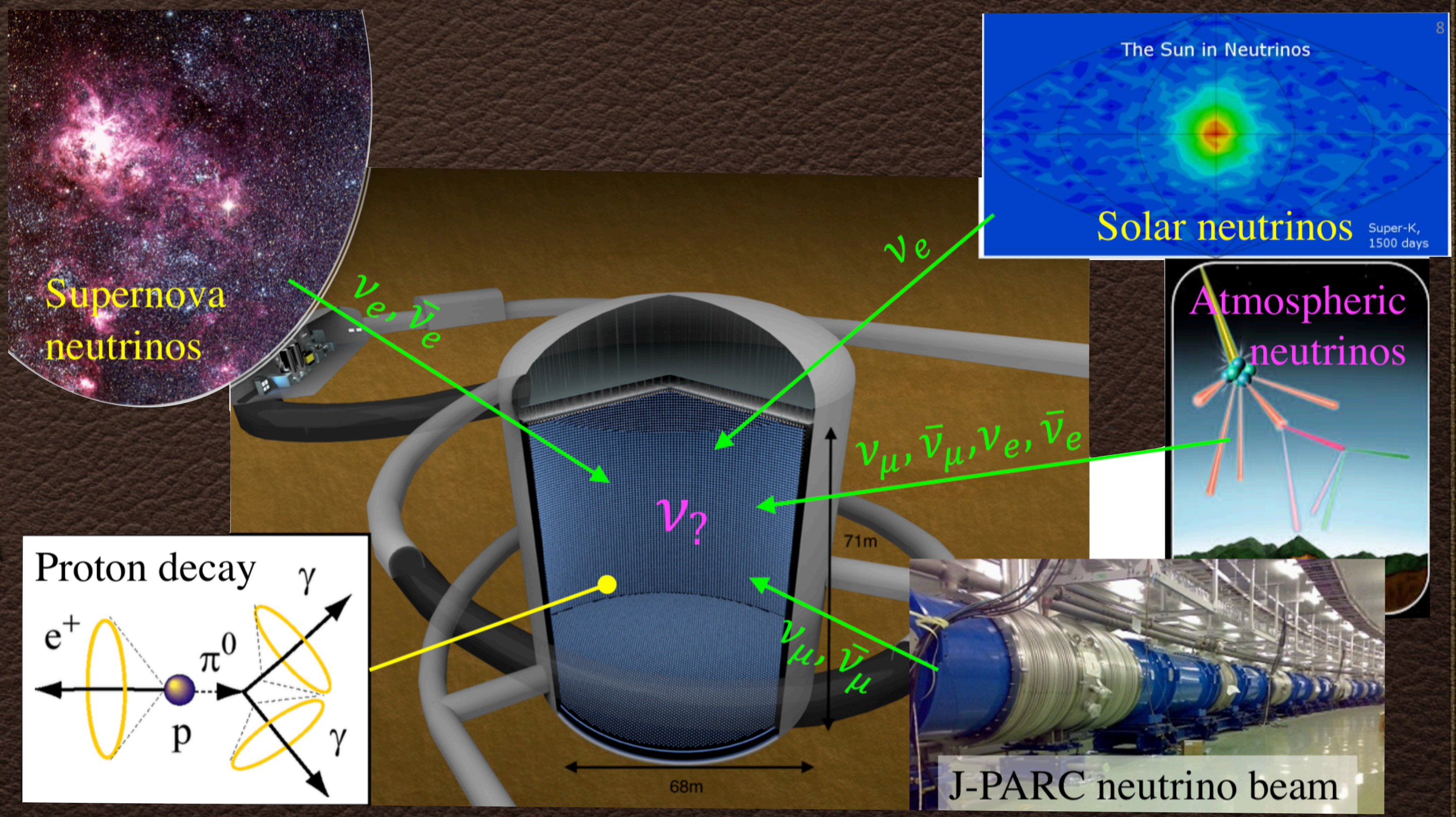
Hyper-Kamiokande

Interdisciplinary Developments in Neutrino Physics, March 28th, 2022

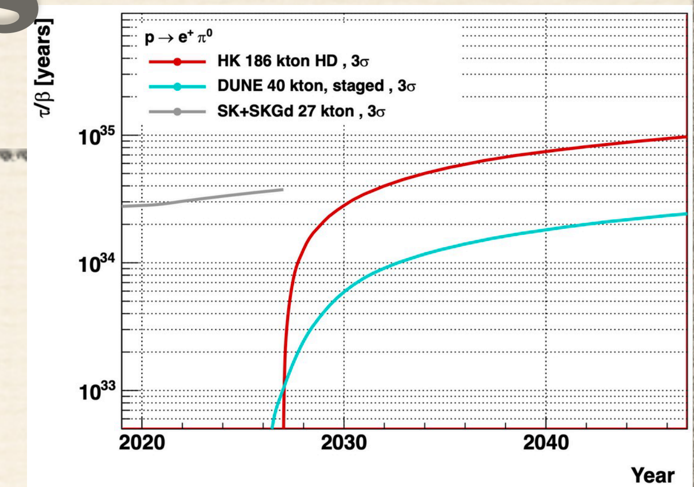
Michael Smy, University of California, Irvine

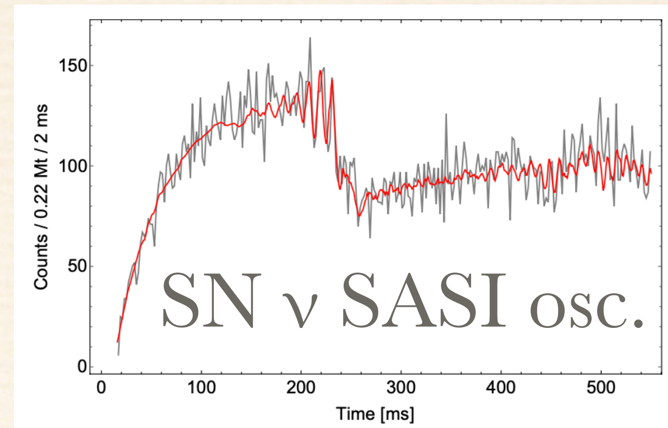


The Kamiokande Series

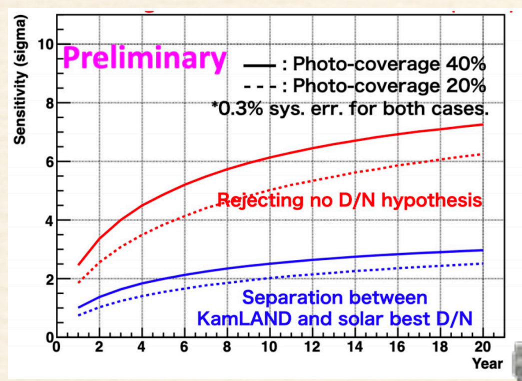
- neutrino oscillations
  - beam and atm. ν's
  - BSM (sterile, NSI, …)
- astrophysics
  - solar & SN ν's
  - dark matter
  - multi messenger
- nuclear physics
  - ν-N interactions
- geophysics
  - matter effects
  - electron density

proton decay





solar ν's



Hyper-K

Super-K

Kamikande

Courtesy S. King, King's College

Hyper-Kamiokande Collaboration

20 countries, 99 institutes, ~500 people as of Jan 2022, and growing

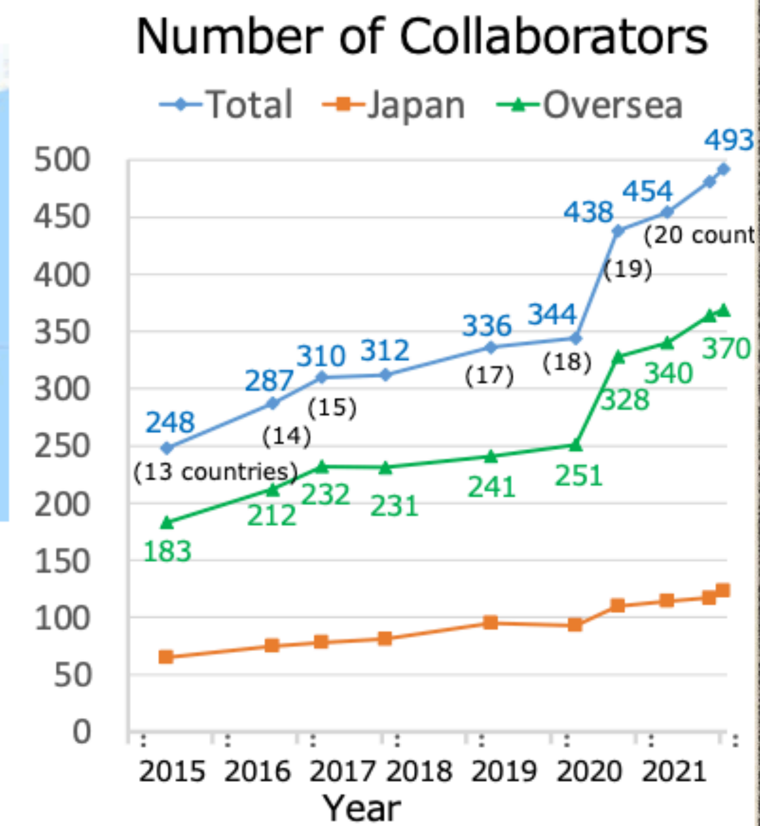
Collaborating Institutes

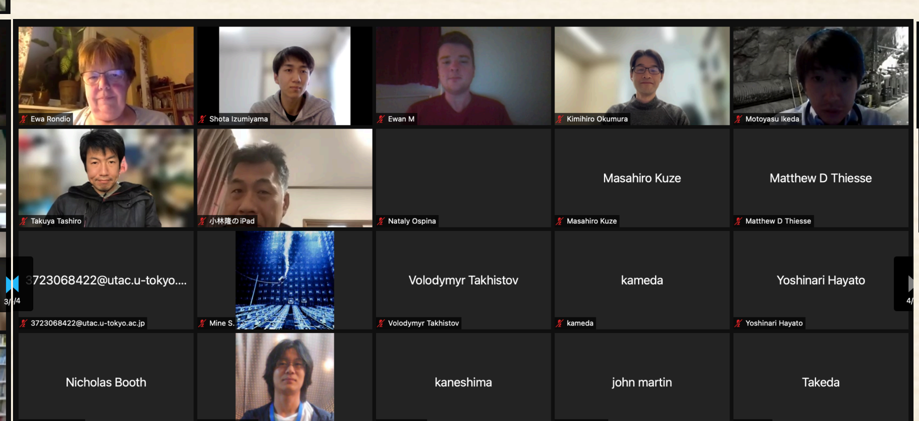
Europe	281 members
Armenia	3
Czech	4
France	27
Germany	1
Italy	55
Poland	38
Russia	22
Spain	35
Sweden	5
Switzerland	13
Ukraine	4
UK	74

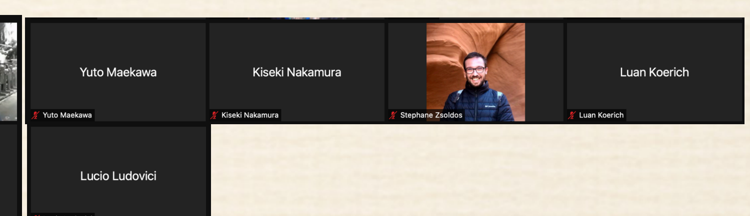
Asia	149 members
India	8
Korea	18
Japan	123

Americas	52 members
Brazil	3
Canada	32
Mexico	8
USA	9

Africa	11 members
Morocco	11







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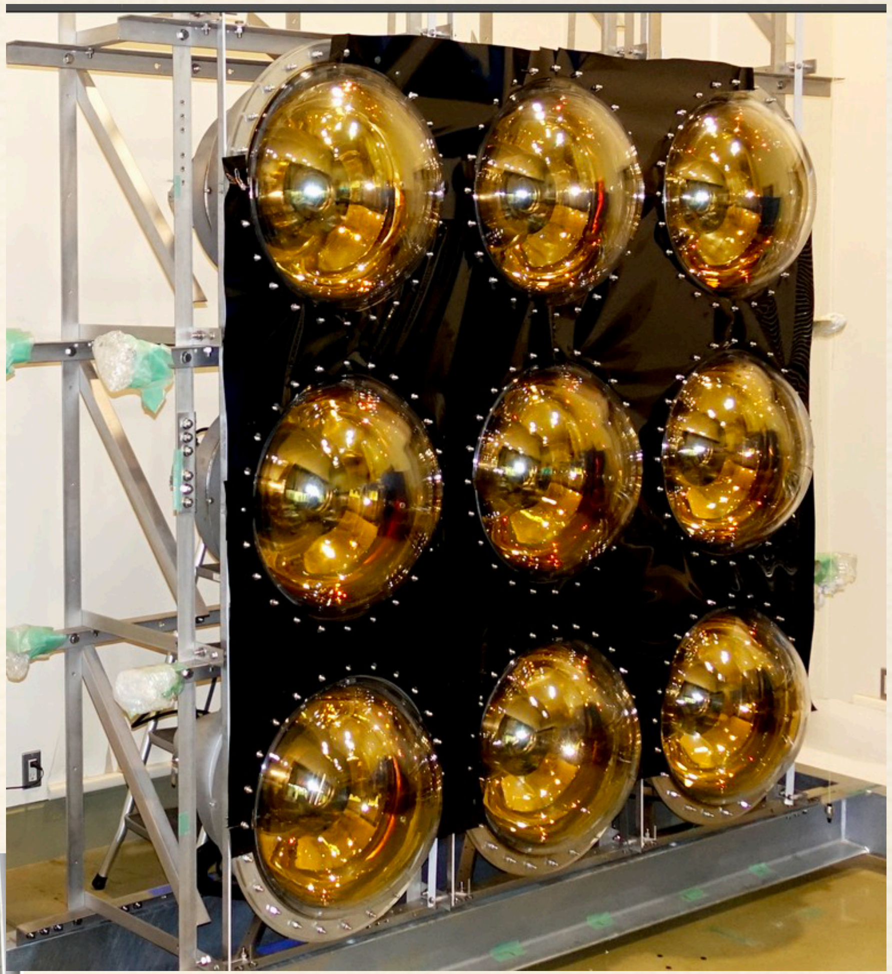
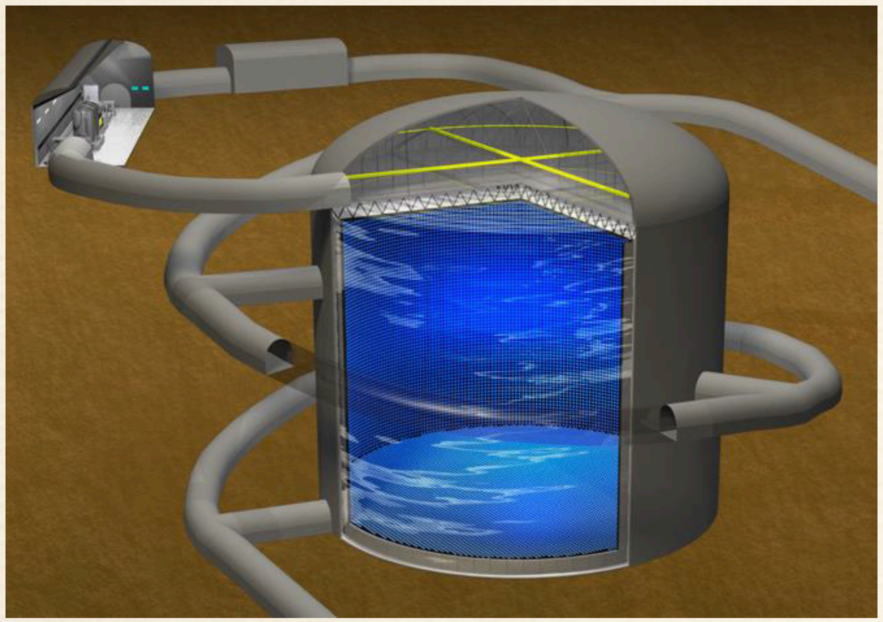
more than a 1,000 words



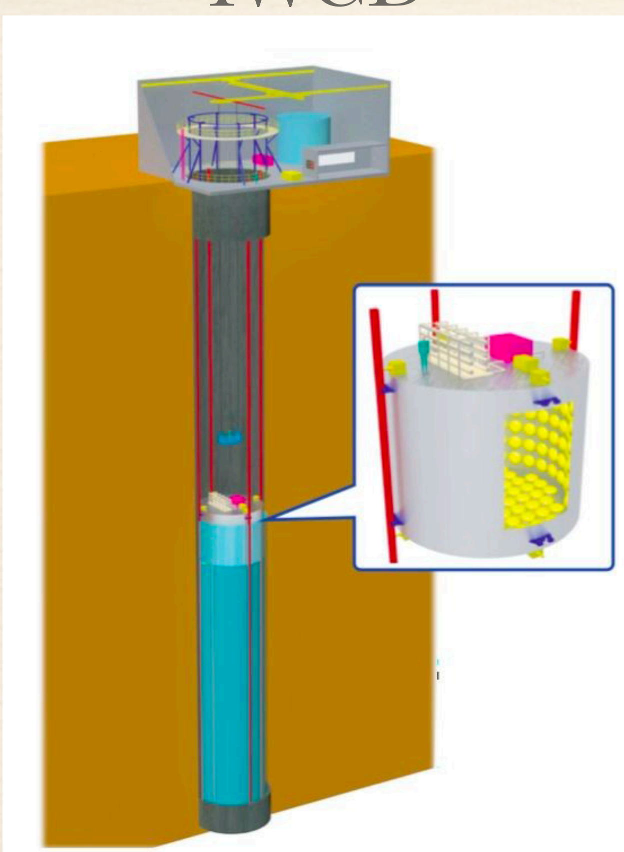
Courtesy S. King,
King's College

Hyper-K: New Detectors

Hyper-K



IWCD



- diameter 68m, height 71m ⟹ cavern diameter 69m, height 73m + dome on top
- tunnel construction almost done, cavern excavation will start soon,
- tank will be built in 2024/2025, PMTs will be installed in 2025/2026, and data collection starts in 2027
- Gd doping not in Hyper-K baseline design
- IWCD: ~1kt scale intermediate Gd-doped water Cherenkov detector with minimal overburden
- diameter ~8m, height ~6m
- uses multi-PMT modules (19 3” PMTs)

