# Hyper-Kamiokande:
## Towards New Discoveries in (Astro)Particle Physics

International Joint Workshop on the Standard Model and Beyond
3rd Gordon Godfrey Workshop on Astroparticle Physics
Sydney, Australia
December 12, 2024

**Patrick de Perio**, on behalf of the HK Collaboration
pdeperio@ipmu.jp http://pdeperio.github.io

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
TRIUMF

# Physics Program



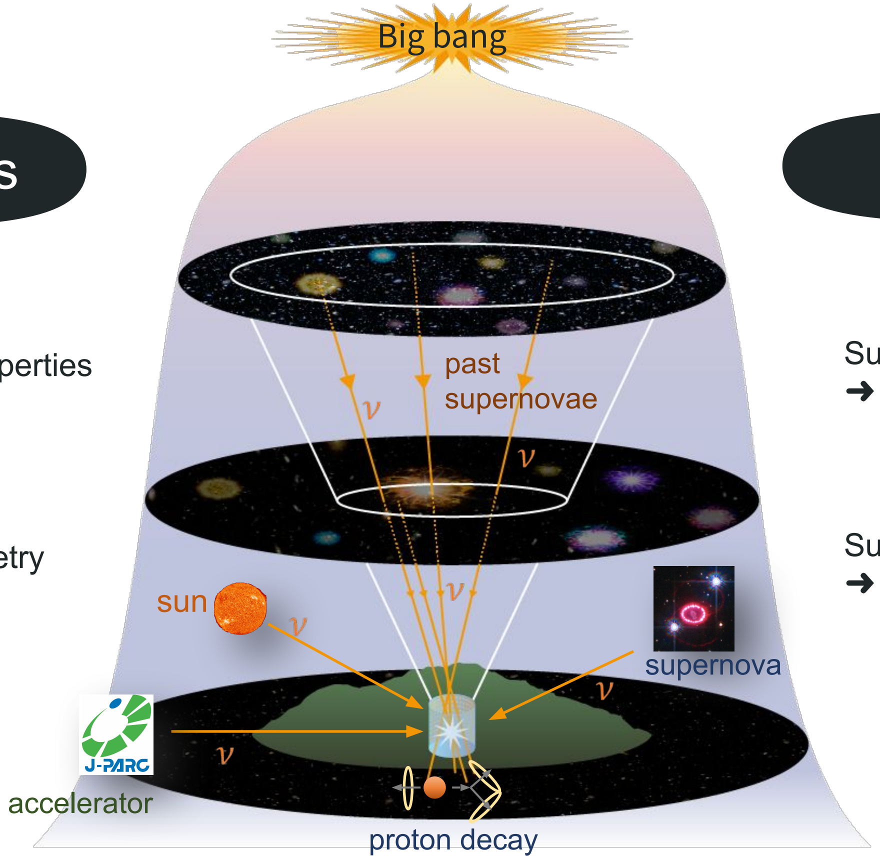
Kei Ieki @ COSMO'24

## Particle physics

Atmospheric/solar neutrinos
➜ Neutrino fundamental properties (mass ordering, mixing)

CP-violation in neutrino
➜ Matter-antimatter asymmetry

Proton decay
➜ Grand unification

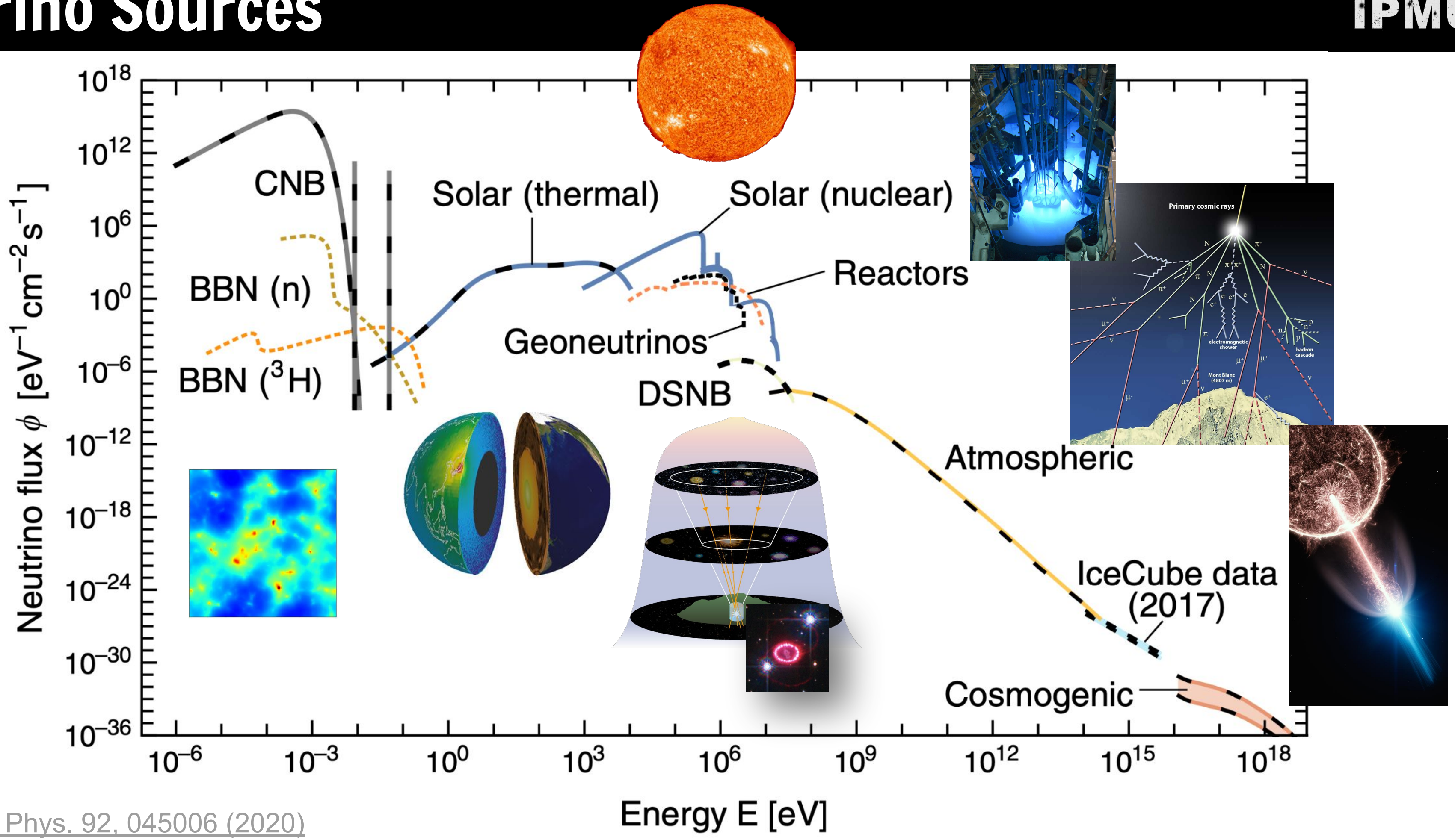



## Astrophysics

Supernova Relic Neutrino (SRN)
➜ Star formation history

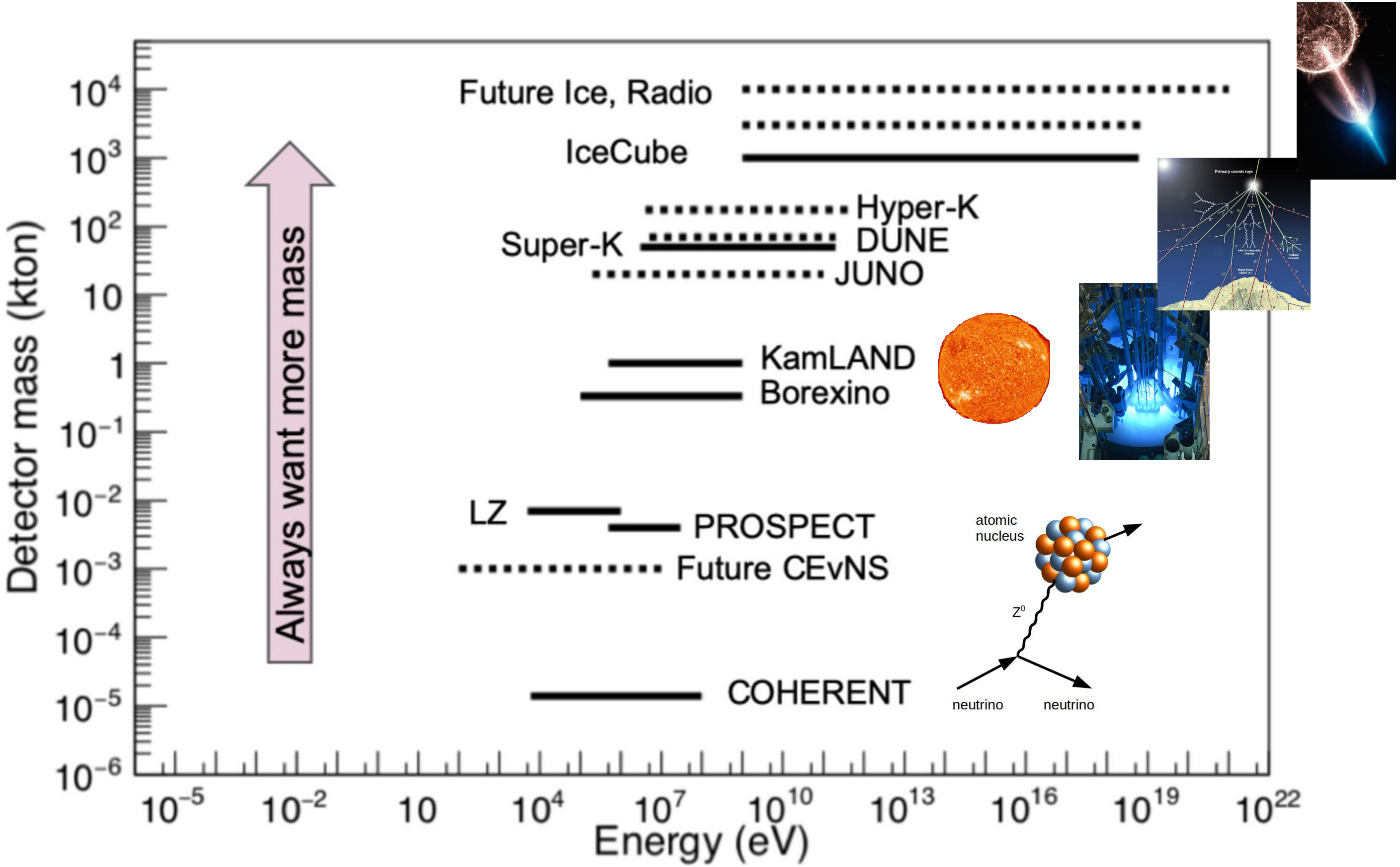
Supernova burst neutrinos
➜ Explosion mechanism

# Neutrino Sources




Rev. Mod. Phys. 92, 045006 (2020)

# Detector Masses and Energy Sensitivities




Kate Scholberg @ TIPP21

# Neutrino Observatories Around the World

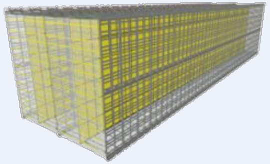
High statistics (≒**large target mass**) & high precision is required

Kei Ieki @ COSMO'24

JUNO

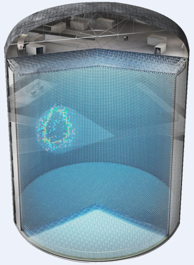
20kt liquid scintillator
+26.6 GW reactor
Data taking 2025~

DUNE



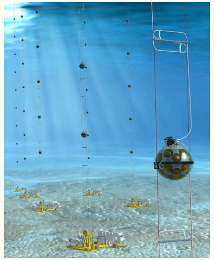
≧40kt liquid Argon TPC
+ >2MW $\nu_\mu$ beam
Data taking 2028~
(phase I)

Hyper-K



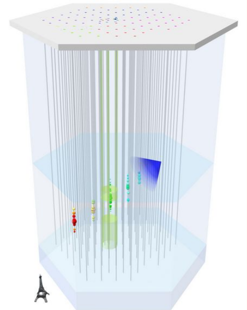
**260kt** pure water
+ 1.3MW $\nu_\mu$ beam
Data taking **2027~**

ORCA KM3NeT



Ocean water
Data taking 2020~
(construction ongoing)

ICECUBE

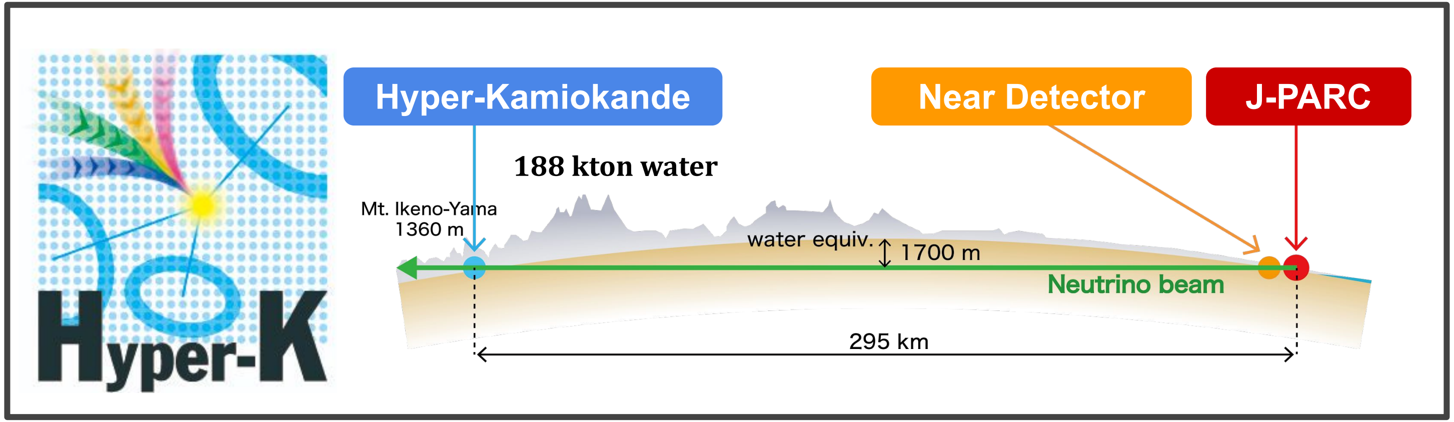


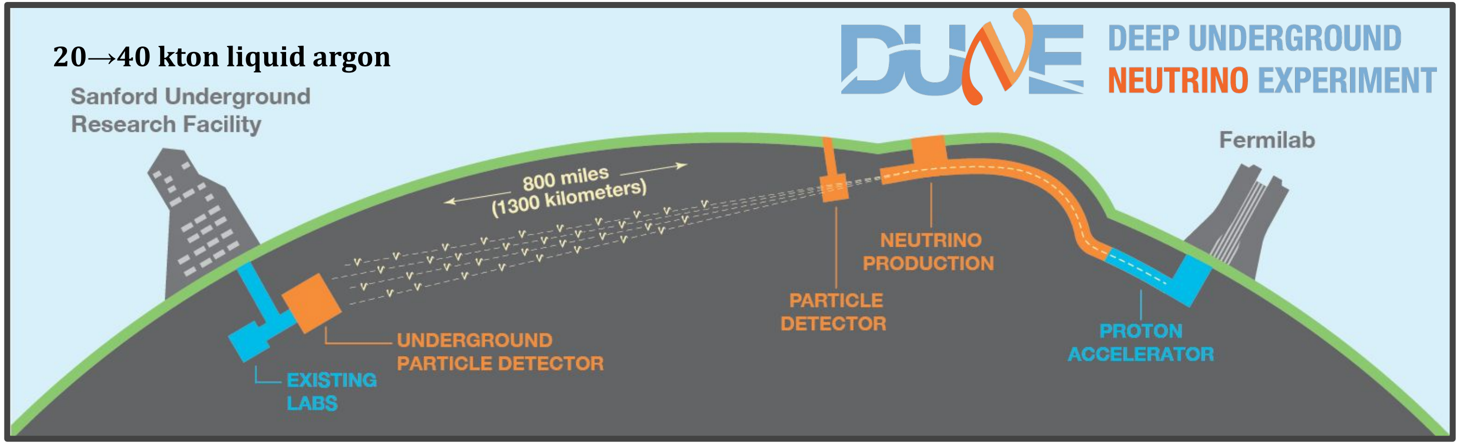
South pole ice
Data taking 2005~
(upgrade planned)

Low energy threshold (~MeV)
High intensity neutrino source

O(km$^3$) scale detector
to detect TeV~PeV neutrinos

# Next Generation Long-Baseline Experiments



# Generations of Kamiokande

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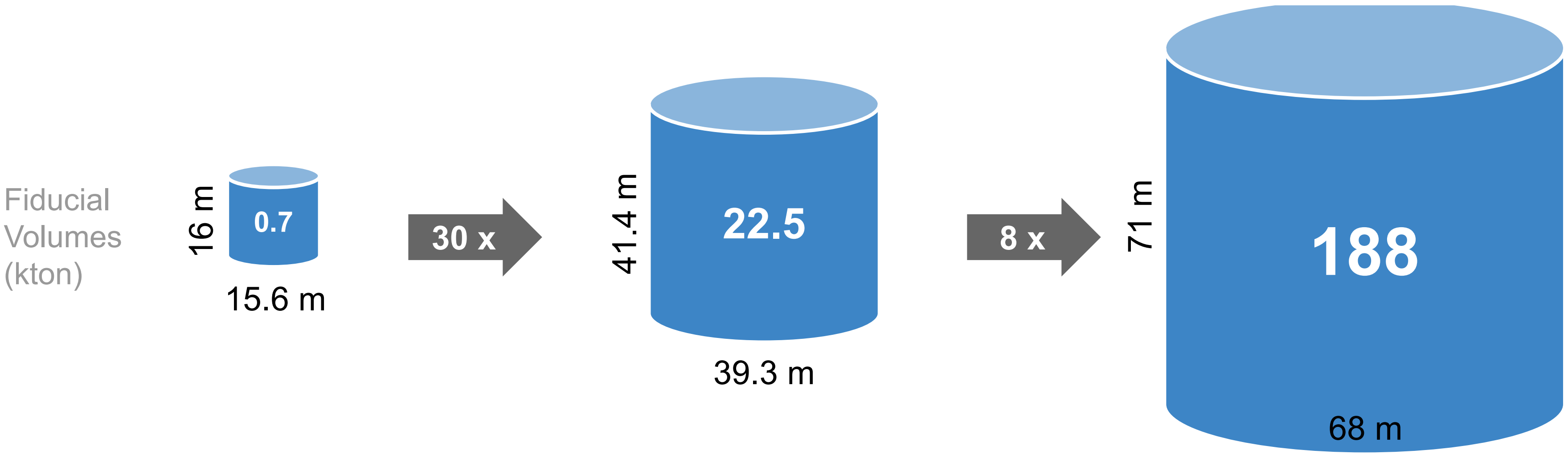
## Kamiokande    Super-Kamiokande    Hyper-Kamiokande




| 1983 - 1996 | 1996 - ongoing | 2027 and beyond |
|---|---|---|
| • Atmospheric (Atm) and solar neutrino “anomaly”<br>• Supernova 1987A<br>***Birth of neutrino astrophysics*** | • Proton decay (world-leading limits)<br>• Neutrino oscillation (Atm, solar, beam)<br>***Co-discovery of neutrino oscillations*** | • Extended search for proton decay<br>• Precision measurement of oscillations, including CP violation<br>• Neutrino astrophysics |

