Future Projects For Neutrino Physics

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CERN, Geneva, Switzerland

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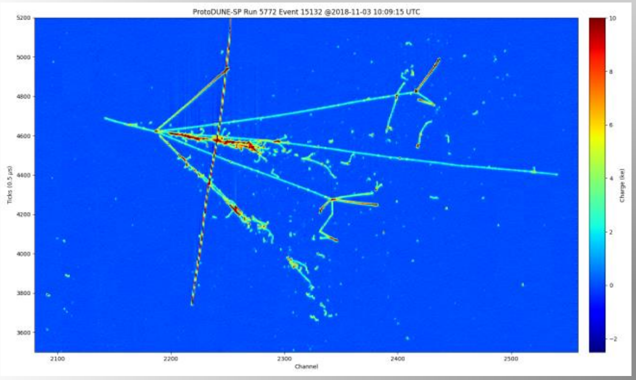
INFIERI

Outline

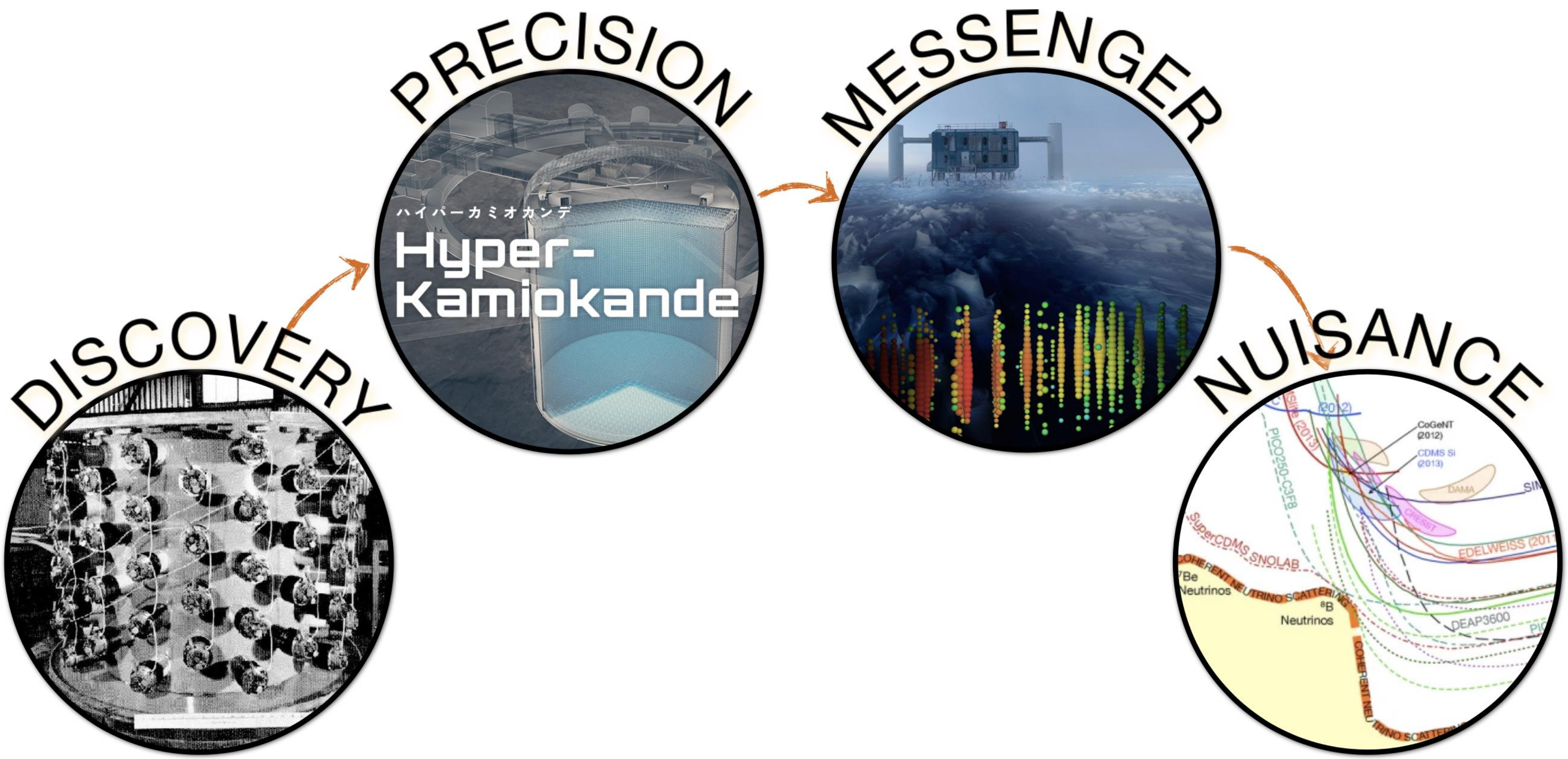


Pion event in the ProtoDUNE at CERN

Not a comprehensive review but examples of directions in experimental neutrino physics

- Introduction to neutrinos
- Next generation of oscillation experiments
- Neutrino properties: mass and Majorana/Dirac nature
- Anomalies/Sterile Neutrino Search
- Large neutrino telescopes
- New techniques
- Neutrino experiments at the LHC
- Summary

Ongoing Neutrino History



->More massive detectors
->More intense neutrino sources
->New directions eg. coherent scaterring like CEvNS

Neutrinos

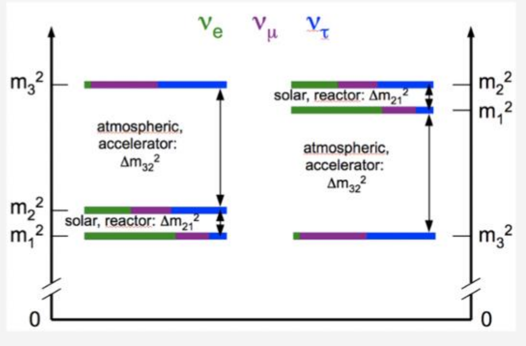
Neutrinos are still mysterious particles

- Have only (left handed) weak interactions
- Are mass-less in the (minimal) SM .. untill 1998
- Are the only neutral fermions in the SM
- Could be Majorana or Dirac fermions
- Neutrinos are produced everywhere
  - Solar neutrinos
  - Atmospheric neutrinos
  - Neutrinos from supernova explosions
  - Primordial neutrinos from the Big Bang
  - Nuclear reactor created neutrinos
  - Accelerator created neutrinos
  - Geoneutrinos, Radioactive decay, even from your body…

Neutrinos

Neutrino experiments today -> Open Questions!

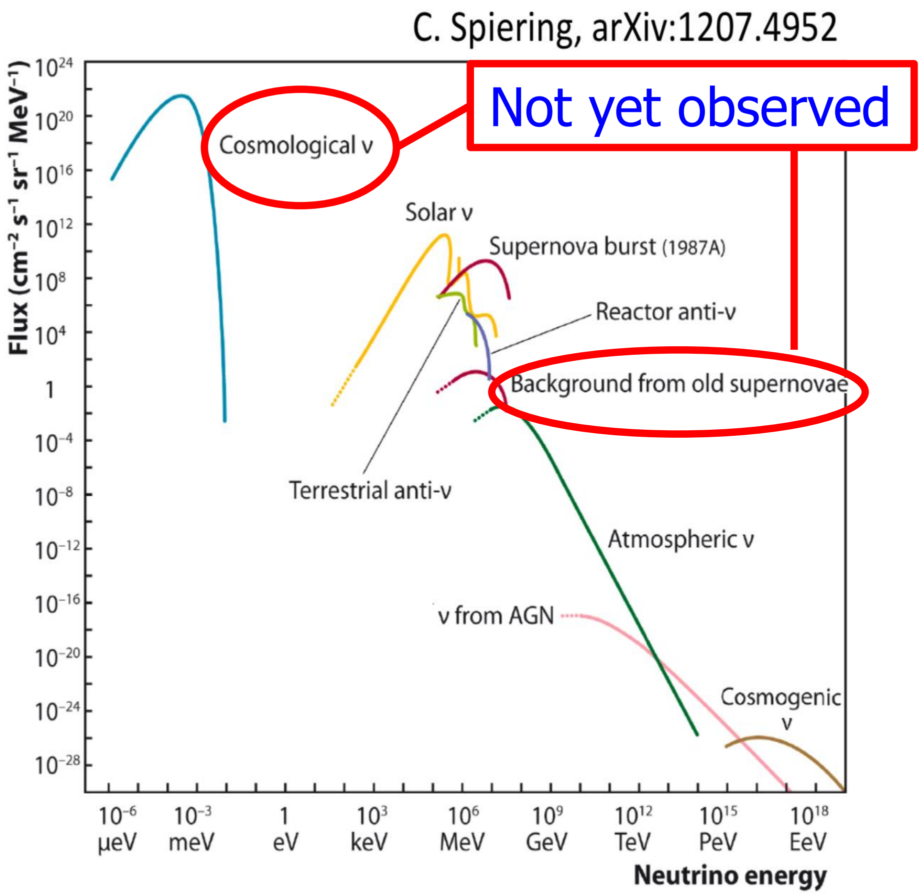
- Neutrino mass values? Origin of the Masses?
- Neutrino mass hierarchy? Normal or Inverted?
- CP violation in the lepton sector? Are neutrinos key the baryon asymmetry in the Universe?

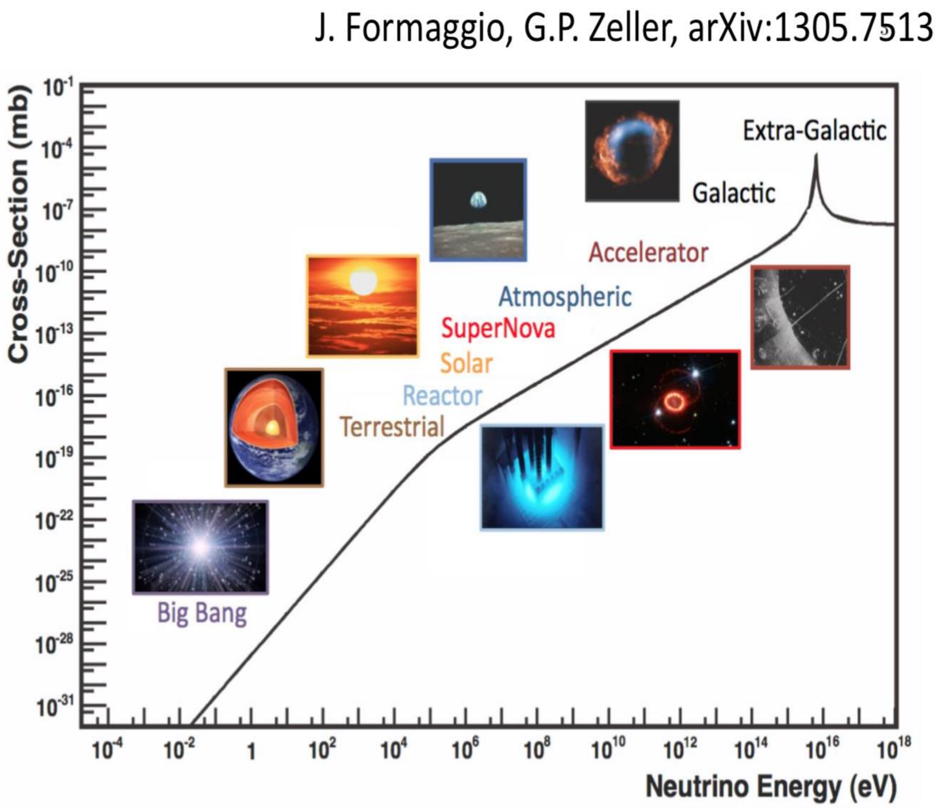


- Are neutrinos their own antiparticles? -> LNV processes
- Do right-handed/sterile/heavy neutrinos exist?
- Are there non-standard neutrino interactions?
- Neutrinos and Dark Matter?
- Testing of CPT..
- Neutrinos are Chameleons: They can change flavour!!

Neutrinos are an essential part of our Universe and our very existence, and can provide answers to some of the key fundamental questions today

Neutrino Sources, Flux and Cross Sections





Cosmological and background from old supernovae neutrinos not yet observed!

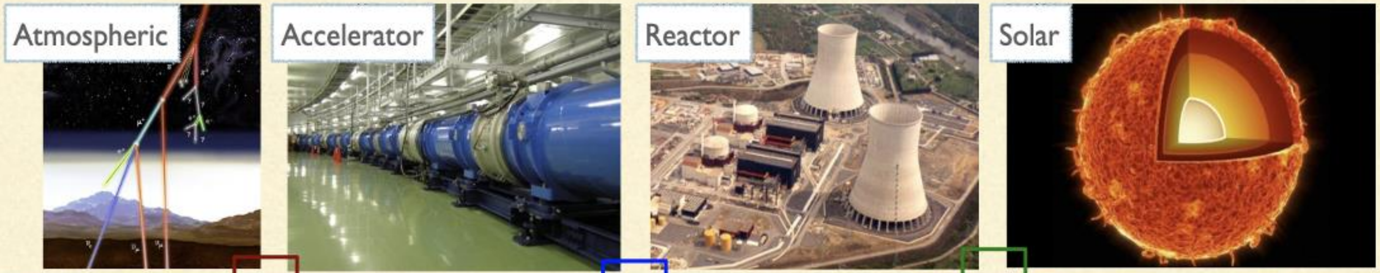
Neutrino Oscillations

- Since >20 years an active field of study and data from many experiments collected:
  - Long baseline accelerator experiments (LBL)
  - Short baseline reactor experiments
  - Atmospheric neutrinos
  - Solar Neutrinos
  - Neutrinoless double beta decay experiments

LBL experiments in the US and Japan
SuperKamiokande, Icecube

Neutrino Oscillations

Neutrino mixing: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

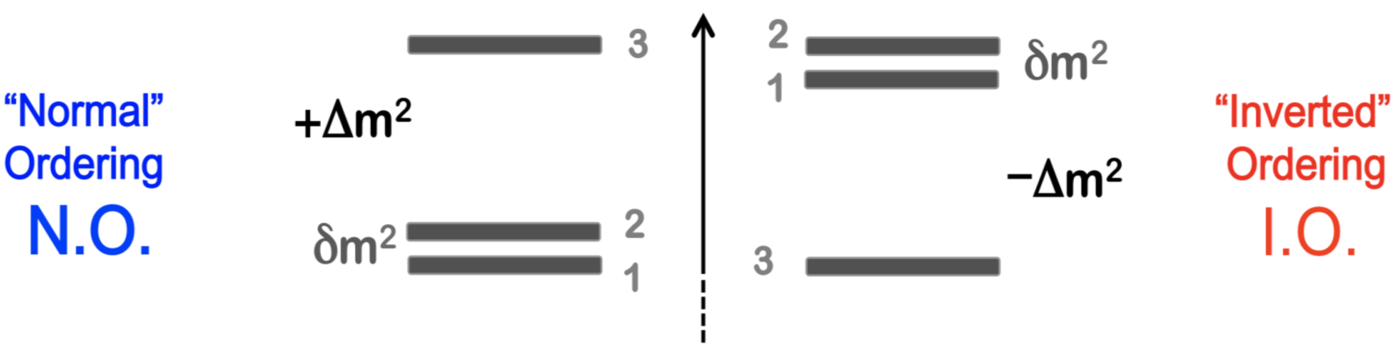


$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

$\Delta m^2_{ij} = m^2_i - m^2_j$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\cdot \begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mass [squared] spectrum (E ~ p + $m^2/2E$ + "interaction energy")



+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density

What do we expect from future facilities

In the next 15 years or so we expect to have:

- Precise Oscillation parameters from DUNE, T2HK, JUNO,… Will the precision be sufficient?
- CP violation established (5σ), phase measured to 10-20 degrees or better. Sufficient precision?
- Mass ordering of the neutrino mass states! Many actors in this field
- Direct neutrino mass searches down to 0.2 eV?
- Majorana or Dirac Nature of neutrinos?
- Detect Cosmic Neutrinos from the Big Bang?
- Detect the Diffuse Supernova Neutrino Background?
- Applications in real life using neutrinos…??

Experiments for Oscillations

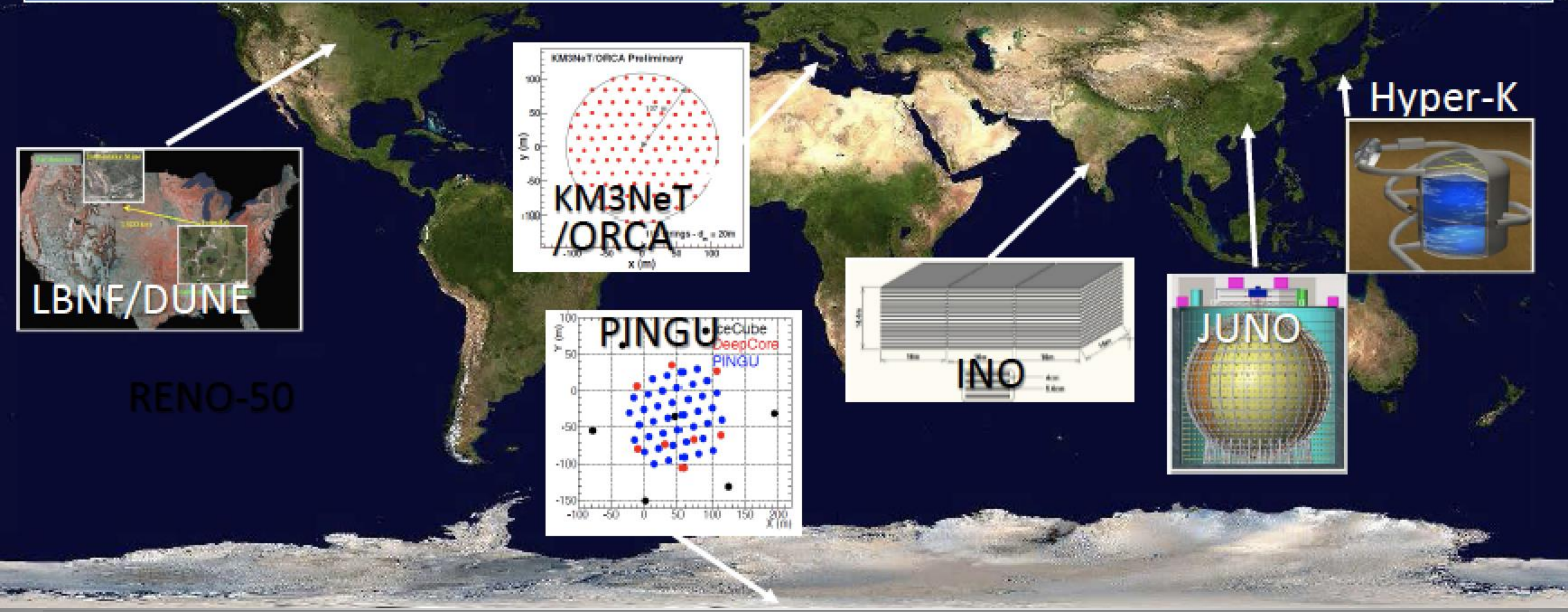
Future (possible) experiments

- New long baseline experiments
  - T2HK/DUNE have been discussed
  - Experiments at the European Spalation Source ?
  - P2O experiment.
- New reactor experiments
  - JUNO, SuperChooz?
- New atmospheric neutrino experiments
  - INO? Large Detectors like IceCube/KM3NET/PO…
- Other ideas:
  - Neutrino factory? Beams at large collider complexes

Future Neutrino Experiments

Anticipated next neutrino experiments across the globe

We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.



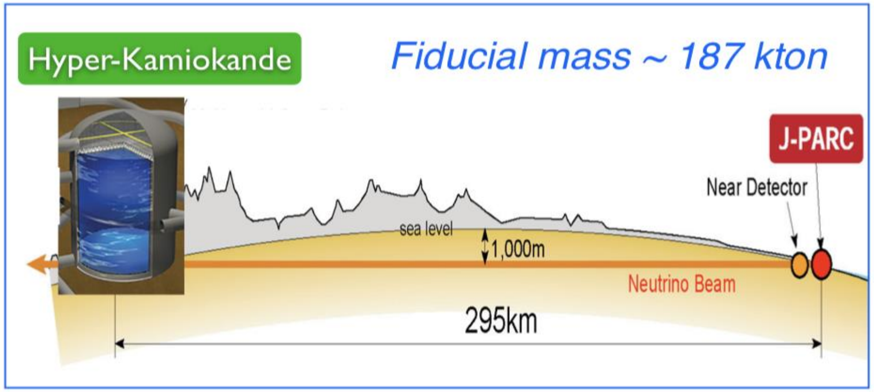
Future Neutrino Experiments

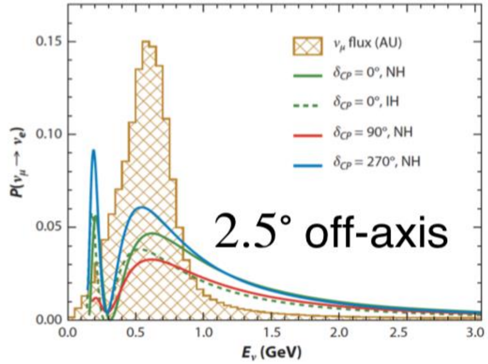
CERN

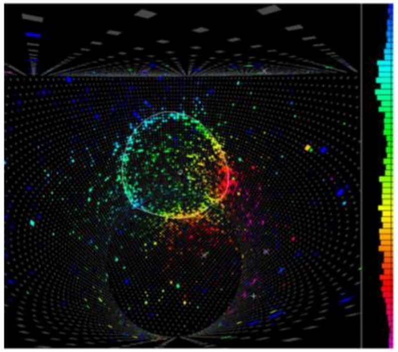
Long-baseline experiments: T2HK and DUNE

See talks yesterday morning

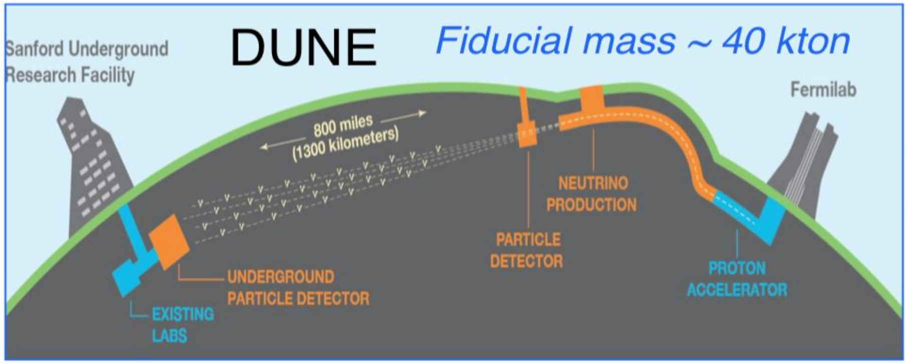
- Towards the measurement of the CP violating phase and Mass Hierarchy
  - ✦ Search for different $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities

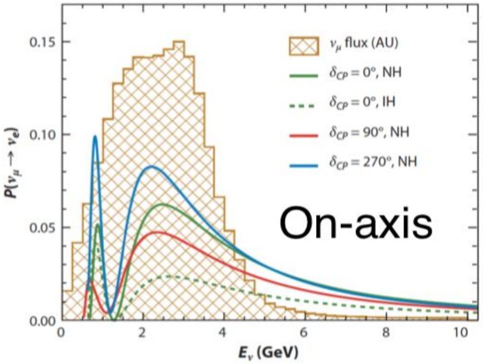


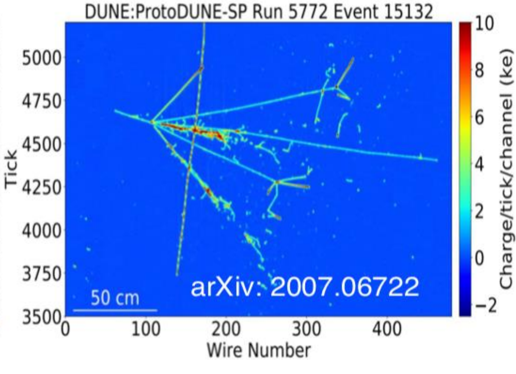




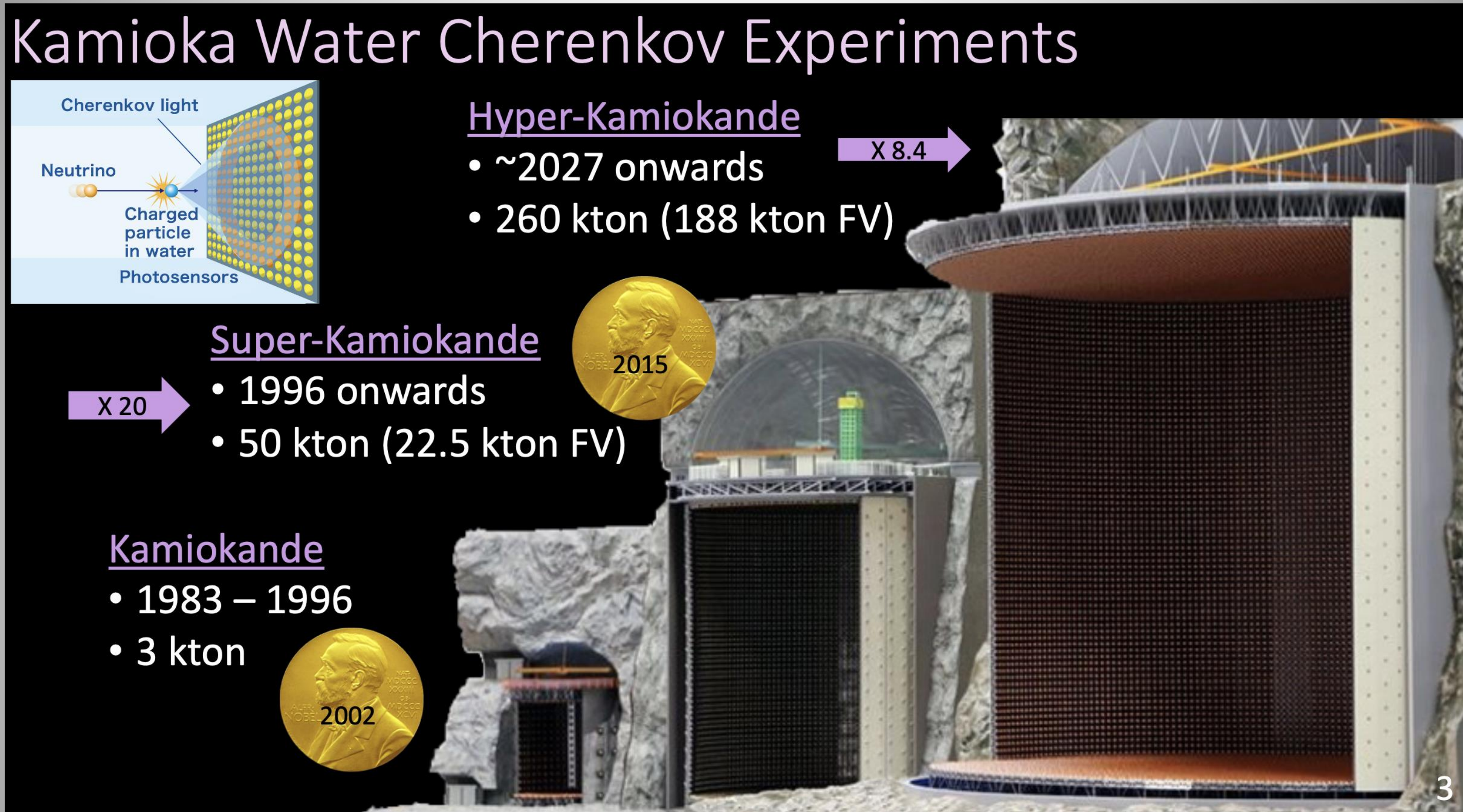
Annu. Rev. Nucl. Part. Sci. 2016. 66:47–71







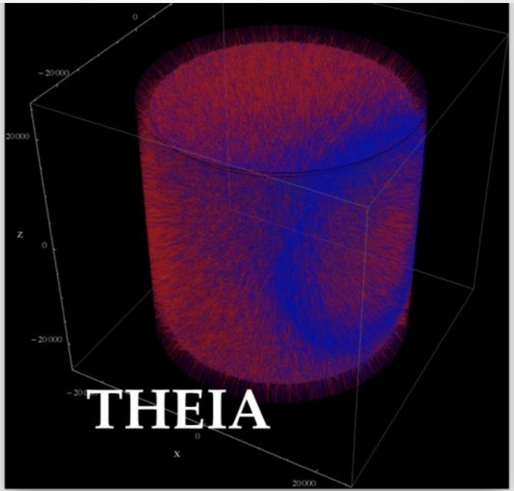
The Hyper-K/T2HK Experiment

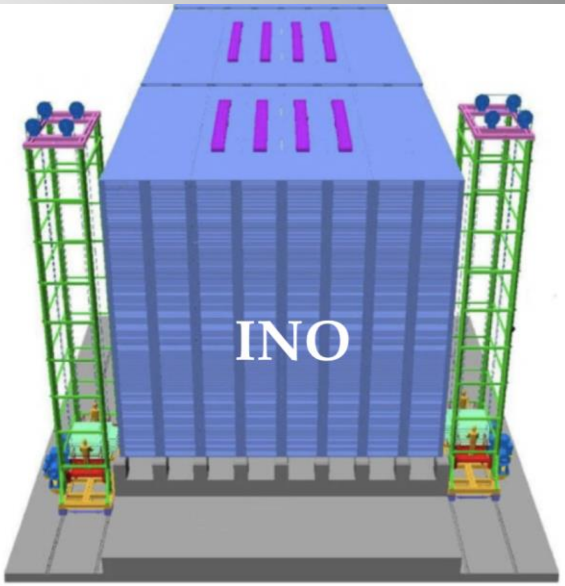


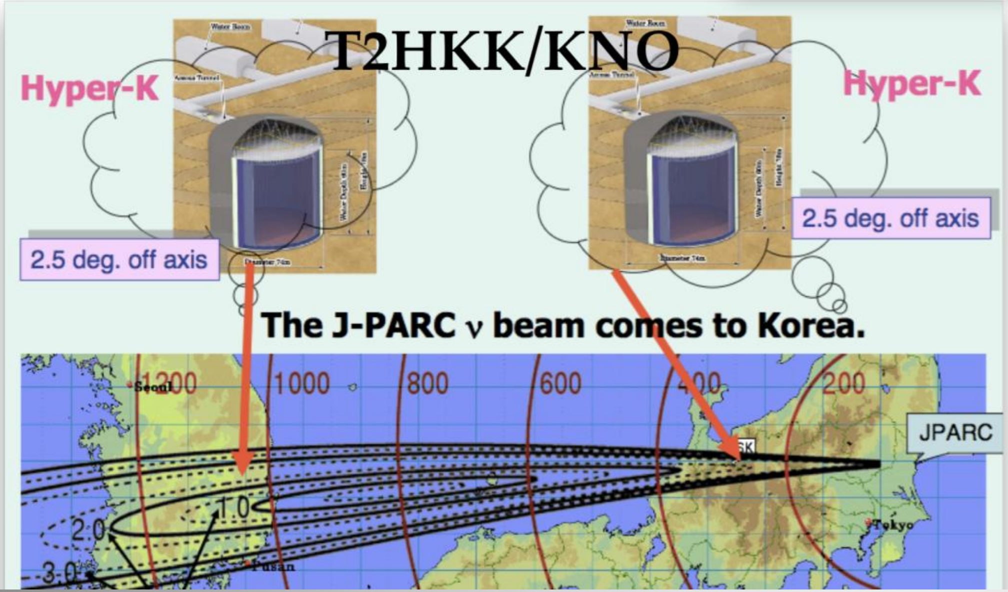
- Hyper-Kamiokande is the next generation neutrino experiment in Japan
  - 260 kton Underground water Cherenkov far detector
  - 1.3 MW upgraded neutrino beam from JPARC
  - Upgraded and additional near detectors

Beyond DUNE/T2HK

- More like **observatories**, very broad physics programs
- Precision tests of 3-flavor mixing, new physics, and much more than just oscillation experiments
- Exact goals will depend on where we will be with next generation!

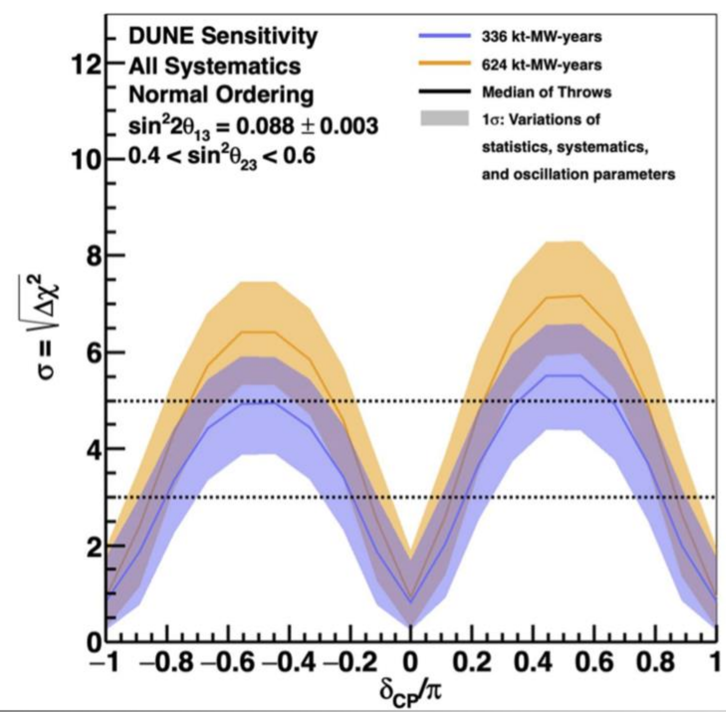


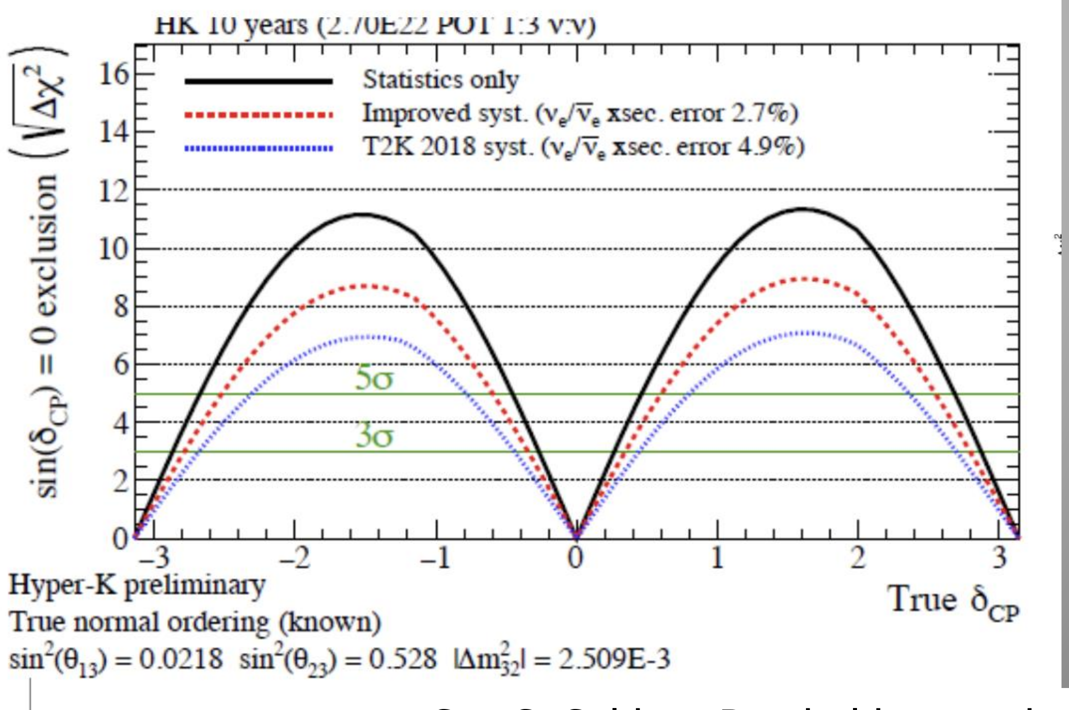




Future Neutrino Experiments

- ~270° (-90°) seems slightly favored
- Combined analysis may give more preference, but not stable yet
- DUNE & HyperK can give a more definite answer
- Further improvement may come from KNO, ESSnuSB, and THEIA





See S. Soldner-Rembold yesterday

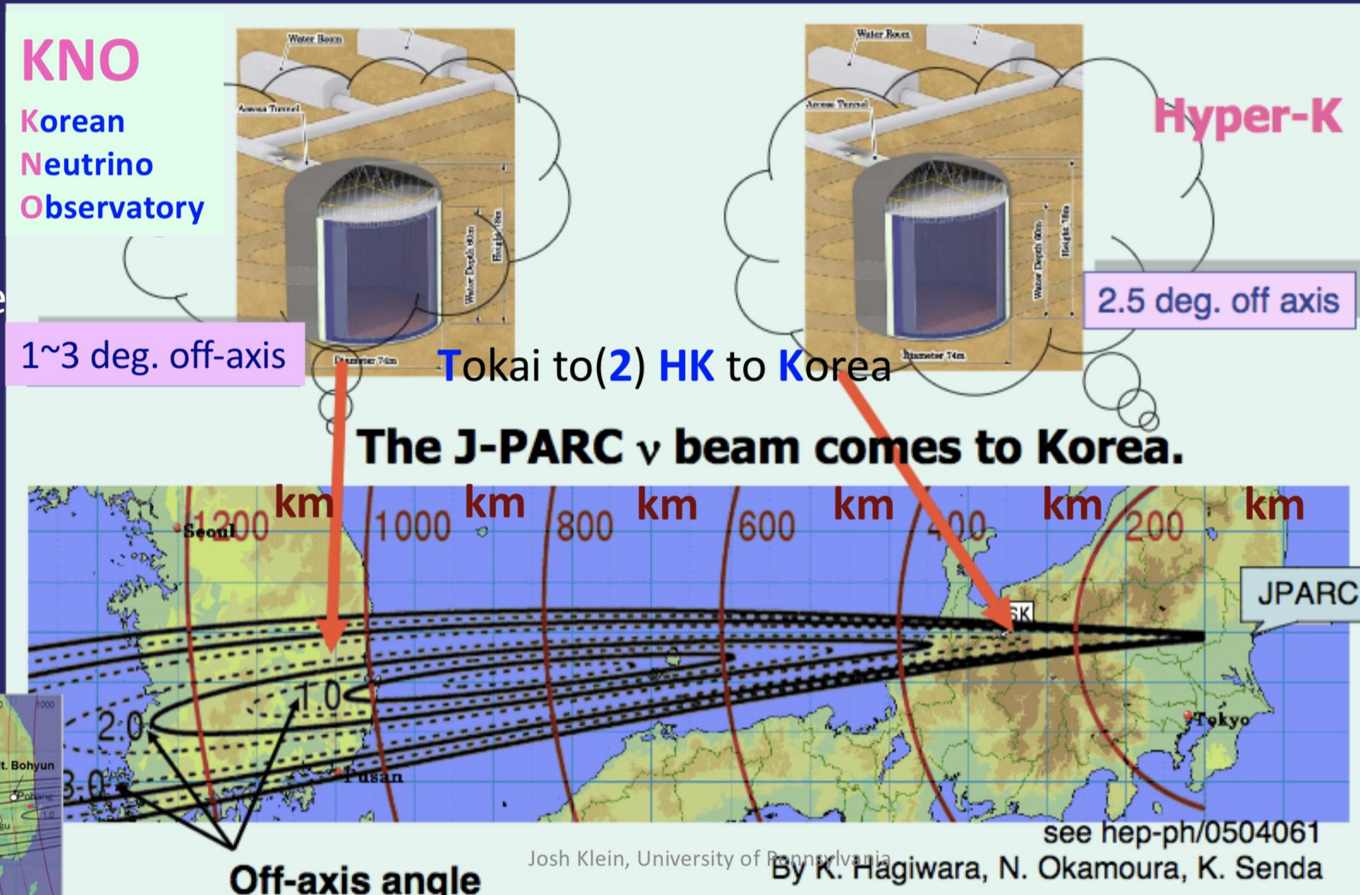
Next Generation Experiments

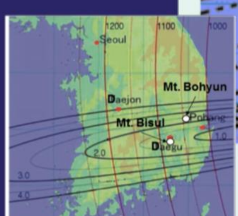
T2HKK/KNO

Goal: Precision measurements of PMNS parameters+broad program

Remarkable luck: J-PARC beam re-emerges in Korea—Hyper-Kamiokande is the “near detector”

