Short-baseline reactor neutrino experiments

outline

1. **Short-baseline reactor neutrino experiments**
2. **Inverse beta decay (IBD) measurements**
3. **Electron recoil measurements**
4. **Coherent elastic neutrino-nucleus scattering (CEVNS) measurements**
5. **R&D of near field reactor monitoring neutrino monitor**
6. **Conclusions**

Teppei Katori (香取哲平)
King’s College London
Fundamental Physics Using Reactor (FPUR2022), May 30, 2022

1. Short-baseline reactor neutrino experiments

2. Inverse beta decay (IBD) measurements

3. Electron recoil measurements

4. Coherent elastic neutrino-nucleus scattering

5. R&D reactor monitoring neutrino monitor

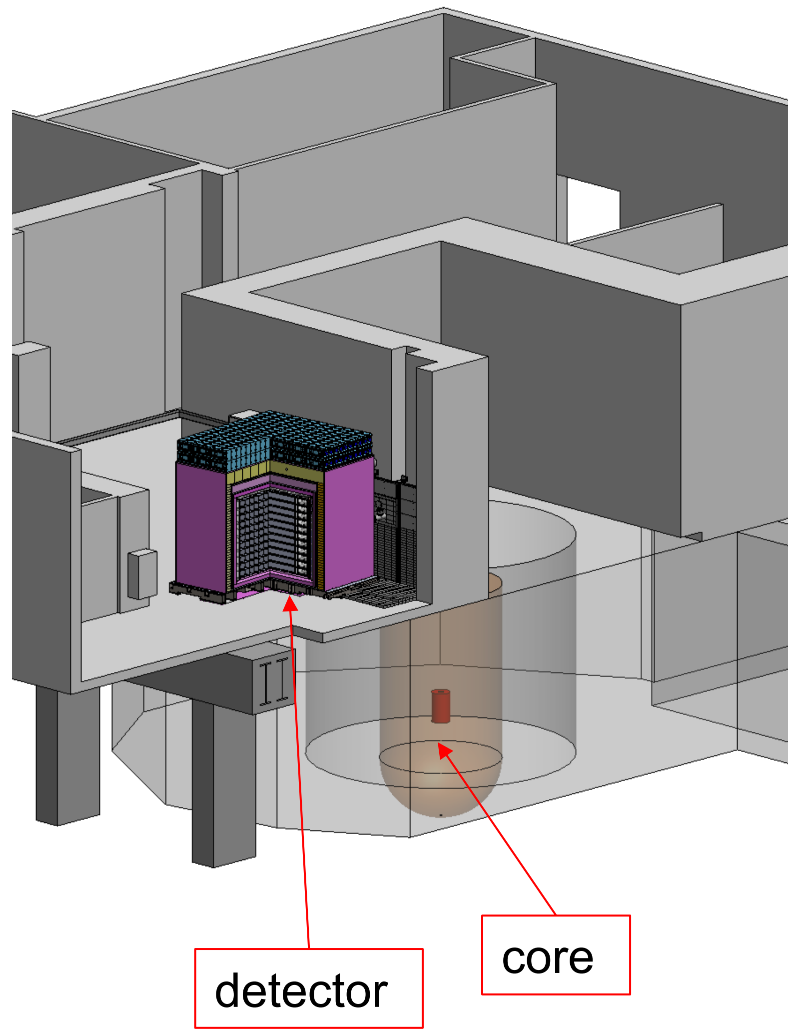
6. Conclusions

1. Short-baseline reactor neutrino experiments

e.g.) PROSPECT

Reactor
- research reactor
- compact core
- highly enriched uranium

Detector
- sensitive to low energy (=liquid scintillator)
- close distance (~8m)



1. Detector design

Detector location

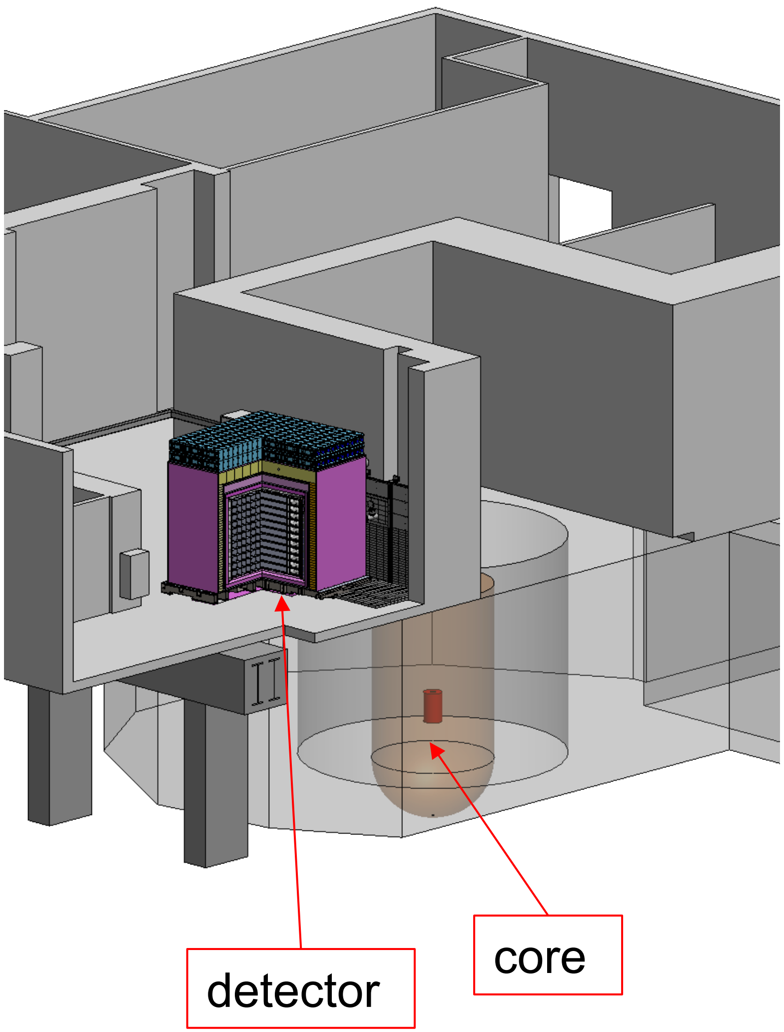
- In general, closer is better
- Nice to have dedicated lab space

Detector material

- Liquid scintillator is popular, but flammable
- Solid scintillator, Gd-loaded water, water-based scintillator, HPGe, etc

Background rejection

- Cosmic rays, neutrons, gamma rays
- Passive shielding
- Active veto (segmentation)
- Pulse shape discrimination



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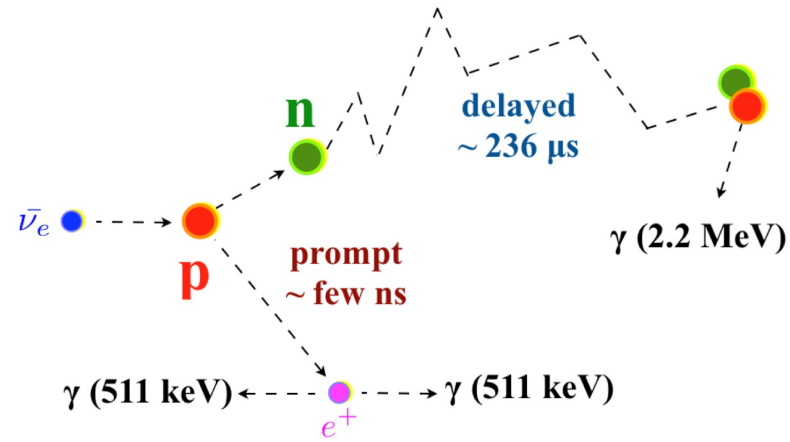
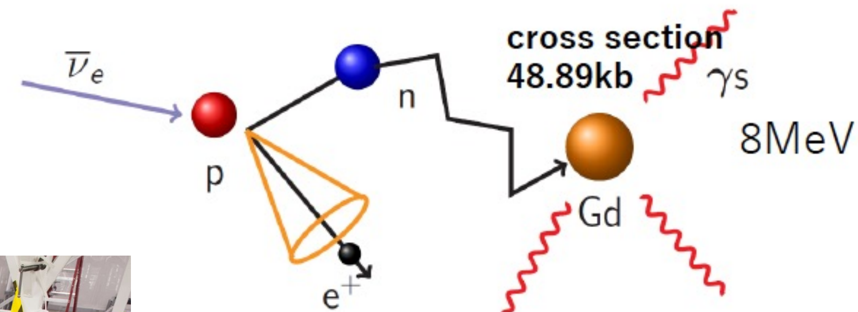
2. IBD measurements



Coincidence measurement

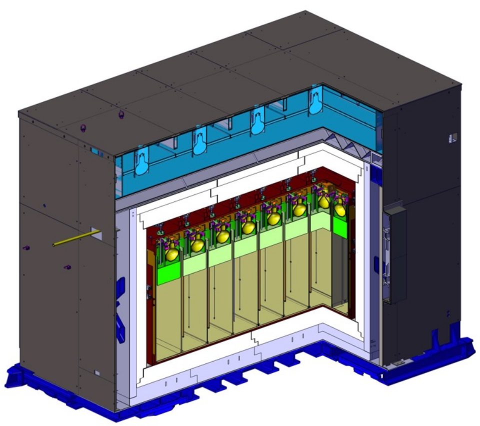
IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$

Neutron capture: $n + p \rightarrow d + \gamma$



High-neutron capture cross-section

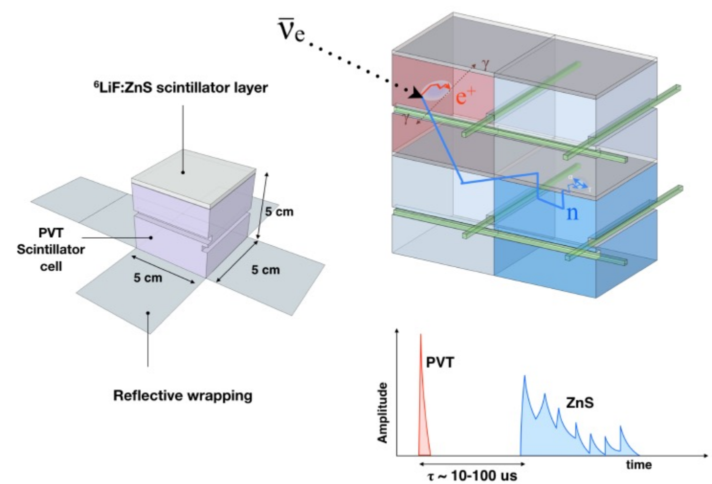
- Gd-doped or ^{6}Li-doped
- water, liquid scintillator, plastic scintillator



STEREO

PROSPECT

SoLid

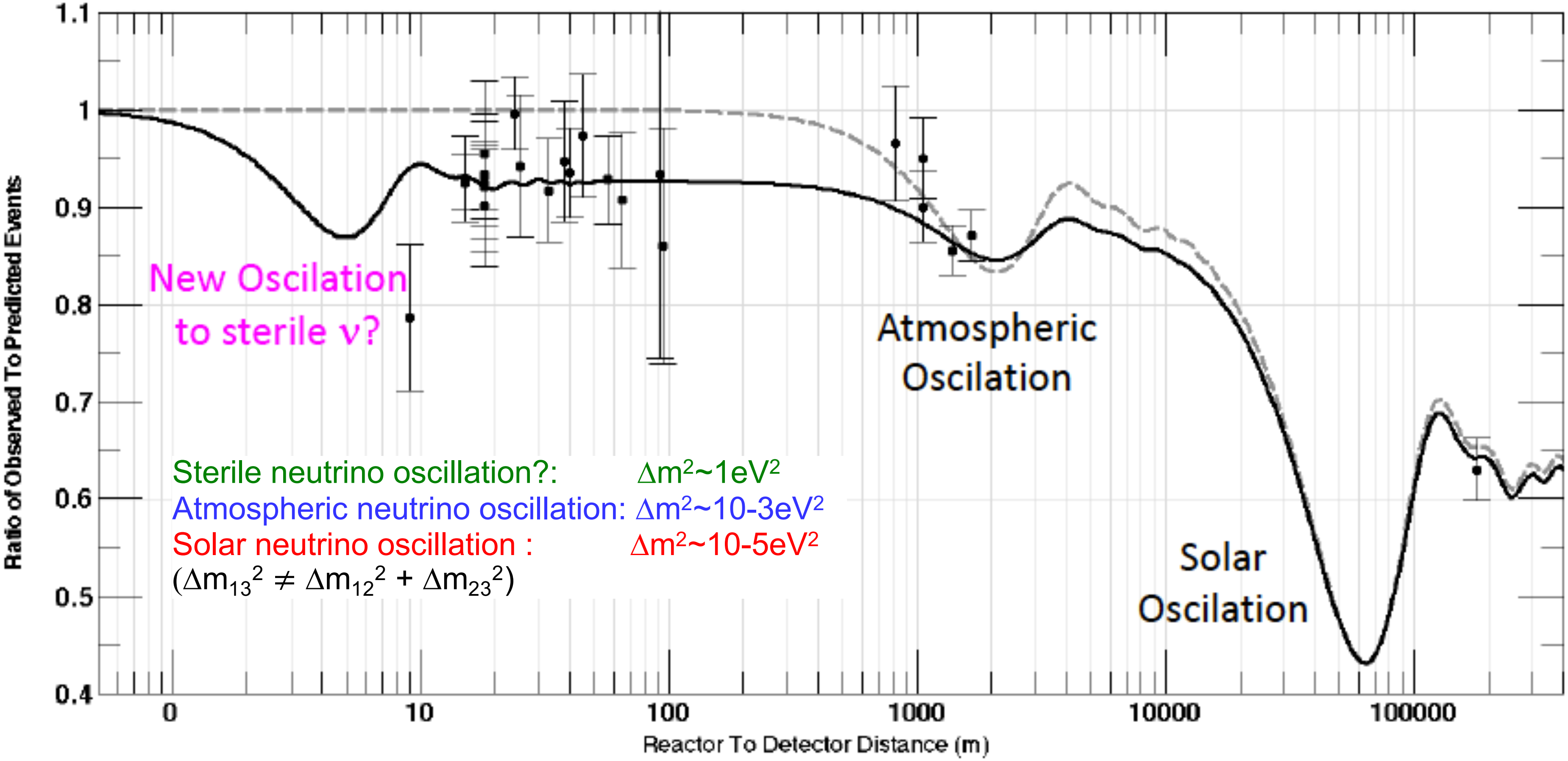


2. Reactor neutrino anomaly

$$P(\nu_e \longrightarrow \nu_s) = sin^2 2\theta sin^2\left(1.27\Delta m^2(eV^2)\frac{L(m)}{E(MeV)}\right)$$

