“Team Submarine” Presents…

Deep Co*ν*er
(Deep Communications Over Neutrinos Experimental Research)

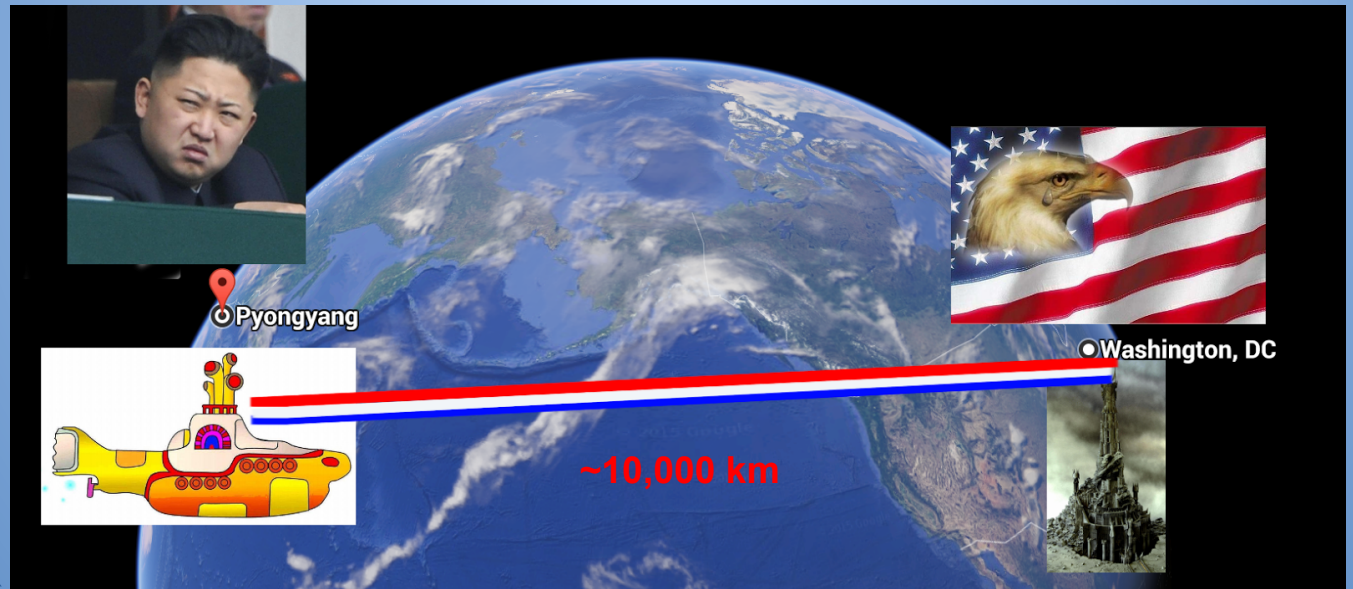
Mandate :

The Pentagon wishes to communicate with submarines that are submerged along the coast of North Korea by using a neutrino beam located in Washington DC. This is a bit stream with the presence/absence of pulsed neutrinos at 1 second intervals. If the desired bit rate is 1 bit/s with <1% error rate, how intense must the initial neutrino beam be? What type of neutrino beam would you prefer and what is the most practical design for the submarine's detector?

Our Collaboration

General Objective

- Generate a pulsed beam of neutrinos which encodes data.
- This beam should be directed through the Earth to a submerged Submarine.
- A detector in this area must be able to see the resulting events.
- These events can then be reconstructed into communiques.



