Neutrinos, neutrons and Nuclear Arms Control

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UK-China Verification Dialogue Workshop
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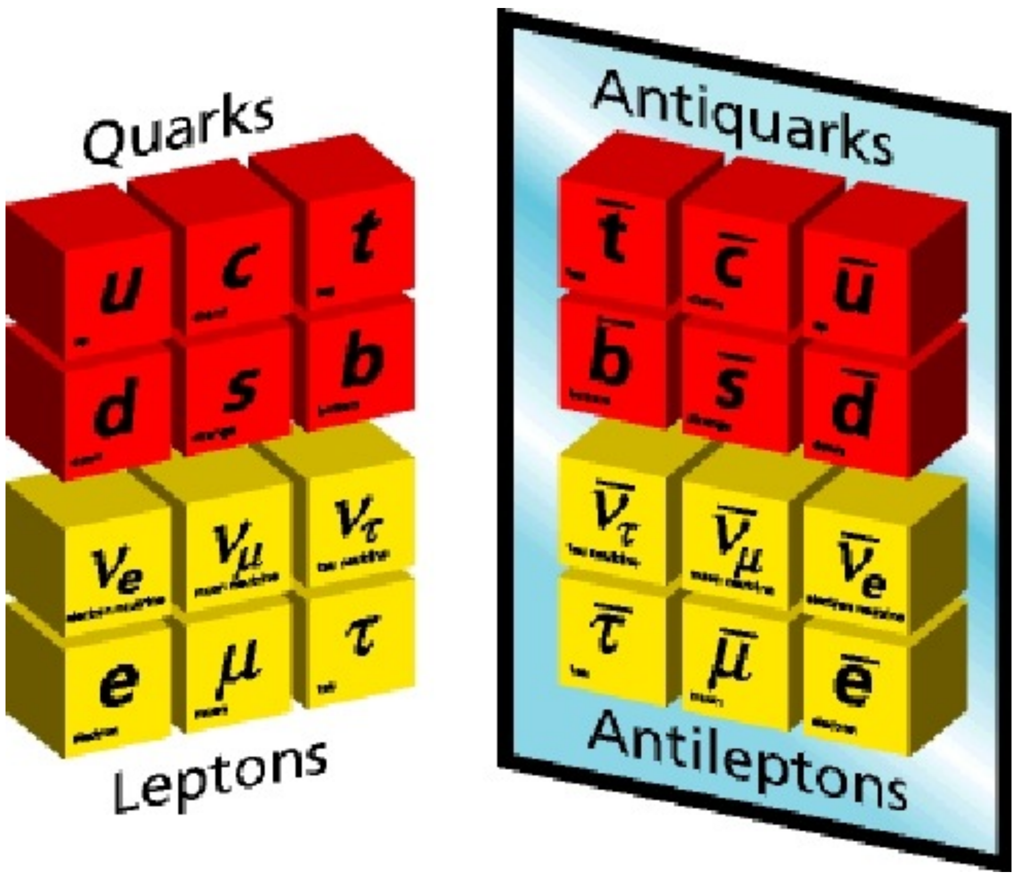
Outline

- (Anti)Neutrinos at a glance
- Anti-Neutrinos from reactors and their detection
- NPT, IAEA and anti-neutrinos
- Neutron detection and search for “dark matter”
- International collaborations and role of China

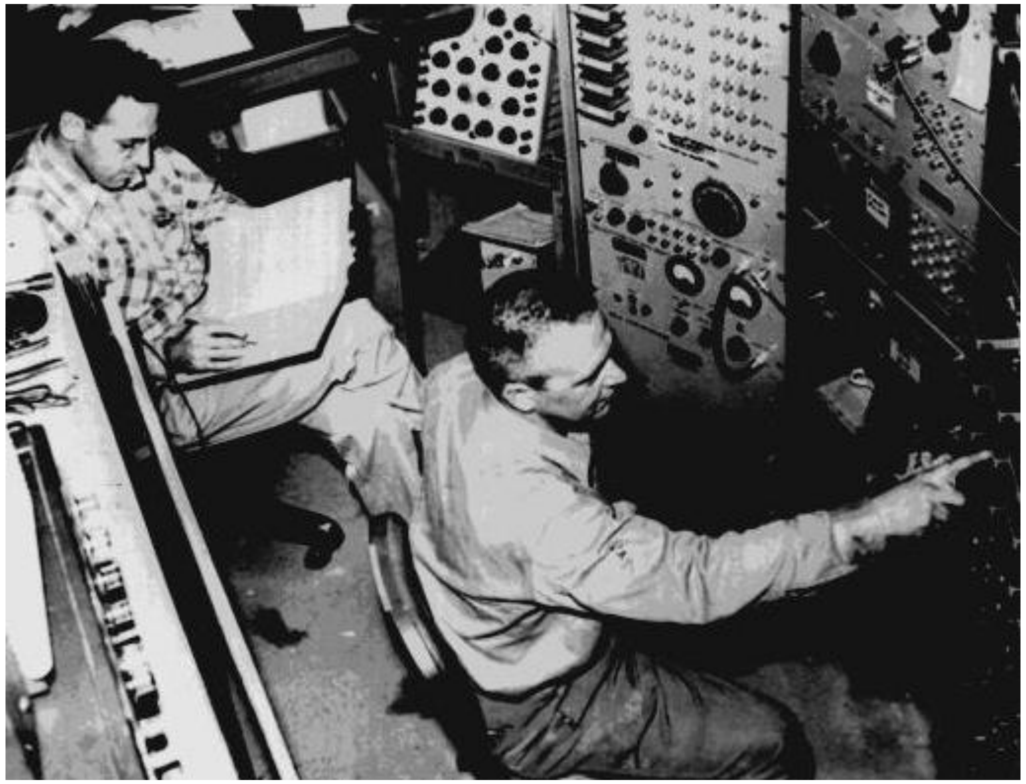
Neutrinos



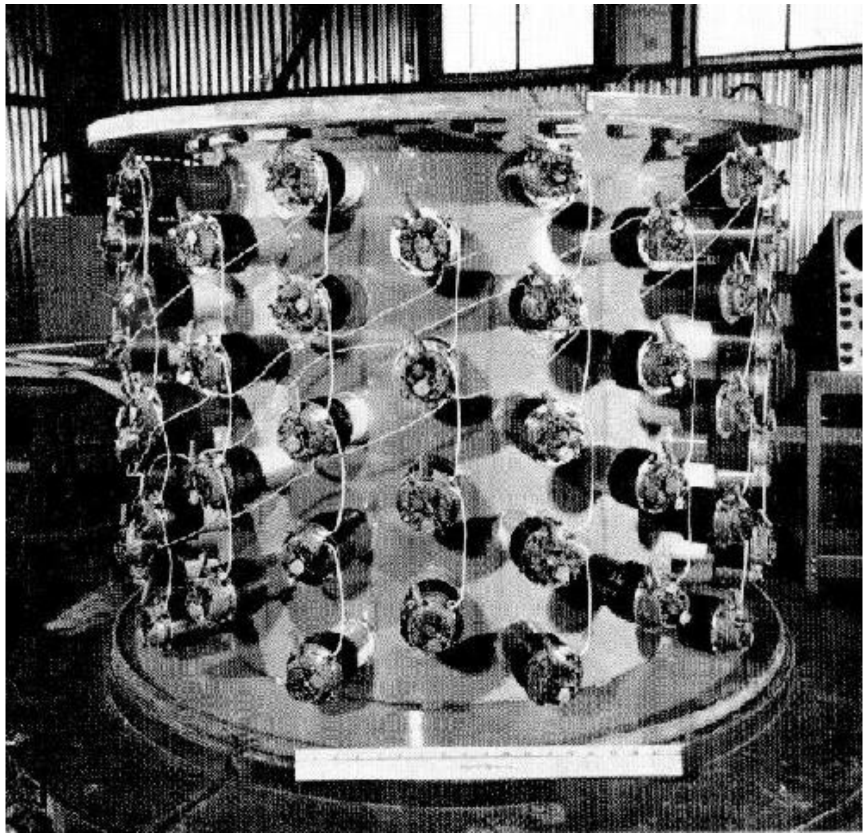
- **Second** most **abundant** (known) particle in **Universe** (after photon)
- Recently discovered to have tiny but **non-zero mass**
- May hold key to “**New Physics**”,
  - ⋆ why we leave in world dominated by matter (almost no anti-matter)
- Extremely **hard to detect** (electrically neutral — only weak interactions)

Neutrino flux at Earth (mostly from the sun):
6.5×10^{10} particles/cm^2/sec

Neutrino Detection



- Interact only via weak interactions
- Mean free path at 1 MeV is ~ 10^6 km !
- Need very intense flux and very large detectors
- Reactor produces antineutrino flux ~ $10^{17} m^{-2} s^{-1}$



First observation in 1956 in a **nuclear reactor**

F. Reines (Nobel prize 1995):

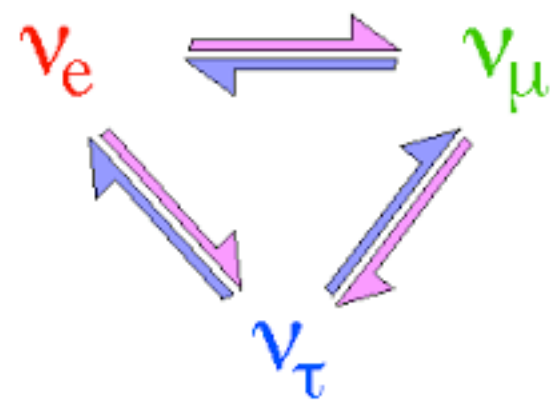
"… the most tiny quantity of reality ever imagined by a human being"

This reaction was used in 1956 observation ⟶ $\bar{\nu}_e + p \rightarrow e^+ + n$

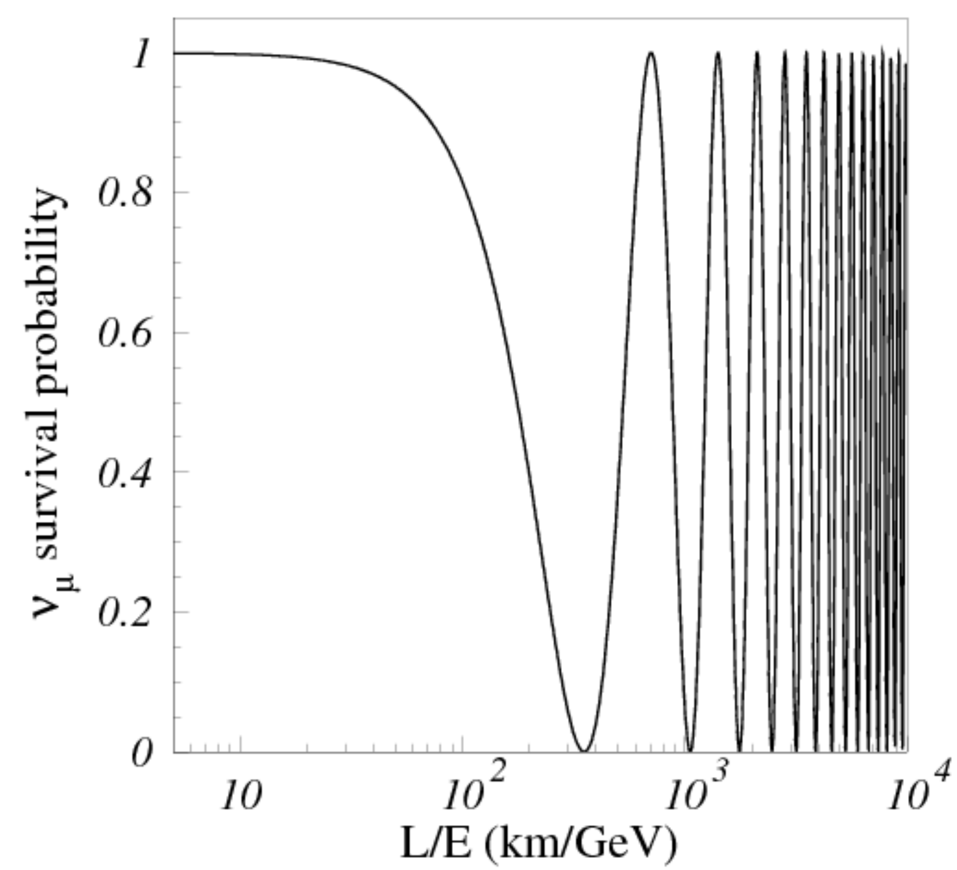
Still main reaction used to detect reactor (anti)-neutrinos

Neutrino Oscillations and role of reactors.

