New detectors and laboratories Session:

Nucleon Decay Searches

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Topics in Astroparticle and Underground Physics
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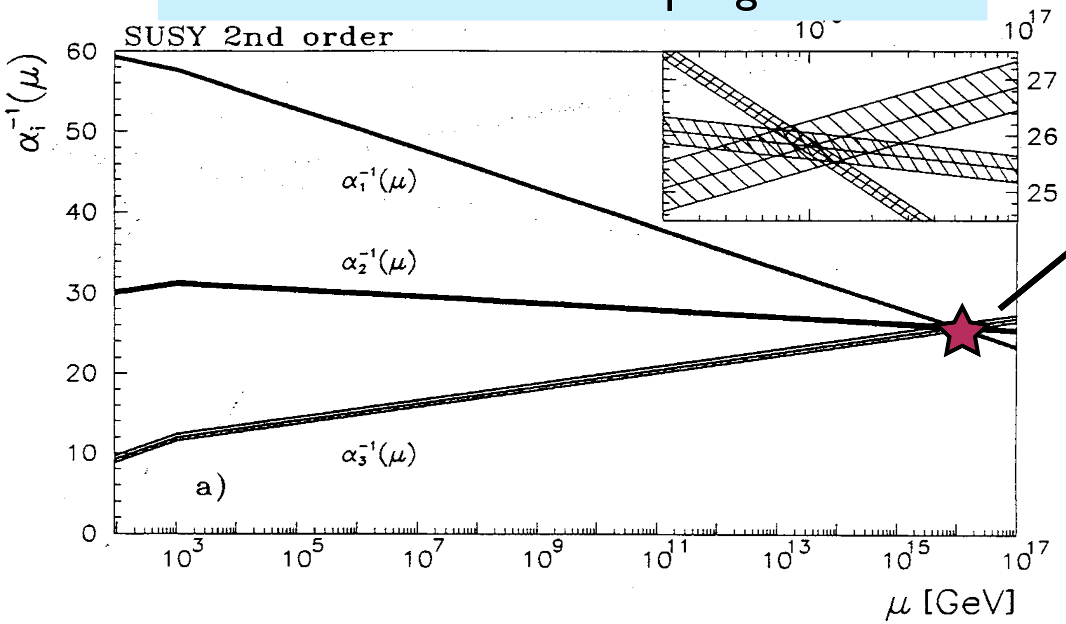
Motivation of Nucleon Decay Searches

Unification of three coupling constants



Grand Unification?

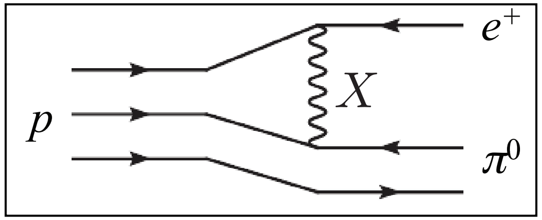
Unification of Forces and Particles
$G \supset SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
(Quark, Lepton) multiplets

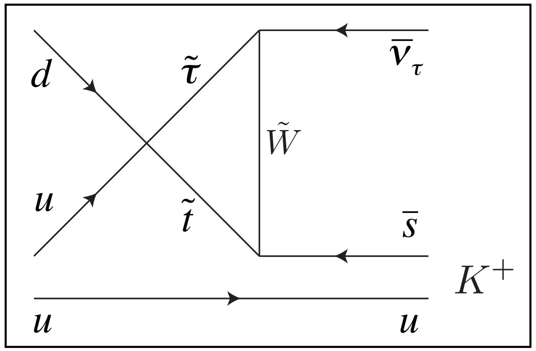
↓

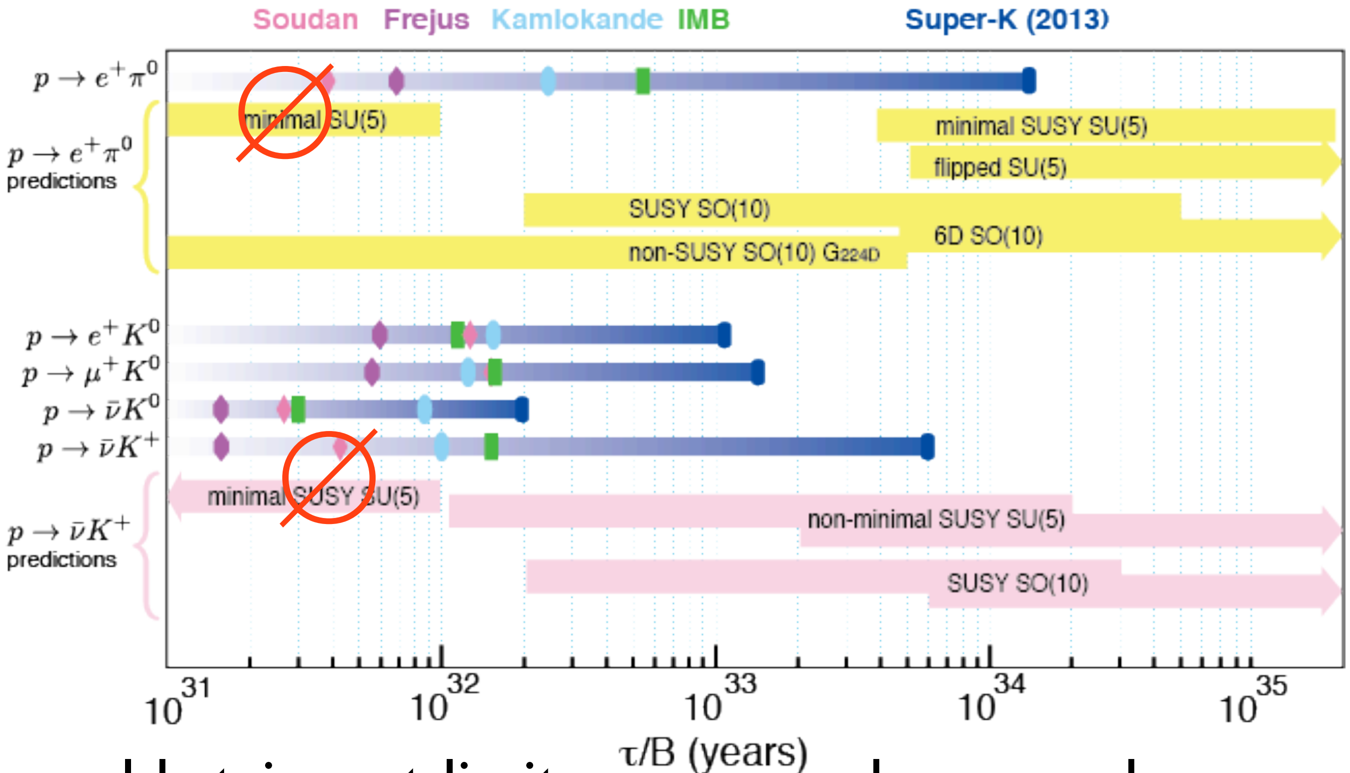
Prediction *Spontaneous Nucleon Decay*

- **Tiny ν masses** suggest physics with similar energy scale
- Understand **large ν mixing** and small quark mixing in an unified way
- **Unique direct test of GUTs**
  - Nucleon decay searches have already provided **constraints on GUT models**
  - $O(10^{16})$GeV is not **reachable by accelerators**
- **Baryon number violation** is required by cosmology
- B (and L) is an **unexplained conserved quantum number**

