Chooz **L**iquid**O** **U**ltranear **D**etector

Jeff Hartnell

For the CLOUD Collaboration

University of Sussex

NuPhys 2023, King's College London

20th December 2023

Outline

- LiquidO Technology
  - Opaque scintillator + optical fibres
  - See previous talk by David Petyt
- CLOUD
  - Site
  - Detector
  - Physics
    - Phase-I
    - Phase-II
    - Phase-III
- SuperChooz

C L O U D

European Innovation Council

UK Research and Innovation

(Multi-year project funded from: Dec/22)

European Innovation Council

UK Research and Innovation

CLOUD

International collaboration

- EDF (France) — first time in neutrino science
- LP2I Bordeaux (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)
- Pennsylvania State University (USA)
- Pontifícia Universidade Católica do Rio de Janeiro (Brazil)
- Queen's University (Canada)
- 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)

⟹ 20 institutions in 11 countries

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

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

https://antimatter-otech.ijclab.in2p3.fr/ [AMOTech]
https://liquido.ijclab.in2p3.fr/nucloud [via LiquidO]

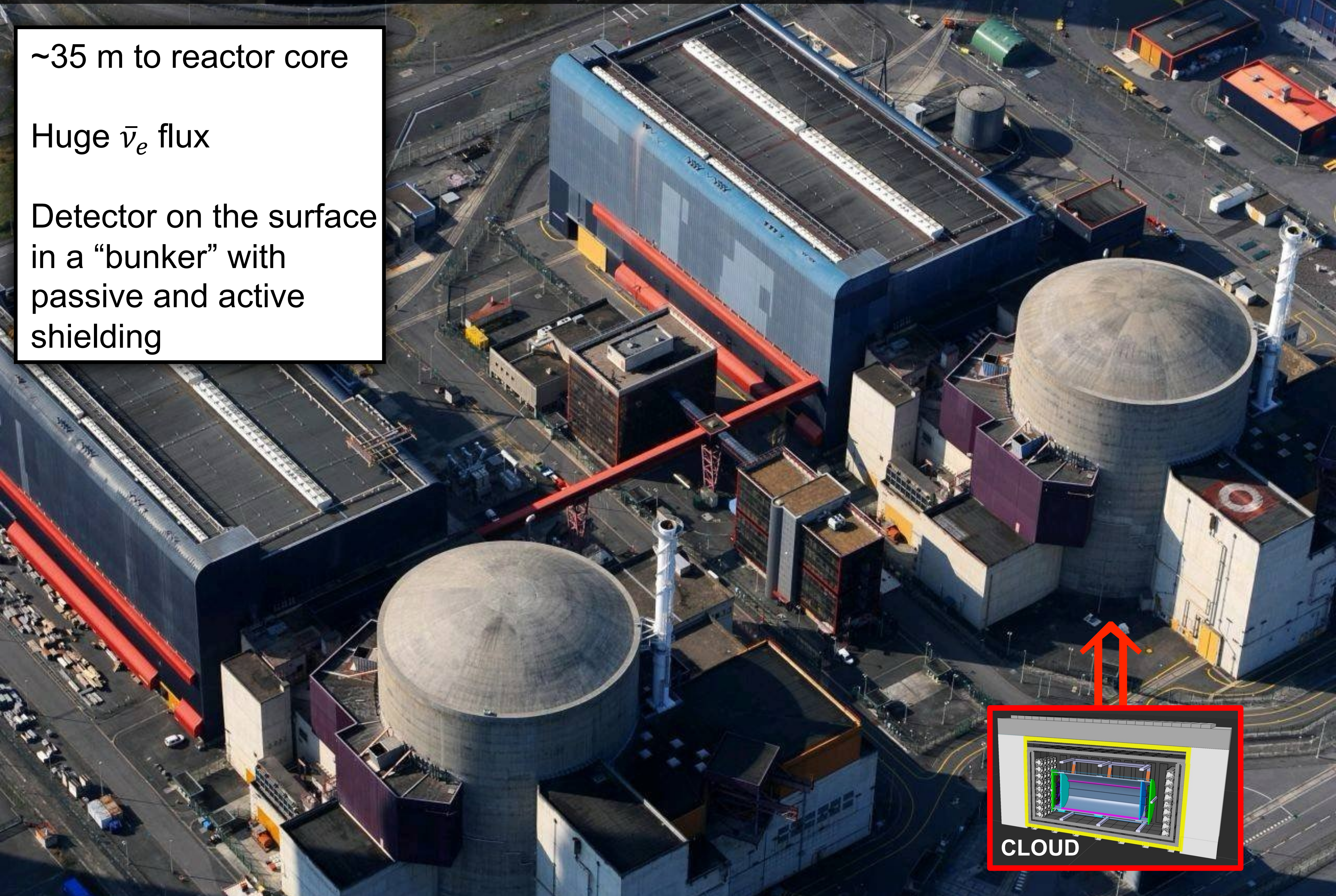
Site

“Ultra Near” Detector Site

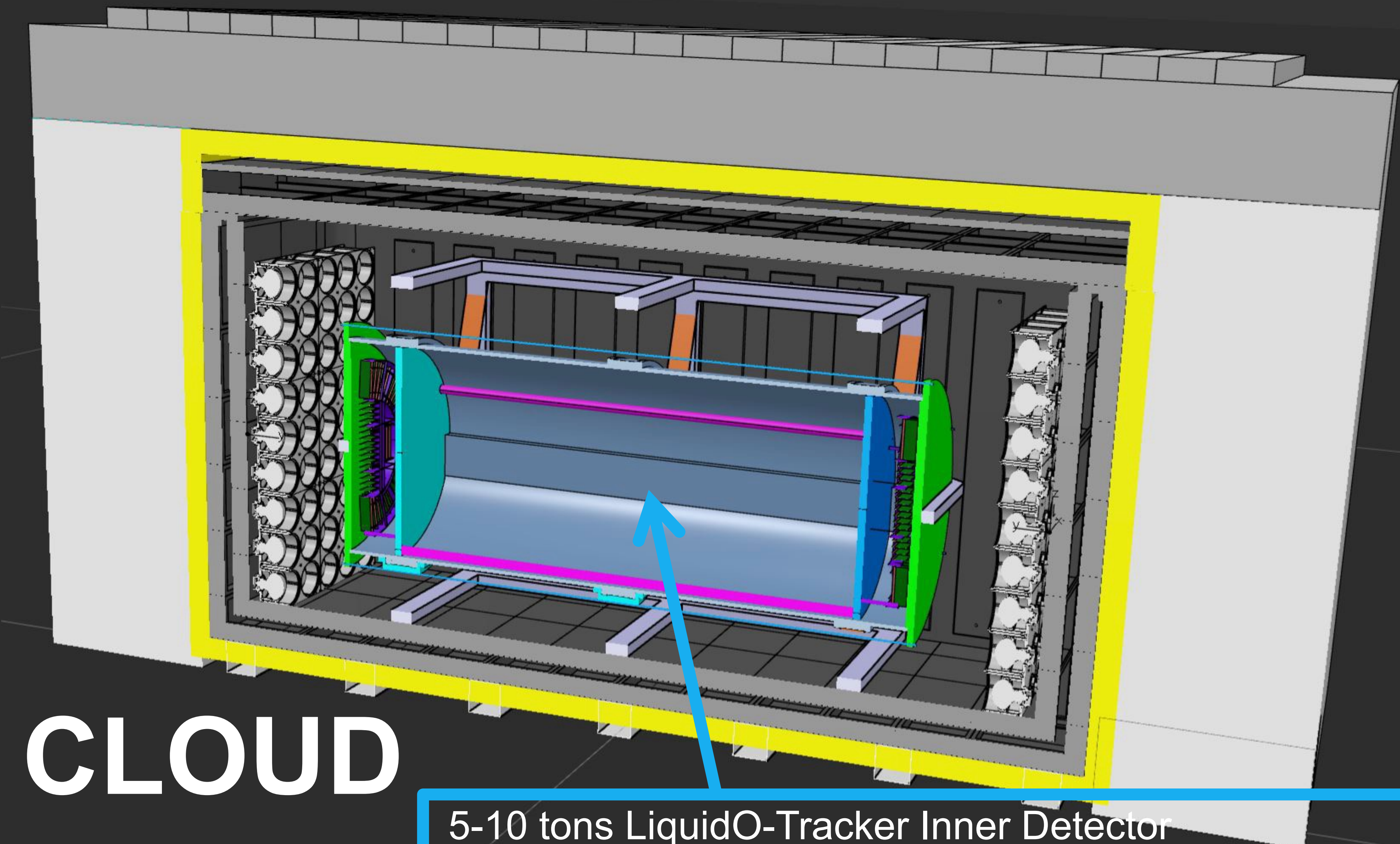
~35 m to reactor core

Huge $\bar{\nu}_e$ flux

Detector on the surface in a “bunker” with passive and active shielding



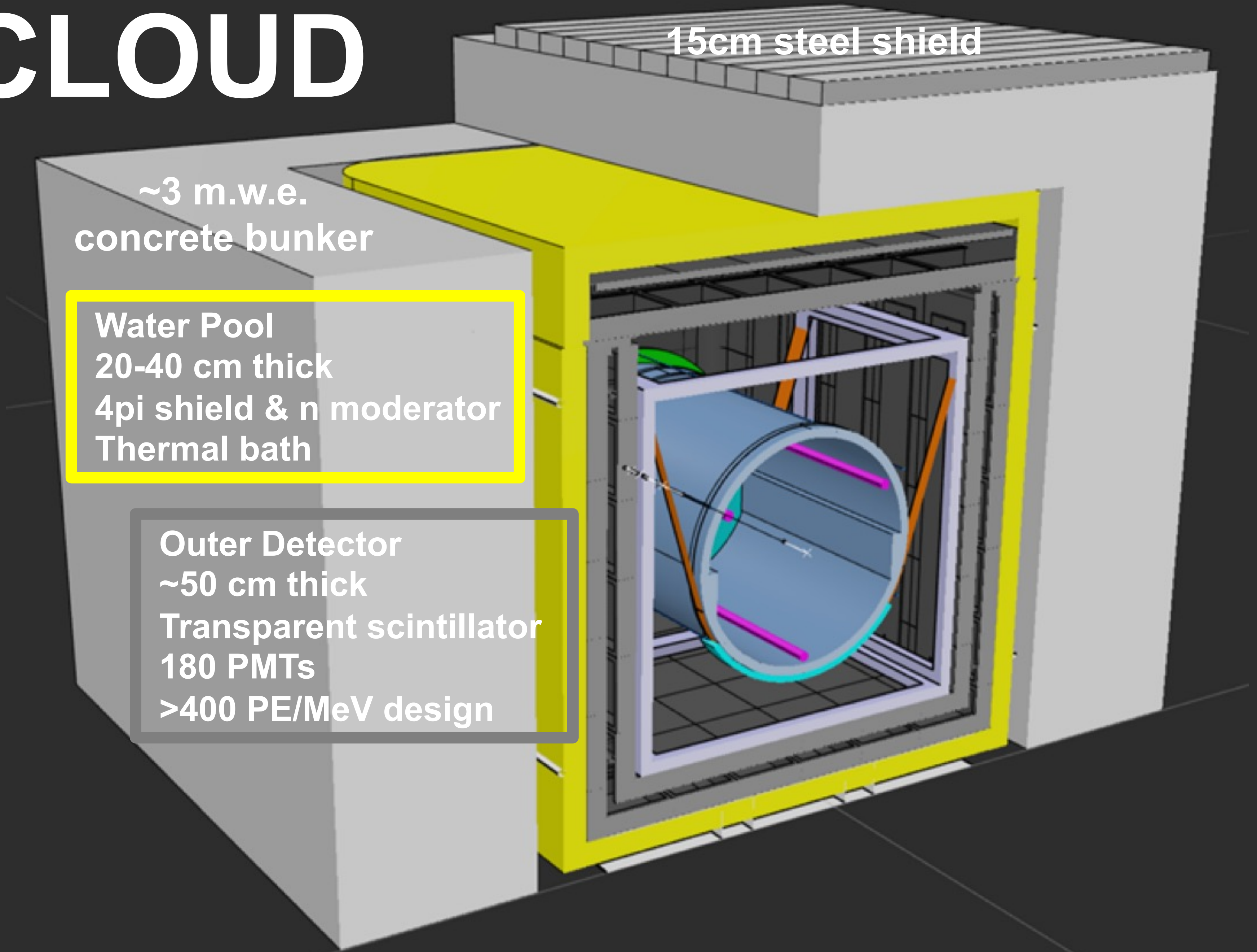
Detector



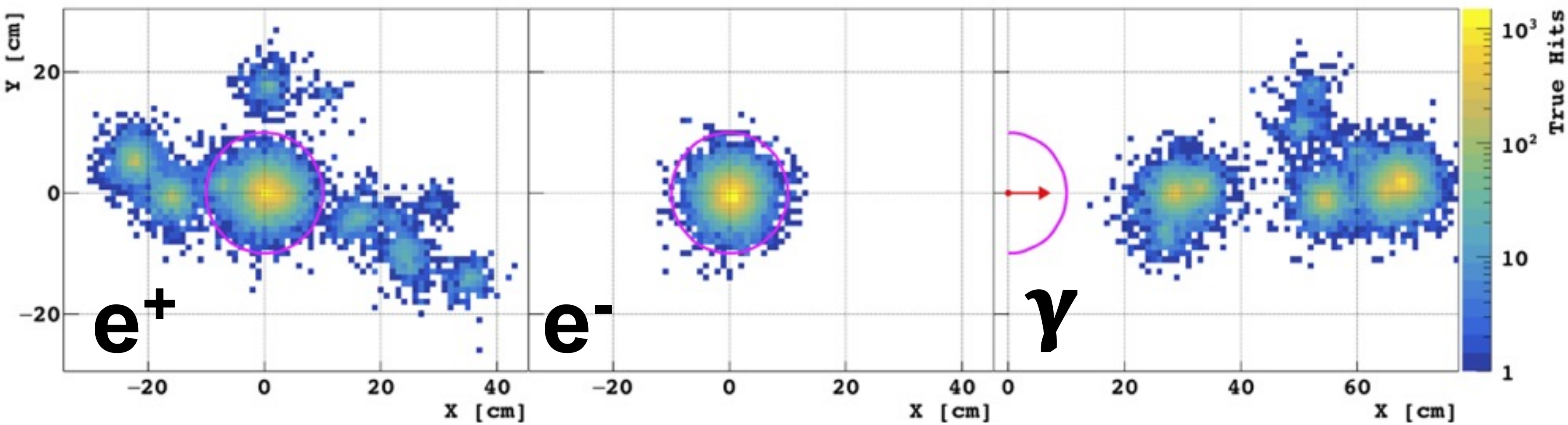
CLOUD

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

CLOUD


15cm steel shield
~3 m.w.e.
concrete bunker
Water Pool
20-40 cm thick
4pi shield & n moderator
Thermal bath
Outer Detector
~50 cm thick
Transparent scintillator
180 PMTs
>400 PE/MeV design

