Teleconference, 1st December, 2020

POSITRINO Final Review

Positioning, Navigation and Timing using Neutrino Particles

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POSITRINO
Summary

Use of Neutrino for PNT: Motivation

- POSITRINO **Objective**: **assess early feasibility of a PNT System based on Neutrino particles.**

- **Fundamental and contradictory Challenge**:
  - the property which makes Neutrinos attractive for PNT is the low interaction with matter, allowing to reach places inaccessible to GNSS signals
  - this property also implies difficulties in the neutrino detection: low detection rates, very large and heavy detectors

Research questions:

- how **feasible** is to imagine an operational PNT services based on neutrino particles in the coming decades?
- what **steps** need to be taken **to advance the technology**?

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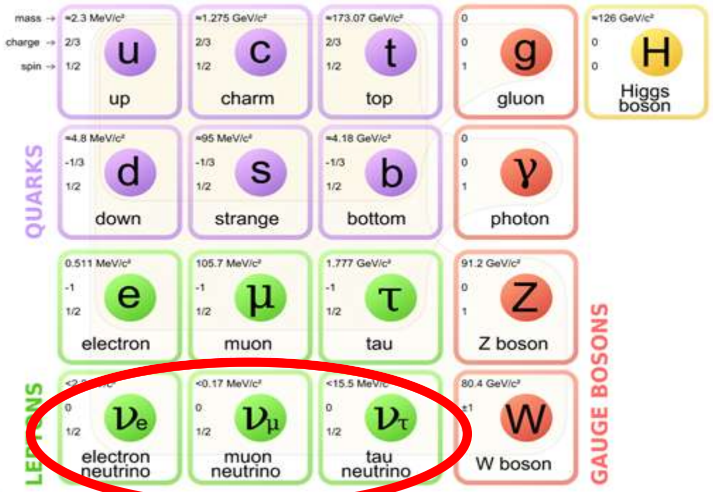
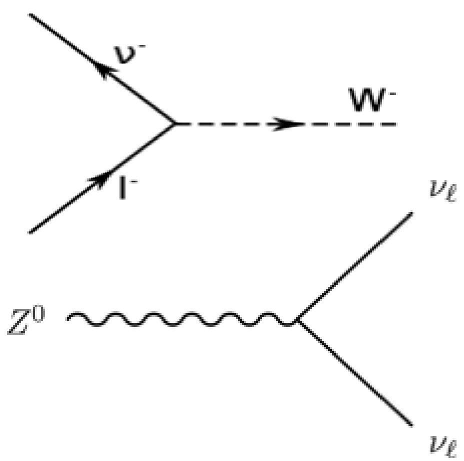
Use of Neutrino for PNT: Motivation

- Neutrinos are:
  - among the most abundant particles in universe,
  - nearly massless,
  - travel at speeds near speed of light,
  - are electrically neutral
  - can be generated through man-made sources like nuclear reactors and particle accelerators or by natural sources like the sun.
- Neutrinos only interact via weak force and gravity. Since gravitational interaction is extremely weak and weak force has very short range, **neutrinos can travel long distances unimpeded through matter, reaching places inaccessible for example to GNSS signals**.





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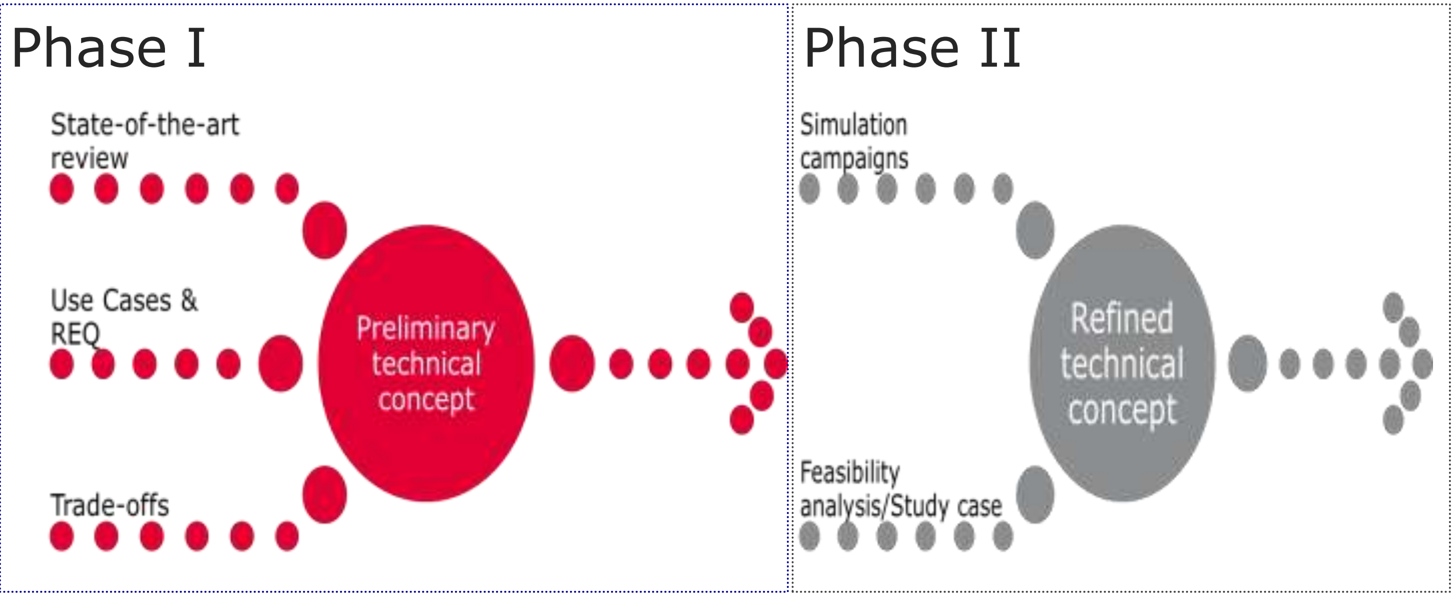
Project in a snapshot



