CLOUD: fundamental reactor antineutrino physics using the novel LiquidO detection technology

Thiago Bezerra, for the CLOUD Collaboration

EPS-HEP 2025 Conference, Marseille

11th July 2025

What is CLOUD?

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- **C**hooz **L**iquid**O** **U**ltra-near **D**etector

What is CLOUD?

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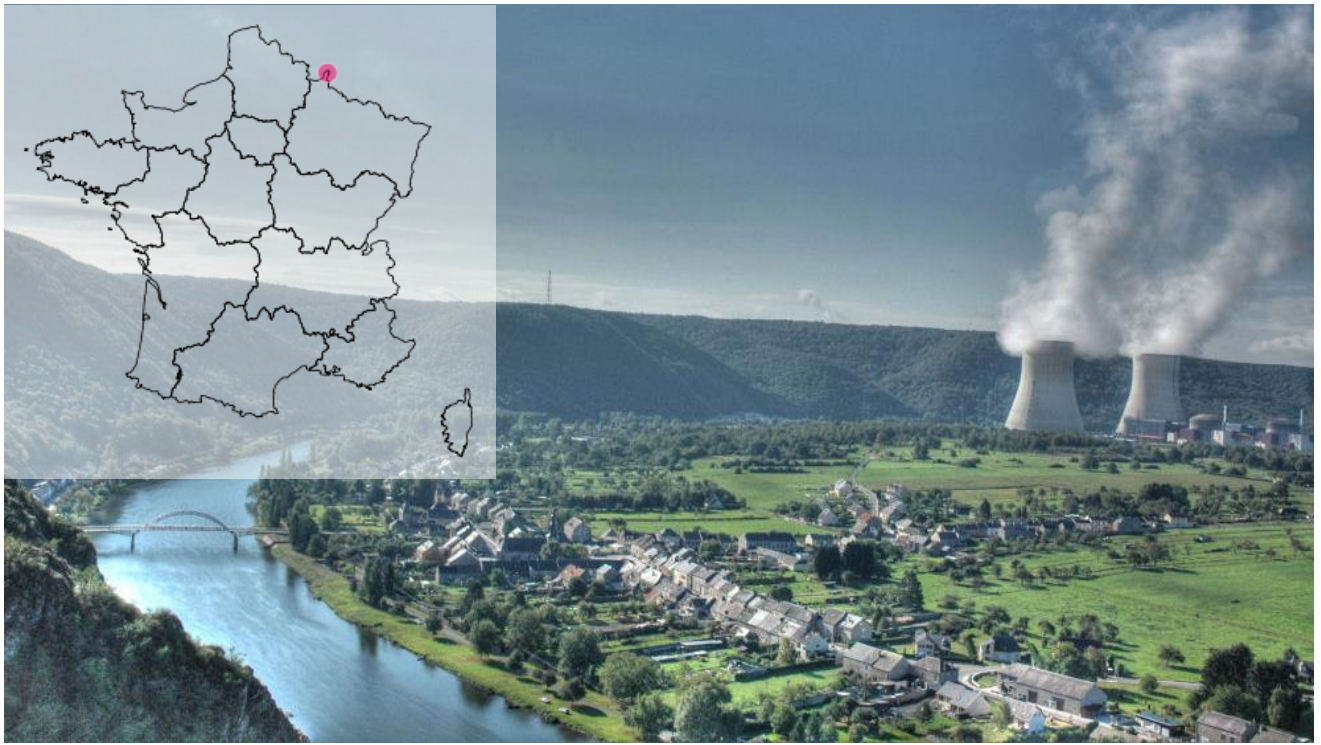
- **C**hooz **L**iquid**O** **U**ltra-near **D**etector

- Powerful reactor site
  - ~10^{21} ν/s per core
- Home of CHOOZ and Double Chooz experiments



Eur. Phys. J. C **27**, 331–374 (2003)
Nat. Phys. 16, 558–564 (2020)