Reactor neutrino anomaly

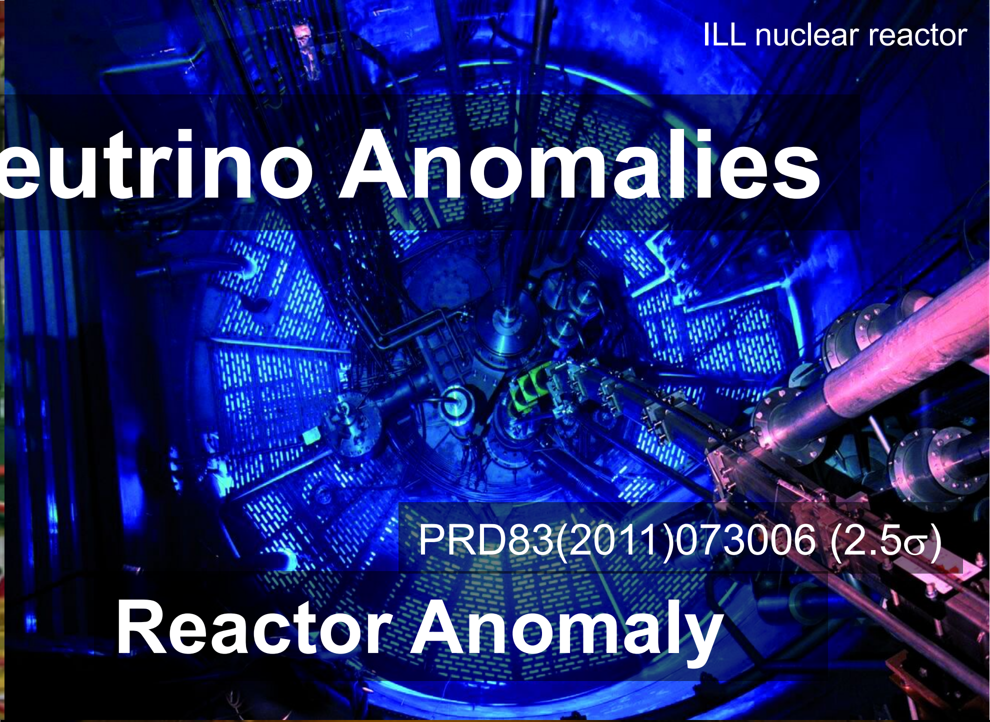
- 3% reduction of flux? (sterile neutrino oscillation?)



Short-Baseline Neutrino Anomalies

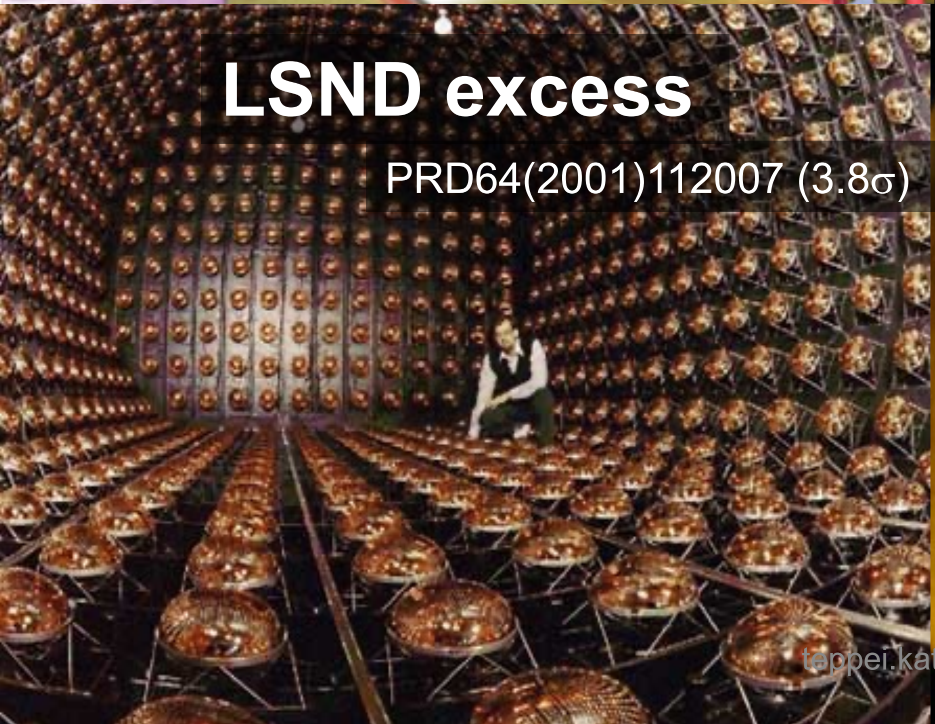
Gallium Anomaly

PRC83(2011)065504 (3.0σ)



Reactor Anomaly

PRD83(2011)073006 (2.5σ)



LSND excess

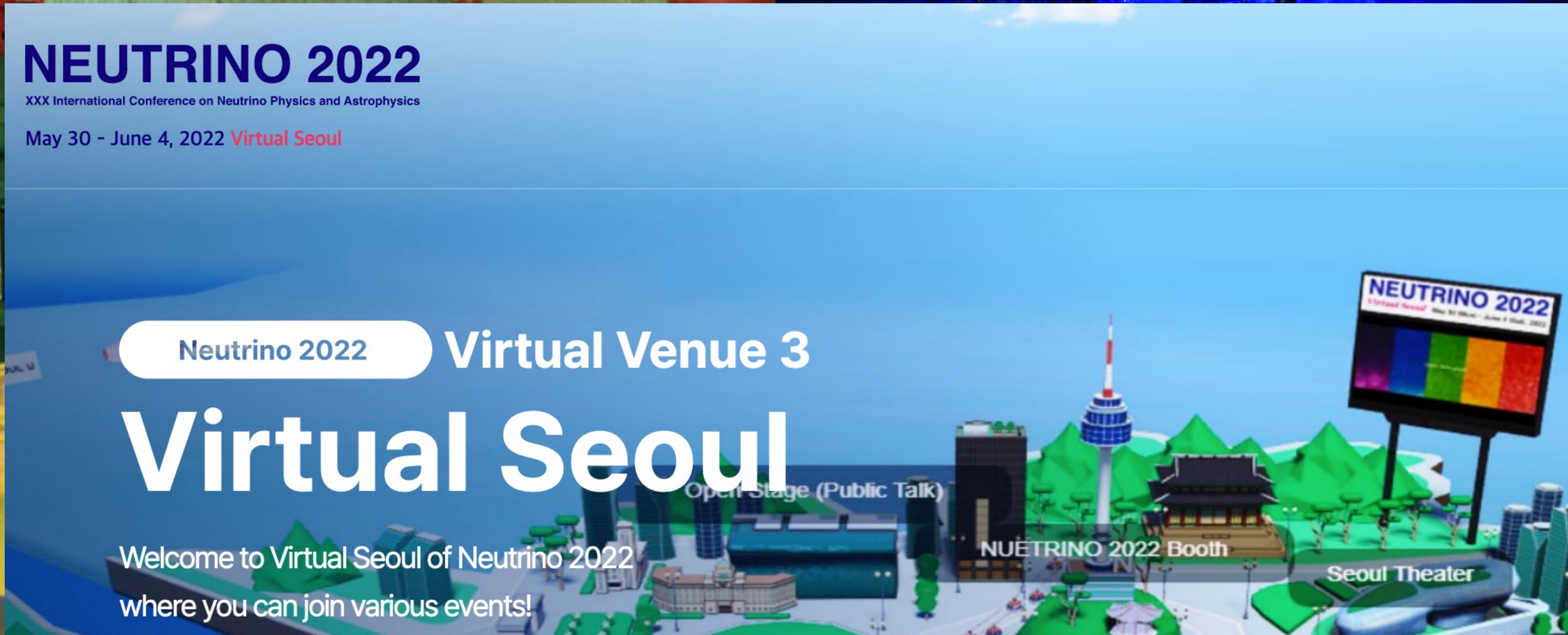
PRD64(2001)112007 (3.8σ)

MiniBooNE excess

PRL121(2018)221801 (4.7σ)

SAGE

reactor



.5σ)

LS

cess

221801 (4.7σ)

S1: Sterile Neutrino I

Date/Time: May 30, 22:15-23:45 [KST], May 30, 15:15-16:45 [CEST], May 30, 08:15-09:45 [CDT, US]

Session Chair: Eligio Lisi (INFN)

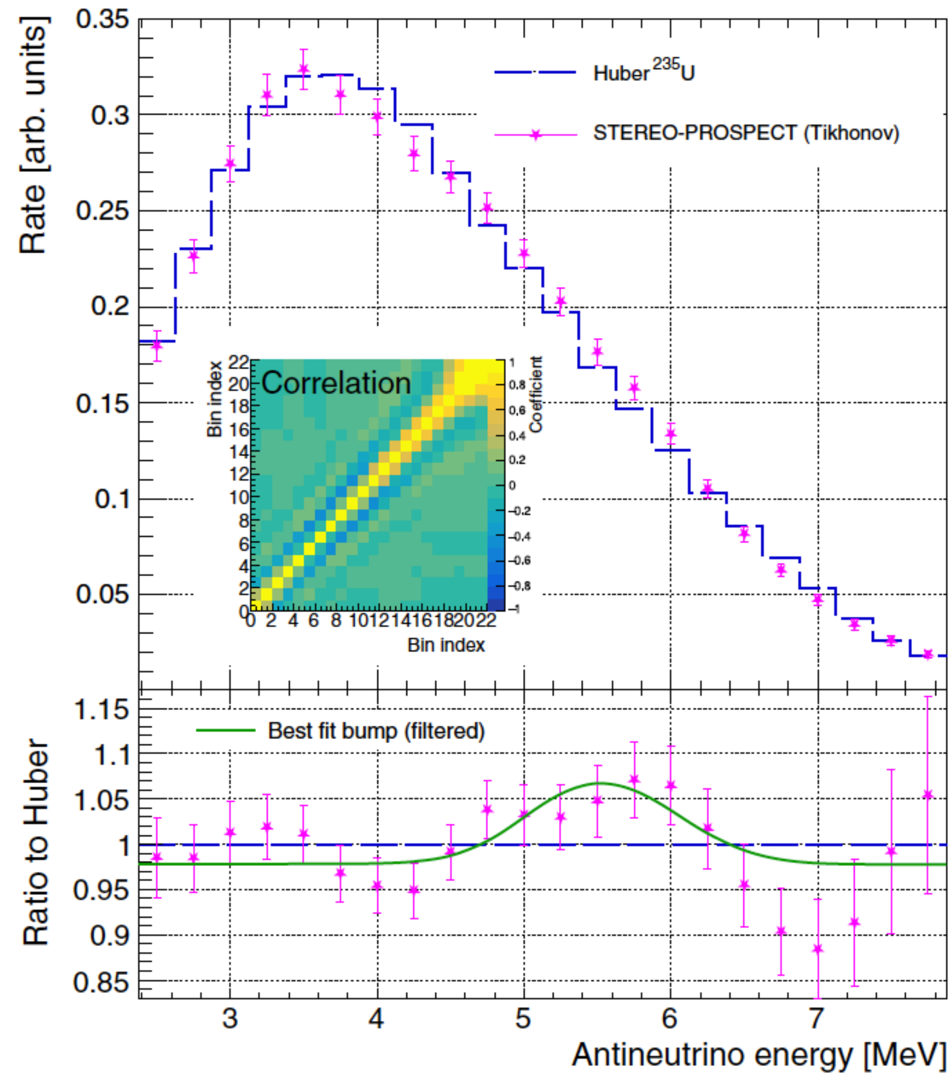
Time [KST]	Talk Title	Speaker
22:15	Quo Vadis, Sterile Neutrino? - The Current Status of Searches for a 4th Neutrino	Joachim Kopp *(CERN & JGU Mainz)*
22:55	Experimental results with reactors	Matthieu Licciardi *(CNRS - LPSC Grenoble)*
23:25	NEOS-II new results	Jinyu Kim *(IBS/CUP)*

