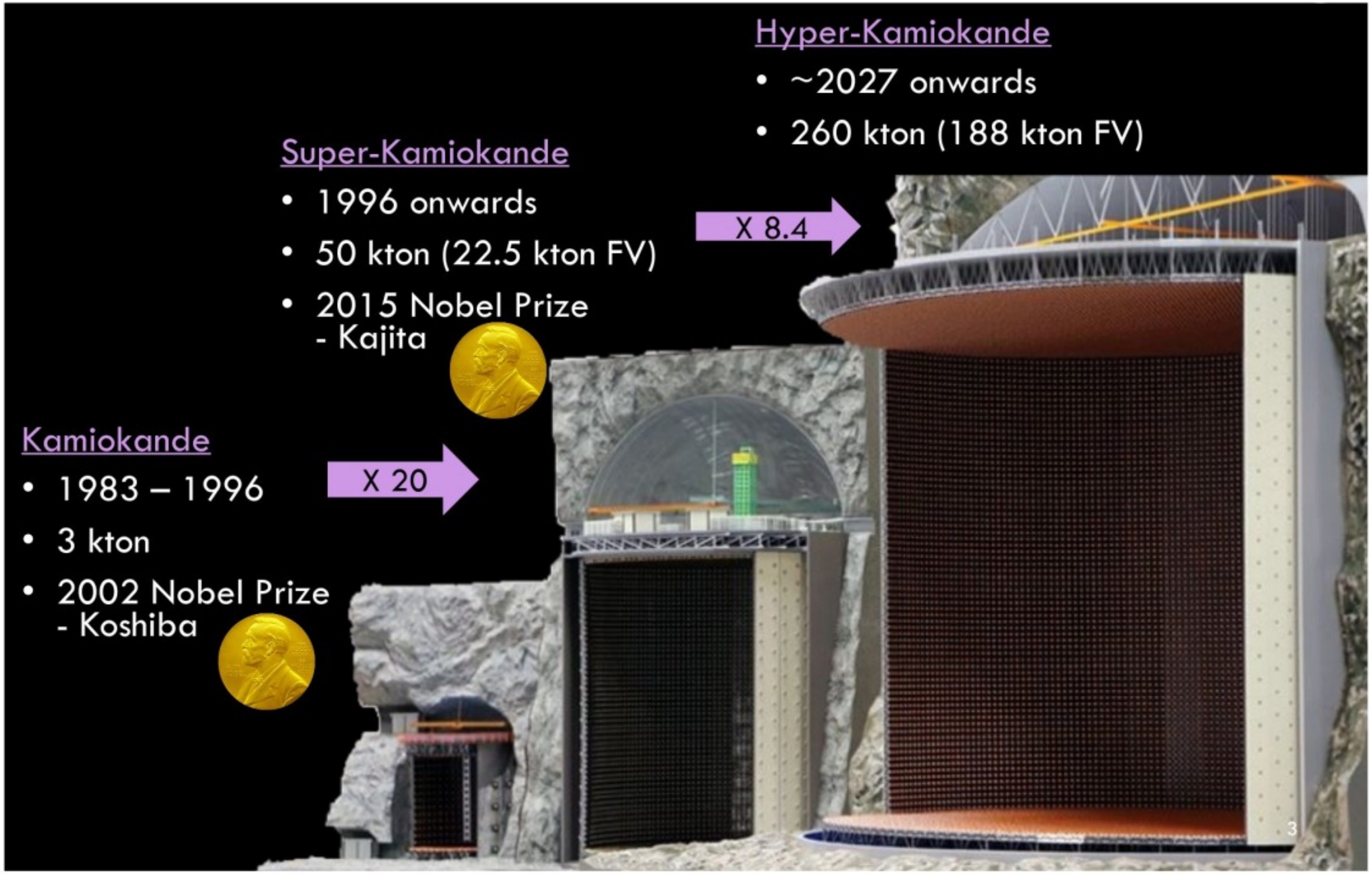
Hyperkamiokande

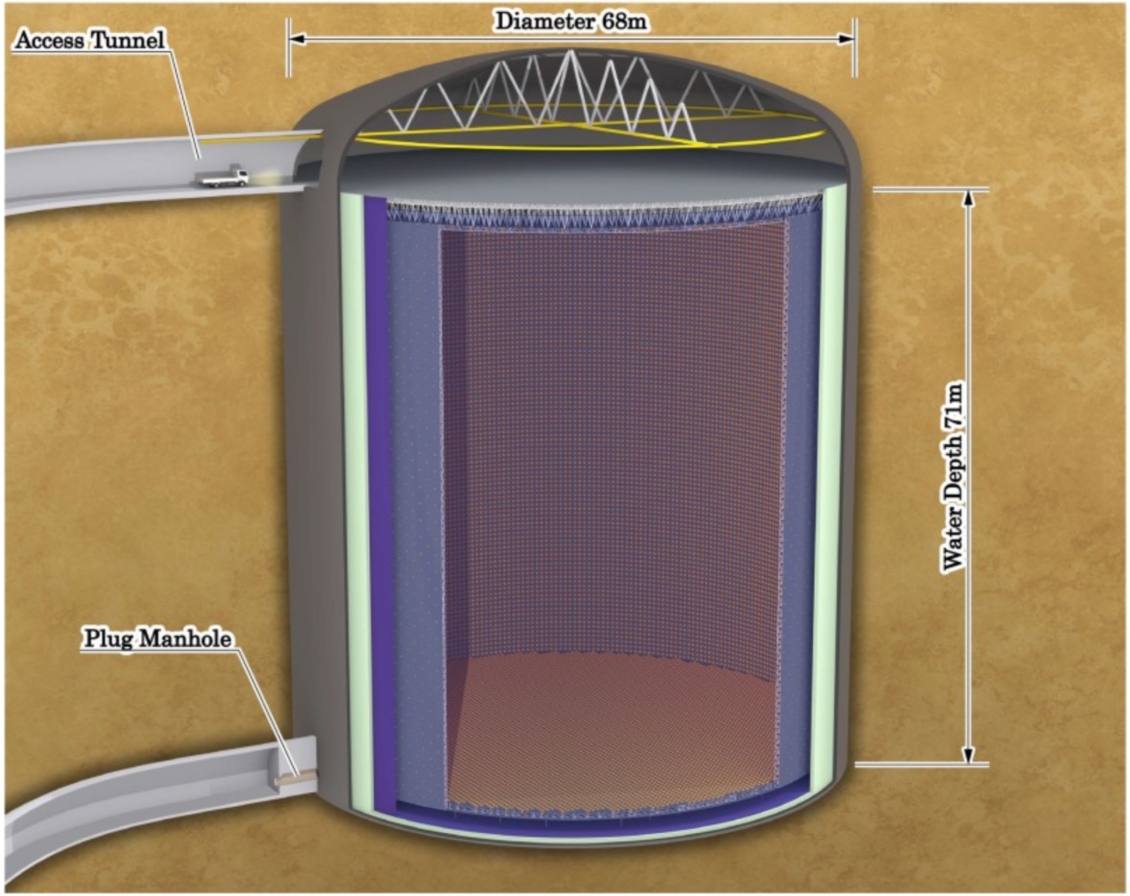
Eugenio Berti

30 September 2024

Introduction



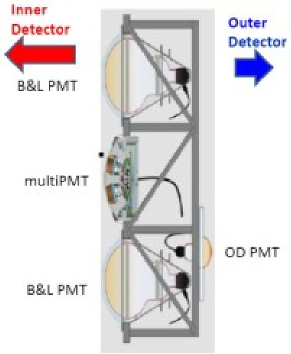
Far detector
Geometry

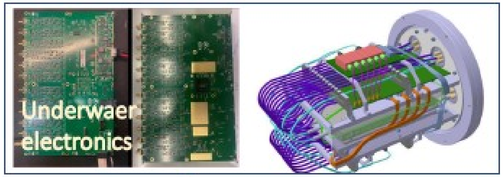


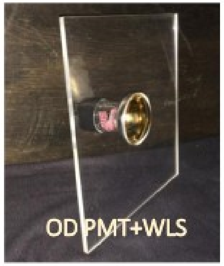
- **Inner Detector (ID)**
  - 64.8m diameter, 65.8m height
  - 40k PMTs, 50 cm, will be installed
  - 800 Multi-PMT modules will be integrated as hybrid configuration
- **Outer Detector (OD)**
  - 1m (barrel) or 2m (top/bottom) thick
  - 3-inch PMT + WLS plate
  - Walls are covered with high reflectivity Tyvek sheets

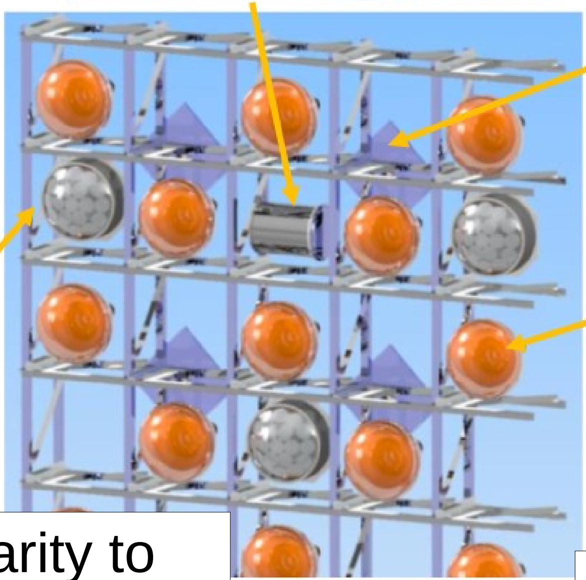
Energy Threshold ~ 5 MeV
Energy Resolution ~3%
Time resolution ~ 1 ns
Vertex Resolution ~10 cm

Far detector
Sensors







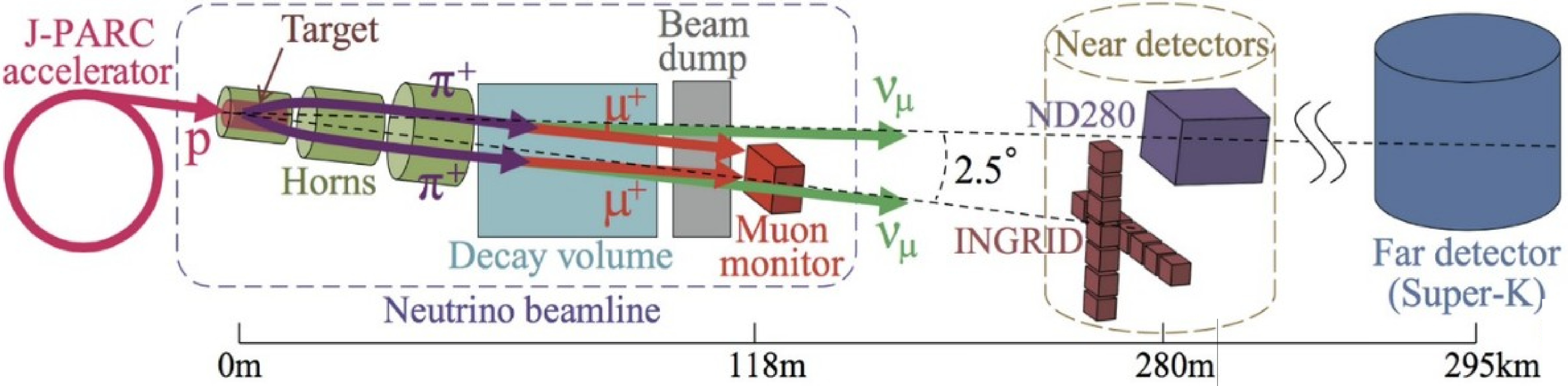


mPMT for increased granularity to improve vertex and angular resolution (especially for *multi-ring* events and at edges of fiducial volume)

PMT with doubled single photoelectron detection efficiency with respect to SK

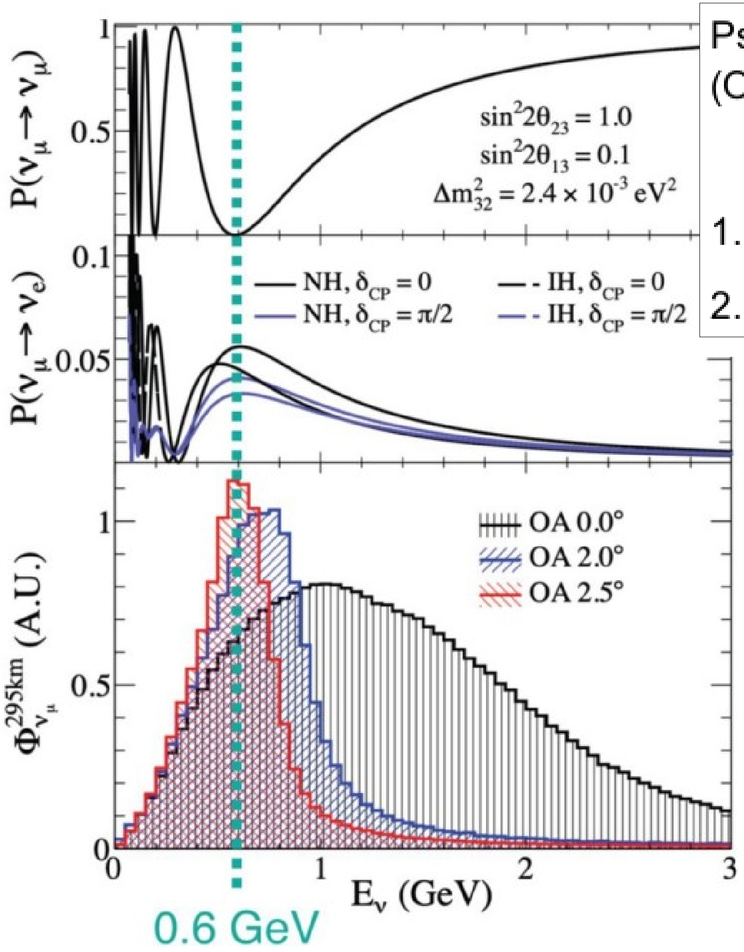
Tokai to Kamioka

Configuration similar to T2K but with improved beam line and near detectors



IWCD
1km

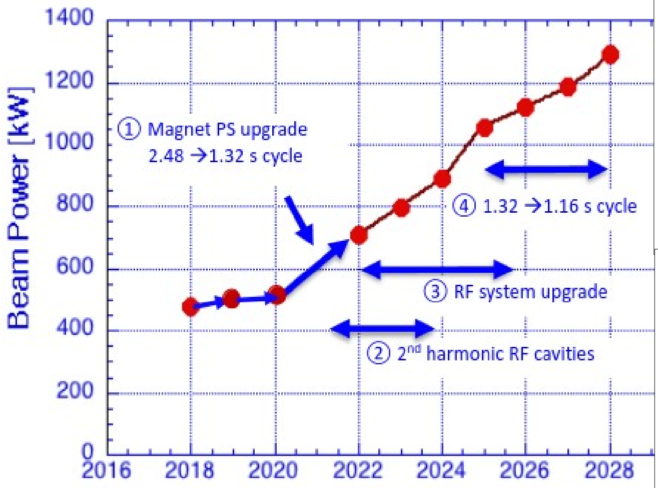
Beam line



Pseudo-monochromatic beam by Off-Axis:
(OA = 2° ~ 2.5°):

$$\text{Off-Axis: } E_\nu = \frac{0.43\, E_\pi}{1+\gamma_\pi^2\theta^2_{dec}}$$

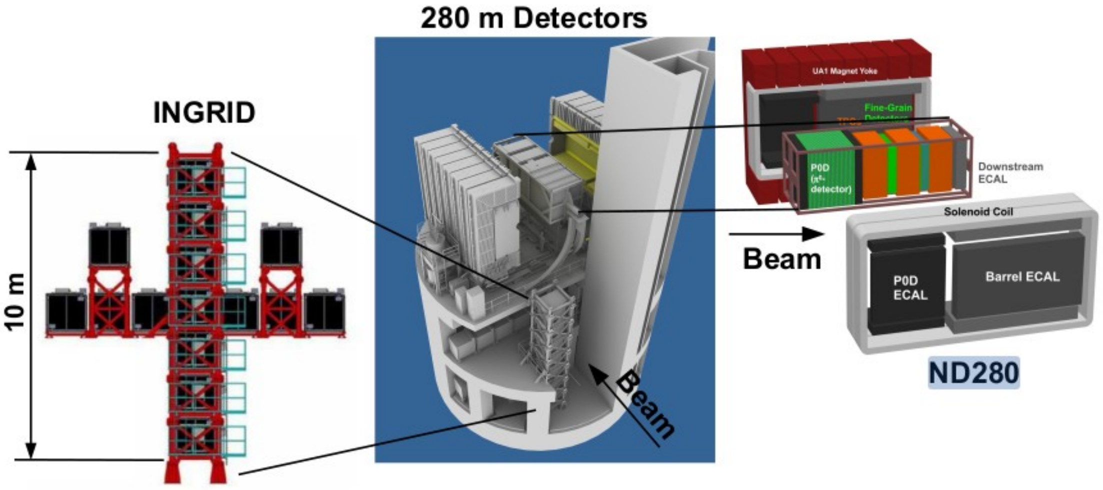
1. Tune peak at oscillation max
2. Minimize high-energy feed down at osc. max



Goal is 1.3 MW
with
330 Tproton/pulse
1.16 s cycle time

The ratio of integrated beam power for ν_μ and $\bar{\nu}_\mu$ mode should be 1:3