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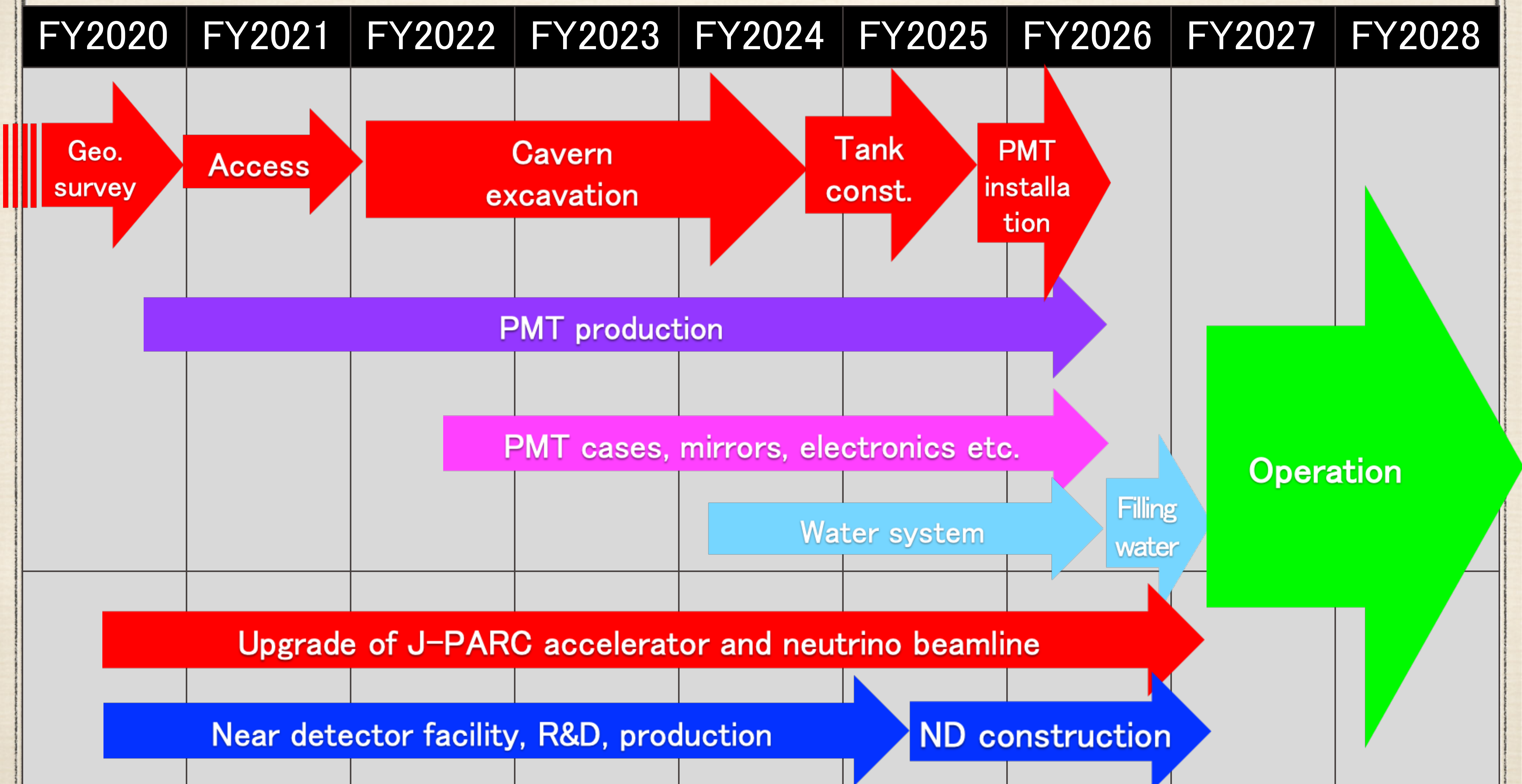
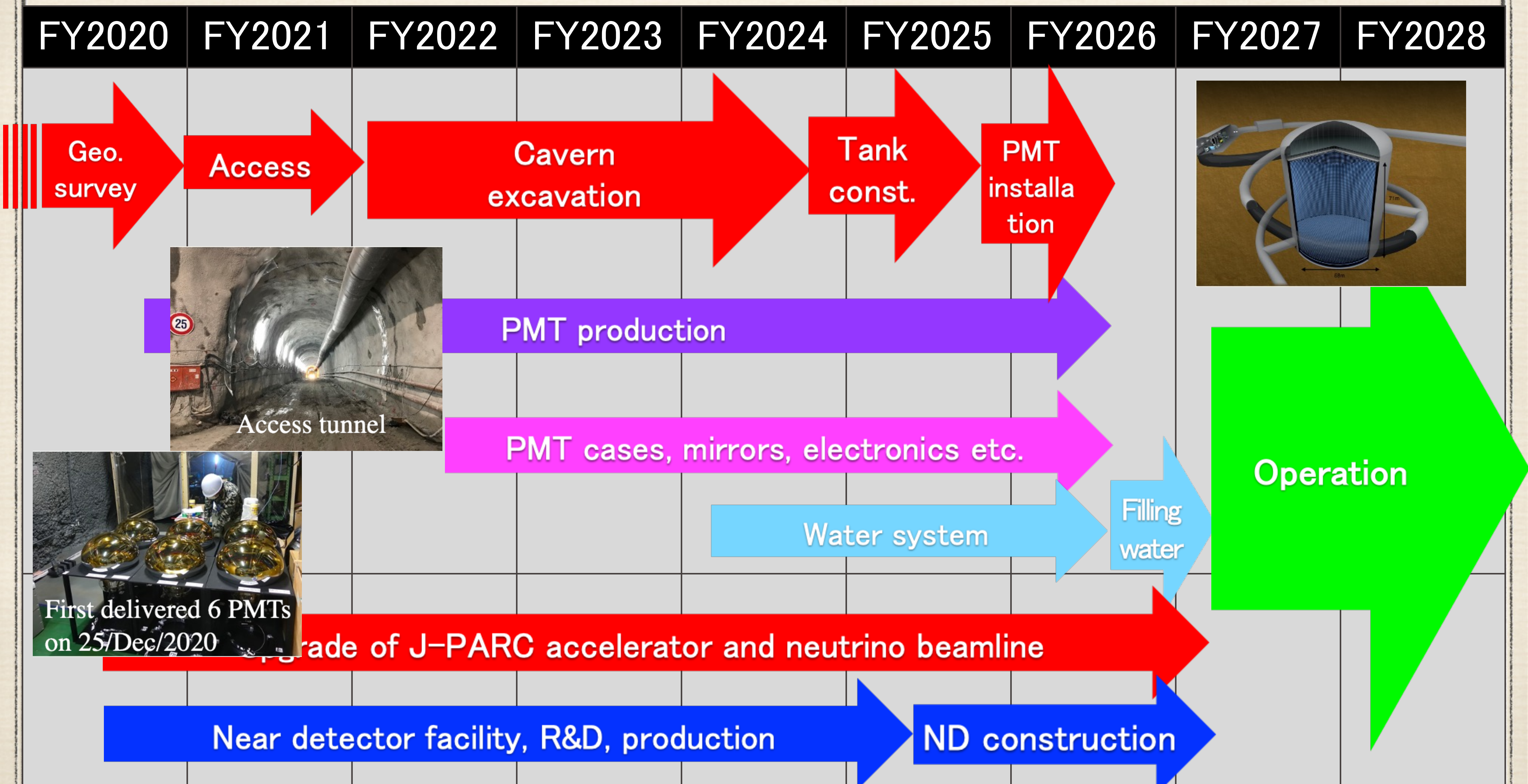
Hyper-Kamiokande Schedule



Hyper-Kamiokande Schedule



Photosensors: 20” PMTs

Inner Detector

	Super-K	Hyper-K
	11,129 20” PMTs	20,000 20” PMTs (JPN) (+addition PDs) (Overseas))
photo-coverage	40%	20%
single photon efficiency/PMT	~12%	~24%
dark noise	~5kHz (typical)	4kHz (average)
time resolution (one p.e)	~3ns	~1.5ns

- PMT production has started on time for 20” ‘Box & Line’ dynode PMTs
- 300 PMTs this month
- 20,000 by 2026 (according to the Japanese budget profile)

2020/12 First six PMTs delivered to Kamioka

Courtesy F. Di Lodovico, King’s College

Photosensors: mPMTs vs 20” PMTs

	mPMT: 19 x 3” PMTs	20” ‘B&L’ PMT
photo-cathode area	870 cm^2	2000 cm^2
effective light yield	~ 1 hit/MeV/5,000 mPMTs	~6 hits/MeV/20,000 PMTs
dark noise	19 x 200-300 Hz	~4kHz (typical)
transit time spread	1.3ns	2.7ns
comments	• granularity • directionality • better time resolution	• performance confirmed • high photon detection efficiency

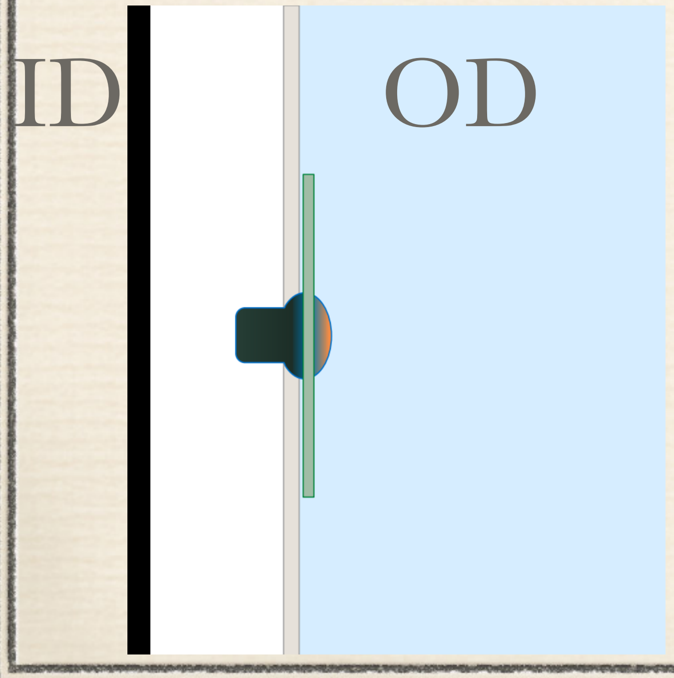
- complementary measurements of Cherenkov light
- systematic error reductions

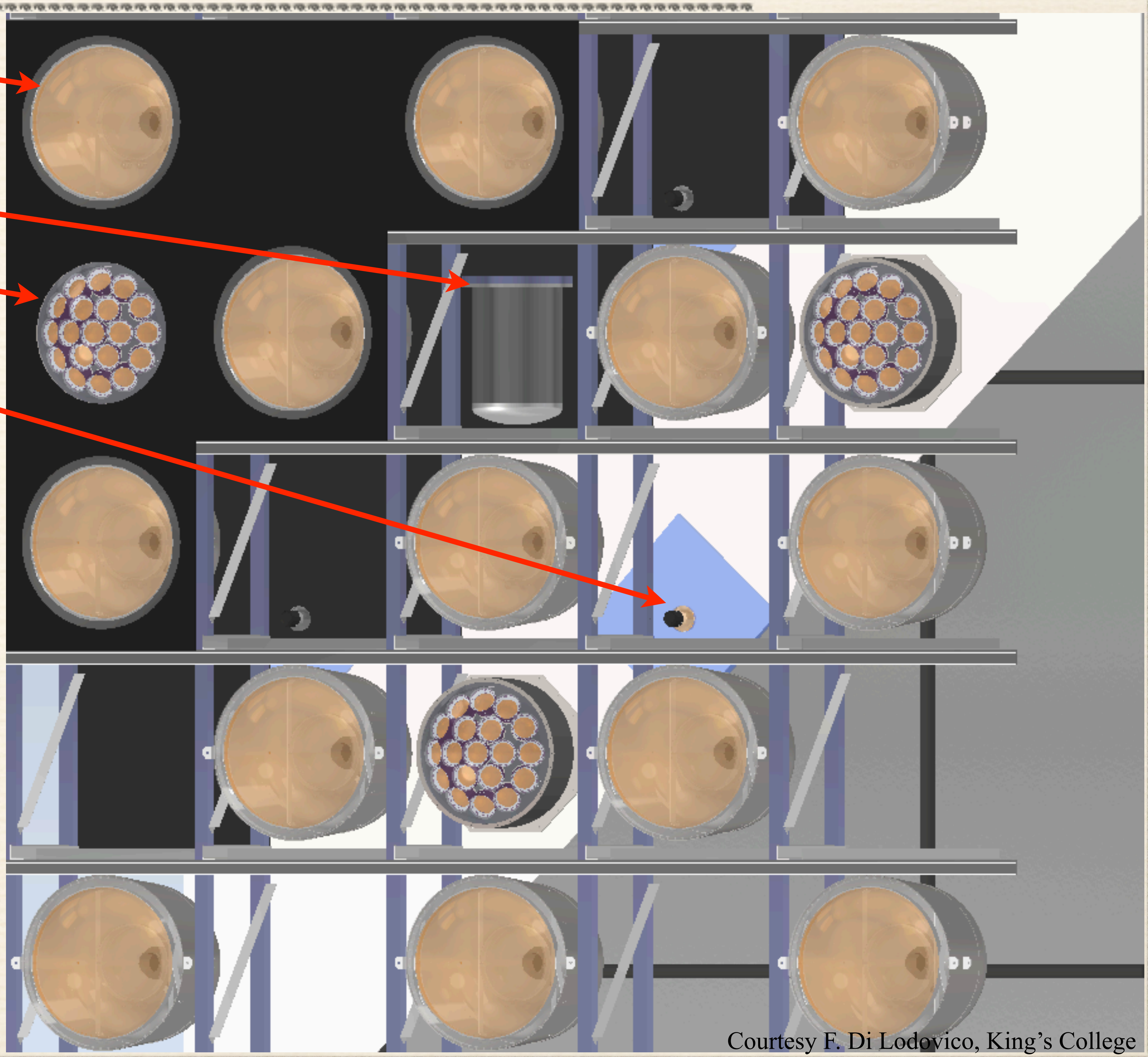
Courtesy S. King, King’s College

Courtesy F. Di Lodovico, King’s College

Photosensor Configuration

- ID 20" 'B&L' PMTs
- in-water electronics (ID and OD)
- ID mPMTs
- OD 3" PMT with wavelength shifter plate
- OD separated from ID by black sheet and reflective Tyvek





Courtesy F. Di Lodovico, King's College

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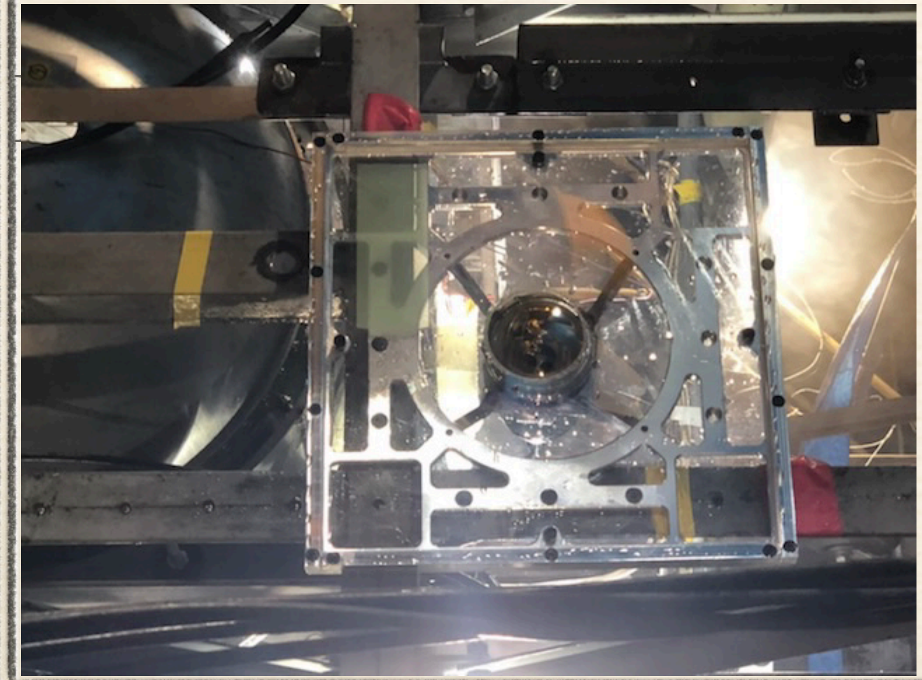
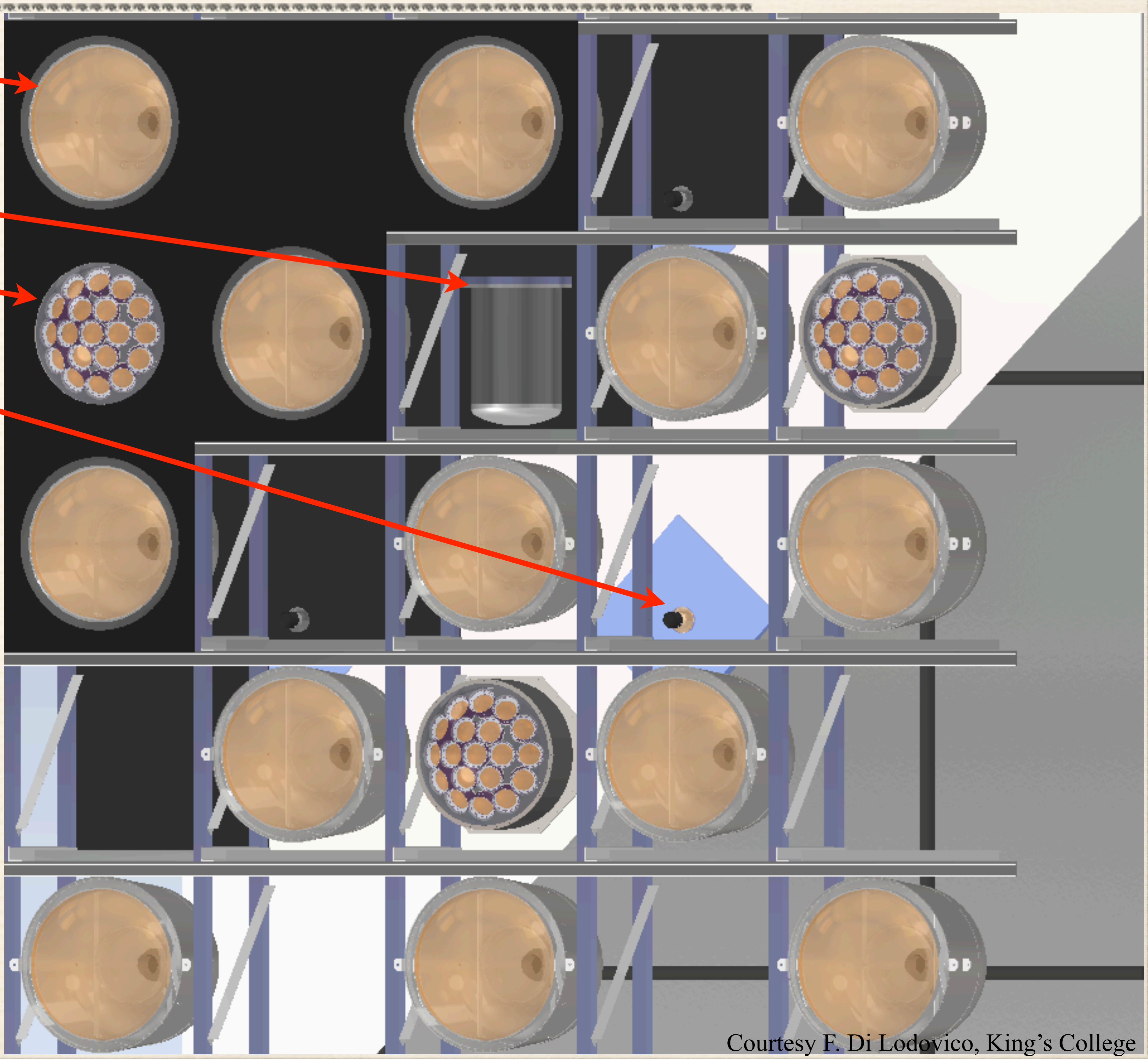
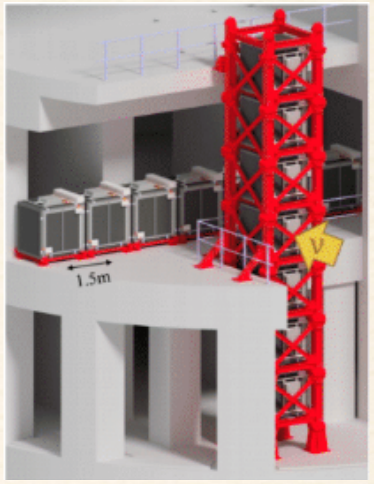




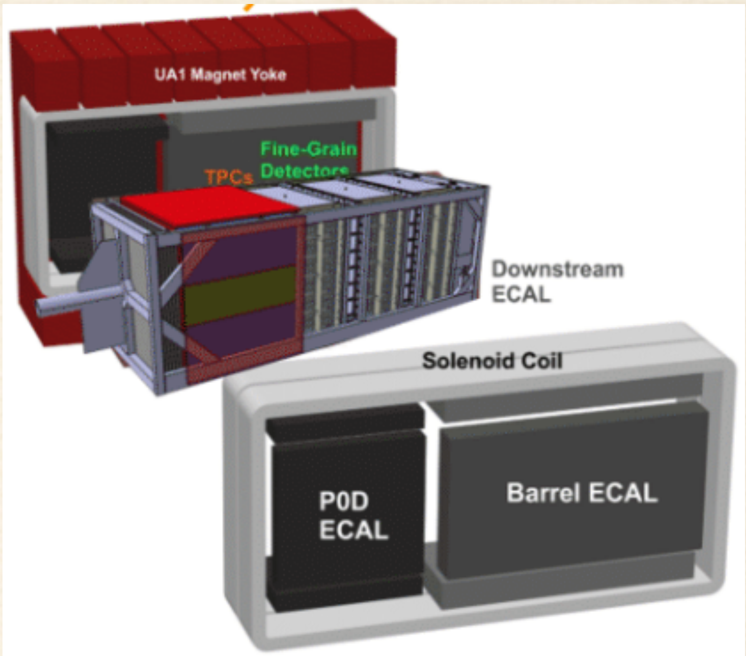
Courtesy F. Di Lodovico, King’s College

Near Detectors

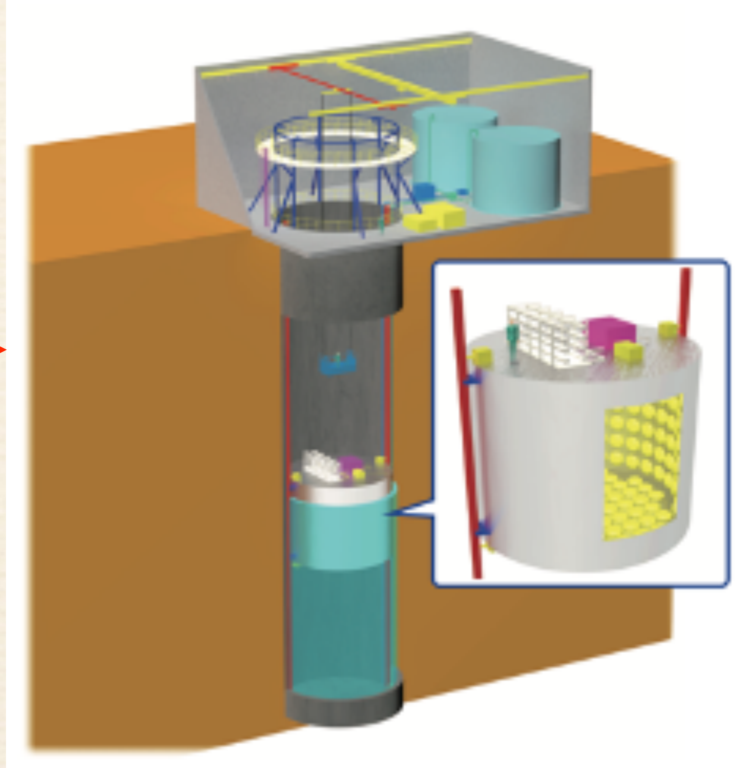
- critical for beam oscillation measurements: understand J-PARC beam, neutrino cross sections, detector systematics
- beam monitor (INGRID)
  - on and off axis
  - measure beam direction, monitor intensity



- ND 280
  - off axis
  - magnetized tracker: charge separation of wrong-sign background



