Searches for Baryon Number Violation

Ed Kearns Boston University

Baryon number

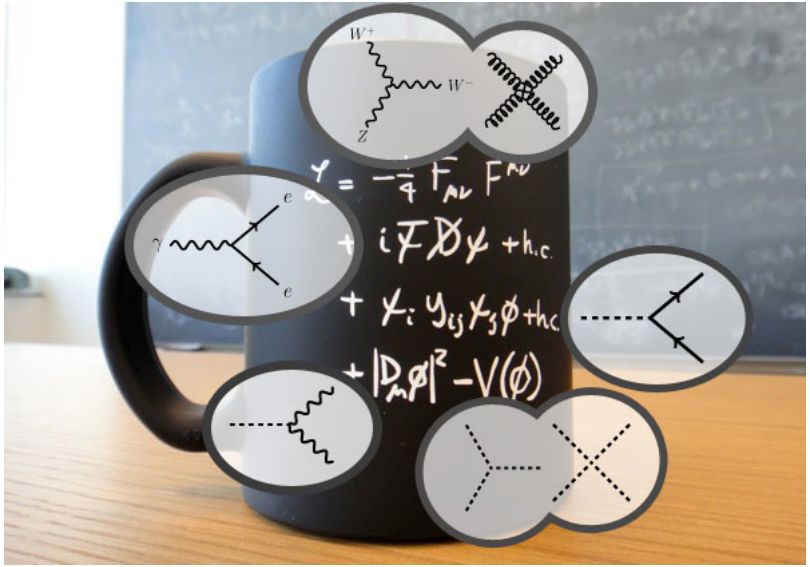
Origins: baryon number conservation formulated by:

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

Conserved in the Standard Model*



*imperfectly due to anomalies, but with irrelevantly long lifetimes

but the Standard Model is incomplete …

Baryon number violation

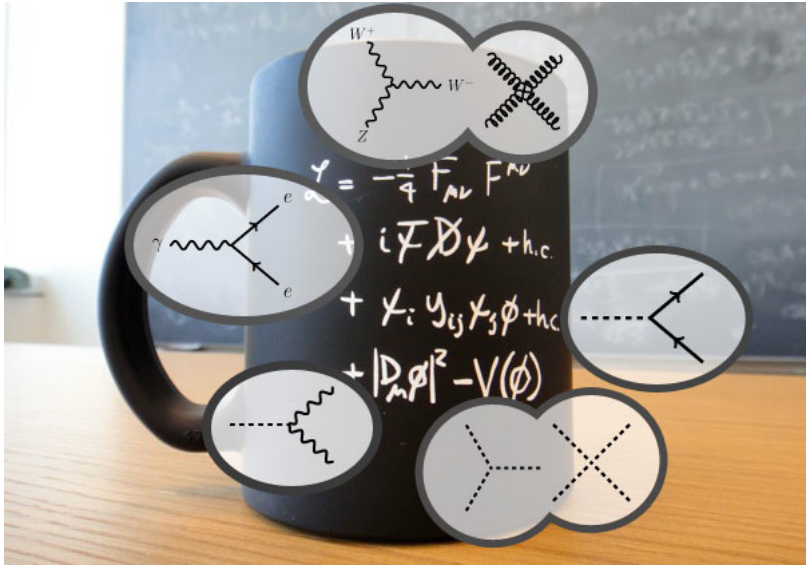
BNV: anticipated for BAU (Sakharov Condition #1)

BNV: natural consequence of Grand Unified Theories
– nucleon decay
– violation of B and L

BNV: possible consequence of new physics below the GUT scale
– nnbar oscillation
– di-nucleon decay
– violate B only

Other new physics: dark matter induced BNV, extra dimensions, dark sector,
better not to assume too much and just look?

The Standard Model is incomplete.

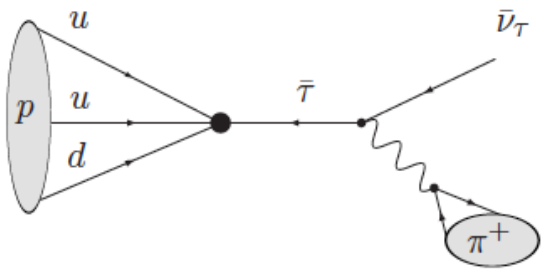


Some BNV processes studied with accelerators

Category	Example	Branching fraction	Experiment
Z decays	$Z \longrightarrow p\ e$	$< 1.8 \times 10^{-6}$	OPAL
tau decays	$\tau \longrightarrow \text{pbar}\ \gamma$	$< 10^{-5} - 10^{-7}$	LHCb, CLEO, Belle
Heavy meson decay	$B^0 \longrightarrow \Lambda^0\ e^+$	$< 10^{-5} - 10^{-8}$	CLEO, BaBar
Heavy baryon decay	$\Lambda^0 \longrightarrow \pi^-\ e^+$	$< 10^{-5} - 10^{-7}$	CLAS
Top quark	$\text{tbar} \longrightarrow b\ u\ e^-$	$< 10^{-3}$	CMS

But arguably (Marciano, 1995) some of these processes may be better constrained by nucleon decay.

nucleon decay is most constraining

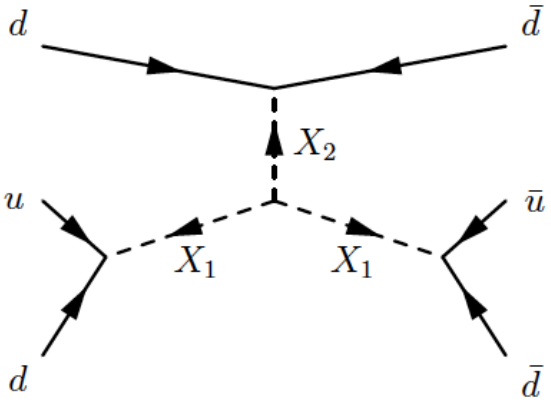


Hou, Nagashima, Soddu hep-ph/0509006

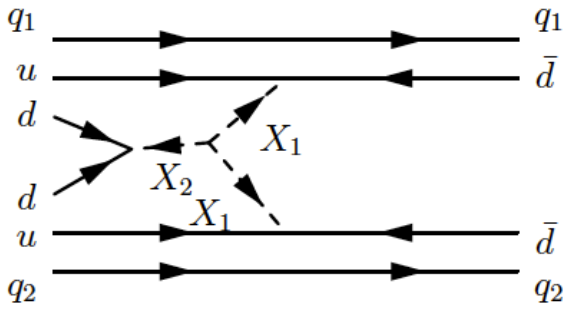
ΔB = 2

violates B-L, needed for BAU

nnbar oscillation
(free neutron or inside nucleus)



dinucleon decay



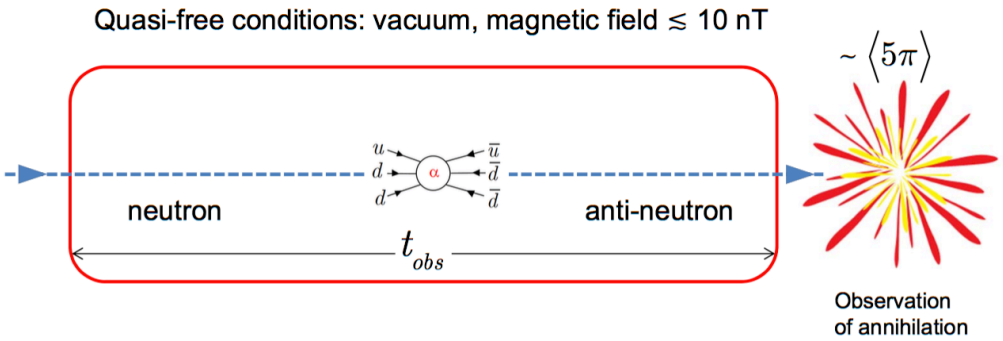
$$\delta m_{n\bar{n}} = \frac{1}{\tau_{n\bar{n}}} = \langle \bar{n} | L_{\Delta B=2} | n \rangle = \frac{1}{M^5} \langle \bar{n} | UDDUDD | n \rangle \sim \frac{\Lambda^6}{M^5}$$

