Searches for Nucleon Decay and Baryon Number Violation with Super-Kamiokande Experiment

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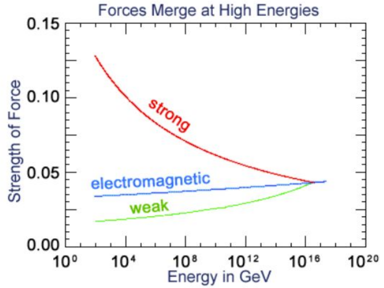
for the Super-Kamiokande Collaboration

Do protons decay?

- Lightest baryon (proton) stable
- ***B***-number proposed to explain matter stability [Weyl, 1929; Stueckelberg, 1939; Wigner, 1949]
- In Standard Model (SM) ***B*** not fundamental, accidental global symmetry

  … long history of such symmetries later found violated (e.g. C, P)
- Already in SM ***B*** is violated by non-perturbative effects [t'Hooft, 1976]
- SM incomplete, ***B*** viol. in many theories (baryogenesis, GUTs, SUSY, extra-dim...)
- Global symmetries expected to be violated by quantum gravity e.g. [Harlow, Ooguri, 2018]
- Proton decay can be essential for fate of astrophysical objects [Adams, Laughlin, 1997]

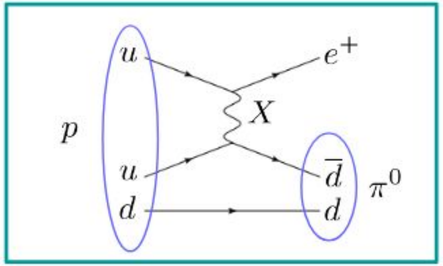
Grand Unified Theories (GUTs)



- Unify SM gauge groups [Georgi, Glashow, 1974; Fritzch, Minkowski, 1975] $SU(5)$ $SO(10)$
  → charge quantization, coupling unification, anomaly cancellation…
- **Leptons** ↔ **quarks** interact → nucleon decay

typically dominant: $p \to e^+\pi^0$ $SU(5)$

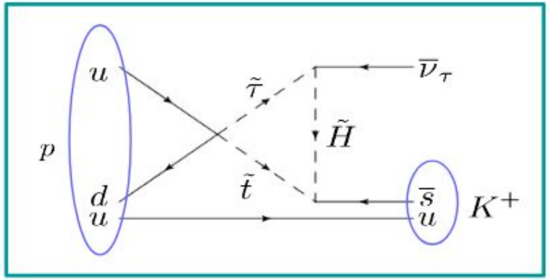
$\tau = \frac{1}{\Gamma} \propto \left[\frac{M_X^2}{\alpha^2}\right]^2$



→ prediction $\tau \sim 10^{29-36}$ yrs
→ minimal model ruled out
(IMB-3, Kamiokande, Super-K)

$p \to \overline{\nu} K^+$

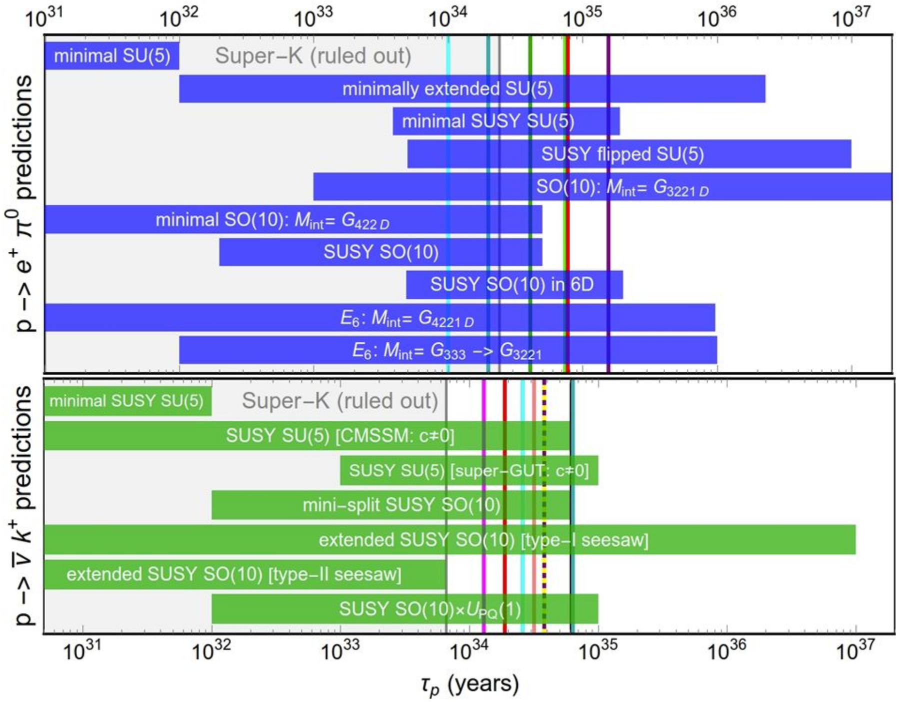
SUSY $SU(5)$



$\tau = \frac{1}{\Gamma} \propto \left[\frac{M_s M_T}{\alpha^2}\right]^2$

→ prediction $\tau \sim 10^{29-36}$ yrs
→ minimal (TeV-)SUSY model ruled out
by Super-K [Kobayashi+ (SK), *PRD*, (2005)]

Proton Lifetime Predictions



Snowmass-2021 Whitepaper [Dev et.al., *J.Phys.G*, 2024]

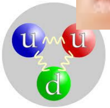
Model	Ref.	Modes	τ_N (years)
Minimal $SU(5)$	Georgi, Glashow [2]	$p \to e^+\pi^0$	$10^{30} - 10^{31}$
Minimal SUSY $SU(5)$	Dimopoulos, Georgi [11], Sakai [12] Lifetime Calculations: Hisano, Murayama, Yanagida [13]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{28} - 10^{32}$
SUGRA $SU(5)$	Nath, Arnowitt [14, 15]	$p \to \bar{\nu}K^+$	$10^{32} - 10^{34}$
SUSY $SO(10)$ with anomalous flavor $U(1)$	Shafi, Tavartkiladze [16]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$ $p \to \mu^+K^0$	$10^{32} - 10^{35}$
SUSY $SO(10)$ MSSM (std. $d=5$)	Lucas, Raby [17], Pati [18]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{33} - 10^{34}$ $10^{32} - 10^{33}$
SUSY $SO(10)$ ESSM (std. $d=5$)	Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d=5$)	Babu, Pati, Wilczek [19, 20, 21], Pati [18]	$p \to \bar{\nu}K^+$ $p \to \mu^+K^0$ $B \sim (1-50)\%$	$\lesssim 2 \cdot 10^{34}$
SUSY $SU(5)$ or $SO(10)$ MSSM ($d=6$)	Pati [18]	$p \to e^+\pi^0$	$\sim 10^{34.9\pm1}$
Flipped $SU(5)$ in CMSSM	Ellis, Nanopoulos and Wlaker[22]	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{36}$
Split $SU(5)$ SUSY	Arkani-Hamed, *et. al.* [23]	$p \to e^+\pi^0$	$10^{35} - 10^{37}$
$SU(5)$ in 5 dimensions	Hebecker, March-Russell[24]	$p \to \mu^+K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$
$SU(5)$ in 5 dimensions option II	Alciati *et.al.*[25]	$p \to \bar{\nu}K^+$	$10^{36} - 10^{39}$
GUT-like models from Type IIA string with D6-branes	Klebanov, Witten[26]	$p \to e^+\pi^0$	$\sim 10^{36}$

[Bueno+, *JHEP, 2007*]

- Significant uncertainties in model predictions, many viable models within experiment reach

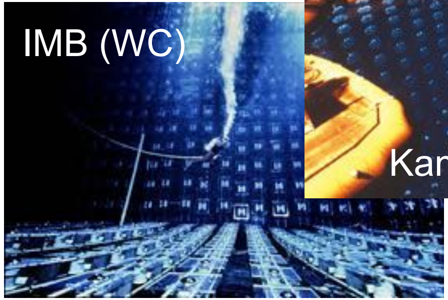
How to search?