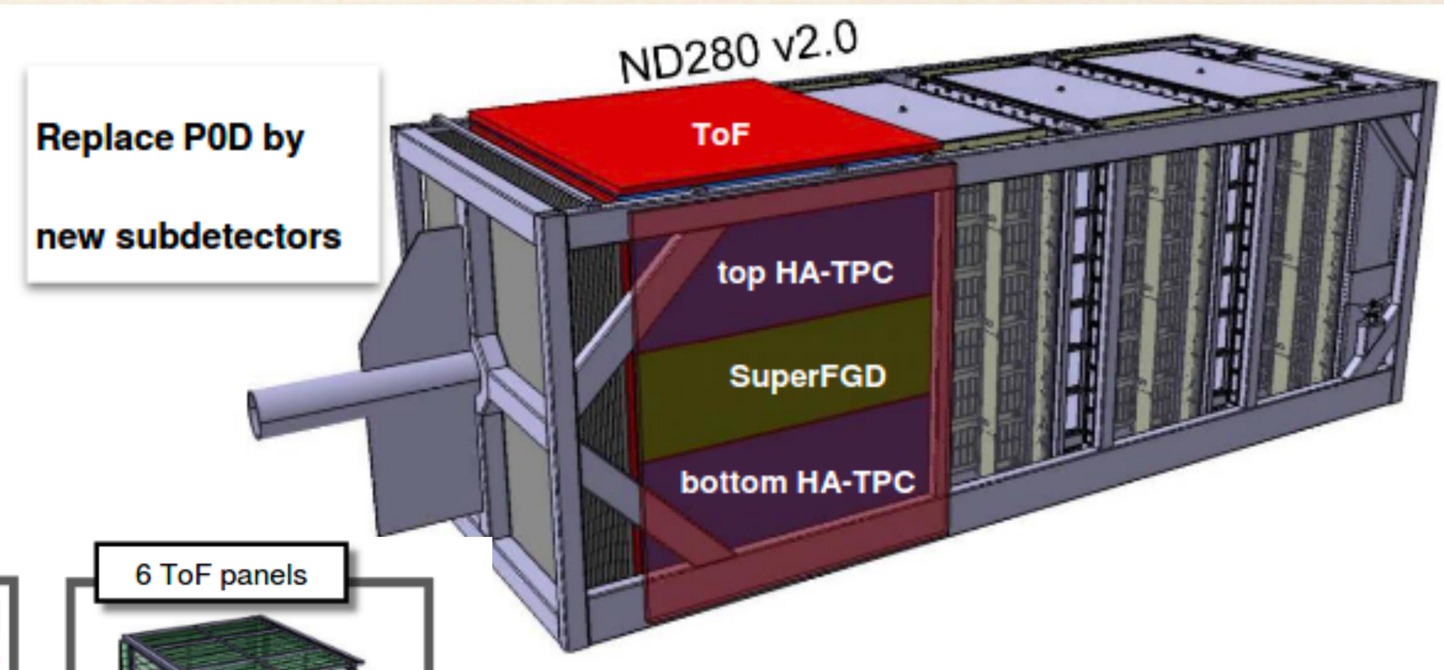
- IWCD
  - off axis
  - water Cherenkov detector like Hyper-K
  - cross sections as a function of neutrino energy (determined from axis angle)

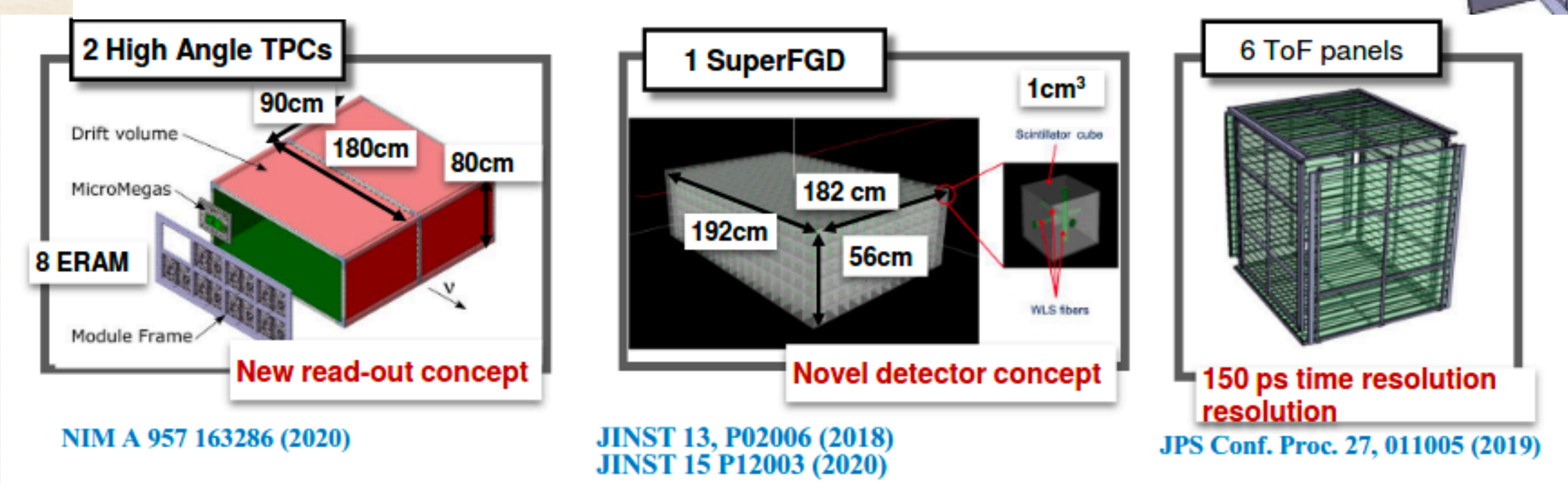


Near Detectors

- T2K upgrade: ND280 2.0 replace P0D with three
- new detectors

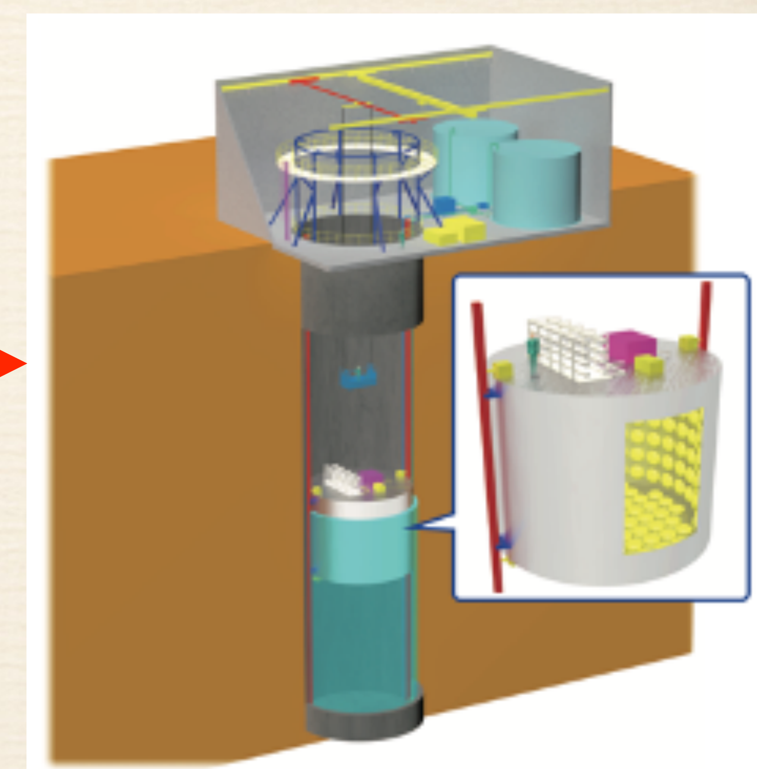
Courtesy T2K (M. Batkiewicz-Kwaśniak,
The H. Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences, Cracow)



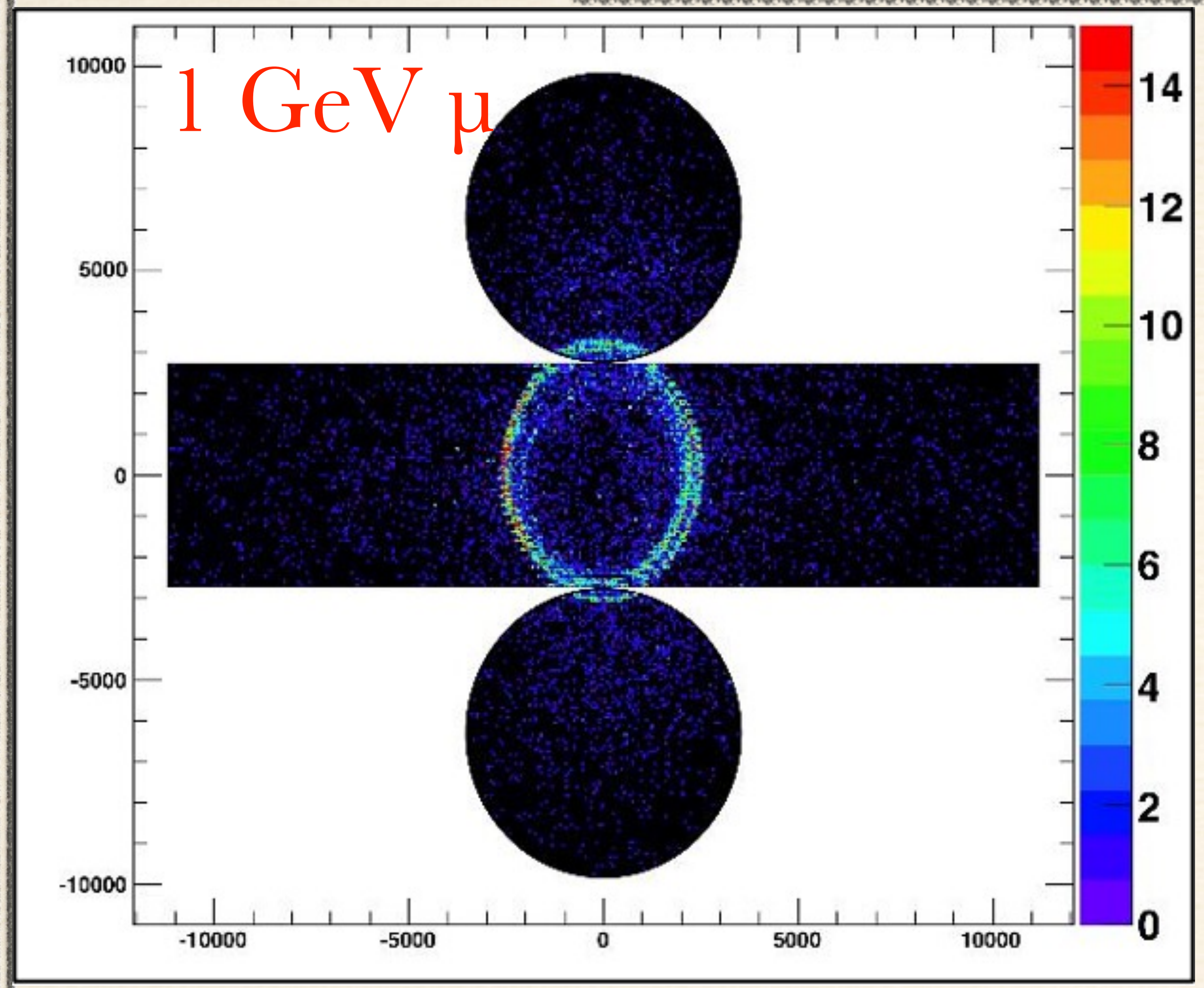


sign

- IWCD
  - off axis
  - water Cherenkov detector like Hyper-K
  - cross sections as a function of neutrino energy (determined from axis angle)

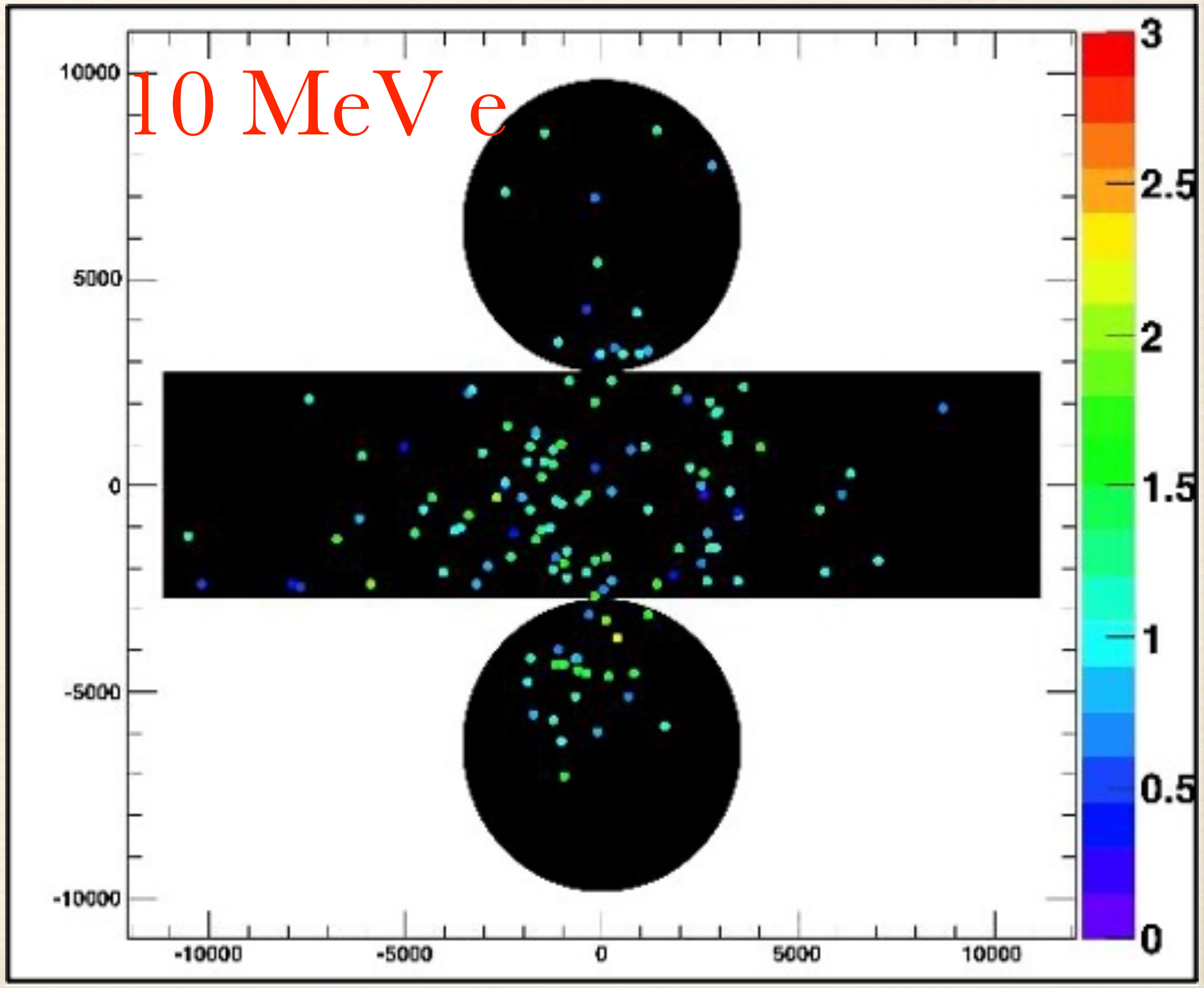


Hyper-K Event Reconstruction



neutrino interactions

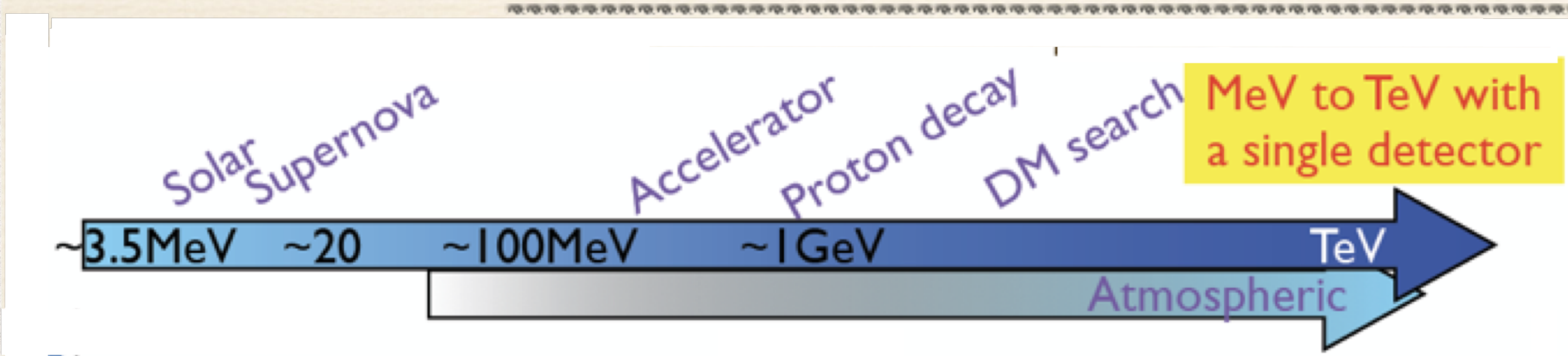
- CC interaction $\nu_{\mu/e}+N \rightarrow \mu/e+X$
- NC interaction $\nu+N \rightarrow \nu+X$
- ES interaction $\nu_x+e \rightarrow \nu_x+e$



- PMT time: vertex
- "rings": directions
- "brightness": momentum
- "sharpness": particle ID

Courtesy T. Yano, ICRR

Hyper-K Physics Signals



	material	Fiducial Mass (kton)
Super-K	Water	22
Hyper-K	Water	**190**
Dune	Argon	40
JUNO	Liq. Scinti	20

- Low Energy O(1 MeV to 10 MeV):
  - solar ^{8}B and hep neutrinos: ~130/day (above 4.5 MeV recoil electron kin. energy)
  - reactor neutrinos
- Medium Energy O(30 MeV):
  - supernova neutrinos
- High Energy O(100 MeV to 1TeV):
  - atmospheric neutrinos
  - nucleon decay
  - JPARC neutrino beam
  - astrophysical neutrinos