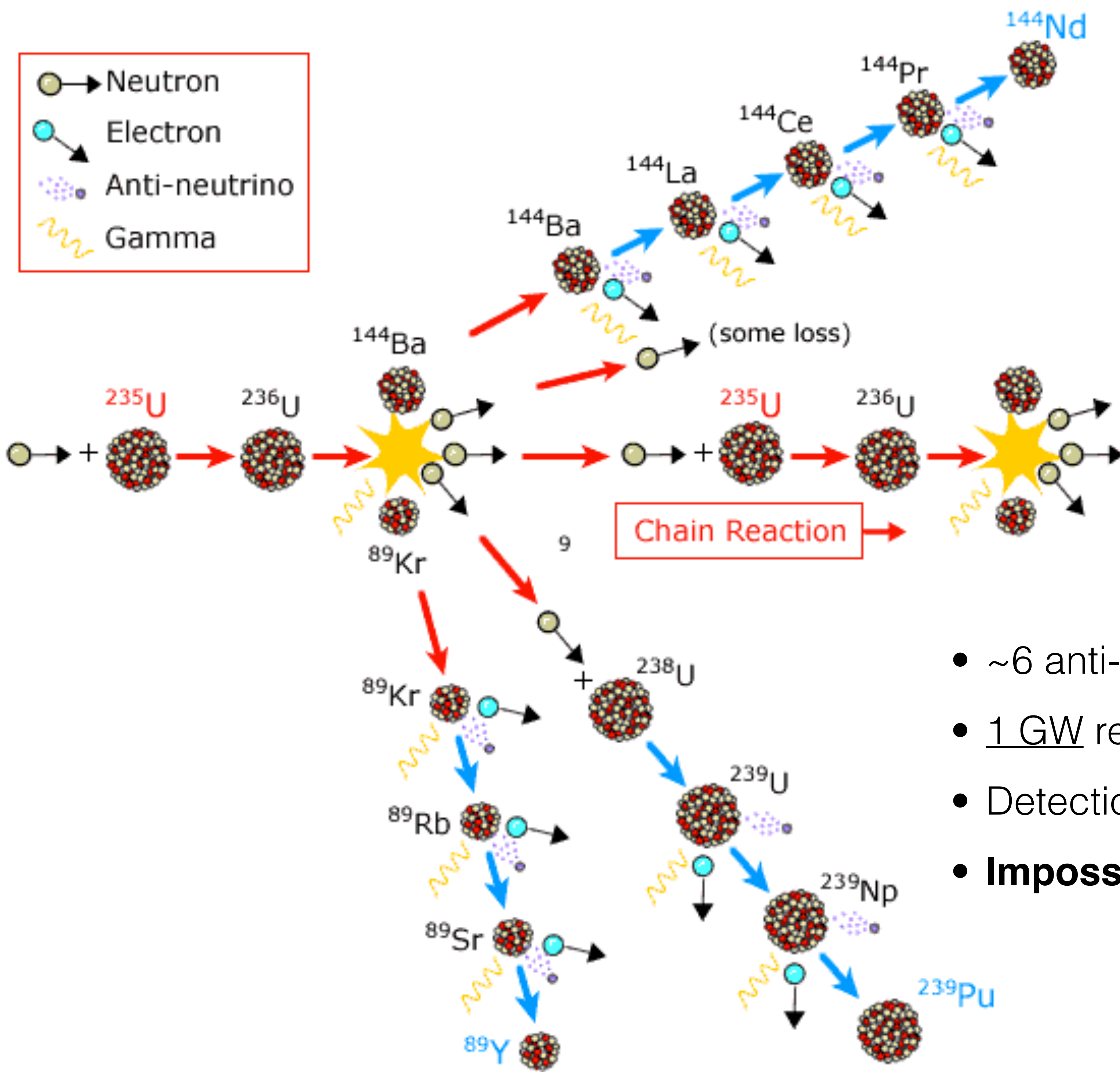
- Observation of **neutrino oscillations** (1998-2002) and subsequent measurements of oscillation parameters — one of the **biggest discoveries** in particle physics
- **Complementary** to Higgs boson and other physics pursued at **LHC**
- Latest “big thing” (2012) — discovery of “**θ_{13} mixing angle**” —- came from **reactor neutrinos**
- Perhaps our best hope for “**New Physics**”
- One of the **hottest topics** in particle physics — lots of development and investment, truly **international effort**

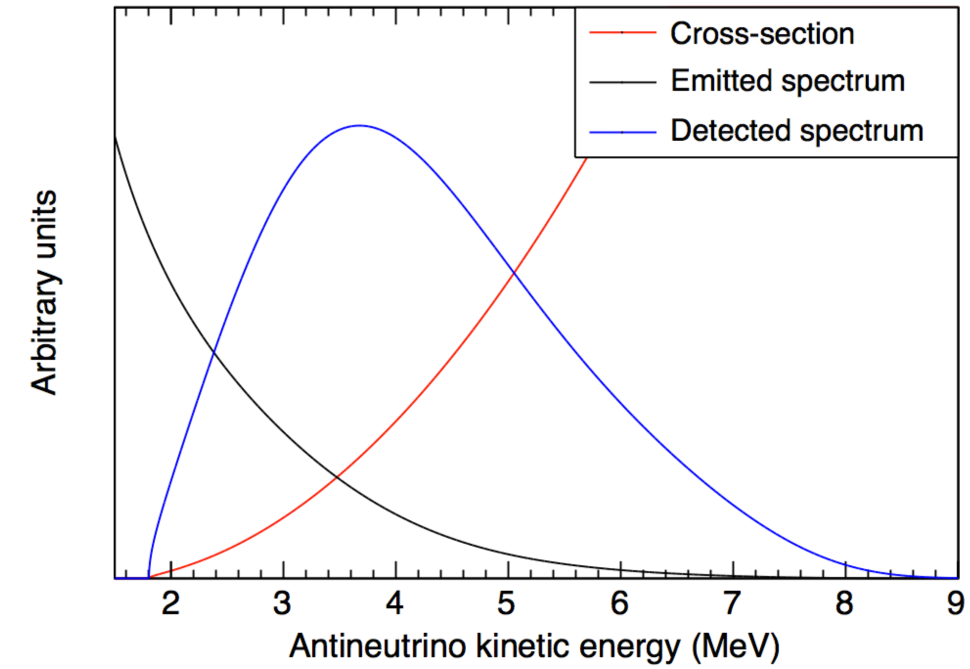


oscillations ⇒ non-zero neutrino mass



Antineutrino from nuclear reactor

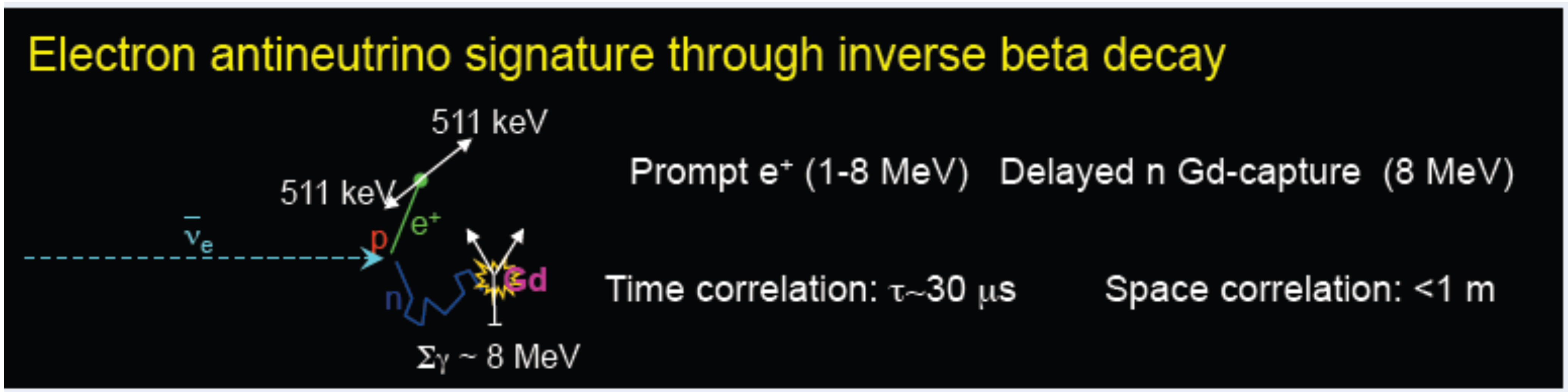




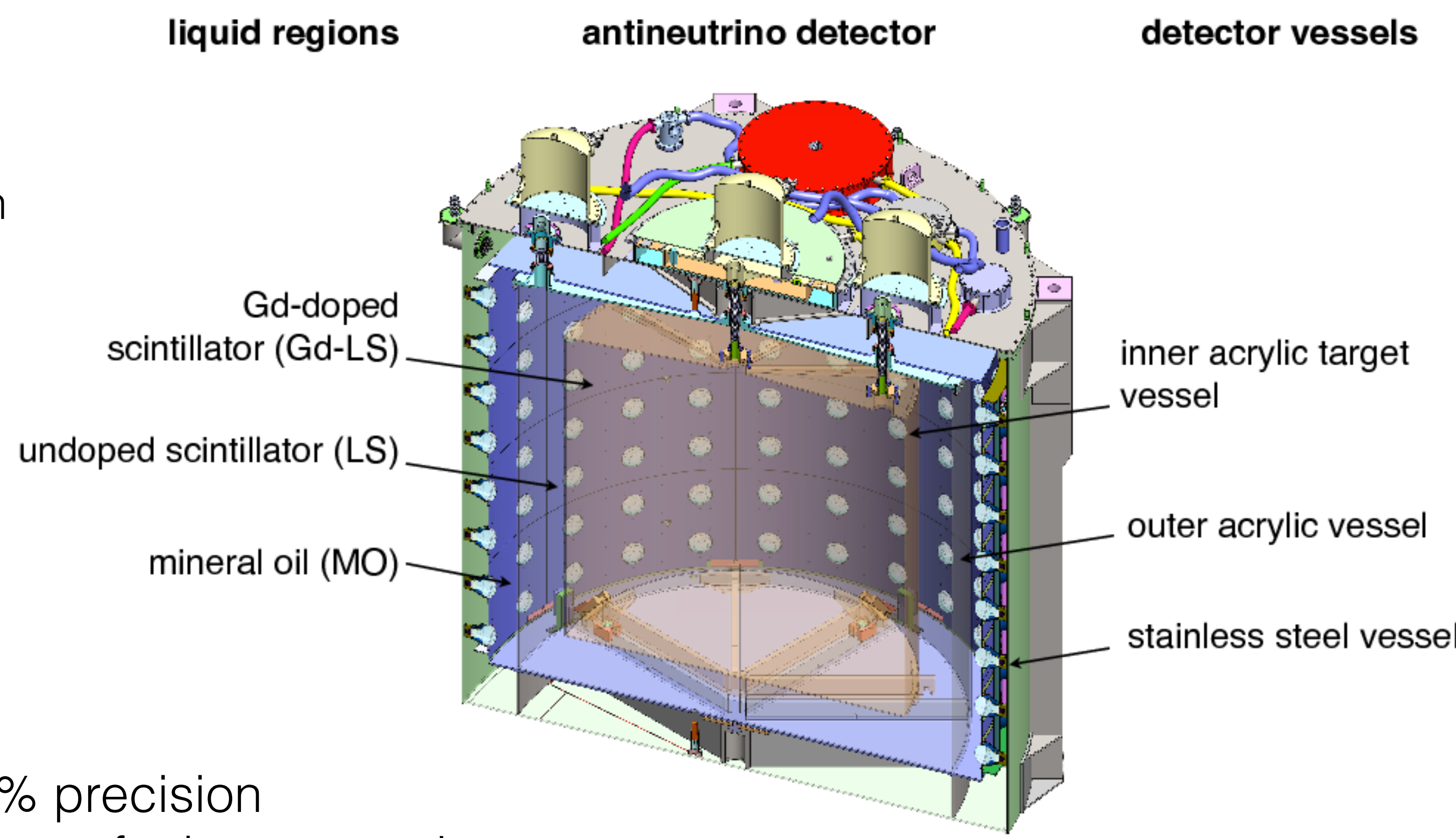
- ~6 anti-ν's per fission
- 1 GW reactor produces ~1.5 x 10^{20} anti-ν's/sec
- Detection possible despite small cross section
- **Impossible to shield!**

Antineutrino Detectors

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



- A lot of detector development, liquid and plastic scintillators, water Cerenkov dopants to increase neutron cross-section (Gd, Cd etc), photodetectors
- Understanding of backgrounds, improved modelling
- Cost reduction for Mton detectors — remote reactor monitoring (focus on water Cerenkov detectors)



