Experimental Searches for Proton Decay

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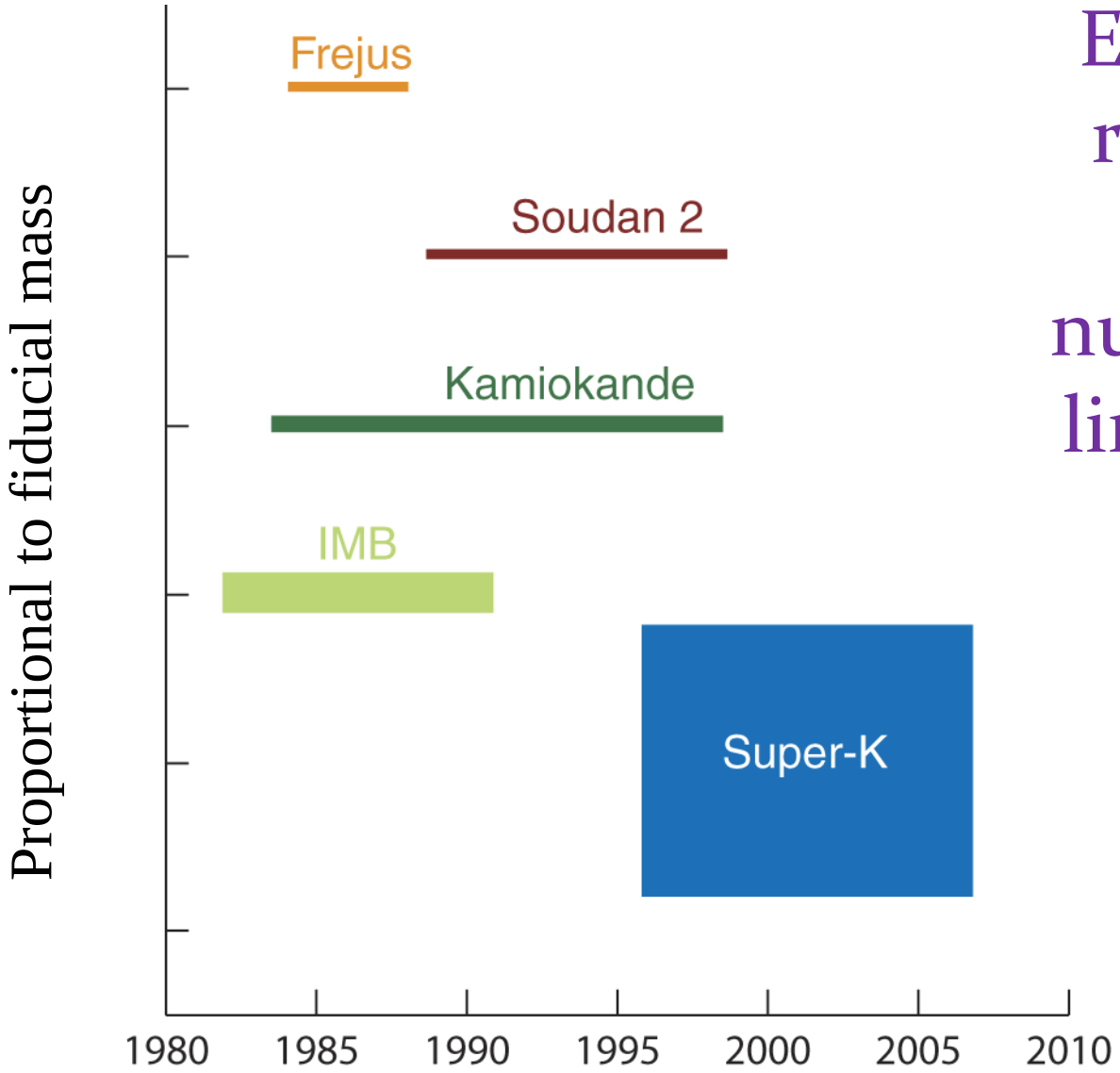
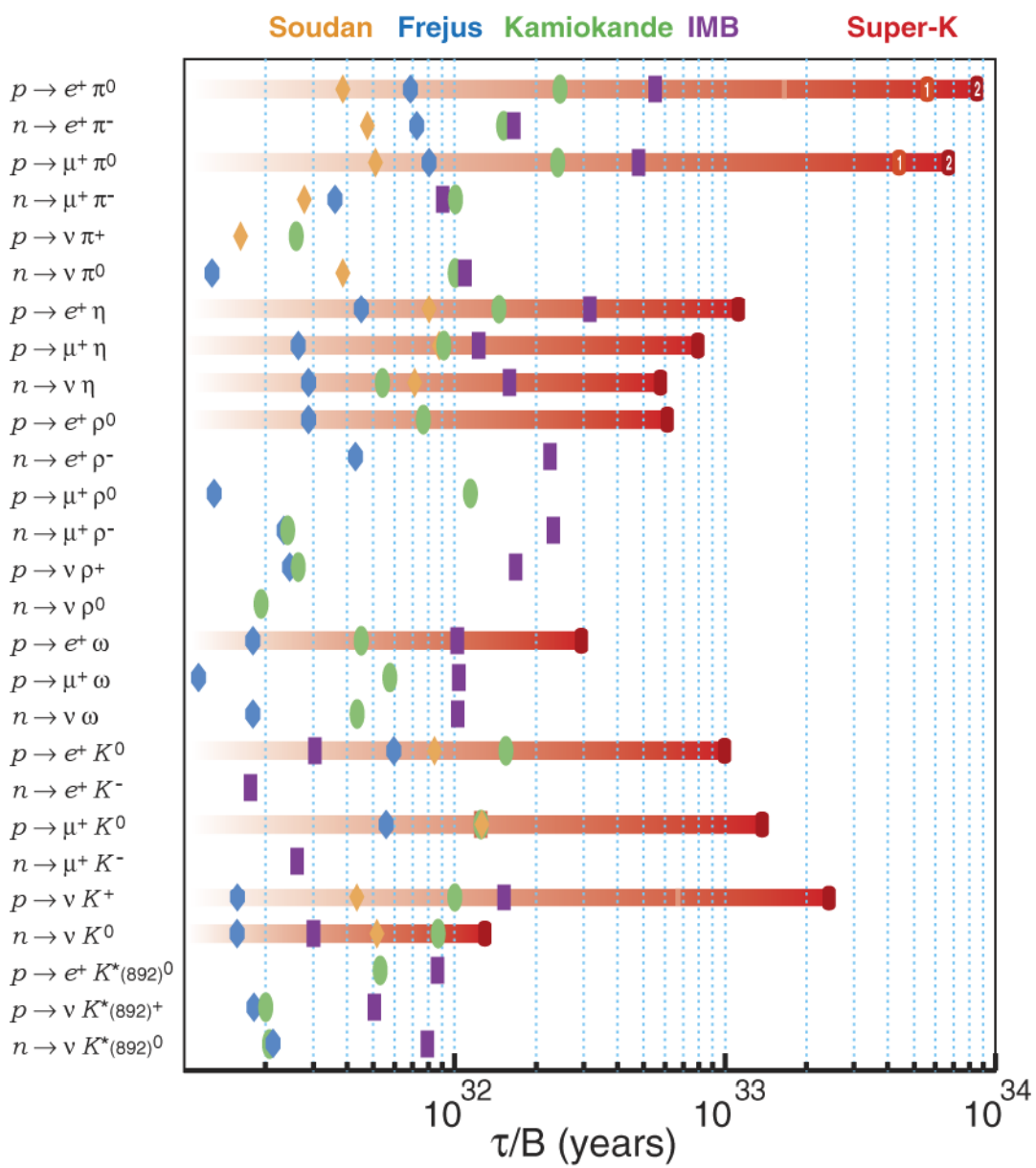
- generalities
- nnbar oscillation
- proton decay modes
  - results from Super-K
  - background studies
  - photocathode coverage
- looking forward

NNN07-Hamamatsu
Workshop on Next Generation Nucleon Decay and Neutrino Detectors 2007



Experiments represented with best nucleon decay limits in PDG

Antilepton plus meson modes



IMB has most in PDG (for now)

Super-K has only searched for favored channels (for now)

Iron tracking detectors can compete in very few modes (too small)

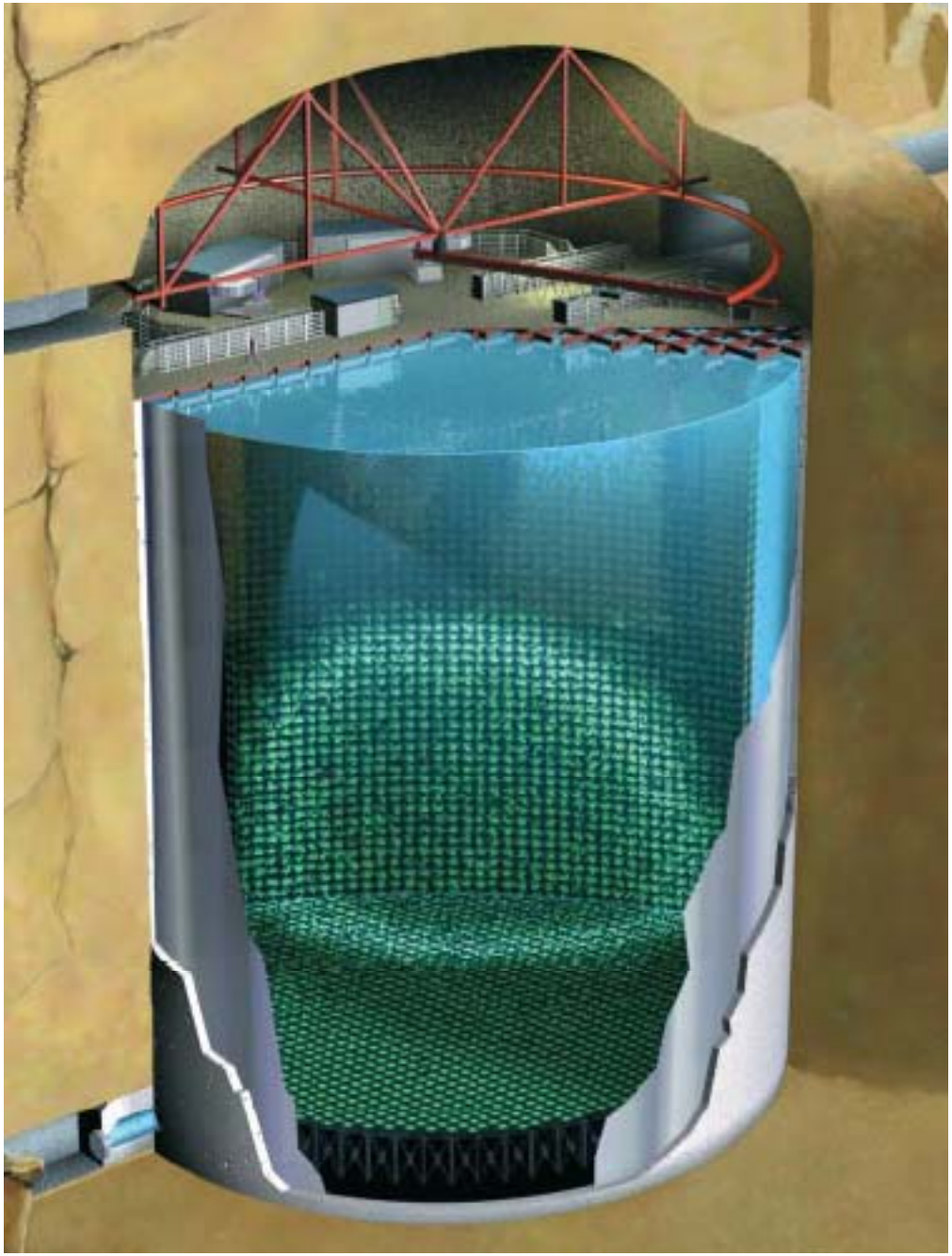
There are good reasons to cover many of these modes…

Beyond antilepton plus meson

And we should search broadly and not be constrained by favored theories. We are testing fundamental symmetries– always worthwhile.