# Generations of Kamiokande

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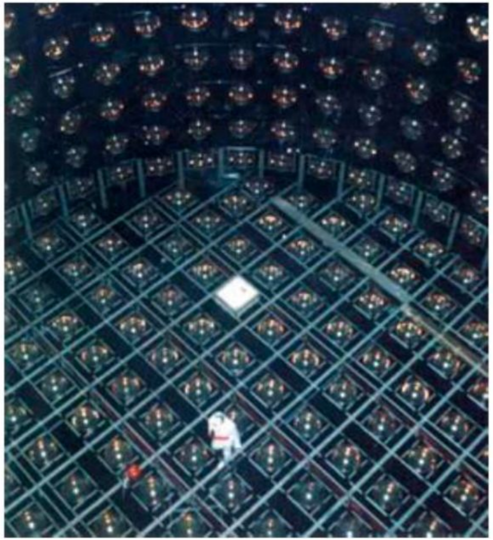
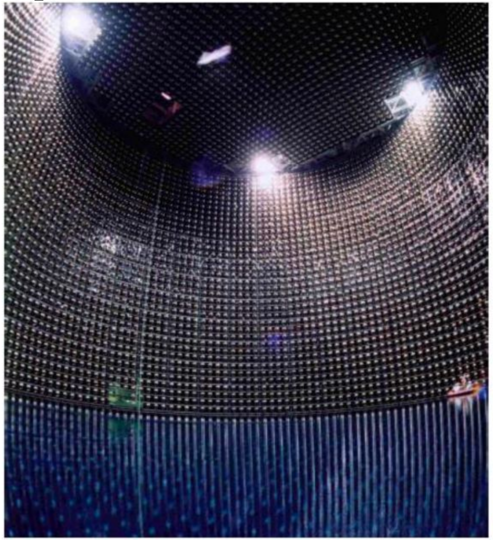
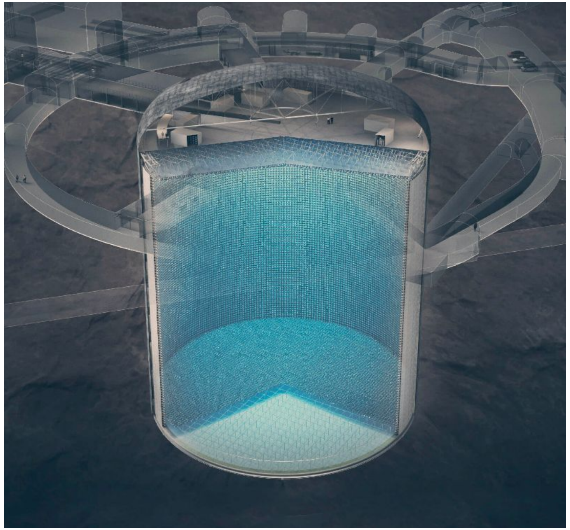
|  |  |  |
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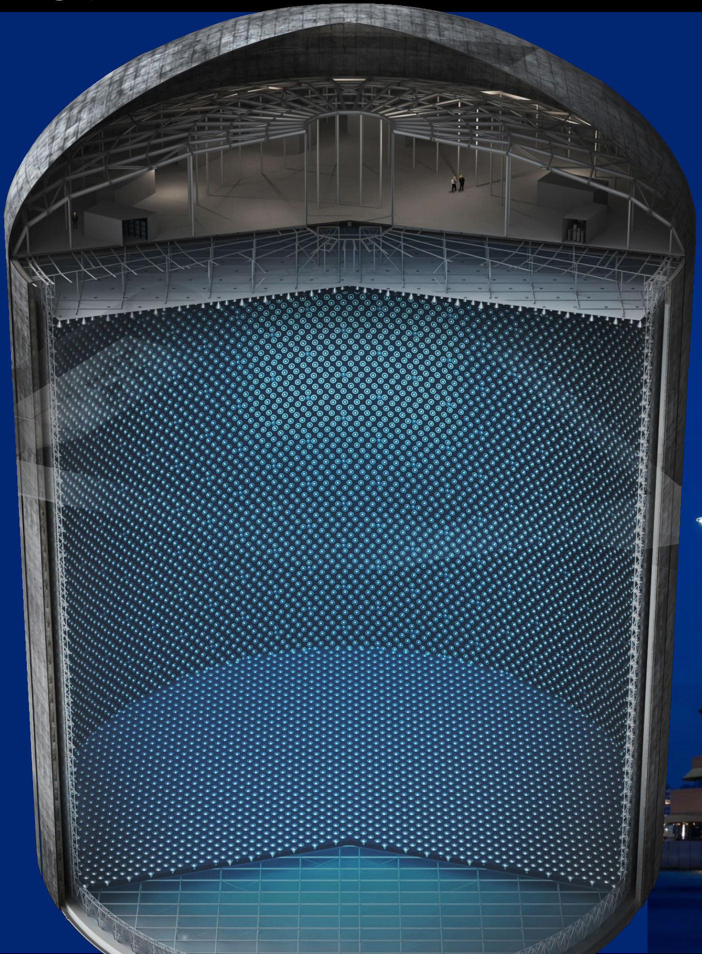
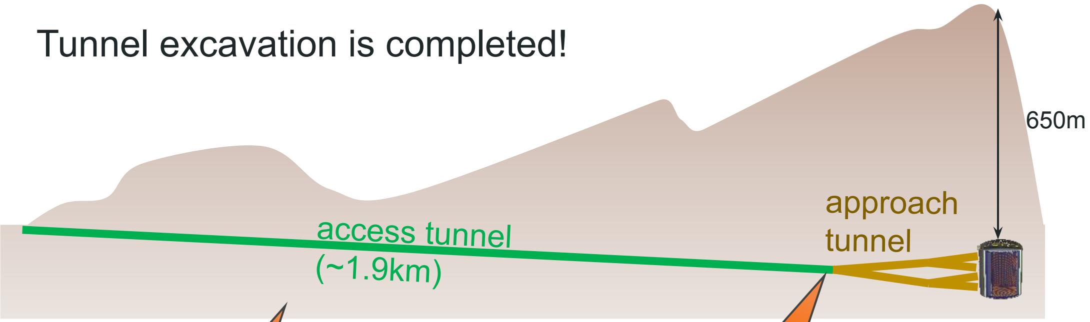
# Hyper-Kamiokande to Scale

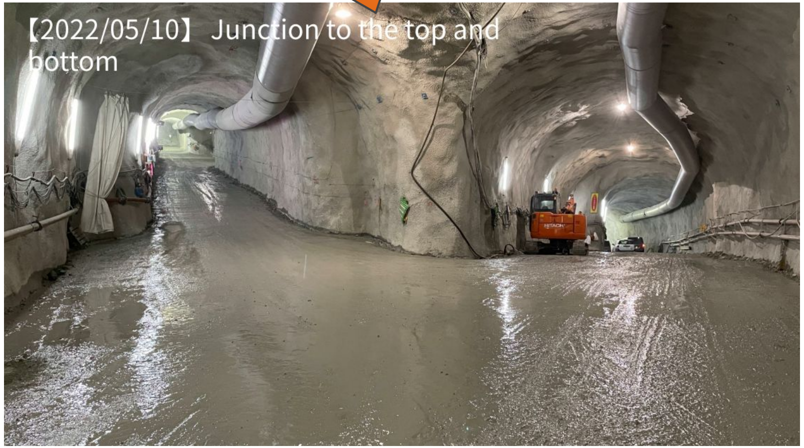


# Far Detector Tunnel Excavation (~2022)

Tunnel excavation is completed!

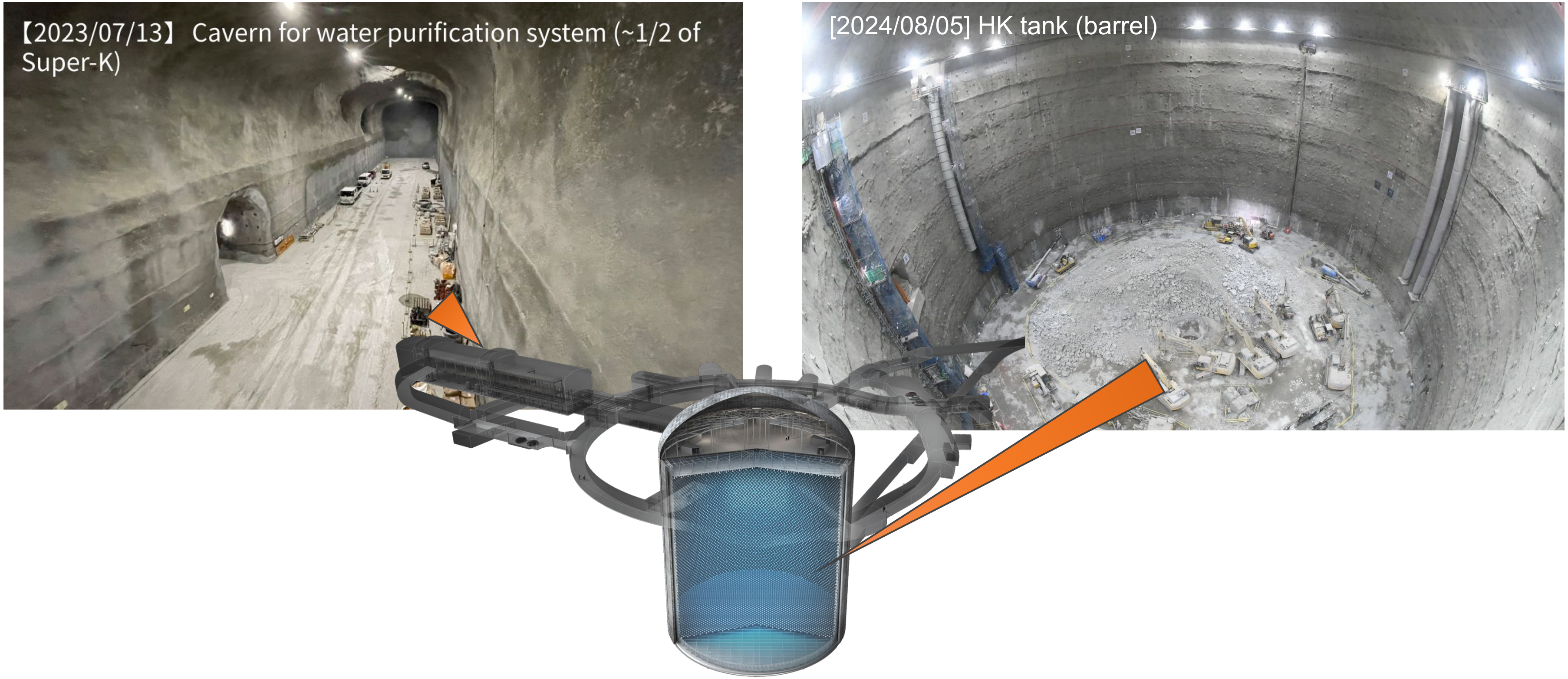







# Far Detector Cavern Excavation

Excavation of the barrel section of the tank is ongoing!



# PMT Production and Quality Assurance

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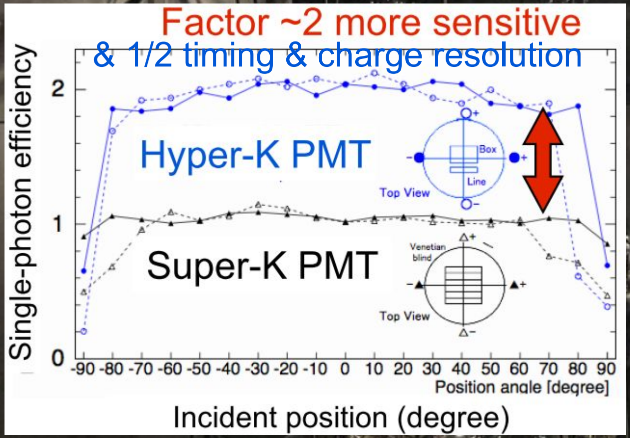
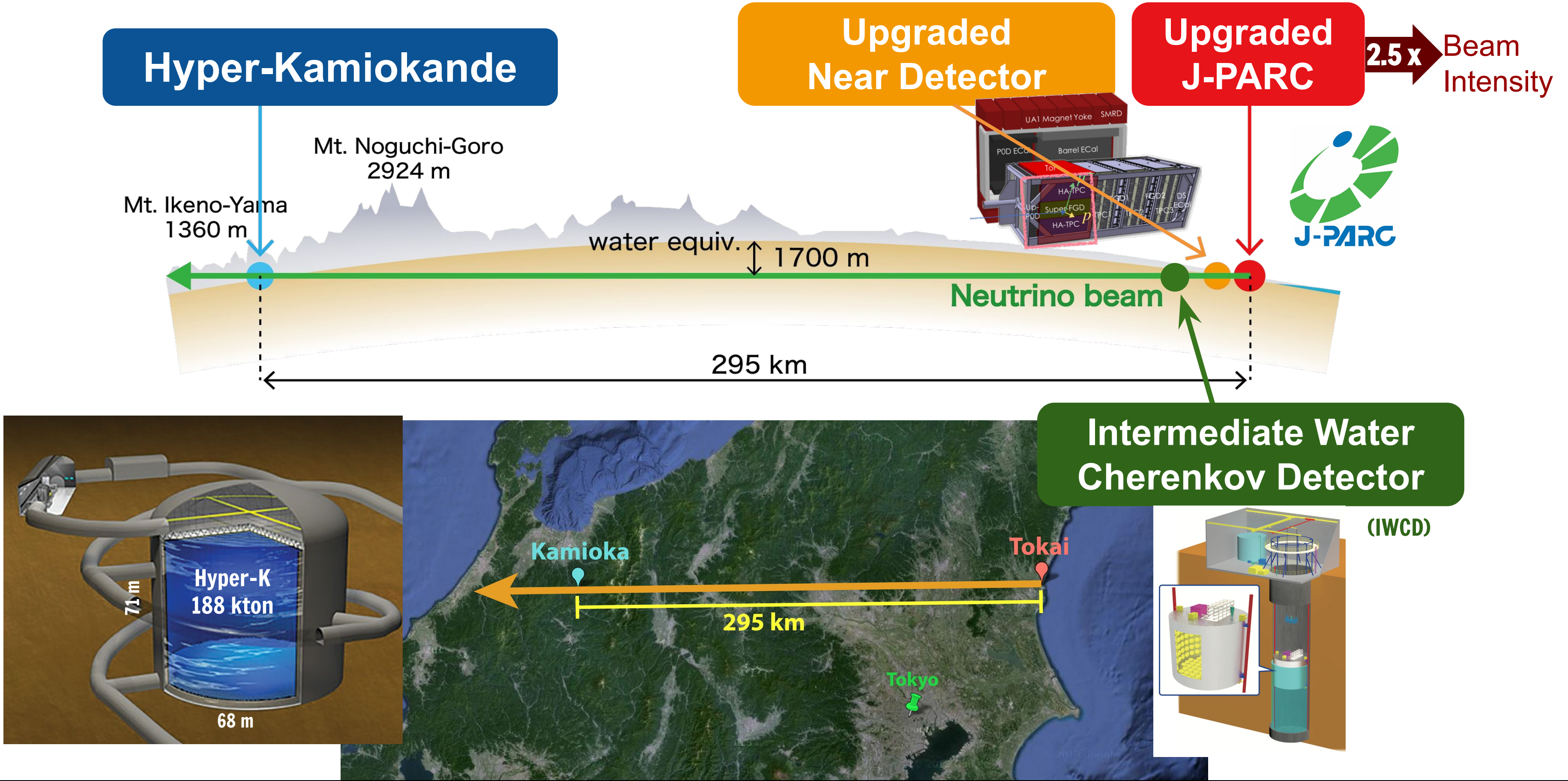


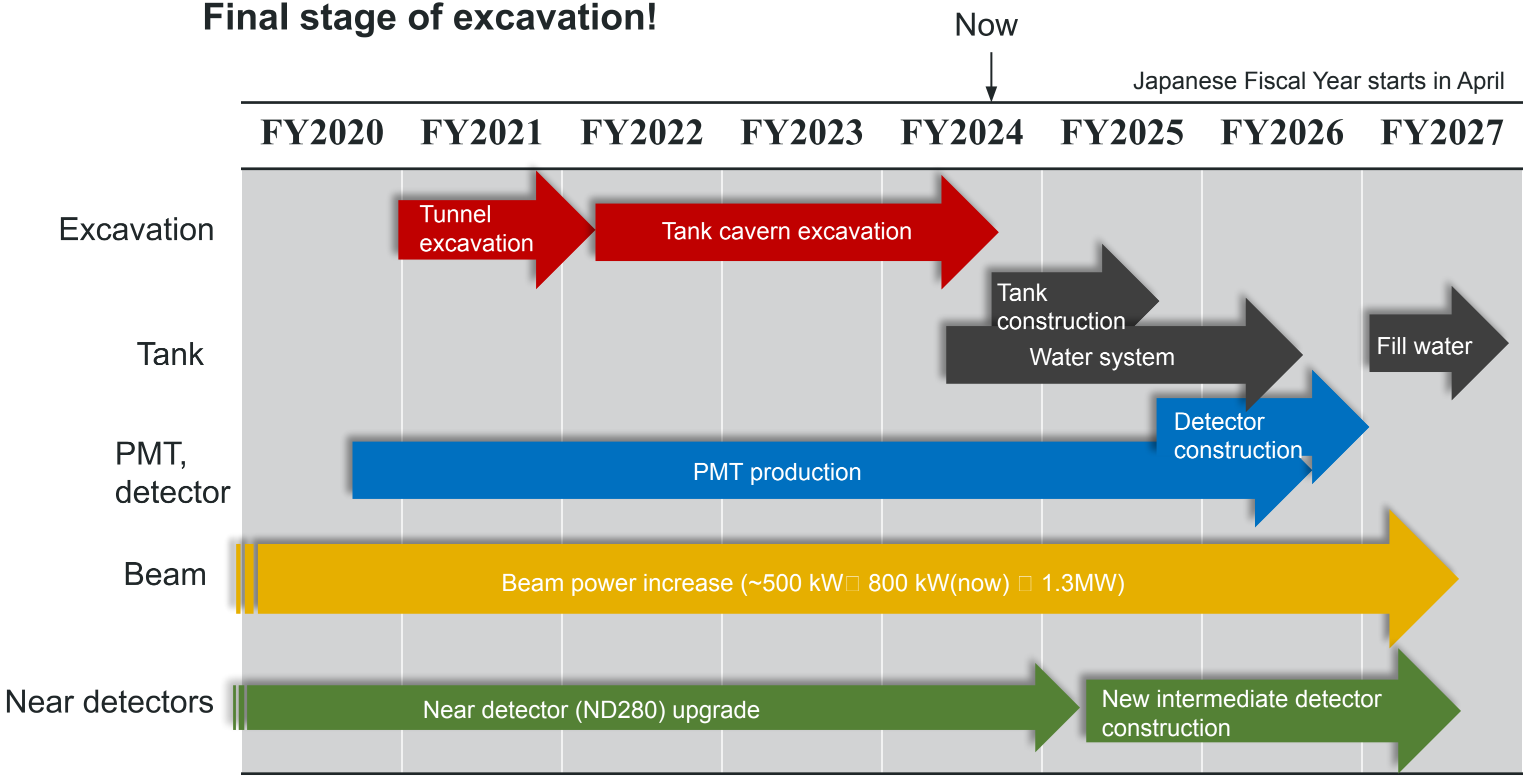

- ~>11000 PMTs (out of 20000) have been delivered
- Screening and evaluation at Hamamatsu and Kamioka
  - Signal check & visual inspection of the glass and sealing
  - Two dark rooms testing 100 PMTs in each

# Hyper-Kamiokande: Long-Baseline Neutrino Experiment

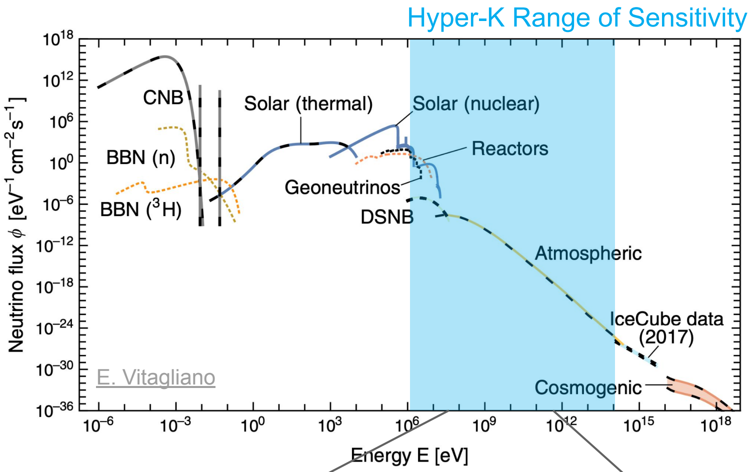


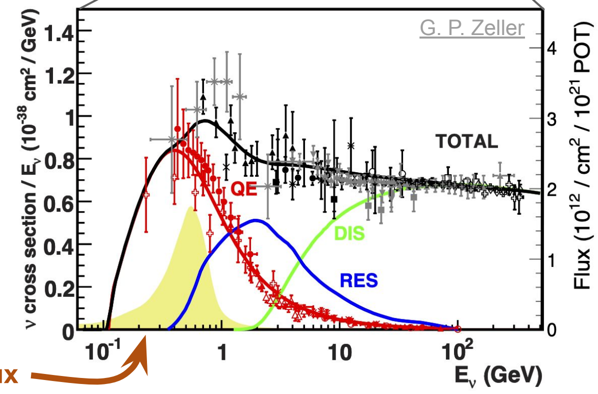
# Hyper-K Schedule

**Final stage of excavation!**



# Neutrino Interactions

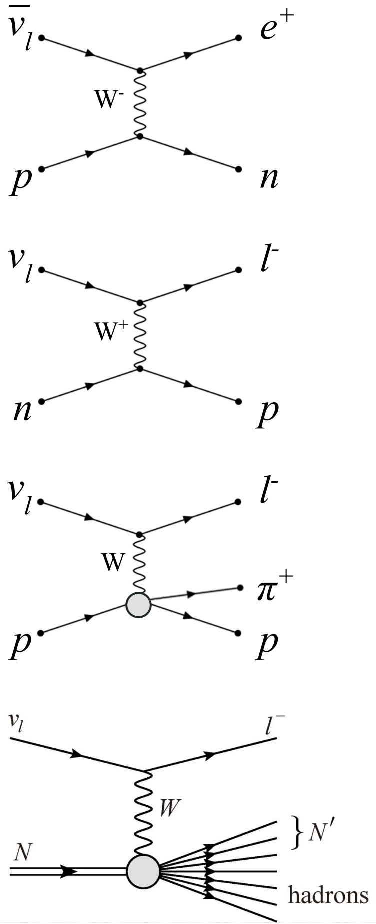



T2K (~HK) Accelerator Neutrino Flux

Increasing energy

| | |
|---|---|
| $\mathcal{O}(1)$-$\mathcal{O}(10)$ MeV | IBD |
| $\mathcal{O}(100)$ MeV | CCQE |
| $\mathcal{O}(1)$ GeV | CC RES |
| $\mathcal{O}(10)$ GeV | CC DIS |



