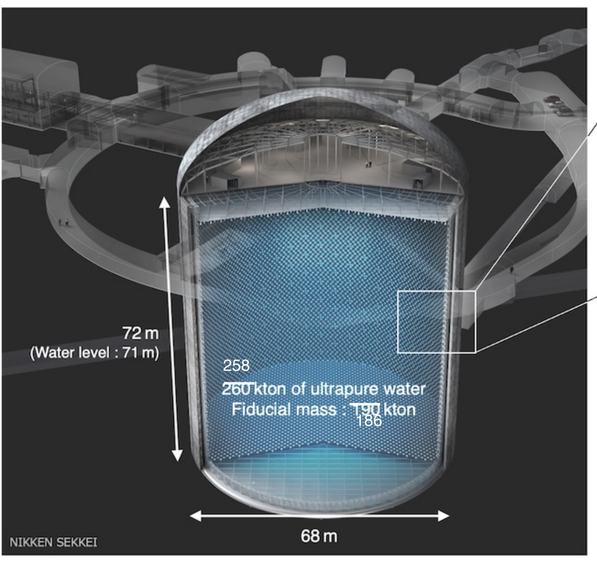
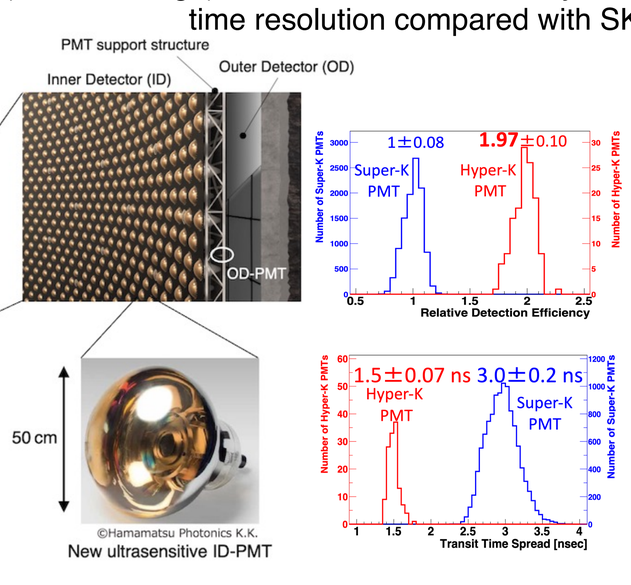
#19 Overview of the Hyper-Kamiokande nucleon decay search program and its discovery reach

(cf. #23 Sensitivity study for the $p \to \bar{\nu}K^+$ proton decay mode at Hyper-Kamiokande)

① Hyper-Kamiokande (HK)

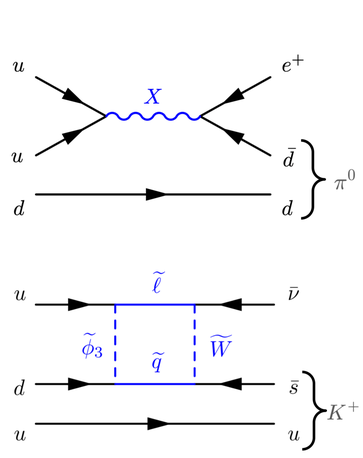
- Next generation Water Cherenkov Detector with **~ Super-Kamiokande (SK) × 8 fiducial volume, 186 kton, scheduled to start data-taking from 2028**
- Wide physics target including **search for nucleon decay**, exploration of leptonic *CP* violation, determination of neutrino mass ordering, advancement of neutrino astronomy etc…
- 20k ultrasensitive 50 cm Hamamatsu PMT (20% coverage) with twice better efficiency and time resolution compared with SK

