Future Experiments for Proton Decay

Ed Kearns
Boston University
May 25, 2013
ISOUPS
Asilomar, CA

Many people think proton decay is important…

P5 (2008)
The panel recommends designing the detector in a fashion that allows an evolving capability to measure neutrino oscillations and to search
for proton decays and supernovae neutrinos

EPP2010 (2005)
Action Item 5: A Staged Neutrino and Proton Decay Research Program

HEP Future Facilities Roadmap (2003)
Scientific potential: "absolutely central". Specific Facility: "Don't know enough yet".

NRC– Committee on the Physics of the Universe
Eleven Science Questions for the New Century (2003)
#8 Are protons unstable?

D. Gross *et al*. Ten Questions for the New Millenium (NYT August 15, 2000)
#3. What is the lifetime of the proton and how do we understand it?

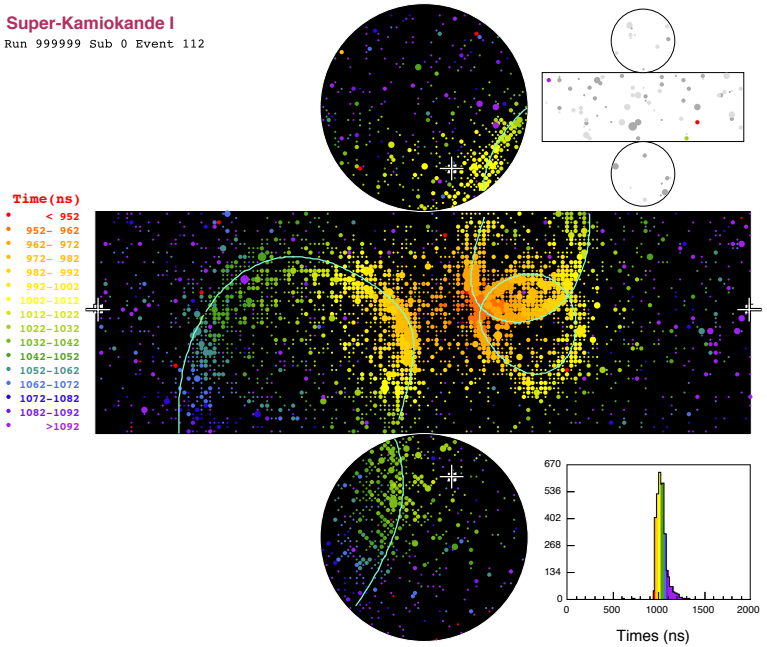
D. Mermin rebuttal Ten Questions (Phys. Today, Feb. 2001)
#9. What indeed is the lifetime of the nucleus of the neutral hydrogen atom?

… here is why

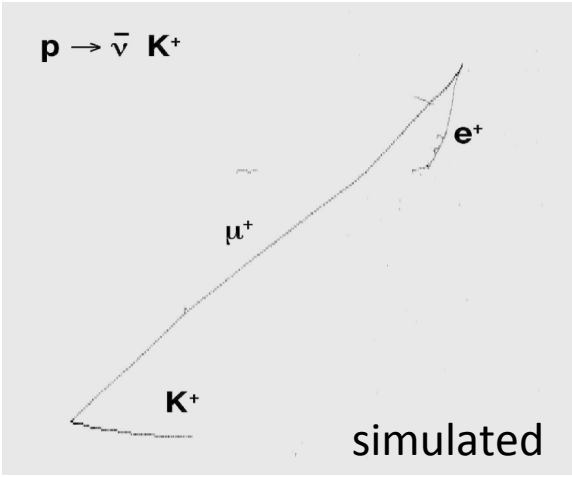
- Tests a fundamental, but unexplained conservation law: baryon number.
- Experimental hint of running coupling unification.
- Grand Unified Theories make specific predictions: decay modes, lifetimes, branching ratios.
- Probes scales forever inaccessible to accelerators.
- New force carrying particles.
- Deep connections with other fields: cosmology, inflation, BAU, neutrino mass.
- Exotic connections with theory: strings, orbifolds, Planck scale, extra dimensions.
- Even if no signal, limits are very constraining on theory.

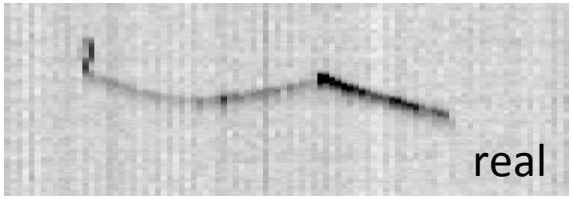
Single Event Discovery is Possible

Water Cherenkov

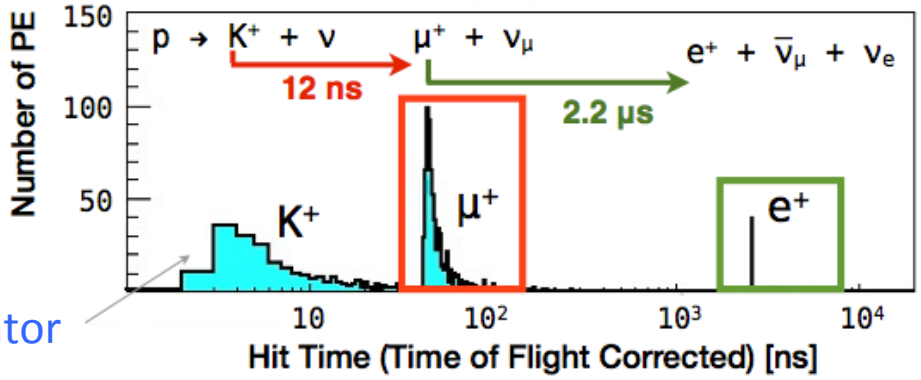


LAr TPC

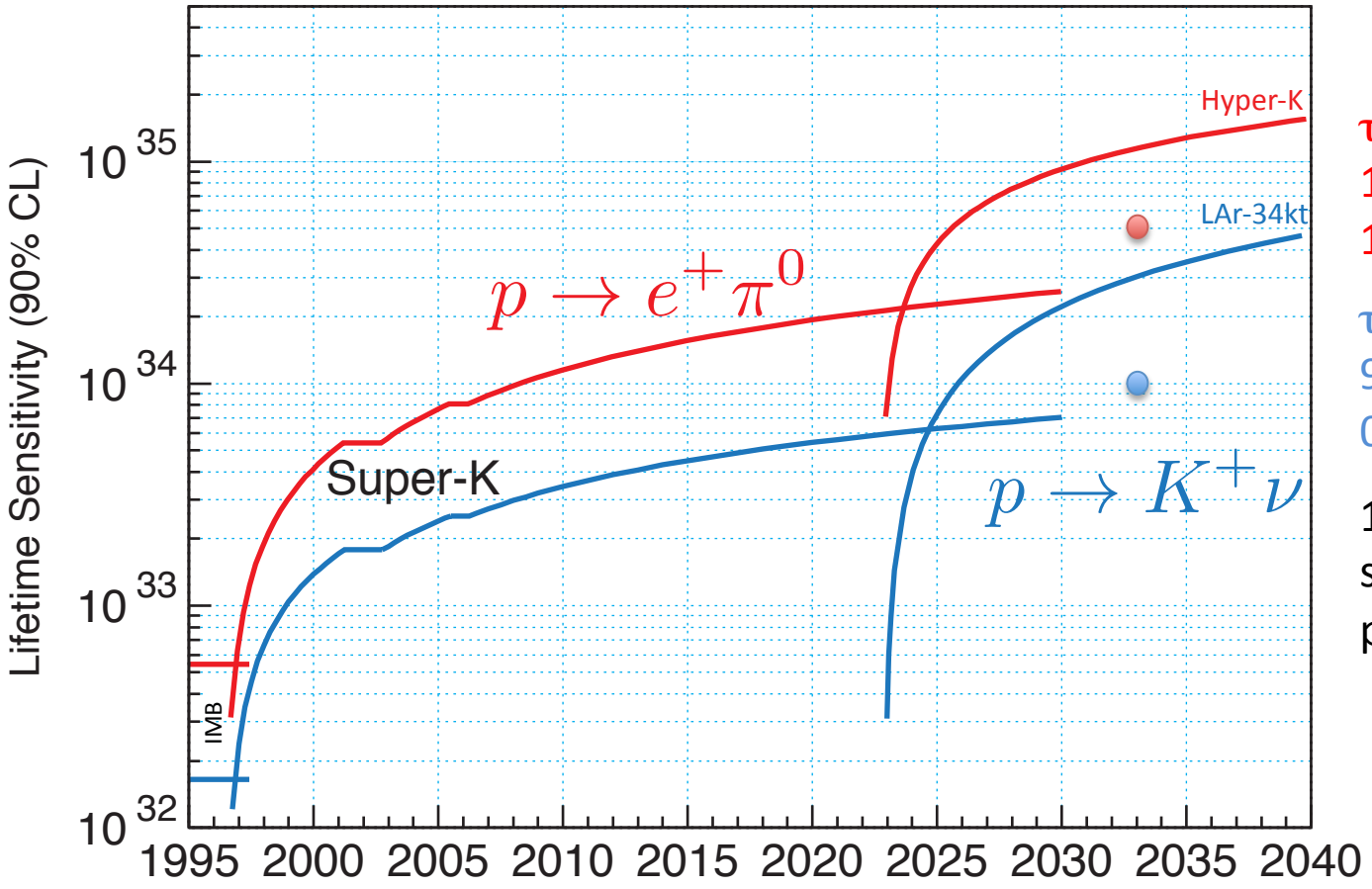




Liquid Scintillator



Proton Decay Search Territory



τ/B = 5e34
17 evts
1 BG

τ/B = 1e34
9 evts
0.3 BG

10 year sample points

~ 0.5 Mt yr exposure by Super-K before next generation experiments

now

Starting time? Guess 1 decade from now.
Adjust starting time as you wish.

