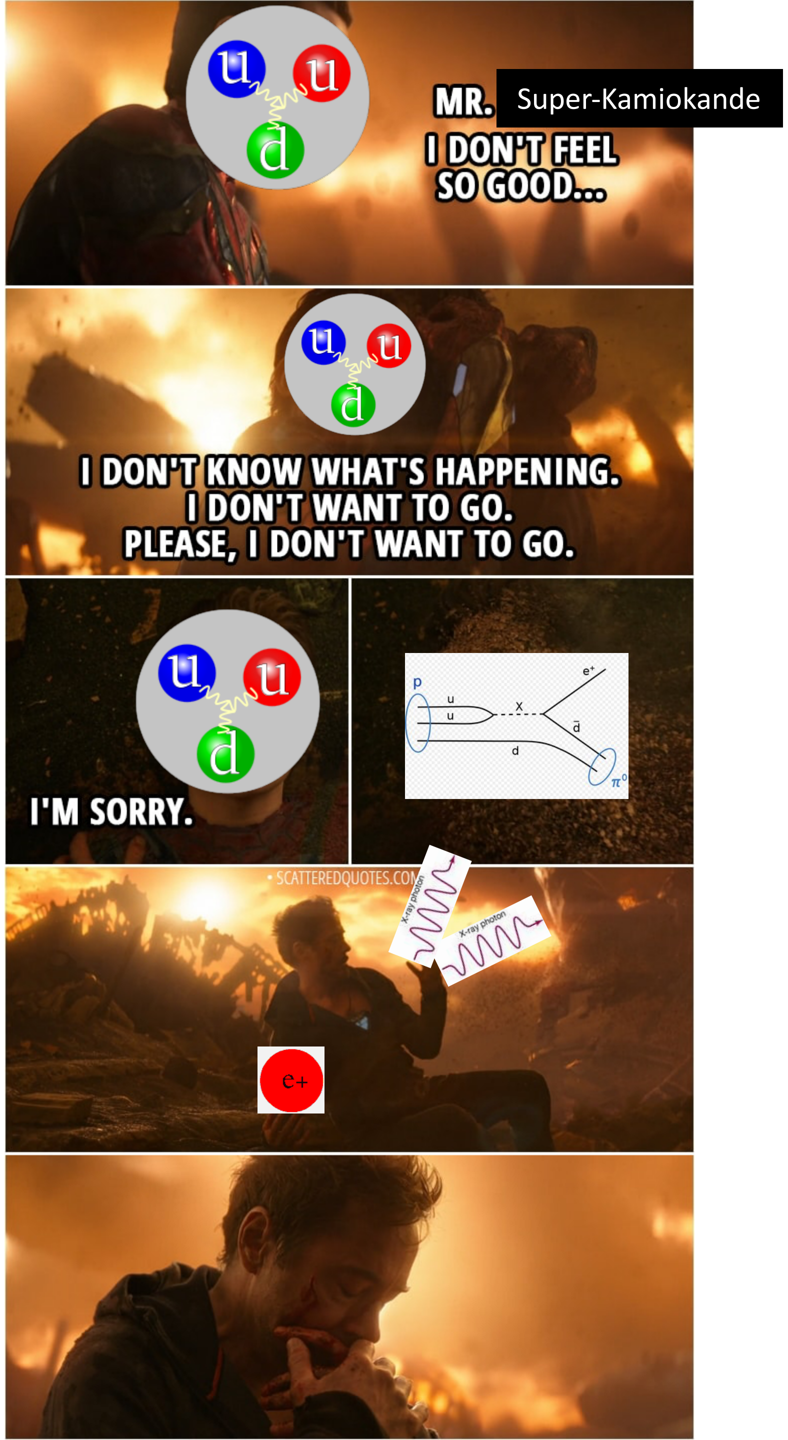


Now don't hang on
Nothing lasts forever but the Earth and Sky
It slips away

All we are is dust in the wind

-Kansas

Proton Decay

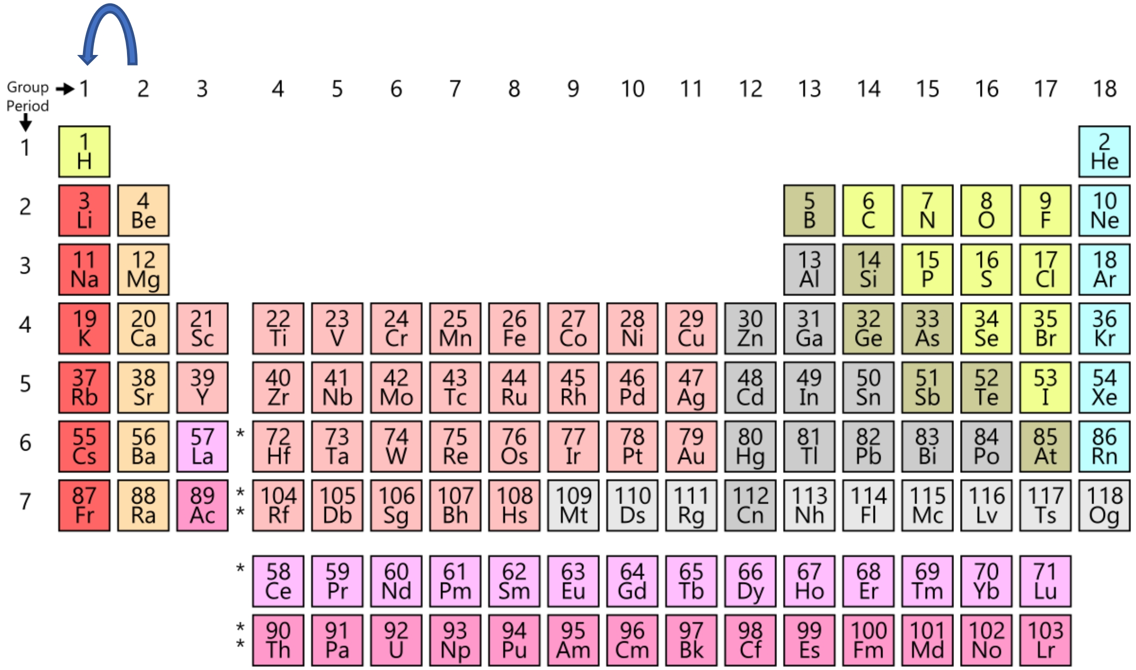
Patrick McCormack

October 17, 2019

Protons decay all the time

- Don't believe me?