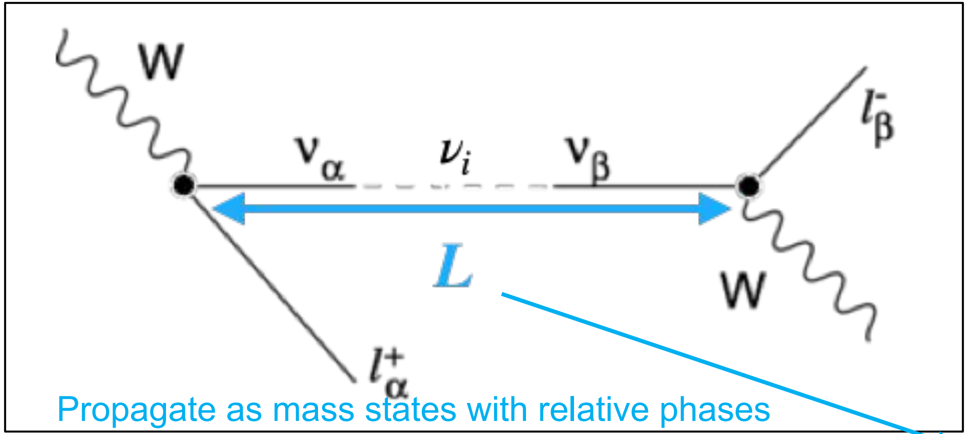
# Three-Flavour Neutrino Oscillation Paradigm

Julia Gehrlein, Day 4 (next talk)

Flavor Eigenstate $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$ Hamiltonian Eigenstate $\nu_1, \nu_2, \nu_3$

Superposition (Unitary transf.)

Produced as weak/flavour state




Interact as weak/flavour state

Mixing matrix (oscillation) parameters

ν mass[2] differences

$$P(\nu_\alpha \rightarrow \nu_\beta) = 4 \sum Re \left( U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \right) \sin^2 \left[ \frac{\Delta m^2_{ij}}{4} \frac{L}{E} \right] + \cdots$$

Oscillation probability

ν energy

# Neutrino Oscillation Formalism (PMNS)

$c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$.

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

Flavor Eigenstate

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Hamiltonian Eigenstate $\nu_1, \nu_2, \nu_3$

Superposition (Unitary transf.)

# Experimental Constraints on PMNS

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$c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$.

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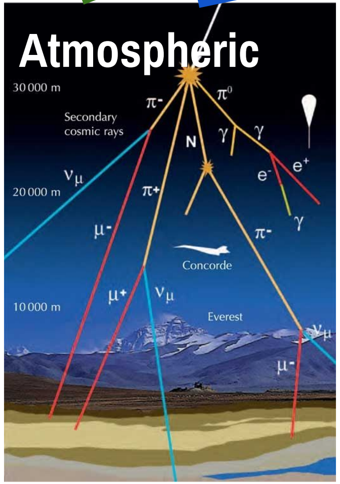
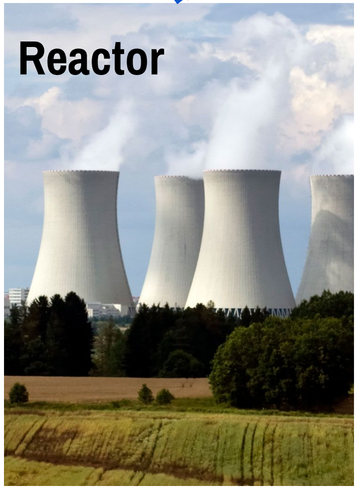
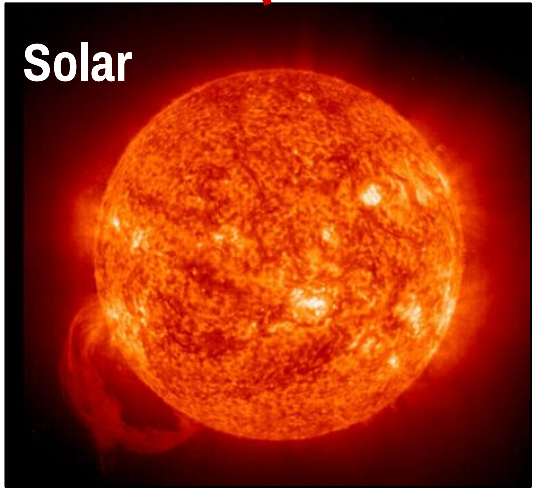




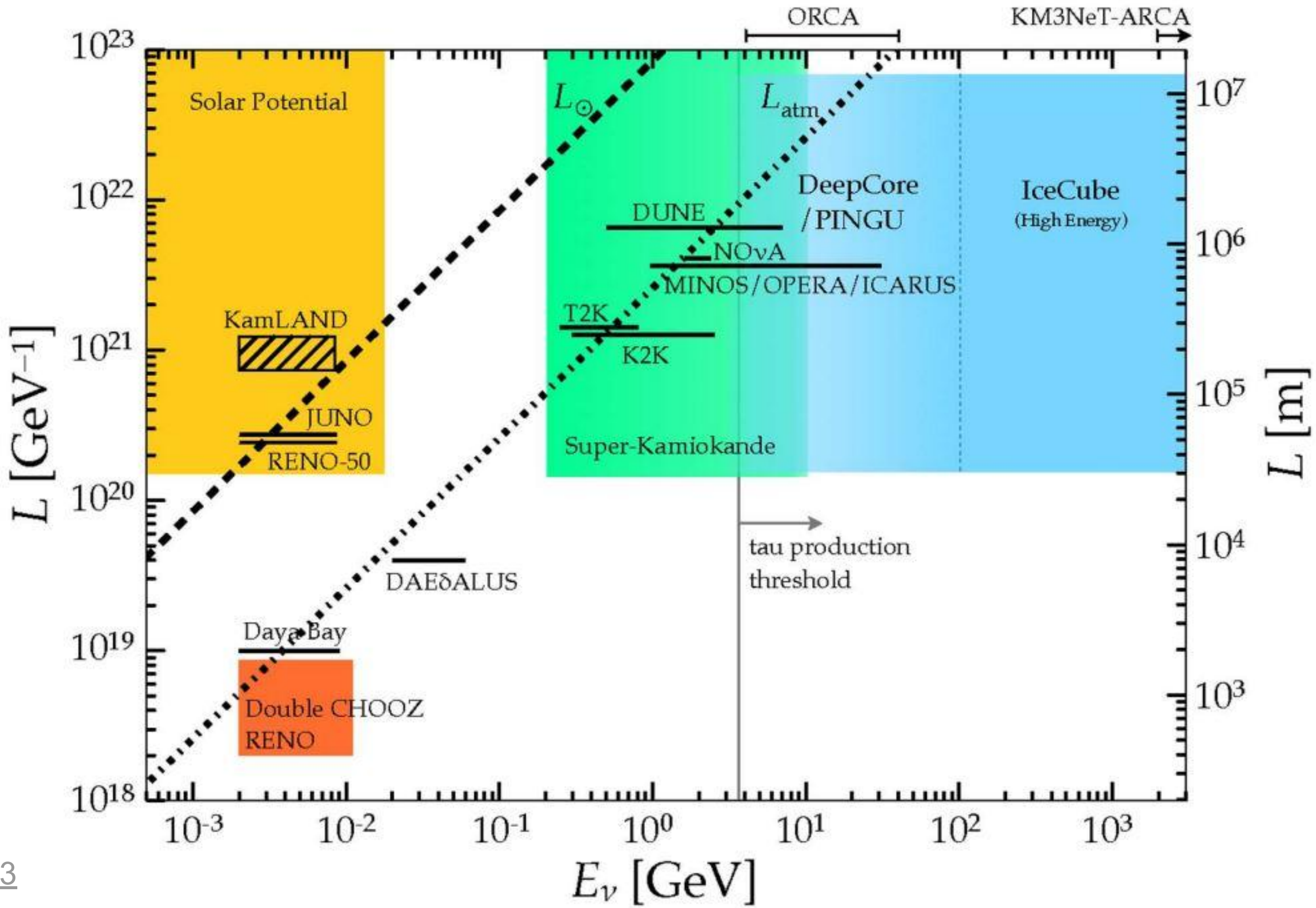
GeV-scale




MeV-scale

# Neutrino Oscillation L/E Scales




IJMP A 2021 36:13

# Neutrino Knowns and Unknowns

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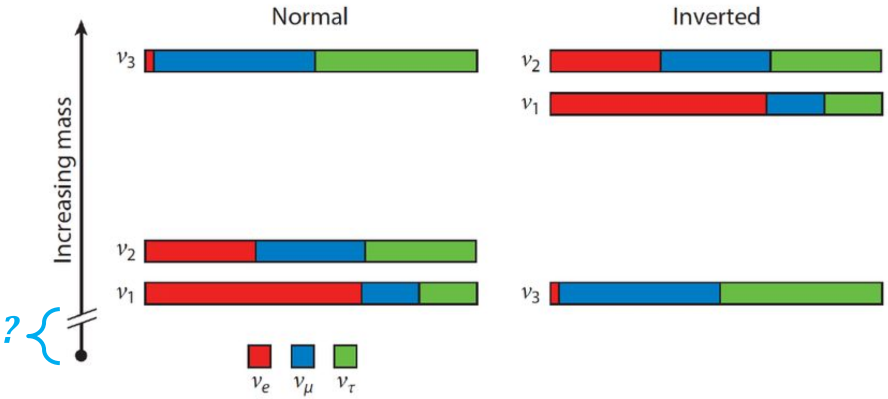
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}$$

$$\times \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$.




**KNOWNS** (~1$\sigma$ accuracy)

$\Delta m_{31}^2$ / eV$^2$ = 2.51 x 10$^{-3}$ (1.0%)
$\Delta m_{21}^2$ / eV$^2$ = 7.55 x 10$^{-5}$ (2.7%)
$\sin^2\theta_{13}$ = 0.0220 (2.6%)
$\sin^2\theta_{12}$ = 0.304 (5.4%)
$\sin^2\theta_{23}$ = 0.564 (3-4%)

**UNKNOWNS** (>1$\sigma$ hints)

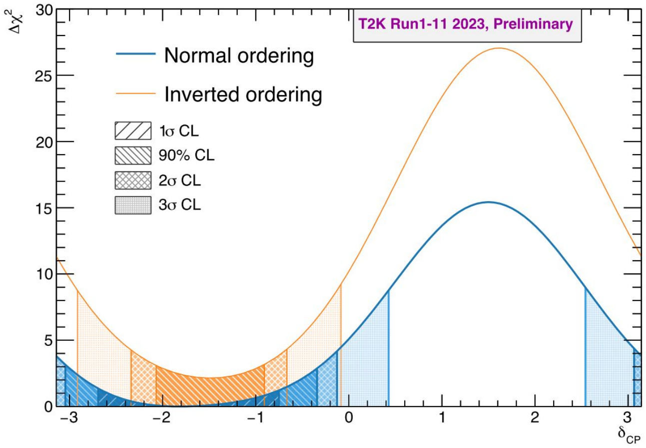
Dirac or Majorana
Mass ordering (1.6-2.7$\sigma$ NO)
Absolute mass (<sub-eV)
Dirac CP phase $\delta_{cp}$ (2.9$\sigma$ CPV)
Octant of $\theta_{23}$

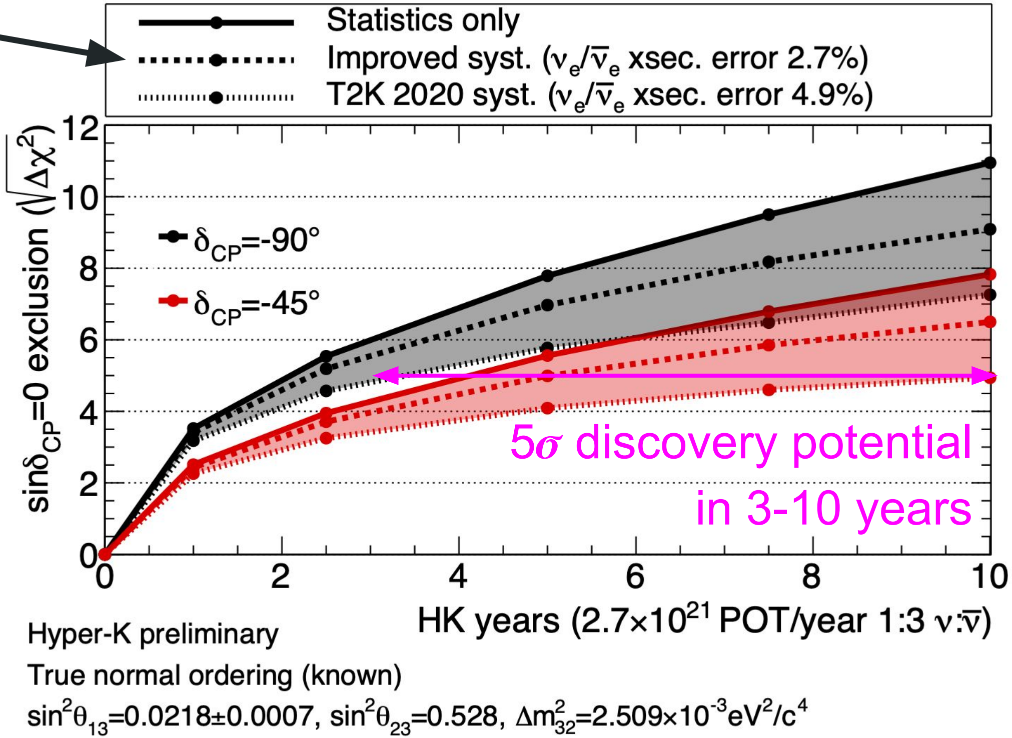
Mariam Tórtola @ NEUTRINO2024

Shao-Feng Ge, Day 5

# CP Violation ($\delta_{CP}$) in Neutrinos

- Potential source of matter-antimatter asymmetry in the universe (leptogenesis)
- Systematic errors will be important
  - ➢ New and upgraded near detectors
- From "discovery" to "measurement"
  - ➢ Physics behind the mixing matrix

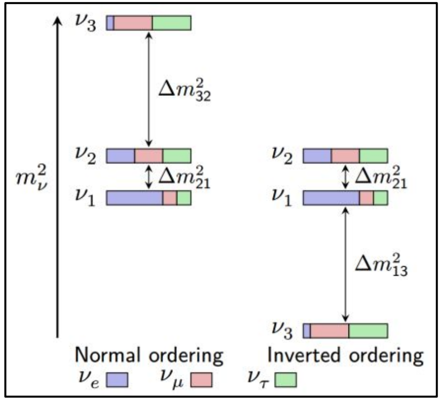


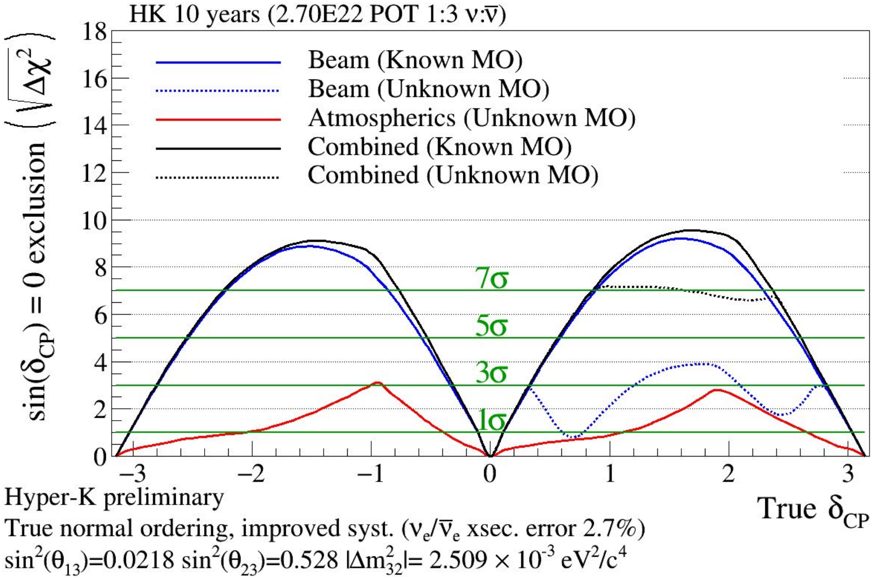



# Neutrino Mass Ordering in Hyper-K

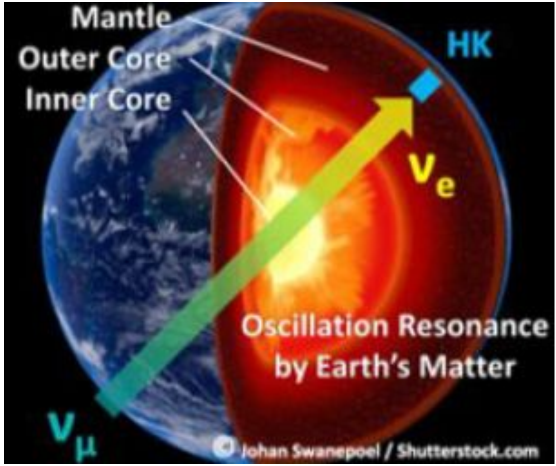
- Combination of beam and atmospheric data → Improves sensitivity to $\delta_{CP}$ and MO
- HK (2027~) determines MO at **$5\sigma$ in 6-10 years**, depending on the true value of $\sin^2\theta_{23}$
- JUNO (2025~) will reach $3\sigma$ in 5-7 years; DUNE (2031~) will reach $5\sigma$ in 1-3 years

Mass ordering




Atmospheric $\nu$ oscillation



# Neutrino-Nucleus Interactions

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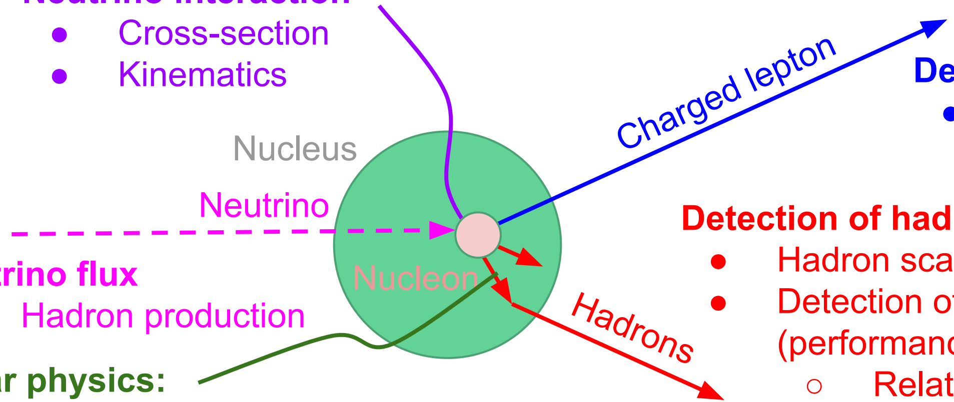
- We cannot see neutrinos directly
- Must infer neutrino properties (energy and type) from the products of an interaction
- Challenges vary across experiments: different target nuclei and detection techniques

