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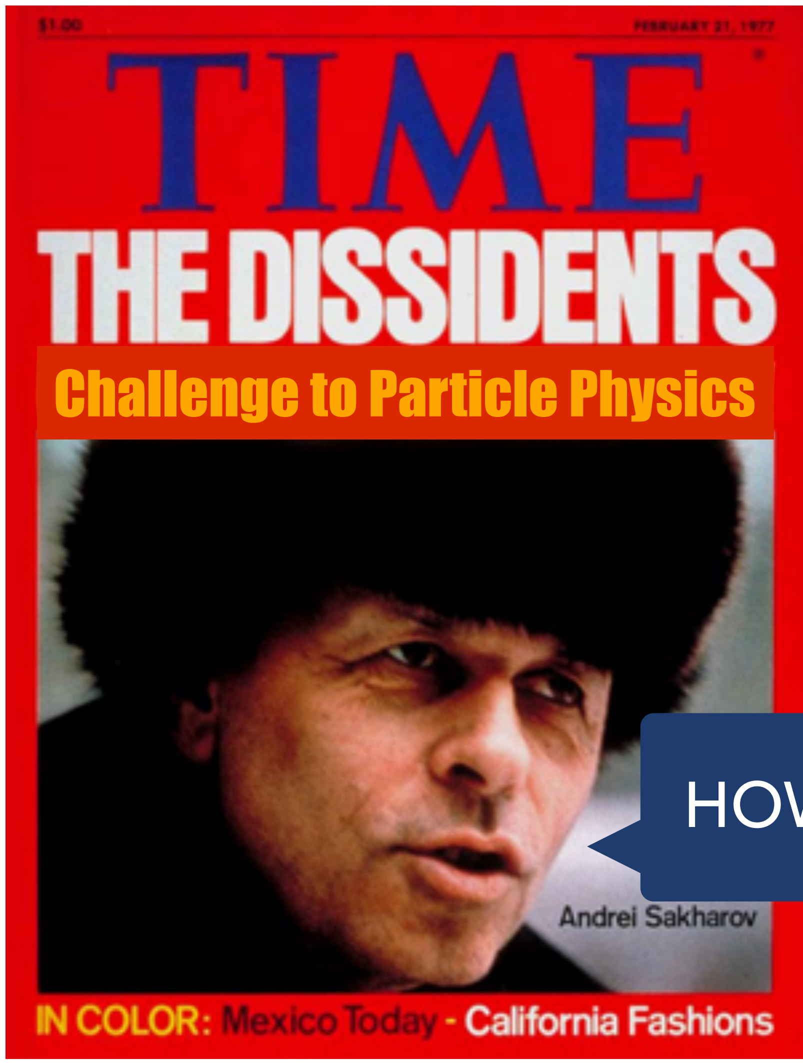
ON BEHALF OF THE HK PROTO COLLABORATION

HYPER-KAMIOKANDE

A NEXT GENERATION NEUTRINO OBSERVATORY TO SEARCH FOR CP VIOLATION IN THE LEPTON SECTOR

2016 LAKE LOUISE WINTER INSTITUTE

MATTER DOMINATED UNIVERSE



SAKHAROV CONDITIONS:

- BARYON NUMBER (B) VIOLATION
- VIOLATION OF C, CP SYMMETRY (CPV)
- DEPARTURE FROM THERMAL EQUILIBRIUM

HOW DID THIS HAPPEN?

$$\frac{\Delta B}{N_\gamma} \sim \mathcal{O}(10^{-10})$$

- Extremely small?
- Extremely large?
  - Known sources of CPV (quark CKM) cannot produce this asymmetry

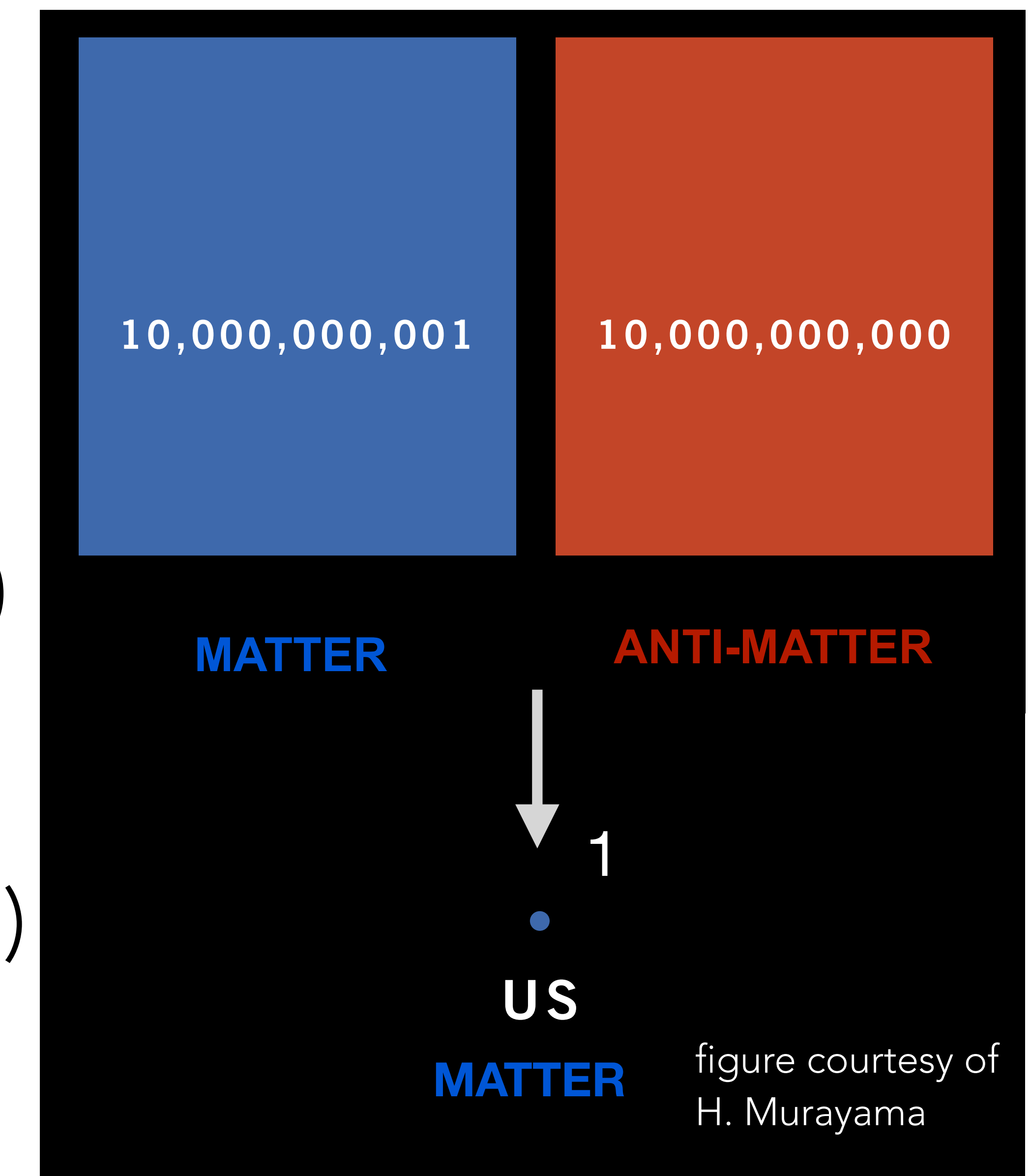


figure courtesy of H. Murayama

Further **exploration** and **elucidation** of possible CPV sources is critical

NEUTRINO OSCILLATIONS

- $\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2(1-x)\Delta}{(1-x)^2}$$
$$-\alpha \sin 2\theta_{13} \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+\alpha \sin 2\theta_{13} \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+\alpha^2 \times \sin^2 2\theta_{12} \cos 2\theta_{23} \times \sin\Delta \frac{\sin^2[x\Delta]}{x^2}$$

$$\mathcal{A}_{CP} \propto \frac{\cos\theta_{23} \sin 2\theta_{12}}{\sin\theta_{23} \sin\theta_{13}} \sin\delta_{CP}$$

M. Freund, Phys.Rev. D64 (2001) 053003

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{32} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{32}}$$

Observe/measure CP violation induced by $\boldsymbol{\delta_{CP}}$

Possibility to resolve $\boldsymbol{\theta_{23}}$ octant if $\neq \pi/4$

- ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4 2\theta_{13} \sin^2\theta_{23} + \sin^2 2\theta_{13} \sin^2\theta_{23}\right) \sin^2\Delta \qquad \Delta \equiv \frac{\Delta m^2_{32} L}{4E}$$

Precision measurement of $\boldsymbol{2\theta_{23}}$ and $\boldsymbol{\Delta m^2_{31}}$