	τ/B (10^{30} years)	
Radiative decays:		
$p \to e^+ \gamma$	7300	Super-K preliminary
$n \to \nu \gamma$	39	IMB
Once suggested for atmospheric ν anomaly (Mann 1992):		
$p \to e^+ \nu \nu$	17	IMB
$n\bar{n}$ oscillation ★		
$n \to \bar{n}$	72	Soudan 2
"Invisible" mode: ★		
$n \to \nu \nu \nu$	0.58	Kamland
B-L violating modes and di-nucleon decay (Frejus limits):		
$n \to e^+ e^- \nu$	74	Δ(B-L)=2 ΔB=1
$p \to \mu^+ \pi^+ K^+$	5.4	Δ(B-L)=2 ΔB=1
$pn \to e^+ n$	100	Δ(B-L)=0 ΔB=1
$pn \to \pi^0 \pi^0$	3.4	Δ(B-L)=2 ΔB=2
$pp \to e^+ e^+$	5.8	Δ(B-L)=0 ΔB=2
New decay modes:		
$p \to e^- \pi^+ \pi^+ \nu \nu$	?	(Applequist, Dobrescu et al. hep-ph/0107056)

… what else??



Super-Kamiokande

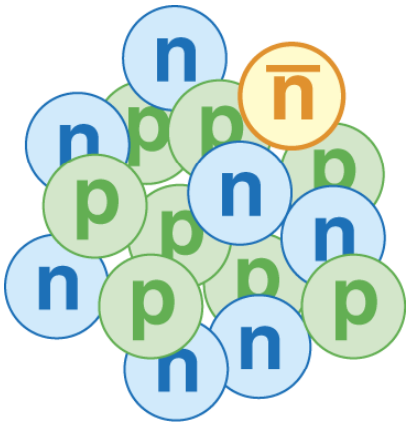
22.5 kton fiducial volume
7.5×10^{33} p + 6×10^{33} n

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

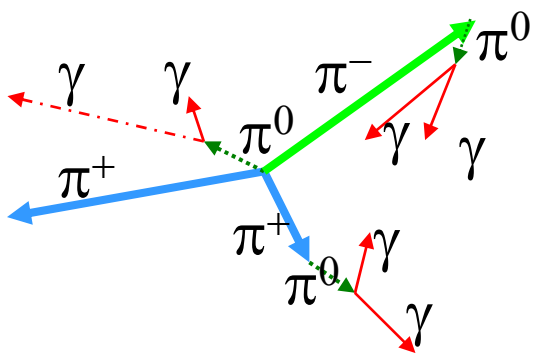
SK-III: May 2006-
Restored 40% coverage
Outer detector segmented (top | barrel | bottom)

SK-future:
Replace all electronics - 2008
Add Gadolinium - 20??



Neutron – antineutron Oscillation

- Antineutron annihilates with nearby *n* or *p*
- Energy release ~ 2× nucleon mass
- High multiplicity ~ 4π/event
- Isotropic distribution
- Final state simulation from bubble chamber data

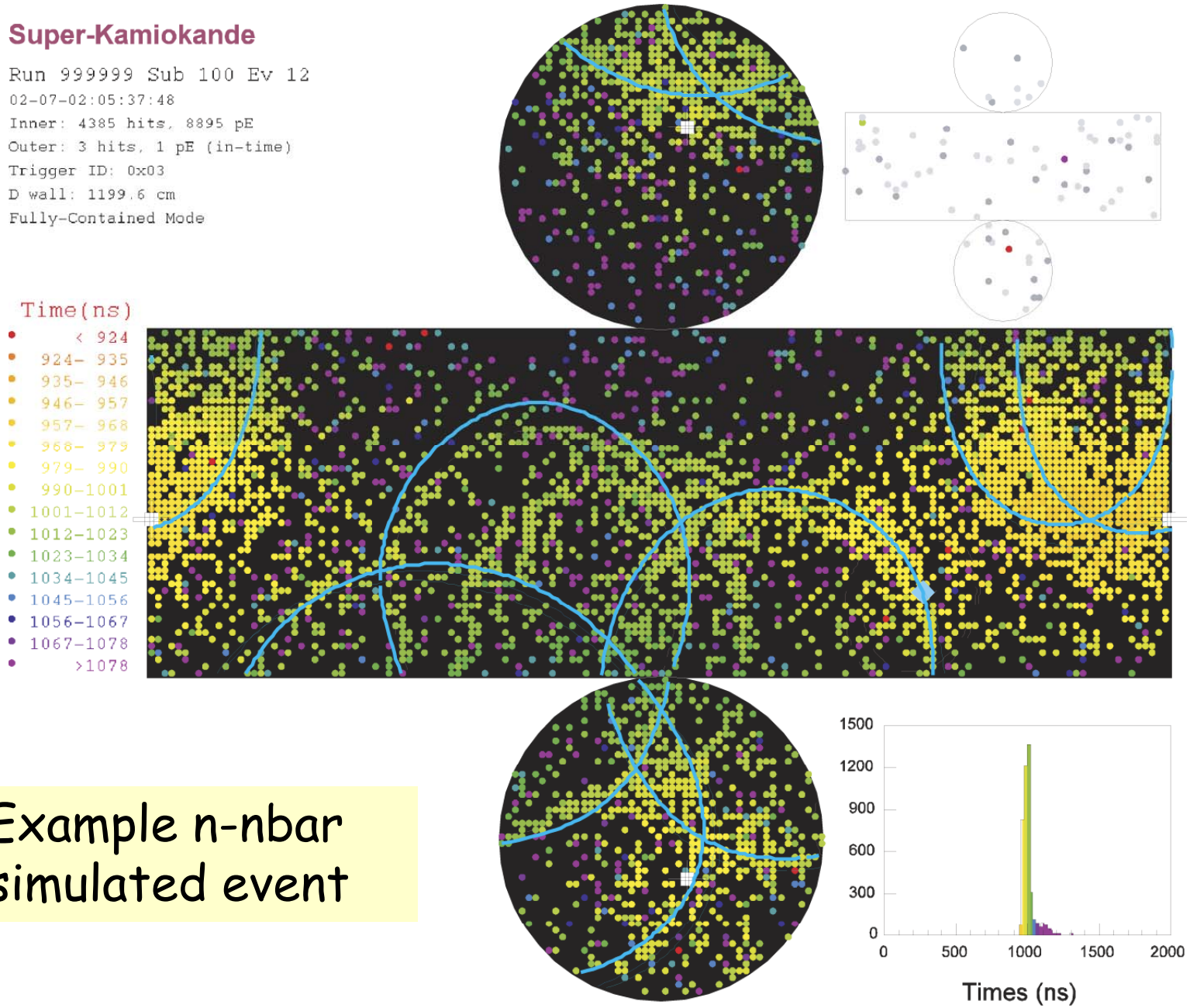


$\bar{n} + p$

$\pi^+\pi^0$	1%
$\pi^+\pi^0\pi^0$	8%
$\pi^+\pi^0\pi^0\pi^0$	10%
$\pi^+\pi^+\pi^-\pi^0$	22%
$2\pi^+\pi^-2\pi^0$	36%
$2\pi^+\pi^-\omega$	16%
$3\pi^+2\pi^-\pi^0$	7%

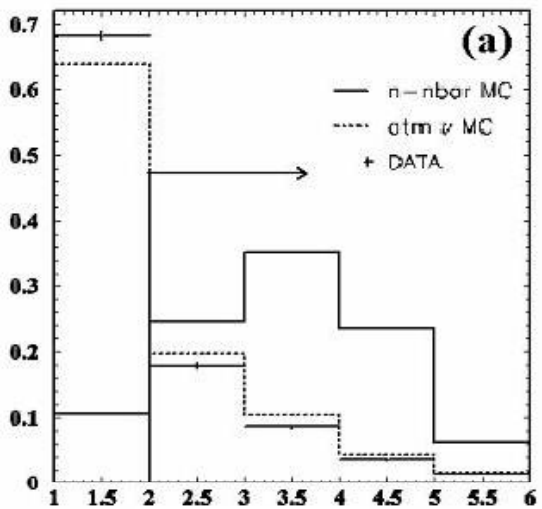
$\bar{n} + n$

$\pi^+\pi^-$	2%
$\pi^0\pi^0$	1.52%
$\pi^+\pi^-\pi^0$	6.48%
$\pi^+\pi^-\pi^0\pi^0$	11%
$\pi^+\pi^-\pi^0\pi^0\pi^0$	28%
$2\pi^+2\pi^-$	7%
$2\pi^+2\pi^-\pi^0$	24%
$\pi^+\pi^-\omega$	10%
$2\pi^+2\pi^-\pi^0\pi^0$	10%



Example n-nbar simulated event

Event Selection



# of rings

Fully-contained, fiducial volume

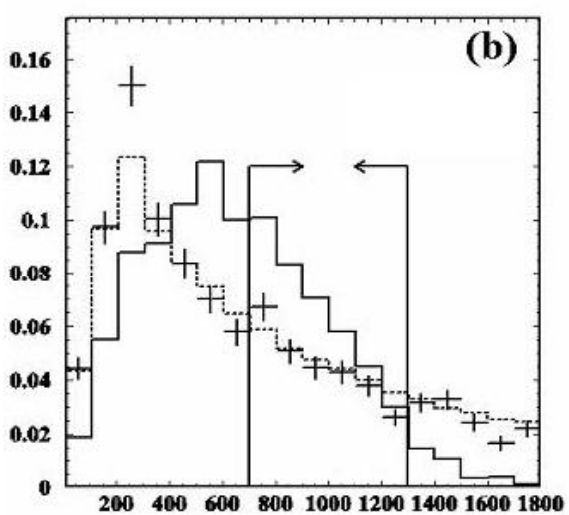
Optimize $\varepsilon/\sqrt{BG}$

(a) #of rings >= 2

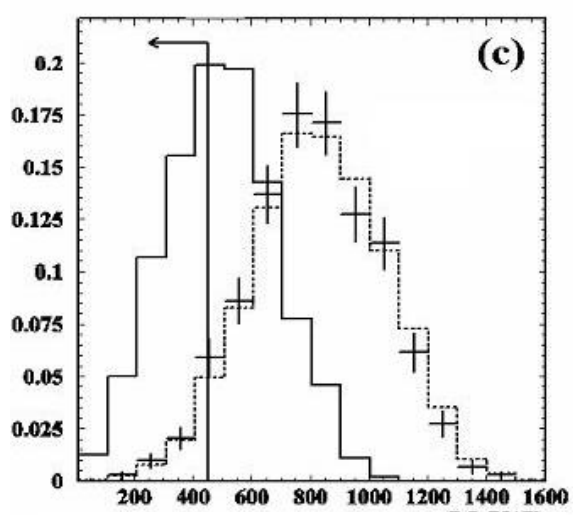
(b) 700 < visible energy < 1300 MeV

(c) low net momentum: $0 < P_{tot} < 450$ MeV/c

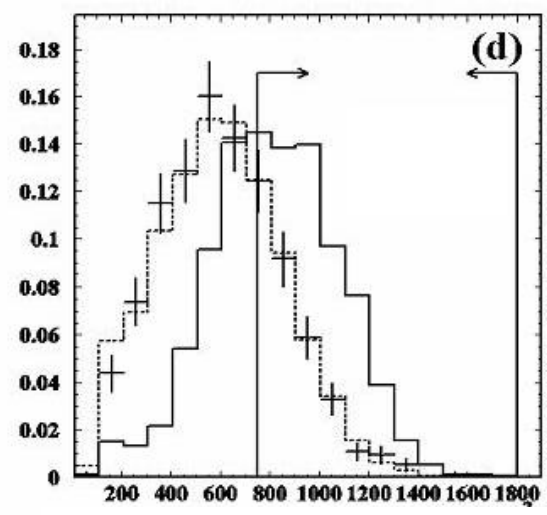
(d) high mass: $750 < M_{tot} < 1800$ MeV/c^2



Visible Energy (MeV)



Net Momentum (MeV/c)



Total Mass (MeV/c^2)

Results:

10.4 % detection efficiency
sys. uncertainty 15.2%
(mostly intranuclear scattering)

