# Proton Decay

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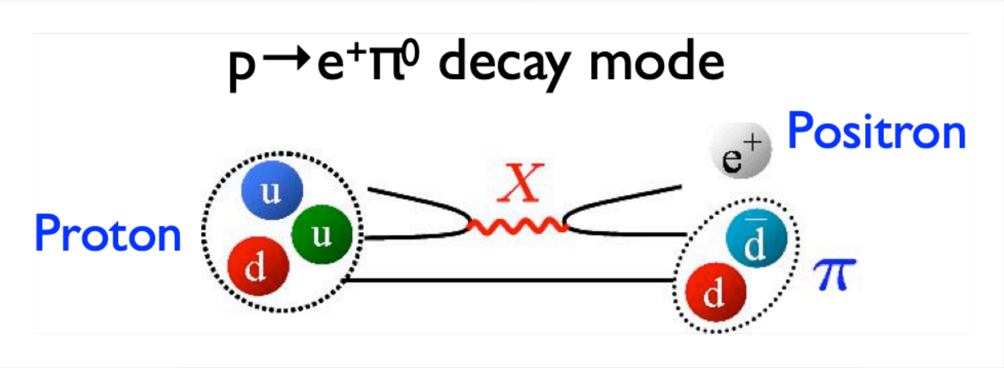
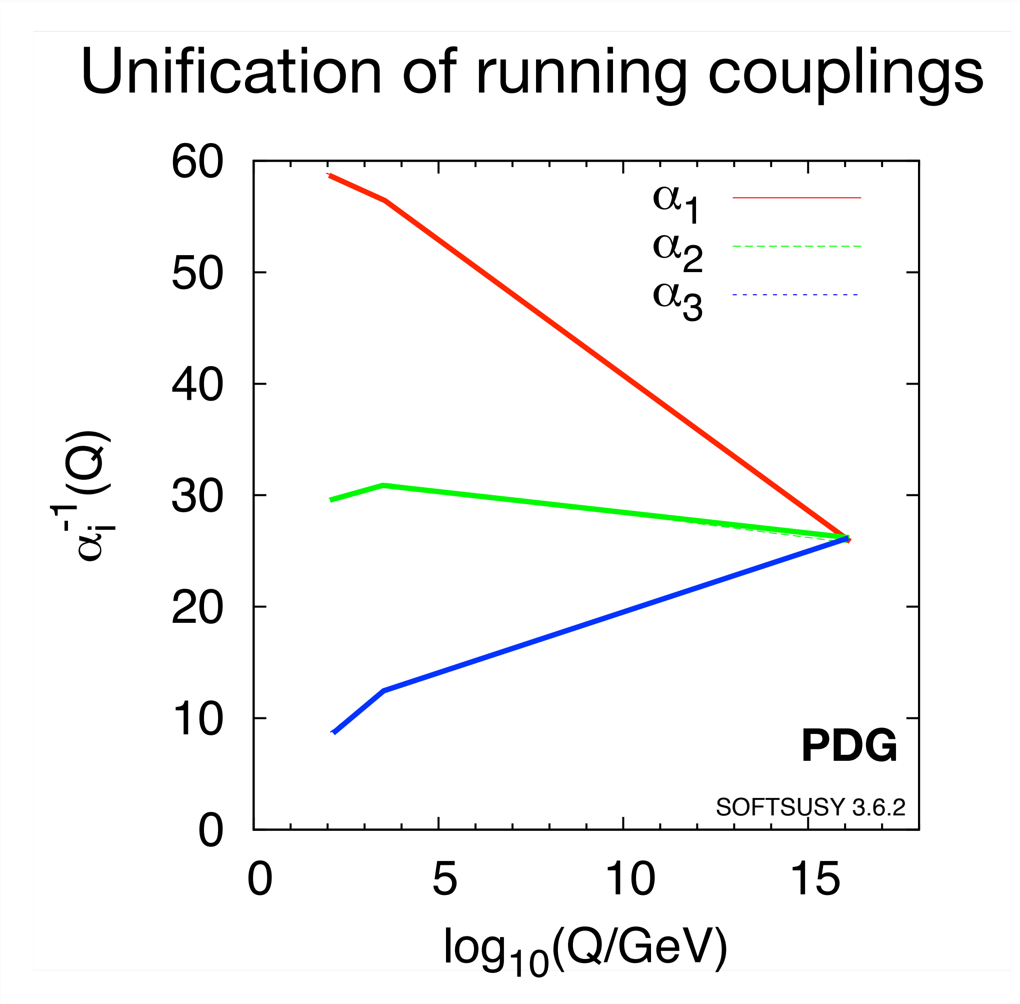
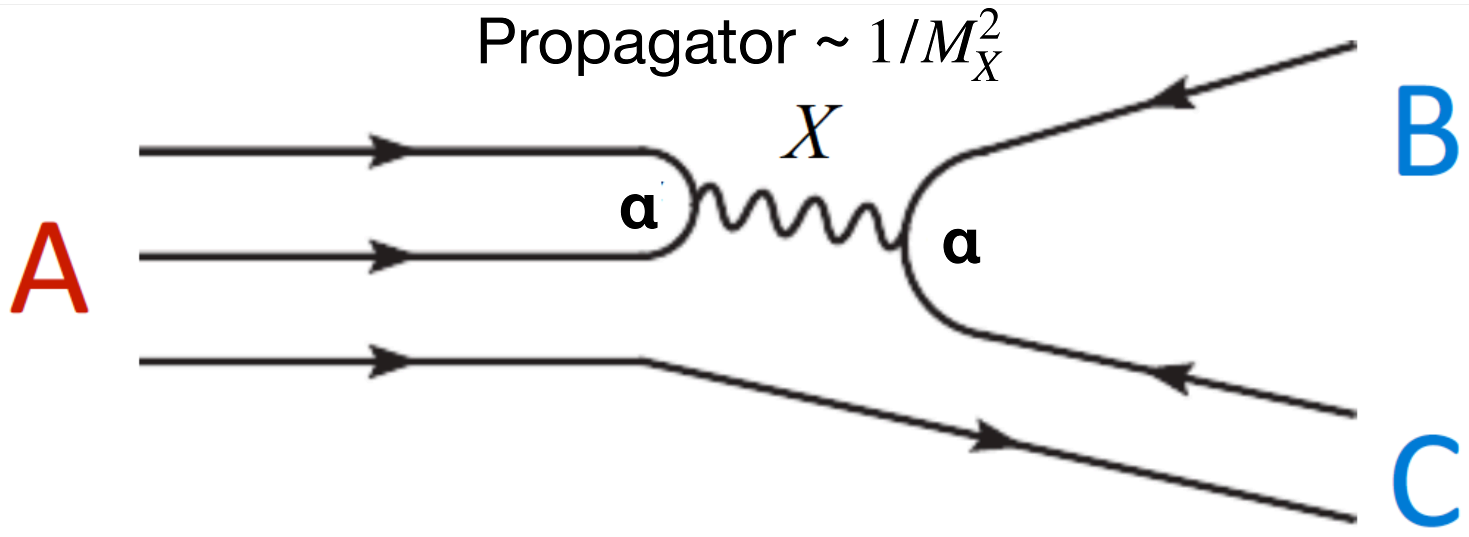
# Proton decay?

- **Proton decays: baryon number *B* and lepton number *L* are not conserved**
  - ex. p→$e^+\pi^0$
- In the Standard Model, baryon number *B* and lepton number *L* are conserved
- **➜ Observation of proton decay clear evidence of beyond the SM**
- Proton decay requires a conversion of quark to lepton
- →Unification of quarks and leptons: justifies equality of electric charge between proton and electron
- Grand Unified Theory (GUT): unification of forces and particles (at $10^{15\text{-}16}$ GeV): baryon number is necessarily violated → proton decay





# Proton decay rate



arXiv:2306.02401

**Life time of particle A**

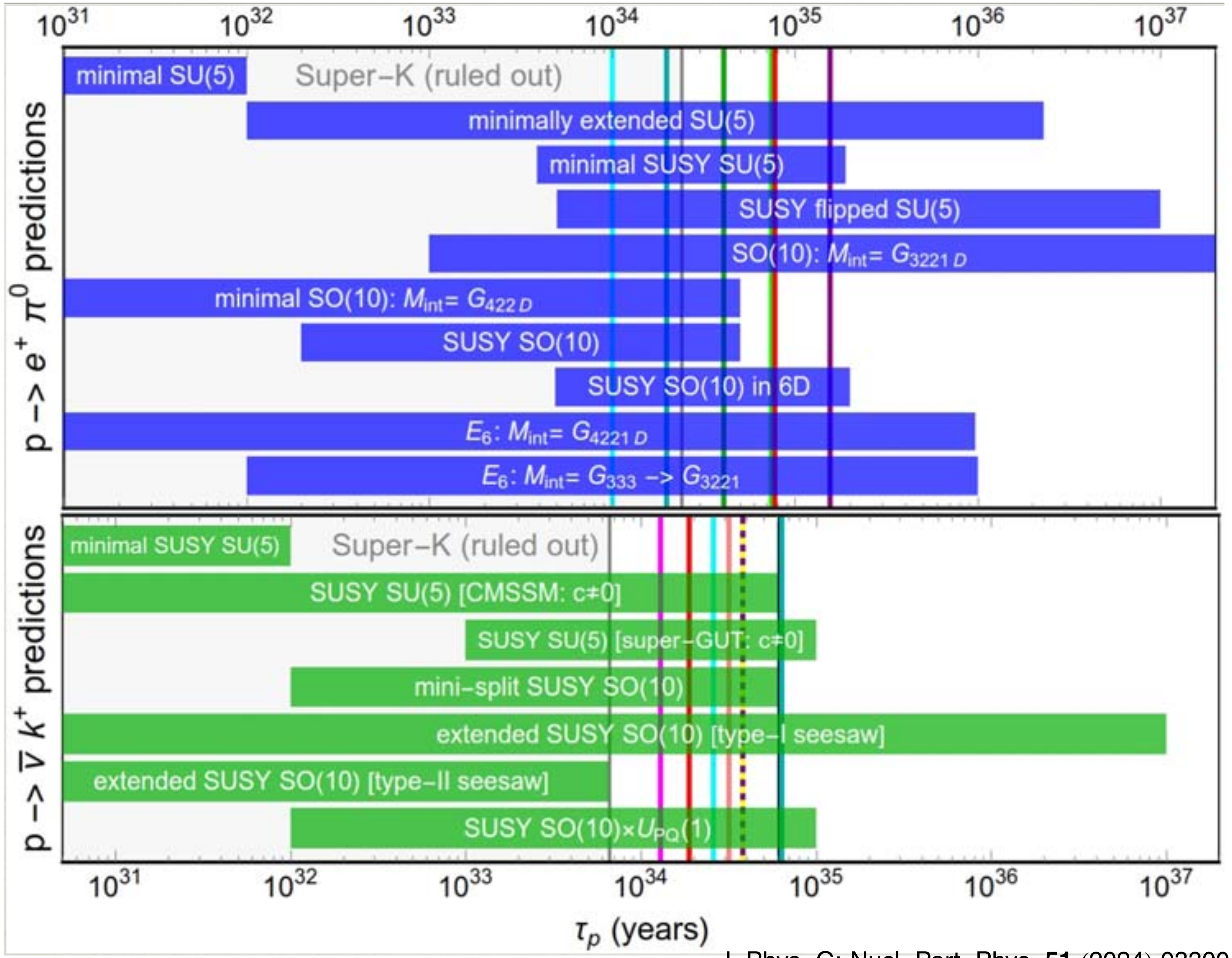
$$\tau = \frac{1}{\Gamma(A \to BC)} \propto \frac{M_X^4}{\alpha^2 m_A^5}$$

- GUT models predict interactions through new super-heavy gauge bosons, *X*, which can mediate proton decay
- Proton lifetime prediction depends on the choice of $M_X$, α and other parameters, operators — model dependence
  - ex. unification at $M_X \sim 10^{14}$, $\alpha \sim 1/40 \rightarrow \tau \sim 10^{30}$
- Search for proton decay constrain those parameters (even if non-observation)
- In GUTs, protons dominantly decay into **$e^+\pi^0$** (in non-SUSY theories) or **$\bar{\nu}K^+$** (in SUSY theories)

# Theoretical predictions

**p→e+π0**

**p→ν̄K+**



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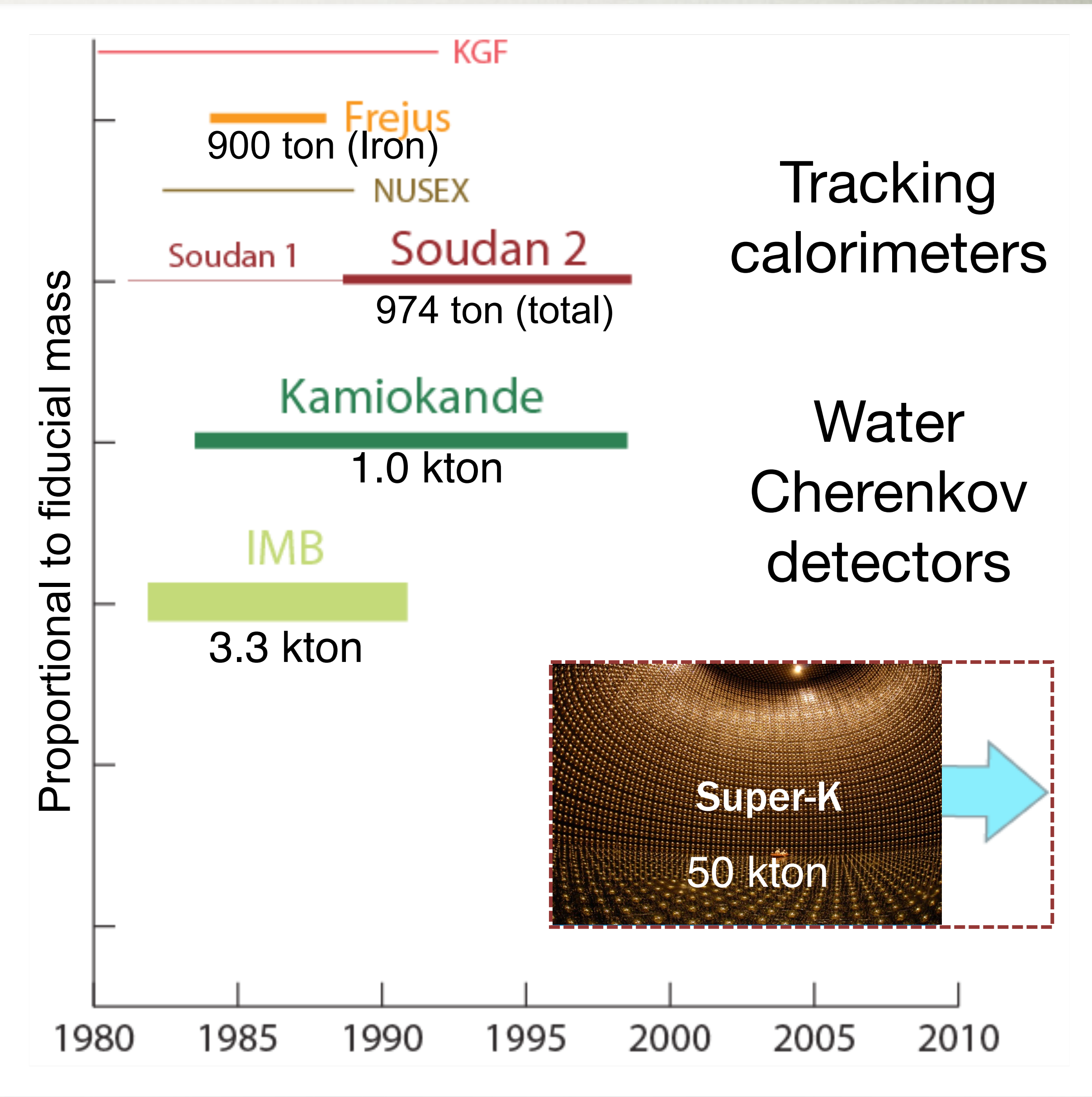
- Numerous and various models continue to be proposed
- Proton lifetime predictions are uncertain by 2-3 or more orders of magnitude
- **Predictions of τ/B ~ $10^{30}$ ~ $10^{37+}$ years**

