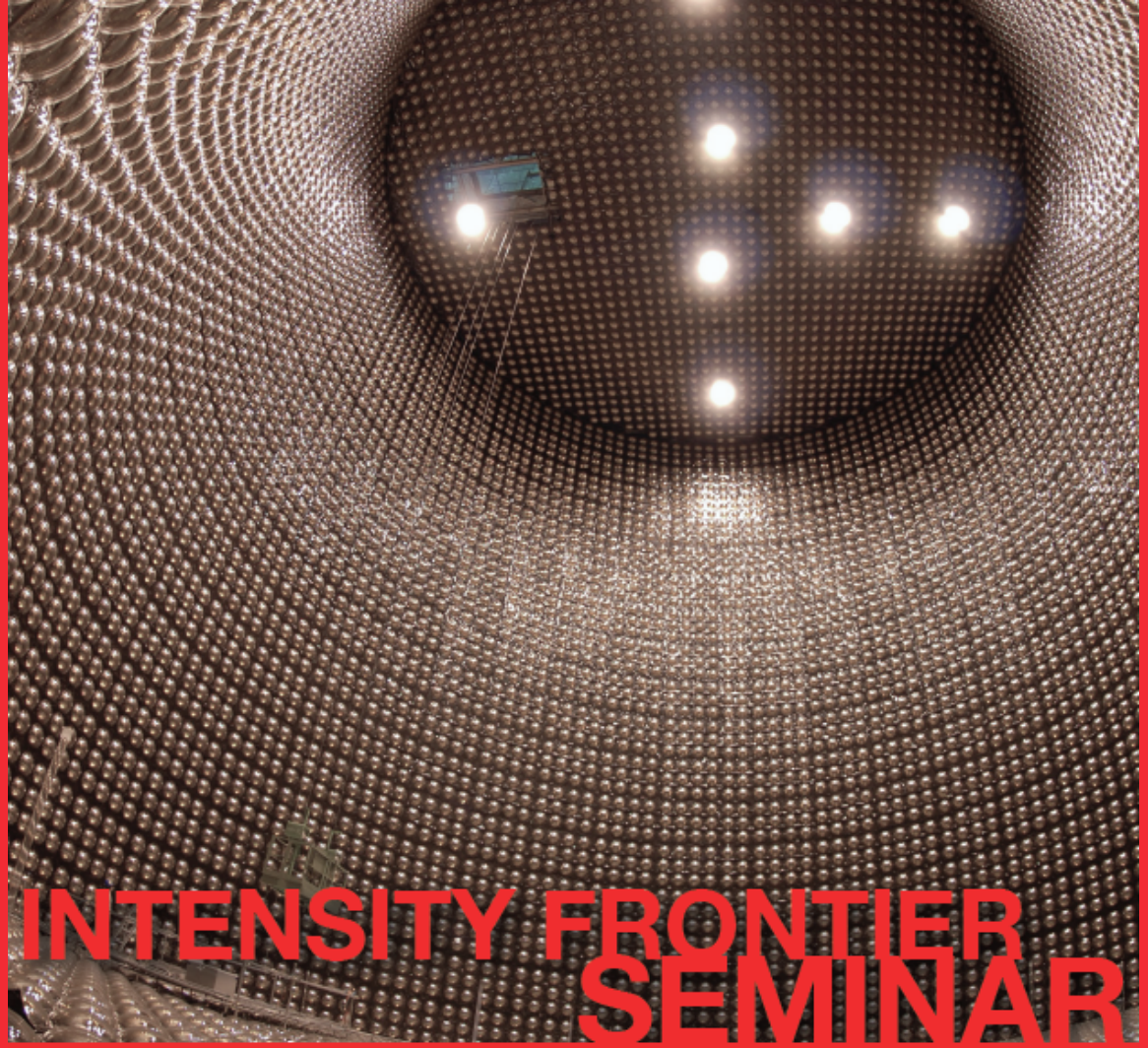


Proton Decay

Professor Ed Kearns, Boston University

11 am, October 31th | Hornet's Nest (WH8XO)

In the Standard Model, proton decay is forbidden by Conservation of Baryon Number

Origins: baryon number conservation formulated by:
Weyl (1929), Stueckelberg (1938), Wigner (1949), Lee & Yang (1950)
to explain stability of matter.

[9] It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino.

E. Wigner (1949)

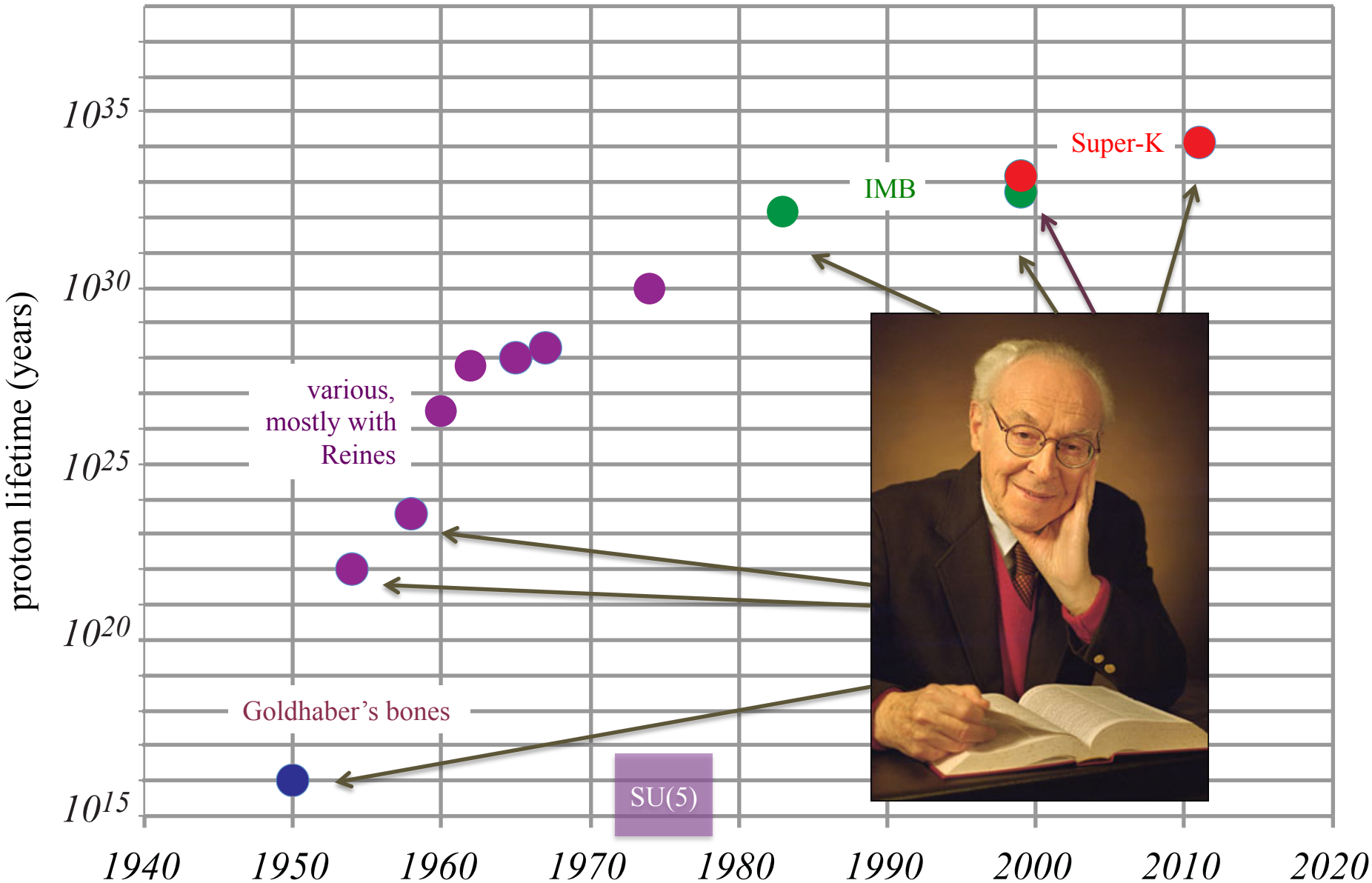
Phenomenological Lifetime Limits (1950s)

Maurice Goldhaber observes that life requires $t > 10^{16}$ years.

"Why did these three learned gentlemen, Weyl, Stückelberg, and Wigner, feel so sure that baryons are conserved? Well, you might say that it's very simple: **they felt it in their bones**. Had their bones been irradiated by the decays of nucleons, they would have noticed effects considerably exceeding "permissible radiological limits" if the nucleon lifetime were $<10^{16}$ years and if at least 10% of the nucleon rest mass were to appear as radiation absorbable in the body. That is a fairly sensitive measurement, but one can do much better by a deliberate experiment."

Goldhaber: Isotope abundance requires $\tau > 10^{23}$ years.

Proton Decay - History



Sakharov Conditions (1960s)

Sakharov, A. JETP 5: 24-27 (1967)

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

Matter-Antimatter asymmetry requires baryon number violation.

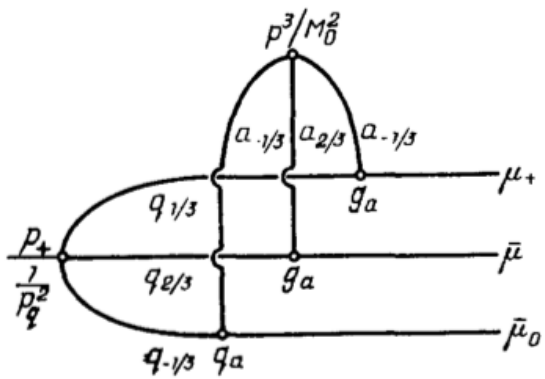


FIG. 1.

Cutting off the logarithmic divergence at $p_q = M_0$, we find the decay probability

$$\omega \sim \frac{m_P^5 g_a^6 [\ln(M_0/m_a)]^2}{M_0^4}.$$

The lifetime of the proton turns out to be very large (more than 10^{50} years), albeit finite.

N.B. May be another *B*-violation process, such as n-nbar oscillation.

Unify Quarks and Leptons

Is Baryon Number Conserved?

Jogesh C. Pati*
International Centre for Theoretical Physics, Trieste, Italy, and Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy, and Imperial College, London, England
(Received 3 August 1973)

Pati – Salam $SU(2)_L \times SU(2)_R \times SU(4)_C$

$$Q = \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}$$

- Leptons are treated as a fourth color
- Explains quantization of electric charge
- Still 3 gauge couplings
- No gauge mediated proton decay

Unify Quarks and Leptons and Forces

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

It makes just one easily testable prediction, $\sin^2\theta_w = \frac{3}{8}$. It also predicts that the proton decays—but with an unknown and adjustable rate.

First Grand Unified Theory (GUT)

Grand Unified Theories

Embed Standard Model SU(3)⊗SU(2)⊗U(1) in a larger symmetry group

E.g. SU(5)

$$\bar{5} = \begin{pmatrix} \bar{d}_g \\ \bar{d}_r \\ \bar{d}_b \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 = \begin{pmatrix} 0 & \bar{u}_b & -\bar{u}_r & -u_g & -d_g \\ & 0 & \bar{u}_g & -u_r & d_r \\ & & 0 & -u_b & -d_b \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L$$

representations

$$24 = \left(\begin{array}{ccc|cc} G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & \bar{X}_1 & \bar{Y}_1 \\ G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & \bar{X}_2 & \bar{Y}_2 \\ G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & \bar{X}_3 & \bar{Y}_3 \\ \hline X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{array}\right)$$

generators

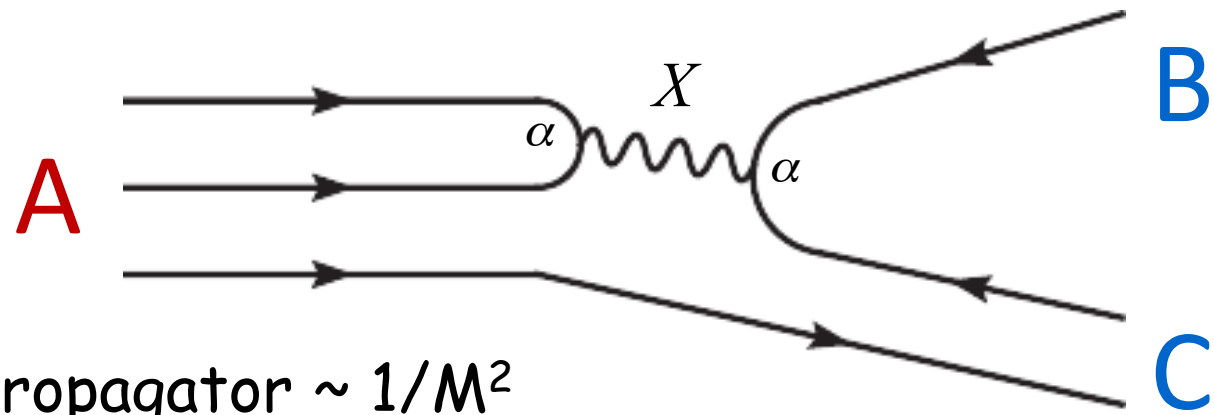
Consequences:

- Single (unified) coupling
- Charge quantization: $Q_d = Q_e/3$, $Q_u = -2Q_d \Rightarrow Q_p = -Q_e$
- New gauge interactions (X, Y bosons) ⇒ proton decay
- Other predictions of SU(5):
  - magnetic monopoles (not found)
  - value of weak mixing angle (not so good)
  - massless neutrinos (oops!)

or SO(10)

$$16 = \begin{pmatrix} \nu_e \\ u_r \\ u_g \\ u_b \\ e^- \\ d_r \\ d_g \\ d_b \\ \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \\ e^+ \\ \bar{u}_r \\ \bar{u}_g \\ \bar{u}_b \\ \bar{\nu}_e \end{pmatrix}_L$$

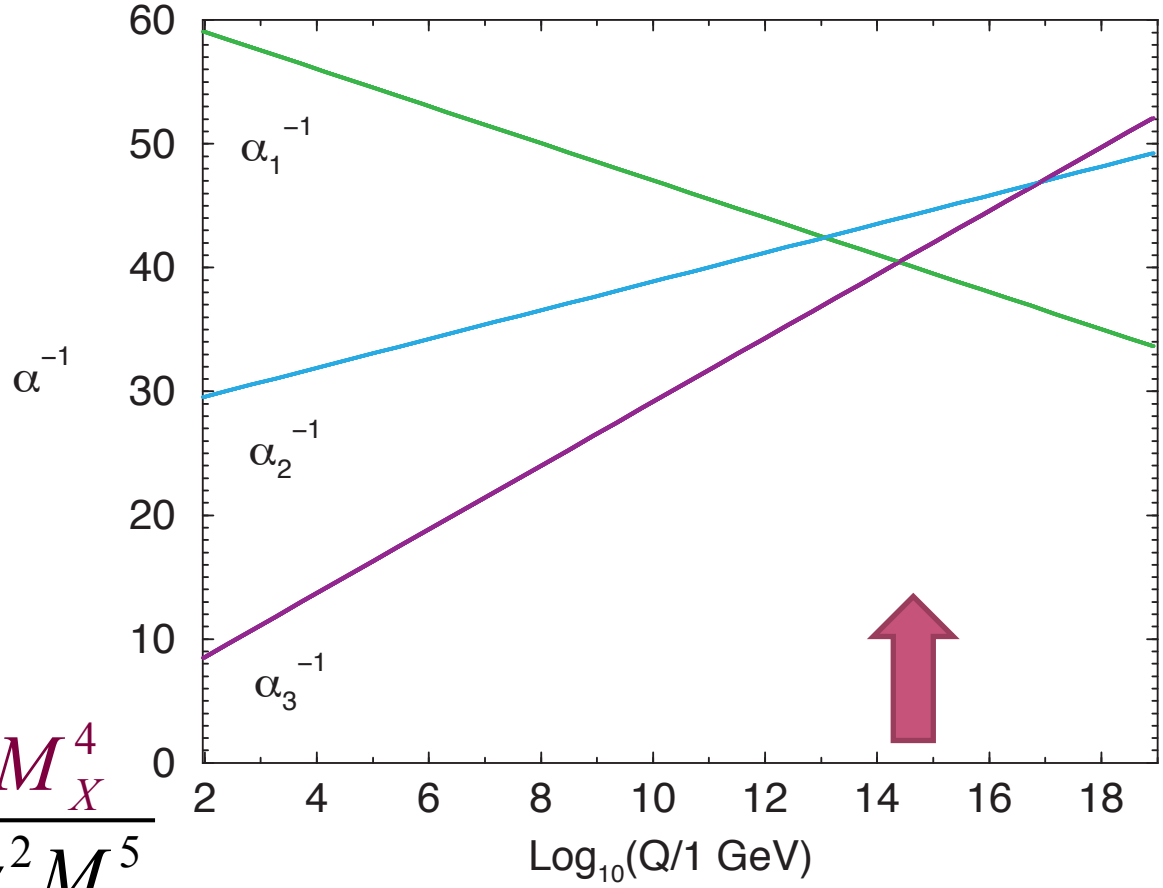
The only way to probe the grand unification scale is by virtual particle exchange