- Continue Super-K exposure
- Improve analysis
- Search in new channels

Near Future

- Next generation experiments
  - Detector R&D
  - Experiment proposals

Next Future

Technique	Examples	Comments
Water Cherenkov	22.5 kton Super-K 560 kton Hyper-Kamiokande	Best for $e^+\pi^0$ Good for all modes
Liquid Argon	34 kton LBNE LAr TPC 20 kton LBNO 2-phase TPC	Best for $K^+\nu$ Good for many other modes
Scintillator	50 kton LENA Next gen. reactor (DB2) ? Water-based LSc ?	Specific to $K^+\nu$

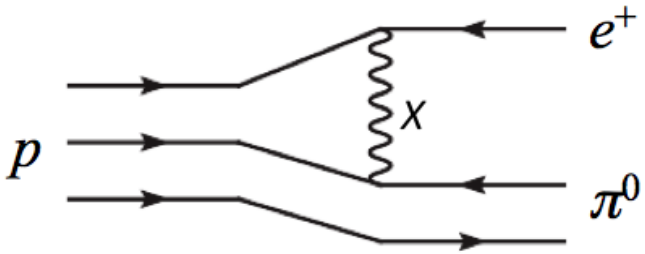
How to Improve

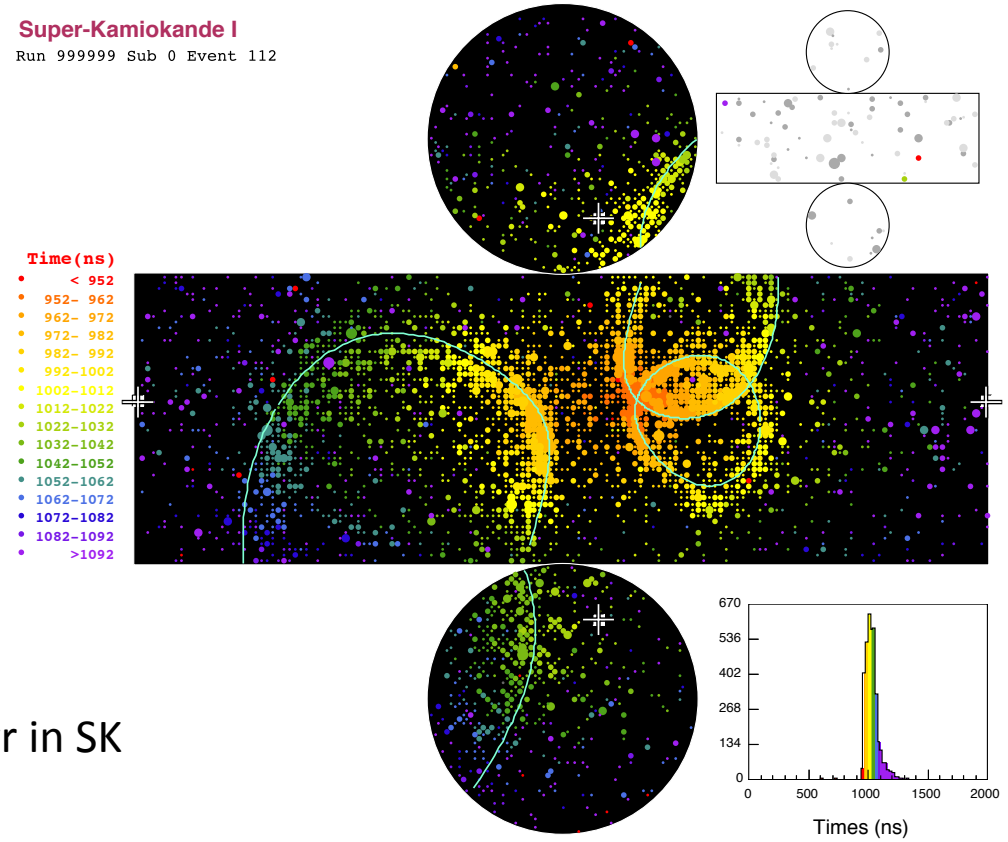
- Sensitivity is based on:

$$\frac{\tau}{B} = \frac{N_0 \ \Delta t \ \epsilon}{n_{obs} - n_{bg}}$$

- Achieve: higher efficiency, lower background rate
- Also important: improve accuracy of model (signal and/or BG) (which may increase or reduce sensitivity)
- Also: reduce systematic uncertainty
- None of this is easy – gains will be small and hard fought
- Increase exposure – gains with SK are now marginal

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



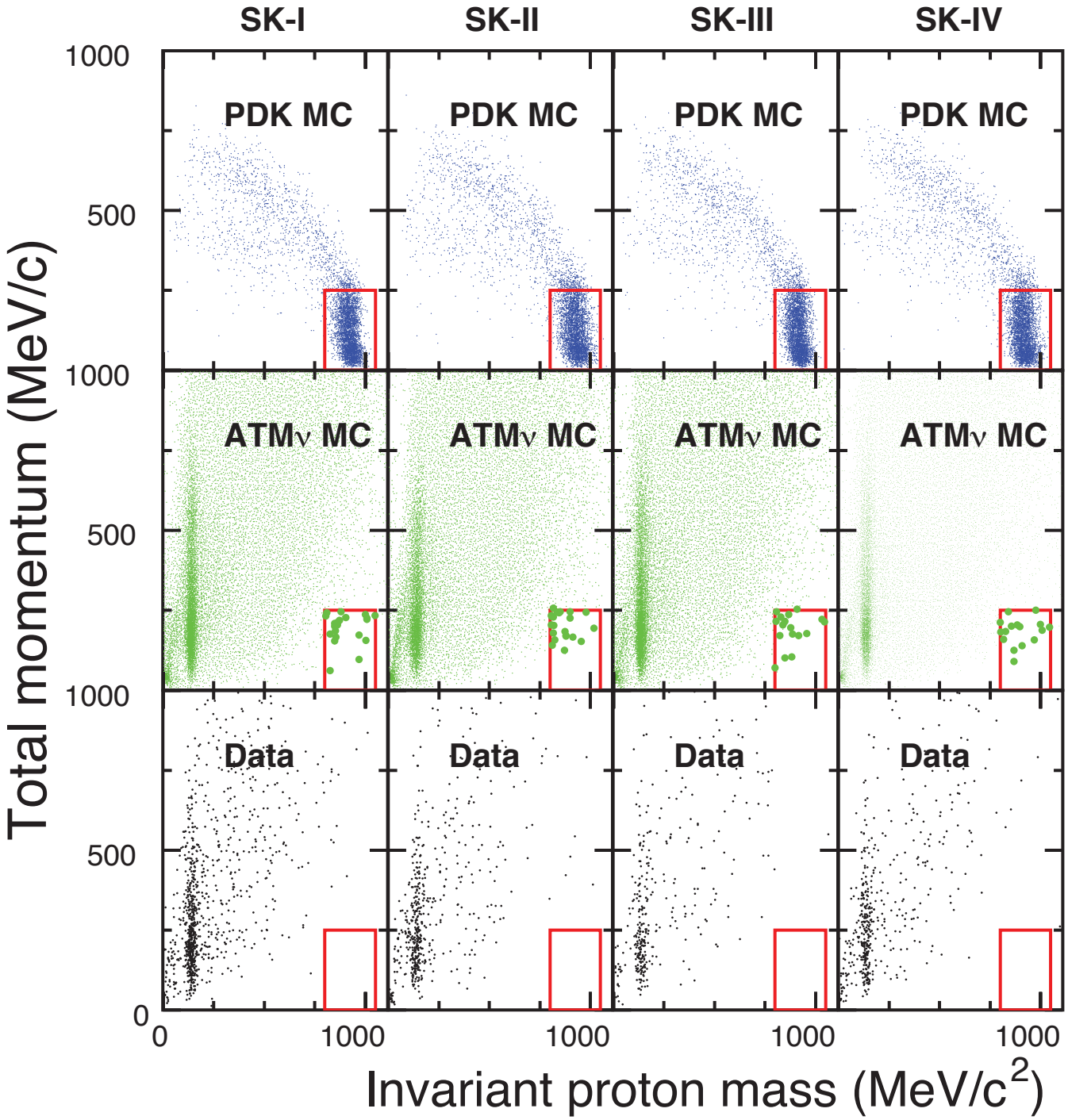


Simple signature: back-to-back reconstruction of EM showers.

Efficiency ~45% dominated by nuclear absorption of π^0

Low background ~0.2 events/100 ktyr in SK

Relatively insensitive to PMT density.



Super-Kamiokande
SK 1+2+3+4
$\tau/B > 1.3 \times 10^{34}$yr
PhysRevD.85.112001

Efficiency and Background

EFFICIENCY	SK1	(20% coverage) SK2	SK3	(new electronics) SK4
$e^+\pi^0$	44.6 ± 0.7 %	43.5 ± 0.7 %	45.2 ± 0.7 %	45.0 ± 0.7 %
$\mu^+\pi^0$	35.5 ± 0.7 %	34.7 ± 0.6 %	36.3 ± 0.7 %	43.9 ± 0.7 %

- Determined by Super-K proton decay Monte Carlo simulation
- 20% coverage is OK (planned for Hyper-K)

BKG RATE (ev/Mt y)	SK1	(20% coverage) SK2	SK3	(new electronics) SK4
$e^+\pi^0$	2.1 ± 0.5	2.2 ± 0.5	1.9 ± 0.5	1.6 ± 0.4
$\mu^+\pi^0$	2.6 ± 0.5	2.1 ± 0.4	2.6 ± 0.5	3.6 ± 0.5

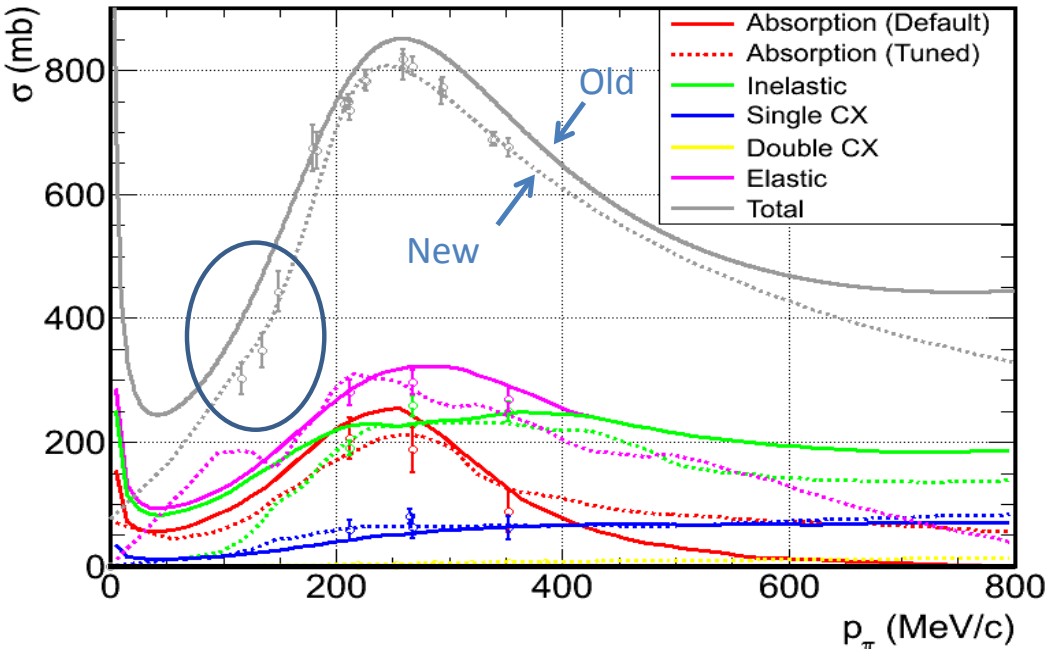
- Background rate checked using K2K near detector:

