Detection of Antineutrinos from Nuclear Reactors and Geological Sources

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PRISMA+
DETECTOR LAB

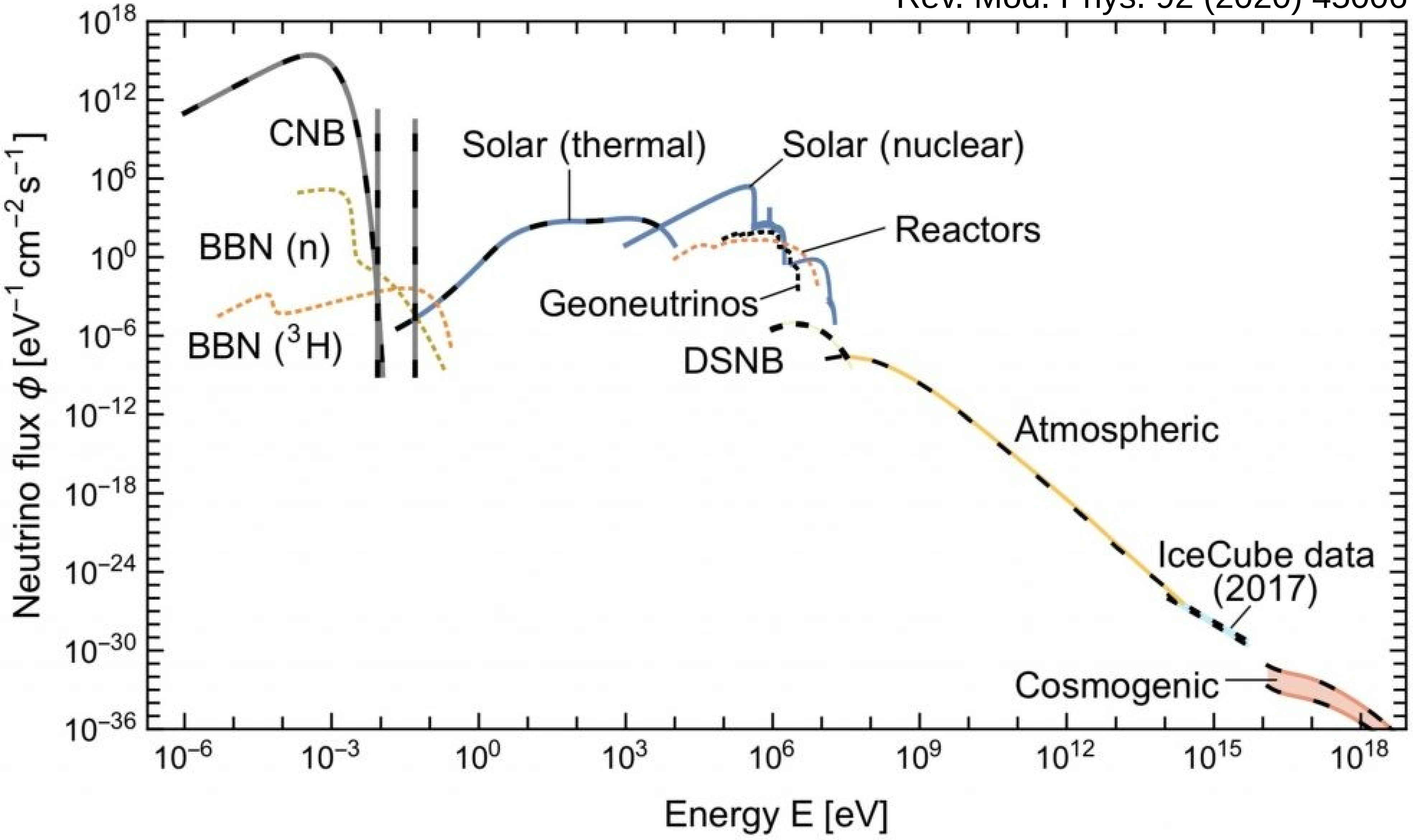
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Outline

- Antineutrinos and the Inverse Beta Decay
  → for coherent scattering see next talk
- Reactor Neutrinos
- Geoneutrinos
- Summary

Neutrino Sources

Rev. Mod. Phys. 92 (2020) 45006

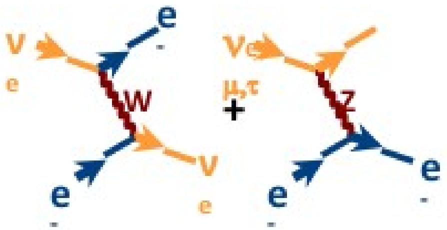


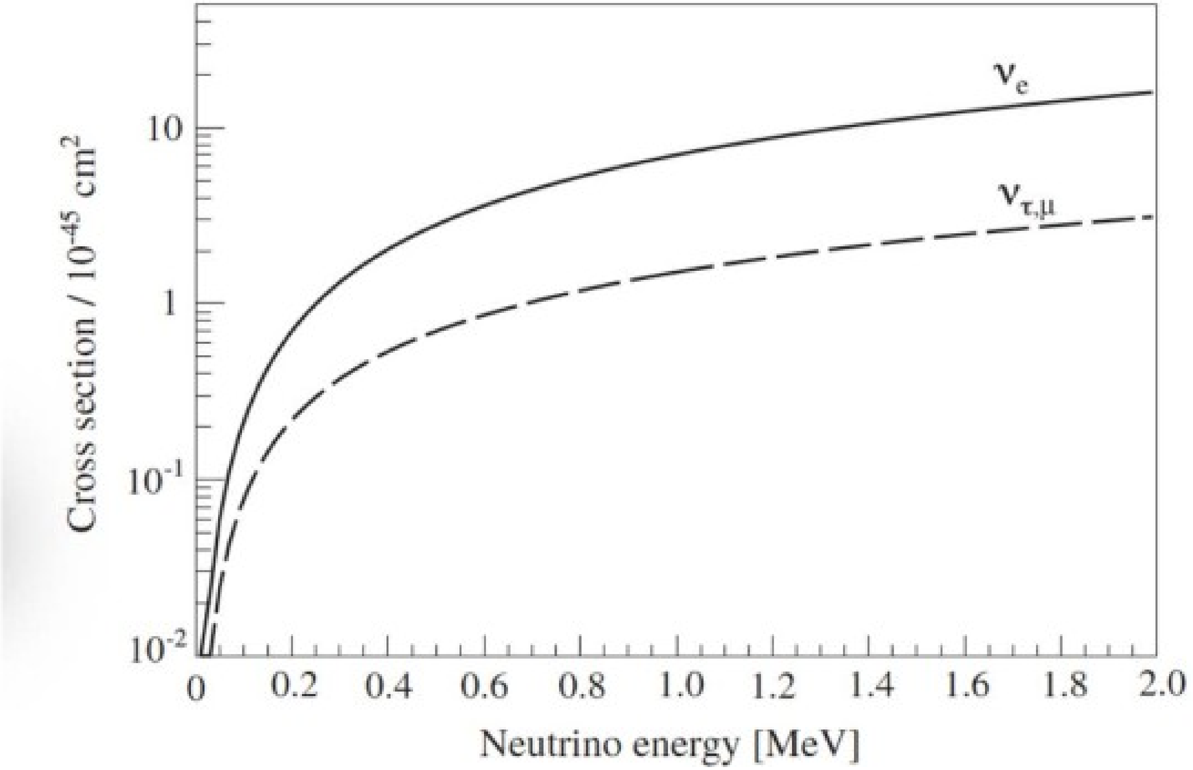
Neutrino Elastic Scattering

Neutrinos detected through elastic scattering: singles

@ 1-2 MeV for electron flavour: ~10^{-44} cm^2

for μ,τ flavours about 6 x smaller cross section



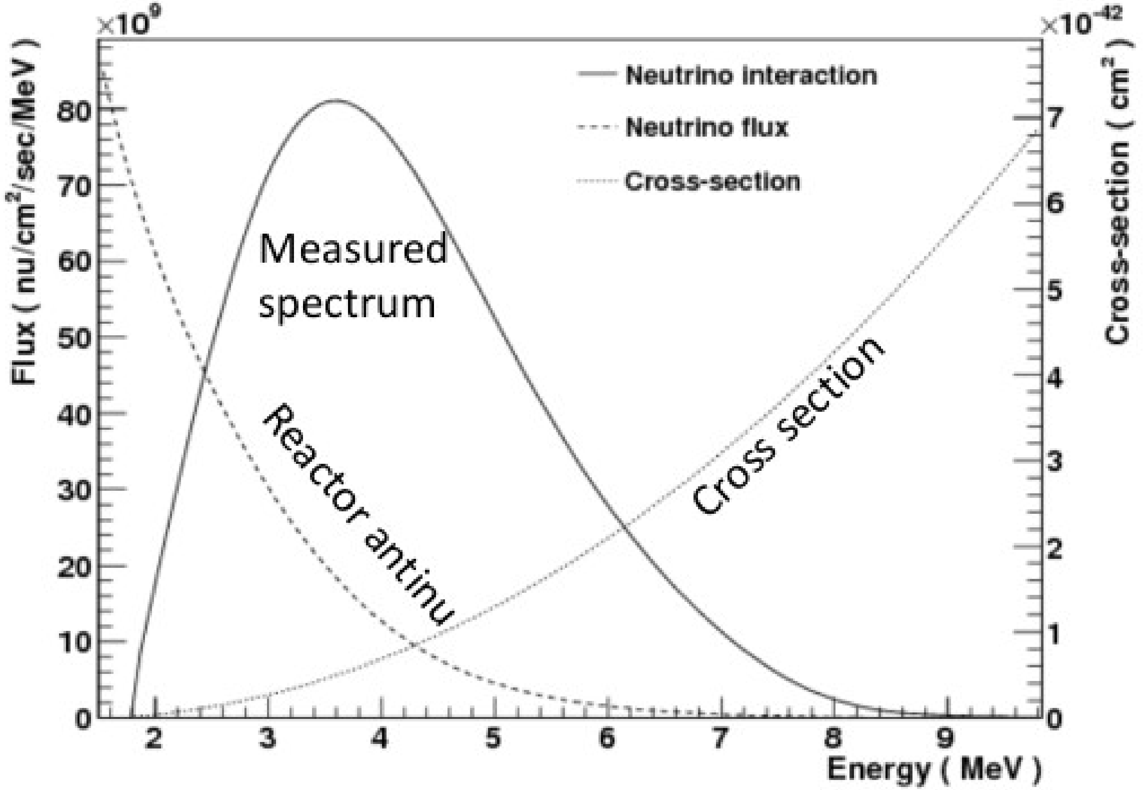


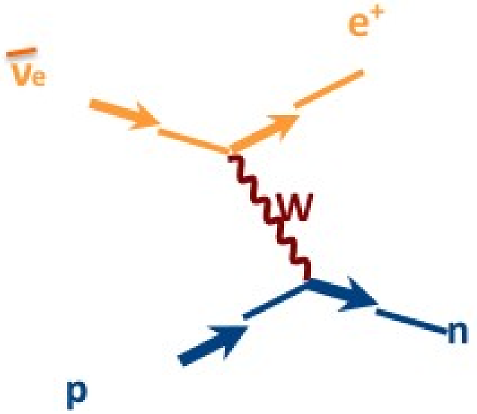
Inverse Beta Decay

only works for electron antineutrinos (energy threshold due to rest mass of partner lepton and nucleon)

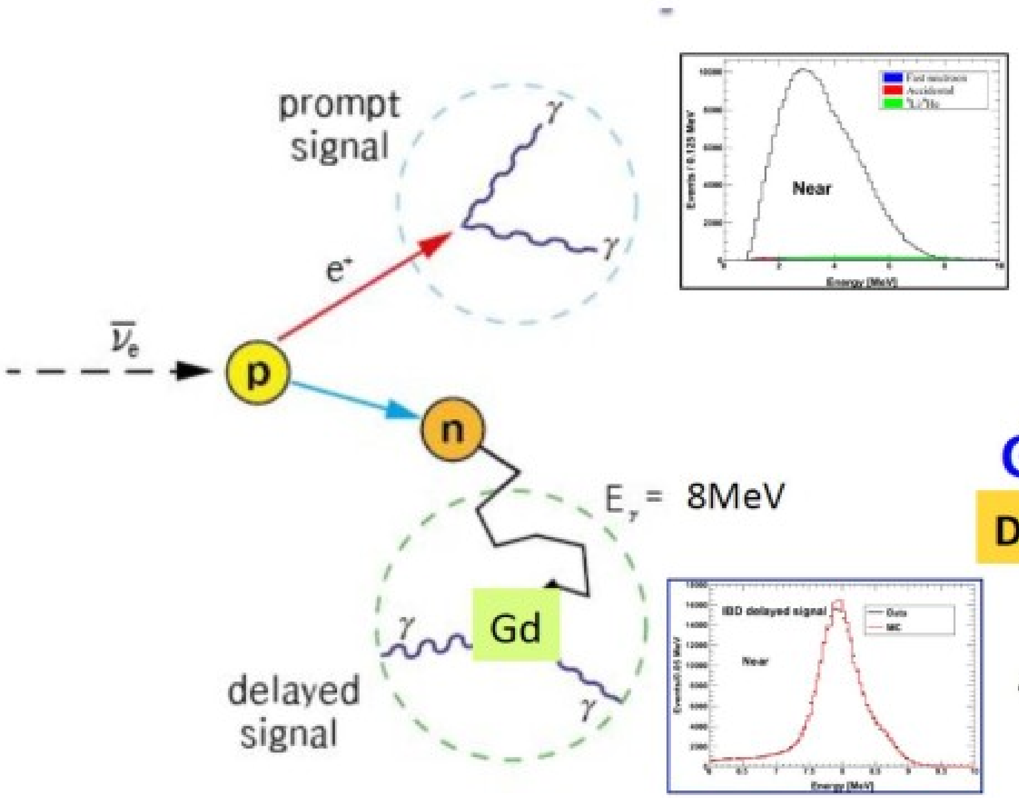
Energy threshold = 1.8 MeV

@ few MeV for electron flavour: ~10^{-42} cm^2 (~100 x more than scattering)





IBD Detection



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

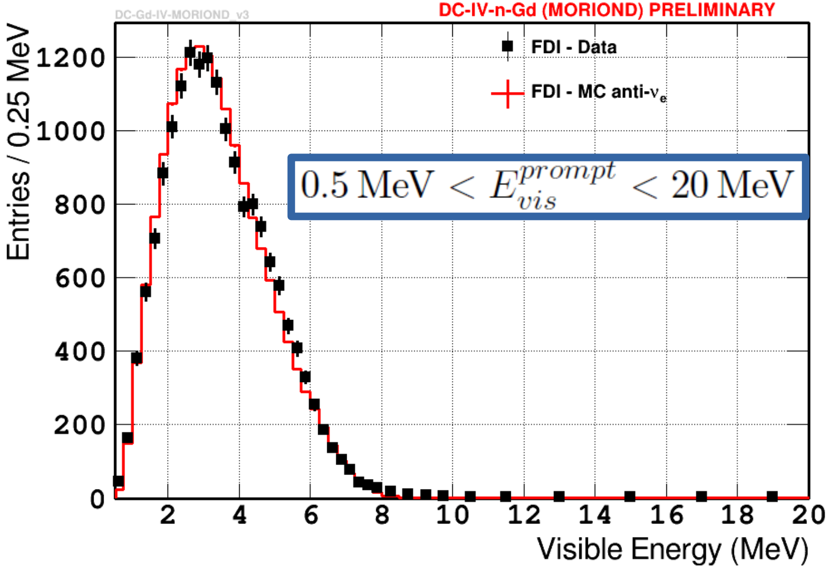
Inverse Beta Decay
(IBD)

Gd capture		H capture
Delayed signal		**Delayed signal**
~30 μs	or	~200 μs
~8 MeV		~2.2 MeV

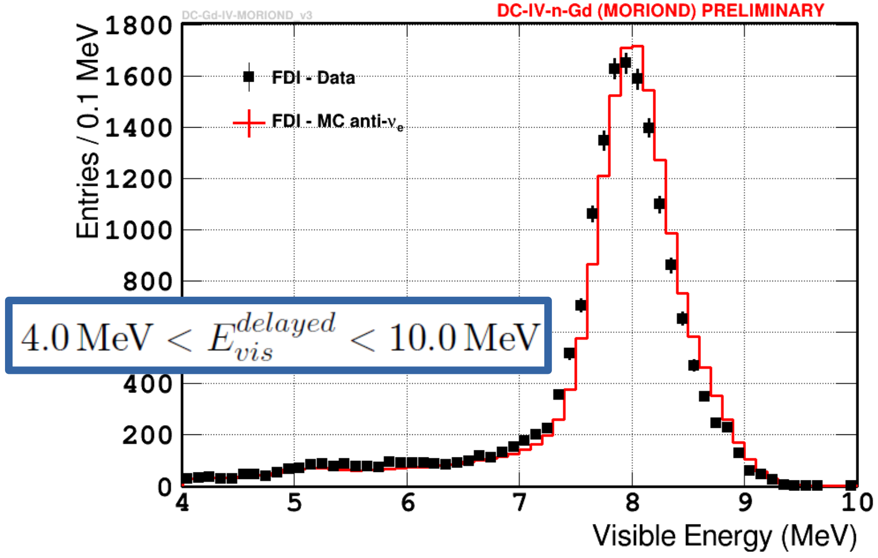
- Prompt signal (e⁺) : 1 MeV 2γ's + e⁺ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by **Gd** in ~30 μs
  or 2.2 MeV " by H in ~200 μs

