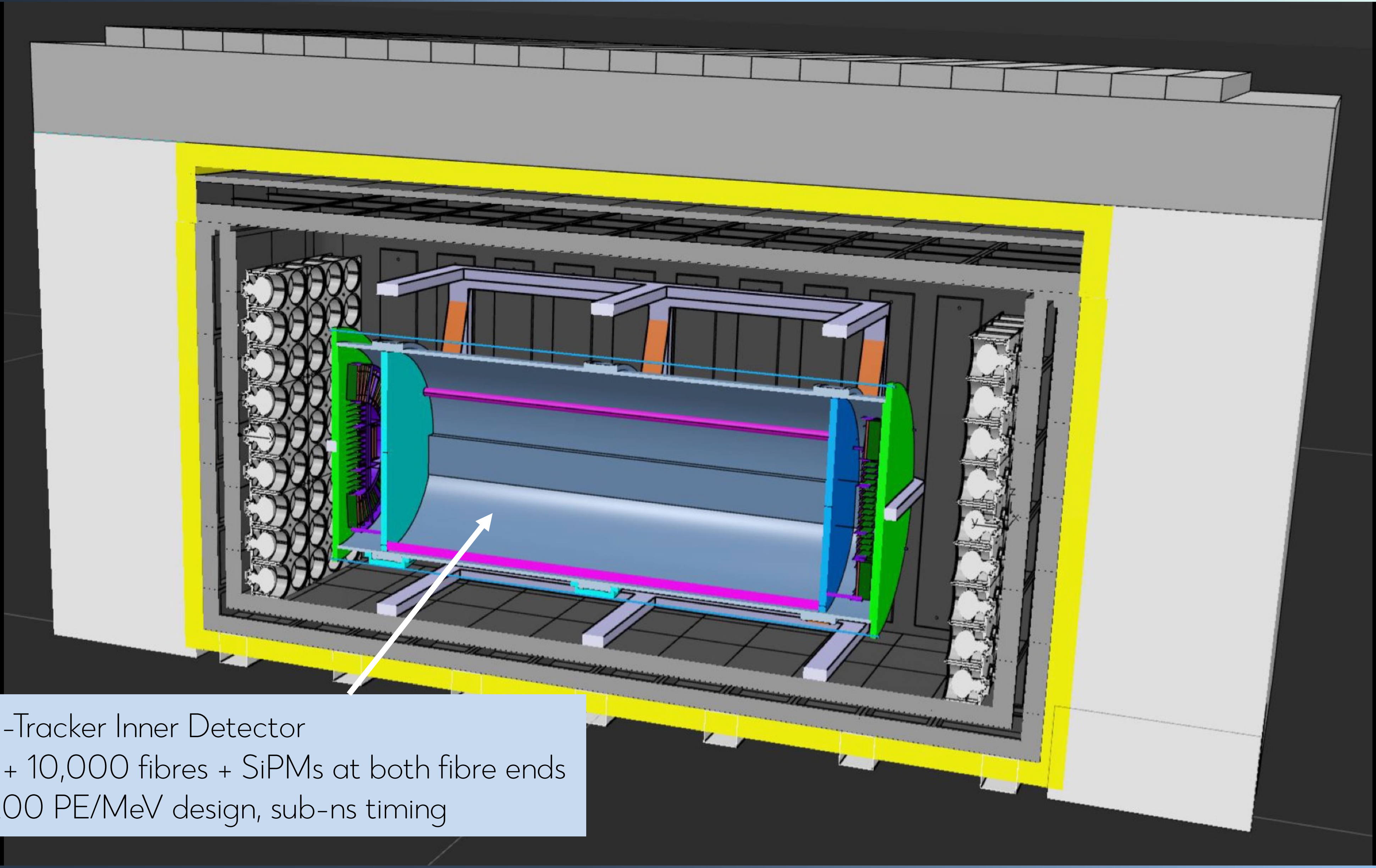


IGLOO [~3mwe]
- Concrete bunker
- DC's iron steel shield (15cm thick)

Water Pool [20,40]cm thick and/or PE tank [10,20] cm
4π shield & neutron moderator

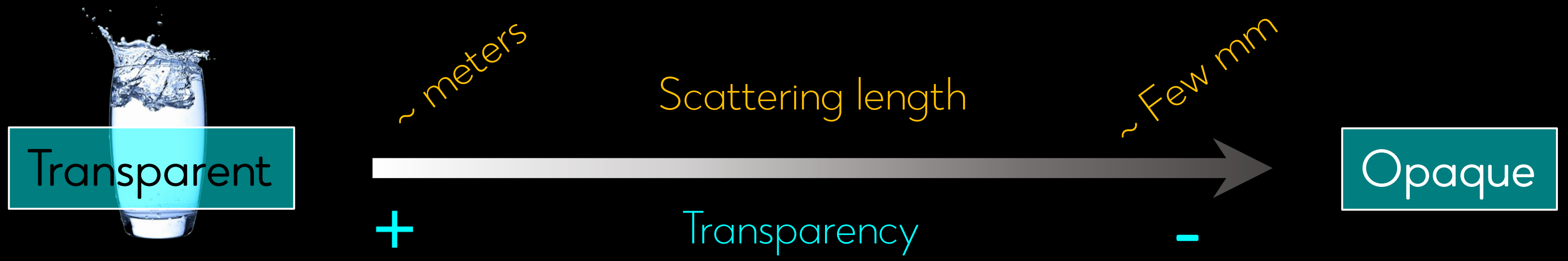
ARMOUR (or outer-detector) [~0.5m thickness]
- transparent scintillator (LAB + PPO + Bis-MSB)
- ≤180 DC-PMTs & highly reflecting walls
- designed light yield ≥400pe/MeV

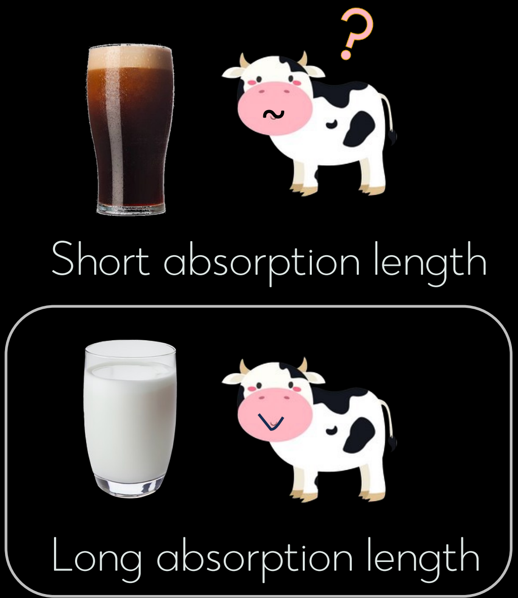
The detector

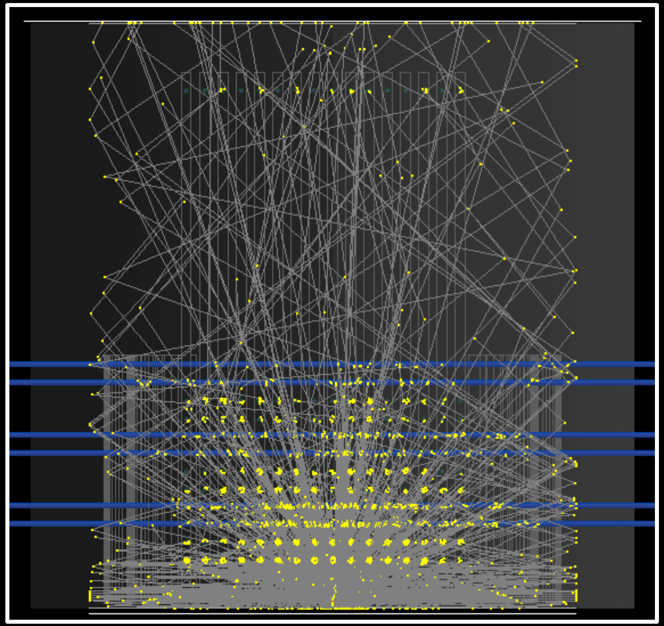


5-10 tons **LiquidO**-Tracker Inner Detector
Opaque scintillator + 10,000 fibres + SiPMs at both fibre ends
~1.8 m diameter, >200 PE/MeV design, sub-ns timing

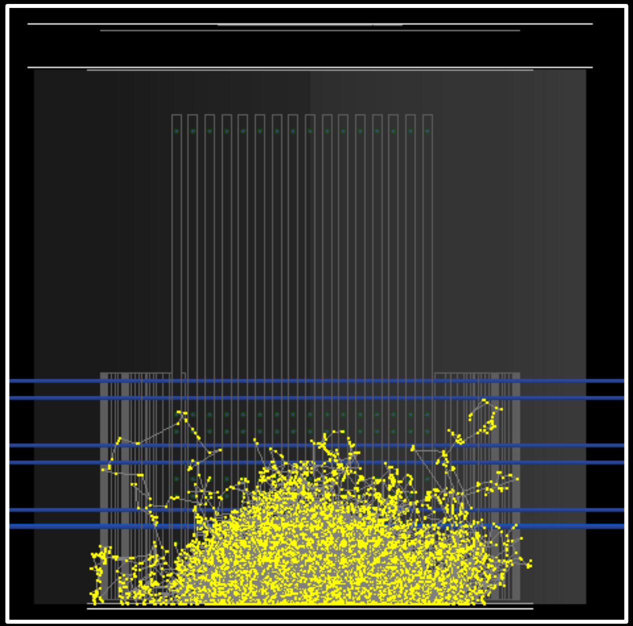
LiquidO: new detection approach







Transparent: Today's technology
Topology information washed out



Opaque: LiquidO technology
Light clustering

Stochastic light confinement near its creation point by using opaque medium (short scattering length)

LiquidO: new detection approach

Transparent

~ meters

Scattering length

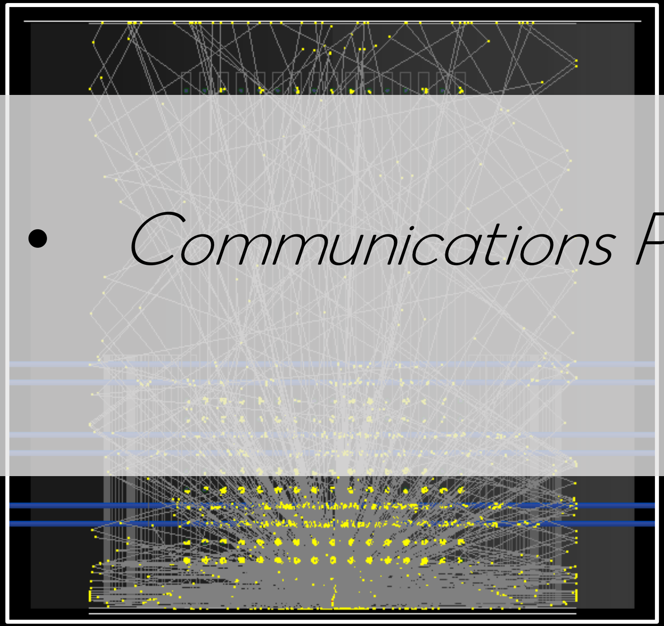
~ Few mm

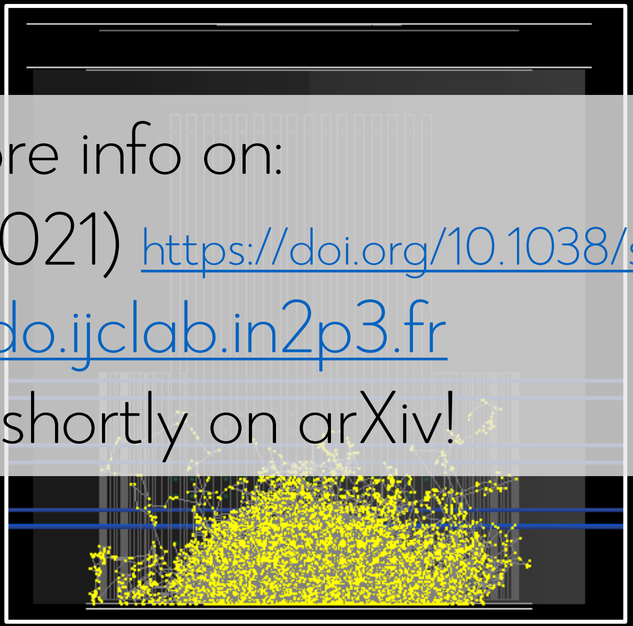
Opaque

Short absorption length

\+ Transparency -

Long absorption length





Much more info on:

- *Communications Physics* 4, 273 (2021) https://doi.org/10.1038/s42005-021-00763-5
- https://liquido.ijclab.in2p3.fr
- New paper shortly on arXiv!

Stochastic light confinement near its creation point by using opaque medium (short scattering length)

Transparent: Today's technology
Topology information washed out

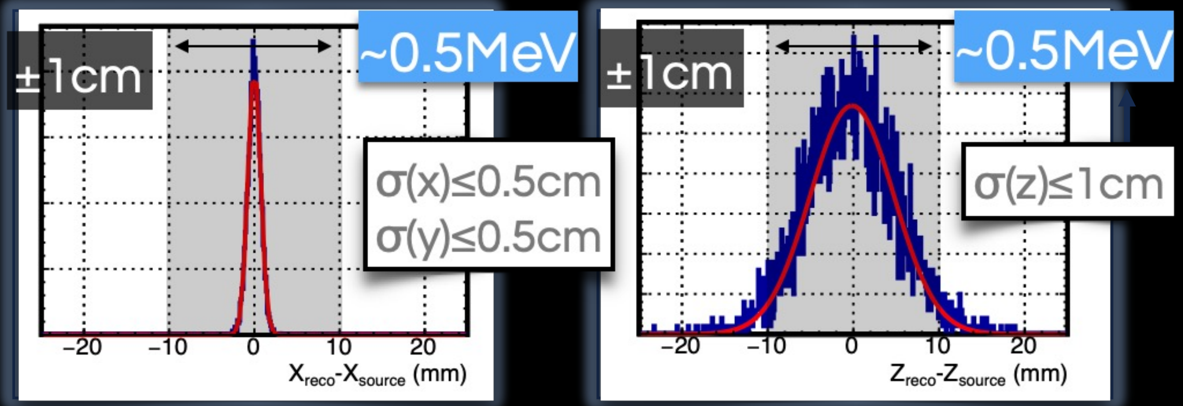
Opaque: LiquidO technology
Light clustering

Innovative detection technique

Opaque scintillator

- ★ Originally using NoWaSH (NW) (New opaque Wax Scintillator, Heidelberg)
- ★ Linear Alkyl Benzene (~80 wt.%) + PPO (~0.3 wt.%) + Paraffin Wax (~20 wt.%) arXiv:1908.03334
- ★ For CLOUD the paraffin concentration will be reduced by an order of magnitude to just ~2 wt.%.
- ★ LiquidO R&D extensive field: new μCrystal scintillators arXiv:1807.00628, water-based opaque scintillator arXiv:2406.13054, emulsion...(under study)

- ★ Maximal light collection by a dense array of WLS fibers
- ★ Fast time resolution (electronics + SiPMs) (< 1 ns)
- ★ Excellent vertex resolution (mm scale)

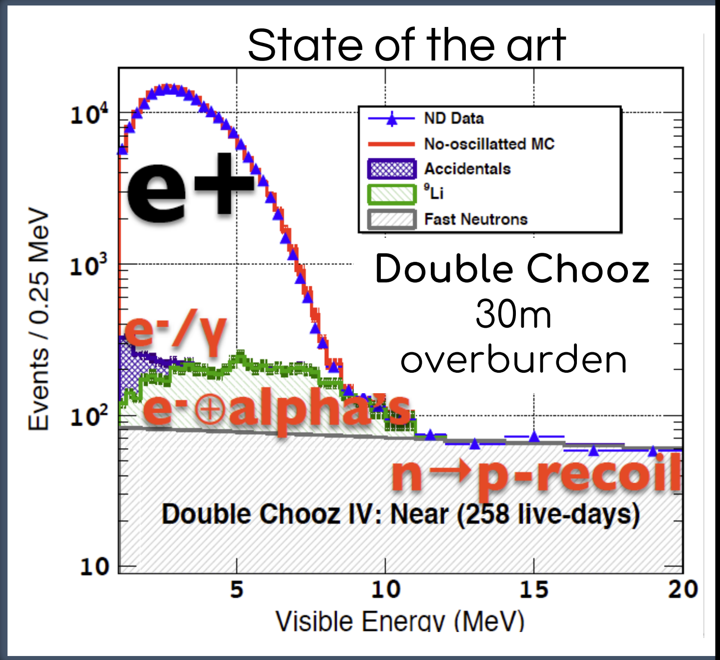


Neutrino fundamental research

- CLOUD-I: reactor neutrinos
- CLOUD-II: solar neutrinos
- CLOUD-III: geoneutrinos

CLOUD-I: reactor neutrinos

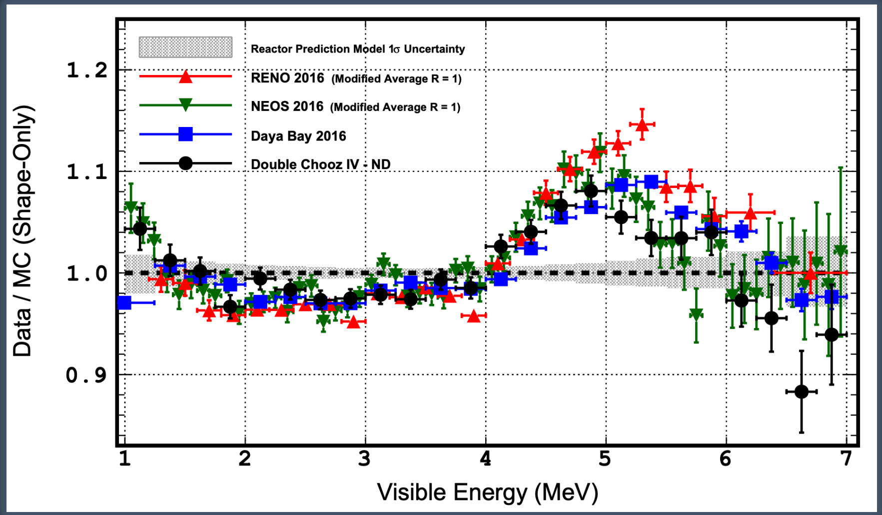
- Goal 1: LiquidO technology ultimate demonstration
- Goal 2: Most precise reactor $\bar{\nu}_e$ flux measurement <1%, U/Pu composition



[Nat. Phys. 16, 558–564 (2020)]

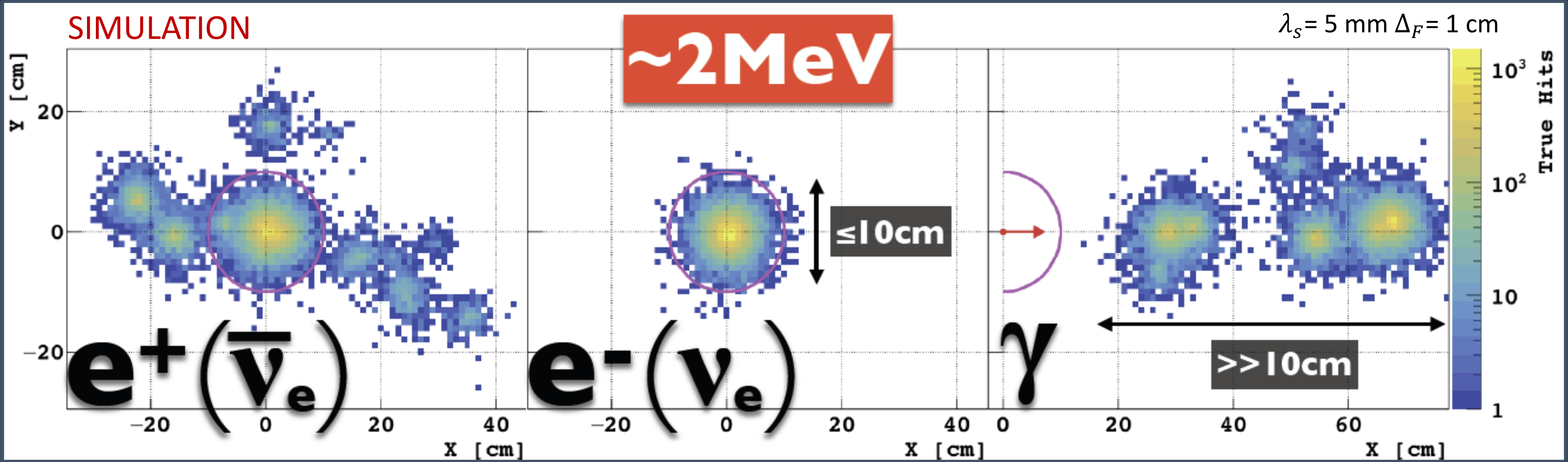
But CLOUD will be on surface close to the reactor