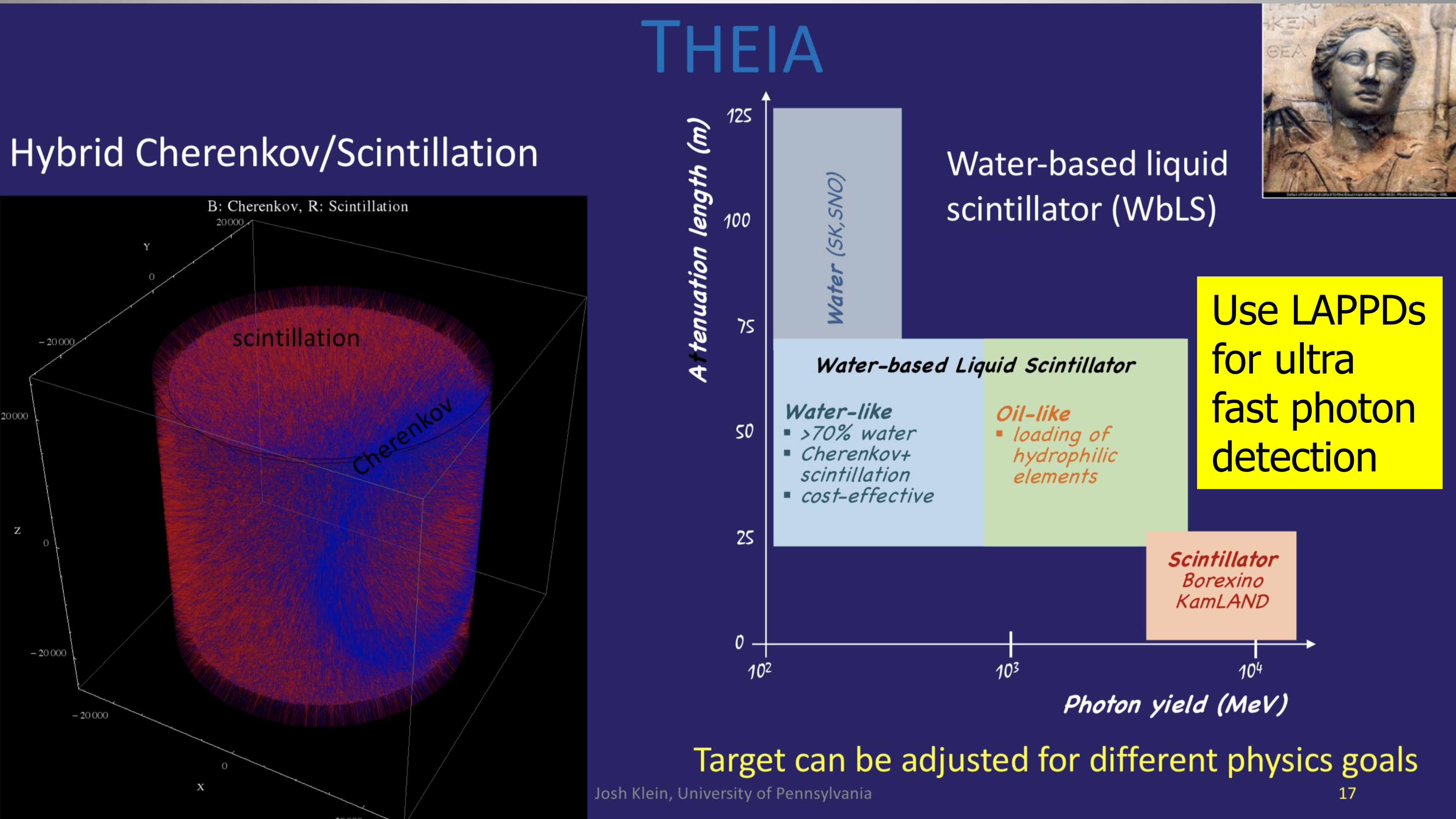
~1000 m overburden provides broad program





Access to the second oscillation maximum -> increased sensitivity to CPV
Further distance -> larger matter effects -> increased sensitivity to MO/NSI

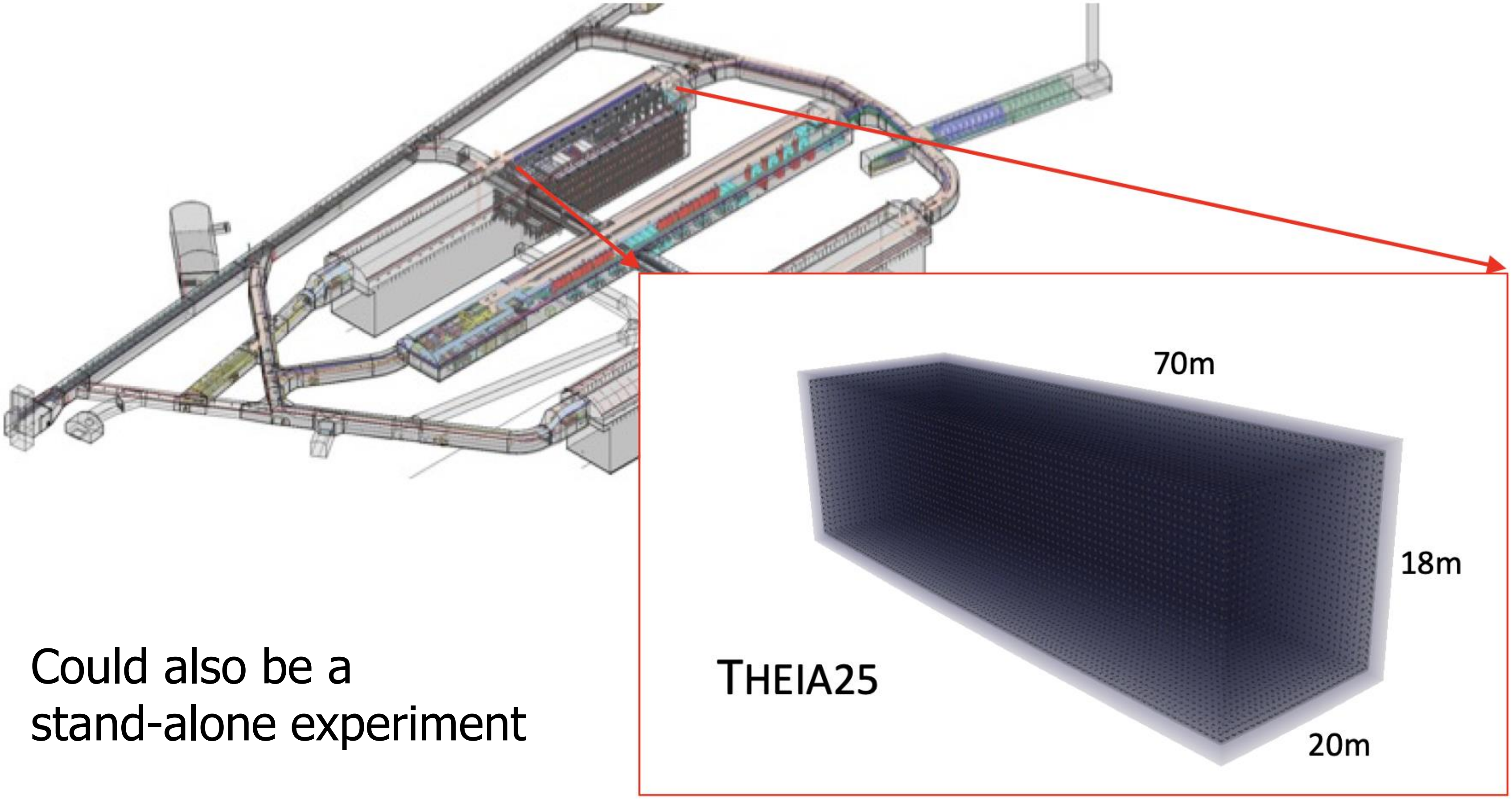
Next Generation Experiments



Use LAPPDs for ultra fast photon detection

Maybe a technology option for the DUNE 4th detector (> 2030)?

Next Generation Experiments



Could also be a stand-alone experiment

Physics coverage: next-generation neutrinoless double beta decay search, to supernova neutrino detection, nucleon decay searches, and measurement of the neutrino mass hierarchy and CP violating phase.

Next Generation Experiments

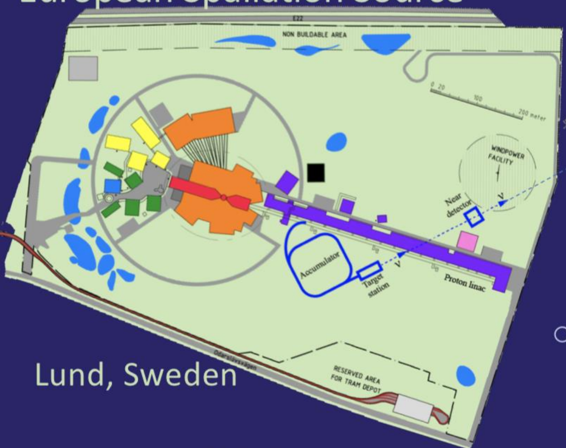
European Spallation Source, Lund

ESSνSB

ESS NEUTRINO SUPER BEAM

Goal: CPV via targeted measurements at 2nd Oscillation Max

Neutrino Superbeam at European Spallation Source



Lund, Sweden

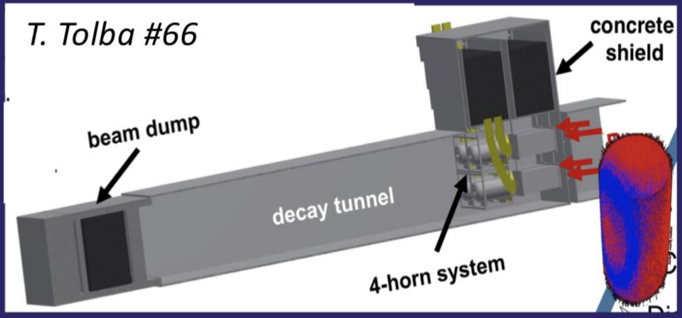
360 km

540 km

Also about 10^{20} μ/year produced---provides R&D opportunity for Neutrino Factory or muon collider

@ Far Site:

- Megaton-scale underground Water Cherenkov detector
  Allows broad program including PDK, astrophysical νs



- 5 MW/2.5 GeV protons
- accumulation ring of ~400 m
  - Shortens pulse from 2.86 ms to few μs
  - Required by 350 kA horn
  - Also allows for decay-at-rest experiments using neutron target
- 4 target/horn system, 25 m decay tunnel
  - ~300 MeV neutrinos
- near detector

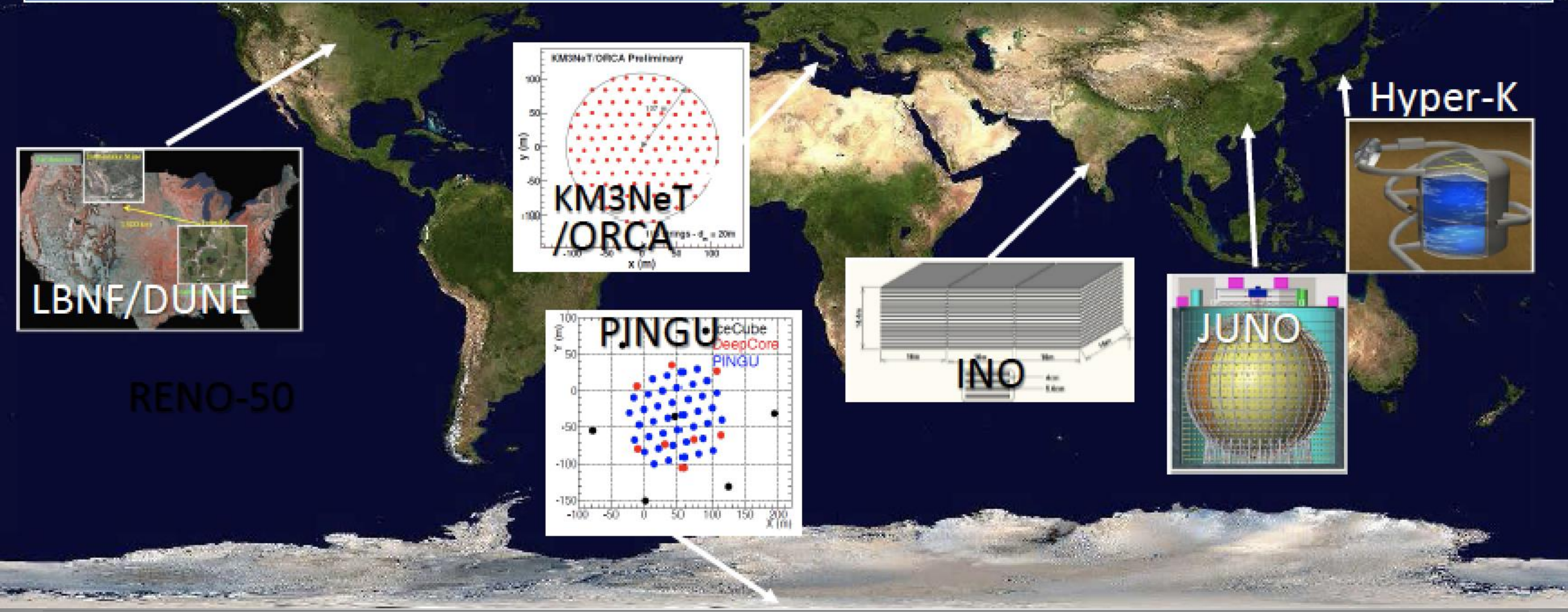
Experiments ready by ~2035?

Will be discussed in a bit more detail

Future Neutrino Experiments

Anticipated next neutrino experiments across the globe

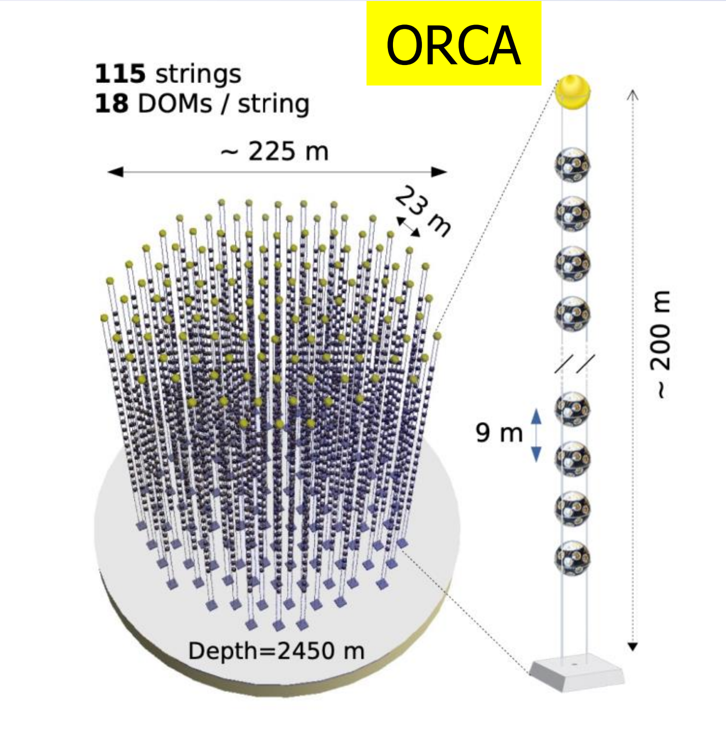
We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.

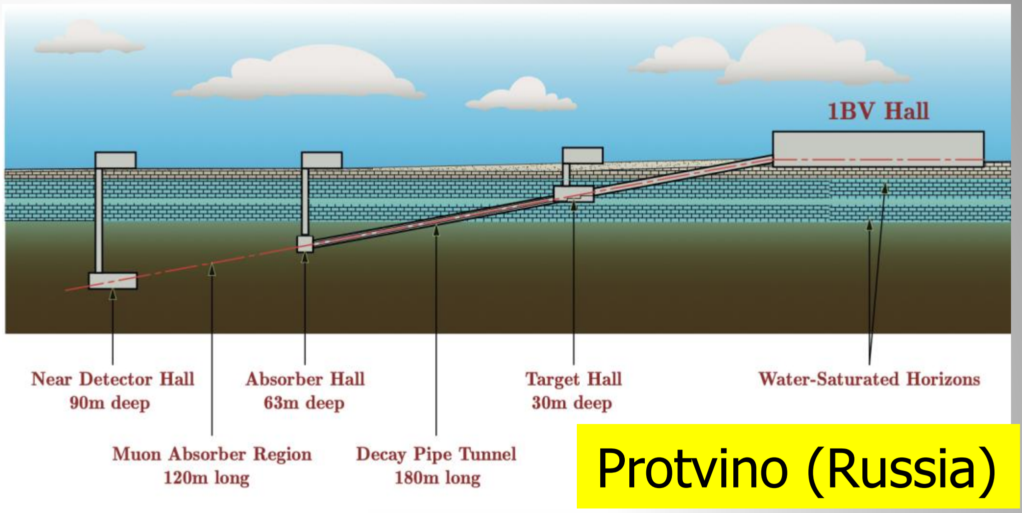


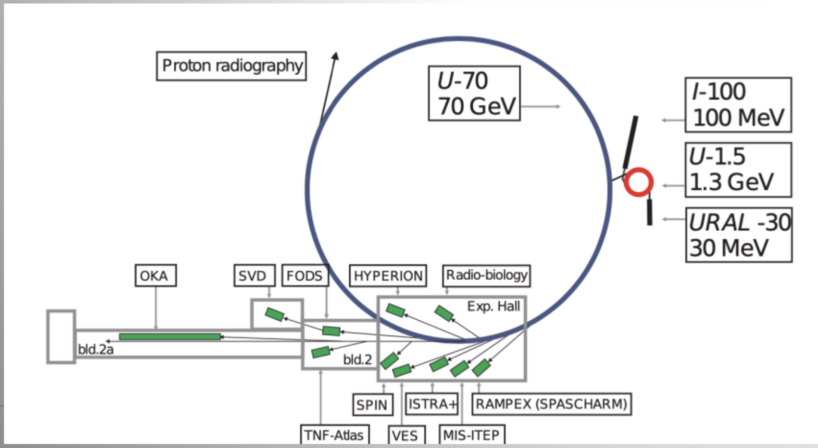
P2O Project Proposal

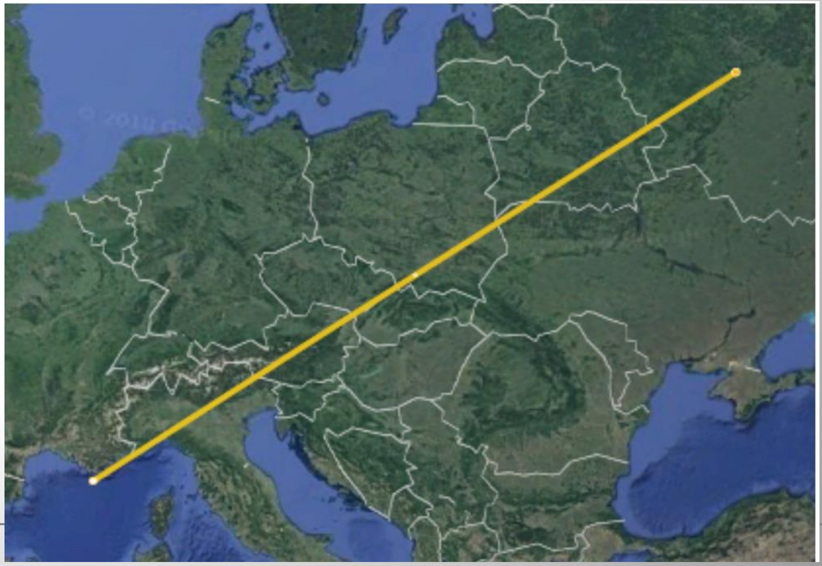
arXiv:1902.06083v3

P2O Project

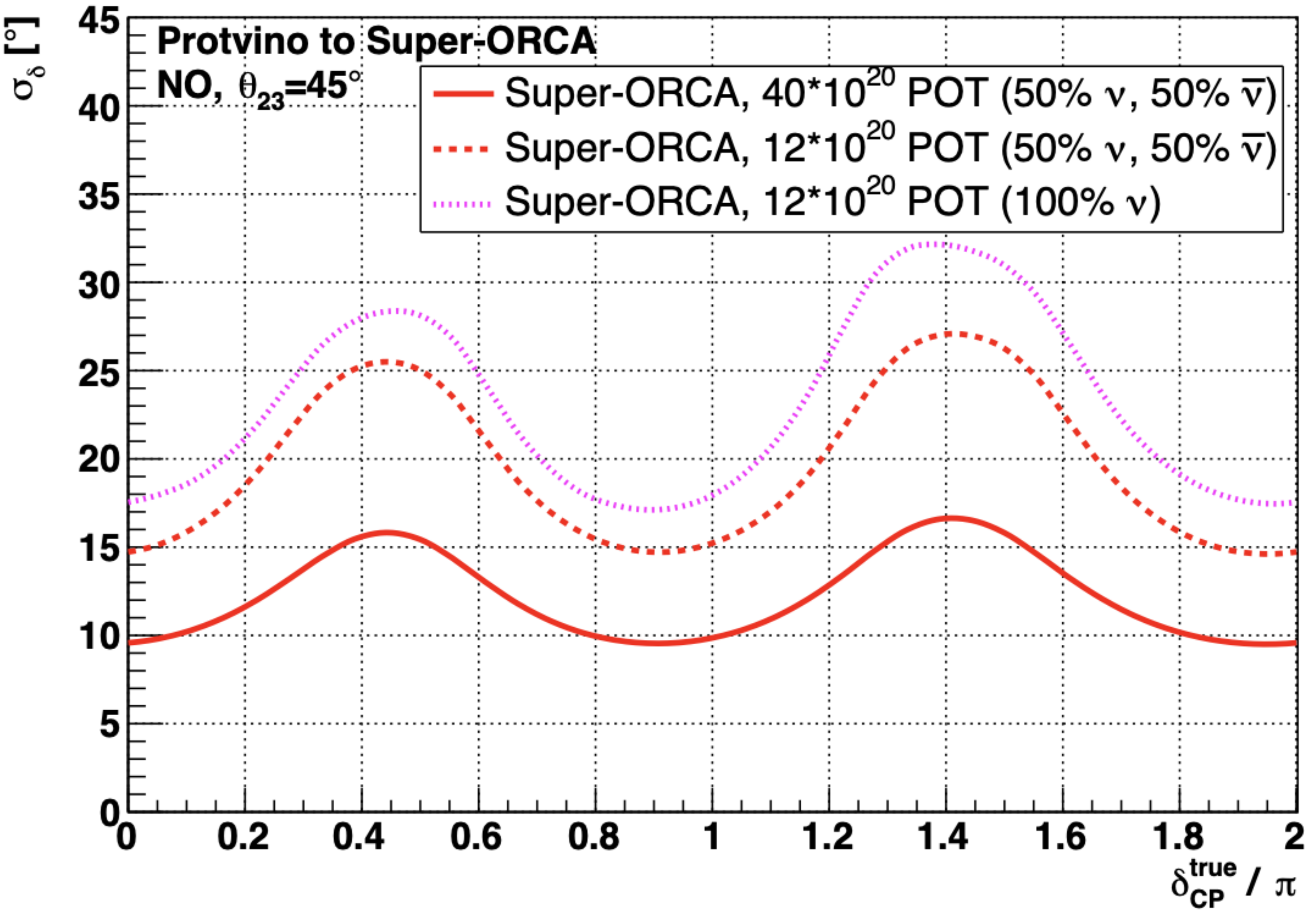

ORCA
115 strings
18 DOMs / string
~ 225 m
23 m
9 m
~ 200 m
Depth=2450 m


1BV Hall
Near Detector Hall
90m deep
Absorber Hall
63m deep
Target Hall
30m deep
Water-Saturated Horizons
Muon Absorber Region
120m long
Decay Pipe Tunnel
180m long
Protvino (Russia)


Proton radiography
U-70
70 GeV
I-100
100 MeV
U-1.5
1.3 GeV
URAL -30
30 MeV
OKA
SVD
FODS
HYPERION
Radio-biology
Exp. Hall
bld.2a
bld.2
SPIN
ISTRA+
RAMPEX (SPASCHARM)
TNF-Atlas
VES
MIS-ITEP



P2O Project



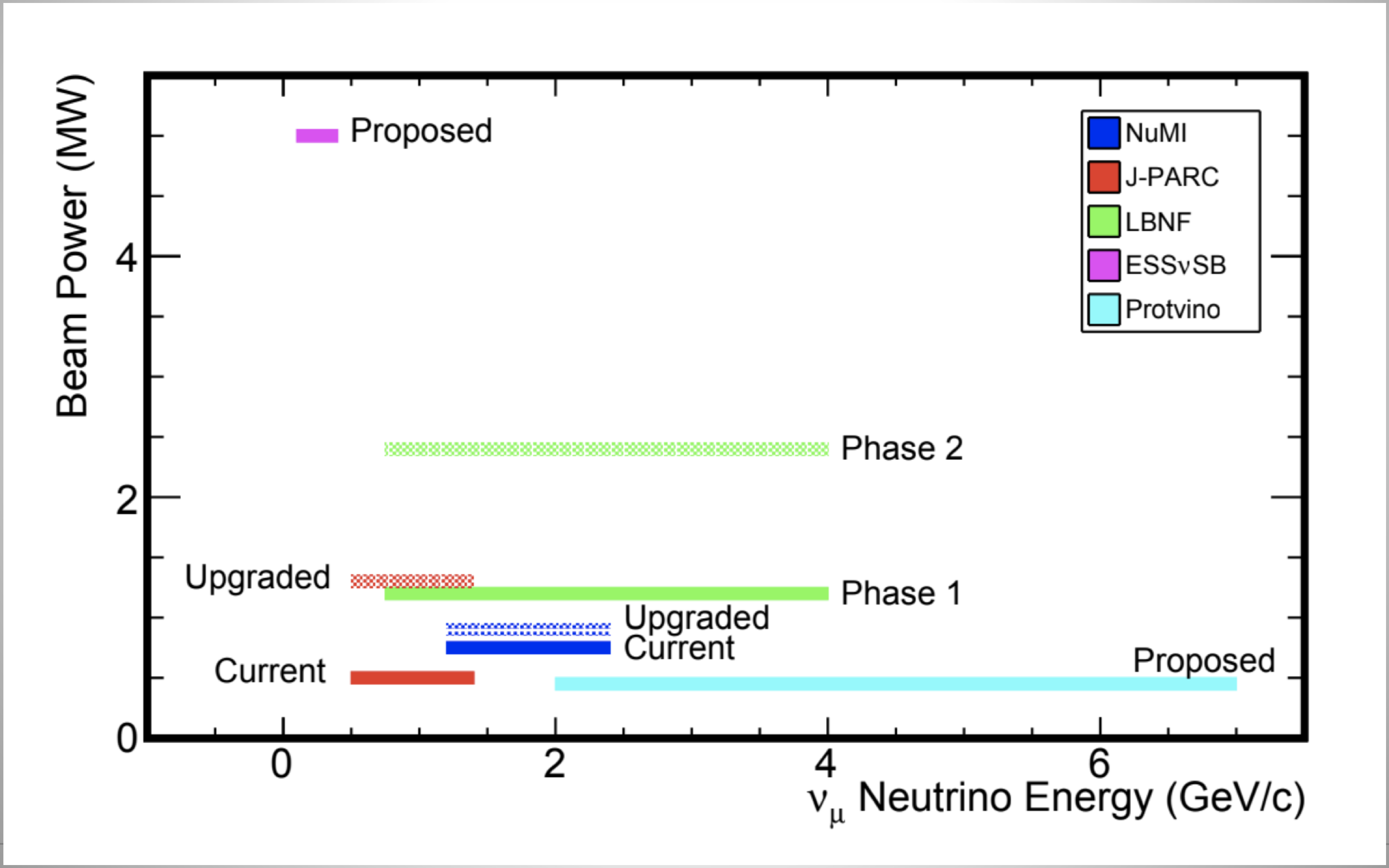
Significant improvements still possible with neutrino flavor tagging -> see later

Figure 15: Resolution on δ_{CP} as function of the true δ_{CP} value for Super-ORCA with the 450 kW beam operating for 3 years with 100% ν beam (dotted line) and 50% ν/50% $\bar{\nu}$ beam (dashed line) and 10 years with 50% ν/50% $\bar{\nu}$ beam (solid line).

Snowmass 2021

arXiv:2211.08641

Long Baseline Experiments Beam Power



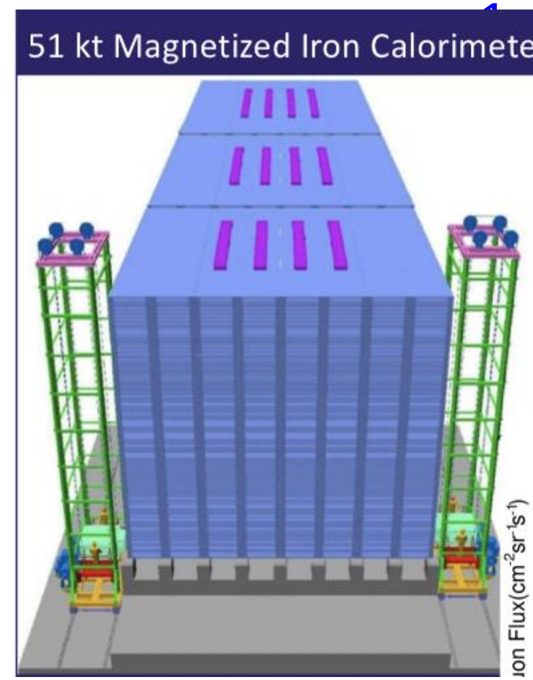
Long Baseline Experiments

Experiment	T2K		T2HK	NOνA	DUNE	P2O	
Location	Japan		Japan	USA	USA	Russia/Europe	
Status	operating		proposed	operating	construction	proposed	
Accelerator facility	J-PARC		J-PARC	Fermilab	Fermilab	Protvino	
Baseline	295 km		295 km	810 km	1300 km	2595 km	
Off-axis angle	2.5°		2.5°	0.8°	0°	0°	
1-st max $\nu_\mu \to \nu_e$	0.6 GeV		0.6 GeV	1.6 GeV	2.4 GeV	4 GeV	
Detector	SuperK		HyperK	NOνA	DUNE	ORCA	Super-ORCA
Target material	pure water		pure water	LS	liquid Ar	sea water	
Detector technology	Cherenkov		Cherenkov	LS	TPC	Cherenkov	
Fiducial mass	22 kt		186 kt	14 kt	40 kt	8000 kt	4000 kt
Beam power	500 kW		1300 kW	700 kW	1070 kW	450 kW	450 kW
ν_e events per year (NO)	~ 20		230	~ 20	250	3500	3400
$\bar{\nu}_e$ events per year (IO)	~ 6		165	~ 7	110	1200	1100
NMO sensitivity ($\delta_{\rm CP} = \pi/2$)	-	-	4σ	1σ	7σ	8σ	$> 8\sigma$
CPV sensitivity ($\delta_{\rm CP} = \pi/2$)	1.5σ	3σ	8σ	2σ	7σ	2σ	6σ
1σ error on $\delta_{\rm CP}$ ($\delta_{\rm CP} = \pi/2$)			22°		16°	53°	16°
1σ error on $\delta_{\rm CP}$ ($\delta_{\rm CP} = 0$)			7°		8°	32°	10°
Year / data taking years	2018	2026	10 yr	2024	10 yr	3 yr	10 yr
Refs.	[27]	[29]	[2, 30]	[3, 31]	[4, 5]		

The INO Neutrino Observatory

arXiv:1505.07380

- The India-based Neutrino Observatory (INO) Project is the plan to build a world-class underground laboratory at approx. -1200 m for non-accelerator based high energy and nuclear physics research in India. The laboratory will consist of a large cavern of 132x26x20m and several smaller caverns.
- Construction of a Iron Calorimeter (ICAL) detector for studying neutrinos, consisting of 50k tons of magnetized iron plates arranged in stacks with gaps in between where 2x2m RPCs are inserted.
- Neutrino energy range >1 GeV, angular precision 1 degree, magnetic field(!)….
- the
  nd
-