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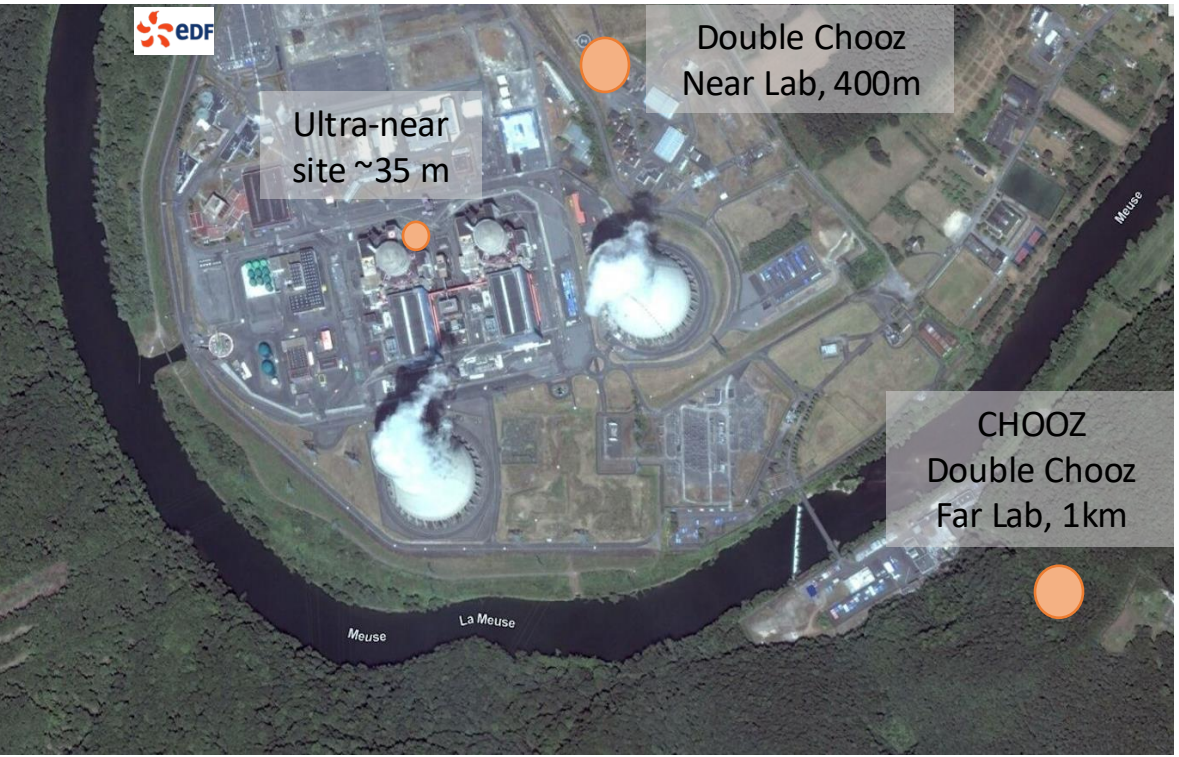

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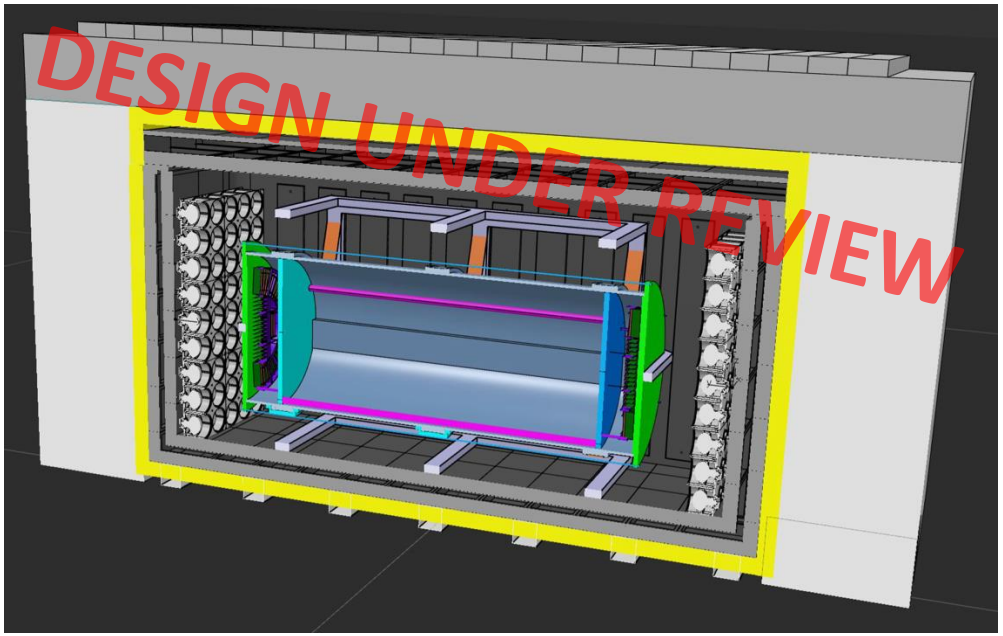

https://antimatter-otech.ijclab.in2p3.fr/

- 5-10 tons **LiquidO** Detector
- 10,000 WLS fibres
- SiPMs dual read-out
- 1.8 m diameter
- > 200 PE/MeV design

What is CLOUD?

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- **C**hooz **L**iquid**O** **U**ltra-near **D**etector

Why LiquidO?