# Search for proton decay

- A large detector is fundamentally important for proton decay search, which contains a huge number of protons as a detector medium
    - A detector with a small number of protons take $10^{\sim 30}$ years to observe one proton decay
- Super-Kamiokande, the current largest proton decay experiment, sets the most stringent limit on the proton lifetime, ex. $p \rightarrow e^{+}\pi^{0}$, $p \rightarrow \bar{\nu}K^{+}$
    - Super-K has $\sim 10^{34}$ protons in the detector (water)

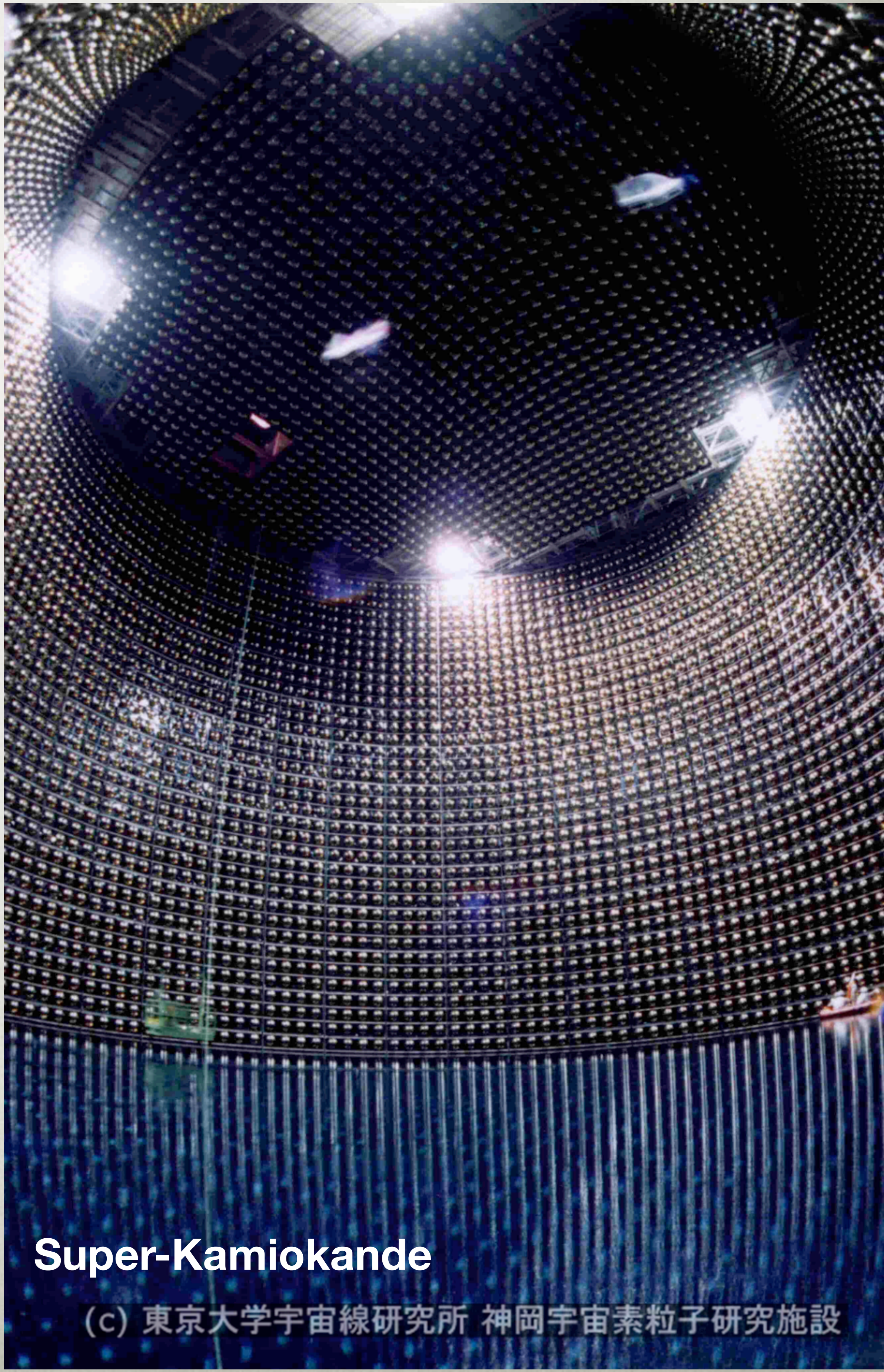


Original figure by E. Kearns

# Super-Kamiokande

- 42m (H) x 39m (D) large water Cherenkov detector filled with 50 kton ultra-pure water
- Fiducial mass 27.2 kton
  - (conventional 22.5 kton)
  - ~$10^{34}$ protons in Super-K
    - Hydrogen (free proton) ~$10^{33}$
- Data taking from 1996 and on-going now

- Excellent particle identification (μ and e)
  - Mis-PID rate <1% at ~1GeV
- Good energy resolution
  - ~3% at ~1GeV



**Super-Kamiokande**

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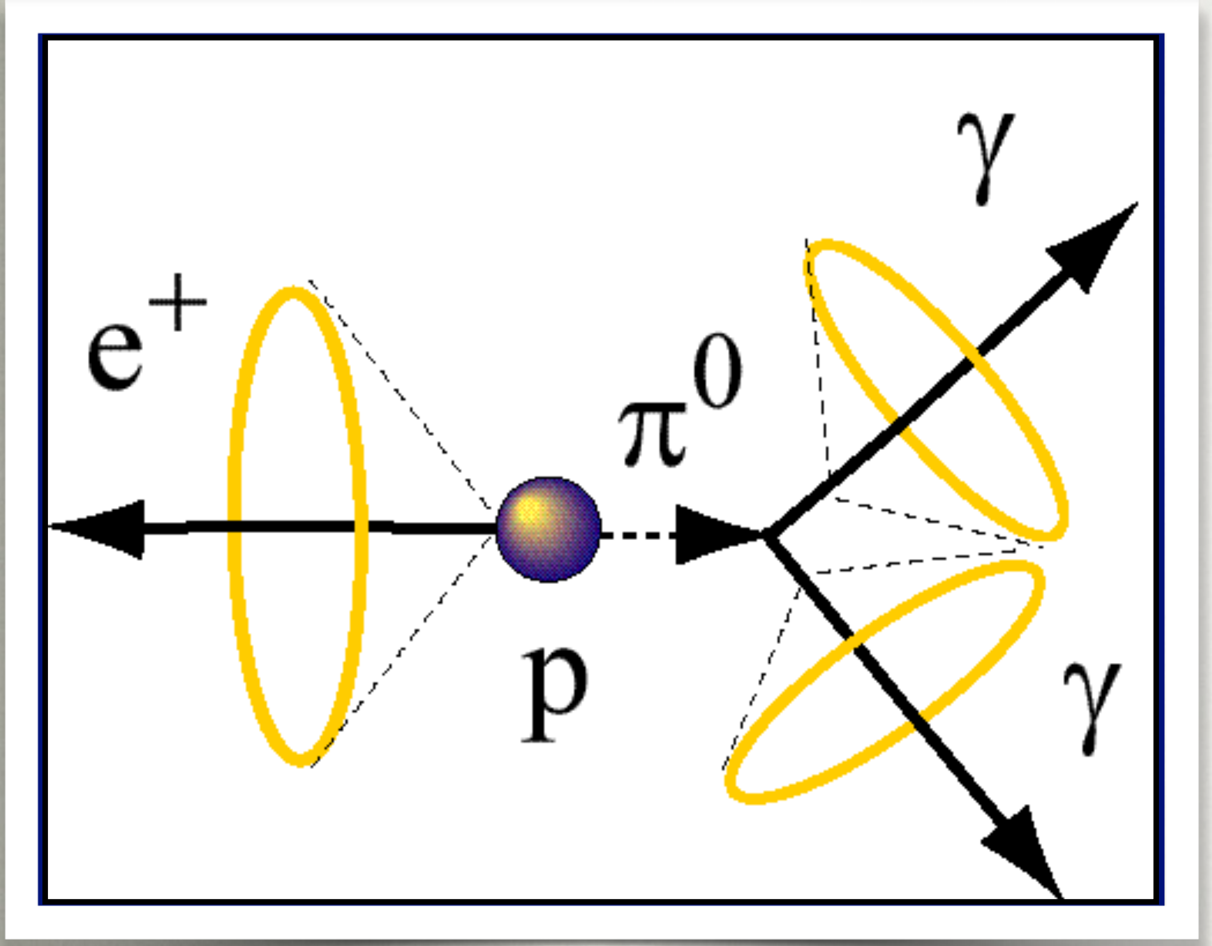
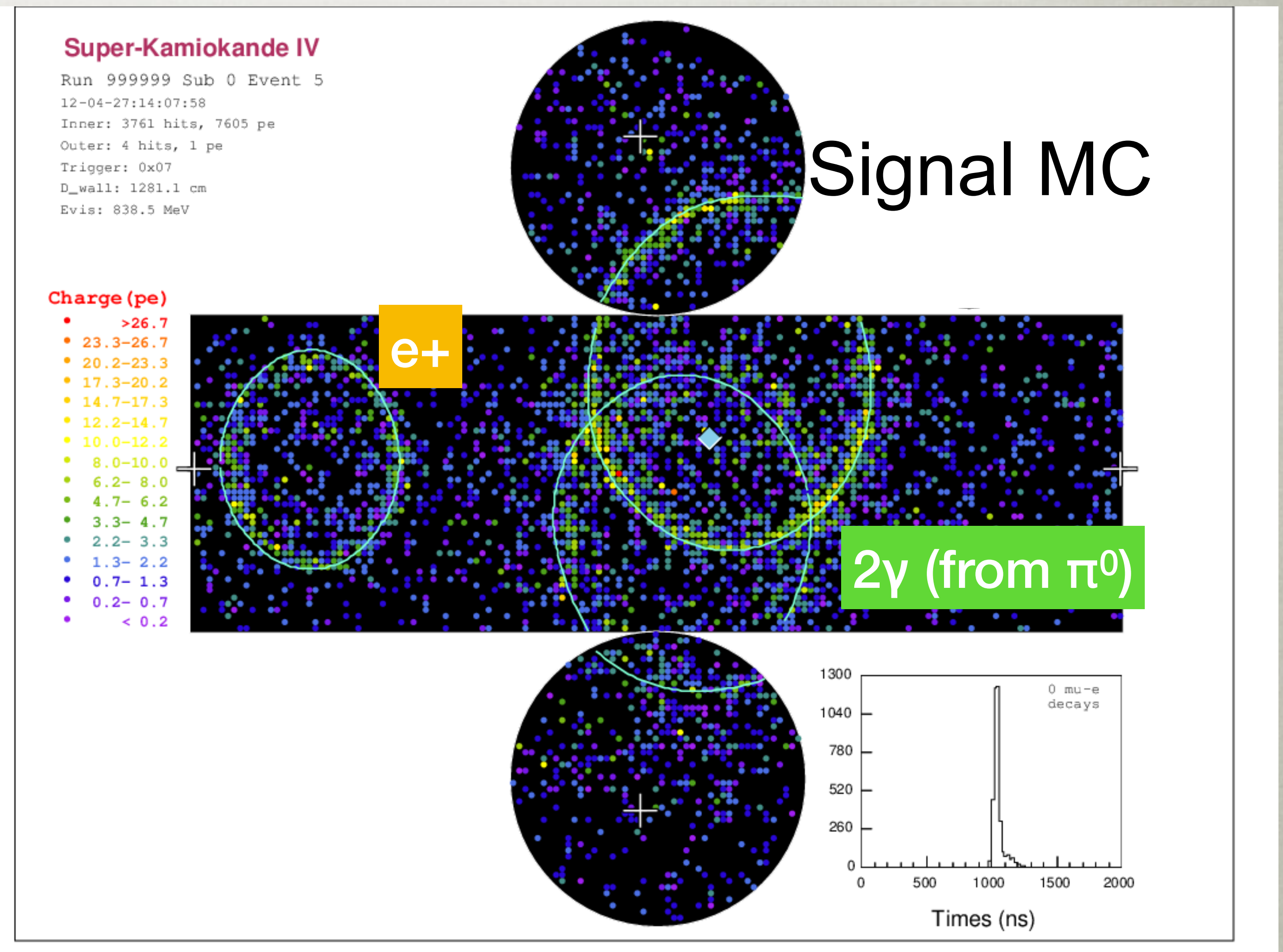
# Search for $p \rightarrow e^{+}\pi^{0}$ in Super-K