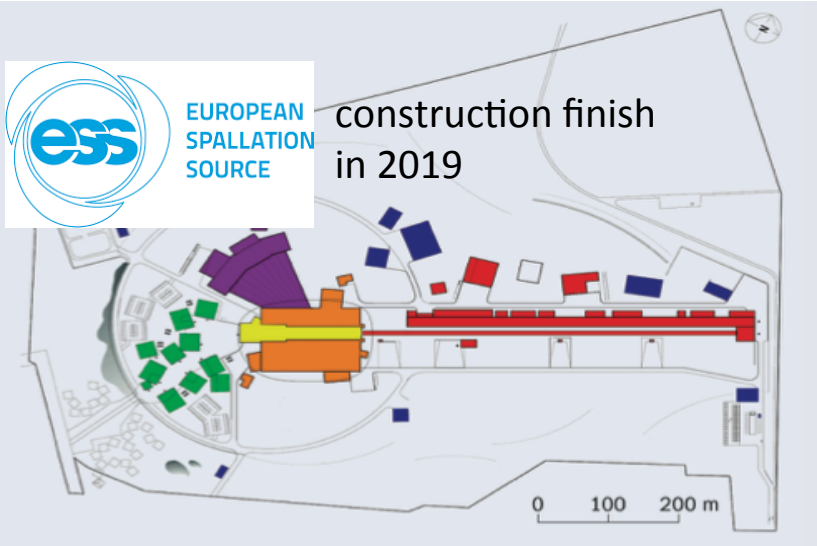
$\Lambda \approx 200$ MeV

$\tau \approx 10^8$ s

$M > 10^6$ GeV

Future Free Neutron Oscillation Experiment



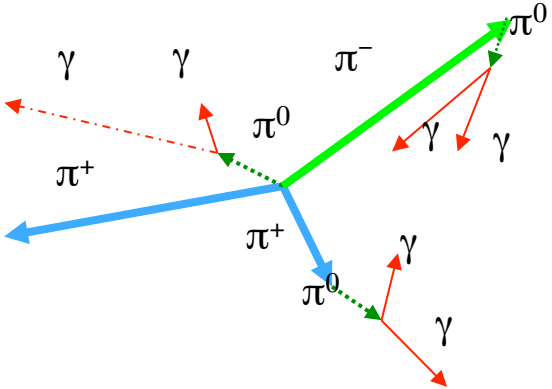


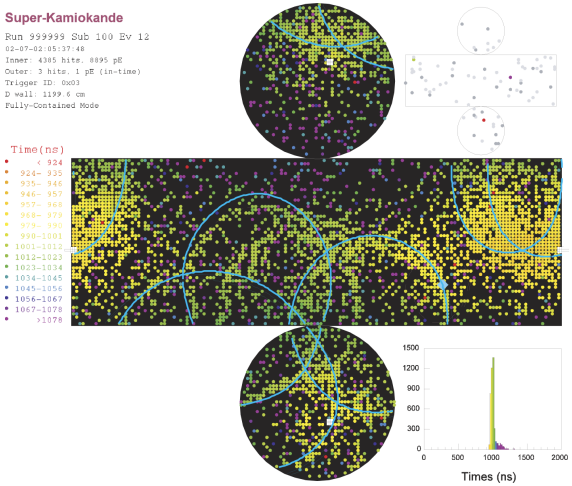
More neutrons, 200 m oscillation channel
Sensitivity ∝ $N_n t^2$
Improvement over previous free nnbar limit by factor by 500 – 1000

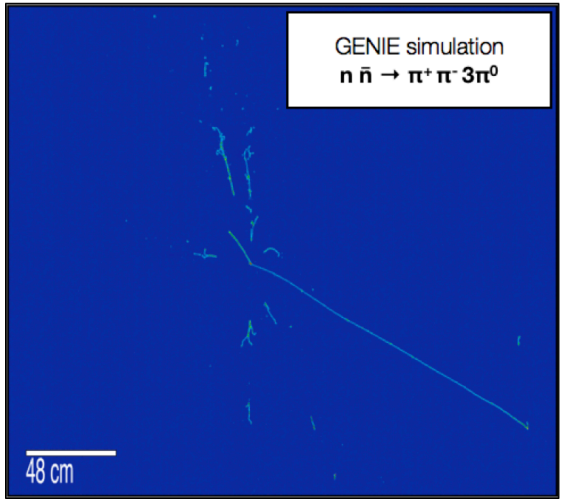
D. G. Phillips, W. M. Snow et al, Phys. Rep. 612, 1 (2016), arXiv:1410.1100

theory and experiment plenary talks tomorrow (Mohapatra, Snow)

nnbar in nuclei







Liquid Argon TPC parallel talks (Josh Barrow, Jeremy Hewes), Result from SNO (Marc Bergevin)

(and plenary talks – Snow, Mohapatra)

Grand Unified Theories

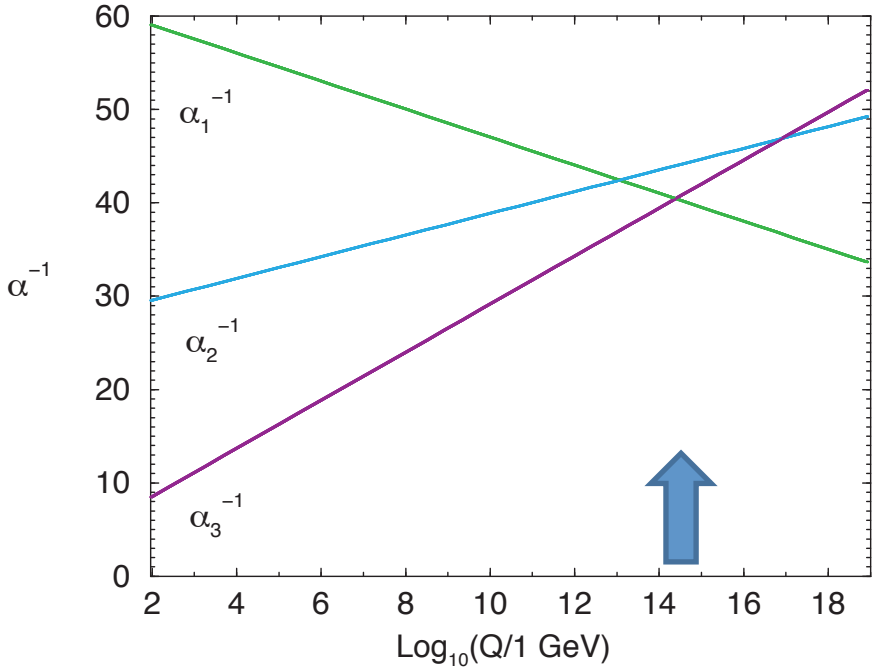
assume the Standard Model, SU(3)⊗SU(2)⊗U(1),
is part of a larger symmetry group, e.g. SU(5):

$$\bar{5} = \begin{pmatrix} \bar{d}_g \\ \bar{d}_r \\ \bar{d}_b \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 = \begin{pmatrix} 0 & \bar{u}_b & -\bar{u}_r & -u_g & -d_g \\ & 0 & \bar{u}_g & -u_r & d_r \\ & & 0 & -u_b & -d_b \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L \qquad 24 = \left(\begin{array}{ccc|cc} G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & \bar{X}_1 & \bar{Y}_1 \\ G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & \bar{X}_2 & \bar{Y}_2 \\ G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & \bar{X}_3 & \bar{Y}_3 \\ \hline X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{array}\right)$$

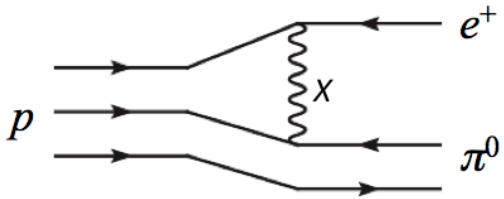
Consequences:

- 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,
  value of weak mixing angle (poor), massless neutrinos (oops!)
- There are other groups, e.g. SO(10) that accommodate massive neutrinos

Circumstantial Evidence



Gauge mediated



$$\tau = \frac{M_X^4}{\alpha\ m_p^2}$$

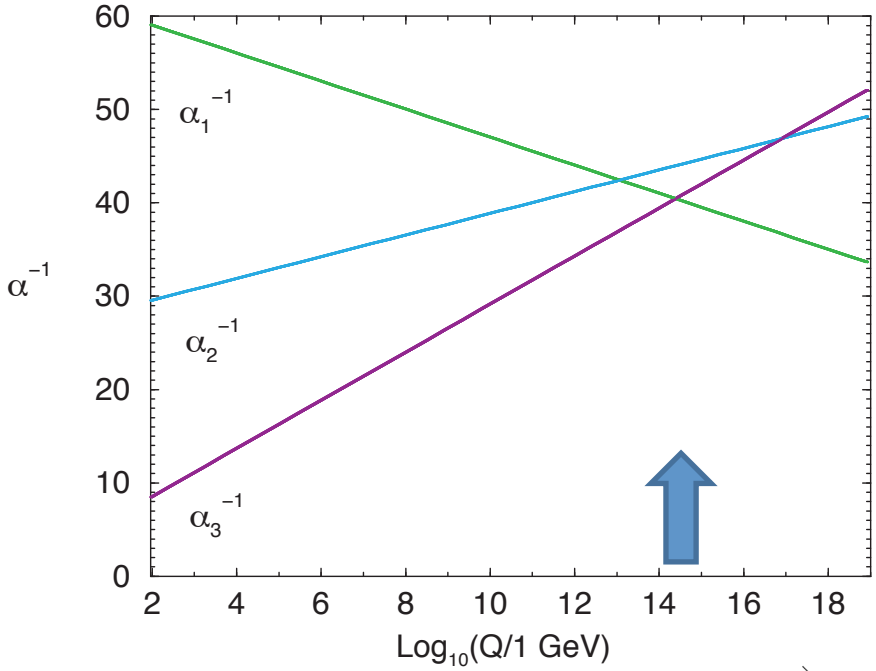
$$\tau(e^+\pi^0) = 4.5\times10^{29\pm1.7}\ years\ \text{(predicted)}$$