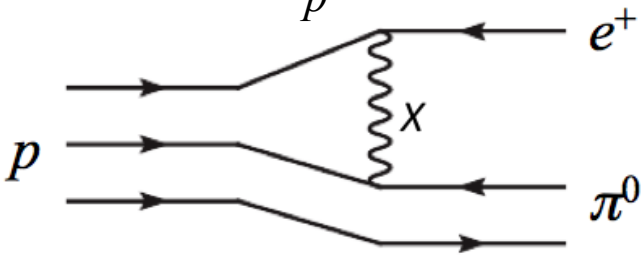
propagator ~ $1/M^2$

$$\Gamma(A \rightarrow BC) = \frac{1}{\tau} \approx \frac{\left|\langle BC | A \rangle\right|^2 \left|\vec{p}_B\right|}{m_A^2} \approx \frac{\alpha^2 m_p^5}{M_X^4}$$

Gauge Coupling Unification



$$\tau \approx \frac{M_X^4}{\alpha^2 M_p^5}$$



$$\tau(e^+\pi^0) = 4.5\times10^{29\pm1.7}\ \textit{years}\ \text{(predicted)}$$

How can we find proton decay if protons live for 10^{31} years?

watch 1 proton for 10^{32} years

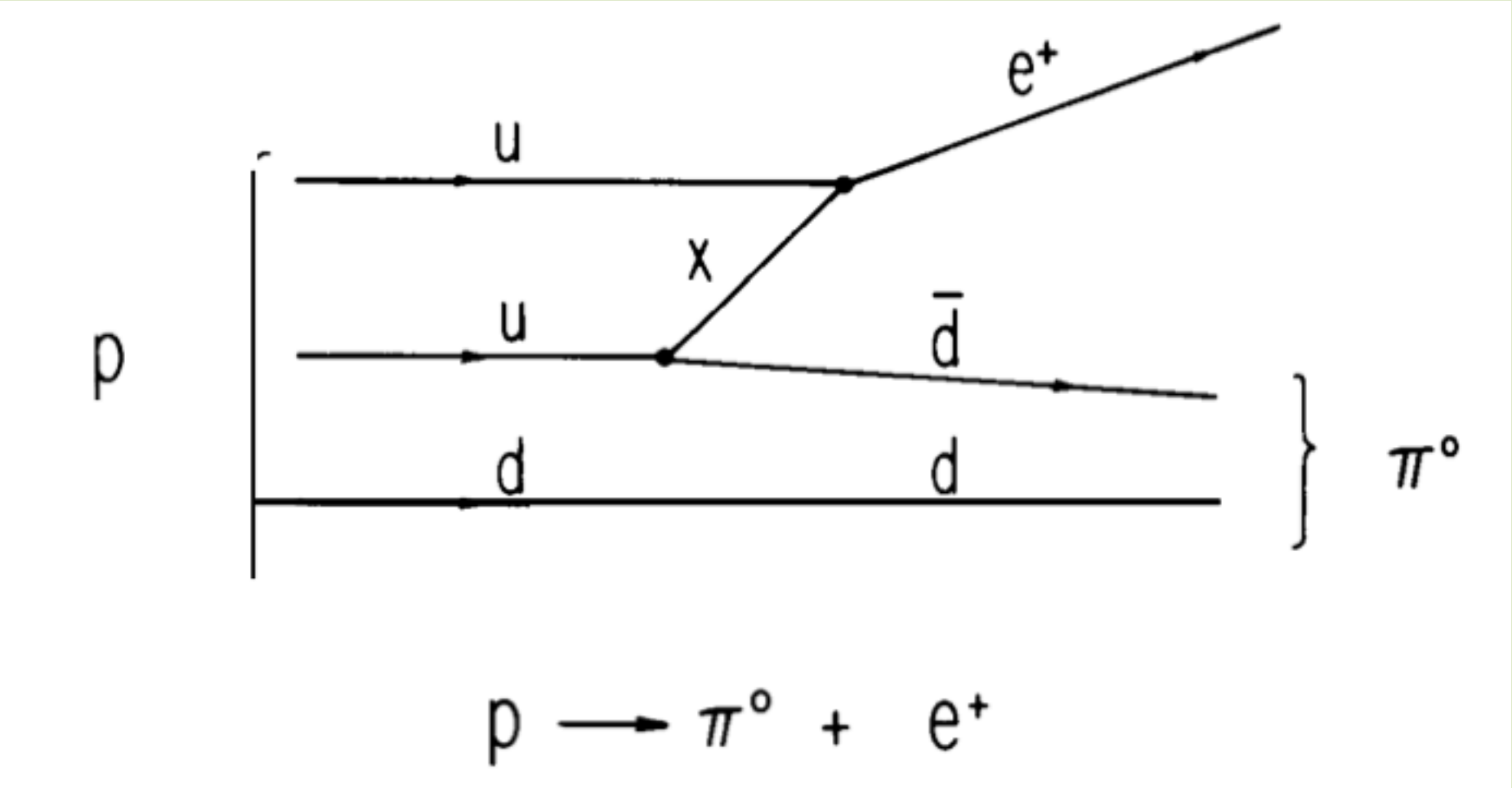
or

watch 10^{32} protons (~kton) for one year

Easy!

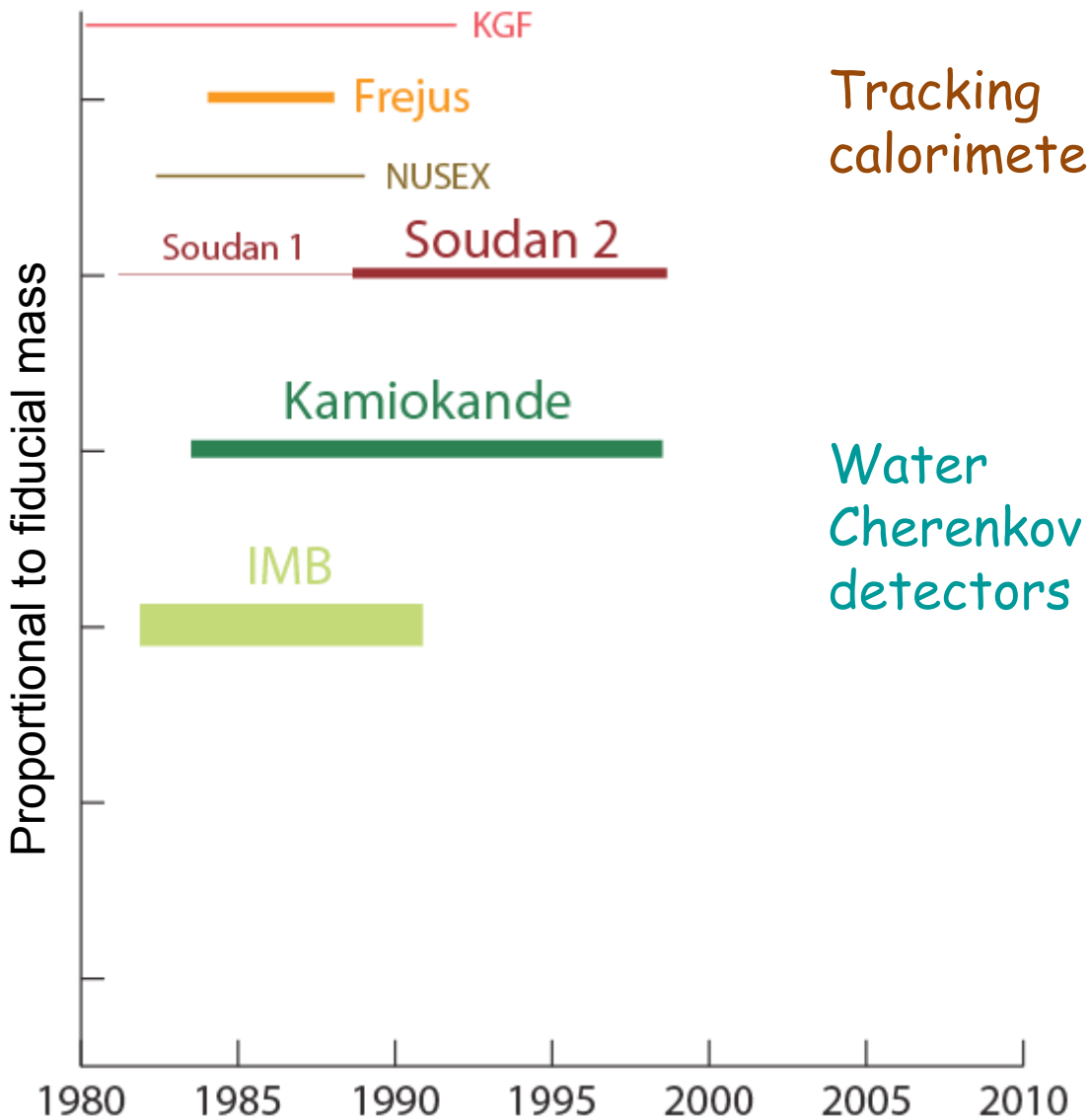
The race was on!! ...

Proton Decay

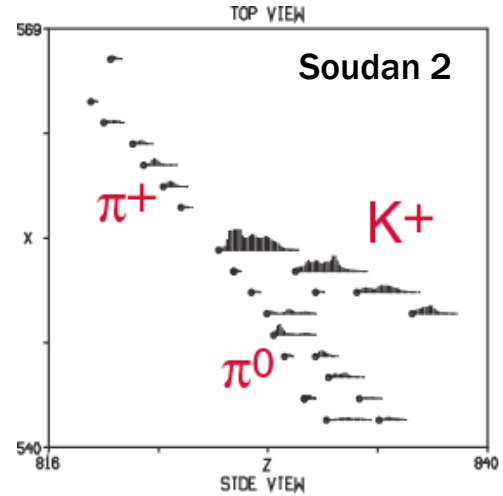


SLIDE FROM ARGONNE IF SNOWMASS MEETING 2013

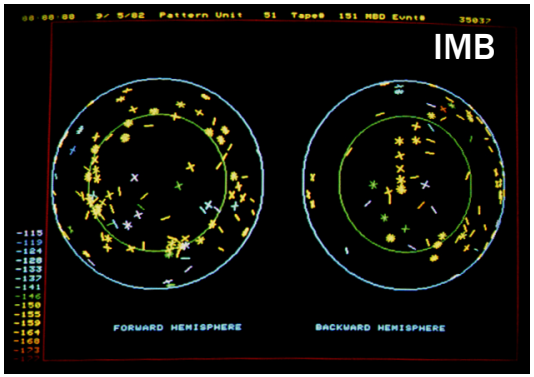
Treasure hunt: from which Nobel Lecture is this diagram taken?



Tracking calorimeters



Water Cherenkov detectors

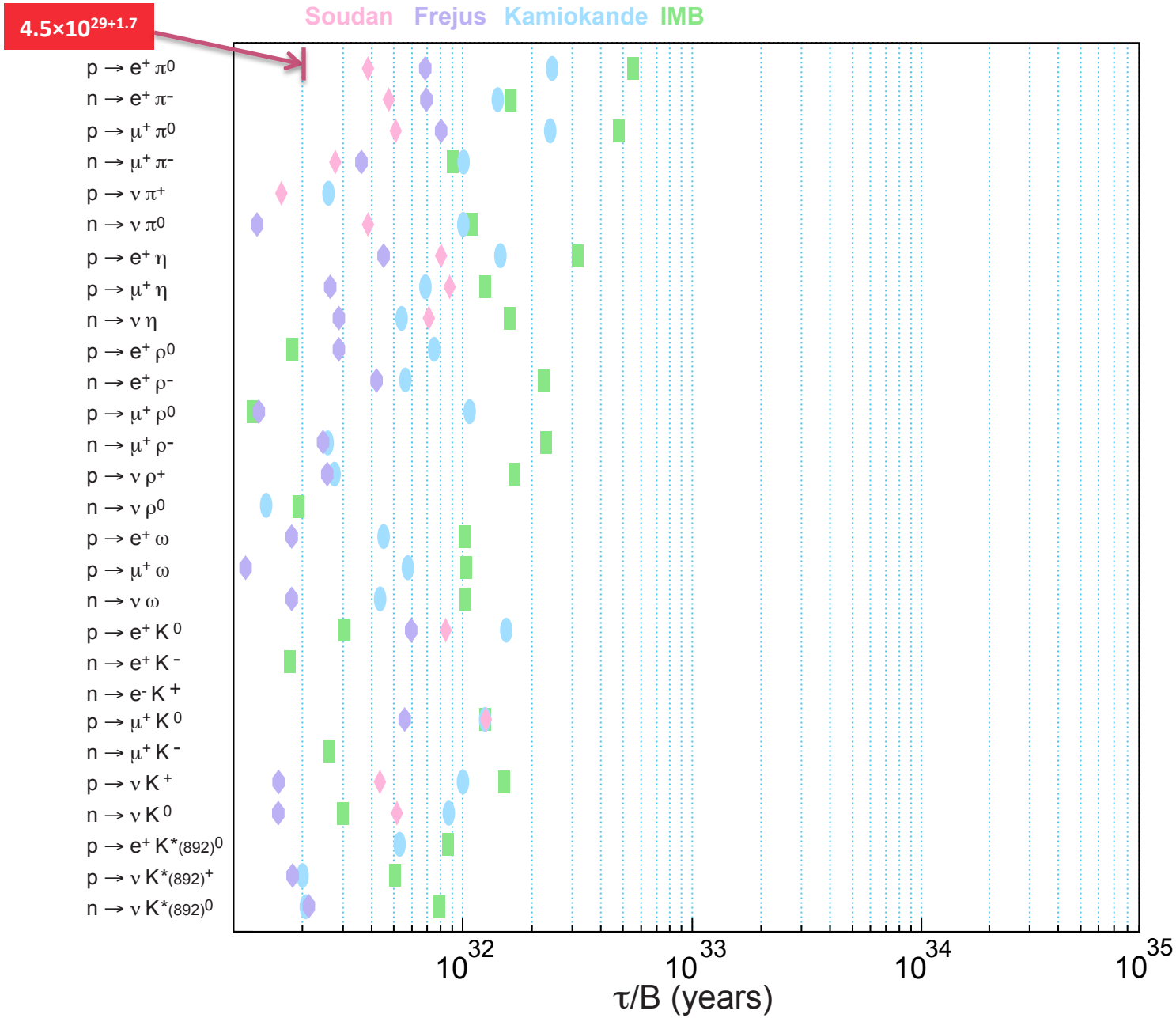


IMB Experiment

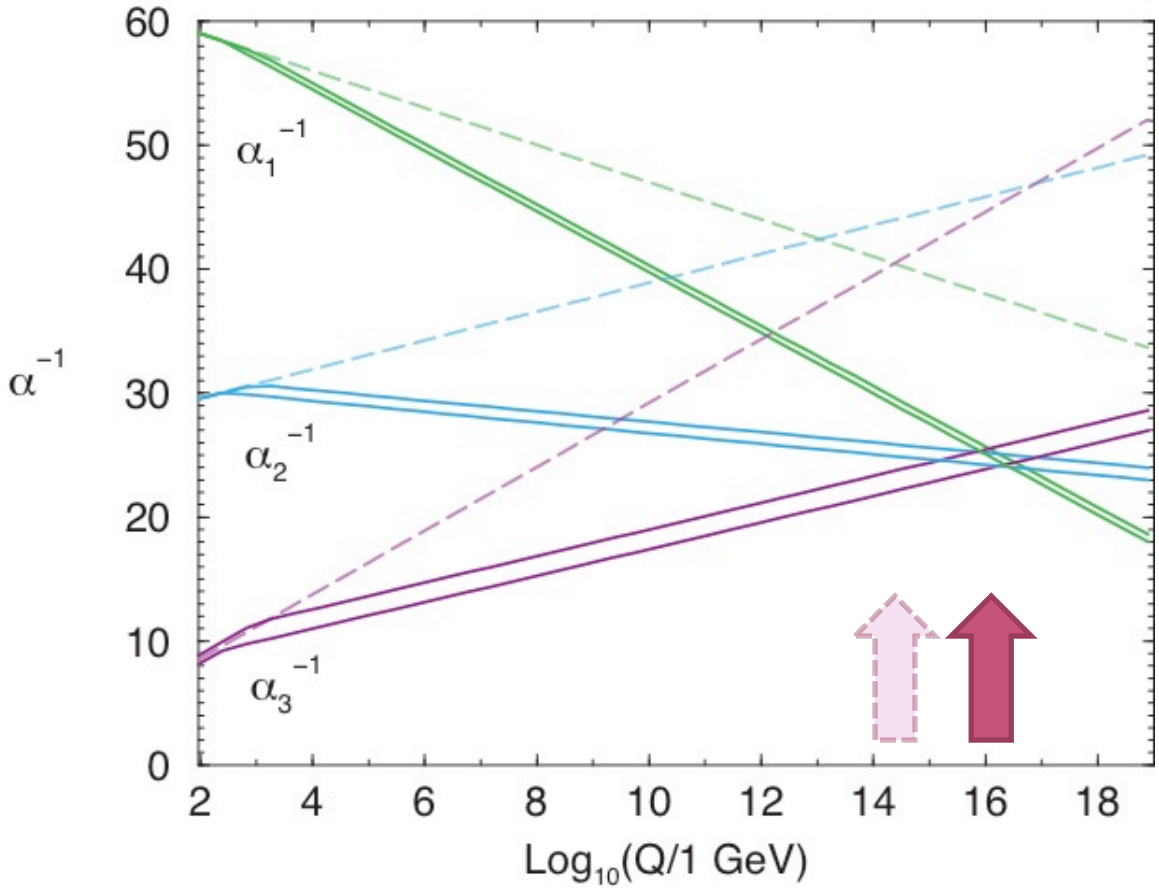
Morton Salt Mine, Ohio
610 meters deep – 1570 mwe
3.3 kton (fiducial volume)
2000 PMTs, 4% coverage
935 events in 851 live-days
no proton decay found
$\tau(e^+\pi^0) > 5.5 \times 10^{32}$ years (1990)

similar results from Kamiokande (1 kton)
both saw SN 1987a, both uncovered atmospheric neutrino anomaly
Kamiokande also measured solar neutrinos