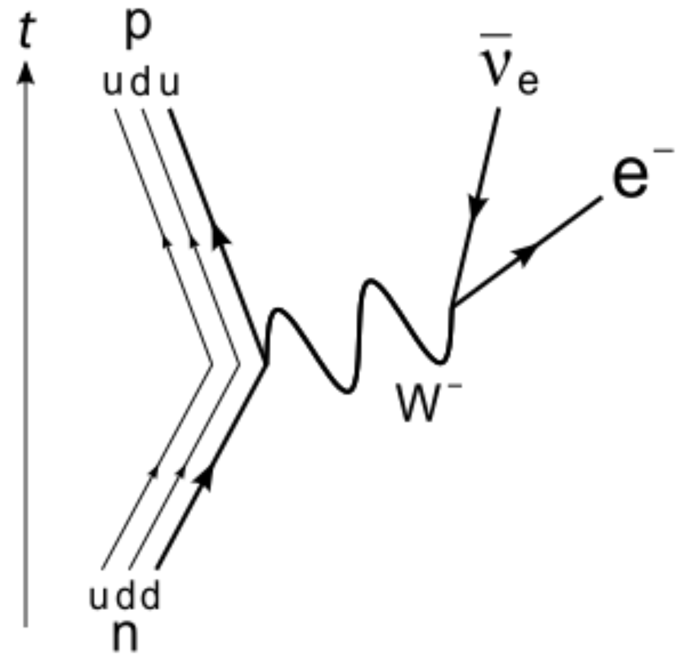
- ${}^{23}_{12}\mathrm{Mg} \rightarrow {}^{23}_{11}\mathrm{Na} + \mathrm{e}^{+} + \nu_e$
  - $\tau \approx 11\mathrm{s}$



Well that's boring…

What about free* protons?

- Free* neutrons decay, so why not protons?
  - $\tau \approx 15\text{m}$
- $n \to p + e^- + \bar{\nu}_e$ is kinematically allowed though!
- Is there a SM process that can allow proton decay?
  - Must preserve baryon number
  - Must preserve lepton number
  - (and get the kinematics right!)

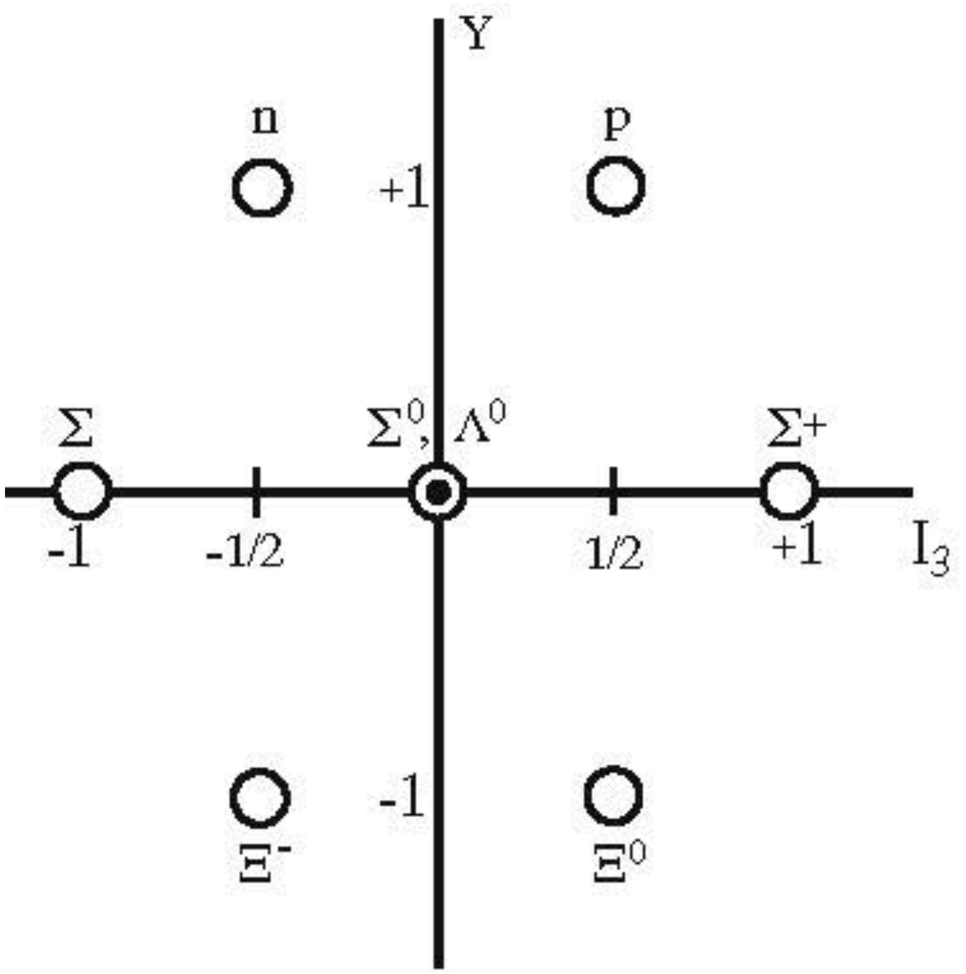


*not bound in a nucleus

Conclusions

- Protons are the lightest baryon
- No allowable decays!

- Thanks! See y’all next week!



Not so fast, my friend

Not so fast, my friend

- What if the SM isn't all there is?