NEUTRINO ECONOMICS

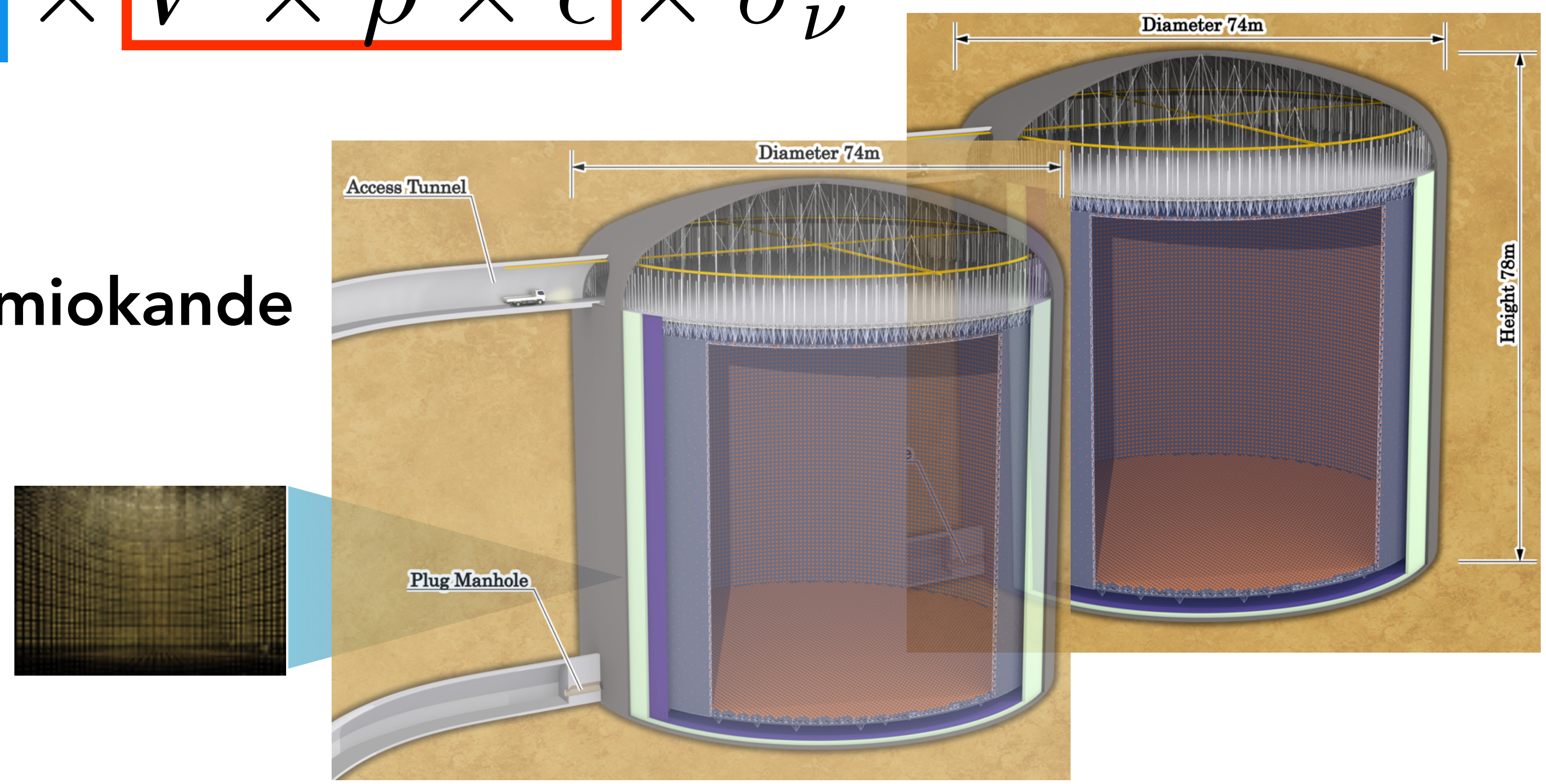
More intense neutrino beam

- 400 kW → 750 kW →1.3 MW

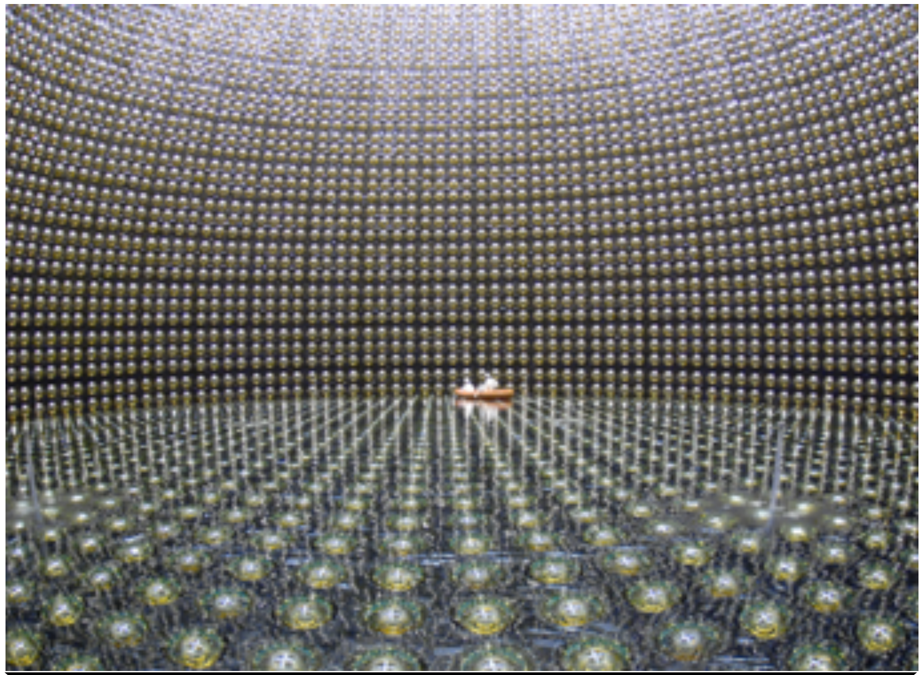
$$N \propto \boxed{\Phi_\nu} \times \boxed{V \times \rho \times \epsilon} \times \sigma_\nu$$

Large Detector

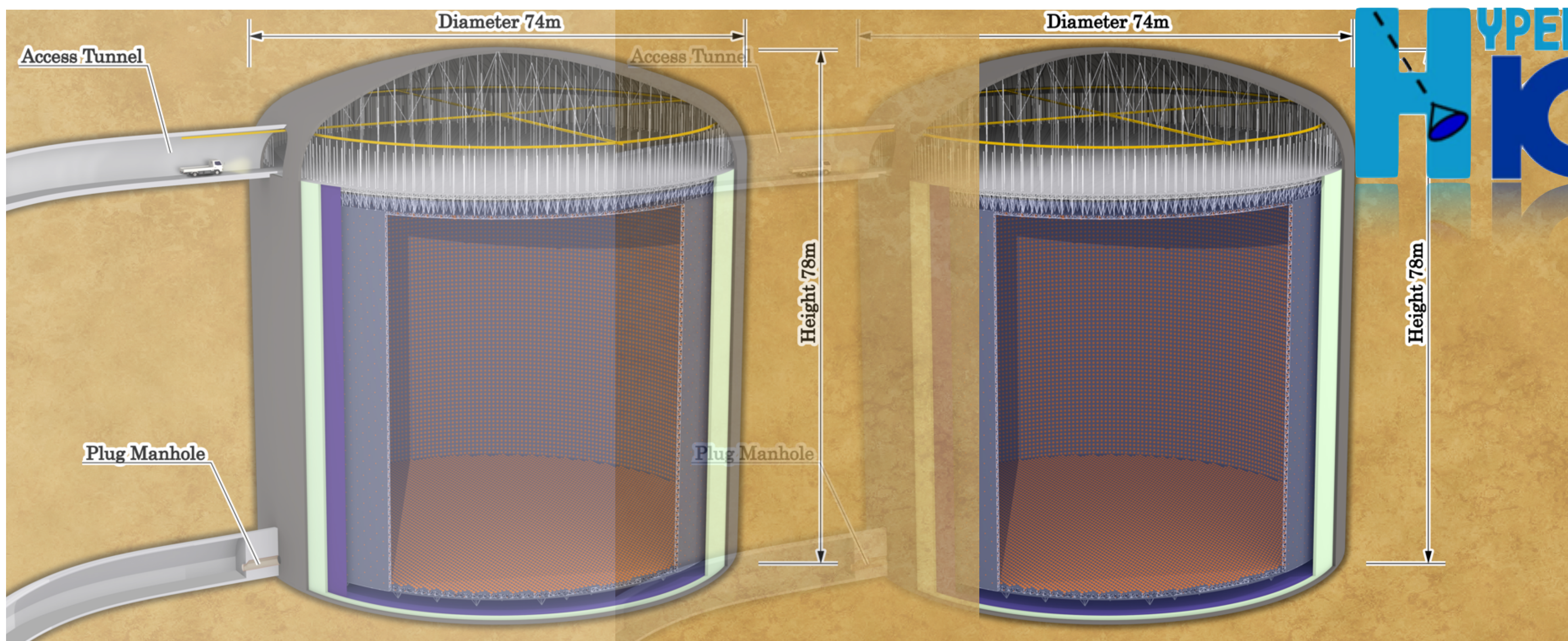
- Super-Kamiokande →Hyper-Kamiokande



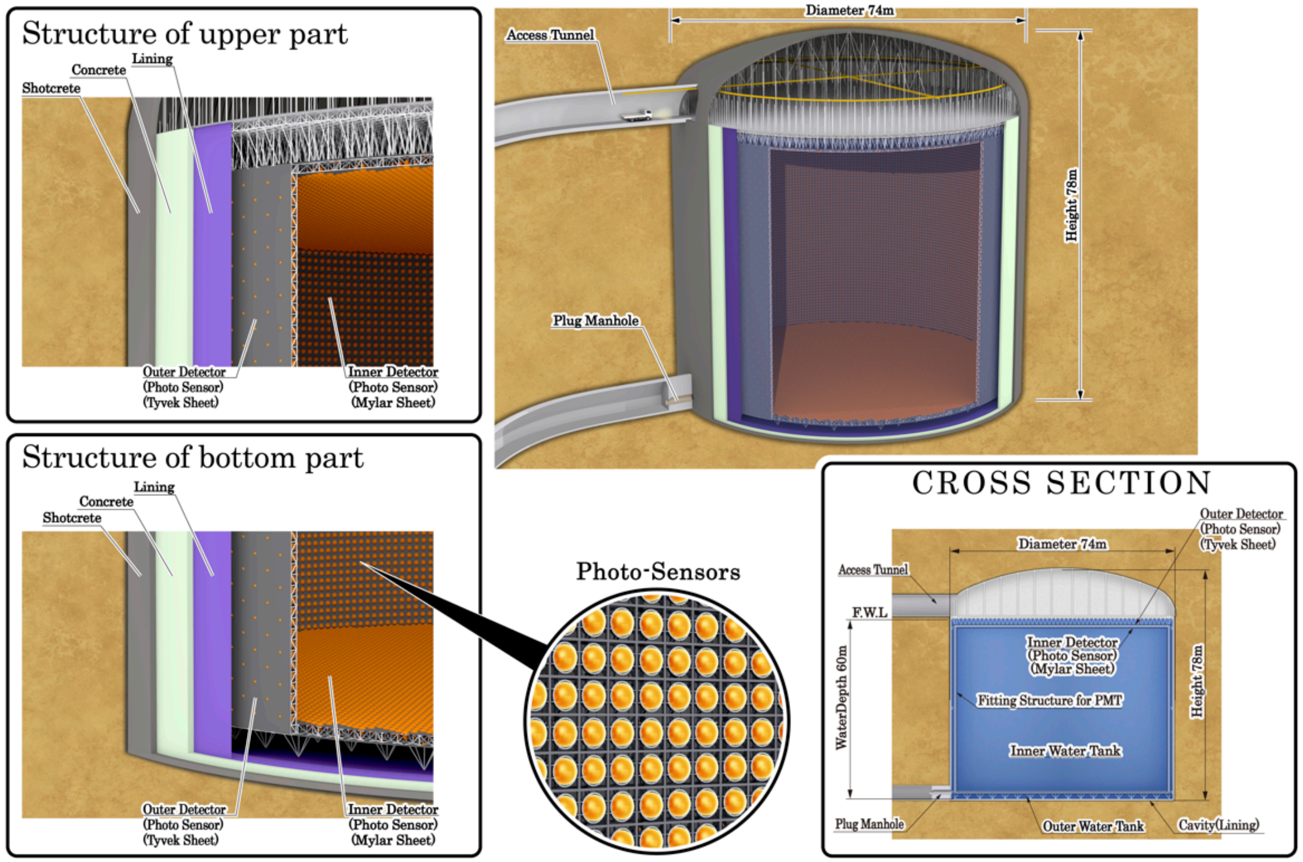
SUPER→HYPER KAMIOKANDE



- (new) Baseline design:
  - 2 large cylindrical tanks
    - staged construction with 2nd tank 6 years later
  - 50 kT → 516 kT total volume
    - 22.5 kT → 374 kT fiducial volume (16x SK)
  - 11k 20″ PMTs → 80k 20″ PMTS (40%)
    - ~2 x photodetection efficiency relative to SK