0. High-level mission
1. High-level system REQ
2. High-level roadmap for an E2E Proof-Of-Concept
3. Preliminary cost analysis

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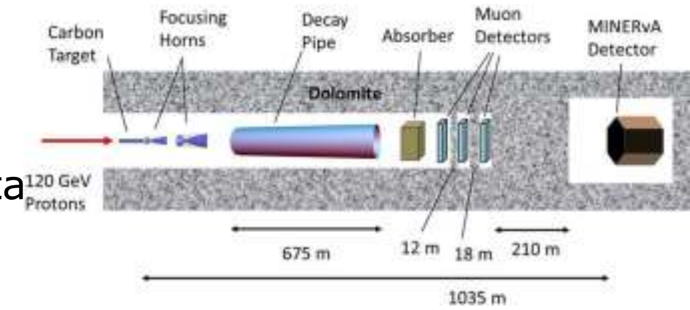
Use Cases and preliminary Neutrino PNT concept

Starting point: State-of-the-art

- Activities for using neutrinos for communication or PNT applications:
  - **Demonstration of communication** at FERMILAB: using Neutrino beam at main Injector (NuMI) (data sender) and MINERvA detector at 1km. Decoded data rate 0.1 bits/s BER of 1%.



  - **Submarine Neutrino communication**: neutrinos for communication with submarines coming from muon decays

  - **Solar Neutrinos for Navigation:** patent describing a method to navigate using celestial/solar neutrinos based on the neutrino arrival angle.

  - Coherent elastic neutrinos-nucleus scattering (CEnNS) rather big cross and **small detectors (15 Kg)** -> **miniaturization** of user equipment and enough detection rate

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Literature review: A-priori Gaps and Limitations

- System **investment**
- User **Equipment Cost**
- Operational constraints at user level: **size**, **weight** and **power consumption**
  - Miniaturization
- PNT **performances**, linked to neutrino source flux and detection rate
- **Timeframe** (TRL)
- System **coverage**:
  - Neutrinos Collimated in Beams: intersection between cones from different sources
  - Spherically generated neutrinos: flux decreasing as 1/d^2
- **Technology competitors**

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Navigation with Neutrinos: Expected Possible Benefits

- **Ubiquitous PNT service**: subsurface, buildings, oceans -> applications

- Potential added value for applications for which other technologies are not suitable

- A potential back-up for GNSS in defense applications in case of severe GNSS disruption (jamming, spoofing, scintillation).

- Enabler of new applications? Benefits to scientific community?

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Use Cases and Requirements

Submarine Navigation

Submarine tracking

Space positioning

Space tracking

Mining

Subsurface construction

Back-up PNT

- **Submarine Navigation** selected as the Benchmark Applications for POSITRINO Study:
  - A-priori technical feasibility
  - Importance of the application
  - Competing technologies not fully suitable

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Use Cases and Requirements

- Requirements for Neutrino PNT Concept defined for potentially most promising applications in terms of:
  - Weight, size and power consumption of Neutrino Detector (usually very big) taking into account operational constraints of applications.
  - Coverage area: regional for submarine navigation, local for e.g. sub-surface construction
  - Accuracy requirements with target to improve accuracy achievable with other technologies