Upper bounds on the decay rates



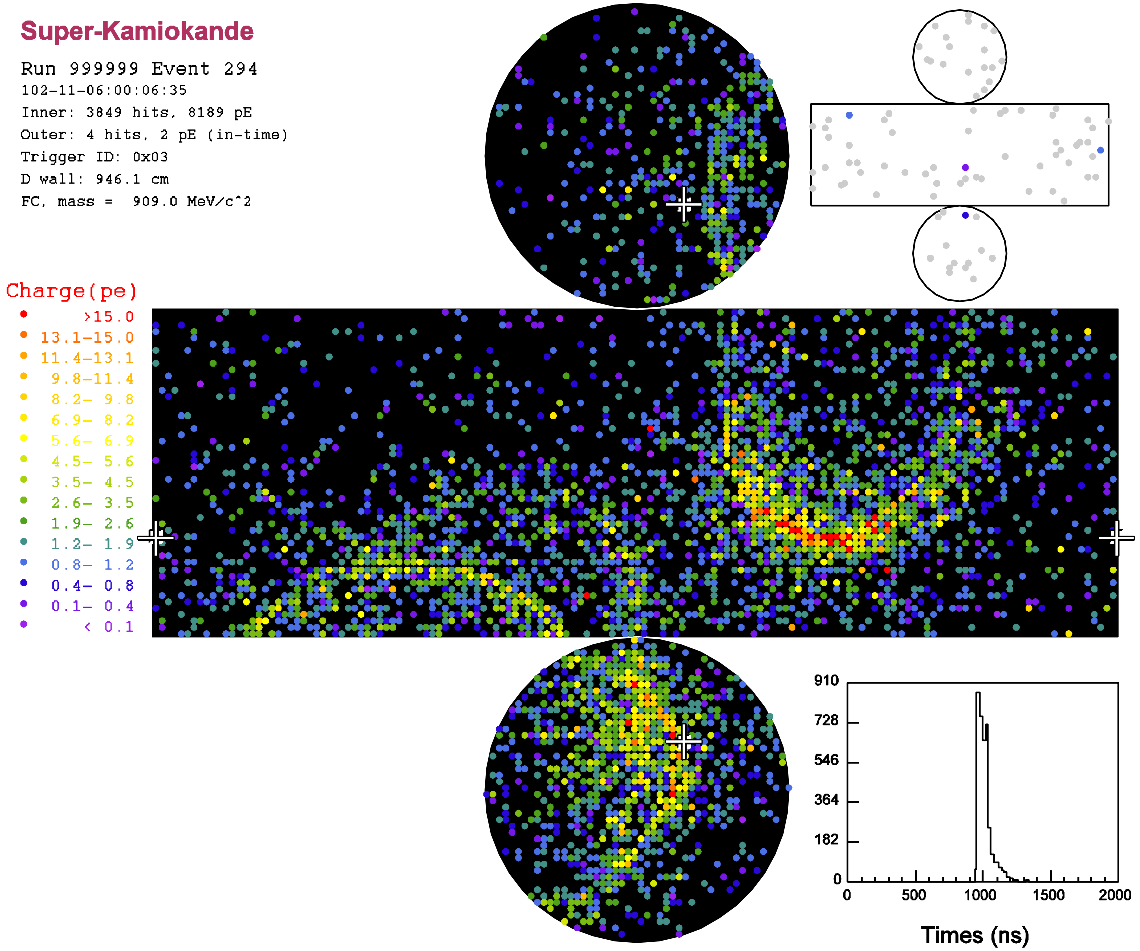




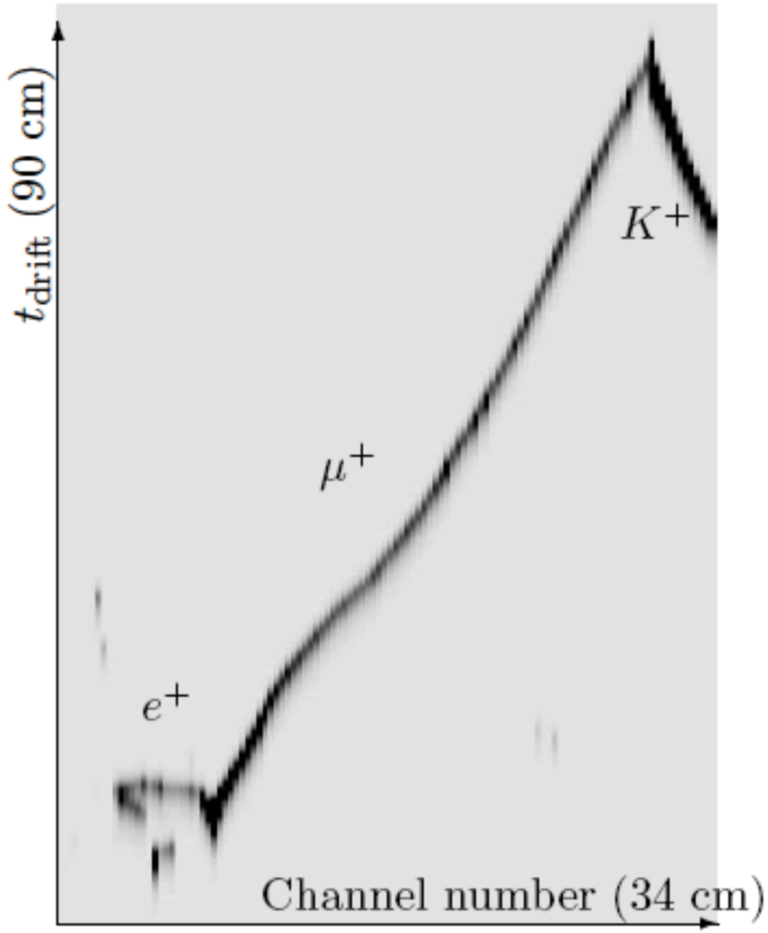
- Super-K provides world stringent limits on many decay modes
  - $\tau(p \to e^+\pi^0) > 1.4\times10^{34}$ years (90%C.L., 260kton・years)
  - $\tau(p \to \nu K^+) > 5.9\times10^{33}$ years (90%C.L., 260kton・years)
- No significant signal excess so far ➡ Giving constraints on GUT models
  - Constraints on SUSY models (e.g. R-parity conservation)
  - minimal *SU(5) and* minimal SUSY *SU(5) are considered to be excluded.*

discovery might be around the corner

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



$p \rightarrow \nu + K^{+}$ in Liq.Argon TPC



Single event discovery is possible for several decay modes.

Experimental challenges

$$\text{lifetime limit} \propto \frac{\varepsilon VT}{N_{limit}} = \begin{cases} \frac{\varepsilon}{2.3} \times VT & \text{(BKG free)} \\ \frac{\varepsilon VT}{\sqrt{BVT}} = \frac{\varepsilon}{\sqrt{B}} \times \sqrt{VT} & \text{(BKG dominant)} \end{cases}$$

ε: efficiency
V: detector volume
T: data daking time (exposure)
Nlimit: limit on the number of signal

- Require big detector "**MASS**"
  - Next target volume is **10kiloton~1Megaton** (Super-K=50kiloton)
- **Background rate must be under control**
  - **Improved BG rejection** is required as size of detectors and exposure scale up (Super-K, next generation detectors)
  - Keep **signal efficiency high**
  - **Improved knowledge of BG** is required to extract convincing signal

- This talk will cover;
  - Super-K with efforts to improve searches
  - Next generation experiments to go beyond the Super-K

Super-Kamioka Nucleon Decay Experiment

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13

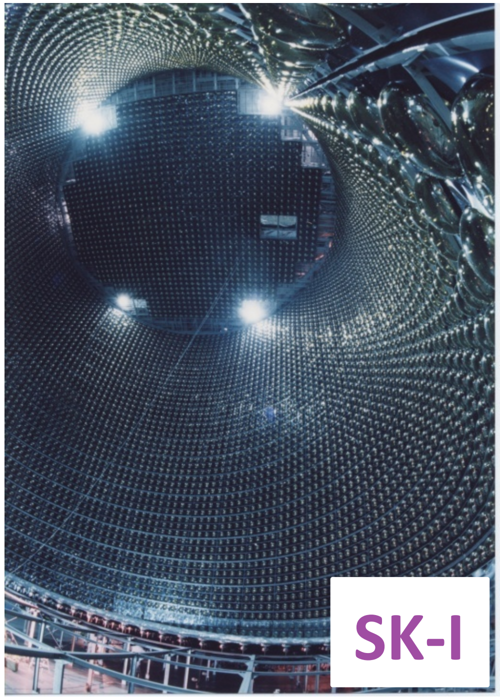
phase-I
4.1years
91.7ktyr

phase-II
2.2years
49.2ktyr

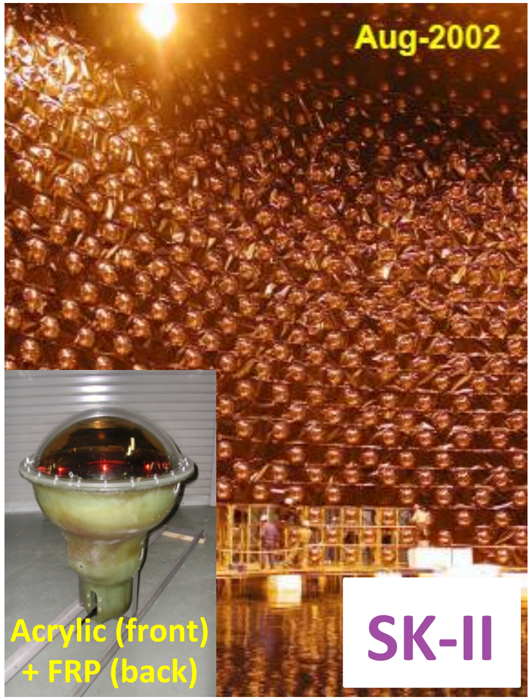
phase-III
1.4years
31.9ktyr

phase-IV
3.9years
87.3ktyr

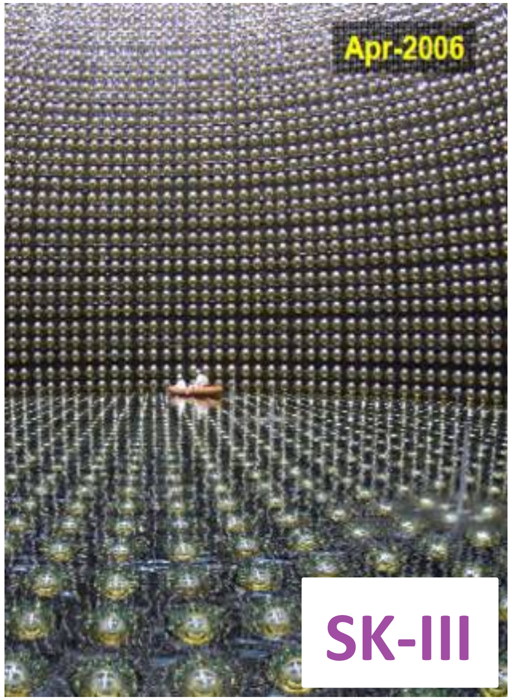
Super-K total ~12years or 260 ktyr



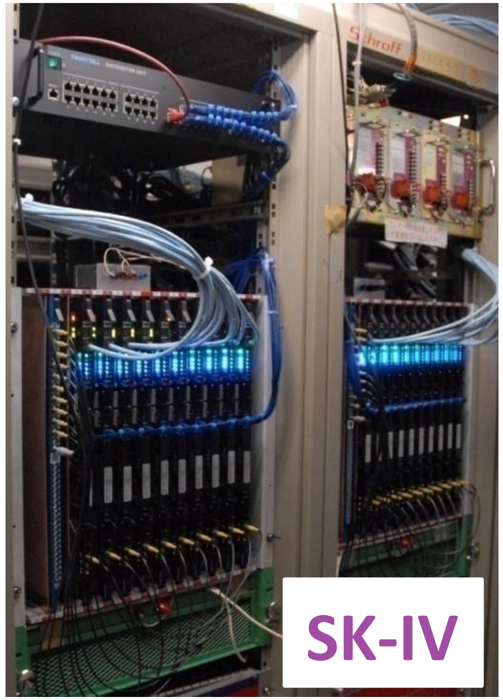
11,146 ID PMTs
(40% coverage)



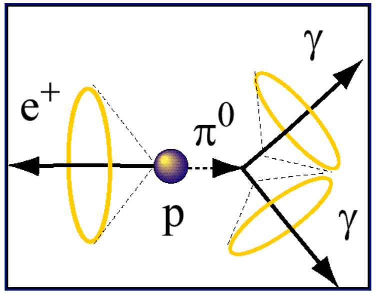
5,182 ID PMTs
(19% coverage)



11,129 ID PMTs
(40% coverage)