IBD Detection

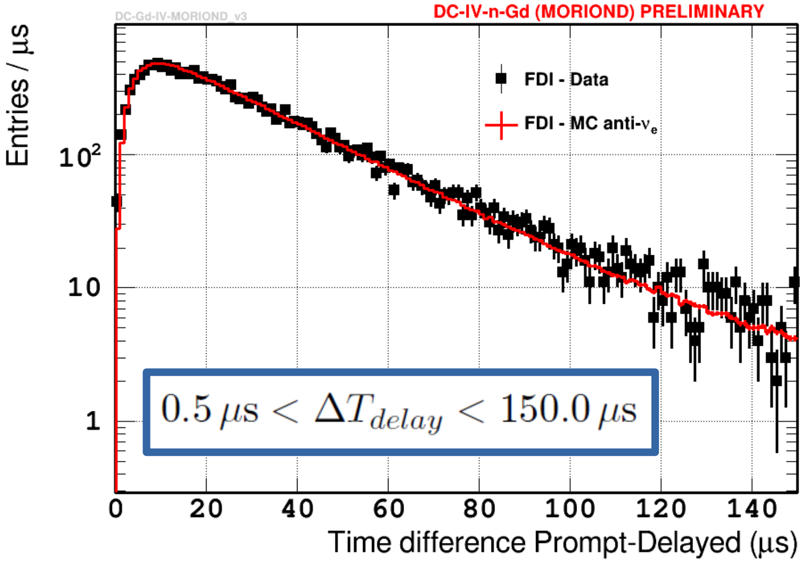
Example from Double Chooz
Gd analysis



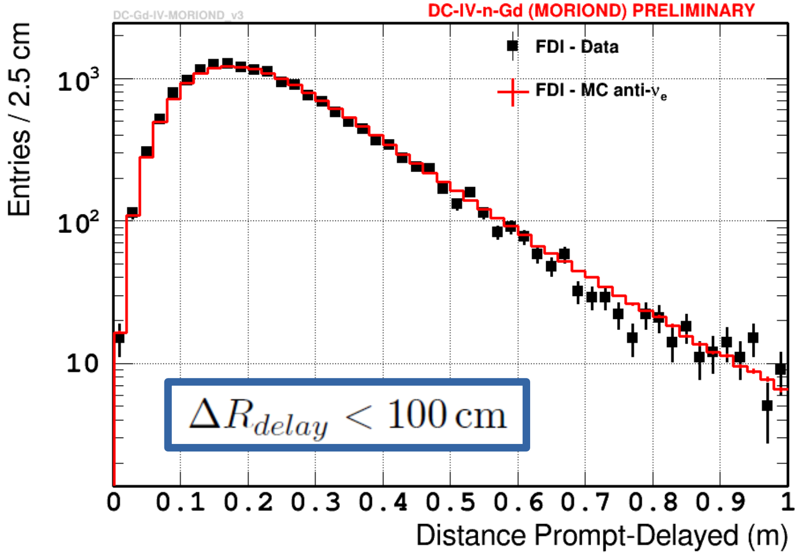
$$0.5\,\mathrm{MeV} < E_{vis}^{prompt} < 20\,\mathrm{MeV}$$



$$4.0\,\mathrm{MeV} < E_{vis}^{delayed} < 10.0\,\mathrm{MeV}$$



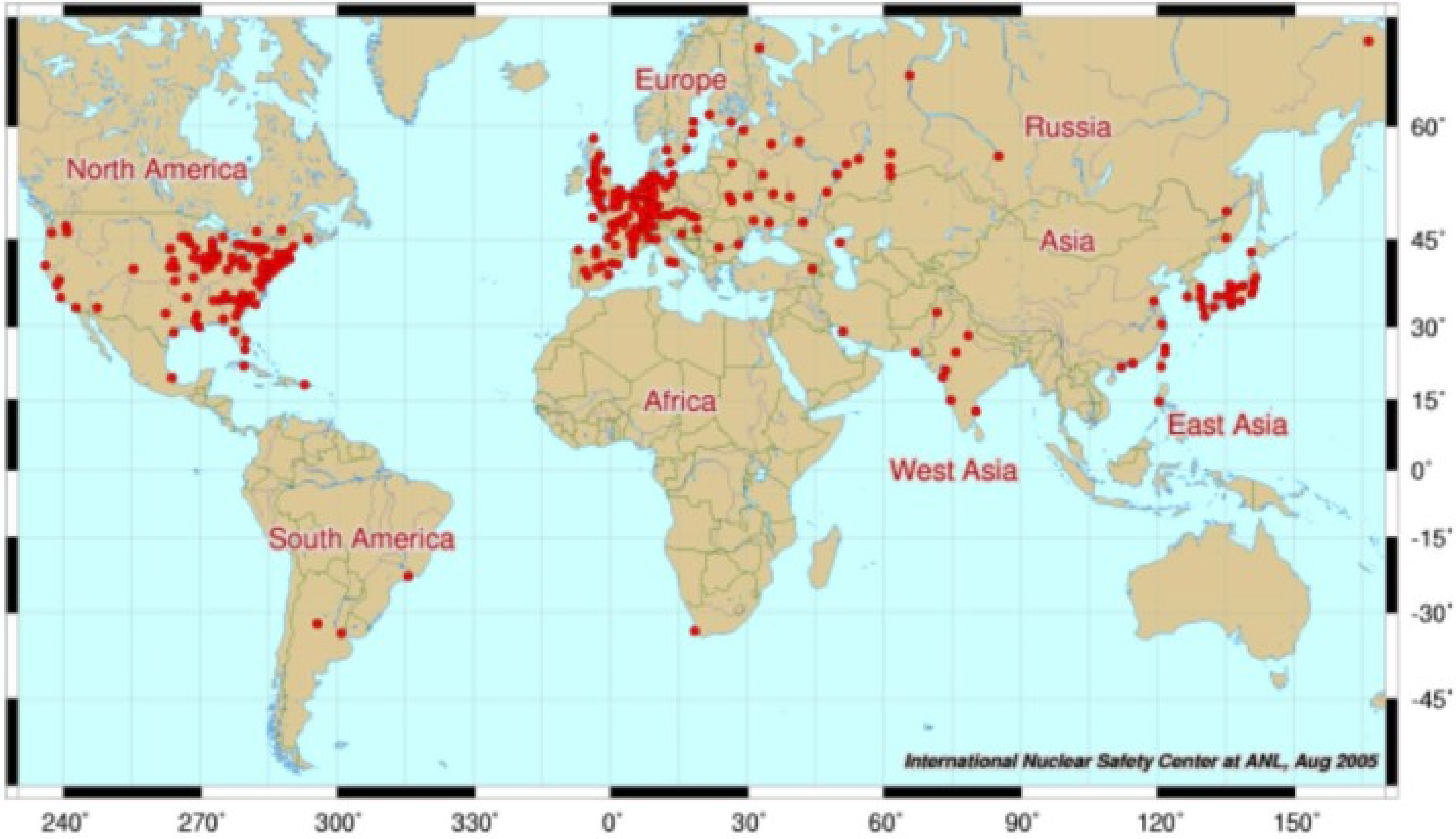
$$0.5\,\mu\mathrm{s} < \Delta T_{delay} < 150.0\,\mu\mathrm{s}$$



$$\Delta R_{delay} < 100\,\mathrm{cm}$$

Reactor Neutrinos

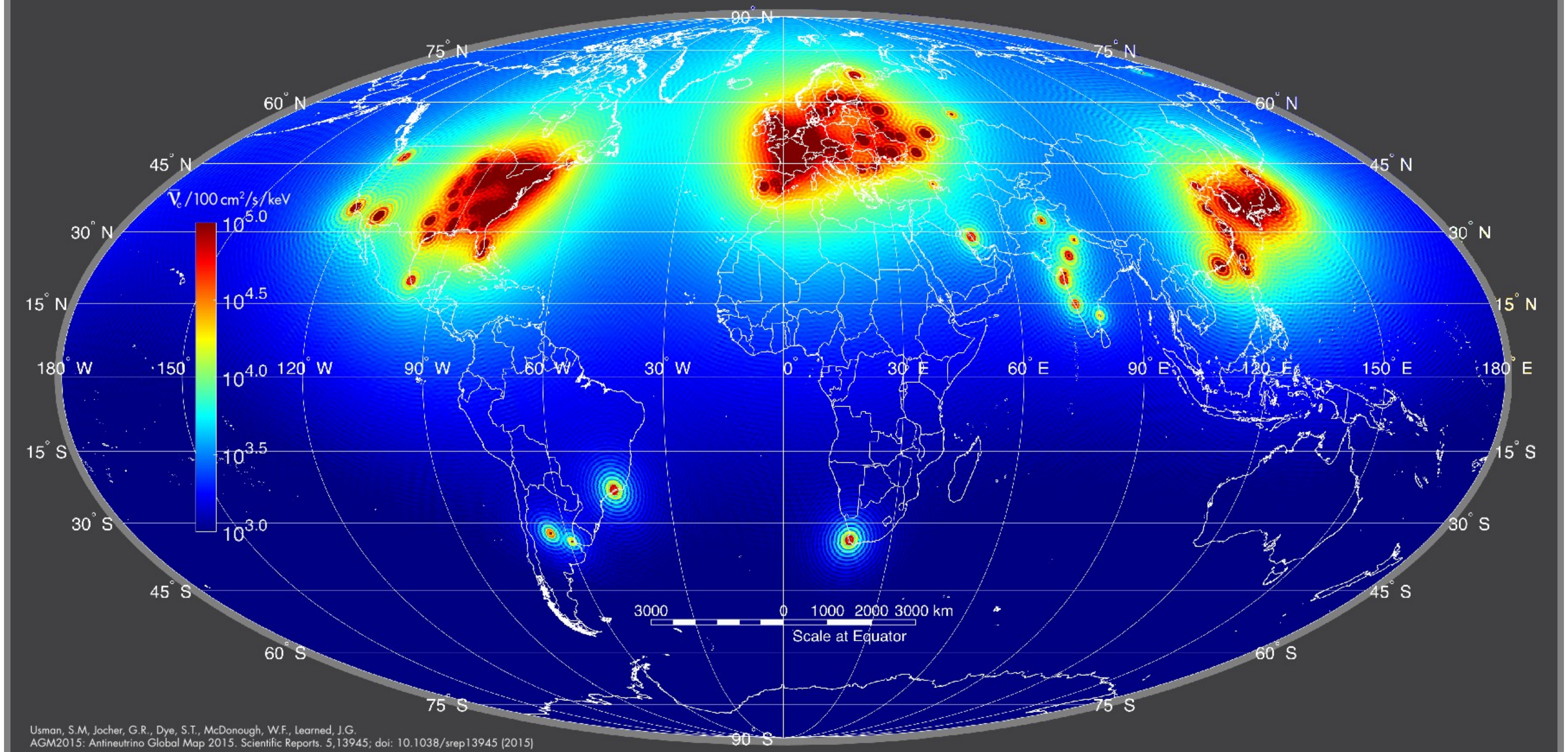
Reactor Neutrinos



International Nuclear Safety Center at ANL, Aug 2005

Reactor Neutrinos

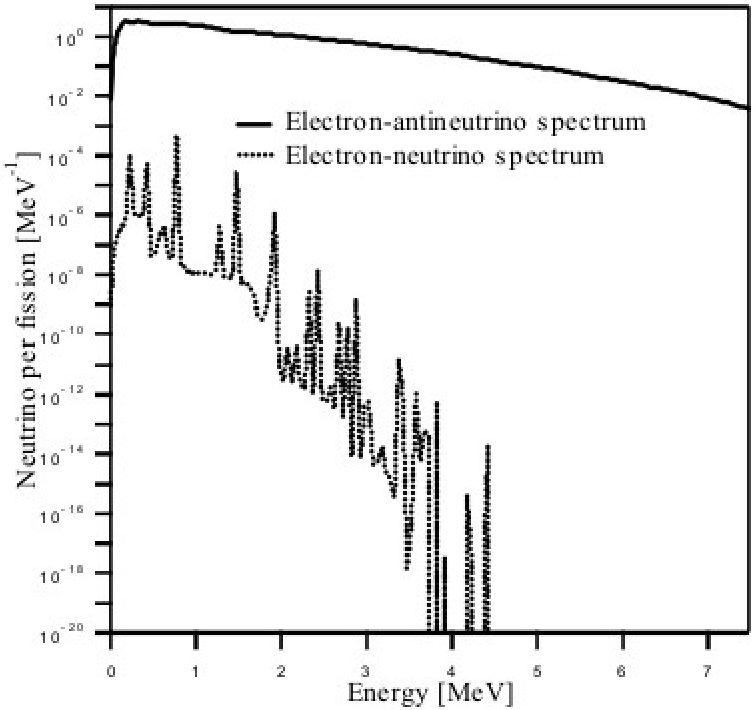
3 MeV reactor antineutrino flux worldwide:

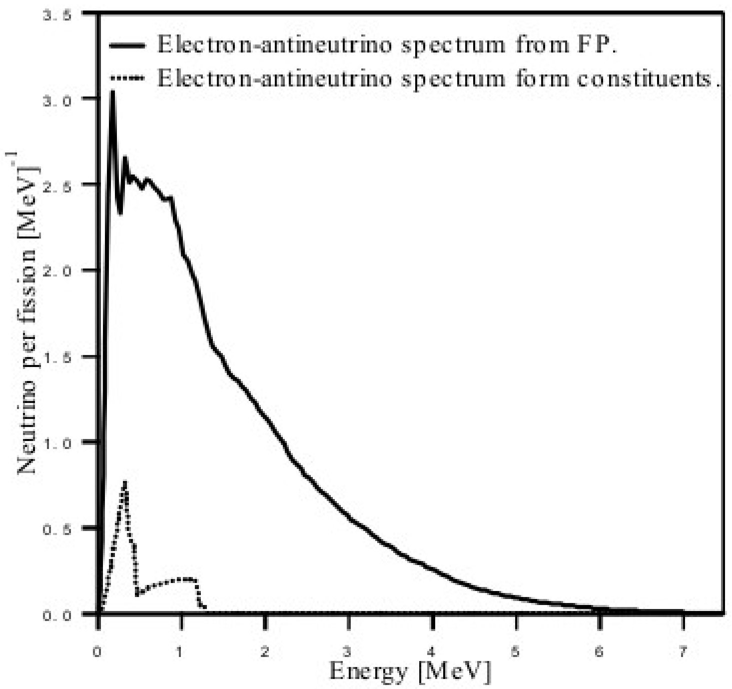


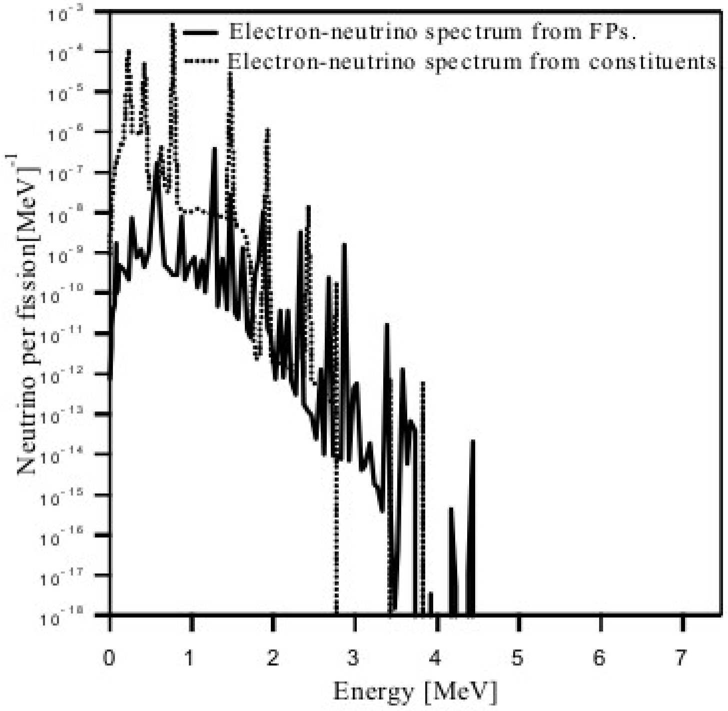
Usman, S.M, Jocher, G.R., Dye, S.T., McDonough, W.F., Learned, J.G.
AGM2015: Antineutrino Global Map 2015. Scientific Reports. 5,13945; doi: 10.1038/srep13945 (2015)