Antilepton + meson, 2-body decay modes, conserves B-L



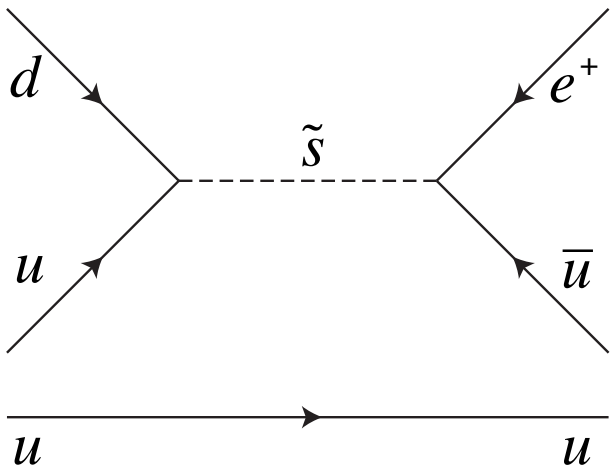
No e^+pi^0 seen -- solved by SUSY



Unification scale pushed up...

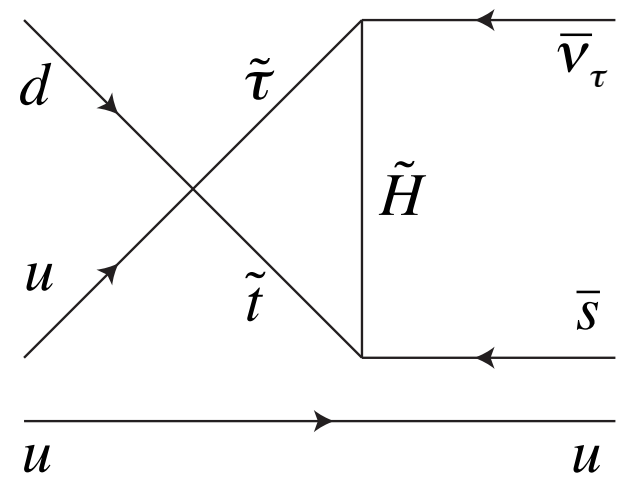
$$\tau(e^+\pi^0) \approx 10^{35-38} \text{ years}$$

Some problems introduced by SUSY …



Rapid proton decay:
Dimension = 4 operators
e.g. $U^c D^c D^c$ and QLD^c
M_{squark} ~ 1 TeV
proton lifetime ~ 1 second
that's OK – **saved by R-parity**

$$\tau \approx \frac{M_{\tilde{s}}^4}{m_p^5}$$



Dimension = 5 operators:
e.g. $QQQL$
proton lifetime ~ $10^{29\text{-}35}$ years
something new to look for!

dimension counting: powers of $(\text{mass})^D$ for each field
fermion D = 3/2, boson D = 1, Lagrangian terms must be D=4

Modes beyond $e^+\pi^0$, νK^+

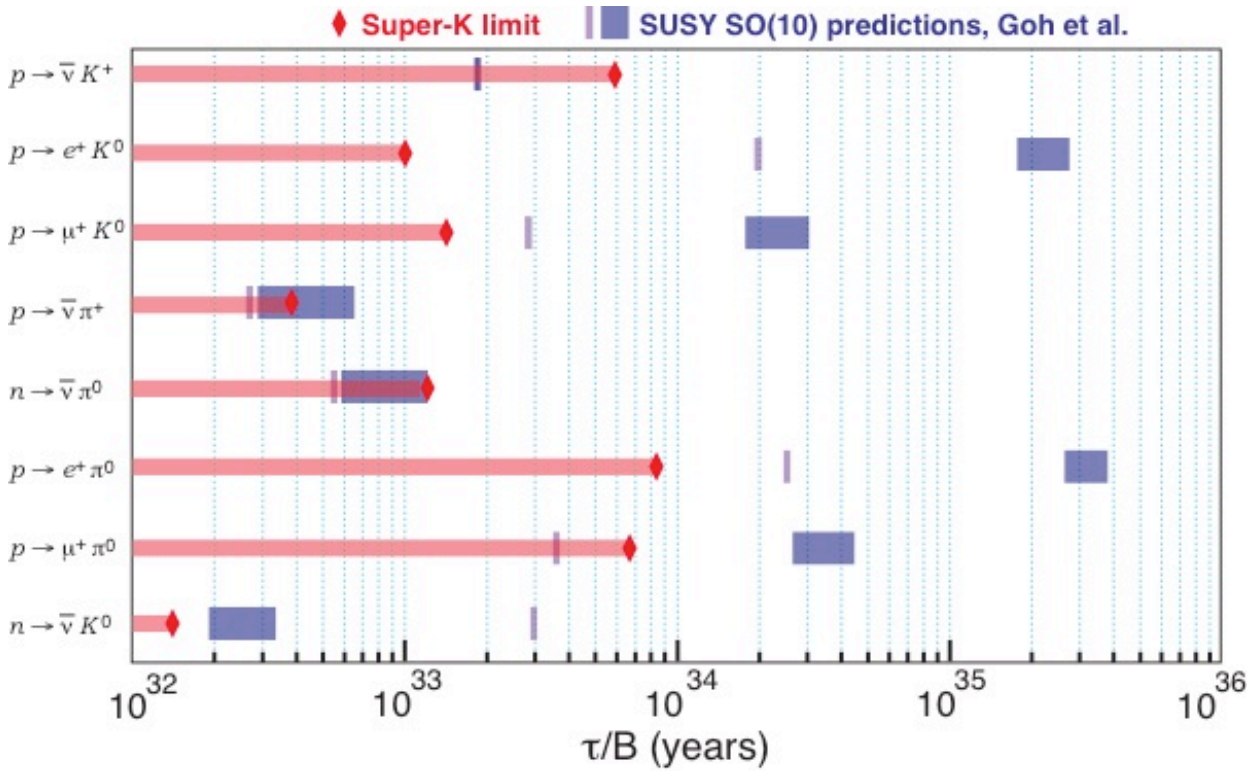
$p \rightarrow antilepton + meson$	BR's predicted
$p \rightarrow \mu^- \pi^+ K^+$	$B+L$ (many other modes)
$n \rightarrow \bar{n}$	$\Delta B = 2$, TeV < scale < GUT
$pp \rightarrow K^+ K^+$	$\lambda''_{uds} < 10^{-8}$
$p \rightarrow e^- \pi^+ \pi^+ \nu\, \nu$	6 dimensions
$n \rightarrow \nu\, \nu\, \nu$	invisible
$p \rightarrow e^+ \nu\nu$	$3-body$

there is plenty to look for and we should not assume too much ...