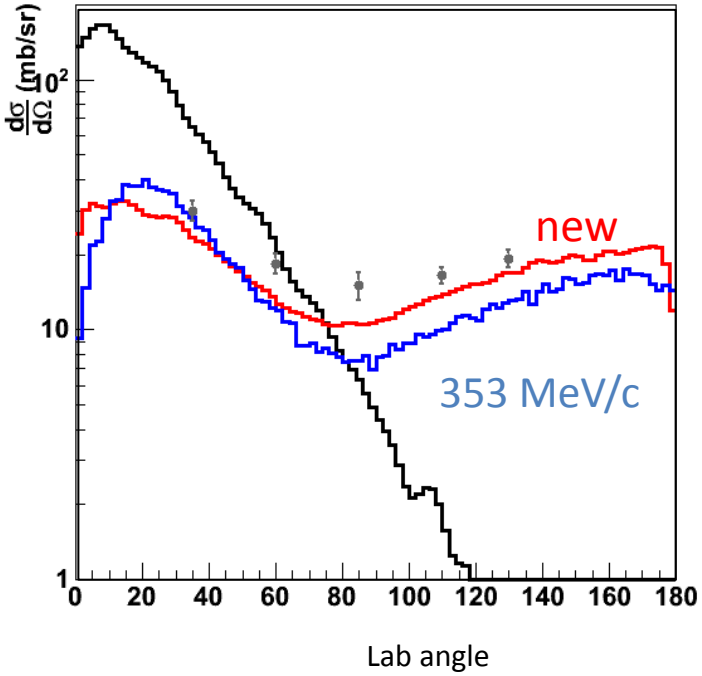
$$e^+\pi^0 \text{ BG} = 1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{sys.}) \text{ evts/Mt} \cdot \text{yr}$$

PHYSICAL REVIEW D 77, 032003 (2008)

Improved Pion Interaction Model

E.g. Pion interaction Monte Carlo (NEUT) – intranuclear scattering



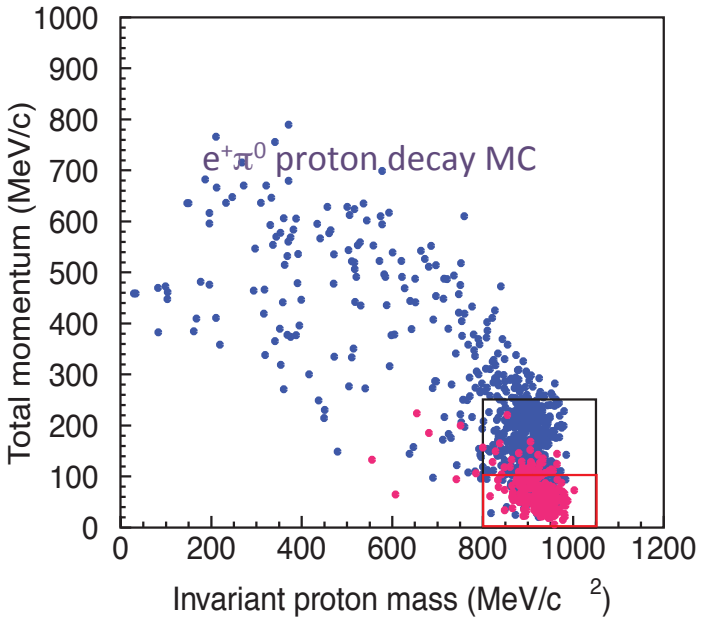


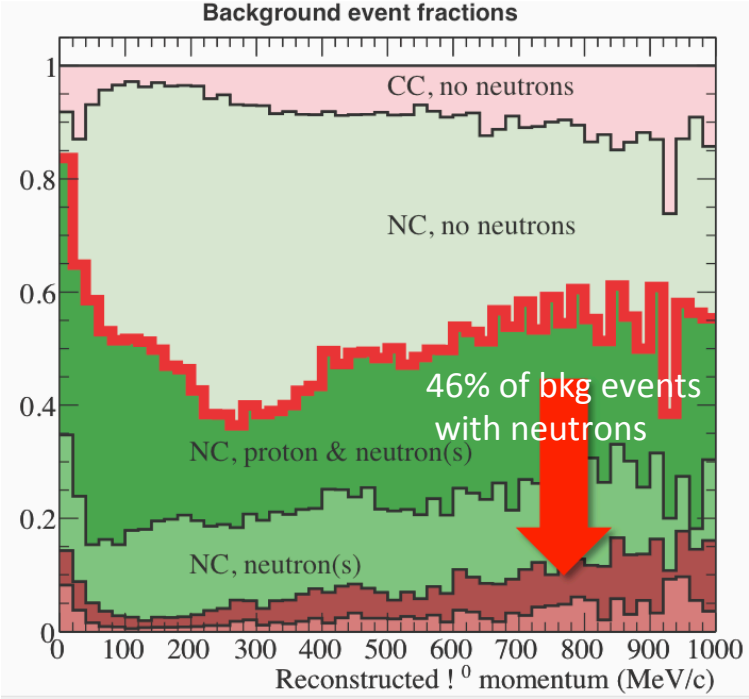
Efficiency for $p \longrightarrow e^{+}\pi^{0}$ is now estimated at 40% (was 45%)

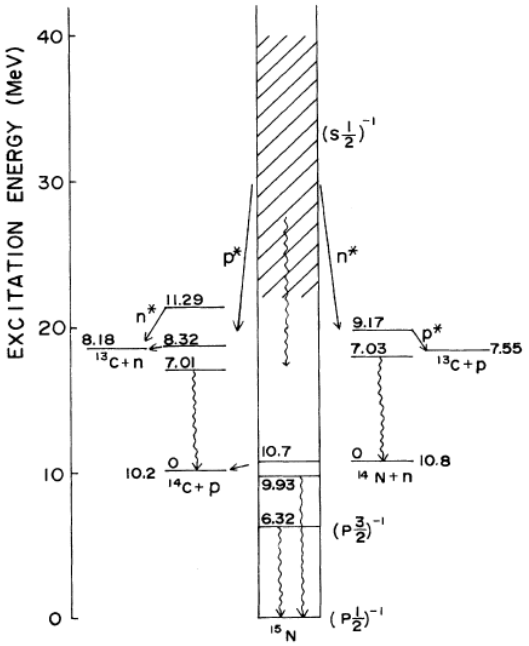
Background rate stays the same

Background Reduction Strategies

- Tight Cuts on Free Proton
  - efficiency ~ 17%
  - BG 0.015 evts/100 kton yr
  - change over around 10-20 Mton yr
- Gadolinium
  - high energy neutrino events are accompanied by n
  - assume proton decay is not accompanied by n
    - * surely not for free proton
    - * also not for γ-tag states
  - consider Gd addition to WC to increase n-capture tag efficiency
  - Gadolinium R&D underway at SK







Nuclear Physics of Proton Decay in ^{16}O

Spectroscopic factors measured in $^{16}O(e,ep)^{15}N$ experiment

Gamma-ray emission measured in $^{16}O(p,2p)^{15}N$ experiment

Hole	Residual	States	(k)	E_γ	E_p	E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5	0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0	~20	0.02
	7.03	2^+	^{14}N	7.03	0	~13	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	1.6	~11	0.01
	g.s.	0^+	^{14}C	0	~21	0	0.02
	7.01	2^+	^{14}C	7.01	~14	0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~11	~2	0.03
$(j)_p^{-1}$	others		many states	≤3–4			0.16

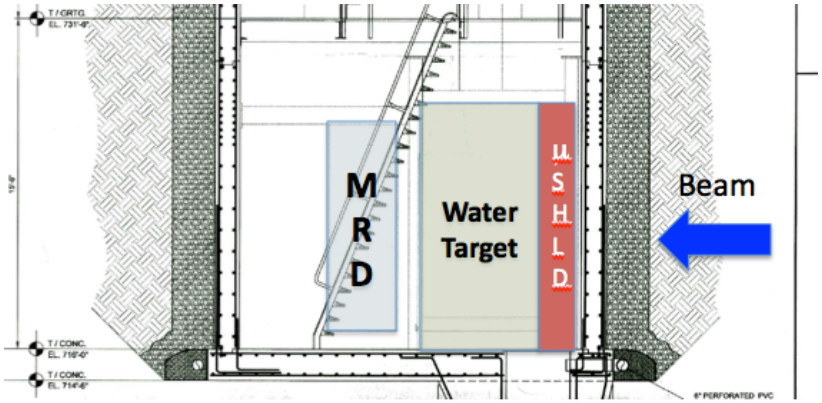
some gammas

few neutrons

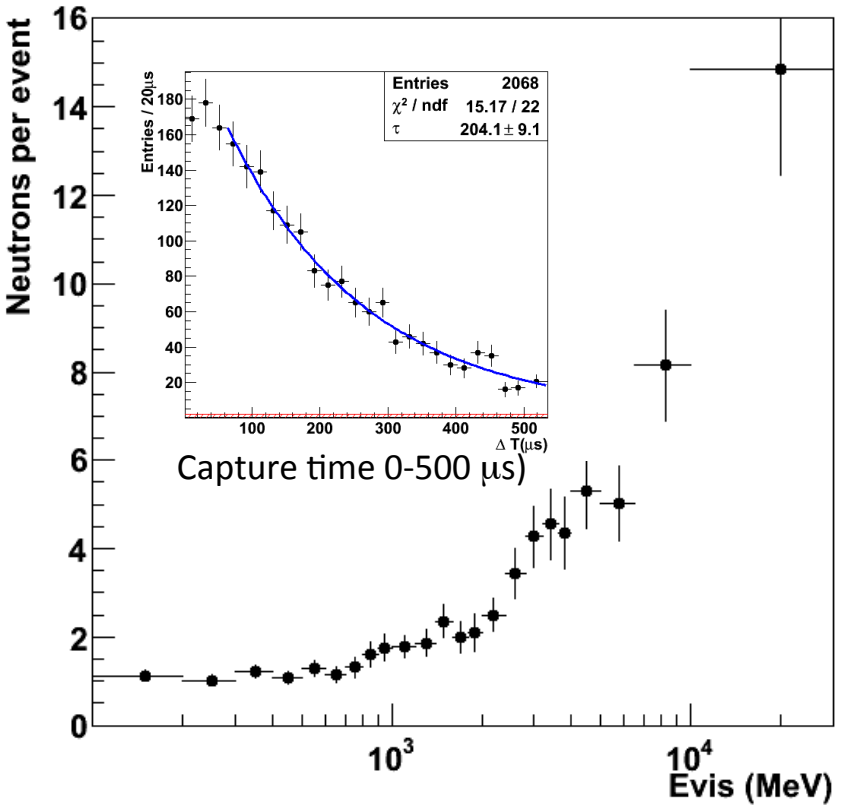
H. Ejiri Phys. Rev. C48 (1993)

