Searches for Baryon Number Violation in Neutrino Experiments

J. Pedro Ochoa-Ricoux

University of California at Irvine

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Outline

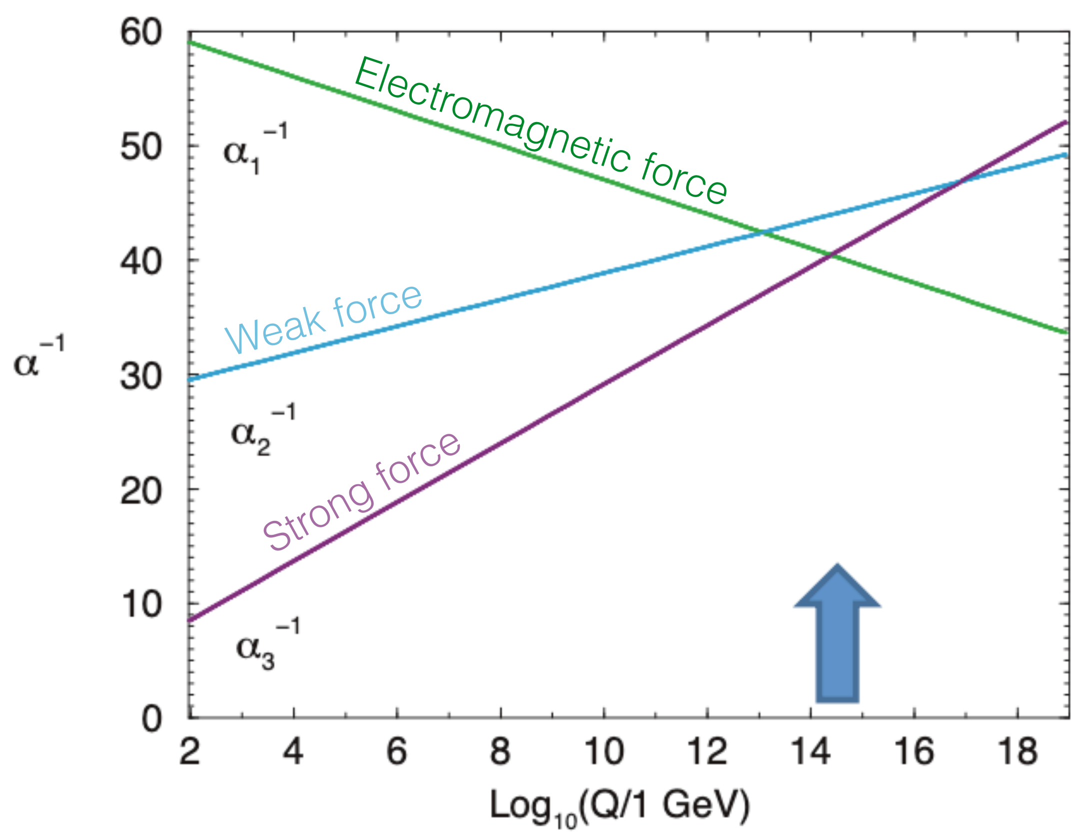
- Motivation
- Ongoing Experiments
- Next Generation Experiments
- Summary & Conclusions