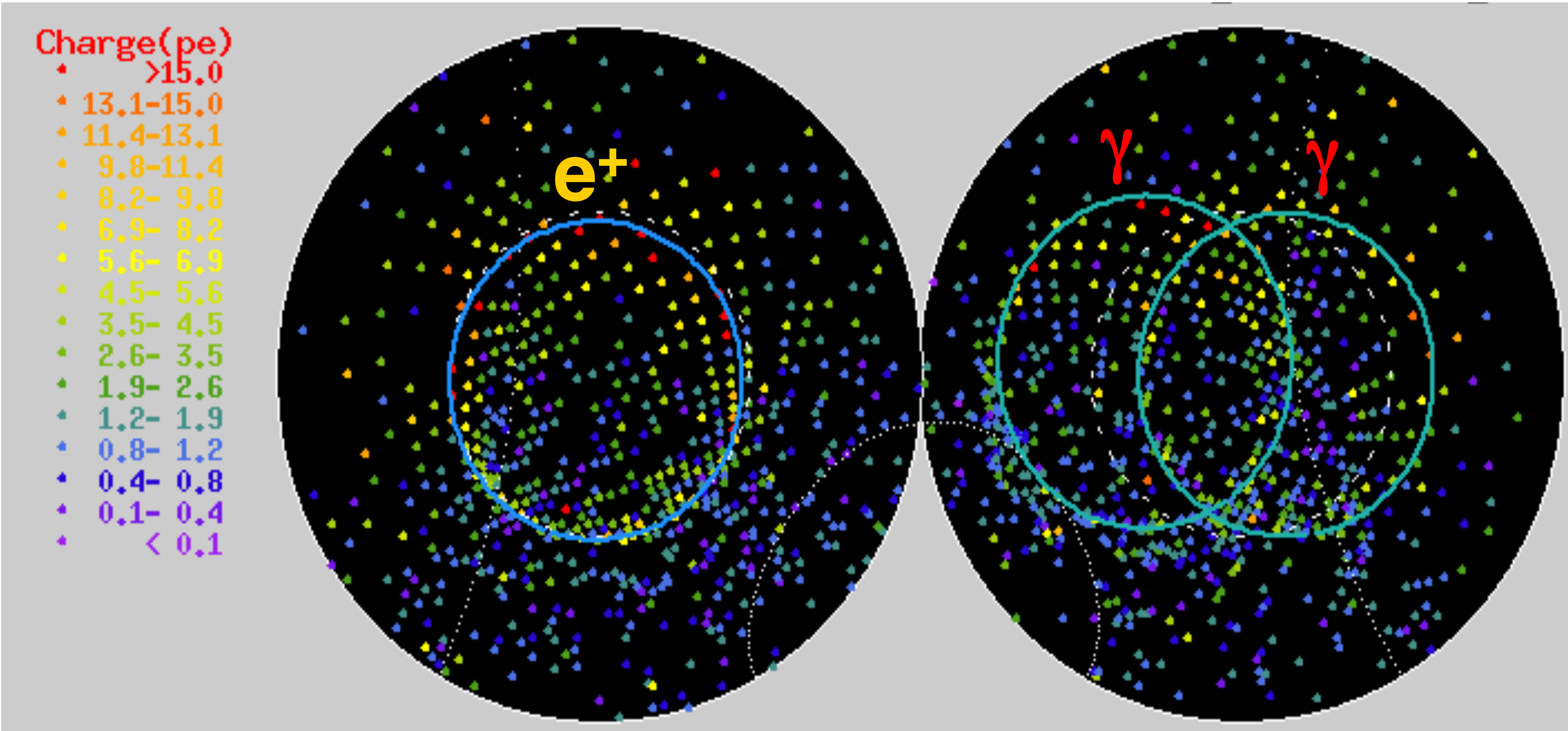
Electronics
Upgrade



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

Super-K cut

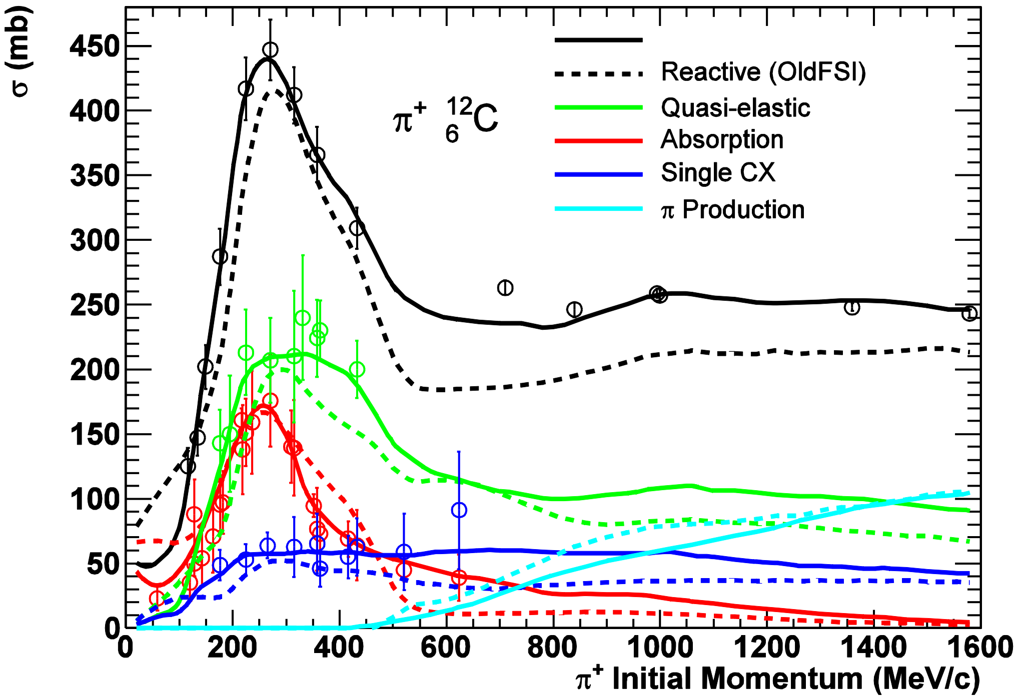
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050\ MeV/c^2$
  $P_{total} < 250\ MeV/c$



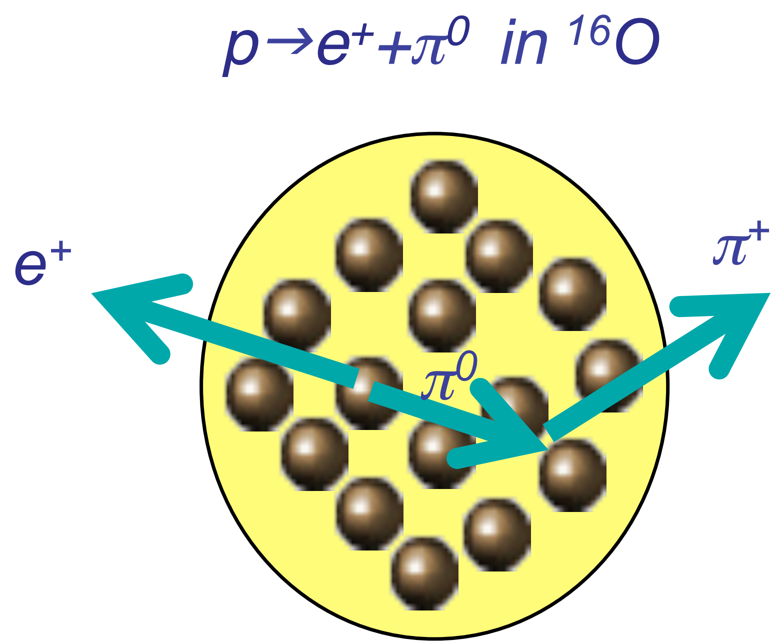
SK-II (half PMT) forward-backward display for $p \rightarrow e^{+} + \pi^{0}$

Nuclear effect

- For proton decays in ^{16}O nuclei
  - nuclear binding energy, Fermi momentum, nucleon-nucleon correlation, secondary interactions of decay mesons



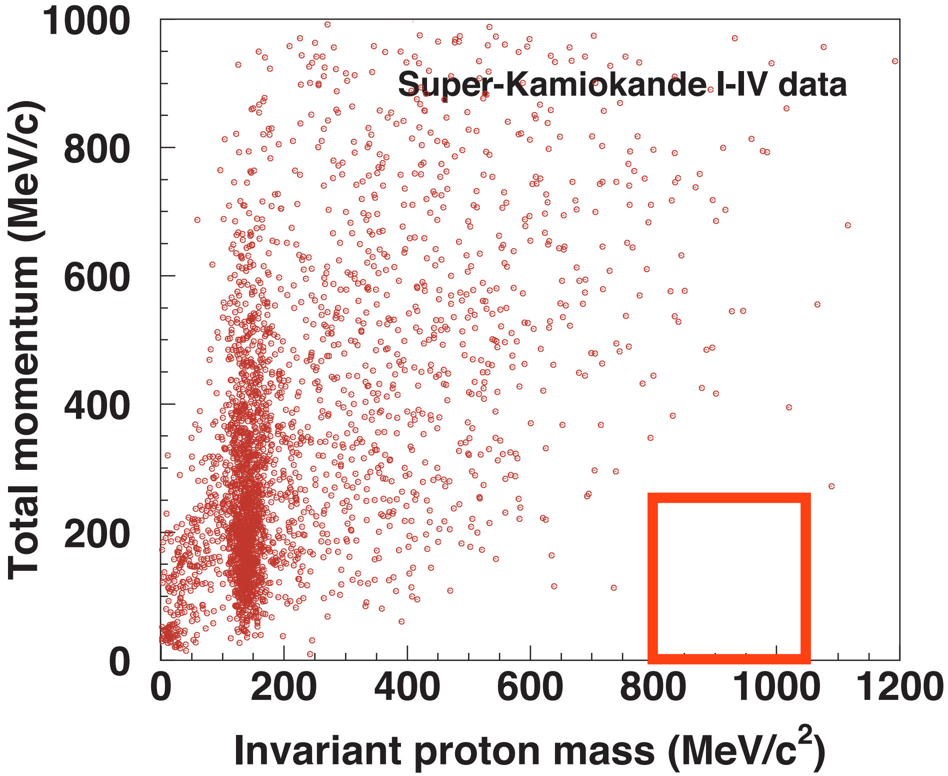
Tuning of π cross sections in Carbon.

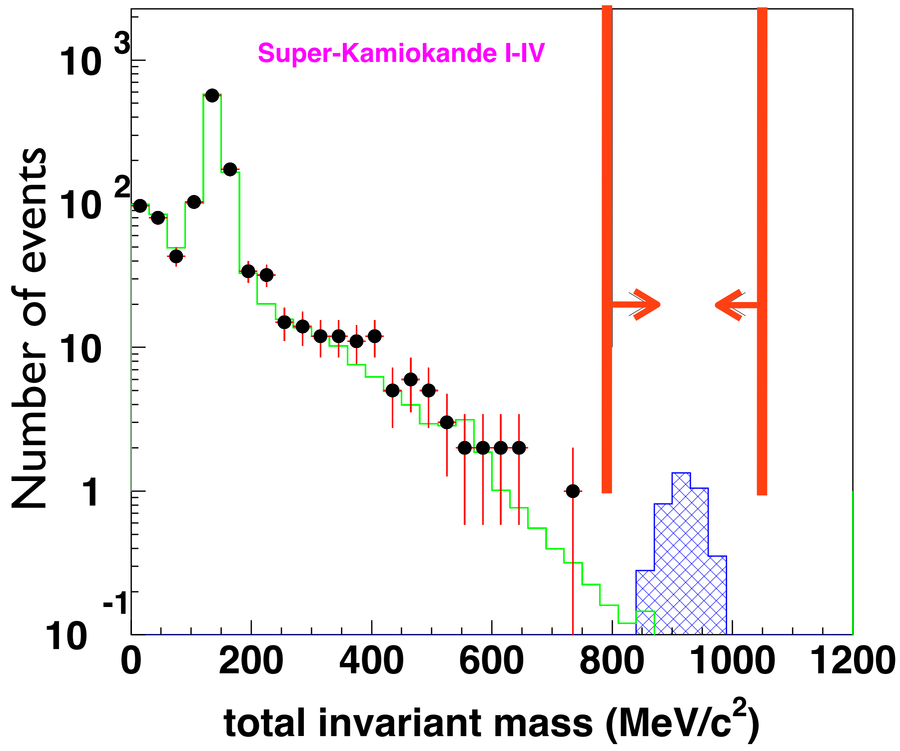


~40% π^0 escape w/o interactions
→major source of inefficiency and systematics

- For free proton decays in hydrogen
  - NO nuclear effects
  - high & accurate signal efficiency is expected
    e.g. 87% (28%) efficiencies for $p \rightarrow e^+ + \pi^0$ decays in H (^{16}O)

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





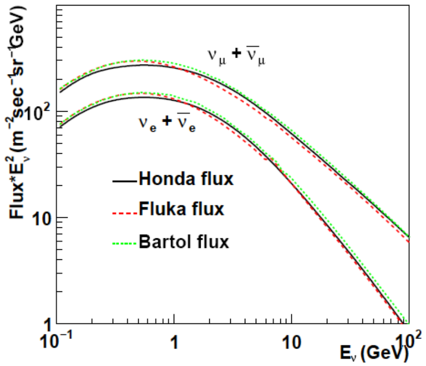
$p \rightarrow e^+ + \pi^0$

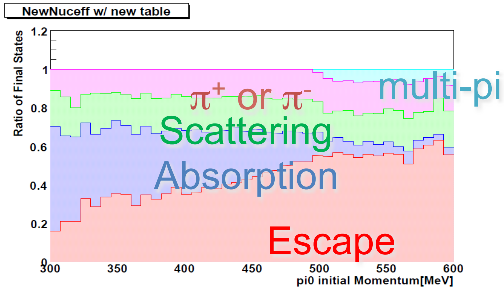
- detection efficiency = 40%
- atmospheric ν BG = 0.7 events in 260kton×years
  2.7±0.3(stat.)±1.2(syst.) (Mton×years)$^{-1}$
- τ_{proton}/Br > 1.4 ×10^{34} years @ 90%C.L.