The European Spallation Source

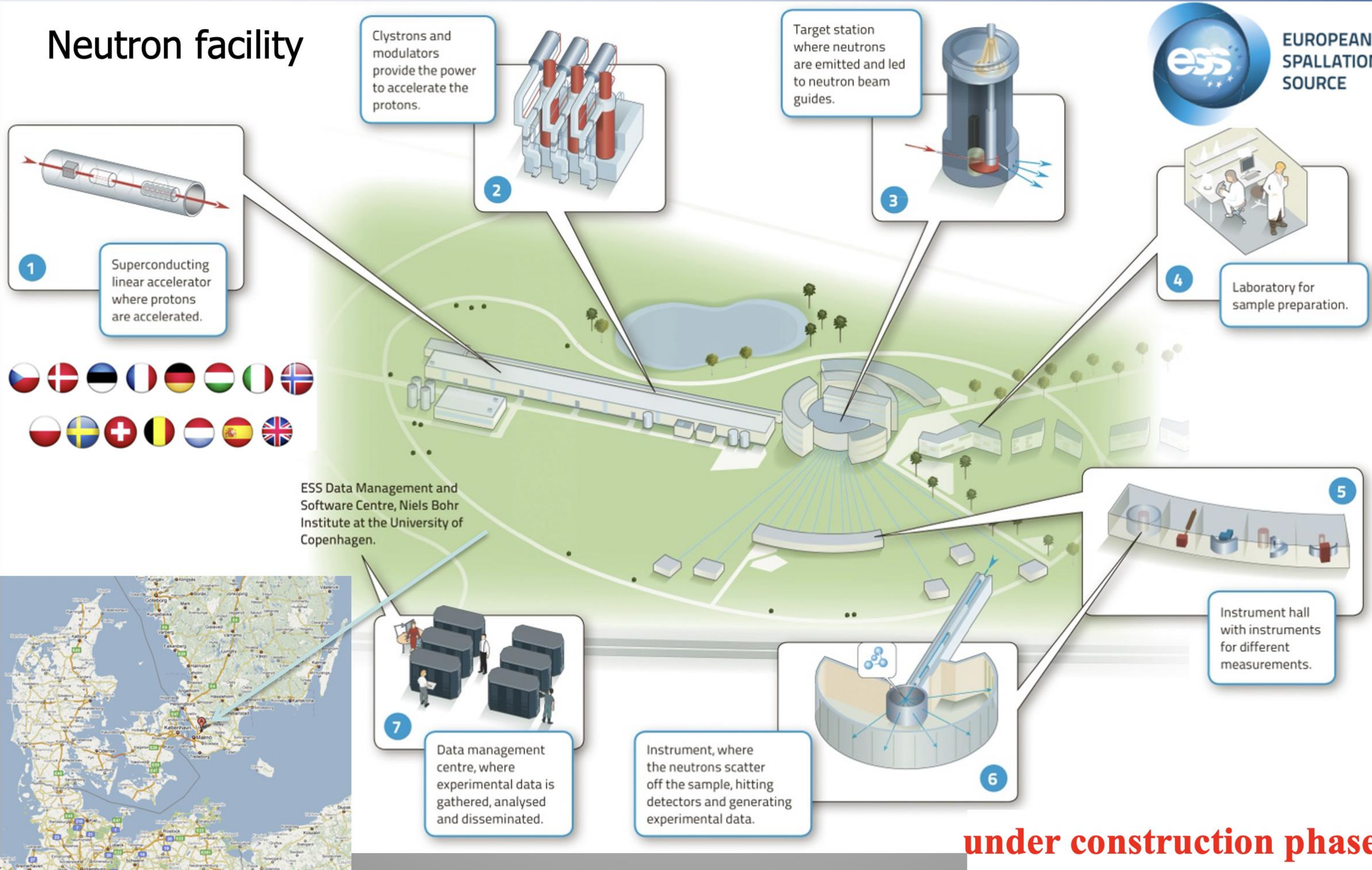
ESS Neutrino Super Beam Plus

Co-funded by the European Union

The European Spallation Source neutrino Super Beam and muon synergies

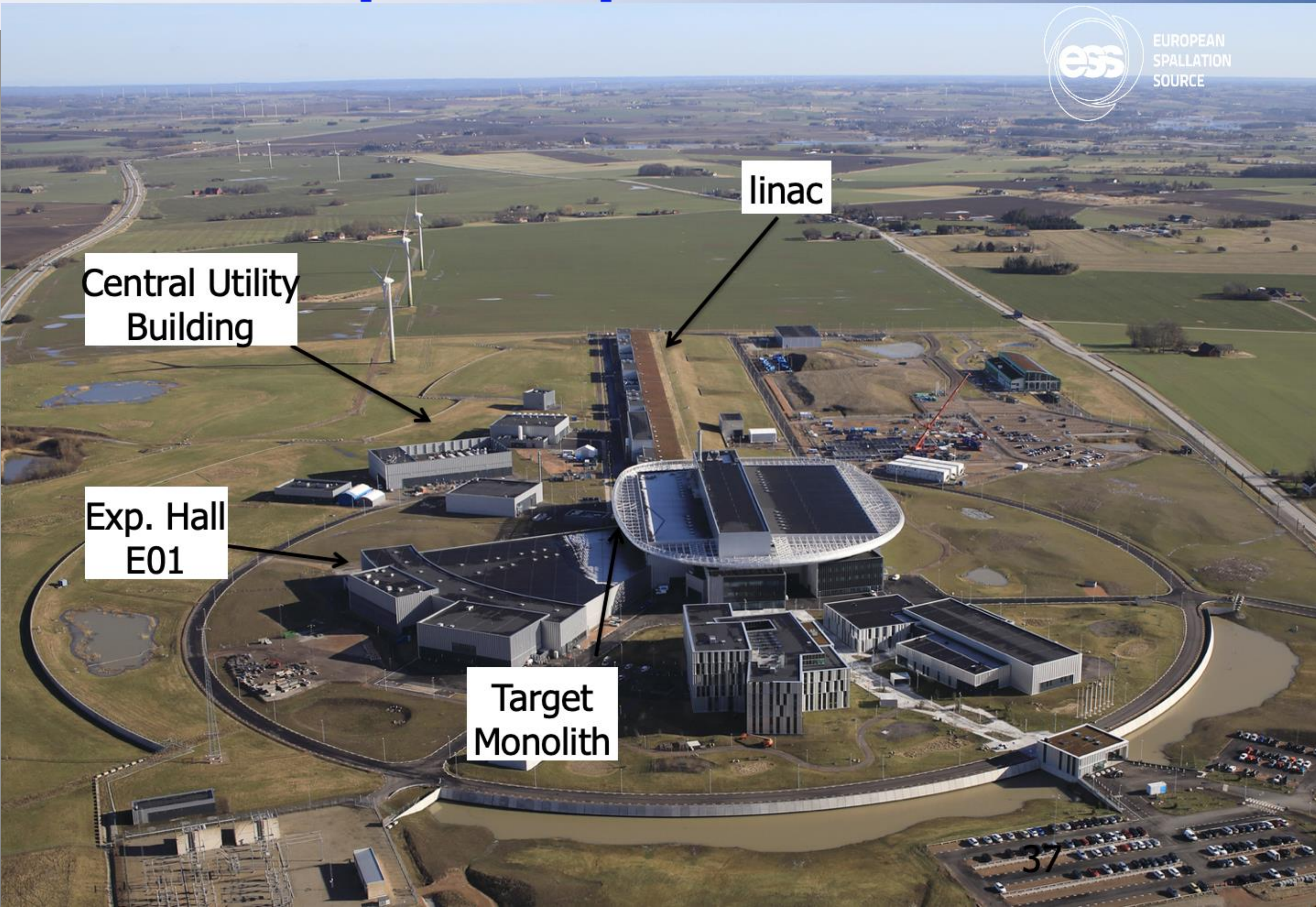
European Spallation Source

Neutron facility



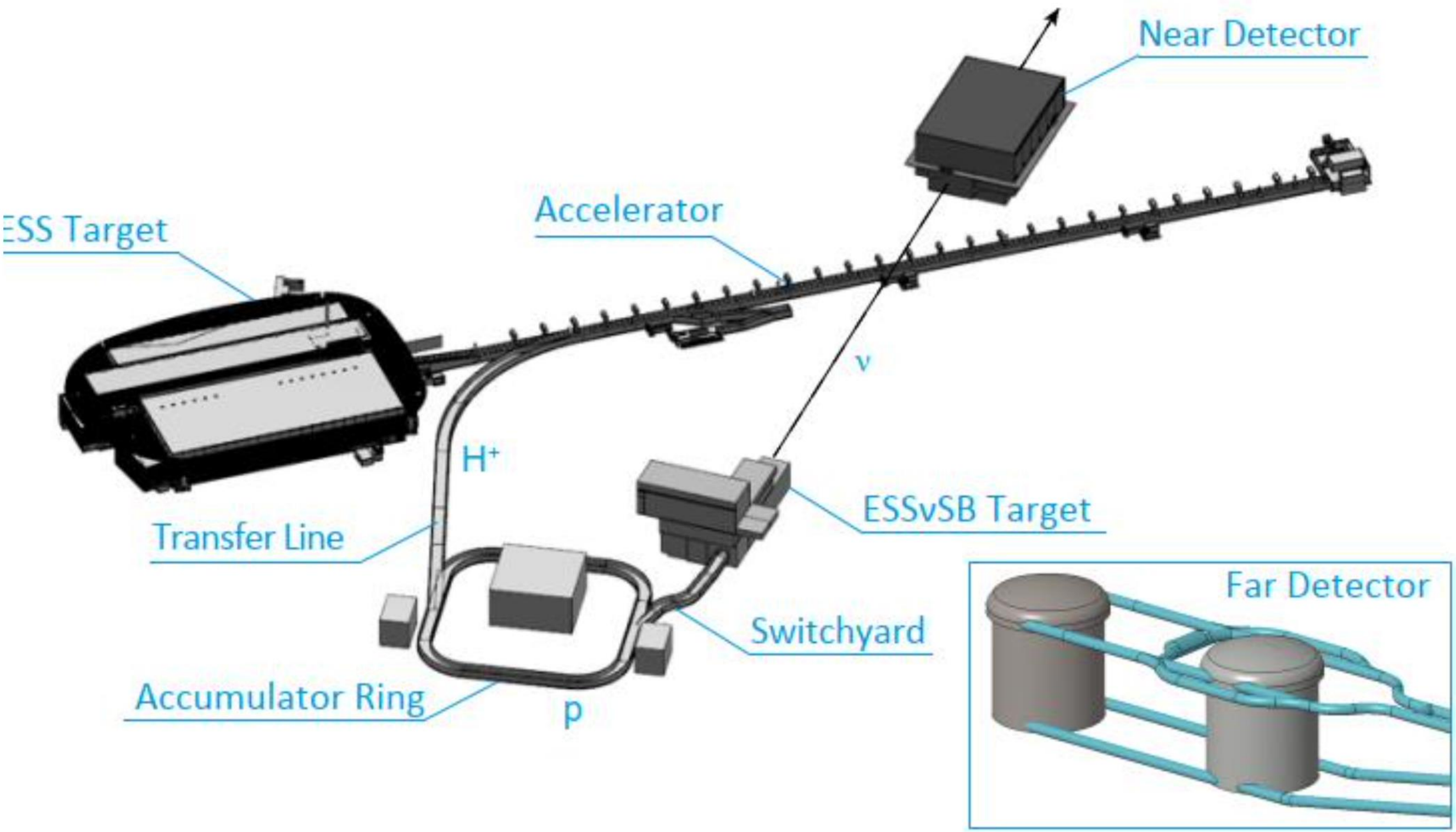
under construction phase
(~2 B€ facility)

European Spallation Source



ESSnuSB

ESSnuSB lay-out

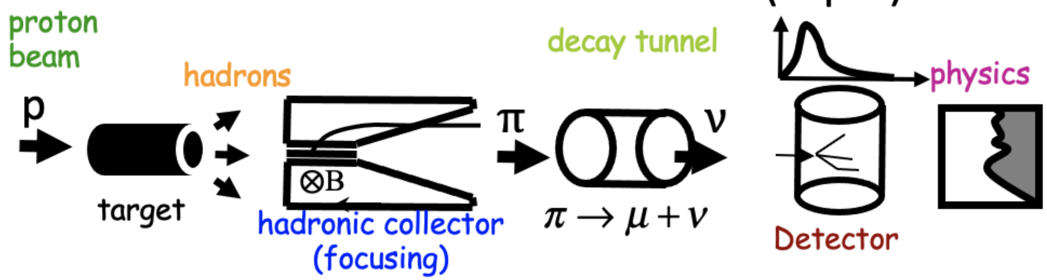


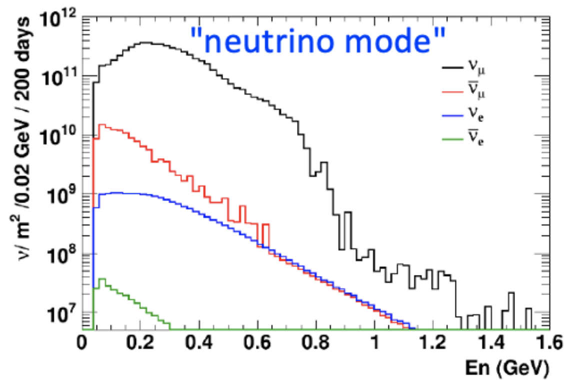
Having access to a powerful proton beam…

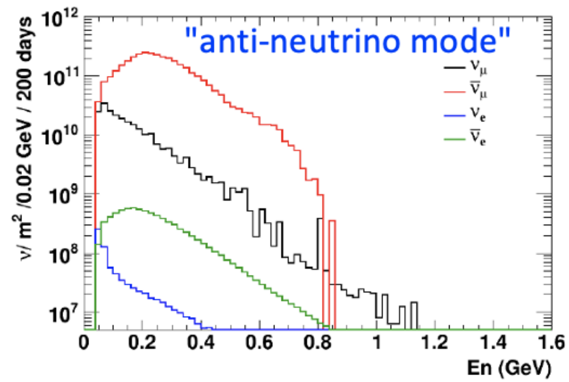
What can we do with:

- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- $>2.7\times10^{23}$ protons/year

conventional neutrino (super) beam







- almost pure ν_μ beam
- small ν_e contamination which could be used to measure ν_e cross-sections in a near detector

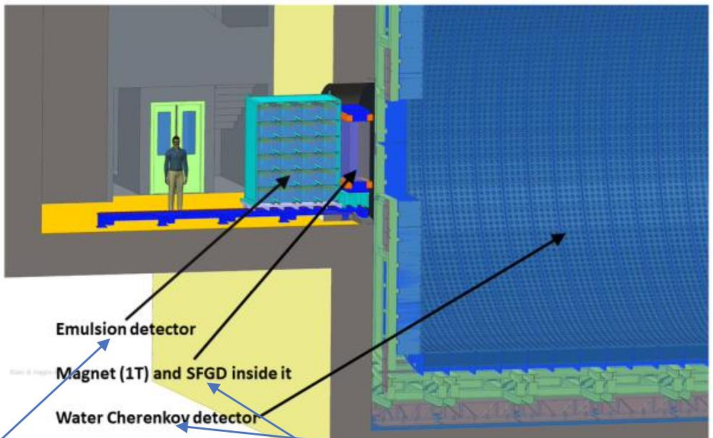
	ν Mode		$\bar{\nu}$ Mode	
	$N_\nu(10^{10}/m^2)$	%	$N_\nu(10^{10}/m^2)$	%
ν_μ	583	97.5	23.9	6.55
$\bar{\nu}_\mu$	12.8	2.1	340	93.2
ν_e	1.93	0.3	0.08	0.02
$\bar{\nu}_e$	0.03	0.01	0.78	0.21

at 100 km from the target, per year (in absence of oscillations)

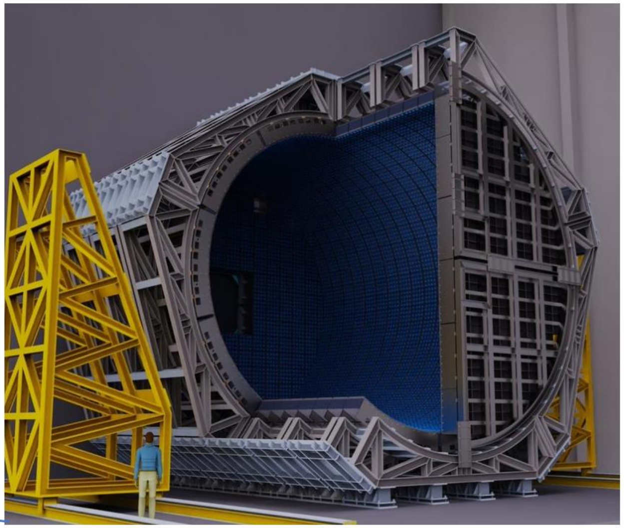
ESSnuSB

Emulsion detector + scintillator cube detector (in magnet) + Water Cerenkov

The Near Detector



Near Detector underground station



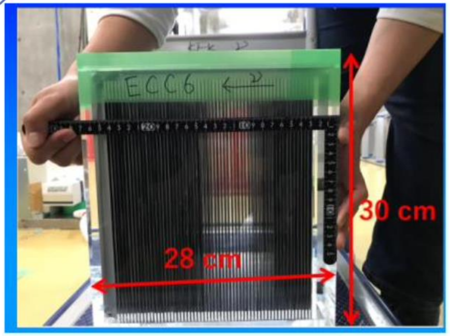
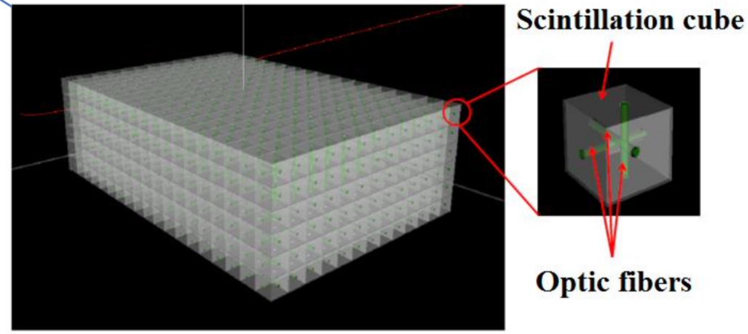
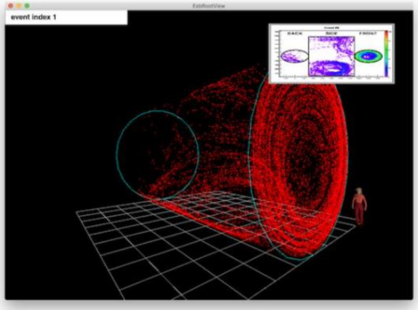


Figure 6.42: A photograph of the NINJA ECC element using water as target.





The super Fine-Grained Detector sFDG

ESSnuSB

Large Water Cerenkov with diameter and height ~78m, at a 360 km distance

The Far Detector

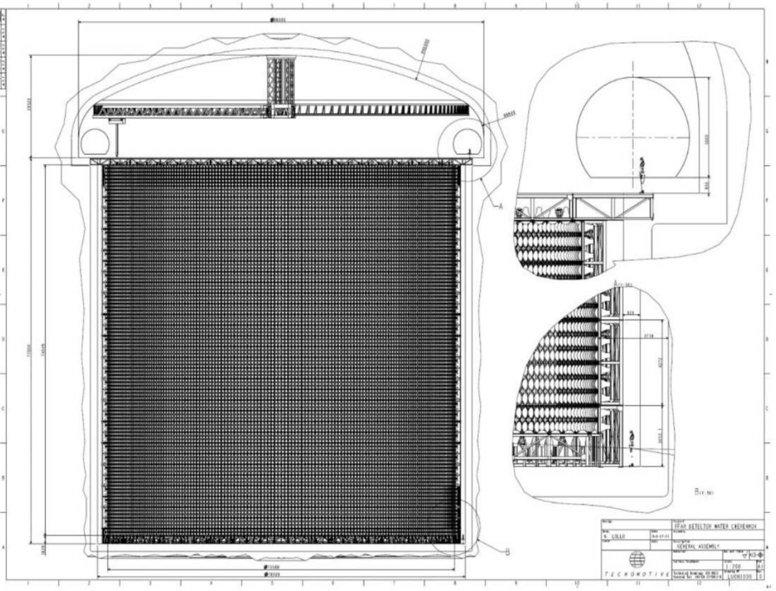
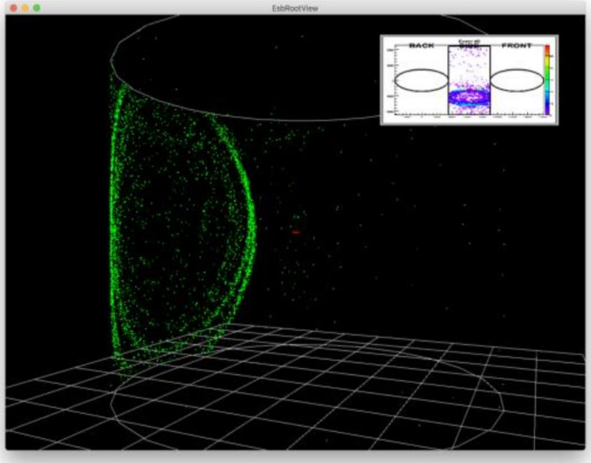


Figure 6.48: Overall view of a single far-detector tank with indicated dimensions.



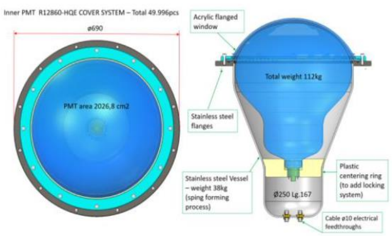
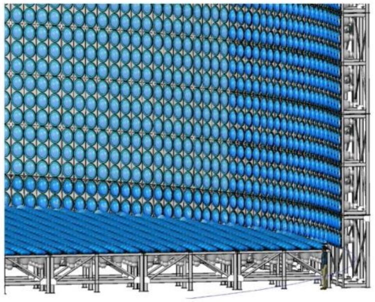


Figure 6.50: A schematic view of an inward-facing 20 inch PMT embedded in a protective cover.



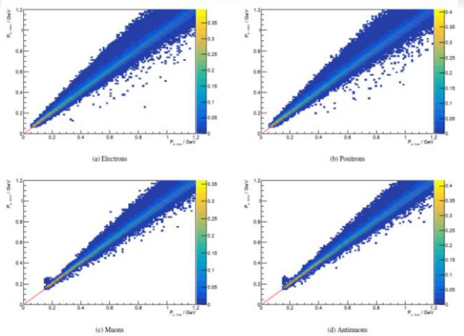
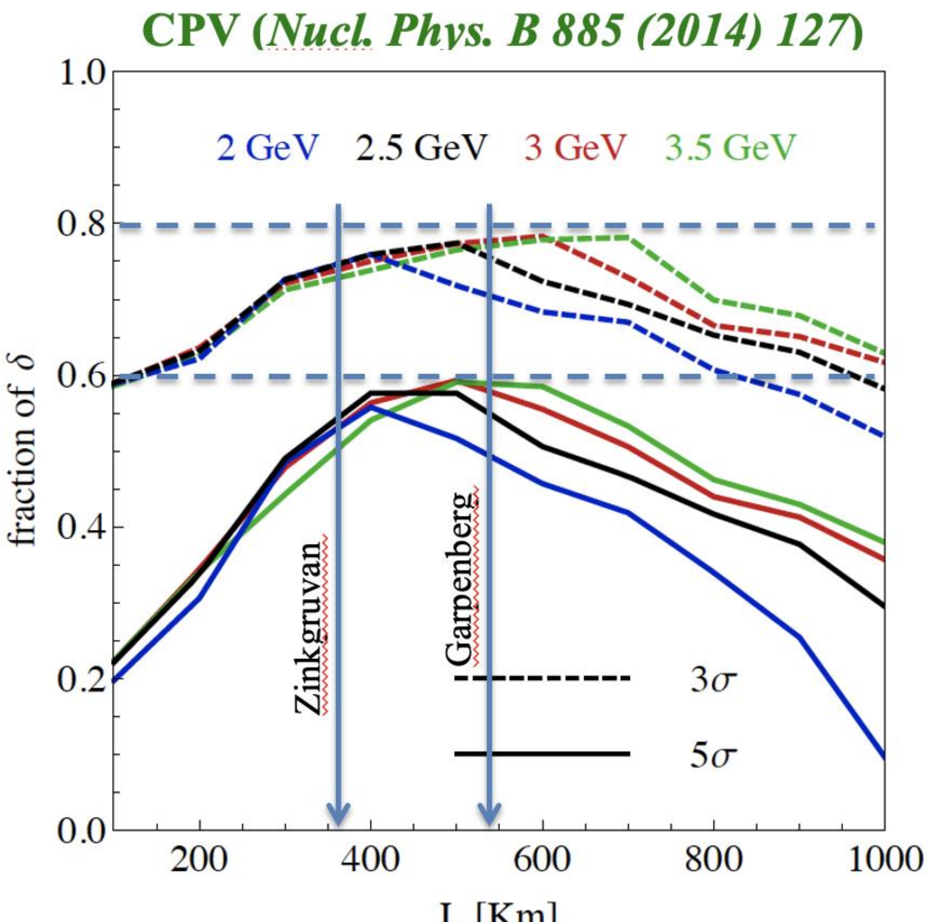


Figure 6.58: Distribution of reconstructed momentum as a function of true momentum for different flavours of charged leptons. These plots were produced using the charged lepton production.

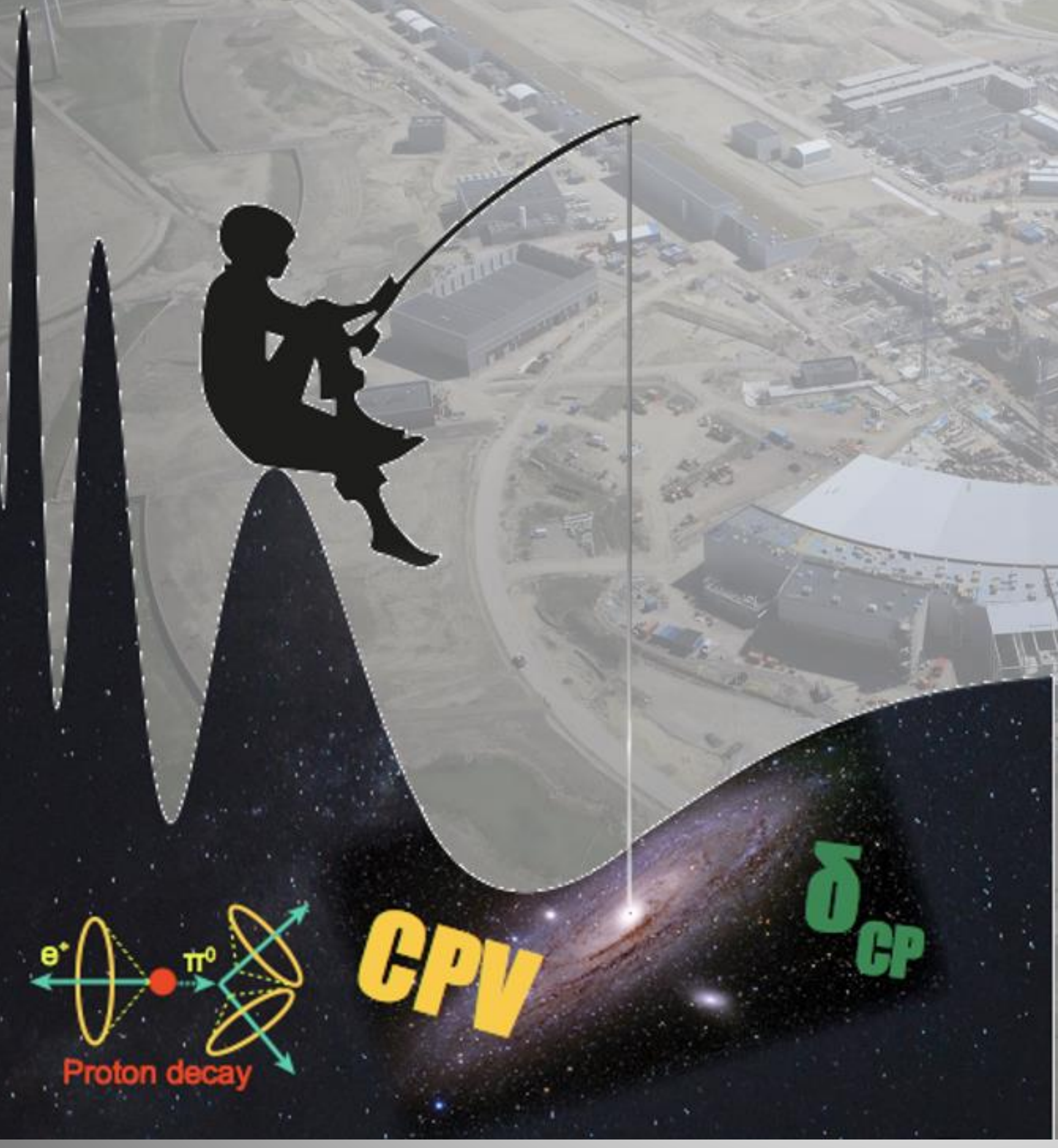
Far Detector Location Options



Candidate active mines

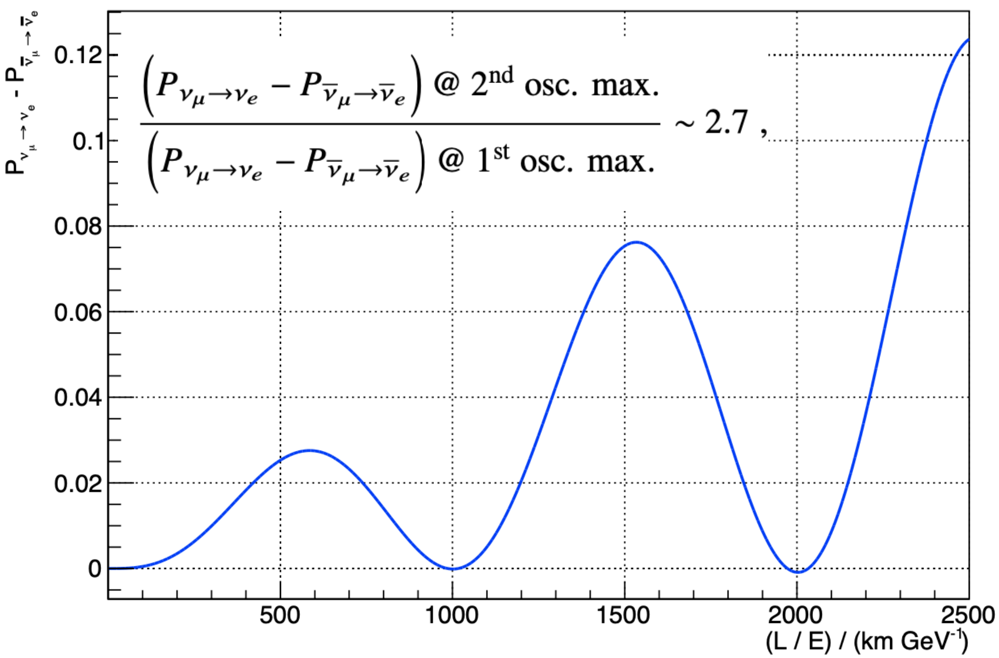
- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/backg.)**

Use all this ESS linac power to go to the 2nd oscillation maximum



but why?

ESSnuSB

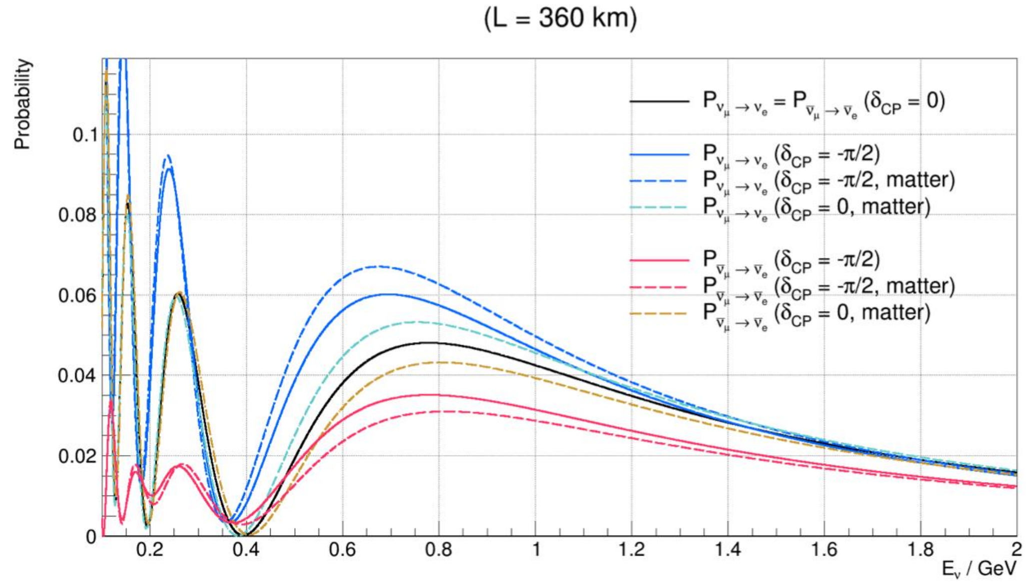


CPV effect stronger in the second maximum than the first

Parameter	Best-Fit Value $\pm 1\sigma$ Range
$\sin^2\theta_{12}$	0.304 ± 0.012
$\sin^2\theta_{13}$	0.02246 ± 0.00062
$\sin^2 2\theta_{23}$	0.9898 ± 0.0077
Δm^2_{21}	$(7.42 \pm 0.21) \times 10^{-5}$ eV^2
Δm^2_{31}	$(2.510 \pm 0.027) \times 10^{-3}$ eV^2

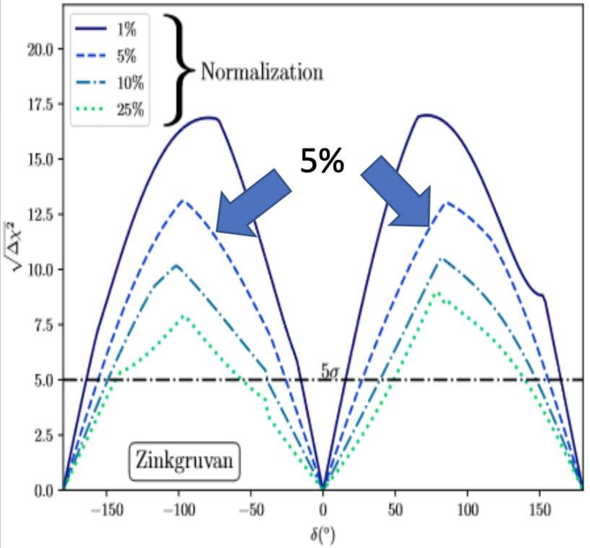
Matter efects are stronger in the first maximum compared to the second

However: less neutrinos at the second maximum

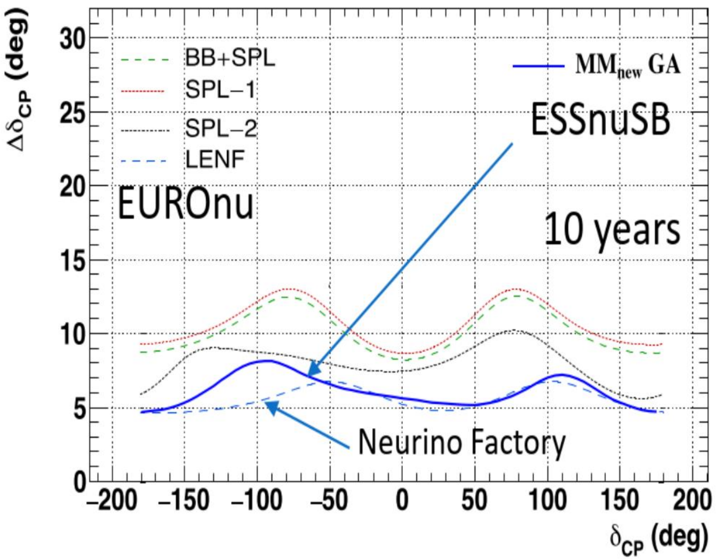


ESSnuSB

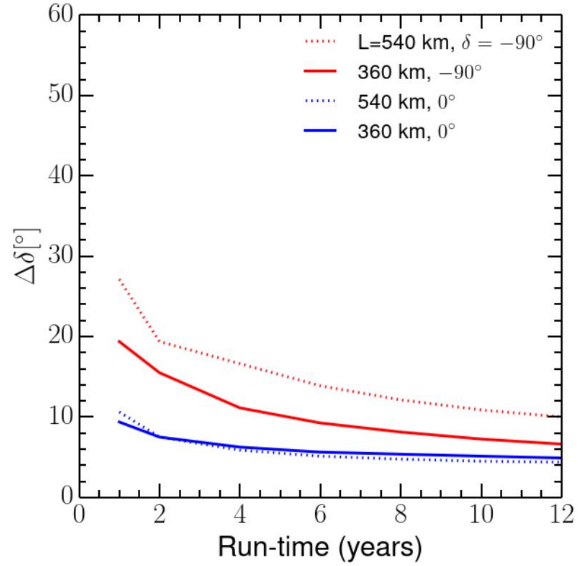
Performance for CPV discovery and δ_{CP} measurement



Discovery potential vs δ_{CP} angle after 10 years with 5% normalization error providing 70% coverage of all δ_{CP} vaues



Error in δ_{CP} angle vs δ_{CP} angle after 10 years with 5% normalization error



Error in δ_{CP} angle vs run time with 5% normalization error

- ESS construction has started!
- Discussion on upgrades –such as ESSnuSB-- starting in ~2025
- New Funding for an ESSnuSB design study (for 4 years) in place

Future Reactor Neutrino Facilities

JUNO and SuperChooz

Short Baseline Experiments

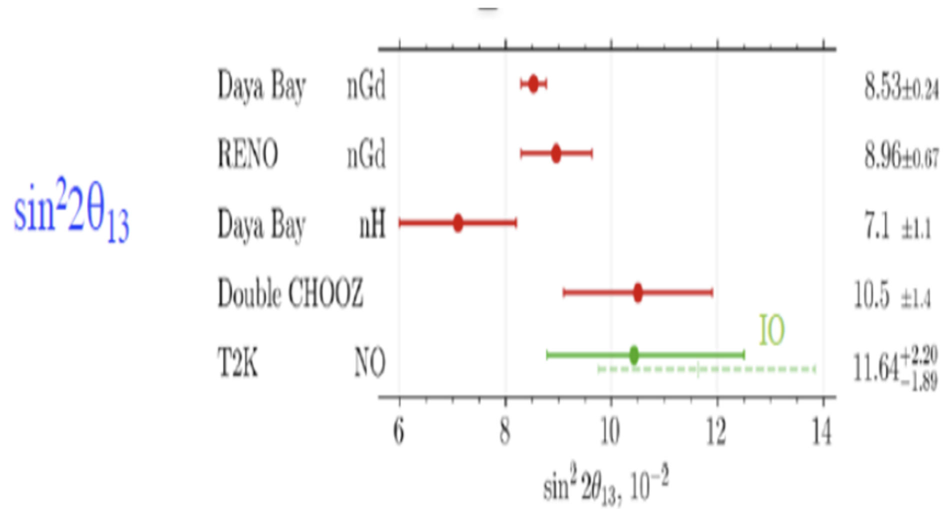
Measuring the mixing angle θ_{13}:

Daya Bay (China)
Eight anti-neutrino detectors
(liquid scintillator based)
within 2 km of 6 reactors

RENO (South Korea)
Two anti-neutrino detectors
(liquid scintillator based)
~up to 1.5 km of 6 reactors

Double Chooz (France)
Two anti-neutrino detectors
(liquid scintillator based)
within 0.4-1 km of the reactors

Results



Phys. Rev. Lett. 130, 161802 (2023

- New results from Daya Bay nGd capture:

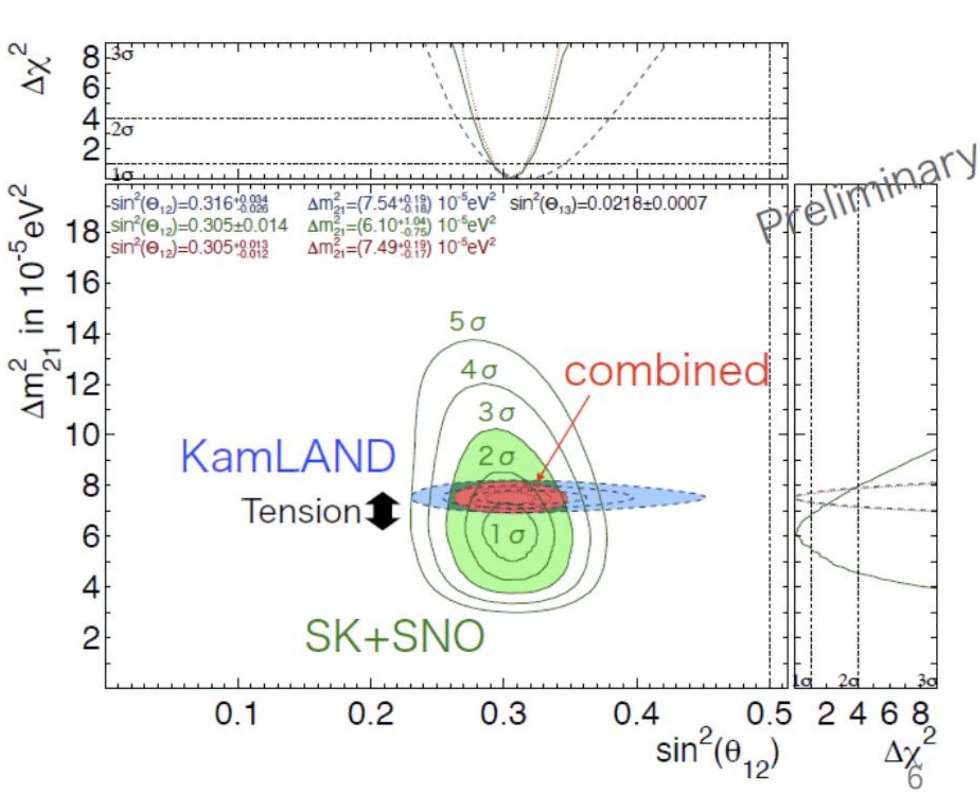
Best-fit results: $\chi^2/\text{ndf} = 559/518$

$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +(2.466^{+0.060}_{-0.060}) \times 10^{-3}\text{eV}^2$ (2.4% precision)

Inverted hierarchy: $\Delta m^2_{32} = -(2.571^{+0.060}_{-0.060}) \times 10^{-3}\text{eV}^2$ (2.3% precision)

Solar Neutrino Parameters



$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$

$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$$

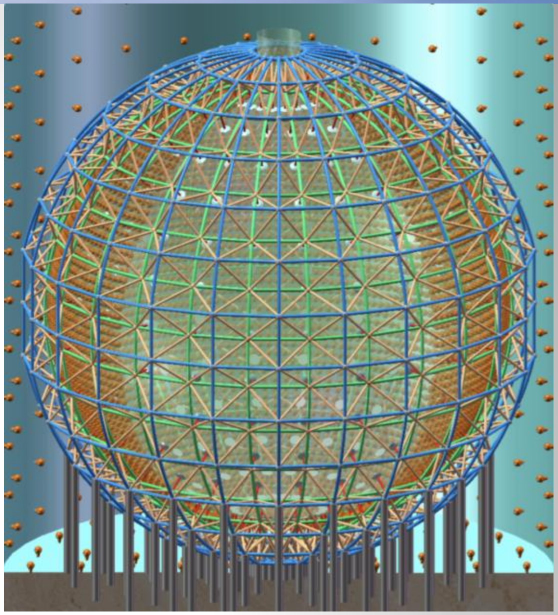
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$$