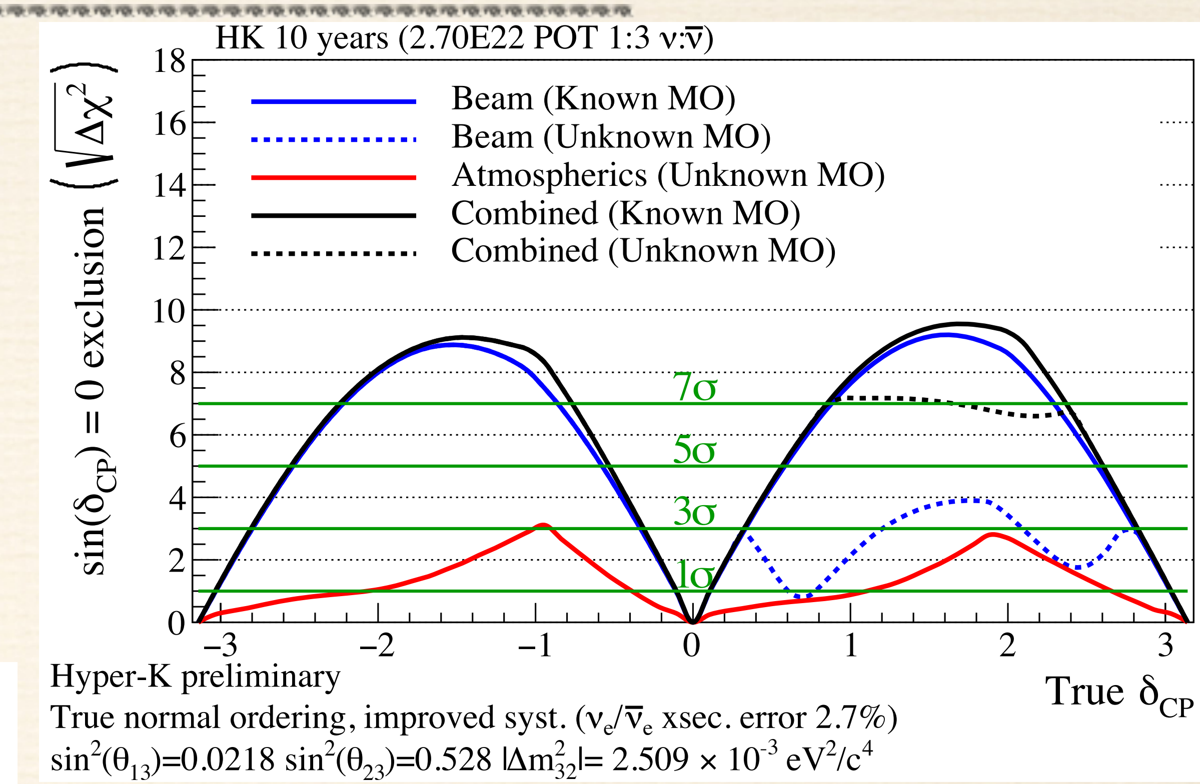
Courtesy F. Di Lodovico, King's College

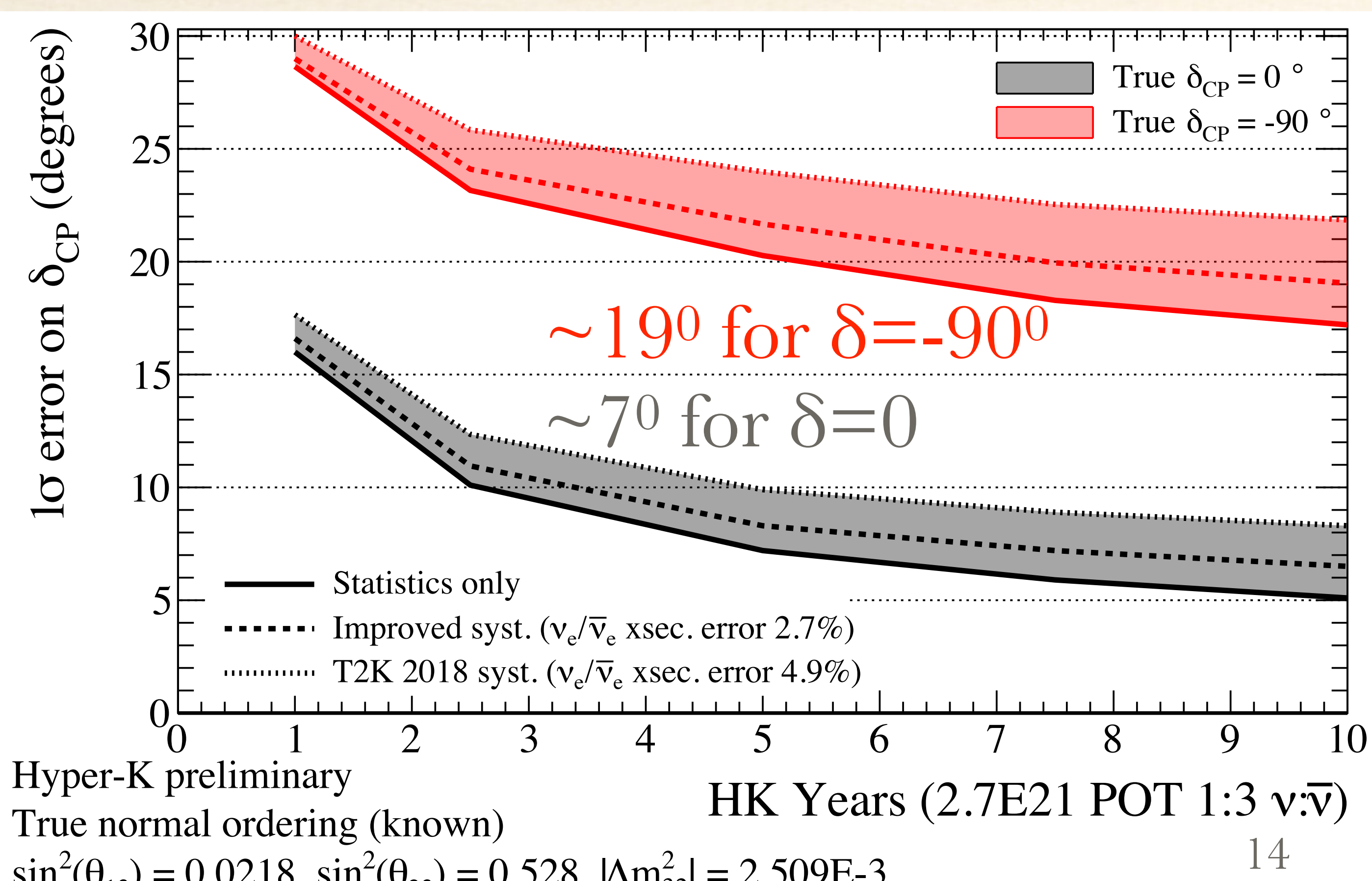
Accelerator Neutrinos

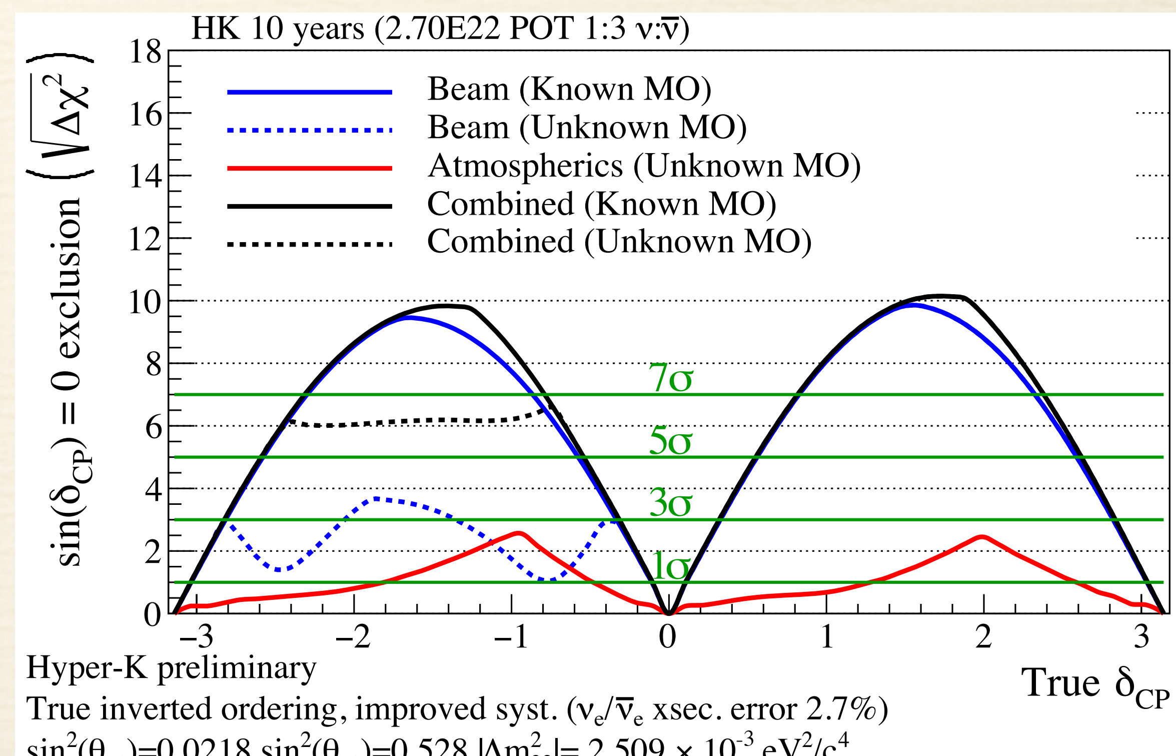
- DUNE “philosophy”
  - long baseline to be sensitive to matter effects
  - high energy, wide-band beam to measure oscillation pattern for neutrinos and anti-neutrinos
  - fine-grained detector to be able to use all (CC) cross section channels
  - near detector to characterize beam and measure “unoscillated" spectra
- Hyper-K “philosophy”
  - shorter baseline to reduce correlation between CPV and matter effects
  - low energy, narrow-band beam to focus on CCQE
  - inexpensive water Cherenkov detector with limited tracking ability; can afford larger fiducial mass and use it for atmospheric neutrino measurements of matter effects
  - near detectors to characterize beam, and an additional intermediate detector to measure “unoscillated spectra” (using the “Nu-prism” beam angle technique)
- neutrino oscillation measurements of both experimental programs are complementary leading to a more robust understanding of the underlying physics and a smaller impact of systematic effects (e.g. cross section uncertainties)

Accelerator Neutrinos: CPV Sensitivity

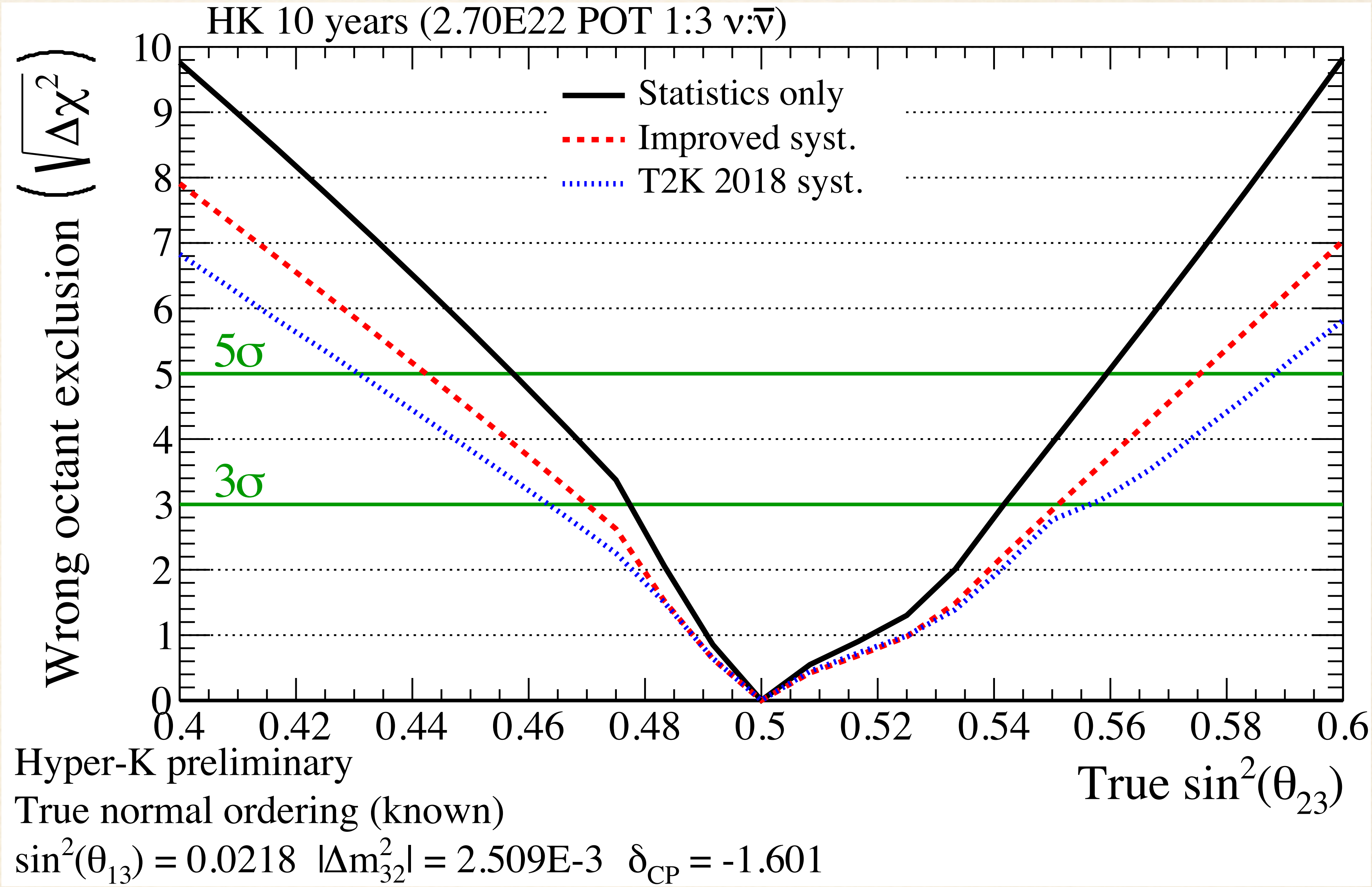
- good chance to discover leptonic CPV
- measure CPV phase
- best 5σ coverage of δ if mass ordering is known
- use atmospheric neutrinos to help remove mass ordering ambiguity







Accelerator Neutrinos: Octant Sensitivity

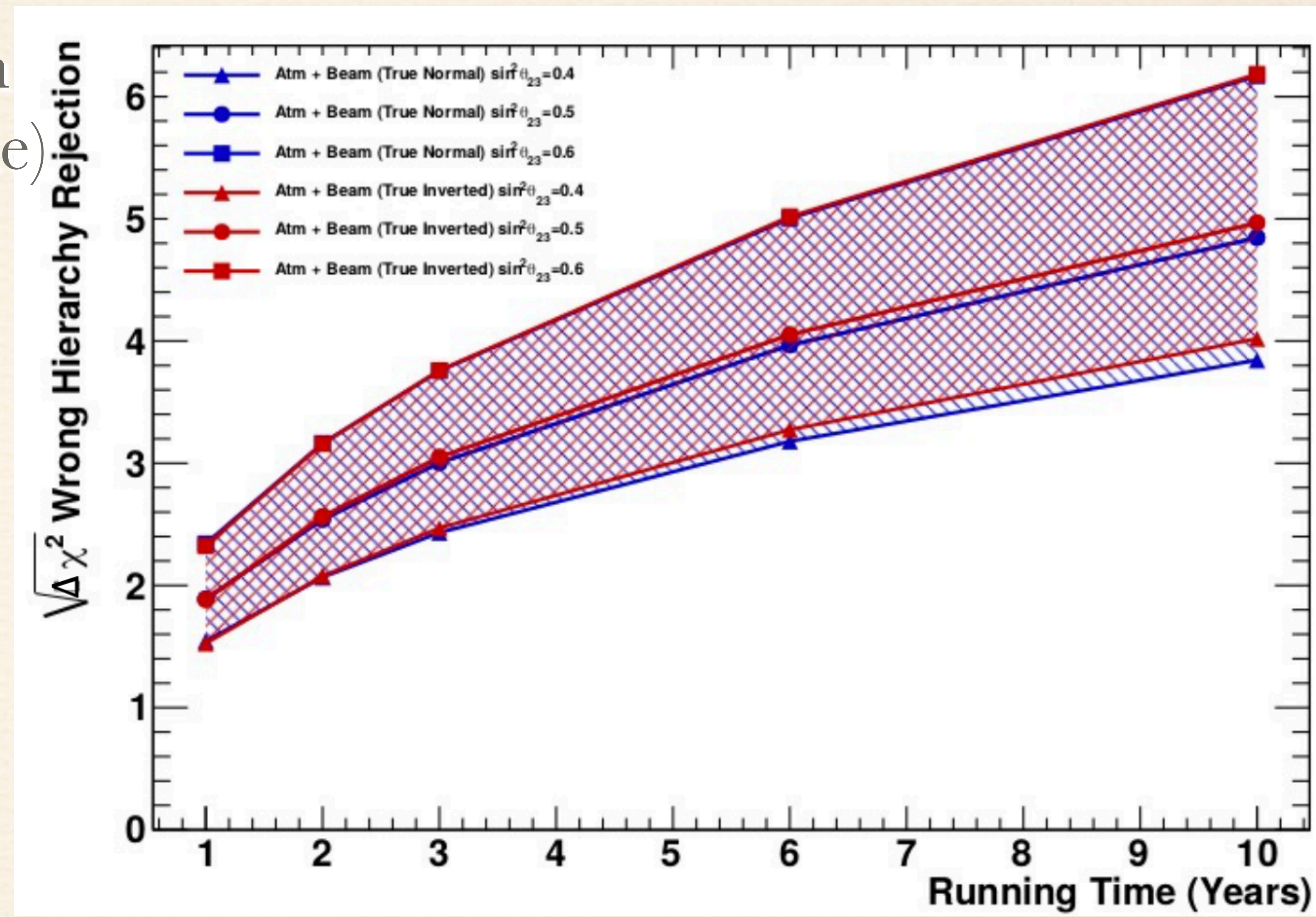


- for known, normal ordering
- improved systematics: exclude wrong octant at >5σ unless $0.47<\sin^2\theta_{23}<0.55$
- T2K 2018 systematics: exclude wrong octant at >3σ unless $0.46<\sin^2\theta_{23}<0.55$

Michael Smy, UC Irvine

Atmospheric Neutrinos

- baselines up to 12,000km (measured by zenith angle)
- strong matter effects on neutrinos passing deep inside the earth:
  - normal ordering: $\nu_\mu \rightarrow \nu_e$ is enhanced
  - inverted ordering: $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ is enhanced

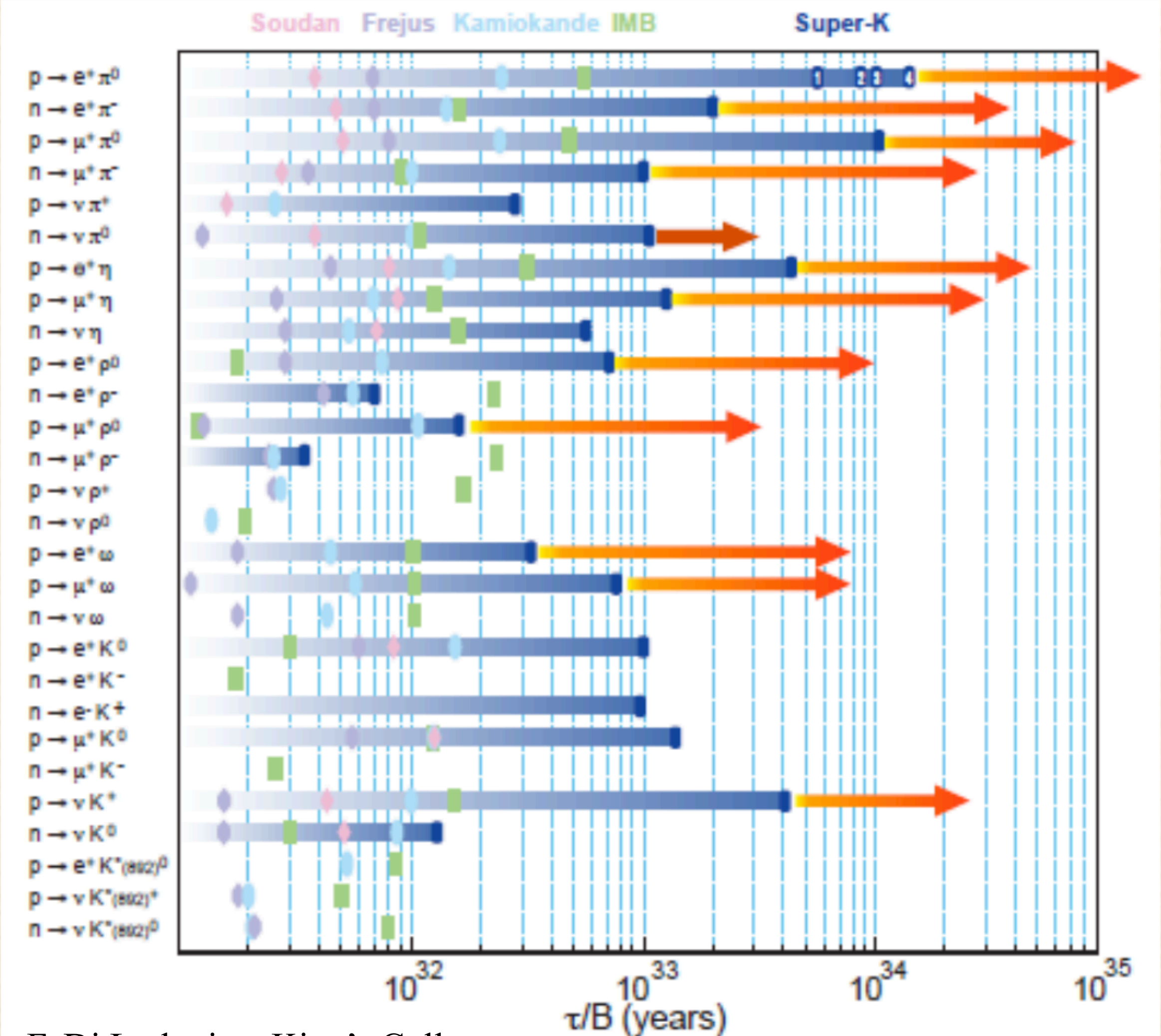


- beam + atmospheric data exclude wrong ordering by 4-6σ depending on $\sin^2\theta_{23}$
- synergy of beam and atmospheric analysis (event reconstruction, MC generation systematic error evaluation, etc.)