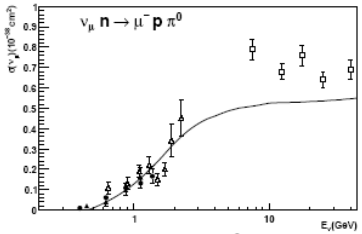
NOTE: Accurate prediction of BG is getting more important.
Further BG reduction is also desired.

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

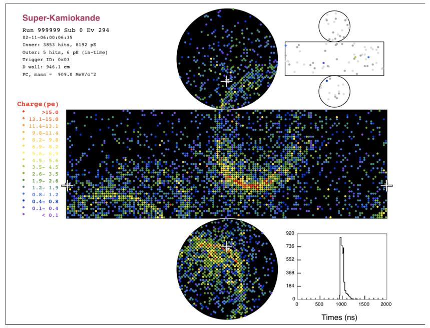
- BG calculation based on atmν flux, cross sections, and detector response







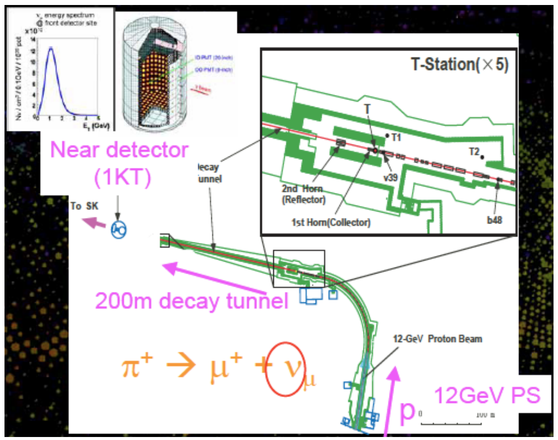
(c) $\nu_\mu n \rightarrow \mu^- p \pi^0$



• Atmospheric ν flux calculations	
– Spectrum shape	~8%
– Flavor ratio	<1%
• Neutrino interaction simulation (NEUT)	
– CC single π^0	10%
– CC multi pion production	7%
– CC QE	8%
– NC	2%
• 2ndary pion interaction in water	25%
• 2ndary nucleon interaction in water	25%
• Detector resolution	22%

Total uncertainty 44%

- Confirmation by K2K accelerator ν



PRD77:032003,2008

- BG rate was confirmed by K2K accelerator ν beam
  - BG=1.63+0.42/-0.33(stat.)+0.45/-0.51(syst.) (Mt×yrs)$^{-1}$ (Eν<3GeV)
  - Consistent w/ simulation 1.8±0.3(stat.)

- Further improvements are foreseen by future cross section measurements

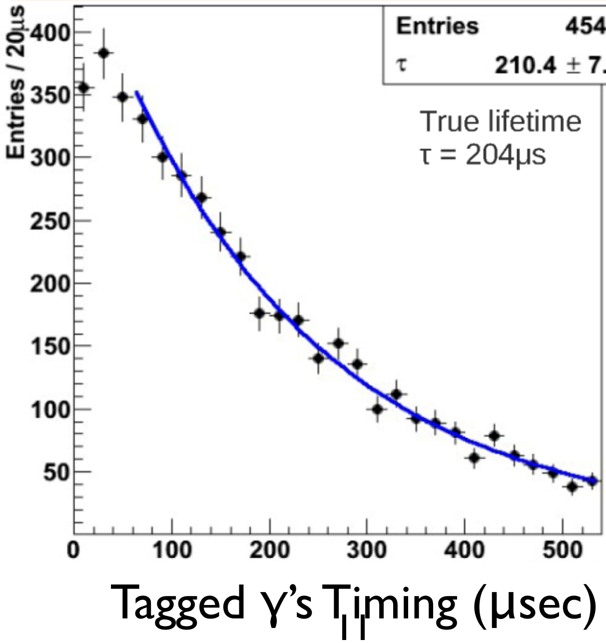
Potential BG reduction by neutrons

Beacom and Vagins PRL93:171101(2004)

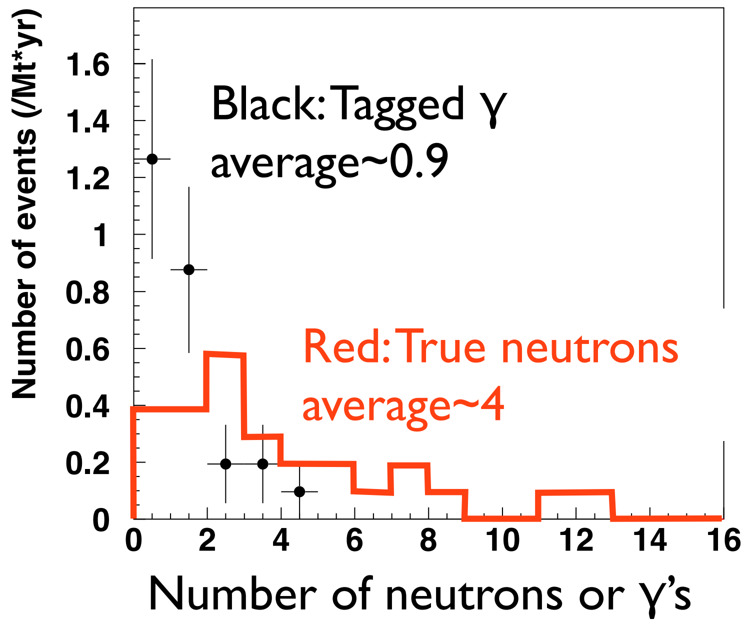
- We expect that neutrino events are often accompanied with neutrons (e.g. $\bar{\nu}_e+p\rightarrow e^++\pi^0+n$, recoiled protons kick neutrons in water etc.)
- neutron emission probability in proton decay is expected to be small.

Since SK-IV we have started recording faint signature of neutrons;
$n+p\rightarrow d+\gamma$(2.2MeV, τ~200μsec)
by new high speed pipelined electronics. Gd study is on-going.