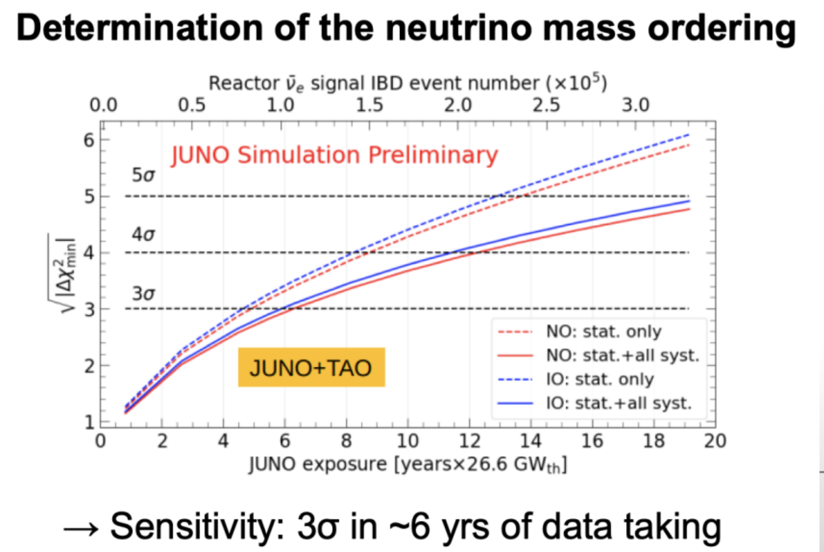
- Tension between solar & reactor result still there, 1.5σ.
- JUNO can simultaneously measure Δm^2_{21} and θ_{12} using reactor antineutrinos and solar neutrinos with a great precision.
- HyperK will improve the solar neutrino result

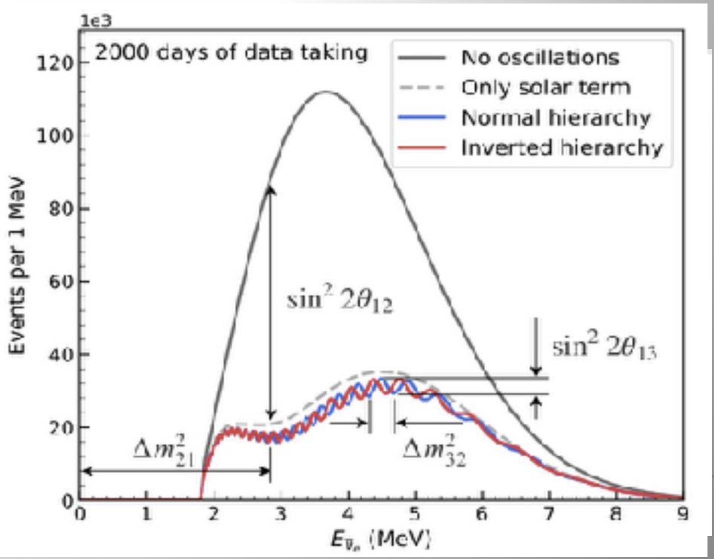
The JUNO Experiment

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton multi-purpose liquid scintillator detector (~20 times the size of present detectors, including 18000 20″ PMTs) expected to start data taking in 2024

With an energy resolution of 3% at 1 MeV, JUNO determines the mass ordering with a significance of 3 sigma within six years

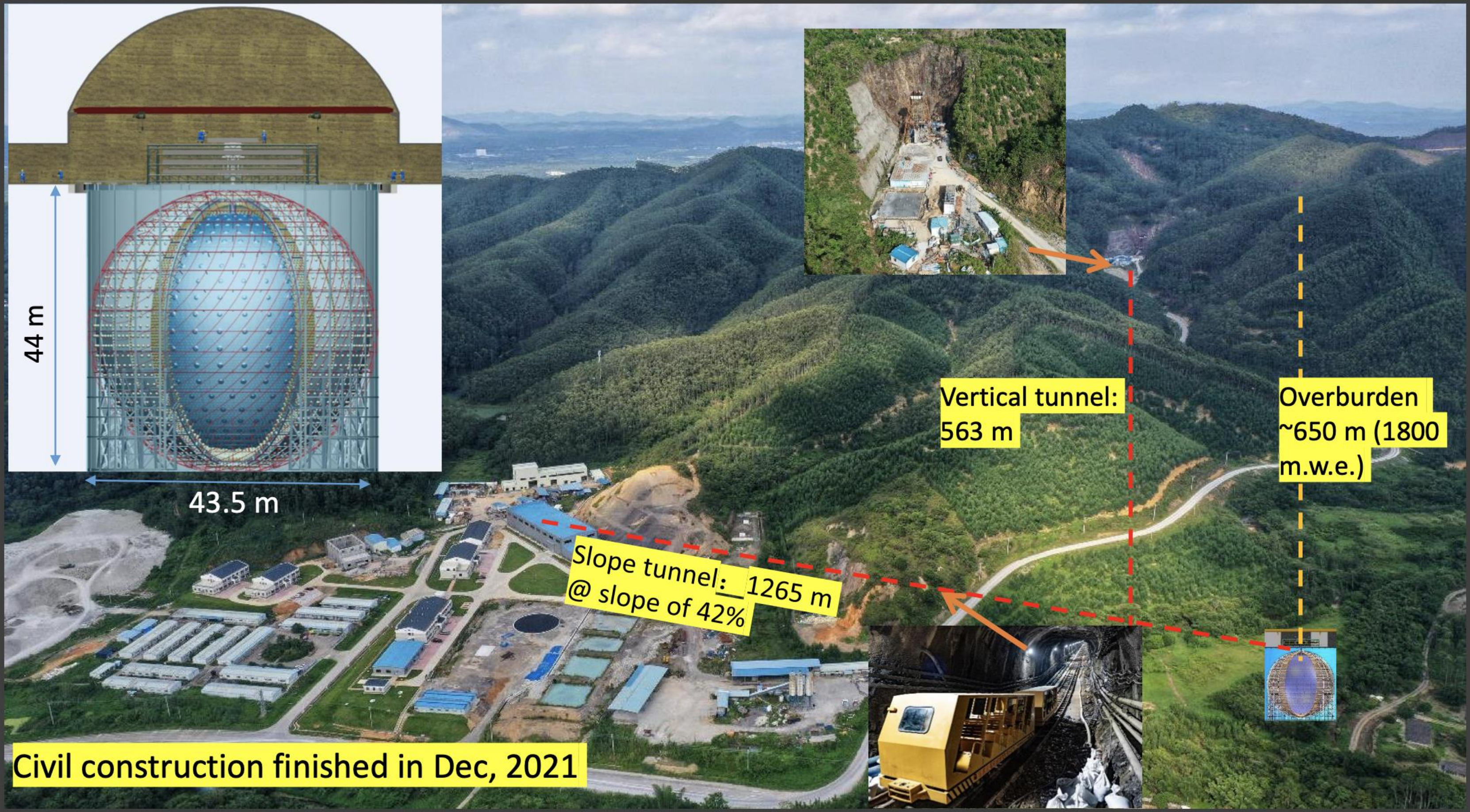






JUNO

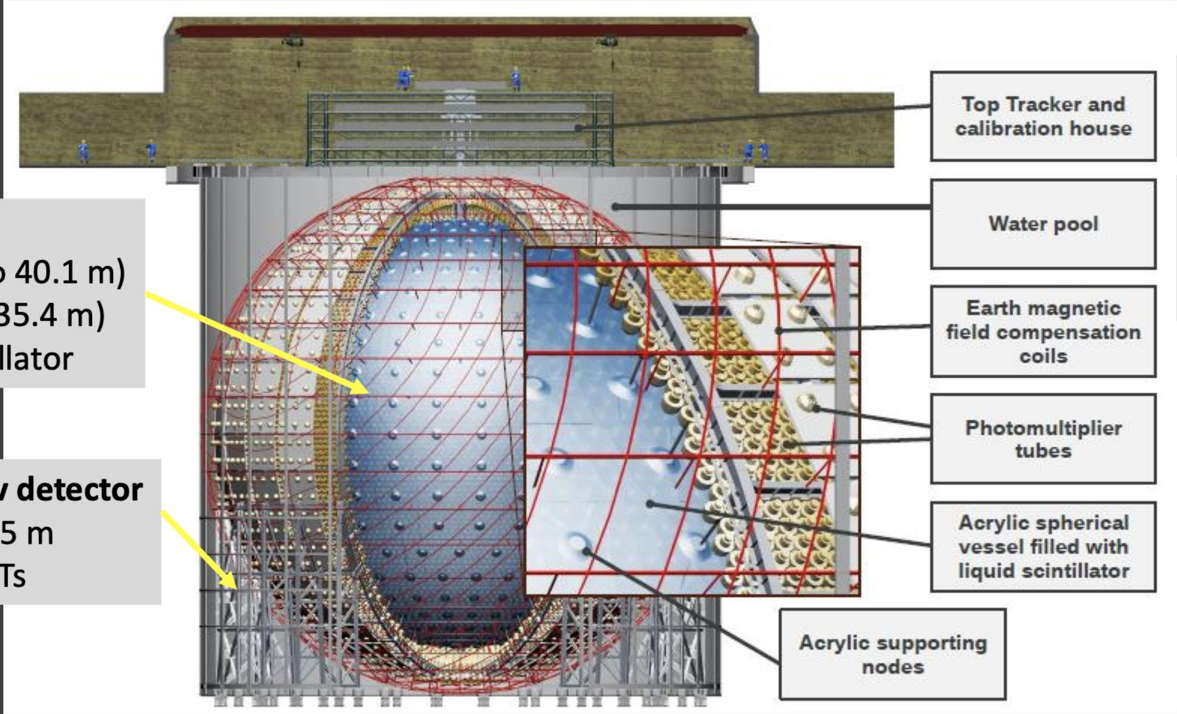
Jiangmen Underground Neutrino Observatory



The JUNO detector

Central detector
Steel structure (ϕ 40.1 m)
Acrylic vessel (ϕ 35.4 m)
20 kt liquid scintillator

Water Cherenkov detector
H = 44 m, D = 43.5 m
2400 20-inch PMTs



Top tracker
3 plastic scintillator layer

Water pool dimension
height: 44 m
diameter: 43.5 m

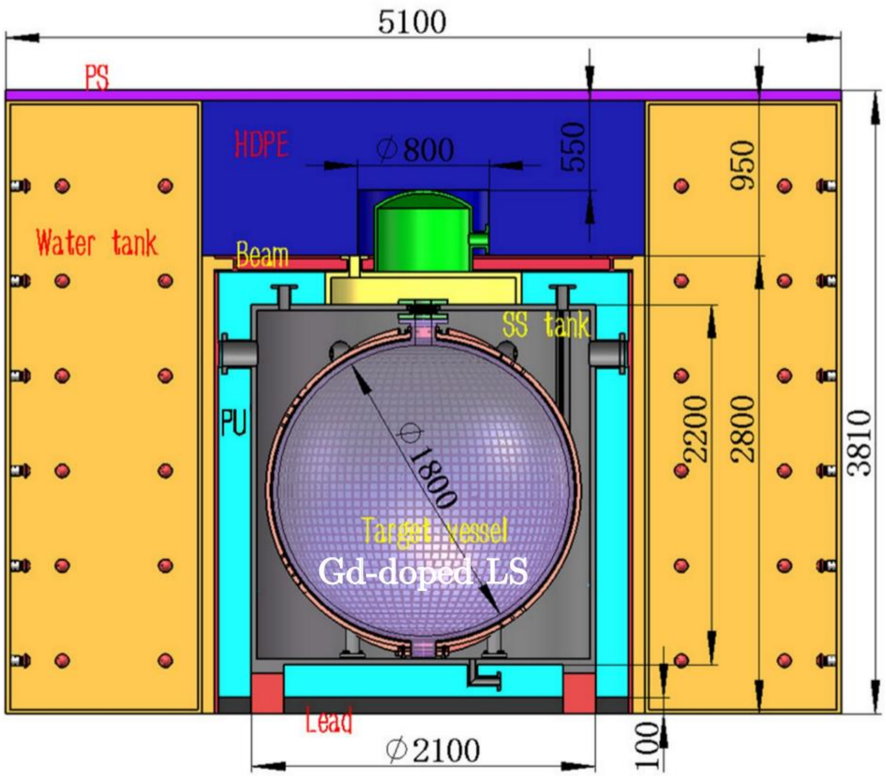
Light collection
17612 20-inch PMTs
25600 3-inch PMTs

The largest liquid scintillator detector
Unprecedented energy resolution

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~ 300 ton	~ 1 kton	20 kton
Coverage	~ 12%	~ 34%	~ 34%	~ 78%
Energy resolution	~ 8% /√E	~ 5% /√E	~ 6% /√E	~ 3% /√E
Light yield	~ 160 p.e. /MeV	~ 500 p.e. /MeV	~ 250 p.e. /MeV	> 1345 p.e. /MeV

JUNO

JUNO-TAO detector



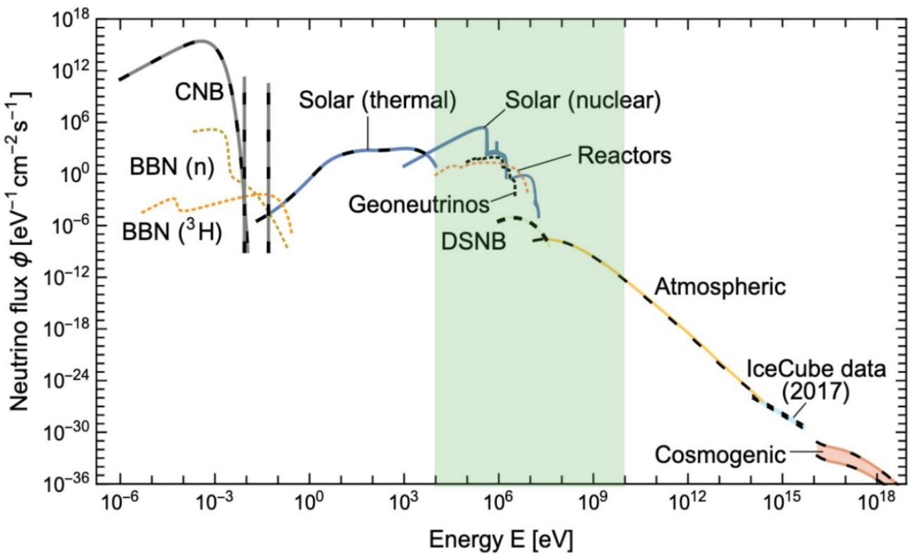
arXiv:2005.08745

- Provide a reference spectrum for JUNO, eliminating the possible model dependence due to fine structure in the reactor antineutrino spectrum in determining the neutrino mass ordering
- ~40 m from one of Taishan's 4.6 GW_{th} reactor core
- 1 ton fiducial volume with Gd-LS
- 10 m^2 SiPM of 50% photon detection efficiency operated at -50°C
- ≥94% photo-coverage
- 30× JUNO event rate

JUNO

JUNO: physics potential

JUNO energy region

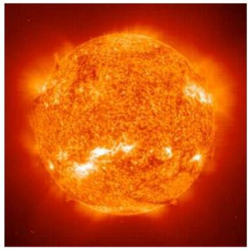


E. Vitagliano et al., Rev. Mod. Phys. 92 (2020) 045006
Note: fluxes are averaged

Reactor

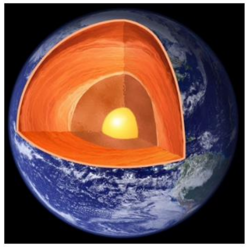
~50/day

Solar



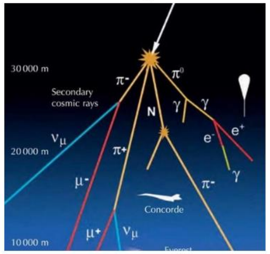
~2000/day

Geo



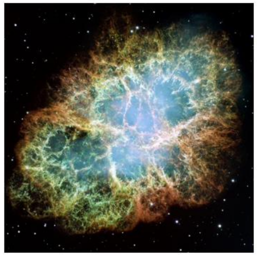
~1/day

Atmospheric



10-20/day

Supernova



O(1000)/s for core-collapse SN @10kpc

DSNB: few/year

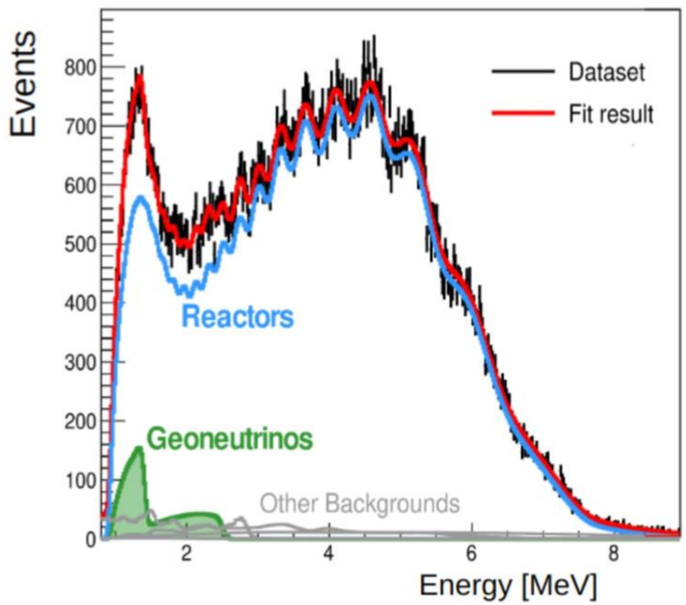
+ New Physics

Proton decay
NSI
Sterile neutrinos
Neutrino magnetic moment
.
.

JUNO

Geoneutrinos

$$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\ \text{MeV}$$
$$^{235}U \rightarrow {}^{207}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.4\ \text{MeV}$$
$$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \text{MeV}$$
$$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e + 1.31\ \text{MeV}\ (89.3\%)$$
$$^{40}K + e^- \rightarrow {}^{40}Ar + \nu_e + 1.505\ \text{MeV}\ (10.7\%)$$



- Geoneutrinos help study the abundance of radioactive elements inside the crust and mantle, as well as the amount of heat emitted from them
- High statistics: more events in one year (~400) than global geoneutrino sample accumulated to date
- JUNO also has the potential for the discovery of mantle geoneutrinos
- Updated sensitivity results since 2016 (Ran Han et al. 2016 Chinese Phys. C 40 033003). Paper under preparation.

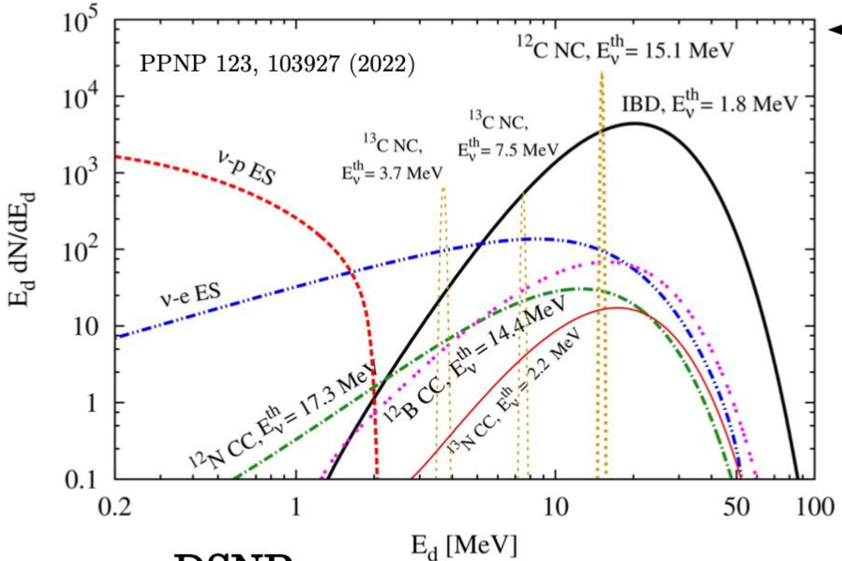
Experiment (years)	Borexino (8.9 years)	KamLAND (14.3 years)	JUNO (6 years)	JUNO (10 years)
$^{238}U + {}^{232}Th$ (fixed Th/U)	~17%	~15%	~10%*	~8%*

PRELIMINARY

*Reported for the first time at the MMTE workshop, 2023, Paris, France
https://indico.in2p3.fr/event/30001/contributions/126865/

JUNO

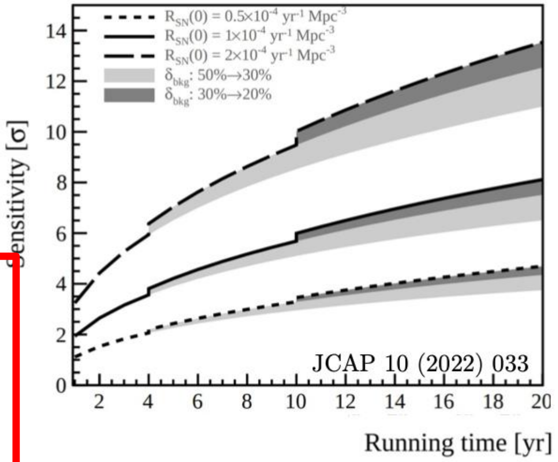
Supernova neutrinos



Core-collapse SN in our vicinity:

- Large SN neutrino sample with high energy resolution and low threshold (~0.02 MeV with multi-messenger trigger)
- Capability to detect pre-SN neutrinos from close SN-candidates

DSNB:



- Diffuse Supernova Neutrino Background: flux of neutrinos reaching the Earth from all the core-collapse supernovae in the universe
- Potential to observe DSNB with ~3σ significance in ~3 years assuming a nominal reference model

JUNO

Installation will be finalized in 2023/2024
First data run expected in 2024

SuperChooz

The Proposal

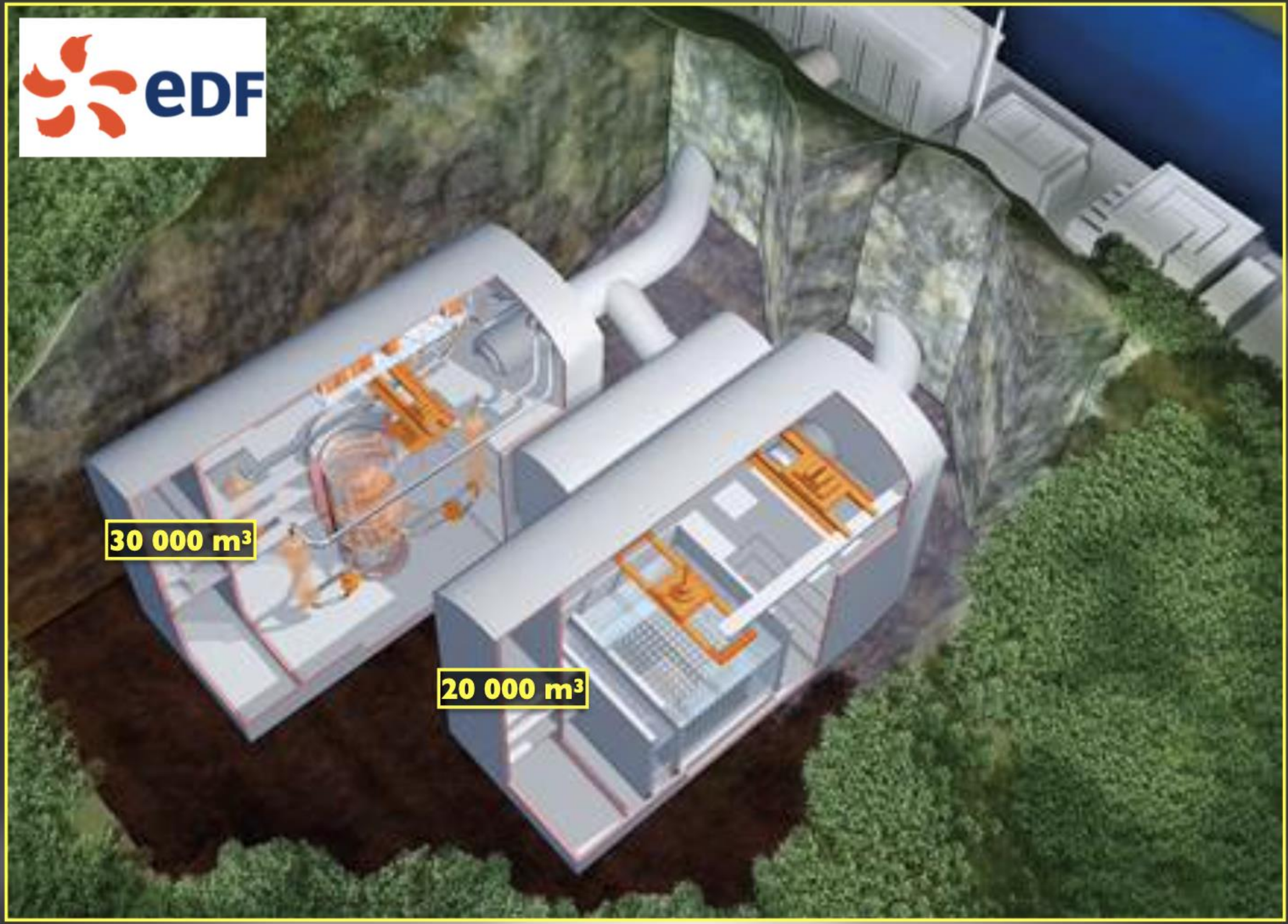
A new very large reactor experiment at Chooz nuclear power plant, consisting of a 10 kton far detector + two near detectors to the two nuclear reactors.

Use a new technology of an opaque liquid, called LiquidO, in which light is locally trapped. A promising technique to allow precision neutrino studies.

September 2022: IN2P3/EDF have agreement to explore the feasibility for an experimental facility of this size at Chooz.

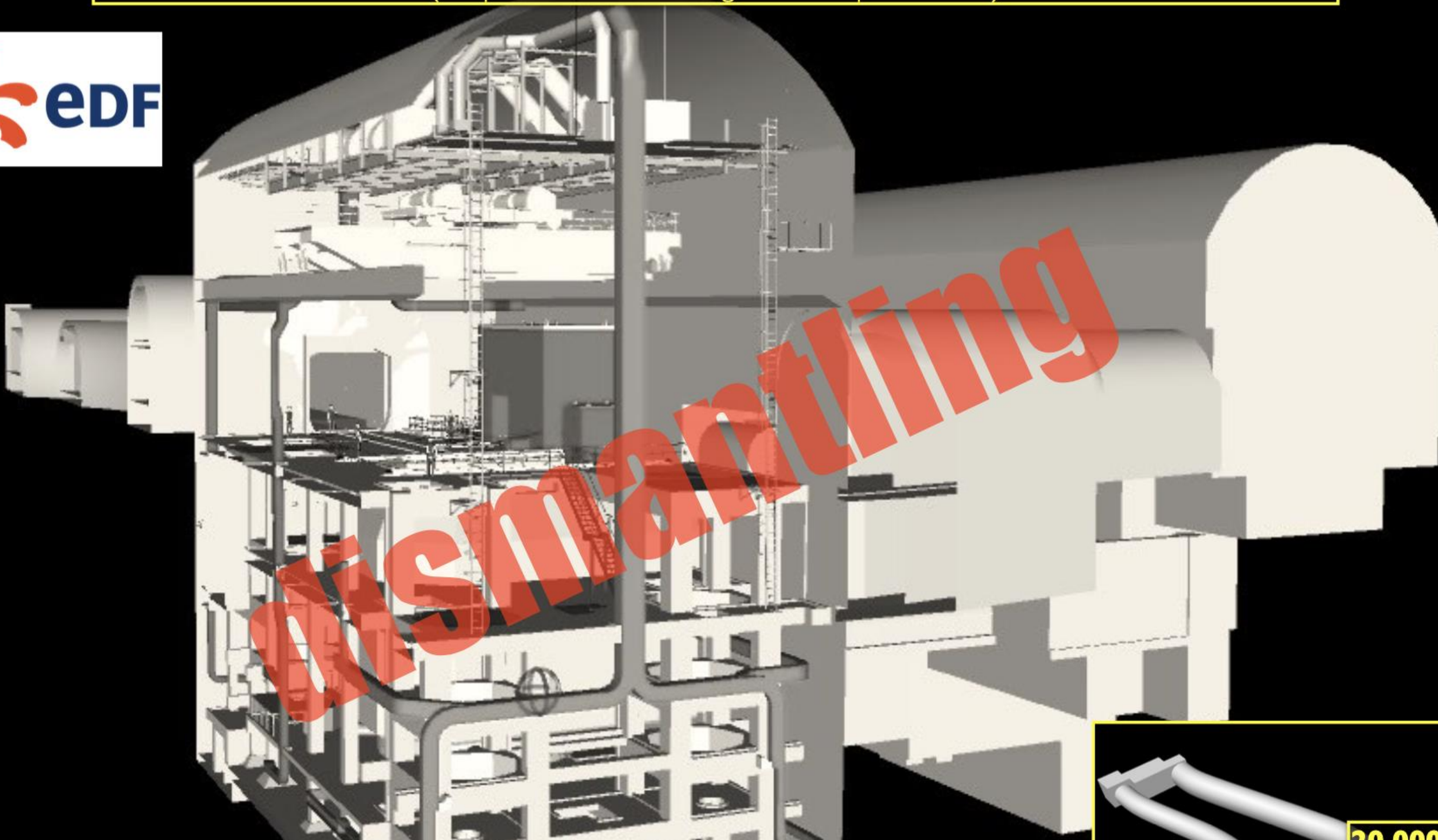
the reactor (source)…

Chooz-B nuclear reactor plant: 2x N4 reactors [4.2$GW_{thermal}$ each]

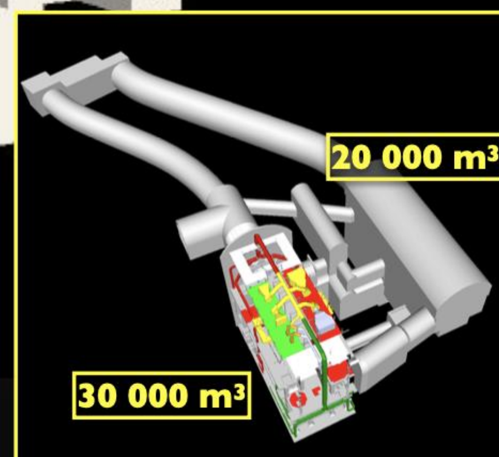


Chooz-A former nuclear reactor

huge caverns (already built) of the **size of Super-Kamiokande** right next to **Chooz reactors!**
(unique site in France-Belgium / Europe / World?)

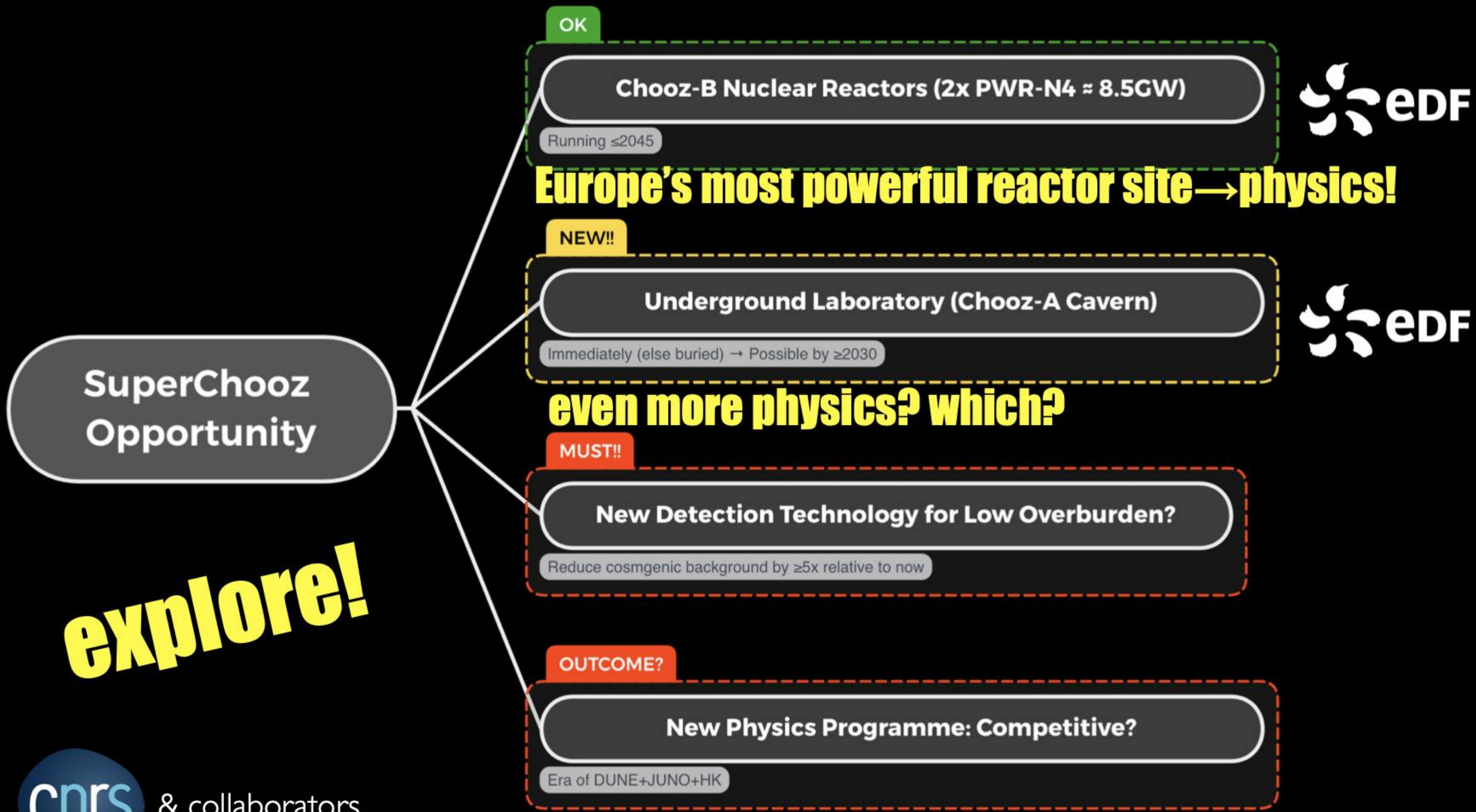


Chooz-A for science?



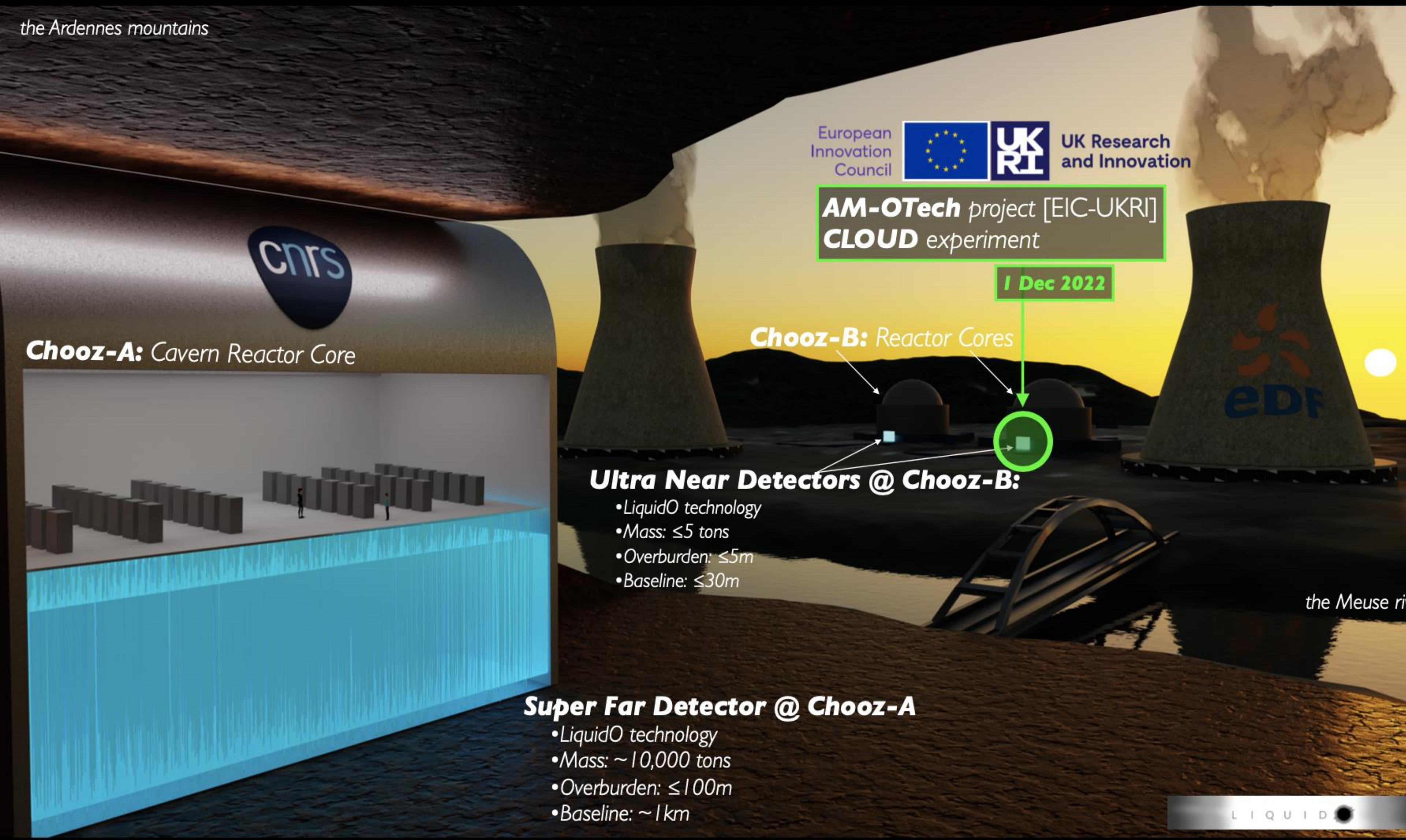
ISSUE!!! overburden <100m rock (or <300 mwe)

(2018) SuperChooz opportunity…



cnrs & collaborators.