Near detectors
at 280 m from target



ND280 (off axis – E_ν~0.6 GeV)
- constraint ν flux
- constraint ν cross section

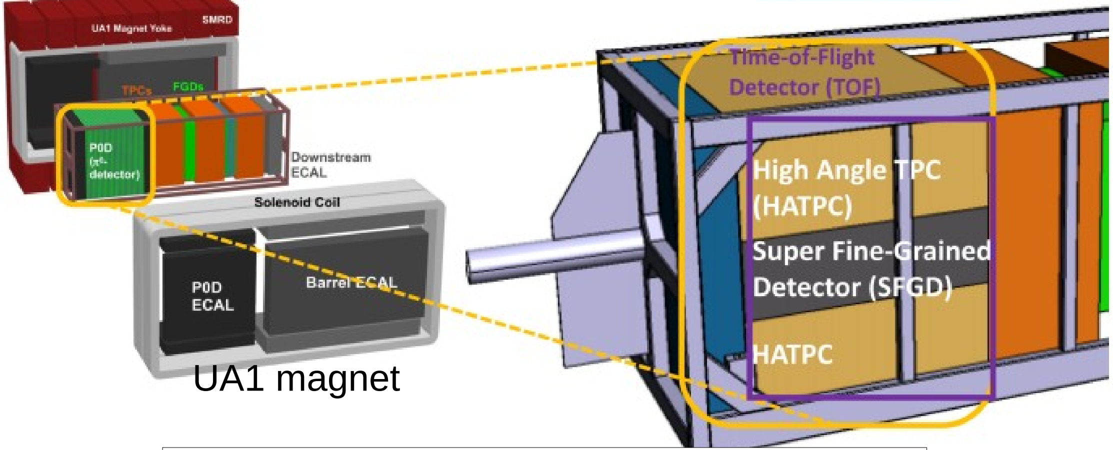
→ Uncertainty on the this part of models reduced to 3% in SK

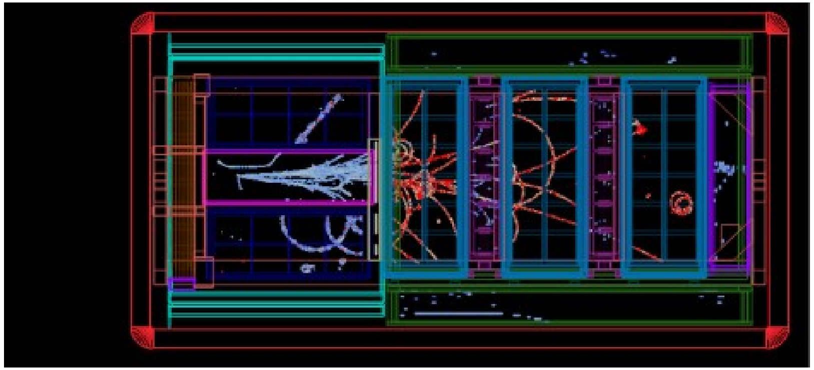
INGRID (on axis - E_ν~2.2 GeV)
- constraint ν beam direction
- monitor ν beam profile

Near detectors are mandatory to study $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ and corresponding $\bar{\nu}$ processes!

ND280 Upgrade

(Technical Design Report on T2K, arXiv:1901.03750)





SFGD → Increase mass for ν interaction and granularity for event reconstruction

HATPC → Increase angular acceptance

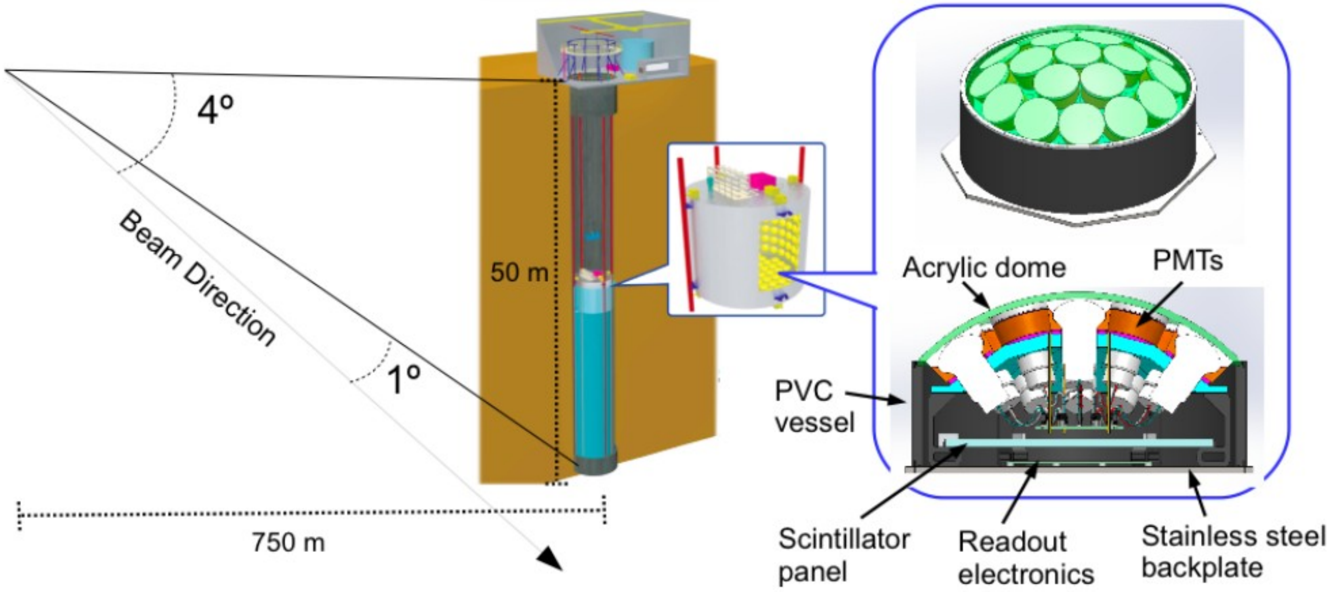
TOF → Improve veto for external tracks

\+

Improved detection efficiency for neutrons

Lower energy threshold for protons

Intermediate detector
at ~1 km from target

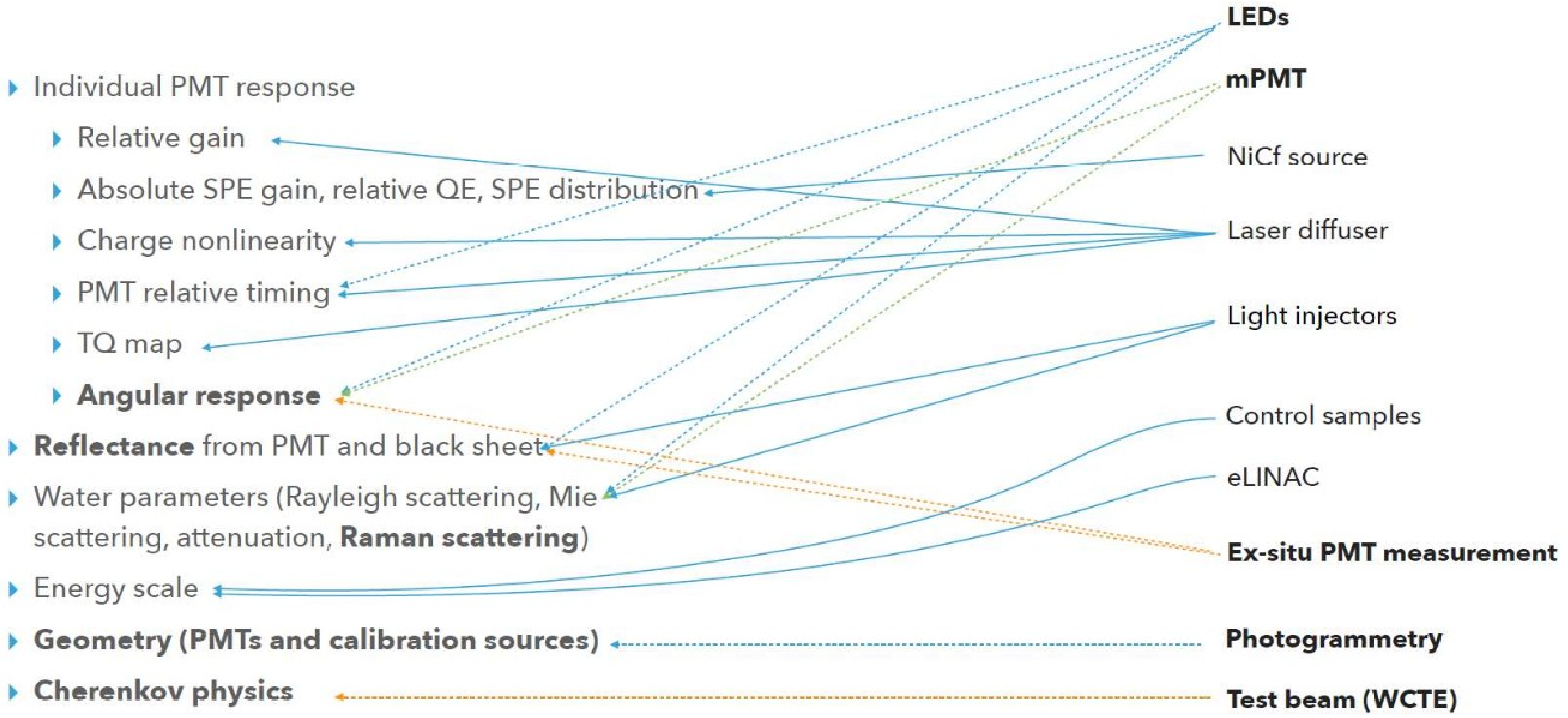


IWCD
- same principle as the far detector
- same solid angle as the far detector

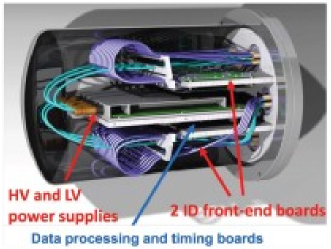
No need of a subtraction analysis!

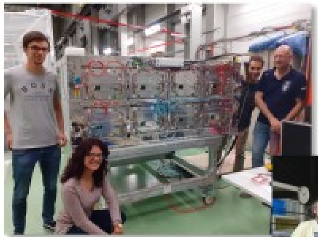
About *the total systematic error in ν_e appearance channel*:
Near detectors in T2K allows for error reduction from 13 to 5%,
HK aims to decrease them to **2%** thanks for ND280 and IWCD.

Detector calibration



INFN Contribution





Multi-PMT

not mPMT for IWCD

300 mPMTs by INFN (**project leader**), 808 mPMTs total. Derived from KM3NeT DOMs.

Electronics

20' PMTs Front-end digitizer, **project leader**, INFN design chosen vs Japan and France.

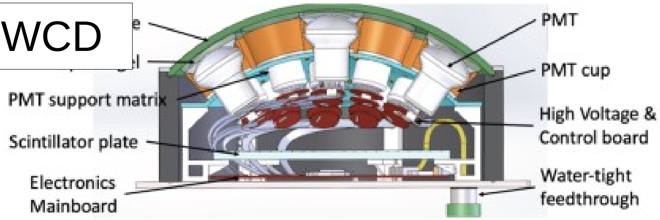
Timing distribution

Computing

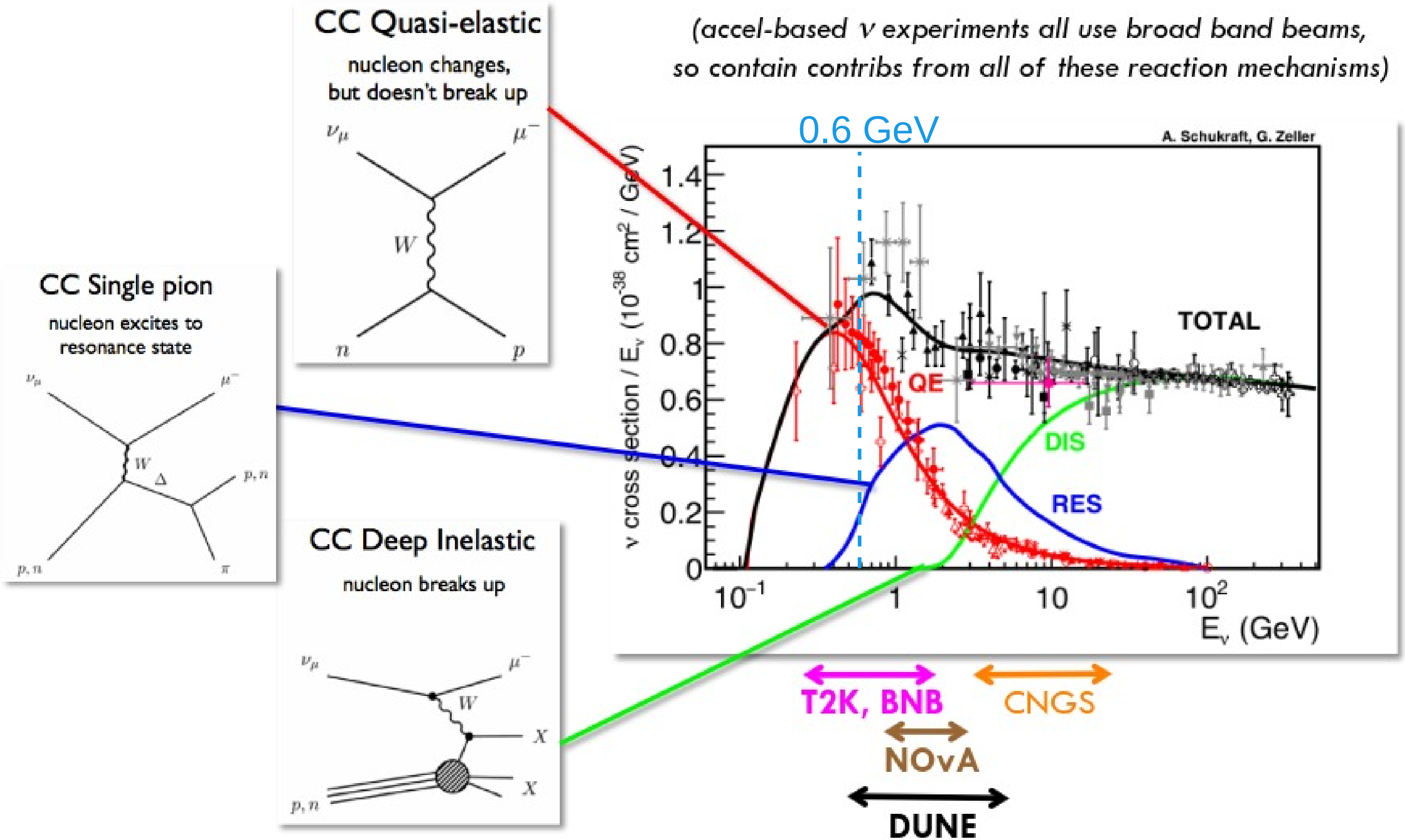
~25% computing power of Hyper-K 2022-26 at CNAF, collaborative tools, analysis tools

High Angle TPCs

Just installed: two new TPCs for the near detector upgrade of T2K (**will be part of the near detector of Hyper-K**)



Interaction processes
High energy



Interaction processes
Low energy

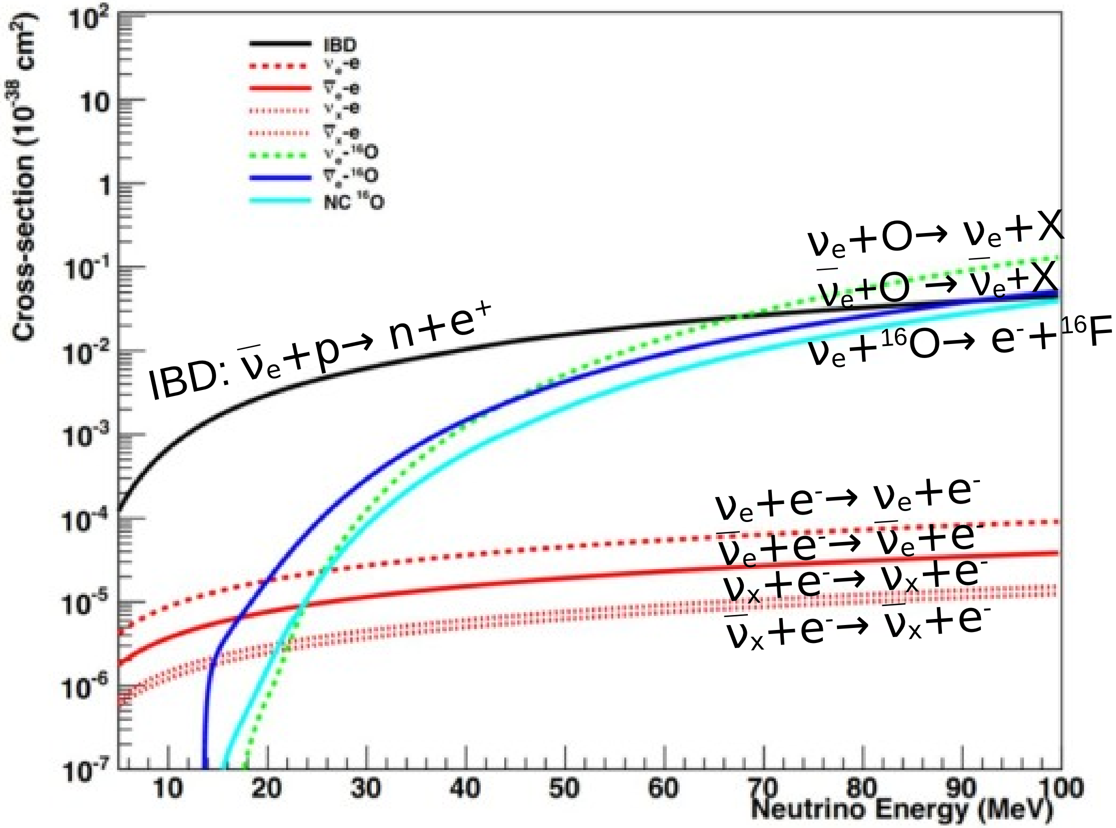
Interaction probability for astrophysical neutrinos

