Safeguarding naval reactors

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What is the problem?

The Treaty on the Non-proliferation of Nuclear Weapons (NPT) allows for the withdrawal of SNM from safeguards, to move it to military non-explosive uses (INFCIRC/153 §14).

aka Naval Loophole

- For propulsion, i.e. naval reactors on military vessels, esp. submarines
- Nuclear powered vessels are currently used only by weapon states
- Brazil has a long-standing nuclear submarine program
- Problem gained urgency with tri-partite Australia UK US agreement (AUKUS) to share nuclear submarine technology with Australia

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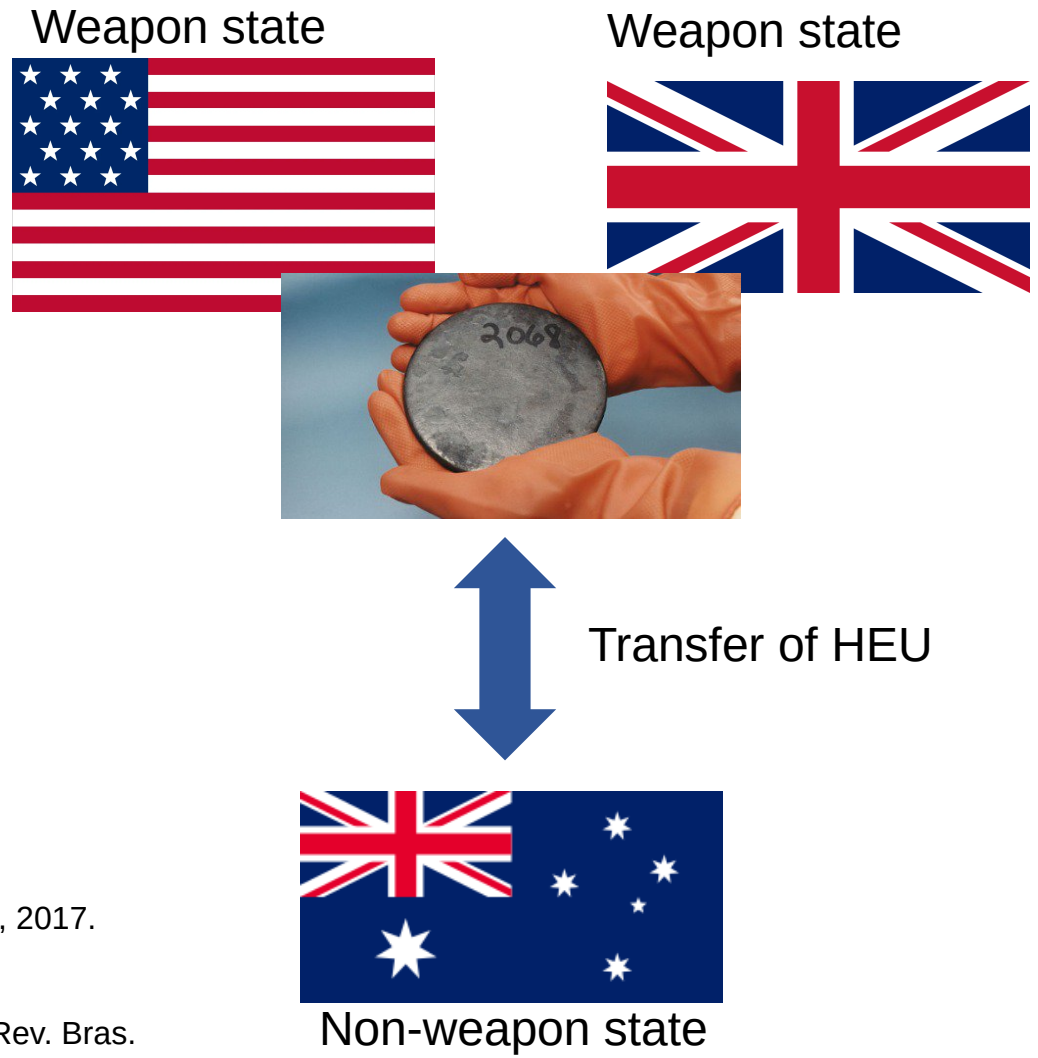
AUKUS implications