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



[Nat. Phys. 16, 558–564 (2020)]

CLOUD-I: particle identification



- ★ **Discrimination** of individual low energy e⁺, e⁻ and γ events
- ★ Matter/Antimatter separation
- ★ Powerful Background Rejection

Essential for CLOUD

CLOUD-I: reactor neutrinos

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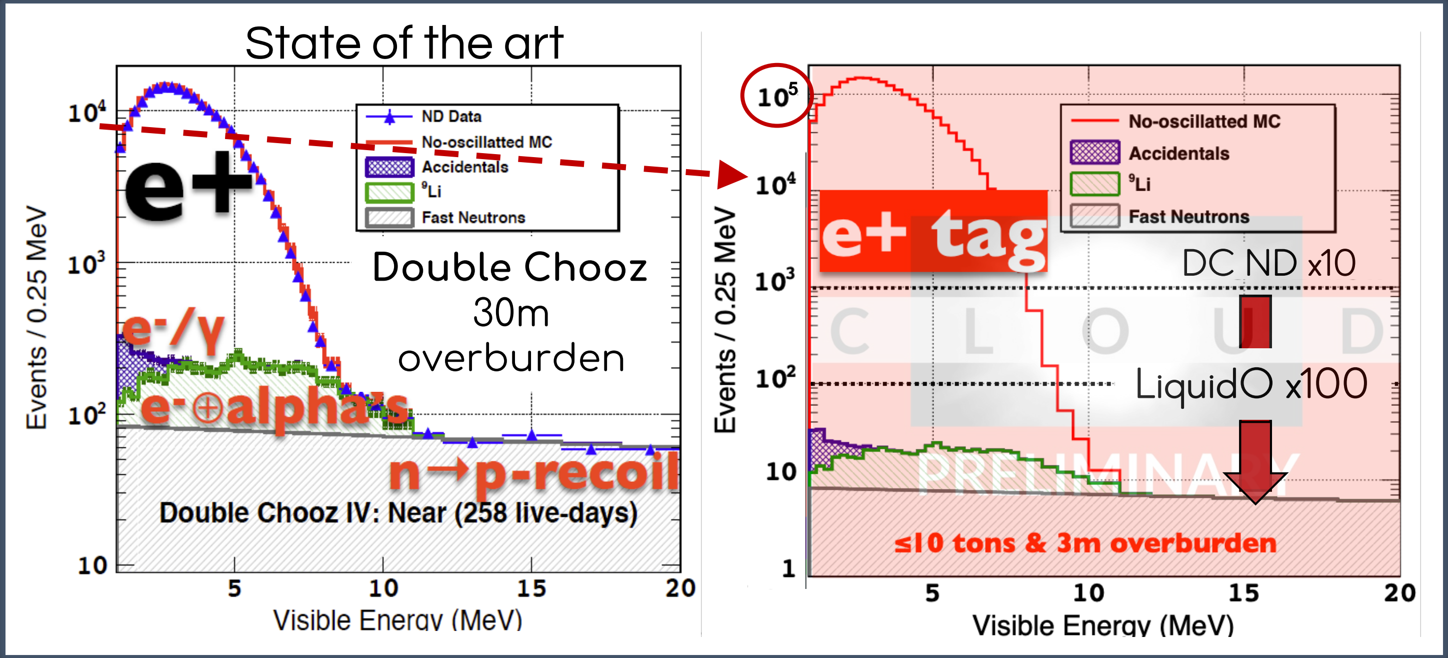

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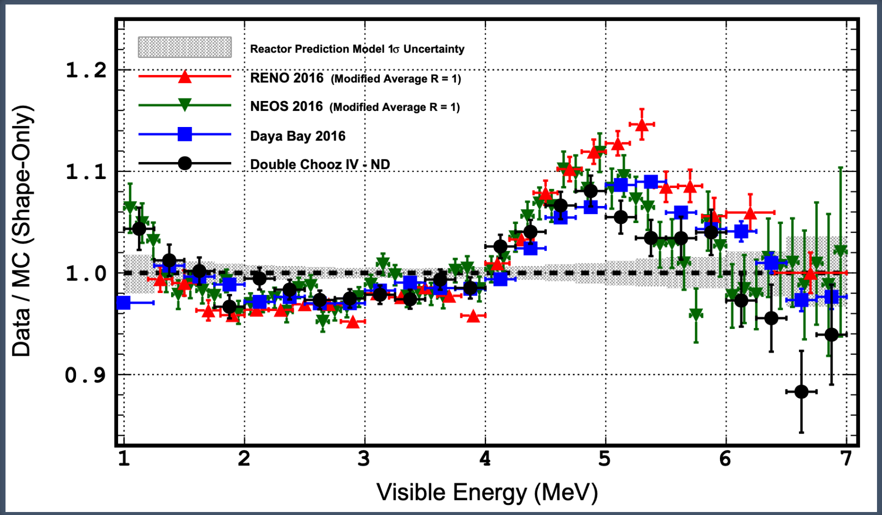

Nat. Phys. **16**, 558–564 (2020)

★ ≥10,000 IBD $\bar{\nu}_e$ interactions per day and 10 tons [≥3M interactions/year]

★ LiquidO can improve ≥3x today's BG control (PID + vertex precision)

★ S/BG >100 with Reactor-ON (unprecedented)

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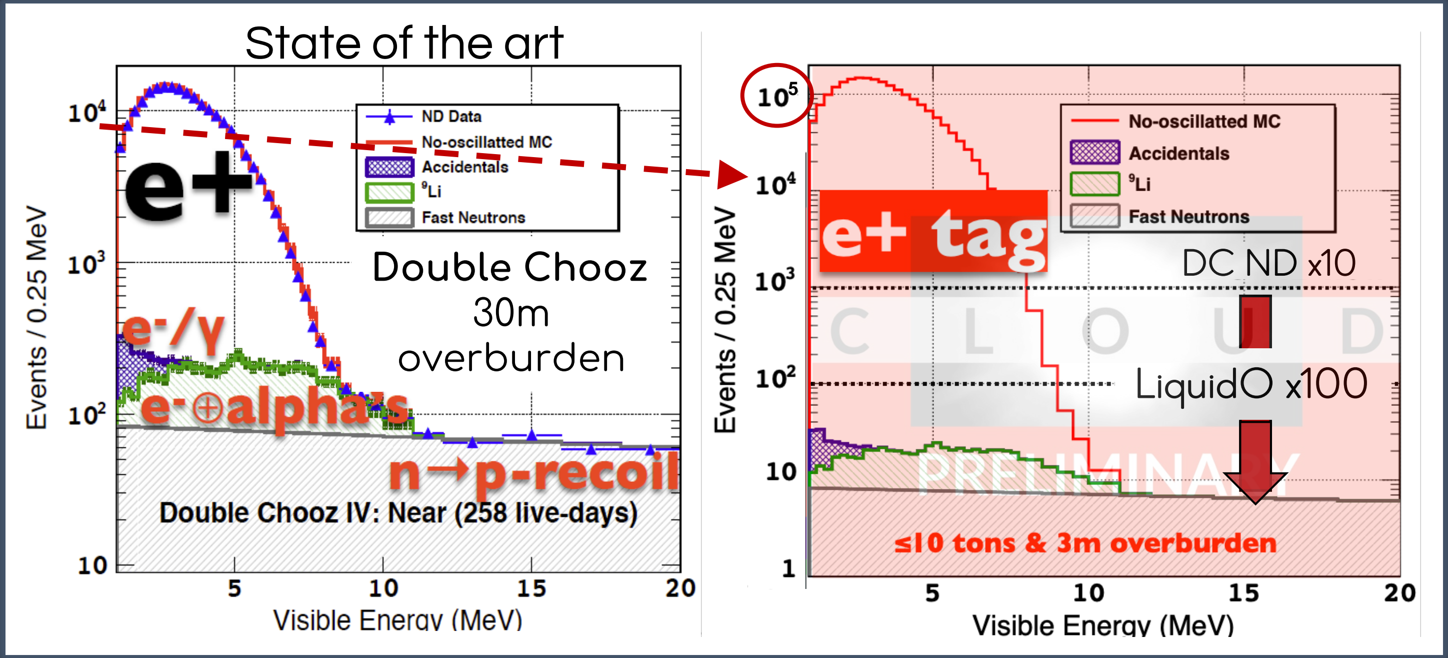

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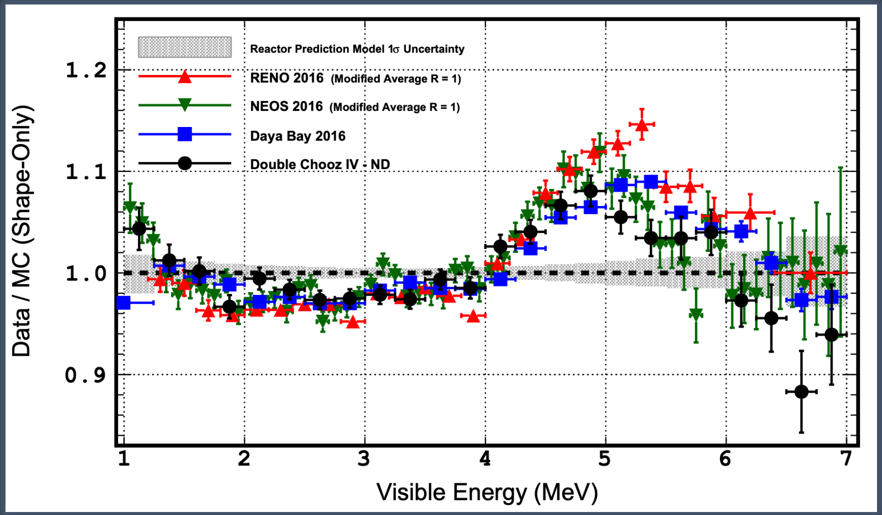


Nat. Phys. 16, 558–564 (2020)

★ S/BG >1 with Reactor-OFF (unprecedented)

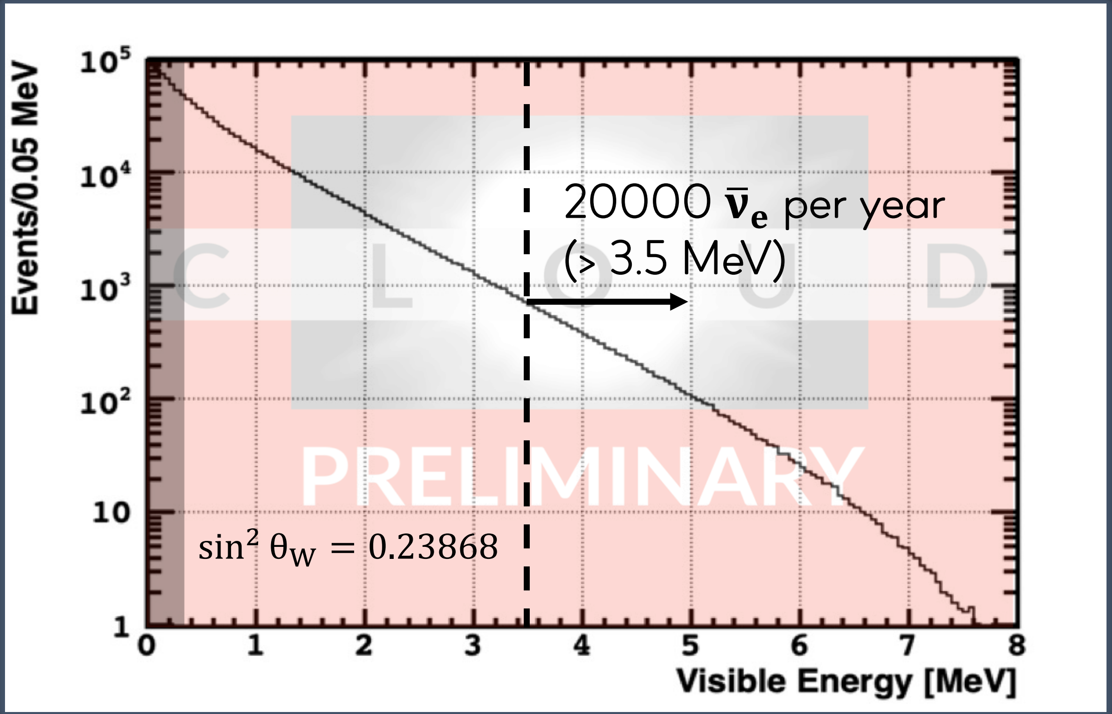
- Goal 3: Accurate monitoring reactor ON-OFF-ON transitions – Unique information for reactor prediction model validation

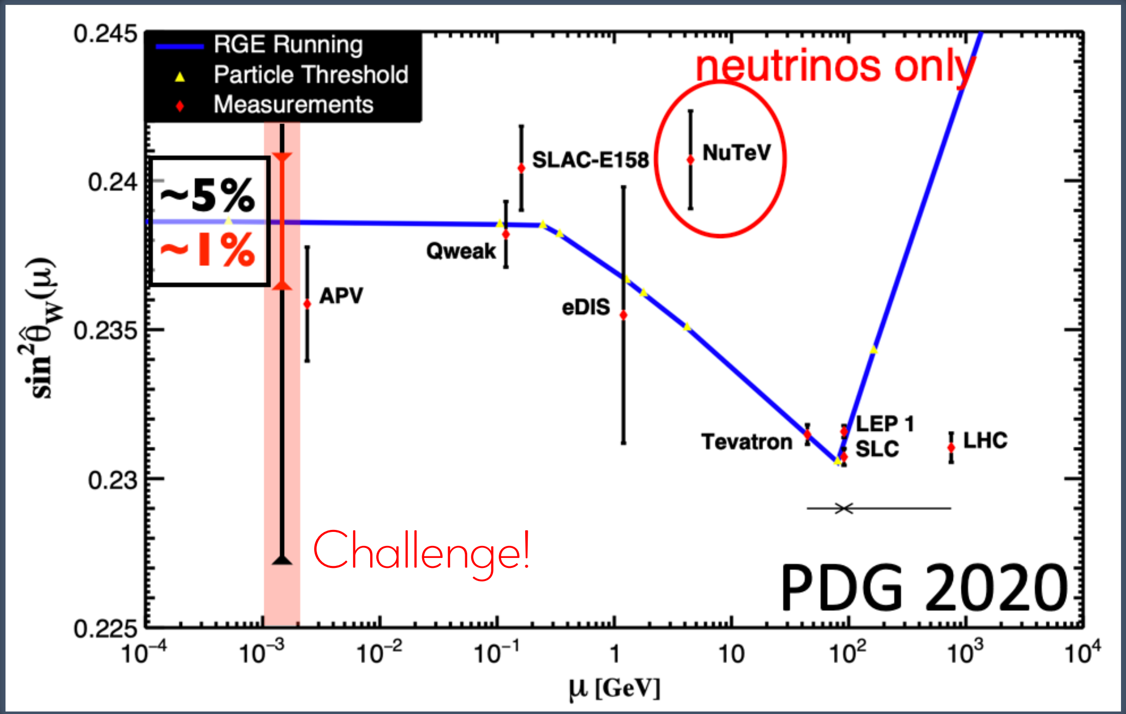
CLOUD-I: reactor neutrinos

- ★ Electron elastic scattering ~5,000 $\bar{\nu}_e$ per day for 10 tons ID
- ★ Challenge: Isolate electrons – Require:
  - Electron classification
  - Fiducial volume
  - Higher energies –> reduction of the detected rate

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

- ★ Probe of $\sin^2\theta_W$ at very low energy using antineutrinos





Neutrino fundamental research

- CLOUD-I: reactor neutrinos
- CLOUD-II: solar neutrinos
- CLOUD-III: geoneutrinos

CLOUD-II: Indium loading

$$\nu_e + {}^{115}\text{In} \rightarrow {}^{115}\text{Sn}^* + e^-$$

prompt

$\tau = 4{,}76\ \mu s$

delay

- e_1^- / γ_1 E = 116 keV (e/γ)=0.96
- \+
- γ_2 E = 497 keV

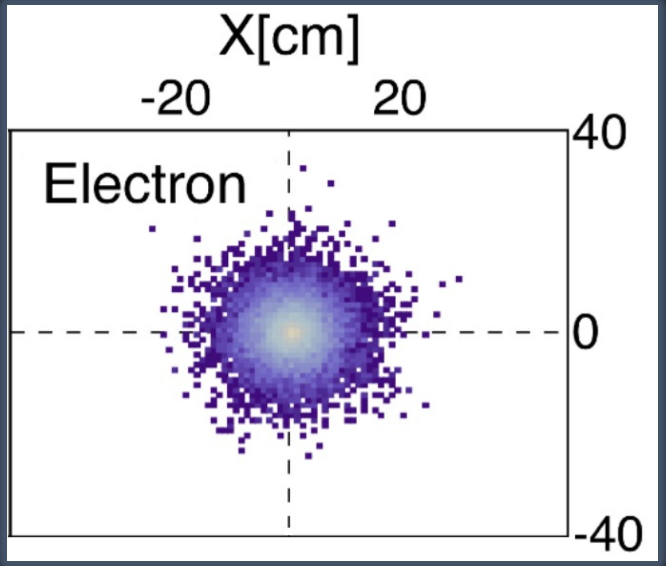
THREE-FOLD COINCIDENCE

BG-less ($\lesssim 10^{-15}$ g/g)

Low threshold = 114 keV (95.5% of pp ν_e)

