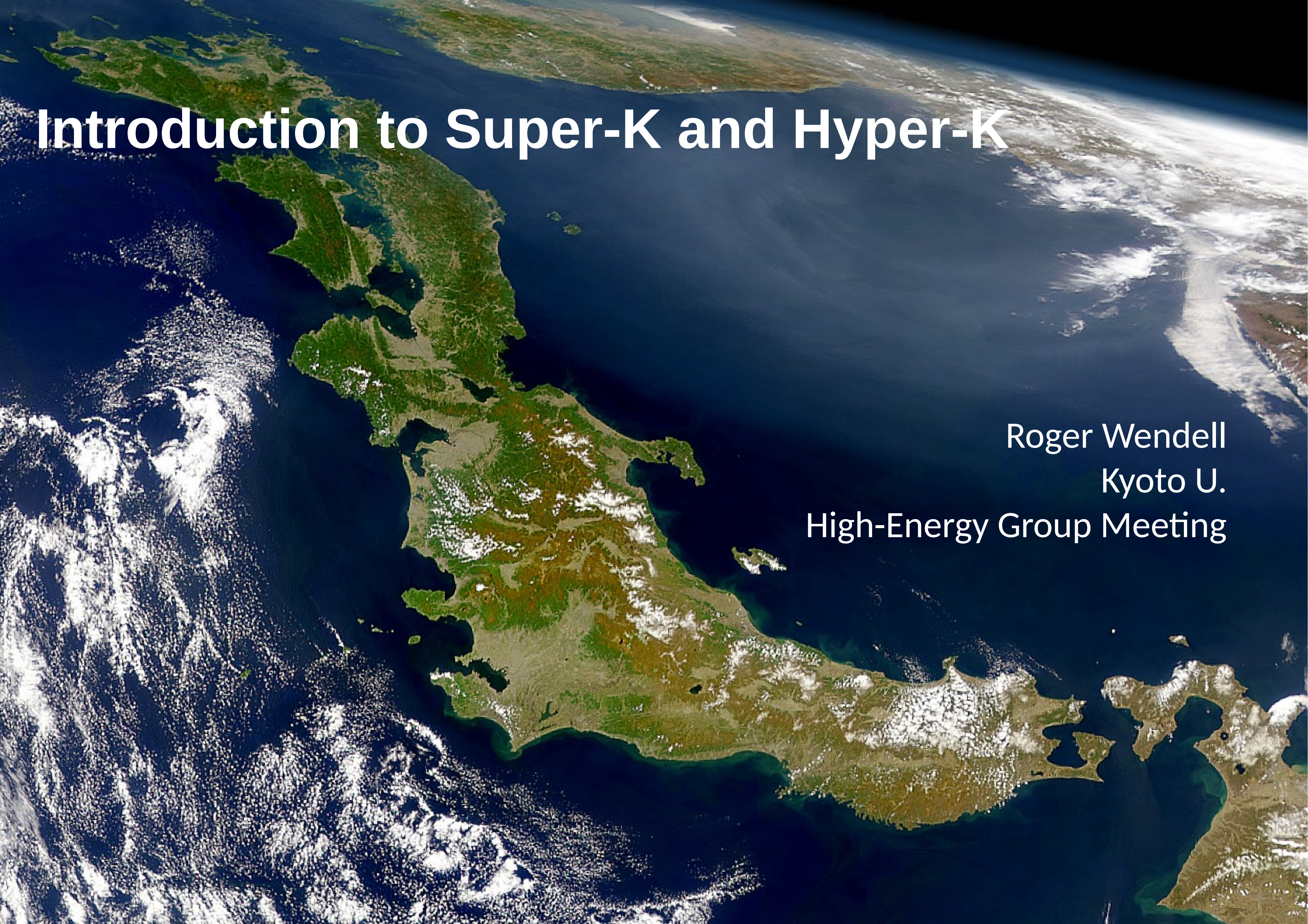
# Introduction to Super-K and Hyper-K

Roger Wendell
Kyoto U.
High-Energy Group Meeting



# First Things First

- Super-Kamiokande has been operating for 20 years

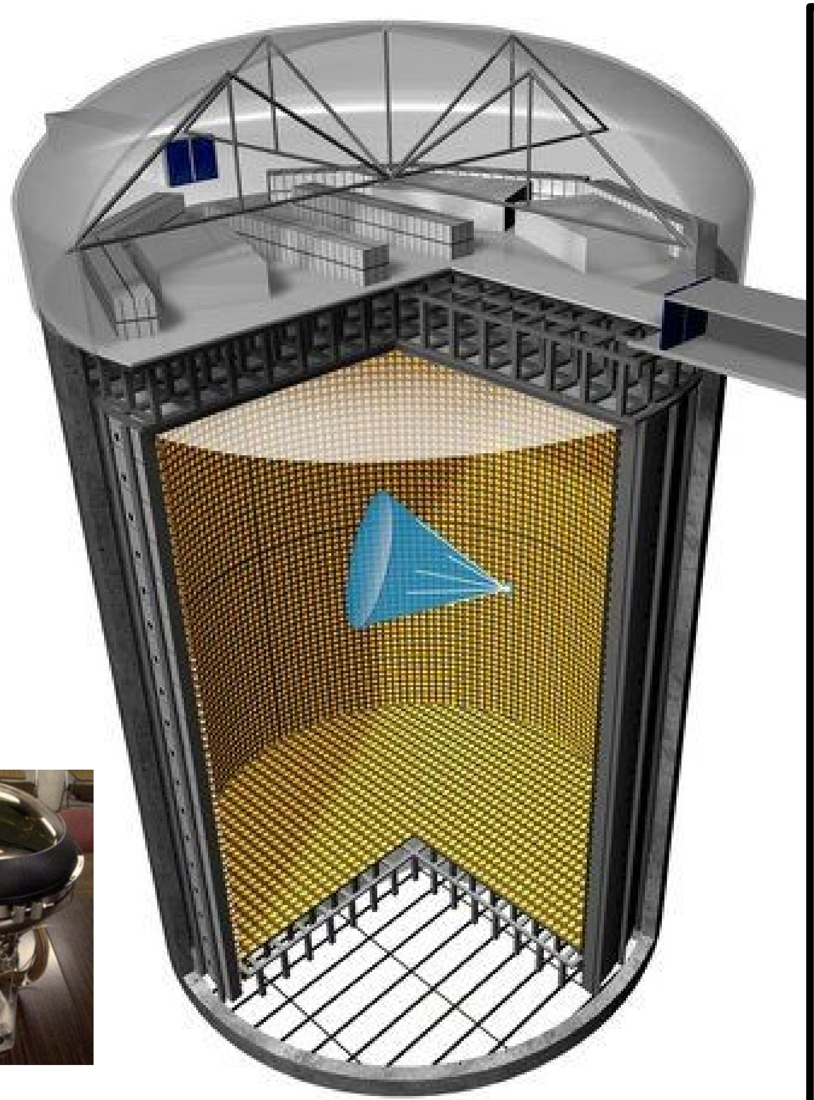
- It is a large experiment, with many physics topics
  - Atmospheric neutrino oscillations
  - Exotic neutrino oscillations
  - Solar neutrino flux and oscillation measurements
  - Relic supernova neutrino searches
  - Proton decay searches
  - Indirect dark matter searches
  - Astrophysical neutrino search
  - Searches for exotic particles (fractionally charged, Q-balls, monopoles, etc.)
  - etc. etc. etc.

- Masters student projects are similarly varied
  - Analysis, calibration, and detector development projects

# A Look At Recent Master Thesis on Super-K

- スーパーカミオカンデ装置におけるレイリー散乱測定 NEW
  T. Nakajima, Master Thesis, Univ. of Tokyo, Jan. 2015 (PDF 3.2MB)
- 大気ニュートリノにおける東西効果及び太陽活動が大気ニュートリノのフラックスに与える NEW
  影響に関する研究 I. Kametani, Master Thesis, Univ. of Tokyo, Jan. 2014 (PDF 7MB)
- スーパーカミオカンデにおける中性子信号を用いた陽子崩壊探索 NEW
  Y. Haga, Master Thesis, Univ. of Tokyo, Jan. 2014 (PDF 7MB)
- スーパーカミオカンデ検出器におけるラドン濃度測定と 超新星爆発ニュートリノバースト探索 Y. Nakano, Master Thesis, Univ. of Tokyo, Jan. 2013 (PDF 8.35MB)
- スーパーカミオカンデ実験における太陽フレアニュート リノの探索 NEW
  M. Miyake, Master Thesis, Univ. of Nagoya, Jan. 2012 (PDF 18MB)
- T2K 長基線ニュートリノ実験のための後置検出器スーパーカミオカンデの較正
  K. Iyogi, Master Thesis, Univ. of Tokyo, Jan. 2011 (PDF 10.8MB)
- 超级神冈实验中弱作用重粒子的直接寻找研究(A Direct Search for Weakly Interacting Massive Particles in the Super-Kamiokande Experiment)
  Y. Heng Master Thesis, Tsinghua University, Jun. 2010 (PDF 40MB)
- T2K長基線ニュートリノ振動実験の後置検出器スーパーカミオカンデのアップグレード
  Y. Kouzuma Master Thesis, Univ. of Tokyo, Feb. 2010 (PDF 5.2MB)
- Slide 4 ーカミオカンデにおける検出器較正と超新星爆発ニュートリノバーストの探索
  T. Yokozawa Master Thesis, Univ. of Tokyo, Jan. 2010 (PDF 7.4MB)

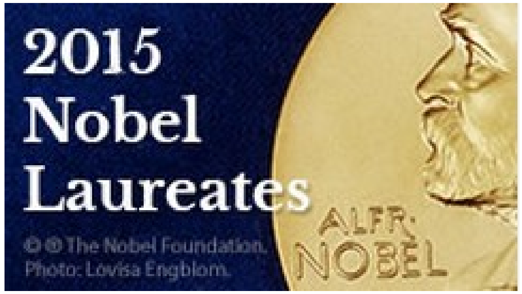
# Super-Kamiokande: Introduction



**Four Run Periods:**
**SK-I (1996-2001) SK-II (2003-2005)**
**SK-III (2005-2008) SK-IV (2008-Present)**

- 22.5 kton fiducial volume
- Optically separated into
  - Inner Detector 11,146 20” PMTs
  - Outer Detector 1885 8” PMTs
- No net electric or magnetic fields
- Neutrino direction and energy are unknown
  - Hard to reconstruct directly
- Excellent PID between showering (e-like) and non-showering (m-like)
  - ~ 1% MIS ID at 1 GeV
- As of Today: 4972 days of data
  - 51,000 Events
- Multipurpose machine
  - Solar and Supernova Neutrinos
  - Atmospheric Neutrinos
  - Nucleon Decay
  - Far detector for T2K

# A Big Year for Neutrinos And Their Oscillations




Takaaki Kajita (SK)

Art McDonald (SNO)

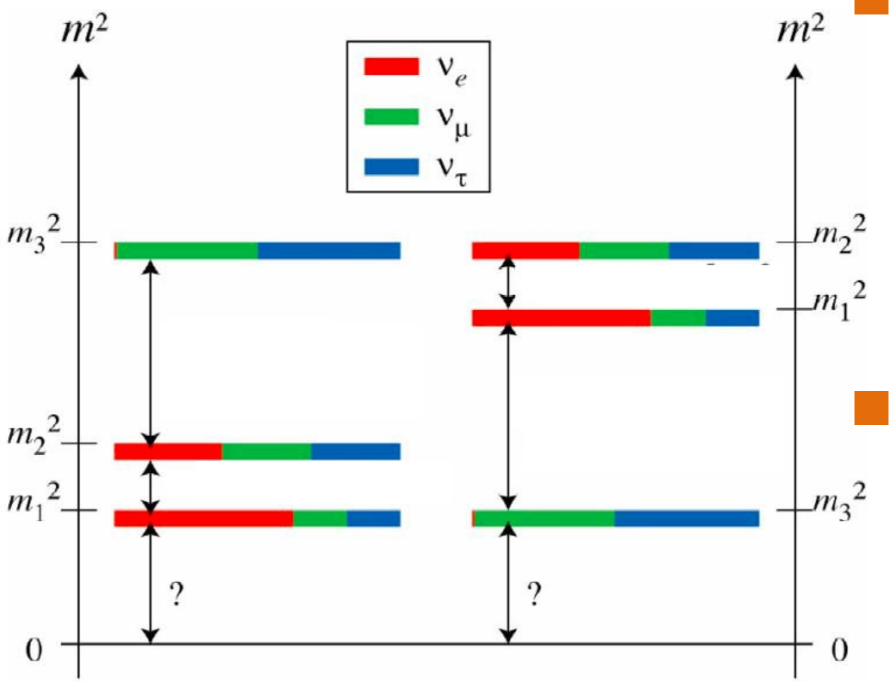
Ko Nishikawa (T2K)    Yoichiro Suzuki (SK)    Takaaki Kajita (SK)

- Neutrino Oscillation Discovery at Super-Kamiokande recognized with 2015 Nobel Prize
- Both the Super-Kamiokande and T2K collaborations have been awarded the Breakthrough Prize in Fundamental Physics, 2016 … time to take the next step!

# Status of Neutrino Oscillations

Atmospheric | Solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 0 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

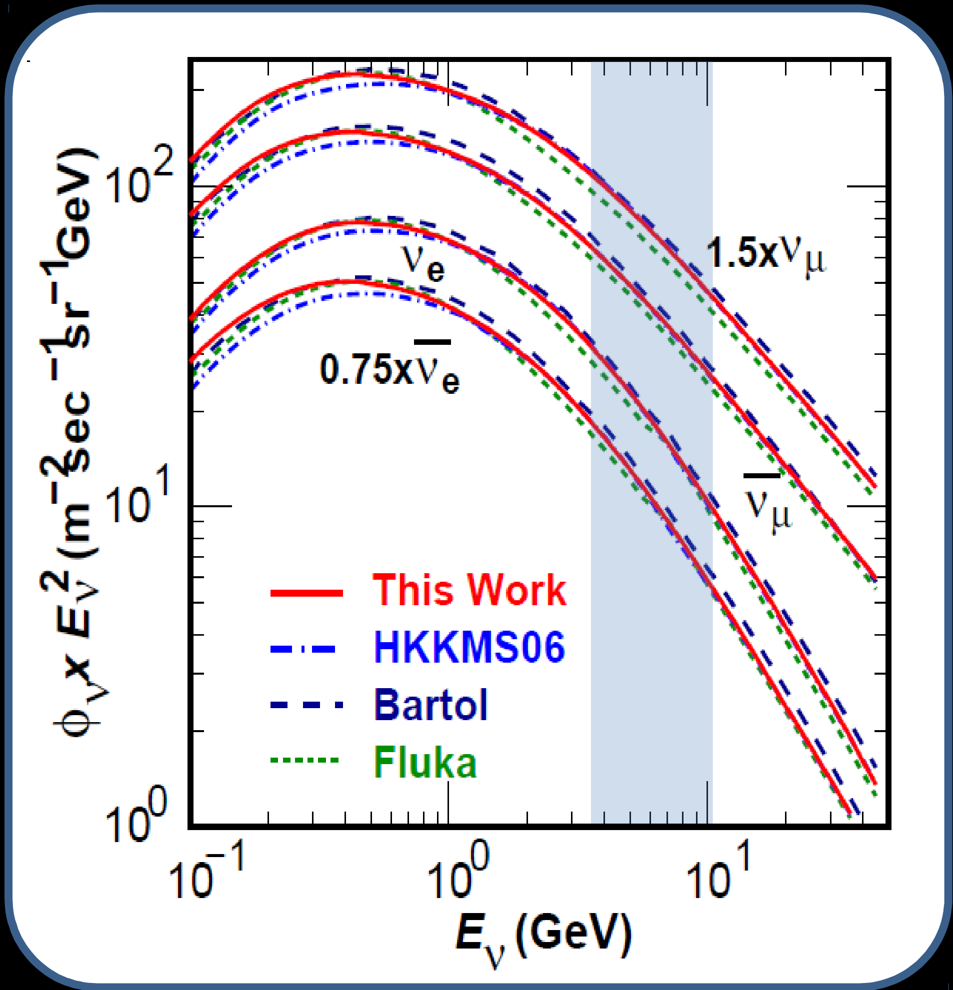



Normal Hierarchy | Inverted Hierarchy

- Mixing between all three neutrino flavors has been observed
  - $\theta_{12} = 33.4 \pm 0.8°$
  - $\theta_{13} = 8.8 \pm 0.4°$
  - $\theta_{23} = 45.8 \pm 3.2°$ (octant?)
- Two Mass Differences
  - $\Delta m^2_{12}$ ~ 7.5e-5 eV$^2$
  - $|\Delta m^2_{32}|$ ~ 2.4e-3 eV$^2$ (hierarchy?)
- CP-phase ,$\delta$cp remains largely unkown
  - [-1,-0.14] π and [0.87,1]π 90% C.L.
- Absolute value of mass states is unknown

# Atmospheric Neutrinos

# Atmospheric Neutrino Generation



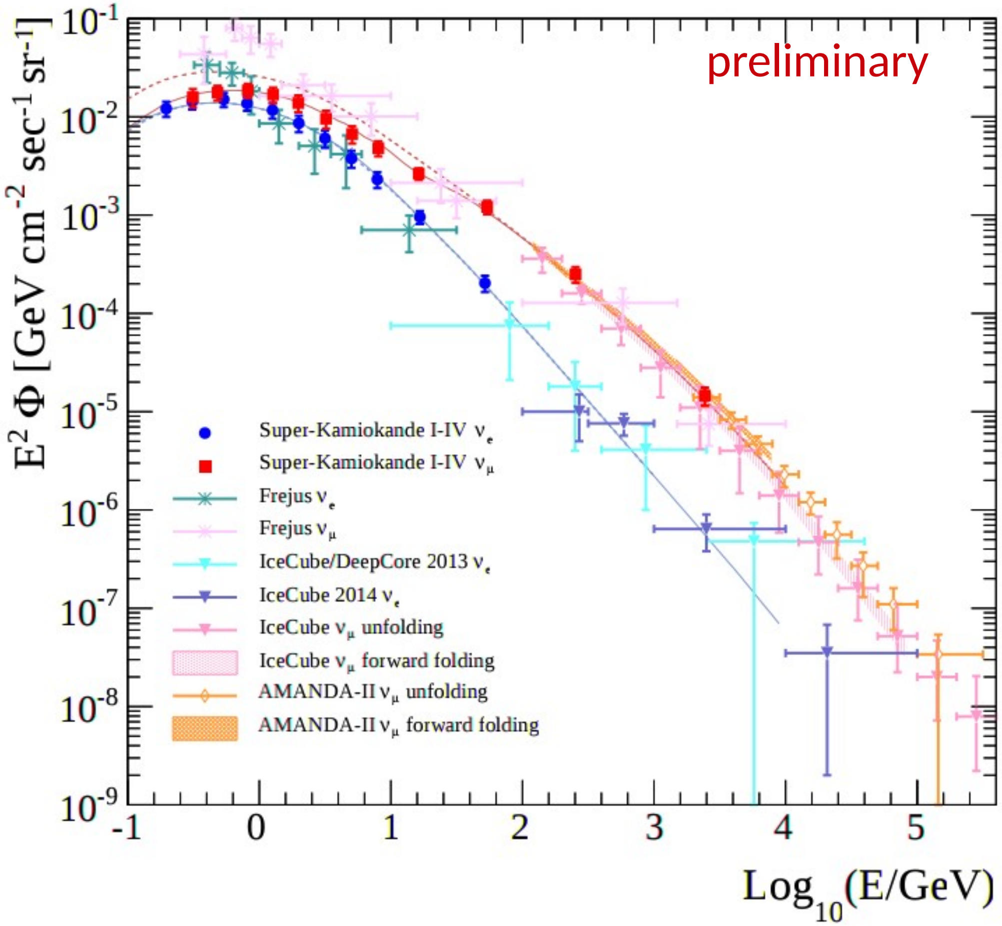

- Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos

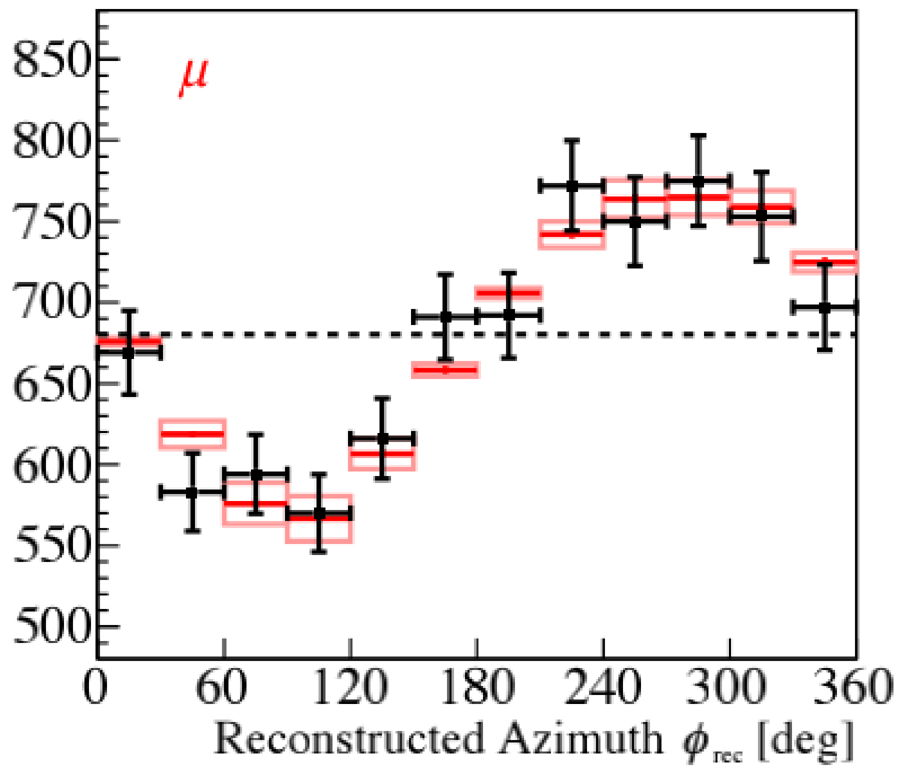
$$P + A \rightarrow N + \pi+ \ + x$$

$$\mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Primary cosmic rays Isotropic about Earth
- νs travel 10 – 10,000 km before detection
- Both neutrinos and antineutrinos in the flux
  - ~ 30% of final analysis samples are antineutrinos
- Flux spans many decades in energy ~100 MeV – 100TeV+
- Excellent tool for broad studies of neutrino oscillations
  - Access to sub-leading effects with high statistics