- US and UK use HEU for submarine propulsion → AUKUS likely will involve HEU fueled submarines
- On-shore safeguards probably could be similar to what is done for civilian applications w/o disclosing details of fuel element design



T. E. Shea, The Nonproliferation and Disarmament Challenges of Naval Nuclear Propulsion, 2017.
S. Philippe, Safeguarding the military naval nuclear fuel cycle, Journal of Nuclear Materials Management XLII, 40 (2014).
E. P. L. D. Costa, Brazil's nuclear submarine: A broader approach to the safeguards issue, Rev. Bras. Polít. Int., 60 (2017).

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Safeguards of fuel while on board?

- Conventional techniques relying on C&S methods are difficult to implement if parts of or the entire the vessel are off limits
- No safeguards access while at sea, obviously
- Need to reconsider goals: verification that propulsion is nuclear as proxy for actual knowledge of where the HEU is
- One proposal (Shea, 2017):
  - Observe neutron flux in reactor compartment via neutron activation of suitable “seals”, so-called flux tabs
  - Use managed access to install and retrieve while in port

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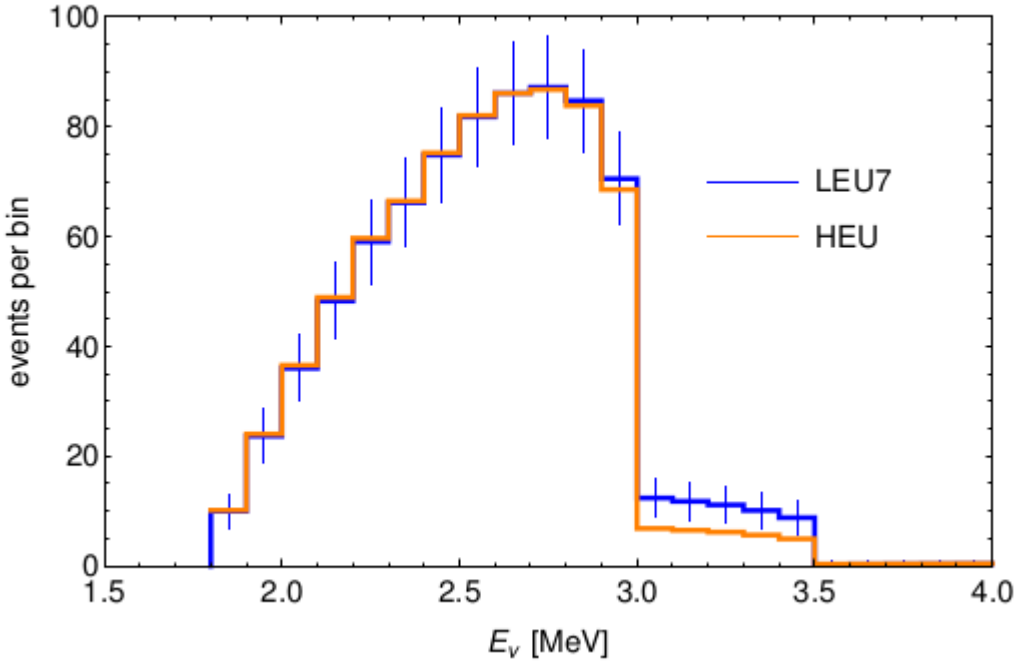
Neutrinos instead of flux tabs

- In port reactor is shut down
- Rely on beta decay of fission fragments 144Ce and 106Ru:
- -Percent level FY
- -Neutrinos above detection threshold
- -Half-lives of 411d and 536d
- Assume two patrols per year: 120 days at sea, 60 days in port and a 150MW reactor running at 1/4 power while at sea



Typical event rate spectra in 10 ton detector based on inverse beta decay,
7m from reactor core over a 60 day period.