- Already in 1950s, Goldhaber argued on general grounds $\tau > 10^{18}$ yrs
  → Many searches with different methods since

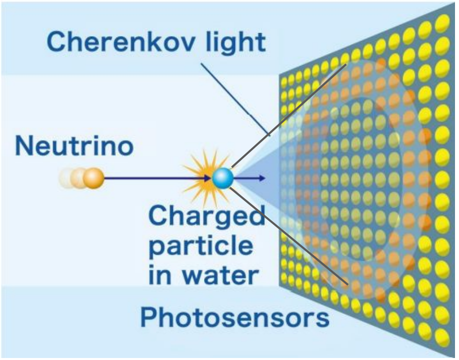


- Proton lives $\tau > 10^{30}$ yrs, how to test?
  - Look at 1 proton VERY long time ❌
  - Look at many protons for few years ✓

- **Large-scale water Cherenkov (WC) detectors - excellent targets**
  - Cheap, easily scalable (e.g. iron calorimeters are difficult)
  - Proven technology
  - H_2O includes 2 hydrogen "free protons" (high selection efficiency, low uncertainty)

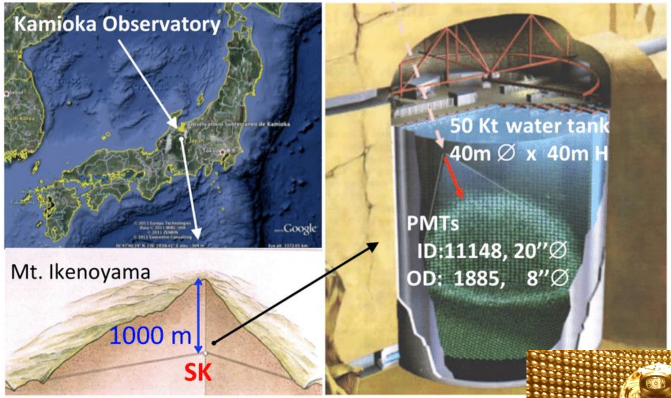


Water Cherenkov Ring Imaging and State-of-the-Art

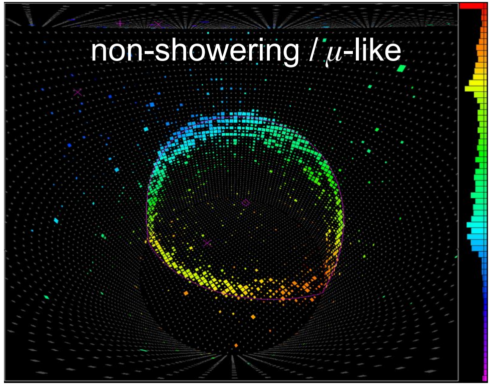


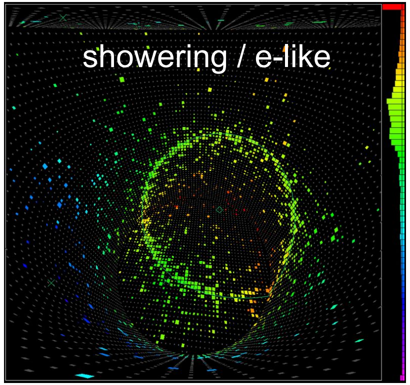
state-of-the-art

Super-Kamiokande (SK, Super-K)



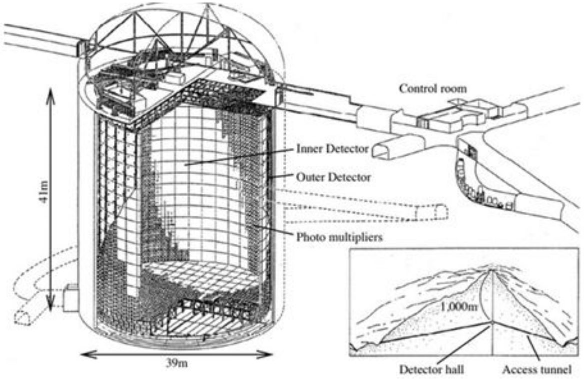
real SK data (1998)

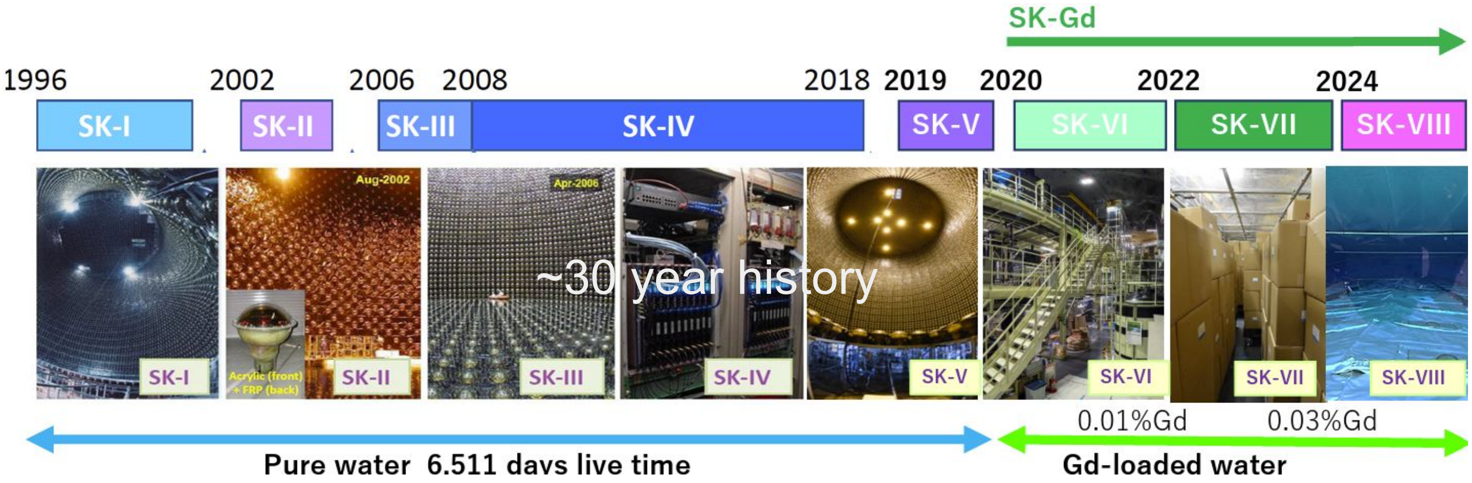


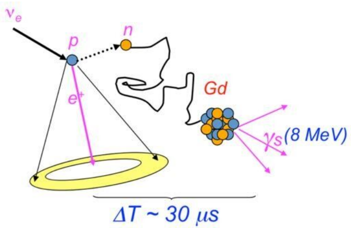


The Super-Kamiokande (SK) Experiment

- ~50 kton WC experiment
  - ~22.5 kton target fiducial volume
- 1 km underground (2700 m.w.e.) in Kamioka mine
- Inner (outer) detector: ~11,000 (~2,000) PMTs
- Since ~2020 doped with Gadolinium(Gd), ~0.03 w%
  - SKGd neutron capture efficiency ~75% (water: ~20%)