Disclaimer: rely heavily on white paper in arXiv:2203.08771

Motivation

Motivation

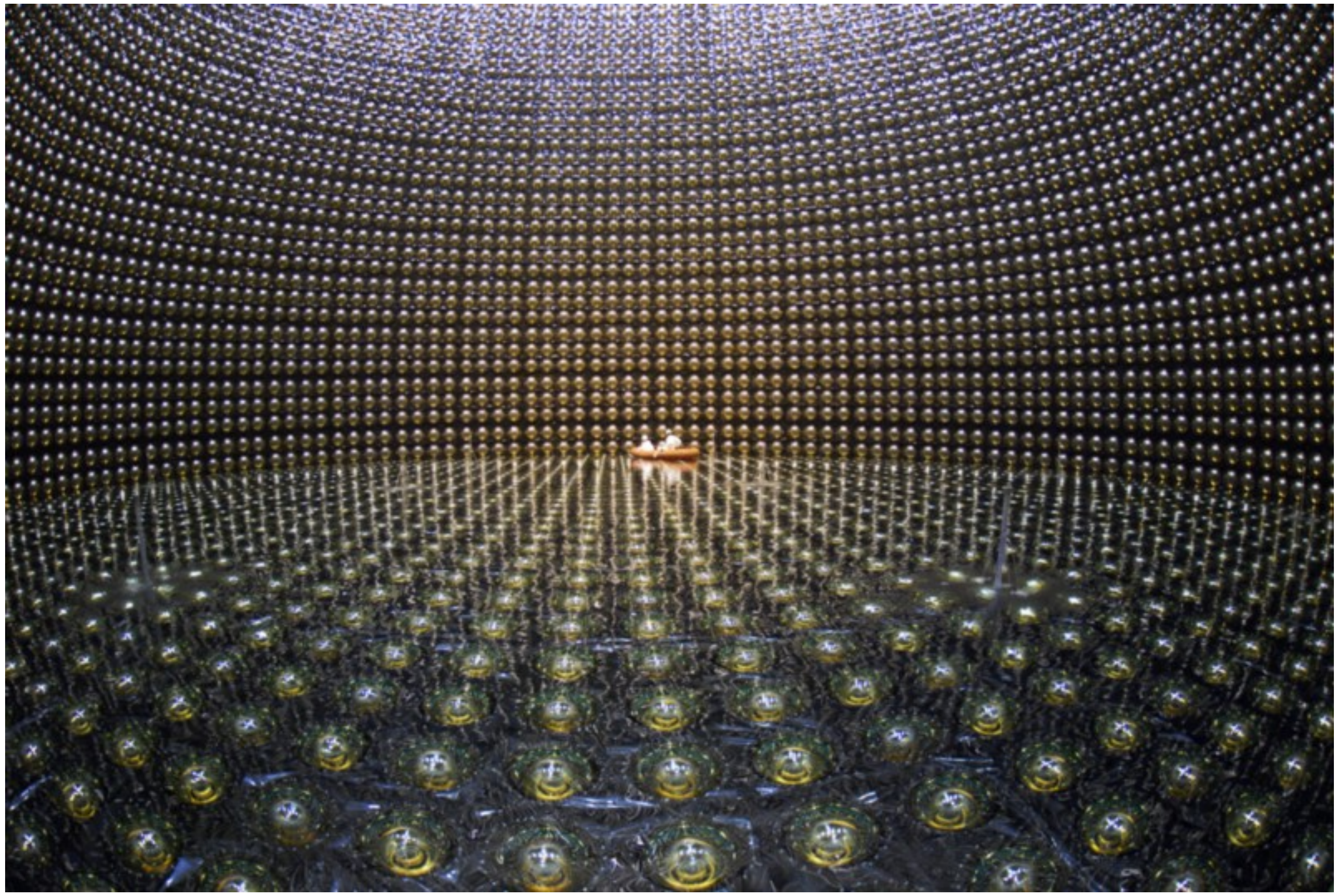
- Baryon Number Violation (BNV) is well-motivated from a theoretical standpoint:
  - Baryon number conservation invoked to explain apparent stability of matter since 1929 but with no compelling justification
  - Observed matter-antimatter asymmetry in the universe requires BNV as one of the Sakharov conditions
  - Many well-motivated theories beyond the Standard Model (SM), including Grand Unified Theories (GUTs), predict nucleon decay and other forms of BNV
    - GUTs also unify the strong, weak, and electromagnetic forces into a single force, as well as quarks with leptons and particles with antiparticles



Nucleon lifetime depends on model considered and unification scale (see next slide)

Neutrino Experiments and BNV

- Searching for nucleon decay is one of the best ways to constrain BNV
  - Unification scale ($> 10^{15}$ GeV) inaccessible with accelerator-based experiments
  - **Strategy**: cannot observe a proton for $\sim 10^{33}$ years, but can observe $\sim 10^{33}$ protons in $\sim$years
- Detector requirements for neutrino physics and proton decay are often very well aligned
  - Large, highly-instrumented detector masses
  - Long exposure times
  - Good shielding and overburden
  - Low-enough threshold
- The world's best limits on nucleon decay come from neutrino experiments
  - Or, the best neutrino physics are done in proton decay experiments