**Neutrino interaction**
- Cross-section
- Kinematics




**Detection of charged leptons**
- PID and efficiency are relatively well known

**Detection of hadrons**
- Hadron scattering in detector
- Detection of short tracks or weak Cherenkov rings (performance strongly depends on the detector)
    - Relatively large uncertainty in detection efficiency

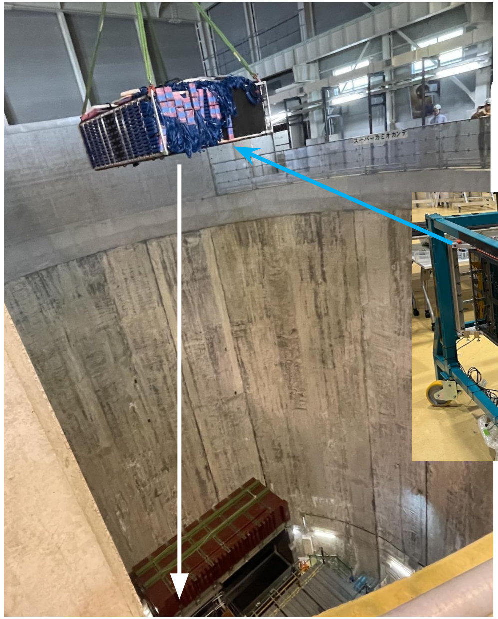
**Neutrino flux**
- Hadron production

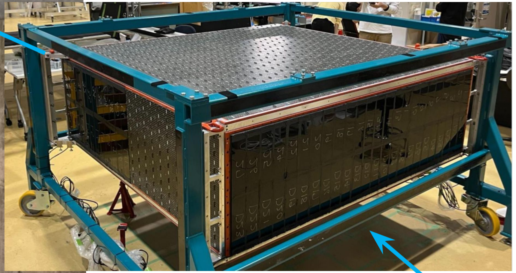
**Nuclear physics:**
- Nucleon momentum (Fermi motion)
- Multi-nucleon correlations
- Hadron scattering in nucleus (FSI)

These depend on the target nucleus

# Near Detector (ND280) Upgrade

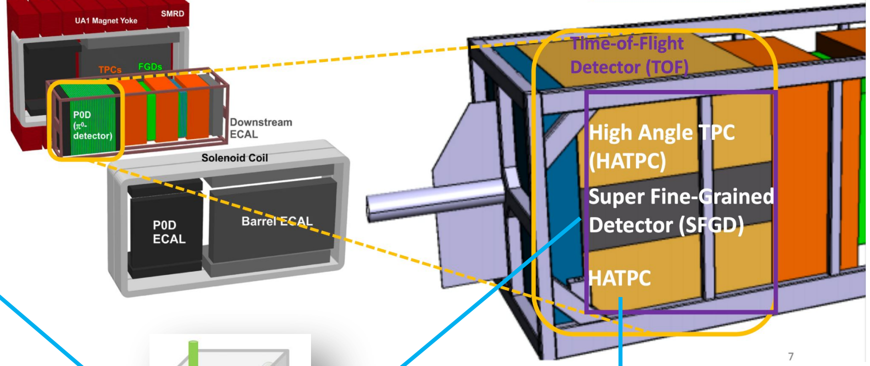
C. Giganti @ NEUTRINO2024

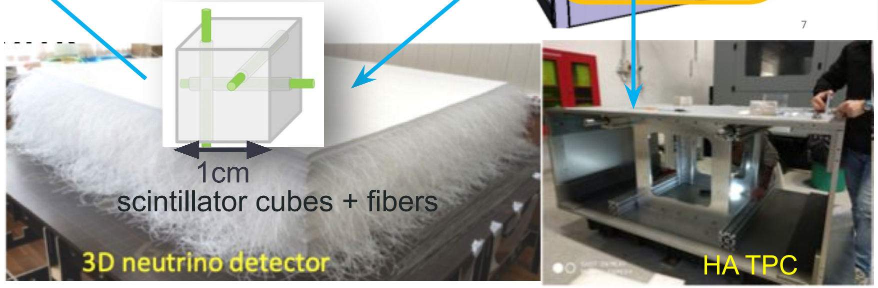




- Measures $\nu$ beam flux & cross section at 280m downstream of the $\nu$ source
  - Further consideration (ND280++) required for Hyper-Kamiokande

(Technical Design Report on T2K, arXiv:1901.03750)

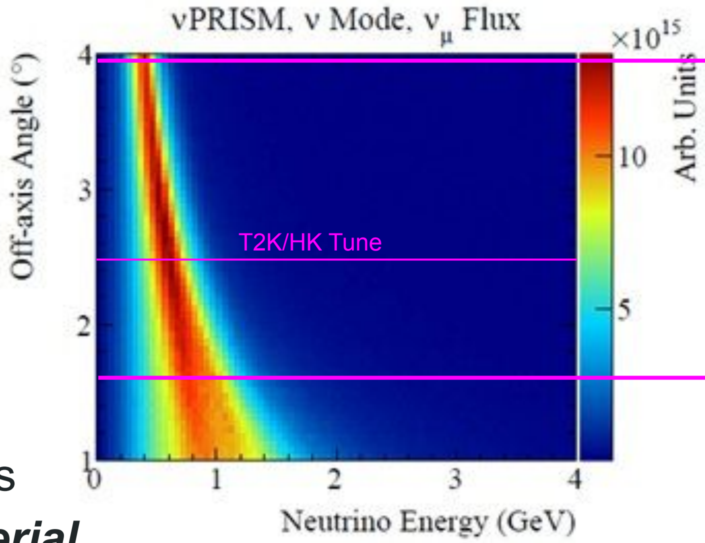


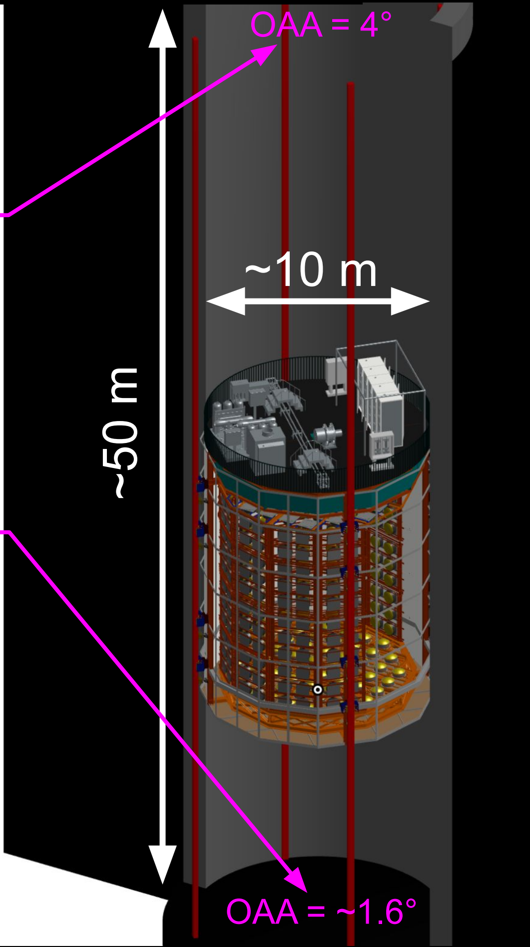




- Central part upgraded in 2024: Super-FGD, High-Angle TPCs, ToF
  - ➢ Improved angular acceptance of lepton tracks, lower the threshold for hadrons

# The Intermediate Water Cherenkov Detector (IWCD)

- New detector at ~830 m away from the beam source
- Measure $\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} / \frac{\sigma(\overline{\nu_e})}{\sigma(\overline{\nu_\mu})}$ a significant systematic for the CPV measurement
- Oscillated energy spectrum very different from unoscillated spectrum
  - ➢ Measure neutrino beam at different energies with ***same detector material***

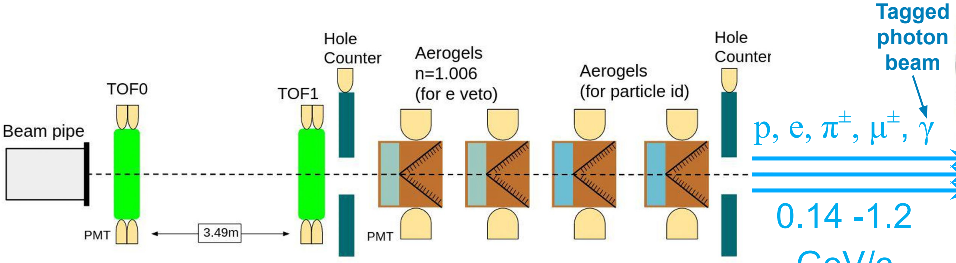


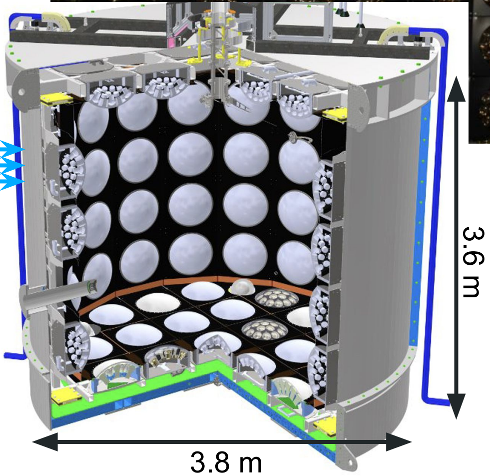




- **nuPRISM concept: Move IWCD vertically** → vary OOA → different neutrino energy spectra → improved neutrino interaction measurements

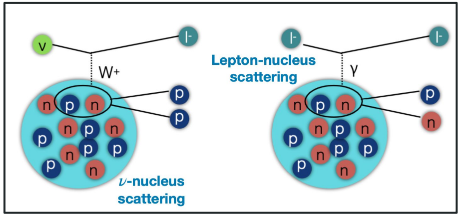
# The Water Cherenkov Test Experiment (WCTE)

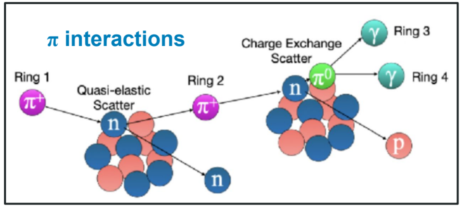
- Prototype of IWCD @ CERN
- Demonstrator for new photosensor, calibration, and ML event reconstruction and simulation technologies
- Constrain neutrino experiment modeling



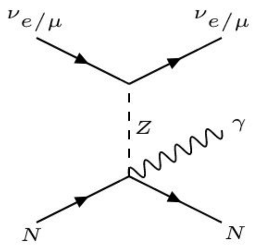


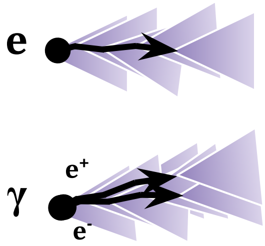


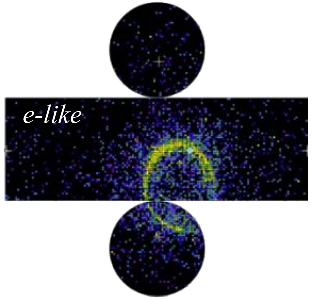



# Gamma (γ) Identification

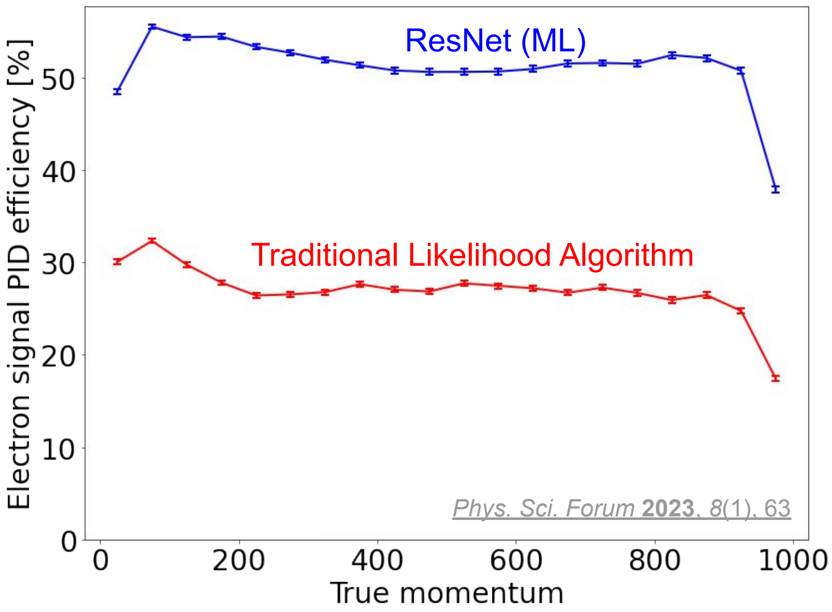
- NCγ is a significant poorly understood background for CPV
  - ➢ Need data driven constraints



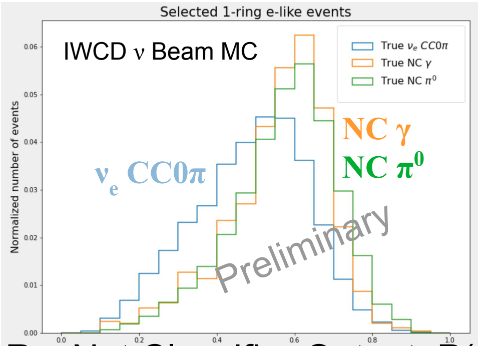




*e* efficiency when rejecting 80% of *γ*




- *γ* and *e* almost indistinguishable in water Cherenkov detectors

- ML shows promise with some statistical separation
  - ○ To be tested in WCTE

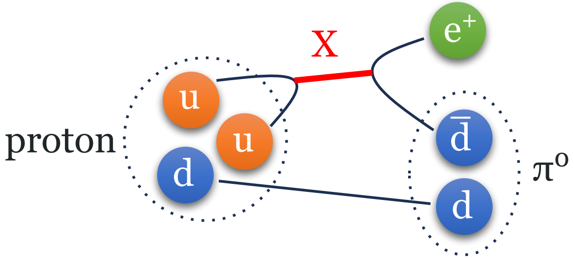



ResNet Classifier Output: P(γ)

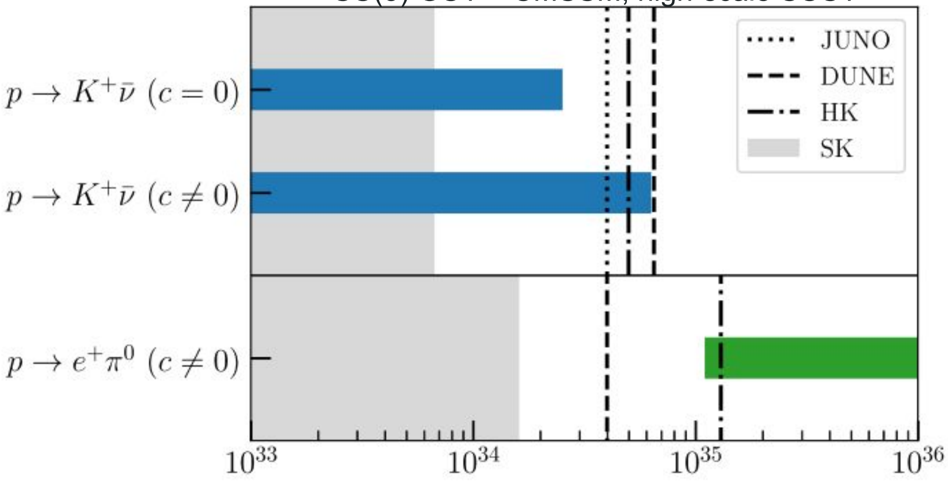
# Nucleon Decay

John Gargalionis, Day 1

- Probe of new physics: **GUT, SUSY-GUT**
- Minimal SU(5) model is already ruled out, but SUSY GUT models are still viable



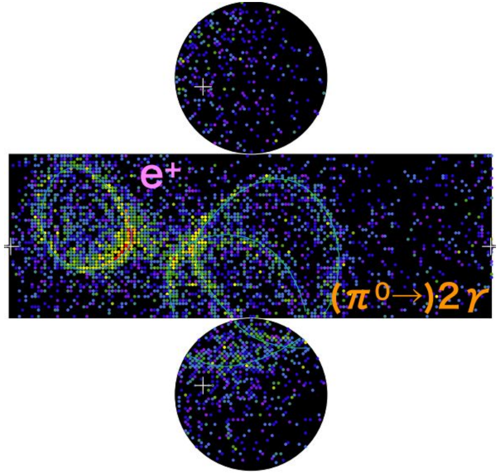

SU(5) GUT + CMSSM, high-scale SUSY




Eur. Phys. J. C80, 332 (2020)

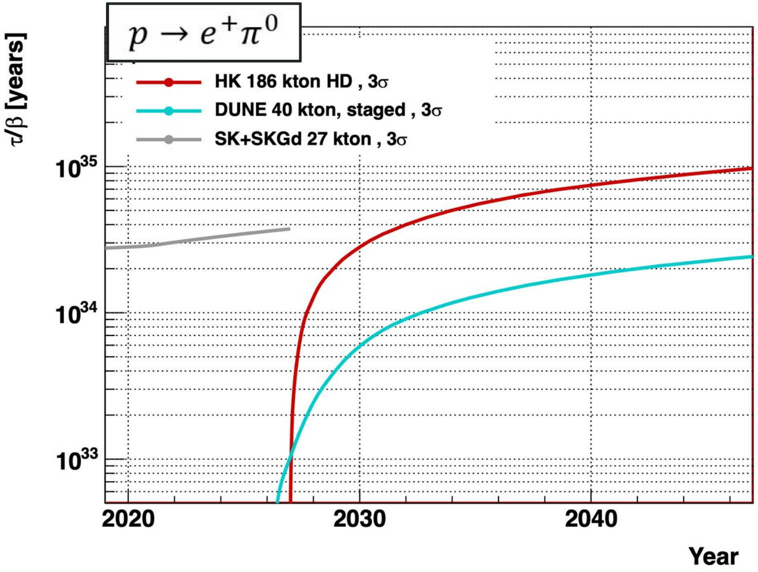
Lifetime (years)

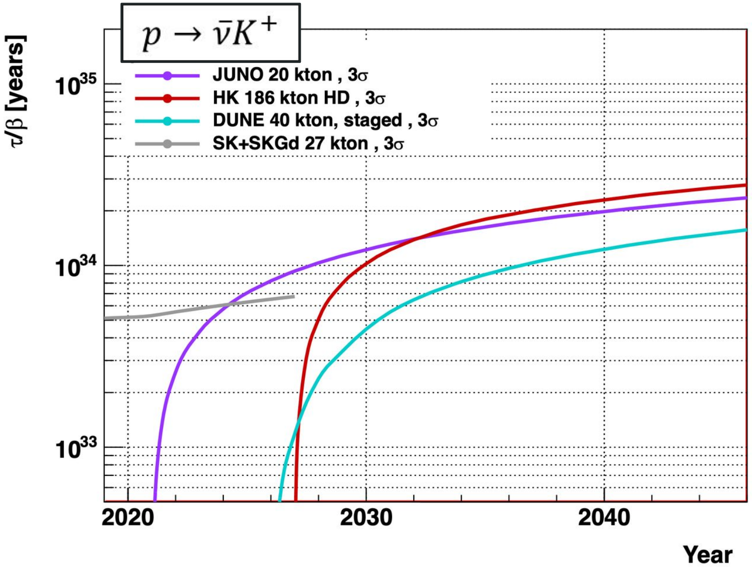
$p \to e^+\pi^0$ (SK, simulation)



# Nucleon Decay in Hyper-K

- HK advantage: large mass → many protons, and free protons in $H_2O$
  - Less degradation of efficiency by Fermi motion and nuclear effects
- **World-leading sensitivity** in two golden channels ($p \to e^+\pi^0$, $p \to \bar{\nu}K^+$)
  - JUNO and DUNE also have advantages on detecting $K^+$ in $p \to \bar{\nu}K^+$ channel
  - Search of sub-dominant modes helps to test different GUT groups, flavour structure