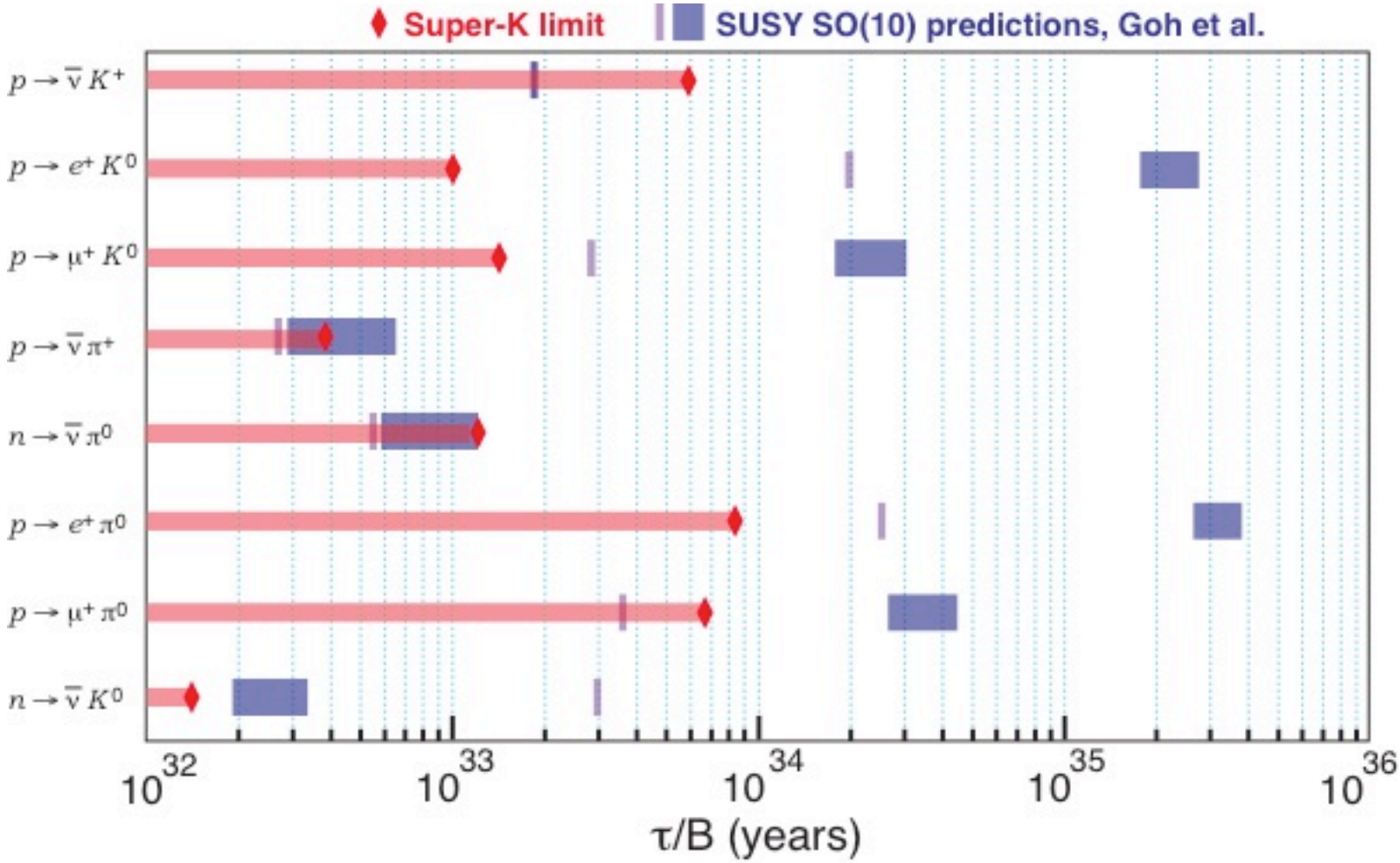
Combining searches: model dependent

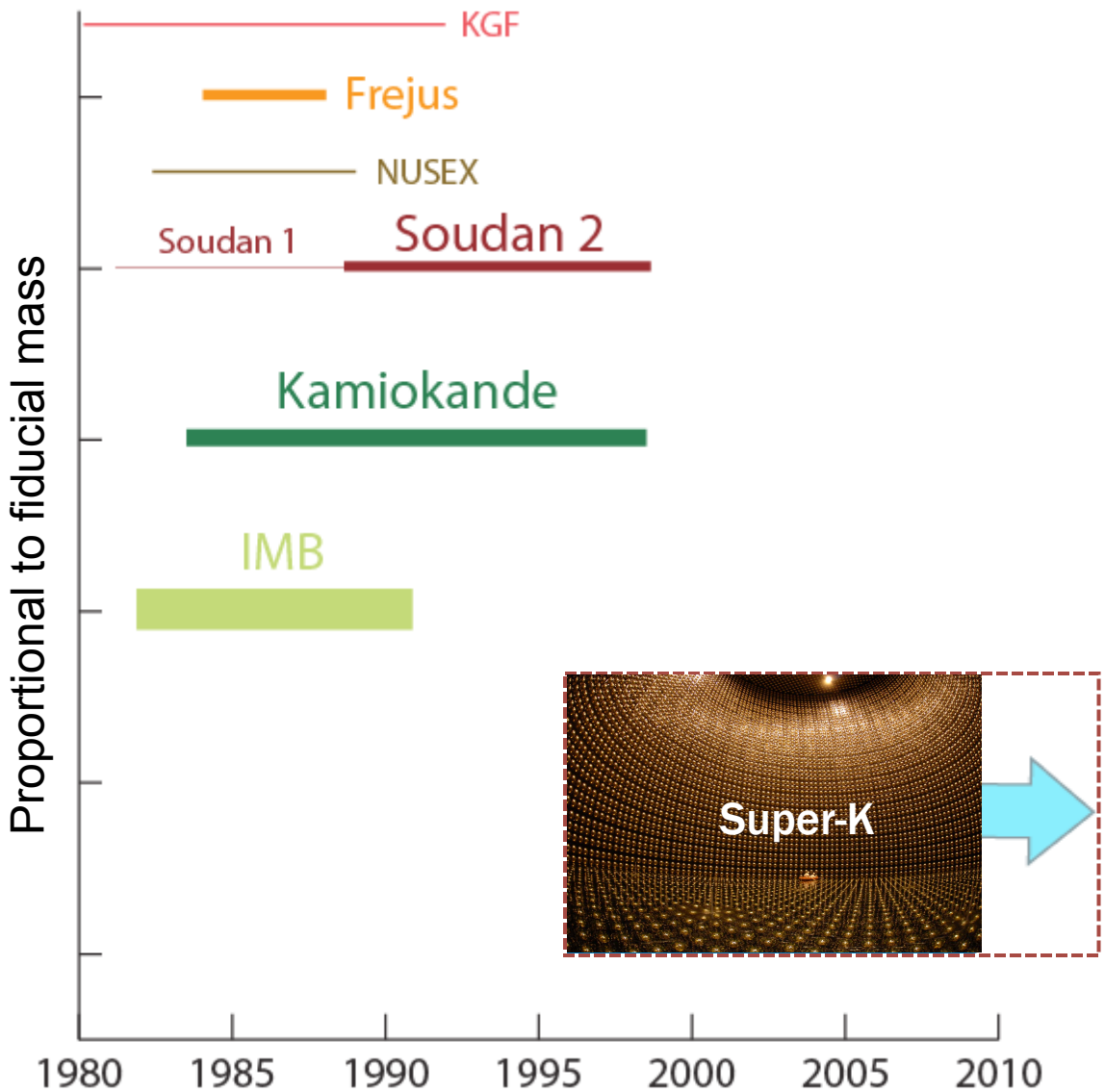
SUSY SO(10), B-L broken by 126-Higgs†

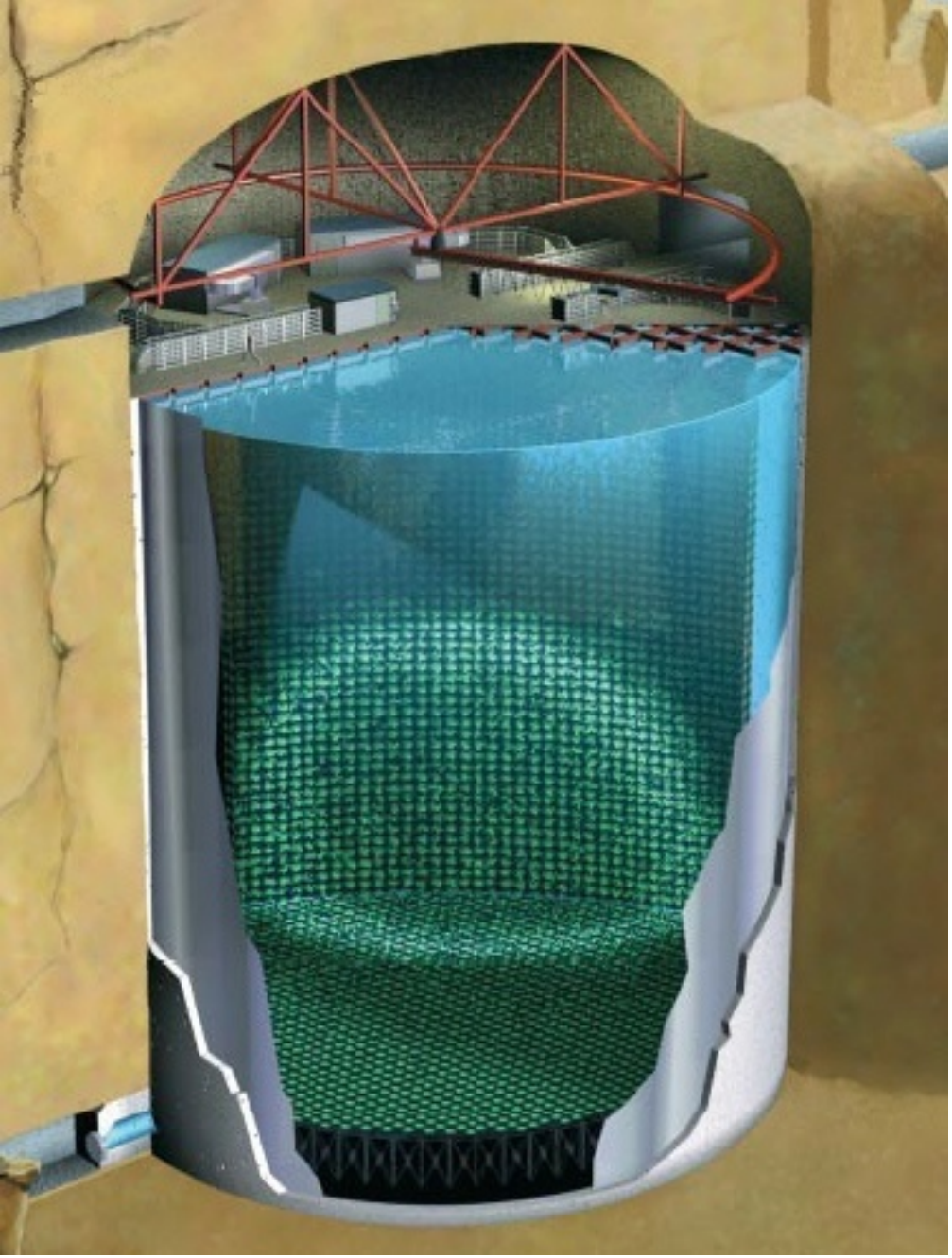
- predicts neutrino mixing well
- scan over parameter space – find unconstrained branching fraction
  - case 1: maximize $n \rightarrow \nu\, \pi^0$, case 2: maximize $n \rightarrow \nu\, K^0$
  - N.B.: old $\nu\, K^+$ limit used as fixed constraint



† H.S.Goh, R.N.Mohapatra, S.Nasri, S-P. Ng, Phys Lett B587:105-116 (2004)


Super-K limit
SUSY SO(10) predictions, Goh et al.
$p \to \bar{\nu} K^+$
$p \to e^+ K^0$
$p \to \mu^+ K^0$
$p \to \bar{\nu} \pi^+$
$n \to \bar{\nu} \pi^0$
$p \to e^+ \pi^0$
$p \to \mu^+ \pi^0$
$n \to \bar{\nu} K^0$
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
τ/B (years)


KGF
Frejus
NUSEX
Soudan 1
Soudan 2
Kamiokande
IMB
Super-K
Proportional to fiducial mass
1980
1985
1990
1995
2000
2005
2010



Super-Kamiokande

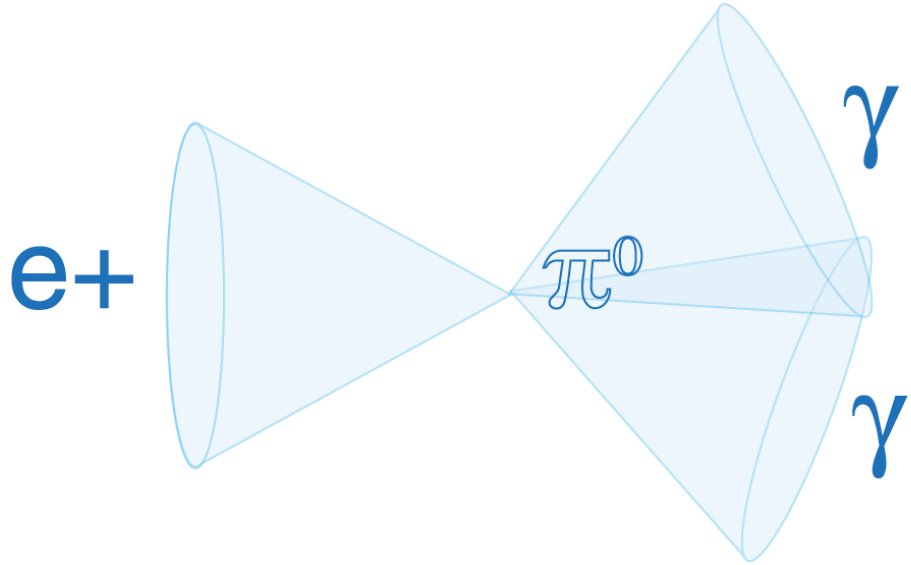
22.5 kton fiducial volume
$7.5\times10^{33}\,p + 6\times10^{33}\,n$

SK-I: 1996 - 2001
11146 50-cm inner PMTs , 40% coverage
1885 20-cm outer PMTs

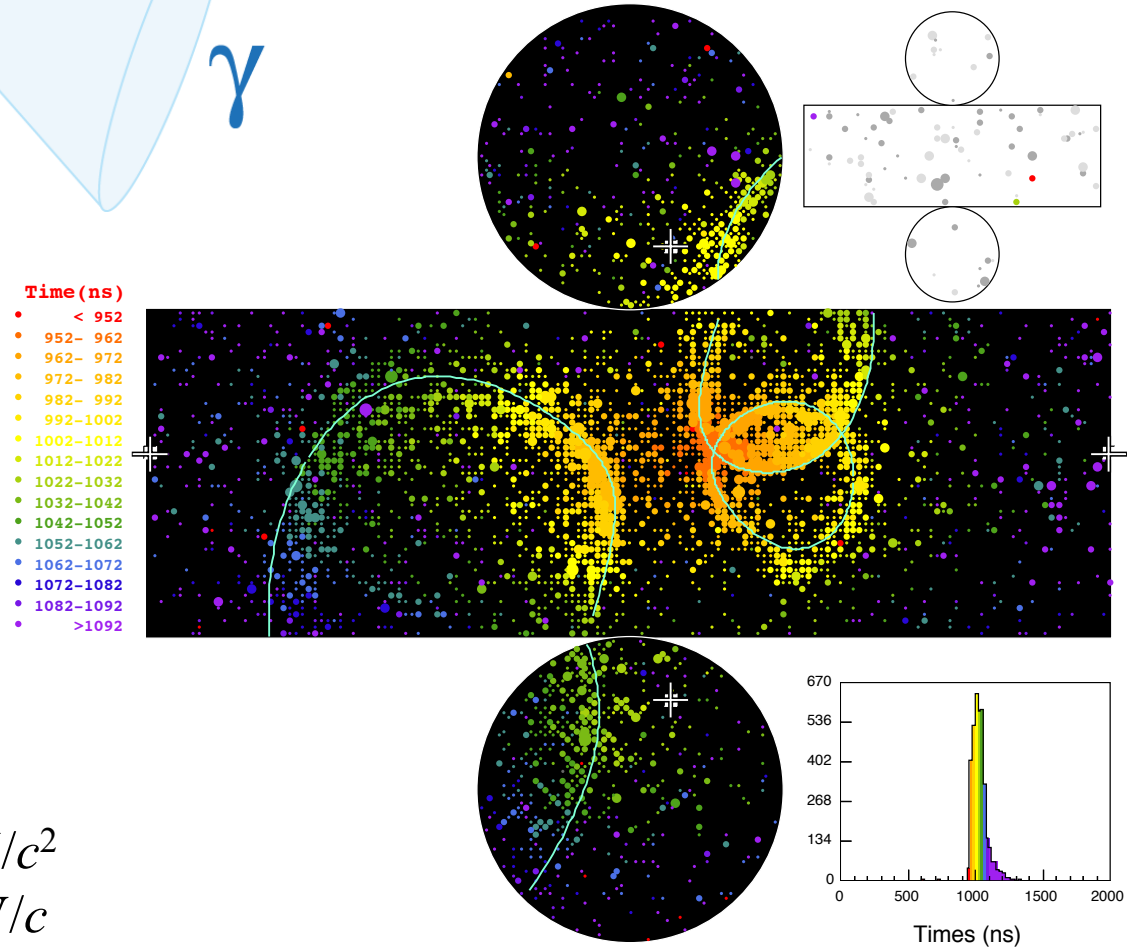
SK-II: Jan 2003 - Oct 2005
Recovery from accident
5182 50-cm inner PMTs
Acrylic + FRP protective
Outer detector fully restored

SK-III: May 2006 - August 2008
Restored 40% coverage
Outer detector segmented (top | barrel | bottom)

SK-IV: September 2008 -
SK-IV Replace all electronics – 2008
T2K beam – late 2009
Add gadolinium – next ??



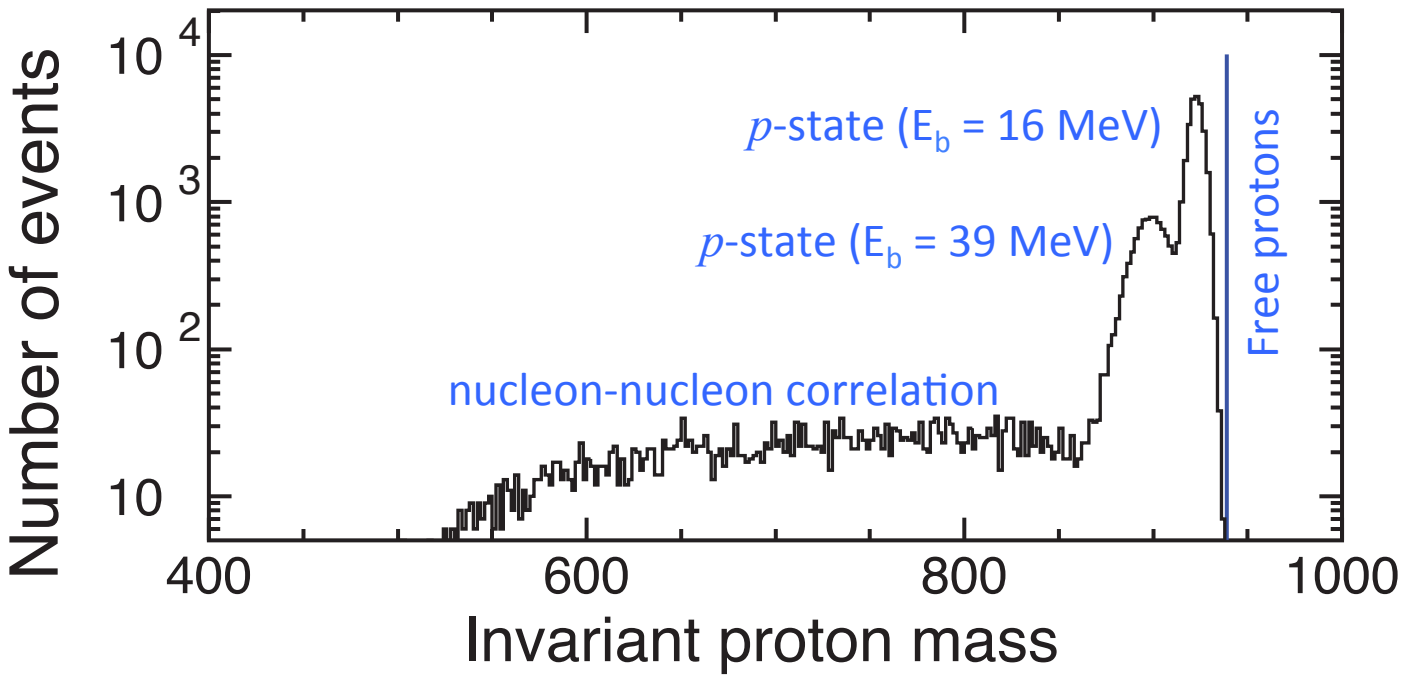
$$p \rightarrow e^+ \pi^0$$



Good event criteria:

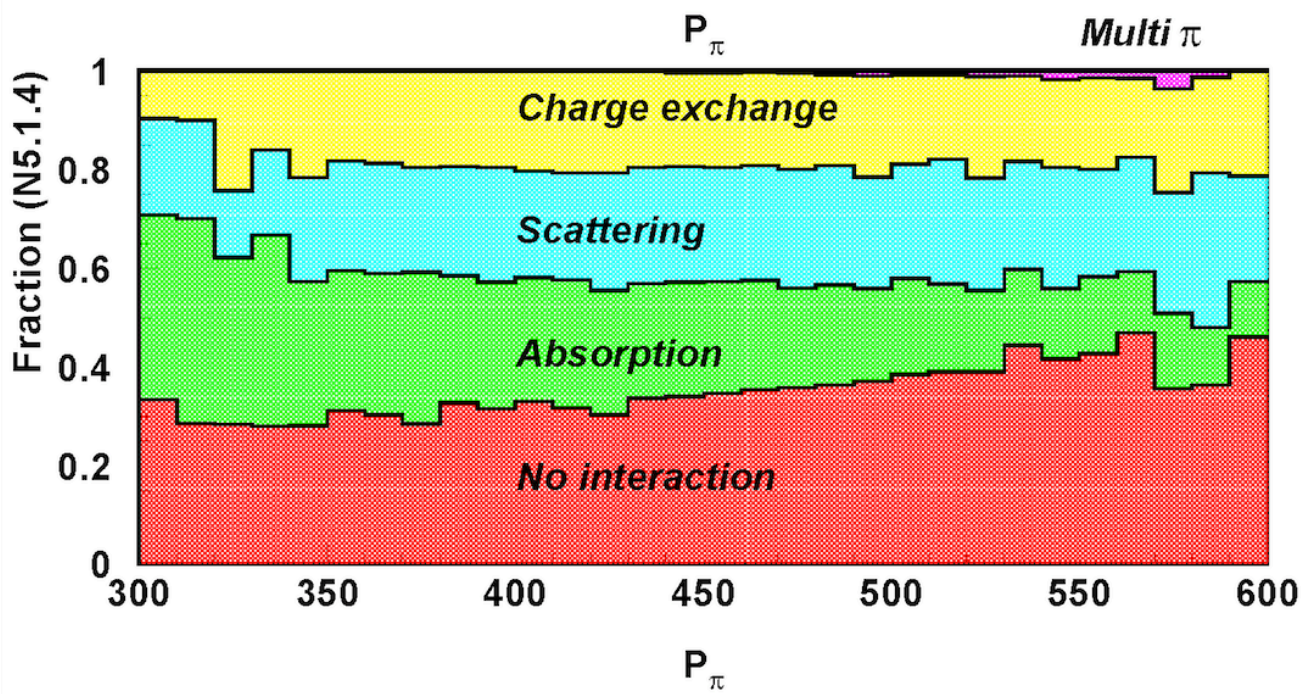
- Fully contained
- Fiducial volume
- 2 or 3 rings
- All rings are EM showers
- π^0 mass 85-185 MeV/c^2
- No μ-decay electrons
- Mass range 800-1050 MeV/c^2
- Net momentum < 250 MeV/c

Proton Decay Signal Prediction (Monte Carlo)



- Effective mass in ^{16}O
- Correlation with other nucleons
- Fermi motion – by shell
- Initial position (Woods-Saxon)
- Nuclear de-excitation γ
- pion-nuclear interactions
  - Elastic Scattering
  - Charge Exchange
  - Absorption

Proton Decay Signal Prediction (Monte Carlo)

