Hyper-Kamiokande

Justyna Łagoda

NCBJ

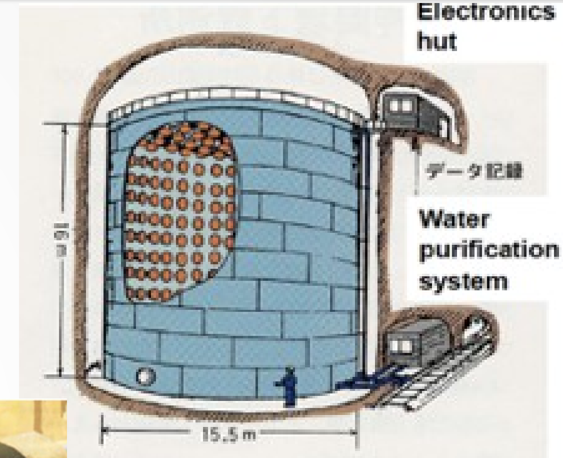
WIN 2019, Bari

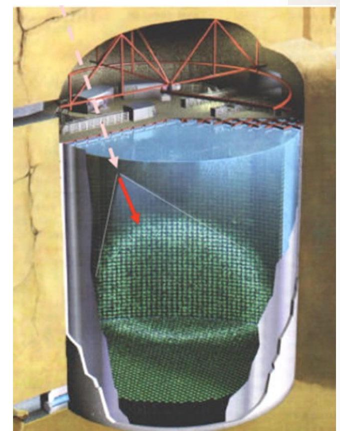
Outline

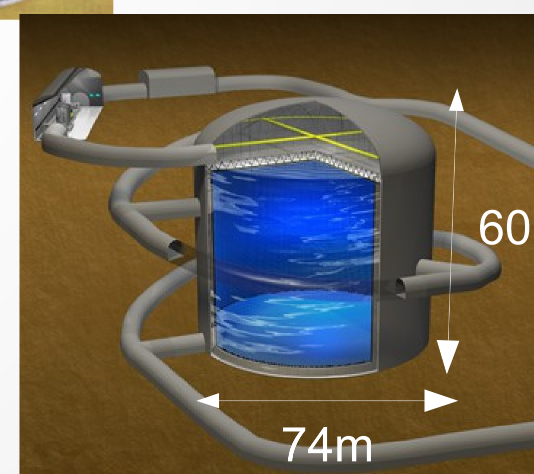
- Water Cherenkov detectors in Japan
- Hyper-Kamiokande technical design
- physics program
  - beam neutrinos
  - atmospheric neutrinos
  - solar neutrinos
  - supernova neutrinos
  - nucleon decay searches
- summary

Water Cherenkov detectors in Japan

- **Kamiokande** 4.5 (0.68) kton
  (1983-1996) PMT coverage 20%
  - neutrinos from SN1987a, deficit of atmospheric neutrinos
- **Super-Kamiokande** 50 (22.5) kton
  (1996-) PMT coverage 40%
  - oscillations of solar and atmospheric neutrinos
  - world leading limit on proton lifetime
  - ν_e appearance
- mature, known, scalable technology
- **Hyper-Kamiokande** 258 (187) kton
  (~2027-) PMT coverage 40%
  - proto-collaboration formed January 2015
  - ~300 people, ~80 institutes



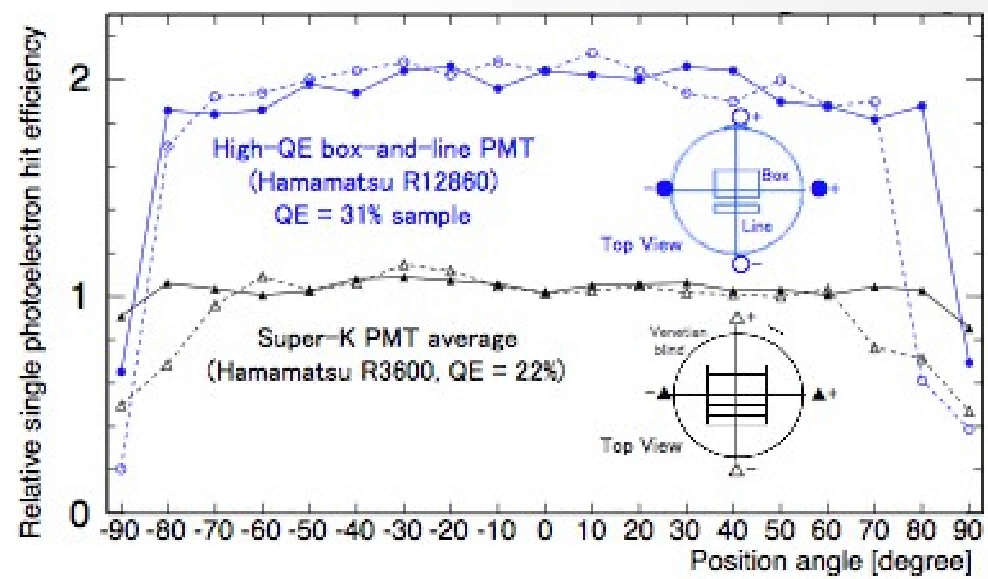




The photodetectors

- new Hamamatsu 50 cm B&L PMT with improved dynode and higher pressure tolerance
  - 2x better photon efficiency
  - improved charge and timing resolution (1 ns)
  - 40 000 in the inner detector
  - 40% photocoverage

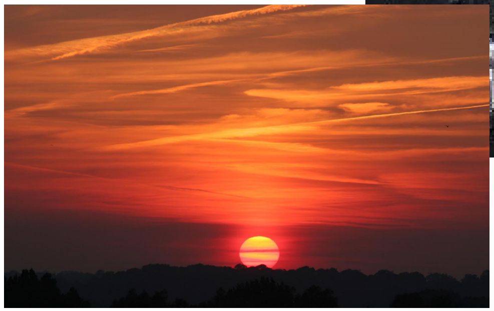
  → almost 2x better overall photon efficiency than Super-K

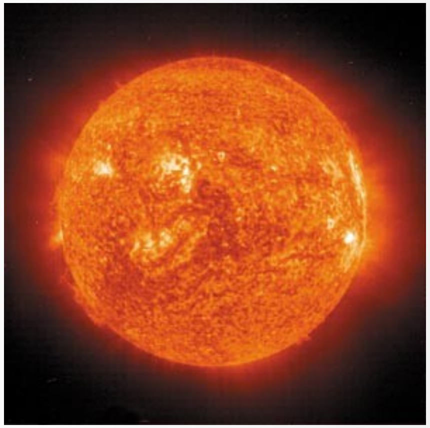


- other considered solutions
  - multiPMT – arrays of 19 smaller (8 cm) PMTs
  - possible light collection devices (reflectors, photon traps etc.)
- outer detector: 10-20k PMT of 8 cm diameter
- covers to protect PMT from sudden pressure changes

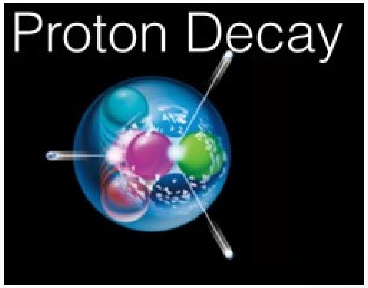
poster →
by A.C.Ruggeri

Physics program





- neutrino oscillations
  - with beam and atmospheric neutrinos
  - CP violation
  - precise measurement of θ_{23}
  - mass hierarchy determination
- neutrino astrophysics
  - precise measurement of solar neutrinos, sensitivity to address solar and reactor neutrinos discrepancy.
  - supernova burst and relic supernova neutrinos
- searching for nucleon decay
  - sensitivity 10x better than Super-K (10^{35} years)
  - all visible modes can be advanced
- and other



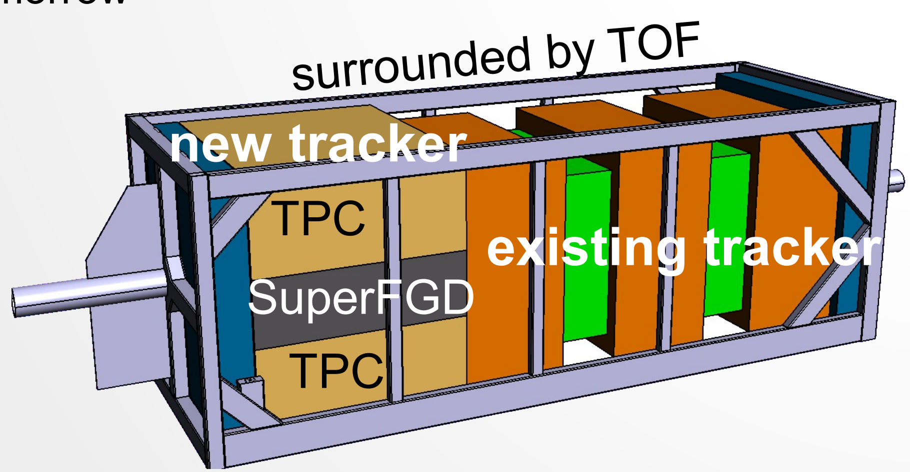
Location and beam neutrinos

- candidate site 8 km south of Super-K
  - the same baseline (295 km) and off-axis angle as Super-K
- the J-PARC beamline
  - 2.5 degree off-axis
  - narrow band beam at ~600MeV
- upgrade of beam power
  - 0.75 MW upgrade starting in 2021 (currently ~485 kW)
  - increasing repetition rate to 0.86 Hz → 1.326 MW by 2026
  - 3.2e14 protons per pulse
- upgrade power supplies for horns
  - design current of 320 kA (wrt 250 kA)
  - 10% higher neutrino flux.
  - reduction of wrong-sign neutrino contamination by 5-10%.

Near and Intermediate Detectors

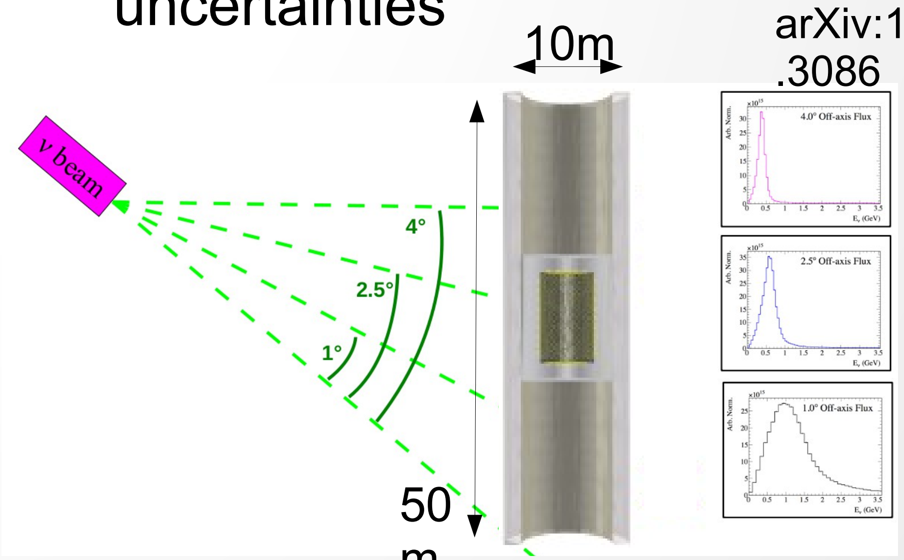
- upgrade of ND280 near detector to reduce systematic uncertainties
  - expanded angular acceptance
  - lower energy threshold
  - systematic uncertainties ~18% (2011) → ~9% (2014) → ~6% (2016) → 4% (2020...)?