Antineutrino Global Map 2015, Sci.Rep. 5 (2015) 13945

Reactor Neutrinos

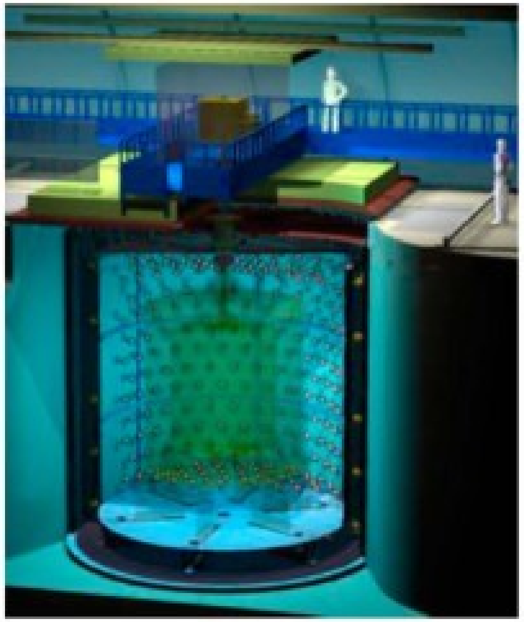

T. Nishimura et al., AIP 769, 1702 (2005)

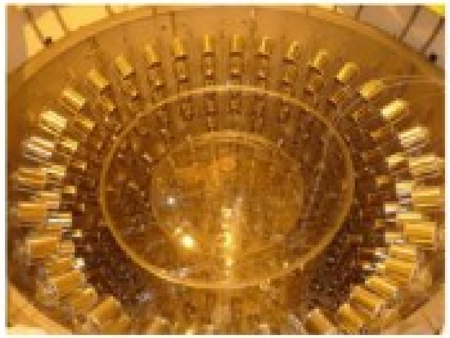

T. Nishimura et al., AIP 769, 1702 (2005)

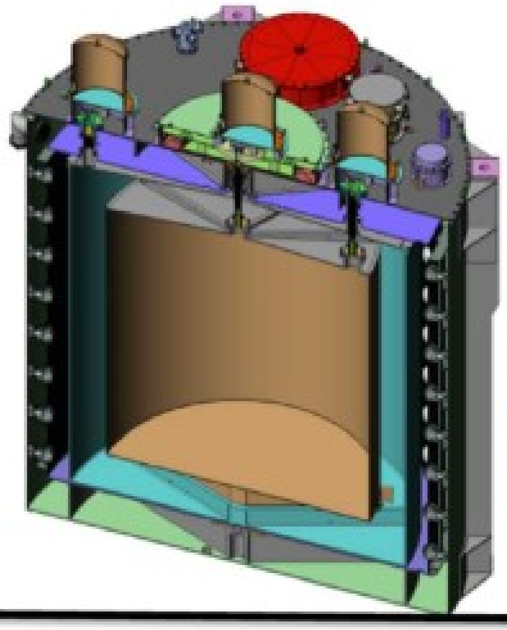

T. Nishimura et al., AIP 769, 1702 (2005)

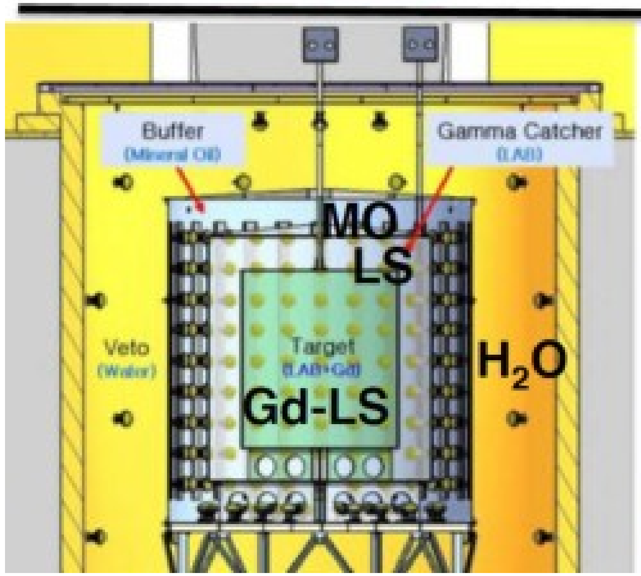
Reactor spectra:
→ dominated by anti-neutrinos from decay chains of neutron-rich fission products (FP)
→ small contributions from secondary (anti-)neutrinos from constituents of reactor vessel/structures

Double Chooz / RENO / Daya Bay







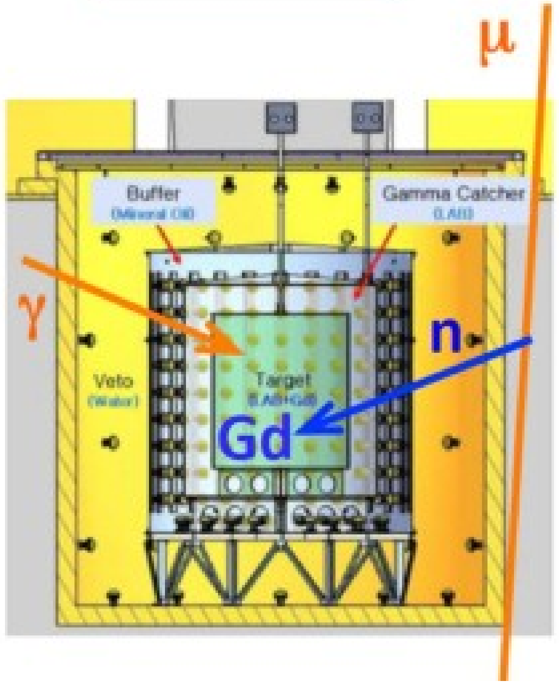


1. Cylindrical structure (four layers)
2. Neutrino Target: liquid scintillator with 0.1 % Gd doping

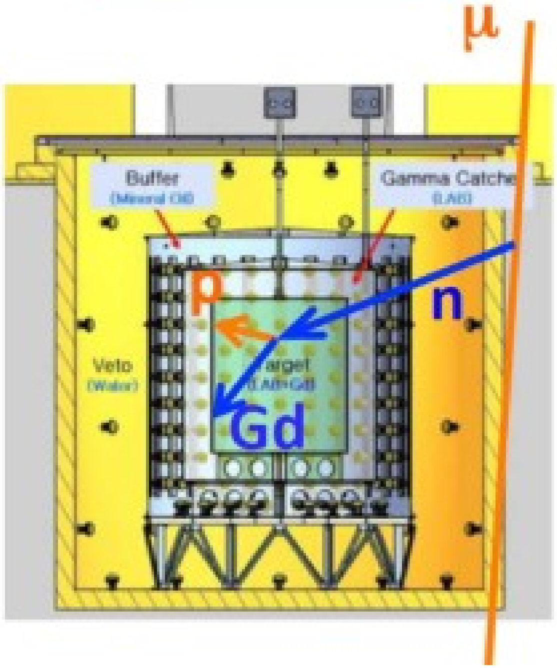
Typical Backgrounds to IBD

- Accidental coincidence between prompt and delayed signals
- Fast neutrons produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)
- ^{9}Li/^{8}He β-n followers produced by cosmic muon spallation

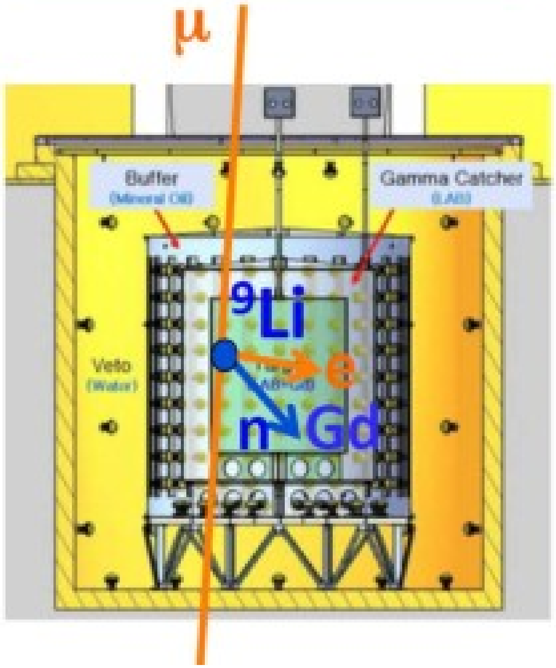
Accidentals



Fast neutrons

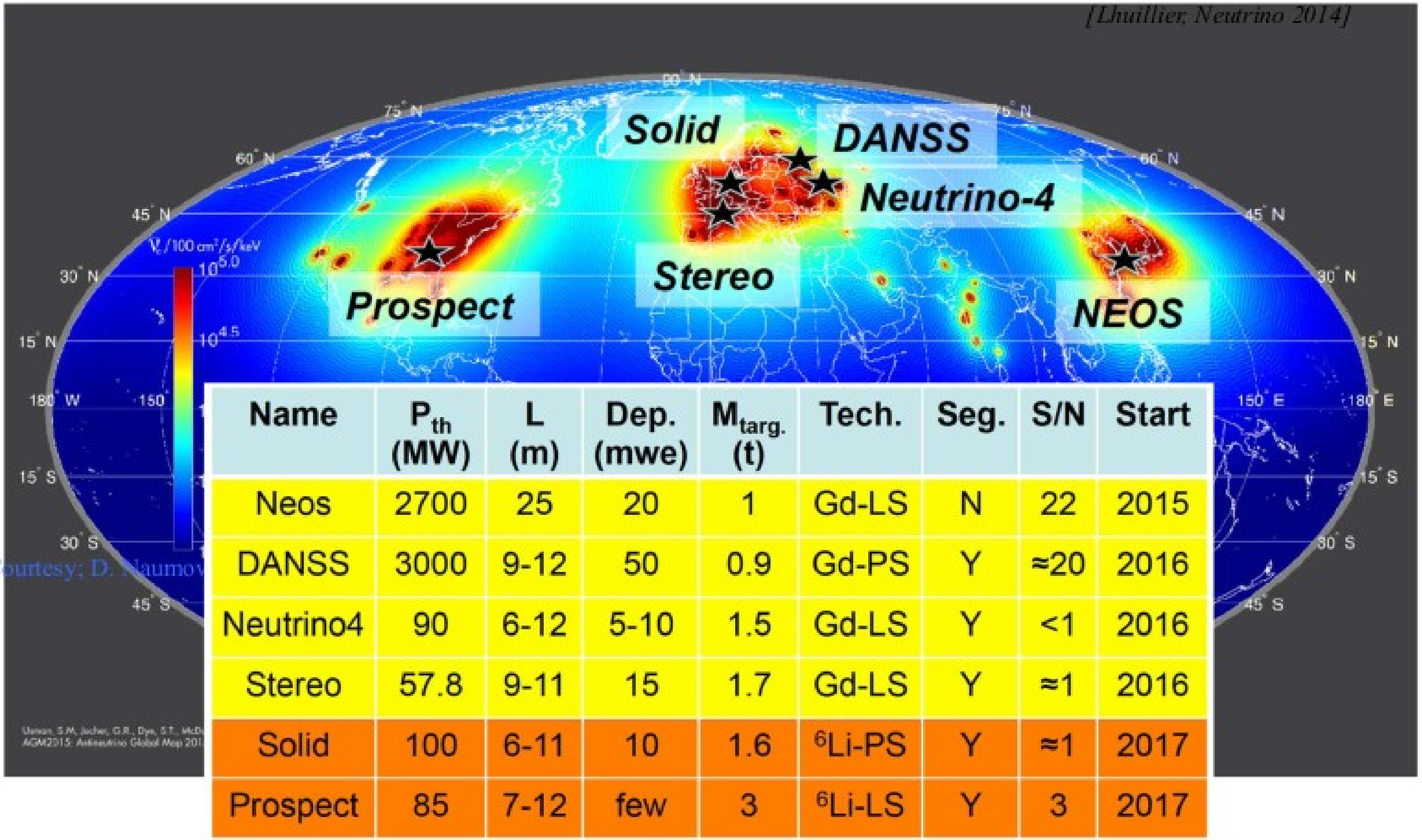


^{9}Li/^{8}He β-n followers



Sterile Reactor Neutrino Experiments

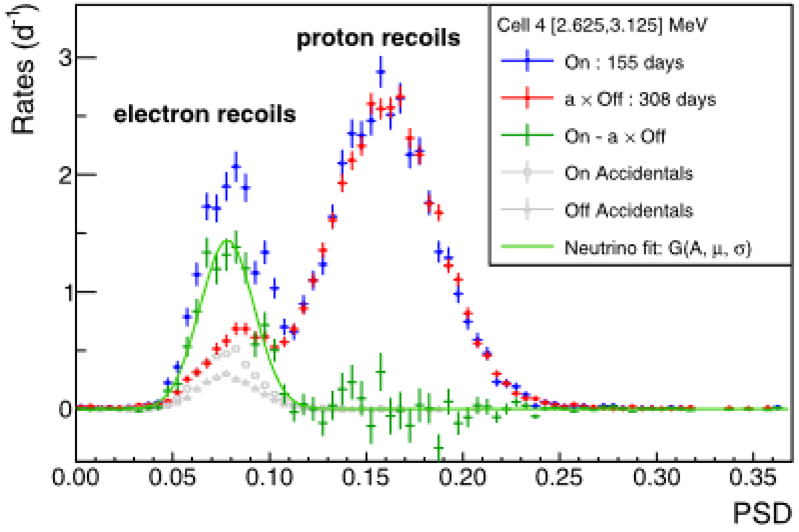
Several recent very-short baseline reactor neutrino experiments



[Lhuillier, Neutrino 2014]

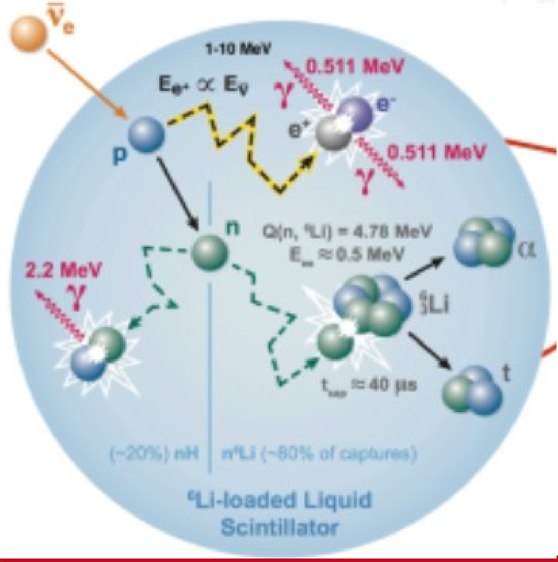
Name	P_{th} (MW)	L (m)	Dep. (mwe)	$M_{targ.}$ (t)	Tech.	Seg.	S/N	Start
Neos	2700	25	20	1	Gd-LS	N	22	2015
DANSS	3000	9-12	50	0.9	Gd-PS	Y	≈20	2016
Neutrino4	90	6-12	5-10	1.5	Gd-LS	Y	<1	2016
Stereo	57.8	9-11	15	1.7	Gd-LS	Y	≈1	2016
Solid	100	6-11	10	1.6	^{6}Li-PS	Y	≈1	2017
Prospect	85	7-12	few	3	^{6}Li-LS	Y	3	2017

Pulse shape discrimination against neutron background



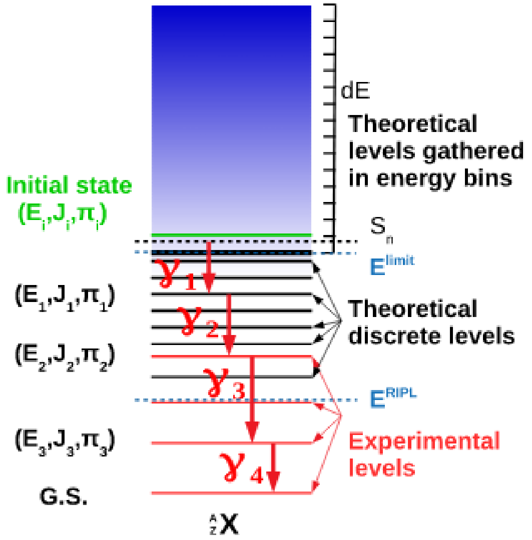
Nature 613 (2023) 257

Lithium: alpha+tritium upon neutron capture → localisation of capture



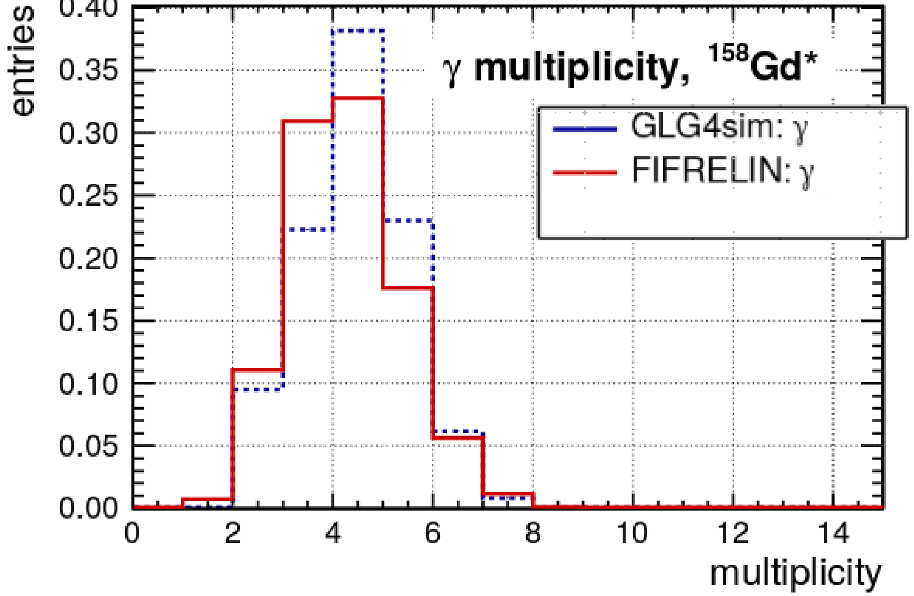
Gamma Cascade

- Improved model of gamma cascade after neutron capture by Gd via dedicated nuclear simulation tool FIFRELIN
- Of special importance in smaller detectors with less containment of gammas
- FIFRELIN tool models de-excitation of Gd-nuclei using all available experimental data plus nuclear models (RIPL-3, CGCM, CTM, FGM)
- FIFRELIN yields gammas of higher energy compared to Geant4-based GLG4sim simulation
  - → also including conversion electrons

