SNIFR - Submarine Neutrino Identification For Reconnaissance

Applied Antineutrino Physics 2023

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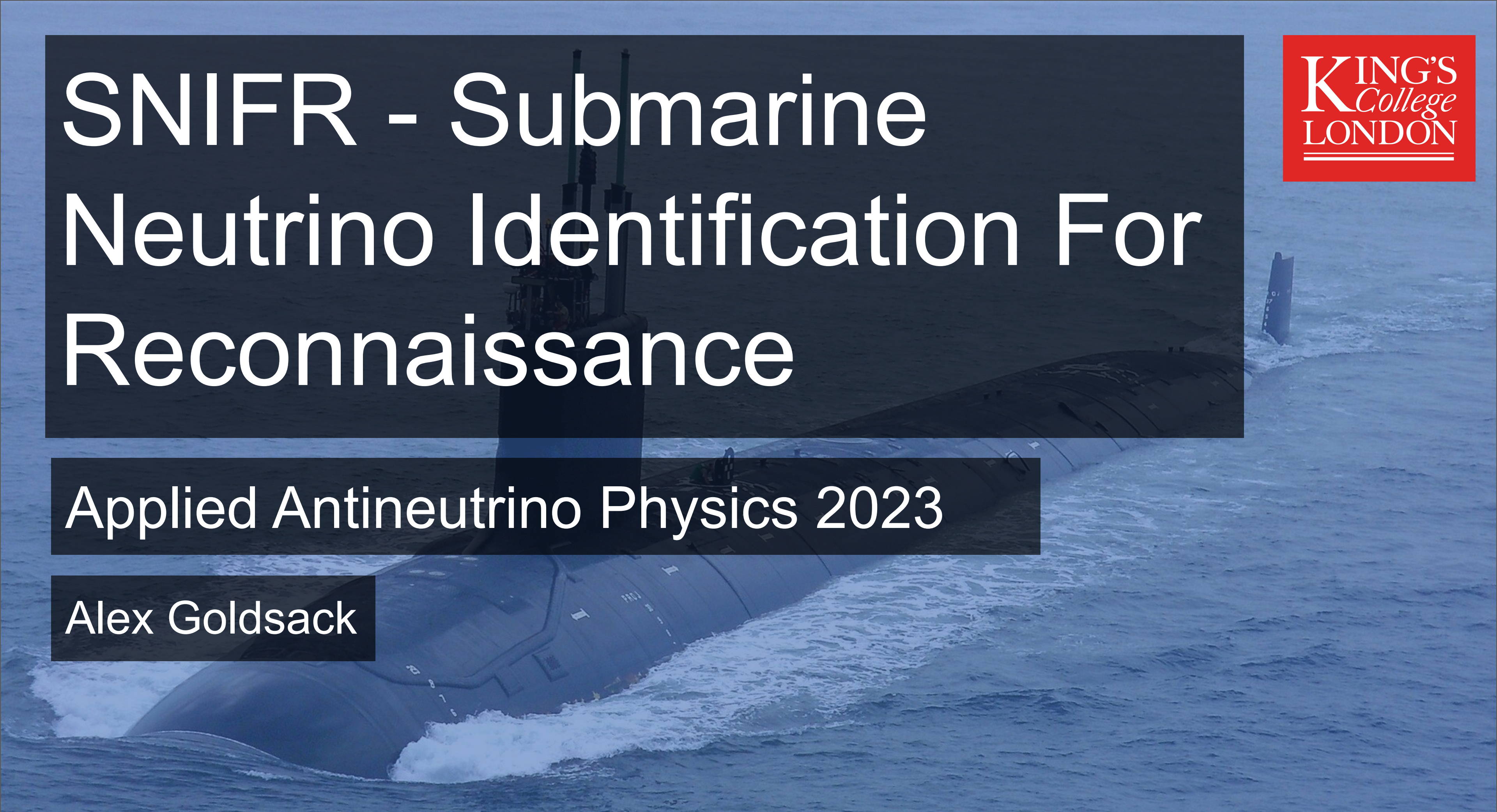