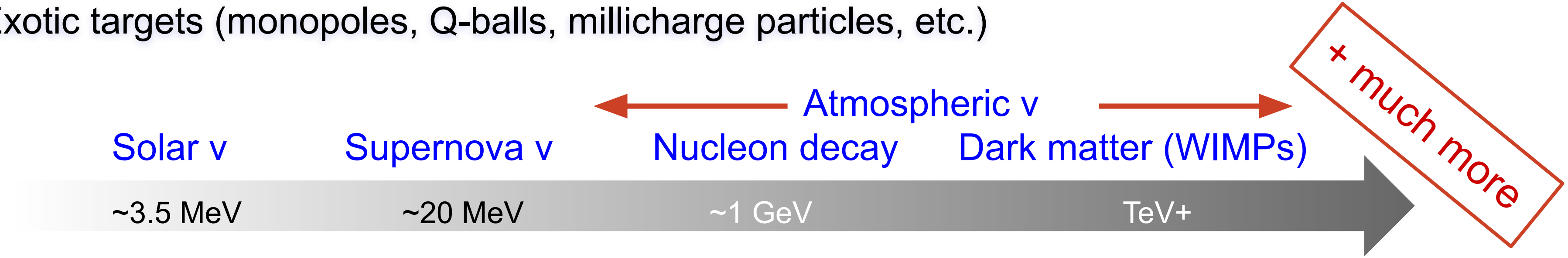
A Multipurpose Discovery Experiment

- **Outstanding detector performance**
  - Excellent ring-imaging capabilities; proven over 25+ years
  - Particle ID > 99%, energy resolution at 1 GeV ~ percent-level

discovery of neutrino oscillations

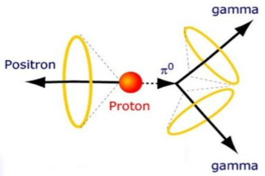
2015

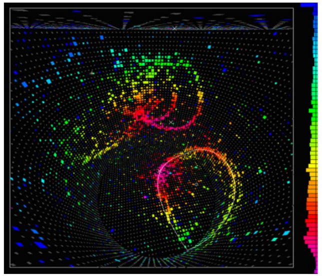
- **Exceptional physics capabilities** (energy range: ~ few -10^4 MeV)
- Precision fundamental ν-oscillation studies (atmospheric, accelerator, Lorentz inv., NSI, sterile)
- Precision solar neutrino physics (fluxes, spectral distortions, day/night effect, NSI, g-modes)
- Neutrino astronomy, supernova and beyond (multimessenger, burst, diffuse background, etc.)
- World leading sensitivity to B-violating processes (proton decay, di-nucleon decays, etc.)
- Dark matter searches: indirect (Sun, Earth, Galactic Center), direct (via cosmic-ray boost, etc.)
- Exotic targets (monopoles, Q-balls, millicharge particles, etc.)

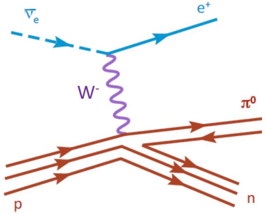


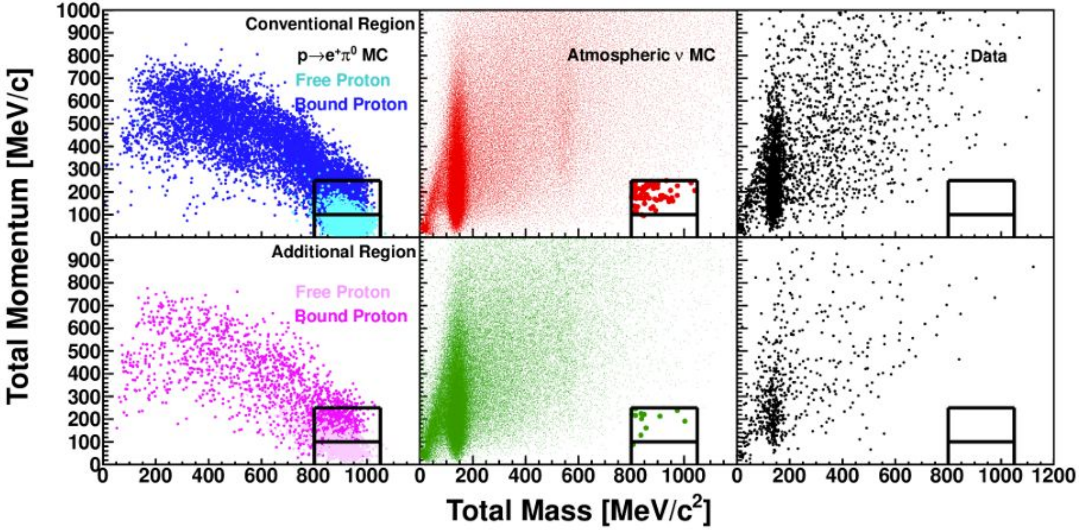
$p \rightarrow e^+\pi^0$ Search

- **Motivation:** Typically dominant GUT channel
- Final state (positron + 2 gammas) fully visible
  → can reconstruct proton mass/momentum, clean channel









typical atm.-ν back.
(benefit from n-tag)

- Exposure: 450 kton*yr
- Signal efficiency: 38.6% (SK I-IV)
- Expected background:

0.05 ev. in $P_{\rm tot} < 100$ MeV

0.58 ev. in $100 \leq P_{\rm tot} < 250$ MeV

[Abe+ (SK), PRD, 2020]

No candidates, lifetime limit (90% CL)

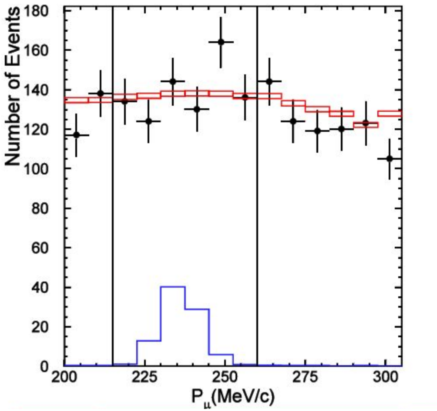
$> 2.4 \times 10^{34}$ yrs.