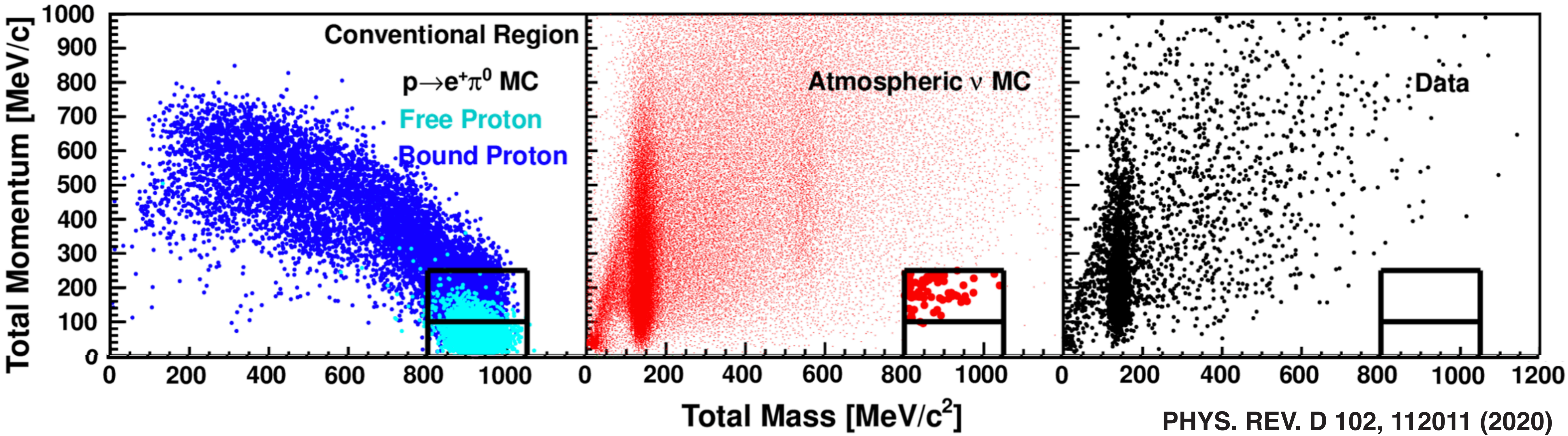




- **Positron and $\pi^{0}$ run back-to-back**
  - Momentum 459 MeV/c
- **All particles in the final state are visible with Super-K**
  - **Able to reconstruct proton mass and momentum**

- Event selection:
  - All particles are fully contained in FV
  - 2 or 3 rings (two of them from π0)
  - All particles are e-like, w/o Michel-e
  - $85 < M_{\pi 0} < 185$ MeV/c²
  - $800 < M_{p} < 1050$ MeV/c²
  - $100 < P_{tot} < 250$ or $P_{tot} < 100$MeV/c
  - Neutron-tagging (SK-IV~)
    - Further reduce bkg by ~50%

# Search for $p\to e^+\pi^0$ in Super-K



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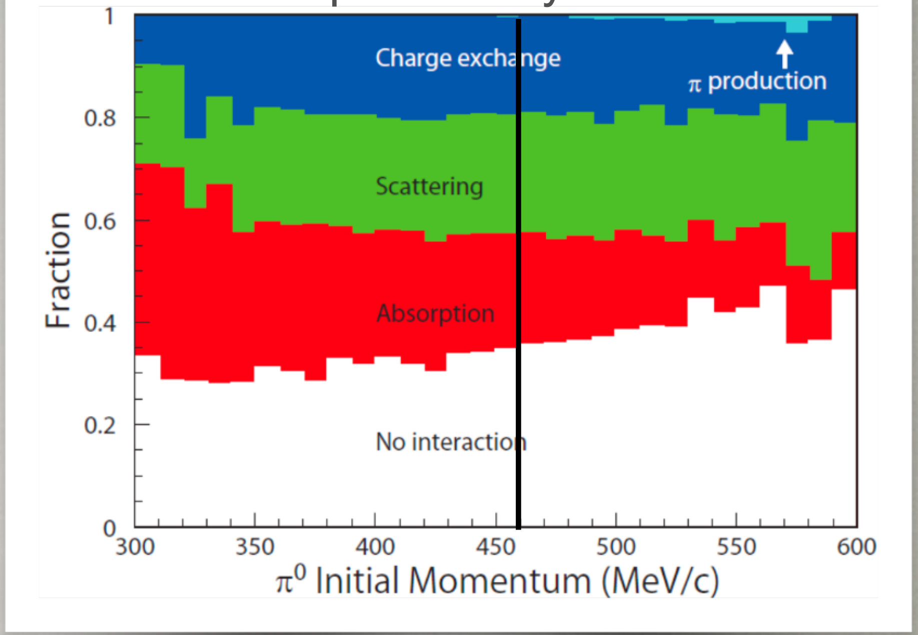
- Signal selection efficiency: ~40%
  - cf. ~80% for free proton decay
  - → Inefficiency due to “nuclear effect” (see next slides)
- Expected background in signal region (SK-I~IV):
  - Lower $P_{tot}$: 0.06 events ←free proton enriched signal region
  - Upper $P_{tot}$: 0.58 events
- No evidence of the proton decay with ~17y exposure
- **$\tau/B(p\to e^+\pi^0) > 2.4\times10^{34}$ years** at 90% C.L.

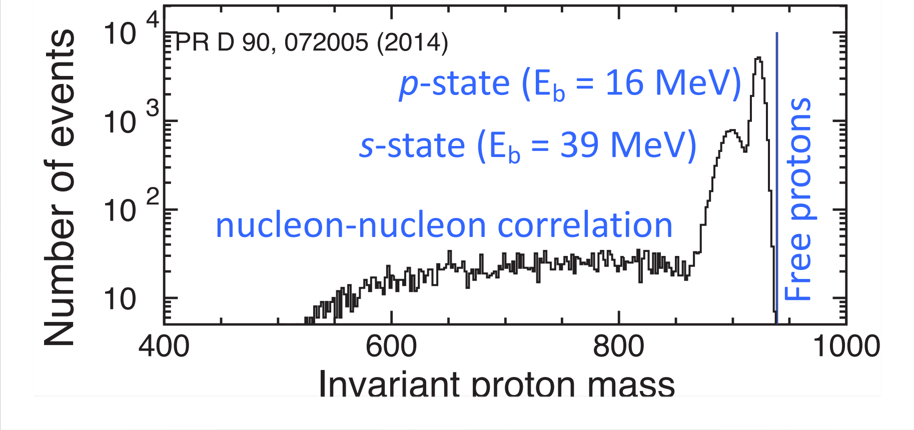
# Nuclear modeling of proton decay signal

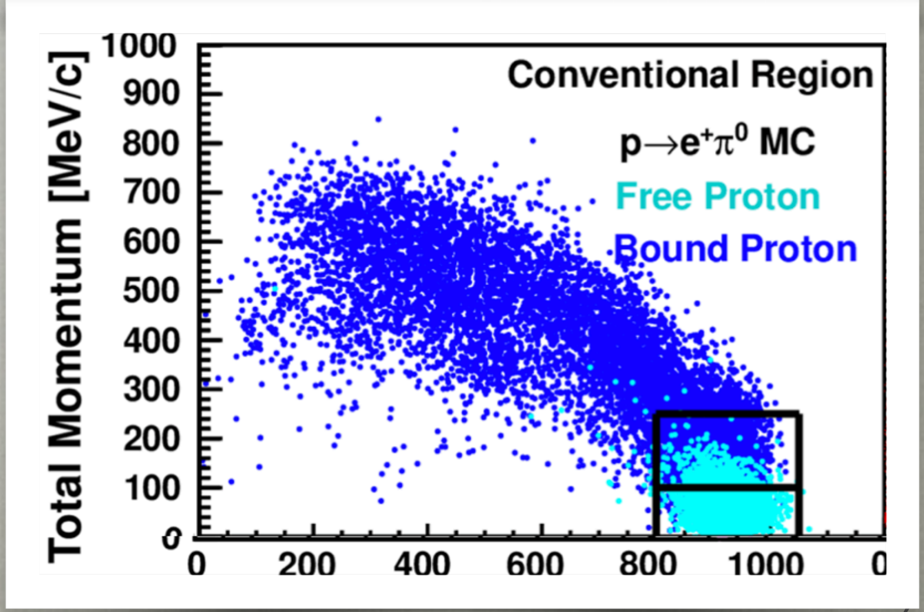
- One of major causes of signal inefficiency is due to **final state interaction (FSI) of π inside the parent nucleus**
  - ~50% of $\pi^0$ are affected by interactions with nucleons in the parent nucleus (scattering, absorption, charge exchange)
- **Bound proton** influenced with Fermi motion, binding energy, correlation with other nucleons that also cause signal inefficiency
- **An advantage of water Cherenkov detector is to have 'free protons'**
  - cf. $p \rightarrow e^+\pi^0$ signal selection efficiency:
    in oxygen: ~40%,
    in hydrogen: 80+%

Interaction probability of $\pi^0$ in $^{16}O$



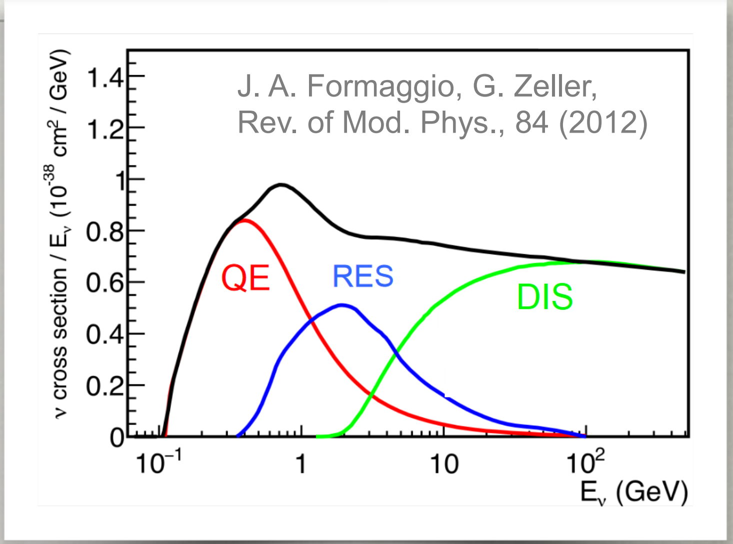
Invariant proton mass

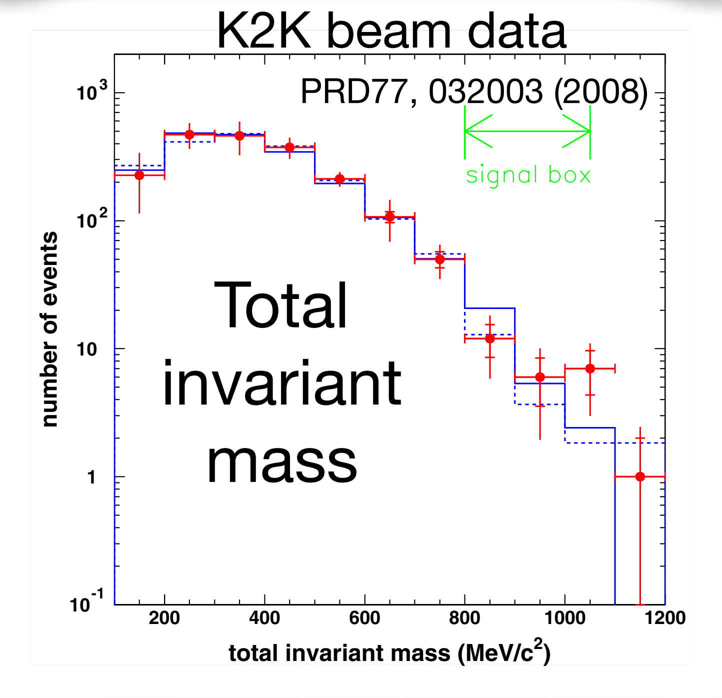




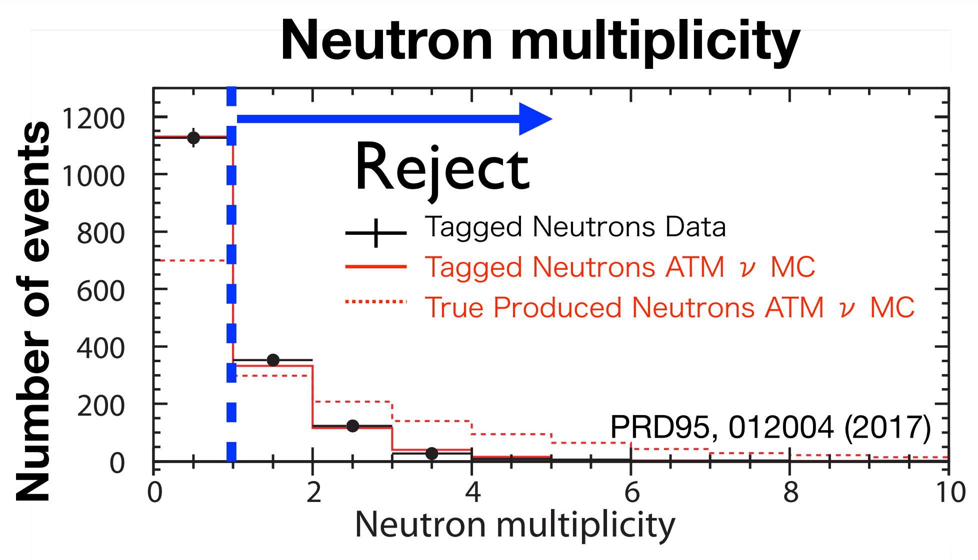
# Background in proton decay search

- **Background for proton decay search**
  - Sole background: atmospheric neutrinos
  - Background fraction in $p \to e^+\pi^0$ search
    - CC resonance, multi-π (DIS): ~70%
    - CC QE + secondary interaction producing π: ~20%
    - NC interactions: ~10%
  - Neutrino interaction models have uncertainties
  - **➜ Background rate prediction confirmed with ν beam data of K2K-1KT Cherenkov detector**





- **Reducing background**
  - ~60% of atm-ν bkg are accompanied with neutrons — neutrons captured by hydrogen (~200μs) & emit 2.2 MeV γ-ray ($p+n \to d+\gamma$)
  - Dead-time free electronics in SK-IV~ allows to identify the 2.2MeV γ-ray, **'neutron-tagging'**
    - Tagging efficiency ~25%
  - **➜ Atmospheric ν bkg further reduced by ~50% with neutron-tagging**

