

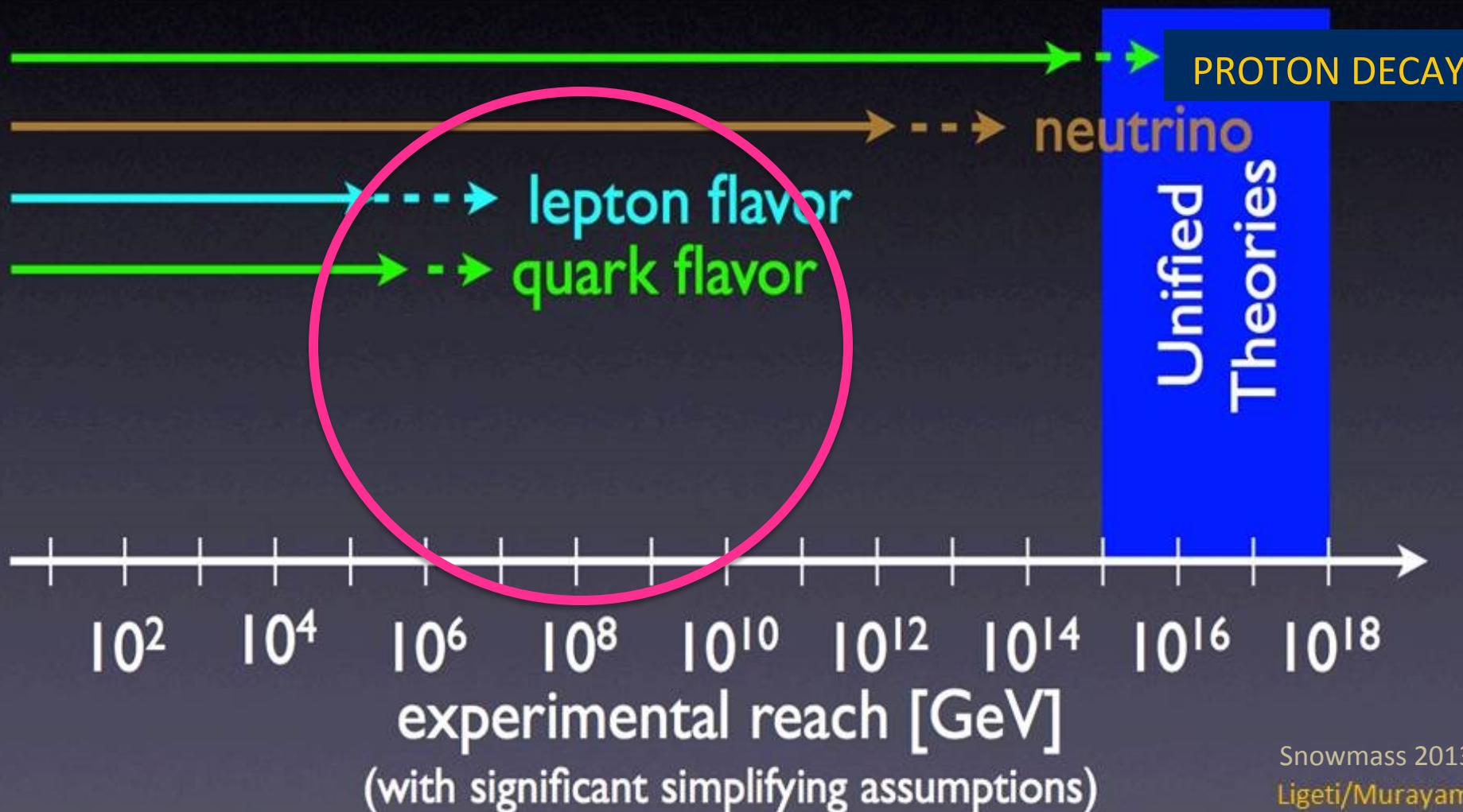
## Searching for Nucleon Decay with Super-Kamiokande

Ed Kearns

Boston University



# New Physics mass scales probed by Intensity frontier

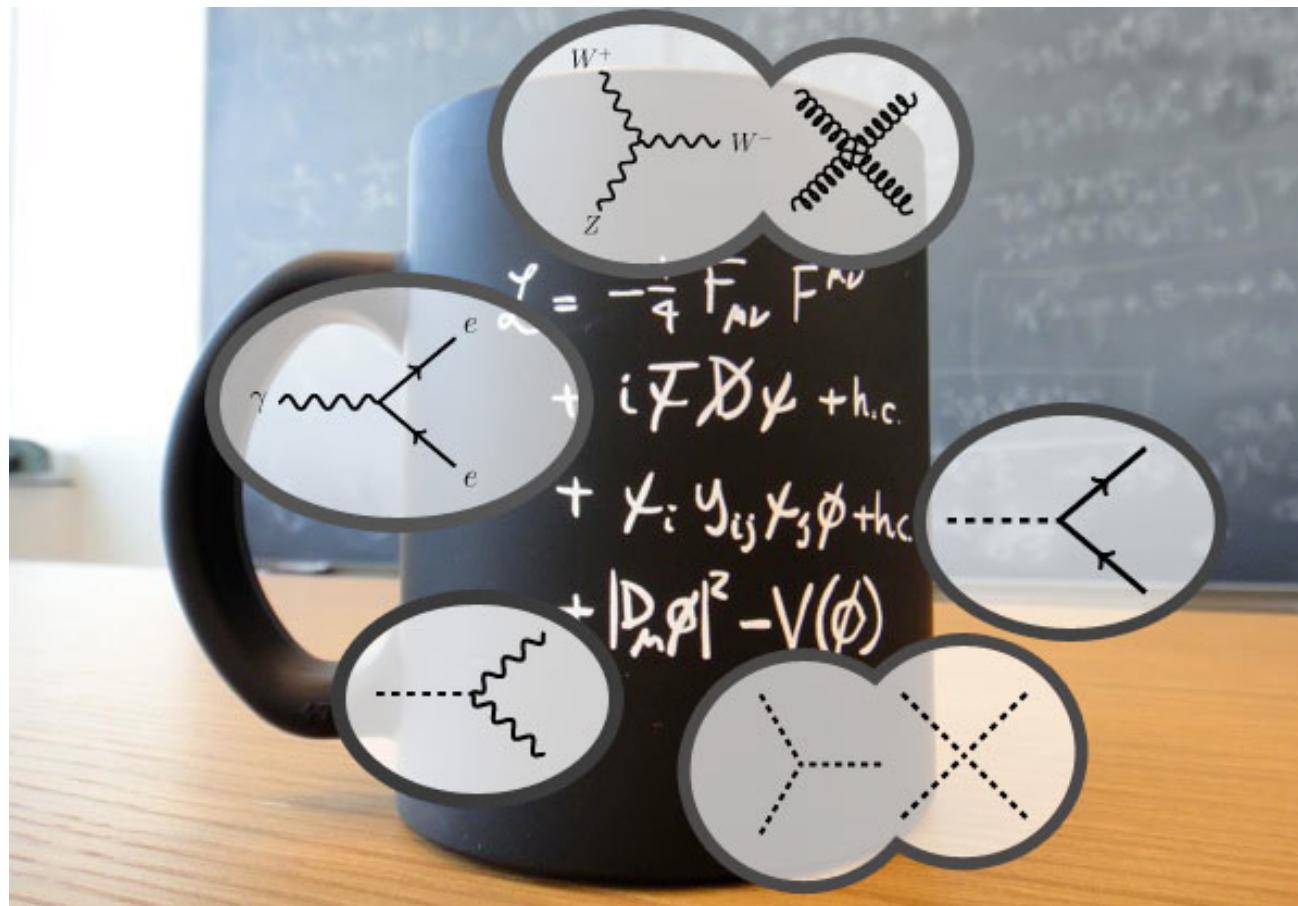


Muon g-2, MU2E,  
heavy flavor physics,  
lepton flavor violation,  
rare kaon decays,  
dipole moments ...

BARYON  
NUMBER  
VIOLATION

Snowmass 2013  
Ligeti/Murayama

# The Standard Model Lagrangian conserves Baryon Number\*



The Standard Model may be part of a bigger picture...

\*up to exceptionally long lifetimes, but not perfectly, due to *anomalies* – not a consideration for us today

# Grand Unified Theories

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

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

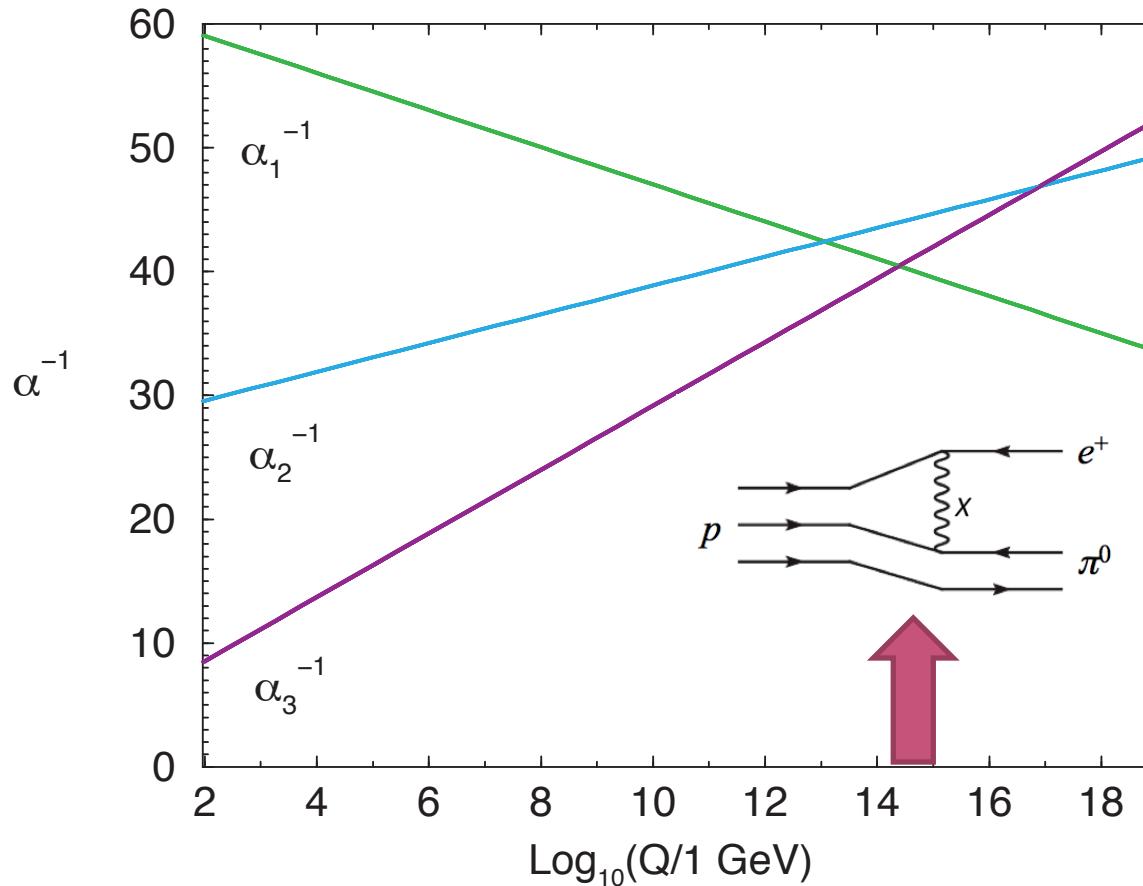
representations

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**)  $\Rightarrow$  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