p →νK⁺ Search

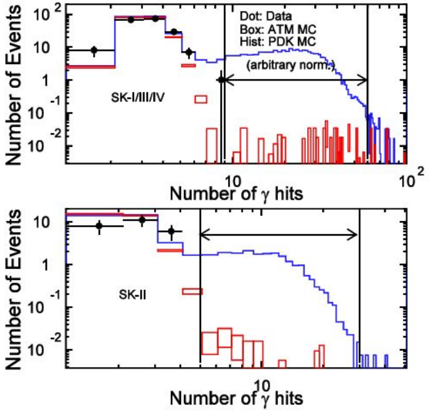
- **Motivation:** Typically dominant SUSY GUT channel
- Invisible ν, can't reconstruct proton mass/momentum
- Momentum of K^+ ~339 MeV below Cherenkov threshold (invisible) → analyze decays

$K^+ \rightarrow \nu\mu^+$: 64 %
$K^+ \rightarrow \pi^+\pi^0$: 21 %

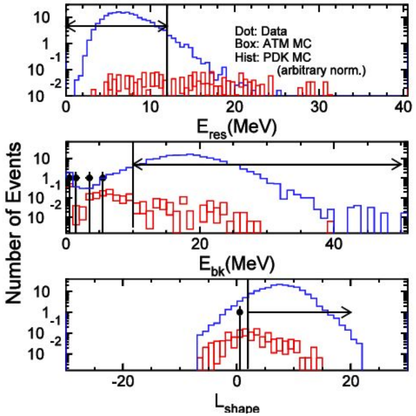
A $(K^+ \to \mu^+\nu)$
μ momentum fit



B $(K^+ \to \mu^+\nu)$
nuclear de-excitation γ tag



C $(K^+ \to \pi^0\pi^+)$
reconstruct pions



combine analyses

- Exposure: 365 kton*yr
- Signal eff.: ~10% (SK I-IV)

No excess,
lifetime limit (90% CL)

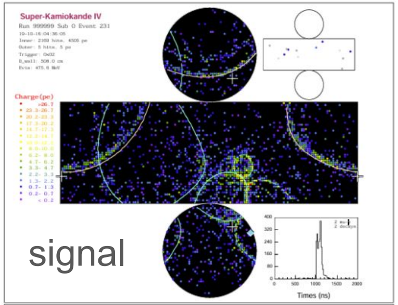
$> 8.2 \times 10^{33}$ yrs.

[Abe+ (SK), PRD, 2014] (Updated)

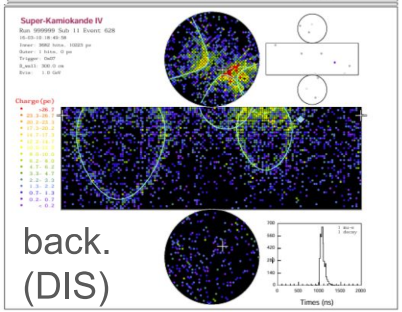
Neutron-Antineutron Oscillations

- **Motivation:** $\Delta B = \Delta(B-L) = 2$, neutrino mass connections, new intermediate scales, etc.
- Capture of $\overline{n}$ by ^{16}O nucleons (n, p) produces mesons (~pions) → reconstruct initial state
- Complicated final-state interactions with multi-ring signatures

example simulations

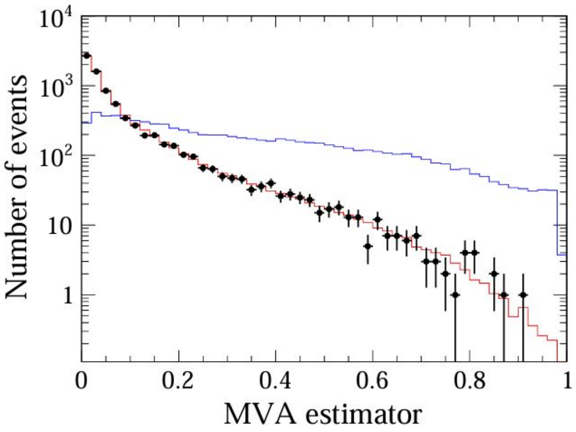


signal



back. (DIS)

Multivariate analysis allows ~2x sensitivity



[Abe+ (SK), PRD, 2021]

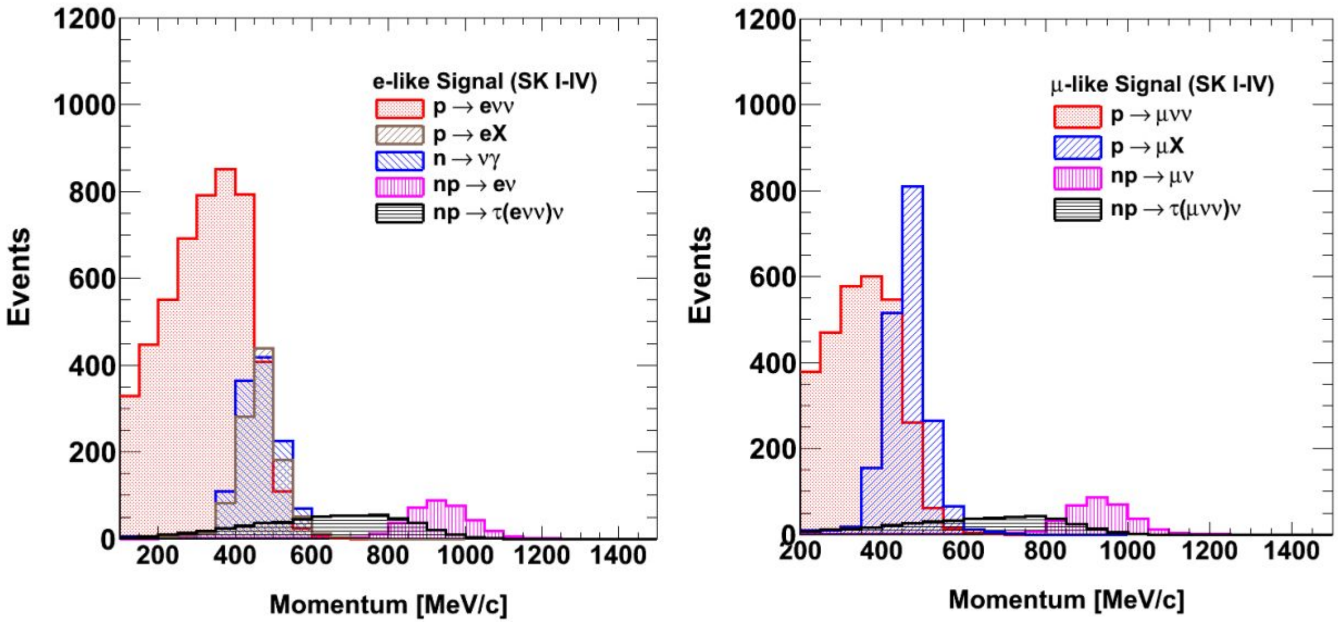
- Exposure: 370 kton*yr
- Signal efficiency: ~4% (SK I-IV, MVA)
- Expected background: 9.3 ± 2.7 ev.
- Observed: 11 ev.