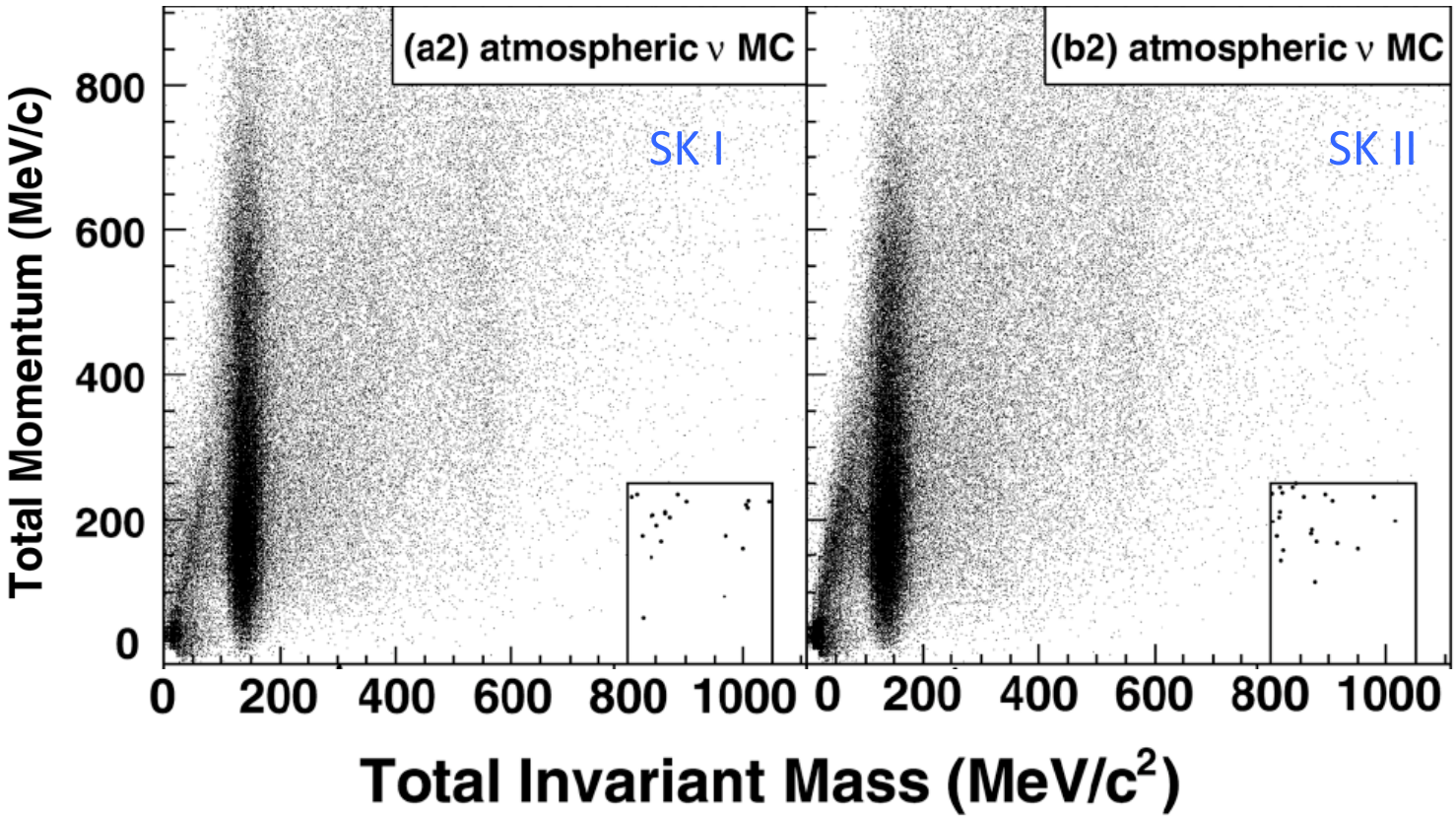


- Effective mass in ^{16}O
- Correlation with other nucleons
- Fermi motion – by shell
- Initial position (Woods-Saxon)
- Nuclear de-excitation γ
- pion-nuclear interactions
  - Elastic Scattering
  - Charge Exchange
  - Absorption

efficiency ~ 40% (new treatment, 2013)
main source of inefficiency:
π^0 absorption in ^{16}O nucleus
Total systematic uncertainty in efficiency 44%

Atmospheric Neutrino Background

500 years equivalent

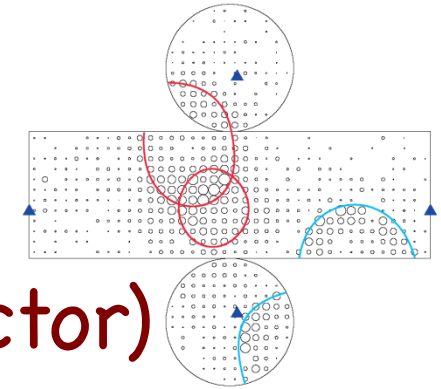


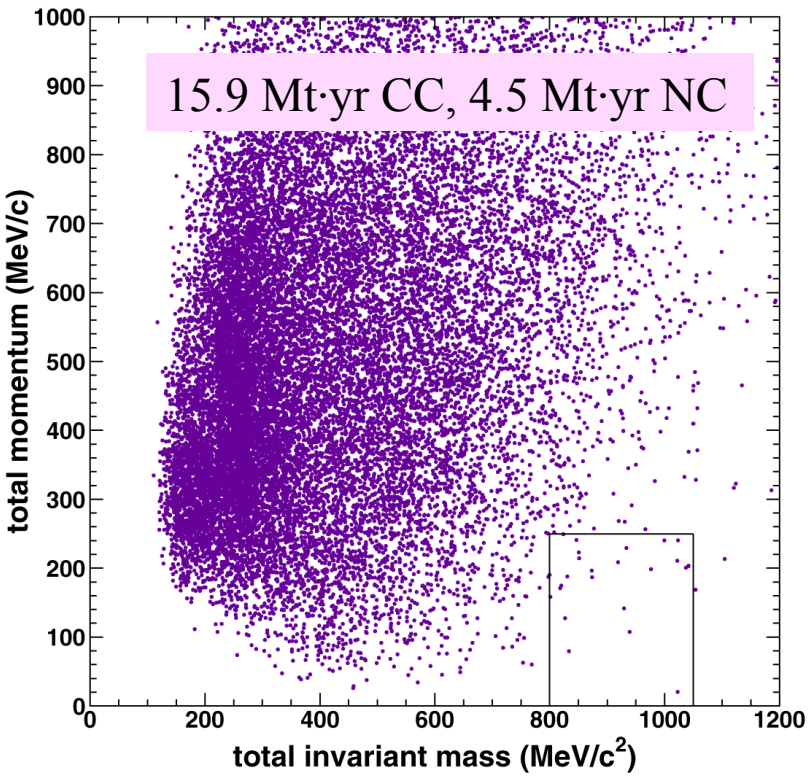
Handful of events survive 500 yr MC

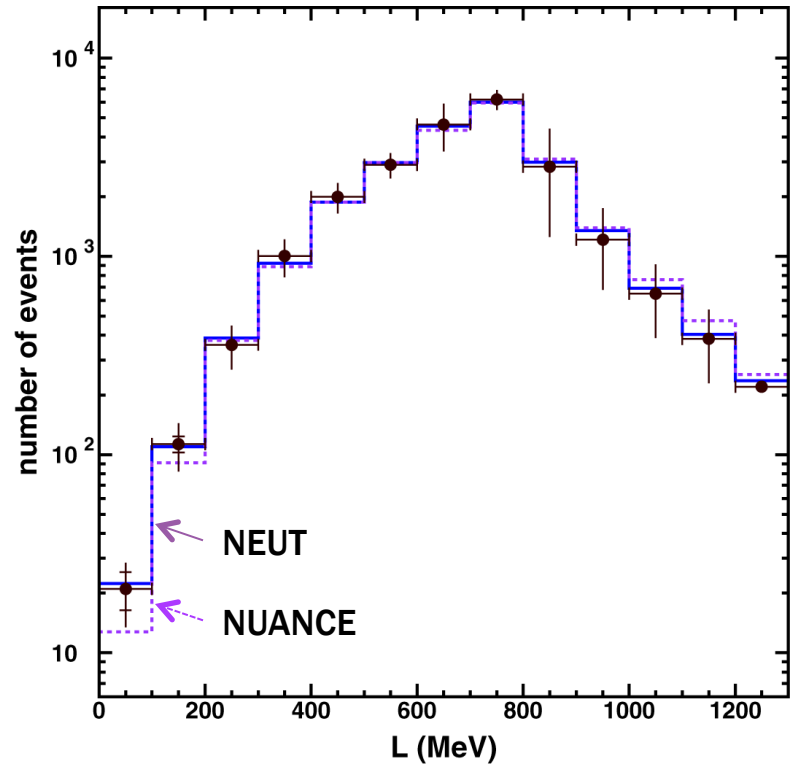
- Neutrino Flux (E, flavor)
- Cross sections:
  - quasielastic
  - 1-π, multi-π
  - DIS
- Pauli blocking
- Intranuclear scattering
- ν oscillations

$$2.7 \pm 0.3 \pm 1.2 \quad \text{events/Mton/yr}$$

Direct measurement of proton decay background using K2K neutrino beam (1KT near detector)



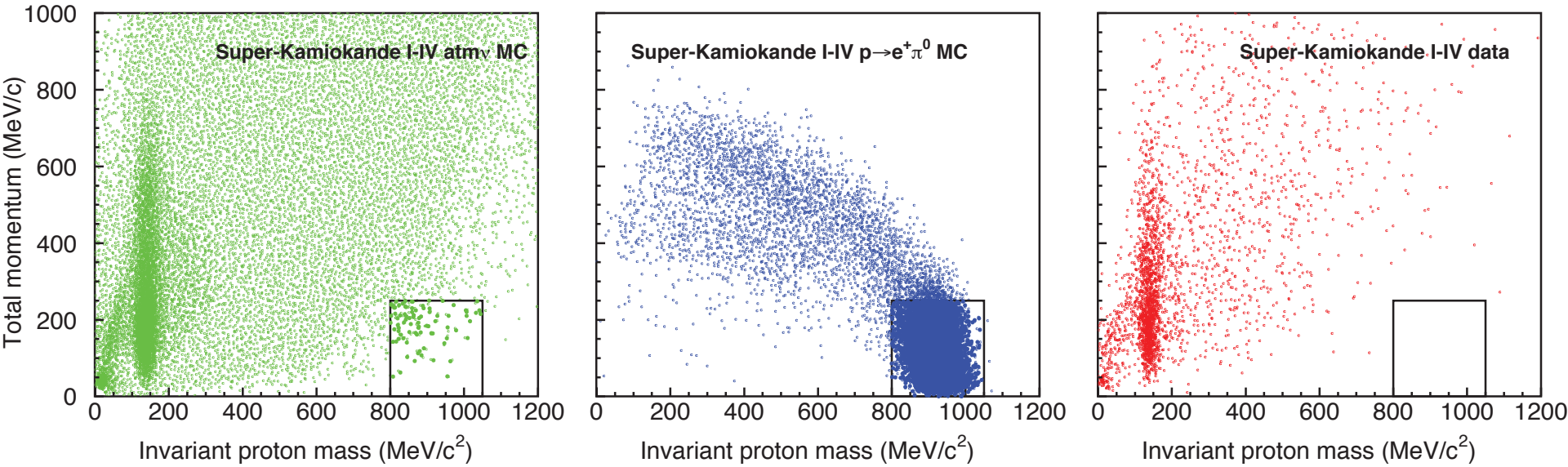




$$e^+\pi^0 \text{ BG} = 1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{sys.}) \text{ evts/Mt} \cdot \text{yr}$$

Super-K I+II+III+IV 260 kt-yr combined result

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



Result: no candidate proton decay events.

Setting a limit

a simple calculation of the rate if we measured something:

$$\frac{\tau}{B} = \frac{\lambda\varepsilon}{n-b}$$

n = number of observed events

b = expected number of background events

λ = exposure = $N_{proton} \cdot \Delta t$

ε = efficiency

0 events detected
0.7 expected BG but doesn't matter
260 kton y
40% efficiency

$$\frac{\tau}{B} = \frac{\lambda\varepsilon}{S_{90}}$$

$$S_{90} = \frac{\int_0^{S_{90}} P_{poiss.}(n, x+b)\,dx}{\int_0^{\infty} P_{poiss.}(n, x+b)\,dx}$$

⇐ a simple calculation of a 90% CL limit, but...
does not take into account n=0 properly (see F&C)
and does not take into account systematic uncertainty

$$\tau / B > 1.5 \times 10^{34} \text{ years}$$

treatment of limit using Bayes theorem to incorporate systematic uncertainty:

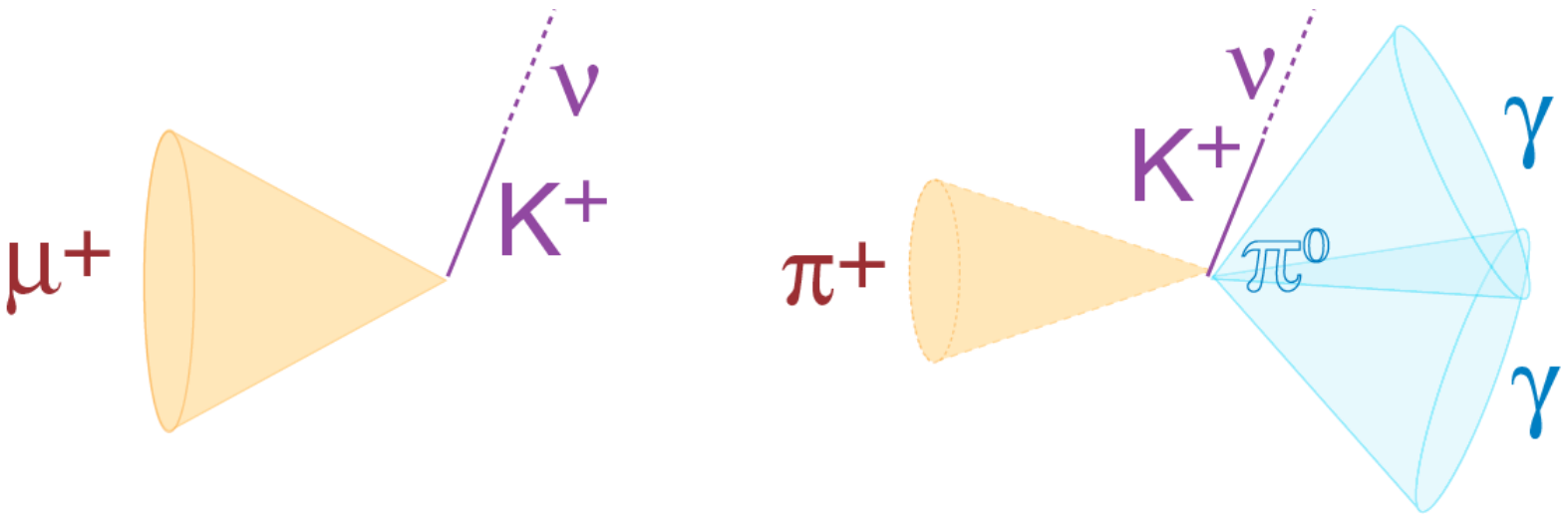
$$P(\Gamma \mid n) = \iiint \frac{e^{-\Gamma\lambda\varepsilon + b}(\Gamma\lambda\varepsilon + b)^n}{n!} P(\Gamma)\, P(\lambda)\, P(\varepsilon)\, P(b)\, d\Gamma\, d\lambda\, d\varepsilon\, db$$

$$\boxed{\tau / B(e^+\pi^0) > 1.4 \times 10^{34} \text{ years}}$$

Super-K preliminary 260 kton y

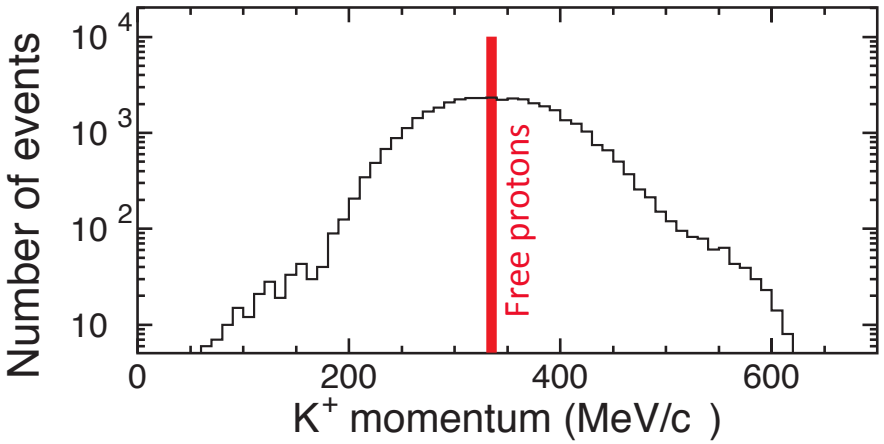
$p \rightarrow K^+ \nu$

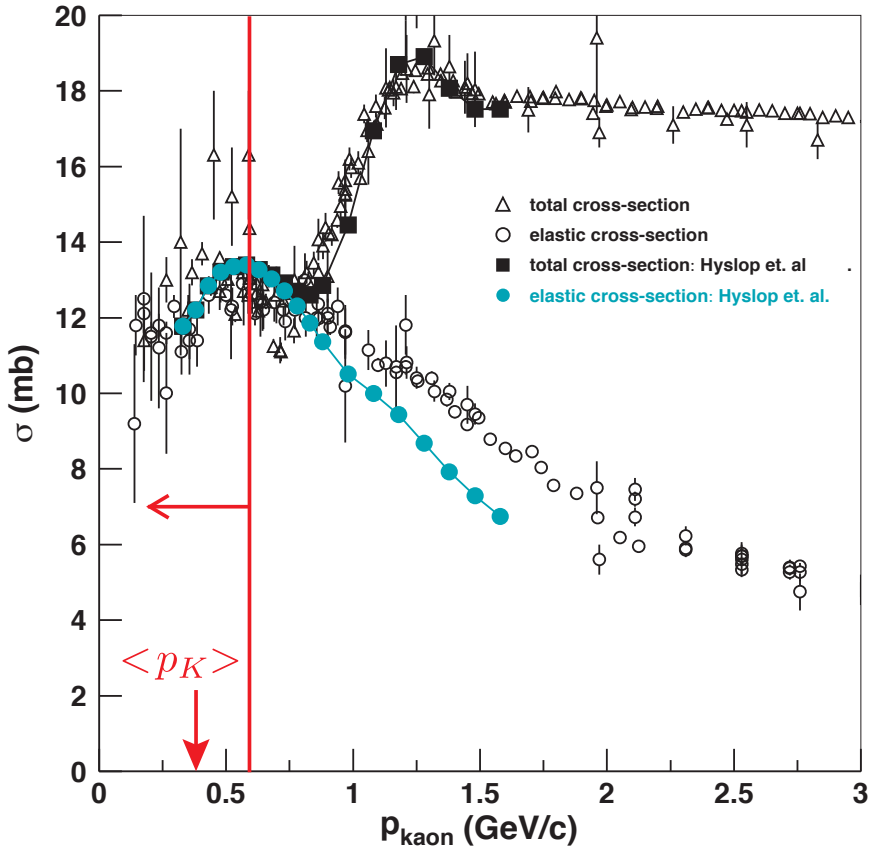
$K^+ \rightarrow \pi^+ \pi^0$	21%
$K^+ \rightarrow \mu^+ \nu_\mu$	65%