IBD (90%)
- Dominant process
- Non-directional e^+
- Gd loading in water

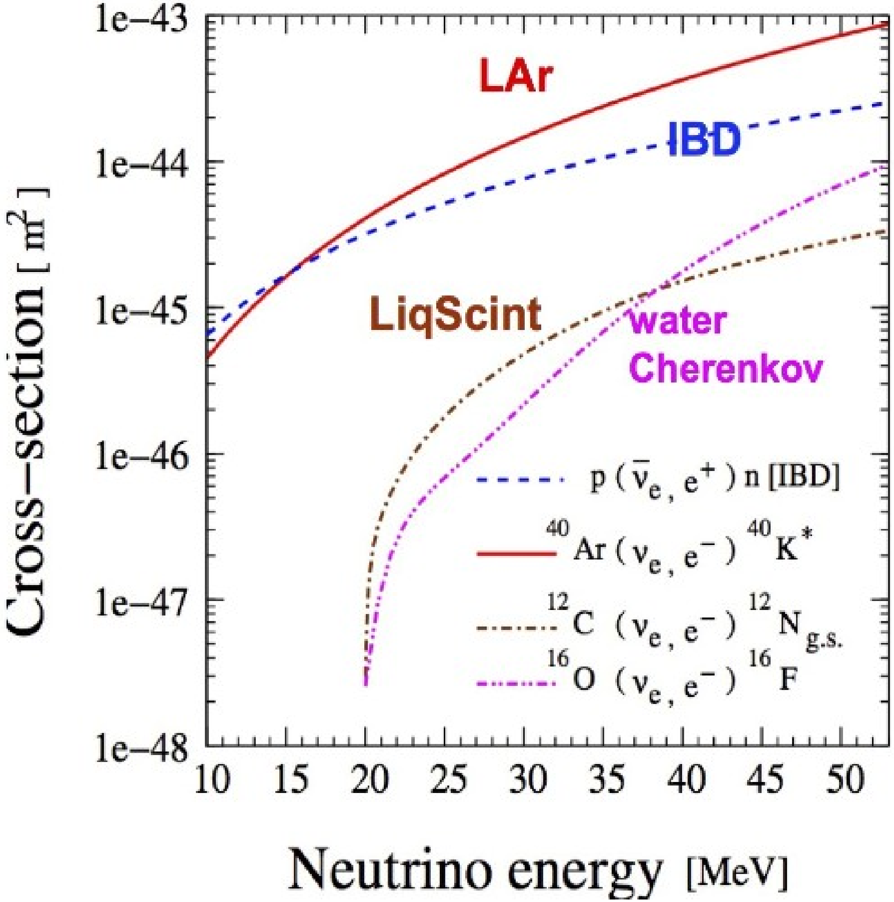
To better distinguish $\bar{\nu}_e$ from ν_e and backgrounds using delayed 8 MeV γ from neutron capture

Important for SRN

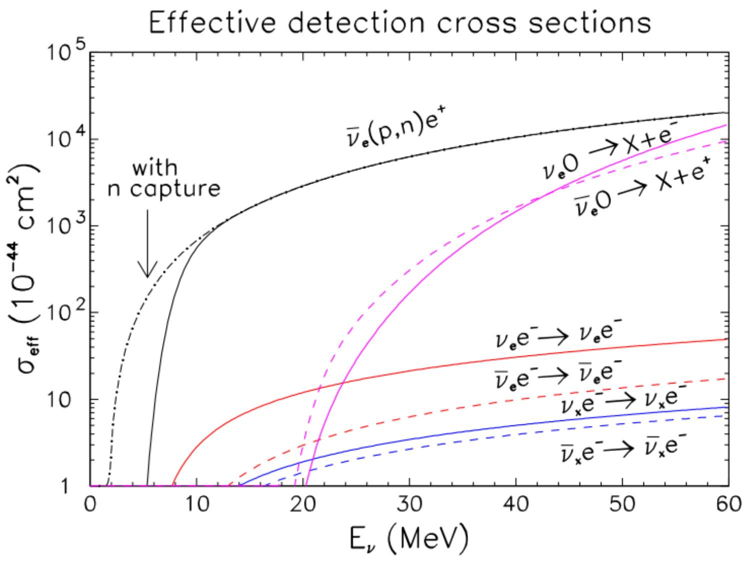
Elastic CC/NC (5%)
- good directionality



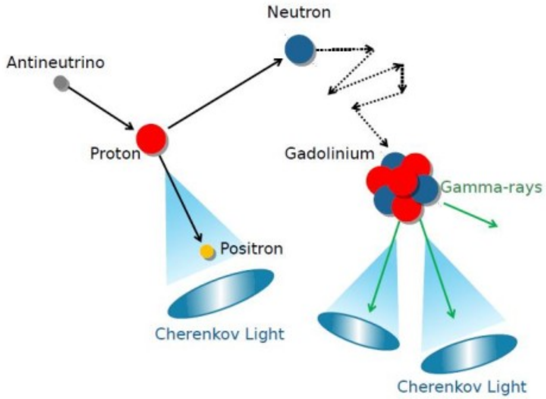
Interaction processes
Medium comparison



Gadolinium loading

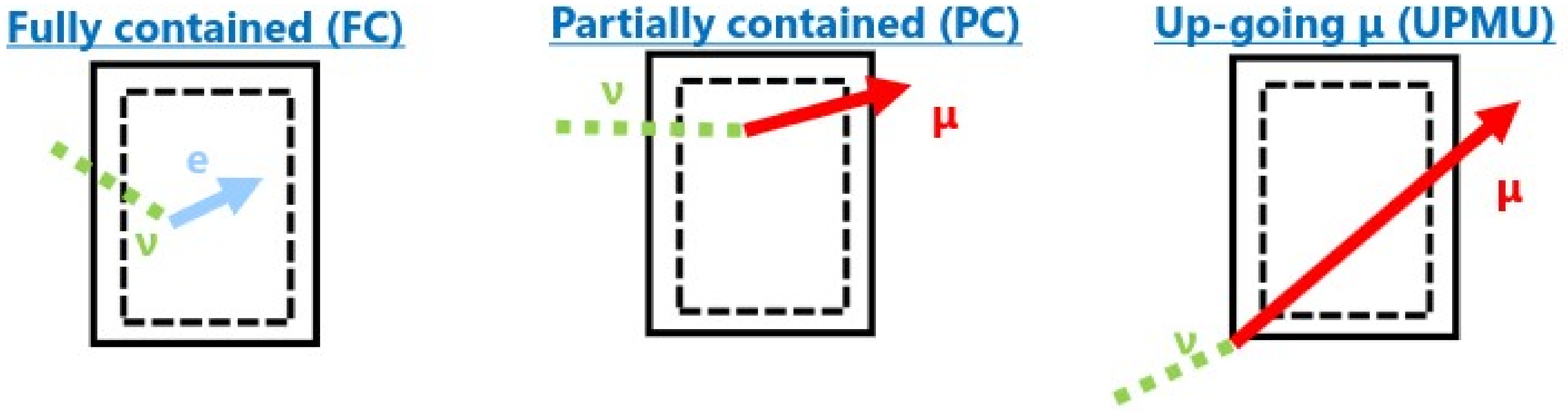


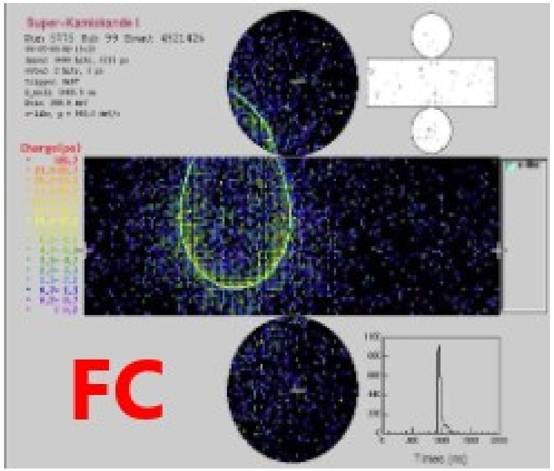
0.1% loading increases neutron capture cross section by 10^5 strongly improving sensitivity at low energy and source pointing resolution

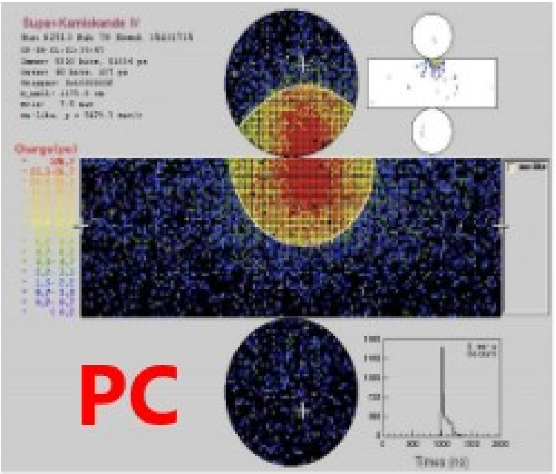


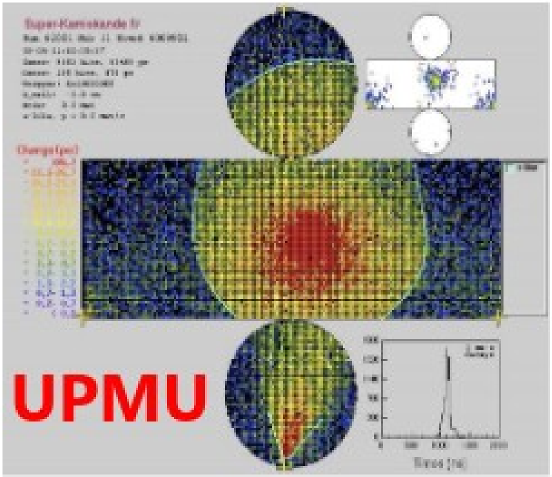
	H_2O	H_2O + 0.1% Gd
Thermal capture cross section (s)	~ 0.3 barns	~49,000 barns
Capture time (t)	~220 μsec	~30 μsec
Energy released	2.2 MeV (single γ)	~8 MeV (γ cascade)

Event categories



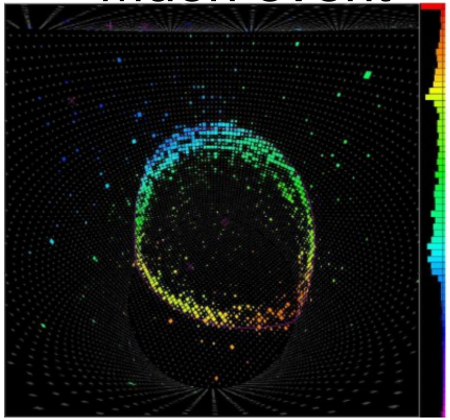




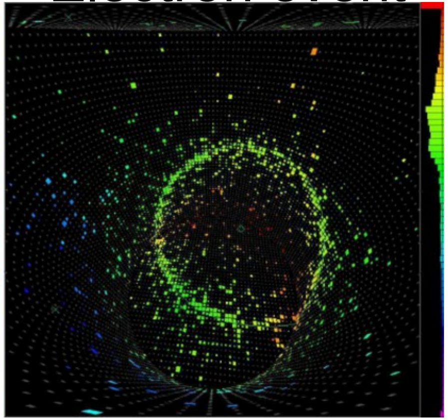


Event identification

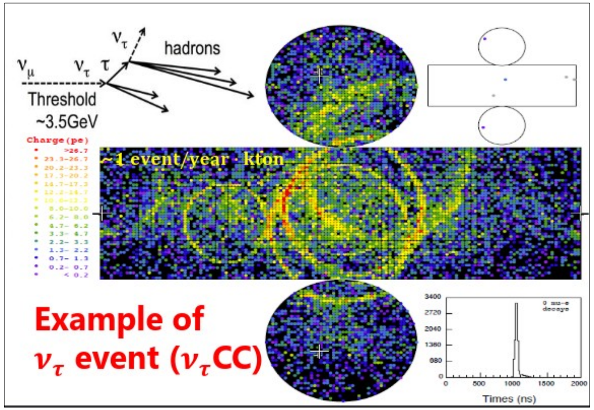
Muon event

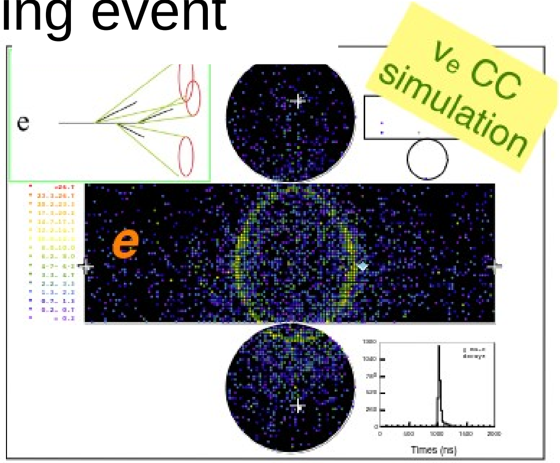


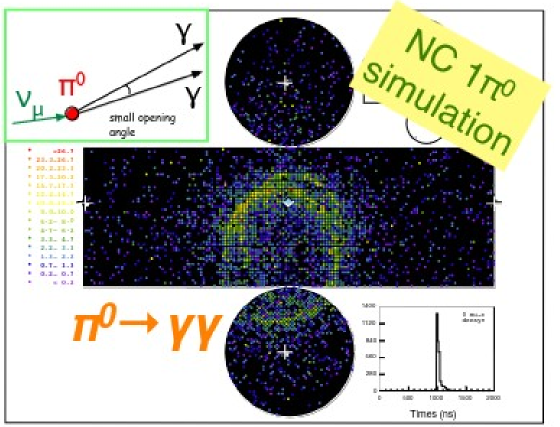
Electron event



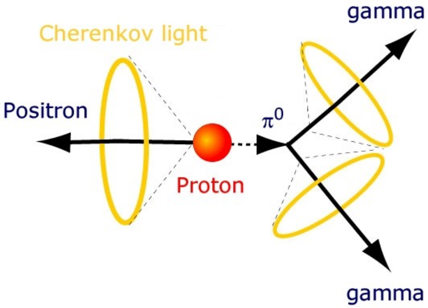
Multi-Ring event







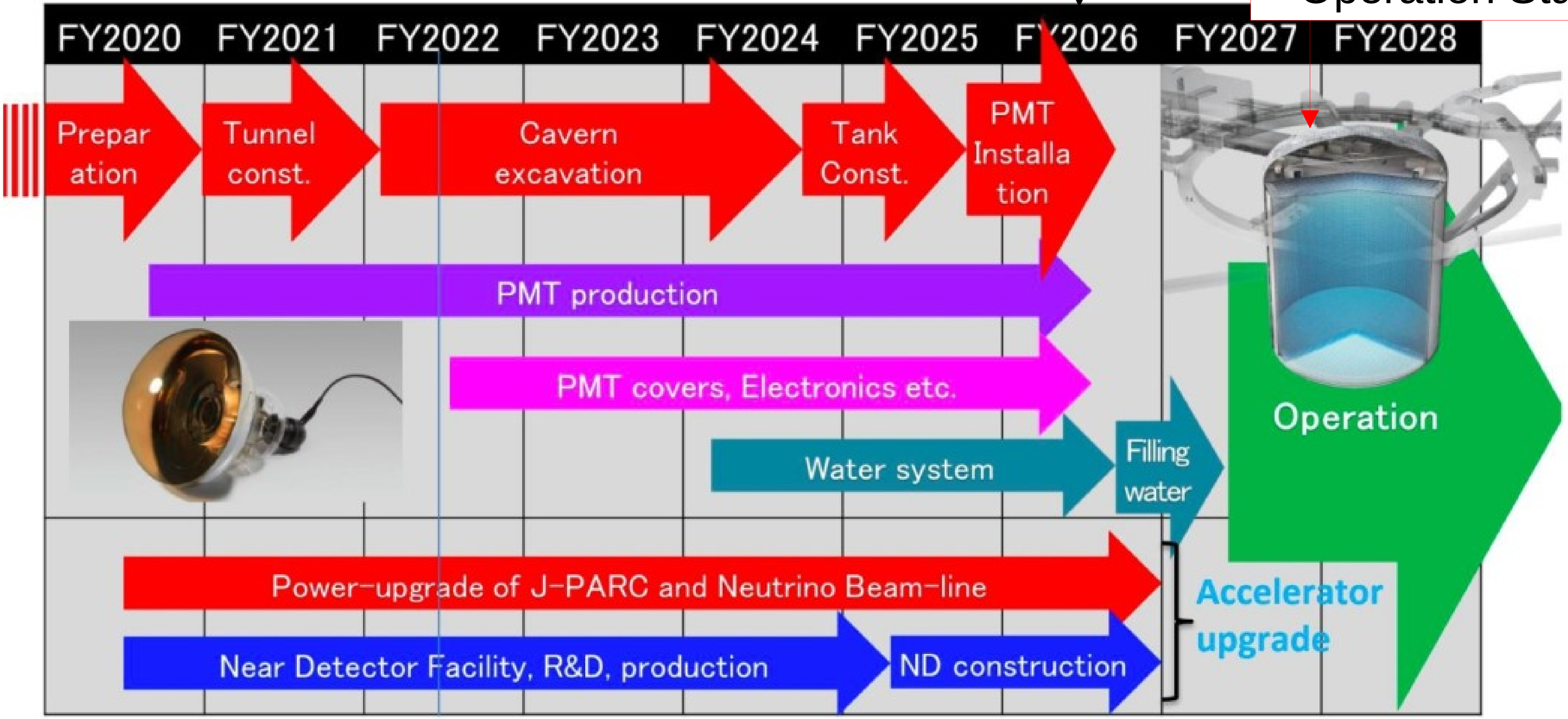
Multi-Ring events covers different processes like ν_τ interaction, π^0 production via Δ resonance, proton decay $p \rightarrow e^+ + \pi^0$,...