No excess, lifetime limit (90% CL)

$T_{n-\bar{n}}(10^{32}$ years)	R $(10^{23}$/s)	$\tau_{n\to\bar{n}}(10^8$ s)
3.6	0.517	4.7

$$T^{\text{bound}}_{n-\bar{n}} = R \cdot \tau^2_{n\to\bar{n}}$$

Spectral Searches with Missing Energy



No excess, lifetime limits (90% CL)

$\geq$ few $\times\ 10^{32}$ yrs.

[Takhistov+ (SK), *PRL*, (2014); Takhistov+ (SK), *PRL*, (2015); + ongoing analyses]

- Look for visible energy-momentum, distribution important (e.g. ν, massless invisible X), highlighted in [Chen, Takhistov, *PRD*, (2014)]

SK Broadly Set Most Sensitive Limits

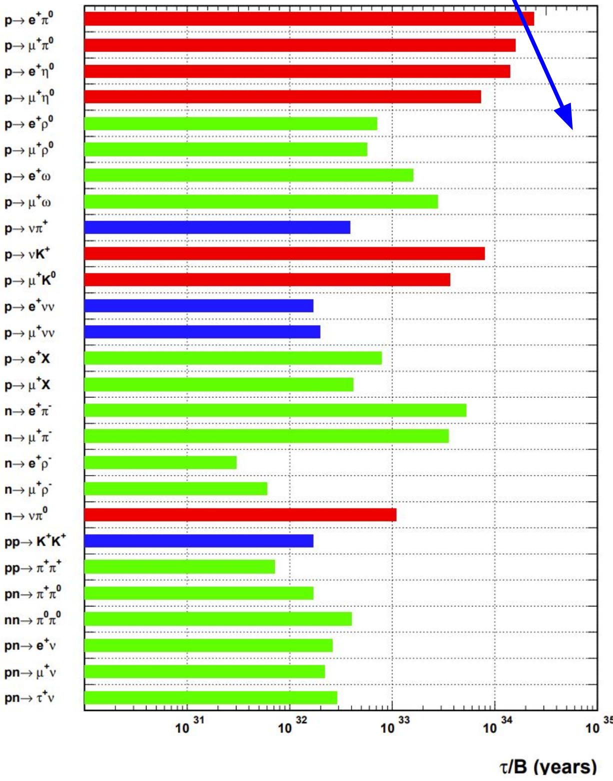
- SK already broadly probed ~50 channels
(including dinucleon decays, decays to >2 final states…)

- Analysis strategy depends on channel specifics
→ visible Cherenkov rings, backgrounds, etc.

- **Occasional candidates consistent with background, no evidence of nucleon decays**
→ <u>leading limits on nucleon decays</u>

… are we done?
No, unexplored frontier ahead !

$\tau \sim 10^{35}$yrs



Very Many Channels Never Searched

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$p \to e^- + e^+ + e^+$	0	793 [65]
$p \to e^- + e^+ + \mu^+$	0	529 [65]
$p \to e^+ + e^+ + \mu^-$	0	529* [65]
$p \to e^- + \mu^+ + \mu^+$	0	6 [64] (359* [65])
$p \to e^+ + \mu^- + \mu^+$	0	359 [65]
$p \to \mu^- + \mu^+ + \mu^+$	0	675 [65]
$p \to e^+ + 2\nu$	0,2	170 [81]
$p \to \mu^+ + 2\nu$	0,2	220 [81]
$p \to e^- + 2\pi^+$	2	30 [62] (82* [65])
$p \to e^- + \pi^+ + \rho^+$	2	
$p \to e^- + K^+ + \pi^+$	2	75 [65]
$p \to e^+ + 2\gamma$	0	100 [82] (793* [65])
$p \to e^+ + \pi^- + \pi^+$	0	82 [65]
$p \to e^+ + \rho^- + \pi^+$	0	
$p \to e^+ + K^- + \pi^+$	0	75* [65]
$p \to e^+ + \pi^- + \rho^+$	0	
$p \to e^+ + \pi^- + K^+$	0	75* [65]
$p \to e^+ + 2\pi^0$	0	147 [65]
$p \to e^+ + \pi^0 + \eta$	0	
$p \to e^+ + \pi^0 + \rho^0$	0	
$p \to e^+ + \pi^0 + \omega$	0	
$p \to e^+ + \pi^0 + K^0$	0	
$p \to \mu^- + 2\pi^+$	2	17 [62] (133* [65])
$p \to \mu^- + K^+ + \pi^+$	2	245 [65]
$p \to \mu^+ + 2\gamma$	0	529* [65]
$p \to \mu^+ + \pi^- + \pi^+$	0	133 [65]
$p \to \mu^+ + K^- + \pi^+$	0	245* [65]
$p \to \mu^+ + \pi^- + K^+$	0	245* [65]
$p \to \mu^+ + 2\pi^0$	0	101 [65]
$p \to \mu^+ + \pi^0 + \eta$	0	
$p \to \mu^+ + \pi^0 + K^0$	0	
$p \to \nu + \pi^+ + \pi^0$	0,2	
$p \to \nu + \pi^+ + \eta$	0,2	
$p \to \nu + \pi^+ + \rho^0$	0,2	
$p \to \nu + \pi^+ + \omega$	0,2	
$p \to \nu + \pi^+ + K^0$	0,2	
$p \to \nu + \rho^+ + \pi^0$	0,2	
$p \to \nu + K^+ + \pi^0$	0,2	

no limits

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$nn \to \pi^0 + \phi$	2	
$nn \to 2\eta$	2	
$nn \to \eta + \rho^0$	2	
$nn \to \eta + \omega$	2	
$nn \to \eta + \eta'$	2	
$nn \to \eta + K^0$	2	
$nn \to \eta + K^{*,0}$	2	
$nn \to \eta + \phi$	2	
$nn \to 2\rho^0$	2	
$nn \to \rho^0 + \omega$	2	
$nn \to \eta' + \rho^0$	2	
$nn \to K^0 + \rho^0$	2	
$nn \to K^{*,0} + \rho^0$	2	
$nn \to \rho^0 + \phi$	2	
$nn \to \rho^- + \rho^+$	2	
$nn \to K^+ + \rho^-$	2	
$nn \to K^{*,+} + \rho^-$	2	
$nn \to K^- + \rho^+$	2	
$nn \to K^{*,-} + \rho^+$	2	
$nn \to 2\omega$	2	
$nn \to \eta' + \omega$	2	
$nn \to K^0 + \omega$	2	
$nn \to K^{*,0} + \omega$	2	
$nn \to \omega + \phi$	2	
$nn \to \eta' + K^0$	2	
$nn \to \eta' + K^{*,0}$	2	
$nn \to K^- + K^+$	2	170* [116]
$nn \to K^+ + K^{*,-}$	2	
$nn \to K^- + K^{*,+}$	2	
$nn \to 2K^0$	2	
$nn \to K^{*,0} + K^0$	2	
$nn \to K^0 + \phi$	2	
$nn \to 2K^{*,0}$	2	
$nn \to K^{*,-} + K^{*,+}$	2	

