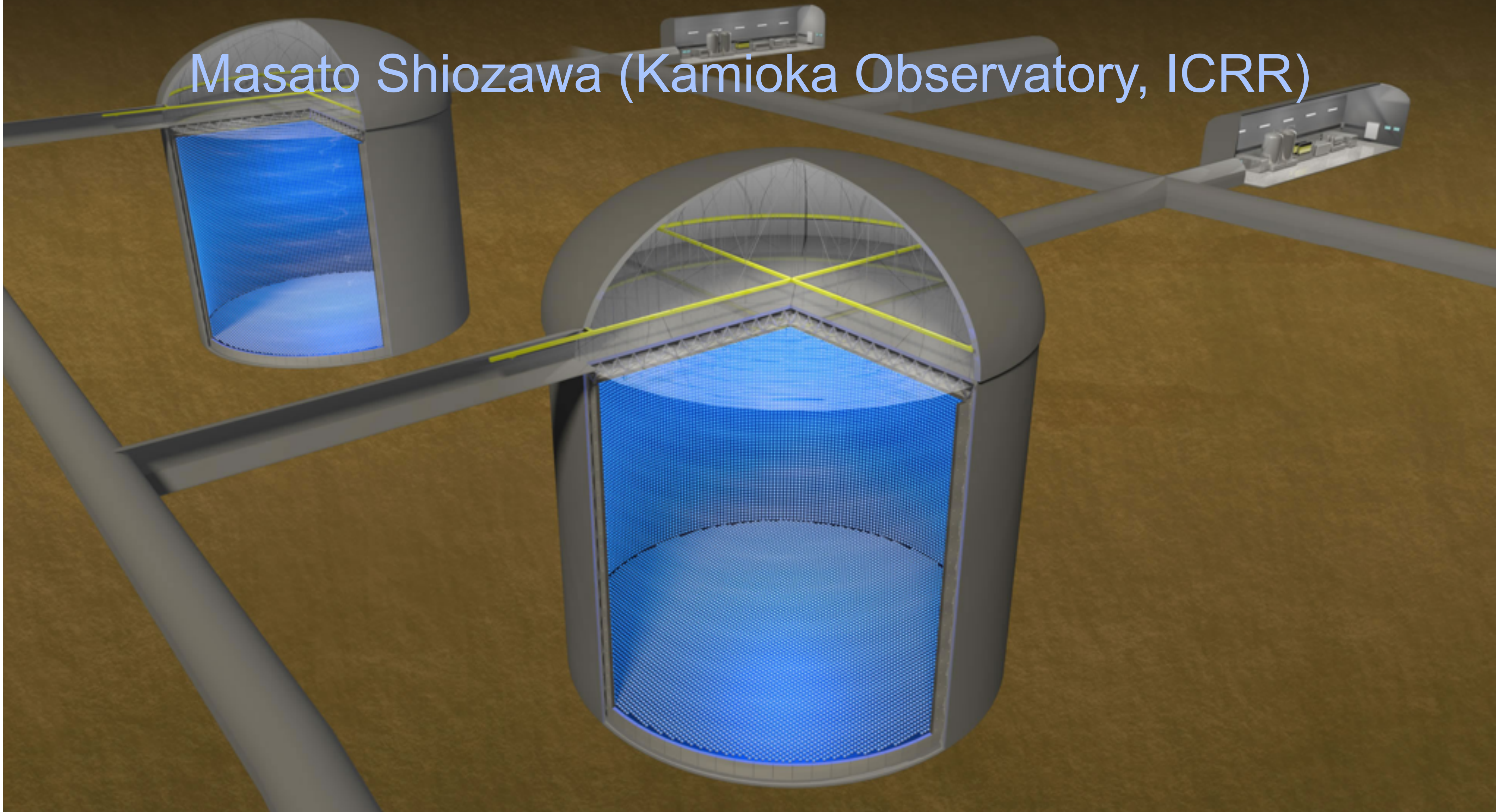
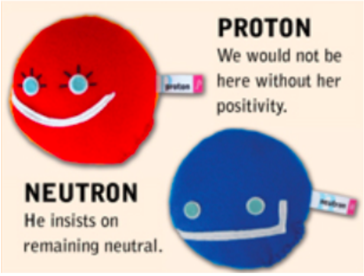
Hyper-Kamiokande project

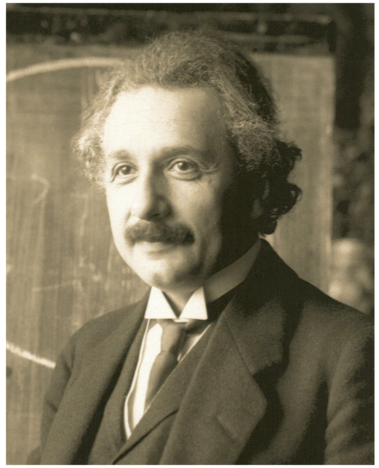
Masato Shiozawa (Kamioka Observatory, ICRR)



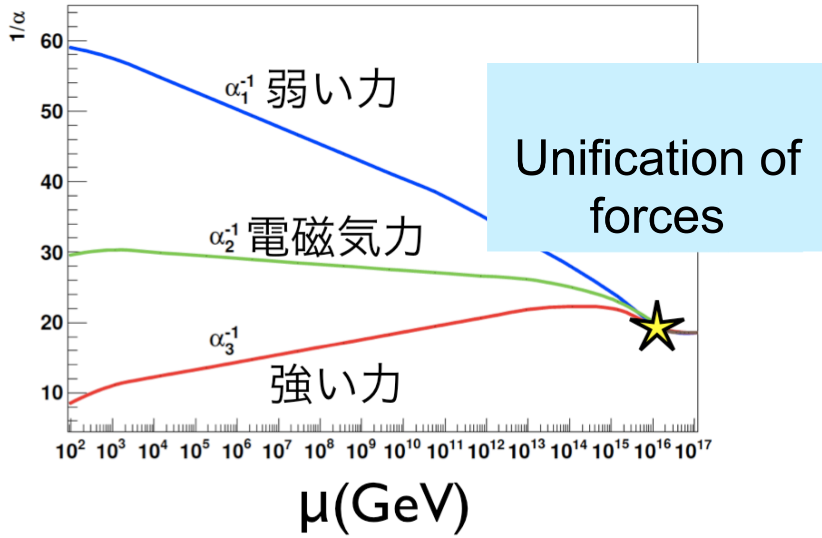


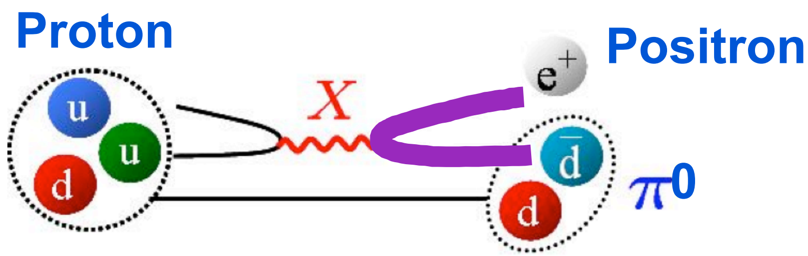
Does proton decay?

Direct evidence for particles unification

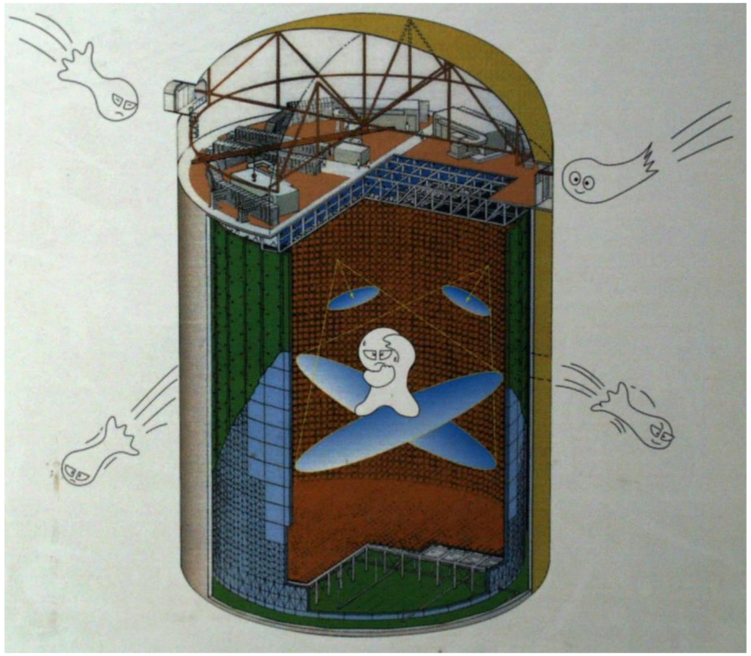


- Standard model is just an approximation of unified theory
  (many of us believe)
- In grand unified theory,
  - Three forces are unified
  - $Q_{e-}:Q_u:Q_d$ = 3:2:1
  - Accommodate tiny ν mass
  - Prediction of proton decays
- Proton decay experiments
  - Direct probe to GUT
  - Explore new paradigm of particles





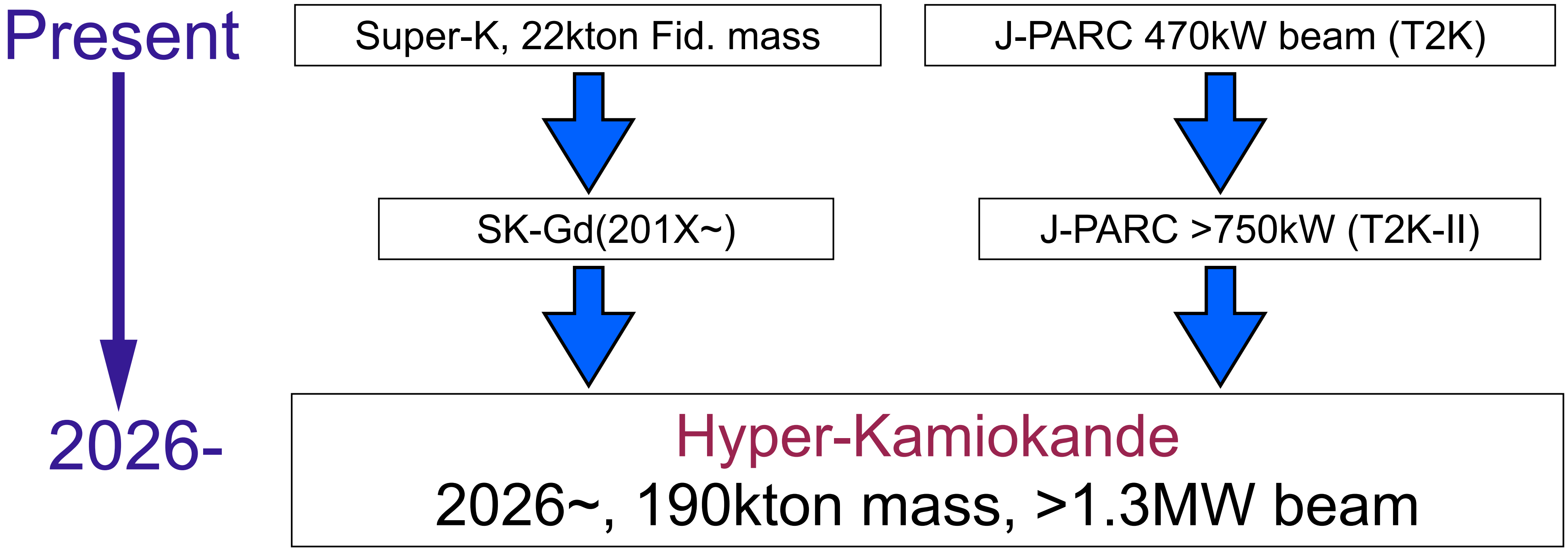
Direct transition between positron (lepton) and d-quark



Neutrino

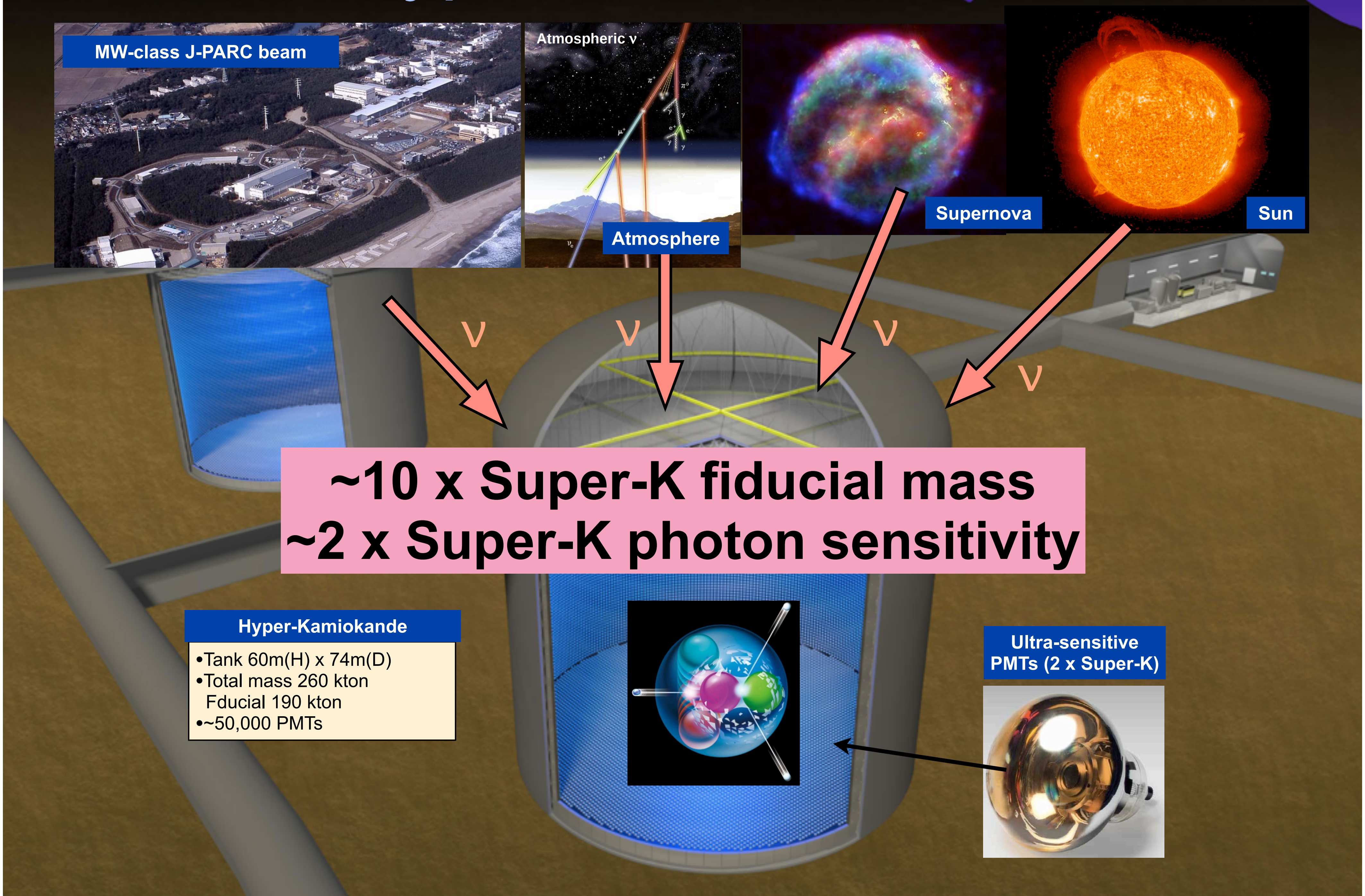
Messenger from nature

- Neutrino does mix
- Particle-antiparticle asymmetry? (CP violation?)
  - Key to understand universe's matter dominance
- Tiny (<10^{-6} of electron) neutrino masses
- Neutrino mass ordering?
  - Feasibility of $0\nu\beta\beta$ discovery experiments
  - What is the origin of tiny ν mass & large mixing?
- What's roles of neutrinos in nature?
  - Driver of Supernova explosion?
  - Probe to the interior of Sun, Earth, Universe

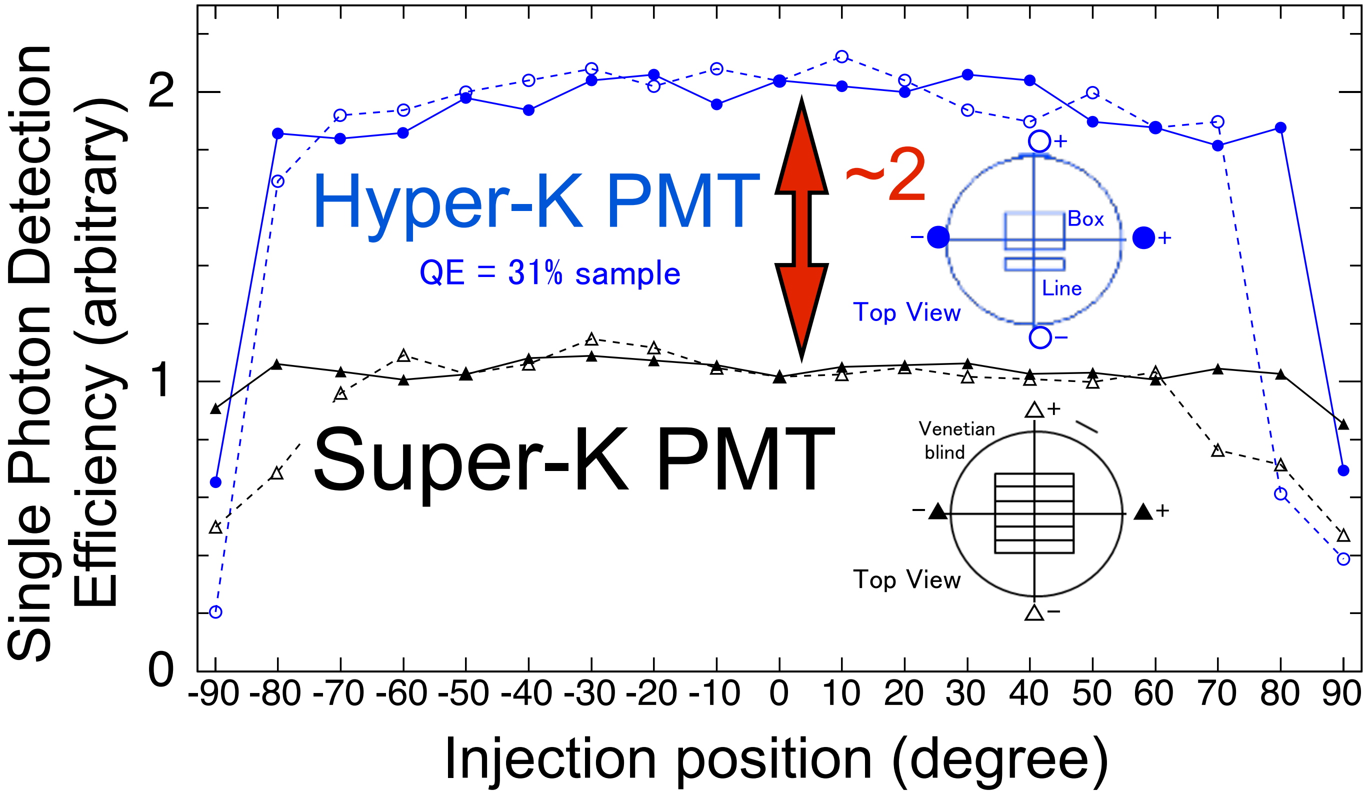


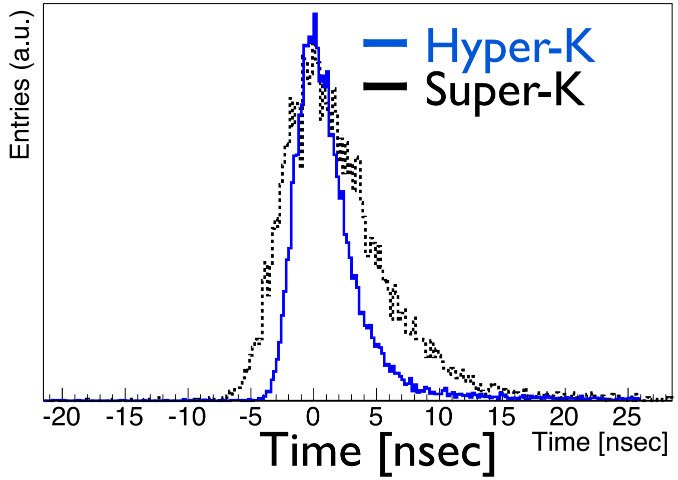
- **Japan-based seamless program to get timely results**
- **Rich physics, big chance of discoveries**

Hyper-Kamiokande



50cmΦ Hyper-K PMT





- Efficiency x 2, Timing resolution x 1/2
- Pressure tolerance x 2 (>100m)
- Enhance detector performance

by better detection of faint signal, e.g. solar ν, SN ν, proton decay & background signature

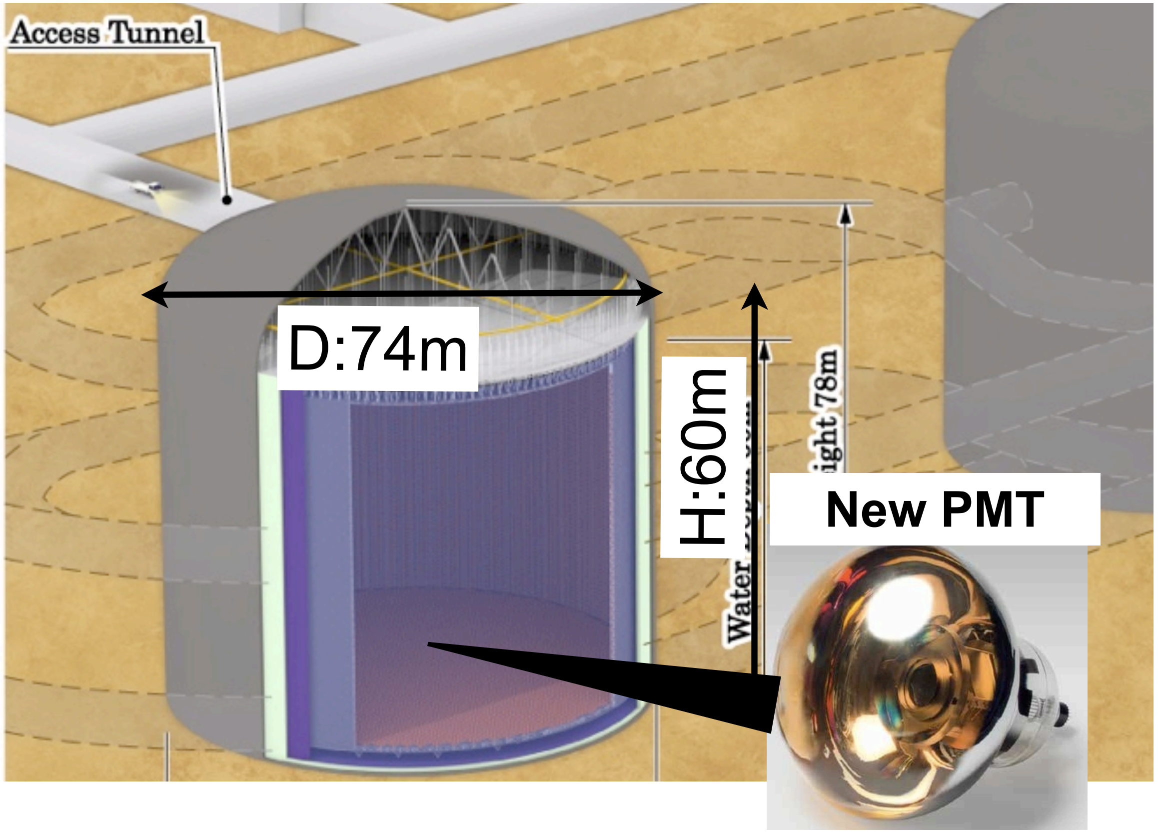
Hyper-Kamiokande tank design

HK Design Report : KEK Preprint 2016-21, ICRR-Report-701-2016-1

- Fid. mass 190 kton, an order of mag. larger than Super-K
- Light yield: ~2 x Super-K