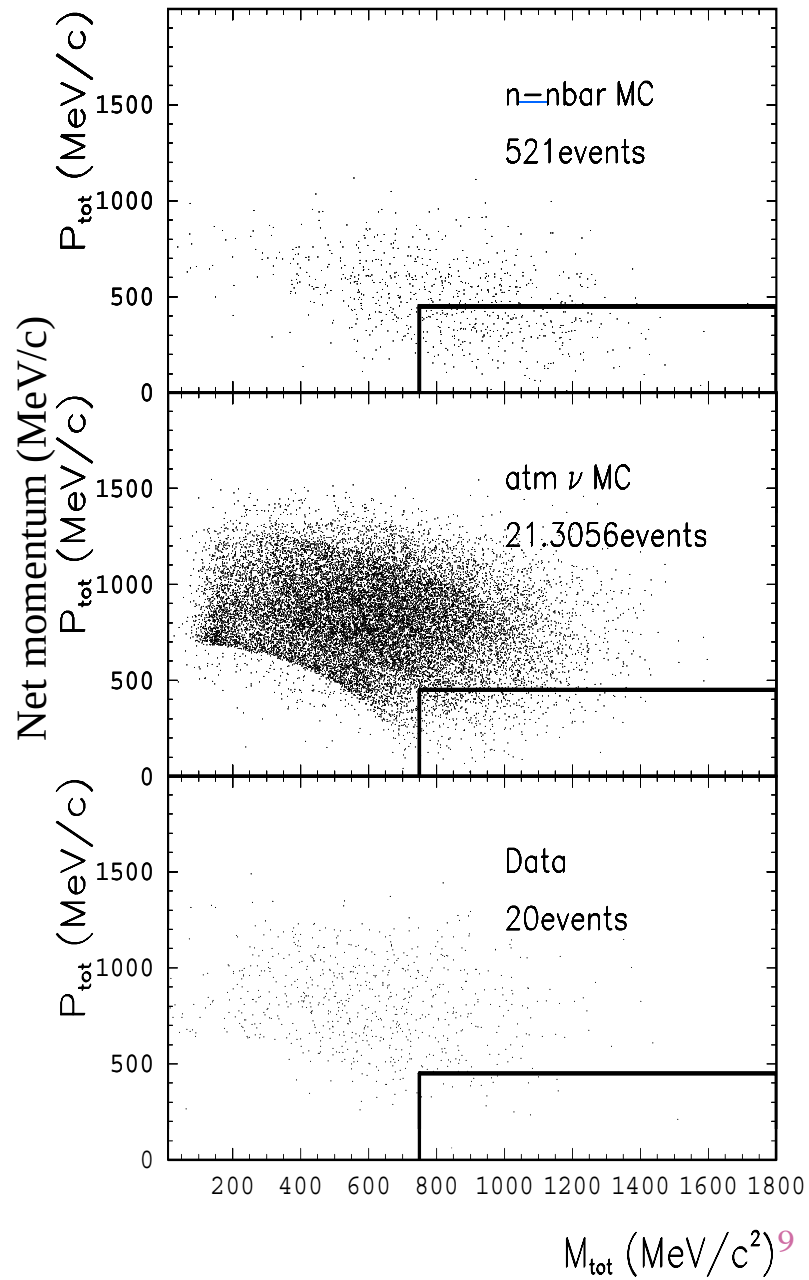
21.3 background events
ν osc. effects are included
sys. uncertainty 32%
(mostly flux, cross sections)

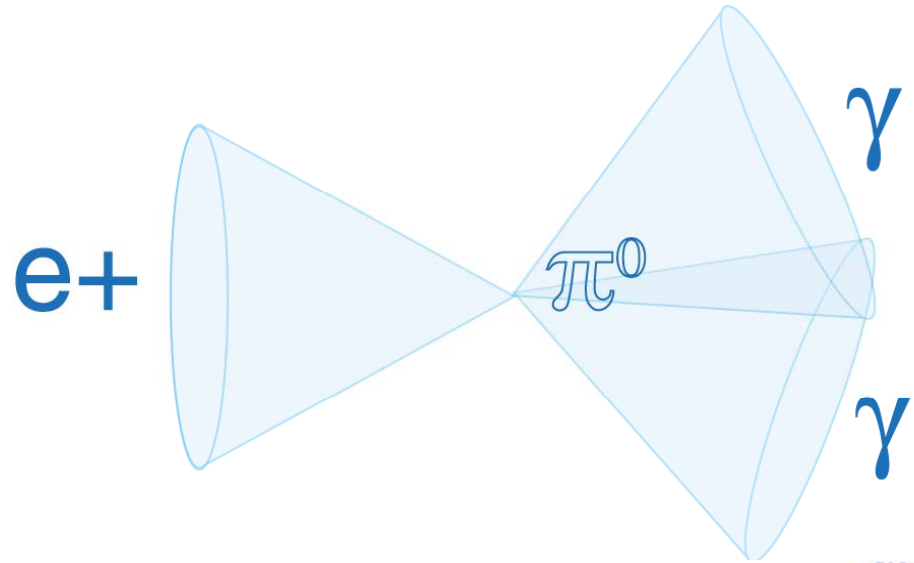
20 candidates

$$\tau_{bound} = \frac{1}{\Gamma_{\text{limit}}} = 1.77 \times 10^{32} \text{ yrs } (90\% \text{ CL})$$

$$\sqrt{\tau}/(R = 1\times10^{23} s^{-1}) = T_{free} > 2.36\times10^{8} s$$

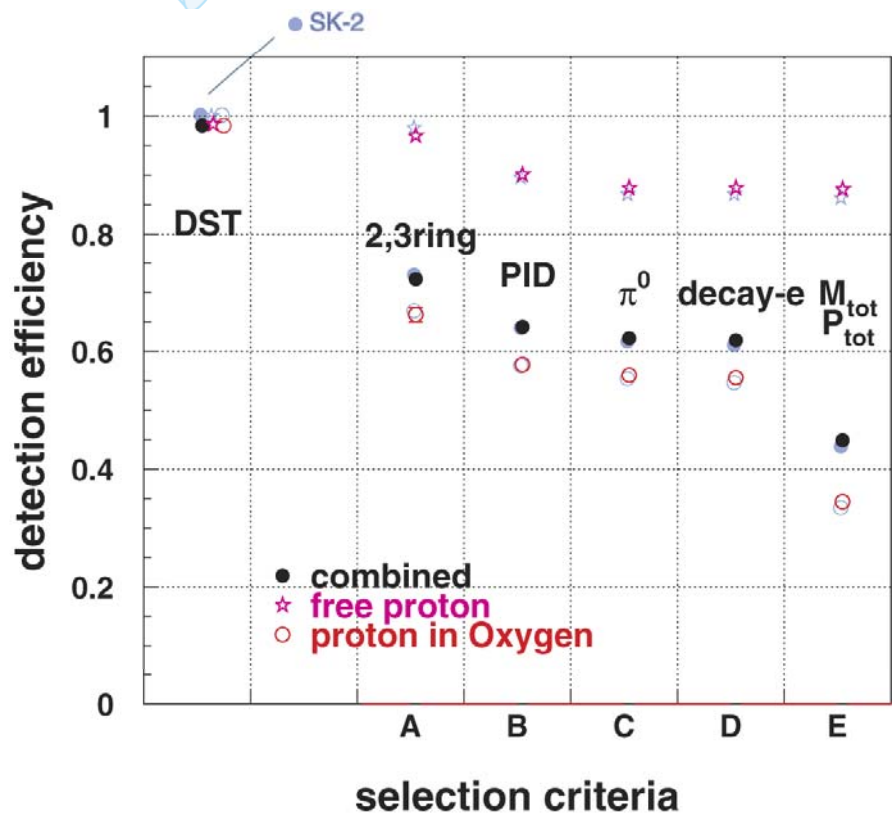
$$cf \text{ ILL Reactor Expt: } T_{free} > 0.86\times10^{8} s$$



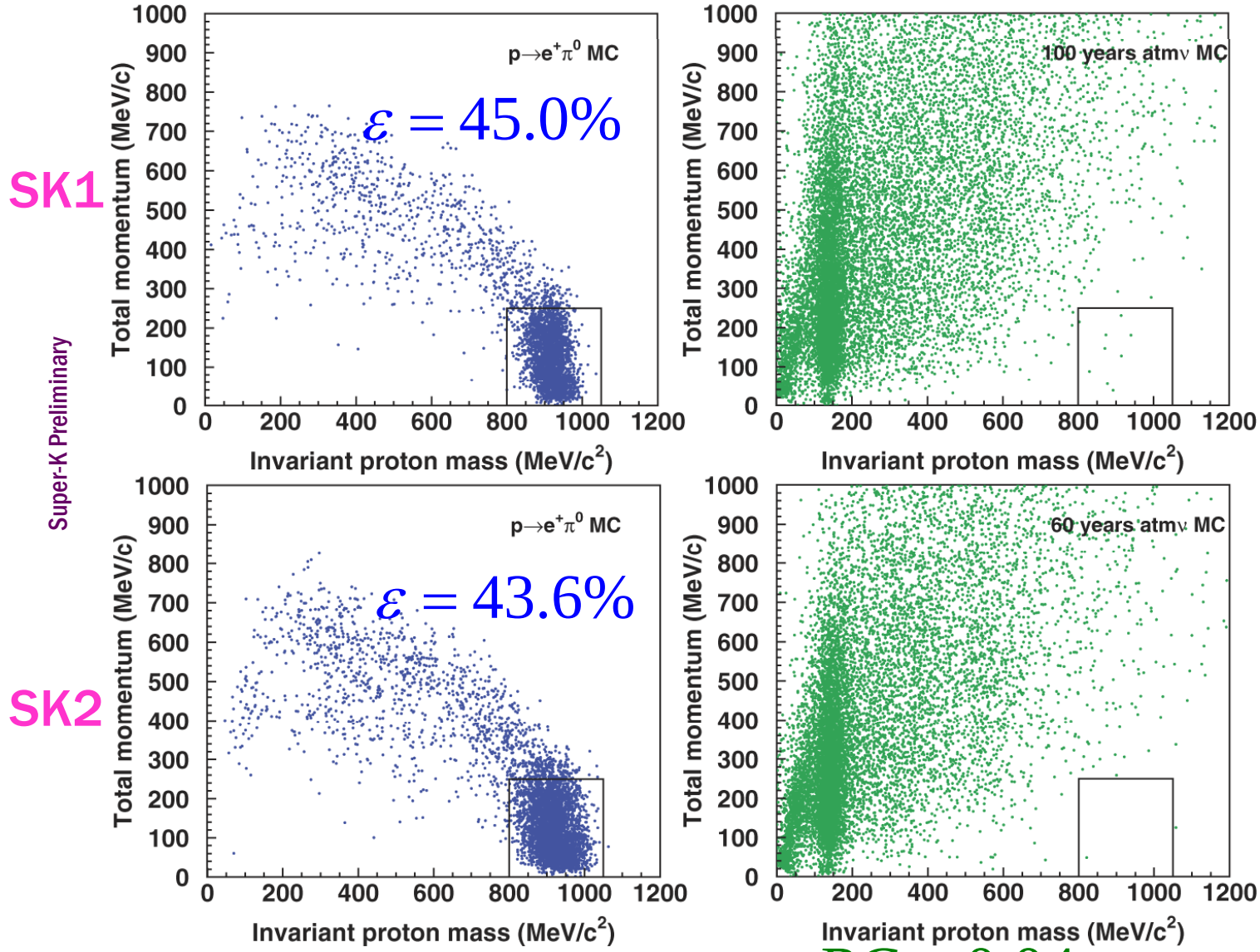


Event selection criteria:

- Fully contained, Fiducial volume
- 2 or 3 rings
- All rings are e-like
- π^0 mass 85-185 MeV/c^2
- No μ-decay electrons
- Mass range 800-1050 MeV/c^2
- Net momentum < 200 MeV/c