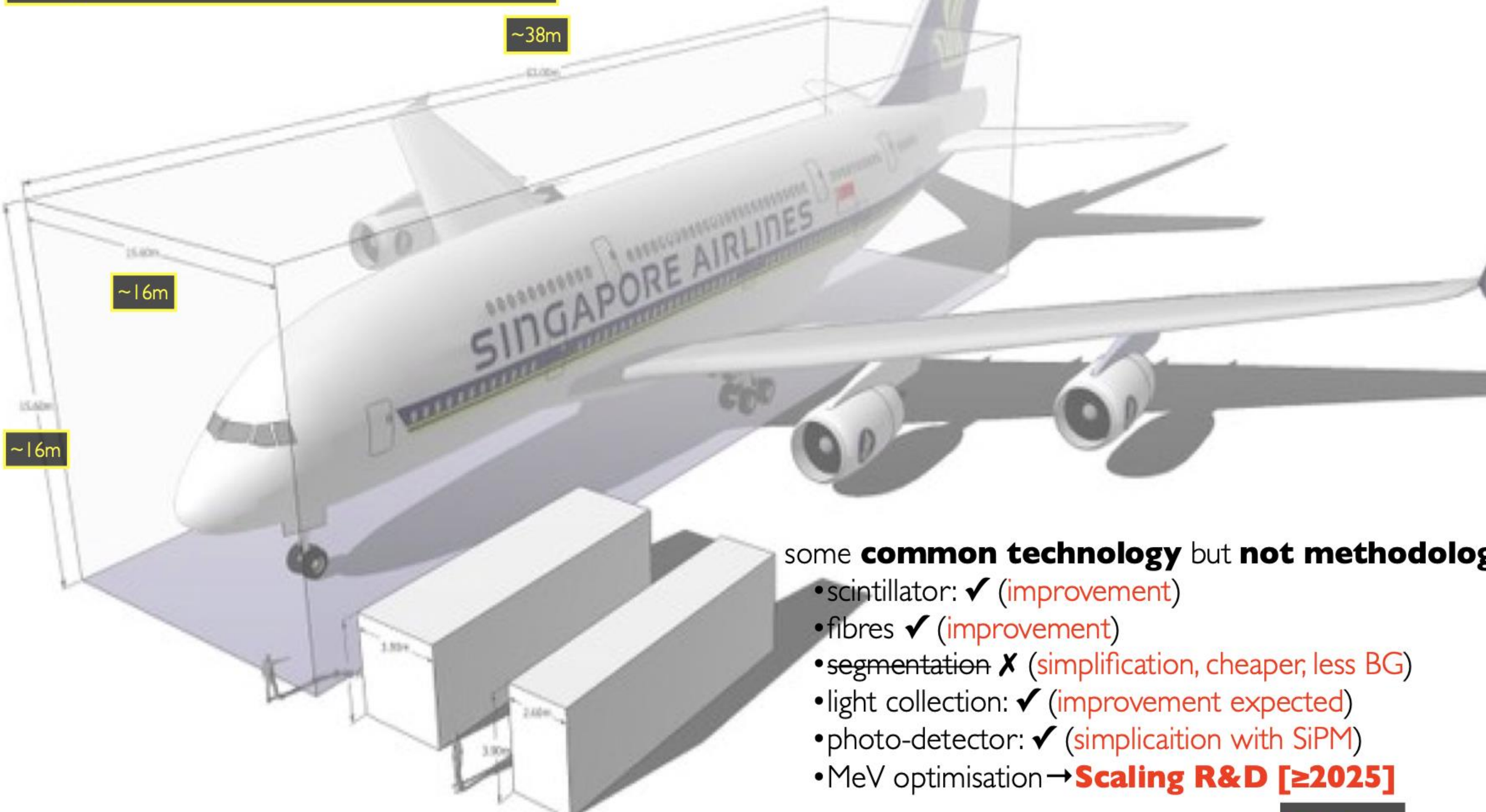
SuperChooz experimental setup…



experimental demonstration III — done!

a priori no showstopper

SuperChooz : ~9 700 m³



some **common technology** but **not methodolog**

- scintillator: ✔ (improvement)
- fibres ✔ (improvement)
- ~~segmentation~~ ✗ (simplification, cheaper, less BG)
- light collection: ✔ (improvement expected)
- photo-detector: ✔ (simplicaition with SiPM)
- MeV optimisation → **Scaling R&D [≥2025]**

soon...

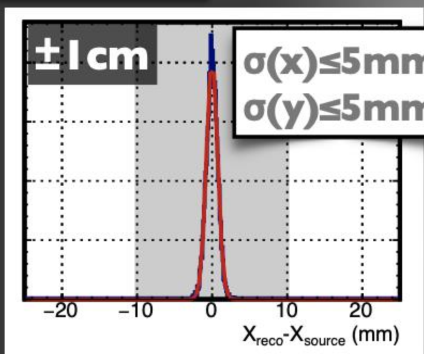
SuperChooz (~10kton) similar dimensions as **NOvA (~14kton)** & one module of **DUNE (~10kton)**

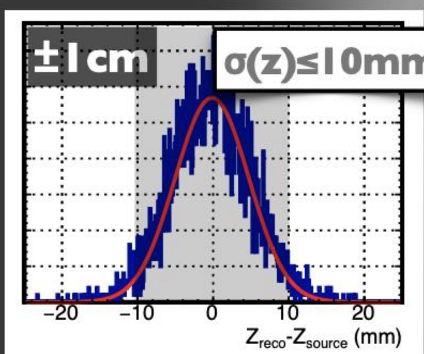
LiquidO ↔ stochastic light confinement

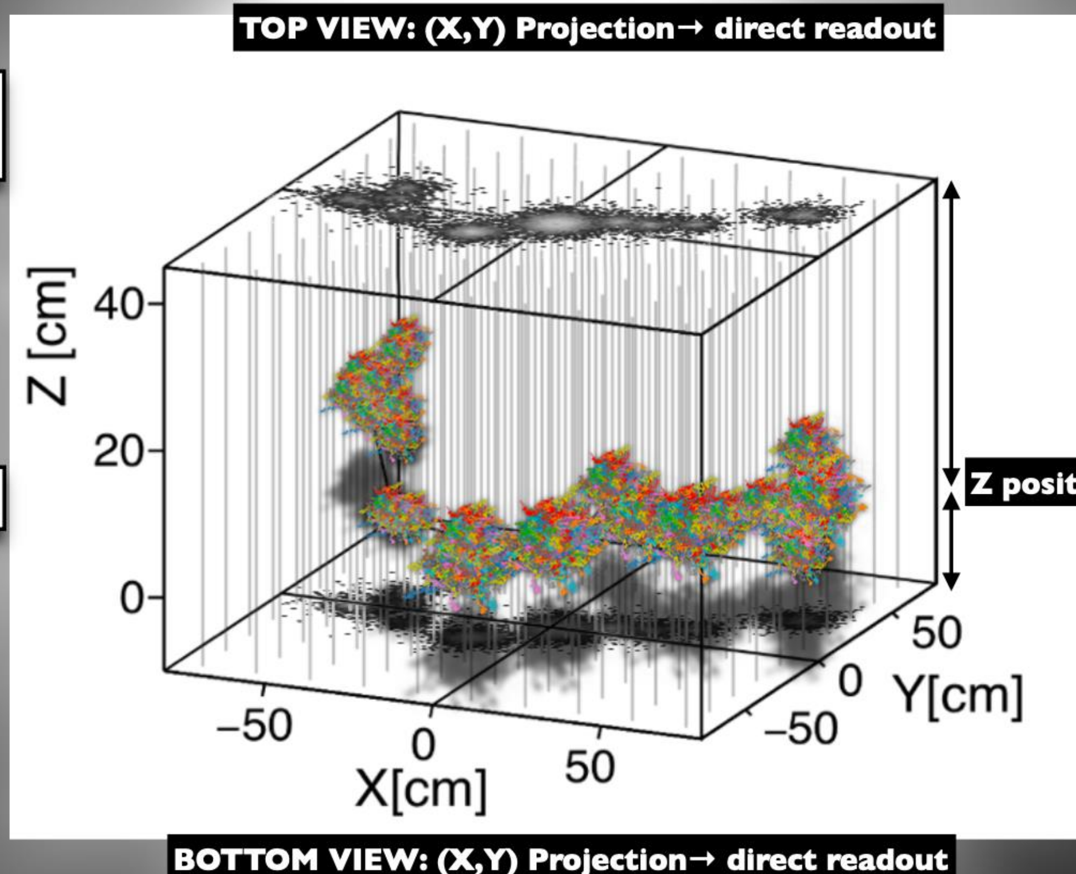
Topology (X,Y) direct & native (PID)→ possible **sub-mm vertex precision**

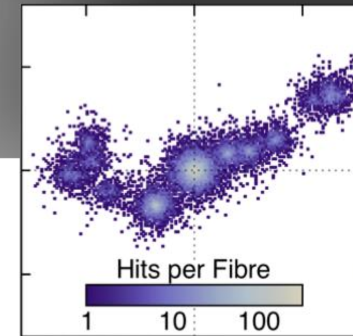
Vanilla LiquidO: 1D lattice (fibres along Z-axis only)

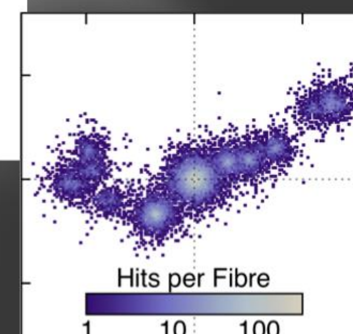
~0.5MeV











LiquidO can have up 3 orthogonal fibre lattice orientations (3D)

status on neutrino oscillation knowledge.

SuperChooz is designed impact much of ***SM picture*** (3 families) [synergy]

SuperChooz explore the ***SM***'s consistency/completeness→ **BSM discovery?**

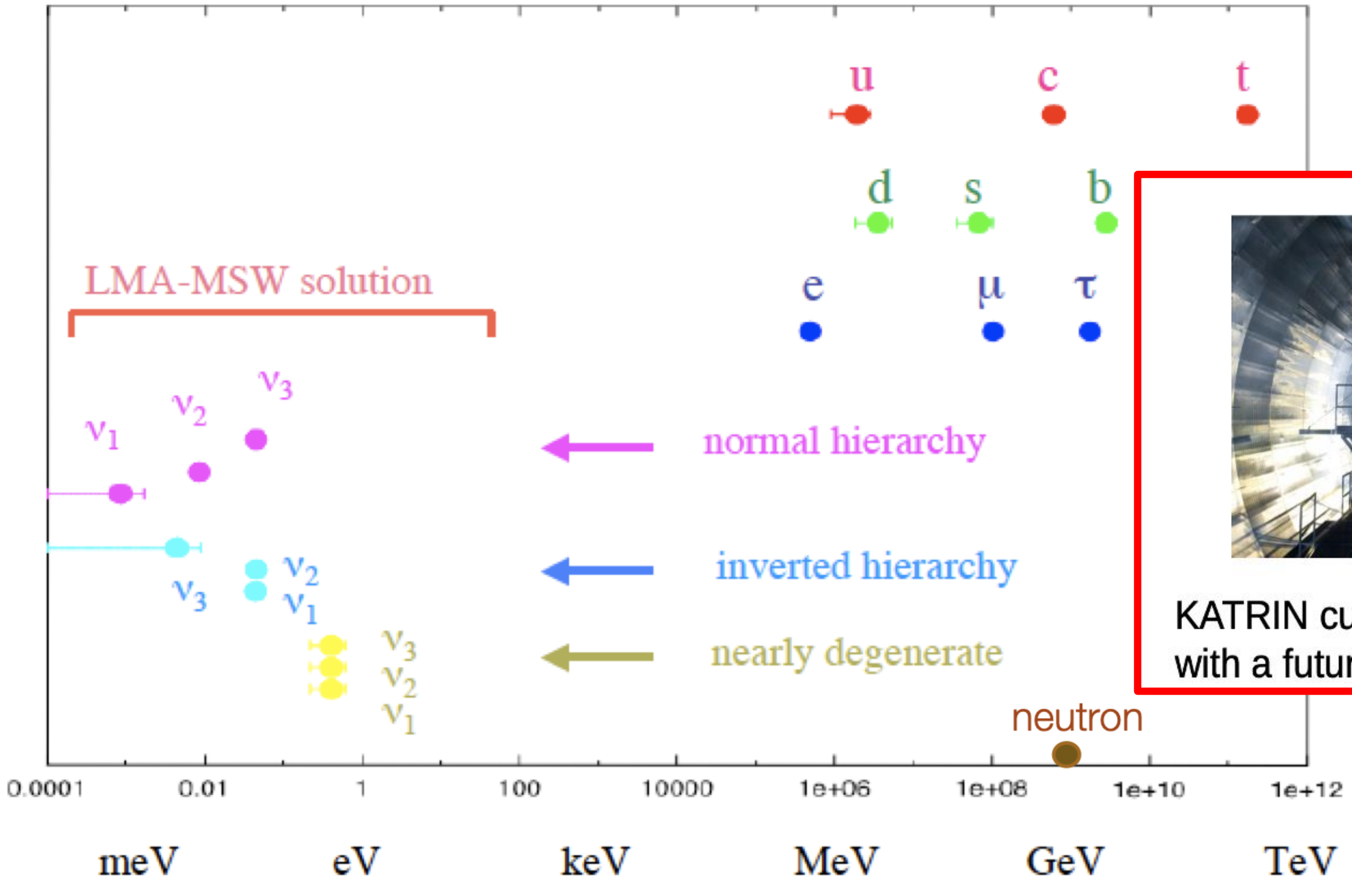
	today			≥2030		
	best knowledge		global	foreseen	dominant	source
θ_{12}	3,0 %	SK⊕SNO	2,3 %	≤0.5%	JUNO⊕**SC**	reactor⊕solar
θ_{23}	5,0 %	NOvA+T2K	2,0 %	≲1.0%?	DUNE⊕HK [**SC**]	beam (octant)
θ_{13}	1,8 %	DYB+DC+RENO	1,5 %	**≤0.5%**	**SC**	reactor
$+\delta m^2$	2,5 %	KamLAND	2,3 %	<0.5%	JUNO⊕**SC**	reactor⊕solar
$\|\Delta m^2\|$	3,0 %	T2K+NOvA & DYB	1,3 %	<0.5%	JUNO⊕DUNE⊕HK⊕**SC**	reactor⊕beam
Mass Ordering	**unknown**	SK et al	NMO @ ≤3σ	@5σ	JUNO⊕DUNE⊕HK	reactor⊕beam
CP	**violation?**	T2K+NOvA	3/2π @ ≤2σ	**@5σ?**	DUNE⊕HK [**SC**]	beam driven
CPT	**violation?**	—	—	**<1%?**	**SC**	reactor⊕solar
Unitarity	**violation?**	—	—	**<1%?**	**SC**	reactor⊕solar
Baryon#	**violation?**	—	—		JUNO⊕DUNE⊕HK⊕SC	

reactor⊕solar main channels of **SuperChooz→ low energy atmospherics under study…**

Neutrino Properties
Neutrino mass?
Majorana or Dirac?

Neutrino Mass

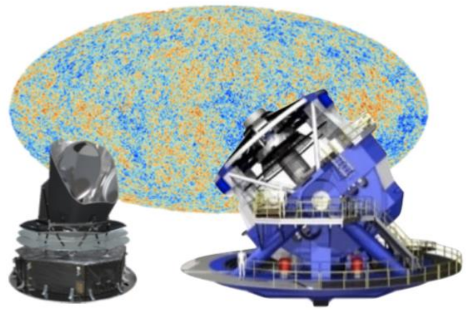
The smalness of the neutrino mass $m_\nu \ll m_{e,\,u,\,d}$

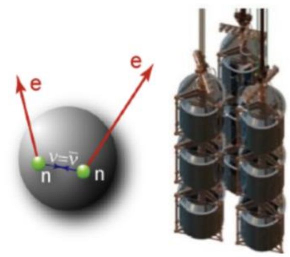


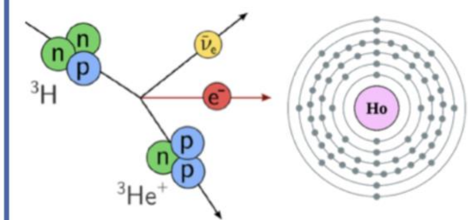
KATRIN current limit is 0.8eV with a future sensitivity of 0.2eV

Neutrino Mass Measurents

Complementary paths to the ν mass scale



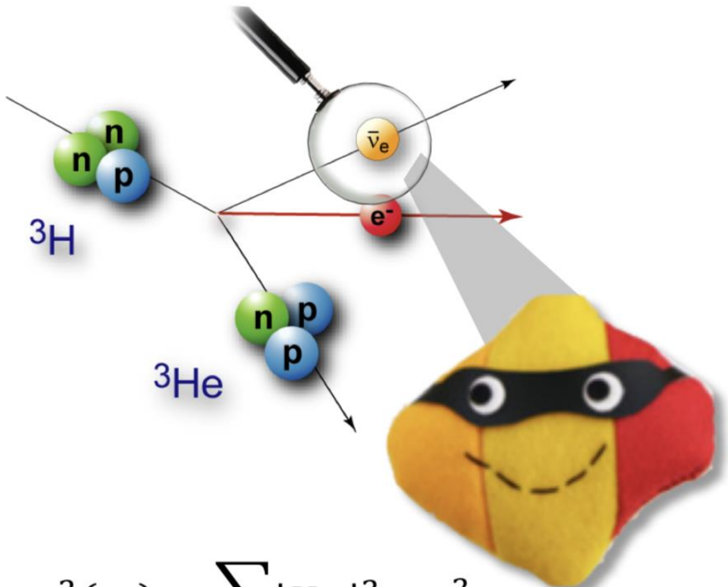




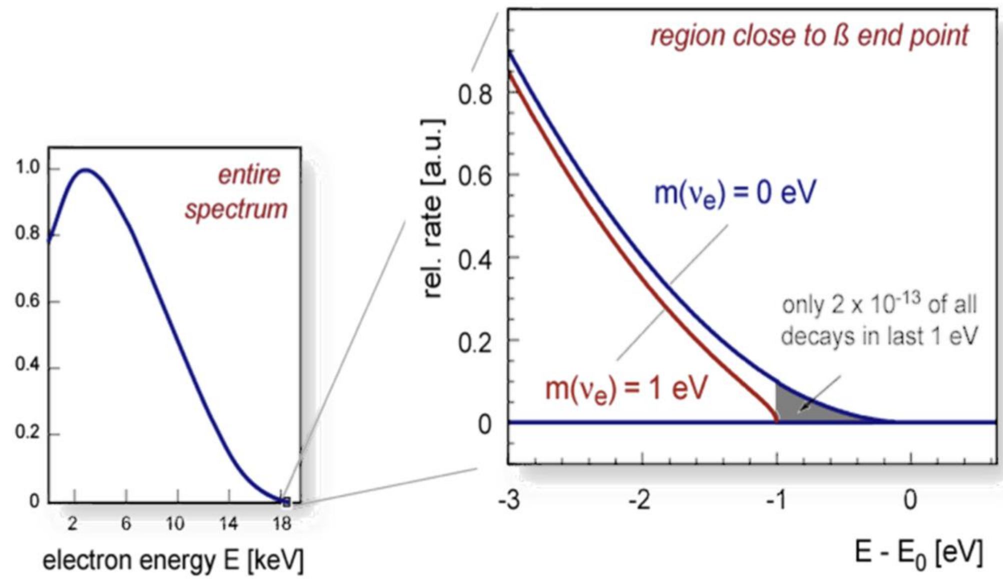
	Cosmology	Search for 0νββ	Kinematics of weak decays
Method	Structure of Universe at early and evolved stages	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\|\sum_i U^2_{ei}\, m_i\right\|^2$	$m^2_\beta = \sum_i \|U_{ei}\|^2\, m^2_i$
Model assumptions	Multi-parameter cosmological model (ΛCDM)	- Majorana nature of neutrinos? - No BSM contributions other than m(ν)?	Only kinematics; “**direct**” measurement

Neutrino Mass Measurents

The KATRIN experiment: endpoint measurement of tritium decay

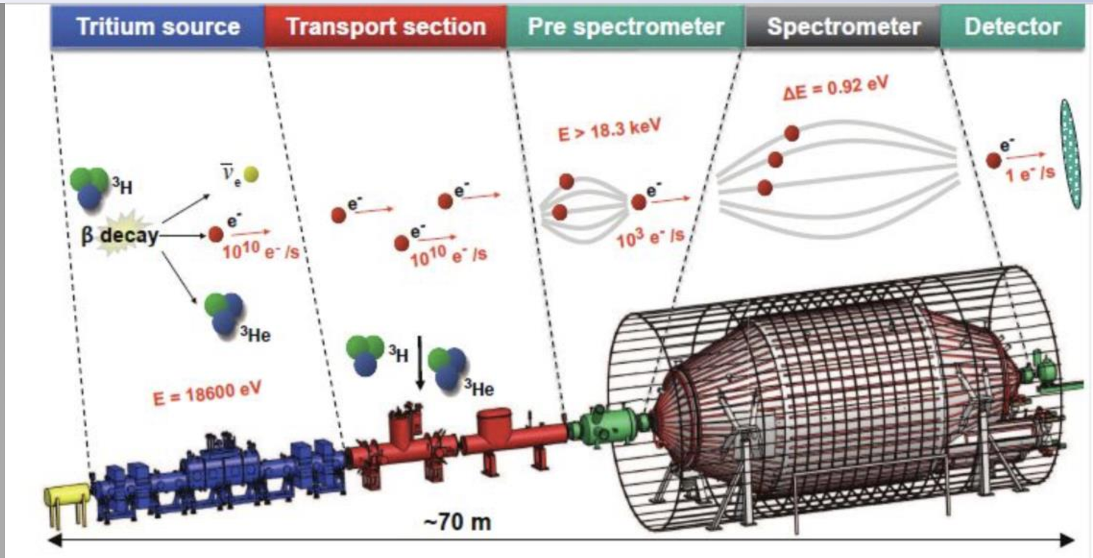


$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



What is measured really in this experiment is the effective electron anti-neutrino mass defined by $m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$ with U_{ei} the PMNS mixing elements

KATRIN Experiment: the Mass of ν_e



The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to measure the mass up to projected sensitivity of 0.2eV

To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

Recent result $M\nu_e < 0.8$ eV (May 2021)

Future Projects

β decays: New Projects

- ECHO & HOLMS: calorimetric sensors coupled to ^{163}Ho implanted sources
  - Obtained neutrino mass limit: ~ 150 eV
  - Promise: ~ 1eV

Usable to ~0.1 eV?

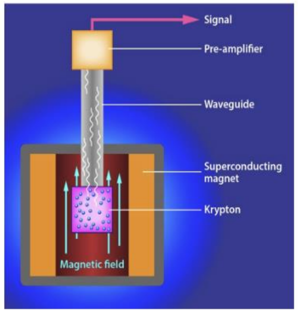
- Project 8: Cyclotron Radiation Emission Spectroscopy(CRES)
  - Phase I: prove of principle
  - Phase II successful
    - Uncertainties understood
    - m_β < 178 eV @90% C.L.
  - Phase III:
    - Atomic T system & Larger cavity
    - Goal in 5 years: m_β < 0.4 eV
  - Phase IV: 5 years ?
    - Goal: m_β < 0.04 eV

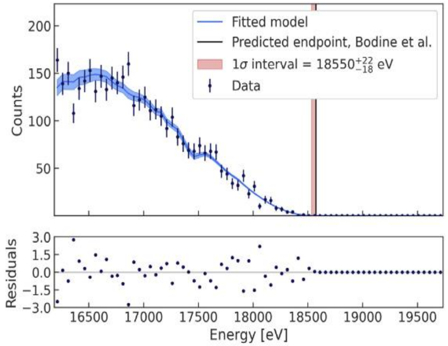
$$^{163}_{67}\mathrm{Ho} \to {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

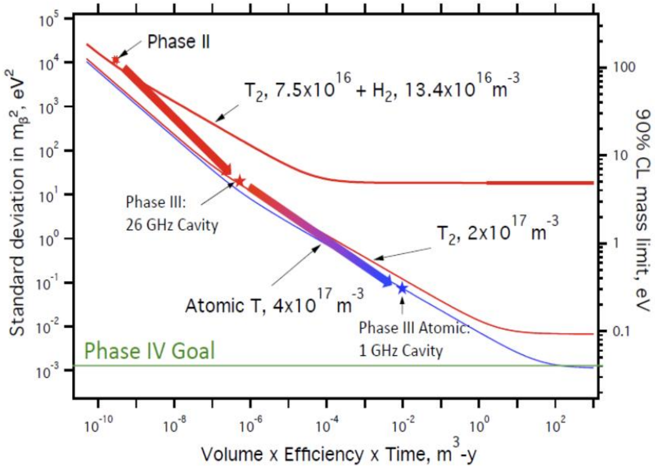
$$^{163}_{66}\mathrm{Dy}^* \to {}^{163}_{66}\mathrm{Dy} + E_C$$

- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = (2.833 ± 0.030^{stat} ± 0.015^{syst}) keV

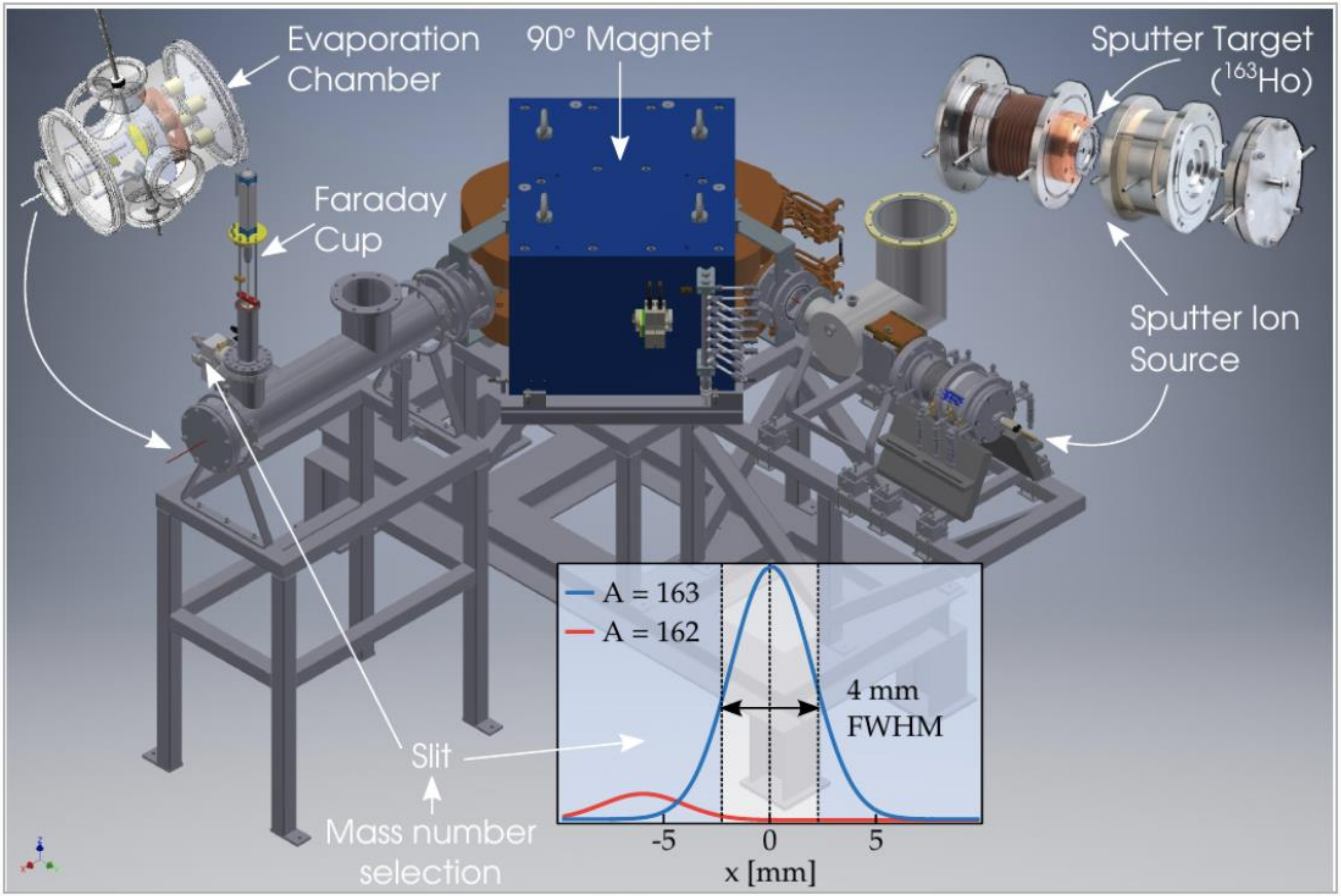
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501





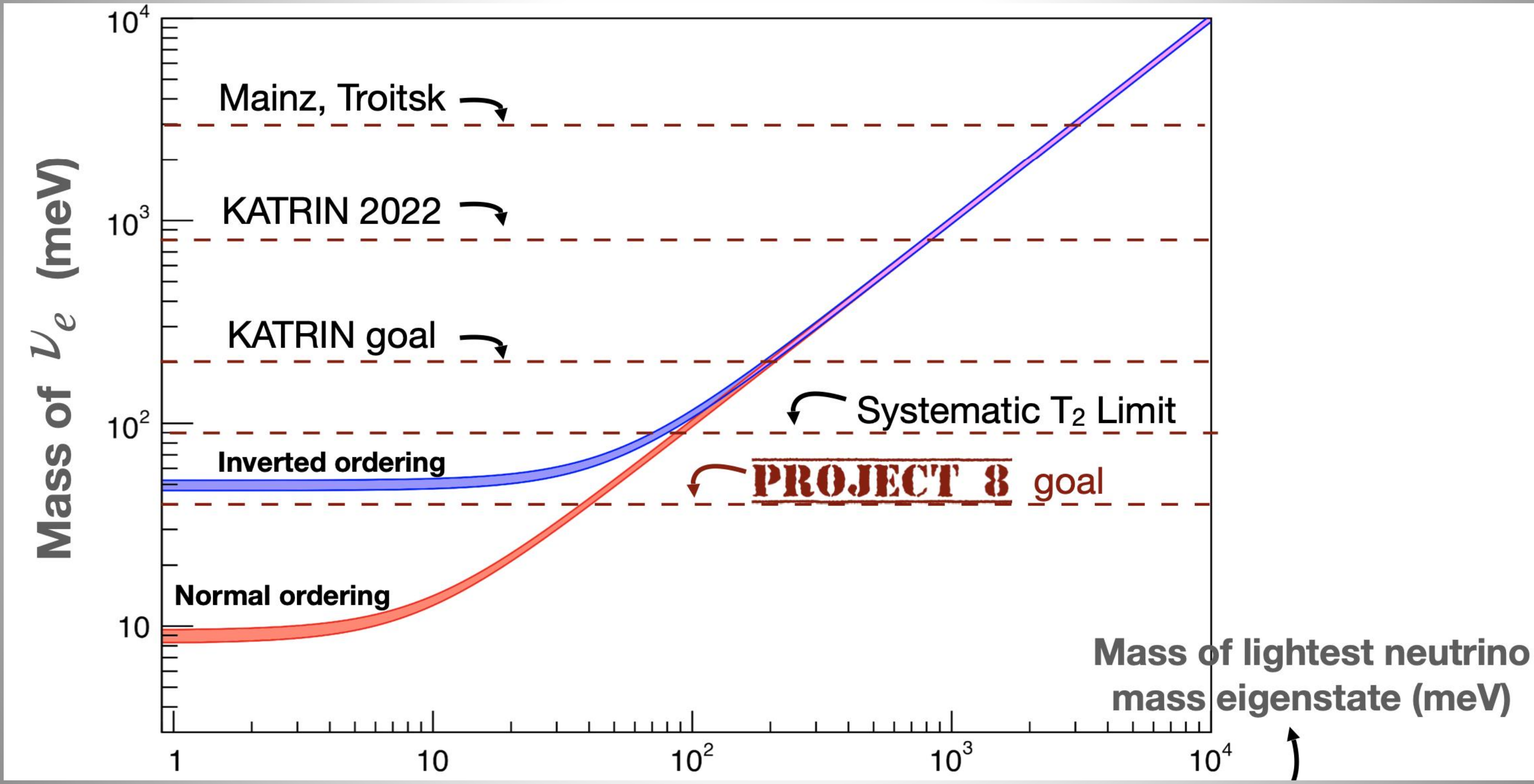


The HOLMES experiment



Future Projects

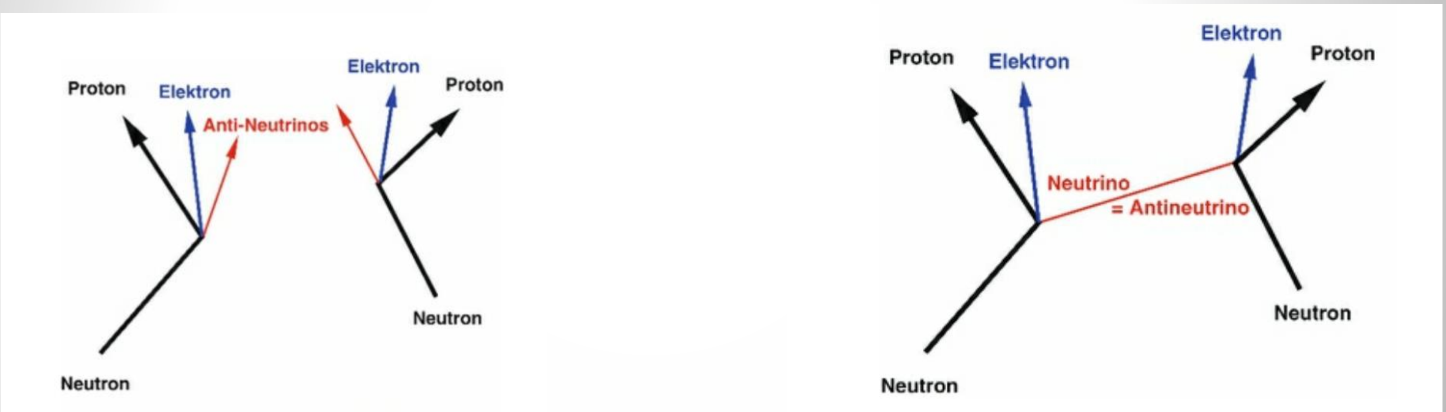
The Projected Expected Sensitivity of PROJECT8

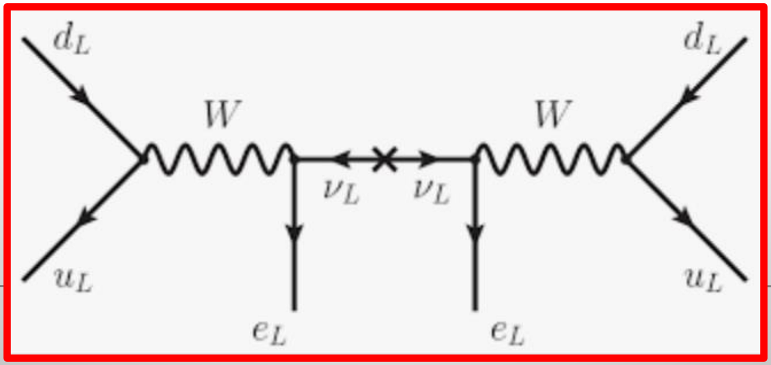


Results by 2035?

Neutrinoless Double Beta Decay

- Are neutrinos their own antiparticle? We do not know this yet!
- The highly anticipated experimental test is the observation of neutrino-less double beta decay, ie two simultaneous beta-decays within one nucleons, without neutrino emission
- This would be the first evidence of lepton number violation!





