Baryon Number Violation Report to Snowmass

✔ Origin of Universe

✔ Unification of Forces

✔ New Physics Beyond the Standard Model

Neutrino Physics

✔ Proton Decay

✔ $n \to \overline{n}$

Ed Kearns, Boston University
Kaladi Babu, Oklahoma State

Particle Physics at the Intensity Frontier

Intensity Frontier Workshop

25-27 April 2013 *Argonne National Laboratory*

- So many possible NY times titles:
  - ... found that the proton is not stable

08:45 Why are we here

Presenter(s): Yuval GROSSMAN *(Cornell University)*
Room: Bldg. 362, Auditorium

09:15 Early LHC Findings and The Intensity Frontier

Presenter(s): William MARCIANO *(BNL)*
Room: Bldg. 362, Auditorium

09:45 The Curiosity Frontier

Presenter(s): Roni HARNIK *(FNAL)*
Room: Bldg. 362, Auditorium

LHC/ Proton Decay Complementarity

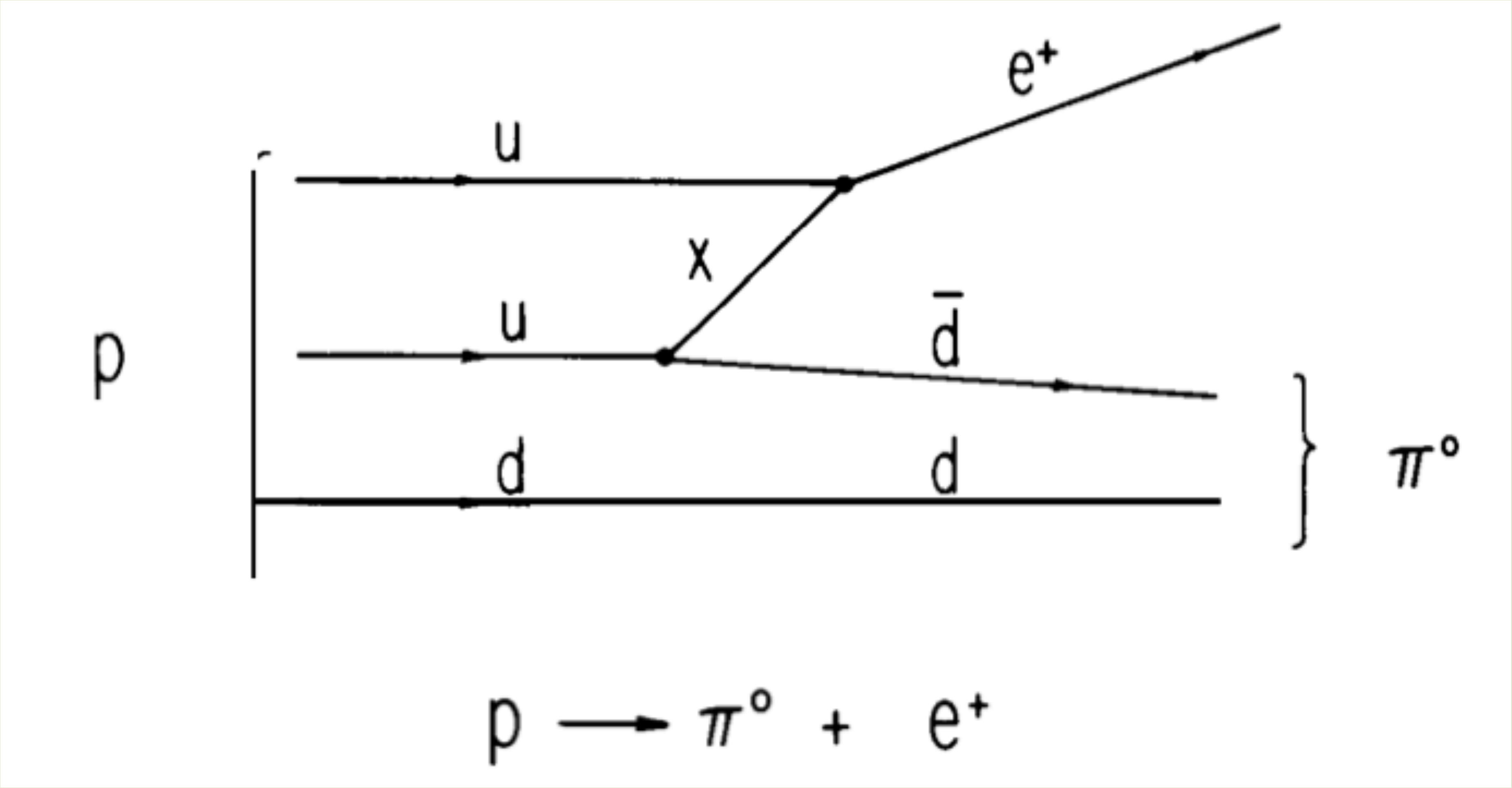
Together They Squeeze SUSY

Almost a No Lose Theorem

* Do the forces unify? LBNE/proton decay

Not too Shabby!