Design Principle

- The rate of neutrinos detected at the submarine is given by:

Neutrinos detected [s^{-1}]

Neutrino flux through detector [$s^{-1}m^{-2}$]

Neutrino scattering cross-section [m^{-2}]

Neutrinos produced [s^{-1}]

Beam radius at detector [m]

$$d\nu_{det.}/dt = \phi_\nu \cdot \sigma_\nu \cdot N_{targets}$$

$$\sim \frac{d\nu_{prod}/dt}{\pi r_{beam}^2} \cdot E_\nu \cdot m_{detector}$$

- Need an intense+thin beam, a large detector and/or high neutrino energy
- Optimal parameter choice depends on beam design
- For the case of a neutrino factory:

$$r_{beam} \sim \frac{0.1}{E_\mu} \cdot d \qquad E_\nu \sim E_\mu$$

$$d\nu_{det.}/dt \sim d\nu_{prod}/dt \cdot E_\mu^3 \cdot m_{detector}$$

- Here the most effective option is to **increase the muon energy**

Detector Options

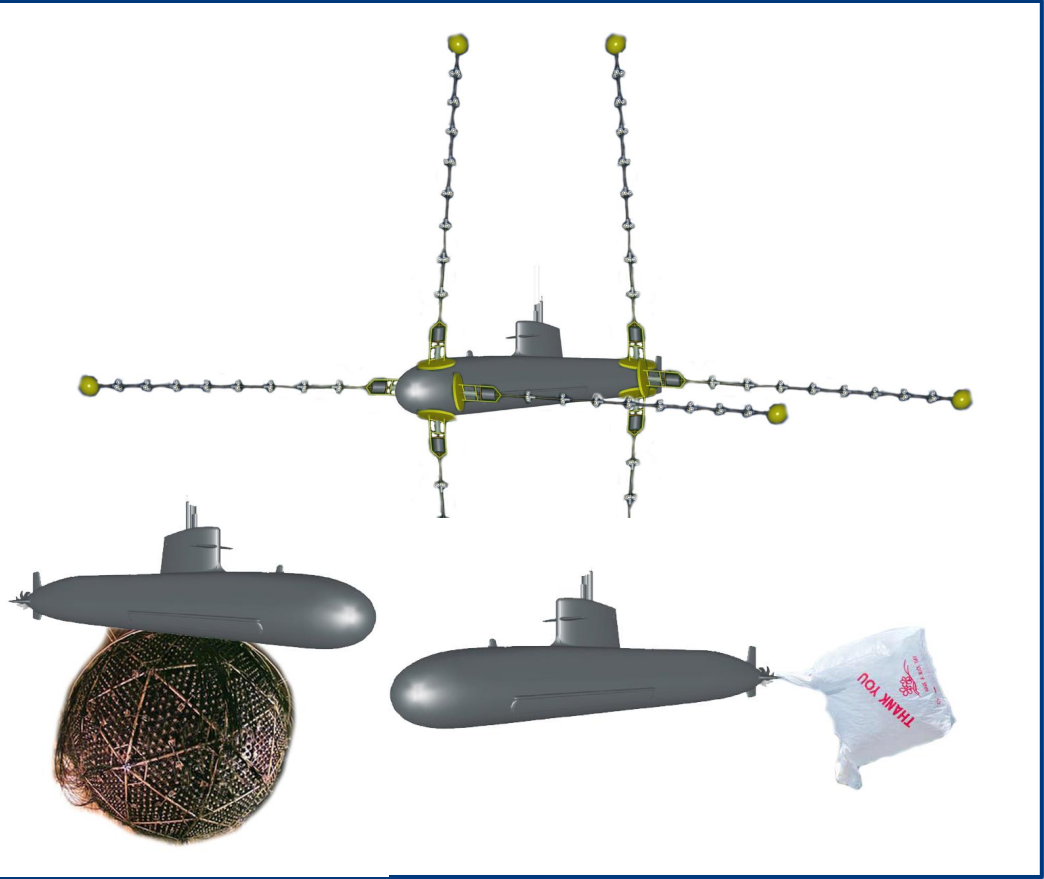
We considered several different designs for the detector:

- Bag of clean water+PMTs to tow behind sub (Cherenkov or WBLS)
- Extending arms with PMTs on them from all sides (Cherenkov)
- Submarine hull as target, scintillator on the inside (Scintillator)
- Submarine ballast as detector (Scintillator or Cherenkov)