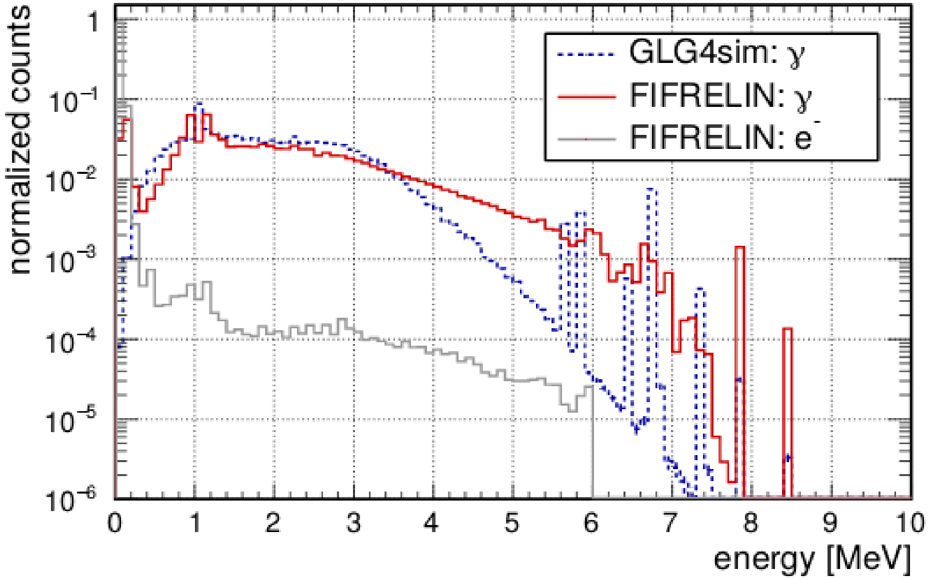


arXiv:1905.11967

zenodo.2653786



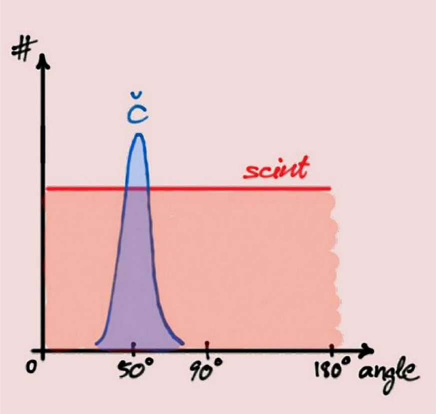
arXiv:1905.11967

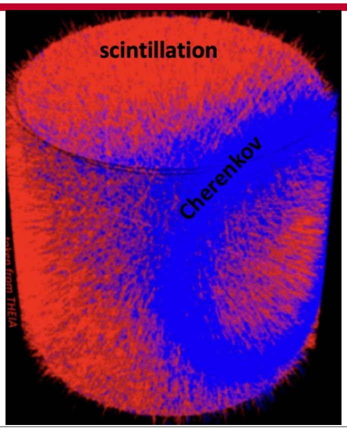


New Ideas on Reactor Neutrinos

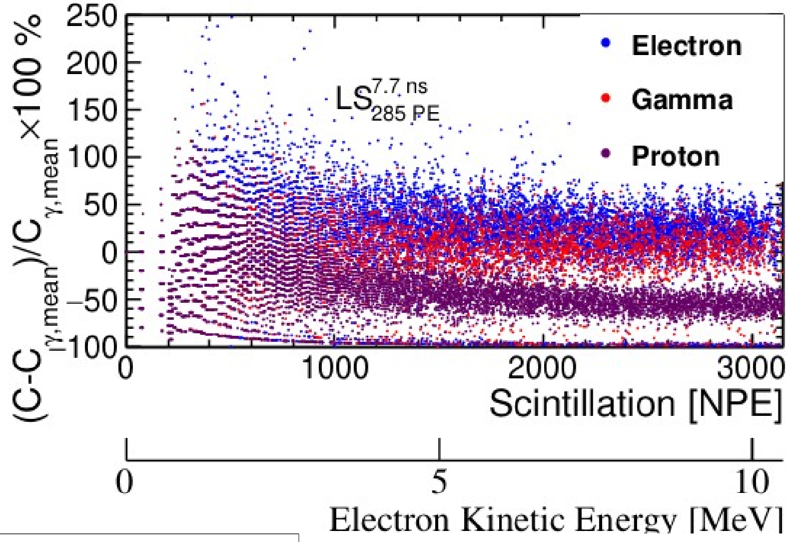
Cherenkov / Scintillation Separation

Direction
→ PMT granularity



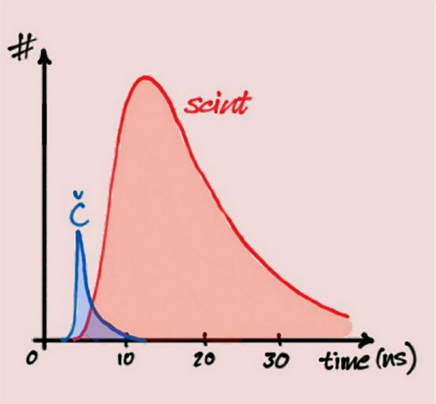


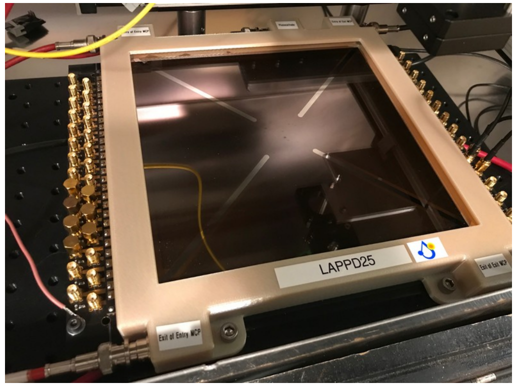
Courtesy of Ben Land



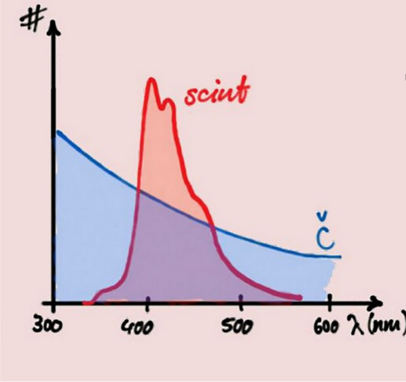
JINST 18(2023)P02004

Timing
→ fast electronics
→ LAPPD
  → TTS ~60ps
→ EPJC 82(2022)169



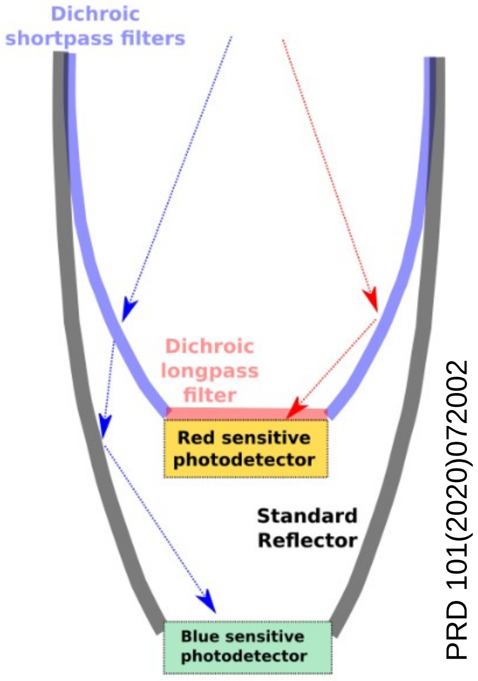


Spectral sorting
→ Dichroicons
  → wavelength filter
→ PRD 101(2020)072002



Courtesy of Michael Wurm

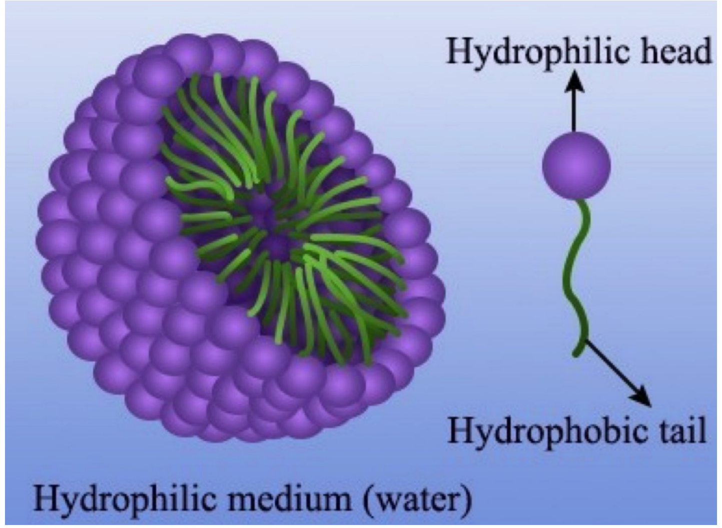
PRD 101(2020)072002



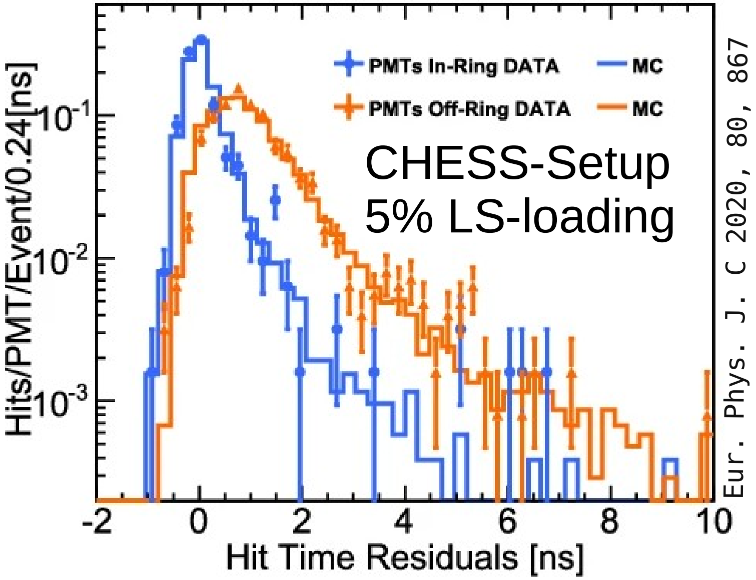
PRD 101(2020)072002

Added benefits:
→ directionality
  → Cherenkov-cone
→ particle ID
  → particle-dependent ratio of Cherenkov and scintillation light

Hybrid Scintillator – Cherenkov/Scintillation



IJAC 13 (2017) 663-672



Eur. Phys. J. C 2020, 80, 867

Water-based scintillator:

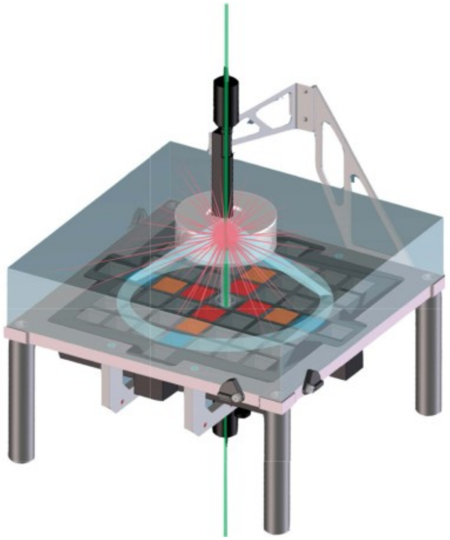
→ organic micelles
  suspended in water
  with surfactant interface

→ 1 – 10% scintillator loading

→ keep directional information
  from Cherenkov light

CHESS

→ spatial separation of Cherenkov and scintillation light



Phys. Rev. C 2017, 95, 055801

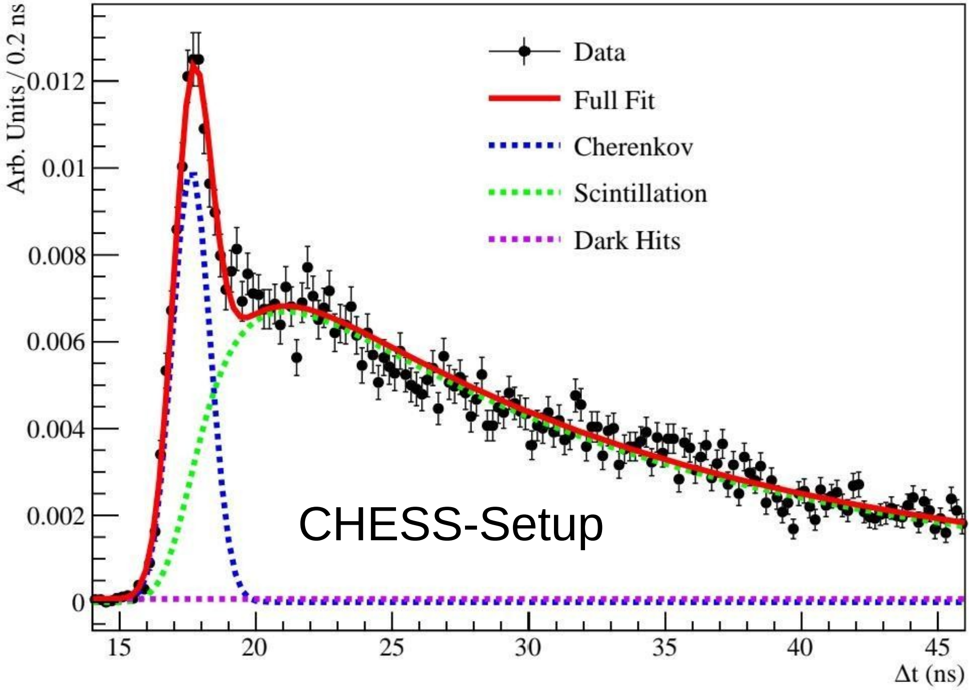
Slow scintillator:

→ slow fluorophores / slow solvents

→ high light yield scintillators (>10000 ph/MeV)

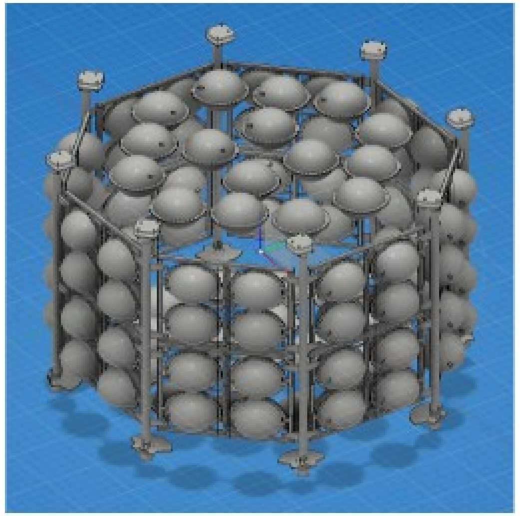
→ intrinsically slow scintillation pulse form

→ τ = >10 ns



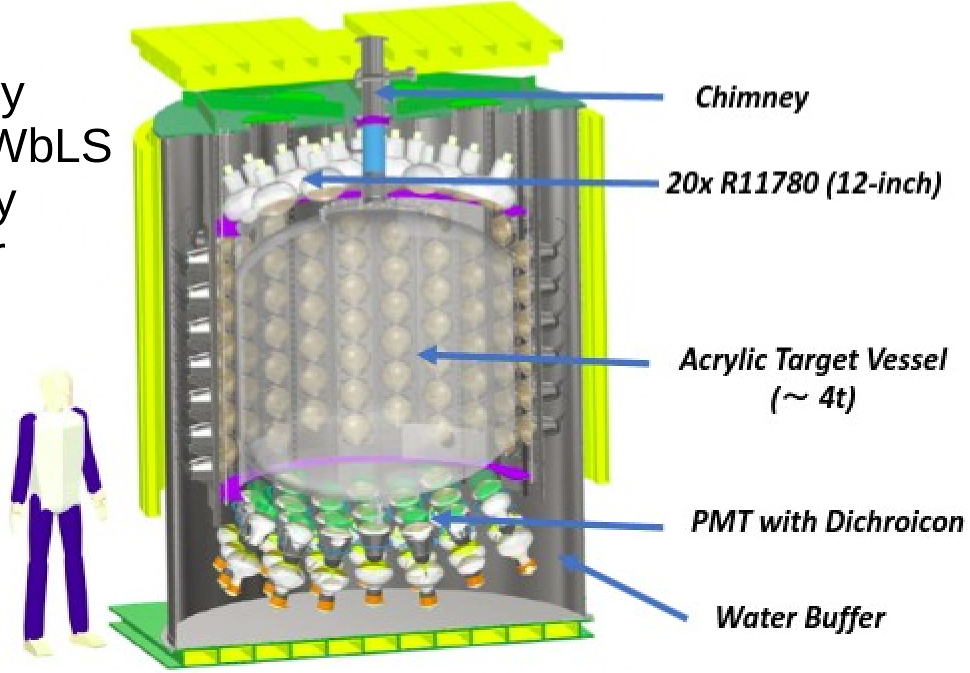
H. Steiger et al.