# Gauge Coupling Unification

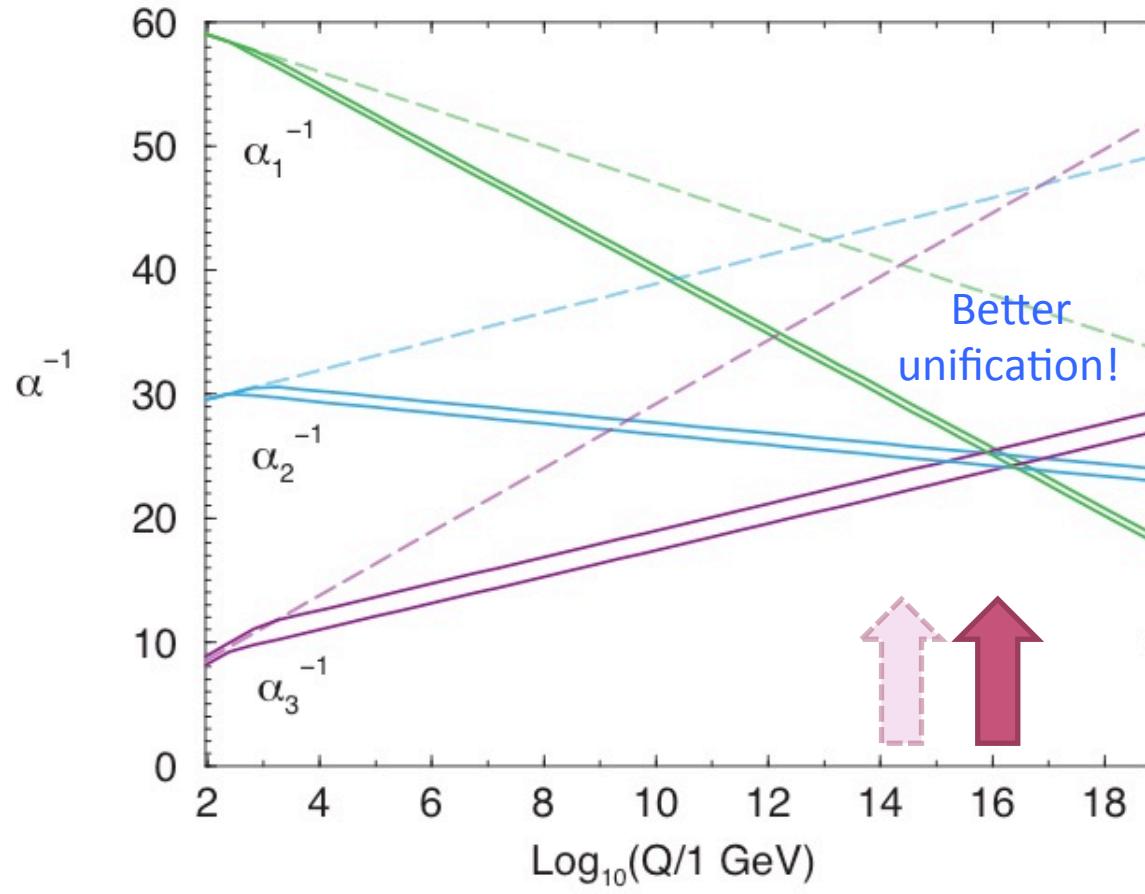


$$\tau \approx \frac{M_X^4}{\alpha^2 M_p^5}$$

$$\tau(e^+ \pi^0) = 4.5 \times 10^{29 \pm 1.7} \text{ years (predicted)}$$

$$\tau(e^+ \pi^0) > 5.5 \times 10^{32} \text{ years (IMB/1990)}$$

# No $e^+\pi^0$ seen? maybe solved by SUSY

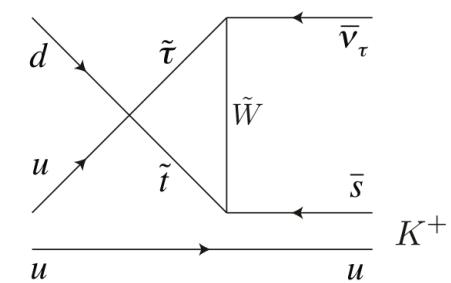


Unification scale pushed up ✓

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

But new modes now present

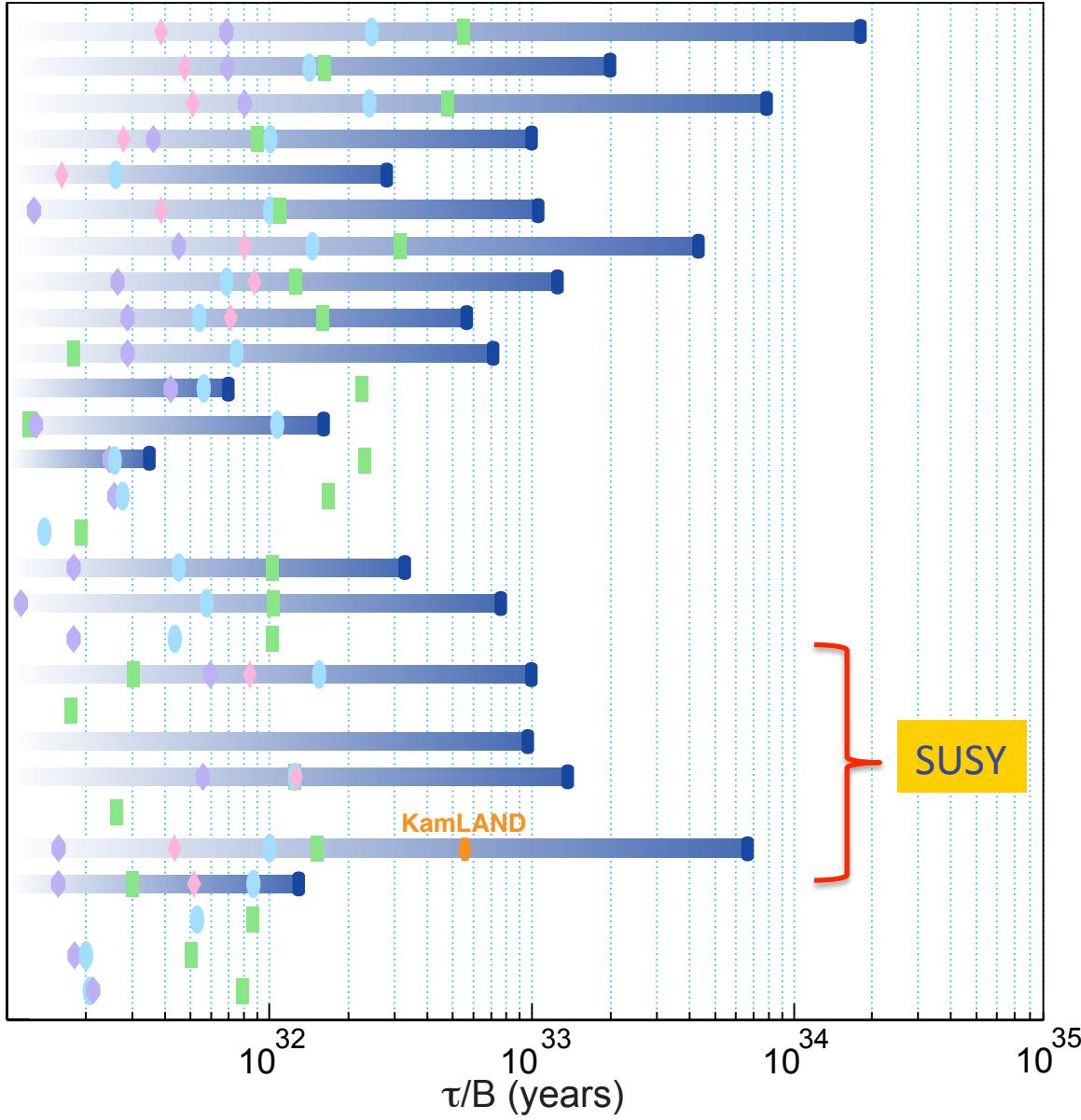
$$\tau(\nu K^+) \approx 10^{29-35} \text{ years}$$