# Atmospheric ν Flux Measurement (2015) [ E.Richards Thesis ]

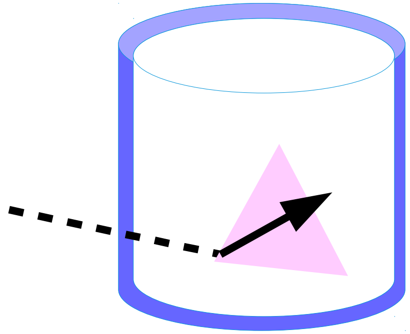


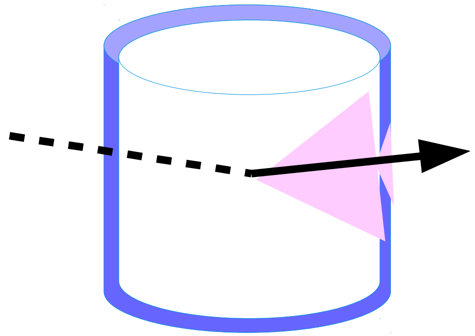

- Measurement of νe (E < 100 GeV) and νμ (E< 1 TeV) fluxes
  - Good agreement with current models (Honda et. al 2011 shown)
- Dipole asymmetry now confirmed at seen at 6.0σ (μ-like) and 8.0σ (e-like)

# Super-K Atmospheric ν Analysis Samples

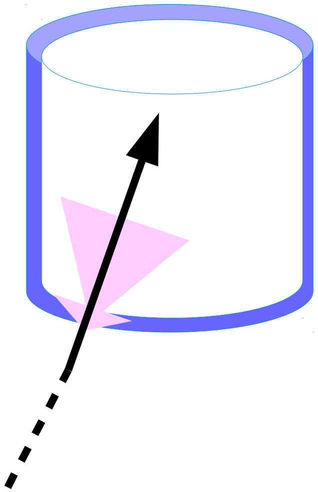
**Fully Contained (FC)**

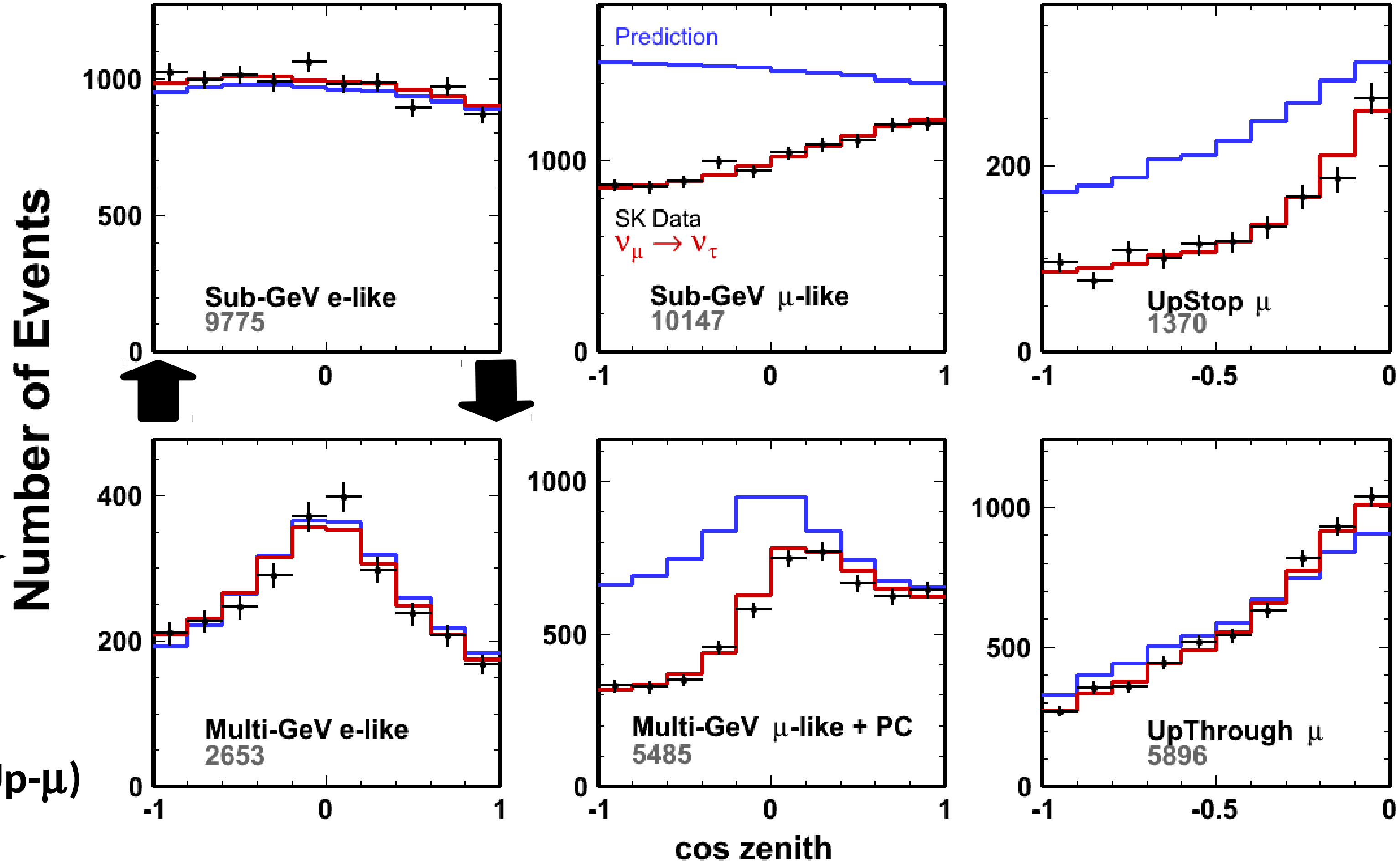


**Partially Contained (PC)**



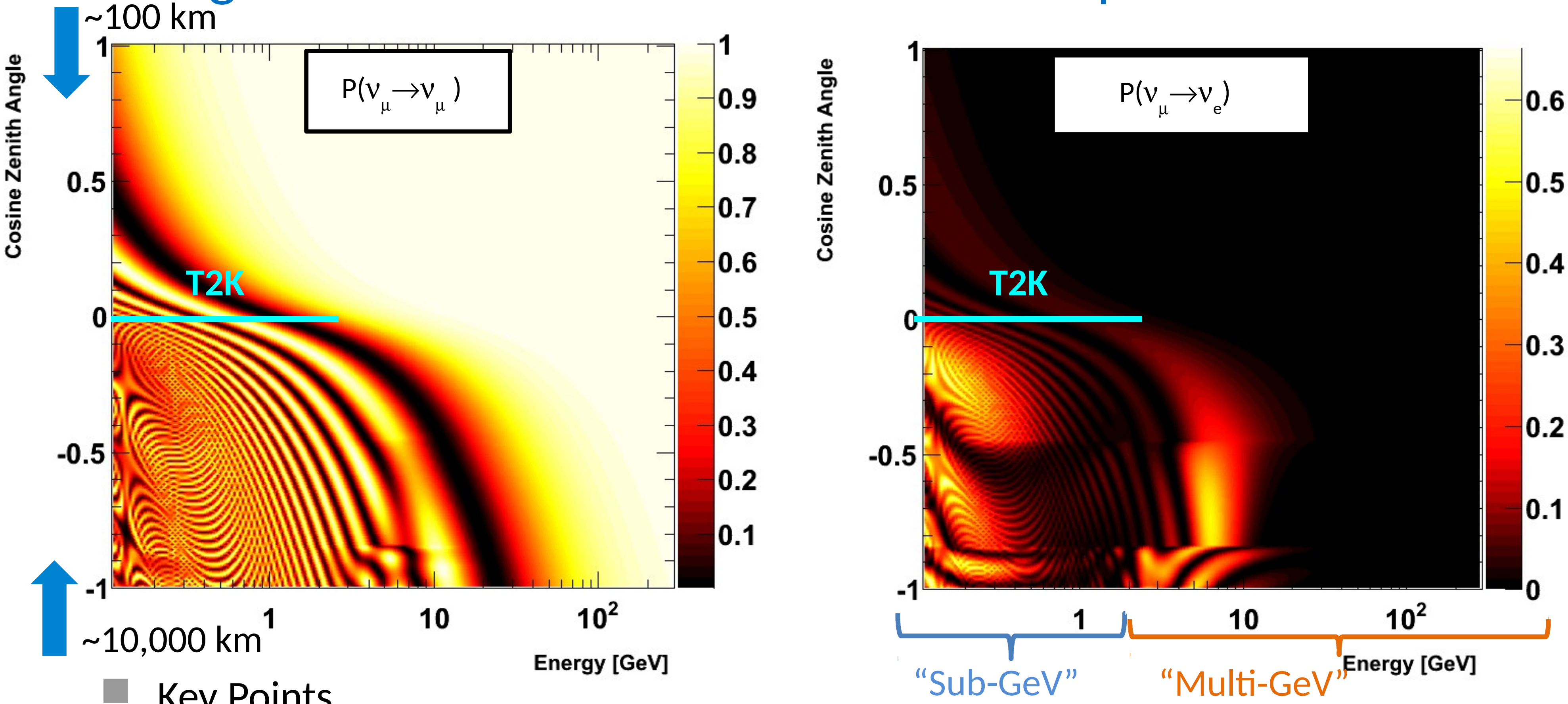
**Upward-going Muons (Up-μ)**






- In total **19** analysis samples
  - 51,000 Events ( x10 more than in 1998 )
- Dominated by $\nu_\mu$->$\nu_\tau$ oscillations
- We are now interested in subdominant contributions to this picture : three-flavor effects, Sterile Neutrinos, LIV, etc.

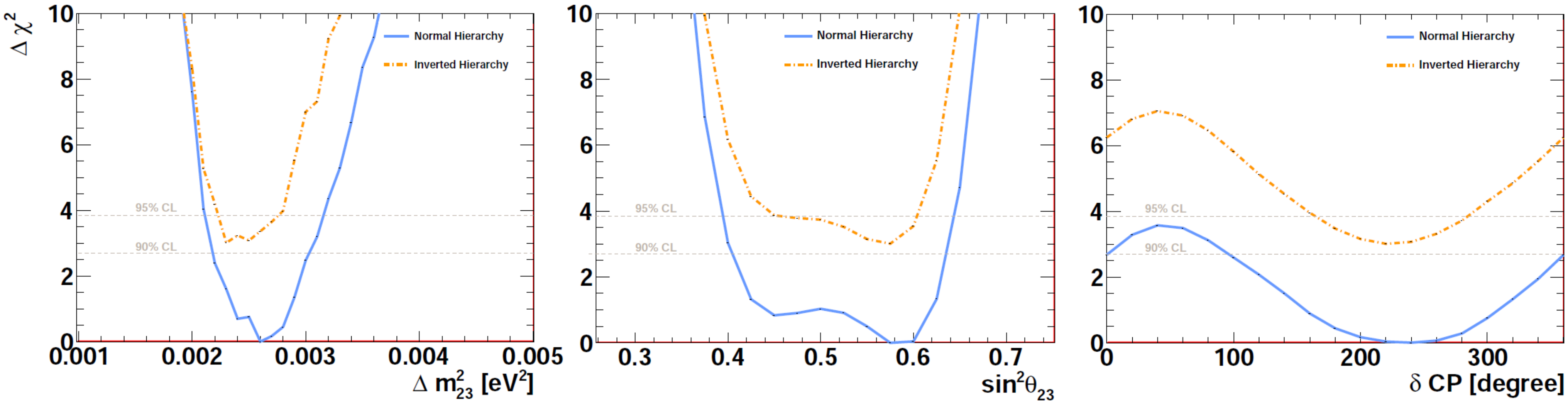
# Searching for Three-Flavor Effects: Oscillation probabilities




- Key Points
  - No $\nu_\mu \rightarrow \nu_e$ Appearance above ~20 GeV,
  - Resonant oscillations between 2-10 GeV (for $\nu$ or $\bar{\nu}$ depending upon MH)
  - No oscillations above 200 GeV
  - No oscillations from downward-going neutrinos above ~5 GeV
  - Expect effects in most analysis samples, largest in upward-going $\nu_e$
  - Sensitive to most of the MNS mixing parameters

# $\theta_{13}$ Fixed Analysis (NH+IH) SK Only [S. Hirota]

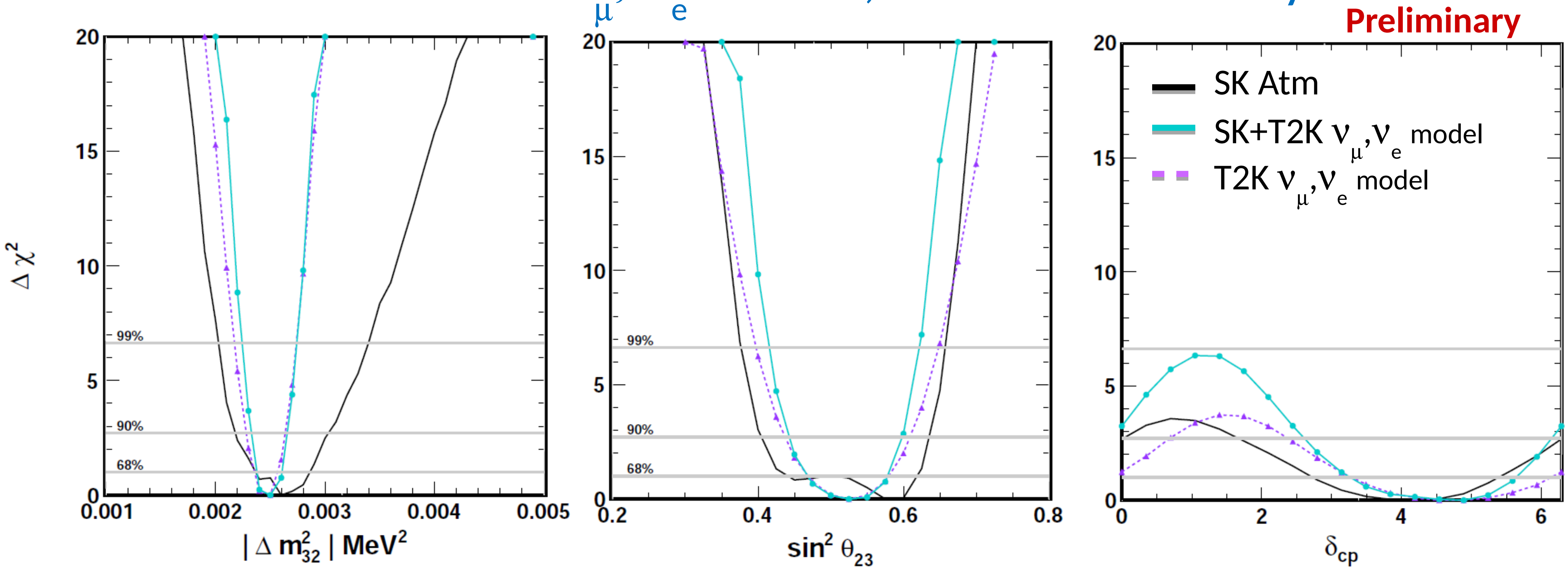
**Preliminary**




- Offset in these curves shows the difference in the hierarchies
- **Normal** hierarchy favored at: $\chi^2_{NH} - \chi^2_{IH} = -3.0$ , not significant
  - Preference for matter over vacuum oscillations at ~1 σ (82% C.L.)

- T2K's measurements of atmospheric mixing parameters are more precise
- Both experiments favor large values of δcp
  - What if we **combine** the two experiments?

# Theta13 **Fixed** SK + T2K $\nu_\mu, \nu_e$ Model, Normal Hierarchy




- **Model** and fit T2K beam spectrum using atmospheric neutrino MC
- $\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (-3.0 SK only )
- **CP** Conservation ($\sin\delta_{cp}$ = 0 ) allowed at (at least) 90% C.L. for both hierarchies
- Combined measurement shows promise

Next Step: Officially combine the two experiments for the best possible precision [ M. Jiang (Kou) ]

# Challenges for a combined analysis of SK and T2K



- Lots of work to do (a working group is needed)

- Interaction model unification
- Application of T2K near detector constraint to SK Atmospheric MC
  - What kind of constraints can T2K make on higher energy MC

- Unify systematic error estimation
  - Shared estimation with atmospheric neutrinos
  - Bottom-up detector error parameterization?

- Unify systematic error response treatment between T2K and Super-K
  - Systematic error response is very different in T2K (nearly event-by-event, correlations) and Super-K (bin-by-bin, uncorrelated )

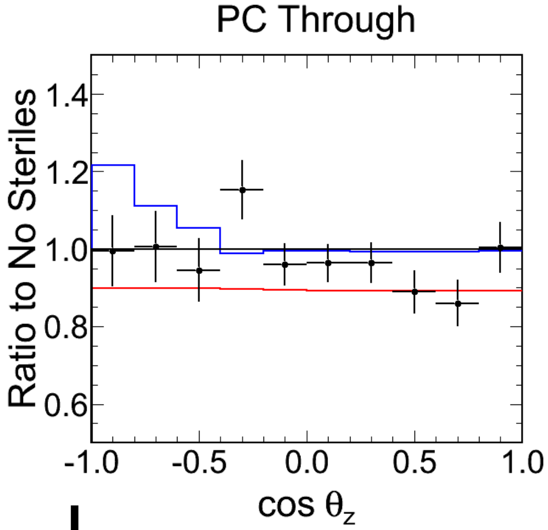
- Which analysis samples
  - T2K is moving towards improved reconstruction algorithm (fiTQun), but Super-K is focused on older reconstruction, which has a wider range of application currently

# Recent Exotic Searches

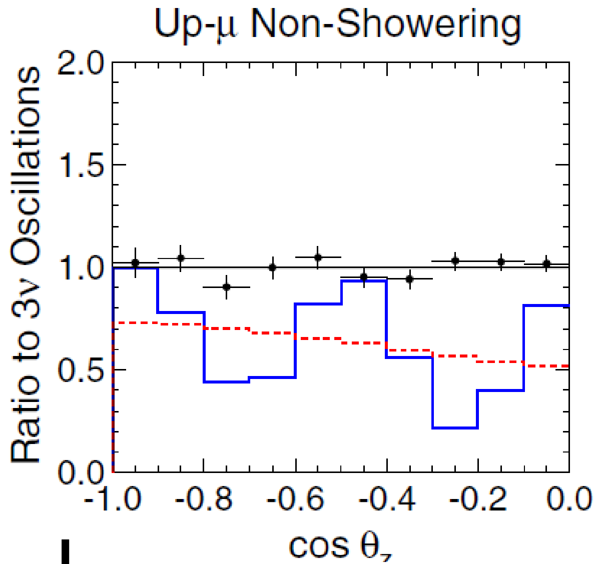
- Because the standard PMNs oscillation parameters are now known very well, its possible to use atmospheric neutrinos to search for other exotic processes

