Hyper-Kamiokande non-oscillation program

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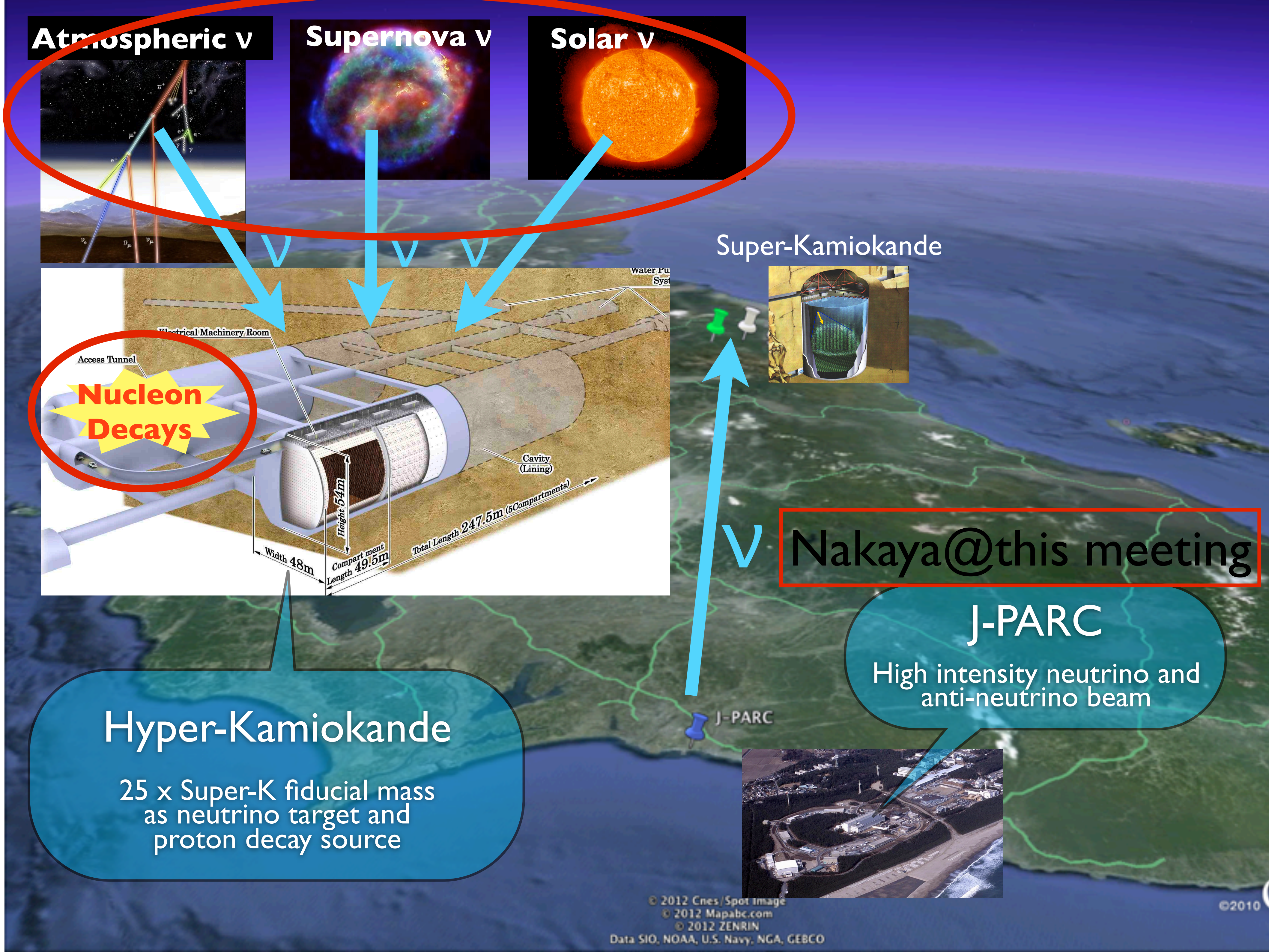
Second Int. Meeting for Large Neutrino Infrastructures
April 21, 2015



Atmospheric ν
Supernova ν
Solar ν
ν
ν
ν
Super-Kamiokande
Electrical Machinery Room
Access Tunnel
Nucleon Decays
Cavity (Lining)
Height 54m
Width 48m
Compart ment Length 49.5m
Total Length 247.5m (5Compartments)
ν
Nakaya@this meeting
J-PARC
High intensity neutrino and anti-neutrino beam
J-PARC
Hyper-Kamiokande
25 x Super-K fiducial mass as neutrino target and proton decay source
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Multi-purpose detector, Hyper-K

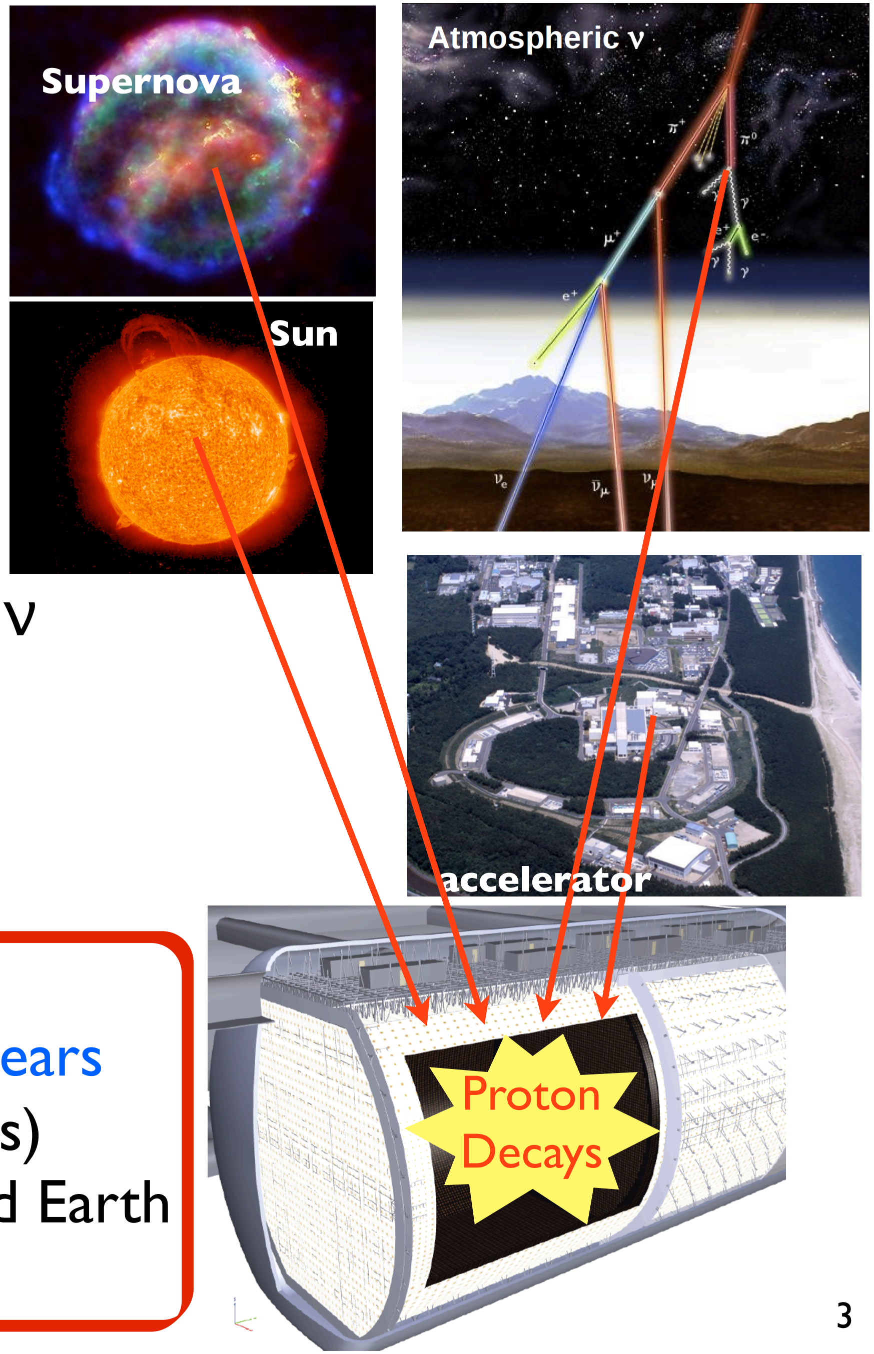
Letter of Intent, Hyper-K WG, arXiv:1109.3262 [hep-ex]

LBL study, Hyper-K WG, arXiv:1502.05199 and accepted by PTEP

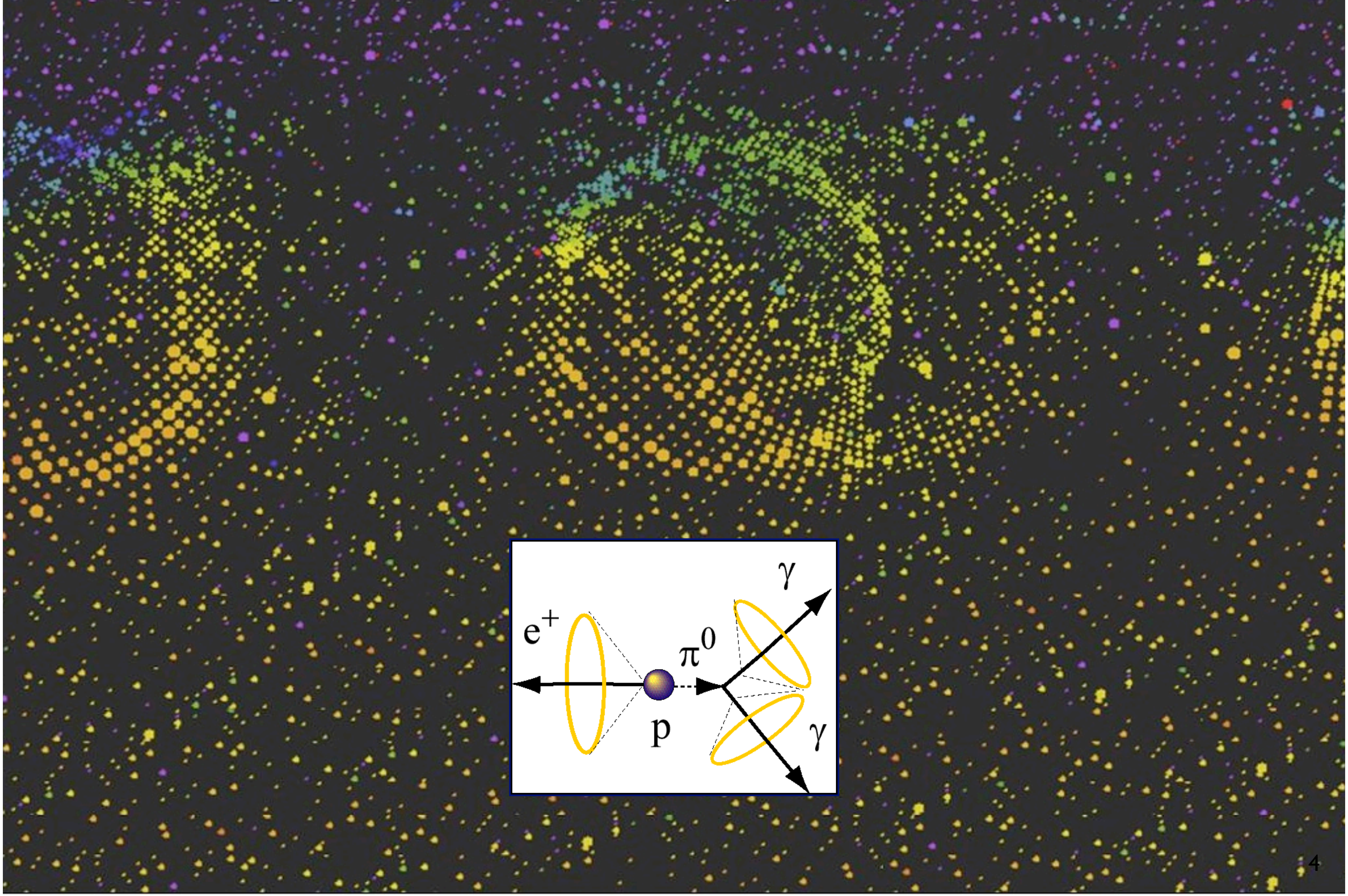
- Proton decay 3σ discovery potential
  - 5×10^{34} years for $p\rightarrow e^{+}\pi^{0}$
  - 1×10^{34} years for $p\rightarrow \nu K^{+}$

- Comprehensive study on ν oscillations
  - CPV (76% of δ space at 3σ), <20° precision
  - MH determination for all δ by J-PARC/Atm ν
  - θ_{23} octant: $\sin^2\theta_{23}<0.47$ or $\sin^2\theta_{23}>0.53$
  - <1% precision of Δm^2_{32}
  - test of exotic scenarios by J-PARC/Atm ν