An argument from aesthetics

- In the Standard Model fermions are put into irreducible representations of the gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Our fields are: $q_R, u_L^c, d_L^c, l_L, e_R^c$
- Their respective irr. reps:
  - $\left(3, 2, \frac{1}{6}\right), \left(3^*, 1, -\frac{2}{3}\right), \left(3^*, 1, \frac{1}{3}\right), \left(1, 2, -\frac{1}{2}\right), (1, 1, 1)$

An argument from aesthetics

- What a mess!

Wouldn’t it be nice

- What if we could find some way to explain this weird combination of gauges AND quantum numbers?
- That’d be Grand
- That’d be Unified
- Well it’s “just a theory”

One big group

- $SU(5)$ is the smallest group that contains $SU(3)\times SU(2)\times U(1)$
- It's easy to imagine breaking a 5x5 matrix into a 3x3 and a 2x2 chunk
- Like $\begin{bmatrix} SU(3) & 0 \\ 0 & SU(2) \end{bmatrix}$
- One generator is even
- $\frac{1}{2}Y = \begin{bmatrix} -\frac{1}{3} & & & & \\ & -\frac{1}{3} & & & \\ & & -\frac{1}{3} & & \\ & & & \frac{1}{2} & \\ & & & & \frac{1}{2} \end{bmatrix}$, which makes a nice $U(1)$

One big group

$$\begin{bmatrix} d_R^c \\ d_R^c \\ d_R^c \\ l_L \\ l_L \end{bmatrix}$$

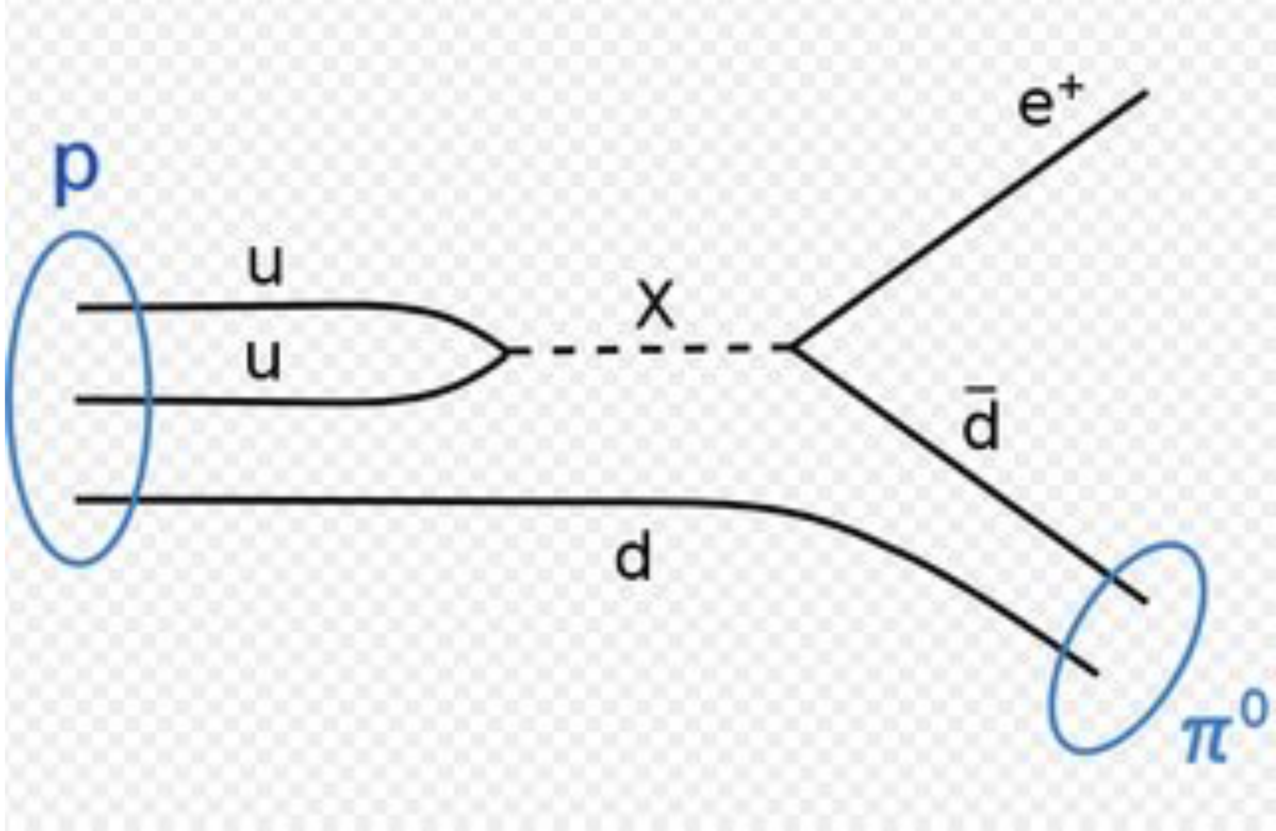
- Break up the antifundamental representation:
  - $5^* \rightarrow \left(3^*, 1, \frac{1}{3}\right) \oplus \left(1, 2, -\frac{1}{2}\right)$
- The antisymmetric tensor representation becomes:
  - $10 \rightarrow \left(3, 2, \frac{1}{6}\right) \oplus \left(3^*, 1, -\frac{1}{2}\right) \oplus (1, 1, 1)$
- So we just use the Higgs mechanism to cause the symmetry breaking we need, and voila!

The consequences

- So now we get our 12 massless SM gauge bosons, and 12 massive ones!
- What can those massive bosons do?
- Wait… they can change quarks into leptons?!