CERN-SPSC-2018-001, talk by Y.Kudenko tomorrow



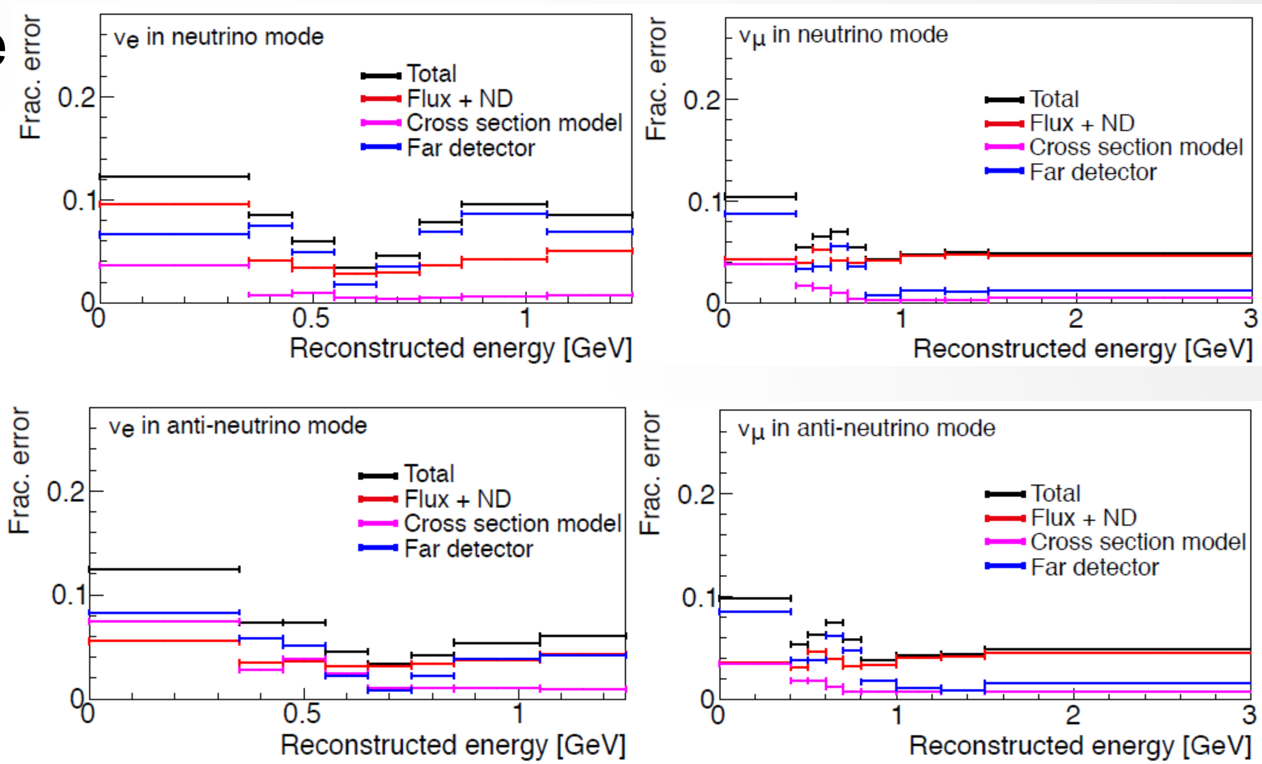
- N61 intermediate water Cherenkov detector
  - distance 1-2 km
  - Gd loading
  - off-axis angle spanning coverage (1-4º)
  - energy dependence of neutrino interactions
  - further reduction of systematic uncertainties

arXiv:1412.3086



Expected systematics

- based on T2K experience with some assumptions on better knowledge of the neutrino beam, interactions and detector

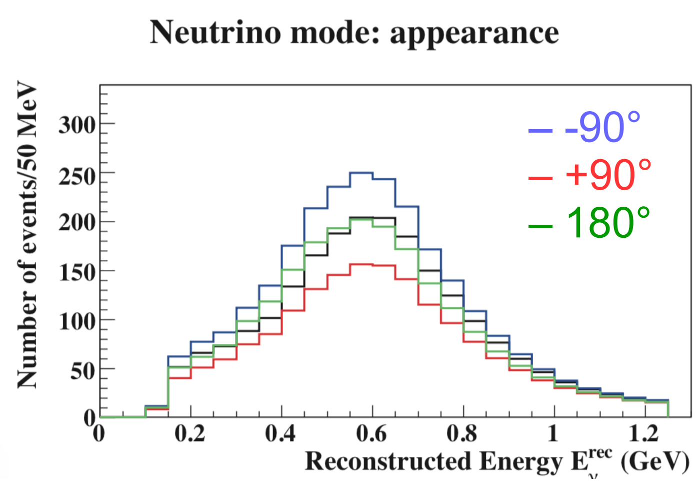


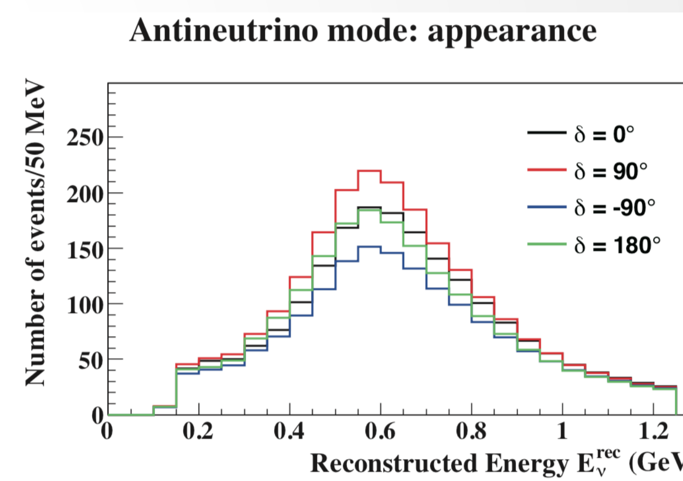
		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0%	0.5%	0.7%	3.2%
	Disappearance	3.3%	0.9%	1.0%	3.6%
$\overline{\nu}$ mode	Appearance	3.2%	1.5%	1.5%	3.9%
	Disappearance	3.3%	0.9%	1.1%	3.6%

Expected numbers of events

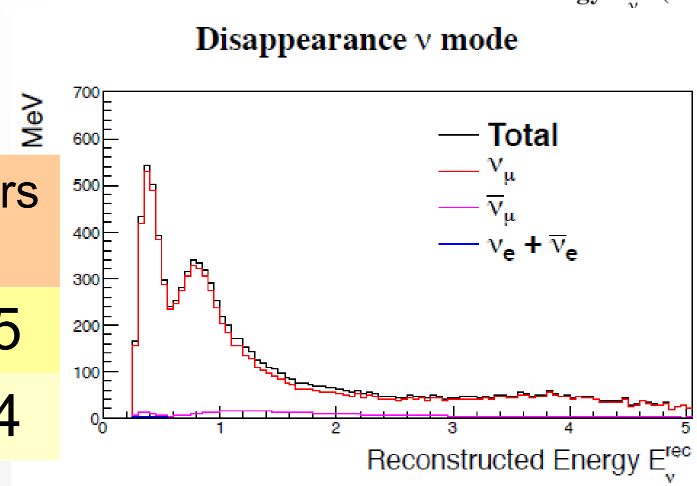
- 10 years exposure
  - $2.7 \cdot 10^{22}$ POT
  - $\nu:\bar{\nu}$ data taking 1:3
- ν_e appearance
  - shape information can be used to distinguish different values of δ_{CP}
- ν_μ disappearance

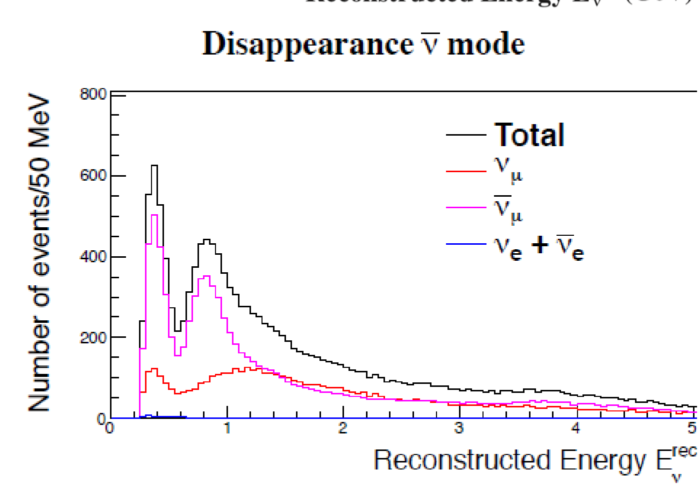
$\delta_{CP} = 0$	right-sign $\nu_\mu \rightarrow \nu_e$ CC	wrong sign $\nu_\mu \rightarrow \nu_e$ CC	ν_μ, $\bar{\nu}_\mu$ CC	intrinsic beam ν_e	NC
ν beam	**1643**	15	7	259	134
$\bar{\nu}$ beam	**1183**	206	4	317	196





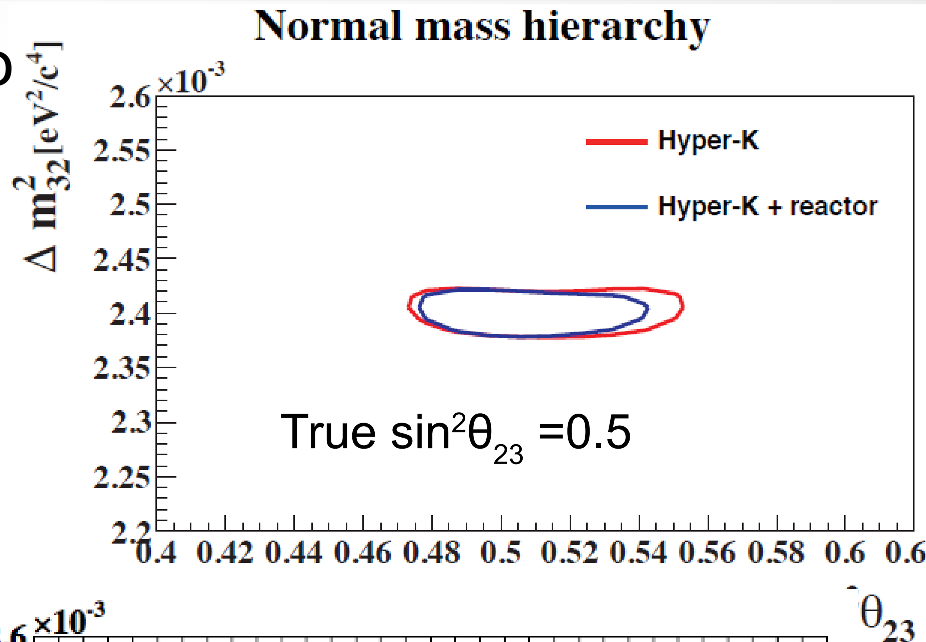
	$\nu_\mu + \bar{\nu}_\mu$ CCQE	ν_μ CC nonQE	others
ν beam	**6391**	3175	515
$\bar{\nu}$ beam	**8798**	4315	614