2. Reactor neutrino anomaly 2

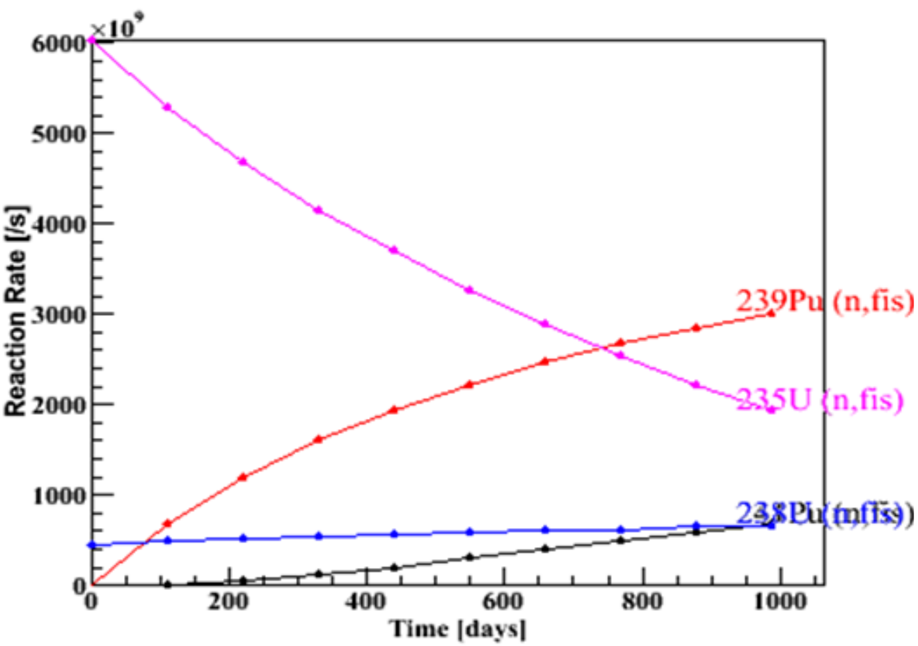
Reactor neutrino anomaly

- 3% reduction of flux? (sterile neutrino oscillation?)
- 5 MeV bump (2.4σ)

PROSPECT and STEREO joint analysis
(high-rich uranium research reactor)



Time evolution of neutrino source elements



1. Short-baseline reactor neutrino experiments

2. Inverse beta decay (IBD) measurements

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4. Coherent elastic neutrino-nucleus scattering

5. R&D reactor monitoring neutrino monitor

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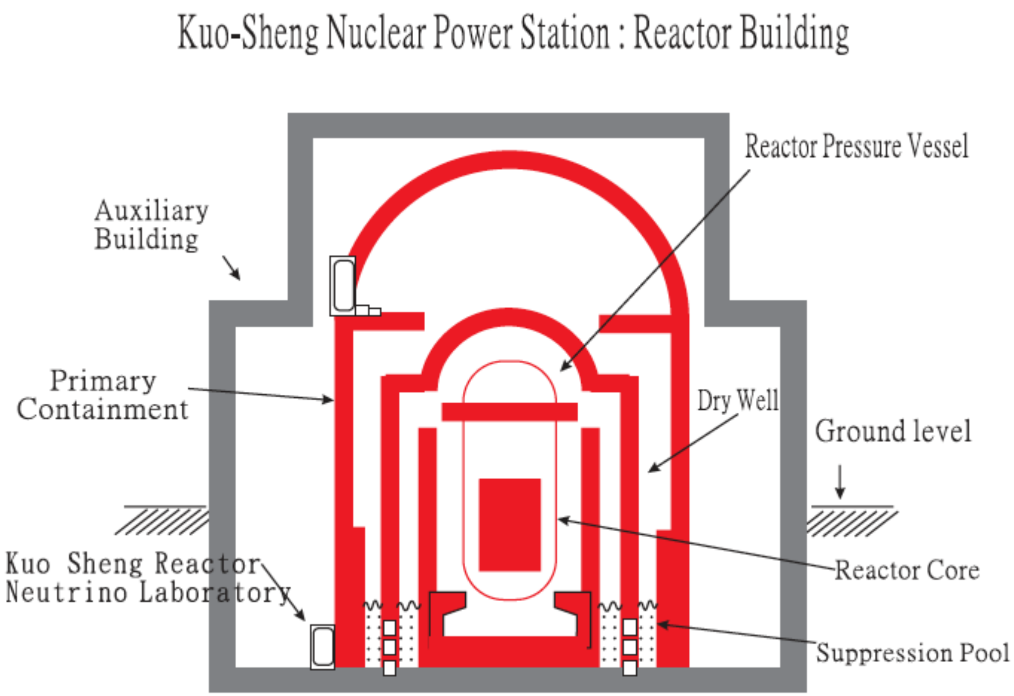
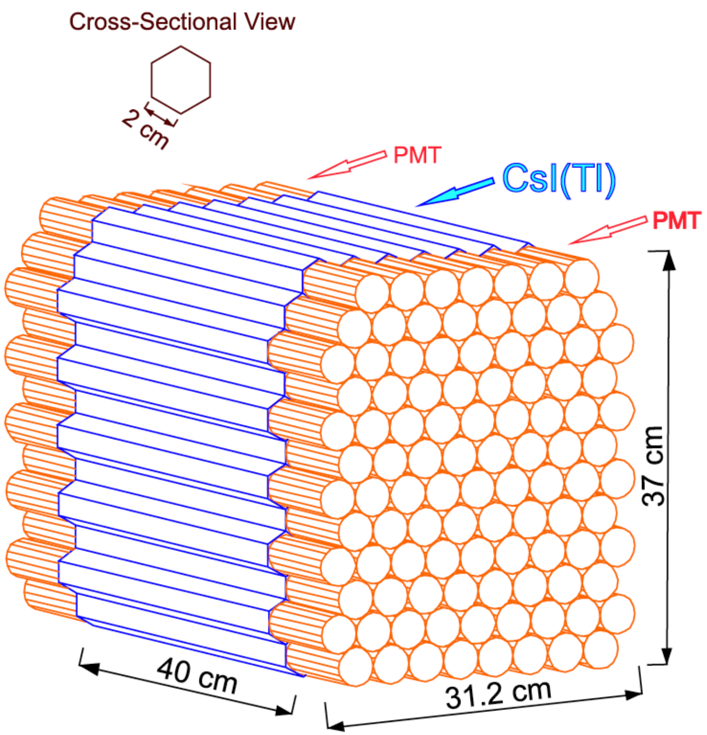
3. TEXONO (Taiwan)

Electron antineutrino - electron elastic scattering

- ES: $\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$
- CsI (Tl) crystal array (187kg)
- S/B ~1/30
- Test of SM





TEXONO, PRD81(2010)072001

3. TEXONO (Taiwan)

Electron antineutrino - electron elastic scattering

- ES: $\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$
- CsI (Tl) crystal array (187kg)
- S/B ~1/30
- Test of SM
- Best limit on neutrino magnetic moment

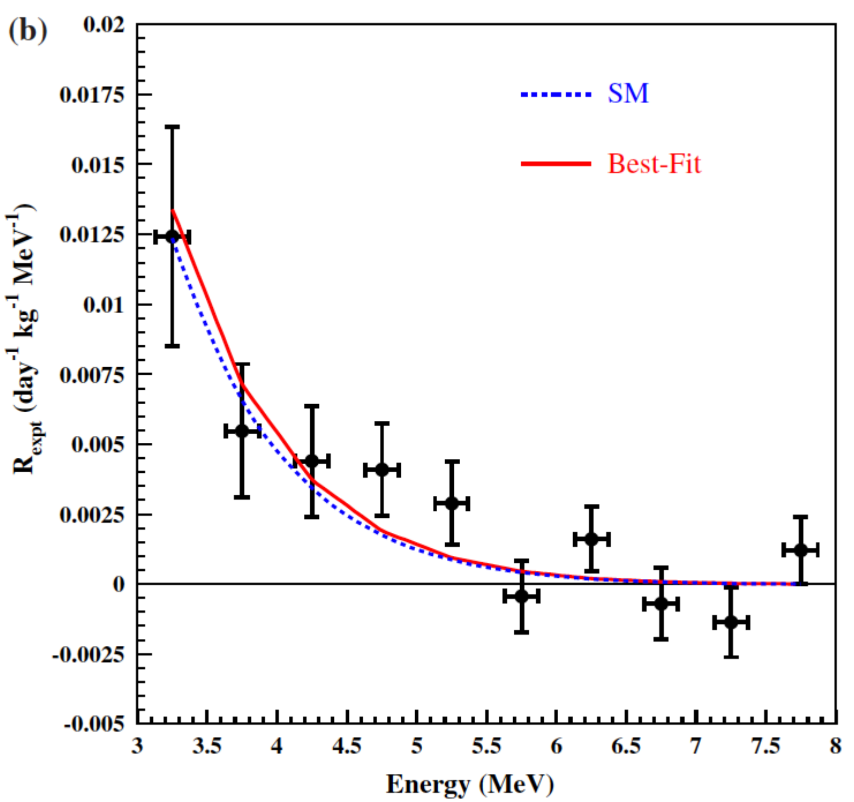
$$\sin^2\theta_W \longrightarrow \sin^2\theta_W + \left(\frac{\sqrt{2}\pi\alpha_{em}}{3G_F}\right)\langle r^2_{\bar{\nu}_e}\rangle,$$

neutrino charge radius

$$\left[\frac{d\sigma}{dT}(\bar{\nu}_e e)\right]_{SM} = \frac{G_F^2 m_e}{2\pi}\cdot\left\{4(\sin^2\theta_W)^2 \times\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_e T}{E_\nu^2}\right] + 4\sin^2\theta_W\left[\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_e T}{2E_\nu^2}\right] + \left(1-\frac{T}{E_\nu}\right)^2\right\}.$$

neutrino magnetic moment

$$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} = \frac{\pi\alpha_{em}^2\mu_\nu^2}{m_e^2}\left[\frac{1-T/E_\nu}{T}\right].$$



1. Short-baseline reactor neutrino experiments
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3. Electron recoil measurements
4. **Coherent elastic neutrino-nucleus scattering**
5. R&D reactor monitoring neutrino monitor
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COHERENT, Science10.1126/science.aao0990 (2017)
The COHERENT Experimental Program (Snowmass21 study), ArXiv:2204.04575

4. Coherent elastic neutrino-nucleus scattering (CEvNS)

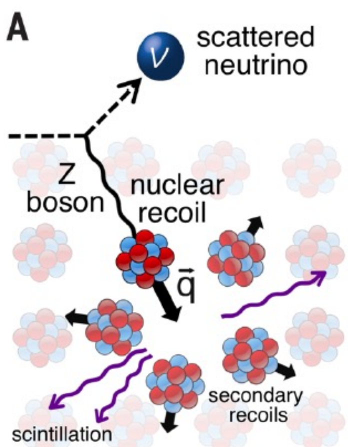
COHERENT (USA)

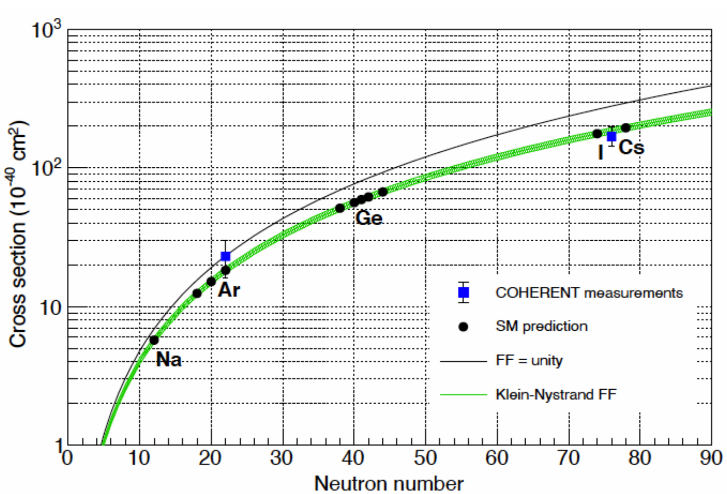
- CEvNS: $\nu + A \rightarrow \nu + A$
- SNS (spallation neutron source) at ORNL

