Nucleon Decay EXPERIMENTS

BLV circa 2020

SnowMass2021

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Case Western Reserve University EST. 1826
think beyond the possible

zoom

Scientific Perspective of Nucleon 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.
- Even if no signal, limits are very constraining on theory.

Theoretical Outlook from Experimental Perspective

- Numerous and various models exist.

- Lifetime predictions are not precise –
  typically uncertain by 2-3 orders of magnitude.

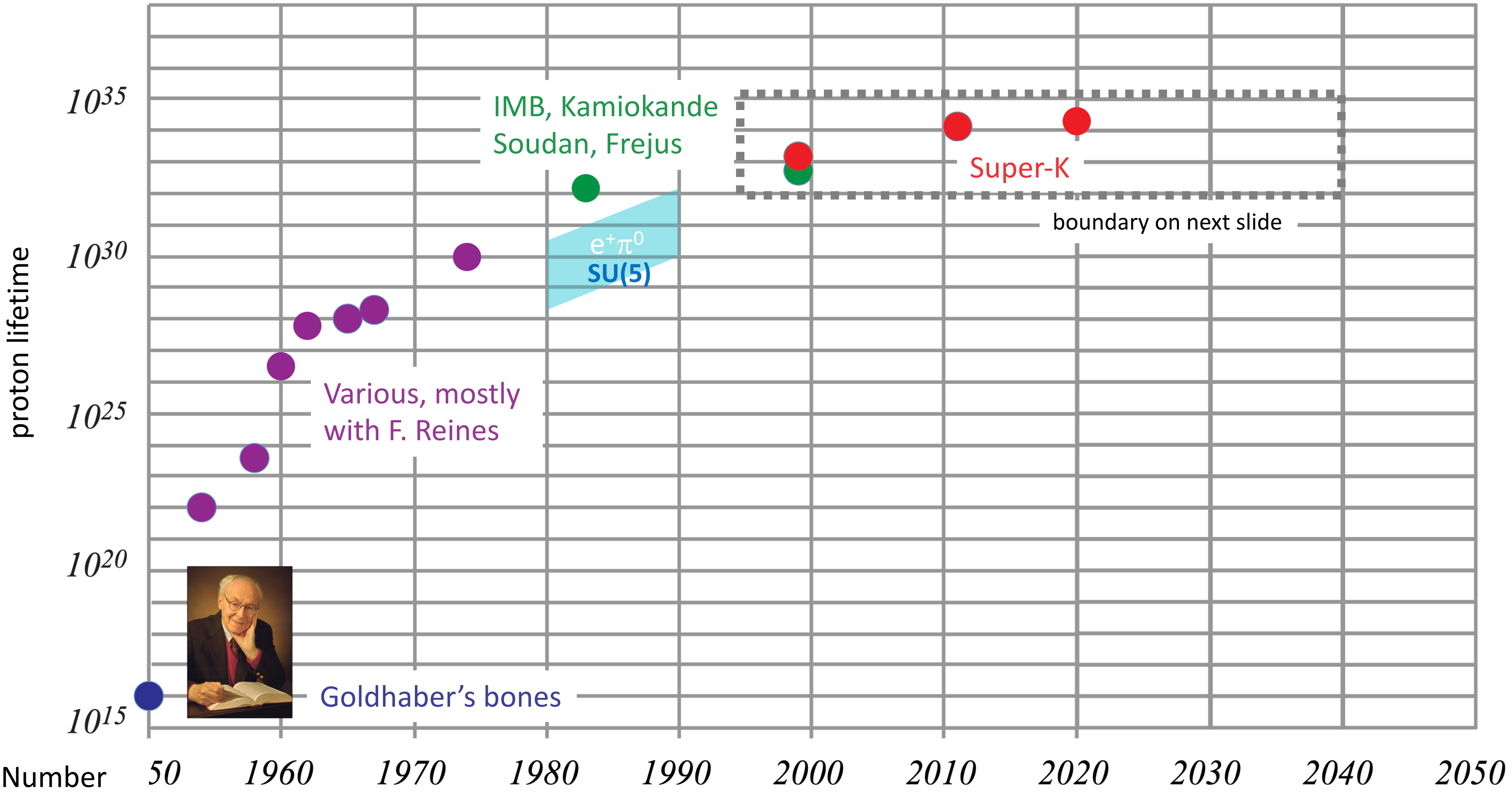
- There are two favored and benchmark decay modes:
  $e^+\pi^0$ (gauge mediated) and νK^+ (SUSY D=5)
  good for water — good for LAr and Liq. Scint.

- There are other modes and processes:
  $\mu^+\pi^0$ (flipped), μ^+K^0 (SUSY), invisible modes, dinucleon decay,
  three-body modes, leptonic modes, B+L conserving modes ...

  Ideally, we wish to cover all possibilities

- Some theories suppress or exclude nucleon decay.

Historical Perspective



Baryon Number
E. Wigner (1949)

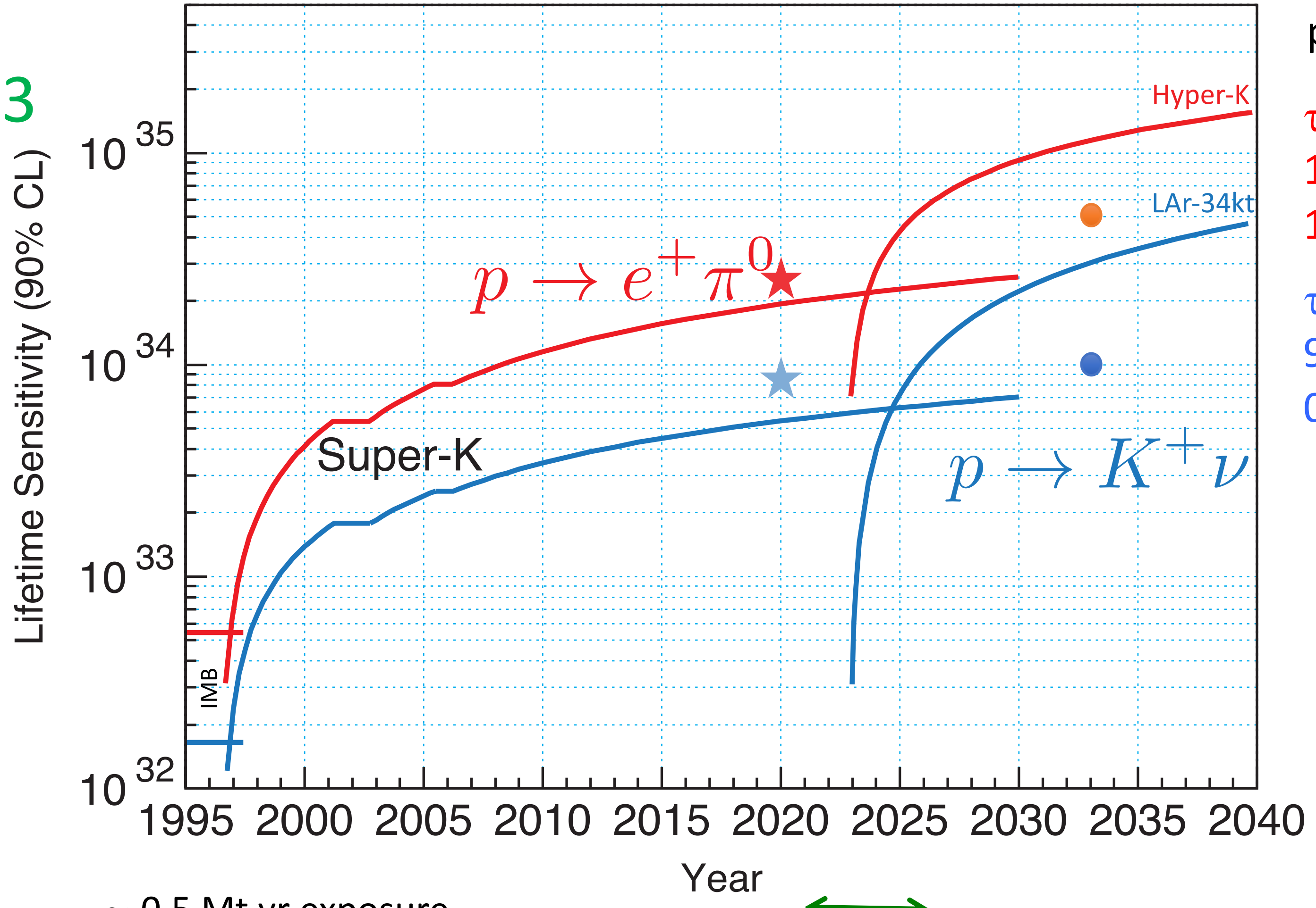
Particle Physics at the Intensity Frontier

Intensity Frontier Workshop

25-27 April 2013 Argonne National Laboratory

Retrospective: Snowmass 2013

★ = prelim. SK (2020)



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.

Before we look ahead, let's take a quick look at recent work from Super-K

18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40

SK-Gd

Hyper-K including T2HK

Big job for Super-K collaboration in 2018:

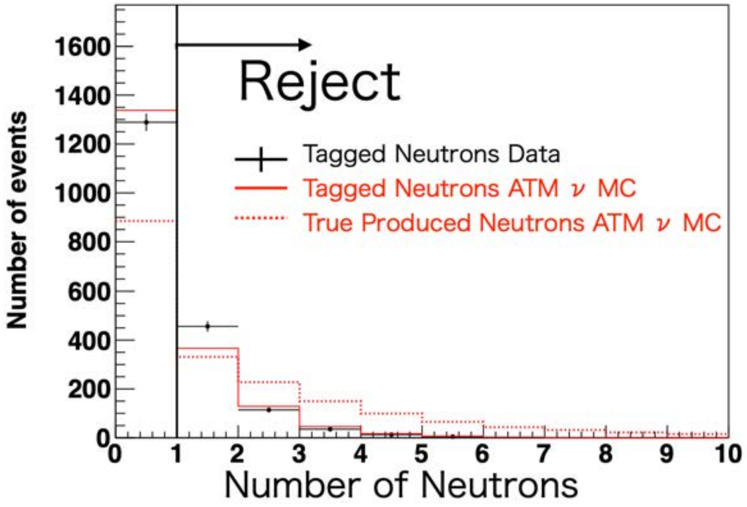
Fix leak
Clean structure
Replace PMTs
Upgrade water system
Work fast: no T2K beam

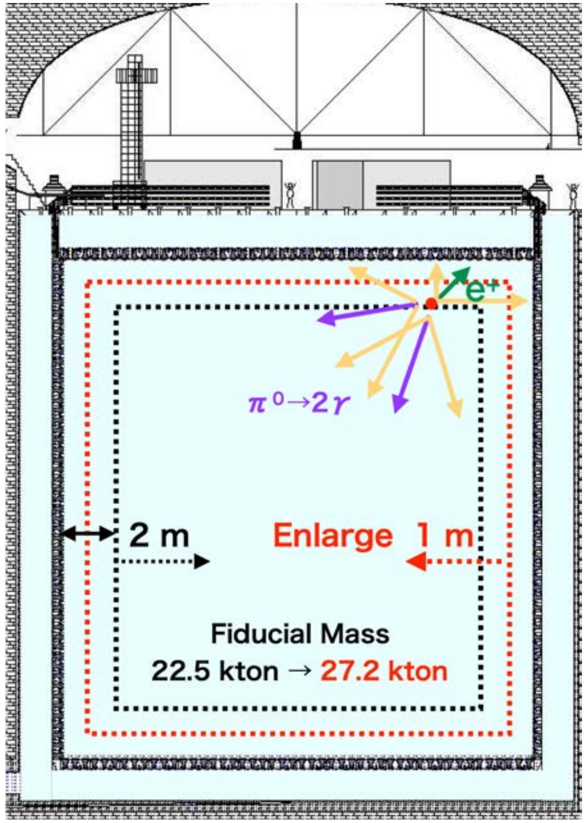
250 persons
11 countries
2751 person-shifts

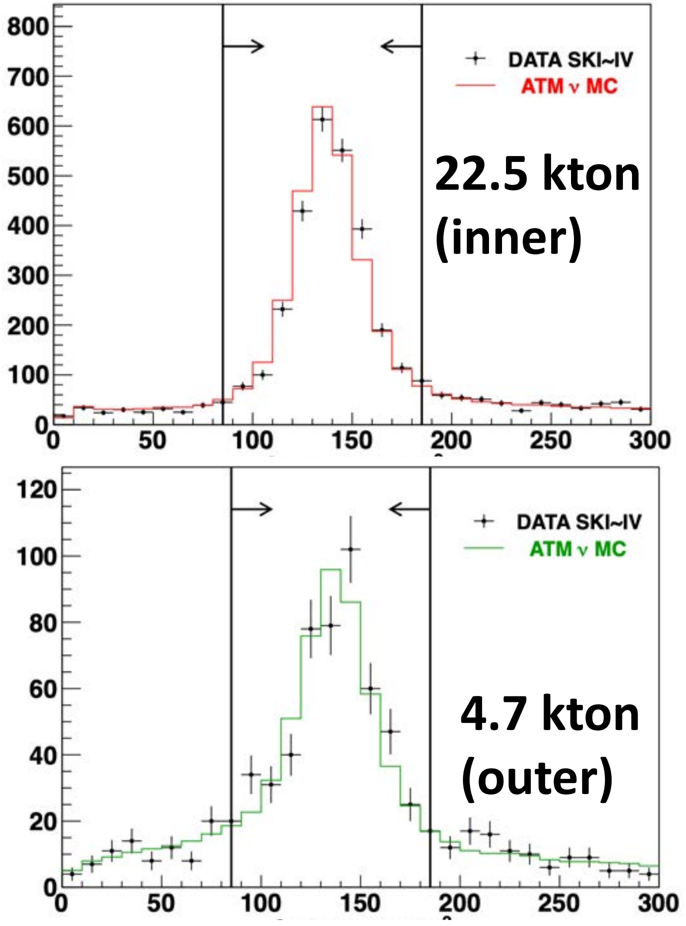
6

Improvements to SK analysis

Nonstop effort since 2013:
Neutron capture on hydrogen (25% eff.)
Expanded fiducial volume
Two box search (free proton)
Improved reconstruction software