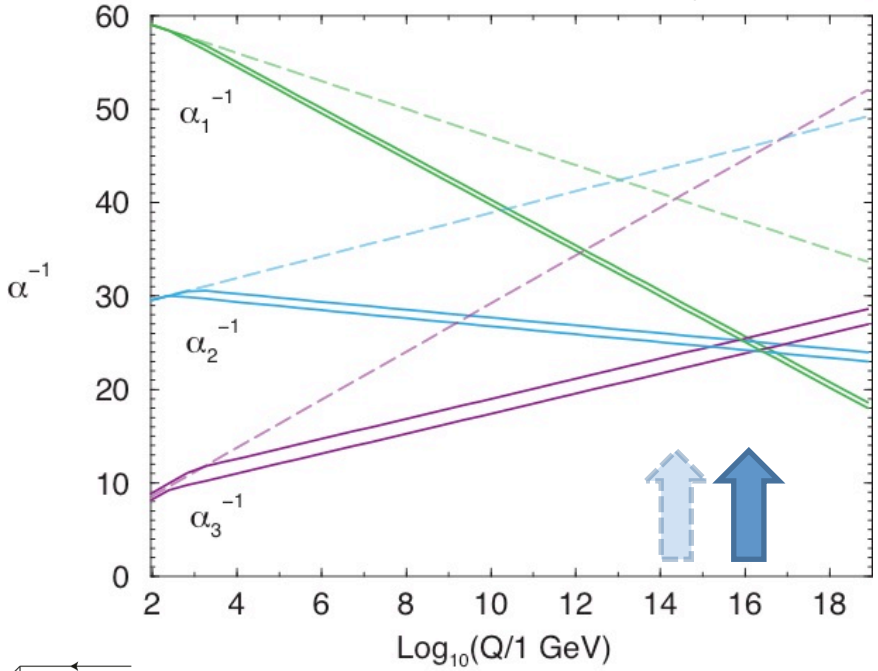
$$\tau(e^+\pi^0) > 5.5\times10^{32}\ years\ \text{(IMB/1990)}$$

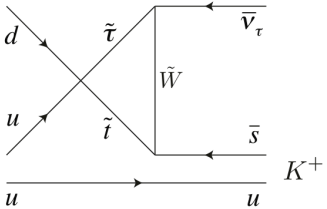
SUSY GUTs ➠

Unification scale pushed up ✔

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





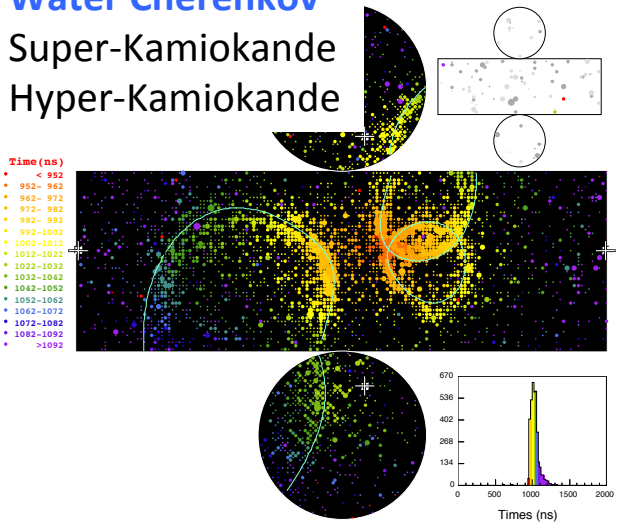


But new modes now present (D=5)

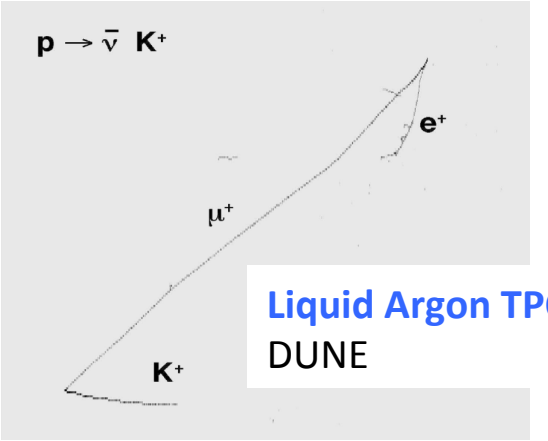
$$\tau(\nu K^+) \approx 10^{29-35} \text{ years}$$

Benchmark Proton Decay Signatures

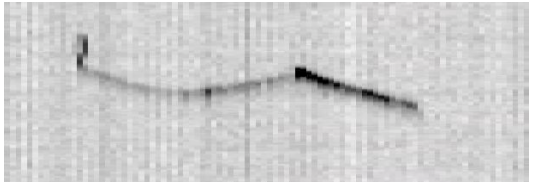
Water Cherenkov
Super-Kamiokande
Hyper-Kamiokande



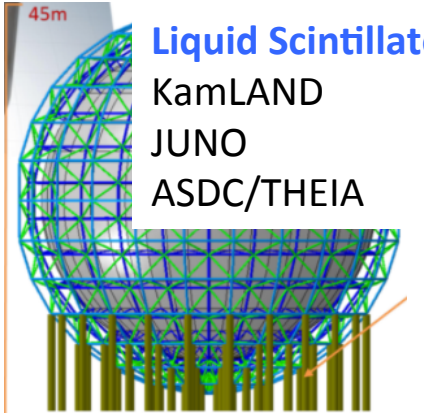
most massive – superior for $e^+\pi^0$
broad search capabilities
kaons below Cherenkov threshold



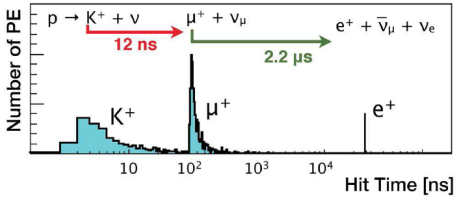
Liquid Argon TPC
DUNE



fine grained detail
visible kaon track
heavy nucleus, no free protons



Liquid Scintillator
KamLAND
JUNO
ASDC/THEIA

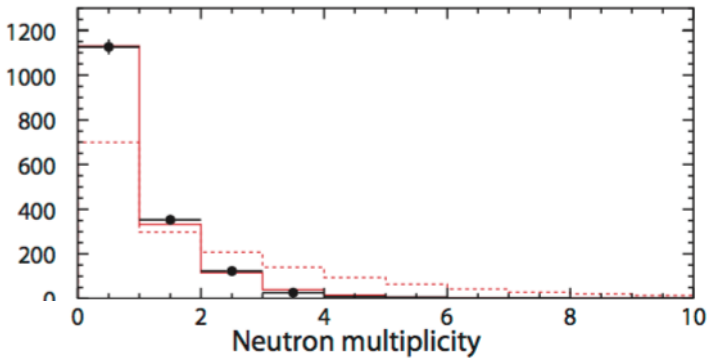


clean timing signature
specialize in charged kaon
(also invisible mode)

e+ pi0 search in Super-K

- 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**
- ***SK-IV only: veto event if n-capture***

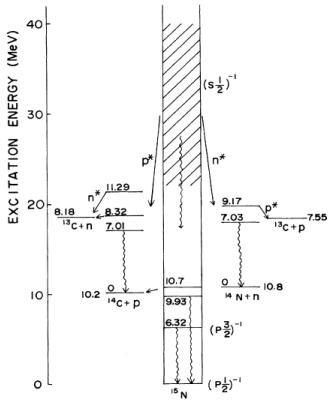
New "two box"strategy.
Low momentum
associated with free proton.
No nuclear effects,
Lower background

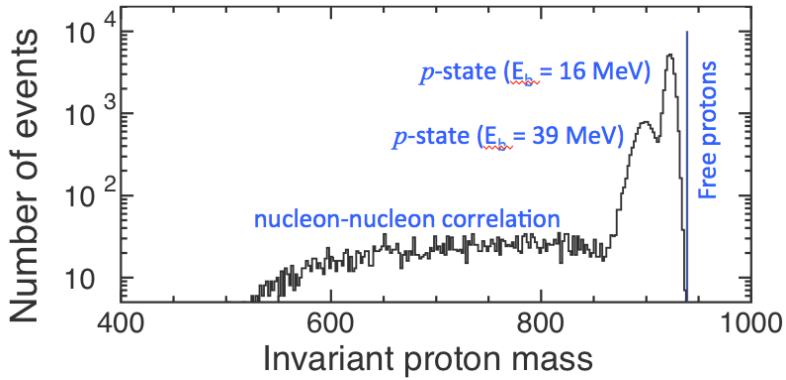


Signal Efficiency (%)	SK-I	SK-II	SK-III	SK-IV w. n cap.
100 < p_{net} < 200 MeV/c	20.4 ± 3.1	20.2 ± 3.1	20.5 ± 3.2	19.4 ± 1.2
p_{net} < 100 MeV/c	18.8 ± 0.9	18.3 ± 1.0	19.6 ± 1.3	18.7 ± 1.2
Background (evts)	**SK-I**	**SK-II**	**SK-III**	**SK-IV w. n cap.**
100 < p_{net} < 200 MeV/c	0.22 ± 0.06	0.12 ± 0.04	0.06 ± 0.02	0.15 ± 0.05
p_{net} < 100 MeV/c	0.03 ± 0.01	0.01 ± 0.003	0.003 ± 0.001	0.02 ± 0.01