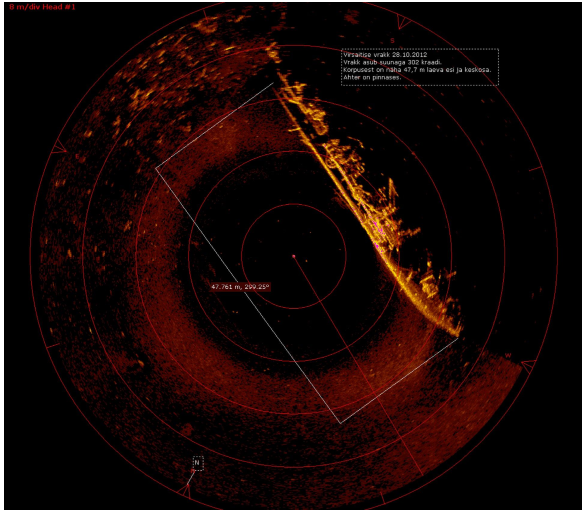
US Virginia-class submarine underway in Groton, Connecticut, July 2004 - U.S. Navy photo by General Dynamics Electric Boat

Managing Expectations

- This talk is **not**:
  - Representing an actual experiment/project.
  - An exhaustive study.
  - Detailing detector design.
  - An original idea.
- This talk **is**:
  - A reassessment of an old idea through the lens of modern technology.
  - Based on a mix of hand-wavy calculations and my experience on SK(Gd).
  - My crackpot side-interest.
  - Aiming to promote discussion.

SONAR - **So**nic **N**avigation **A**nd **R**anging.

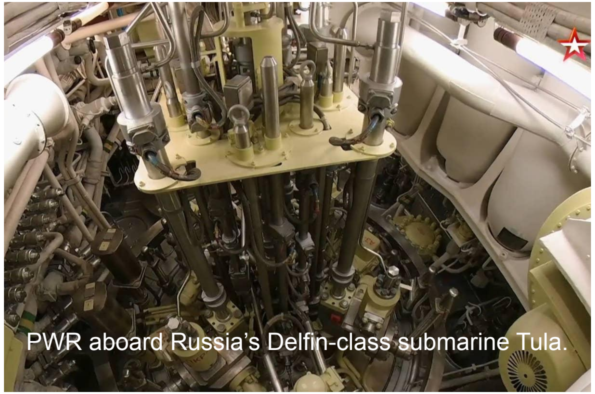
- Primary method for tracking and identifying submarines in a military context.
- Active SONAR fires sonic pulses and listens to the reflections.
  - Classic “ping” nowadays a rising tone to provide a range of resolutions and ranges.
- Incredibly precise at short range, often used to map underwater structures.
- Active pings are **very** powerful, not used lightly.
  - Immediately reveals position of active SONAR source.
  - Strong enough to be used as a lethal defence against divers.
  - Range is environment-dependent, but around 300km for the longest range but more often <100km (probably less) [1].
- Passive SONAR listens.
  - Sonic profile can identify specific vessels.
  - Very difficult to make a nuclear sub completely silent (reactor).
  - Range is highly dependent on environment + vessel, can be extremely far in the right conditions (very hard to quantify).

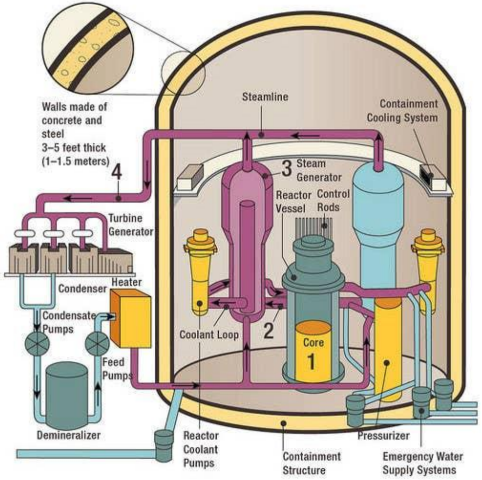


[1] - Sonar and seismic impacts, Australian Government

Nuclear Submarine Reactors + Neutrinos

- Most nuclear subs are powered by PWRs.
- Submarine reactors produce up to ~100-200 MWth, 10X less than commercial reactors.
- Can't easily switch off their reactor and still function - always producing neutrinos.
    - Decays when not critical will still produce neutrinos when shutdown, at ~7% the full rate with a half life of a few hours.
- Detecting submarine neutrinos would give a clear indication of a nuclear sub.
- But neutrino detectors aren't small.
- And submarines don't like to sit by the coast, static, while detectors accumulate enough data to identify…


PWR aboard Russia's Delfin-class submarine Tula.



SNIFR Proposition

- Proposition: take a neutrino detector, put it on a big ship, and scour the seas for submarines.

+

= SNIFR!

NuBoats??