Courtesy F. Di Lodovico, King's College

Nucleon Decay

- Hyper-K will be the biggest nucleon decay experiment
- sensitivity to many channels, not just the iconic $p \rightarrow e^+\pi^0$ and (SUSY) $p\text{->}\nu K^+$



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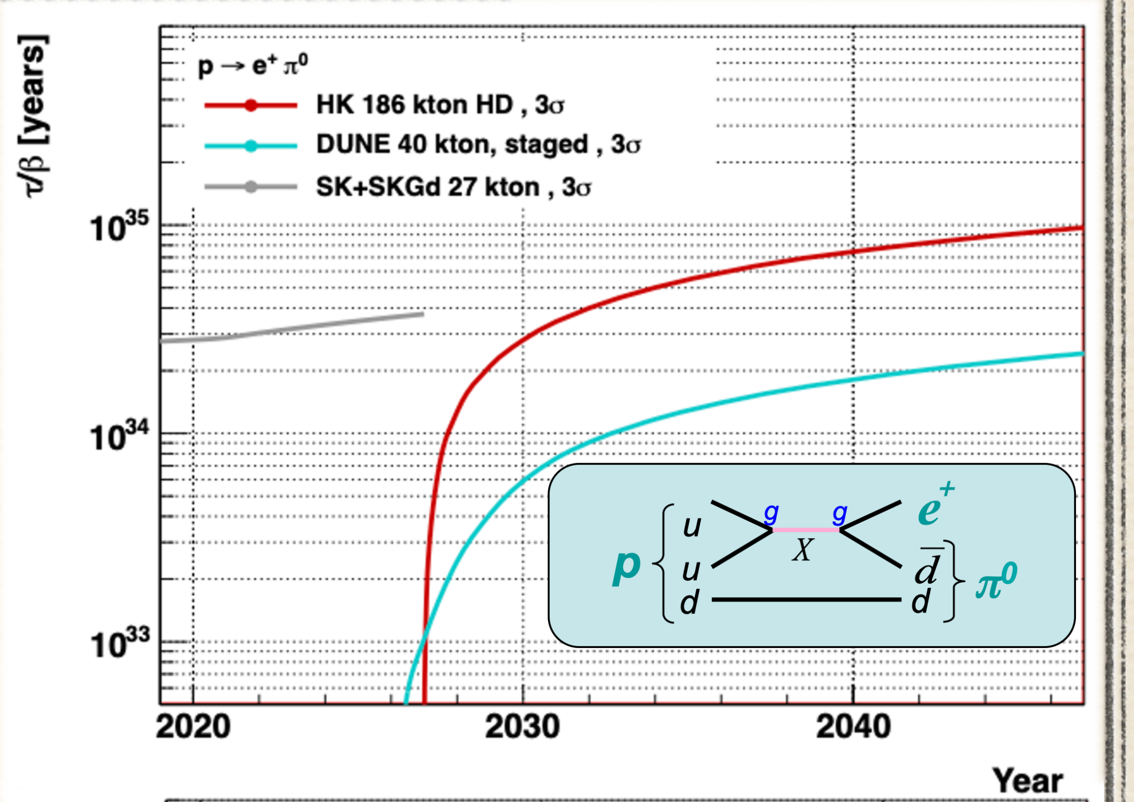
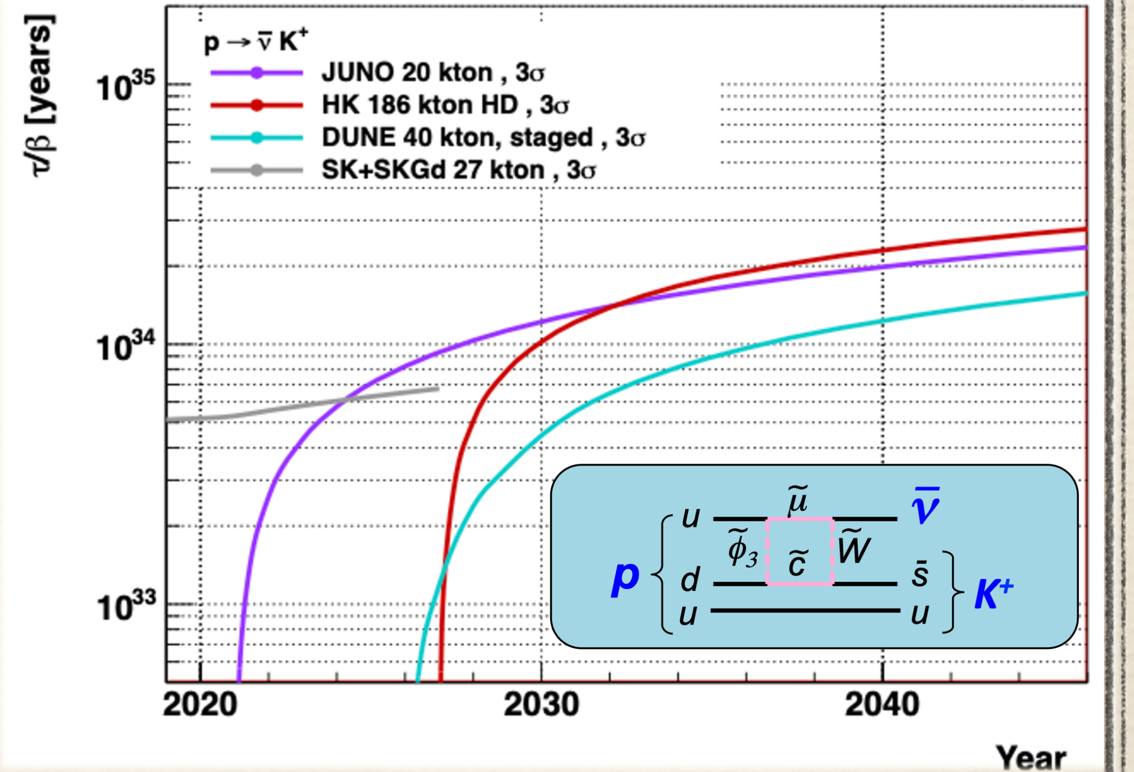
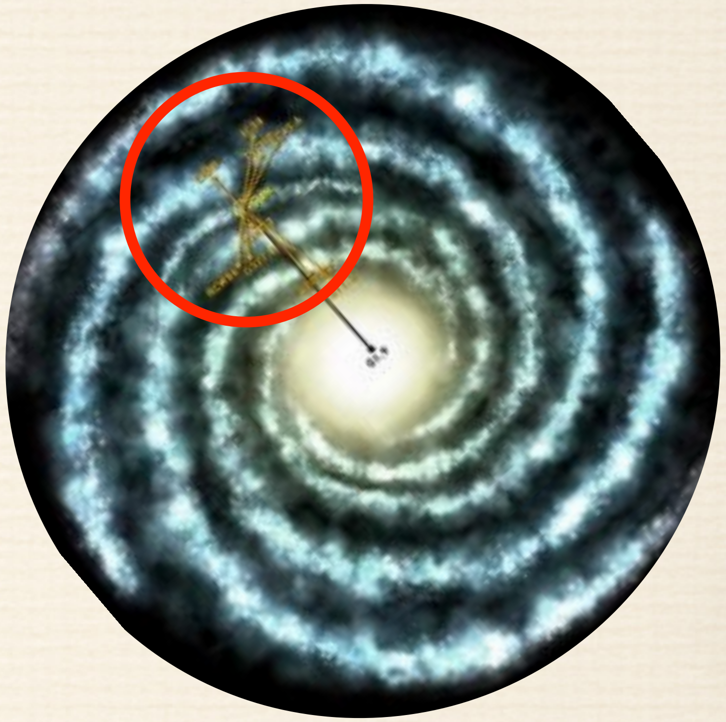




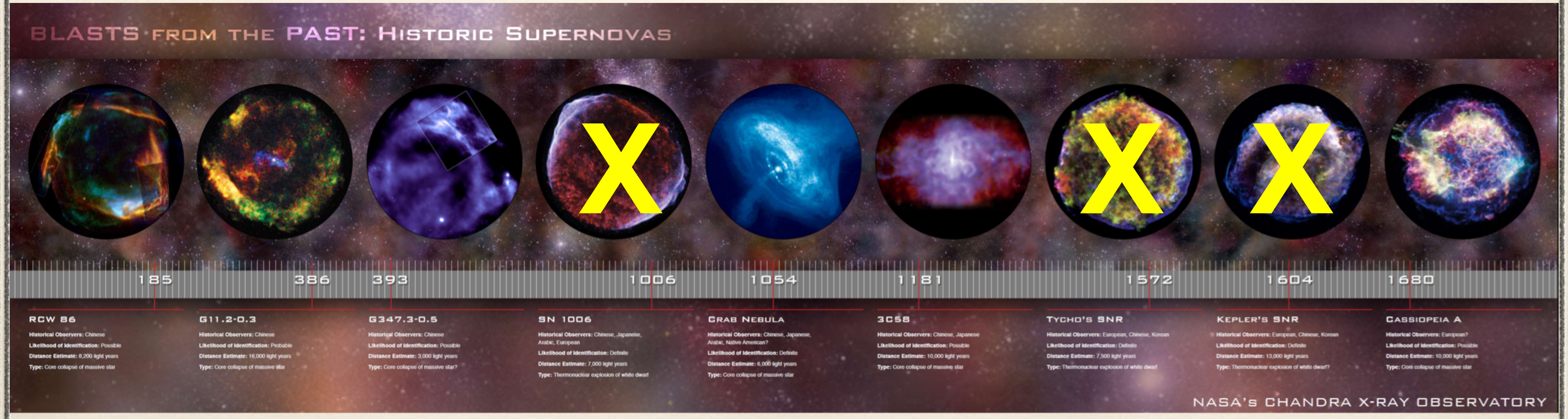
Neutrinos from Rare, Nearby (=Galactic) Core-Collapse Supernovae

- only six recorded CC explosions in ~1800 years in Milky Way (9 SN remnants in milky way)
- see only ~20%: ~2 CCSN/century

… and SN1885a (M31) SN 1987a (LMC)



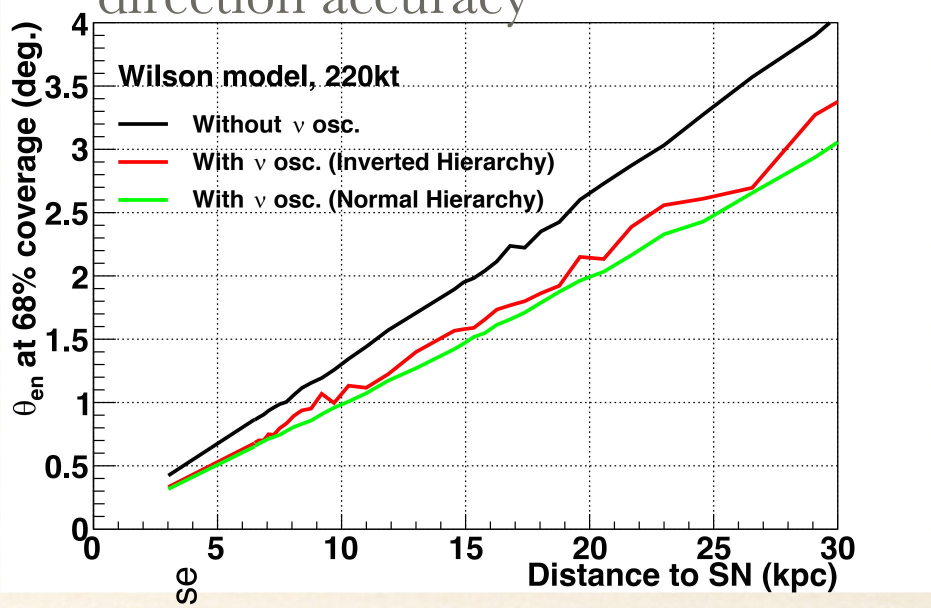
from: M. Vagins, WATCHMAN meeting at Virginia Tech in 2013



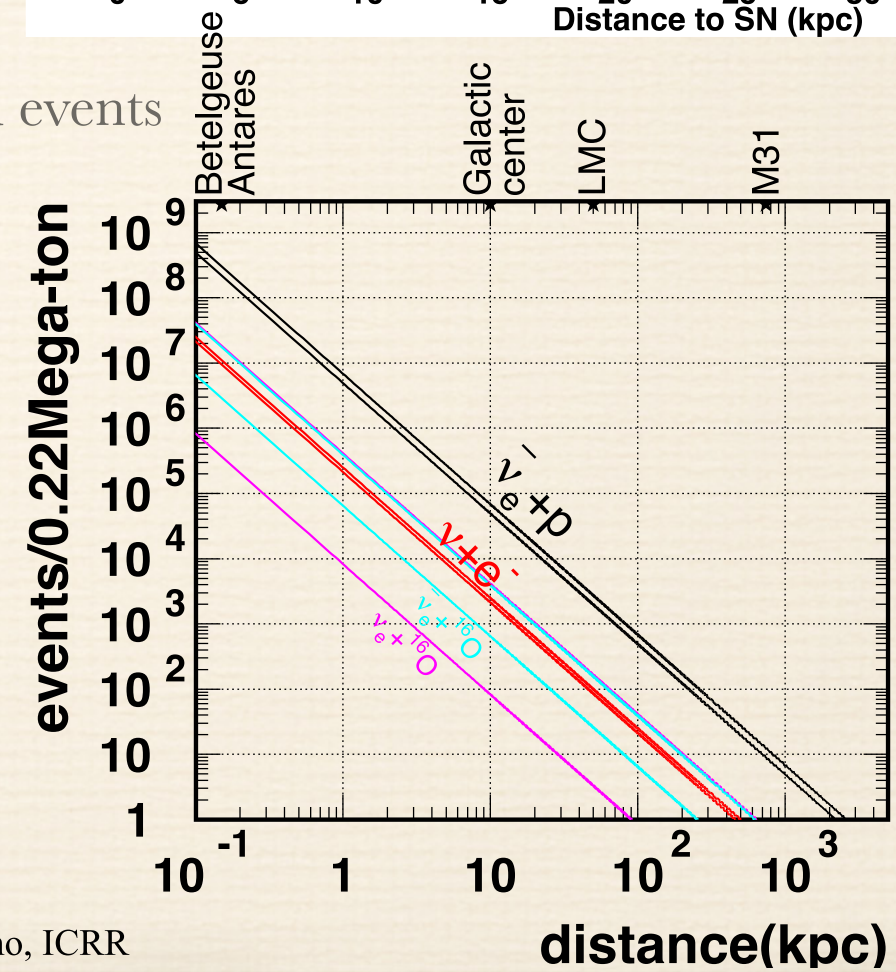
Neutrinos from Core Collapse Supernovae in Hyper-K

- 50,000 to 80,000 events expected from a core collapse SN at the galactic center (8.5 kpc)
- 6-10 events expected for a core collapse SN in M31 (750kpc)
- compare to 11 neutrinos detected at Kamiokande and 8 at IMB at 50kpc
- astrophysics
  - explosion mechanism
  - proto-neutron star formation
  - black hole formation
- neutrino physics
- multi-messenger
  - early alert with direction
  - useful for gravitational wave, gamma-ray and X-ray telescopes

direction accuracy



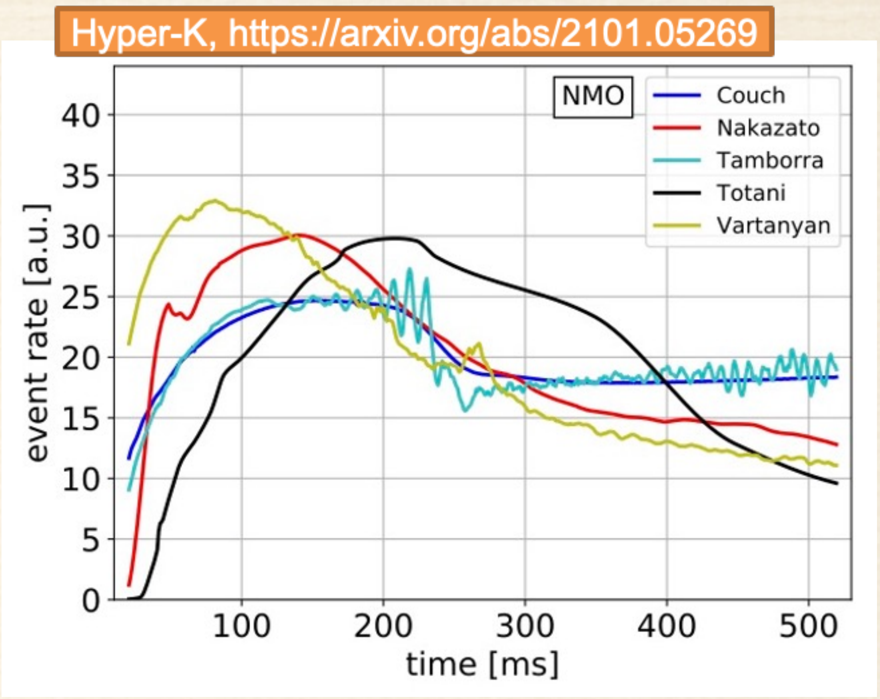
observed events

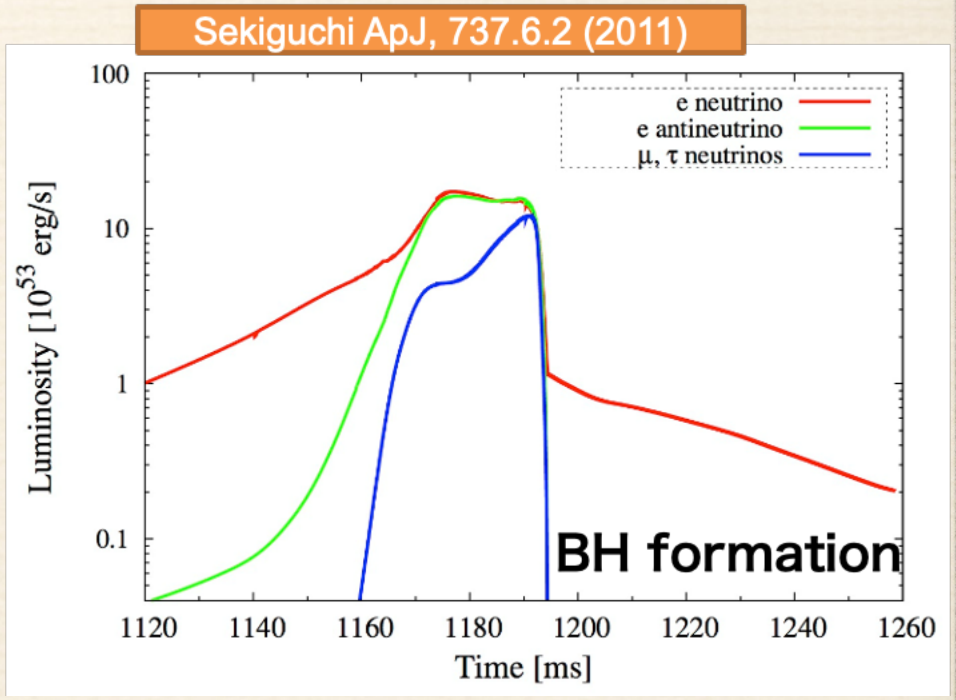


Courtesy T. Yano, ICRR

Supernova Model Discrimination

- precise measurement of time profile and energy spectrum
- chance to observe the explosion mechanism (SASI/Rotation/Convection)
- by observing neutrinos from nearby galactic can understand dim supernovae/BH formation
- Hyper-K can distinguish five recent SN models (https://arxiv.org/abs/2101.05269)
- even with just 300 events (~60-100kpc) can identify SN model with >97%





Courtesy T. Yano, ICRR

Supernova Model Discrimination

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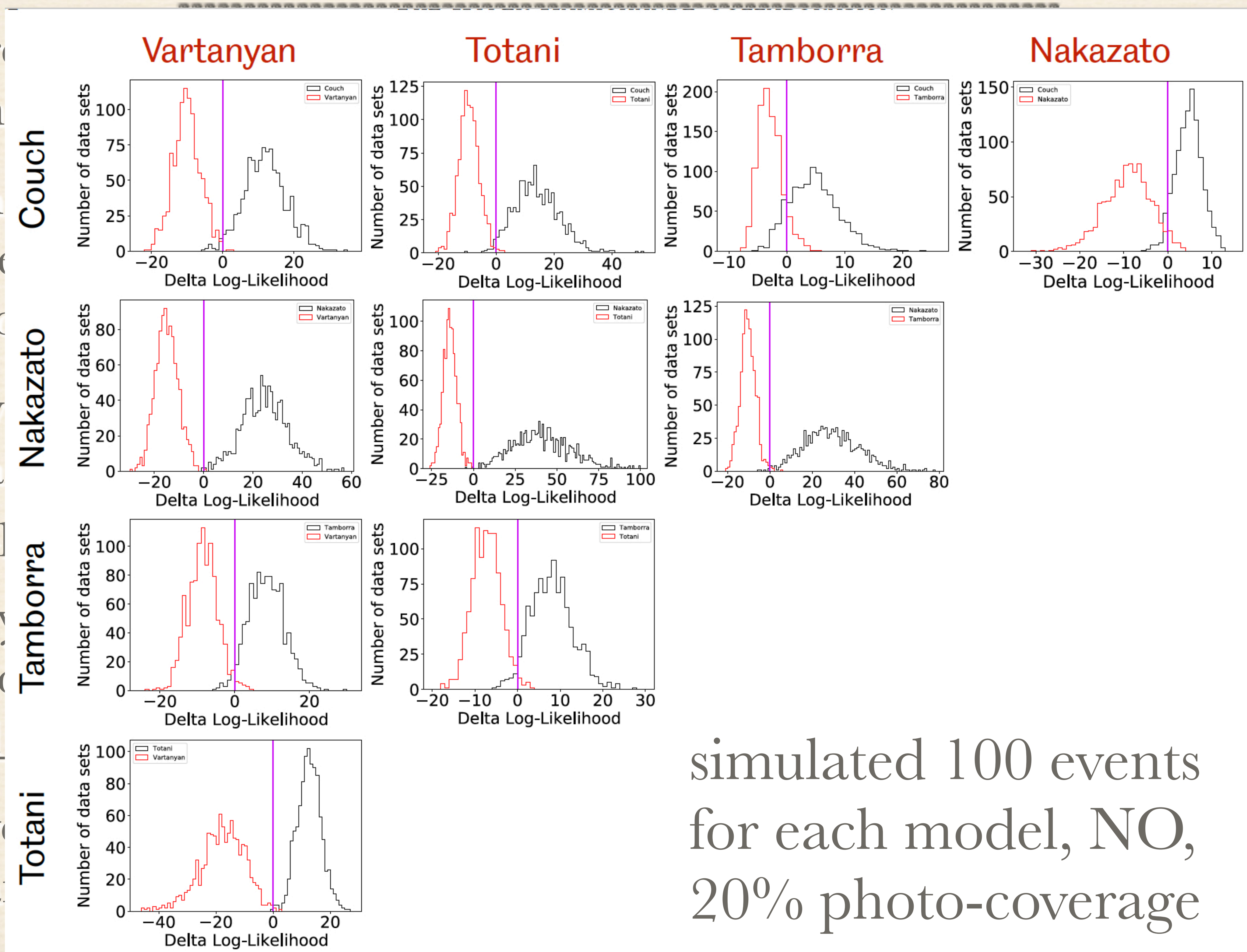
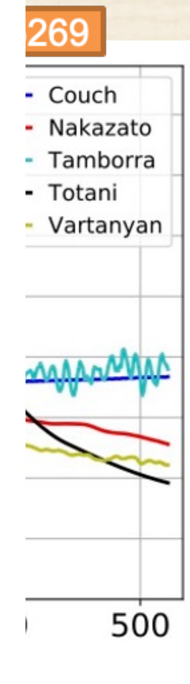
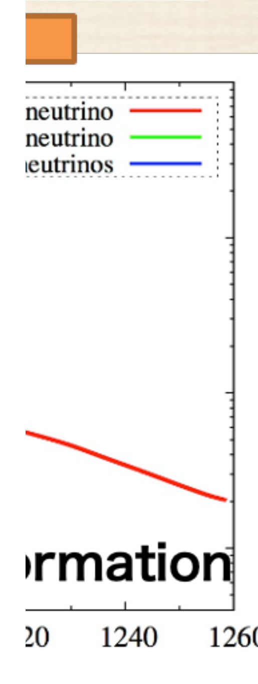


