Proton Decay

William Matava

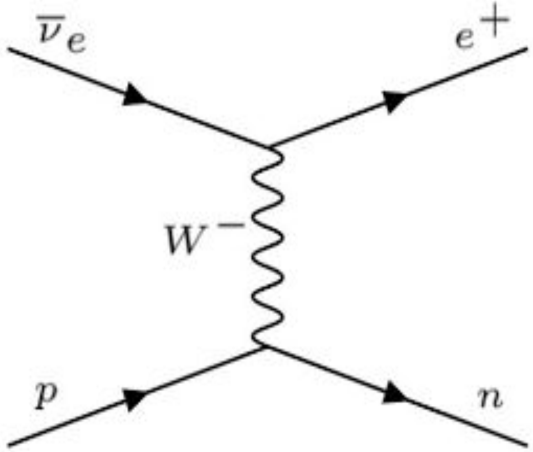
Roadmap

- What/Why proton decay?
- Iron-Calorimeter-Based Searches
  - Frejús Experiment
  - Soudan Experiments
- Water-RICH-Based Searches
  - IBM Experiment
  - (Super)-Kamiokande Experiment
- Where We are Now
  - Current limits
  - Future experiments

What/Why Proton Decay?

‘Proton Decay’ in the Standard Model

- We know protons can decay inside nuclei: $p \to n \, \nu_e \, e^+$
  - Only energetically permissible due to nuclear potential
- If we’re looking free-proton decay:
  - Lightest baryon => Can’t decay to another baryon
  - Baryon number +1 => Needs to decay to at least one baryon
- Nothing interesting here…



Proton Decay Modes in BSM Physics

- B and L conservation are baked into the standard model
  - GUTs relax these symmetries!
- Ex: 'dimension 6' operators (B-L conservation):
  - $\mathcal{L}_6 \approx \frac{1}{M^2} qqql + \text{h.c.}$
  - Proton can decay to anti-lepton and meson!
- Dominant decay path is model dependent
  - Pick your favorite GUT!

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

$$p \to \mu^+ \, \pi^0$$

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

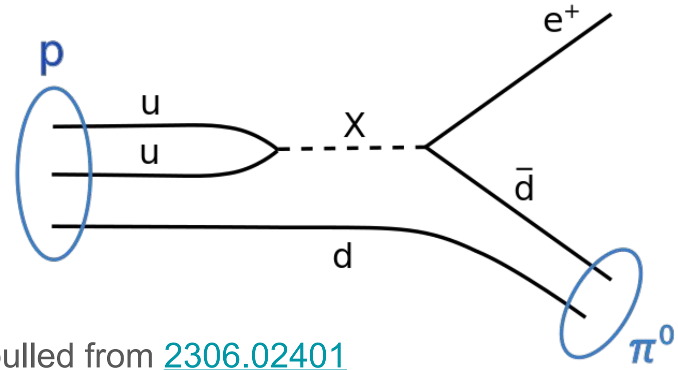


Diagram pulled from 2306.02401

Diversity in Lifetimes

- Theorists can't agree on the total lifetime of a proton should be
  - For reference, I have $O(10^{28})$ protons in me!
  - I'll be waiting between 1 and 10^{11} years to feel one decay…

Model class	References	Lifetime [years]
Minimal SU(5)	Georgi & Glashow [21]	$10^{30} - 10^{31}$
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Table pulled from 2306.02401

Detector Shopping List

- A **bunch** of protons
  - High mass
    - (ton-yrs. exposure will start to scratch the lower bounds)
  - Scalable/cheap
  - Ideally ‘free’ protons (hydrogen)
- Sensitivity to relativistic leptons; photons
  - Neutral pion decays to two gammas
  - Need particle identification (resolve individual tracks!)
- Low backgrounds
  - Radiopurity considerations
  - Underground laboratory