(Single tank parameters)

- Cylindrical tank : H60m×D74m
- Total Mass 260 kiloton
  Fiducial Mass 190 kiloton
- Photo-sensors (inner detector) : 40,000 pieces giving 40% photo-cathode coverage



- New PMT enables the water tanks to be smaller, thereby reducing construction costs, without sacrificing its physics
- 2-tanks in stage: priority to realize the 1st tank ASAP

Hyper-K proto-collaboration

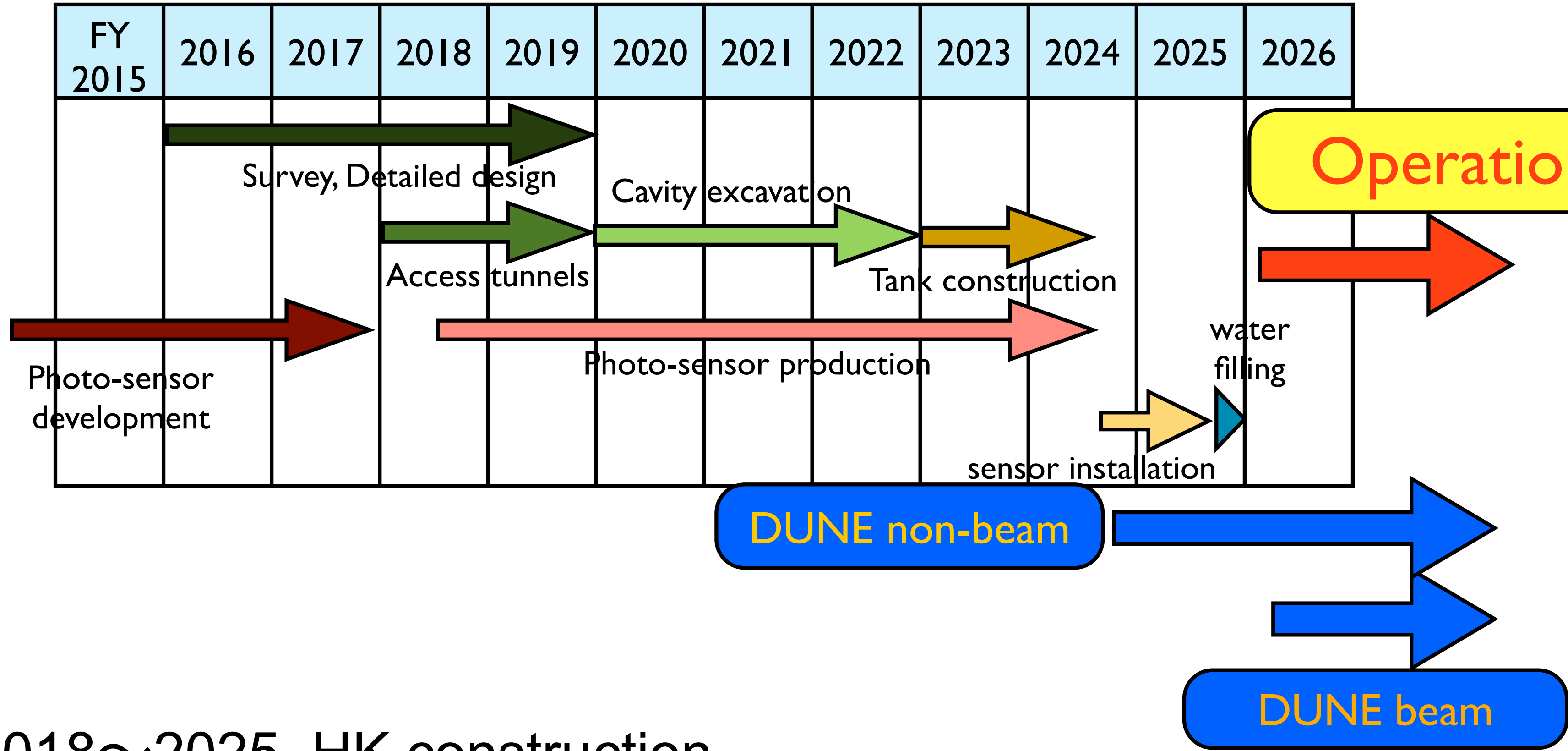
Inaugural Symposium@Kashiwanoha, January 2015

Hyper-K meeting@London, July 2016

- **Hyper-K proto-collaboration has been established and is growing**
  - 15 countries, 73 institutes, ~300 members, ~75% from abroad

- MoU between 2 host institutes: UTokyo/ICRR and KEK/IPNS
- Int. Hyper-K Advisory Committee to develop the program

Notional Timeline (1st Tank)



- 2018～2025 HK construction
- 2026～ CPV study

  Atm・Solar・Supernova v study, Proton decay searches

Toward approval


提言

第23期学術の大型研究計画に関する
マスタープラン
（マスタープラン2017）

平成29年（2017年）2月8日
日本学術会議
科学者委員会
学術の大型研究計画検討分科会

- Science Council of Japan has selected Hyper-K as one of **Important Large Scale Project** in Materplan2017

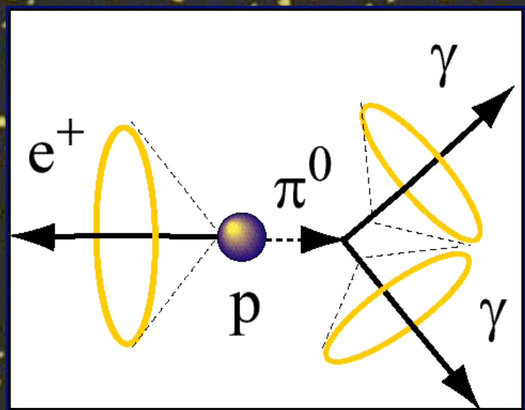
- MEXT (Japanese funding agency) will revise the list of important large-scale projects (Roadmap) in this summer

- UTokyo/ICRR are preparing for the **MEXT review** and **construction budget request**

Contents

- Overview of Hyper-Kamiokande Done!
- Proton decay search
- Accelerator ν study
- Atmospheric ν study
- ν astrophysics and astronomy

Proton Decays
- present and future -

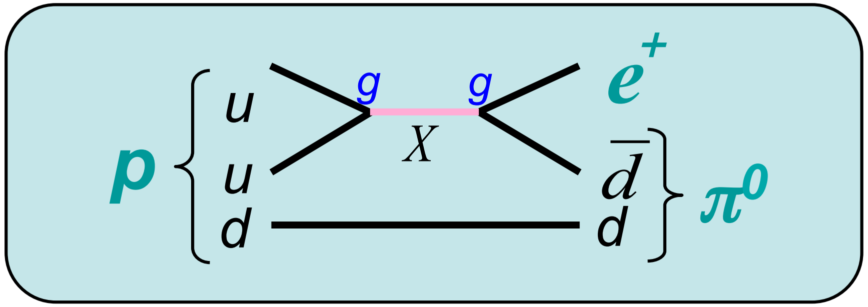


Motivation of Nucleon Decay Searches

- Only way to directly prove GUT

- Two major modes predicted by many models

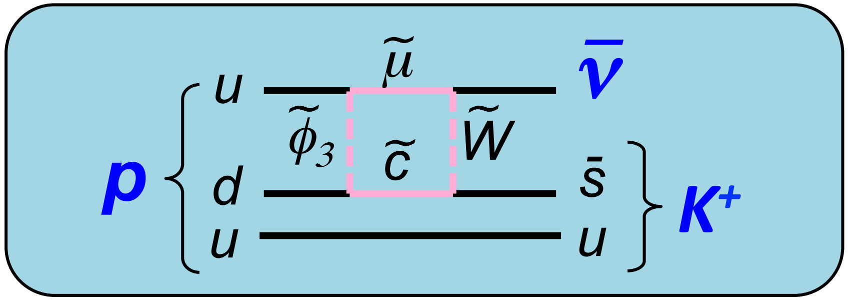
Mediated by gauge bosons



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

$$\Gamma(p \to e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY mediated



$p \to \nu K^+$

$$\Gamma(p \to \bar{\nu} K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

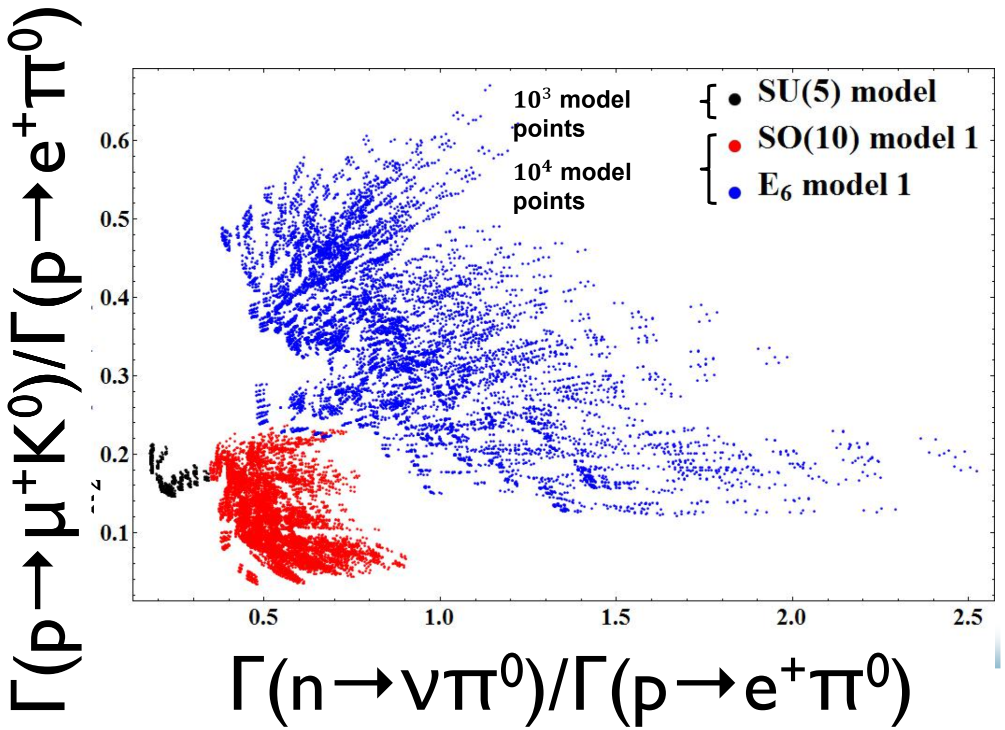
- We need to pursue both decay modes for discovery, given the variety of predictions

※Searches for other modes are also important

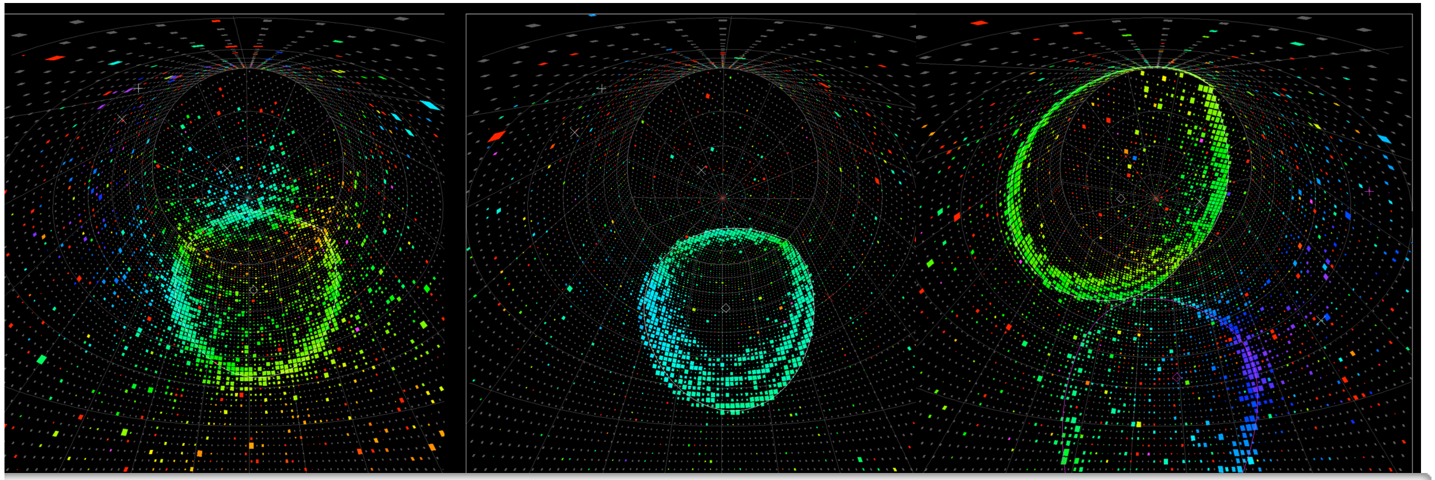
Other modes are also important

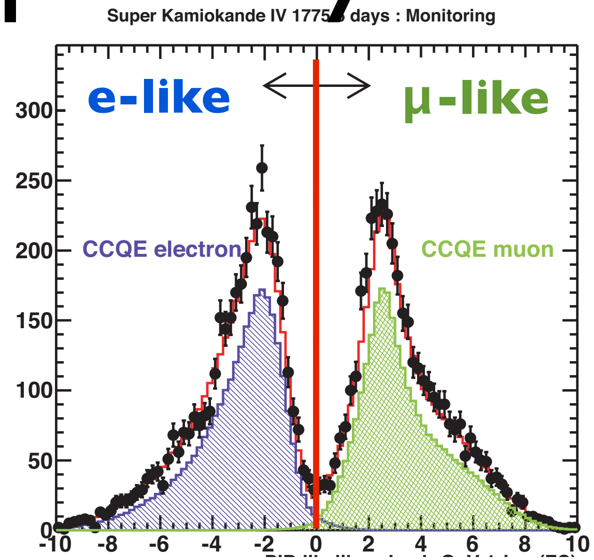
- First discovery might happen in exotic decay modes.
  - Many models predicts branching ratio of $p \to e^+\eta$, $e^+\rho$, $e^+\omega$ are 10~20%
  - Flipped SU(5) (Ellis) predicts $Br(p \to e^+\pi^0) \sim Br(p \to \mu^+\pi^0)$

- We expect to identify details of unification picture, e.g. gauge group and other symmetries
  - $\Gamma(n \to \nu\pi^0)/\Gamma(p \to e^+\pi^0)$ depends on SU(5), SO(10), E_6 (Y. Muramatsu)



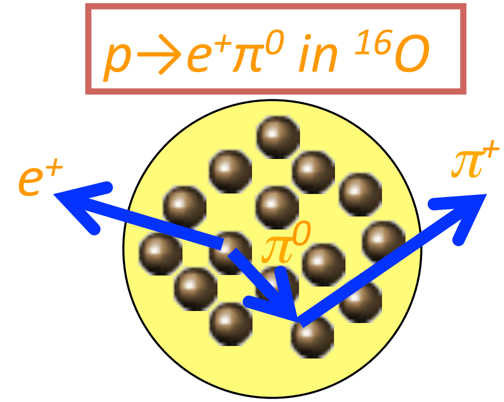
Water Ch. detector for p-decays

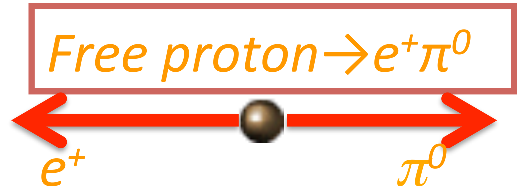




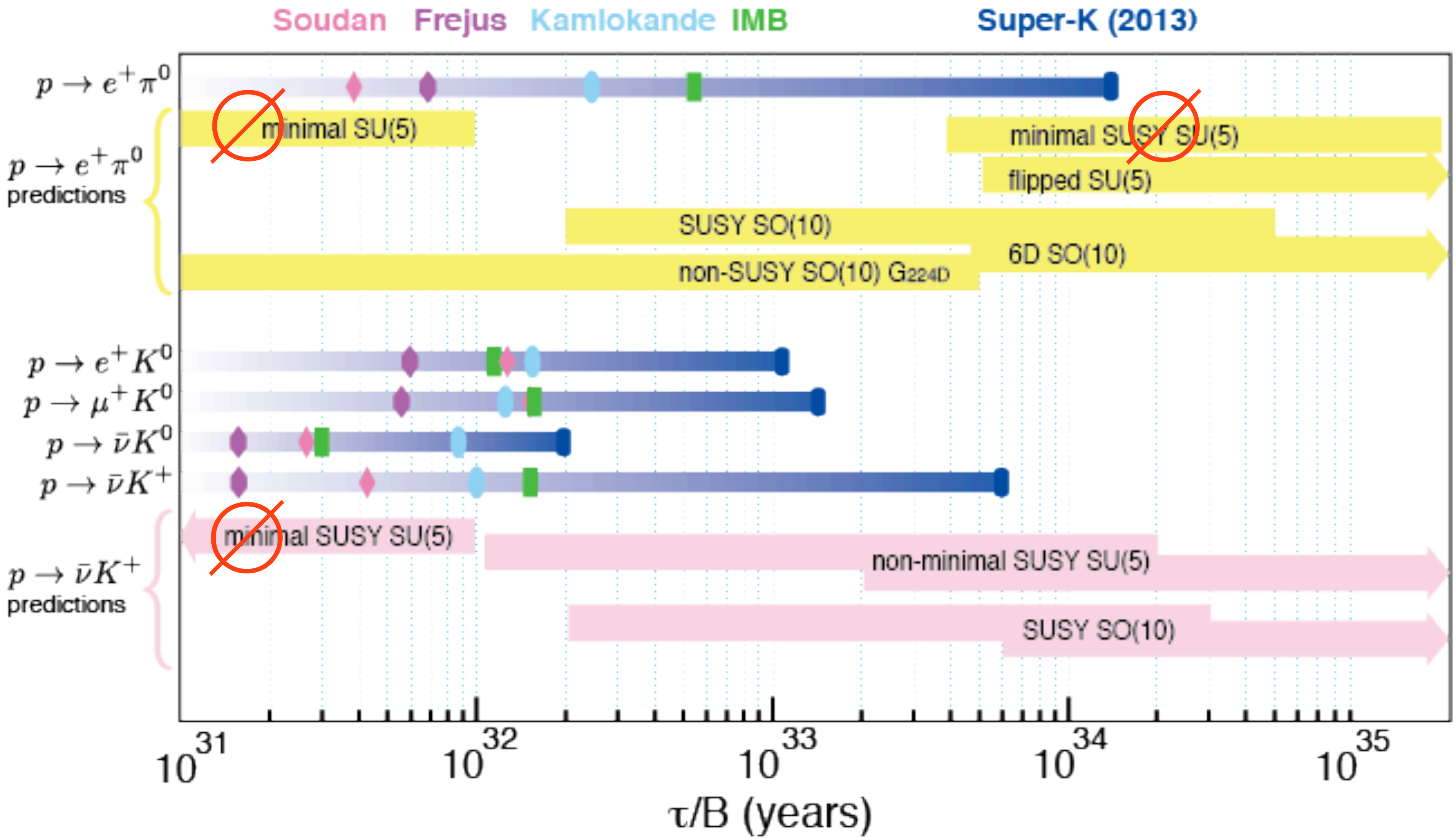
PID likelihood (atmν)

- **High mass is possible** (1Mton ~ 20×Super-K)
  - **$p \rightarrow e^+\pi^0$, νK^+, and more** can be searched with unprecedented sensitivities
- **Excellent & well-proven performance**
  - Good ring-imaging capability at ~1GeV
  - Excellent particle ID (e or μ) capability > 99%
  - Energy resolution for e and μ ~3%
- **Free protons are available**
  - No nuclear effect, Fermi motion
  - High efficiency & good S/N separation

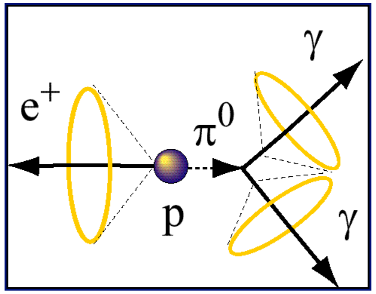




Experimental limits and models



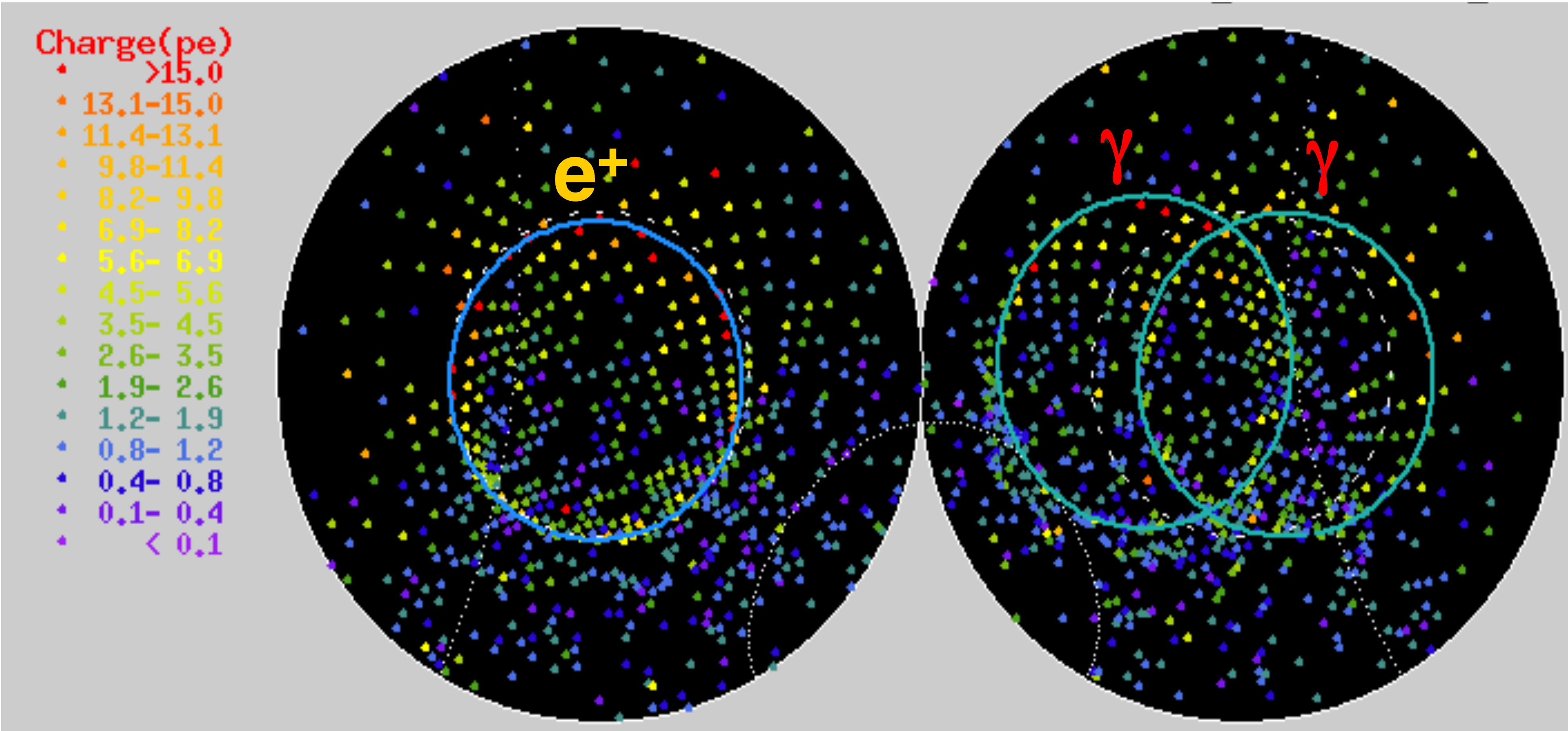
- Super-K provides world stringent limits
- Many models predict $\tau = O(10^{34\text{-}35})$ years
  - Discovery could be around corner!