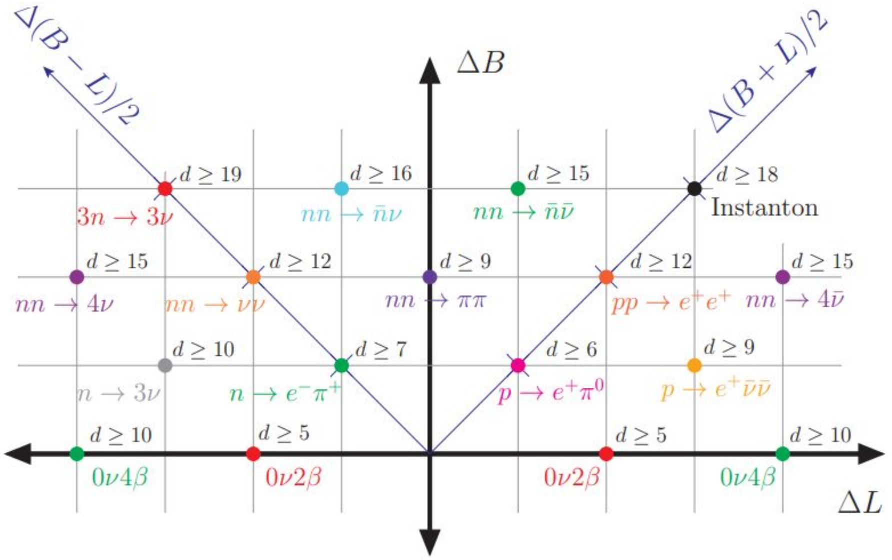
no limits

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [65]
$n \to \nu + e^- + \mu^+$	0,2	83 [65]
$n \to \nu + e^+ + \mu^-$	0,2	83* [65]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [65]
$n \to 3\nu$	0,2,4	0.58 [83]
$n \to e^- + \pi^+ + \pi^0$	2	29 [62] (52* [65])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [65]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [62]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	
$n \to \mu^- + \pi^+ + \pi^0$	2	[illegible] [62] (74 [illegible])
$n \to \mu^- + \pi^+ + \eta$	2	
$n \to \mu^- + \pi^+ + K^0$	2	
$n \to \mu^- + K^+ + \pi^0$	2	
$n \to \mu^+ + \pi^- + \pi^0$	[illegible]	74 [65]
$n \to \mu^+ + \pi^- + \eta$	0	
$n \to \mu^+ + \pi^- + K^0$	0	
$n \to \mu^+ + K^- + \pi^0$	0	
$n \to \nu + 2\gamma$	0,2	219 [65]
$n \to \nu + \pi^- + \pi^+$	0,2	
$n \to \nu + \rho^- + \pi^+$	0,2	
$n \to \nu + K^- + \pi^+$	0,2	
$n \to \nu + \pi^- + \rho^+$	0,2	
$n \to \nu + \pi^- + K^+$	0,2	
$n \to \nu + 2\pi^0$	0,2	
$n \to \nu + \pi^0 + \eta$	0,2	
$n \to \nu + \pi^0 + \rho^0$	0,2	
$n \to \nu + \pi^0 + \omega$	0,2	
$n \to \nu + \pi^0 + K^0$	0,2	

no limits

no limits

no limits



Not exhaustive list

[Heeck, Takhistov, *PRD*, (2019)]

New Broad Program: Non-Canonical Nucleon Decays

Novel probes of light new physics: axion-like particles, dark photons, sterile ν's…

$\mathcal{O}$	Operator	$(\Delta B, \Delta L)$	Dim	Decay modes	New Field(s)
$\mathcal{O}_{d^2uN}$	$\epsilon^{abc}(d_a N)(d_b u_c)$	$(1,1)$	6	$p(n) \to \pi^{+(0)} N$	sterile neutrinos
$\mathcal{O}_{Dd^2u\bar{N}}$	$\epsilon^{abc}(d_a \sigma_\mu N^\dagger)(d_b D^\mu u_c)$	$(1,-1)$	7	$n \to N\gamma$ $p(n) \to \pi^{+(0)} N\gamma$	sterile neutrinos
$\mathcal{O}_{du^2e\phi}$	$\epsilon^{abc}(d_a u_b)(e u_c)\phi$	$(1,1)$	7	$p \to e^+\phi$ $p(n) \to e^+\pi^{0(-)}\phi$	dark scalars, majorons
$\mathcal{O}_{d^2Q\bar{L}X}$	$\epsilon^{abc}(Q_a^i \sigma^\mu d_b)(d_c L_i^\dagger)X_\mu$	$(1,1)$	7	$n \to \nu X$ $p \to \nu\pi^{+(0)} X$ $p(n) \to e^+\pi^{0(-)} X$	dark photons
$\mathcal{O}_{dQ^2\bar{L}\bar{H}\phi}$	$\epsilon^{abc}(Q_a^i Q_b^j)(L^\dagger{}_i d_c)H_j^\dagger\phi$	$(1,1)$	8	$p \to e^+\phi$ $p(n) \to e^+\pi^{0(-)}\phi$	dark scalars, majorons
$\mathcal{O}_{Dd^2QLa}$	$\epsilon^{abc}(\partial^\mu a)(Q_a^i \sigma^\mu d_b)(d_c L_i^\dagger)$	$(1,1)$	8	$p(n) \to \nu\pi^{+(0)} a$ $p(n) \to e^+\pi^{0(-)} a$	axion-like particles
$\mathcal{O}_{Dd^2u\bar{N}a}$	$\epsilon^{abc}(\partial^\mu a)(d_a \sigma_\mu N^\dagger)(d_b u_c)$	$(1,-1)$	8	$n \to Na$ $p(n) \to \pi^{+(0)} Na$	axion-like particles with sterile neutrinos
$\mathcal{O}_{duQe\bar{L}N}$	$\epsilon^{abc}(e u_a)(Q_b^i \sigma_\mu d_c)(N^\dagger \sigma^\mu L_i^\dagger)$	$(1,1)$	9	$p \to e^+\nu N$ $n \to e^+e^- N$	sterile neutrinos
$\mathcal{O}_{du^2eN^2}$	$\epsilon^{abc}(d_a u_b)(e u_c)(NN)$	$(1,3)$	9	$p \to e^+ NN$	sterile neutrino

- Many novel possibilities mediated by motivated BSM particles
- Multi-nucleon decays possible (dinucleon, trinucleon…)
- Mixed scenarios possible
- Tests of light new physics over decades in mass below ~ few GeV

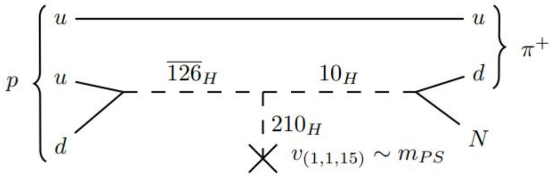
[Fridell, Hati, Takhistov, *PRD Lett.* (2024); + *in preparation* & others]

→ ***SK uniquely positioned to lead this***

Non-Canonical and Dark Matter-Induced Decay Signatures

Ex.)

