Nucleon Decay EXPERIMENTS

Snowmass Community Planning Meeting - Virtual

SnowMass2021

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Abbreviated Theoretical Perspective

- Effective theories identify baryon number violating processes. Numerous specific models exist in GUT, SUSY frameworks.

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

- Lifetime predictions are not precise – typically uncertain by 2-3 orders of magnitude. "Prediction" often constrained from below by existing limits.

- 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.

Ideally, we wish to cover all possibilities, but we can focus on the benchmarks for planning purposes.

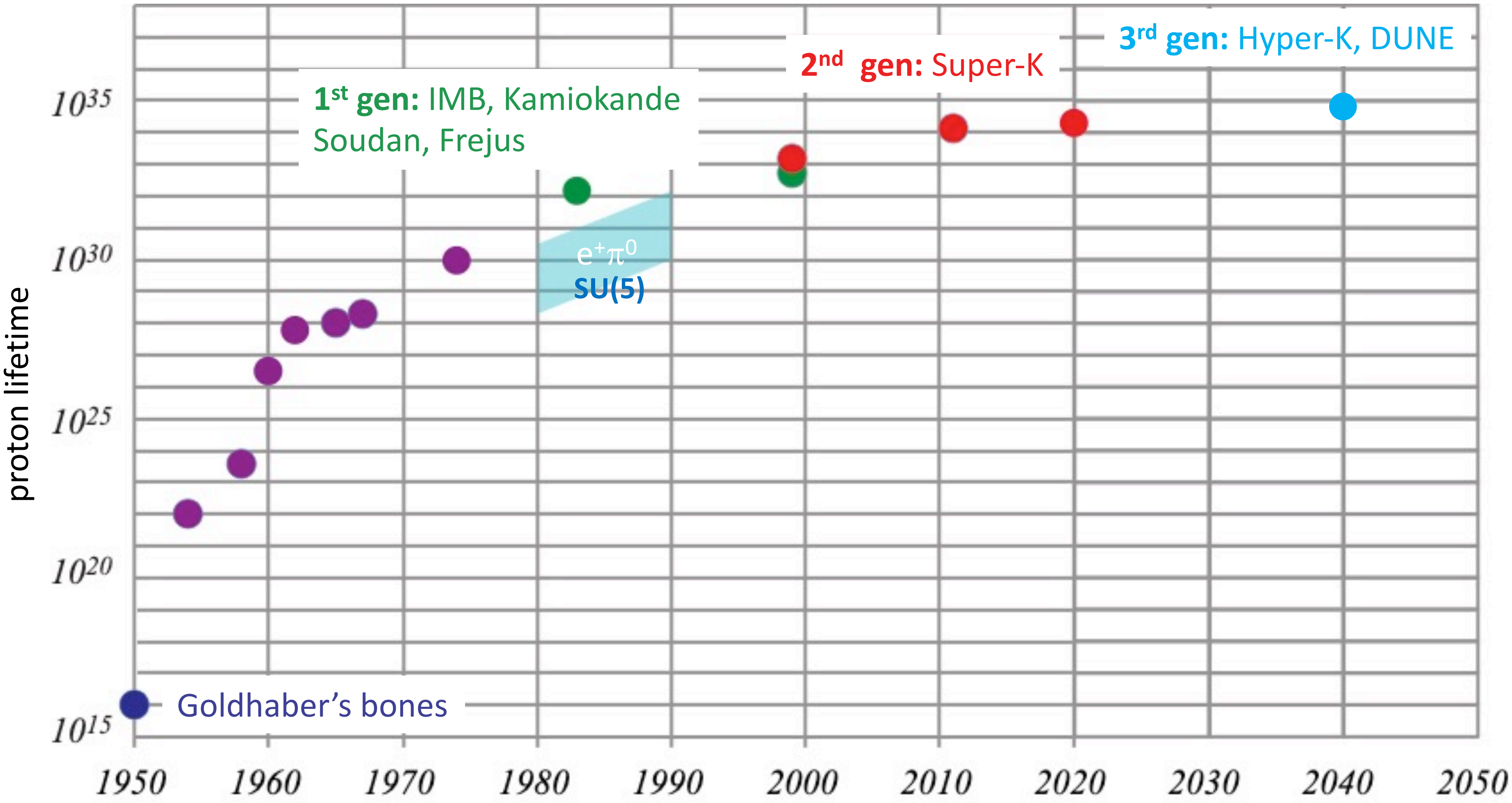
Historical Perspective

Progress by one or two orders of magnitude

3rd gen

2nd gen

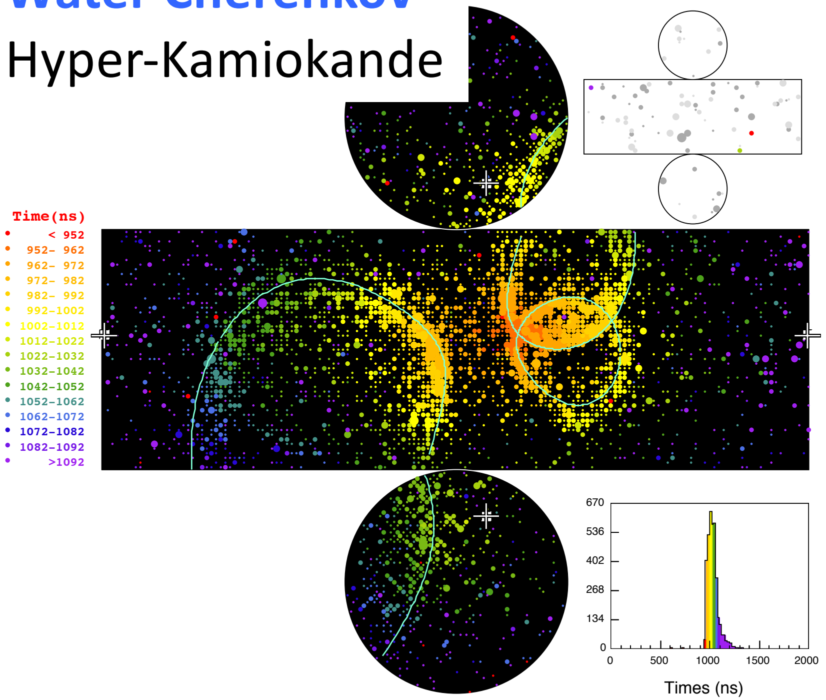
1st gen



Baryon Number
E. Wigner (1949)

