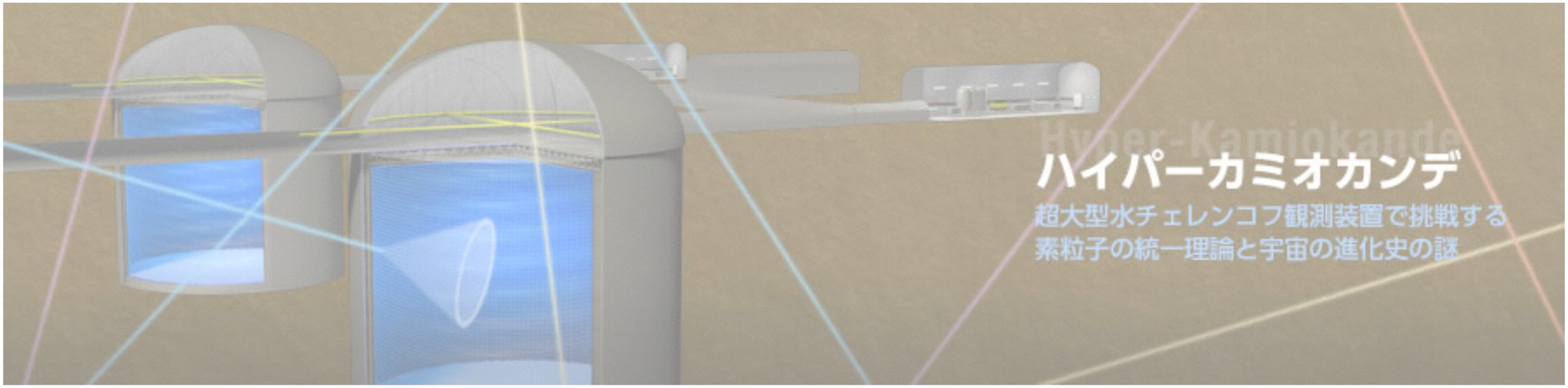

HK physics potential

Masashi Yokoyama
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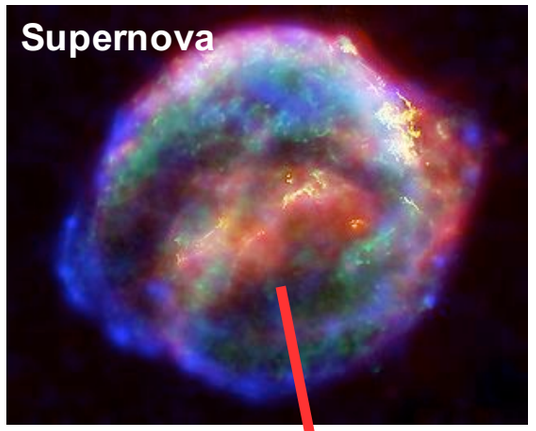
東京大学
THE UNIVERSITY OF TOKYO

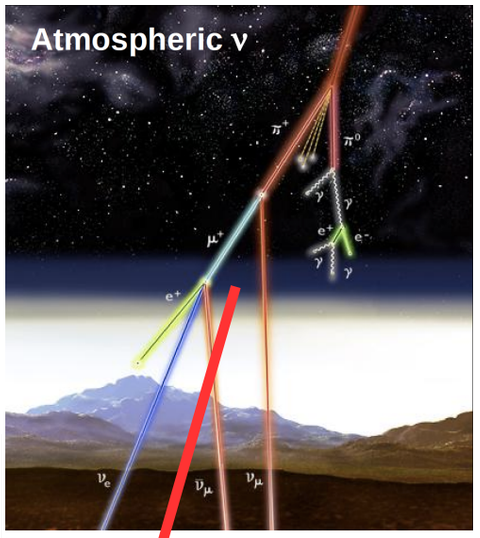
SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

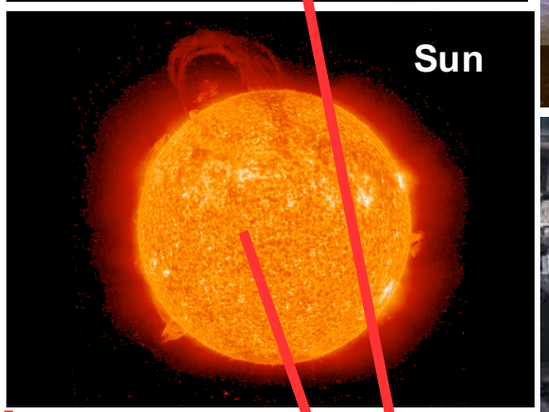
7th open meeting for HK
July 10, 2016 @ London

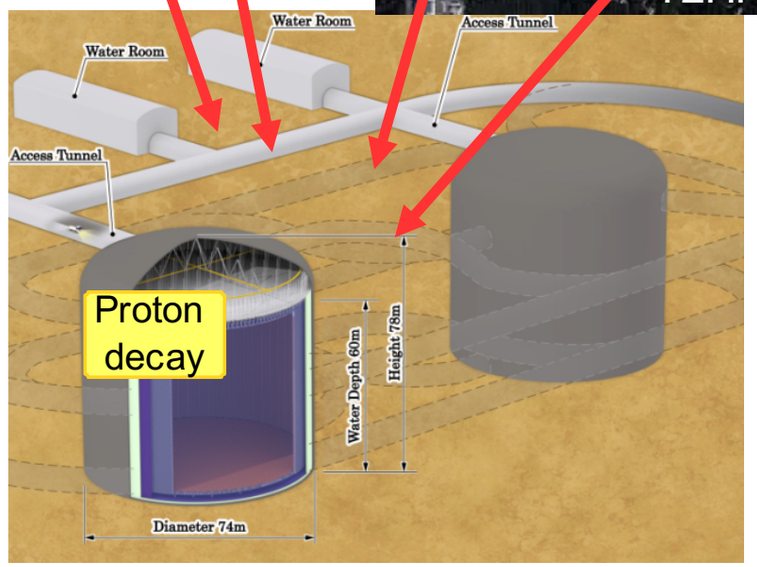
Broad science program with Hyper-K

- Neutrino oscillation physics
  - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
  - Possible discovery with ~×10 better sensitivity than Super-K
- Neutrino astrophysics
  - Precision measurements of solar ν
  - High statistics measurements of SN burst ν
  - Detection and study of relic SN neutrinos
- Geophysics (neutrinography of interior of the Earth)
- Maybe more (unexpected)





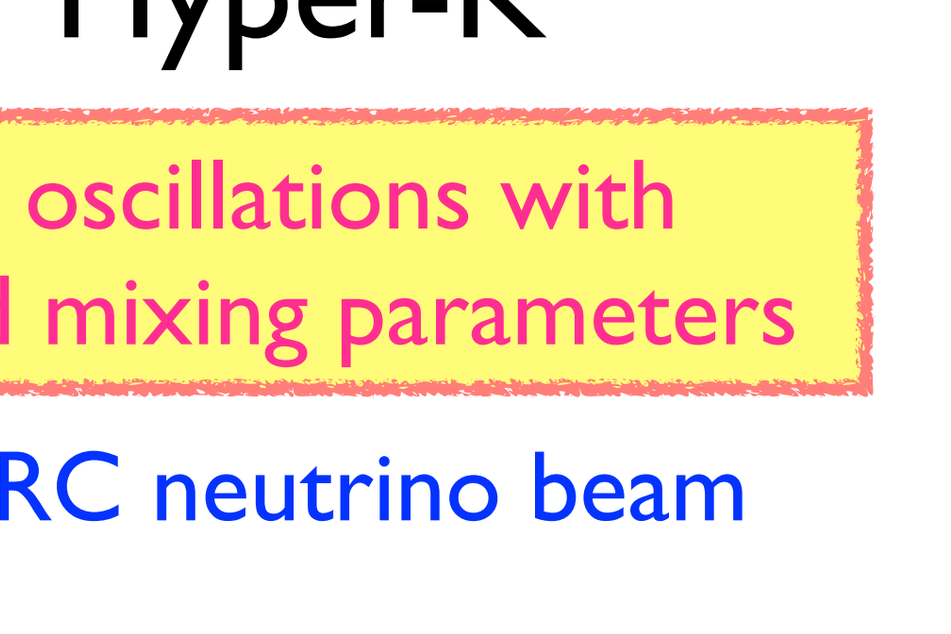




ν oscillation study w/ Hyper-K

Reveal a full picture of neutrino oscillations with precision measurements of CP and mixing parameters

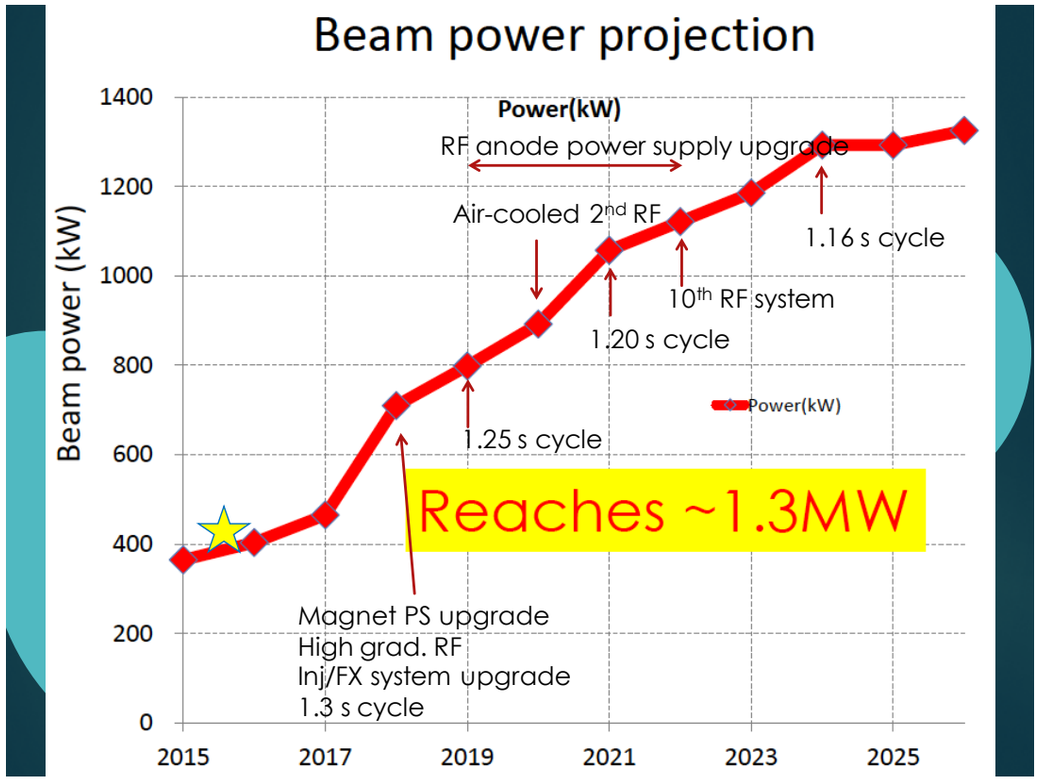
- Long baseline experiment with J-PARC neutrino beam
  - Same configuration as T2K
    - Well understood beam and systematics (NA61 etc.)
    - Reliable sensitivity estimate based on T2K results
  - Main focus on **CP asymmetry**
- Atmospheric neutrino
  - Complementary to beam ν: mass hierarchy and θ_{23} octant
- Solar neutrino



J-PARC ν beamline designed to have the same off-axis for Super-K & Hyper-K

Long baseline experiment

J-PARC and neutrino beam



KEK Project Implementation Plan Review

- Priority of new projects to be promoted with a major budget request was discussed.

KEK-PIP Advisory Committee Meeting

from Sunday, 22 May 2016 at **08:00** to Monday, 23 May 20
at **KEK Tsukuba (TBA)**

Description **Advisory Committee Members**

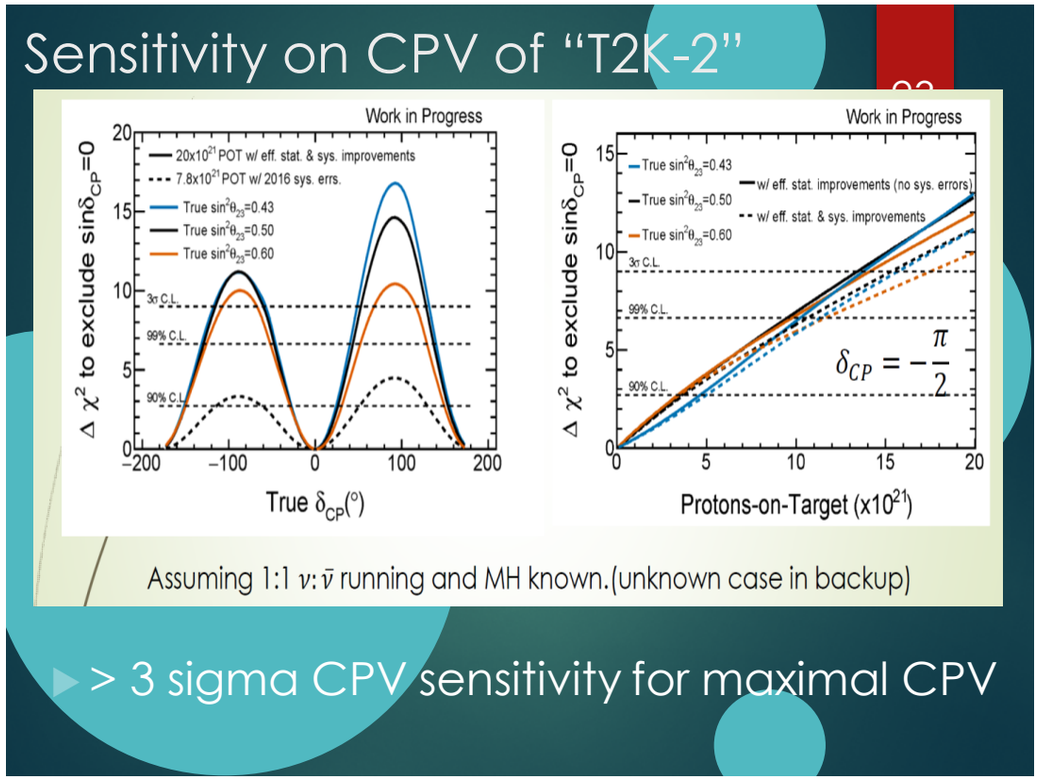
Tatsuya Nakada (Lausanne)
Nigel Smith (SNO lab)
Carlos Wagner (ANL)
Tadafumi Kishimoto (Osaka, RCNP)
Kenneth Hicks (Ohio)
Christine Davies (Glasgow)
Ki-bong Lee (Postech)
Yoshiyuki Amemiya (Tokyo)
Yasuhiro Iwasawa (Dentsudai, UEC)
Jun Akimitsu (Okayama/Hiroshima)
Michael Sullivan (SLAC)
Mei Bai (Juelich)

Project to be prioritized:
- COMET II
- J-PARC upgrade for Hyper Kamiokande
- Hadron Hall Extension
- H-line and g-2/EDM
- LHC and ATLAS
- Super Computer
- RNB

Separate prioritization
- Light Source

Go to day

PIP review concluded that “J-PARC upgrade for HK is the highest priority”.

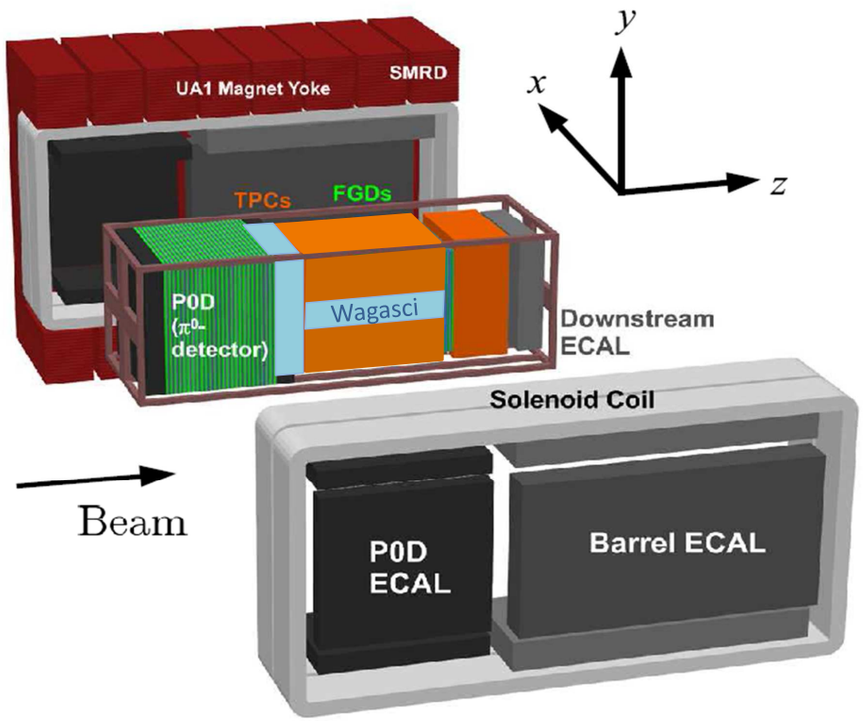


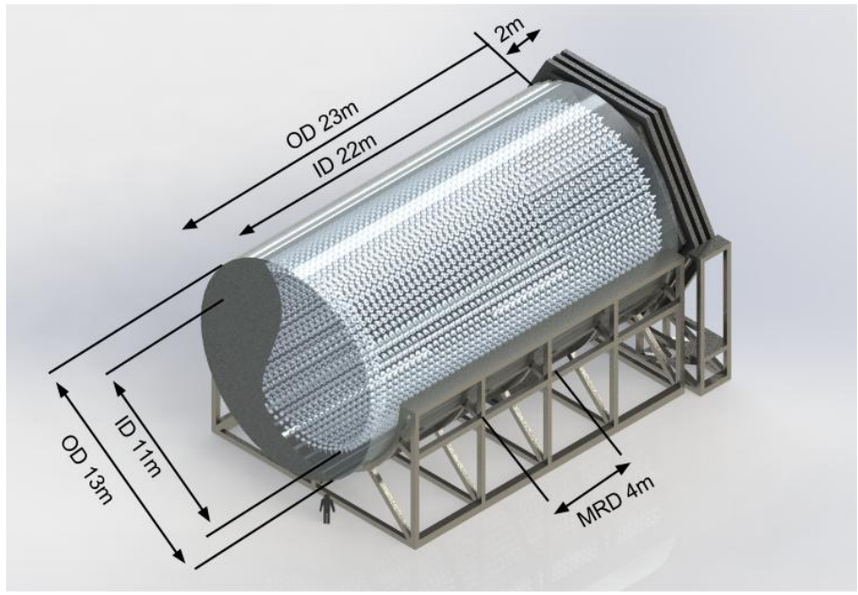
- Already covered by Kobayashi-san
- 1.3MW will be realized before the start of HK
  - Highest priority in KEK-PIP review
  - Seamless evolution of program: T2K → T2K-II → HK

Near Detectors

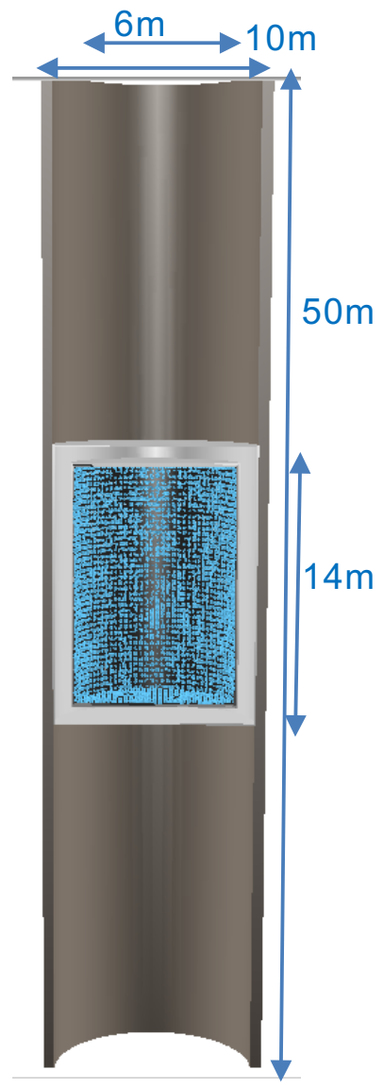
See later talks

- Operation of the magnetized ND280 off-axis detector should continue for HK, with potential upgrades
- Intermediate (at ~1,2 km) WC detector being investigated. Two proposals:
  - Off-axis angle spanning orientation.
  - Gd loading, magnetized μ range detector.
- Will merge in unique detector/ collaboration.





arXiv:1606.08114 [physics.ins-det]