Nuclear Physics of Proton Decay

- 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

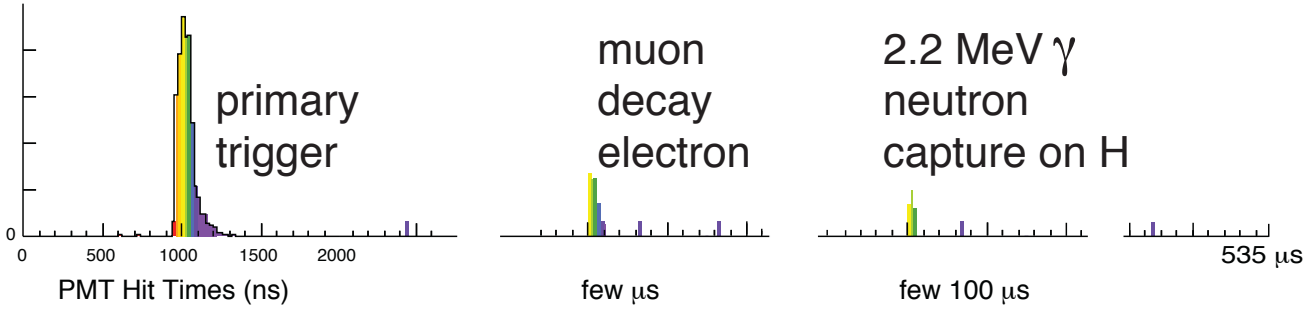


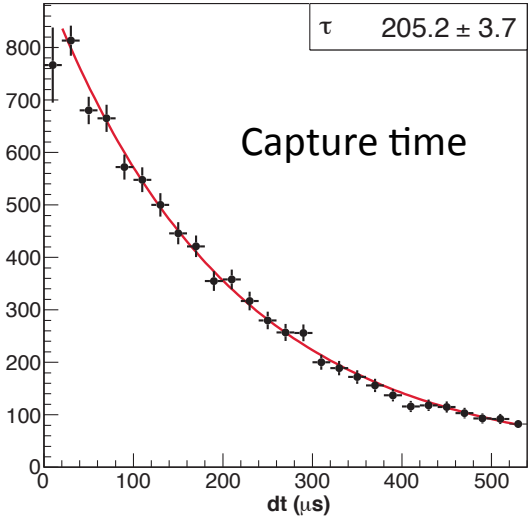


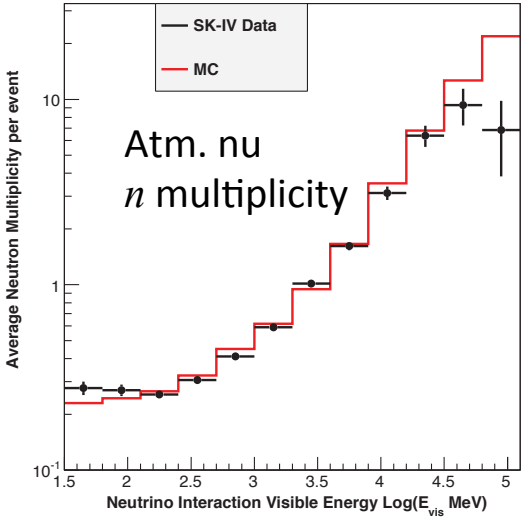
H. Ejiri Phys. Rev. C48 (1993)