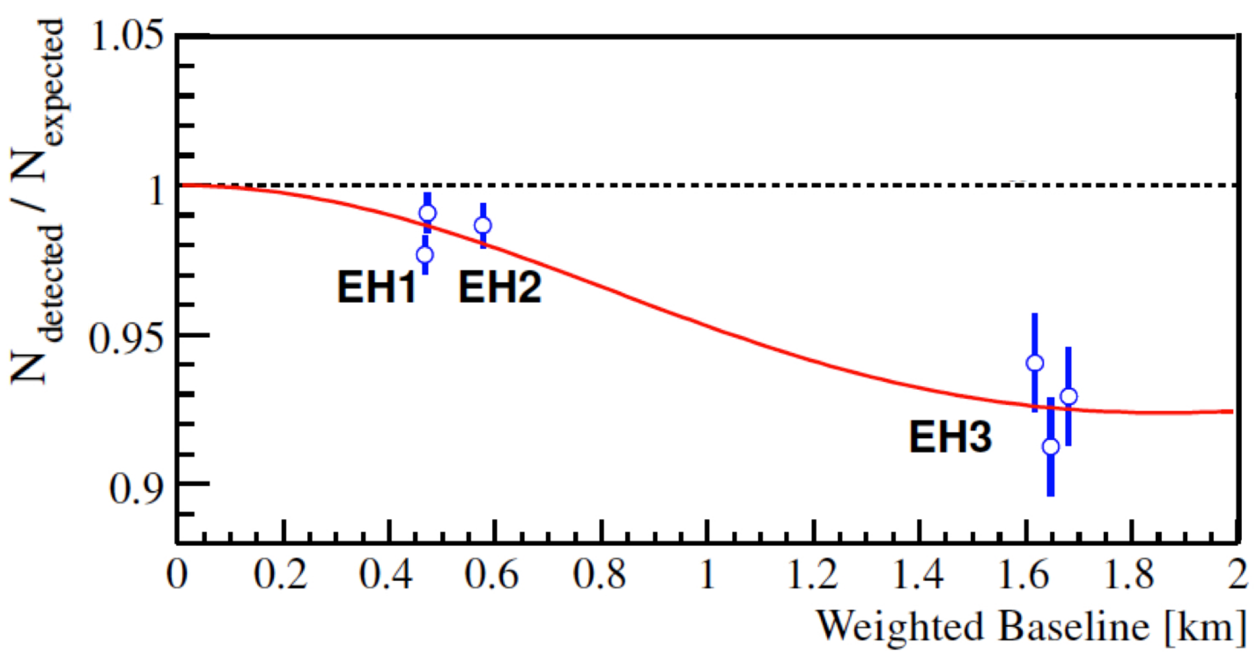
1,000-10,000 events per day, 1-10% precision of number of anti-ν's —> # fissions —> fuel consumption

$$\#event/day \approx 730 \times MW_{th} \times \frac{L_m^3}{D_m^2} \times \varepsilon$$

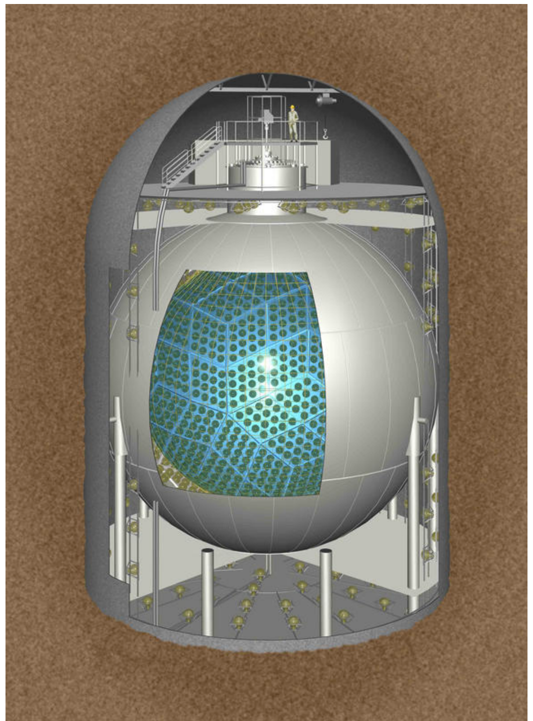
Energy spectra of anti-ν's are **different** for **U** and **Pu**

Truly international effort with China playing a key role

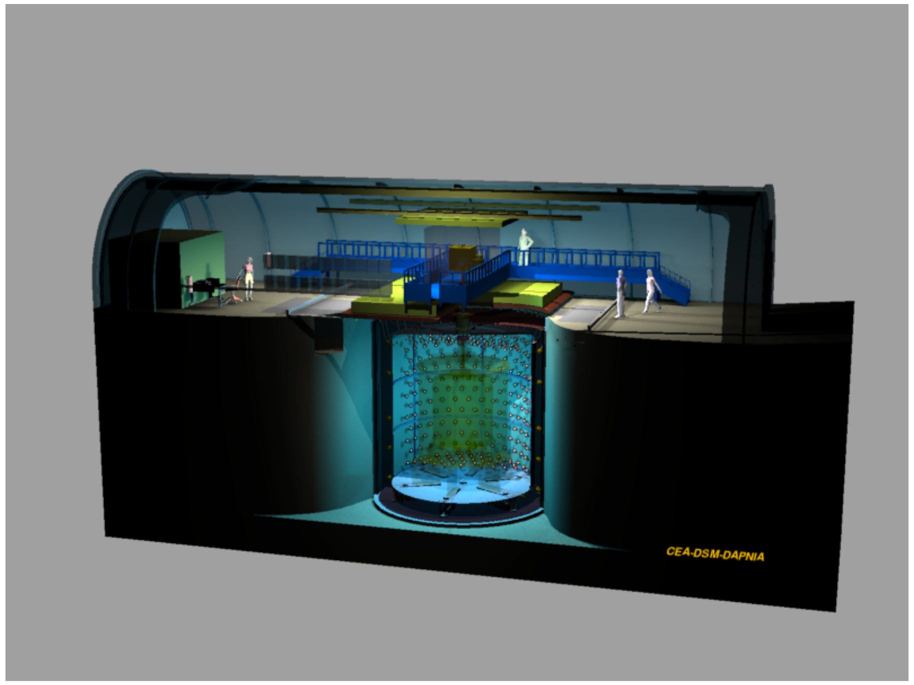
First θ_{13} measurement in Day Bay reactor in China



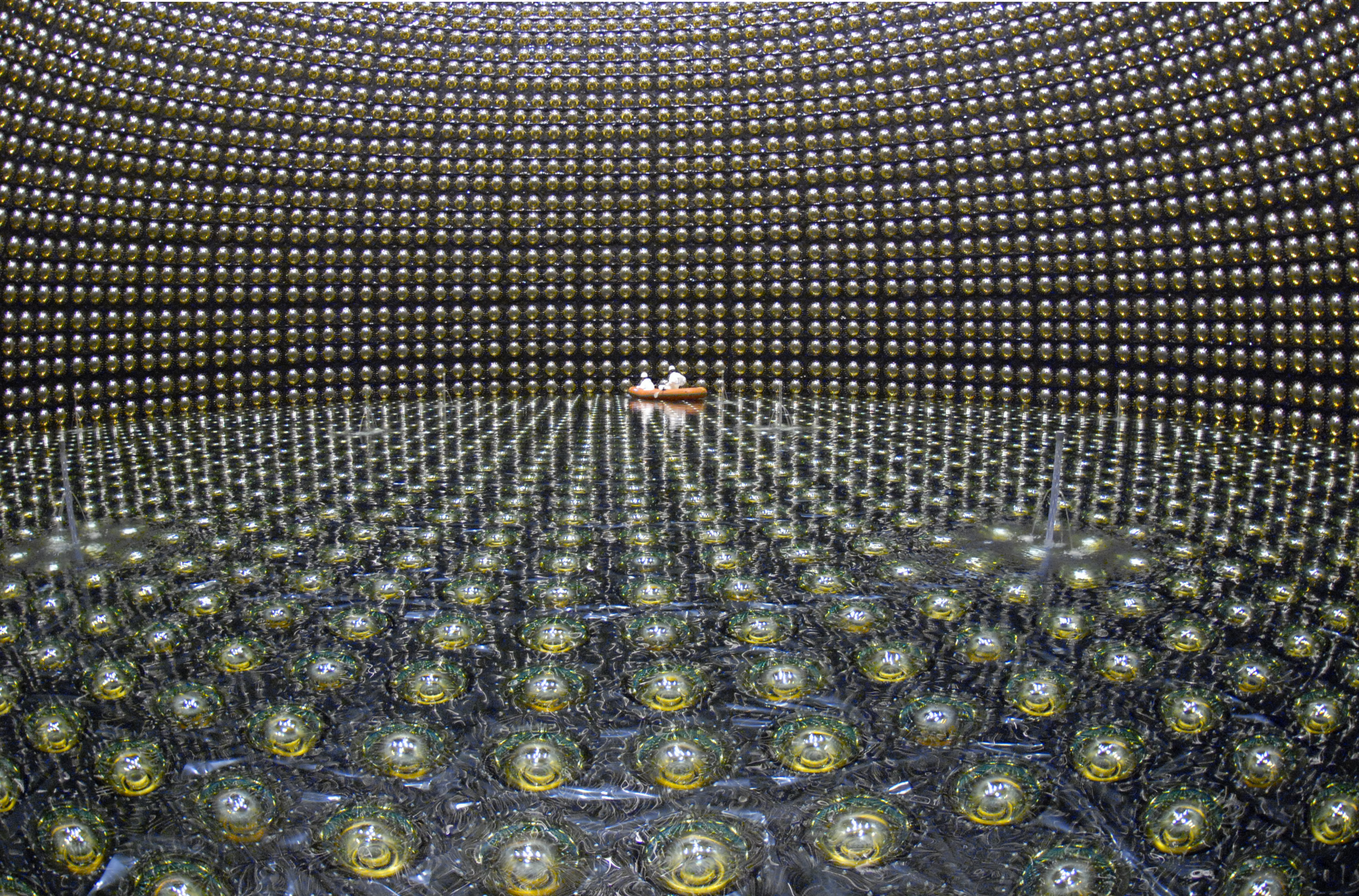
Future plans:
JUNO, 20kT scintillator detector



Other reactor neutrino experiments:
Double Chooz in France,
RENO in Korea, KamLAND in Japan

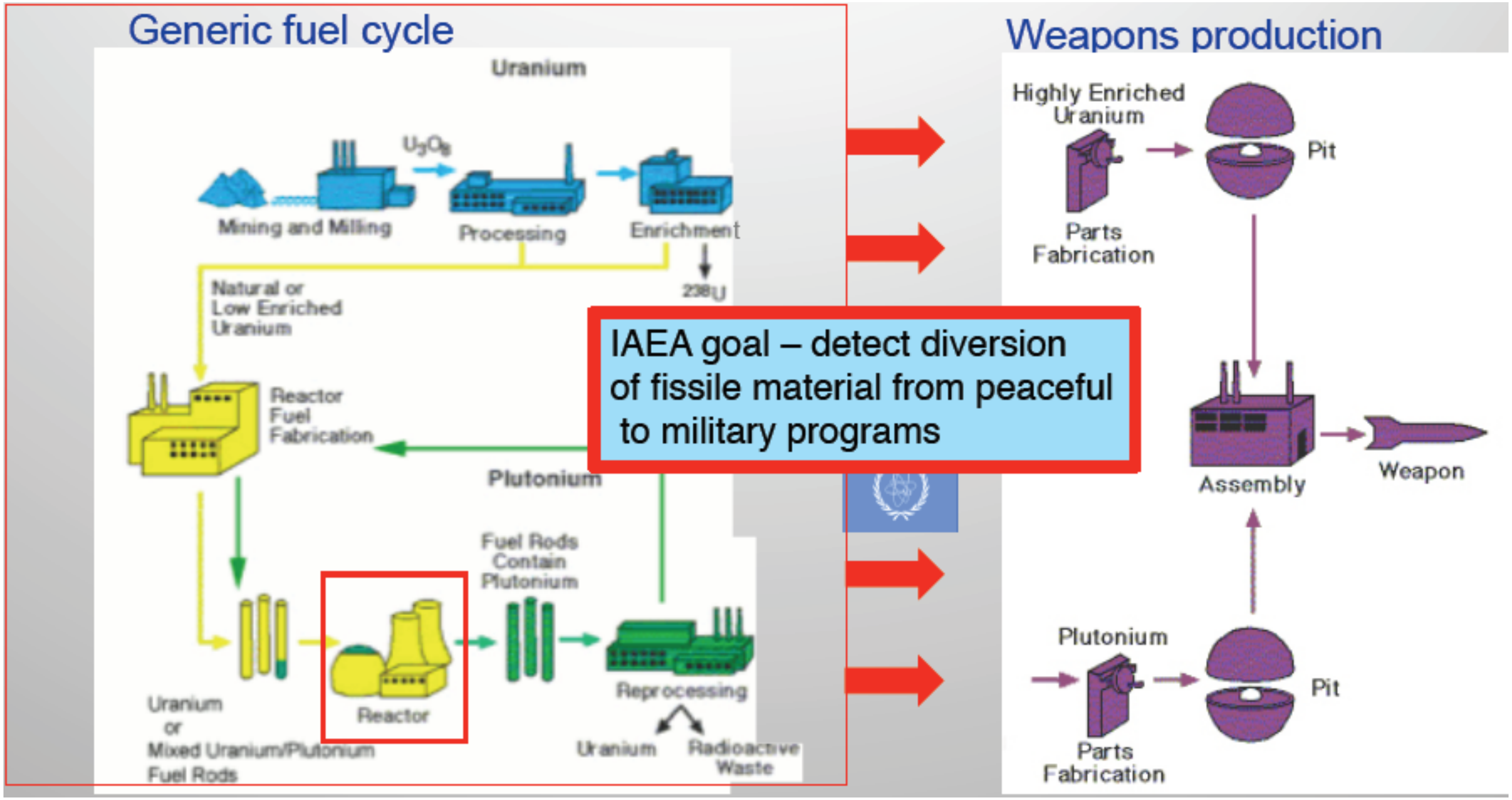


Development of very large cost effective detectors based on success of SuperKamiokande (Japan)



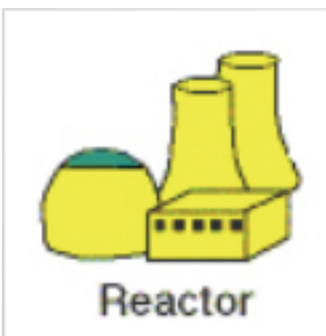
Can antineutrinos help with nuclear arms control?