The *novel* opaque scintillation technique

Two types of opacity

Short *absorption* length
Short scattering length

Long *absorption* length
Short scattering length

Light paths

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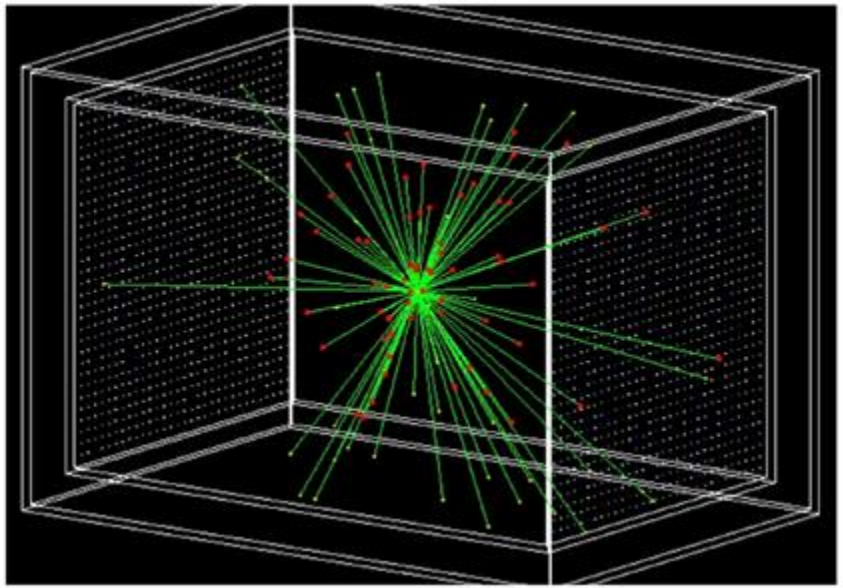
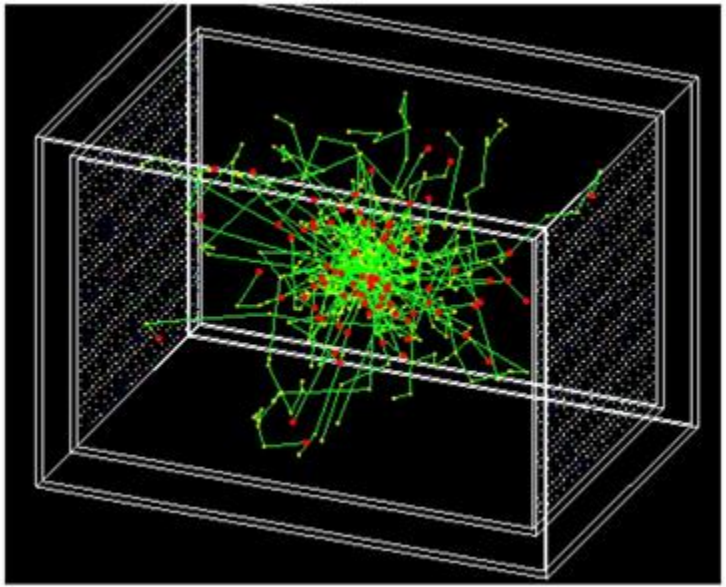
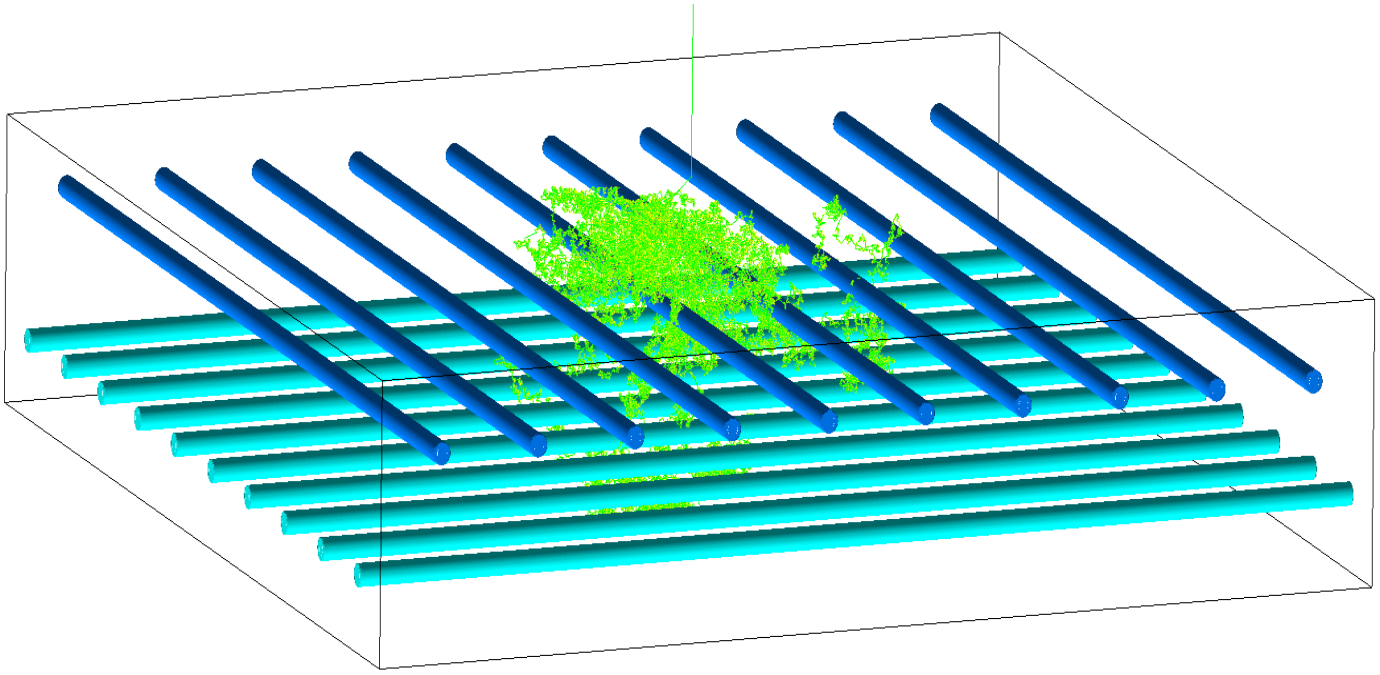