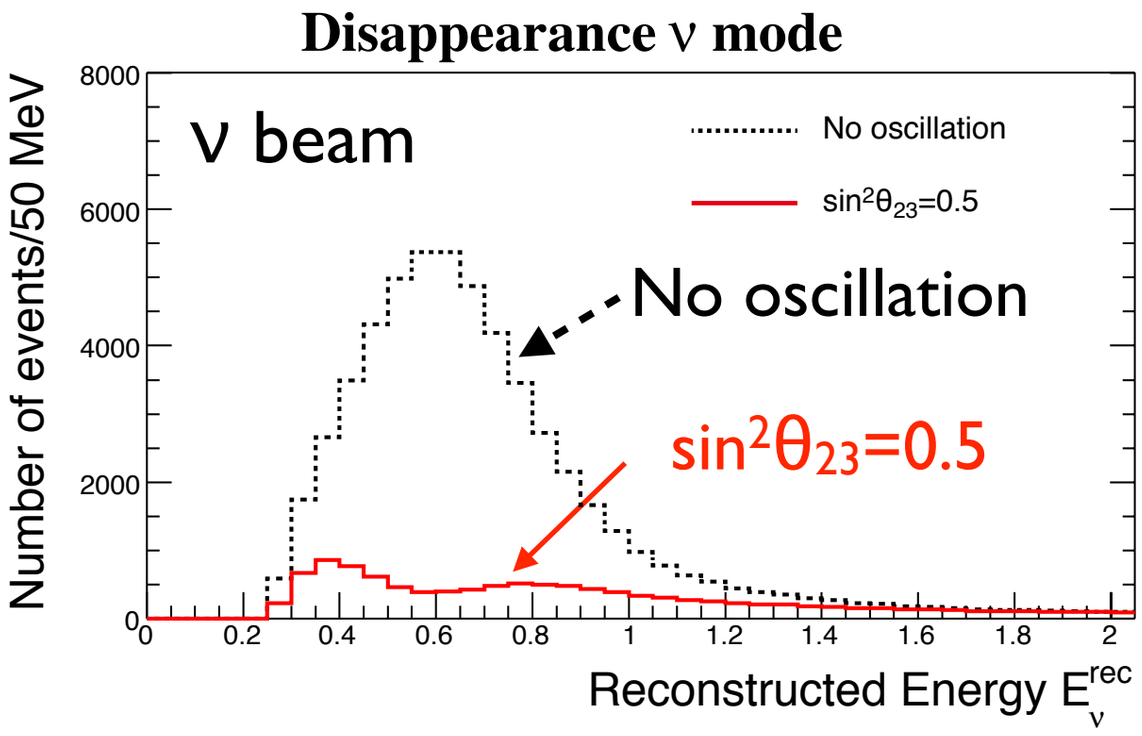


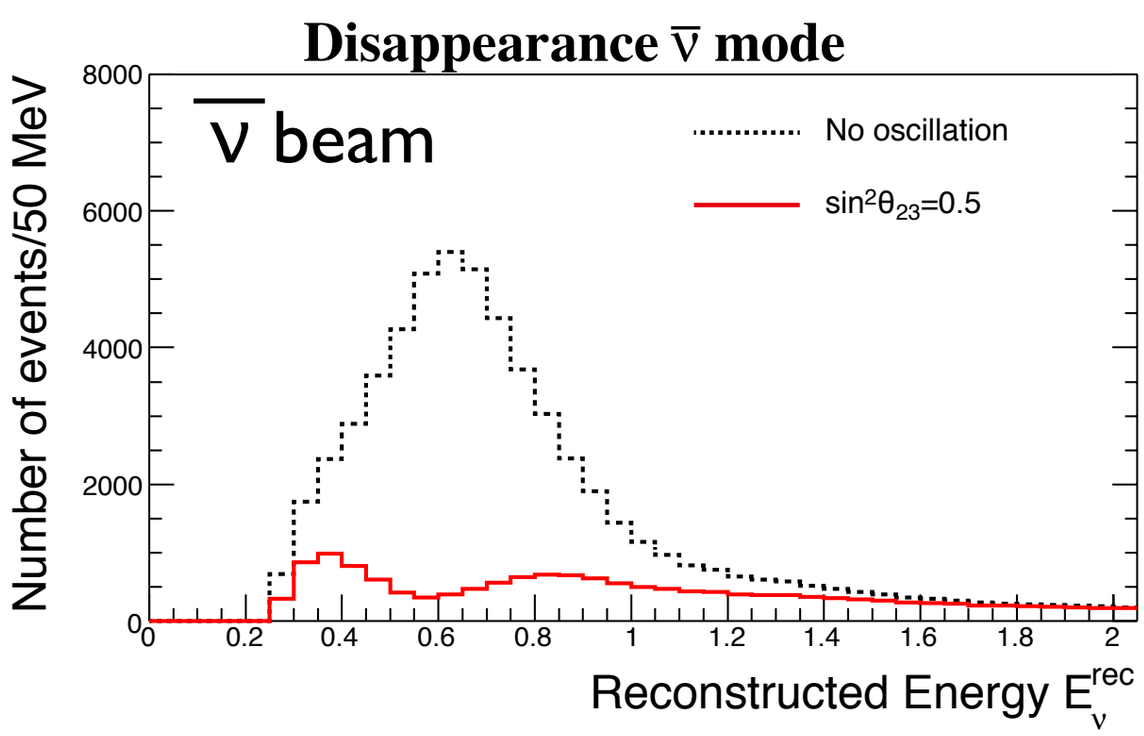
arXiv:1412.3086 [physics.ins-det]

Expected events

1.3MW, 10×10^7sec, $\nu:\bar{\nu}=1.3$

ν_μ disappearance





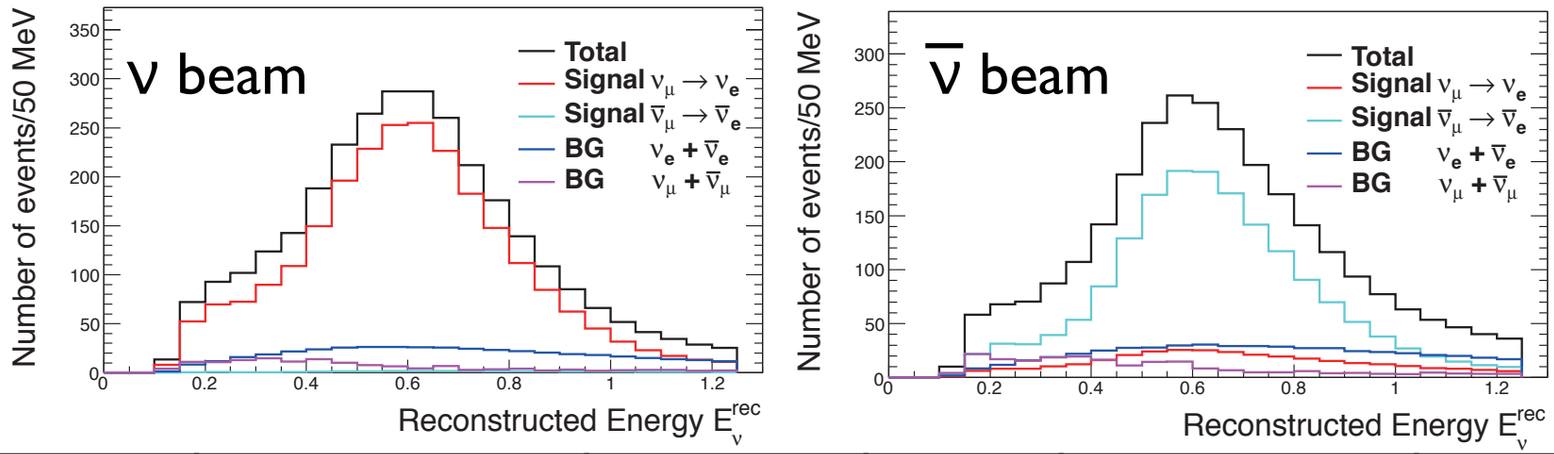
	$\nu_\mu+\bar{\nu}_\mu$ CCQE	ν_μCC nonQE	Others
ν beam	8947	4444	721
$\bar{\nu}$ beam	12317	6040	859

Expected events

1.3MW, 10×10^{7}sec, $\nu:\bar{\nu}$=1.3

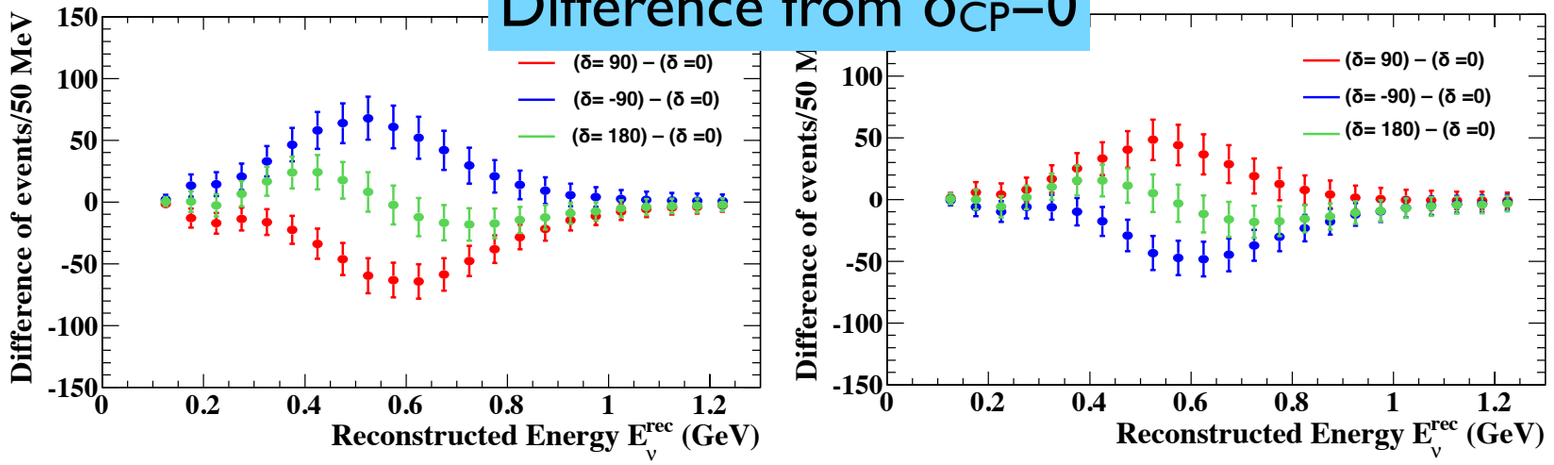
ν_e appearance

Using fiTQun for π^0 rejection



for δ=0	Signal (νμ→νe CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu e/\bar{\nu} e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

Difference from δ_{CP}=0



δ=0 and 180° can be distinguished using shape information

Assumed systematic uncertainties

Extrapolation from T2K experience

- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
  - Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric ν control sample and fundamental detector response understanding with improved calibration

Uncertainty on the expected number of events at Hyper-K (%)

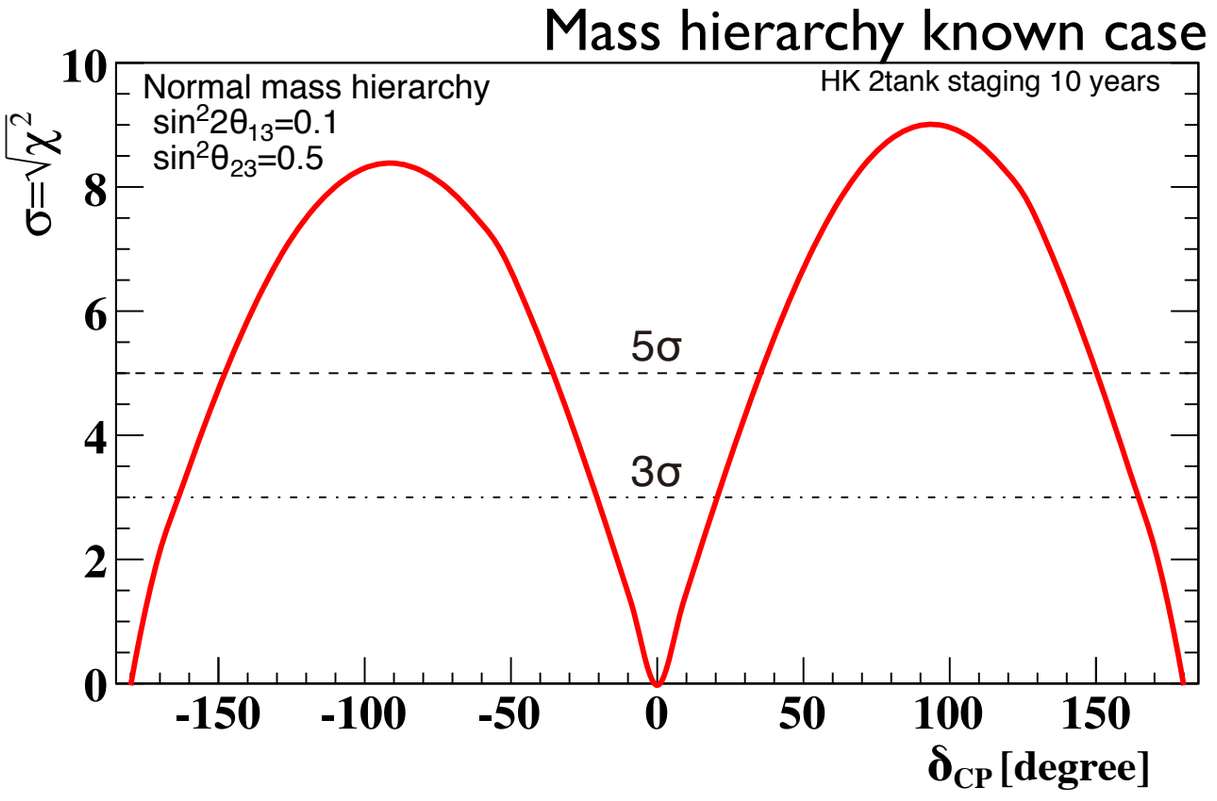
	ν mode		anti-ν mode	
	νe	νμ	νe	νμ
Flux&ND	3.0	3.3	3.2	3.3
XSEC model	0.5	0.9	1.5	0.9
Far Det. +FSI	0.7	1.0	1.5	1.1
Total	3.2	3.6	3.9	3.6

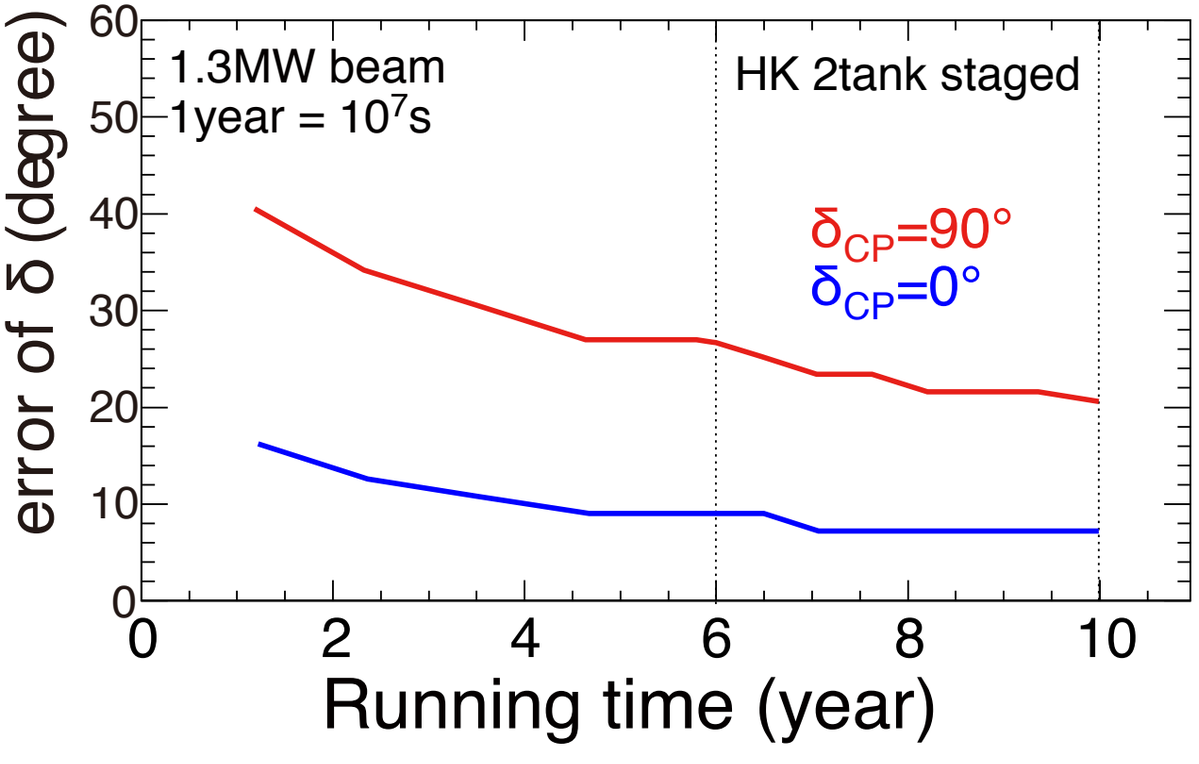
- Further reduction by new near detectors under study
- Benefit from experience with T2K(-II)

CPV sensitivity

- Exclusion of $\sin\delta_{CP}=0$
  - >8σ(6σ) for δ=-90°(-45°)
  - ~80% coverage of δ parameter space with >3σ
- From discovery to δ_{CP} measurement:
  - ~7° precision possible

		sinδ=0 exclusion		error	
		>3σ	>5σ	δ=0°	δ=90°
PTEP	7.5MWy	76%	58%	7.5°	19°
2 tanks	13MWy	78%	62%	7.2°	21°





θ_{23} and Δm^2_{32}

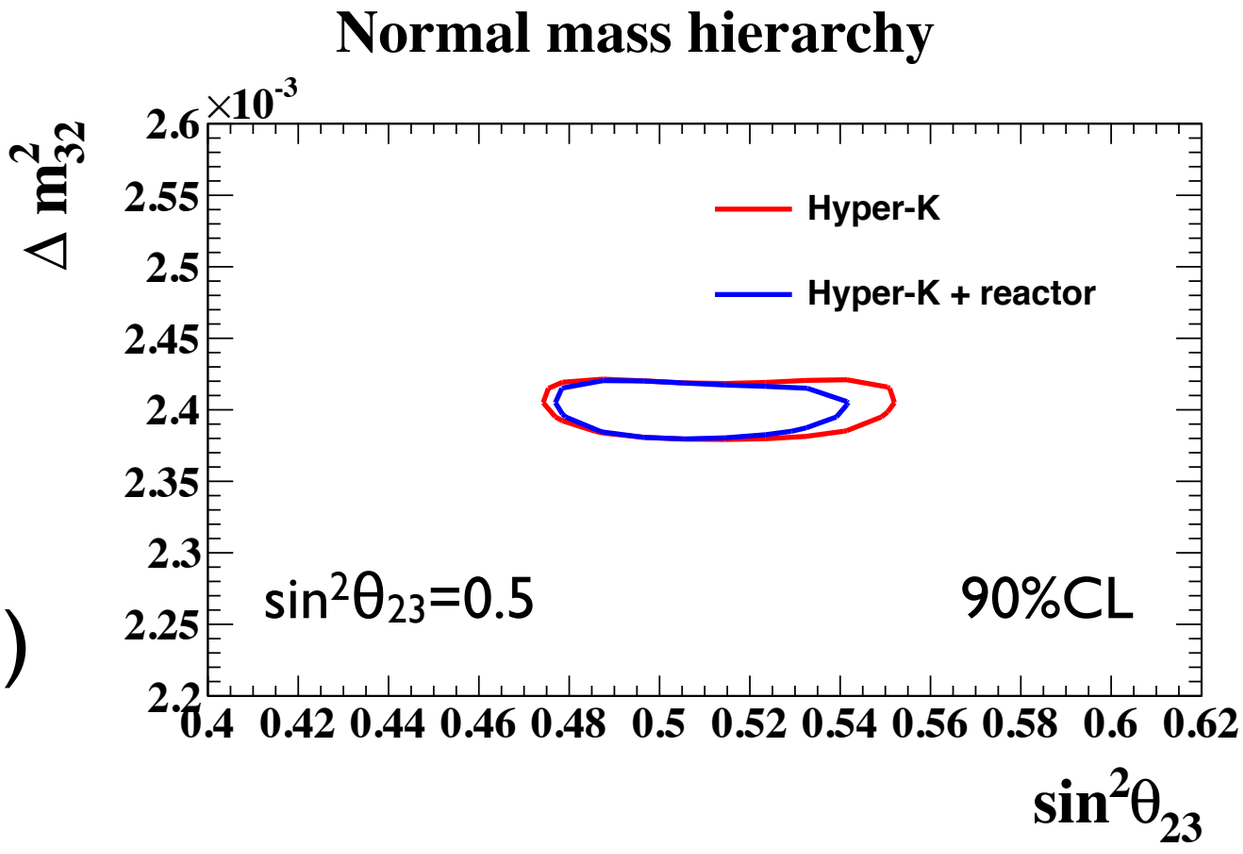
$\delta(\Delta m^2_{32}) \sim 1.4 \times 10^{-5} eV^2$