Neutron Production Experiments

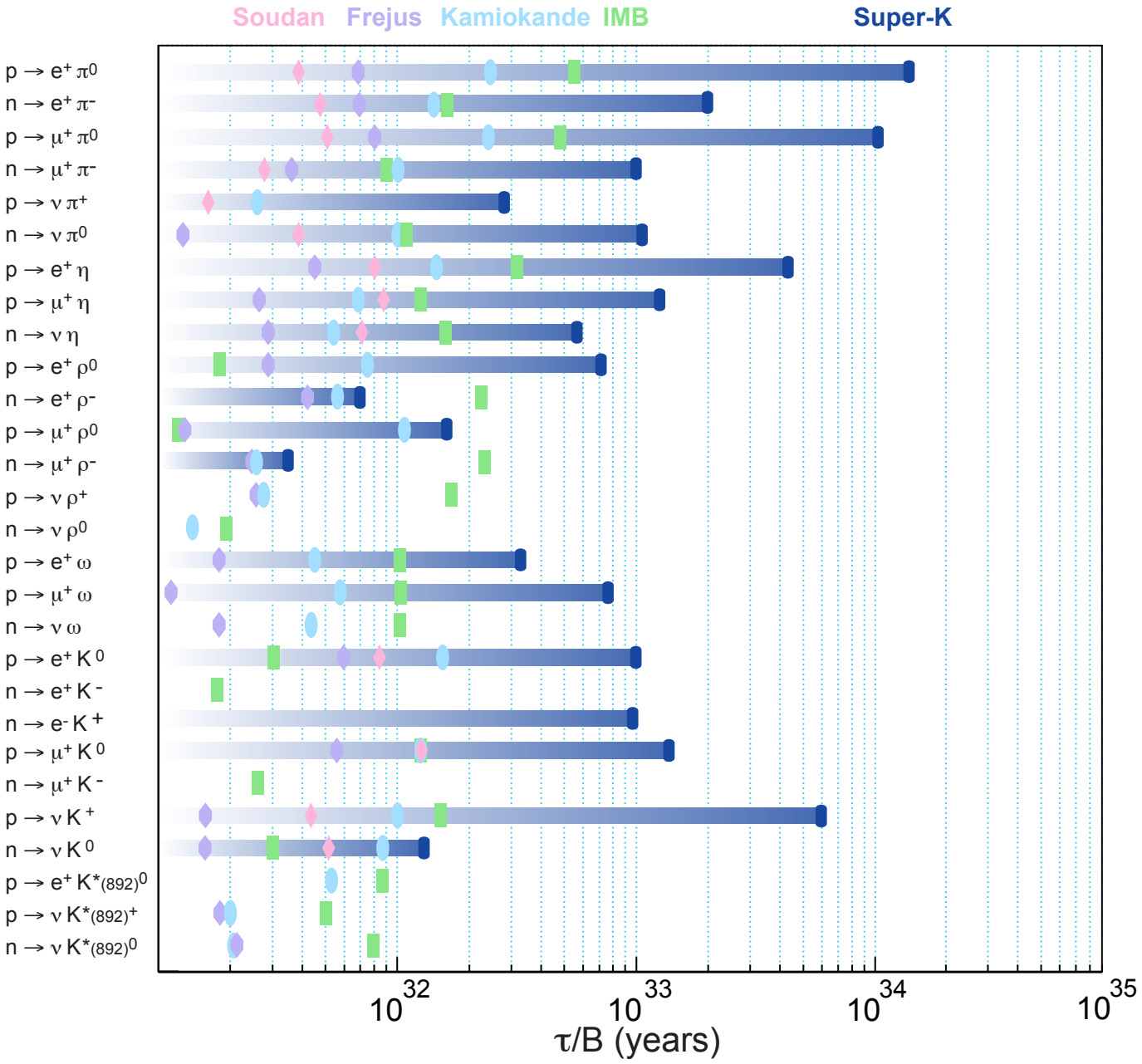
- New SK electronics (SK4 only) allows search for neutron associated with atmospheric neutrinos (capture on free proton, 2.2 MeV γ).
- Other current, near future, and recent past experiments can also search. T2K, SciBooNE e.g.
- Dedicated new experiment (ANNIE) proposed.



SK4 Preliminary
Efficiency corrected n yield



Antilepton + Meson Two-Body Modes



There are many interesting modes

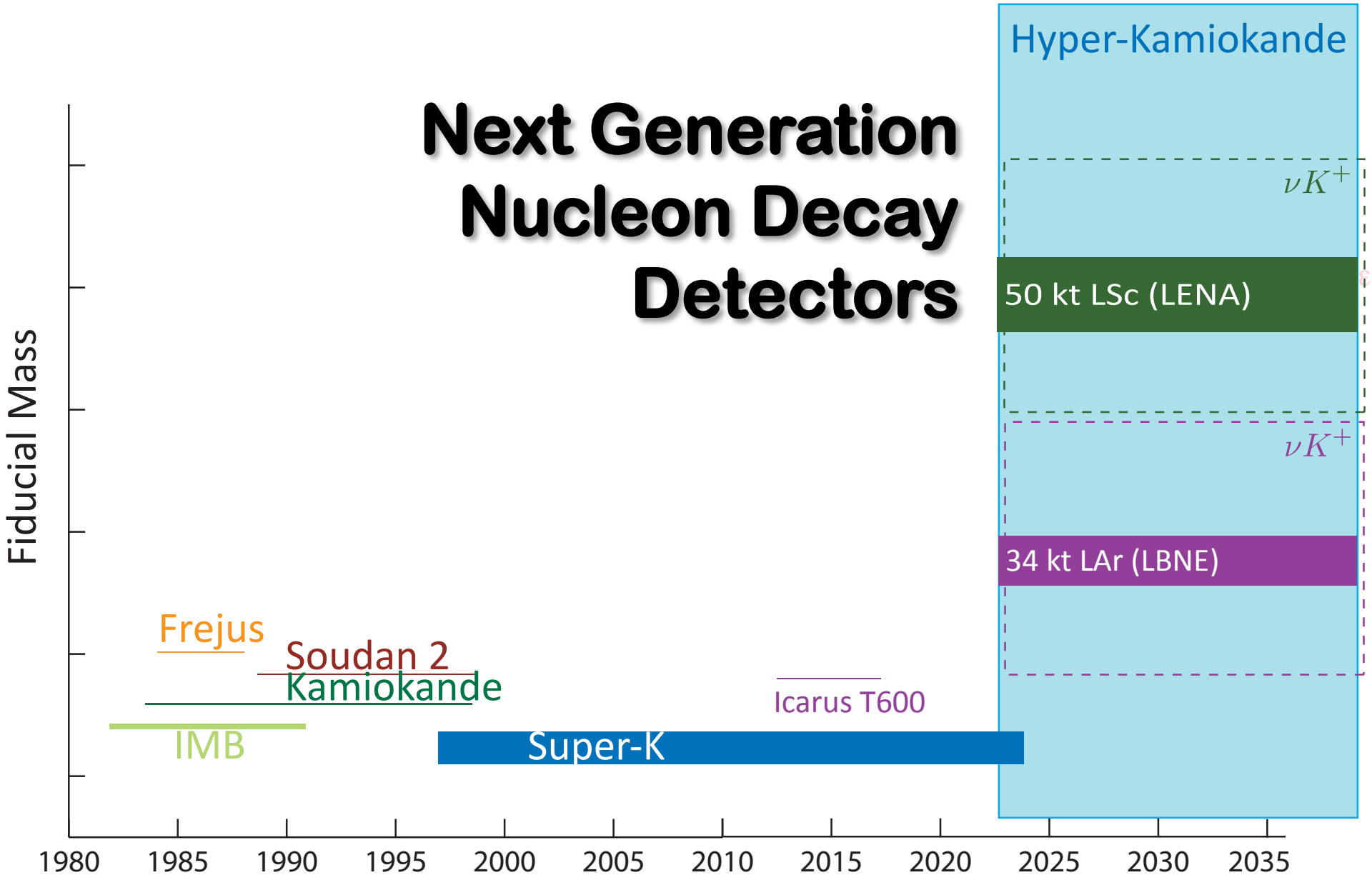
		× 10^{30} years	
τ_1	$N \to e^+\pi$	13000 SK1+2+3+4*	
	...	$> 158\ (n),\ > 8200\ (p)$	90%
τ_{16}	$N \to \mu^+ K$	1600 SK1+2+3**	
	...	$> 26\ (n),\ > 120\ (p)$	90%
τ_{19}	$N \to \nu K$	5900 SK1+2+3+4 preliminary	
	...	$> 86\ (n),\ > 670\ (p)$	90%

22 antilepton + meson modes (B-L)*
7 antilepton + mesons (3-body) modes
12 lepton + meson modes (B+L)***
16 more exclusive modes
5 inclusive modes
13 dinucleon decay modes ****

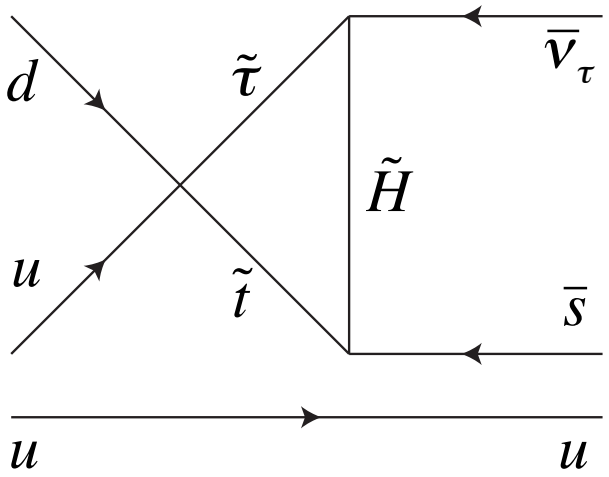
* H. Nishino *et al.* Phys.Rev.D.85.112001 (12 modes)
** C. Regis *et al.* Phys.Rev.D.86.012006 (K_S + K_L)

*** Super-K preliminary
$n \longrightarrow e^- K^+$ $\tau/B > 9.9 \times 10^{32}$ yr (90% CL)

**** Super-K preliminary
$pp \longrightarrow K^+K^+$ $\tau/B > 1.7 \times 10^{32}$ yr (90% CL)
$\lambda''_{112} < 8 \times 10^{-9}$


Next Generation
Nucleon Decay
Detectors
Hyper-Kamiokande
νK^+
50 kt LSc (LENA)
νK^+
34 kt LAr (LBNE)
Fiducial Mass
Frejus
Soudan 2
Kamiokande
IMB
Super-K
Icarus T600
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035