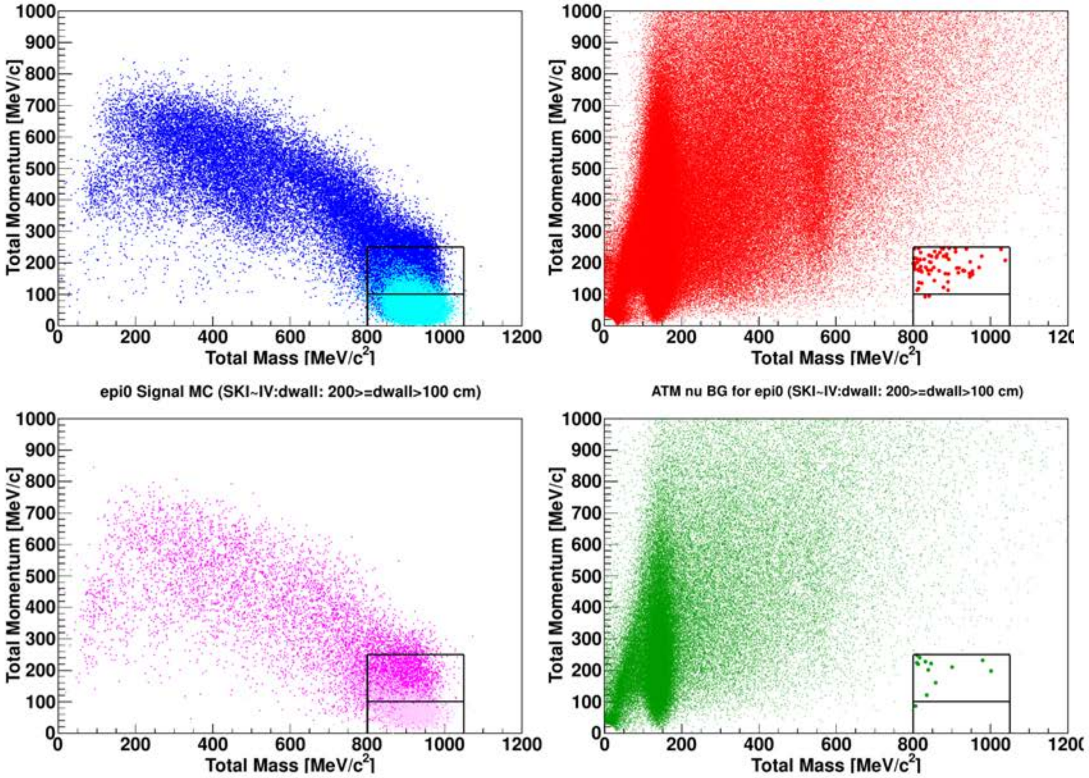




π^0 mass (MeV/c^2)

See A. Takenaka, NuPhys 2019 https://indico.cern.ch/event/818781/

Super-K $e^+\pi^0$ 2020 (preliminary)



22.5 kton inner FV

4.7 kton outer FV

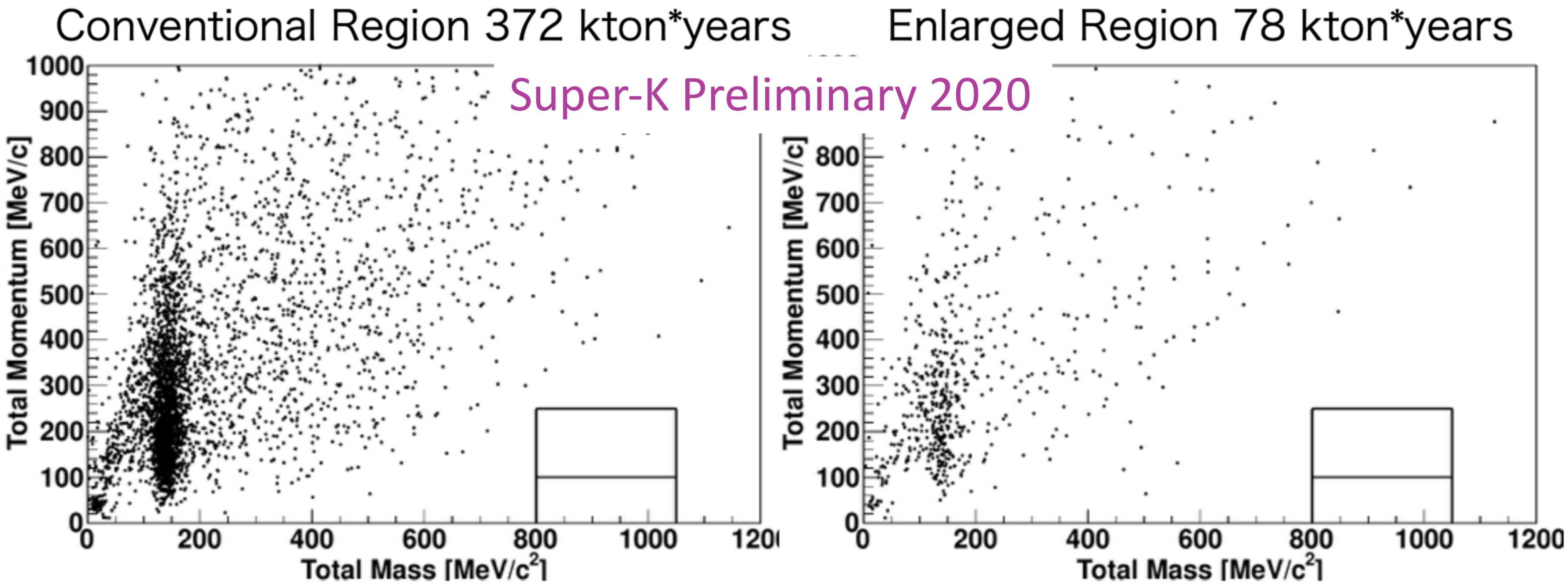
Signal Efficiency (%)	SK-I	SK-II	SK-III	SK-IV w. n cap.	New 4.7 kton FV (SK I-IV)
$100 < p_{net} < 200$ MeV/c	21.0 ± 3.5	20.2 ± 3.2	21.1 ± 3.2	19.8 ± 3.3	**15.5 ± 2.6**
$p_{net} < 100$ MeV/c	19.9 ± 1.9	18.1 ± 1.8	20.3 ± 1.8	19.6 ± 1.6	**10.3 ± 1.4**

Background (evts/Mt y)	SK-I	SK-II	SK-III	SK-IV w. n cap.	New 4.7 kton FV (SK I-IV)
$100 < p_{net} < 200$ MeV/c	1.4 ± 0.6	2.2 ± 0.8	1.6 ± 0.6	1.0 ± 0.5	**0.10 ± 0.05**
$p_{net} < 100$ MeV/c	< 0.01	0.17 ± 0.14	< 0.01	< 0.01	**0.01 ± 0.01**

background reduction with neutron capture on hydrogen

Low background achieved with decent efficiency

Studying suitability for $p \to \nu K^+$ and others



$$\tau/B(e^+\pi^0) > 2.4 \times 10^{34} \text{ years}$$

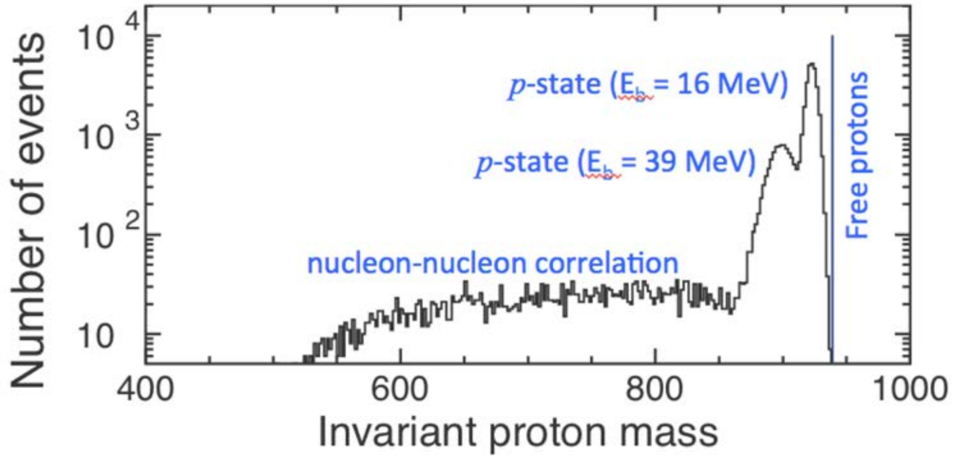
Published = 1.6e34

also … $$\tau/B(\mu^+\pi^0) > 1.6 \times 10^{34} \text{ years}$$

Published = 0.8e34
(1 candidate near upper box edge remains)

Nuclear Modeling is Important

- 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
- Similar issues cause uncertainty in atm. Bkg.



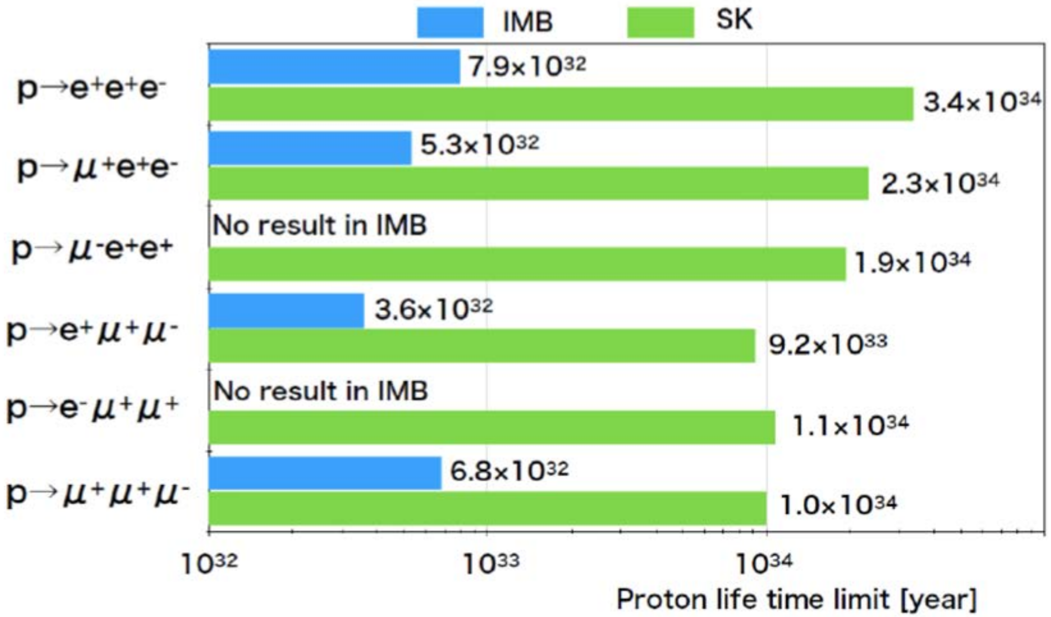
H. Ejiri Phys. Rev. C48 (1993)

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

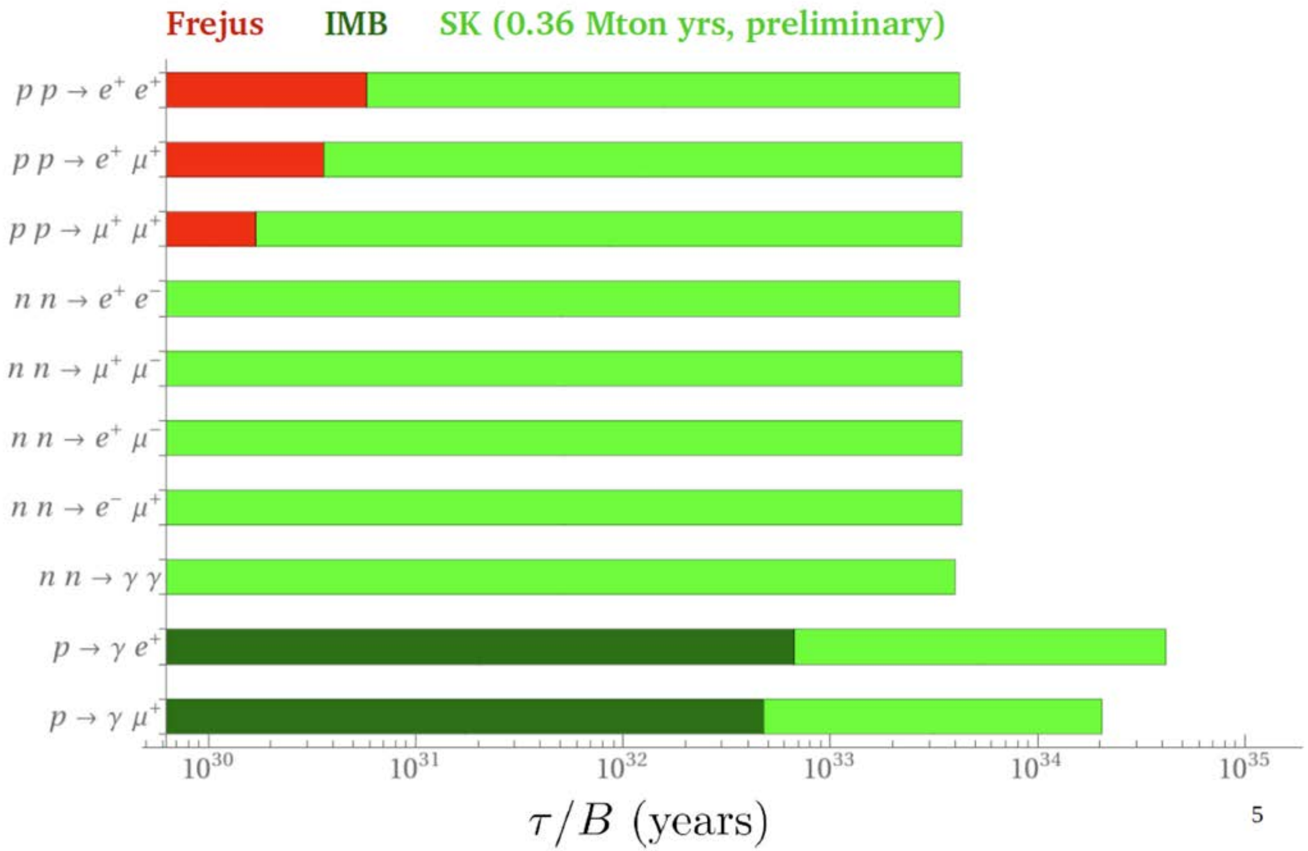
Trouble for decay in the nucleus

Exotic Nucleon and Dinucleon Decay Modes

SK preliminary (paper in progress)