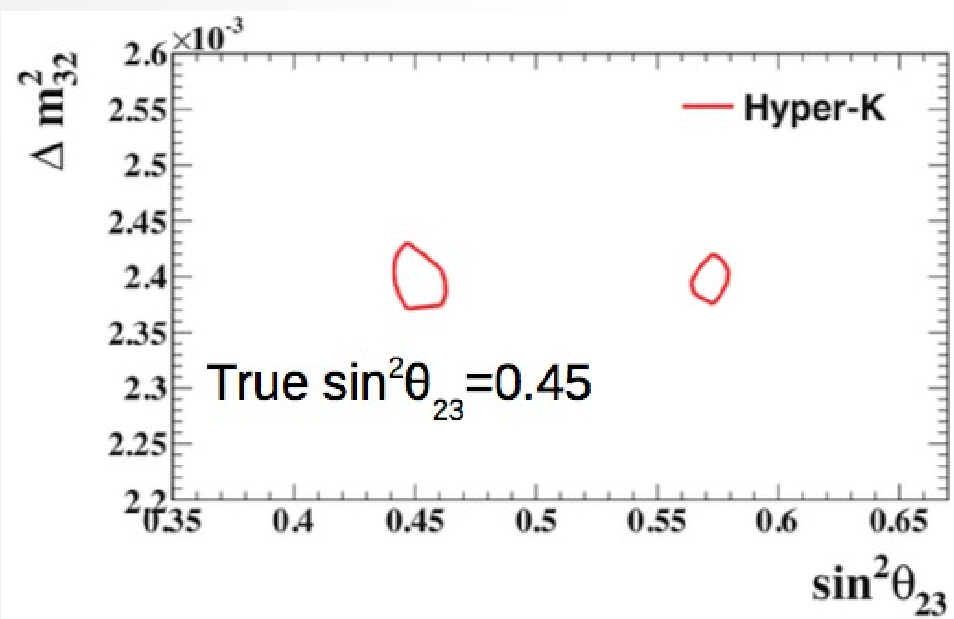


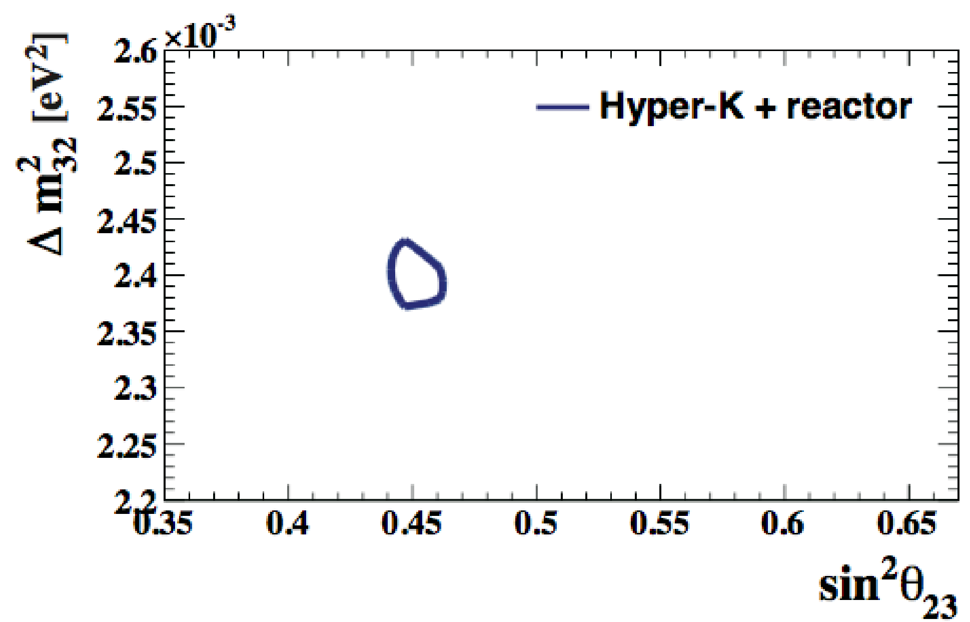


Precise measurements of θ_{23}

- joint fit of ν_μ and ν_e samples allows to precisely measure $\sin^2\theta_{23}$ and Δm^2_{32}
- expected precision
  - ~0.017 at $\sin^2\theta_{23} = 0.5$
  - ~0.006 at $\sin^2\theta_{23} = 0.45$



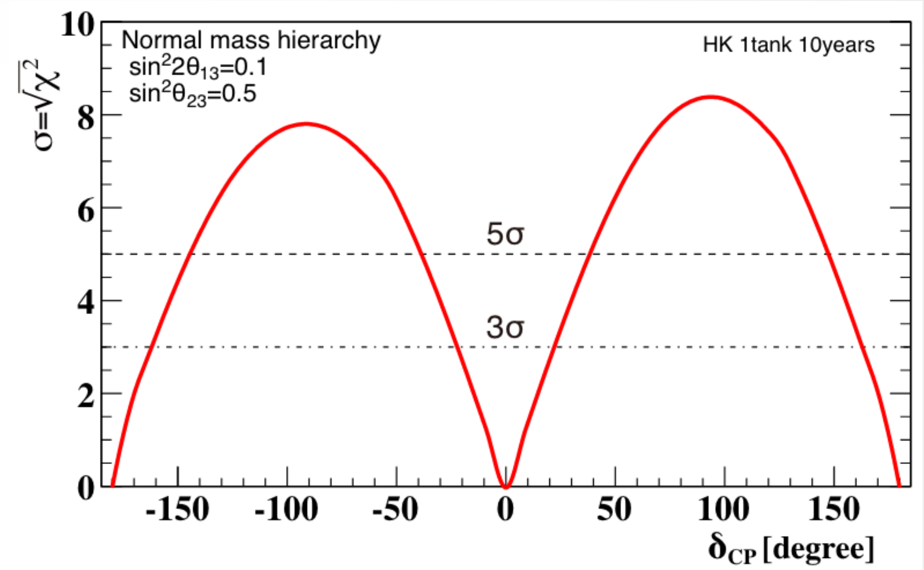


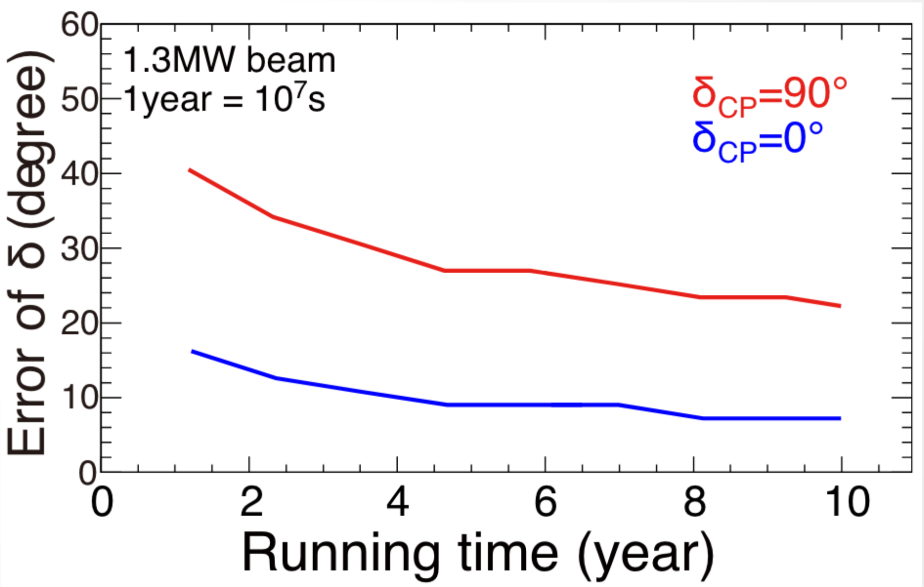


- for non-maximal θ_{23} the reactor constraint breaks octant degeneracy

CPV sensitivity

- exclusion of $\sin\delta_{CP} = 0$ with
  - ~8σ if true $\delta_{CP} = \pm 90°$
  - > 5σ for 57% of δ_{CP} values
  - > 3σ for 76% of δ_{CP} values
- δ_{CP} resolution
  - 23° precision at $\delta_{CP} = \pm 90°$
  - 7.2° precision at $\delta_{CP} = 0°$ or 180°
- combination with atmospheric data enhances the sensitivity