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

Super-K cut

- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050$ MeV/c^2
  $P_{total} < 250$ MeV/c



SK-II (half PMT) forward-backward display for $p \rightarrow e^{+} + \pi^{0}$

Recent improvement (1)

Beacom and Vagins PRL93:171101(2004)

Neutron tagging to reduce background events

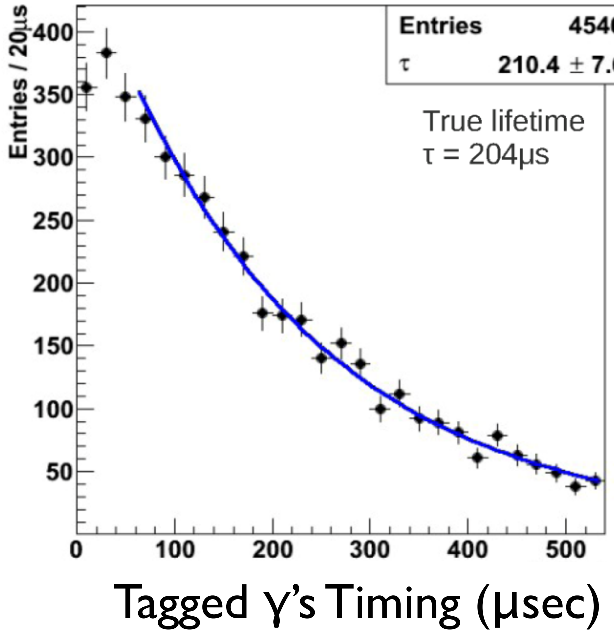
•BG: often accompanied with neutrons by neutrino primary interactions and secondary int. in water

▸proton decay: neutron emission from residual nucleus is small.

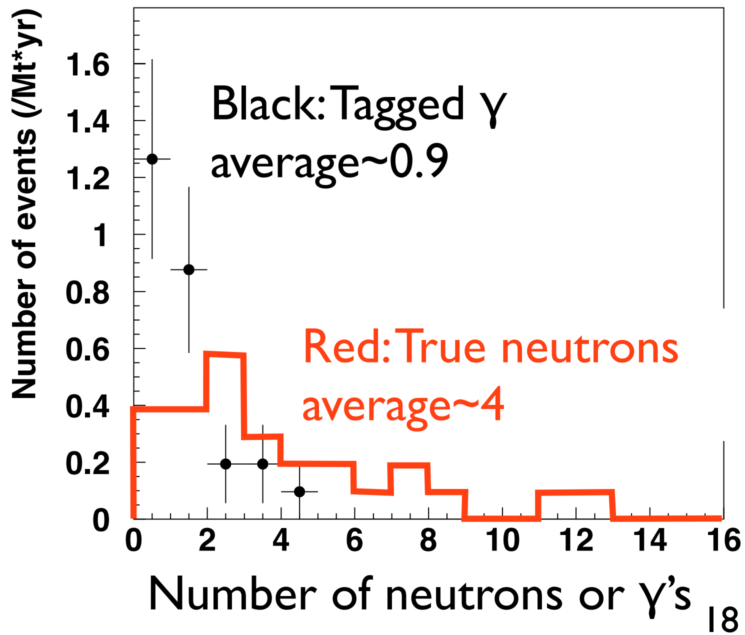
Since SK-IV we have started recording faint signature of neutrons;

n+p→d+γ(2.2MeV, τ~200μsec), BG reduction by ~2

SK-IV 1297days atmν Data



p→e⁺π⁰ BG Monte Carlo



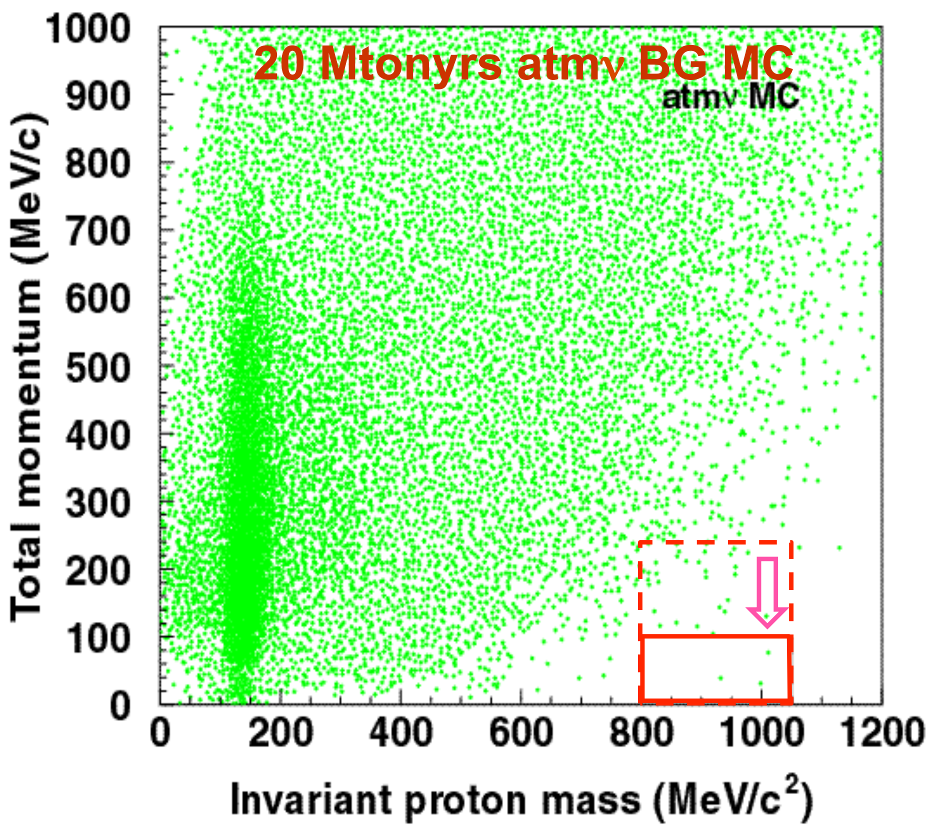
Recent improvement (2)

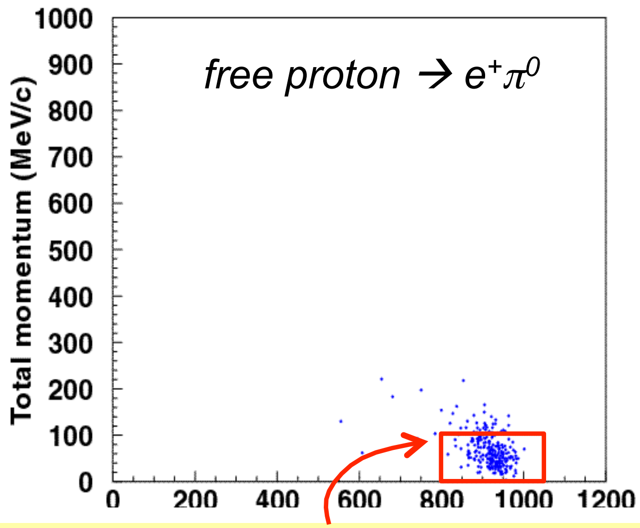
Shiozawa, talk@NNN00-Fermilab

Tight momentum cut to make BG-free box

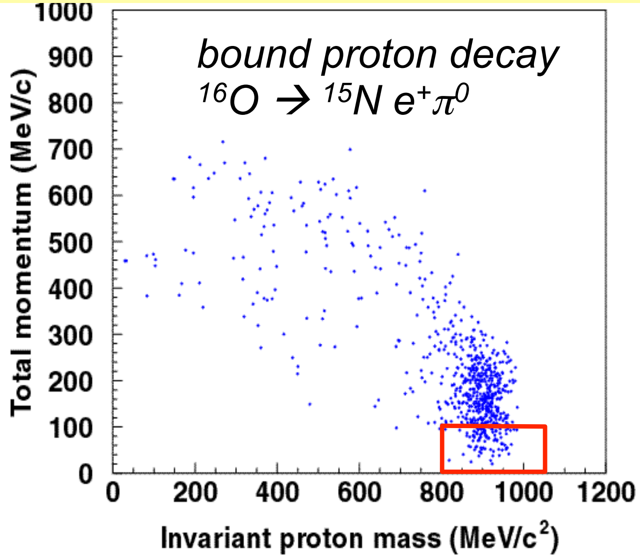
- Ptot < 250 MeV/c (SK cut)
  BG=**2.2** ev/Mtonyrs, eff.=***44%***

  BG reduction by ~15
- Ptot < 100 MeV/c (tighter cut)
  BG=***0.15***ev/Mtonyrs, eff.=***17.4%***



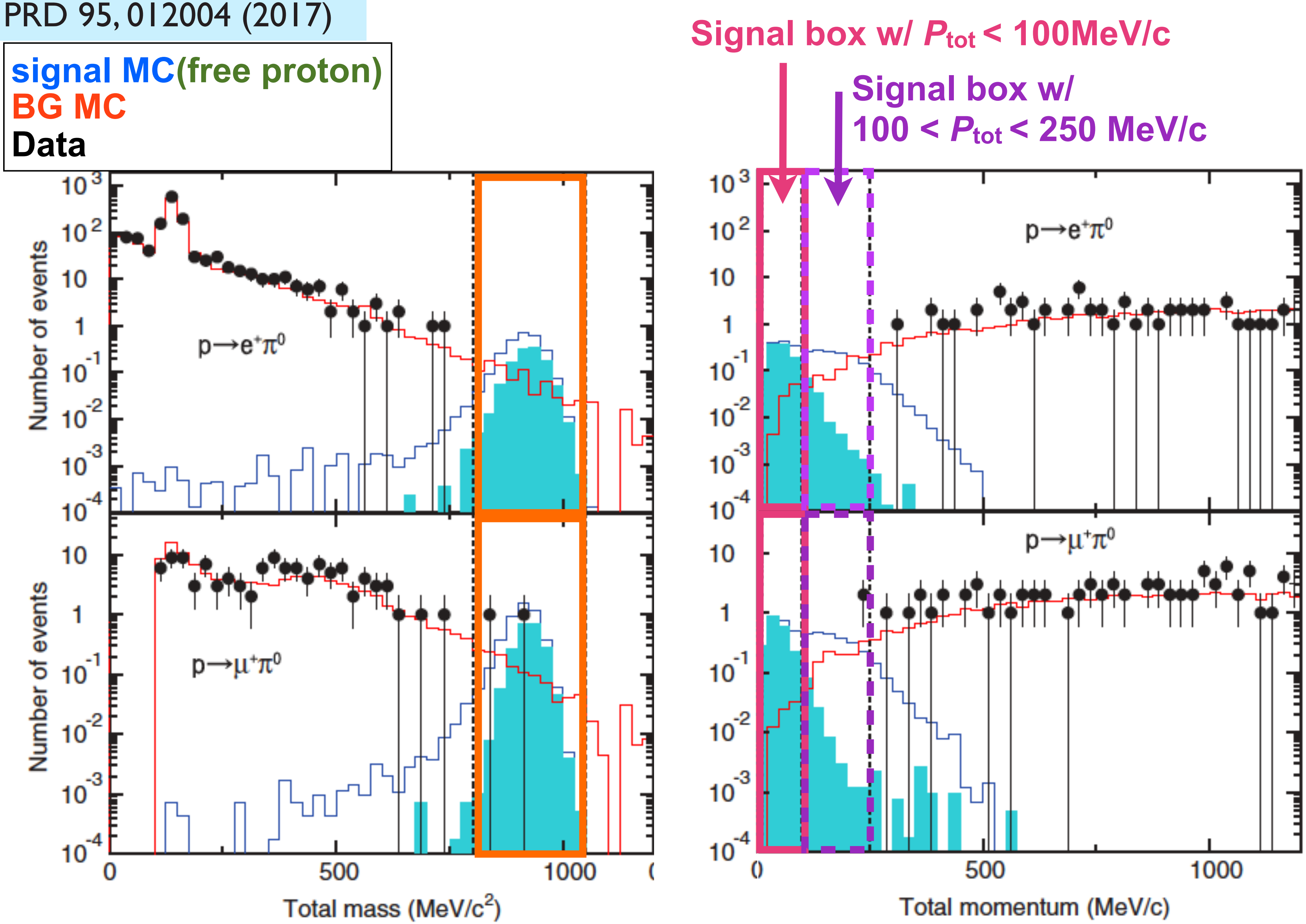


main target is *free proton decays*



Proton decays into lepton+meson

PRD 95, 012004 (2017)

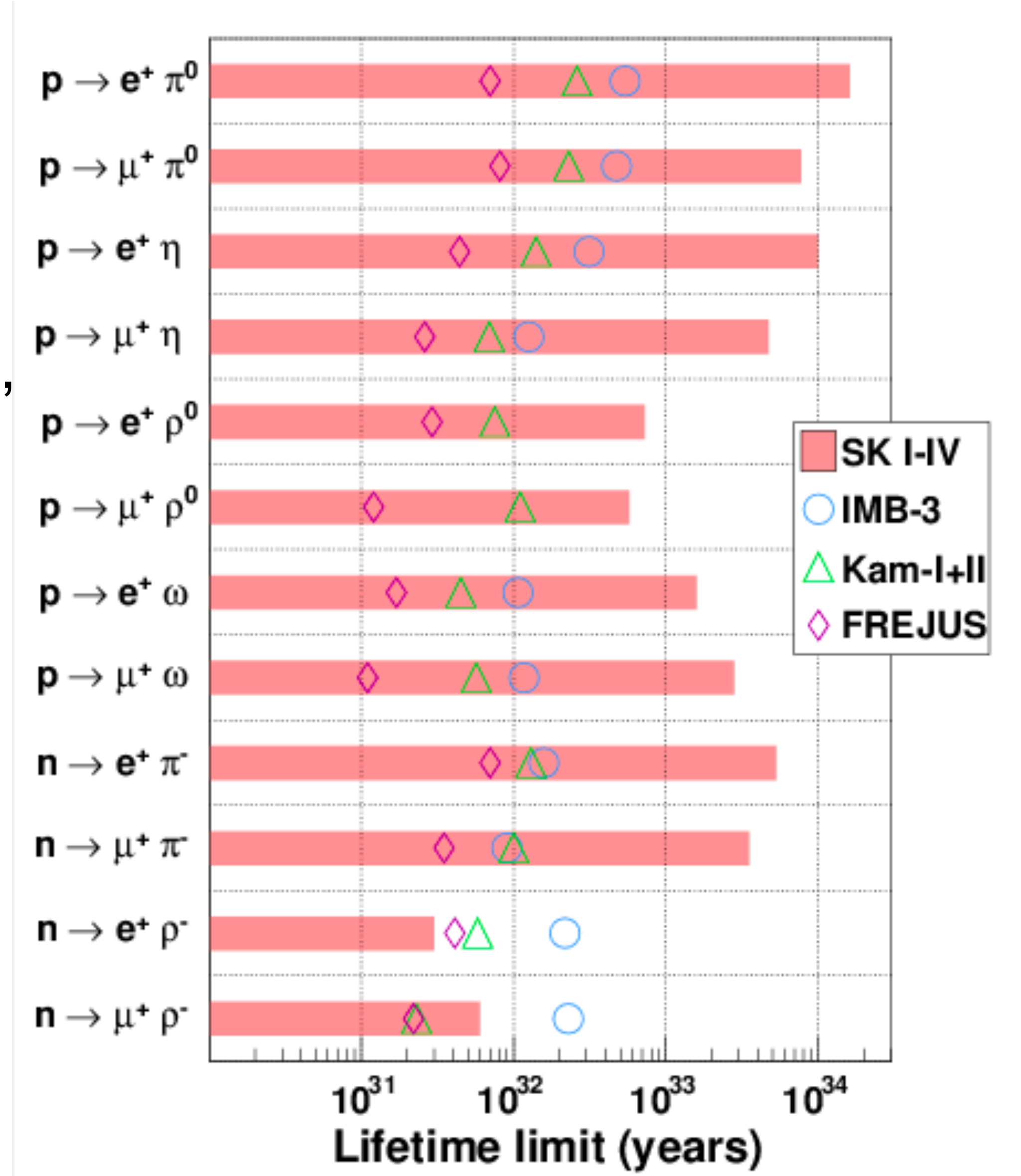


Proton decays into lepton+meson

PRD 95, 012004 (2017)

paper under preparation

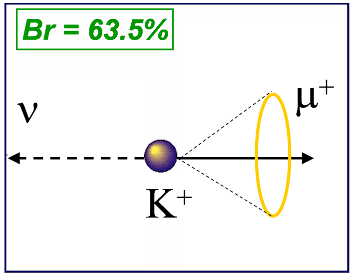
- $p \rightarrow e^+ \pi^0$
  - 0 candidates (40% eff. & 0.61BG)
  - $\tau_p/Br > 1.6 \times 10^{34}$ yrs
- $p \rightarrow \mu^+ \pi^0$
  - 2 candidates (40% eff. & 0.87BG), one is rejected after energy re-calibration
  - $\tau_p/Br > 7.7 \times 10^{33}$ yrs



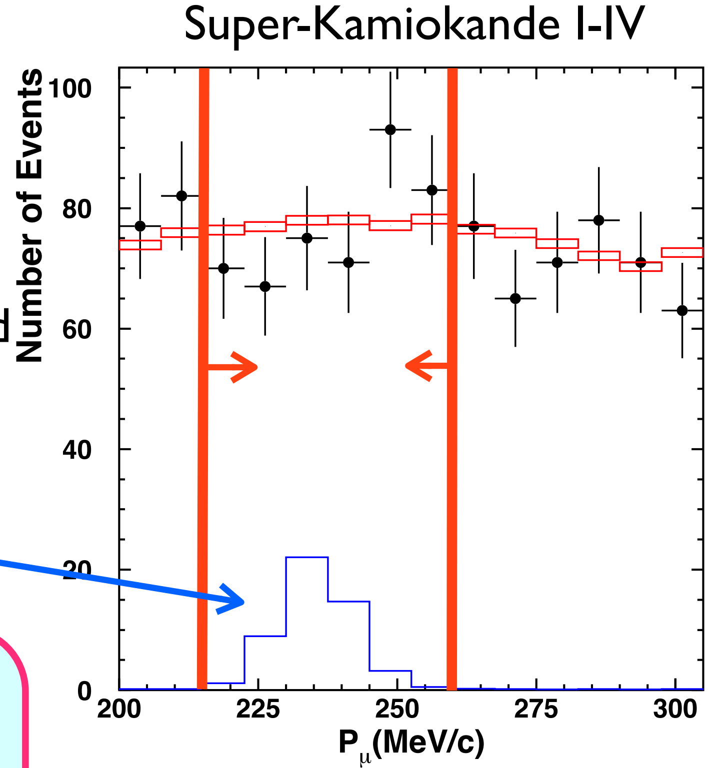
$p \to \nu + K^+$ searches

PRD90, 072005 (2014)

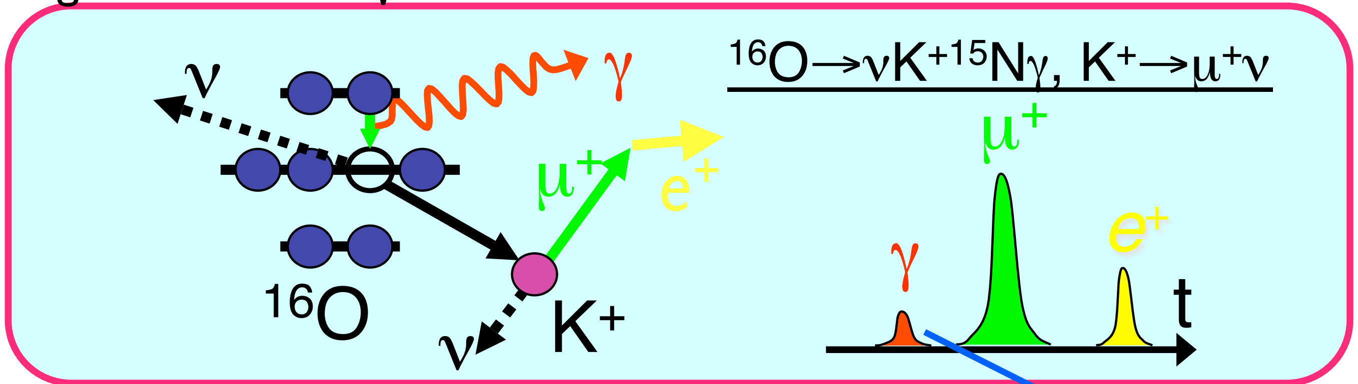
(I) $K^+ \to \mu^+\nu$, $\mu^+ \to e^+\nu\nu$

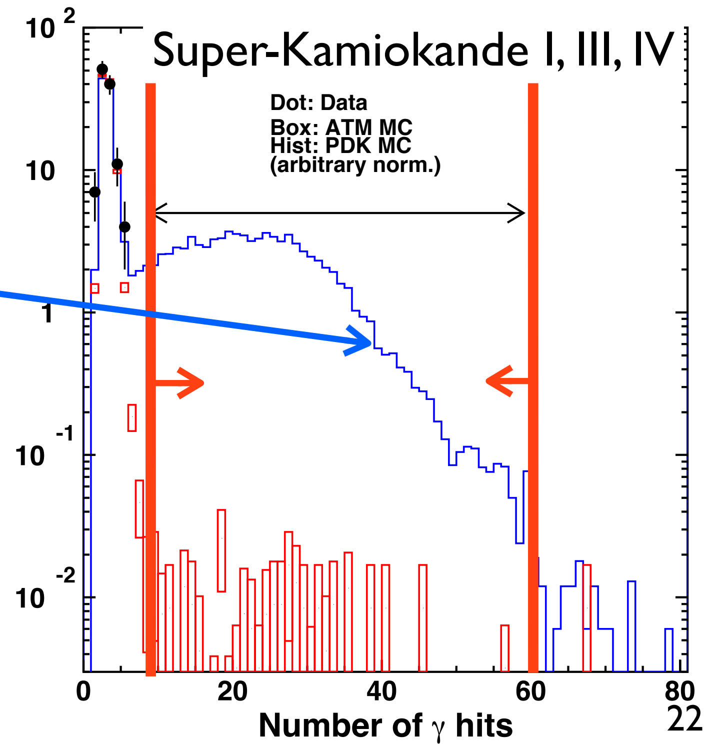


K^+ is below Cherenkov threshold → 236MeV/c μ and muon decay electrons



Tag de-excitation γ from $^{15}N^*$ to reduce BG





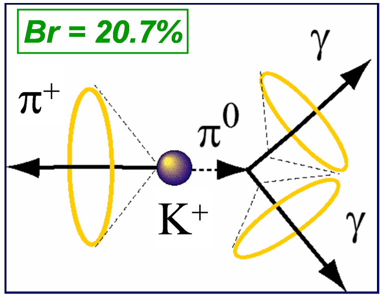
Many efforts to improve analyses

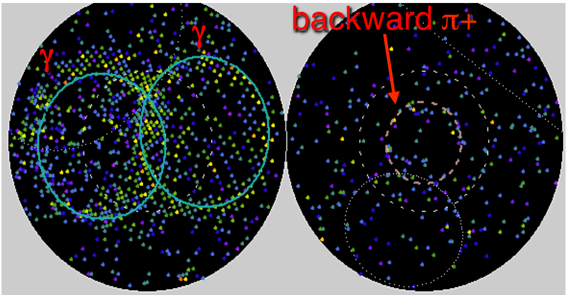
1. γ tagging efficiency algorithm has been improved.
2. high muon decay electrons efficiency in SK-IV electronics.
3. better momentum reconstruction is employed.