B. K. Cogswell, P. Huber ,PRL **128**, 241803

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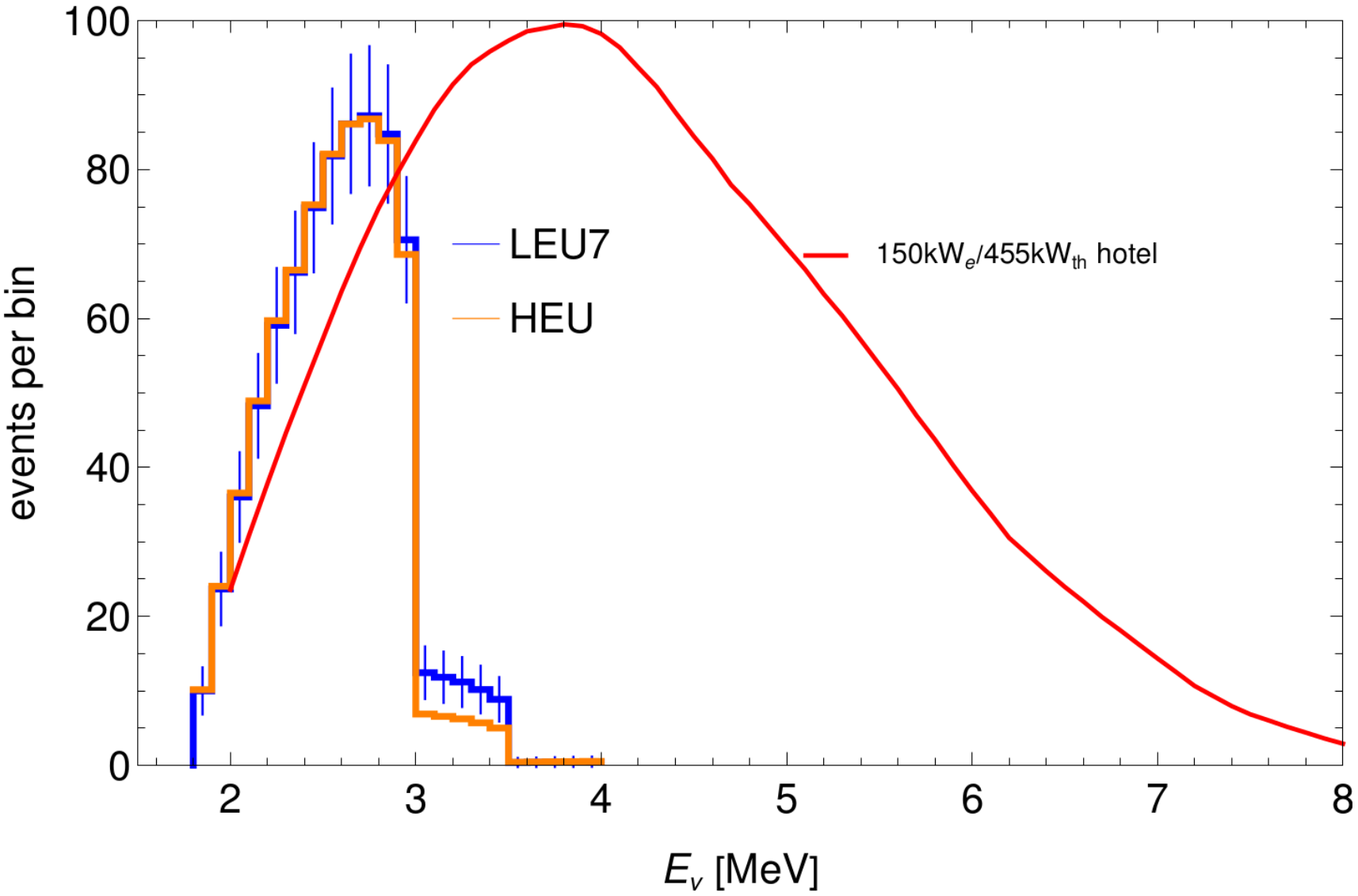

790 events for CeRuLEAN (10 ton, 10m, 60 days)
3200 events for hotel load

Hotel load based on master thesis of T.Ippolito which is the only open source reference with any quantitative details on naval reactors.