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	$\leq 3-4$			0.16

Neutron capture on hydrogen



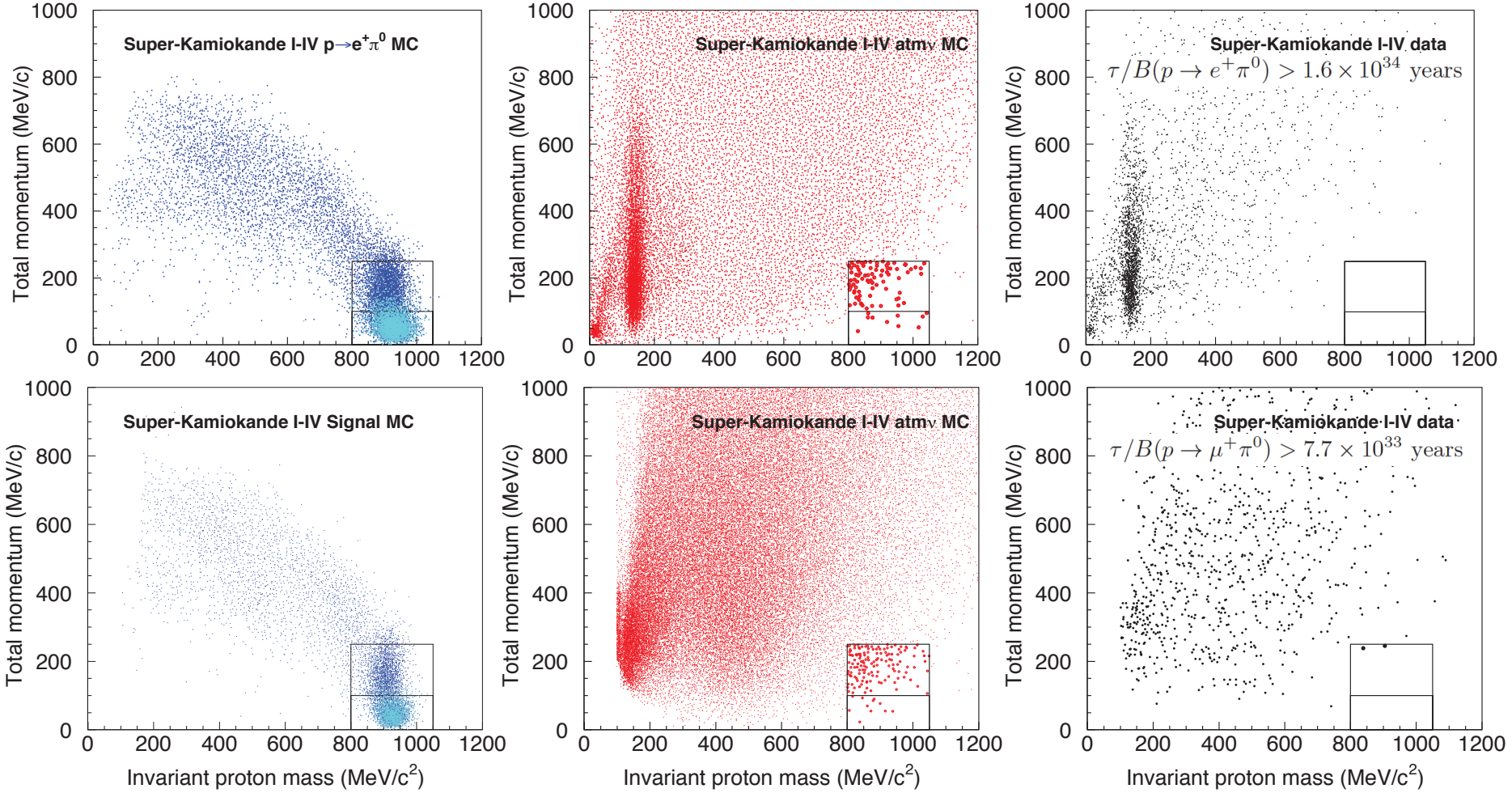




Atmospheric neutrino background is frequently accompanied by neutron production

Detection efficiency = 20.5%
Can increase to ~90% with capture on Gd

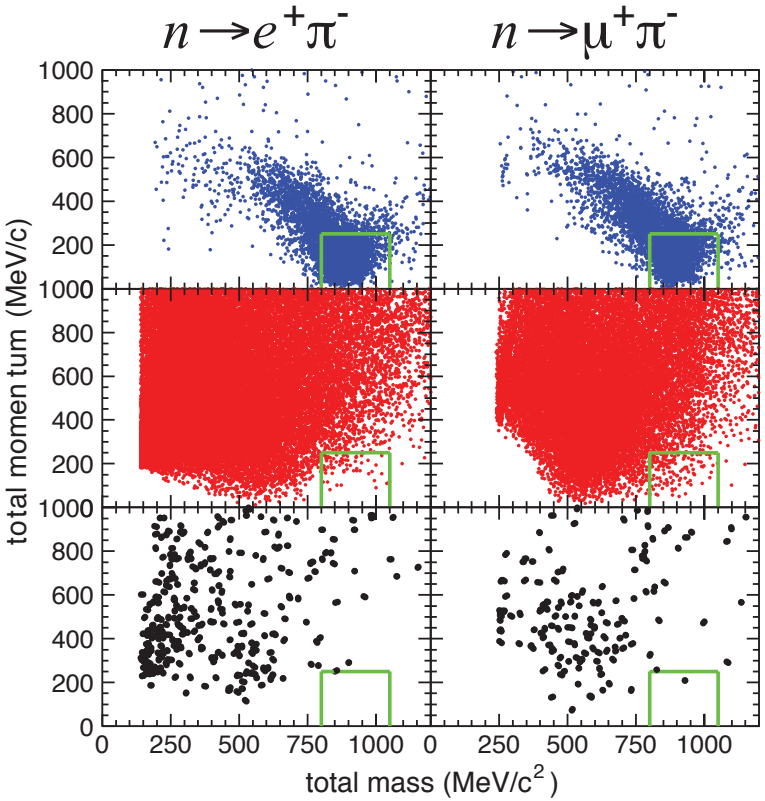
SK-Gd construction in 2018 or 2019



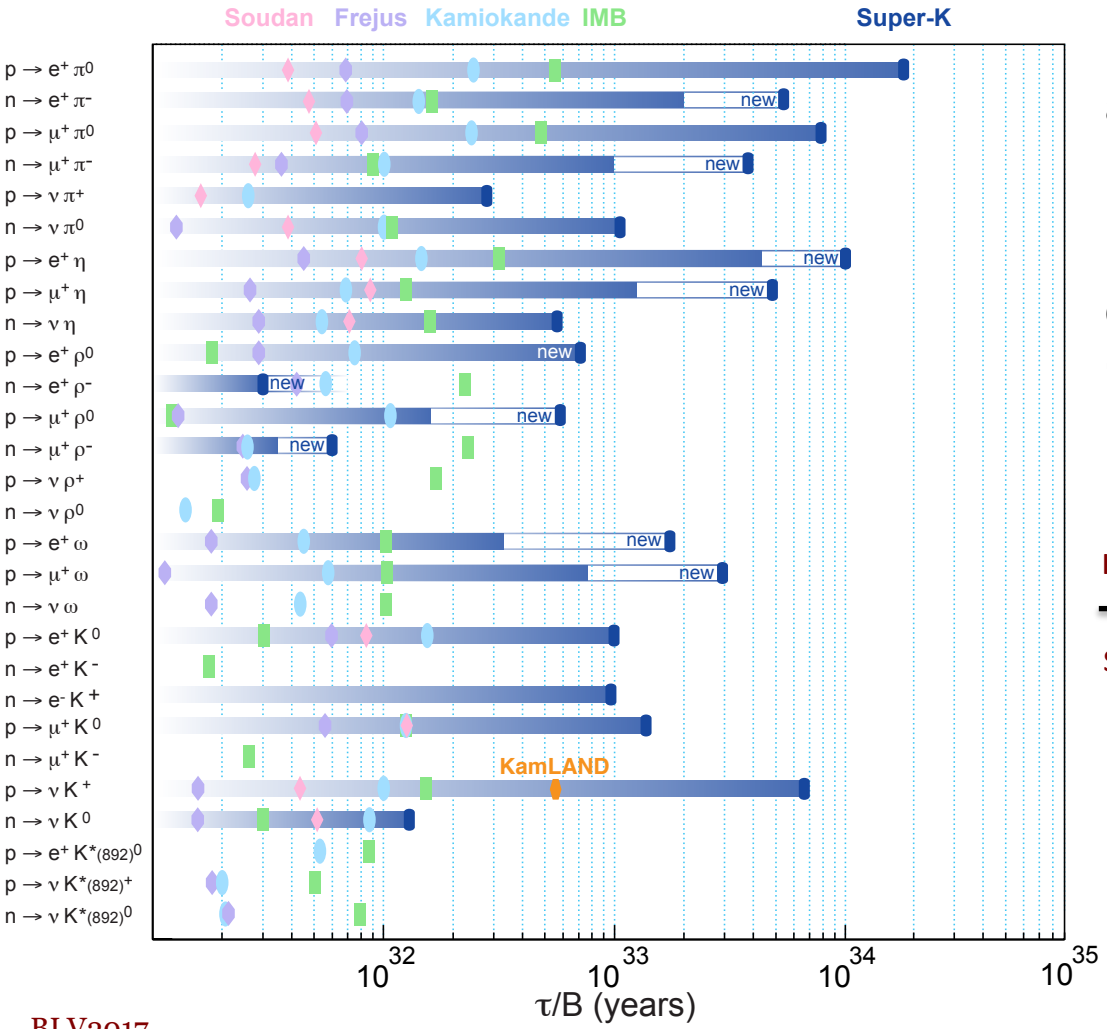
Super-K Data (306 kt y)

antilepton plus other mesons

Modes	Background (events)	Candidate (events)	Probability (%)	Lifetime Limit ($\times 10^{33}$years) at 90% CL
$p \to e^+\eta$	0.78±0.30	0	-	10.
$p \to \mu^+\eta$	0.85±0.23	2	20.9	4.7
$p \to e^+\rho^0$	0.64±0.17	2	13.5	0.72
$p \to \mu^+\rho^0$	1.30±0.33	1	72.7	0.57
$p \to e^+\omega$	1.35±0.43	1	74.1	1.6
$p \to \mu^+\omega$	1.09±0.52	0	-	2.8
$n \to e^+\pi^-$	0.41±0.13	0	-	5.3
$n \to \mu^+\pi^-$	0.77±0.20	1	53.7	3.5
$n \to e^+\rho^-$	0.87±0.26	4	1.2	0.03
$n \to \mu^+\rho^-$	0.96±0.28	1	61.7	0.06
total	8.6	12	15.7	-



Phys. Rev. D in preparation (19 p.)
ready to submit very soon!



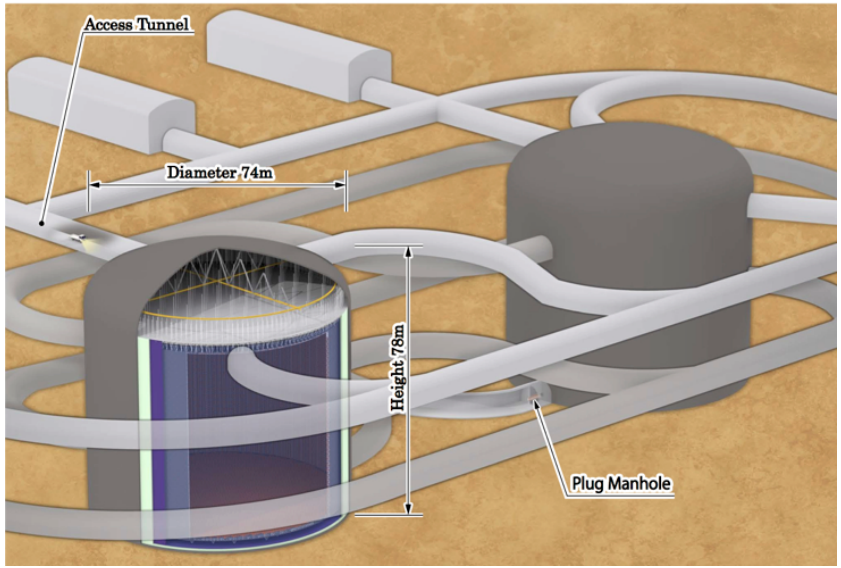
antilepton
plus
meson

conserves
(B-L)

non-strange mesons

strange mesons

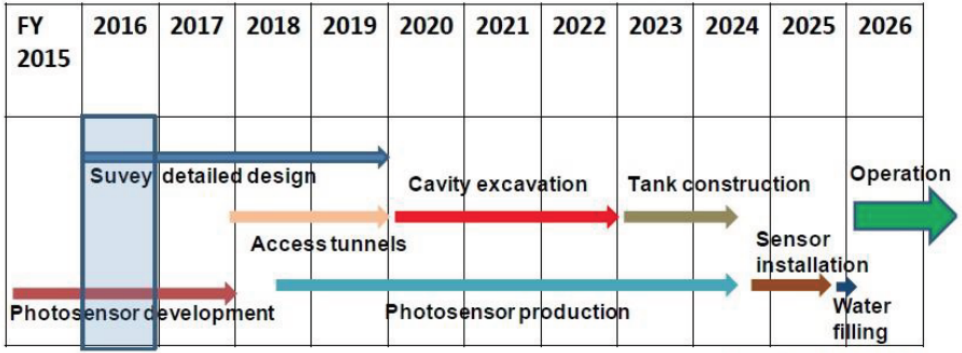
Hyper-Kamiokande



Two tank – staging strategy

Each tank:

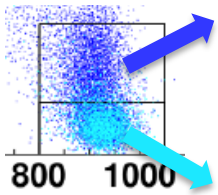
- 260 kton total, 188 kton fiducial mass
- 40000 50-cm high QE PMTs
- 74 m ⌀ x 60 m high
- 1800 mwe oveburden