Proton Decay



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

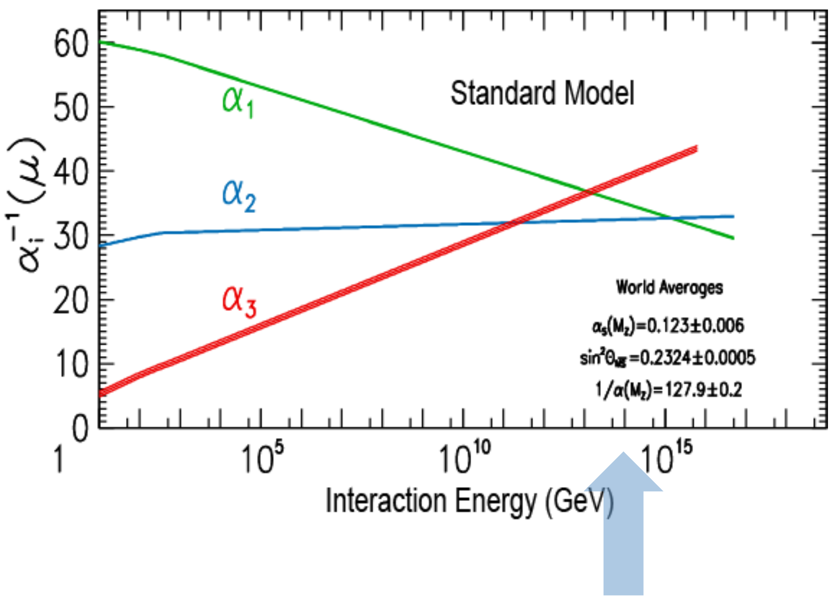
Scientific Impact of Proton Decay

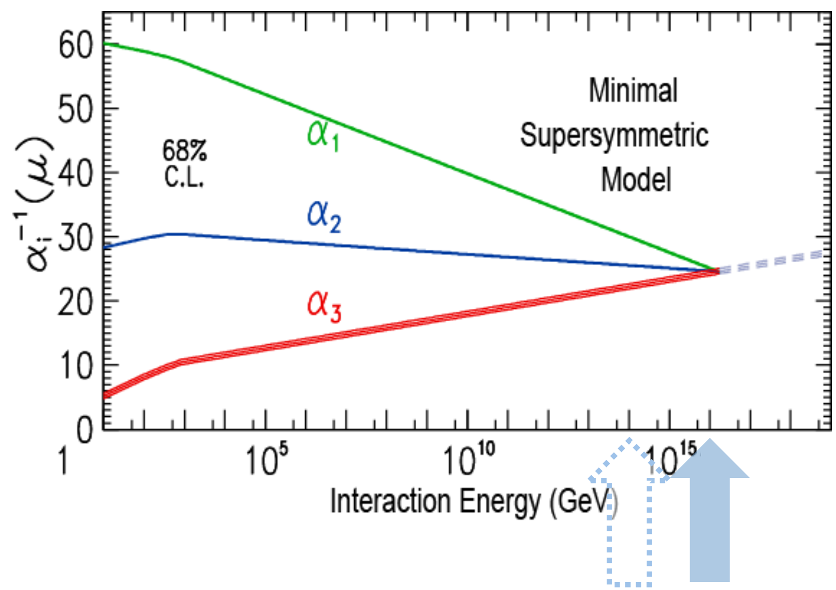
- Tests a fundamental, but unexplained conservation law: baryon number.
- Grand Unified Theories make specific predictions: decay modes, lifetimes, branching ratios.
- Probes scales forever inaccessible to accelerators.
- New force carrying particles.
- Deep connections with other fields: cosmology,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

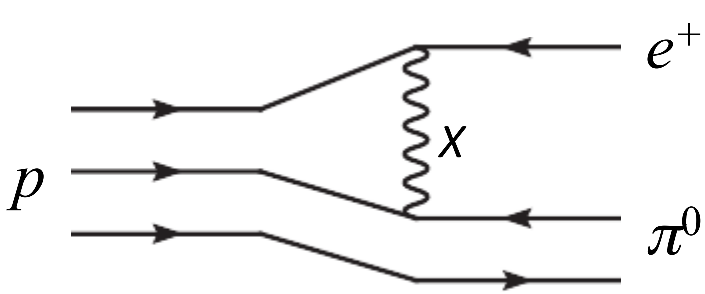
Theoretical Outlook

- Numerous and various models exist.
- Lifetime predictions are not precise – typically uncertain by 2-3 orders of magnitude.
- There are two favored and benchmark decay modes:
  $e^+\pi^0$ (gauge mediated) and νK^+ (SUSY D=5)
  good for water / good for LAr and Liq. Scint.
- There are other modes and processes:
  $\mu^+\pi^0$ (flipped), μ^+K^0 (SUSY), $\nu\pi^+$ and $\nu\pi^0$, etc.
  among a total of 27 two-body antilepton+meson
- There are also invisible modes, dinucleon decay, three-body modes, B+L conserving modes ...
- Some theories suppress or exclude nucleon decay.

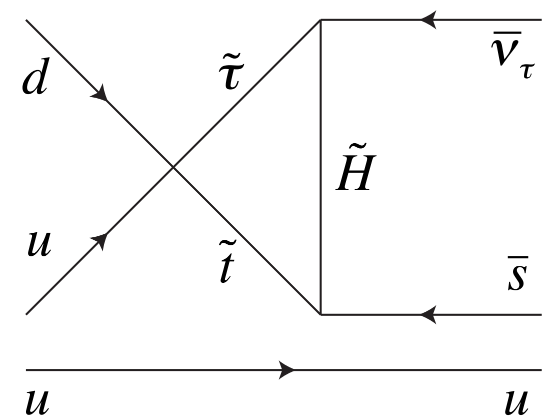
Unification of Running Coupling Constants







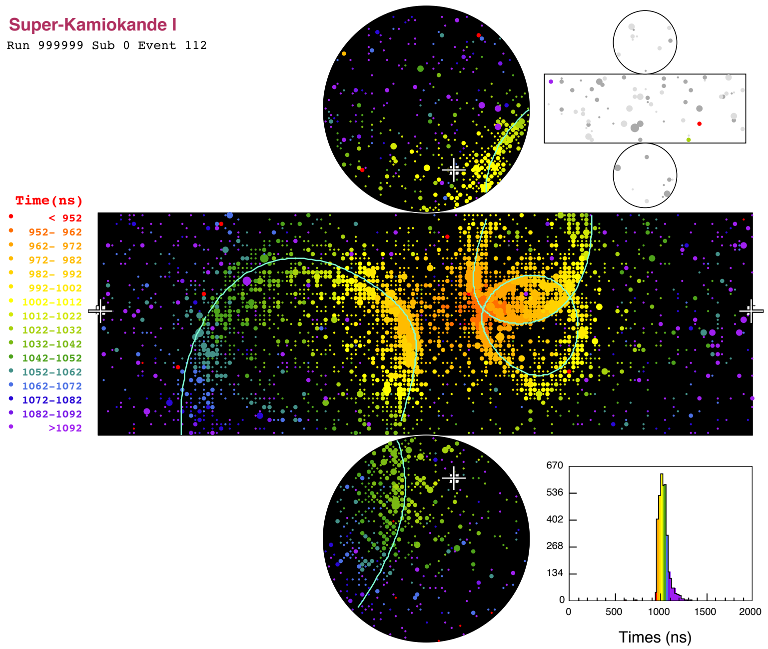
$\tau/B = 4.5 \times 10^{29\pm1.7}\text{years} \quad \mathrm{SU}(5)$



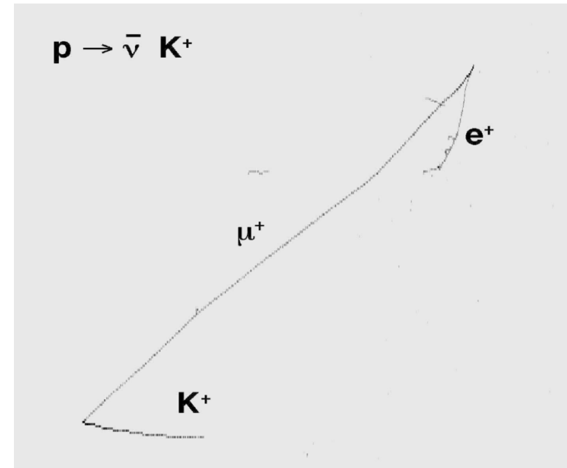
$\tau/B = 10^{29-35}\text{years} \quad \mathrm{SUSY}$