https://arxiv.org/abs/1811.12430



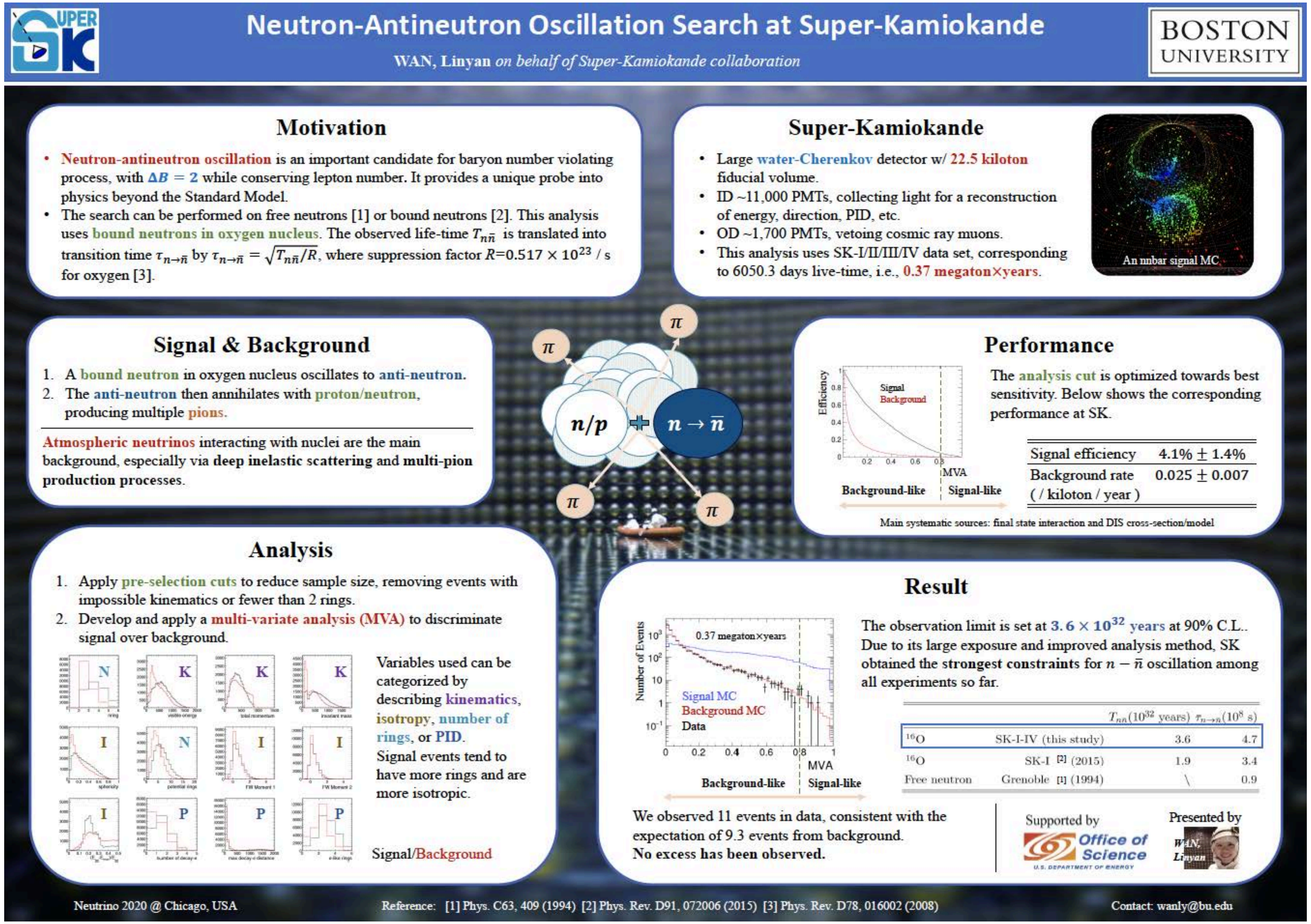
2015: see also https://arxiv.org/abs/1504.01041 for dinucleon decay to pions and https://arxiv.org/abs/1409.1947 and https://arxiv.org/abs/1508.05530

$n\bar{n}$

New: SK 1 (old) + 2/3/4 (new)
Refined analysis (multivariate)
Updated intranuclear absorption (more).
Affects signal and background

Exposure [n years]	Effic.	Bkgd.	Cand.	$T_{nucl.}(10^{32})$ [yr]
SK-I 91 kton y	12%	24.1	24	1.9 $\tau > 2.4 \times 10^8$ s
SK I-IV 370 kton y	4.1% ±1.4%	9.3 ±2.6	11	3.6 $\tau > 4.7 \times 10^8$ s

Unfortunately, search is very much background limited.



Linyan Wan, Neutrino 2020, https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-43.pdf

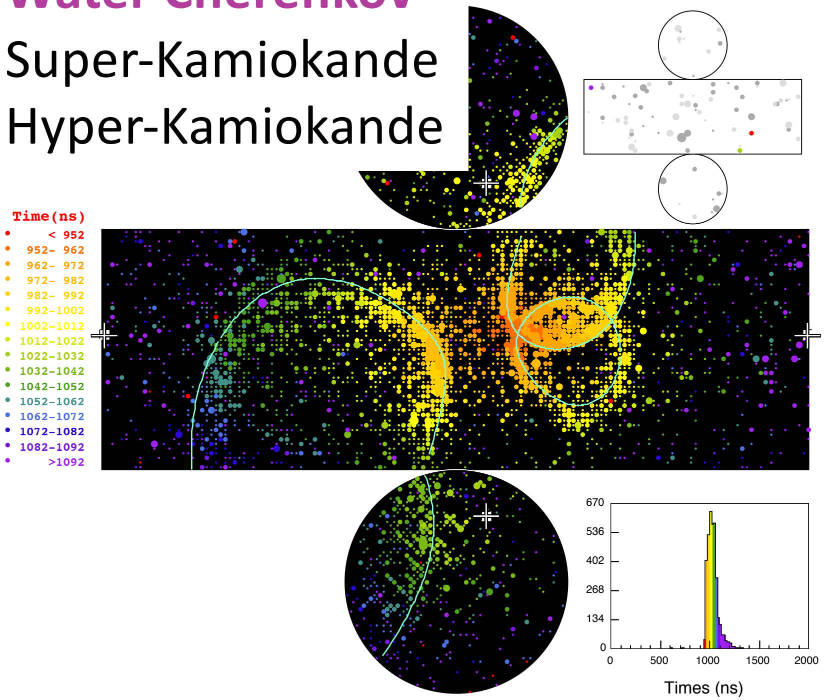
and upcoming ΔB=2 workshop:

New experiments that can have an impact

Water Cherenkov

Super-Kamiokande

Hyper-Kamiokande



most massive – superior for $e^+\pi^0$

broad search capabilities

free proton advantage

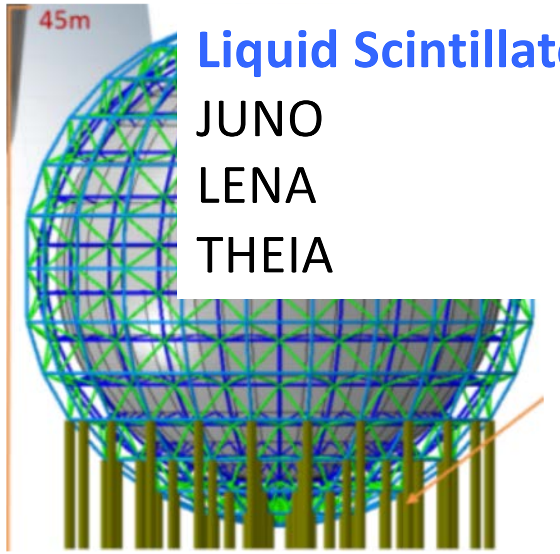
kaons below Cherenkov threshold

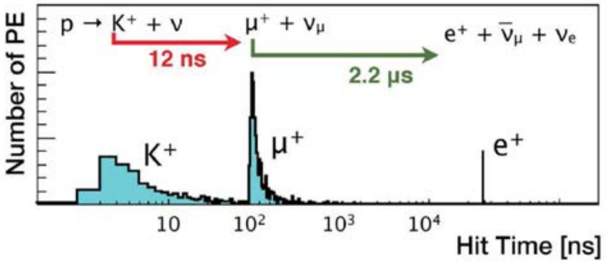
Liquid Scintillator

JUNO

LENA

THEIA





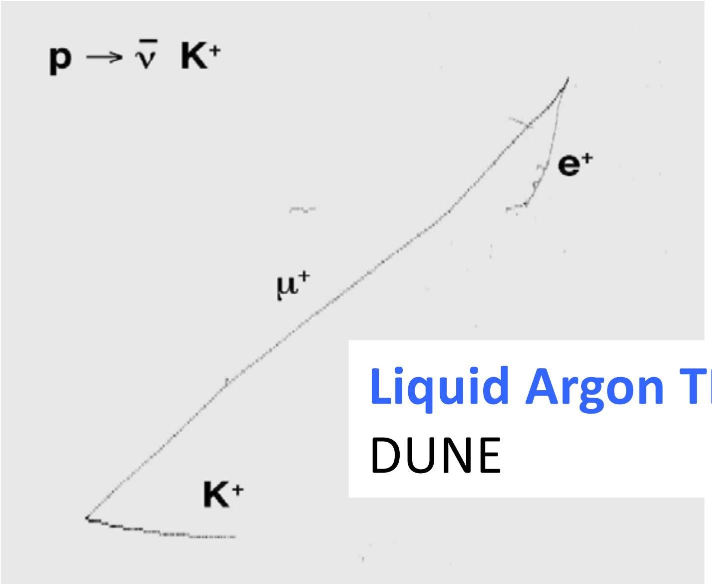
clean timing signature

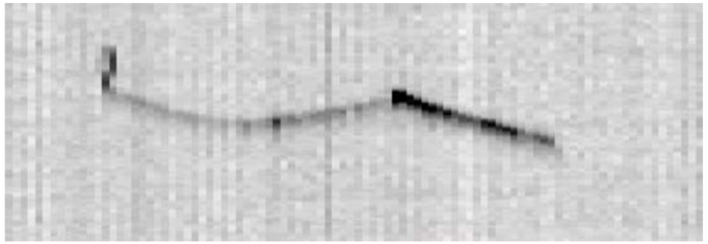
specialize in charged kaon

(also invisible mode)

Liquid Argon TPC

DUNE



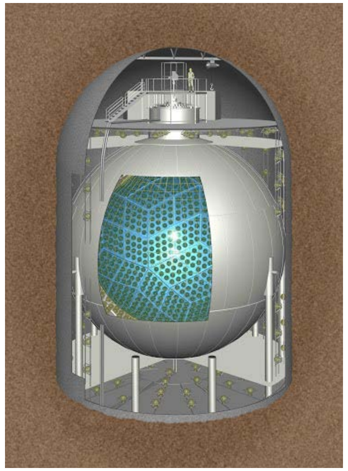


fine grained detail

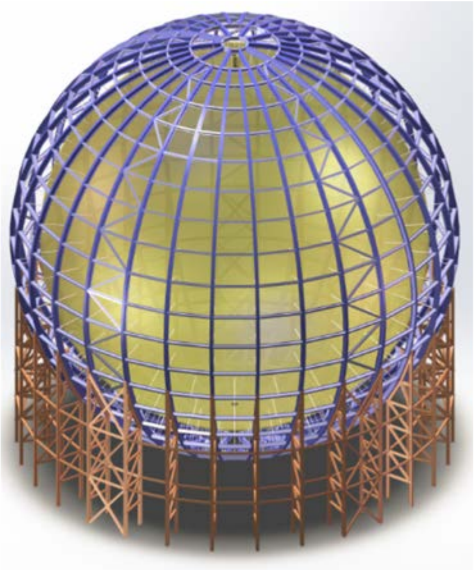
visible kaon track

heavy nucleus, no free protons

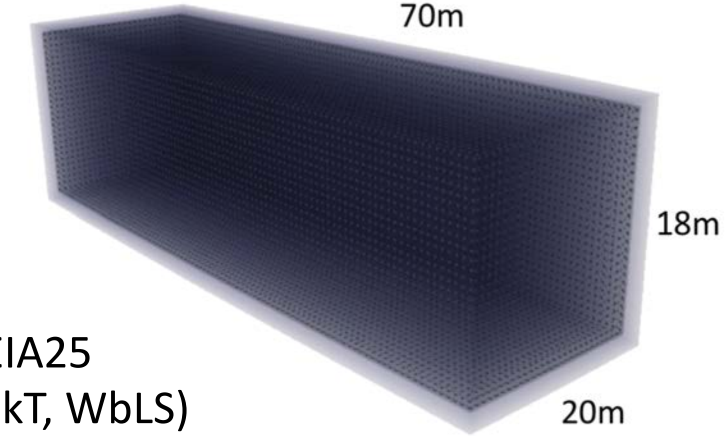
Large Liquid Scintillator Detectors



KamLAND (1 kt)



JUNO (20 kt)