SK-IV 1297days atmν Data



$p\rightarrow e^+\pi^0$ BG Monte Carlo



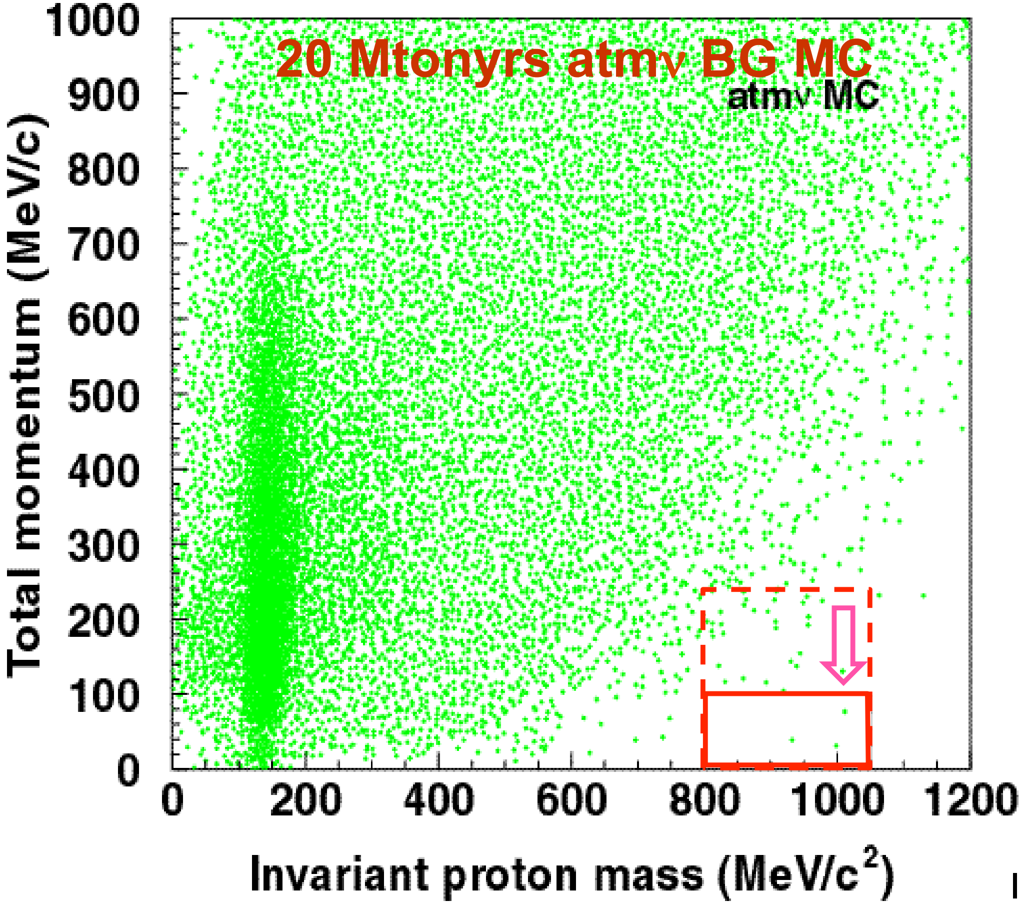
Potential BG reduction by tighter cut

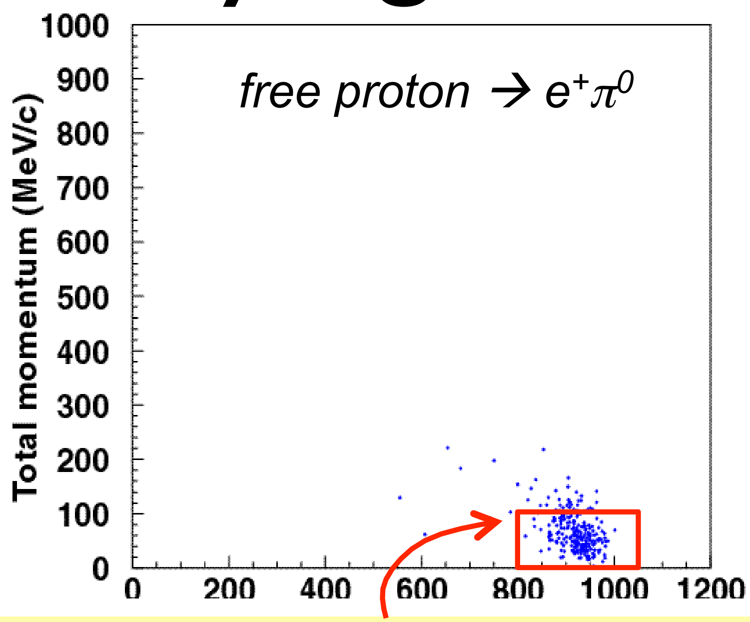
Shiozawa, talk@NNN00-Fermilab

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

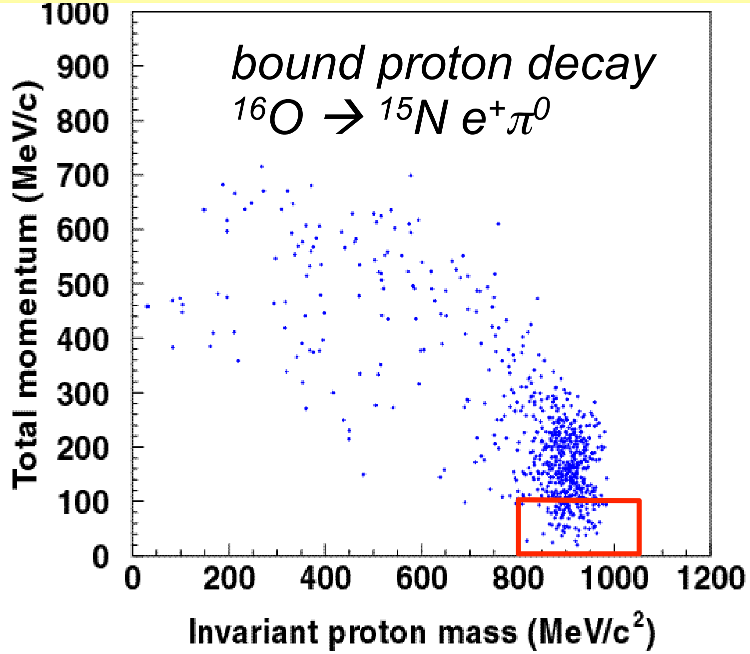
  ⇩ *BG reduction by ~15*

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



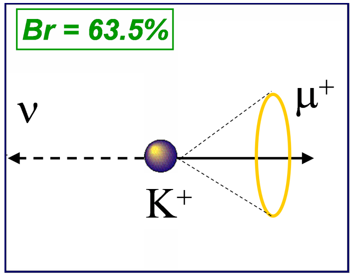


main target is *free proton decays*

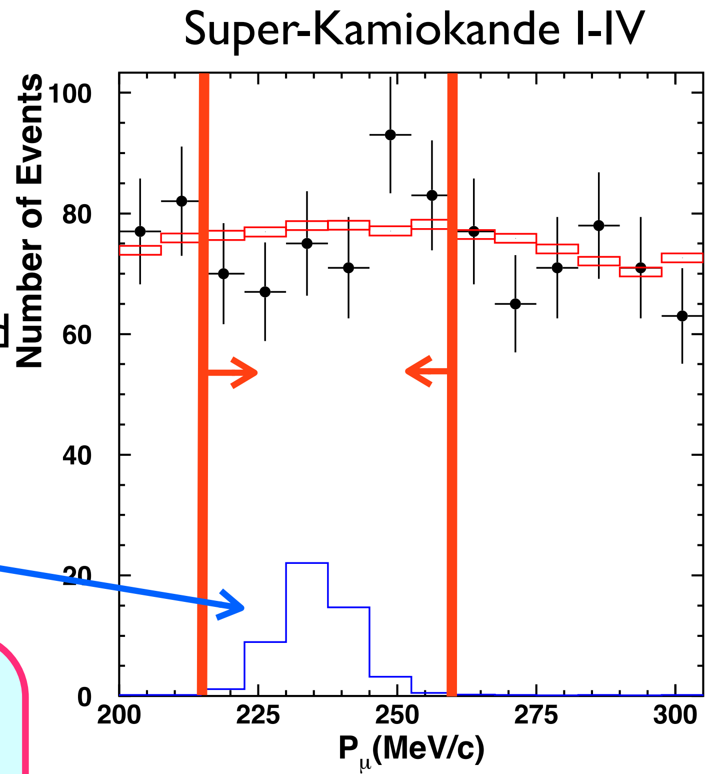


$p \rightarrow \nu + K^+$ searches

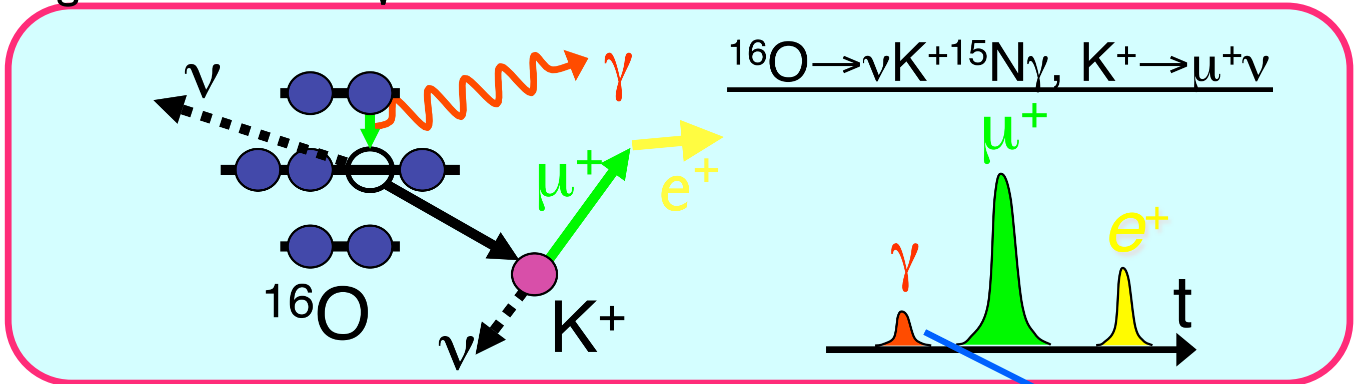
(I) $K^+ \rightarrow \mu^+\nu$, $\mu^+ \rightarrow e^+\nu\nu$