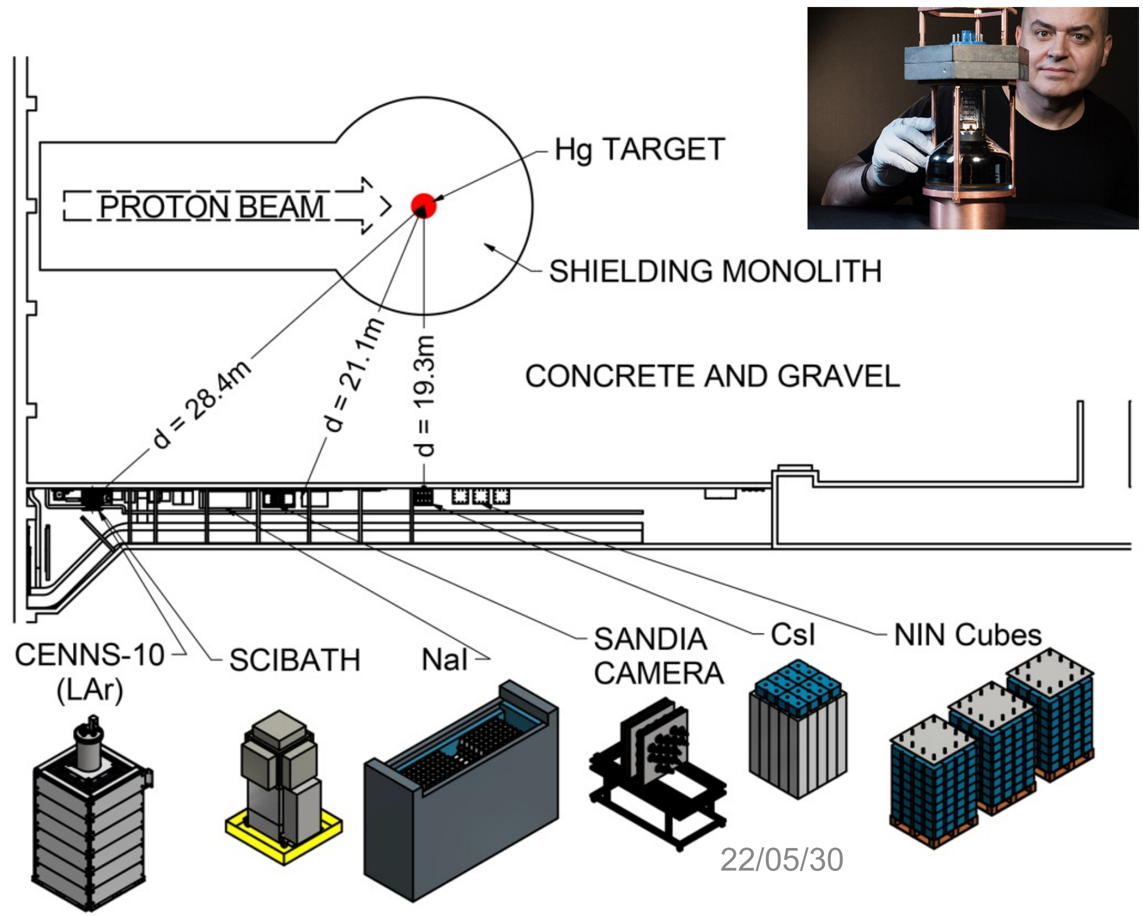
Science REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering







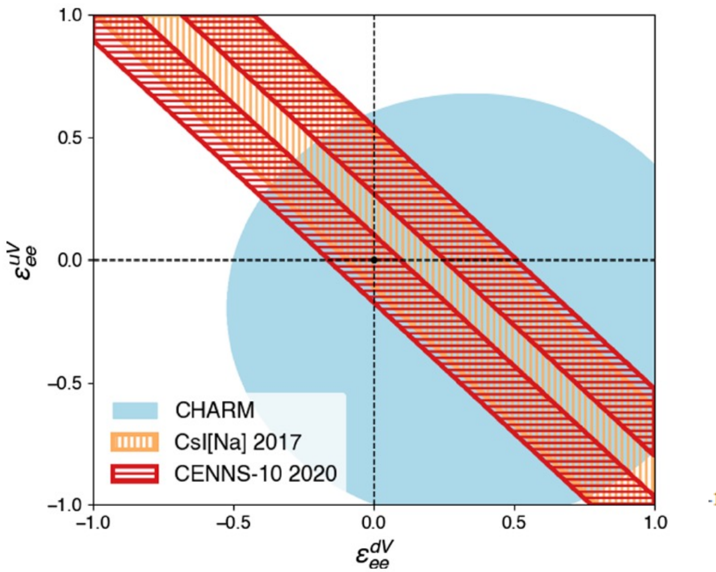
Beyond the Standard Model effects on Neutrino Flavor, (Snowmass21 study), ArXiv:2203.10811
The COHERENT Experimental Program (Snowmass21 study), ArXiv:2204.04575

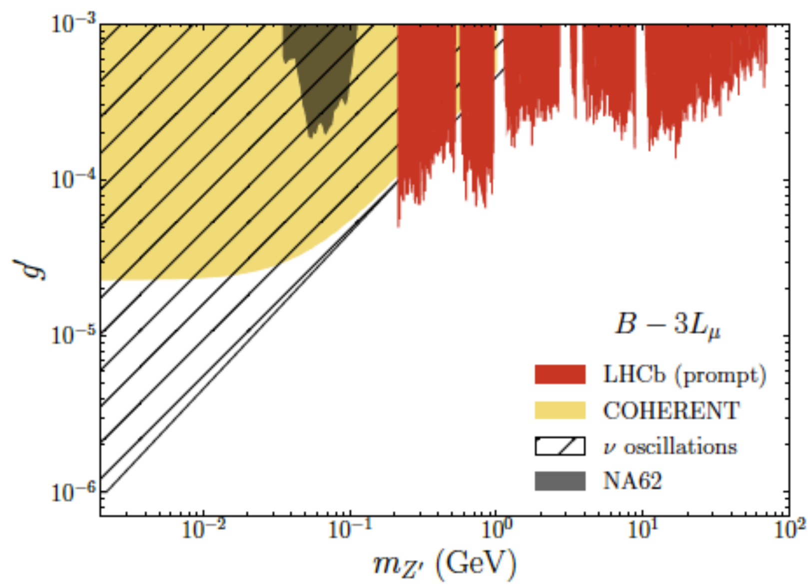
4. Coherent elastic neutrino-nucleus scattering (CEvNS)

COHERENT (USA)

- CEvNS: $\nu + A \rightarrow \nu + A$
- SNS (spallation neutron source) at ORNL
- Test of SM
- Best limit on some non-standard interaction (NSI) models

$$\mathcal{L} = \sum_{q,\alpha,\beta} 2\sqrt{2} G_F \varepsilon^q_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta\right)\left(\bar{q}\gamma_\mu(1-\gamma^5)q\right)$$





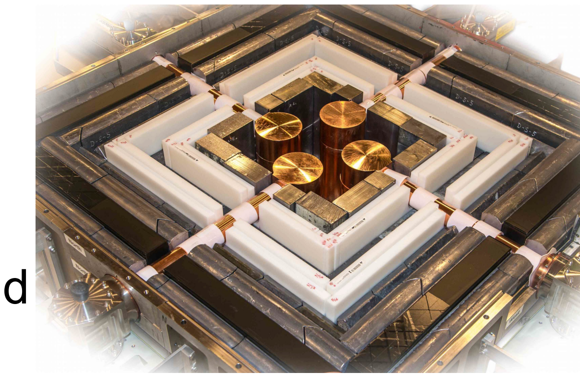
CONNIE, JHEP05(2022)017
CONUS, PRL126(2021)041804

4. CEvNS at nuclear reactor

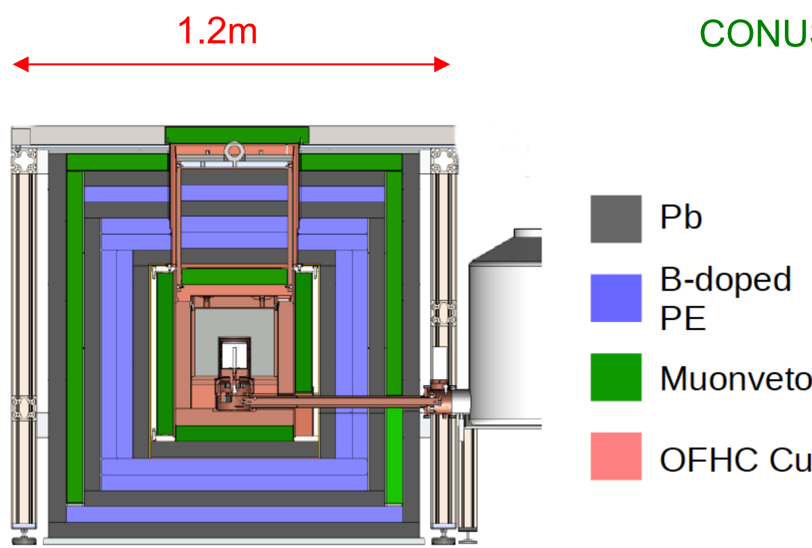
CONNIE (Brazil)
- CCD camera (36.2g of silicon)

CONUS (Germany)
- 3.7kg HPGe detector

Difficulties
- No beam time information to suppress background
- BeamON vs beamOFF to subtract beam-unrelated bkgd
- How to suppress beam-related background?
  - different operation condition?
  - different core?



CONUS



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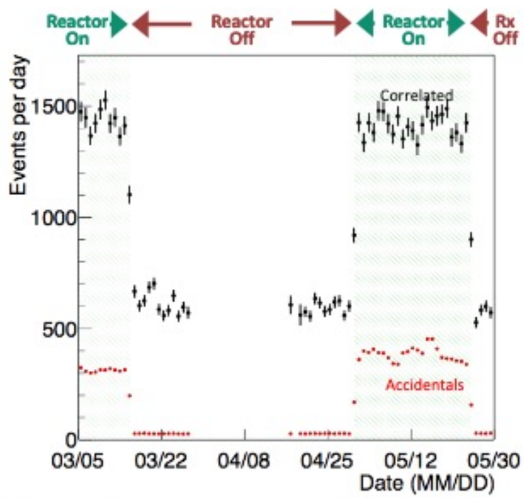
5. Near-field fission reactor monitoring neutrino detector

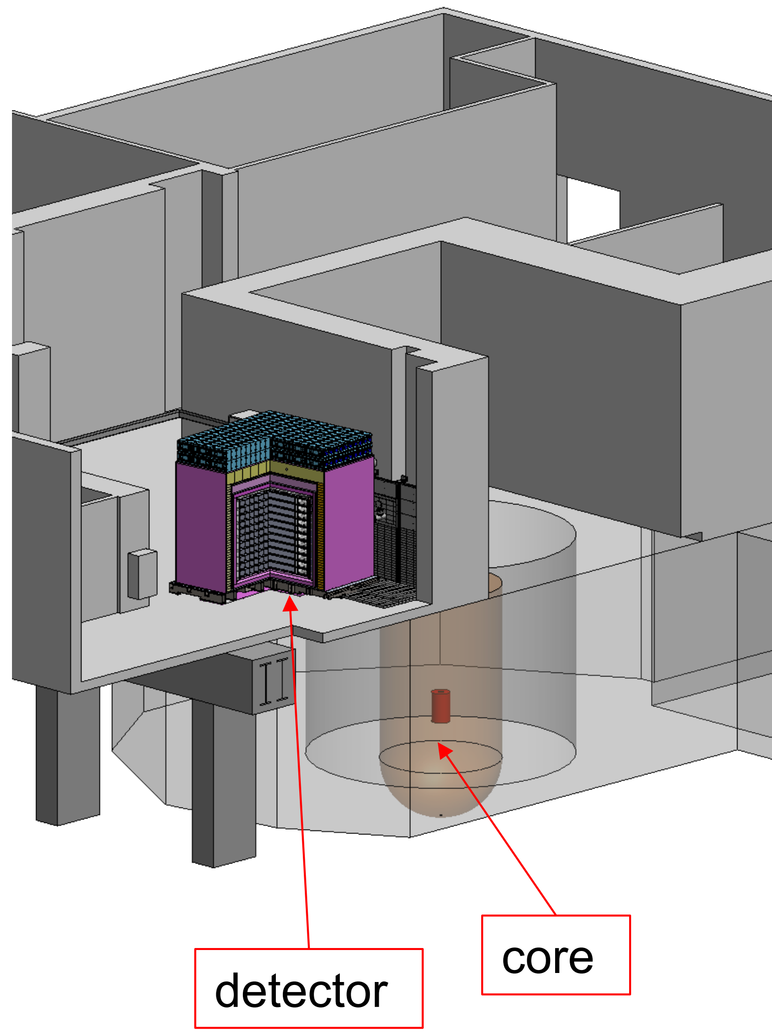
Requirements from IAEA

- Aboveground operation
- Packaging/mobility, easy to install
- Safe material to use at reactor sites