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

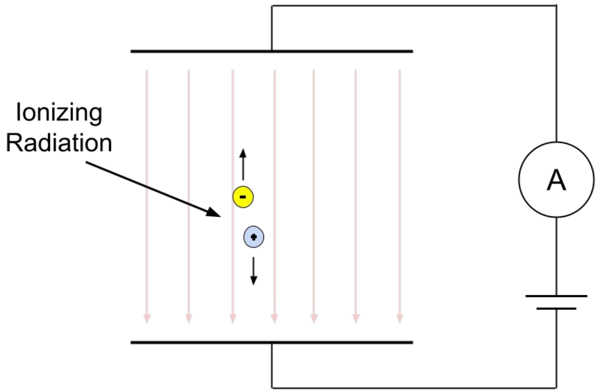
$$p \longrightarrow \mu^{+}\ \pi^{0}$$

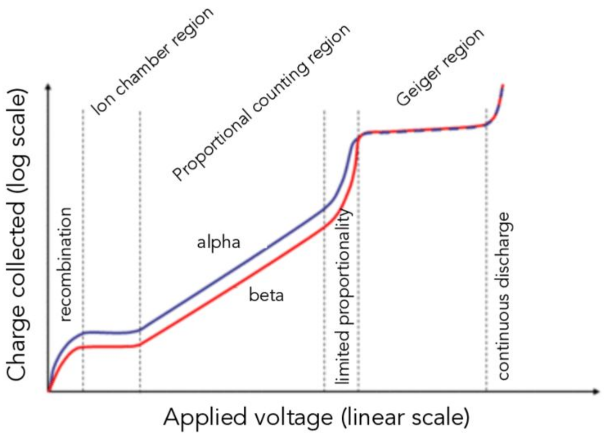
$$p \longrightarrow \nu\ K^{+}$$

Iron-Calorimeter Detectors

Gas Ionization Detectors

- Biased capacitor with ionizable gas as a dielectric
  - Impingent radiation produce e⁻ via primary ionization
  - e⁻ pulled to electrode, producing secondary ionization (gain!)
  - Electrons reach electrode, read as a current
- Bias determines amount of secondary ionization
  - Geiger Mode:
    - All ionizations looks the same (counter)
  - Proportional Mode
    - Signal scales w/ original ionization
- Cons:
  - Dead Time
  - No position sensitivity





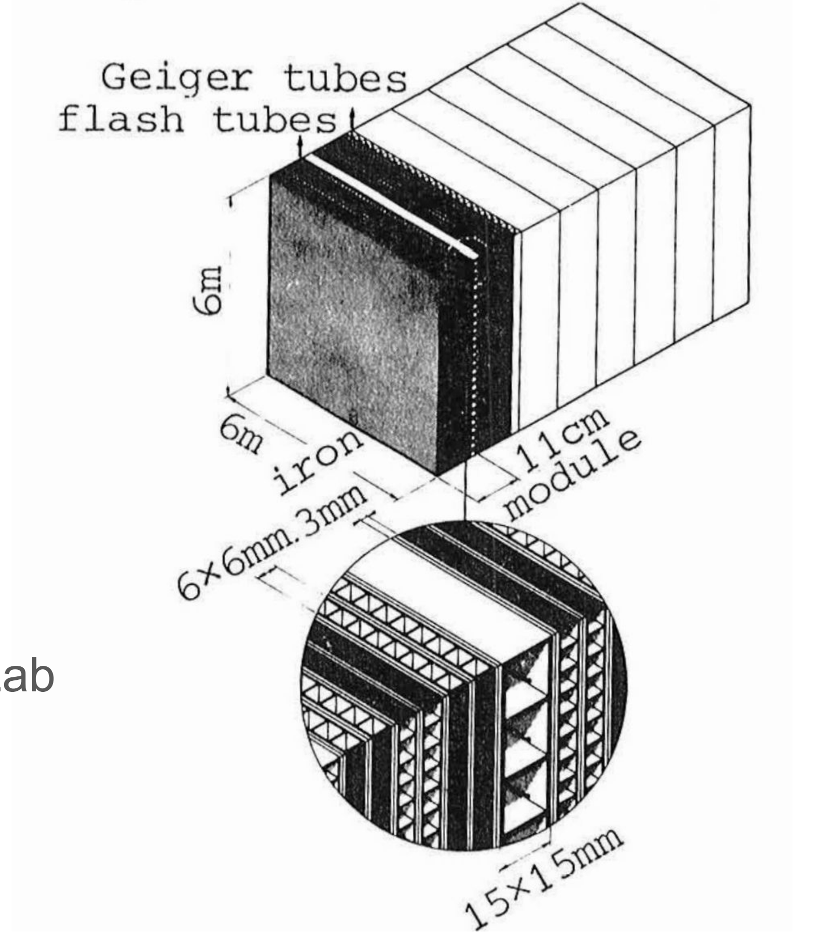
Plot pulled from [Wikipedia]

