The Hyper-Kamiokande experiment

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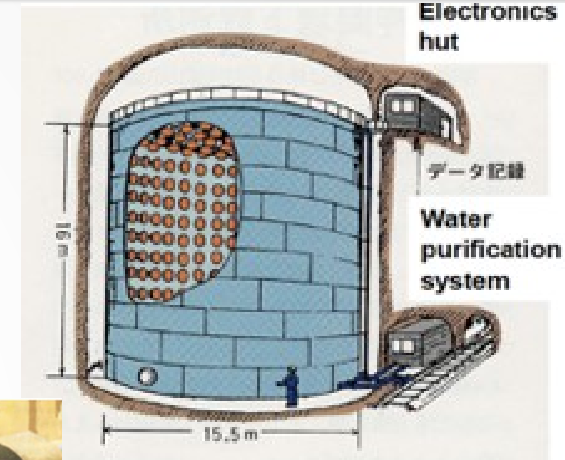
Outline

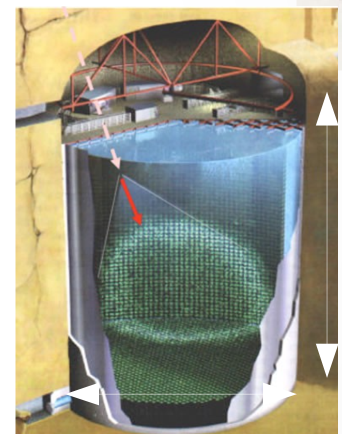
- Water Cherenkov detectors in Japan
- Hyper-Kamiokande technical design
- physics program
  - beam neutrinos
  - atmospheric neutrinos
  - solar neutrinos
  - supernova neutrinos
  - nucleon decay searches
- summary

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

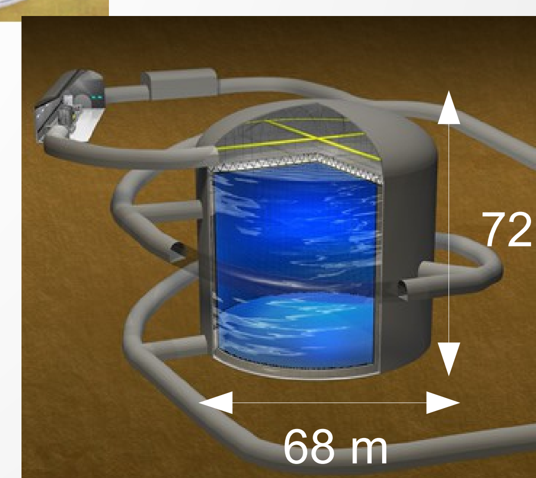
- **Hyper-Kamiokande** 260 (188) kton
  (~2027-) PMT coverage 40%





40 m

40 m



HK history

- LOI: 2011 (arXiv:1109.3262)
- proto-collaboration formed January 2015
  - ~300 people, ~80 institutes
- MEXT Large Projects Roadmap:2017
- design report: 2018
- seed funding: 2018
- approval: early 2020

12/February/2020

東京大学 THE UNIVERSITY OF TOKYO　KEK High Energy Accelerator Research Organization　J-PARC

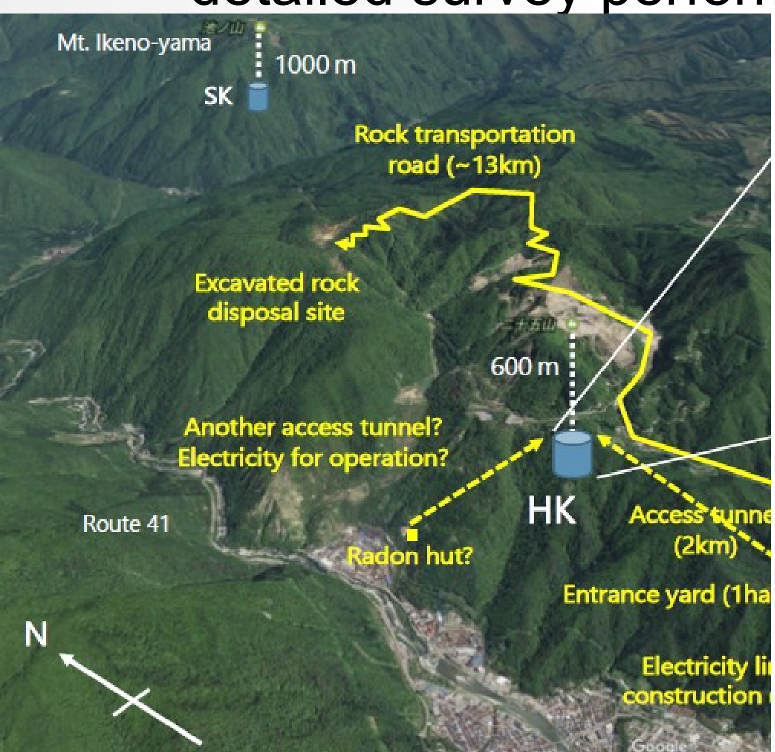
The University of Tokyo
High Energy Accelerator Research Organization (KEK)
Japan Proton Accelerator Research Complex (J-PARC) Center

Hyper-Kamiokande (HK or Hyper-K) project is the world-leading international scientific research project hosted by Japan aiming to elucidate the origin of matter and the Grand Unified Theory of elementary particles. The project consists of the Hyper-K detector, which has an 8.4 times larger fiducial mass than its predecessor, Super-Kamiokande, equipped with newly developed high-sensitivity photosensors and a high-intensity neutrino beam produced by an upgraded J-PARC accelerator facility.

The supplementary budget for FY2019 which includes the first-year construction budget of 3.5 billion yen for the Hyper-Kamiokande project was approved by the Japanese Diet. The Hyper-K project has officially started. The operations will begin in 2027.

Location

- candidate site 8 km south of Super-Kamiokande
- Tochibora mine
  - under Mt. Nijugo-yama
  - overburden ~650m (~1755m.w.e.)
  - geological conditions: detailed survey performed

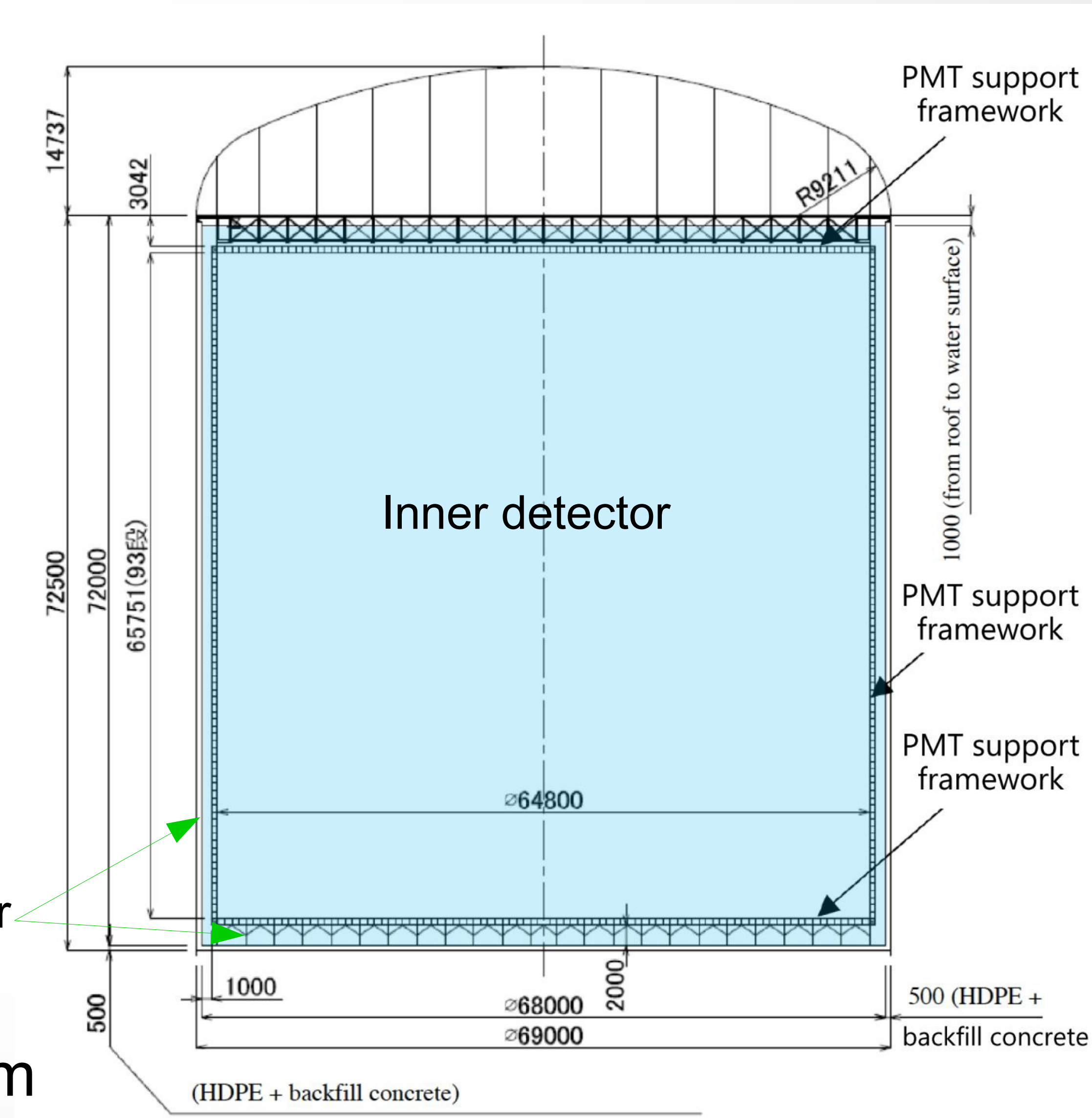


the same baseline (295 km) and off-axis angle wrt J-PARC as Super-Kamiokande

Cavern and tank

Tank size	H 72 m × Φ 68 m
Water height	71 m
ID volume	217.0 kt
Fiducial volume	188.4 kt
ID surface	19991.1 m^2

- total mass 260 kt
- cavern can be built with existing technologies
- outer detector to constrain the external background

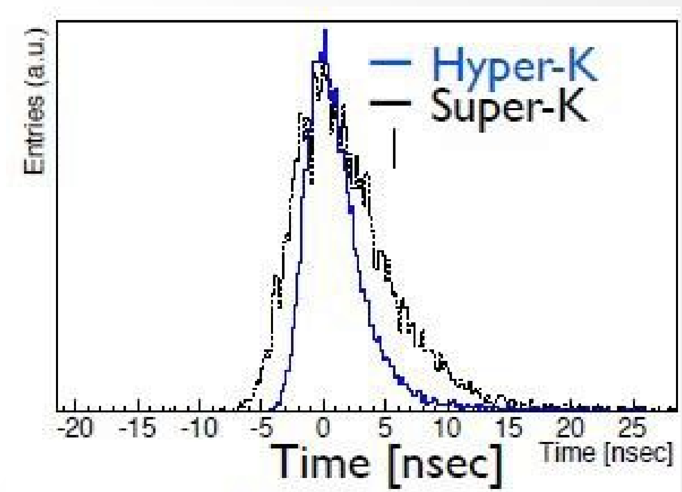


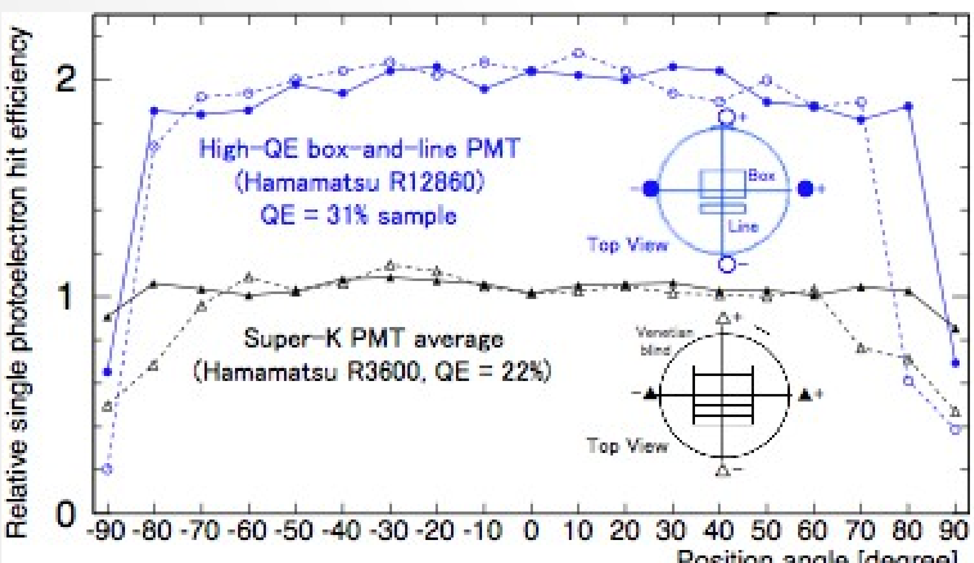
- possibility of loading gadolinium into Hyper-K

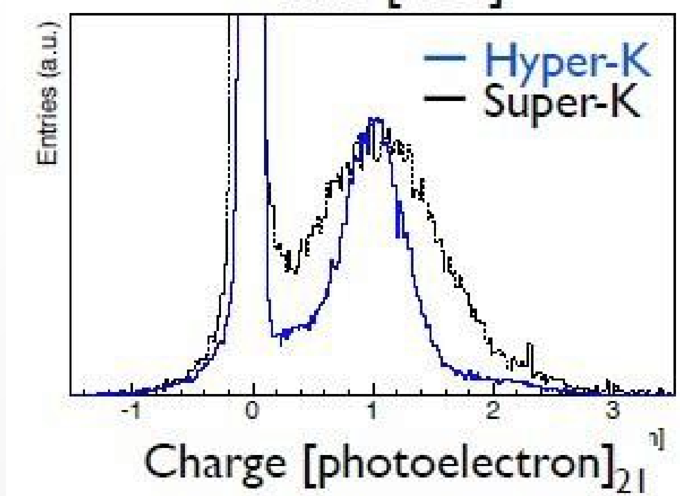
Barrel region 1m thick
endcaps 2m thick

The photodetectors – basic design

- new Hamamatsu 50 cm B&L PMT with improved dynode
  - quantum efficiency 30% at 390 nm (~1.4xSK)
  - collection efficiency 95% at 10^7 gain (~1.3xSK)
  - improved charge and timing resolution (~1 ns)
    → almost 2x better overall photon efficiency
  - lower dark rate
  - new glass: lower radioactivity, higher pressure tolerance
- 40 000 in the ID → 40% photocoverage





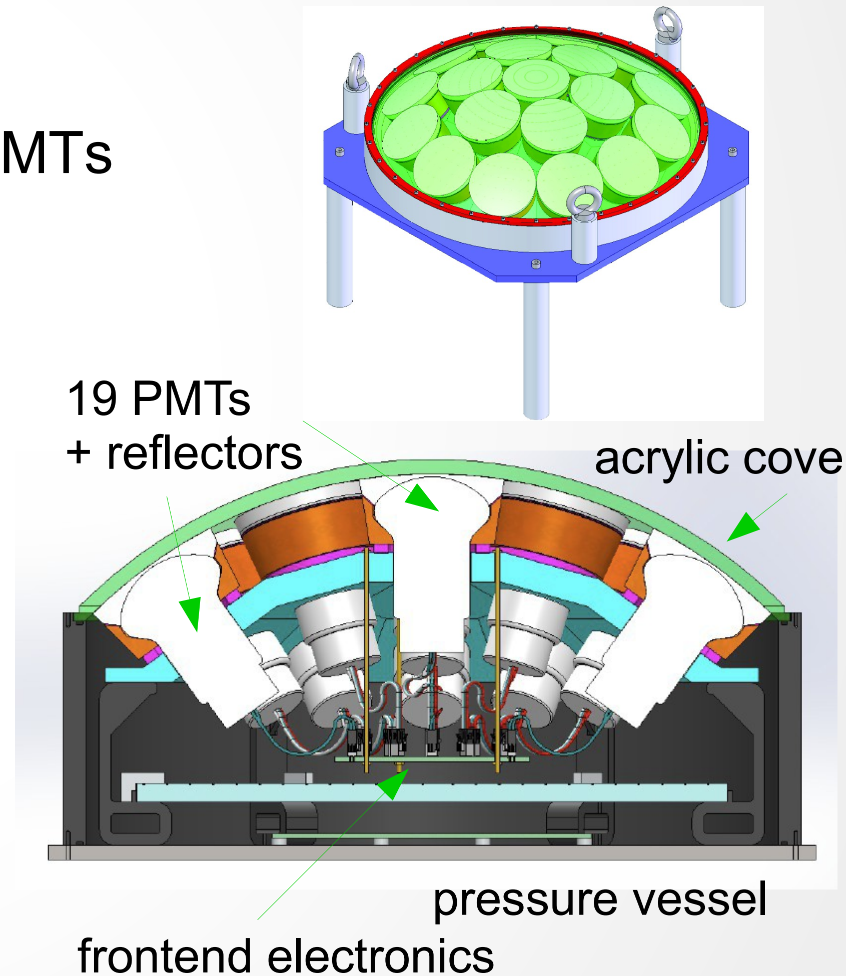


The photodetectors

- acrylic covers to protect PMT from sudden pressure changes

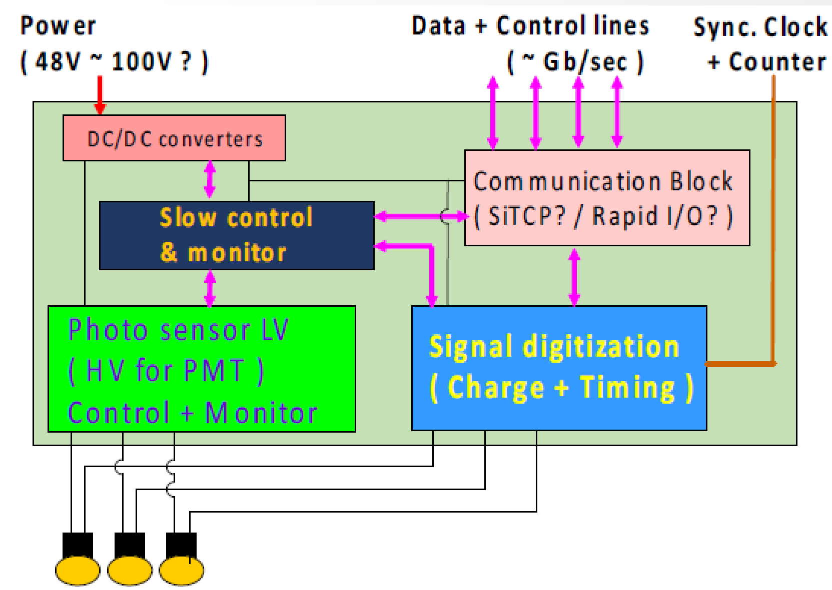
- other considered solutions
  - multiPMT – arrays of 19 smaller (8 cm) PMTs
    - increase of photocathode area
    - superior photon counting
    - improved angular acceptance
    - extension of dynamic range
    - intrinsic directional sensitivity
    - local coincidences
  - possible light collection devices (reflectors, photon traps etc.)