## Antilepton + meson nucleon decays (conserves B-L)

**Soudan**   **Frejus**   **Kamiokande**   **IMB**   **Super-K**

- $p \rightarrow e^+ \pi^0$
- $n \rightarrow e^+ \pi^-$
- $p \rightarrow \mu^+ \pi^0$
- $n \rightarrow \mu^+ \pi^-$
- $p \rightarrow \nu \pi^+$
- $n \rightarrow \nu \pi^0$
- $p \rightarrow e^+ \eta$
- $p \rightarrow \mu^+ \eta$
- $n \rightarrow \nu \eta$
- $p \rightarrow e^+ \rho^0$
- $n \rightarrow e^+ \rho^-$
- $p \rightarrow \mu^+ \rho^0$
- $n \rightarrow \mu^+ \rho^-$
- $p \rightarrow \nu \rho^+$
- $n \rightarrow \nu \rho^0$
- $p \rightarrow e^+ \omega$
- $p \rightarrow \mu^+ \omega$
- $n \rightarrow \nu \omega$
- $p \rightarrow e^+ K^0$
- $n \rightarrow e^+ K^-$
- $n \rightarrow e^- K^+$
- $p \rightarrow \mu^+ K^0$
- $n \rightarrow \mu^+ K^-$
- $p \rightarrow \nu K^+$
- $n \rightarrow \nu K^0$
- $p \rightarrow e^+ K^{*(892)}{}^0$
- $p \rightarrow \nu K^{*(892)}{}^+$
- $n \rightarrow \nu K^{*(892)}{}^0$



SUSY

KamLAND

# Theoretical Outlook

- ❖ Numerous models exist. Lifetime predictions are not precise: typically uncertain by 2-3 orders of magnitude. Some theories suppress or exclude nucleon decay.
- ❖ There are two favored and benchmark decay modes:  
 $e^+\pi^0$  (gauge mediated) and  $\bar{\nu}K^+$  (SUSY D=5)
- ❖ **There are other modes and processes:**  
B-L conserving (like the above)  
B+L conserving  
nucleon decay to 3-body final states, maybe all leptons  
dinucleon decay  
neutron-antineutron oscillation ( $\Delta B=2$ )

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

# Super-Kamiokande

**SK-I: 1996 - 2001 (91.7 kt y)**

11146 50-cm inner PMTs , 40% coverage

1885 20-cm outer PMTs

**SK-II: Jan 2003 - Oct 2005 (49.2 kt y)**

Recovery from accident

5182 50-cm inner PMTs

Acrylic + FRP protective

Outer detector fully restored



**SK-III: May 2006 - Aug 2008 (31.9 kt y)**

Restored 40% coverage

Outer detector segmented (top | barrel | bottom)

**SK-IV: Sep 2008 – now (133.5 kt y)**

SK-IV All new electronics— record every photon

Detect neutron capture, better  $\mu$ -decay efficiency

**Current total exposure: 306 kt y**

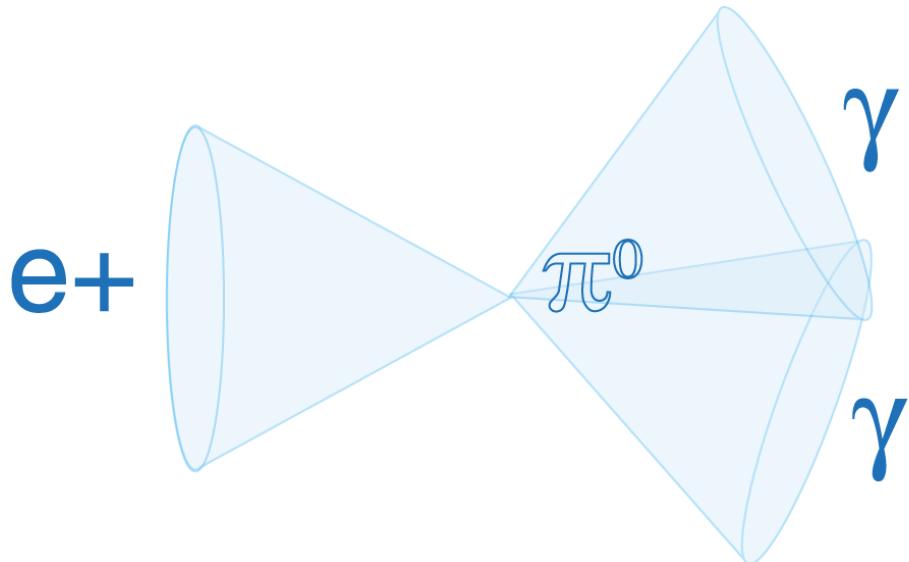
**SK-Gd:**

Add gadolinium – increase neutron tag efficiency

Date to be determined – coordinate with J-PARC schedule for T2K.

22.5 kton fiducial volume

$7.5 \times 10^{33}$  protons +  $6 \times 10^{33}$  neutrons



# Signal:

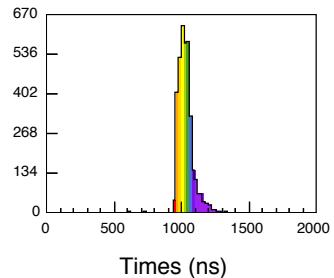
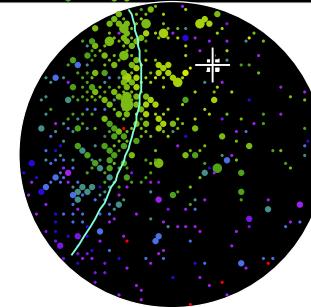
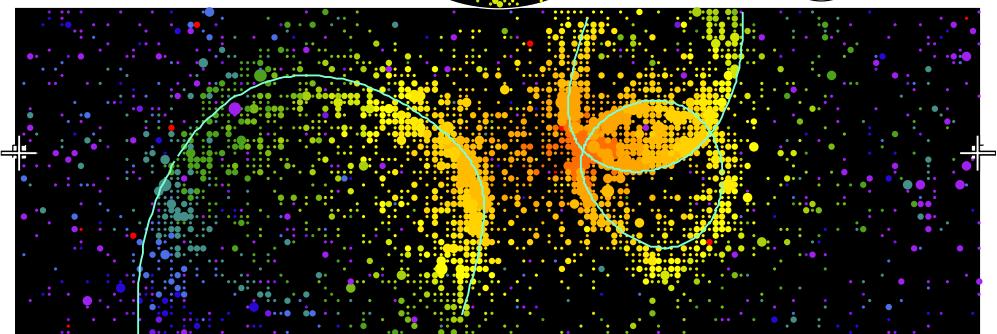
$$p \rightarrow e^+ \pi^0$$

## Good event criteria:

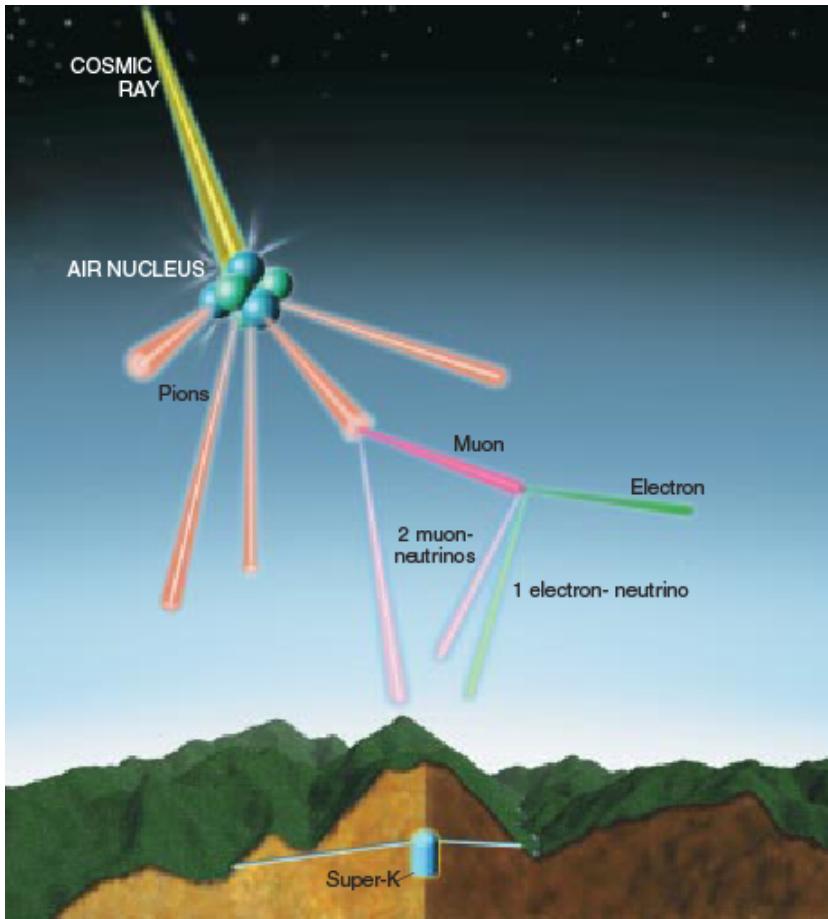
- Fully contained
- Fiducial volume
- 2 or 3 rings
- All rings are EM showers
- $\pi^0$  mass 85-185 MeV/ $c^2$
- No  $\mu$ -decay electrons
- Mass range 800-1050 MeV/ $c^2$
- $p_{net} < 250$  MeV/ $c$
- tight cut:  $p_{net} < 100$  MeV/ $c$
- SK4 only: *absence of neutron capture tag*

Time(ns)

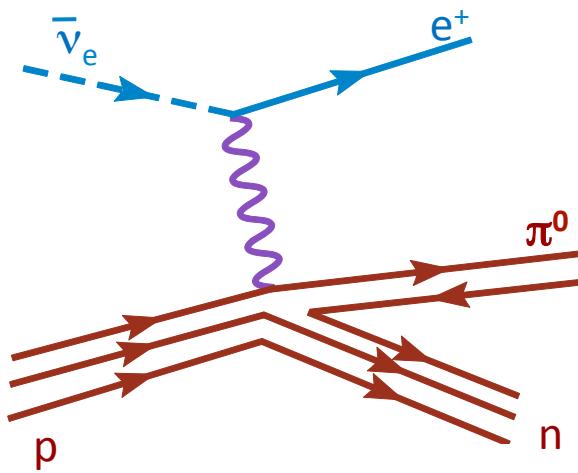
- < 952
- 952- 962
- 962- 972
- 972- 982
- 982- 992
- 992-1002
- 1002-1012
- 1012-1022
- 1022-1032
- 1032-1042
- 1042-1052
- 1052-1062
- 1062-1072
- 1072-1082
- 1082-1092
- >1092