Nuclear interaction is negligible
Kaon momentum is 340 MeV/c: is below Cherenkov threshold of 740 MeV/c
Essentially a search for kaon decay at rest

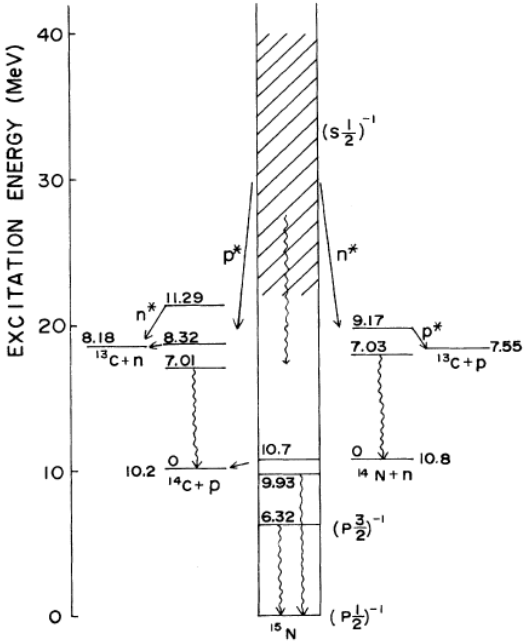
Kaon simulation





Kaon escapes nucleus > 99.7% of the time

Kaon decays at rest 89% of the time



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

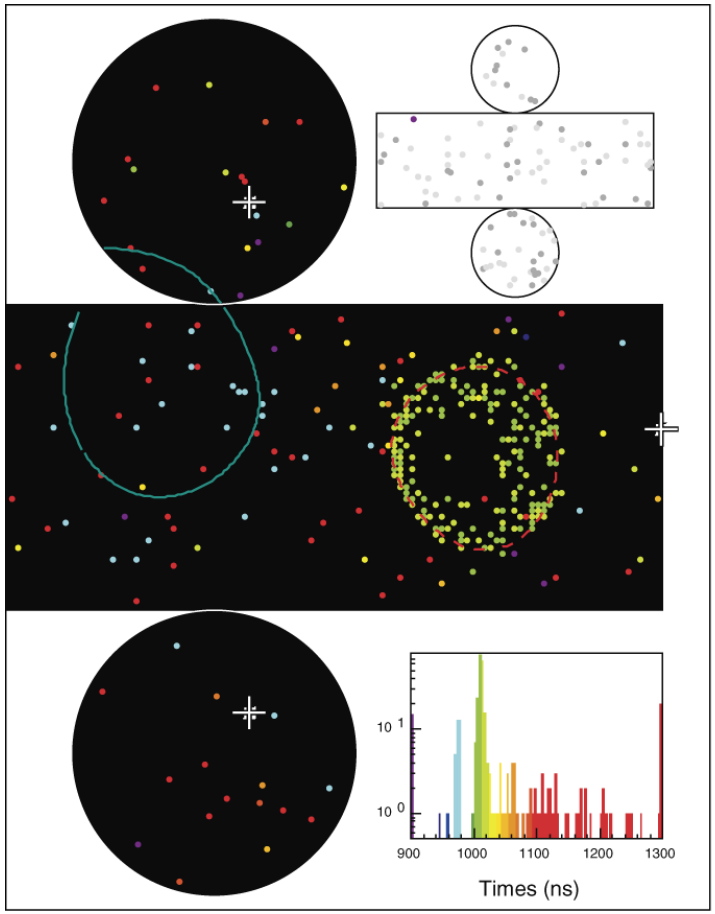
some gammas

few neutrons

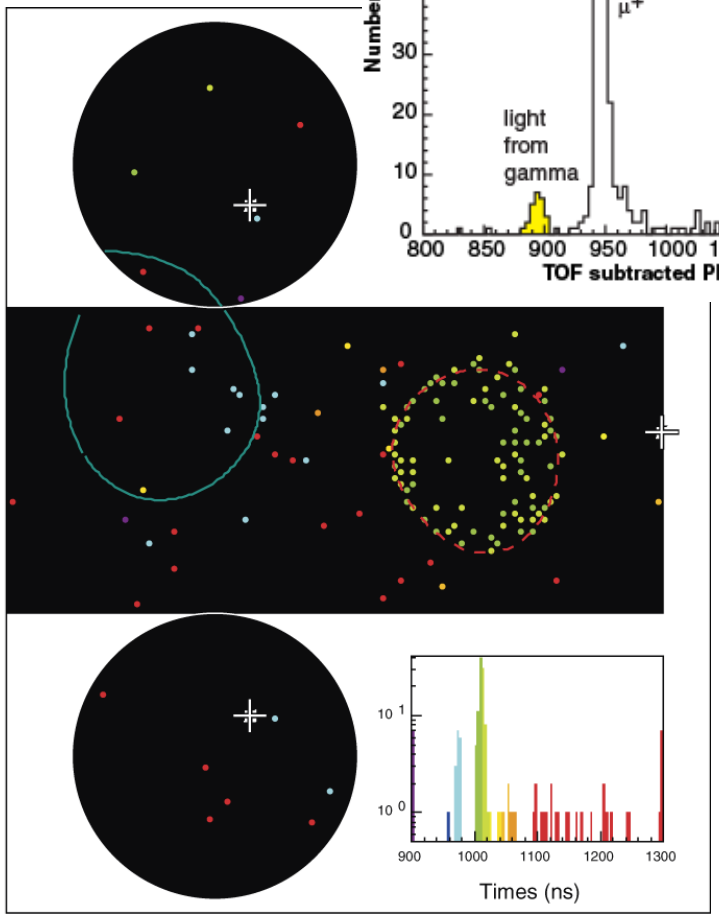
H. Ejiri Phys. Rev. C48 (1993)

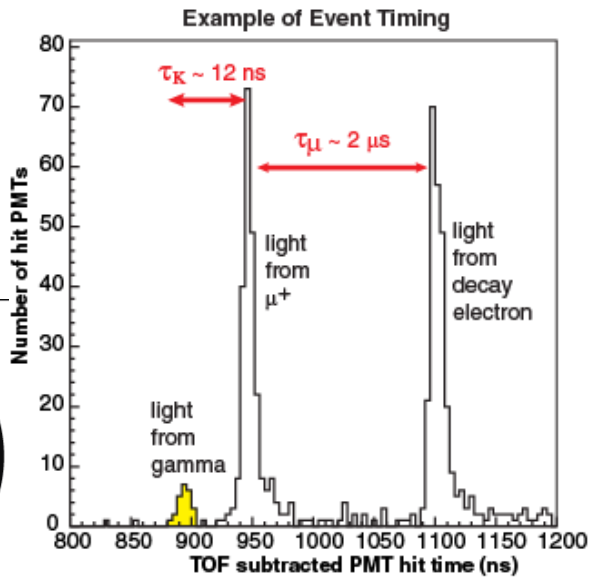
Prompt-gamma tag for ^{16}O

SK I



SK I x 0.5 = SK II





Super-K I+II+III+IV 260 kt-yr combined result

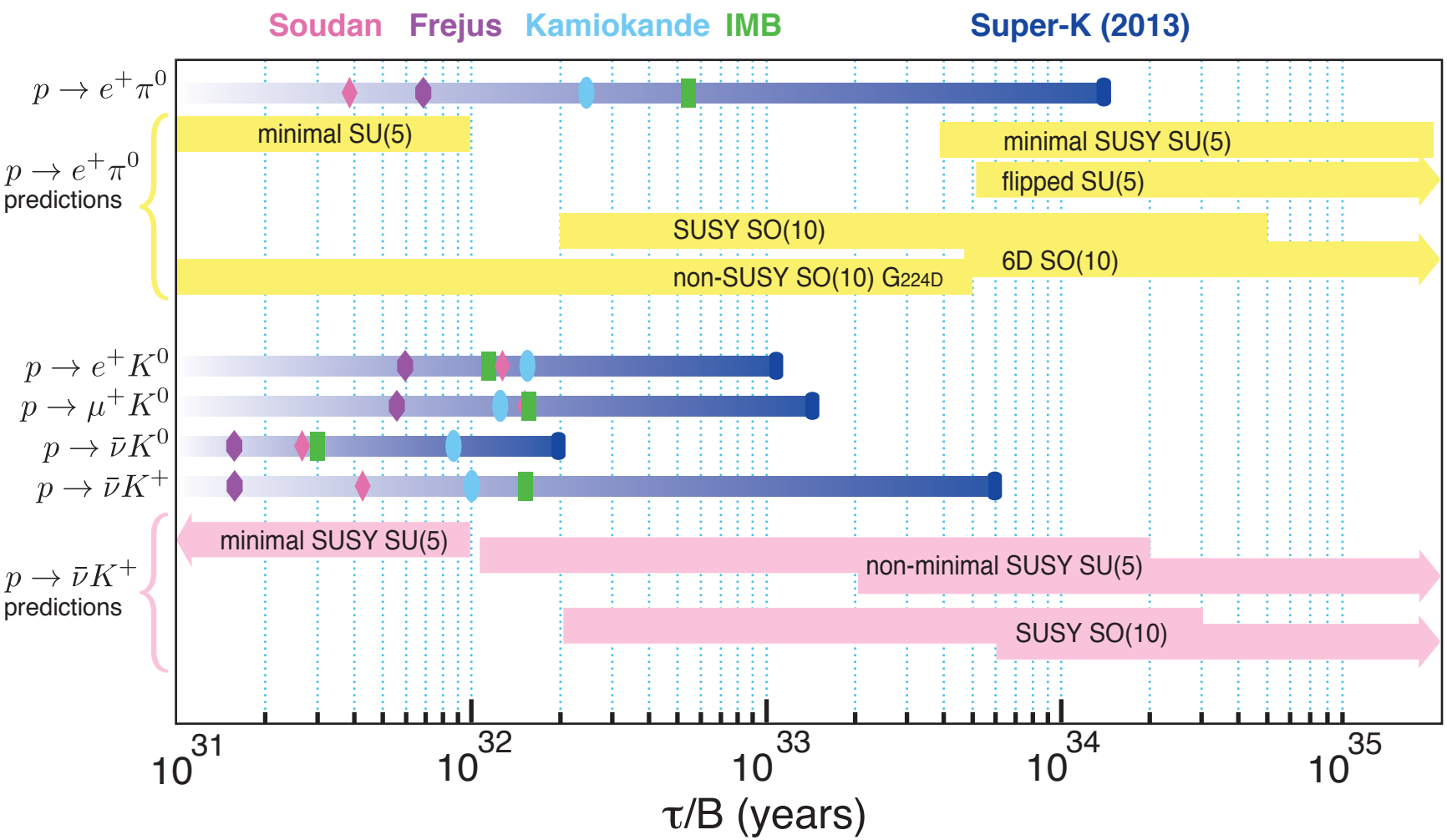
$$p \to \nu K^+$$

γ-tag and $\pi^+\pi^0$	SK1	(20% coverage) SK2	SK3	(new electronics) SK4
Efficiency	15.7 %	13.0 %	15.6 %	19.1 %
Background rate (/100 kty)	0.28	0.62	0.31	0.35

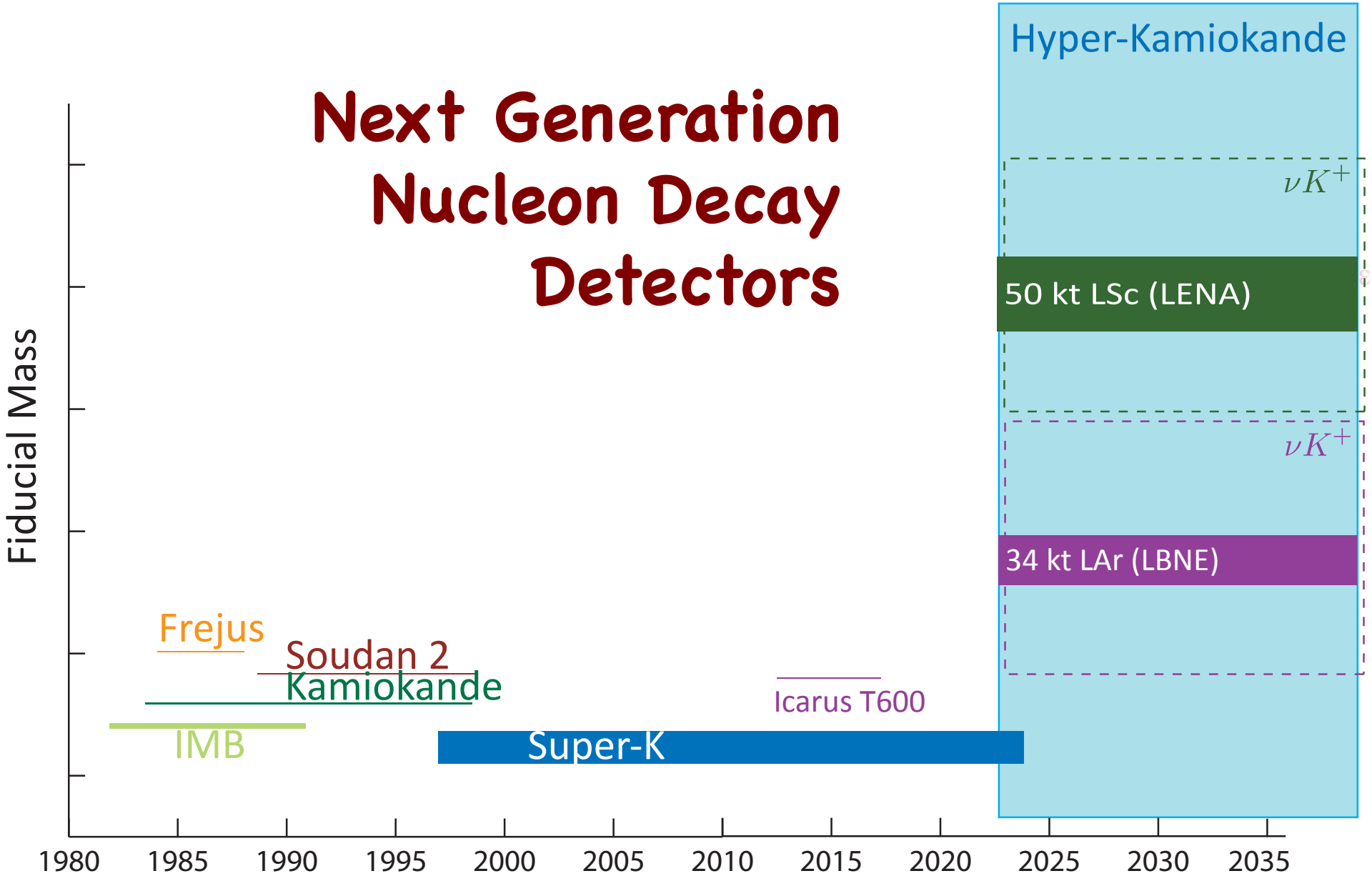
New efficiencies and background rates after analysis improvement
Super-K Preliminary 2013: No candidates, 260 kton yr (SK 1+2+3+4)
Include spectrum fit to single-muon events in final limit