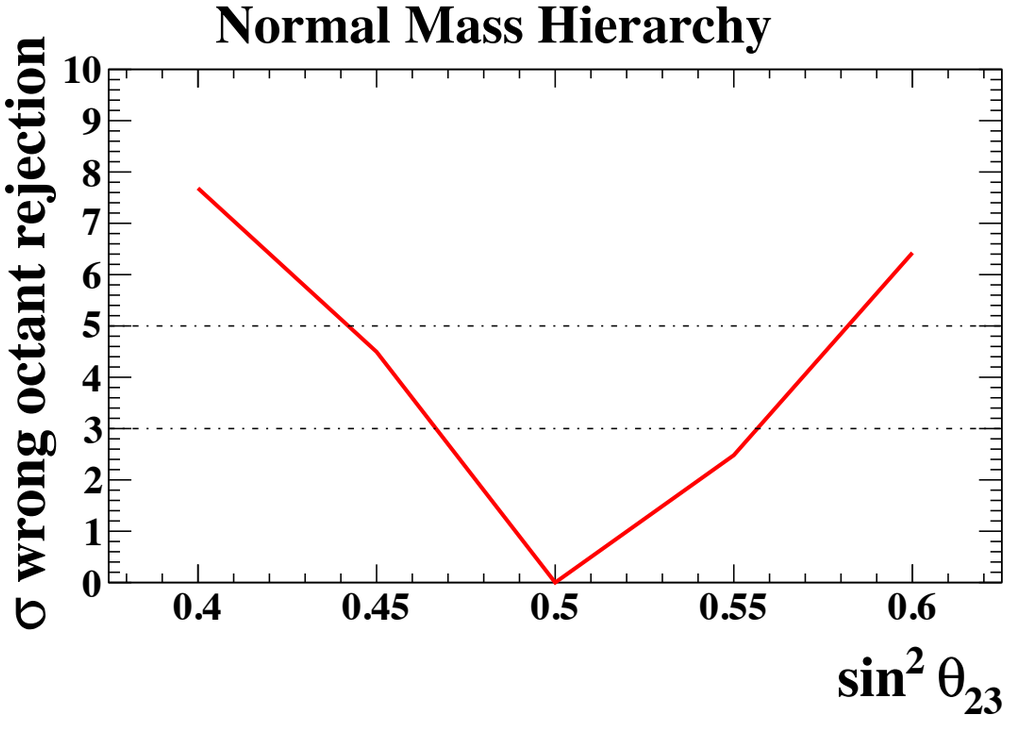
→ Mass hierarchy sensitivity
in combination with reactor

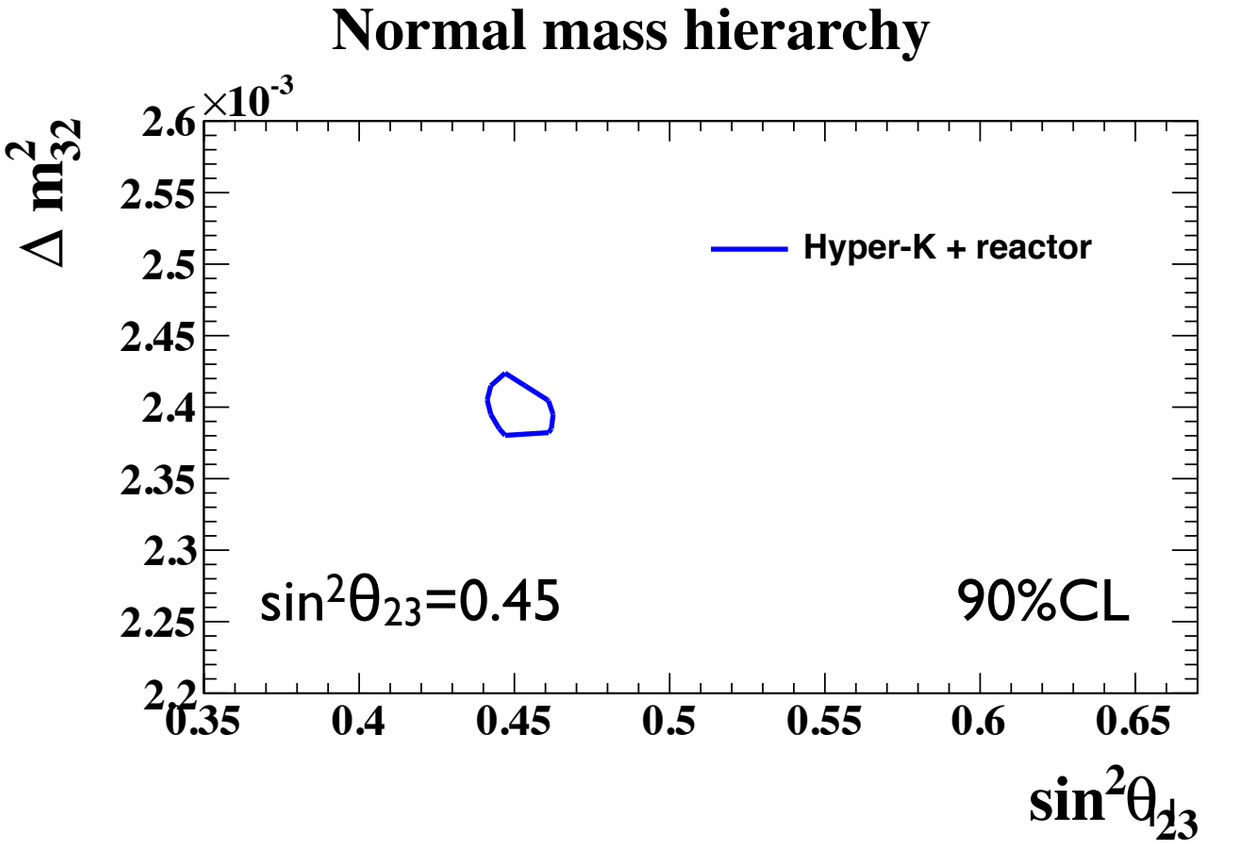
$\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23}=0.5$)

~ 0.006 (for $\sin^2\theta_{23}=0.45$)

→Octant determination,
input to models

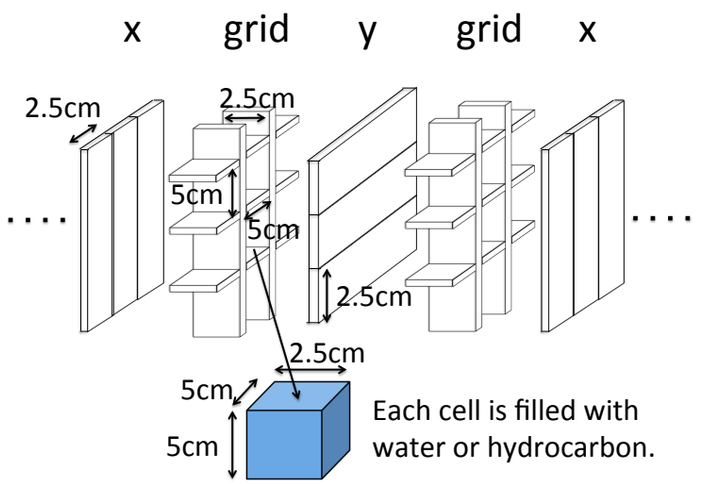


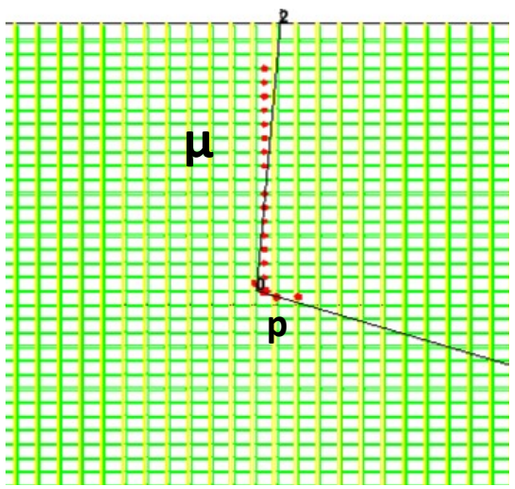




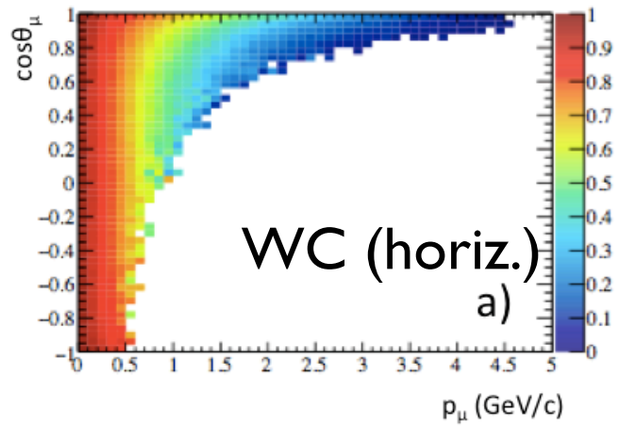
Near detector measurements

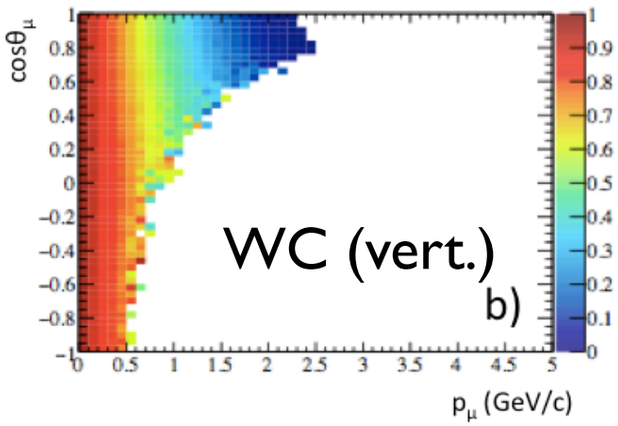
- Cross section measurements with large statistics and high quality data
  - Larger phase space to reduce model dependence
  - Expected number of events after selection per 10^{21} POT:
    - ~40k ν_μ CC events /1ton @ 280m
    - ~1M ν_μ and ~20k νe events for 2kton intermediate detector
- Exotic physics searches
  - Sterile neutrino
  - Lorentz/CPT violation
  - Heavy neutral lepton
  - …

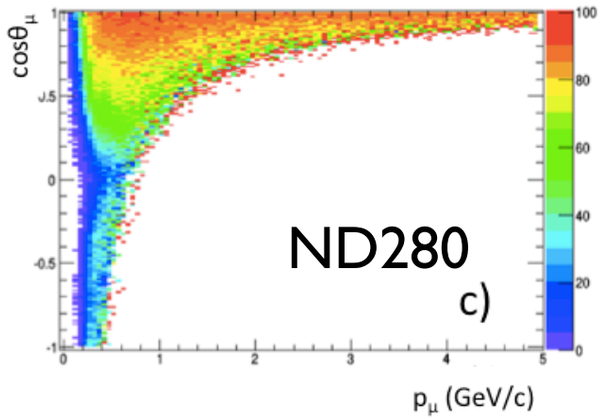


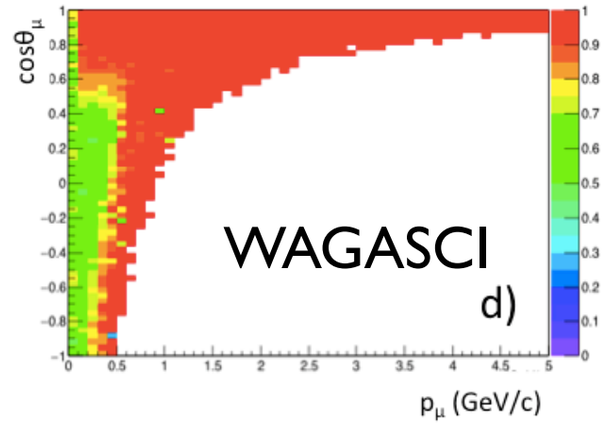


"WAGASCI" 3D-grid scintillator concept for large angular acceptance



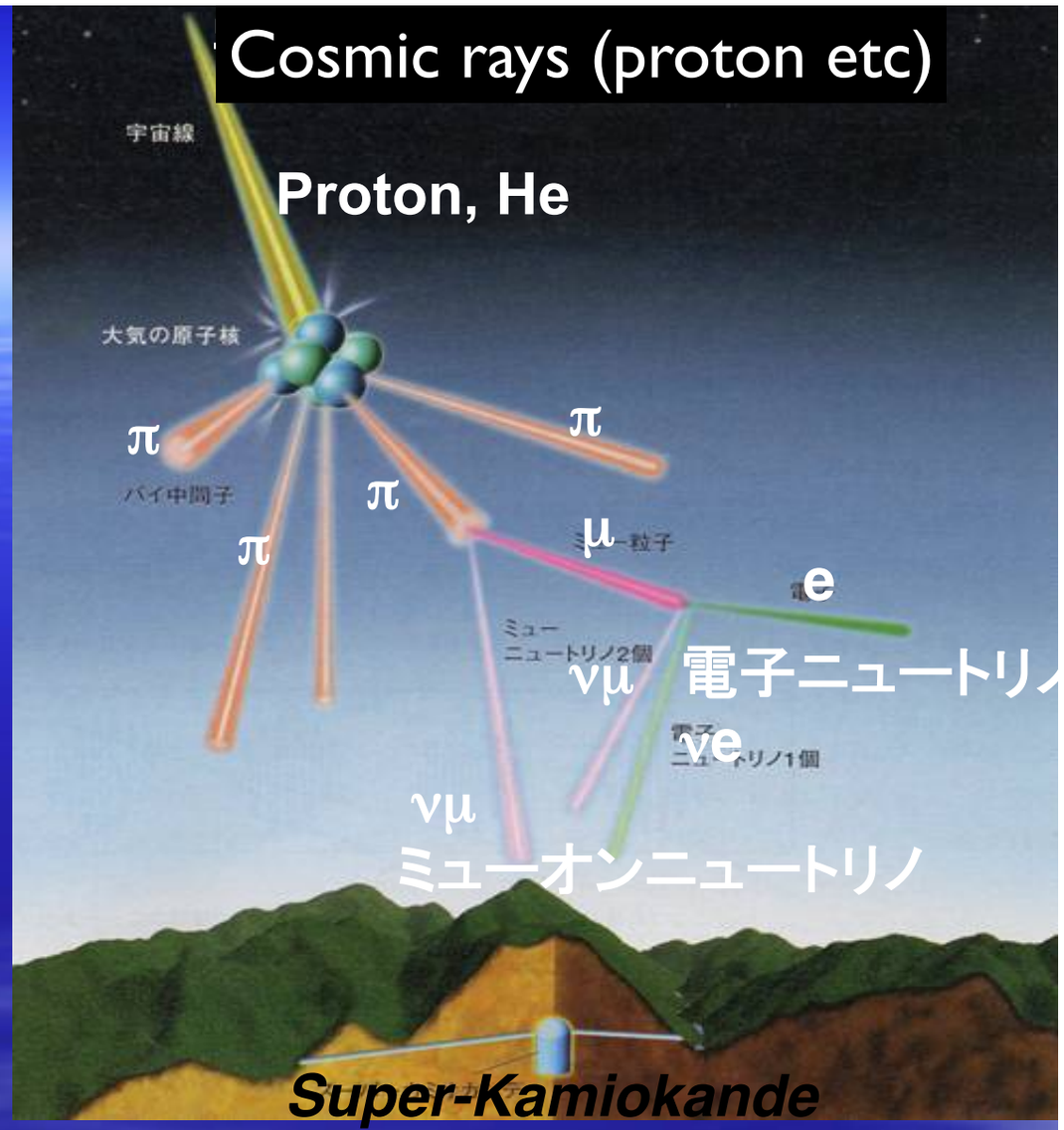






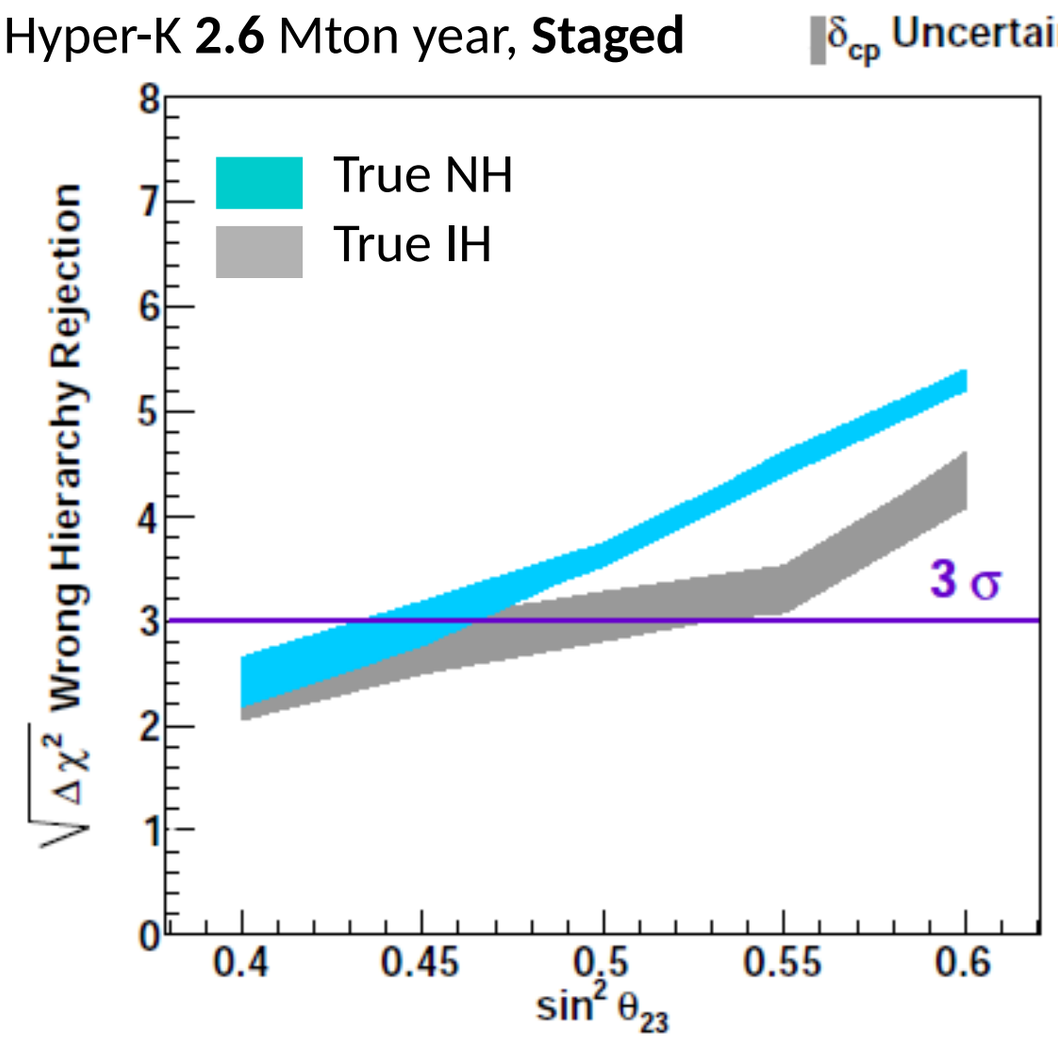
Muon efficiency

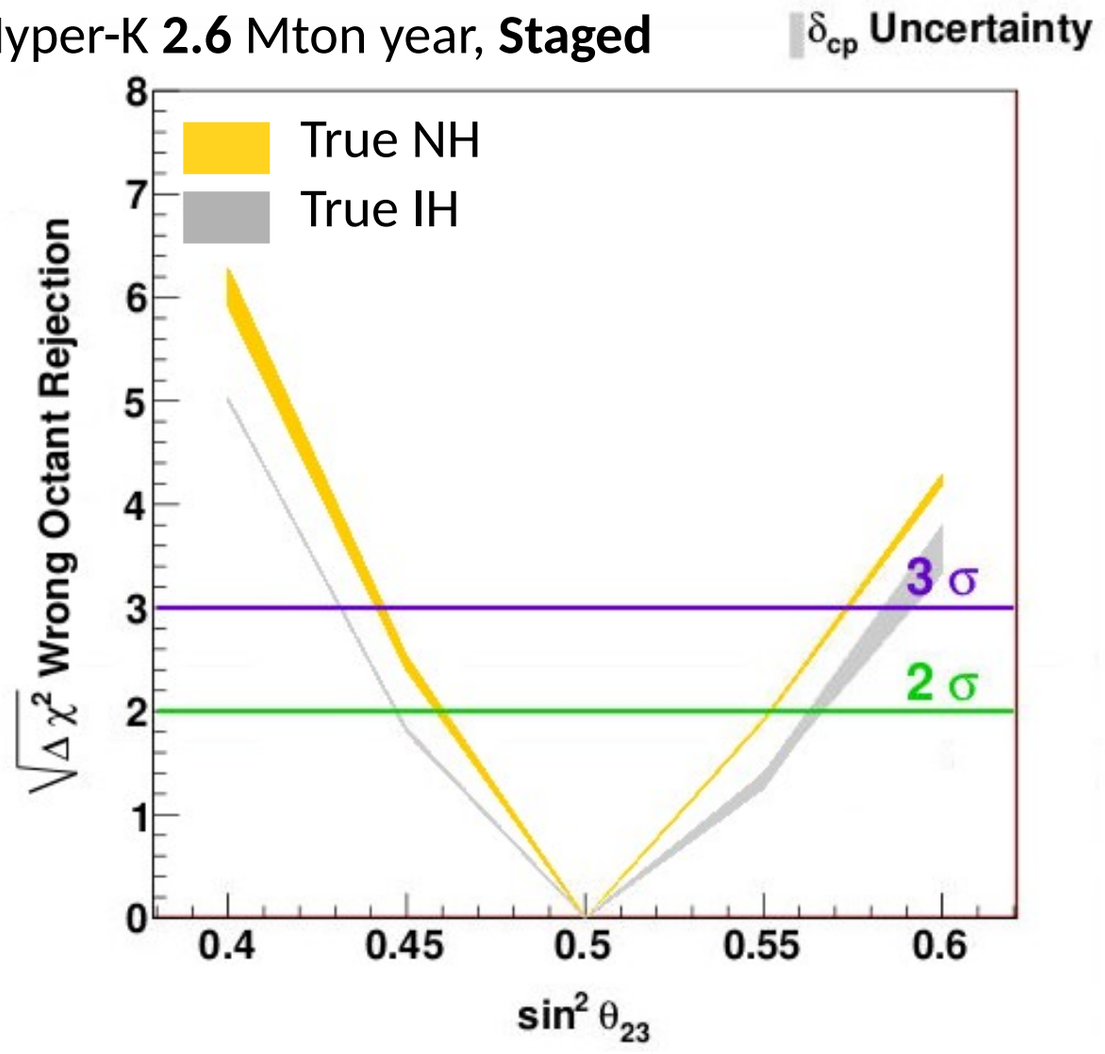
Atmospheric ν's



- Wide range of ν energy (0.1 GeV ~ 10^4 GeV and beyond)
- Wide range of ν baseline (10km downward ~ 13,000km upward)
- ν_μ:ν_e ~ 2:1 at production
- ν oscillation study by high statistical data (>40,000 events in Super-K) and all three flavors (ν_e, ν_μ, ν_τ)
- Unique tests of ν's exotic property (4th ν, Lorentz violation, etc)