NuDAR vs. SONAR

Neutrino Detection And Ranging
(though ranging is a bit of a stretch…)

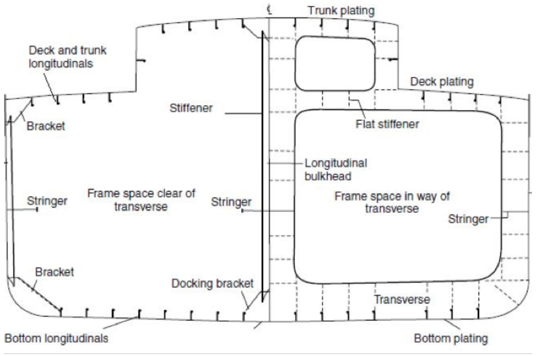
- Let's compare this to SONAR…
- Advantages:
  - Entirely passive - no "pinging", just "sniffing" for neutrinos.
  - Environment/situation independent - neutrino backgrounds are effectively constant with weather and location on the sea.
  - Don't need your vessel to be quiet.
- Disadvantages:
  - Imprecise ranging - nu flux is proportional to reactor output. Knowledge of current reactor output is needed to predict flux, and interaction rate must be high to draw ranging conclusions.
  - No directionality - IBD products are (effectively) uncoupled from neutrino direction. Would need to triangulate positions with multiple detectors, made worse by ranging issues.
  - No source categorisation - can (sometimes) identify submarines by their sonic signature. No way of discerning different reactor types.
  - Requires long exposure time ~hours in range of sub (discussed later).

Detector Technology

- Detector requirements:
  - Sensitive to reactor neutrinos/IBD.
  - Can handle surface cosmic flux (spallation) + other BGs (the sea is full of mysteries…).
  - Highly-scalable, ideally modular.
  - Hardy - able to withstand potentially rough seas.
  - Relatively power-conservative.
  - Safe to keep on a ship.
- Gd-loaded water Cherenkov.
  - Very scalable, sensitive to IBD but PMTs with enough photocoverage are somewhat delicate, surface-level backgrounds will be difficult to remove. Very little granularity.
- Scintillator.
  - Highly sensitive to low energy events (+ backgrounds?). Potentially expensive at scale and requires clean environment. Can be segmented and modularised.
- Liquid Argon.
  - Very good tracking and particle ID. Very expensive at scale, requires cryogenics which may not play well on a ship, delicate wires.

Vessel

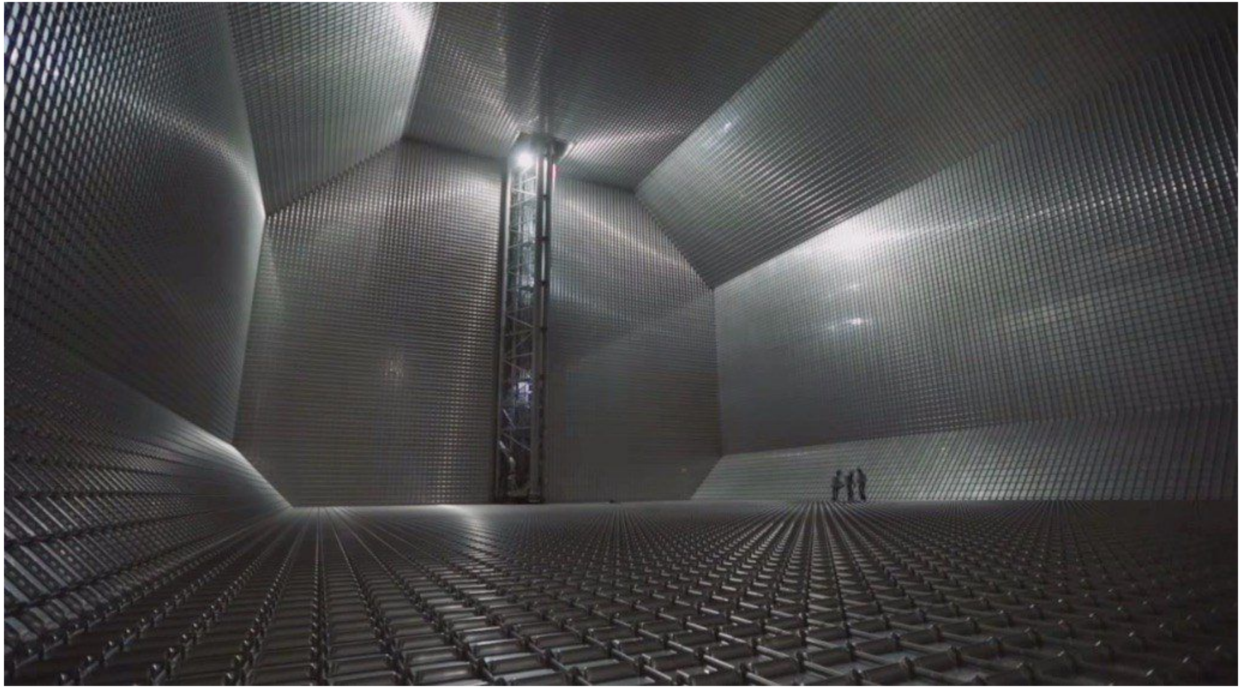
- Oil tankers benefit liquid-based detectors but are closed-top => difficult install.
- Cargo ship is much more accessible, infrastructure to move heavy equipment into the hold already exists.
- Very very large capacity far in excess of 100kt, ~$100M.
- Build the detector around matching the 20-foot container design?
- Many sub detectors (natural segmentation) each in a container with external connections.