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

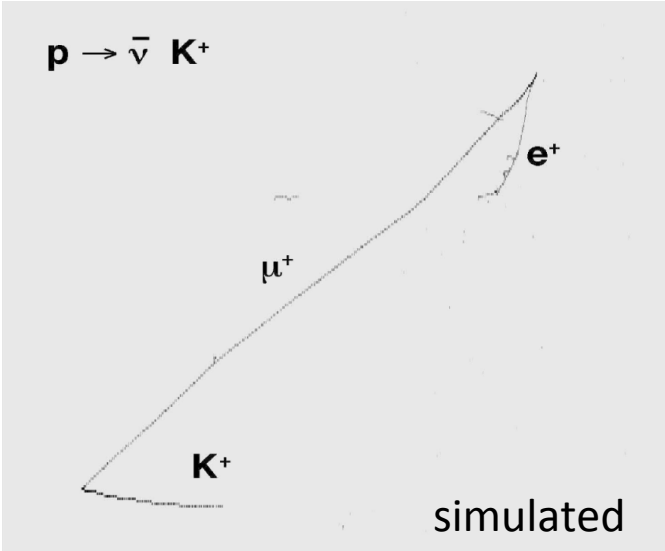
Limits in context with theory

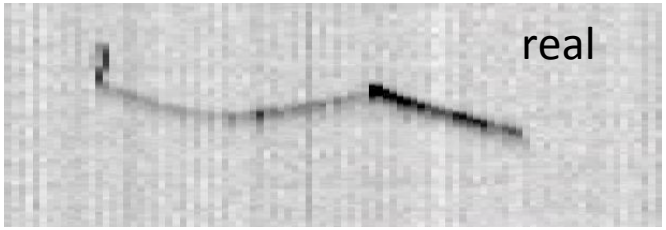


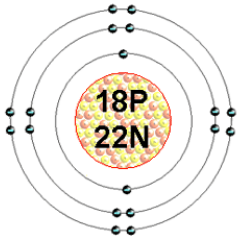
Next Generation Nucleon Decay Detectors

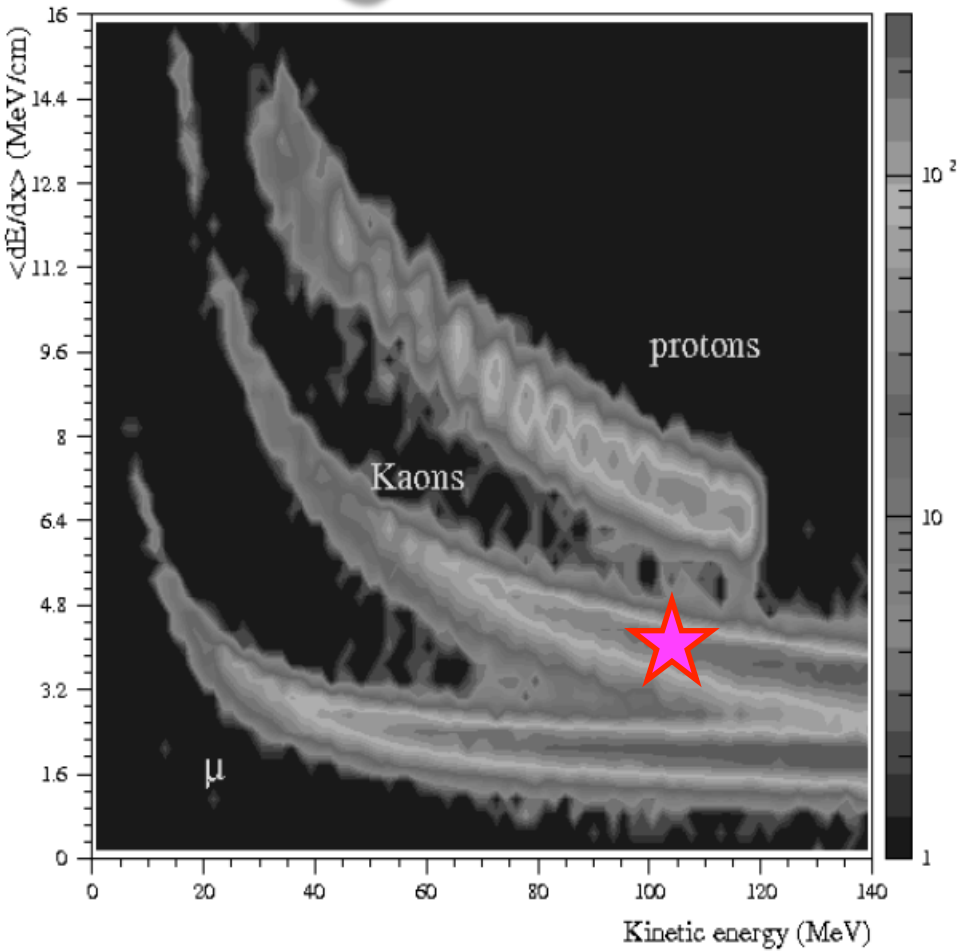


νK^+ in a Liquid Argon TPC





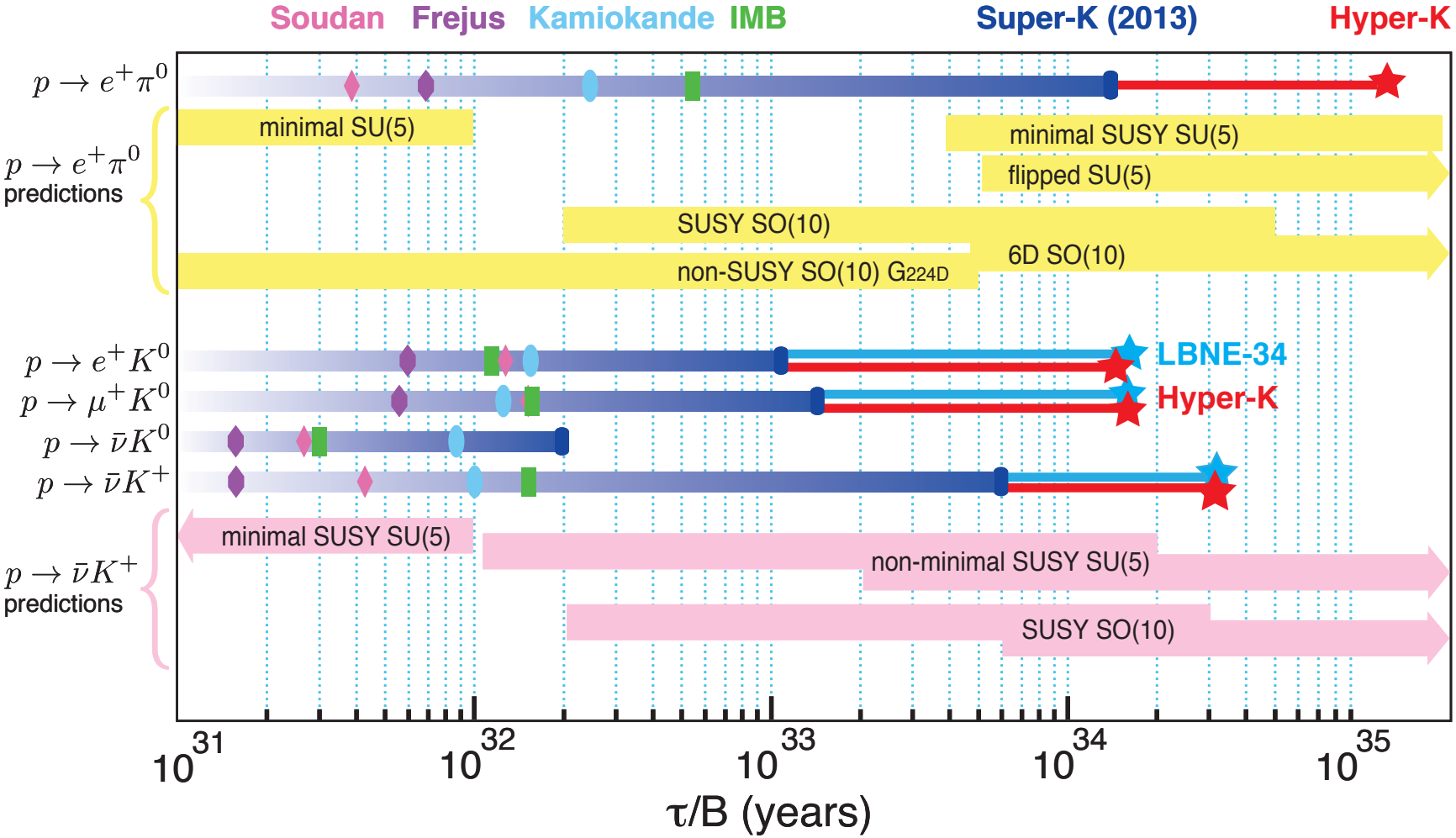




Assumed to be 96.8% efficient
Background rate ~ 0.1 events/100 kt yr

Bueno et al.

Limits in context with theory



We are in an interesting region, (chance of observation!)
but we aren't going to be conclusive

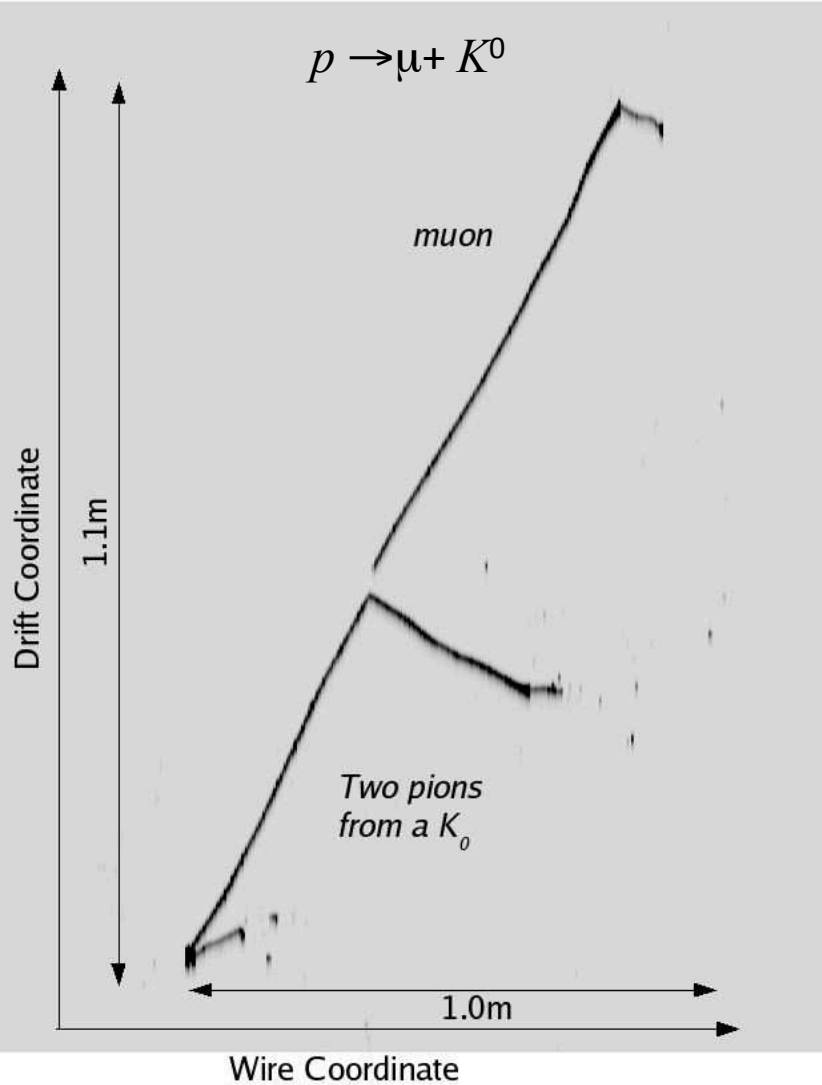
LAr TPC does well with many modes

- 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

Similar
90% CL
sensitivity

But LAr is
low background

Many people think proton decay is important…

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?

+ Snowmass 2013

+ P5 2014 … ???

There is no (confirmed) direct experimental evidence for either baryon or lepton number nonconservation, so why are many physicists so convinced it must occur in nature and why are we at a workshop on baryon and lepton number violation?

Stuart Freedman – Day 1 of BLV 2011 Workshop

Answers:

(a) because a matter-dominated universe exists
(b) because testing fundamental symmetries is our job as physicists
(c) because there are well-motivated theories that suggest it may be observable
(d) because we know how to push forward by an order-of-magnitude
(e) because it comes for free with a big underground neutrino detector

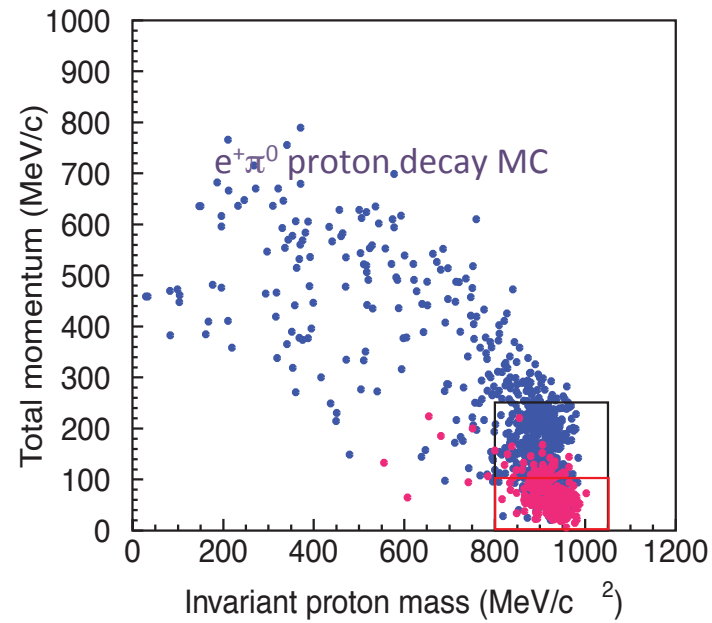
+ wishful thinking that has not yet come true:

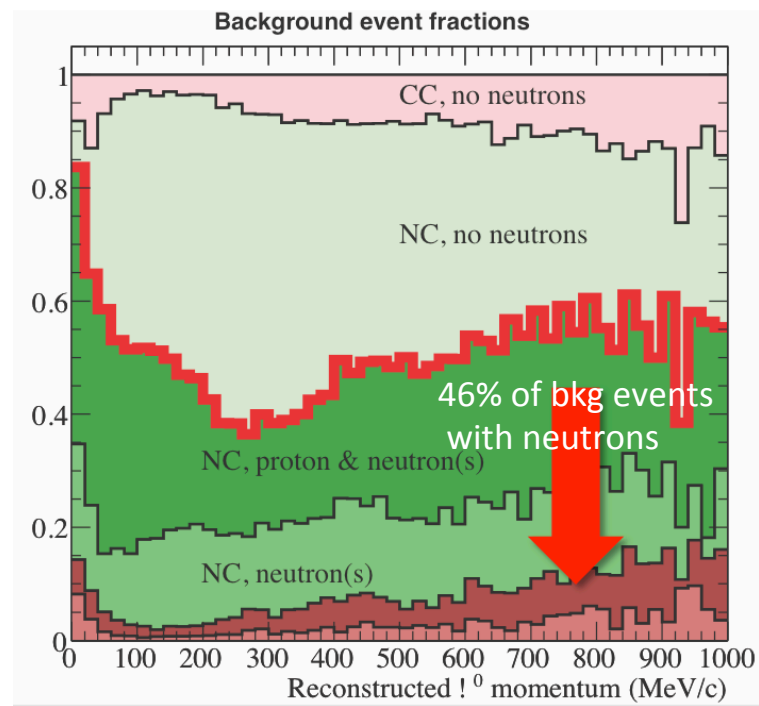
(f) evidence of SUSY at the LHC
(g) candidate events at Super-K