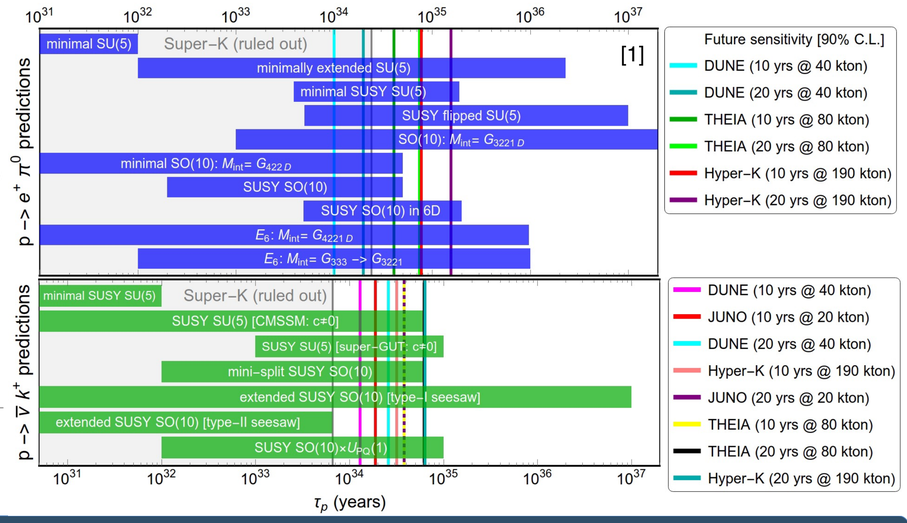




② Nucleon decay

- Grand Unified Theories (GUTs) which unify the strong, weak and electromagnetic interactions generally predict nucleons to decay into final states with lighter leptons and hadrons
- **Nucleon decay could open a window onto physics at the GUT scale (~10^{16} GeV)**, far beyond the reach of direct searches at particle accelerators
- A discovery would offer a direct probe of the fundamental structure of grand unification, shedding light on the choice of **GUT gauge group, SUSY vs. non-SUSY realizations, the pattern of symmetry breaking, and the structure of Yukawa couplings**
- Minimal SU(5) GUT is already ruled out by SK proton decay search
- **<u>Major modes</u>**
  - $p \to e^+\pi^0$ generally predicted in non-SUSY GUTs
  - $p \to \bar{\nu}K^+$ generally predicted in SUSY GUTs

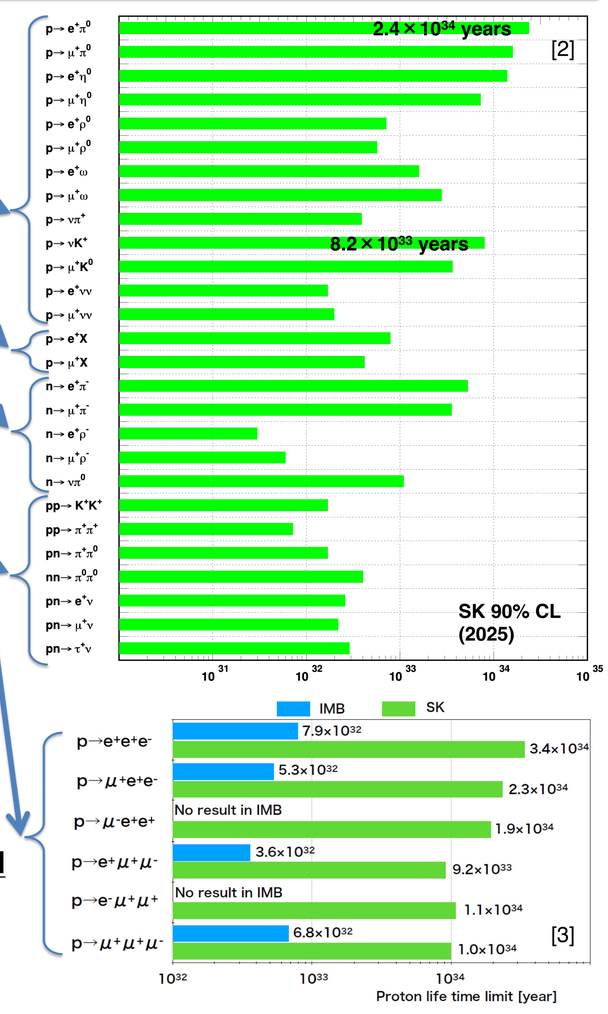




③ Nucleon decay search landscape

- A wide variety of nucleon decay modes are possible, and **SK conducts extensive searches with world-leading sensitivities**
  - **Exclusive proton decay search to lepton + meson**
  - **Inclusive proton decay search to lepton + X**
  - **Exclusive neutron decay search to lepton + meson**
  - **Di-nucleon decay**
  - **Proton decay to three charged leptons**
  - **Tri-nucleon decay**
    - $^{16}O(ppp) \to {}^{13}C\pi^+\pi^+e^+$ [4]

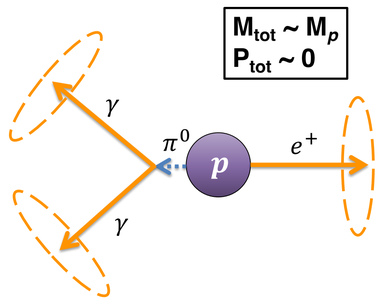
  etc…
- The dominant nucleon decay mode is highly model-dependent, depending on the underlying GUT / flavor structure and its realization
- Different models can therefore predict very different decay signatures, making it **<u>essential for HK to search comprehensively across all experimentally accessible nucleon decay modes</u>**