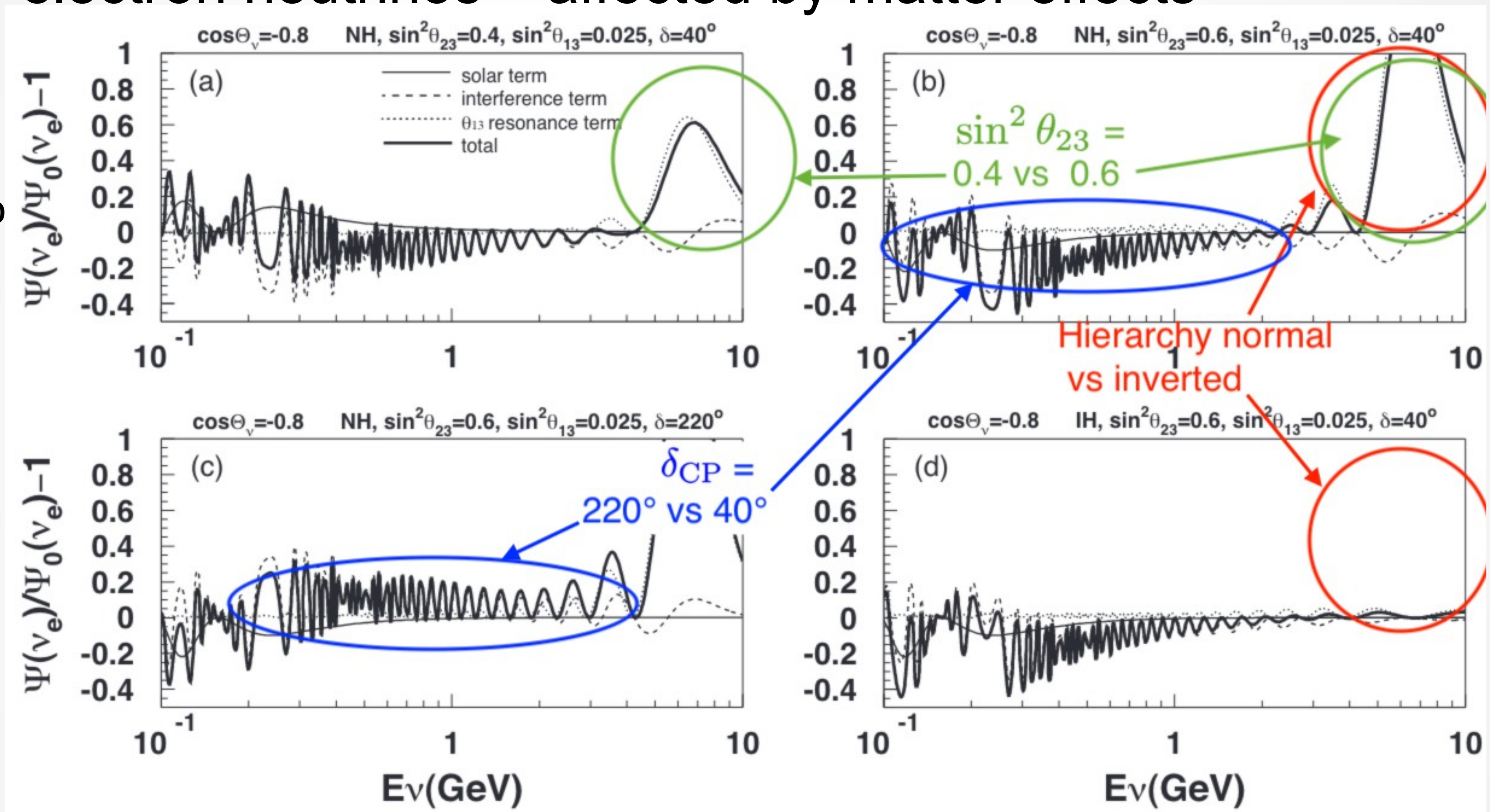




Atmospheric neutrinos

- flux of electron neutrinos – affected by matter effects

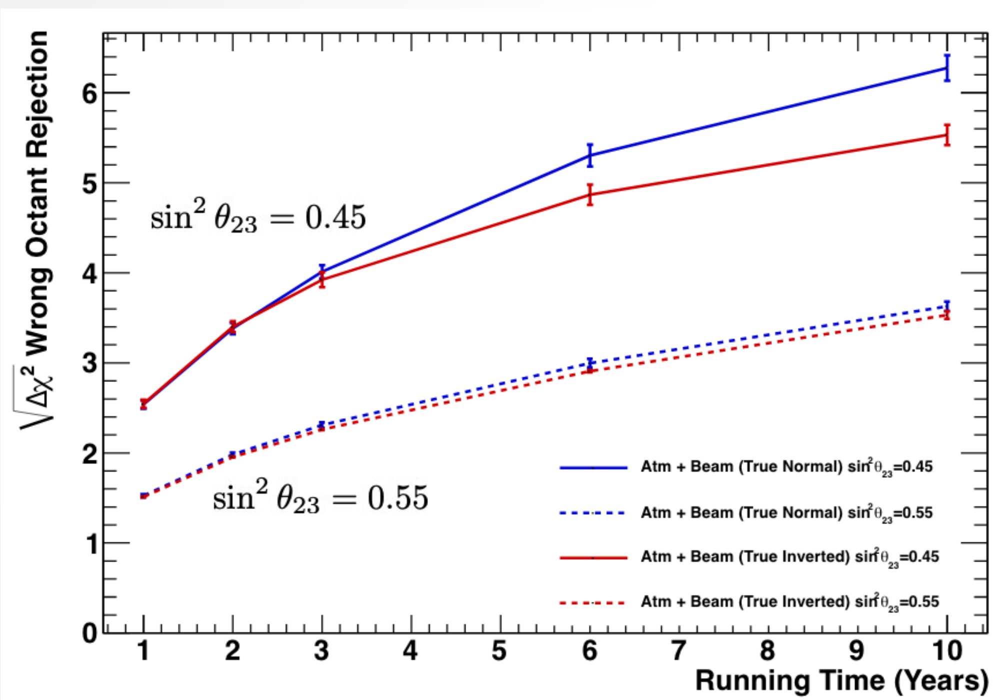
ν_e flux relative to no oscillations

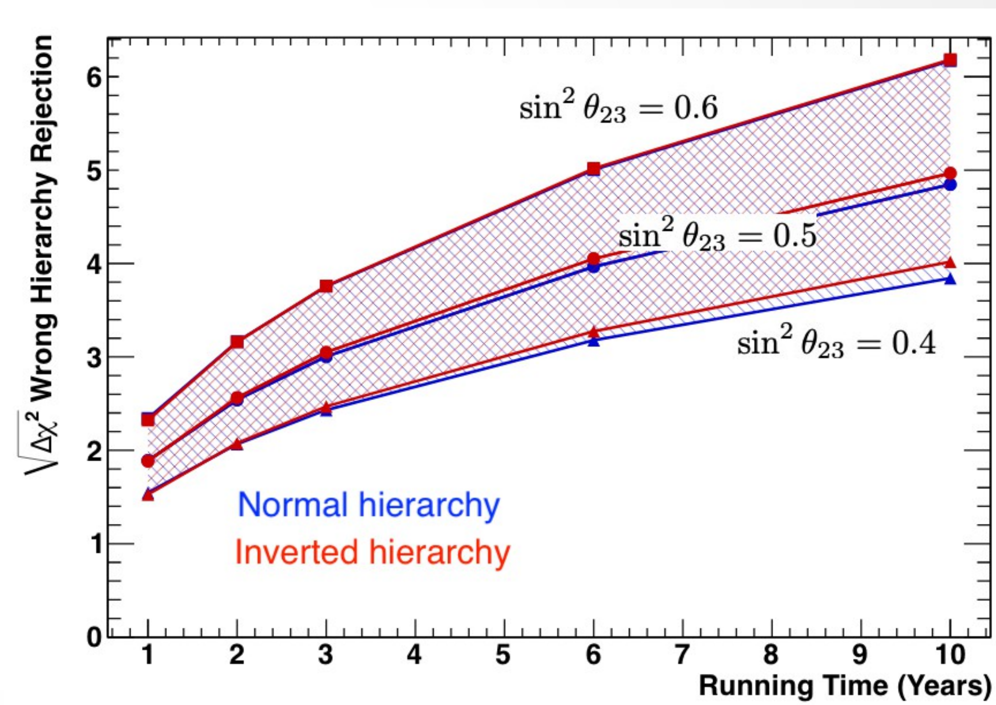


- presence of a resonance in multi-GeV region → mass hierarchy
- magnitude of the resonance → θ_{23} octant
- scale and direction of the effect at 1 GeV → δ_{CP}

Atmospheric+beam neutrinos

- improved performance for octant determination
- 3σ ability to reject the incorrect mass hierarchy after 5 years



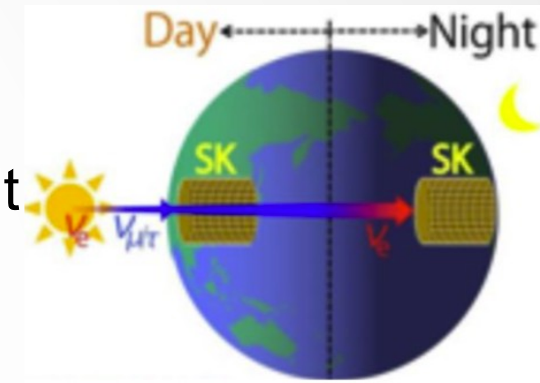


wrong octant rejection
3σ for $|\theta_{23} - 45°| \geq 2.3°$

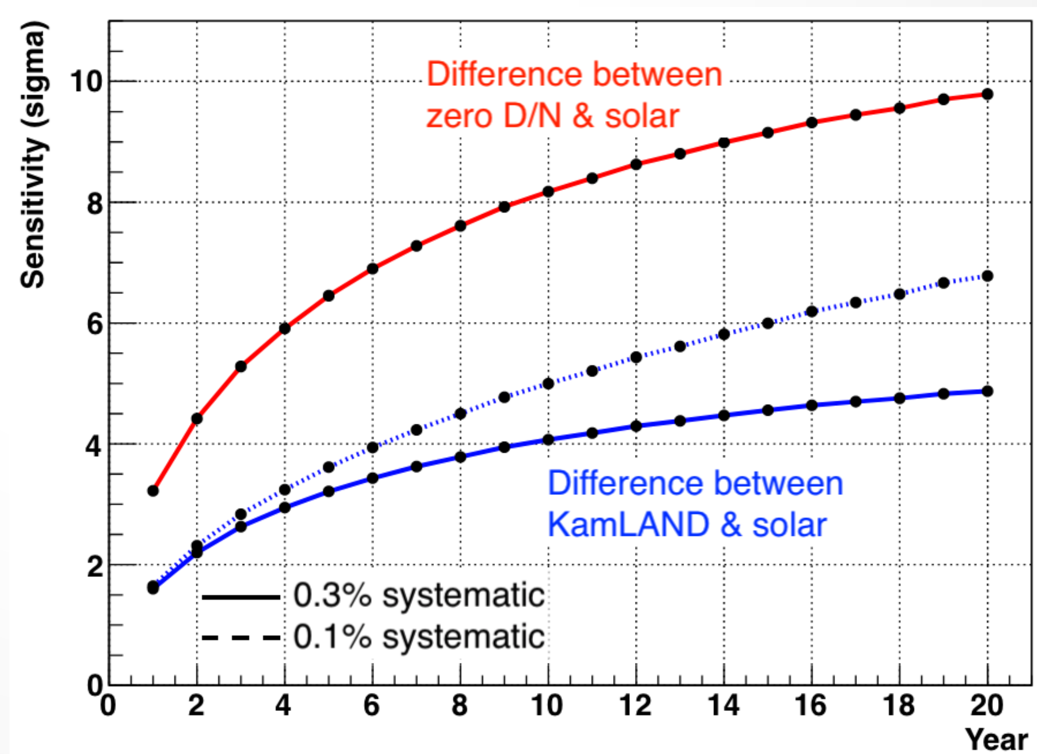
wrong hierarchy
rejection

Solar neutrinos

- tension ~2σ between Kamland and global solar analysis in Δm^2_{21}
  - from the recent Super-K result of the solar neutrino day-night asymmetry and energy spectrum shape
  - day-night asymmetry caused by electron component regeneration in Earth (3σ indication in Super-K)
  - few percent higher event rate at night

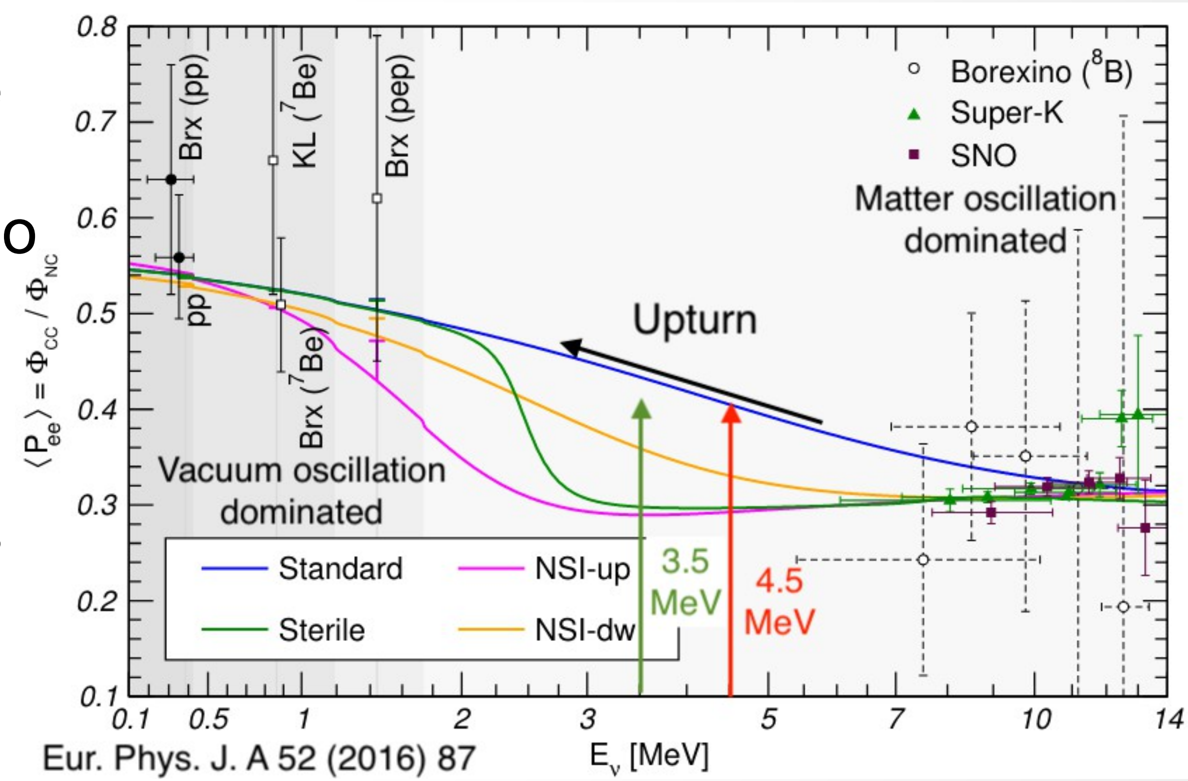


- Hyper-K goal:
  precise measurement of Δm^2_{21} and
  day-night asymmetry
  - expected >5σ sensitivity
- new physics needed if the tension is a real effect



Solar neutrino spectrum upturn

- transition region between the vacuum oscillations and matter-dominated energy regions
- precise measurement of the spectrum shape allow to distinguish the usual neutrino oscillation scenario from exotic models
- 5σ discovery sensitivity to spectrum upturn in 10 years thanks to lower energy threshold (3.5 MeV)
  - 3σ for 4.5 MeV