- outer detector: 10-20k PMT of 20 cm diameter, 1% coverage



Electronics and DAQ

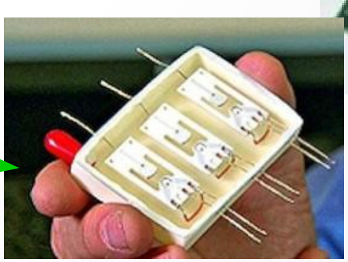
- front-end electronics
  - submerged in the water
    - shorter cables → less weight and no degradation of the signal
    - inability to do repairs → redundant, fail-safe system and careful design to avoid failures and lost of region of the detector
    - watertight front-end boxes (24 channels) and watertight fibre optic connectors
  - low power consumption (<1 W/channel)



- DAQ system above water has to be able to record:
  - trigger for the total number of hits seen in a sliding time-window exceeding a certain threshold
  - no dead time
  - delayed energy depositions after triggered event
  - large amount of events in short time (supernova burst)

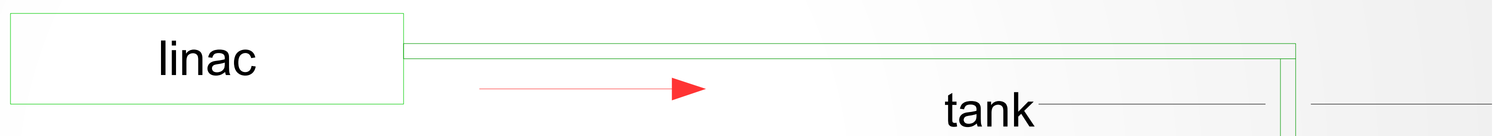
Calibration

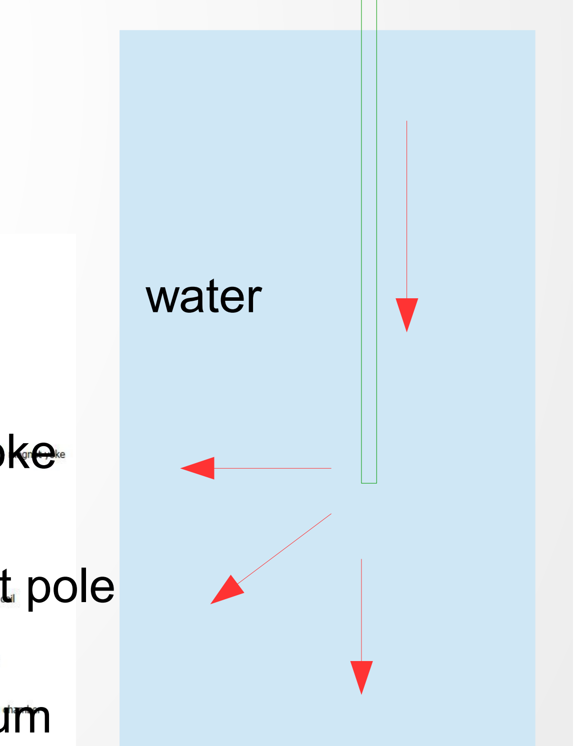
- PMT response, readout electronics, the optical properties of detector material, e.g. water, PMT (glass bulb and housing material), black sheet, and tyvek sheet
  - “relative" photo-detection efficiency (quantum efficiency x collection efficiency) of each single PMT for single photon level of light → important for the low energy physics
  - PMT/electronics linearity for the full dynamic range → important for high-energy physics
  - water optical properties, absorption and scattering of light → all analyses
- various calibration sources:
  - light sources (laser, laser diodes)
  - radioactive sources
  - neutron generators
  - linear accelerator
  - off-timing hits sources
  - physics events such as cosmic rays, Michel electrons etc.



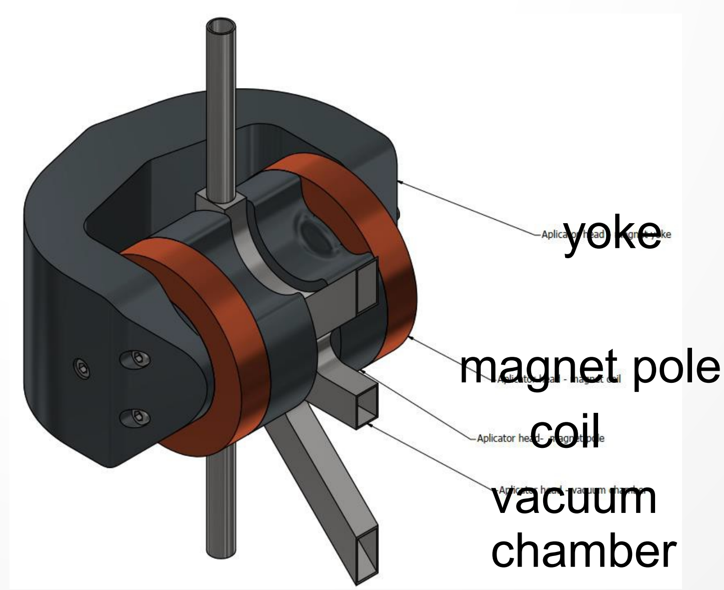
Calibration – LINAC

- to calibrate the absolute energy scale, energy resolution, vertex and direction resolution of low energy electrons
- NCBJ Accelerator Division involved

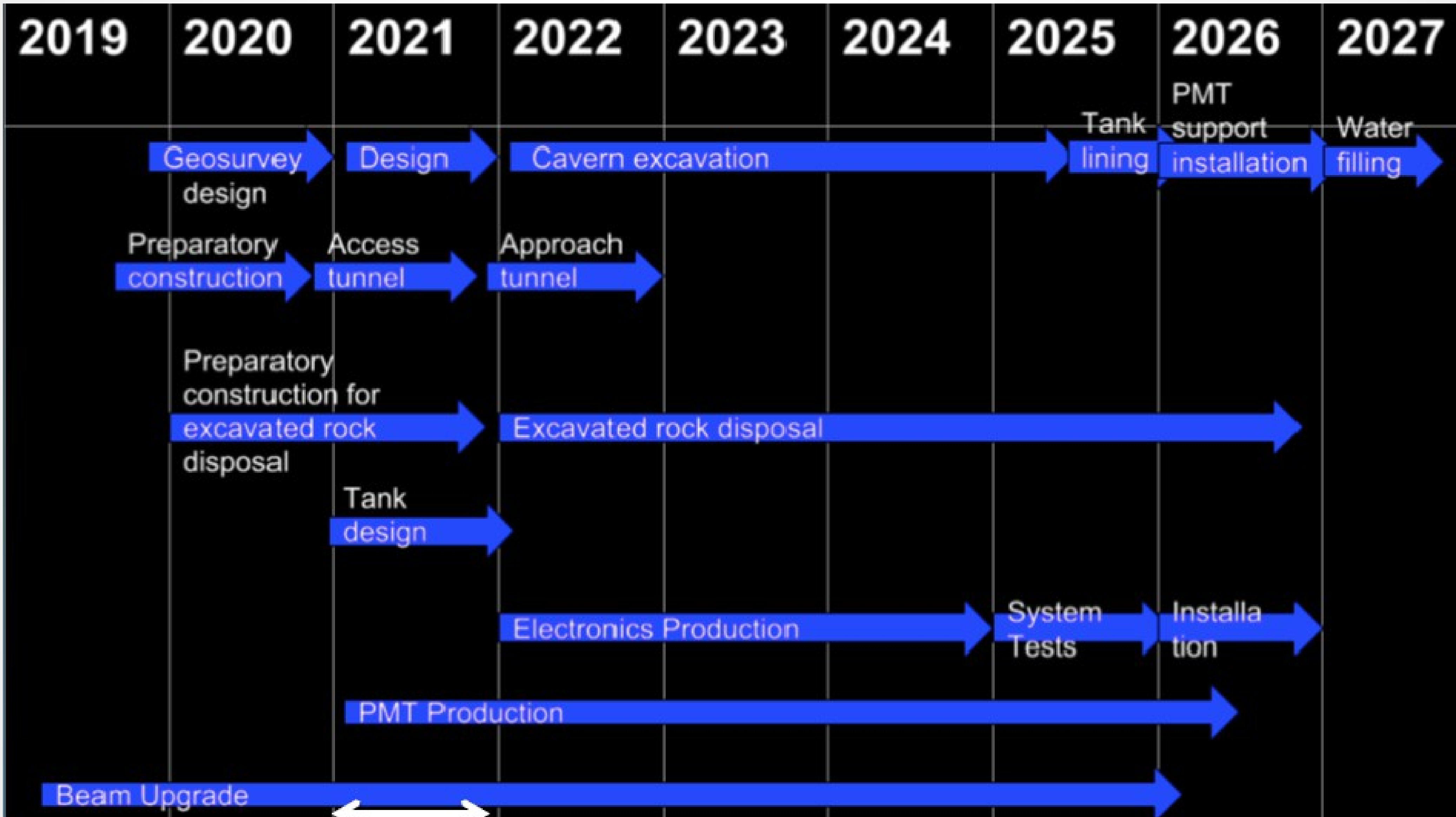




- first assumptions of HK linac parameters:
  - energy range 4-20 MeV
  - much longer beam pipe in comparison to SK
  - bending of the beam at the end of beam pipe
    - multi direction head
    - dipole magnet limited by port
  - one electron/pulse



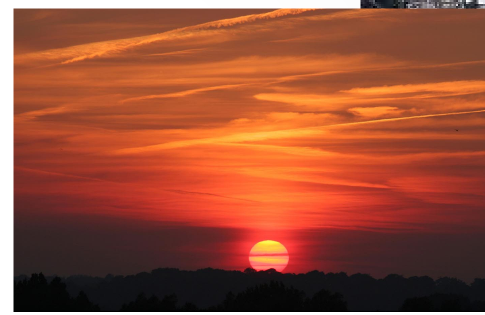
Timeline



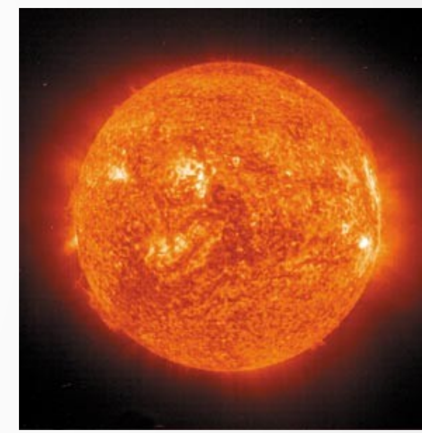
2019
2020
2021
2022
2023
2024
2025
2026
2027
Geosurvey design
Design
Cavern excavation
Tank lining
PMT support installation
Water filling
Preparatory construction
Access tunnel
Approach tunnel
Preparatory construction for excavated rock disposal
Excavated rock disposal
Tank design
Electronics Production
System Tests
Installa tion
PMT Production
Beam Upgrade

Physics program

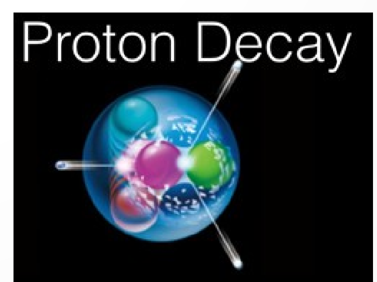
- neutrino oscillations
  - with beam and atmospheric neutrinos
  - CP violation
  - precise measurement of θ_{23}
  - mass hierarchy determination



- neutrino astrophysics
  - precise measurement of solar neutrinos, sensitivity to address solar and reactor neutrinos discrepancy.
  - supernova burst and relic supernova neutrinos



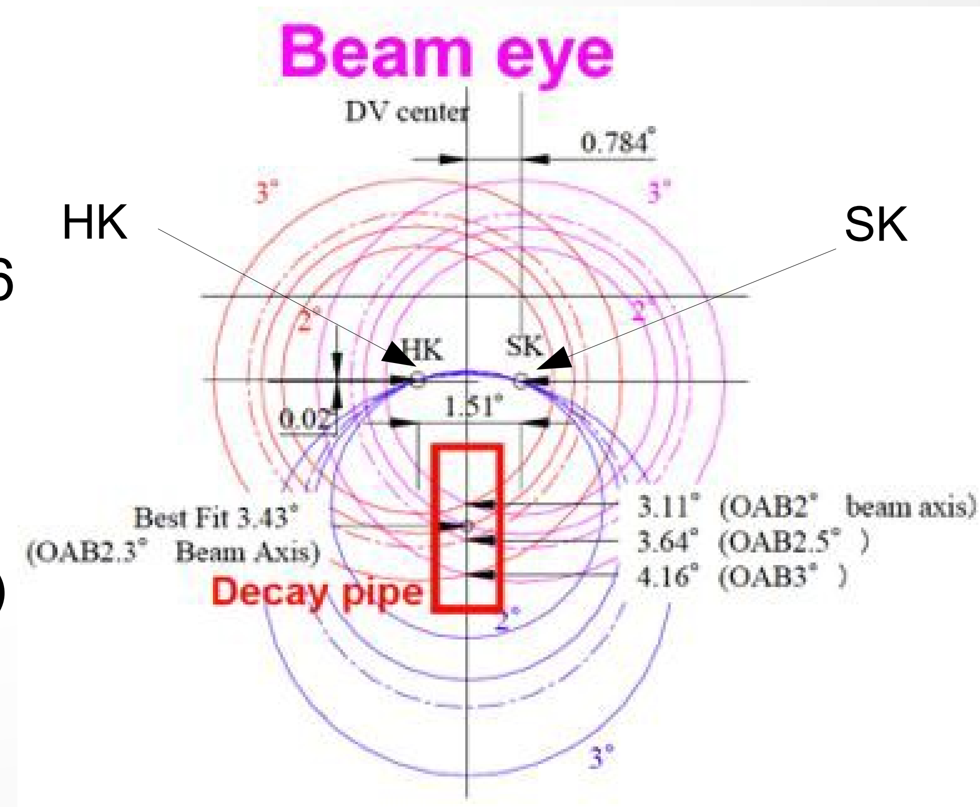
- searching for nucleon decay
  - sensitivity 10x better than Super-K (10^{35} years)
  - all visible modes can be advanced



- other: indirect Dark Matter search, geophysics, neutrinos from solar flares etc.

Beam neutrinos (T2HK)

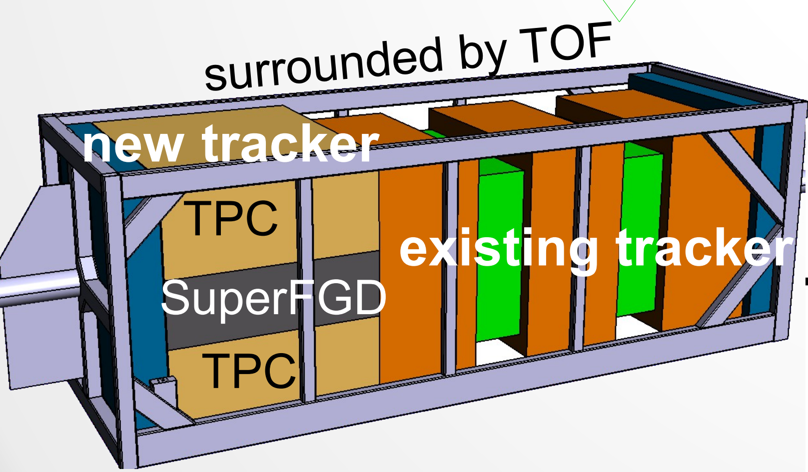
- the same baseline (295 km) and off-axis angle (2.5º) as Super-K
- narrow band beam at ~600MeV
- neutrino or antineutrino beam mode
- upgrade of **beam power**
  - 0.75 MW upgrade starting in 2021 (currently ~515 kW)
  - increasing repetition rate from 0.4 to 0.86 Hz → **1.326** MW by 2026
  - 3.2e14 protons per pulse (now $2.45 \cdot 10^{14}$ ppp)
- upgrade power supplies for horns
  - design current of 320 kA (wrt 250 kA)
  - +~20% higher neutrino flux.
  - reduction of wrong-sign neutrino contamination by 5-10%.