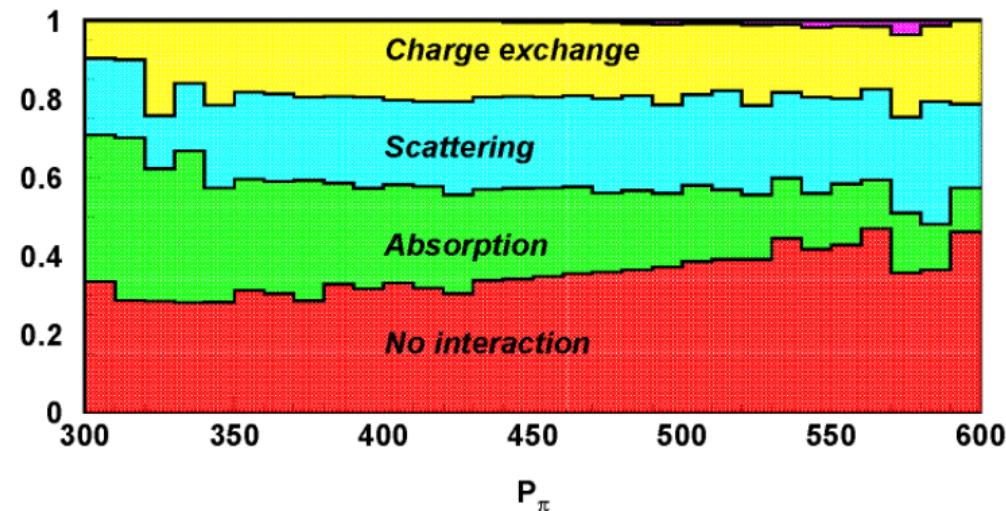
# Background: Atmospheric Neutrinos



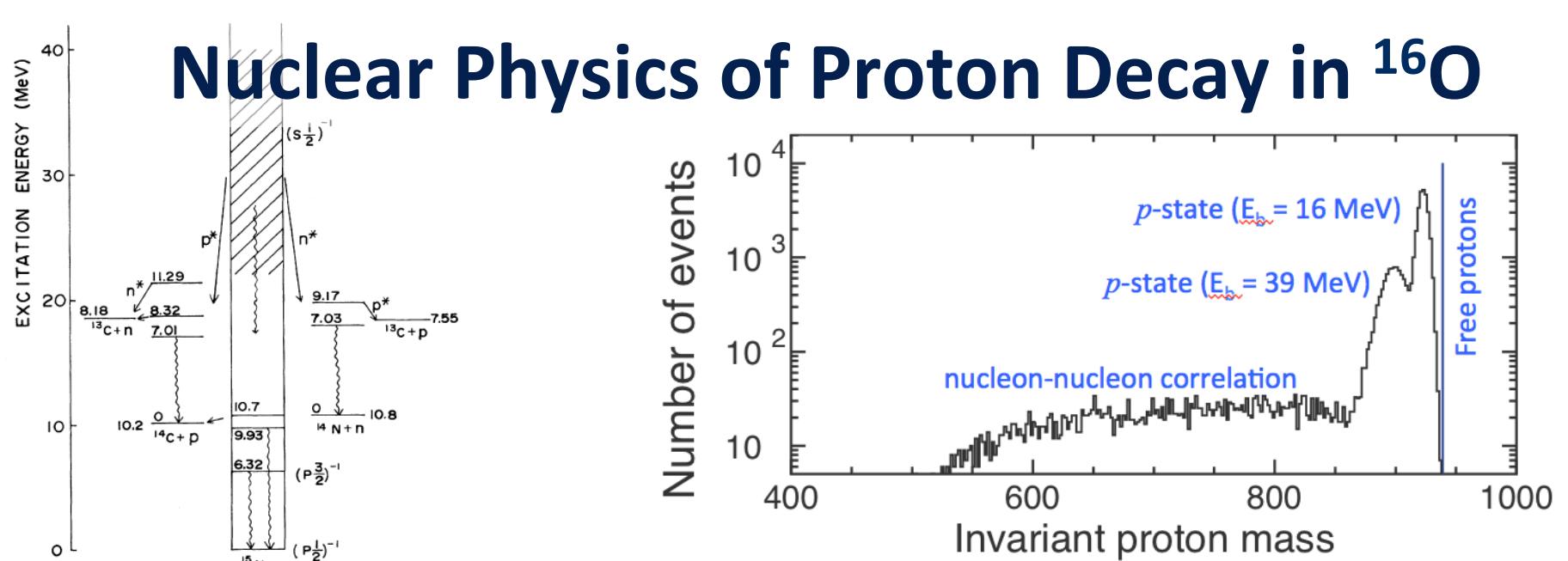
Background rate uncertainty typically 40-60%, dominated by hadronic interaction uncertainty.



Significant effort goes into modeling neutrino interactions, especially intranuclear pion reactions.



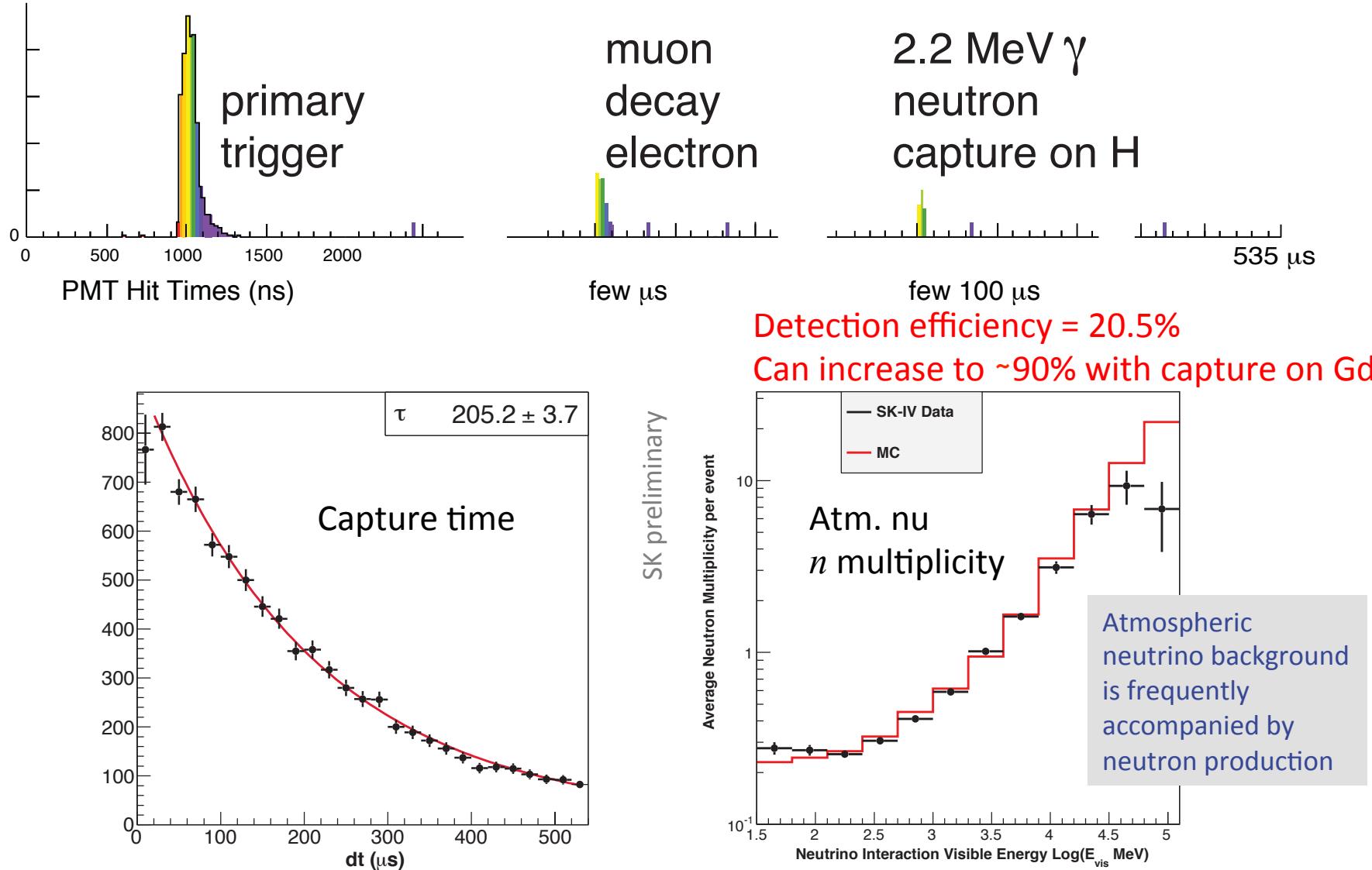
# Nuclear Physics of Proton Decay in $^{16}\text{O}$