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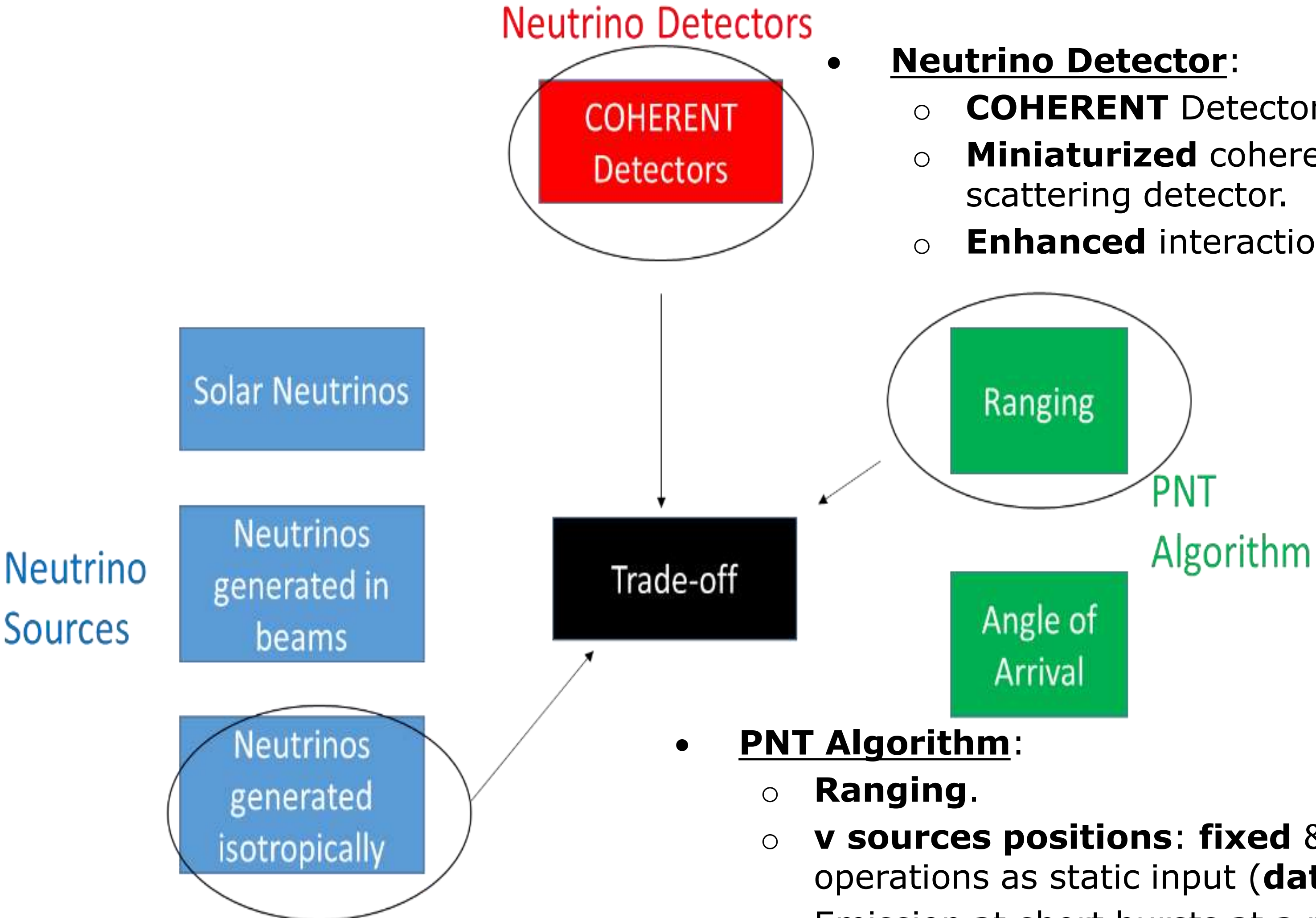
Baseline Technical Concept



- **<u>Neutrino Detector</u>**:
  - **COHERENT** Detectors.
  - **Miniaturized** coherent elastic neutrino scattering detector.
  - **Enhanced** interaction **cross-section.**

- **<u>PNT Algorithm</u>**:
  - **Ranging**.
  - **v sources positions**: **fixed** & introduced before operations as static input (**database**)
  - Emission at short bursts at a pattern->**source identification** performed based on timing
  - V sources & detector **synchronized** using clocks

- **<u>Neutrino Sources</u>**:
  - **Isotropic** Source.
  - **High energy** neutrinos through pion decay at rest.

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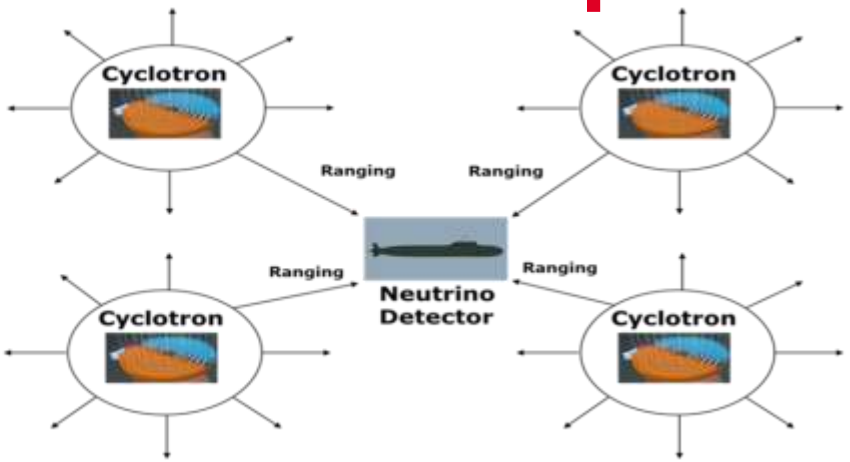
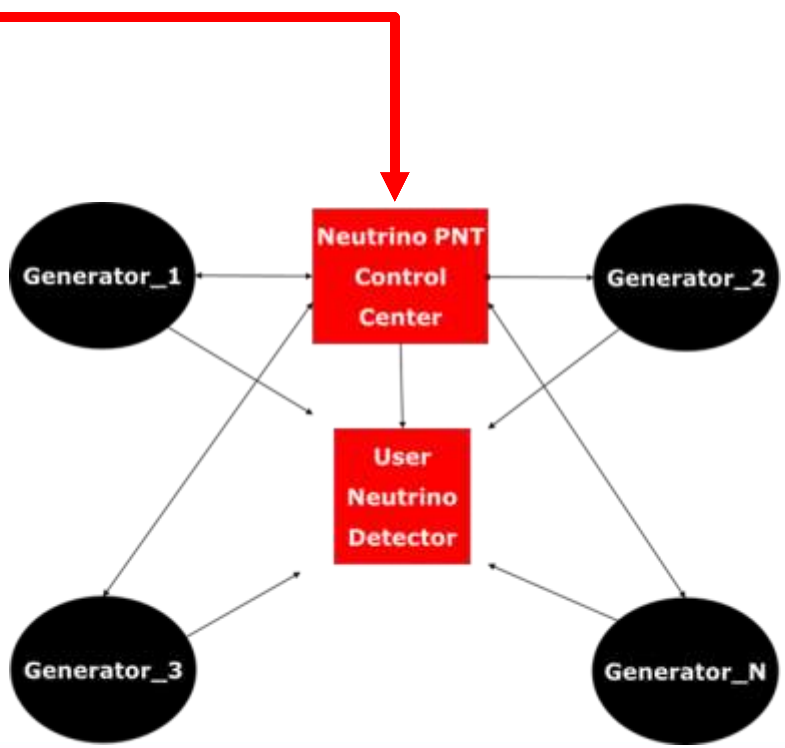
Baseline Technical Concept