The Super-Kamiokande detector

Motivation

- Expected nucleon lifetime from various GUT models ⟶

  (table from arXiv:2203.08771)

  - Estimates span many orders of magnitude

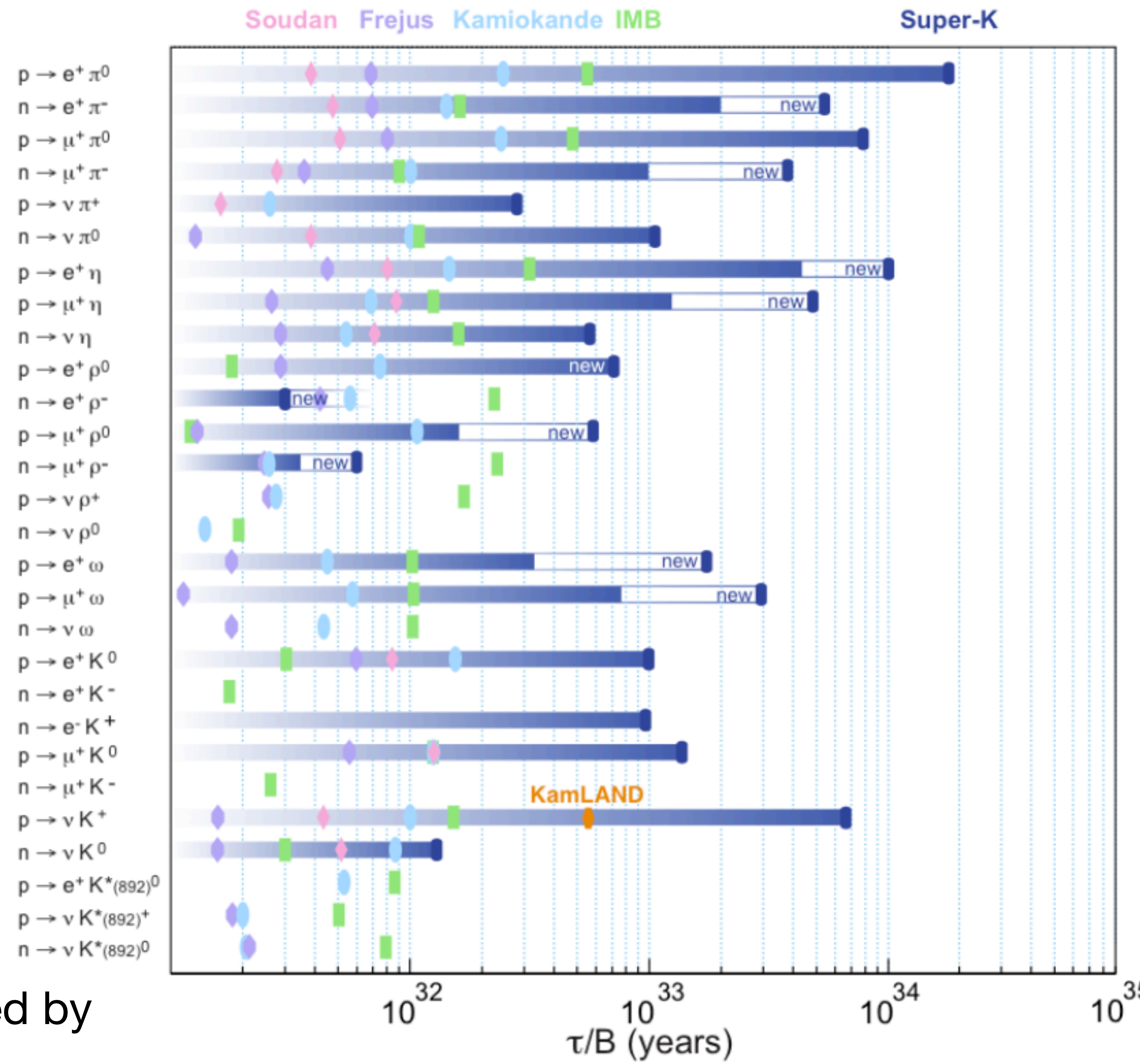
- Important to explore this space with multiple experiments:
  - Potential confirmation
  - Observation of multiple channels important for determining symmetries of underlying model