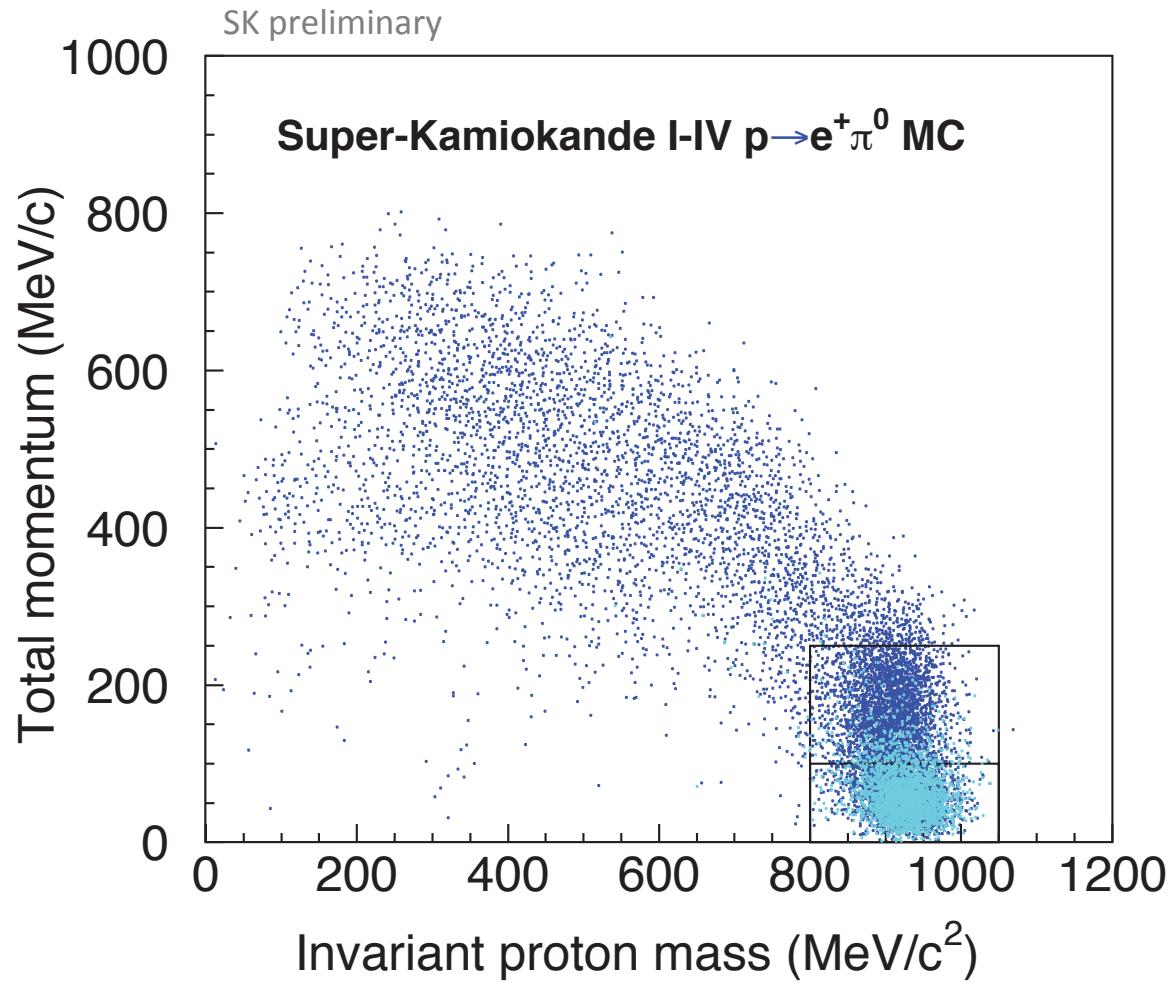
Hole	Residual	States	(k)	$E_\gamma$	$E_p$	$E_n$	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	$^{15}\text{N}$	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	$^{15}\text{N}$	6.32	0	some gammas	0.41
	9.93	$\frac{3}{2}^-$	$^{15}\text{N}$	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	$^{15}\text{N}$	0	0.5	0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

# Neutron capture on $^1\text{H} \rightarrow 2.2 \text{ MeV } \gamma$

Enabled by SK-IV electronics with deadtime-less DAQ + software trigger

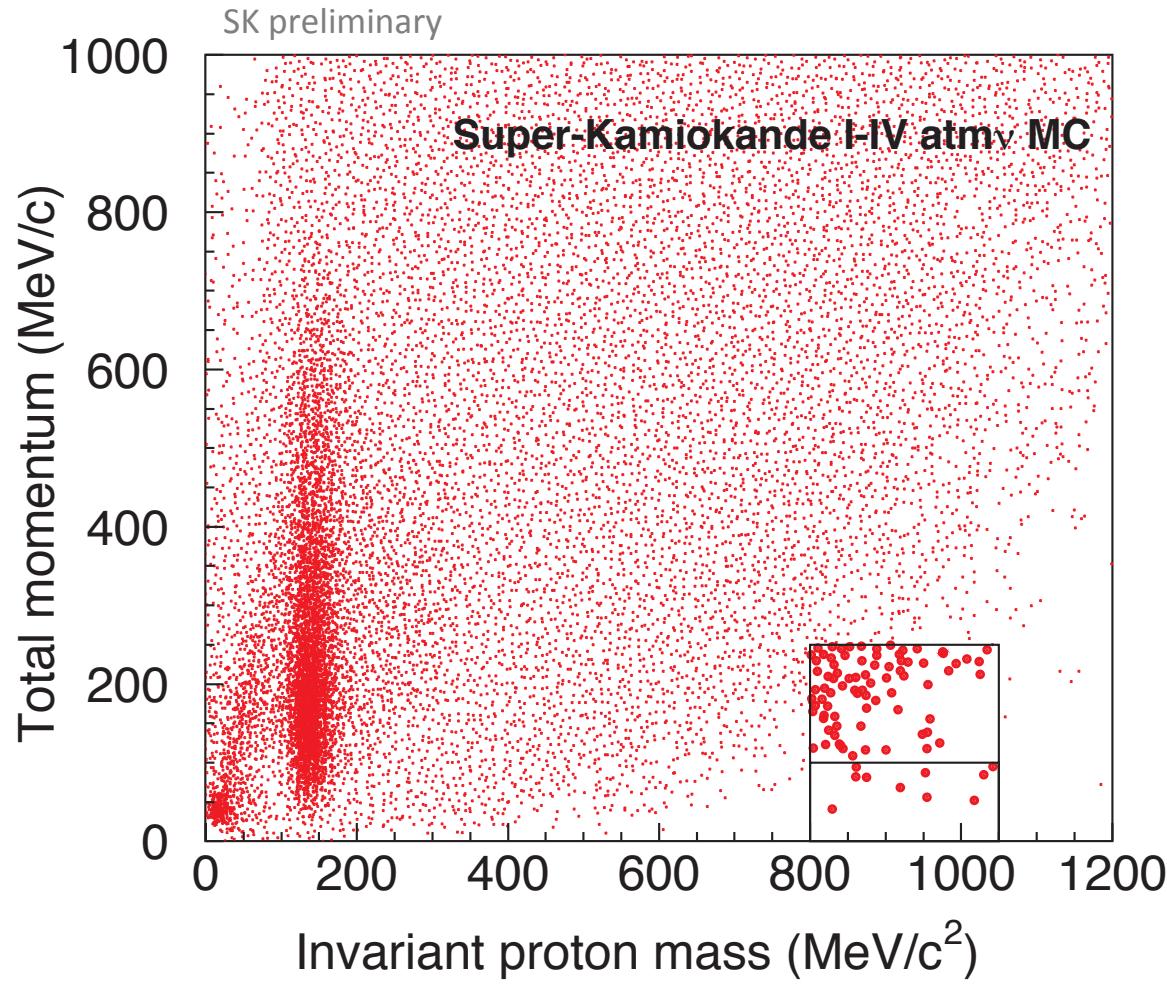


$p \rightarrow e^+ \pi^0$   
**Signal MC**



Signal Efficiency (%)	SK-I	SK-II	SK-III	SK-IV w. n cap.
$100 < p_{net} < 200 \text{ MeV}/c$	$20.4 \pm 3.1$	$20.2 \pm 3.1$	$20.5 \pm 3.2$	$19.4 \pm 1.2$
$p_{net} < 100 \text{ MeV}/c$	$18.8 \pm 0.9$	$18.3 \pm 1.0$	$19.6 \pm 1.3$	$18.7 \pm 1.2$

$p \rightarrow e^+ \pi^0$   
**Atmospheric**  
 **$\nu$  bkg MC**

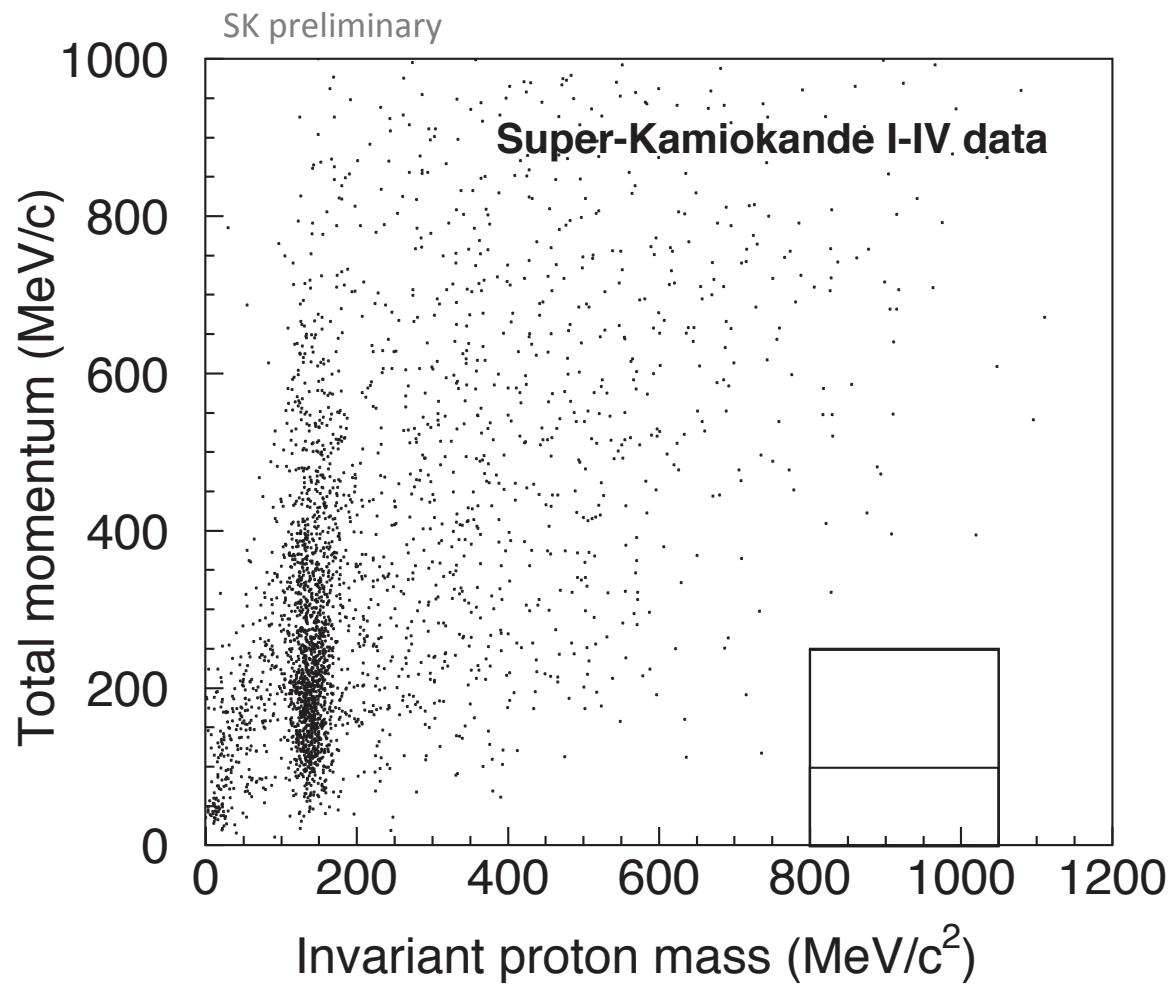


bkg rate is  
reduced in  
half by n-tag

Background (evts)	SK-I	SK-II	SK-III	SK-IV w. n cap.
$100 < p_{net} < 200$ MeV/c	$0.22 \pm 0.06$	$0.12 \pm 0.04$	$0.06 \pm 0.02$	$0.15 \pm 0.05$
$p_{net} < 100$ MeV/c	$0.03 \pm 0.01$	$0.01 \pm 0.003$	$0.003 \pm 0.001$	$0.02 \pm 0.01$

Monte Carlo estimates. Background rate also measured using K2K 1KT near detector.