- **<u>Neutrino Control Center functions</u>**:
  - Clock Synchro ν Sources & User Equipment
  - Service Provision and Maintenance
  - Monitorization of performances
  - Dissemination of Notice to Users under abnormal functioning
  - Host User Service Center:
    - Precise position of Neutrino Sources available for the configuration of the User Equipment.
    - Disseminate alerts in advance to users under variation of any ν Source Position



- **<u>Definition of the Neutrino PNT Operational Concept</u>**

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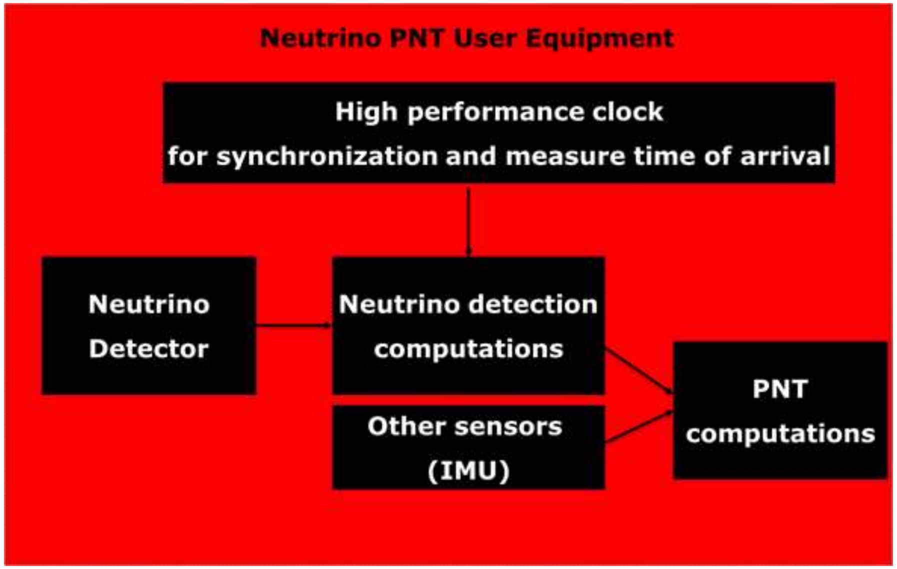
Baseline Technical Concept: User Equipment sub-systems



Key requirements:

- User equipment needs good performance clock (e.g. atomic clock) for synchronization to the System and for accurately measure the Neutrino time-of-arrival at the 1ns level

- For the complete Neutrino PNT concept (System + User Equipment) the cost driver are the neutrino generators
- Minimize Size, Weight and Power Consumption

Baseline Technical Concept: candidate PNT algorithms

- **PNT Algorithm: Encoding & decoding info in Neutrino flux very challenging (very low transmission rate):**

- **Proposed PNT algorithm based on Ranging with Time Windows**

  - Identification of the Neutrino Source from which each signal detected neutrinos come,
  - Estimation of the time of emission,
  - Estimation of the neutrino range based on the time-of-emission information and the measured time-of-reception,
  - PNT Estimation: Trilateration computations from neutrinos coming from different sources, taking also into account the propagation of the position of the moving User based on other sensors

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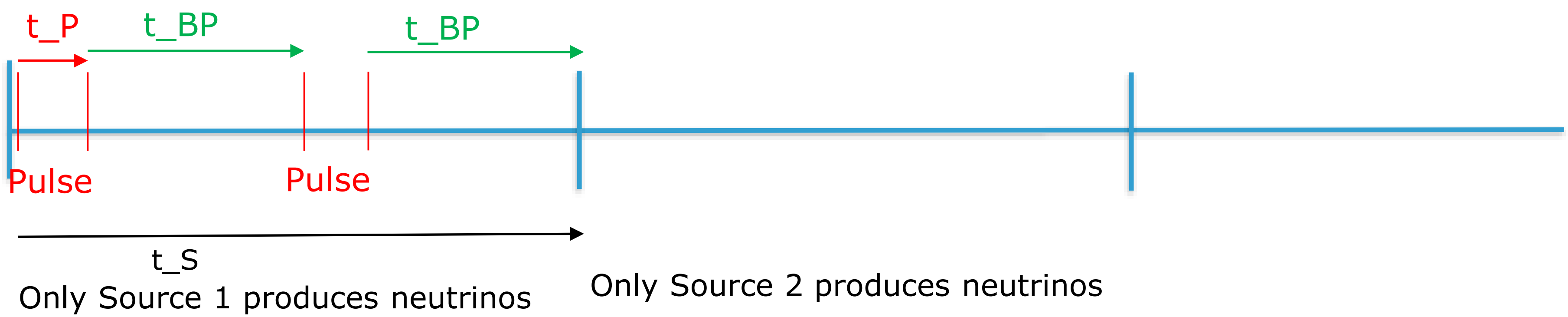
Baseline Technical Concept: proposed PNT algorithm