3^{rd} Generation Nucleon Decay Experiments

Water Cherenkov
Hyper-Kamiokande



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

broad search capabilities

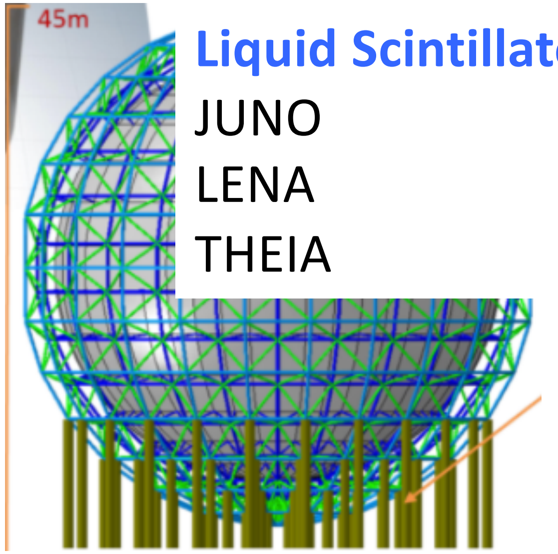
free proton advantage

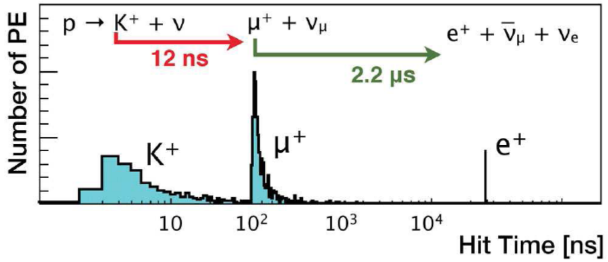
kaons below Cherenkov threshold

Liquid Scintillator
JUNO

LENA

THEIA



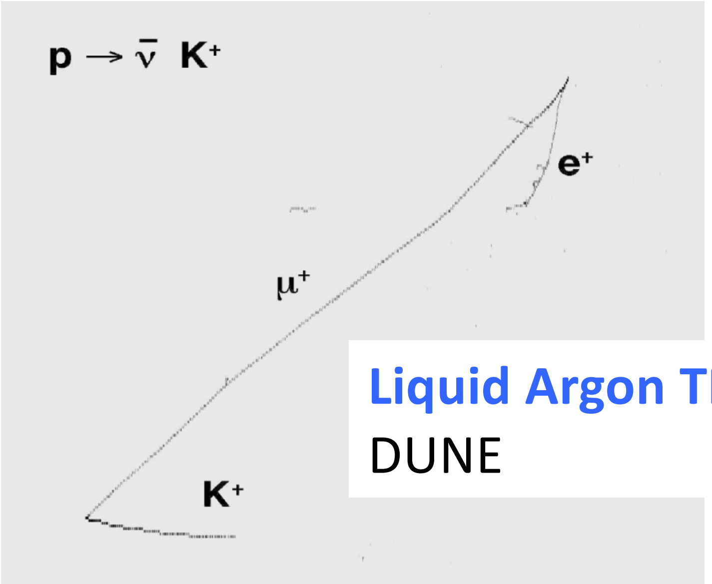


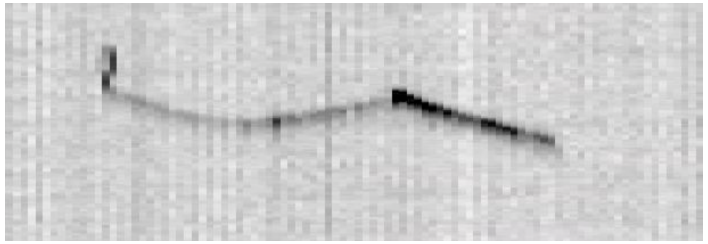
clean timing signature

specialize in charged kaon

(also invisible mode)

Liquid Argon TPC
DUNE





fine grained detail

specialize in kaons, displaced vtx

visible kaon track

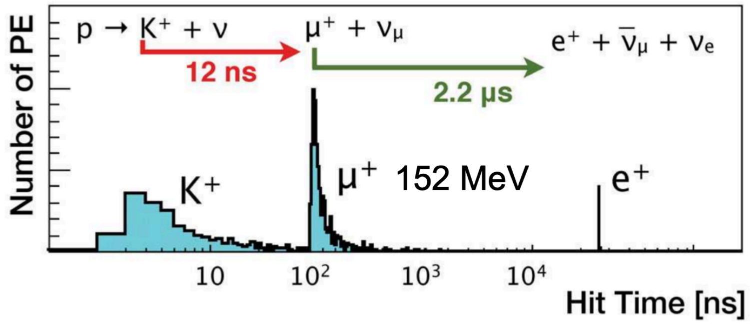
heavy nucleus, no free protons

JUNO

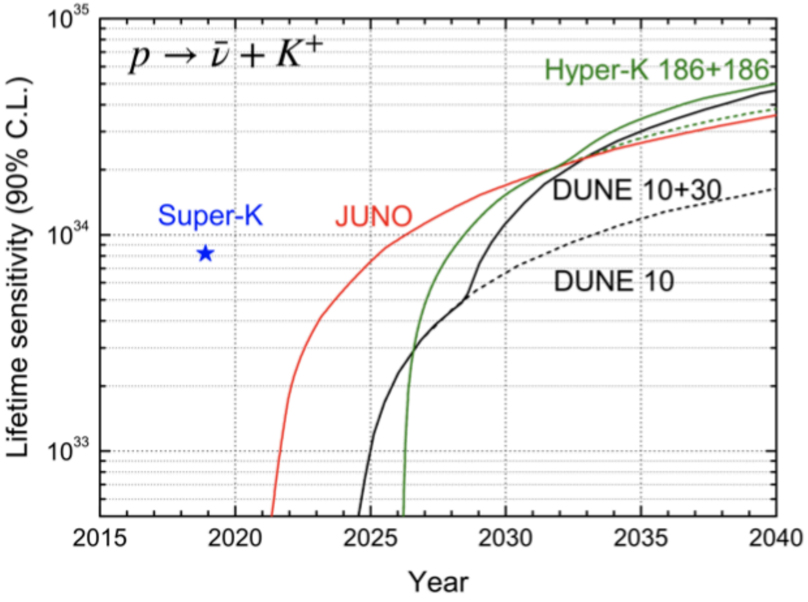
20 kton liquid scintillator
Primary physics goal is determination of neutrino mass ordering using reactor neutrino oscillation.
Also geo, supernova, solar, …