***PROSPECT** measurement of the HFIR antineutrino flux with >1:1 S:B on the earth's surface*

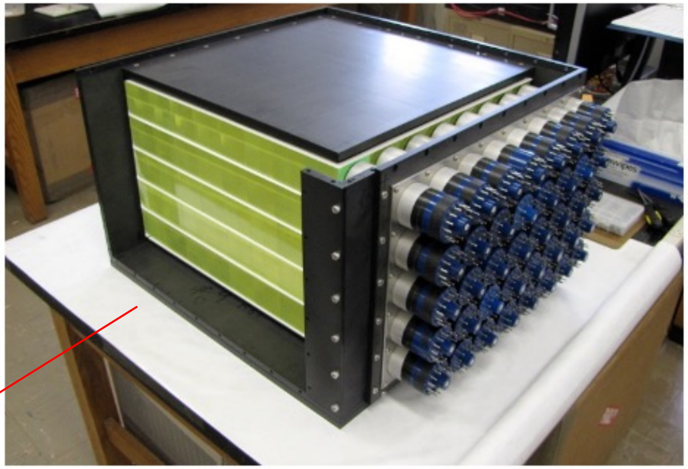
IAEA
International Atomic Energy Agency
Atoms for Peace

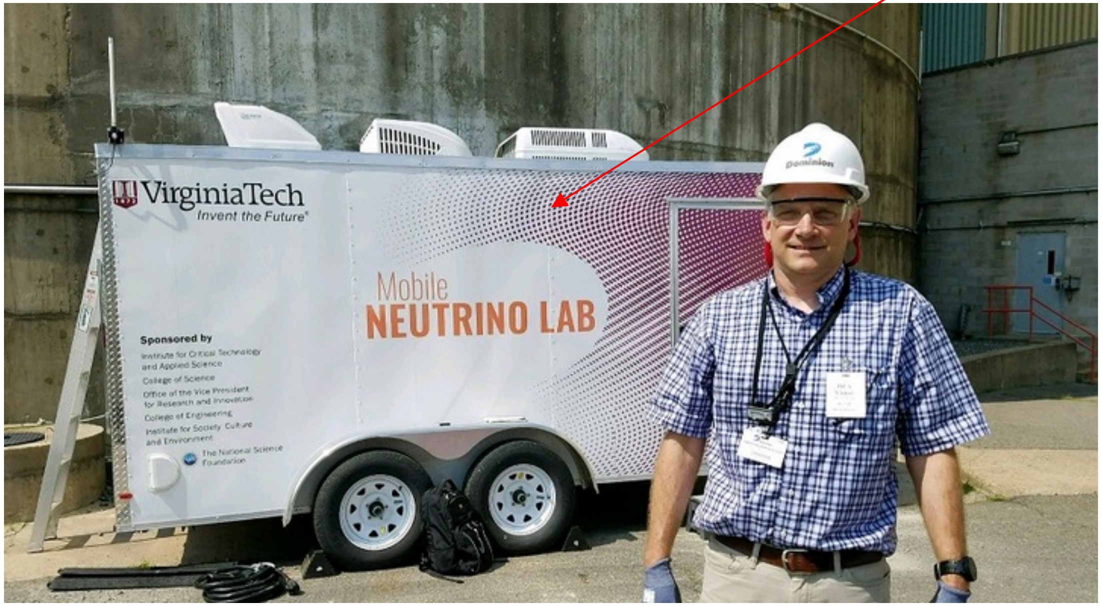


5. Near-field fission reactor monitoring neutrino detector

Requirements from IAEA
- Aboveground operation
- Packaging/mobility, easy to install
- Safe material to use at reactor sites

Mini-CHANDLER
- 6Li-loaded ZnS scintillator
- Movable





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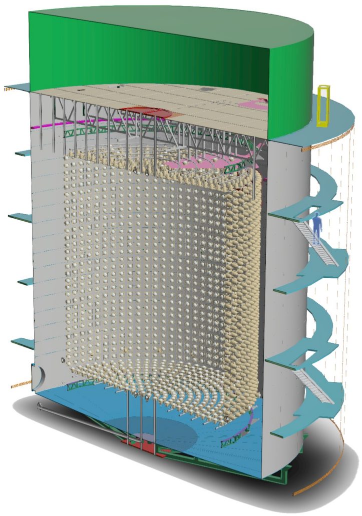
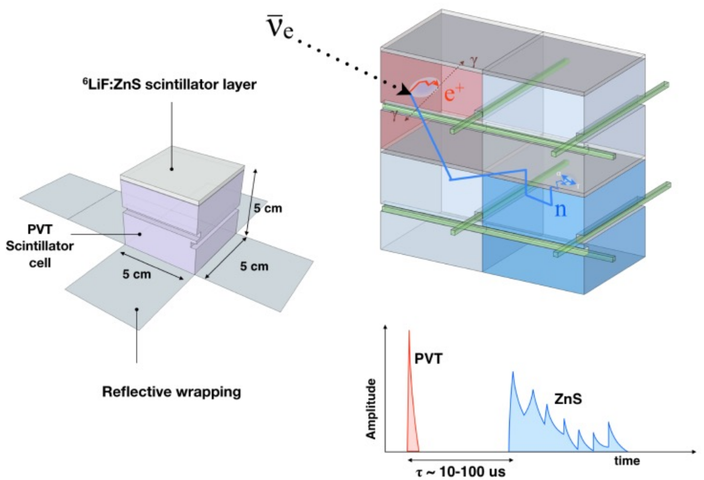


SoLid

- 3-d scintillator + WLS fiber
- ^{6}Li-loaded layer



WATCHMAN

- Gd-loaded water Cherenkov detector

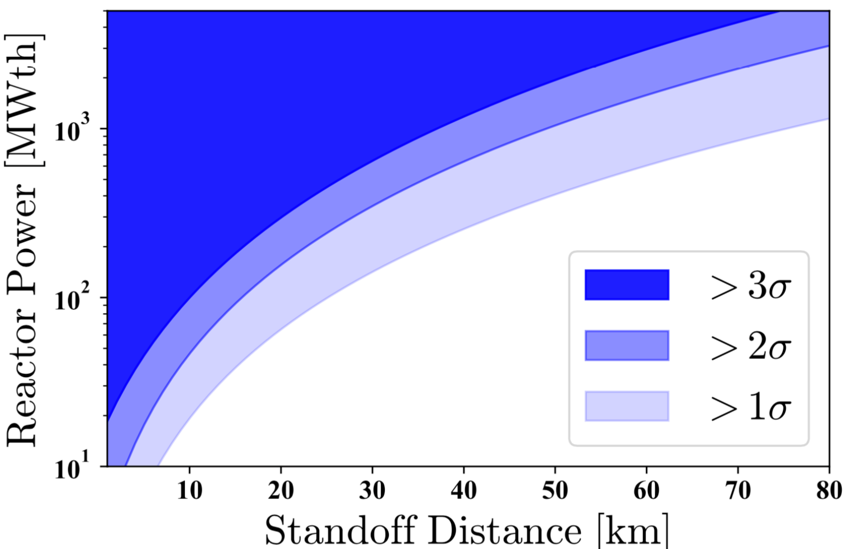
Water-based quantum dot

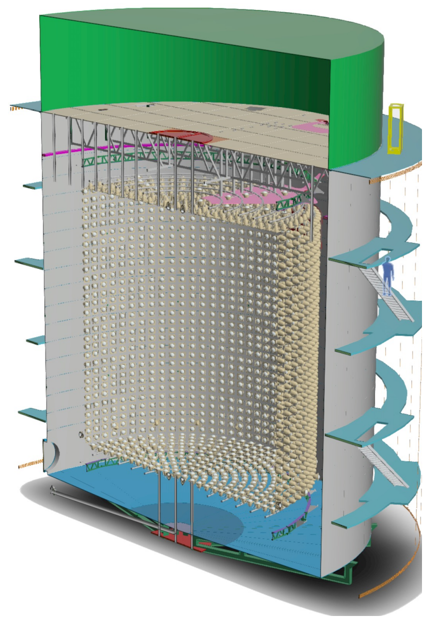
- CdS nanocrystal
- hydrophilic oleic layer
- neutron capture

5. Far-field fission reactor monitoring neutrino detector

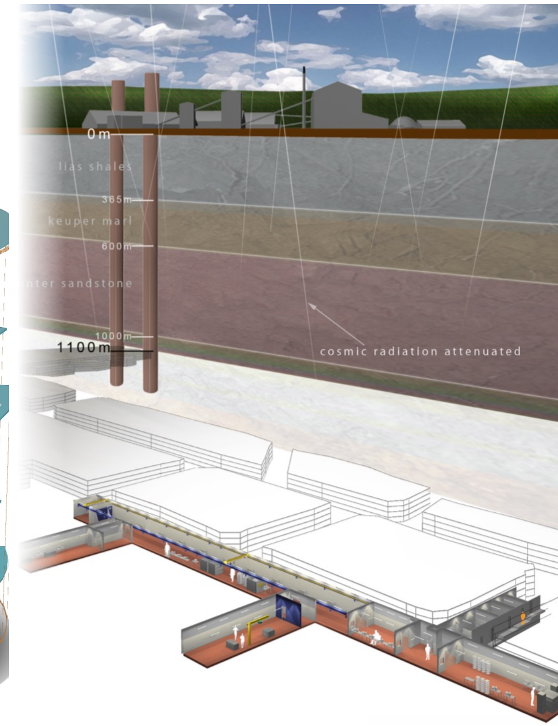
WATCHMAN

- Gd-loaded water Cherenkov detector
- 20m height 20m diameter tank
- Detect GWth reactor within ~50km.





Boulby Underground Laboratory



NEUTRINO 2022

XXX International Conference on Neutrino Physics and Astrophysics

May 30 - June 4, 2022 Virtual Seoul

12:00 ⏱ 27+3m

Neutrino science and nuclear security

Speaker Patrick Huber (Virginia Tech)

KING'S College LONDON

Conclusion

Fission reactor neutrinos can be detected by
- IBD → reactor anomaly 1, reactor anomaly 2, sterile neutrino searches
- Electron elastic scattering → measurements of neutrino electromagnetic properties
- CEvNS → test of the Standard Model

Detectors can be
- near the core
- sensitive to low energy
- good background rejection

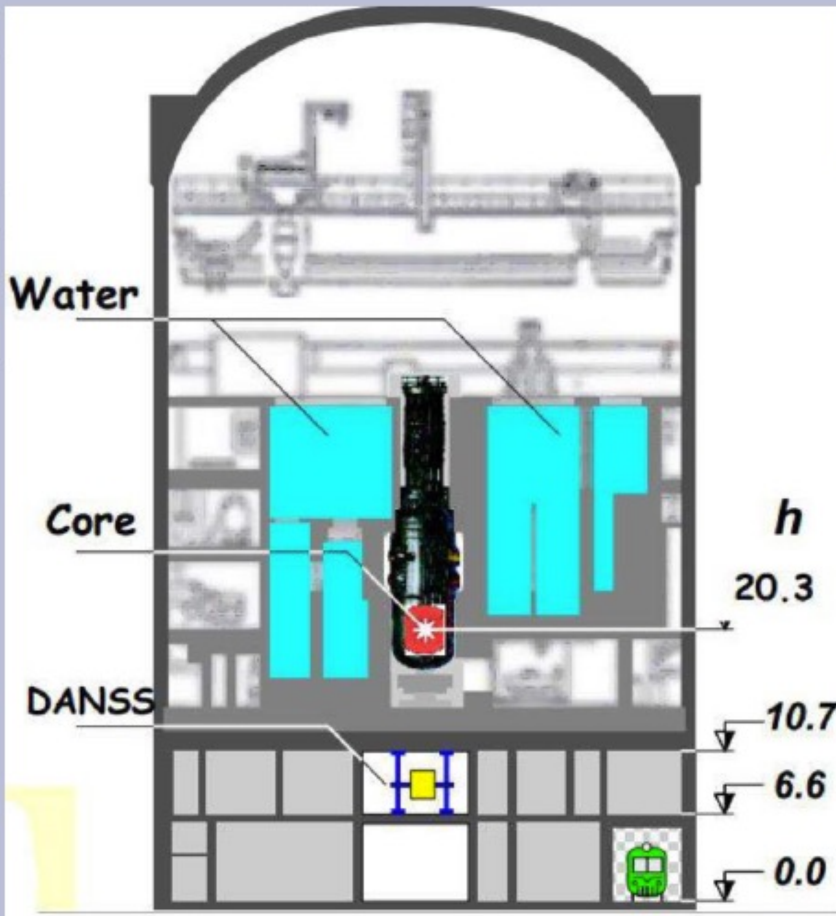
Development of fission reactor monitoring neutrino detector is an active field

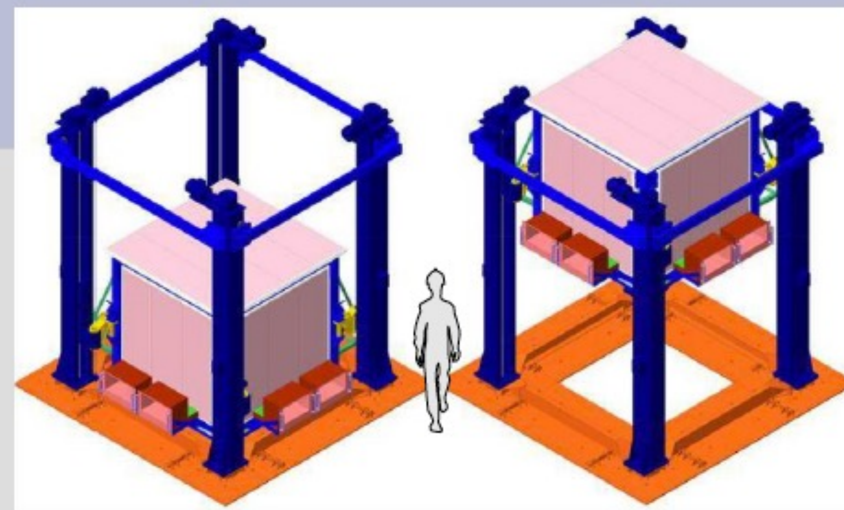
Thank you for your attention!