That submarine has 1/3 the displacement and reactor power of that of a Virginia class sub.

Both CeRuLEAN and hotel load are small signals relative to what miniCHANDLER and PROSPECT see.

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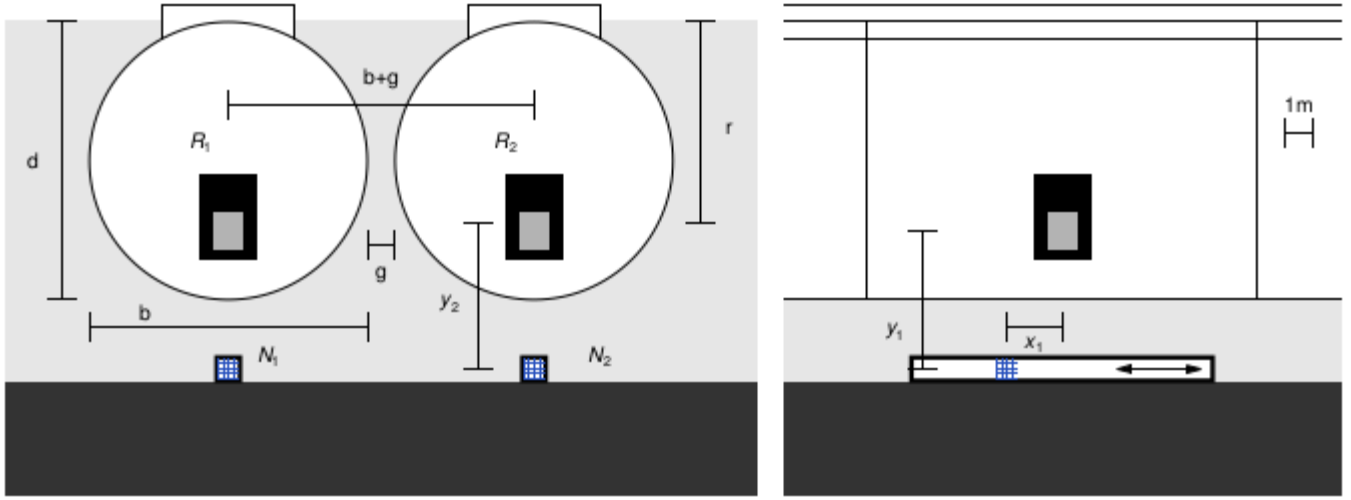
Detector deployment and operation



- Detector below submarine → reduces cosmic ray backgrounds to manageable levels
- Allow owner to adjust reactor/detector distance to conceal actual fuel consumption
- Background from close-by subs?

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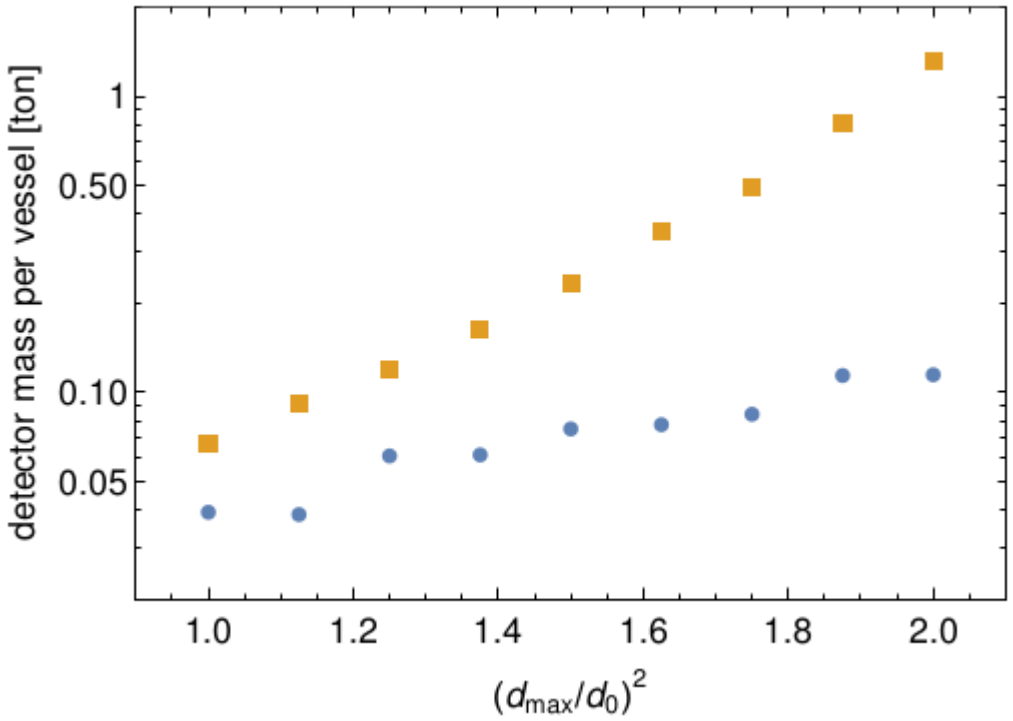
Single vessel results