$p \rightarrow e^+ \pi^0$   
**Super-K Data**  
(306 kt y)



$$\begin{aligned} P(\Gamma|n_1, n_2) = & \frac{1}{A} \iiint \frac{e^{-(\Gamma\lambda_1\epsilon_1 + b_1)} (\Gamma\lambda_1\epsilon_1 + b_1)^{n_1}}{n_1!} \\ & \times \frac{e^{-(\Gamma\lambda_2\epsilon_2 + b_2)} (\Gamma\lambda_2\epsilon_2 + b_2)^{n_2}}{n_2!} \\ & \times P(\Gamma) P(\delta_\epsilon) P(\delta_\lambda) P(\delta_b) d\delta_\epsilon d\delta_\lambda d\delta_b \end{aligned}$$

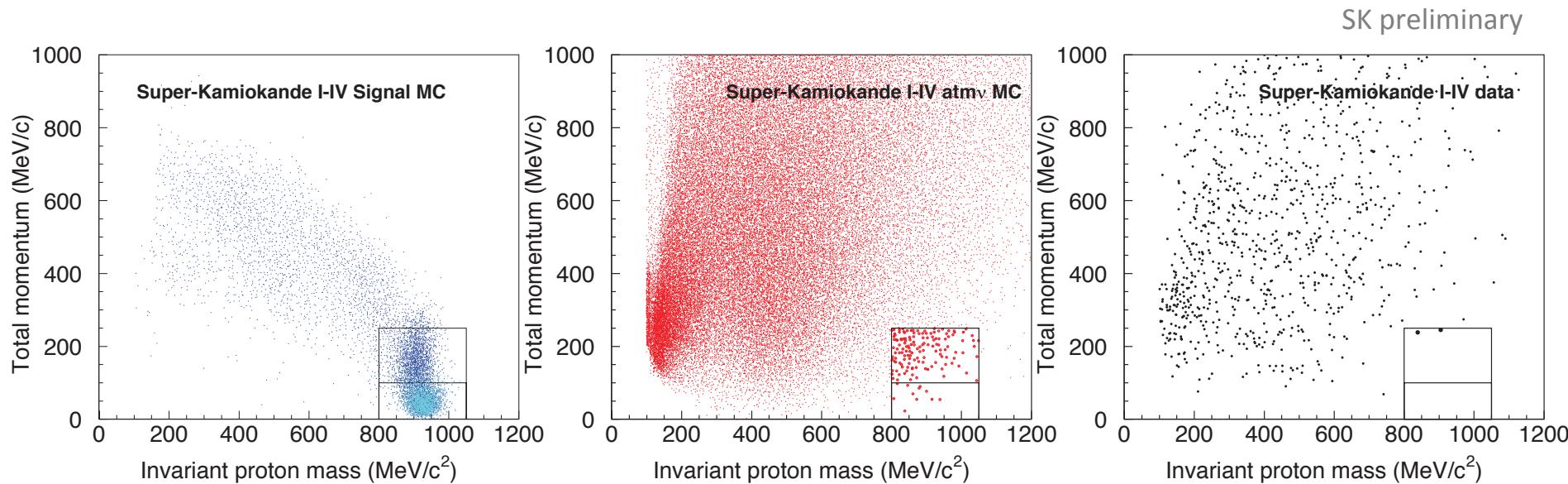
$\boxed{\frac{\tau}{B} > 1.67 \times 10^{34} \text{ y}}$

$p_{net}$  regions combined,  
systematic errors incorporated:

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

“flipped” SU(5)\* predicts high branching ratio with 2<sup>nd</sup> generation lepton

SK analysis proceeds as with  $e^+\pi^0$  with additional requirement of =1 muon decay



Signal efficiency  
31.7% - 38.3%

Background estimate:  
 $0.87 = 0.82 + 0.05$  events

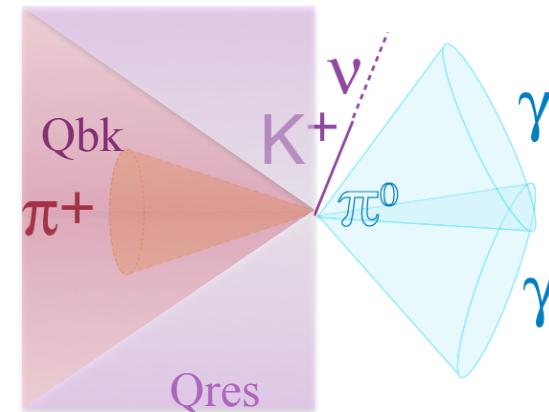
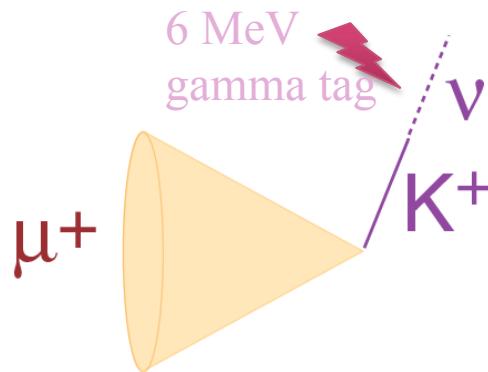
**Result:** two candidate proton decay events.  
Consistent with background.

$$\frac{\tau}{B} > 7.78 \times 10^{33} \text{ y}$$

\* J. Ellis, Nanopoulos, & Walker,  
Phys. Lett. B 550, 99 (2002).

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

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



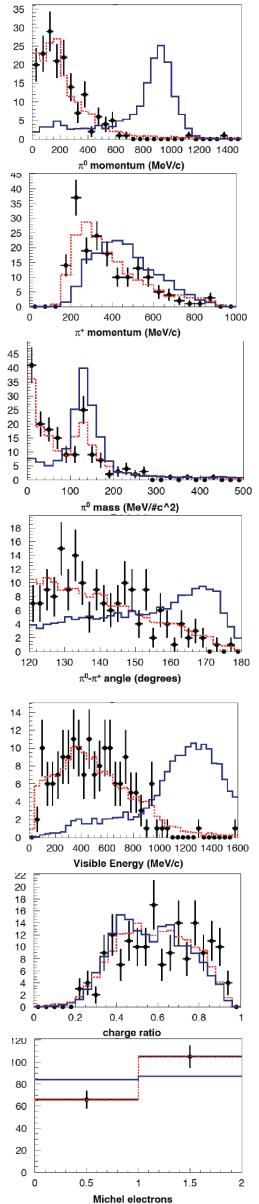
$\gamma$ -tag plus $\pi^+\pi^0$	SK1	(20% coverage) SK2	SK3	(new electronics) <b>SK4 → w. n-cap</b>
Efficiency	15.7 %	13.0 %	15.6 %	<del>18.9 %</del> → 17.5 %
Background rate (ev/100 kty)	0.28	0.63	0.38	<del>0.4</del> → 0.19 %

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

SK preliminary

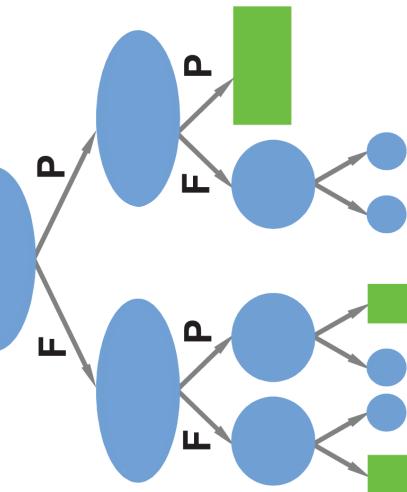
$$\frac{\tau}{B} > 6.61 \times 10^{33} \text{ y}$$