- Ranging Windows Algorithm

t_S = Time during which Source X produces neutrino pulses. Used for source discrimination.
t_M = Time Measurement: instant in which the Neutrino is detected. It can be estimated with an atomic clock synchronized to the system
t_P = time of duration of neutrino pulse. The time of emission of a neutrino within the same pulse would be indistinguishable
t_BP = time between pulse: should be larger than v_neutrino x maximum distance source-detector to be able to determine from which pulse the neutrino detected comes -> t_BP > c_nu x max_distance



Accuracy: depends on the accuracy of t_M (order 1ns) and on the length of t_P
- t_P has to be balanced between target accuracy and high neutrino detection rate

Assumption: Vehicle (i.e. Submarine) equipped with **other sensors** (IMU). Trilateration at different epochs

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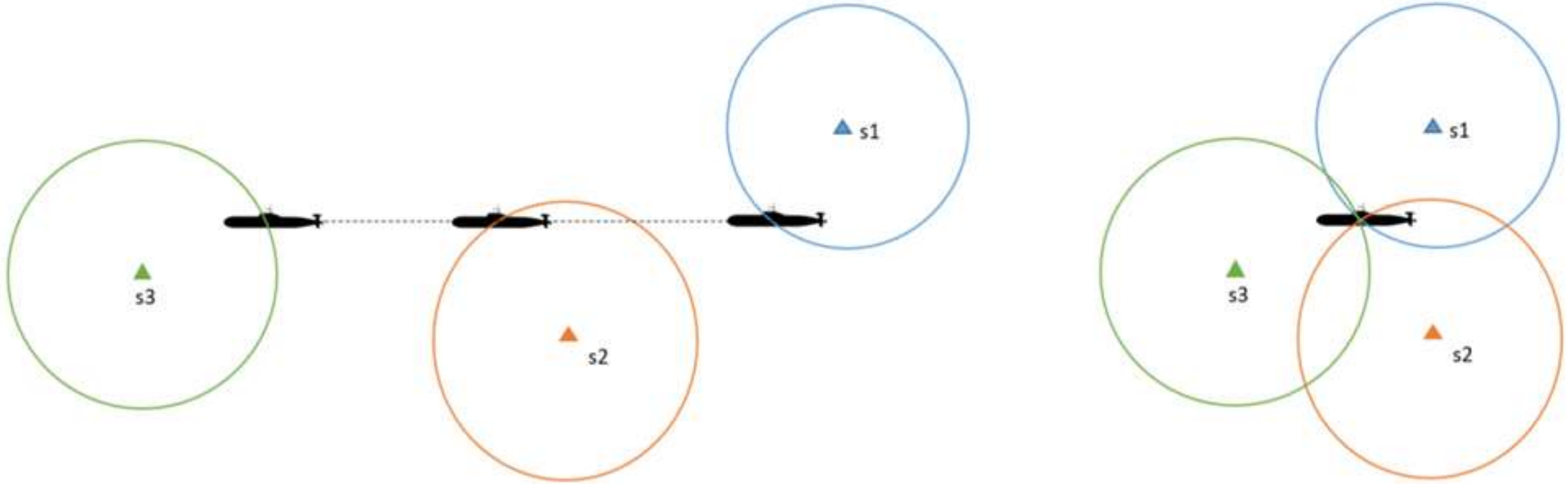
Baseline Technical Concept: proposed PNT algorithm

- Assumed that Neutrino PNT User Equipment will be integrated with IMU
- Low neutrino detection rate -> trilateration at different epochs
- We propose a **Sequential Equivalent Trilateration algorithm**
  - At each instant in which a neutrino is detected the position and its accuracy is updated based on the beam direction and propagated with the inertial sensors until a new neutrino is detected