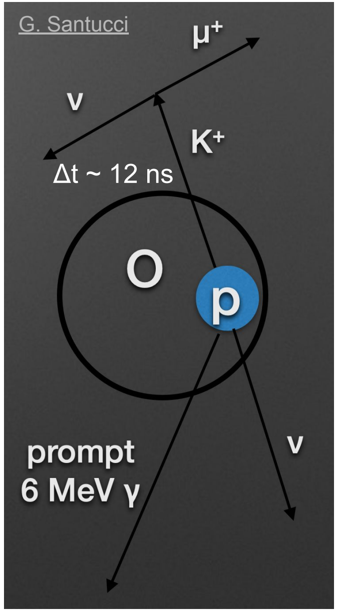


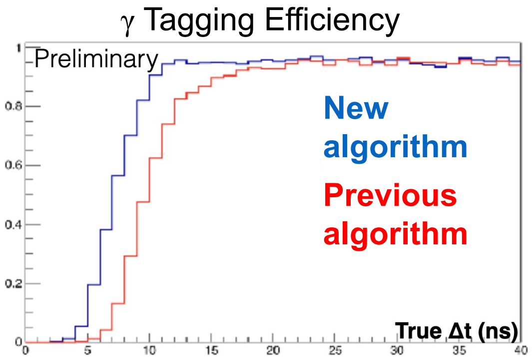



# Nucleon Decay Analysis Prospects

- Ongoing reconstruction developments on analysis side to improve sensitivities

- New algorithm: Fit $\mu + \gamma$ tracks, assuming same vertex at different times

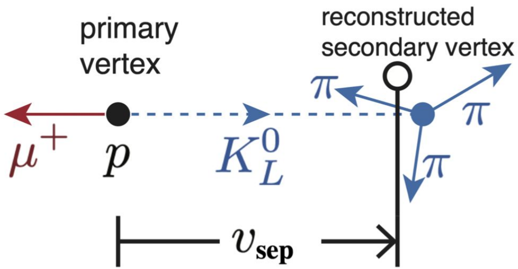


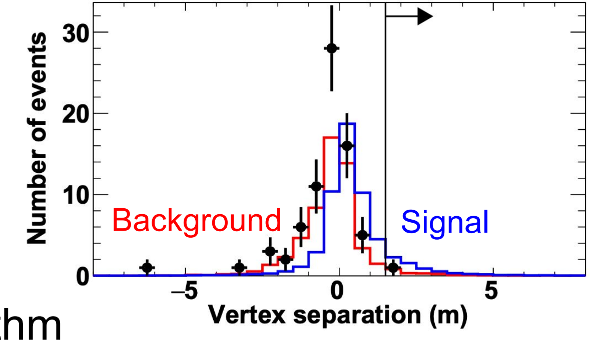

- 9.4% → 13.9% (1.5x) efficiency gain with similar background

arXiv:2208.13188

- New algorithm: Assume second vertex for additional rings after the first

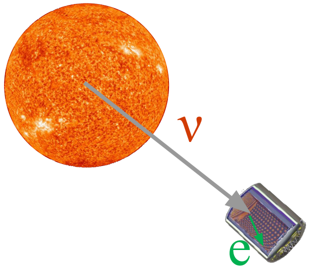


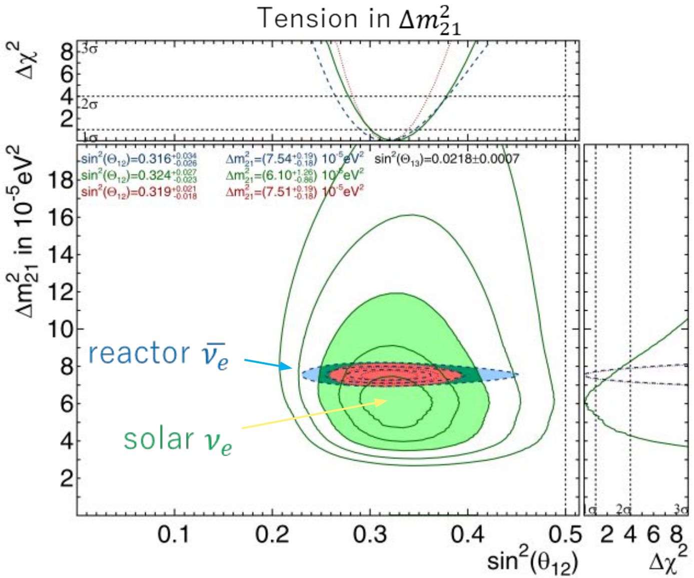

- Improved background rejection (~⅓) with similar efficiency (~90%) compared to previous algorithm

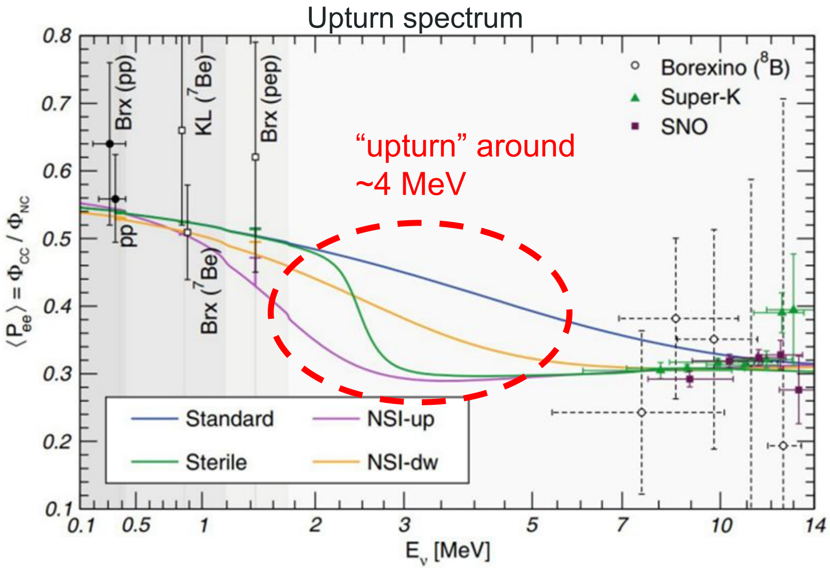


# Solar Neutrinos in Hyper-K

- Recent measurements focus on (non-standard) neutrino oscillation in matter of sun and earth.
- $\sim 1.5\sigma$ tension exists between the $\Delta m^2_{21}$ in solar ($\nu_e$) and reactor ($\bar{\nu}_e$) data.
  → CPT violation? Non-Standard Interaction (NSI) in matter?
- NSI models can also be tested in the $P(\nu_e \to \nu_e)$ spectrum "upturn".
  →HK can observe "upturn" at >3 $\sigma$ in 10 years.



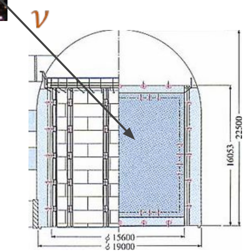



# Supernova Burst Neutrinos

Meng-Ru Wu, Day 4

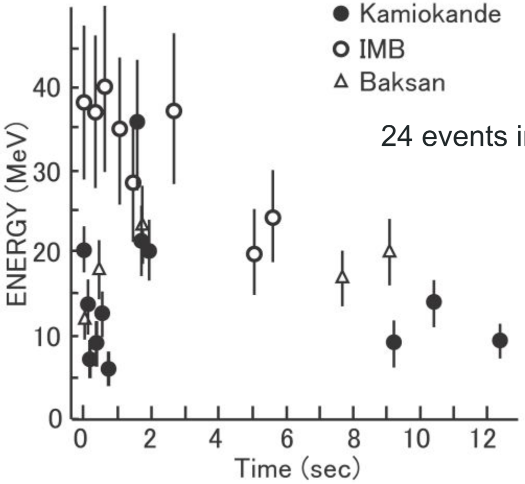
- Neutrinos carry out 99% of the energy from supernova.
- SN1987A at 50 kpc: first and the only detection of supernova burst neutrino
  Confirmed that neutrinos bring most of the burst energy only in 10 sec.

SN1987a




Kamiokande
(1st gen)

Neutrinos observed in 1987a

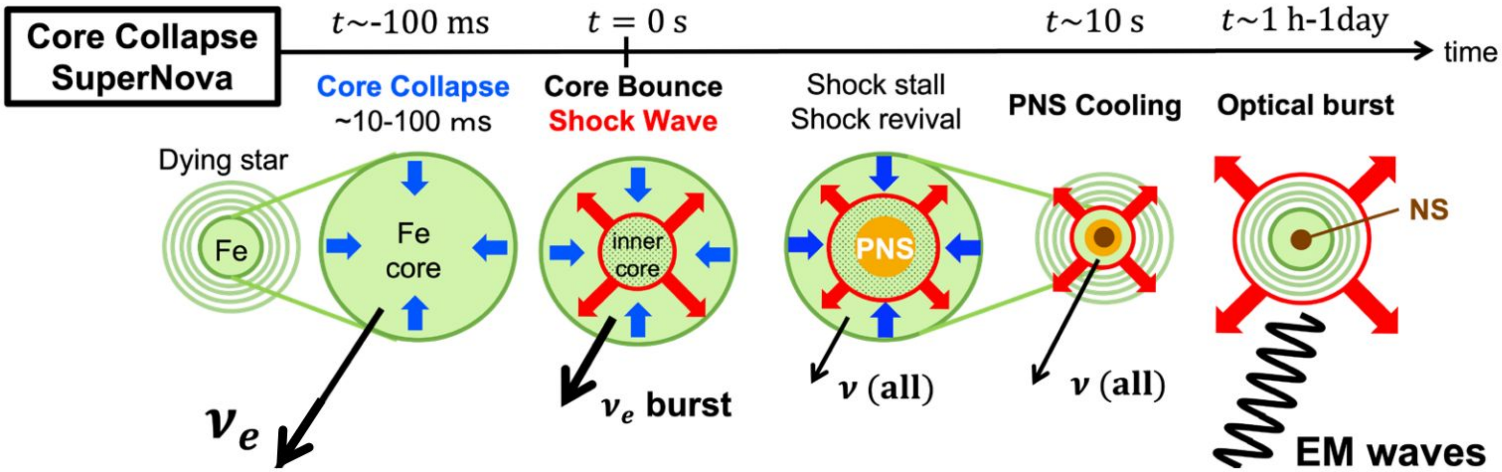



24 events in total

# Supernova Burst Neutrinos

Meng-Ru Wu, Day 4

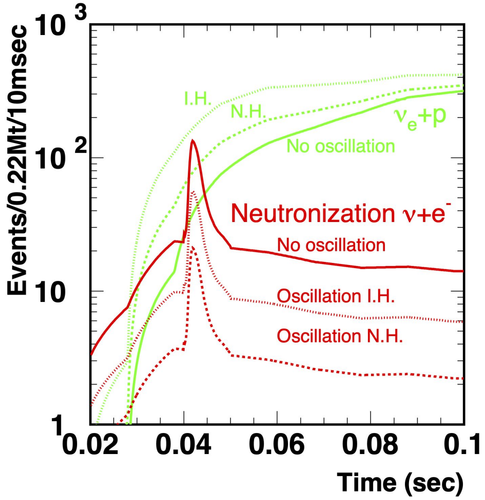
- Neutrinos carry out 99% of the energy from supernova.
- SN1987A at 50 kpc: first and the only detection of supernova burst neutrino
  Confirmed that neutrinos bring most of the burst energy only in 10 sec.
- **Explosion mechanism** is still unclear. Explosion fails in many simulations.
  Multi-dimensional effect such as SASI (Standing Accretion Shock Instability) is required for explosion to happen.



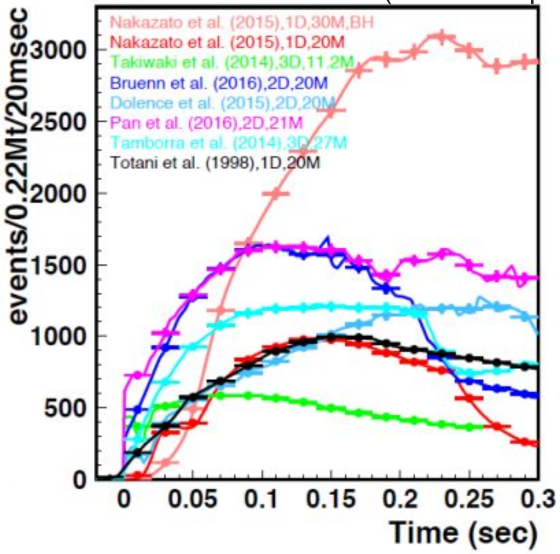
# Supernova Burst Neutrinos in Hyper-K

Meng-Ru Wu, Day 4

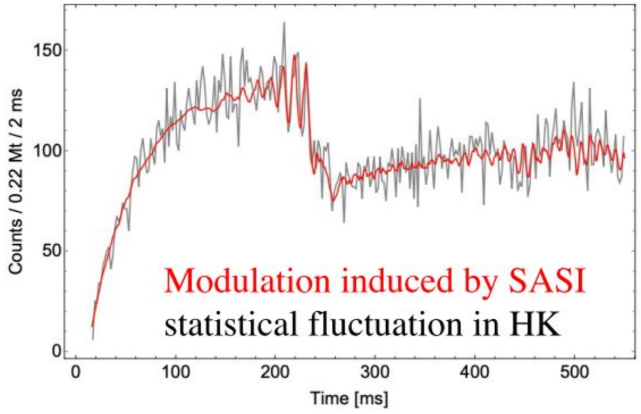
- HK advantage: large statistics, direction reconstruction
  → Model discrimination, access to ~1 Mpc (Andromeda galaxy)
- Distinguish explosion models from rate, energy variation in time
- ~70k events expected at ~10 kpc (SN in this galaxy)




Event rate simulations (SN at 10 kpc)




Detailed time structure



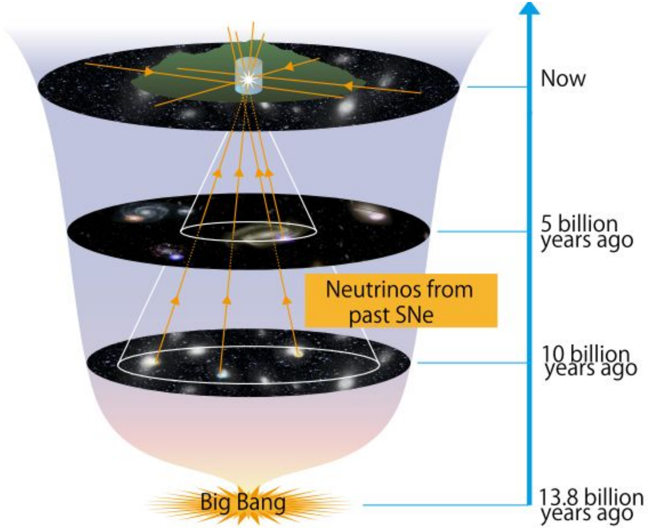
# Supernova Relic Neutrinos (SRN)

- Neutrinos from past core-collapse supernova
  → Flux depends on supernova rate, fraction of black-hole formation etc.

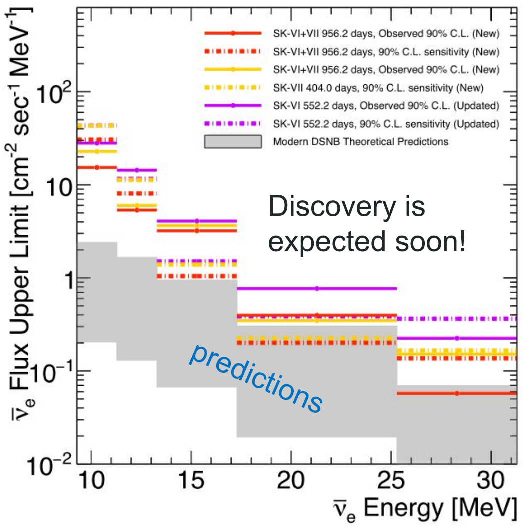
$$\phi \propto \int [\text{SN rate}] \times [\text{SN } \nu \text{ emission}] \times [\text{cosmic expansion}]$$

large uncertainty: effect of dust, failed supernovae forming blackholes, etc.

- Potential to open a new window in neutrino astronomy



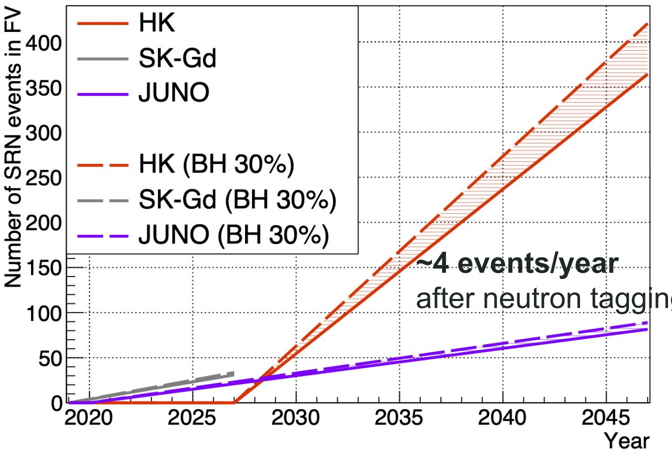

SRN flux upper limits



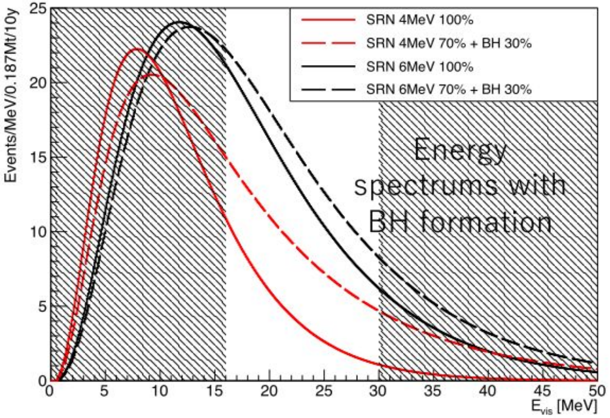
# Supernova Relic Neutrinos (SRN) in Hyper-K

- HK aims for precise flux & spectrum measurement.
- Expect to reach >4σ in 10 years
  - JUNO also has high sensitivity (~5σ in 10 years for optimistic scenario)

Expected number of events




Black hole formation rate affects the SRN spectrum




SRN signal window: 16-30 MeV

# Global Competition

KAVLI IPMU

Liangjian Wen @ FB23

| Exp. | Time | Mass ordering | CP phases | Precision Meas. | CCSN burst @ 10 kpc | DSNB | Geo-ν | Solar | Proton Decay (sensitivity@10 y) |
|---|---|---|---|---|---|---|---|---|---|
| **JUNO (20 kt)** | 2024 | **3-4 σ** *6 y* | — | **$\sin^2\theta_{12}$ (0.5%), $\Delta m^2_{21}$ (0.3%), $\Delta m^2_{31}$ (0.2%),** *6 y* | **all-flavor ν (IBD, eES, pES)** | **3σ**, *3 y* | **~400/y** | **$^7$Be, pep, CNO, $^8$B** | > 9.6x10$^{33}$ y ($\bar{\nu}K^+$) |
| DUNE (17 kt*4) | 2030 | **>5 σ** *1-3 y* | 5σ (50%) *10 y* | $\Delta m^2_{32}$ ~0.4%, $\sin^2\theta_{23}$~*1.1% *, 15 y* | **$^{40}$Ar CC & NC, eES** | $^{40}$Ar CC | — | $^8$B, hep | >8.7x10$^{33}$ y ($e^+\pi^0$) >1.3x10$^{34}$ y ($\bar{\nu}K^+$) |
| HyperK (260 kt) | 2027 | **3-5 σ** *10 y* | **5σ (60%)** *10 y* | $\Delta m^2_{32}$ ~0.6%, $\sin^2\theta_{23}$~*1.6% *, 10 y* | **eES, IBD** | *3σ, 6 y* | — | $^8$B, hep | **>7.8x10$^{34}$ y ($e^+\pi^0$) >3.2x10$^{34}$ y ($\bar{\nu}K^+$)** |
| ORCA (7 Mt) | Un-known | **2-4 σ** *3 y* | — | $\Delta m^2_{32}$ ~2% , *3 y* | rate excess | — | | | |
| IceCube Upgrade | 2026 | **2-4 σ** *7 y* | — | $\Delta m^2_{32}$ ~1.3% , *3 y* | rate excess | — | | | |

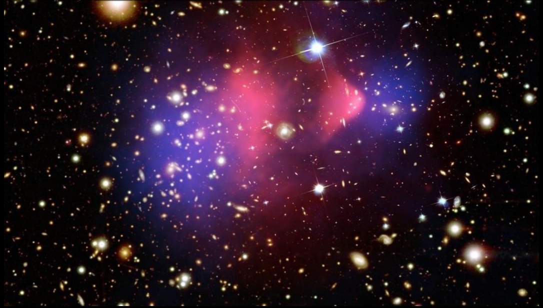
** Upper octant assumption*

eES: ν-electron scattering, pES: ν-proton scattering, IBD: inverse beta decay

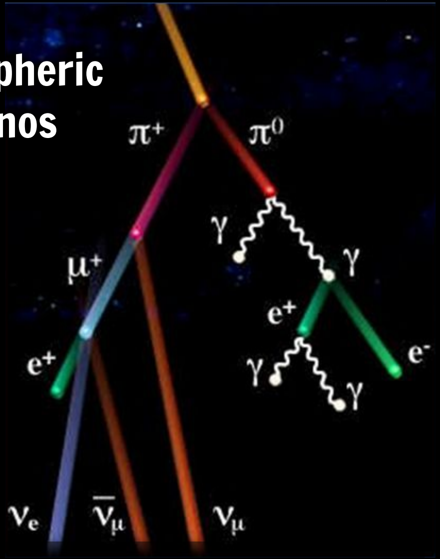
# Rich Science with Future Experiments

Supernova, SRN
(multi-messenger: GW...)