- Hypothesis test with 90% detection probability with 5% false positive rate
- What detector mass is required to achieve test goal within 60 days?



Blue circles depict single vessel case. d0=5m.

Even for large power masking factors ~100kg detector works

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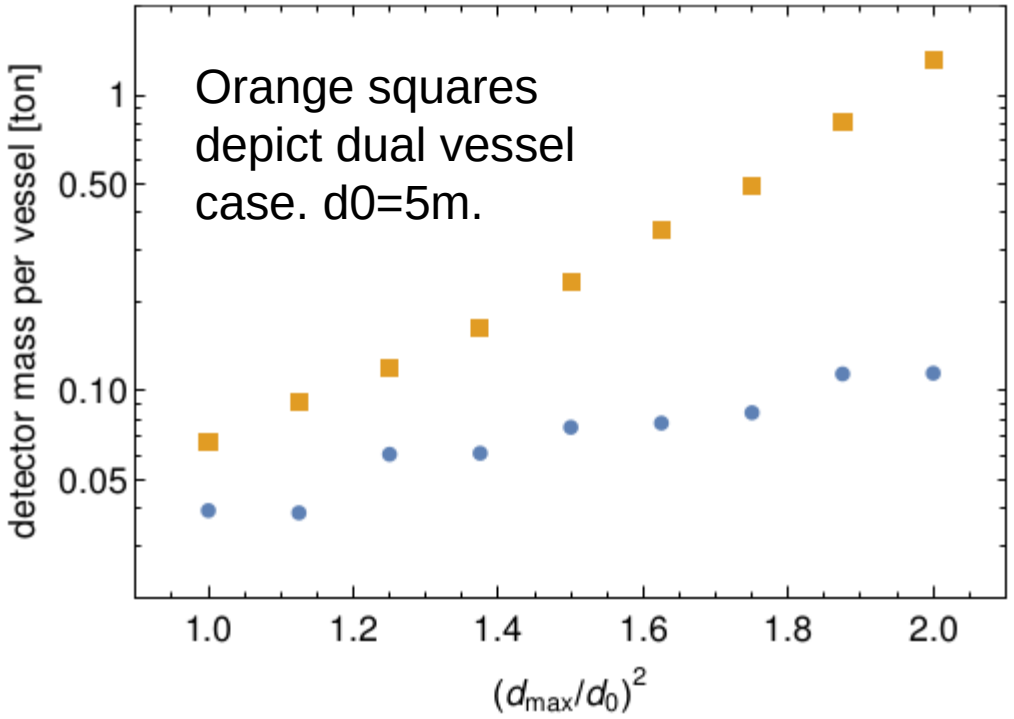
Dual vessel results

- Assume two vessels berthed side-by-side
- No knowledge about reactor state of the “other” vessel
- 2 detectors, 2 independent power masking factors
- With a bit of game theory one can work out the worst case
- 10-fold increase in detector mass.