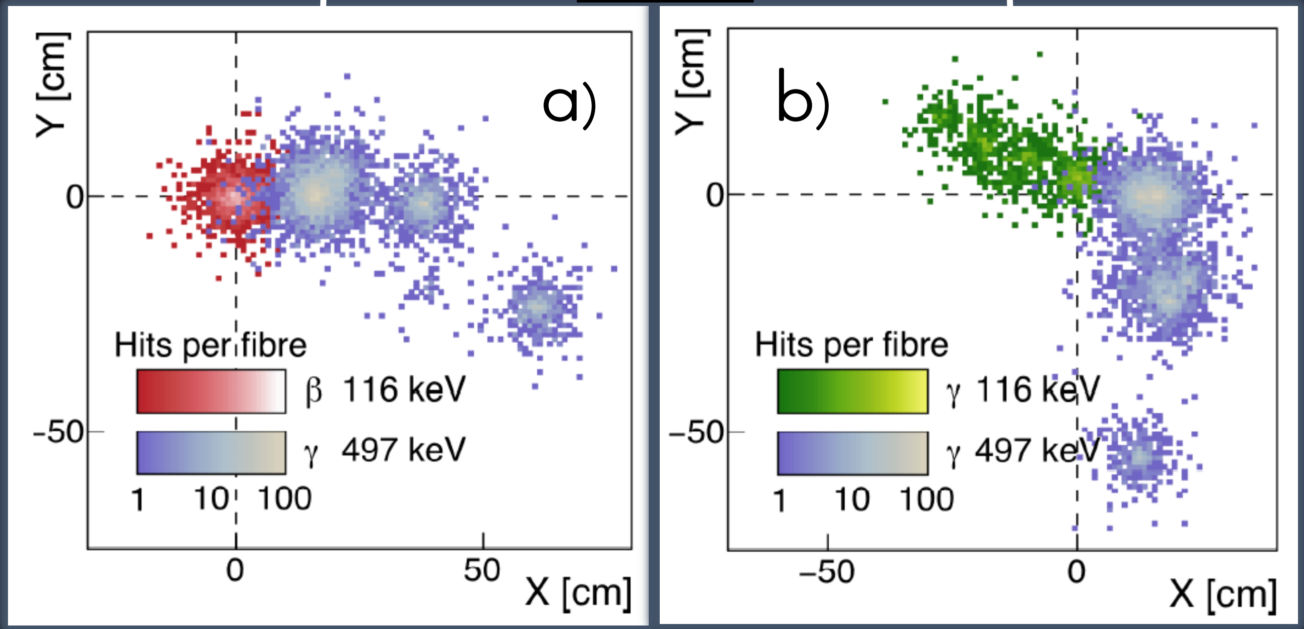
$$E_{vis} = E_\nu - \text{threshold}$$

Prompt



\+

Delay

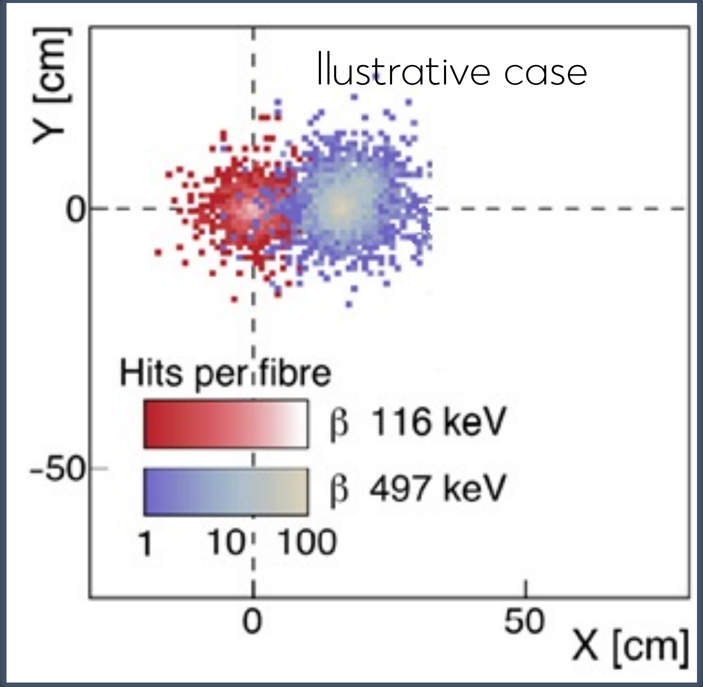


CLOUD-II: Indium loading

- pp $\nu_e \sim$ 60 CC interactions / (ton year)
- α (^{115}In) = 0.26 Bq/g = 8.24 x 10^{12} β / (ton year) ⟵ Most important background

Expected S/BG > 100

Thanks to PID <10% of the signal can be mimic by ^{115}In beta-decay



Assuming:

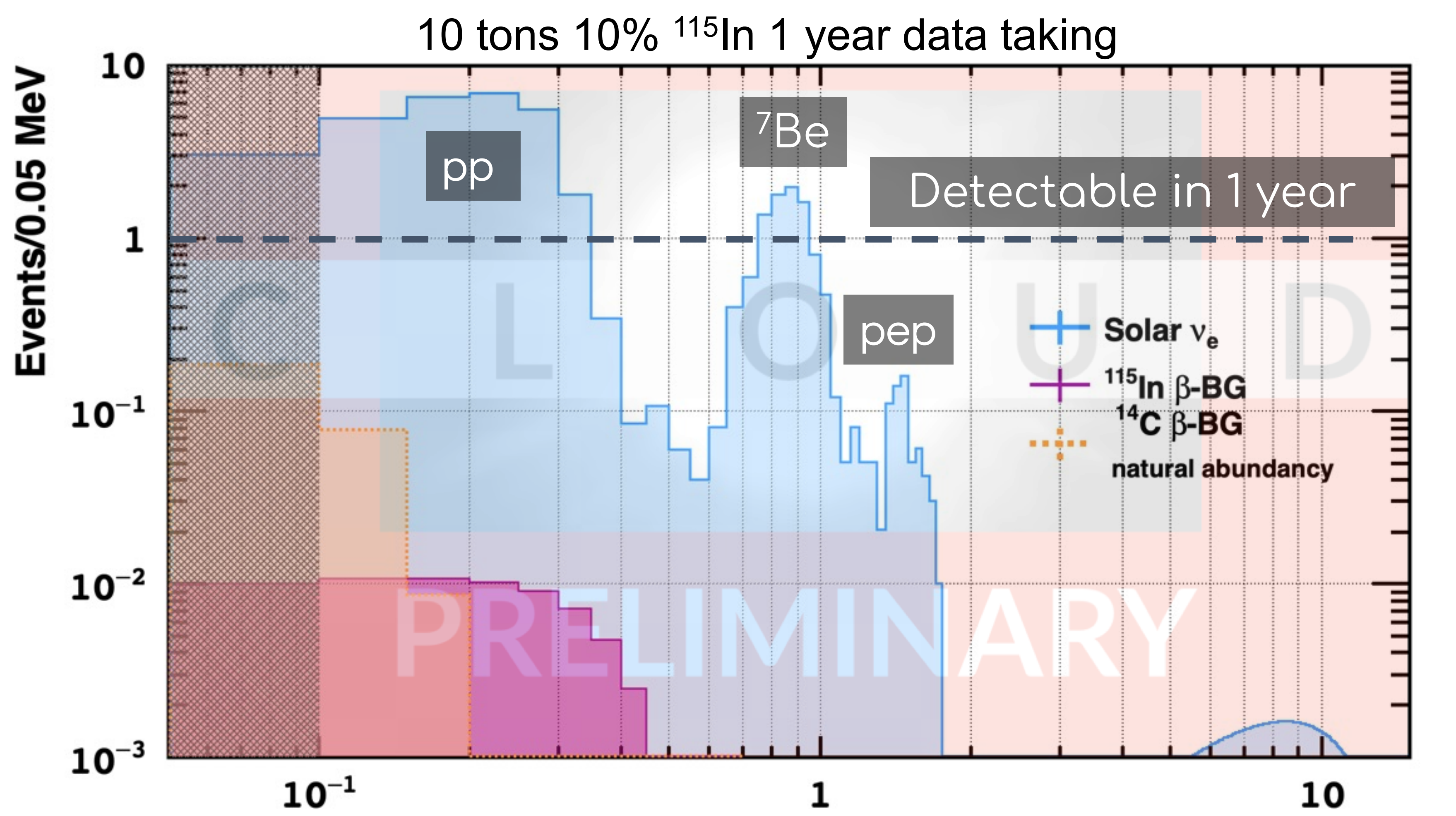
1. (prompt-delayed) time coincidence
   - Signal: $\tau = 4{,}76\ \mu$s
   - BG β-decay: uncorrelated events

2. (prompt-delayed) space coincidence
   - Signal: sphere < 5mm
   - BG β-decay: r^3

3. Delayed energy
   - Signal: Total delay energy = 612.6 keV
   - BG β-decay: endpoint = 497.489 keV

Demands good energy resolution

CLOUD-II: solar neutrino spectra



* LENS background model – Under feasibility study for CLOUD

- Demonstrator for pp-solar neutrino detection with ^{115}In-tagging
- Solar-pp ~25 ν_e/year
- Solar-7Be ~9 ν_e/year
- ^{115}In + ^{14}C intrinsic background ~negligible (w/LiquidO)
- Possibility to detect intrinsic reactor neutrinos (β+ decay and E.C. of fission products or reactor structural elements)

Neutrino fundamental research

- CLOUD-I: reactor neutrinos
- CLOUD-II: solar neutrinos
- CLOUD-III: geoneutrinos

CLOUD-III: Copper loading

- Electron antineutrino CC with copper nucleus arXiv:2308.04154

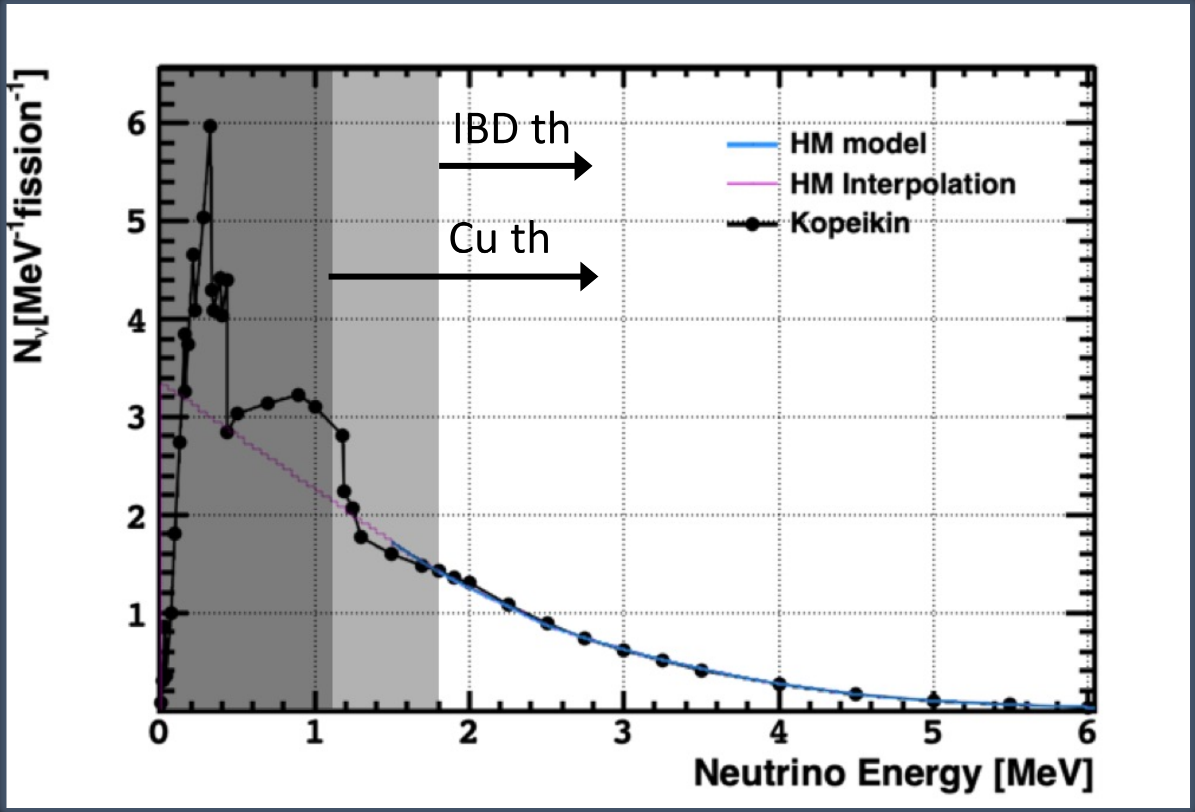
$\bar{\nu}_e + {}^{63}Cu \rightarrow e^+ + {}^{63}Ni^*$

→ γ 87 keV [if Ni was excited]

- High abundance (69%)
- Fast delayed coincidence (τ = 1.7 μs)
- Signature:
  – Prompt positron
  – Delayed gamma, close-by spatially

- Proof of principle for ^{40}K geo-neutrinos (extremely challenging topic)
  - Endpoint ^{40}K 1.311 MeV

- Lower threshold (1.2 MeV, below usual 1.8 MeV)
  - see unmeasured part of reactor spectrum



SuperChooz experiment

See next talk by Anatael Cabrera

Neutrino Physics session (Saturday 20th)

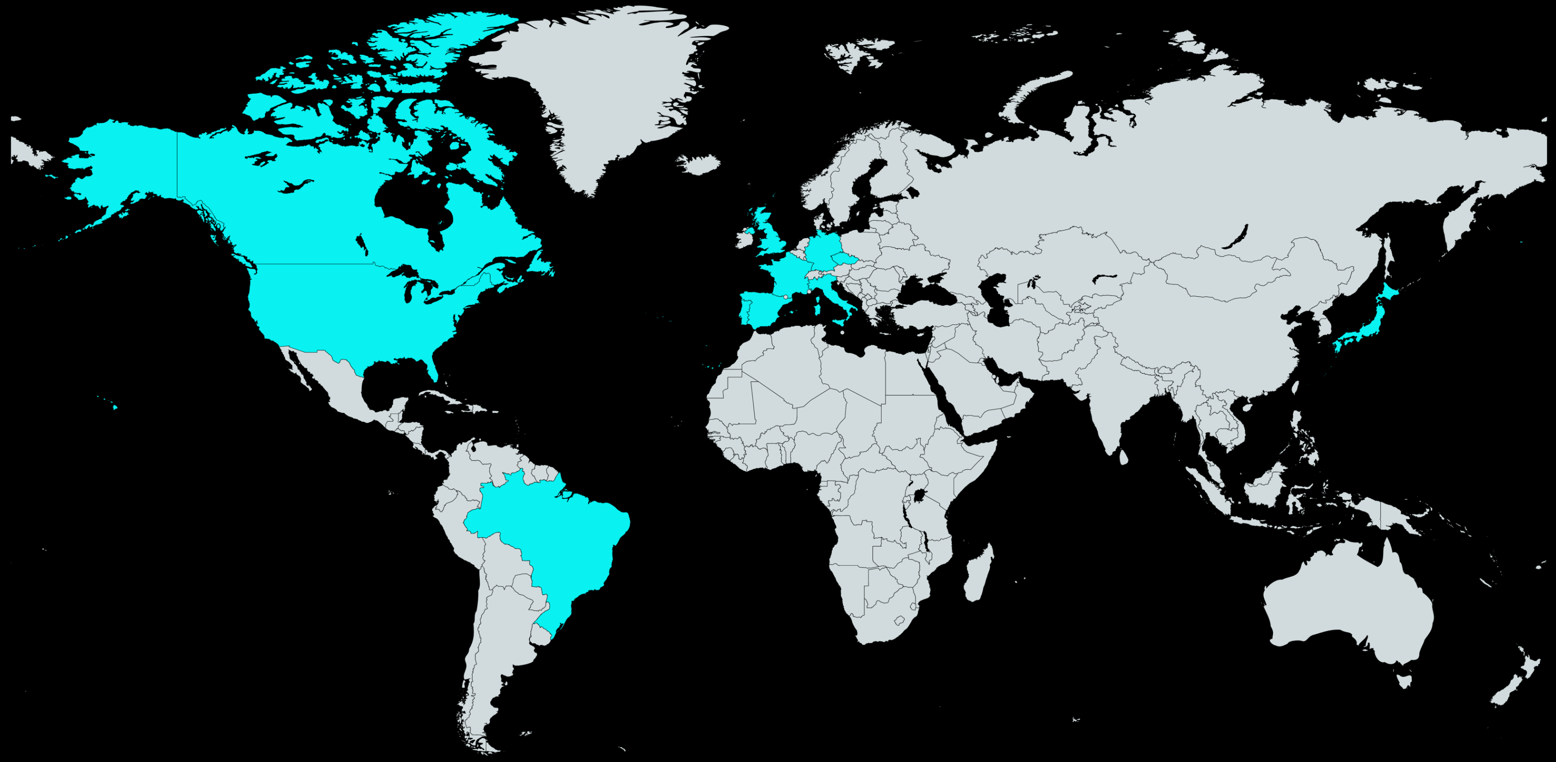
https://indico.cern.ch/event/1291157/contributions/5904064/

SuperChooz experiment

SUPERCHOOZ

CLOUD collaboration

CLOUD INTERNATIONAL COLLABORATION

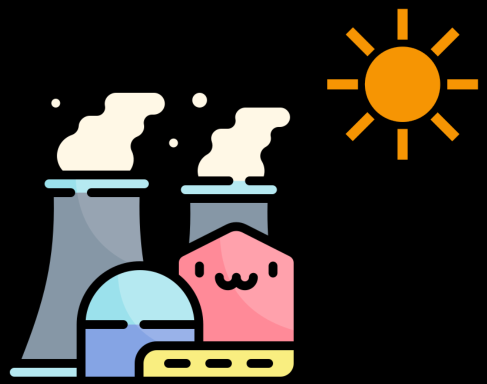


21 institutions in 11 countries

- EDF (France)
- Brookhaven National Laboratory (USA)
- Charles University (Czechia)
- CIEMAT (Spain)
- IJCLab / Université Paris-Saclay (France)
- Imperial College London (UK)
- INFN-Padova (Italy)
- Instituto Superior Técnico (Portugal)
- Johannes Gutenberg Universität Mainz (Germany)
- LP2i / Université de Bordeaux (France)
- Pennsylvania State University (USA)
- Pontifícia Universidade Católica do Rio de Janeiro (Brazil)
- Queen's University (Canada)
- Rutherford Appleton Laboratory (UK)
- Subatech / Nantes Université (France)
- Tohoku University / RCNS (Japan)
- Universidad de Zaragoza (Spain)
- Universidade Estadual de Londrina (Brazil)
- University of California Irvine (USA)
- University of Michigan (USA)
- University of Sussex (UK)

What to remember?

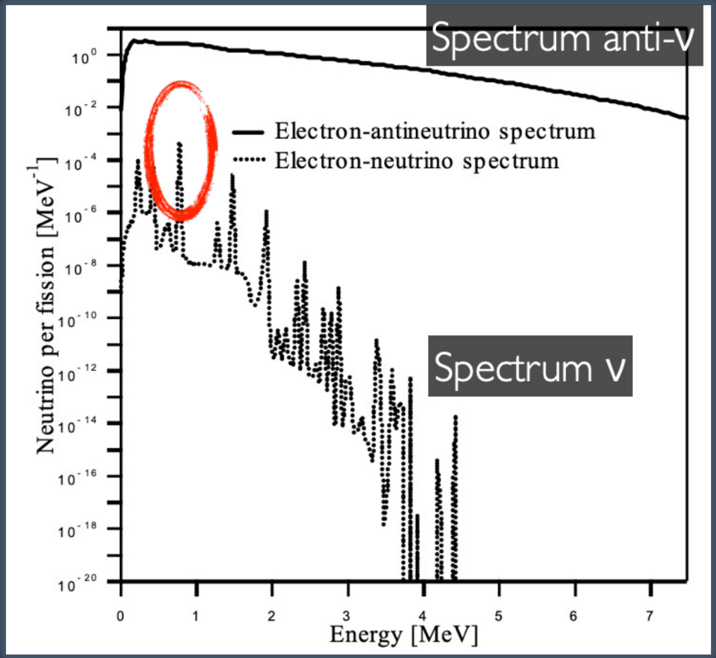
- CLOUD demonstrator for LiquidO's detection capabilities
- CLOUD-I [AntiMatter-Otech funded]
  - Most precise absolute antineutrino flux measurement
- CLOUD-II and CLOUD-III: under feasibility study
  - Solar neutrino with new indium-loaded opaque scintillator
  - Reactor flux at low energies with new copper-loaded opaque scintillator + ^{40}K geoneutrinos
- Cutting-edge neutrino physics continue to be done with reactor and solar neutrinos



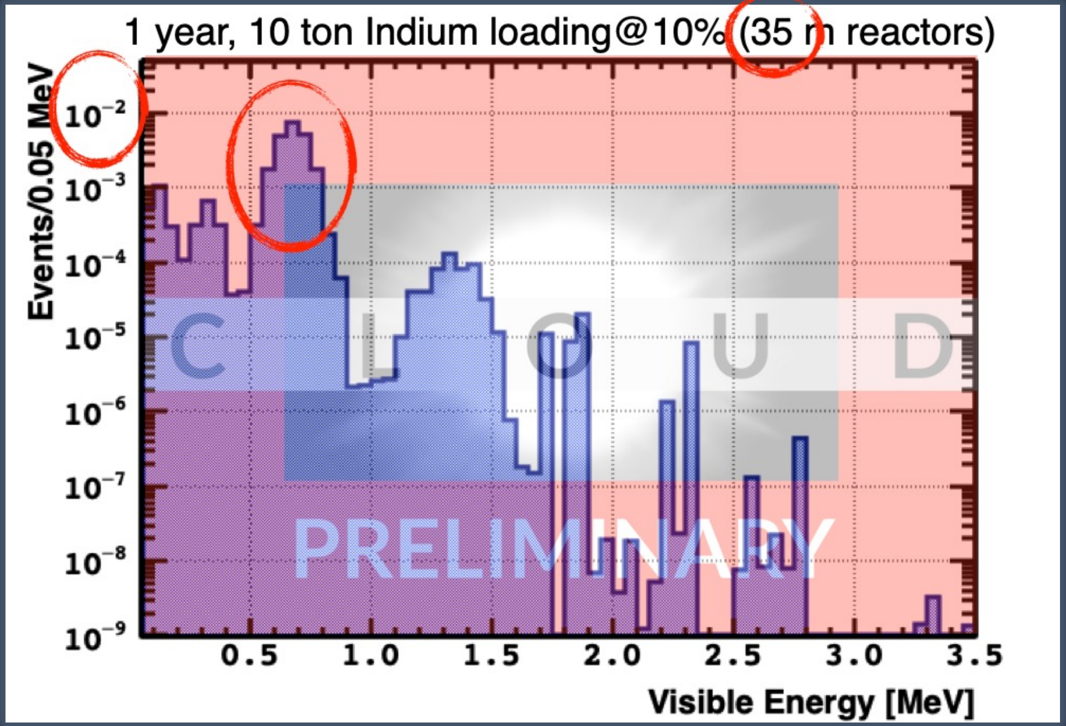
Thank you very much!