Proton decay

- Competitive sensitivity to proton decay searches
- Triple coincidence signal



Yue Meng Neutrino 2020



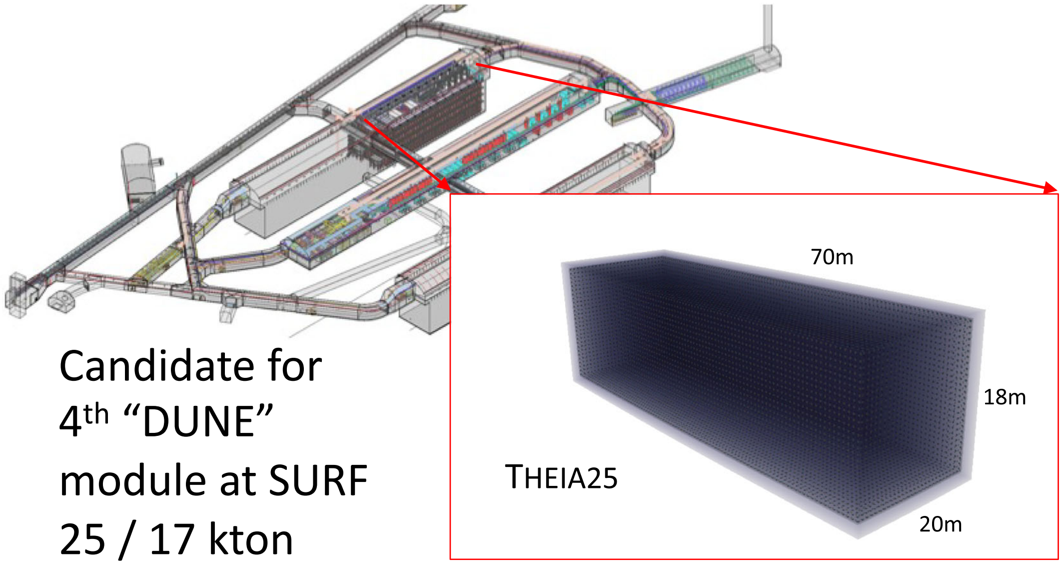
Should enter new territory before DUNE/HK turn on

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
4th "DUNE"
module at SURF
25 / 17 kton

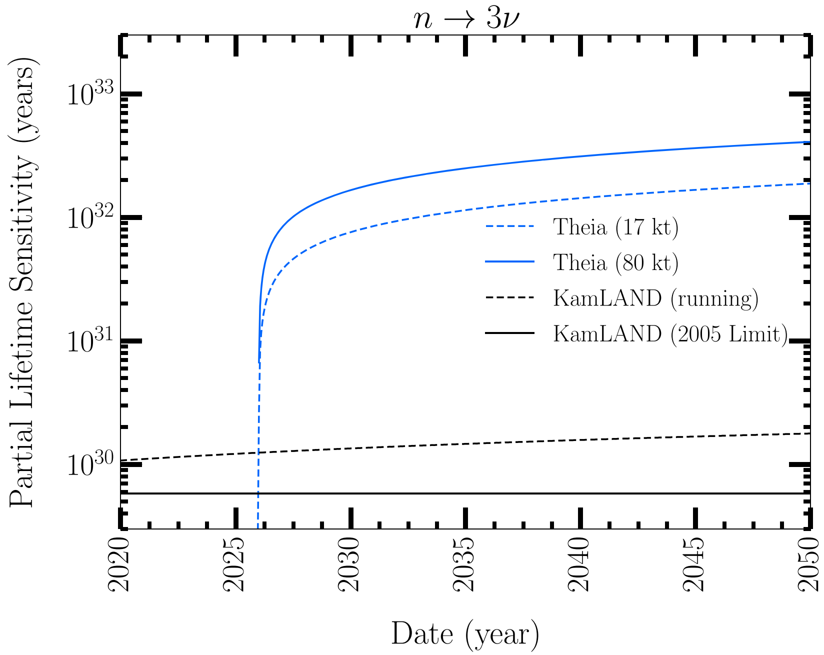
https://www.bnl.gov/dmo2019/

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"

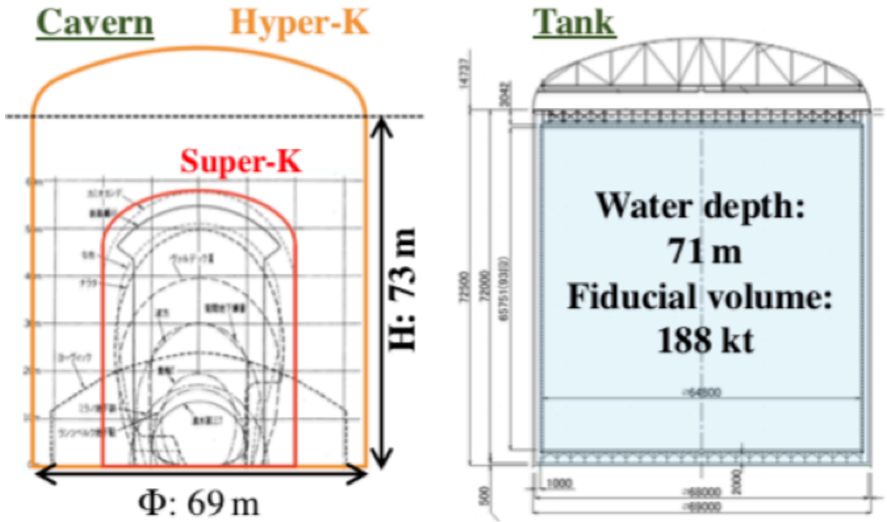


Enabled due to great depth if at SURF (reduced cosmic ray spallation)
Triple coincidence: $^{12}C \rightarrow {}^{11}C \rightarrow {}^{10}C + \gamma \ (\tau = 19\ s)$

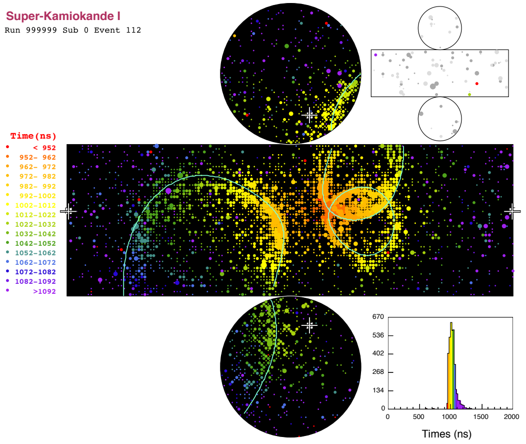
THEIA should benefit from Snowmass Community Planning input