Timeline

June 2026
PMT Installation

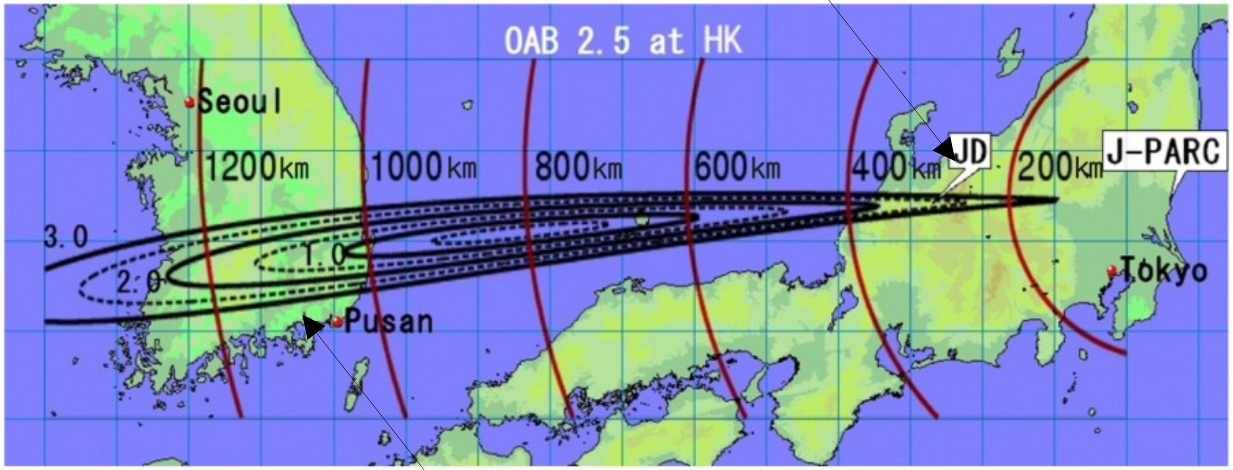
December 2027
Operation Start



Possible developments

NO

Build a second tank identical to the first one in Kamioka (295 km)

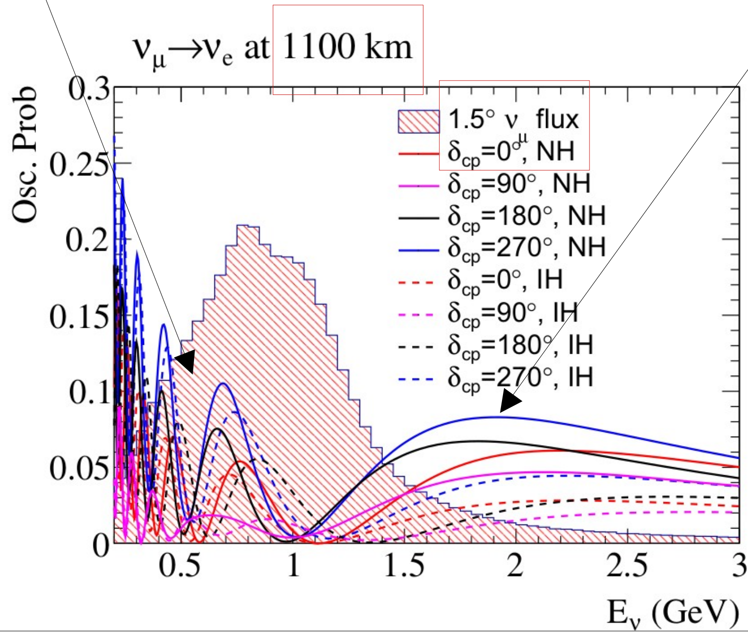


Build a third tank identical to the first one in Korea (1000-1300 km)

MAYBE

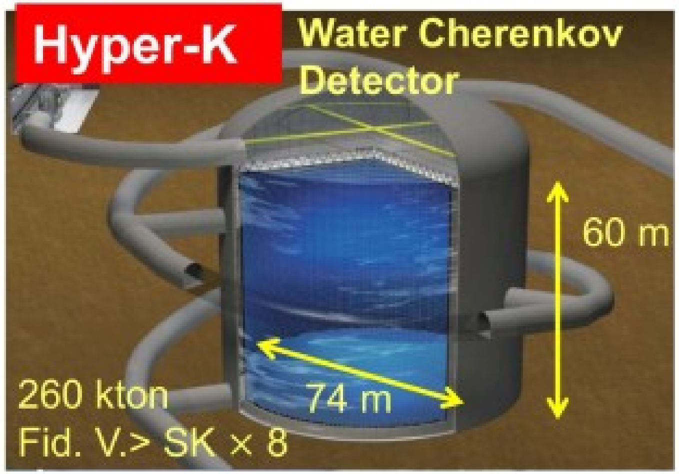
Sensibility to δ_{CP} parameter

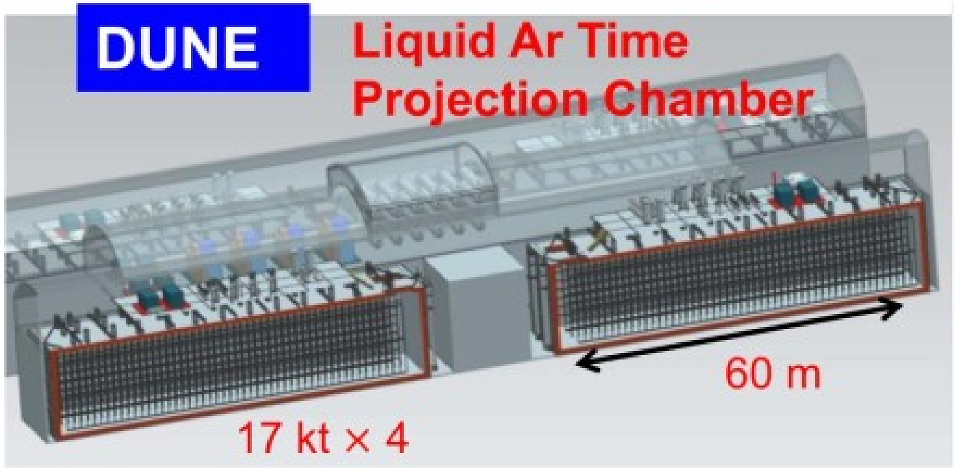
Clear separation hierarchies



The two different baselines help in solving the degeneracy between oscillation parameters/matter effects

HyperKamiokande vs DUNE

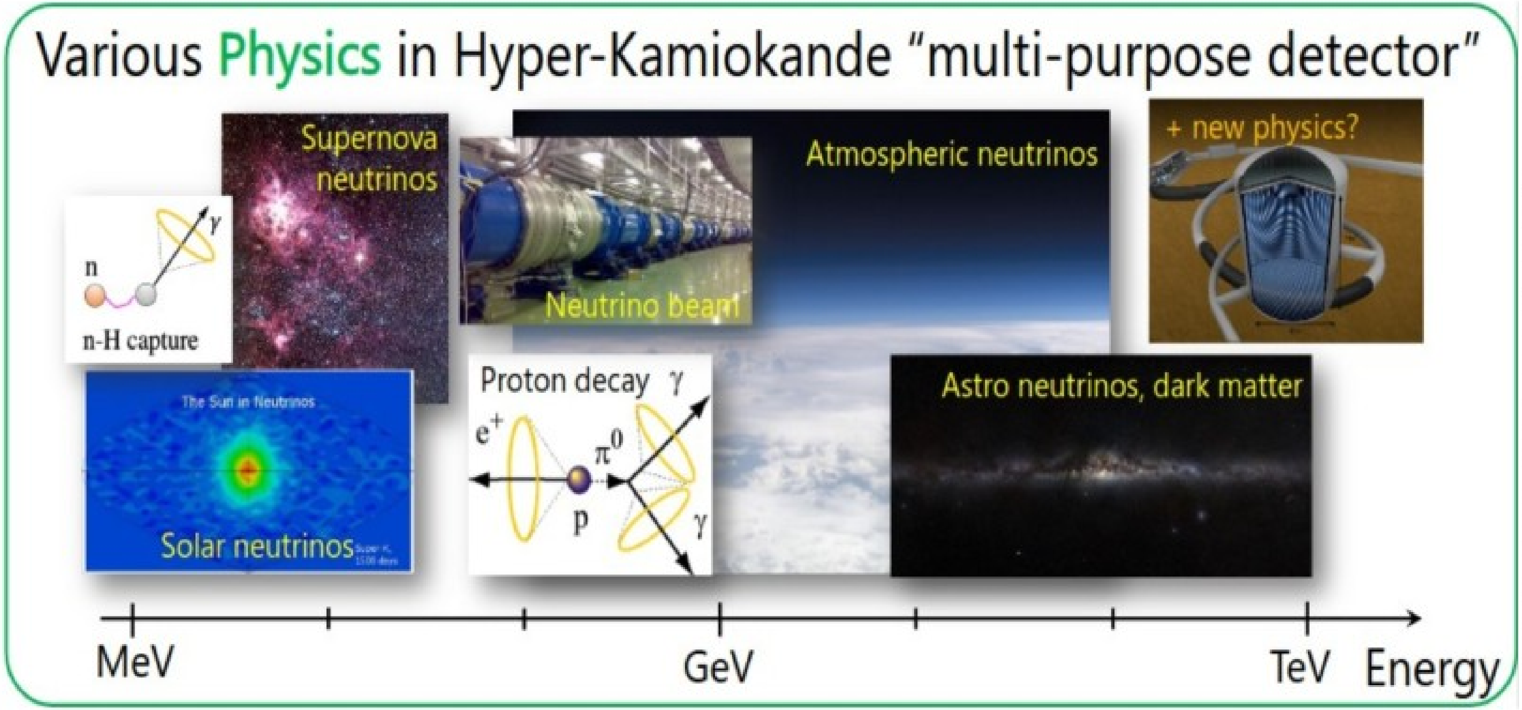


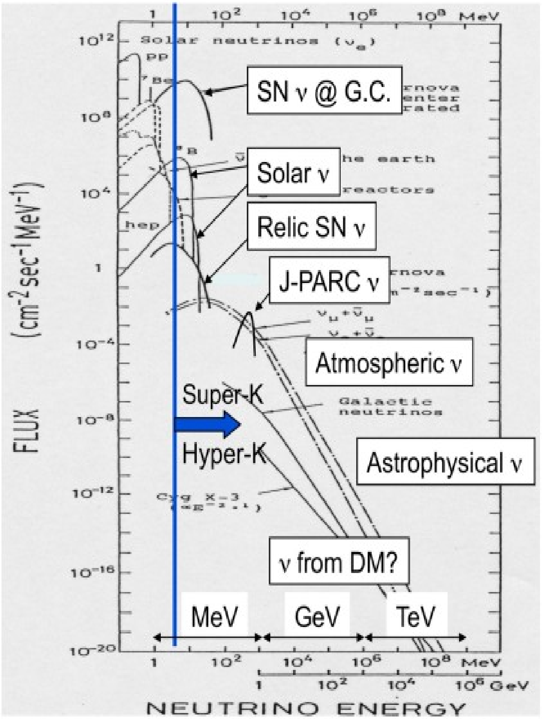


Multi-purpose experiments, similar goals, a different, complementary approach:

- Baselines and energy ranges: narrow band beam vs wide band beam
- Detector masses: fiducial 190 kton vs 20 (40) kton
- Detection process: at 10 MeV mainly IBD (antinue) vs CC (nue)
- Detector technology: water Cherenkov vs liquid Argon TPC

Physics motivation





Short Reference

In case of just two neutrino families

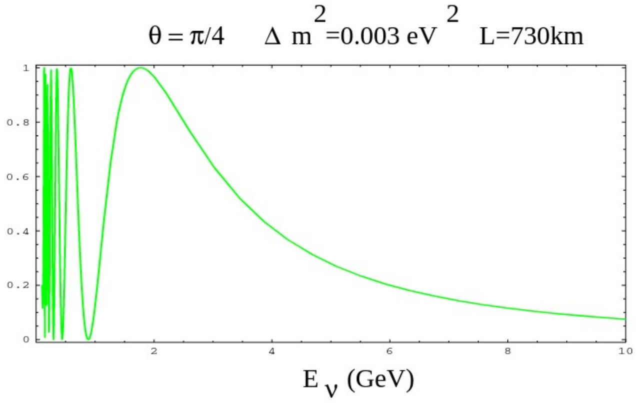
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

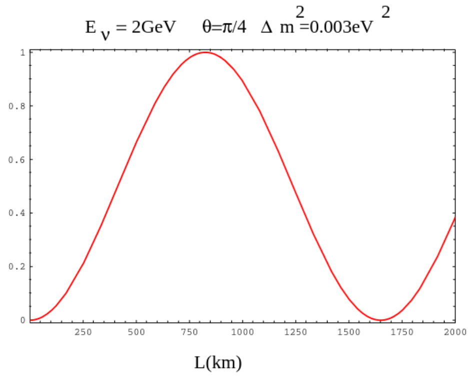
Sensitivity is maximum if baseline is

$$L_{\rm osc}\ ({\rm km}) = 2\pi \frac{E_\nu({\rm GeV})}{1.27\Delta m^2({\rm eV}^2)}$$

Solar ~ 1MeV/100km
Atmospheric ~ 1GeV/100km (10MeV/1km)

Experimental parameters:
- 2 mass^2 differences
- 3 mixing angle terms
- 1 CP violation phase





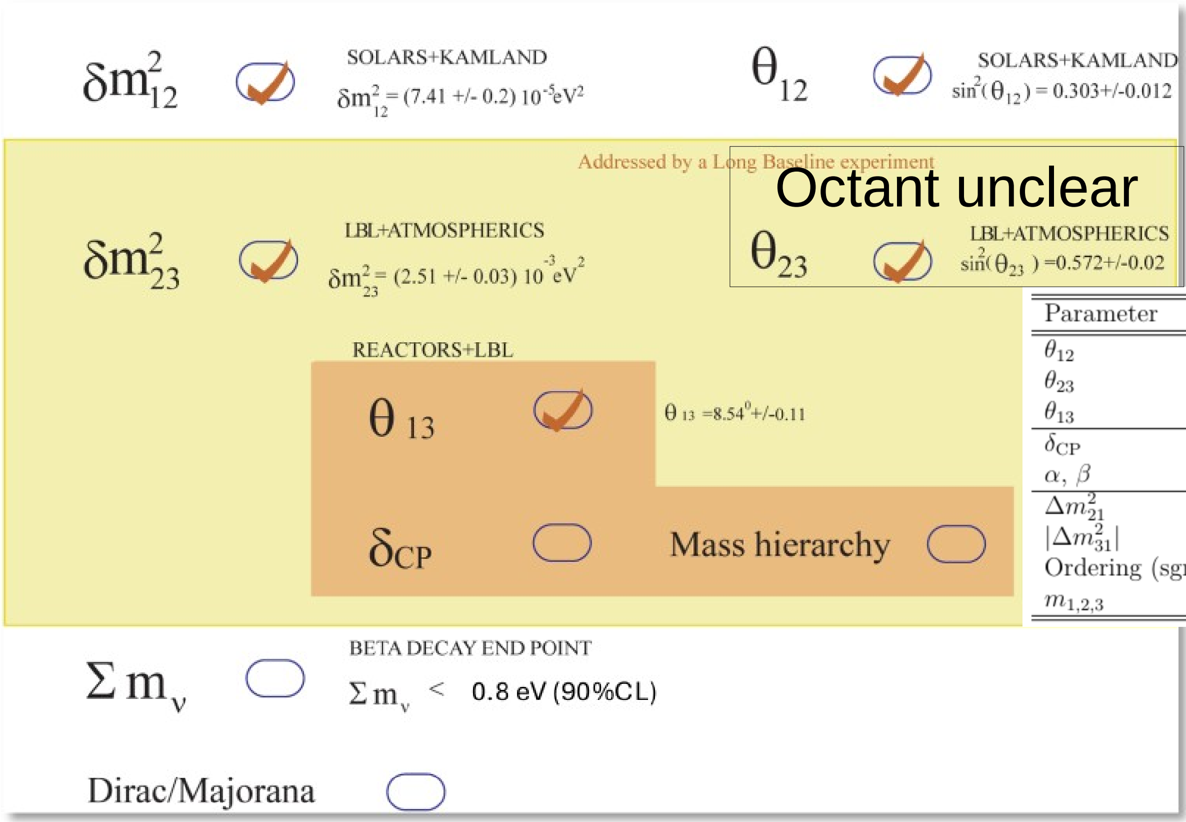
In the real case (three neutrino families)