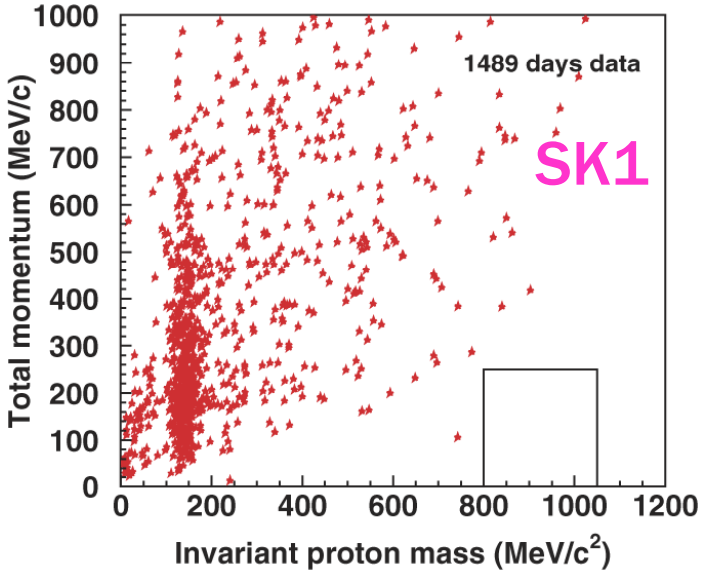


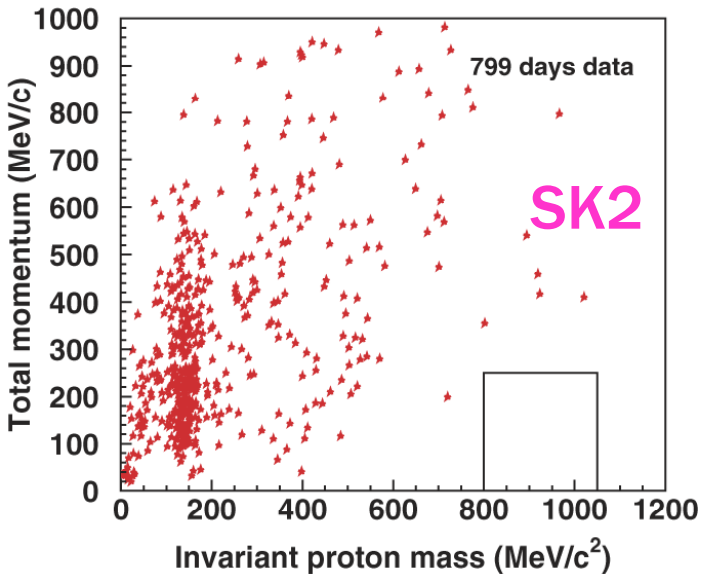
$BG = 0.4\ evts$



$BG = 0.04\ evts$

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





	SK-I	SK-II
Detection efficiency	45.0%	43.6
Background estimate	0.40	0.04
Exposure	1489.2 d (91.6 kt·yr)	798.6 d (49.1 kt·yr)
Data	0	0
Lifetime limit (90% CL)	5.5×10^{33} yr	2.9×10^{33}yr

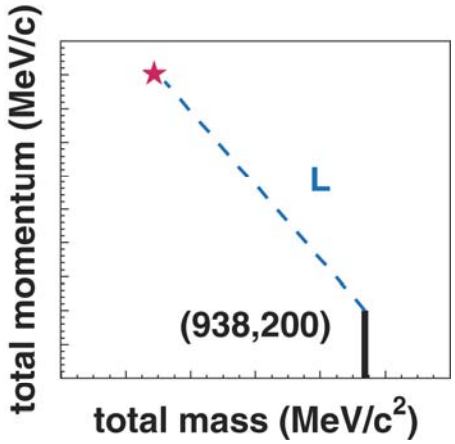
$$\tau / BR > 8.4\times10^{33}\ yr \ \text{(90\% CL)}$$

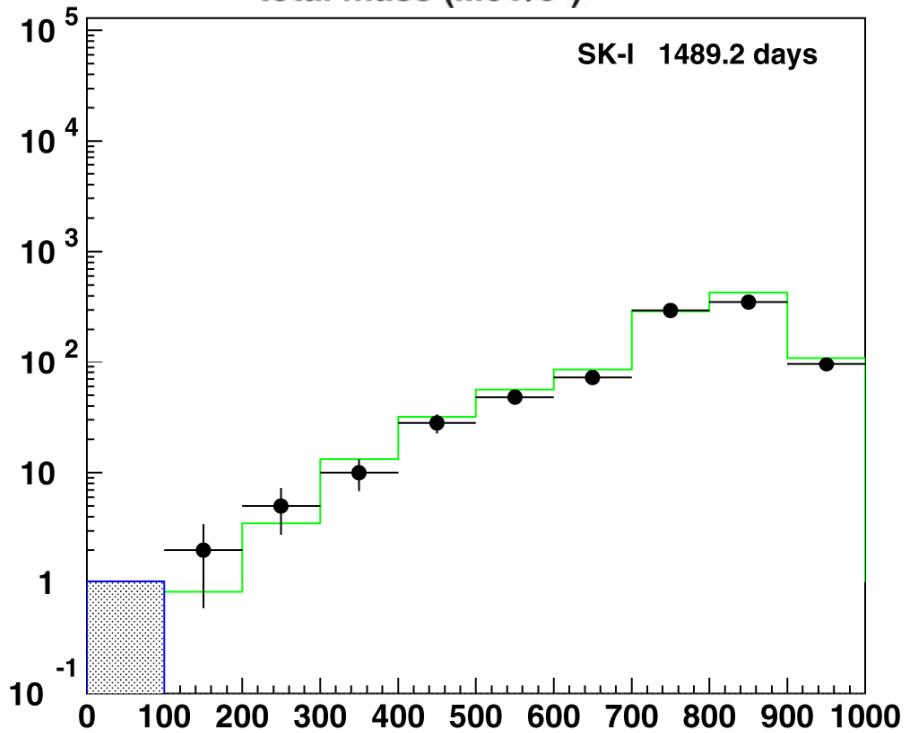
Super-K Preliminary

Background prediction:

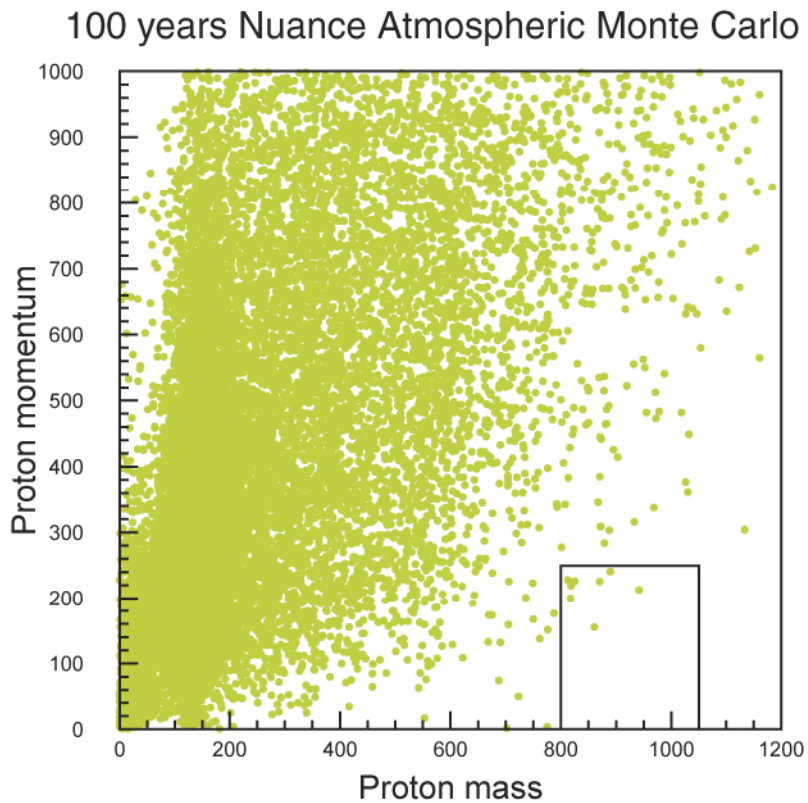
(a) data vs MC

(b) independent MC code



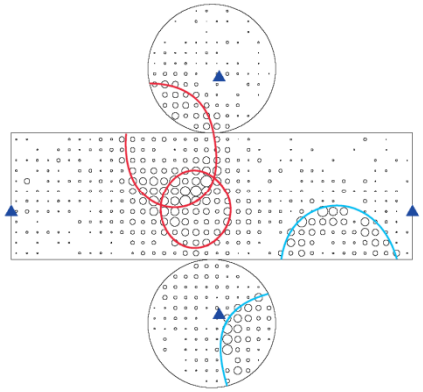


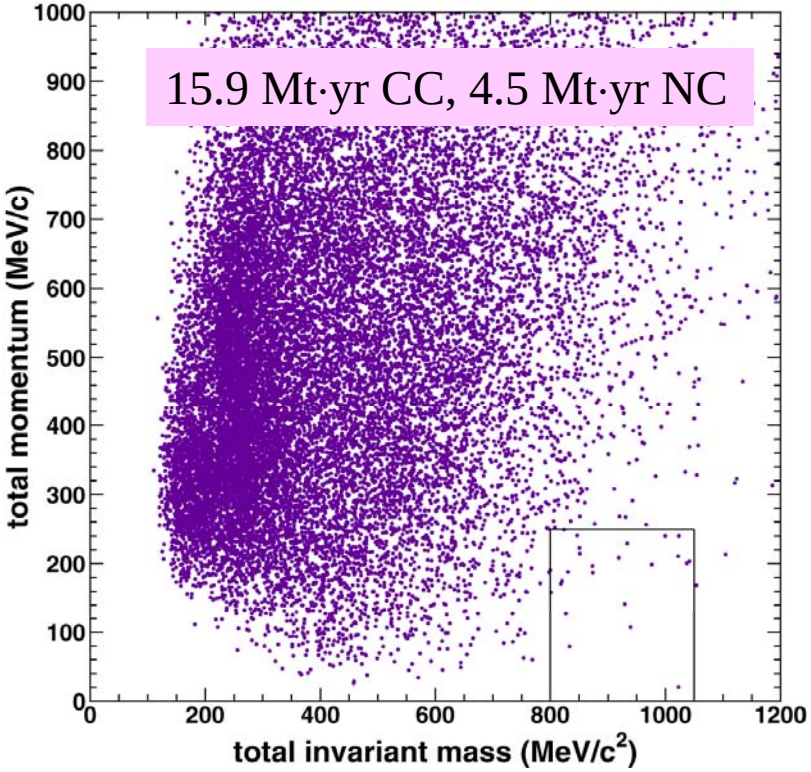
distance L in mass vs. momentum plot

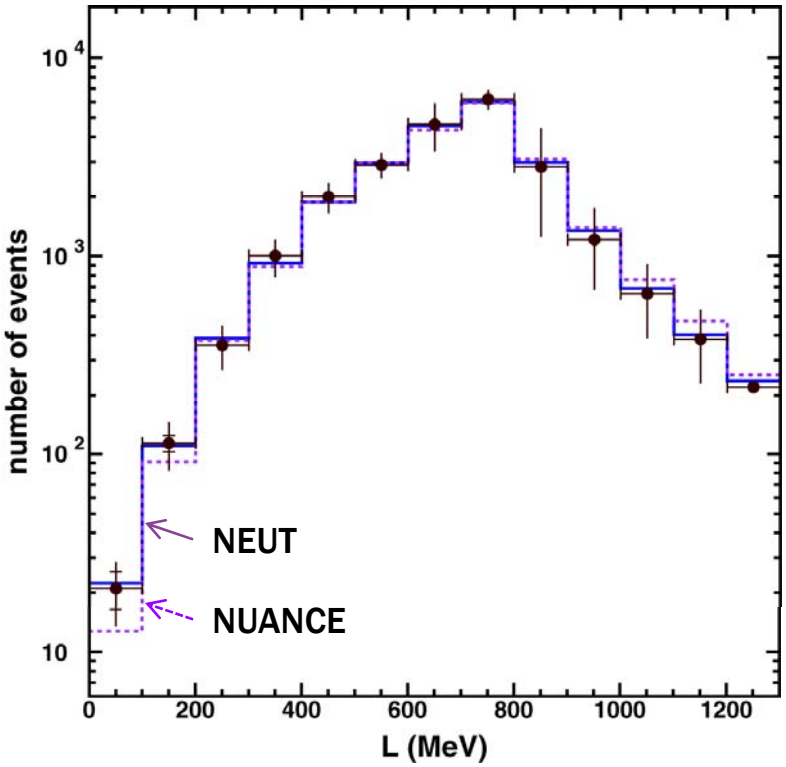


Consistent BG estimate of 0.21 evts/100 kt.yr

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

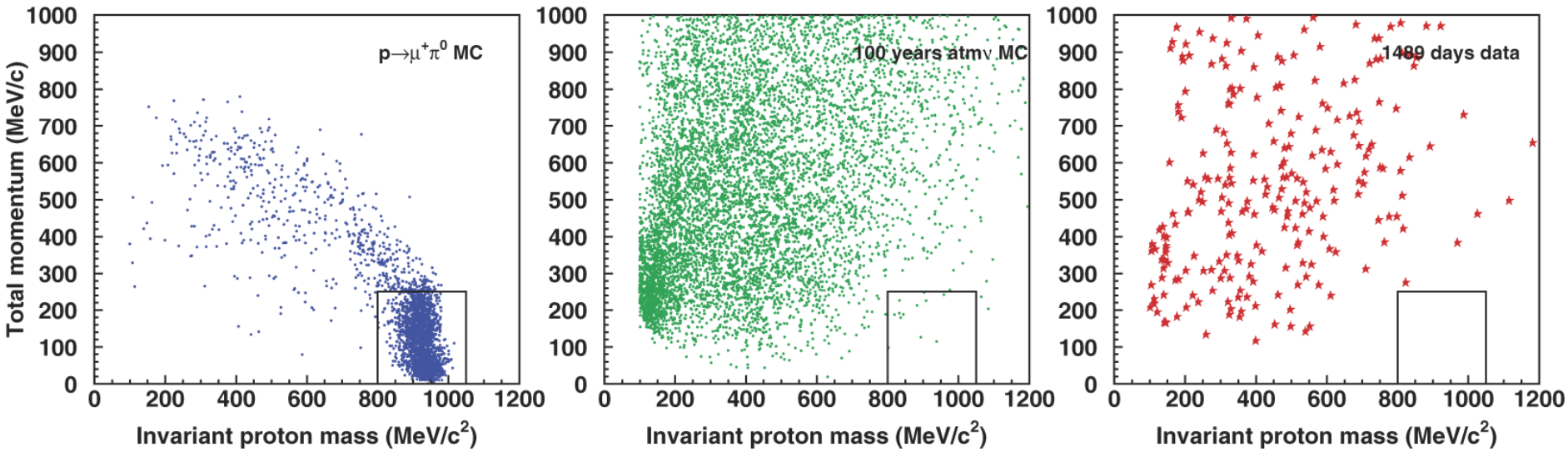






$$e^+\pi^0 \text{ BG} = 1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{sys.}) \text{ evts/Mt} \cdot \text{yr}$$