LiquidO-Tracker provides high-resolution imaging for particle identification



Distinguish positrons from point-like energy depositions (e.g. electrons, protons, alphas)

Physics

Protons

- Inverse Beta Decay (IBD)

$$\bar{\nu}_e \quad + \quad p^+ \rightarrow e^+ \quad + \quad n$$
$$\hookrightarrow \gamma + \gamma \qquad \hookrightarrow \gamma$$

- 1.8 MeV threshold
- Signature:

  e^+ promptly loses kinetic energy and annihilates

  n-capture on a p^+ gives 2.2 MeV γ in delayed coincidence ($\tau = 215\ \mu s$)

Electrons

- Elastic Scattering on electrons (NC+CC channel)

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

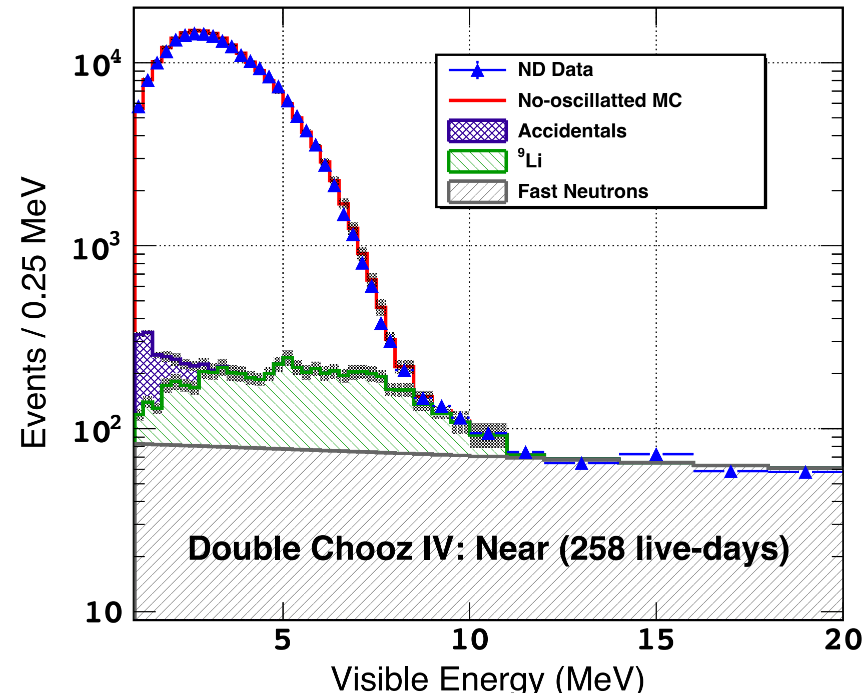
- Signature:

  Single energetic e^-


C L I U D

CLOUD-I Physics

- >10,000 IBD per day
- S/BG >100 (unprecedented)
  - Precision reactor characterisation
  - <1% flux measurement, U/Pu composition
- Reactor OFF measurements
  - Quantify backgrounds
  - Reactor fuel monitoring
  - ON-OFF-ON transitions

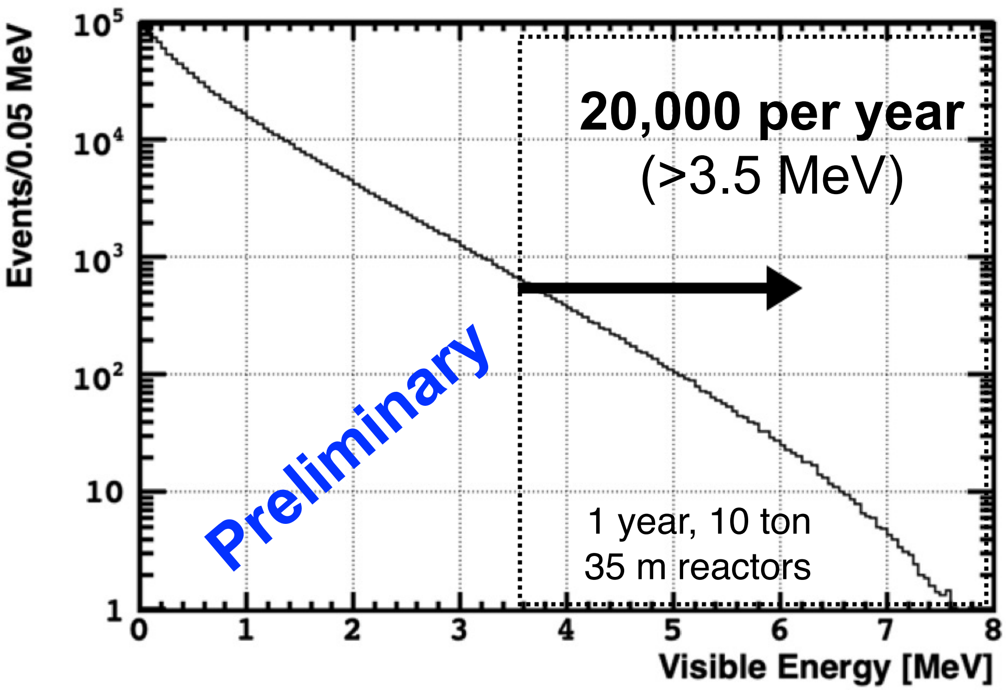


Improvements with LiquidO event classification

- Reject accidentals involving betas, p-recoils and alphas
  - Prompt: Not positrons
  - Delayed: Not a gamma
- Reject cosmogenic ^{9}Li beta
  - Not a positron
  - Precise muon tracking
- Reject fast neutron p-recoil
  - Not a positron

CLOUD-I Physics

- Electron elastic scattering
  - 5,000 per day
- Challenge:
  - Isolate electrons
  - Require
    - Electron classification
    - Fiducial volume
    - Higher energies
- Probe of $\sin^2(\theta_w)$ at very low energy using antineutrinos




C L II U D

Indium Loading in Scintillator

- Electron neutrino CC with indium nucleus

$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^*$$
$$\hookrightarrow \gamma/e^- \ (116\ keV) + \gamma\ (497\ keV)$$

- Very low threshold (114 keV)
- High natural abundance (96%)
- Fast delayed coincidence ($\tau = 4.8\ \mu s$)
- Signature: multi-fold coincidence
  - Require right particles in right places at right times with right energies…
  - LiquidO precision imaging means
    - can require 1st e^- to be in same cubic cm of the detector as the 2nd e^-
    - can require a nearby gamma-like event has 497 keV in time with 2nd e^-

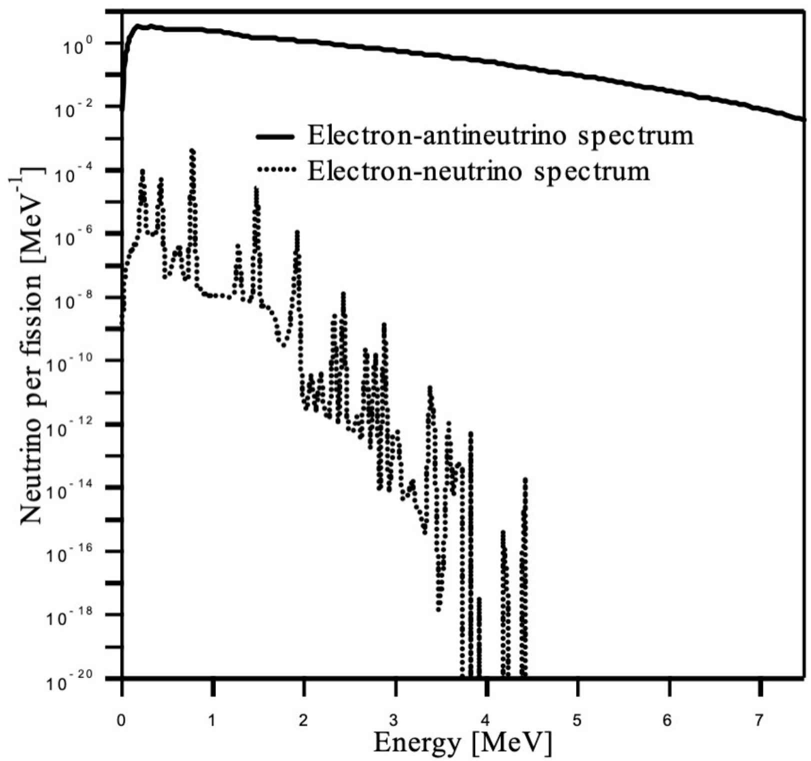
Ok, so why are we talking about electron **neutrinos** in a reactor talk?