BACKUP

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





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%

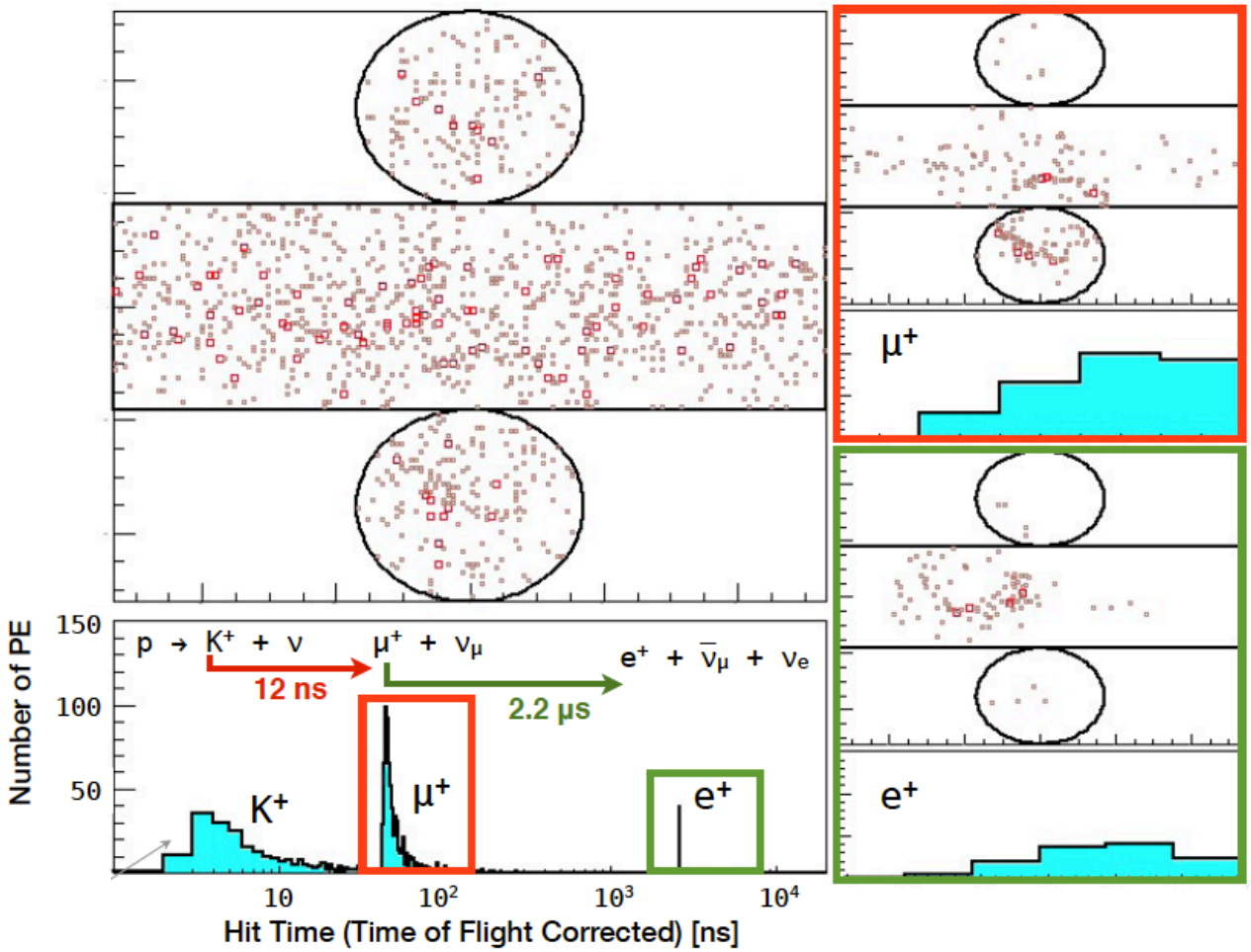
Background rate ~ 1/yr/50 kton

Astroparticle Physics 35 (2012) 685–732

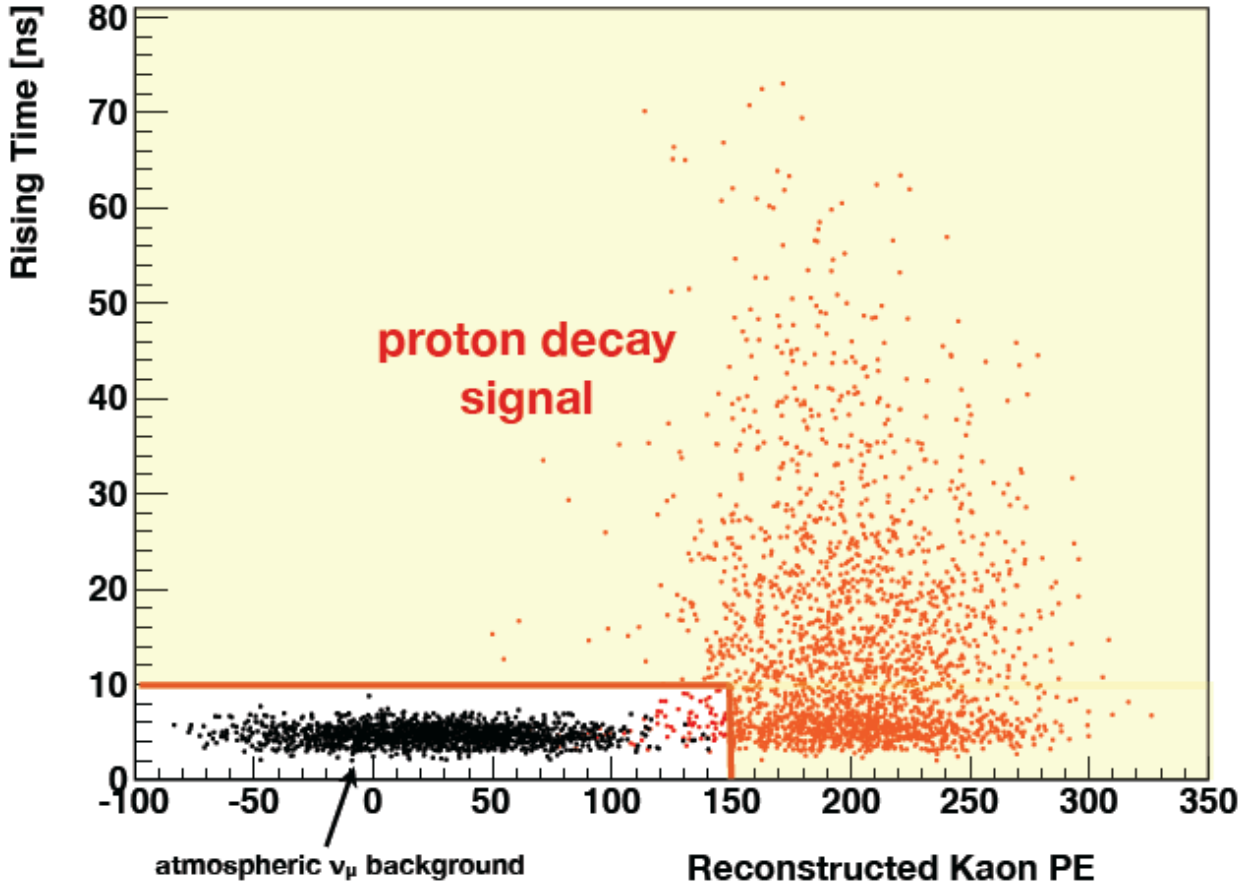
A Large Water-Based Liquid Scintillation Detector in Search for Proton Decay $p \to K^+\bar{\nu}$ and Other Physics

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



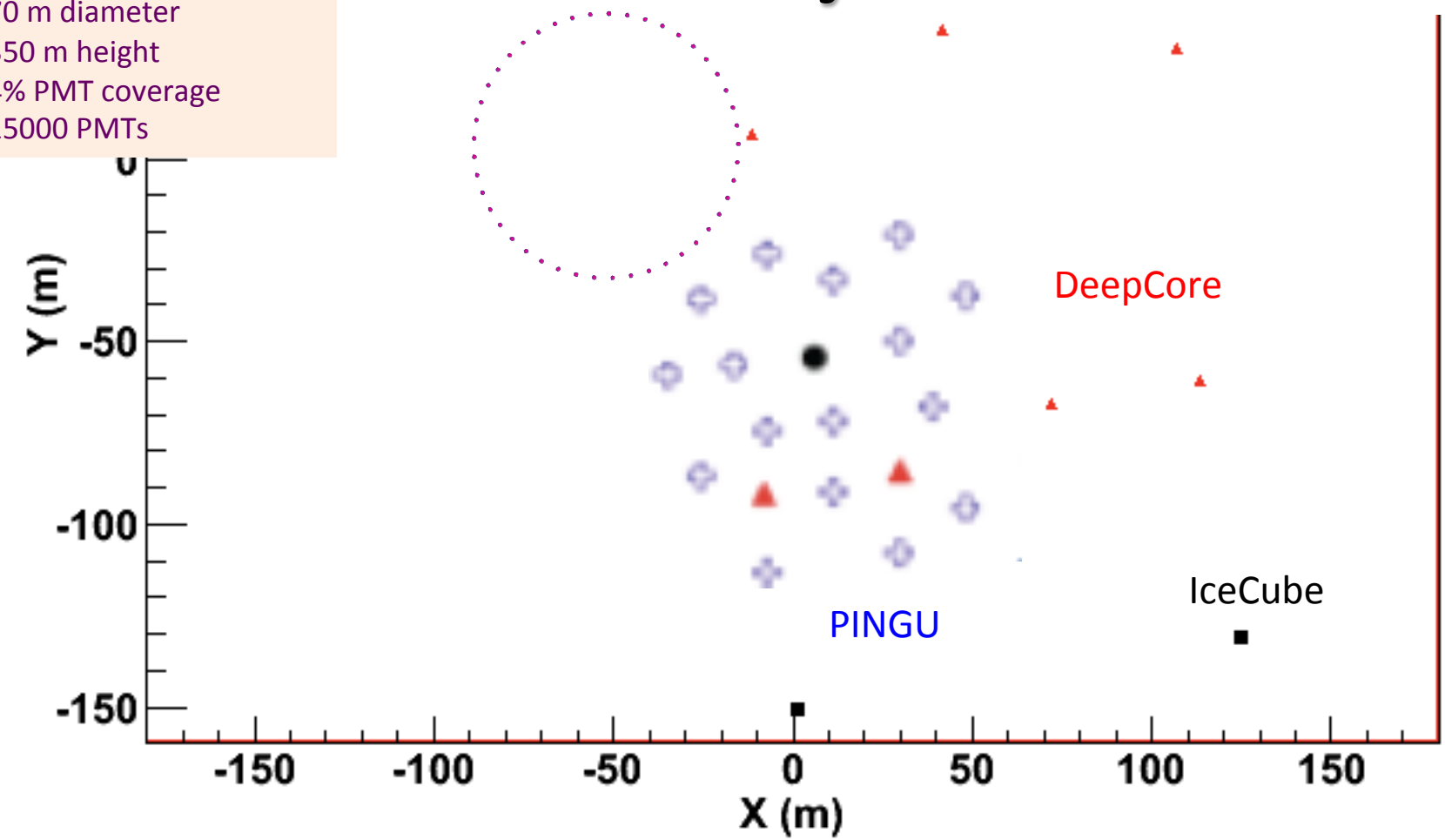
D. Jaffe (BNL)
Argonne IF Mtg
April 2013

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

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

Pure speculation… High density proton decay cylinder in ice

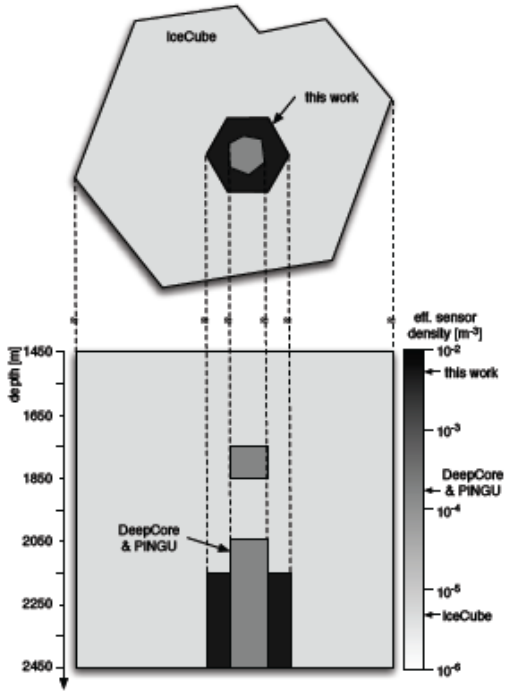
1 Mton could consist of:
44 strings
1 m x 5 m spacing
70 m diameter
350 m height
4% PMT coverage
15000 PMTs



Few % coverage comparable to IMB. Focus on “bright” signatures like e+pi0.
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

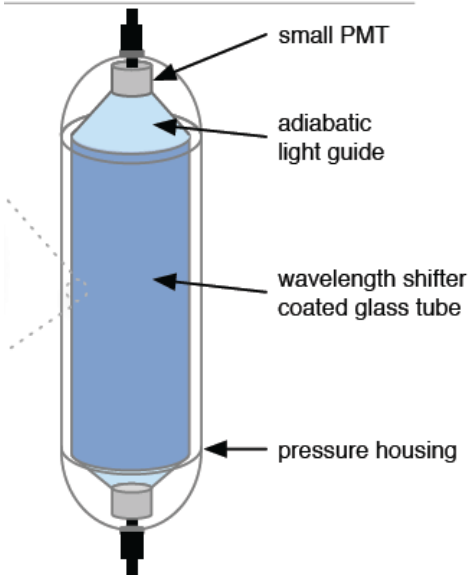
MICA: Megaton Scale Ice Cherenkov Array

Rough idea of 10 MTon detector layout



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

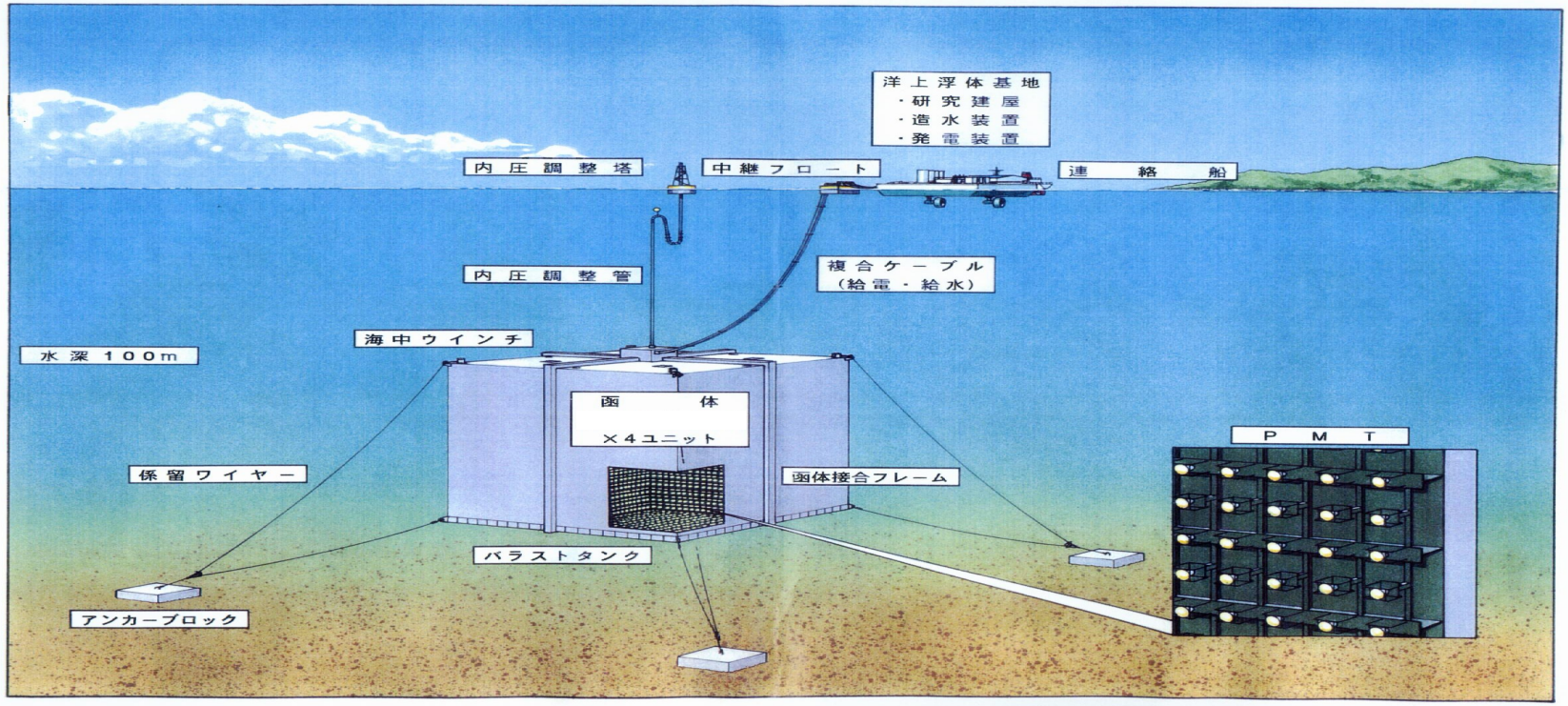
Possible costs of $500M / Mton ??



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* $e^+\pi^0$