$p \rightarrow \nu + K^+$ searches

PRD90, 072005 (2014)

(II) $K^+ \rightarrow \pi^+ \pi^0$





- π^0 efficiency was improved by dedicated π^0 finding algorithm
- Shape information of π^+ hits for BG reduction

$p \rightarrow \nu + K^+$
- 260 kton×years exposure (SK-I+II+III+IV)
- $\tau_{proton}/Br > 5.9 \times 10^{33}$ years @ 90%CL

Summary of prompt γ and ππ searches

PRD72,052007
SK-I paper in 2005 91.7 kt y 14.6% 1.3 evts.

	data livetime	$p \rightarrow \nu K^+$ signal efficiency	atmos. ν estimated bkg.	atmos. ν bkg. rate (evts/Mt/y)
SK-I	91.7 kt y	$15.7 \pm 0.2\%$	0.3 evts.	2.8 ± 0.4
SK-II	49.2 kt y	$13.0 \pm 0.2\%$	0.3 evts.	6.2 ± 0.8
SK-III	31.9 kt y	$15.6 \pm 0.2\%$	0.1 evts.	3.1 ± 0.5
SK-IV	87.3 kt y	$19.1 \pm 0.2\%$	0.3 evts.	3.5 ± 0.4

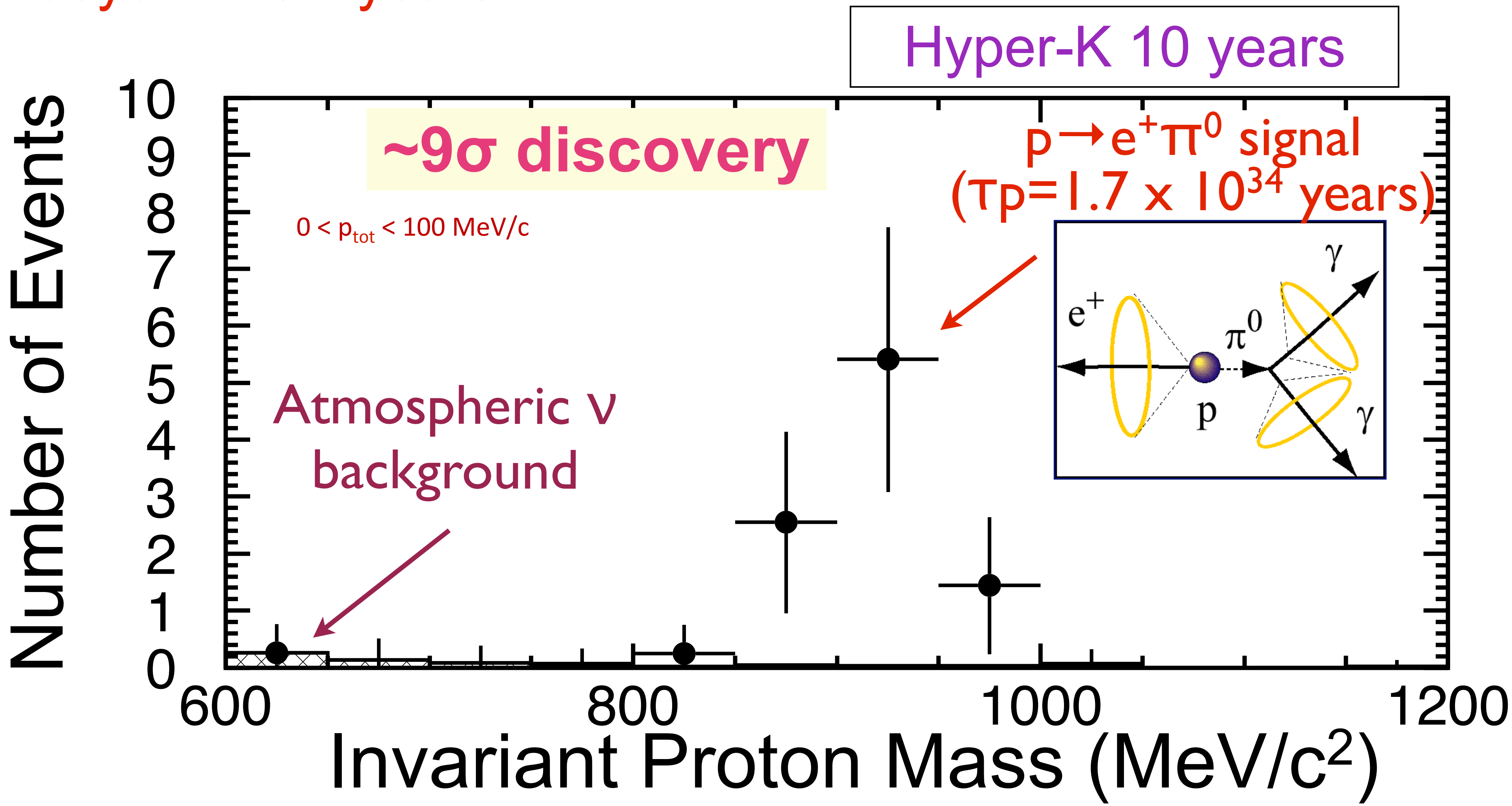
Summary of Super-K

- $p \rightarrow e^+ + \pi^0$ reached to 10^{34} yrs
- $(p,n) \rightarrow (e^+, \mu^+) + (\pi, \eta, \rho, \omega)$ $10^{32} \sim 10^{34}$ yrs
- SUSY favored $p \rightarrow \nu K^+ > 5.9 \times 10^{33}$ yrs
- No excess in K^0_S, K^0_L, $\nu\pi^0$, $\nu\pi^+$
- test many decay modes
  - di-nucleon decays ($|\Delta B|=2$)
  - $pp \rightarrow K^+K^+ > 1.7 \times 10^{32}$ years
  - $pp \rightarrow e^+e^+ > 10^{33}$ years
  - $np \rightarrow (e^+, \mu^+, \tau^+) + \nu$
  - neutron-antineutron oscillations
  - $p \rightarrow (e^+, \mu^+) + \nu\nu$, $(e^+, \mu^+) + X$
  - radiative decays $p \rightarrow (e^+, \mu^+) + \gamma$

Still single event discovery is possible.
Discovery could be around corner.

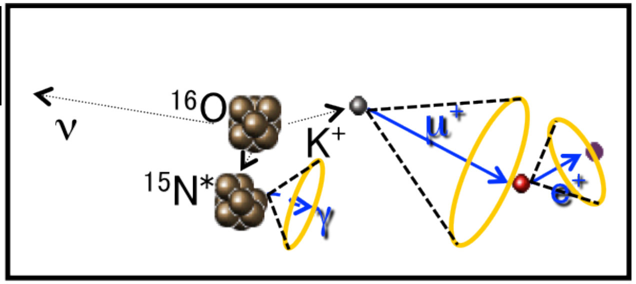
$p \rightarrow e^+\pi^0$ search in Hyper-K

- Hyper-K is only realistic approach to proton lifetime beyond 10^{35} years

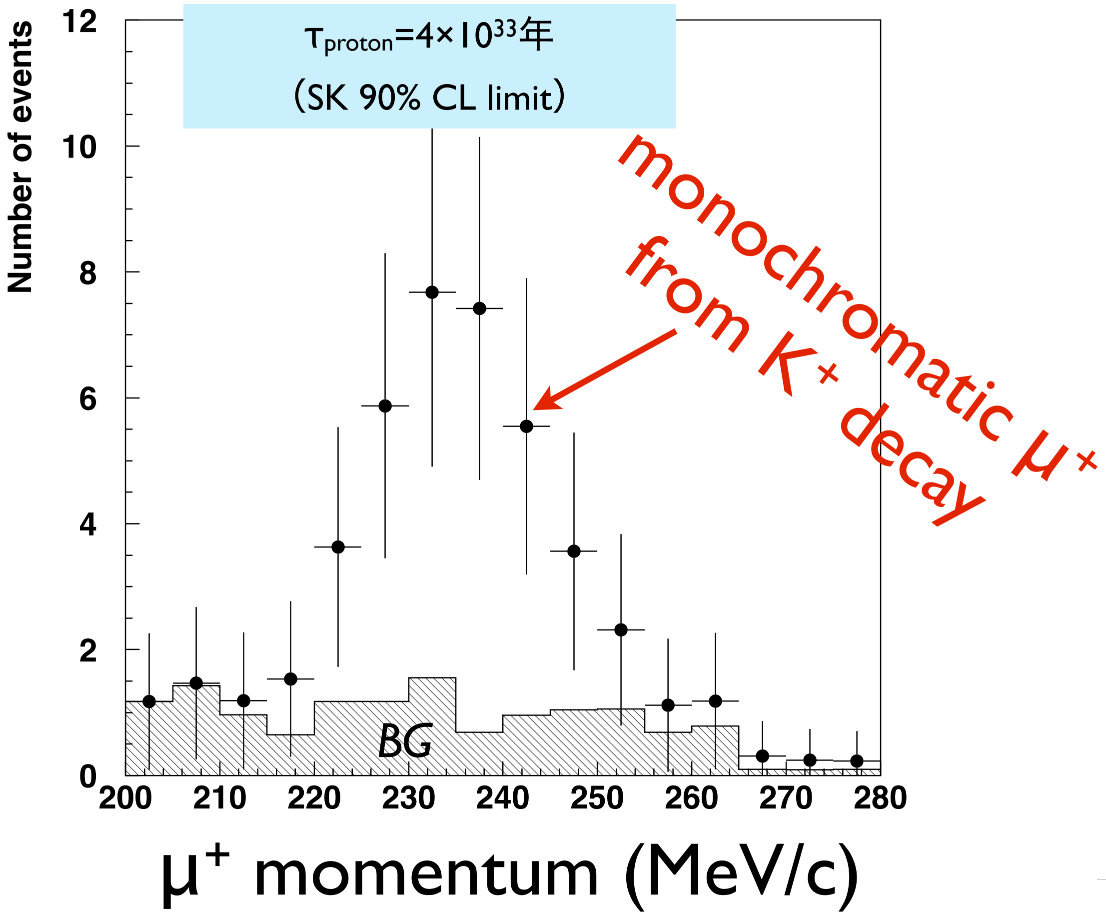


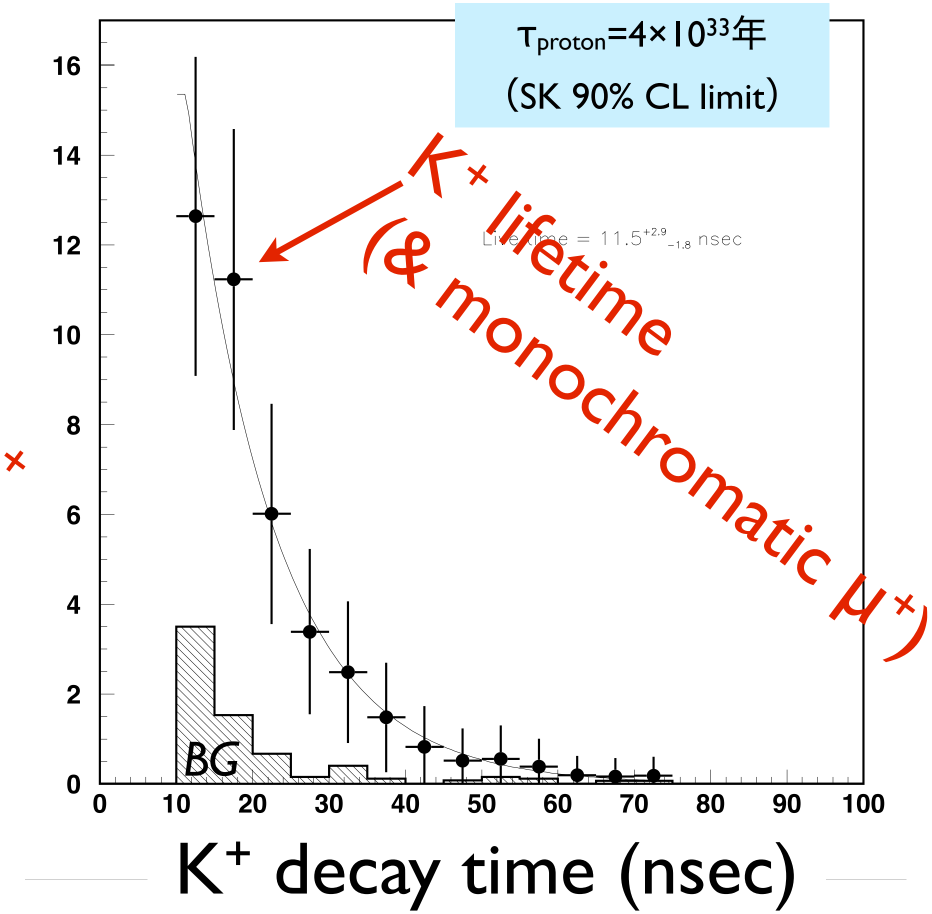
Proton decay ($p \rightarrow \nu K^+$) search

$p \rightarrow \nu K^+$



- Discovery reach (3σ)
  - $\tau(p \rightarrow \nu K^+) \sim 1 \times 10^{34}$years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \rightarrow \nu K^+) > 3 \times 10^{34}$years (HK 10yrs)



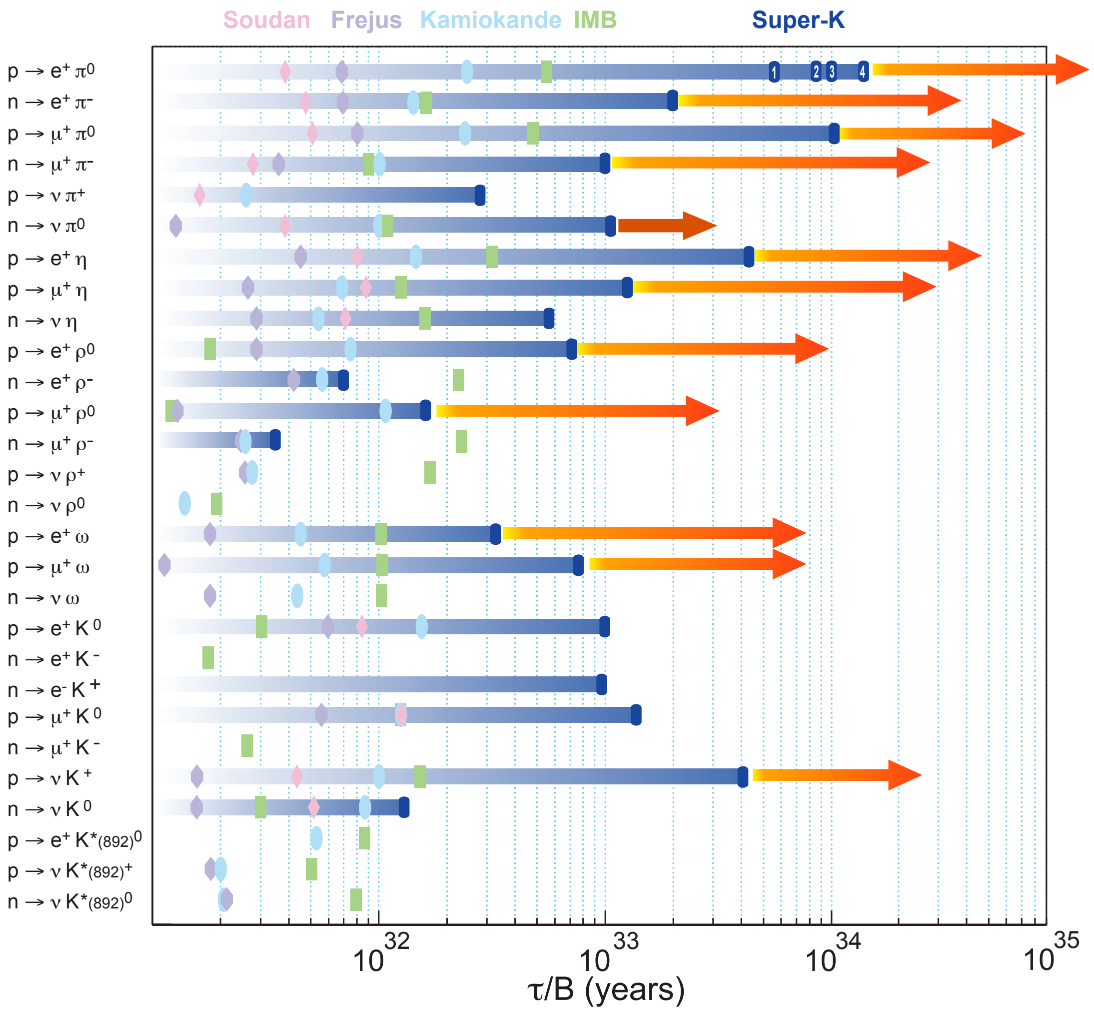


Experimental test on Supersymmetry

Hyper-K's sensitivities

Improvements in many modes by a factor ~10

Good chance for discovery!



- *p→e⁺+π⁰*
  - τ_{proton}/Br > 1×10^{35} years @90%CL
  - 5Mton×years (9 Hyper-K years)
- *p,n→(e⁺,μ⁺)+(π,ρ,ω,η)*
  - O(10$^{34\sim35}$)years
- *SUSY favored p→ν+K⁺*
  - 3×10^{34} years
- K⁰ modes, νπ⁰, νπ⁺ possible
- Others
  - (B-L) violated modes
  - radiative decays *p*→e⁺γ, μ⁺γ
  - neutron-antineutron oscillations (|ΔB|=2)
  - di-nucleon decays (|ΔB|=2)
    - pp→XX..., nn→XX...

Neutrino Oscillations

$(\nu_e, \nu_\mu, \nu_\tau)^T = U_{\alpha i}^{MNS} (\nu_1, \nu_2, \nu_3)^T$

U^{MNS}: Maki-Nakagawa-Sakata matrix

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

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \frac{(m_i^2 - m_j^2)L}{4E_\nu}$$

$$(\pm)2\sum_{i>j} \mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \frac{(m_i^2 - m_j^2)L}{2E_\nu}$$

Matter-effect is omitted here

Neutrino Oscillation Parameters: 6 = 4 matrix elements and 2 mass-squared differences

θ_{23}~45±5° Δm^2_{23}=2.4×10^{-3}eV^2	θ_{12}~34±3° Δm^2_{21}=7.6×10^{-5}eV^2	θ_{13}~9°	δ=unknown
Atmospheric, Accelerator Neutrinos	Solar, Reactor Neutrinos	Accelerator, Reactor Neutrinos	Accelerator, Atmospheric Neutrinos

Mass Hierarchy ($\Delta m^2_{32}=m^2_3-m^2_2>0$ or $\Delta m^2_{32}<0$) is unknown

Octant of θ_{23} or $\theta_{23}=\pi/2$ is also interesting question

CP violation

Only known CPV source=KM phase
Other CPV necessary for the matter-dominated universe

→ Search for CPV in lepton sector

- Leptogenesis scenario only with ν's Dirac CP phase

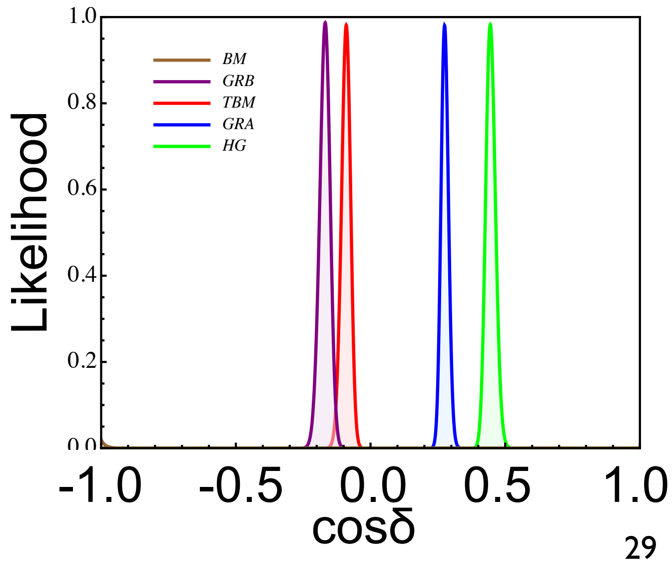
S. Pascoli et al., PRD 75, 083511 (2007) PDG review 2014

$|\sin\delta| >\sim 0.6$

- Flavor symmetry prediction on δ_{CP}

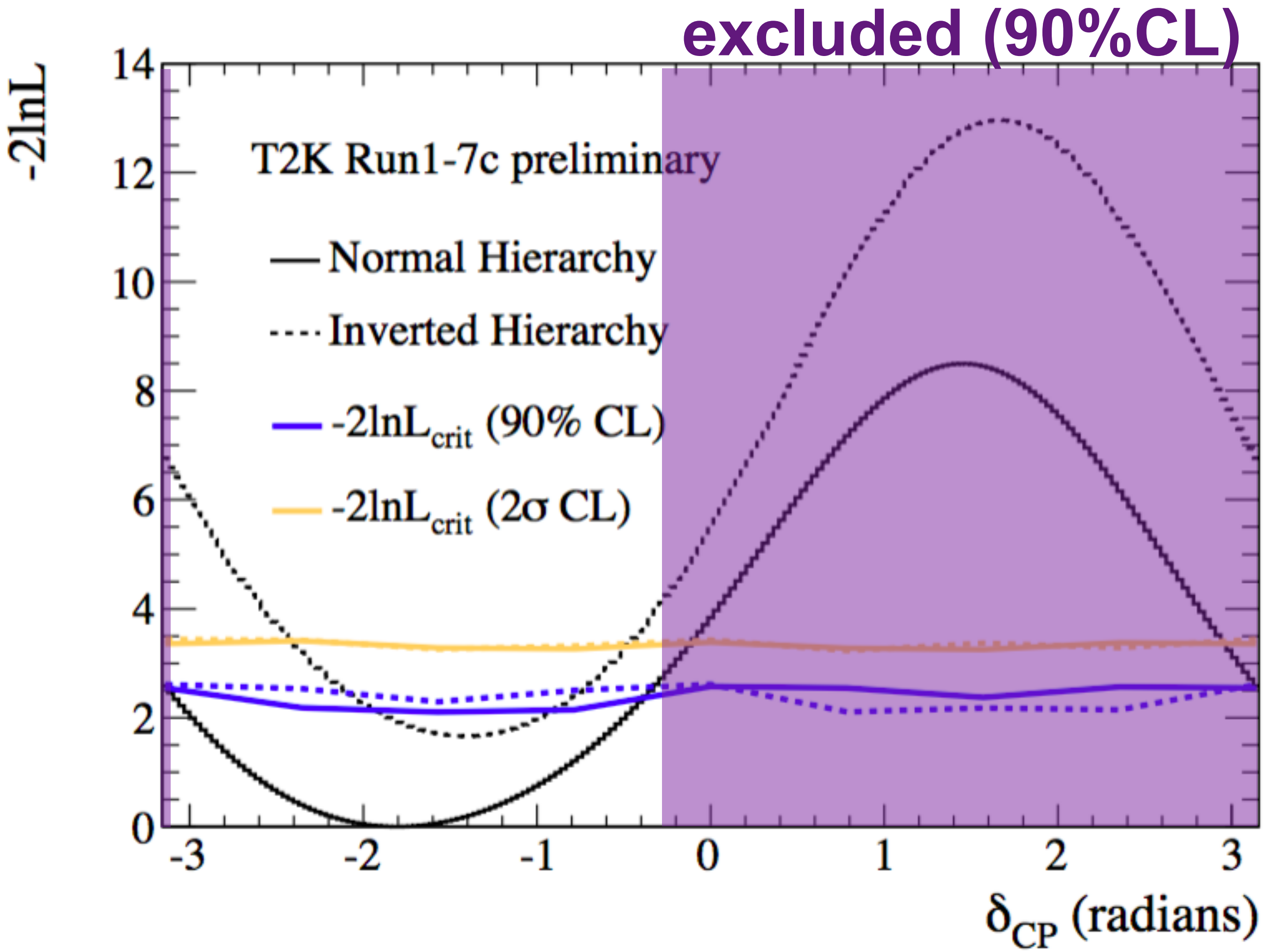
e.g. Petcov 1504.02402v1 (right plot)