- Astrophysical neutrino observatory
  - Supernova up to 2Mpc distance, ~1SN /10 years
  - Supernova relic ν signal (~200ν events/10yrs)
  - Dark matter neutrinos from Sun, Galaxy, and Earth
  - Solar neutrino ~200ν events/day



Proton Decays

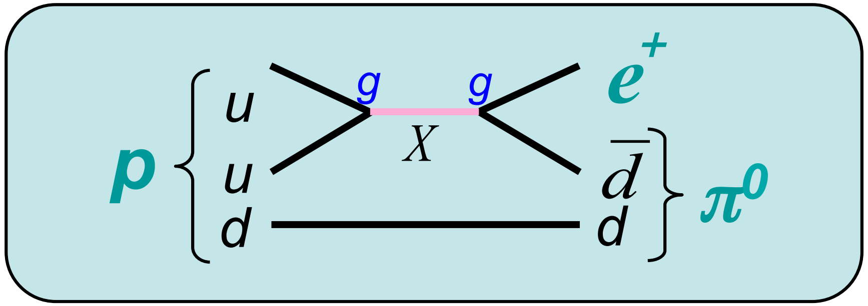


Motivation of Nucleon Decay Searches

- Only way to directly prove GUT

- Two major modes predicted by many models

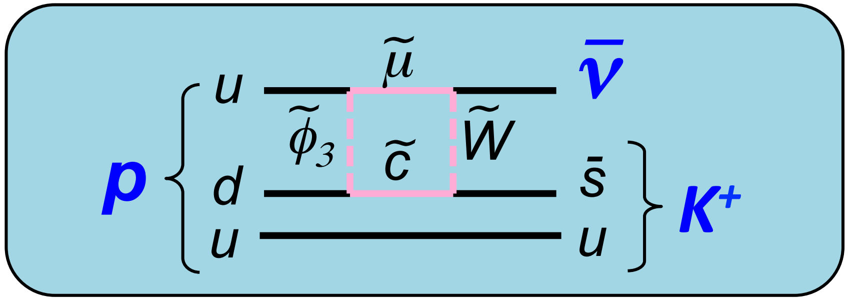
Mediated by gauge bosons



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

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

SUSY mediated



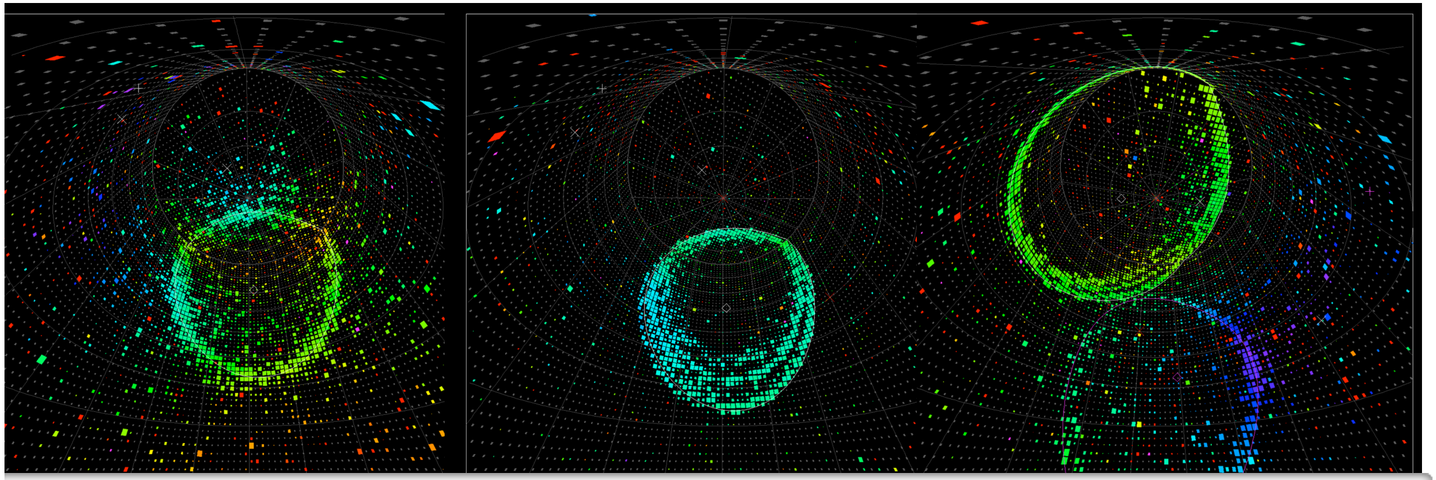
$p \rightarrow \nu K^+$

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

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

※Searches for other modes are also important

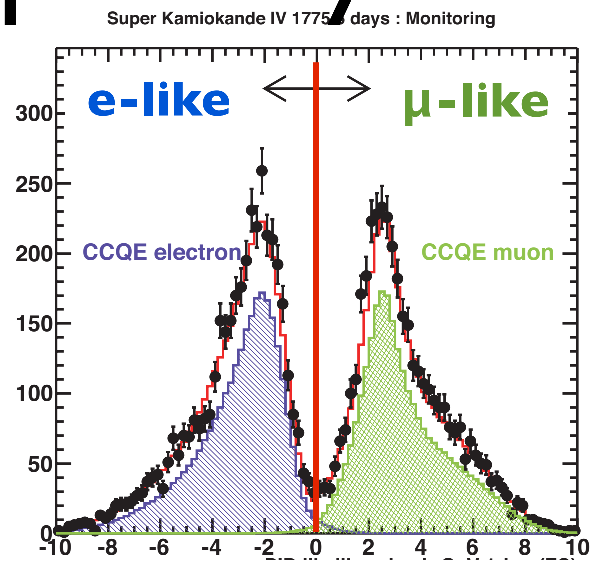
Water Ch. detector for p-decays



- **High mass is possible** (1Mton ~ 20×Super-K)
  - **$p \rightarrow e^+\pi^0$, νK^+, and more** can be searched with unprecedented sensitivities

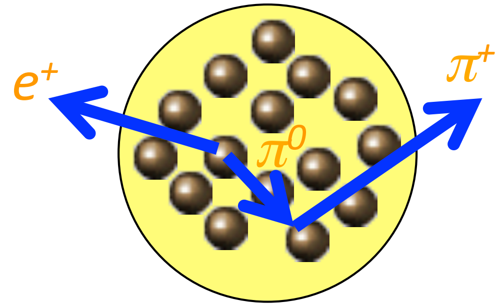
- **Excellent & well-proven performance**
  - Good ring-imaging capability at ~1GeV
  - Excellent particle ID (e or μ) capability > 99%
  - Energy resolution for e and μ ~3%

- **Free protons are available**
  - No nuclear effect, Fermi motion
  - High efficiency & good S/N separation

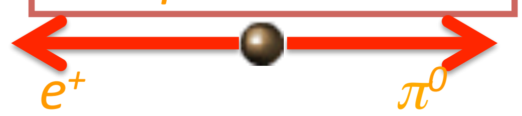


PID likelihood (atmν)