Iron-Calorimeters

- One ionization detector isn't much good for proton decay
  - We need to be able to reconstruct tracks of leptons and gammas!
- Idea: Get a bunch of independent ionization detectors together
  - Position resolution limited by size of detectors!
- Separate detectors with sheets of iron
  - Particles flying through iron will produce secondary particles to interact in ionization chamber
  - dE/dx also helps with PID

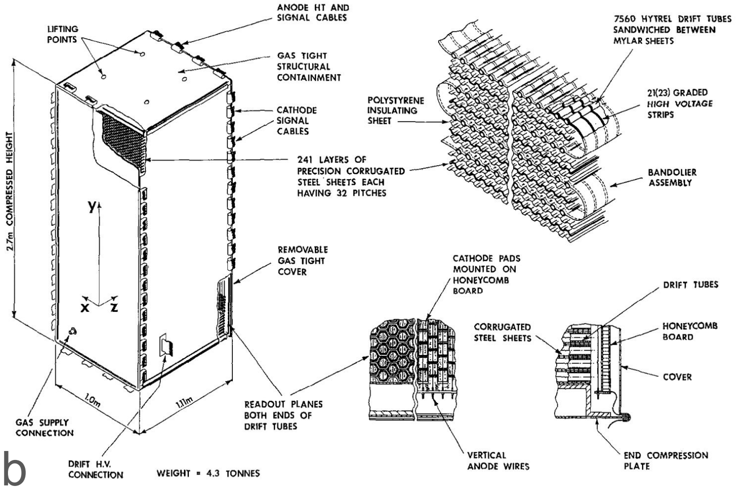
Frejús Experiment

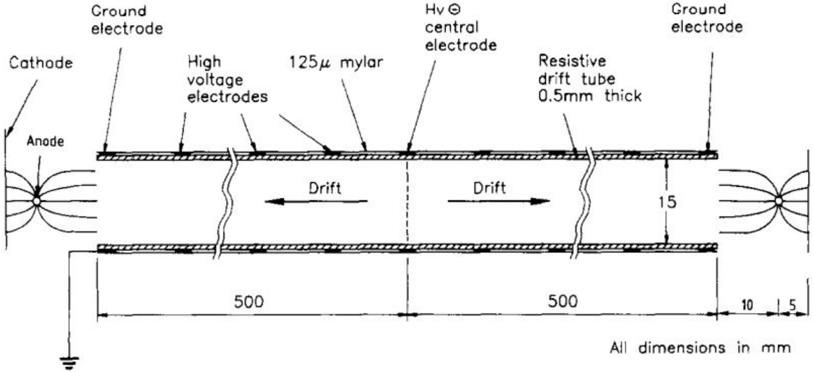
- 912-Layer ‘Sandwich’
  - ‘Flash tubes’ (5x5 mm^2)
    - Gaseous ionization chambers
    - O(1s) dead time; triggered by geiger tubes
    - Operated in proportional-mode
  - Geiger tubes’ (15x15 mm^2)
    - ~coaxial gaseous ionization chambers
    - Used for triggering; in geiger mode
  - Iron layers (provide attenuation; PID)
- Original occupant of Modane Underground Lab
  - Operational from 1984 to 1988



Soudan Experiments

- High density ionization drift chambers
  - 7650 close-packed cylindrical drift tubes (x/y res.)
    - Separated by corrugated iron sheets
  - Electrons drift along long dimension
    - Drift time => z resolution (TPC!)
- Original experiment at Soudan Underground Lab
  - Soudan I (30 T) operational from 1981-1982
  - Soudan II (960 T) operational from 1989-2001