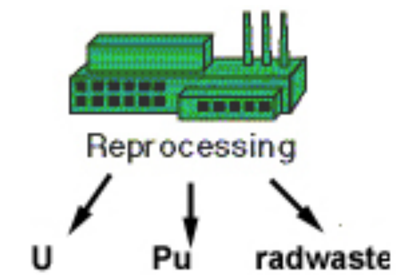
The IAEA "Safeguards" Regime monitors the flow of fissile material through the nuclear fuel cycle in 170 countries



Goal of antineutrino measurements — track fissile inventories in operating nuclear reactors

IAEA monitors ~220 reactors worldwide but never **directly** measures in-core fissile content





1. Check input/output declarations
2. Item accountancy
3. Containment and Surveillance

1. “Gross defect” detection
2. Item accountancy
3. Containment and Surveillance

1. Check declarations
2. Item accountancy

Concerns:

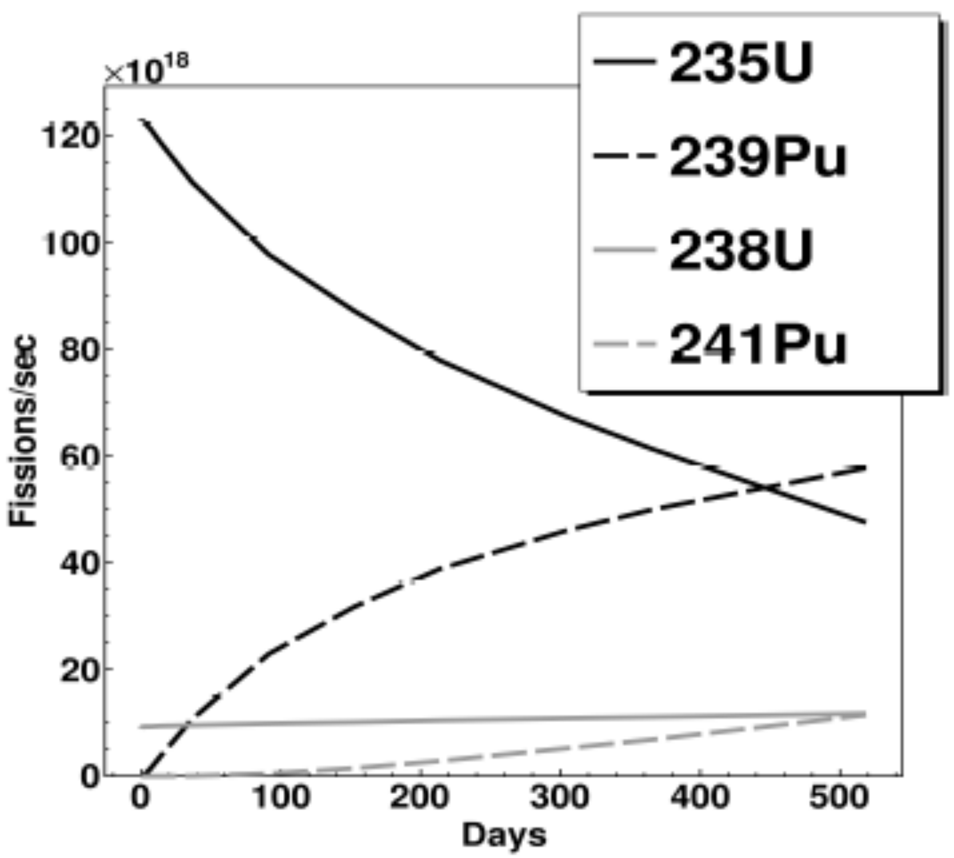
- Operators **report** Fuel Burnup and Power History
- **No** direct **Pu Inventory** (unless and until fuel is reprocessed)

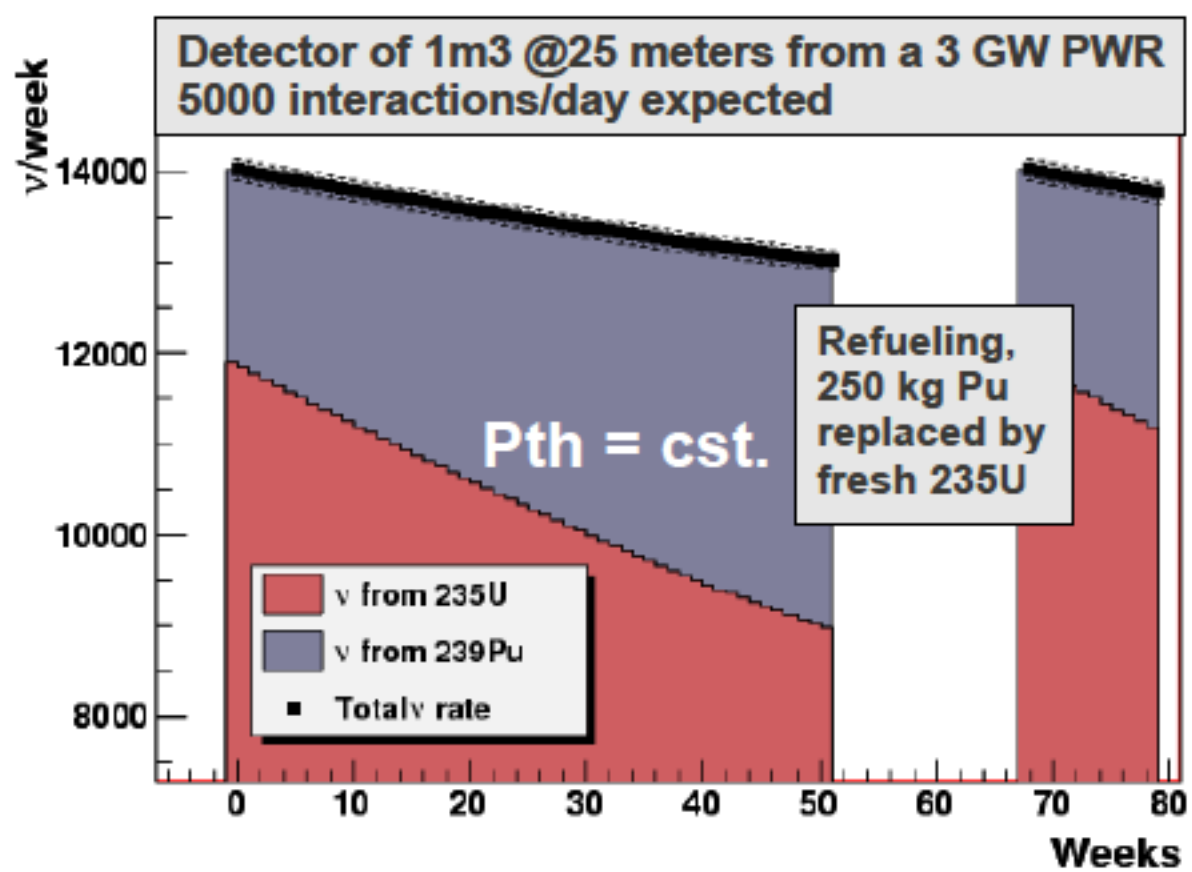
Antineutrino from nuclear reactor

- As reactor fuel burns, the composition changes —> **Burnup**
- Antineutrino flux and energy spectrum change with time and composition

$$N^{\nu} \sim \left[1 + f\left(\frac{M_U}{M_{Pt}}\right)\right] P_{th}$$

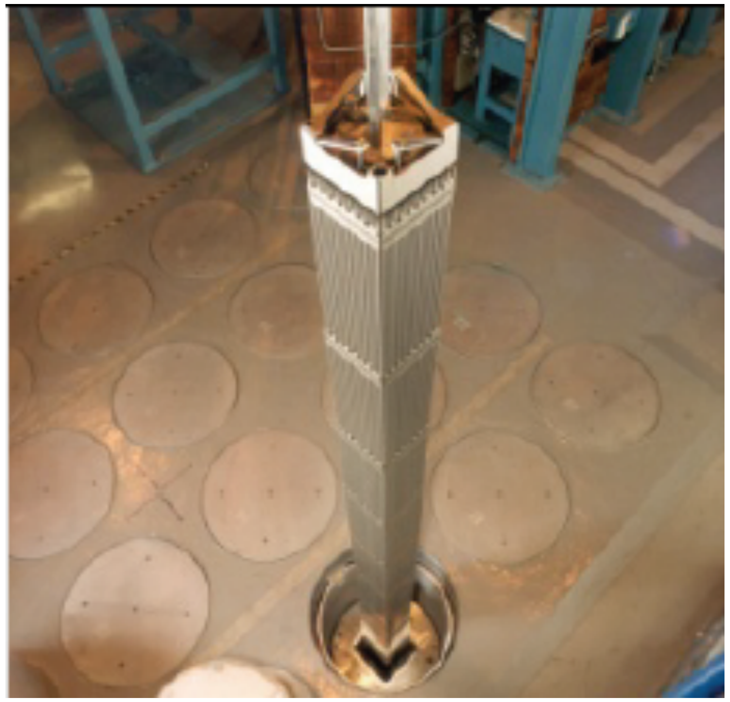
- Any sudden **change in core composition** causes change in antineutrino rate/spectrum —> **can be detected**





IAEA particular interest — Pu disposition

- *A long-sought goal* of managing Pu that has been declared surplus to military needs.
- *Purpose*: convert it to a form that is much harder to recover for use in a weapon
- *Currently preferred method*: manufacture MOX fuel (Pu/U) and irradiate it in a reactor — "**Spent Fuel Standard**", **SFS**

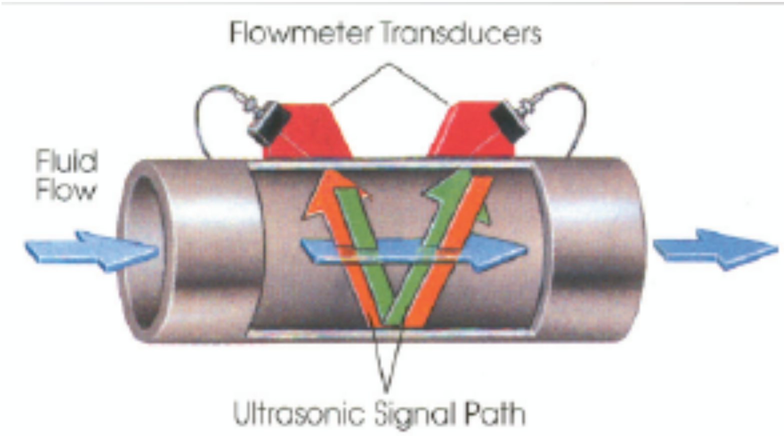


- Verifying **SFS** requires knowledge of fuel **burnup** for each assembly
- **Burnup** measures energy extracted from fuel (or number of fissions that have occurred)

- **Burnup** is strongly correlated with
  - Total neutron irradiation history
  - Fission product concentrations
  - Transmutation of heavy elements
  - **Total antineutrino flux**