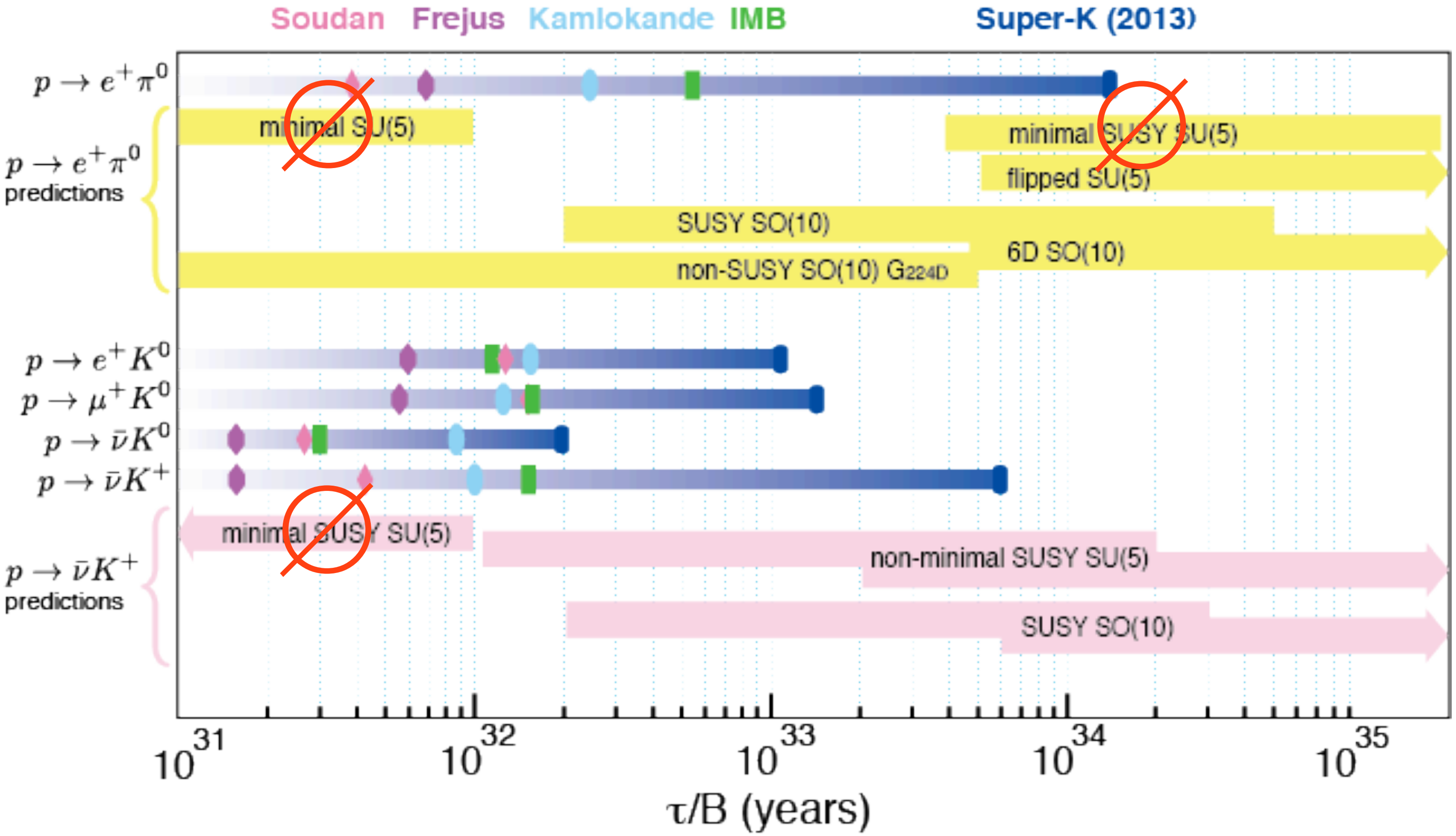
$p \rightarrow e^+\pi^0$ in ^{16}O



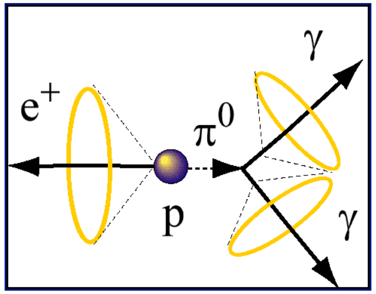
Free proton $\rightarrow e^+\pi^0$



Experimental limits and models



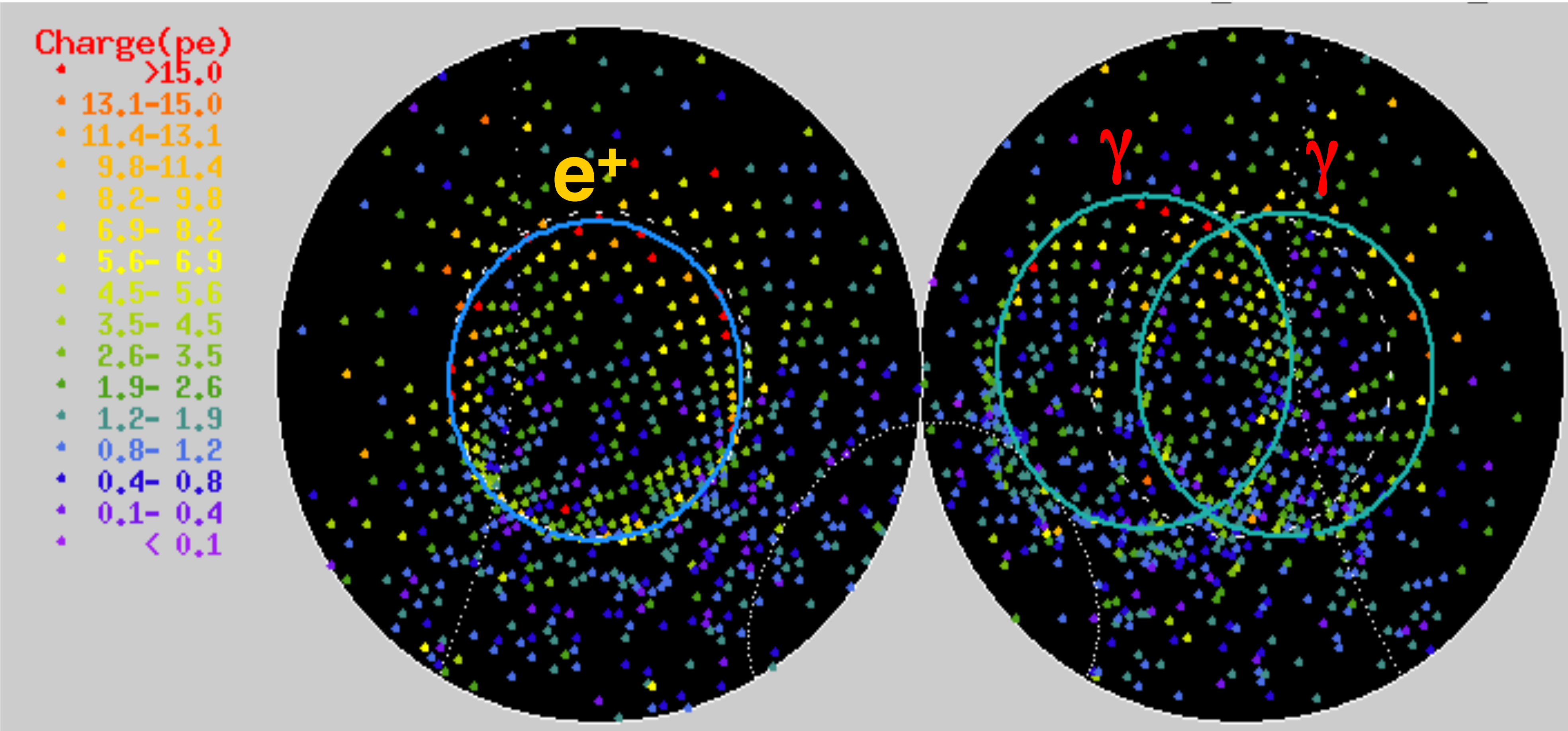
- **Super-K provides world stringent limits**
  - $\tau(p \to e^+\pi^0) > 1.4\times10^{34}$ years (90%C.L., 260kton・years)
  - $\tau(p \to \nu K^+) > 5.9\times10^{33}$ years (90%C.L., 260kton・years)
- **Many models predict $\tau = O(10^{34\text{-}35})$ years**
  - Discovery could be around corner!



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

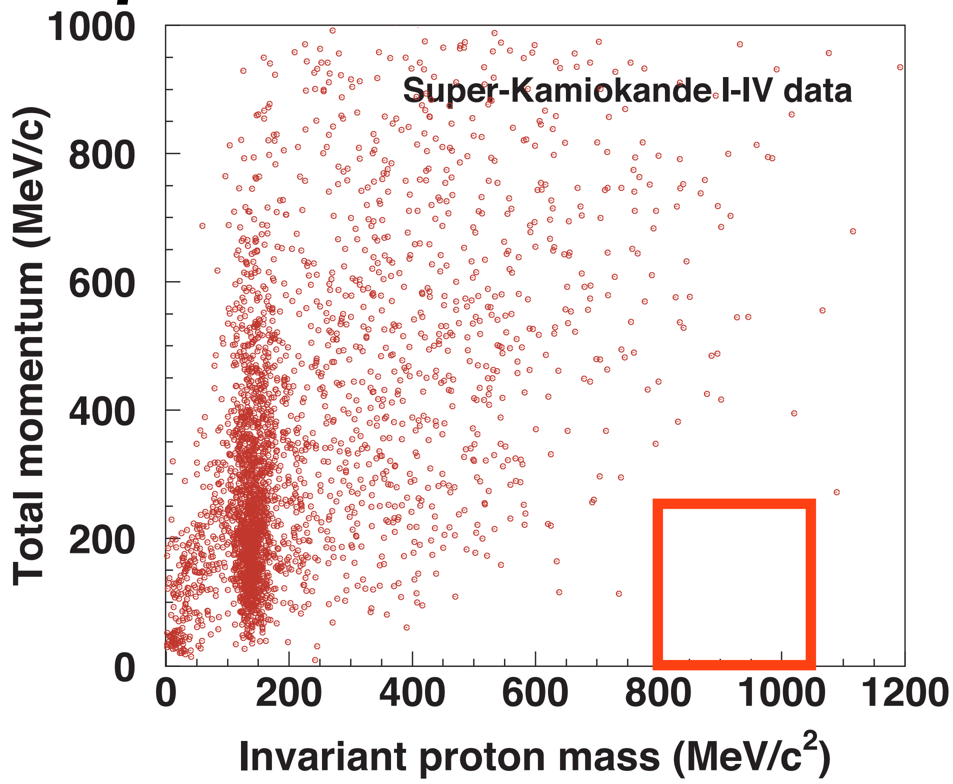
Super-K cut

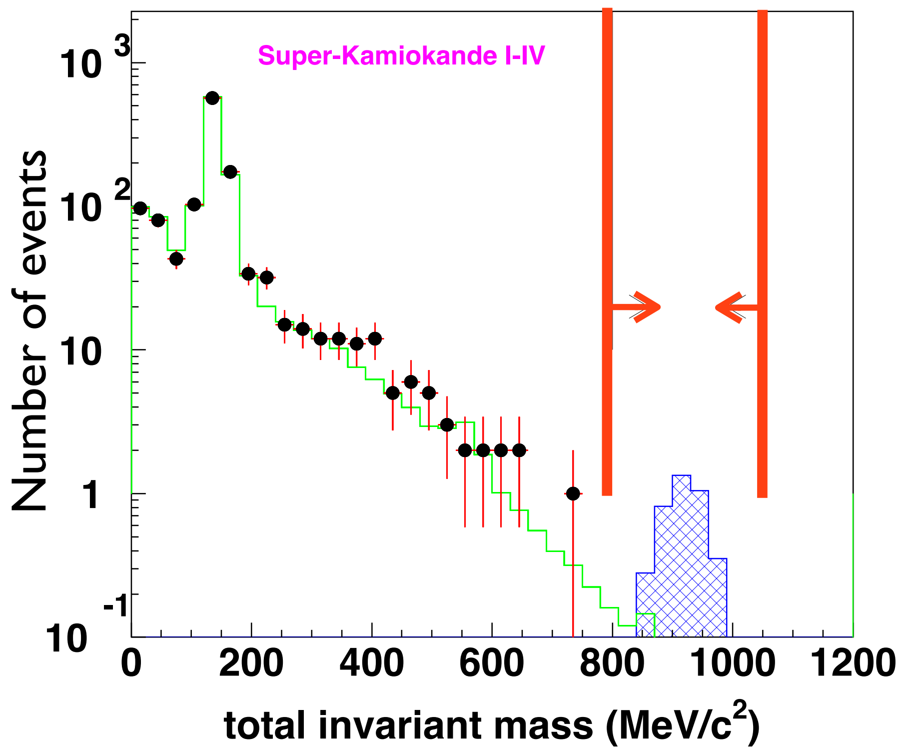
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050\ MeV/c^2$
  $P_{total} < 250\ MeV/c$



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

$p \rightarrow e^+ + \pi^0$ in SK I-IV (260kt×yrs)





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

- detection efficiency = 40%
- atmospheric ν BG = 0.7 events in 260kton×years
  2.7±0.3(stat.)±1.2(syst.) (Mton×years)$^{-1}$
- τ_{proton}/Br > 1.4 ×10^{34} years @ 90%C.L.

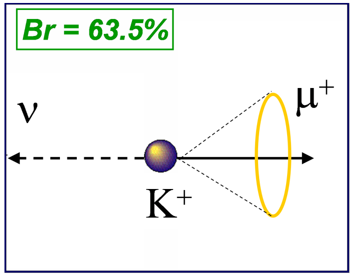
▸ Succeed to keep the background low. More reduction is under study.

▸ BG rate was confirmed by K2K accelerator ν beam

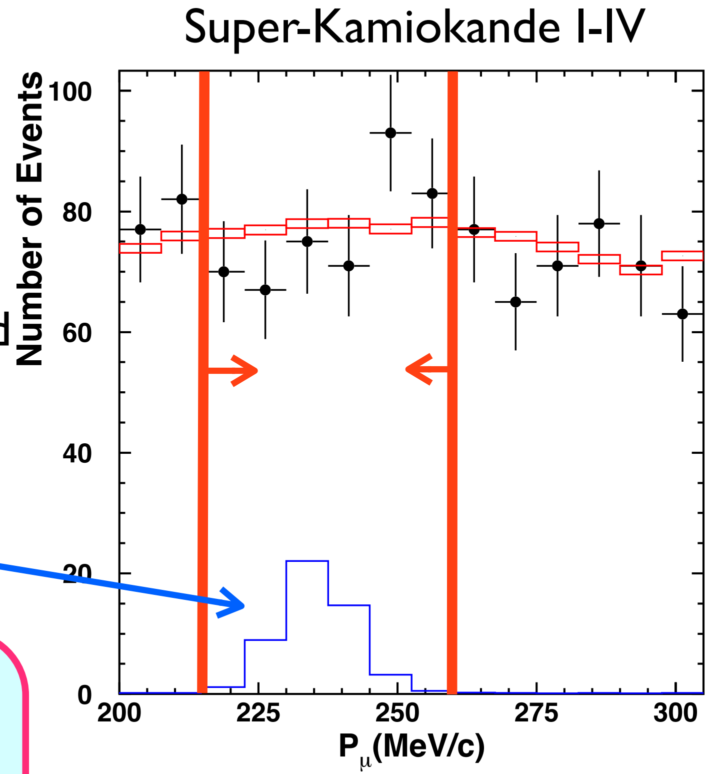
PRD77:032003,2008

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

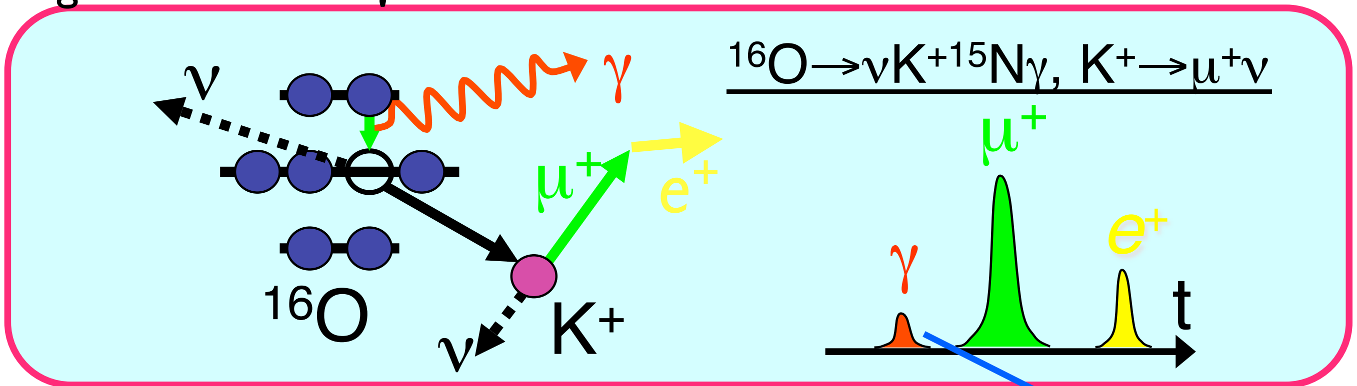
(I) $K^+ \rightarrow \mu^+\nu$, $\mu^+ \rightarrow e^+\nu\nu$