Single Event Discovery is Possible

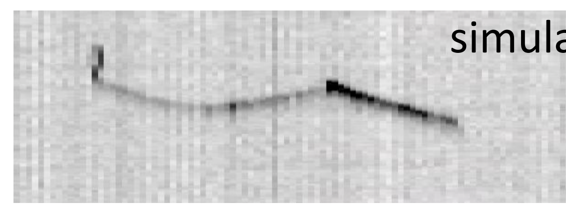
Water Cherenkov



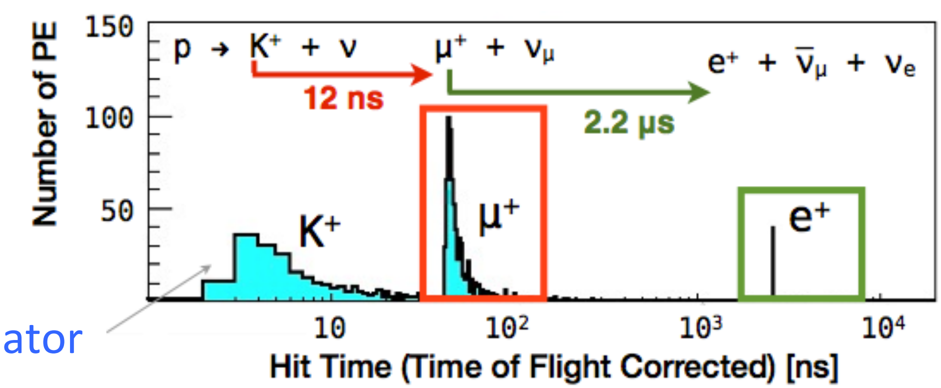
LAr TPC



simulated



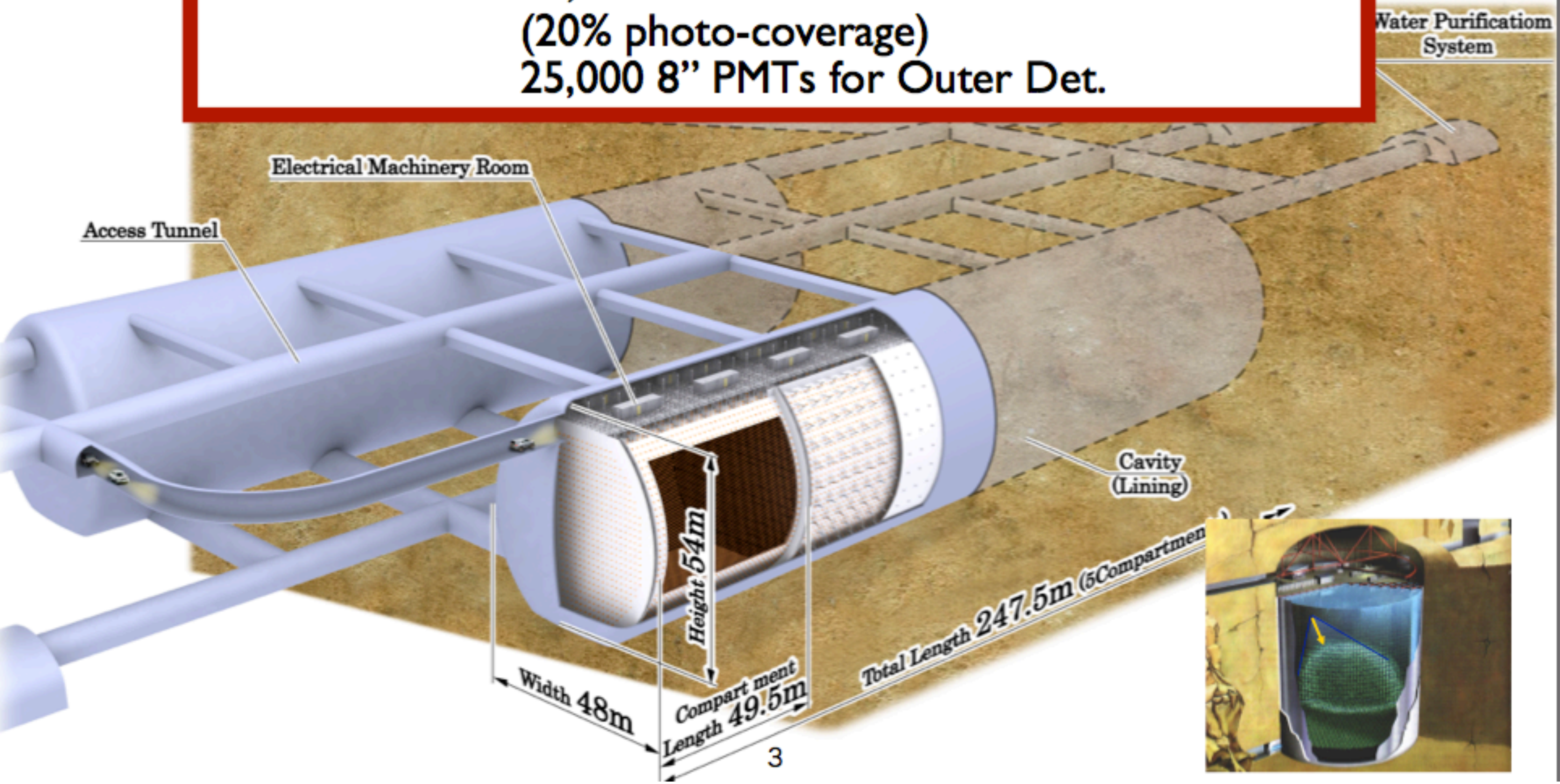
real



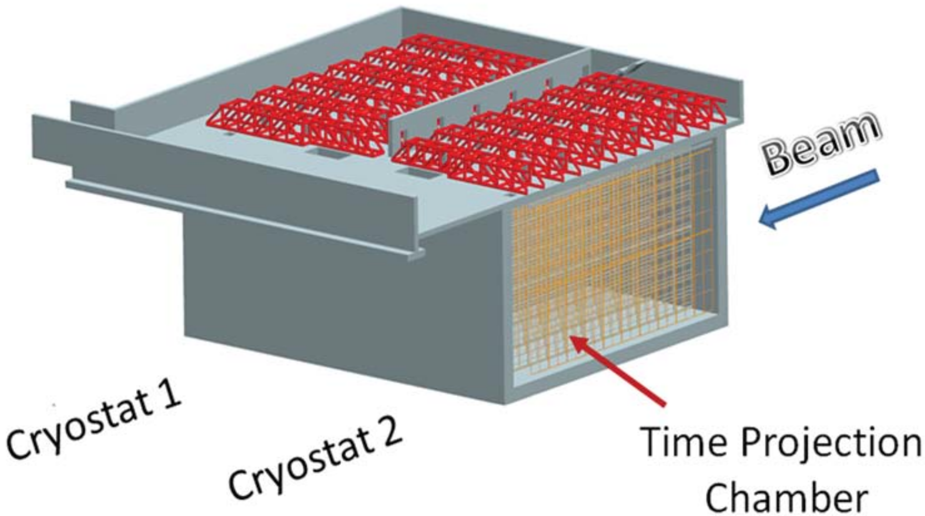
Liquid Scintillator

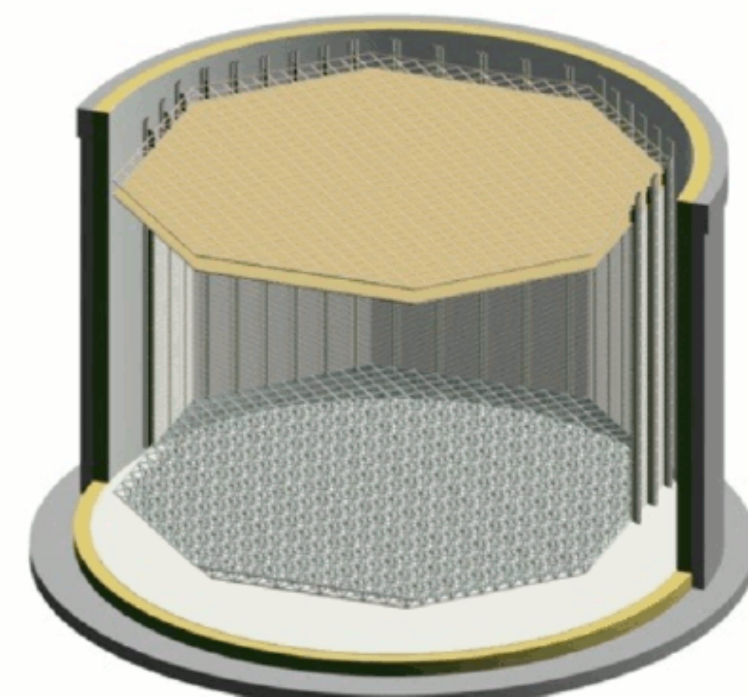
Hyper-Kamiokande

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20” PMTs for Inner Det.
	(20% photo-coverage)
	25,000 8” PMTs for Outer Det.