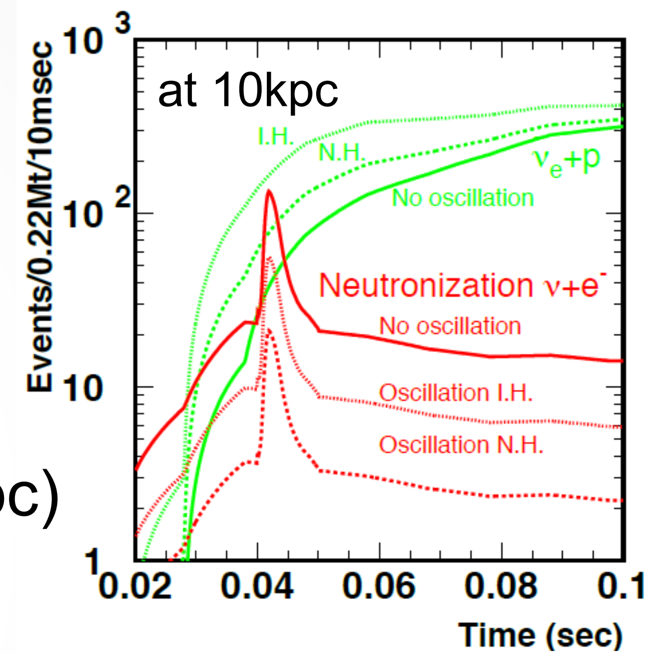


Eur. Phys. J. A 52 (2016) 87

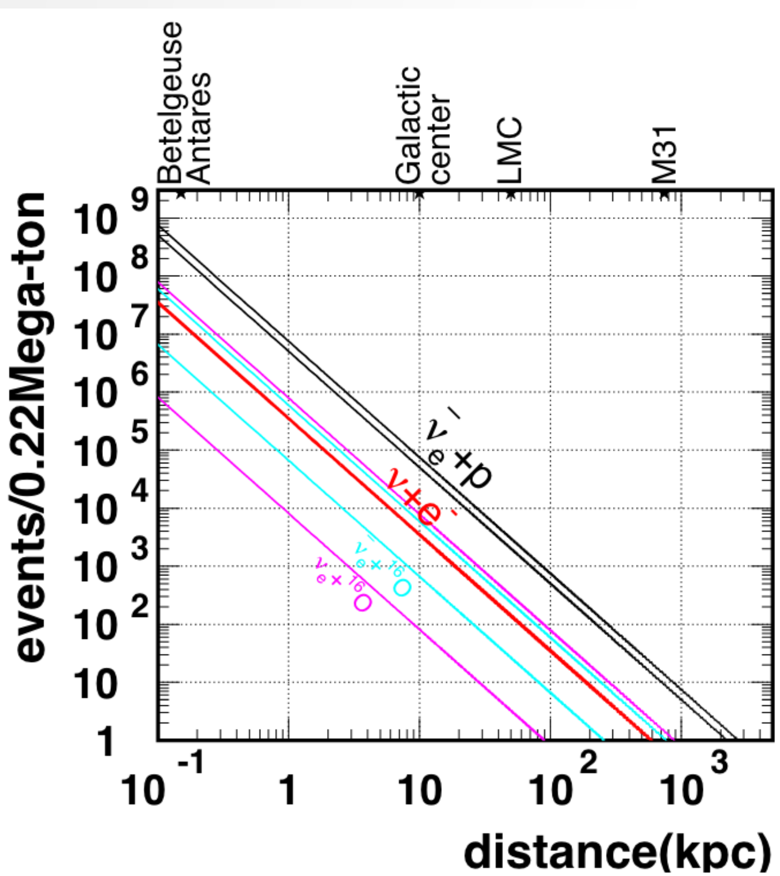
- other possible measurements
  - first measurement of *hep* component (2-3σ) providing more information on the Sun core
  - time variation measurement (with rate of 200ν/day) → monitoring of the Sun core temperature

Supernova burst neutrinos

- ν_e from neutronization peak – elastic scattering on electrons (directional information, accuracy 1-1.3° expected for supernova at 10kpc)
- $\bar{\nu}_e$ from cooling phase – inverse beta decay

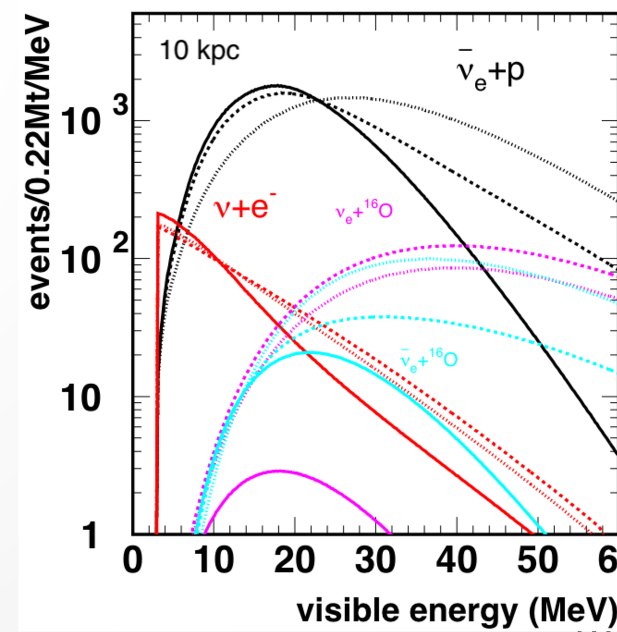


expectations:
50-80k events (10kpc)
2-3k (SN1987a)



information on
- neutrino oscillations and properties (mass, mass hierarchy)
- core-collapse supernova models

Early warning for telescopes

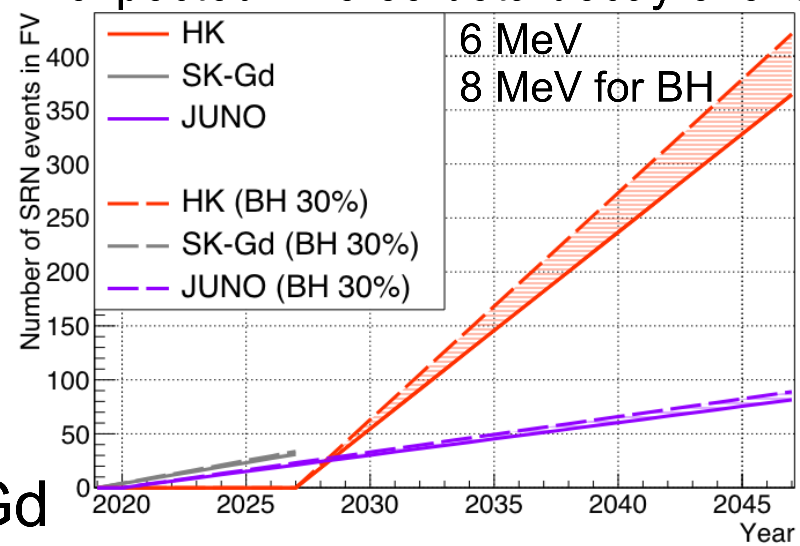


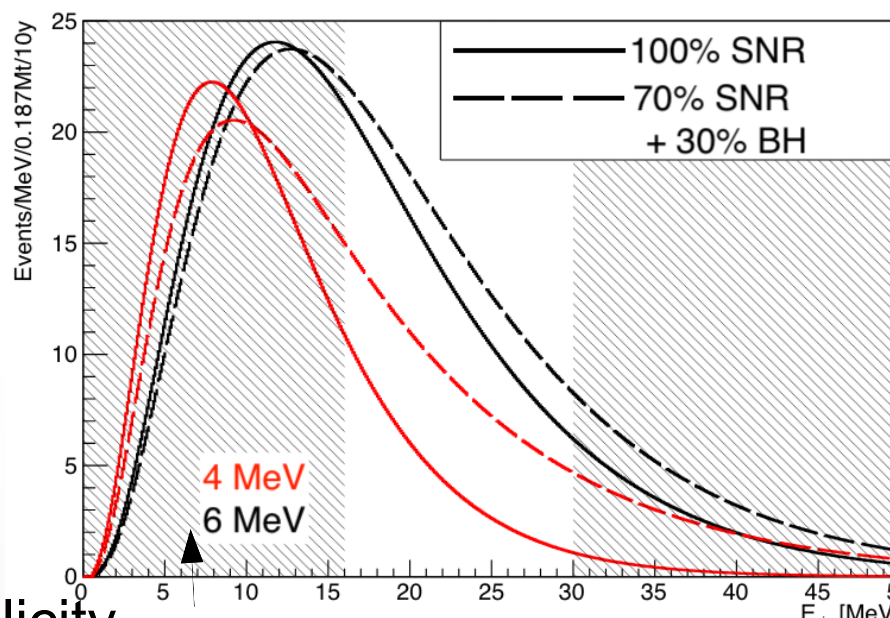
Supernova relic neutrinos

or diffuse supernova neutrino background

- expected flux few tens/cm²/sec
- search limited by background:
  - spallation for low energies
  - atmospheric neutrinos for high energies
- first measurement may be done by SK-Gd
- Hyper-K may measure the spectrum
- different search window (~16-30 MeV),
  - complementary to SK-Gd searches (10-20 MeV)
  - contribution of extraordinary supernova bursts (like black hole formation, BH): provides information on the star formation history and metallicity

expected inverse beta decay events

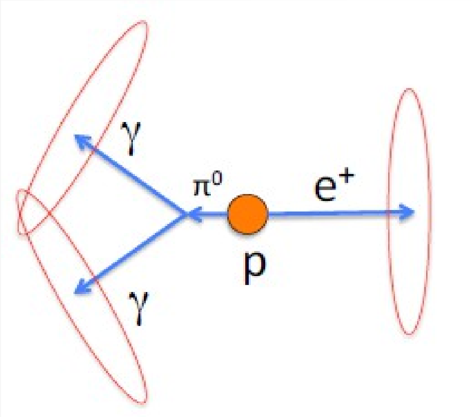




ν temperature
8 MeV for BH formation

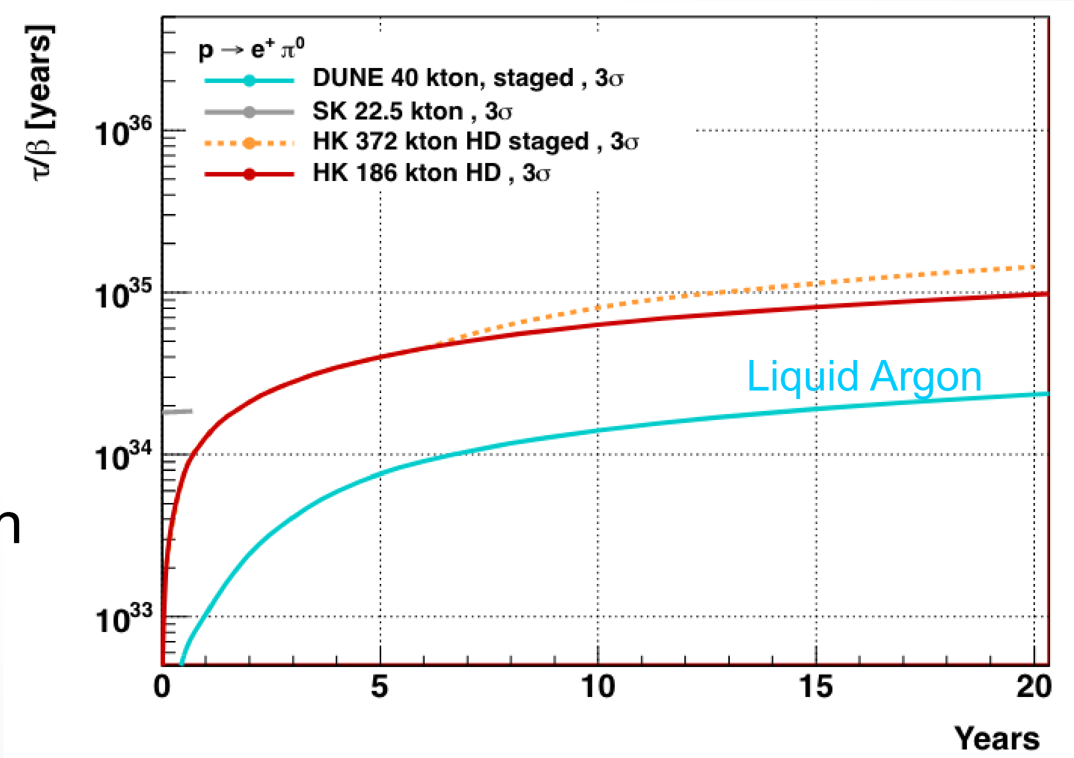
Search for $p \to e^+\pi^0$ decay

- decay mode $p \to e^+\pi^0$ is favoured by many GUTs



e^+ and photons are detected as e-like rings → final state is fully reconstructed (practically background free)