# Exotic Oscillation Results (2015)

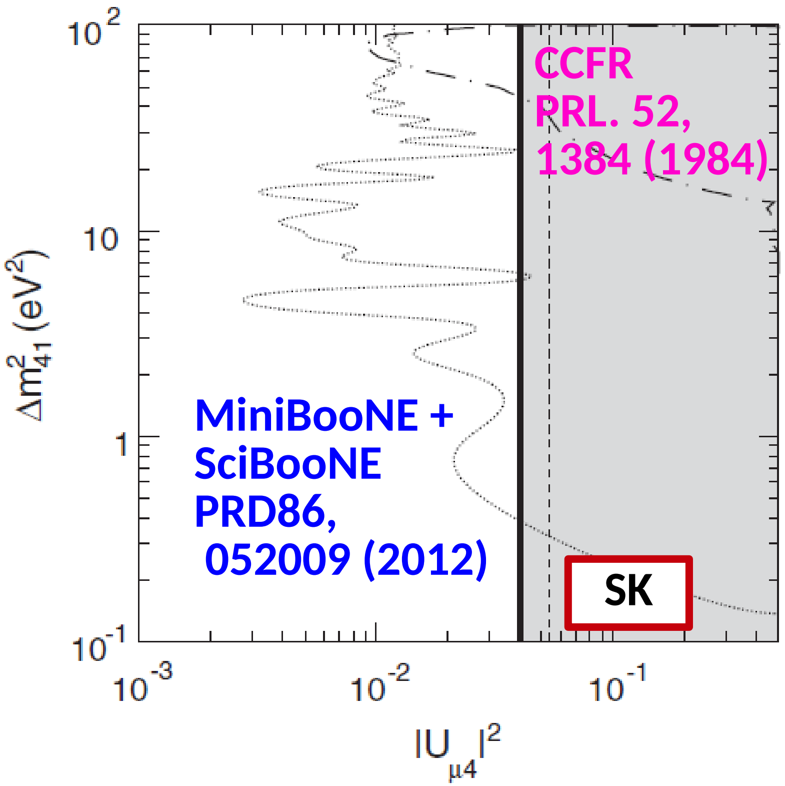


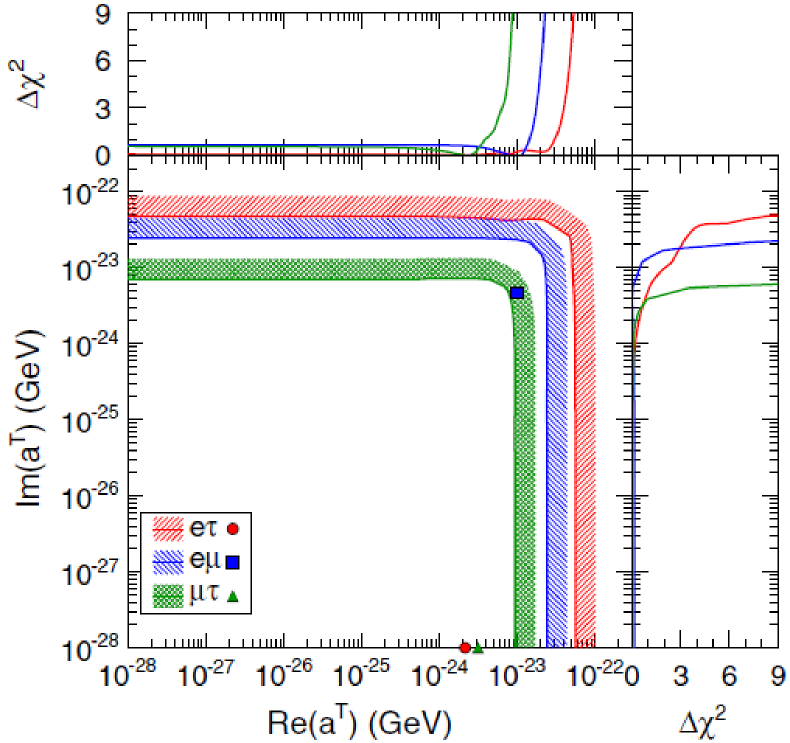



**Sterile Neutrinos**



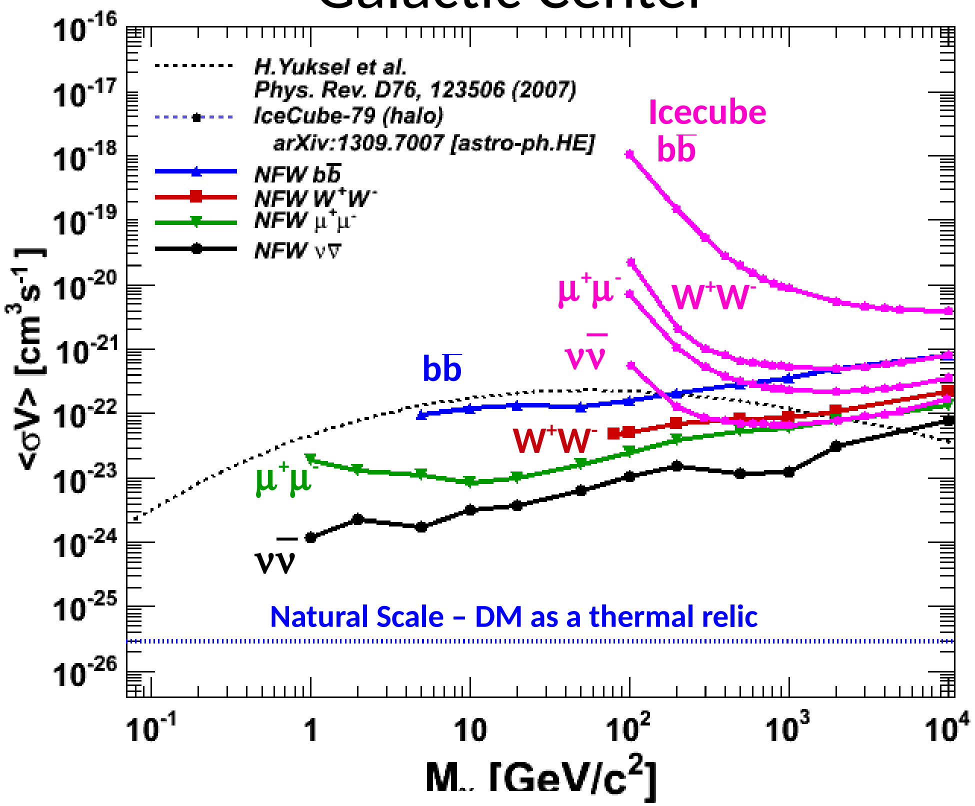

**Lorentz Invariance Violation**



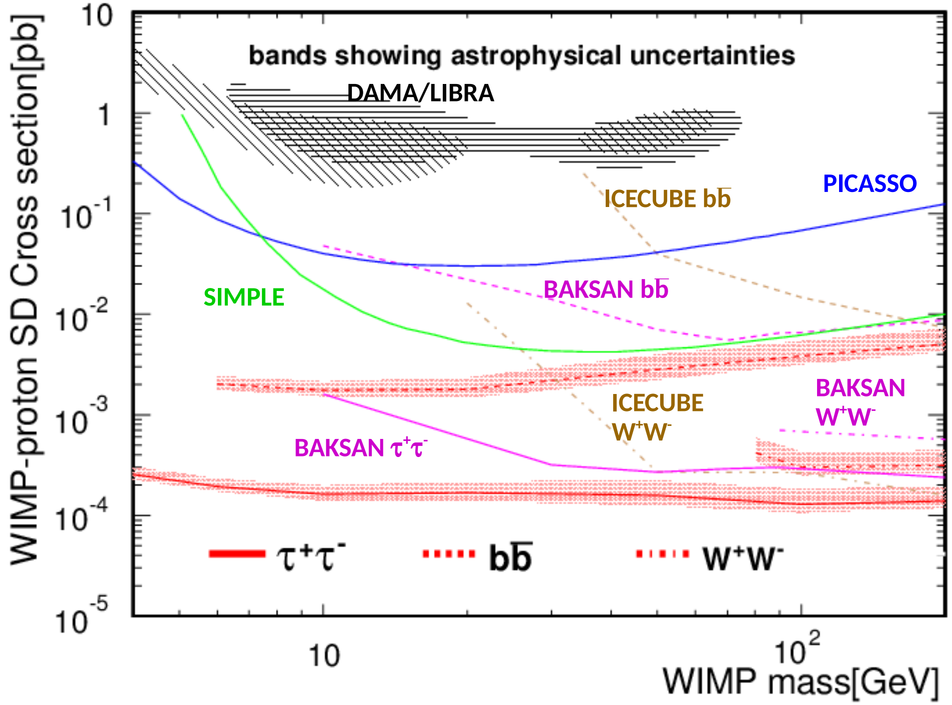



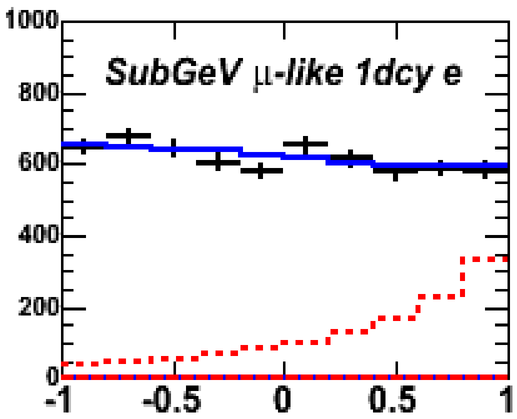
# Indirect Dark Matter Searches

Galactic Center




Sun



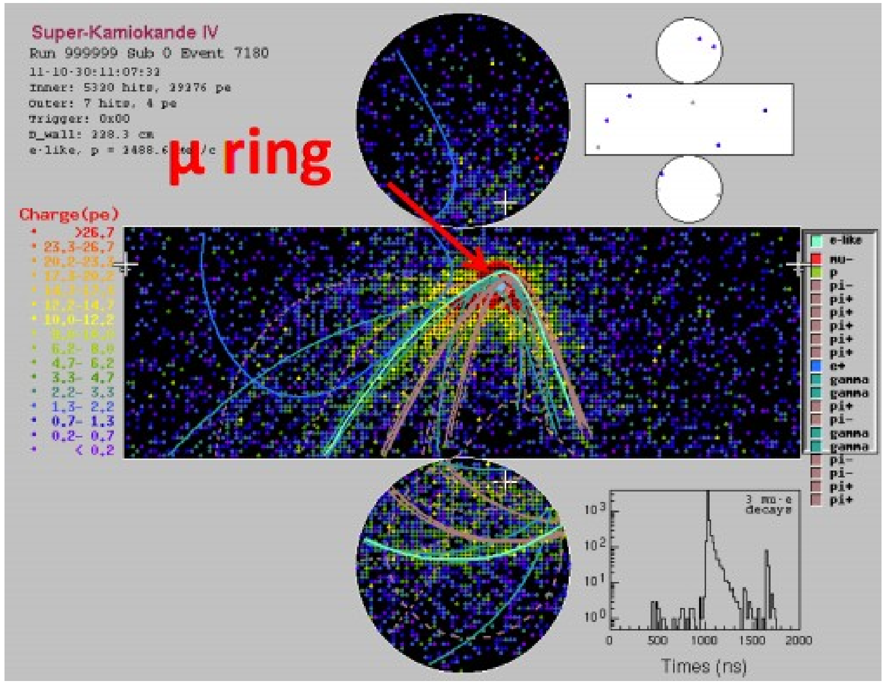

cos θ (Galactic Center)

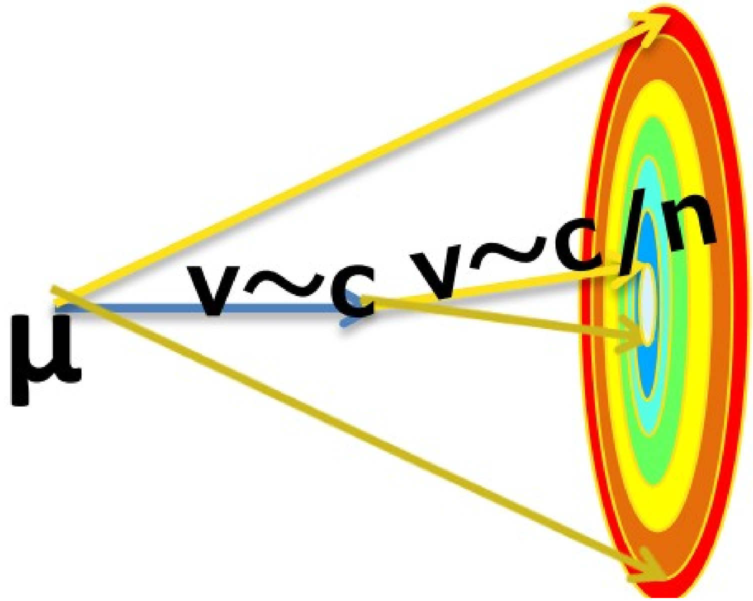
- Search for excess of neutrinos (dark matter-induced) above atmospheric neutrino background
  - Looking at the center of the galaxy
  - Looking at the sun

# Future of These Measurements

- Several analysis improvements are planned to increase Super-K's sensitivity to the open questions in neutrino physics
- Many of these analyses are predominantly statistics limited, so accumulating more data is essential

# Looking Towards the Future



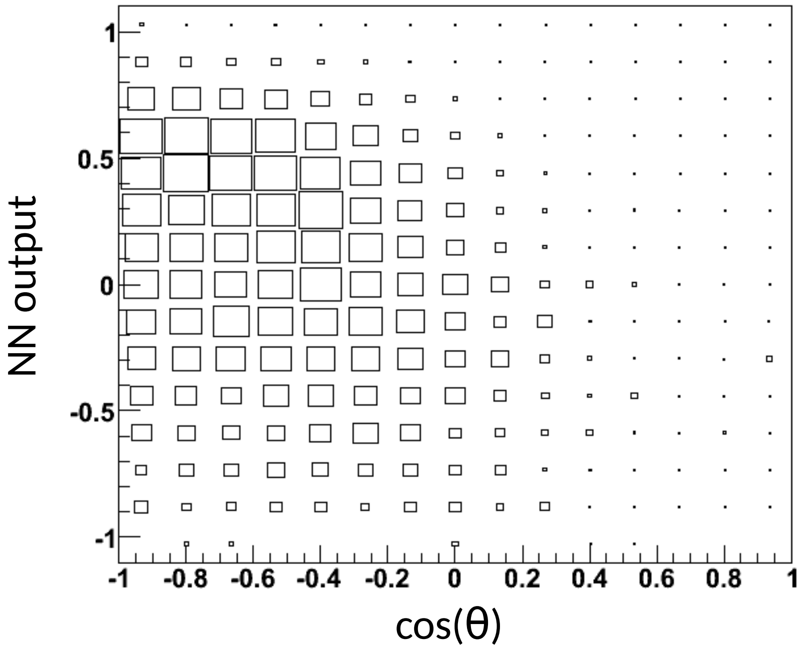




Reject muon backgrounds in hierarchy-sensitive sample by adding time likelihod to reconstruction

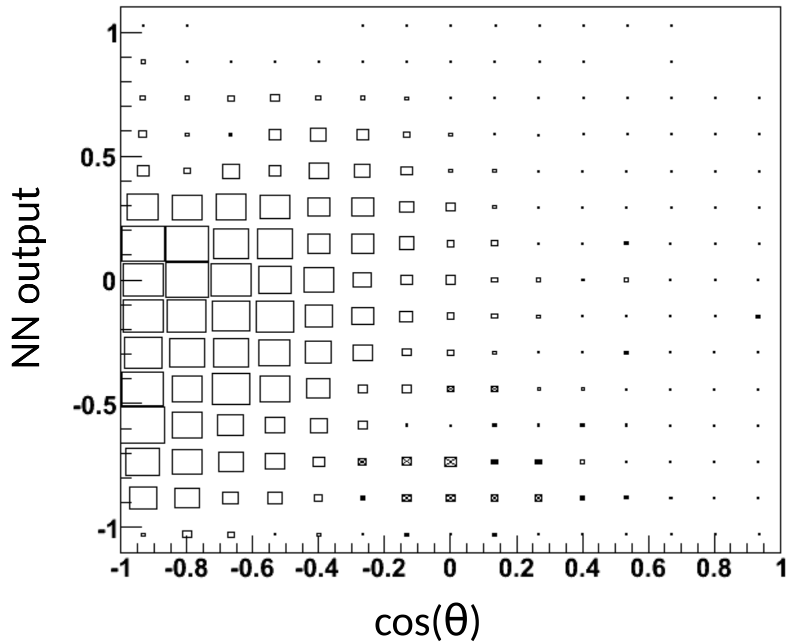
- Expanded fiducial volume
- PID Improvement with advanced reconstruction methods [S.Hirota]
  - Reject CCνμ and NC backgrounds in e-like samples
- Constrain τ background with NN (see previous talk)
  - Main background to hierarchy search
  - Meausurement of cross section normalization
- n-H / n-Gd neutron tagging
  - Improved energy reconstruction
  - NC background reduction
  - Neutrino / Antineutrino separation

# Looking Towards the Future

CC $\nu\tau$ Events




Mass Hierarchy Sensitive $\nu_e$ Events

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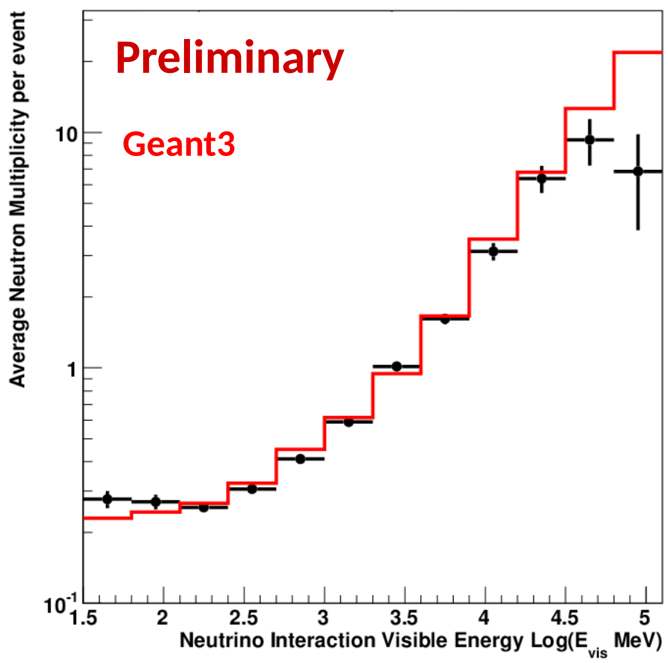
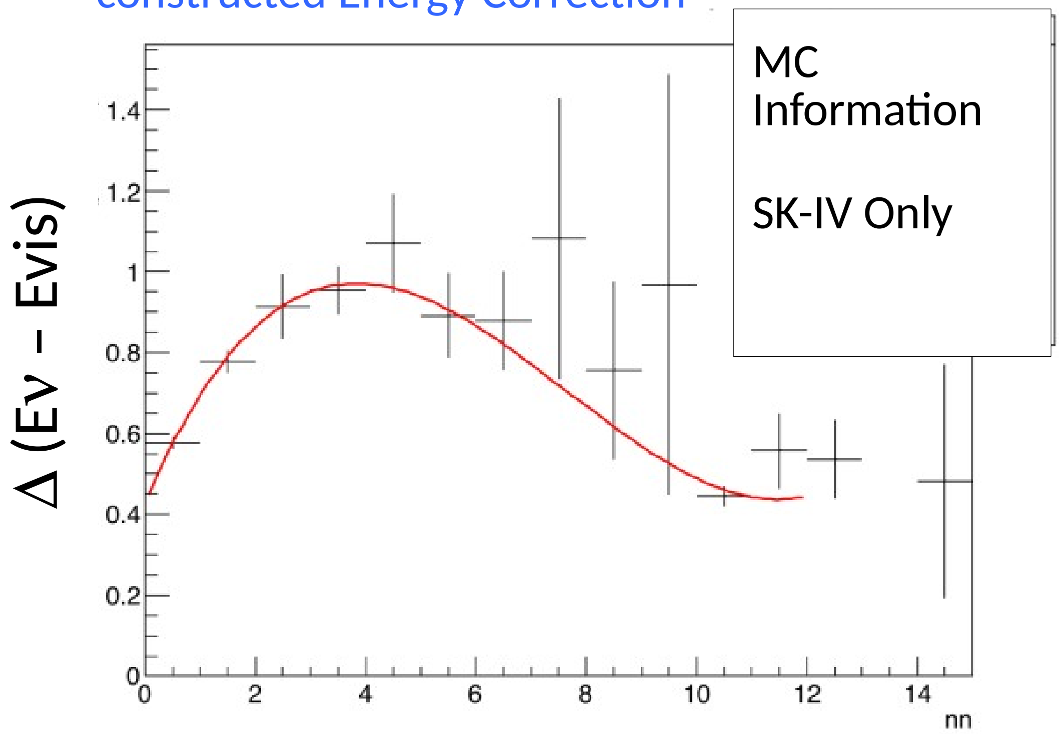
# Looking Towards the Future




constructed Energy Correction

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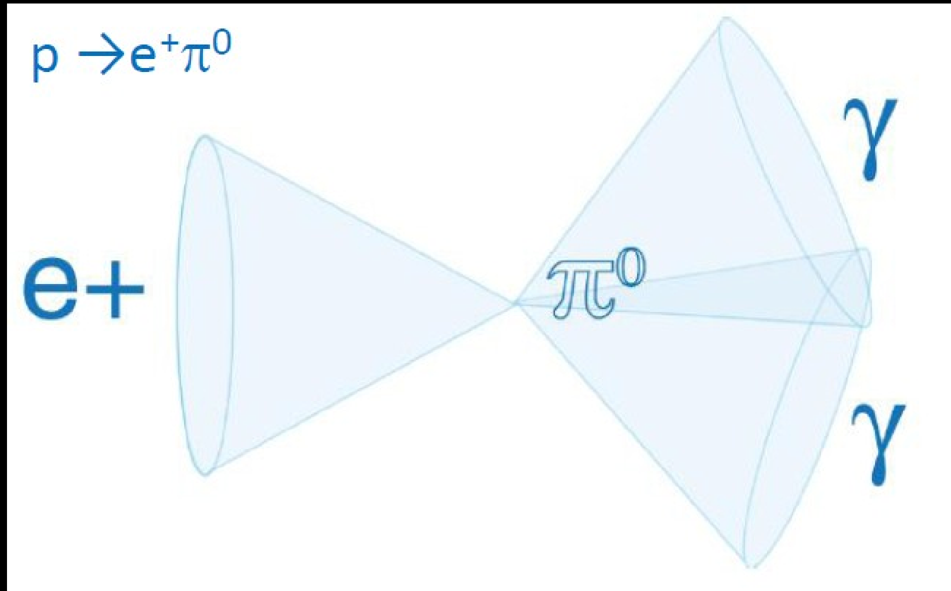
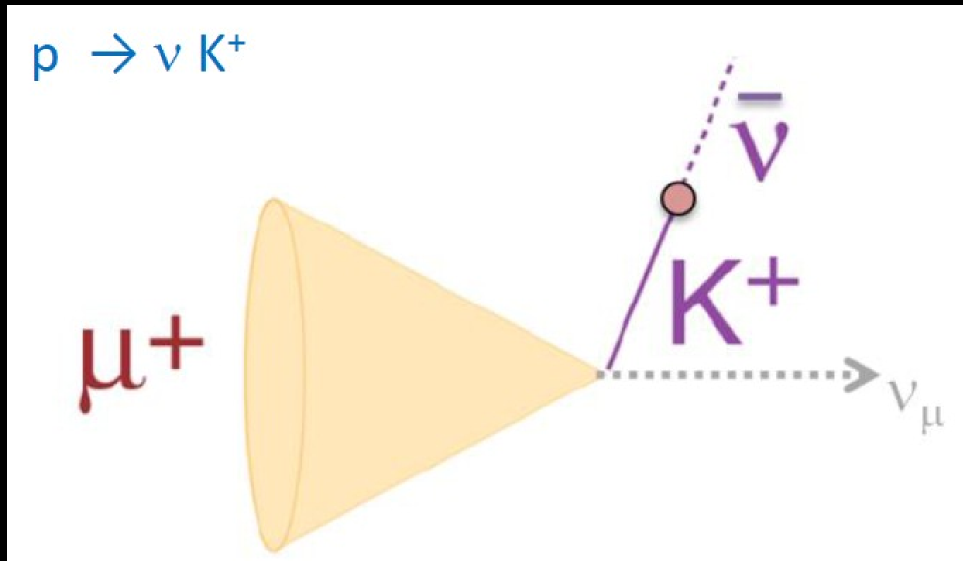
| 2.2 MeV γ Selection | |
|---|---|
| Efficiency | **20.5%** |
| Background / Event | **0.018** |