Back-up

Extra: neutrinos from reactors?

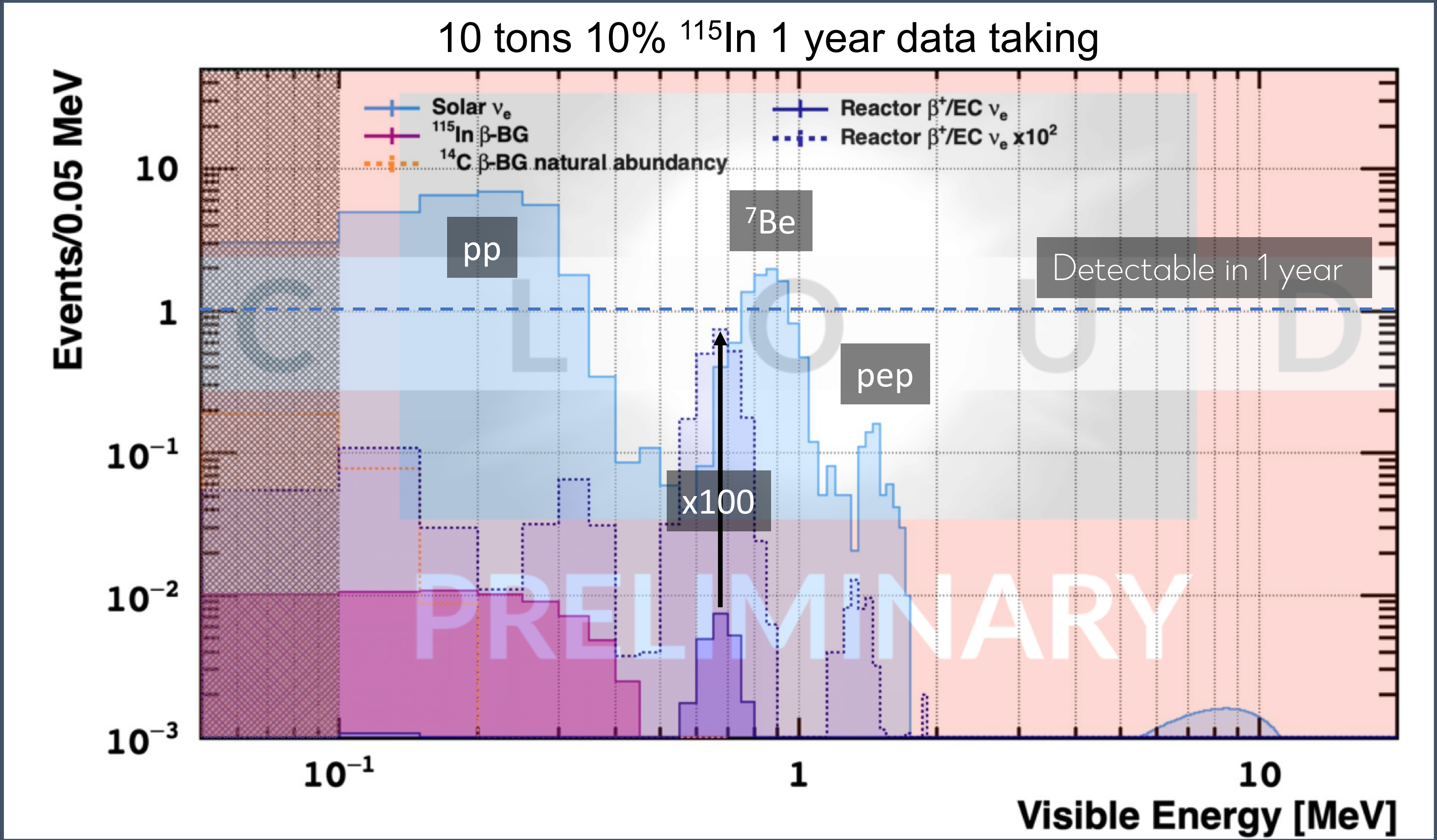


- ν_e from the β^+ decay and E.C. of Fission Products
  - The FP yields of these nuclides are as small as the order of 10^{-7} [fission^{-1}].
- ν_e from the β^+ decay and E.C of Structural Elements
  - Pressure vessel, control rods, coolants, cladding tubes exposed to high neutron flux



- 10-ton detector is too small
- Unless prediction is wrong?
- What else could we measure?

Expected neutrino spectra in CLOUD



Solar-pp ~25 ν_e/year

Solar-^{7}Be ~9 ν_e/year

^{115}In intrinsic bkg ~negligible (w/LiquidO)

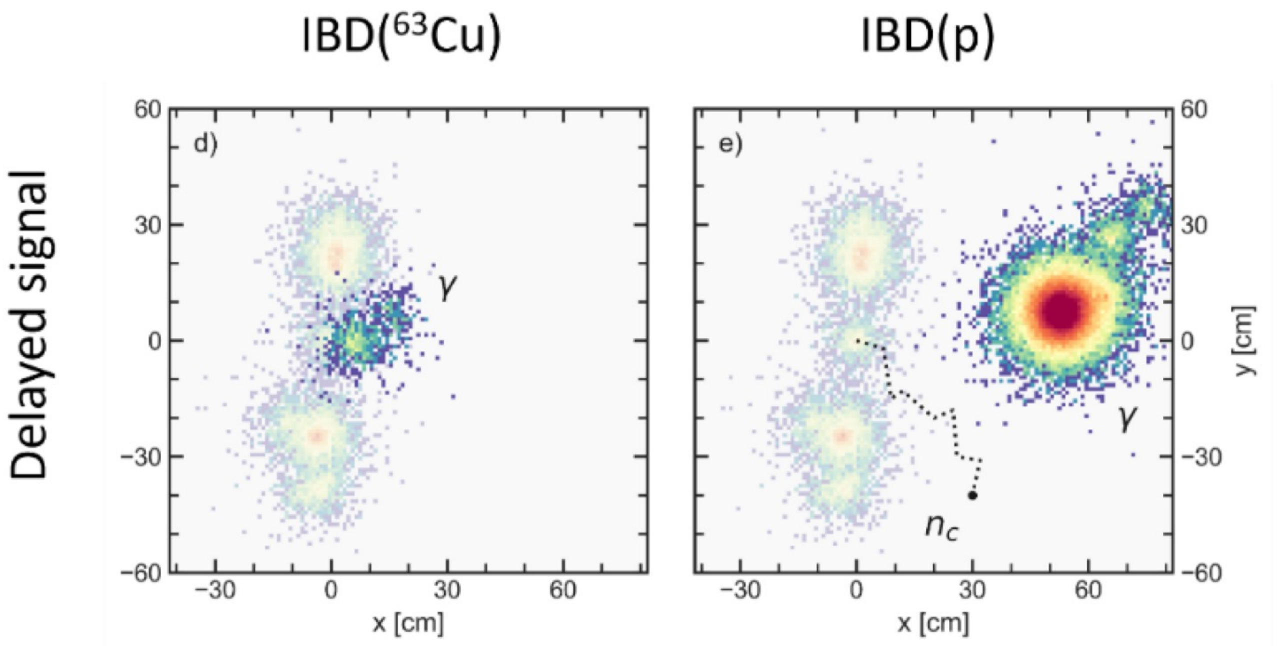
^{14}C intrinsic bkg ~negligible (w/LiquidO)

Intrinsic reactor neutrinos ~none?

Plot uses LENS background model – Under feasibility study for CLOUD

Demonstrator for future SuperChooz experiment!

Copper loading

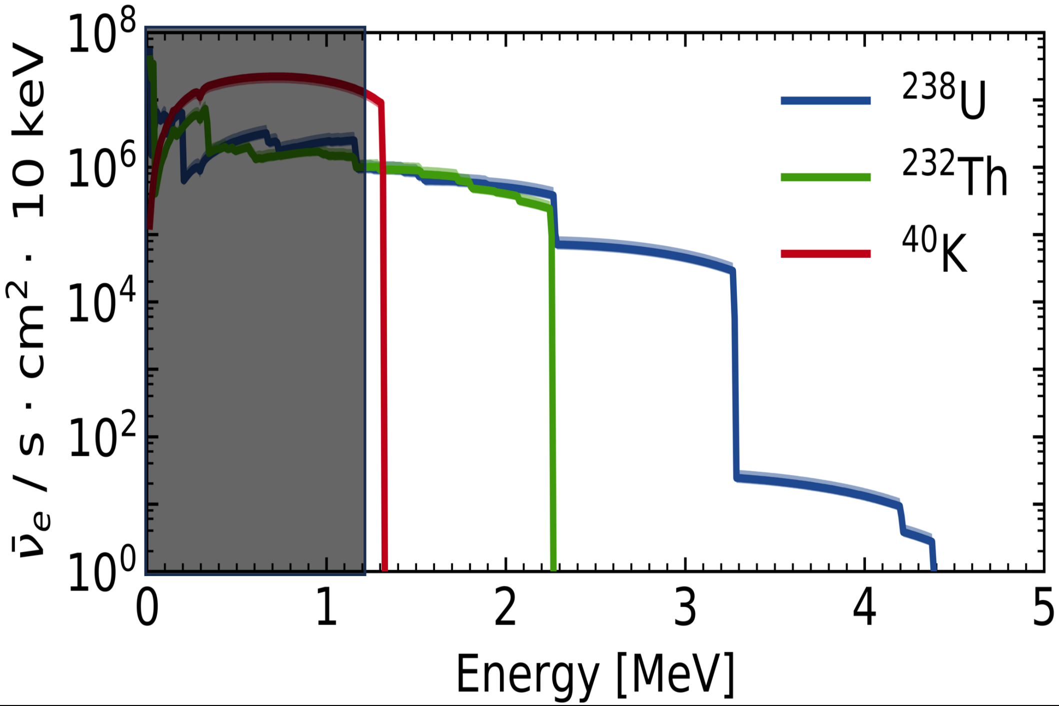


$$\bar{\nu}_e + {}^{63}Cu \rightarrow {}^{63}Ni^* + e^+$$

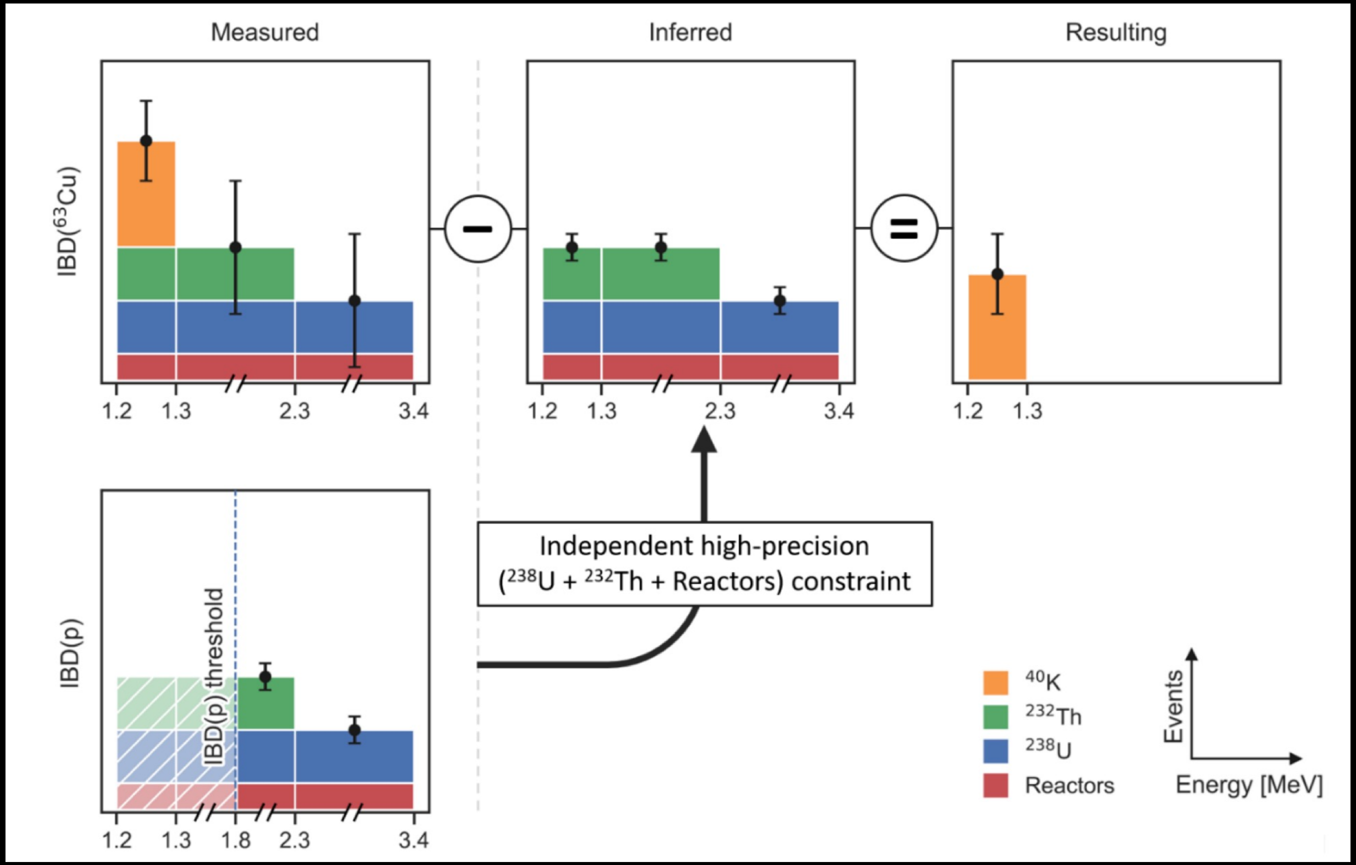
- $e^+ + e^- \rightarrow 2\gamma$
- ${}^{63}Ni^* \rightarrow {}^{63}Ni + \gamma$

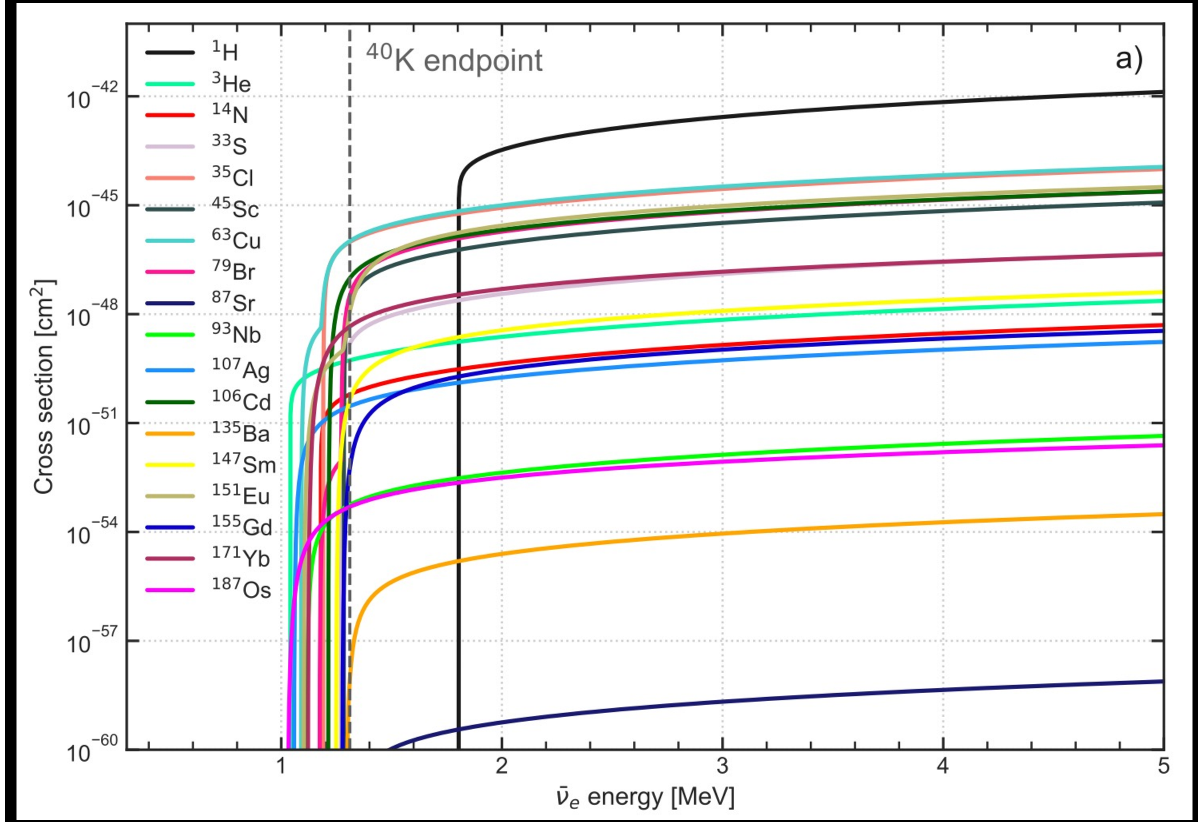
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- $e^+ + e^- \rightarrow 2\gamma$
- $n + p \rightarrow d + \gamma$
- $n + {}^{63}Cu \rightarrow {}^{64}Cu + \gamma's$
- $n + {}^{65}Cu \rightarrow {}^{66}Cu + \gamma's$