3σ discovery potential reaching t ~ 10^{35} yrs

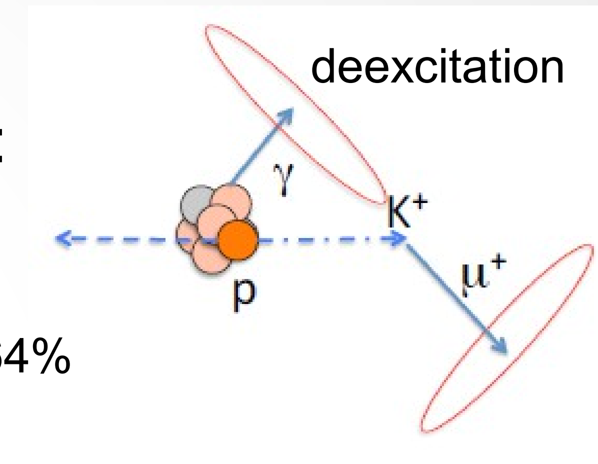


- analysis similar as in SK but with neutron tagging (veto) thanks to improved PMTs
  - neutron capture in water n(p,d)γ (2.2 MeV)
  - efficient tagging of prompt γ from residual nuclei deexcitation
  - ~50% reduction of atmospheric background

Search for p→$\bar{\nu}$K$^+$ decay

- favored by SUSY GUTs
- kaon not visible in Water Cherenkov detector: reconstructed from decay products
  - monochromatic muon (236 MeV) +prompt deex. photon (6.3 MeV)
  - excess in muon spectrum

  } $K^+ \to \mu^+ \nu$, BR 64%
  - or search for $K^+ \to \pi^0 \pi^+$ decay (BR 21%) p = 205 MeV/c (slightly above the threshold)

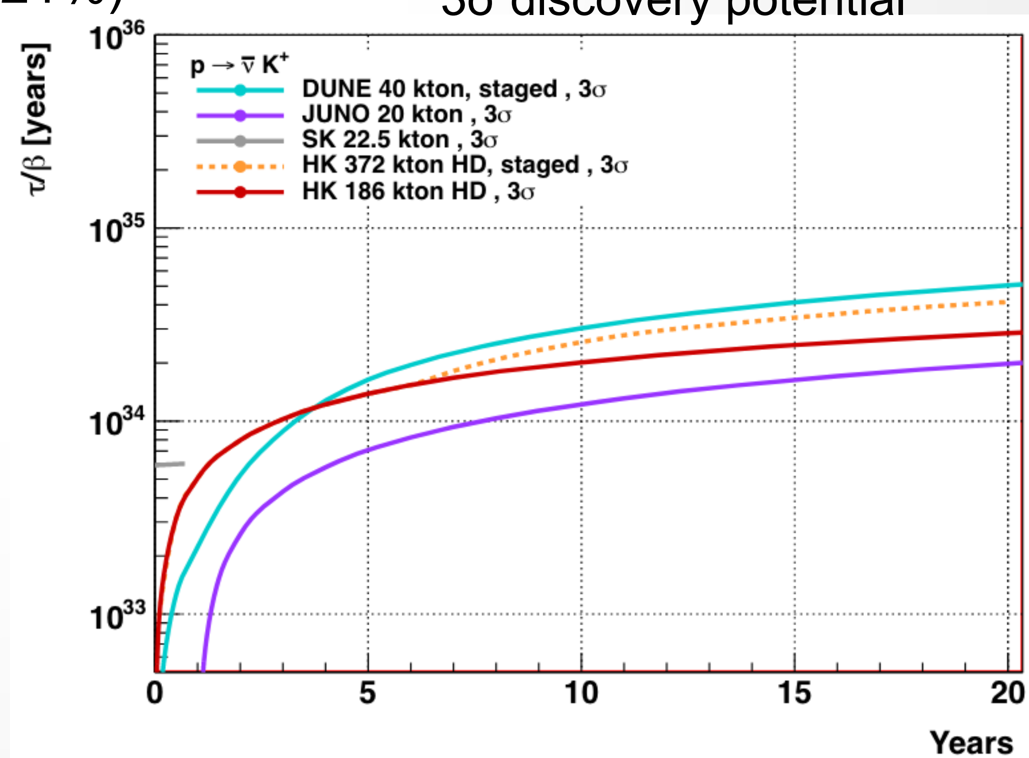


Partial lifetimes limits (90% C.L., 10 y exposure)

- $7.8 \cdot 10^{34}$ years for $p \to e^+ \pi^0$

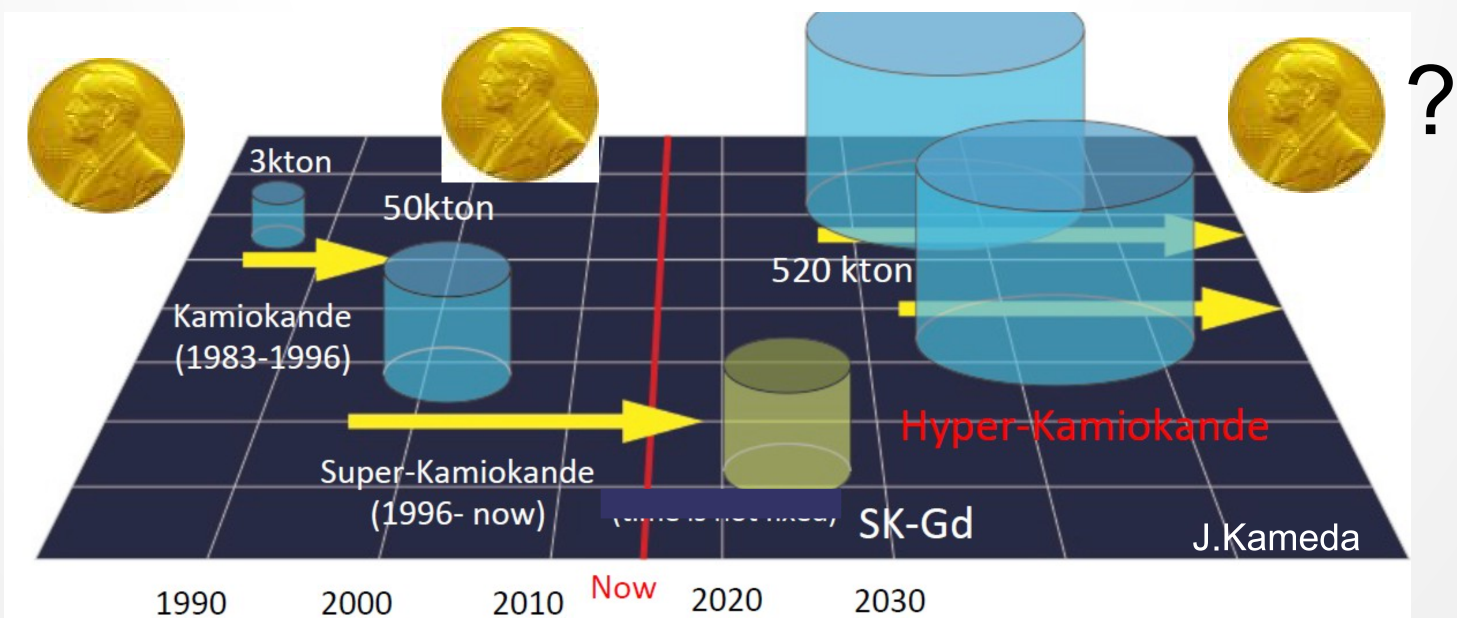
  $3.24 \cdot 10^{34}$ years for $p \to \bar{\nu} K^+$
- basically one order of magnitude improvement for many other nodes

3σ discovery potential



Conclusions

- Hyper-Kamiokande is multi-purpose project with long term, wide physics program
  - high sensitivity to CP violation and other oscillation measurements
  - neutrino astrophysics
  - sensitivity to nucleon decay over 5 times higher than current limits
- construction to start in April 2020 (data taking in ~2027)
- plan to build a second tank in the future (in Korea?)
- an updated TDR in preparation



Backup slides

What so special about $\nu_\mu \rightarrow \nu_e$ channel?

- allows for CP violation studies

$$P(\nu_\mu \rightarrow \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$ dominant term

$$+8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$

$$-8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$ CP violation

$$+4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \sin^2\Delta_{21}$$

matter

$$-8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{aL}{4E_\nu} (1 - 2 s_{13}^2) \cos\Delta_{32} \sin\Delta_{31} + 8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2 s_{13}^2) \sin^2 \Delta_{31}$$

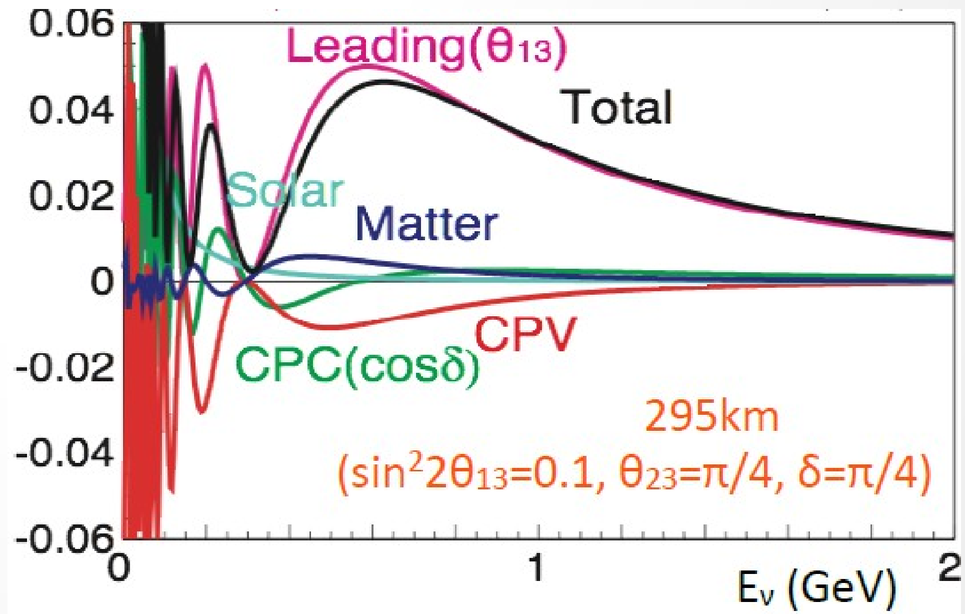
for $\bar{\nu}$

$$\delta_{CP} \rightarrow -\delta_{CP}$$

$$a \rightarrow -a \qquad a = 2\sqrt{2} G_F n_e E_\nu$$

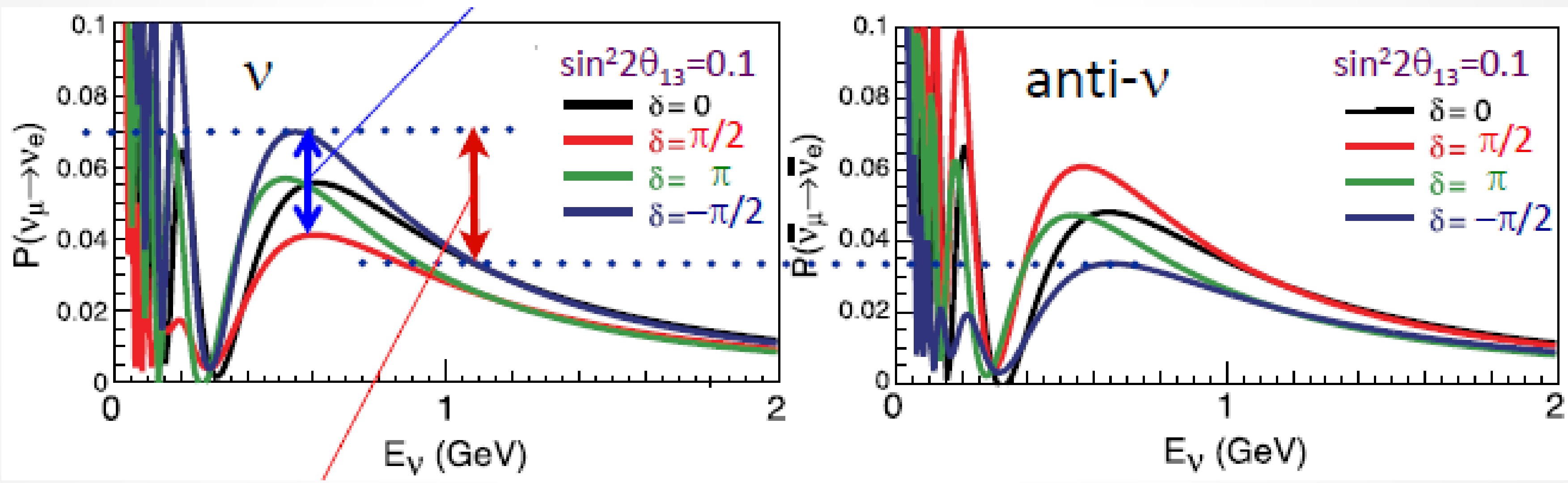
n_e related to matter density

subleading effect,
can be as large as 30%
of dominant



How to look for CP violation?