We need not only CPV discovery, but also precision measurement



Hint of leptonic CP Violation

T2K : J-PARC ν beam + Super-K

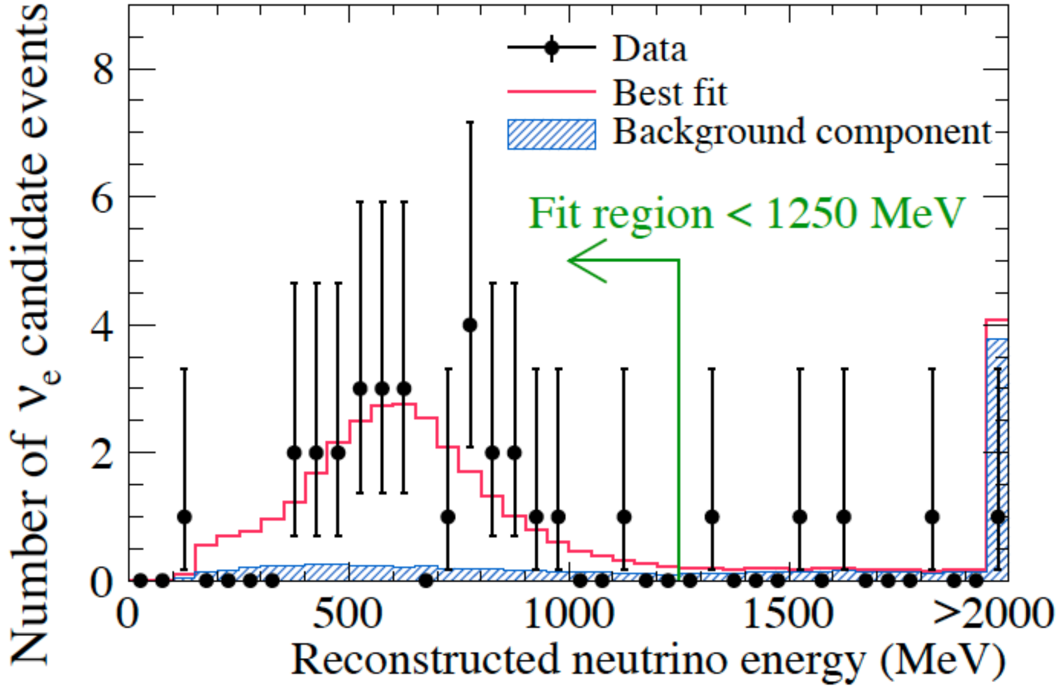


T2K2016 w/ reactor
$\sin^2\theta_{13}=0.085\pm0.005$
$\delta_{CP}=[-3.13,-0.39]$

T2K may start indicating maximal CP violation of $|\sin\delta_{CP}| \sim 1$ ($\delta_{CP} \sim -\pi/2$)

- **Urgent topic** (world consensus)
- **Technology established, need more intense beam and larger detector!**

T2K : NBB + water Cherenkov



"Clean $\nu_\mu \rightarrow \nu_e$ appearance measurement" has been established! $\rightarrow$make CPV test possible

- S/N~10 or so, clean ν_e appearance signal can be observed.
- Key elements are

(i) narrow-band sub-GeV clean ν_μ beam,

(ii) 300km baseline, and

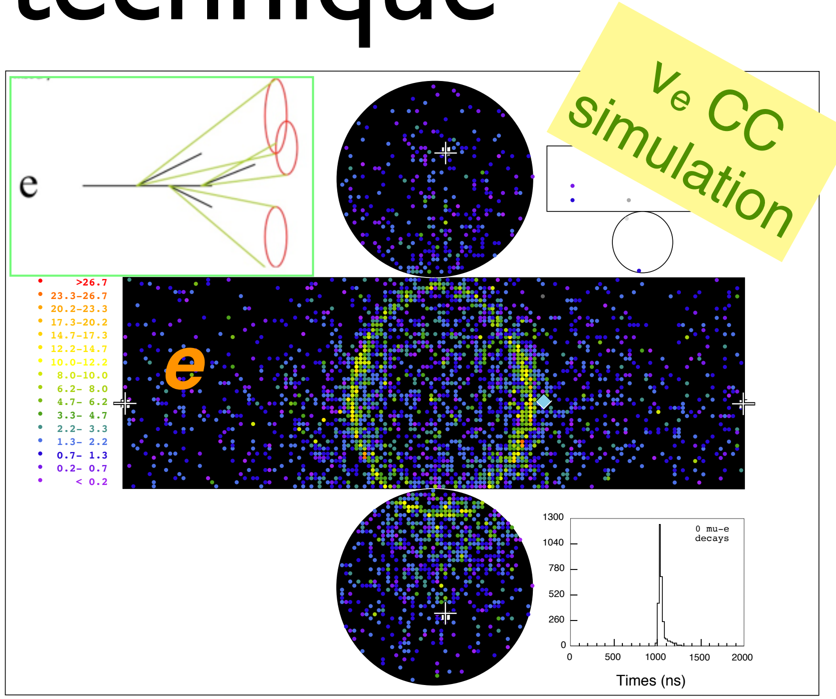
(iii) high performance large water Cherenkov detector

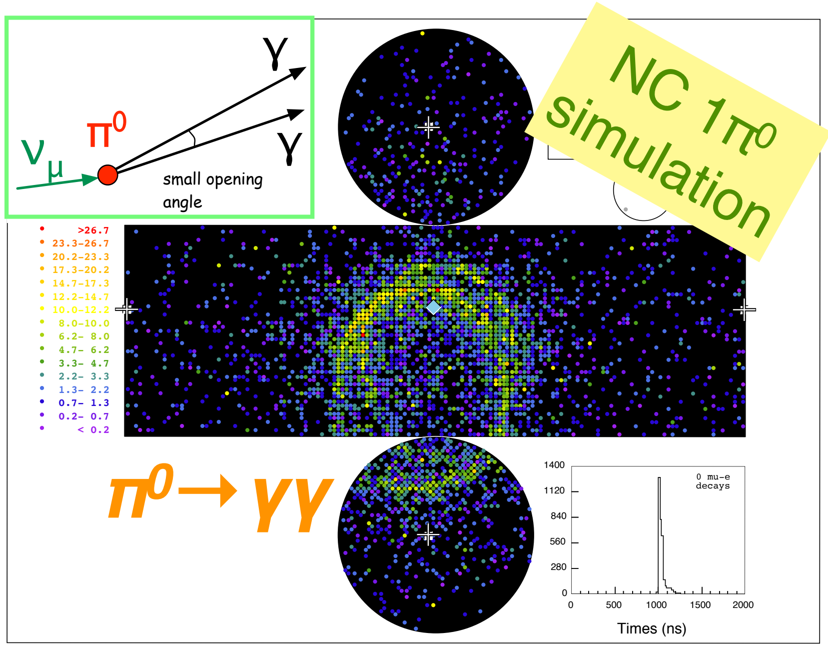
Water Cherenkov technique

- For νe appearance in T2K (J-PARC beam)
  - νe signal efficiency ~60%
  - BG ν_μ+antiν_μCC<0.1%, NCπ^0~1%

  (0.1<E^{rec}_ν<1.25GeV, can be optimized in future)

- Excellent particle ID capability > 99%
- Energy resolution for e and μ ~3%
- Energy threshold ~5MeV
  - Supernova ν, solar ν...
- Stable operation
  - energy scale stability ~1%
  - livetime for physics analyses > 90%



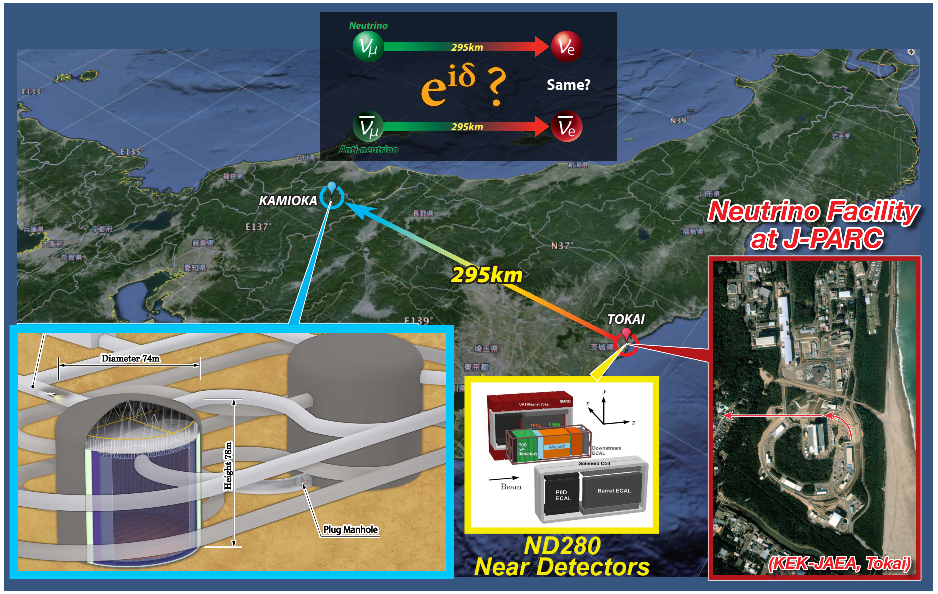


Excellent detector performance

&

Scalablity

Long baseline exp. w/ J-PARC



Sensitivity study

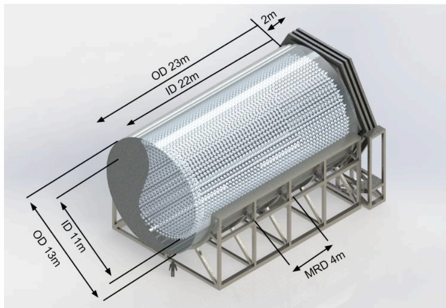
- New Hyper-K tank design with provision of 1.3MW J-PARCν beam
- Systematic uncertainties based on T2K are taken into account

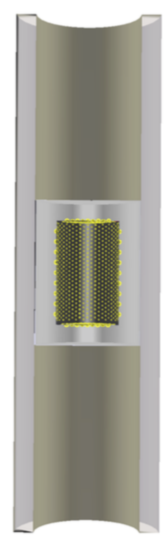
•Operation of the magnetized ND280 off-axis detector should continue for HK with potential upgrades

•Two possibilities of a generic intermediate WC detector with the following potential features:

Off-axis angle spanning orientation,

Gd loading, Magnetized μ range detector

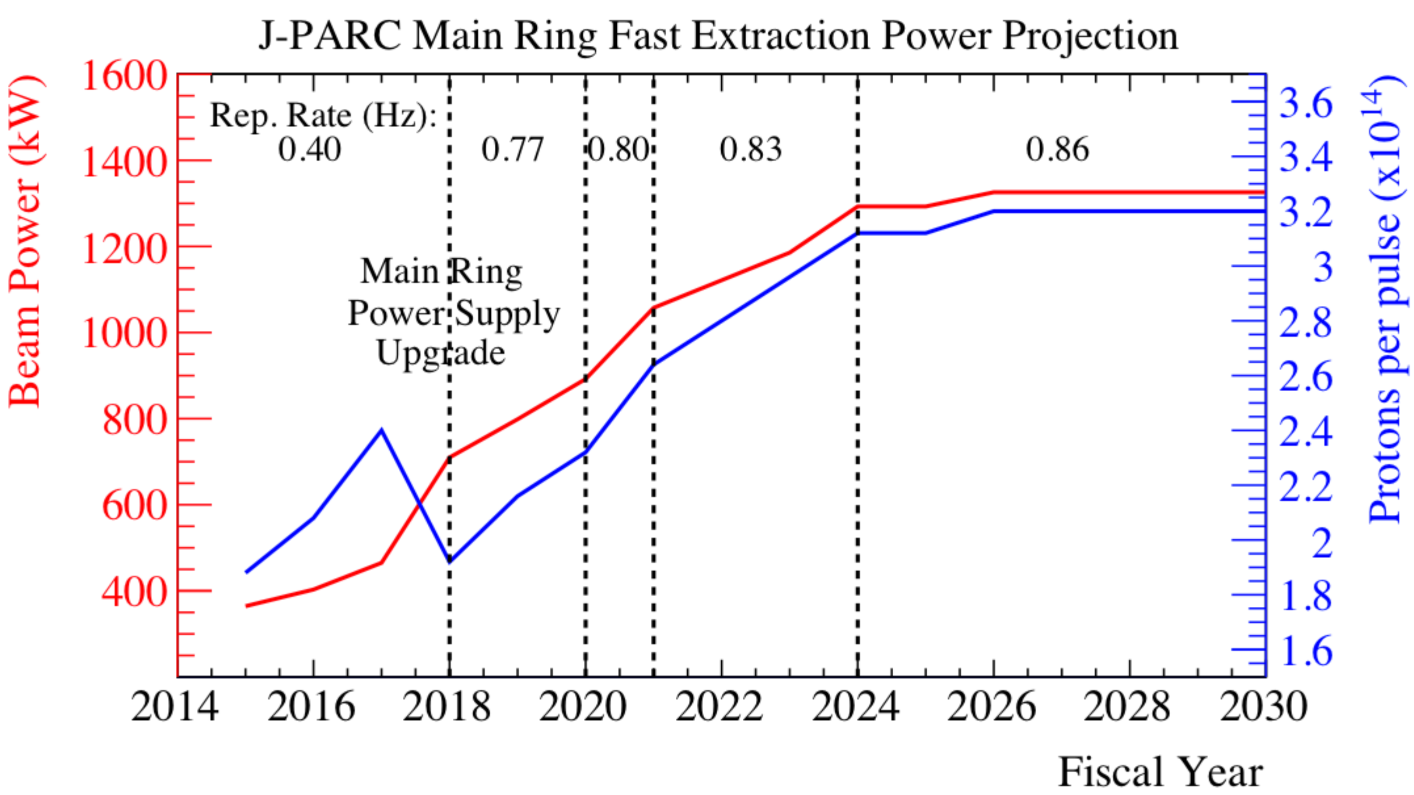




•Ongoing study on locating 2nd detector in Korea

Upgrade of J-PARC Neutrino Beam

- Continuous upgrade plan of the neutrino beam intensity
  - 0.48 MW stable operation at present
  - 0.75 MW by MR upgrade starting in ~2019
  - 1.326 MW by 2026 by increasing rep. rate to 0.86 Hz

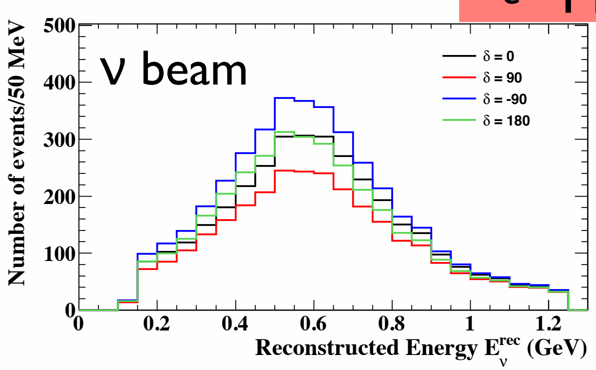


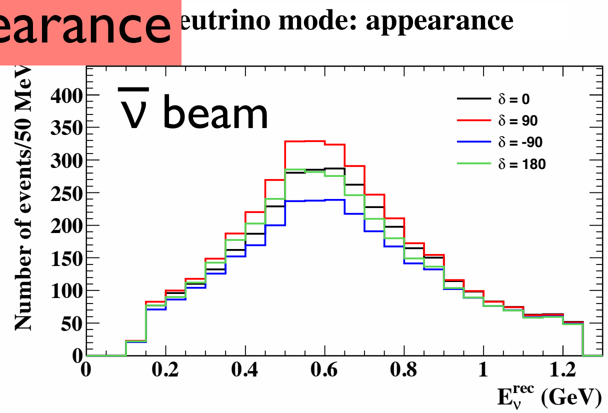
KEK Project Implementation Plan (KEK-PIP) put first priority to “J-PARC upgrade for Hyper-Kamiokande”

Expected events

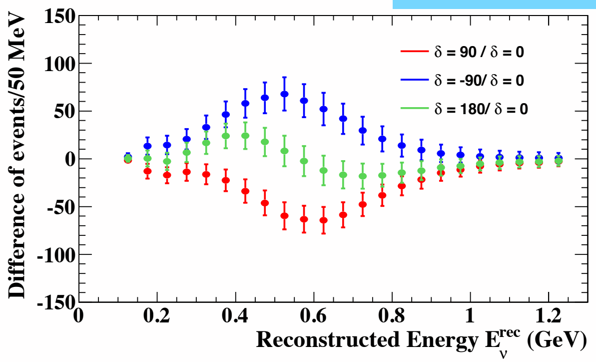
10 years (13MW×10^7s)

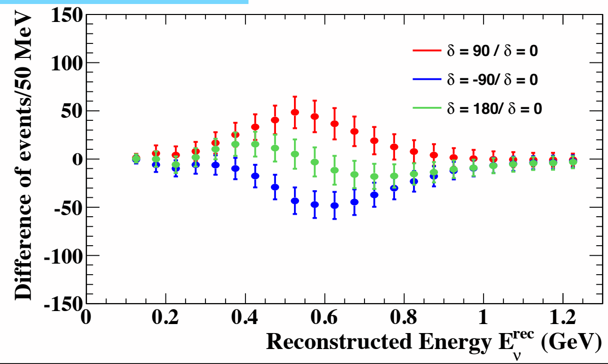
ν_e appearance





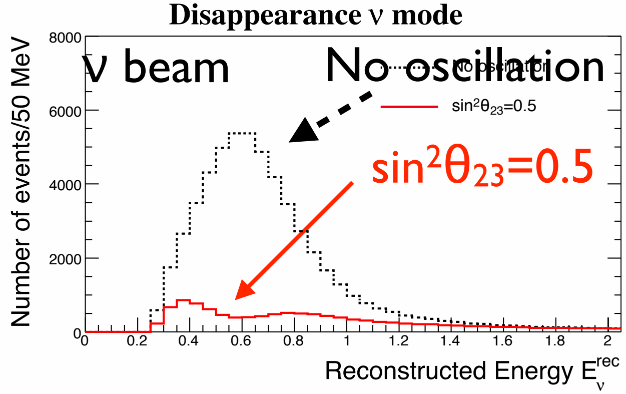
Difference from δ_{CP}=0

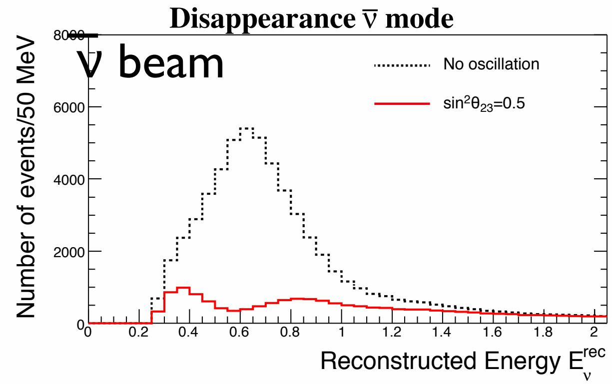




for δ=0	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

ν_μ disappearance





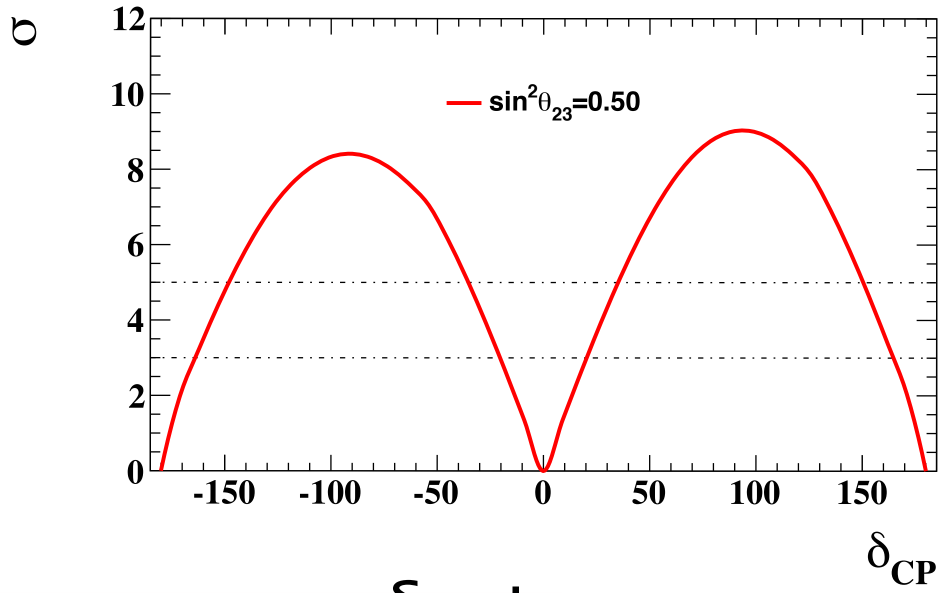
	$\nu_\mu+\bar{\nu}_\mu$ CCQE	ν_μCC nonQE	Others
ν beam	8,947	4444	721
$\bar{\nu}$ beam	12317	6040	859

CPV sensitivity

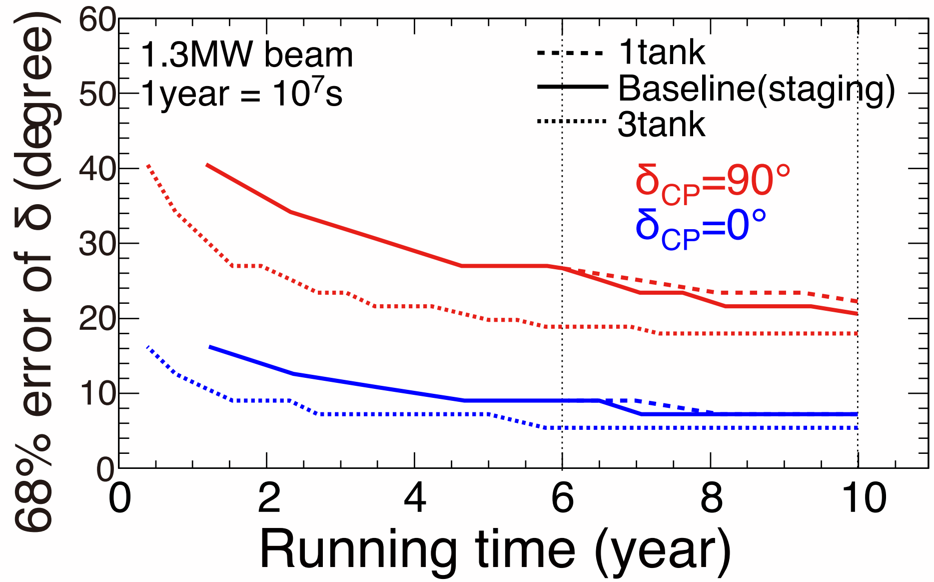
J-PARC ν beam + Hyper-K

- Exclusion of $\sin\delta_{CP}=0$
  - 8σ for δ=-90°
  - 80% coverage of δ parameter space for CPV discovery w/ >3σ
- δ_{CP} precision measurement
  - 20° for δ=-90°
  - 7° for δ=0°

$\sin\delta_{CP}=0$ exclusion



δ_{CP} 1σ error



Precision measurements

NEW x 9 years ($11.25 MW \times 10^7 s$)