LBNE GLACIER/LBNO





- Two very different technical designs.
- Essential to get LBNE underground, 34 kton is goal.
- At least 20 kton is preferred for GLACIER
  – proton decay needs MASS.

LENA

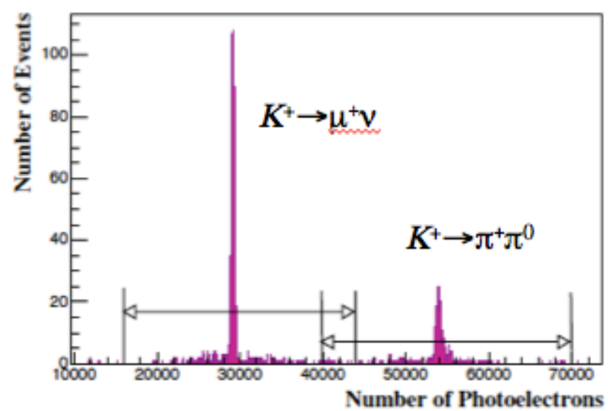
Low Energy Neutrino Astronomy

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

$p \longrightarrow \nu K+$

Efficiency estimate ~ 65%

Background rate ~ 1/yr/50 kton



A massive new generation reactor neutrino detector such as Daya Bay 2 could pursue these modes.

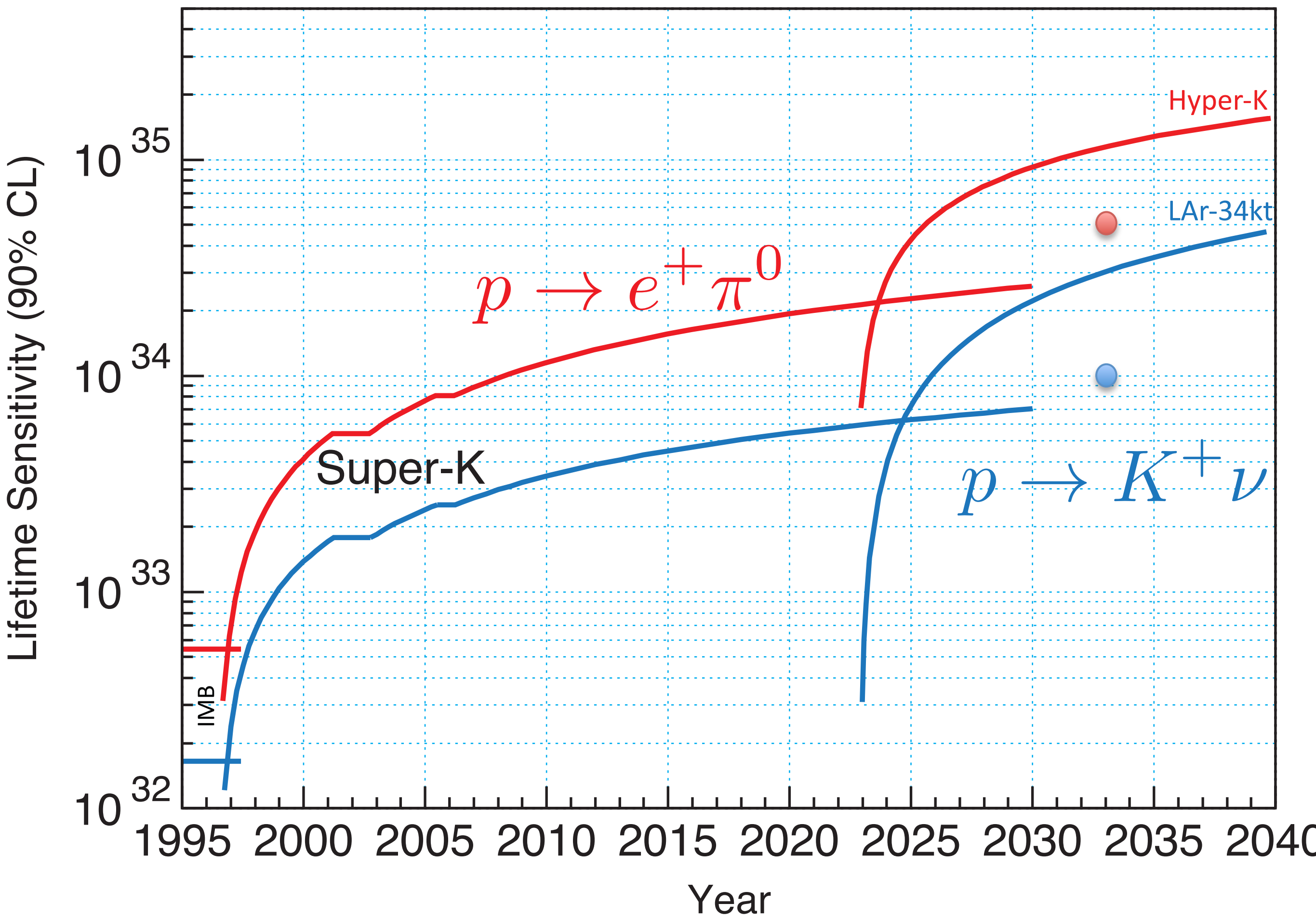
Efficiency and Background Rates

A. Bueno et al.
hep-ph/0701101

	Mode	Super-K Water Ch.		LAr (generic)	
		Efficiency	BG Rate (/Mt y)	Efficiency	BG Rate (/Mt y)
B-L	$e^+\pi^0$	**45%**	**2**	45% (?)	1
B-L	νK^+	15%	2*	**97%**	**1**
B-L	$\mu+ K^0$	8%	8	**47%**	**<2**
B+L	$\mu^- \pi^+ K^+$	?	?	**97%**	**1**
B+L	$e^- K^+$	10%	3	**96%**	**<2**
$\Delta B=2$	n nbar	12%	260	**?**	**?**

For many modes, high efficiency and low BG rate makes up for smaller mass of Lar detectors

* New analysis (Miura, BLV Heidelberg)