Upcoming Hybrid Detectors



BUTTON
→ at Boulby
→ 30 tonnes WbLS
→ reactor detection

Eos
→ at Berkeley
→ 4 tonnes WbLS
→ technology demonstrator

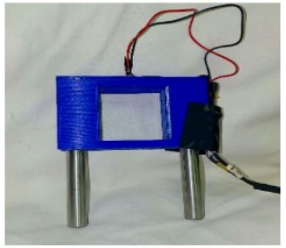


Fast timing

Large Area Picosecond Photo-Detector (LAPPD):

50 ps timing
Imaging

Fast, high efficiency



Wavelength-shifting plate with SiPM strip readout:

50% efficiency at peak
Timing < 100 ps

Spectral sorting

Dichroicons: light cones with dichroic filters:

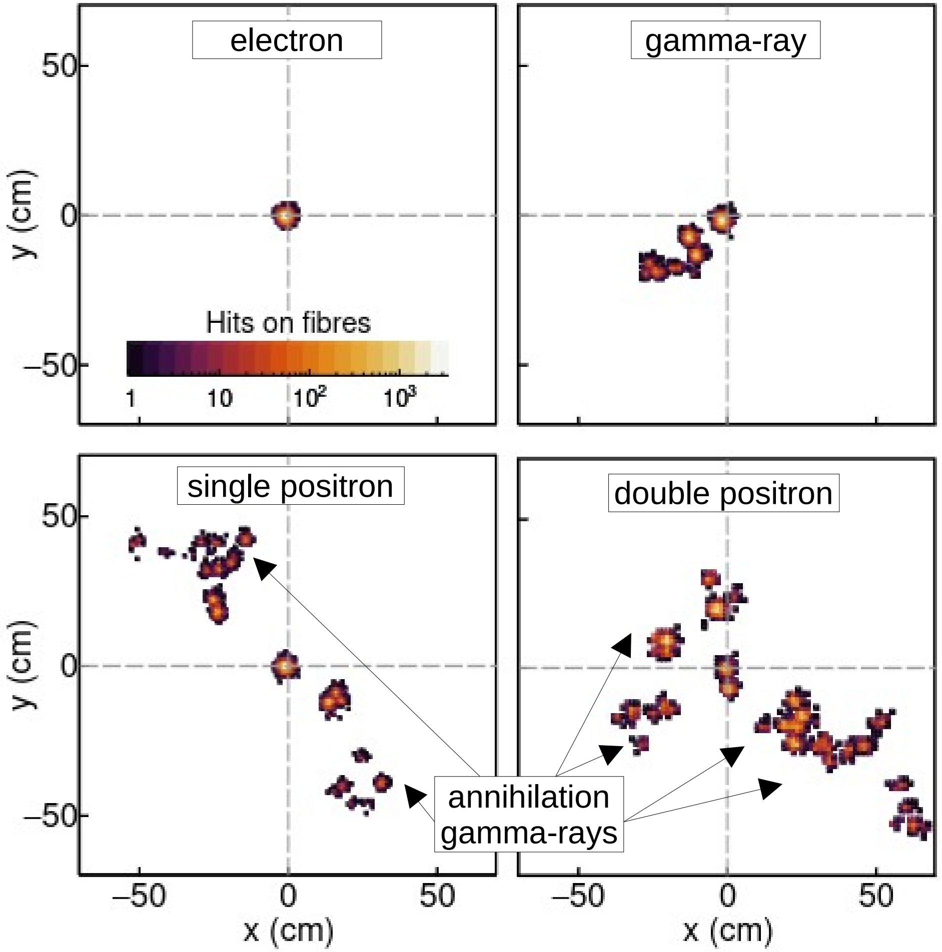
Increased light collection
Photon sorting by wavelength

Other projects:
→ ANNIE
→ Brookhaven Demonstrator
→ NuDot
→ NuDoubt^{++}

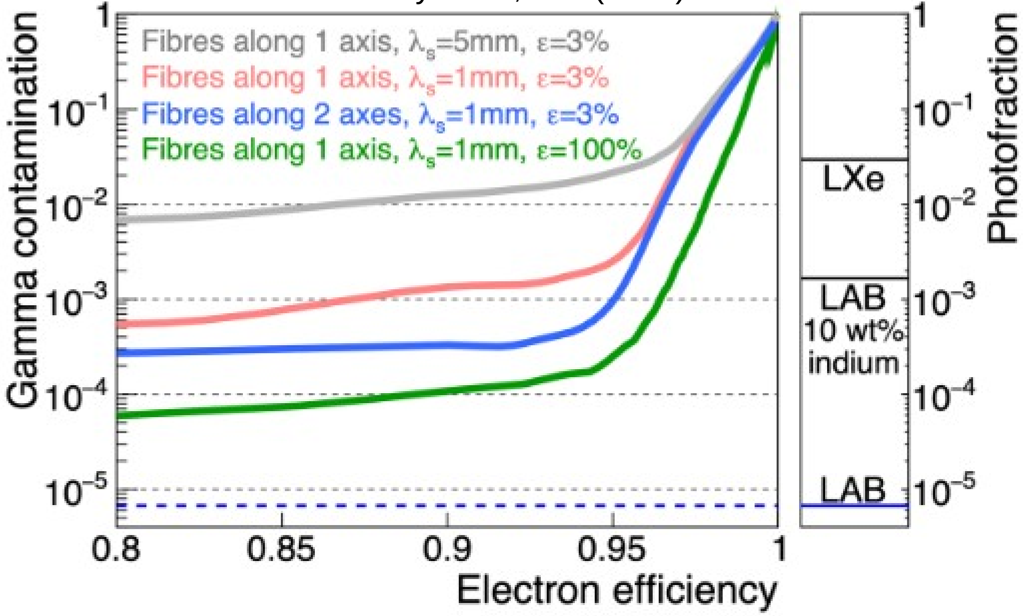
Particle ID through Opacity

Transparent liquid scintillator:
energy depositions converted into scintillation light in >20cm conversion zone

2.8 MeV total energy, simulation, 1 cm fibre pitch,
2 mm scattering length, arXiv:2407.05999



2 MeV electron/gamma, 1 cm fibre pitch, simulation
Communication Physics 4, 273 (2021)



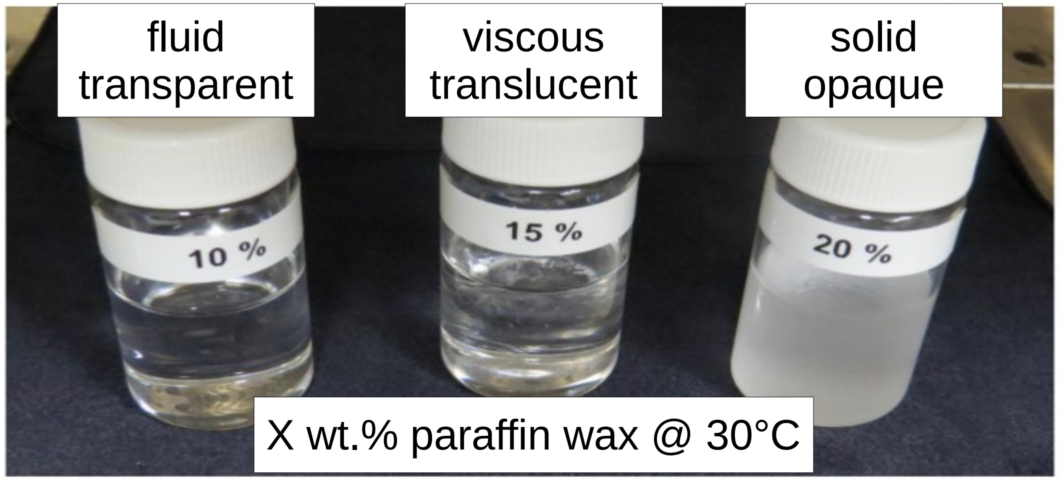
Energy depositions happen on smaller scale

→ opaque medium confines lights to its point of creation
→ light-readout via grid of wavelength-shifting fibres
→ particle-ID through vertex resolution at cm-scale
→ e.g. electron/gamma discrimination of 1000/1 possible

Opaque Scintillator

wax-based opaque scintillator (NoWaSH, JINST 14 (2019) P11007):

- → e.g. 90% LAB + 10% wax + PPO as fluor
- → opaqueness through scattering without absorption (Mie scattering, scattering length of millimetres)
- → scattering length tunable via
  - → wax type
  - → wax concentration
  - → temperature (in some NoWaSH formulations)
- → high isotope loading possible
  - → relaxed requirement on absorption length
  - → proof of principle via boron / TBB

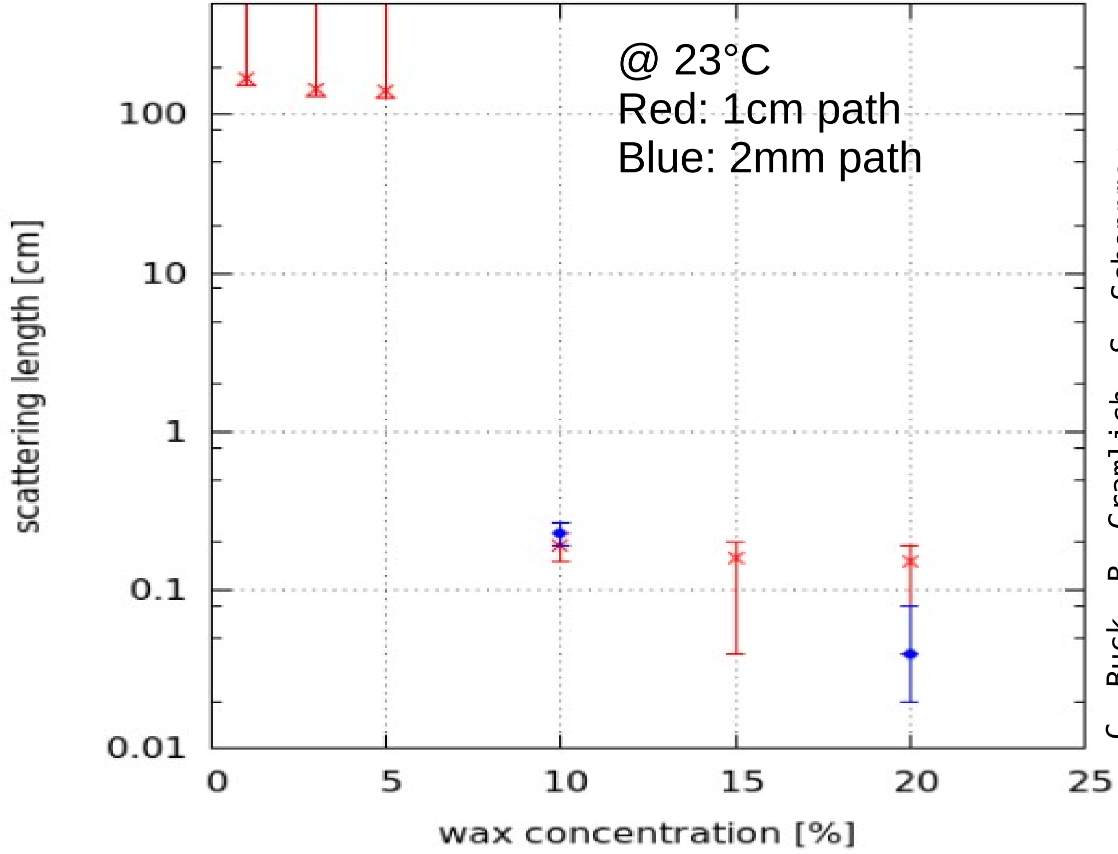


fluid
transparent

viscous
translucent

solid
opaque

X wt.% paraffin wax @ 30°C



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

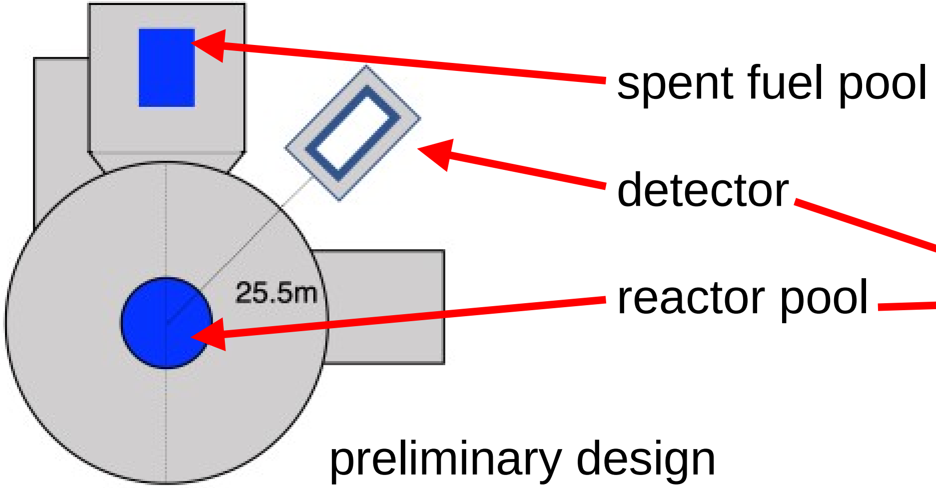
Upcoming Opaque AntiMatter-OTech/CLOUD

Chooz B nuclear reactor site in France
4.2 GW thermal power (single core)

AntiMatter-OTech (innovation project):
→ reactor monitoring

European Innovation Council

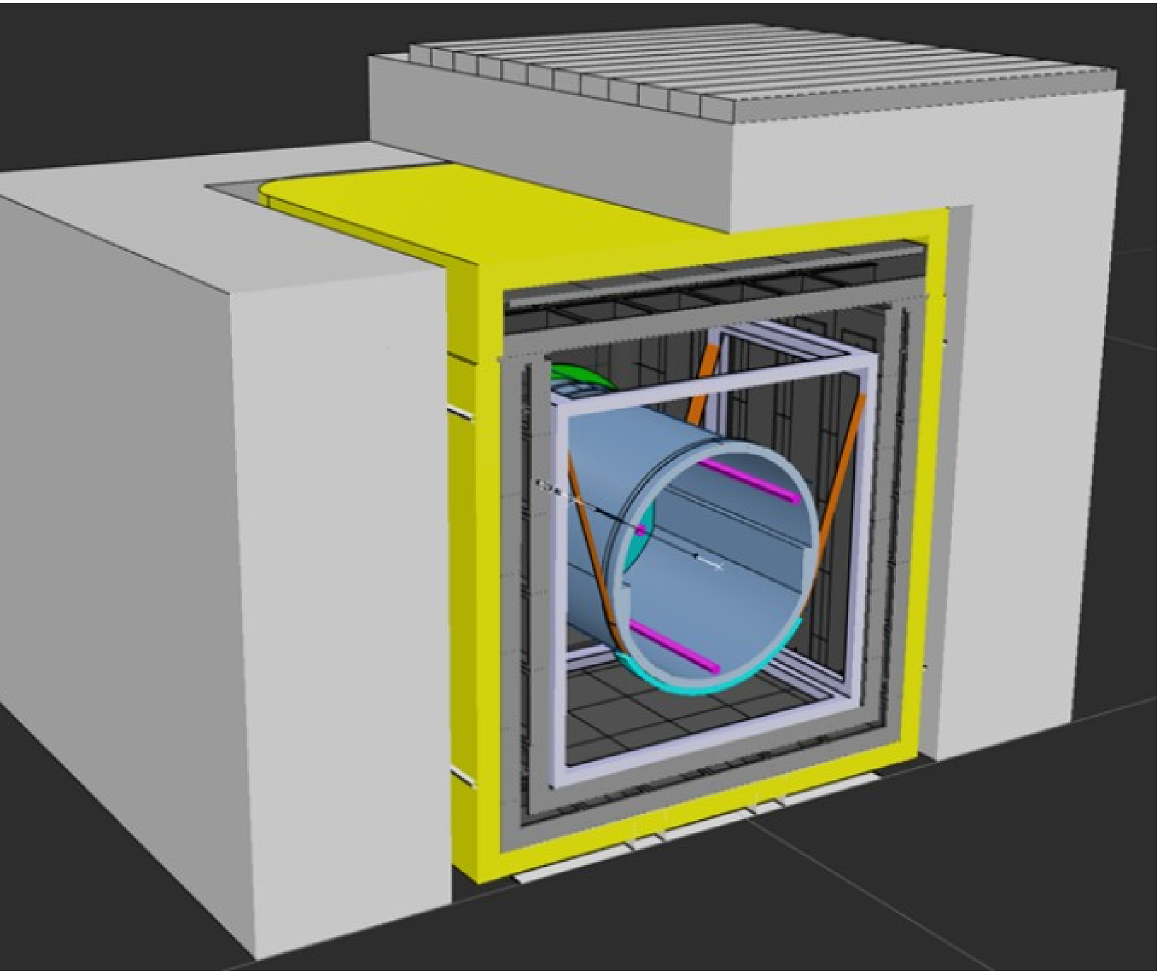
UK Research and Innovation

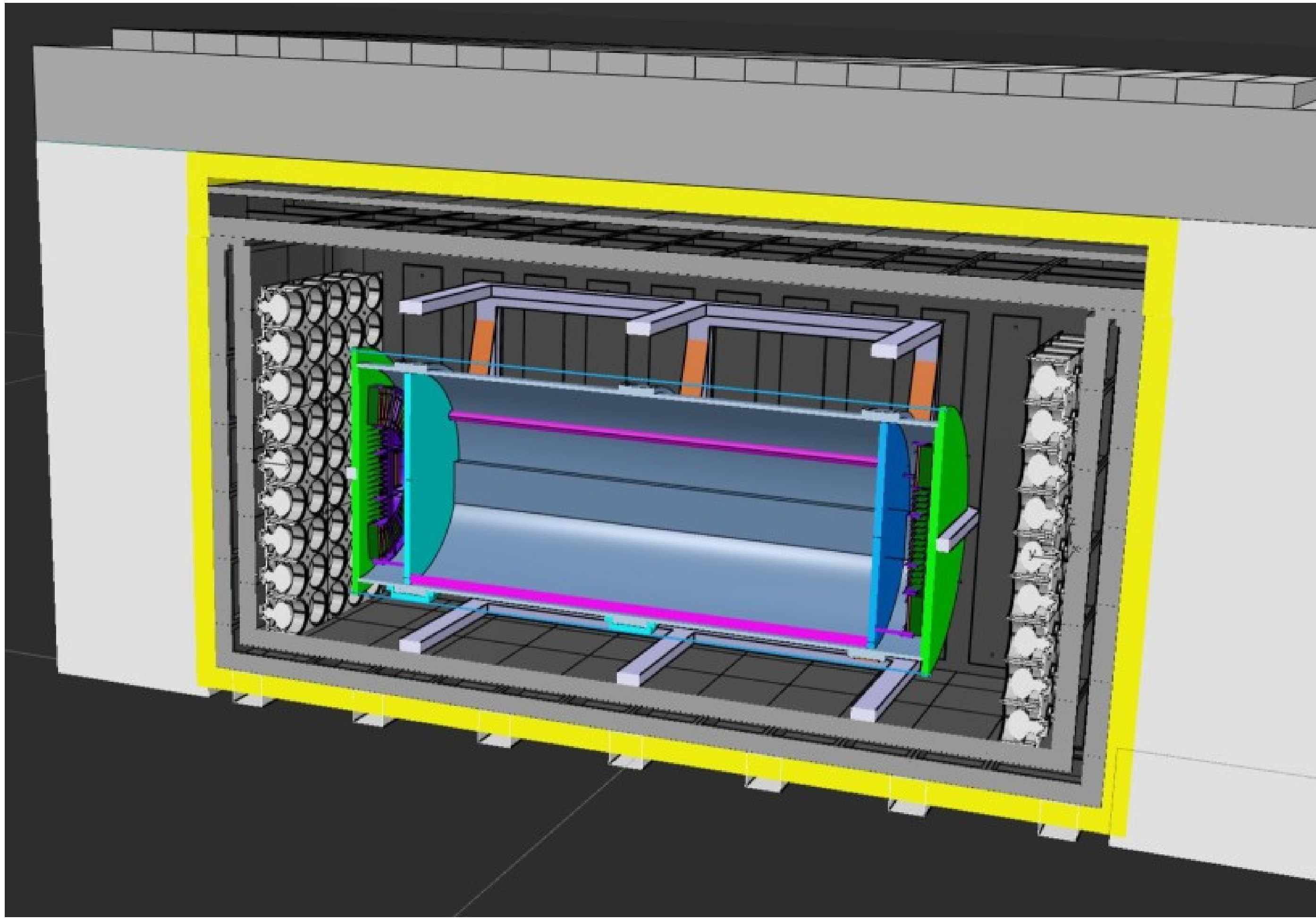


preliminary design

CLOUD (fundamental physics extension to AntiMatter-OTech)
→ phase I: reactor physics
→ phase II: solar neutrinos
→ phase III: geo-neutrinos