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



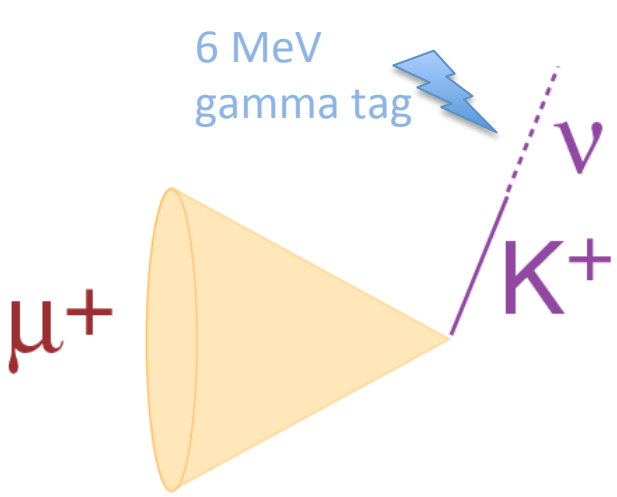
SUSY, better gauge unification
D=5 operator

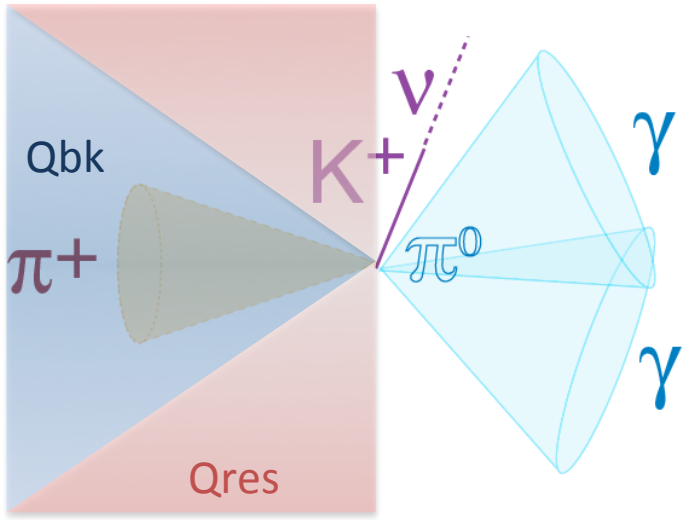
Water: charged kaon below Cherenkov threshold but
Look for $\pi^+\pi^0$ from kaon decay at rest
^{16}O gamma can be used to tag in WC

Liquid Scintillator: Kaon decay energy and time
well measured in LS (ε ~ 65%)

LAr TPC: Charged kaon leaves track
with correct dE/dx (ε ~ 97%)

νK^+ in Water Cherenkov





γ-tag and $\pi^+\pi^0$	SK1	(20% coverage) SK2	SK3	(new electronics) SK4
Efficiency	15.7 %	13.0 %	15.8 %	18.9 %
Background rate (/100 kty)	0.3	0.6	0.4	0.4

New efficiencies and background rates after analysis improvement
Super-K Preliminary 2013: No candidates, 260 kton yr (SK 1+2+3+4):

$$p \to \nu K^+ \quad \tau/B > 5.9 \times 10^{33} \text{ years}, 90\%\text{CL}$$

LENA

Low Energy Neutrino Astronomy

- 51 kt liquid scintillator (FV)
- 32m x 100m
- 30000 PMTs (30% with Winston cones)
- Water Cherenkov veto

$p \longrightarrow \nu K+$

Efficiency estimate ~ 65%

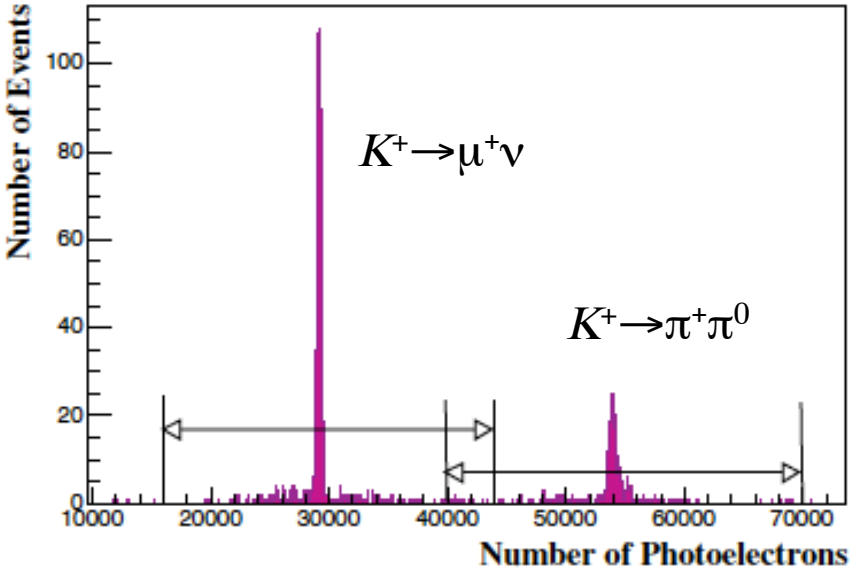
Background rate ~ 1/yr/50 kton

Astroparticle Physics 35 (2012) 685–732

νK^+ in Liquid Scintillator

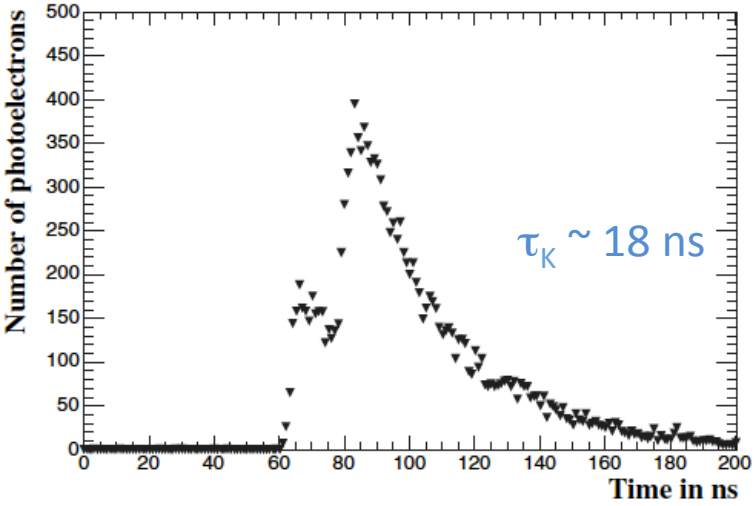
Plots from LENA

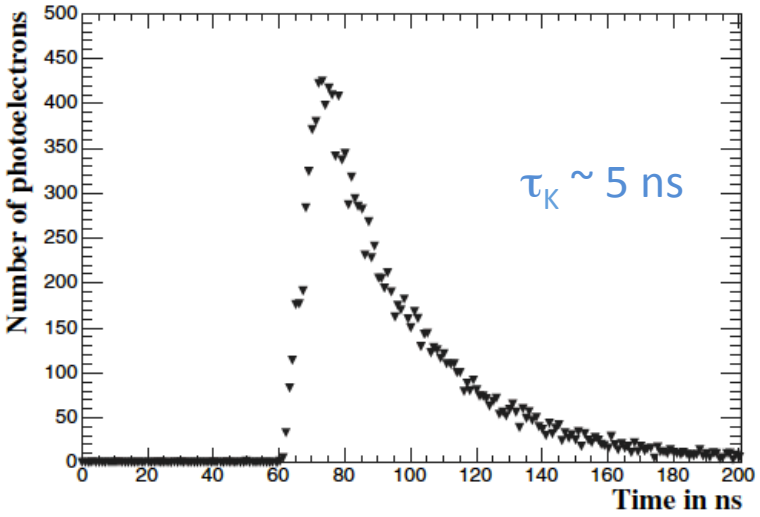
Energy Response



- 200 photoelectrons/MeV (40x Super-K)

Residual Timing Distributions (single events)