Uh Oh

- There's a "very weak" force that causes proton decay*

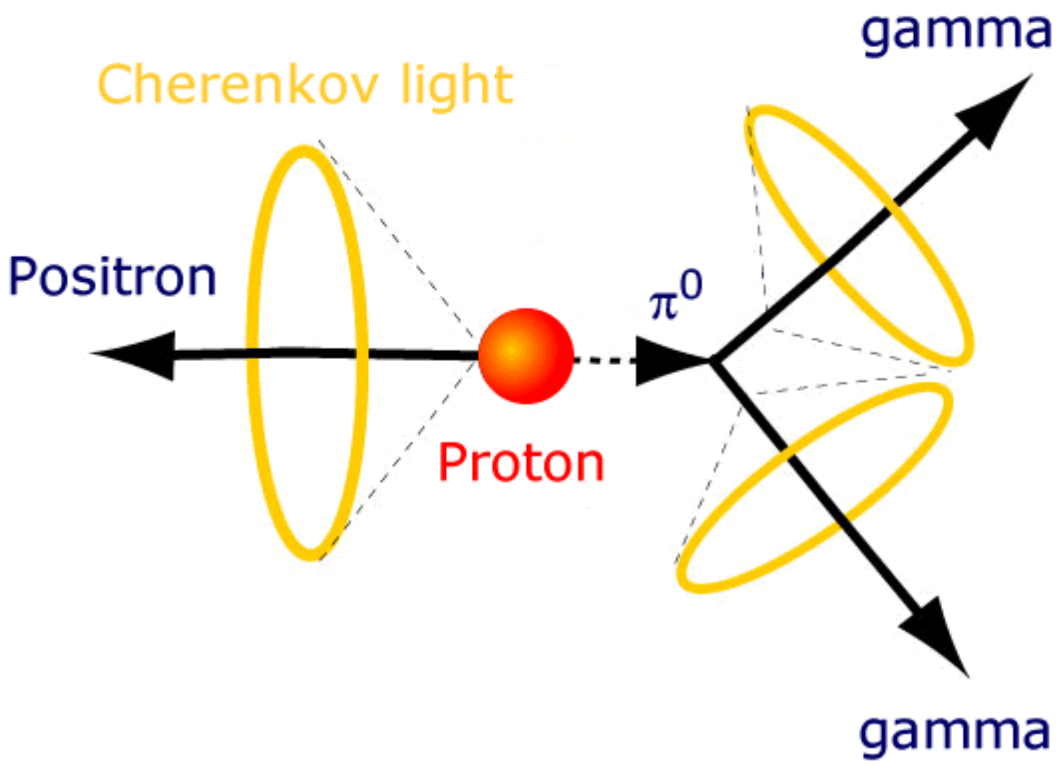


*editor's note: B-L is preserved in this theory!

I’ll believe it when I see it

- But how can I see it?
- This is a seminar about low energy experiments
- Illustration:

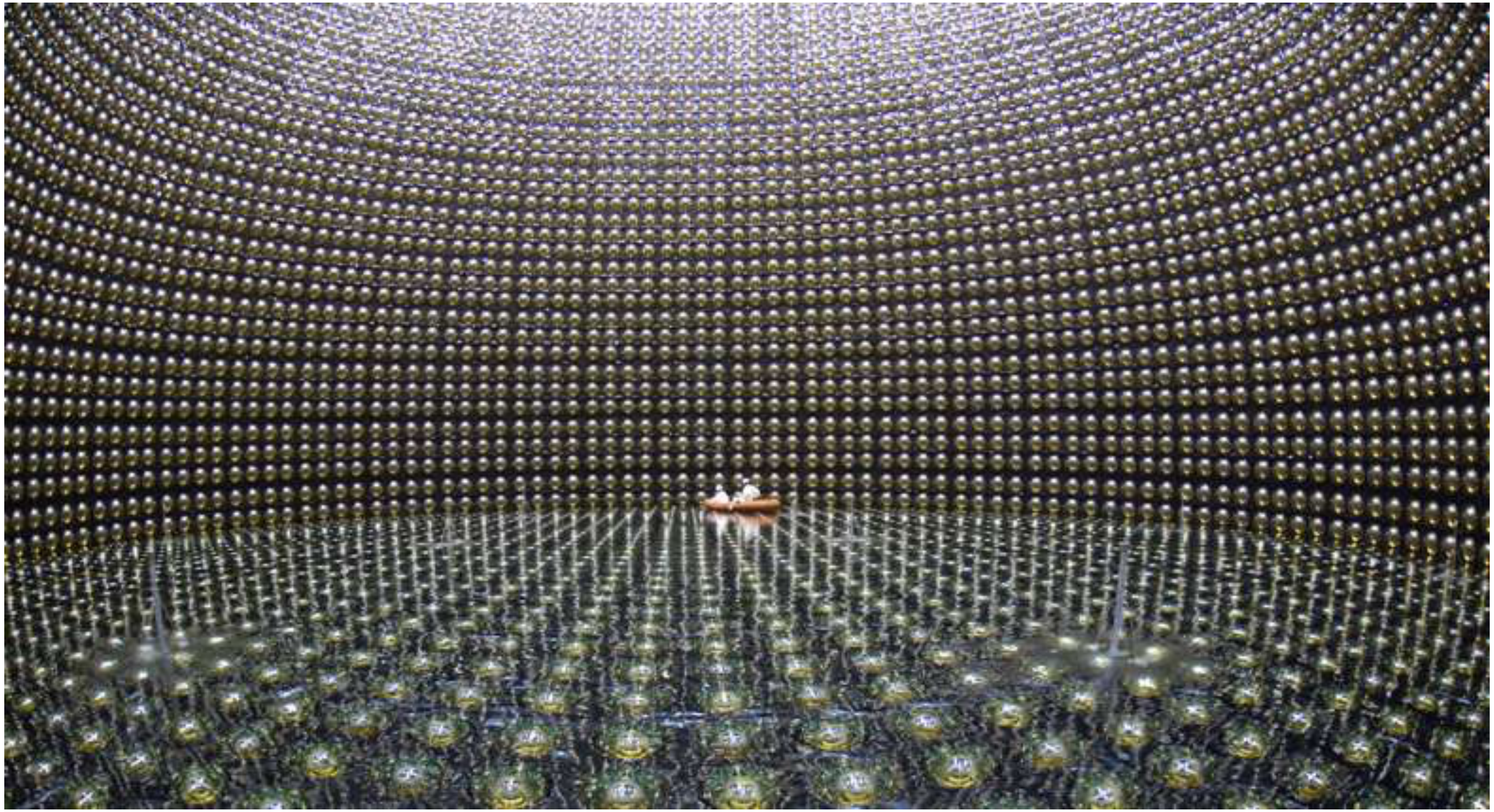
What a decay would probably look like



- You’re gonna need a lot of photodetectors

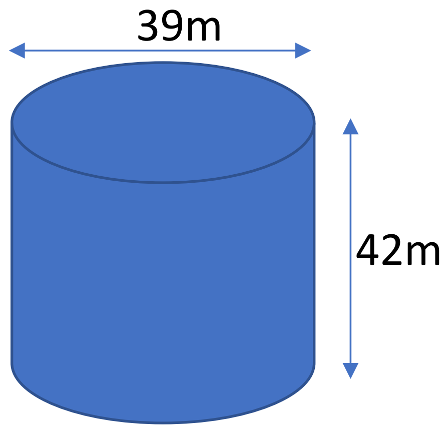
Super-Kamiokande

- You might know it as the neutrino experiment that has pictures like:



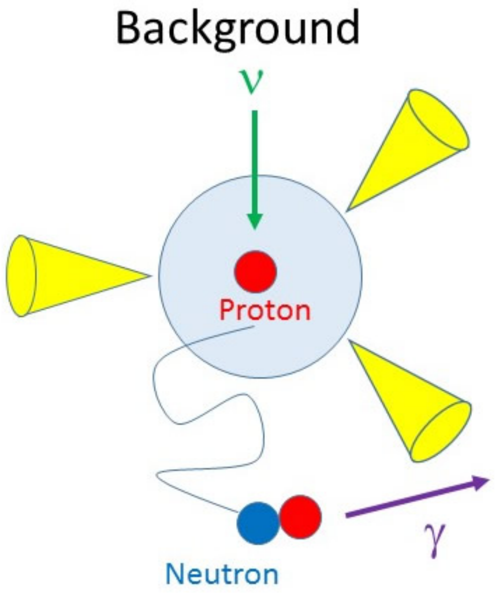
Super-Kamiokande

- Under a km of mountain in Japan
- 50,000 tons of water in a stainless steel tank
  - That's $7{\times}10^{33}$ protons for those keeping track
- 11,000 inward facing photodetectors
  - 2,000 outward facing detectors (used to establish lower limit on energy in neutrino event with exiting particle)

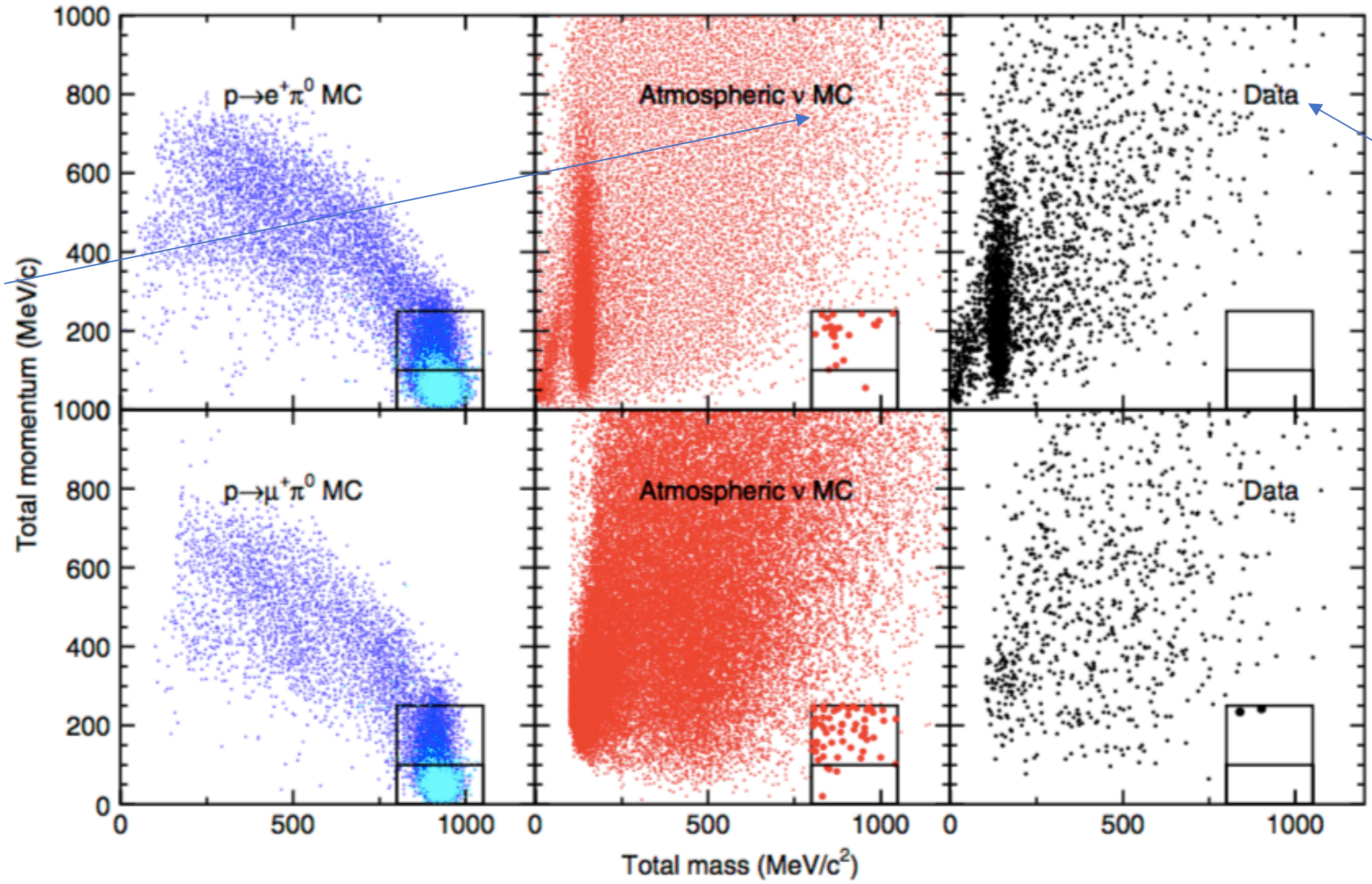


Super-Kamiokande

- Main search was for $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$
- All decay products are detectable, so full event should be reconstructible, meaning low backgrounds
  - Main background comes from neutrinos
  - Helped by neutron tagging
- Look for fully contained events with 2 or 3 cherenkov rings, no tagged neutrons, reconstructed mass 80-1050 MeV, and momentum less than 250 MeV (and a few other cuts)