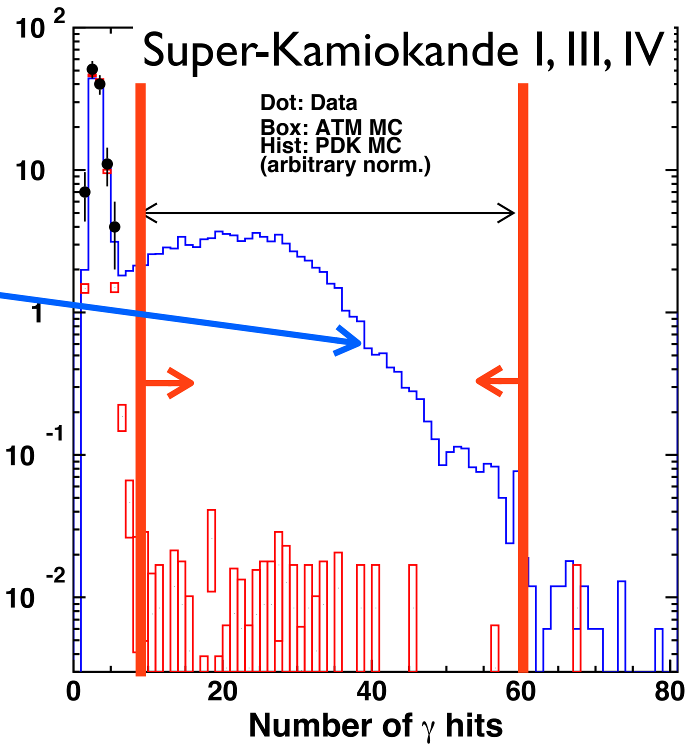


K^+ is below Cherenkov threshold
→ 236MeV/c μ and muon decay electrons



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



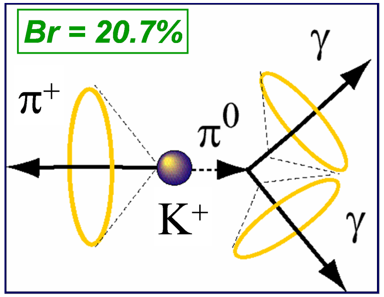


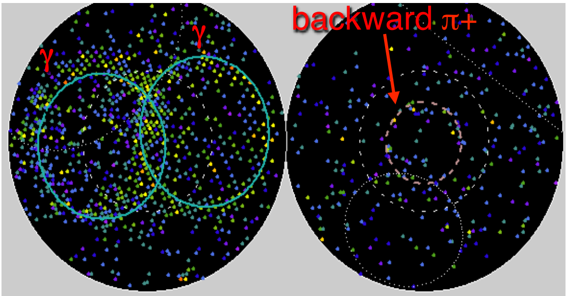
Many efforts to improve analyses

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





- 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 -

	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

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

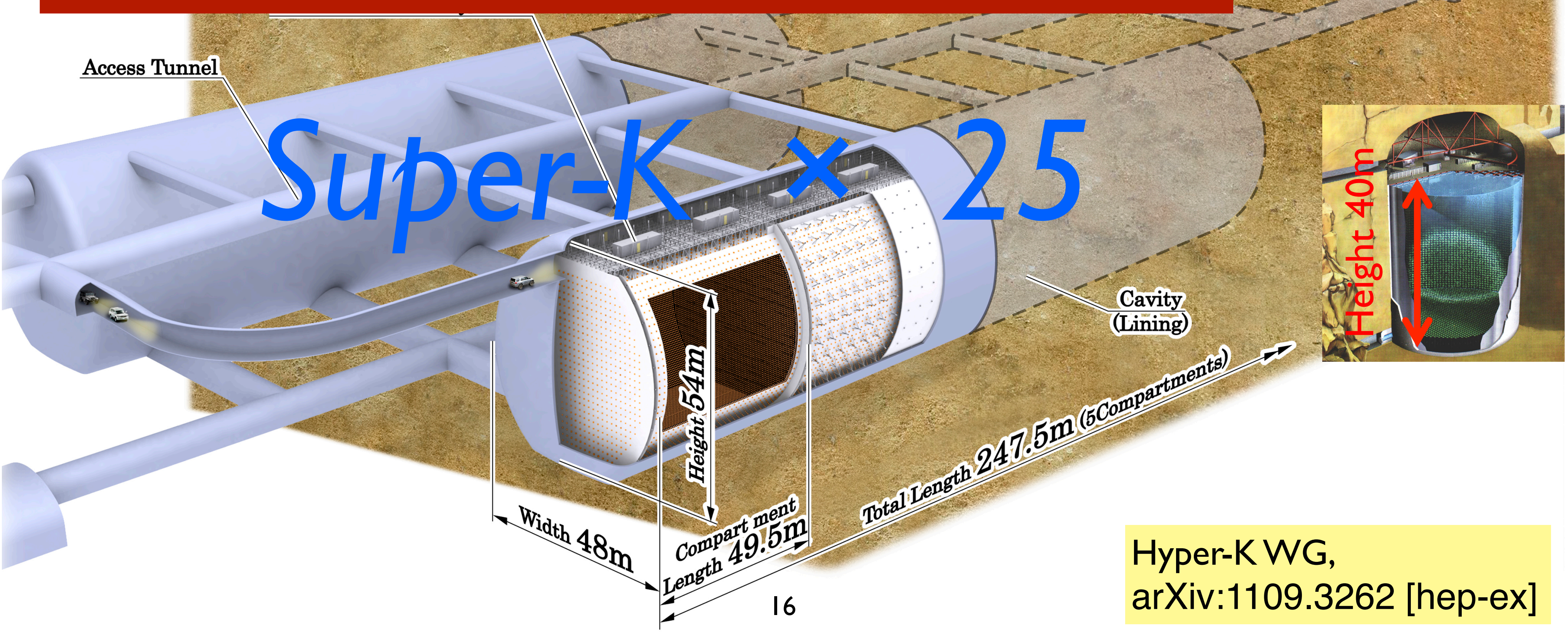
Summary of Super-K

- $p \rightarrow e^+ + \pi^0$ reached to 10^{34} years
- $(p,n) \rightarrow (e^+,\mu^+) + (\pi,\eta,\rho,\omega)$ $10^{32} \sim 10^{33}$ years
- SUSY favored $p \rightarrow \nu K^+ > 5.9 \times 10^{33}$ years
- No excess in K^0_S, K^0_L, $\nu\pi^0$, $\nu\pi^+$
- It is important to 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
  - neutron-antineutron oscillations
  - radiative decays $p \rightarrow (e^+,\mu^+) + \gamma$
  - invisible decays $p \rightarrow \nu\nu\nu$

No nucleon decay evidence so far.
Sensitivity(limit) improvement of Super-K is now moderate.

Gigantic Water Cherenkov Detector: Hyper-Kamiokande

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Photo-sensors	99,000 20”Φ PMTs for Inner Det.
	(20% photo-coverage)
	25,000 8”Φ PMTs for Outer Det.

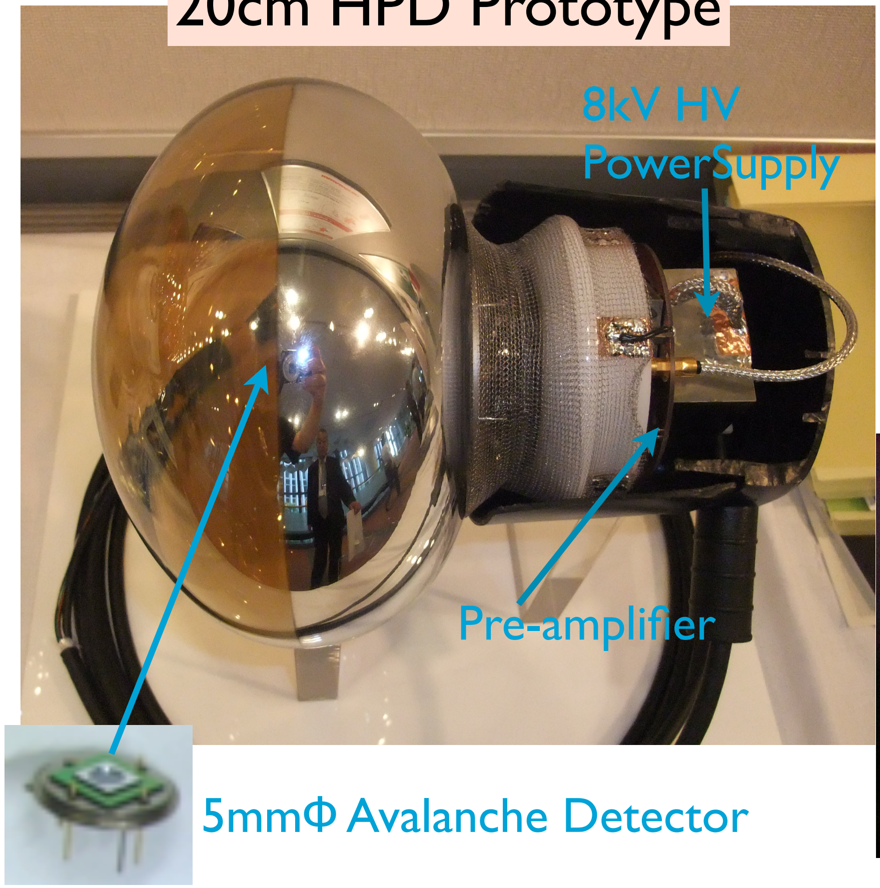


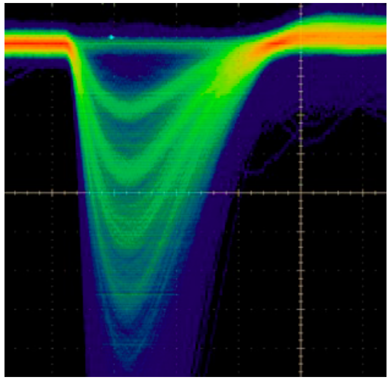
Hyper-K WG, arXiv:1109.3262 [hep-ex]

Photo-detector R&D

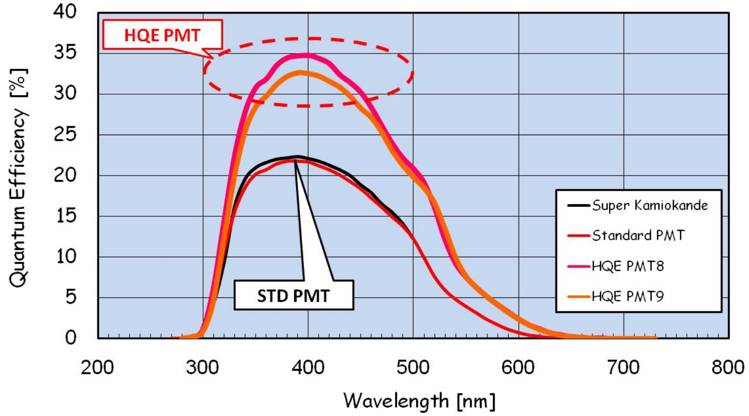
- Candidates
  - 50cm Super-K PMT
  - [NEW] High QE 50cmΦ Hybrid Photo Detector (HPD)
  - [NEW] High QE re-designed 50cm PMT
- Test of 20cm HPD and 50cm HQE PMT in water tank from August 2013
- 50cm HPD prototype expected in August 2013