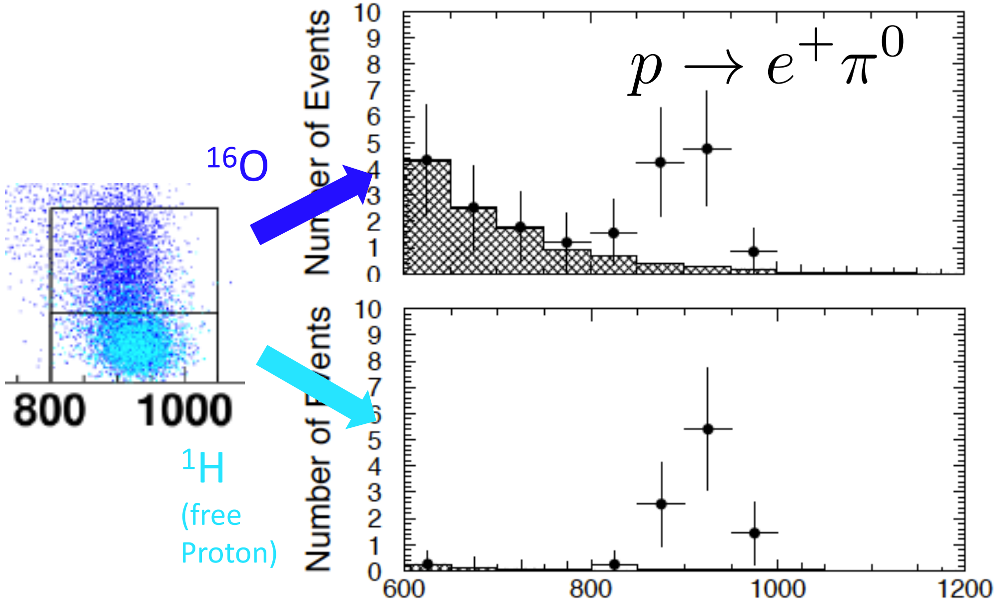
Hyper-Kamiokande 2027 -

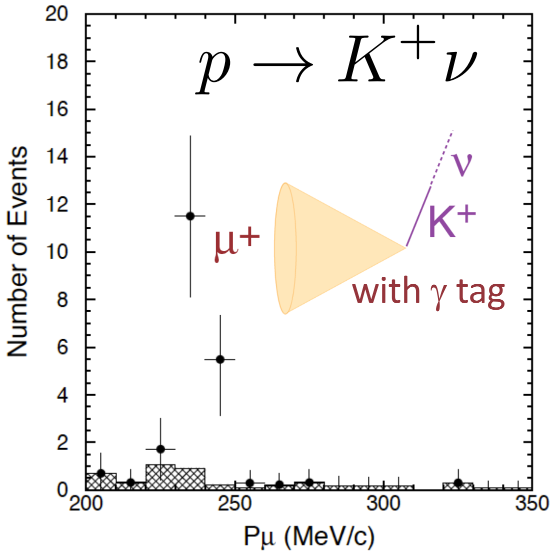
most massive – superior for $e^+\pi^0$
broad search capabilities
free proton advantage
kaons below Cherenkov threshold



+ potential 2nd module, maybe in S. Korea

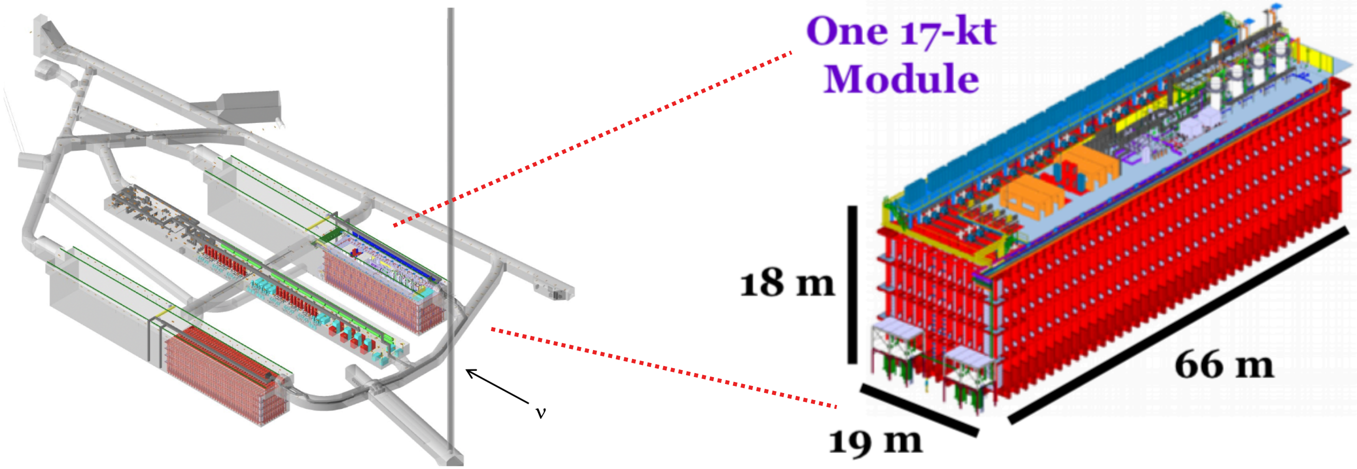






Minimal US involvement in Hyper-K at this time.

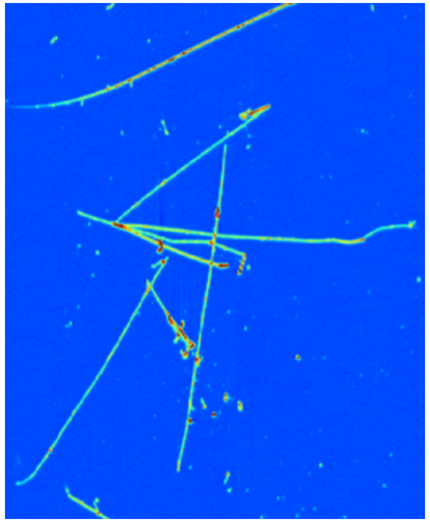
DUNE (Deep Underground Neutrino Experiment)



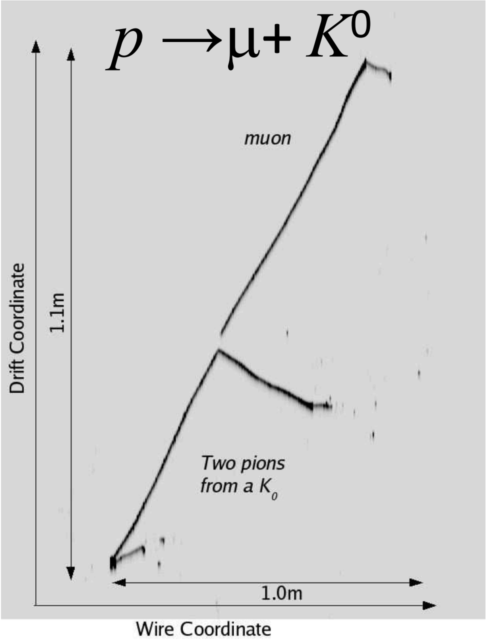
1.5 km deep in SURF (South Dakota)
modular … up to 40 kt total fiducial mass
Single and dual phase modules
4^{th} module under open study

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)