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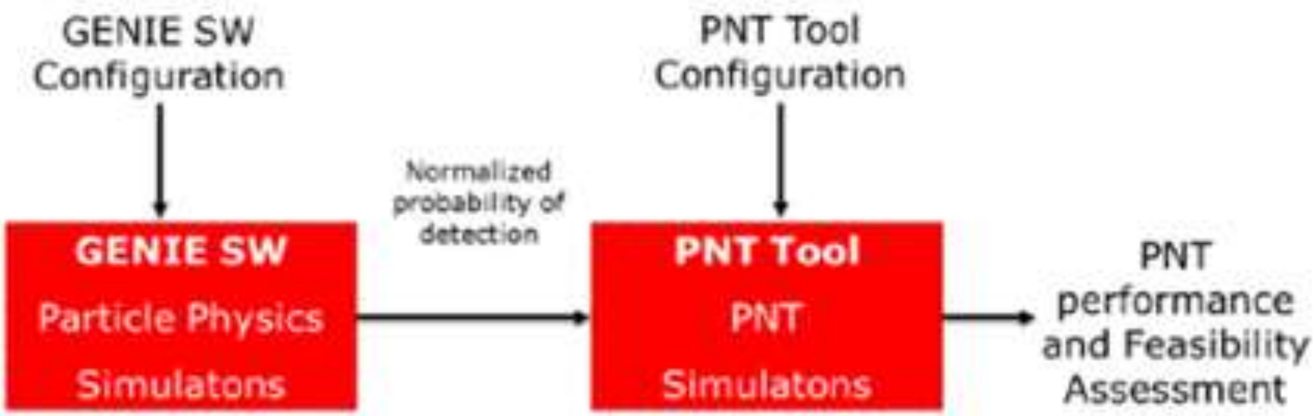
Feasibility Assessment based on simulations

Simulation Methodology and Tools



- Simulations using Particle Physics SW to estimate the probability of detection of neutrinos arriving to the detector
- Simulations using PNT Tool to estimate PNT performance
- Different scenarios with different sets of relevant design parameters for the Neutrino PNT System

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Study Case: Mediterranean Sea

Assuming **max distance source-detector 1000km as design hypothesis**

Ex: distribution of Neutrino sources (red ellipsis) to cover Mediterranean Sea with > 3 Neutrino sources with distance <1000km to any point.

16 Neutrino sources distributed around Mediterranean

Assuming very rough cost estimation of each Neutrino source in range 50 M. Euros. Cost of Neutrino Sources is main driver for Neutrino PNT system, approximate cost for deployment of Neutrino PNT System with a Service Coverage comprising Mediterranean Sea would of order of 1000 M. Euros.

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Simulations Configuration parameters

- Configuration for Submarine Navigation application

Configuration parameter	Values Scenario-SUBMARINE-1	Values Scenario-SUBMARINE-2	Values Scenario-SUBMARINE-3
Typical distance Neutrino sources - detector	1000km	100km	10km Un-realistic. For assessing DAEDALUS Flux
Probability of detection of a signal neutrino arriving to the detector	9.43e-14 / kg of detector Output from GENIE SW Simulations		
Ranging window parameter t_P **Note: for a neutrino PNT requirement accuracy of 10km**	For an accuracy target of 10km: 7 10^{-5} s For an accuracy target of 1km: 7 10^{-6} s		
Ranging window parameter t_BP **Note: assuming a coverage area of the order 1000km**	3.3 10^{-3} s		
Neutrino flux generated in the neutrino sources	Free parameter since the feasibility of the Neutrino PNT system will be studied as a function of this parameter. Equal or higher than the reference value from DAEδALUS of 4 x 10^{22} neutrinos per flavour per year		
Neutrino detector weight	1000kg 10000kg A typical weight of a submarine is in the order thousands of tones		
Performances of other sensors (IMU)	Position (TDRMS): 1NM/24h Specifications of Inertial Navigation System for Submarines SAFRAN SIGMA 40XP		

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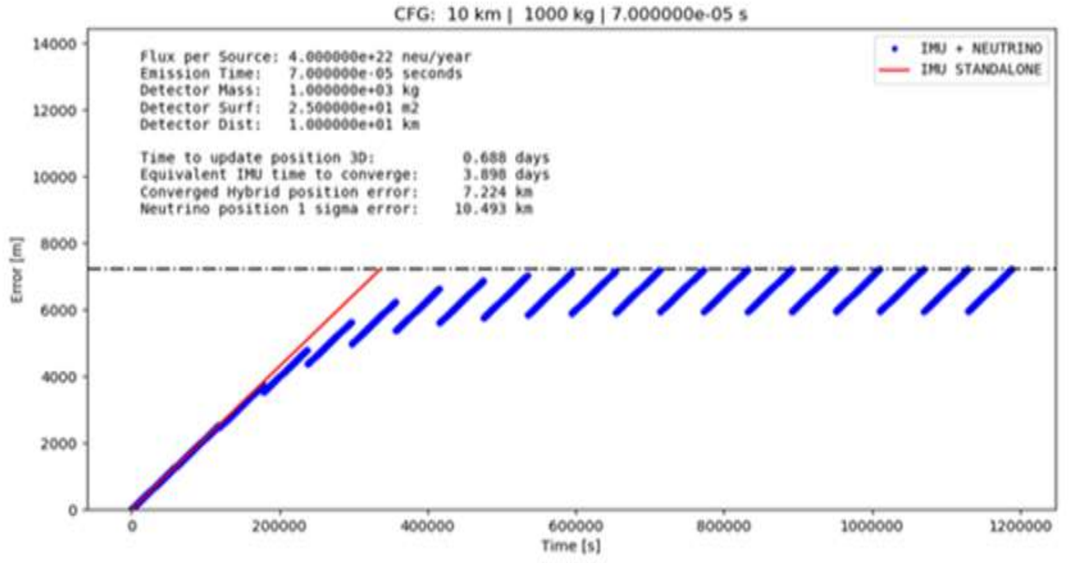
Simulations Results