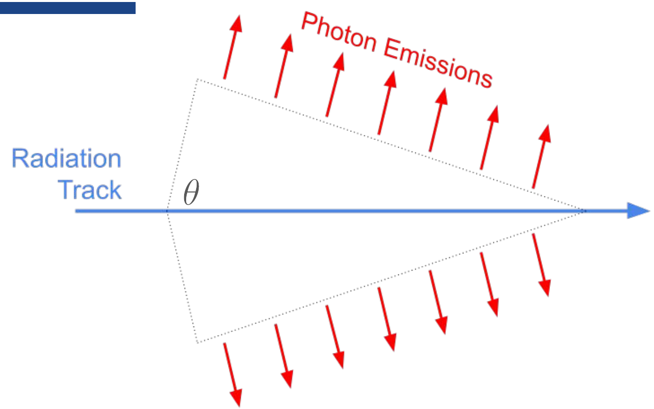


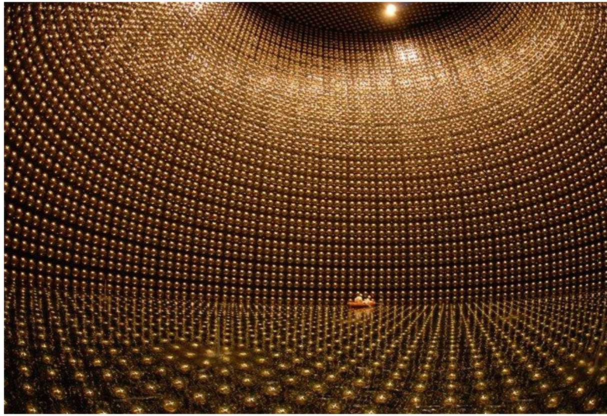
Figures pulled from *The Soudan 2 Proton Decay Experiment*

Water-RICH Detectors

Ring-Imaging Cherenkov (RICH) Detectors

- Iron and gas are expensive…
- Idea: Fill a tank with water; look for cherenkov light!
  - Threshold: $\beta > \frac{1}{n}$
  - Opening Angle: $\cos\theta = \frac{1}{n\beta}$
  - PMTs along the outer wall to detect light
- Advantages:
  - 'Cheap' (water has n ~ 1.33)
    - Allow developing kT/MT scales!
    - Ultra-purity helps with transparency; radiopurity
    - 2 H's per molecule (free protons!)
  - Multipurpose (neutrino physicists will help!)
  - Really cool pictures