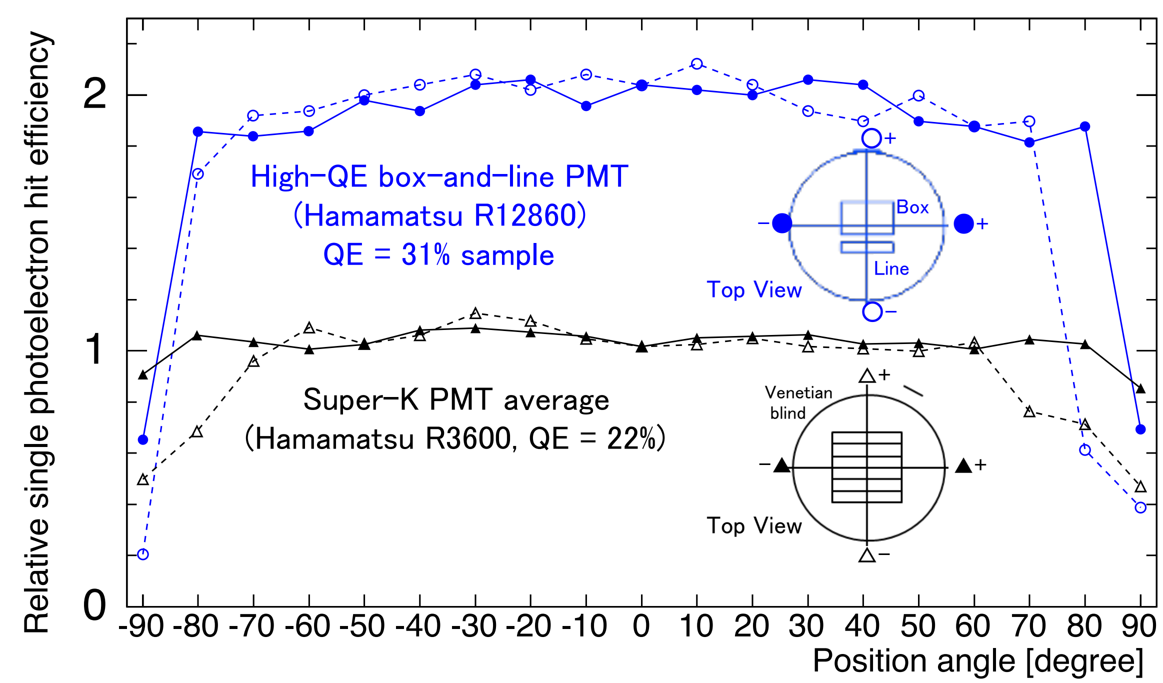


HYPER-KAMIOKANDE



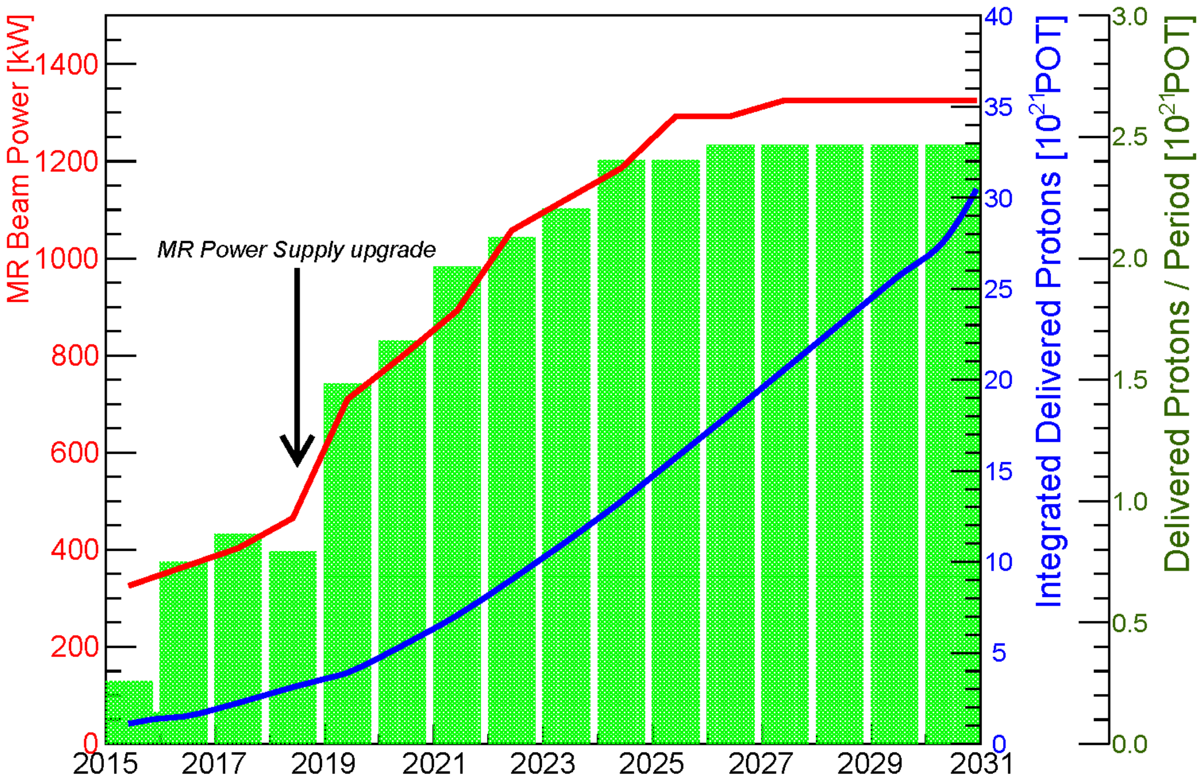
- Smaller relative to previous design
  - 990 (560) kT volume with 20% photocathode area.
- "High Density" photosensor:
  - same photocathode area as SK (40%)
  - large improvements in
    - detection efficiency (~2x SK)
    - timing resolution (2-3 ns → 1 ns)

- Improved detectors, higher density allow
  - improved performance
  - qualitatively new capabilities



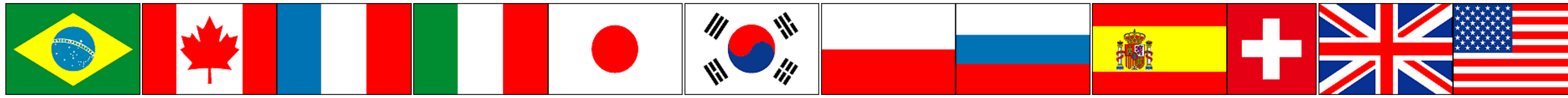
Very broad range of physics. Focus on ν oscillations here

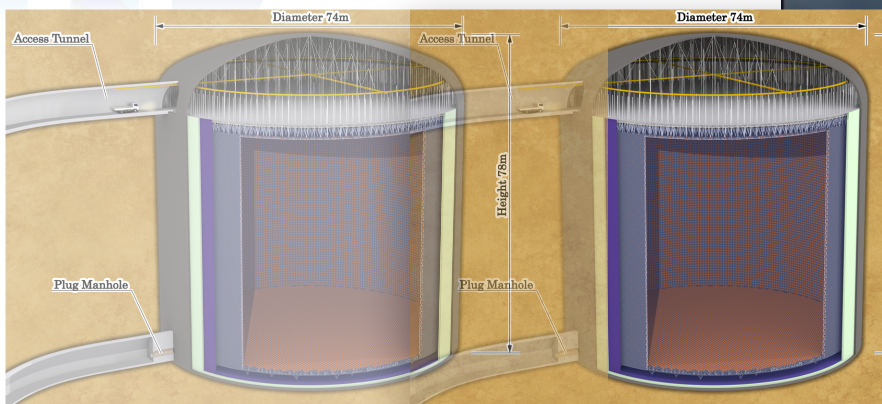
J-PARC MAIN RING UPGRADE



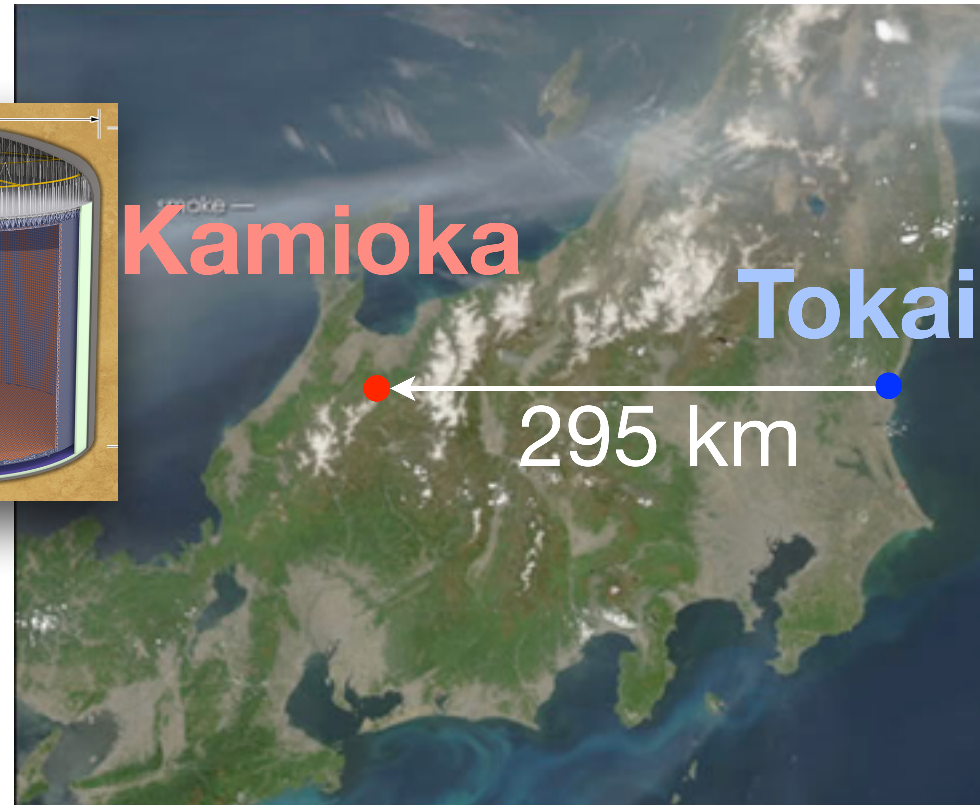
JFY	2014	2015	2016	2017	2018	2019	2020
	Li. current upgrade		New PS buildings				
FX power [kW] (study/trial)	320	> 360	400	450	700	800	900
SX power [kW] (study/trial)	-	33 - 40	50	50-70	50-70	~100	~100
Cycle time of main magnet PS New magnet PS	2.48 s R&D	Large scale 1st PS		Mass production installation/test	1.3 s	1.3 s	1.2 s
High gradient rf system 2nd harmonic rf system VHF cavity	Manufacture, installation/test R&D	R&D, manufacture, installation/test					
Ring collimators		Add.collimators (2 kW)	Add.collimators (3.5kW)				
Injection system FX system	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, LF septum, HF septa manufacture /test						
SX collimator / Local shields			Local shields				
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS					

- Potential for high power neutrino running at J-PARC
  - Currently ~390 kW operations with 2.48 sec acceleration cycle
    - with power supply upgrade (1.3 sec cycle) equivalent to >740 kW beam
    - design power of 750 kW is within reach!
- **MR power supply upgrade approved!**
  - now looking to 1 MW power and beyond to **1.3 MW**
  - **investigating extended T2K run to ~2026 ("T2K Phase II")**
  - **prepare 1.3 MW beam for HK**





Hyper-Kamiokande



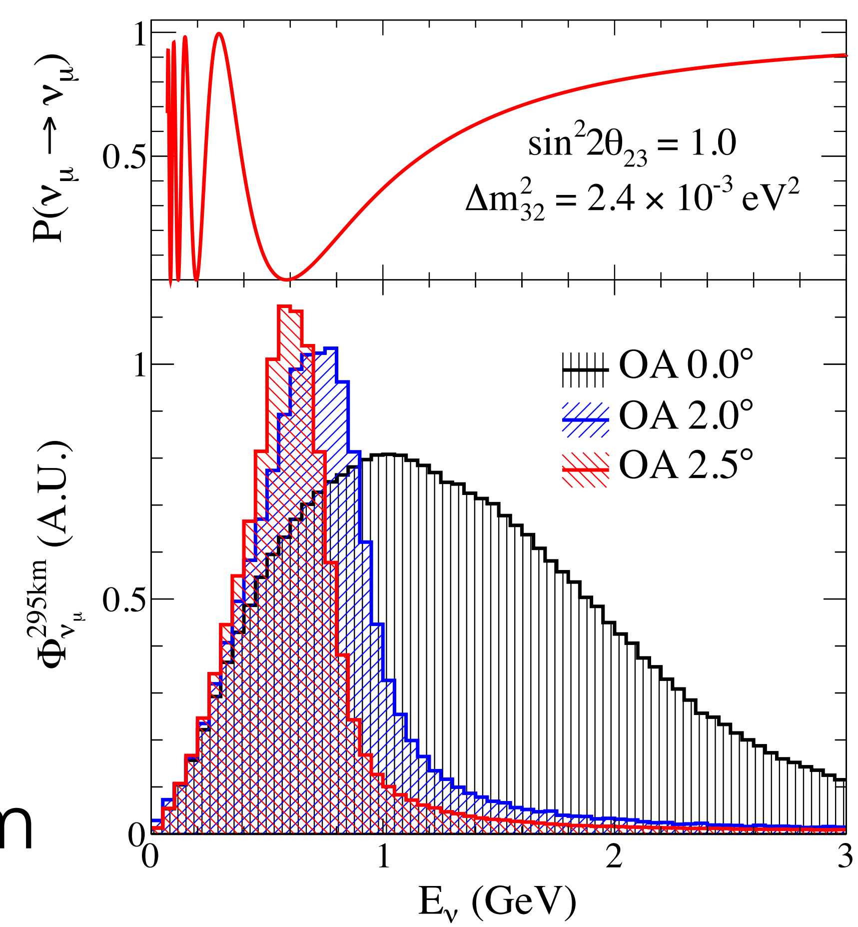
J-PARC

2.5° off-axis
narrow band beam

The Long Baseline Program at Hyper-Kamiokande

Intense ~600 MeV ν_μ and $\overline{\nu}_\mu$ beams to study

- $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ appearance and ν_μ disappearance at HK
  - search for CP violation in neutrino oscillations
  - measure θ_{23}, Δm^2_{32} to few percent (non-maximal? octant?)
- Sensitivities with 1.3 MW x 10 x 10^7 sec exposure
  - 2.7×10^{22} POT = 10 “Snowmass" years



Just one part of an rich physics program

WČ PRINCIPLE

$\nu_\ell + n \to \ell^- + p$ **Signal "CCQE"**

- Appears as single μ/e-like ring
- E_ν by energy/direction of ring relative to beam
  - assumes CCQE kinematics

Backgrounds

$$\nu_\ell + (n/p) \to \nu_\ell + (n/p) + \pi^0$$
$$\nu_\ell + (n/p) \to \ell^- + (n/p) + \pi$$