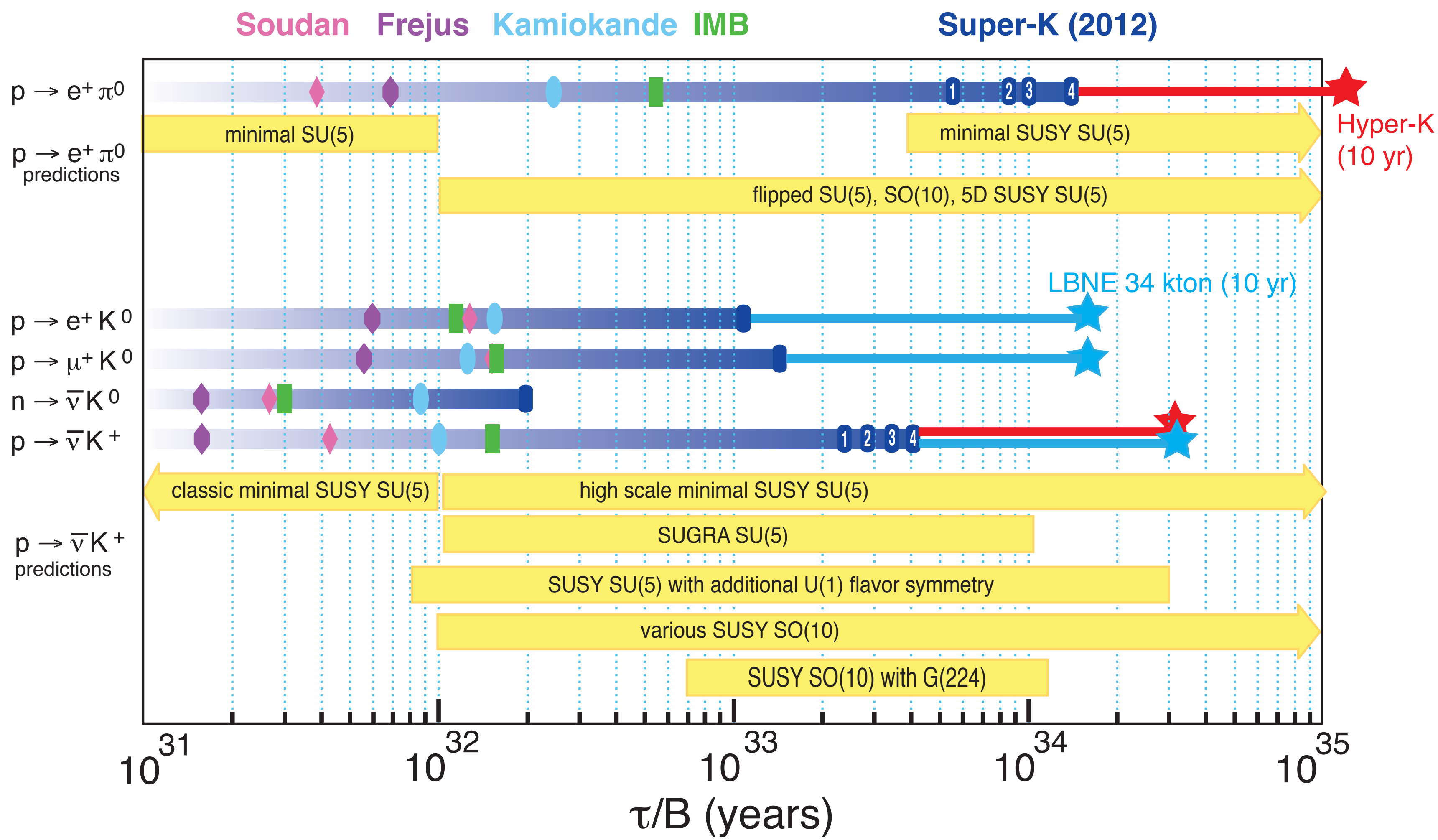
10 year sample points

τ/B = 5e35
17 evts
1 BG

τ/B = 1e34
9 evts
0.3 BG

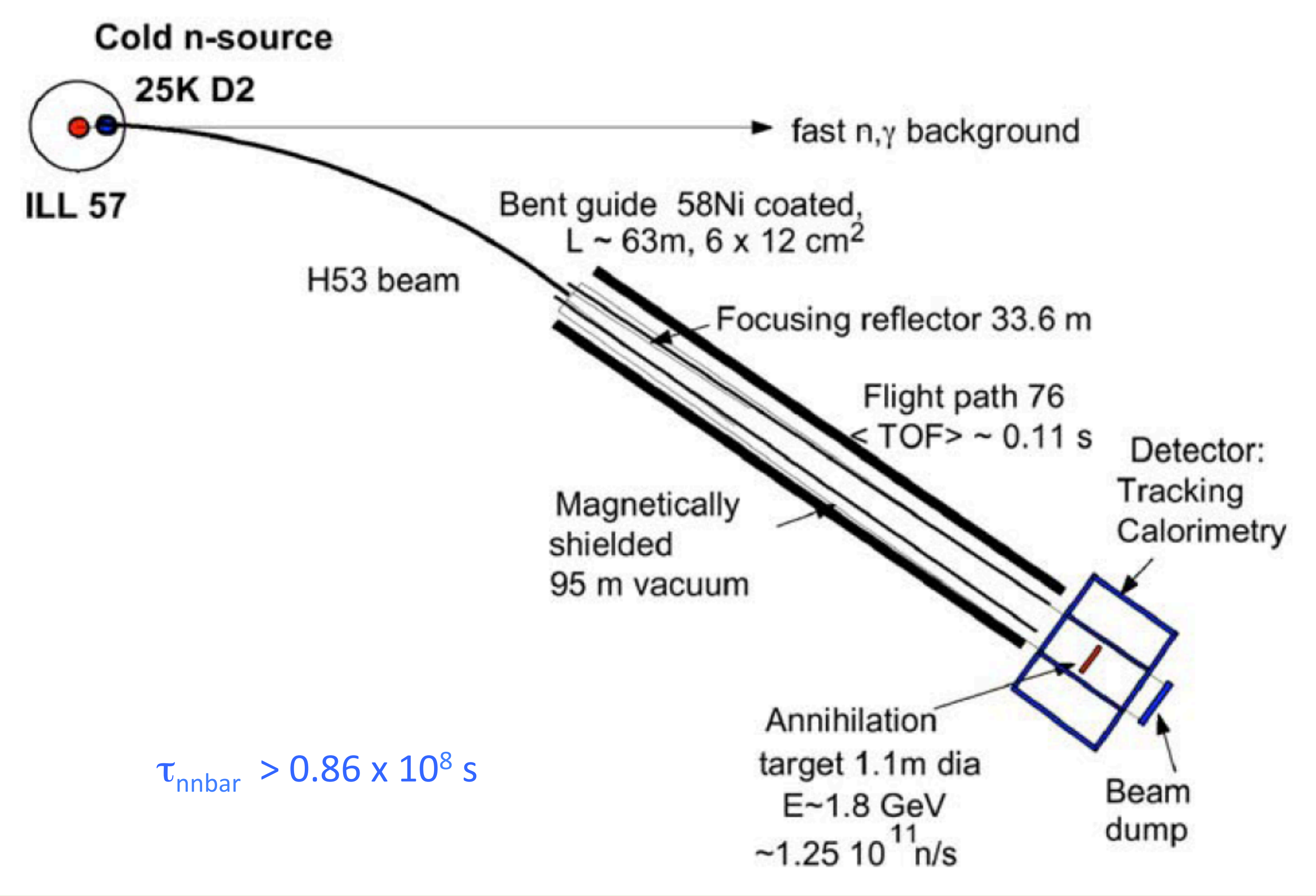
~ 0.5 Mt yr exposure by Super-K before next generation experiments

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



Soudan
Frejus
Kamiokande
IMB
Super-K (2012)
p → e+ π0
minimal SU(5)
minimal SUSY SU(5)
Hyper-K
(10 yr)
p → e+ π0
predictions
flipped SU(5), SO(10), 5D SUSY SU(5)
LBNE 34 kton (10 yr)
p → e+ K0
p → μ+ K0
n → ν̄ K0
p → ν̄ K+
classic minimal SUSY SU(5)
high scale minimal SUSY SU(5)
p → ν̄ K+
predictions
SUGRA SU(5)
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)

Neutron Antineutron Oscillation



$\tau_{nnbar} > 0.86 \times 10^8$ s

Motivation

- Analogous to $K^0 \longleftrightarrow K^0$-bar mixing
  sensitive to new physics

- With no experimental sign of proton decay,
  we need to seek alternative source of B-violation

- BAU connection

- B-L connection with neutrino mass

- $\tau = 10^8$ s probes scales at 100-TeV

- Variety of models, including GUT. Some predictive/falsifiable.