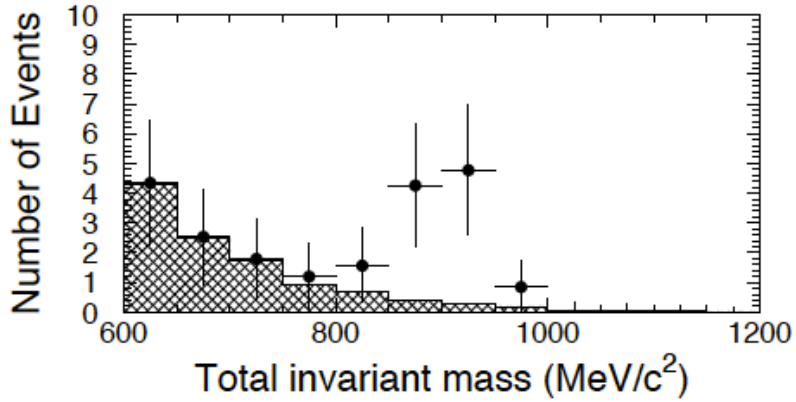


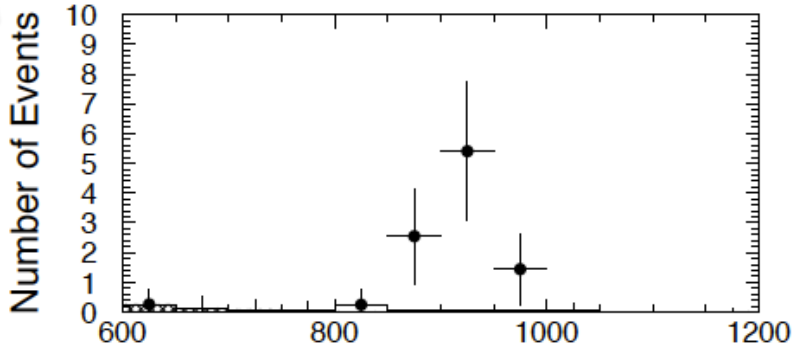
Maximize detector performance – less mass than originally discussed

Proton decay signal (at SK limit)

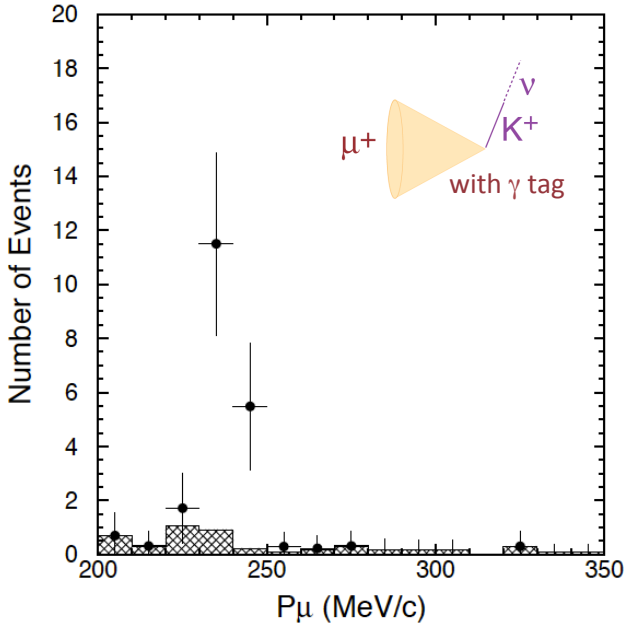
$$p \rightarrow e^+\pi^0$$



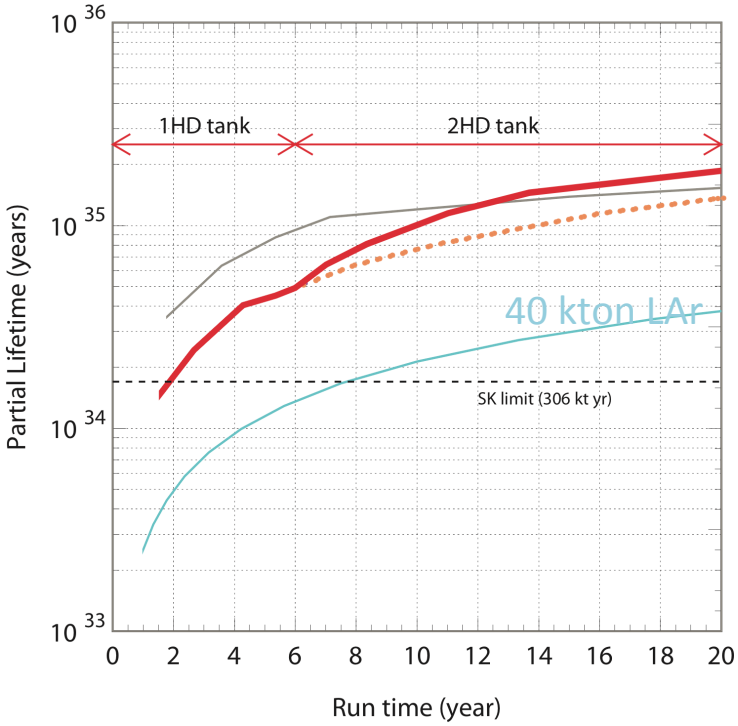


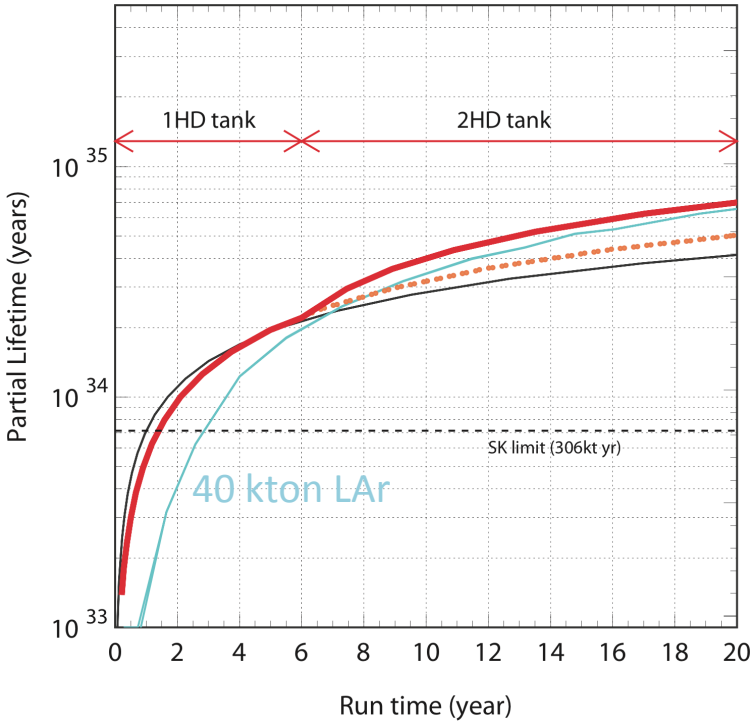


$$p \rightarrow K^+\nu$$



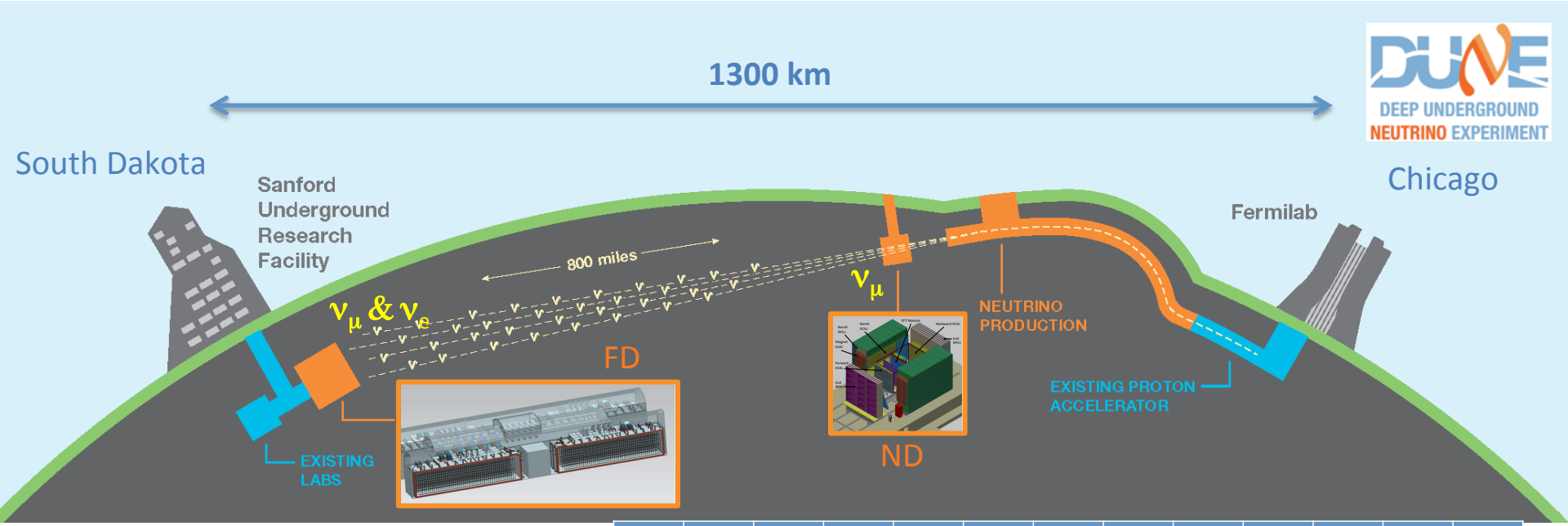
Tick tock protons!!!