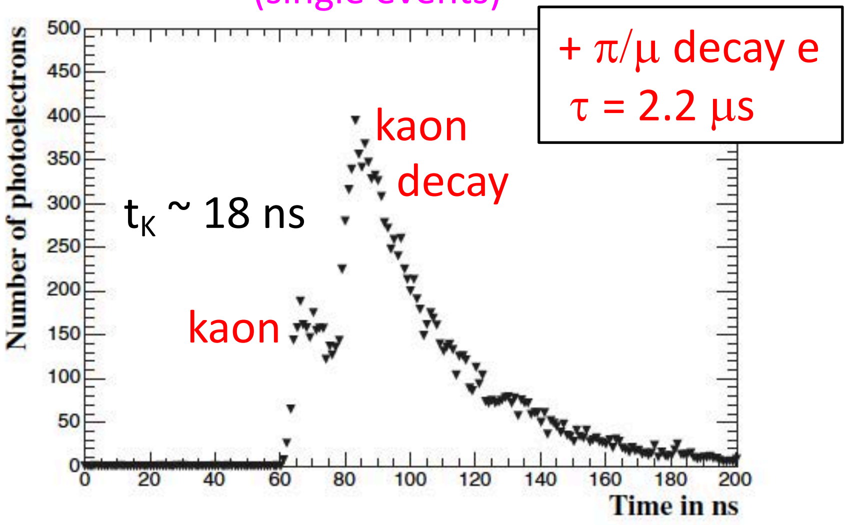
THEIA25
(17 kT, WbLS)

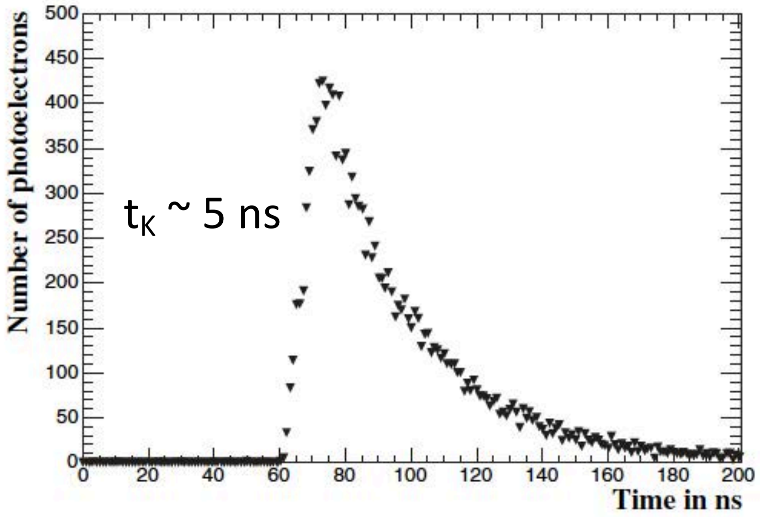
LENA (50 kt)

$p \to \nu K^+$ in Liquid Scintillator

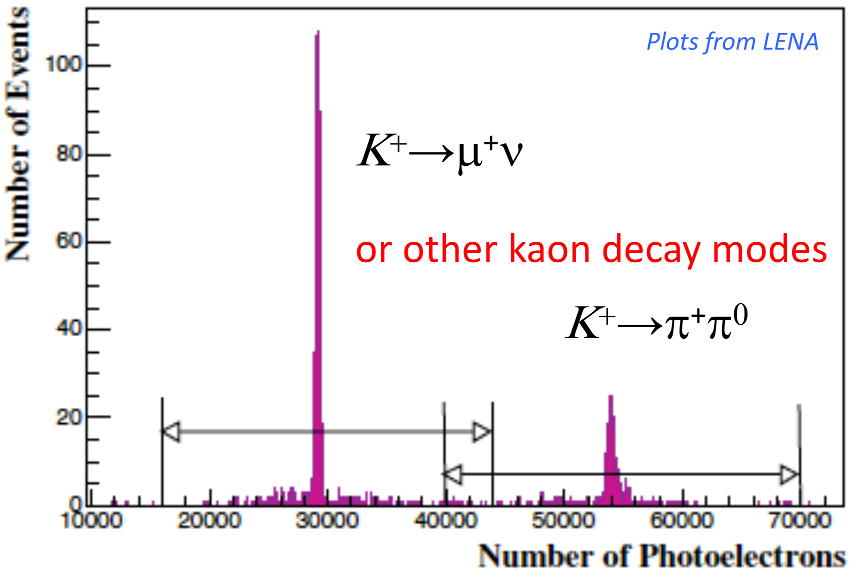
Timing Response

(single events)





Energy Response



200 photoelectrons/MeV in LSc

90 photoelectrons/MeV in WbLSc
(water-based liquid scintillator)

5 Cherenkov p.e./MeV in SK

Search for the Proton Decay Mode $p \to \overline{\nu} K^+$ with KamLAND PRD92, 052006 (2015)

Proof of principle: KamLAND

Efficiency = 0.44 ± 0.05
Background = 0.9 ± 0.02 events
Events = 0

$$\frac{\tau}{B} > 5.4 \times 10^{32}\ \text{y}$$

N.B. Efficiency is near required level but background rate must be reduced

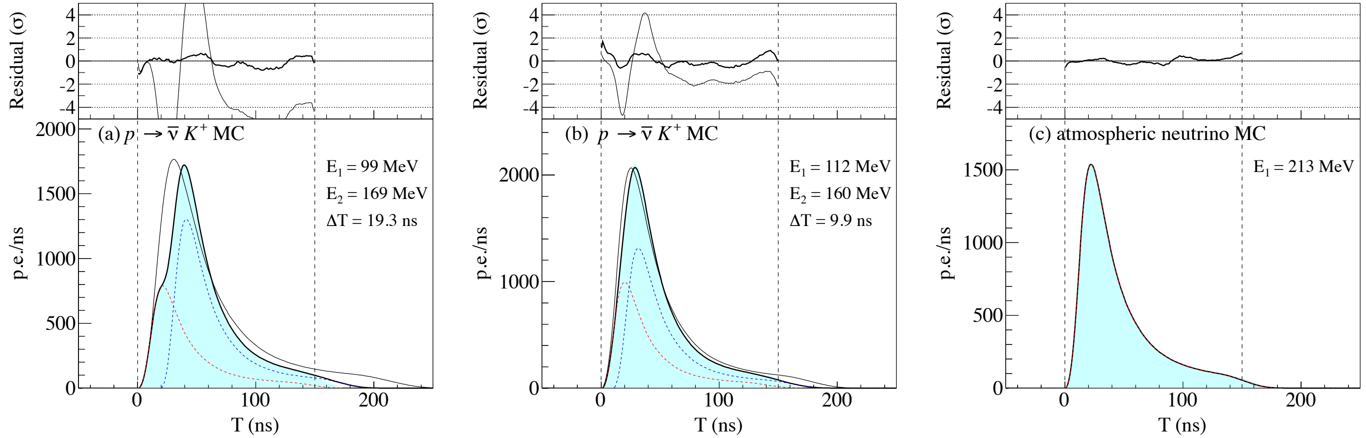
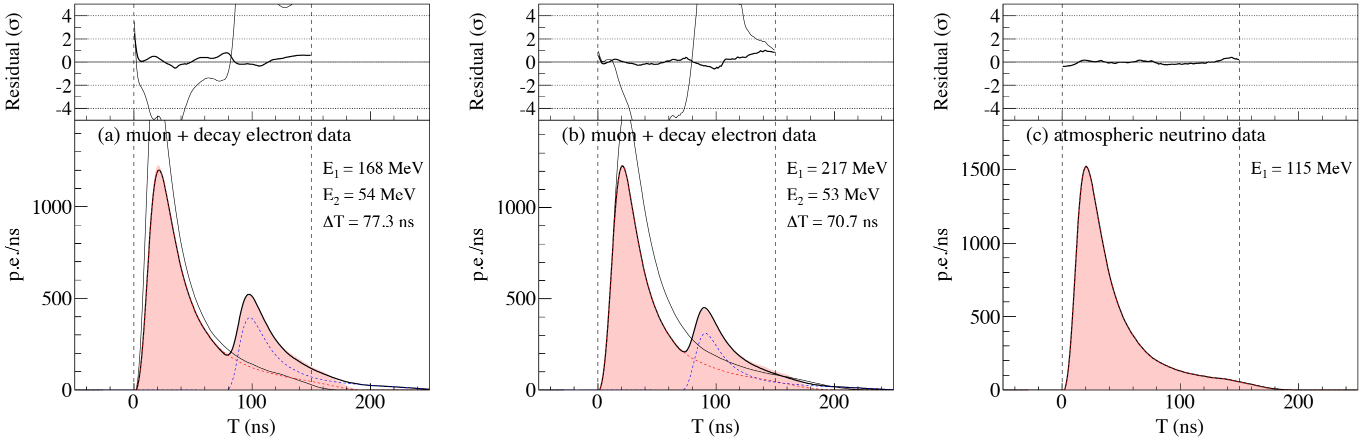


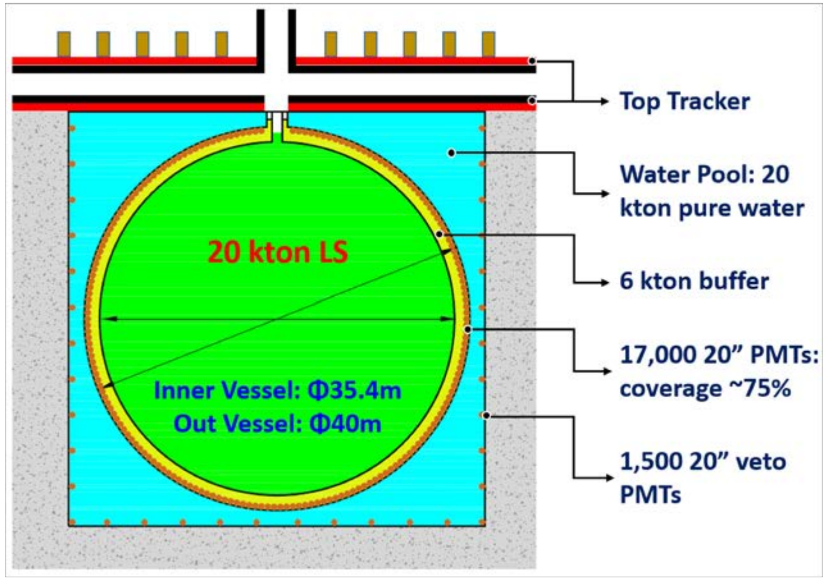
FIG. 4: Typical waveform shape (shaded) expected from: (a) and (b) $p \to \overline{\nu} K^+$ MC example events and (c) an atmospheric neutrino MC event, together with the best-fit curves from the multi-pulse fit (solid thick line) and from the single-pulse fit (solid thin line). In the upper panel, the residuals from the best-fit are shown to identify multi-pulse events. The fitted energies and, for the multi-pulse fits, time differences between the first pulse from the K^+ (red dashed line) and the second pulse from the μ^+ decay daughter of the K^+ (blue dashed line) are also shown. The shape parameters (see text) for each fit are (a) $\log(L_{shape}) = 0.06$ and (b) $\log(L_{shape}) = 0.02$.



JUNO

arXiv:1508.07166v2

Jiangmen Underground Neutrino Observatory



Cavern excavation in progress through 2020
Detector ready in 2022

Yue Meng Neutrino 2020

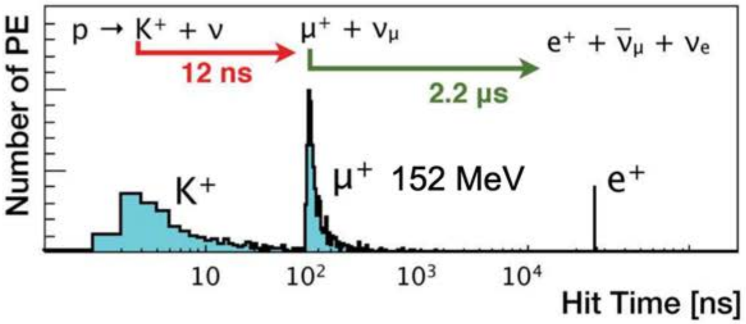
Experiment	Daya Bay	Borexino	KamLAND	JUNO
Target mass [tons]	8 x 20	~300	~1,000	20,000
Photo electron collection [p.e./MeV]	~160	~500	~250	~1200
Energy resolution	~8.5%	~5%	~6%	~3%
Photocathode coverage	12%	34%	34%	75%
Energy calibration uncertainty	0.5%	1%	2%	<1%

JUNO

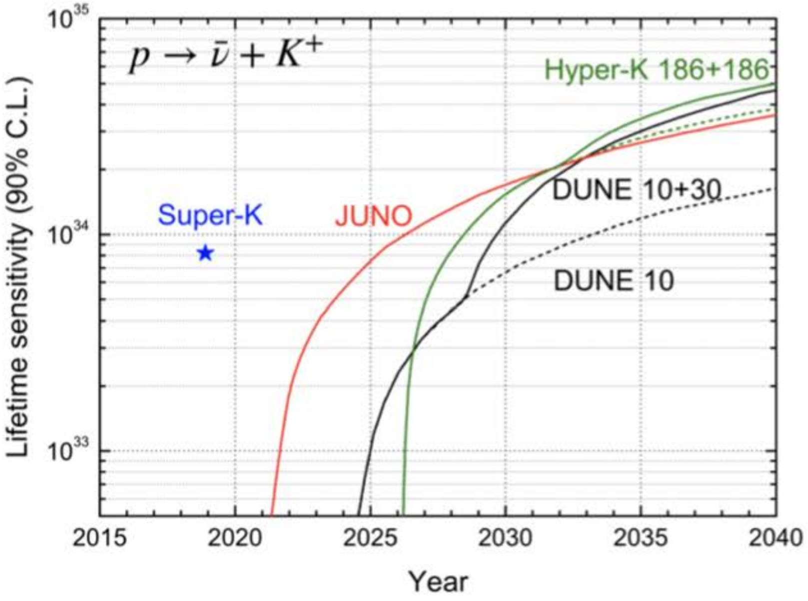
Primary physic goal is determination of neutrino mass ordering using reactor neutrino oscillation.
Also geo, supernova, solar, …