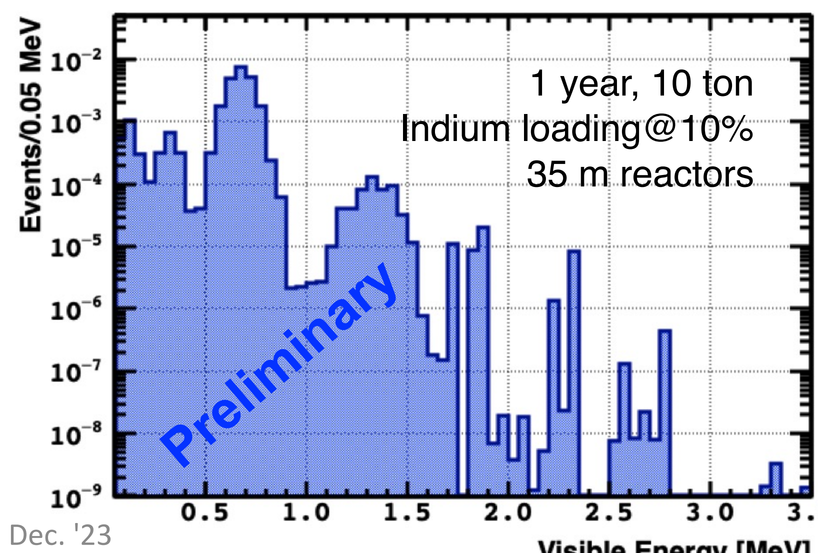
Reactors produce electron **antineutrinos**… right?

CLOUD-II Physics

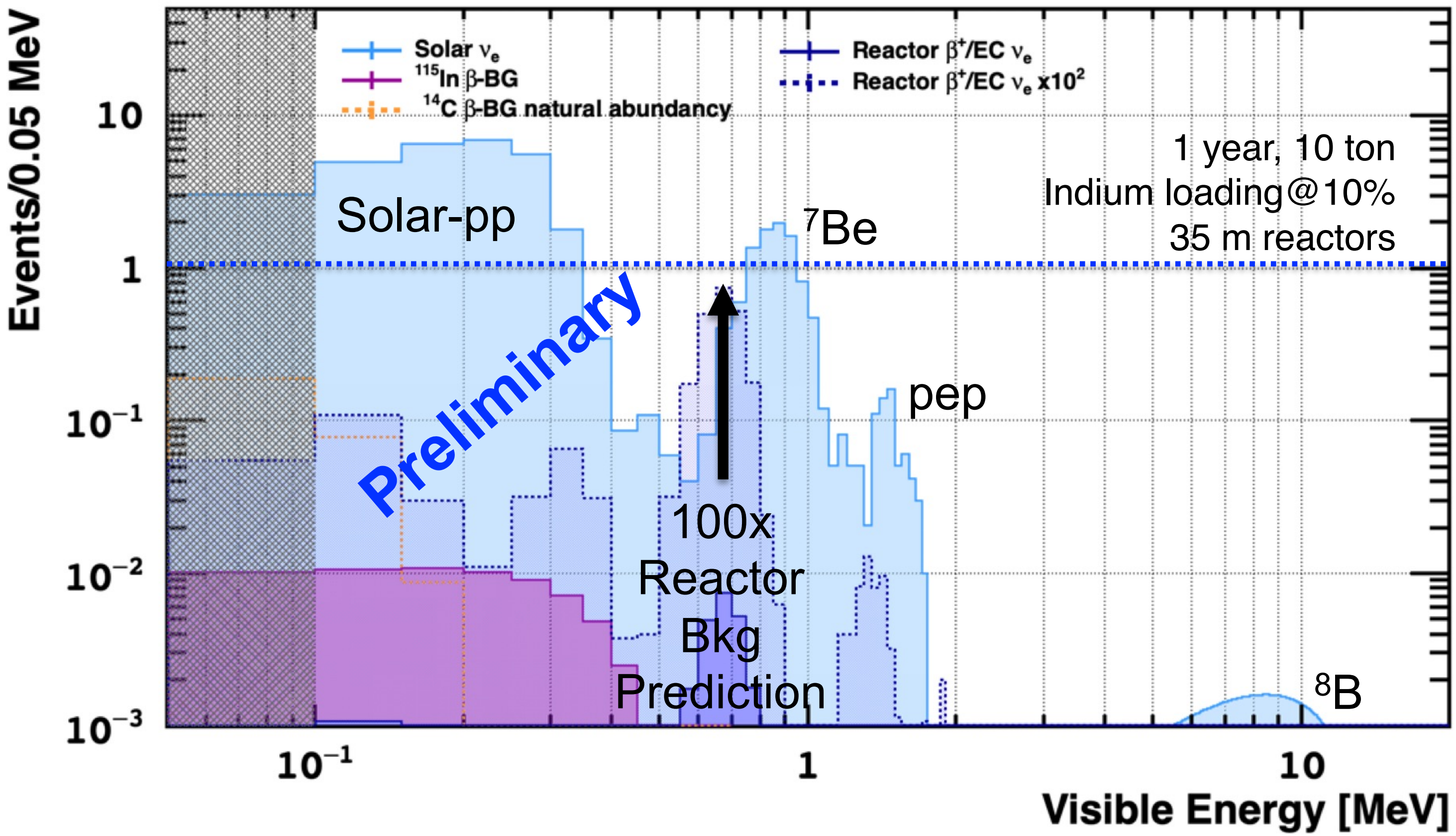
- Fission also produces electron neutrinos
  - Albeit at a vastly reduced rate
- Never been seen
  - Ray Davis tried this first
- 10-ton detector is too small
- Unless prediction is wrong?
- What could we measure?

T. Nishimura et al., AIP Conference Proceedings 769, 1702 (2005)
https://doi.org/10.1063/1.1945337





What's the Solar Neutrino Spectrum?



Solar-pp
~25/year

Solar-^{7}Be
~9/year

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

^{14}C
~negligible

- Plot uses LENS background model
  - Under feasibility study for CLOUD
- Demonstrator for future SuperChooz expt.