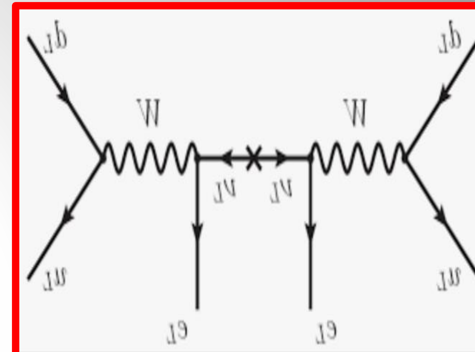
Neutrinoless Double Beta Decay

GERDA (GERmanium Detector Array) experimemt at LNGS (Gran Sasso/IT)

Final results: arXiv:2009.06079

127.2 kg.year exposure between 2011-2019

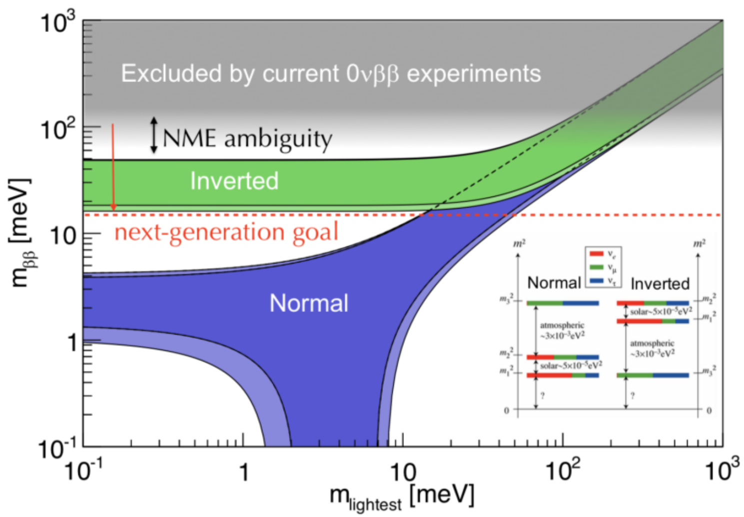
Experiment now completed
No $0\nu\beta\beta$ signal observed ☹



upper mass limit: $m_{\beta\beta} < 79 - 180$ **meV**

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3\text{x}10^{25}$ yrs
- Future goal: ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal

$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{NN}\, m_\pi^2}{g_A^2} M_{\rm cont}^{0\nu} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



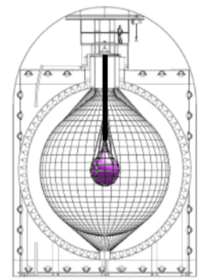
ββ decays: KamLAND-Zen

- Load 3% ^{136}Xe(91% enriched) into LS
- Fill LS into a balloon at the center of KamLAND
- Improvement of KamLAND-Zen 800 over KamLAND-Zen 400:
  - ^{136}Xe amount doubled
  - Balloon produced in class-1 cleanroom: 10 times less ^{232}Th background
  - New rejection method for C & Xe spallation products
- Reached the IO region for the first time

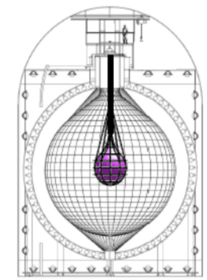
$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \text{yr at 90\% C.L.}$$

$$m_{\beta\beta} < 36 - 156\ \text{meV}$$

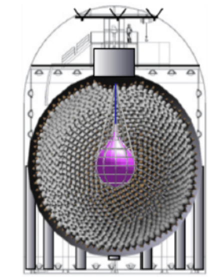
Past
KamLAND-Zen 400
320-380 kg of Xenon
Data taking in 2011 - 2015



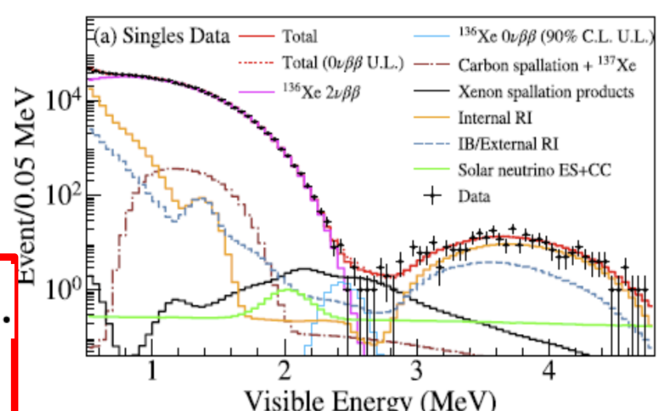
Present
KamLAND-Zen 800
~750 kg of Xenon
DAQ started in 2019

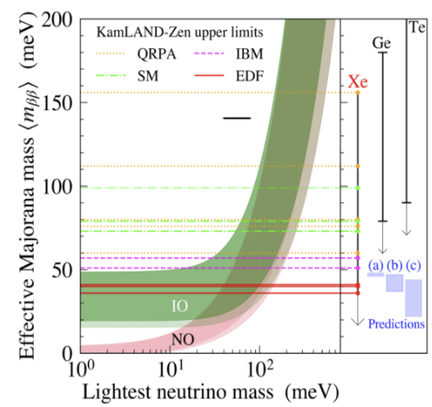


Future
KamLAND2-Zen
~1 ton of ^{136}Xe
Better energy resolution



Reanalysis —combined→ **1st result** arXiv:2203.02139v1 [hep-ex]
& Long paper in preparation





Neutrinoless Double Beta Decay

The next challenge: experiments with > 1 ton mass exposure

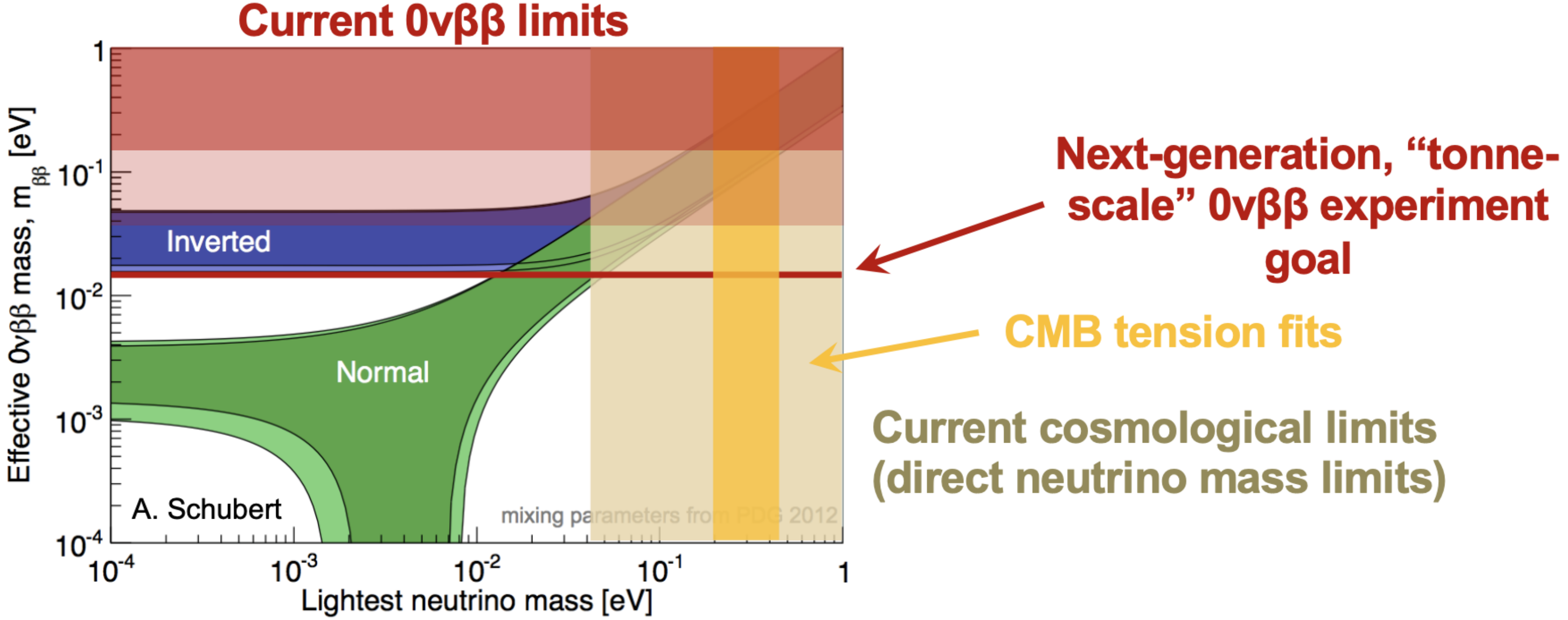
Experiments

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	$^{116}Cd/^{130}Te$	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

Neutrinoless Double Beta Decay

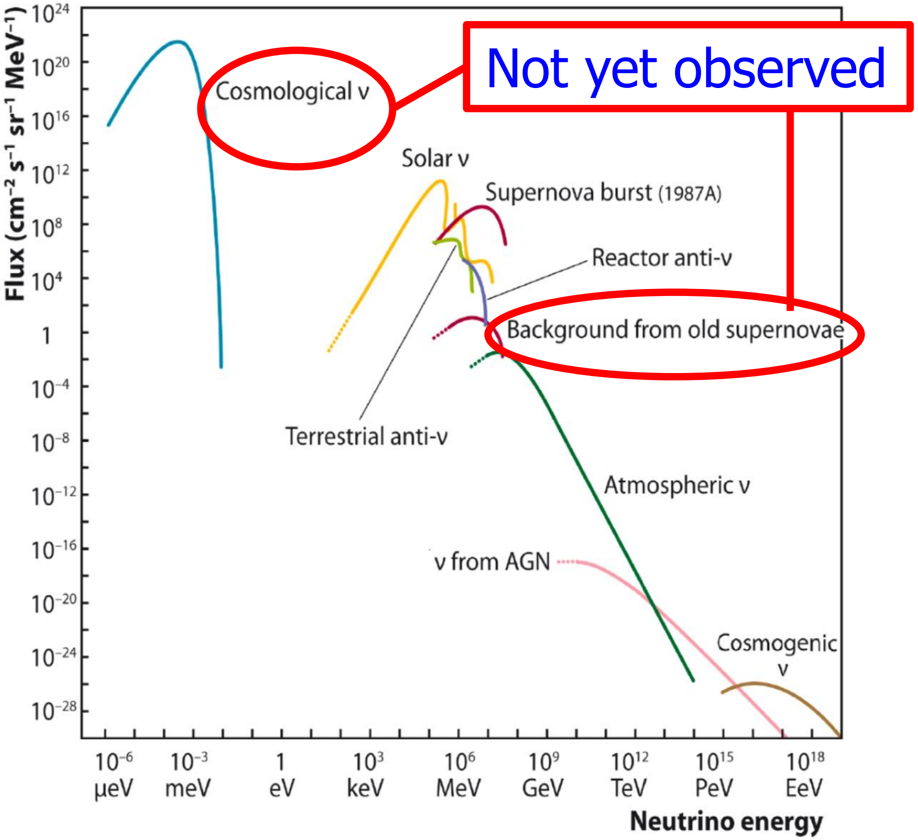
Prospects for a one ton scale $0\nu\beta\beta$ experiment

- Half-life of 0νββ related to neutrino mass scale
  - $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M_{0\nu}|^2\left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$
  - $\langle m_{\beta\beta}\rangle = \left|\sum U_{ei}^2 m_i\right|$

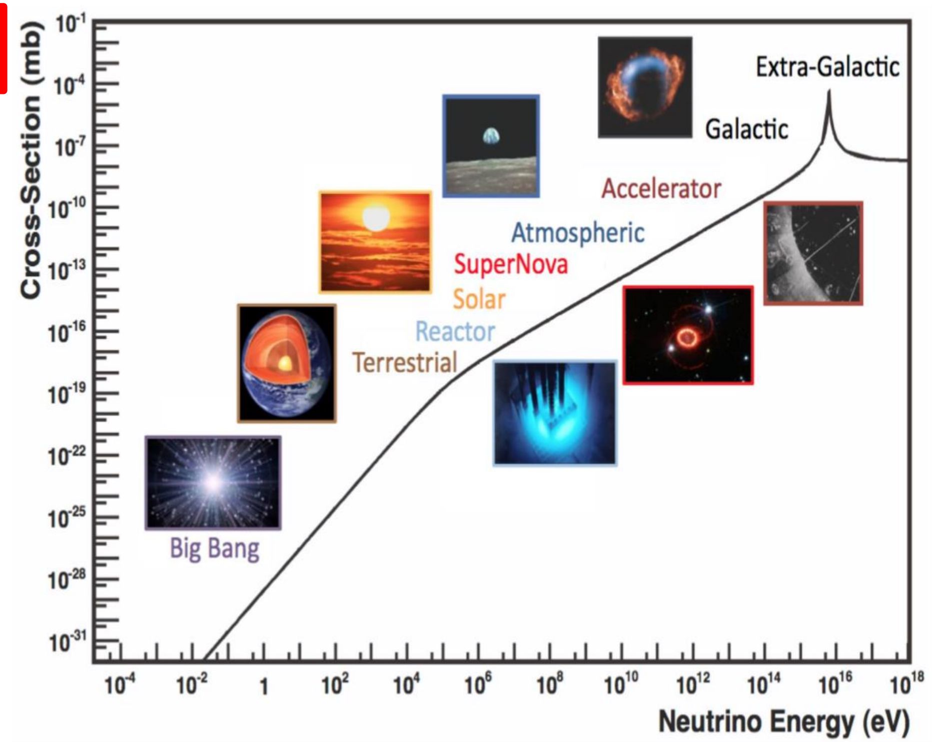


Cosmological Neutrino Background CνB

C. Spiering, arXiv:1207.4952



J. Formaggio, G.P. Zeller, arXiv:1305.7513



Cosmological and Diffuse Supernova Neutrino Background not yet observed!
DSNB can be observed in JUNO (and perhaps Super-K) in the next years
What about the Cosmological Neutrino Backround?

Search for Cosmological Neutrinos

- These are neutrinos produced during/just after the Big Bang. They decoupled about a second after the Big Bang and thus contain information from close in time to the event. E.g. photons decoupled after after 380.000 years.
- These neutrinos are also called the Cosmic Neutrino Background (C**ν**B). It is estimated that today the C**ν**B has a temperature of roughly 1.95 K. The neutrinos have energies in the sub-eV range and does thus have very tiny cross sections.
- The PTOLEMY experiment –in preparation– is taking up that challenge

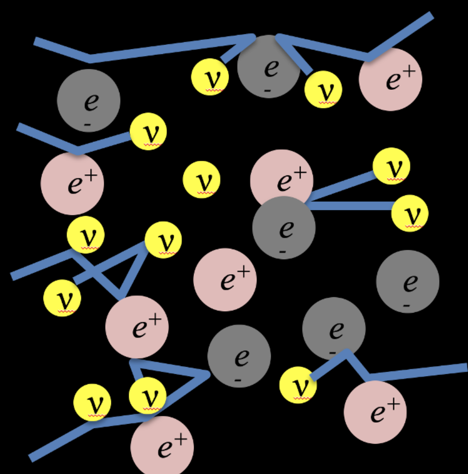
Search for Cosmological neutrinos

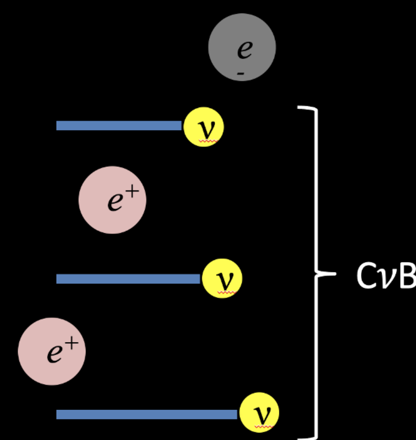
Formation of the CνB…

Interaction rate: $\Gamma_{\text{weak}} \sim G_F^2 T^5$

Expansion rate: $H \sim M_{\text{pl}}^{-2} T^2$

The CνB is formed when neutrinos decouple from the cosmic plasma.





Neutrinos "free-stream" to infinity.

($T_{\odot\text{core}} \sim 1$ keV)

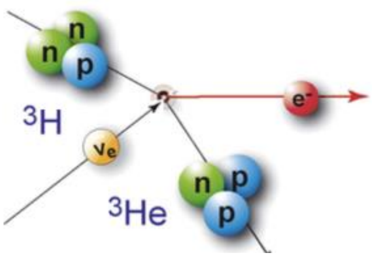
Above $T \sim 1$ MeV, even weakly-interacting neutrinos can be produced, scatter off e^+e^- and other neutrinos, and attain thermodynamic equilibrium

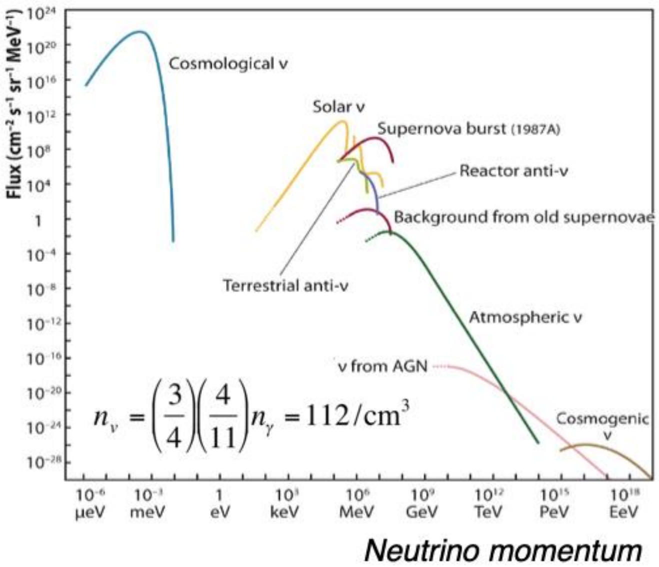
Below $T \sim 1$ MeV, expansion dilutes plasma, and reduces interaction rate: the universe becomes transparent to neutrinos.

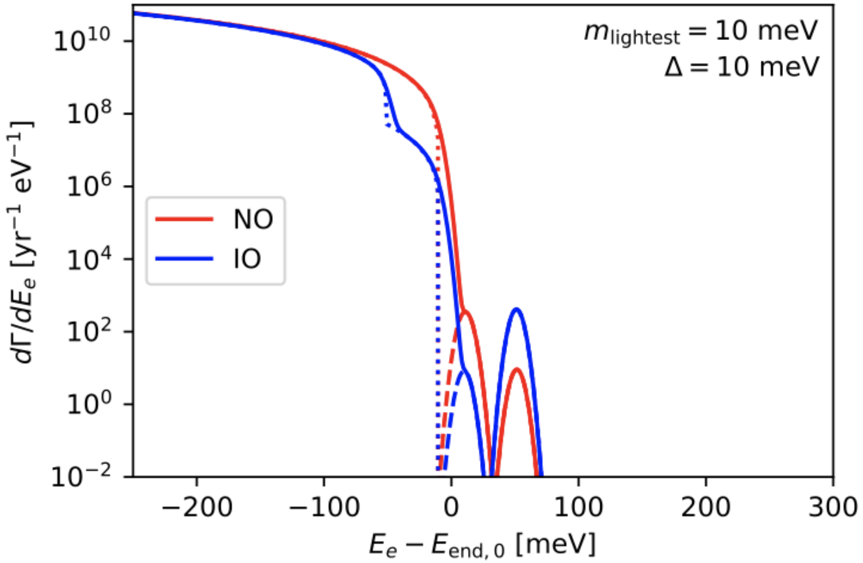
PTOLEMY Experiment

- Tiny kinetic energy neutrinos
- Absorption on unstable nucleus (tritium)
- Analyse the beta-spectrum endpoint

S. Weinberg, Phys. Rev. 128:3, 1457 (1962)
Alfredo G Cocco *et al* JCAP 06 (2007) 015

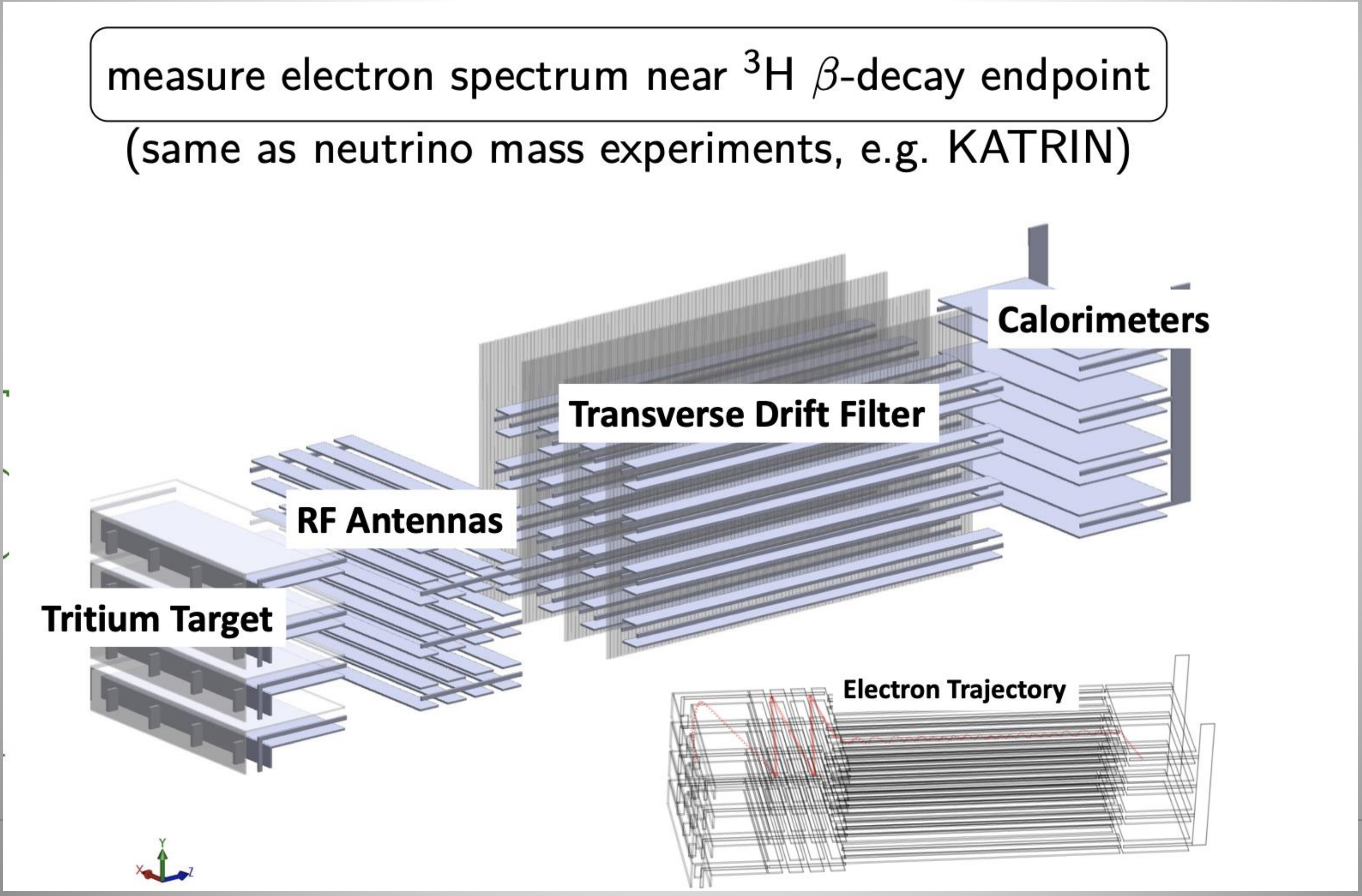






PTOLEMY Experiment

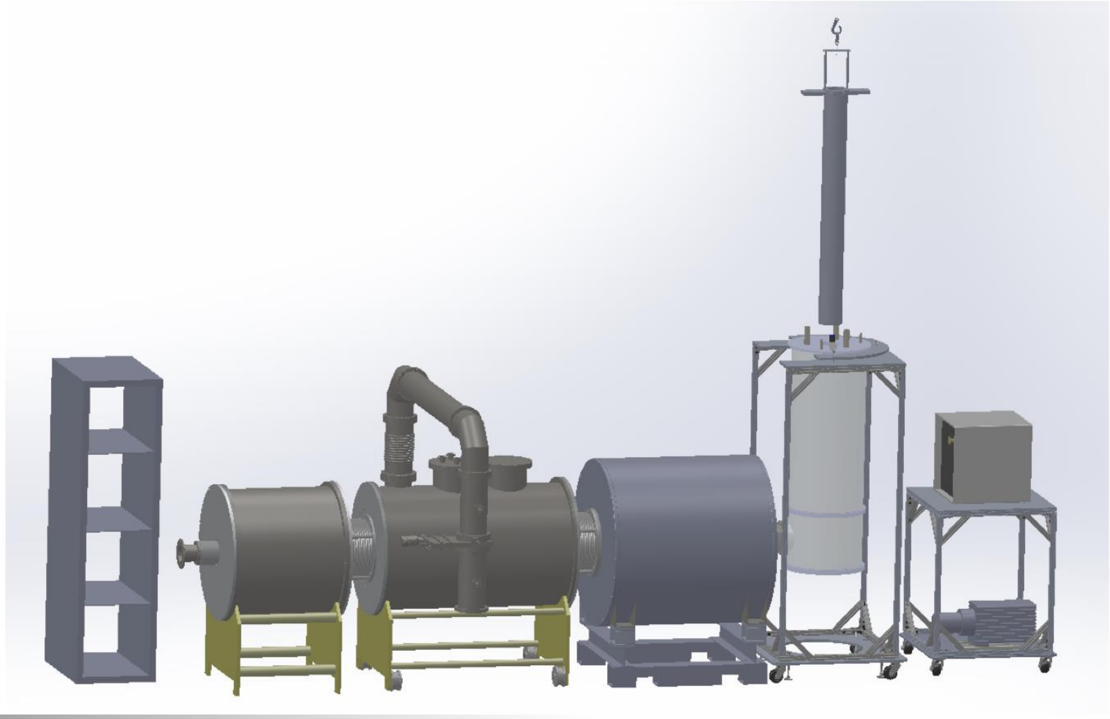
A design for an electromagnetic filter for precision energy measurements at the tritium endpoint



PTOLEMY Experiment

measure electron spectrum near ^3H β-decay endpoint

(same as neutrino mass experiments, e.g. KATRIN)



But it will be a technological challenge!

[^3H amount, low background, energy resolution, . . .]

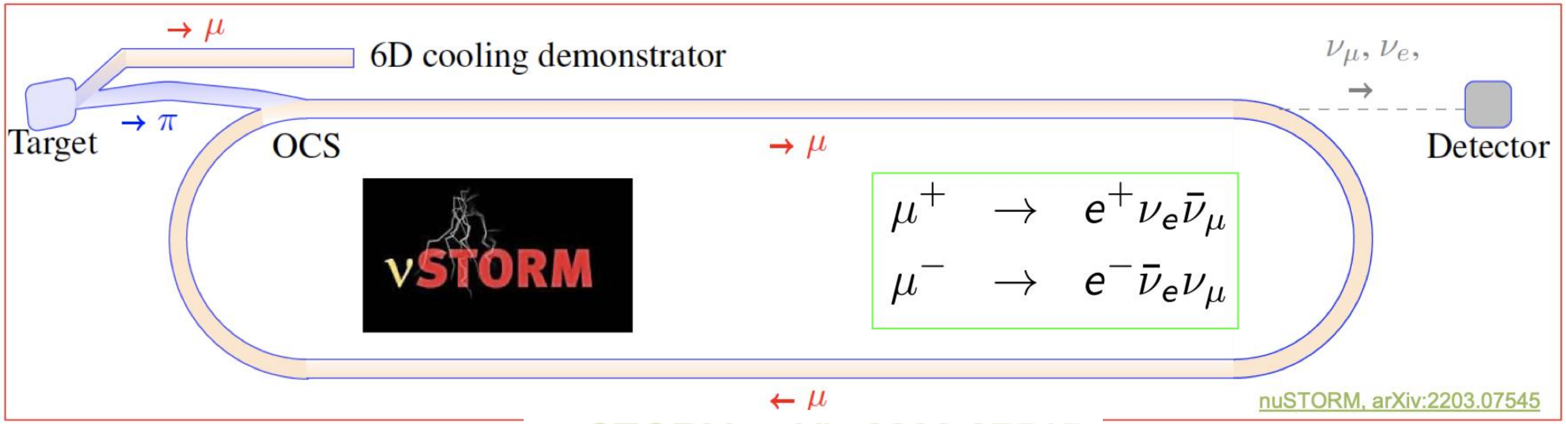
"Phased" development ongoing since a number of years
First observation in 5 to 10 years?

New/developed Ideas

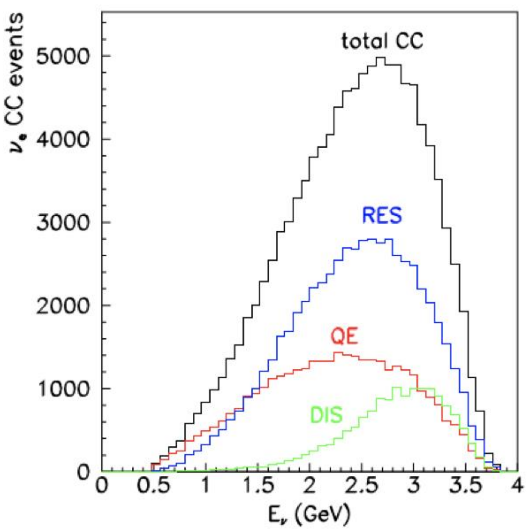
Small Neutrino Factory NuStorm
Neutrino Flavor Tagging

NuStorm: Muon Storage Ring

The road toward a powerful ν_e source: short baseline

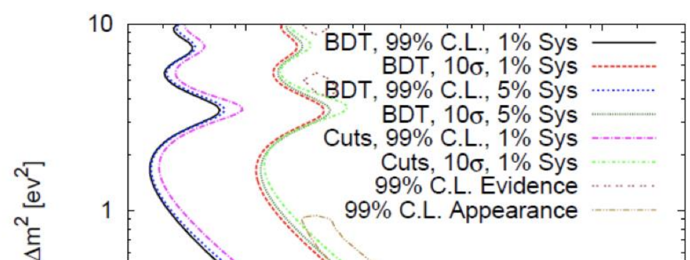


nuSTORM, arXiv:2203.07545



μ^+ Channel	N_{evts}	μ^- Channel	N_{ev}
$\bar{\nu}_\mu$ NC	844,793	$\bar{\nu}_e$ NC	709,57
ν_e NC	1,387,698	ν_μ NC	1,584,00
$\bar{\nu}_\mu$ CC	2,145,632	$\bar{\nu}_e$ CC	1,784,09
ν_e CC	3,960,421	ν_μ CC	4,626,48

arXiv:1308.6822v1

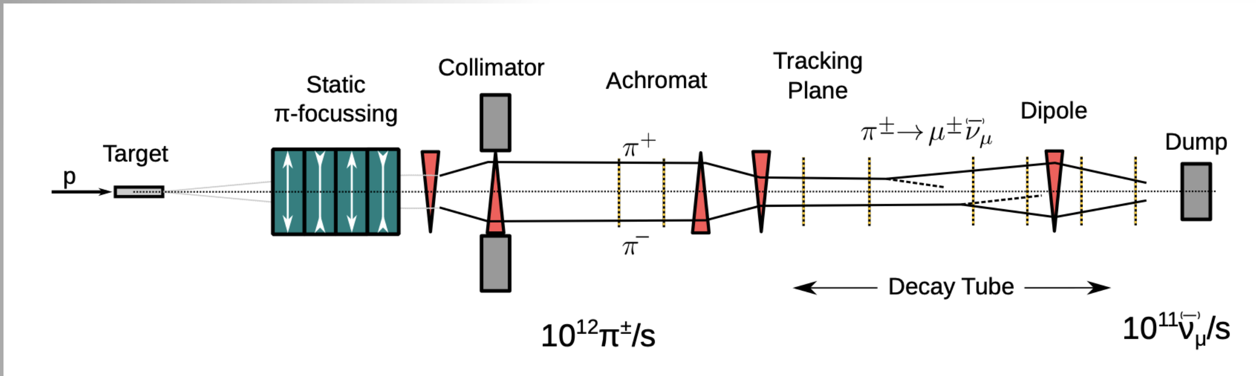


- **Scientific objectives:**
  1. %-level ($\overset{(-)}{\nu}_e N$) cross sections
     - Multi differential / E_ν scan
  2. BSM searches
     - E.g. steriles beyond FNAL SBN
  3. Muon collider demonstrator

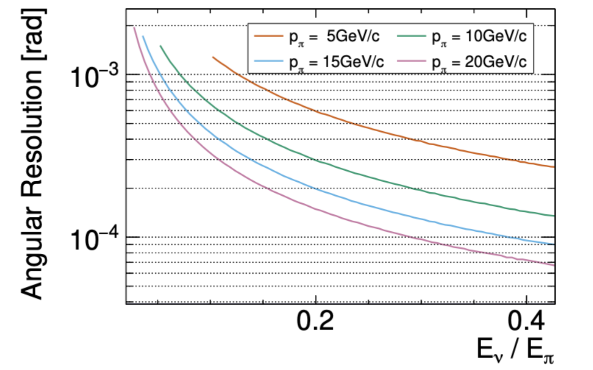
Neutrino Tagging

A new tool for accelerator based neutrino experiments?
Tag Flavor/type of each individual neutrino at creation.
Technology (tracking/timing) available. Example for P2O

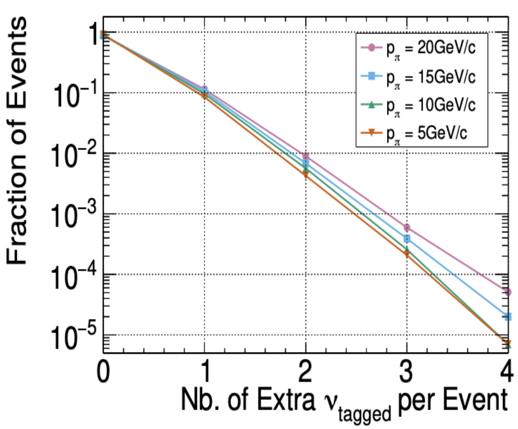
2122.12848



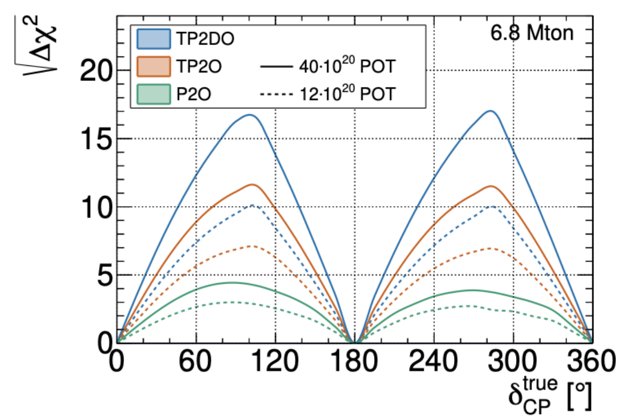
Angular resolution



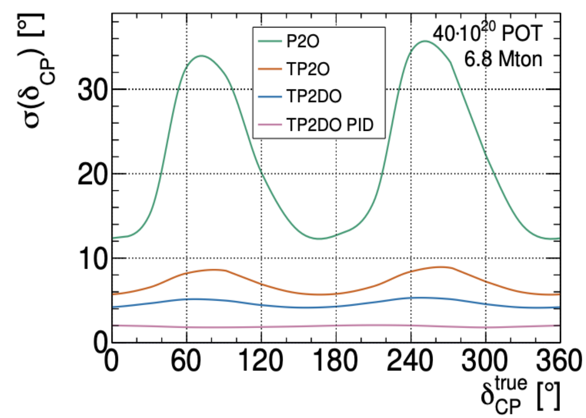
Occupancy



Sensitivity to δ_{CP}

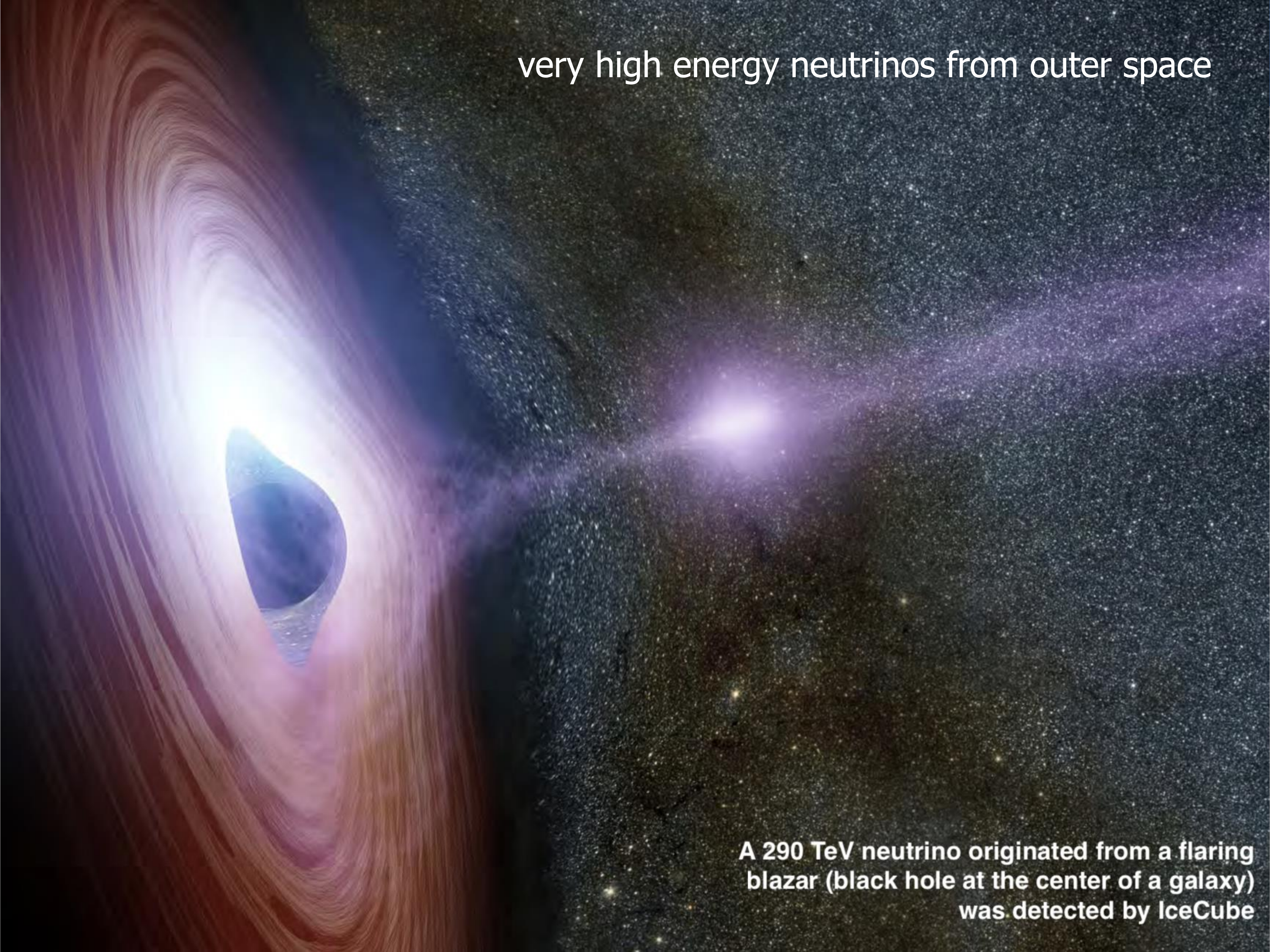


Precision on δ_{CP}



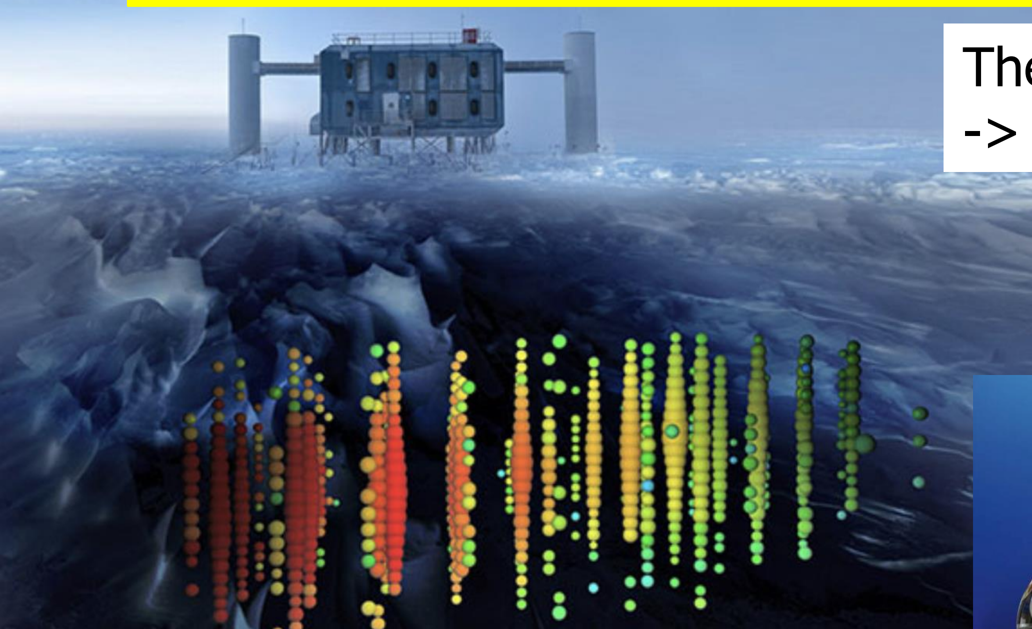
Astrophysical Sources of Neutrinos

very high energy neutrinos from outer space



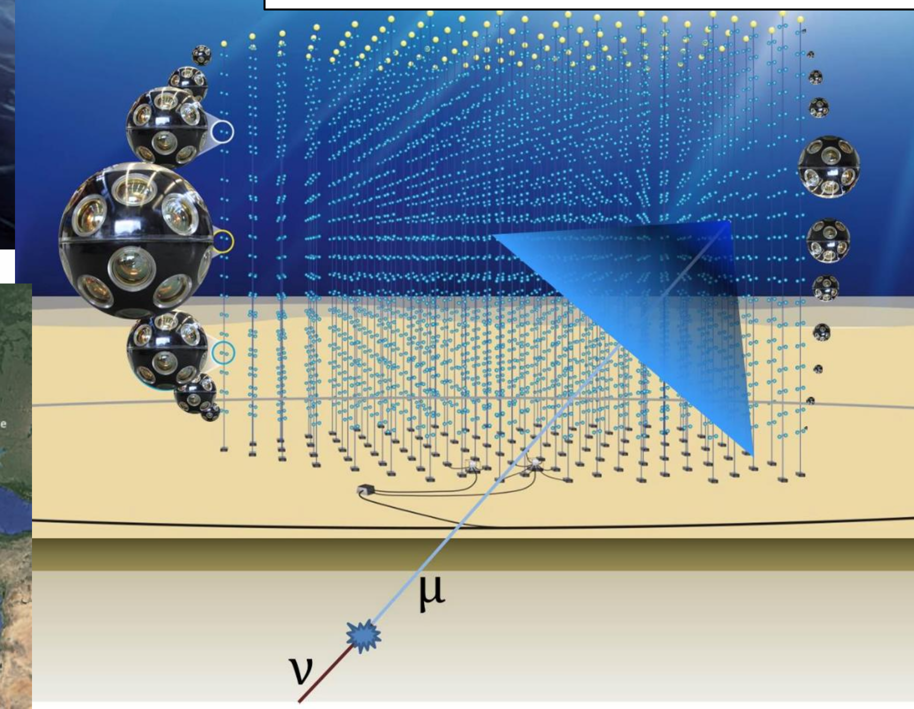
Neutrino Astronomy

Build gigantic detectors 1 km^3 of size and beyond…
Use the resources of planet Earth