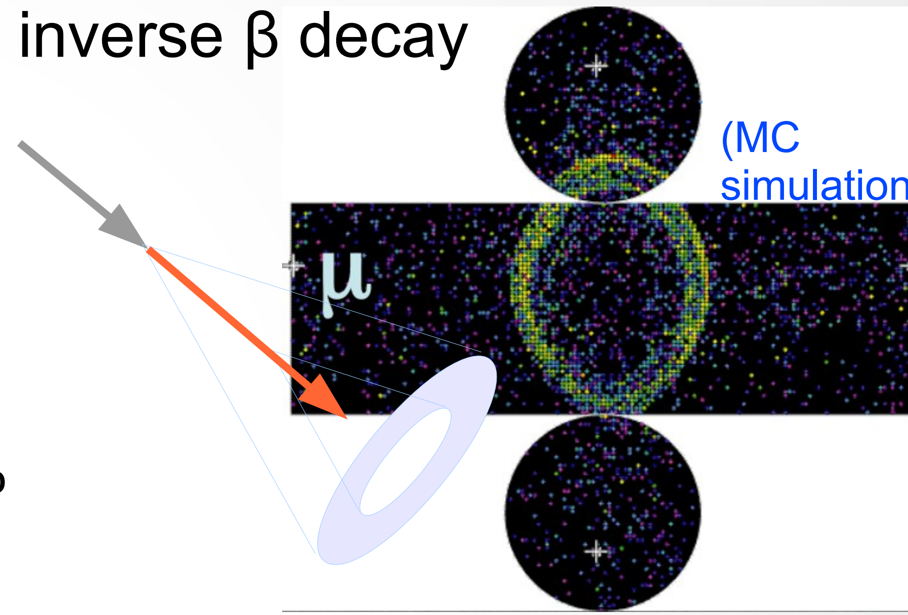
- method 1: use θ_{13} from reactor experiments for predictions and compare to neutrino data

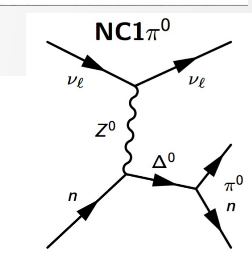


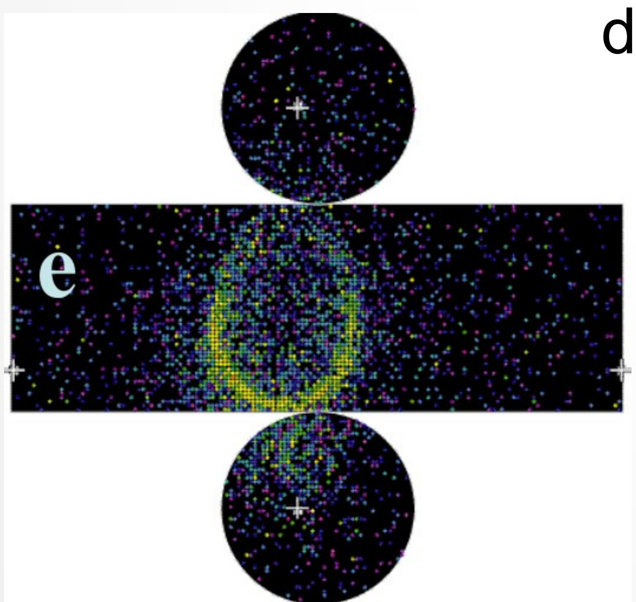
- method 2: compare measured $P(\nu_\mu \rightarrow \nu_e)$ with $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- method 3 (for wide band beams): compare 1st and 2nd maximum

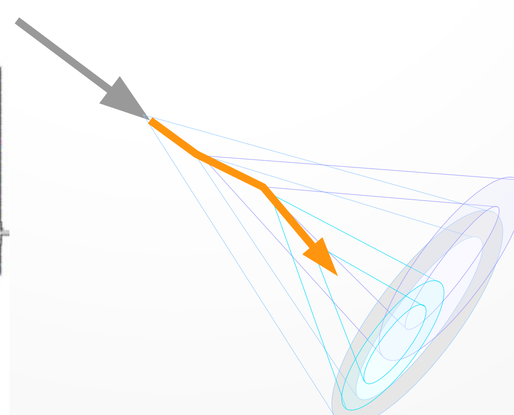
Neutrino interactions in WC

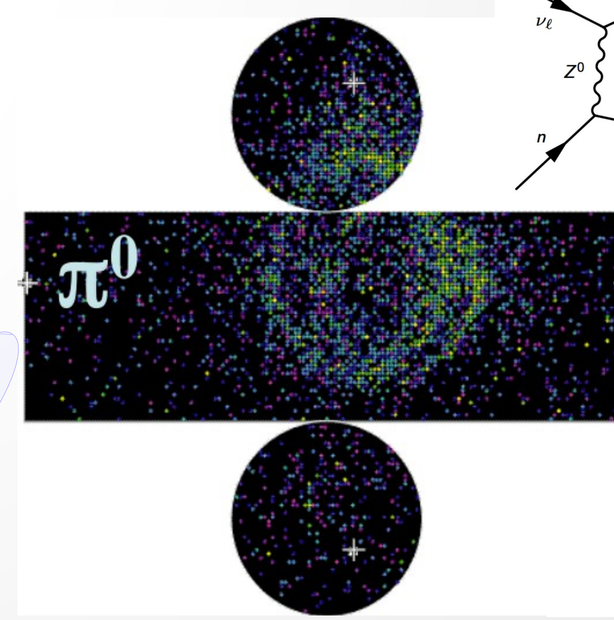
- low energies: scattering on electrons, inverse β decay
  - CC interactions observed only for ν_e
- high energies: scattering on nuclei
- ΔE/E ~10% for 2-body kinematics
- very good μ/e separation
  - muons misidentified as electrons: <1%
- π^0 detection (2 e-like rings)
- delayed signal detection (Michel electrons, deexcitation)