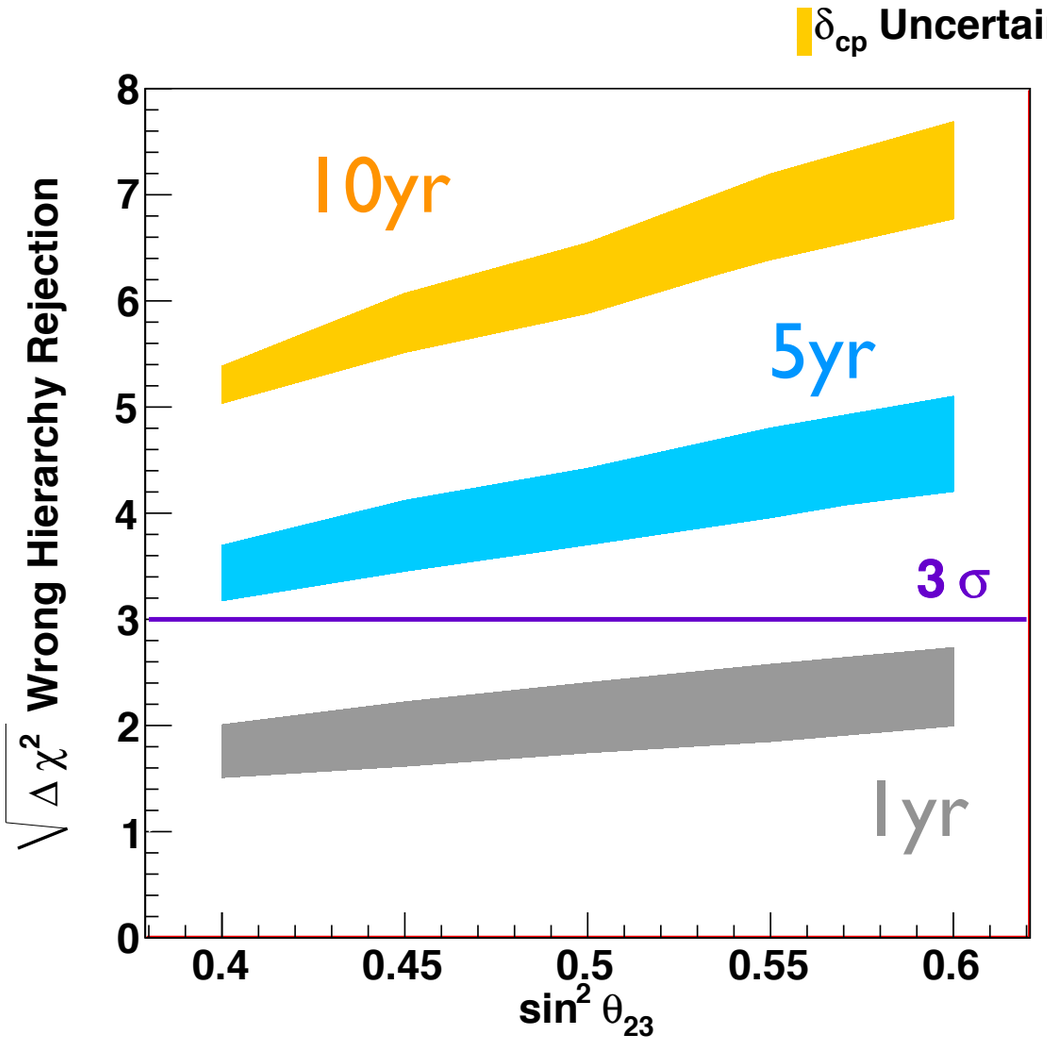
Atmospheric ν

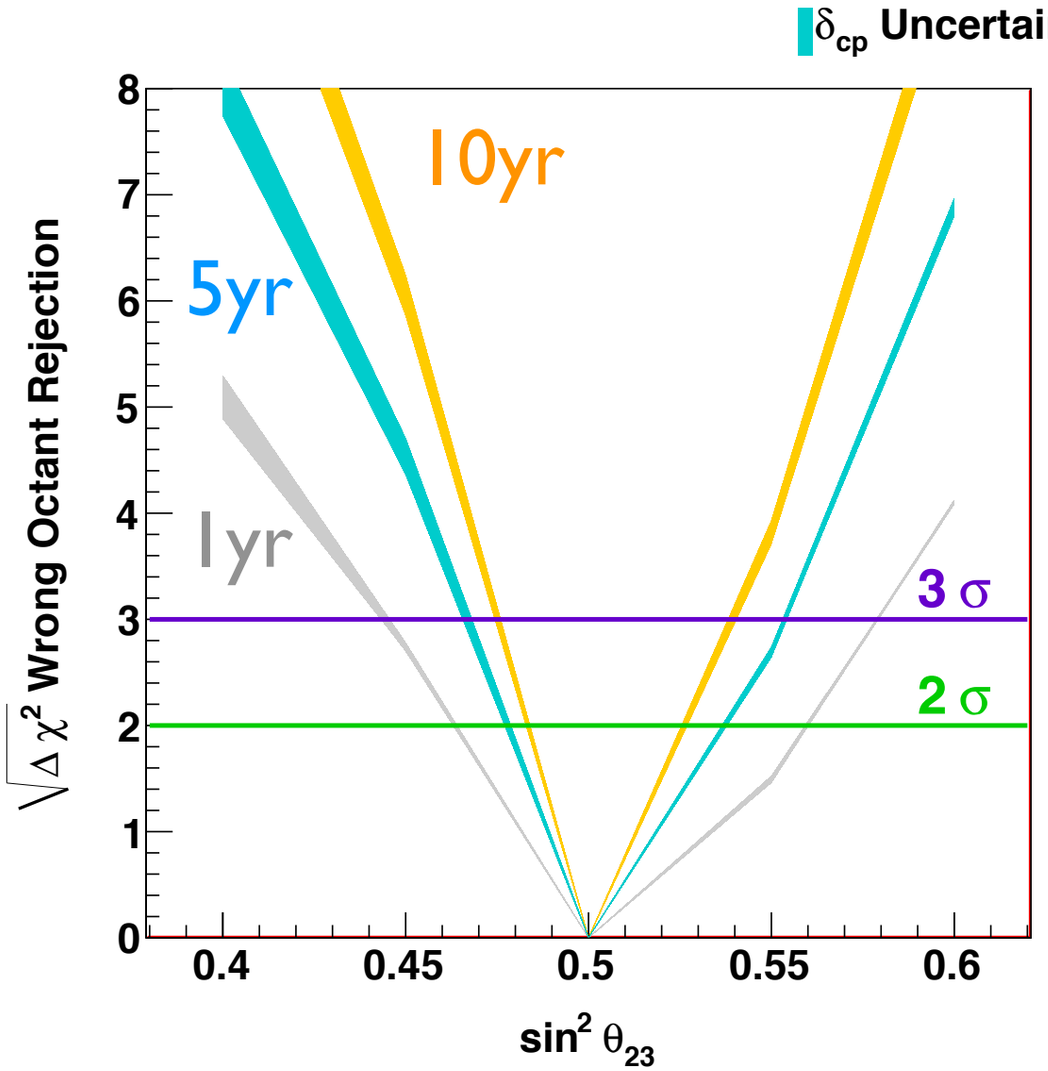




- ~>3σ sensitivity to the mass hierarch with atm ν only
- >3σ octant determination for $|\theta_{23}\text{-}45°|>4°$

Beam + Atm ν



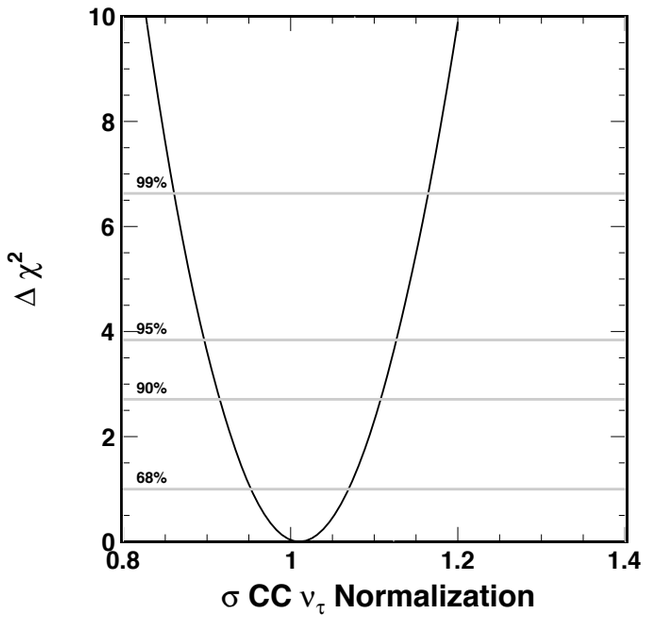


- Complementary information from beam and atm ν
- Sensitivity enhanced by combining two sources!

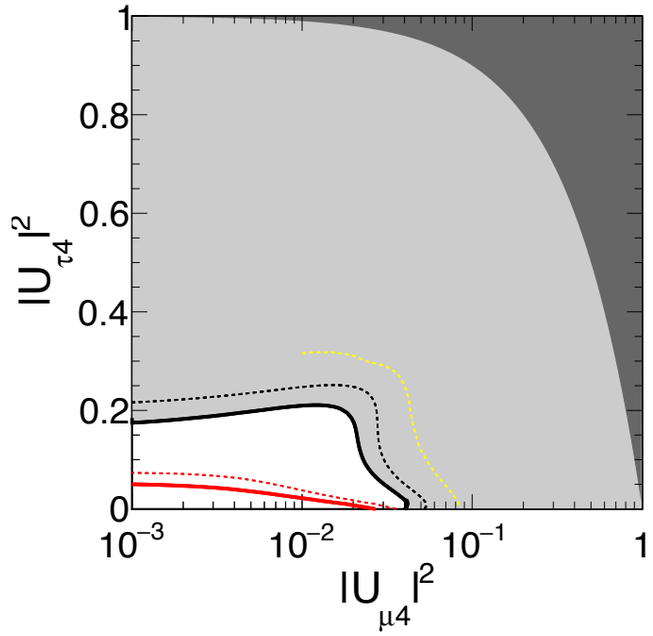
Other science with atm ν

- ν_T cross section measurement
- Sterile neutrino
- Lorentz violation
- Geophysics
  - Information on the chemical composition of Earth's outer core using matter effect

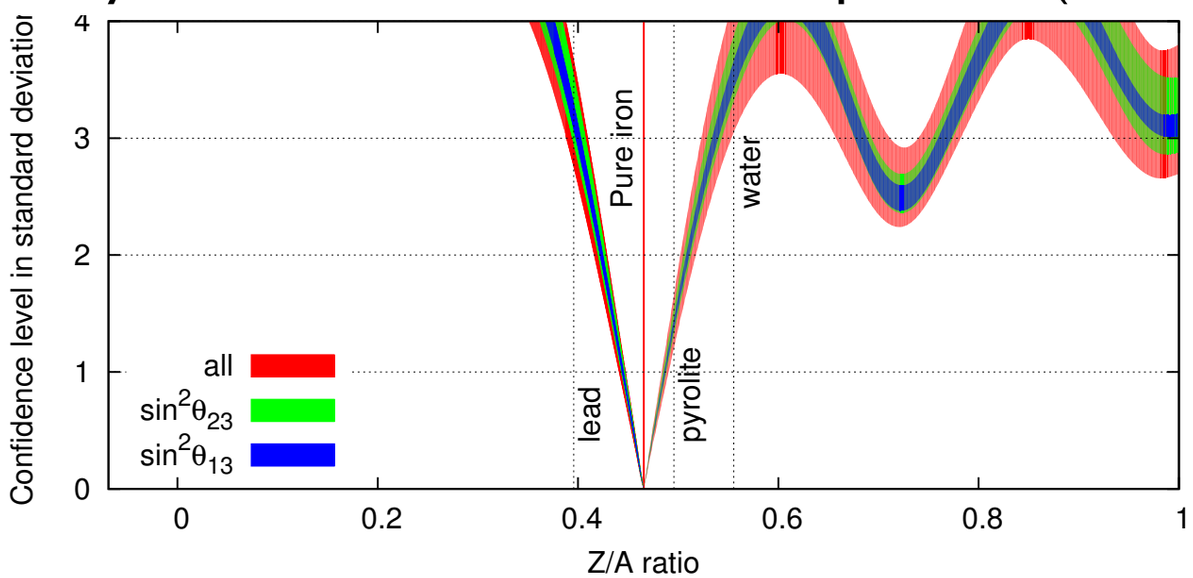
ν_T cross section



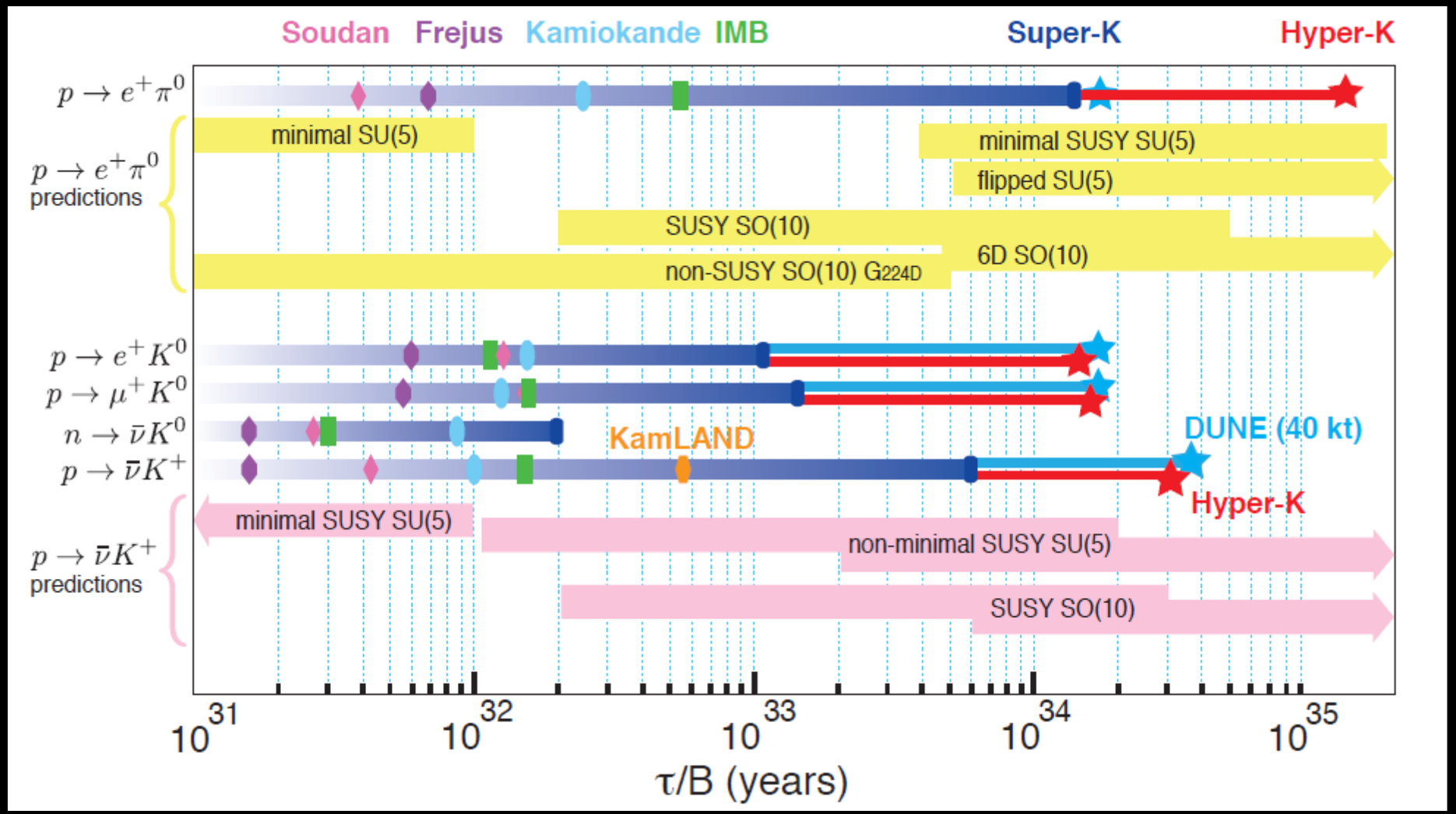
Sterile limit



Sensitivity to outer core chemical composition (10Mtyr)