Proton decay

- Competitive sensitivity to proton decay searches
- Triple coincidence signal



Yue Meng Neutrino 2020



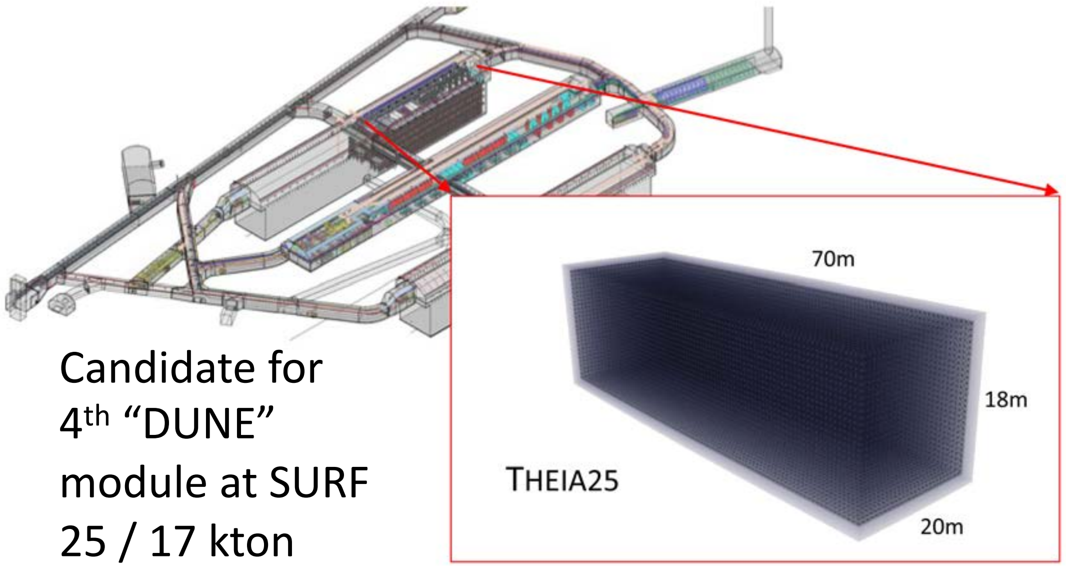
Should enter new territory before DUNE/HK turn on

6.75×10^{33} protons
85% kaon decay modes x 65% signal efficiency
Background 0.5 events in 10 years

$$\frac{\tau}{B} > 1.9 \times 10^{34}$$

THEIA: an advanced optical neutrino detector

https://doi.org/10.1140/epjc/s10052-020-7977-8



Candidate for 4^{th} "DUNE" module at SURF 25 / 17 kton

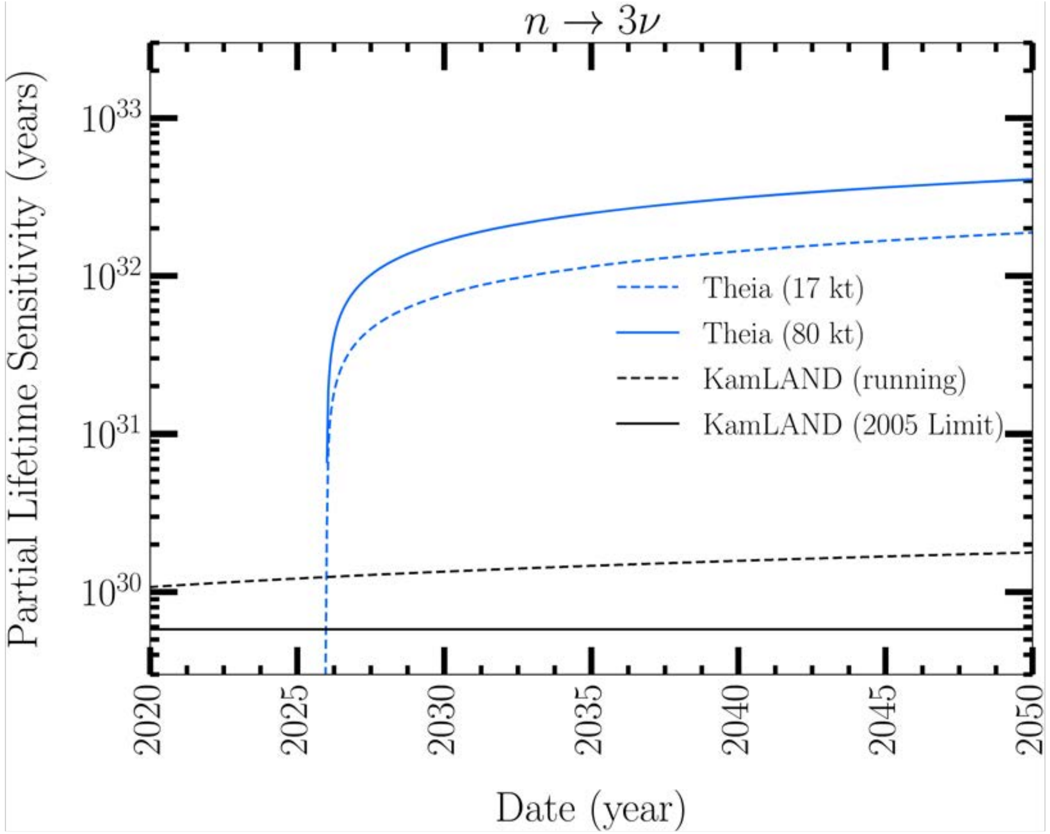
https://www.bnl.gov/dmo2019/

Broad program:
Beam neutrinos at SURF
Solar, reactor, geo, supernova neutrinos
Neutrinoless double beta decay

For $p \rightarrow K^+\nu$ assume same efficiency and backround rate as JUNO.

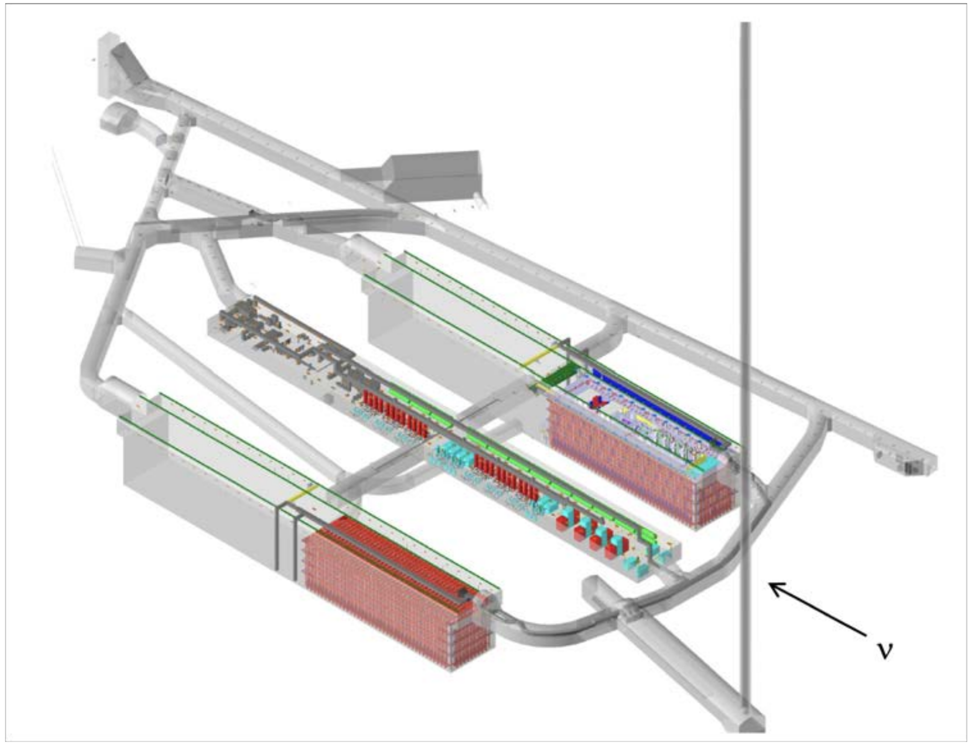
Aspirational 100 kt detector may cover many modes like SK/HK

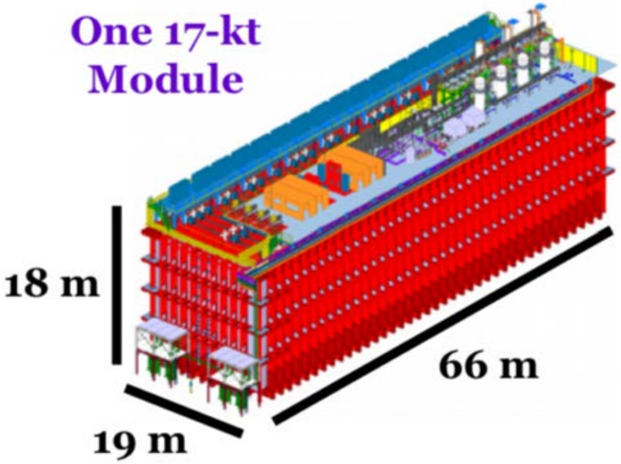
Most impressive capability
For nucleon decay: "invisible mode"



Enabled due to great depth if at SURF (reduced cosmic ray spallation)
Triple coincidence: ${}^{12}C \rightarrow {}^{11}C \rightarrow {}^{10}C + \gamma\ (\tau = 19\ s)$

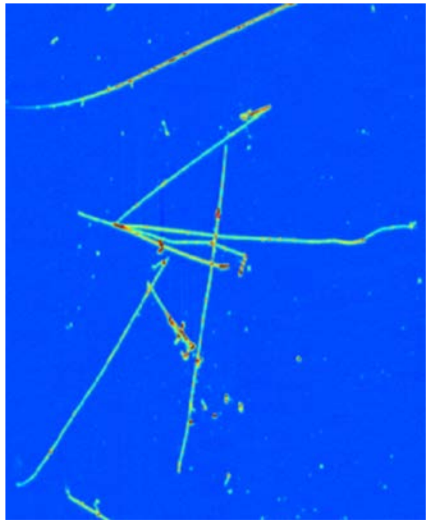
DUNE (Deep Underground Neutrino Experiment)



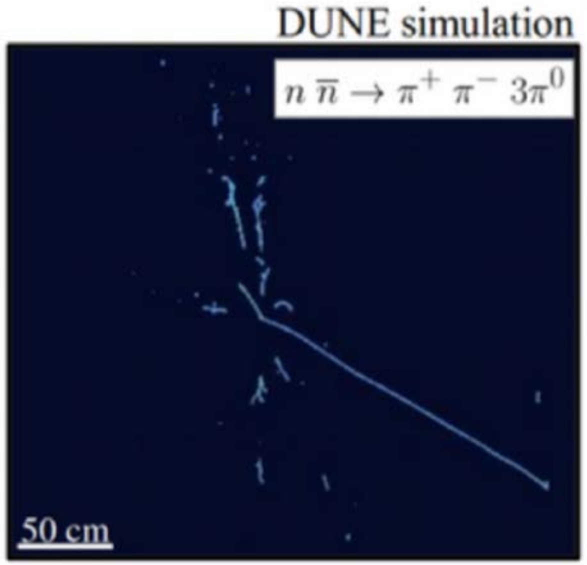


Liquid Argon Time Projection Chamber (LArTPC)

1.5 km deep in SURF (South Dakota)
modular … up to 40 kt total fiducial mass
Single and dual phase modules
4th module under open study

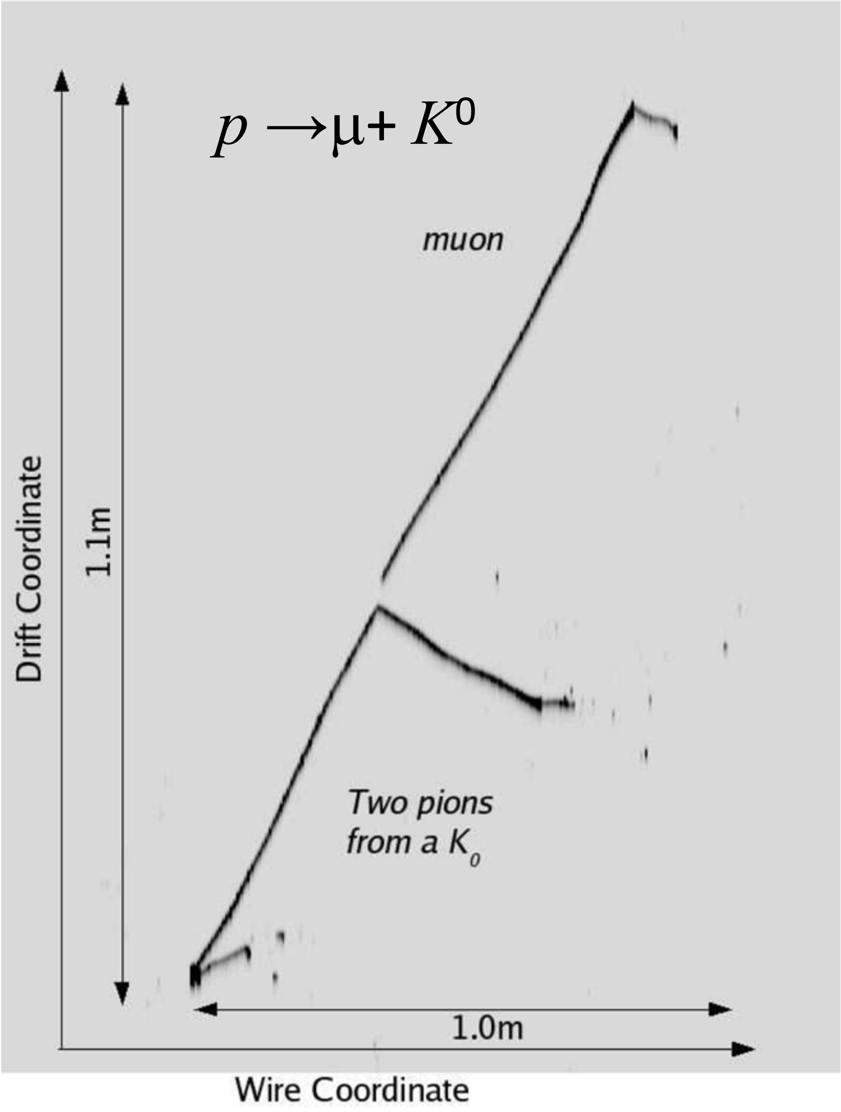


ProtoDUNE surface data



LArTPC 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.