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



	SK-I	SK-II
Detection efficiency	35.6%	35.5%
Background estimate	0.4	0.2
Exposure	1489.2 d (91.6 kt·yr)	798.6 d (49.1 kt·yr)
Data	0	0
Lifetime limit (90% CL)	6.7×10^{33} yr (combined)	

$p \rightarrow K^+ \nu$

Nuclear interaction negligible: ⇒ K^+ escapes nucleus and decays at rest (90%)

Momentum of K^+ is 340 MeV/c: below Cherenkov threshold

Essentially: Search for K+ decay at rest

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

gamma tag search

monoenergetic muon search

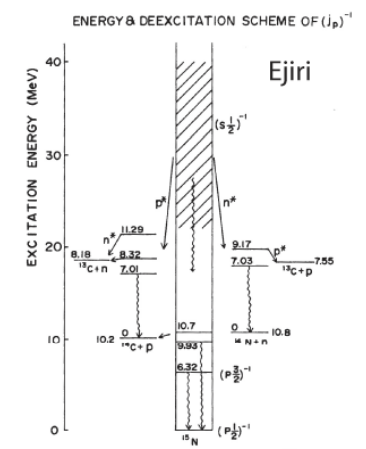
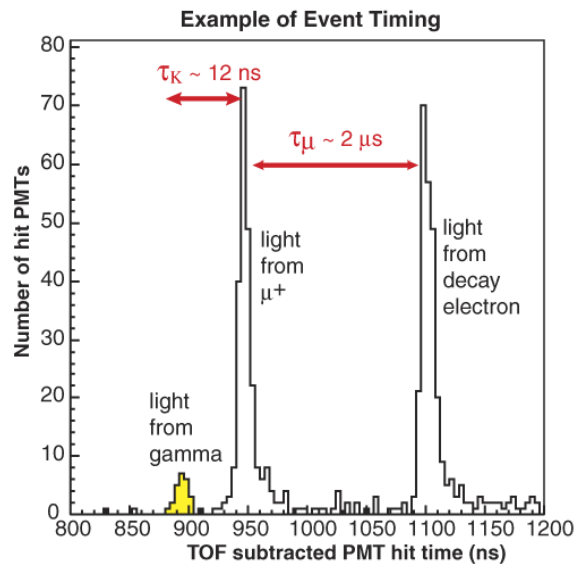
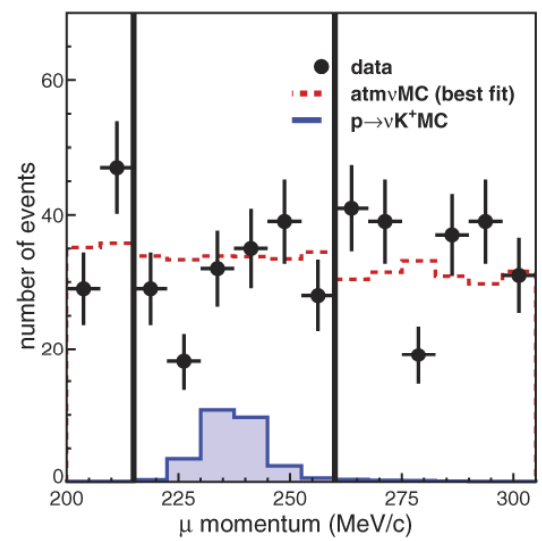
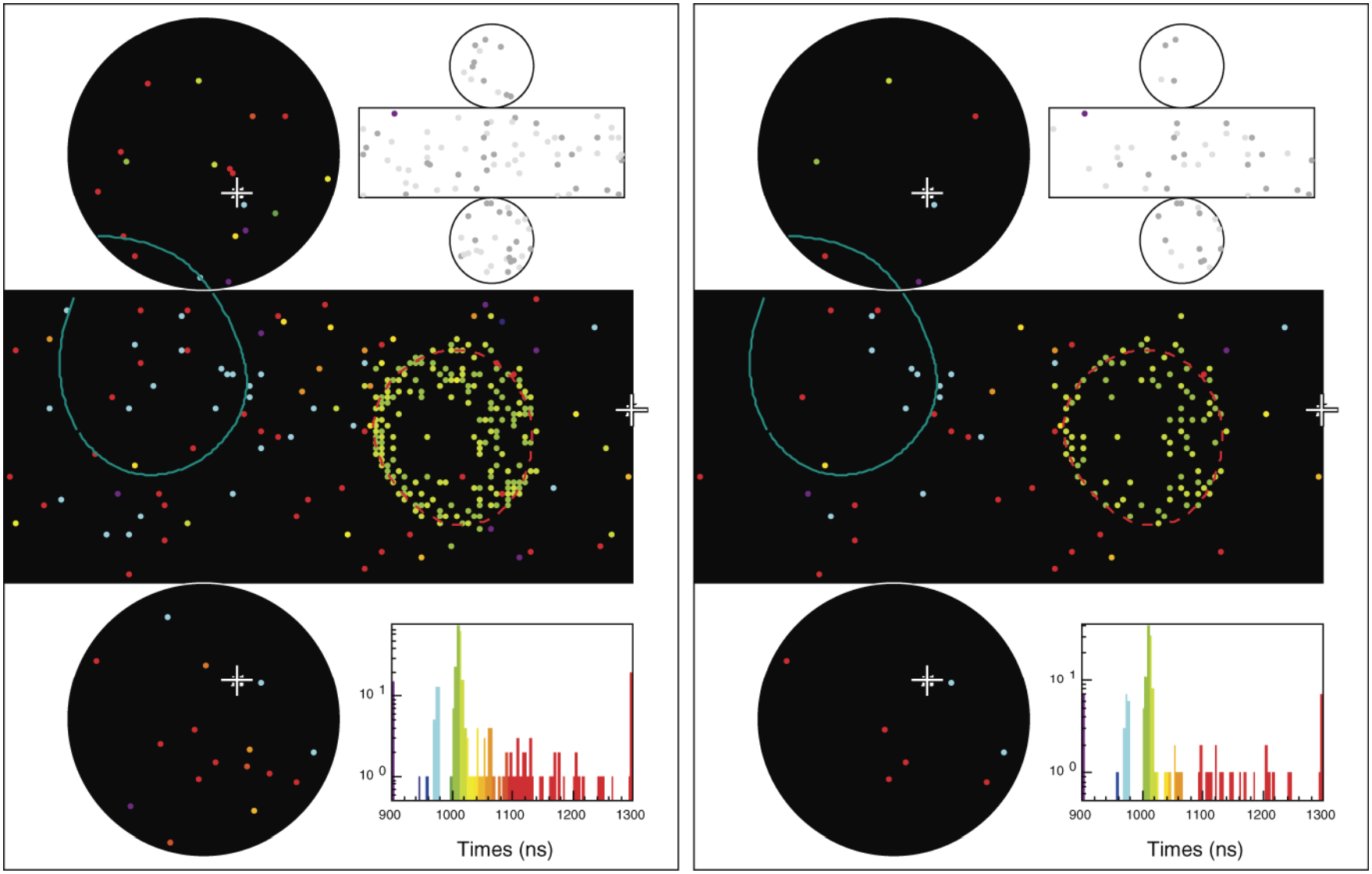


FIG. 2. Level scheme of proton-hole states in ^{15}N and their deexcitation modes. Energies are given in units of MeV. p^* and n^* are the protons and neutrons emitted from the continuum (unbound) region, respectively.





from SK-I result
M. Kobayashi et al.
PRD 72 (2005) 052007

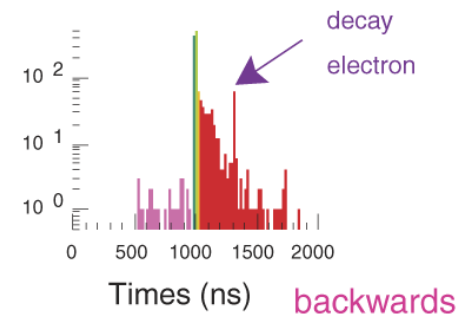

10 1
10 0
900
1000
1100
1200
1300
Times (ns)
10 1
10 0
900
1000
1100
1200
1300
Times (ns)

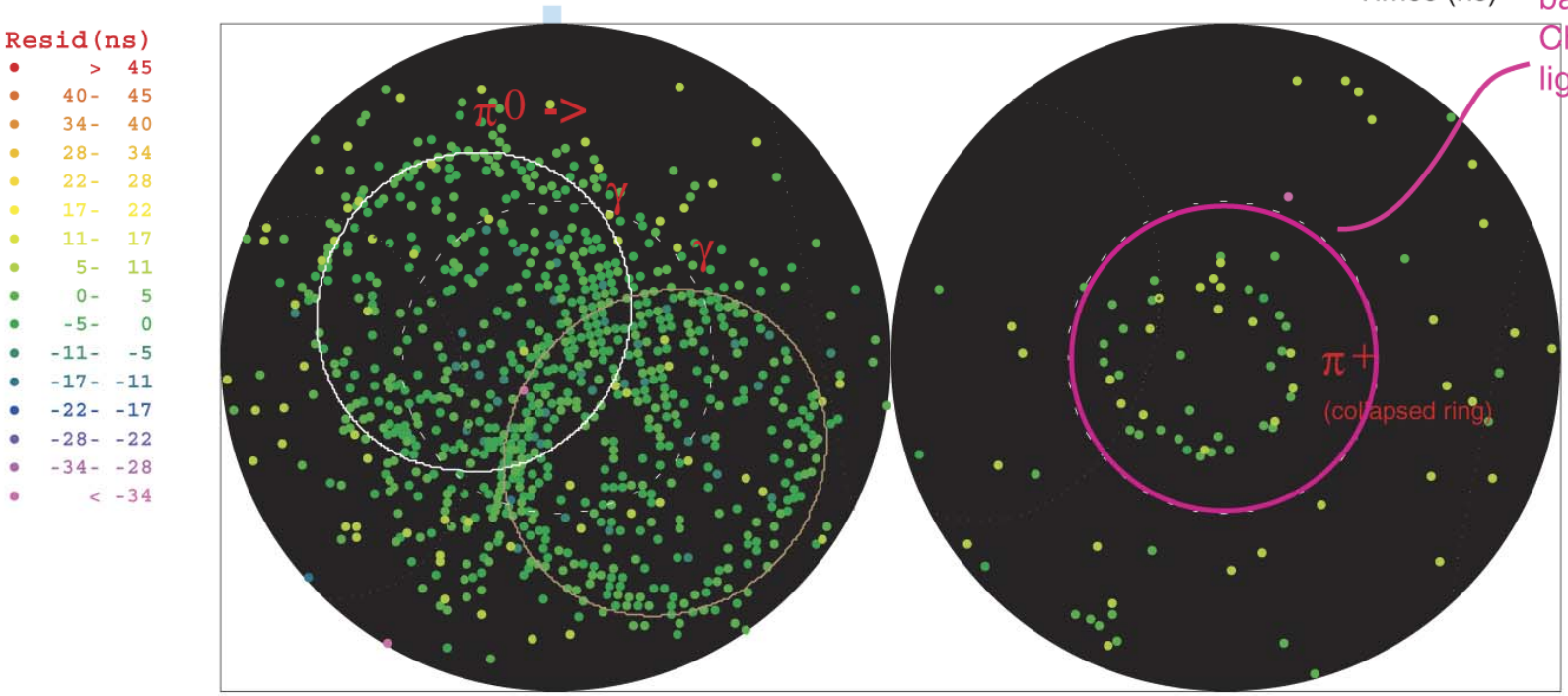
Super-Kamiokande

Run 1000000 Event 474
1997-06-25:12:59:29
Time to prev. event: 0.0us
Inner: 1395 hits, 2128 pE
Outer: 16 hits, 9 pE (in-time)
Trigger ID: 0x03