Transparent scintillator
Straight paths



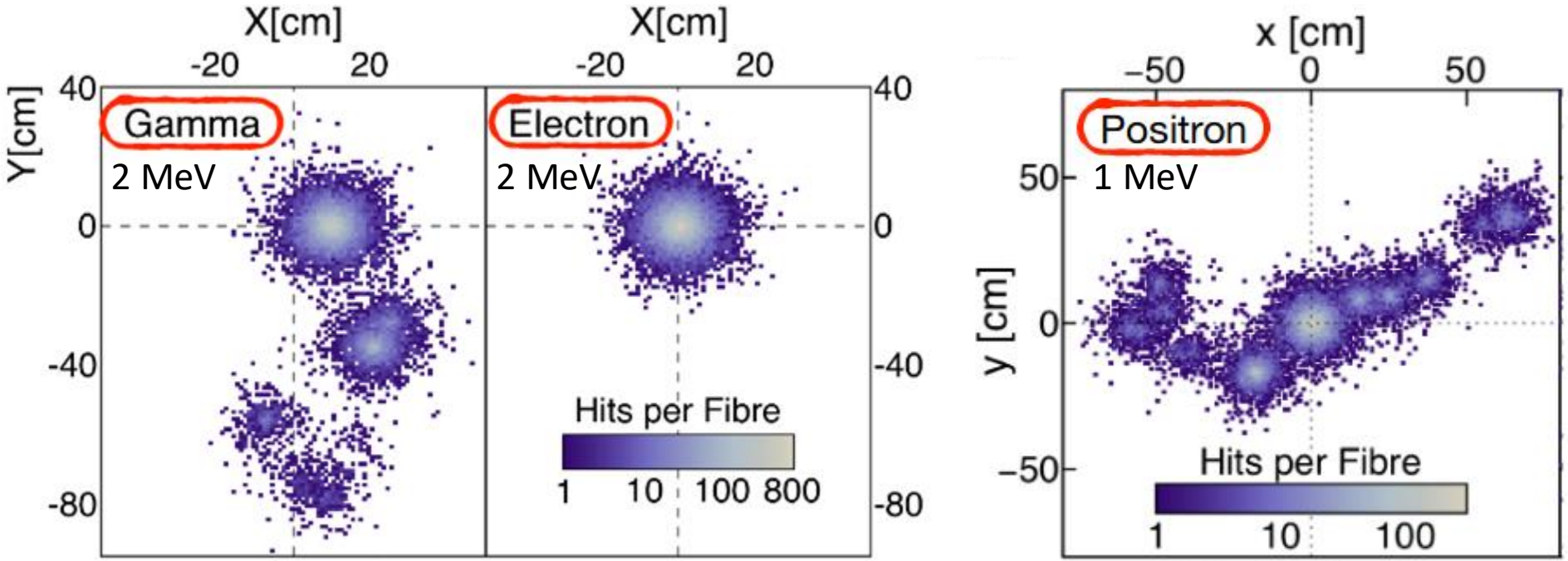
Opaque scintillator
Random walk

Extracting light from the energy deposition local



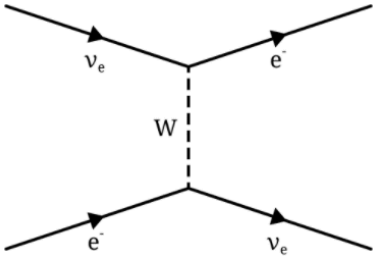
Readout: wavelength shifting fibres + SiPMs

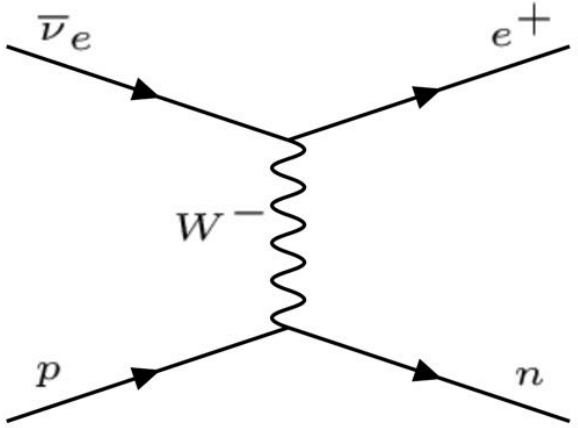
Powerful particle identification



Cannot separate *efficiently* these 3 on an event-by-event basis with transparent scintillator!