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Mixing is governed by PMNS matrix

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & c_{23}c_{13} \end{bmatrix}$$

Standard model



Parameter	Main method(s)	Source(s)	Status
θ_{12}	Oscillations	solar, reactor	known
θ_{23}	Oscillations	atmospheric, accelerator	known
θ_{13}	Oscillations	reactor, accelerator	known
δ_{CP}	Oscillations	accelerator	hints
α, β	Rare processes	double beta decay	unknown
Δm^2_{21}	Oscillations	reactor, solar	known
$\lvert\Delta m^2_{31}\rvert$	Oscillations	reactor, accelerator, atmospheric	known
Ordering (sgn Δm^2_{31})	Oscillations	reactor, accelerator, atmospheric	hints
$m_{1,2,3}$	Kinematics	β decay, cosmology	limits

Goals

Beam neutrinos

ν_e and $\bar{\nu}_e$ appearance → $\boldsymbol{\delta_{CP}}$ and θ_{13}
ν_μ disappearance → θ_{23} and $|\Delta m^2_{23}|$

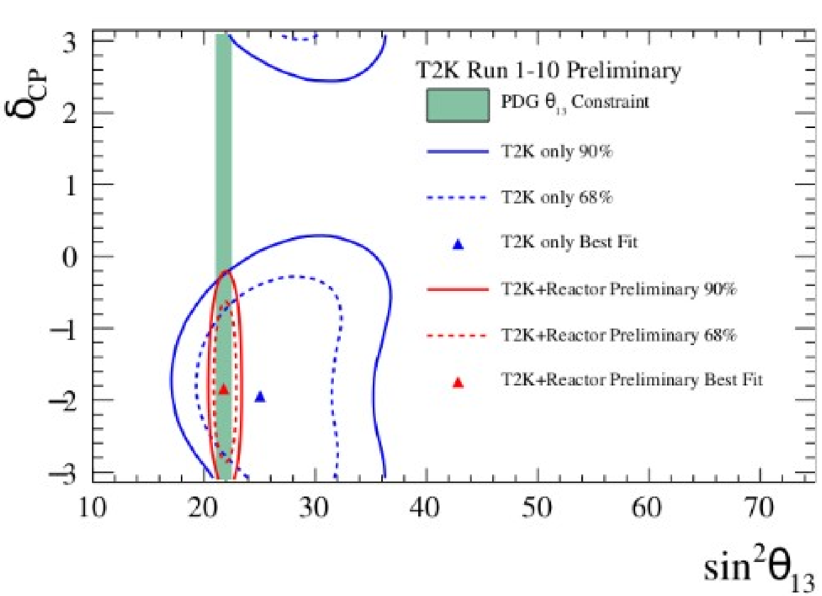
Atmospheric neutrinos

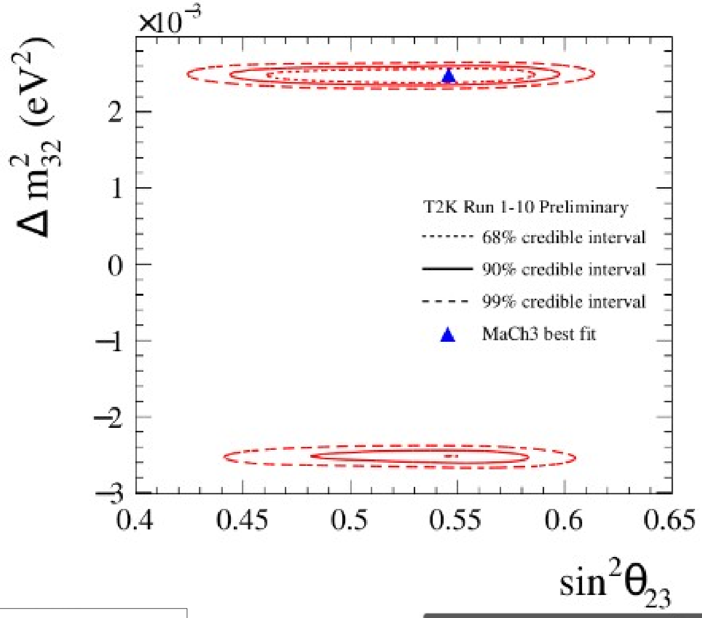
ν_e and $\bar{\nu}_e$ as a function of E and θ_{zenith}
→ sign of $\boldsymbol{\Delta m^2_{23}}$, octant of θ_{23}, δ_{CP}

T2K

"Argomenti di tesi sono lo studio del readout della TPC (Time Projection Chamber) del rivelatore vicino, lo studio della separazione di interazioni di neutrino muonico ed elettronico, lo studio della produzione di pioni neutri in interazioni di corrente neutra di neutrino."

T2K: 2010-2021
T2K-II (with improved beam power and near detector): 2023...2027?





Bayes Factor B(NO/IO) = 3.3
Bayes Factor B(θ_{23}>0.5/θ_{23}<0.5) = 2.6

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

δ_{CP} = 0 and π excluded with 90% CL

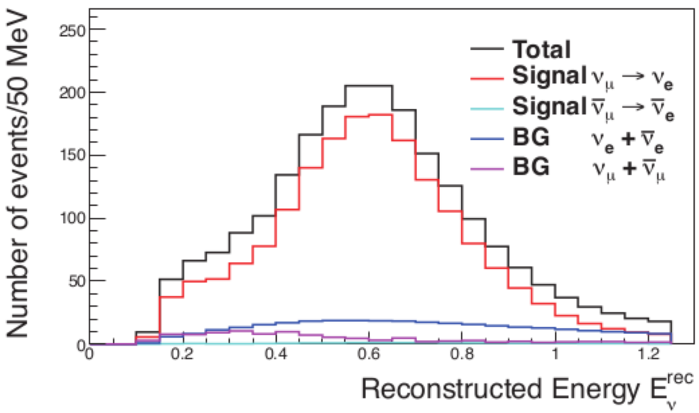
Slight preference of $\sin^2(\theta_{23}) > 0.5$ and $\Delta m^2_{23} > 0$ indicated by bayesian factor

Beam neutrinos
Appearance

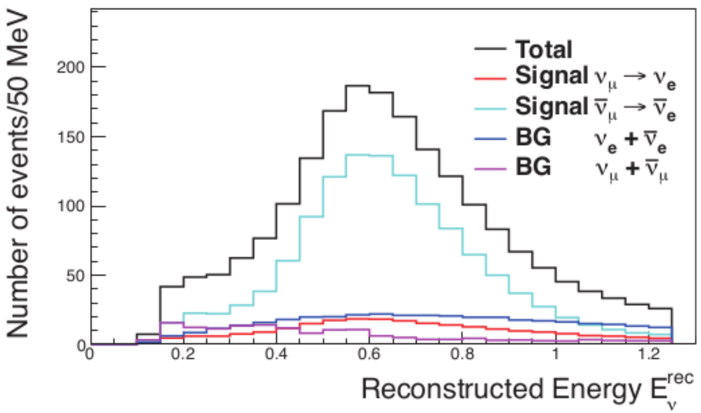
Main backgrounds:
- "wrong flavor" ν_e instead of ν_μ
- "wrong sign" $\bar{\nu}_\mu$ instead of ν_μ
- muon (and 5% kaon) decays

assuming $\delta_{CP}=0$ and $\sin^2(2\theta_{13})=0$

Appearance ν mode



Appearance $\bar{\nu}$ mode



		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	BG Total	
ν mode	Events	1643	15	7	0	248	11	134	400	2058
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\bar{\nu}$ mode	Events	206	1183	2	2	101	216	196	517	1906
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

Dominant background from intrinsic $\nu_e(\bar{\nu}_e)$ in beam

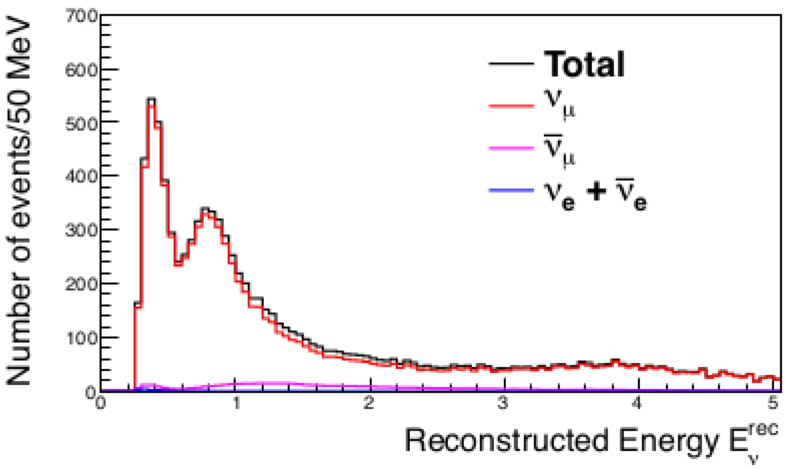
Important **wrong sign** background in $\bar{\nu}_\mu$ beam due to larger ν_e flux (proton beam is positive) and ν_e cross-section

Beam neutrinos
Disappearance

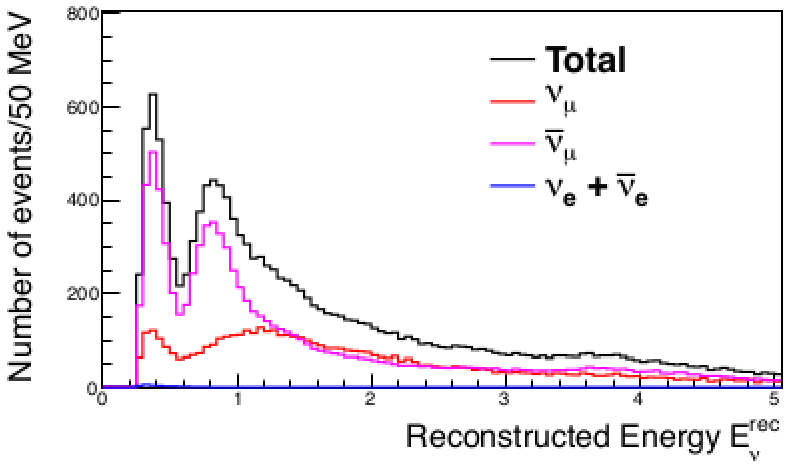
Main backgrounds:
- “wrong flavor” ν_e instead of ν_μ
- “wrong sign” $\bar{\nu}_\mu$ instead of ν_μ
- muon (and 5% kaon) decays

assuming $\delta_{CP}=0$ and $\sin^2(2\theta_{13})=0$

Disappearance ν mode



Disappearance $\bar{\nu}$ mode



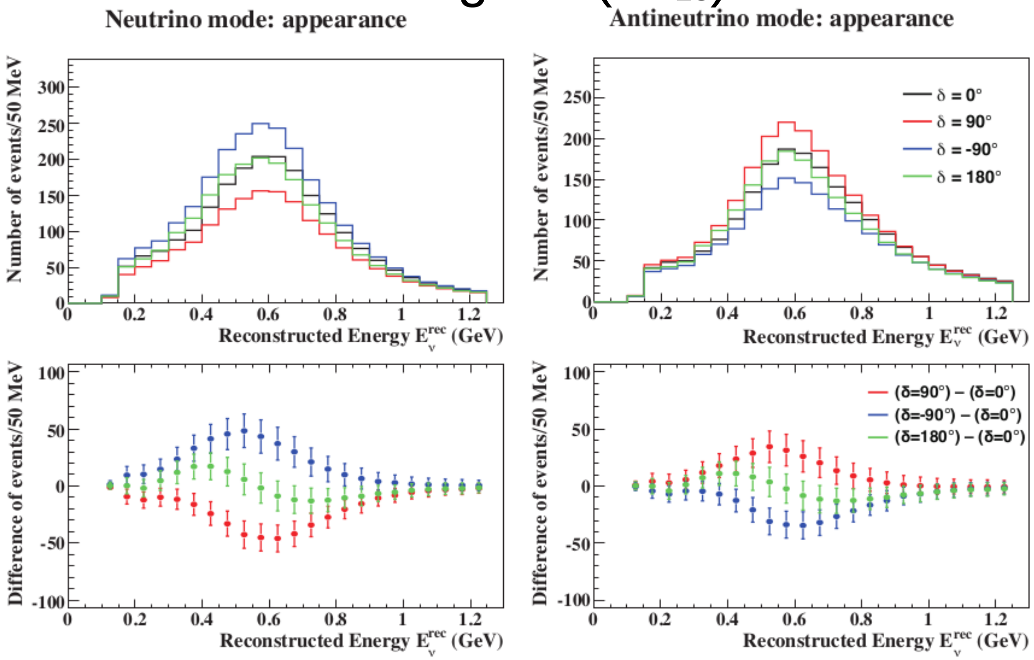
		ν_μCCQE	ν_μCC non-QE	$\bar{\nu}_\mu$CCQE	$\bar{\nu}_\mu$CC non-QE	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu \to \nu_e$	total
ν mode	Events	6043	2981	348	194	6	480	29	10080
	Eff. (%)	91.0	20.7	95.6	53.5	0.5	8.8	1.1	—
$\bar{\nu}$ mode	Events	2699	2354	6099	1961	7	603	4	13726
	Eff. (%)	88.0	20.1	95.4	54.8	0.4	8.8	0.7	—

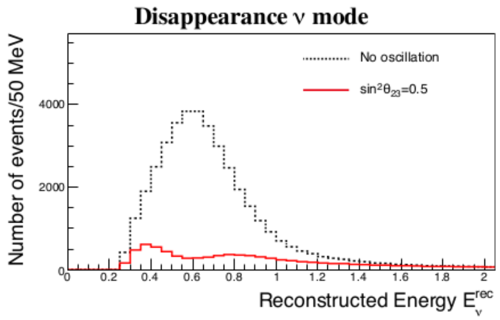
Important **wrong sign** background in $\bar{\nu}_\mu$ beam due to larger ν_e flux (proton beam is positive) and ν_e cross-section

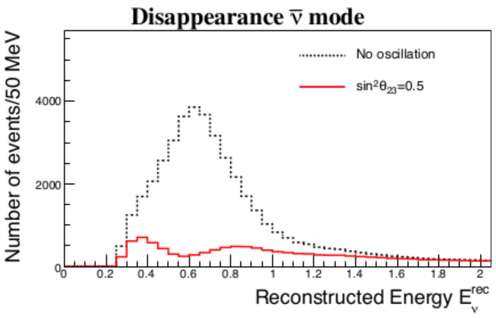
Beam neutrinos
Expectations

Assuming 1 tank for 10 years

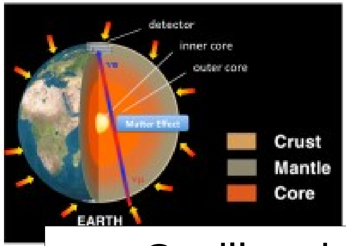
assuming $\sin^2(2\theta_{13})=0$







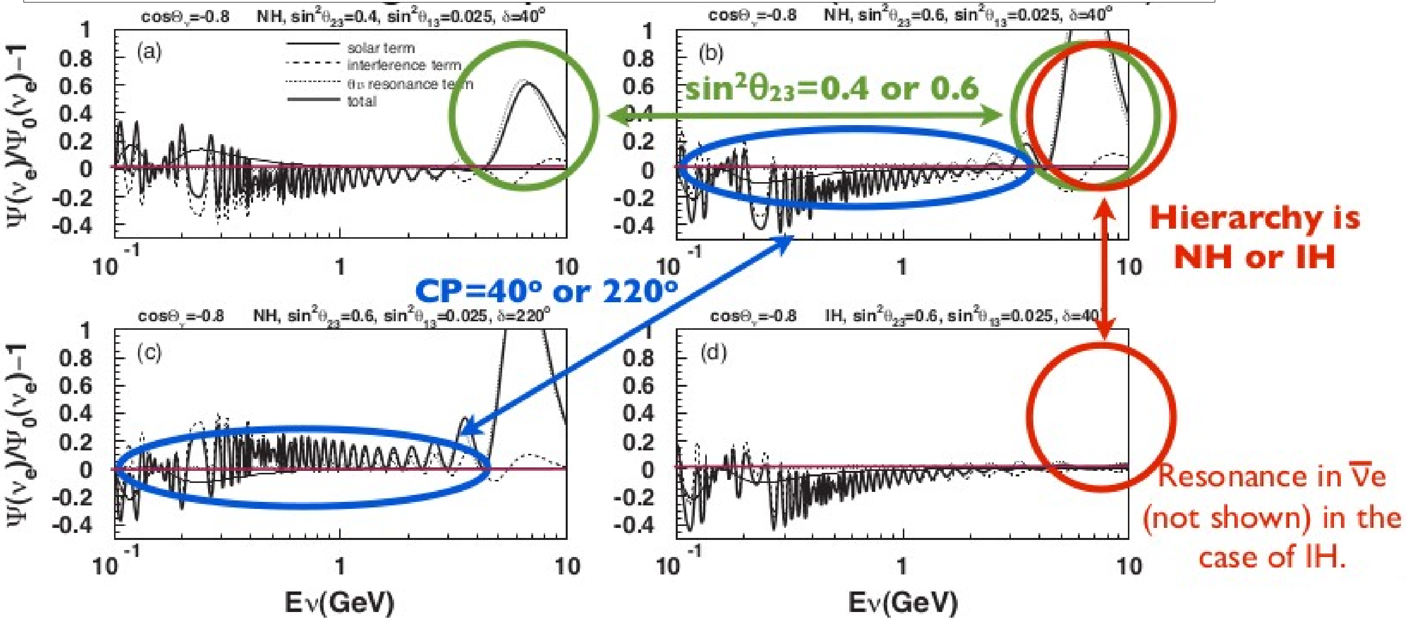
Atmospheric neutrinos
What to look where



Through the matter effect in the Earth, we study on

- Mass hierarchy : resonance in multi-GeV νe or $\overline{\nu}e$
- CP δ : interference btw two Δm^2 driven oscill.
- θ_{23} octant : magnitude of the resonance

Oscillated ν_e flux relative to the non-oscillated flux for upward-going neutrinos with zenith angle $\cos(\theta_{zenith}) = -0.8$



Atmospheric neutrinos

ν_e / $\overline{\nu}_e$ separation – 1 Ring

For CC ν_e:

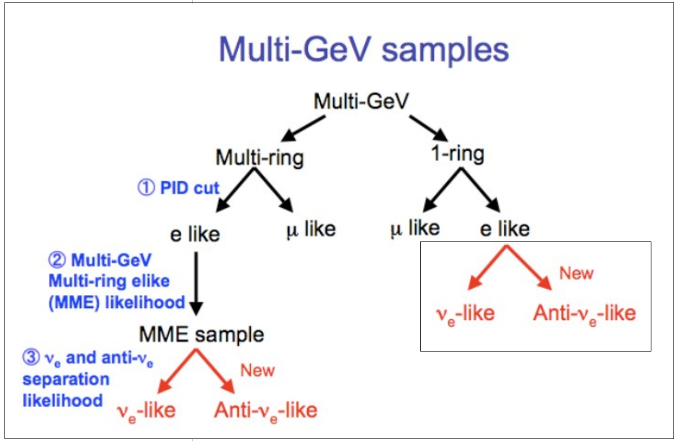
$\nu_e + n \to e^- + N' +$ pions (Total charge for the N' and pion system is +1)

$\nu_e + p \to e^- + N' +$ pions (Total charge for the N' and pion system is +2)

where the pion further decays into

$$\pi^+ \to \quad \mu^+ \quad + \nu + \mu$$
$$\hookrightarrow \quad e^+ + \nu_e + \overline{\nu}_\mu$$

producing decay electrons.