Forward-backward hemisphere view of Monte Carlo event

$$p \rightarrow \nu K^+ \rightarrow \pi^+ \pi^0$$



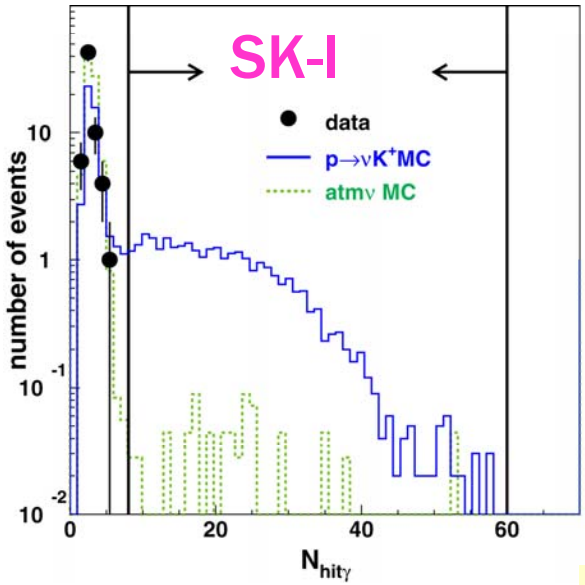


backwards Cherenkov light cone

(only hits in time window drawn)

expect only small amount of light outside backwards cone

$p \rightarrow K^+\nu$ Search

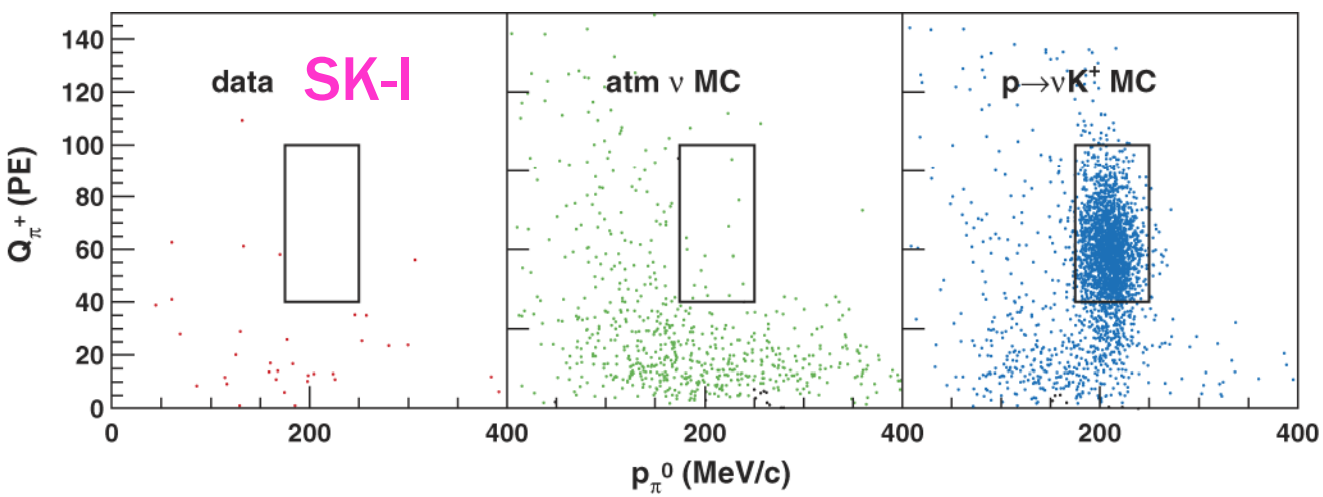


Sensitive to collection of small amount of light (few # hits).

Re-optimization for SK-II	SK-I	SK-II
N_{hit} γ (prompt gamma)	7-60 hits	5-30 hits
Backwards light ($\pi^+\pi^0$)	40-100 p.e.	20-50 p.e.

Plus a few other cuts such as light outside cone, proton rejection cuts

SK-II: Efficiency ↓, background ↑, need more work !



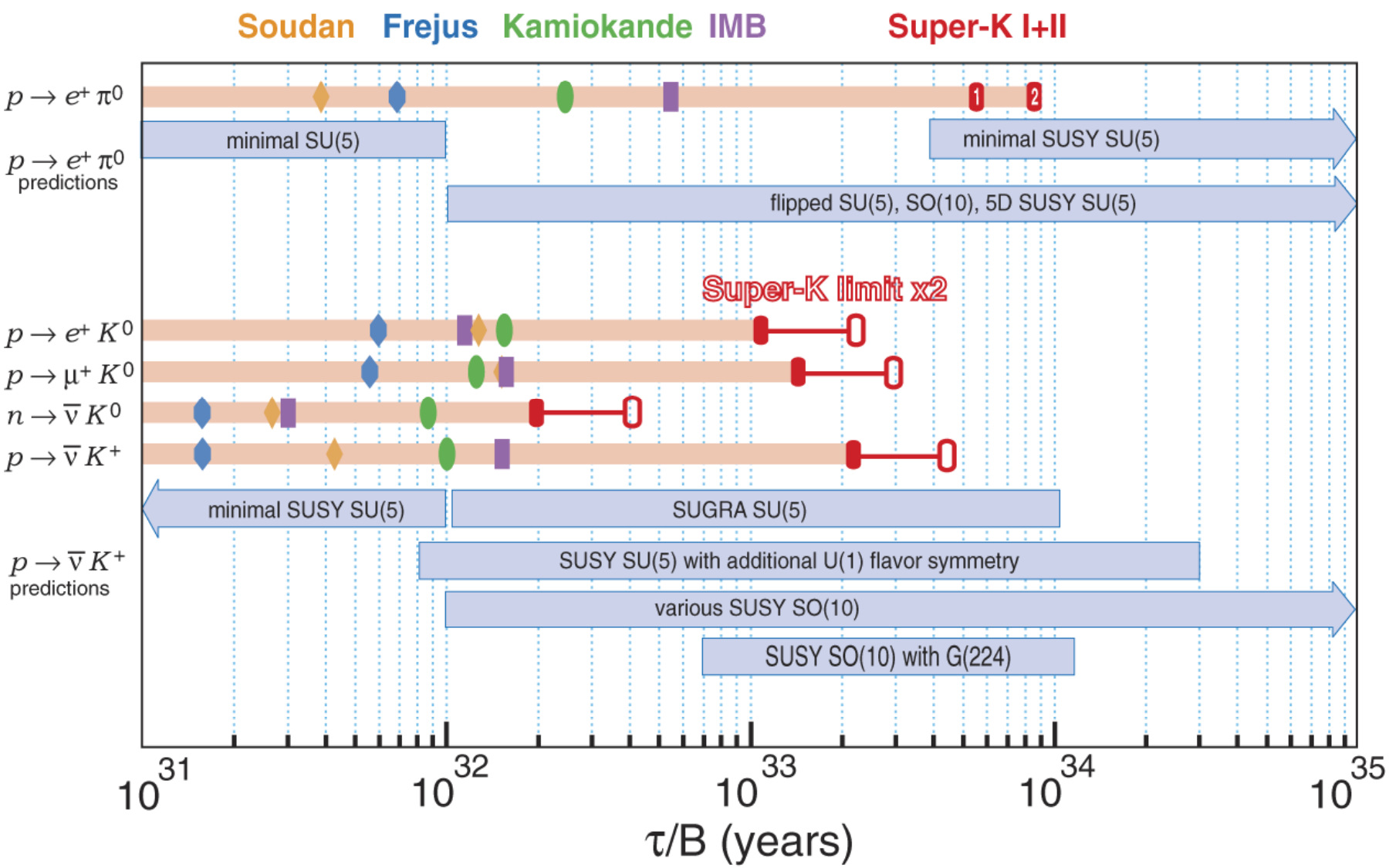
$$\tau / B > 2.3 \times 10^{33}\, yr$$

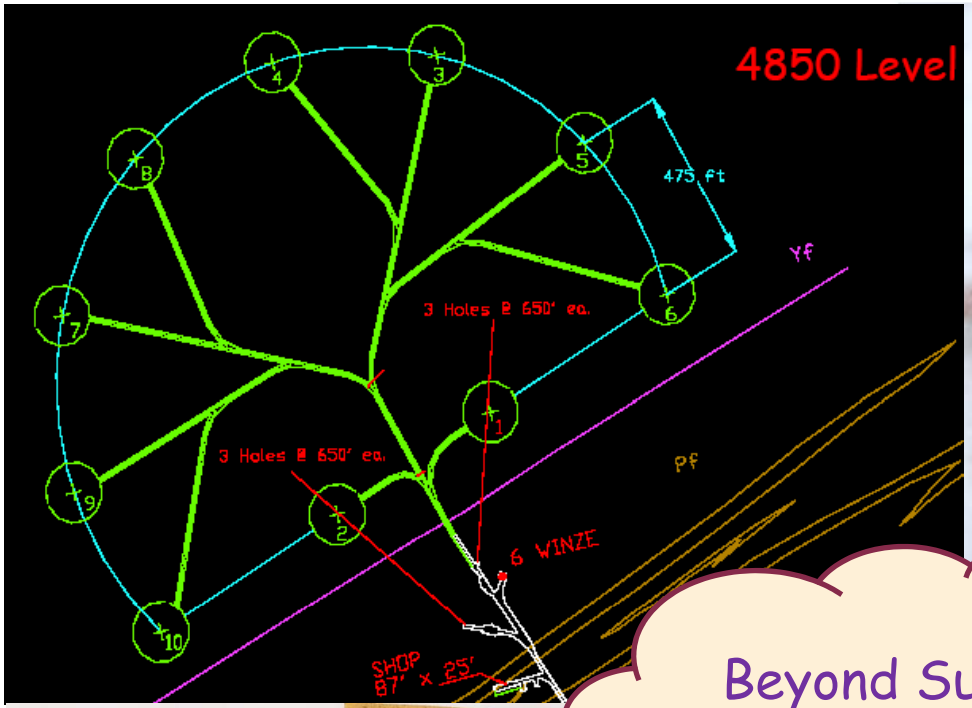
(SK-I, 90% CL)

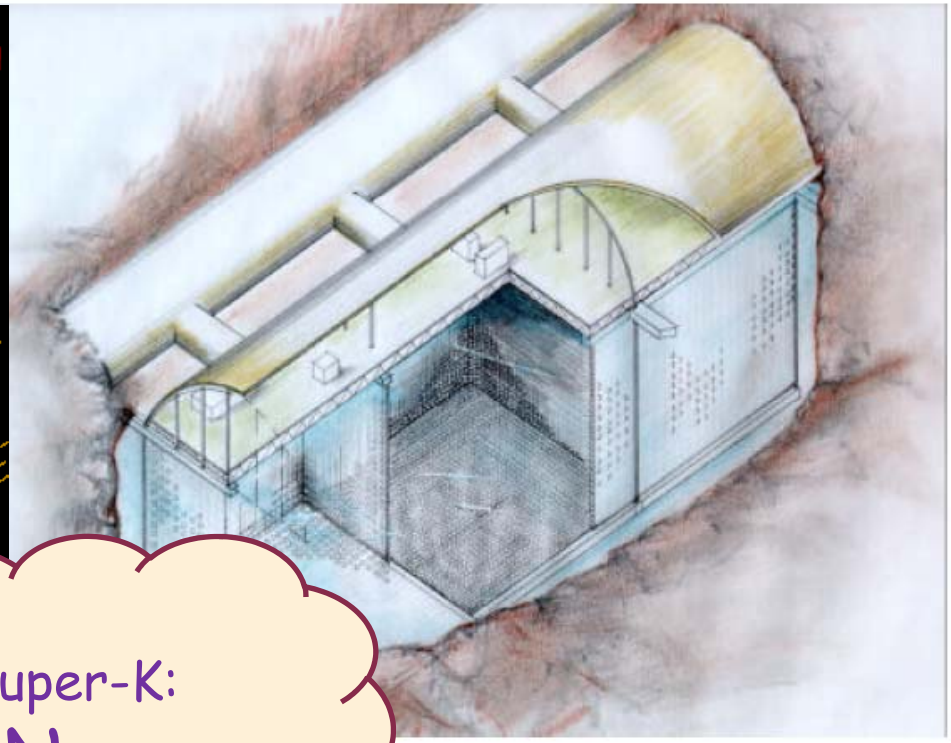
40% or 20% Photon Coverage?