Backup

DANSS (Russia)

The location and movable platform





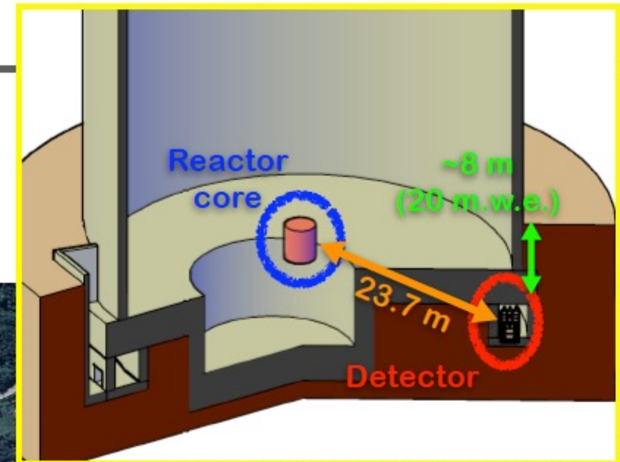
- The DANSS is located at Kalininskaya NPP (KNPP) under 3 GW WWER-1000 reactor (H=3.6 m, ∅ =3.1 m), which provides ~ 50 m.w.e. (6-fold μ reduction and no cosmic n).
- The detector is built on a movable platform. Data are taken at 3 distances 10.9 m (Up), 11.9 m (Middle), and 12.9 m (Down) from the reactor (center to center), changed sequentially 3 times per week.

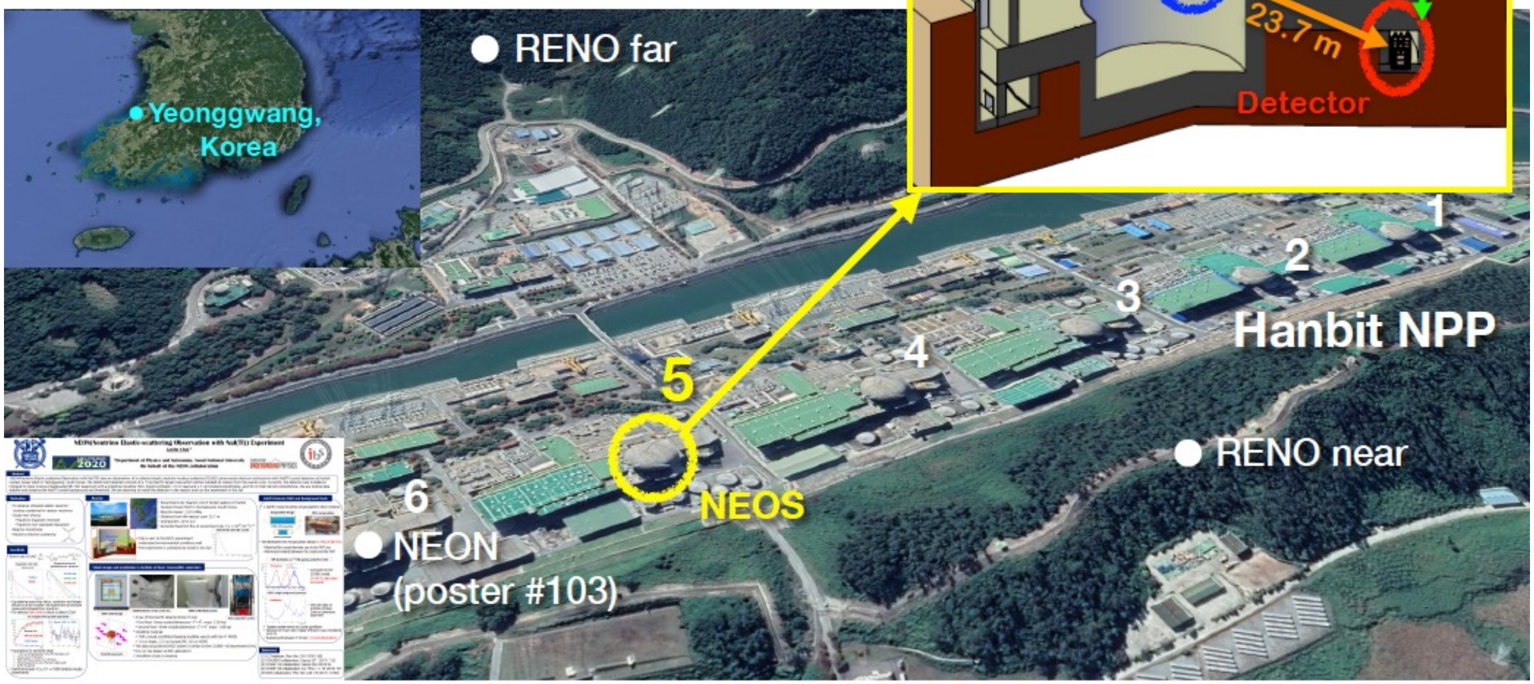
DANSS @ NEUTRINO 2020 shitov@jinr.ru 3/17

NEOS (South Korea)

Experimental Site

- Detector in tendon gallery
  - 23.7-m baseline and 20-m.w.e. overburden
  - Muon rate: ~1/6 of the ground (~28.7 Hz/m²)

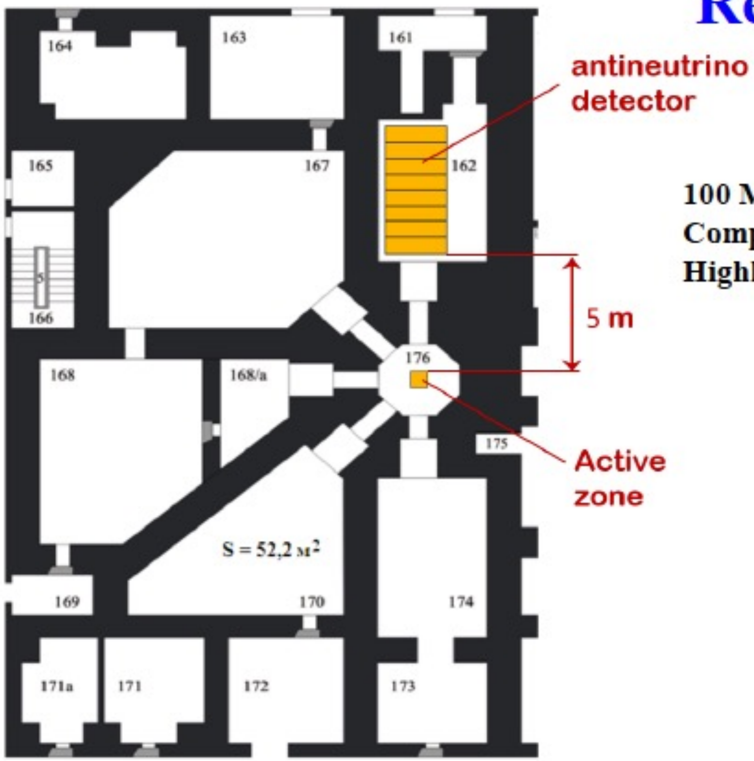




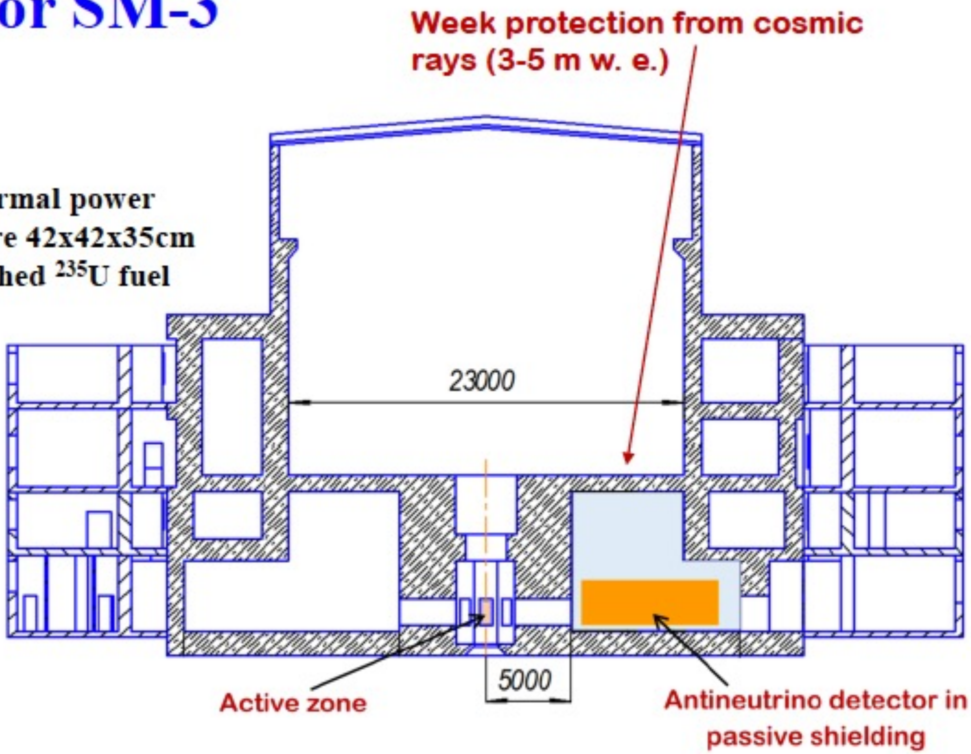
Neutrino 2020 | 6 | Status of NEOS-II — Y. J. Ko@IBS

Neutrino-4 (Russia)

Reactor SM-3



100 MW thermal power
Compact core 42x42x35cm
Highly enriched ^{235}U fuel



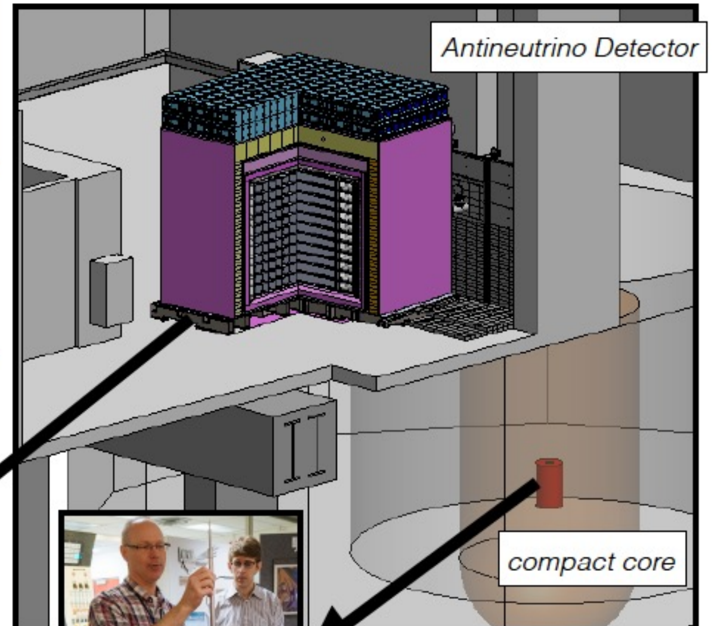
Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances. However, SM-3 reactor, as well as other research reactors, is located on the Earth's surface, hence, cosmic background is the major difficulty in considered experiment.