CL III UD

Copper Loading in Scintillator

- Electron antineutrino CC with copper nucleus

$$\bar{\nu}_e + {}^{63}Cu \rightarrow e^+ + {}^{63}Ni^{(*)}$$
$$\hookrightarrow \gamma\ (87\ keV)\quad \text{[if Ni was excited]}$$

- Lower threshold (1.2 MeV, below usual 1.8 MeV)
- High abundance (69%)
- Fast delayed coincidence ($\tau = 1.7\ \mu s$)
- Signature:
  - – Prompt positron
  - – Delayed gamma, close-by spatially

CLOUD-III Physics

- Make first observation of IBD@Cu
- Lower threshold – see unmeasured part of reactor spectrum
- Measure BR for final state of excited nickel
- IBD@p provide >10,000 positrons a day (with n-capture tag) as a calibration source for classification
  - Will know efficiency of cuts precisely
- Proof of principle for ^{40}K geo-neutrinos (extremely challenging topic)

arXiv:2308.04154

Probing Earth's Missing Potassium using the Unique Antimatter Signature of Geoneutrinos

A. Cabrera[*12α,2,a], M. Chen[†6], F. Mantovani[‡3α,3β], A. Serafini[§3α,3β,13α,13β], V. Strati[¶3α,3β], J. Apilluelo[18], L. Asquith[1], J.L. Beney[11], T.J.C. Bezerra[1], M. Bongrand[11], C. Bourgeois[12α], D. Breton[12α], M. Briere[12α], J. Busto[10], A. Cadiou[11], E. Calvo[8], V. Chaumat[12α], E. Chauveau[4], B.J. Cattermole[1], P. Chimenti[7], C. Delafosse[12α], H. de Kerret[‖a], S. Dusini[13α], A. Earle[1], C. Frigerio-Martins[7], J. Galán[18], J. A. García[18], R. Gazzini[12α], A. Gibson-Foster[1], A. Gallas[12α], C. Girard-Carillo[9α], W.C. Griffith[1], F. Haddad[11], J. Hartnell[1], A. Hourlier[17], G. Hull[12α], I. G. Irastorza[18], L. Koch[9α], P. Laniéce[12α,12β], J.F. Le Du[12α,2], C. Lefebvre[6], F. Lefevre[11], F. Legrand[12α], P. Loaiza[12α], J. A. Lock[1], G. Luzón[18], J. Maalmi[12α], C. Marquet[4], M. Martínez[18], B. Mathon[12α], L. Ménard[12α,12β], D. Navas-Nicolás[12α], H. Nunokawa[15], J.P. Ochoa-Ricoux[5], M. Obolensky[a], C. Palomares[8], P. Pillot[11], J.C.C. Porter[1], M.S. Pravikoff[4], H. Ramarijaona[12α], M. Roche[4], P. Rosier[12α], B. Roskovec[14], M.L. Sarsa[18], S. Schoppmann[9β], W. Shorrock[1], L. Simard[12α], H.Th.J. Steiger[9α,9β], D. Stocco[11], J.S. Stutzmann[11], F. Suekane[16,a], A. Tunc[9α], M.-A. Verdier[12α,12β], A. Verdugo[8], B. Viaud[11], S. M. Wakely[9α], A. Weber[9α], and F. Yermia[11]

[1] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[2] LNCA Underground Laboratory, CNRS, EDF Chooz Nuclear Reactor, Chooz, France
[3α] INFN, Sezione di Ferrara, Ferrara, Italy
[3β] Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Ferrara, Italy
[4] Université de Bordeaux, CNRS, LP2I Bordeaux, Gradignan, France
[5] Department of Physics and Astronomy, University of California at Irvine, Irvine, CA, USA
[6] Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Canada
[7] Departamento de Física, Universidade Estadual de Londrina, Londrina, Brazil
[8] CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain
[9α] Johannes Gutenberg-Universität Mainz, Institut für Physik, Mainz, Germany
[9β] Johannes Gutenberg-Universität Mainz, Detektorlabor, Exzellenzcluster PRISMA[+], Mainz, Germany
[10] Université de Aix Marseille, CNRS, CPPM, Marseille, France
[11] Nantes Université, IMT-Atlantique, CNRS, Subatech, Nantes, France
[12α] Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[12β] Université Paris Cité, IJCLab, Orsay, France
[13α] INFN, Sezione di Padova, Padova, Italy
[13β] Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy
[14] Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic
[15] Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, Brazil
[16] RCNS, Tohoku University, Sendai, Japan
[17] Université de Strasbourg, CNRS, IPHC, Strasbourg, France
[18] Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza, Zaragoza, Spain
[a] Université de Paris Cité, CNRS, APC, Paris, France

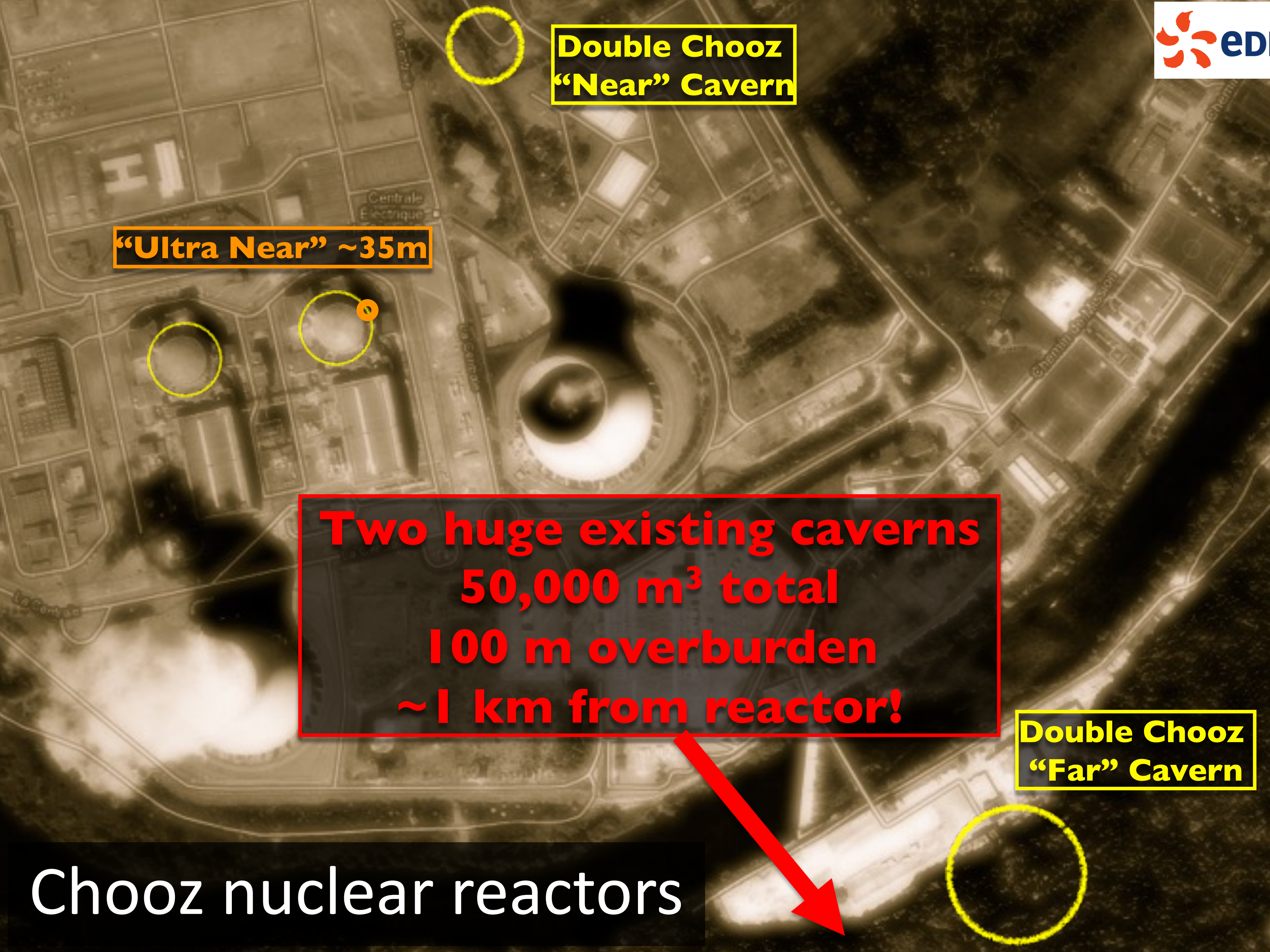
(LiquidO Consortium)