$p \rightarrow \nu K^{+}$ in Liquid Argon Time Projection Chamber (LArTPC)

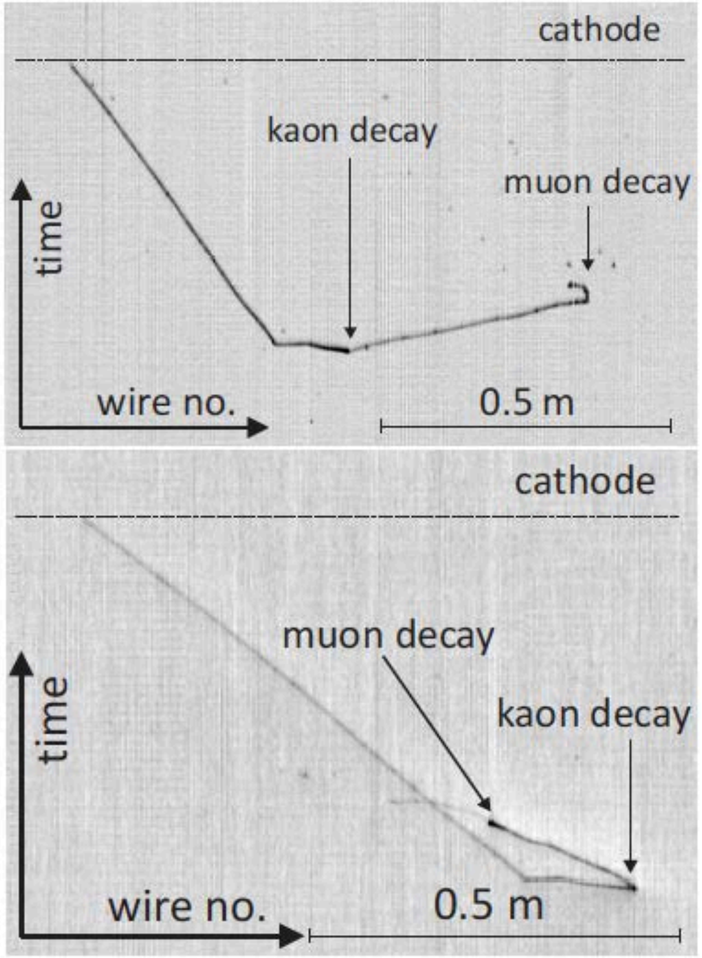
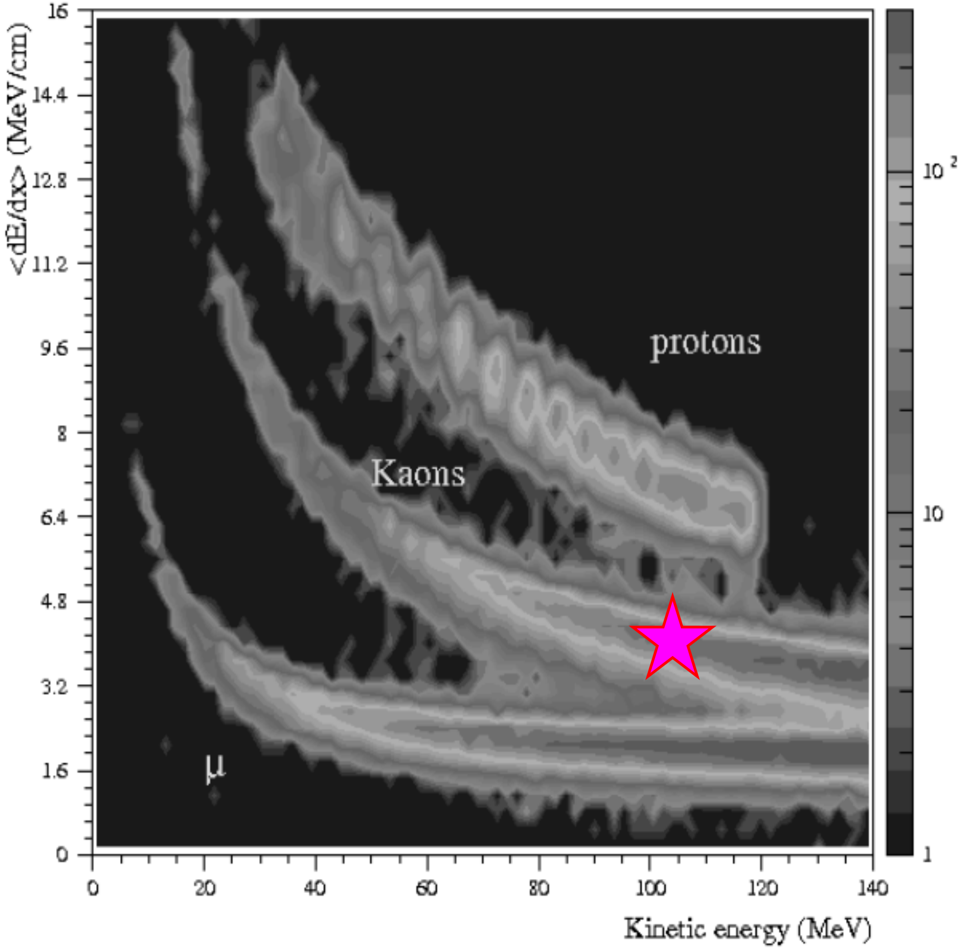


Figure 4.3: Event display for a decaying kaon candidate $K \rightarrow \mu\nu_\mu$ $\mu \rightarrow e\nu_e\nu_\mu$ in the ICARUS T600 detector observed in the CNGS data (K: 90 cm, 325 MeV; μ : 54 cm, 147 MeV; e : 13 cm, 27 MeV). The top figure shows the signal on the collection plane, and the bottom figure shows the signal on the second induction plane [102].

3 mm pitch

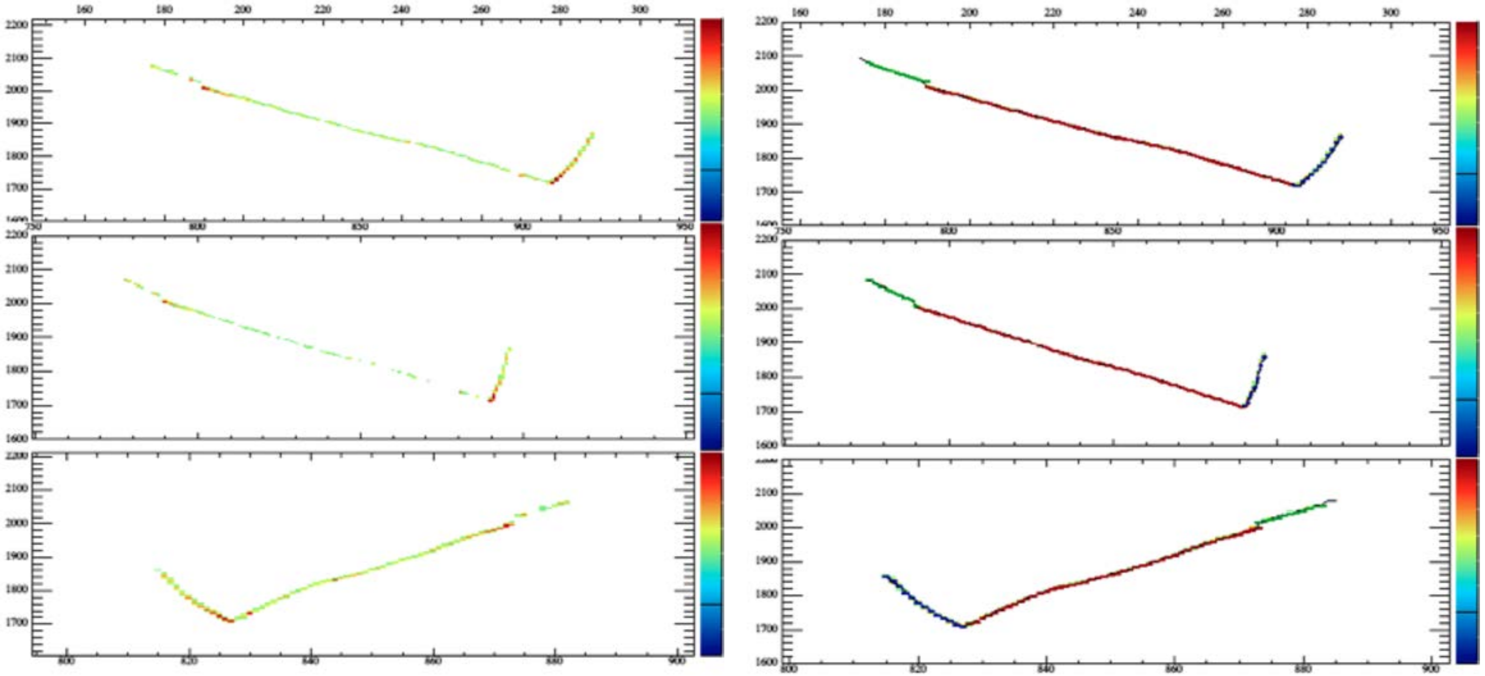
Bueno et al.

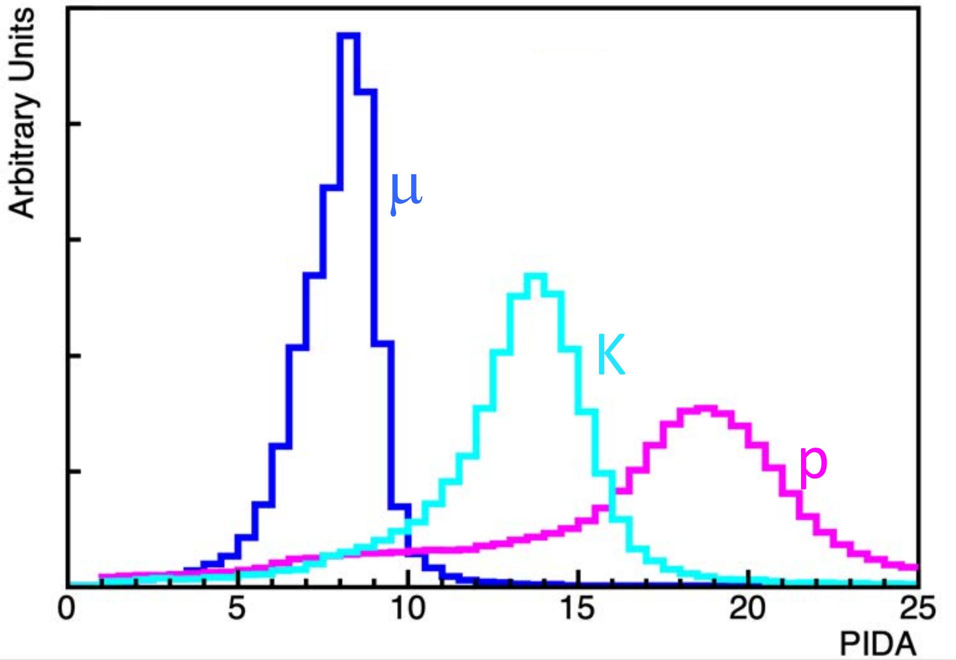


circa 2013: Hand scanning suggested efficiency of 97%
With background rate of 1 evt/Mty was achievable
hep-ph/0701101 (Bueno et al.)

Progress in Event Reconstruction

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





At this time, DUNE is taking the efficiency hit of 30%, with a background rate of 1/Mt y (fully automated analysis, 10 y, 40 kt fiducial mass)

$$\tau/B(K^+\nu) > 1.3 \times 10^{34} \text{ years}$$

Hyper – Kamiokande

High QE Box&Line PMT

×2 pressure tolerance

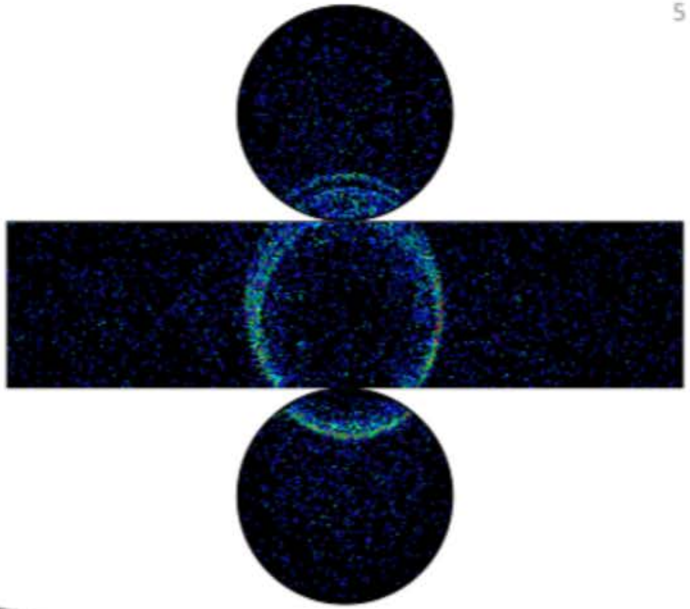
×2 photon detection

×2 timing resolution

Recent update:

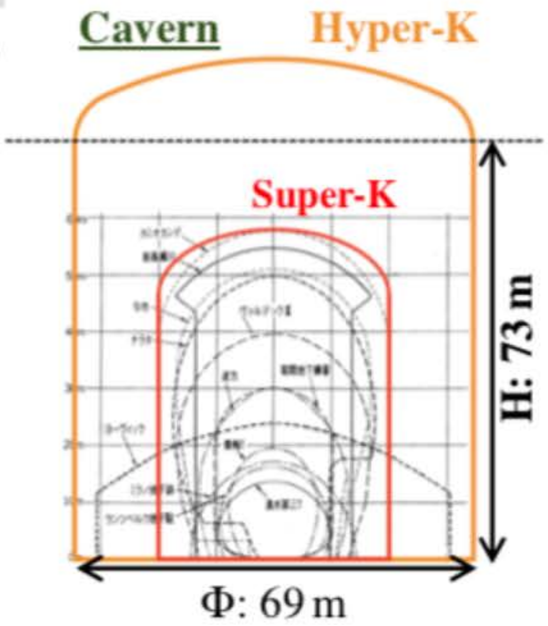
- Lower dark rate (similar level to SK)
- Lower radioactive contamination

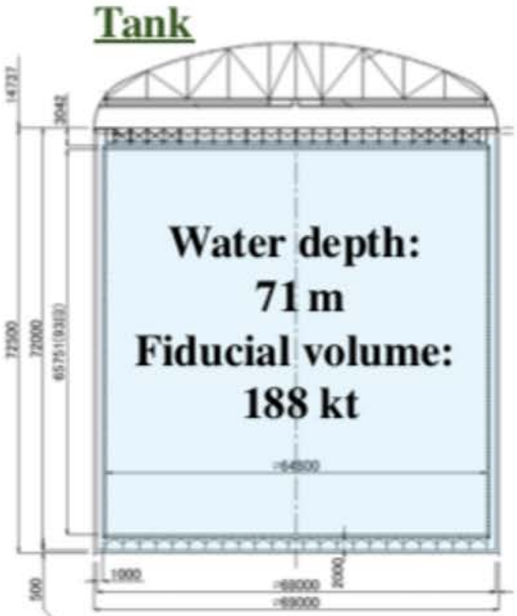
Precision measurement



New detector design (cost reduction)

R&D for large cavern





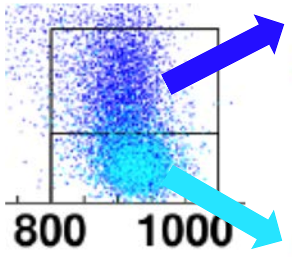
High statistics neutrino data

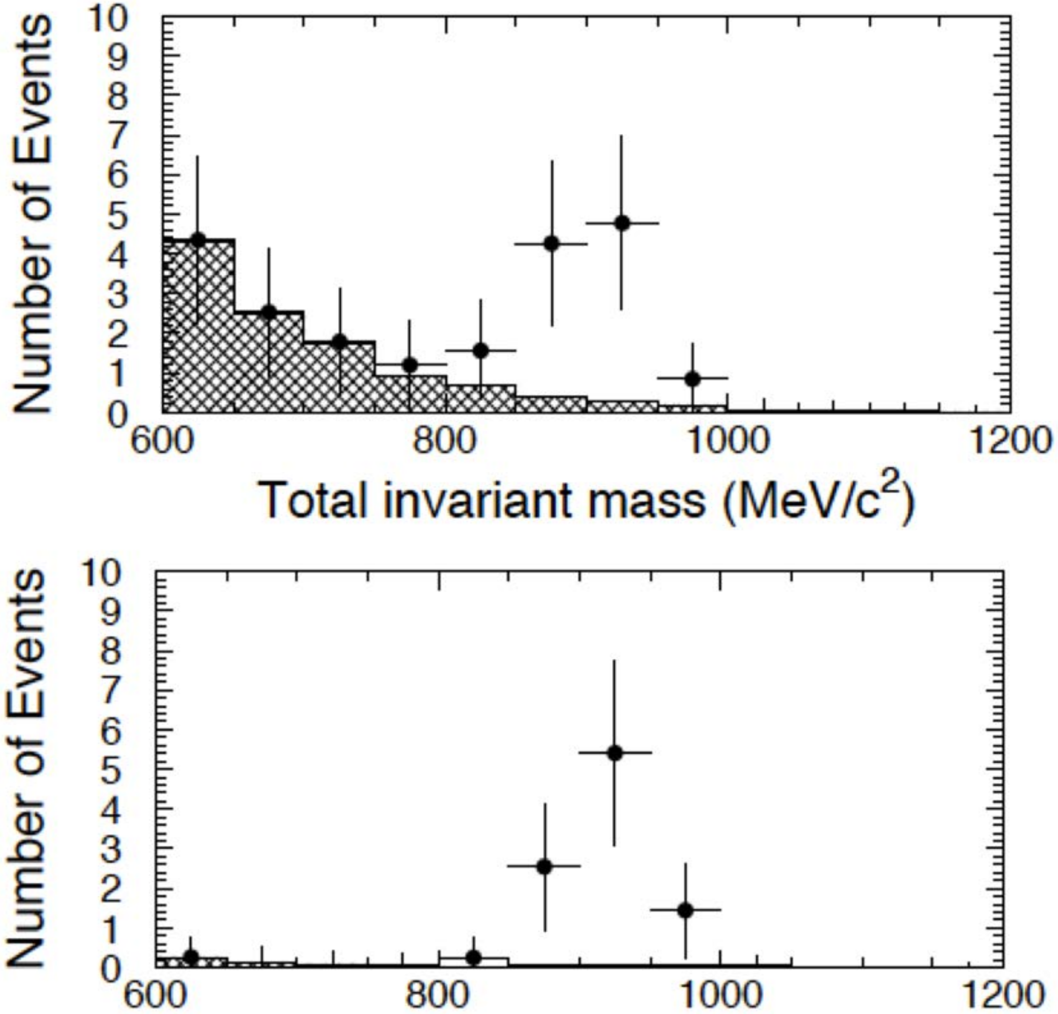
New detector design by synergy of different technologies

M. Ishitsuka, Neutrino 2020

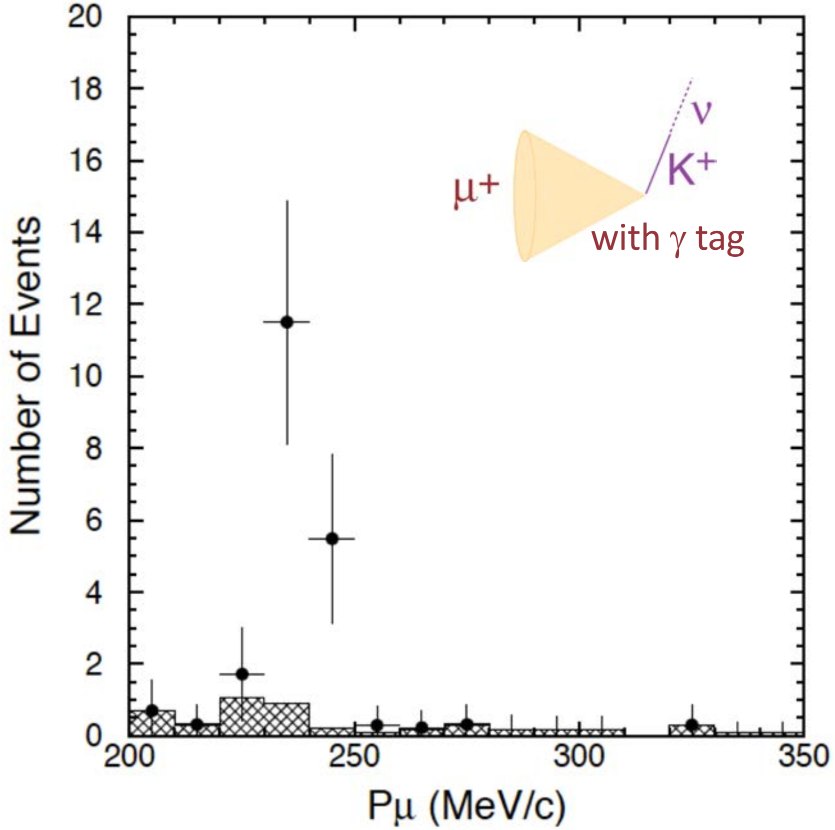
Proton decay signal (at SK limit)

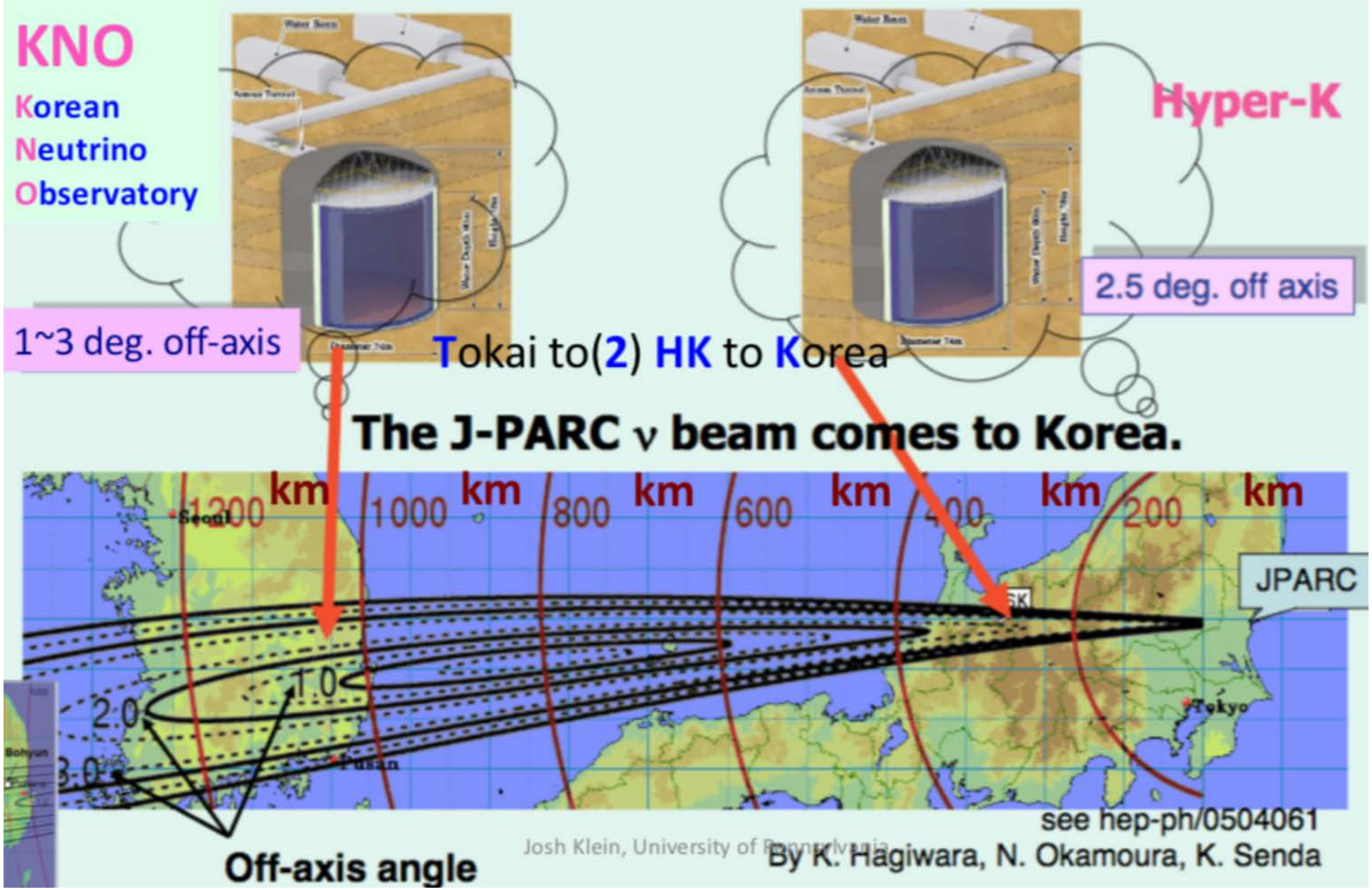
$$p \to e^+\pi^0$$





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





KNO
Korean
Neutrino
Observatory
1~3 deg. off-axis
Hyper-K
2.5 deg. off axis
Tokai to(2) HK to Korea
The J-PARC ν beam comes to Korea.
1200 km
1000 km
800 km
600 km
400 km
200 km
Seoul
Pusan
Tokyo
SK
JPARC
1.0
2.0
3.0
Off-axis angle
Josh Klein, University of Pennsylvania
see hep-ph/0504061
By K. Hagiwara, N. Okamoura, K. Senda

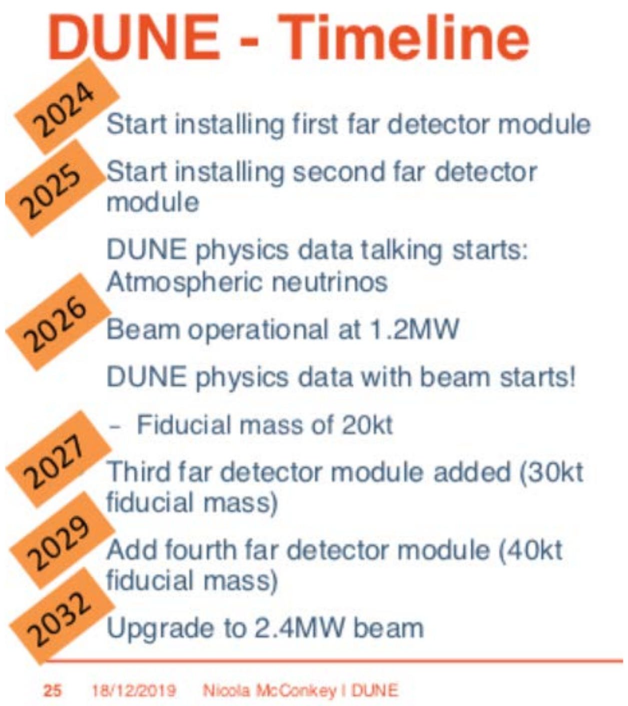
When ?? Everyone wants to know.

JUNO 2022

2019-2021
- Electronics production starts
- Civil construction and lab preparation completed
- Detector construction

2022
- Detector ready for data taking

DUNE 2026


DUNE - Timeline

2024 Start installing first far detector module

2025 Start installing second far detector module

DUNE physics data talking starts: Atmospheric neutrinos

2026 Beam operational at 1.2MW

DUNE physics data with beam starts!