Physics of CLOUD





CLOUD Physics goals

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- Phased experiment
- CLOUD I
  - Pure opaque scintillator
  - Antineutrino detection at **surface**
- CLOUD II
  - **Dopped** opaque scintillator
  - Neutrino detection at **surface**

CLOUD Phase I: Pure Opaque Scintillator

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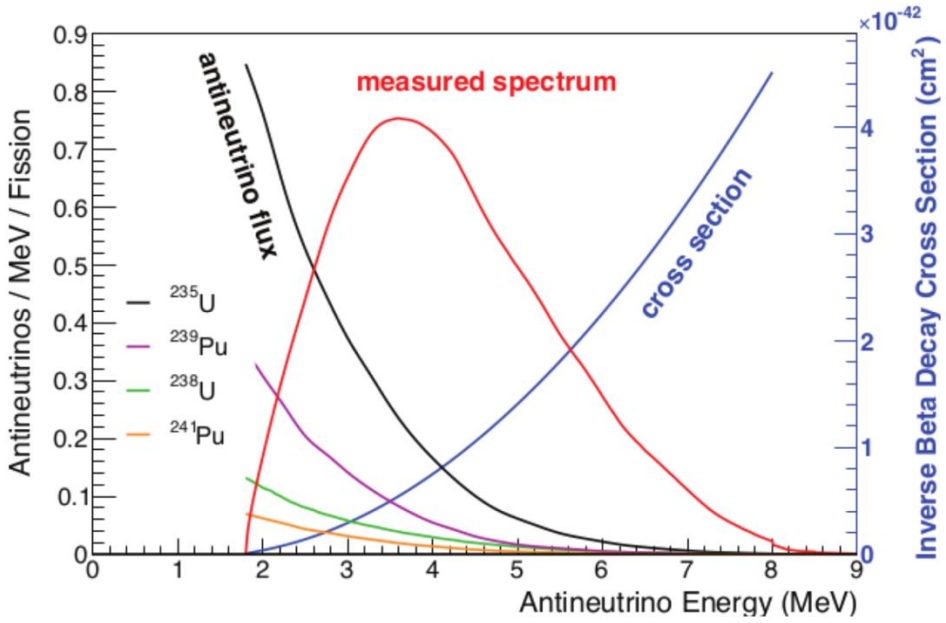
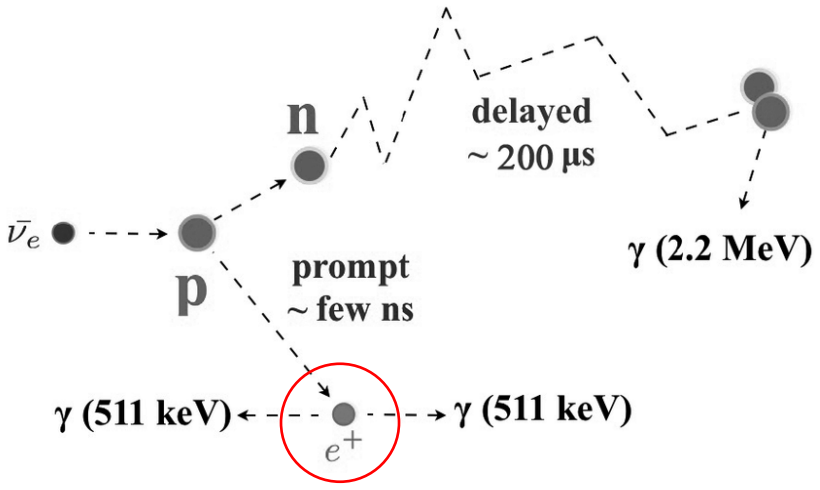
Nuclear reactors are a powerful anti-ν_e source!



Inverse Beta Decay reaction:

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



CLOUD Phase I: Pure Opaque Scintillator

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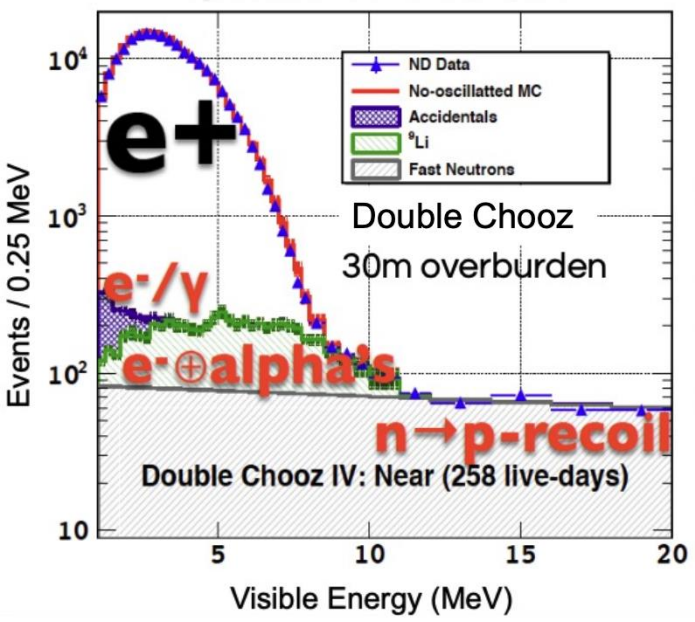
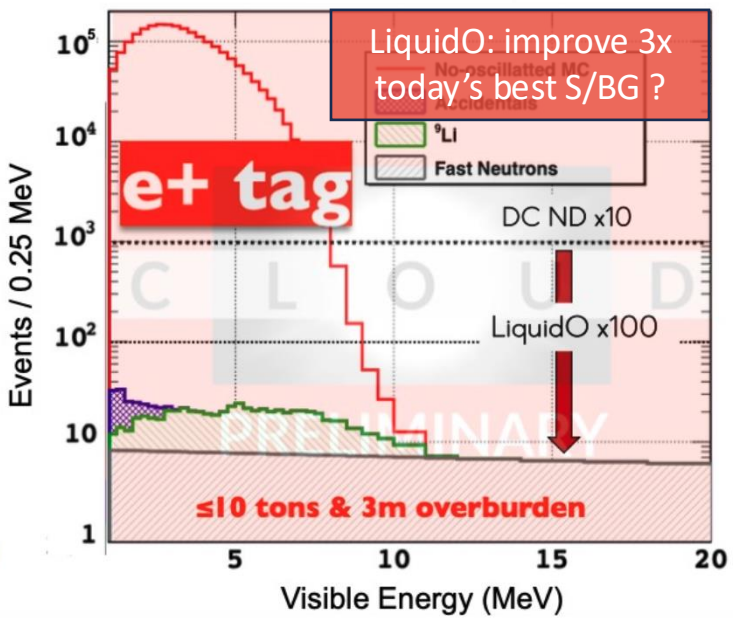
$$\bar{\nu}_e + \mathrm{p} \rightarrow e^+ + n$$