Model	Decay modes	τ_N $(N = p, n)$ [years]	Ref.
Non-SUSY minimal $SU(5)$	$p \to e^+\pi^0$	$10^{30} - 10^{32}$	Georgi, Glashow [16]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p \to e^+\pi^0$	$\lesssim 2.3 \times 10^{36}$	Doršner, Saad [82]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p \to e^+\pi^0$ $p \to \bar{\nu}K^+$	$10^{32} - 10^{36}$ $10^{34} - 10^{37}$	Perez, Murgui [74]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-II seesaw)	$p \to \nu + (K^+, \pi^+, \rho^+)$ $n \to \nu + (\pi^0, \rho^0, \eta^0, \omega^0, K^0)$	$10^{31} - 10^{38}$	Doršner, Perez [64]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-III+I seesaw)	$p \to e^+\pi^0$	$\lesssim 10^{36}$	Bajc, Senjanović [65]
Non-SUSY Extended $SU(5)$ (neutrino mass: 2-loop)	$p \to e^+\pi^0$	$10^{34} - 10^{40}$	Saad [80]
Minimal flipped non-SUSY $SU(5)$	$p \to e/\mu^+\pi^0$	$10^{38} - 10^{42}$	Arbeláez, Kolešová, Malinský [175]
Non-SUSY Minimal $SO(10)$	$p \to e^+\pi^0$	$\lesssim 5 \times 10^{35}$	Babu, Khan [165]
Minimal $SO(10)$ with 45 Higgs	$p \to e^+\pi^0$	$\lesssim 10^{36}$	Bertolini, Di Luzio, Malinský [176]
Minimal non-Renormalizable $SO(10)$	$p \to e^+\pi^0$	$\lesssim 10^{35}$	Preda, Senjanović, Zantedeschi [173]
Non-SUSY Generic $SO(10)$ $M_{\text{int}} : G_{422}$ $M_{\text{int}} : G_{422D}$ $M_{\text{int}} : G_{3221}$ $M_{\text{int}} : G_{3221D}$	$p \to e^+\pi^0$	 $10^{34} - 10^{46}$ $10^{31} - 10^{34}$ $10^{36} - 10^{46}$ $10^{33} - 10^{43}$	Chakrabortty, King, Maji [164]
Non-SUSY Generic E_6 $M_{\text{int}} : G_{4221}$ $M_{\text{int}} : G_{4221D}$ $M_{\text{int}} : G_{333} \to G_{3221}$ $M_{\text{int}} : G_{4221D} \to G_{421}$ $M_{\text{int}} : G_{4221} \to G_{421}$	$p \to e^+\pi^0$	 $10^{27} - 10^{36}$ $10^{27} - 10^{36}$ $10^{32} - 10^{36}$ $10^{26} - 10^{48}$ $10^{25} - 10^{48}$	Chakrabortty, King, Maji [164]
Minimal SUSY $SU(5)$	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	 $10^{28} - 10^{32}$	Dimopoulos, Georgi [42], Sakai [100] Hisano, Murayama, Yanagida [99]
Minimal SUSY $SU(5)$ (cMSSM)	$p \to \bar{\nu}K^+$ $p \to e^+\pi^0$	$\lesssim (2-6) \times 10^{34}$ $10^{35} - 10^{40}$	Ellis et. al. [107]