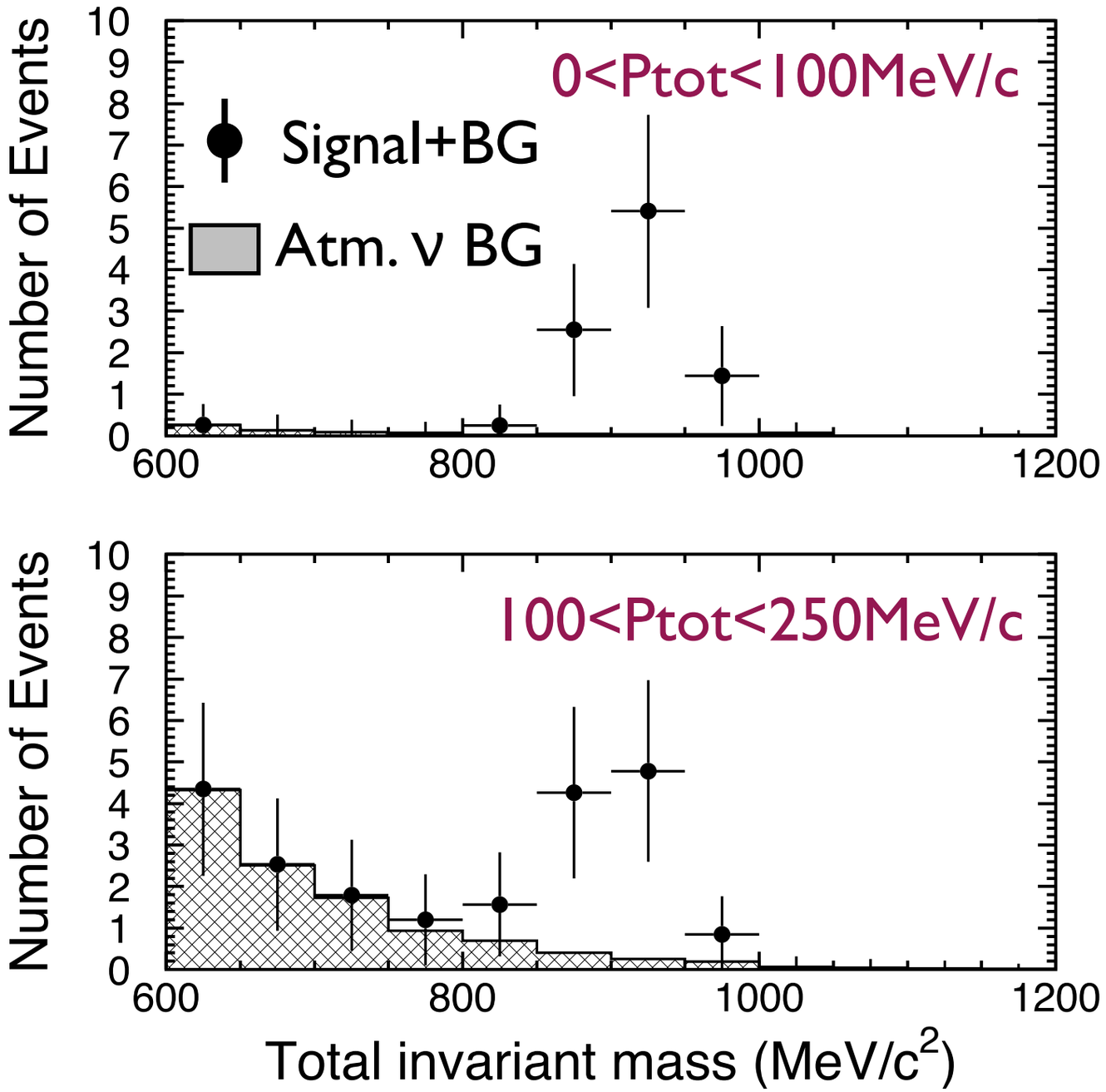


Nucleon Decay Physics Potential



Proton decay signal: $p \rightarrow e^+\pi^0$

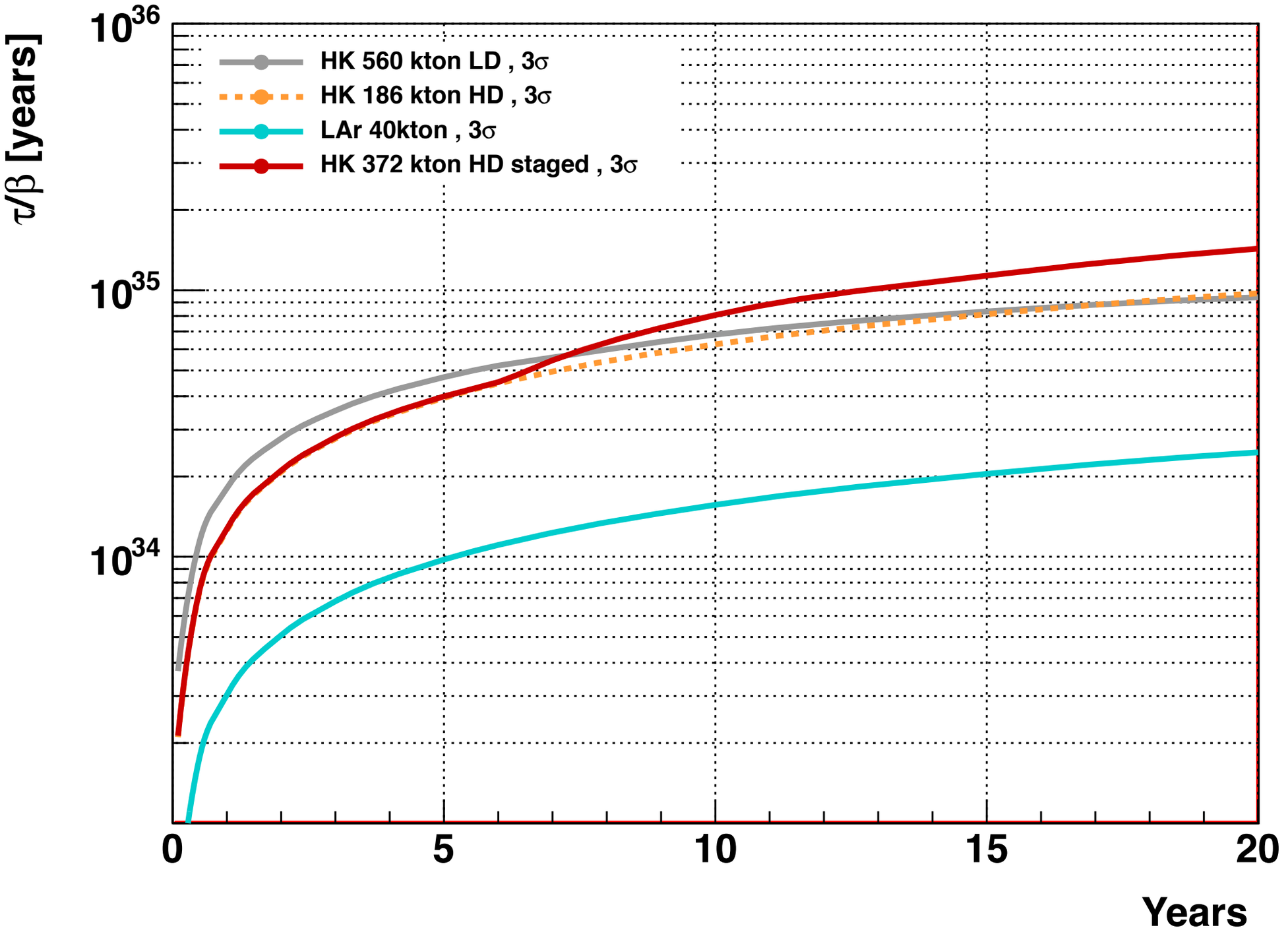
For $\tau p/Br = 1.7\times10^{34}$ years



HK 10 years

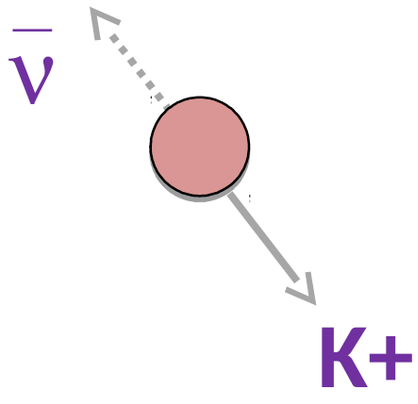
- For lifetime just above the current limit, clear signal can be seen
- Negligible background in the free proton enhanced region
- BG suppression by neutron tagging (thanks to higher photon yield)

$p \rightarrow e^+\pi^0$ sensitivity



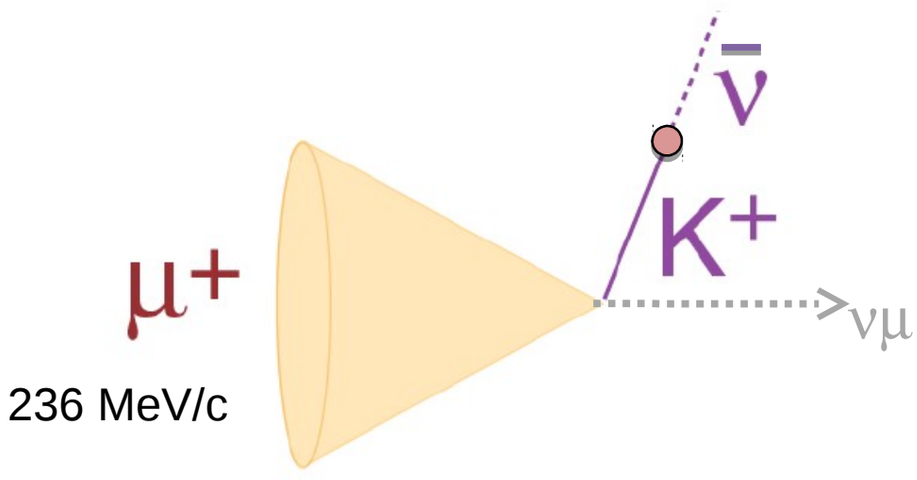
3σ discovery potential reaches ~10^{35} years!

Proton Decay : p → $\bar{\nu}$ K+



- K+ momentum is 340 MeV/c [Cherenkov threshold (749 MeV/c)]
- However, K+ experiences no nuclear interactions and escapes
- Strategy: search for evidence of isolated K+ via its decays
- Cannot reconstruct the original proton mass

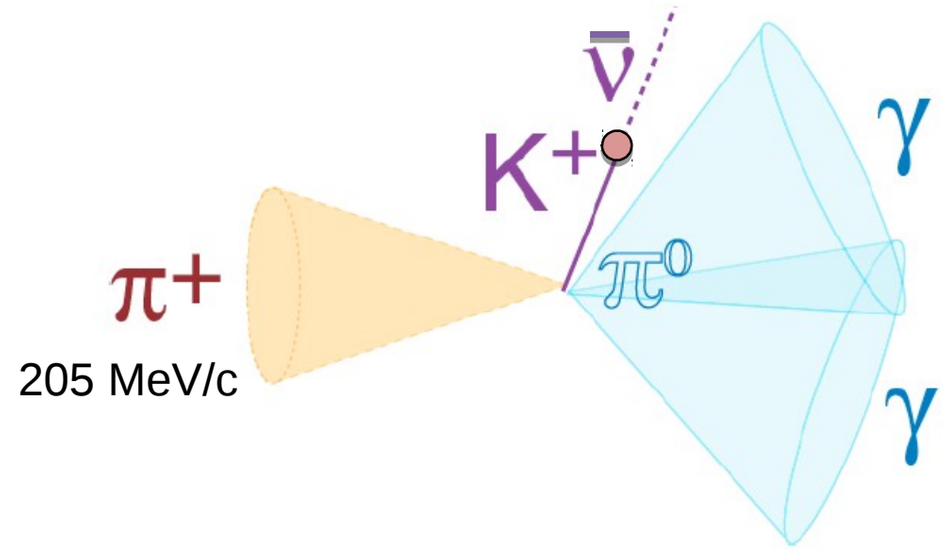
K+ → μ+νμ BR: 65%



Search Methods
- 1) Nuclear deexitation γ, μ, and decay e+
- 2) Monochromatic μ from K+ decay

Faster PMT timing and higher photon yield in the Hyper-K HD design improve signal efficiency

K+ → π+π0 BR: 21%

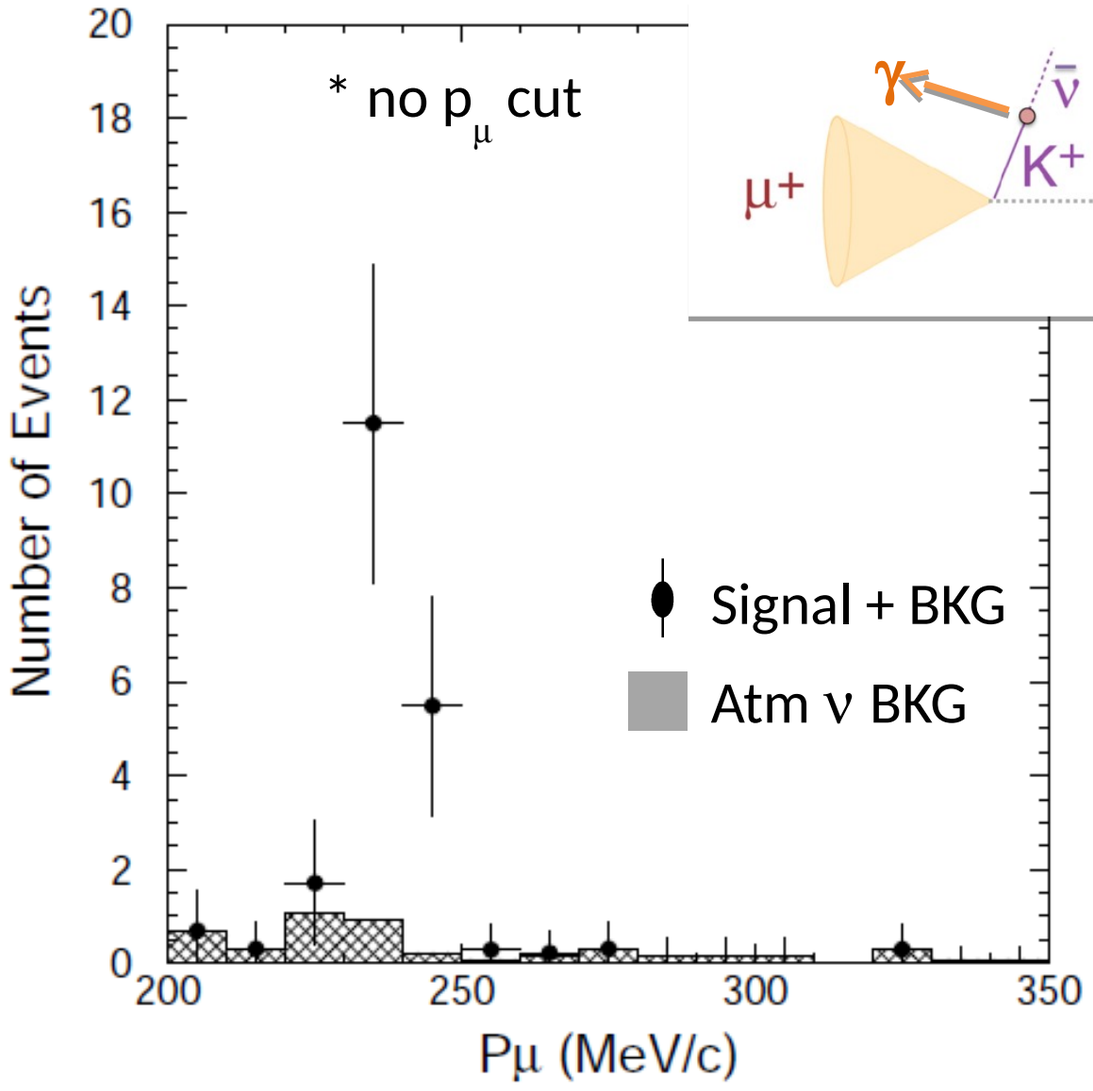


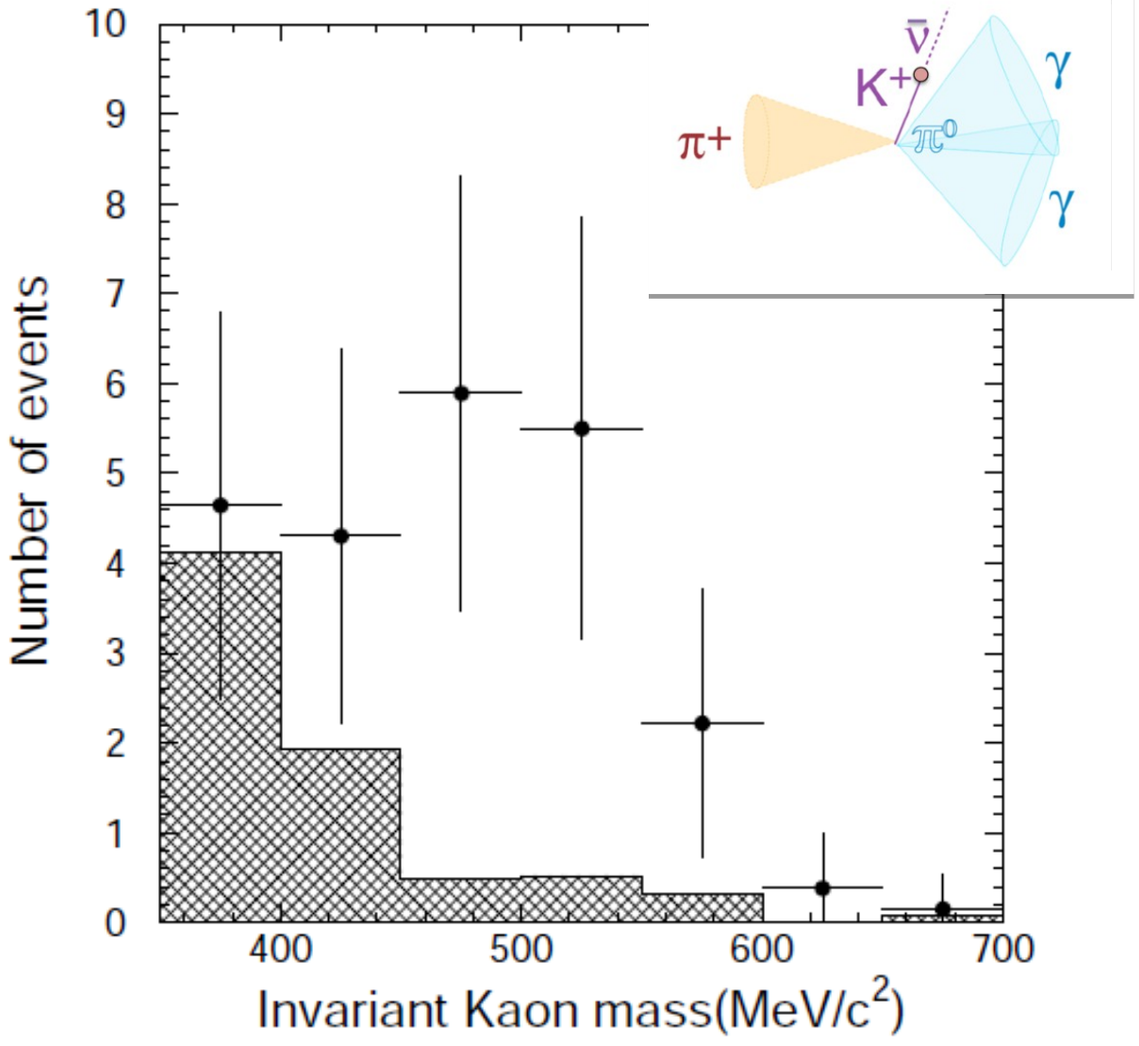
Search Method
- 3) π^+ and two γ from π^0 decay

Borrowed from R.Wendell

Proton Decay at Hyper-K: p → νK+

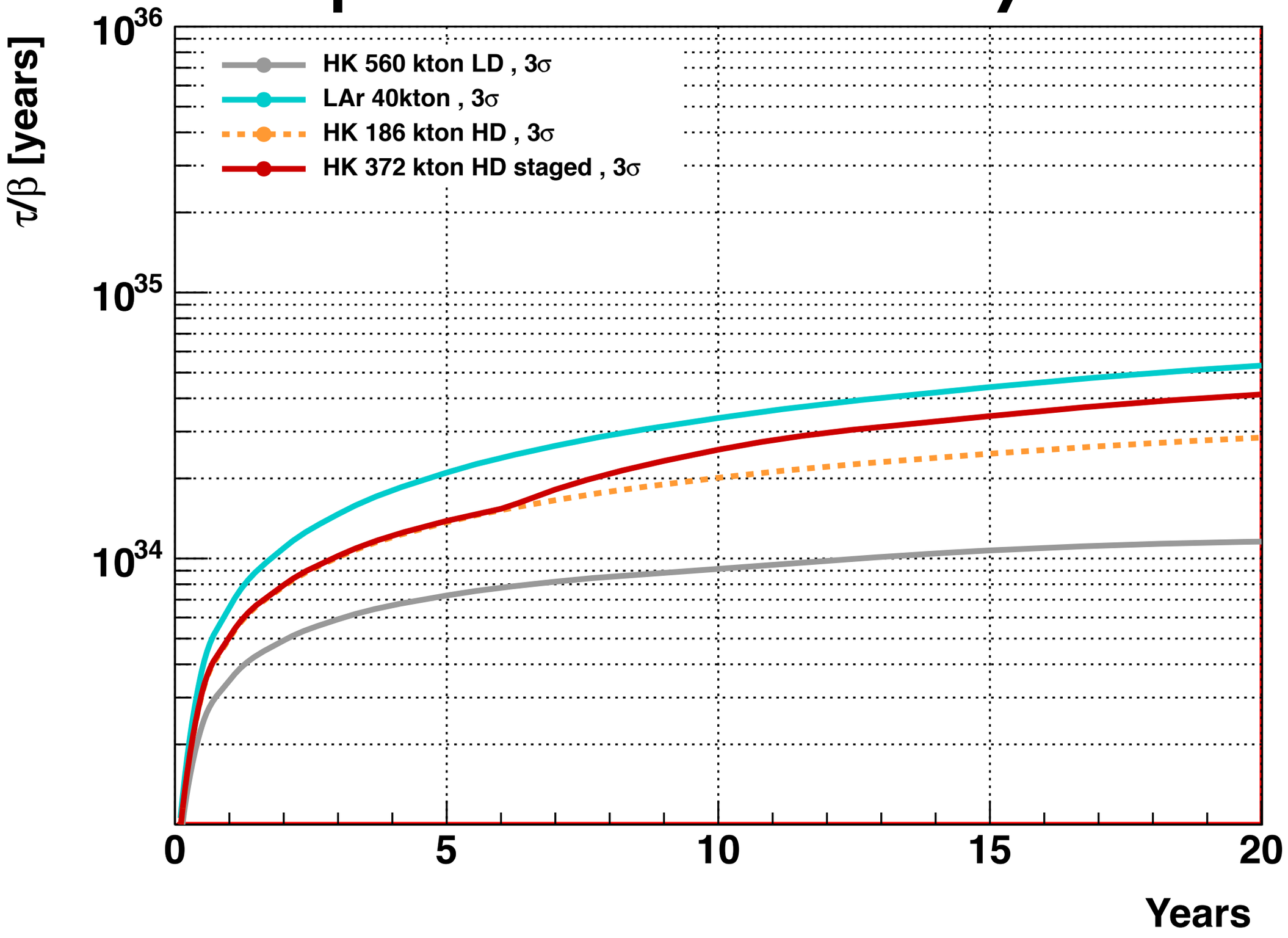
Two HD Tanks, Staged over 10 years





- If proton lifetime is at the current Super-K limit of **6.6×10^{33}** years Hyper-K will observe a nearly monochromatic peak in the momentum distribution of muon candidates tagged with a prompt γ.
- Similarly an excess in the kaon invariant mass distribution will be seen in candidates from the two pion search