AntiMatter-OTech/CLOUD

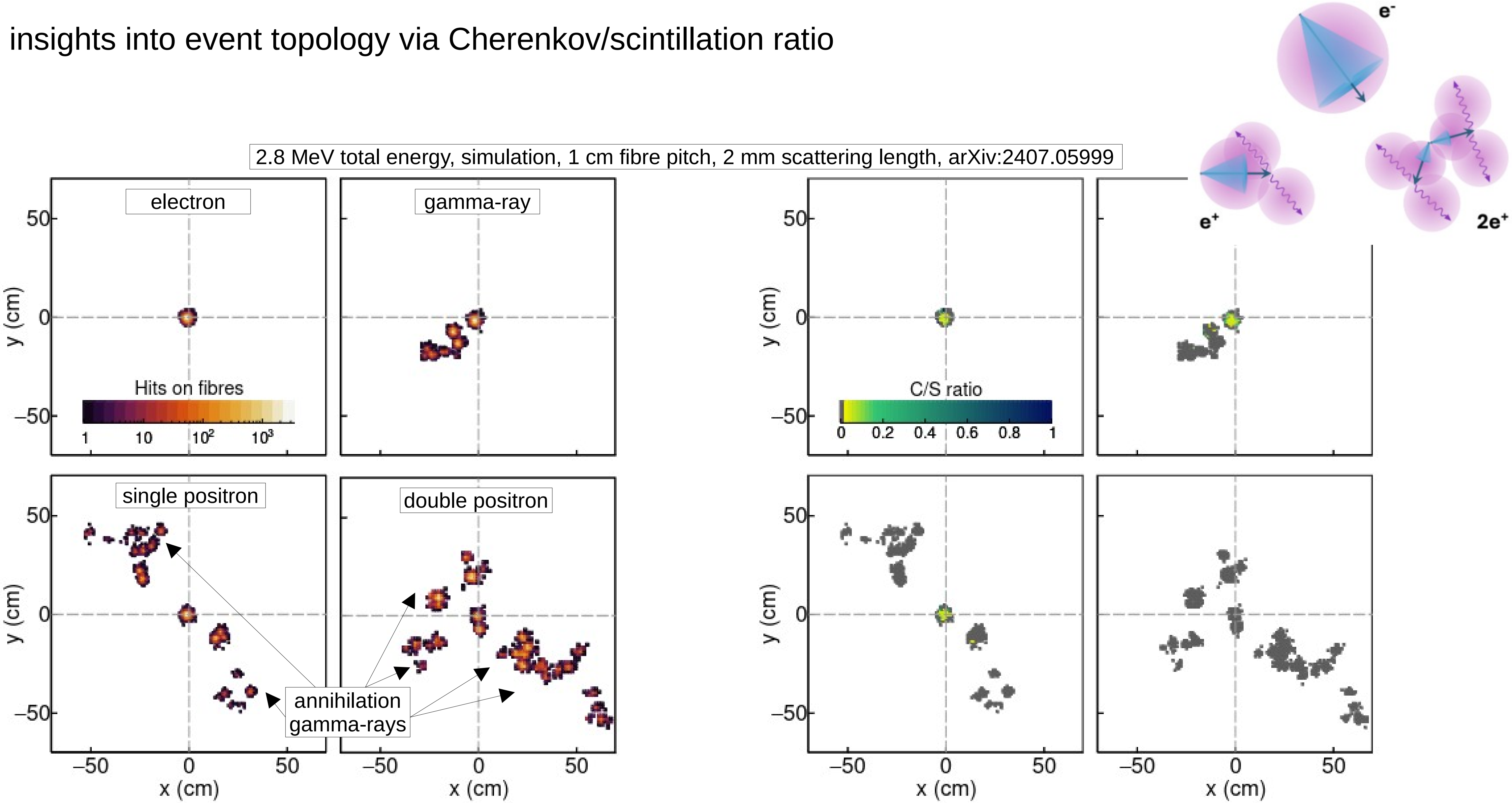




Preliminary design:
Inner detector: ~8 tonnes fiducial opaque scintillator / ~10000 fibres / >200 PE/MeV
Outer detector: transparent scintillator / ~180 PMTs / >400 PE/MeV
Shielding: concrete+iron / ~3 m.w.e.

Combined Hybrid Opaque Scintillator

→ better insights into event topology via Cherenkov/scintillation ratio

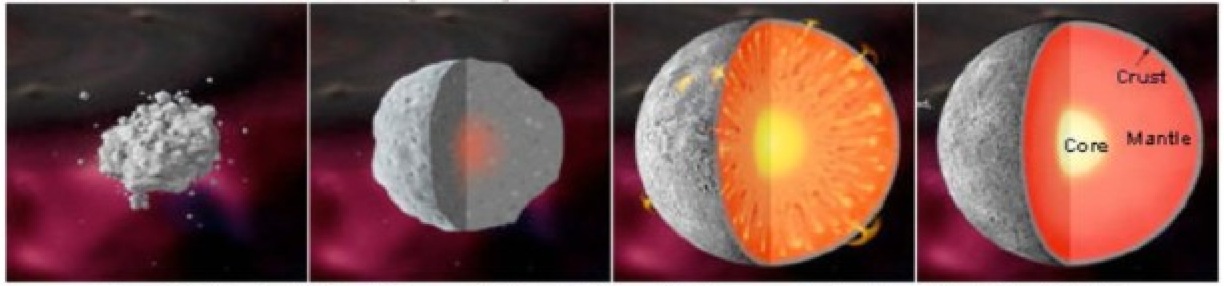


2.8 MeV total energy, simulation, 1 cm fibre pitch, 2 mm scattering length, arXiv:2407.05999

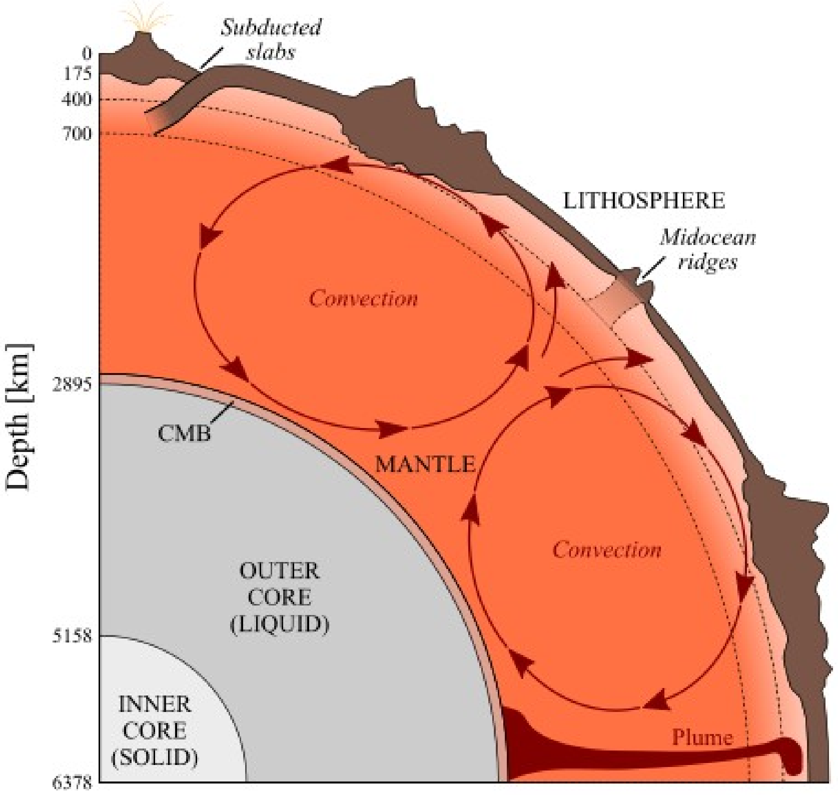
Geological Neutrinos

Earth Models

A Rocky Body Forms and Differentiates

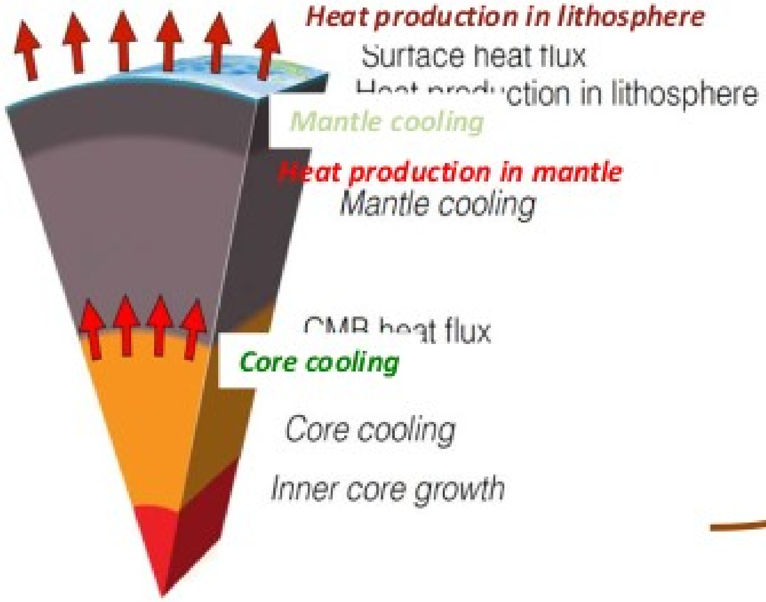


(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)



Integrated surface heat flux:

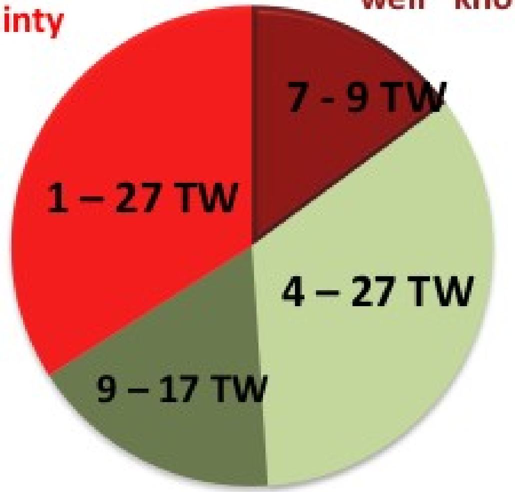
$H_{tot} = 47 \pm 2$ TW



Radiogenic heat
&
Geoneutrinos can help!

Mantle
Big uncertainty

Lithosphere
“well” known



Core cooling

Mantle cooling

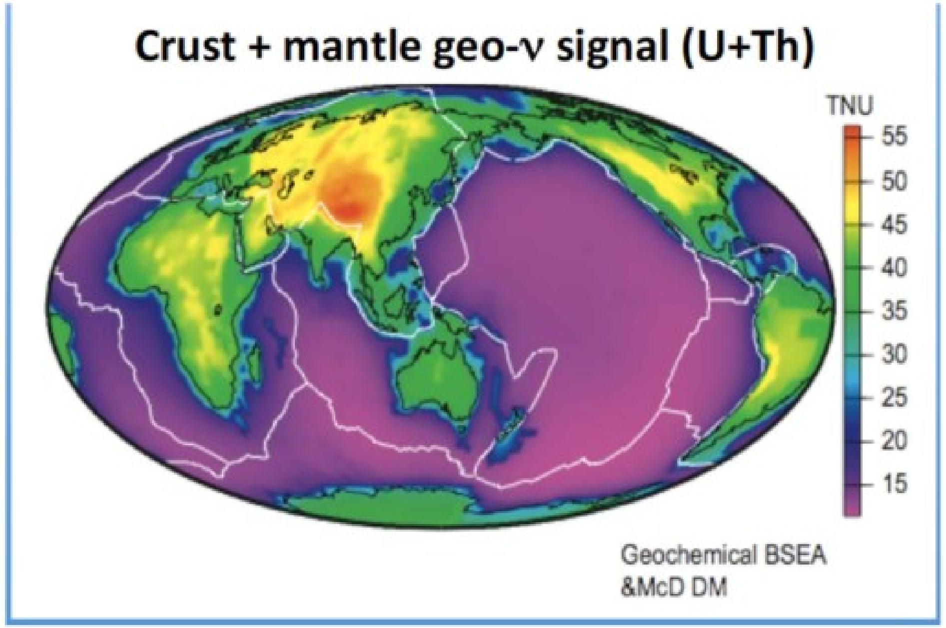
Earth Models

Geology and neutrino physics: geoneutrinos

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV



Crust + mantle geo-ν signal (U+Th)

Geochemical BSEA
&McD DM

1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% detection efficiency

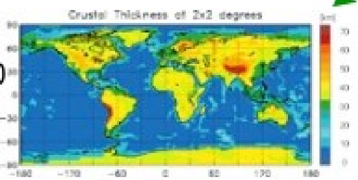
Geoneutrinos are antineutrinos
→ flux on surface: 10^6 /cm^2 /sec

U Th K Composition of Silicate Earth (BSE)

	TW radiogenic power	
	BSE	Mantle
• **"Geochemical"** estimate – Ratios of RLE abundances constrained by C1 chondrites – Absolute abundances inferred from Earth rock samples – *McDonough & Sun (1995), Allègre (1995), Hart & Zindler (1986), Palme & O'Neill (2003),* ***Arevalo et al. (2009)***	20±4	12±4
• **"Cosmochemical"** estimate – Isotopic similarity between Earth rocks and E-chondrides – Build the Earth from E-chondrite material – ***Javoy et al. (2010)*** – also "collisional erosion" models (*O'Neill & Palme 2008*)	11±2	3±2
• **"Geodynamical"** estimate – Based on a classical parameterized convection model – Requires a high mantle Urey ratio, i.e., high U, Th, K	33±3	25±3

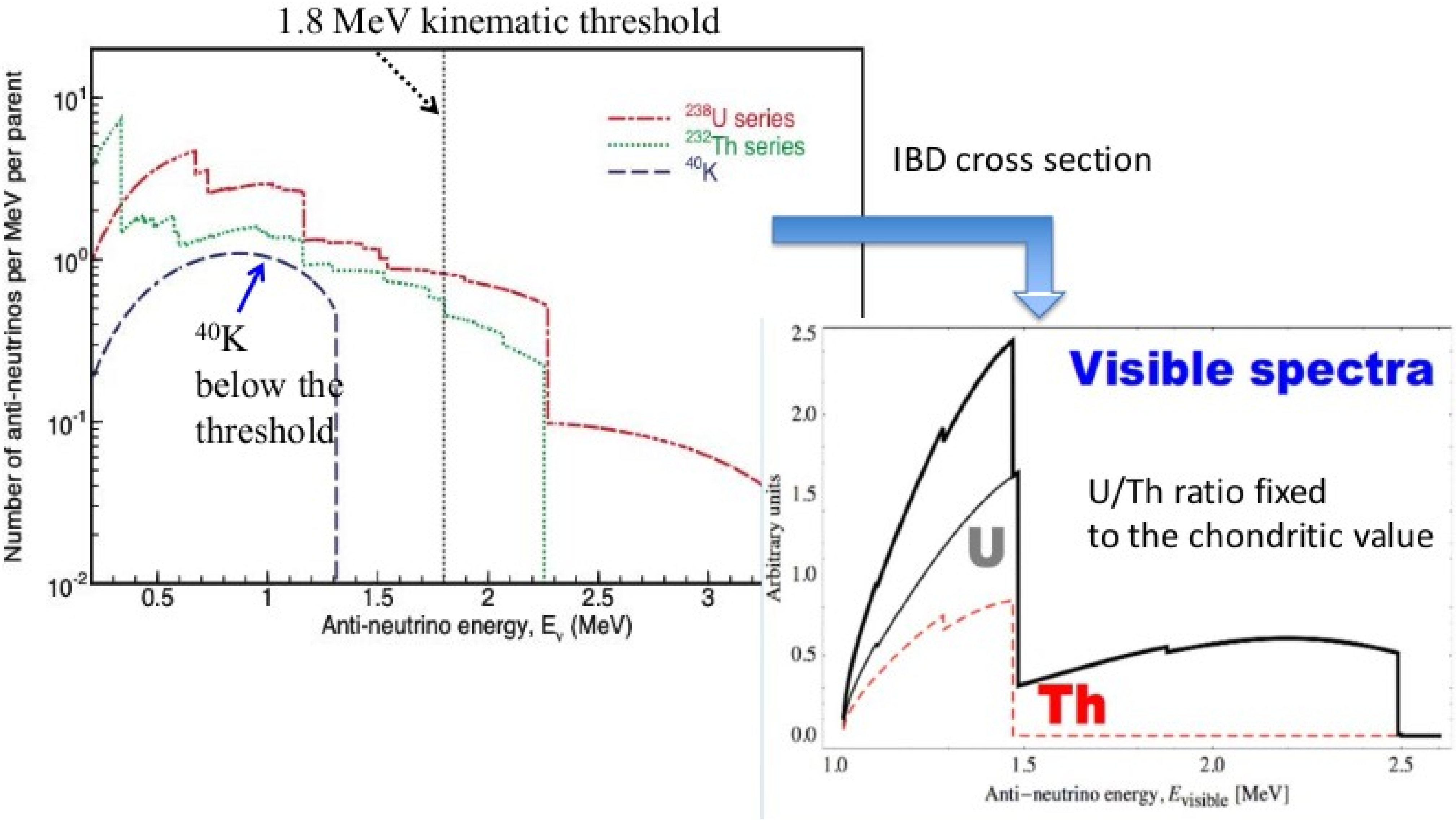
BSE = Mantle + Crust

CRUST2.0 thickness



Oceanic: 0.22 ± 0.03 TW
Continental: 7.8 ± 0.9 TW

Measuring Geoneutrinos



IBD cross section

Visible spectra

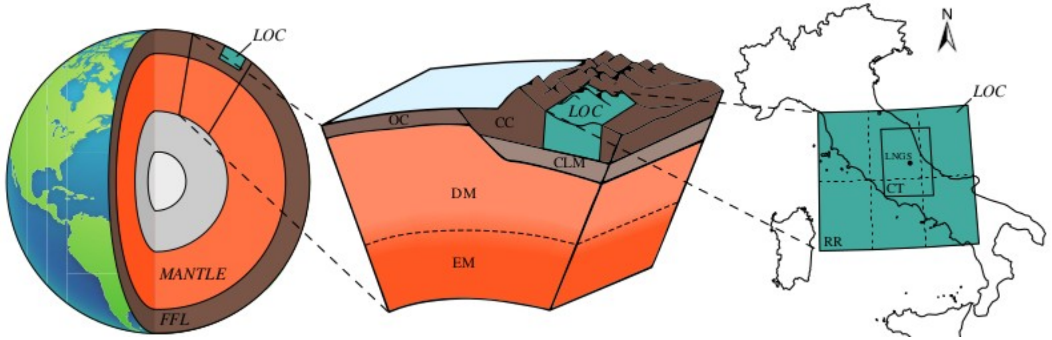
U/Th ratio fixed
to the chondritic value