State of the art



CLOUD



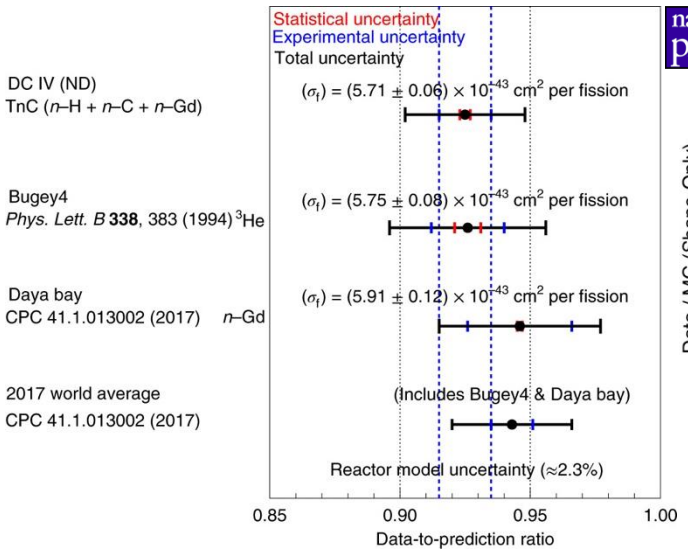
Select > 10,000 IBD daily!

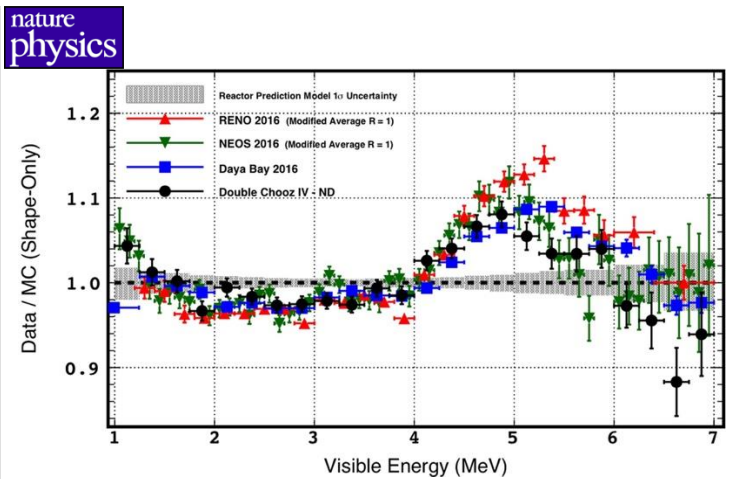
LiquidO PID + vertex precision:

Demonstrate S/BG ~ 100 (unprecedented)

CLOUD Phase I: Pure Opaque Scintillator

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





Nat. Phys. 16, 558–564 (2020)

Select > 10,000 IBD daily!

LiquidO PID + vertex precision:

Demonstrate S/BG ~ 100 (unprecedented)

< 1% flux measurement

Spectrum characterization

CLOUD Phase I: Pure Opaque Scintillator

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

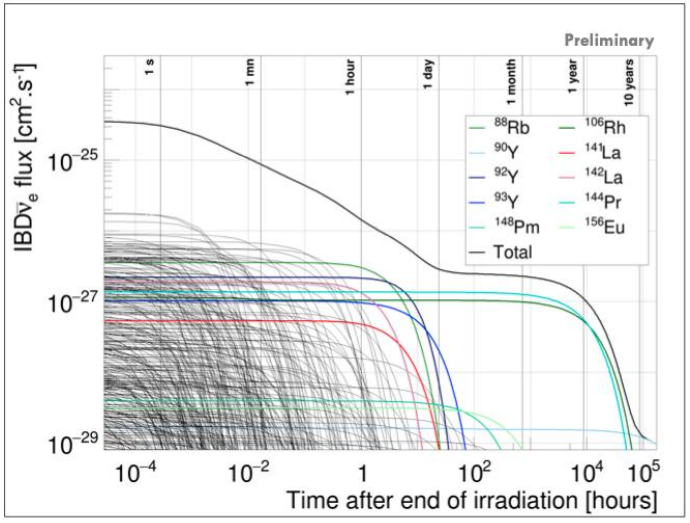
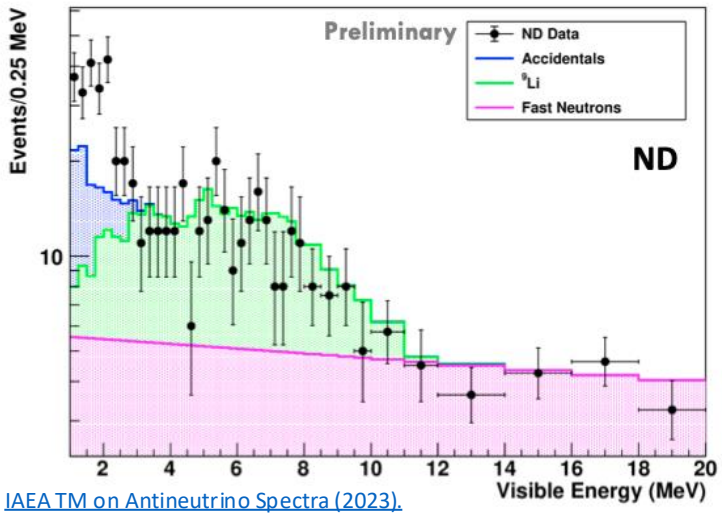