Super-Kamiokande



500 years equivalent

306.3 kiloton-years

Channel	Expected	Data
e+	0.61	0
Mu+	0.87	2

PHYSICAL REVIEW D 95, 012004 (2017)

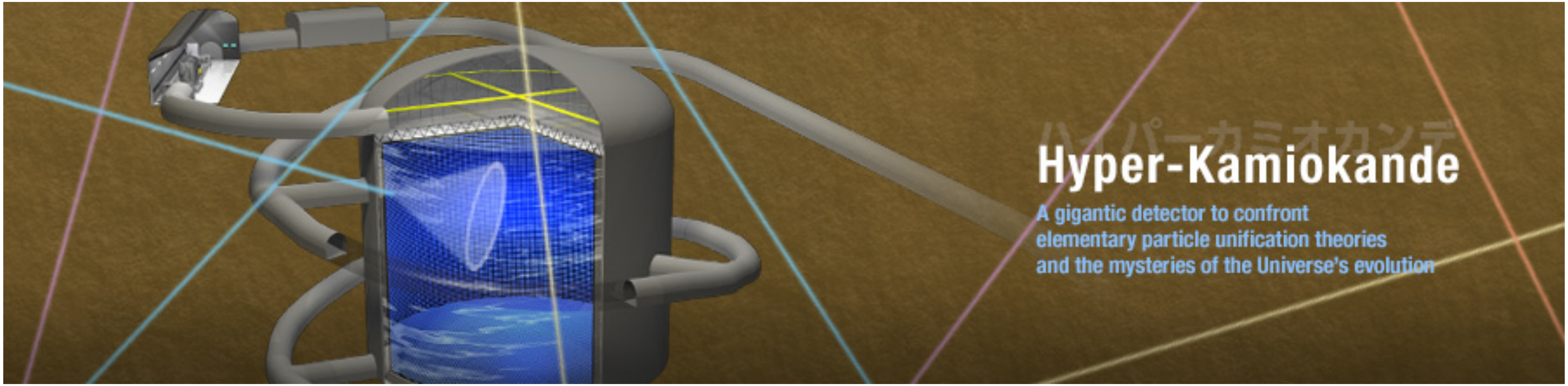
Take it to the limit

- $p \rightarrow e^{+}\pi^{0}$ limit: 1.6×10^{34} years
- $p \rightarrow \mu^{+}\pi^{0}$ limit: 7.7×10^{33} years

- By the way, the plain SU(5) model predicts $\sim 10^{31}$ years, so this model is largely ruled out, but there are other models, such as an SO(10) model and supersymmetric SU(5)

HYPER-KAMIOKANDE

- 260,000 metric tons of water (10x greater fiducial volume than Super-K)
- Upgrade of photodetectors (now 50% more efficient)



http://www.hyperk.org

HYPER-KAMIOKANDE

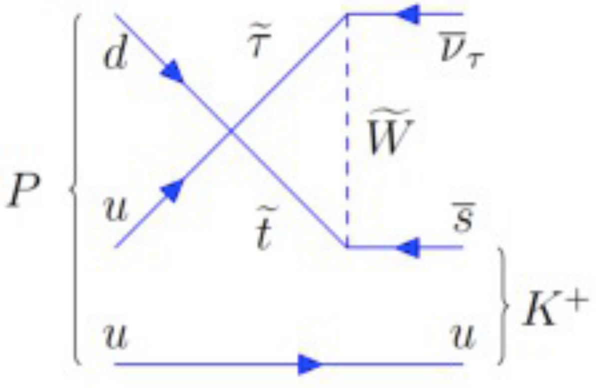
Expected after
0.316 Megaton-years

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \rightarrow e^+\pi^0$	7.8×10^{34}	1.6×10^{34}
$p \rightarrow \overline{\nu}K^+$	3.2×10^{34}	0.7×10^{34}
$p \rightarrow \mu^+\pi^0$	7.7×10^{34}	0.77×10^{34}
$p \rightarrow e^+\eta^0$	4.3×10^{34}	1.0×10^{34}
$p \rightarrow \mu^+\eta^0$	4.9×10^{34}	0.47×10^{34}
$p \rightarrow e^+\rho^0$	0.63×10^{34}	0.07×10^{34}
$p \rightarrow \mu^+\rho^0$	0.22×10^{34}	0.06×10^{34}
$p \rightarrow e^+\omega^0$	0.86×10^{34}	0.16×10^{34}
$p \rightarrow \mu^+\omega^0$	1.3×10^{34}	0.28×10^{34}
$n \rightarrow e^+\pi^-$	2.0×10^{34}	0.53×10^{34}
$n \rightarrow \mu^+\pi^-$	1.8×10^{34}	0.35×10^{34}

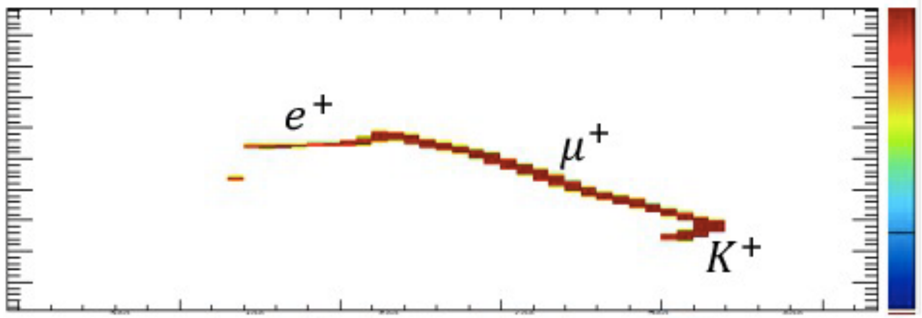
https://arxiv.org/pdf/1805.04163.pdf

DUNE (Deep Underground Neutrino Experiment)