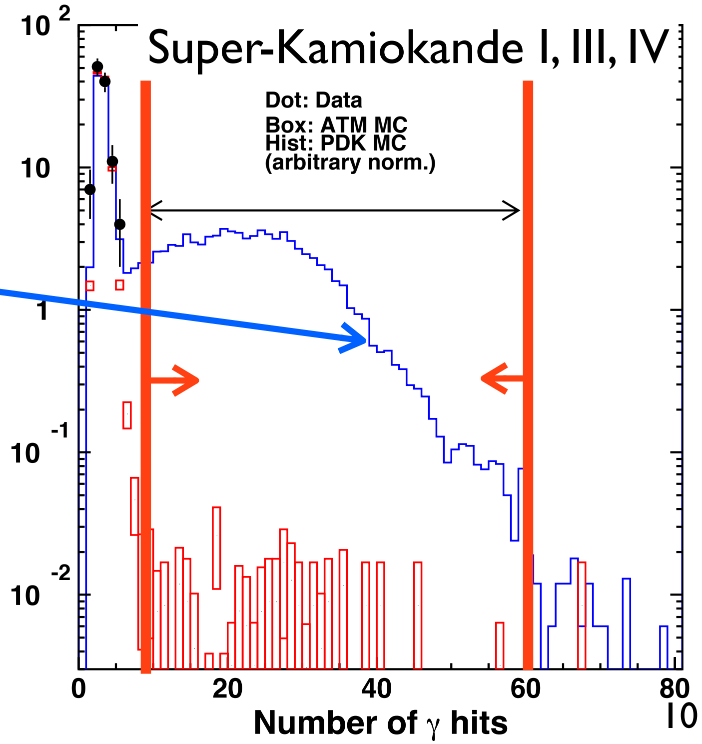


K^+ is below Cherenkov threshold → 236MeV/c μ and muon decay electrons



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





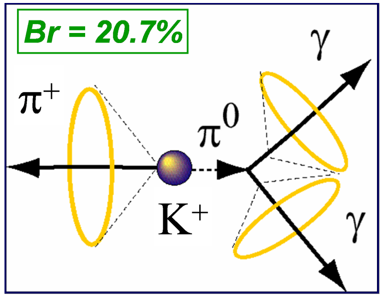
Many efforts to improve analyses

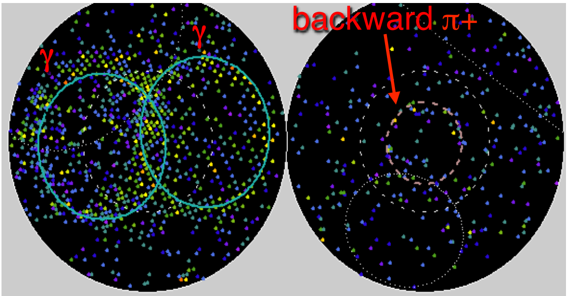
PRD90, 072005 (2014)

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

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

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





PRD90, 072005 (2014)

- 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

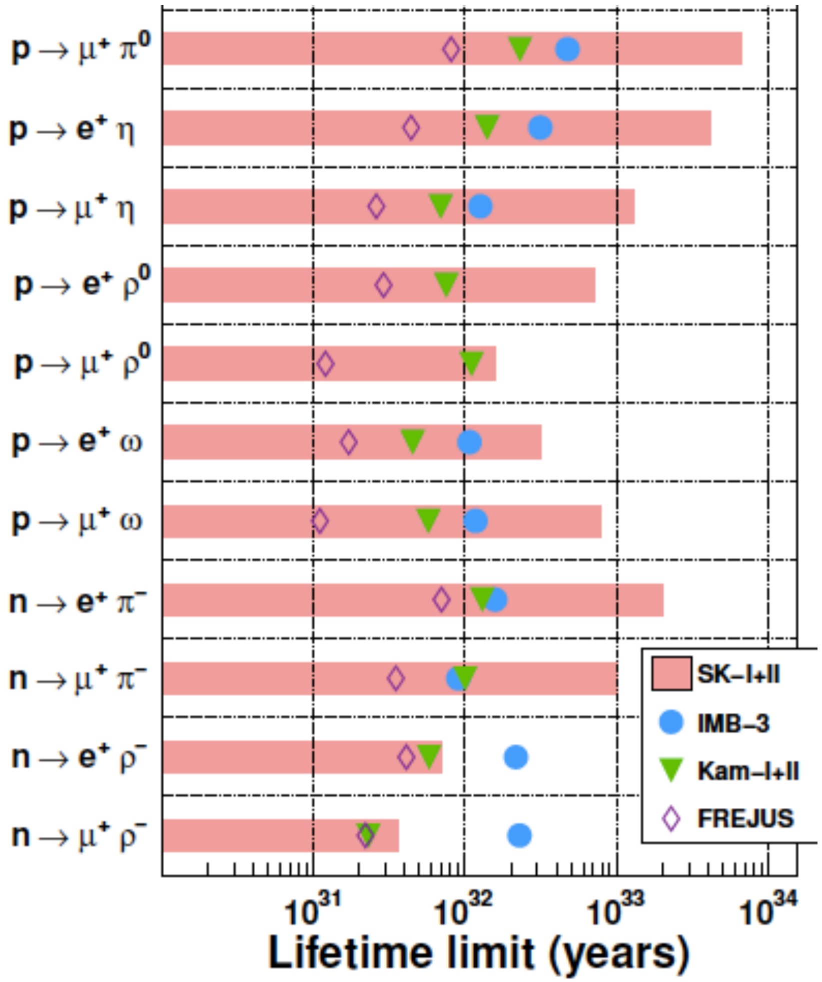
SK-I paper in 2005 | 91.7 kt y | 14.6% | 1.3 evts.

PRD90, 072005 (2014)

	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

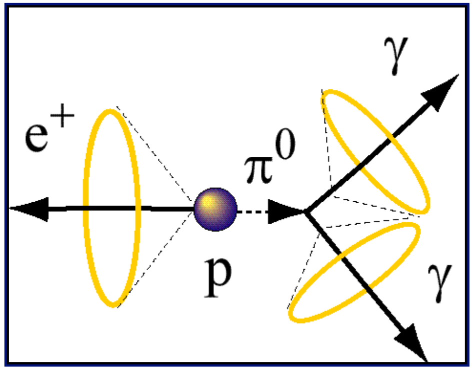
- $p \to e^+ + \pi^0$ reached to 10^{34} yrs
- $(p,n) \to (e^+,\mu^+) + (\pi,\eta,\rho,\omega)$ $10^{32}\sim10^{33}$ yrs
- SUSY favored $p \to \nu K^+ > 5.9\times10^{33}$ yrs
- No excess in K^0_S, K^0_L, $\nu\pi^0$, $\nu\pi^+$
- test many decay modes
  - di-nucleon decays ($|\Delta B|=2$)
  - $pp \to K^+K^+ > 1.7\times10^{32}$ years
  - $pp \to e^+e^+ > 10^{33}$ years
  - $np \to (e^+,\mu^+,\tau^+)+\nu$
  - neutron-antineutron oscillations
  - $p \to (e^+,\mu^+)+\nu\nu$, $(e^+,\mu^+)+X$
  - radiative decays $p \to (e^+,\mu^+)+\gamma$

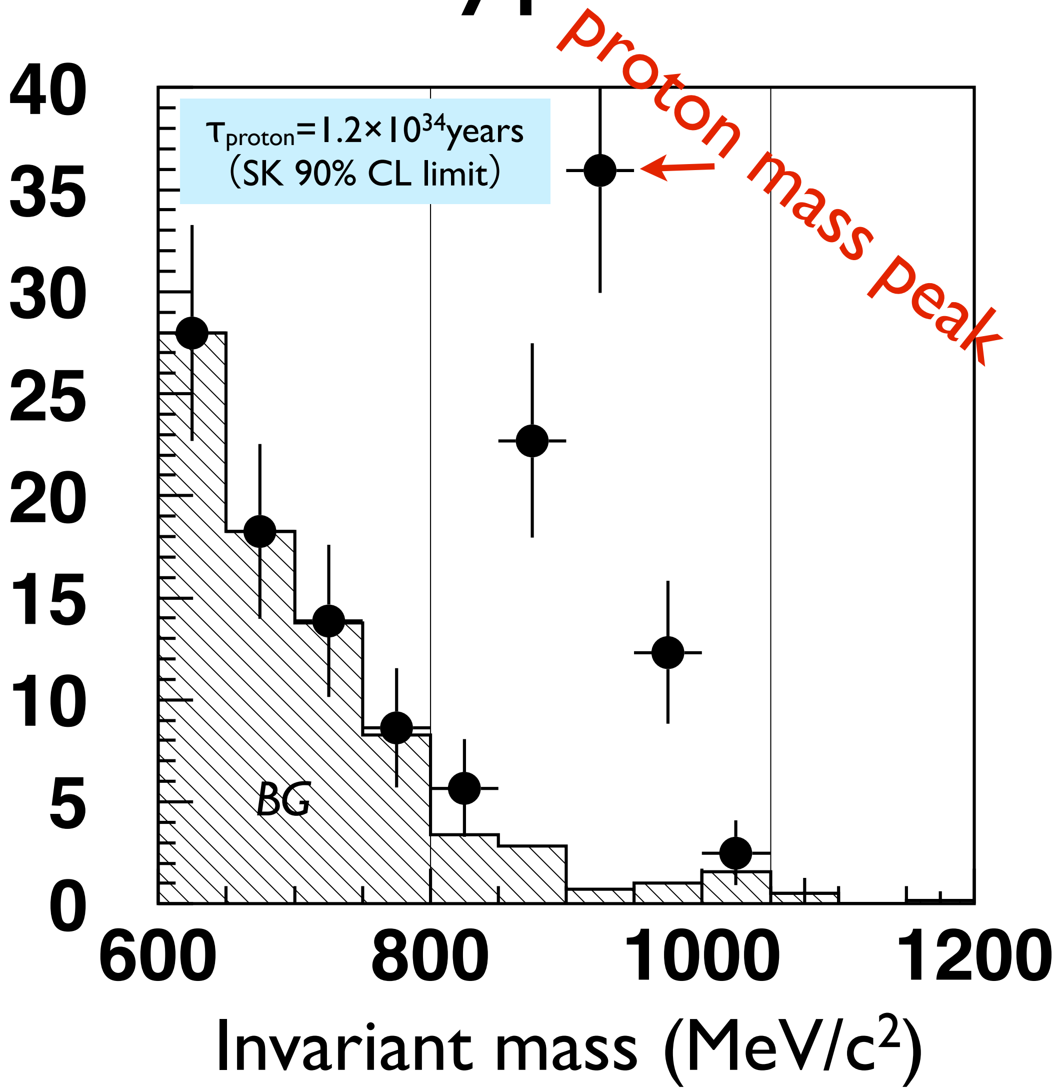


Still looking for signal w/ increasing data

Discovery potential in Hyper-K

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



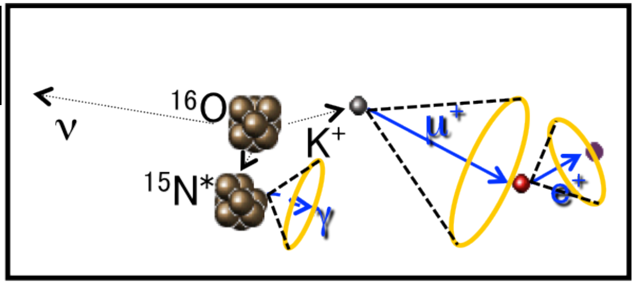


- Discovery reach (3σ)
  - $\tau(p \rightarrow e^+\pi^0) \sim 5\times10^{34}$ years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \rightarrow e^+\pi^0) > 1\times10^{35}$ years (HK 10yrs)

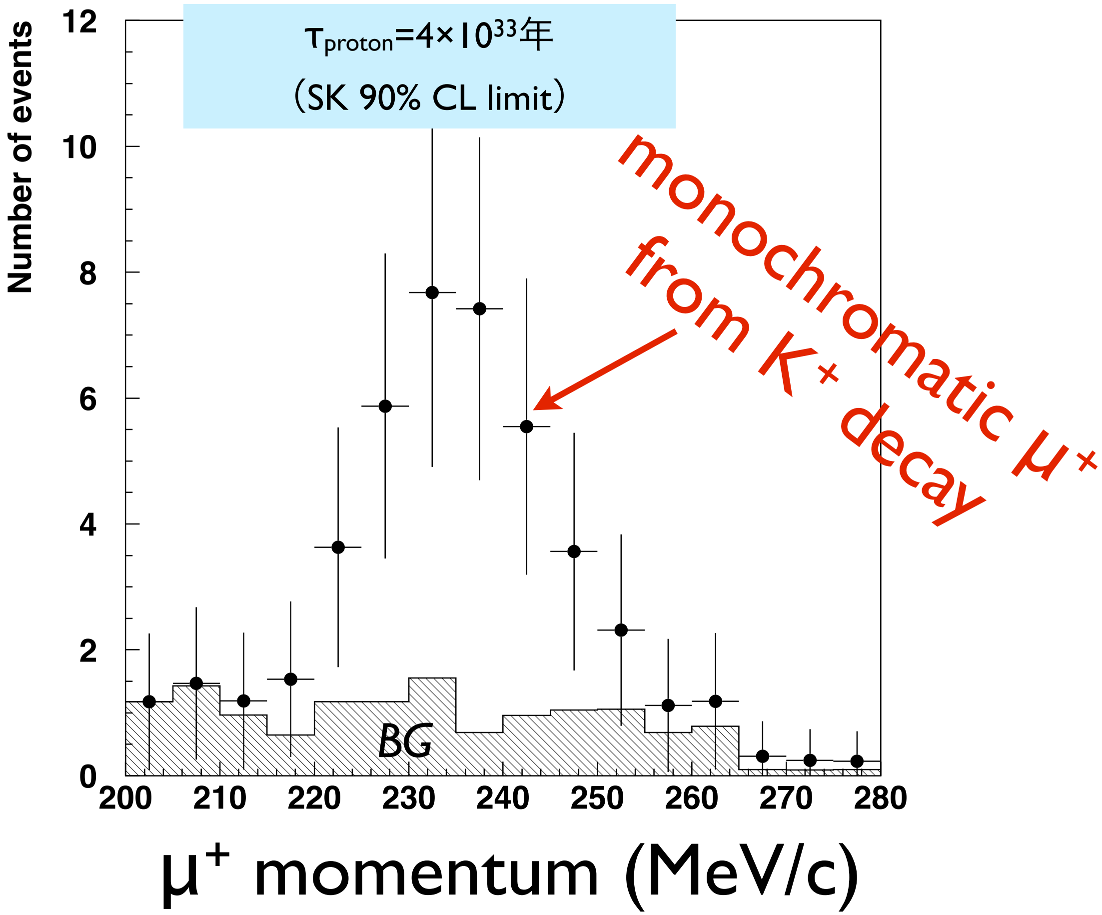
Only realistic proposal to reach the lifetime of 10^{35} years for $p \rightarrow e^+\pi^0$