SUPERCHOOZ

CERN Seminar: ***"The SuperChooz Experiment: Unveiling the Opportunity"***

https://indico.cern.ch/event/1215214/

https://zenodo.org/record/7504162


Double Chooz
"Near" Cavern
"Ultra Near" ~35m
Two huge existing caverns
50,000 m³ total
100 m overburden
~1 km from reactor!
Double Chooz
"Far" Cavern
Chooz nuclear reactors
Centrale
Electrique

Conclusions

- Ground-breaking detector development project
  - 5-10 ton LiquidO precision imaging calorimeter
  - Demonstrator for a wide range of future projects

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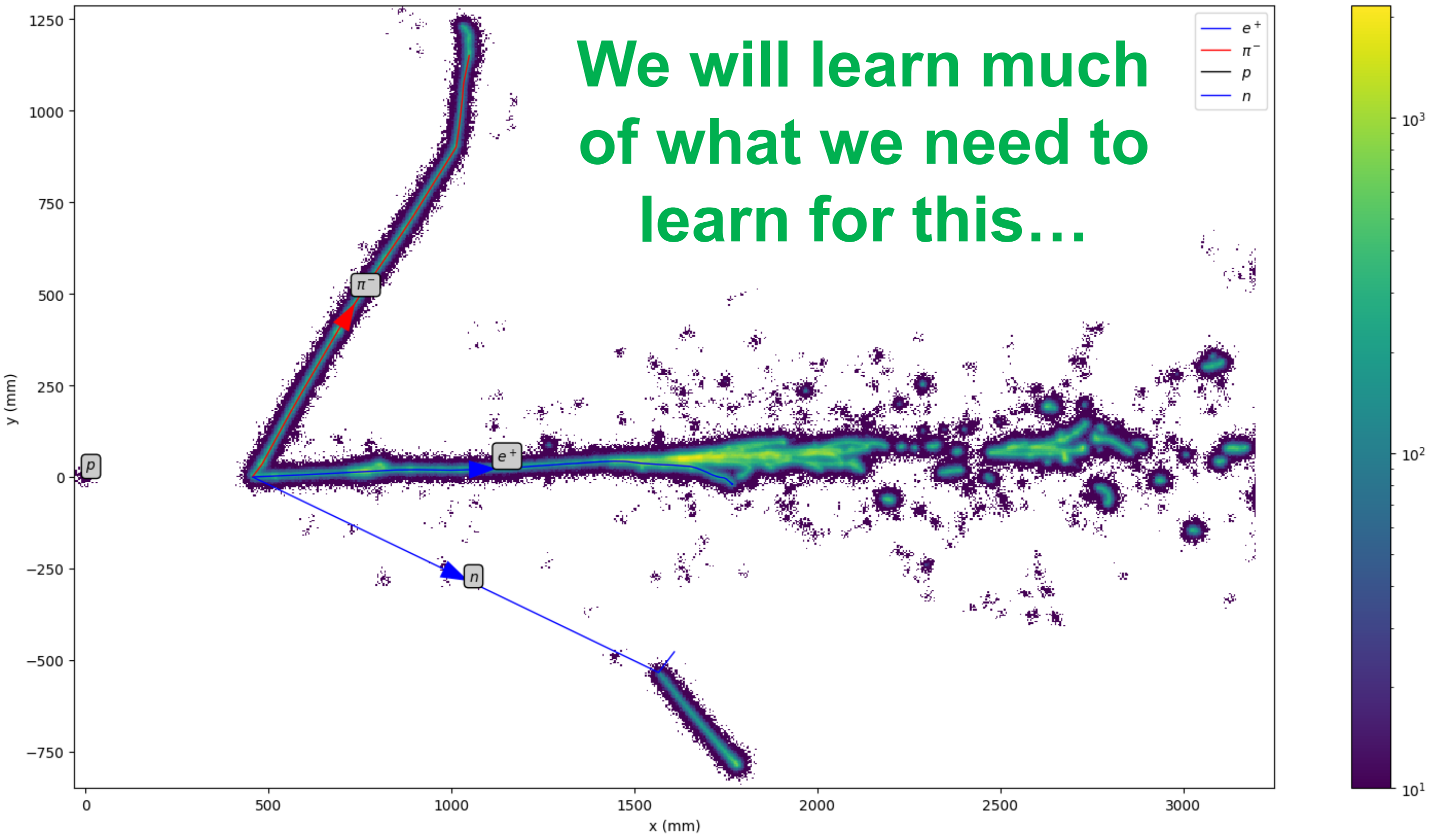
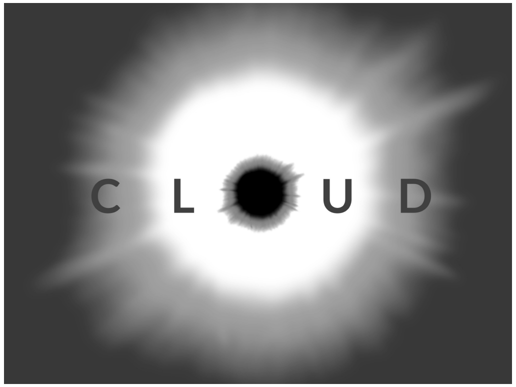


Conclusions

- Ground-breaking detector development project
  - 5-10 ton LiquidO precision imaging calorimeter
  - Demonstrator for a wide range of future projects
- Pure opaque scintillator for phase-I
  - >10,000 $\bar{\nu}_e$ /day from 2025
- Indium loading for phase-II
  - Search for ν_es
- Copper loading for phase-III
  - First demonstration of Cu, lower 1.2 MeV threshold
- Final thought: LiquidO is a whole new way of thinking about the detector and neutrino experiments
  - Expect many great ideas we haven't even imagined yet!