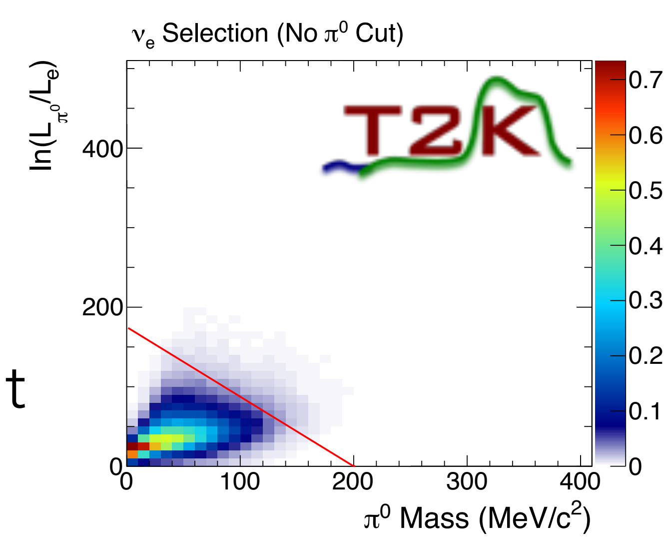
- π^0: ring counting, 2-ring invariant mass
- μ/π^+: ring counting, decay electron cut

reducible

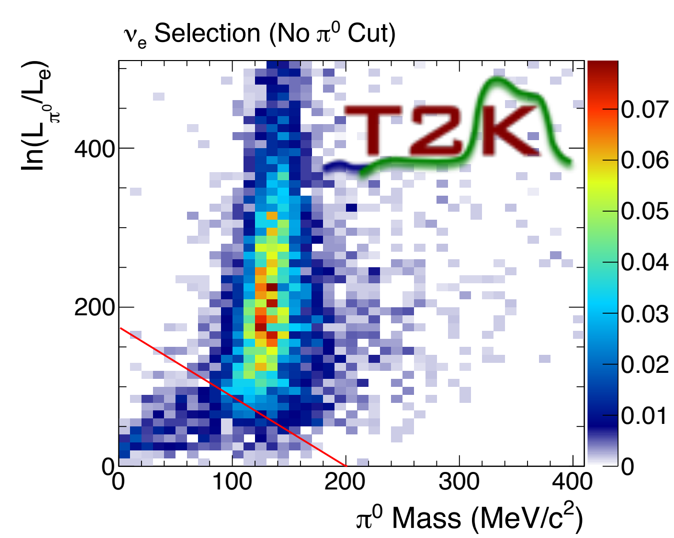
- "intrinsic" ν_e present in ν beam (μ/K decay)

irreducible

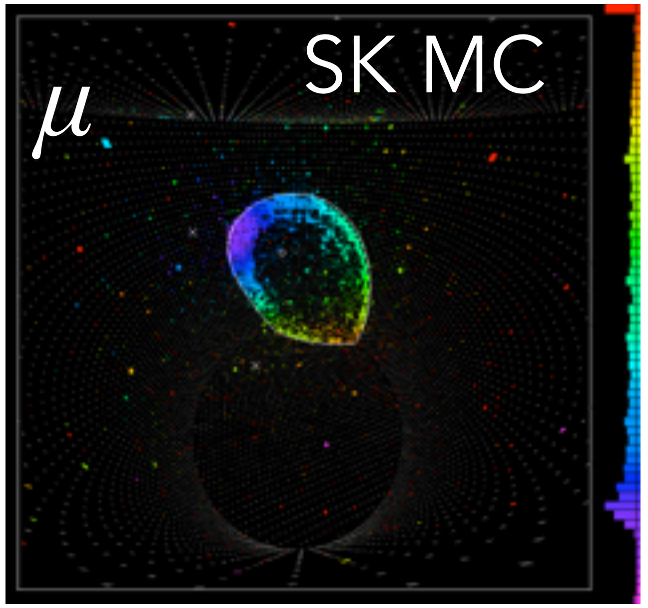
Improvements in π^0 rejection @ T2K → irreducible ν_e background is dominant