**....More Data is key!**

# Nucleon Decay Physics

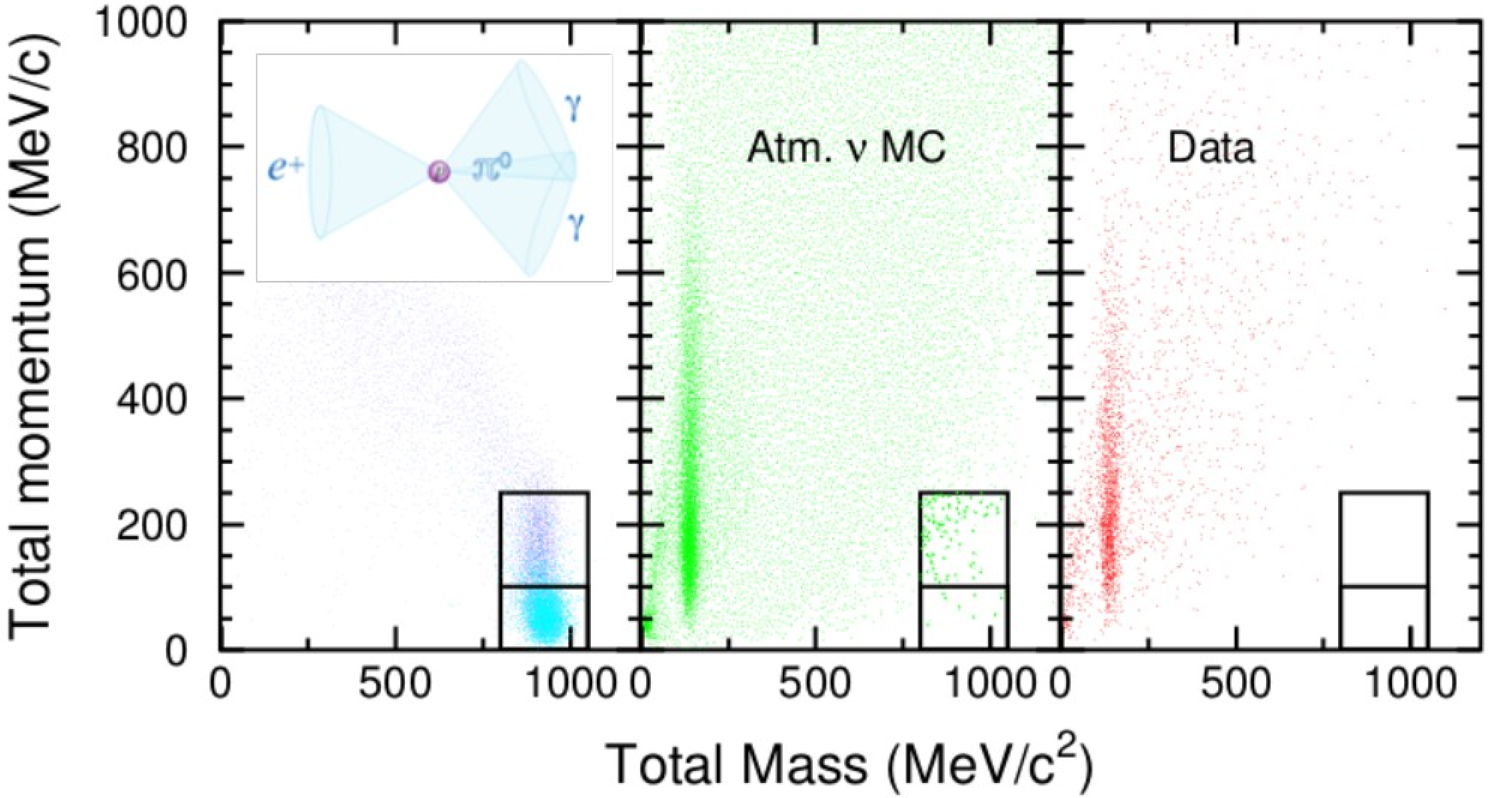
- In the Standard Model the proton is stable and there is (almost) no other type of baryon number violation
- However baryon number violation is needed at some level to explain the current matter dominant universe
- At the same time GUT models, which explain deficiencies in the Standard Model and unify the four forces, predict proton (nucleon) decay
- Nucleon decay searches are an essential piece of searches for new physics!



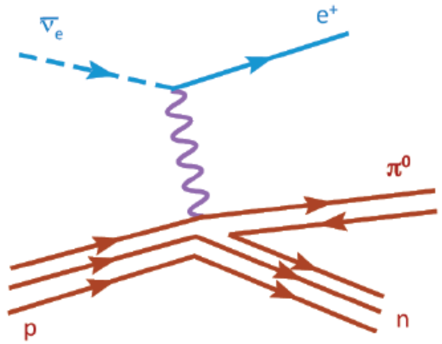



# Proton Decay: $p \rightarrow e{+}\pi 0$





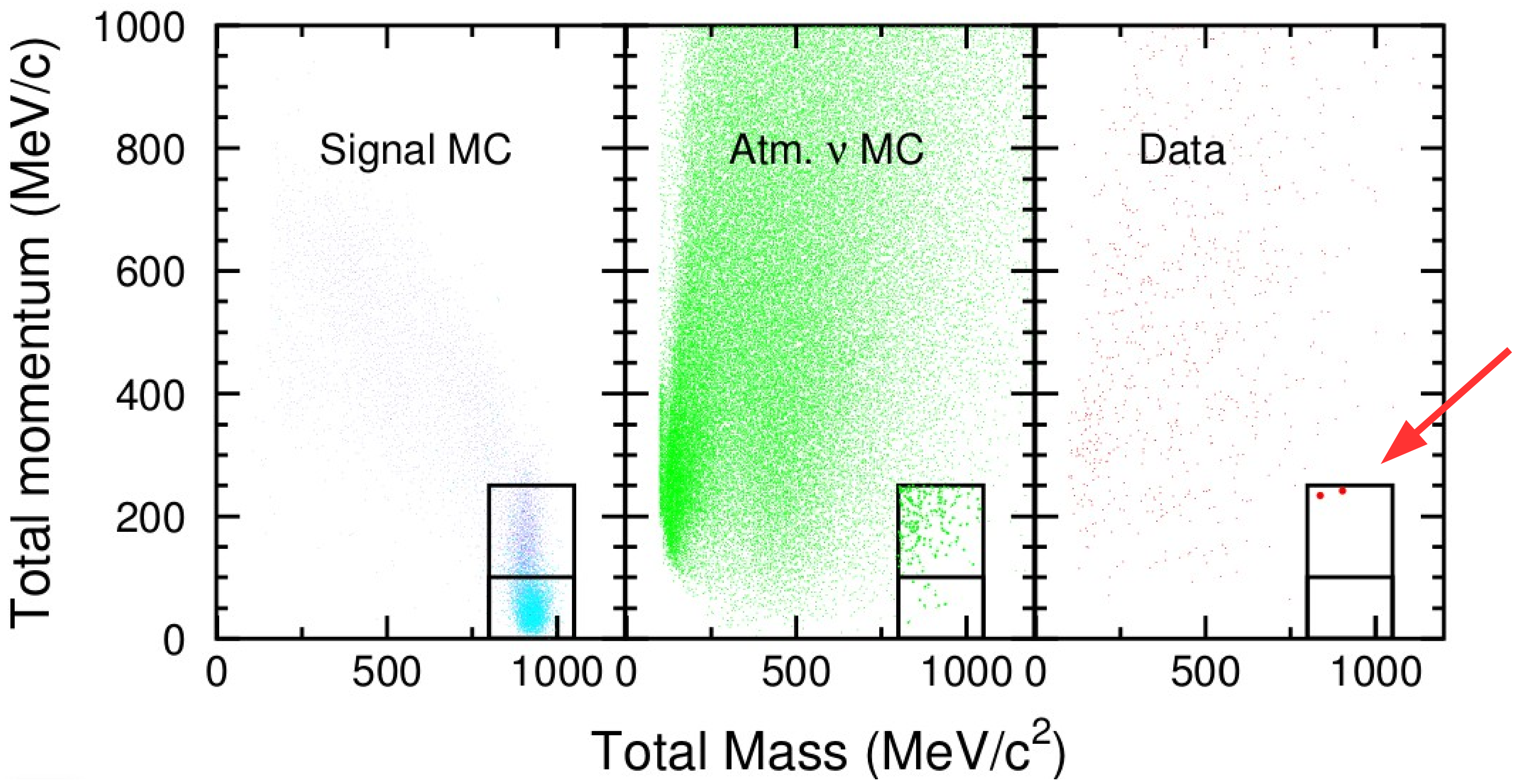

Background



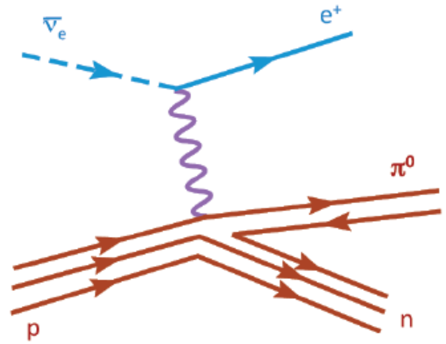

- So far no evidence for proton decay so Super-K has the world's strongest limits:
  - $p \rightarrow e^+\pi^0$ : $\tau > 1.7 \times 10^{34}$ years
  - *Just now entering the range of predictions of modern SUSY GUT Models!*

# Proton Decay: $p \rightarrow \mu^+\pi^0$





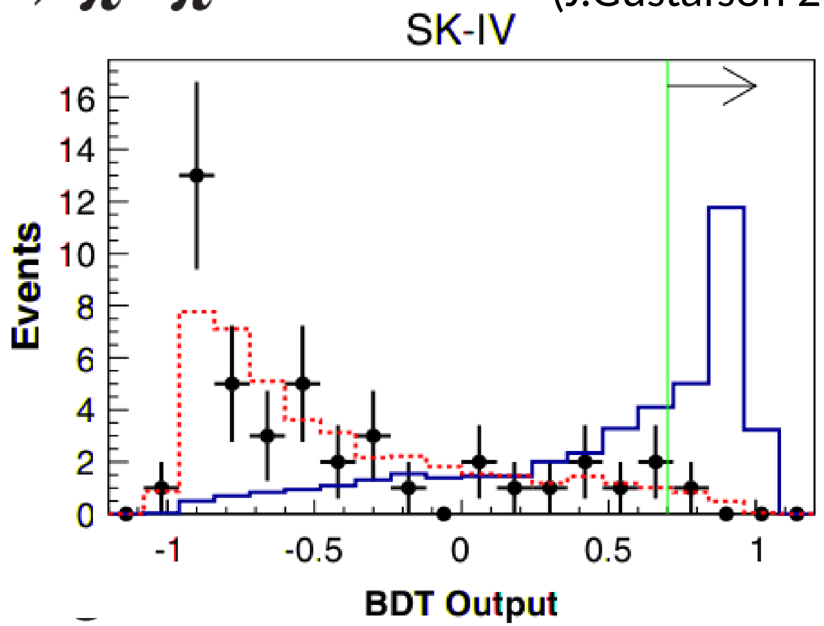

Background



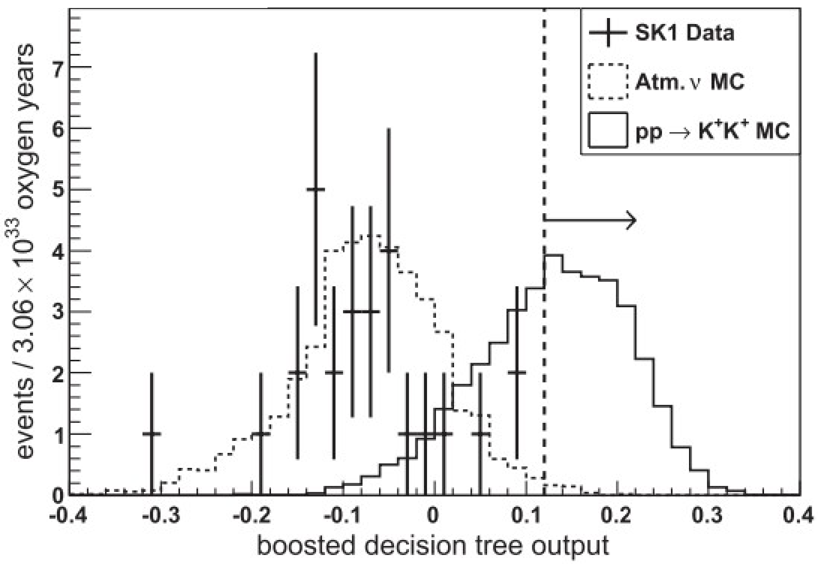

- Recently two events found in the $\mu^+$ channel
  - Consistent with background expectation at p ~ 18%
  - $p \rightarrow \mu^+\pi^0$ : $\tau > 7.8 \times 10^{33}$ years

# Proton Decay Analysis

$pp \rightarrow \pi^+ \pi^+$ (J.Gustafson 2015)



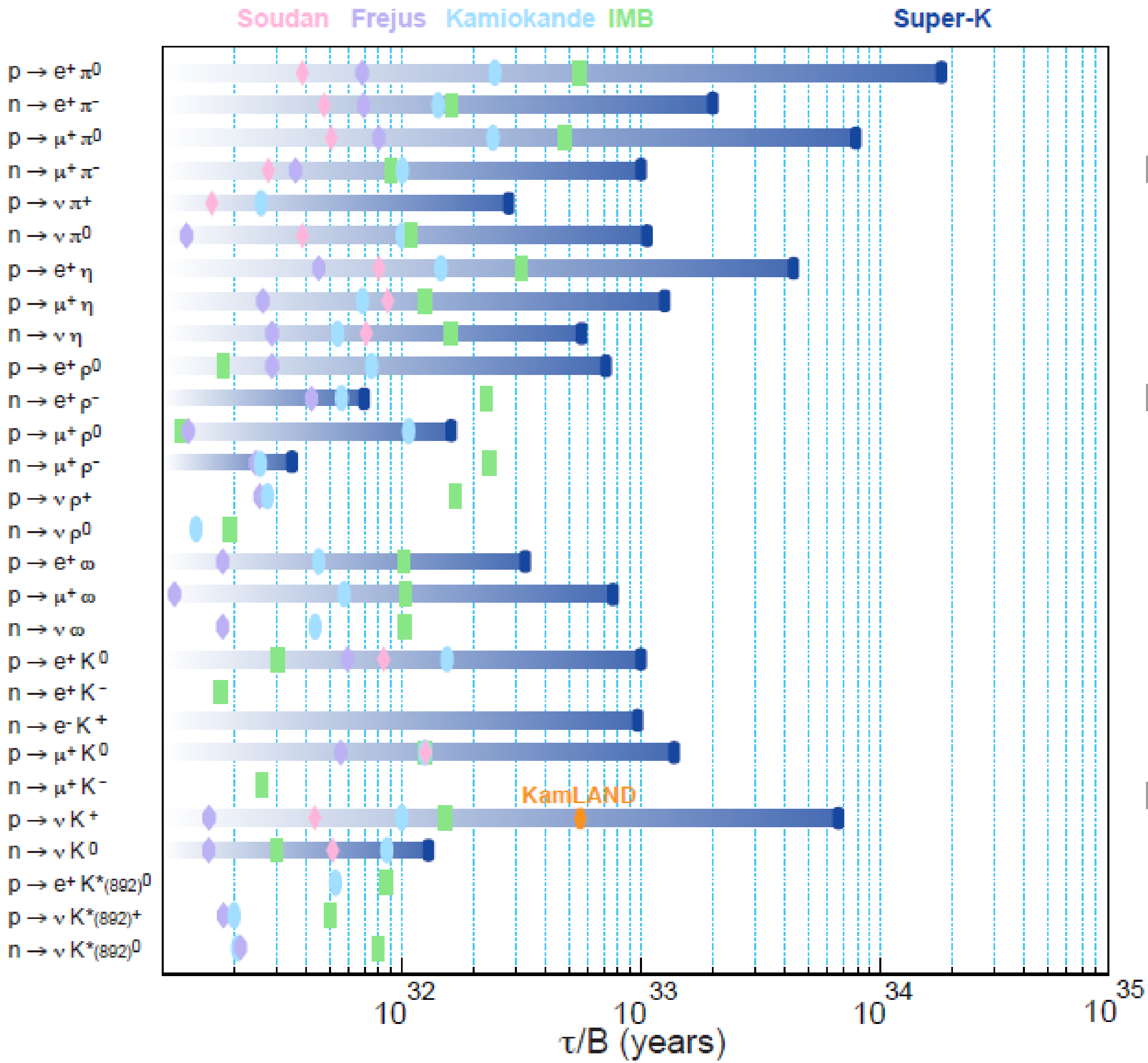

$pp \rightarrow K^+ K^+$ (M. Litos 2015)




- Nucleon decay analyses require special event selections not used in regular atmospheric neutrino analysis
- Construction of new reconstruction algorithms is often helpful: For instance to correctly identify two charged kaons separated in space
- Multivariate analysis (Neural Networks, Boosted Decison trees) used to reduce backgrounds
- Background reduction is critical!
  - Neutron tagging for SK-IV now in use

# Current Limits:

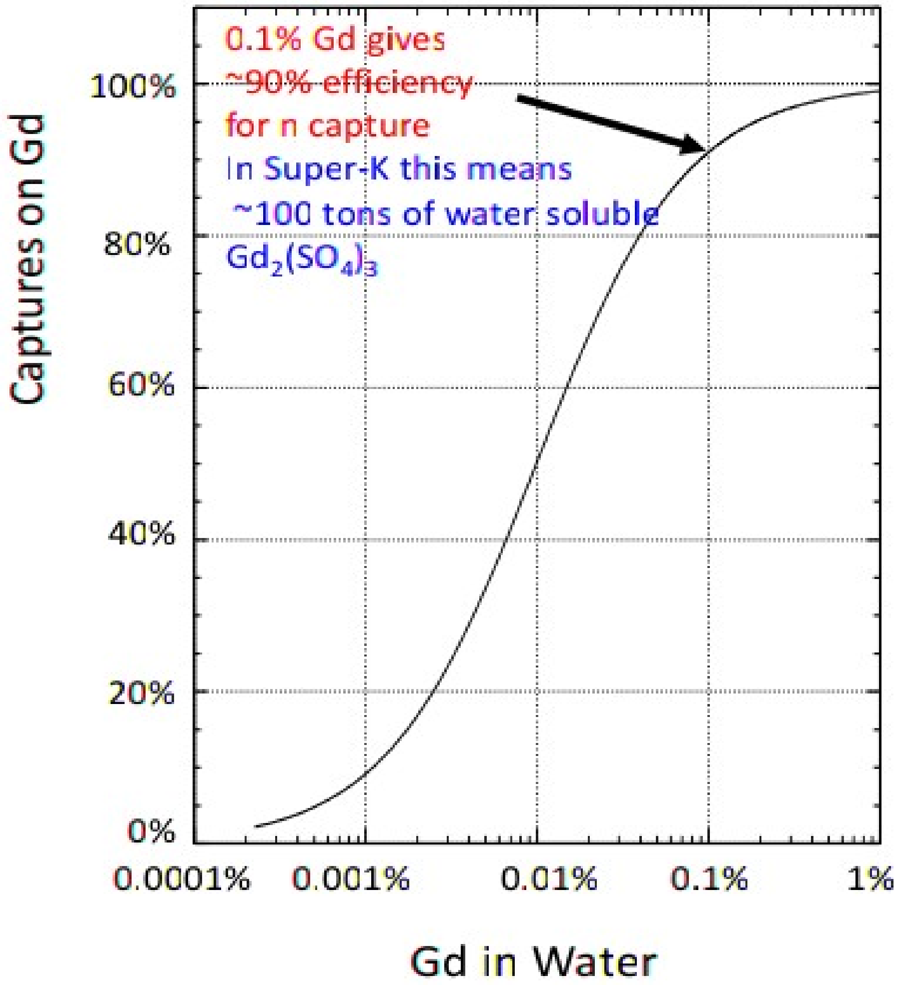


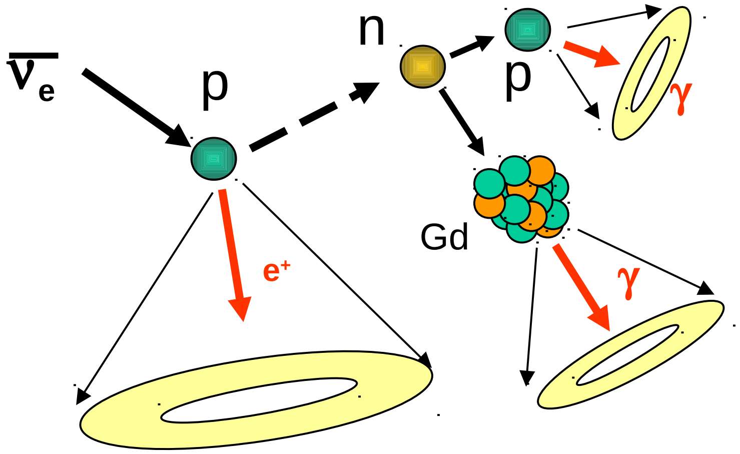



- Still many modes to be studies (not all shown here)
- Every mode can potentially be improved with improved reconstruction algorithms
- Background suppression is key