For CC$\overline{\nu}_e$:

$\bar{\nu}_e + p \to e^+ + N' +$ pions (Total charge for the N' and pion system is 0)

$\bar{\nu}_e + n \to e^+ + N' +$ pions (Total charge for the N' and pion system is -1)

where π^- is more likely to be absorbed by water nuclei and hence no decay electrons are emitted. Therefore, by considering the number of decay electrons, multi-GeV single-ring e-like sample is further separated as follows:

Number of decay electrons $> 0 \to \nu_e$-like

Number of decay electrons $= 0 \to \overline{\nu}_e$-like

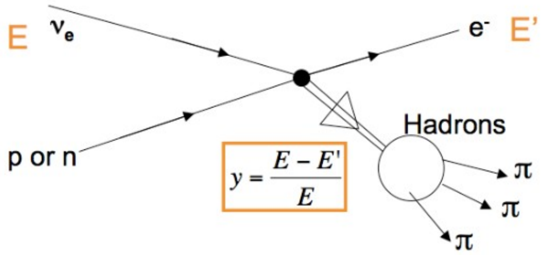
Atmospheric neutrinos
ν_e / $\bar{\nu}_e$ separation – Multi Ring

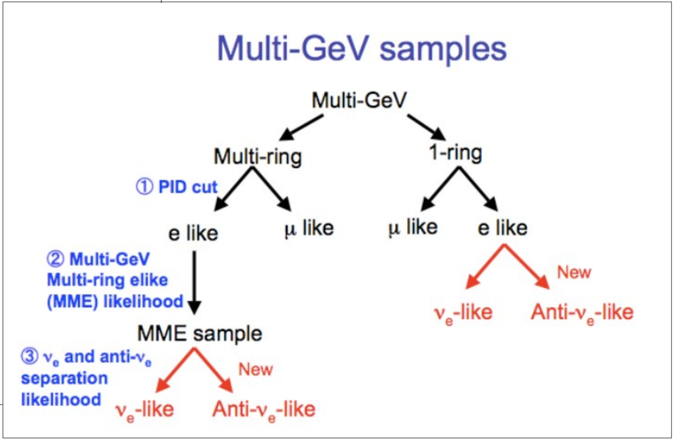
As Feynman y distribution is larger for $CC\nu_e$ than for $CC\overline{\nu}_e$, the outgoing electrons from $CC\nu_e$ interaction with water nuclei tend to have smaller energy. This implies:

- $CC\nu_e$ has smaller momentum fraction for the most energetic ring than $CC\overline{\nu}_e$
- $CC\nu_e$ has more number of rings than $CC\overline{\nu}_e$
- $CC\nu_e$ has larger transverse momentum than $CC\overline{\nu}_e$
- $CC\nu_e$ has more decay electrons than $CC\overline{\nu}_e$

By using the above properties, a likelihood is newly made for the separation into ν_e-like and $\bar{\nu}_e$-like samples. In the ν_e and $\bar{\nu}_e$ separation, the following parameters are used.

1. number of decay electrons
2. number of rings
3. transverse momentum





Atmospheric neutrinos
ν_e / $\bar{\nu}_e$ selection efficiency

$\nu_e + N \rightarrow e^- + X$
$\bar{\nu}_e + N \rightarrow e^+ + X$

Upward ν_e appearance

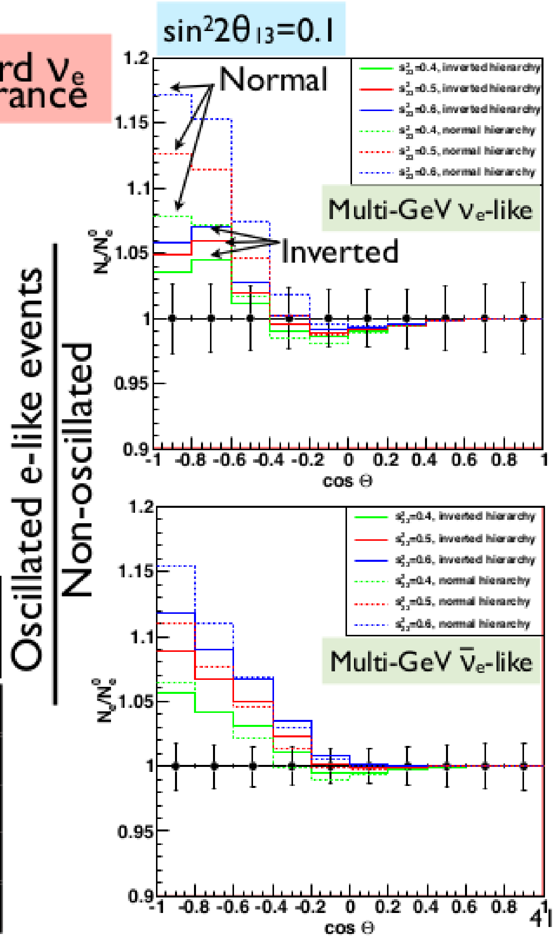
1 Ring
- ν_e CC produce more positive π^+ than ν_e-bar
  - because of negative lepton (e^-)
  - more muon decays

Multi Ring
- More energy transfer to hadronic system
  - more pions and muon decays
  - lower charged lepton energy

Define likelihood to make enhanced samples

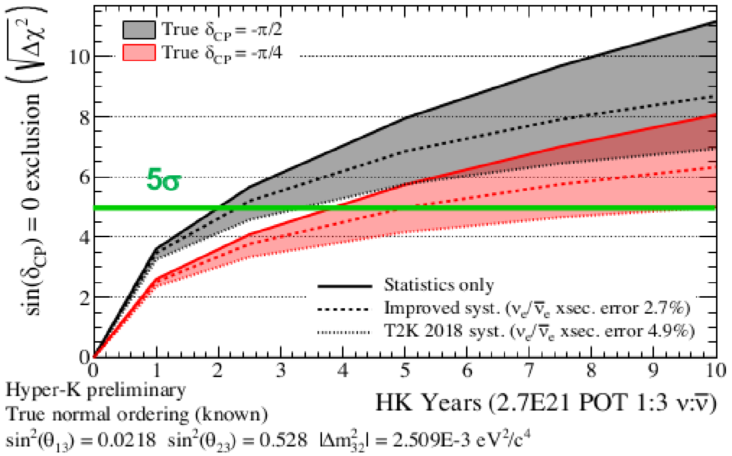
- Multi-GeV (1-ring) νe
- Multi-GeV (1-ring) νe-bar
- Multi-GeV Multi-ring νe
- Multi-GeV Multi-ring νe-bar

	νe CC	anti-νe CC	others	Total
1R νe-like	62%	9%	29%	100%
1R $\bar{\nu}$e-like	55%	37%	8%	100%
MR νe-like	56%	10%	34%	100%
MR $\bar{\nu}$e-like	53%	27%	20%	100%



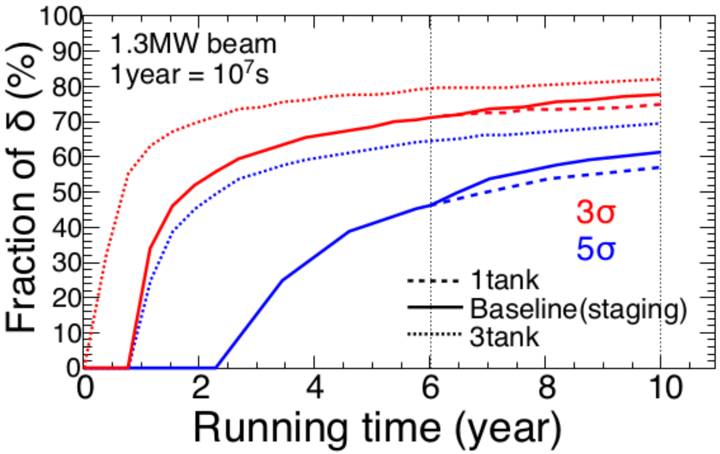
Beam neutrinos
CP violation phase

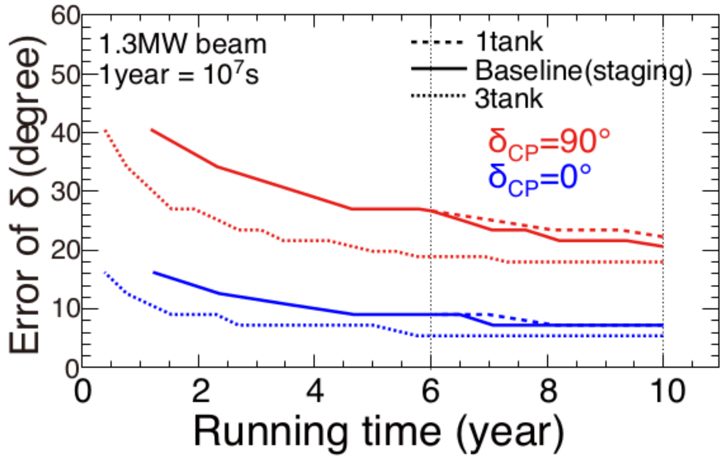
Measure ν_e appearance from ν_μ beam
…and $\bar{\nu}_e$ appearance from $\bar{\nu}_\mu$ beam



If lucky exclude δ_{CP}=0 with 5σ in a few years

In 10 years (and 1 tank), exclude δ_{CP}=0 with 5σ for 58% of possible vales of δ_{CP}

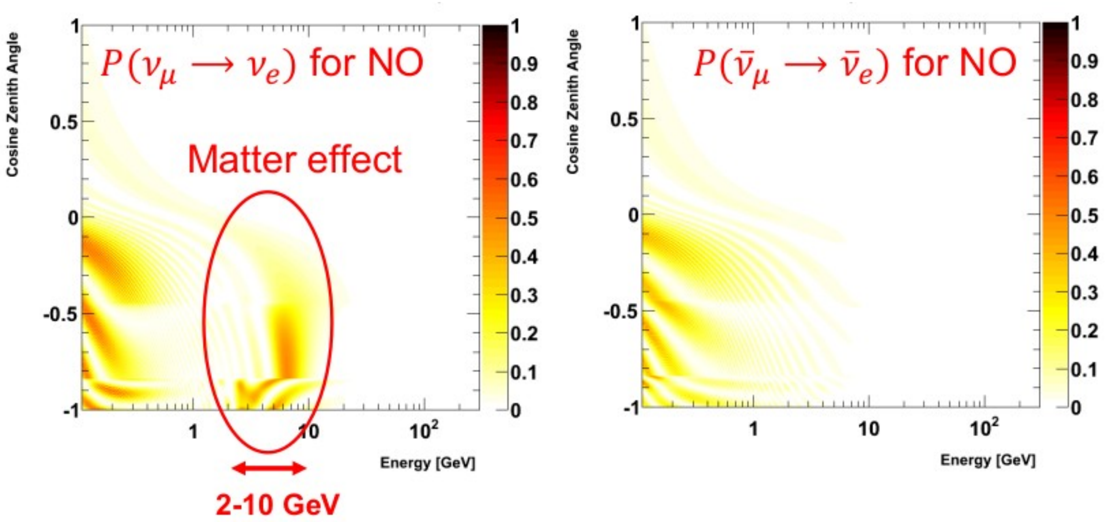




Atmospheric neutrinos

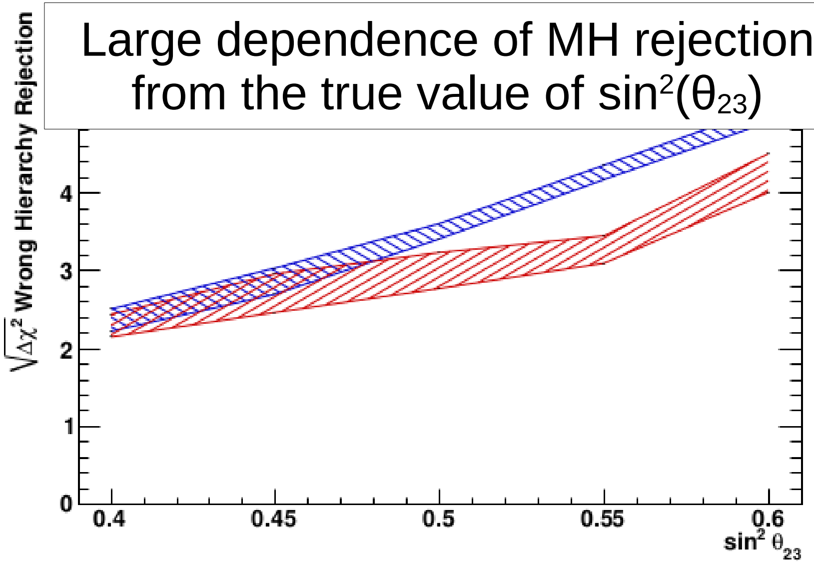
Neutrino Mass Hierrarchy

Measure ν_e and $\bar{\nu}_e$ as a function of energy and zenith angle



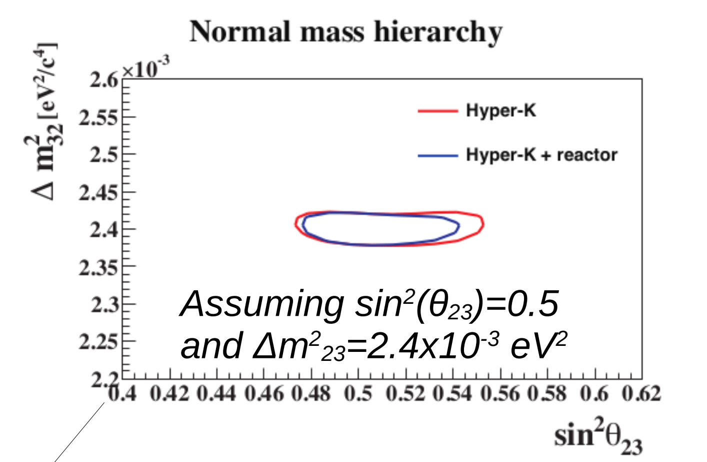
And opposite case with IO instead of NO

Large dependence of MH rejection from the true value of $\sin^2(\theta_{23})$



Beam+Atmospheric neutrinos

Idea

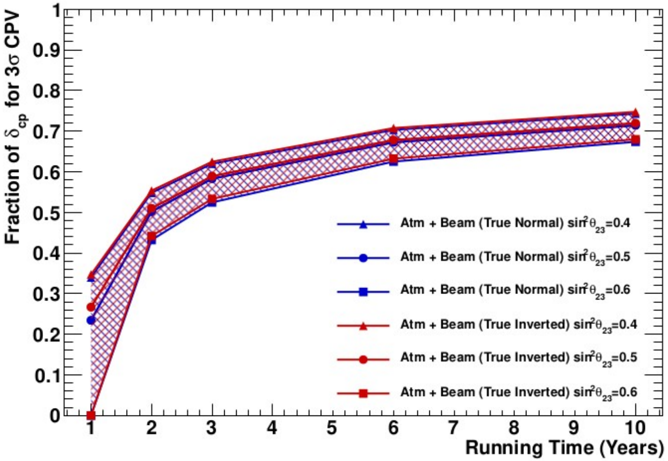


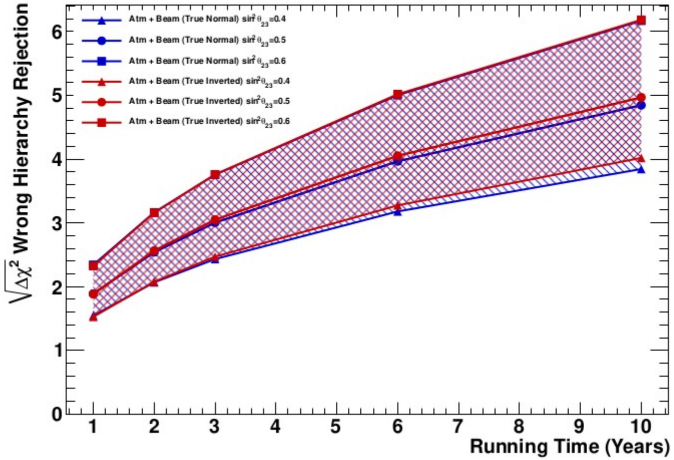
	Beam	Atmospheric
$\sin^2(\theta_{23})$ and $\lvert\Delta m^2_{23}\rvert$	Precise measurements of atmospheric parameters	Limited by not knowing the true baseline for neutrino events
Neutrino mass hierarchy	Limited by small MSW effect because of short baseline	Large sensitivity thanks to the large impact MSW effect

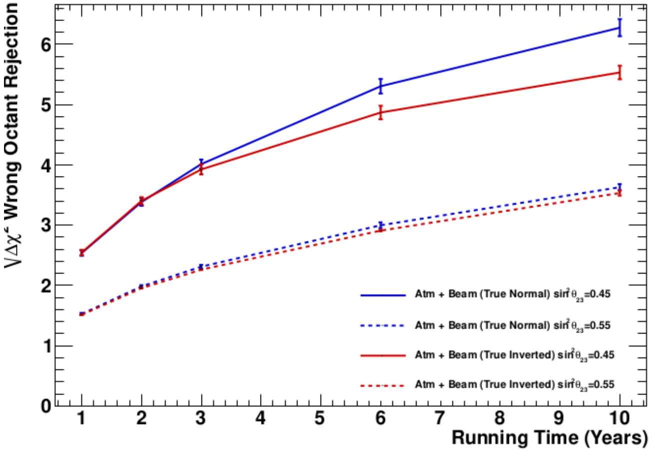
HyperKamiokande is unique since it can combine **beam and atmospheric neutrino measurements** in a simultaneous fit to improve parameter precision!