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

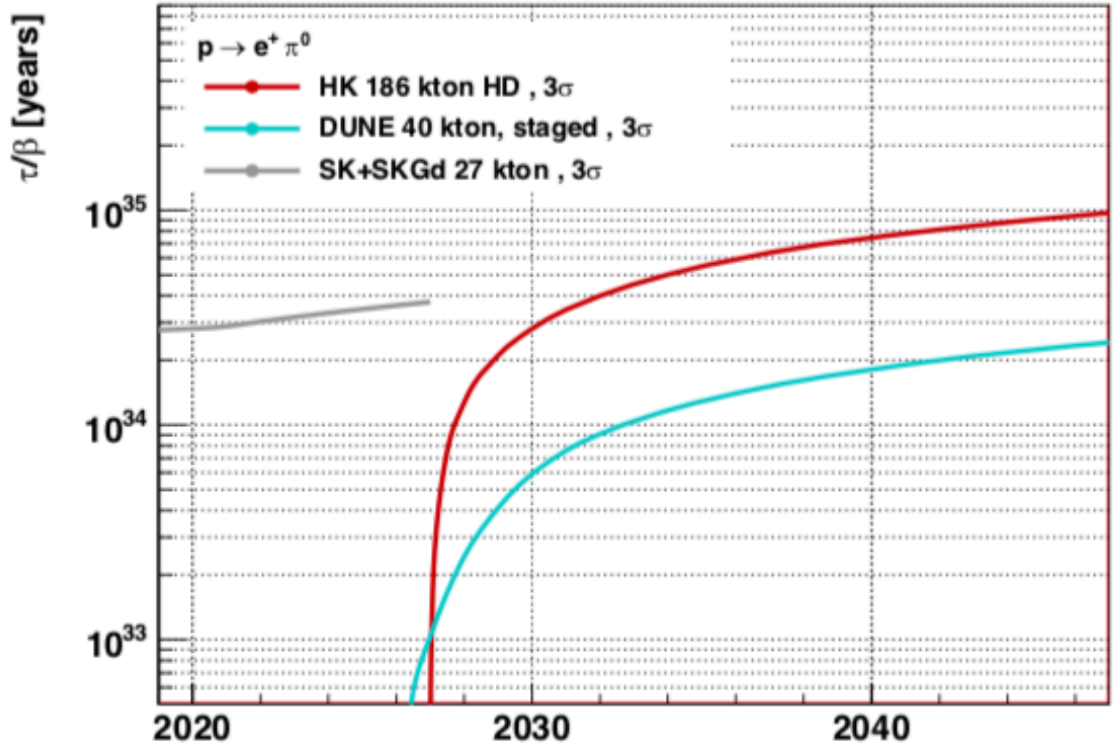


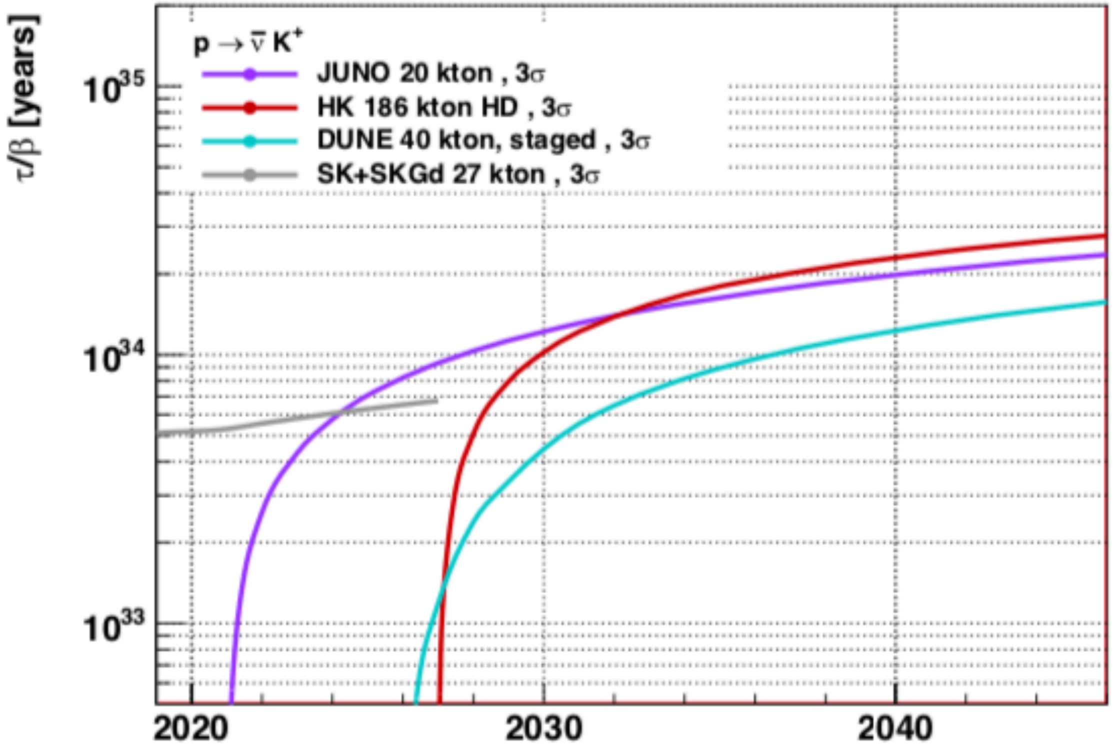
ProtoDUNE surface data



Initial DUNE is on solid footing but expansion to more modules is important to discuss