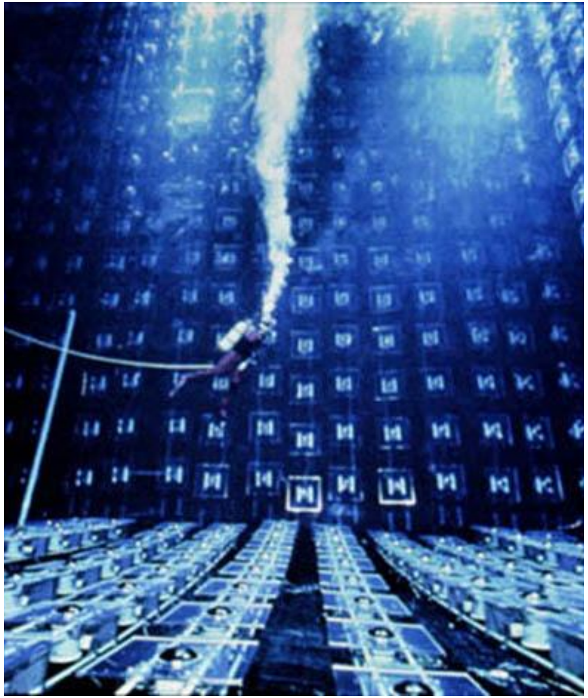




Figures pulled from DOE Office of Science

Irvine-Michigan-Brookhaven (IMB) Experiment

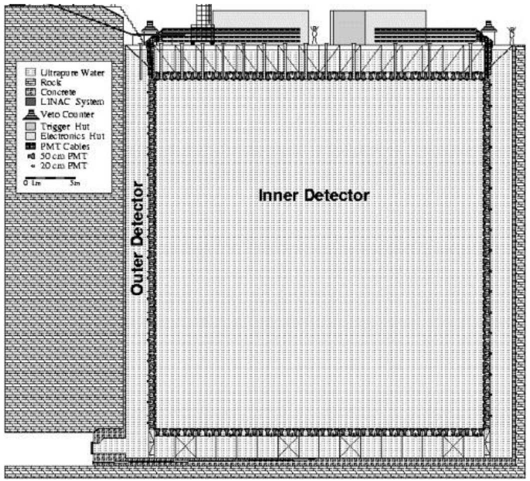
- Water-base RICH detector
  - 8 kTon ultra-pure water
  - ~1 % photocathode coverage
    - <1% of photons detected…
  - No muon veto
- Located in Fairport salt mine
  - Simultaneous to Soudan/Frejus experiments
  - Operational from 1982 to 1991
  - Tragic ending with a leak…



Picture pulled from University of Michigan

(Super) KamiokaNDE

- Water-base RICH detector
  - (50 kTon) 1 kTon of ultra-pure water
  - Inner detector (containing fiducial volume):
    - Bulk of the volume
    - (40%) 20% photocathode coverage
  - Outer detector (muon veto):
    - Optically isolated from ID
- Located at Kamioka Observatory
  - Kamiokande operational 1983-1995
  - Super-K operational from 1996-Present
  - Hyper-K planned for 2027



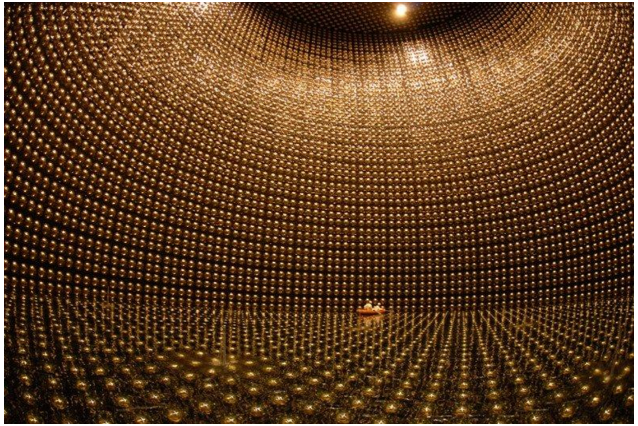


Diagram pulled from [The Super-Kamiokande Detector]

Event Reconstruction @ Super-K

- Raw Signal is list of detections + times
  - Vertex determined by picking position with tightest bounds on photon emission time
  - Directions come from ring shapes/vertex
  - Energy comes from opening angle; signal size
  - PID come from ring shape; more
    - ‘Showering’ particles produce fuzzy ring edges
    - ‘Non-Showering’ particles produce crisp ring edges