- Atmospheric parameters

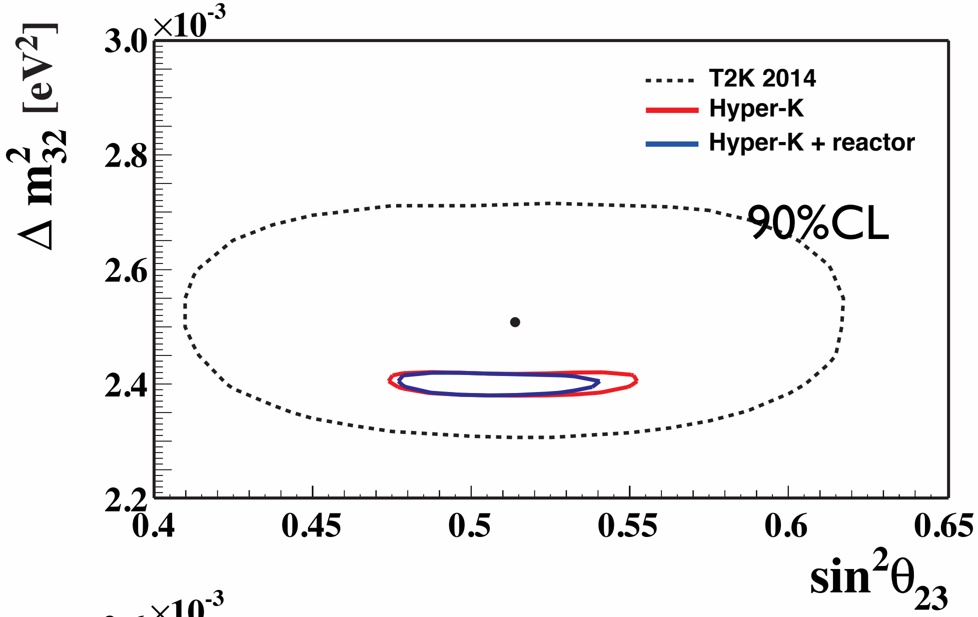
  $\delta(\Delta m^2_{32}) \sim 1.4 \times 10^{-5} eV^2$

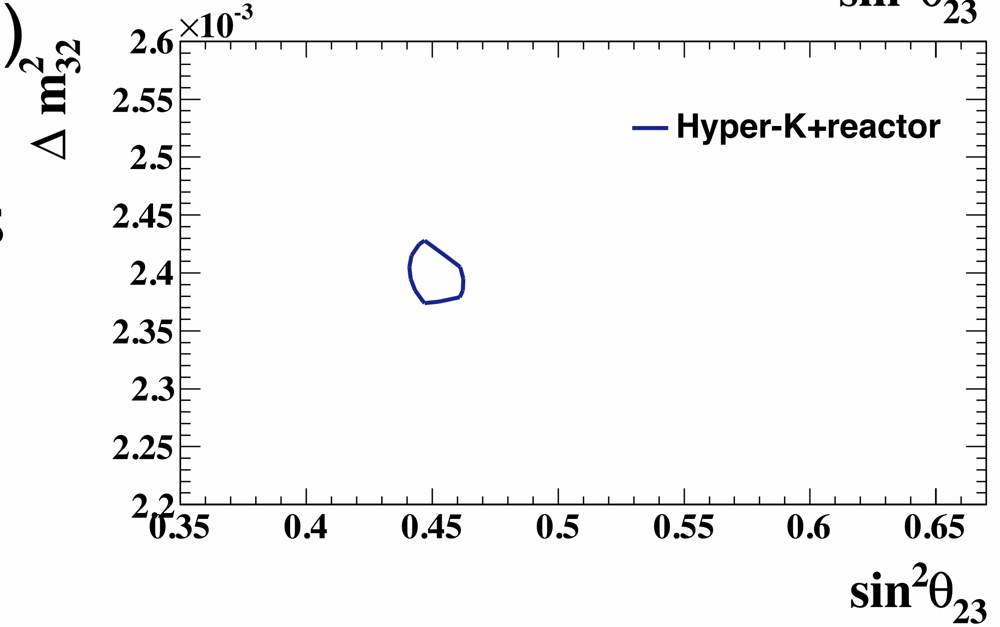
  → Mass hierarchy sensitivity in combination with reactor

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

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

- Near detector measurements
  - Cross sections
  - Exotic physics searches



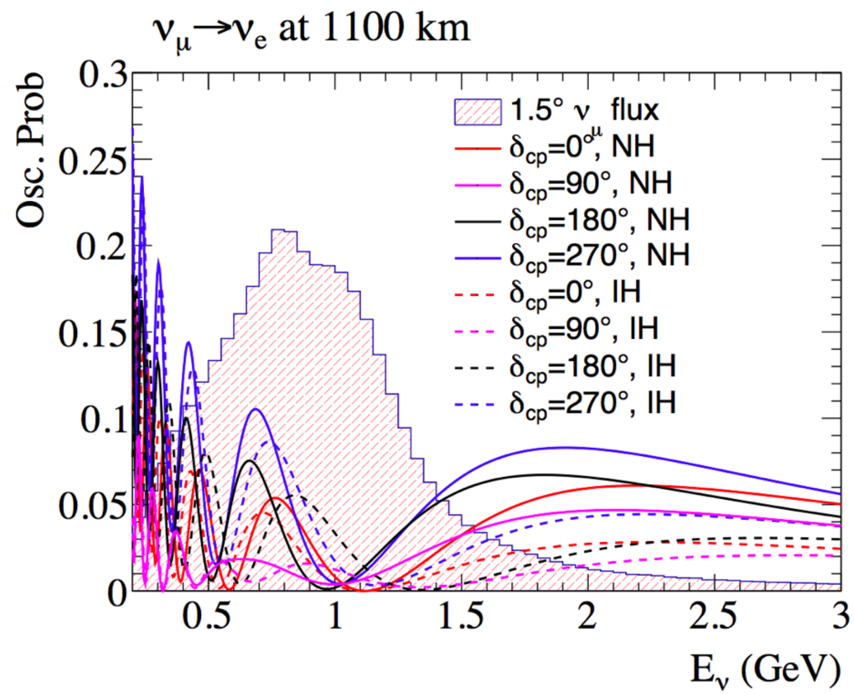


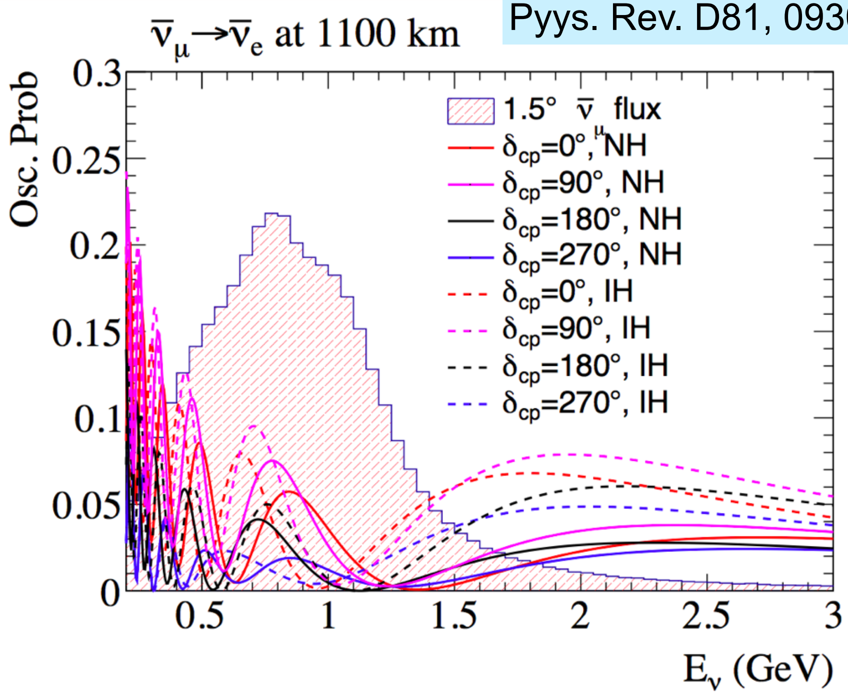
2nd Hyper-K detector in Korea?

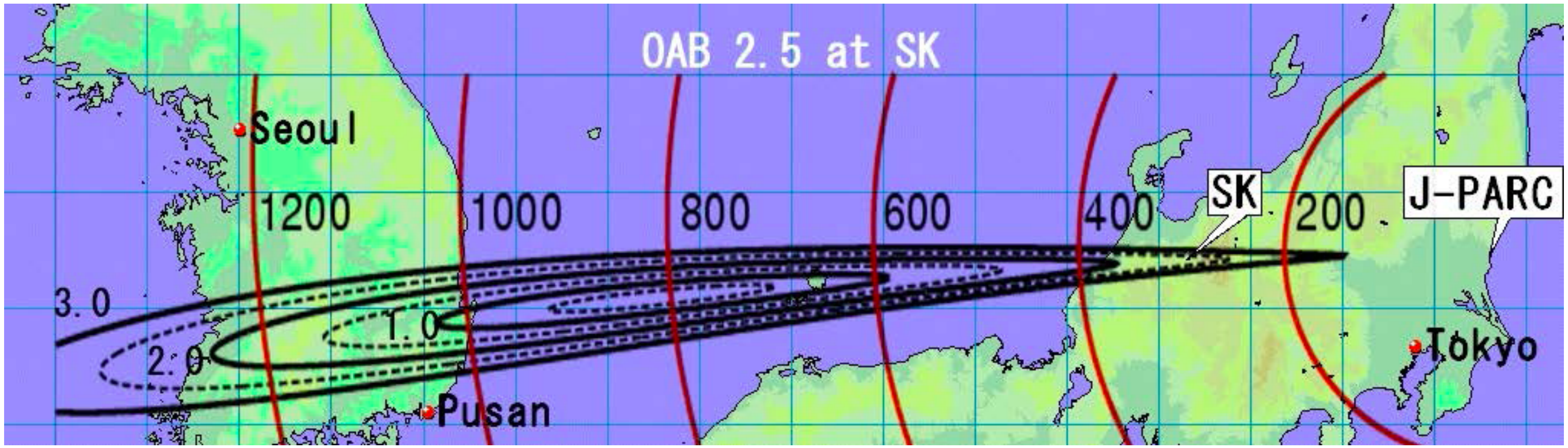
About 10 years ago, this possibility was discussed.

Now this possibility is revisited...

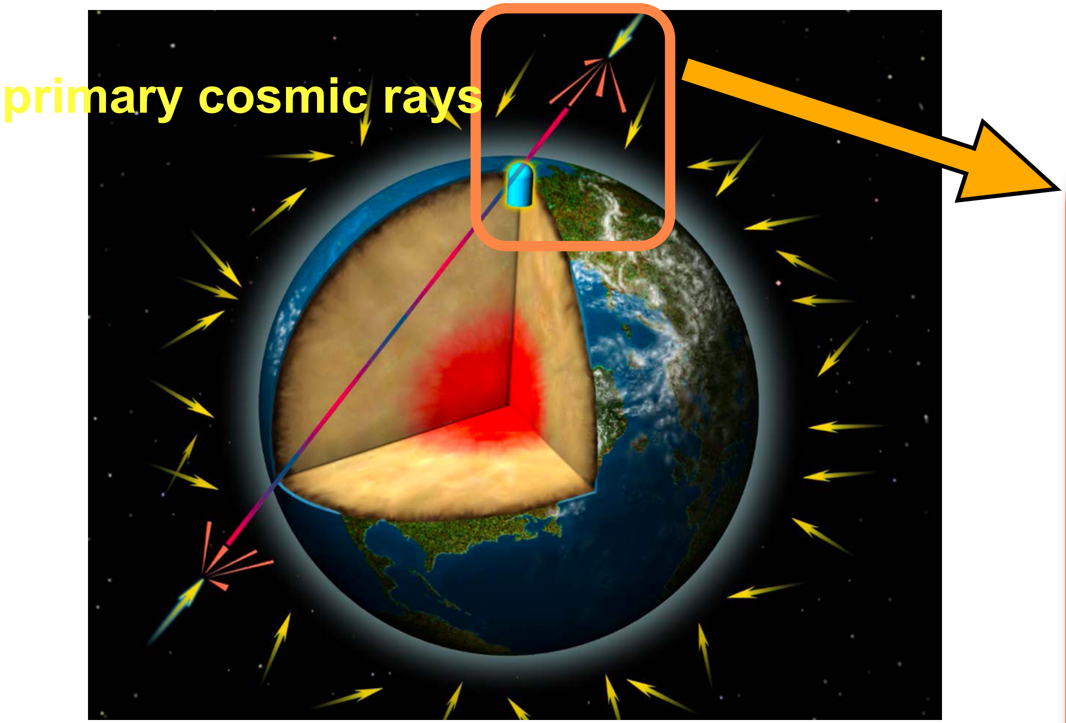
Phys.Rev.D72:033003,2005
Phys.Lett.B637:266-273,2006
Pyys. Rev. D81, 093001, 2010

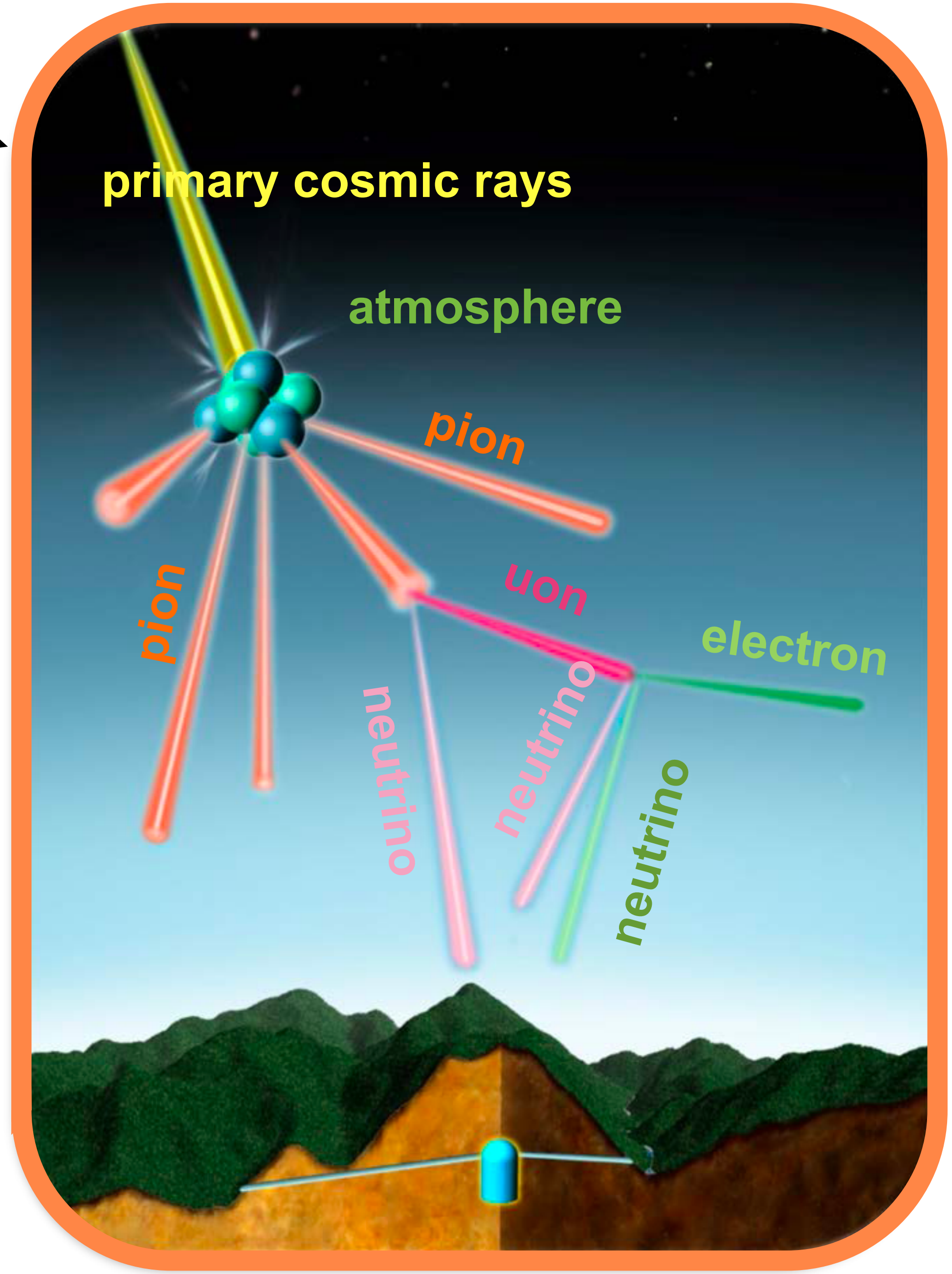






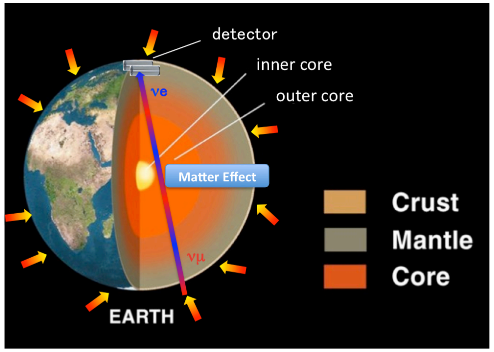
Atmospheric neutrinos





- Wide range of ν energy (0.1 GeV ~ 10^4 GeV and beyond)
- Wide range of ν baseline (10km downward ~ 13,000km upward)
- $\nu_\mu:\nu_e$ ~ 2:1 at production

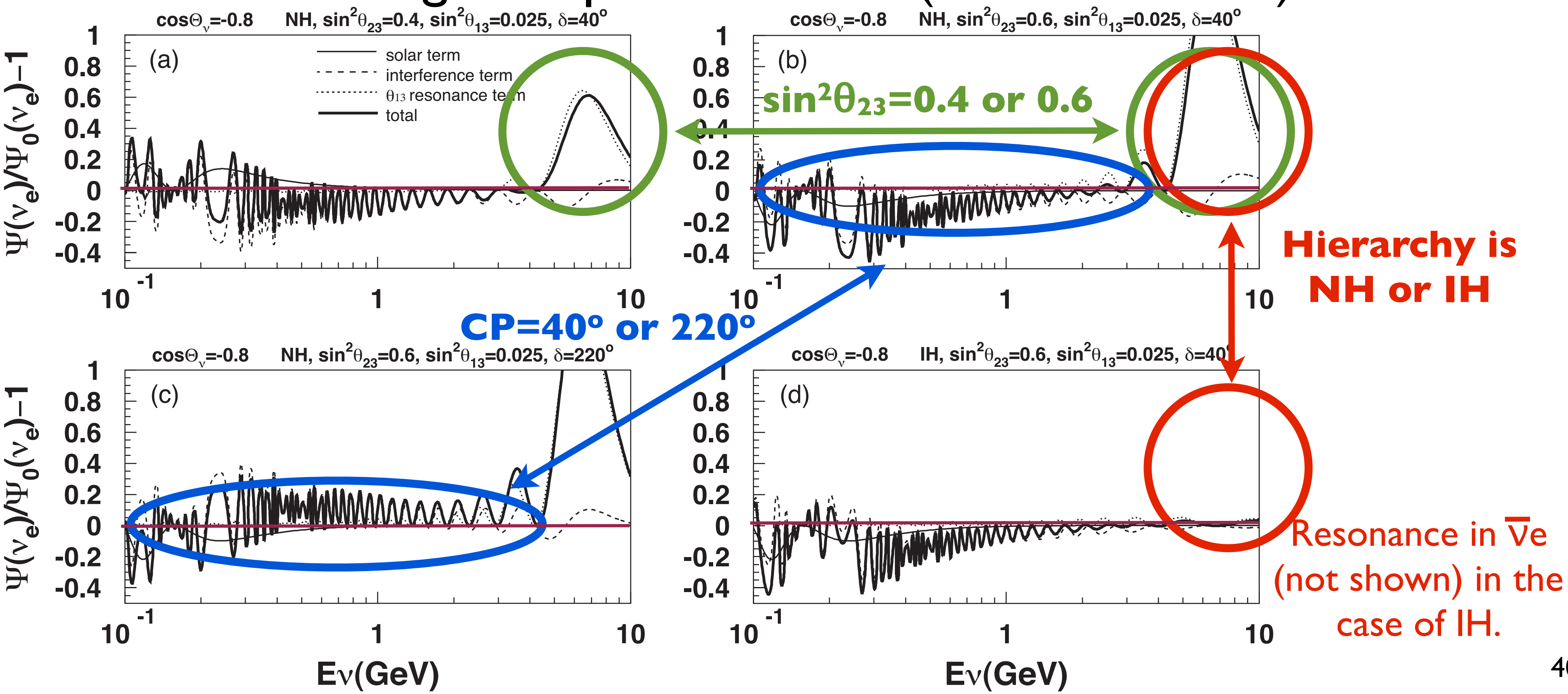
3-flavor oscillation study



Through the matter effect in the Earth, we study on

- Mass hierarchy : resonance in multi-GeV νe or $\overline{\nu}e$
- CP δ : interference btw two Δm^2 driven oscill.
- θ_{23} octant : magnitude of the resonance

"Fractional change of upward ν_e flux ($\cos\Theta_{zenith}$=-0.8)"



ν_e-like and anti-ν_e-like sample

$\nu_e + N \rightarrow e^- + X$
$\bar{\nu}_e + N \rightarrow e^+ + X$

- ν_e CC produce more positive π^+ than ν_e-bar
  - because of negative lepton (e^-)
  - more muon decays
- More energy transfer to hadronic system
  - more pions and muon decays
  - lower charged lepton energy

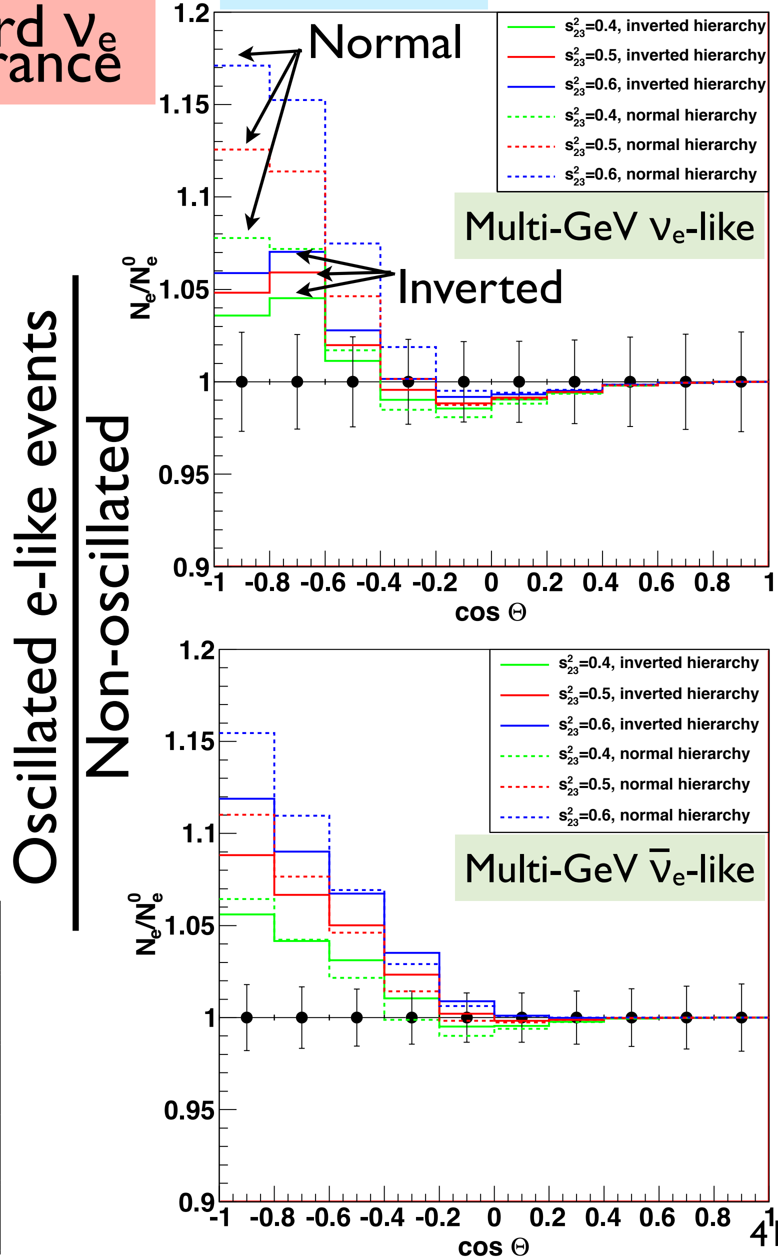
Define likelihood to make enhanced samples