Fig. IBD$\bar{\nu}_e$ flux from a UO_2 (4%) spent fuel assembly irradiated for 45 GWd/t.



IAEA TM on Antineutrino Spectra (2023).

Reactor **OFF** measurement

S/B~1 at **surface**!

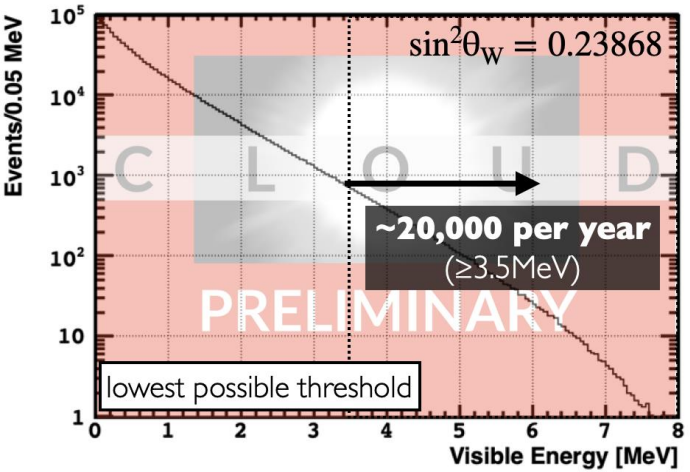
ON-OFF-ON transitions

Feed in prediction models

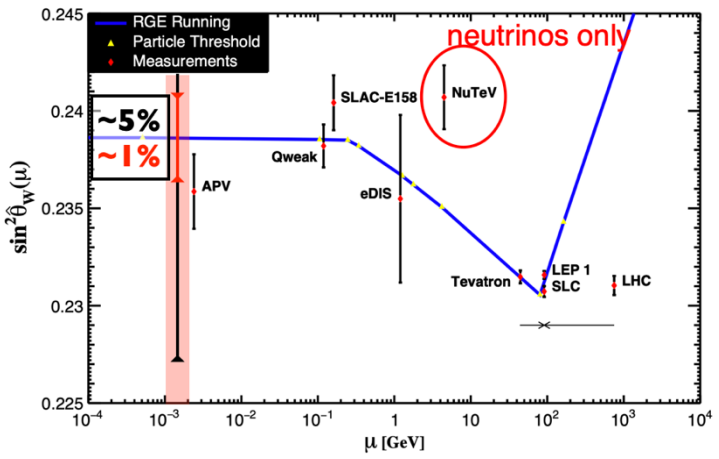
What can we learn with more statistics ?

CLOUD Phase I: Pure Opaque Scintillator

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



E.S. Spectrum (1 year exposure)



> 5,000 Elastic scattering daily

~20,000 a year, above 3.5 MeV

Follows reactor power

Sensitive to NC coupling

Probe $\sin^2\theta_W$ at low energies with $\bar{\nu}_e$'s

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CLOUD Phase II: *Indium* Loading in Scintillator

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- ν_e CC with Indium nucleus

$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^*$$
$$\hookrightarrow \gamma/e^- \, (116\ keV) + \gamma \, (496\ keV)$$

Phys. Rev. Lett. **37**, 259 -262 (1976)

- Very low threshold (114 keV)
- ^{115}In has high natural abundance (96%)
- Fast delayed coincidence (4.8 μs)
- Multi-fold coincidence signature!
  - Required right particles in right places at right times with right energies
  - 1st **e-** to be in the same cubic cm of the detector as the 2nd **e-**
  - Nearby gamma-like event has 497 keV in time with 2nd **e-**