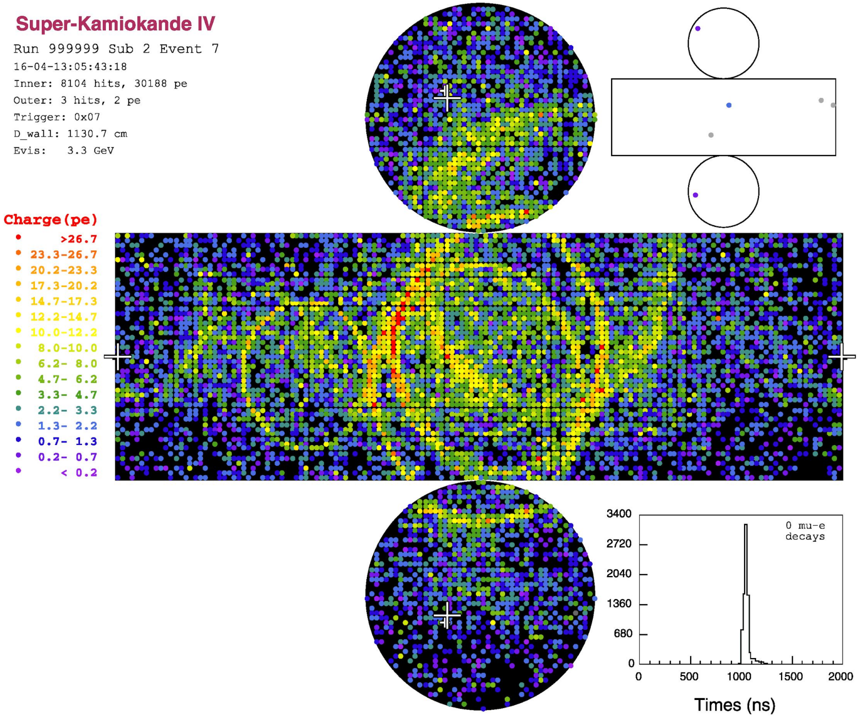


Figure pulled from [*Observation of Astrophysical Neutrinos*]

Background Tagging @ Super-K

- Careful consideration of radiopurity/shielding already taken
  - There's no shielding/tagging neutrinos…
- $p \to e^+\pi^0$ has characteristic 3-ring decay
  - Pion decays to 2 gammas
  - Most backgrounds can be automatically vetoed
- Main background is: $\nu_e \; p \to n \; e \; \gamma \; \gamma$
  - Neutron does not shower, so 3-rings…
  - Neutron can thermalize; be captured by H:
    - $p + n \to d + \gamma(2.2 \text{ MeV})$
    - 2.2 MeV is technically below threshold
    - Reconstructed w/ MC @ ~25% efficiency

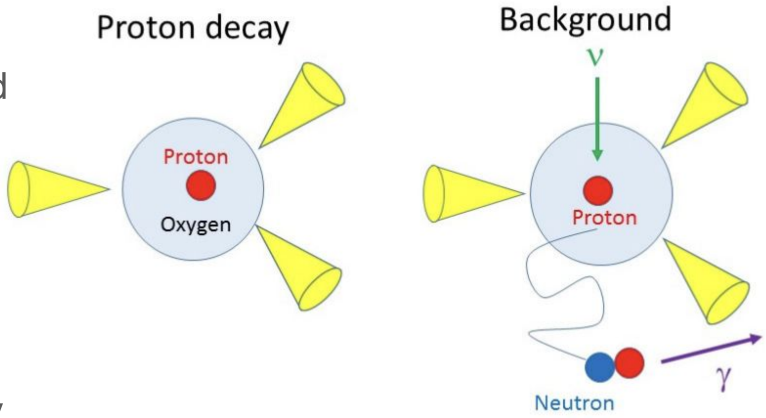


Figure pulled from 2306.02401

How do our Theories Hold up?

- Many theories have been ruled out experimentally
  - Others are currently being squeezed…