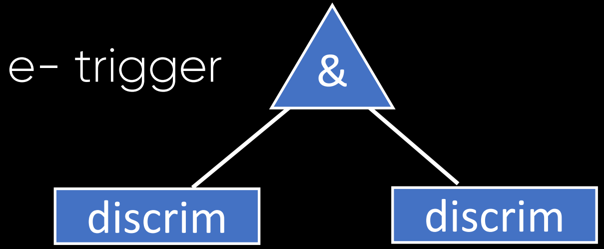


Copper loading

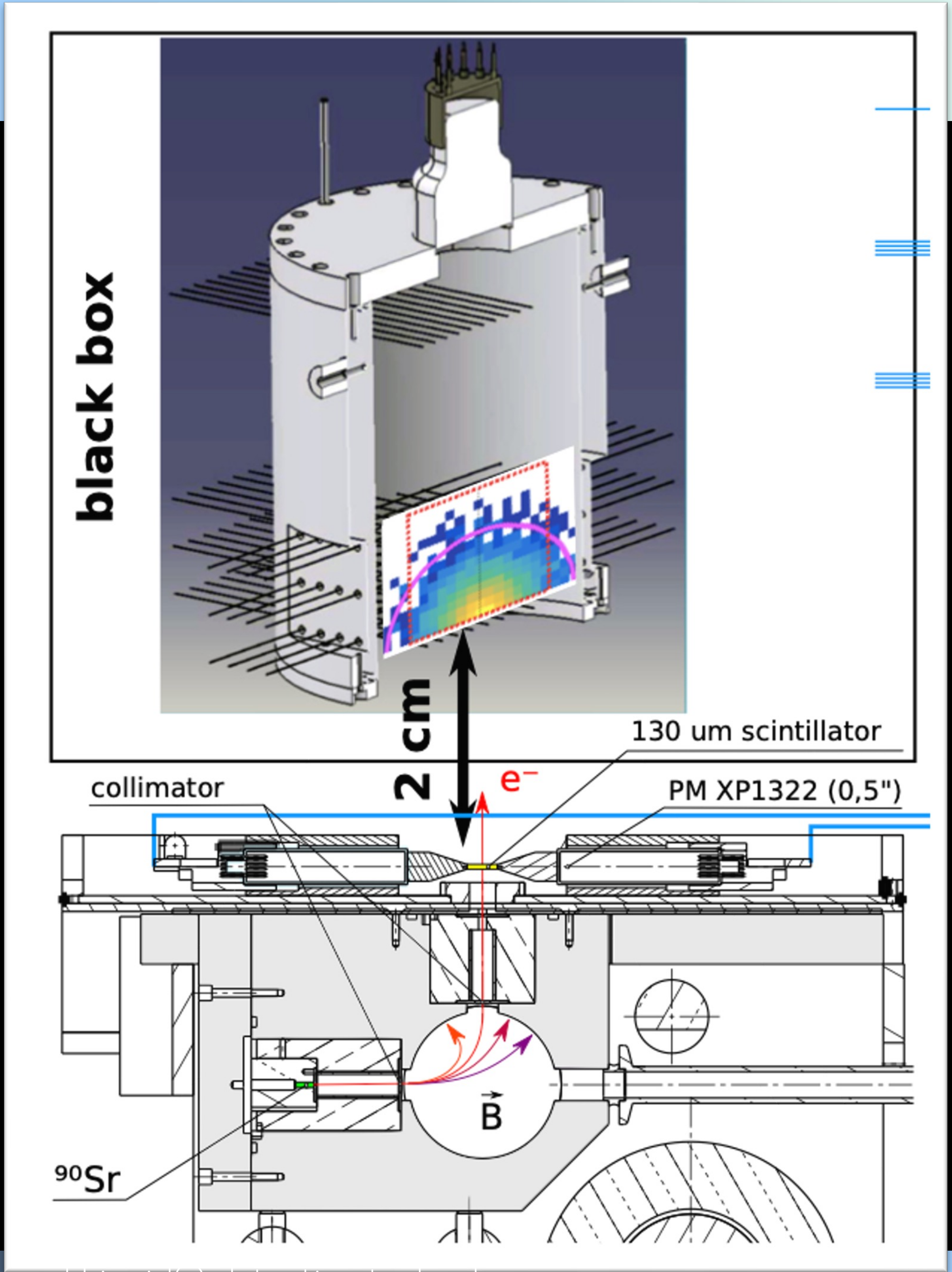




Mini-e⁻ setup

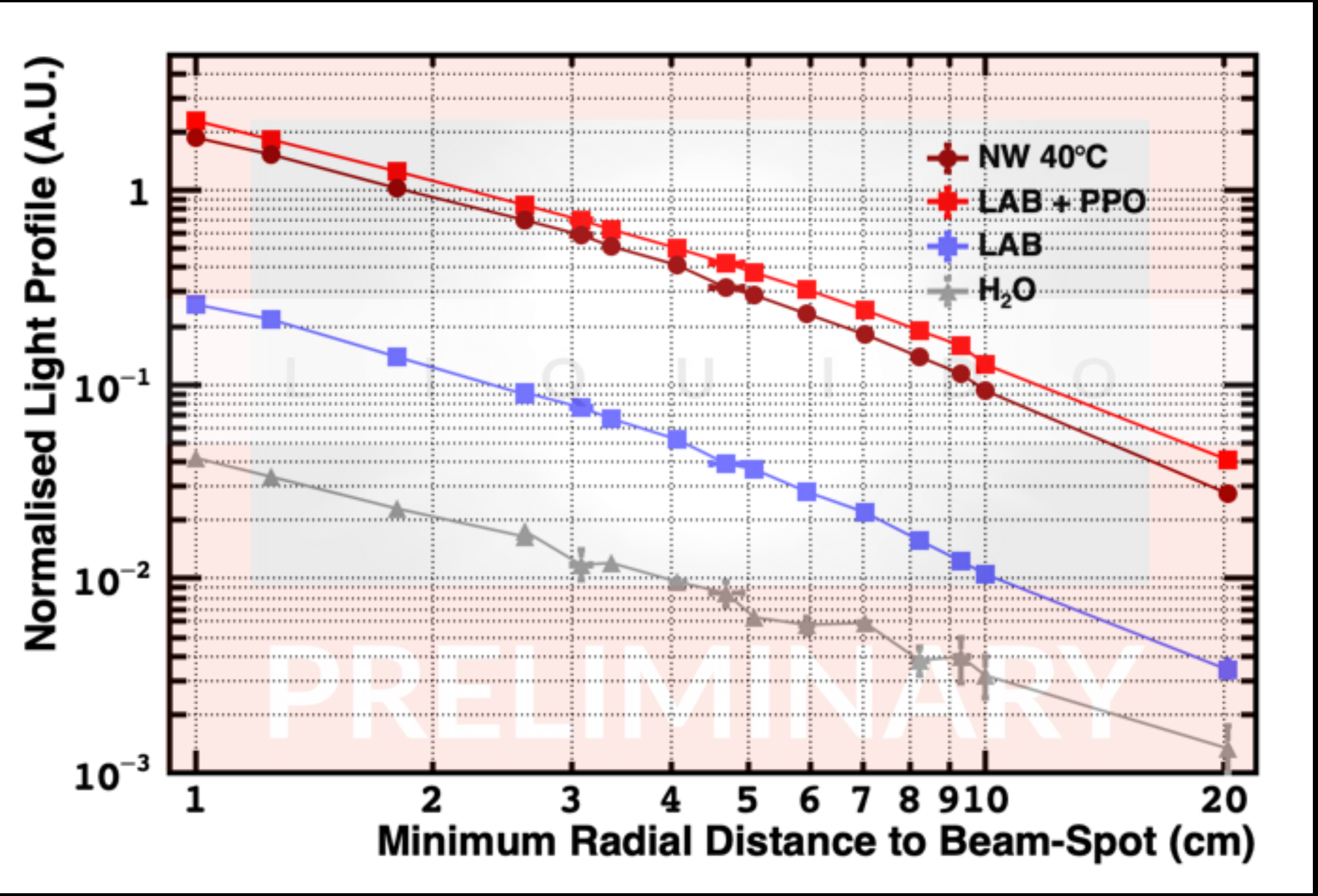


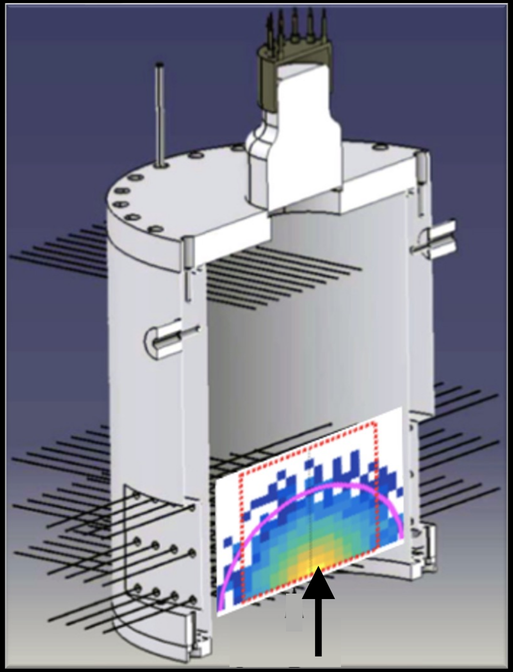
Coincidence between 2 PMT triggers is done directly by wavecatcher



Experimental validation

Light Confinement Demonstration: Transparent vs Opaque





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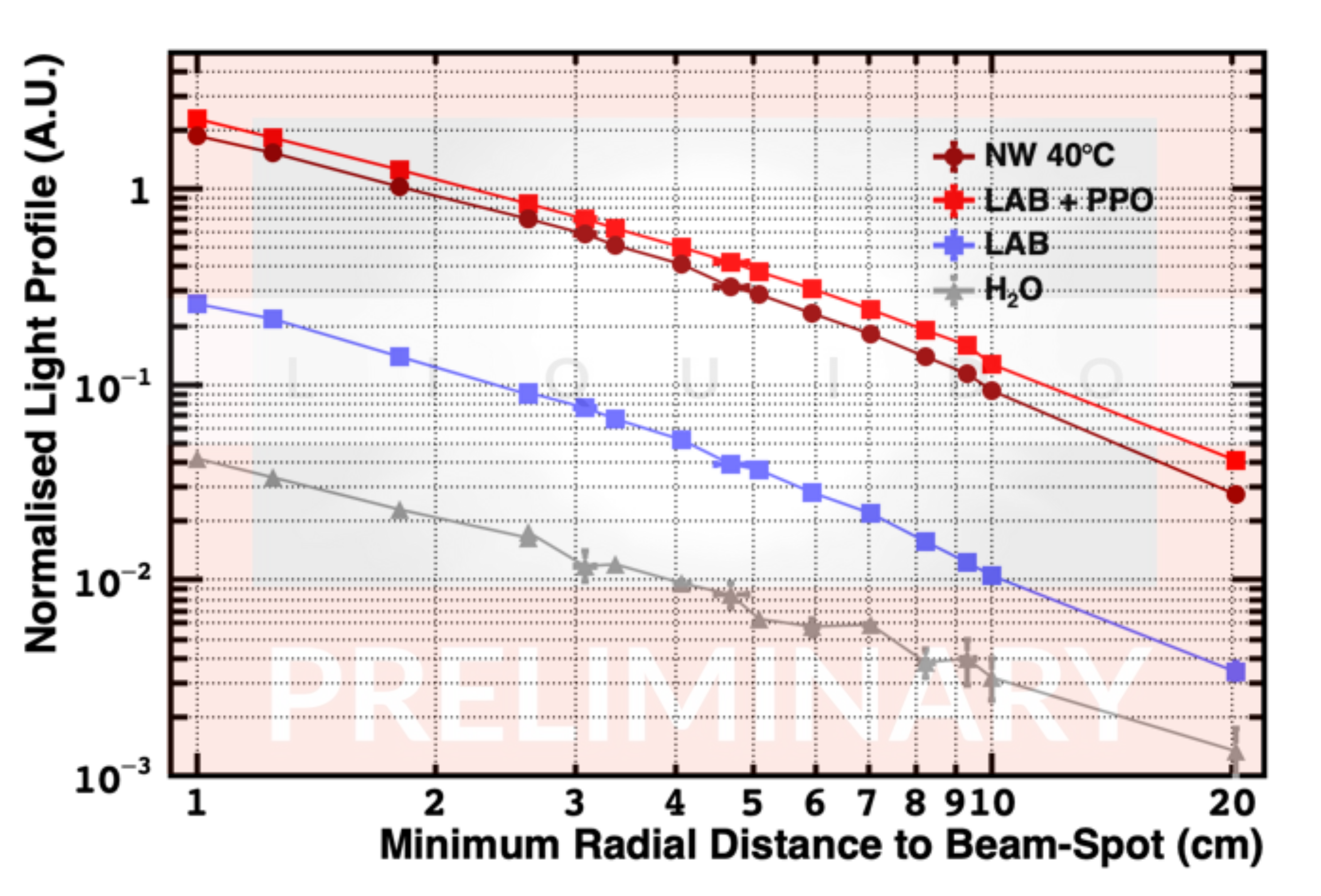
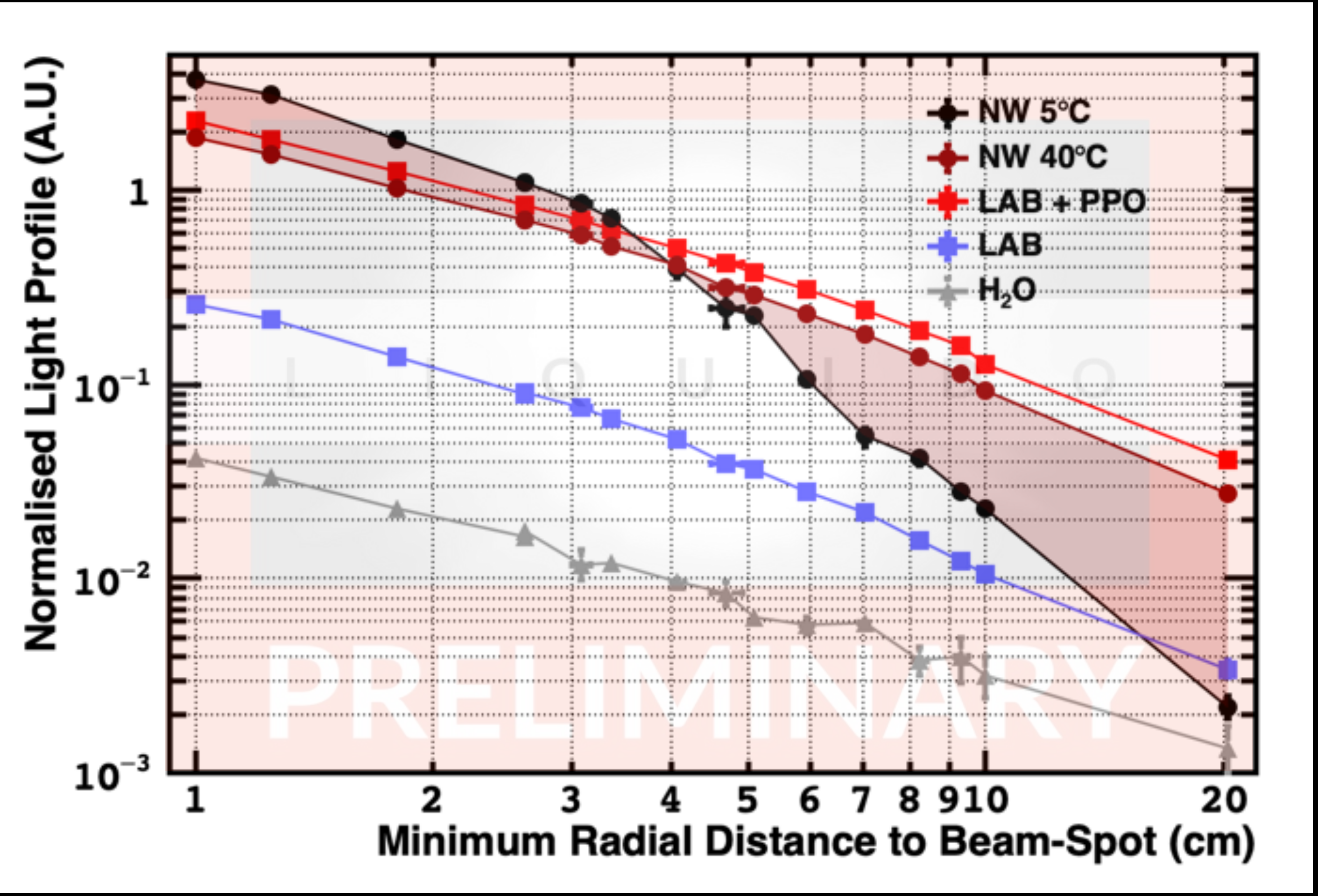


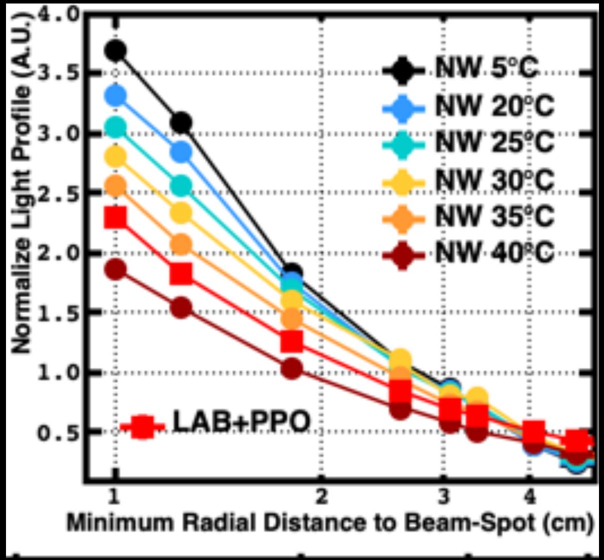
- ★ NW at 40℃: almost as transparent as usual LAB+PPO LS (less light due to 20% paraffine)
- ★ LAB+PPO (3g/L): amount of light increased
- ★ LAB: more light due to scintillation
- ★ Water: Cherenkov