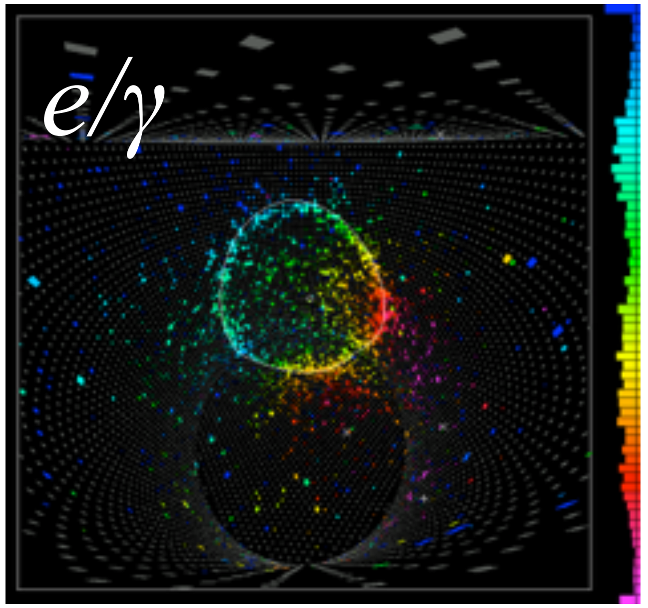


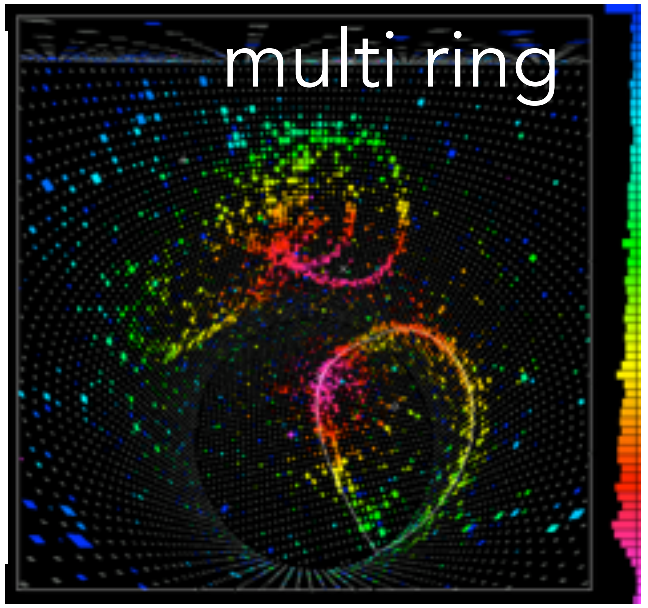
electrons



π^0

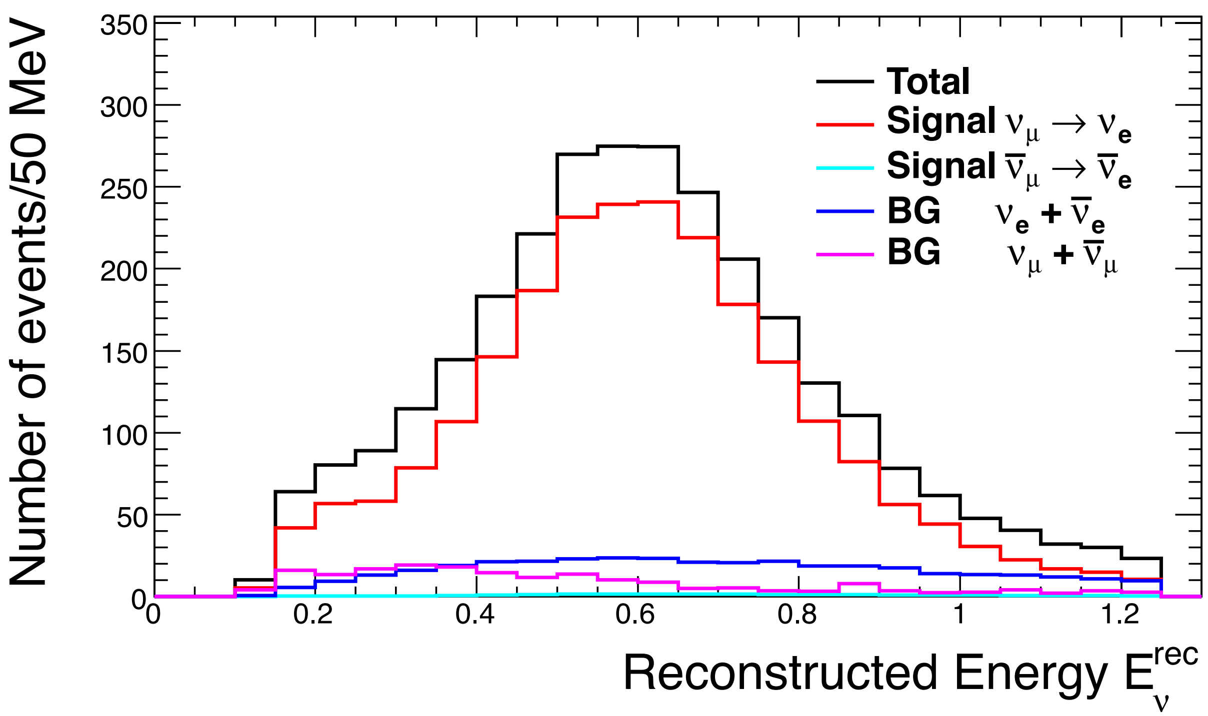




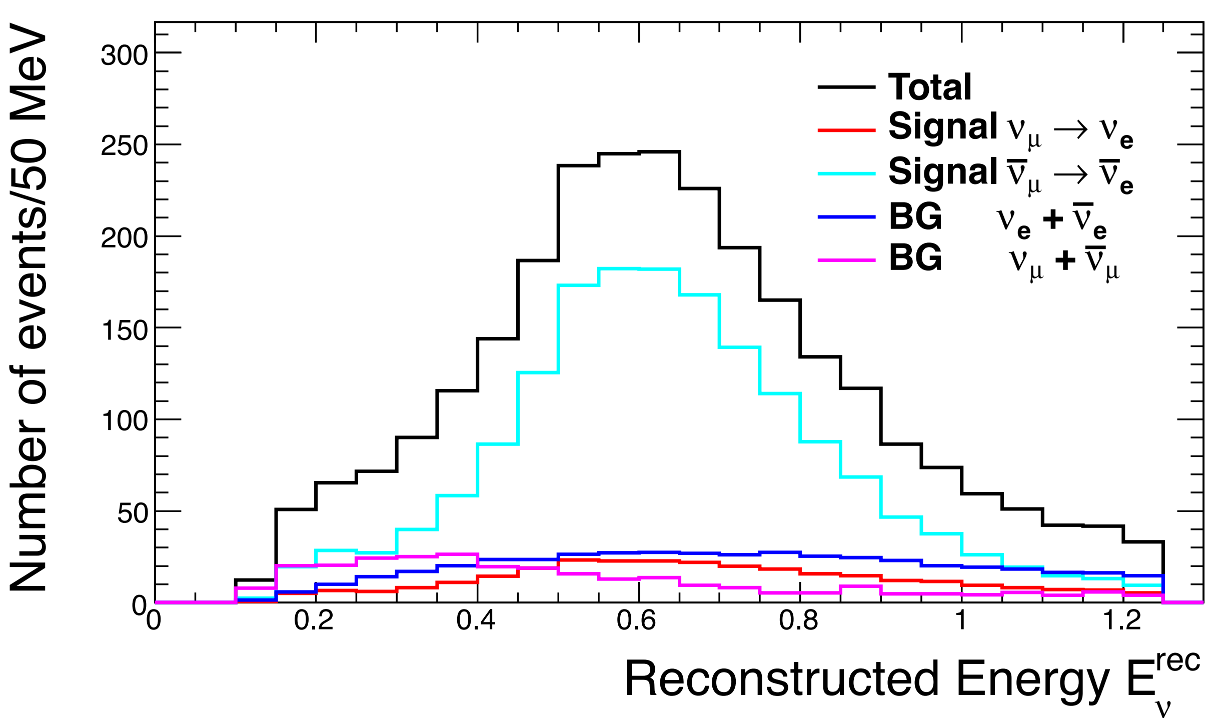


NEUTRINO OSCILLATIONS

Appearance ν mode



Appearance $\bar{\nu}$ mode



$\sin^2 2\theta_{13}$ =0.1, $\sin^2\theta_{23}$= 0.5, δ=0, NH

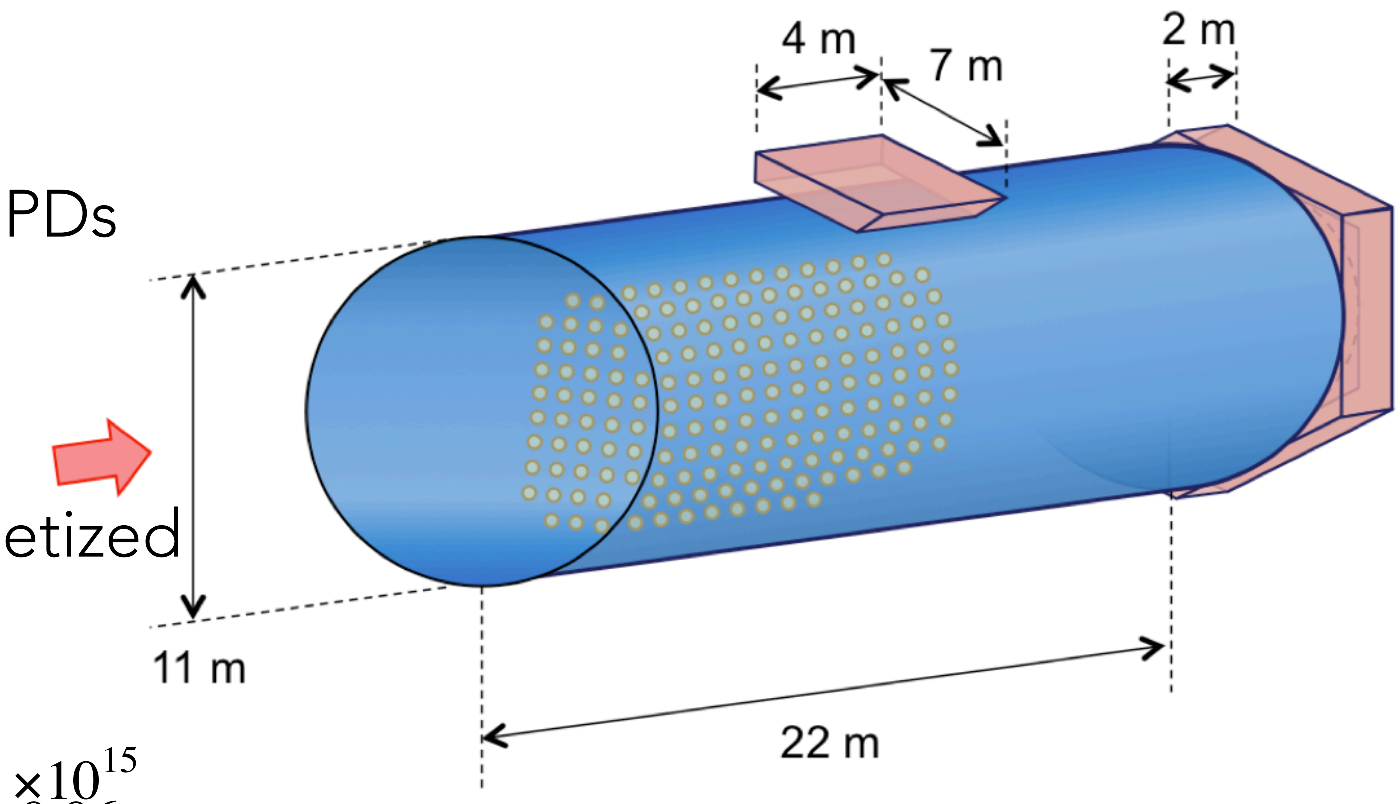
13 MW x 10^7s exposure

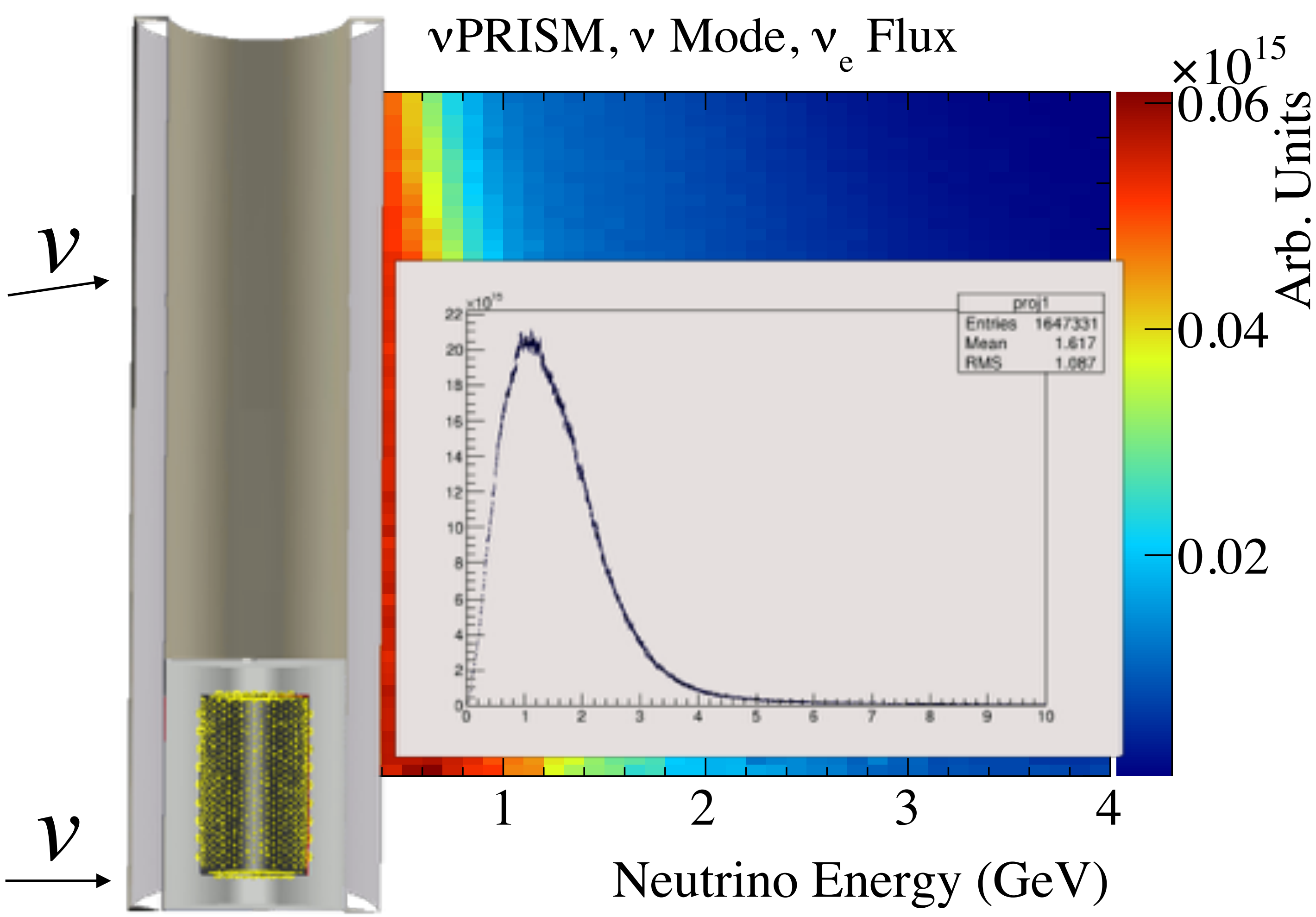
	SIGNAL $\nu_e/\bar{\nu}_e$	WS $\nu_e/\bar{\nu}_e$	ν_μ CC	BEAM ν_e	NC
ν MODE	**2300**	21	10	362	188
$\bar{\nu}$ MODE	**1656**	289	6	444	274

- Dominant background is irreducible intrinsic beam ν_e
  - ν_e ~ 2-3 x NC π^0 background
  - S/B ~ 10 at peak energy
- With ~large θ_{13}, systematics uncertainties on signal and intrinsic background ν_e are important

NEAR DETECTOR CONCEPTS

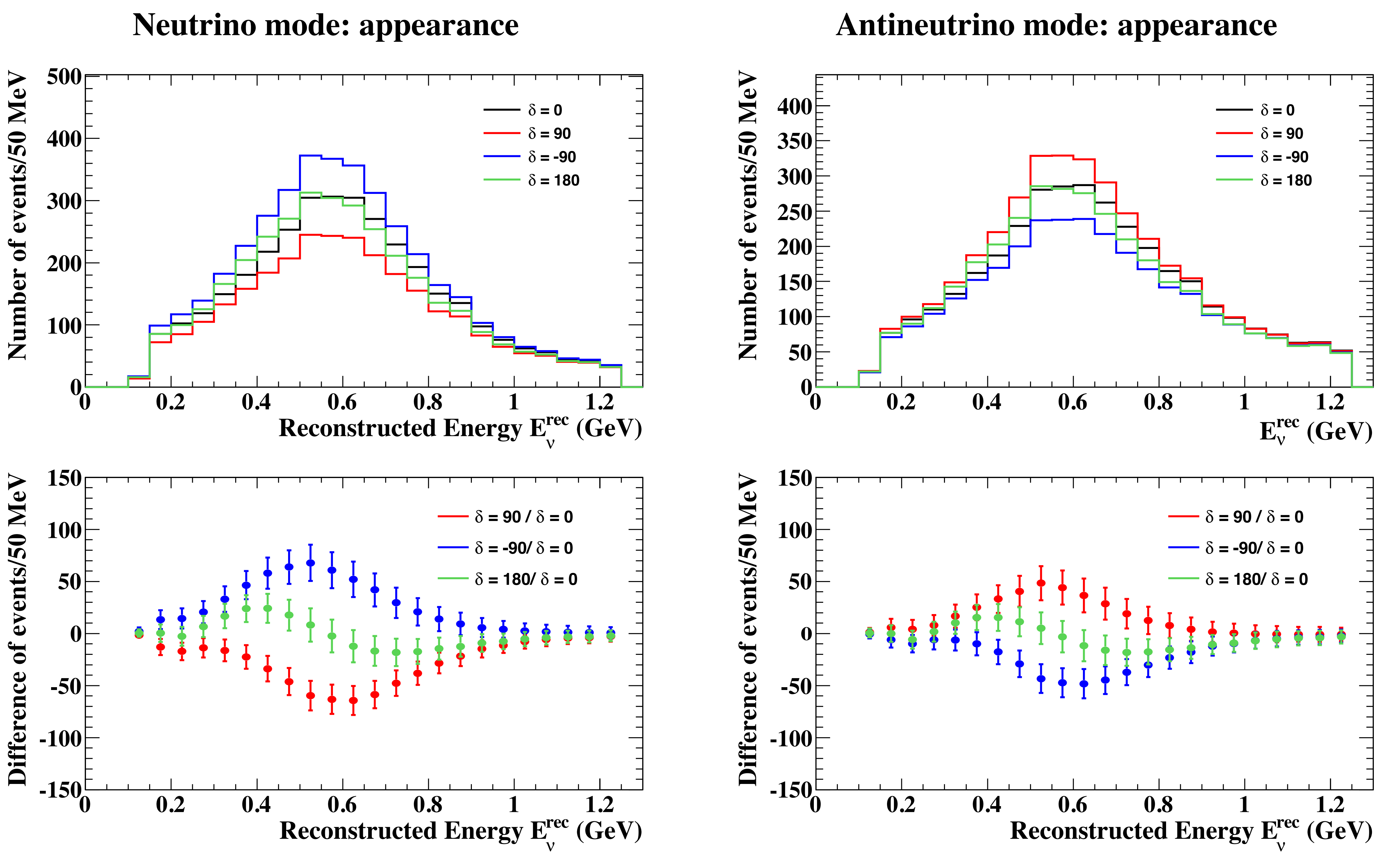
- "TITUS" (2 km)
  - 2 kt WČ detector with HPDs and LAPPDs
  - minimize near/far flux differences
  - Gd for $\nu/\bar{\nu}$ discrimination
  - Muon range detector, possibly magnetized (MIND) for sign selection of muons





- "nuPRISM" (1km)
  - tall (~50 m) WČ detector spanning wide range of off-axis angles
  - effectively isolate response in narrow bands of energy by comparing interactions at different off-axis angles
  - replicate kinematic and other distributions for ~arbitrary neutrino energy spectra