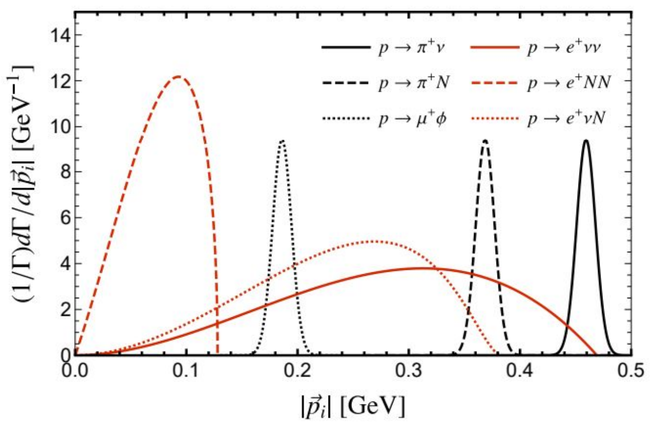
heavy sterile ν's (N) in SO(10) GUT with Pati-Salam



$p \to \pi^+ N$

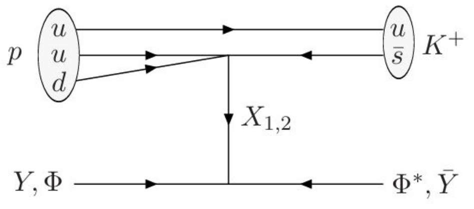
Predicted lifetime can be ~ 10^{34} - 10^{35} yrs ~testable in SK

Ex.)



$m_N = 400$ MeV $m_\phi = 700$ MeV.

Complementary process class: "induced decays" by dark matter with (anti)baryon charge



$m_\Phi, m_Y \sim$ few $\times$ GeV

[Davoudiasl+, PRL, 2010; + others]

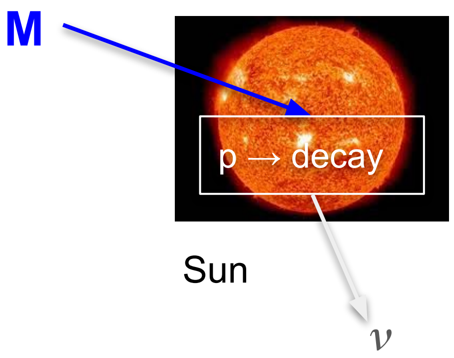
- Conventional searches can misinterpret or completely miss such channels
- Inclusive searches can probe many modes simultaneously [Heeck, Takhistov, *PRD* (2019)]

[Fridell, Hati, Takhistov, *PRD Lett.* (2024)]

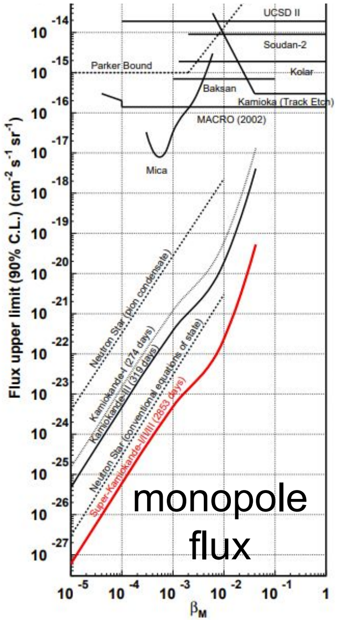
Decay Catalysis by Extended Objects: Monopoles, Q-Balls

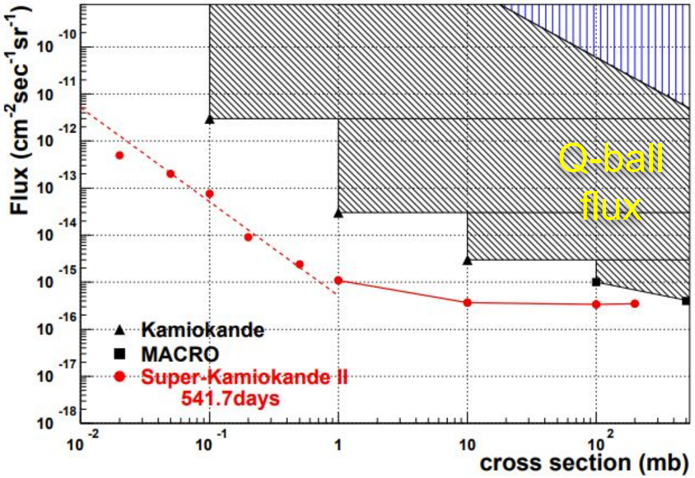
- Heavy monopoles from unified theories can be captured by Sun and catalyze proton decay via Callan-Rubakov process producing neutrinos
- Q-balls naturally appear from field instabilities in e.g. supersymmetric theories, dark matter Q-balls can catalyze nucleon decay in SK when carrying baryon number

$$p \to (\rho^0, \omega, \eta, K^+, \cdots) + e^+(\text{or } \mu^+)$$



[Ueno+ (SK), 2012;
+ Feng (SK), M.S. thesis, 2021]

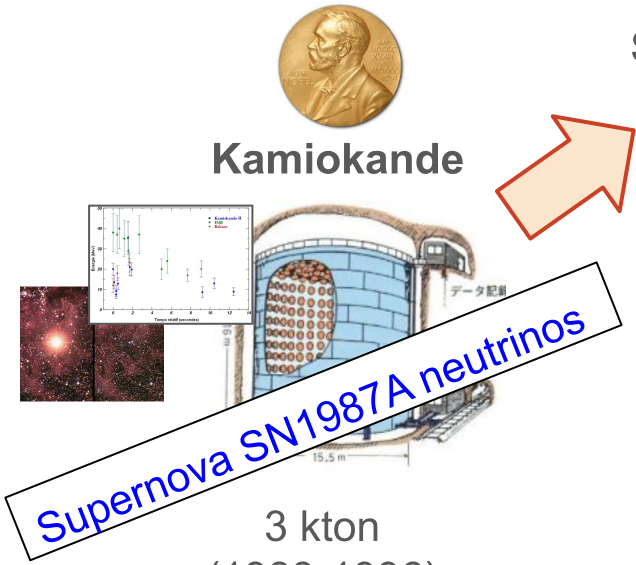


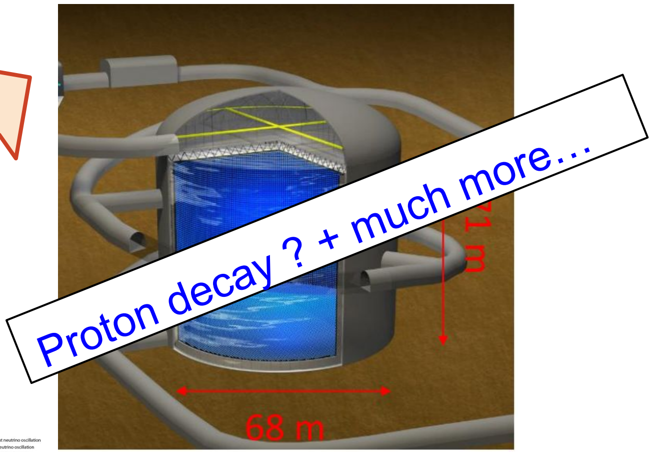


[Takenaga+ (SK), 2007]