$p \to \bar{\nu} K^+$ sensitivity



Sensitivity enhanced by better timing and higher photon yield

Nucleon decay searches

- Will be sensitive to a wide variety of nucleon decay modes
- 3σ potential exceeds current limits by an order of magnitude (or more)

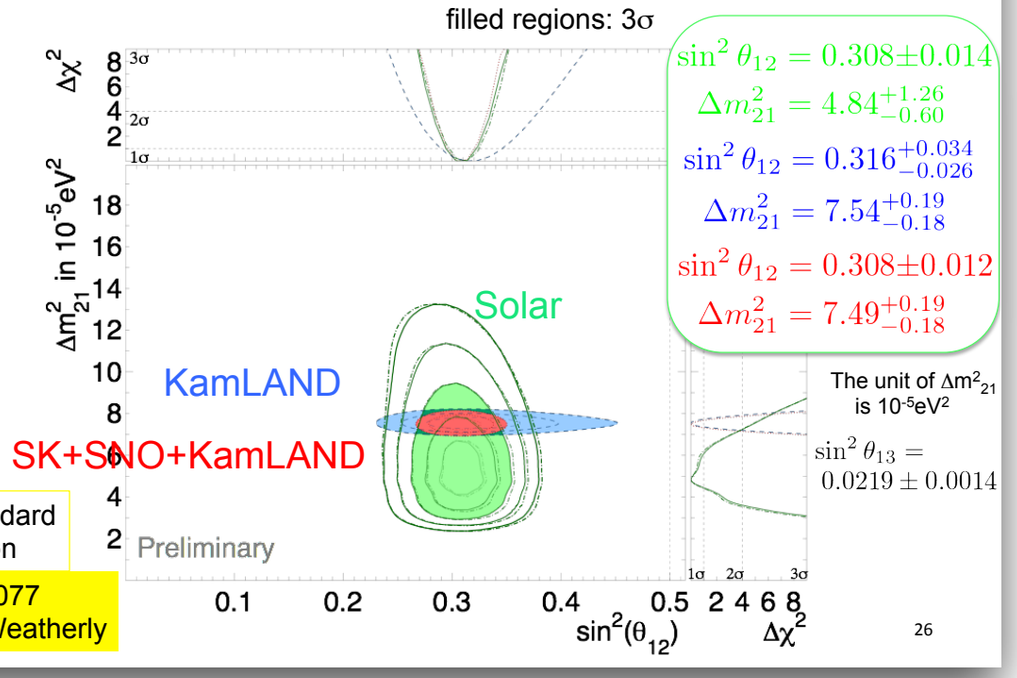
	3σ discovery potential (10yrs)	Current limit (90%CL)
$p \to e^+\pi^0$	8.0×10^{34}	1.4×10^{34}
$p \to \nu K^+$	2.5×10^{34}	0.7×10^{34}
$p \to \mu^+\pi^0$	8.7×10^{34}	1.1×10^{34}
$p \to e^+\eta^0$	4.0×10^{34}	0.4×10^{34}
$p \to \mu^+\eta^0$	8.3×10^{34}	0.1×10^{34}
$n \to e^+\pi^-$	1.7×10^{34}	0.2×10^{34}
$p \to \mu^+\pi^-$	1.1×10^{34}	0.1×10^{34}

Solar neutrino

- Tension between Solar and KamLAND Δm^2_{21}
- Definite observation of D/N asymmetry

Solar vs. KamLAND

The SK spectrum and D/N data favor a lower Δm^2_{21} value than KamLAND's by more than 2σ and mostly determine this parameter in the solar ν oscillation fit.

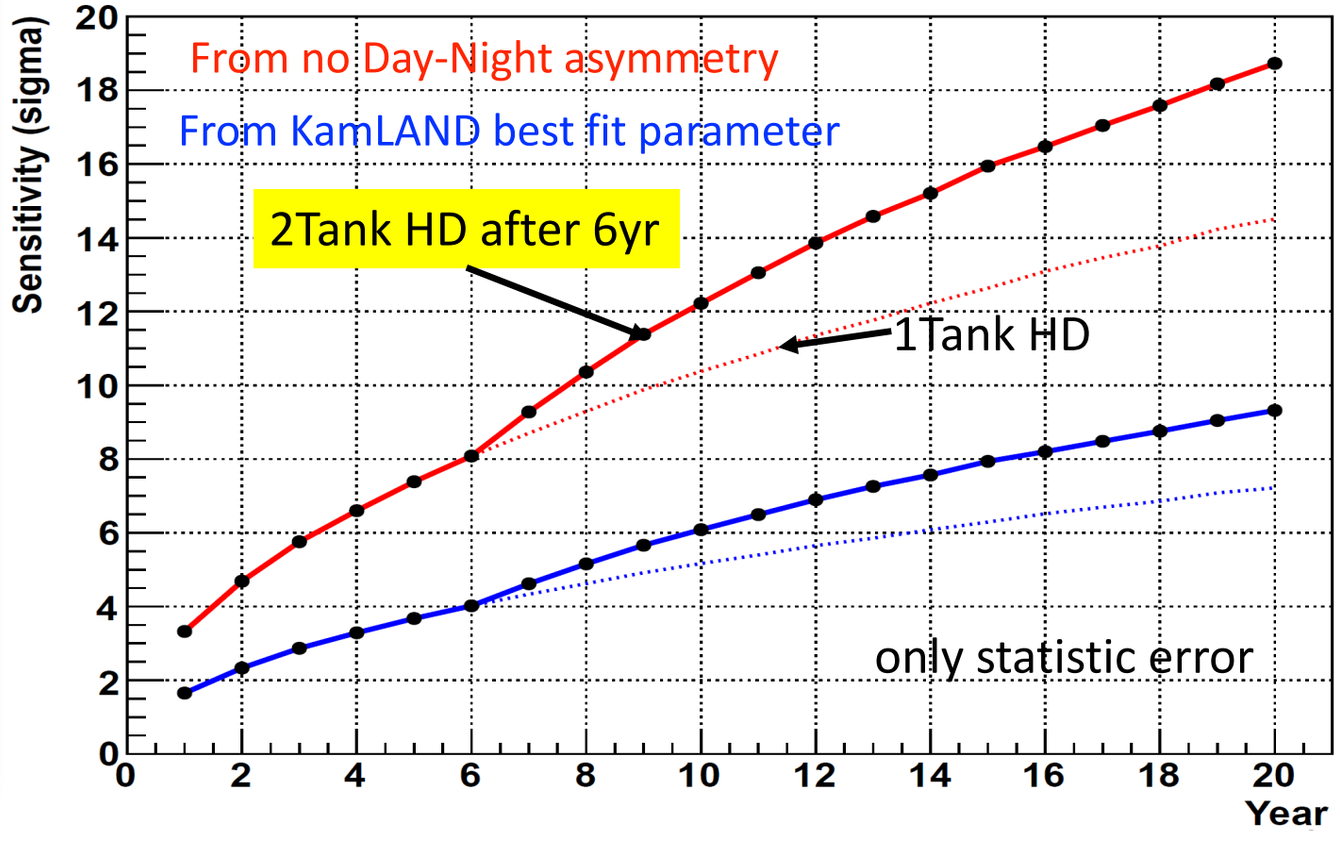


Non standard interaction

See P3.077 Pierce Weatherly

26

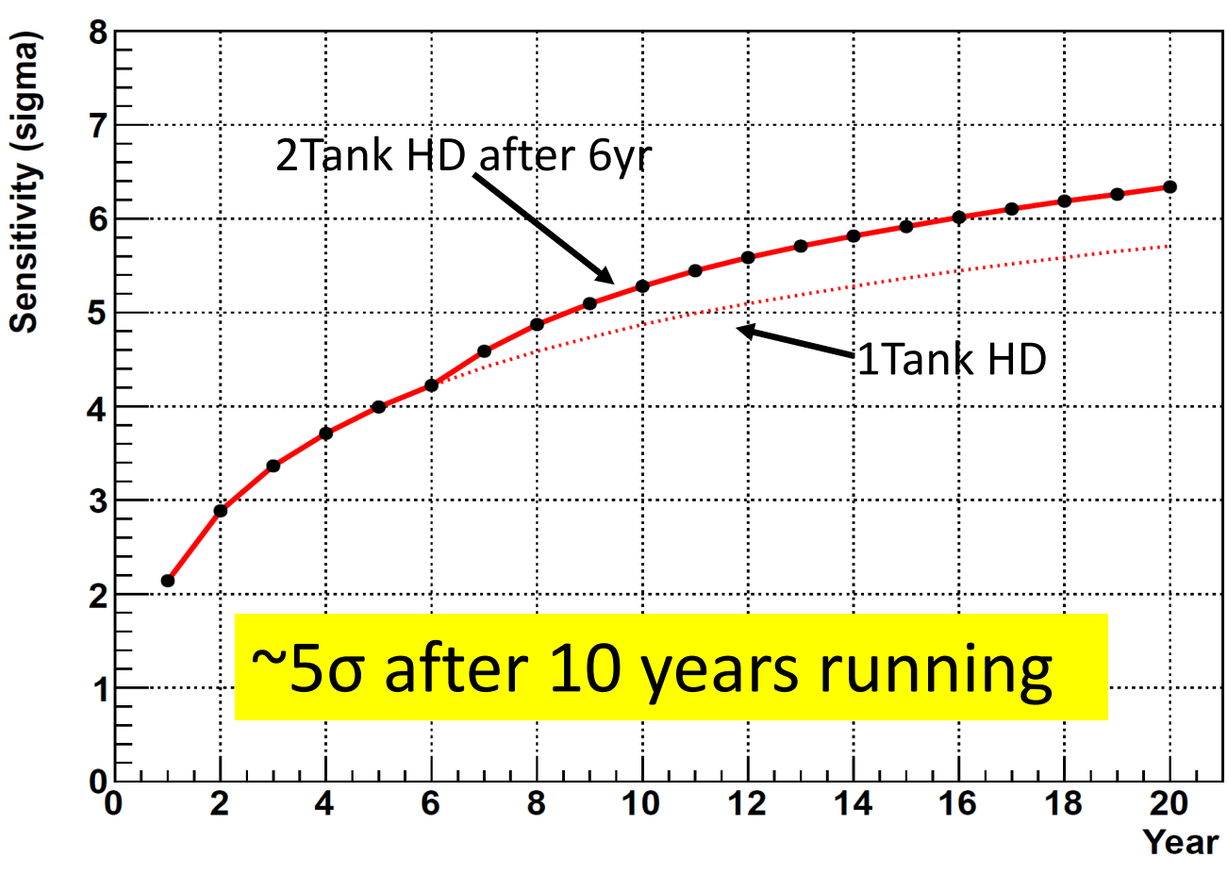
Day/night asymmetry sensitivity



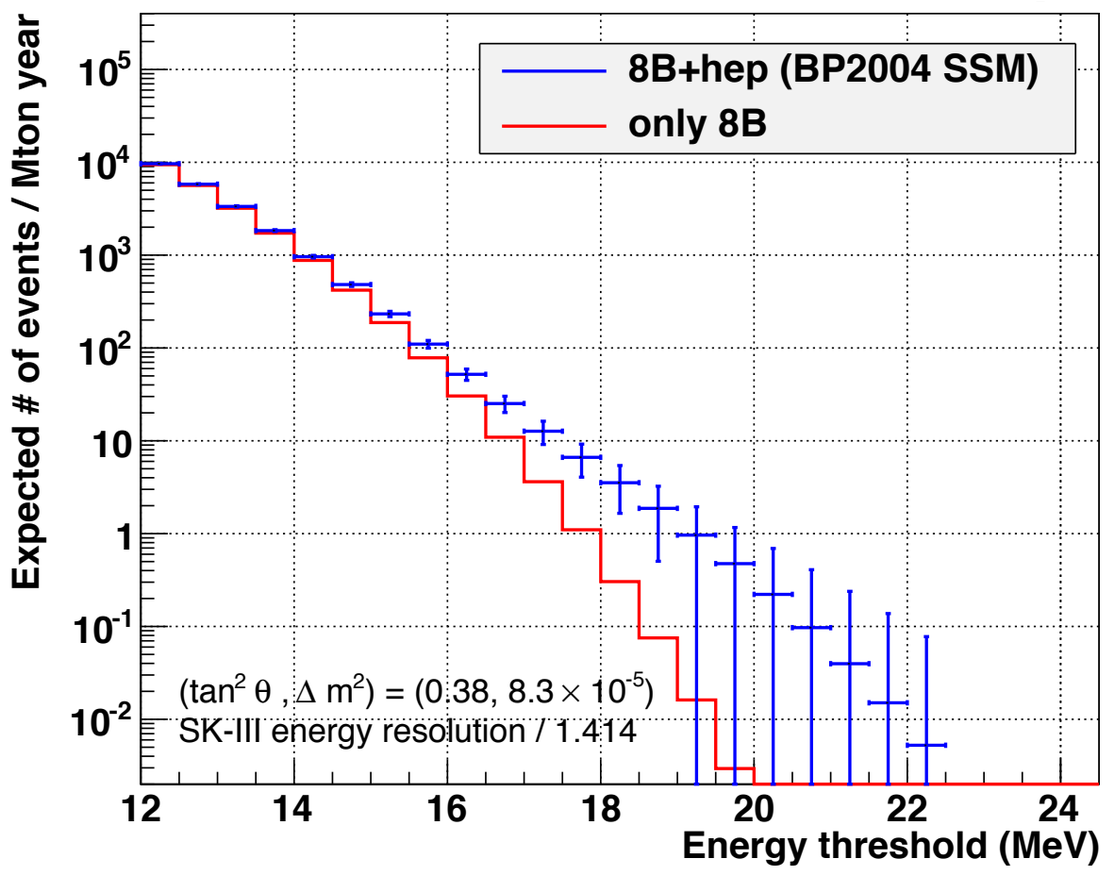
Solar neutrino

- Observation of spectrum upturn to check MSW in Sun
- Observation of hep neutrino: new probe to inside Sun
- Good energy resolution (high performance sensor) and calibration necessary