# Low Energy and the Near Future of SK

# SK-Gd : A Gadolinium Doped Super-Kamiokande

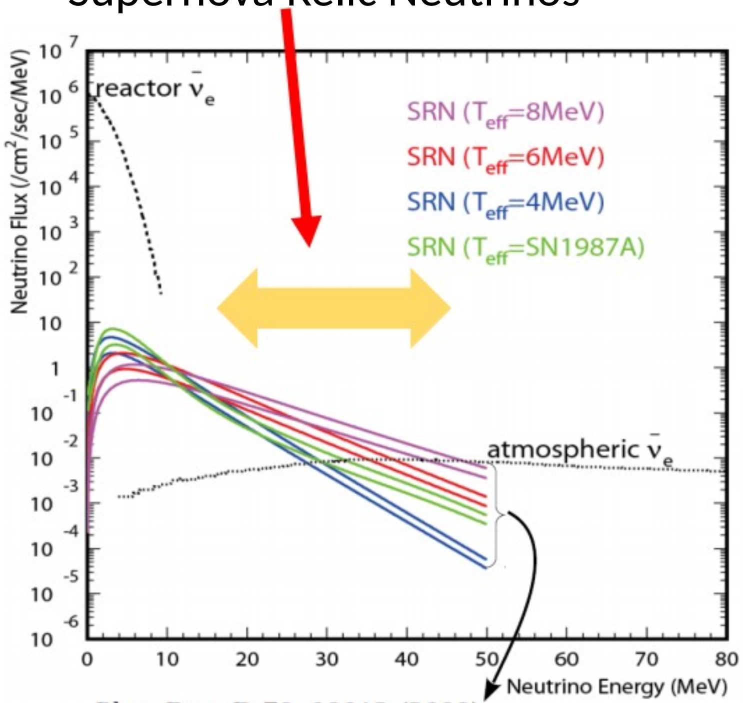


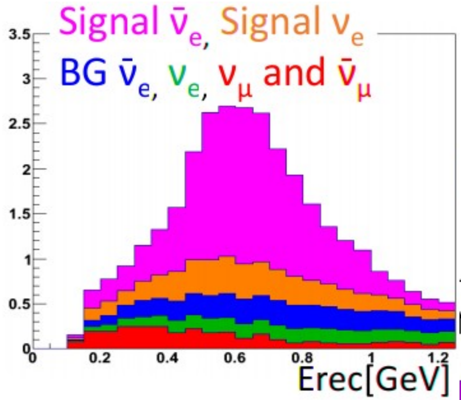

- Super-Kamiokande is planning on dissolving 0.2% Gd into the detector water
  - Project is called **SK-Gd**, time scale is roughly 2018
  - ~ 90% efficient free neutron tagging

# SK-Gd : Many Physics Targets

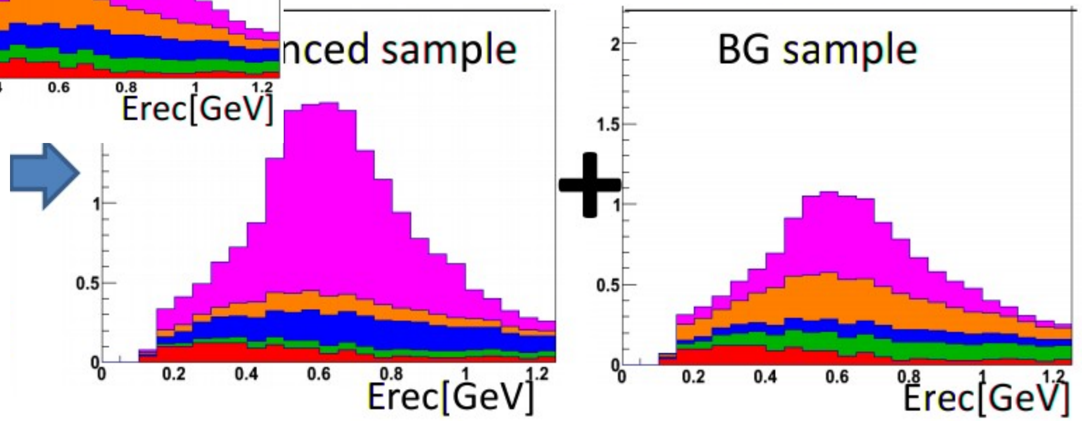
Supernova Relic Neutrinos



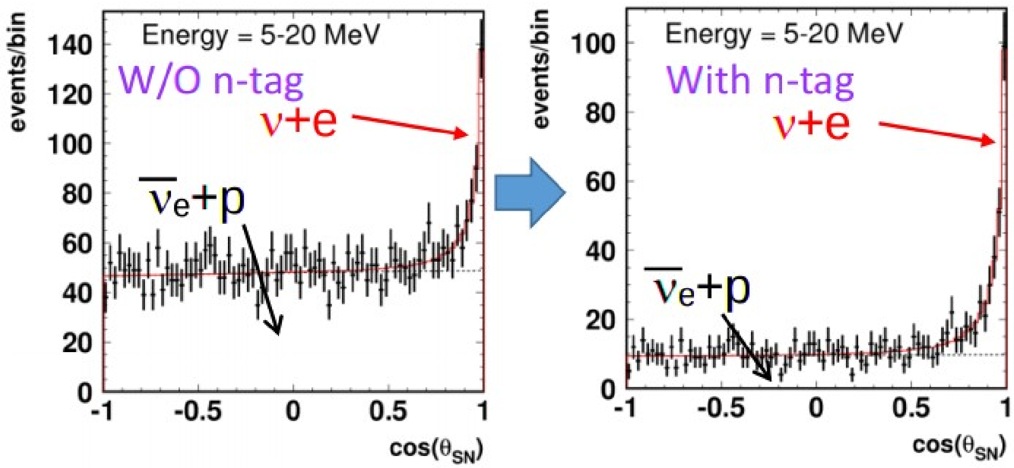

Phys.Rev. D 79, 08013 (2009)



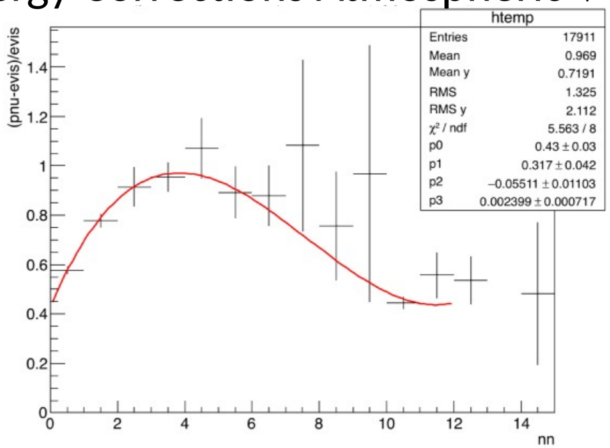

Neutrino and Antineutrino separation for T2K and Atmospheric neutrinos




Supernova Burst Pointing




Missing Energy Corrections Atmospheric ν

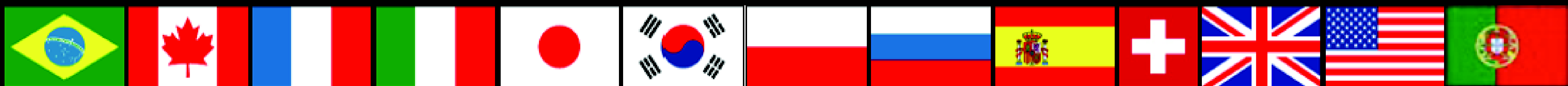


# SK-Gd : A Gadolinium Doped Super-Kamiokande



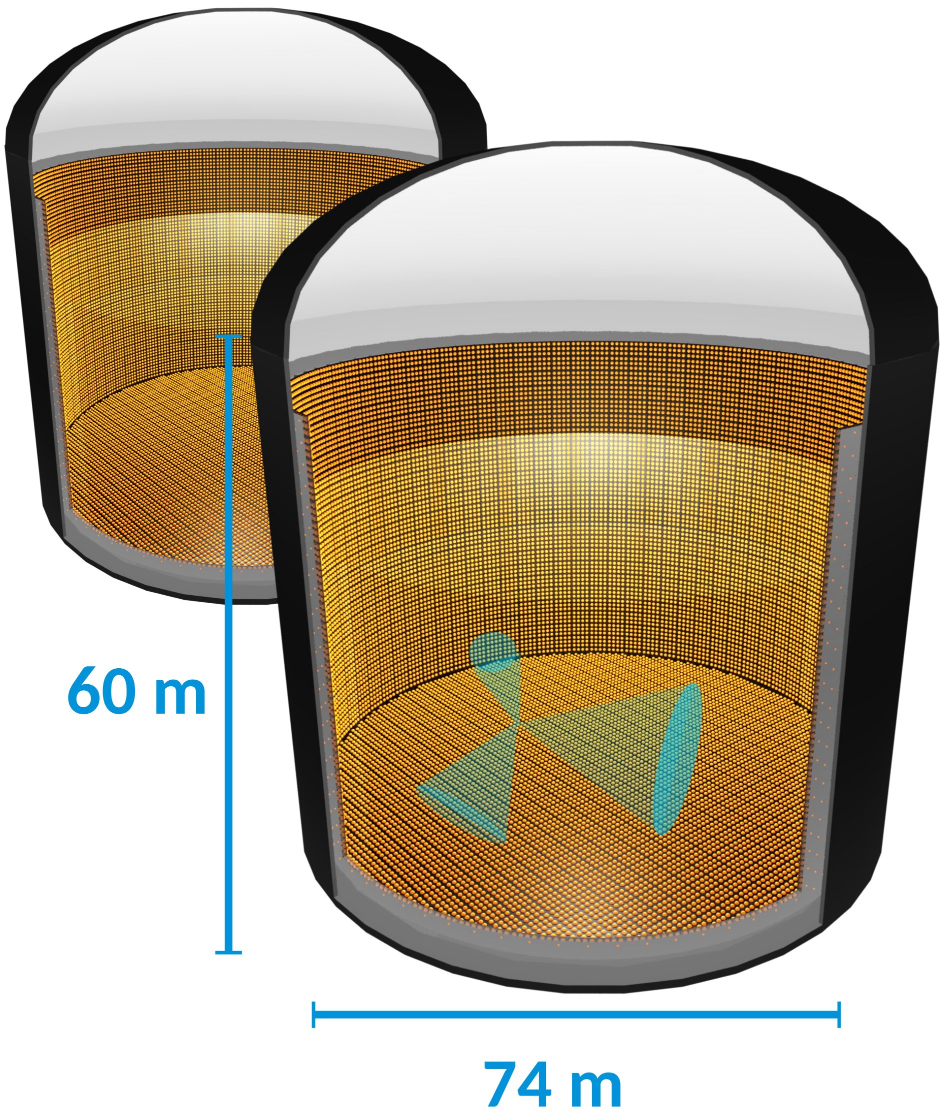
- In many ways SK-Gd will be a new detector
- In the near future there will be a lot of effort needed to understand the gd-loaded detector
- Refurbish and Upgrade the SK detector (hardware work)
- Estimate systematic errors for SK-Gd
- Update analyses to take advantage of the Gd neutron tagging
  - Proton decay background reduction
  - Neutrino antineutrino separation
    - For T2K and Super-K
  - etc.

# Hyper-Kamiokande

23 countries, 261 people (Oct.2015)

# Hyper-Kamiokande: Introduction



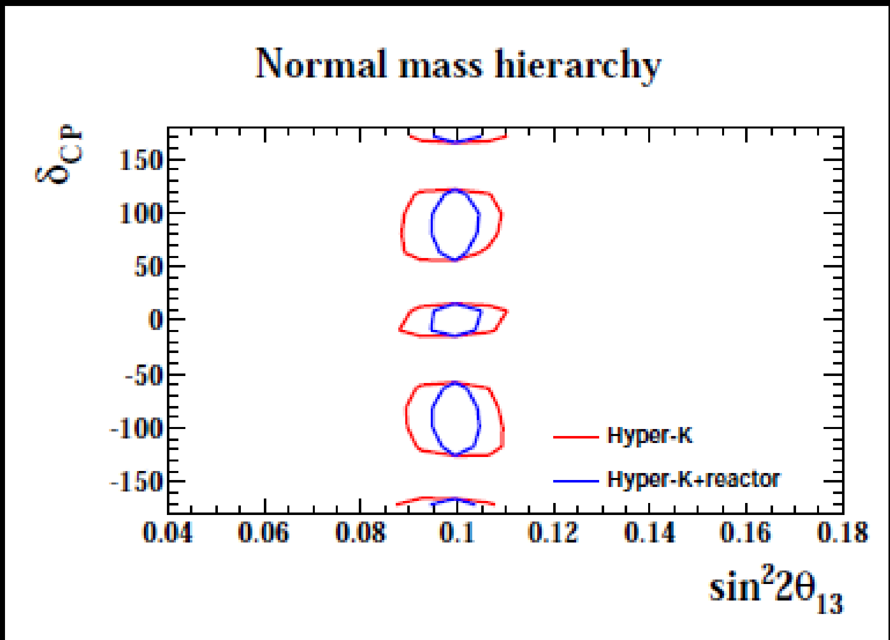

Staged design:
186 kton 6 years,372 kton thereafter

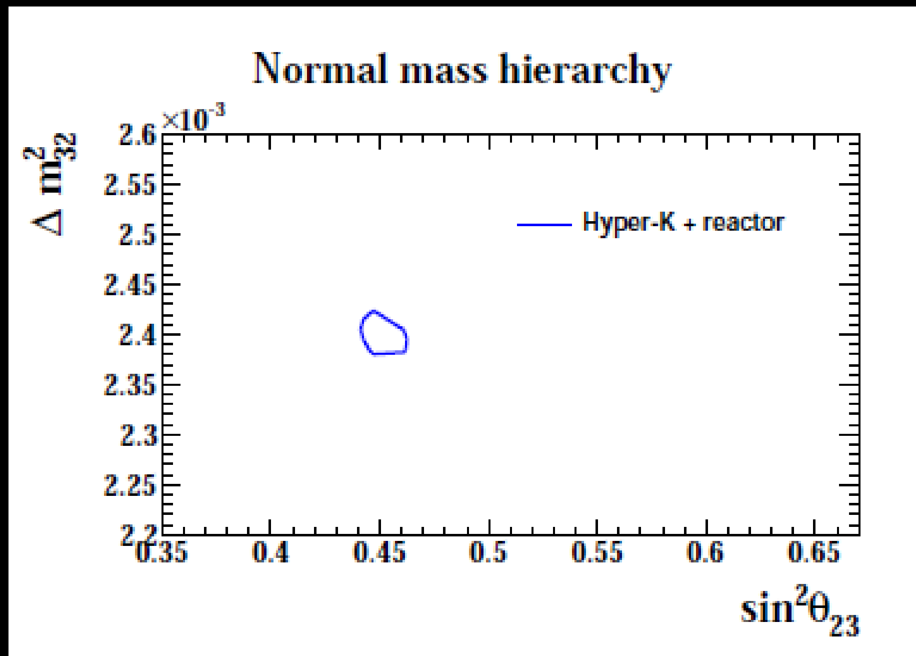
- 186 (×2) kton fiducial volume (2 × 8.3 × SK)
- Optically separated into
  - Inner Detector 40,000 (×2) PMTs (2×4×SK)
    - 40% Coverage (same as SK)
  - Outer Detector 12,000 (×2) PMTs (2×6×SK)
- ID Photosensors will be high QE
  - Single photon detection : 24% (2 × SK )
- Receive 1.3 MW beam from J-PARC
  - Accumulate $2.7 \times 10^{22}$ POT (3 × T2K )
- Multipurpose machine
  - All of the physics of Super-K and T2K
  - Plus more! Geophysics
    - Accessible only with very large detectors
- Not just a larger version of Super-K
  - Improved performance: photosensors, tank materials

# Combination of Beam and Atmospheric Neutrinos

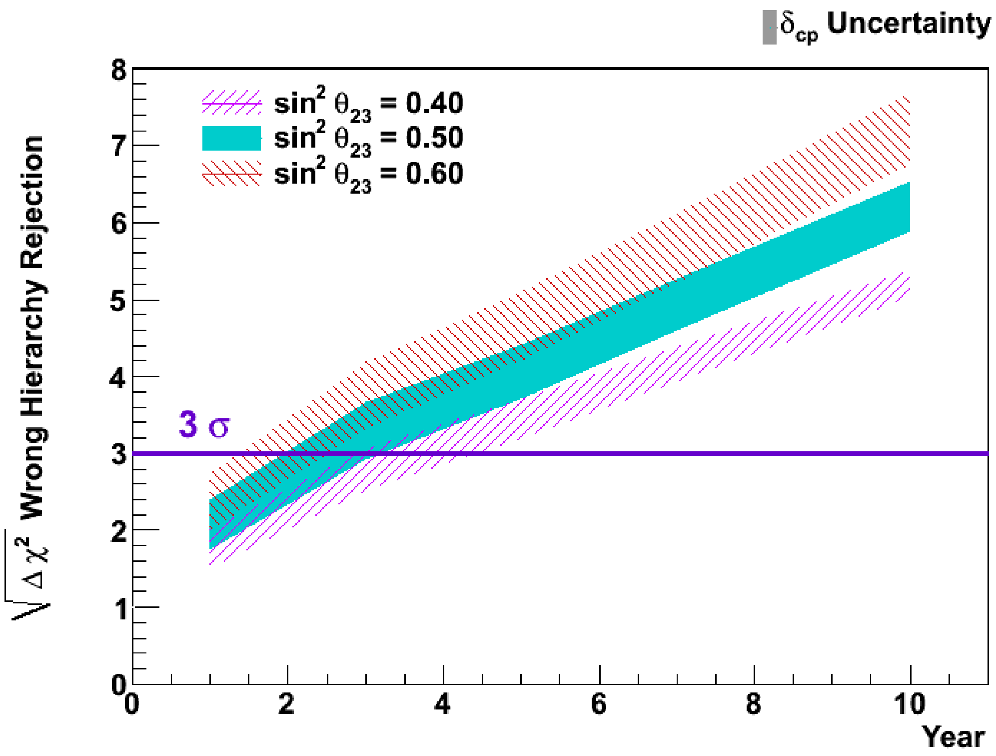
- Beam neutrinos provide tight constraints on mixing parameters that weaken the sensitivity of the (statistics limited) atmospheric neutrino sample to the mass hierarchy for instance

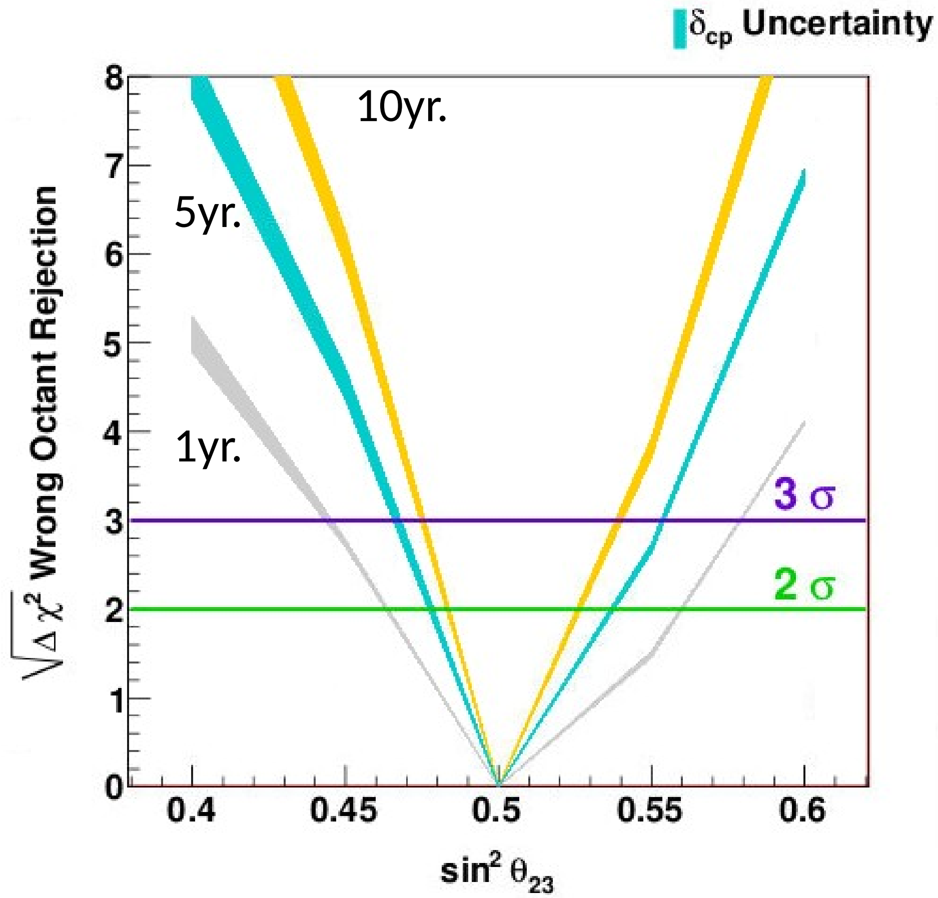
- Sensitivity of the two samples to the CP parameter is largely complementary, such that combined measurement yields better precision.