NN	nn_1	nf_1	fn_1	ff_1
nn_0	1.	1.	1.	1.
nf_0	1.	1.	1.	1.
fn_0	0.99	0.93	1.	1.
ff_0	1.	0.99	1.	1.

NF	nn_1	nf_1	fn_1	ff_1
nn_0	1.	1.	1.	1.
nf_0	1.	1.	1.	1.
fn_0	0.99	0.98	1.	1.
ff_0	1.	1.	1.	1.

FN	nn_1	nf_1	fn_1	ff_1
nn_0	1.	0.09	1.	0.74
nf_0	1.	0.36	1.	0.99
fn_0	0.91	0.04	1.	0.44
ff_0	1.	0.535	1.	0.999

FF	nn_1	nf_1	fn_1	ff_1
nn_0	1.	0.87	1.	1.
nf_0	1.	0.99	1.	1.
fn_0	0.83	0.31	1.	0.99
ff_0	0.98	0.84	1.	1.

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Fleet-wide detector

- Instead of one small detector per boat and 60 days data taking use one large (~10 ton) detector and 1 day data taking
- Avoids dual vessel problem
- Operationally less complicated
- Could be deployed outside secure perimeter of naval base

Base de Submarinos da Ilha da Madeira, Brazil

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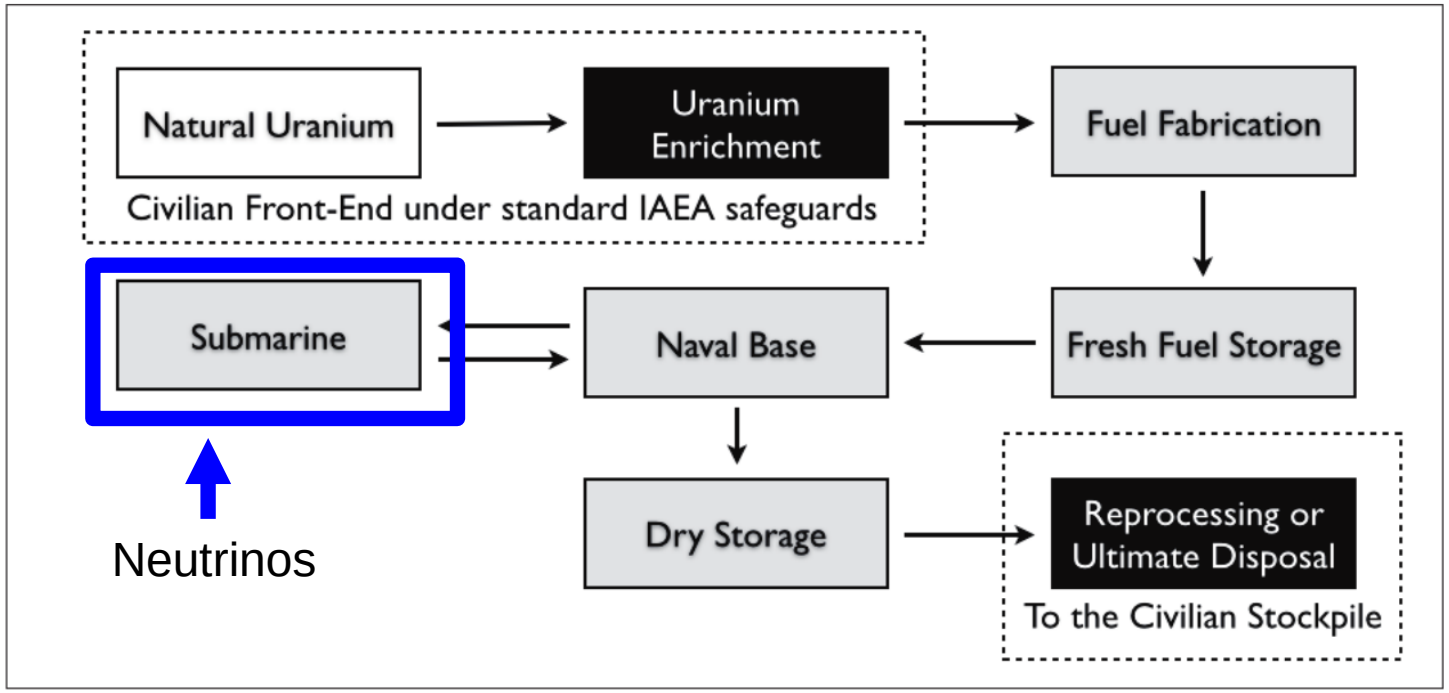
Mission Relevance