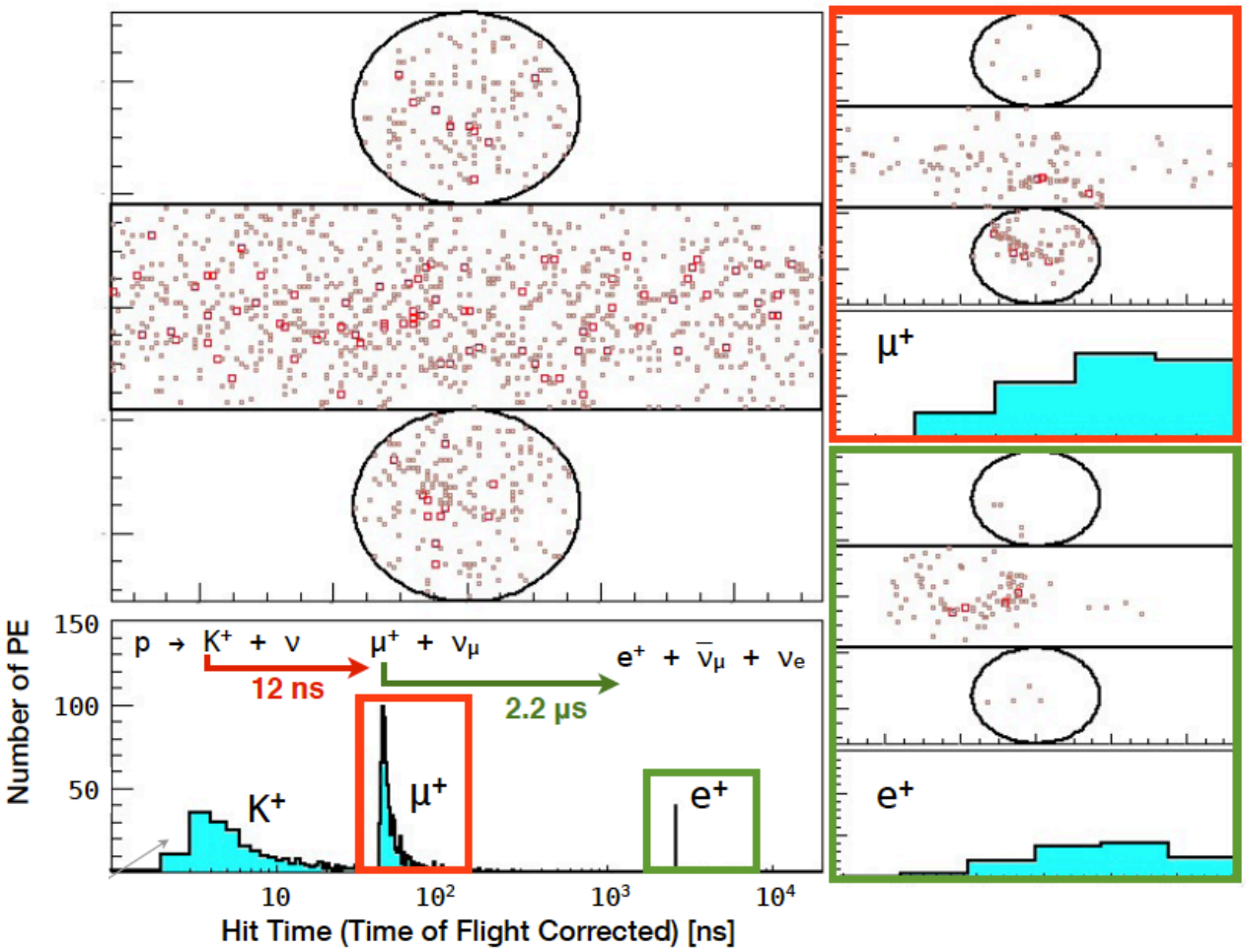




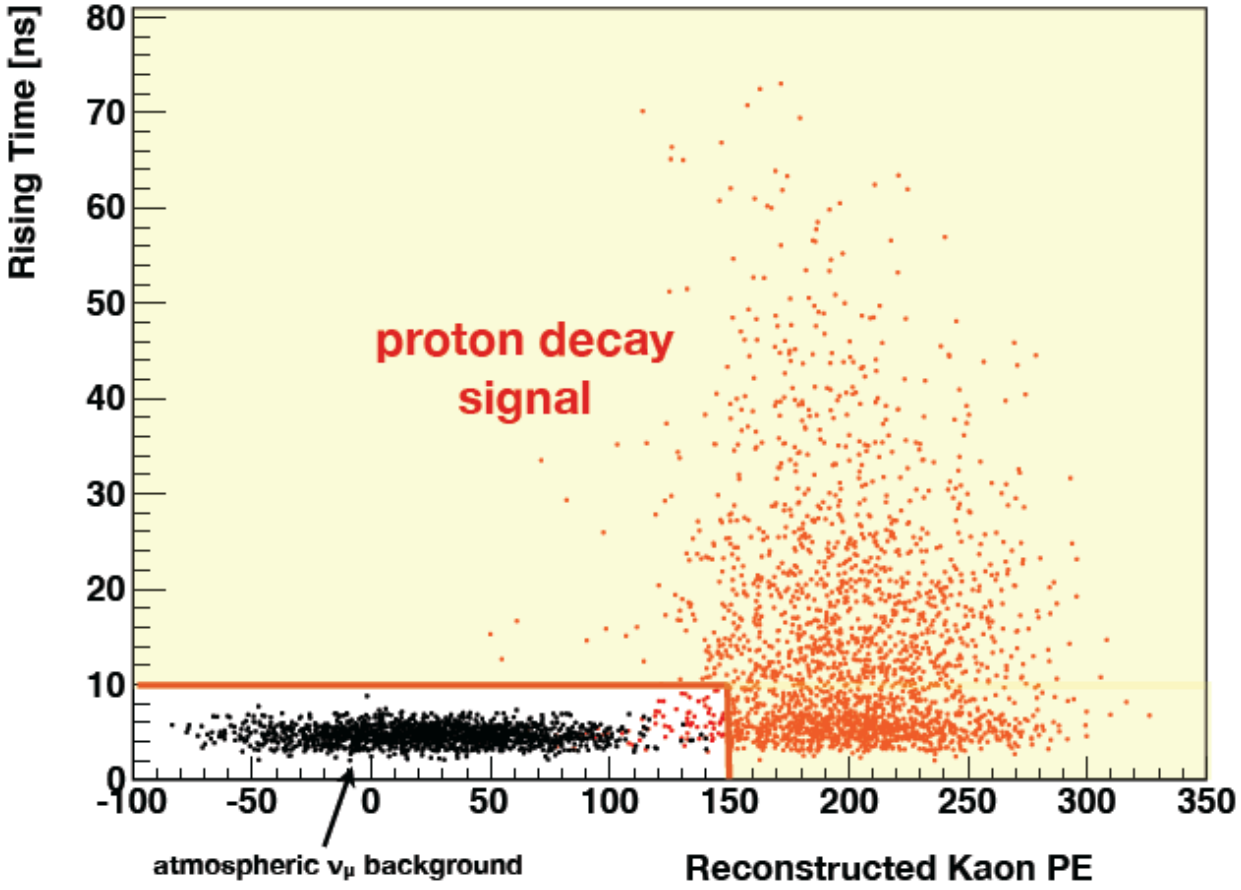
A Large Water-Based Liquid Scintillation Detector in Search for Proton Decay $p \to K^+\bar{\nu}$ and Other Physics

D. Beznosko[1], M.V. Diwan[1], S. Hans[2], K.M. Heeger[3], L. Hu[2], D.E. Jaffe[1], S.H. Kettell[1], J.R. Klein[4], L. Littenberg[1], K.B. Luk[5], R. Rosero[2], G.D. Orebi Gann[5,6], X. Qian[7], R. Svoboda[8], H. Themann[1], B. Viren[1], E. Worcester[1], M. Yeh[2], C. Zhang[1]

A simulated event with 90 scintillation photons/MeV



Water Based Liquid Scintillator – in Super-K

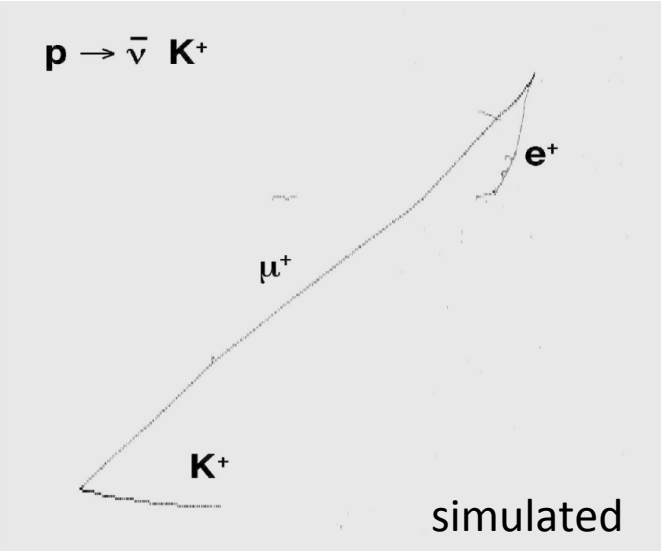


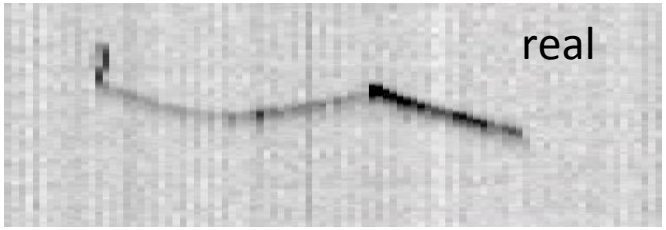
D. Jaffe (BNL)
Argonne IF Mtg
April 2013

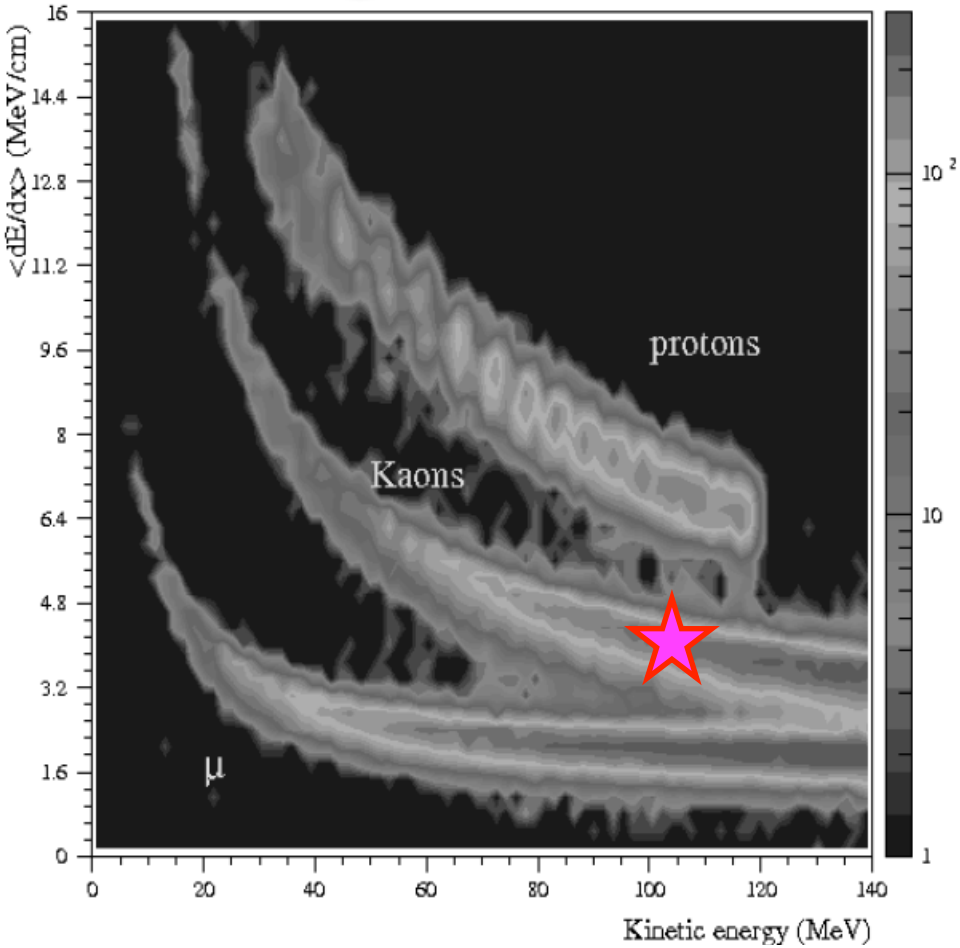
73% efficiency, low background (0.1 events in 225 kt yr)

$$\tau(p \to K^+\bar{\nu}) > 2 \times 10^{34}\text{y at } 90\% \text{ C.L. in } 10 \text{ years}$$

νK^+ in a Liquid Argon TPC



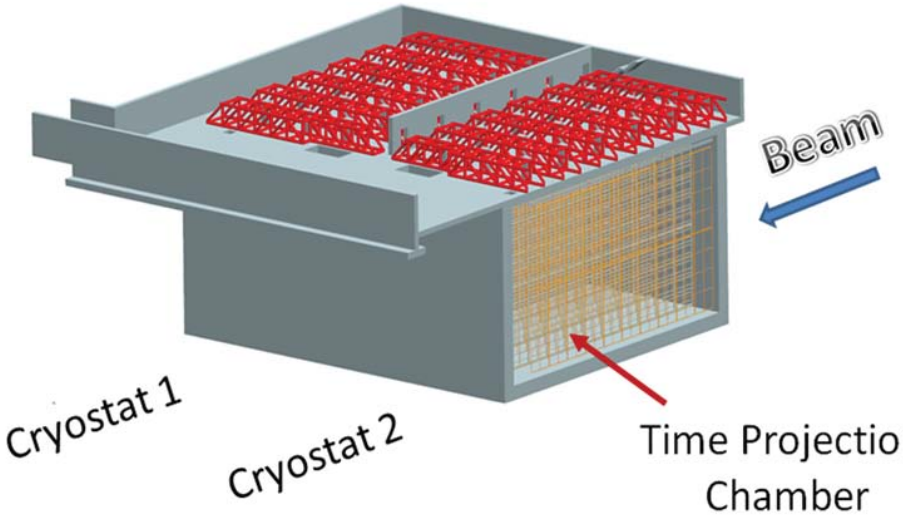




Cuts	(p3) $p \to K^+ \bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no π^0	96.8%	0	0	0	0	57	9
$E_{vis} < 0.8$ GeV	96.8%	0	0	0	0	1	0