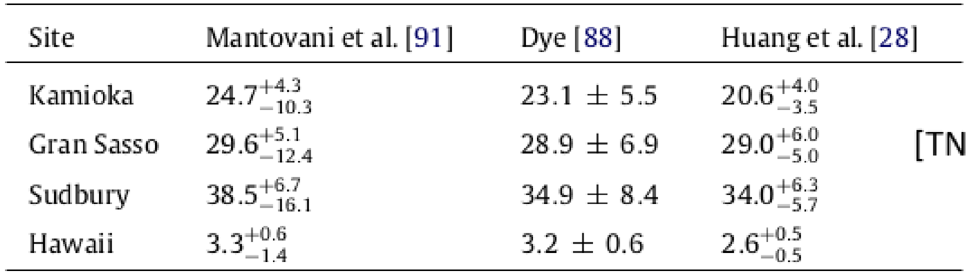
Measuring Geoneutrinos

After removal of expected reactor anti-neutrino flux and subtraction of backgrounds:

Expected geoneutrino signal

- **LOC: Local crust:** about 50% of the expected geoneutrino signal comes from the crust within 500-800 km around the detector, thus local geology has to be known;
- **ROC: Rest of the crust:** further crust is divided in 3D voxels, volumes for upper, middle, lower crust and sediments are estimated and a mean chemical composition is attributed to these volumes (Huang et al. 2013);
- **Mantle = BSE – (LOC + ROC):** this is the real unknown, different BSE models are considered and the respective U + Th mass is distributed either homogeneously (maximal signal) or it is concentrated near to the core-mantle boundary (minimal signal);

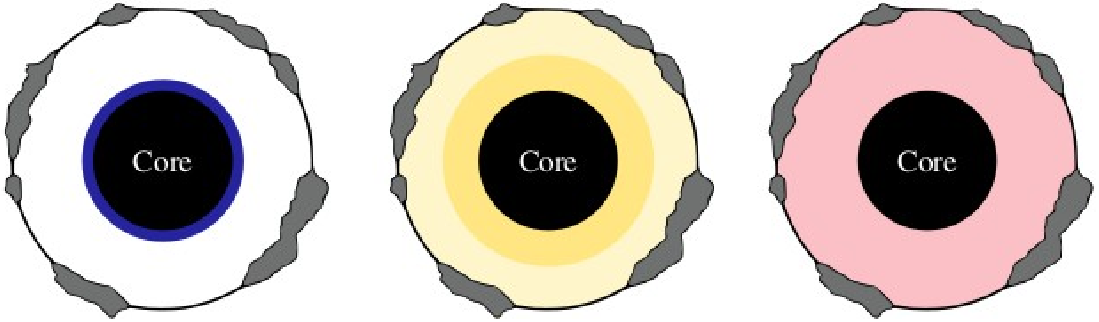




	Site	Mantovani et al. [91]	Dye [88]	Huang et al. [28]
KamLAND	Kamioka	$24.7^{+4.3}_{-10.3}$	23.1 ± 5.5	$20.6^{+4.0}_{-3.5}$
Borexino	Gran Sasso	$29.6^{+5.1}_{-12.4}$	28.9 ± 6.9	$29.0^{+6.0}_{-5.0}$
SNO+	Sudbury	$38.5^{+6.7}_{-16.1}$	34.9 ± 8.4	$34.0^{+6.3}_{-5.7}$
HanoHano	Hawaii	$3.3^{+0.6}_{-1.4}$	3.2 ± 0.6	$2.6^{+0.5}_{-0.5}$

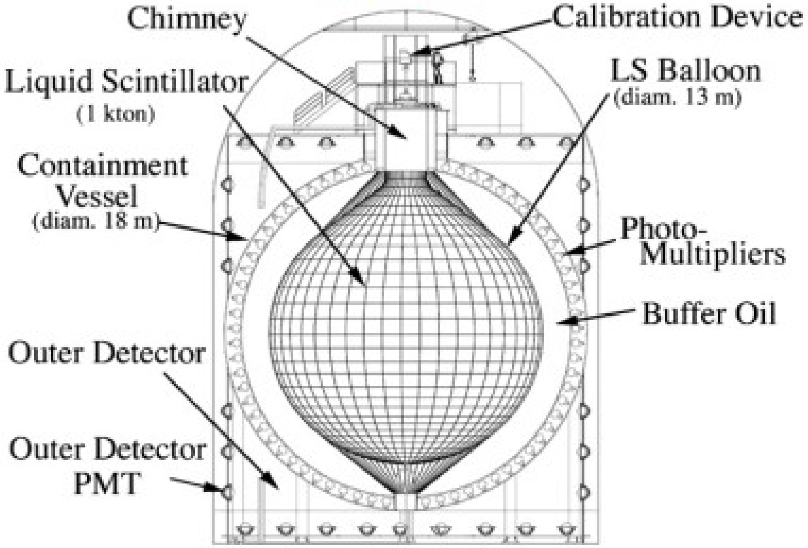
[TNU]

1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% detection efficiency

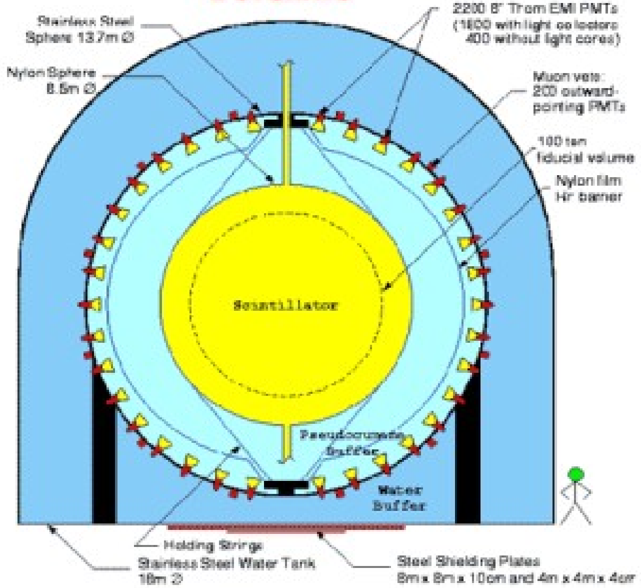


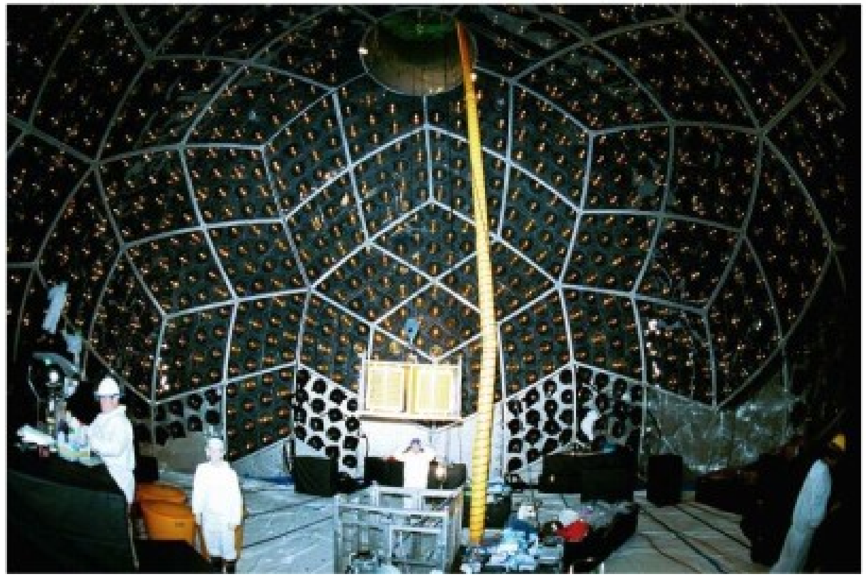
Experiments

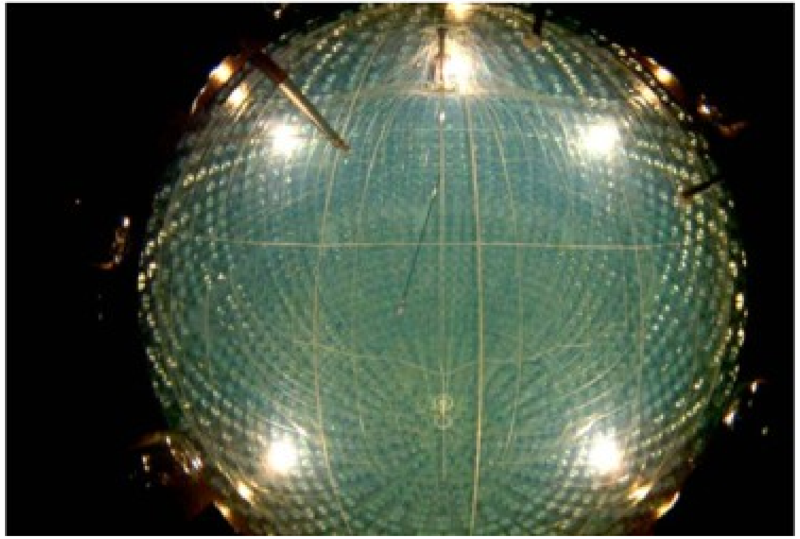
KamLand



Borexino

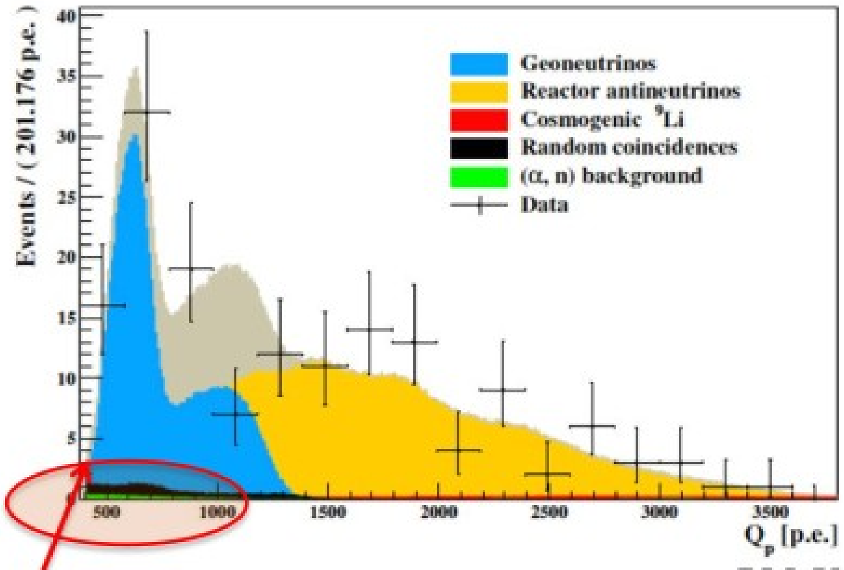






Results

Borexino 2019: **52.6 $^{+9.8}_{-8.9}$** geonu's

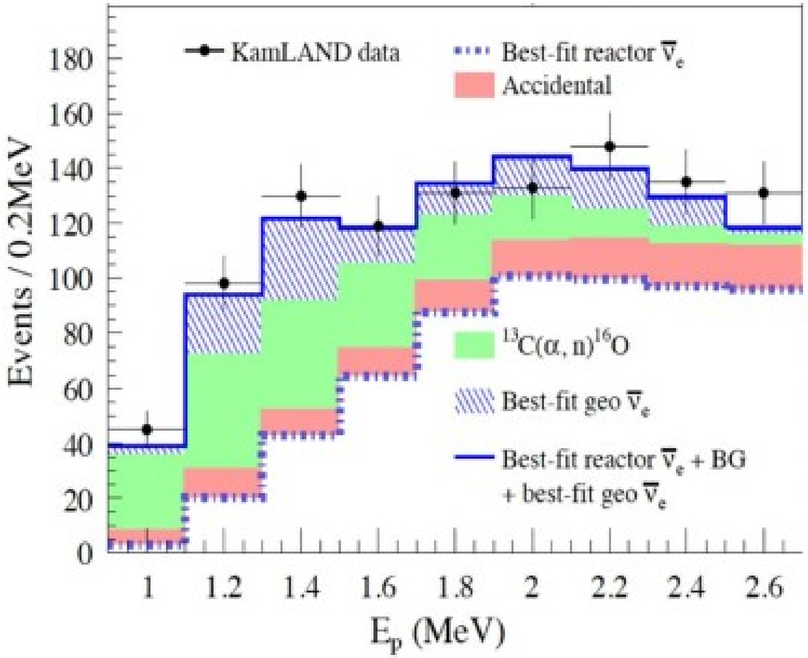


~1 MeV

~7 MeV

PRD 101 (2020) 012009

KamLAND 2013: **116 $^{+28}_{-27}$** geonu's



Phys. Rev. D 88 (2013) 033001

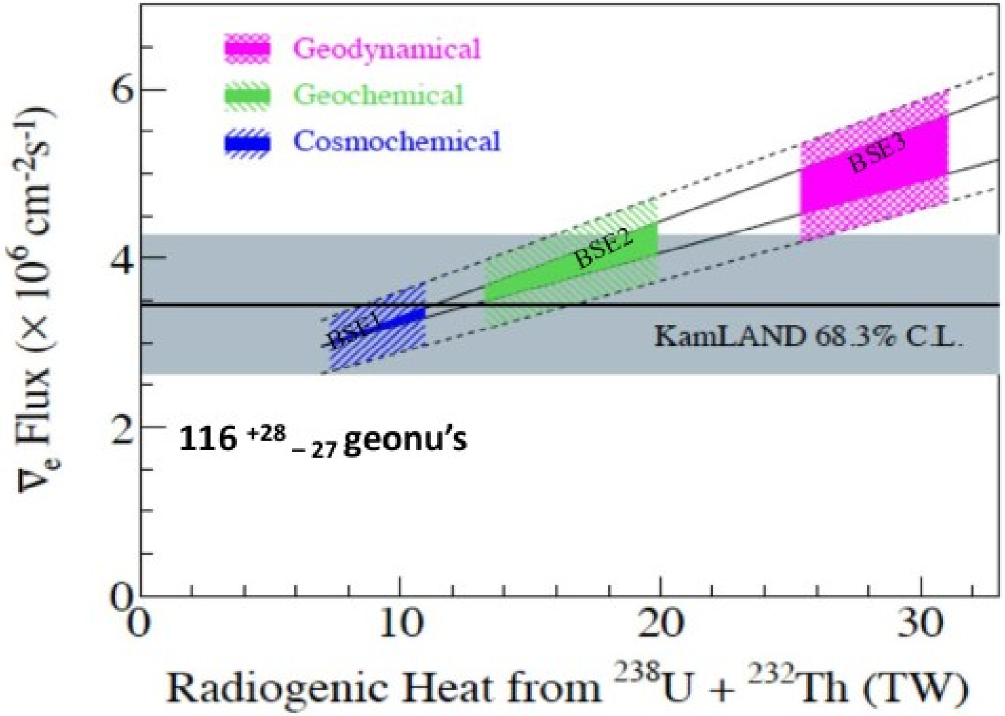
- ✓ Non antineutrino background almost invisible!
- ✓ 1.3 x 10^{32} target-proton year

- ✓ 4.9 x 10^{32} target-proton year

Results

PRD 88 (2013) 033001

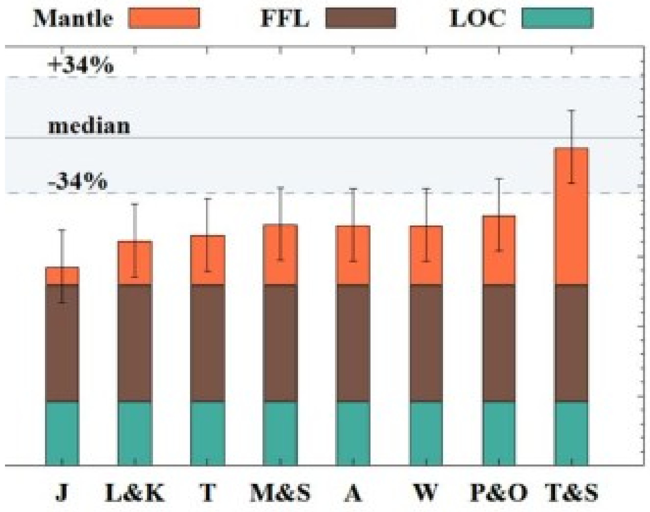
KamLAND geoneutrino results



PHYSICAL REVIEW D 101, 012009 (2020)