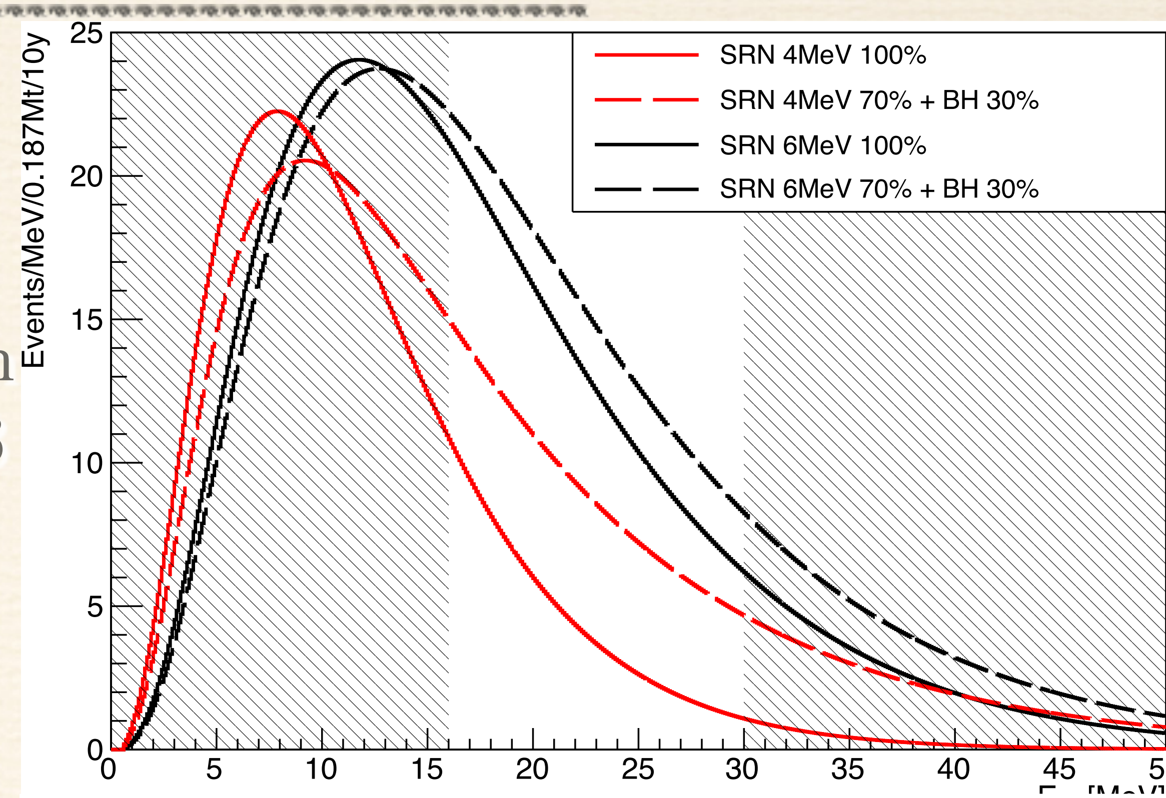
simulated 100 events for each model, NO, 20% photo-coverage

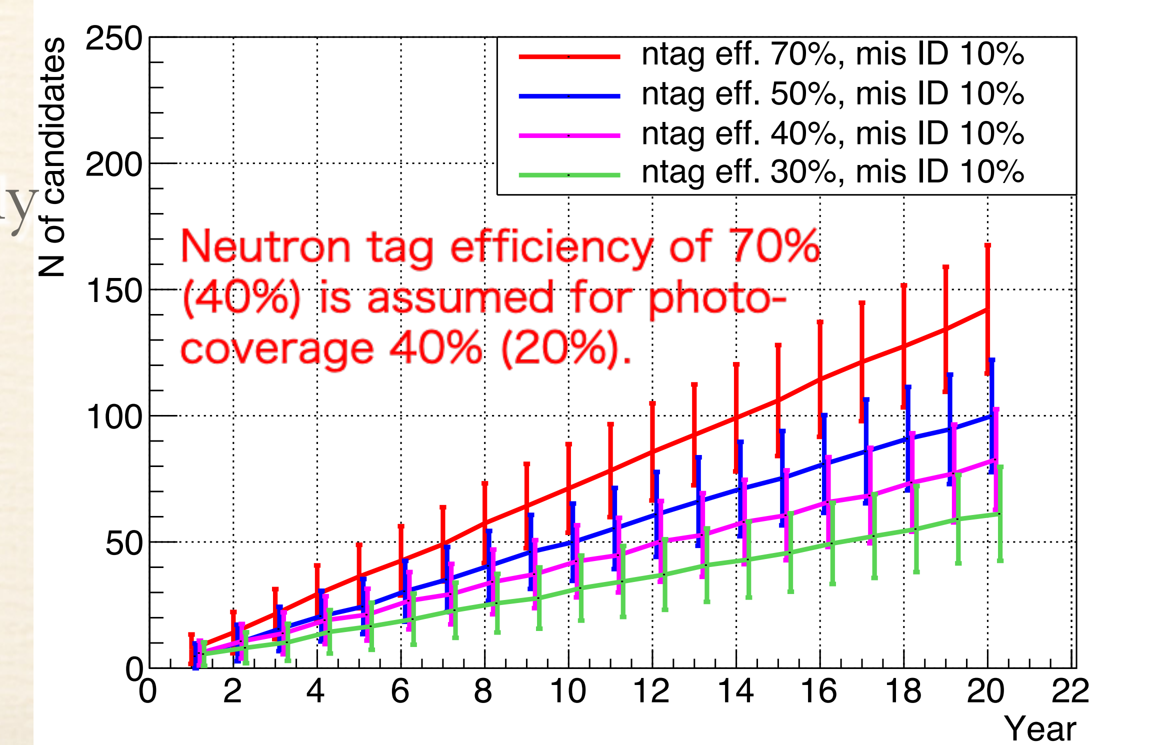




Distant Supernovae Neutrinos

- observation in Hyper-K
  - diffuse, constant ν flux of SN up to z~1
  - see ~70±17 events with >4σ significance in ten years (photo-coverage 40%) or ~40±13 events with >3σ
  - move beyond discovery and study SN neutrinos across the universe!
- physics of Supernovae:
  - test star formation rate (factor of ~2 discrepancy between expected and optically observed SN rate)
  - measure temperature of typical SN (from positron energy spectrum)
  - unusual supernova (optically dim and/or BH formation)

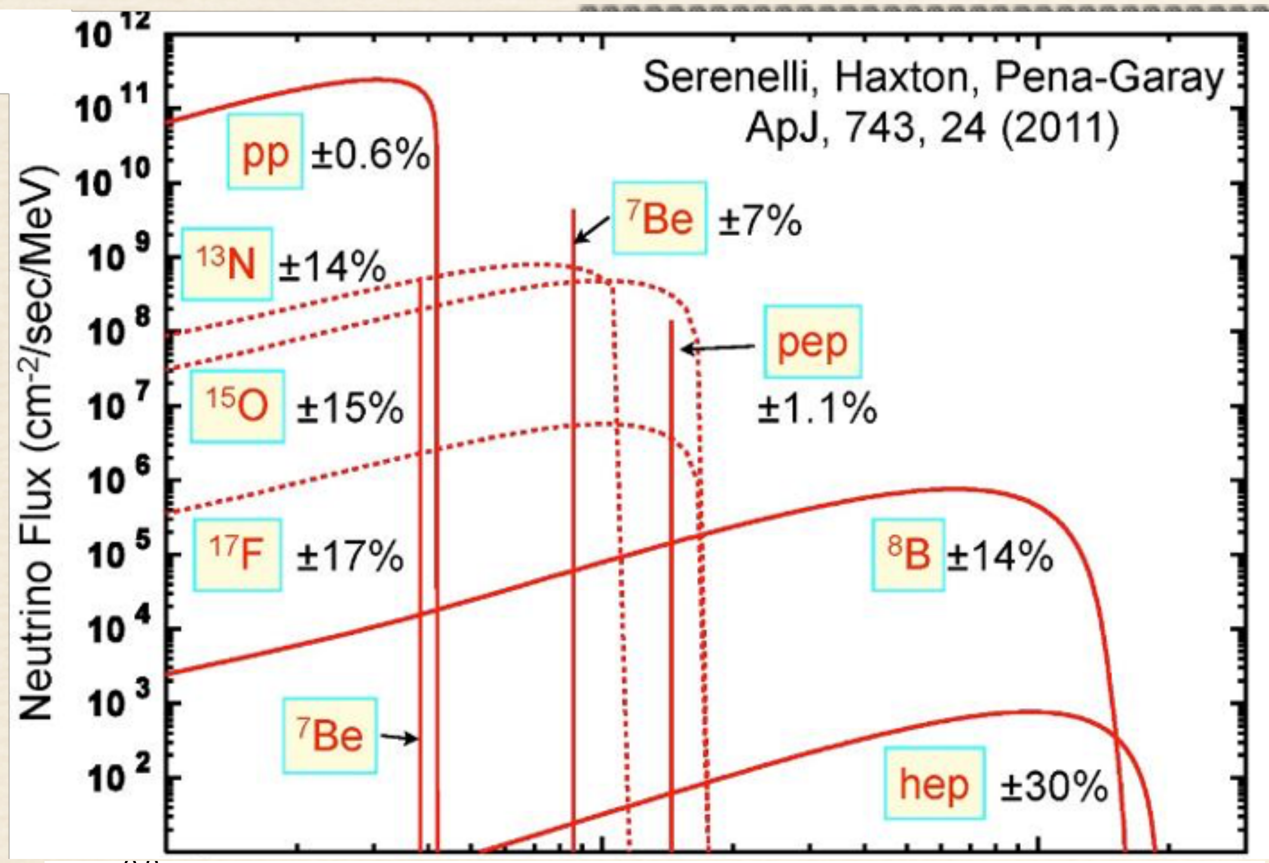




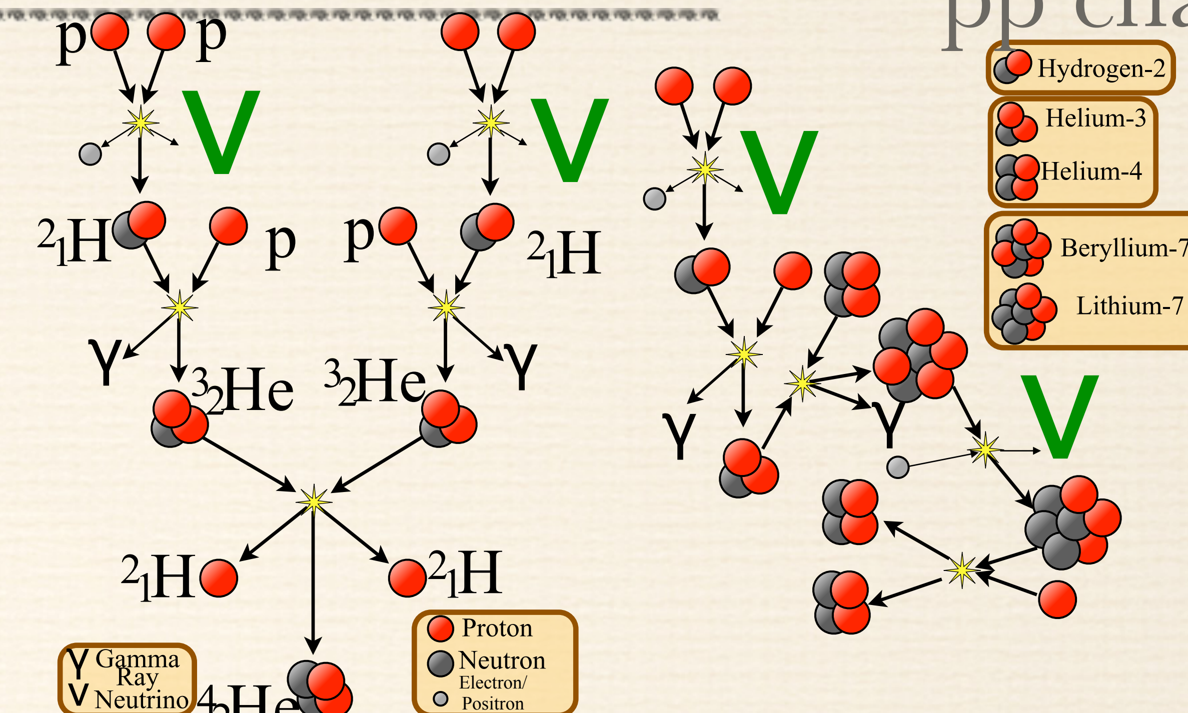
Courtesy T. Yano, ICRR

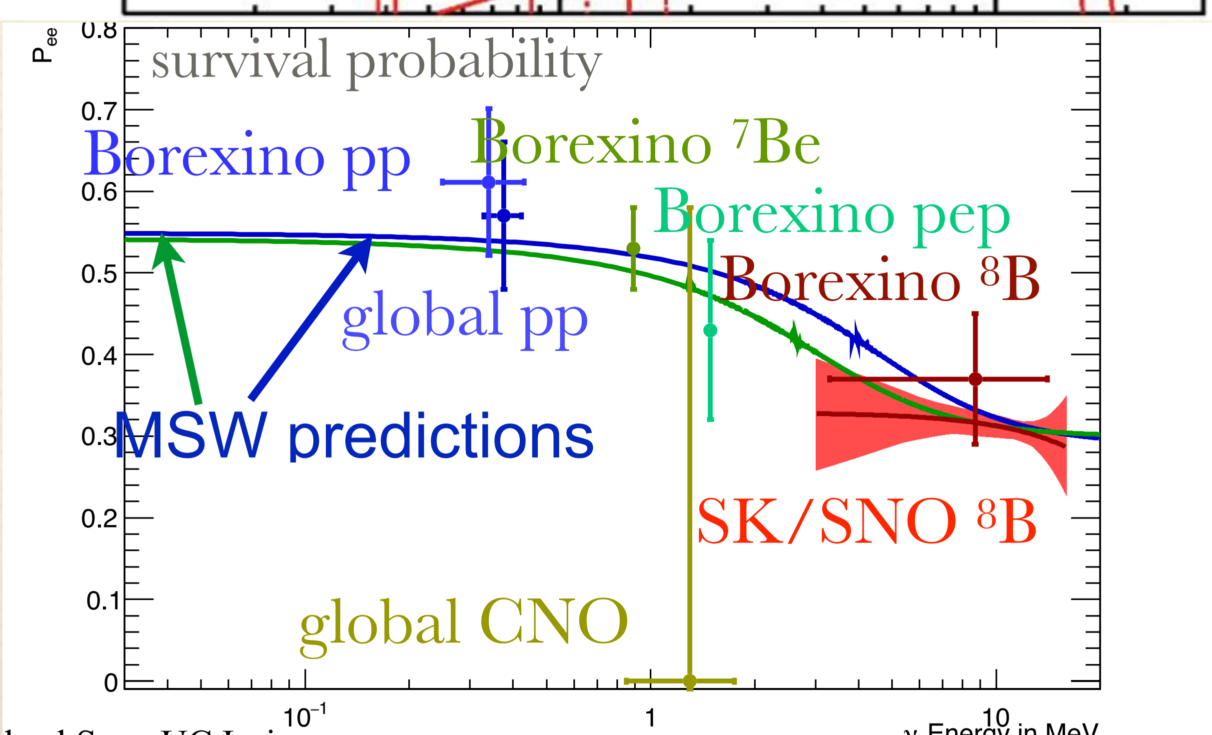
Solar Neutrino Observation

neutrino fluxes



pp chain

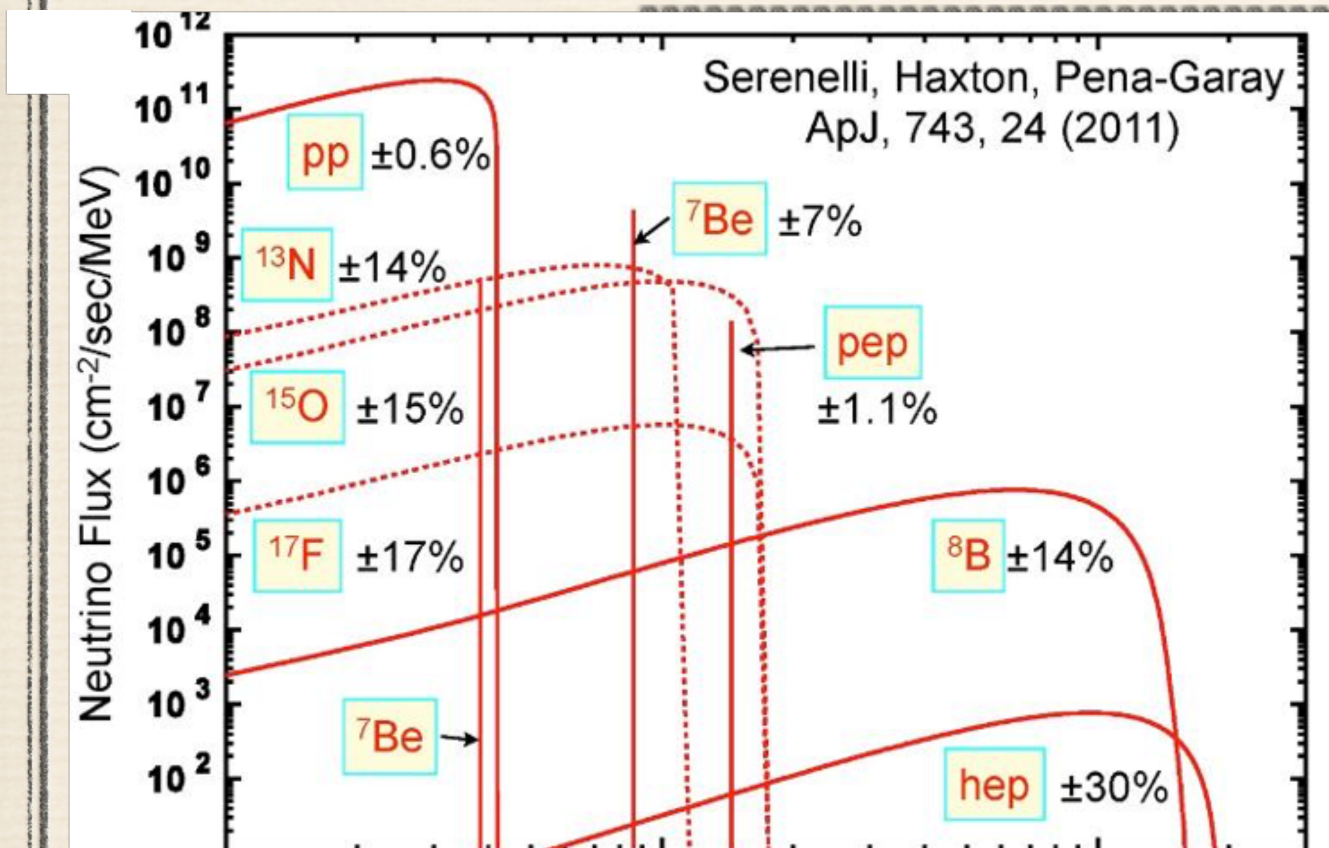


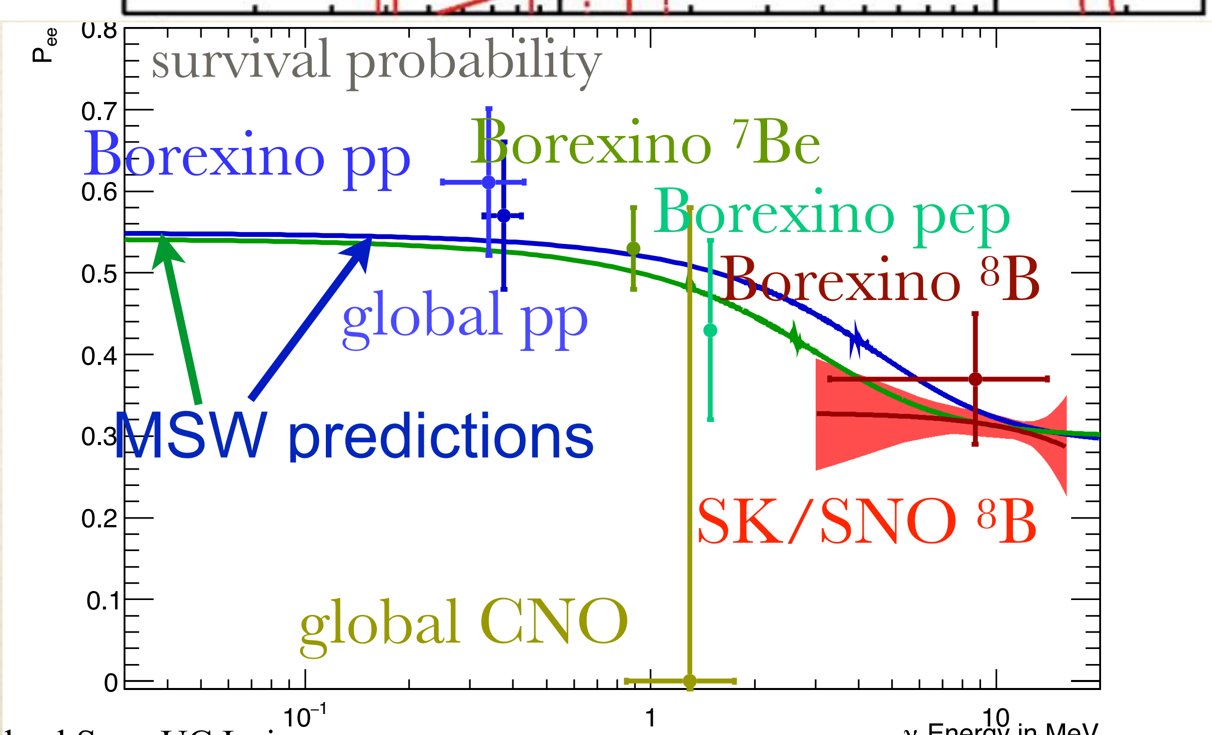


- detect ^{8}B and hep neutrinos (high energy)
- use directionality of recoiling electrons to separate neutrino interactions from radioactive backgrounds
- measure flux (interaction rate) and (recoil electron) spectrum as well as time variations (e.g. day/night asymmetry)
- study MSW, NSI, matter effects, CPT