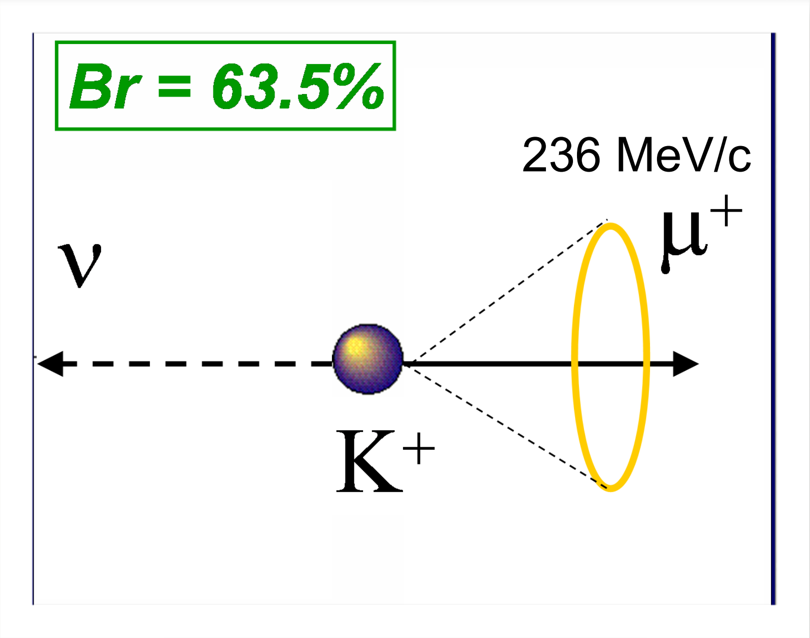


# Search for $p \to \bar{\nu} K^+$ in Super-K

- Final state $K^+$ has momentum of 340 MeV/c
  - Below Cherenkov threshold (560 MeV/c)
- **Identify $K^+$ by finding its decay products**

## $K^+ \to \mu^+ \nu_\mu$

(K+ **leptonic** decay)

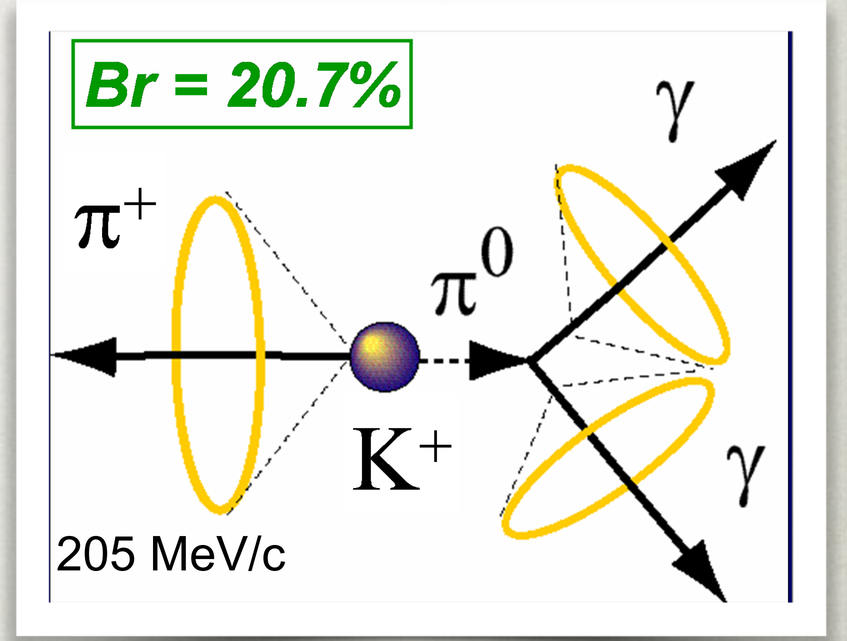


Search Methods

- Nuclear de-exitation γ, μ, and decay e+
- Monochromatic μ from K+ decay

## $K^+ \to \pi^+ \pi^0$

(K+ **hadronic** decay)

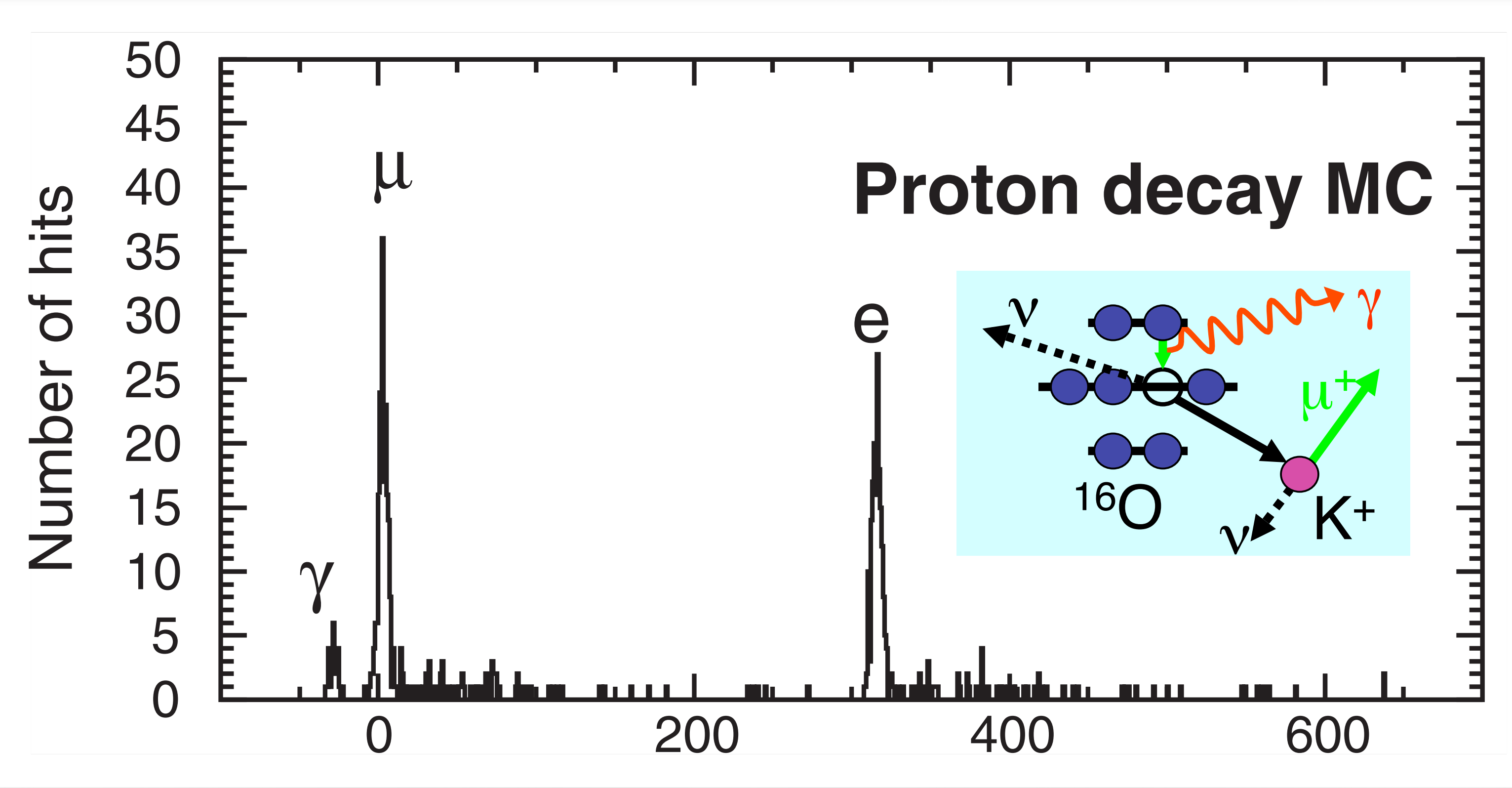


Search Method

- π+ and two γ from π0 decay (π+ Č threshold 156MeV/c)

# Search for $p \to \bar{\nu} K^+$ : K+ leptonic decay

- Proton decays in $^{16}O$ → Excited nucleus ($^{15}N^*$) emits 6.3 MeV γ-ray (~40% probability)
  - $^{16}O \to \bar{\nu} K^+ \, ^{15}N + \gamma$, $K^+ \to \mu + \nu$ (BR=65%), $\mu \to \nu e$
- γ, μ and Michel-e from μ-decay triple coincidence largely reduce the background
- Signal selection efficiency ~10%



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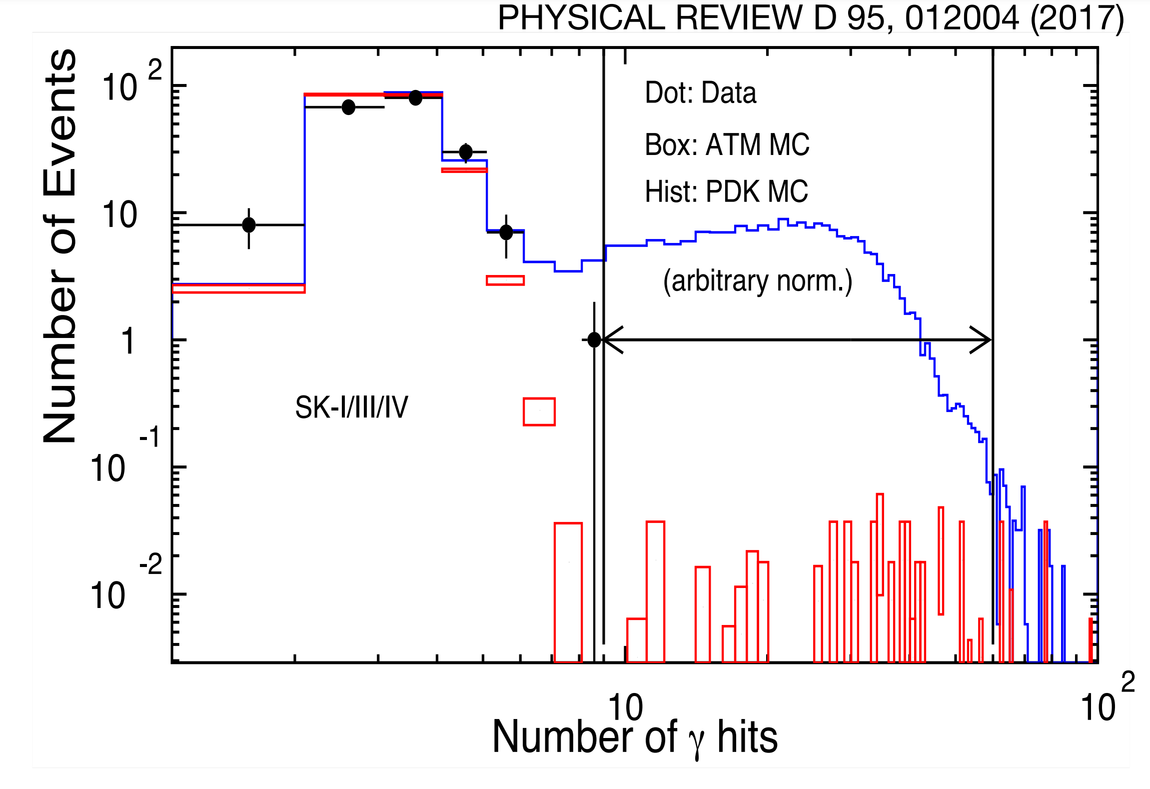
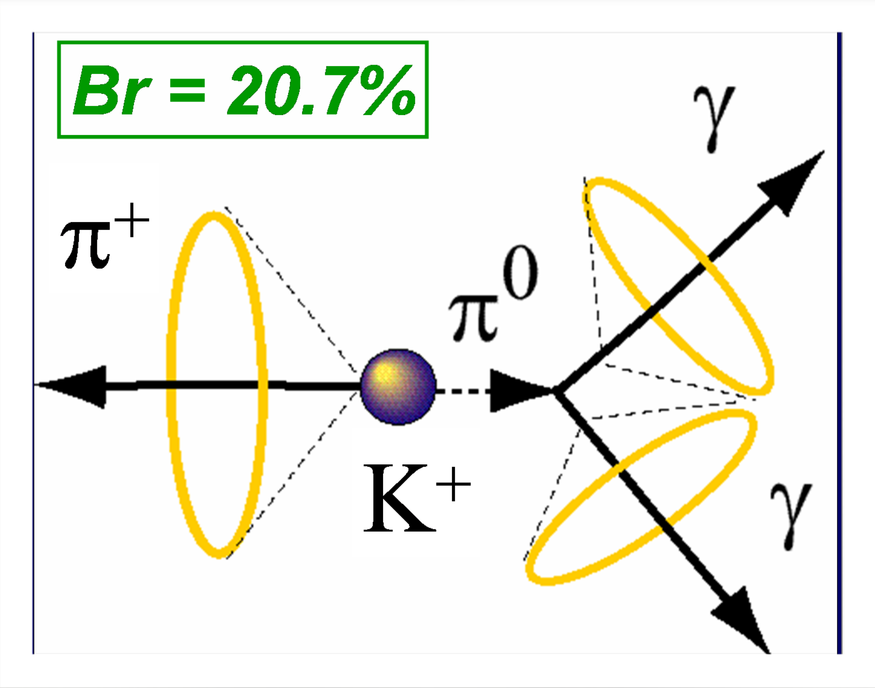
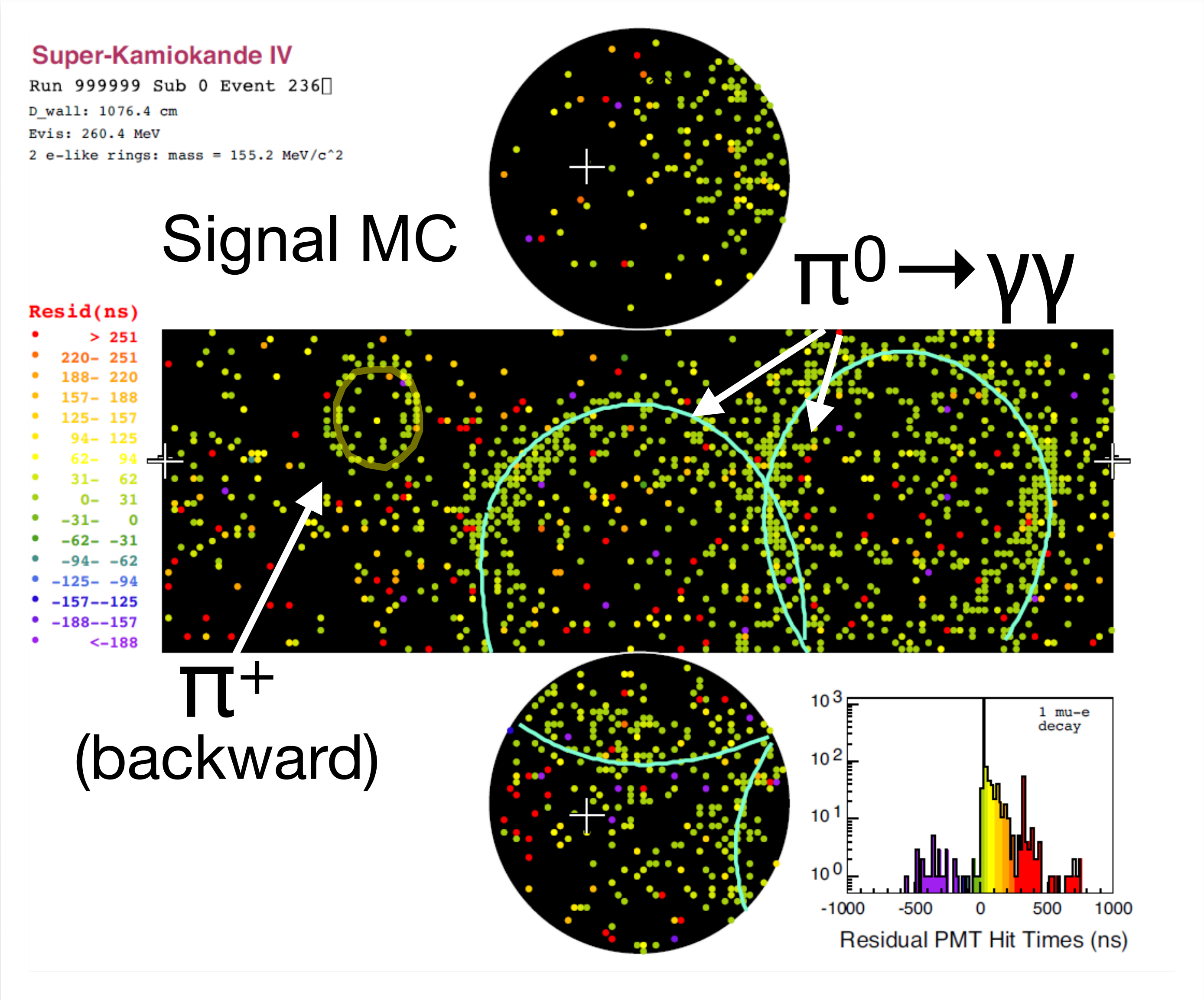