# Combination with Beam Neutrinos : Hierarchy and Octant



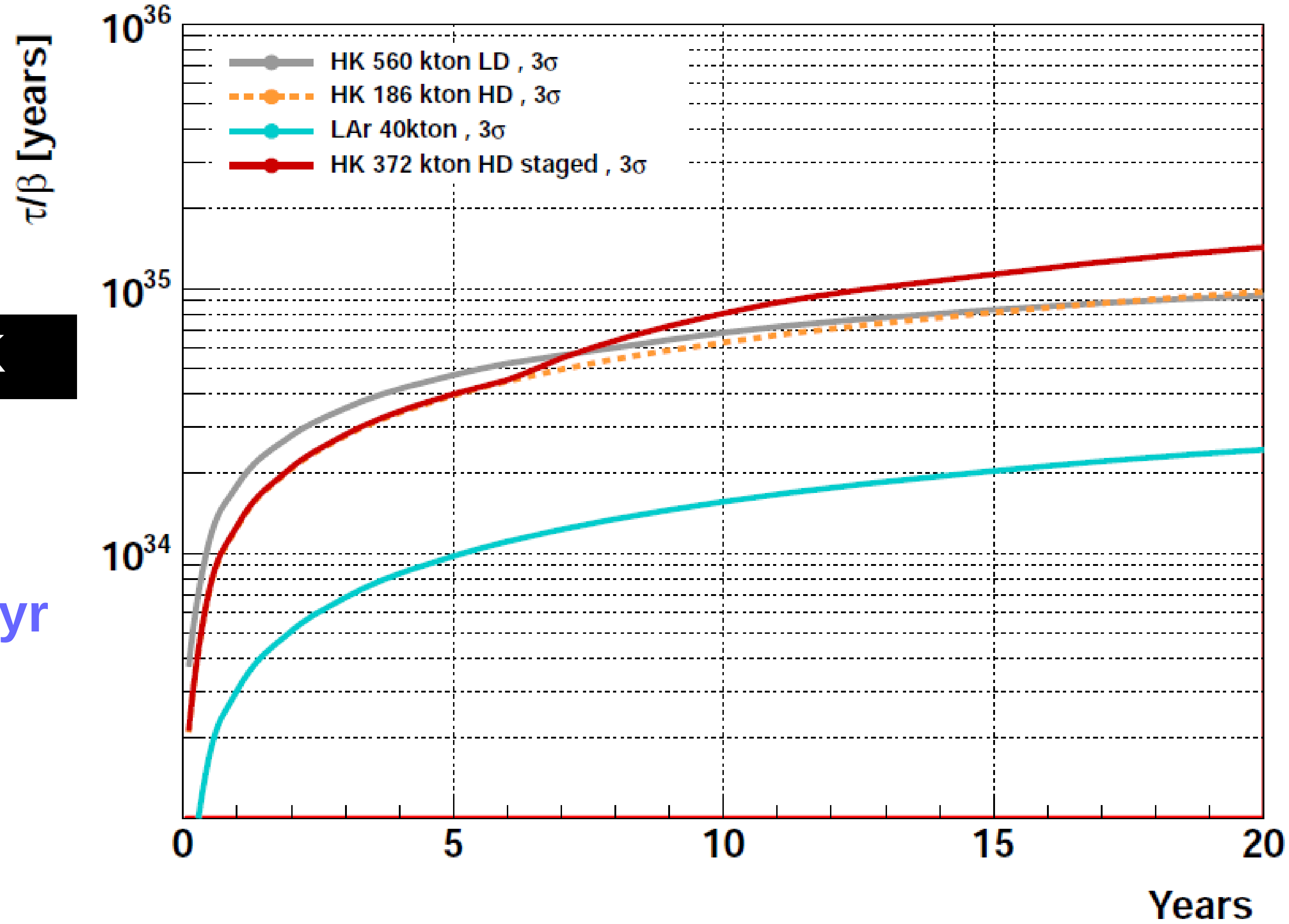

- For the optimal (worst) set of parameters the combined measurement can determine the mass hierarchy with ~1.5 (4.0) years of data
- Here the beam exposure after 10 years is assumed to be $2.7\times10^{22}$ POT , divided in a 1:3 ratio between neutrinos and antineutrinos
  - POT have been scaled evenly for shorter run periods
- 3σ Octant determination possible if $|\theta_{23} - 45°| > 3°$

# Proton Decay Discovery Potential at Hyper-K: 3σ



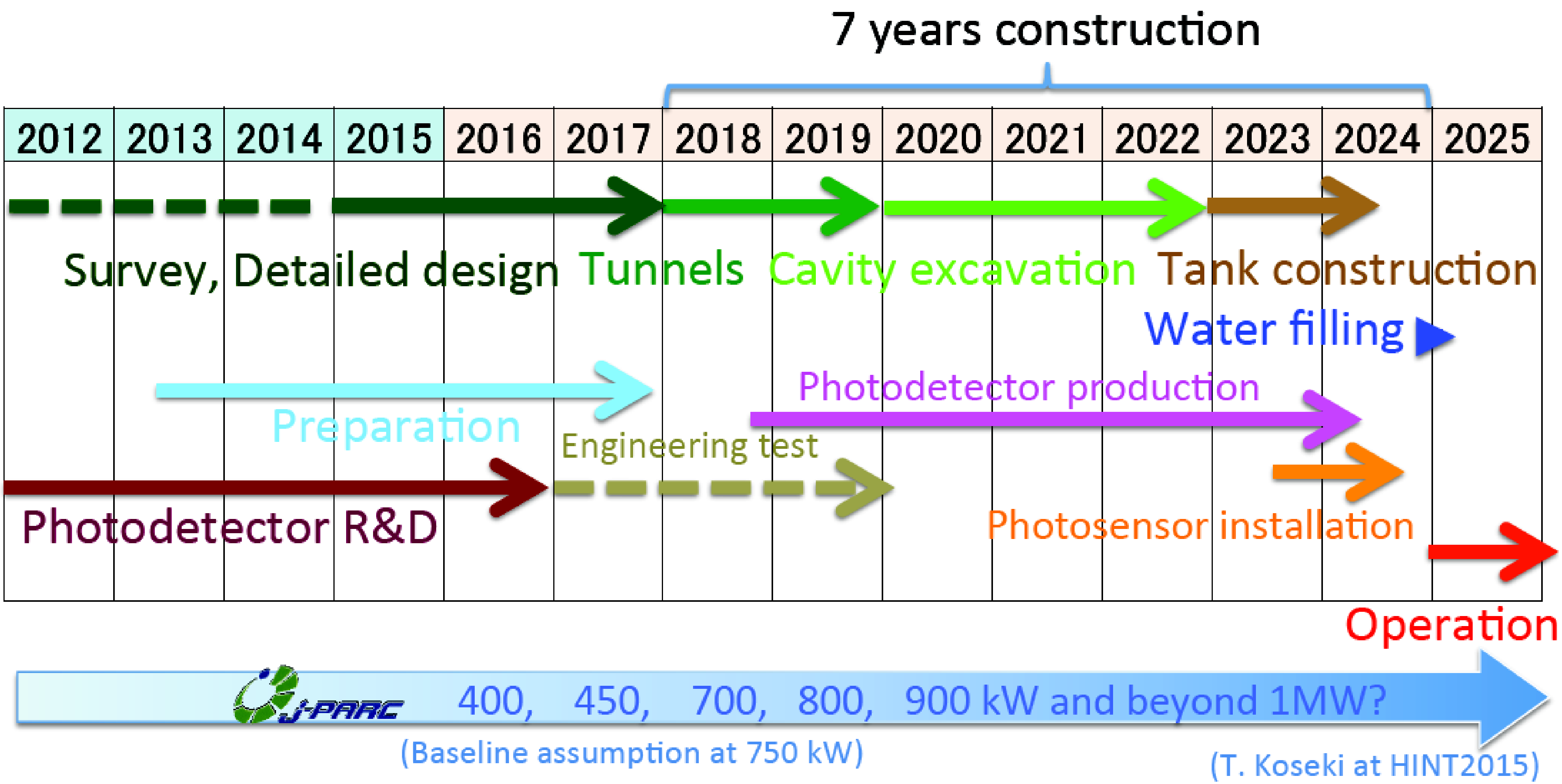
$p \rightarrow e^{+}\pi^{0}$

| | Hyper-K |
|---|---|
| Signal ε | ~39% |
| BG/Mton yr | 0.7 |
| 90% C.L. | **1.0 x $10^{35}$ yr** |




- If proton lifetime is near the current Super-K limit of **1.7x$10^{34}$** years Hyper-K will observe a positive signal at **8.9σ** in 10 years
- 3 σ discovery is possible after 20 years if $\tau < 10^{35}$ yr – Only possible with Hyper-K!

# Hyper-Kamiokande Notional Timeline



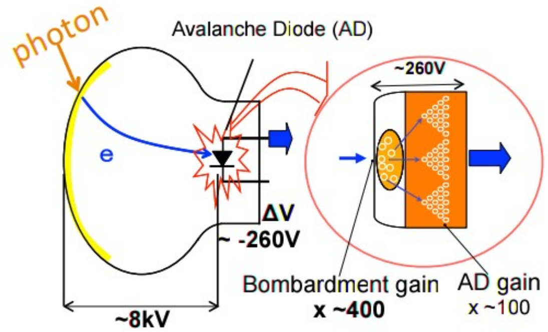

- If the budget proposal is approved, **construction** can start in **2018**
- **Physics** running would then start in **2025**
- J-PARC has already achieved 360 kW operation and is expected 750 kW by 2019
  - Opens the possibility for >= MW operation after 2020

# Hyper-Kamiokande

- Because of its size, Hyper-K will be able to do all of the physics that Super-K does, but with better than an order of magnitude precison

- In addition, it can do some measurements that Super-K cannot do
  - Lepton universality in neutrino oscillations
  - ντ cross section measurements
  - Measure the chemical composition of the Earth's core (Geophysics)
  - etc. etc.

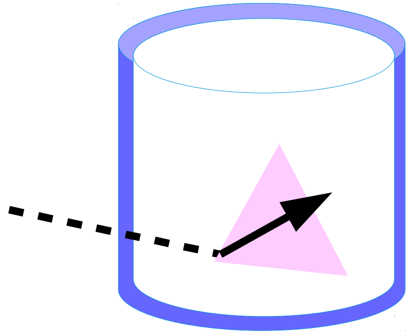
- Several projects for Hyper-K have been performed for Master's thesis
  - Photosensor devolpment and testing (Y.Suda)
  - Photosensor amplifier development (M.Jiang (Kou))
  - Simulation studies (Y.Okajima)
- These students then go on to do Ph.D. thesis work on Super-K or T2K

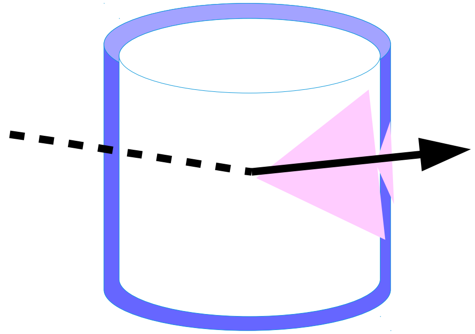
# Supplements

# Super-K Atmospheric ν Event Topologies

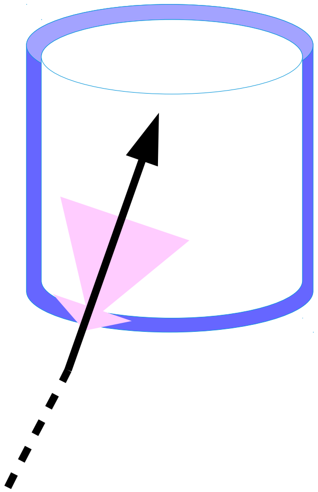
**Fully Contained (FC)**

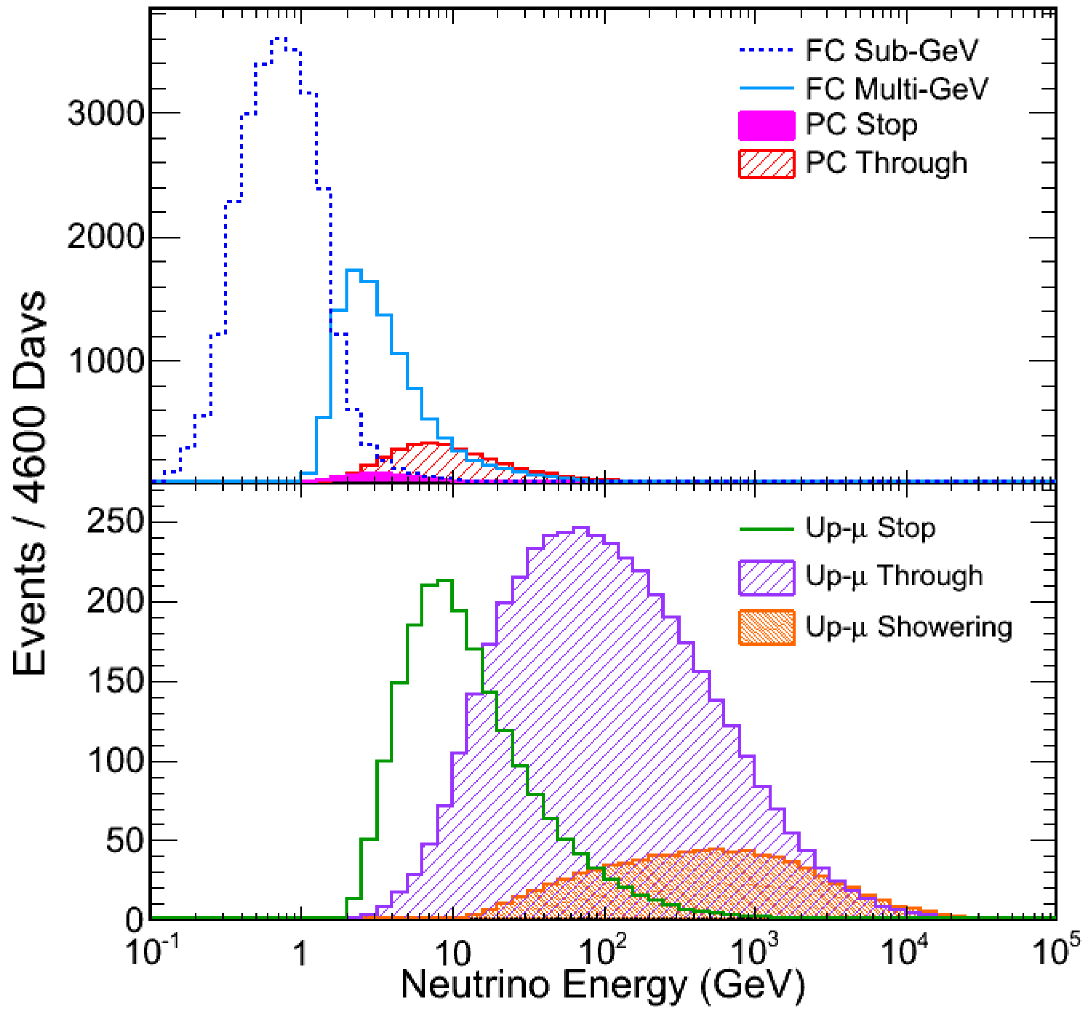


**Partially Contained (PC)**



**Upward-going Muons (Up-μ)**






- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

# Proton Decay: $p \rightarrow e+\pi 0$



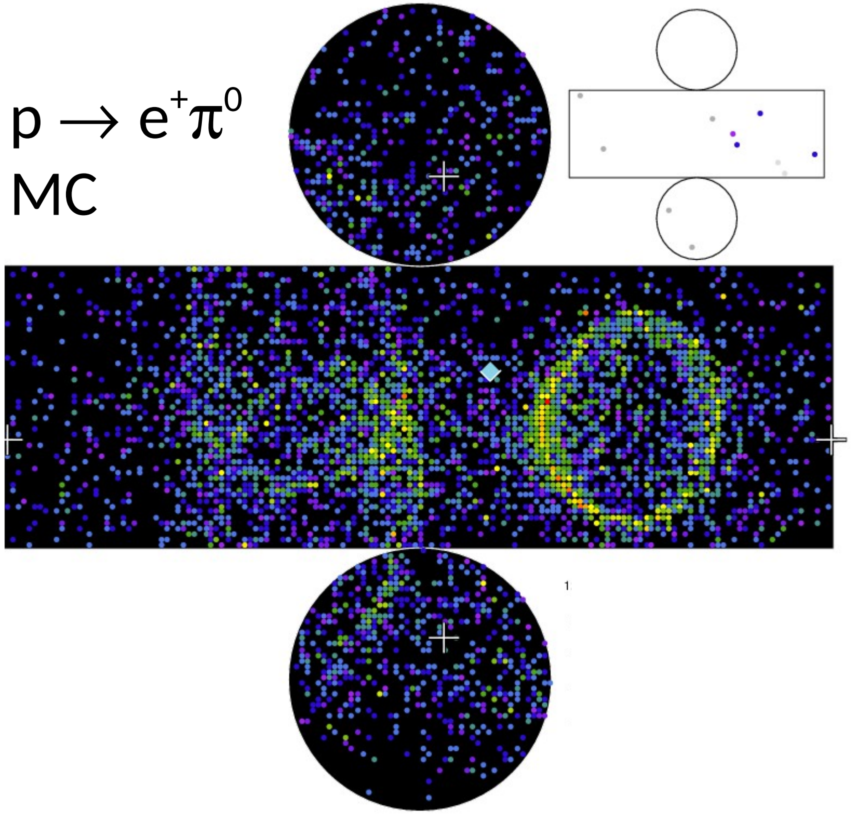
Hyper-K Selection

- 2 or 3 e-like rings
- No decay-e
- $85 < M\pi^0 < 185$ MeV/$c^2$ (3ring)
- $800 < M_p < 1050$ MeV/$c^2$
- $p_{tot} < 250$MeV/c

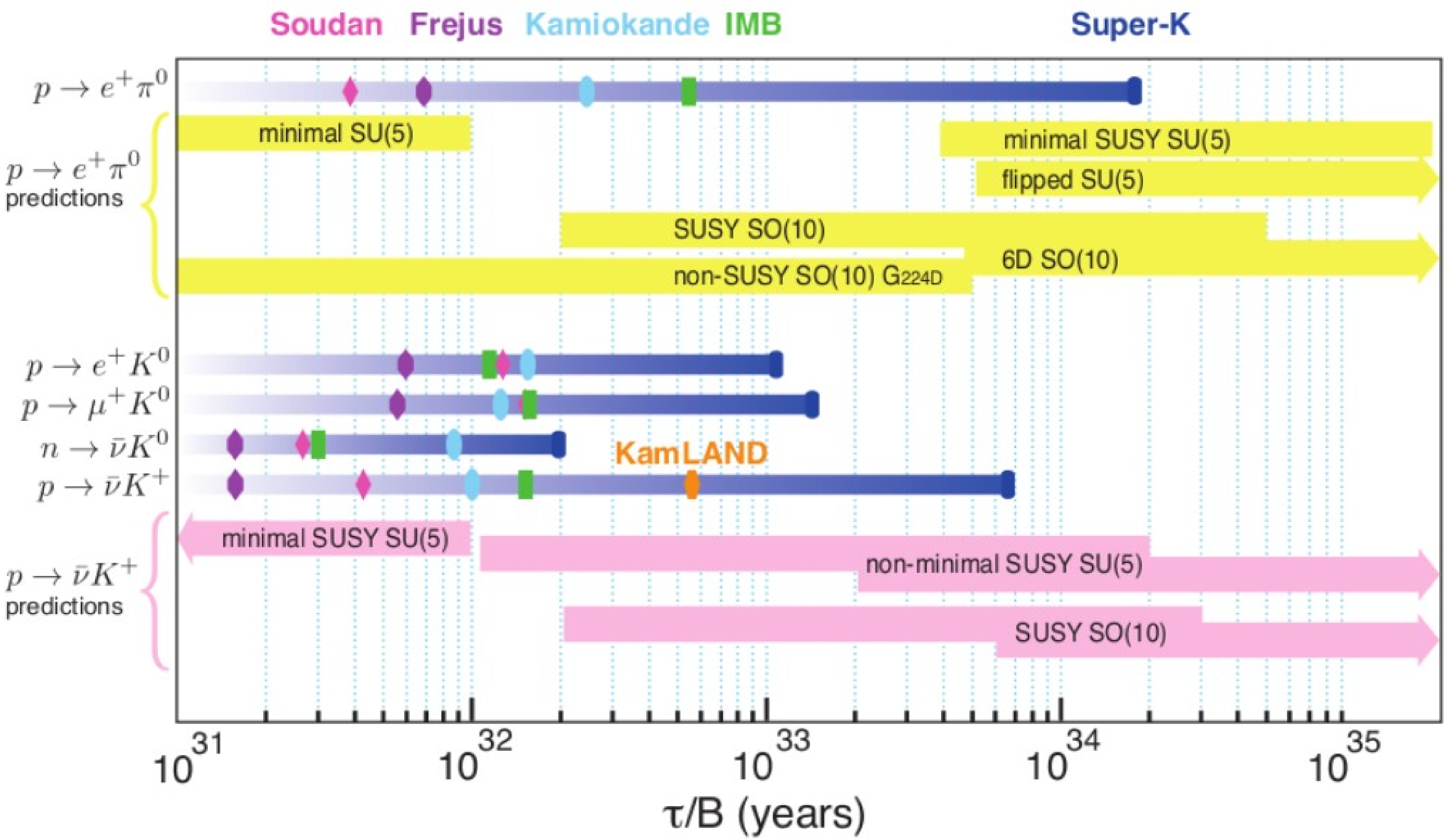
| | Hyper-K | LAr |
|---|---|---|
| Signal ε | ~39% | 45% |
| BG / Mton yr | 0.7 | ~1 |
| 10yr. Sens. 90% | $1.0 \times 10^{35}$ yr | $\sim 10^{34}$ |