SIGNATURE OF CP VIOLATION

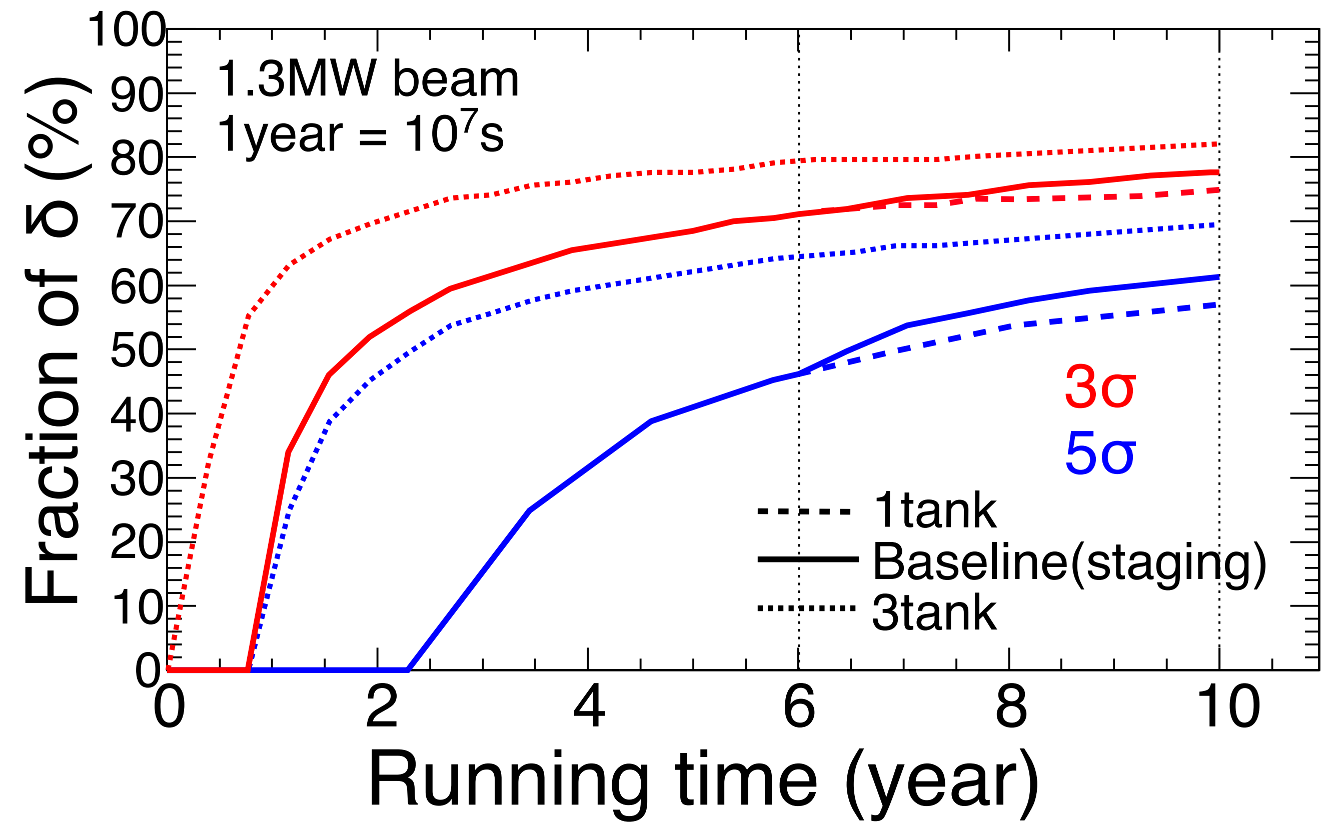


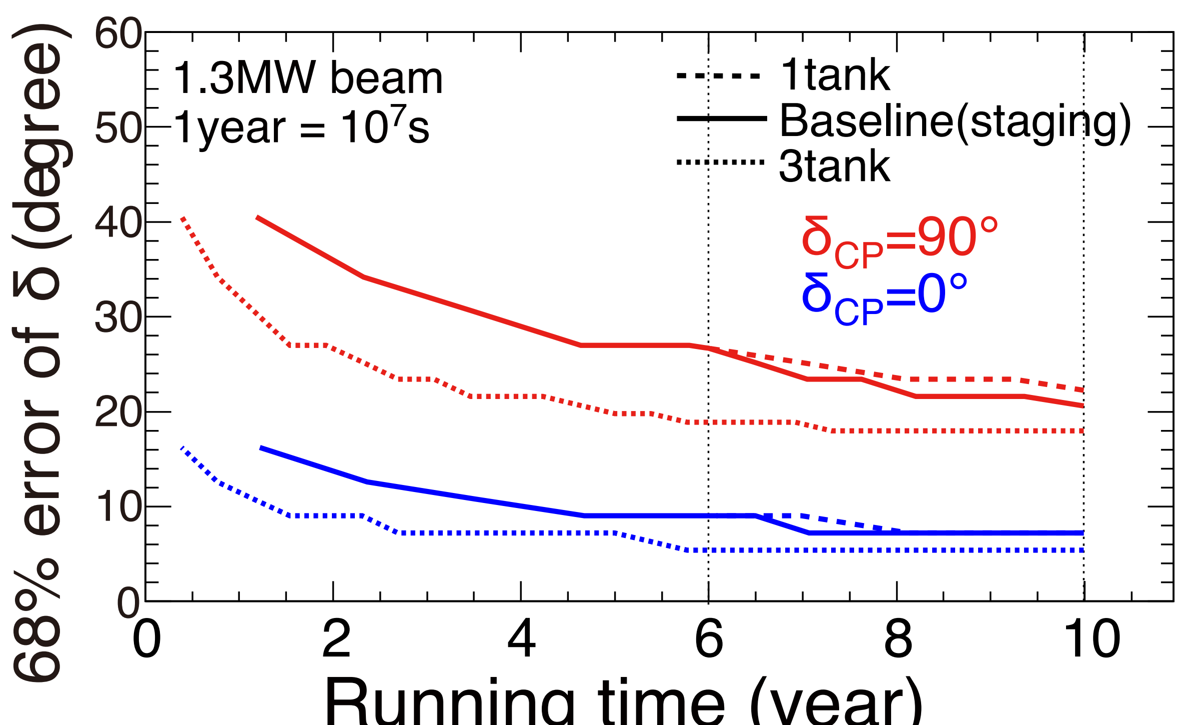
- overall rate asymmetry between neutrino vs. antineutrino oscillations
- distortion of spectrum due to phase shift in either mode

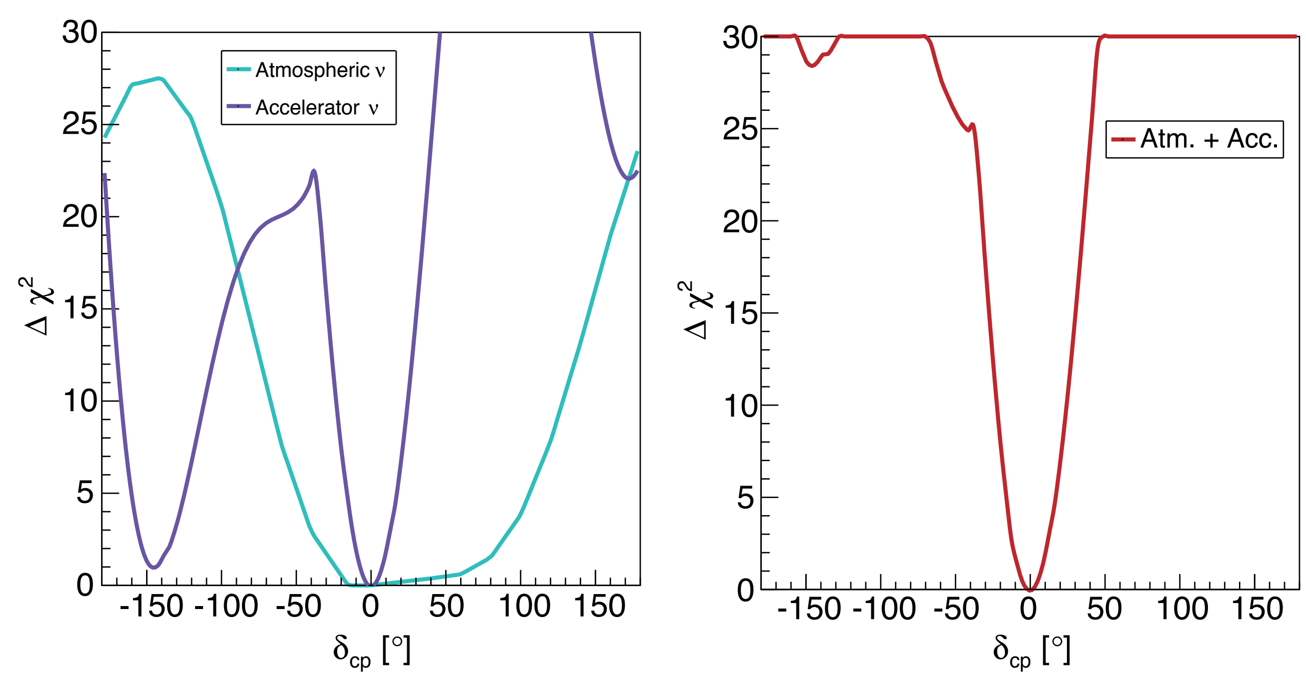
CP VIOLATION SENSITIVTY:

With 1.3 x 10 x 10^7 MW sec

- CP violation can be observed at
  - 3 σ for 80% values of δ_{CP}
  - 5 σ for 65% values of δ_{CP}
- δ_{CP} can be measured with
  - 7° precision for δ = 0
  - 21° precision for δ = ±π/2