- Simulations performed to compare the hybrid solution with neutrinos plus IMU using the PNT algorithm against the solution obtained with the IMU standalone in order to assess whether Neutrinos PNT system would provide an added value for such application

- Sensitivity analysis playing with key design parameters

- Example for accuracy requirement of 10km and 1000kg of detector mass



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Summary of results

Minimum Flux for 10 km position error (t P=$7\cdot10^{-5}$):

Distance to Source	Detector mass	
	1.000 kg	10.000 kg
10 km	$1.9\cdot10^{22}$ neutrinos / year	$1.9\cdot10^{21}$ neutrinos / year
100 km	$1.9\cdot10^{24}$ neutrinos / year	$1.9\cdot10^{23}$ neutrinos / year
1000 km	$1.9\cdot10^{26}$ neutrinos / year	$1.9\cdot10^{25}$ neutrinos / year

Minimum Flux for 1 km position error (t P=$7\cdot10^{-6}$):

Distance to Source	Detector mass	
	1.000 kg	10.000 kg
10 km	$1.9\cdot10^{24}$ neutrinos / year	$1.9\cdot10^{23}$ neutrinos / year
100 km	$1.9\cdot10^{26}$ neutrinos / year	$1.9\cdot10^{25}$ neutrinos / year
1000 km	$1.9\cdot10^{28}$ neutrinos / year	$1.9\cdot10^{27}$ neutrinos / year

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Discussion on Feasibility

- Feasibility of Neutrino PNT concept seems in the limit with current technology
    - Submarines: Neutrino PNT system -> added value for a neutrino flux of 2-3 orders of magnitude larger than DAEDALUS. In future if Neutrino flux generated and/or detection improved, concept would be perfectly feasible
    - Conservative assumptions:
        - DAEDALUS flux as a reference may not be the current cutting-edge technology, potentially with current particle accelerators larger flux can be obtained. In future, flux could be increased within certain limits
        - Detector weight could be increased in submarines? Considered 1 and 10 tones. Submarines weight ~ 10000 tones. With detector weight of 100 and 1000 tones results improved 1-2 orders of magnitude in neutrino flux, making concept more feasible

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Technical Concept

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Consolidation of Neutrino PNT Design

- **Work performed on:**
  - Gather further information on COHERENT detectors
  - Gather further information on Neutrino generated flux
  - Further analysis on background
    - Discussion
    - Additional simulations

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Consolidation of Neutrino PNT Design

- **COHERENT Detectors:**

  - Geometry: **highly segmented crystals**, each read out individually and packed closely together since this design might be beneficial for background mitigation

    - Weight of each individual crystal in range 1-10kg, same order of magnitude as COHERENT CsI experiment:
      - Ex: for Neutrino PNT detector total mass of 1000 tones, ~100000 individual crystals needed.

    - Need of detailed simulations and an analysis for optimization of the signal/background ratio

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Consolidation of Neutrino PNT Design

- **COHERENT Detectors:**
  - Power consumption:
    - COHERENT experiment, central CsI crystal is instrumented by single PMT ~50W and additional 9 PMTs ~500W total
    - Additional electronics for readout use small amount of power, powered by conventional power supply total consumption ~2.4kW
    - Alternative technologies of SiPM/MPPC: lower power consumption ~0.5W and much more compact, complementary to a highly segmented design which could use fibres to guide light and readout all crystals in a row
  - Submarines of 100.000 tones: typical total thermal powers of 300MW.
  - Potential detector would require between 5-50kW depending on technology used

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Consolidation of Neutrino PNT Design

- **Neutrino sources:**

  - Survey of ν generators with emphasis on max fluxes available:

    - Nuclear reactor based sources: fluxes up to 6×10^29 ν/year but don't have ability to be pulsed in short enough time windows to use PNT algorithm and CsI detectors not suitable

    - DUNE experiment will deliver a flux of 2×10^25 ν/year, 3 orders of magnitude larger than reference value considered in POSITRINO from DAEδDALUS. Operates in a higher and broader energy range

    - **ESSnuSB will produce 5×10^23 ν/year, an order of magnitude higher than DAEδDALUS and in same energy range**
      - Similar flux can be achieved using multiple DAEδDALUS cylotrons ~x10, at a total estimated cost of $600M compared to ESSnuSB €1.4B.

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Background Noise

- Particle Physics Simulations conducted for assessing the background competing with the Neutrino Signal

- The reactor electron anti neutrinos induce recoils below the threshold of sensitivity of the detector, the detector is insensitive to this background

- Neutron background from the reactor is well controlled by the shielding that was simulated in this document and the CEvNS signal is above the background.