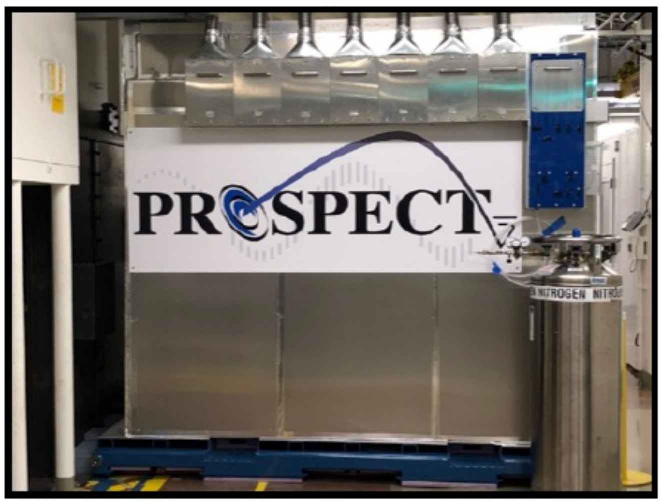
5

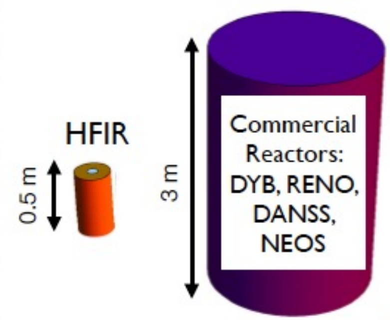
PROSPECT (USA)

PROSPECT Experimental Layout

- A 4-ton ^{6}Li-doped PSD-capable segmented LS detector at the HFIR research reactor
  - HEU reactor: HFIR burns only ^{235}U
  - Very short baseline: 6.7-9.2 meters
  - Compact core: <50cm height, diameter
  - Challenging environment: <1mwe overburden, copious reactor γ





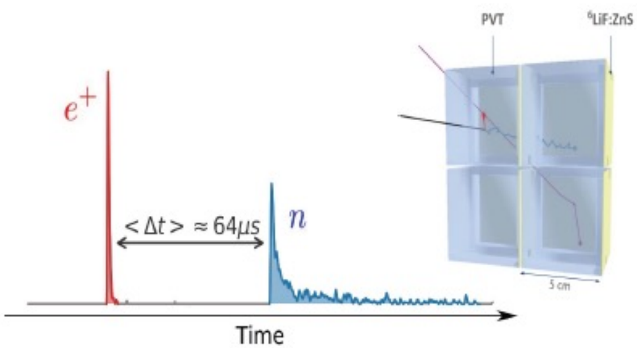


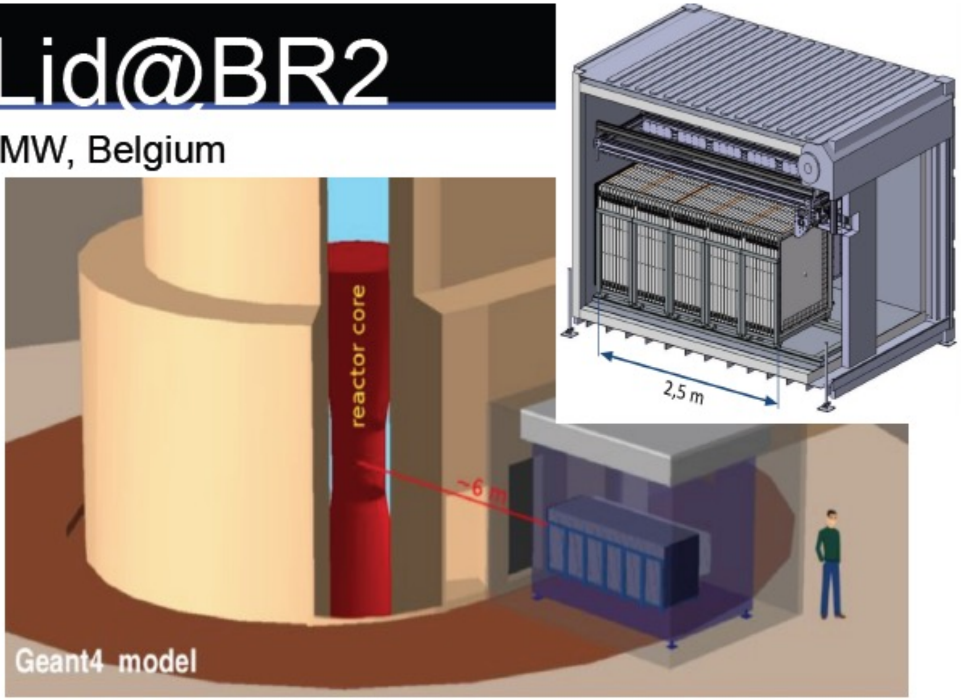
4

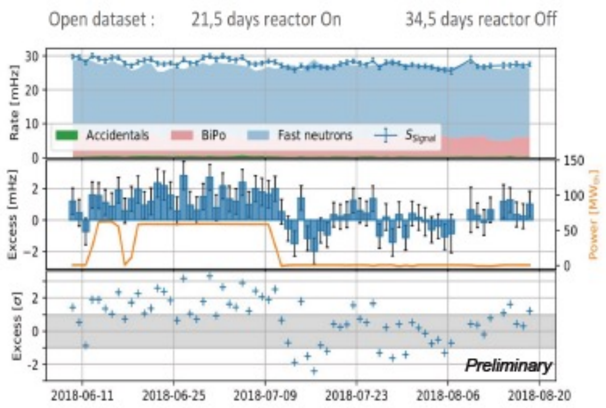
SoLid (Belgium)

SoLid@BR2

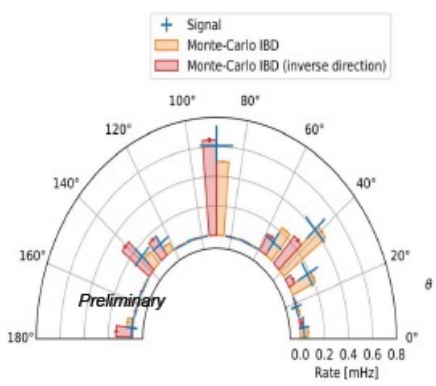
- BR2: Research Reactor HEU P_{th} ≈ 60 MW, Belgium
- SoLid Detector, 1.6t @6-9m
  - Very highly segmented detector
  - PVT covered with Li:ZnS(Ag) foils







≈140 events/day excess, 5.4σ significance over the whole period

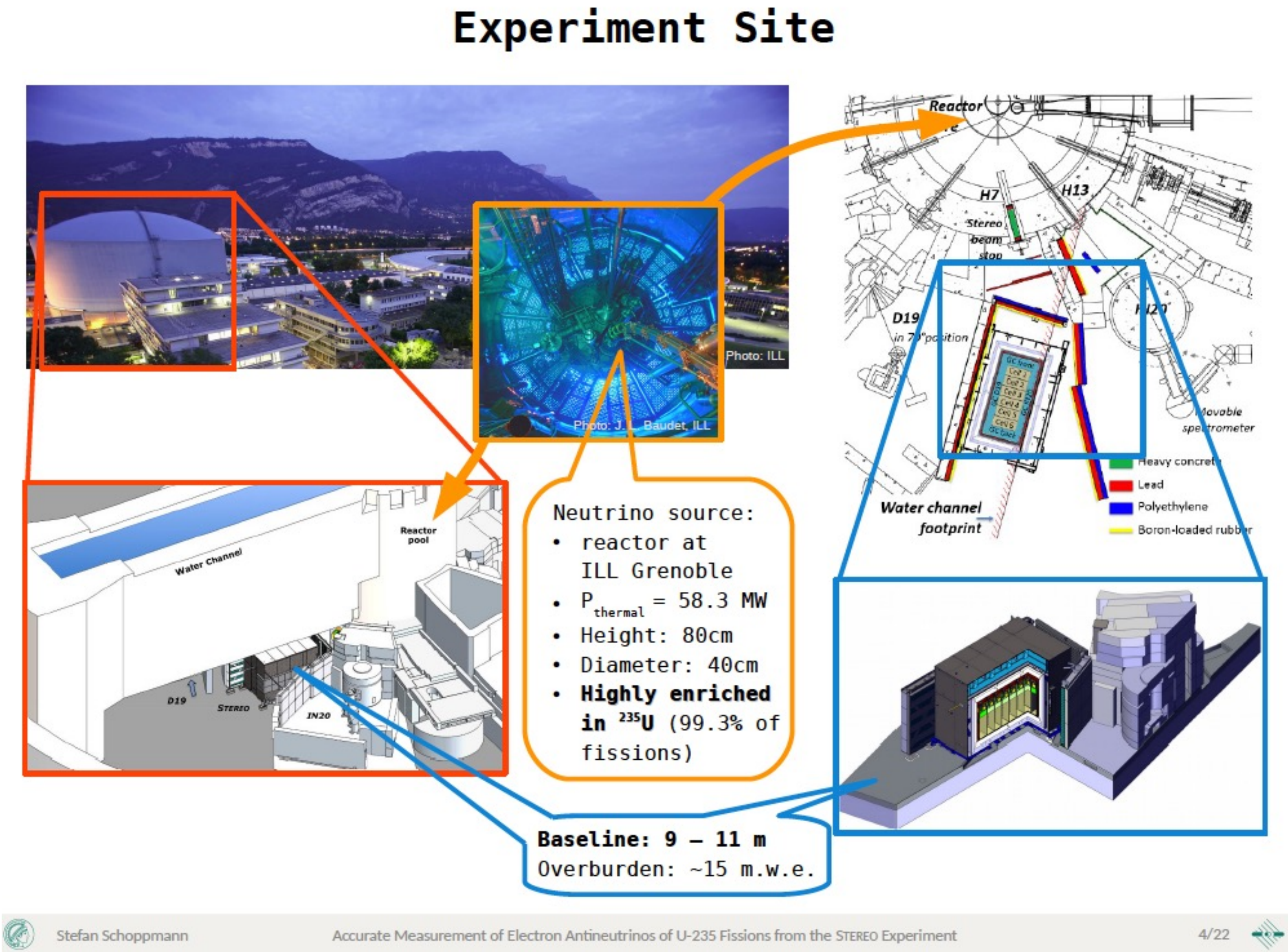


SoLid technology sensitive to $\bar{\nu}_e$ directionality

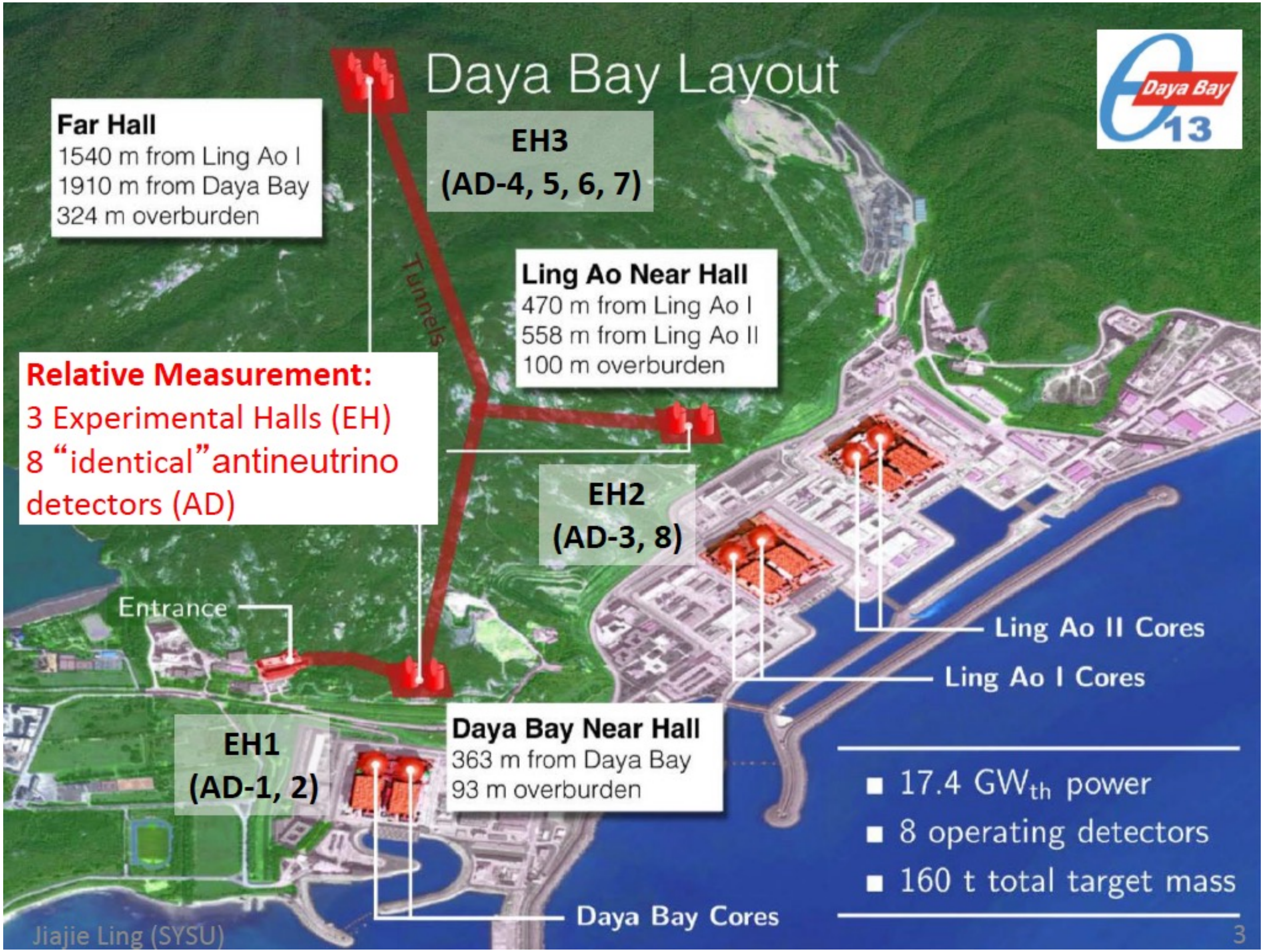
- Evidence of neutrino signal, upcoming oscillation analysis.
- Sensitivity to directionality from very high segmentation.
- Upgrade of MPPC, planned this summer.