Experimental validation

Light Confinement Demonstration: Transparent vs Opaque

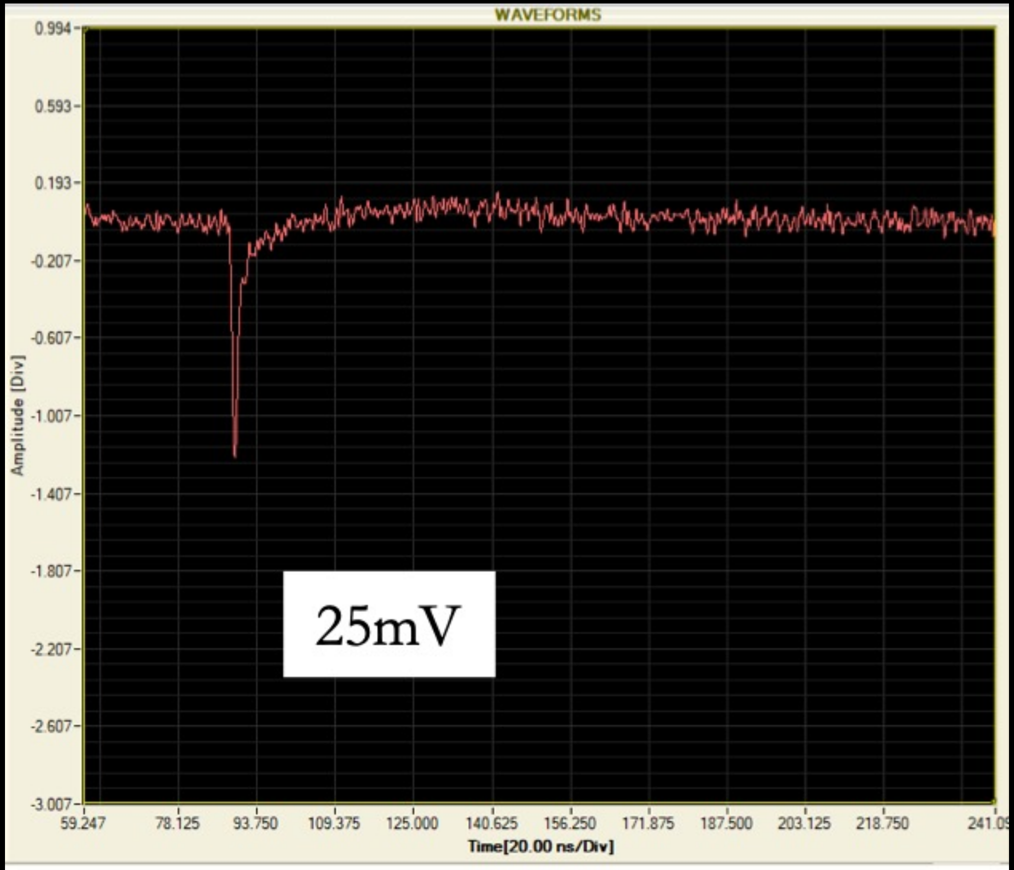


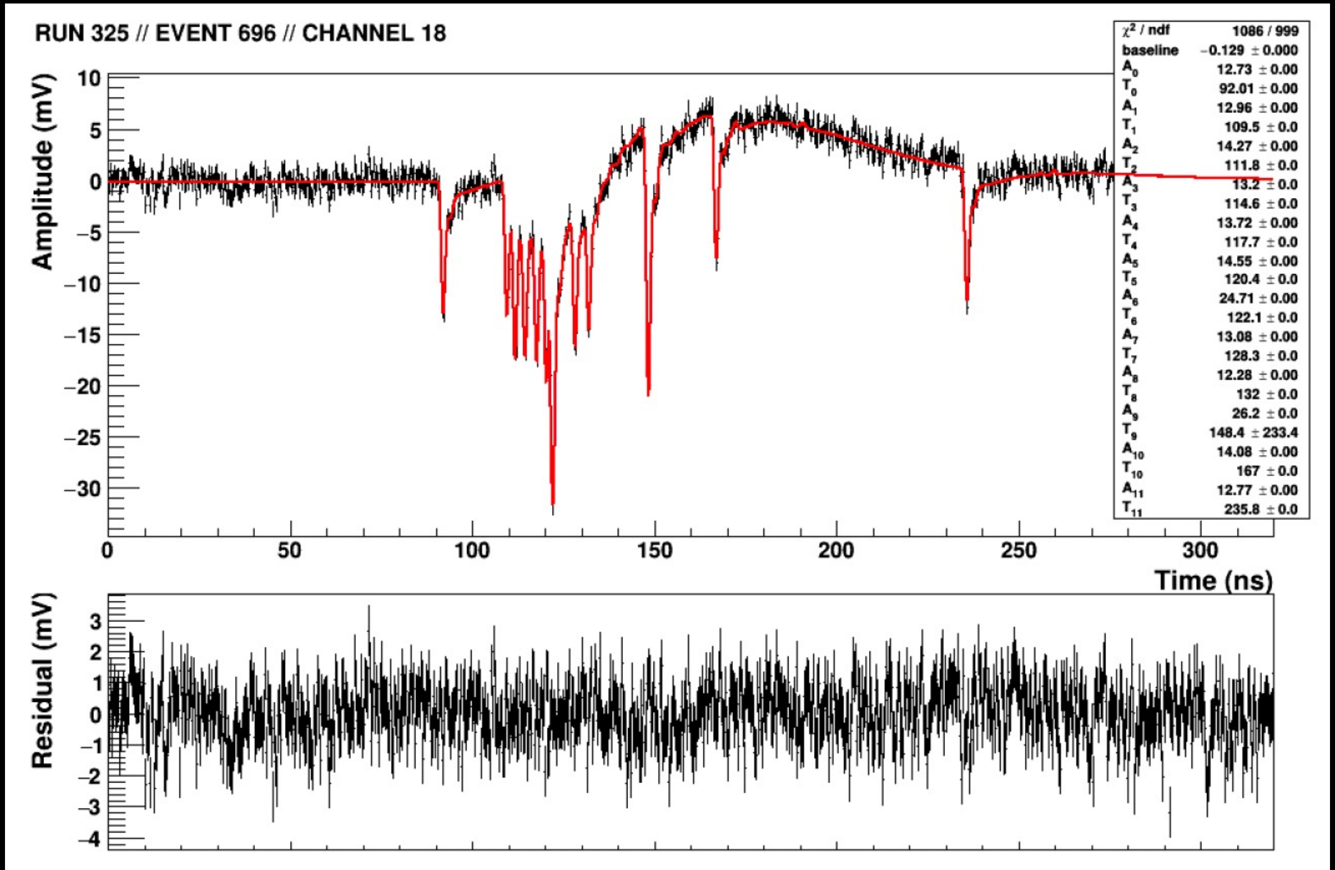
- ★ NW at 40℃: almost as transparent as usual LAB+PPO LS (less light due to 20% paraffine)
- ★ NW at 5℃: opaque
- ★ Faster collection and better light confinement in the opaque mode
- ★ Light Ball formation at ~4cm



Signal reconstruction

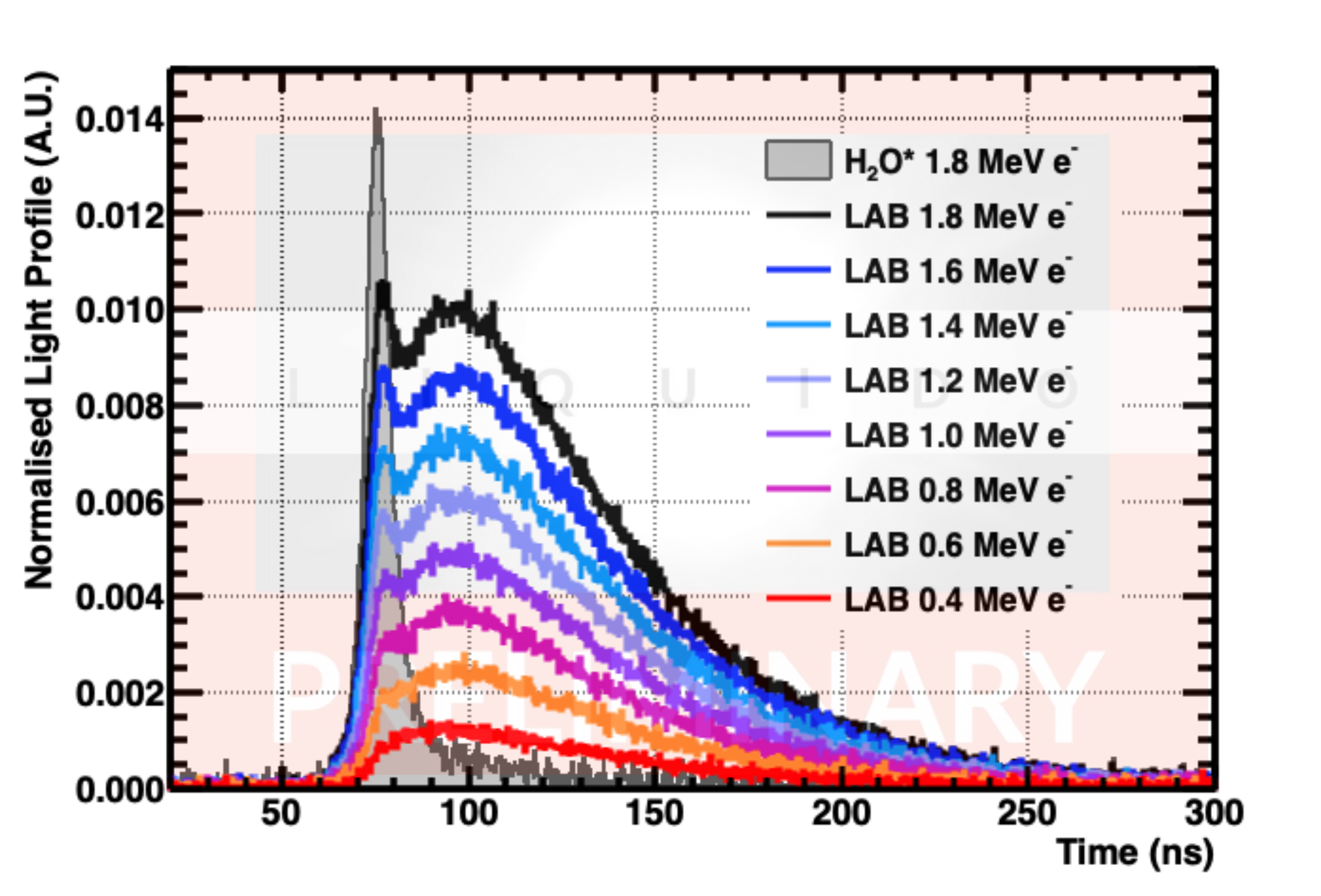
- WaveCatcher + RecoZOR





MINI-II results

LiquidO's timing Potential: Cherenkov vs Scintillation

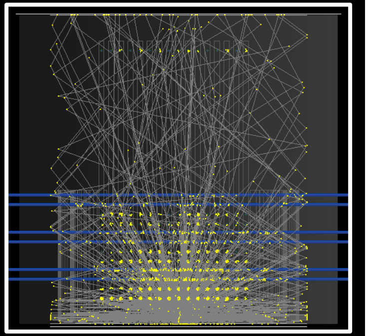


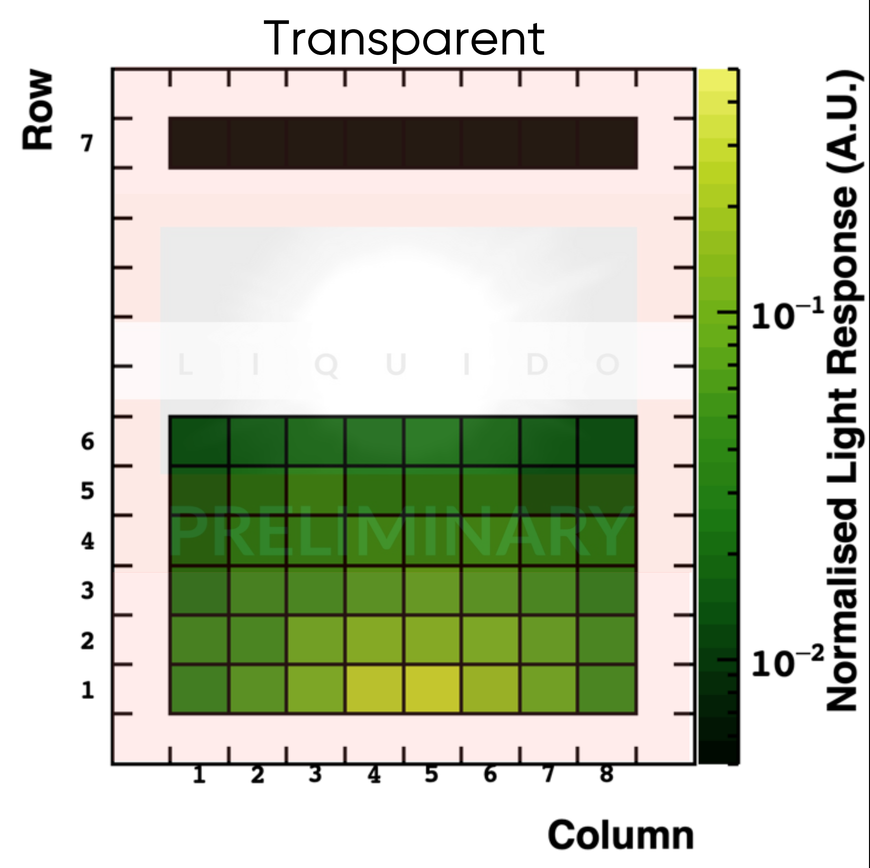
Transparent media regime

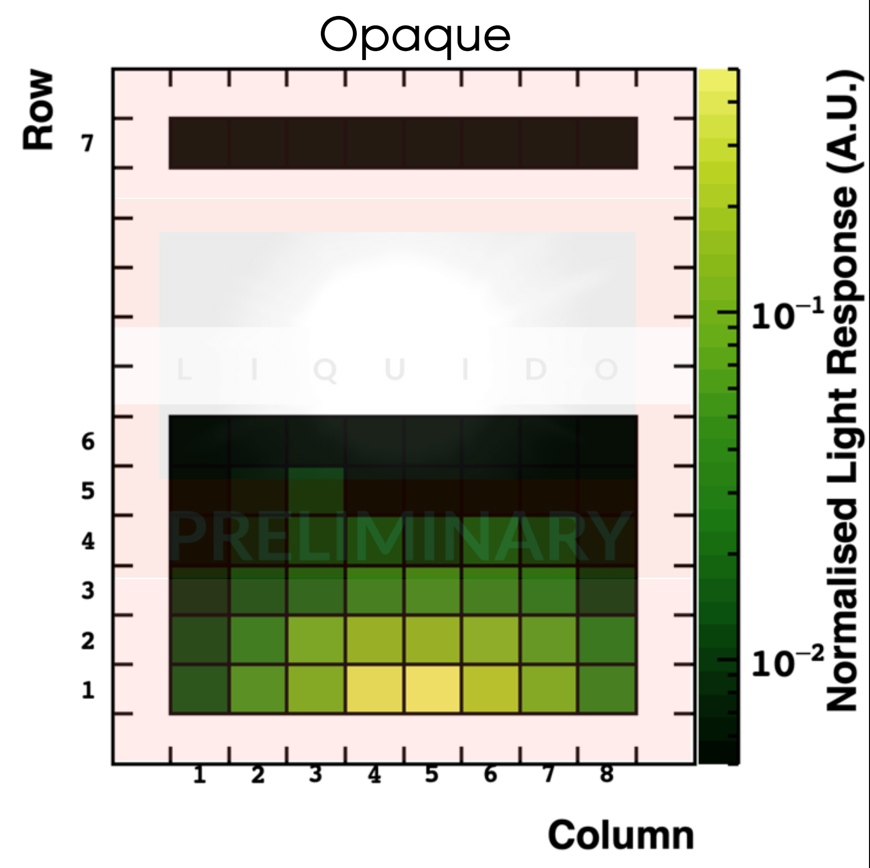
- ★ Liquid scintillator: LAB alone (slow)
- ★ Water data allows confirmation of the Cherenkov peak time position
- ★ Remarkable separation using only timing
- ★ Cherenkov light production threshold

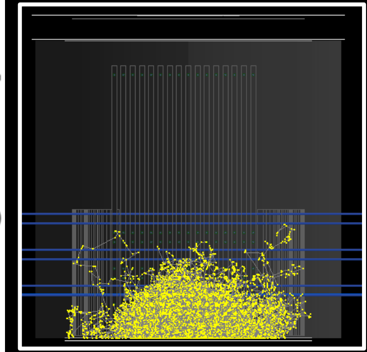
Mini-e⁻ prototype results

Light Confinement Demonstration





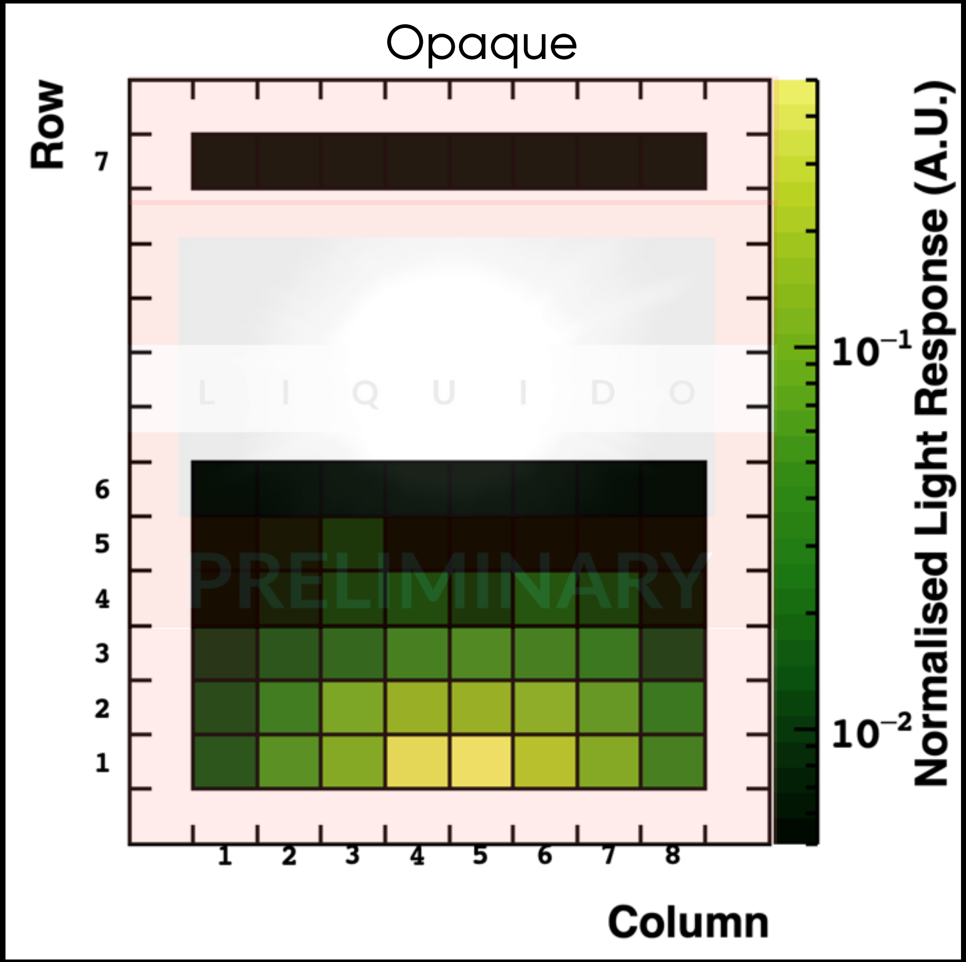


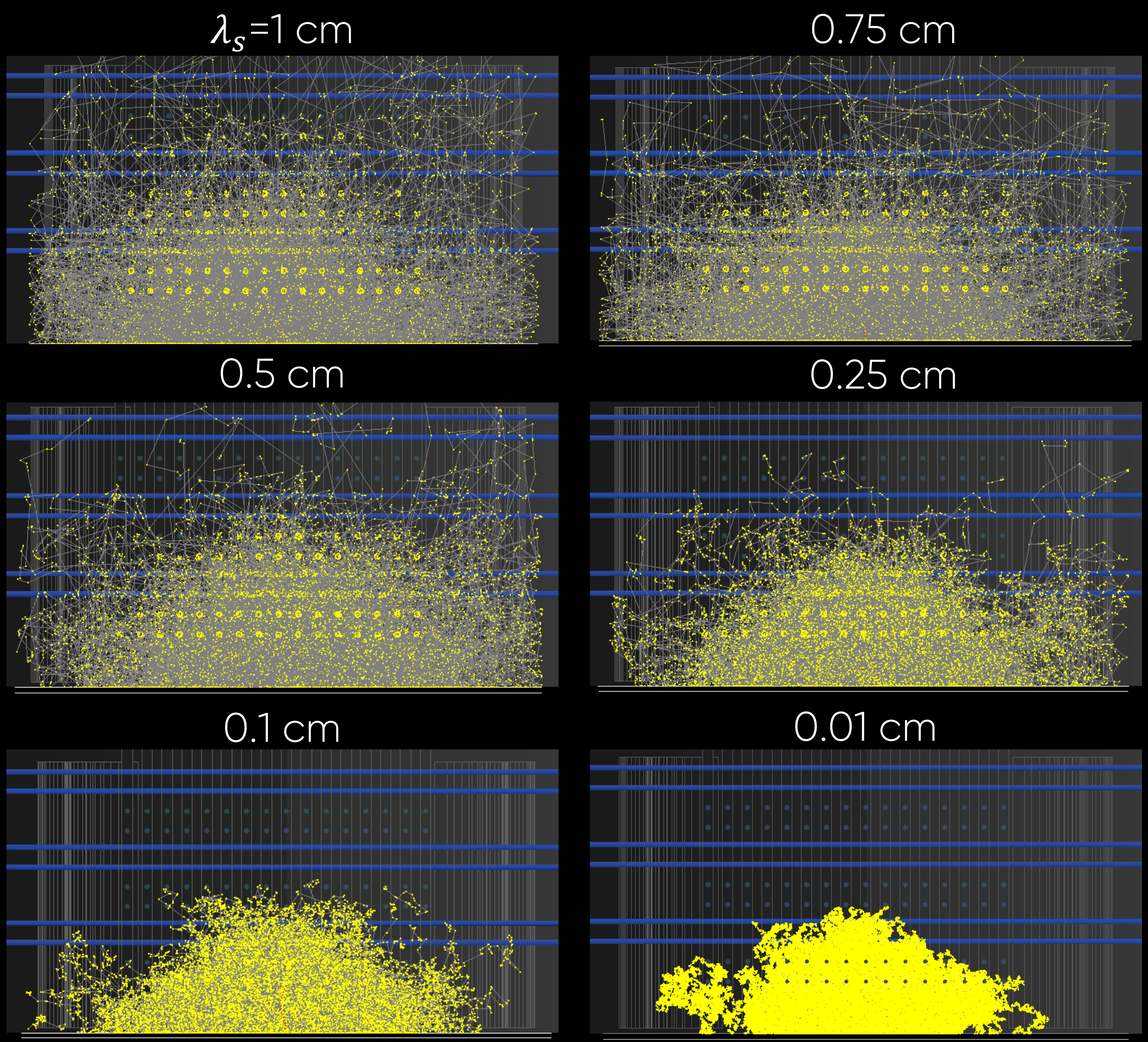


Publication in preparation!!