Model class	References	Lifetime [years]	Ruled out?
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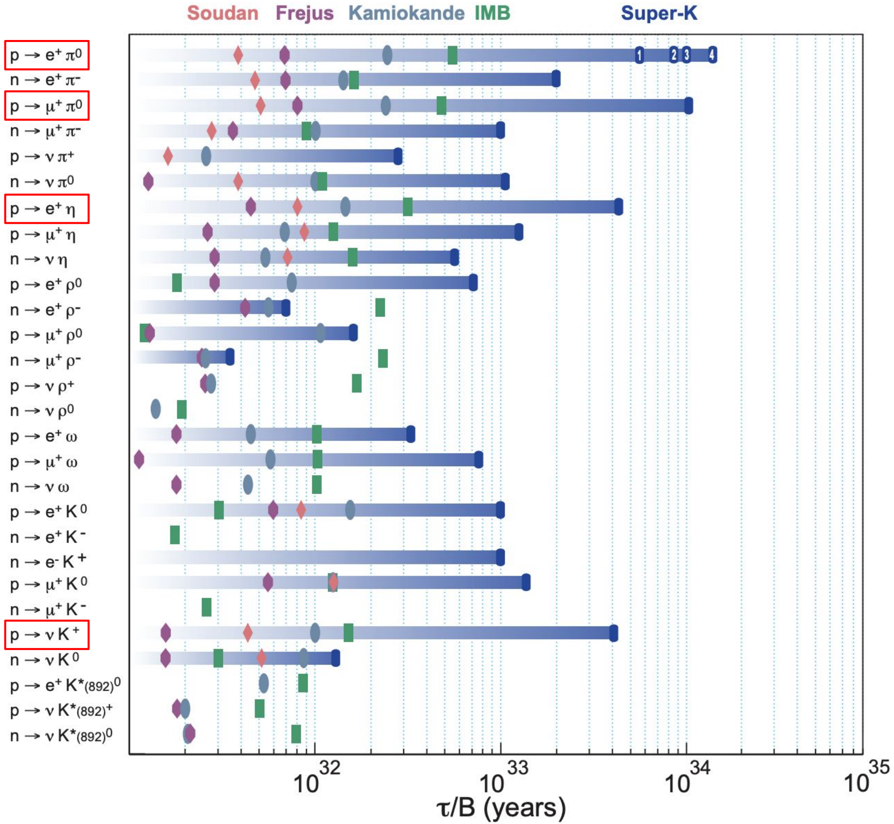
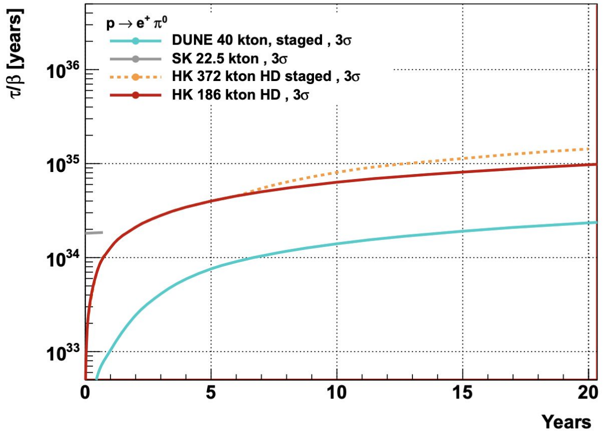
How do our Theories Hold up?

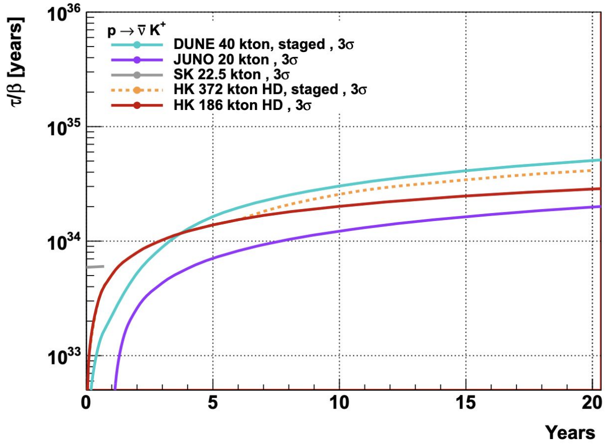
- Cherenkov-based impose strongest limits
  - Note four branches with highest limits:
    - $p \to e^+ \pi^0$
    - $p \to \mu^+ \pi^0$
    - $p \to \nu K^+$
    - $p \to e^+ \eta$



Future Experiments

- Hyper-KamiokaNDE
  - ~10 Super-KamiokaNDE's in mass!
  - Data taking in 2027
- Using DUNE far detector (LAr-TPCs)
  - K^+ is too massive; above cherenkov threshold in water!
  - LAr-TPCs can image K^+ directly, for better efficiency!
- EssnuB far detector
  - Long-baseline neutrino experiment
  - Data taking in ~2037 (?)
- JUNO detector
  - Water-based far detector for med. baseline ν experiment
  - WBLS





Plots taken from 1805.04163

Citations

- General Proton Decay
  - https://arxiv.org/pdf/2306.02401.pdf
- Frejus experiment
  - https://ntrs.nasa.gov/api/citations/19850027771/downloads/19850027771.pdf
- Soudan Experiment
  - https://inspirehep.net/literature/277568
- IMB Experiment
  - https://www.sciencedirect.com/science/article/pii/016890029390998W
- Super-Kamiokande Experiment
  - https://arxiv.org/abs/2010.16098