# Search for $p \to \bar{\nu} K^+$ : $K^+$ hadronic decay



**$K^+ \to \pi^+ \pi^0$:**
**$\pi^+$ and $\pi^0$ run back-to-back with 205 MeV/c**

Signal efficiency ~10%



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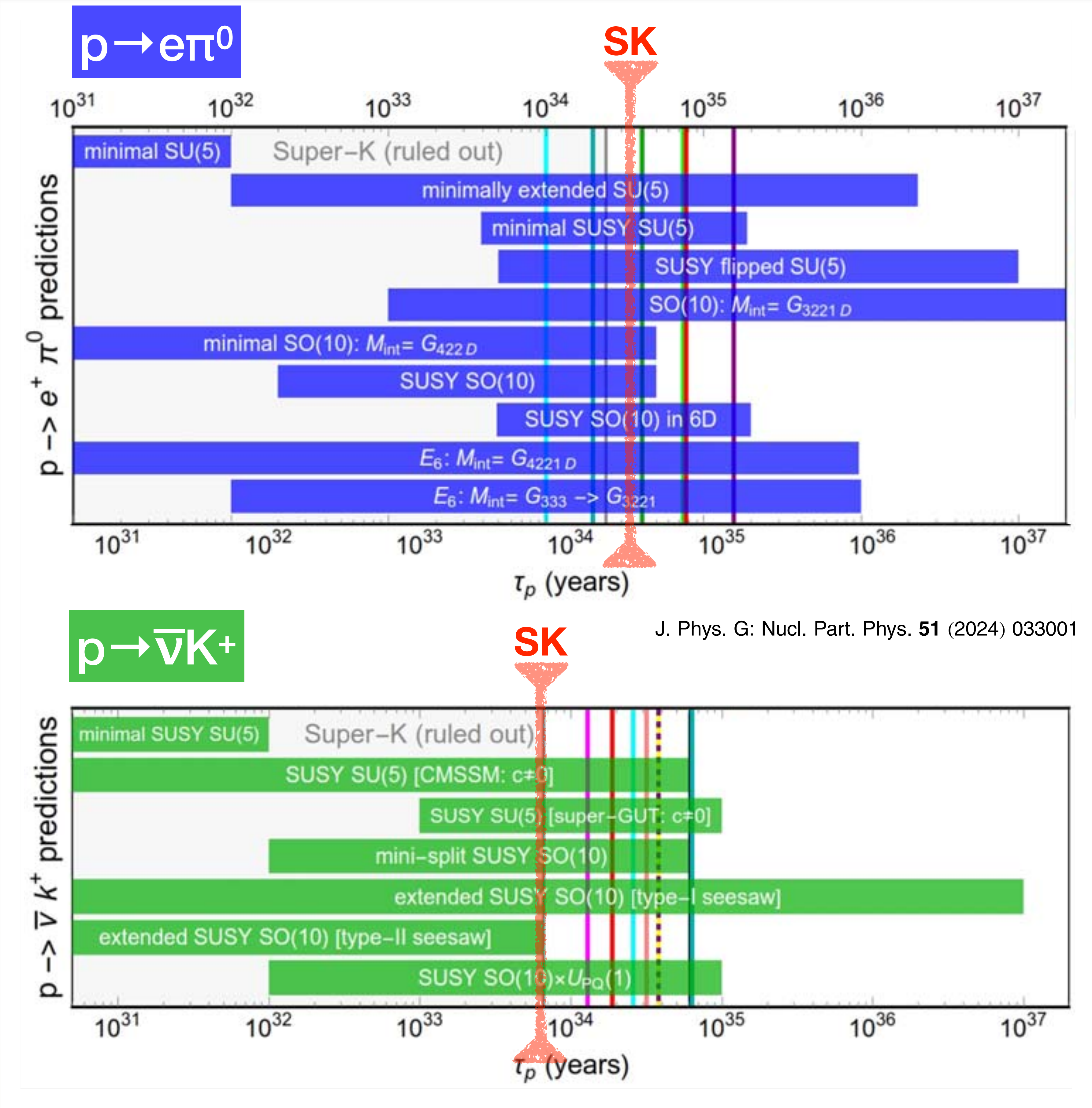
- **Found no evidence of $p \to \bar{\nu} K^+$**
- Lifetime limit combining all search methods:
  **$\tau/Br > 8.2 \times 10^{33}$ years** [preliminary]
    - at 90% C.L. with 365 kt·years (SK-I~IV)

# Results of proton decay searches, so far



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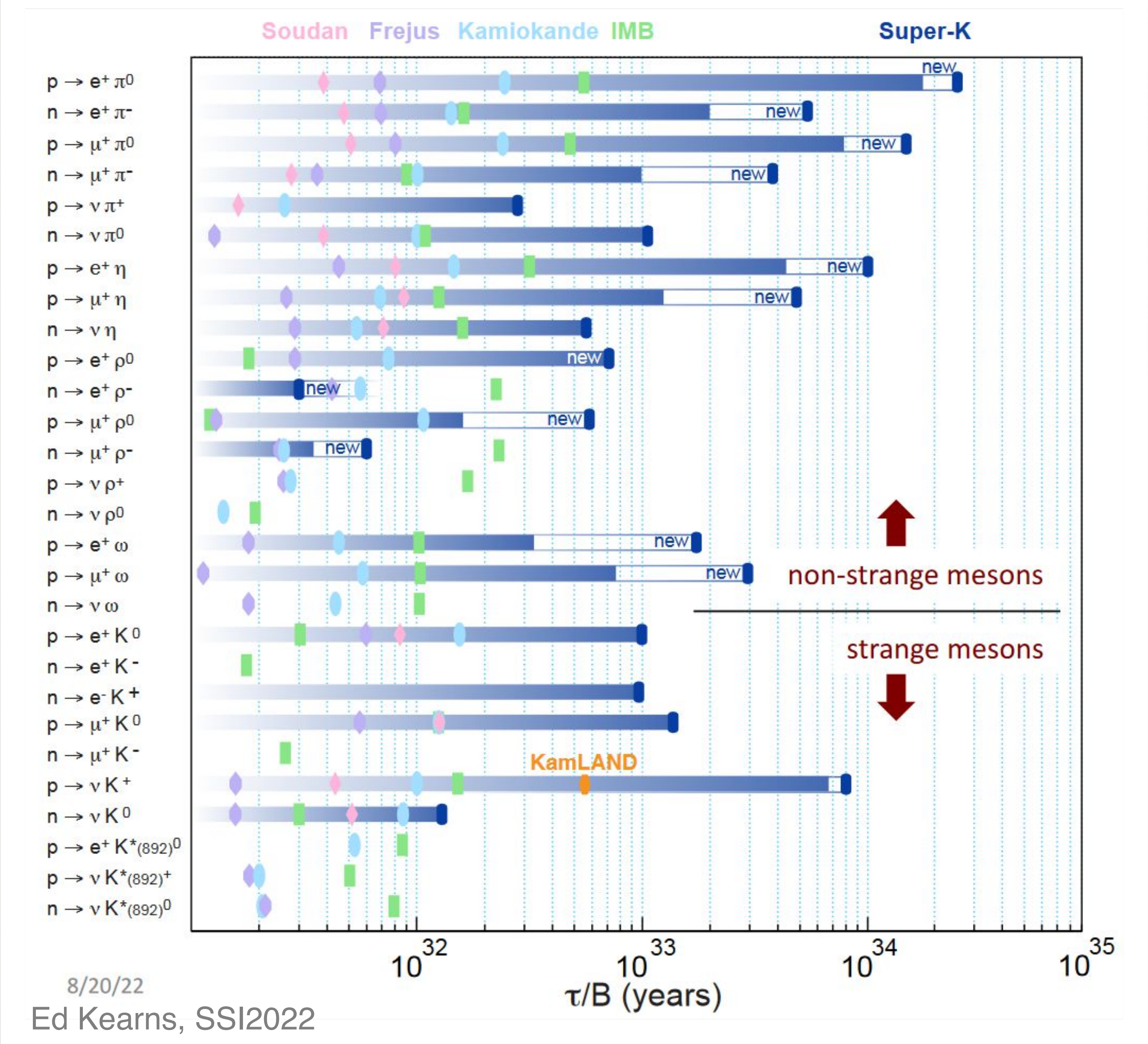
- Super-K sets most stringent lifetime limits for benchmark decay modes: $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$
- Many other decay modes searched with Super-K

# Results of nucleon decay searches, so far

List of all antilepton+meson, 2-body decay modes: conserves B-L



8/20/22

Ed Kearns, SSI2022

- There are many other results for other modes and processes
  - e.g. 3-body, 4-body, dinucleon decays, etc.
- Unfortunately — no signal, all limits, so far

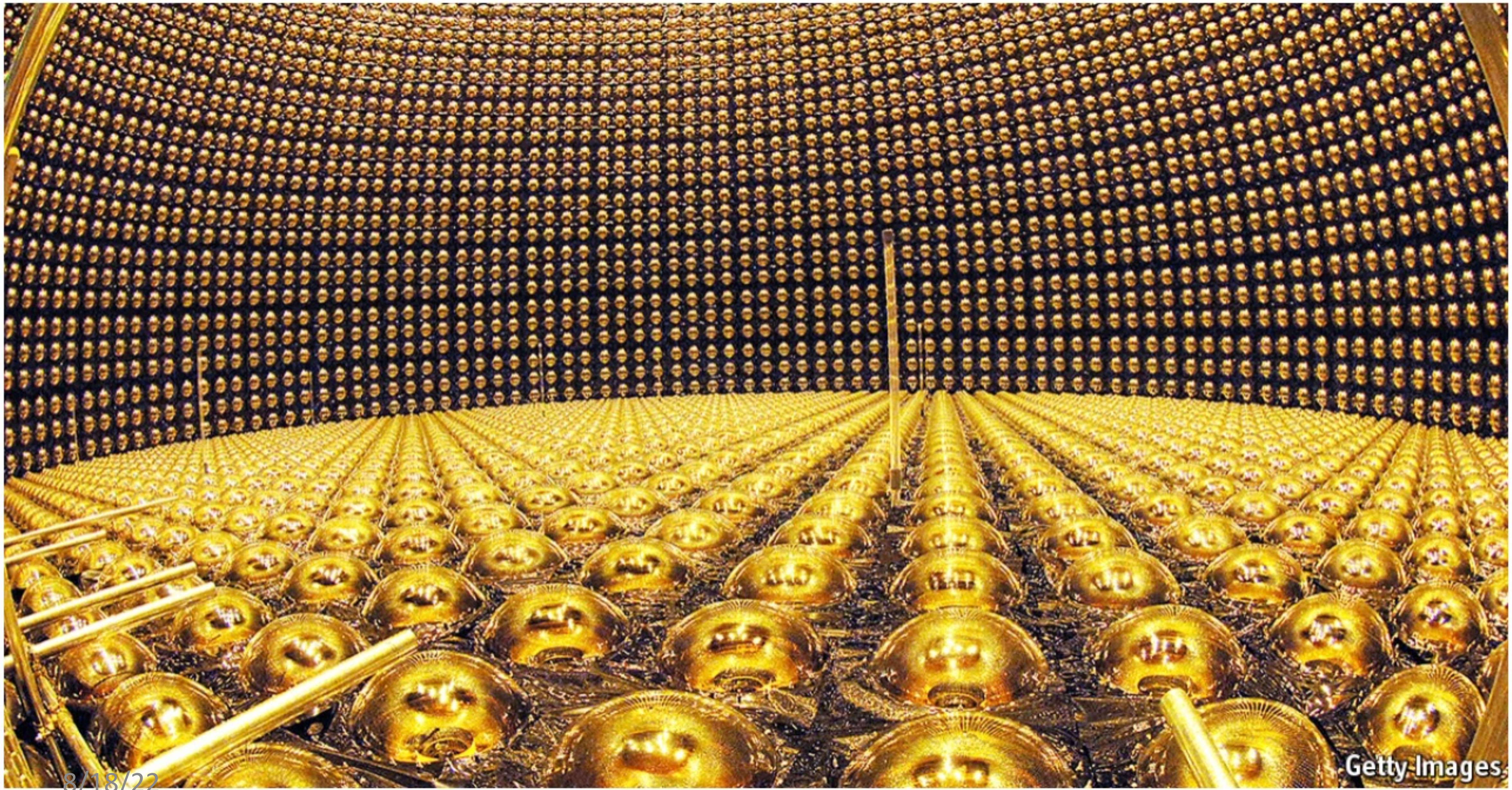
Particle physics

# Fundamental physics is frustrating physicists

The Economist

*No GUTs, no glory*

Jan 13th 2018



https://www.economist.com/news/science-and-technology/21734379-no-guts-no-glory-fundamental-physics-frustrating-physicists