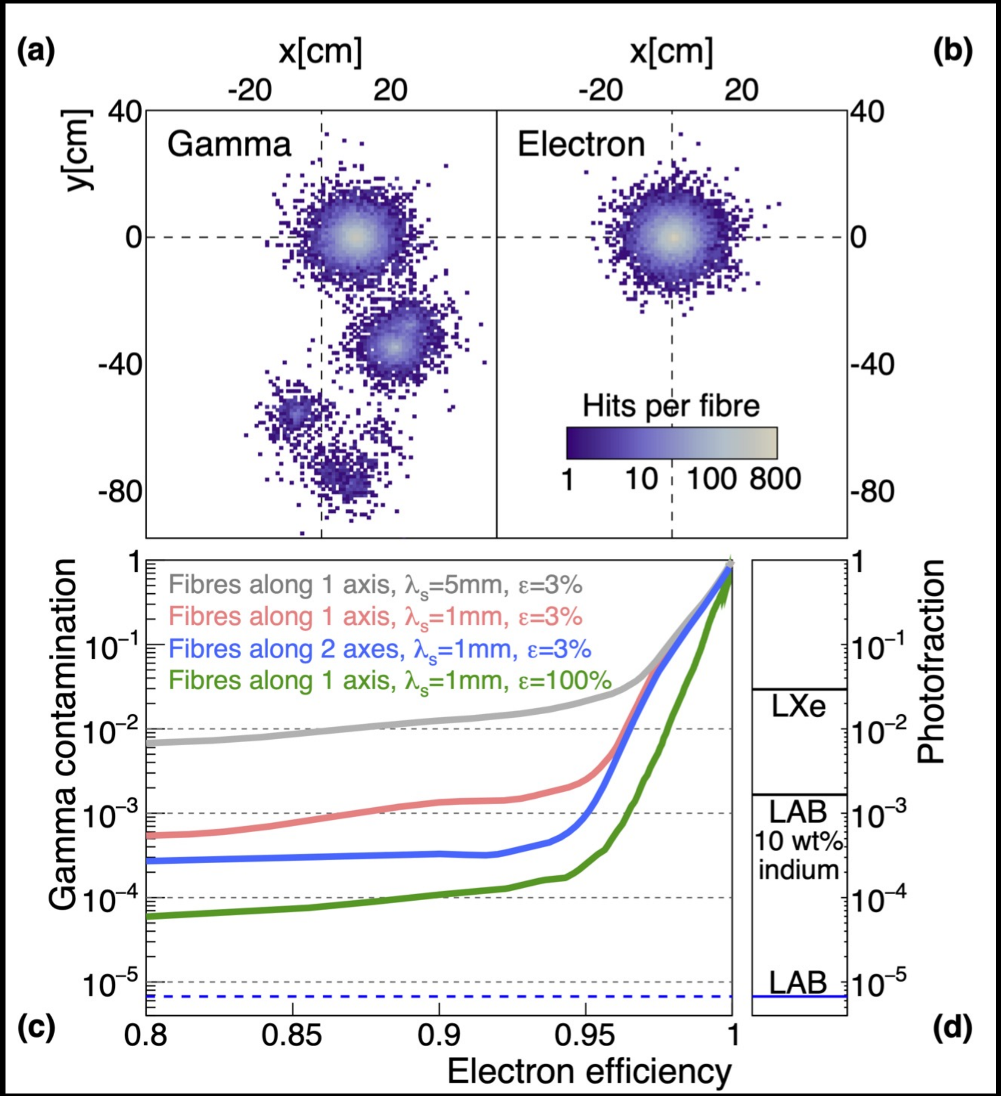
Experimental validation

Light Confinement Demonstration





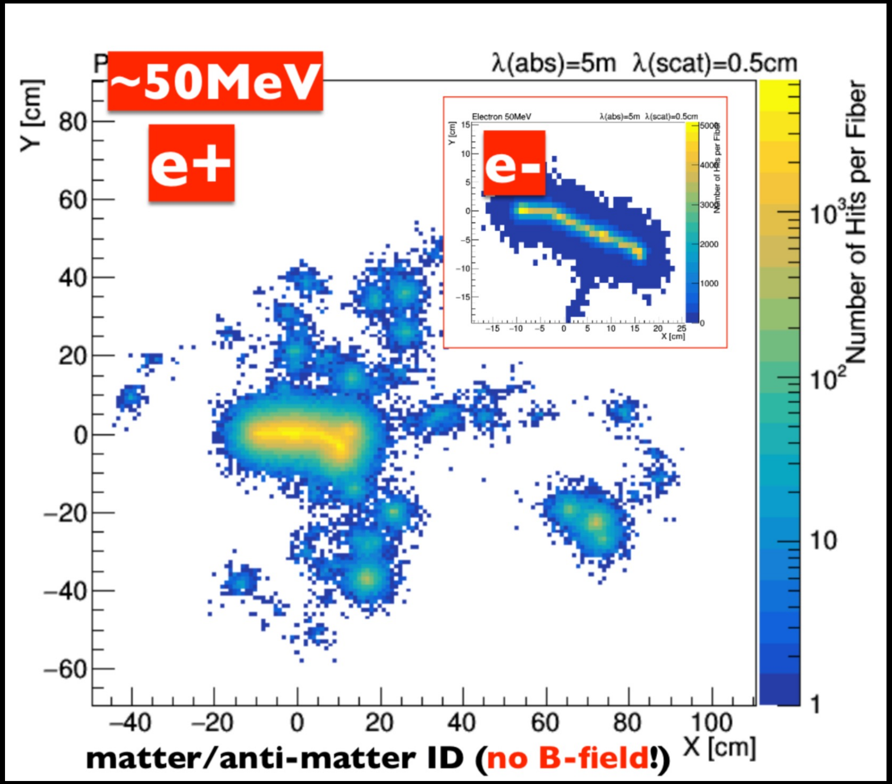
Gamma vs e- discrimination



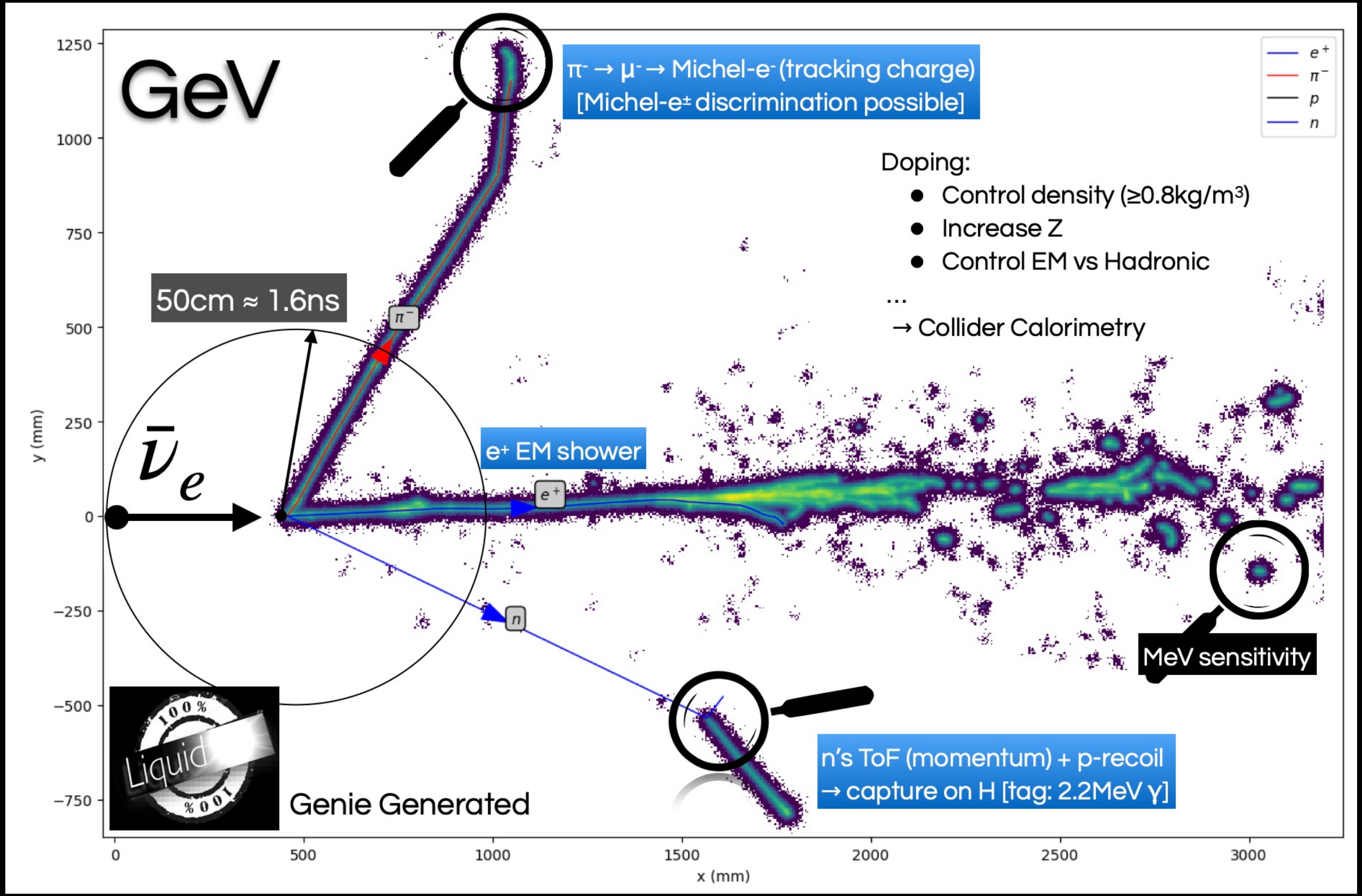
- 1-cm-pitch lattice running along the z-axis
- Probability of misidentifying a γ as an e^- vs. the efficiency of selecting e^-
- mean scattering length λs of either 1 mm or 5 mm
- photon detection efficiency ε of 3% (fibre trapping efficiency (~10%) and SiPM QE (~50%)
- The gray curve shows the probability of misidentifying a 2 MeV γ as an e^- is estimated to be at the 10^{-2} level with an efficiency of 87% for λs=5 mm.

Wide physics potential

From MeV to MultiMeV



From MultiMeV to GeV

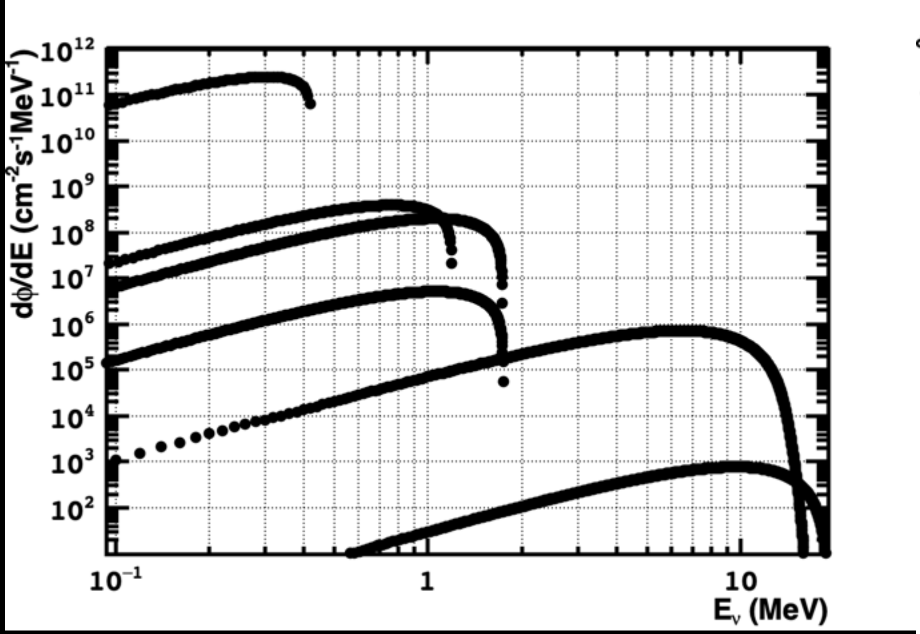


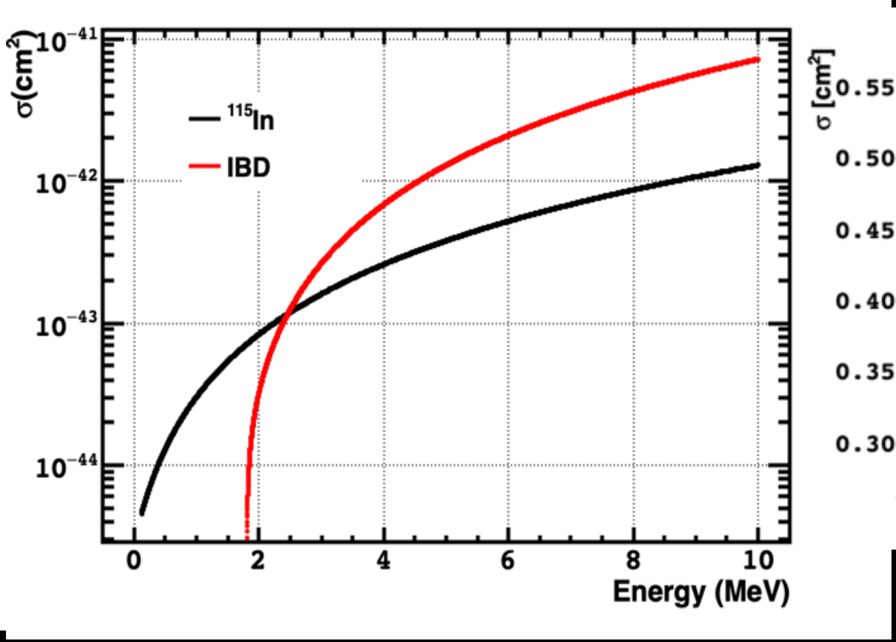
Solar Neutrinos @CLOUD-II

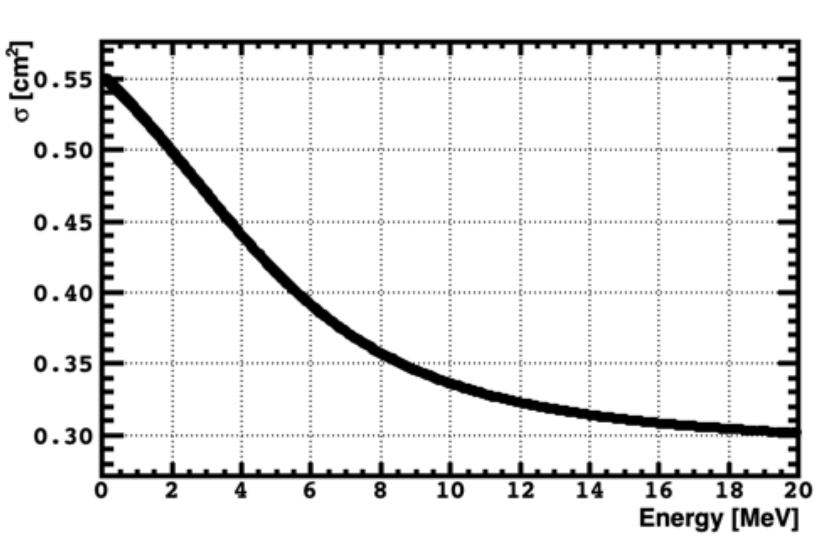
Number of solar ν_e in AMoTech-^{115}In (5 tons InLS (10%^{115}In), 30 m)

Signal = 2.62×10^{27} atoms ^{115}In × (3.15×10^{8})s × ν-flux × cross-section × Pee

- Solar Fluxes http://www.sns.ias.edu/~jnb/SNdata/sndata.html#hepspec
- ^{115}In cross-section
- Survival Probability Pee

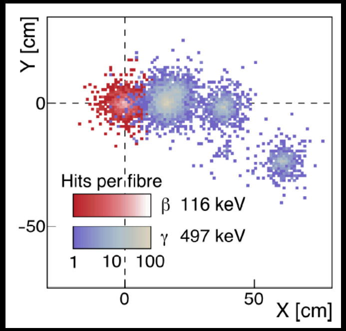


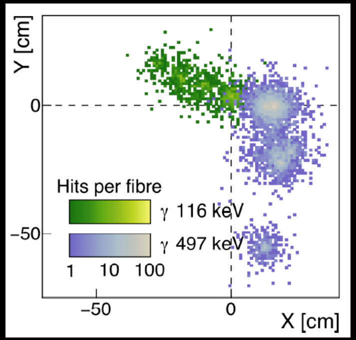




PID 115In

	Branch.	Case	Prompt	Delay	Exclusive	Inclusive	BG discrimination
BG (In)	100%		●	●	100%	100%	-
Signal	51%	a1	●	●	90%	45.9%	YES
		a2	●	● ●	10%	5.1%	PID irreducible
	49%	b1	●		79%	38.71%	YES
		b2.1	●	●	10%	4.9%	YES
		b2.2	●	●	10%	4.9%	YES
		b3	●	● ●	1%	0.49%	PID irreducible





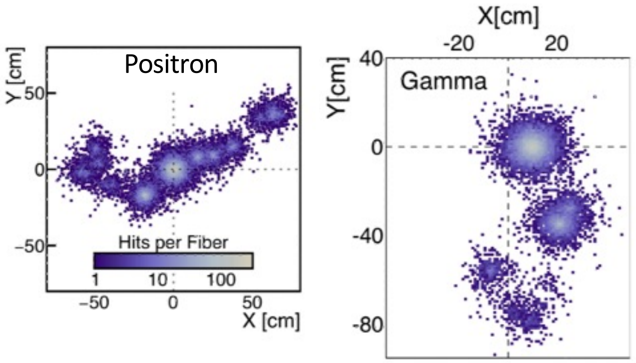
Channel with most complex patter is the most discriminating one