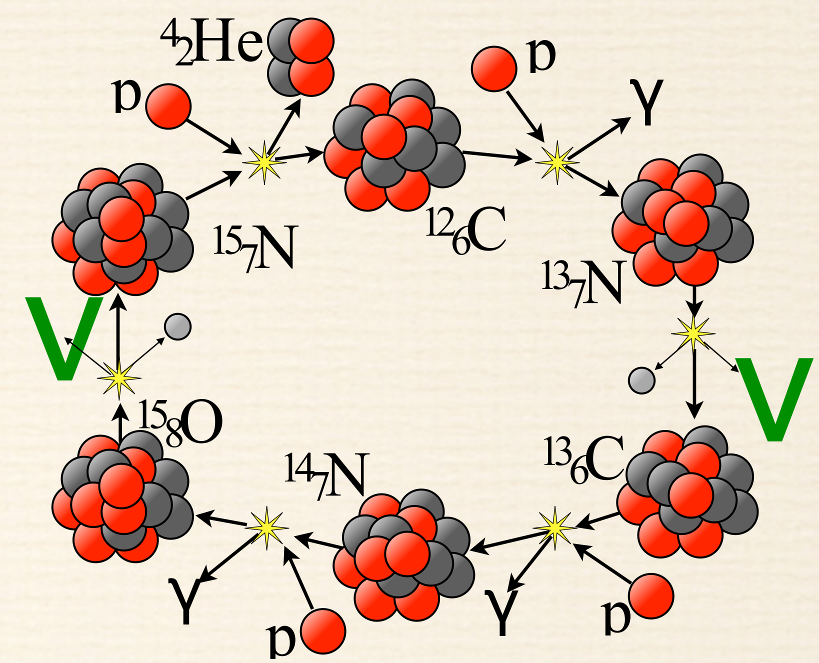
Solar Neutrino Observation

neutrino fluxes





CNO cycle

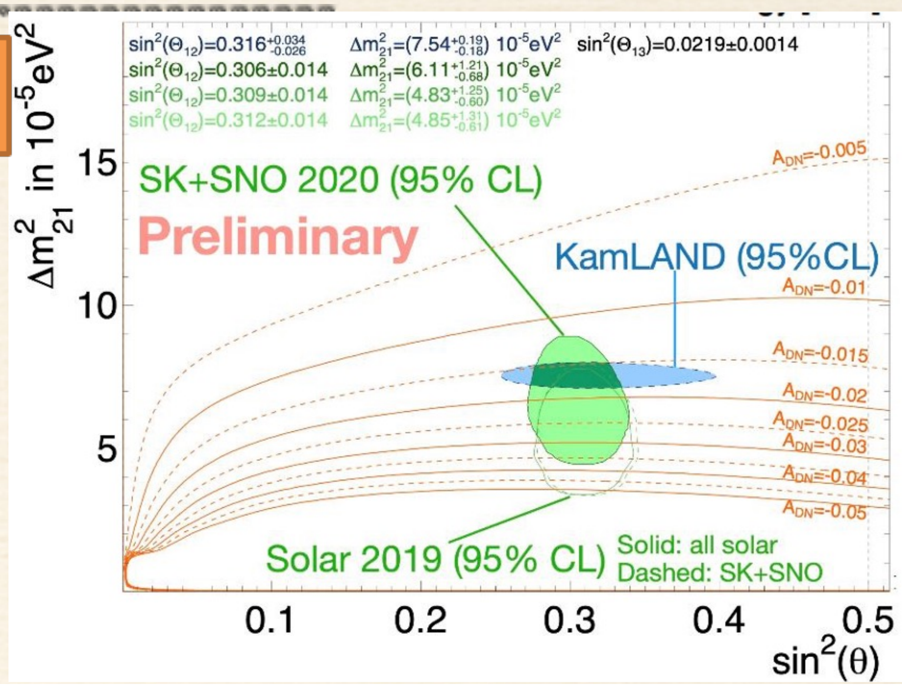


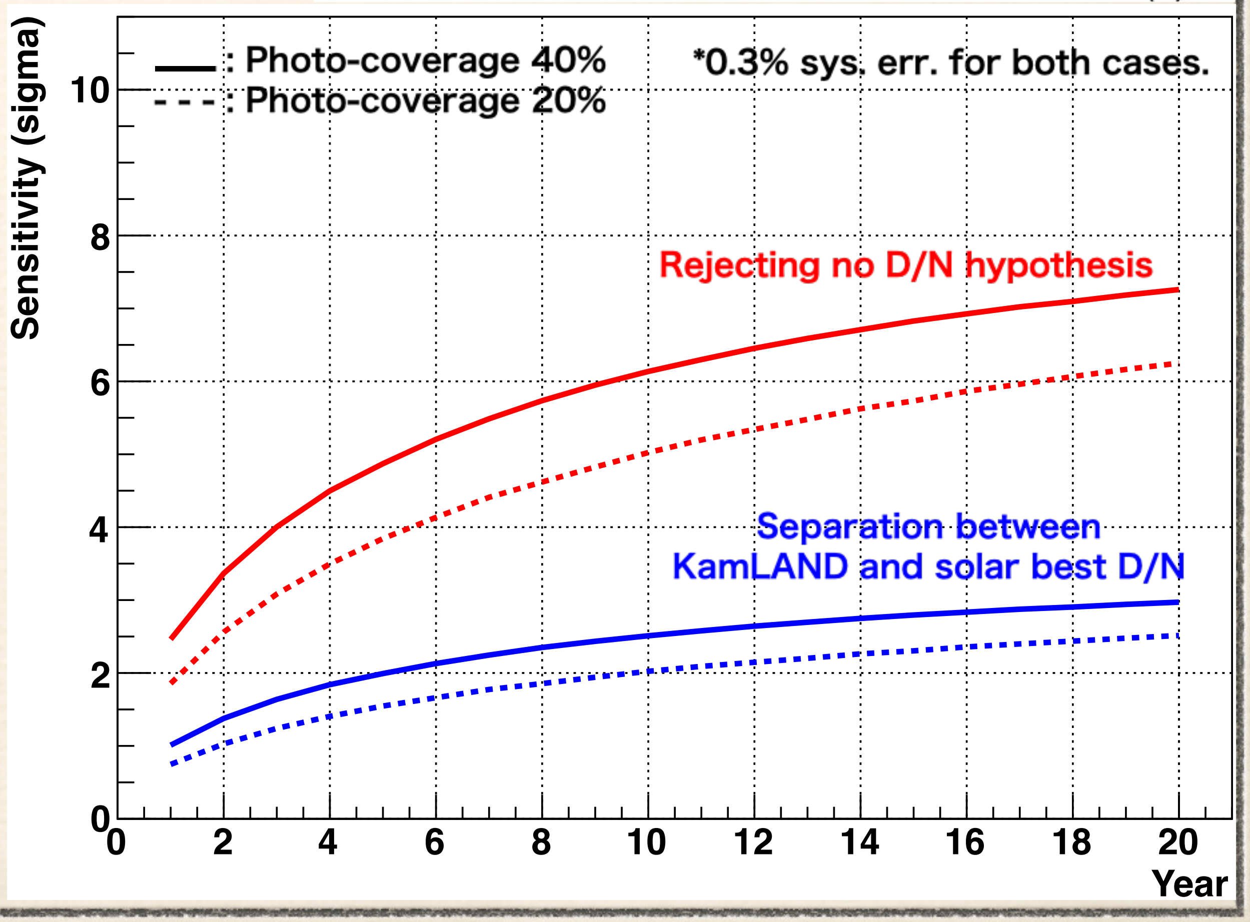
- detect ^{8}B and hep neutrinos (high energy)
- use directionality of recoiling electrons to separate neutrino interactions from radioactive backgrounds
- measure flux (interaction rate) and (recoil electron) spectrum as well as time variations (e.g. day/night asymmetry)
- study MSW, NSI, matter effects, CPT

Solar ^{8}B Neutrino Day/Night Effect

- flavor oscillation due to earth matter density
- requires O(10 MeV) neutrino energy
- starts with ν_2 beam (after MSW)
- "size" and "shape" depends on Δm^2_{21}; characterize size with asymmetry $A_{DN} = \dfrac{r_D - r_N}{0.5(r_D + r_N)}$
- test consistency of neutrino and anti-neutrino (by KamLAND) disappearance measurements of Δm^2_{21}: test CPT invariance

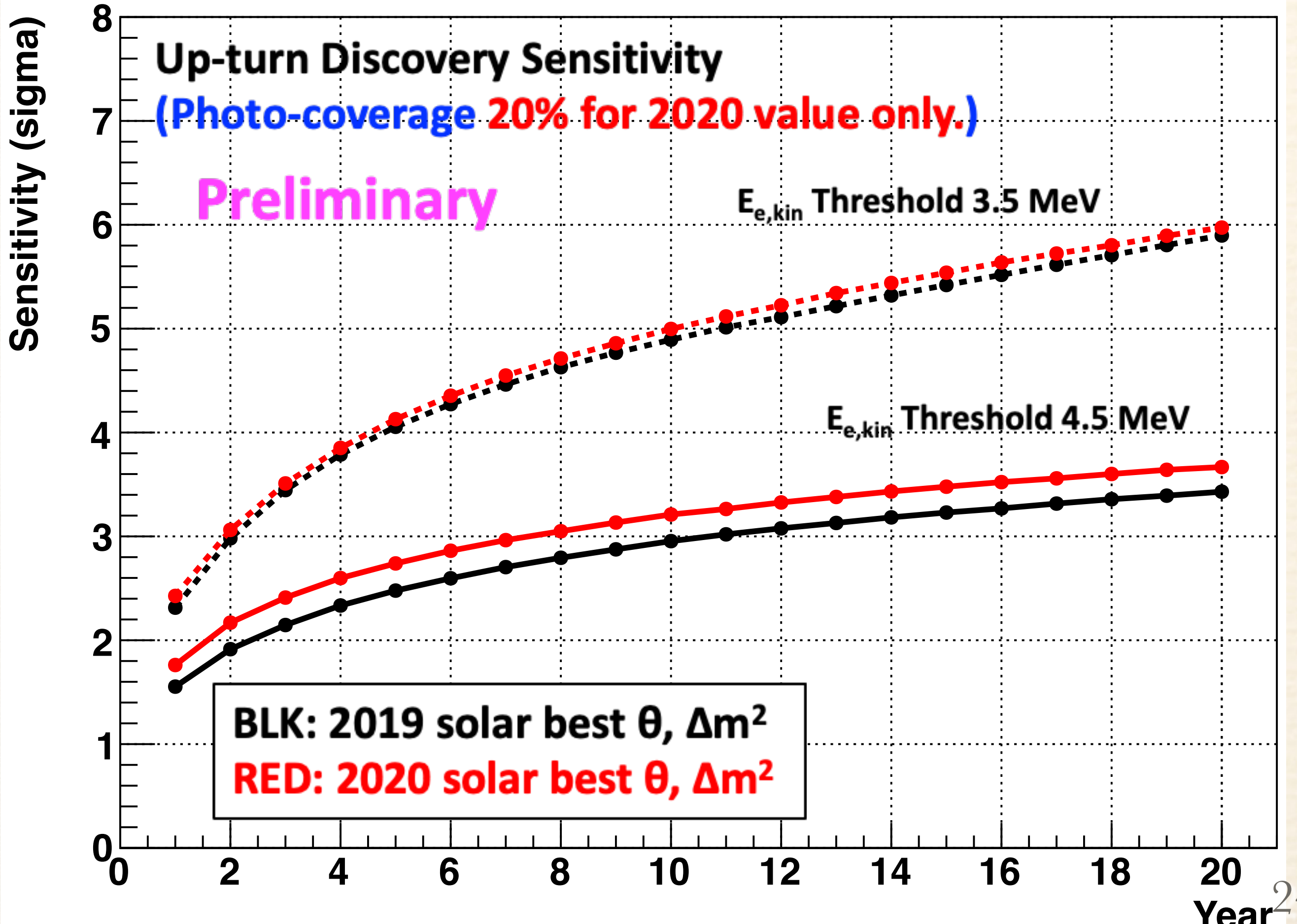
Y. Nakajima, Neutrino 2020

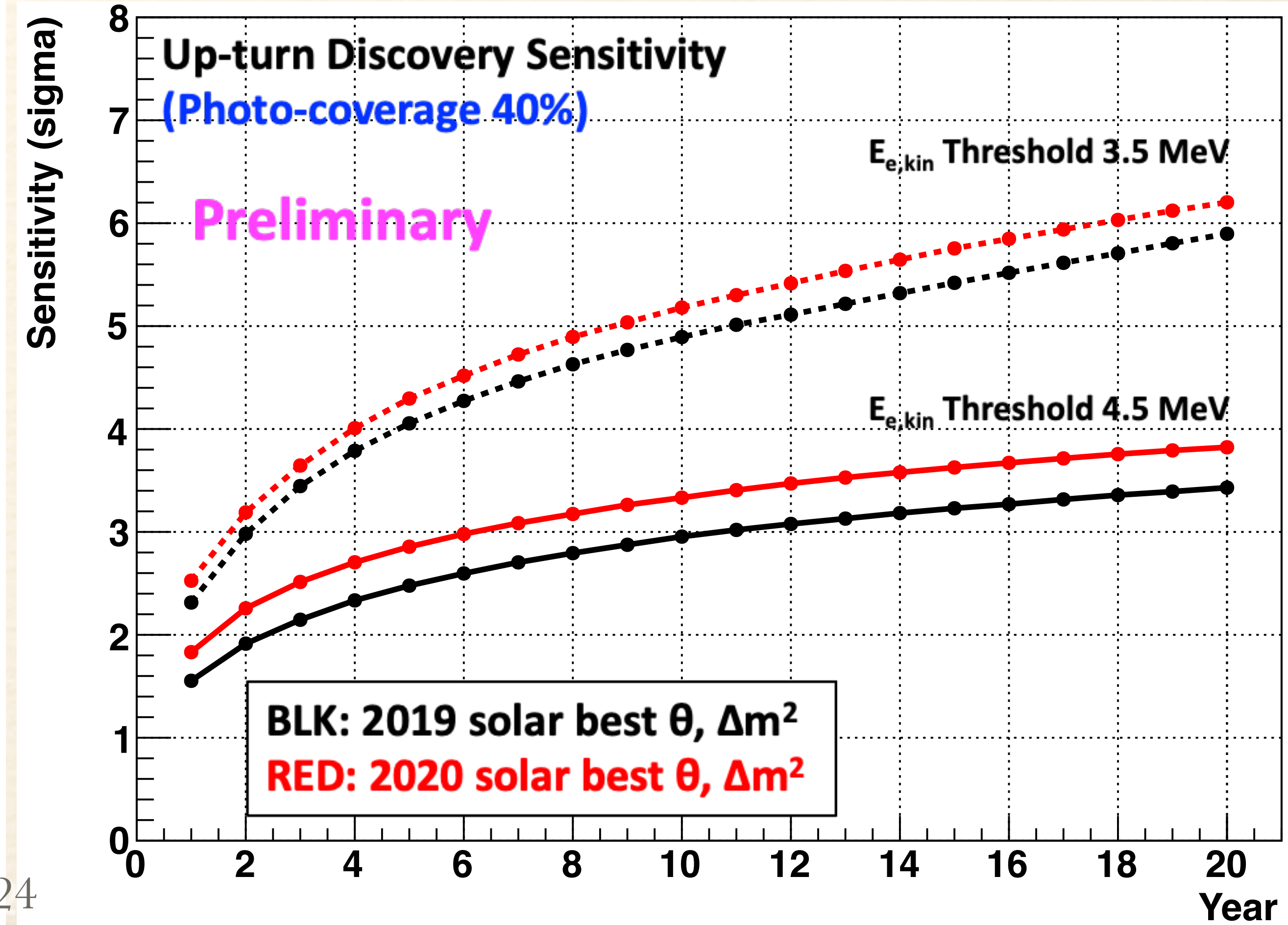




Test MSW Spectral Shape

- transition from averaged vacuum oscillations to adiabatic conversion is about one to ten MeV recoil electron energy, depending on Δm^2_{21}
- NSI or other BSM may modify MSW effect and survival probability
- requires as low an energy threshold and as much photo-coverage as possible
- Hyper-K can observe transition at 3-5σ significance

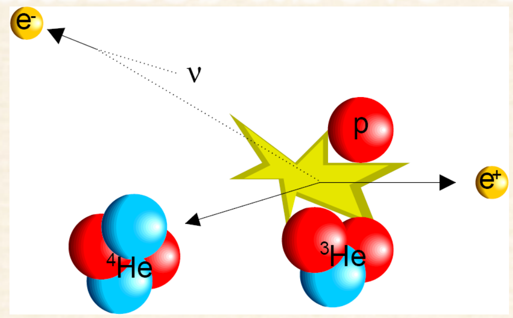


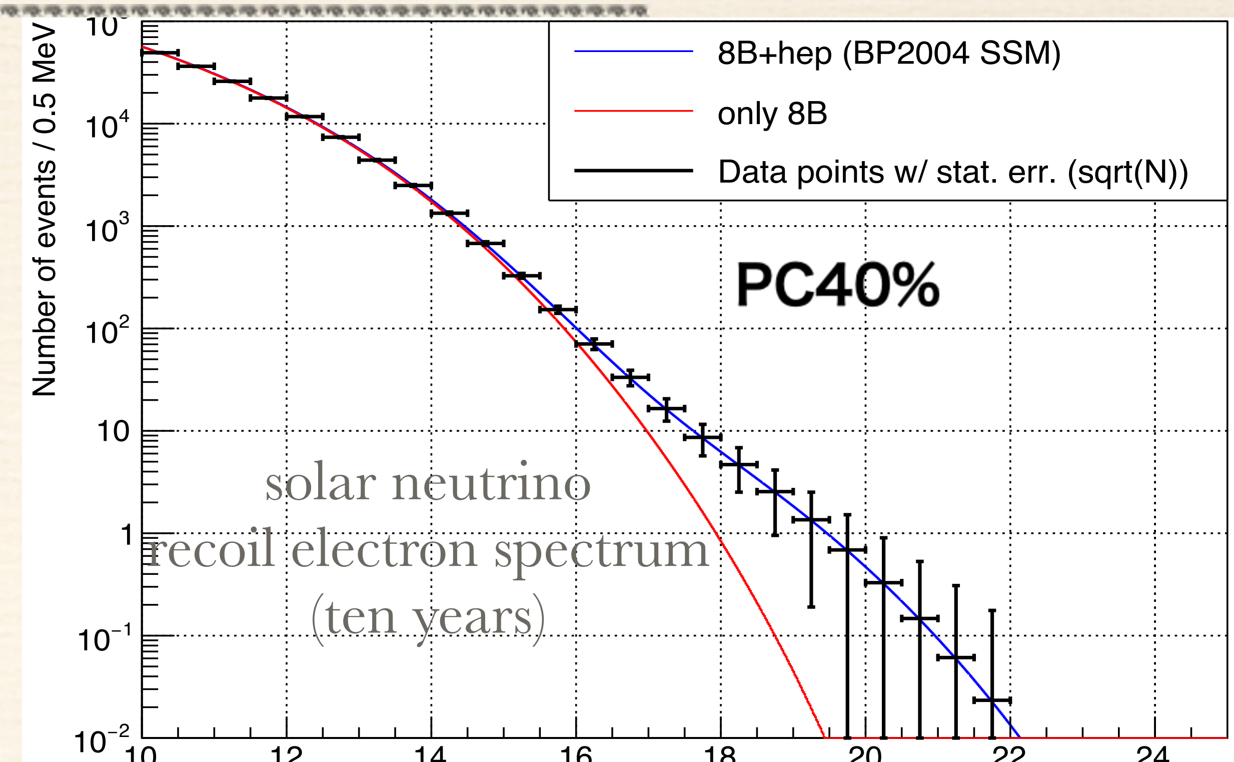


Courtesy T. Yano, ICRR

Other Solar Neutrino Studies

- measure rare hep neutrinos above ^{8}B endpoint
  - so far, unobserved
  - requires good energy resolution (photo-coverage)
  - see with 1.8-3 σ significance in ten years