Beam+Atmospheric neutrinos
Expected sensitivities vs running time

Assuming 1 tank



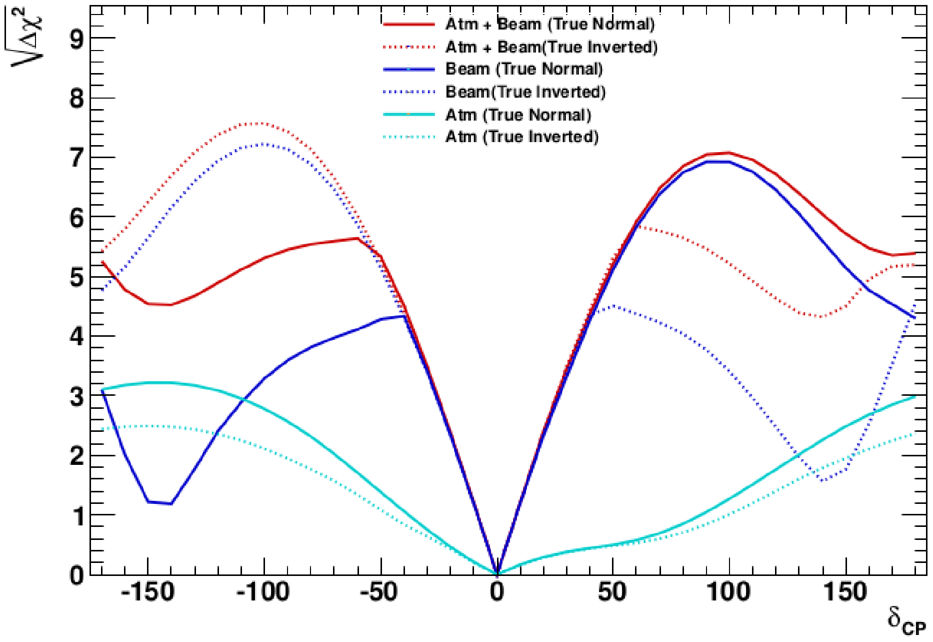




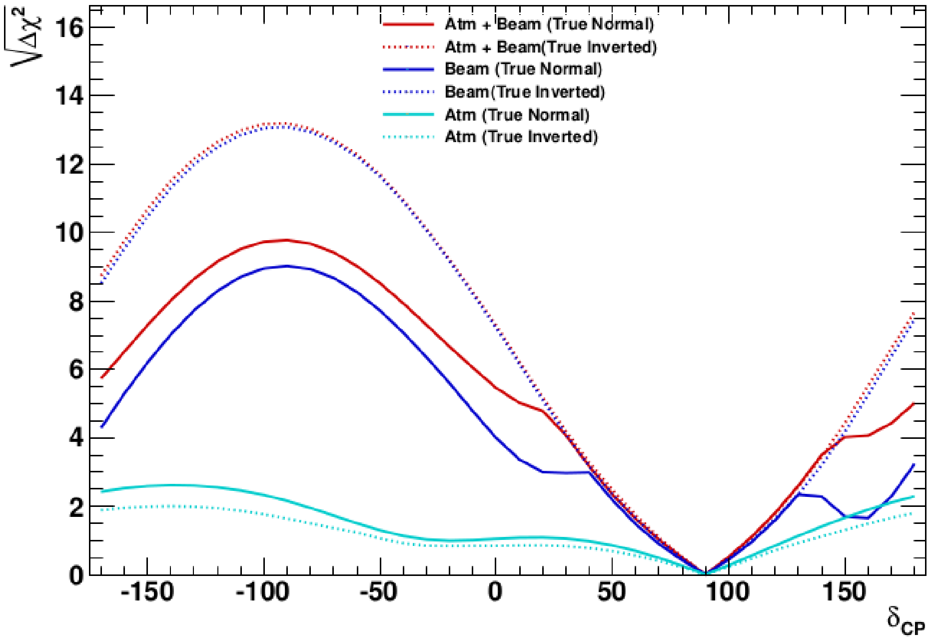
Beam+Atmospheric neutrinos
Constraints on CP violation phase

Assuming 1 tank for 10 years

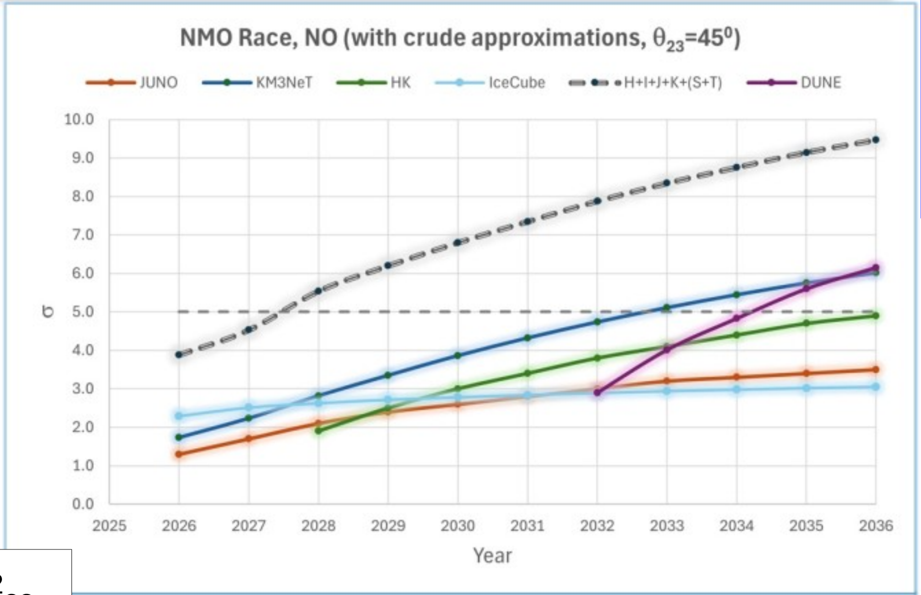
δ_{CP}=0°



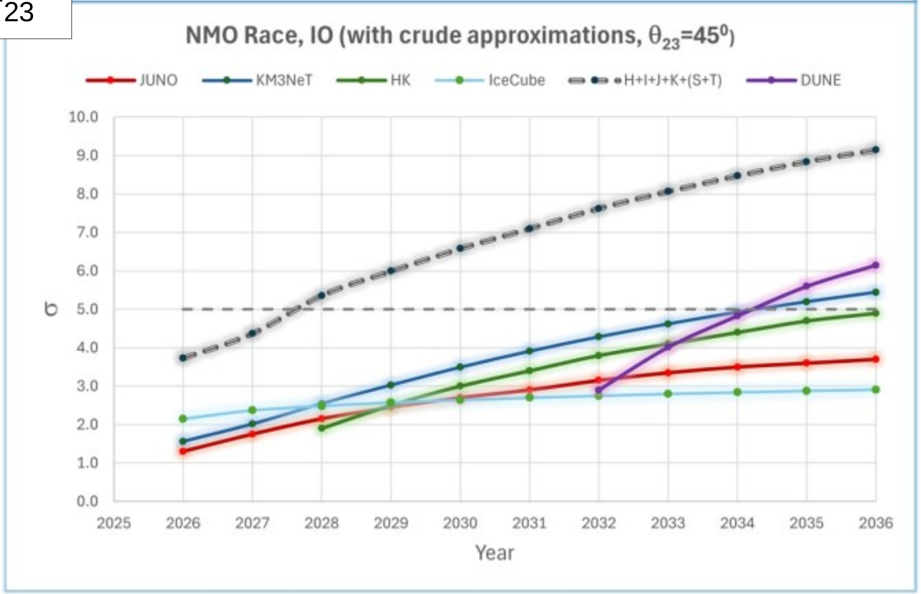
δ_{CP}=90°



Competition on Neutrino Mass Hierarchy



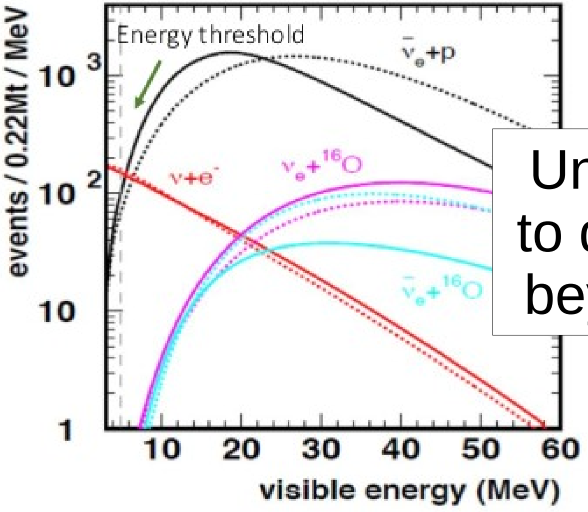
The experimental quantity is the sign of Δm^2_{23}



Neutrinos from SuperNova

(assuming a burst of few tens of seconds)

IBD is not good due to poor directionality, whereas detection and alert system uses ν_e+e for information on low energy tails, ν_e+O for information on high energy tails.

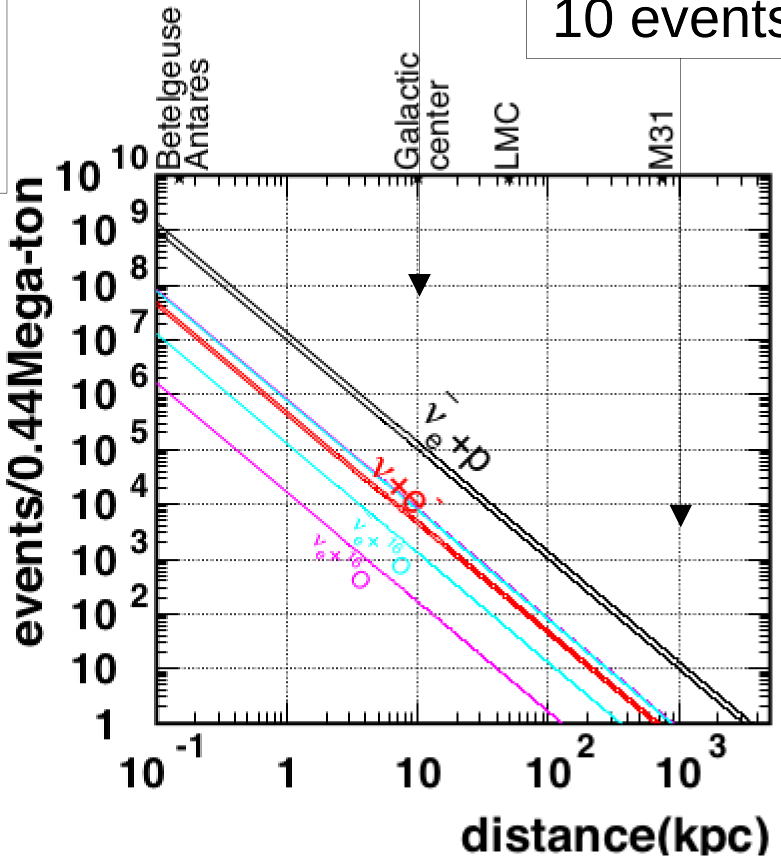


True energy spectra of prompt events in the ID for a supernova at 10 kpc. Solid (dashed) lines correspond to normal (inverted) mass ordering

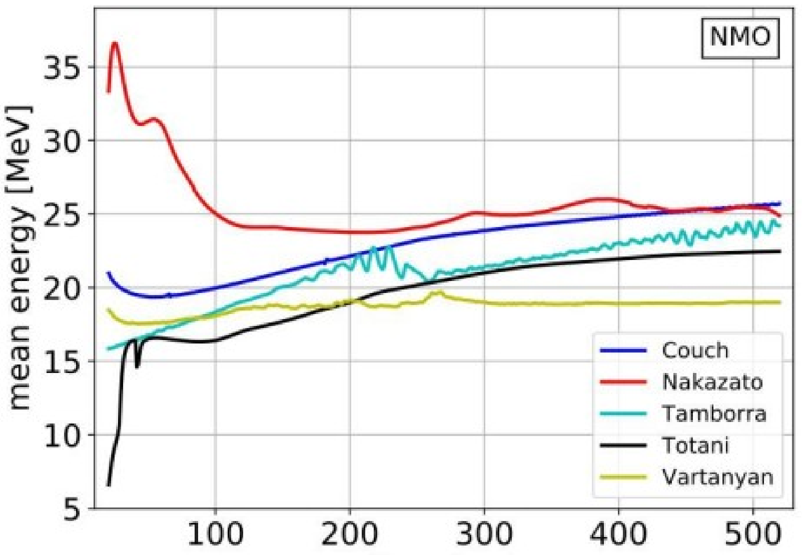
Unprecedented ability to detect SNR neutrino beyond the Milky way!

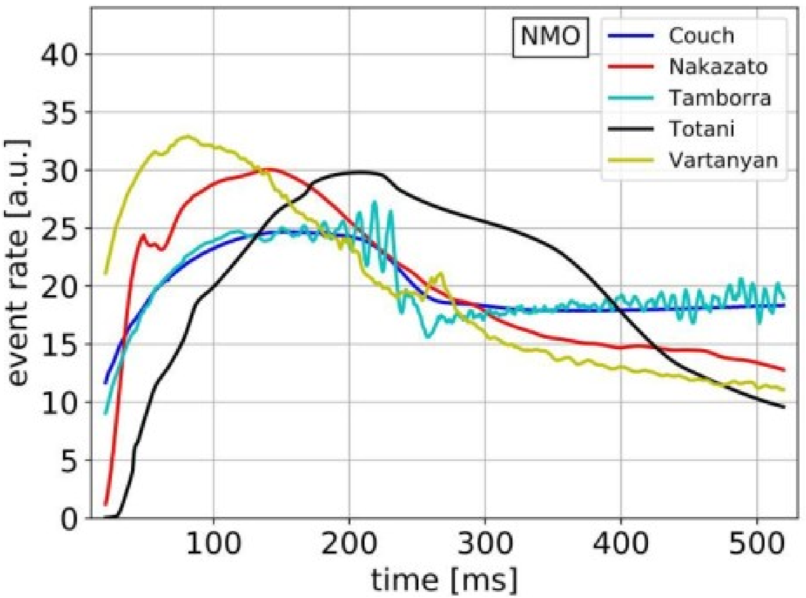
50-100k events

10 events



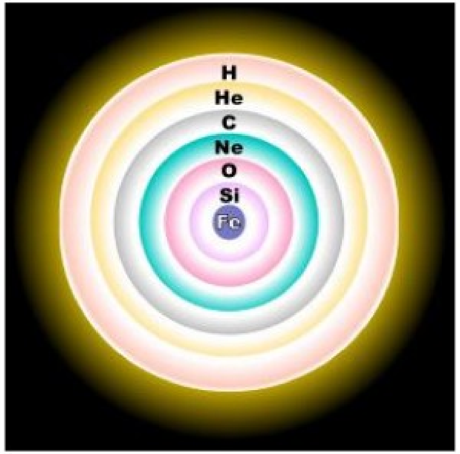
Testing SuperNova Neutrino Models





Discrimination between models based on average energy and event rate as a function of time

Pre-SuperNova neutrinos



A significant fraction of the signal is above threshold for IBD.