	Super-K I (40% coverage)	Super-K II (20% coverage)
Sub-GeV vertex resolution	26 cm (e-like) / 23 cm (μ-like)	30 cm (e-like) / 29 cm (μ-like)
Sub-GeV particle mis-ID	0.81% (e-like) / 0.70% (μ-like)	0.69% (e-like) / 0.96% (μ-like)
Sub-GeV momentum resolution	4.8% (e-like) / 2.5% (μ-like)	6.3% (e-like) / 4.0% (μ-like)
$p \rightarrow e^+\pi^0$ signal efficiency	45.0 ±1.3 ±6.7%	42.2 ±1.2 ±6.5%
$p \rightarrow e^+\pi^0$ background	0.4 (±35%) events/100kty	0.04 (±35%) events/100kty
$p \rightarrow K^+\nu, \gamma$ tag signal efficiency	8.4±0.1 ±1.7%	4.7±0.1 ±1.0%
$p \rightarrow K^+\nu, \gamma$ tag background	0.72 (±28%) events/100kty	1.4 (±30%) events/100kty
$p \rightarrow K^+\nu, \pi^+\pi^0$ signal efficiency	5.5 ±0.1 ±0.7%	5.7 ±0.1 ±0.4%
$p \rightarrow K^+\nu, \pi^+\pi^0$ background	0.59(±28%) events/100kty	1.0(±30%) events/100kty
T2K $CC\nu_e$ likelihood effic.	83.7% (±0.1% stat)	84.8 %
T2K BG likelihood effic.	21.3 %	21.5 %

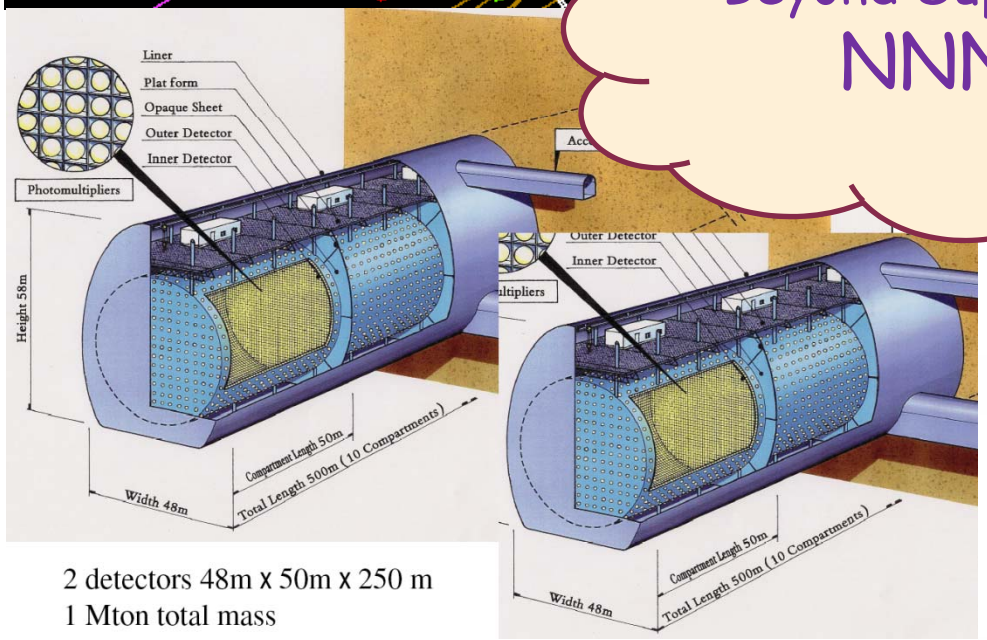
Preliminary numbers, for comparison purposes.
Final published efficiencies and BG may differ.


Soudan
Frejus
Kamiokande
IMB
Super-K I+II
$p \to e^+ \pi^0$
$p \to e^+ \pi^0$ predictions
minimal SU(5)
minimal SUSY SU(5)
flipped SU(5), SO(10), 5D SUSY SU(5)
Super-K limit x2
$p \to e^+ K^0$
$p \to \mu^+ K^0$
$n \to \bar{\nu} K^0$
$p \to \bar{\nu} K^+$
minimal SUSY SU(5)
SUGRA SU(5)
$p \to \bar{\nu} K^+$ predictions
SUSY SU(5) with additional U(1) flavor symmetry
various SUSY SO(10)
SUSY SO(10) with G(224)
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
τ/B (years)

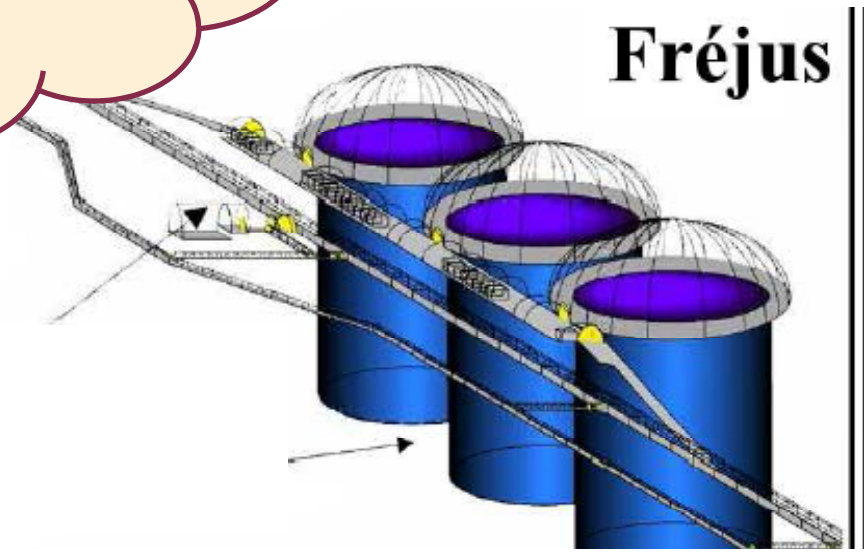


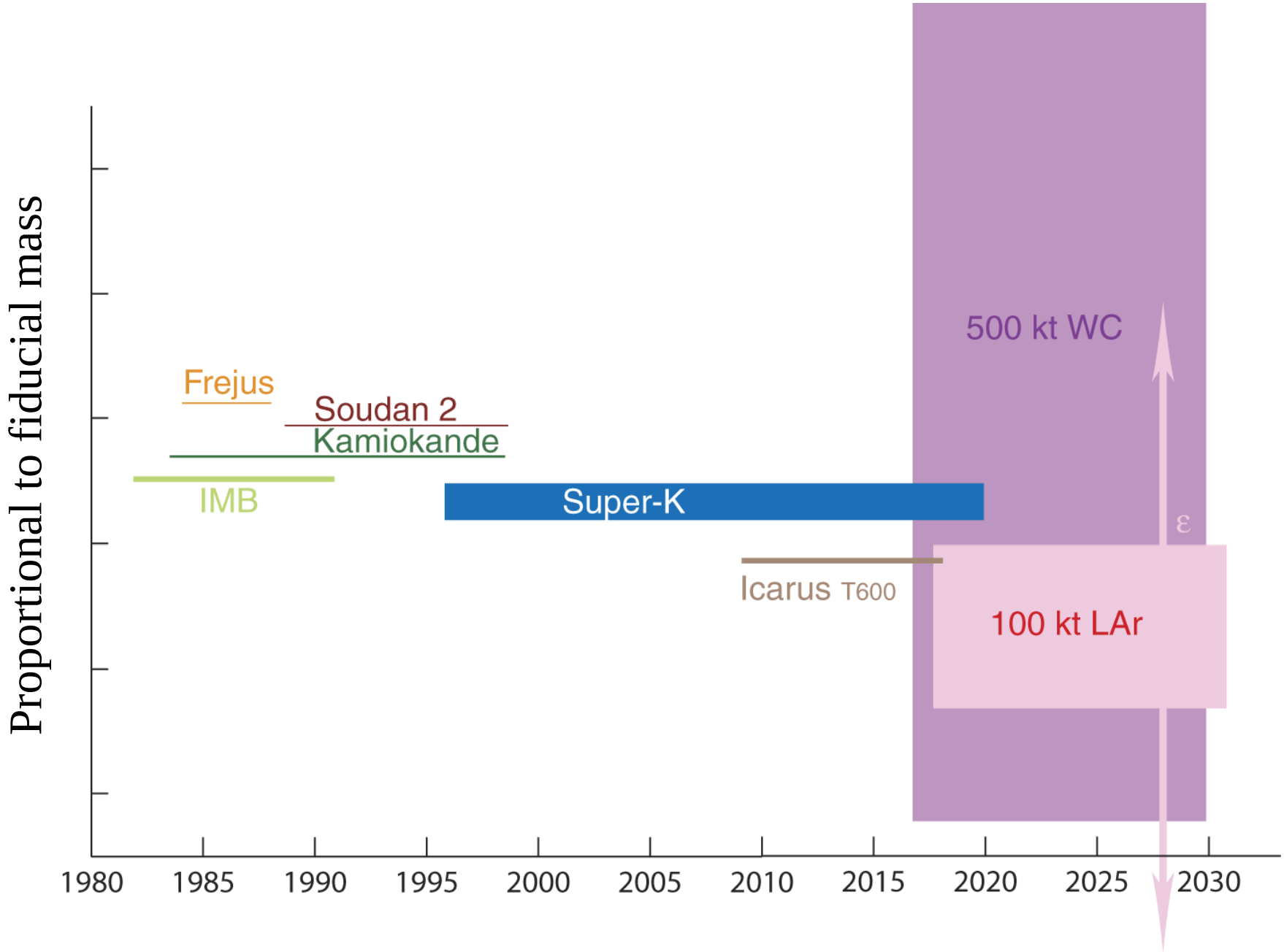


Beyond Super-K:
NNN



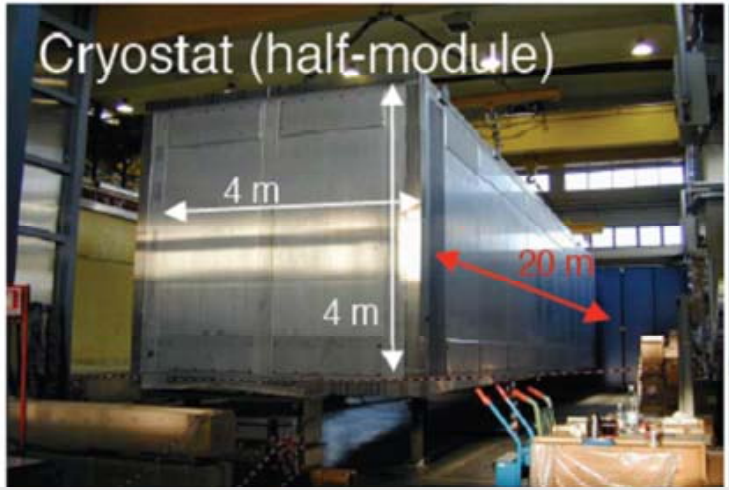
2 detectors 48m x 50m x 250 m
1 Mton total mass