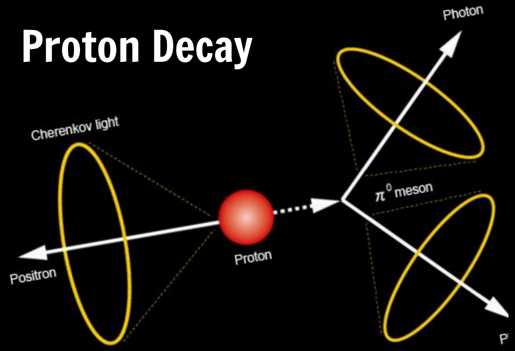
Dark Matter



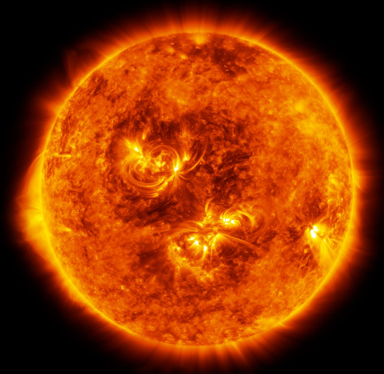
Atmospheric
Neutrinos



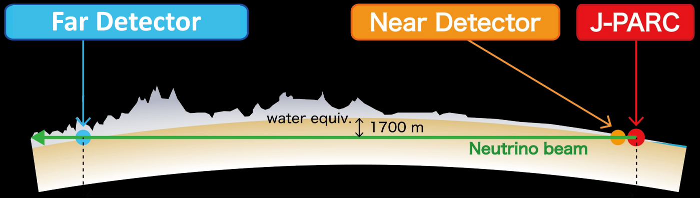

Proton Decay



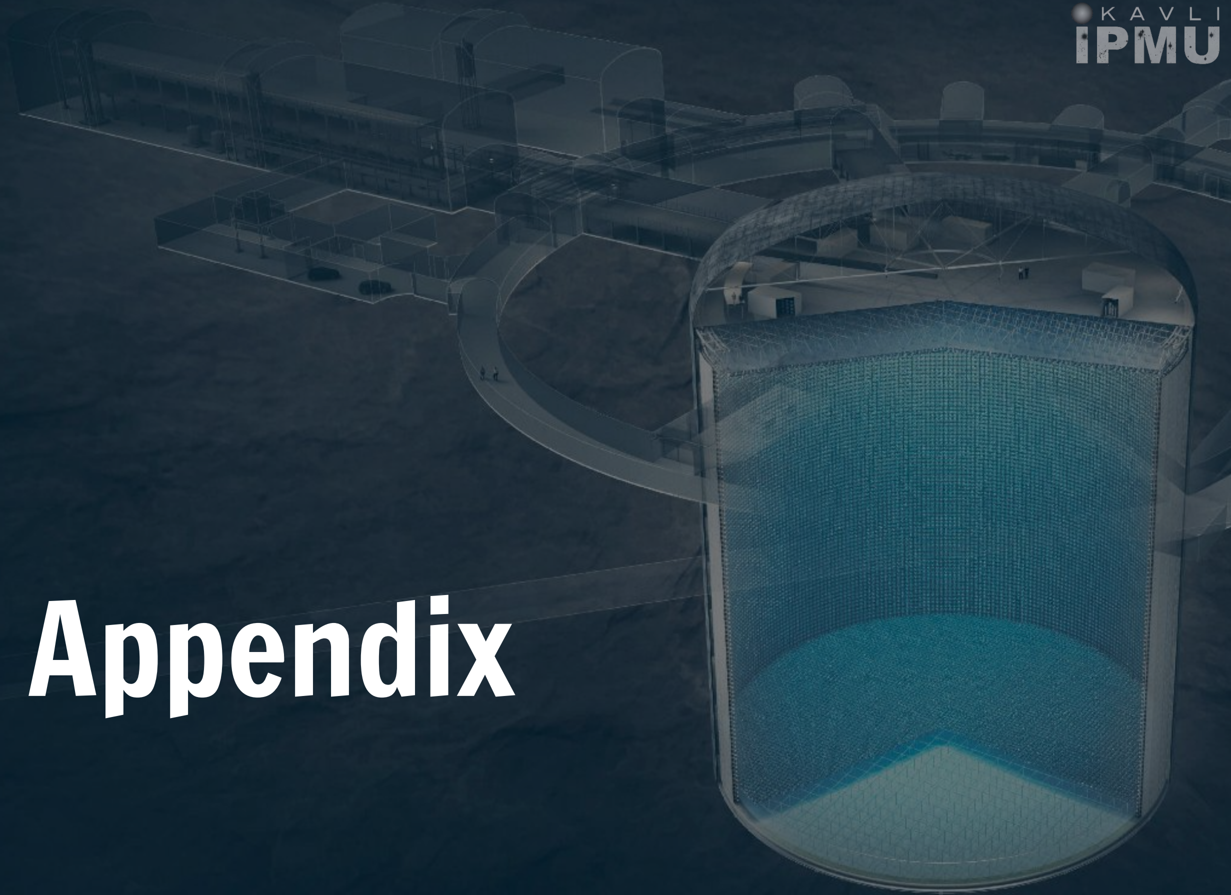

Solar Neutrinos



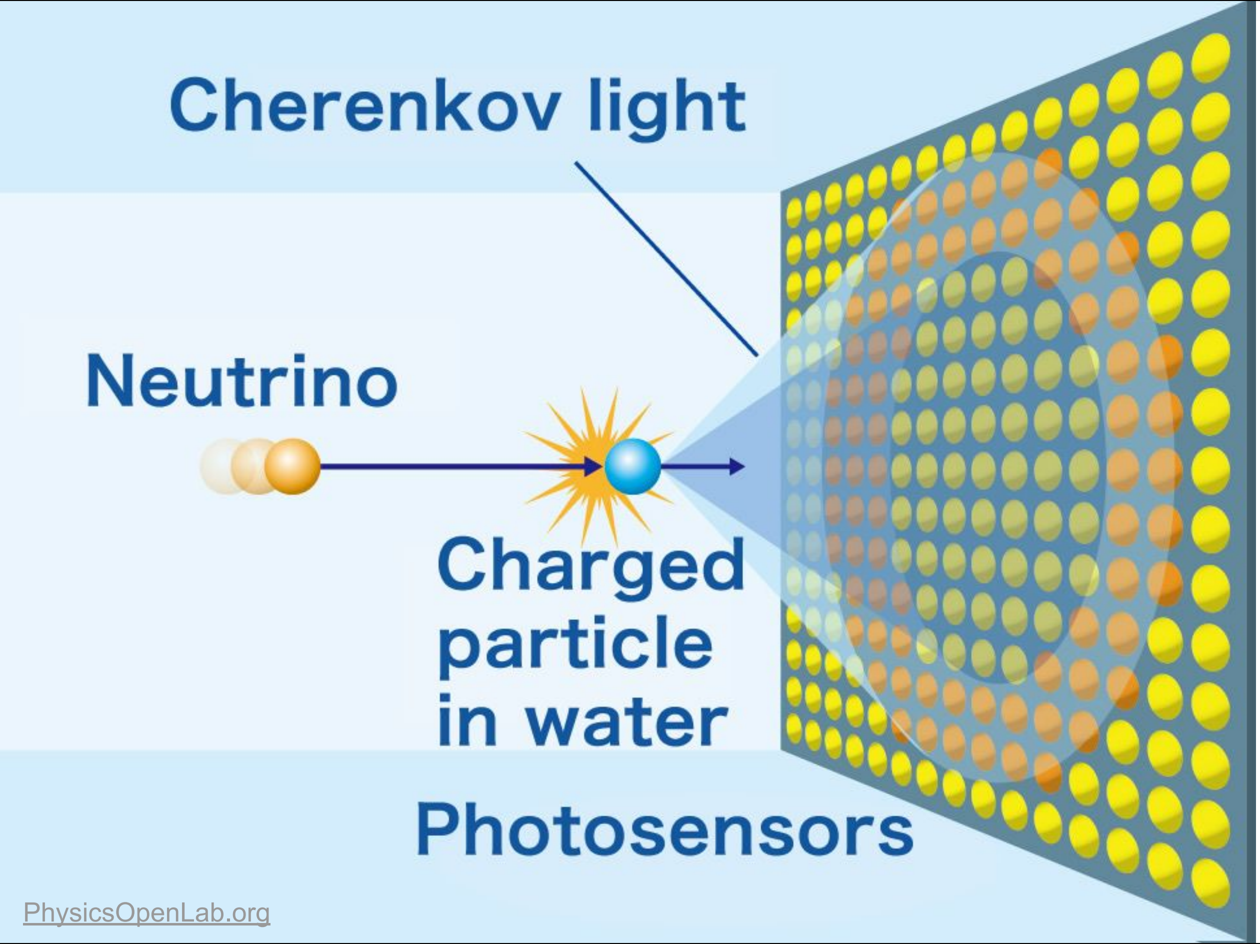
Accelerator Neutrinos



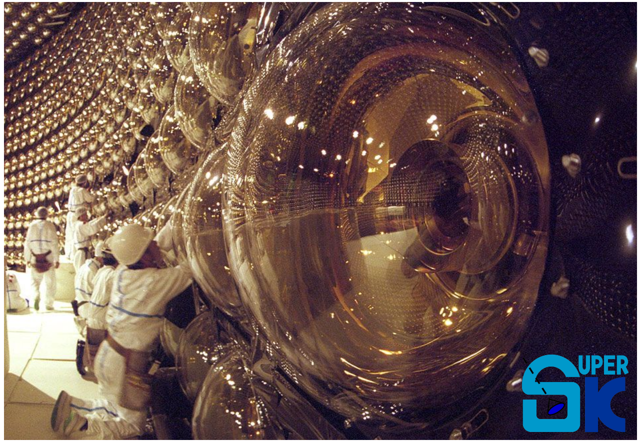
# Appendix

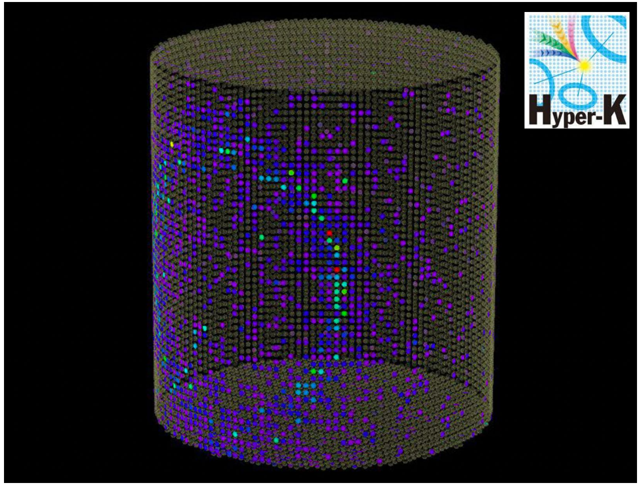


# Water Cherenkov Detector Principle




PhysicsOpenLab.org

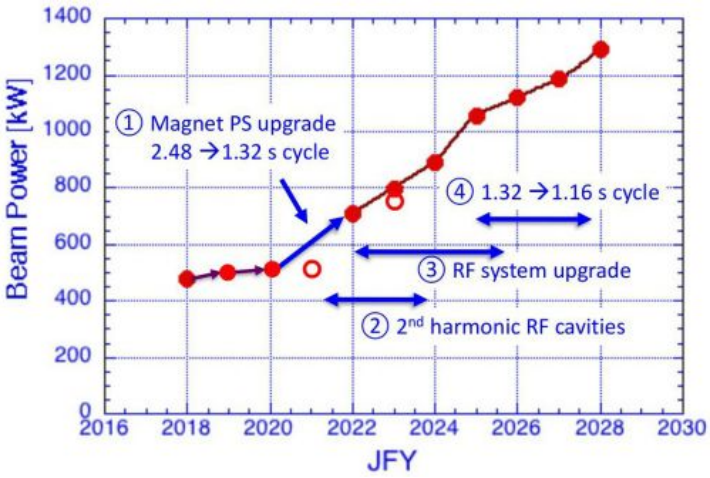


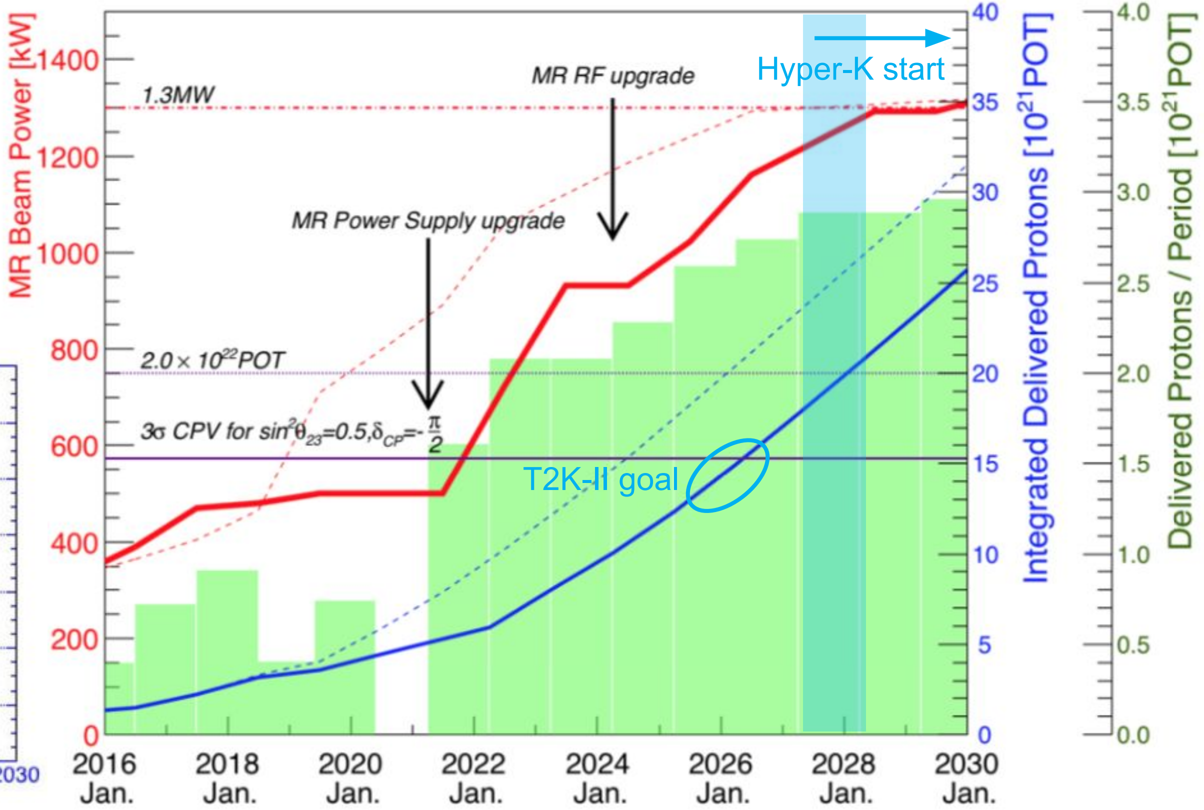
# Beam Line Upgrades Towards T2K-II and Hyper-K

Increase from ~500 kW (2019) to 1.3 MW (2028)

- Cycle time 2.48 → 1.16 sec. (x2)
- Protons per pulse $2.6\times10^{14}$ → $3.3\times10^{14}$ (x1.3)

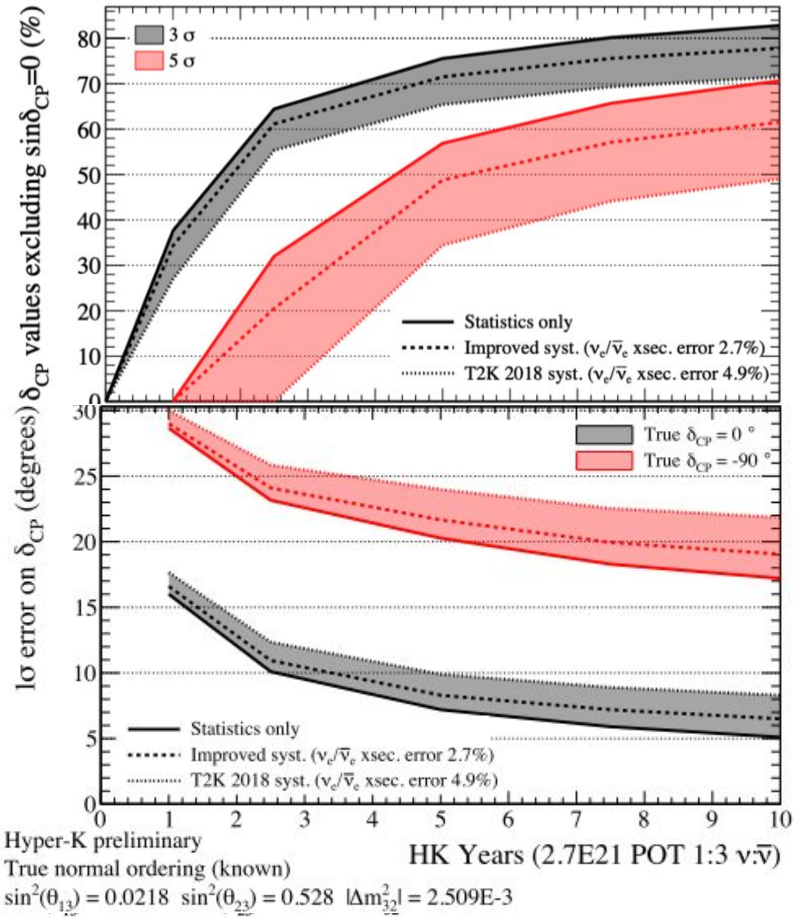


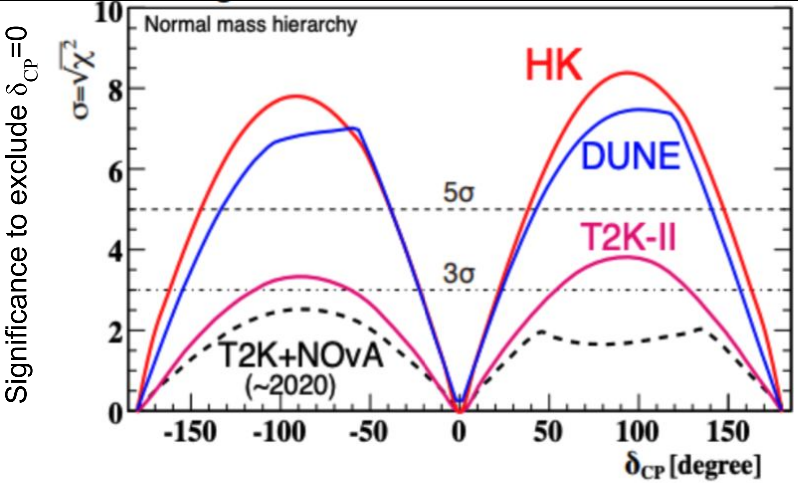

T2K-II Target POT (Protons-On-Target)