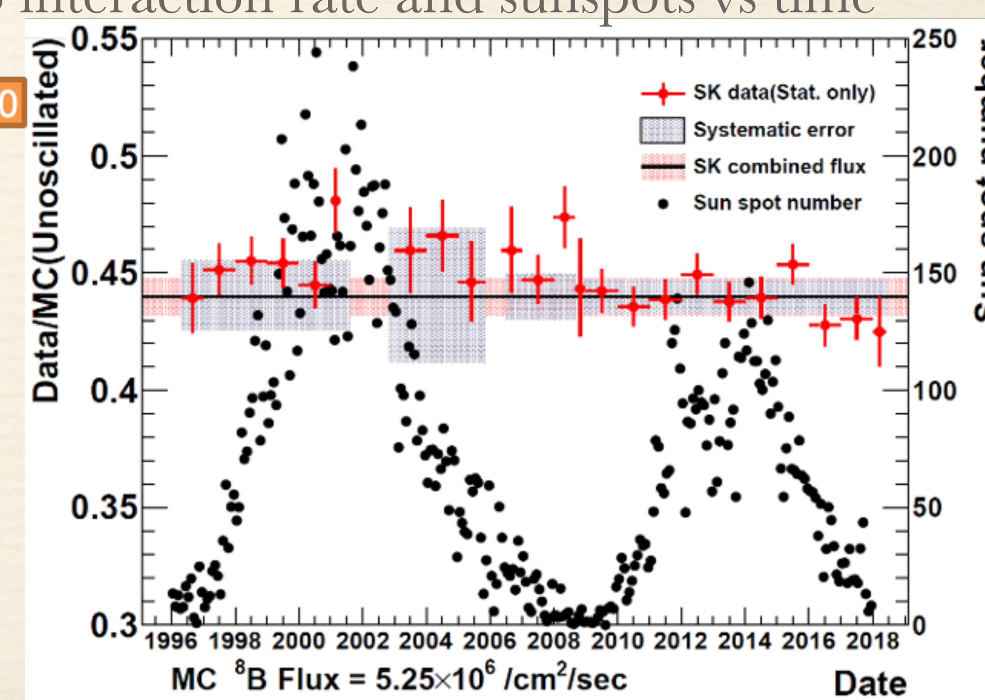
solar neutrino recoil electron spectrum (ten years)

electron kin. energy in MeV

- high statistics flux variation
  - monitor solar “nuclear reactor” with130 events/day above 4.5 MeV
  - compare to 20 events/day for SK

SK: ^{8}B interaction rate and sunspots vs time

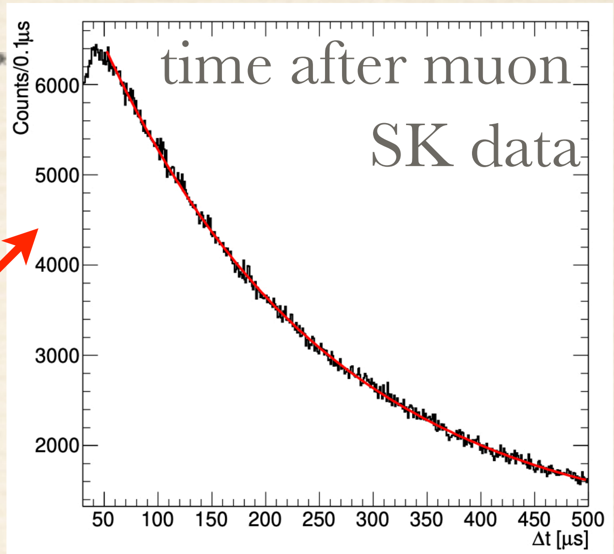
Y. Nakajima, Neutrino 2020



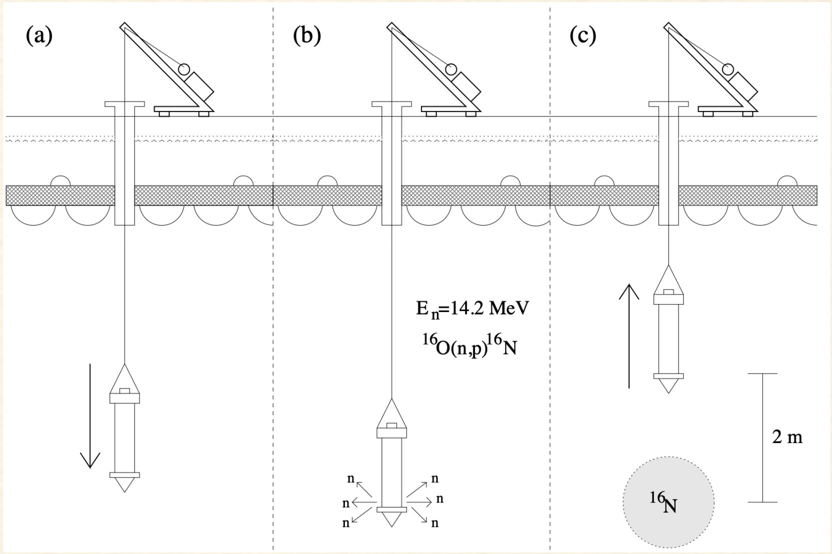
Courtesy T. Yano, ICRR

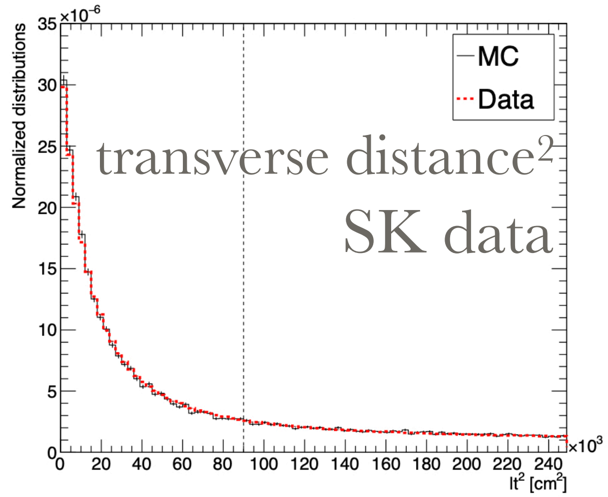
Some Planned US Contributions

- triggering (and reconstruction) of very low energy electrons
  - designed and build a system for Super-K that has high efficiency for electrons>2.5 MeV; see 2.2 MeV gammas from fast neutrons from showering muons!

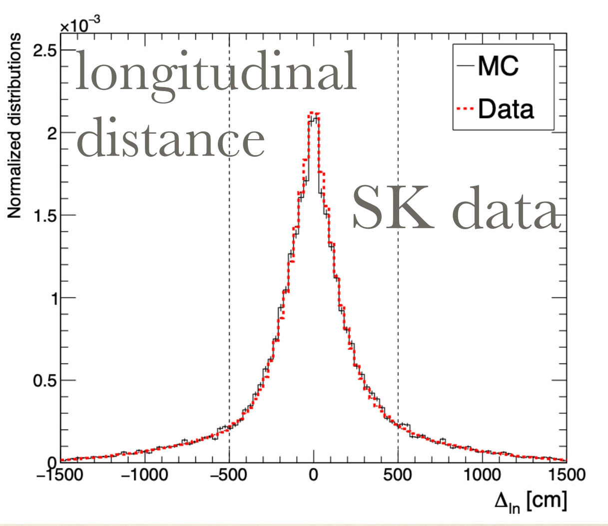


- energy calibration from ^{16}N decays made by (p,n) of 14 MeV neutrons from D-T fusion
  - operated such a system in Super-K; gives precise calibration point at ~7 MeV





- control of cosmogenic radioactivity (dominates 6-22 MeV)
  - Hyper-K's location is not very deep→much, much larger cosmogenic radioactivity than Super-K
  - in Super-K: O(10^3) events/day!



from arXiv: 2112.00092

Some Planned US Contributions

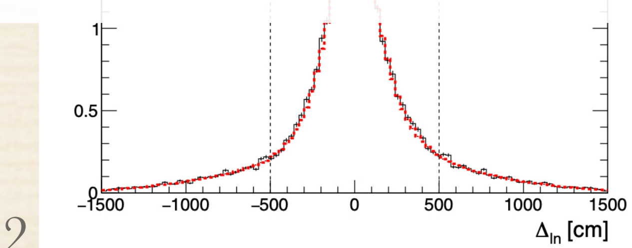
WIT, a Super-K intelligent trigger with 2.5 MeV Energy Threshold

- "sliding 230nsec window" search for events in (calibrated) hit times
- coincidence criterion c= $\sum e^{-\frac{1}{2}\left(\frac{\Delta t_i}{\sigma}\right)^2}$ of hit time residuals Δt_i=PMT time-time of flight-time of emission with σ=5nsec
- list of possible vertices is "guessed" from 4-hit combinations
- fast vertex reconstruction to all hits in the 230nsec window
- full vertex fit to hits within 1.5μsec of the trigger time
- count hits with -6nsec<Δt_i<12nsec; require 10 or larger

Similar system for Hyper-K, investigate machine-learning techniques

larger cosmogenic radioactivity than Super-K

- in Super-K: $O(10^3)$ events/day!



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Michael Smy, UC Irvine

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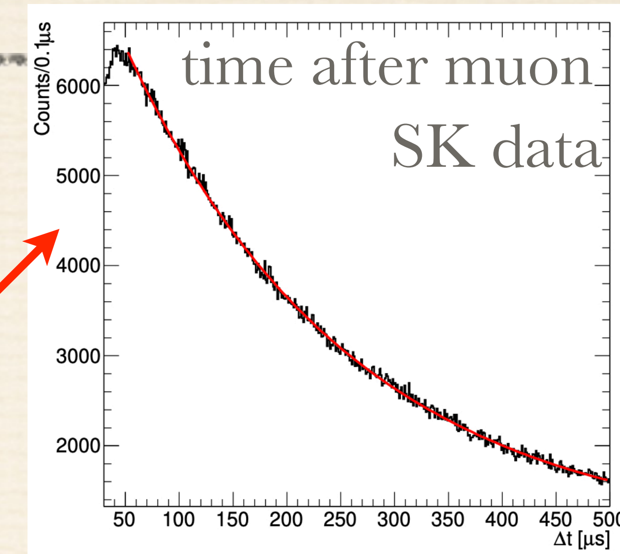

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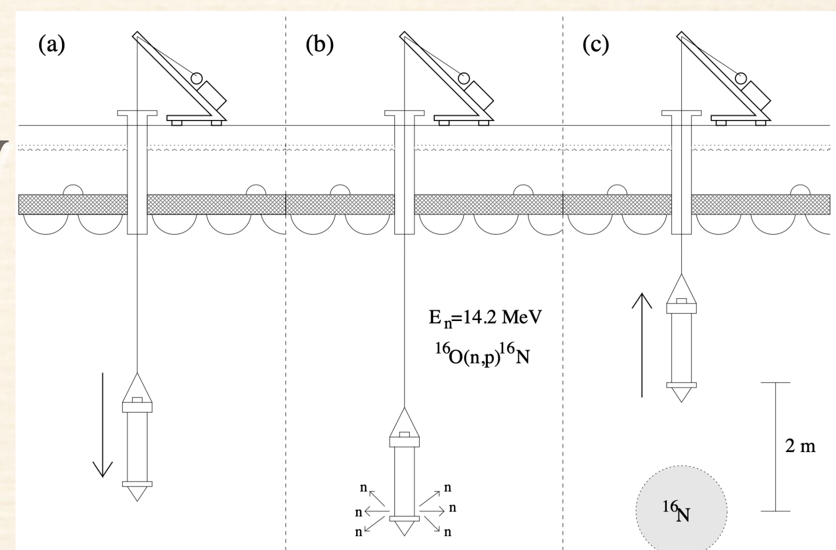

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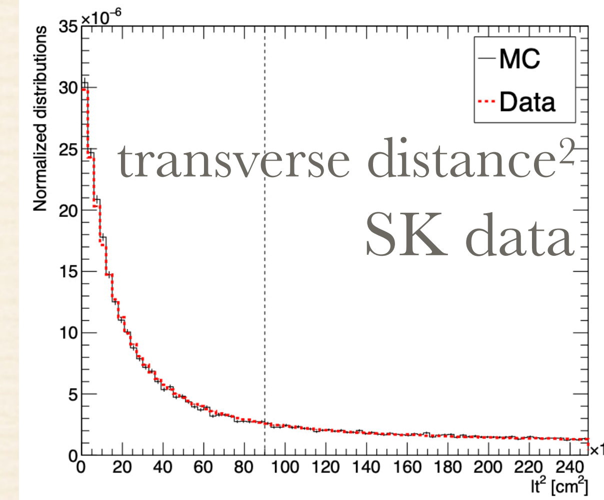

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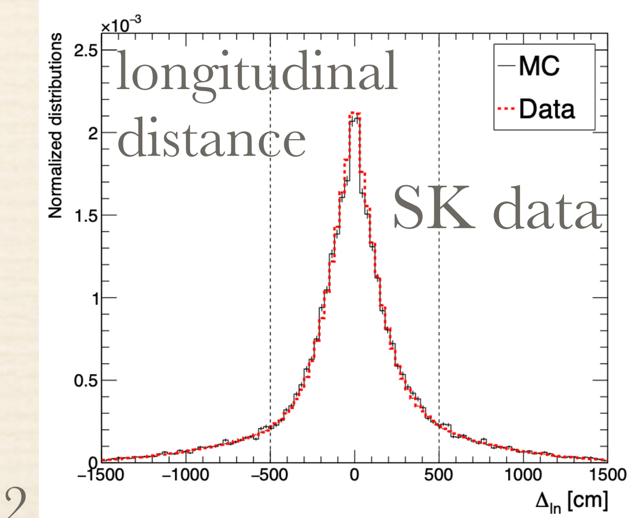
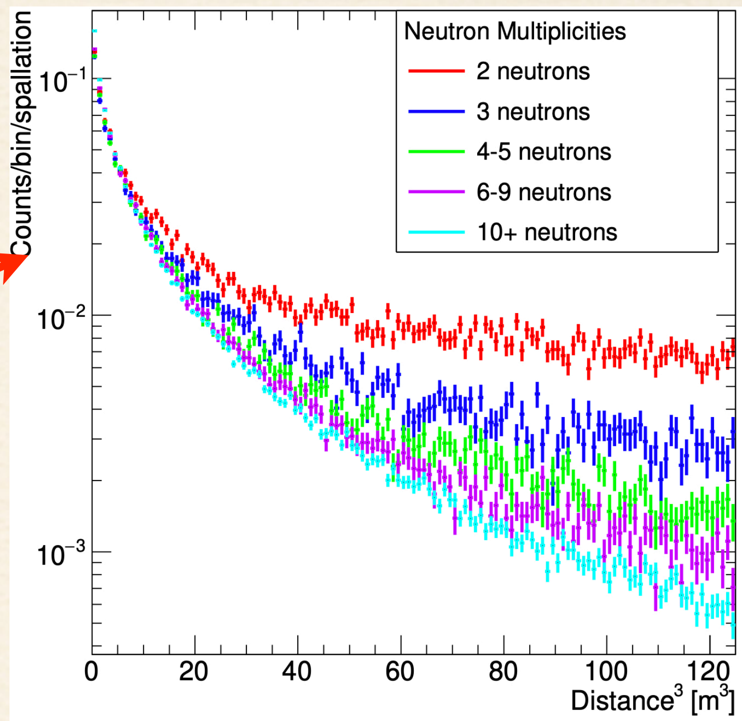


from arXiv: 2112.00092

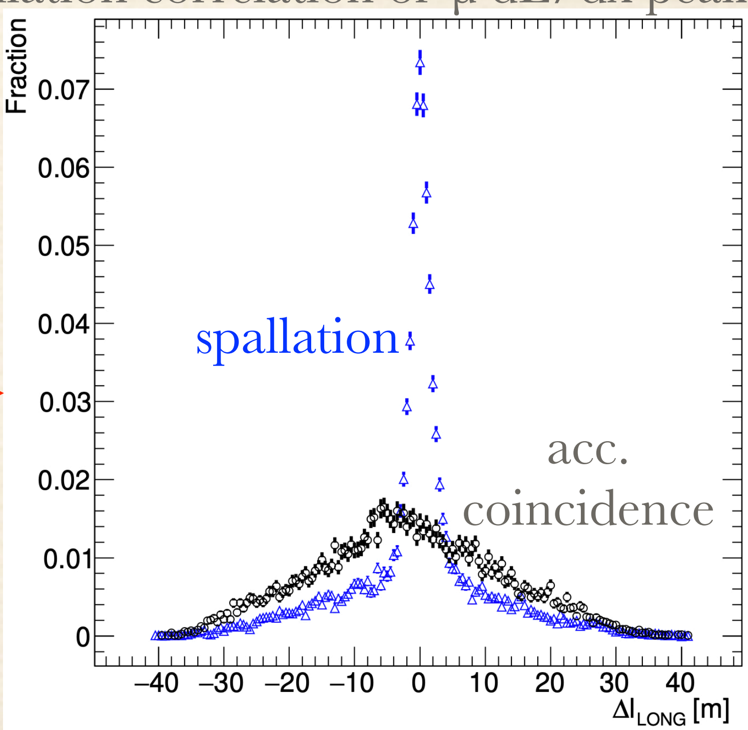
Spallation Decay Tagging in Super-K

- most cosmogenic radioactivity is produced in hadronic showers initiated by energetic muons
- invented three tagging methods:
  - neutron clouds: hadronic showers make many neutrons ("clouds") capturing near muon track
  - multiple spallation: ~50% of spallation results in more than one decay → time and spatial correlation: decays tag each other without need to use muon track
  - reconstruct optical muon "dE/dx" to identify showers and find shower position along track
- results in efficient tag without loosing much signal

spallation correlation of neutron cloud



spallation correlation of μ dE/dx peak



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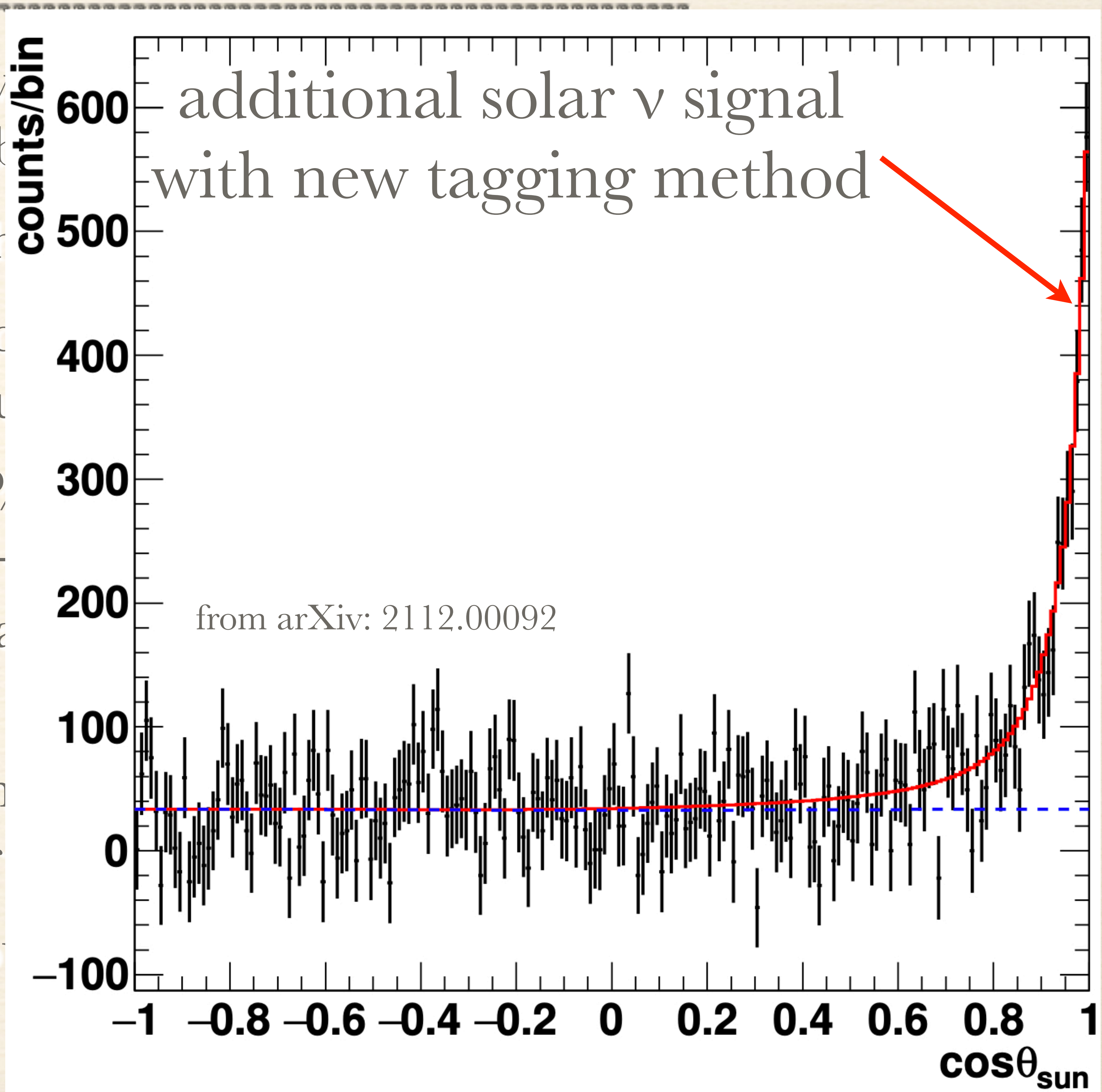

Conclusions

- JUNO, Hyper-Kamiokande and DUNE will dominate neutrino flavor physics in the near future
- Hyper-Kamiokande construction has started, data will come as soon as 2027
- the Hyper-Kamiokande experimental program is complementary to DUNE's
- in addition to neutrino oscillation measurements, Hyper-K offers many other physics topics