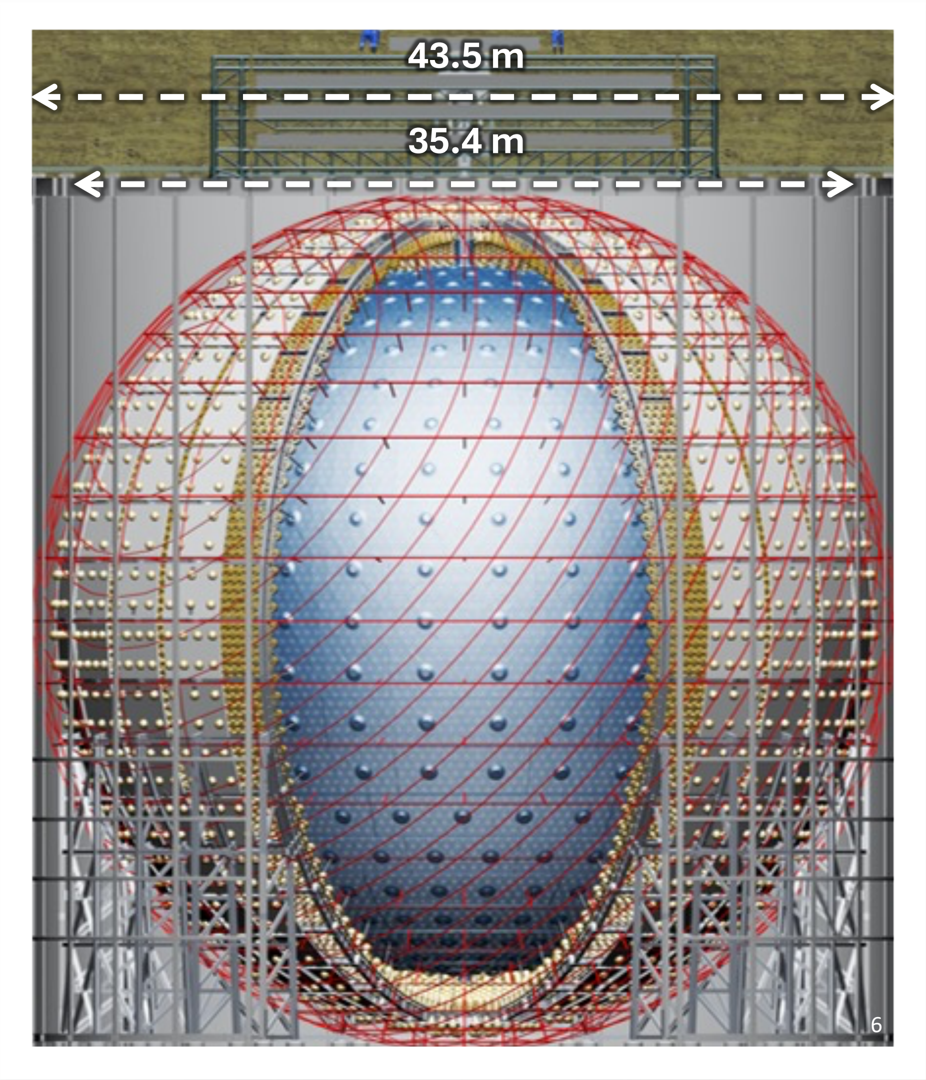
# Next generation nucleon decay detectors

**Detectors just started operation and currently under construction**

- **JUNO**
  - Jiangmen Underground Neutrino Observatory in China
  - Liquid scintillator: 20 kton
  - Data taking started this August
- **DUNE**
  - Deep Underground Neutrino Experiment in the U.S.
  - Liquid argon detector: ~40 kton
  - Data taking starts in 2030
- **Hyper-Kamiokande**
  - Kamioka in Japan
  - Water Cherenkov detector: 260 kton
  - Data taking starts in 2028

# JUNO: liquid scintillator

- Overburden: 650m
- 20 kton of liquid scintillator
  - Number of protons: ~$10^{34}$ (~$10^{33}$ free protons)
- 78% photo-coverage
  - 17,612 20” PMTs and 25,600 3” PMTs
- Very high energy resolution at 1 MeV
- Primary physic goal is determination of neutrino mass ordering using reactor neutrino
- Liquid scintillator filling has been completed and started data taking this August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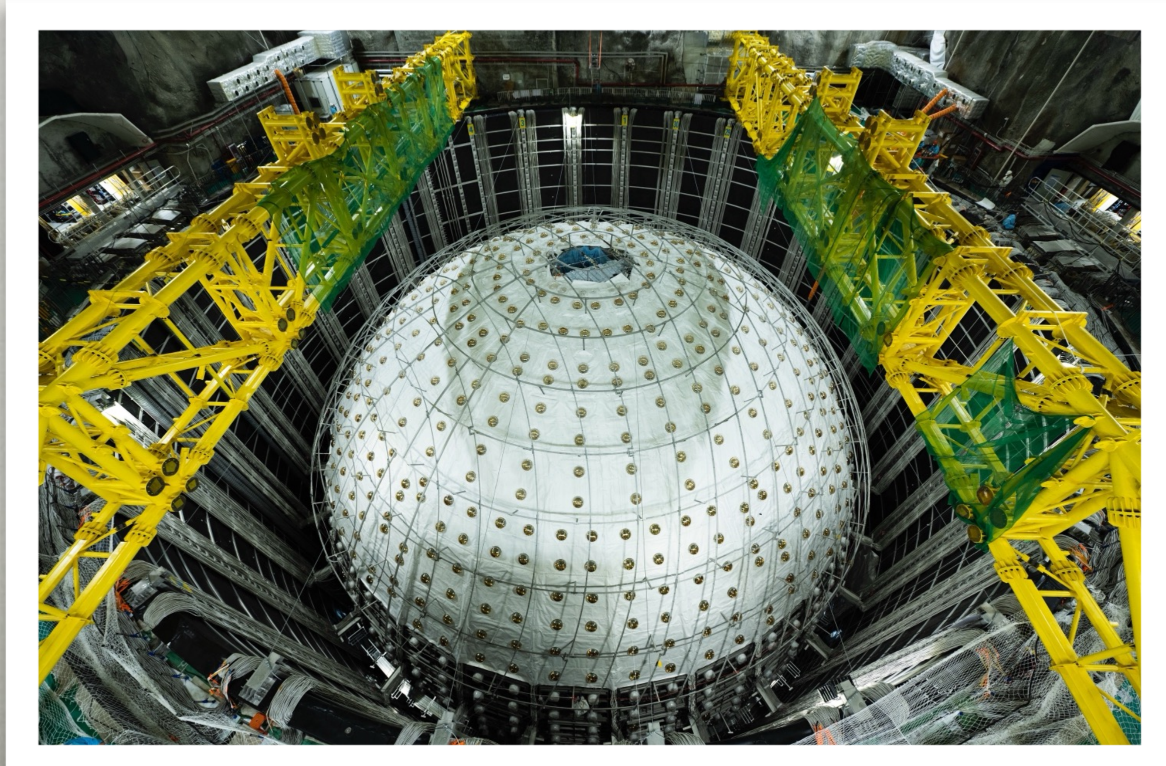
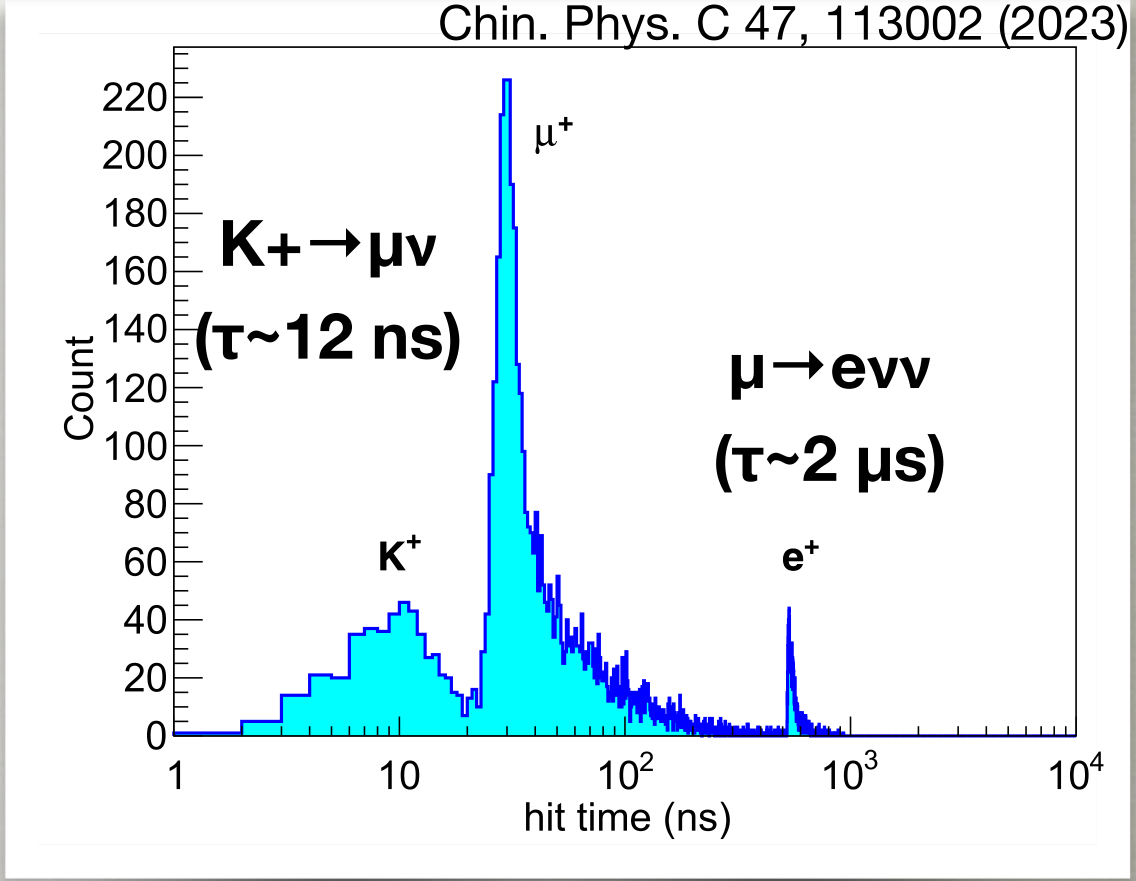
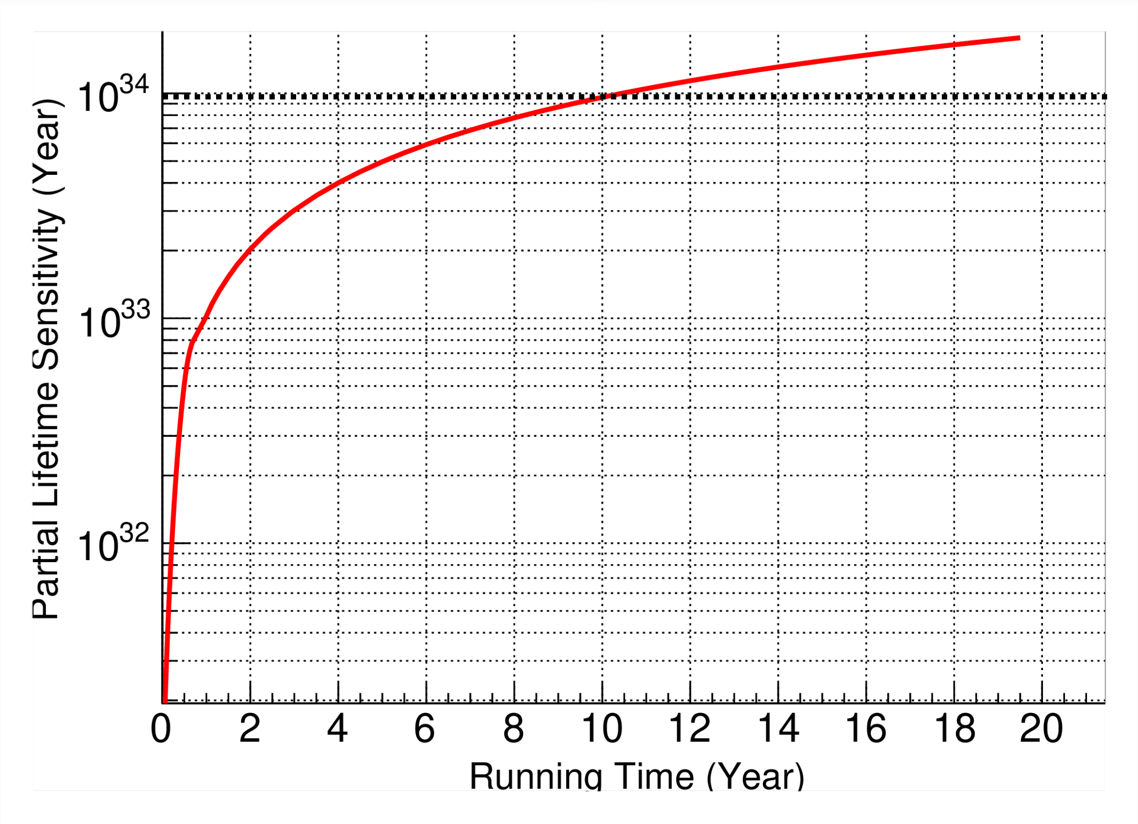