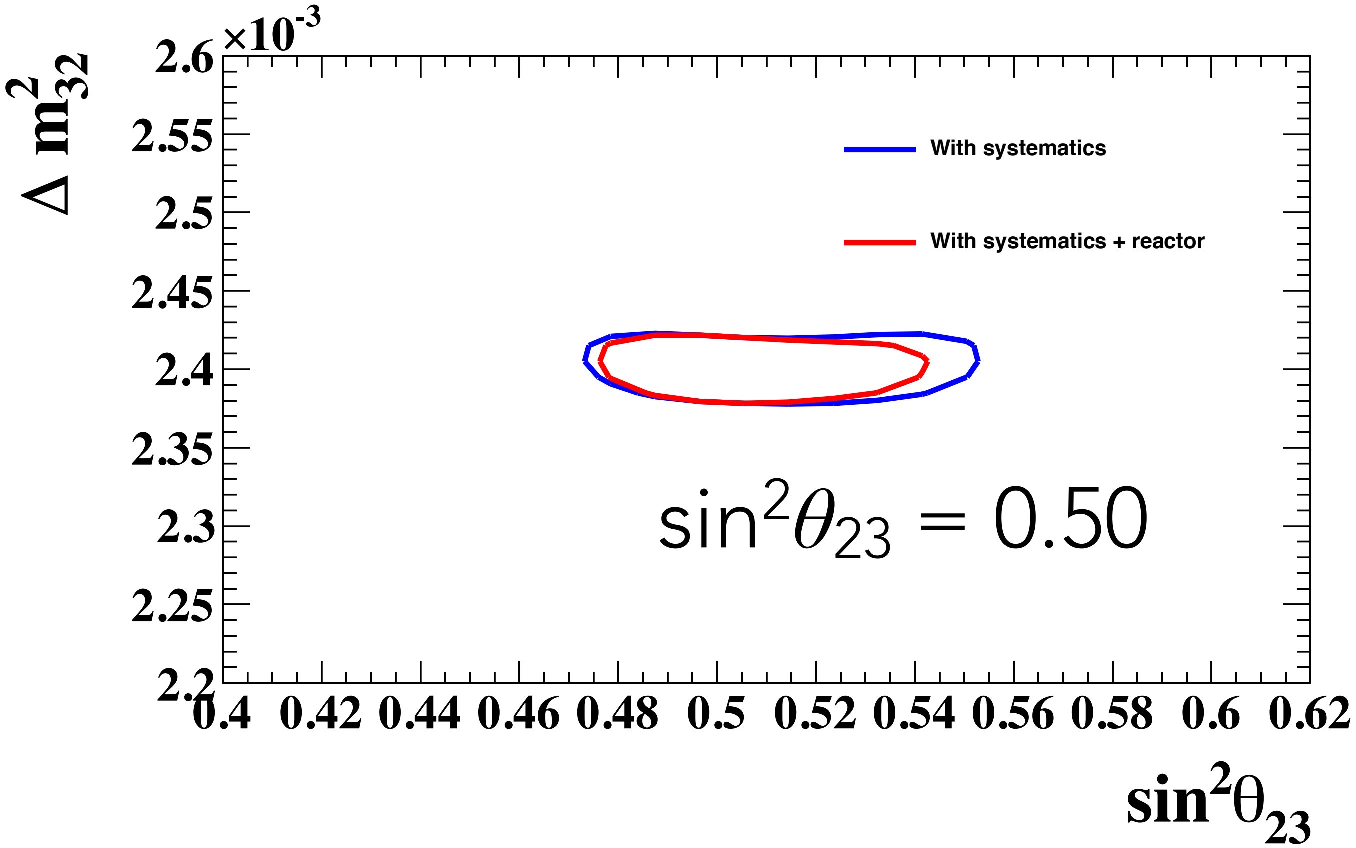


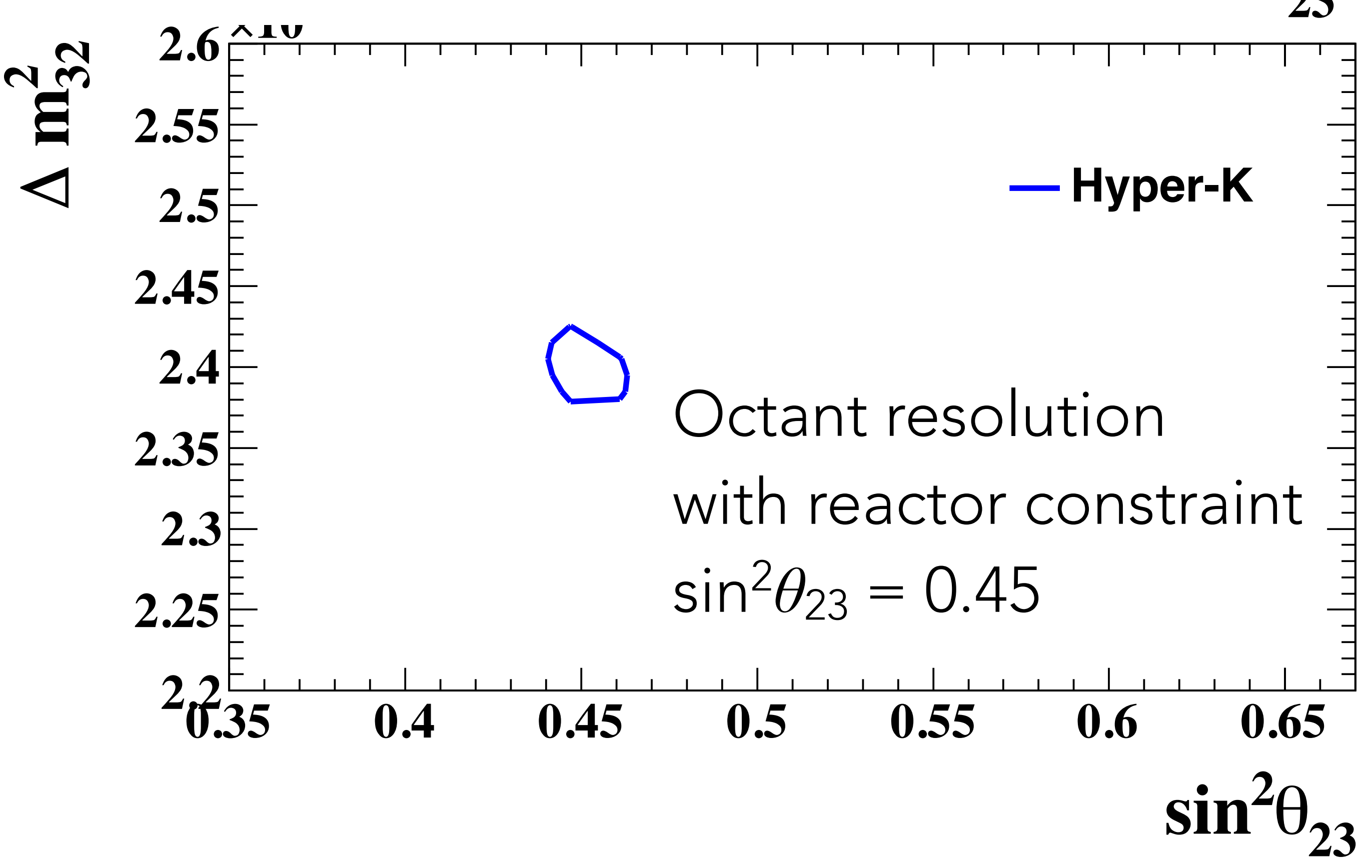




combination of beam and atmospheric ν data can resolve degeneracies

θ_{23} AND Δm^2_{32}



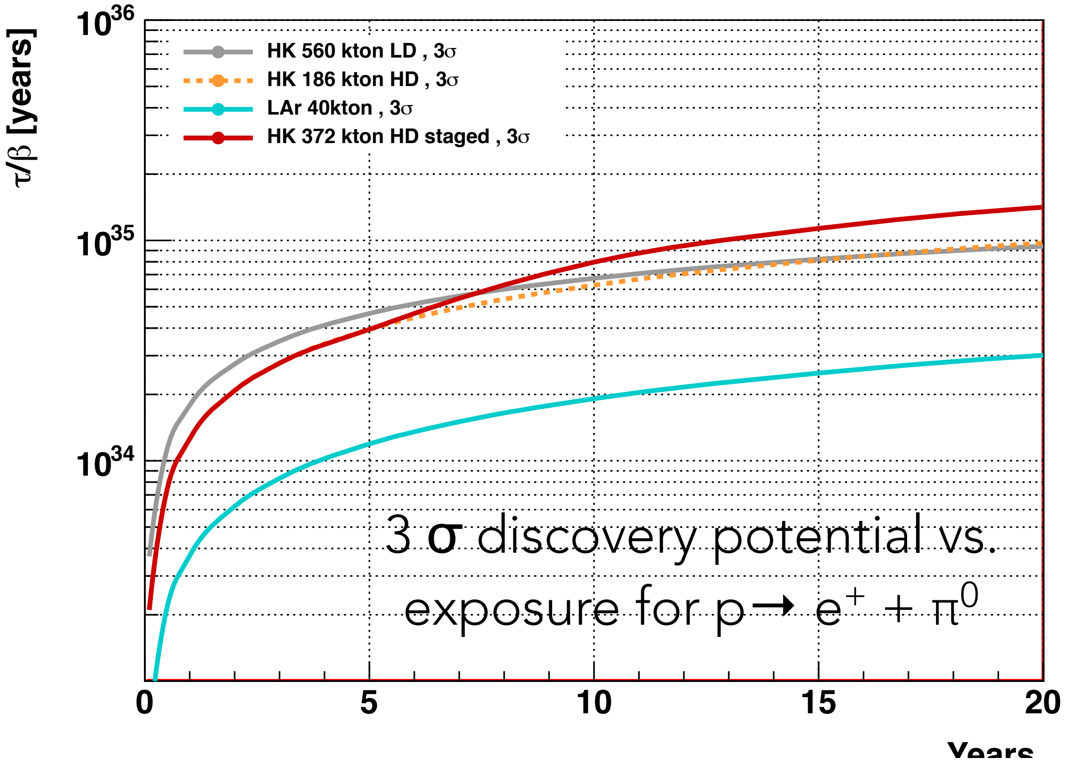


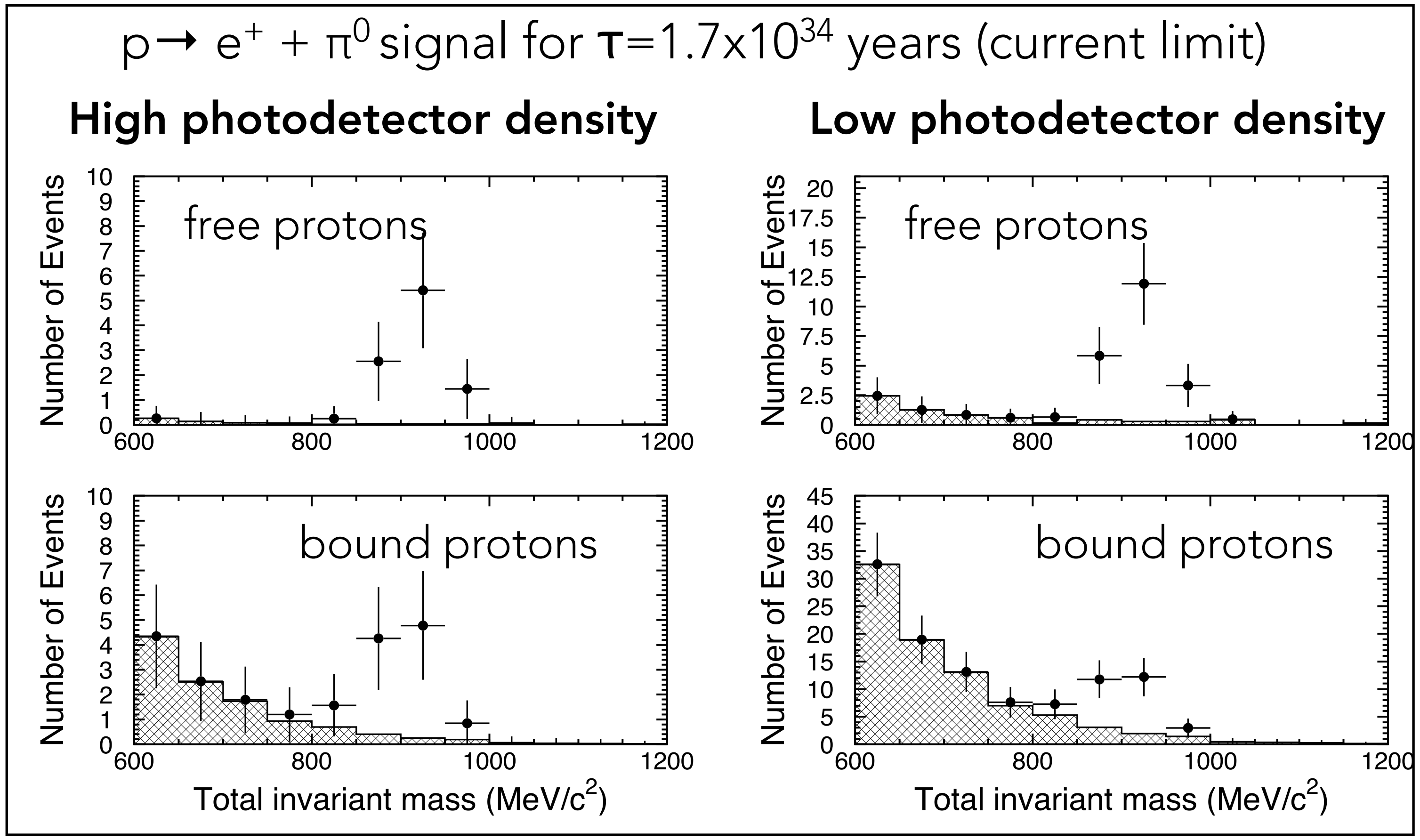
- Precision θ_{23} measurement
- Octant resolution with reactor θ_{13} measurement
  - ~3 σ wrong octant rejection for $\sin^2\theta_{23}$ <0.46 or >0.57

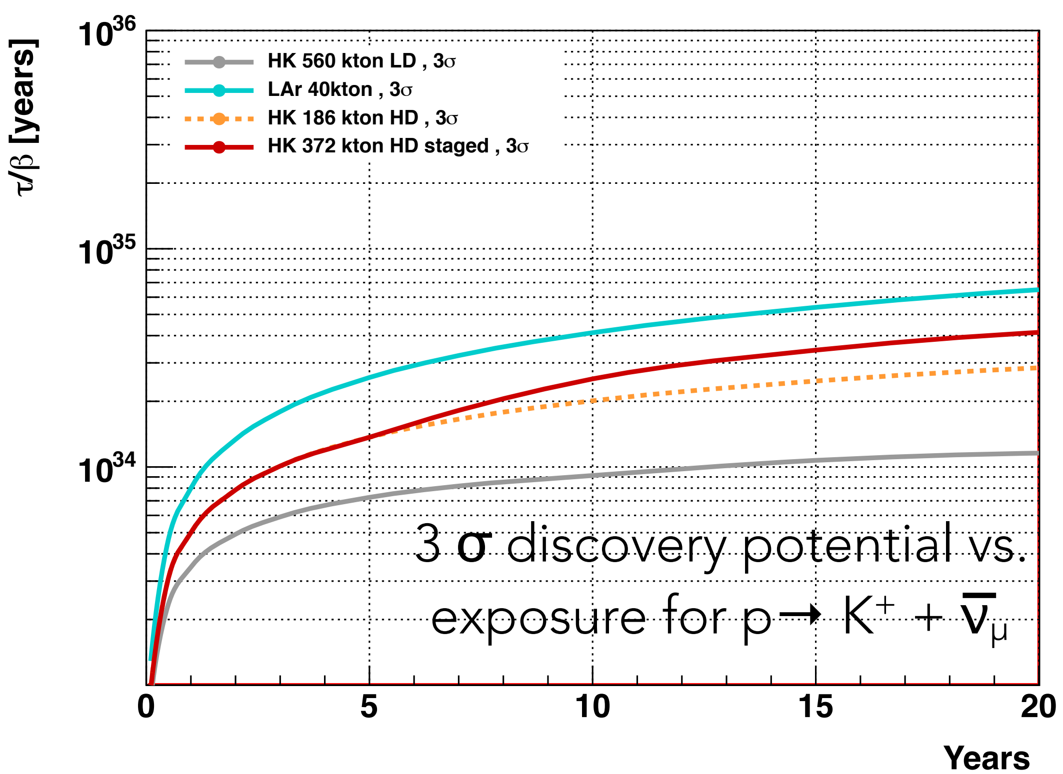
True $\sin^2\theta_{23}$	1σ error $\sin^2\theta_{23}$	1σ error Δm^2_{32} ($/10^{-5}$ eV^2)
0.45	0.006	1.2
0.50	0.017	1.0
0.55	0.009	1.0