- Multi-GeV (1-ring) νe
- Multi-GeV (1-ring) νe-bar
- Multi-GeV Multi-ring νe
- Multi-GeV Multi-ring νe-bar

	νe CC	anti-νe CC	others	Total
1R νe-like	62%	9%	29%	100%
1R $\bar{\nu}$e-like	55%	37%	8%	100%
MR νe-like	56%	10%	34%	100%
MR $\bar{\nu}$e-like	53%	27%	20%	100%

Upward ν_e appearance

$\sin^2 2\theta_{13} = 0.1$

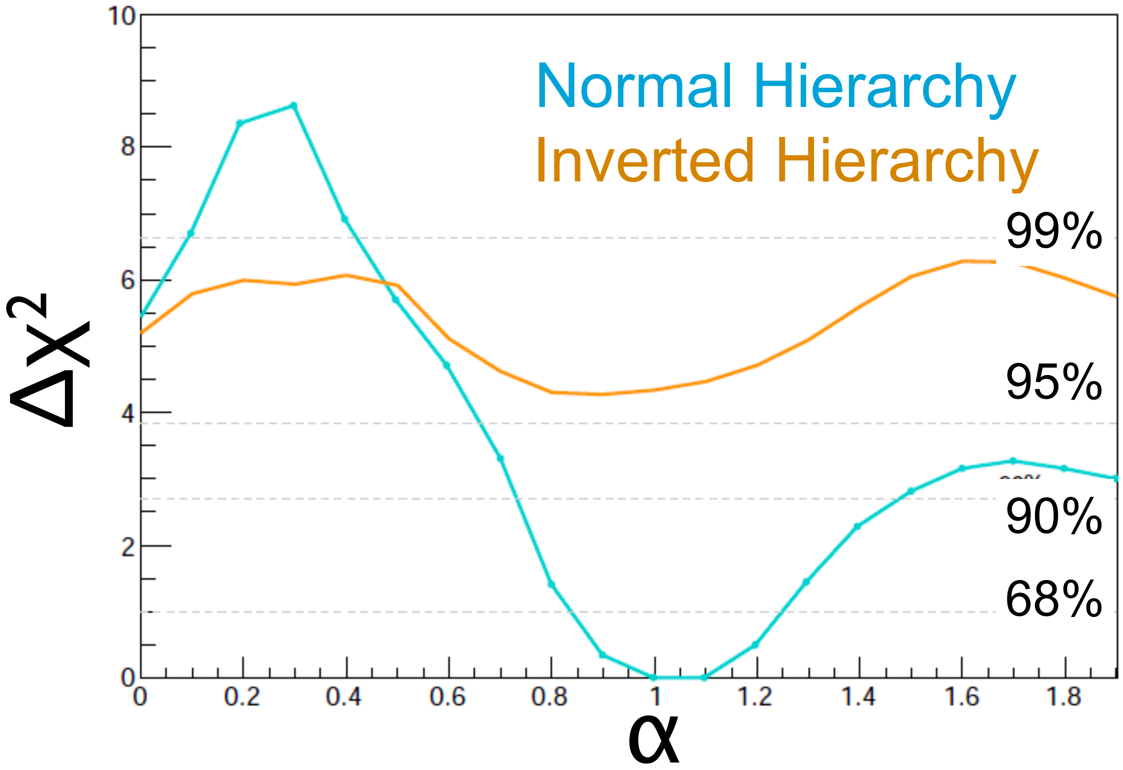


Matter effect fit in Super-K

$$H_{\text{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} \alpha a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U$$

α: scale factor

a=sqrt(2) G_f N_e

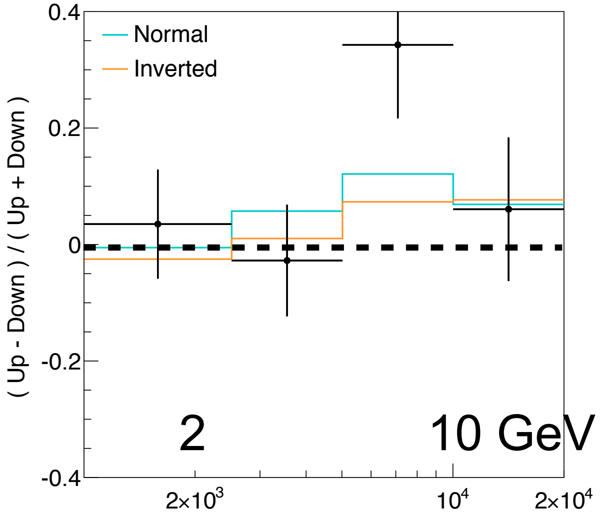


- Best fit α=1 for NH, consistent w/ standard matter effect
- $\Delta\chi^2$=5.2 for α=0, Data disfavors zero matter-effect by >2σ

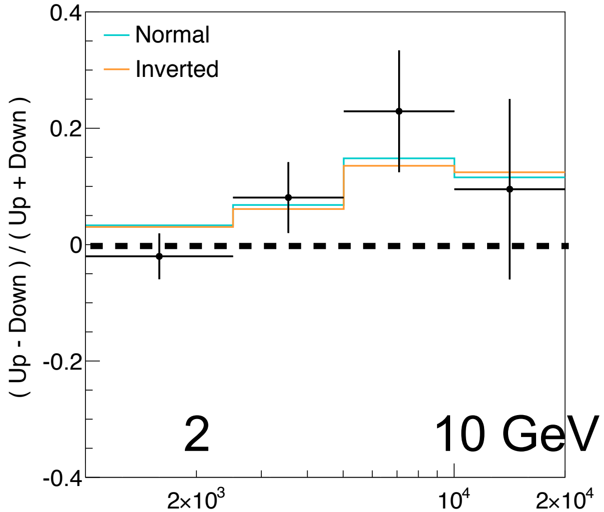
electron's Up/Down ratio

Up(cosΘ<-0.4) to Down(cosΘ>0.4) event ratio for multi-GeV electrons

Multi-GeV ν_e-like



Multi-GeV $\overline{\nu}_e$-like

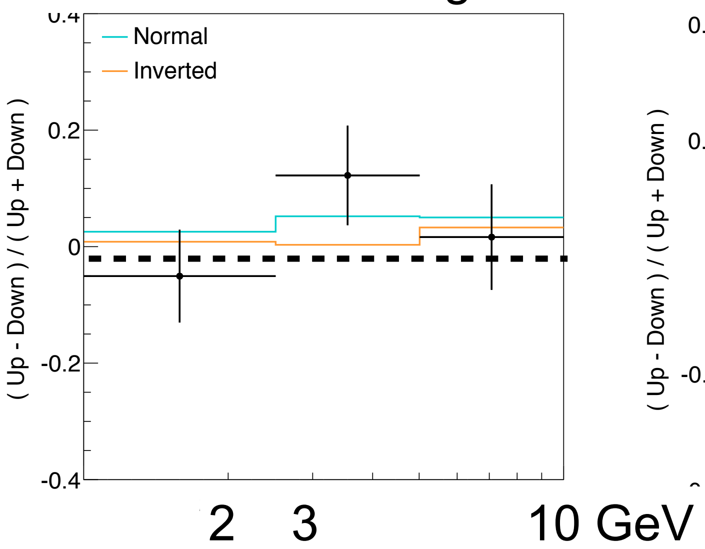


Normal Hierarchy

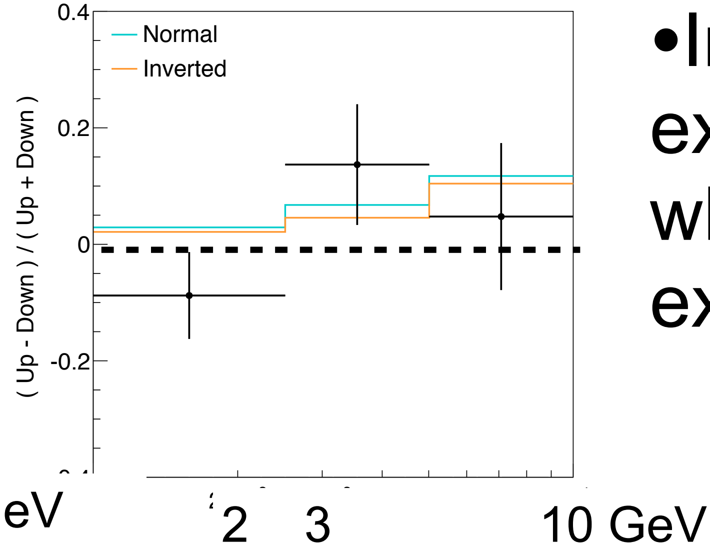
Inverted Hierarchy

- Some data points favors matter-effect

Multi-GeV Mulri-ring ν_e-like

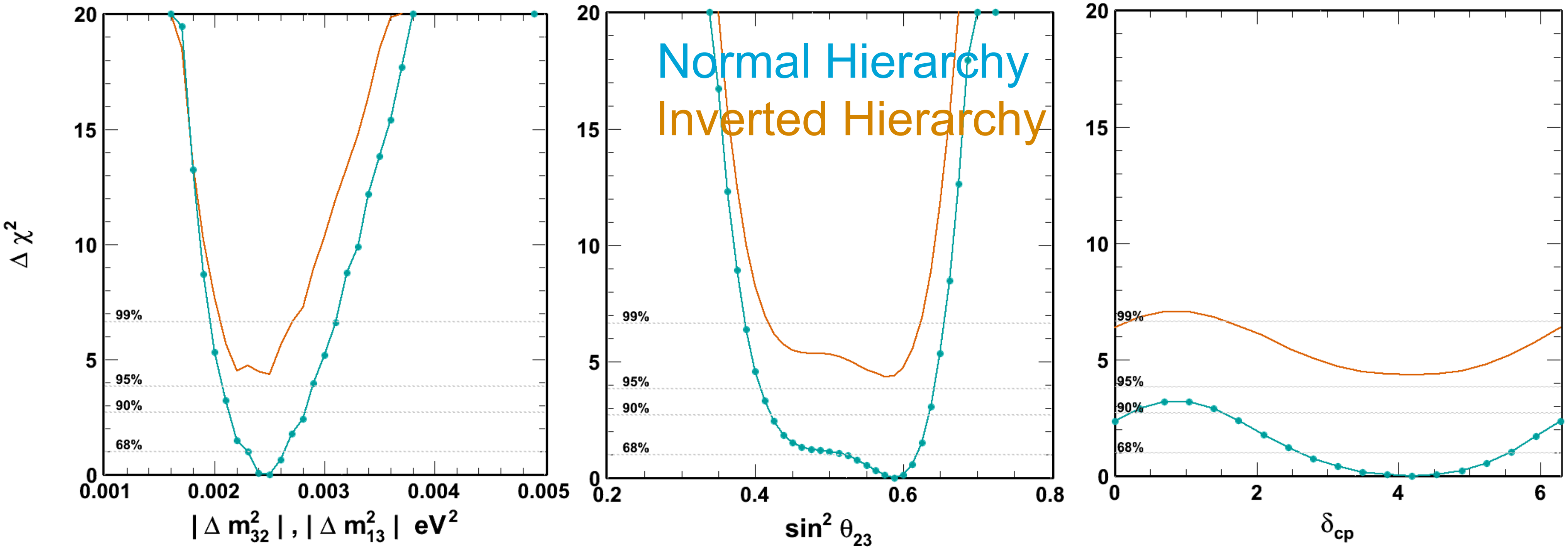


Multi-GeV Mulri-ring $\overline{\nu}_e$-like



- Indication of excess at ~5GeV where resonance is expected to occur

Atmv data fit w/ fixed θ_{13}

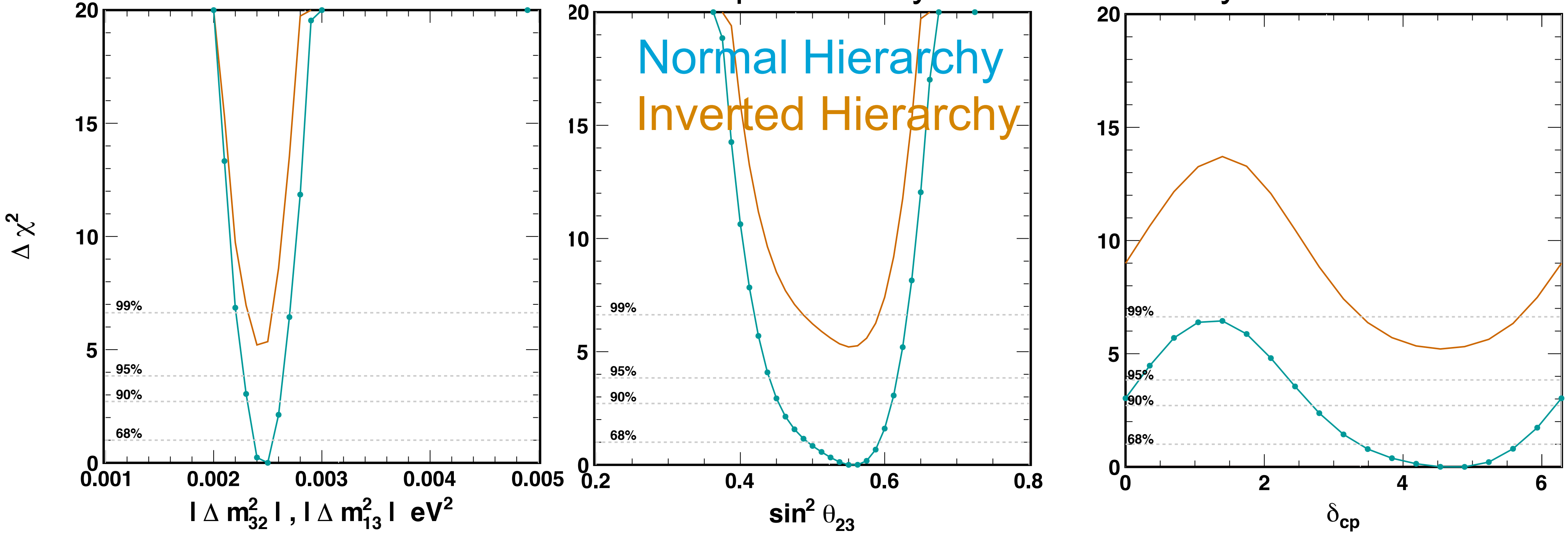


Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ eV^2
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5×10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5×10^{-3}

- Mass hierarchy: $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$ (-3.1 expected)
- Under IH hypothesis, the probability to obtain -4.3 or less is 3.1% ($\sin^2\theta_{23}$=0.6) and 0.7%($\sin^2\theta_{23}$=0.4).
- Under NH hypothesis, it is as large as 45% ($\sin^2\theta_{23}$=0.6)

Atmv data fit w/ T2K

Publicly available T2K data is used as an external constraints
T2K's constraints on θ_{23} and Δm^2_{32} help sensitivity to mass hierarchy



Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

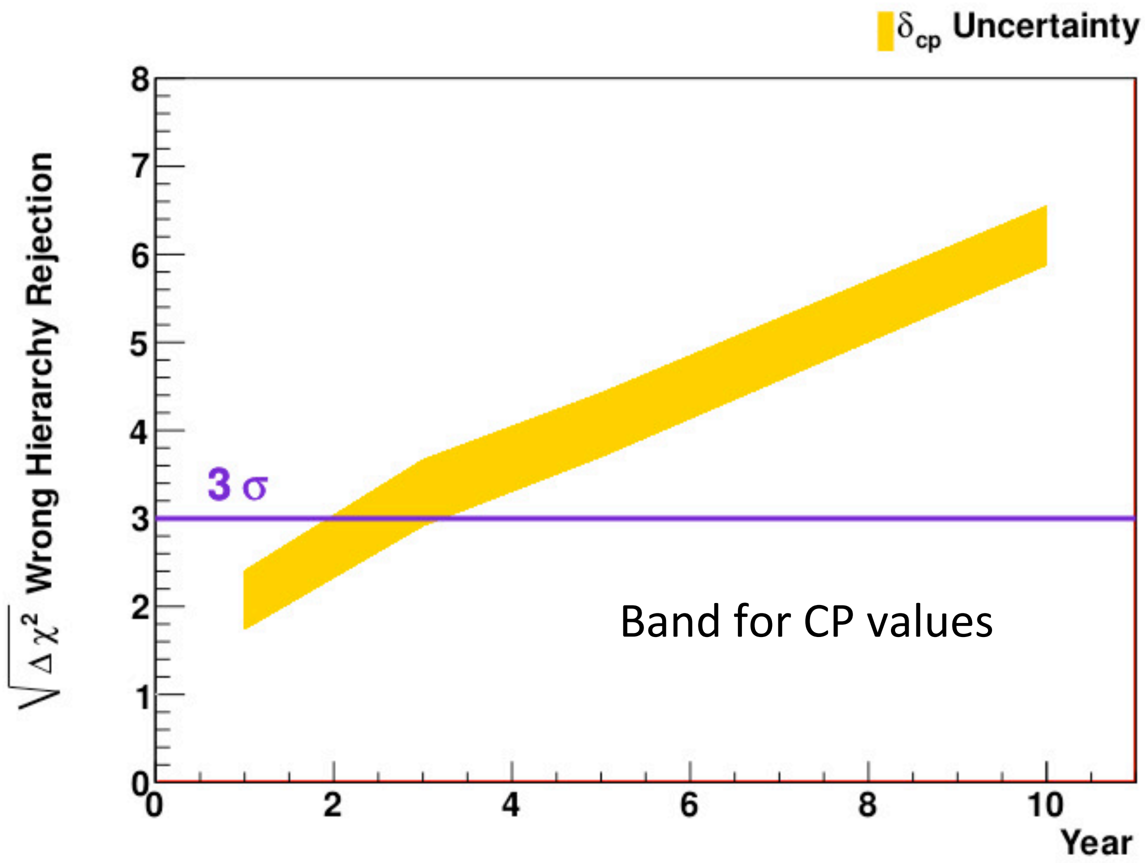
- SK+T2K: $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$ (-3.8 exp'd for SK best point, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain -5.2 or less is 2.4% ($\sin^2\theta_{23}$=0.6) and 0.1%($\sin^2\theta_{23}$=0.4).
- Under NH hypothesis, it is 43% ($\sin^2\theta_{23}$=0.6)

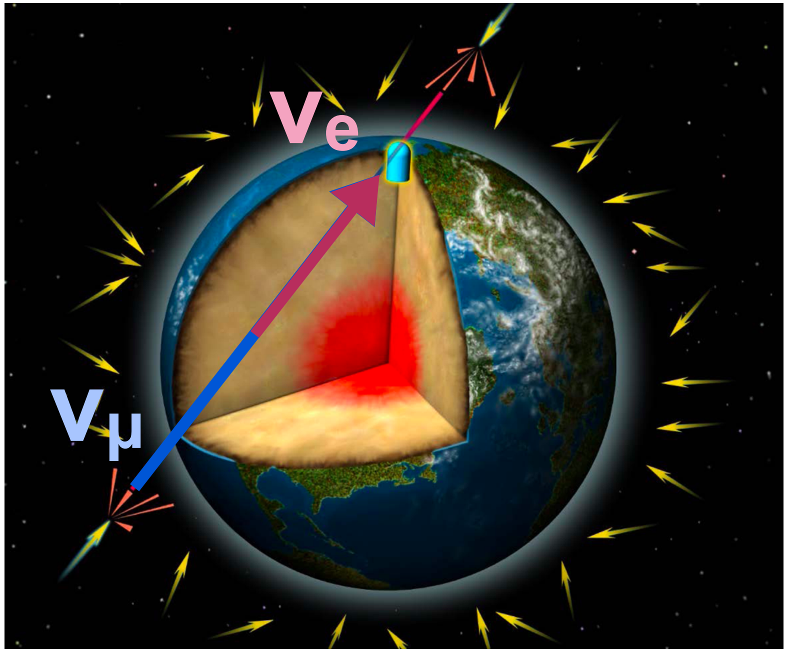
Paper in preparation

Hyper-K sensitivity

Atmosphericv + J-PARC beam

Determination possible by 2~3 years ($\sin^2\theta_{23}$=0.5)





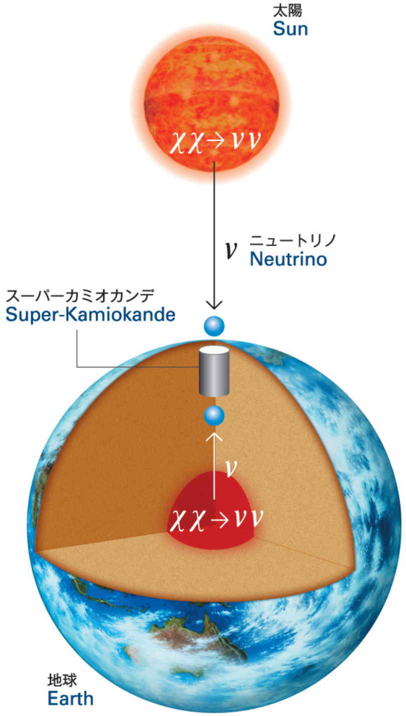
Resonance oscillation (MSW) for

- $\nu_\mu \rightarrow \nu_e$

if Normal Hierarchy

- $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

if Inverted Hierarchy

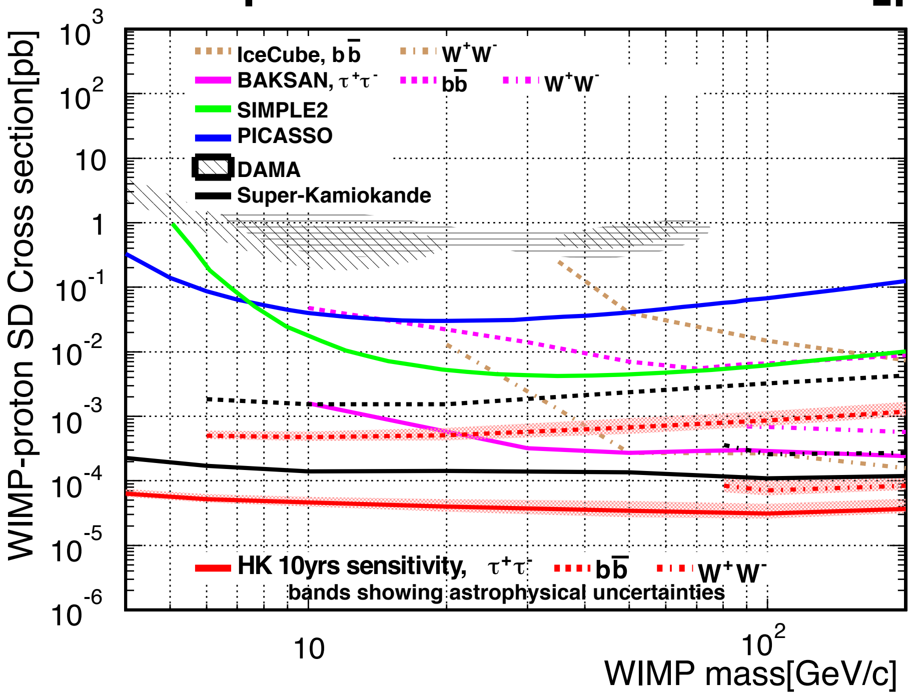


Search for ν's induced by dark matters

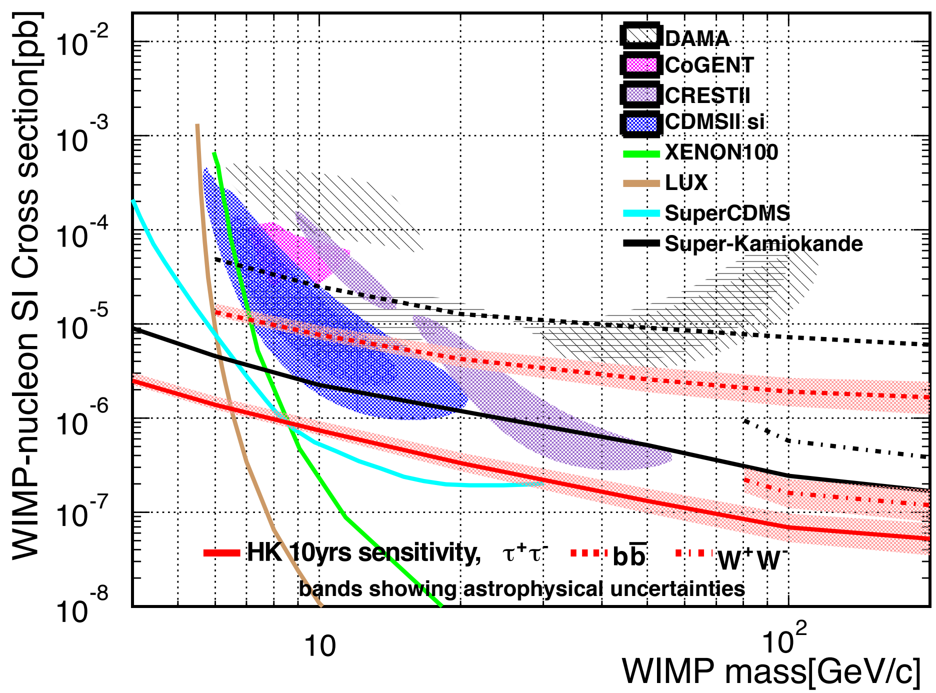
- provide complemental information w/ direct detection experiments
- Sensitive to low mass (GeV/c^2) WIMPs