# JUNO: liquid scintillator

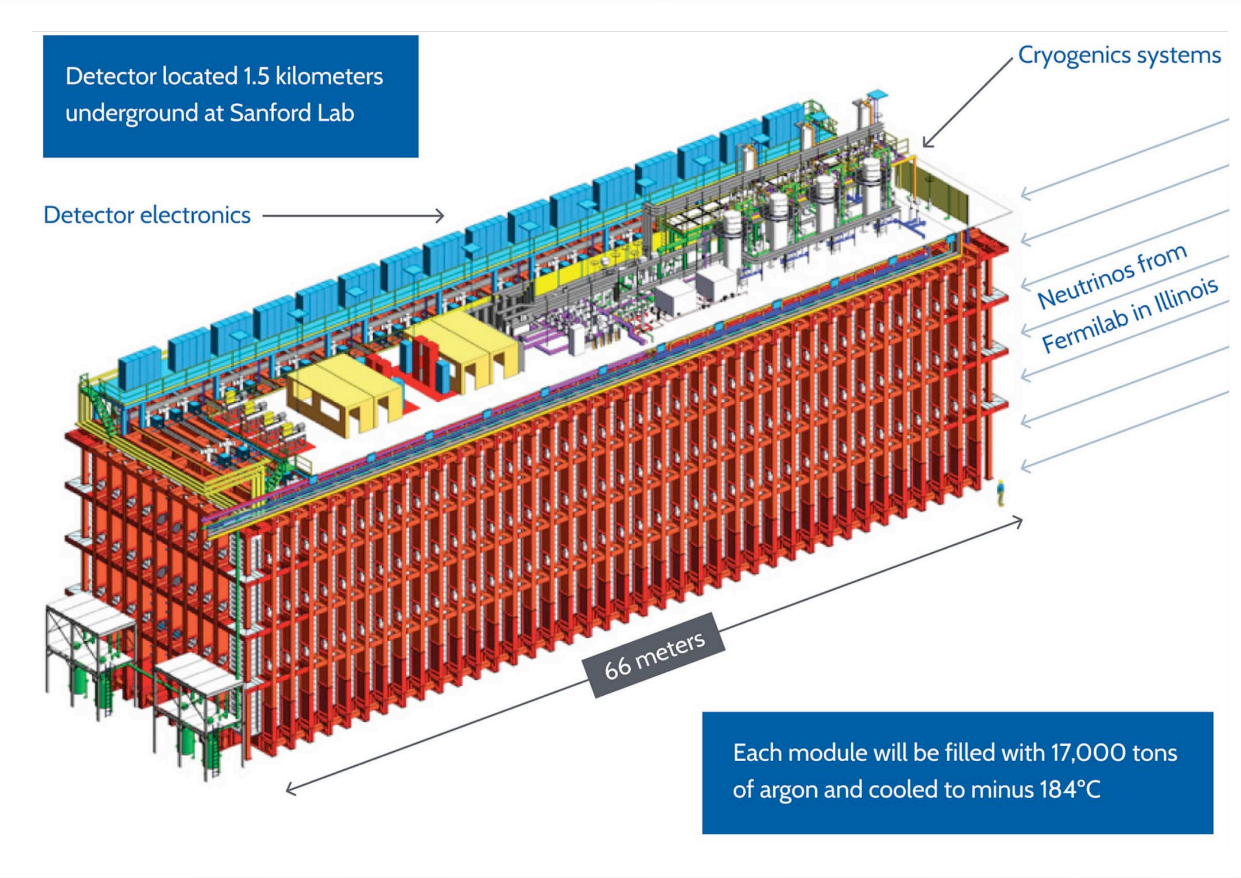
- All of the charged particles inside emit scintillation light
- Good at searching for p→v̄K+ by requiring the triple coincidence: signal efficiency 36.9%, 0.2 bkg (10 years)
  - Great suppression of bkg from atm-ν K production, major bkg is proton from CCQE (p mimics K)
- Reaches the sensitivity of **$10^{34}$ years for p→v̄K+** in 10 years
  - Reach Super-K limit in a couple of years

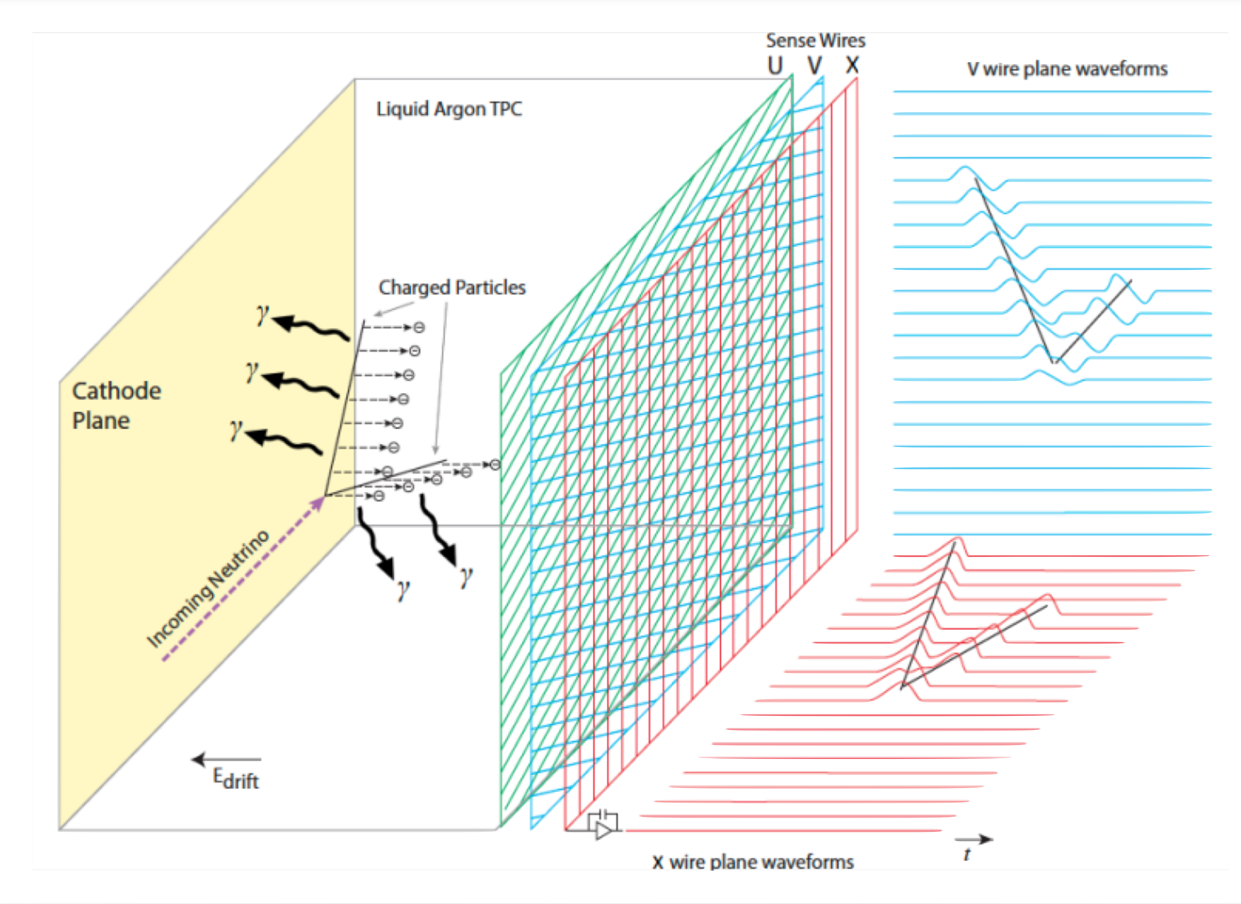




# DUNE: liquid argon TPC

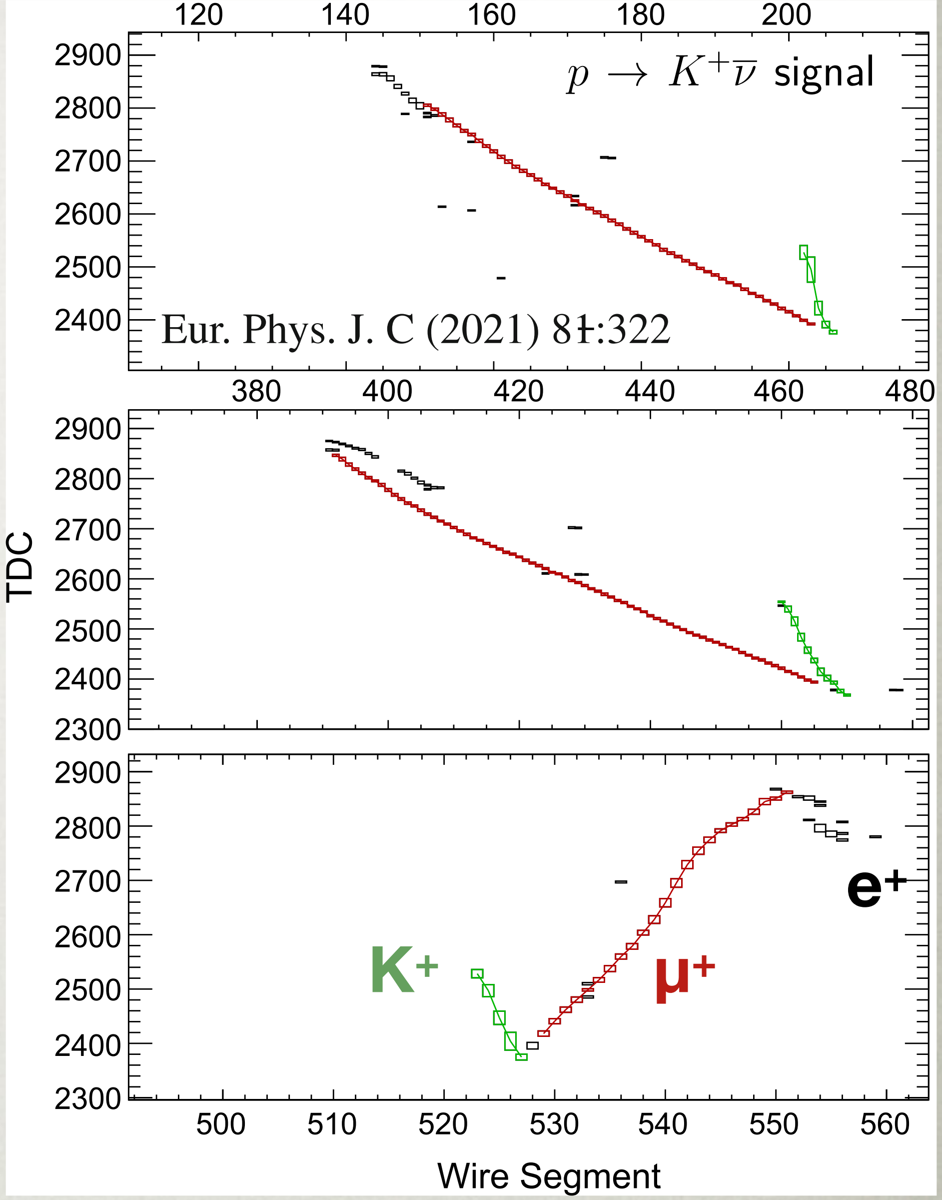
- Overburden: 1,500m
- 40 kton of Liquid argon
  - Number of protons: ~$10^{34}$
- TPC gives 3D particle tracking with excellent resolutions for position and energy
- Primary physic goal is determination of neutrino CP and mass ordering using neutrino beam
- Detector construction on-going and start data taking in 2030

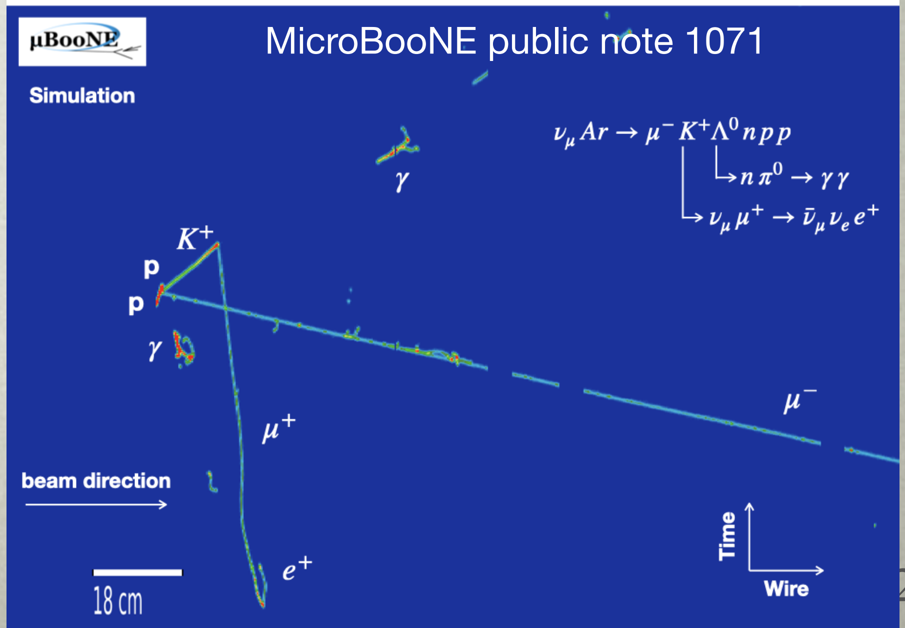




# DUNE: liquid argon TPC

- All charged particles visible
- Good at searching for $p\to\bar{\nu}K^+$
  - Particle type identified by the deposited energy over its track length (dE/dx).
- Atmospheric ν are the main background source (K production)
  - Machine-learning technique separate signals & backgrounds
  - ν-Ar interaction studies on-going
- Signal selection efficiency: ~30%
- Search sensitivity for $\mathbf{p\to\bar{\nu}K^+}$ reach **$\sim10^{34}$ years**
- Also search for $\mathbf{p\to e^+\pi^0}$ mode with search sensitivity **$\sim10^{34}$ years**