Note: these are 3σ sensitivities





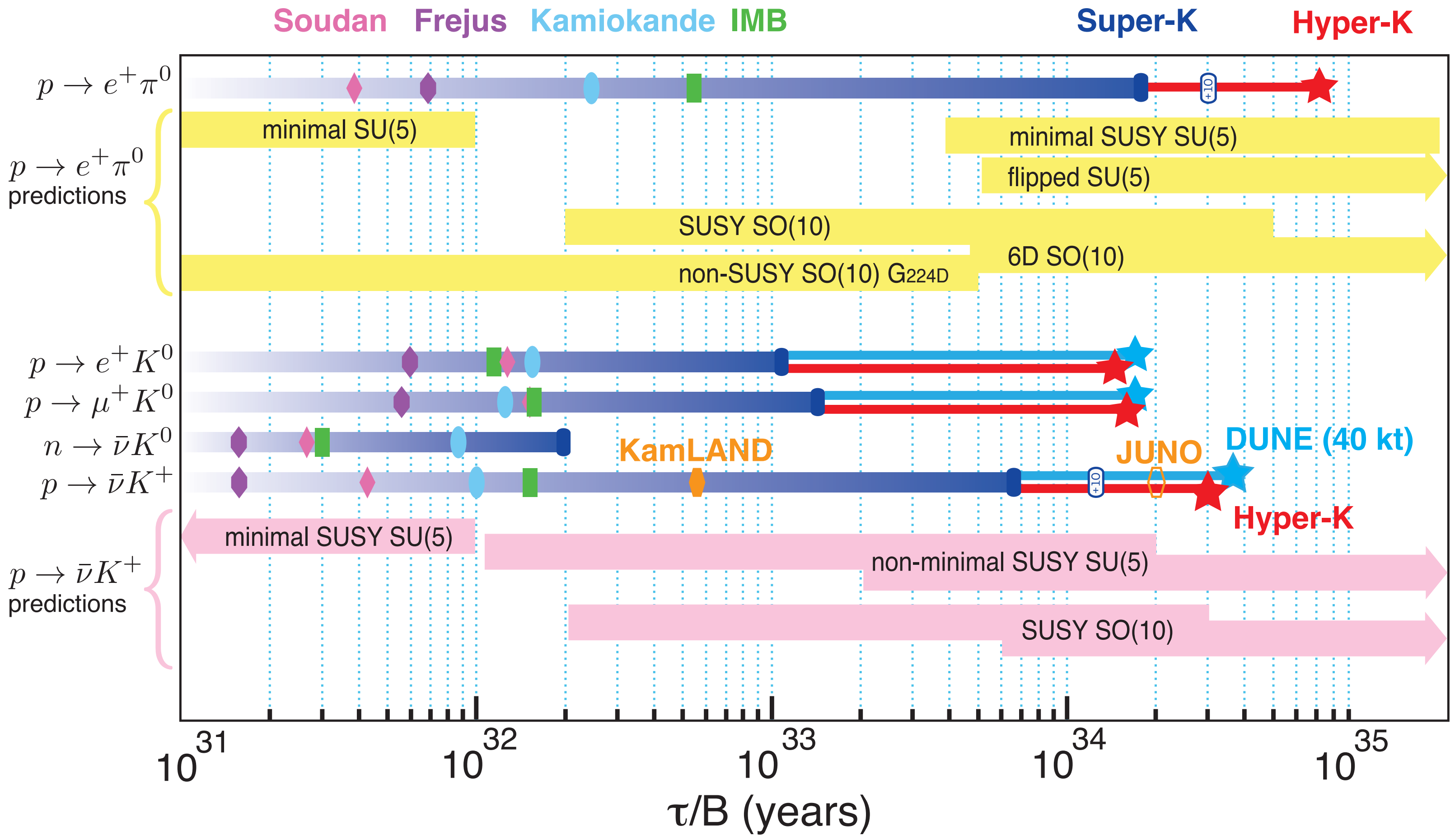
When will experiments commence?
How massive will they be?

Even in the best cases, order of magnitude improvements in benchmark nucleon decay searches are essentially out of reach.

Why is progress so difficult?

- We are reaching the financial and technical limits for super-massive detectors.
- Cost of excavating rock exceeds cost of detector.
- Need a revolutionary approach
  - solution-mined salt caverns? (Monreal*)
  - undersea vessels (TITAND, Y. Suzuki)
  - others? Proton decay on the moon is free of atm. nu background.
- So for now, this topic tags along with massive neutrino detectors.

* https://www.snowmass21.org/docs/files/summaries/UF/SNOWMASS21-UF6_UF0-NF10_NF0-RF4_RF0-CF1_CF0-IF8_IF0_Monreal-002.pdf



Even in the best cases, order of magnitude improvements in benchmark nucleon decay searches are essentially out of reach.

But searches are in motivated territory, and the case for searching for proton decay is as strong as ever.

Messages to Snowmass

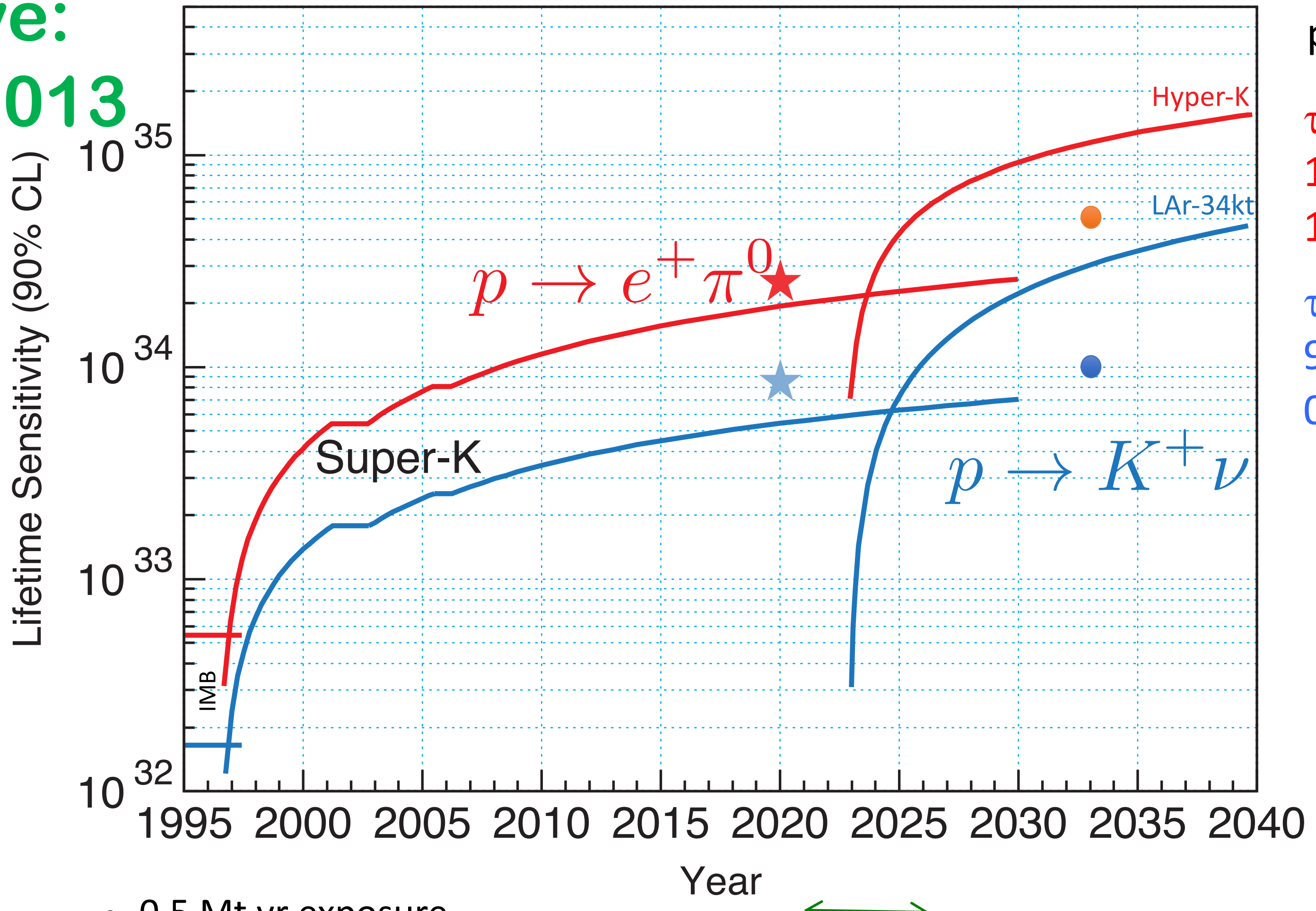
- Experimental searches for Baryon Number Violation remains a valued objective of particle physics. Nucleon decay is the primary means for $\Delta B=1$.
- The next generation nucleon decay experiments are tied into large neutrino detectors and together with neutrino physics establish a broad science program.
- Order of magnitude improvements seem out of reach.
- Ongoing and future searches are in potentially fruitful territory.