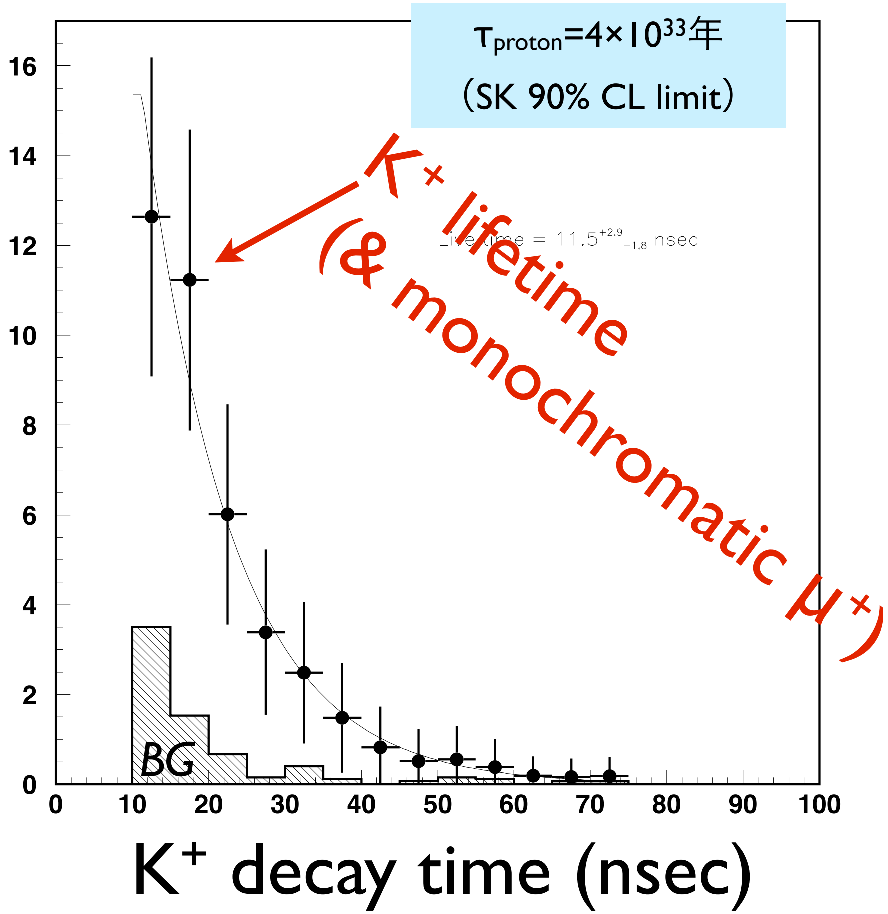
Discovery potential (2)

p→νK⁺



- Discovery reach (3σ)
  - τ(p→νK⁺)~1×10³⁴years（HK 10yrs）
- Limit (90%CL)
  - τ(p→νK⁺)>3×10³⁴years（HK 10yrs）



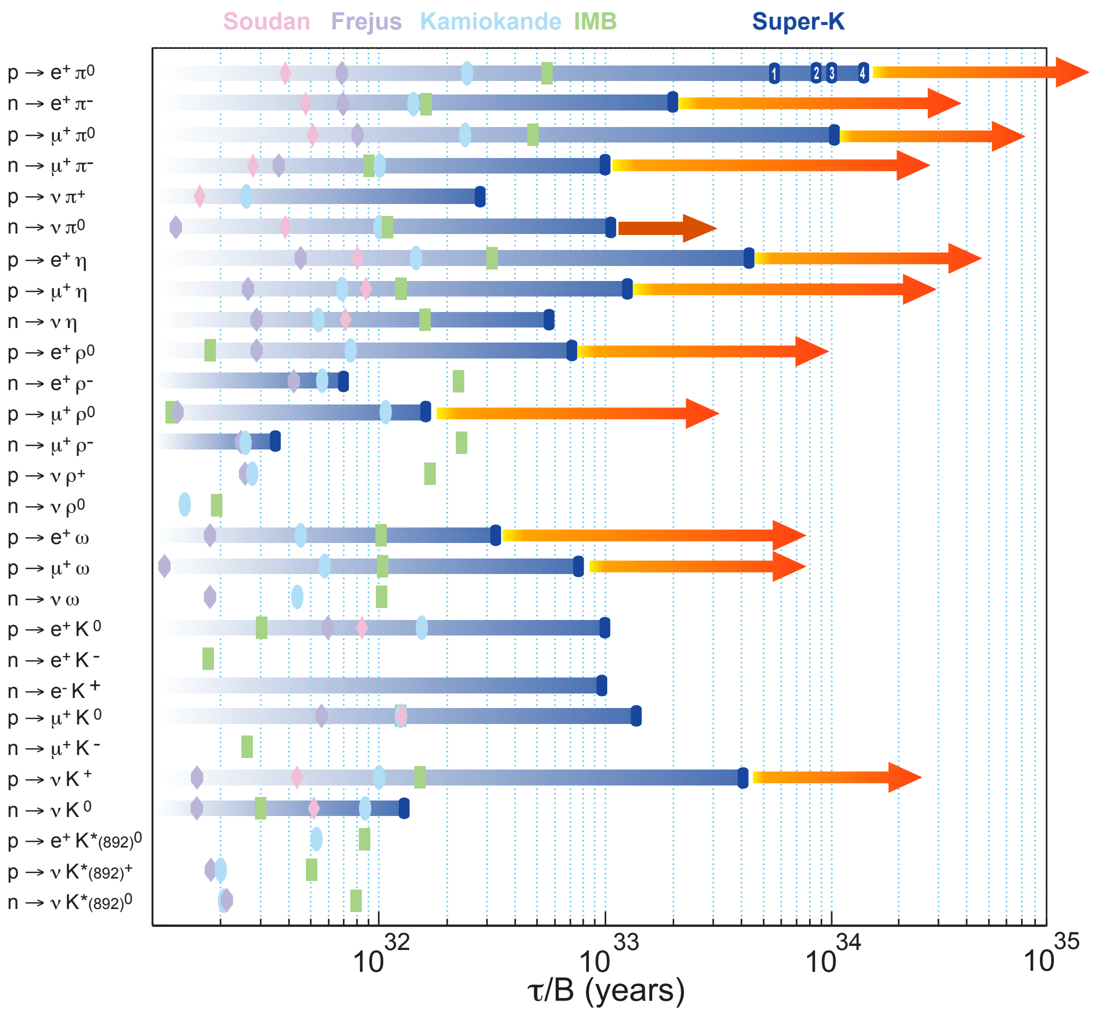


Experimental test on Supersymmetry

Hyper-K's sensitivities

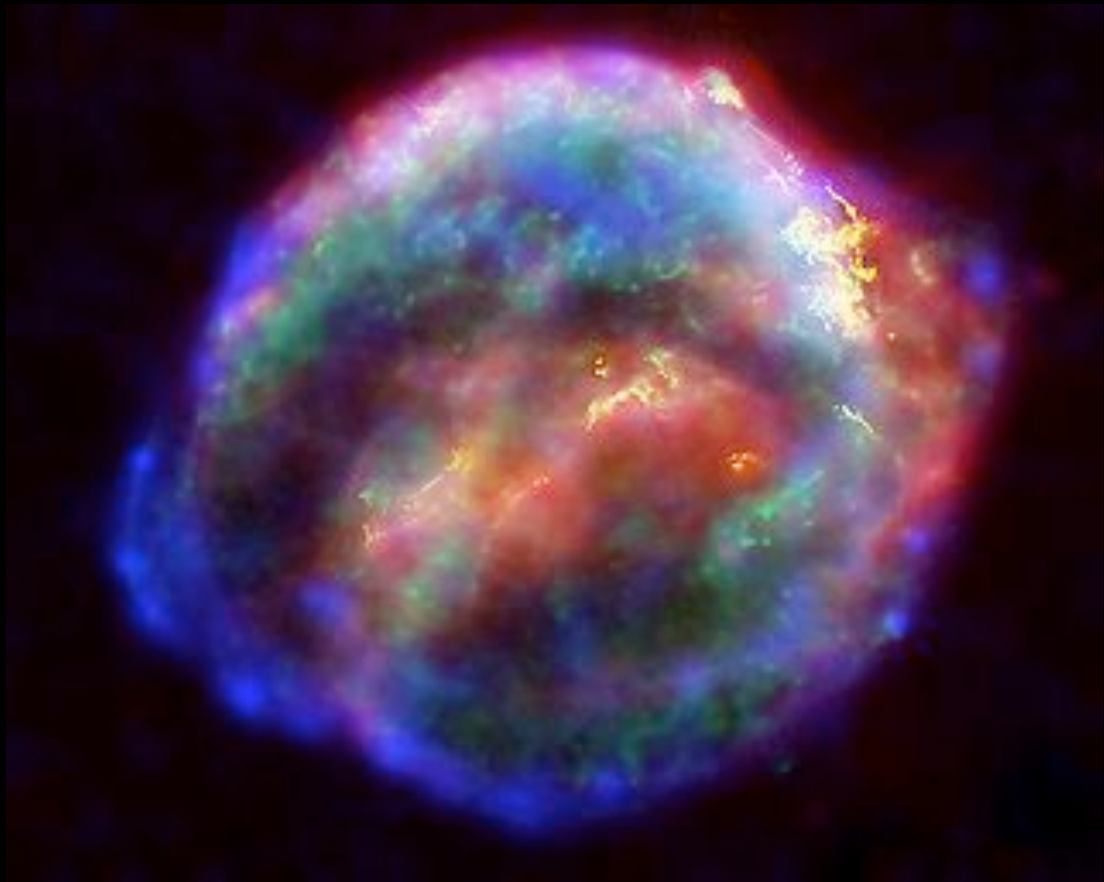
Improvements in many modes by a factor ~10

Open for many decay modes including $p \to e^+\pi^0$, $p \to \nu K^+$



- $p \to e^+ + \pi^0$
  - $\tau_{proton}/Br > 1\times10^{35}$ years @90%CL
  - 5Mton×years (9 Hyper-K years)
- $p,n \to (e^+,\mu^+) + (\pi,\rho,\omega,\eta)$
  - $O(10^{34\sim35})$years
- *SUSY favored* $p \to \nu + K^+$
  - 3×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- Others
  - (B-L) violated modes
  - radiative decays $p \to e^+\gamma$, $\mu^+\gamma$
  - neutron-antineutron oscillations ($|\Delta B|=2$)
  - di-nucleon decays ($|\Delta B|=2$)
    - pp→XX..., nn→XX...