20cm HPD Prototype



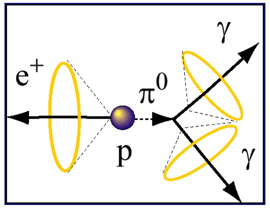


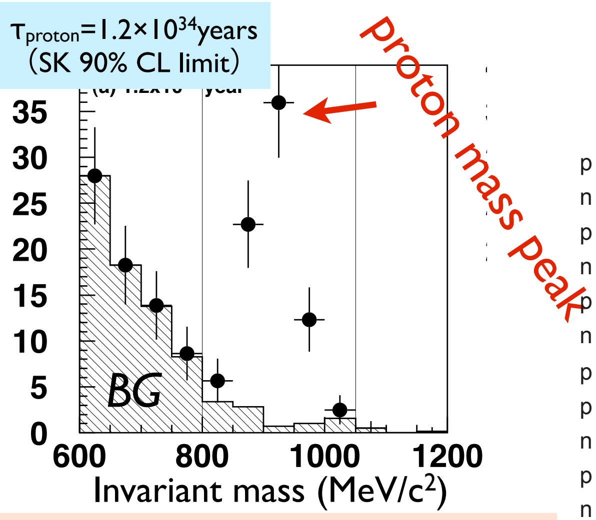
High Quantum Efficiency



GUT tests by Nucleon Decay Searches

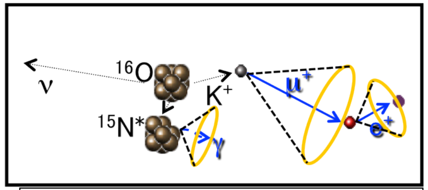
$p \rightarrow e^+\pi^0$

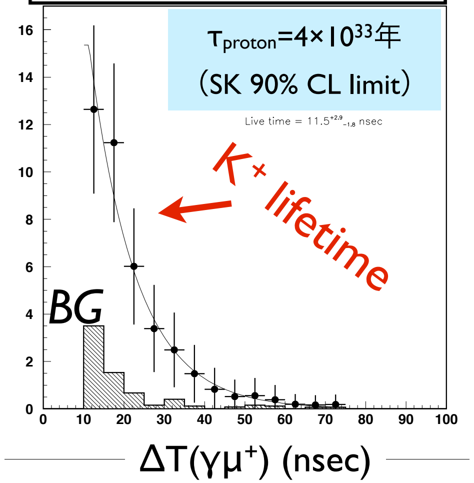




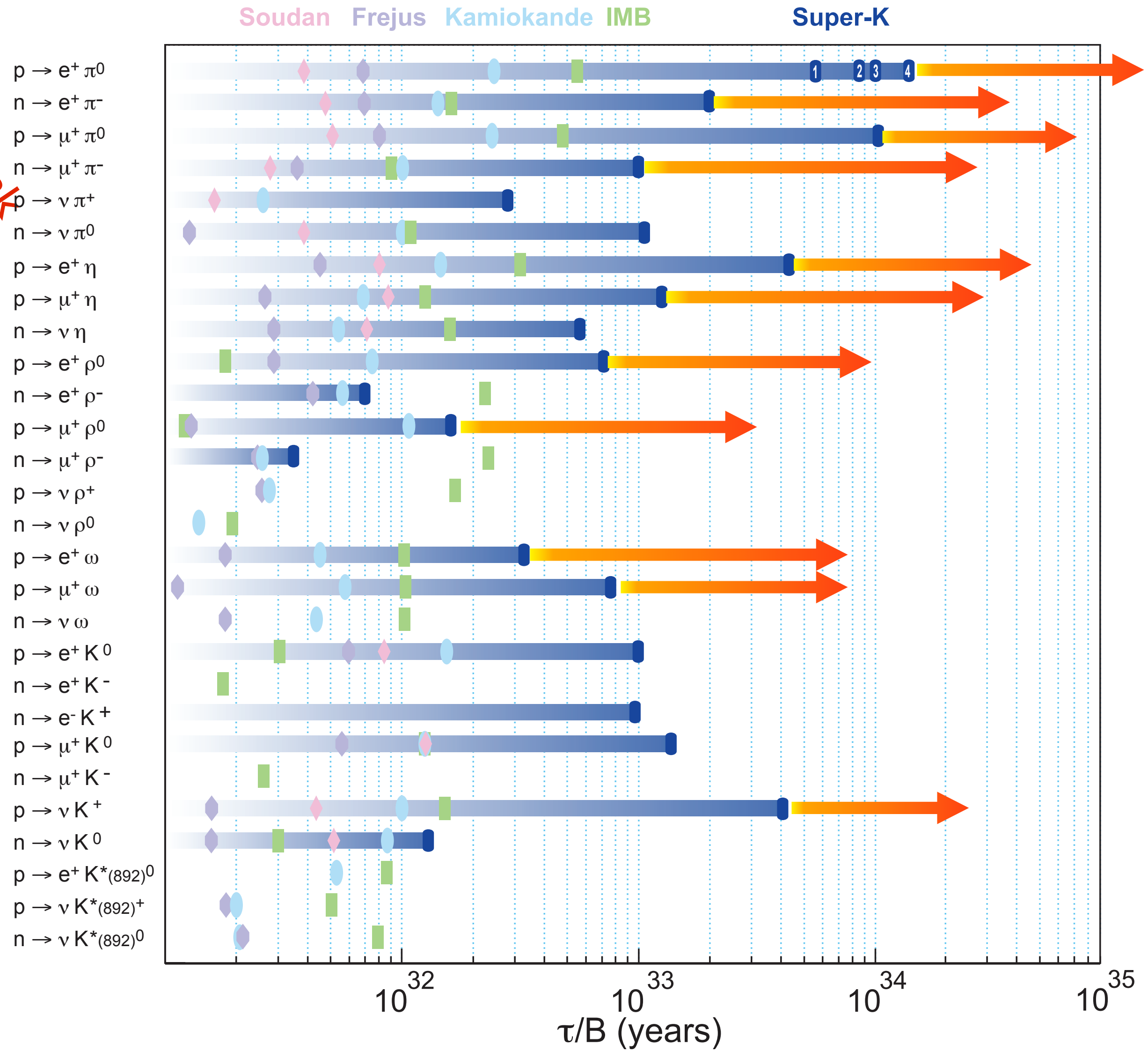
- Discovery reach (3σ) $\tau(p\rightarrow e^+\pi^0)\sim 5.4\times 10^{34}$years (HK 10years)
- Limit (90%CL) $\tau(p\rightarrow e^+\pi^0) > 1.3\times 10^{35}$years (HK 10years)

$p \rightarrow \nu K^+$





- Discovery reach (3σ) $\tau(p\rightarrow \nu K^+)\sim 1.2\times 10^{34}$years (HK 10years)
- Limit (90%CL) $\tau(p\rightarrow \nu K^+) > 3.2\times 10^{34}$years (HK 10years)

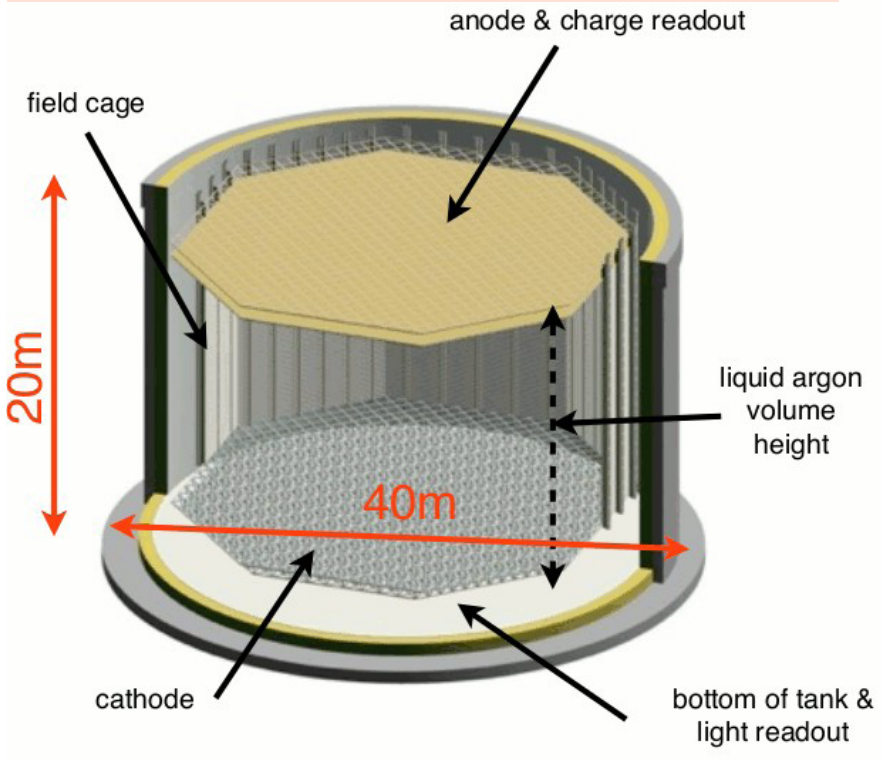


Hyper-K's reaches are $10^{34}\sim 10^{35}$ yrs

Large Liq. Argon TPC detector: LBNO(GLACIER) and LBNE

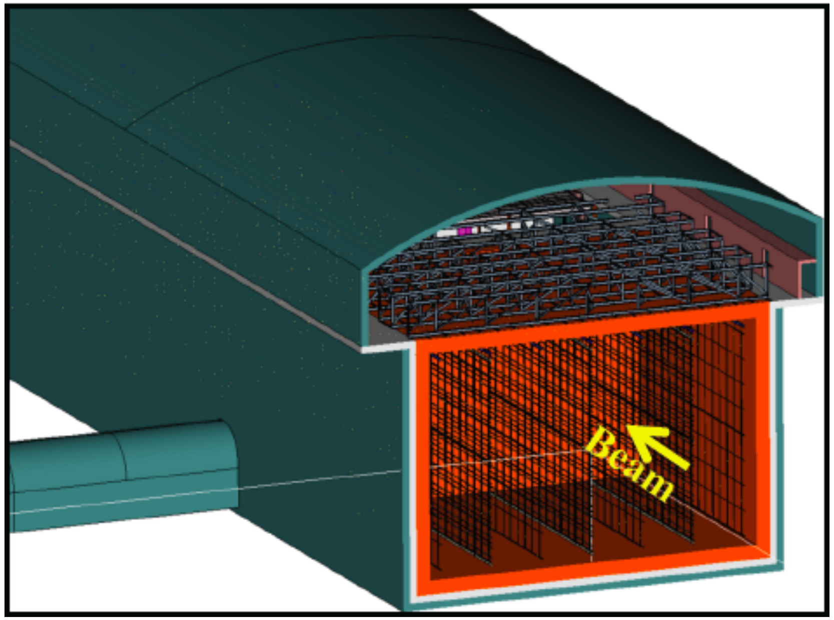
LBNO

Stage 1: >20kt Liq.Ar (+Liq. scintillator?) underground (1,500m)
Stage 2: → 100kt



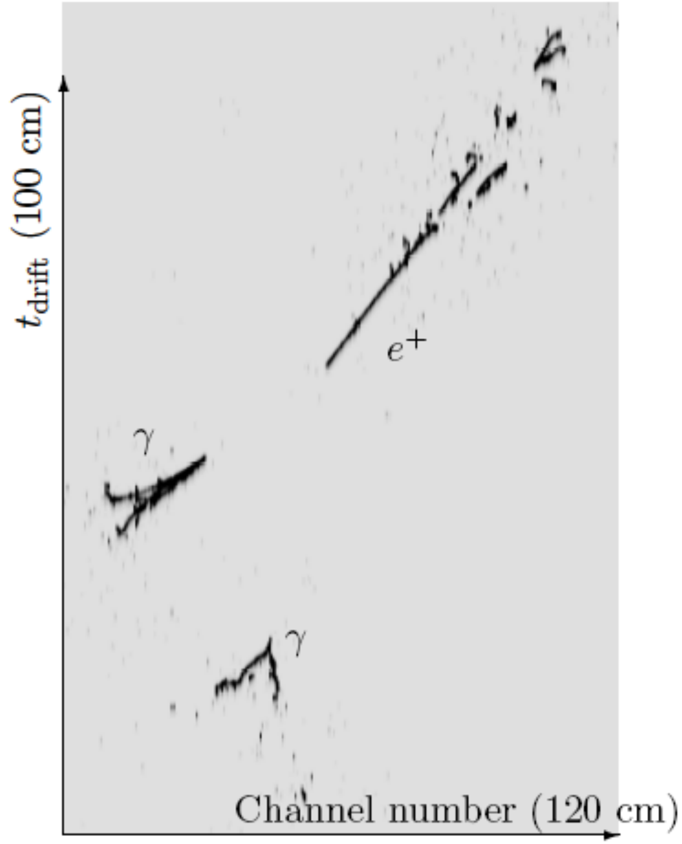
LBNE

Stage 1: 17kton Liq.Ar TPC surface (please go to underground for proton decays)
Stage 2: Additional 20-30kt