- Neutron background induced by cosmic rays has a tail which populates the region of the CEvNs signal, some of this background can be reduced by muon tagging which would require further study

- **System Requirements** derived from analyses have been defined

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System Requirements

System Requirement
The Neutrino Detector shall have a geometry optimized for background mitigation taking also into account the operational constraints of a Submarine.
The submarine shall have available a power consumption of at least 5kW for 10000 crystals with MPPCs/SiPM technology.
The generated Neutrino flux of the Neutrino Sources for the Neutrino PNT System shall be larger than $5.08 \times 10^{23} v$/year
The Neutrino Detector shall possess a shielding which allows to control the neutron background from the reactor
The Neutrino Detector shall implement a muon tagging mechanism to cope with the neutron background induced by gamma rays
The User of the Neutrino PNT system shall be equipped with an IMU
The User Equipment shall process Neutrino measurements, IMU measurements and combine them to build the PNT solution
The Neutrino Sources shall fire neutrinos according to a pattern defined by the Ranging Windows Mechanism

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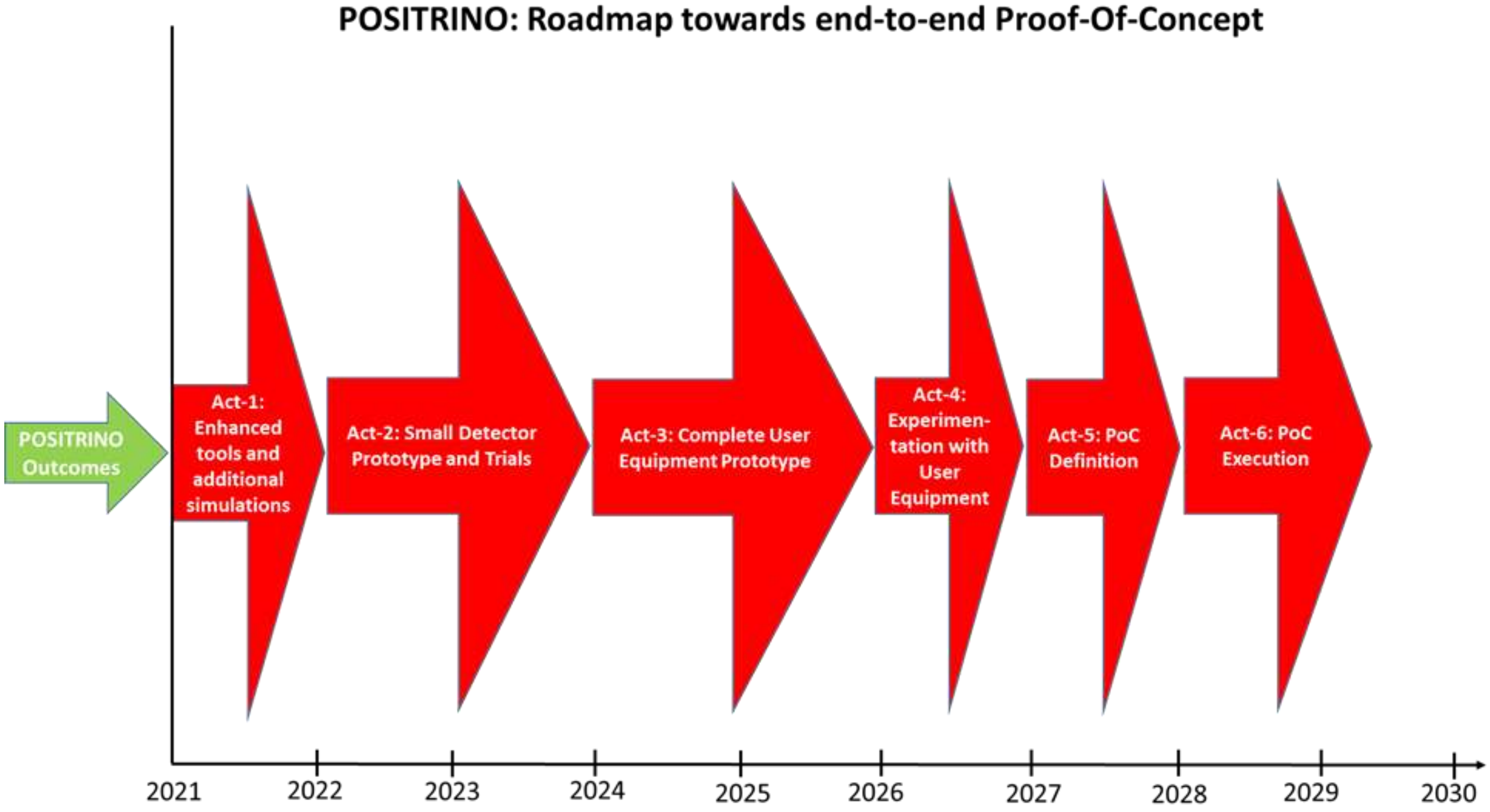
Roadmap towards a Neutrino PNT Proof-Of-Concept

- **For each identified activity:**
  - Detailed description
  - Approximate cost, duration, precedent activities needed etc



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Conclusions

- POSITRINO Project has provided a high-level early design of a Neutrino PNT System and assessed its feasibility
- Neutrino PNT could provide added value for certain applications lacking fully suitable PNT Technologies as Submarine Navigation
- The System would be mainly composed of:
  - Isotropic Neutrino sources firing at bursts following a pattern
  - Control Center
  - User Equipment (Neutrino Detector, clock, IMU and HW&SW for particle physics and PNT computations)
- Simulations conducted showed that the concept is close to be feasible with important but reasonable advances in neutrino generator and detection technology
- Different activities are needed to prepare and execute an End-To-End Proof-Of-Concept in a 10 years timeframe
  - First priority: develop **enhanced tools and conduct additional simulations**

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AOBs

Thank you

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