CLOUD Phase II: *Indium* Loading in Scintillator

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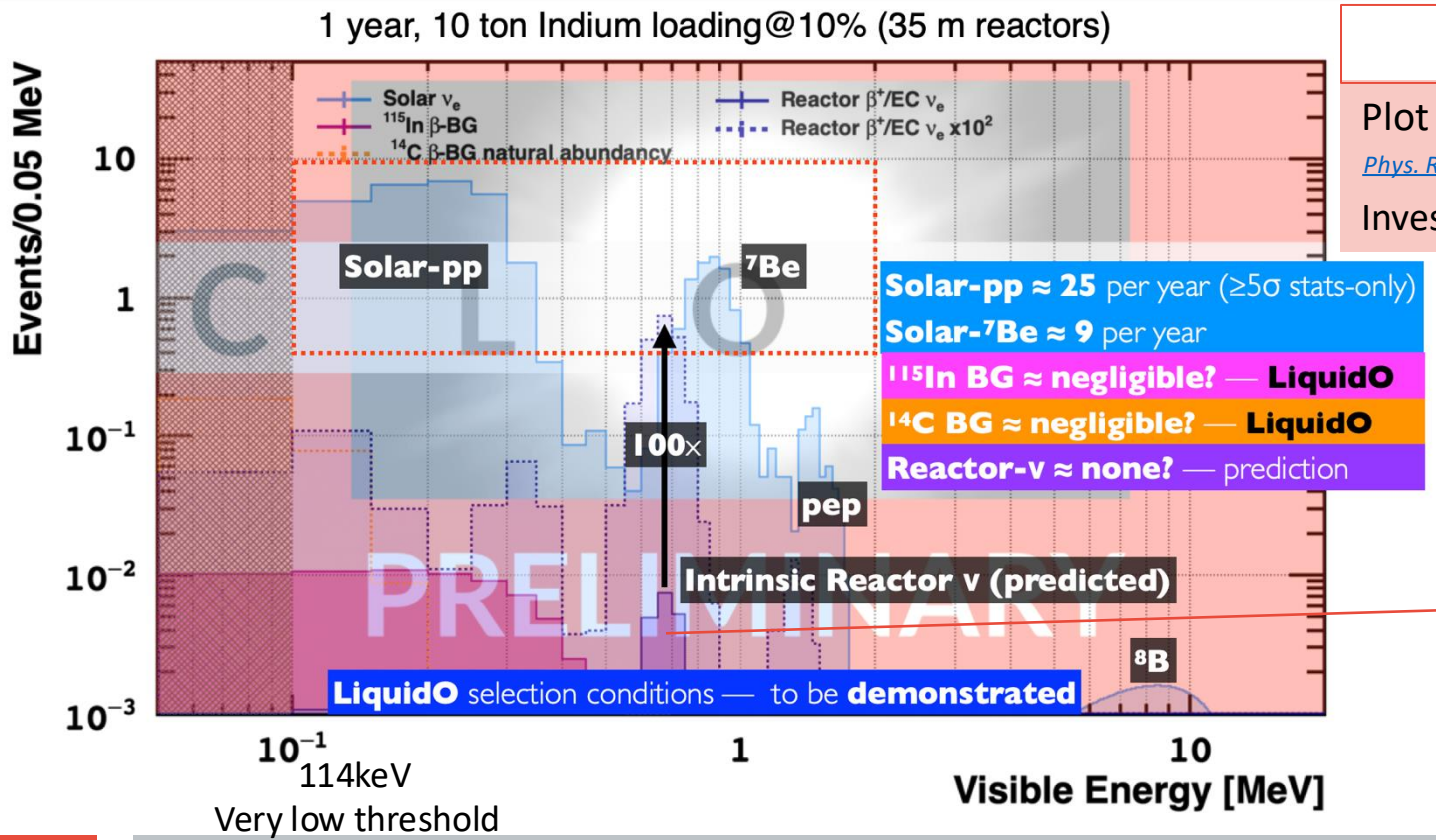
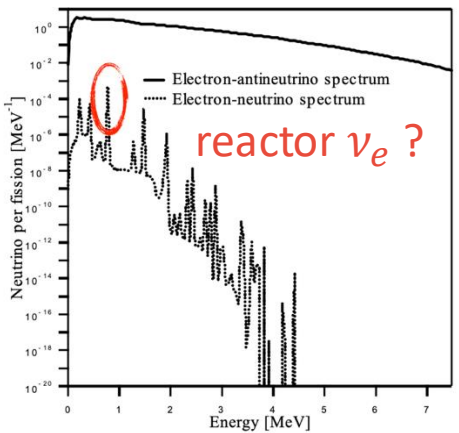


LENS background model

Plot uses expected BG from LENS

Phys. Rev. D **75**, 093006 (2007)

Investigating if it also applies for CLOUD



Take home message

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→ Groundbreaking detector development project

→ 5–10-ton LiquidO precision imaging calorimeter

→ Demonstrator for a wide range of future projects

→ Pure opaque scintillator for phase I (approved and funded)

→ >10,000 IBD/day, <1% reactor ν flux measurement at **surface**

→ Indium loading for phase II (proposal)

→ Search for ν_e's at **surface**

Thank you!

Spokespersons:
- A. Cabrera — CNRS / Université Paris-Saclay (France)
- J. Hartnell — Sussex University (UK)

IB Chair:
- M. Chen — Queen's University (Canada)

Webs:
https://liquido.ijclab.in2p3.fr/nucloud

CLOUD International collaboration

- **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)
- **LIP*** (Portugal)
- **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)

⟹ **21 institutions in 11 countries**

*Laboratory of Instrumentation and Experimental Particle Physics