Supernova



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)

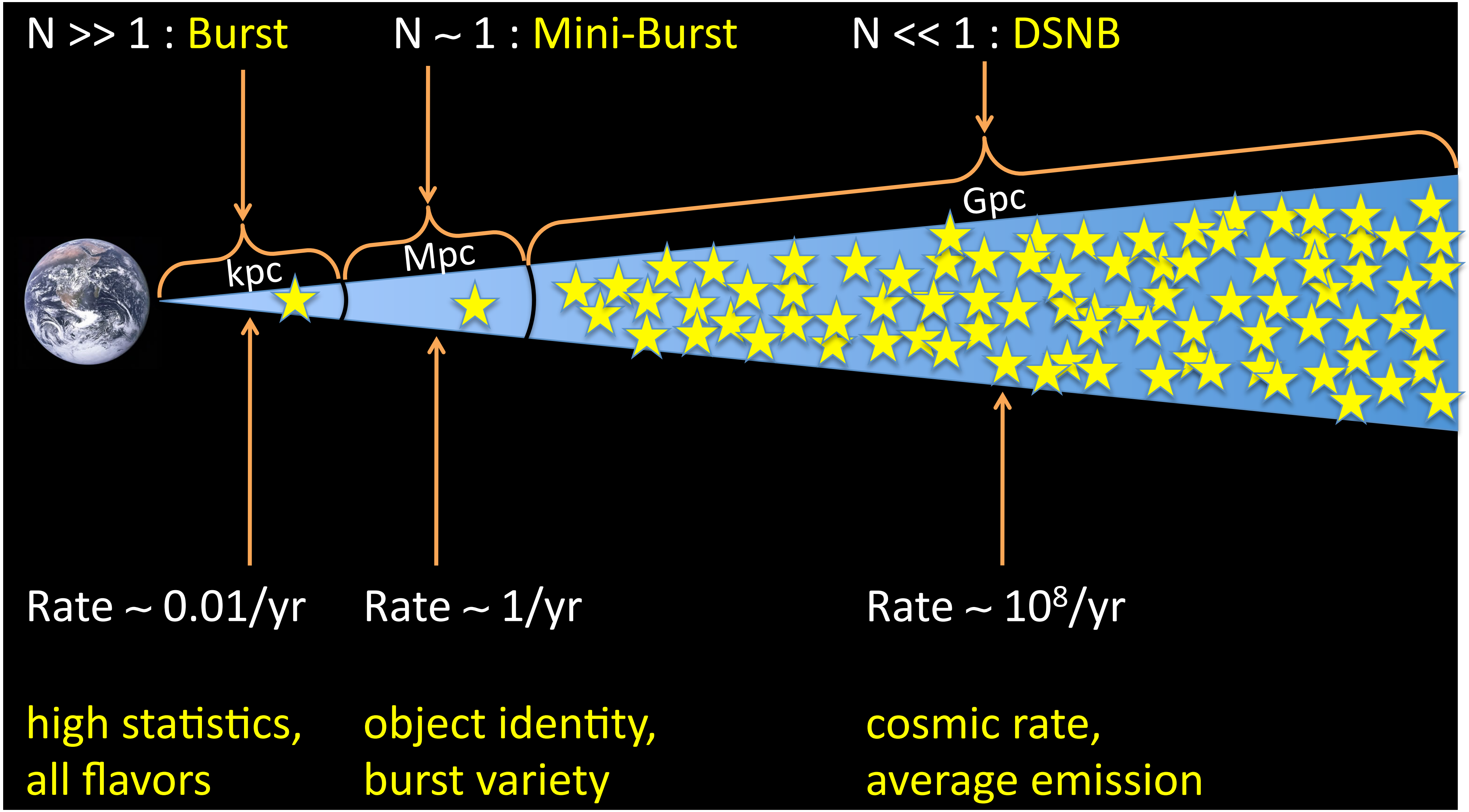
Neutrinos hold the keys to solve many outstanding questions:

- *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

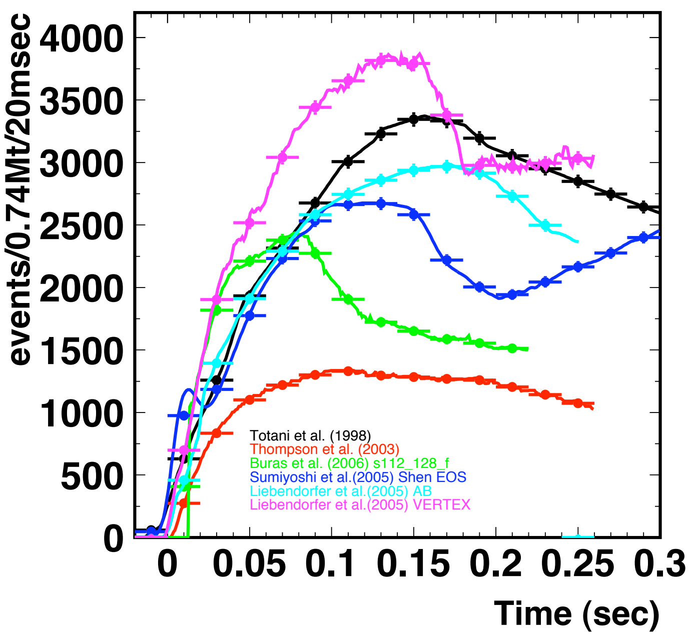
Distance scale and exp'd rate

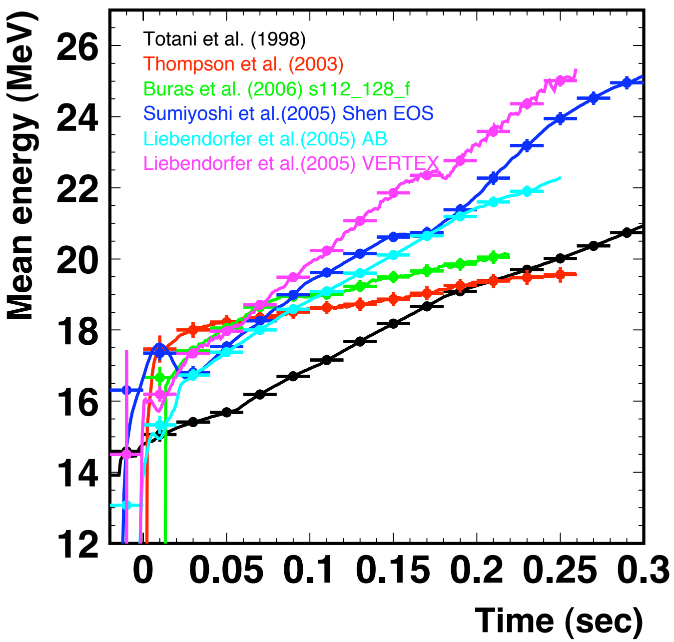
Milky way | Nearby galaxies | distant galaxies

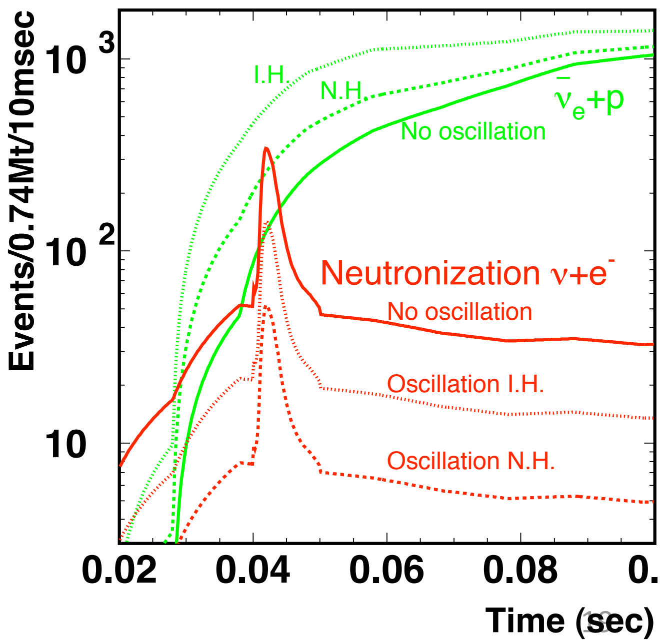


ν burst @ Milky way (10kpc)

- High statistical observation by 200,000 ν events
- Explore core collapse and cooling mechanism (model)
  - Time variation of (ν luminosity, temperature, flavor)
  - νe from neutronization (20~56 evnts)
  - Precise moment when a neutron start is born.
- ν property info. (absolute mass, mass hierarchy)