Our essential detector requirements are:

- Detect enough neutrinos!
- Reject backgrounds (solar, atmos, reactor on sub)
- Can separate by known timing, directionality, or energy
- Do not compromise submarine operations

External Detector Options



- Large detector mass (Mtons)
- Proof of principle from Antares
- Deployable
- Option to use water based liquid scintillator in the bag
- Directionality helps to reject background

- Possible effects to hydrodynamic performance
- Slow to deploy
- Noisy external electronics gives away submarine position

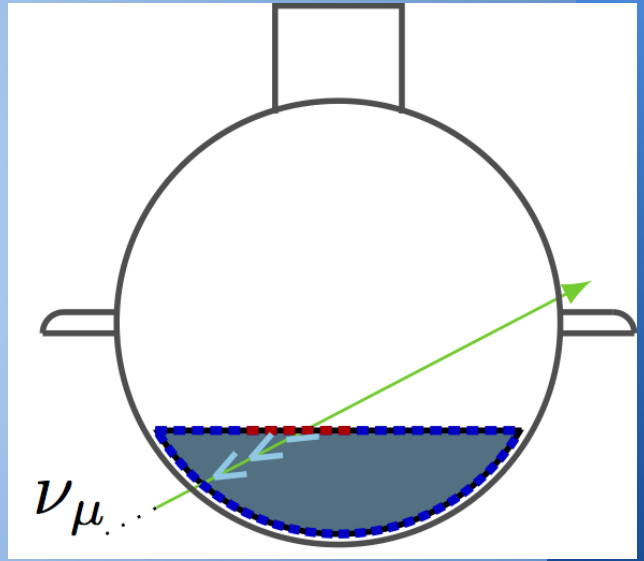
Internal Detector: Ballast Cherenkov

Pros:

- May not require structural changes. Just add photosensors to ballast tank.
- Could use reflective material to lower photosensor coverage needs.
- Potentially cheap and easy.
- Can determine signal over background by photon intensity.

Cons:

- Other ballast tank designs are not as optimal, may require structural changes.



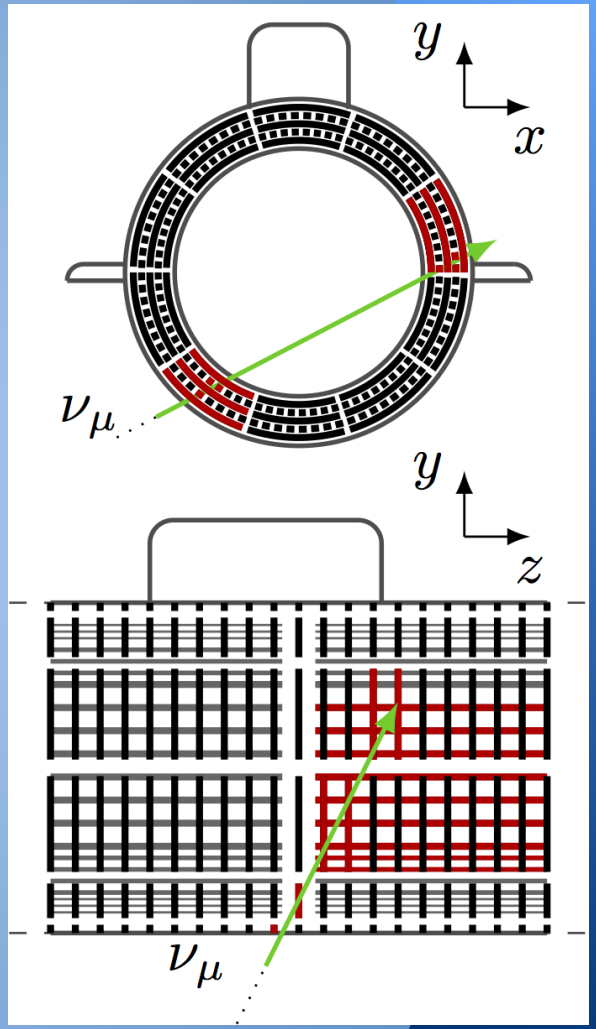
Internal Detector: Wall Scintillator

Pros:

- Coincidence gives directionality - can identify beam events.
- Scintillator + silicon readouts are cheap, low voltage, and understood.
- Bar configurations can be optimised for efficiency and to minimise DAQ electronics.

Cons:

- Would require, possibly substantial, ship-wide modifications.
- muon de/dx at 100 GeV is ~= minimally ionising. Would likely **require** coincidence.
- Timing limited by intrinsic scintillation time.



Beam Options

We considered different designs for the beam:

- Conventional Neutrino Beam
  - Collide protons into target -> pions -> neutrinos
  - Difficult to focus pions -> wide beam
  - Difficult to get large Ev or intense beam (limited by target)

- Neutrino Factory
  - Collide protons into target -> pions -> muons -> storage ring -> neutrinos
  - Accelerating muons gives us a highly focused + high energy beam
  - ~~Expensive~~ (Using DoD funds ~ ∞)

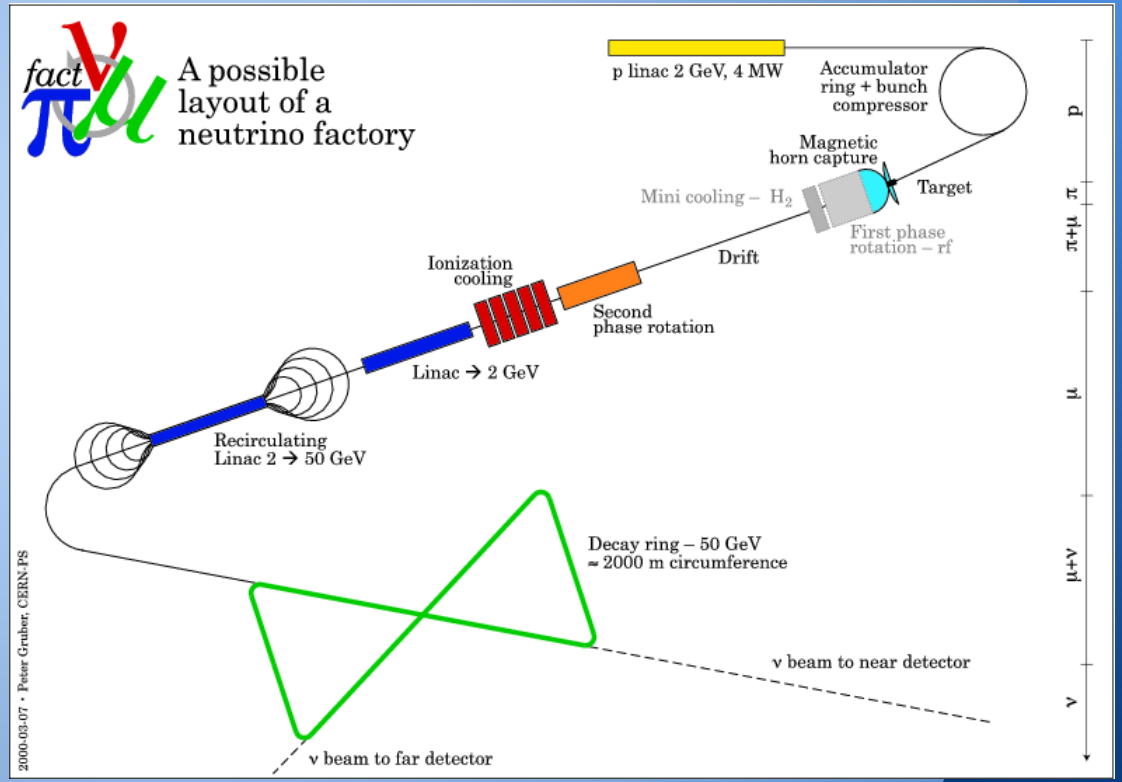
Modified ν Factory ("The Liberator")