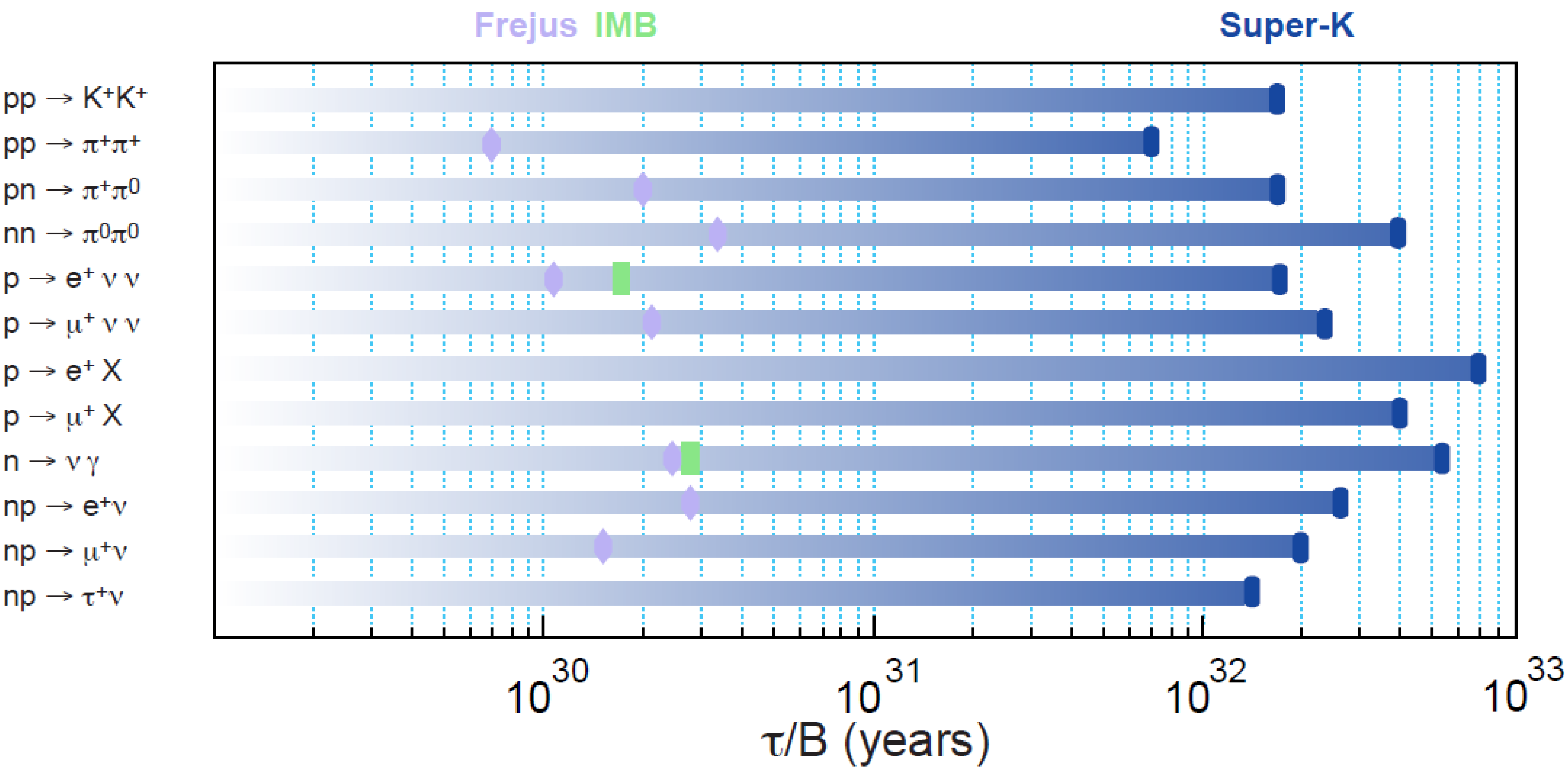
* LAr numbers from JHEP 0704 (2007) 041

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

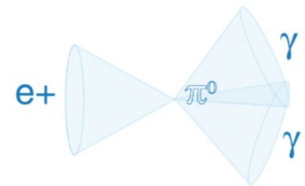


- Efficiency and background rates are similar for Hyper-K and LAr detector
  - This is basically true for other lepton + π modes as well
  - Smaller size of LAr detector makes it less competitive, generally nuclear effects are expected to be larger
- **Hyper-K** is the only effective way to probe this decay beyond existing limits
  - A 40 kton LAr detector would provide supporting evidence if $\tau \sim 10^{34}$ years


Soudan Frejus Kamiokande IMB
Super-K
$p \to e^+\pi^0$
minimal SU(5)
minimal SUSY SU(5)
$p \to e^+\pi^0$ predictions
flipped SU(5)
SUSY SO(10)
6D SO(10)
non-SUSY SO(10) G224D
$p \to e^+K^0$
$p \to \mu^+K^0$
$n \to \bar{\nu}K^0$
KamLAND
$p \to \bar{\nu}K^+$
minimal SUSY SU(5)
$p \to \bar{\nu}K^+$ predictions
non-minimal SUSY SU(5)
SUSY SO(10)
$10^{31}$ $10^{32}$ $10^{33}$ $10^{34}$ $10^{35}$
τ/B (years)

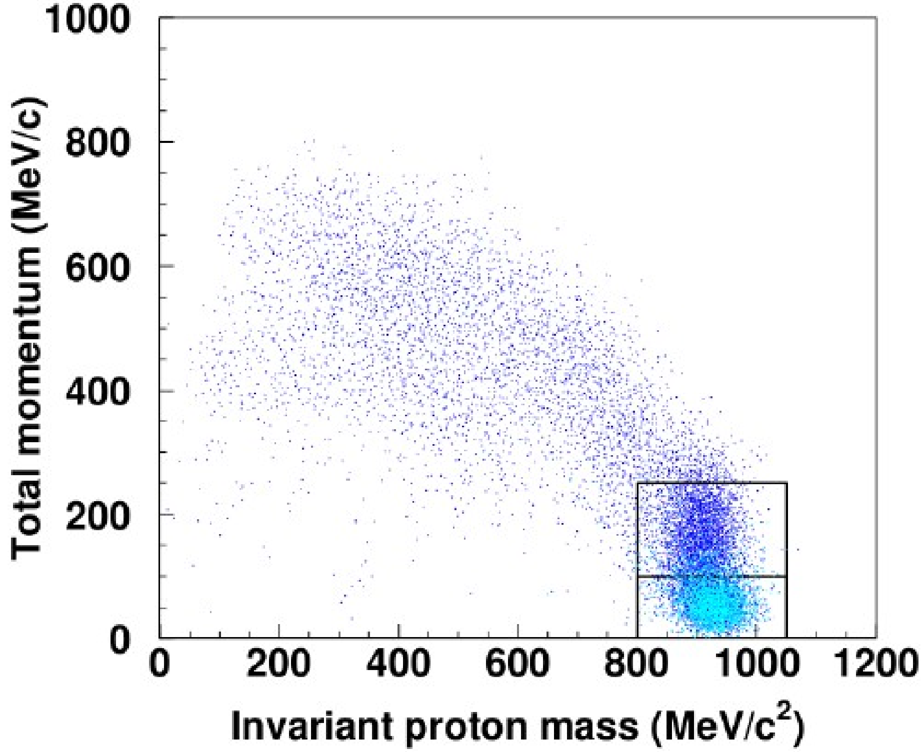

Frejus
IMB
Super-K
pp → K⁺K⁺
pp → π⁺π⁺
pn → π⁺π⁰
nn → π⁰π⁰
p → e⁺ ν ν
p → μ⁺ ν ν
p → e⁺ X
p → μ⁺ X
n → ν γ
np → e⁺ν
np → μ⁺ν
np → τ⁺ν
10^30
10^31
10^32
10^33
τ/B (years)

# Proton Decay: p → e+π0

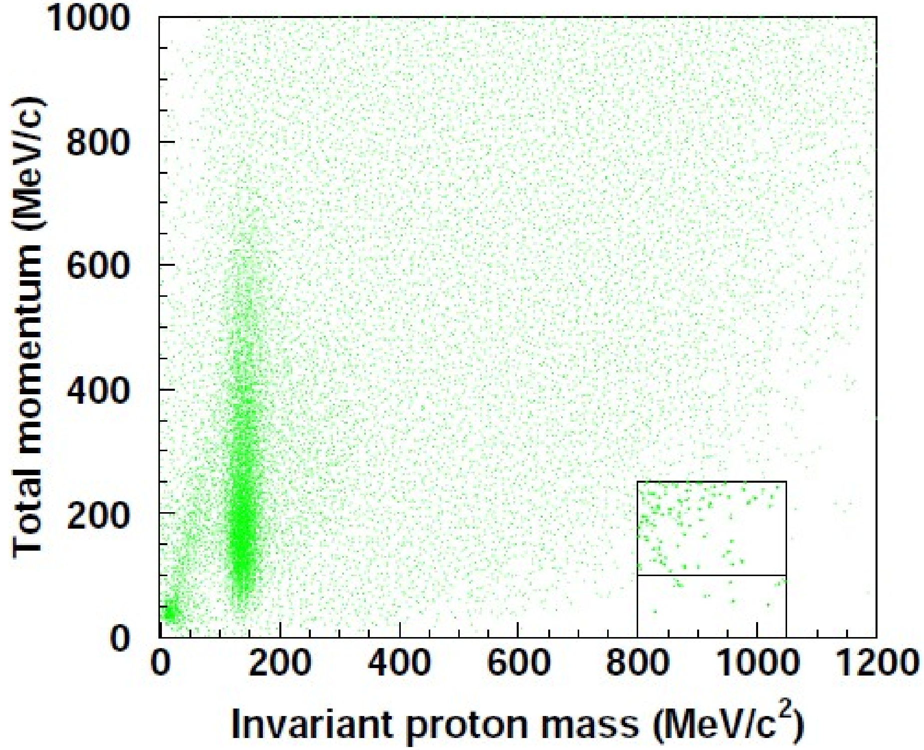



Bound Proton Decays (16O)

Free Proton Decays (1H)




Atm. ν Background 45 Mton yr



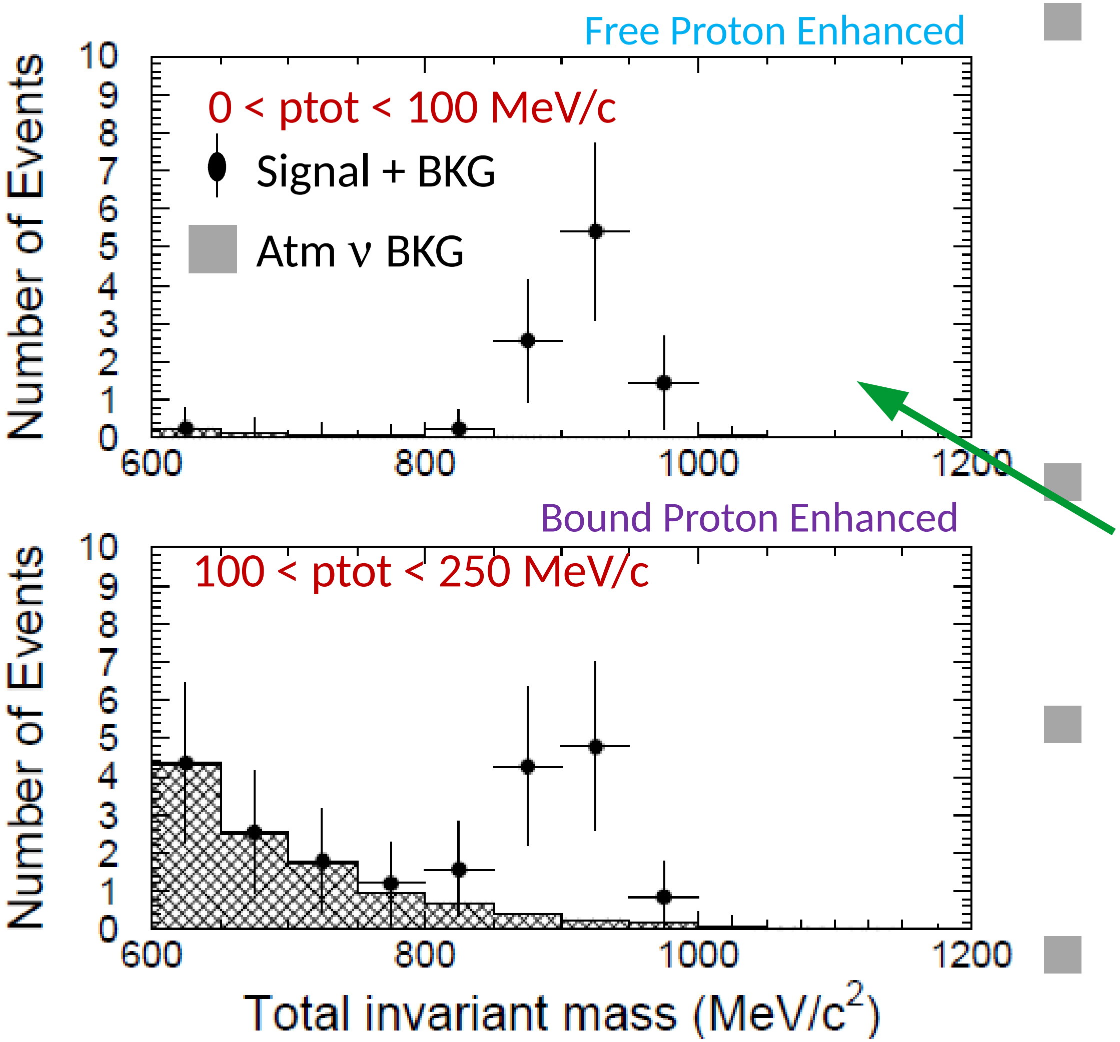

| | $0 < p_{tot} < 100$MeV/c | | | | $100 < p_{tot} < 250$MeV/c | | | |
|---|---|---|---|---|---|---|---|---|
| Design | $\epsilon_{sig}$ [%] | $\sigma_\epsilon$ [%] | Bkg [/Mton·yr] | $\sigma_{Bkg}$ [%] | $\epsilon_{sig}$ [%] | $\sigma_\epsilon$ [%] | Bkg [/Mton·yr] | $\sigma_{Bkg}$ [%] |
| 1TankHD | 18.7 | 6.5 | 0.06 | 32.8 | 19.4 | 14.9 | 0.62 | 31.9 |
| 3TankLD | 18.8 | 5.3 | 0.27 | 29.0 | 20.4 | 15.2 | 2.17 | 31.3 |

- Signal efficiencies and background rates as well as systematic uncertainties have been taken from extensions of SK analyses
- Background reduction for HD Tank is based on 70% efficient neutron tagging

# Proton Decay Signal at Hyper-K: p → e+π0

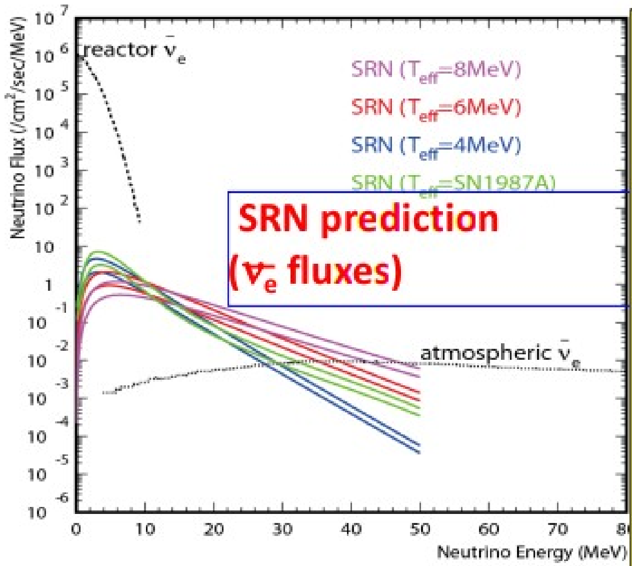


Two HD Tanks, Staged over 10 years




- If proton lifetime is at the current Super-K limit, **$1.7 \times 10^{34}$** years, Hyper-K will observed a very clean signal peak in the reconstructed invariant mass
- Negligible backgrounds in the free proton decay enhanced bin
- Excellent sensitivity to even small signals (long lifetimes)
- All cuts except the invariant mass cut have been applied

# Physics with SK-Gd

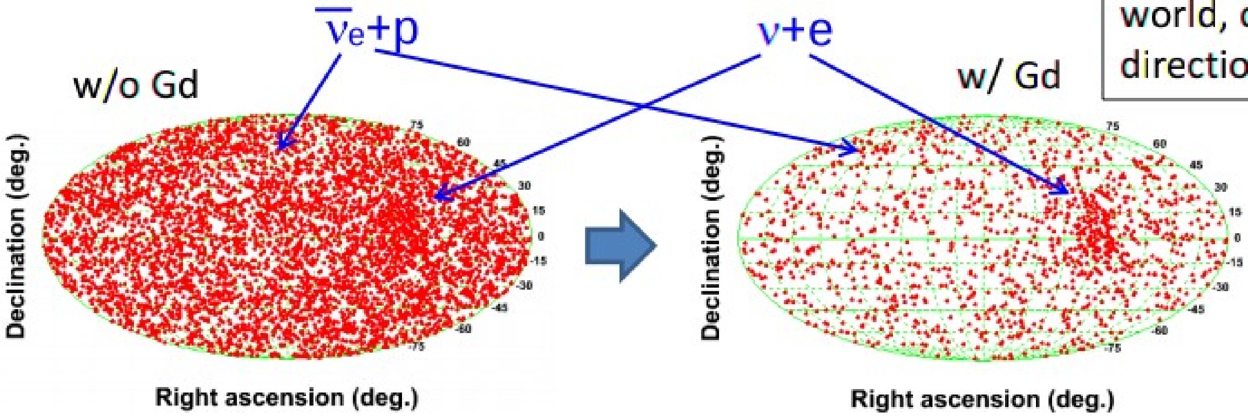



First observation of Supernova Relic Neutrinos

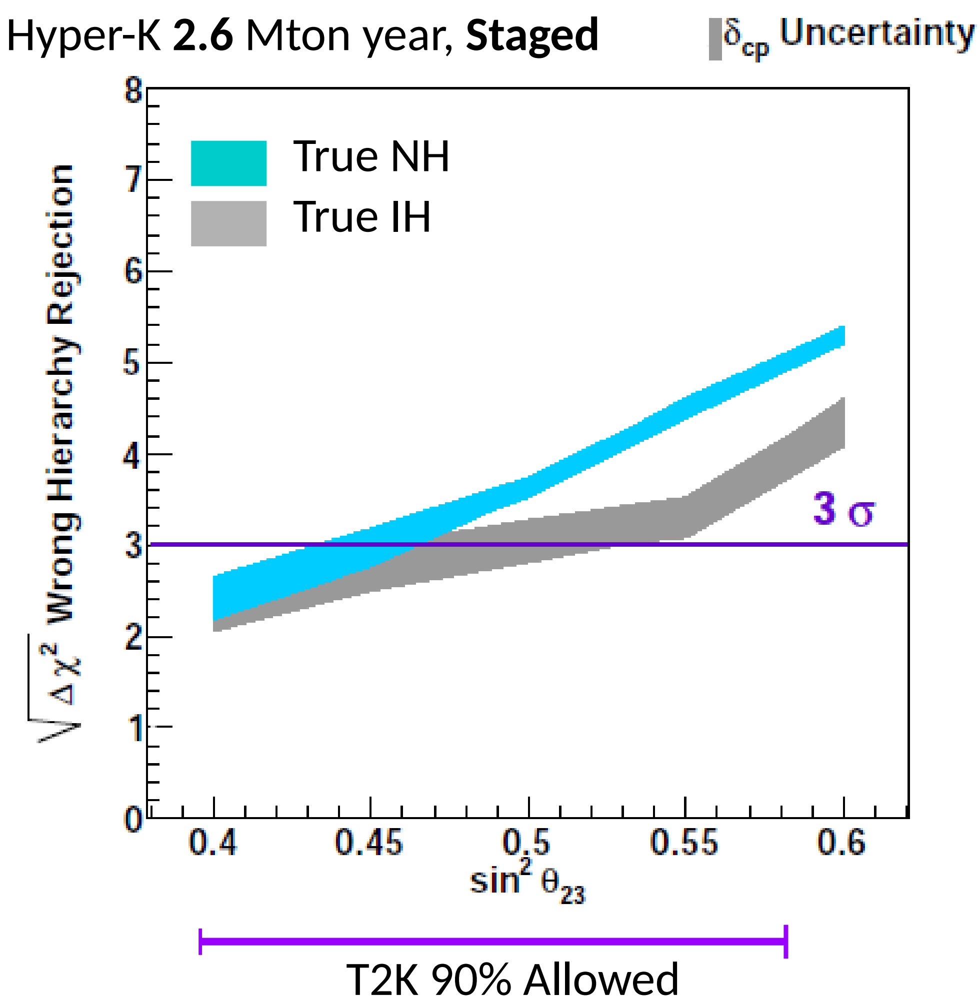
- Supernova neutrinos from the beginning of the universe.
- Expect 1.3 - 6.7 events/year/22.5kt at SK (10-30MeV)
- Solve the "supernova rate problem" (observed rate is almost half of the expectation from star formation rate).
- Competition with future large liquid scintillator detectors (e.g. JUNO).

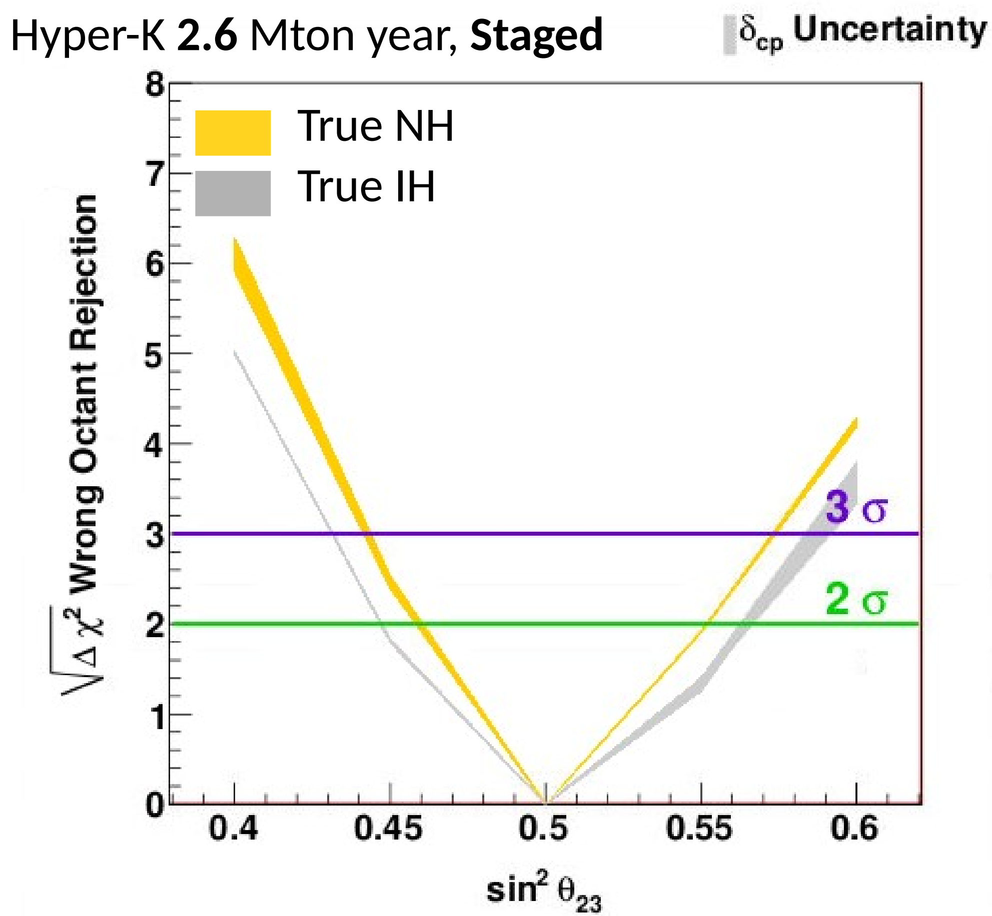
Improve pointing accuracy for supernova bursts.
e.g. 4~5° → 3°(90%CL) for 10kpc

Note that among many neutrino detectors in the world, only SK can give the directional information.