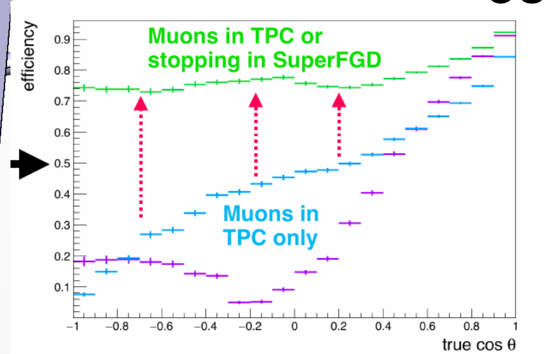


Near detectors

- near detector upgraded complex and fitting method inherited from T2K
  - common systematic uncertainties on neutrino interaction processes constrained by ND280 have been reduced to 3% on the (SK) predicted event rates
- weaknesses of current ND280 setup:
  - angular efficiency (difference in acceptance)
  - low efficiency for low energy hadrons
  - different target nucleus than in far detector
  - near and far detectors do not sample the same neutrino spectrum
    - off-axis coverage
    - oscillations

ND280 upgrade

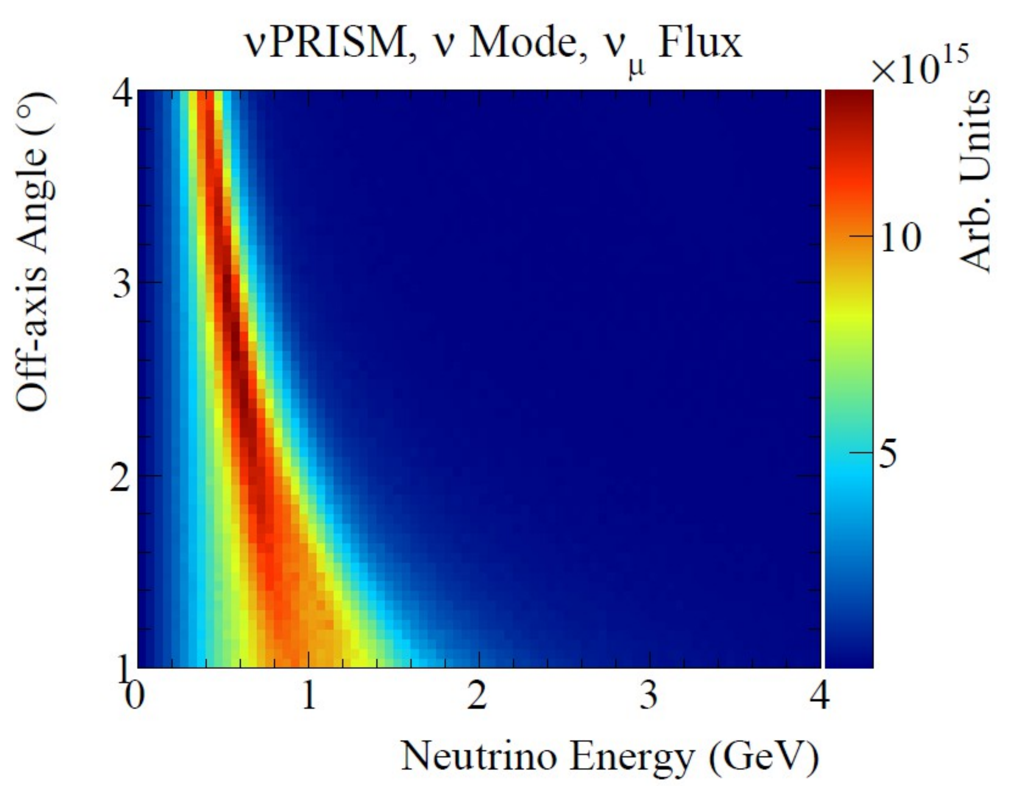




Intermediate Water Cherenkov Detector (IWCD)

IWCD

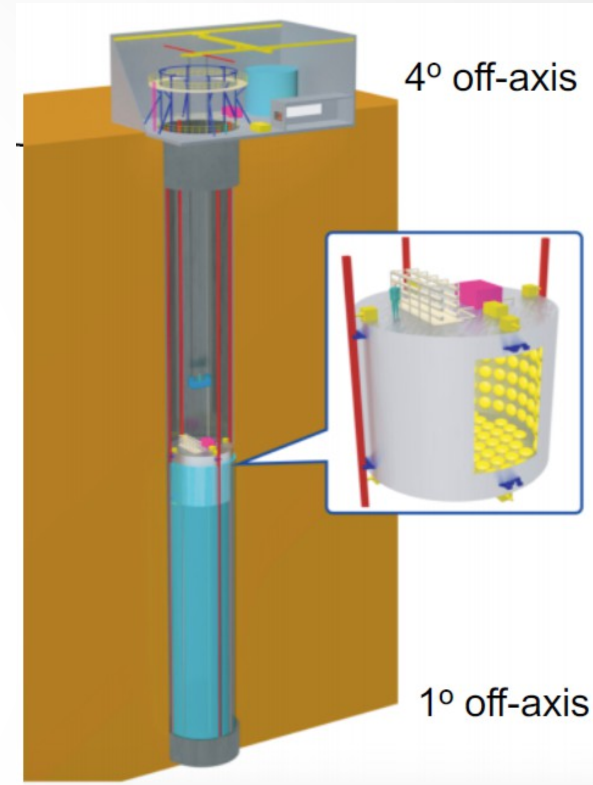
- kiloton size detector to contain ~1GeV muons
- distance 1-2 km to
  - minimize pile-up
  - keep high number of events
  - nearly identical (unoscillated) flux as in the far detector

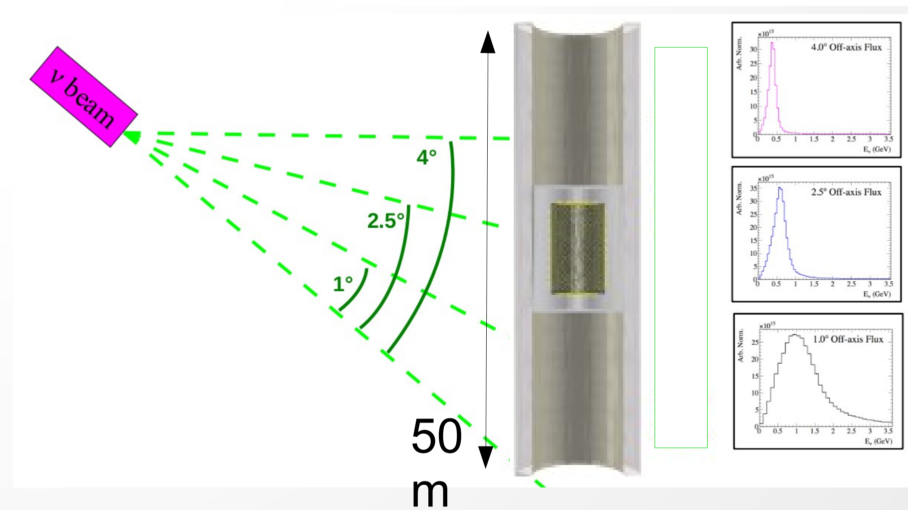


- Gd loading for neutron tagging
- off-axis angle spanning coverage (1-4°)
  - energy dependence of neutrino interactions
  - higher intrinsic ν_e component at higher angles → relative ν_e cross-section measurement
- complementary measurements to ND280 magnetised tracking detector

IWCD

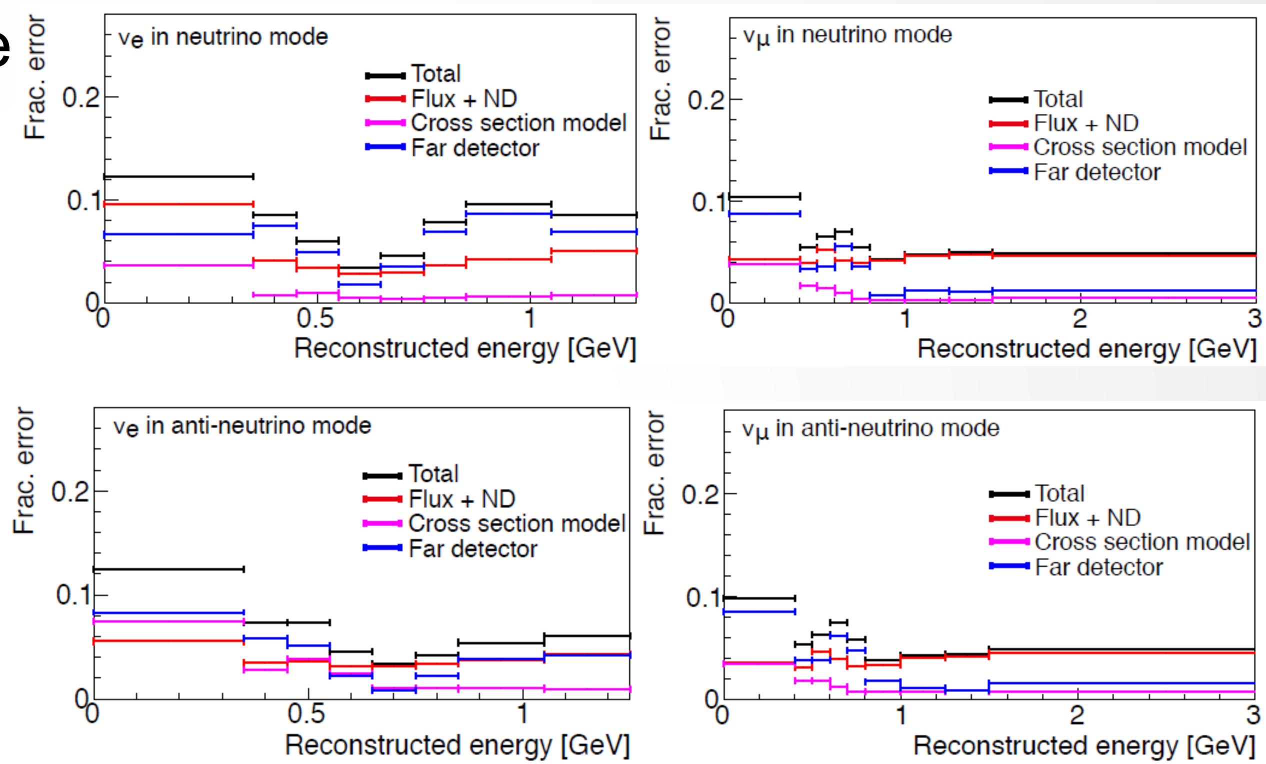
- tank: 8m high, 10m diameter, 628 tons
  - Inner Detector 6m high, 8m diameter
  - Outer Detector 1m thick
- mPMT modules in ID
- instrumented part of the detector can be moved in ~50 shaft by hydraulics/guide rails
- additional physics program
  - cross section measurements
  - search for sterile neutrinos
  - independent supernova alert
- initial phase: detector on the surface near the ND280 at off-axis angle of 6-12º
  - beam tests planned at CERN with 3-4m diameter prototype





Expected systematics

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

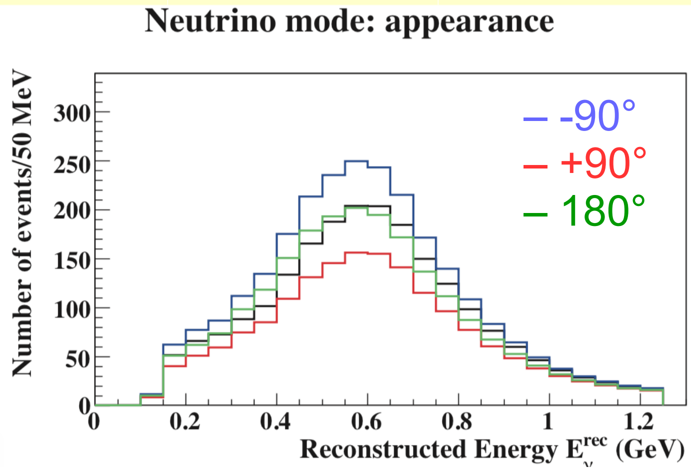


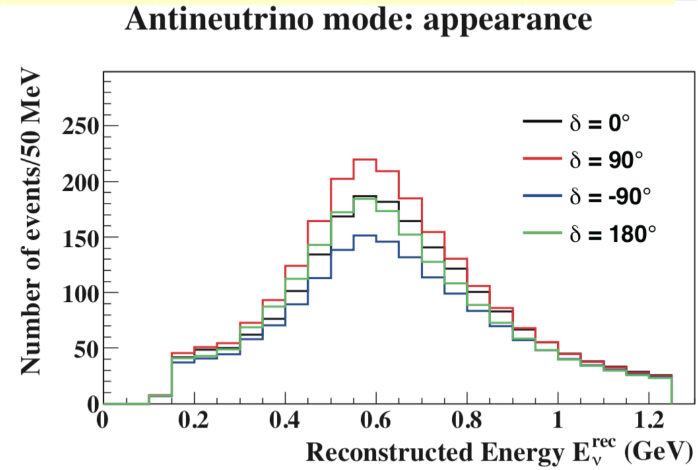
		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0%	0.5%	0.7%	3.2%
	Disappearance	3.3%	0.9%	1.0%	3.6%
$\bar{\nu}$ mode	Appearance	3.2%	1.5%	1.5%	3.9%
	Disappearance	3.3%	0.9%	1.1%	3.6%

Expected numbers of events

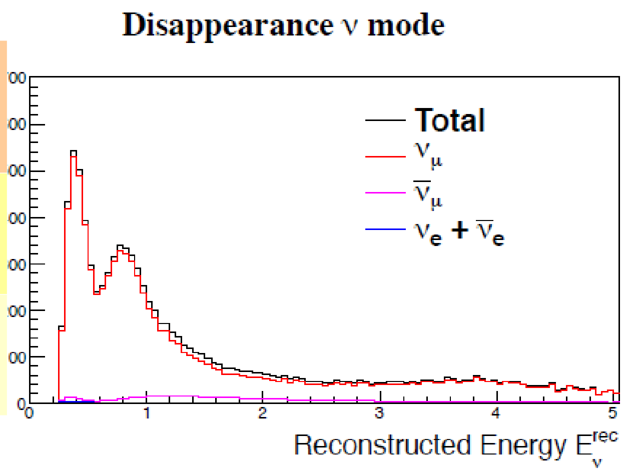
- 10 years exposure
  - $2.7 \cdot 10^{22}$ POT
  - $\nu:\bar{\nu}$ data taking 1:3
- ν_e appearance
  - shape information can be used to distinguish different values of δ_{CP}
- ν_μ disappearance

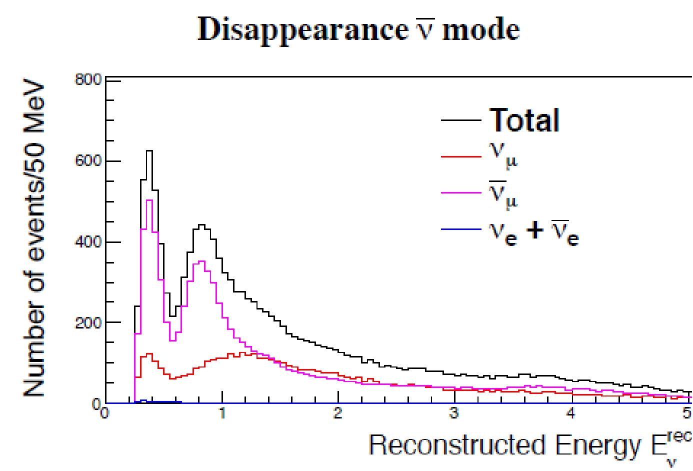
$\delta_{CP} = 0$	right-sign $\nu_\mu \to \nu_e$ CC	wrong sign $\nu_\mu \to \nu_e$ CC	ν_μ, $\bar{\nu}_\mu$ CC	intrinsic beam ν_e	NC	T2K 2019 data
ν beam	**1643**	15	7	259	134	90
$\bar{\nu}$ beam	**1183**	206	4	317	196	15





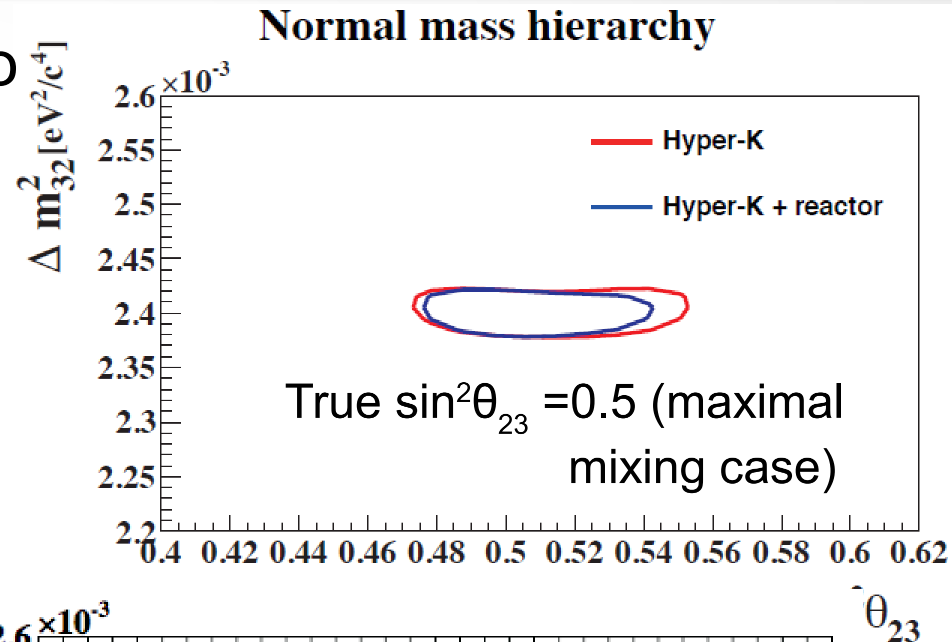
	$\nu_\mu + \bar{\nu}_\mu$ CCQE	ν_μ CC nonQE	other
ν beam (T2K:243)	**6391**	3175	515
$\bar{\nu}$ beam (140)	**8798**	4315	614