ONLY 5.6% OF THE SIGNAL CAN BE MIMIC BY ^{115}In BETA-DECAY

Assuming:
● + ● = ● = ●

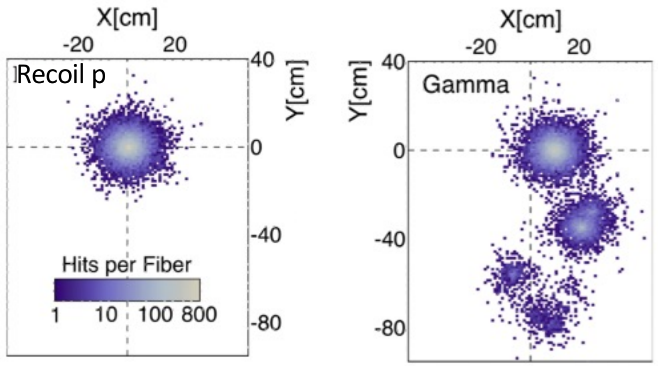
Backgrounds

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



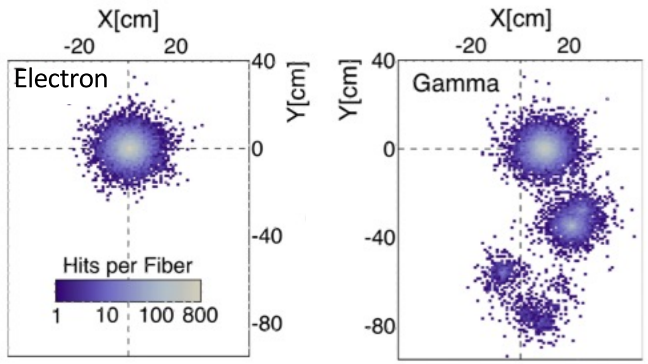
Prompt Delayed

Fast Neutrons



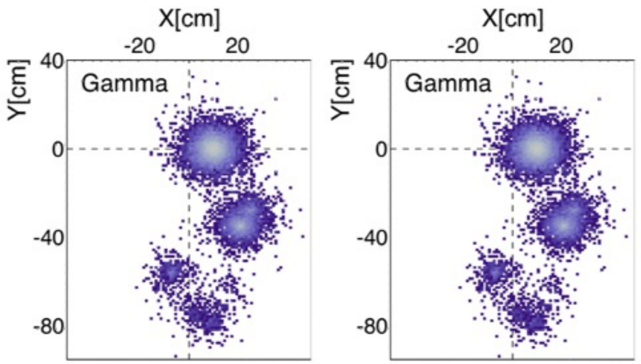
Prompt Delayed

^{9}Li

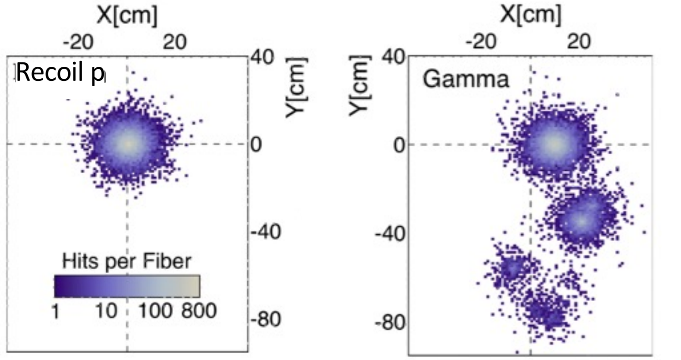


Prompt Delayed

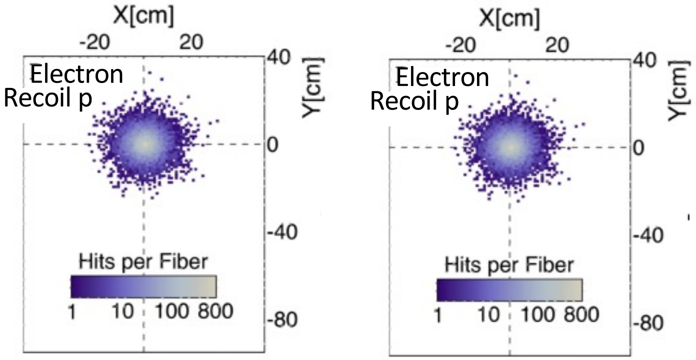
Accidental Coincidences (combinatory) + Radiogenics + Cosmogenics (Neutron Rain)



Prompt Delayed



Prompt/Delayed Prompt/Delayed



Prompt Delayed

Reactor flux measurement

Precise measurement of the reactor antineutrino flux

$\langle\sigma_f\rangle \propto$ total reactor neutrino integrated flux

$$\langle\sigma_f\rangle(t) = \frac{N^{exp}_{\bar{\nu}_e}}{\epsilon N_p}\left(\frac{W_{th}(t)}{4\pi L^2 \langle E_f\rangle}\right)^{-1} \text{cm}^2/\text{fission}$$

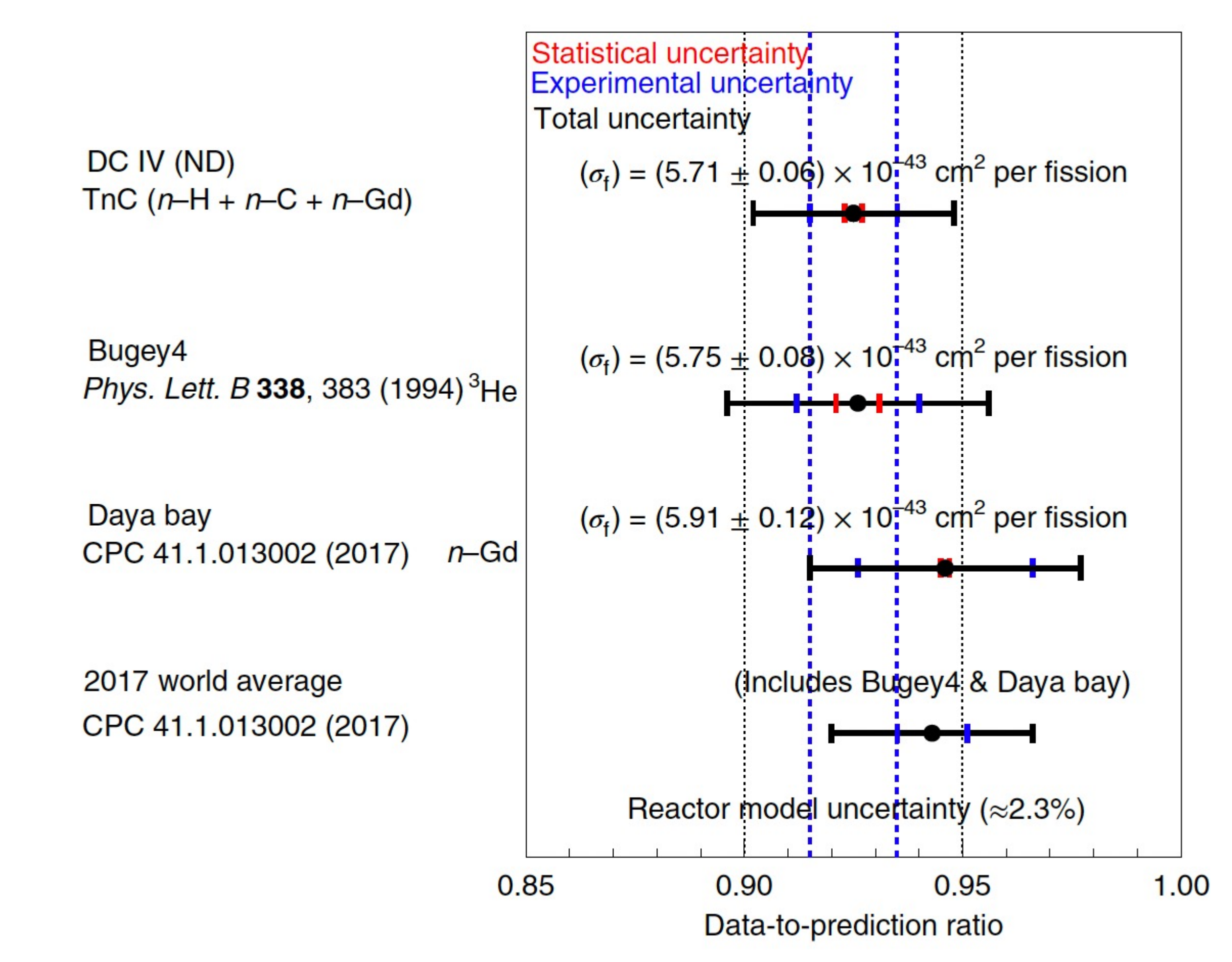
Uncertainty (%)	ND (DC)
Proton Number	0.66
Thermal Power	0.47
Detection Eff	0.24
Background	0.18
Energy per Fission	0.16
θ_{13} Correction	0.16
Statistics	0.22
TOTAL	0.97

Double Chooz

Livetime: 258 days

Rate: ~800 $\bar{\nu}_e$/day

Double Chooz (DC): for the first time, precision below 1%



Differential eES x-section

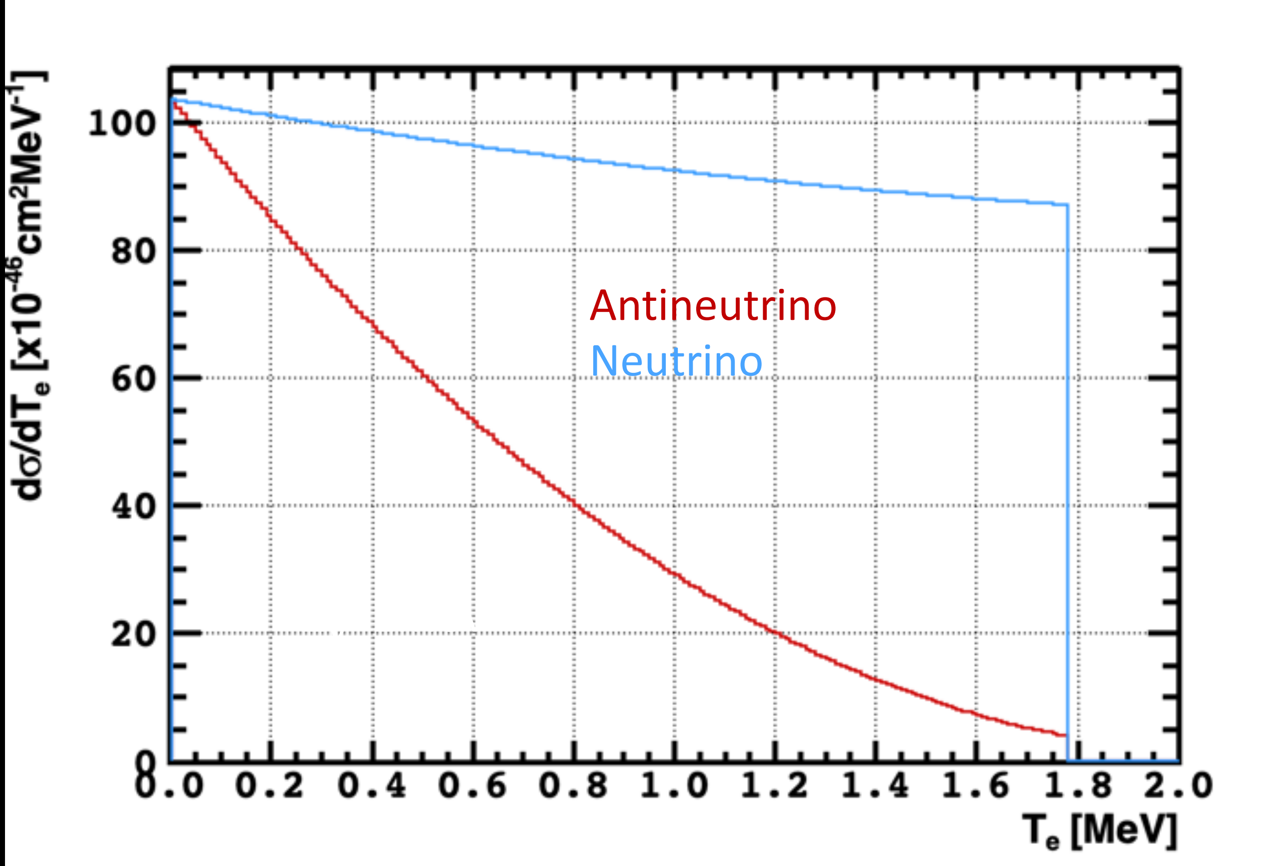
For each antineutrino interaction with a certain energy E_ν, the resulting recoil electron could have a range of energies from 0 MeV to $(T_e)_{max} = E_\nu - \frac{1}{\frac{2}{m_e}+\frac{1}{E_\nu}}$

$$\frac{d\sigma}{dE_\nu dT_e} = \frac{\sigma_0}{m_e}\left[g_L^2 + g_R^2\left(1-\frac{T_e}{E_\nu}\right)^2 - g_L g_R \frac{m_e T_e}{E_\nu^2}\right]$$

$$\sigma_0 = \frac{2G_F^2 m_e^2}{\pi} \simeq 88.06\times10^{-46}\text{cm}^2$$

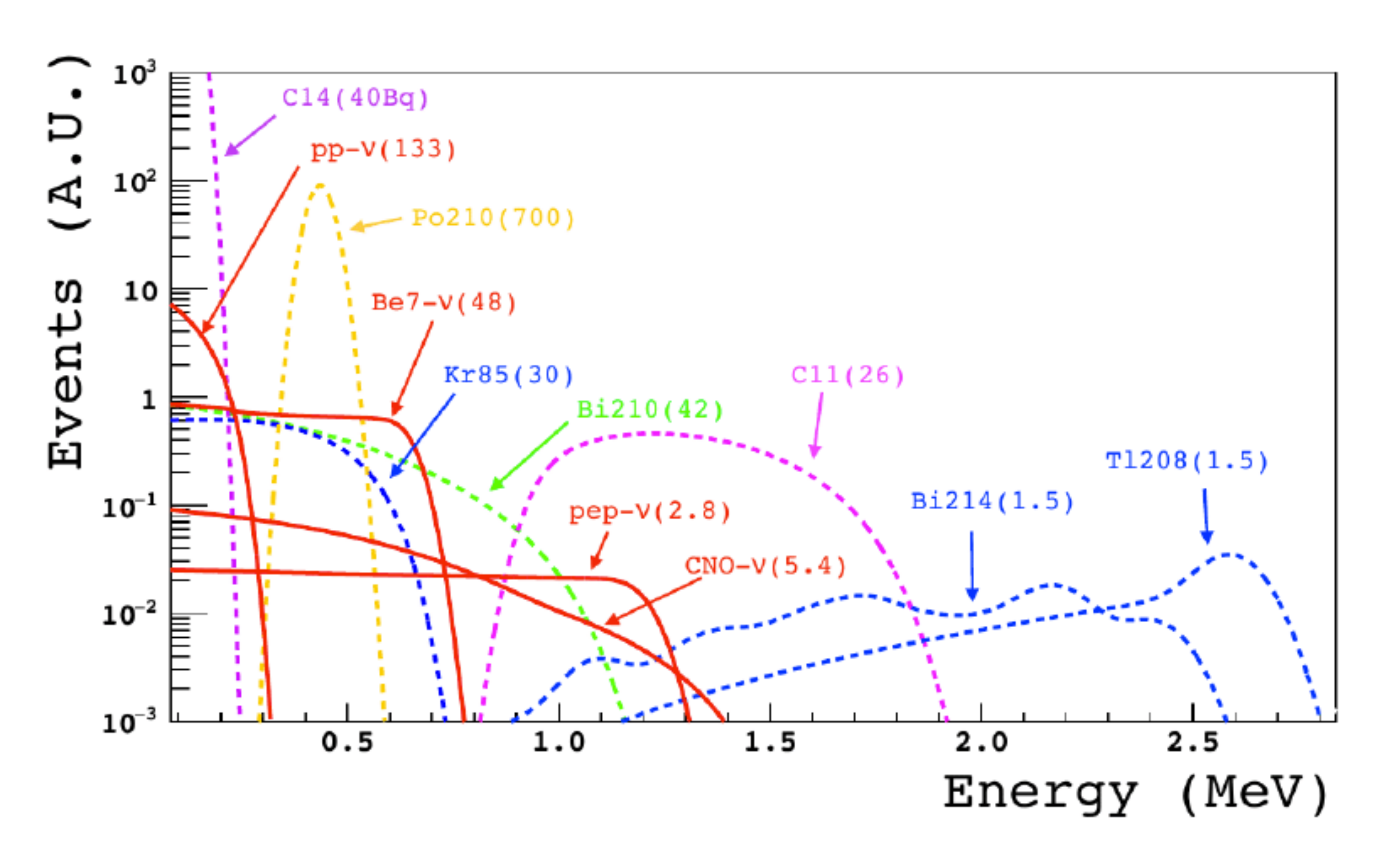
$$g_L(\bar{\nu}_e) = \sin^2\theta_W = 0.2387,$$
$$g_R(\bar{\nu}_e) = \sin^2\theta_W + \frac{1}{2} = 0.7387$$

$$g_L(\nu_e) = \sin^2\theta_W + \frac{1}{2} = 0.7387,$$
$$g_R(\nu_e) = \sin^2\theta_W = 0.2387$$



Antineutrino ES is dominated by NC, neutrino ES by CC

Today's challenge



Elastic Scattering

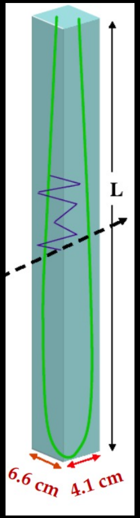
- no PID (e- vs **β**-)
- no coincidence

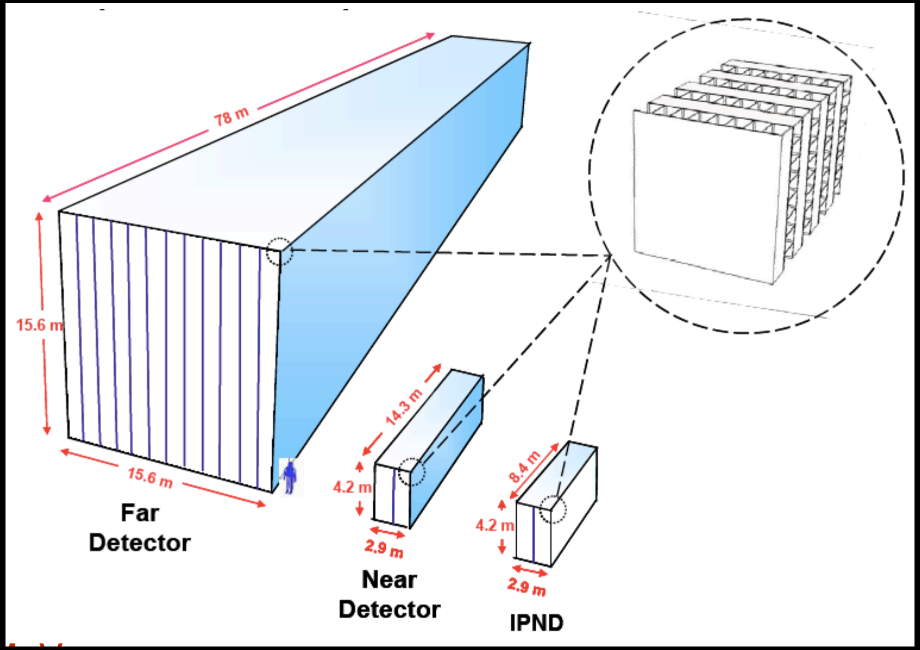
- Heaviside functions from monoenergetic reactions
- Indistinguishable β^{-} from natural radioactivity
- Need to have ultra-radiopure experiments (Borexino $\sim 10^{-20}$g/g)

Scalability

- No showstoppers foreseen when scaling LiquidO to ~10 ktons:
  - Invaluable experience from NOVA
  - Key difference: avoid light losses due to reflection inside the cells

In NOvA the efficiency of light hitting the fibre is ~12%. For LiquidO we expect > 90%





- A NOvA-sized LiquidO would achieve at least 100 PEs/MeV with today's technology→ already excellent for MeV physics
- Rough cost expected to be comparable to NOVA FD
- Other advantages compared to other detectors:
  - Room temperature operation (no need for cryostat)
  - Self-shielding detector

LiquidO beam events