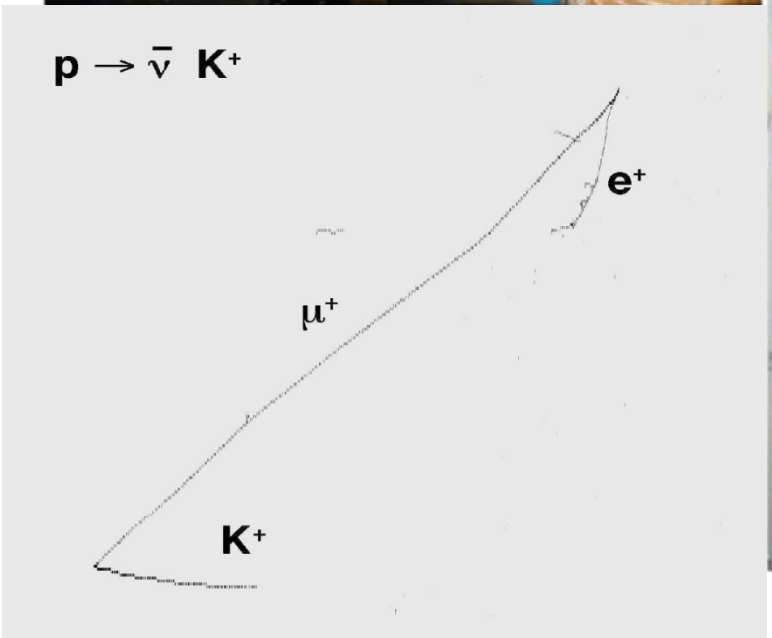


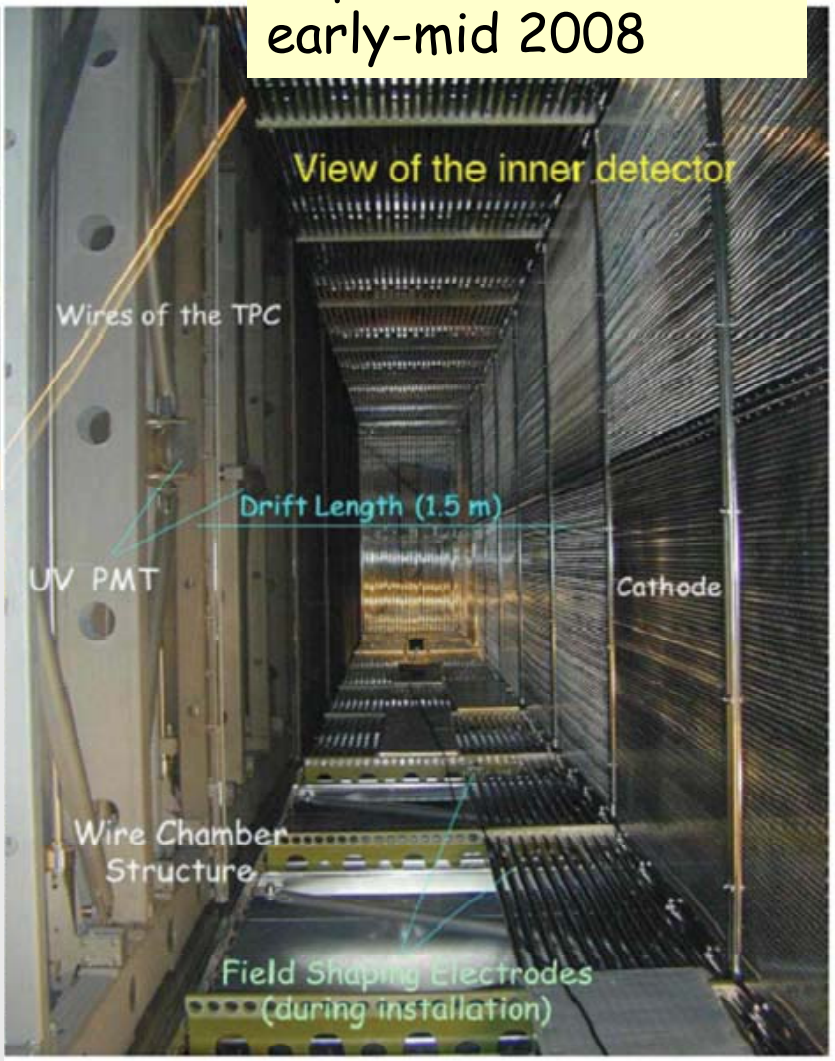

Proportional to fiducial mass
Frejus
Soudan 2
Kamiokande
IMB
Super-K
Icarus T600
500 kt WC
100 kt LAr
ε
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030

ICARUS T600

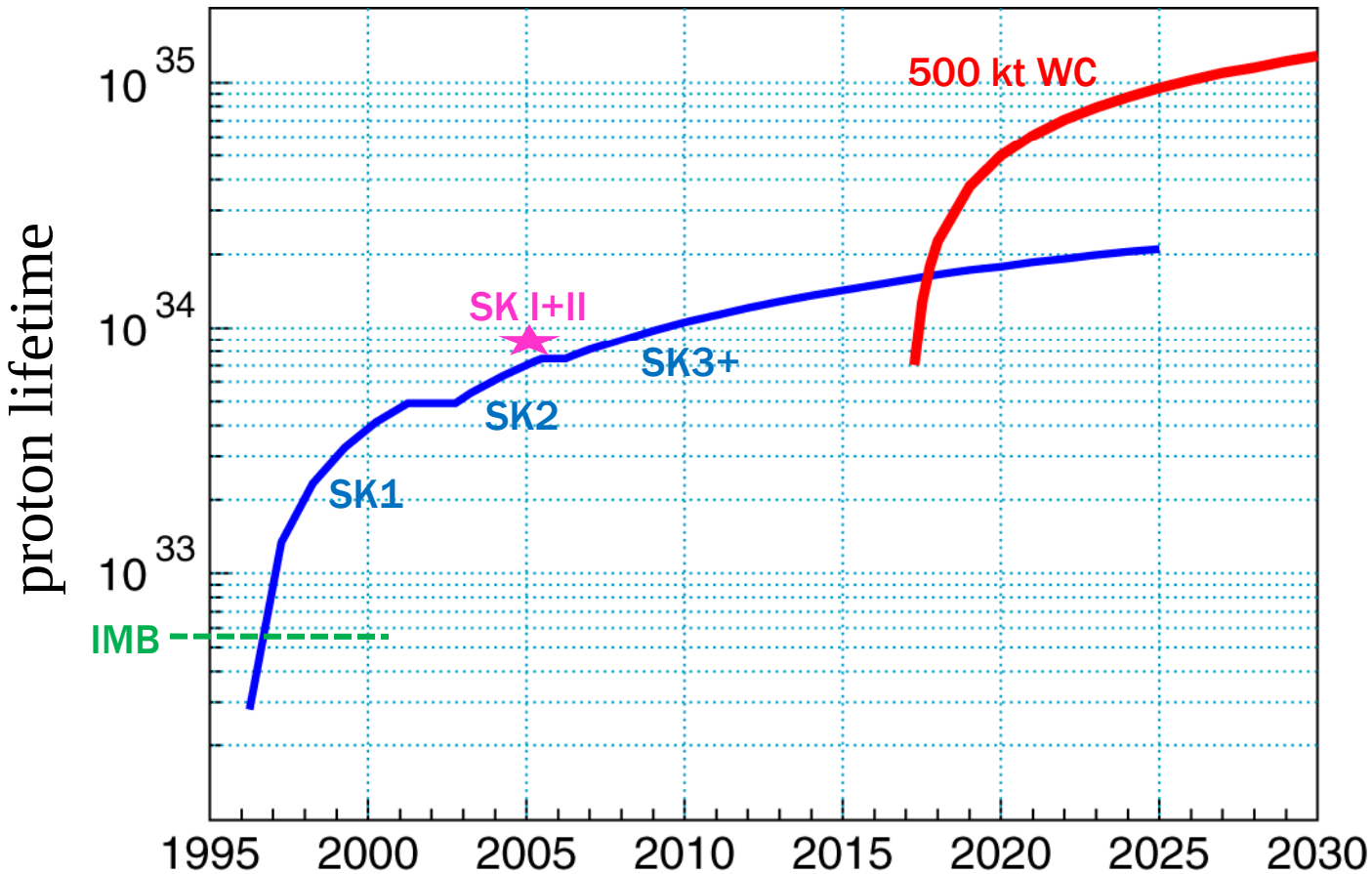
Status: installed in Gran Sasso Lab. Expected to start in early-mid 2008



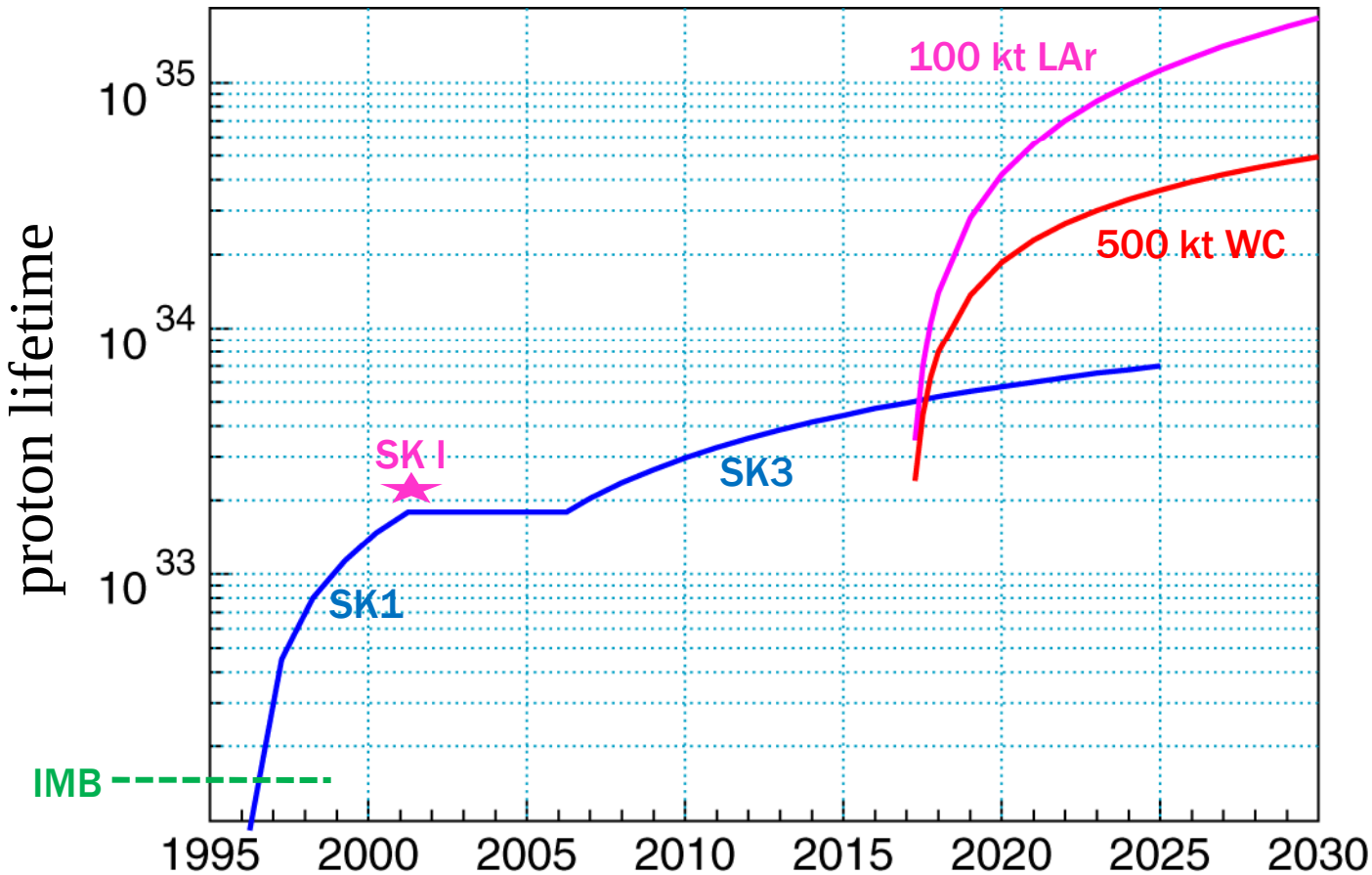




$$p \rightarrow e^{+}\pi^{0}$$



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



Summary & Conclusion

New nnbar result from Super-K (no evidence for)

- competes with best free neutron experiment

Updated searches for $e^+\pi^0$, $\mu^+\pi^0$

- no evidence
- background estimate under control
- 20% photocoverage is quite adequate

20% photocoverage is challenging for $K^+\nu$

- and probably any mode requiring small numbers of hits

and I'm sure we will hear more about the prospects
for the next generation. What will they be? When will they start?