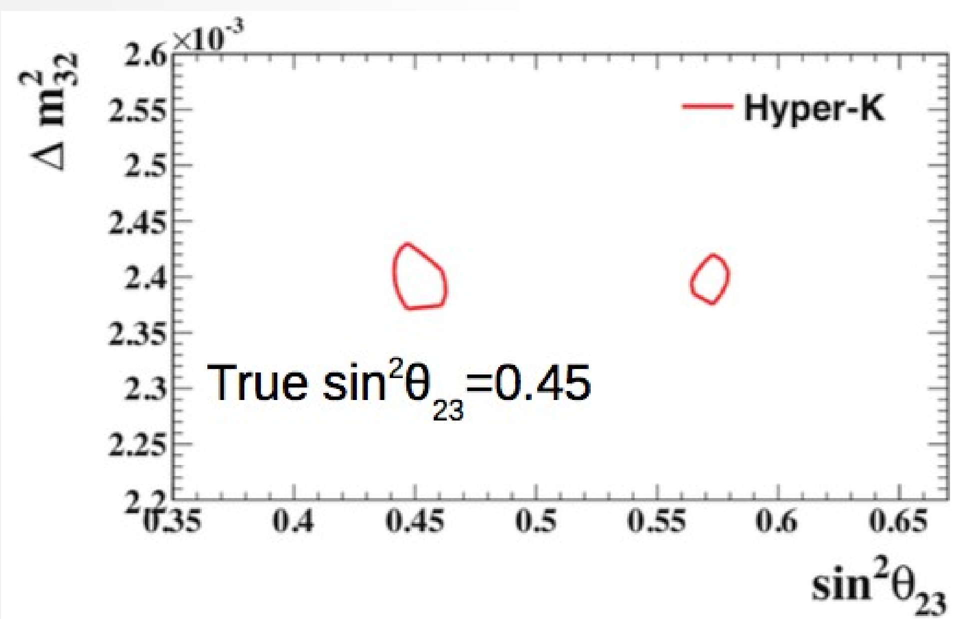


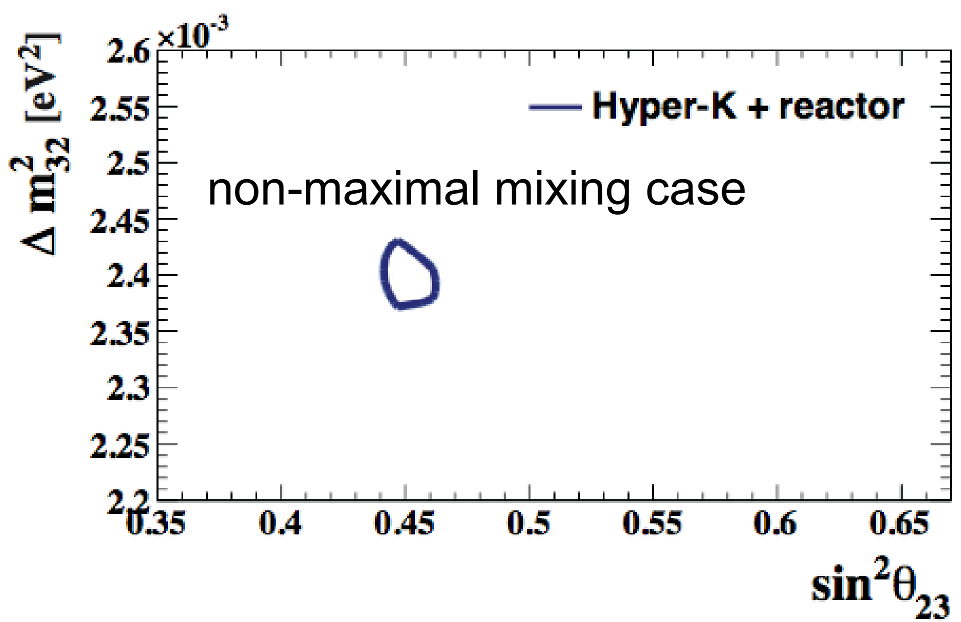


Precise measurements of θ_{23}

- 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 $\sin^2\theta_{23} = 0.45$





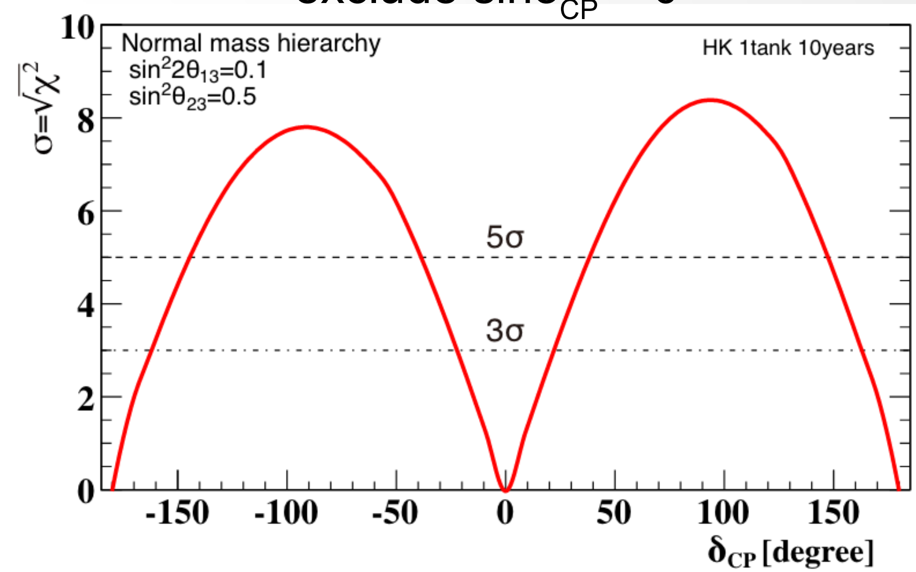


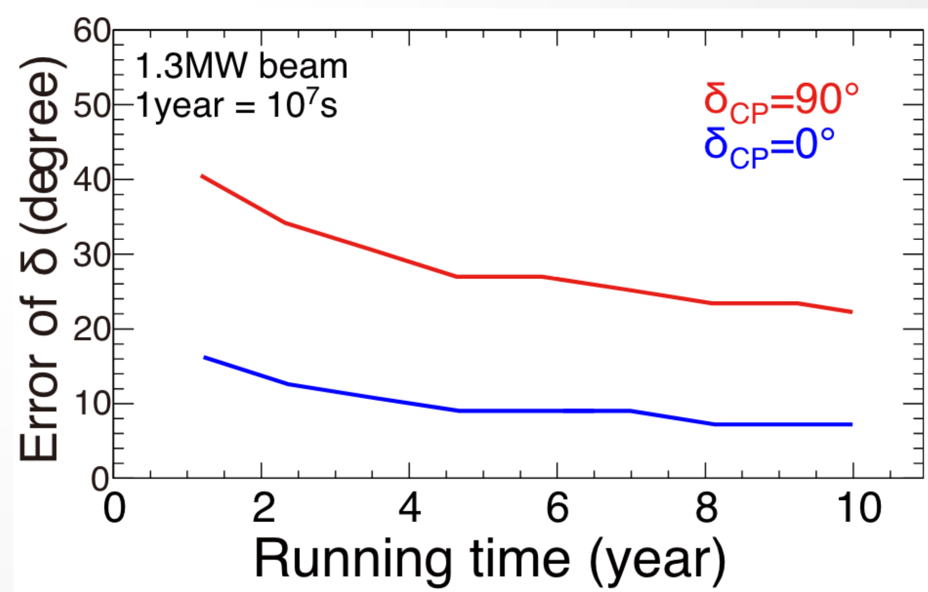
- for non-maximal θ_{23} the reactor constraint breaks octant degeneracy

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
  - 22° precision at $\delta_{CP} = \pm 90°$
  - 7° precision at $\delta_{CP} = 0°$ or 180°
- combination with atmospheric data enhances the sensitivity

expected signicance to exclude $\sin\delta_{CP} = 0$

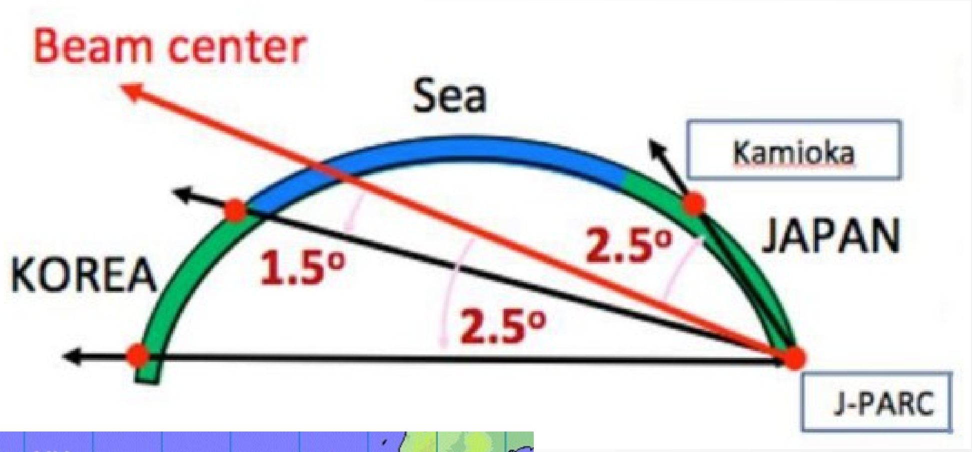


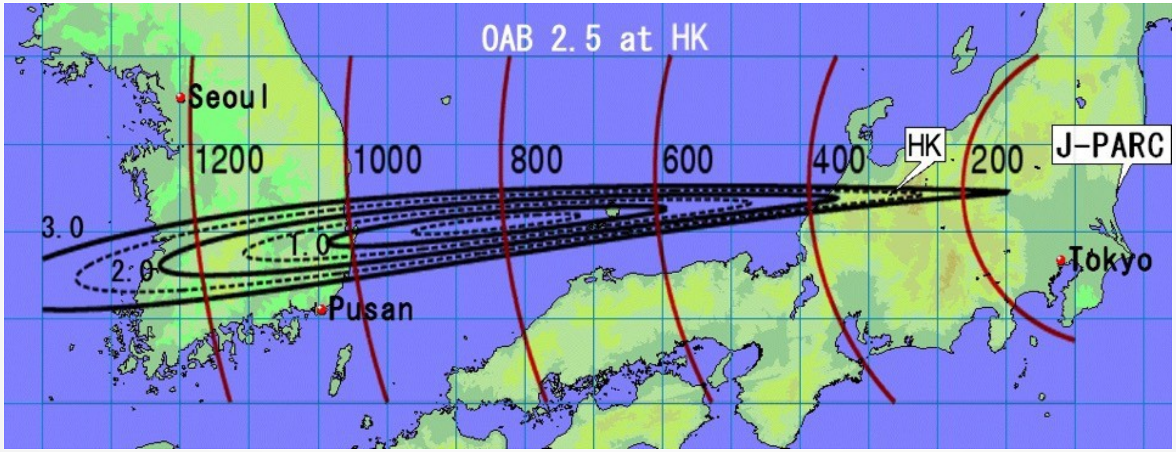


Second tank: T2HKK?

- 2nd tank would improve sensitivities for all HK physics goals

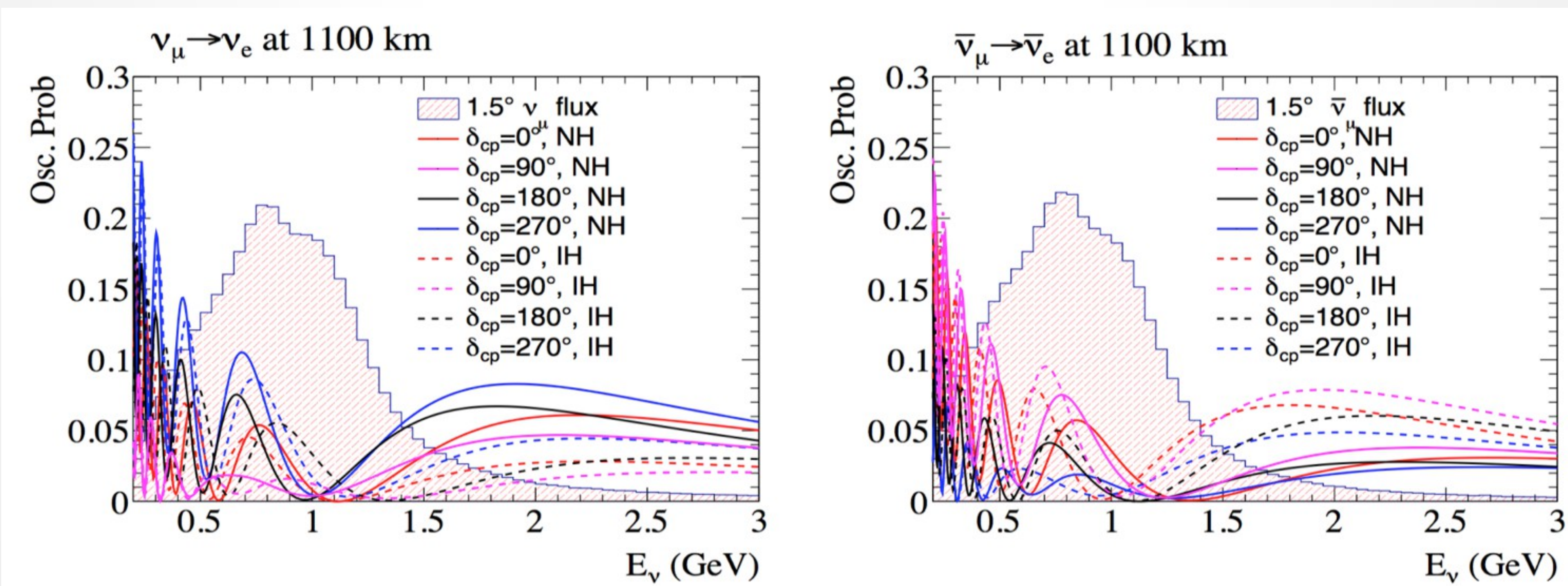
- for beam neutrinos location outside Japan is particularly interesting
- under investigation: build 2nd tank in Korea
  - 1000-1200km baseline
  - 1.3-3.0º off-axis beam
  - enhances sensitivity to mass hierarchy and CP violation





Situation with one tank in Korea

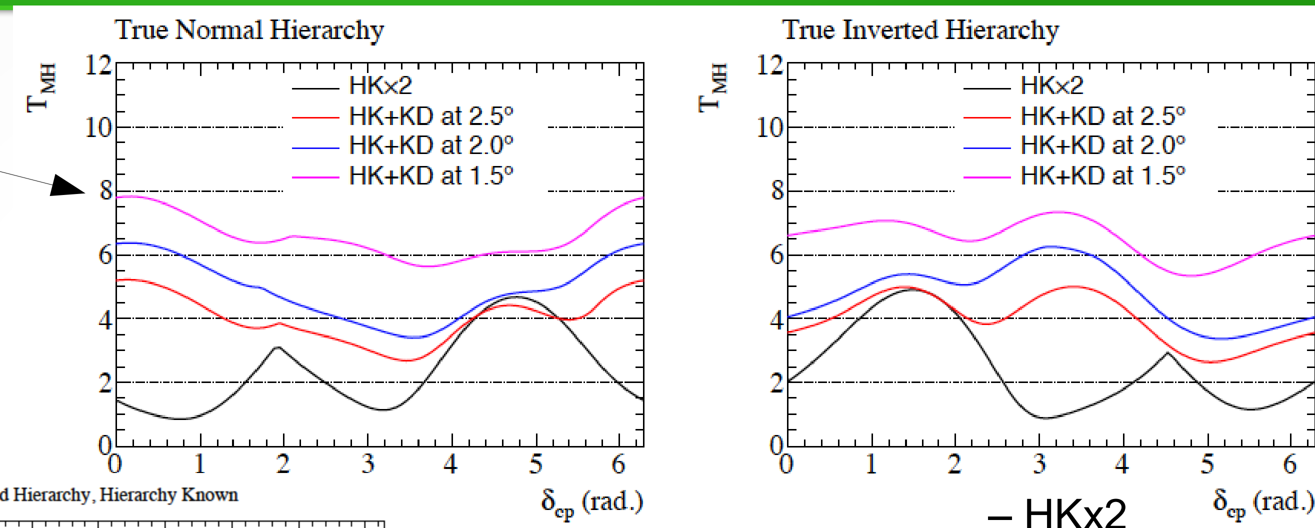
- 1st and 2nd oscillation maxima covered
  - CP asymmetry for $\nu_e/\bar{\nu}_e$ appearance is 3x larger than at 1st maximum
  - larger CP effect → less sensitive to systematic errors
- larger matter effect for longer baseline
  - better sensitivity for mass hierarchy
- smaller number of events because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