Quantum Mechanics of nnbar

For $H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix}$ $\quad P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\frac{\sqrt{\alpha^2+V^2}}{\hbar}t\right]$

where V is the potential difference for neutron and anti-neutron.

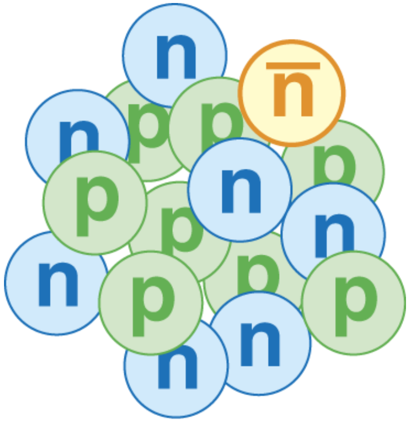
For $\left[\frac{\sqrt{\alpha^2+V^2}}{\hbar}t\right] << 1$ ("quasifree condition") $\quad P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar}\times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$

Experimental figure of merit: number of neutrons x (observation time)^2

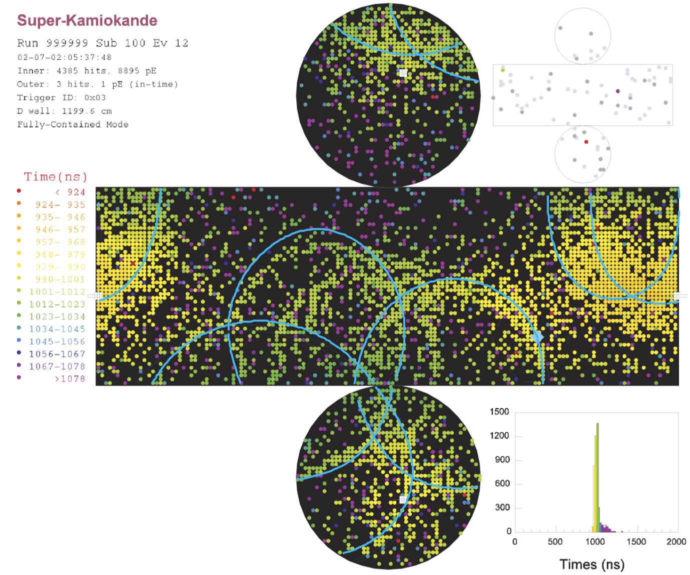
1. **Neutrons in nuclei**
   V_{nucl} is large, nuclear suppression factor $\quad \tau_{n\bar{n}} = \sqrt{\frac{T_{bound}}{5 \times 10^{22} s^{-1}}}$
   require large number of nuclei to compensate for small observation time

2. **Free neutron oscillation**
   Require V_{mag} to be small (shielding to nT)
   Compensate for small number of neutrons with long observation time (slow speed=cold)

Bound neutron antineutron oscillation



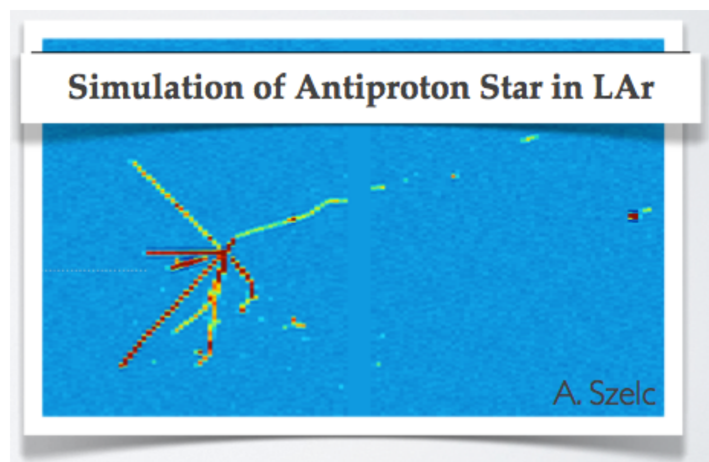
$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%



Super-Kamiokand I result:
12% detection efficiency
24.1 background events
24 candidates
$T_{bound} > 1.9 \times 10^{32}$ years

$\tau_{nnbar} > 3.4 \times 10^8$ s

SNO has a similar result



Promising topic for LAr TPC
need ε and BG estimates
Mind the intranuclear reactions

Free neutron antineutron oscillation

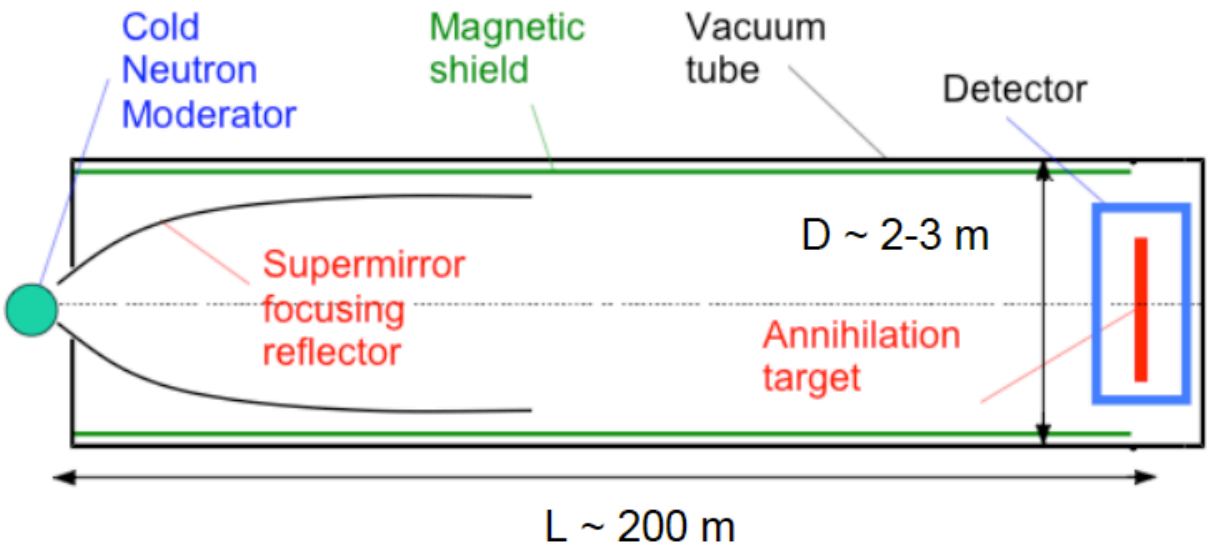
Expression of Interest

Search for Neutron-Antineutron Transformation at Fermilab

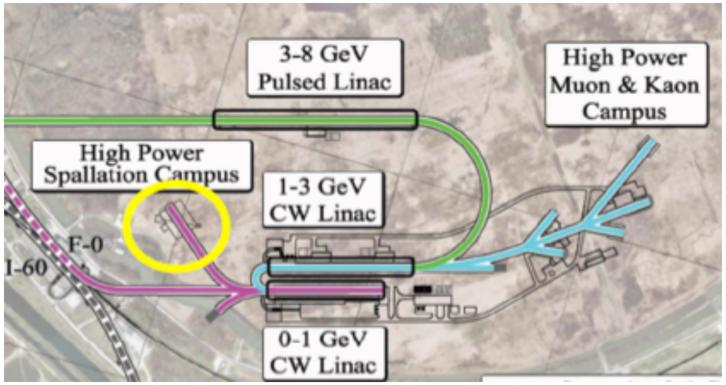
The NNbarX Collaboration

need slow neutrons from high flux source, access of neutron focusing reflector to cold source, free flight path of ~200m