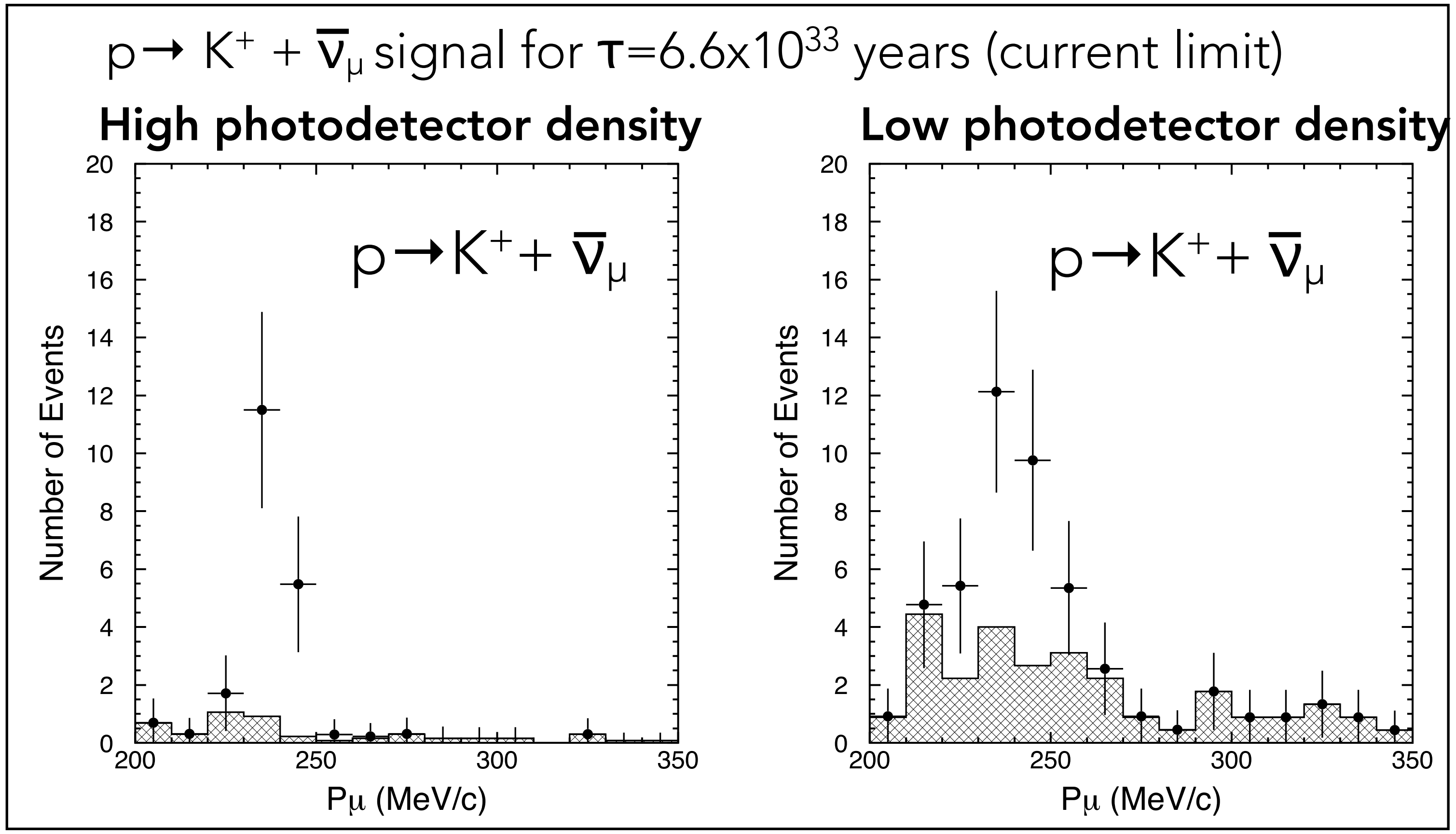
PROTON DECAY

- **"Smoking gun" signature of new physics**
  - generic signature of Grand Unification



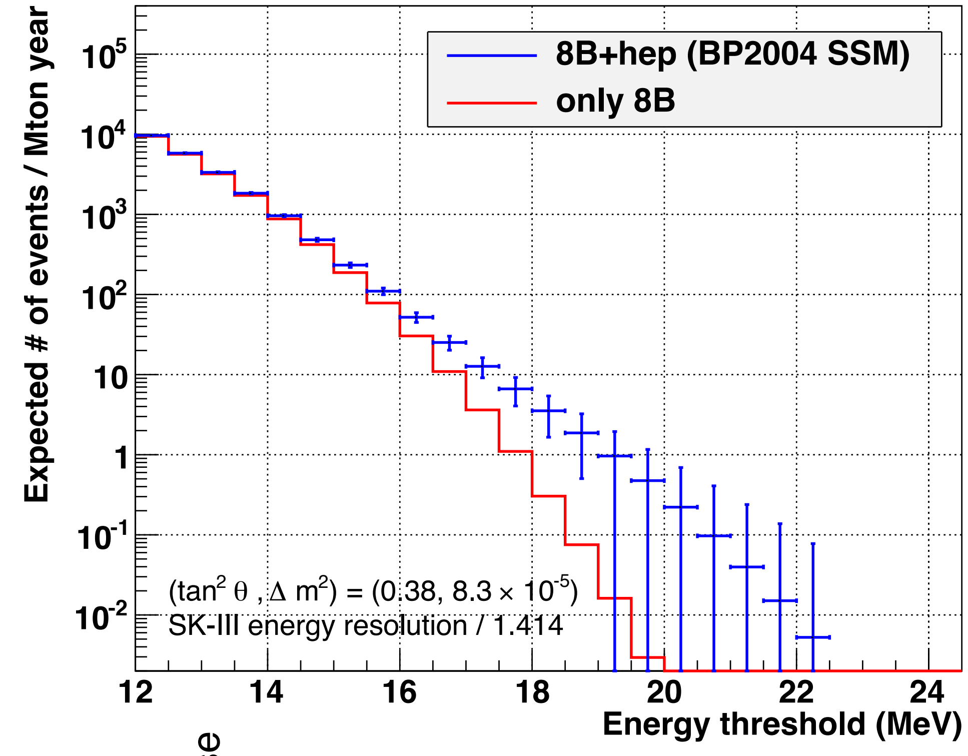


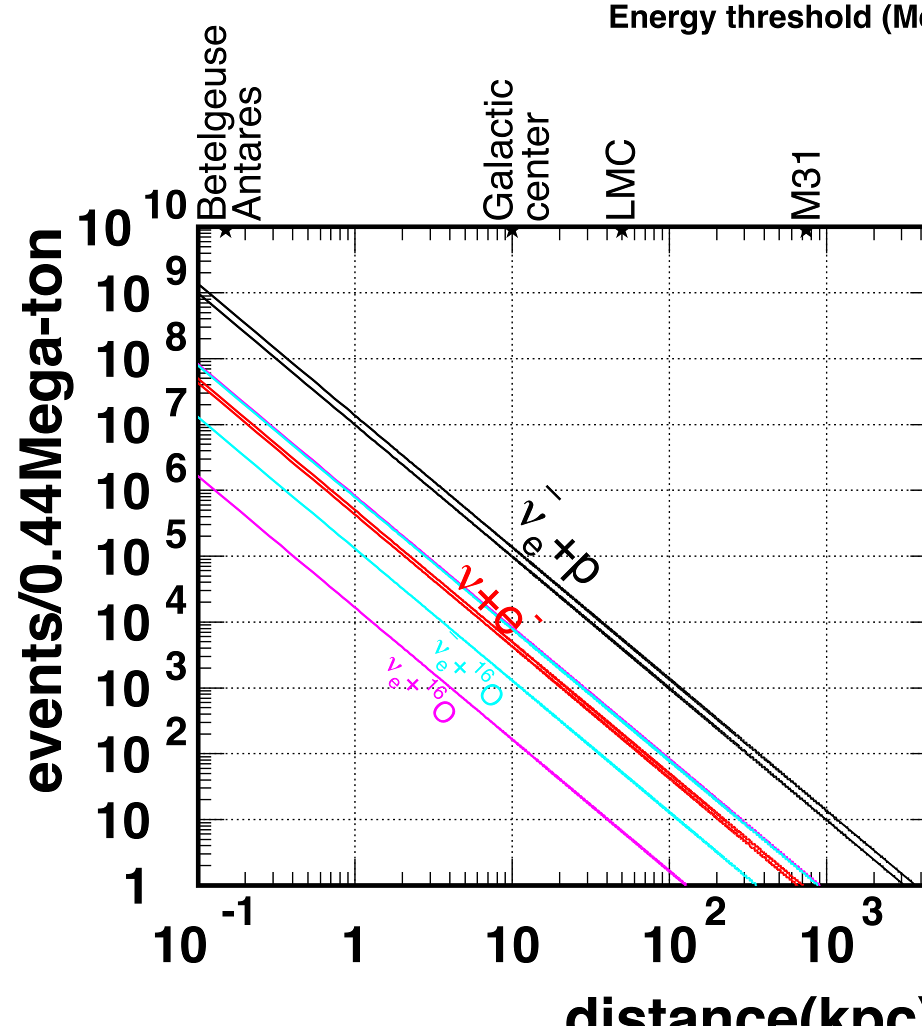




NEUTRINO ASTROPHYSICS

- Solar Neutrinos:
  - detect upturn of solar neutrino spectrum due to MSW transition at ~5 σ
  - definitively detect day/night asymmetry due to matter effect from the earth
  - detection of solar hep neutrinos
  - resolve KamLAND/Solar tension
- Supernova:
  - detect supernova burst neutrinos from as far as Andromeda Galaxy
  - O(100k) in inverse beta decay, elastic scattering interactions for supernova at galactic center
  - probe supernova dynamics and neutrino properties
- Much more . . . (indirect DM, geophysics, etc.)





SUMMARY: SUPER→HYPER PHYSICS

- **Kamiokande:** 3/0.88 kT
  - observation of neutrinos from SN1987a **(Nobel Prize 2002)**
  - observation of solar neutrino deficit with directionality/real-time detector
  - observation of atmospheric neutrino deficit
- **Super-Kamiokande:** 50/22.5 kT
  - discovery of neutrino oscillations in atmospheric neutrinos **(Nobel Prize 2015)**
  - definitive resolution of solar neutrino problem with SNO
  - K2K: first confirmation of ν_μ disappearance in LBL experiment
  - T2K (PHASE II): observation of ν_e appearance, first constraints on δ_{CP}, ...?
- **Hyper-Kamiokande:** 516/374 kT:
  - observation of CP violation in the lepton sector?
  - uncovering the underlying structure of mixing?
  - observation of proton decay? (10x current sensitivity)
  - $O(10^5)$ neutrinos from galactic supernova? intergalactic observation?

We're ready for the next step

BACKUP

STATUS

第 22 期学術の大型研究計画に関する
マスタープラン
（マスタープラン 2014）

平成２６年（２０１４年）２月２８日
日　本　学　術　会　議
科学者委員会
学術の大型研究計画検討分科会

- HK selected as one of top 27 projects of 192 in 2014 “Master Plan” of the Science Council of Japan
- KEK IPNS/ICRR MOU to promote Hyper-Kamiokande signed January 2015
    - international design review underway
- HK will be resubmitted this month to the Science Council of Japan with new baseline design.

Notional timeline