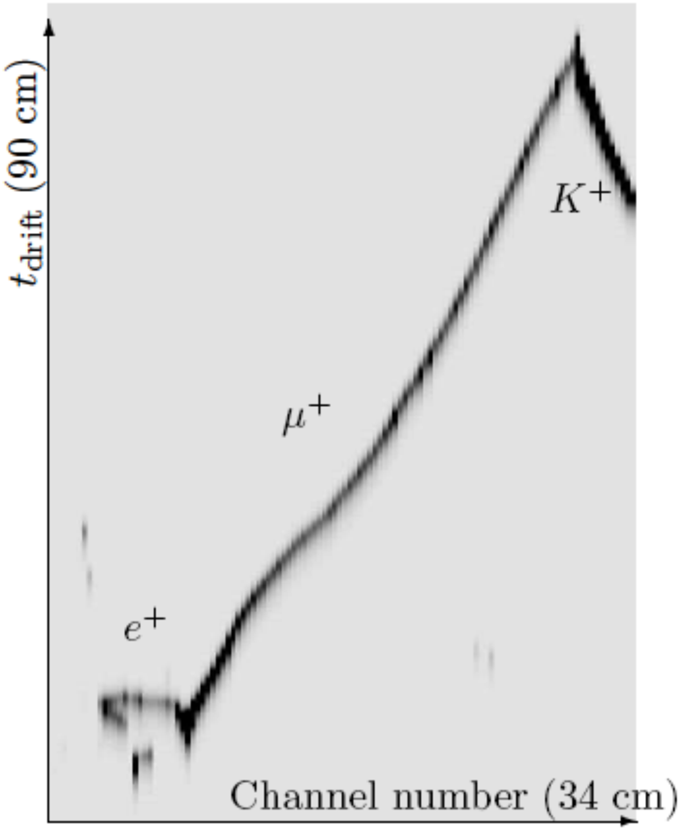


Large Liq. Argon TPC detector

- high granularity
- high tracking capability
- good E resolution



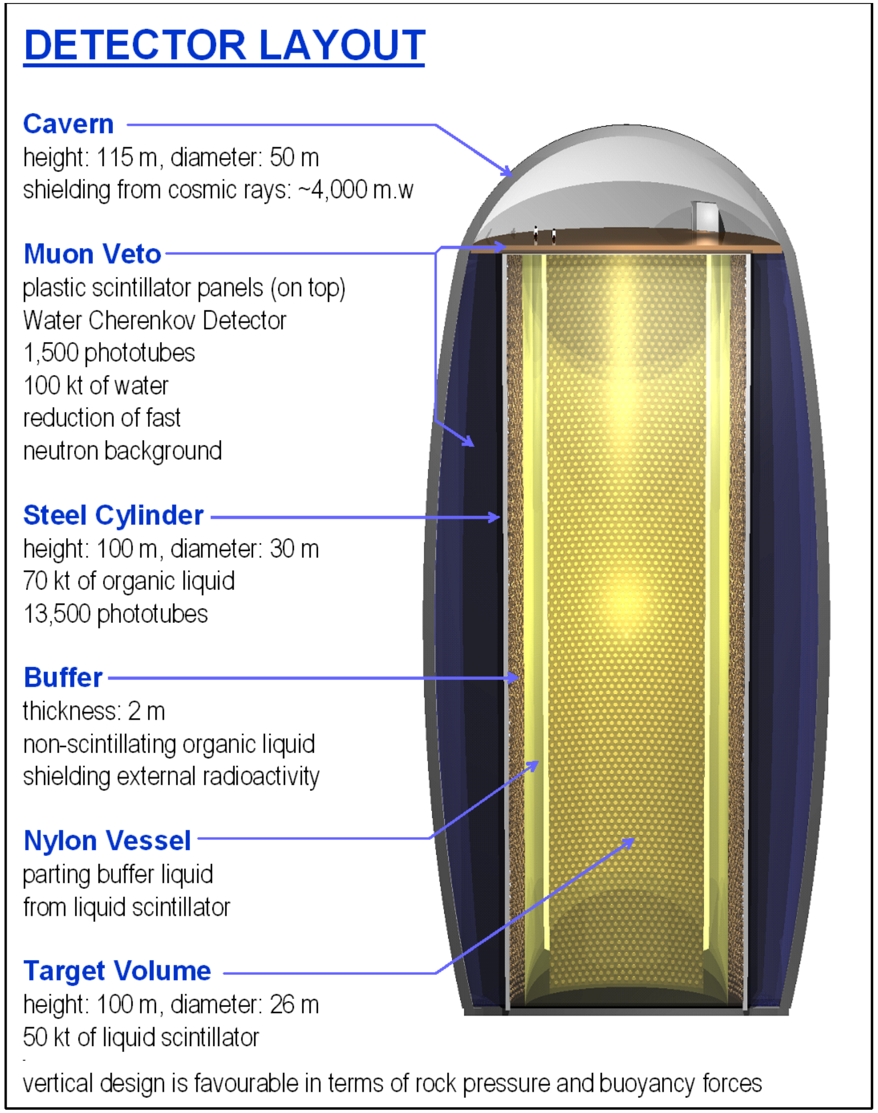
$p \rightarrow e^+ + \pi^0$
- efficiency = 45%, 1BG/Mtyr
- 1×10^{34} years w/ 34kton×10yrs



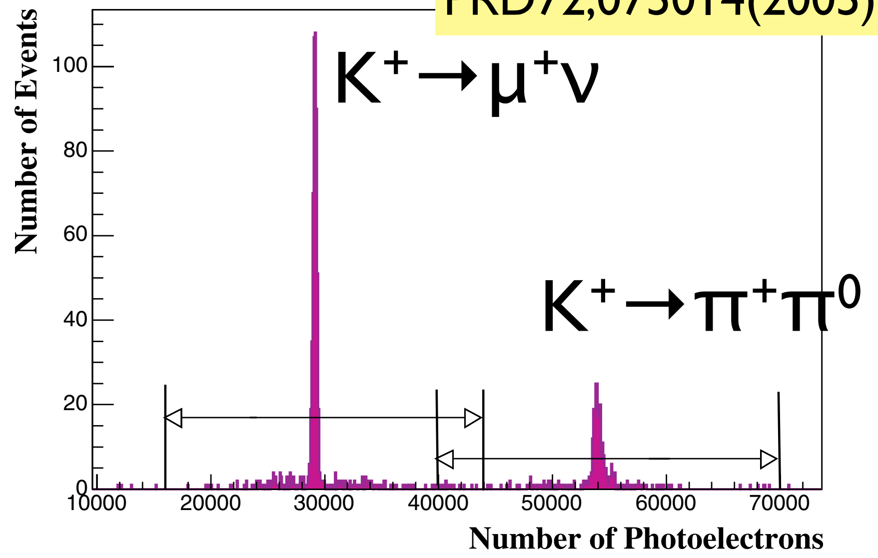
$p \rightarrow \nu + K^+$
- efficiency = 97%, 2BG/Mtyr
- 3×10^{34} years w/ 34kton×10yrs

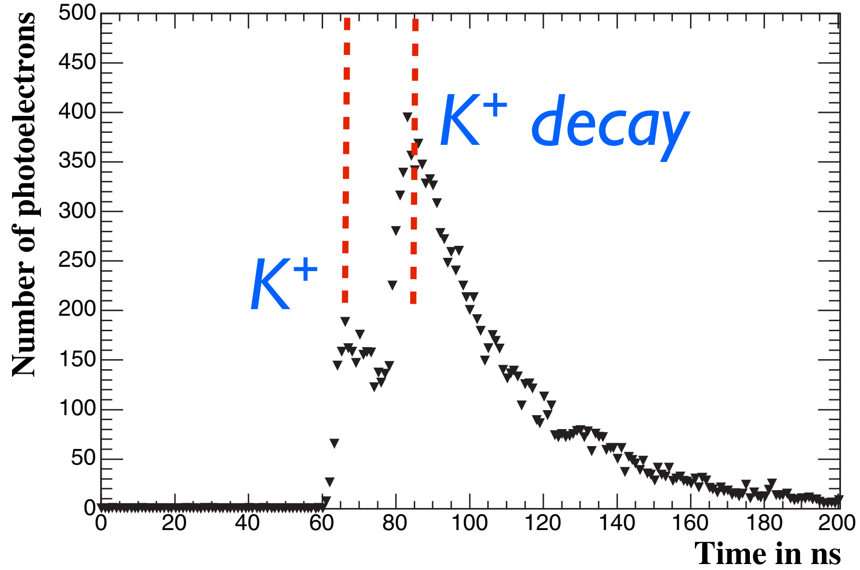
JHEP04(2007)041

LENA: Liquid Scintillator Detector



PRD72,075014(2005)





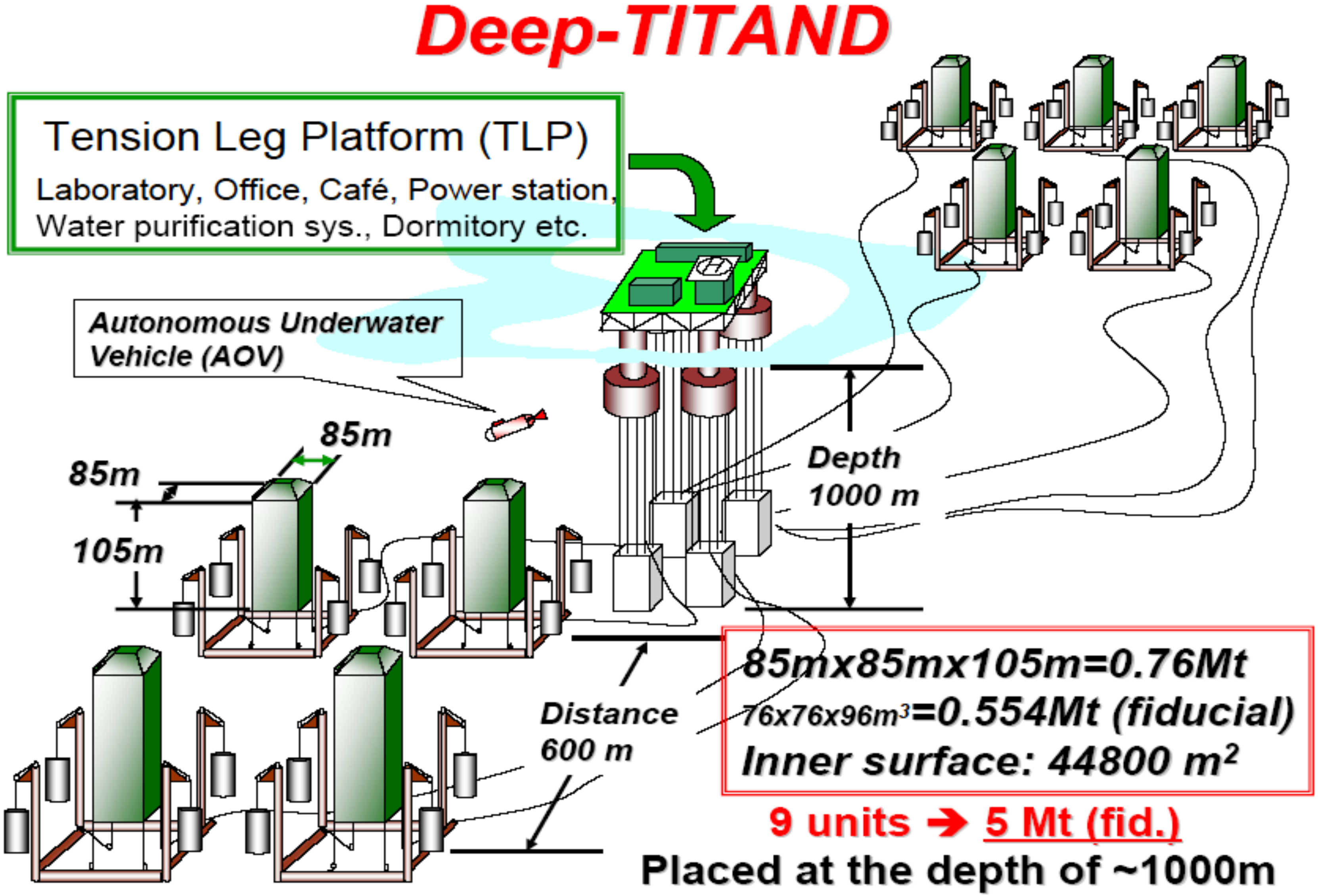
Also R&D of water-based Liq. Scintillator

Minfang Yeh (BNL), Snowmass whitepaper

$p \to \nu + K^+$

- efficiency = 65%, 2BG/Mtyr
- 4 $\times 10^{34}$ years w/ 10yrs exposure

Ideas to go beyond 10^{36} years



under-sea detector

Idea of an under-ice detector (MIKA) under study

Summary

- **Ongoing proton decay experiment**
  - continuous efforts to enhance signal, reduce background neutrino events
  - No evidence so far
- **Next generation nucleon decay detectors are seriously considered.**
  - Extend nucleon decay search sensitivity by a order of magnitude (Water)
    - $\tau_{proton}=10^{34}\sim10^{35}$ years
  - Excellent tracking of many particles including K^+ (Argon)
    - τ_{proton}=a few $\times10^{34}$ years by 34kton×10years
    - similar sensitivity for $p\rightarrow\nu K^+$ in scintillator detectors
  - Aiming to start operation around 2023
    - Having two or more experiments could be crucial to establish proton decays in future.