Current NuFact design:

- 10^{21} nu/year
- up to 50 GeV E_μ

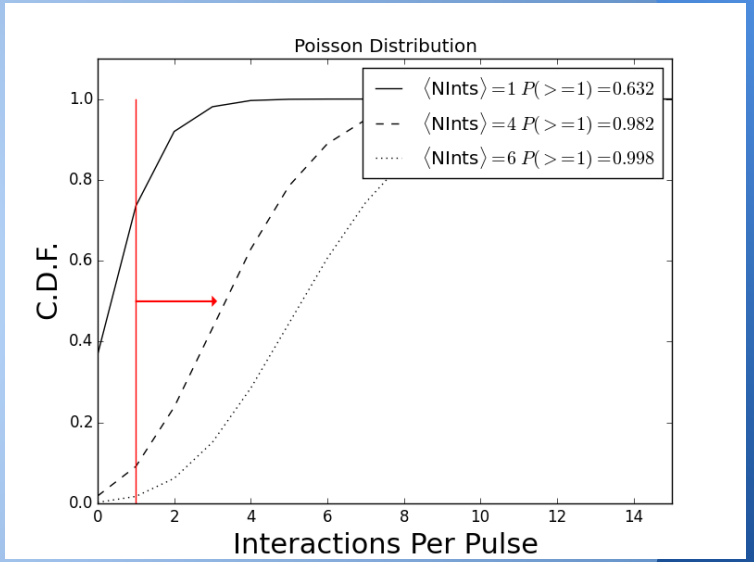
Changes:

- ~150 GeV E_ν
- (E^3 improvement!)



Number of Events Needed

- Require ~ 1% Bit Error Rate (BER).
- Get a BE when when no events occur in the detector during a beam pulse.
- Probability of poisson fluctuation to no events at an expectation of 1 interaction per pulse is ~65%.
- If we expect 4 per pulse, this falls to 1.8%
- Since, on average, we'll have equal amounts of 1's and 0's in the bit stream and a BE only affects the 1's we can half this.
- With an expectation of 4 events at the far detector we therefore have a BER of 0.9%.
- This becomes our goal for the accelerator.