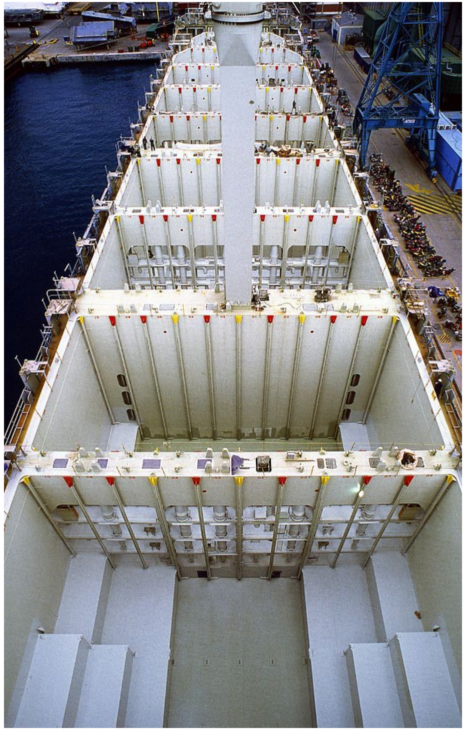


Class	Capacity [DWkT]	New Price
Product Tanker	10-60	$43M
Panamax	60-80	$60.7M
Aframax	80-120	$60.7M
Suezmax	120-200	$60.7M
Very Large Crude Carrier (VLCC)	200-320	$120M
Ultra Large Crude Carrier (ULCC)	320+	$120M

Class	Capacity [TEU]	Capacity $[m^3]$
Small Feeder	<1,000	<38,550
Feeder	1,001-2,000	38,559-77,100
Feedermax	2,001-3,000	77,139-115,650
Panamax	3,001-5,100	115,689-196,605
Post-Panamax	5,101-10,000	196,644-385,500
New Panamax	10,001-14,500	385,539-558,975
Ultra Large Container Vessel	14,501+	559,014+

Vessel





Sensitivity

- What rates do we need to actually identify a submarine?
- Heavily dependent on backgrounds and detection efficiency.
  - Which is in turn dependent on detector technology and would need some MC.
- Also dependent on deployment and how long subs are “in range”.
- Let’s wave some hands…

Sensitivity (Based on SKGd)

- Base the interaction rate on the predicted IBD rate at SK due to the Mihama power plant (P_{MH}=2440 MWth, r_{MH}=146 km away), as calculated in [2].
- IBD rate *N* in a detector of mass *M* for reactor power *P* at distance *r* via:

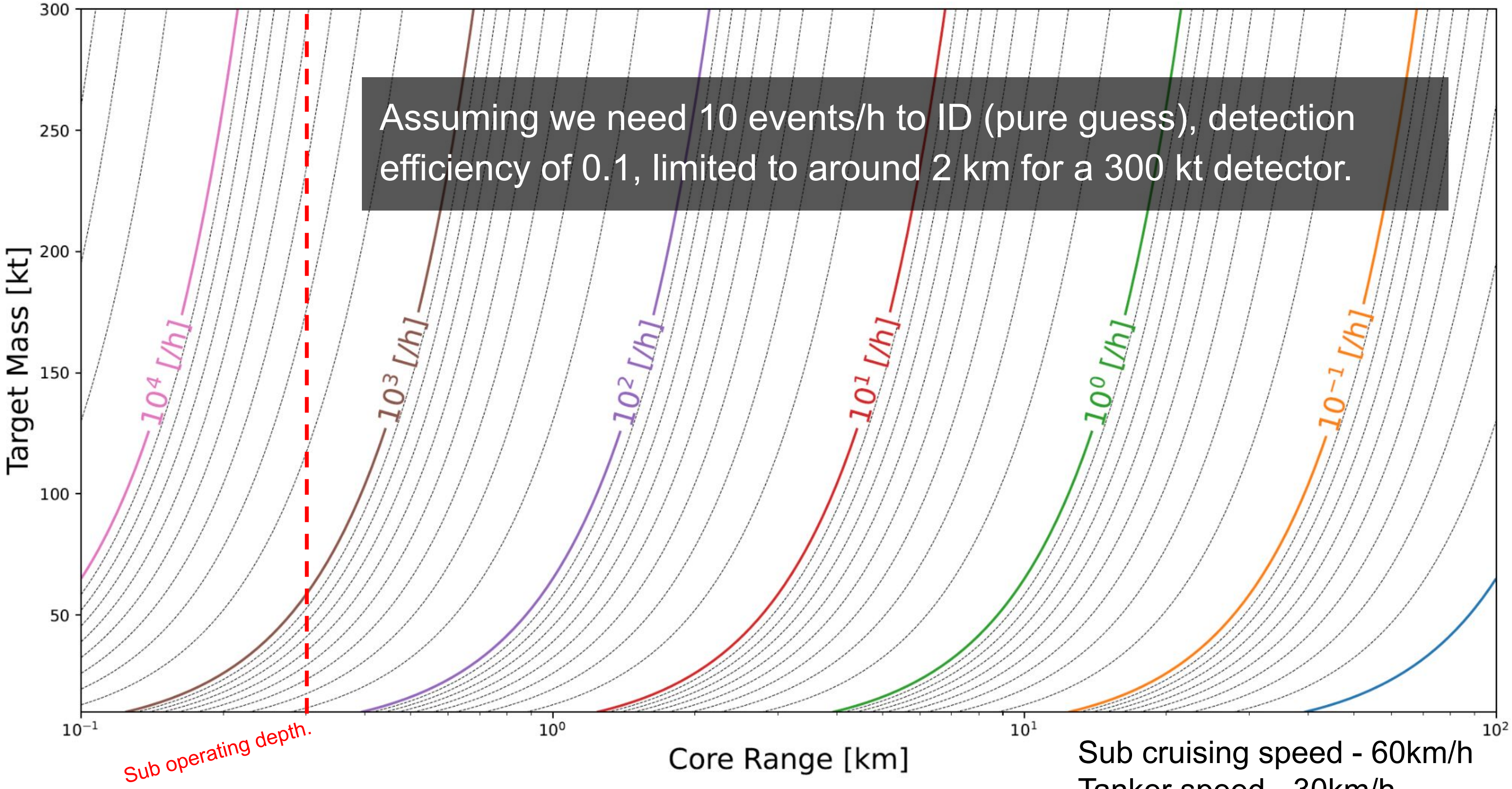
$$N = \frac{M}{M_{SK}} \times \frac{Pr^{-2}}{P_{MH} r_{MH}^{-2}} N_{MH}$$

- Where M_{SK}=22.5 kt is the fiducial mass of SK.
- Subs typically have 100-200 MWth reactors, but likely aren't running close to full power at all times. Assume 50 MWth for conservative estimates.
- For a single vessel, 300 kt is likely an upper limit of target material.

[2] - Reactor neutrinos in a gadolinium-loaded Super-Kamiokande, Alex Goldsack 2022.

Rates from 50 MW Core

- Does NOT consider detection efficiency (SKGd search is 10% efficient)