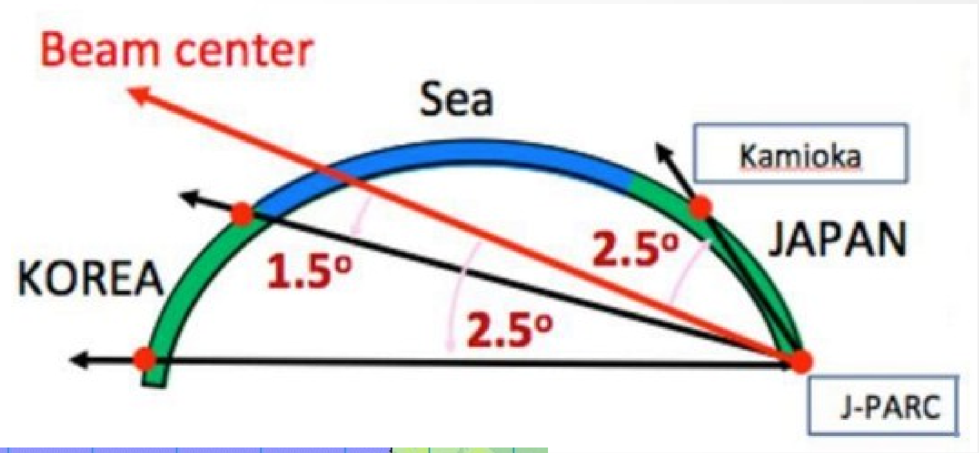


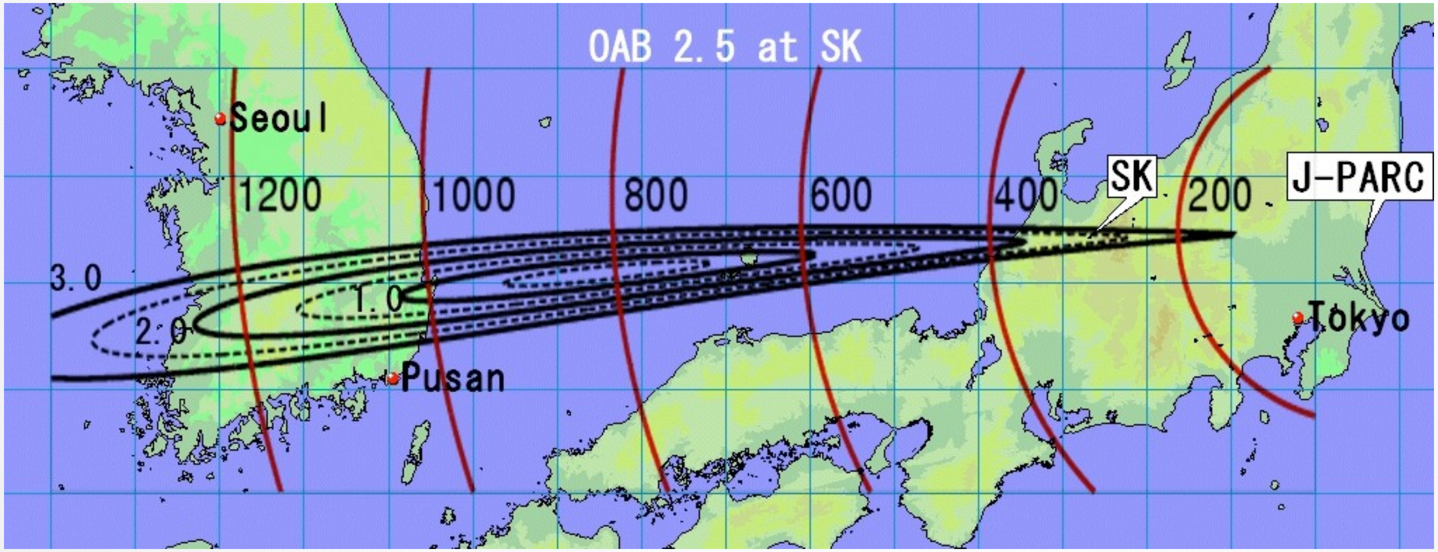




T2HKK

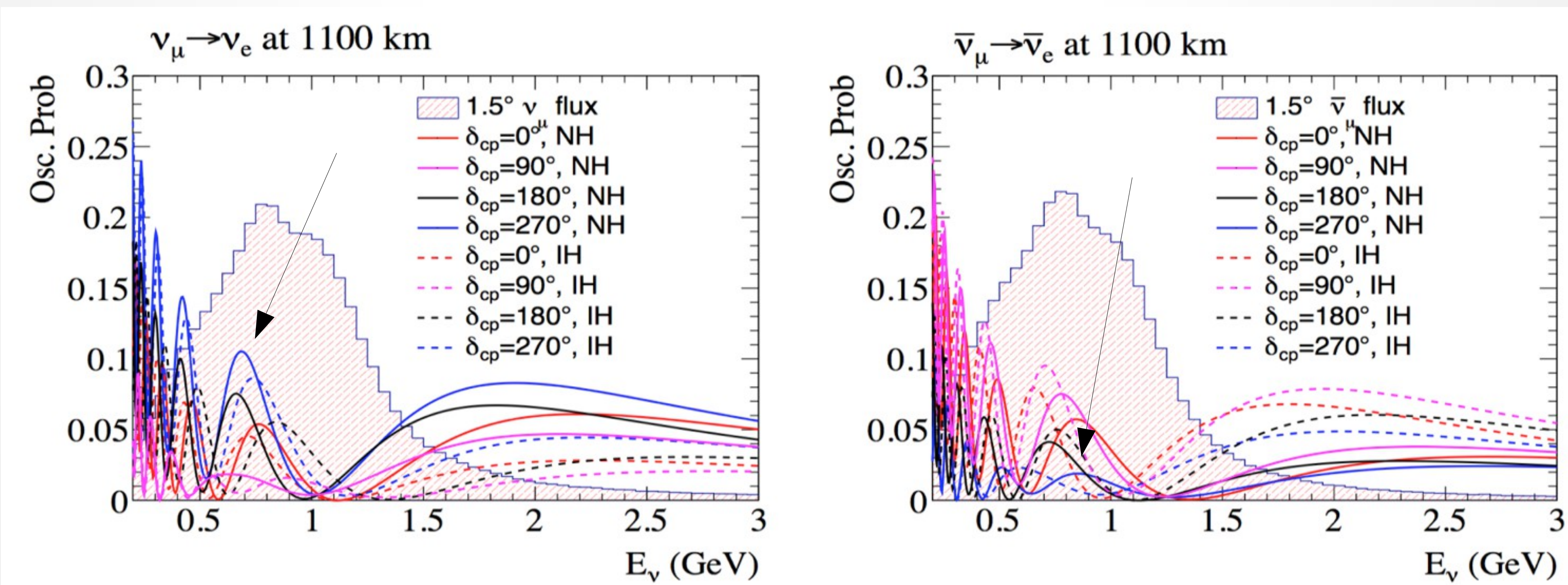
- under investigation: put 2nd tank in Korea
  - 1000-1200km baseline
  - 1.3-3.0º off-axis beam
  - enhances sensitivity to mass hierarchy and CP violation





Situation with one tank in Korea

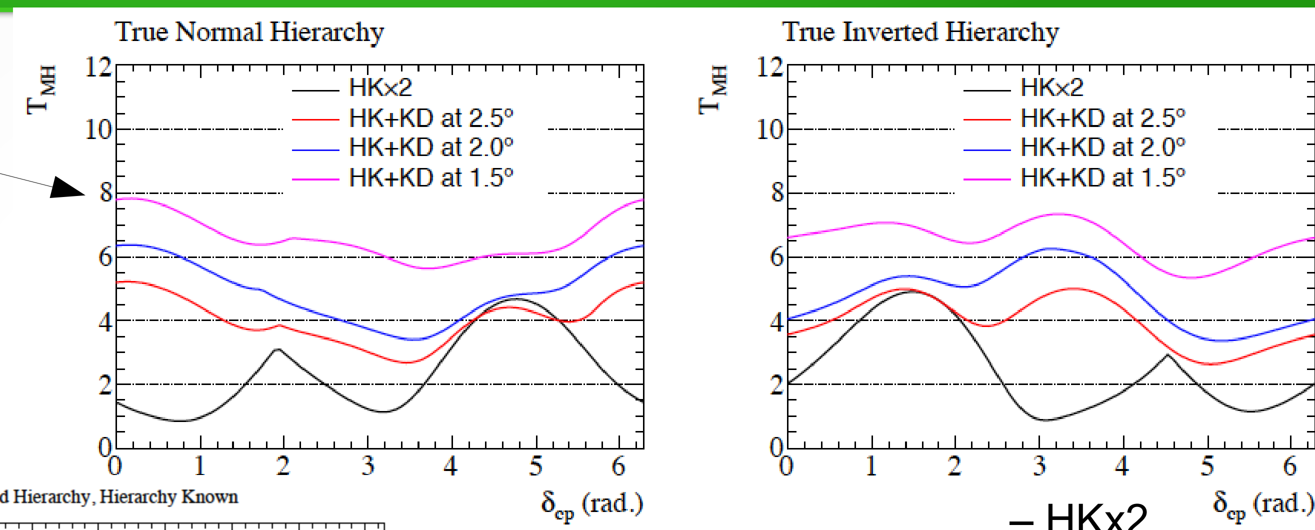
- 2nd oscillation maximum covered
  - CP asymmetry for $\nu_e/\bar{\nu}_e$ appearance is 3x larger than at 1st maximum
  - larger CP effect → less sensitive to systematic errors
- larger matter effect for longer baseline
  - better sensitivity for mass hierarchy
- smaller number of events because of flux reduction



Sensitivities

mass hierarchy

- for 1.5° off-axis
  6-8σ (true NH)
  5.5-7σ (true IH)
  for all δ_{CP}

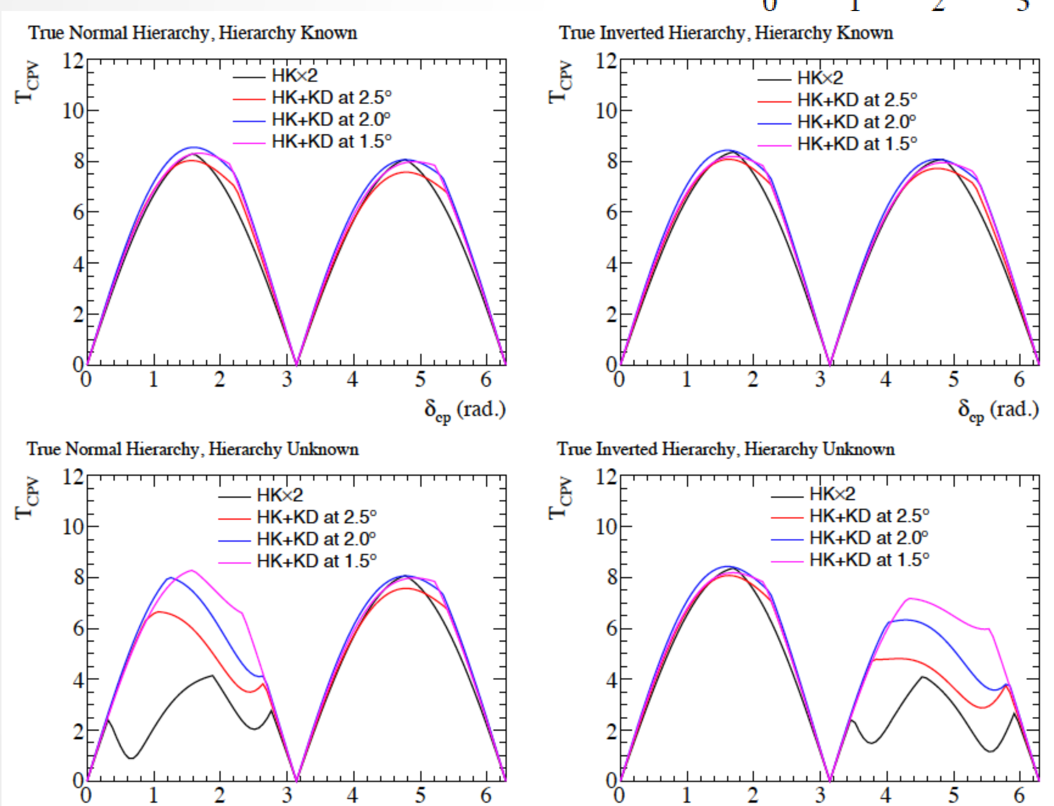


– HKx2
– HK+KD at 2.5°
– HK+KD at 2.0°
– HK+KD at 1.5°

CP violation

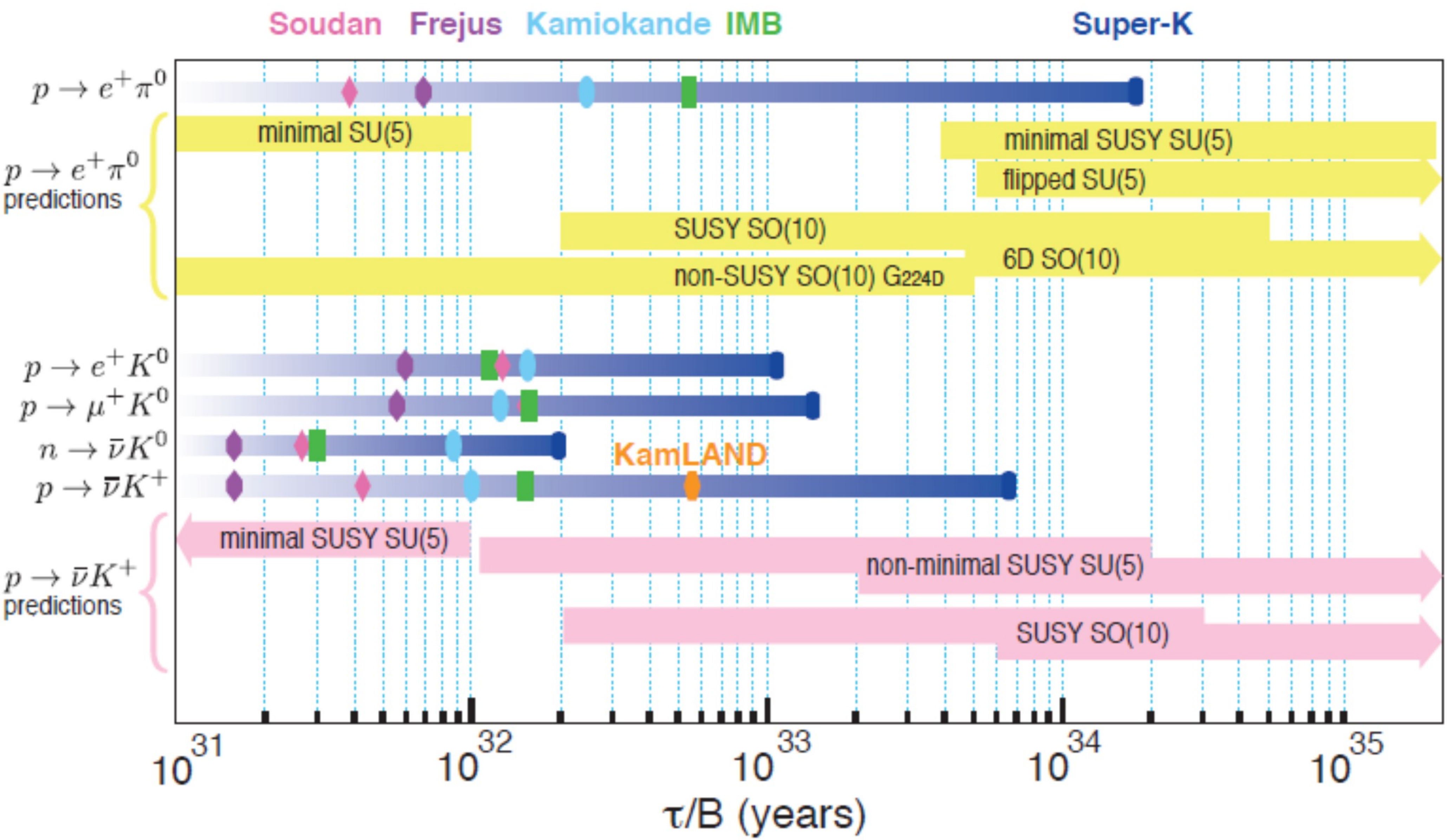
– known hierarchy

– unknown hierarchy



true NH   true IH

Nucleon decays in GUTs



Hints on CP violation from T2K

expected numbers of events

ν: 1.49 x 10^{21} POT
$\bar{\nu}$: 1.63 x 10^{21} POT

δ_{CP}	-0.5π	0	0.5π	π	observed
ν_e CCQE	74.4	62.2	50.6	62.7	75
ν_e CC1π	7.0	6.1	4.9	5.9	15
$\bar{\nu}_e$ CCQE	17.1	19.4	21.7	19.3	15

δ_{CP} = [-2.966, -0.628] (NH)
[-1.799, -0.979] (IH)
@ 90% CL

- CP conserving values (δ_{CP}= 0 or π) disfavored at 2σ level