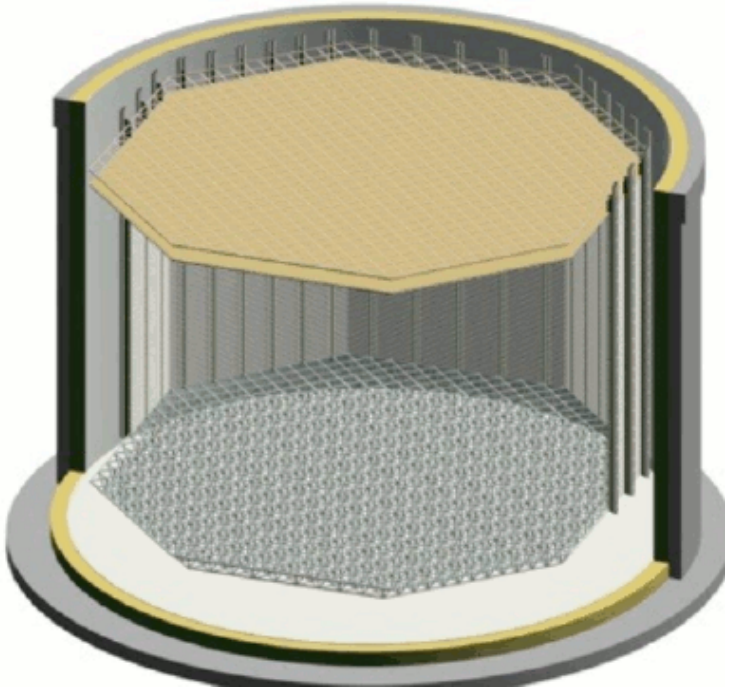
Bueno et al.

LBNE



34 kton

GLACIER/LBNO

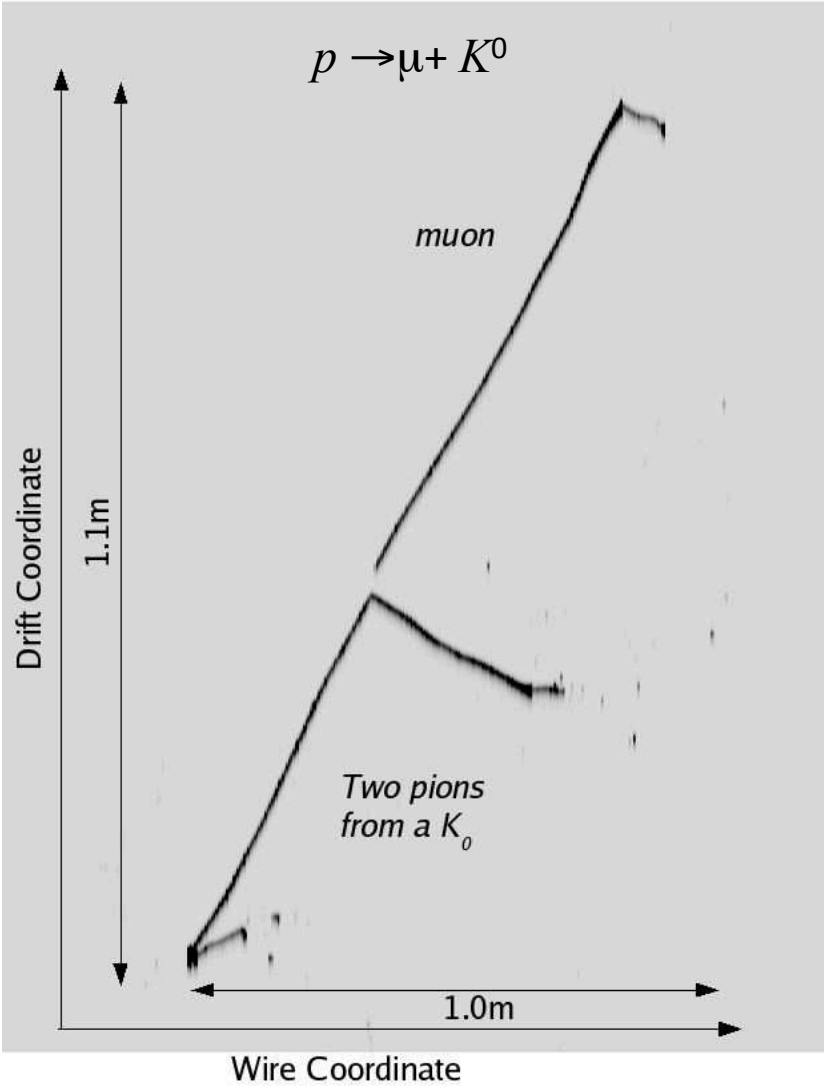


20 + 50 kton

- Two very different technical designs – which is best?
- Validate the 97% efficiency assumption, as well as low bg rate.
- Essential for LBNE to be underground.
- Proton decay needs MASS: 20 to 70 kton being considered

LAr TPC does well with many modes

- Modes with charged kaon in final state (SUSY motivated)
- Modes with displaced vertices ⇒
- Multi-prong modes with no neutrino
- Lepton + light meson are no better than water due to nuclear absorption of the light meson.



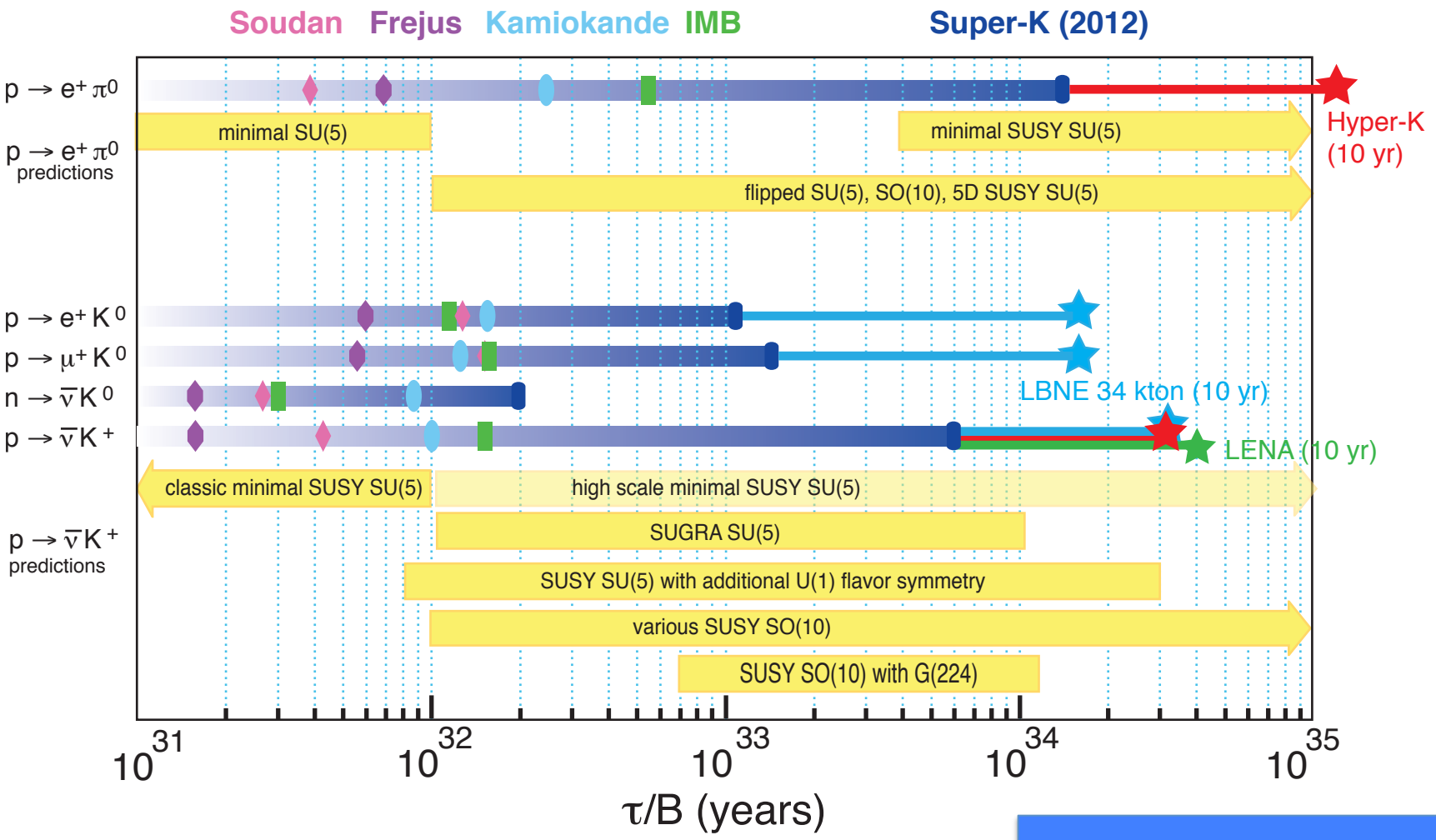
LAr TPC versus Water Cherenkov

	Mode	Super-K Water Ch. Efficiency	Super-K Water Ch. BG Rate (/Mt y)	LAr (generic) Efficiency	LAr (generic) BG Rate (/Mt y)
B-L	$e^+\pi^0$	~~45%~~ → 40%	2	45%	1
B-L	νK^+	19%	4	**97%**	**1**
B-L	$\mu+ K^0$	10%	5-10	**47%**	**<2**
B+L	$\mu^- \pi^+ K^+$	?	?	**97%**	**1**
B+L	$e^- K^+$	10%	3	**96%**	**<2**
$\Delta B=2$	n nbar	12%	260	**?**	**?**