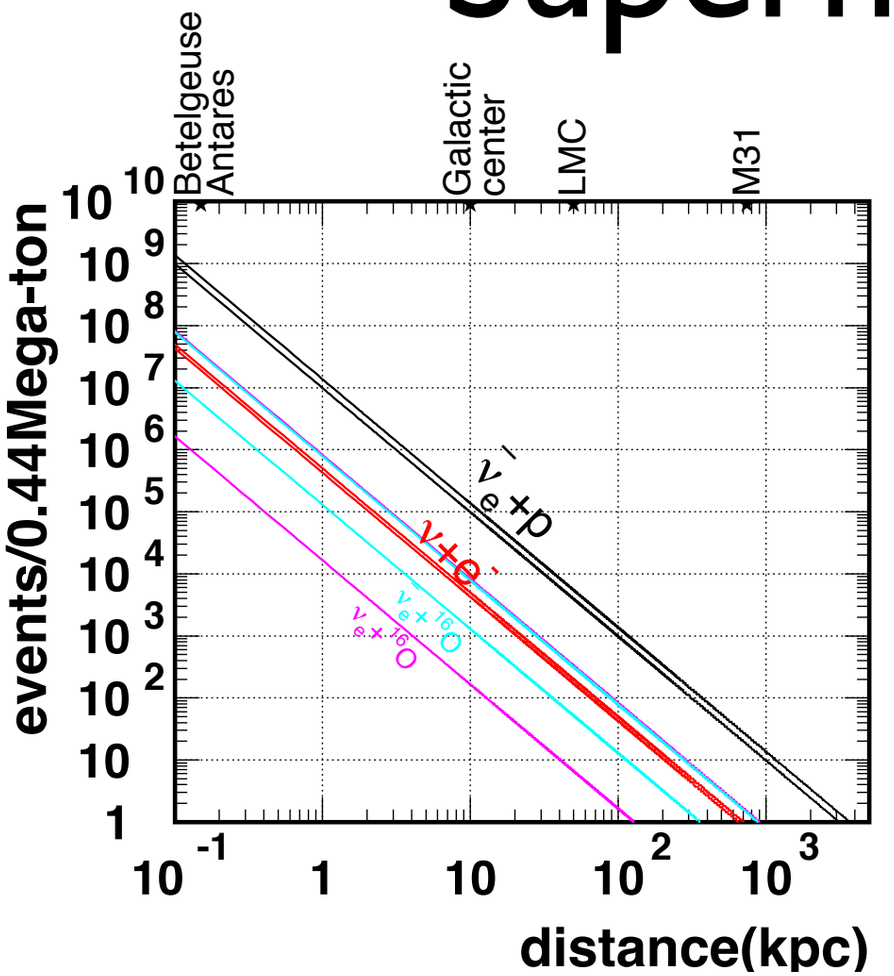
Spectrum upturn sensitivity

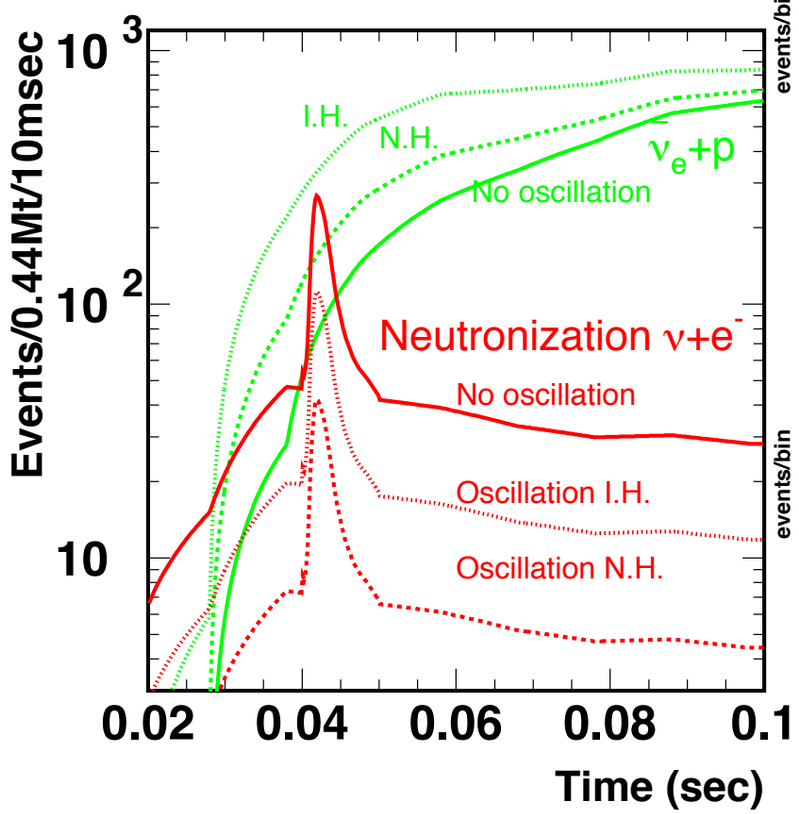


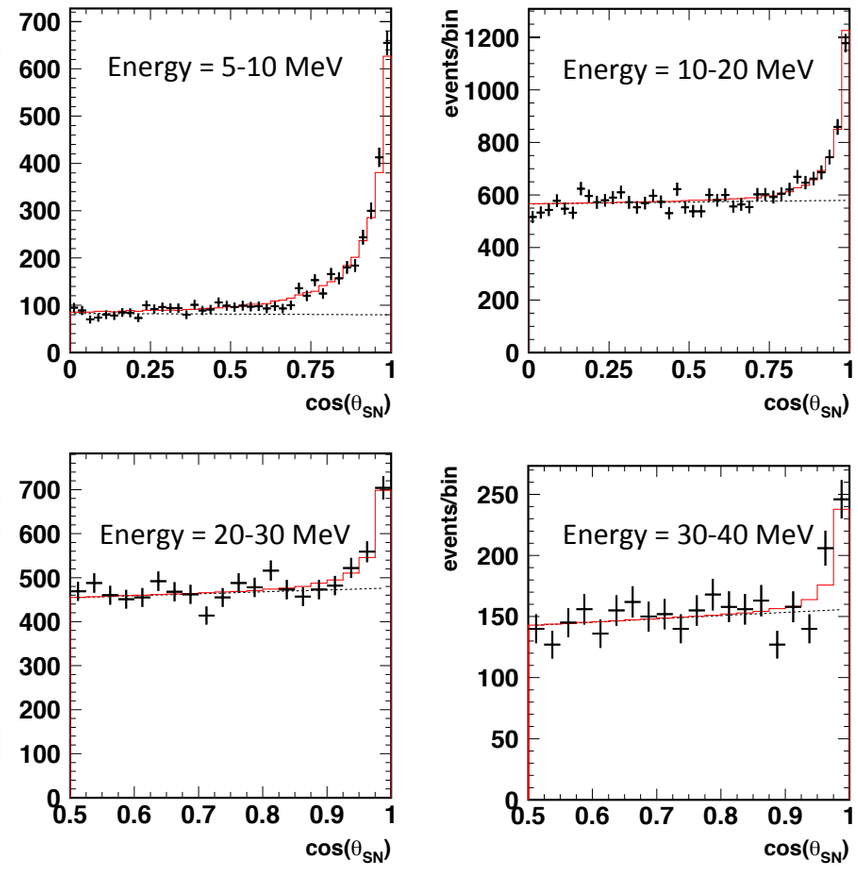
Possible observation of hep ν



Supernova burst neutrino

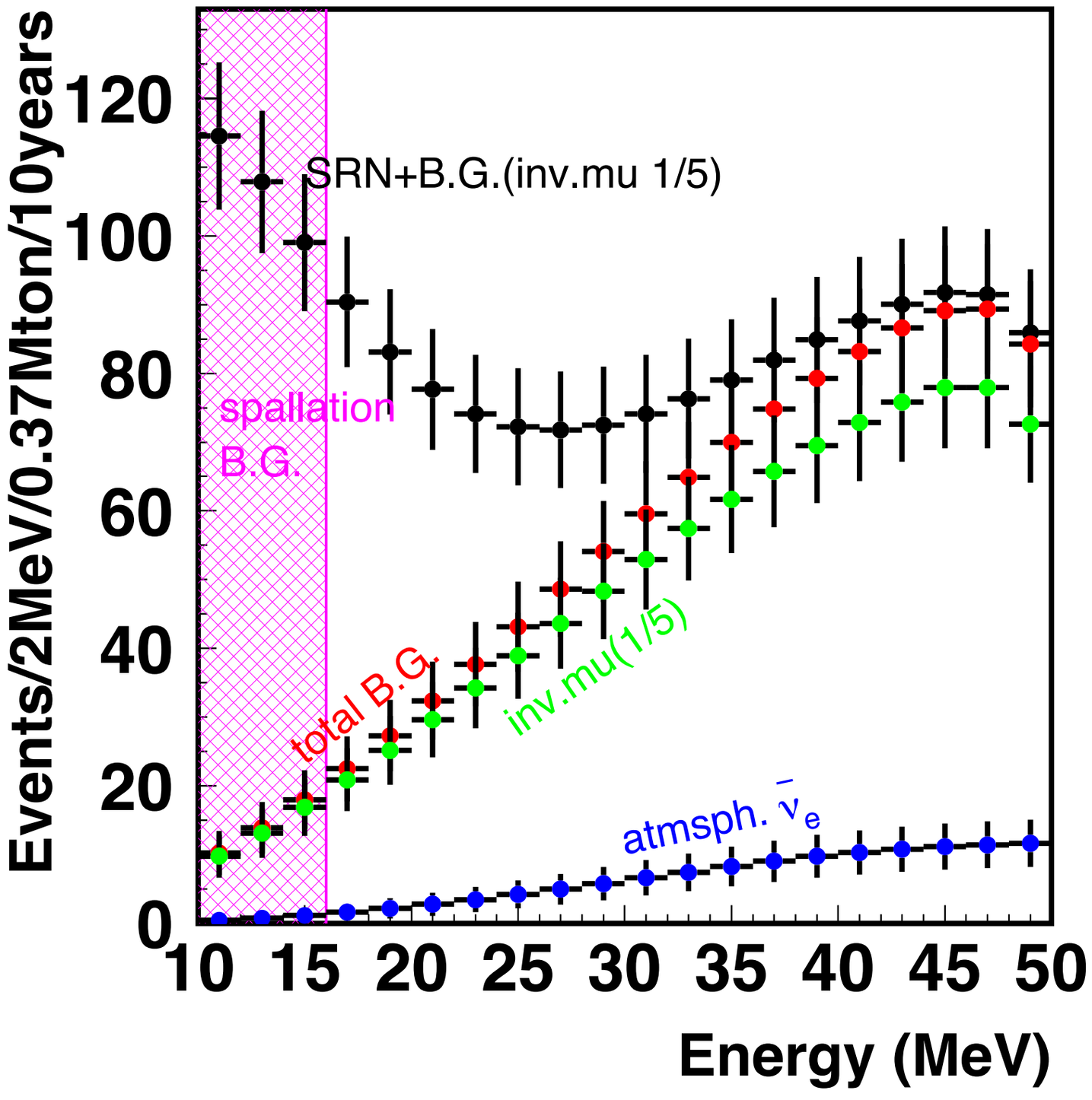






- Large statistics for galactic SN
  - Precise timing and energy information to probe SN mechanism
  - Pointing (2deg@10kpc) and timing for multi-messenger astronomy
- Nearby (>1Mpc) SN
  - Check of dim SN, coincidence with GW telescope, …

SN relic neutrinos

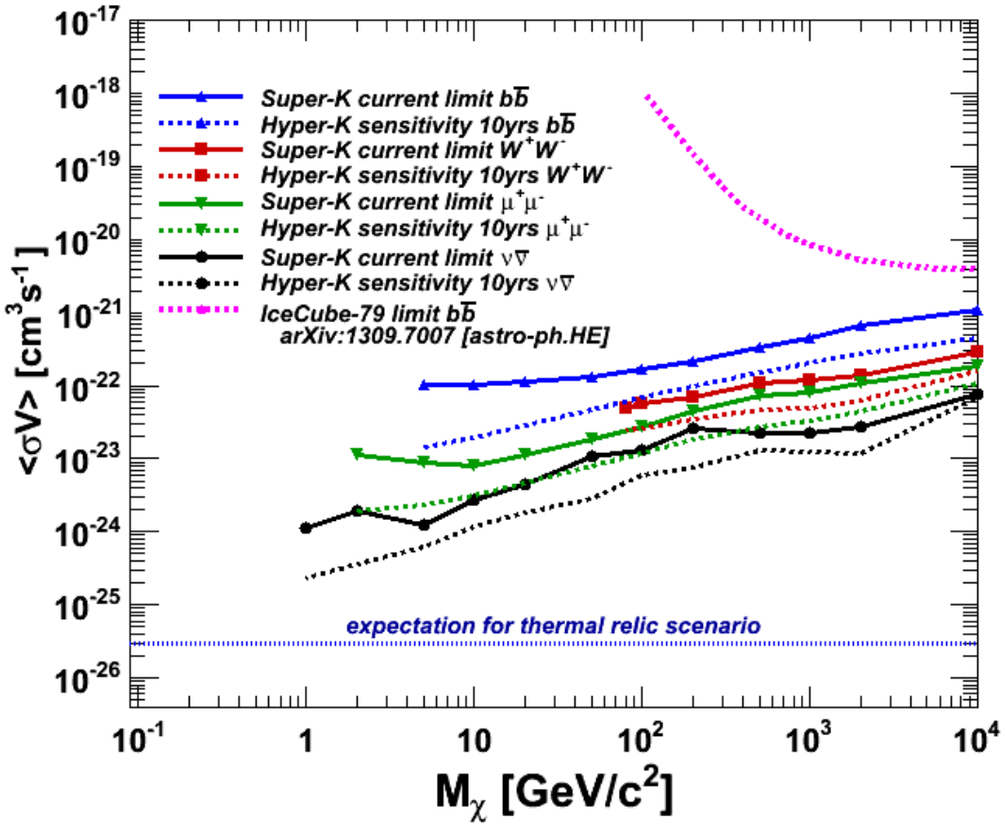


- Diffuse ν from past SN
  - 98±20 events (4.8σ) expected in 10 years
- Measurement will provide information on history of stars

Indirect DM searches

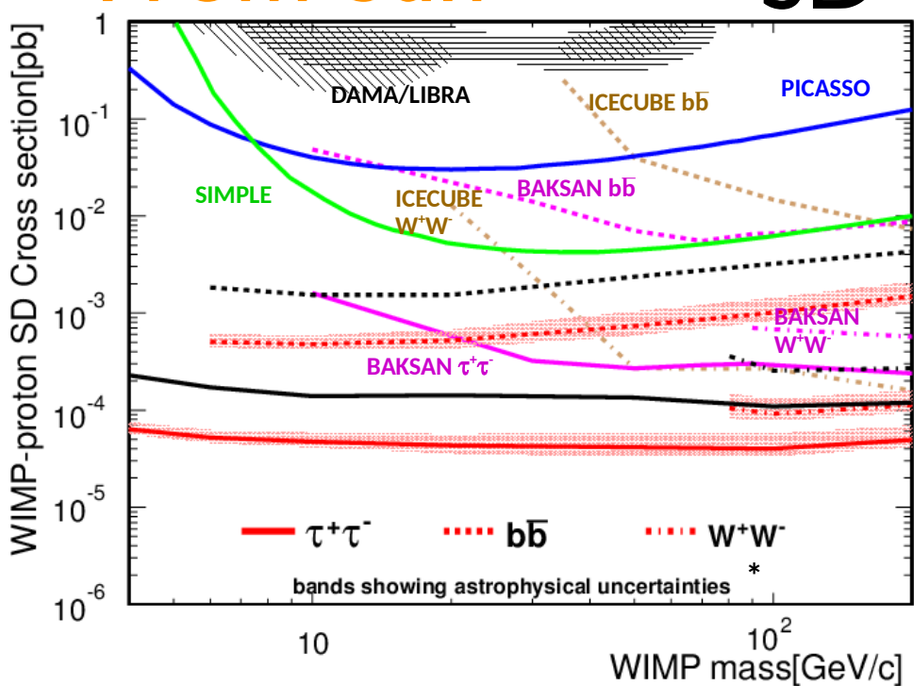
- Unique sensitivities, especially for low mass region
- Improve ×3-10 over SK limit

From Galactic center

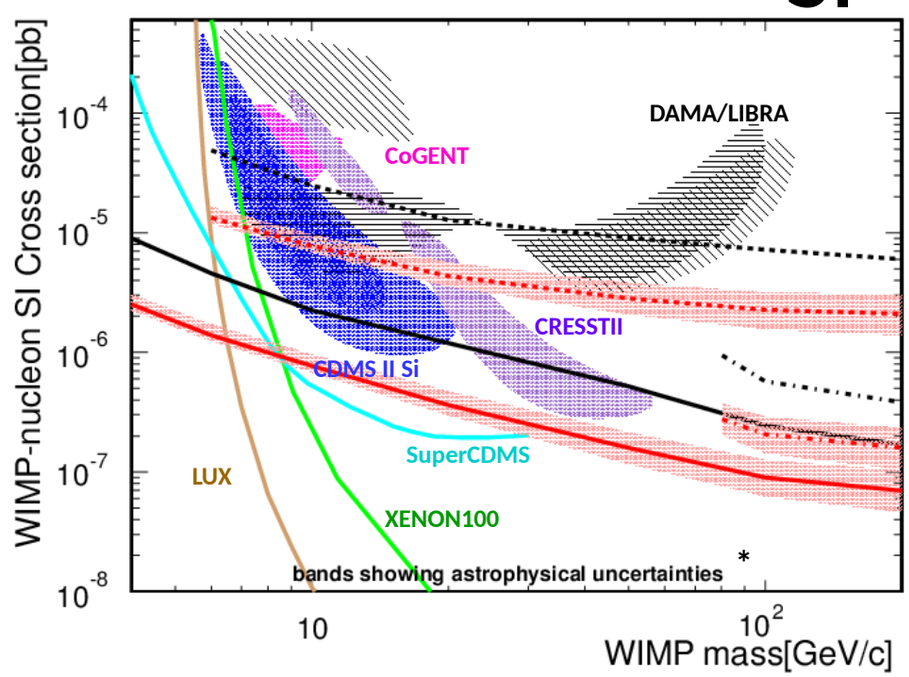


From Sun

SD



SI



Summary of physics potential

		2TankHD w/ staging
LBL (13.5MWyr)	δ precision	7°-21°
	CPV coverage (3/5σ)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MH determination	>5.3σ
	Octant ($\sin^2\theta_{23}$=0.45)	5.8σ
Proton Decay (10 years)	$e^+\pi^0$ 90%CL	1.2×10^{35}
	νK 90%CL	2.8×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	6σ/12σ
	Upturn	4.9σ
Supernova	Burst (10kpc)	104k-158k
	Nearby	2-20 events
	Relic (10 yrs)	98evt/4.8σ

Conclusion

- HK has huge potential for a wide range of science
- Yet we want to further strengthen our science case
  - Beyond discovery of CPV; What can we learn?
    - Optimization of the second tank? (see also next talk)
    - Non-standard scenarios? Sensitivity?
    - Broader science topics? Additional detector capability?
    - ….
- We will welcome your ideas and participation!

Backup

Advertisement

- There are openings for postdoctoral researcher positions on HK/SK and on T2K at U.Tokyo group (M.Yokoyama)

  1. R&D of HK, as well as the physics sensitivity studies of HK and/or the analysis of data from ongoing experiments using the Super-K detector.

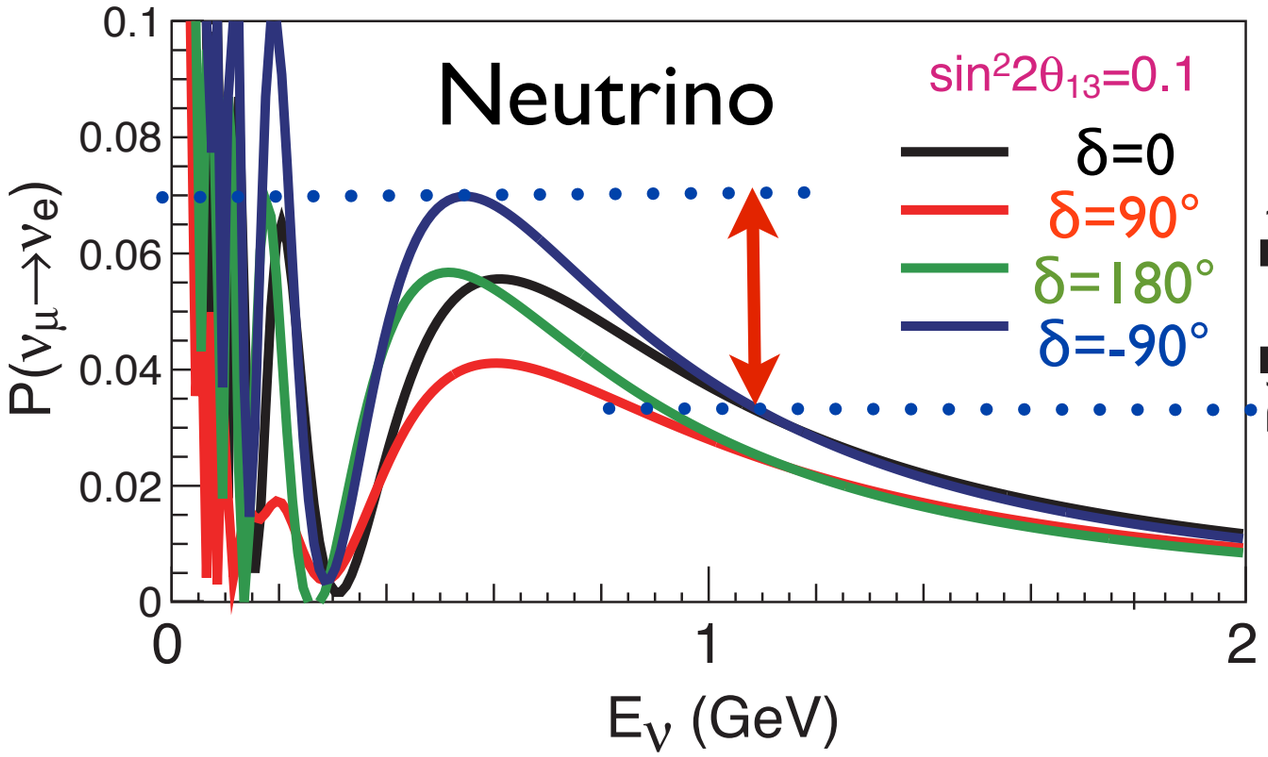
  2. R&D of T2K ND upgrade and data analysis of T2K.

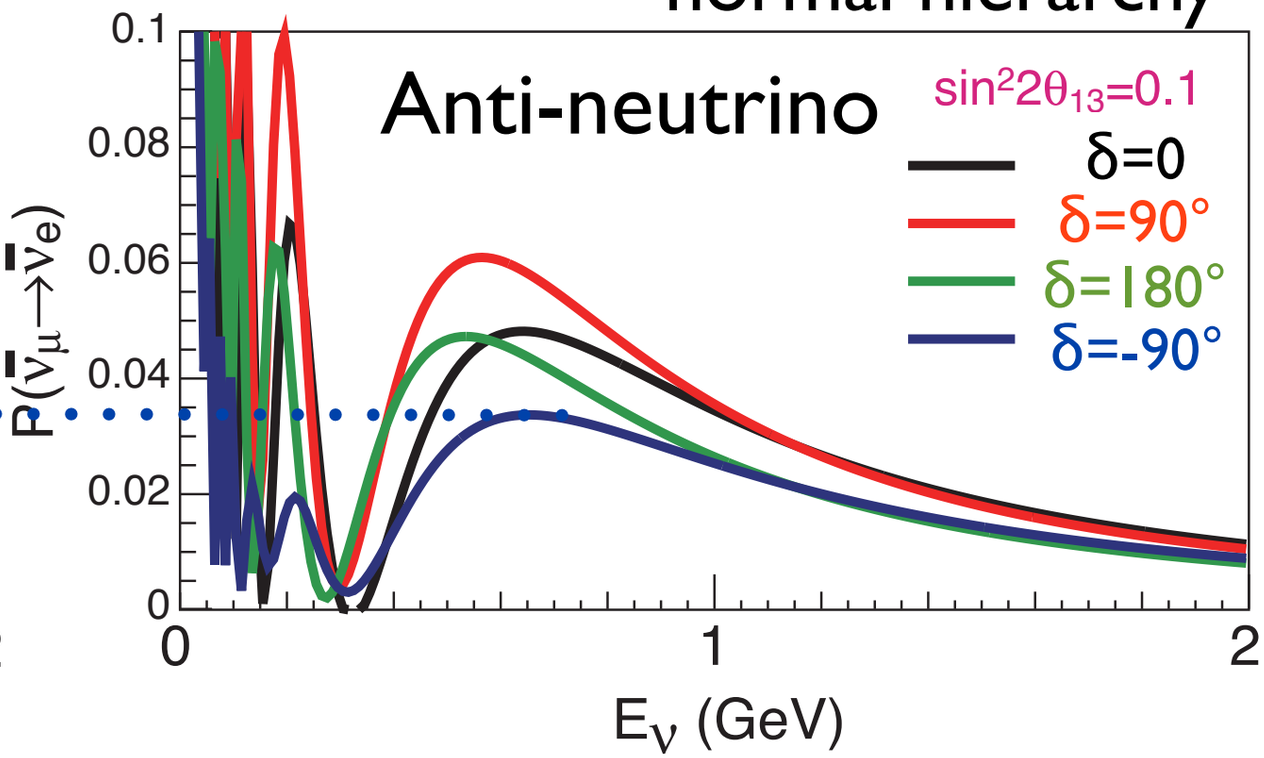
- If there is someone interested, please contact Yokoyama (masashi@phys.s.u-tokyo.ac.jp) ASAP.