– Fiducial mass of 20kt

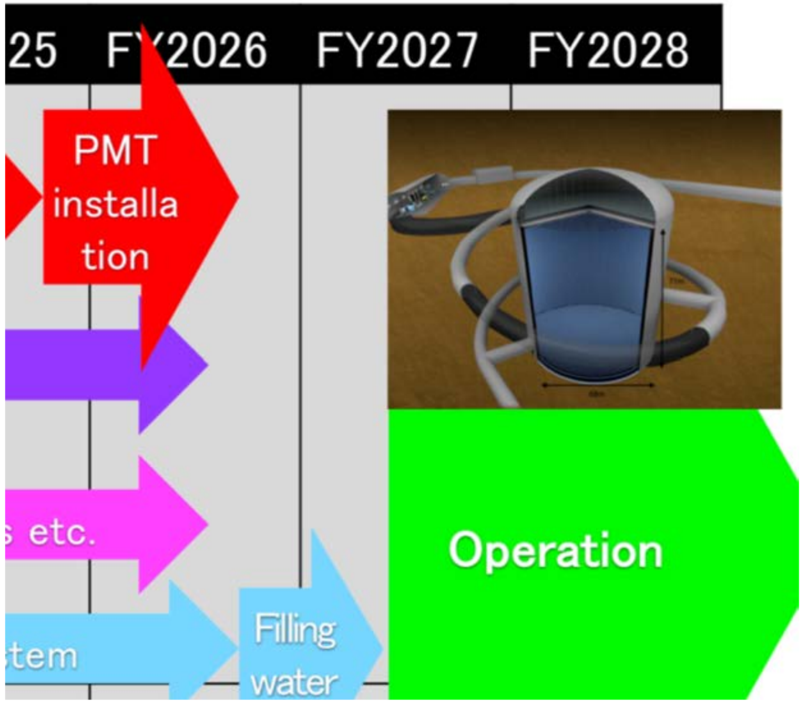
2027 Third far detector module added (30kt fiducial mass)

2029 Add fourth far detector module (40kt fiducial mass)

2032 Upgrade to 2.4MW beam

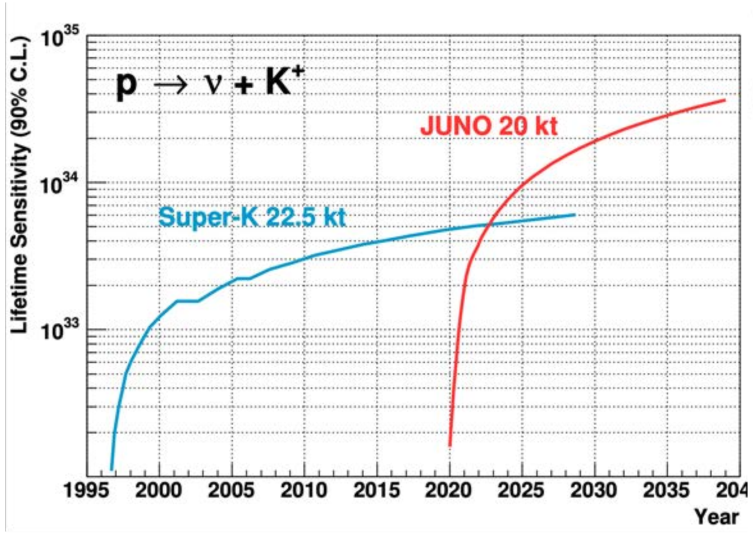
25 18/12/2019 Nicola McConkey I DUNE

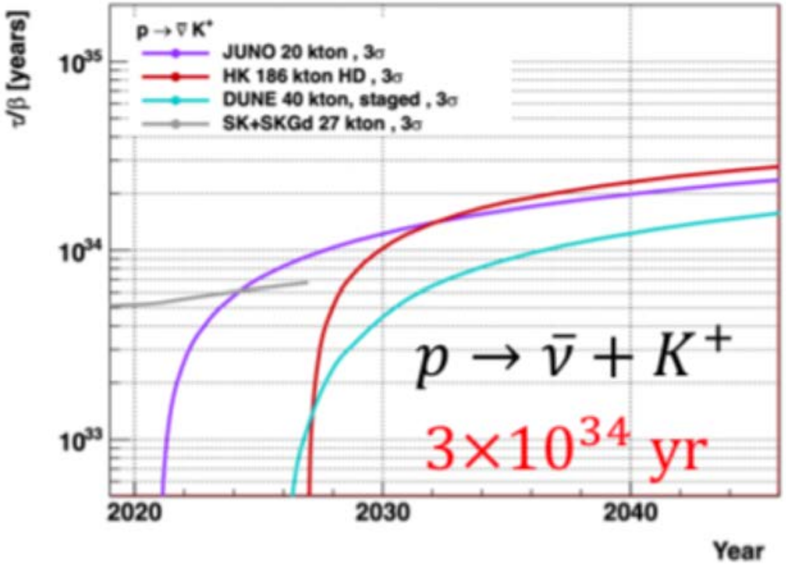
Hyper-K 2027

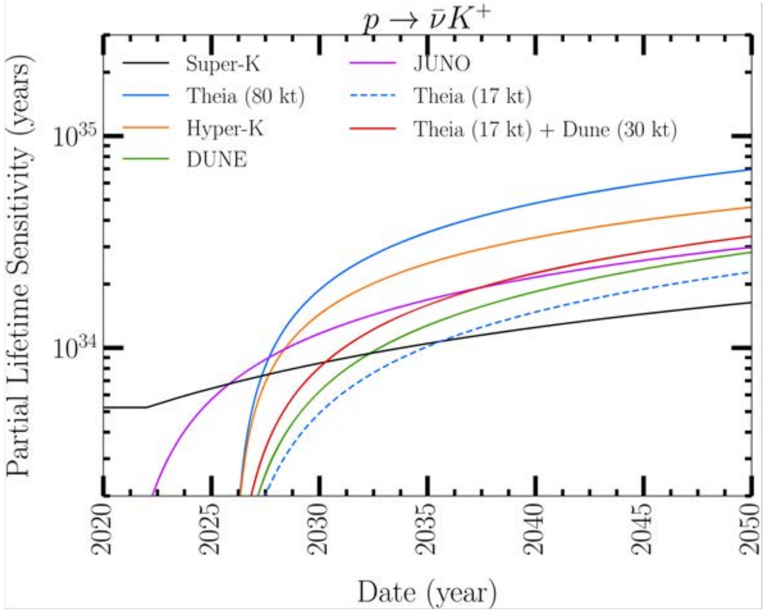


But these estimated dates are subject to … change, of course!

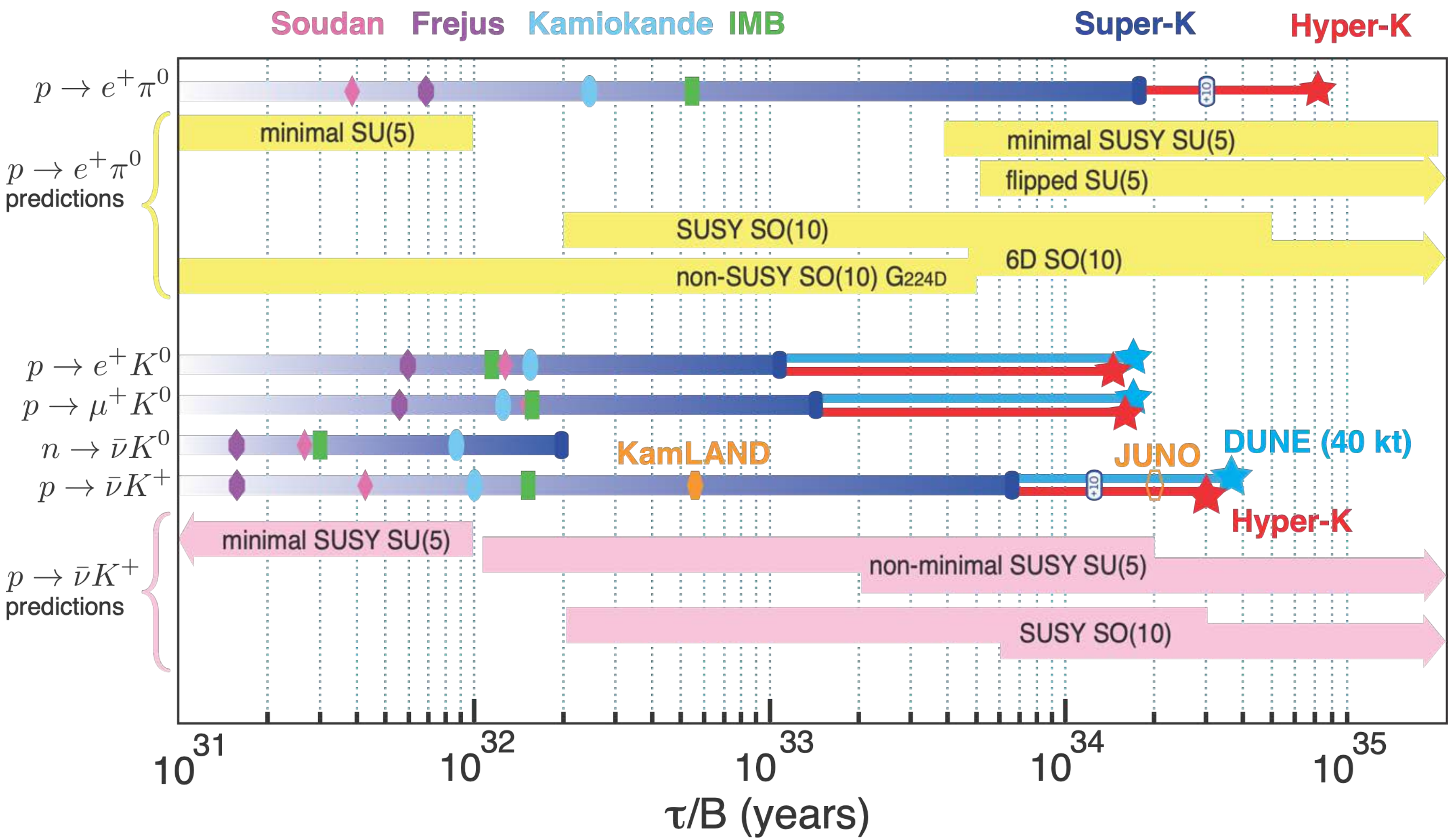
from the published design reports or recent talks …







We probably should capture some neutral, correct, and up-to-date curves



Likewise, this figure or others like it could be updated

Messages to Snowmass

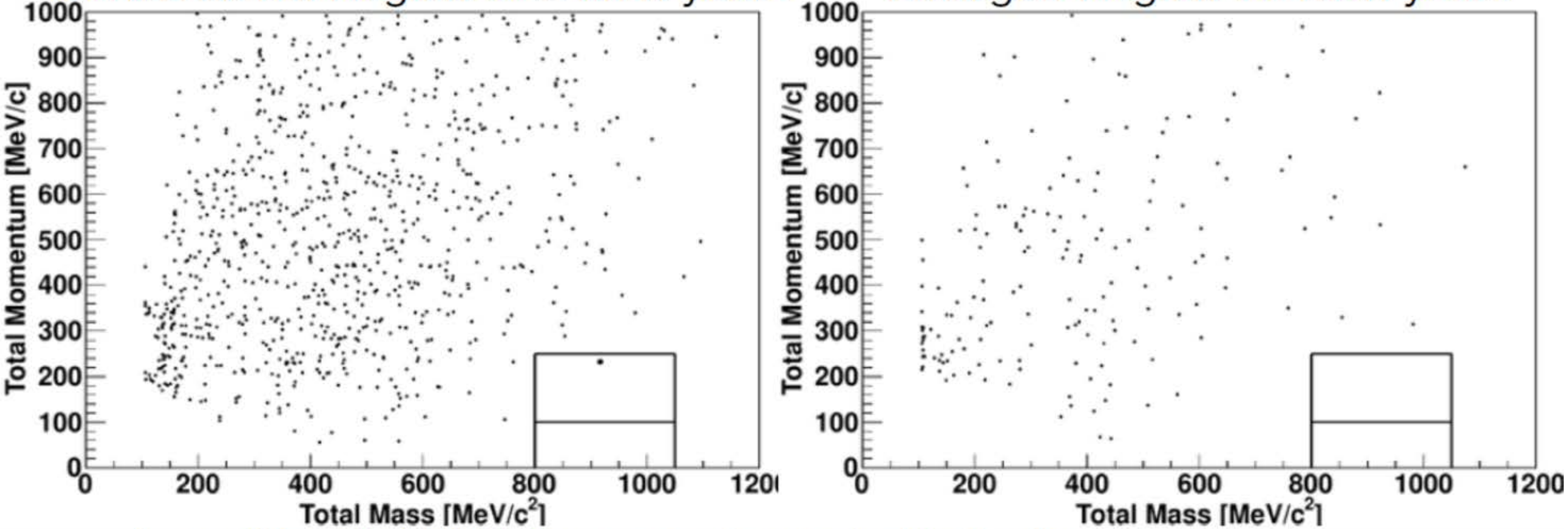
Derived from 2013

- 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.
- The next generation nucleon decay experiments are tied into large neutrino detectors and together with neutrino physics establish a broad science program.
- The next generation experiments are approved and being constructed.

Backup

Data Result $p \to \mu^+ \pi^0$

Data SKI~IV 450 kton*years.



- 1 candidate in BOX2. Same event reported in the last paper.
  - Reasonable reconstruction result.

PRD 95, 012004 (2017)

- No new candidates incl. in enlarged region.
- No significant data excess compared to expected BG (0.89 in BOX2).
- Lower lifetime limit @90%C.L.
  - $\tau / B_{p \to \mu^+ \pi^0}$ > 1.6*10^{34} years (published: 7.7*10^{33} years)
- Most stringent constraint. **~2 times longer than published.**