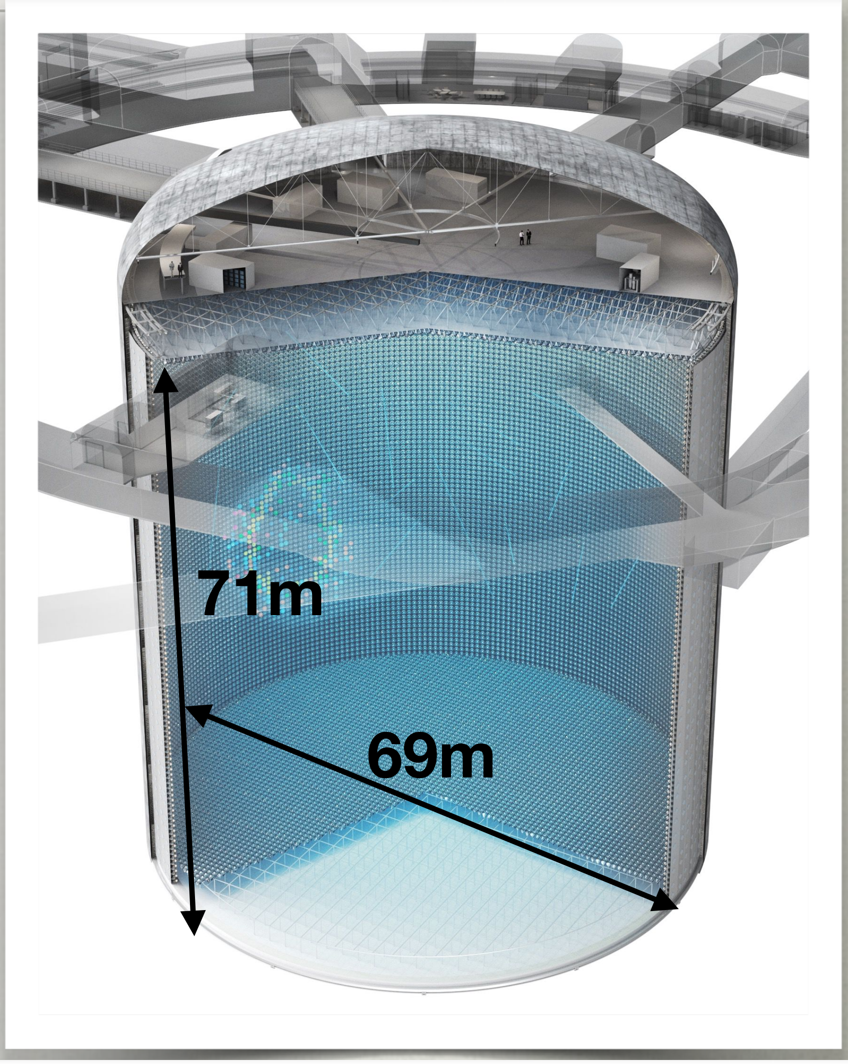


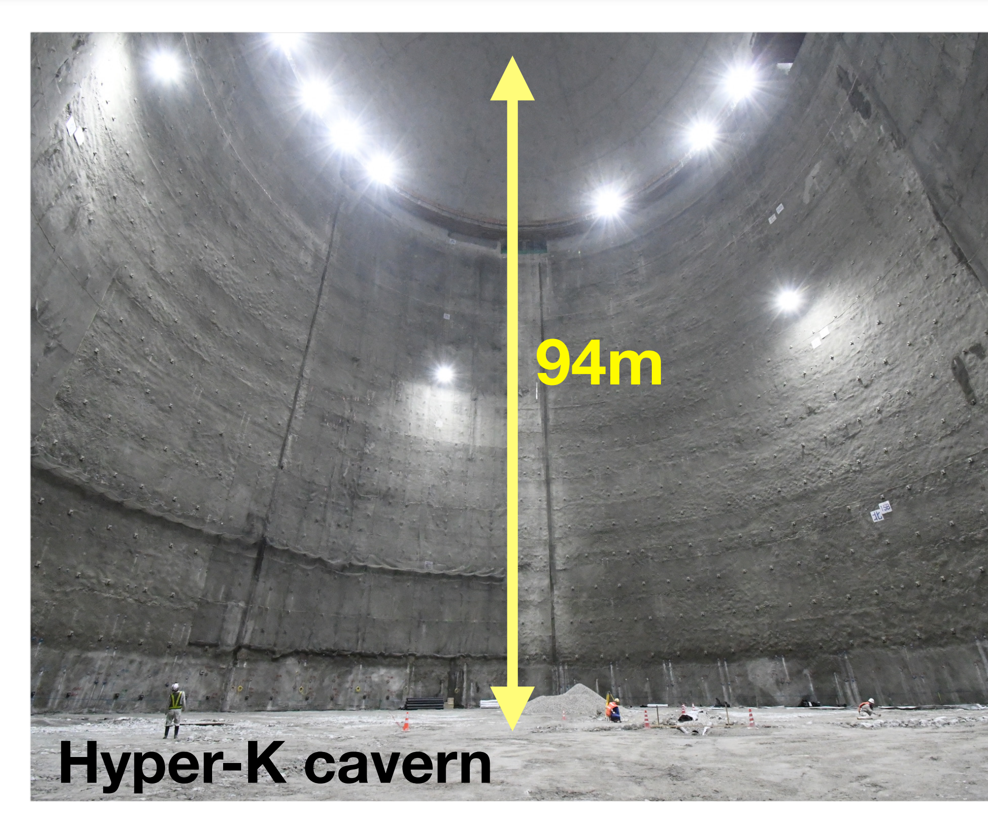


# Hyper-K: water Cherenkov

- Overburden: ~600m
- 260 kton water Cherenkov detector
  - Fiducial mass: ~190 kton
  - Number of protons: ~$10^{35}$ ($10^{34}$ free protons)
- ~20,000 new ϕ50cm PMTs (20% photo-coverage)
- New ϕ50cm PMTs improve nucleon decay discovery potential

- The cavern excavation completed this July and aim to start operation in 2028

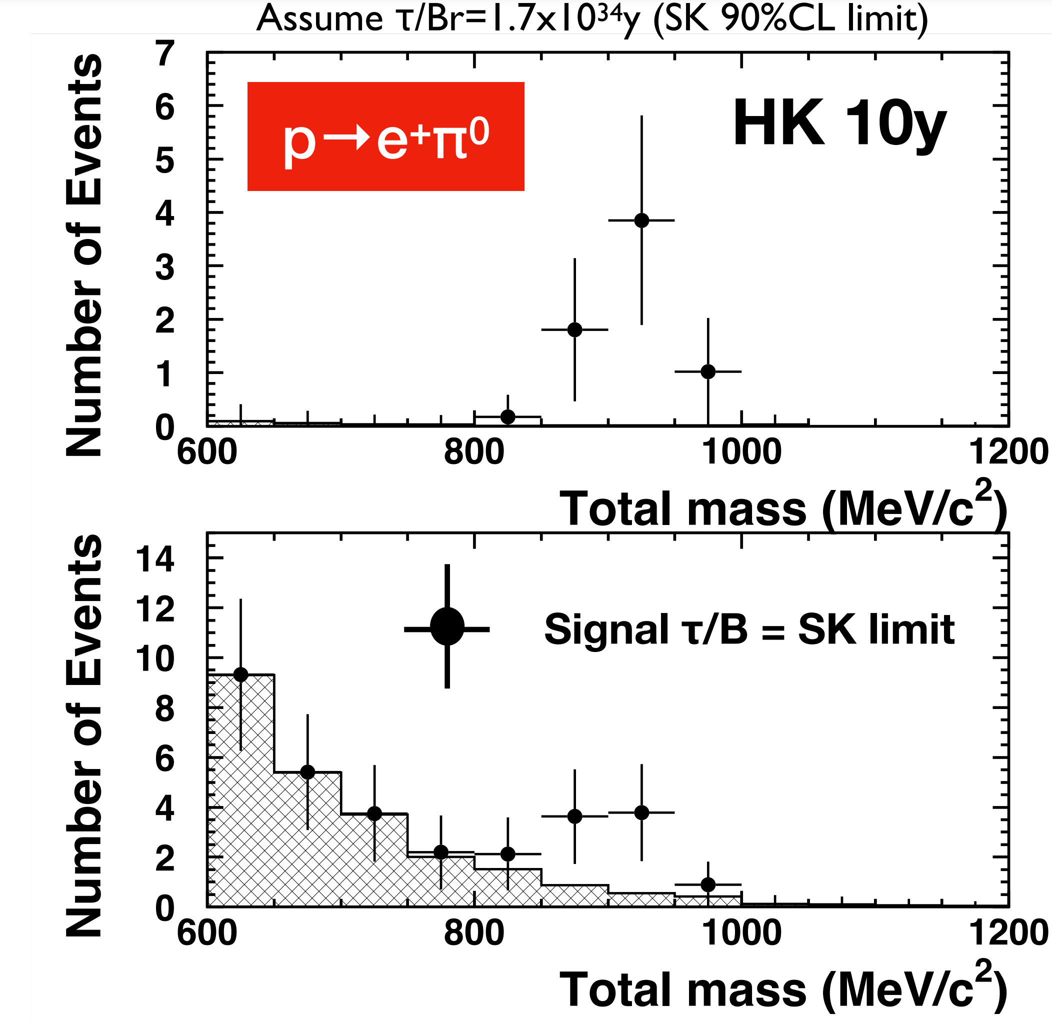


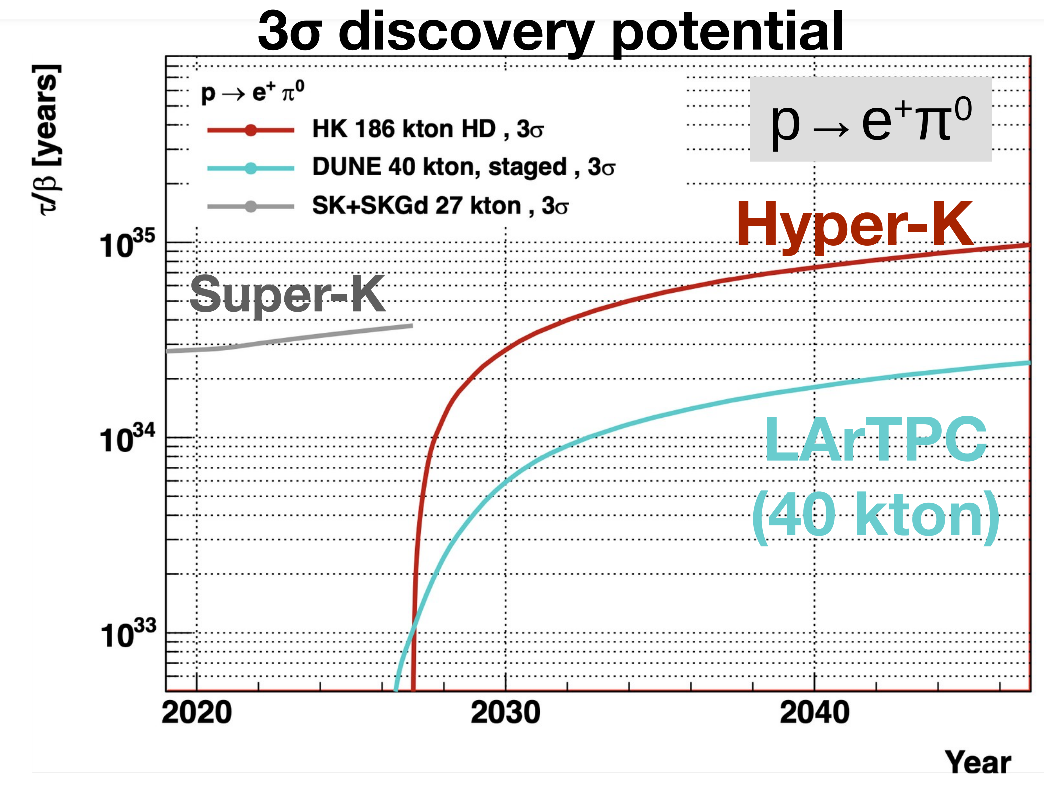


# Hyper-K: water Cherenkov

arXiv:1805.04163

- New ϕ50cm PMTs for Hyper-K have twice better photo-detection efficiency than SK PMTs
- Proton decay background rejection (neutron-tagging) efficiency largely improved:
  - $p \to e^+\pi^0$ expected bkg events 0.06* for ~10 years
  - “Background free” p-decay search
    - ~9σ discovery potential if proton lifetime at the current SK limit ($\tau_p/Br = 1.7 \times 10^{34}$yrs)
- 3σ discovery potential in 20 years:
  - **$p \to e^+\pi^0$: $10^{35}$ years**
  - **$p \to \bar{\nu}K^+$: $10^{34}$ years**

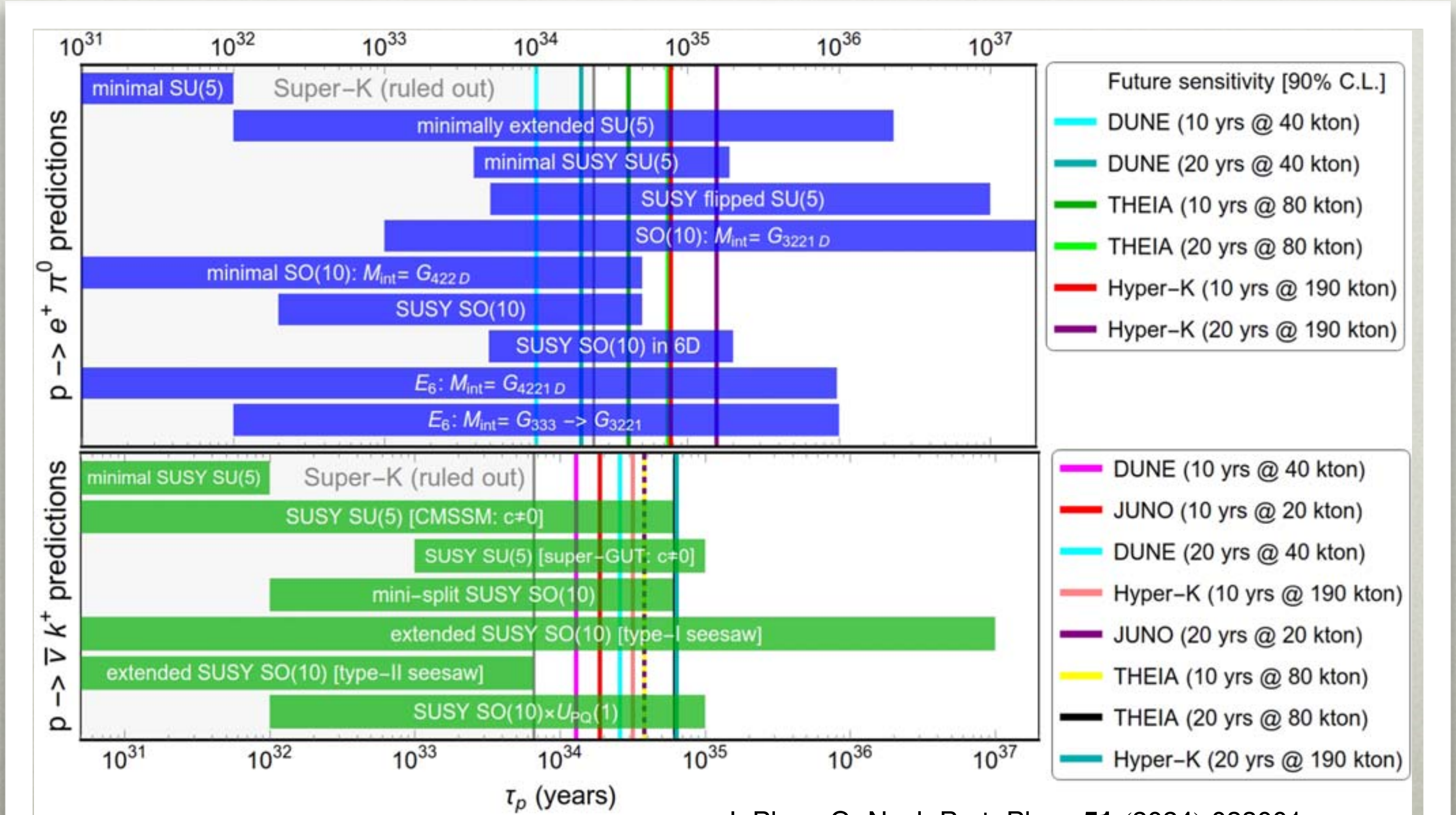

Assume τ/Br=1.7x10³⁴y (SK 90%CL limit)


3σ discovery potential

* # of bkg in the ‘free proton’ enhanced signal region (ptot<100MeV)

# Summary

- Many active searches in many modes, especially the benchmark modes $p \rightarrow e^+\pi^0$, $p \rightarrow \bar{\nu}K^+$
- No observation yet…
- Future searches with next-generation large detectors aim to improve the sensitivity by order of magnitude
- Let's discover conclusive evidences of nucleon decays and open the door to exploring grand unification!



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