GEONEUTRINO SIGNAL AT LNGS

$$47.0^{+8.4}_{-7.7}(stat)^{+2.4}_{-1.9}(sys)TNU$$

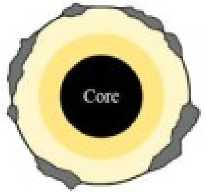


In agreement with expectations

LOC = local crust = (9.2 ± 1.2) TNU

FFL = far-field lithosphere = $(4.0^{+1.4}_{-1.0})$ TNU

MANTLE (U + Th abundances) = BSE model – LITHOSPHERE

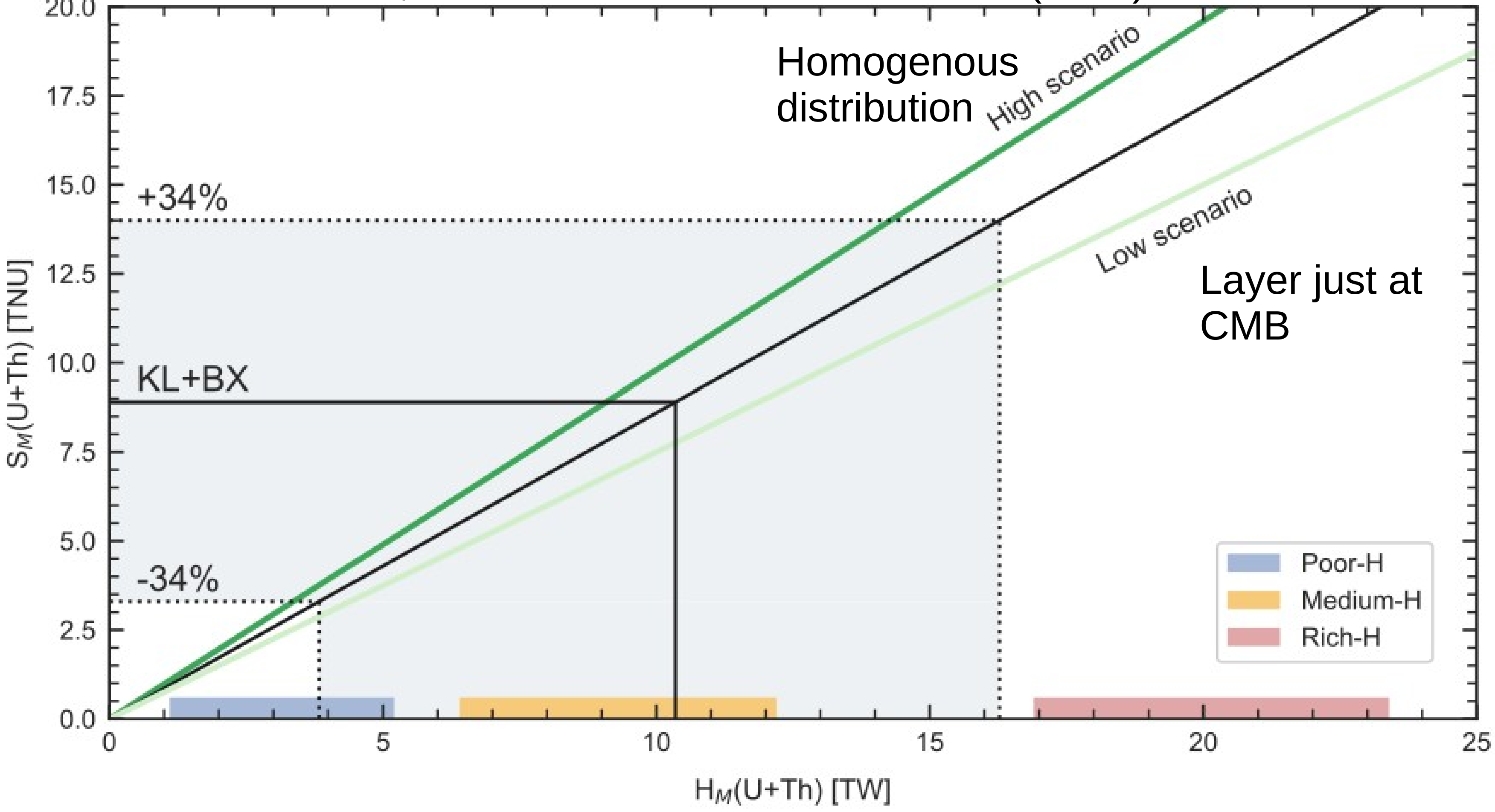


Intermediate scenario
2 layer distribution
of U and Th in the mantle

J: Javoy at al., 2010
L&K: Lyubetskaya and Korenaga, 2007
T: Taylor, 1980
M&S: Mc Donough and Sun, 1995
A: Anderson, 2007
W: Wang, 2018
P&O: Palme and O'Neil, 2003
T&S: Turcotte and Schubert, 2002

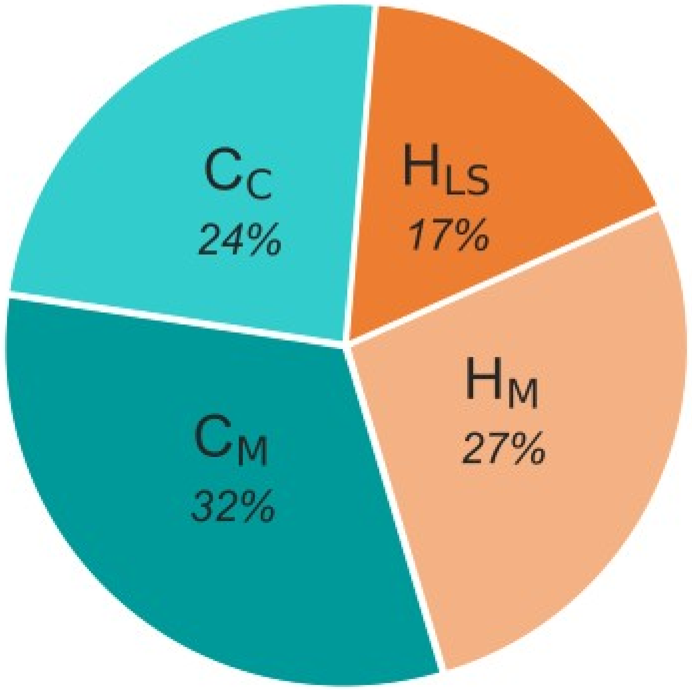
KamLAND + Borexino

G. Bellini et al., La Rivista del Nuovo Cimento 45 (2022) 1–105



Homogenous distribution

Layer just at CMB

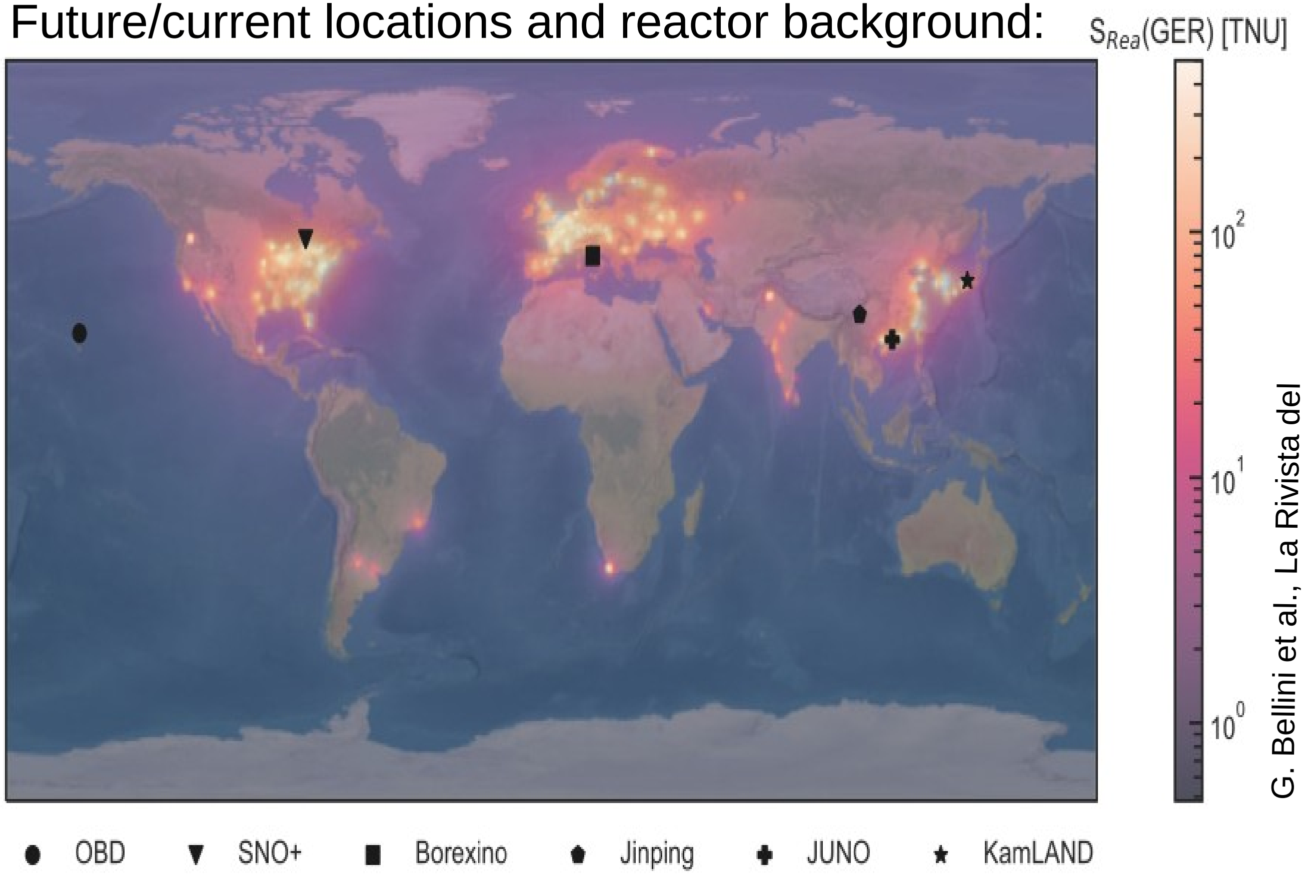


$\text{Cooling}_{\text{Core/Mantle}}$ / $\text{Heat}_{\text{Lithosphere/Mantle}}$

Future Experiments

- **SNO+** (Canada): 780 ton & 30-40 geonus/year; Low cosmogenics;
- **JUNO** (China): 20 kton & 400 geonus/year Should be able to reach the precisions of 17% in the 1st year! *(J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401)*
- **JINPING** (China): 5 kton; deepest lab, far away from reactors, very thick continental crust at Himalayan region; *(PRD 95 (2017) 053001)*
- **HanoHano** (Hawaii): 10 kton underwater detector with ~80% mantle contribution

Future/current locations and reactor background:



G. Bellini et al., La Rivista del Nuovo Cimento 45 (2022) 1–105

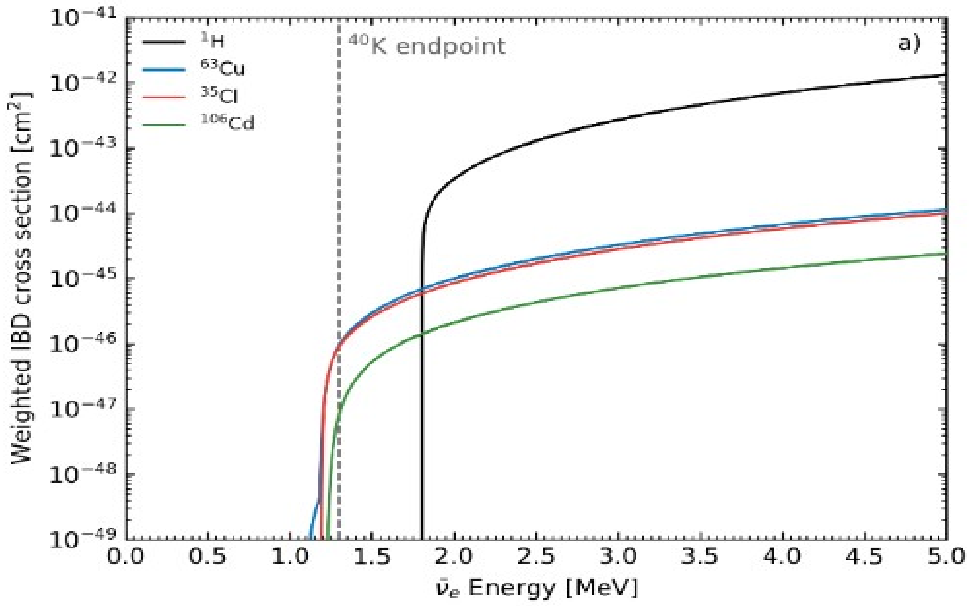
Detecting Geoneutrinos from Potassium

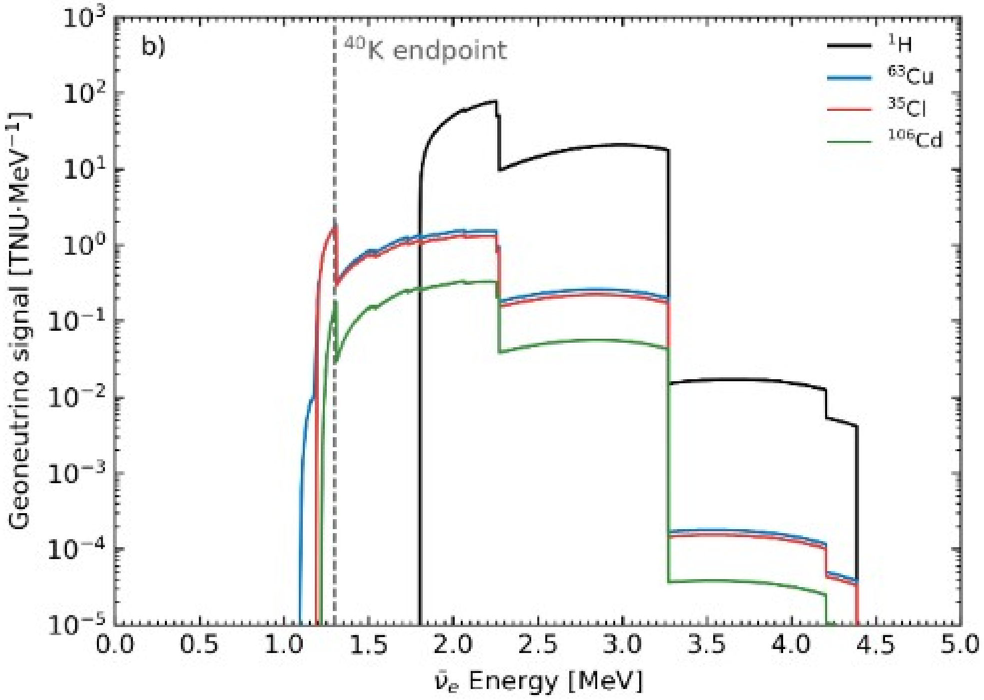
→ detect geoneutrions via inverse beta decay (IBD)

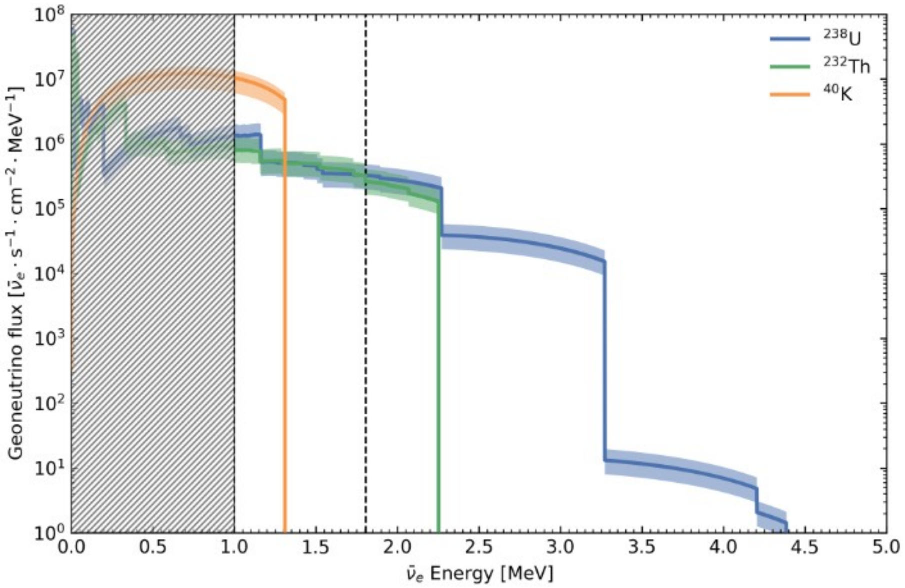
→ load scintillator with isotope to lower energy threshold for IBD, e.g. copper/cadmium

→ large amounts of metal-loading possible in opaque medium due to relaxed requirement on transparency

→ LiquidO: arXiv:2308.04154







Summary

Anti-neutrinos:

→ effective detection through inverse beta decay with high cross-section

Reactors:

→ strong source of anti-neutrinos

→ layered / segmented detectors allow near surface detection

→ new ideas for background discrimination (opaque / hybrid) might allow to go on surface/give directional resolution

Geoneutrinos:

→ unique probe that allows to determine sources of radiogenic heat from mantle

→ testing bulk silicate earth models

→ first experimental results in agreement with most models

→ upcoming experiments allow to probe Earth at different locations