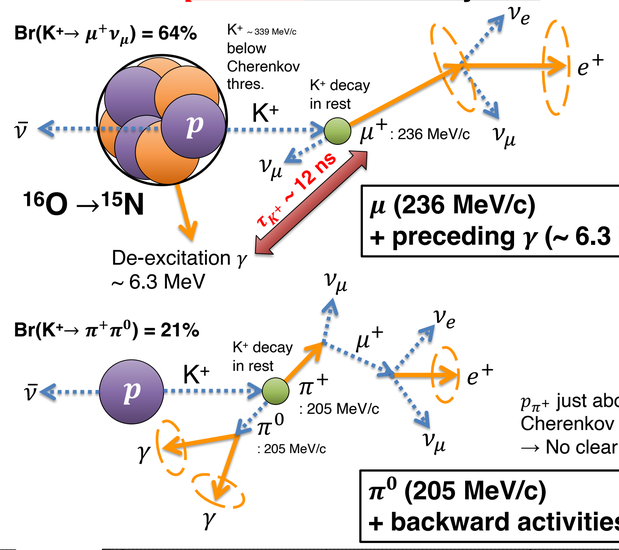
④ Expected sensitivity in Hyper-Kamiokande

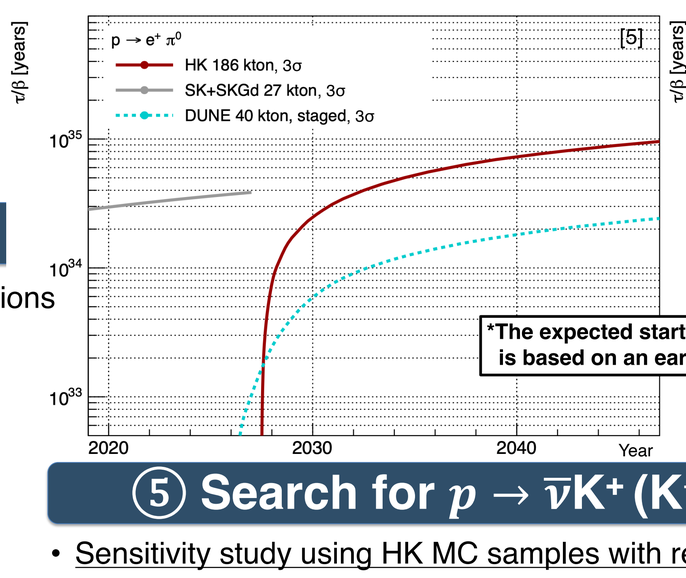
- HK sensitivity is already estimated roughly using SK tools [5]
  - 3σ discovery sensitivity with HK 20 years operation

$p \to e^+\pi^0$: ~ 1 × 10^{35} years



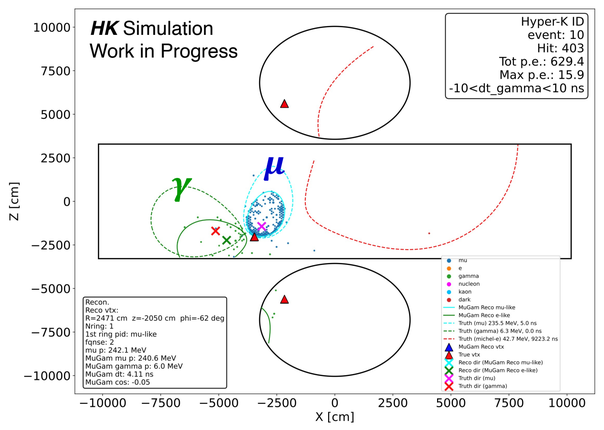
$p \to \bar{\nu}K^+$: ~ 3 × 10^{34} years