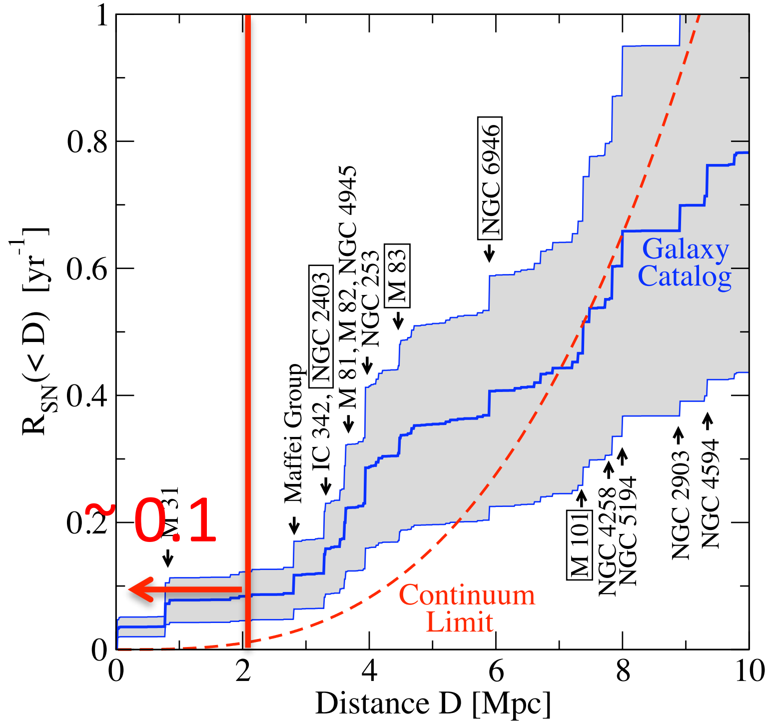




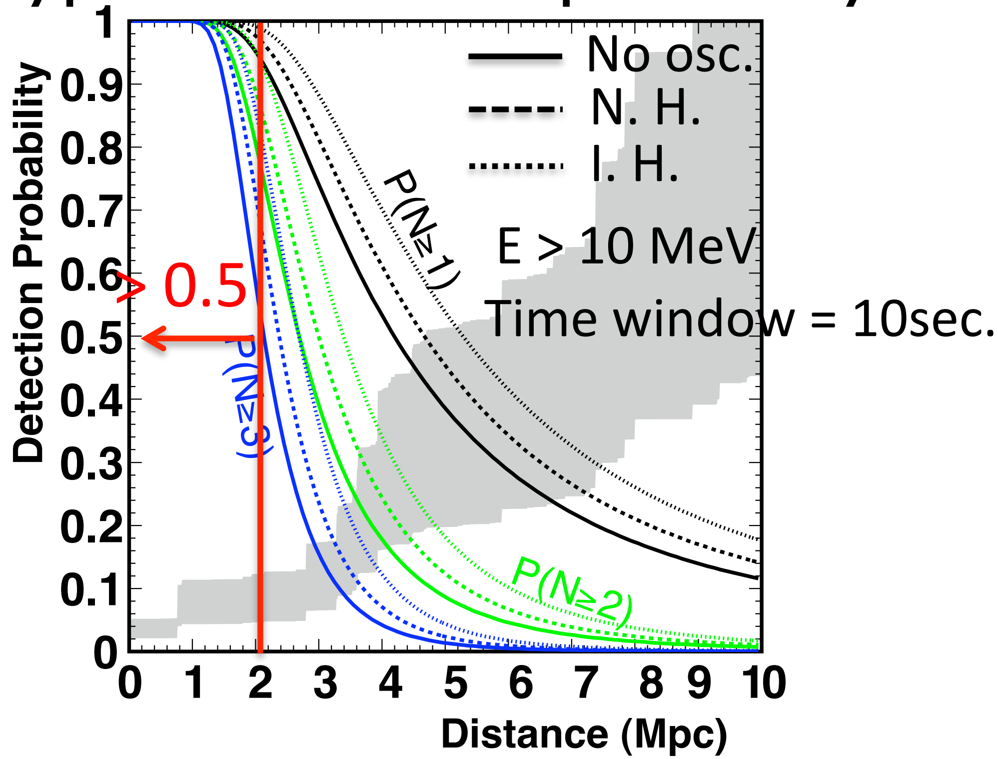


Supernova in nearby galaxies

Cumulative supernova rate



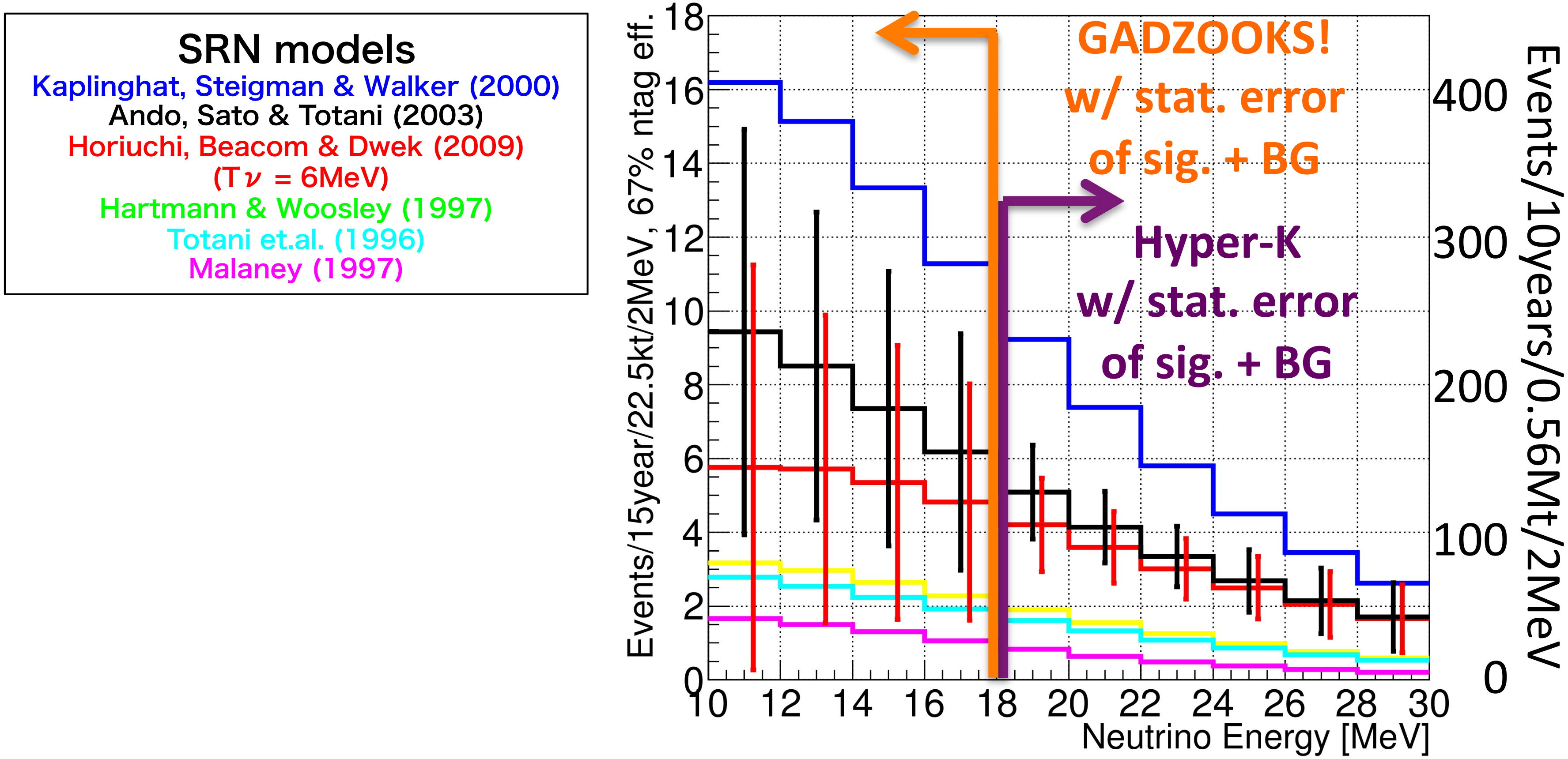
Hyper-K detection probability



- >50% efficiency is expected within 2 Mpc for requiring signal triplets (N>=3)
- Further study ongoing on E threshold and expected BG.

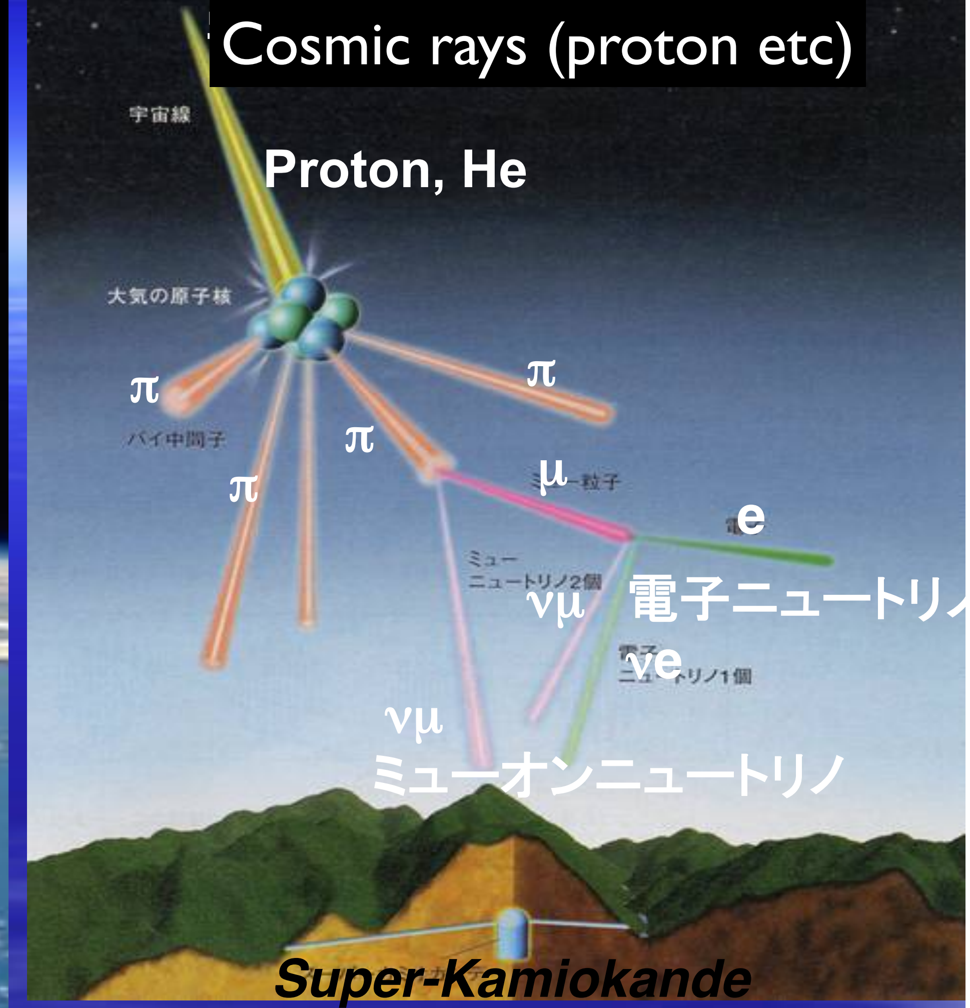
Supernova relic ν (SRN)

- SRN is guaranteed signal which will provide precious information on SN rate and SN ν spectrum



- ~300 SRN / 10 years (>17.5MeV) is expected

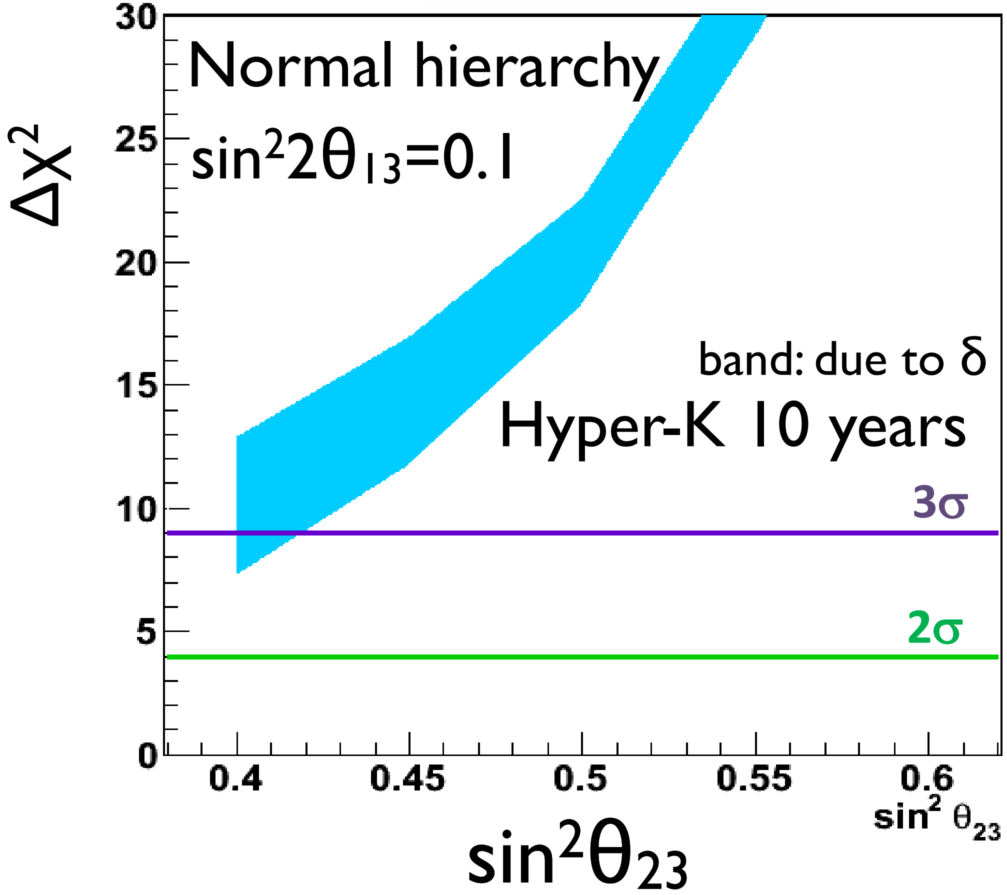
Atmospheric ν's



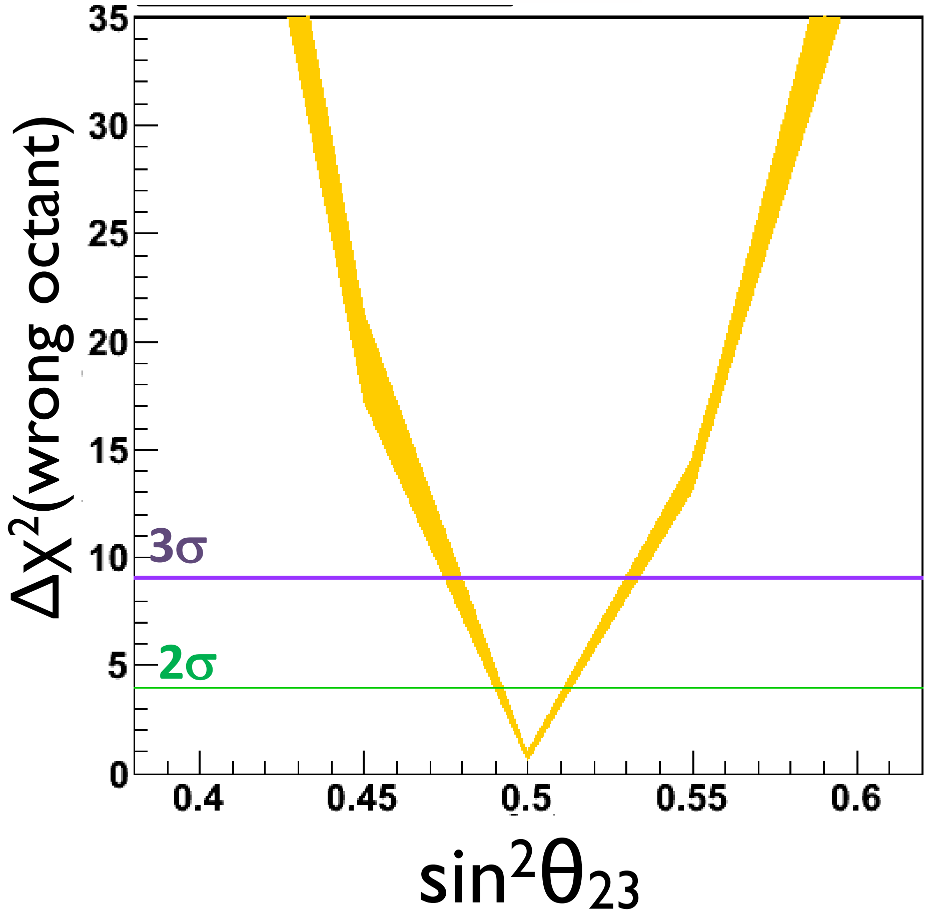
- Wide range of ν energy (0.1 GeV ~ 10^4 GeV and beyond)
- Wide range of ν baseline (10km downward ~ 13,000km upward)
- $\nu_\mu:\nu_e$ ~ 2:1 at production
- ν oscillation study by high statistical data (>40,000 events in Super-K) and all three flavors (ν_e, ν_μ, ν_τ)
- Unique tests of ν's exotic property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