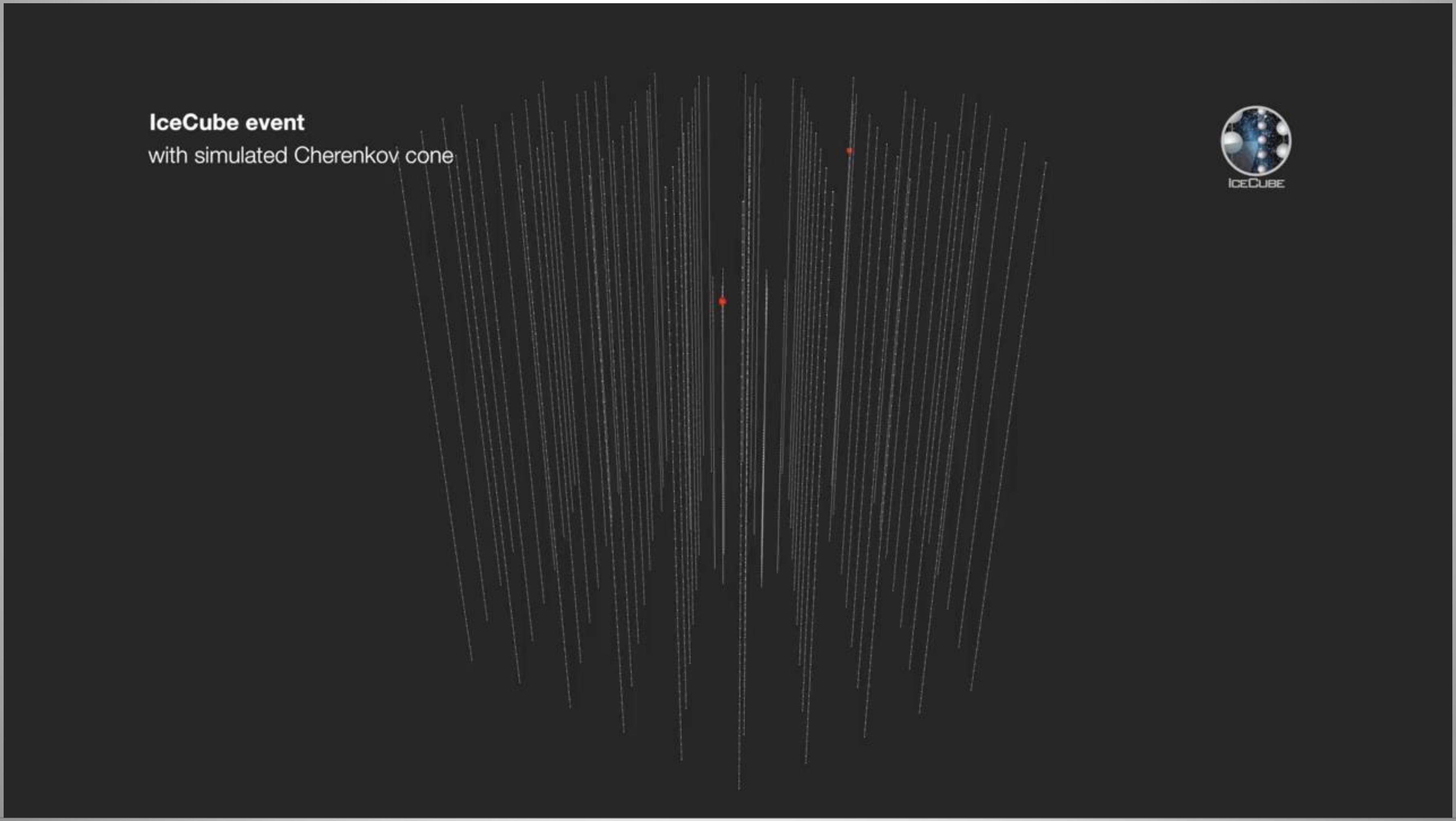
The IceCube Experiment
-> In the ice of Antarctica

The KM3NET Experiment
-> In the Mediteranian sea



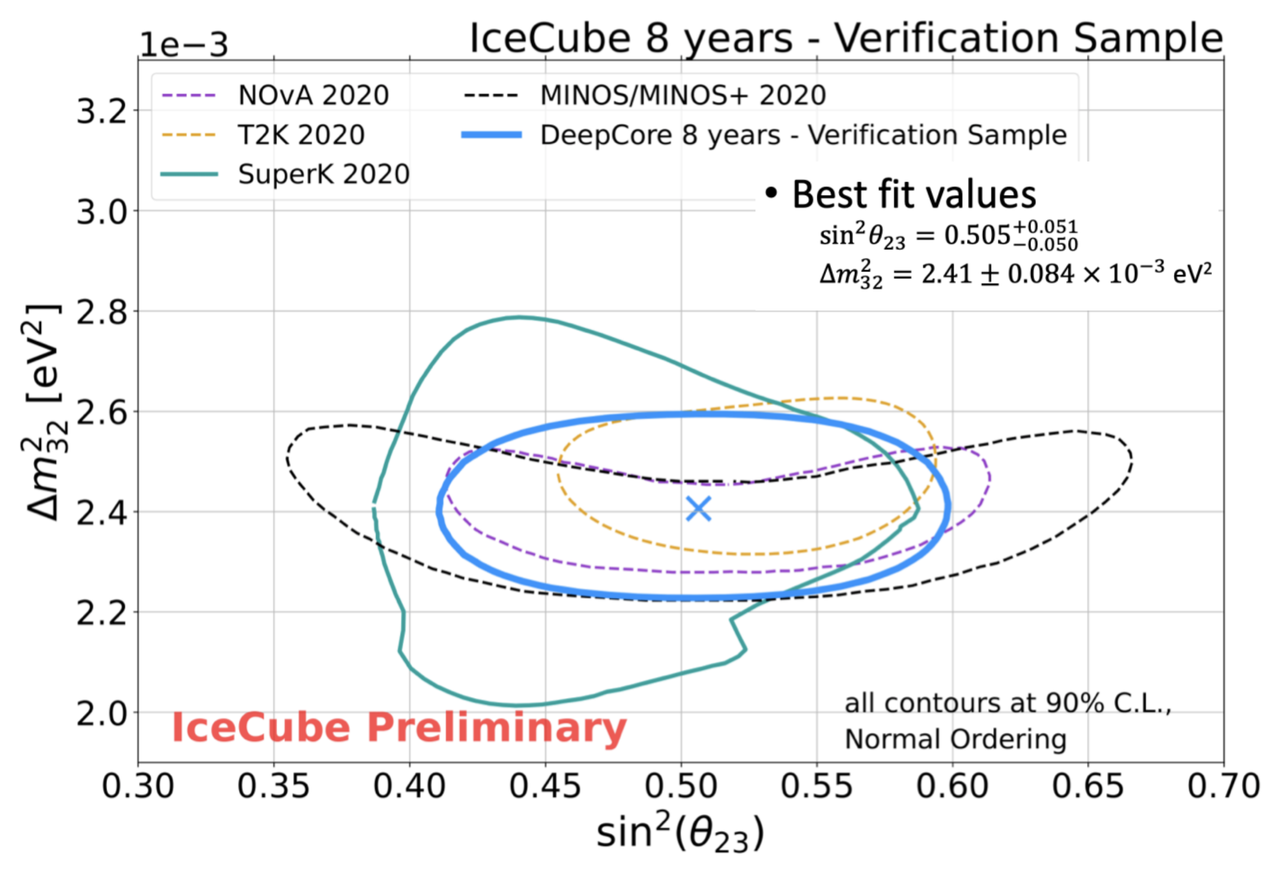
+ANTARES
+Lake Baikal

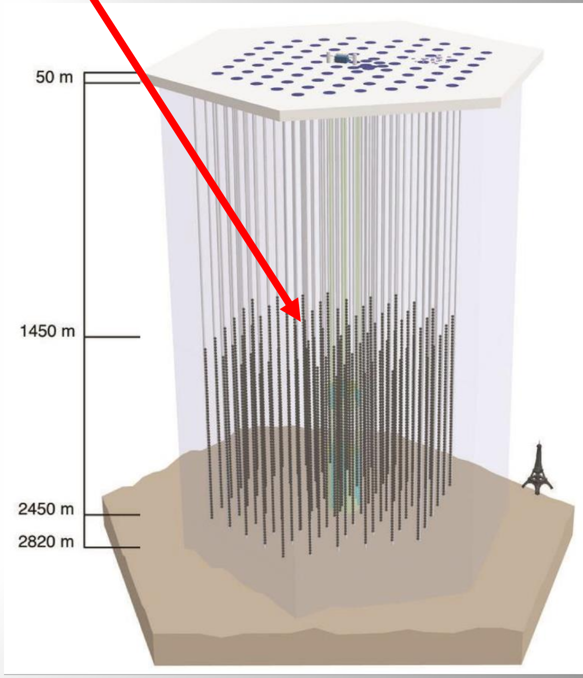
Neutrinos in IceCube



The IceCube Experiment

Result on "atmospheric" PMNS parameters from 8 year data collection with DeepCore

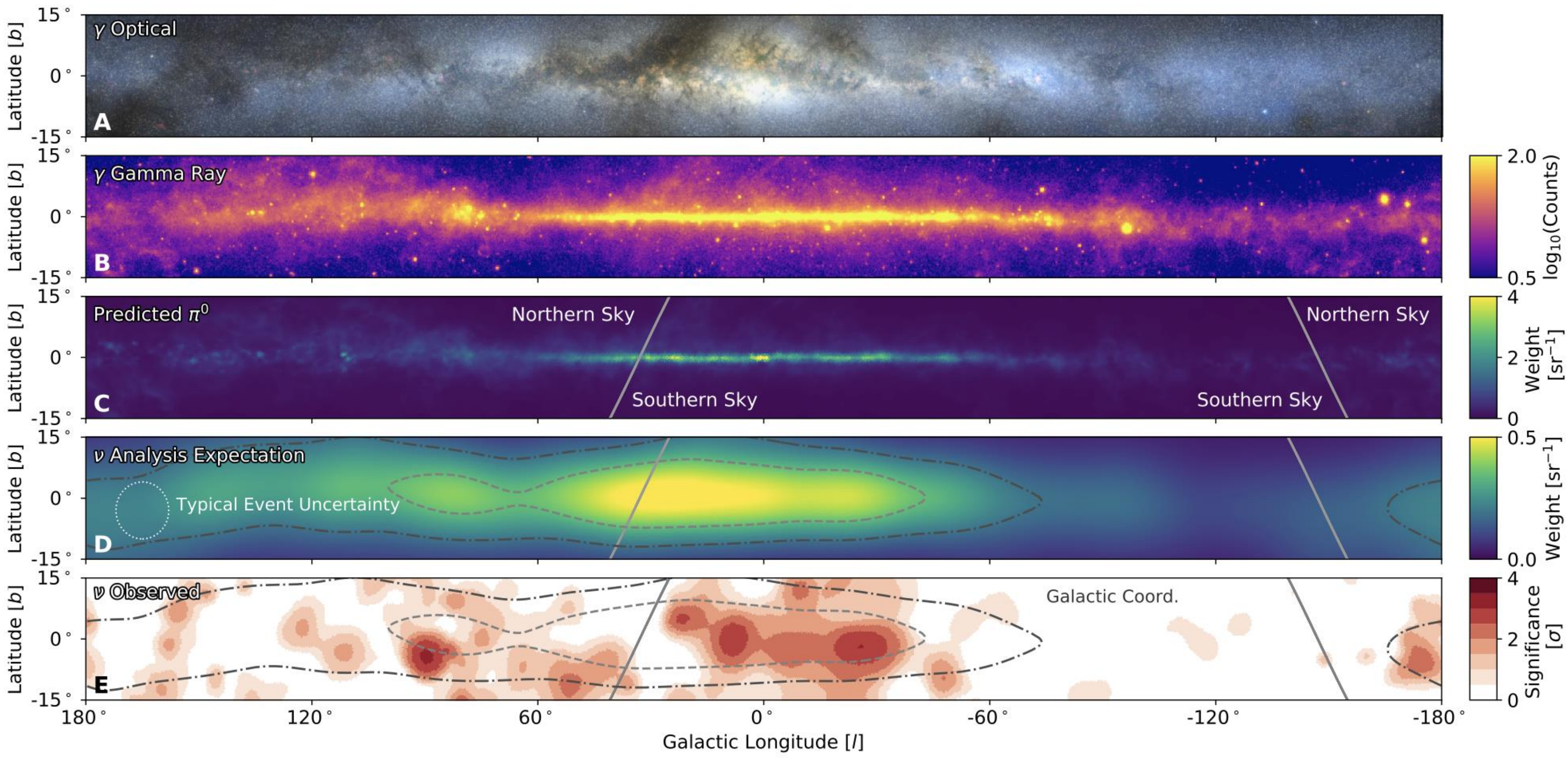




Very competitive measurement….

New from IceCube

The plane of the Milky Way galaxy with neutrinos



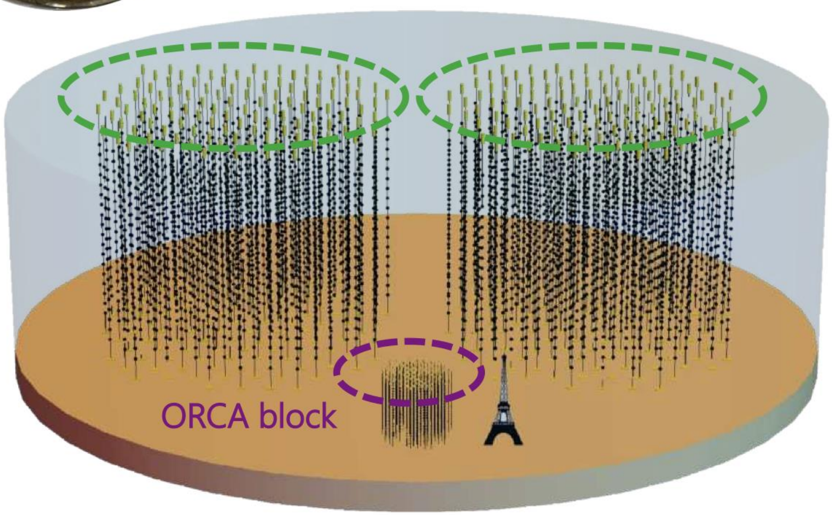
KM3NET

KM3NeT

Telescopes

Neutrino detection technology in KM3NeT

Modular, incremental telescopes
Detection Unit: a string of 18 **Digital Optical Modules**
DOM: instrumented sphere hosting 12 upwards-pointing + 19 downward pointing 3″ PMTs.



	ARCA	ORCA
Location	Italy (Sicily)	France (Toulon)
Anchor depth	3450 m	2450 m
Distance from shore	100 km	40 km
DUs	115×2 blocks	115
DU horizontal spacing	90 m	20 m
DOM vertical spacing	36 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31
Instrumented water mass	1 Gton	7 Mton
DUs deployed	21	18

The Baikal-GVD Experiment

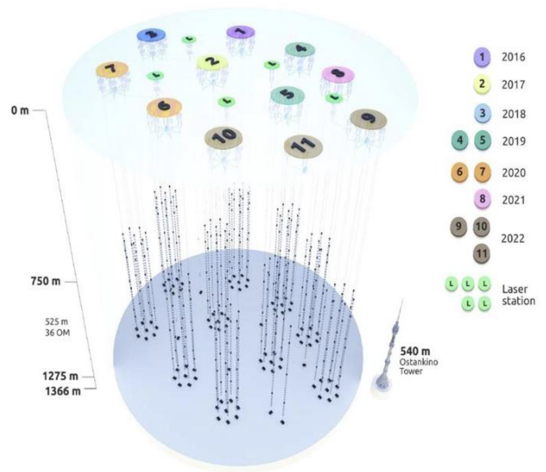
Baikal-GVD Gigaton Volume Detector

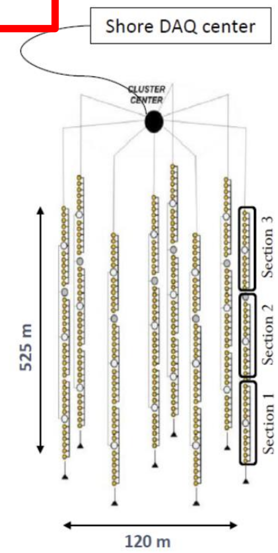
Projects: Baikai-GVD

- Largest neutrino telescope in the Northern Hemisphere and still growing
- Outlook:
  - 2025/2026 – ~ 1km^3 GVD with total of 16-18 clusters
  - 2022-2024 – "Conceptual Design Report" for next generation neutrino telescope in Lake Baikal

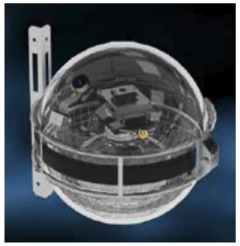
Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032
2025	16	4608
2026	18	5184

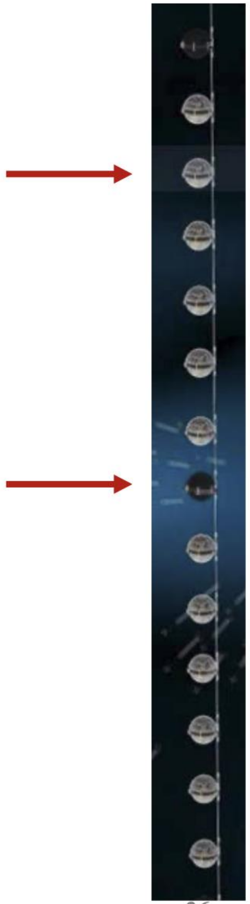




Optical module



Section control module



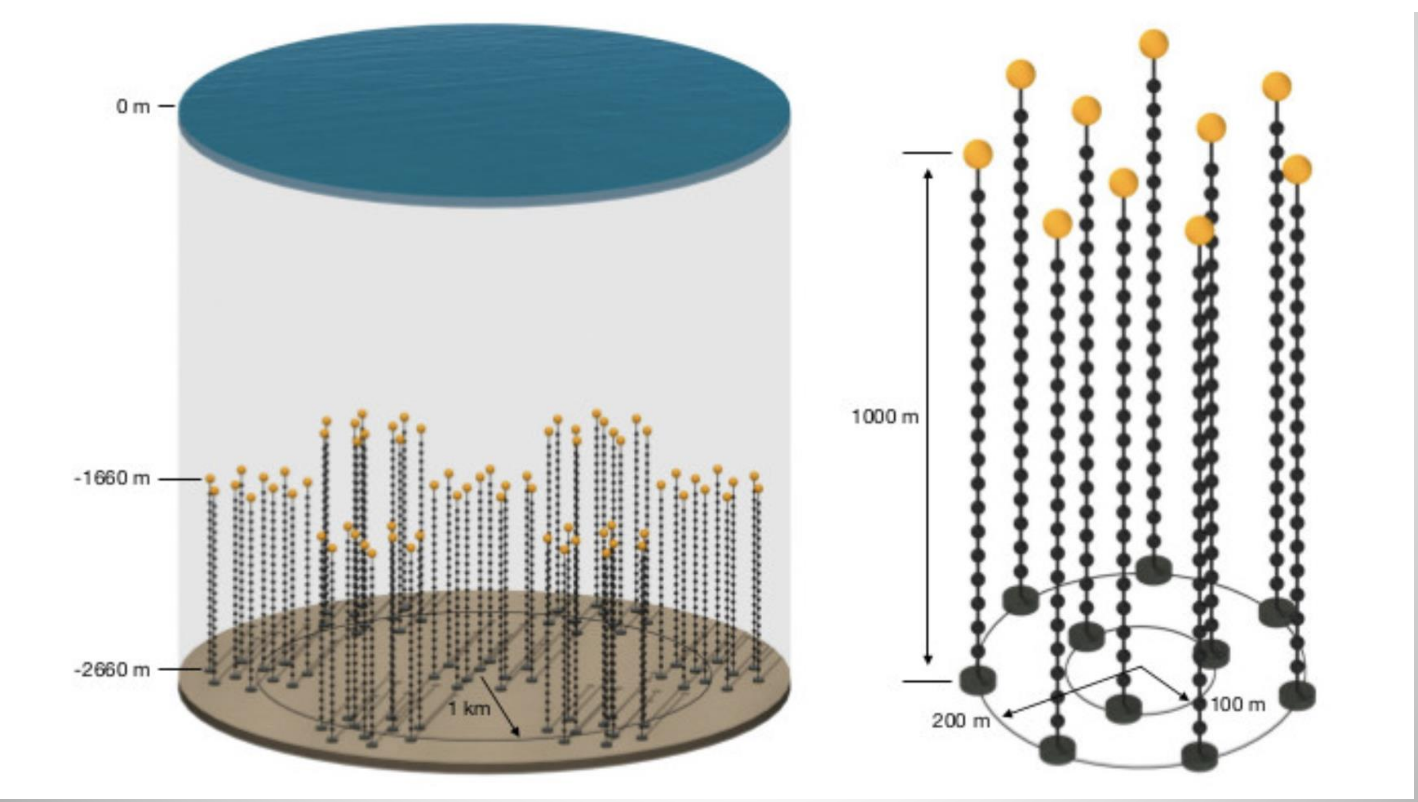
The P-ONE Proposal

The Pacific Ocean Neutrino Experiment

P-ONE

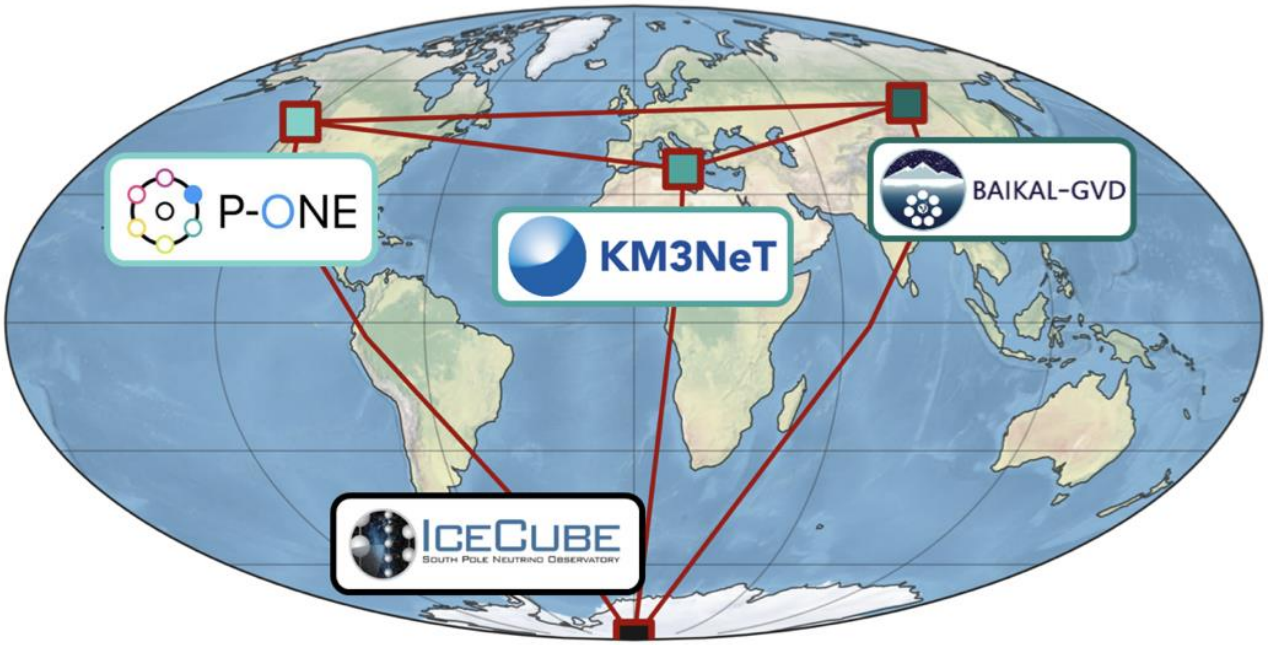
A multi-km^3 neutrino telescope; the first to be hosted by an existing oceanographic infrastructure.

2111.13133



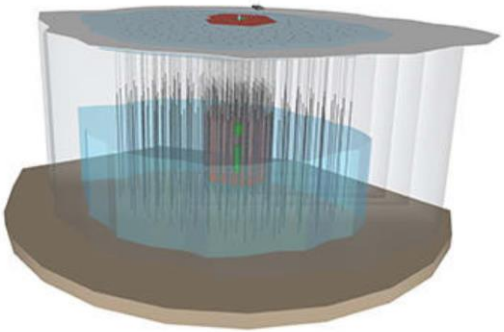
Experiment for energies above 50 TeV. A first segment is planned to be installed in a four weeks sea operation in 2023/24

Large Neutrino Observatories



IceCube PINGU low energy extension

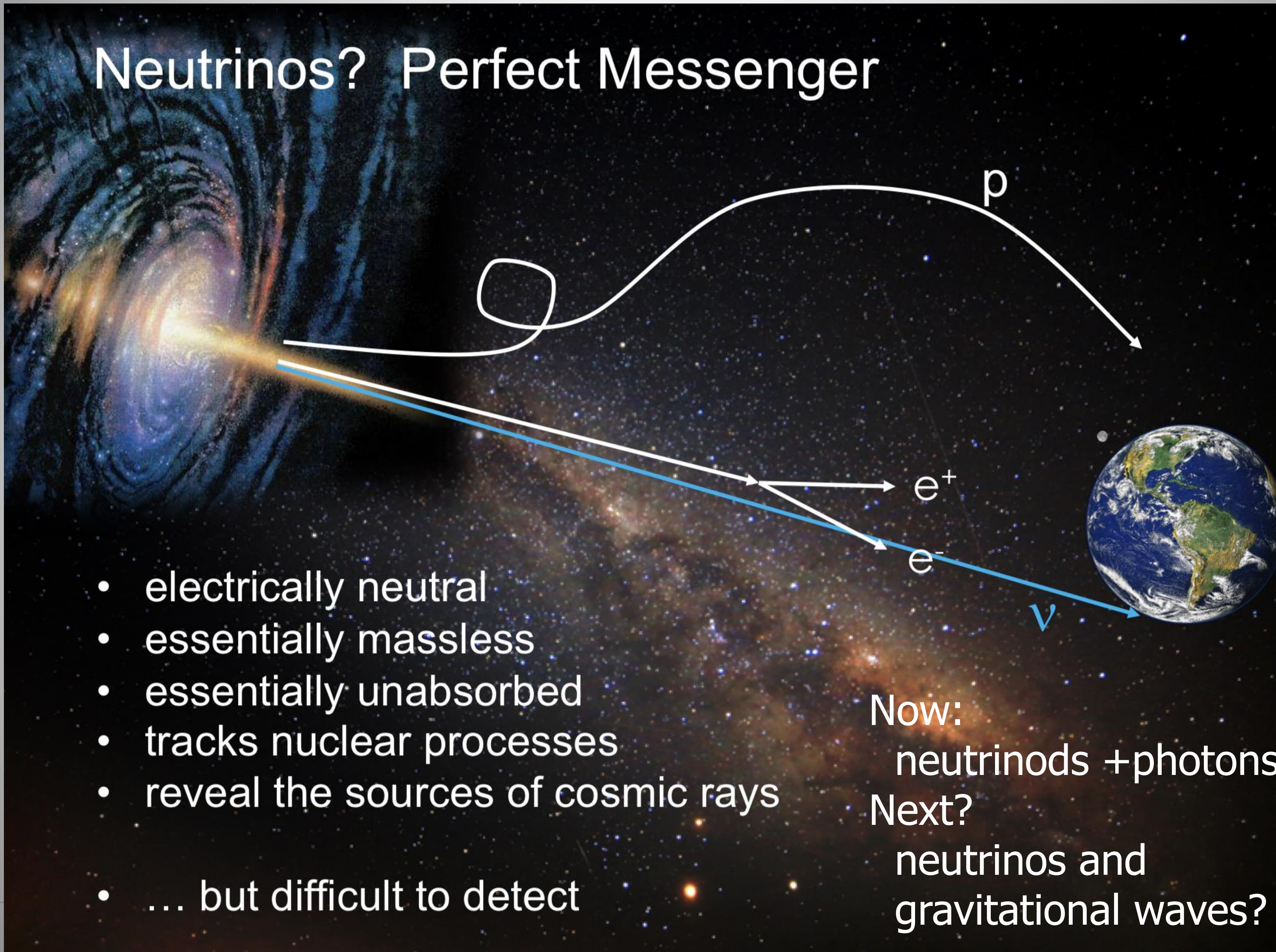
IceCube GEN-2 10 km^3



When combined and used as a single distributed planetary instrument (Planetary Neutrino Monitoring System PLEnUM), it would cover almost the entire sky

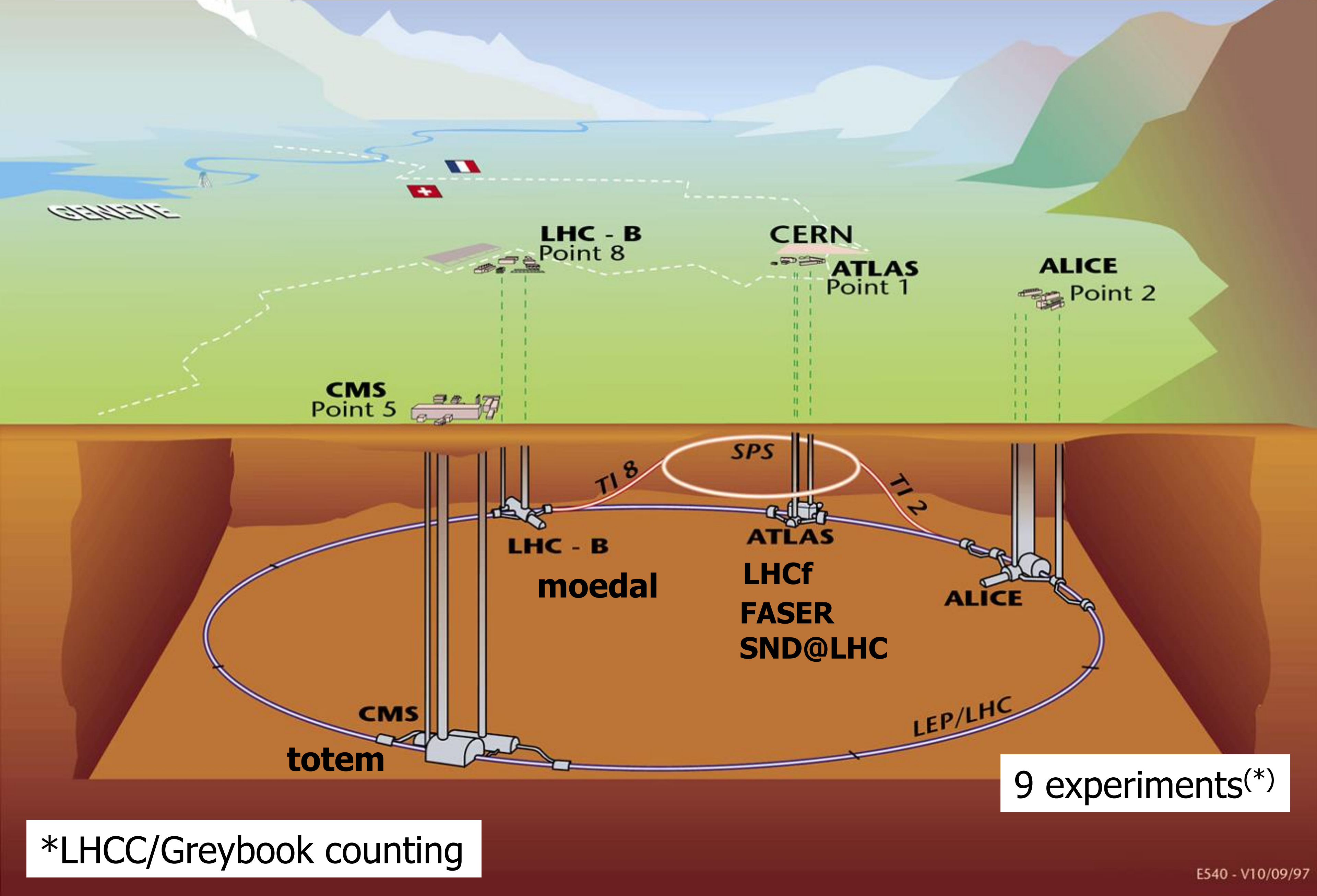
Huge increase of the detection probability for > 50 TeV neutrinos

Multi Messenger Astronomy…



Neutrinos at the LHC!