- Four 10 kiloTon Liquid Argon TPC detectors
- Main mode of interest:



$$p^+ \to K^+\bar{\nu}$$
$$K^+ \to \mu^+\nu_\mu$$
$$\mu^+ \to e^+\nu_e\overline{\nu_\mu}$$



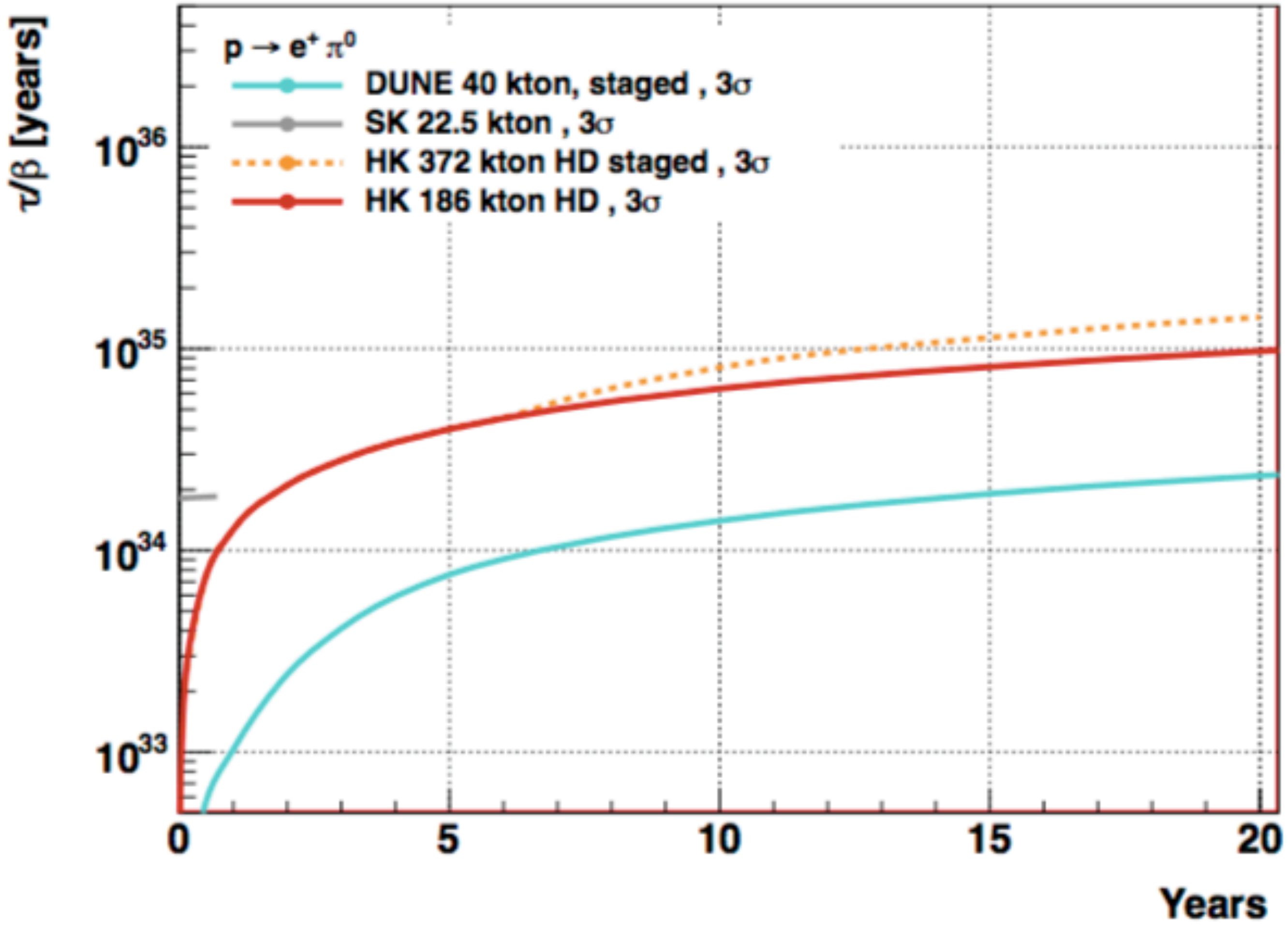
simulated event display (2D)

- LArTPC should be much more efficient for this decay channel than water cherenkov detector