Atmospheric ν

Mass hierarchy



θ23 octant



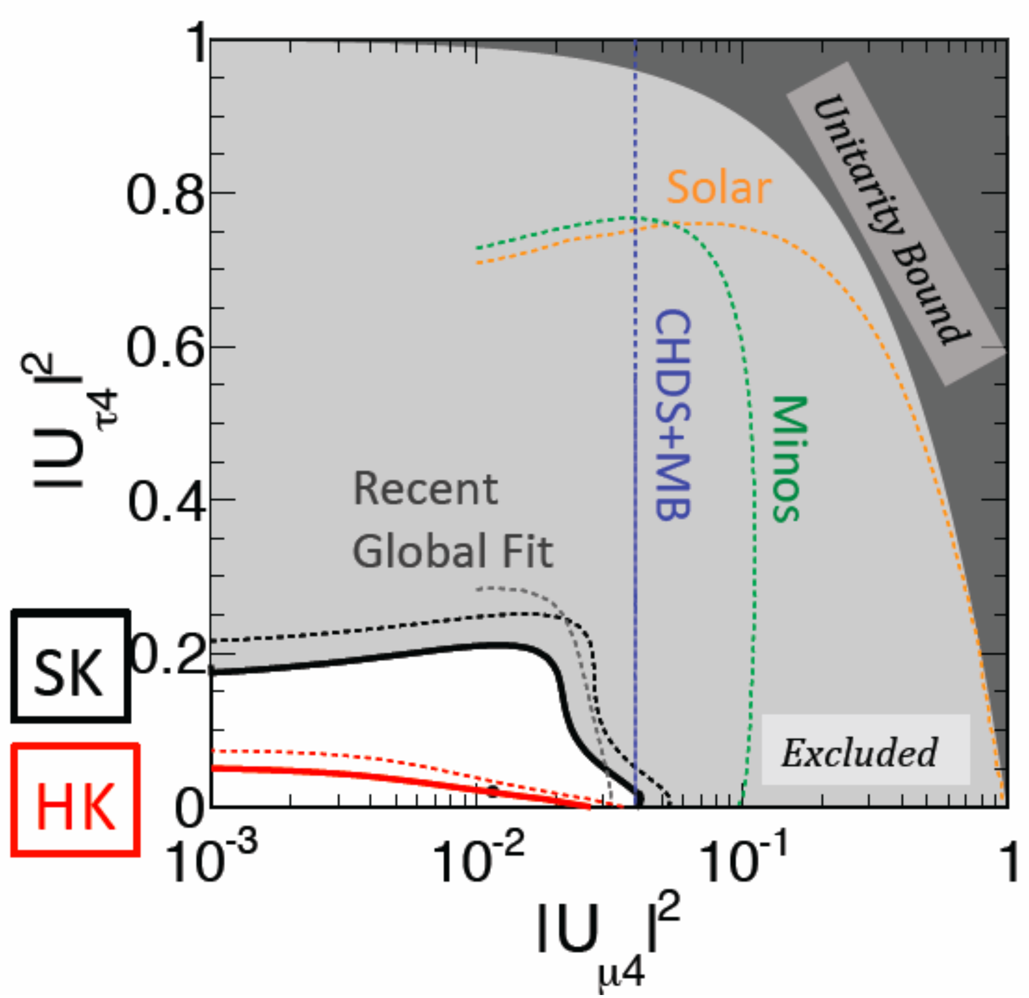
>3σ for allowed $\sin^2\theta_{23}$

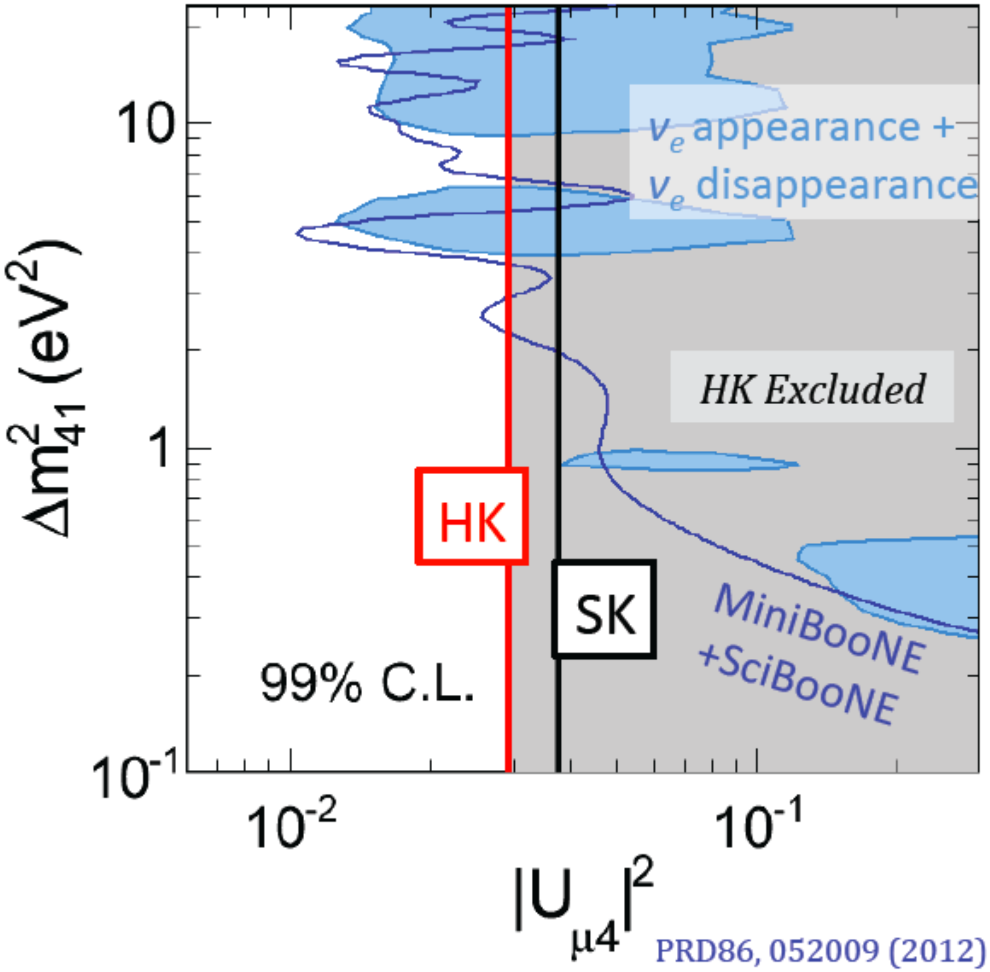
>3σ for $\sin^2\theta_{23}$<0.46or>0.56

Complementary measurements to accelerator ν
Combined analysis of acc + atm ν will enhance capability

Test of Sterile ν by atmospheric ν

Look for **extra overall muon deficit** or **shape distortion**



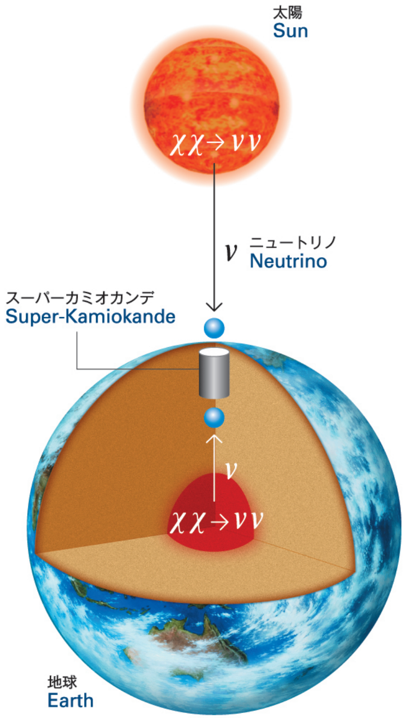


PRD86, 052009 (2012)
JHEP 1305 (2013) 050

$|U_{\tau 4}|^2 < 0.066$ @99%CL
(0.164 in Super-K)

$|U_{\mu 4}|^2 < 0.029$ @99%CL
(0.038 in Super-K)

Complementary to other experiments

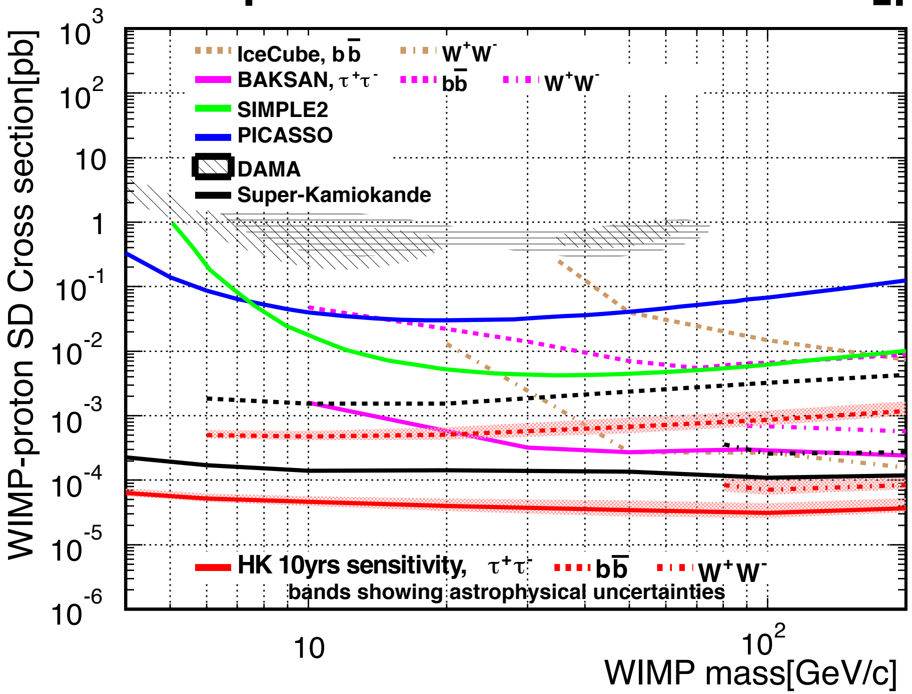


Search for ν's induced by dark matters

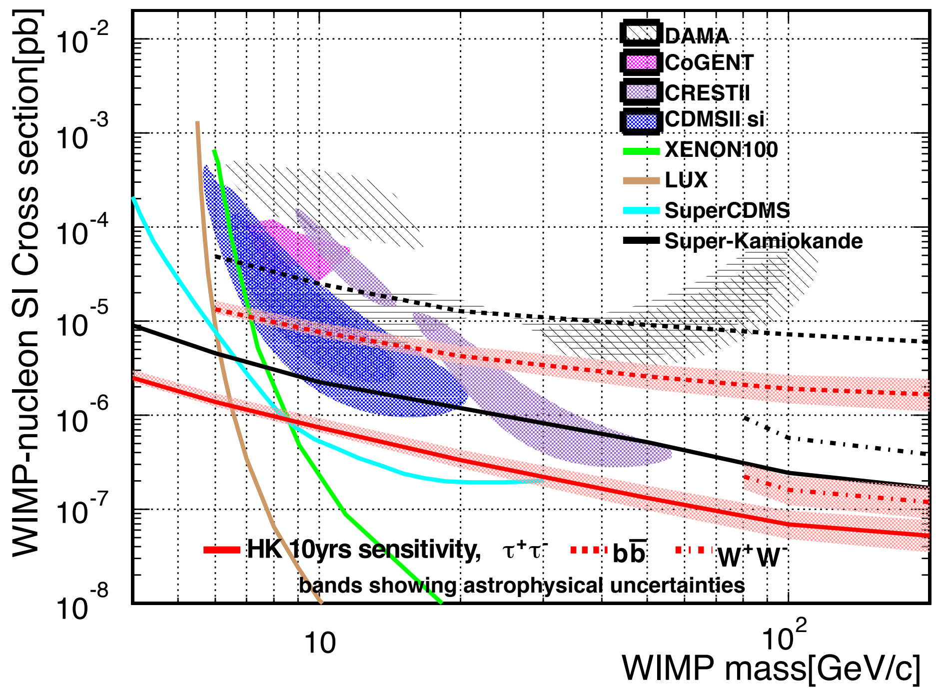
- provide complemental information w/ direct detection experiments
- Sensitive to low mass (GeV/c^2) WIMPs

Expected sensitivity for Solar WIMPs

WIMP-proton cross section[pb]



WIMP-nucleon cross section[pb]



Summary

- **Hyper-K would provide unique opportunities, many discovery potentials**
  - Proton decay searches w/ unprecedented sensitivities
    - **$p \to e^+\pi^0$; 1×10^{35} yrs (5×10^{34} yrs) with 90%(3σ) CL**
    - **$p \to \nu K^+$; 3×10^{34} yrs (1×10^{34} yrs)**
    - **and many other modes**
  - SN ν in our galaxy, nearby galaxies, and distant galaxies (relic SN ν)
    - promising **~300 diffuse ν / 10 yrs**
  - WIMP annihilation ν, tests of exotic scenarios ...
  - CPV (**76% of δ space at >3σ**), **δ precision of <20°, Mass hierarchy determination > 3σ** (Nakaya@this meeting)
  - w/ proven technology

- **Boost promoting the project**
  - Design Report to be submitted to KEK-IPNS/UTOKYO-ICRR in 2015
  - Open for new collaborators
  - Hyper-K EU meeting @ CERN on 27-28 April, 2015

Hyper-Kamiokande EU meeting@CERN 27-28 April 2015

- Meeting to discuss the European effort in Hyper-K
- Open to anyone who has interest in Hyper-K, or is planning to join Hyper-K, or is contributing
- http://indico.cern.ch/e/ThirdEUHyperK

Hyper-Kamiokande EU meeting

27-28 April 2015

CERN

Europe/Zurich timezone

- Overview
- Timetable
- Registration
- Participant List
- Accommodation

- Meeting to discuss the European effort in the Hyper-Kamiokande experiment.
- Open to anyone who has interests in Hyper-K, or is planning to join Hyper-K, or is contributing.
- Detailed information about your Country in Hyper-K can be discussed with your representatives in the Hyper-Kamiokande International Board Representatives, its chair if no representatives are available yet or the international Steering Committee chair.

Starts 27 Apr 2015 11:00
Ends 28 Apr 2015 18:00
Europe/Zurich

CERN
IT Amphitheatre