Sensitivity curves by Hyper-K group (preliminary)

DUNE



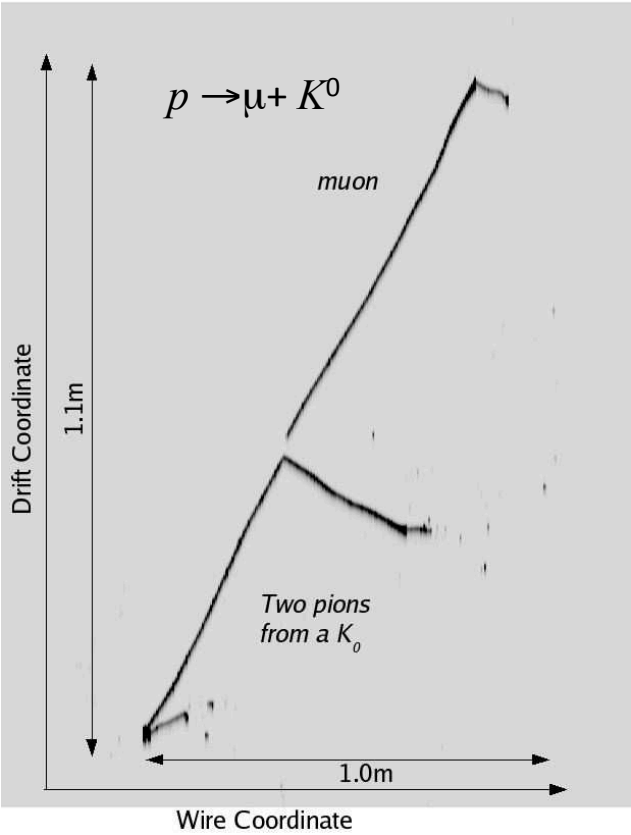
Liquid argon TPC
Single and dual phase
4x 17 kton
40 kton fiducial mass

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
ProtoDUNEs												
	Cavern excavation											
				Cryostat Construction								
						Far Detector Installation						
								Far Detector commissioning				

LAr Shines for Many Modes

- Modes with charged kaon in final state (SUSY)
- Modes with displaced vertices ⇒
- Multi-prong modes with no neutrino
- nnbar background rejection
  - No recoil proton allowed
  - No CC electron (or muon)

- Lepton + light meson likely no better than water due to nuclear absorption of the light meson.



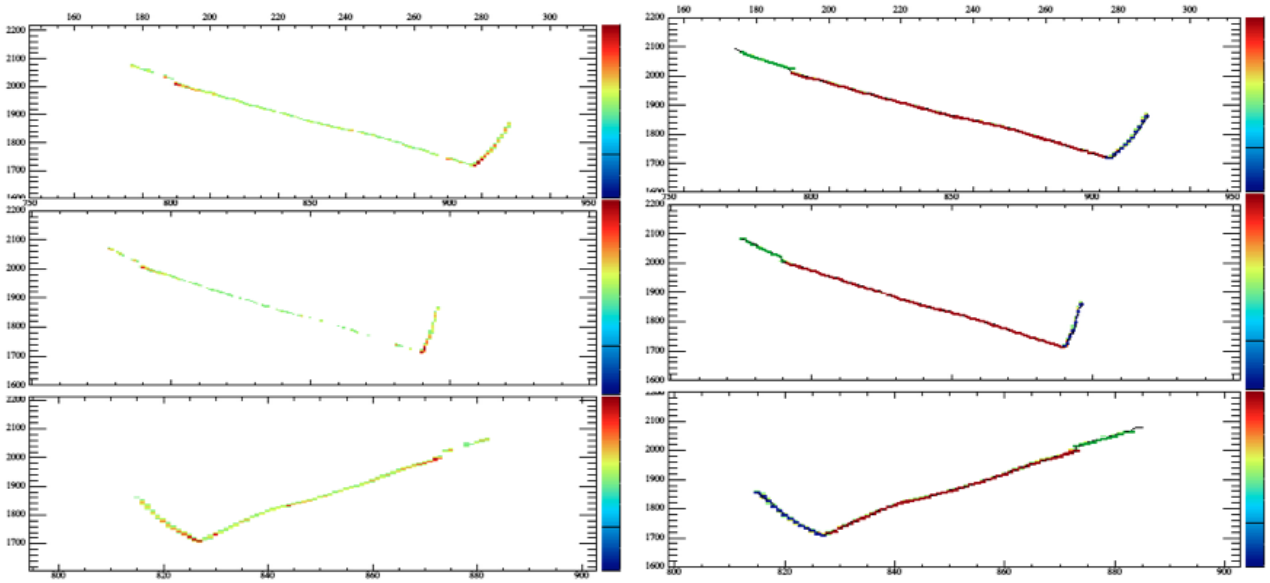
	Mode	Mega Water Ch.		Big LAr (generic, Bueno et al.)	
		Efficiency	BG Rate (/Mt y)	Efficiency	BG Rate (/Mt y)
B-L	$e^+\pi^0$	*38%*	*0.7*	45%	1
B-L	νK^+	*22.5%*	*1.6*	**97%**	**1**
B-L	$\mu + K^0$	*10%*	*5-10*	**47%**	**<2**
B+L	$\mu^- \pi^+ K^+$	?	?	**97%**	**1**
B+L	$e^- K^+$	10%	3	**96%**	**<2**
$\Delta B=2$	n nbar	12%	260	**?**	**?**

Rough and unofficial
SK efficiency & BG
or from HK Design Report

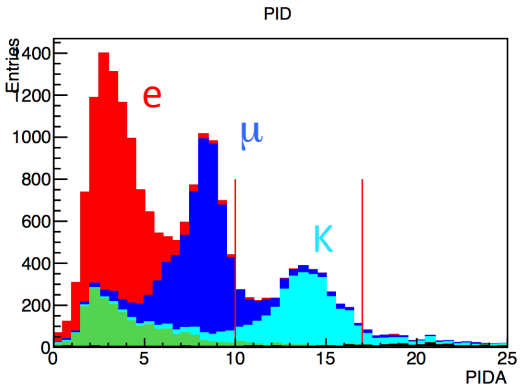
Work underway
to reevaluate these for DUNE
Using full reconstruction