Backup

Particle Physics at the Intensity Frontier
Intensity Frontier Workshop
25-27 April 2013 *Argonne National Laboratory*

Retrospective: Snowmass 2013

★ = prelim. SK 2020
★ (better than projected)



10 year sample points

τ/B = 5e35
17 evts
1 BG

τ/B = 1e34
9 evts
0.3 BG

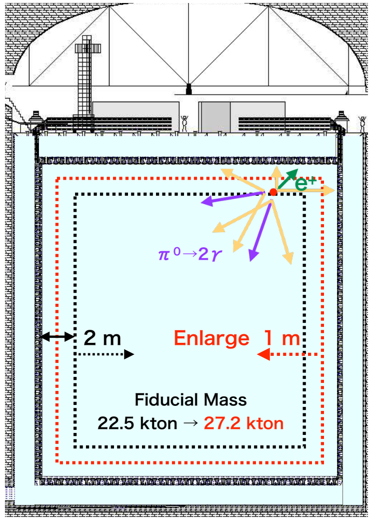
~ 0.5 Mt yr exposure by Super-K before next generation experiments

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

2^{nd} gen: Super-K 1996 – continuing

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**



Nonstop effort since 2013:

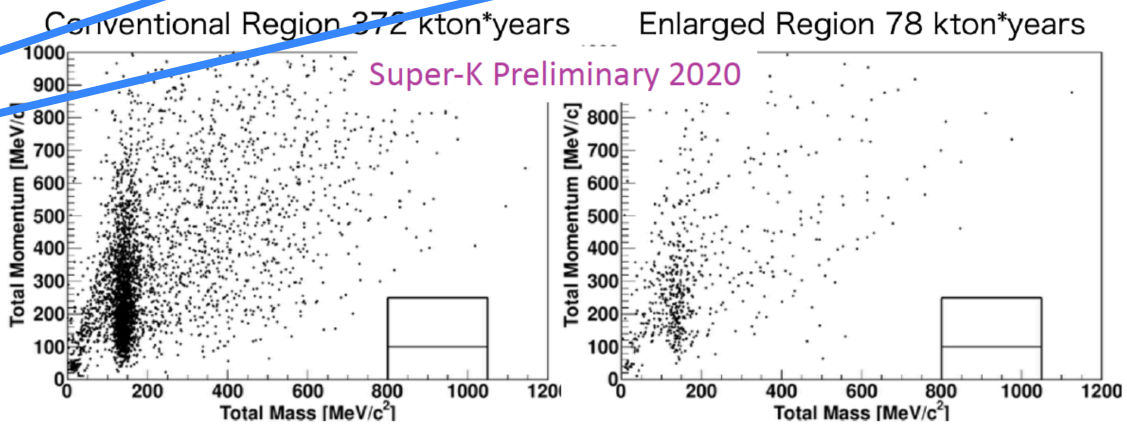
Neutron capture on H (25% eff.)

Expanded fiducial volume

Two box search (free proton)

Improved reconstruction

2020: Add Gd for n-capture



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

Published = 1.6e34

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

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

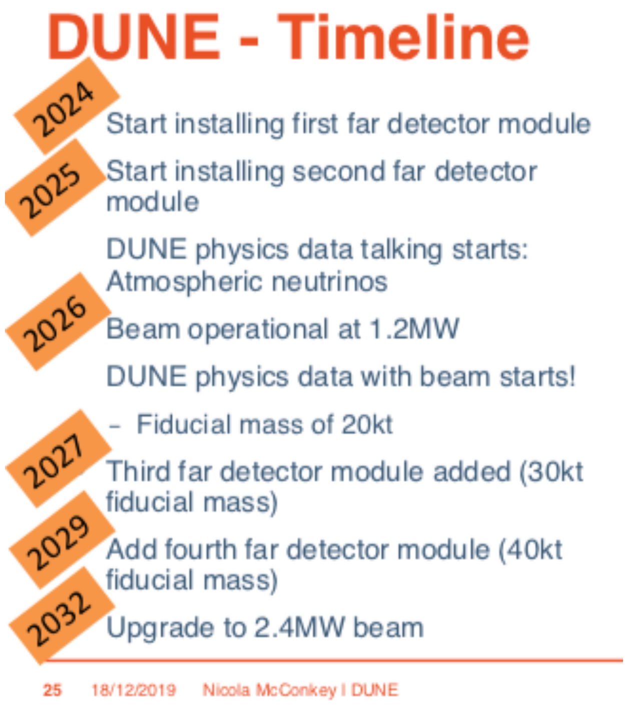
When ?? Everyone wants to know.

JUNO 2022

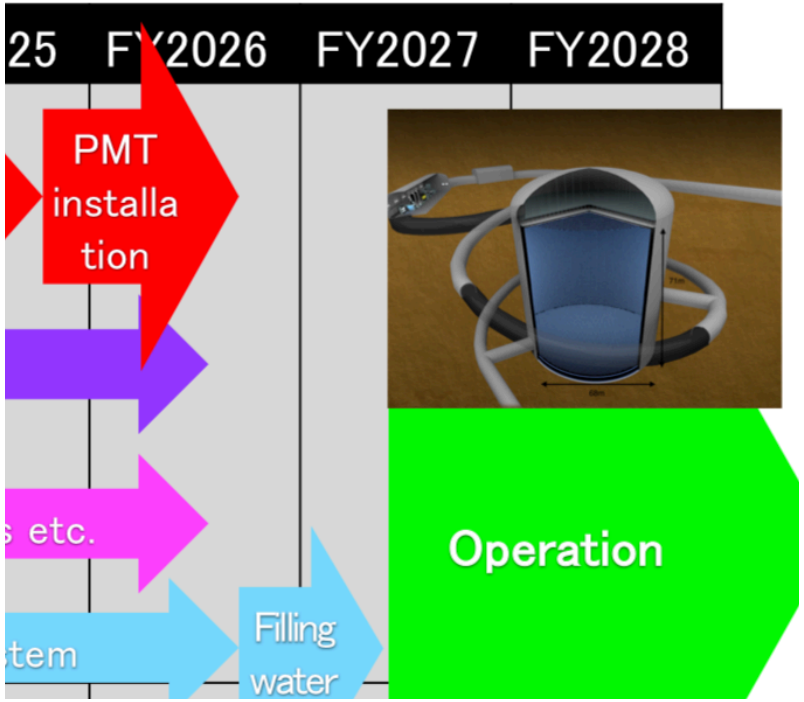
2019-2021
- **Electronics production starts**
- **Civil construction and lab preparation completed**
- **Detector construction**