The End

Backup slides

Indium Loading in Scintillator

- Electron neutrino CC with indium nucleus

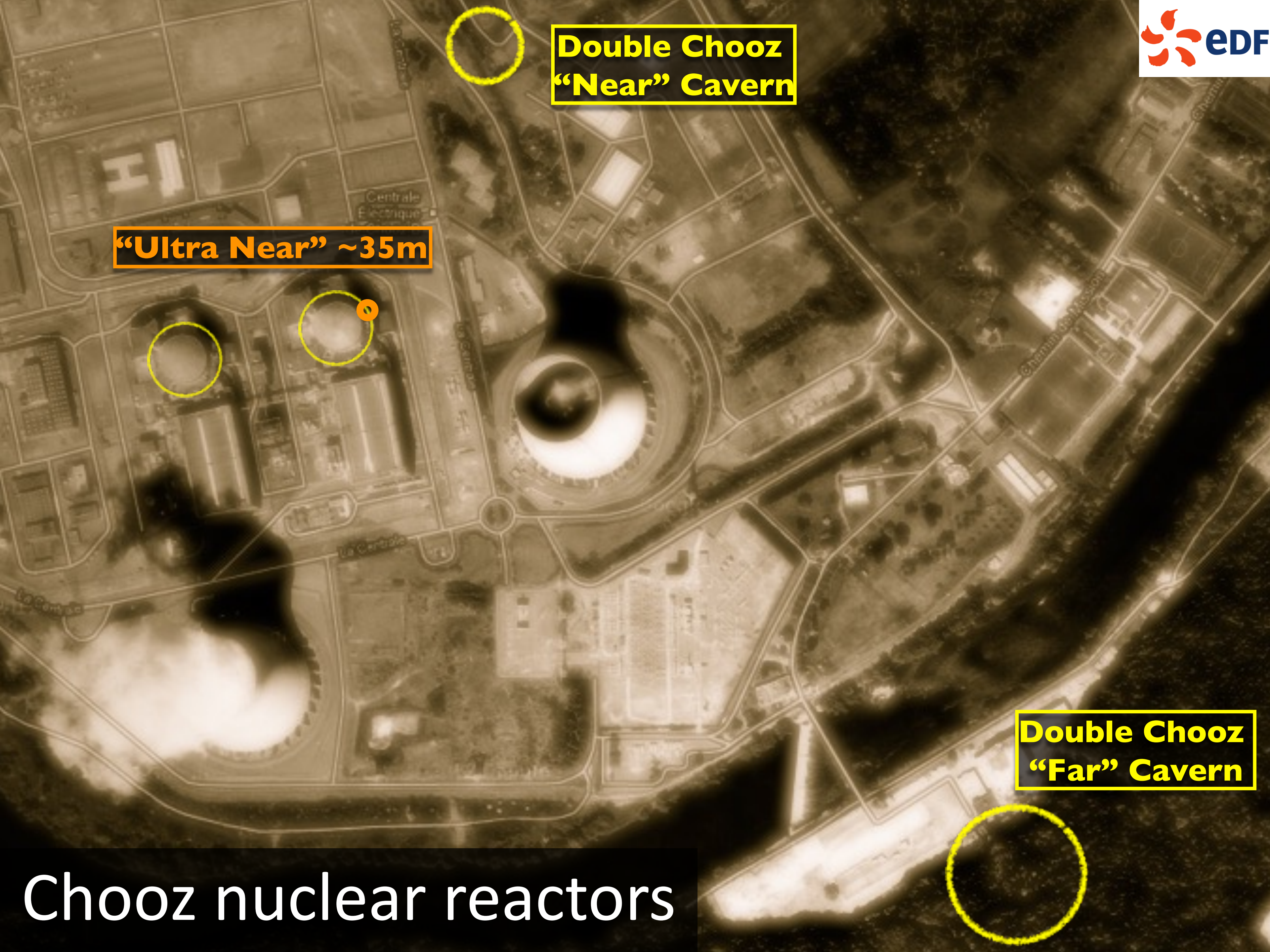
$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^*$$
$$\hookrightarrow \gamma/e^- \; (115.6\; keV) + \gamma\; (497.3\; keV)$$

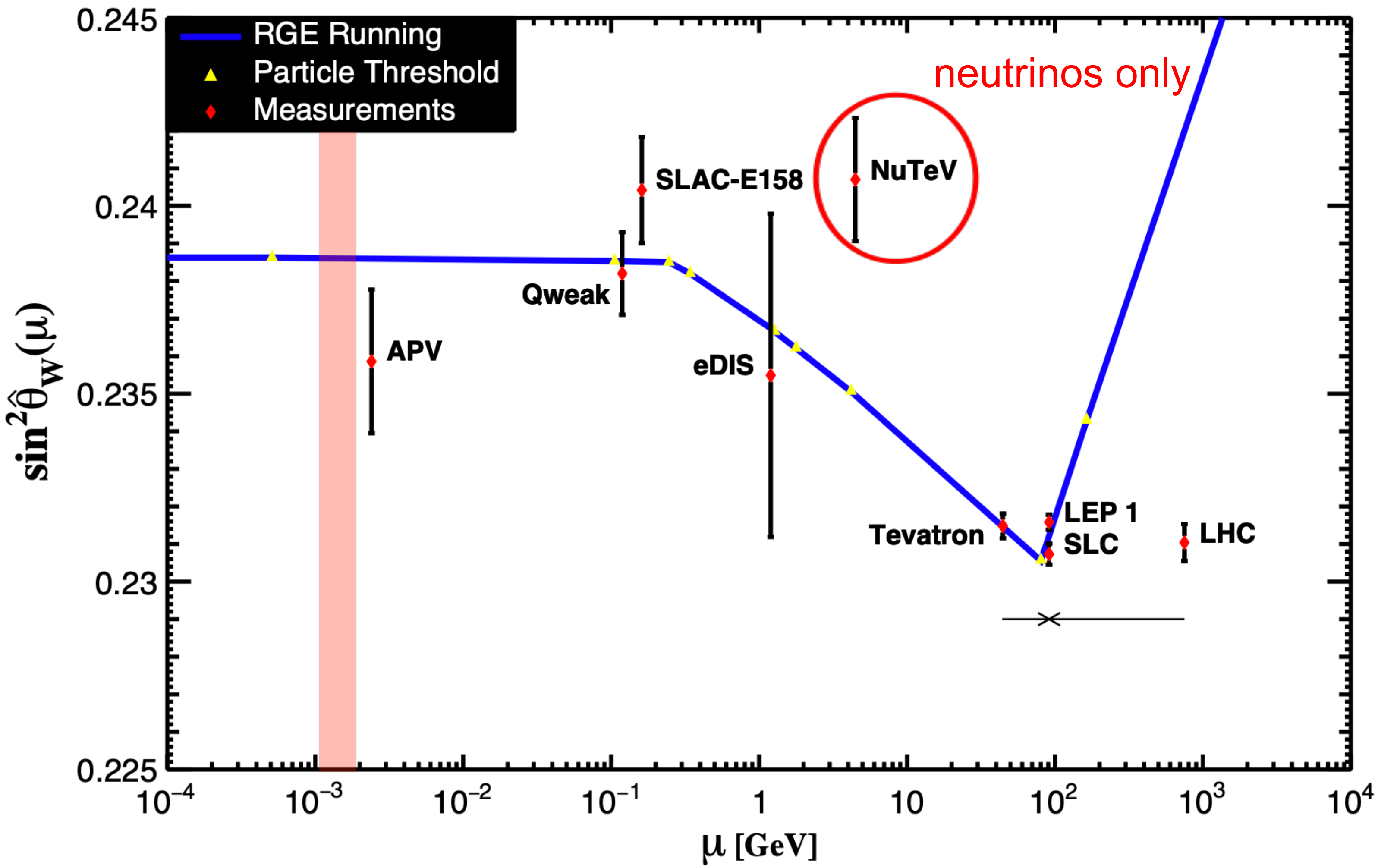
- Very low threshold, 114 keV, high natural abundance (95.7%)
- Signature: multi-fold coincidence
  - Require right particles in right places at right times with right energies…
    - Fast, $\tau = 4.76\ \mu s$, delayed coincidence (Cut1)
      - 50x faster than n-capture
    - Point-like e^- (Cut2) followed by delayed 497.3 keV (Cut3) spatially disperse γ (Cut4) in a loose spatial co-incidence (Cut5)
    - Delayed point-like e^- (Cut6) with 116 keV (Cut7) in tight spatial co-incidence (Cut8) with first point-like e^-
      - Require to be within millimetres (extremely powerful)
  - Apply Cut1 & Cut2 & Cut3 & Cut4 & Cut5 & Cut6 & Cut7 & Cut8 to massively reduce background

Conclusions

- Ground-breaking detector development project
  - ~10 ton LiquidO tracking calorimeter (classify events)
- Pure opaque scintillator for phase-I
  - >10,000 $\bar{\nu}_e$/day from 2025, expect >100 S/B, also elastic scattering
- Indium loading for phase-II
  - Search for ν_e from reactor: expect to see zero; surprises?
  - Solar neutrinos? Tiny detector, on surface, by reactor!
    - Under feasibility study
  - Demonstrator for SuperChooz
    - Spectroscopy of solar neutrinos. Long dreamed…
- Copper loading for phase-III
  - Lower 1.2 MeV threshold, first demonstration; surprises?
- Final thought: LiquidO is a whole new way of thinking about the detector and neutrino experiments
  - Expect many great ideas we haven't even imagined yet!