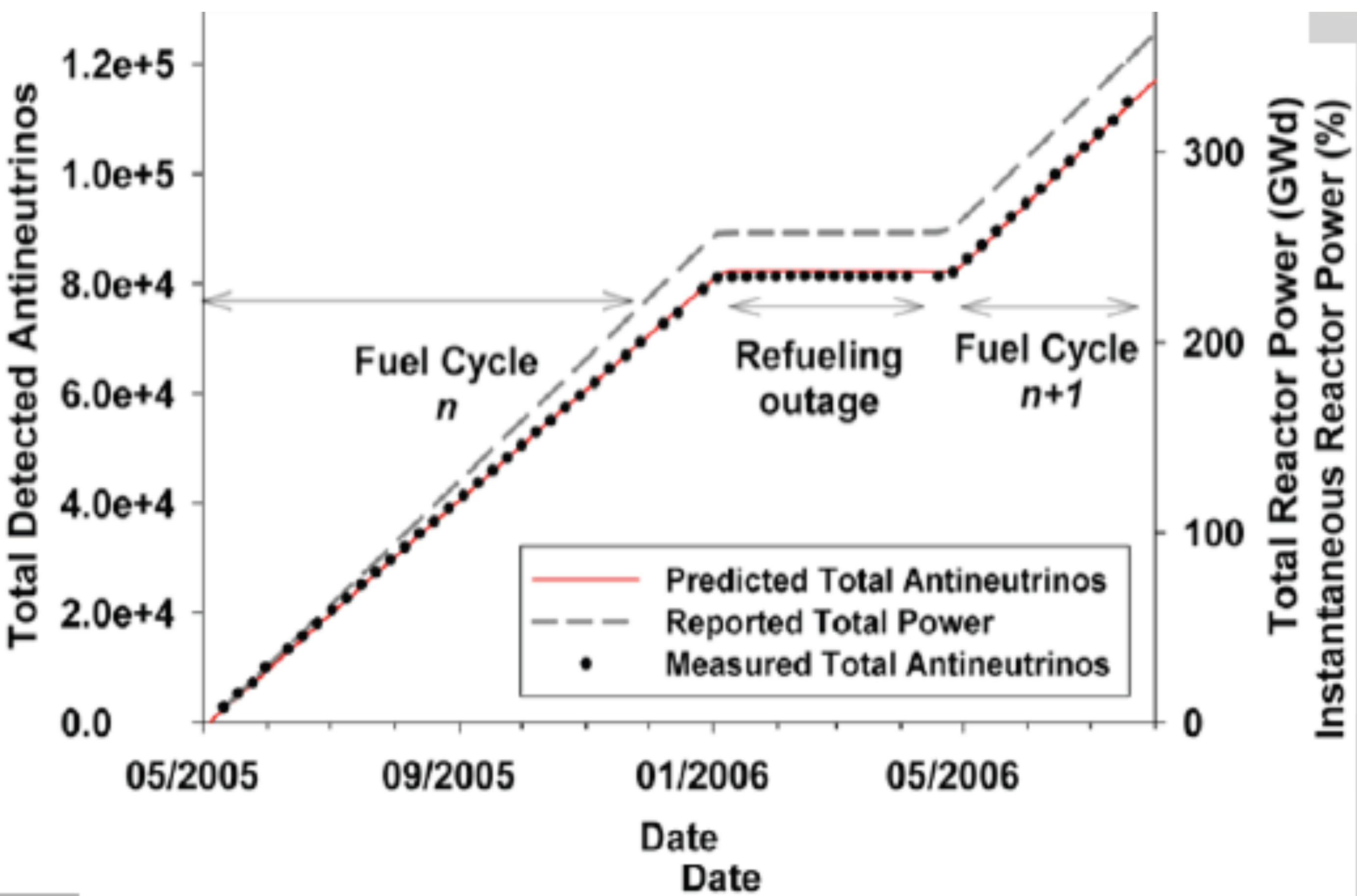
Burnup monitoring

- “Conventional” burnup monitoring — thermo-hydraulic power monitor



- measure temperature difference and flow rate to infer power
- relatively intrusive (connection to sensitive plant systems)
- vulnerable to spoofing

- Alternative: measure integral antineutrino rate as a measure of fuel exposure



Advantages:

- Non-intrusive, no connection to plant systems
- Statistical precision
- Self-calibrating
- Highly tamper resistant, difficult to spoof
- “Continuity of knowledge”

Currently two-type of reactors under evaluation

- Westinghouse PWR with partial MOX loading (common in US)
- Fast breeder BN-600 with partial and full MOX loading (Russian)

Reactor monitoring with antineutrinos — an emerging field

| Done | Running | Proto | In construction|

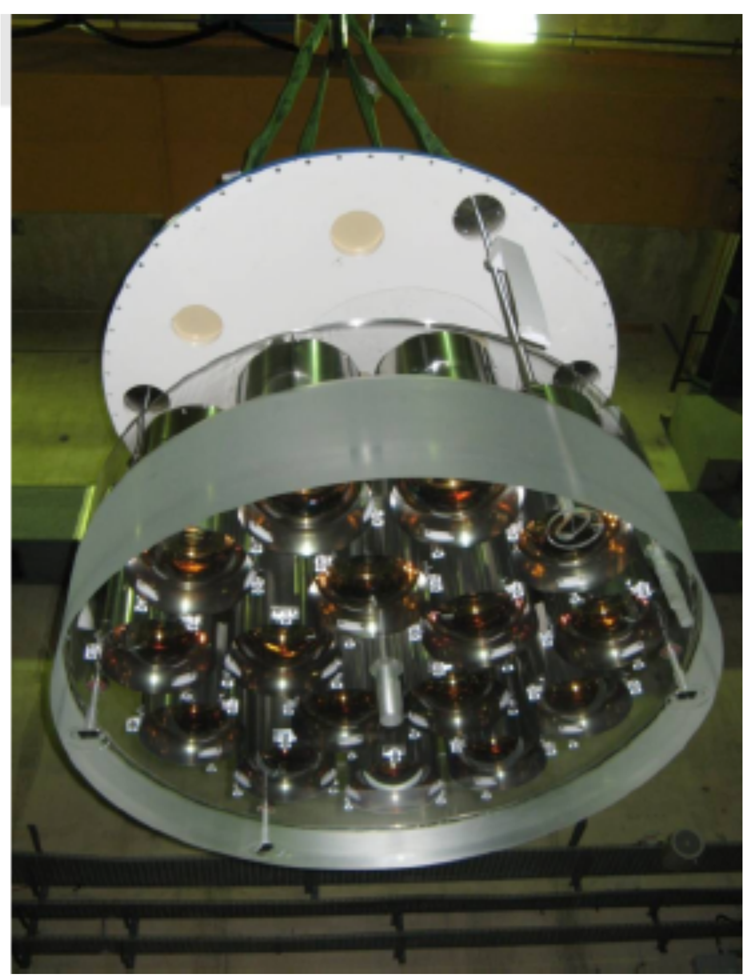
	Site	Techno	Comment
SANDS	San Onofre, US	0.5 t LS @20mwe	Done
SANDS	San Onofre, US	PS & Gd-H2O @20mwe	On Going
ANGRA	Angra, Brazil	LS	On Site R&D
DANSS	KNPP, Russia	Plastic	In construction
Kaska	Joyo, Japan	Gd-LS	Prototype
Panda	Japan	Plastic, Gd foil	Prototype
NUCIFER	Osiris	Gd-LS	Just Funded
Texono	Taiwan	HPGe	On Going – CNS –
Pt Lepreu	Canada	Gd-LS	CANDU, with USA
Cormorad	Italy	Plastic	Prototype
MARS	ILL	Plastic + ^{6}Li	Prototype

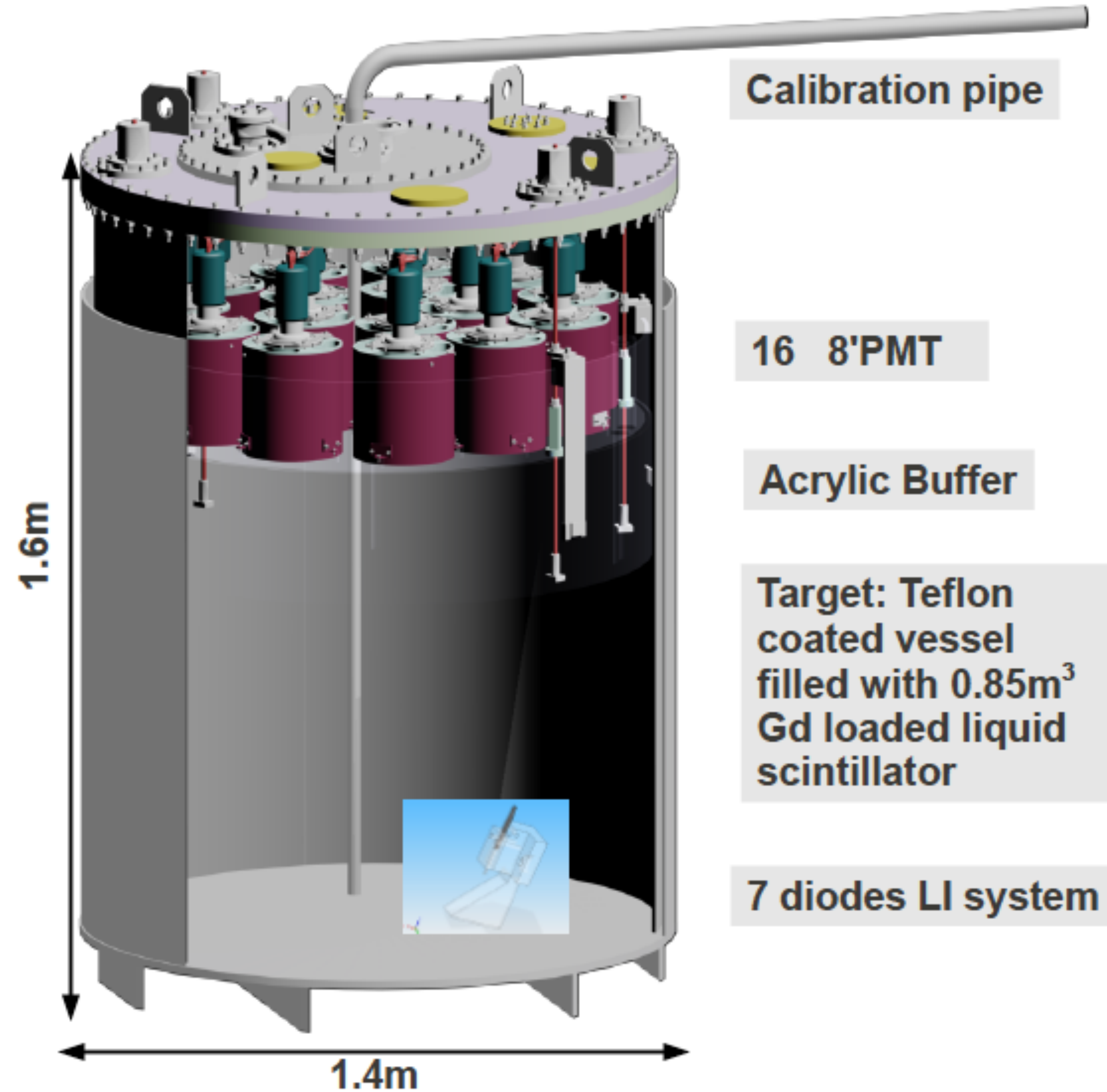
Slide by T. Lasserre, Applied Antineutrino Physics Conference, October 2012

Results from a pioneer SONGS experiment were reviewed at IAEA Novel Technologies meeting in Oct'08 and found to demonstrate the potential for the approach.

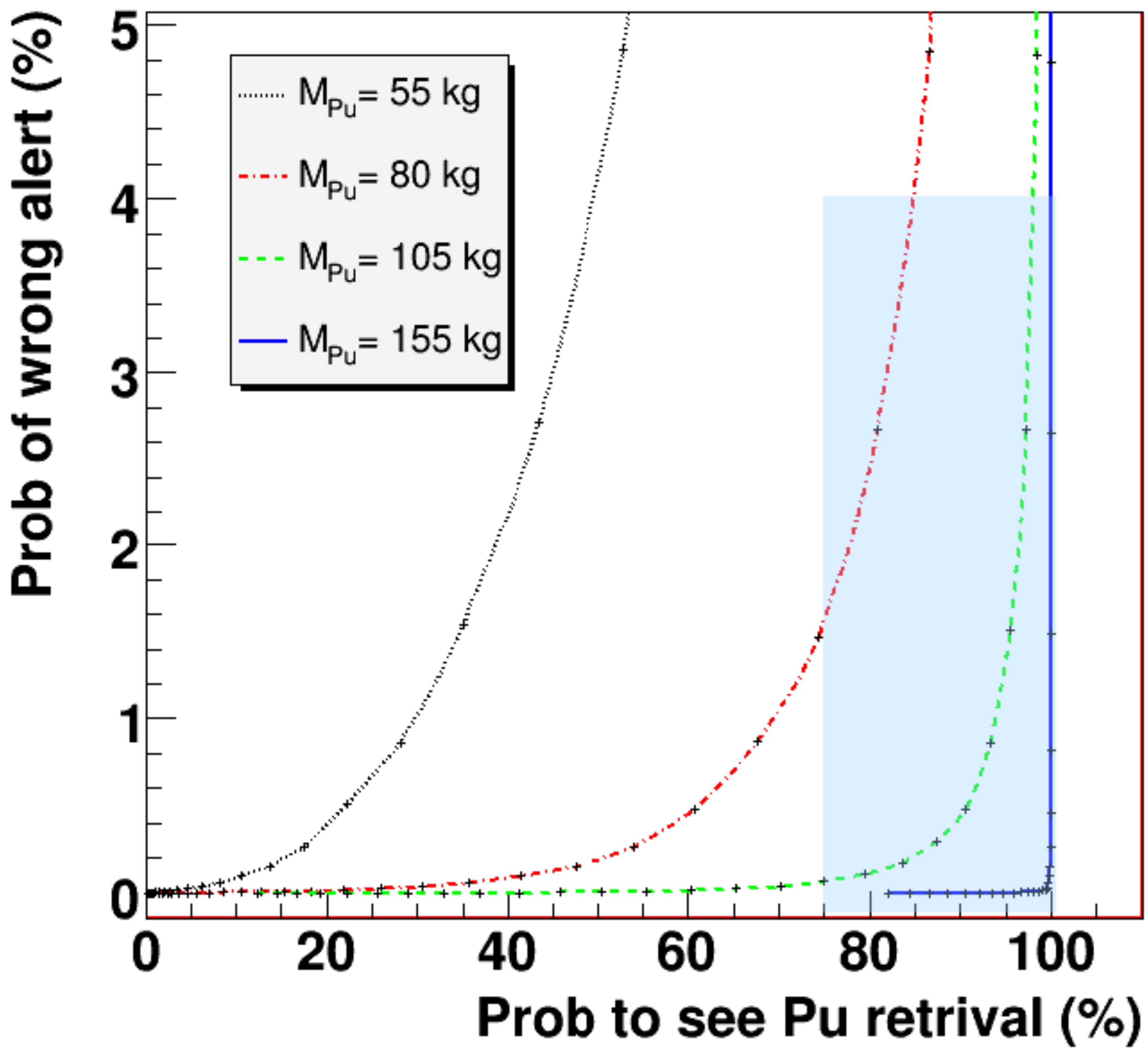
Example: NUCIFER Experiment

- Deployment at a research reactor — Saclay Osiris (France)
- Detector at 7m from 70MW core
- ~700 anti-v events/day expected
- Funded, built, taking data