INPUT  
VARIABLES

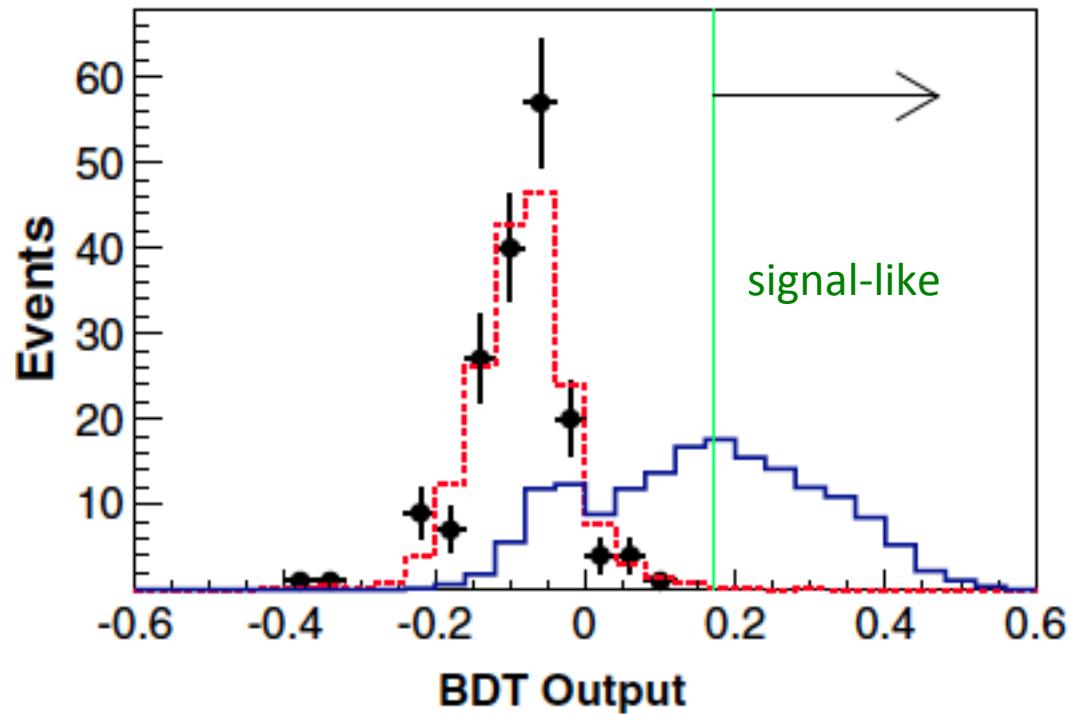


# Dinucleon Decay: $pn \rightarrow \pi^+\pi^0$ $\Delta B=2$

## Boosted Decision Tree



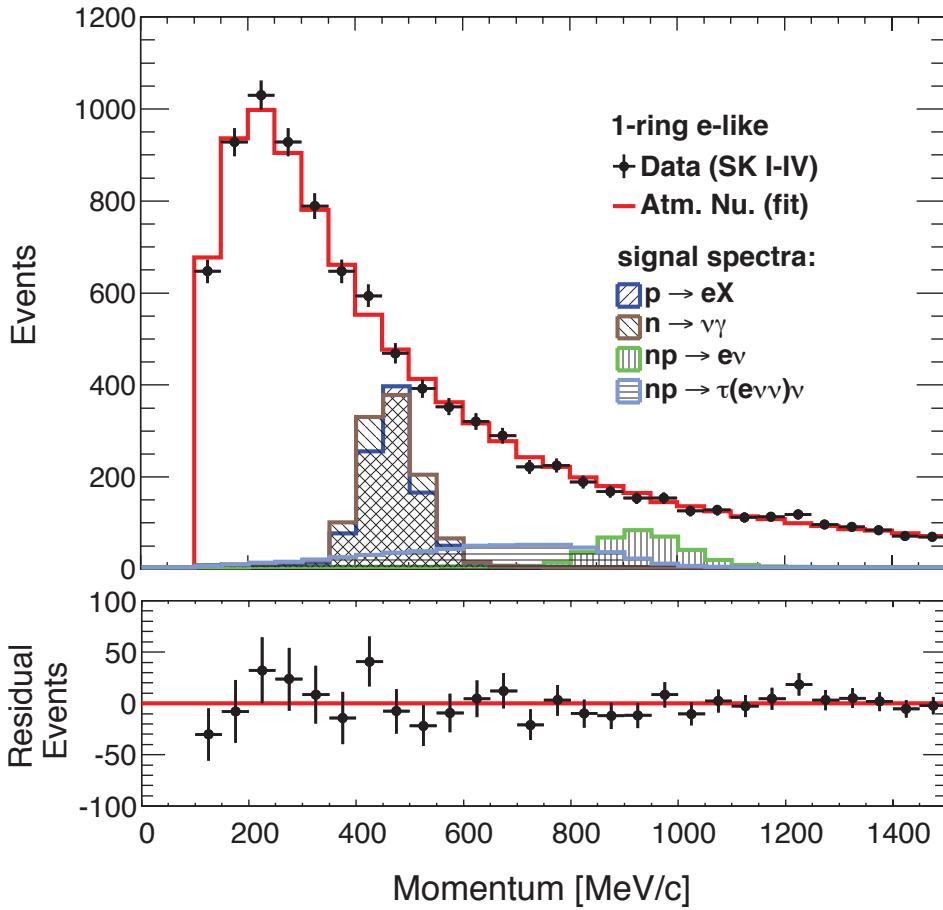
## Multivariate Output



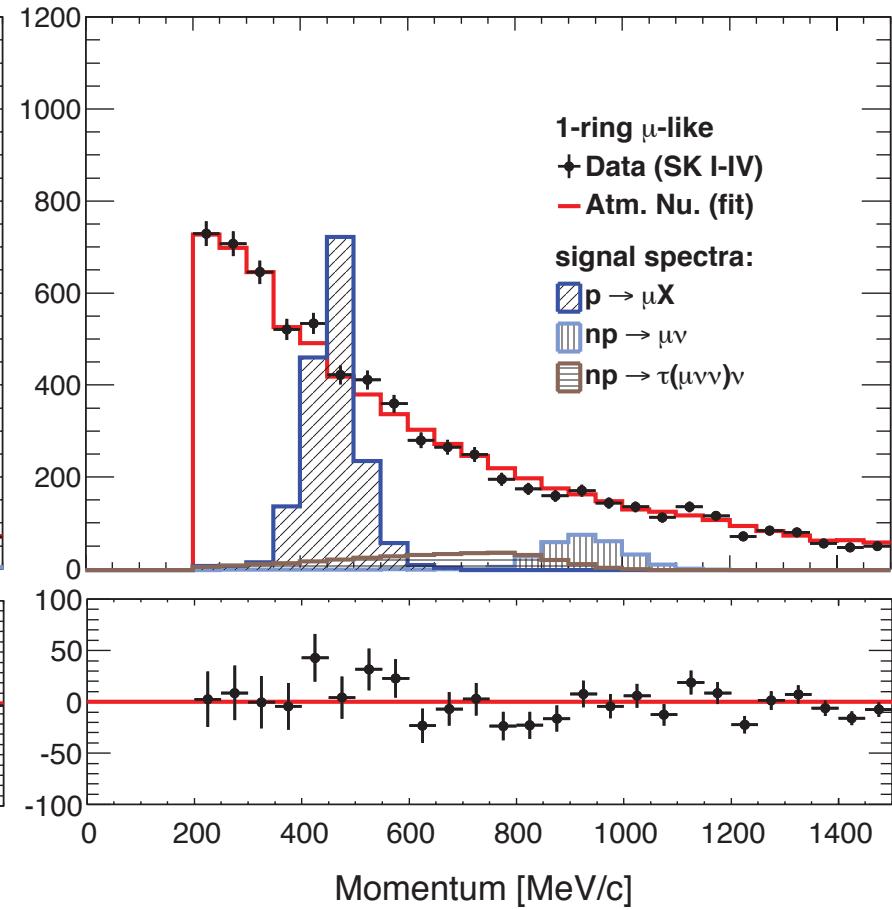
Mode	Frejus limit ( $^{56}\text{Fe}$ )	This analysis ( $^{16}\text{O}$ )
$pp \rightarrow \pi^+\pi^+$	$7.0 \times 10^{29}$ yrs	$7.22 \times 10^{31}$ yrs
$pn \rightarrow \pi^+\pi^0$	$2.0 \times 10^{30}$ yrs	$1.70 \times 10^{32}$ yrs
$nn \rightarrow \pi^0\pi^0$	$3.4 \times 10^{30}$ yrs	$4.04 \times 10^{32}$ yrs