Minimal SUSY $SU(5)$ ($\mathbf{5} + \bar{\mathbf{5}}$ matter fields)	$p \to \bar{\nu}K^+$ $p \to \mu^+\pi^0/K^0, n \to \bar{\nu}\pi^0/K^0$	$\lesssim 4 \times 10^{33}$ $10^{33} - 10^{34}$	Babu, Bajc, Tavartkiladze [177]
SUGRA $SU(5)$	$p \to \bar{\nu}K^+$	$10^{32} - 10^{34}$	Nath, Arnowitt [103, 178]
mSUGRA $SU(5)$ (Higgs mass constraint) NUSUGRA $SU(5)$ (Higgs mass constraint)	$p \to \bar{\nu}K^+$ $p \to \bar{\nu}K^+$	$3 \times 10^{34} - 2 \times 10^{35}$ $3 \times 10^{34} - 10^{36}$	Liu, Nath [111]
SUSY $SU(5)$ or $SO(10)$ MSSM $(d = 6)$	$p \to e^+\pi^0$	$\sim 10^{34.9\pm1}$	Pati [179]
Flipped SUSY $SU(5)$ (cMSSM)	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{37}$	Ellis et. al. [180–182]
Split SUSY $SU(5)$	$p \to e^+\pi^0$	$10^{35} - 10^{37}$	Arkani-Hamed, et. al. [183]
SUSY $SU(5)$ in 5D	$p \to \mu^+K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$	Hebecker, March-Russell[184]
SUSY $SU(5)$ in 5D variant II	$p \to \bar{\nu}K^+$	$10^{36} - 10^{39}$	Alciati et.al.[185]
Mini-split SUSY $SO(10)$	$p \to \bar{\nu}K^+$	$\lesssim 6 \times 10^{34}$	Babu, Bajc, Saad [146]
SUSY $SO(10) \times U(1)_{\text{PQ}}$	$p \to \bar{\nu}K^+$	$10^{33} - 10^{35}$	Babu, Bajc, Saad [147]
Extended SUSY $SO(10)$ Type-I seesaw Type-II seesaw Inverse seesaw	$p \to \bar{\nu}K^+$	 $10^{30} - 10^{37}$ $\lesssim 6.6 \times 10^{33}$ $\lesssim 10^{34}$	 Mohapatra, Severson [186] Mohapatra, Severson [186] Dev, Mohapatra [187]
SUSY $SO(10)$ with anomalous flavor $U(1)$	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$ $p \to \mu^+K^0$	$10^{32} - 10^{35}$	Shafi, Tavartkiladze [188]
SUSY $SO(10)$ MSSM	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{33} - 10^{34}$ $10^{32} - 10^{33}$	Lucas, Raby [189], Pati [179]
SUSY $SO(10)$ ESSM	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$	Pati [179]
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d = 5$)	$p \to \bar{\nu}K^+$ $p \to \mu^+K^0$	$\lesssim 2 \cdot 10^{34}$ $B \sim (1-50)\%$	Babu, Pati, Wilczek [190–192], Pati [179]
SUSY $SO(10) \times S_4$	$p \to \bar{\nu}K^+$	$\lesssim 7 \times 10^{33}$	Dev, Mohapatra, Dutta, Severson [193]
SUSY $SO(10)$ in 6D	$p \to e^+\pi^0$	$10^{34} - 10^{35}$	Buchmuller, Covi, Wiesenfeldt [194]
GUT-like models from Type IIA string with D6-branes	$p \to e^+\pi^0$	$\sim 10^{36}$	Klebanov, Witten [195]