Sensitivities

mass hierarchy

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

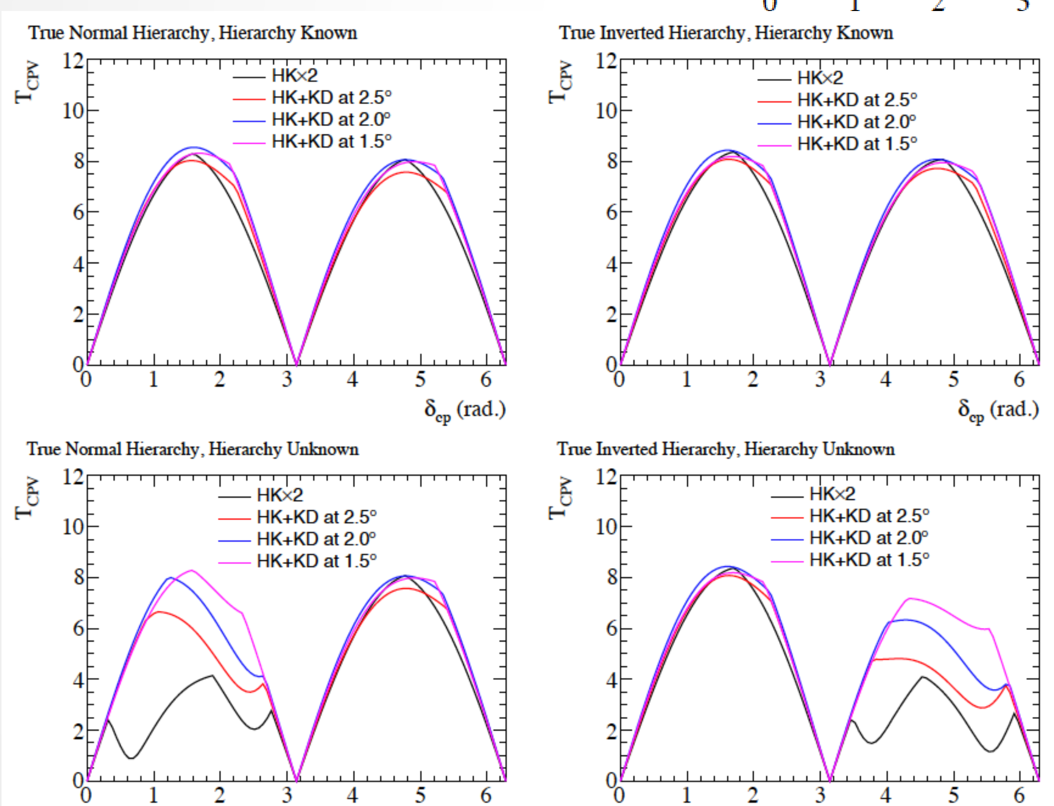


– HKx2
– HK+KD at 2.5°
– HK+KD at 2.0°
– HK+KD at 1.5°

CP violation

– known hierarchy

– unknown hierarchy

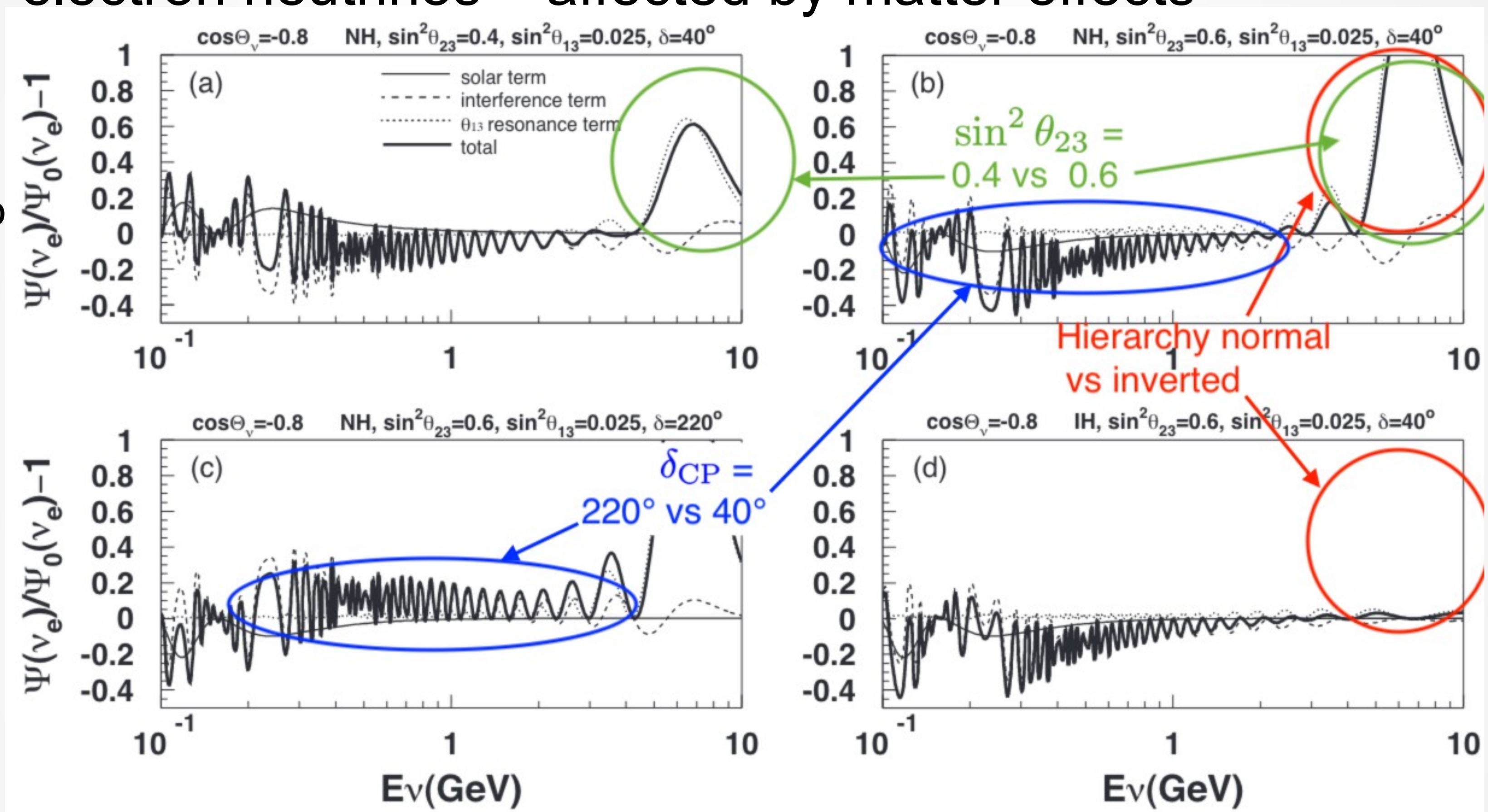


true NH true IH

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}

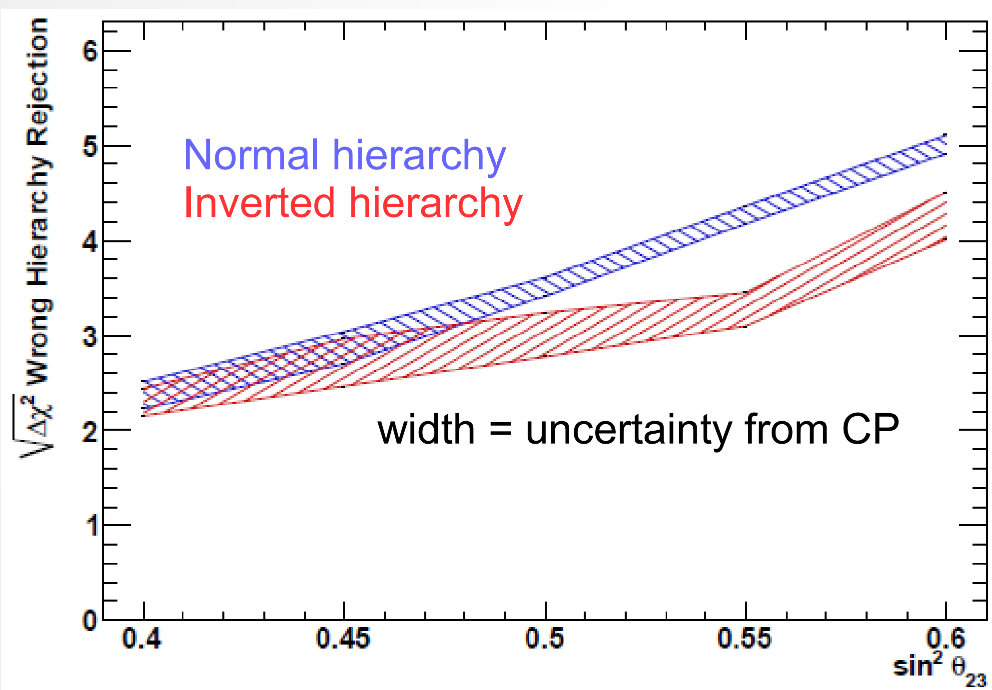
Atmospheric neutrinos

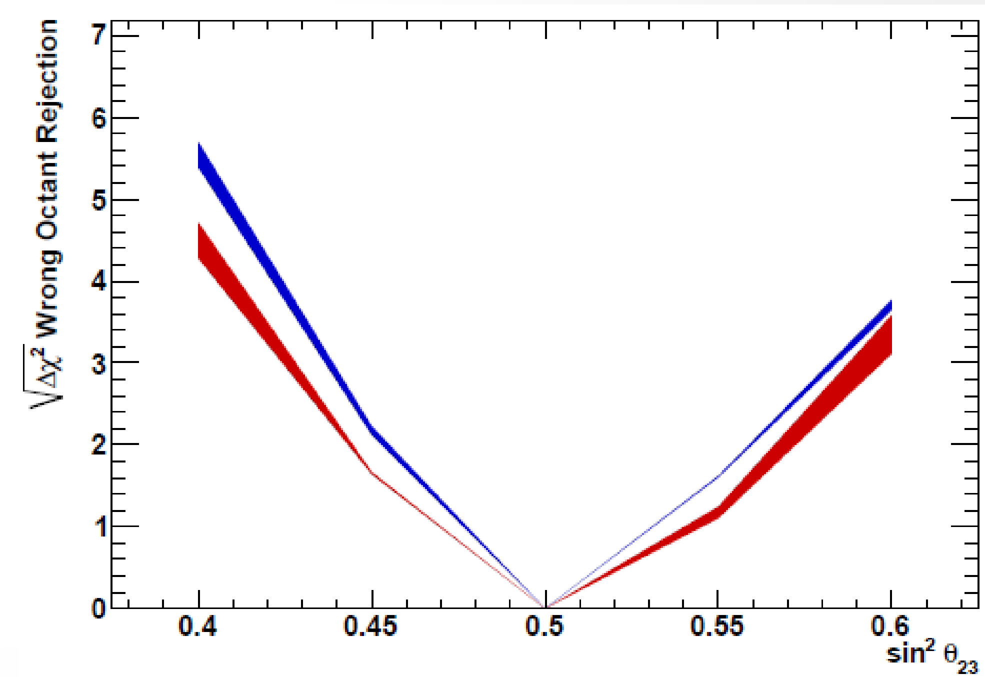
- single tank after 10 years (1.9 Mton year exposure)

mass hierarchy sensitivity

θ_{23} octant sensitivity

as a function of true θ_{23}



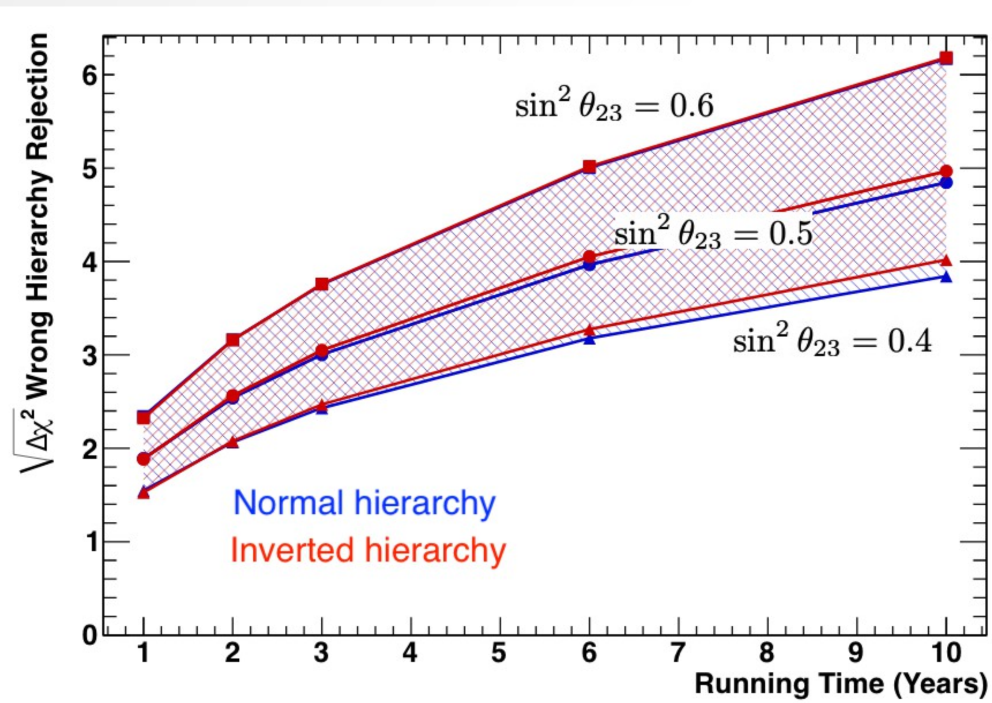


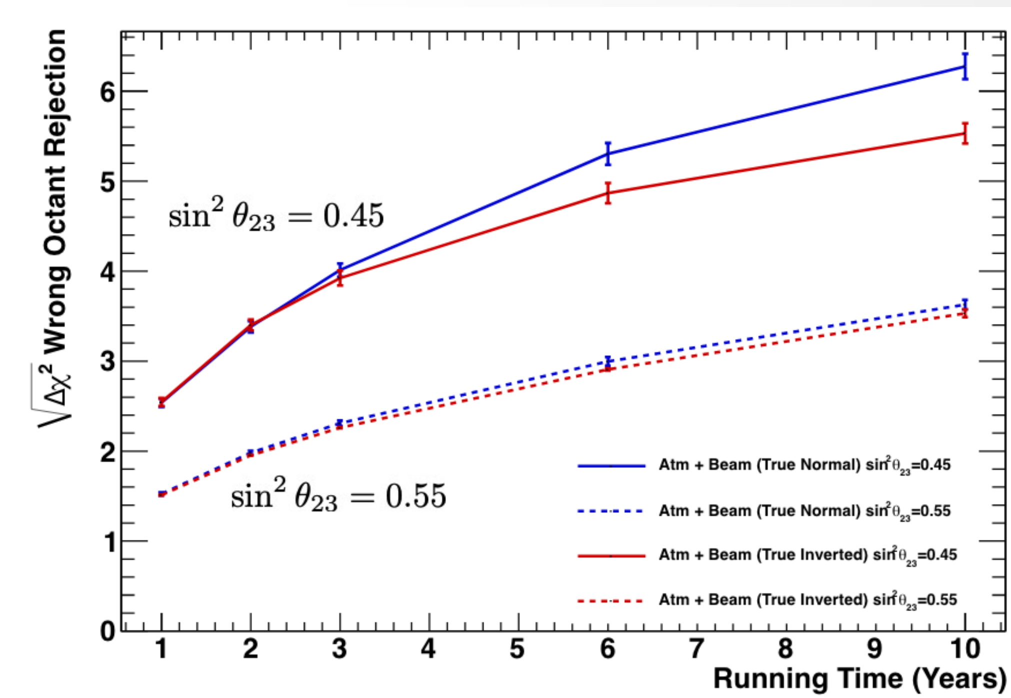
2.2σ-4.9σ

wrong octant rejection
3σ if $|\theta_{23} - 45°| \geq 4°$

Atmospheric+beam neutrinos

- complementary measurement → improved performance
- 3σ ability to reject the incorrect mass hierarchy after 5 years





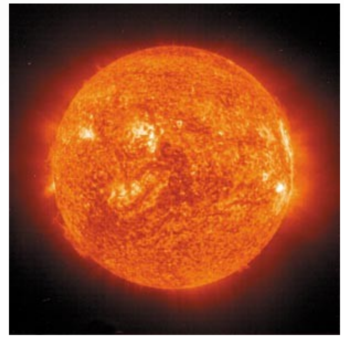
3.8σ-6.2σ

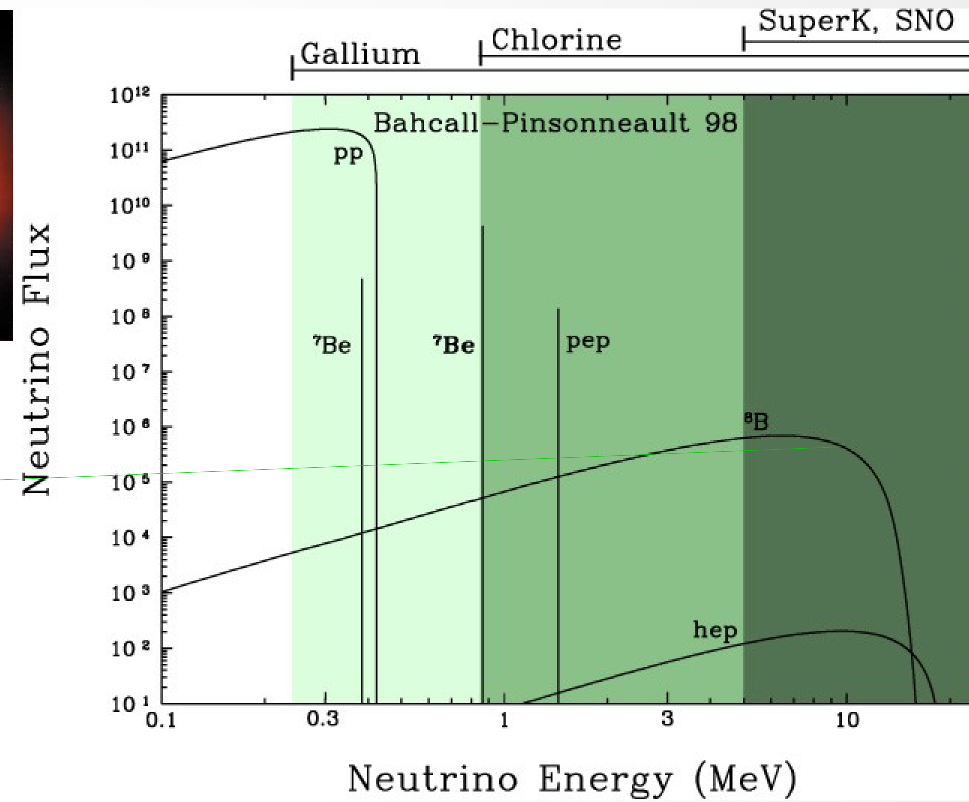
wrong octant rejection
3σ if $|\theta_{23} - 45°| \geq 2.3°$

Solar neutrinos

- reminder:

Reaction	ν flux ($cm^{-2}\ s^{-1}$)	% total ν flux
$p + p \rightarrow {}^2H + e^+ + \nu_e$	6.04×10^{10}	92%
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	4.55×10^{9}	7%
$p + e^- + p \rightarrow {}^2H + \nu_e$	1.45×10^{8}	0.2%
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	4.72×10^{6}	0.007%



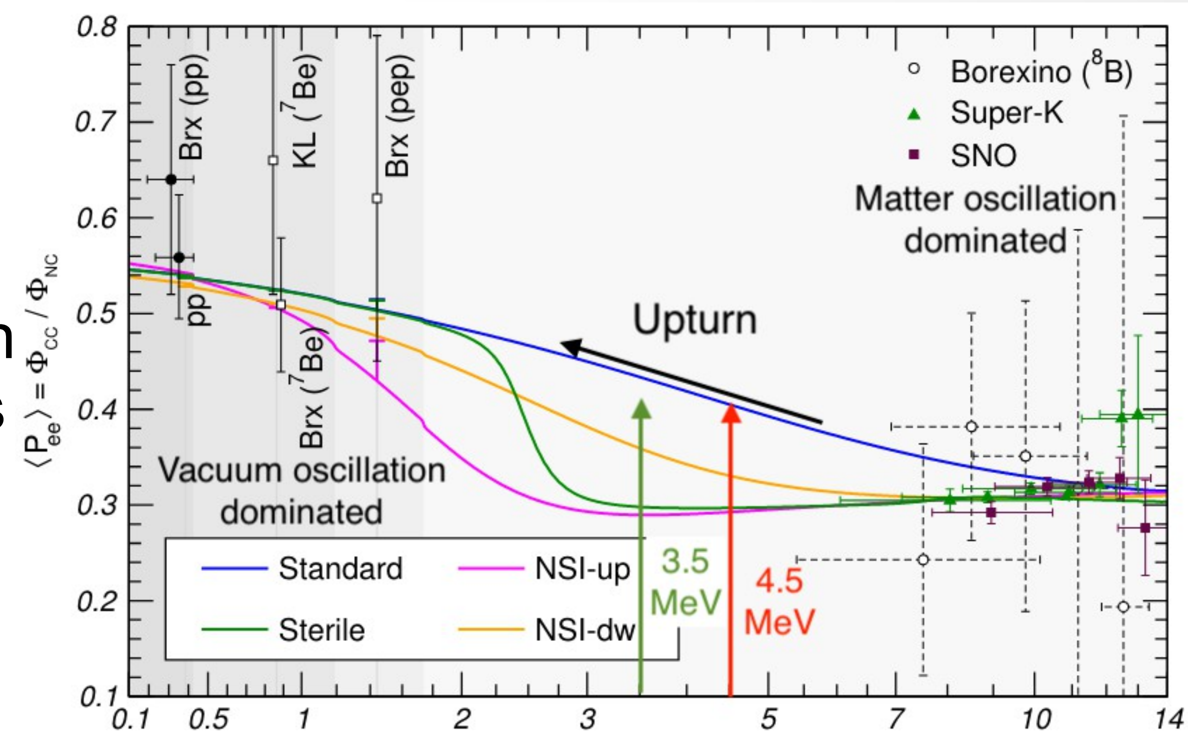


- detection by elastic scattering
  $\nu + e \rightarrow \nu + e$
  (x-sec for ν_e 7x larger than for other flavours)
  - threshold for CC reaction $\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F$: 18 MeV