2022
- **Detector ready for data taking**

DUNE 2026

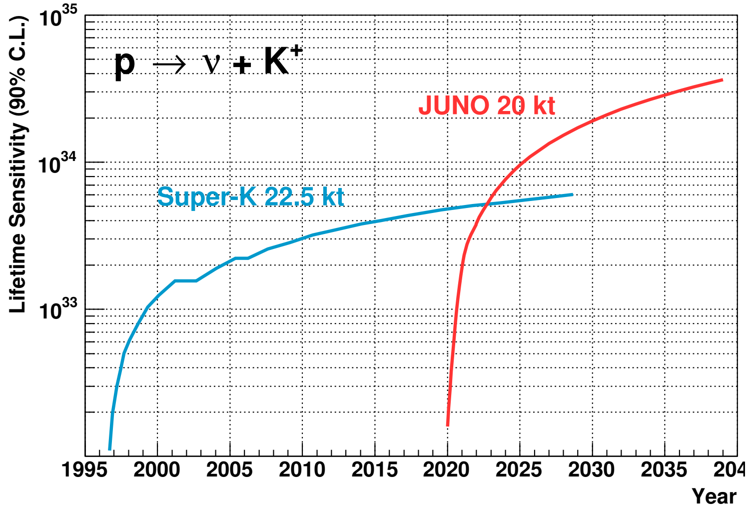


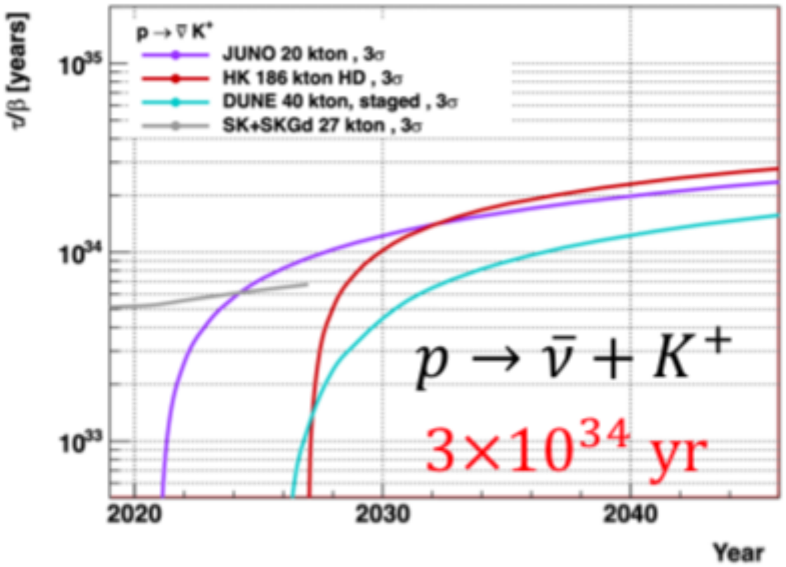
Hyper-K 2027

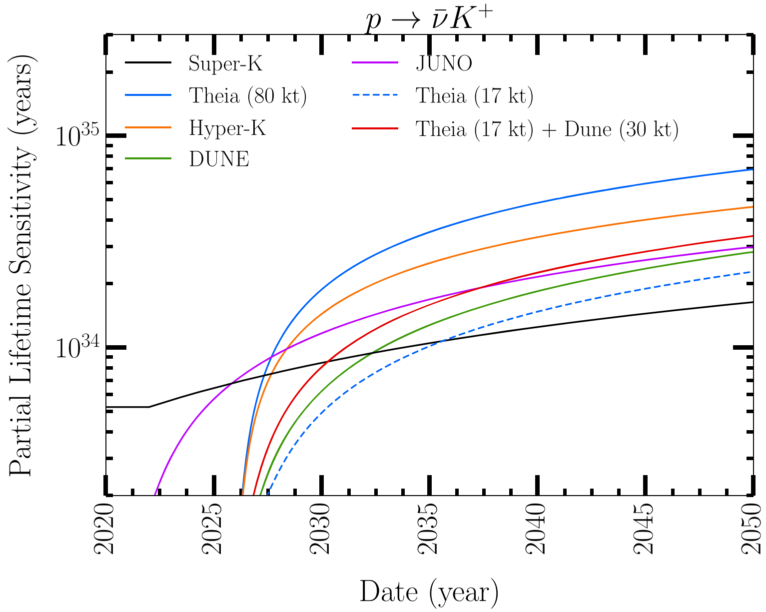


But these estimated dates are subject to … change, of course!

from the published design reports or recent talks …







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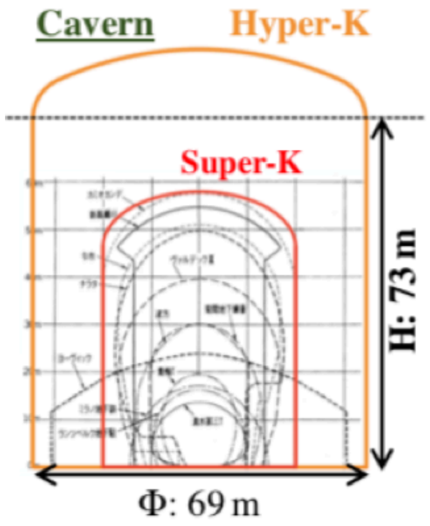

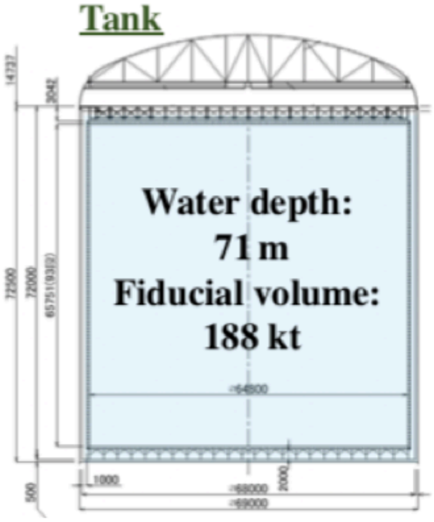

+ potential 2nd module, maybe in S. Korea