Expected sensitivity for Solar WIMPs

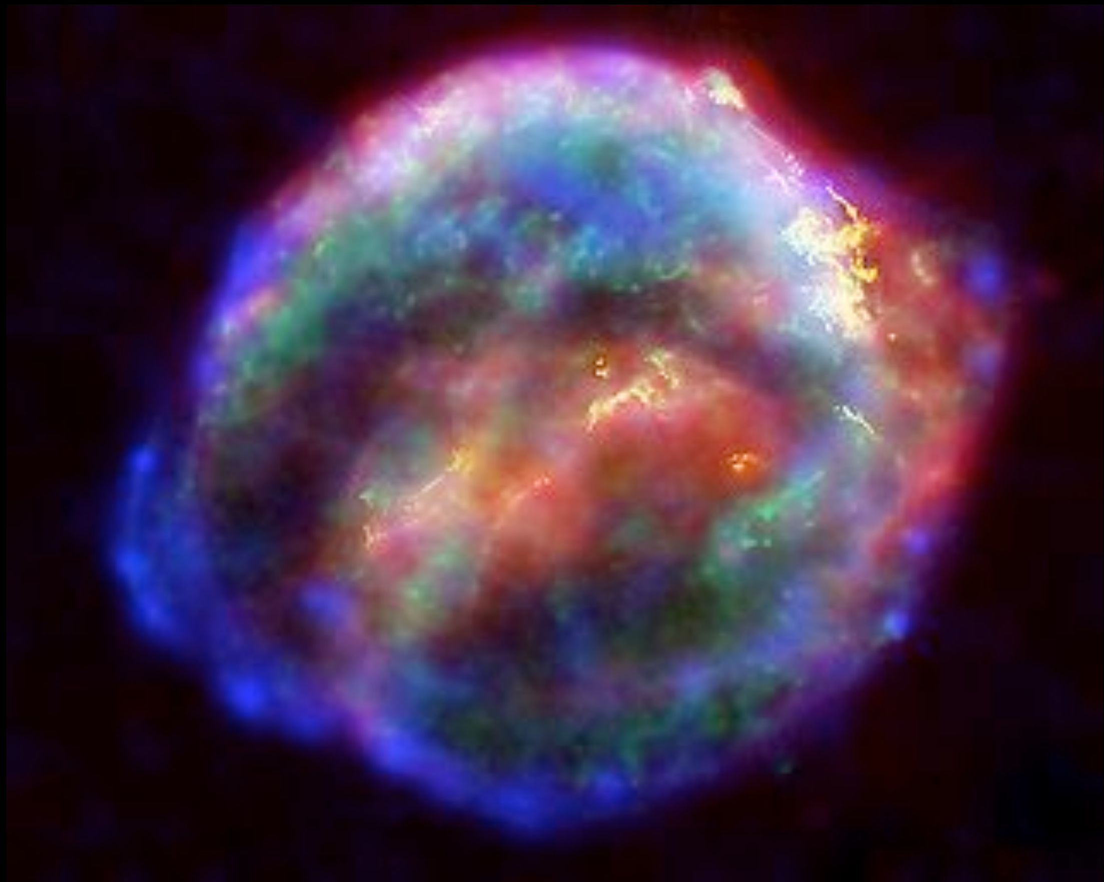
WIMP-proton cross section[pb]



WIMP-nucleon cross section[pb]



ν astophysics, ν telescope



Why Supernova neutrinos?

Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star...

John N. Bahcall, Phys. Rev. Lett. 12, 303 (1964)

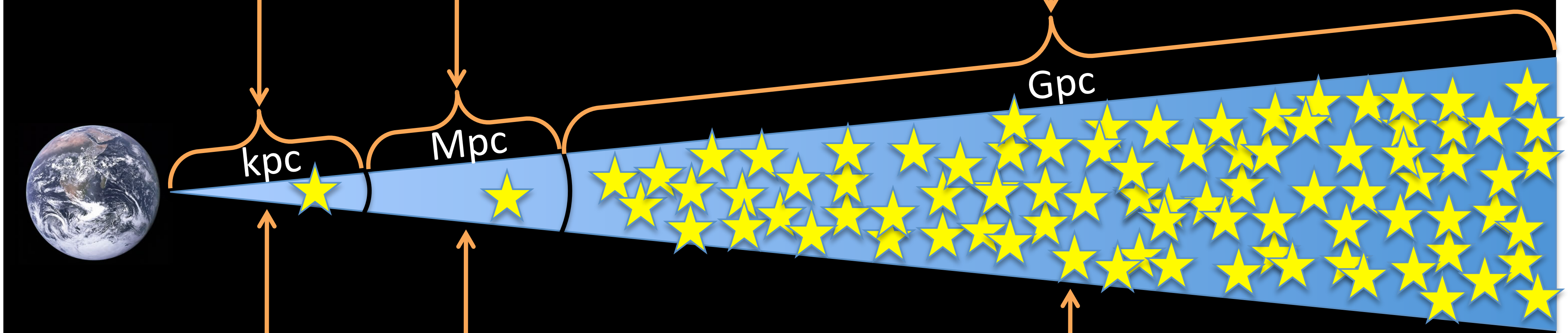
Neutrinos hold the keys to solve many outstanding questions:

- *What is the supernova explosion mechanism?*
- *What is the physics at high temperature and density?*
- *Do black holes form? How and when?*
- *What is the interior environment like?*
- *Was there a jet? An accretion disk?*
- *What nucleosynthesis products are made?*
- *What is the nature of physics at very high neutrino density?*
- *What are the properties of neutrinos?*
- *Which explosions are indeed core collapse?*
- *…etc…*

Slide adopted from Horiuchi@HK meeting

Distance scale and exp'd rate

Milky way	Nearby galaxies	distant galaxies
N >> 1 : Burst	N ~ 1 : Mini-Burst	N << 1 : DSNB



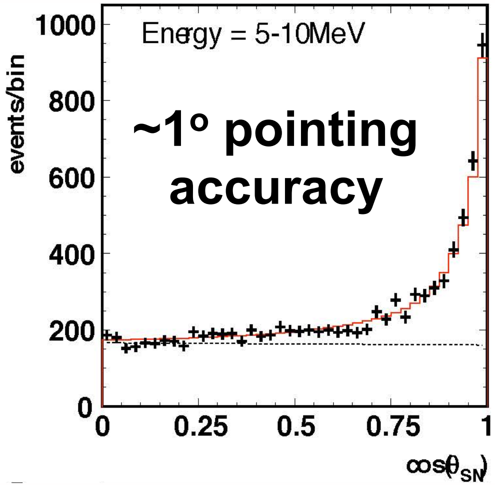
Rate ~ 0.01/yr	Rate ~ 1/yr	Rate ~ 10^8/yr
high statistics, all flavors	object identity, burst variety	cosmic rate, average emission

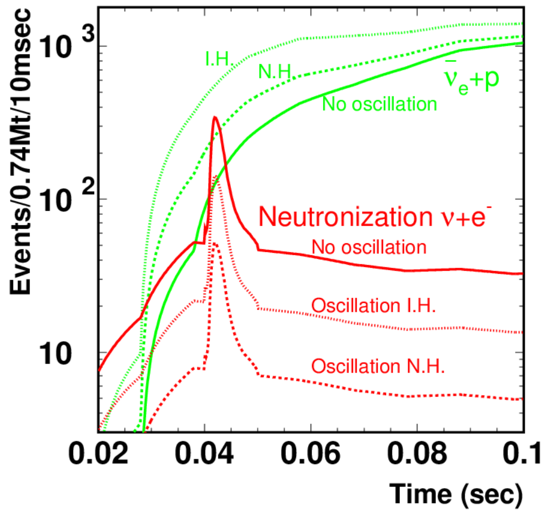
Supernova Burst Neutrinos

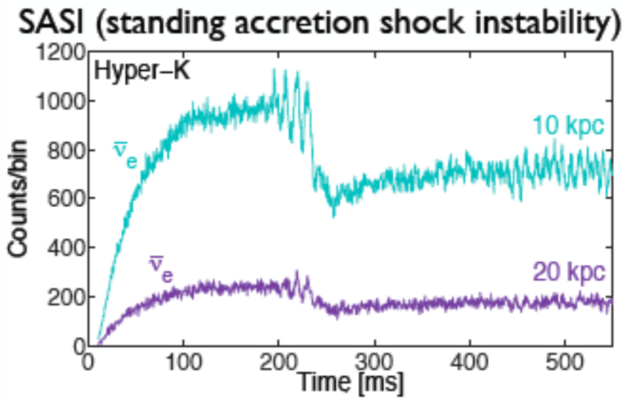
100,000~160,000 ev
(2Tanks 440kt, 10kpc (GC))

ve from neutronization:
12~80 ev

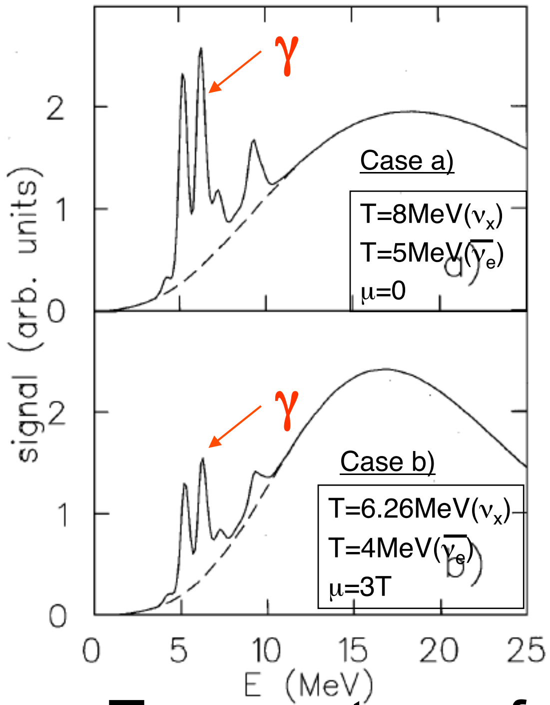
NC: 3,000~5,000 ev
$\nu + {}^{16}O \rightarrow \nu + {}^{16}O^* \rightarrow \gamma$







SN explosion mechanism



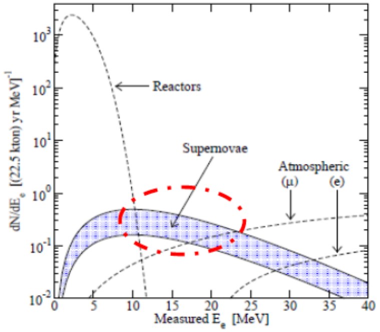
Temperature of interior of SN

• Many information will be extracted: pointing, explosion mechanism (SASI etc), neutronization burst, interior temperature by NC events, instance of NS/BH formation

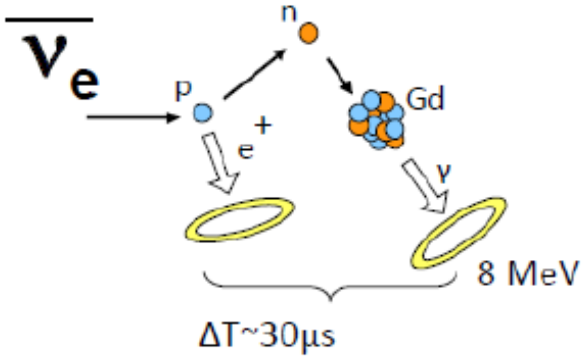
SK-Gd

- Discovery of relic SN neutrinos is expected by O(1) sensitivity improvement
- 0.1% Gd loading to tag $\overline{\nu}e+p\rightarrow e+n$, $Gd+n\rightarrow Gd+\gamma s$

- R&D in test tank and water system construction going on
- Start SK-Gd in a few yrs

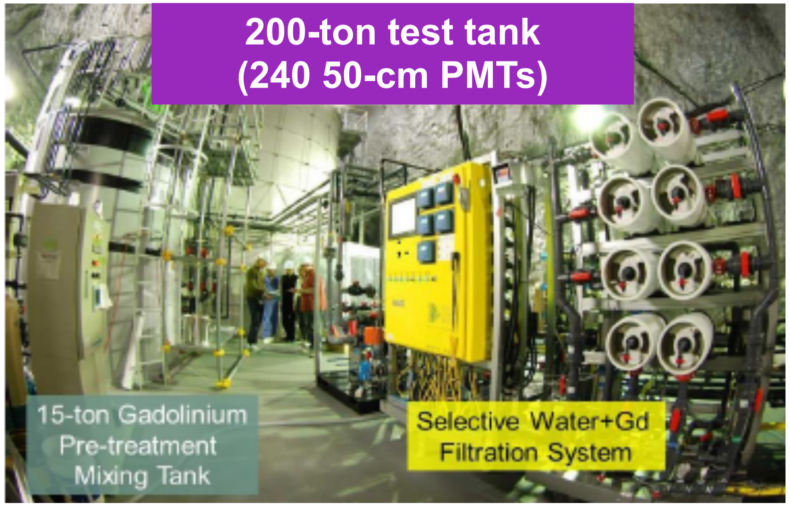


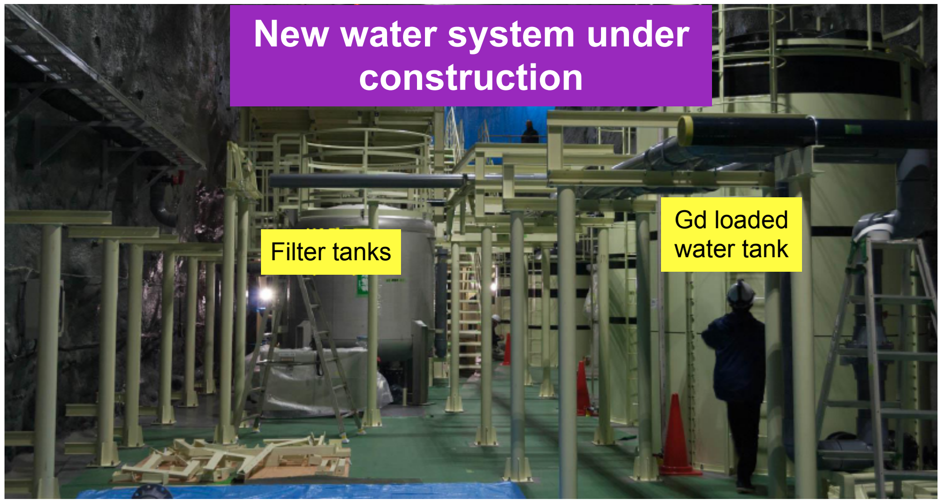
Phys. Rev. Lett. 93 (2014) 171101.



Model Tν	10-16MeV Eve/10yrs	16-28MeV Eve/10yrs	Total (10-28MeV)	Significance 2 energy bin
8 MeV	11.3	19.9	31.2	5.3σ
6 MeV	11.3	13.5	24.8	4.3σ
4 MeV	7.7	4.8	12.5	2.5σ
1987a	5.1	6.8	11.9	2.1σ
BG	10	24	34	---

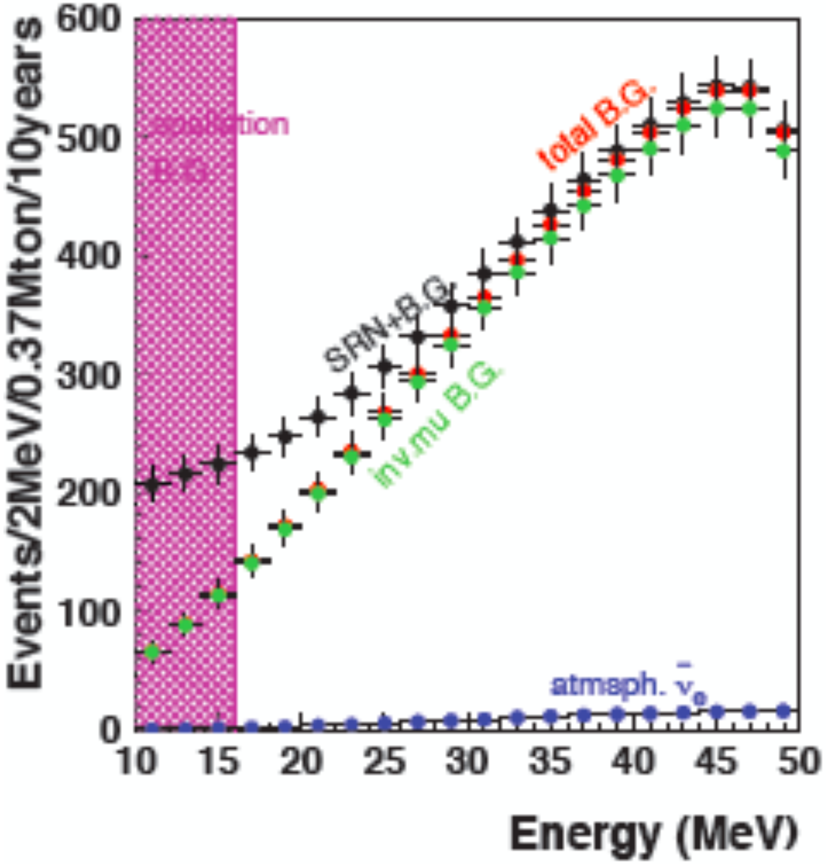
Model: Phys. Rev. D 79 (2009) 083013.



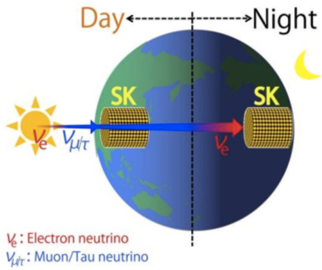


SRN measurement in Hyper-K

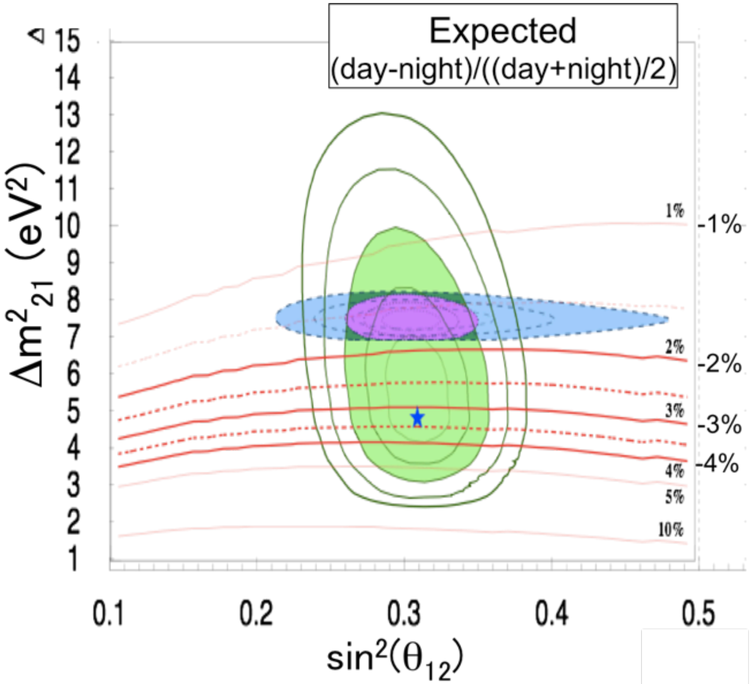
- Guaranteed signal to investigate the averaged SN explosion, and the fraction of dim-SN and BH formation



- ~100 SRN / 10 years (>17.5MeV) is expected



Solar neutrino physics

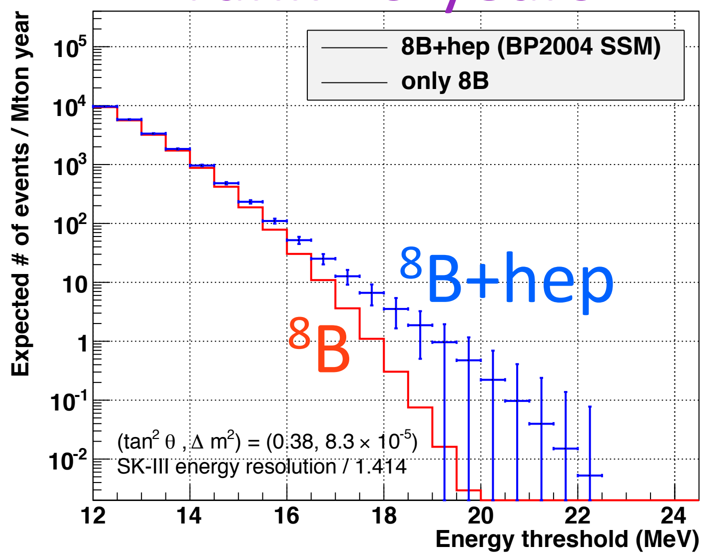


- Precision measurement of solar νe to study ~2σ tension between νe and reactor $\overline{\nu}$e (CPT violation or ?)
- Test various exotic scenarios by spectrum
- ν astronomy
  - Time variation test w/ ~200νs/day
  - First measurement of hepν

Assuming the solar best fit parameters

		Day/Night significance for		Upturn of spectrum
		0 asym.*	KamLAND	
2Tank	10 years	12σ	6σ	4.9σ

1Tank 10-years



Final remark

- Japan-based neutrino program will have rich physics with world-leading science outputs
  - Direct test of GUT
  - Full picture of neutrino oscillations (CPV, mass ordering, and others)
  - Variety of ν astrophysics, telescope
- Hyper-Kamiokande is the flagship experiment in the program
  - Ready-to-go design
  - Budget request is being issued in Japan