- oscillations of solar neutrinos: matter effects in the Sun, θ_{12}, Δm^2_{21}
  - sector 1-2 is also studied with reactor neutrinos (KamLAND)

Solar neutrino spectrum upturn

- transition region between the vacuum oscillations and matter-dominated energy regions
- precise measurement of the spectrum shape allows to distinguish the usual neutrino oscillation scenario from exotic models
- HK can measure the solar upturn to ~5σ (3σ) after 10 years with 3.5 MeV (4.5 MeV) threshold
  - 2.7x higher spallation background than in SK



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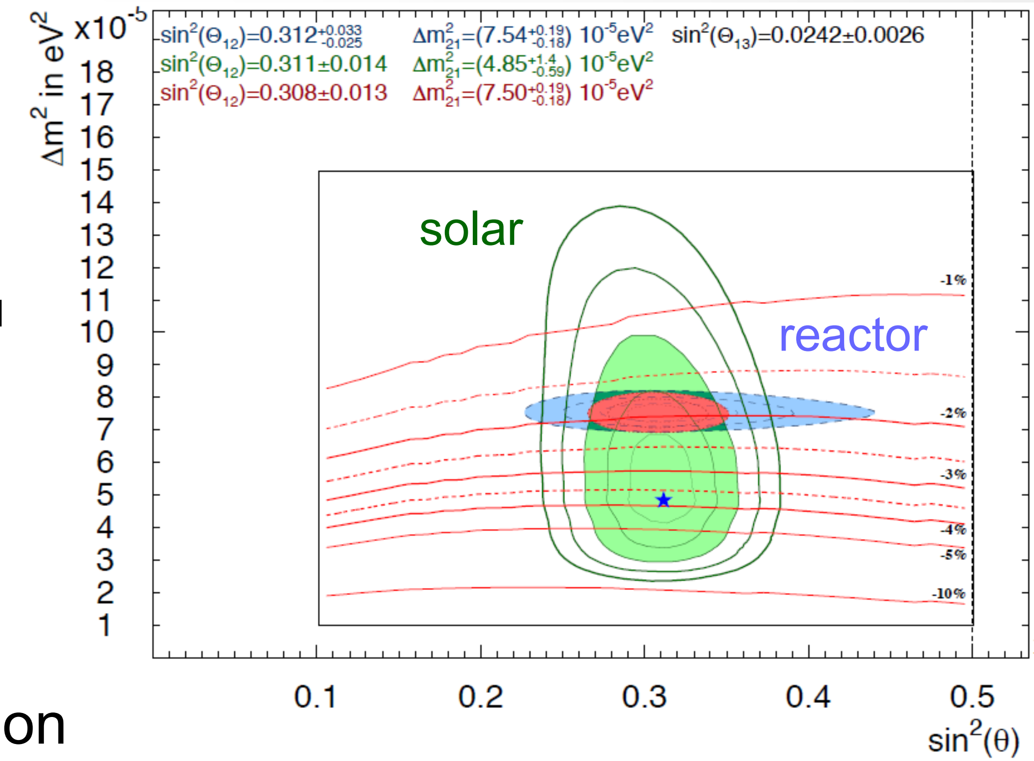
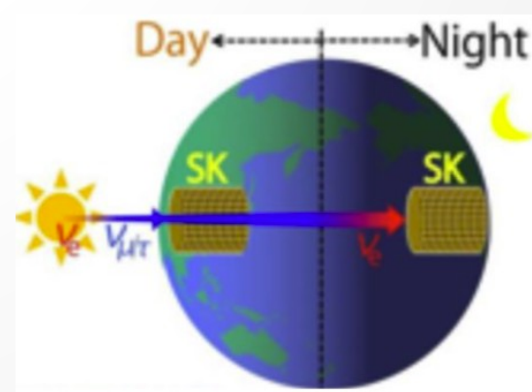
Solar neutrinos

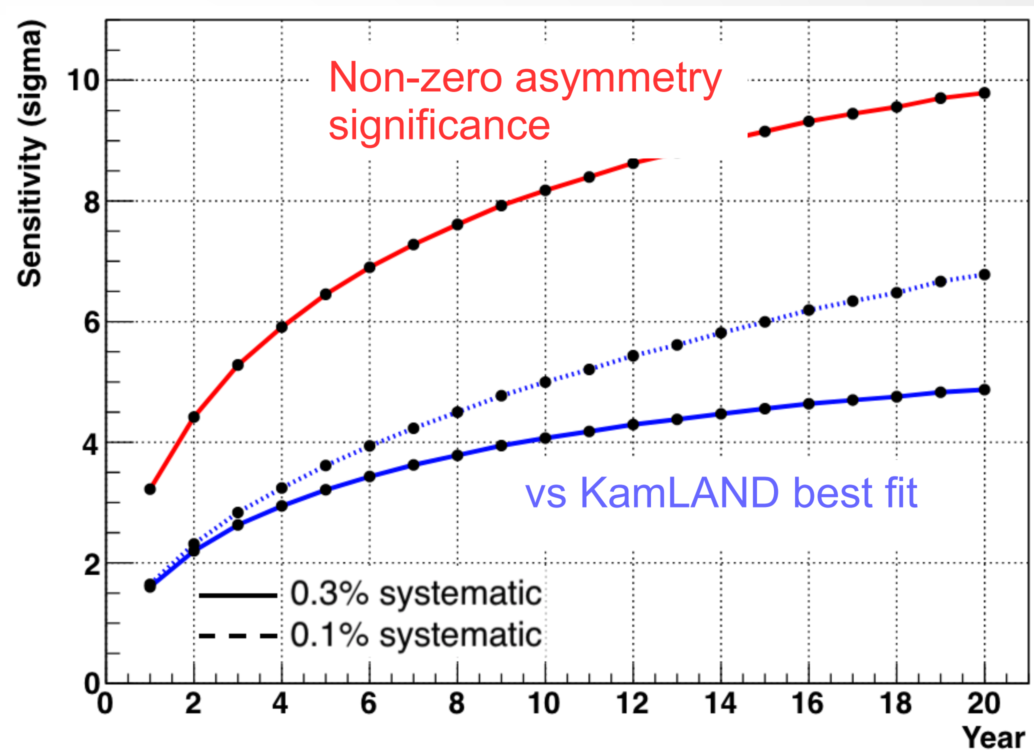
- mixing angle is consistent between solar and reactor experiments
- tension ~2σ between Kamland and global solar analysis in Δm^2_{21}
  - from the Super-K 3σ indication of the solar neutrino day-night asymmetry
    and energy spectrum shape
  - day-night asymmetry caused by electron component regeneration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





Solar neutrinos

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



- other planned measurements:
  - time variation measurement (with rate of 200ν/day) → monitoring of the Sun core temperature
  - first measurement of *hep* component (~2-3σ)
    - more information on the Sun interior around the core
    - solar abundance (chemical composition)

Supernova neutrinos

- reminder:
  - neutrinos carry away 99% of supernova energy
  - two components: short (10ms) neutronization burst

    $$e + p \rightarrow \nu_e + n$$

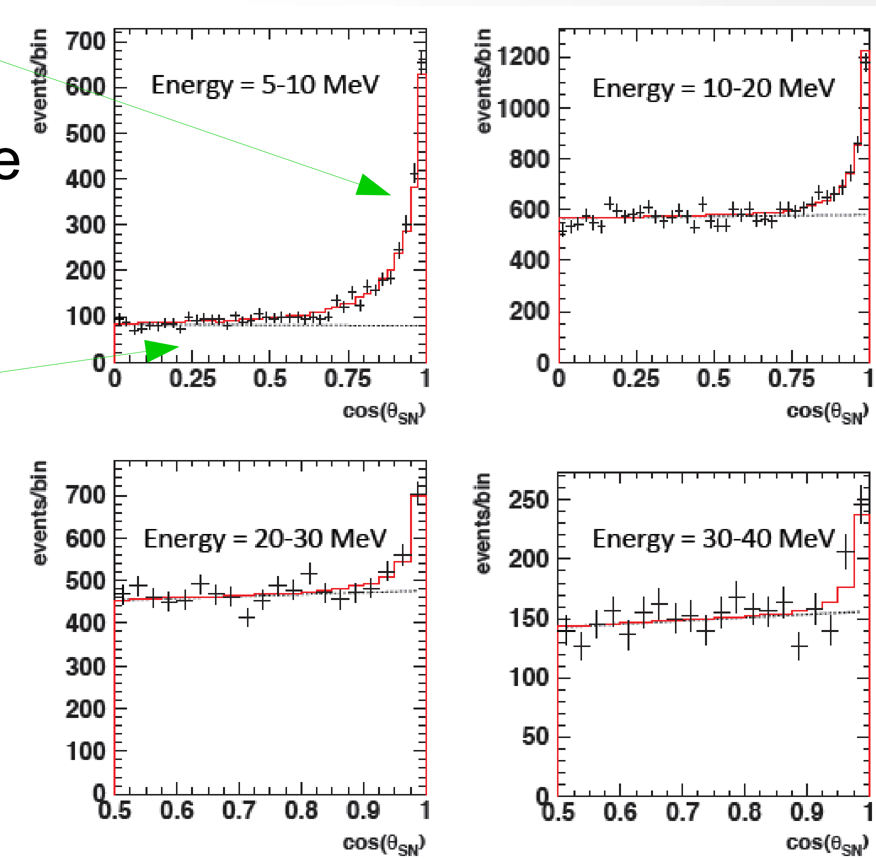
    - detected by elastic scattering on electrons
    - directional information, accuracy 1-1.3° expected for supernova at 10kpc
  - accretion phase (<1s) and cooling phase (several s) → thermal neutrinos

    $$e^+ + e^- \rightarrow Z^0 \rightarrow \nu_x + \bar{\nu}_x$$

    - $\bar{\nu}_e$ detected by inverse beta decay (IBD)

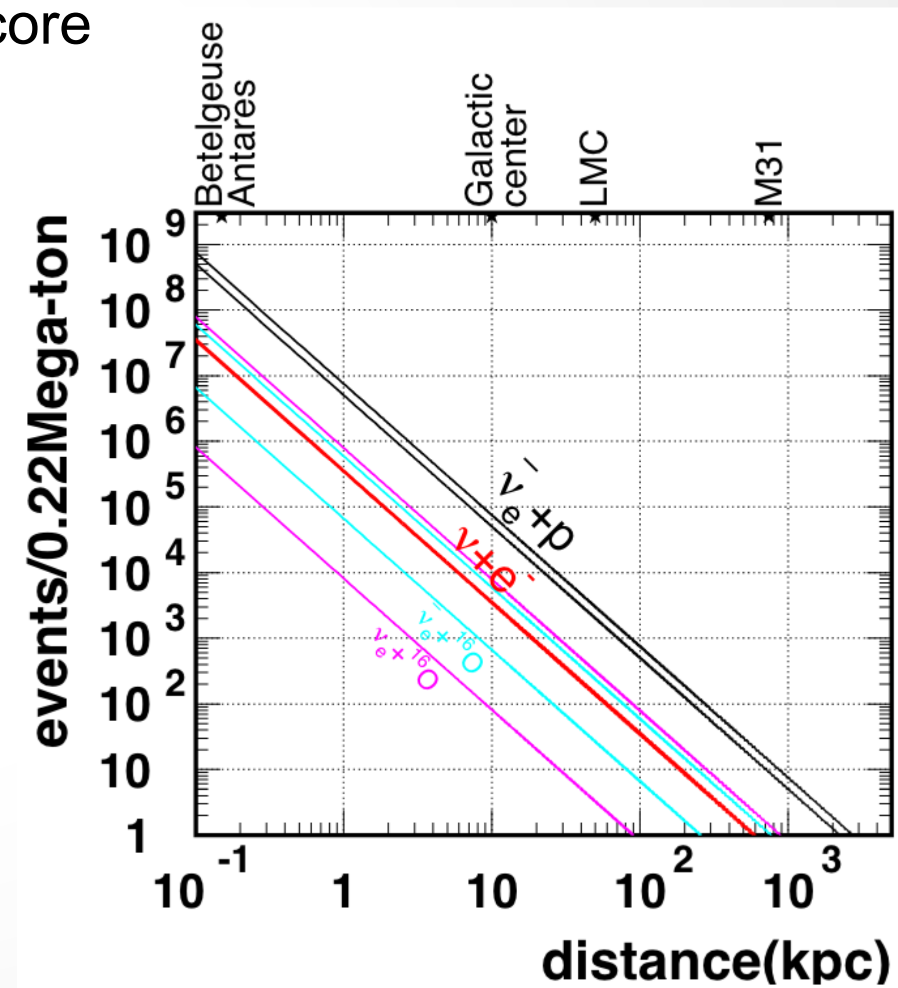
    $$\bar{\nu}_e + p \rightarrow e^+ + n$$

- good localization in time →
  - low radioactive background
  - energies even down to 3 MeV
  - increased FV can be used



Supernova ν event rate

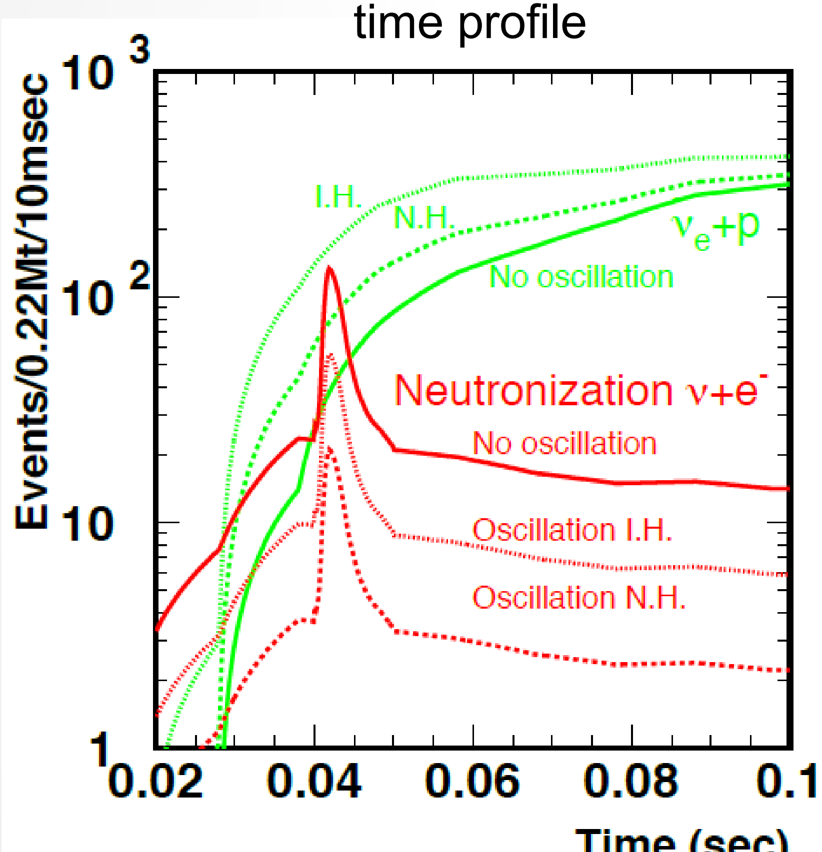
- in simulation the oscillations have to be taken into account
  - MSW effect through the stellar medium, hierarchy dependant
  - also collective effects in high-density core
- expected number of events:
  - 54-90k events (@ 10kpc)
  - 2-3.6k (@ SN1987a)
    - for comparison – 25 neutrinos (in total) observed from SN1987a
- peak event rate of IBD events may reach about 50 kHz at 10 kpc
  - Betelgeuse → ~MHz
- early warning for optical and x-ray telescopes
  - directional accuracy 1-1.3º at 10kpc