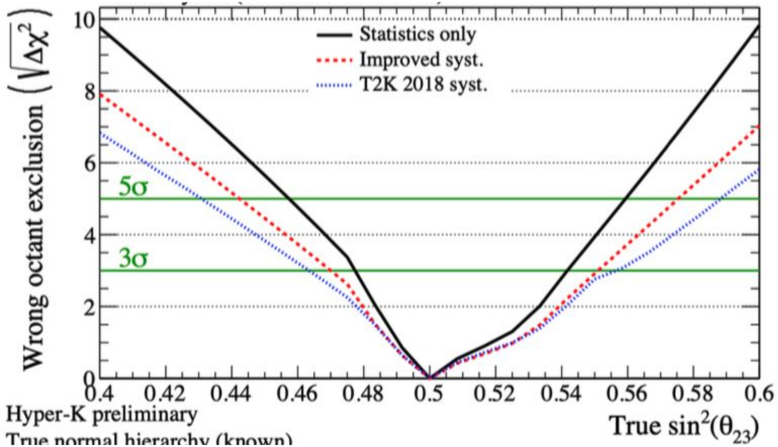


# Hyper-K Long-Baseline Physics





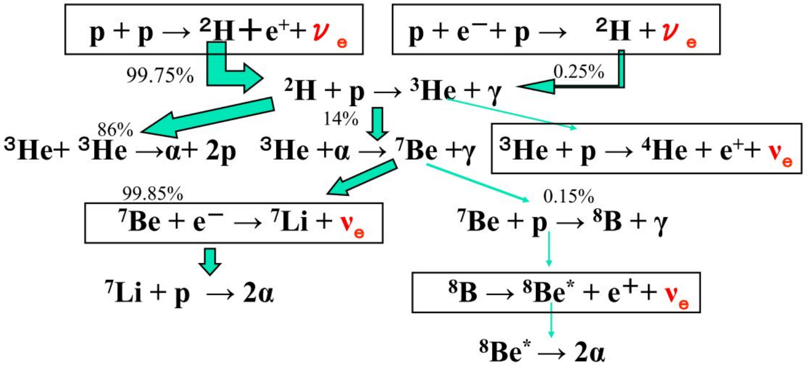



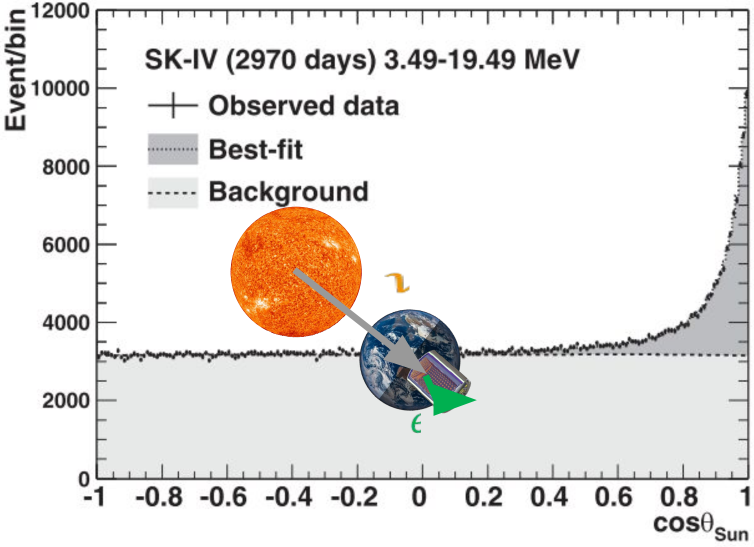
# Solar Neutrinos

- Sun produces ~0-16 MeV $\nu_e$ in the nuclear fusion process.
- Measurement of neutrino flux led to the discovery of neutrino oscillation
- HK advantages: large statistics + directional sensitivity (remove radioactive BG)

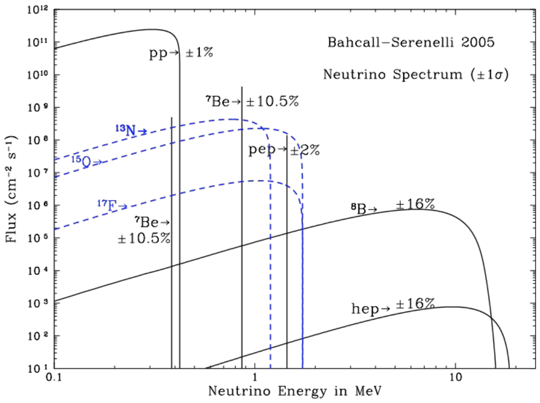
Solar neutrino production (pp-chain)

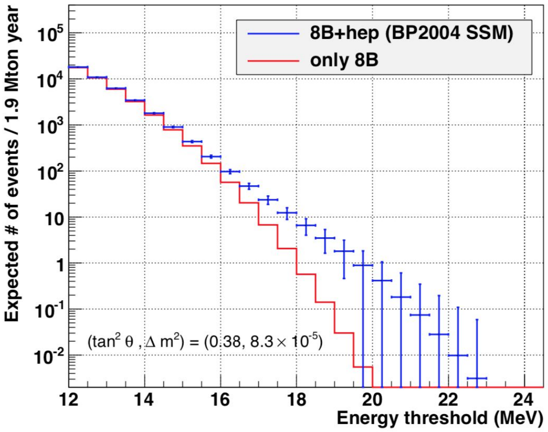


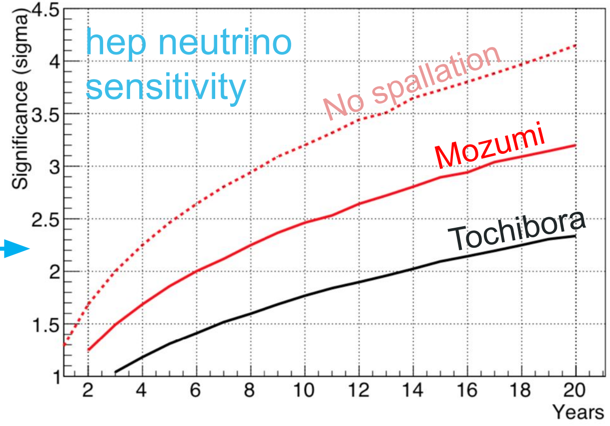

Solar neutrino direction at SK

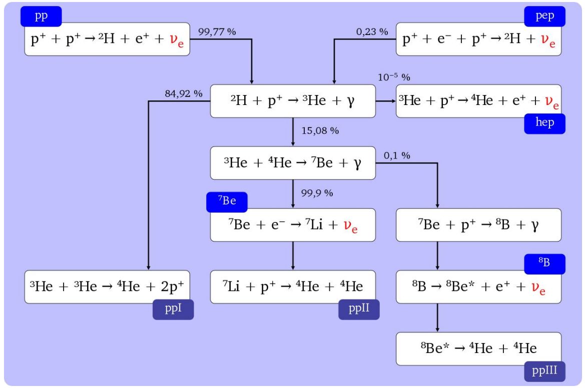


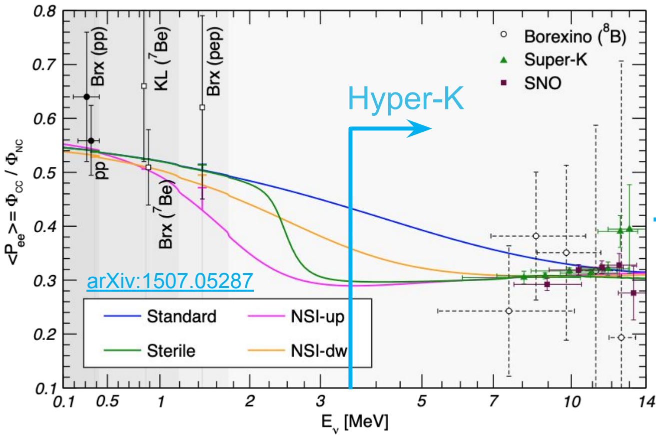
# Solar Neutrinos in Hyper-K

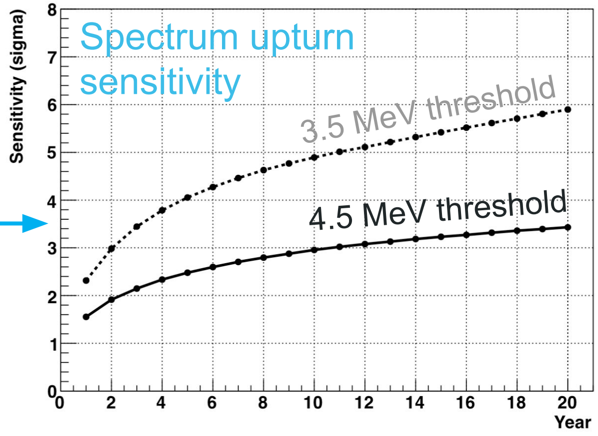


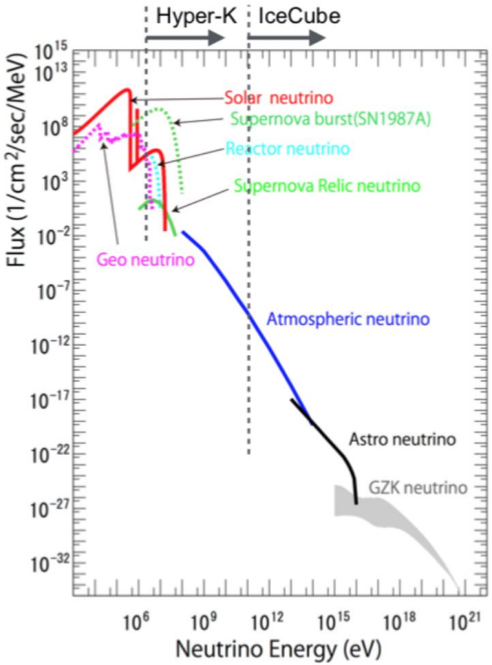



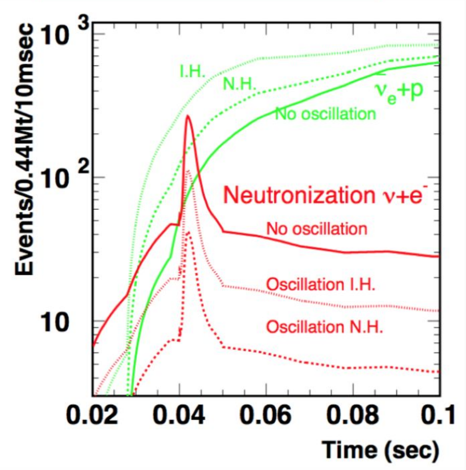



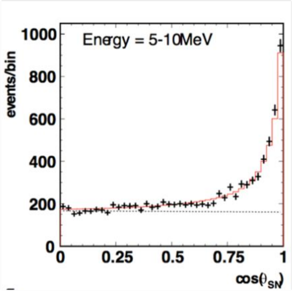



# Supernova Burst in Hyper-K



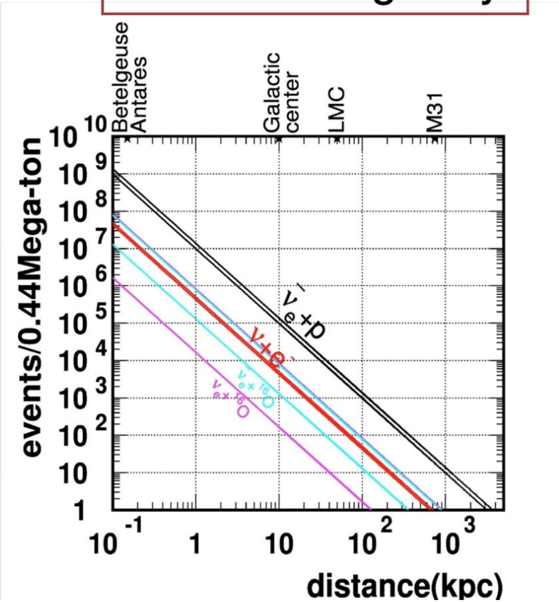

Neutrino carries information of explosion



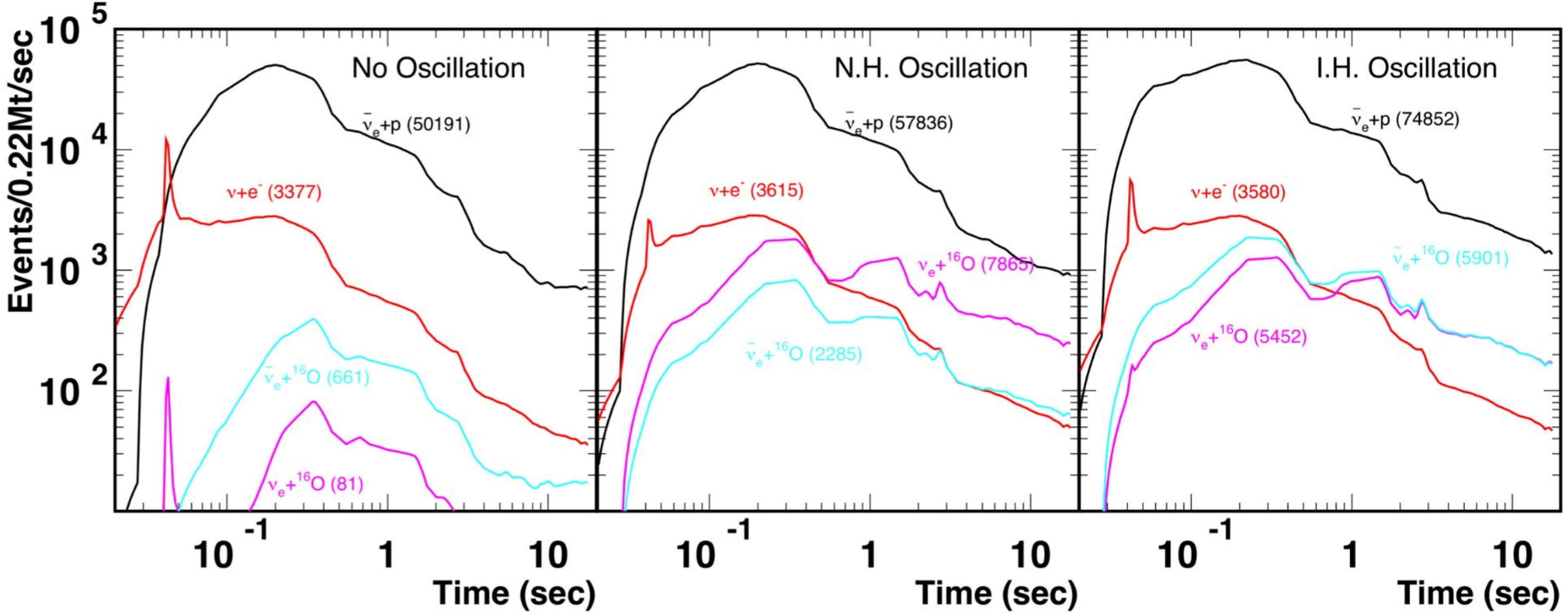




Direction alert for optical measurements ($\nu_e$ elastic)

Reaching Andromeda galaxy



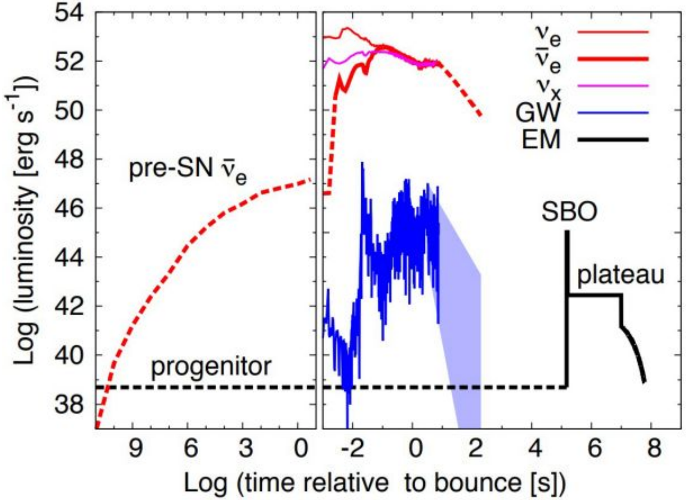
# Supernova Timing Profile



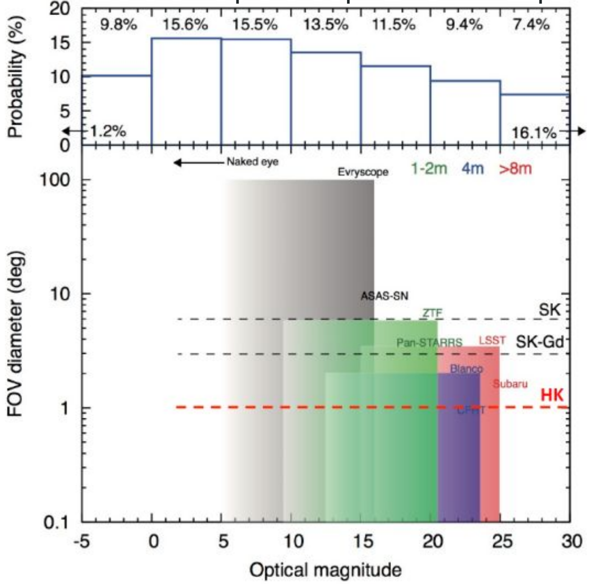
# Supernova Global Alert

- Optical signals will be observed ~2 minutes to ~2 days after neutrinos
  → Supernova alert can be issued
- Pointing (~1-2°) helps **multi-messenger** observation
- Neutrino emission starts even before the explosion
  → pre-supernova alert can also be issued