Ongoing Experiments

Historical Perspective

- Efforts date back to the sixties or even before (F. Reines and many others)
- Experiments in the eighties and nineties reached $\sim 10^{31-33}$ yr
  - IMB, Kamiokande, Soudan, Frejus
  - Note that **KamiokaNDE** stands for "Kamioka Nucleon Decay Experiment"
- Also shown here is limit KamLAND set for $p \rightarrow \bar{\nu}K^{+}$ channel in 2015
- Current limits now dominated by Super-Kamiokande

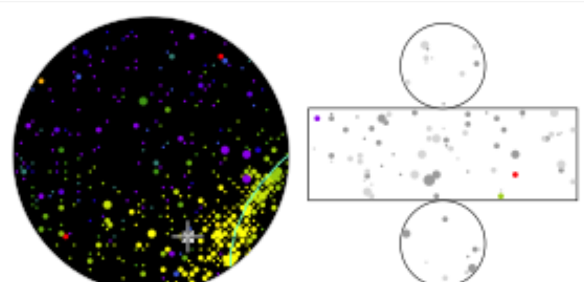


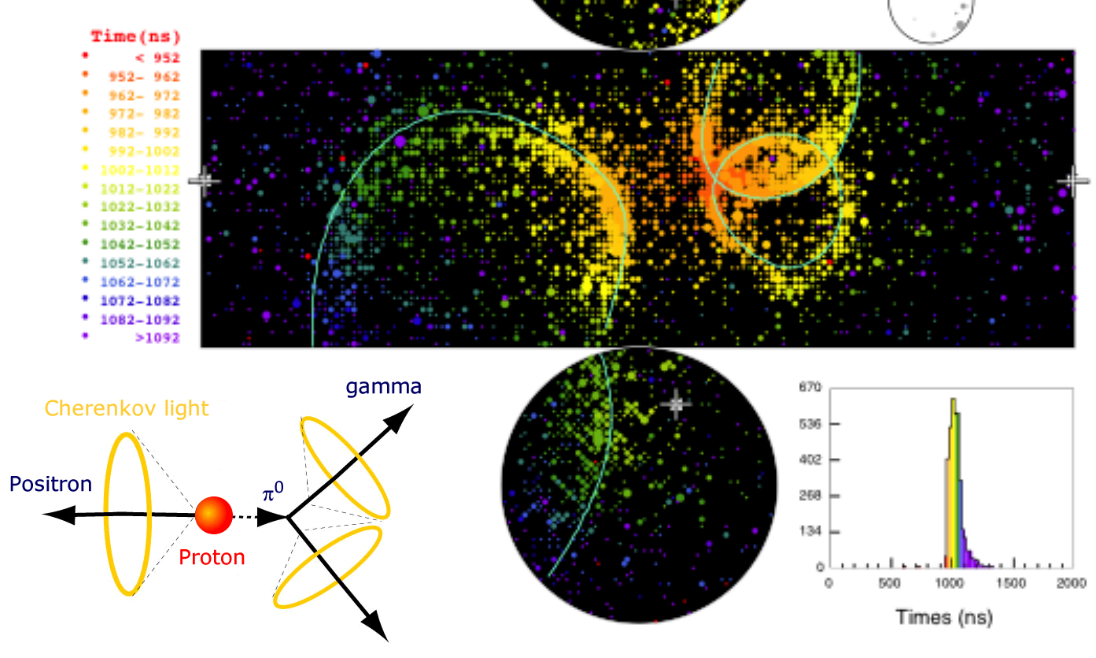
(plot from E. Kearns, 2018)