23

Progress in Event Reconstruction

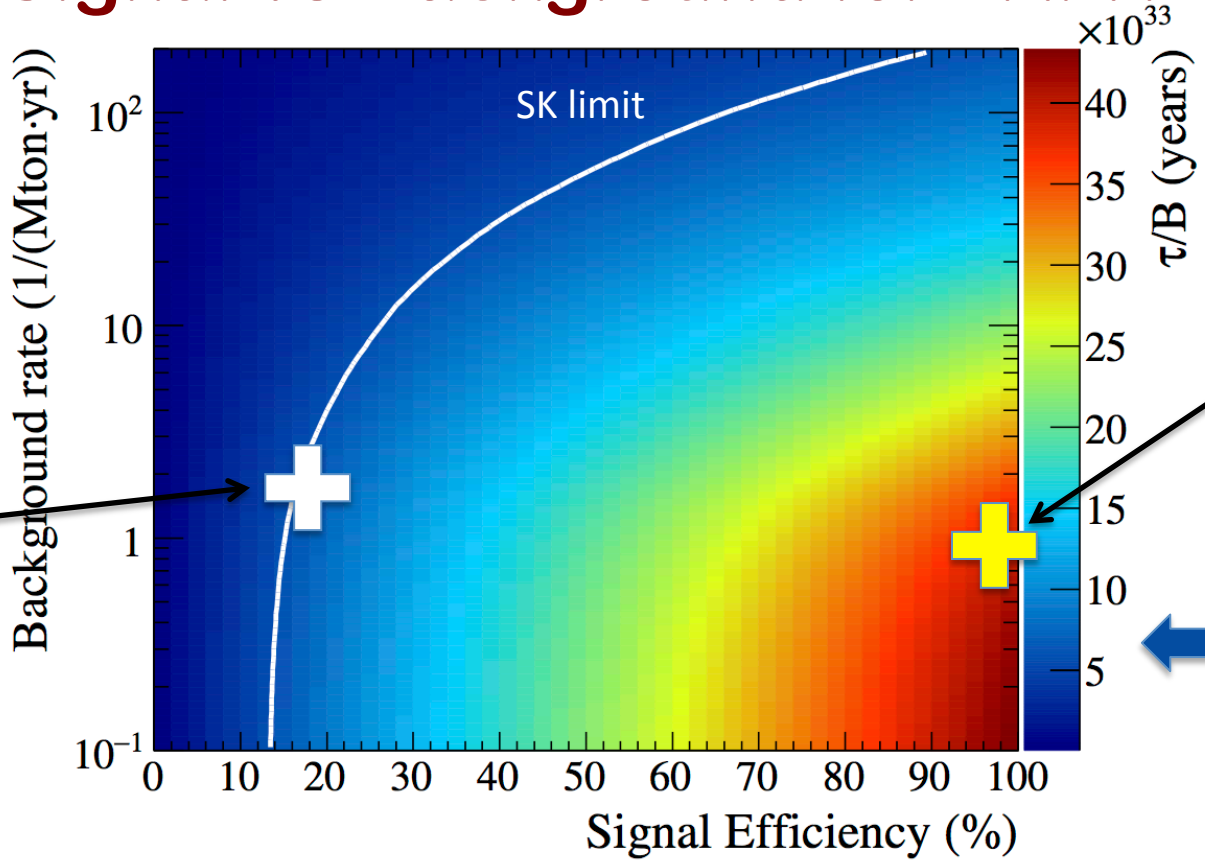


$$p \rightarrow K^+ \nu$$



See talk by A. Higuera, CoS SURF 2017

Work Underway to Understand Signal vs Background for LArTPC



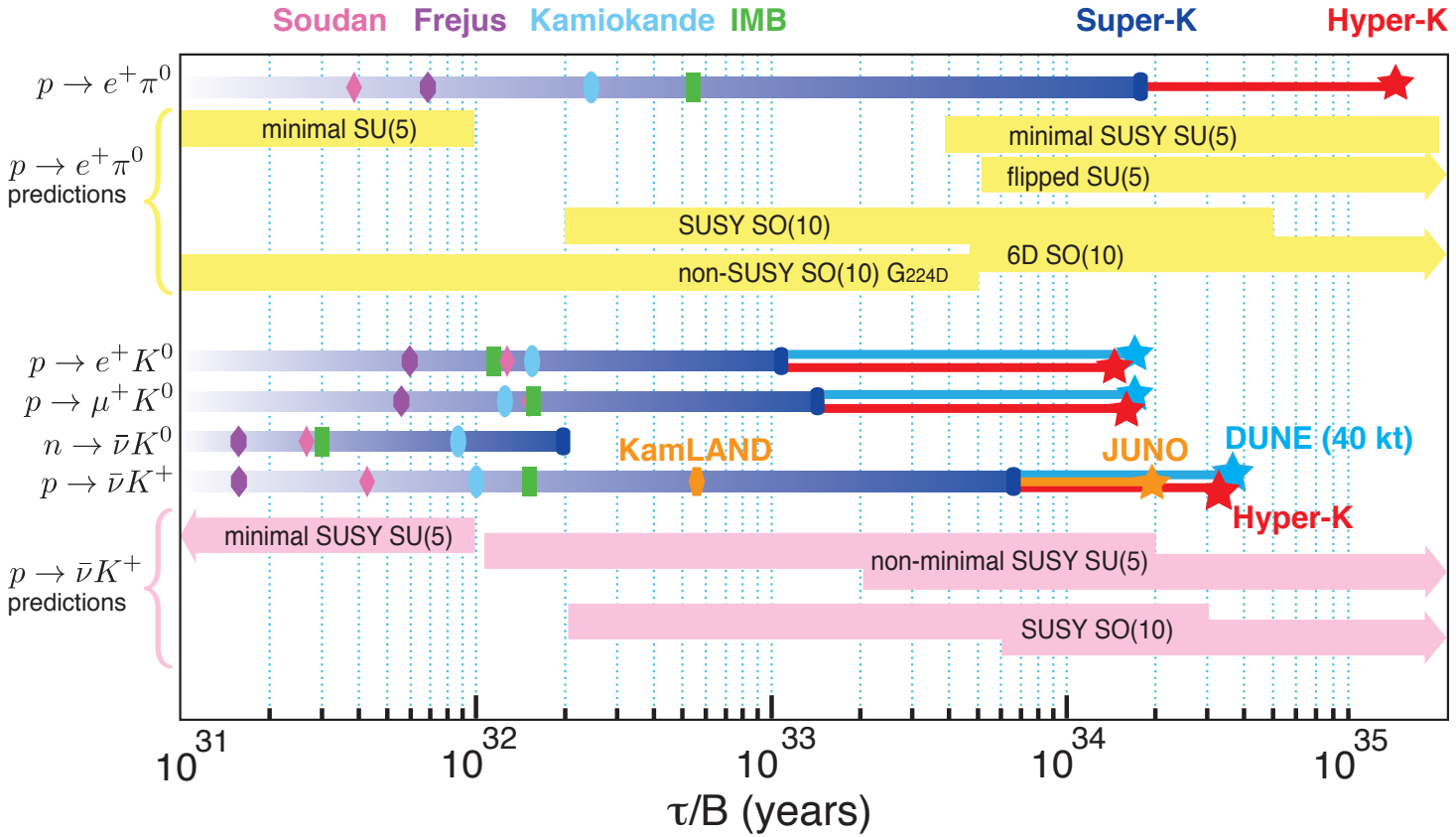
Super-K
17.5% efficient
2 evt/Mt y
(new! with
neutron tag)

Nominal
LArTPC
97% efficient
1 evt/Mt y

A. Bueno et al.
hep-ph/0701101

This color
is at current
SK limit

The decade ahead almost a decade from now

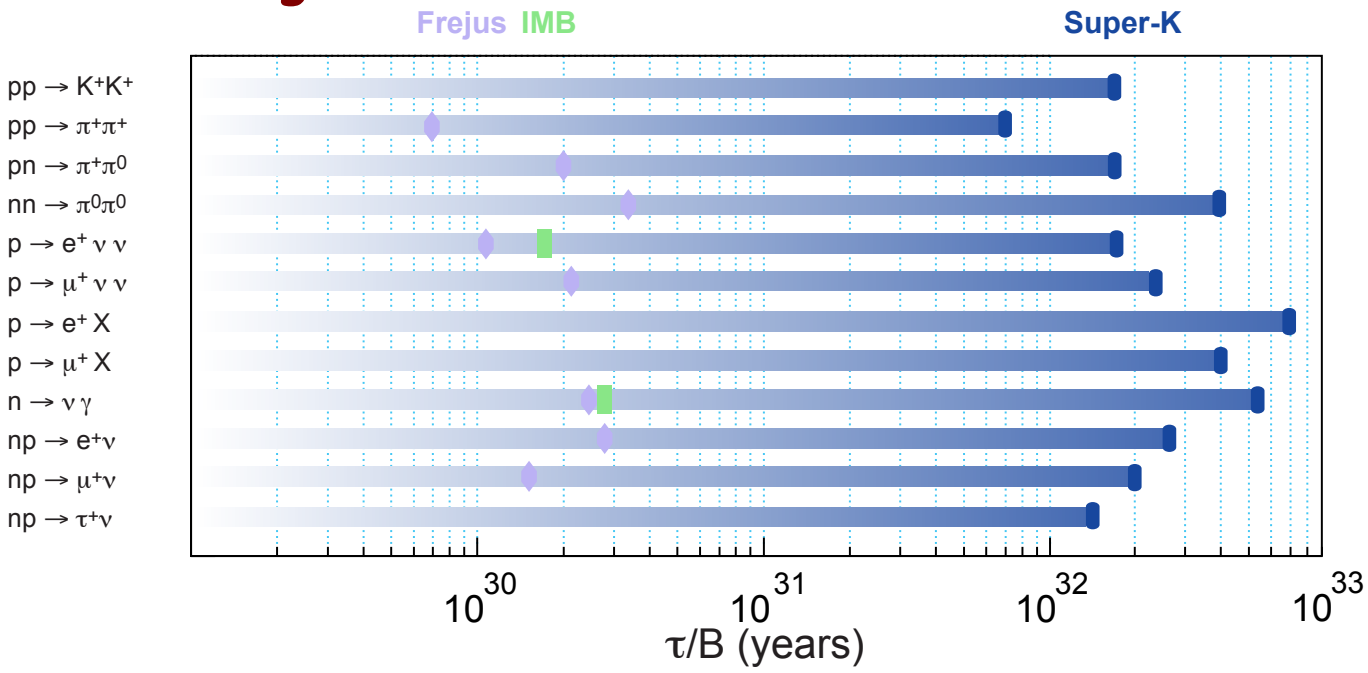


90% CL, 10 year nominal running

Conclusions

- Testing Baryon Number Violation is an essential and high priority objective of particle physics.
- Proton decay experiments have been negative so far, and severely constraining of theory. But the ongoing searches are in potentially fruitful territory.
- We have hitched our star to a big neutrino program.
- 10^{35} by 2035 !!!! – still (barely) possible

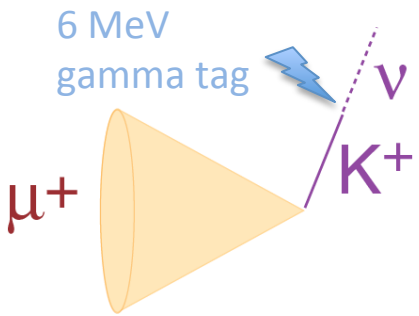
Summary of Recent Exotic Searches

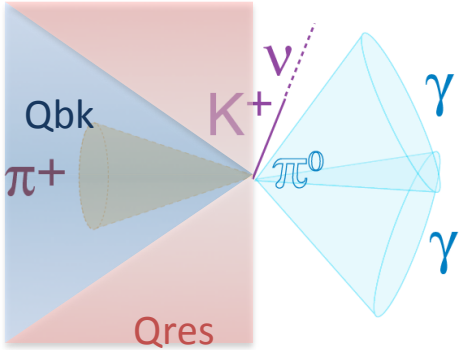


- Generally more than an order of magnitude improvement
- Some searches are entirely new

$p \rightarrow \nu K^+$

Kaon is below Cherenkov threshold. This is a search for kaon decay at rest.





γ-tag plus $\pi^+\pi^0$	SK1	(20% coverage) SK2	SK3	(new electronics) SK4 → w. n-cap
Efficiency	15.7 %	13.0 %	15.6 %	~~18.9 %~~ → 17.5 %
Background rate (ev/100 kty)	0.28	0.63	0.38	~~0.4~~ → 0.19

No candidates, 306 kton yr (SK 1+2+3+4 w. n-cap):

$$\frac{\tau}{B} > 6.61 \times 10^{33} \text{ y}$$