# Spectral Search for Baryon Number Violation

single e-like rings



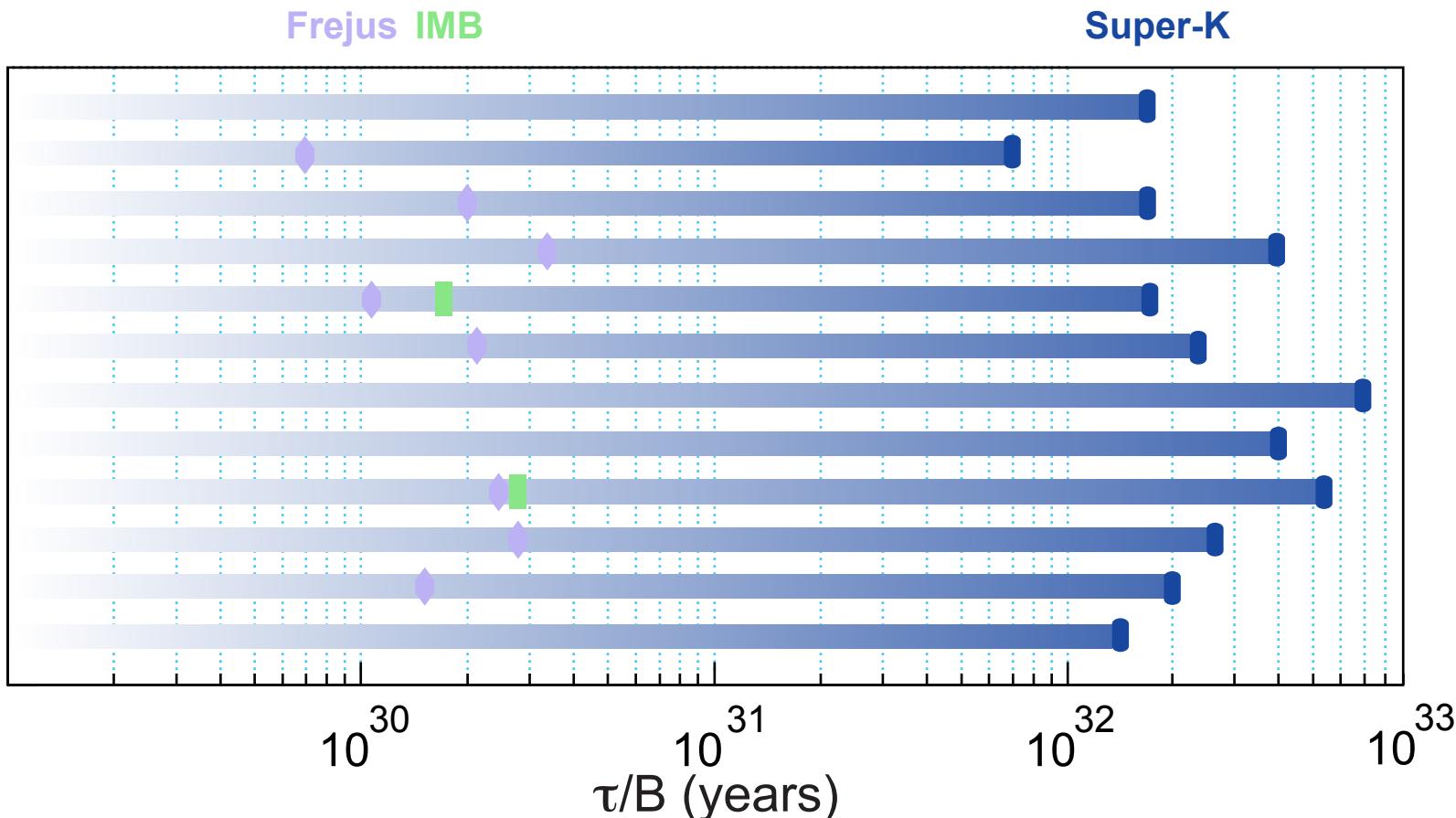
single mu-like rings



Momentum distribution of single rings is well modeled by atmospheric neutrinos

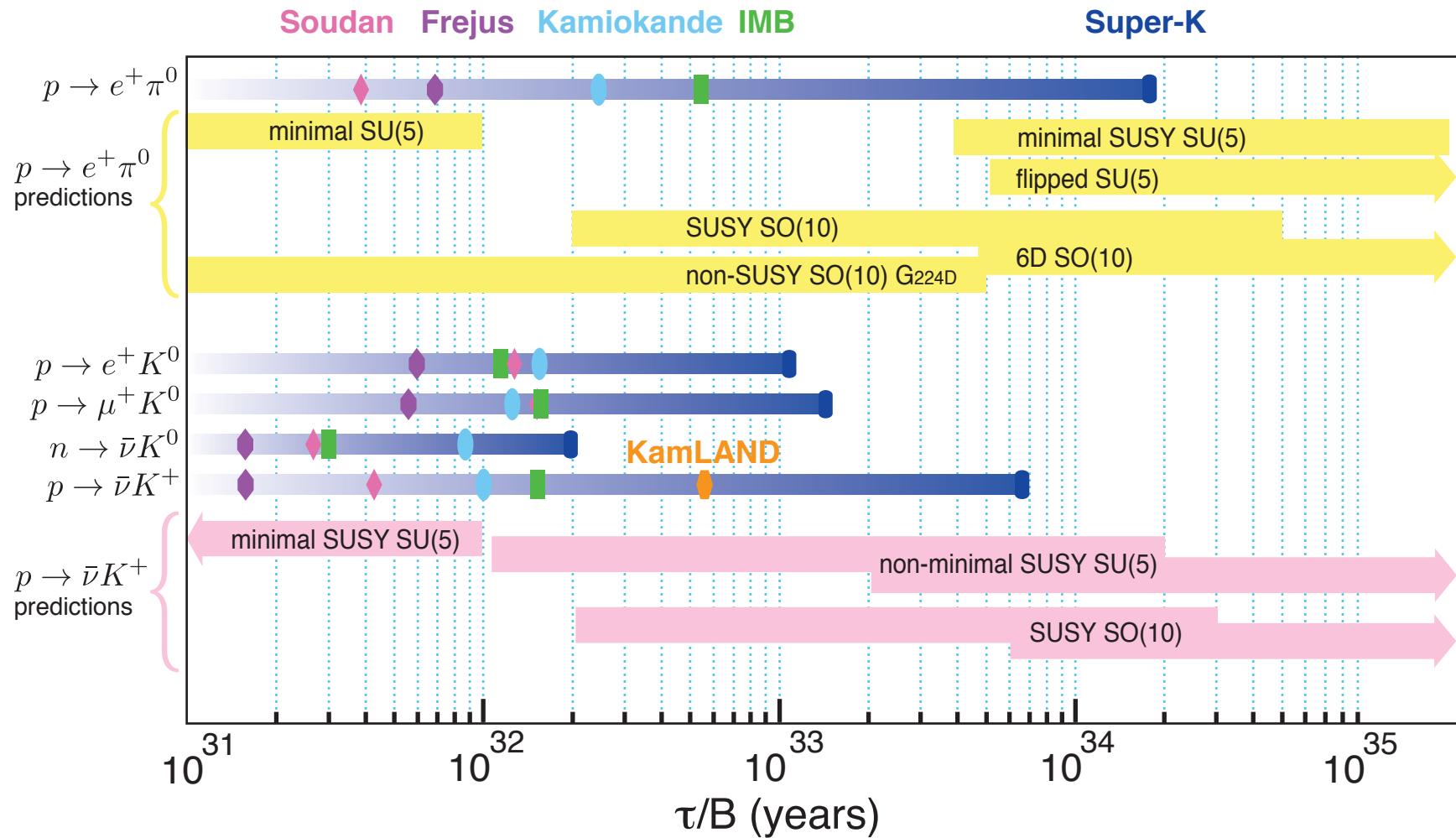
Lifetime limits:  $3 \times 10^{31}$  years to  $8 \times 10^{32}$  years

# Summary of Recent Exotic Searches

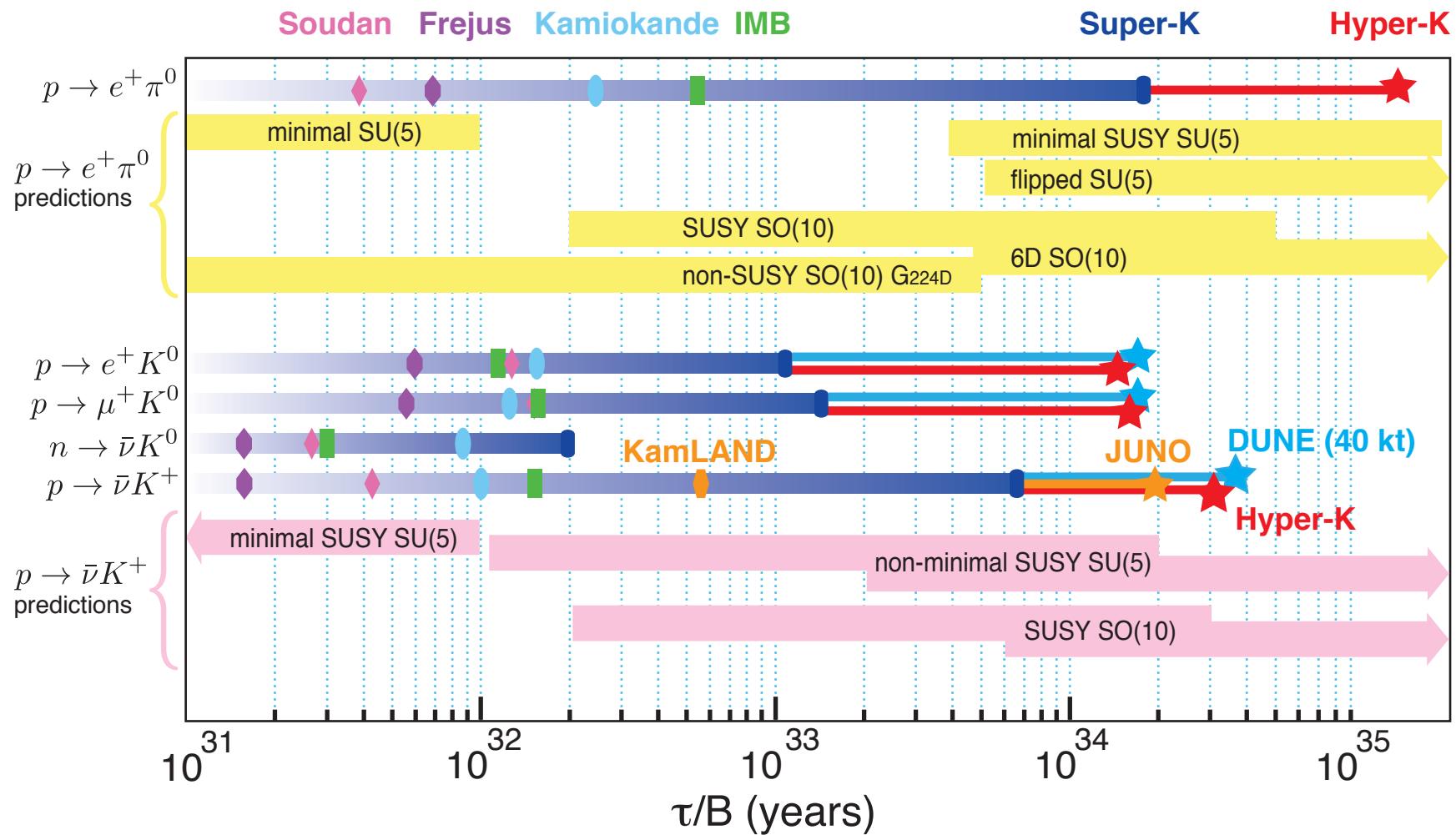


- Generally more than an order of magnitude improvement
- Some searches are entirely new

# Current Benchmark Searches are in Interesting Territory



# Future Benchmark Searches will be in Interesting Territory



# Conclusion

- ❖ Testing Baryon Number Violation is an essential and high priority objective of particle physics
- ❖ In this talk I have presented updated (preliminary) search results (negative unfortunately) in the key benchmark modes
- ❖ We are also searching many other modes, some novel, to cover many possible sources of baryon number violation
- ❖ Neutron capture is being established as a valuable technique for background reduction – and will become a major initiative in the next few years when SK-Gd is implemented

# A recent author list for the Super-Kamiokande Collaboration

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U.S. operation of  
Super-Kamiokande  
is funded by:



Office of Science  
U.S. Department of Energy