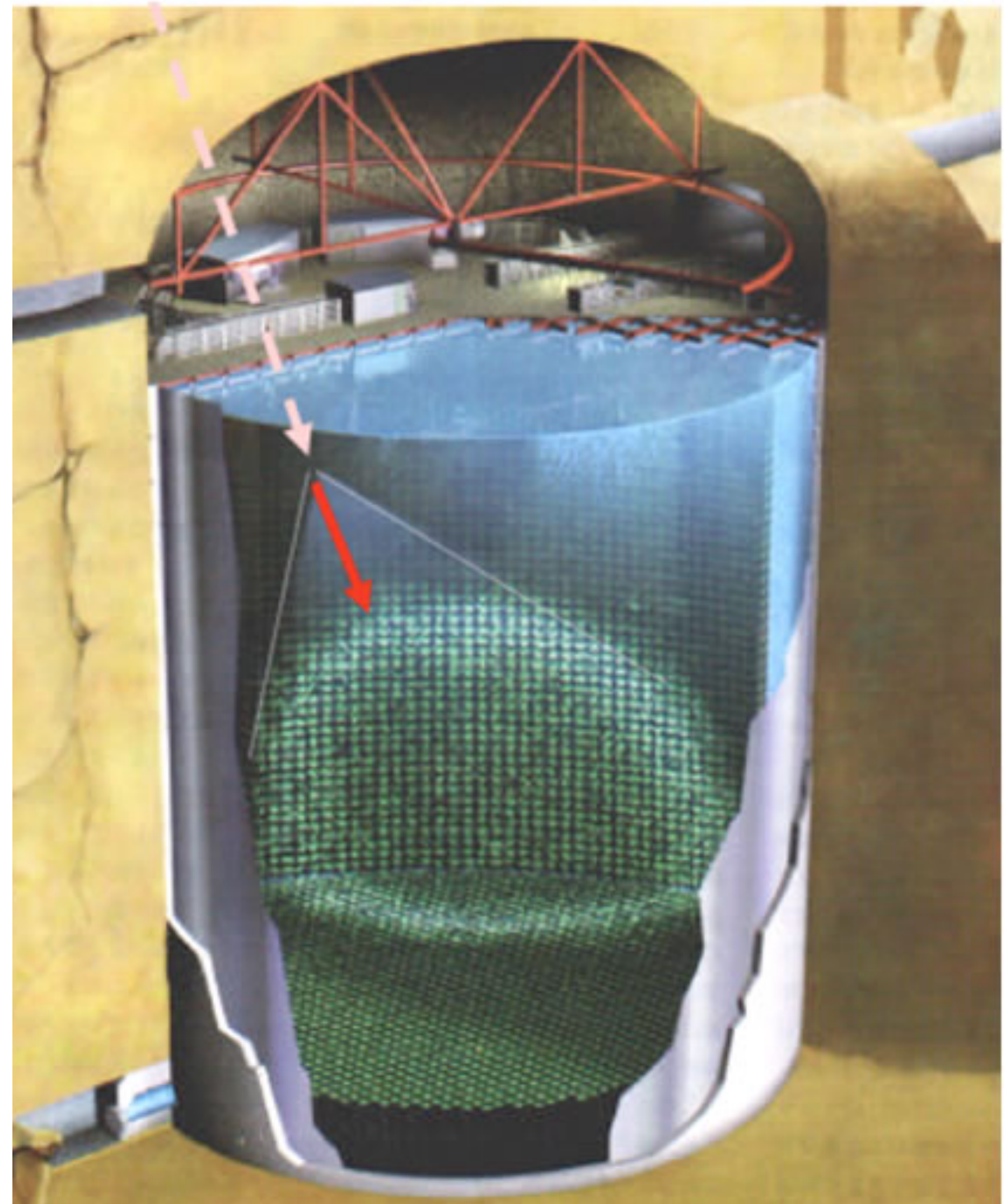
Super-Kamiokande

- Super-Kamiokande (SuperK) is a 2nd generation nucleon decay + neutrino experiment:
  - 22.5 to 27.2 kton of ultrapure water (fiducial)
  - 1 km underground
  - 11,000 50-cm photomultiplier tubes (PMTs)
  - Recently upgraded with gadolinium sulfate to enhance neutron capture