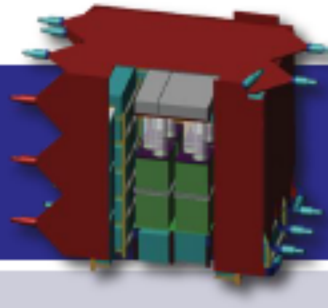


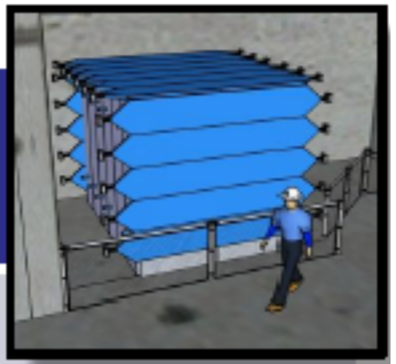


NUCIFER Sensitivity to illicit Pu Retrievals from nuclear reactor core



More examples

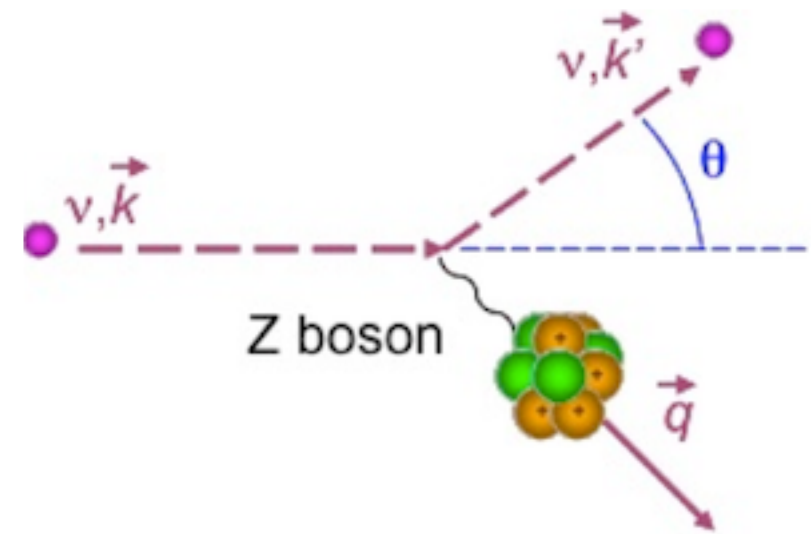




Quantity	SONGS 1	CANDU estimates
Reactor thermal power	3.4 GW	2.2 GW
Core distance	~25 m	~77 m
Relative Flux	1.00	0.08
Detector active mass	0.64 tons	3.6 tons
Deployed Footprint	6 m^2	10 m^2
Overburden	~25 m.w.e.	~ 18 m.w.e.
ν interaction rate * efficiency = detection rate	~ 4000/day * 10% = ~ 400/day	~2000/day *20% = ~ 400/day

Other developments: Coherent Neutrino Scattering

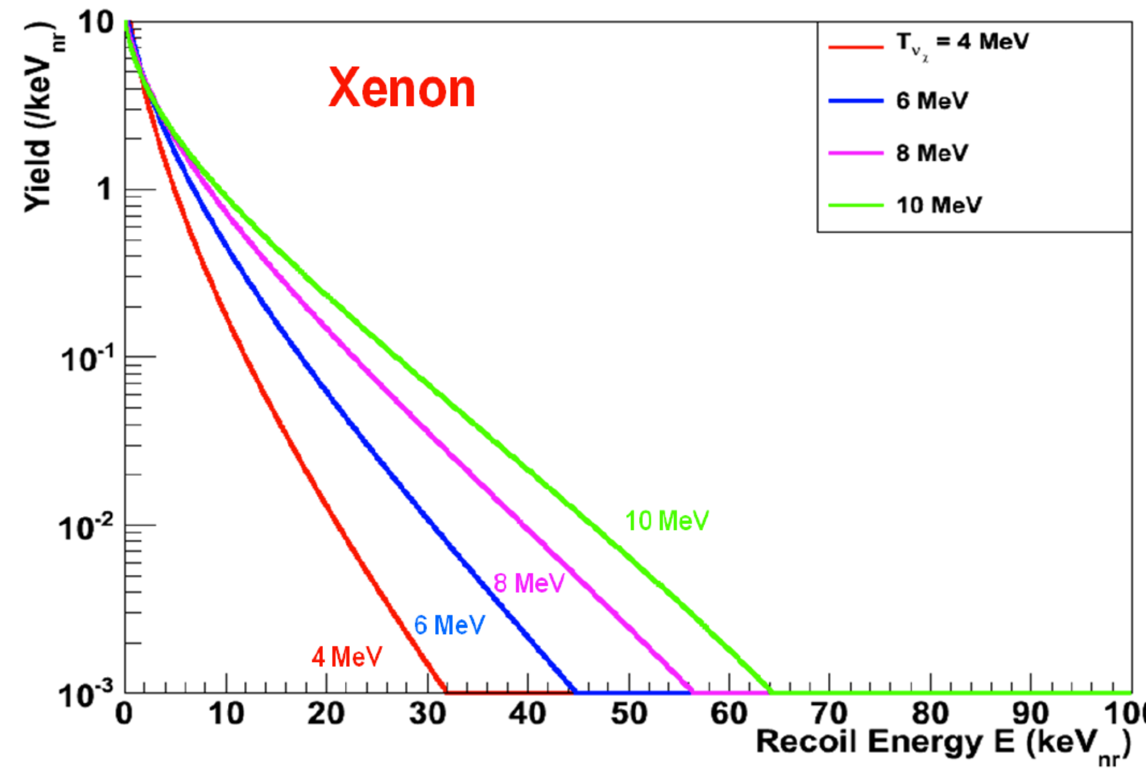
- Neutrino elastic scattering from a nucleus as a whole
- Relevant for ν's of ~ MeV range (good match for reactor anti-ν's)
- A "Standard Model"process that yet to be observed
- Main challenge: tiny energies from nuclear recall —> —> very low thresholds (~1 keV)
- International R&D effort and competition to observe CS for the first time
- Important reward: cross section (probability of interaction) is ~10 higher than "conventional" ν-interaction — much smaller detectors can be used



ionisation caused by nuclear recoil is measured

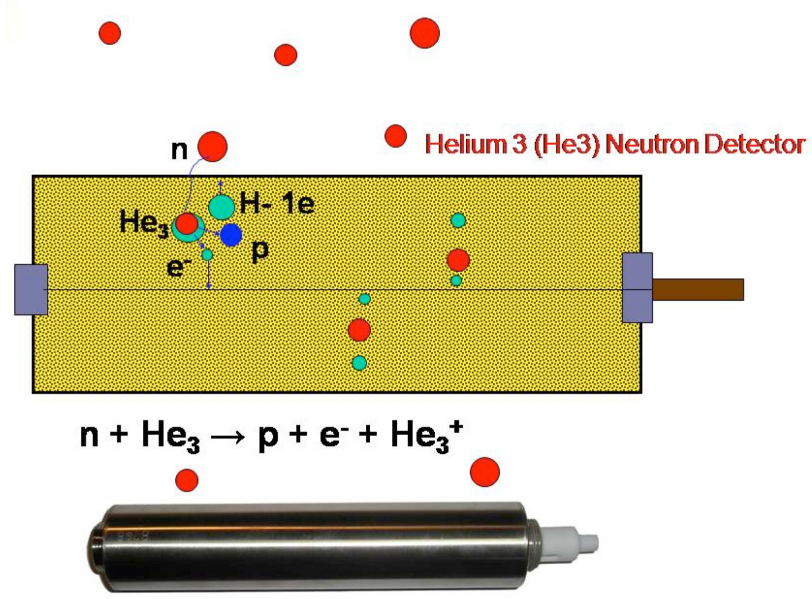
Detector R&D, synergies with dark matter detection focus on ultra-low thresholds

- **B**road **E**nergy **Ge**rmanium detectors (**BEGe**)
- Low temperature bolometers
- Liquid and gaseous noble gas detectors (e.g. LAr, HPAr, LXe, HPXe)



Neutron detection of SNM and it issues

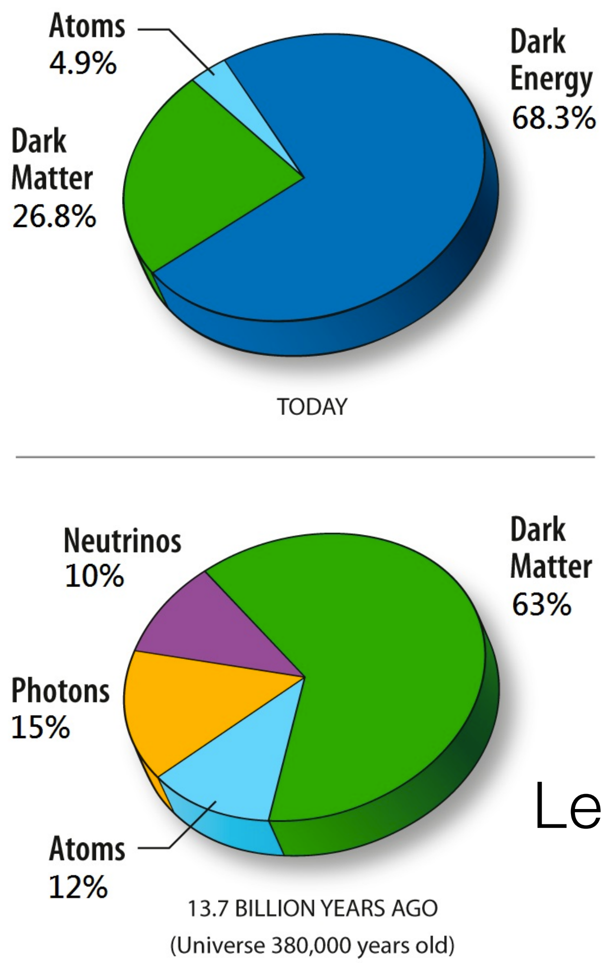
- Non-sensitive to isotope composition but provides clear signature of WGPu and HEU(90%)
- Relatively straightforward for WGPu but not for HEU
  - ~60,000 n/sec per kg WGPu
  - ~1 n/sec per kg HEU
- Neutron time signatures "multiplicity"
- Shortage of He3, other techniques needed
- Gamma background must be tackled

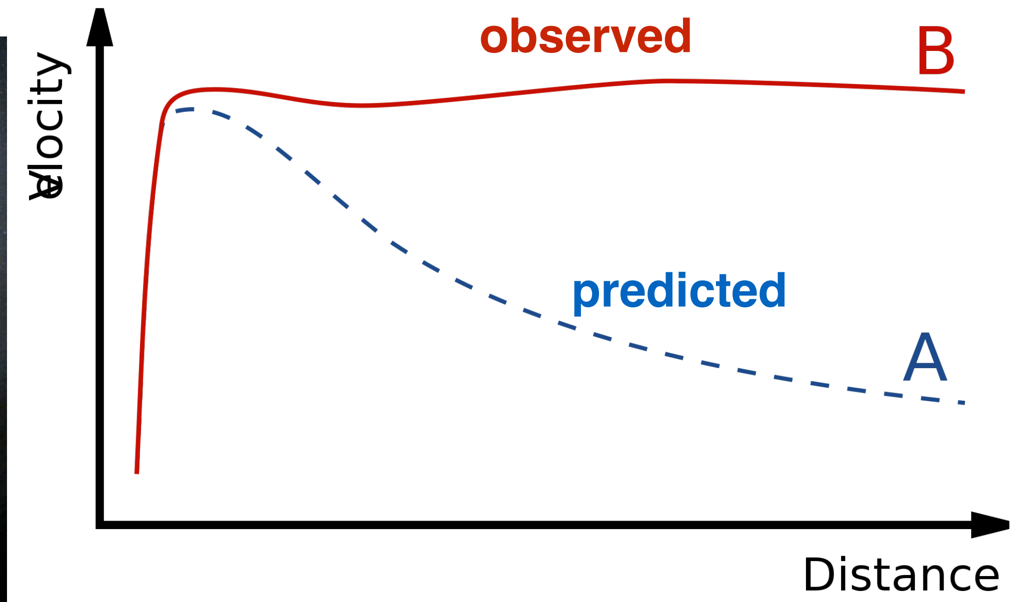


Can fundamental research help?