Measurement of *CP* asymmetry with ν beam

$P(\nu_\mu \rightarrow \nu_e)$: ν_e appearance probability

for 295km baseline,
normal hierarchy





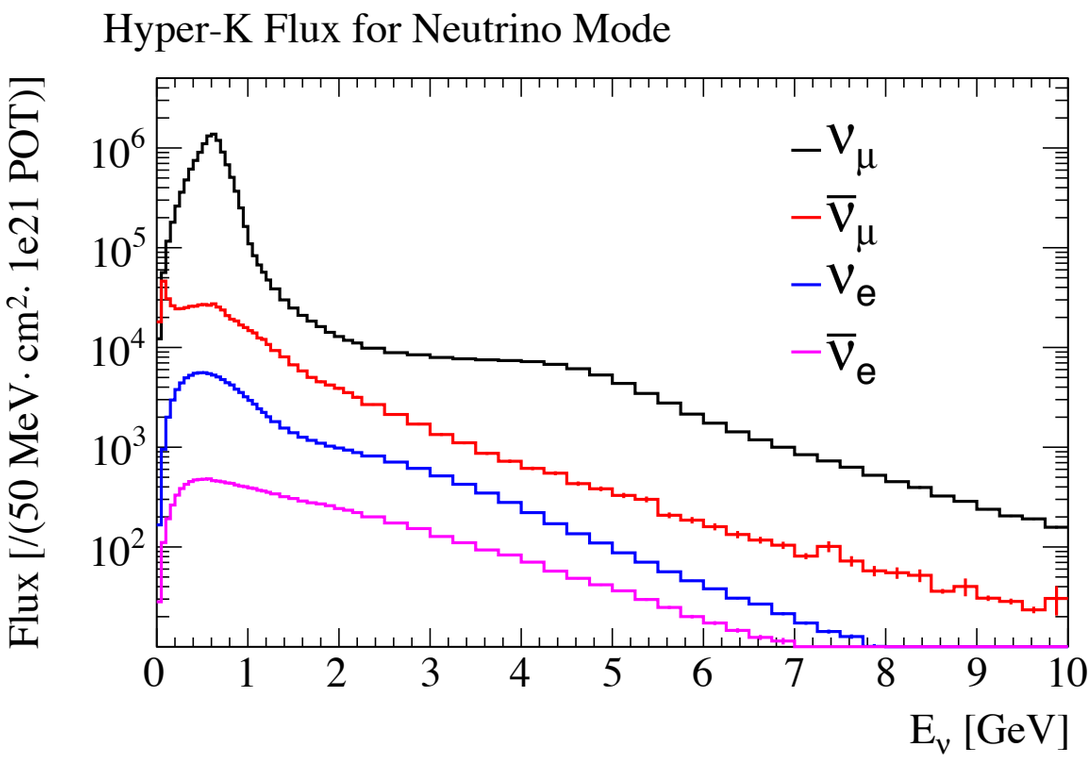
- Comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - Max. ~±25% change from δ=0 case
  - Sensitive to exotic (non-MNS) CPV source

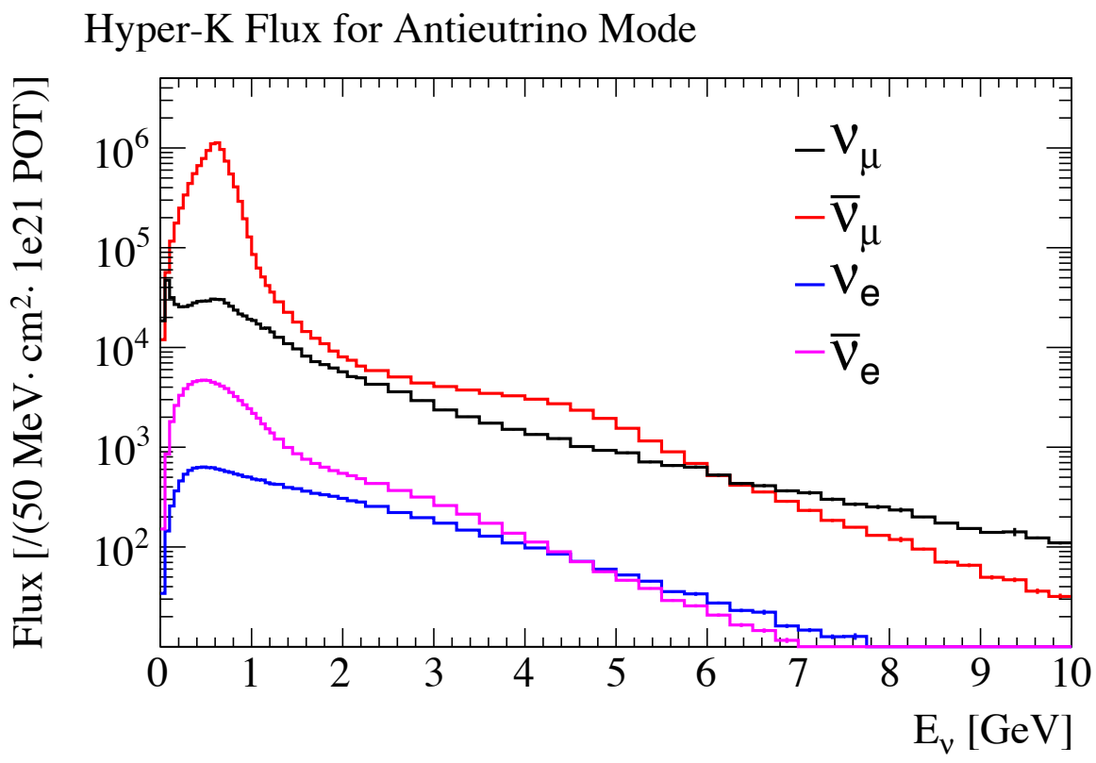
Strength of Hyper-K

- Best sensitivity for CP measurement
  - Relatively short baseline (~300km): less matter effect
  - Off axis beam at 1st oscillation maximum
- Large statistics with good S/N
  - ~2000 appearance signal events expected
  - S/N~10 at appearance peak
- Performance proven with real data
  - Building on experience from T2K/Super-K
  - Further improvement expected as we go

Neutrino energy spectrum

- Well understood by NA61@CERN and T2K
- Anti-ν flux ~80% of ν @peak
  - π production multiplicity
  - Of course, cross section on nucleus differs (by ×~3)
- Beam time ratio of ν:$\bar{\nu}$=1:3 is assumed in sensitivity study
  - Different ratio studied but dependence not large for CPV sensitivity

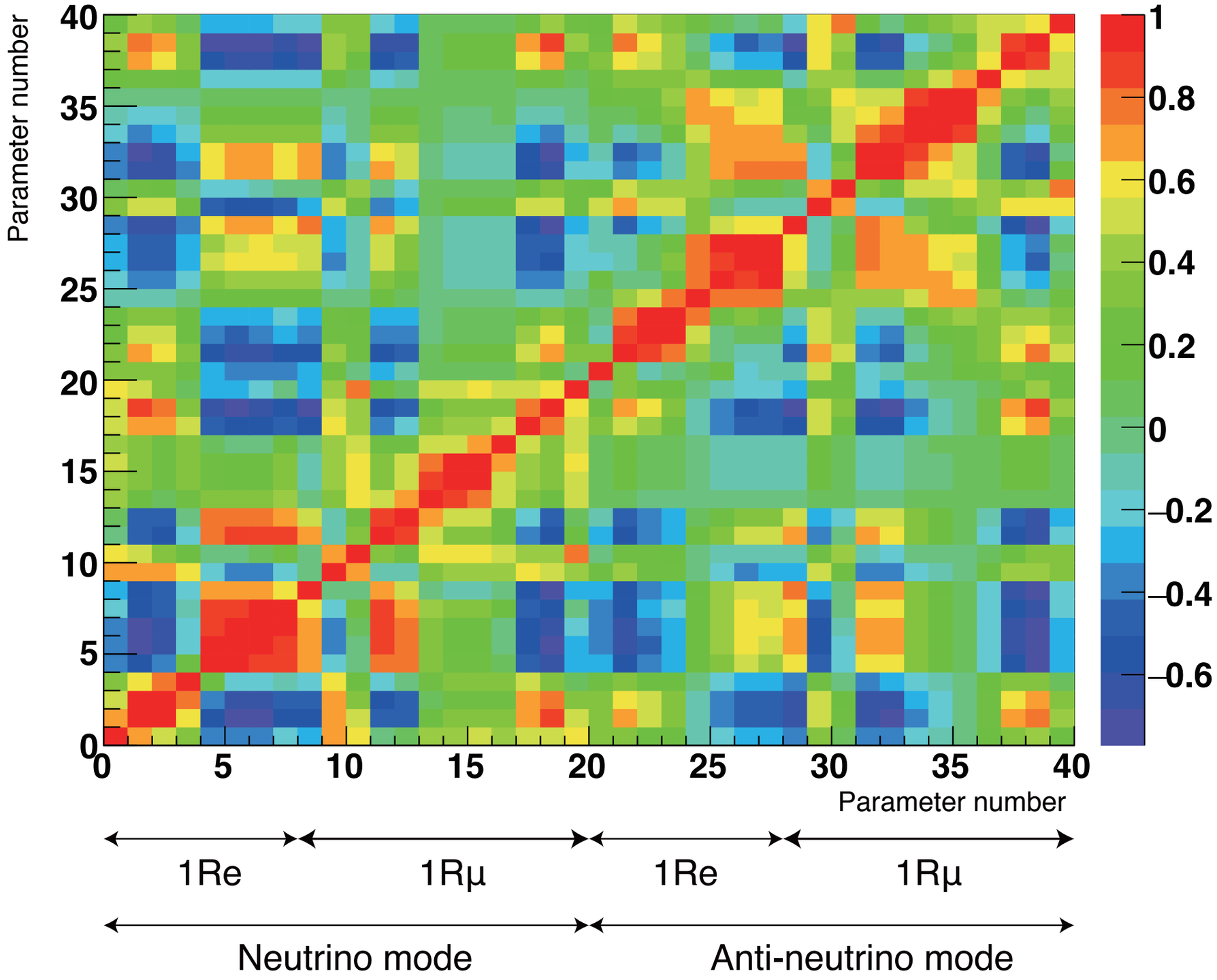




Sensitivity study

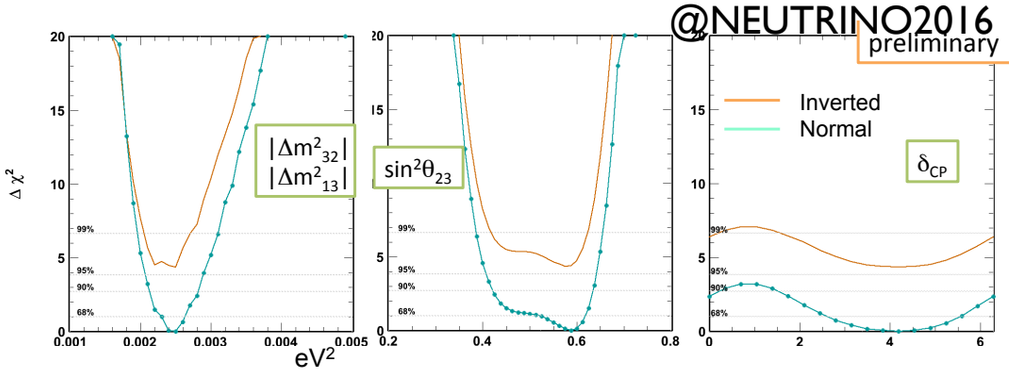
- Based on a framework developed for T2K future sensitivity study (PTEP 2015, 043C01)
  - Fit reconstructed E_ν distributions
  - Both ν_e and ν_μ samples, for ν and anti-ν run
  - Fit $\sin^2\theta_{23}$, Δm^2_{32}, $\sin^2 2\theta_{13}$, δ_{CP}
  - Mass hierarchy assumed to be known
    (from other experiments and/or HK atmospheric ν)
- Systematic error estimated based on T2K experience/prospects
  - Implemented as covariance matrix, including correlation between energy/flavor bins
  - Compared to published (PTEP 2015, 053C02) result which used a conservative estimate, anti-ν error is improved based on progress in T2K anti-ν data analysis
- Assuming 2Tank HD staging (2nd tank from 7th year), 10 years total run

Correlation matrix

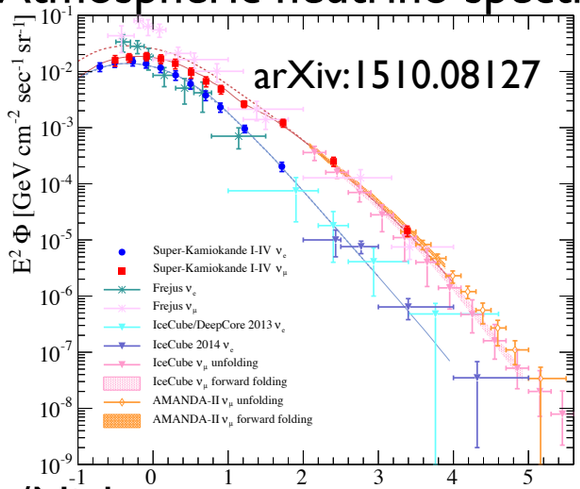


(Part of) recent results using Super-K

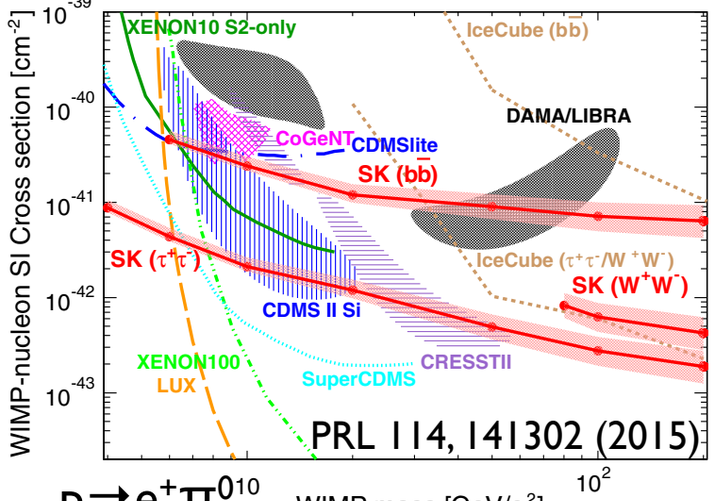
Atmospheric neutrino oscillation



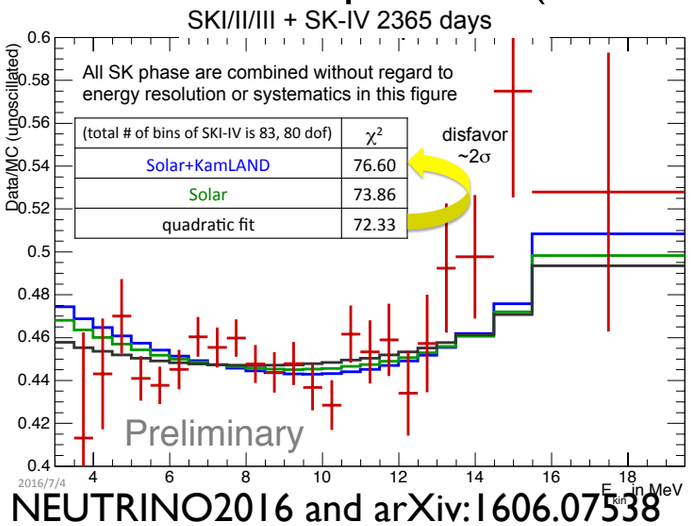
Atmospheric neutrino spectrum



Indirect DM search

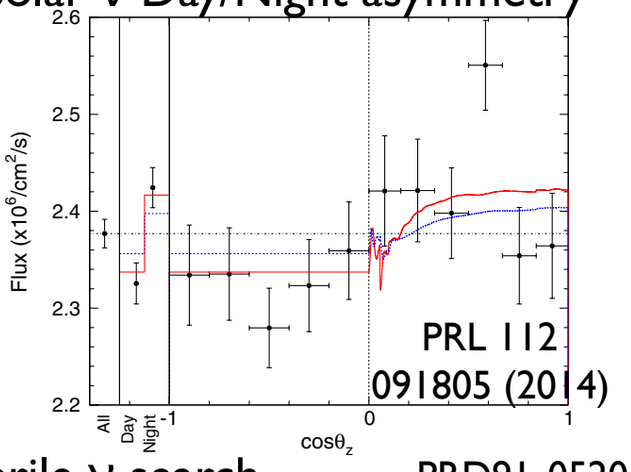


Solar neutrino spectrum (E_{kin}>3.5MeV)

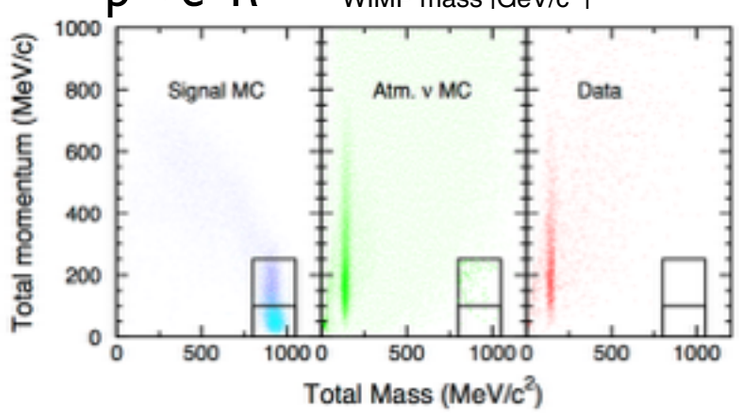


NEUTRINO2016 and arXiv:1606.07538

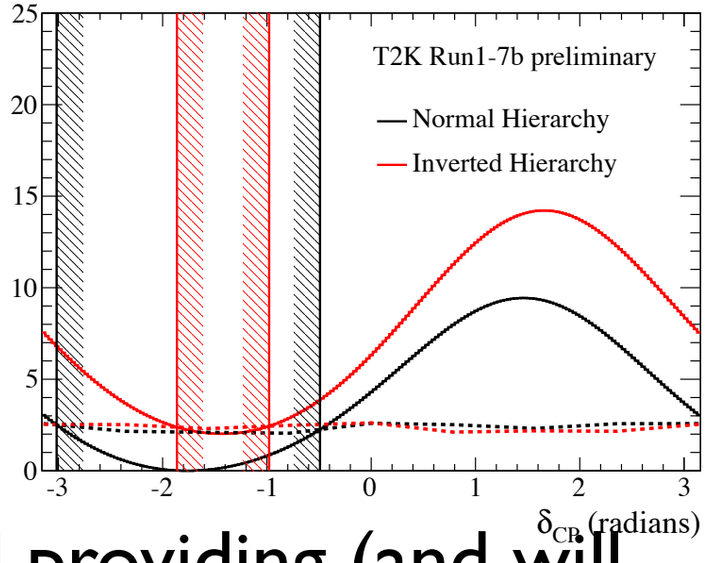
Solar ν Day/Night asymmetry



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

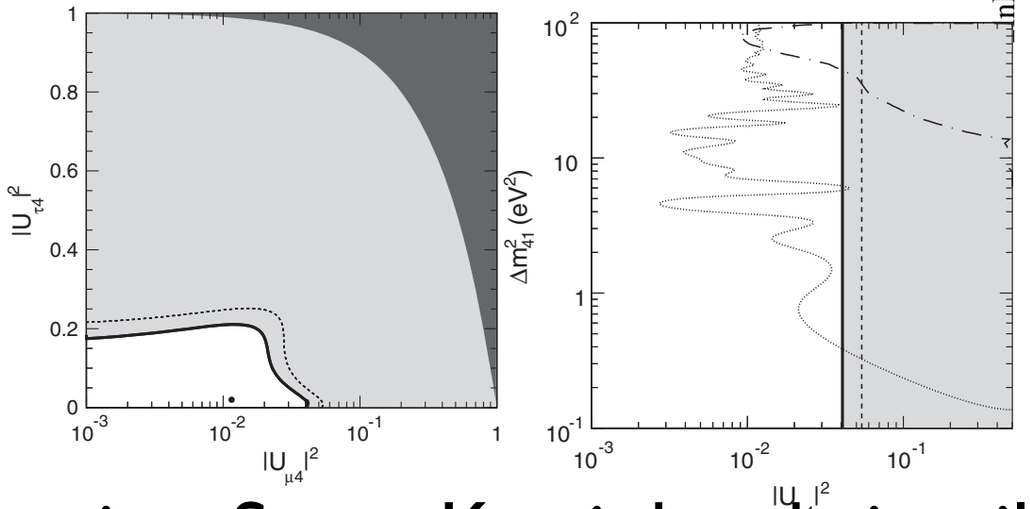


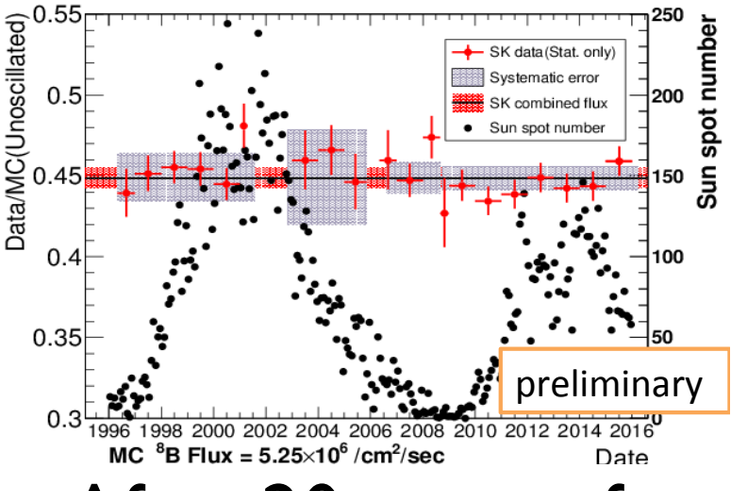
Far detector of T2K



Sterile ν search

PRD91, 052019(2015)





After 20 years of operation, Super-Kamiokande is still providing (and will continue to provide) world-leading results in multiple disciplines!