EDF Nuclear
Power Plant Chooz
London
Ilford
Southend-on-Sea
Croydon
Margate
Maidstone
Canterbury
Kent Downs
AONB
Dover
Folkestone
High Weald
AONB
Hastings
Brighton
Eastbourne
Calais
Coquelles
Dunkirk
De Panne
Ostend
Blankenberge
Knokke-Heist
Bruges
Vlissingen
Middelburg
Goes
Roosendaal
Bergen
op Zoom
Breda
Tilburg
Eindhoven
Turnhout
Antwerp
Ghent
Mechelen
Brussels
Leuven
Hasselt
Kortrijk
Roubaix
Lille
Villeneuve-d'Ascq
Tournai
Boulogne-sur-Mer
Parc naturel
régional des
caps et marais
d'Opale
Le Touquet
Berck
Lens
Arras
Parc Naturel
Régional
Scarpe-Escaut
Mons
Charleroi
Namur
Durbuy
Maubeuge
Dinant
Rochefort
Parc naturel
régional de
l'Avesnois
Abbeville
Le Tréport
Dieppe
Amiens
Saint-Quentin
Saint-Valery-en-Caux
Fécamp
Étretat
Parc naturel
régional des
Ardennes
Charleville-Mézières
Bouillon
Sedan
Laon
Le Havre
Honfleur
Parc Naturel
Régional
des Boucles
de la Seine...
Rouen
Deauville
Pont-Audemer
Beauvais
Compiègne
Soissons
Reims
Parc naturel
régional de
la Montagne
de Reims
Lisieux
Vernon
Évreux
Parc naturel
régional du
Vexin français
Seine
Château-Thierry
Verdun
Saint-Denis
Paris
Châlons-en-Champagne
Boulogne-Billancourt
Versailles
Créteil
Dreux
Bar-le-Duc


Double Chooz
"Near" Cavern
"Ultra Near" ~35m
Double Chooz
"Far" Cavern
Chooz nuclear reactors
EDF


RGE Running
Particle Threshold
Measurements
neutrinos only
NuTeV
SLAC-E158
Qweak
APV
eDIS
Tevatron
LEP 1
SLC
LHC
0.245
0.24
0.235
0.23
0.225
$\sin^2\hat{\theta}_W(\mu)$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
μ [GeV]

A7. Attempt to Observe the $Cl^{37}(\bar{\nu},e^-)Ar^{37}$ Reaction Induced by Reactor Antineutrinos.* RAYMOND DAVIS, JR., *Brookhaven National Laboratory*, AND DON S. HARMER,† *Brookhaven National Laboratory and Georgia Institute of Technology*.—An experiment has been performed to test whether fission product antineutrinos will invert the electron capture decay of Ar^{37} by the reaction $Cl^{37}(\bar{\nu},e^-)Ar^{37}$. Three thousand gallons of carbon tetrachloride were exposed to the high antineutrino flux from a production reactor at the Savannah River plant. The argon-37 was isolated and counted in a low-level counter.[1] The cross section for this process was found to be less than 0.25×10^{-45} cm², a factor of 20 below the cross section calculated assuming neutrino-antineutrino identity. The result is consistent with the principle of lepton conservation. Argon-37 was observed in the experiment produced by cosmic radiation and fast neutrons. The Ar^{37} observed in the experiment can be used to set an upper limit on the product of the solar neutrino flux and the average cross section for the neutrino capture reaction: $\phi\bar{\sigma}<1.1\times10^{-33}$ disintegrations sec⁻¹.

* Research performed in part under the auspices of the U. S. Atomic Energy Commission.

† Present address: Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia.

[1] R. Davis, Jr., "Radioisotopes in scientific research," *Proceedings of the First UNESCO International Conference, Paris, 1957* (Pergamon Press, London, 1958), Vol. 1, p. 728.

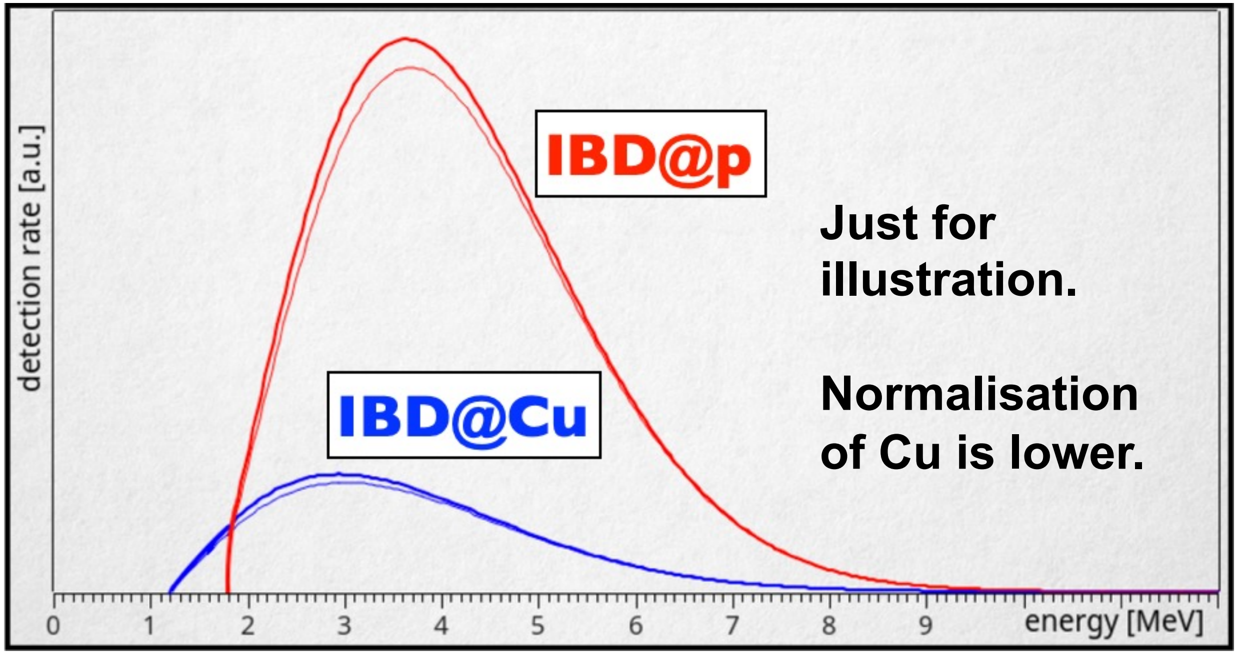
R. Davis and D. S. Harmer,
Attempt to Observe the Cl37(vbar,e−)Ar37 Reaction Induced by Reactor Antineutrinos,
Bull. Am. Phys. Soc. 4, 217 (1959).

https://archive.org/details/sim_bulletin-of-the-american-physical-society_1959-04-30_4_4/page/216/mode/1up

Also this earlier one:

Raymond Davis, Jr.
Attempt to Detect the Antineutrinos from a Nuclear Reactor by the Cl37(¯v, e−)A37 Reaction
Phys. Rev. 97, 766 – Published 1 February 1955

https://journals.aps.org/pr/abstract/10.1103/PhysRev.97.766



IBD@p
IBD@Cu
detection rate [a.u.]
0
1
2
3
4
5
6
7
8
9
energy [MeV]
Just for illustration.
Normalisation of Cu is lower.