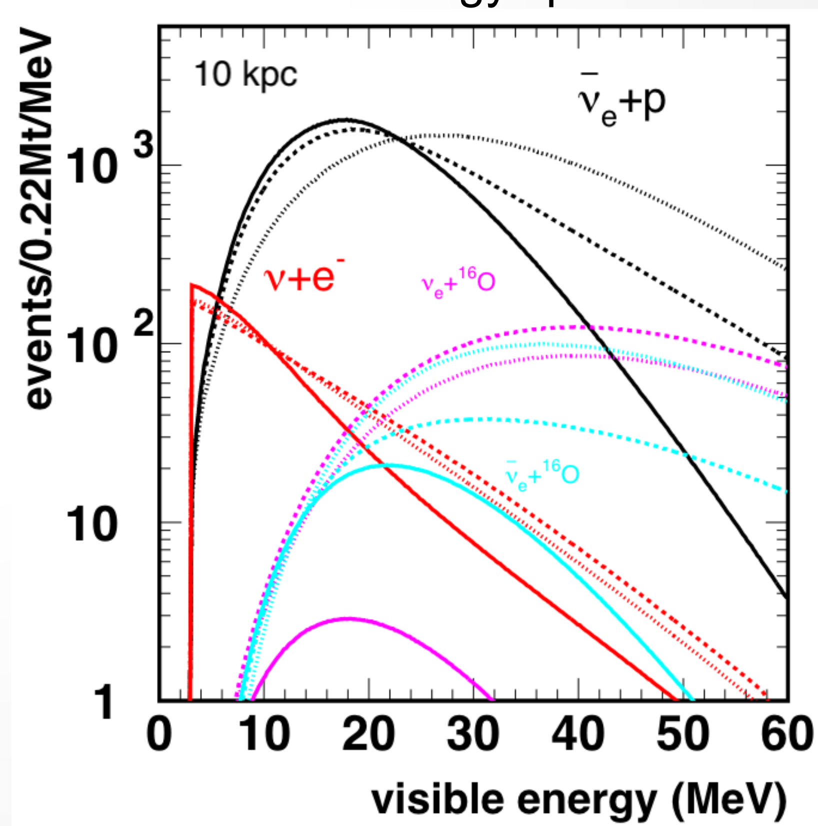
Supernova ν time and spectrum

- simulations for 10 kpc
- arrival time → sharp rise → neutrino mass, shape – mass hierarchy, multidimensional dynamics of the core-collapse supernovae
- energy spectra (extracted from visible energy)
  - ΔE/E ~20% at 10-20MeV

time profile



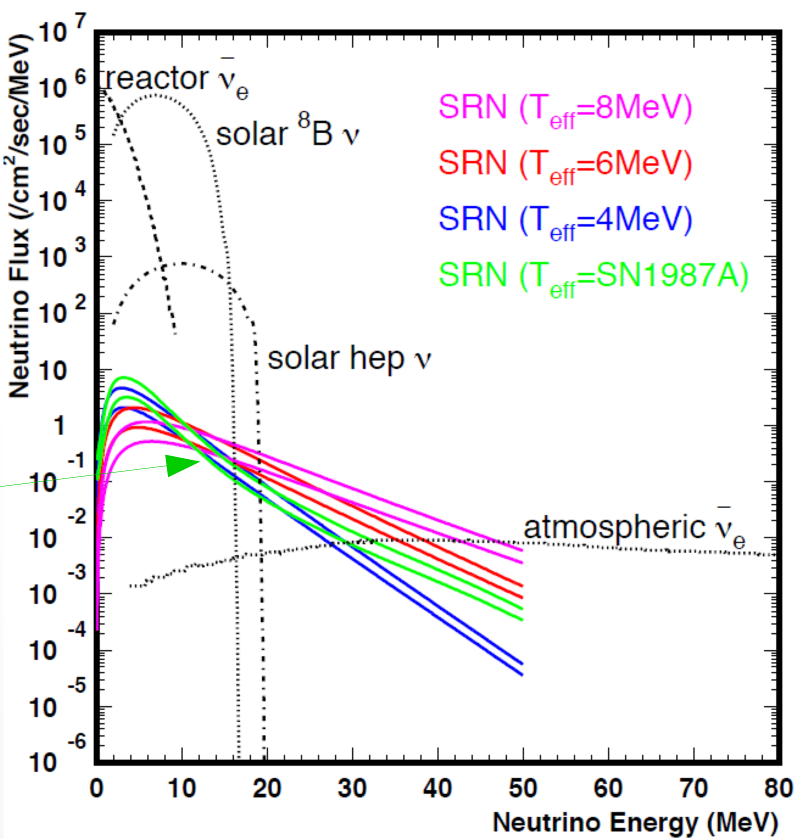
visible energy spectra



Supernova relic neutrinos

or diffuse supernova neutrino background

- expected flux few tens/cm^2/sec
- history of heavy elements synthesis
- search limited by small flux and background:
  - 0.8-5 IBDs/year above 10 MeV in SK
  - spallation for low energies
  - atmospheric neutrinos for higher energies (decay electrons from under-threshold muons)
- first measurement may be done by SK-Gd with tagging of neutron produced in IBD
  - energy range 10-20 MeV
  - neutron capture efficiency 90% with 0.1% of Gd



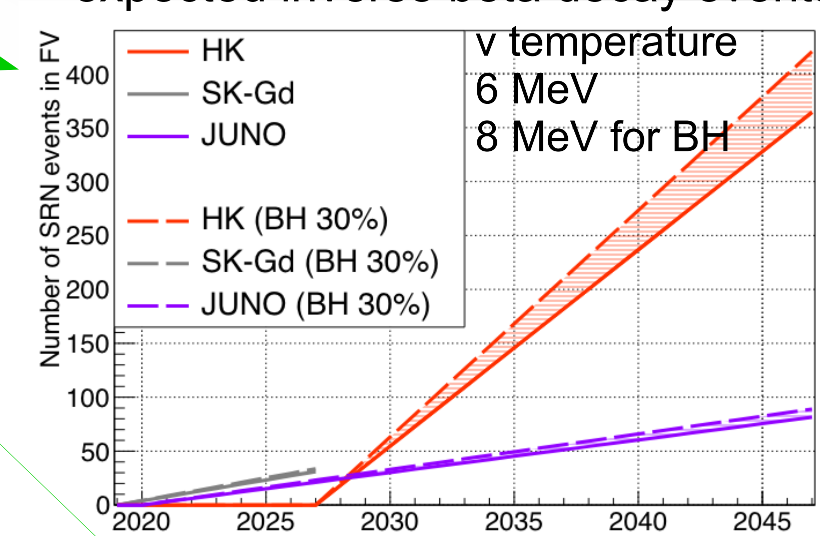
Supernova relic neutrinos in HK

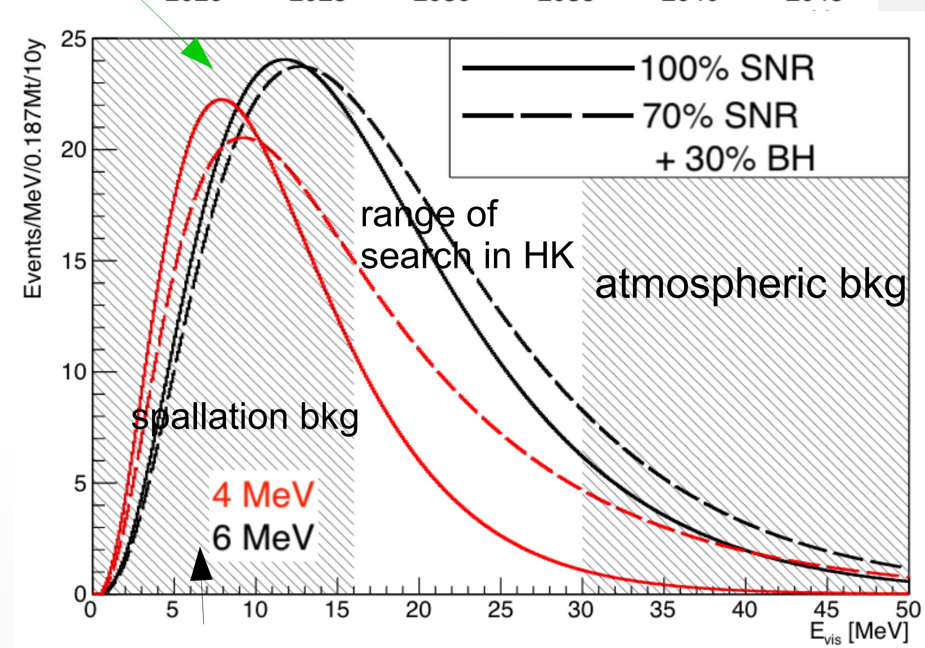
- higher statistics expected in HK
  - possibility to measure spectrum
- neutron tagging by

  n + p → d + γ(2.2 MeV)

  with 70% efficiency
- 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

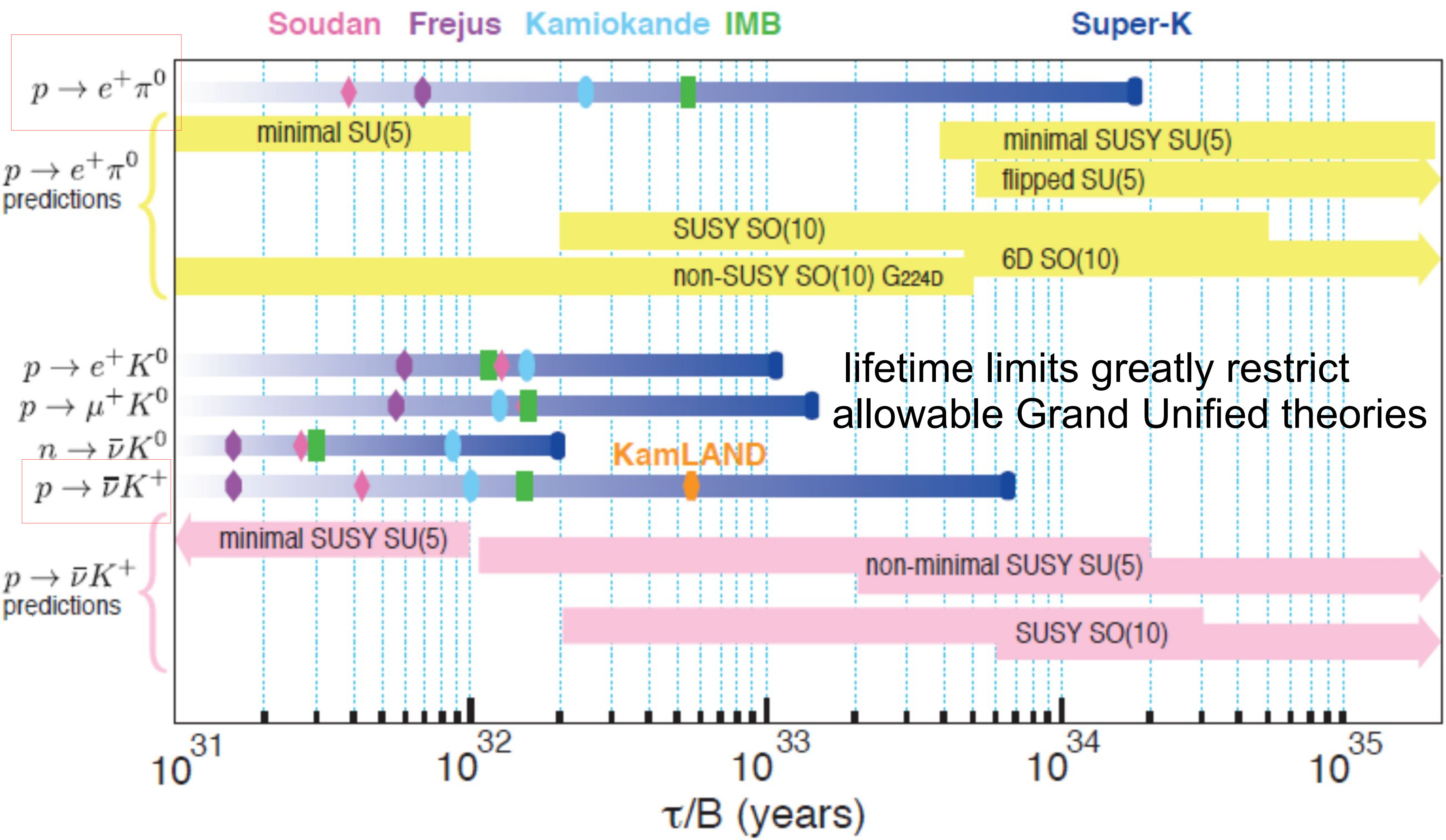




ν temperature
8 MeV for BH formation

Nucleon decays in GUTs

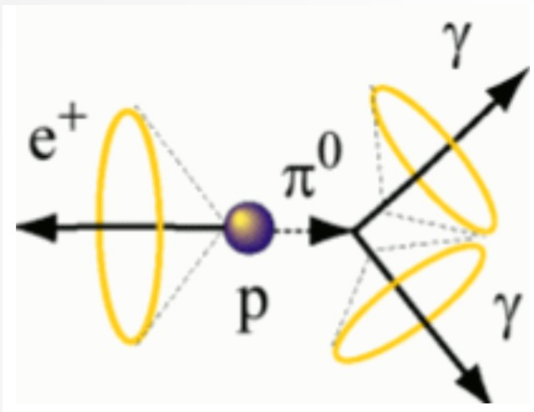
Baryon number violation has never been experimentally observed



lifetime limits greatly restrict allowable Grand Unified theories

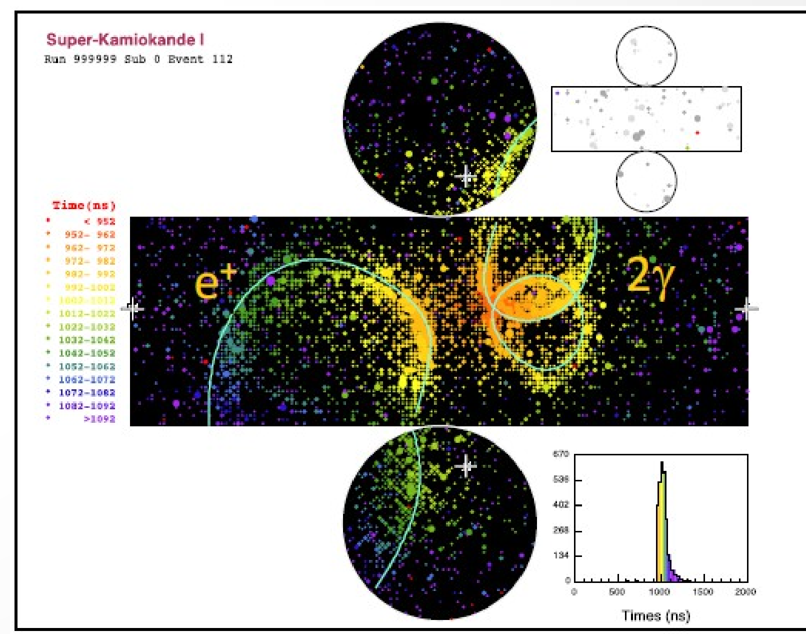
Search for $p \to e^+\pi^0$ decay

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



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

- possible to fully reconstruct the proton mass
- background coming from atmospheric neutrinos
  - producing pions directly or in the secondary interactions
  - often accompanied by neutrons
- analysis similar as in SK but with neutron tagging (veto) thanks to improved PMTs



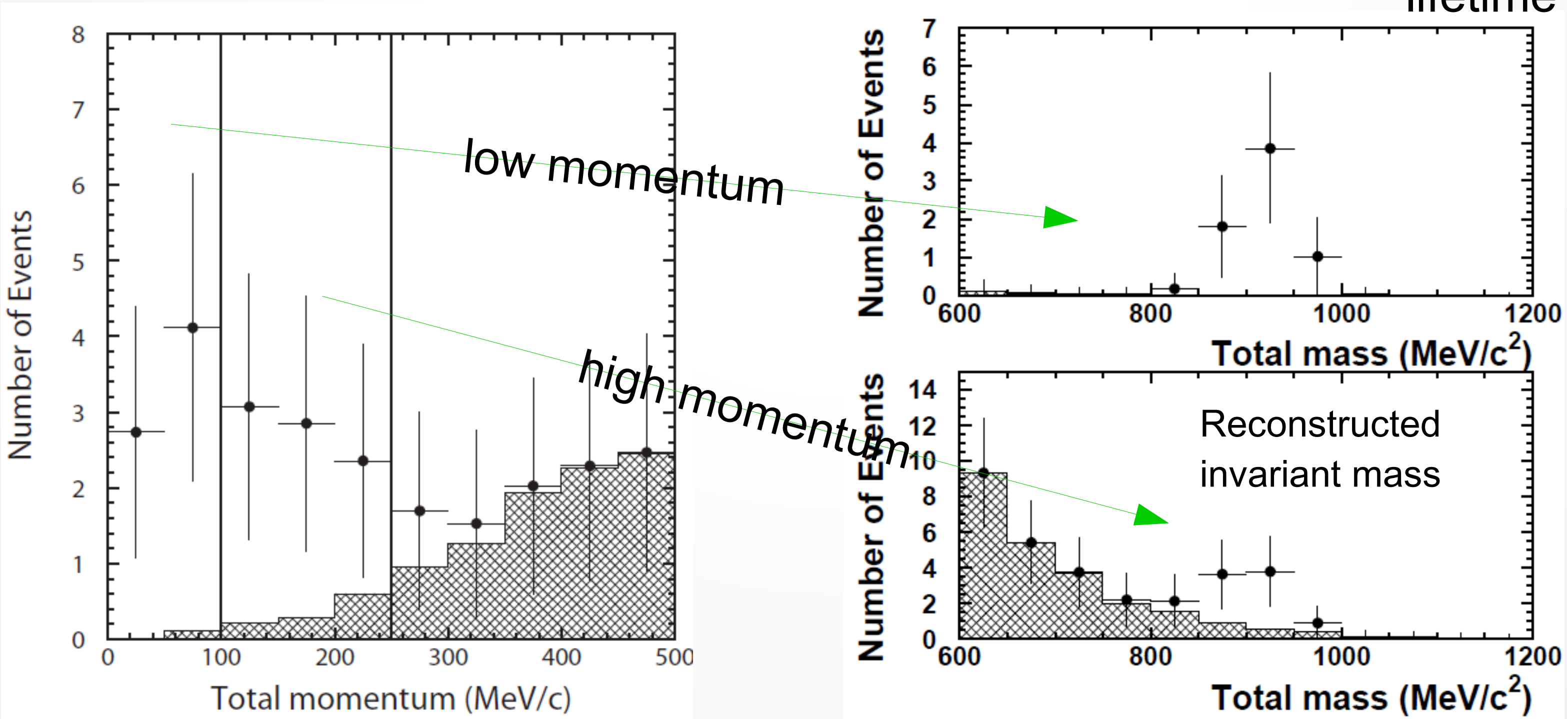
Search for $p \to e^+\pi^0$ decay

- neutron tagging for background rejection
  - 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
- water: 2 free protons (no nuclear effects) + 8 bound protons

  → very low total momentum

  (very small atmospheric background)