Instruments for direct detection of **dark matter** — most sensitive **neutron detectors**

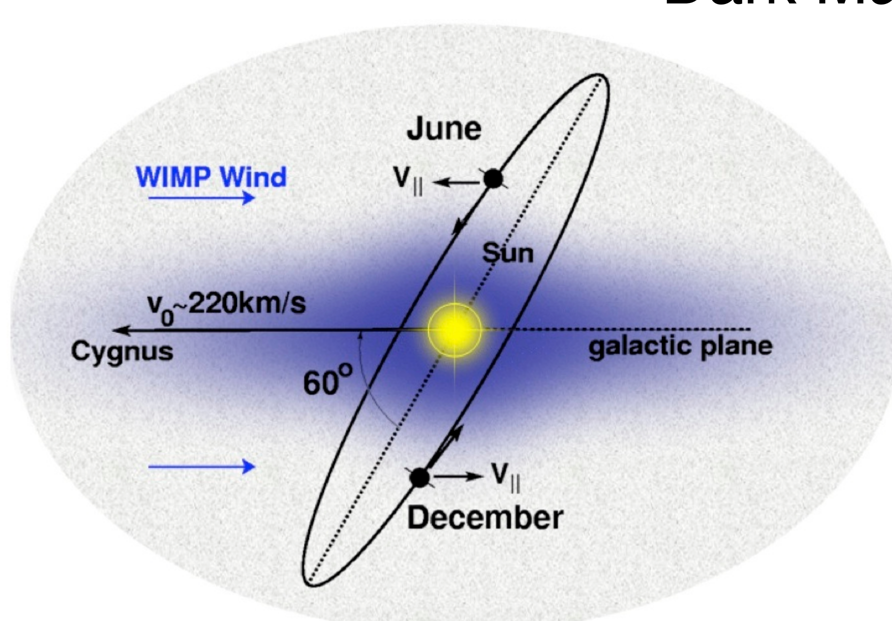
Dark Matter — we know it is there.
We don’t know what is made of.

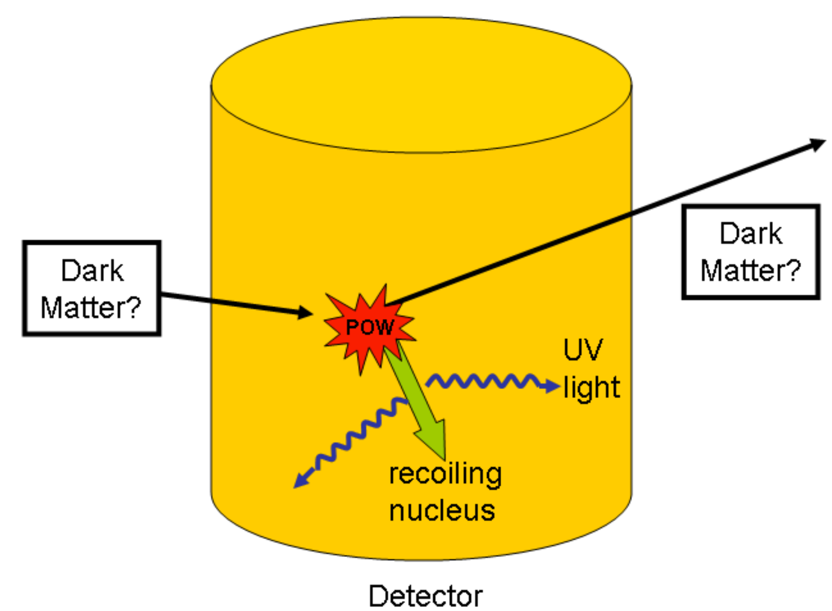




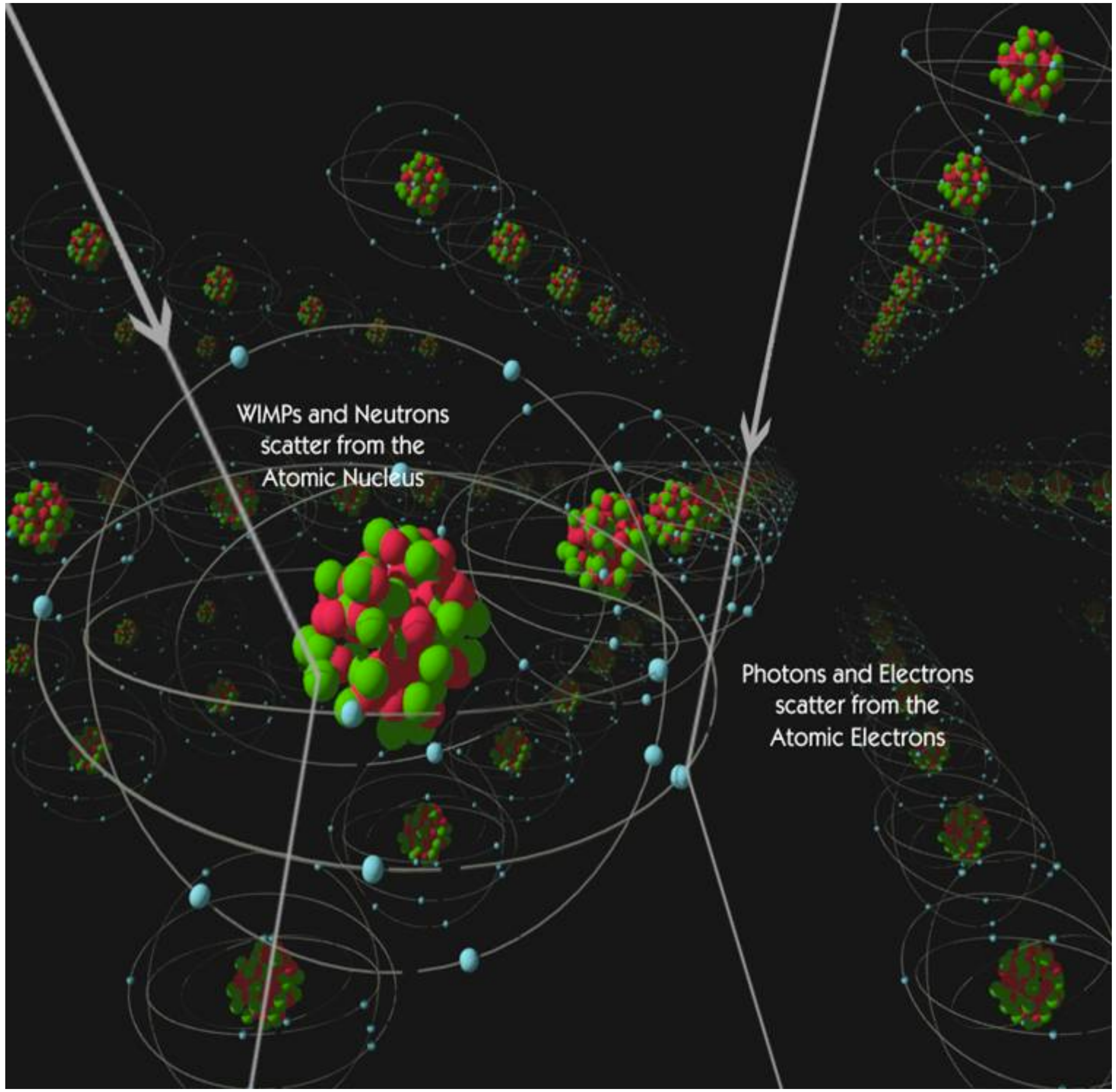
Leading candidate: **W**eakly **I**nteracting **M**assive **P**article — **WIMP**

Dark Matter direct detection:



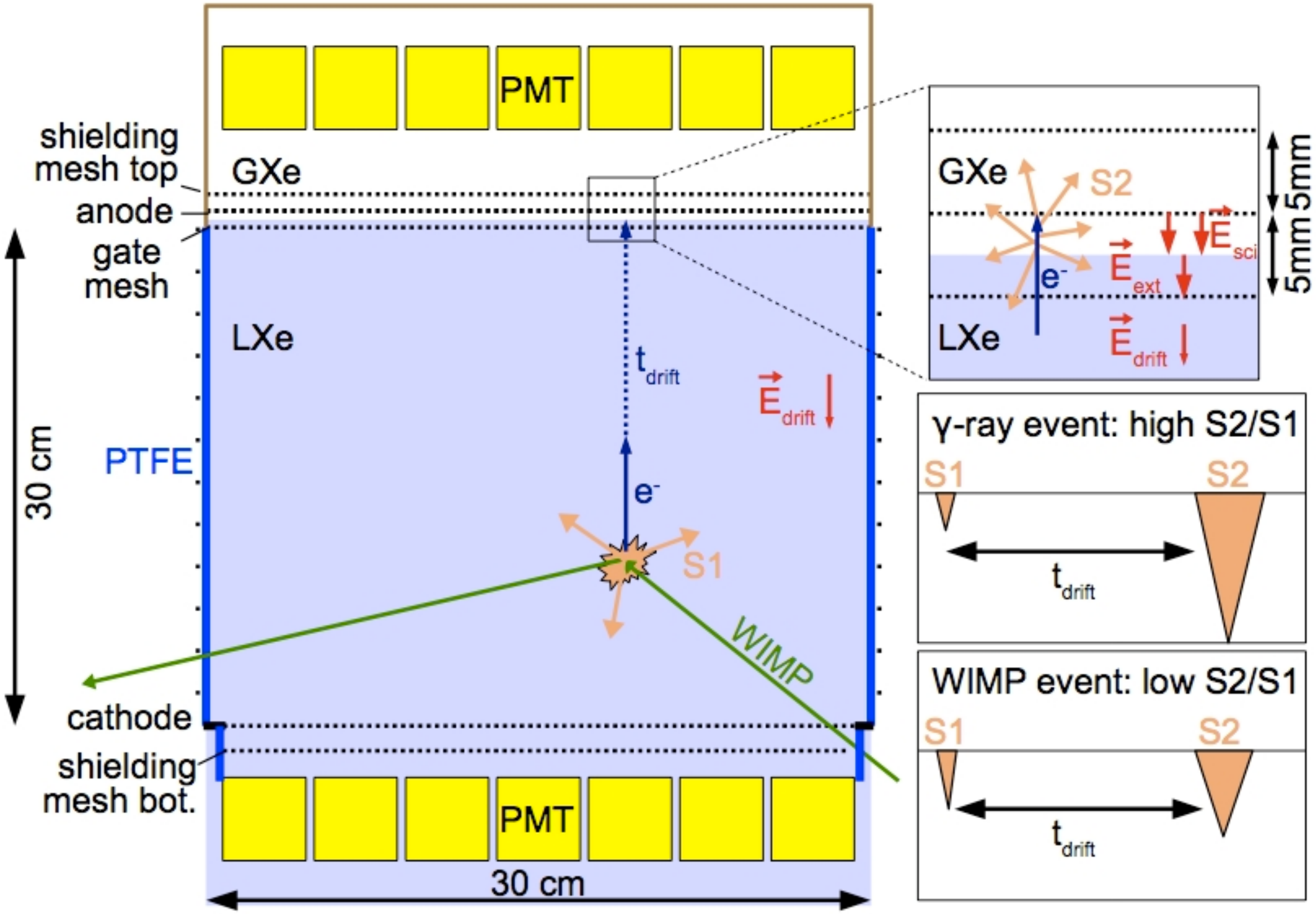


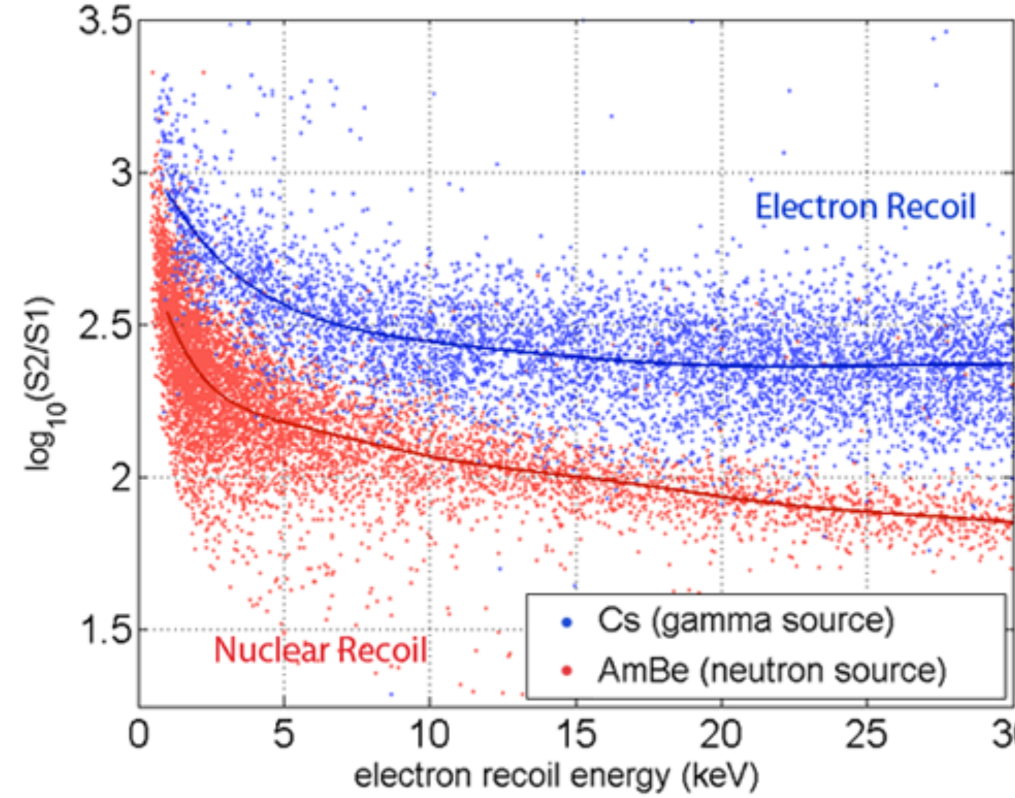
Direct Dark Matter Detection

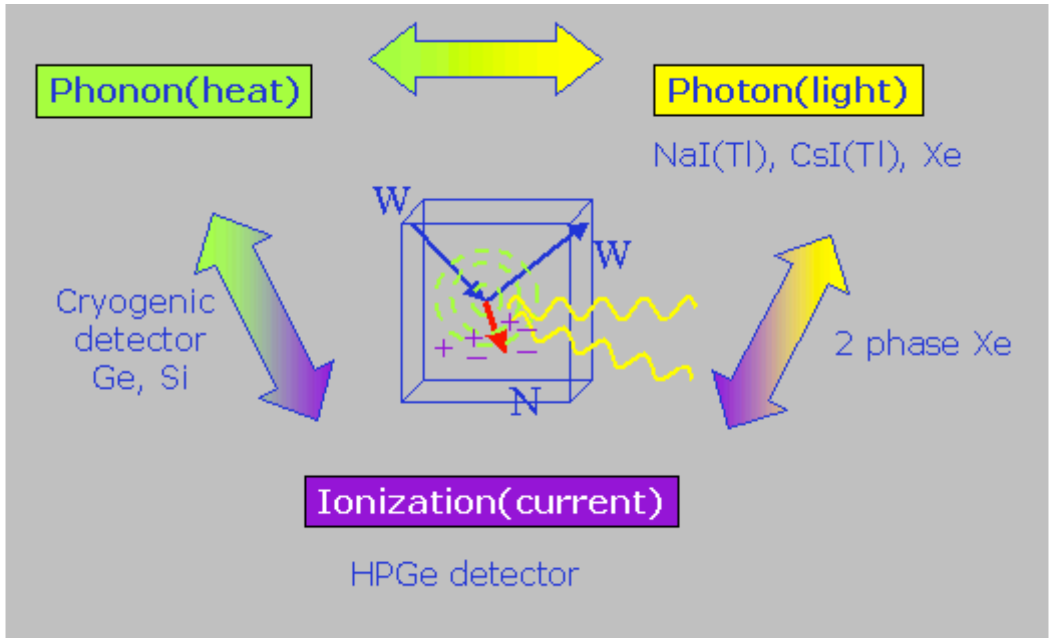


- WIMP interactions with matter are identical to neutron's
  - At issue: remove gamma background
- State-of-the-art dark matter instruments — most sensitive neutron detectors

Dark Matter LXe detector



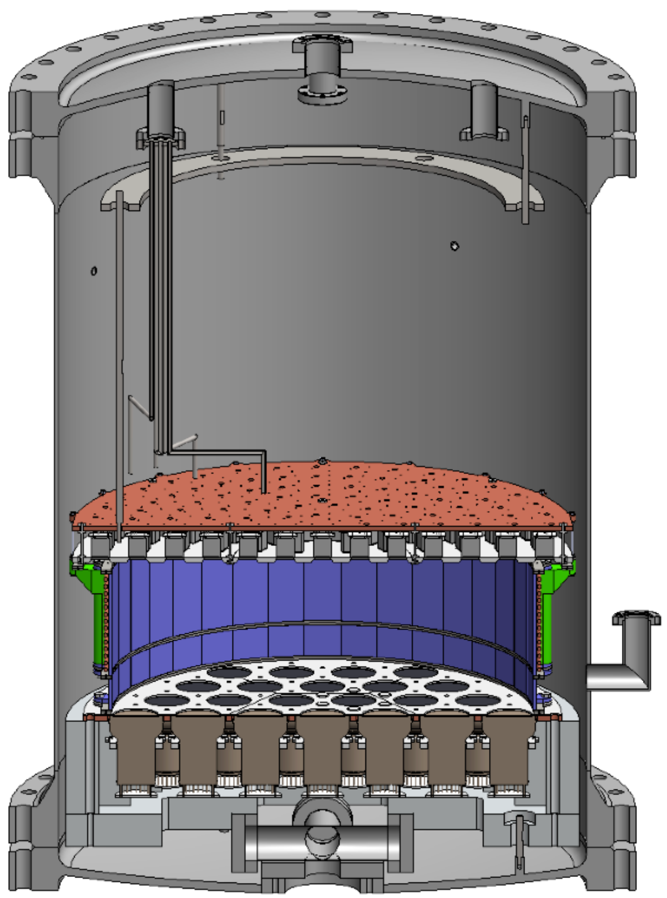




- A highly competitive (and collaborative!) field
- Many different technologies
  - LAr and LXe
  - Gaseous detectors
  - Semi-conductors
  - Bolometers
  - Scintillators and scintillating bolometers

<u>Unexplored</u> opportunity for SNM detection

PandaX — A direct dark matter detection experiment in China



Two-phase LXe position sensitive detector
1 ton of LXe

CJPL Underground Laboratory
Sichuan province

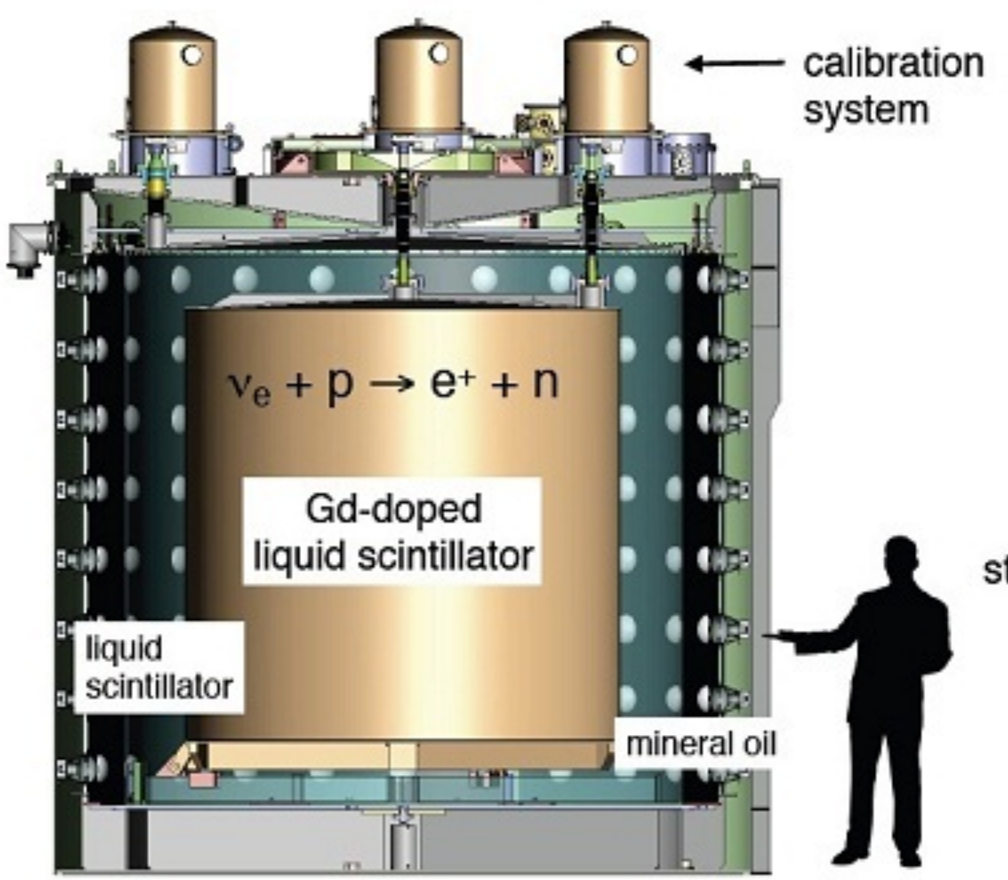
Concluding Remarks

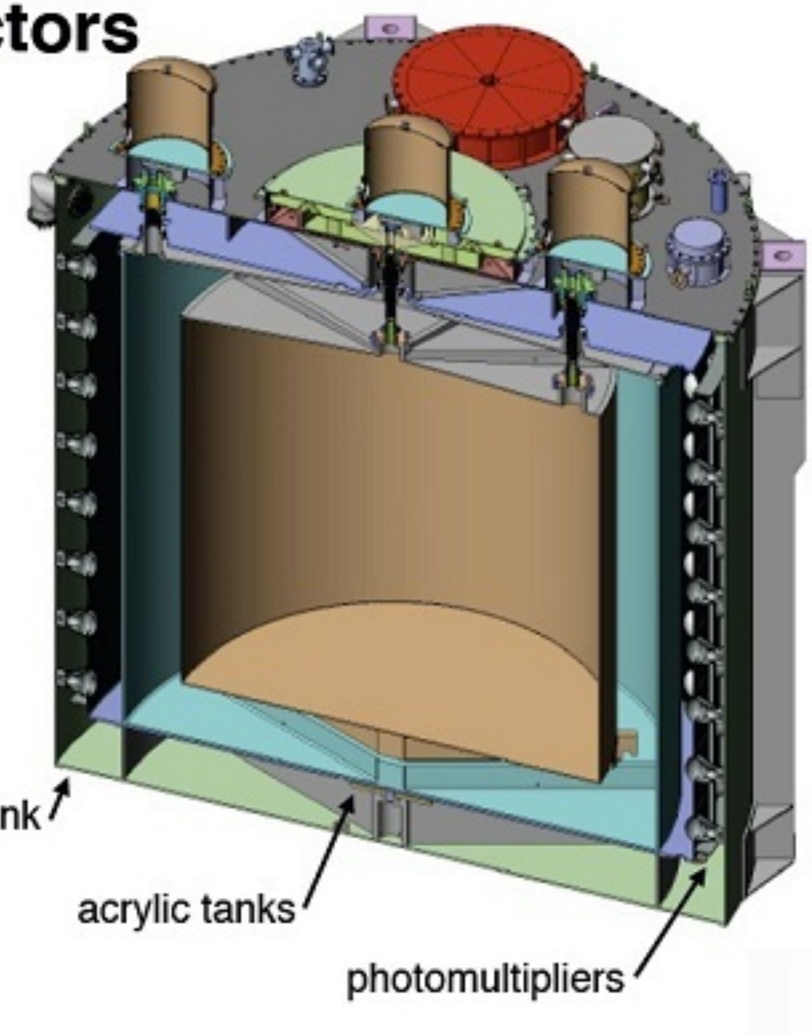
- **Antineutrino detectors** have unique abilities to **non-intrusively monitor** reactor operational status, power and **fissile content** in real-time;
- Several detectors, built specifically for safeguard applications, have demonstrated **robustness** of this **technique** at operating power reactors. Several more are planned;
- Implementation in safeguards regime can be aided by further **input from IAEA** on the needs at specific reactors;
- Promising **technological breakthroughs** are possible leading to more compact detectors and/or ability to detect less powerful reactors at a greater distance;
- **Novel technologies** developed for direct **dark matter** detection can increase sensitivity and reliability of **SNM detection**;
- Increased **international cooperation** in particle physics in the last ~25 years have led to profound fundamental discoveries and **enhanced detector capabilities** which can be used in arms control;
- **China** has played an **increasingly important role** in both fundamental research (neutrino physics, dark matter) and instrumentation development;
- Closer cooperation between **Fundamental Research** and **Arms Control** communities is important in addressing verification challenges;

BACKUP

The Daya Bay Antineutrino Detectors

8 “identical”, 3-zone detectors
no position reconstruction, no fiducial cut needed





target mass:	20t per detector
detector mass:	~ 110t
photosensors:	192 PMTs

Daya Bay nuclear power complex (Guangdong, China)

At 2.9 GW per reactor, the complex produces ~3x10[21] anti-ν’s per sec

Hidden nuclear Reactors

- **A possibility to monitor a country without cooperation?**

- Neutrino rate:

$$450 \text{ events} \times \left(\frac{100 \text{ km}}{D}\right)^2 \times \left(\frac{P}{10 \text{ MW}}\right) \times \left(\frac{1}{1 \text{ Megaton water}}\right) \times \left(\frac{t}{1 \text{ year}}\right)$$

- Challenge: Mega Ton Scale water-based antineutrino detectors
  - Gadzook
  - Prohibitive cost → Invent low-cost photodetectors, …

- Beyond IAEA mandates

Arxiv:1011.3850 → Summary & Conclusions

- **Futuristic option of using very large neutrino detectors to detect clandestine nuclear reactors. Development not unrealistic within the next 30 years, not taking into account financial constraints**

- **Detector modules of 138,000 tons, fitting inside an oil supertanker, and using liquid scintillator technology**

- **Assess the detectability of clandestine reactor at any Earth location**

- **We modeled the non-neutrino background evolution as a function of the detector's operating depth**
  - Detectors could also be deployed at depths ranging from 0. 5 km to 2 km
  - A 300 MW reactor could be detected after 6 months with a single detector located 300 km away, operating at a depth greater than 1,500 m
  - A 50 MW reactor could be detected after 1 year with 5 detector modules a at 200 km

- **A few 138,000 ton neutrino detectors have the capability localize clandes-tine reactors from across borders.**