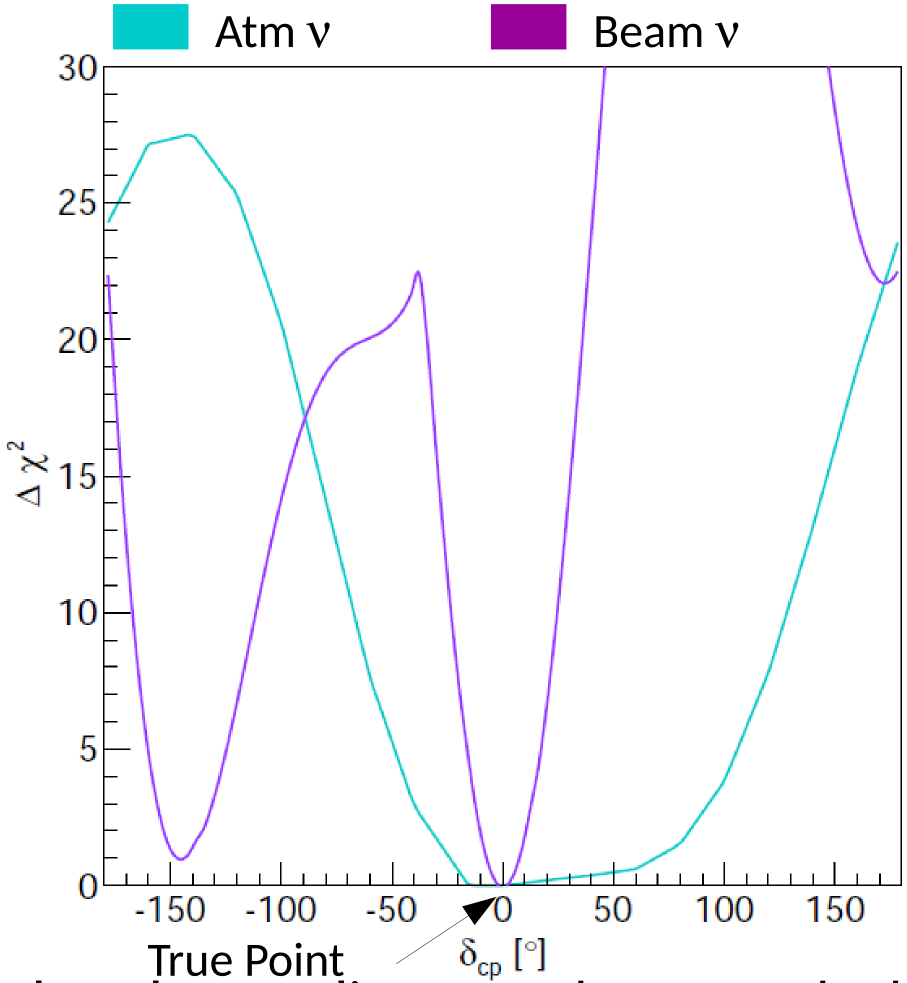
# Hyper-K Sensitivity 10 Years, Staging Scenario




- Expect better than ~3σ sensitivity to the mass hierarchy using atmospheric neutrinos alone
- 3σ Octant determination possible if $|\theta_{23} - 45°| > 4°$

# Combination with Beam Neutrinos : δcp



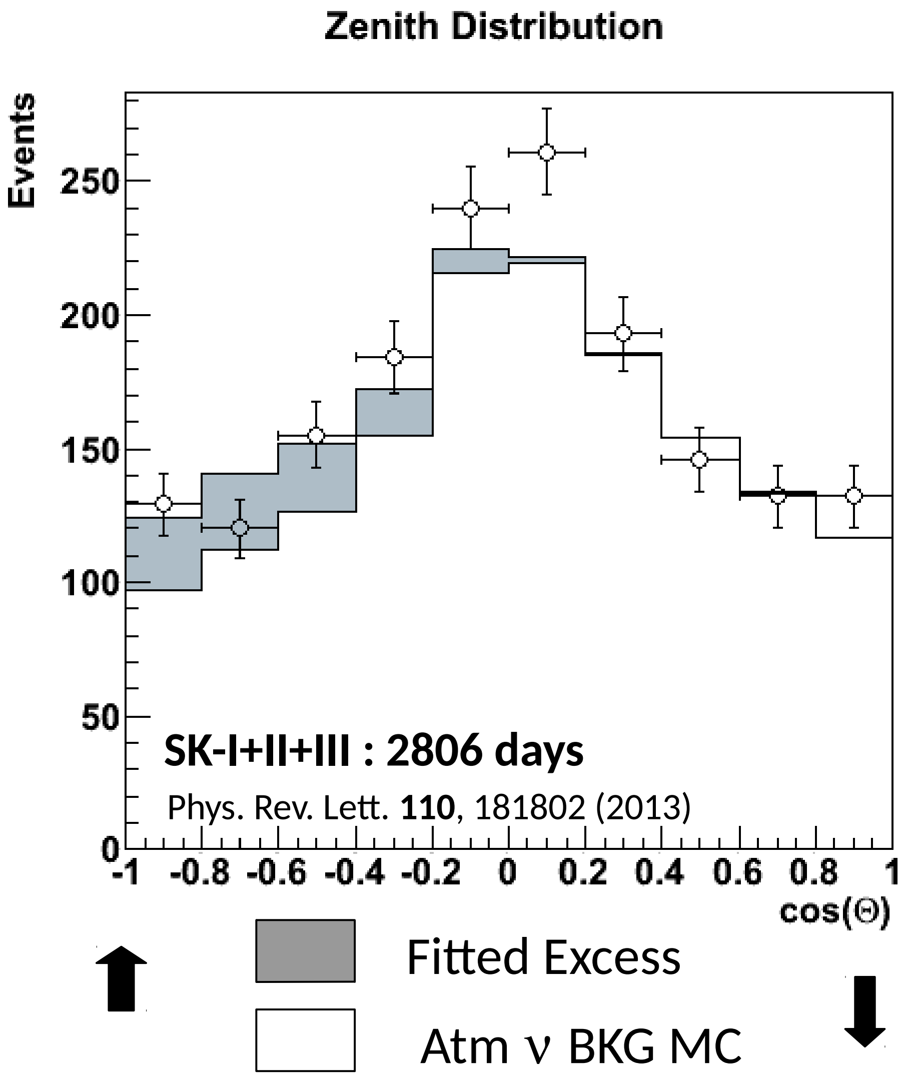

- Sensitivity to $\delta_{cp}$ is largely complimentary between the beam and atmospheric neutrino samples
- Constraint on $\delta_{cp}$ improves with their combination
- Atmospheric ν sensitivity is limited by flux and cross section uncertainties

# Oscillation-induced $\nu_\tau$ measurements

- Incorporate t NN information into oscillation analysis

| per/ 100 kton yr. | Hyper-K | LAr |
|---|---|---|
| Signal CC ντ | 40.2 | 28.5 |
| Background | 448.7 | 44.8 |
| S /√B , 10 years | 9.6 | 8.5 |

- HK Numbers are upward-going event rate
- LAr numbers based on PRD82, 093012




- After 10 years Hyper-K will have O(1,000) ντ events that can be used to study
  - CC $\nu_\tau$ cross section, leptonic universality, etc.
- Fit for CC $\nu_\tau$ cross section normalizaton
- After 5.6 Mton years Hyper-K constraint on this parameter would be about 7%

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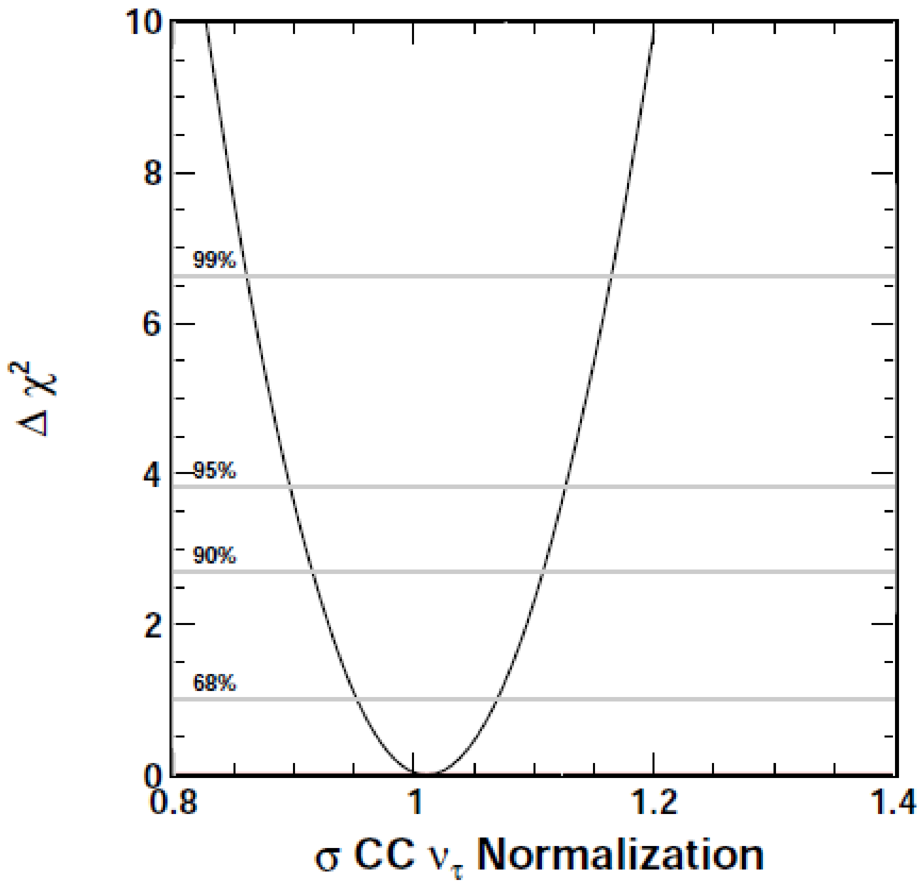


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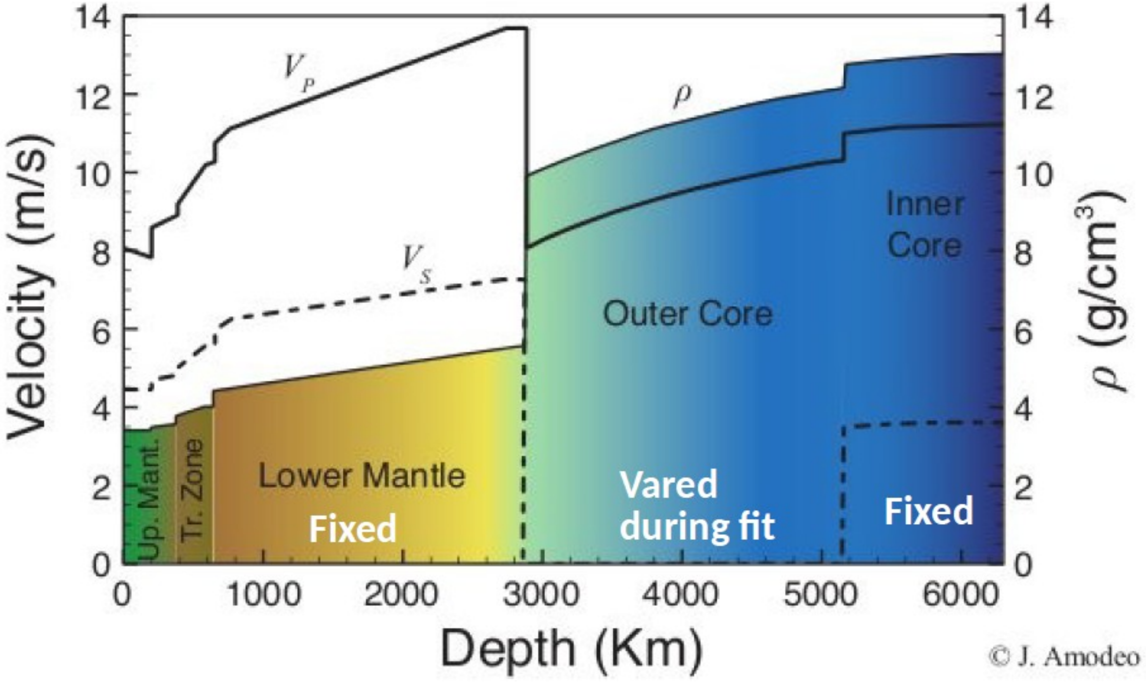
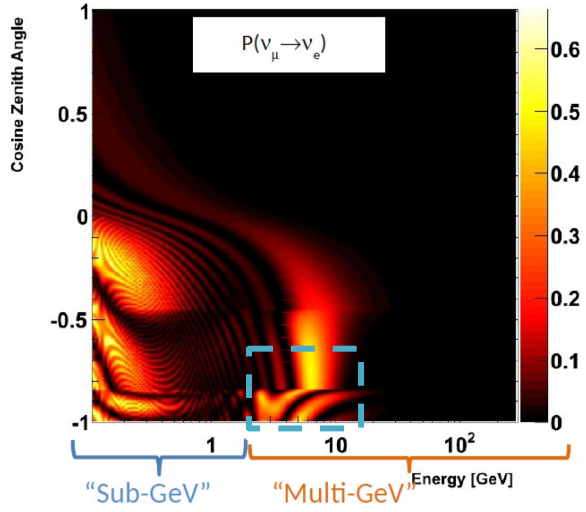
# Geophysics: Chemical composition of Earth's Outer Core



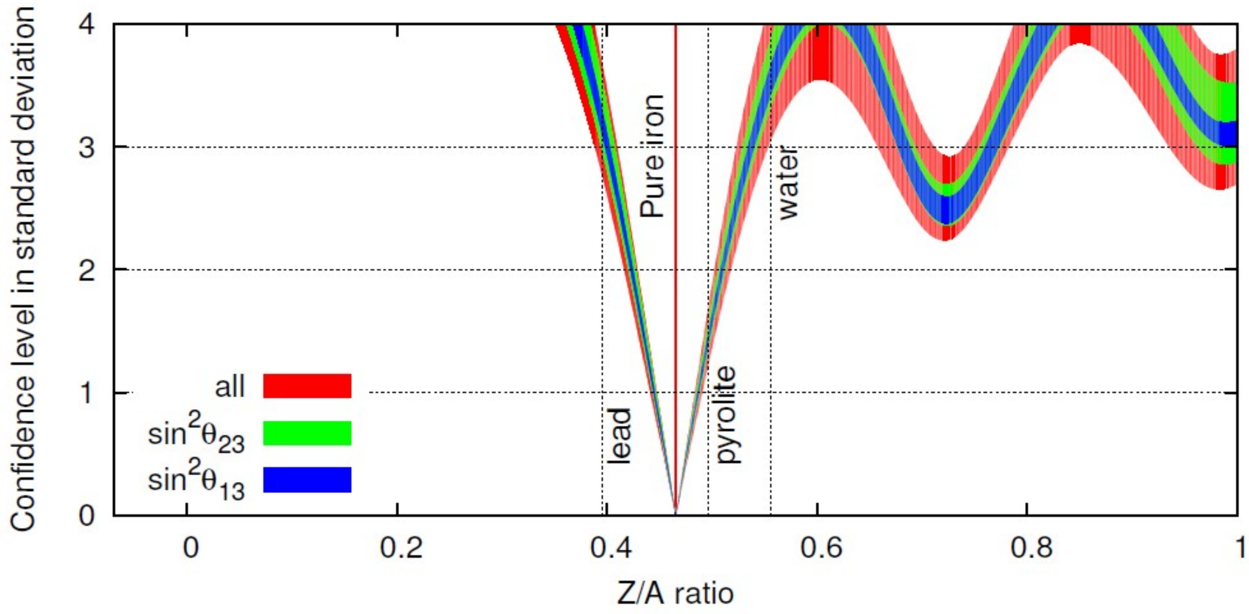



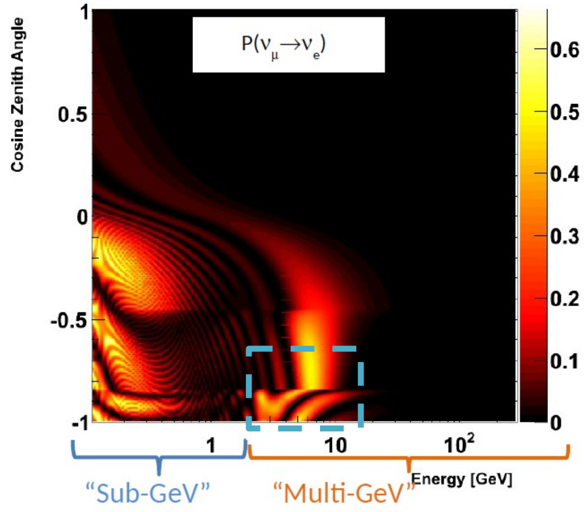

- Density profile of the Earth is well known from seismology
  - Outer core is thoughts to be made of Fe+Ni and some other light element (unknown)
- Chemical composition of the Earth's core (Z/A ratio) is essential to understanding the formation of the Earth and its magnetic field
- Hyper-K can begin making measurements in this as yet unopened field
- <u>Any measurement</u> is of interest to the geophysics community , even if errors are large
- With a 10 Mton year exposure Hyper-K can exclude a lead- and water-based cores
- Technique is complementary to that of large neutrino telescopes

# Geophysics: Chemical composition of Earth's Outer Core



Sensitivity to Outer Core Chemical Composition, 10 Mton yr

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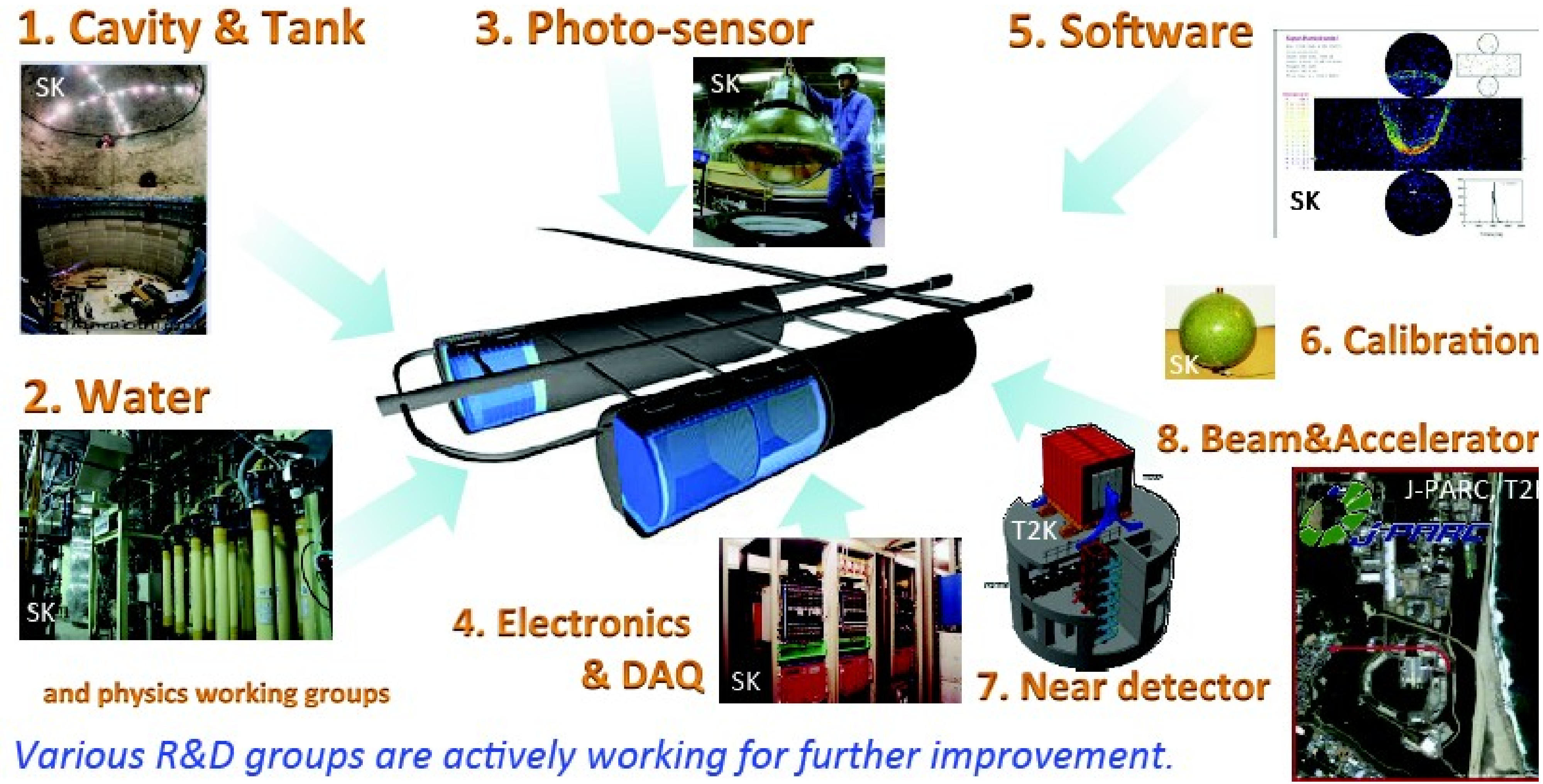
# Hyper-Kamiokande: Development Efforts




- Aiming to build a *better* detector than predecessors
  - Not just something bigger!
- Build from Super-K / T2K experiences while developing independent tools for Hyper-K
- Development efforts across the board (too many to discuss today!)