The Flagship Project of CERN: the Large Hadron Collider

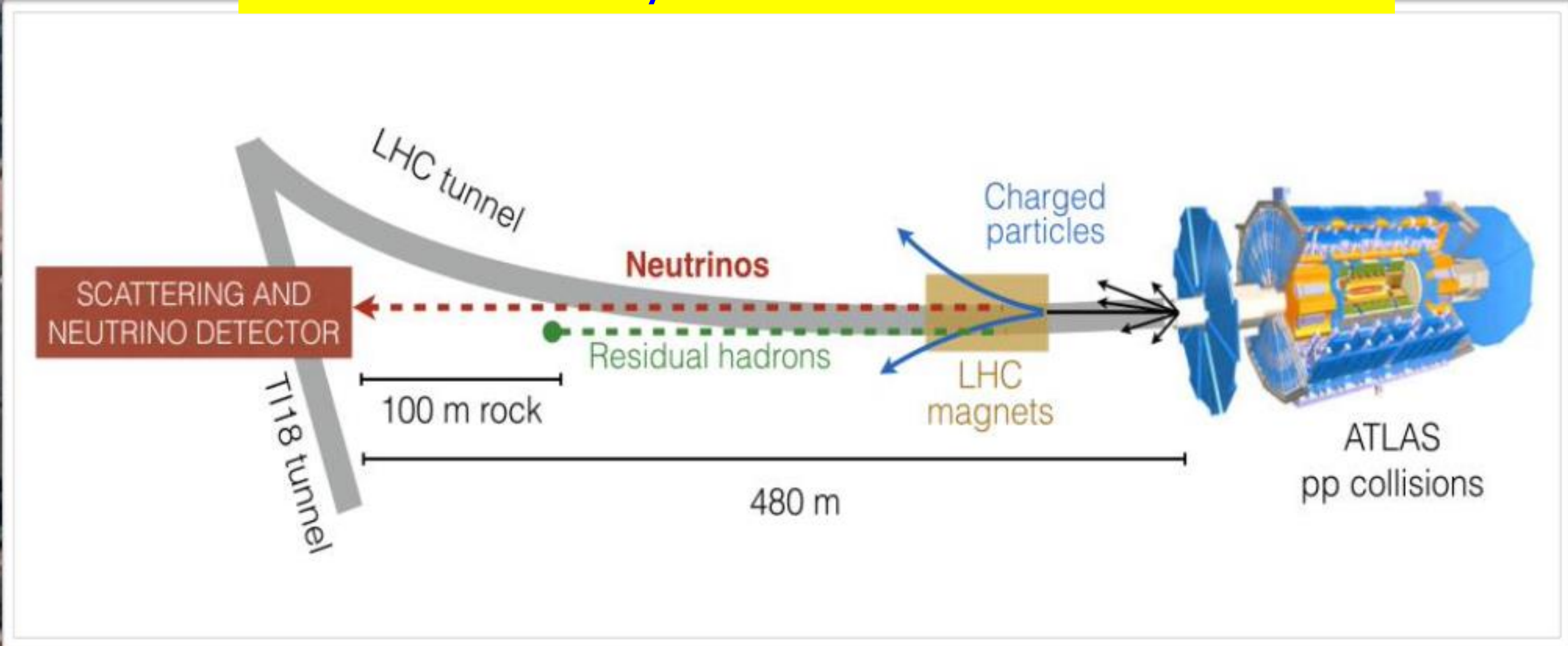


9 experiments(*)

*LHCC/Greybook counting

Measuring Neutrino Interactions @ LHC

SND@LHC and FASERν are 480m forward of the IPs and can study TeV-neutrinos



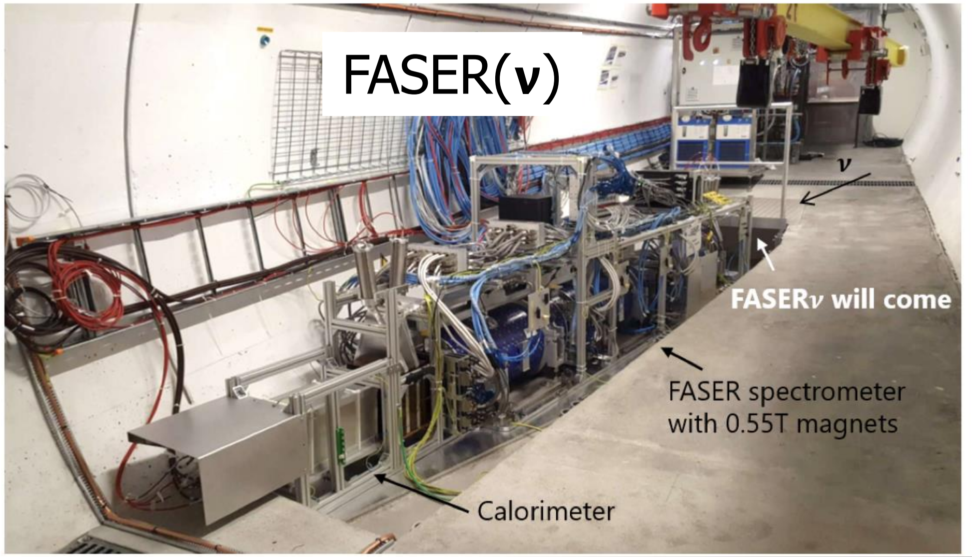
FASER was approved in 2019. FASERν (extension with emulsion) in 2020.
SND@LHC was proposed in 2020 and approved in 2021.
Both experiments take now data with the start of the Run-3 at the LHC

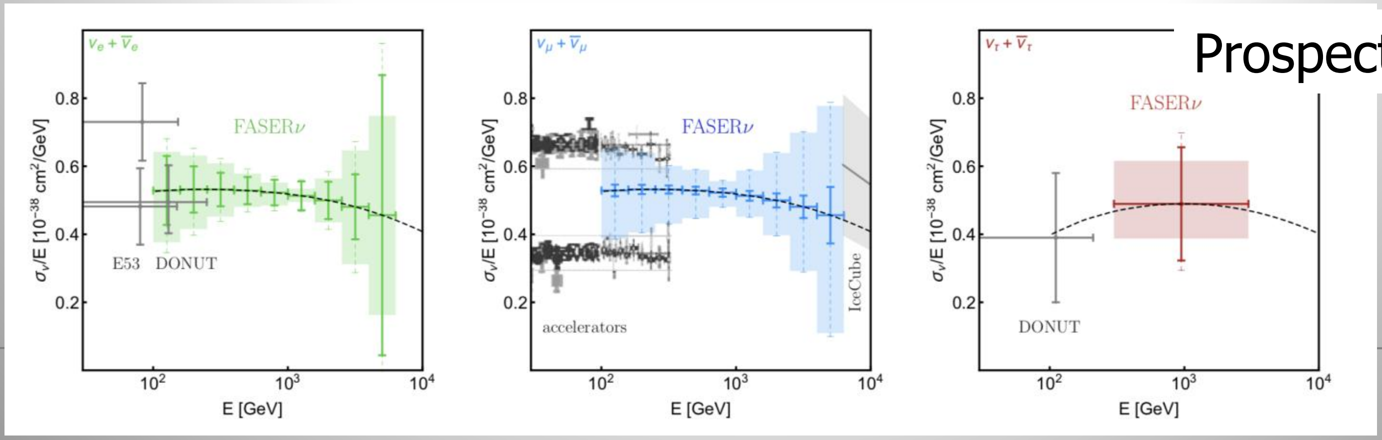
Neutrinos @ the LHC: SND@LHC & FASERν

SND@LHC: approved March '21

SND= Scattering and Neutrino Detector

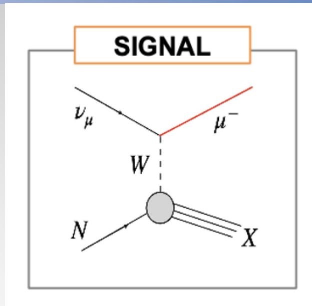
SND@LHC/FASERν are 480m forward and can study TeV-neutrinos with emulsion and tracking+muon/calo detectors



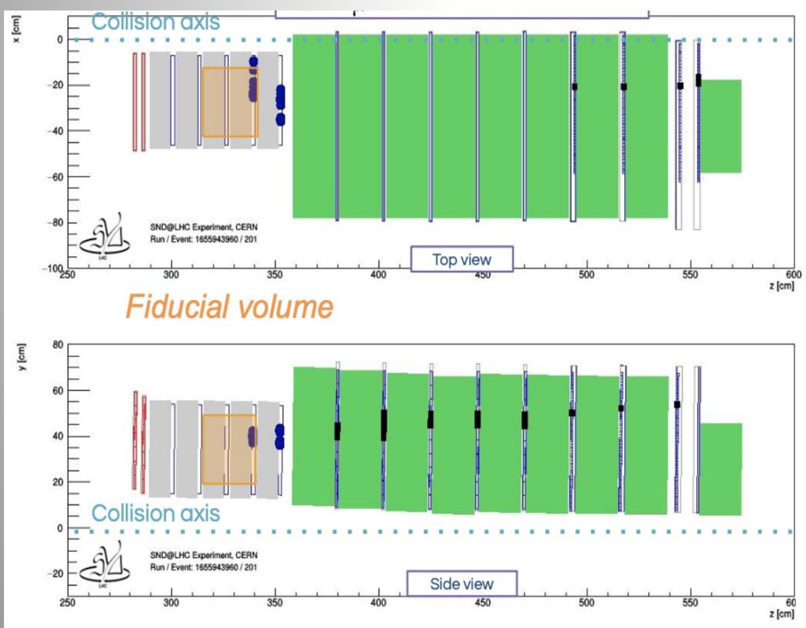


First Results from FASER and SND@LHC

Direct observation of neutrinos produced at the LHC in the charged current muon channel



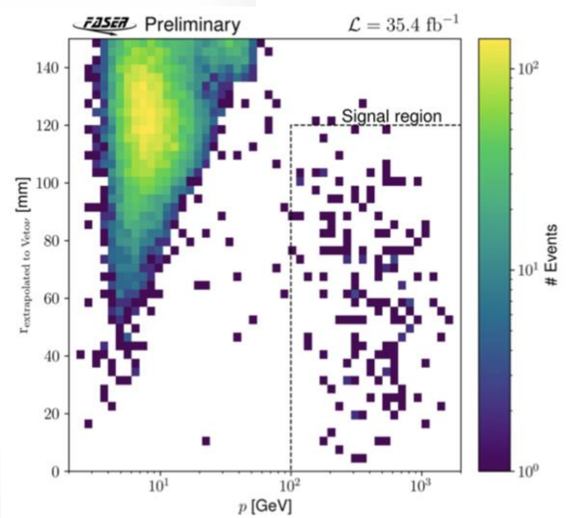
SND@LHC (off-axis) 2305.09383



- Observed ν_μ **candidates**: 8 (expected 5)
- Preliminary estimate of background yield: 0.2

FASER (on-axis)

2303.14185



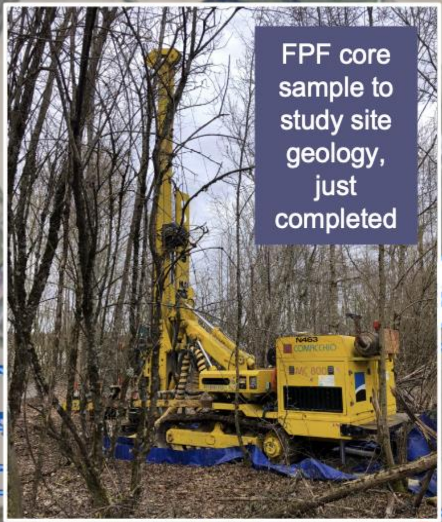
153 observed events in signal region

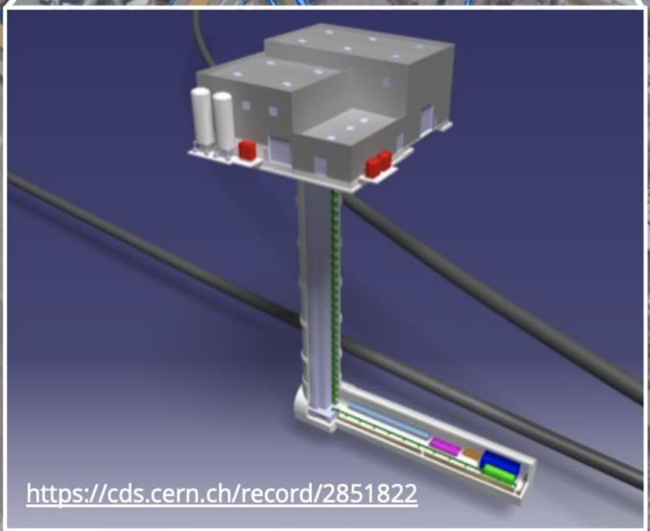
An Option for the FUTURE:
The Forward Physics Facility

FORWARD PHYSICS FACILITY

- A comprehensive site selection study by the CERN Civil Engineering group has identified an ideal location ~600 m west of ATLAS.

ATLAS
LHC
LOS



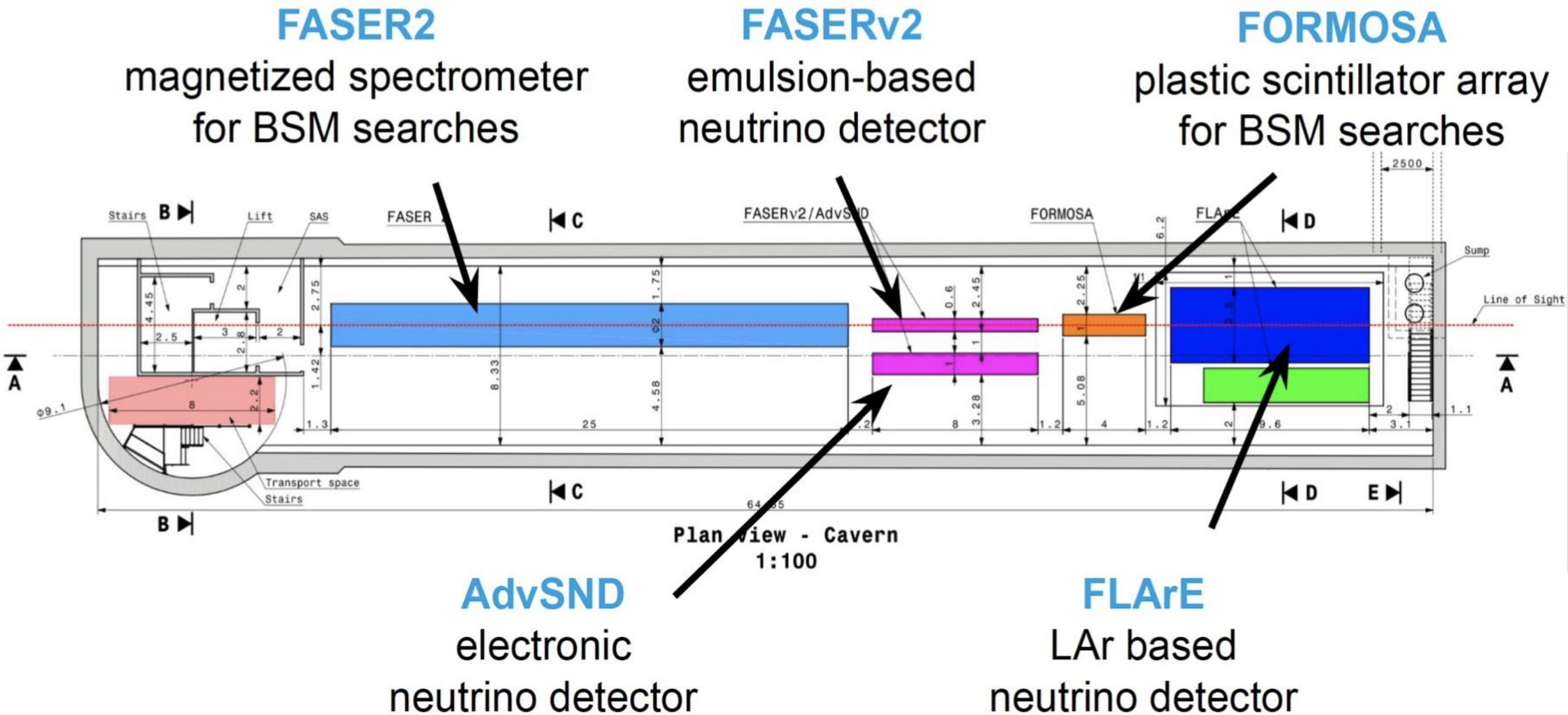


- The site is on CERN land in France
- The cavern is 65 m-long, 9 m-wide/high
- Shielded from ATLAS by 200m of rock
- Disconnected from LHC tunnel
- Vibration, safety studies: can construct FPF without disrupting LHC operations
- Radiation studies: can work in FPF while LHC is running (HL-LHC starts 2029)

CERN GIS

Experiments for the FPF

- At present there are 5 experiments being designed for the FPF.
- Diverse technologies optimized for particular SM and BSM topics.
- FPF covers $\eta > 5.5$, experiments on LOS cover $\eta \gtrsim 7$.



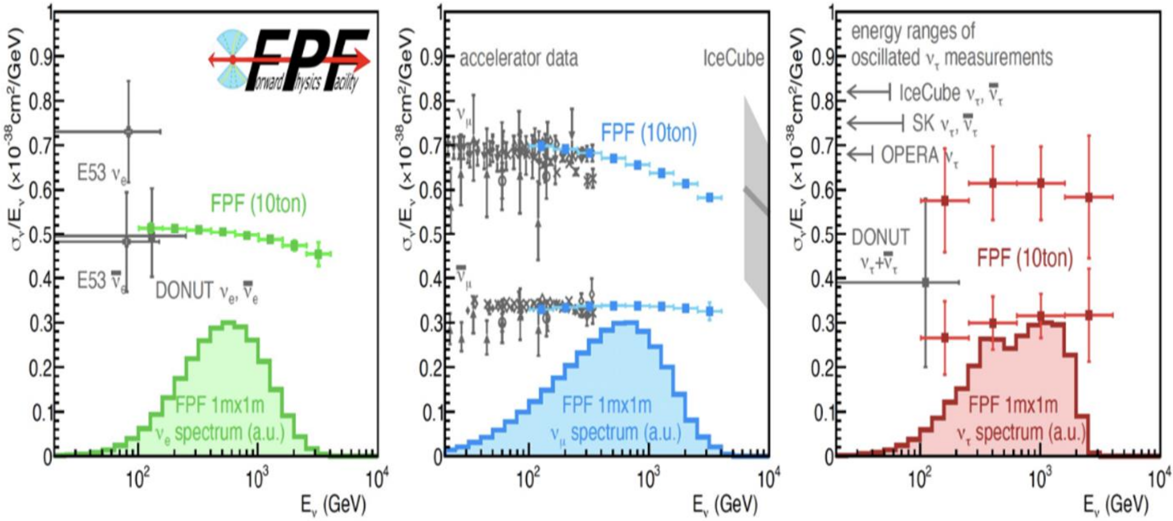
FPF: Neutrino Measurements

- Pathfinder experiments FASERν and SND@LHC have recently directly observed collider neutrinos for the first time.

  Moriond 2023
  2303.14185

- FPF experiments FLArE, FASERν2, and AdvSND will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, $10^4\ \nu_\tau$ interactions at ~TeV energies.

- Implications for
  - neutrino properties
  - QCD ($x{\sim}10^{-7} - 0.1$, DIS)
  - astroparticle physics



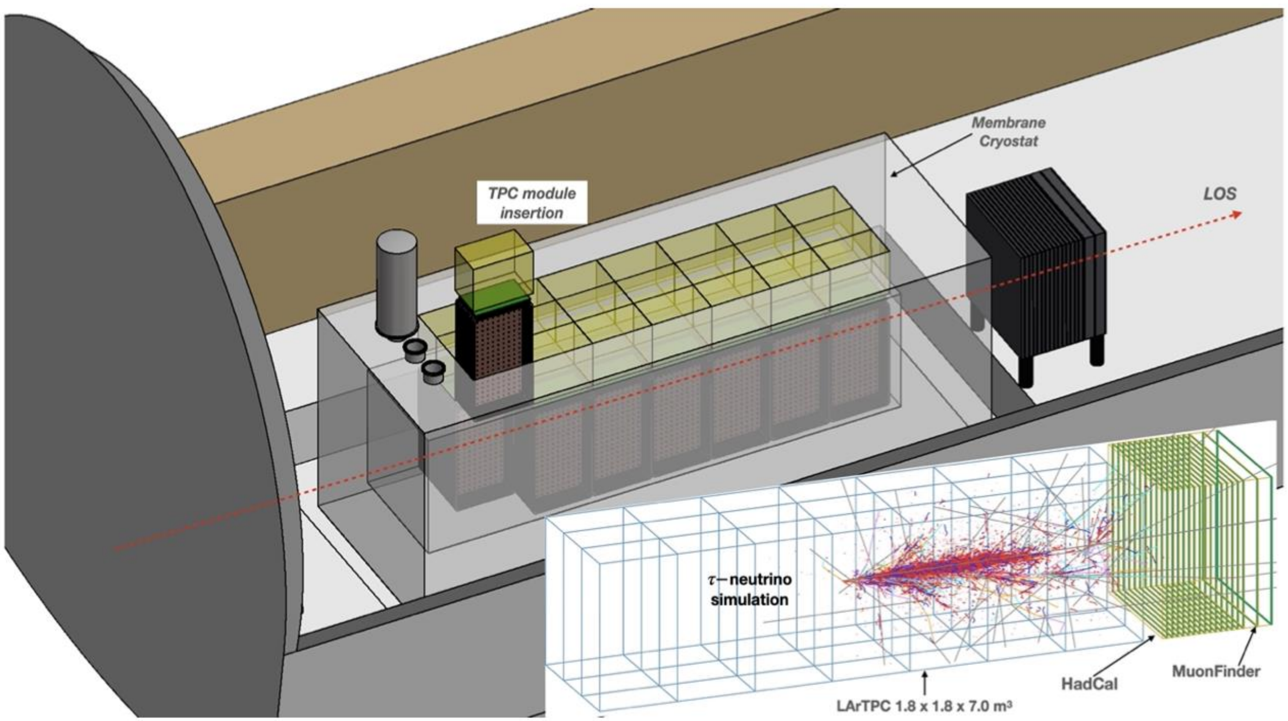
Expected precision with 3 ab^{-1} data at the end of the HL-LHC

Forward Liquid Argon Experiment: FLArE

- On-axis LArTPC neutrino and light DM detector
- 1.8 m x 1.8 m x 7 m, ~10 ton LAr mass

	Value	Remarks
LAr detector fiducial mass	>10 tons	
Active dimensions	1.8 m × 1.8 m × 7 m	not including cryostat
Cryostat dimensions	3.5 m × 3.5 m × 9.6 m	membrane type
TPC modules/drift length	3 × 7 (gap: ∼30 cm)	short gap TPC
TPC height	1.8 m	
Spatial resolution	<1 mm	in drift and tranverse dimension
Charge readout	pixels	pixel/wire hybrid approach possible
Trigger and light readout	SiPMs/WLS-plates	needed for neutrino trigger and time
Background muon rate	$\sim 1/\text{cm}^2/\text{s}$	at luminosity $5 \times 10^{34}/\text{cm}^2/\text{s}$
Neutrino event rate	$\sim 50/\text{ton}/\text{fb}^{-1}$	for all flavors of neutrinos
Hadronic calorimeter (hadmu)	$\sim 6 - 10\lambda$	interactions lengths
Dimensions	1.8 m × 1.8 m × 1.05 m (depth)	Fe/scint sandwich
Muon tagger and momentum	1 Tesla magnetized Fe/scint	same as the hadmu

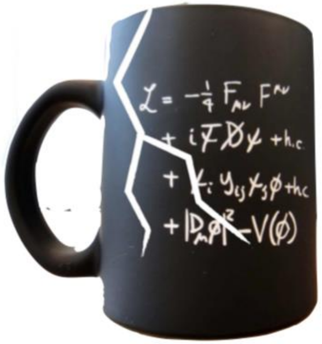
Modelled on (Proto)DUNE



FLArE with simulated 500 GeV tau neutrino

Conclusion

- Many new projects on all fronts in preparation for the near and somewhat further future.
- Neutrino physics is a very active area!
- And maybe neutrinos will have still some surprises for us to show….



THE END

Further reading

Snowmass Neutrino Frontier Report

Frontier Conveners: Patrick Huber,[1] Kate Scholberg,[2] Elizabeth Worcester,[3]

Topical Group Conveners: Jonathan Asaadi,[4] A. Baha Balantekin,[5] Nathaniel Bowden,[6] Pilar Coloma,[7] Peter B. Denton,[8] André de Gouvêa,[9] Laura Fields,[10] Megan Friend,[11] Steven Gardiner,[12] Carlo Giunti,[13] Julieta Gruszko,[14, 15] Benjamin J.P. Jones,[4] Georgia Karagiorgi,[16] Lisa Kaufman,[17] Joshua R. Klein,[18] Lisa W. Koerner,[19] Yusuke Koshio,[20] Jonathan M. Link,[1] Bryce R. Littlejohn,[21] Ana A. Machado,[22] Pedro A.N. Machado,[23] Kendall Mahn,[24] Alysia D. Marino,[25] Mark D. Messier,[26] Irina Mocioiu,[27] Jason Newby,[28] Erin O'Sullivan,[29] Juan Pedro Ochoa-Ricoux,[30] Gabriel D. Orebi Gann,[31, 32] Diana S. Parno,[33] Saori Pastore,[34] David W. Schmitz,[35] Ian M. Shoemaker,[1] Alexandre Sousa,[36] Joshua Spitz,[37] Raimund Strauss,[38] Louis E. Strigari,[39] Irene Tamborra,[40] Hirohisa A. Tanaka,[41] Wei Wang,[42] Jaehoon Yu,[4]

Liaisons: K S. Babu,[43] Robert H. Bernstein,[44] Erin Conley,[2] Albert De Roeck,[45] Alexander I. Himmel,[46] Jay Hyun Jo,[47] Claire Lee,[48] Tanaz A. Mohayai,[46] Kim J. Palladino,[49] Vishvas Pandey,[46] Mayly C. Sanchez,[50] Yvonne Y.Y. Wong,[51] Jacob Zettlemoyer,[46] Xianyi Zhang,[52] and

arXiv:2211.08641

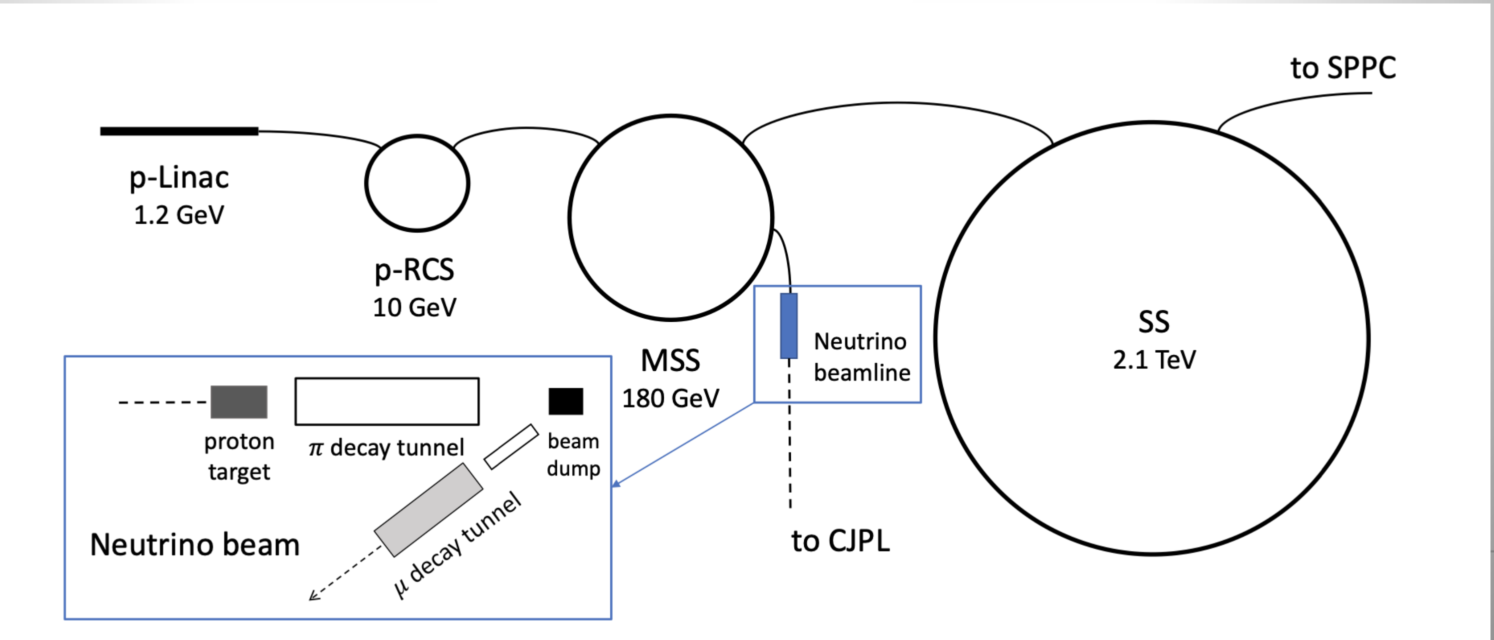
Backup

LBL Neutrino Experiments in China?

China Accelerator Projects and undergound labs

Accelerator facility	JUNO			CJPL		
	Baseline	1^{st} maximum	2^{nd} maximum	Baseline	1^{st} maximum	2^{nd} maximum
CAS-IMP	1759 km	3.6 GeV	1.2 GeV	894 km	1.8 GeV	600 MeV
CiADS	221 km	450 MeV	150 MeV	1389 km	2.8 GeV	940 MeV
CSNS	162 km	330 MeV	110 MeV	1329 km	2.7 GeV	900 MeV
Nanjing	1261 km	2.6 GeV	850 MeV	1693 km	3.4 GeV	1.1 GeV
SPPC	1871 km	3.8 GeV	1.3 GeV	1736 km	3.5 GeV	1.2 GeV

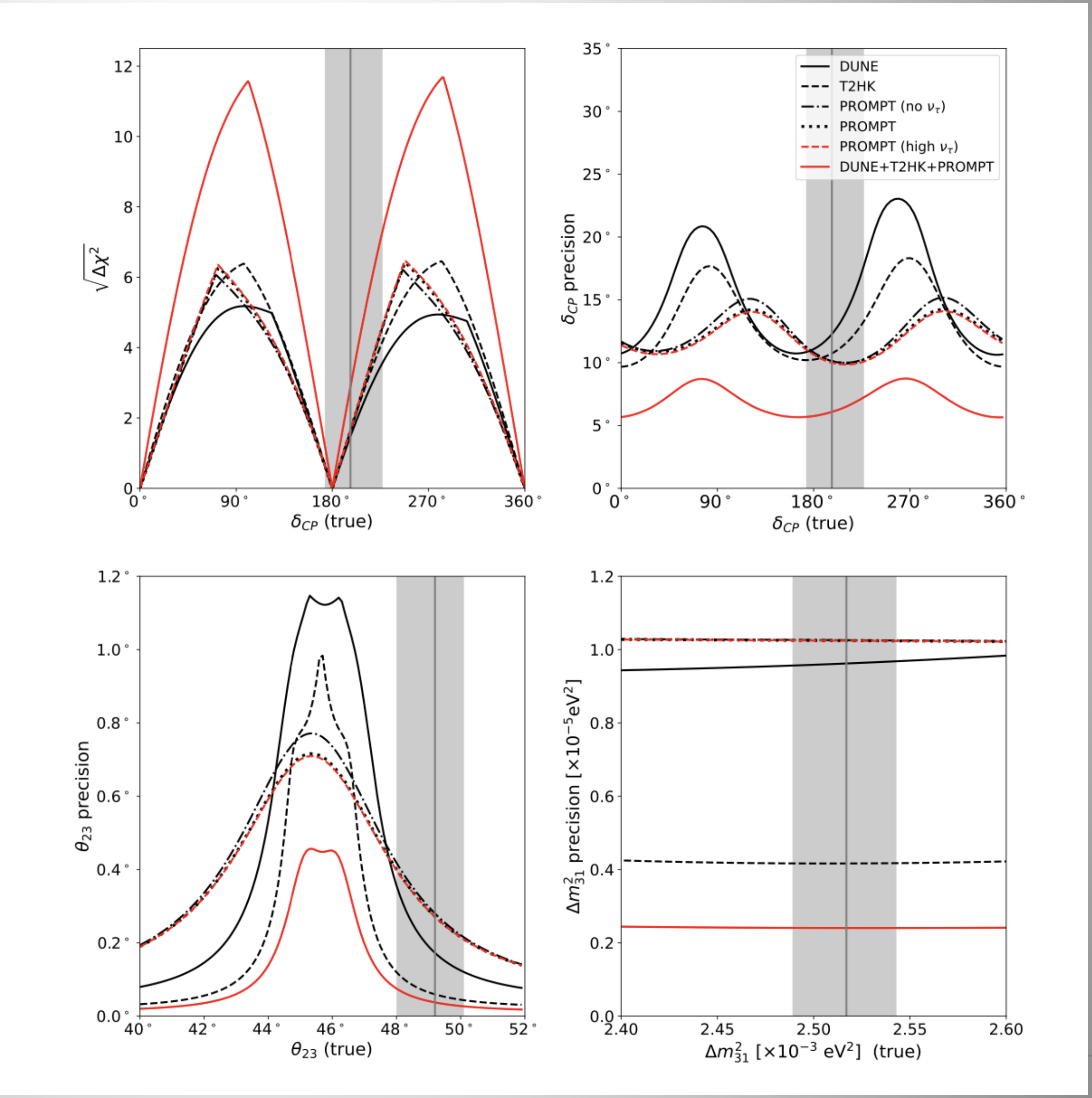
Example: Future SPPC collider pre-accelerator 3.2 MW (near Beijing)



LBL Neutrino Experiments in China?

2202.13595
2108.11107

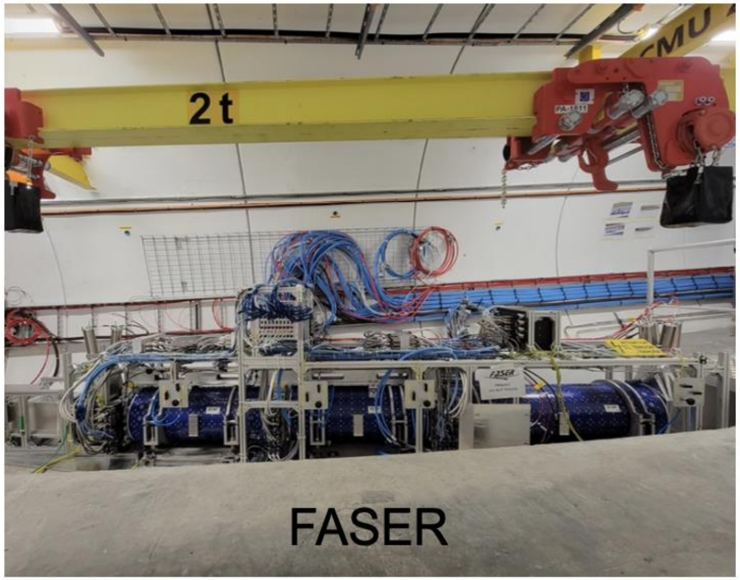
Assuming a 50 kton Magnetized Hybirid (emulsion/Iron) Detector (PROMPT)

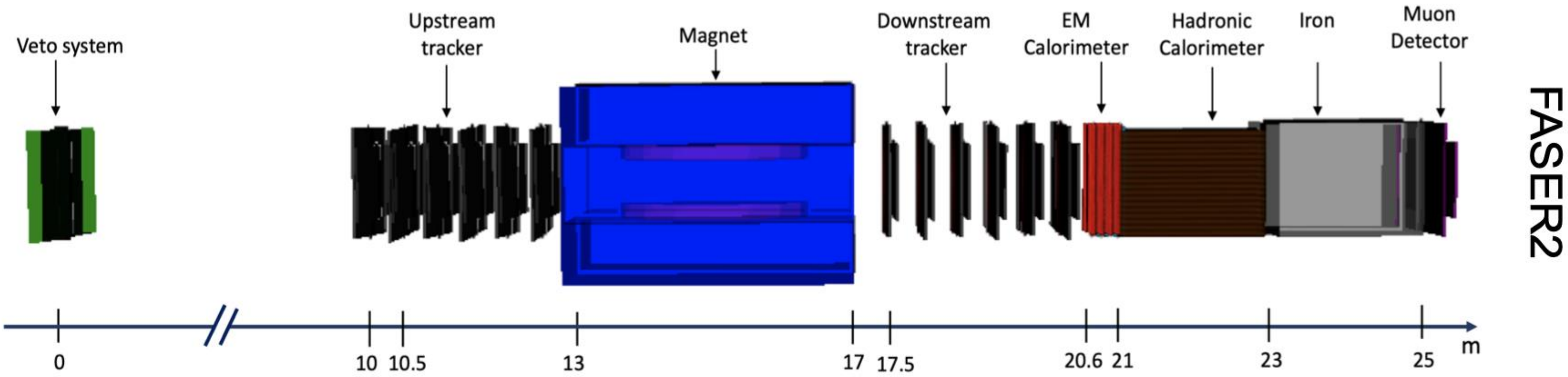


FASER2

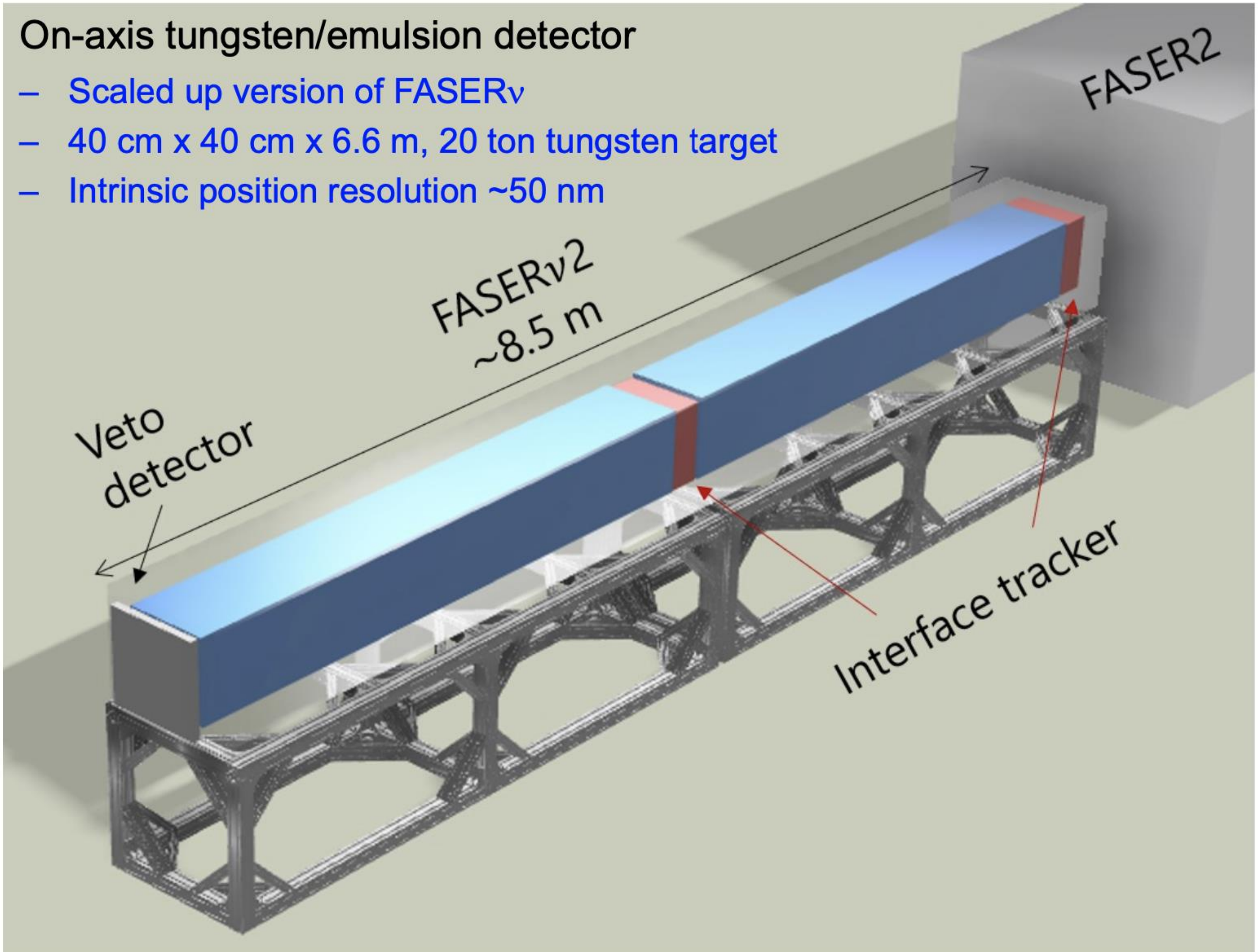
- On-axis magnetic spectrometer
  - Superconducting magnet with 4 Tm bending power
  - Trackers based on LHCb's SciFi detector

- FASER → FASER2
  - R = 10 cm, L = 1.5 m (V = 0.05 m^3) → 3 m x 1 m x 10 m (V = 30 m^3)
  - Luminosity ~ 30 fb^{-1} → 3 ab^{-1}
  - Sensitivity increases over current bounds by ~60,000 for many models





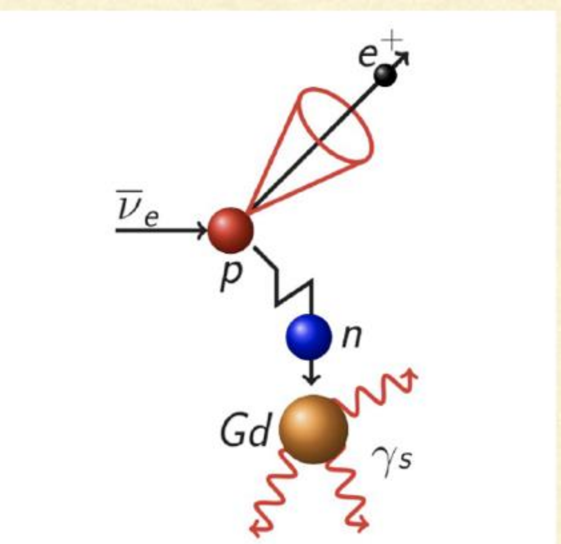
FASERnu



On-axis tungsten/emulsion detector
– Scaled up version of FASERν
– 40 cm x 40 cm x 6.6 m, 20 ton tungsten target
– Intrinsic position resolution ~50 nm
FASER2
FASERν2
~8.5 m
Veto
detector
Interface tracker

T2K Future

- Gadolinium now added to SK water: not yet used in analysis but neutron signal seen
- Significant enhancement in neutron capture: anti-neutrino events tagging
- Also the T2K neutrino beamline upgrade on-going



8 MeV γ cascade

Accumulate more data in the next years

- Reduce systematics uncertainties
- Replica of the beam target has been put proton beam of NA61 this summer
- Reach 3σ for non-CPV rejection prior to Hyper-Kamiokande
- T2K+HK atmospheric joint fit

+ upgrade of the ND280 near detector