Rough and unofficial
SK efficiency & BG - ETK

A. Bueno et al.
hep-ph/0701101

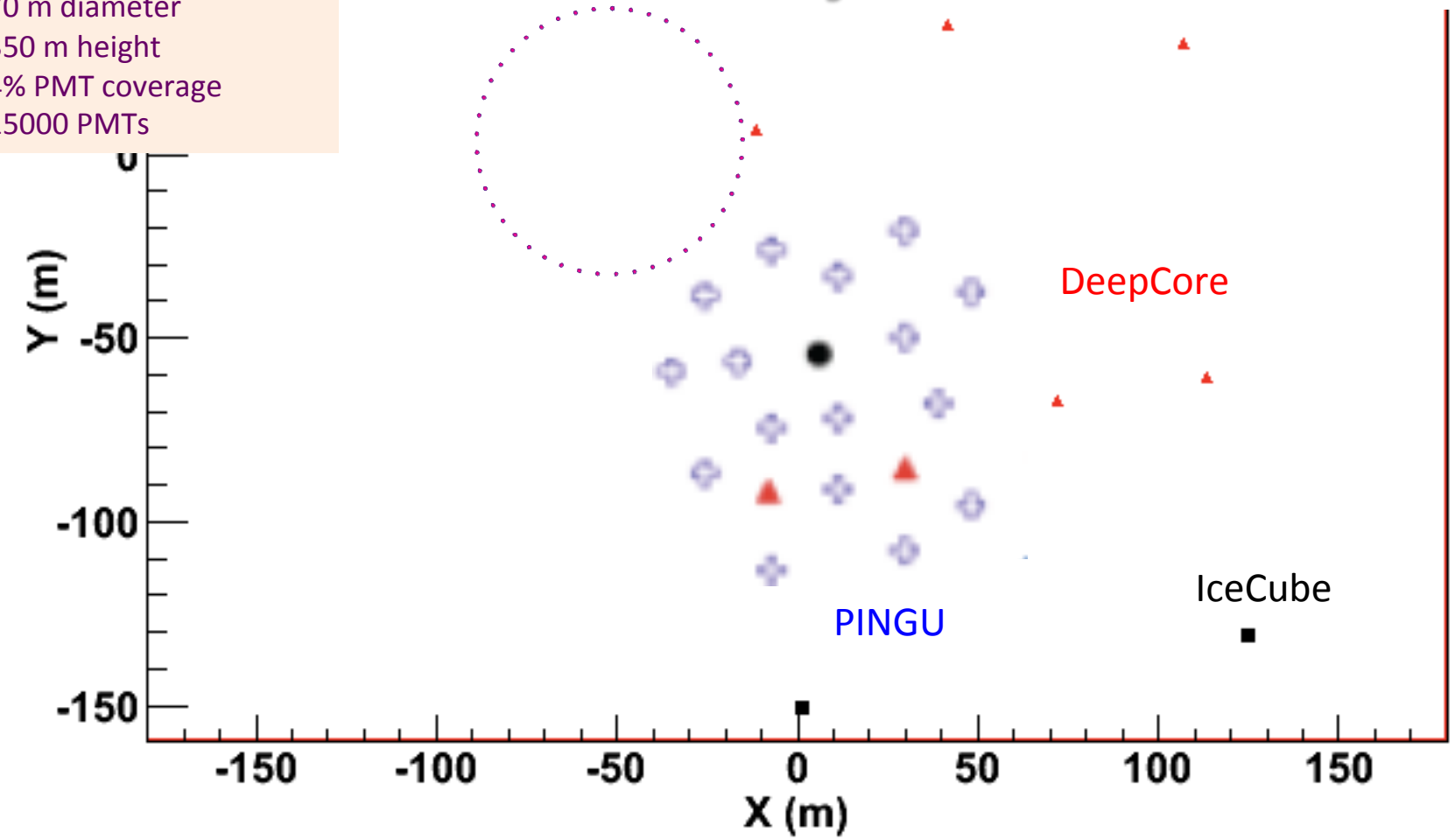
Experimental Limits Confronting Theory



But how do we get to 10^{35} and beyond?

Pure speculation…
High density proton decay cylinder in ice

1 Mton could consist of:
44 strings
1 m x 5 m spacing
70 m diameter
350 m height
4% PMT coverage
15000 PMTs

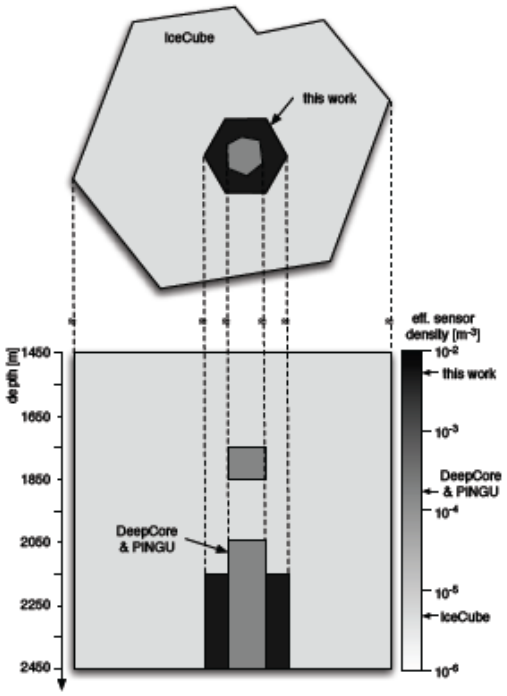


Few % coverage comparable to IMB.
But can background rates be managed while maintaining efficiency?
Effic = 0.5*SK = 0.2, bgrate = 5*SK = 20 evts/Mt y, 90% CL sensitivity ~ 1e35 yrs

Focus on “bright” signatures like e+pi0.

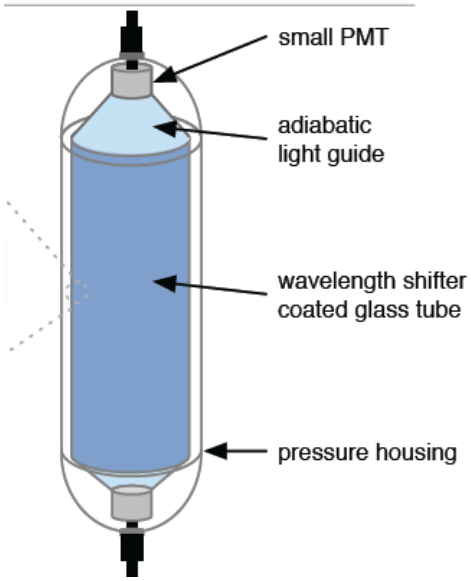
MICA: Megaton Scale Ice Cherenkov Array

Rough idea of
10 MTon
detector layout



Drilling ice and deploying strings of PMTs is now a well-established technical effort.

Possible costs of $500M / Mton ??

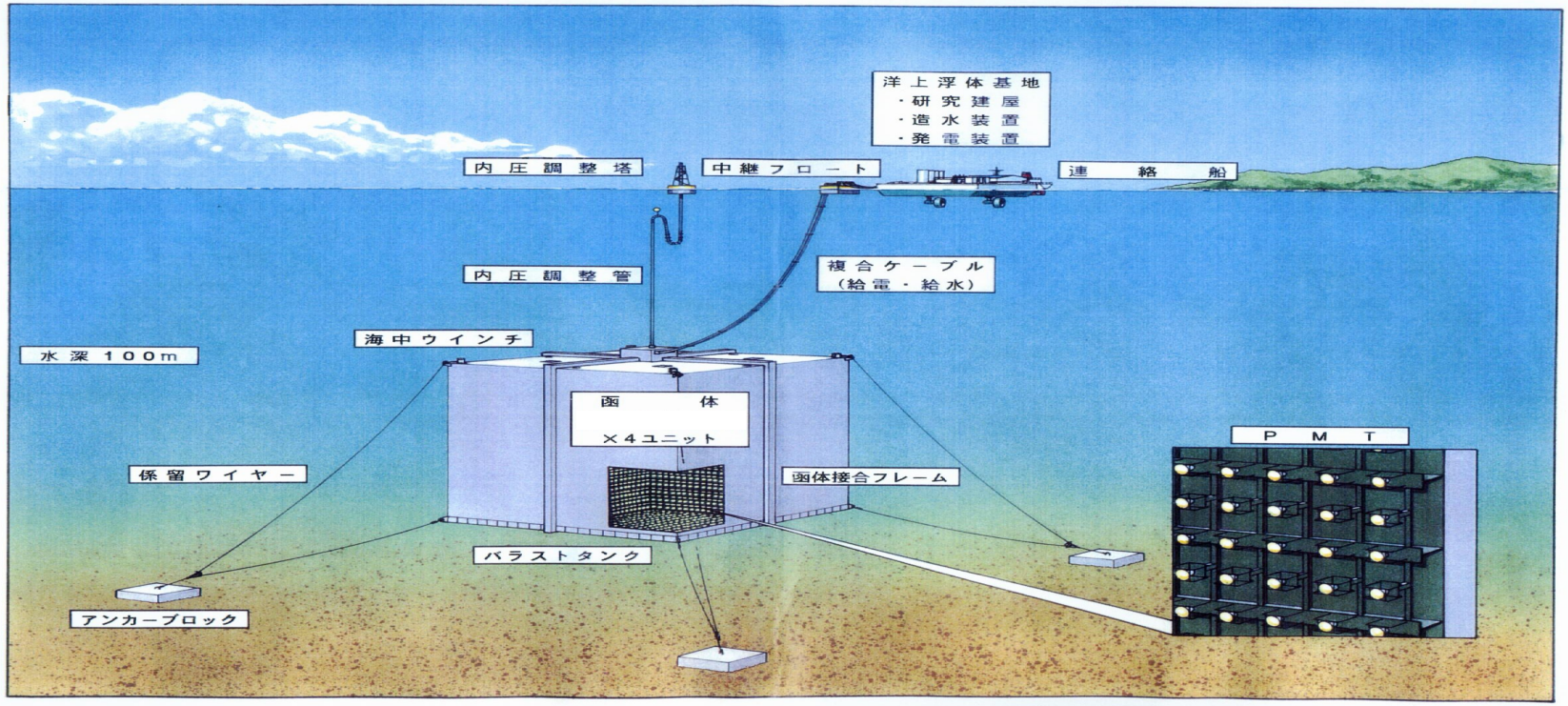


D. Cowen (Penn State)
Argonne IF Mtg
April 2013

Please build the modules with up-down symmetry for the sake of contained atmospheric neutrino studies!

Undersea Array of WC Detectors

TITAND Y. Suzuki (20th Anniv of SN1987a)



浮沈式陽子崩壊実験装置イメージ図

5 Mton Scale

Background reduction by tight momentum requirement + neutron tagging:
Sensitivity approaching 10^{36} *years (90% CL) for* $e^+\pi^0$

Conclusion

- A next generation experiment is needed to gain an order of magnitude in nucleon decay sensitivity.
- The motivations are as strong as ever, and would be strengthened by:
  - Candidate events at Super-K
  - Signs of SUSY at the LHC – good news for LAr and LSc
- What we need:
  - MASS! Nothing beats mass.
  - Low background rates – less-than-one to few-events per 10 yr.
  - Cost reduction.
  - Running time. 10 years exposures are de facto.
  - A neutrino beam, because it seems that this is the only way to get the detector we need!