- Verification of nuclear nature of propulsion
- Operational details hidden behind information barrier (power masking)
- No on-board access required



S. Philippe, Safeguarding the military naval nuclear fuel cycle, Journal of Nuclear Materials Management XLII, 40 (2014).

- Effective safeguards under difficult conditions

In the AUKUS case it is unclear if front end technology would be transferred.

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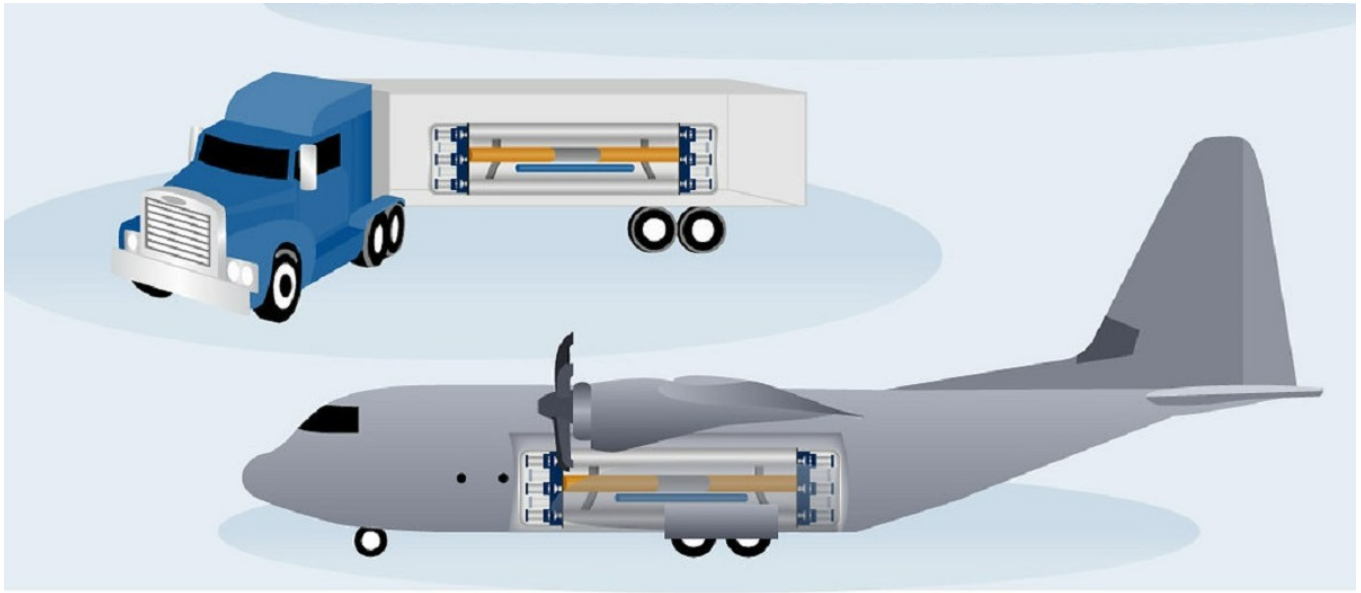
Thoughts about civilian reactors

- Civilian reactors probably multi-MW
- On-board access seems not a problem
- Mobile reactors may not be unique to ships
- → micro reactors (PELE, Marvel, Oklo)



What would a neutrino measurement provide one couldn't get otherwise by simpler means?

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Summary

- AUKUS deal will set a precedent, either way
- Important to get it right, esp. as global tension increases
- U.S. and Royal Navy sensitivity around nuclear propulsion disqualifies conventional technology
- Neutrino signatures can test for nuclear nature of propulsion, secure built-in information barrier
- No on-board access needed

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