Slide from G. Lehaut (LPC Caen

STEREO (France)



DayaBay (China)



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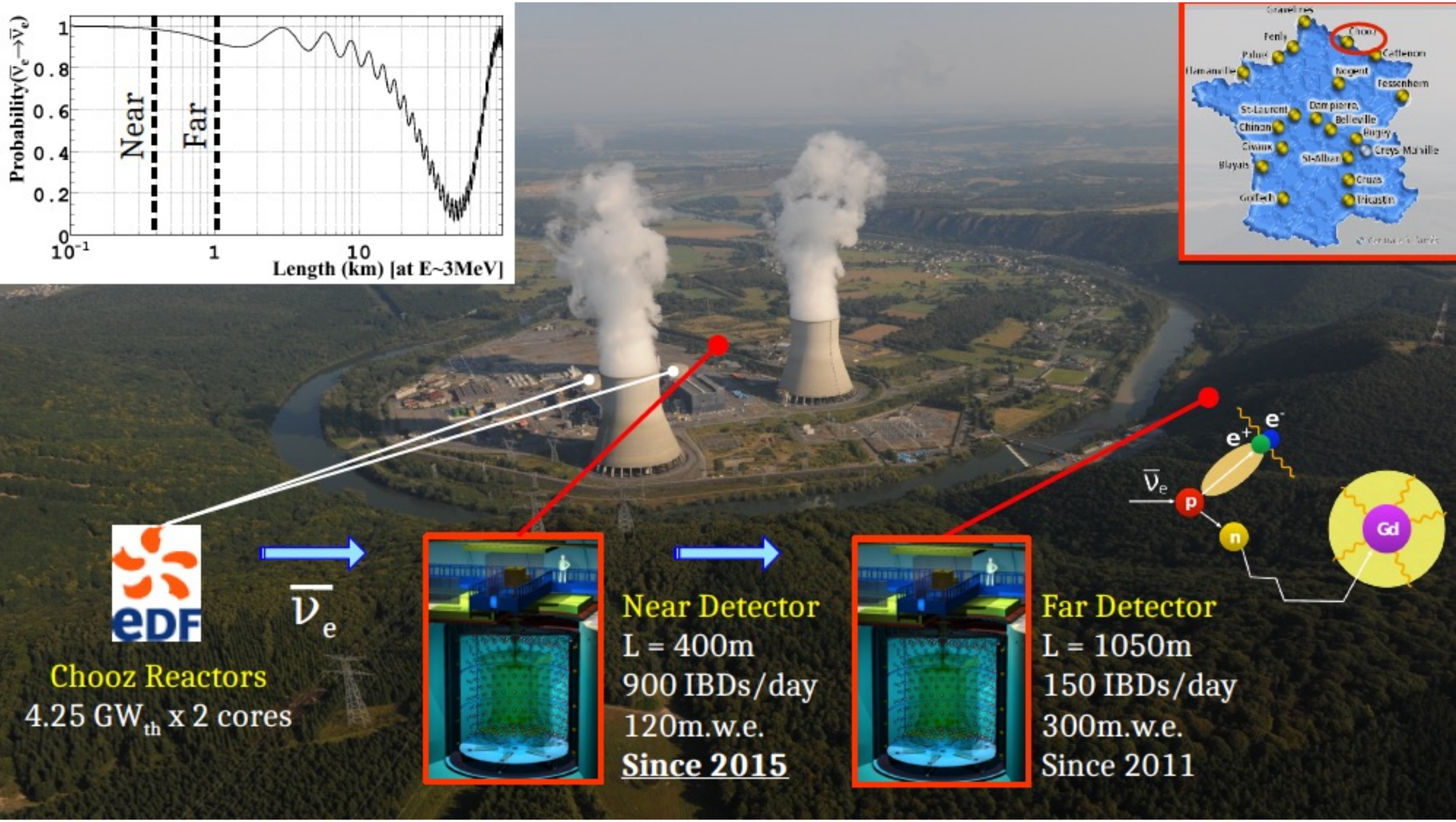
Double Chooz (France)



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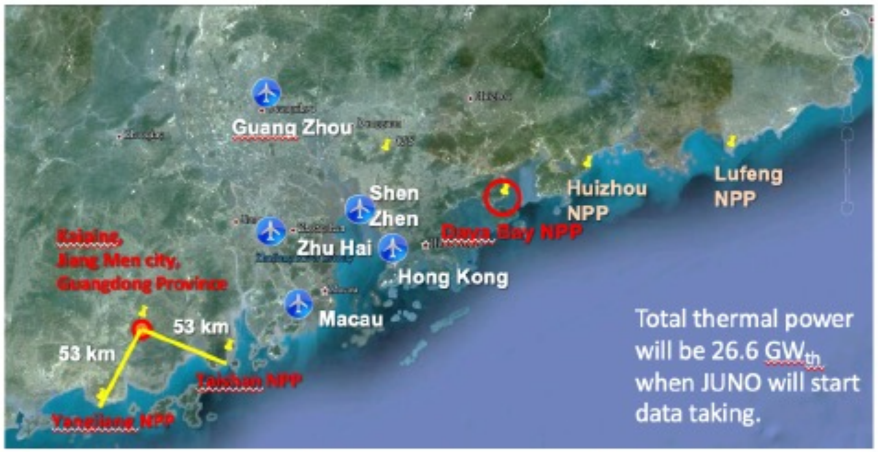
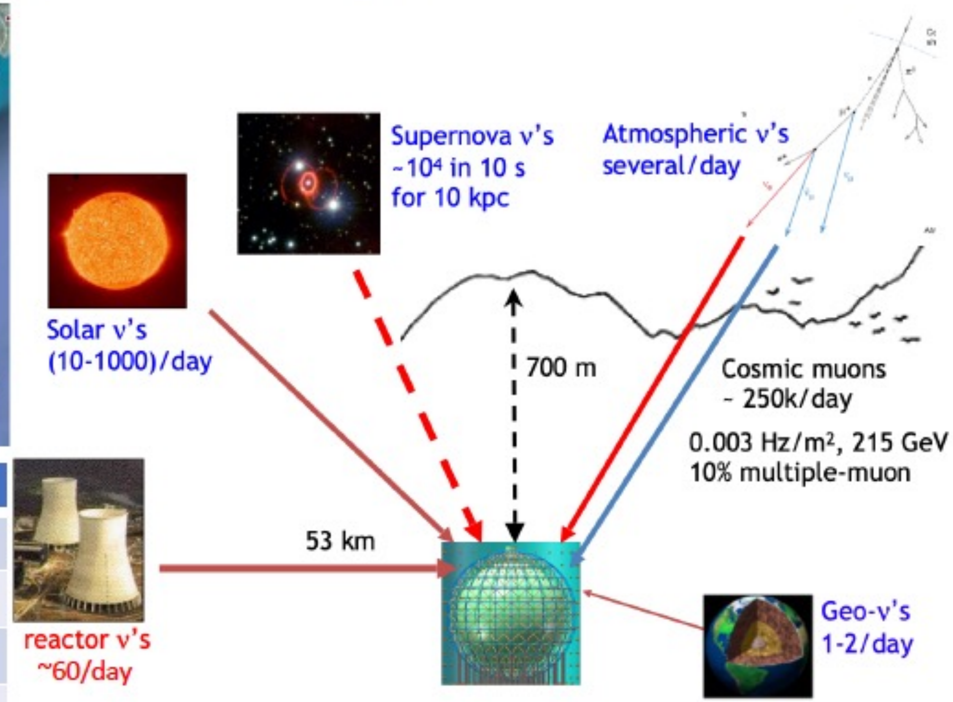
JUNO (China)

Jiangmen Underground Neutrino Observatory (JUNO)

- JUNO has a rich program in neutrino physics and astrophysics



Nuclear power plant	Status	Power
Daya Bay	Operational	17.4 GW
Huizhou	Planned	17.4 GW
Lufeng	Planned	17.4 GW
Yangjiang	Operational	17.4 GW
Taishan	Operational	9.2 GW (2 reactors online now)



From J. Pedro Ochoa-Ricoux's Nufact 2019

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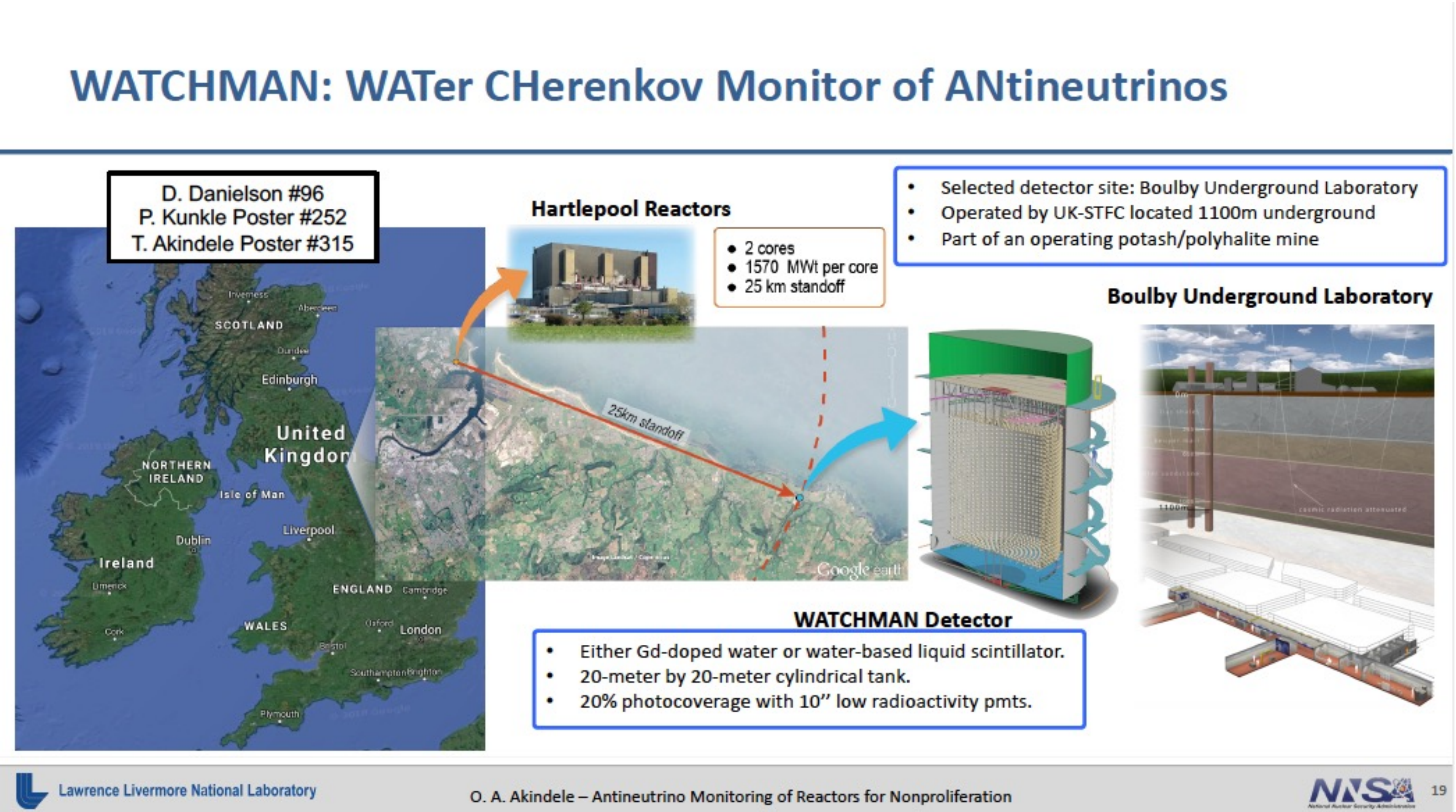
Watchman (UK)


WATCHMAN: WATer CHerenkov Monitor of ANtineutrinos
D. Danielson #96
P. Kunkle Poster #252
T. Akindele Poster #315
Hartlepool Reactors
• 2 cores
• 1570 MWt per core
• 25 km standoff
• Selected detector site: Boulby Underground Laboratory
• Operated by UK-STFC located 1100m underground
• Part of an operating potash/polyhalite mine
Boulby Underground Laboratory
SCOTLAND
Edinburgh
United Kingdom
NORTHERN IRELAND
Isle of Man
Liverpool
Dublin
Ireland
ENGLAND
WALES
London
25km standoff
Google earth
WATCHMAN Detector
• Either Gd-doped water or water-based liquid scintillator.
• 20-meter by 20-meter cylindrical tank.
• 20% photocoverage with 10" low radioactivity pmts.
Lawrence Livermore National Laboratory
O. A. Akindele – Antineutrino Monitoring of Reactors for Nonproliferation
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RENO (South Korea)