Improvement on ILL experiment by factor of ~1000 in transition probability is possible with horizontal experiment at Project X with existing n optics technology, sources, and moderators. Vertical experiment also possible



Technical Hurdles / Opportunities

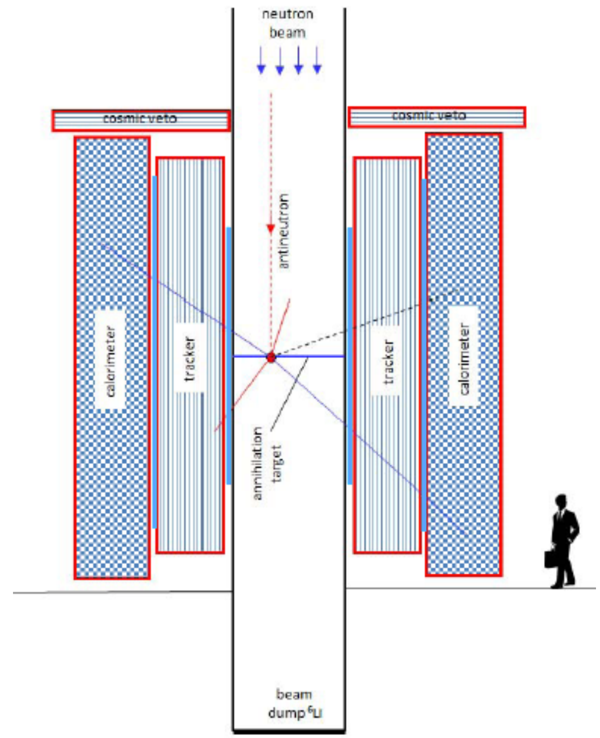


Spallation source at Project X

- only small apertures available at SNS, reactors
- want access to focusing reflector
- want longer running time (ILL was only 1 year)
- other beneficiaries? E.g. nEDM

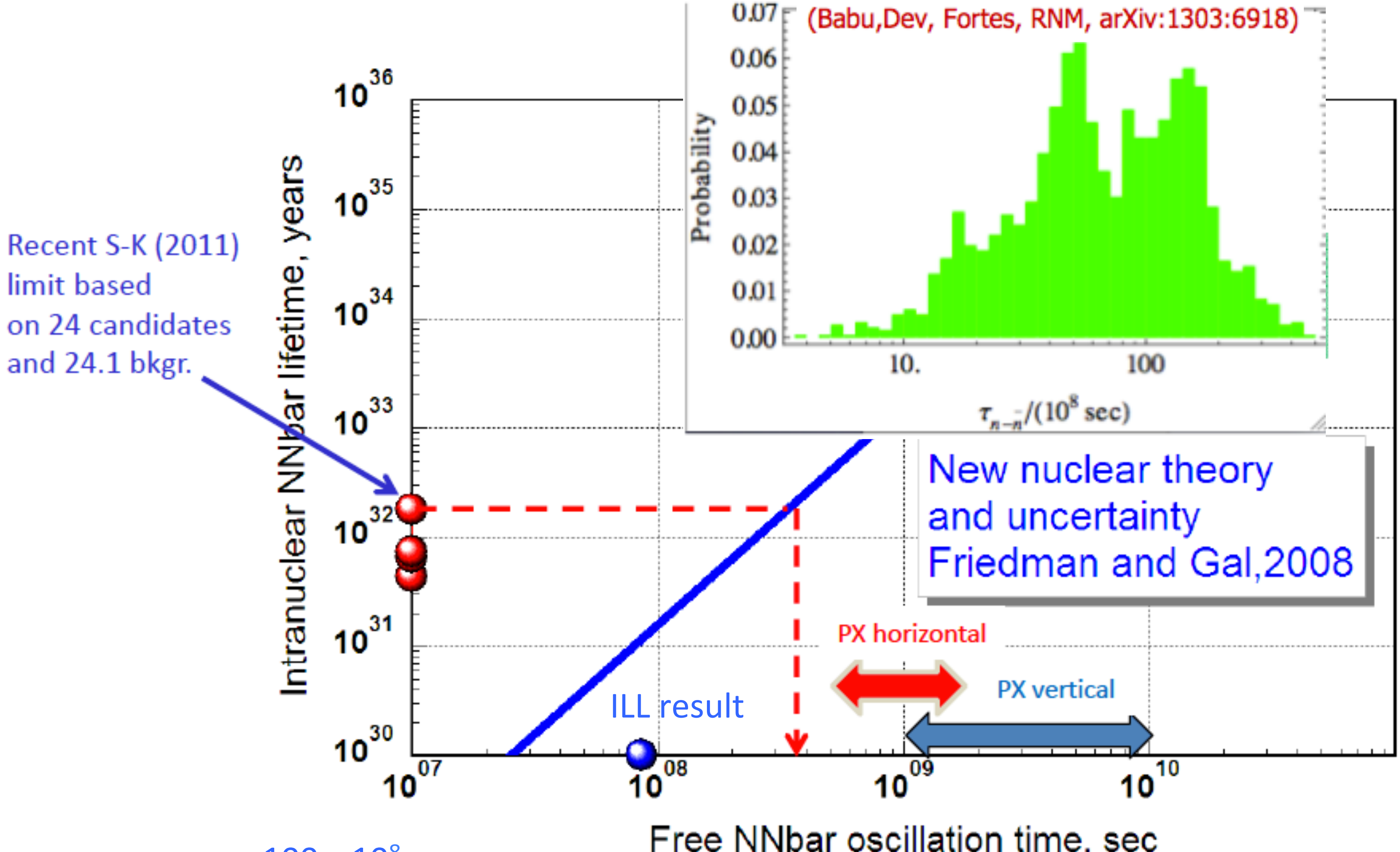
Improvements in neutron reflector, e.g. diamond powder nanoparticles (!)

Vertical flight path (200 m) considered as upgrade / 2nd stage



Interesting detector system. Should reject possible fast (bunch structure) backgrounds

Goal: zero-background experiment



τ_{nnbar} > 100 x 10^8 s

Up to X50 improvement in τ_{nnbar} over ILL experiment

X30 improvement in τ_{nnbar} over Super-K/SNO

Messages

- Testing Baryon Number Violation remains an essential and valued 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.
- Next generation experiments are in the works, and should achieve the next factor of 10, but it won’t be cheap or fast.
- The next generation nucleon decay experiments are tied into large neutrino detectors and together with neutrino physics establish a broad science program.