Q-ball dark matter flux ~ $\Phi_Q \sim \frac{\rho_{\rm DM}}{M_Q} v$

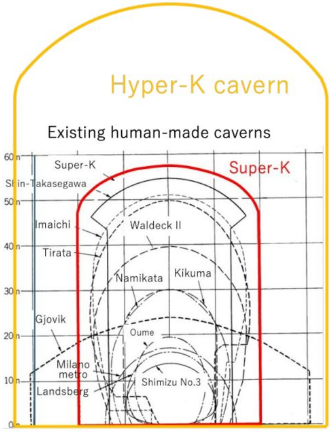
Into the Future with Hyper-Kamiokande (Hyper-K, HK)

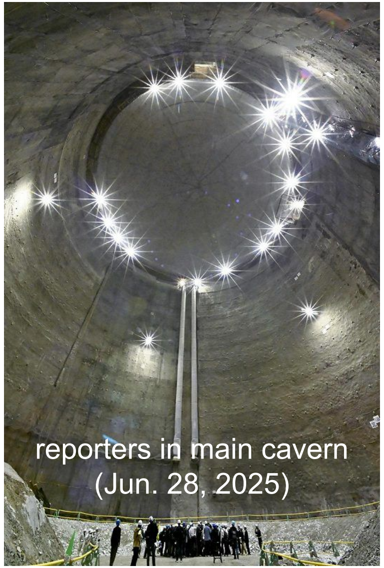


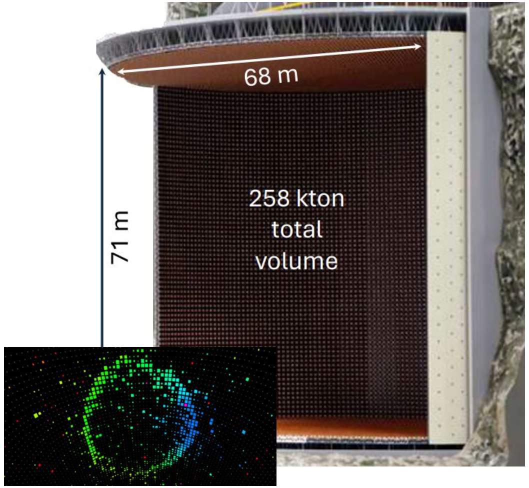


The Hyper-Kamiokande Experiment

- **Next generation flagship neutrino observatory in Japan**
  - ~ 8.4 x SK fiducial mass
- **Big construction progress**
  - cavern excavation → *complete* (*2025*) ✓
- **Engineering marvel**
  → largest man-made cavern in world
- **Operation start 2028**
  - R&D of all stages finalizing
  - PMT mass production continues



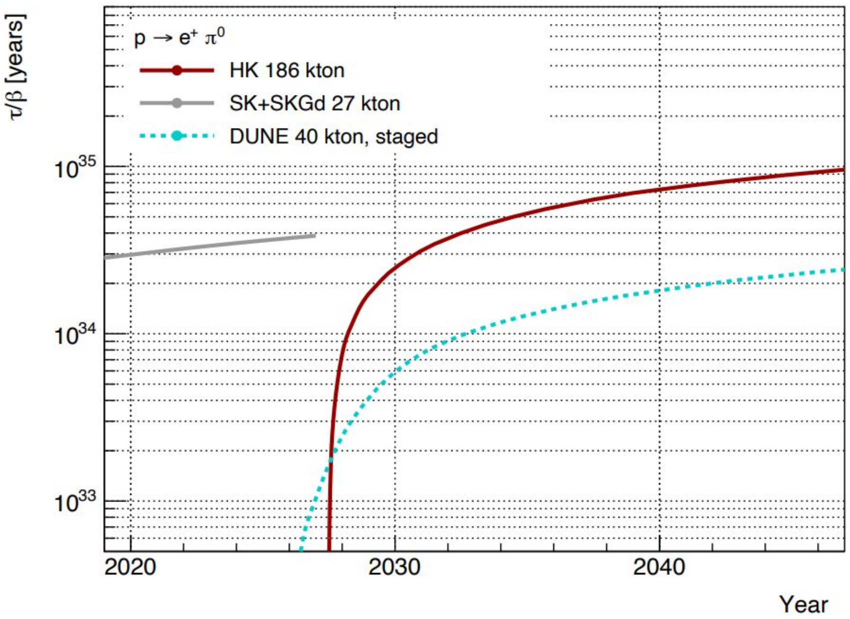


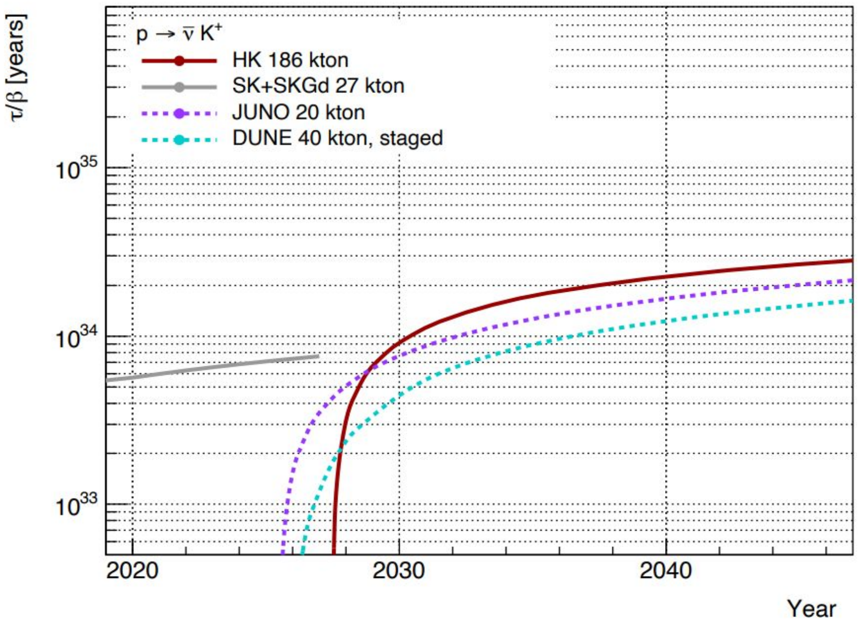


	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% (×2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton

Going Beyond Existing Reach

- Uniquely positioned to broadly lead nucleon decay searches
- Only approved experiment capable of reaching $\tau \sim 10^{35}\,\mathrm{yrs}$





[HK Collab., (2025) arXiv: 2506.16641]

Conclusions

- Super-Kamiokande is an exceptional multipurpose experiment and has established the world's most sensitive limits on a wide range of nucleon decay and baryon number violation processes
- Wide range of searches are pursued, covering conventional channels, multi-nucleon decays, n–n̄ oscillations and other modes
- No evidence for nucleon decay has been observed, with lifetime limits reaching ~ few x 10^{34} yrs → SK already excluded variety of theoretical models
- SK has broad search program ahead. Ongoing analyses and SK-Gd upgrade will further expand sensitivity and discovery potential
- Hyper-Kamiokande will build on this foundation with a broad nucleon decay program, extending searches to new frontiers and capabilities of uniquely probing lifetimes approaching ~10^{35} yrs lifetime