Burning Stage	Duration	ν_e ($\bar{\nu}_e$) fraction	Average ν energy
C	300 years	42.5%	0.71 MeV
Ne	140 days	39.8%	0.99 MeV
O	180 days	38.9%	1.13 MeV
Si	2 days	36.3%	1.85 MeV

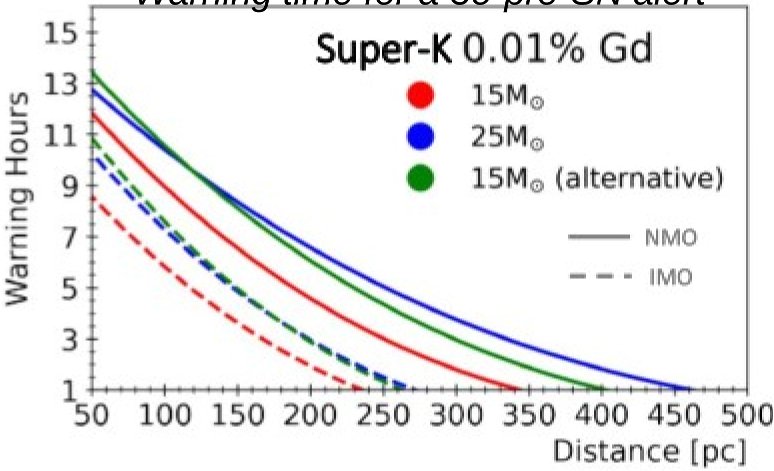
Last burning stage

Energy released by each pre-Supernova phase

Large benefits from Gd loading

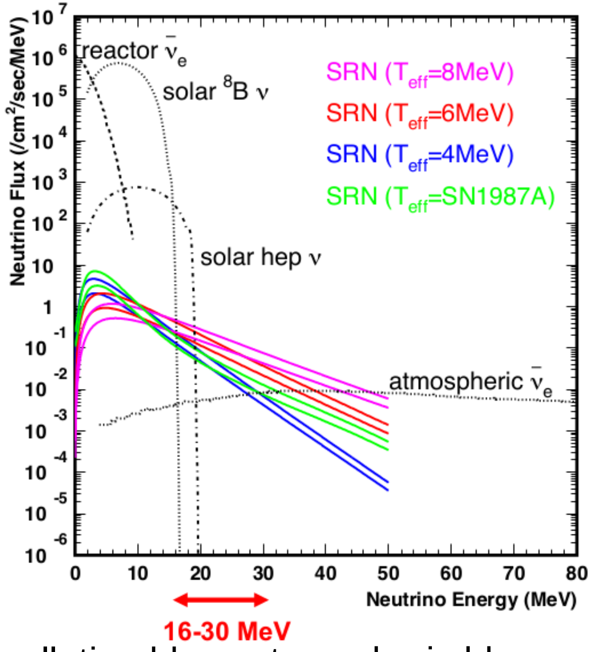
Important role as alert of an imminent SN for multi-messenger astronomy

Warning time for a 3σ pre-SN alert



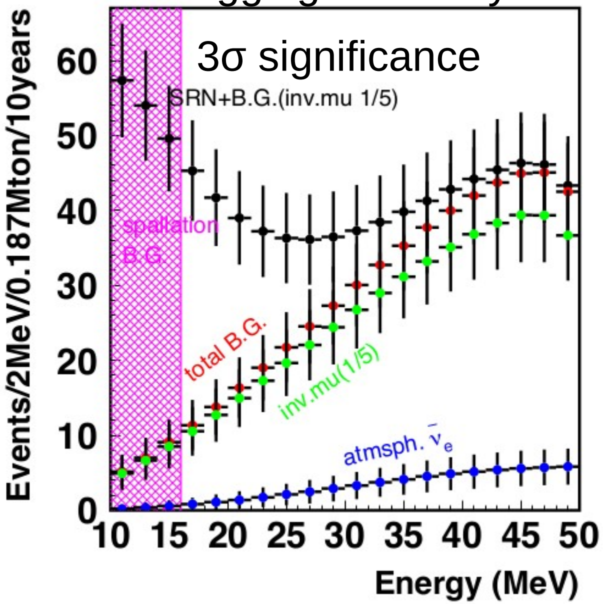
SuperNova relic neutrinos (SNR)

(Undiscovered!) Diffuse neutrino background coming from past SN



spallation bkg atmospheric bkg

Expected flux in 10 y with 67% neutron tagging efficiency



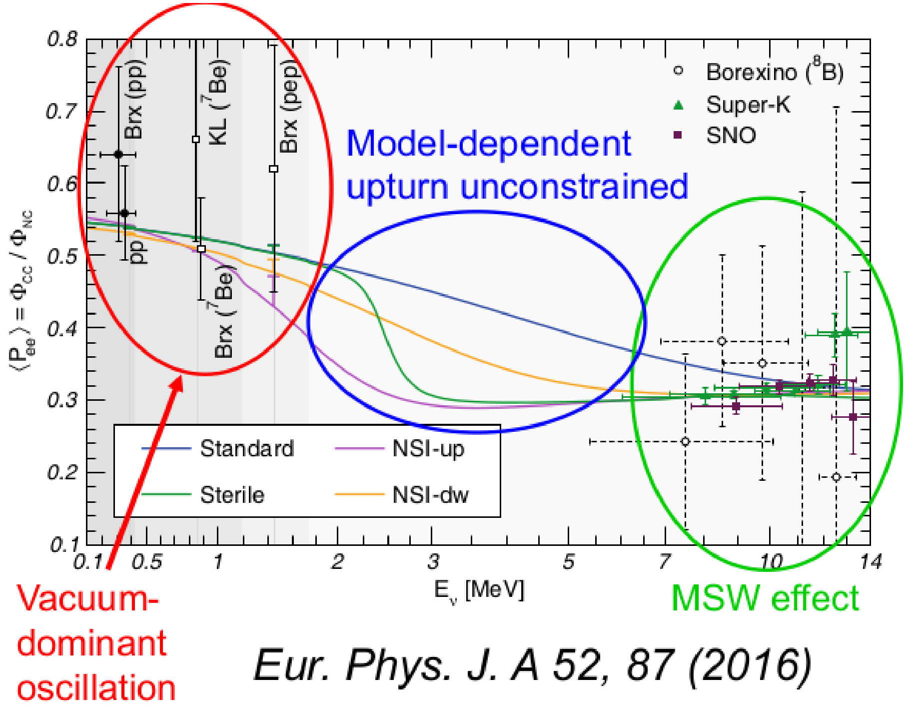
Spallation bkg: delayed decay of isotope generated by muon induced hadronic showers

Invisible muon bkg: electron generated in water by sub-luminal μ

Neutron captures to identify isotopes

Solar neutrino
Upturn

Upturn transition between vacuum and MSW-dominant oscillation



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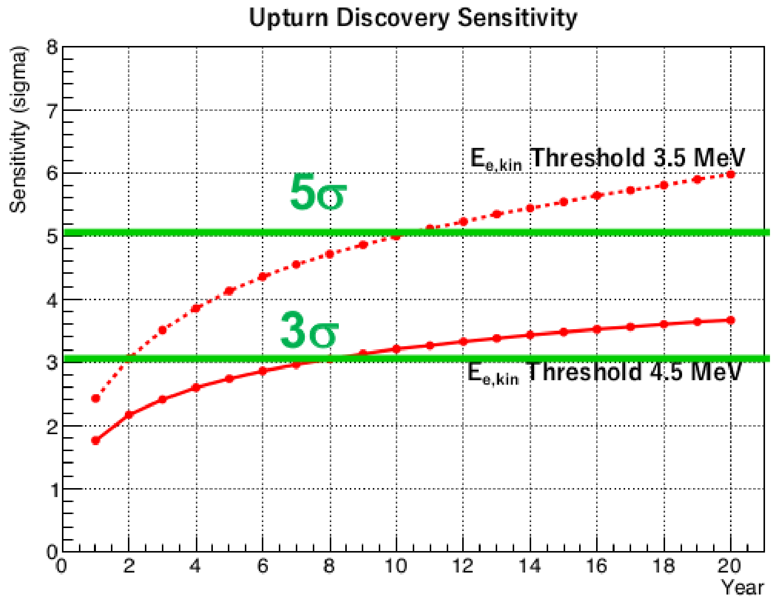
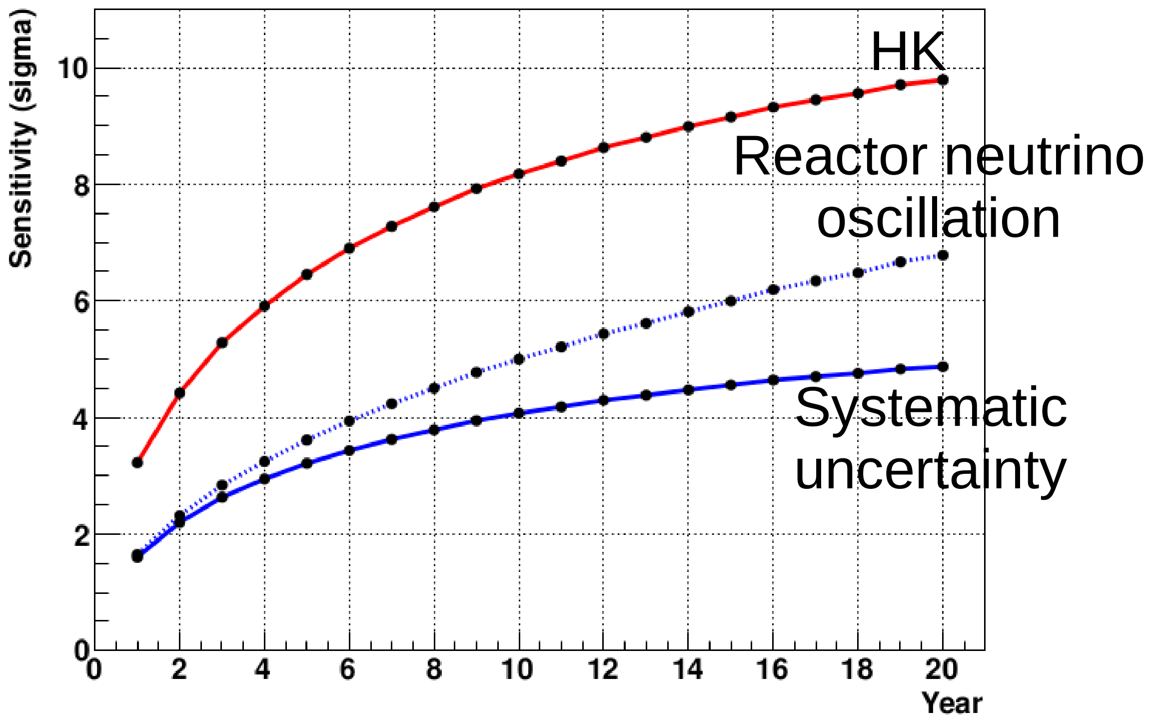


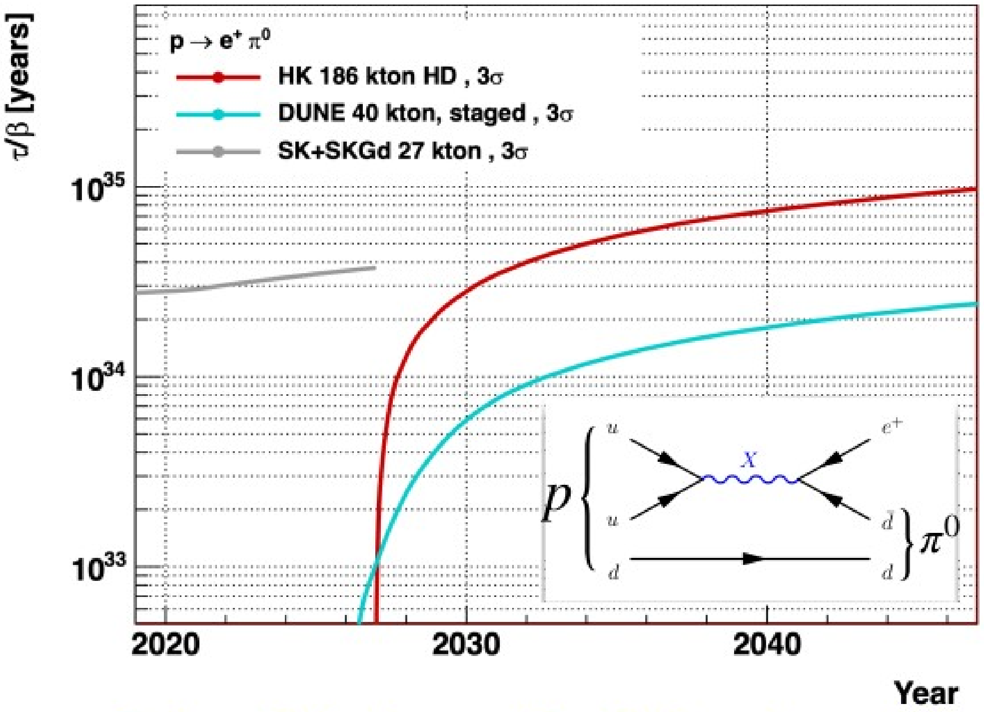
Solar neutrino
Day-night asymmetry

Asymmetry due to MSW effect

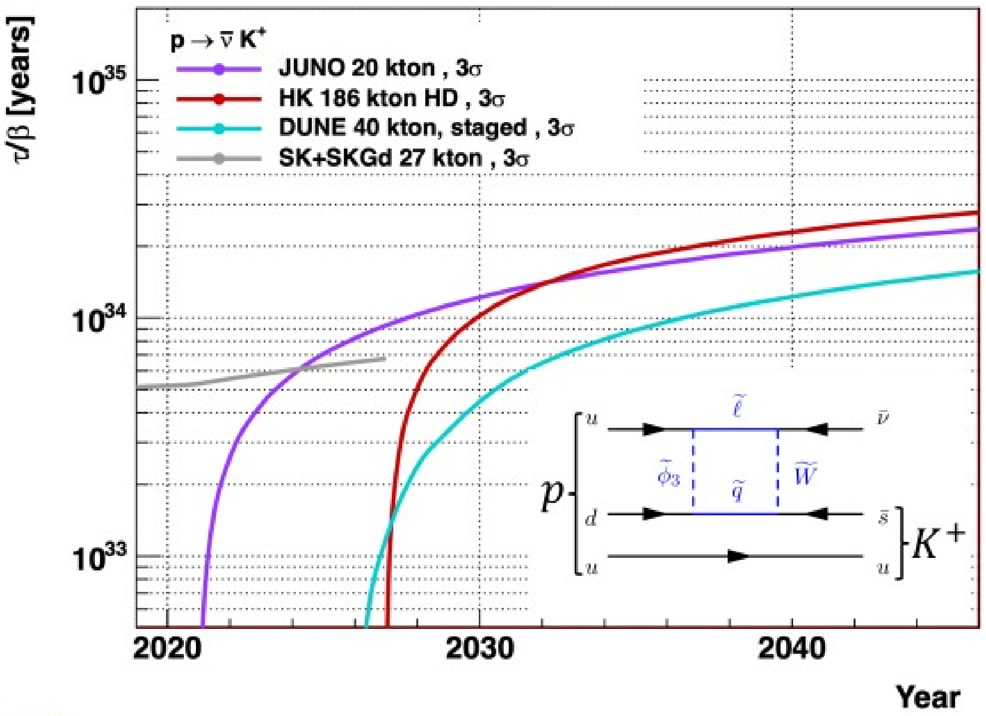


Proton decay

$p \to e^+\pi^0$



$p \to \overline{\nu}K^+$



Only realistic chance of achieving $\tau(p \to e^+\pi^0) > 10^{35}$ years

Expected sensitivities

Prospect is relative to **two** identical tanks:
operating for 10 years (1st) 4 years (2nd)

Neutrino beams	Physics Target	Sensitivity
Beam (1.3 MW $\times$ 10^7 sec)	δ_{CP} (0°,90°)	7°-21°
	CPV coverage ($3\sigma/5\sigma$)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	± 0.015
Atmospherics+Beam	MH determination ($\sin^2\theta_{23}$=0.40)	$> 5.3\sigma$
	Octant ($\sin^2\theta_{23}$=0.45)	5.8σ
Proton Decay (90% C.L.)	$p \to e^+ + \pi^0$	1.2×10^{35} yrs
	$p \to \bar{\nu} + K^+$	2.8×10^{34} yrs
Solar	Day/Night (from 0/ from KamLAND)	$12\sigma/6\sigma$
	Upturn	$\sim 5\sigma$
Supernova	Burst	104k-158k
	Nearby galaxies	2~20 events
	Relic	98 events/4.8σ

Collaboration

Collaboration	About 400 people from all around the world but still growing
Publication	Need 1 year of activity in the collaboration before signing papers
Shift/meeting	• At least 2 weeks of shifts in Kamioka per year • Take into account other 2 weeks in Japan per year • There are around 8 meetings in Japan per year
INFN	SK and T2K are different collaborations, but HK will be a single one
Laboratory	• Quality assurance of mPMTs and electronics • Other similar activities in conflict with French group • Collateral R&D activities with Padova group
Analysis	• There are Italian contributions to T2K • Room for micromegas signal reconstruction • Not large activities on HK so far
Analysis policy	• SK analysis is divided in low energy and high energy with informal policies • T2K analysis requires analysis note and a more formal review committee • HK will likely follow T2K style but this point has not been discussed yet