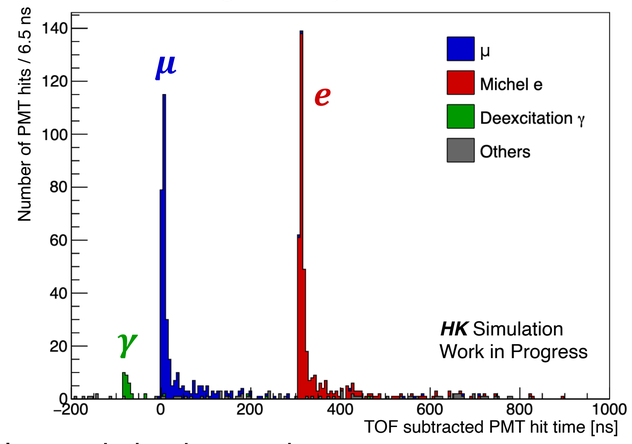




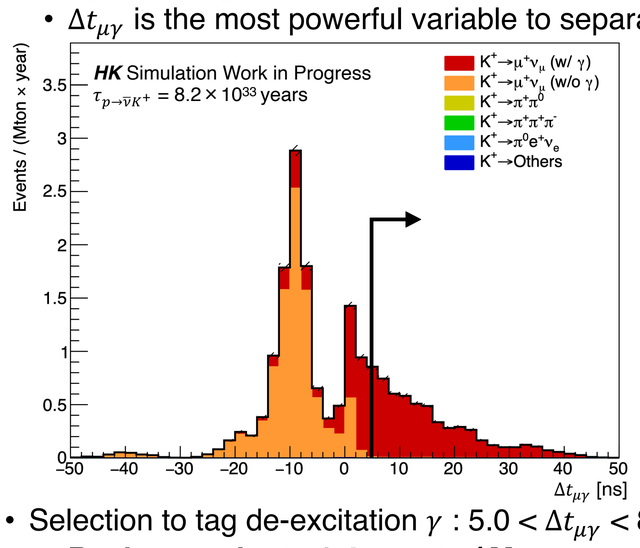
⑤ Search for $p \to \bar{\nu}K^+$ ($K^+ \to \mu^+\nu$) + de-excitation γ

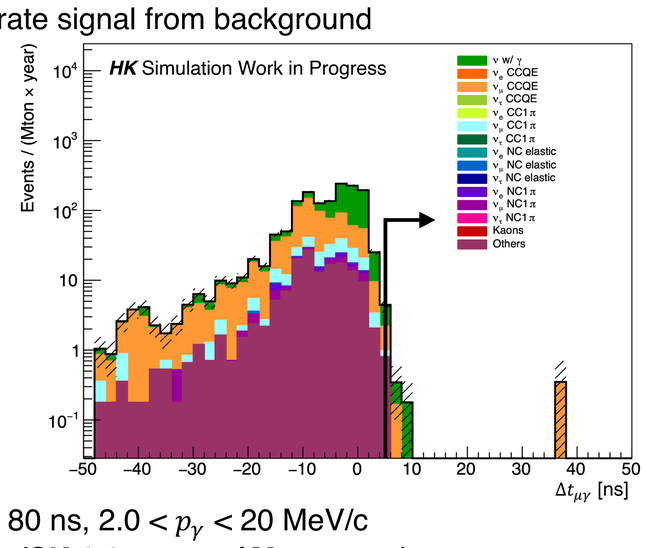
- <u>Sensitivity study using HK MC samples with realistic detector geometry and PMT performance</u>





- Background MC : Atmospheric neutrino samples, main backgrounds are
  - **ν_μ CCQE + de-excitation γ : True $\Delta t_{\mu\gamma}$ = 0 ns**
    → Fake $\Delta t_{\mu\gamma}$ arises from μ vertex mis-reconstruction and imperfect TOF subtraction
  - **ν_μ 2p2h** : Cherenkov light from the recoil proton mimics the de-excitation γ
- Basic selections
  - In fiducial volume, one μ-like ring + one Michel electron, 215 < p_μ < 255 MeV/c
  - Background rate 1770 events / Mton·year
  - Signal rate 19.4 events / Mton·year at $\tau_{p\to\bar{\nu}K^+}$ = 8.2 × 10^{33} years
- Developed a **<u>dedicated maximum-likelihood fitter to tag de-excitation γ</u>** which assumes **one μ-like ring + one low momentum e-like ring**
  - $\Delta t_{\mu\gamma}$ is the most powerful variable to separate signal from background





- Selection to tag de-excitation γ : 5.0 < $\Delta t_{\mu\gamma}$ < 80 ns, 2.0 < p_γ < 20 MeV/c
  - **Background rate 1.4 events / Mton·year (SK 1.1 events / Mton·year)**
  - **Signal rate 5.4 events / Mton·year at $\tau_{p\to\bar{\nu}K^+}$ = 8.2 × 10^{33} years (Eff. 13.3%, cf. SK 8.4%)**

⑥ Summary & Prospects

- **<u>HK will search for a wide range of nucleon decay modes with unprecedented sensitivity</u>**
- For $p \to \bar{\nu}K^+$ ($K^+ \to \mu^+\nu$) with de-excitation γ, a dedicated maximum-likelihood fitter improves the signal efficiency by ~58 %
- Further improvement with better muon vertex resolution and neutron tagging
- By addressing both experimental systematics (e.g., muon energy scale) and theoretical uncertainties (e.g., the de-excitation γ-emission probability), and combining with the $K^+ \to \pi^+\pi^0$ mode, we aim to establish a robust $p \to \bar{\nu}K^+$ discovery reach for HK

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[1] arXiv:2203.08771
[2] M. Nakahata, 6th KMI Inter. Sympo.
[3] M. Miura, BLV2019
[4] SK, arXiv:2609.25681
[5] HK, arXiv:2506.16641

UTokyo Hyper-Kamiokande