MC: 10 year exposure
lifetime 1.7e34 y



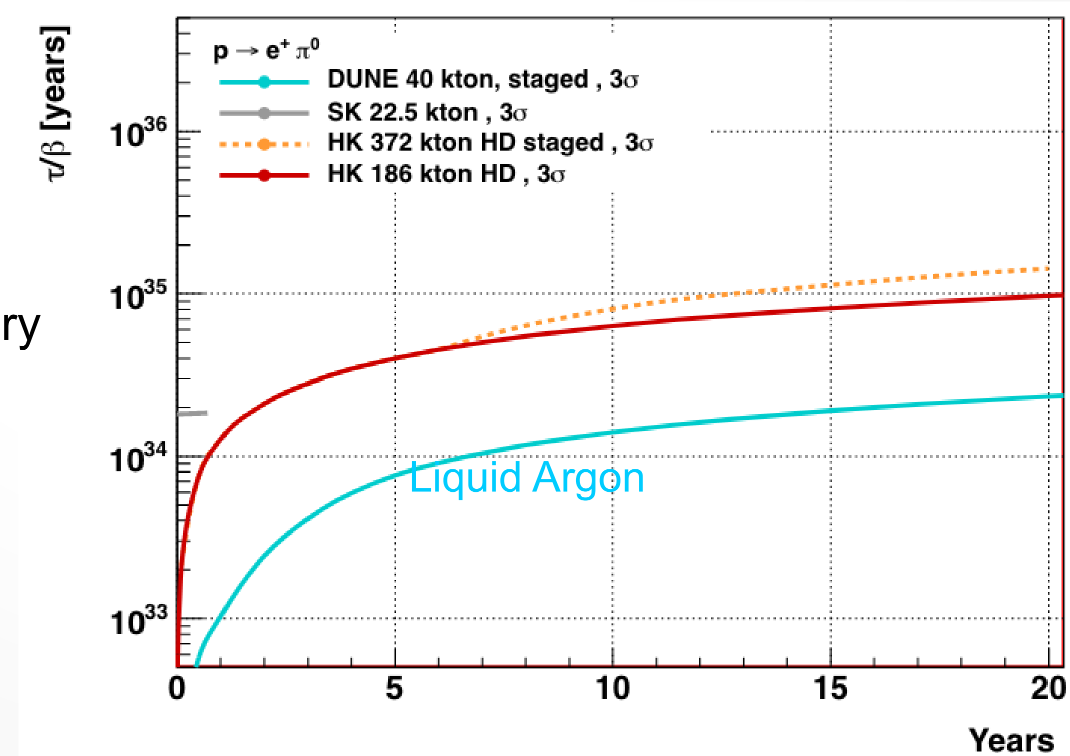
Search for $p \rightarrow e^+\pi^0$ decay

- > 10^{35} years: 3σ discovery with 4.0 Mton yr

$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

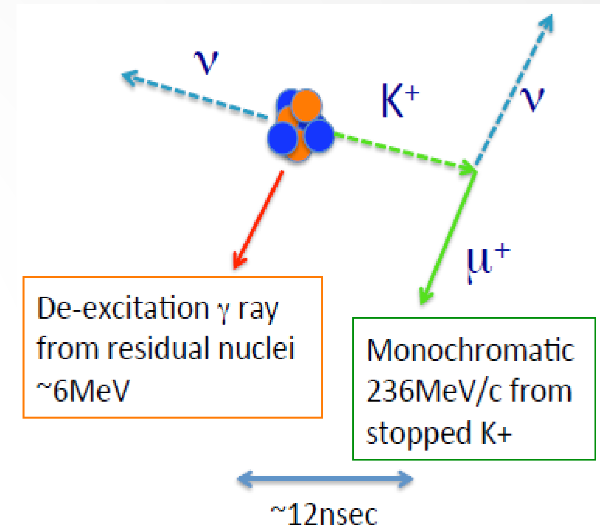
- if proton lifetime is at current Super-K limit ($1.7 \cdot 10^{34}$ y) Hyper-K will observe a signal
  - at 3σ after 2 years
  - at 9σ after ~15 years

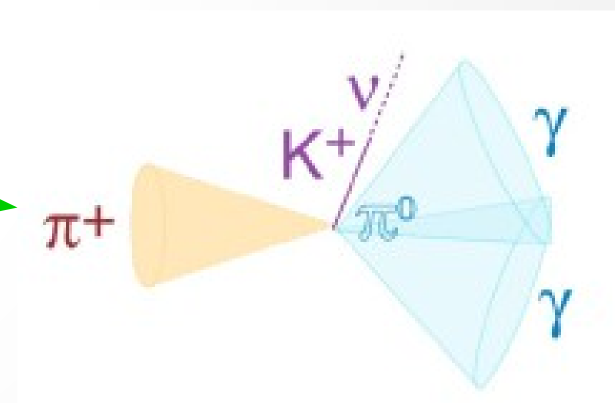
3σ discovery potential



Search for $p \rightarrow \bar{\nu} K^+$ decay

- final state containing second generation quarks favored by SUSY GUTs
- kaon (340 MeV/c) below Cherenkov threshold (749 MeV/c)
  → reconstructed from decay products
  - $K^+ \rightarrow \mu^+ \nu$ (BR 64%)
    - monochromatic muon (236 MeV) +prompt deexcitation photon (6.3 MeV)
    - excess in muon spectrum
  - $K^+ \rightarrow \pi^0 \pi^+$ decay (BR 21%)
    - $p_{\pi+}$ = 205 MeV/c (slightly above the threshold, difficult to reconstruct)
- benefits from enhanced light collection

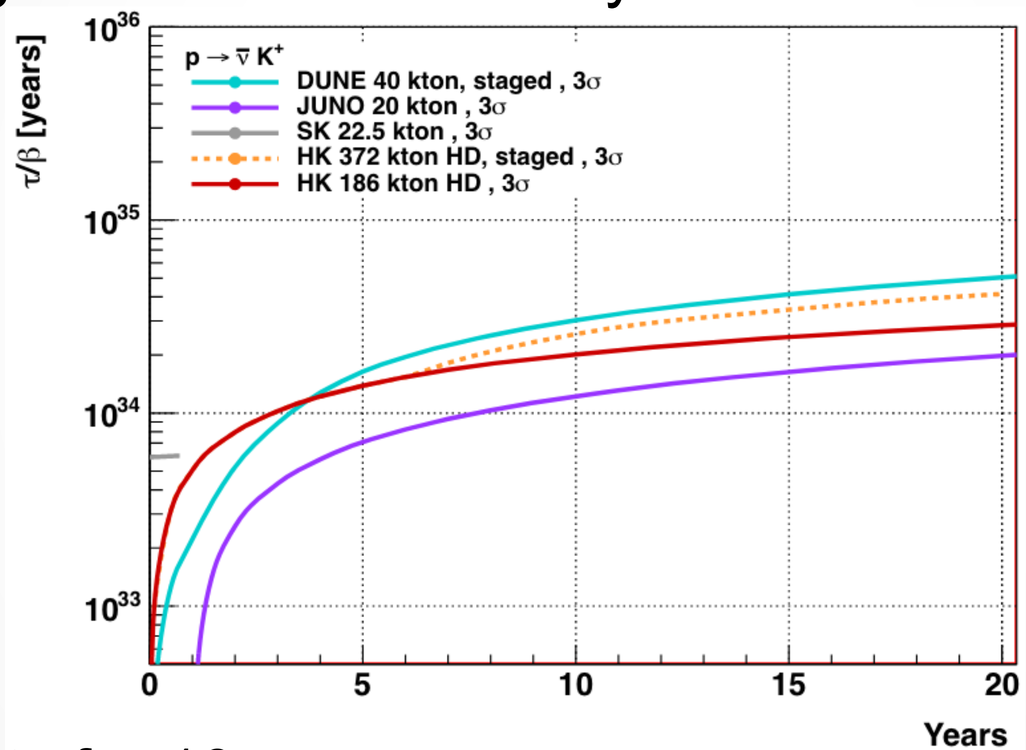




Prompt γ		$\pi^+\pi^0$		p_μ Spectrum	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2	31.0	1916.0

Search for p→$\bar{\nu}K^+$ decay

- discovery potential higher in liquid Argon
- if proton lifetime at current Super-K limit ($6.6\cdot10^{33}$ y) Hyper-K will observe a signal at 8.6σ after ~15 years

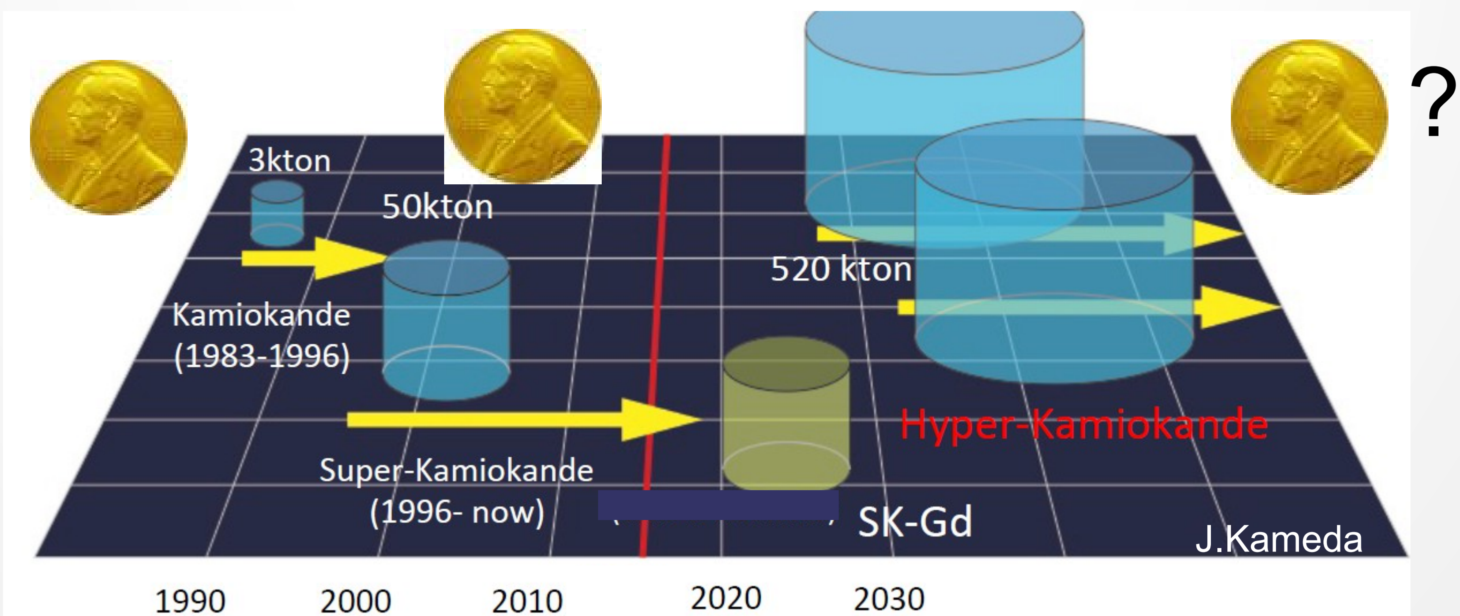


3σ discovery potential

- 90% sensitivity for 10 y exposure
  - $7.8\cdot10^{34}$ years for $p \rightarrow \pi^0 e^+$
  - $3.2\cdot10^{34}$ years for $p \rightarrow \bar{\nu}K^+$
- basically one order of magnitude improvement for many other modes

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 (ready soon)



Backup slides

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

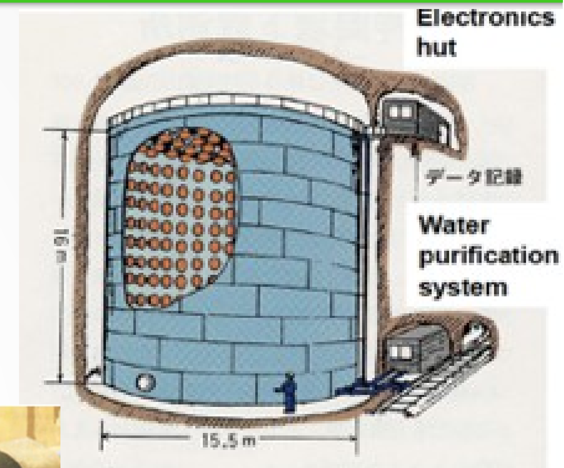
  – world leading limit on proton lifetime

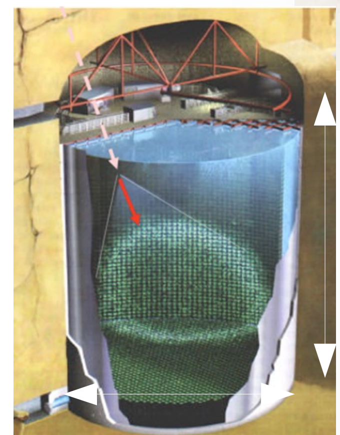
  – ν_e appearance

- mature, known, scalable technology

- **Hyper-Kamiokande** 260 (188) kton

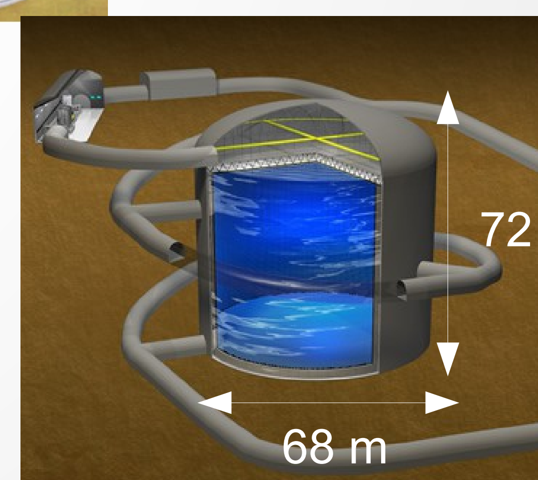
  (~2027-) PMT coverage 40%





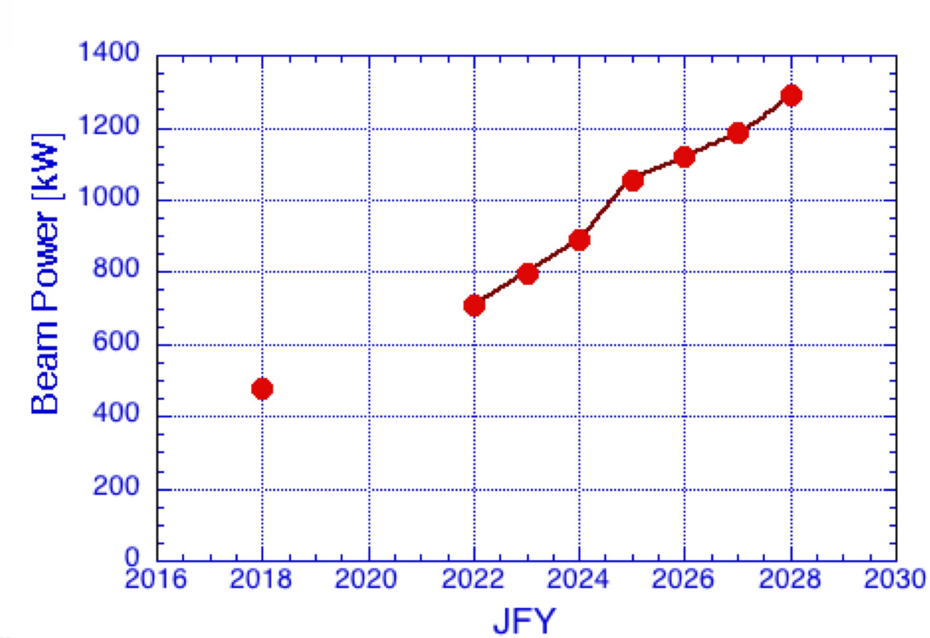
40 m

40 m

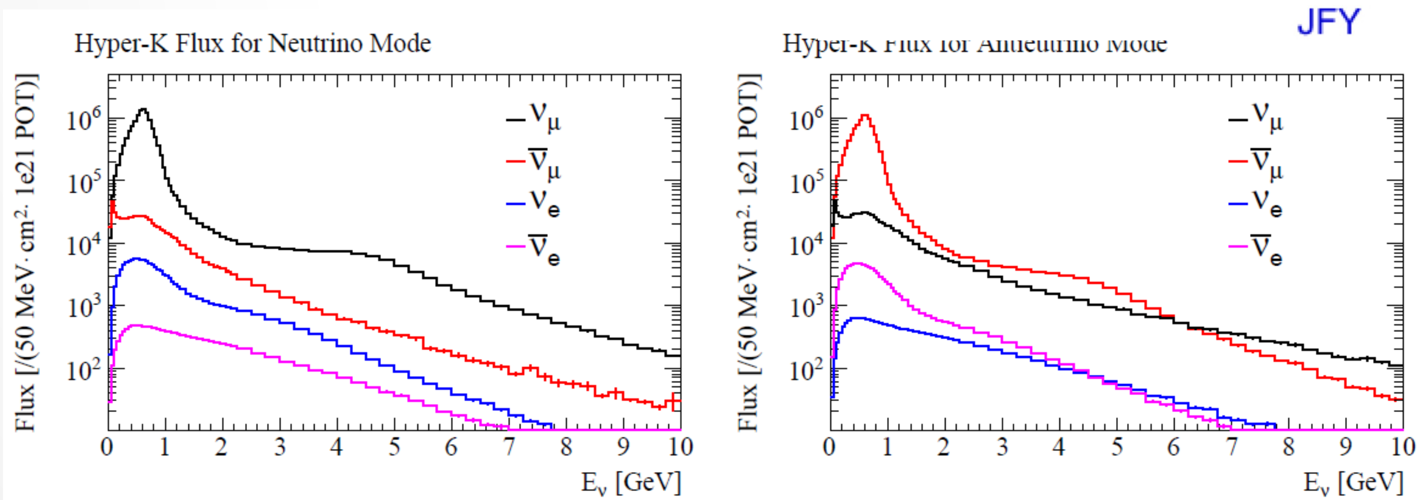


Beam spectrum

- expected beam power:



- upgrade power supplies for horns
  - design current of 320 kA (wrt 250 kA)
  - +~20% higher neutrino flux.
  - reduction of wrong-sign neutrino contamination by 5-10%.



thin target data from NA61/SHINE are applicable to the flux calculation, while replica target data may be used if the target geometry does not change signicantly.

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

- allows for CP violation studies

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

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

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

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

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

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