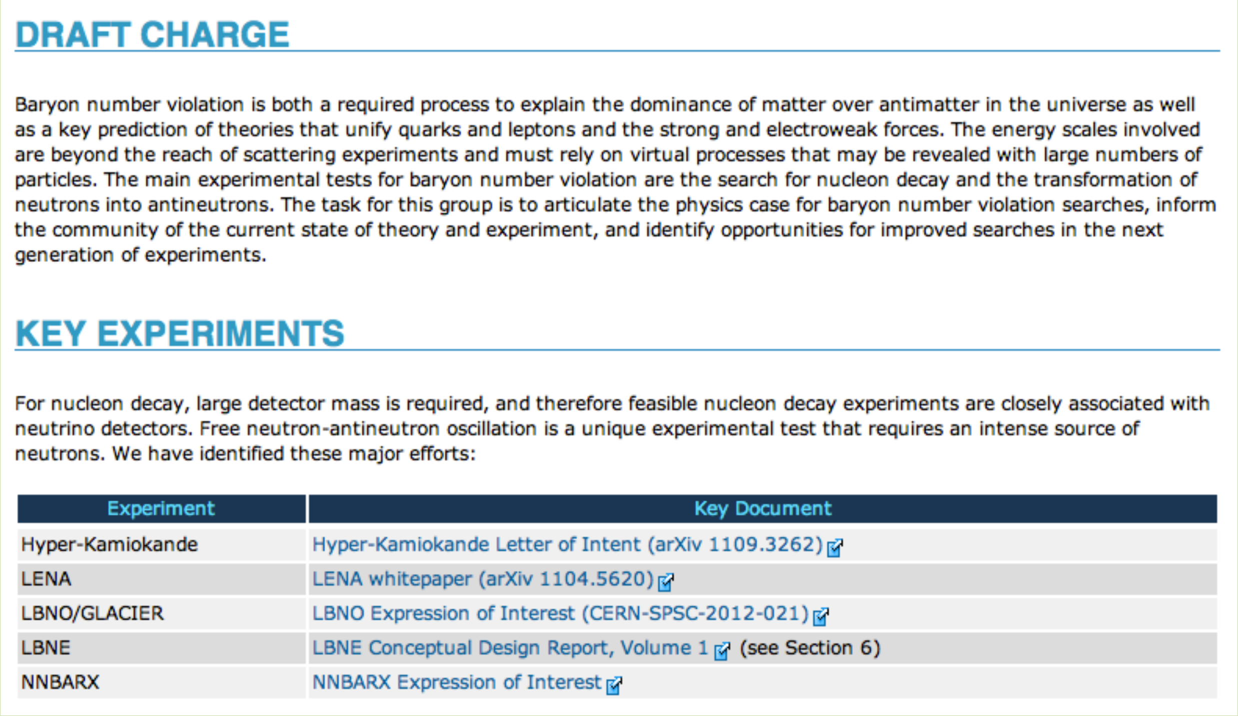
Messages (continued)

- We need new ideas on how to take nucleon decay search to the next scale (beyond 1e35). Deep ice?
- A free neutron antineutron is an appealing method to pursue BNV, perhaps in the absence of proton decay.
- Observation of neutron antineutron oscillation would signal new physics at the 100 TeV scale and may fit in with new physics at higher scales.
- There is a specific proposal being evaluated for operation with Project X (NNBARX). The reach in free lifetime can be as high as 50x better than the current result.

Thank you to all of the participant in the BNV sessions!

Please continue to work with us for the Snowmass write-up.

http://www.snowmass2013.org/tiki-index.php?page=Baryon+Number+Violation



DRAFT CHARGE

Baryon number violation is both a required process to explain the dominance of matter over antimatter in the universe as well as a key prediction of theories that unify quarks and leptons and the strong and electroweak forces. The energy scales involved are beyond the reach of scattering experiments and must rely on virtual processes that may be revealed with large numbers of particles. The main experimental tests for baryon number violation are the search for nucleon decay and the transformation of neutrons into antineutrons. The task for this group is to articulate the physics case for baryon number violation searches, inform the community of the current state of theory and experiment, and identify opportunities for improved searches in the next generation of experiments.

KEY EXPERIMENTS

For nucleon decay, large detector mass is required, and therefore feasible nucleon decay experiments are closely associated with neutrino detectors. Free neutron-antineutron oscillation is a unique experimental test that requires an intense source of neutrons. We have identified these major efforts:

Experiment	Key Document
Hyper-Kamiokande	Hyper-Kamiokande Letter of Intent (arXiv 1109.3262)
LENA	LENA whitepaper (arXiv 1104.5620)
LBNO/GLACIER	LBNO Expression of Interest (CERN-SPSC-2012-021)
LBNE	LBNE Conceptual Design Report, Volume 1 (see Section 6)
NNBARX	NNBARX Expression of Interest

Backups follow

Fermilab Physics Advisory Committee Meeting
2012 October 15-17

Comments and Recommendations

The previous state-of-the-art experiment (at ILL, Grenoble) provided the current lower limit on the n-$\bar{n}$ oscillation time of about 10^8 s. An interesting increase of sensitivity is projected for NNbarX, by a factor of 20–30 for a first proposed phase with a horizontal detector layout. A second stage with a vertical layout could give a further factor of 100, corresponding to probing the oscillation time up to 10^{10} s. The vertical layout would be more challenging to construct, but would allow the use of very slow neutrons (which would suffer excessive gravitational deflection in a horizontal layout). The main improvements in sensitivity reportedly come from increase of the neutron flux delivered to the annihilation target, optimized with super-mirrors or diamond nanoparticle reflectors, and from extending the observation time through increased length of the vacuum vessel or the use of slower neutrons. A dedicated spallation source would be required at Project X, a challenging design with cryogenic moderator surrounding the solid metal target.

Fermilab PAC recommendation sets for horizontal option a "minimal sensitivity goal" of ~ 30 or $\tau_{free} = 5 \times 10^8$ s

Hyper-K in Japanese future strategy discussions

- Recommendation by HEP future projects committee (Feb.2012) http://www.jahep.org/office/doc/201202_hecsubc_report.pdf
  - Two large-scale projects recommended
    - ILC
    - Large neutrino/nucleon decay detector (Hyper-K/LAr)
- Final draft of KEK roadmap (Jan. 2013) includes Hyper-K http://kds.kek.jp/conferenceDisplay.py?confId=11728
- Cosmic ray physics community endorses Hyper-K as a next large-scale project
- ICRR future plan under discussion

Planning process in Japan

- In 2013-14, Science Council of Japan is going to update the *Master Plan* for large scale projects (for all fields of science).
  - Large neutrino/nucleon decay detector (Hyper-K/LAr) was listed on the previous versions of the *Master Plan* (2010/2011).
  - We (re-)submitted a proposal with Hyper-K as *the* project.
  - 25-30 projects will be selected as priority.
- The *Master Plan* is expected to be an important input to the Japanese government.

LBNE is…

- A new neutrino beam at Fermilab
  - 700 kW proton beam, 2.3 MW capable
- A near neutrino detector
- An optimal 1300 km baseline: Fermilab-SURF
- A 34 kt Liquid Argon TPC with 4850′ overburden

- An optimized cost/time effective path to the science

- This conceptual design…
  - Completed a successful CD-1 Director's Review (March 2012)
  - Updated cost estimate (July 2012):
    ~$1.5B (incl. contingency + escalation)

LBNE update, continued

December 2012: CD-1 approval for $867M first phase DOE funding

- We have completed an extensive cost/schedule for 10 kt LAr far detector (LBNE10) on the surface but the design is **not** fixed
- ***CD-1 approval explicitly allows for scope change enabled by new partners***

First phase goal: *greater than 10 kt* far detector *underground* and a *full capability near detector*

In the past 3 months there has been considerable progress towards international partnerships (encouraged by European Strategy statement