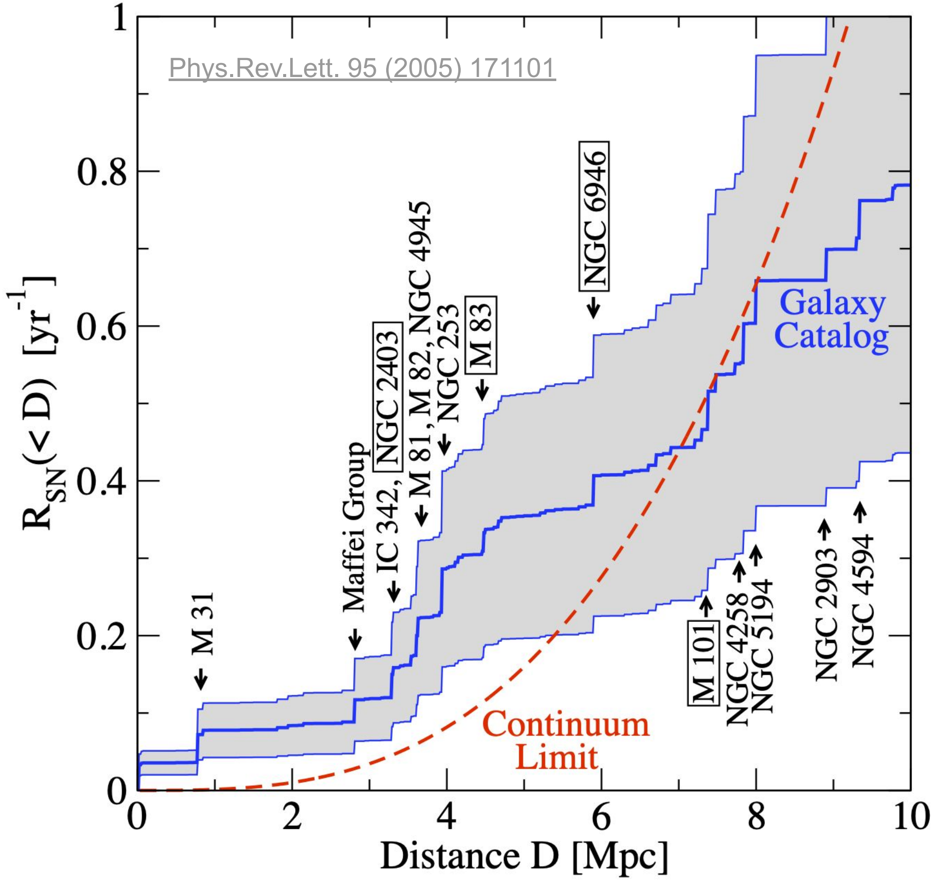
$\nu$ flux before/after explosion

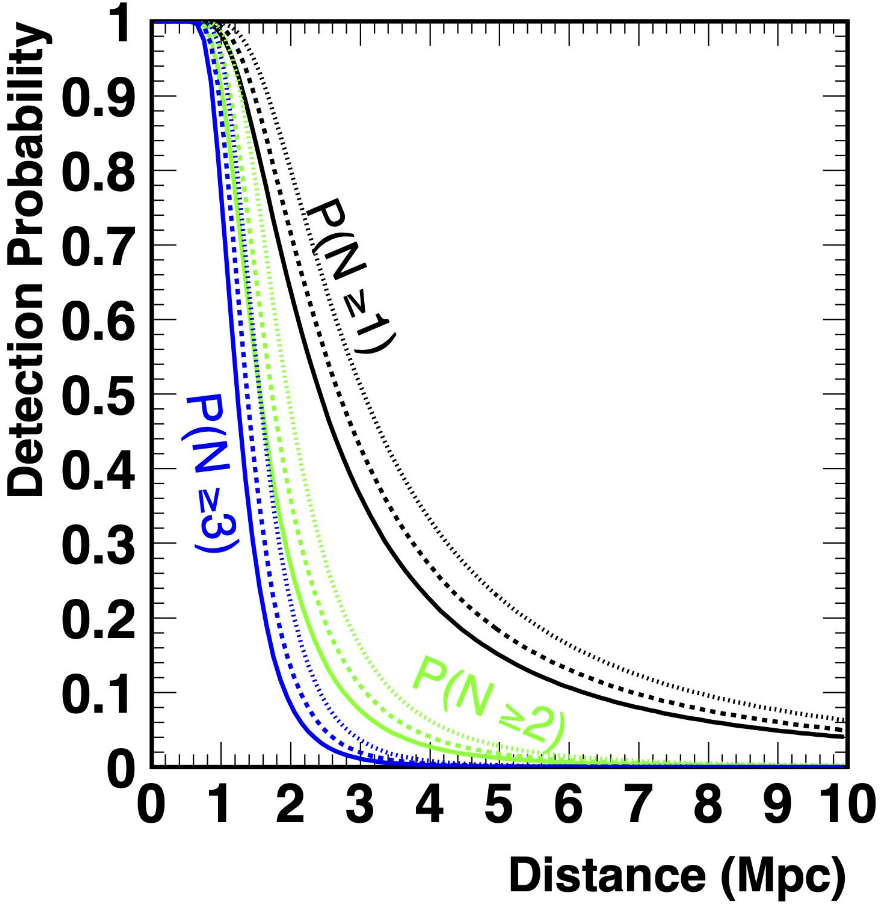



FOV of telescopes compared with HK pointing

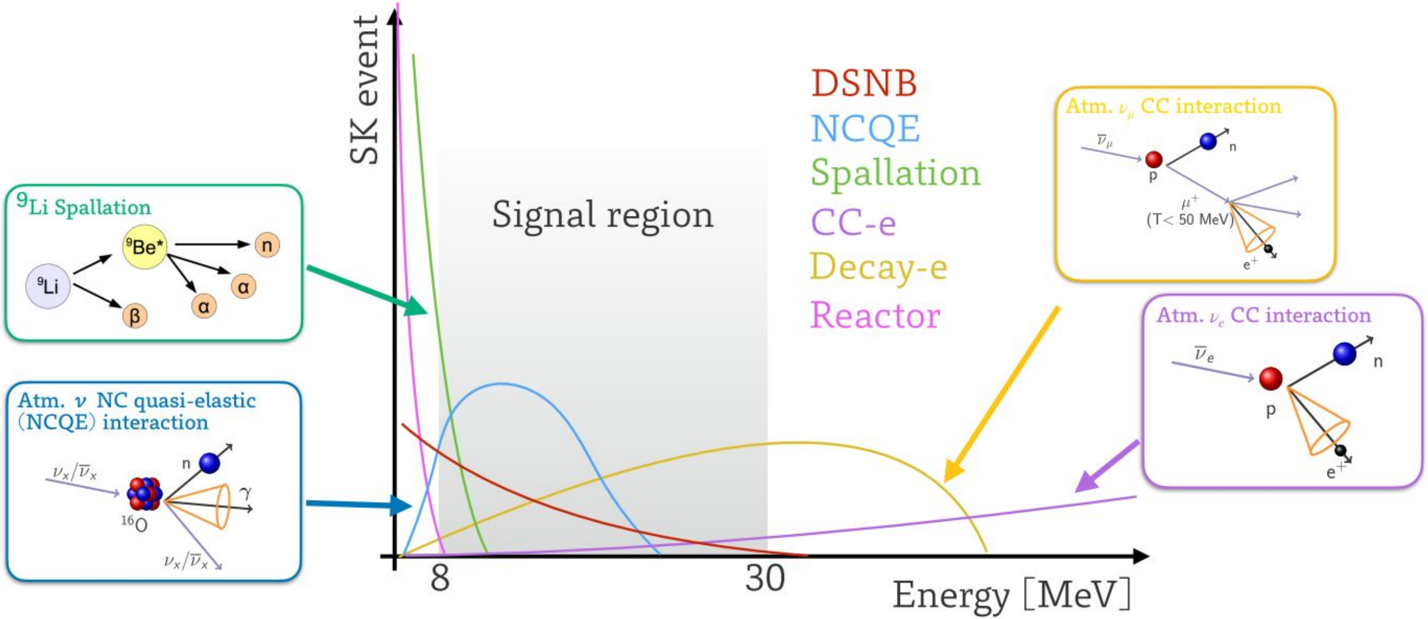


# Extragalactic Supernovae



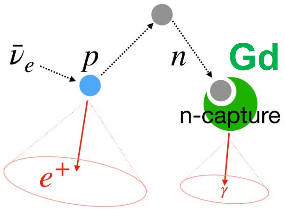
# SRN search window



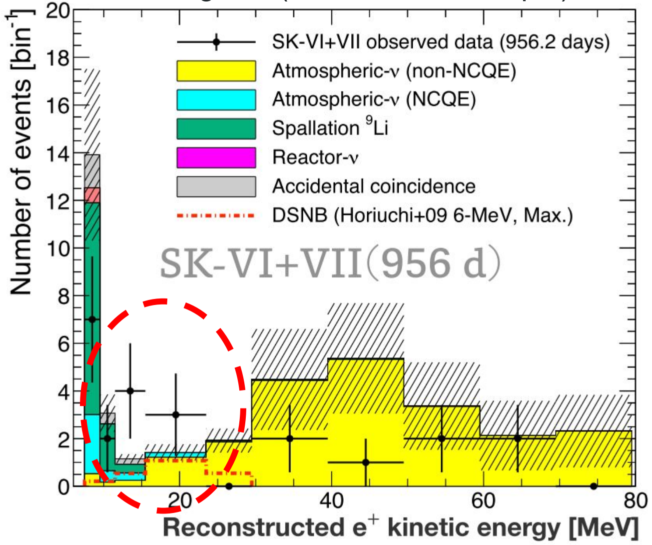

M. Harada, Neutrino2024

# Supernova Relic Neutrinos (SRN) in Super-K

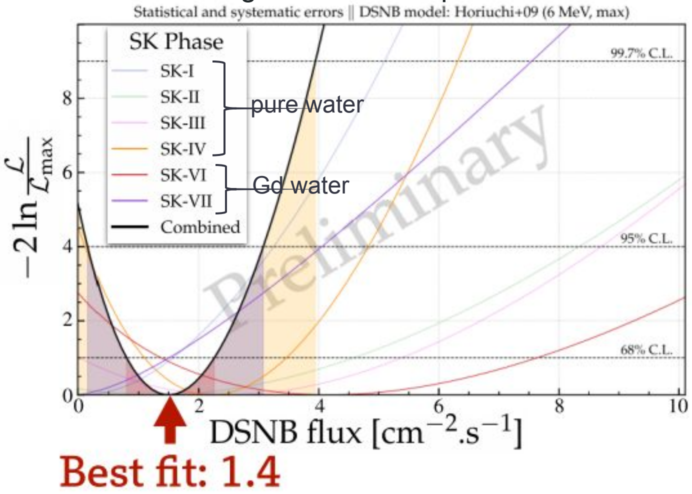
- Main detection channel: $\bar{\nu}_e + p \rightarrow e^+ + \boldsymbol{n}$
  In SK, gadolinium (Gd) was added to pure water in 2020~.
  → Significantly improved SRN efficiency by n-Gd capture signal
- Combining pure- & Gd- water data, **2.3 $\boldsymbol{\sigma}$ excess** of the SRN signal is observed by spectrum fit of signal and sideband samples.




SRN signal? (SK-Gd data example)

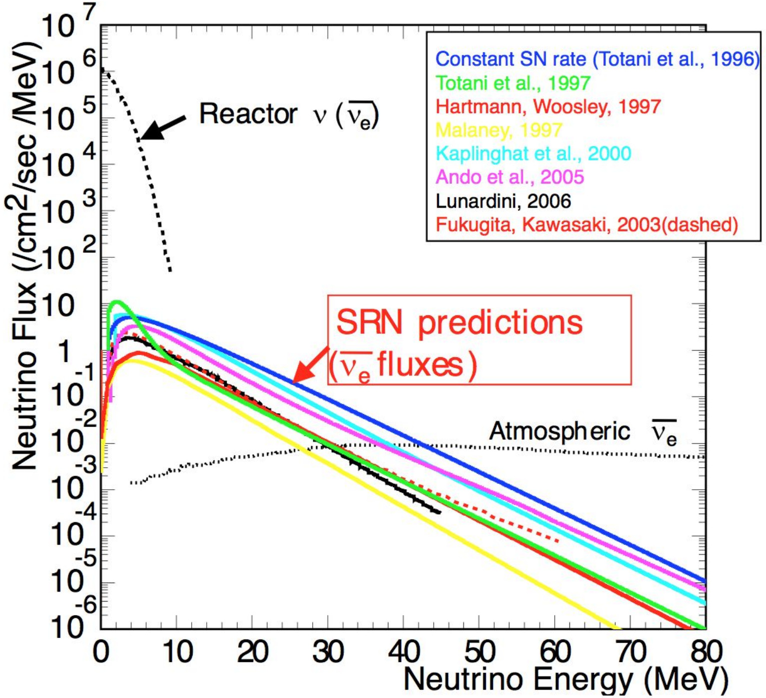


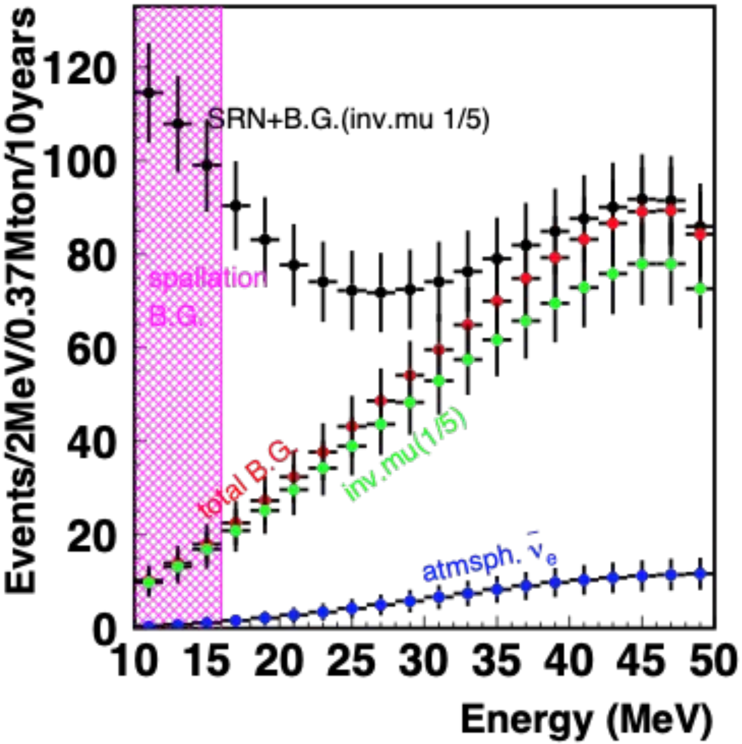

Fitting results from spectrum fits



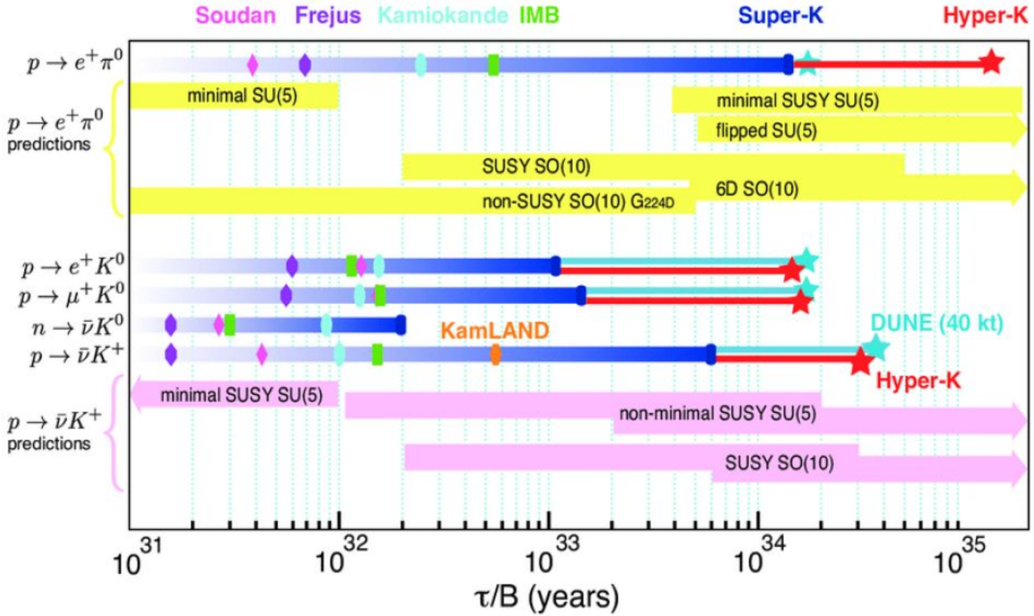
# Hyper-K Supernova Relic Neutrinos

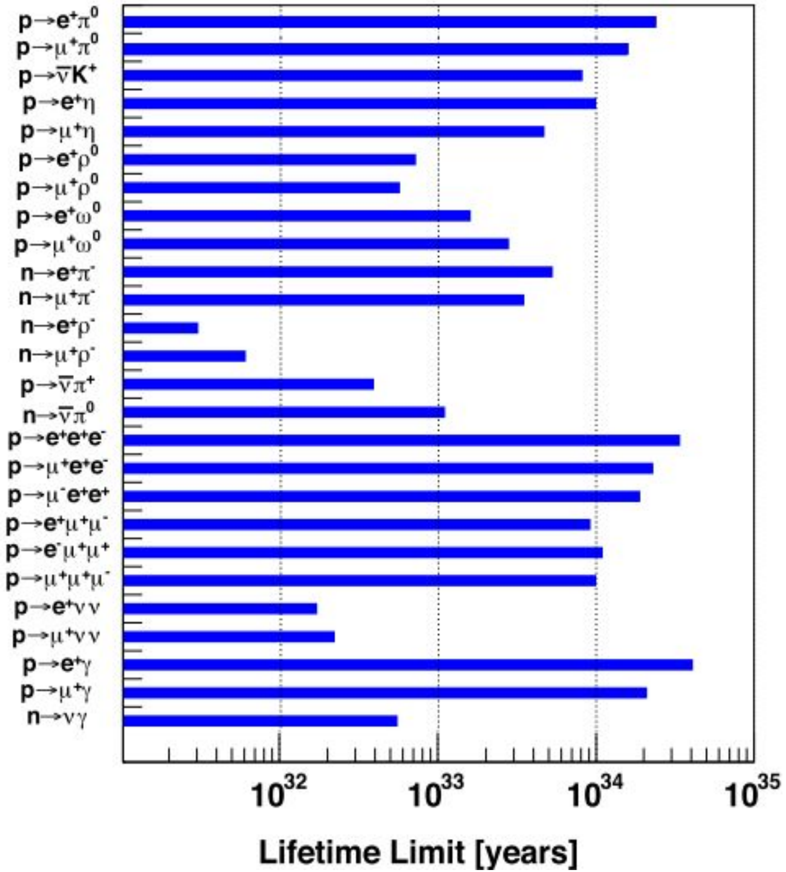
SRN can be observed by HK in 10y with ~70±17 events. It is > 4σ for SRN signal.

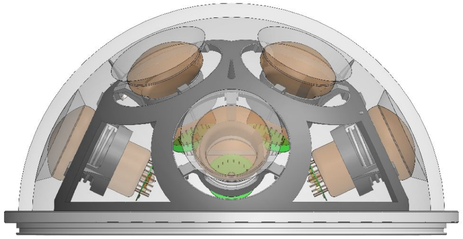


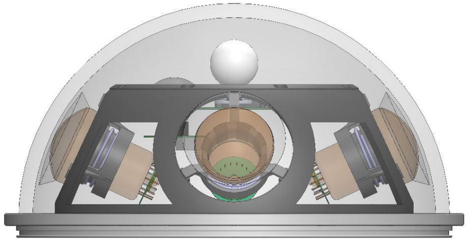



# Nucleon Decay

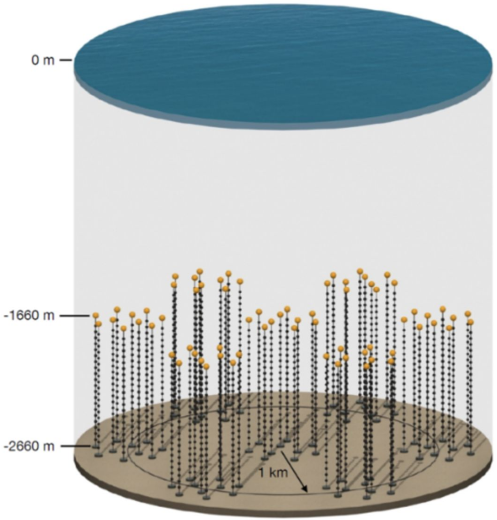


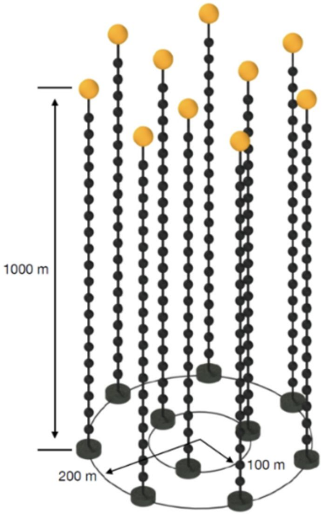



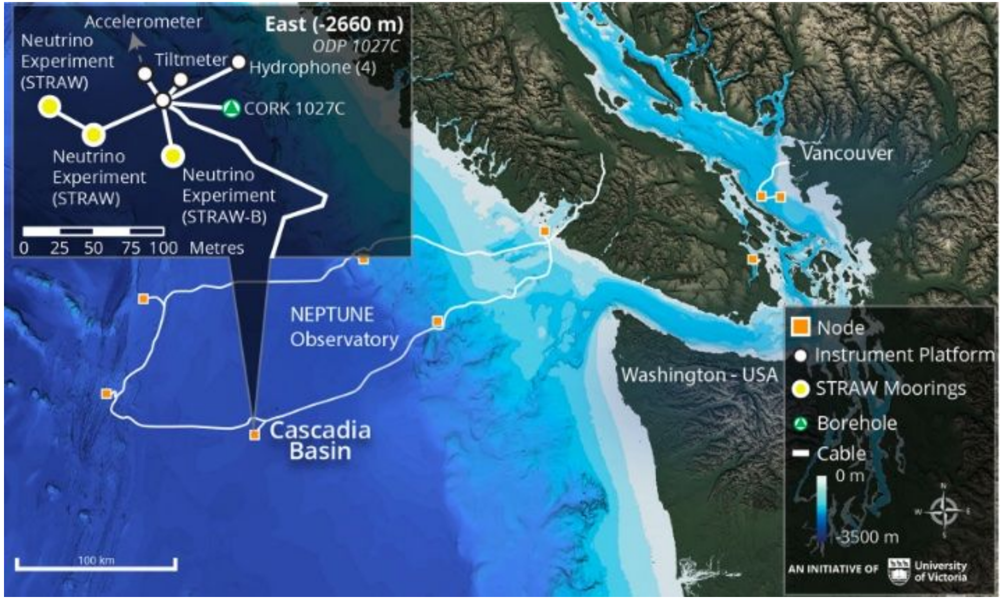




P-ONE


0 m
-1660 m
-2660 m
1 km


1000 m
200 m
100 m


East (-2660 m)
ODP 1027C
Accelerometer
Neutrino Experiment (STRAW)
Tiltmeter
Hydrophone (4)
CORK 1027C
Neutrino Experiment (STRAW)
Neutrino Experiment (STRAW-B)
0 25 50 75 100 Metres
Vancouver
NEPTUNE Observatory
Washington - USA
Cascadia Basin
Node
Instrument Platform
STRAW Moorings
Borehole
Cable
0 m
-3500 m
100 km
AN INITIATIVE OF
University of Victoria