$$1 - e^{-\lambda}/2 > 99\%$$

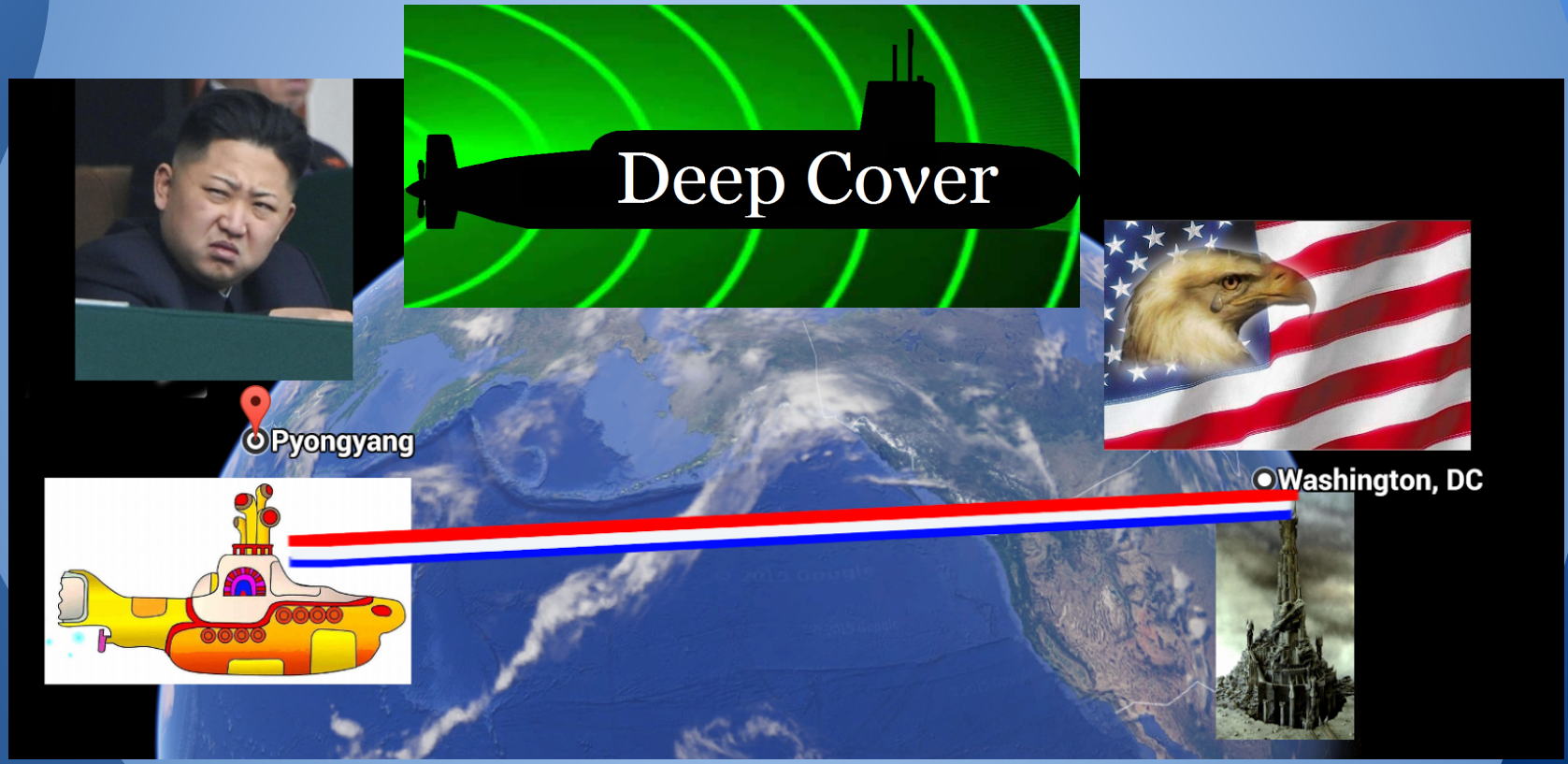
Choosing beam/target

Design	M_{det} (kt)	E_{nu} (GeV)	Intensity(nu/year)	Neutrino Detection Rate (nu/s)
Conventional Beam + PMT wings/bag	2E3	5	1E19	4E-5
NuFact Design Proposal + PMT wings/bag	2E3	18	1E21	1.5
Modified NuFact + Submarine Target	**10**	**150**	**1E21**	**4.2**

- Our modified neutrino factory allows us to avoid cumbersome/noisy external detector
- Total North Korean coastline is ~ 2500 km. Beam diameter at submarine ~ 80km, therefore the submarine may need to travel to receive communications.

N.B We assume a flat intensity profile across the beam diameter.

Conclusion

- Increasing the muon acceleration in the standard neutrino factory design allows small, covert and affordable detectors requiring minimal changes to the existing submarine fleet.
- High neutrino rate and ability to determine directionality ensures 1bit/s communication.
- Very thin beam allows extension to principal to other locations (requires neutrino factory on a 3D turntable -> additional costs).
- ~O($15 billion construction) = <3% DoD Budget for 1 year or 1% of the JSF fighter program cost.
- Higher muon energy would further improve performance; only limited by over extension of muon lifetime causing a background in subsequent bit.
- Possible radiation hazard close to beam.

Thanks for Listening