DUNE

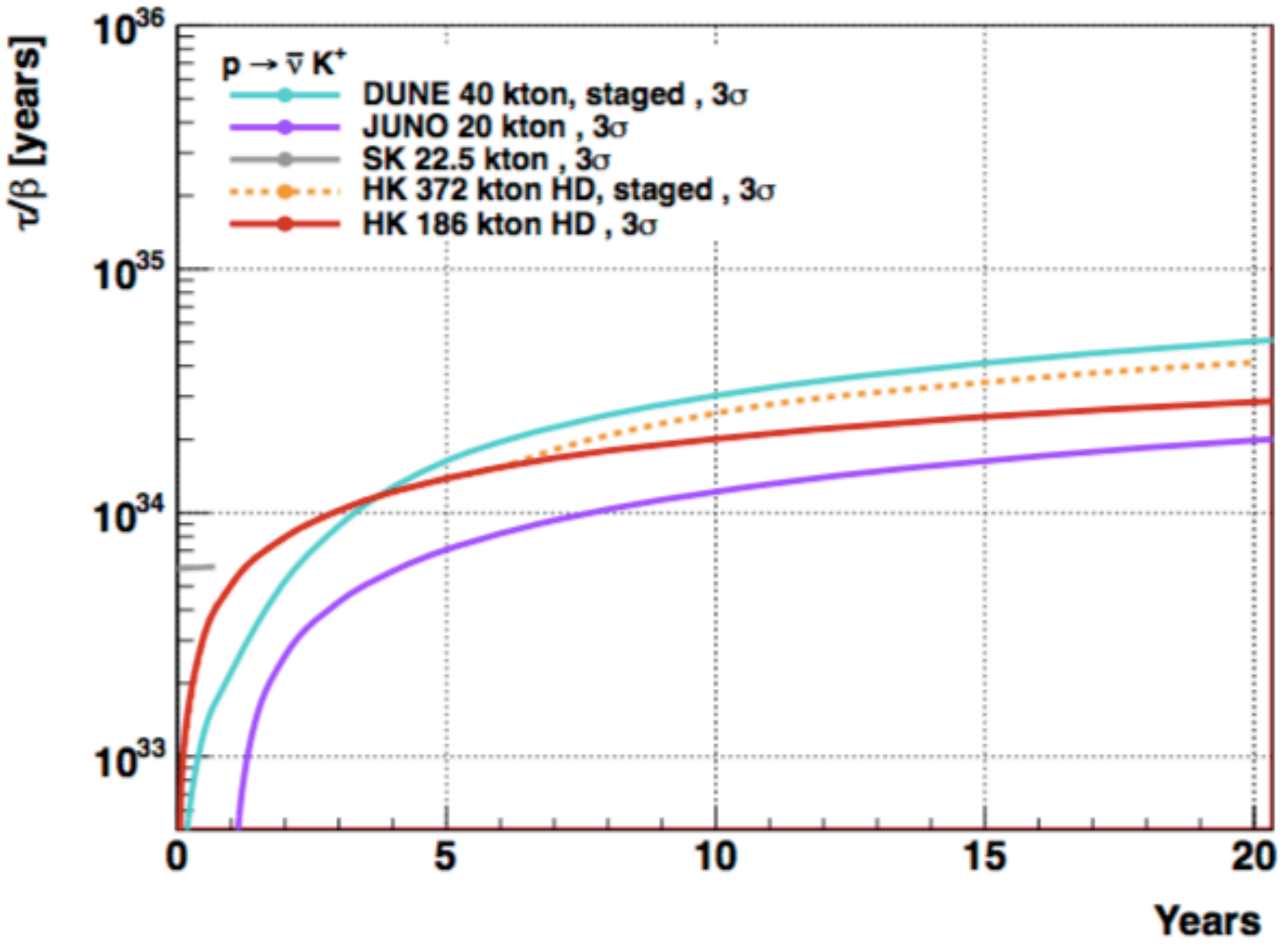
- Major background comes from cosmic muons interacting with rock and making kaons
- To make fiducial cuts you need to know interaction location in drift region!
- They’re adding in a photon detection system (mostly just silicon photomultipliers), which can isolate interaction origin to a few mm
- Also useful for triggering on non-beam events

Expected 3σ results



https://arxiv.org/pdf/1805.04163.pdf

Expected 3σ results



https://arxiv.org/pdf/1805.04163.pdf

References

- **GUT Theory**: A. Zee, “Group Theory in a Nutshell for Physicists”
- **Super-K Search**: http://www-sk.icrr.u-tokyo.ac.jp/sk/_pdf/articles/PhysRevD.95.012004.pdf
- **Super-K detector**: The Super-Kamiokande detector, Nucl. Instrum. Methods Phys. Res., Sect. A 501, 418 (2003); Calibration of the Super- Kamiokande detector, Nucl. Instrum. Methods Phys. Res., Sect. A 737, 253 (2014).
- **Hyper-K**: https://arxiv.org/pdf/1805.04163.pdf
- **DUNE**: Proton decay search: https://absuploads.aps.org/presentation.cfm?pid=13079; Photon detector: https://indico.fnal.gov/event/10271/contribution/8/material/slides/0.pdf; General: http://www.dunescience.org

Backup

What does a Super-Kamiokande event look like

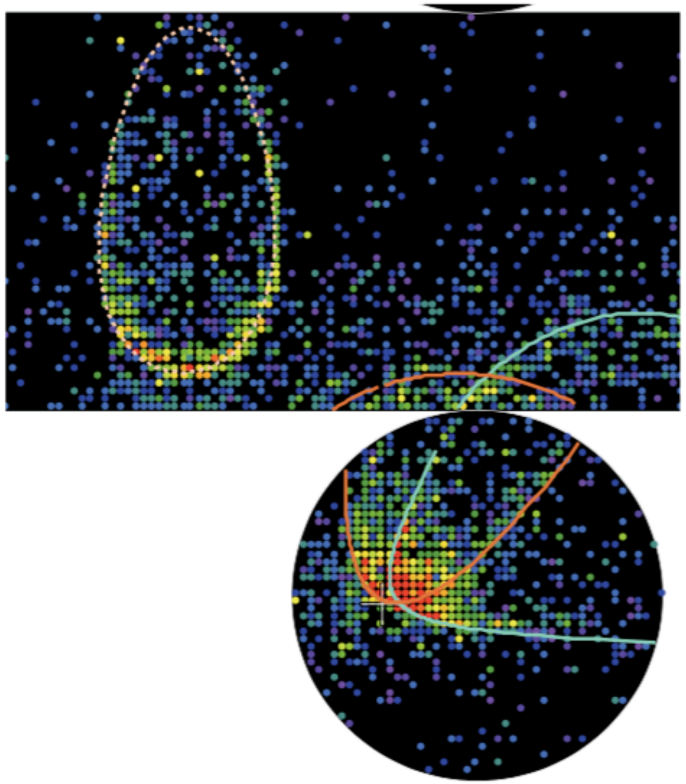


FIG. 5. Event display of the second candidate event, zoomed to the region of the rings. The blue solid line and the tan dashed line show the reconstructed e-like and μ-like rings, respectively. The dark orange solid line shows an additional e-like ring that was identified in the initial ring counting process, but it is rejected by the ring correction because it is too close in angle to the other e-like ring (blue line). As a result, this event is judged as a two-ring event.