Sub cruising speed - 60km/h
Tanker speed - 30km/h

Viability

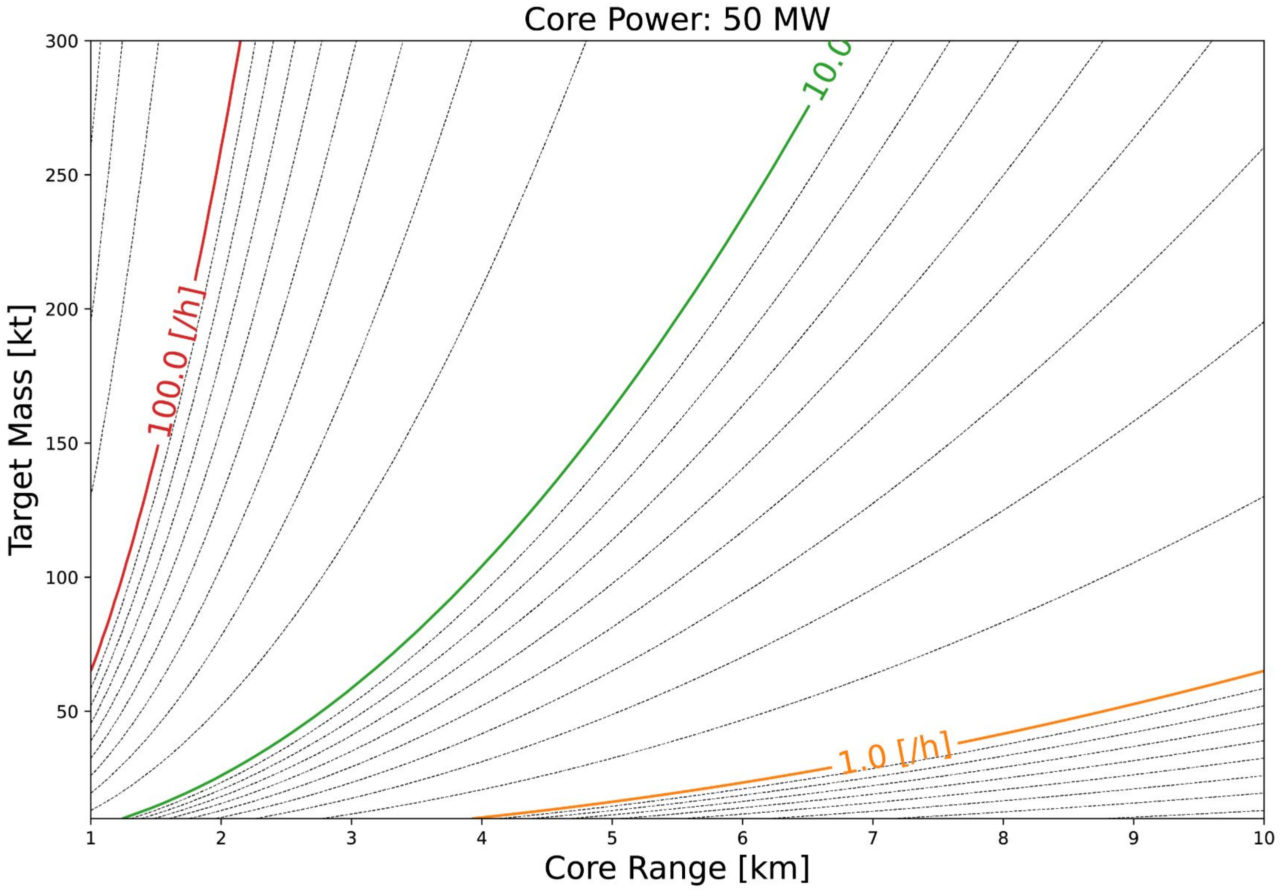
- Hard to evaluate the range given SONAR’s environmental factors and the (understandable) lack of documentation.
- Ranges ~km are comparable to passive SONAR in unfavourable situations.
- Environment invariance is main advantage over SONAR, as well as it being uncounterable (subs can’t go neutrino-quiet).
- Cost of an aircraft carrier is ~$1-10B, large SNIFR ship is likely ~$0.5-1B.
    - Based on costs of modern neutrino experiments.
    - Quite a hard sell for a ship with effectively one use.
- Could have a fleet of SNIFR vessels blanketing areas/hunting, or shadowing other ships, or run a few on commercial routes and cross your fingers.
- If subs like to shadow commercial shipping lanes to hide their sound, this is *very* viable…

Summary

- SONAR has long been the main method to track nuclear submarines.
- SONAR suffers from heavy environment dependence and other limitations.
- The neutrinos produced from the submarine's reactor can't be shielded.
- If measured with significance, this would provide an environment-independent method to identify nuclear subs that cannot be countered.
- SNIFR proposes building a large-scale detector on an oil tanker or cargo ship.
- Not clear which technology is best suited given the unique deployment.
  - Gd-loaded WC, scintillator and LAr are considered.
- Preliminary rate studies have been performed based on SK studies.
- "NuDAR" won't have long range in single-vessel deployment, ~1km.
- May still provide a viable alternative sub-tracking technique to SONAR.
- Especially in multi-vessel deployment.

Backup

Close Range Interaction Rates



Long Range Interaction Rates