Example of simulated $p \rightarrow e^{+}\pi^{0}$ event







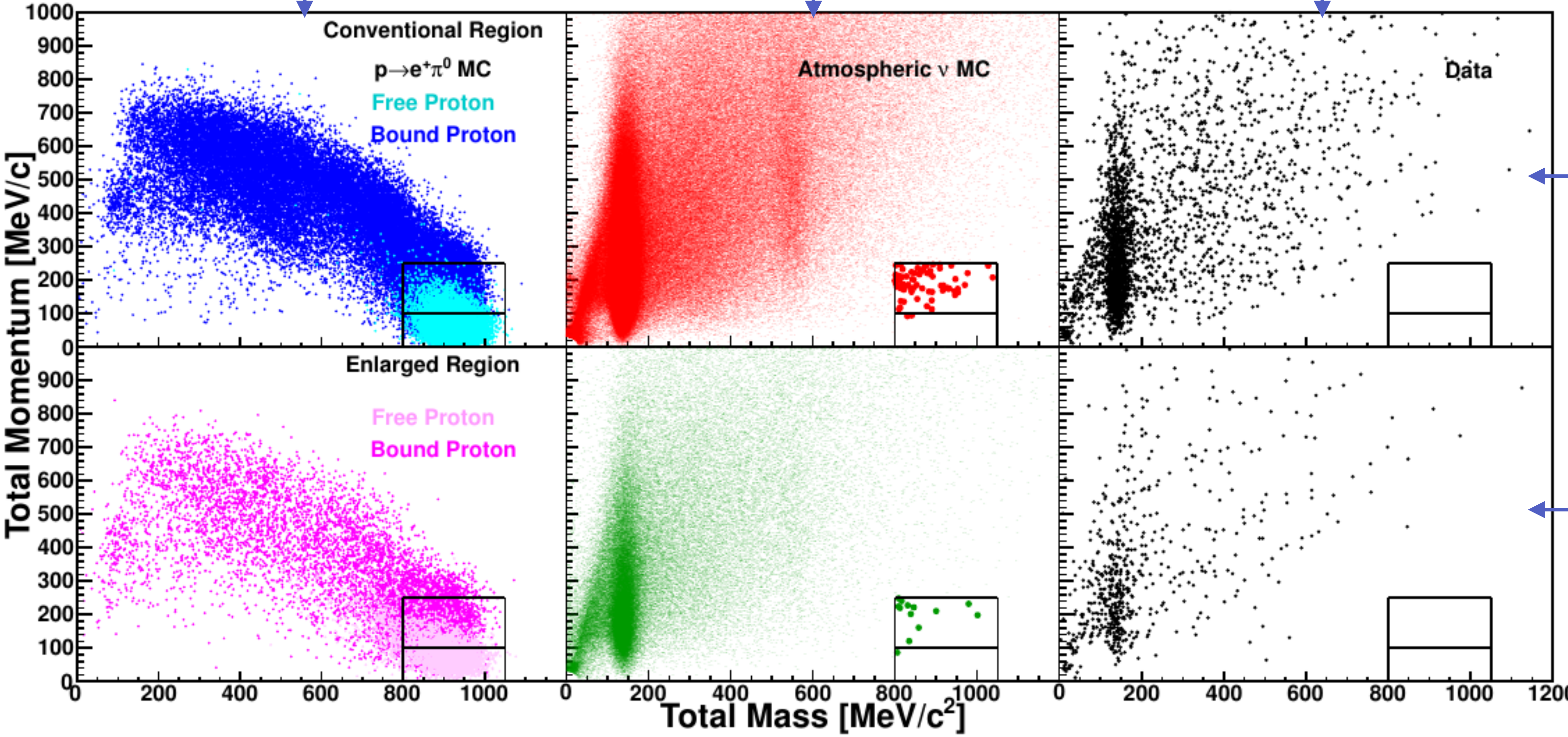
Example from SuperK

- Example: search for $p \to e^+\pi^0$

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

Predicted background (atmospheric ν interactions)

Data



Original fiducial volume, at least 200 cm from PMT plane

Additional fiducial volume between 100 and 200 cm from PMT plane

PRD 102, 112011 (2020)

(signal for decays in ^{16}O is degraded with respect to that from free protons)

Latest Limits from SuperK

- Operating since 1996!
  - Set a very high bar of **450 kt-yr** of exposure

Channel	Comment	Exposure	Limit	Reference
$p \to e^+\pi^0$	$d = 6$ operators, e.g. SU(5)	450 kt·y	2.4×10^{34} y	[55]
$p \to \mu^+\pi^0$	flipped SU(5)	450 kt·y	1.6×10^{34} y	[55]
$p \to \nu K^+$	$d = 5$ SUSY operators	260 kt·y	5.9×10^{33} y	[472]
$p \to \mu^+ K^0$	SUSY SO(10)	173 kt·y	1.6×10^{33} y	[474]
$pp \to K^+K^+$	RPV SUSY	92 kt·y	1.7×10^{32} y	[372]
$p \to e^+e^+e^-$	lepton flavor symmetries	370 kt·y	3.4×10^{34} y	[475]
$n \to \bar{n}$	$\Delta B = 2$	370 kt·y	3.6×10^{32} y	[328]
$np \to \tau^+\nu$	extended Higgs sector	273 kt·y	2.9×10^{31} y	[476]
$n \to \nu\gamma$	radiative	273 kt·y	5.5×10^{32} y	[476]
$p \to e^+\nu\nu$	Pati-Salam	273 kt·y	1.7×10^{32} y	[294]

Also limit on free neutron-antineutron oscillation ($n - \bar{n}$) lifetime of 4.7×10^8 s (see next slides)

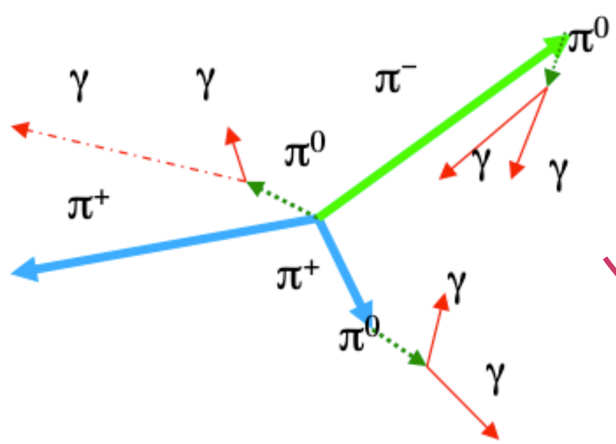
(table from arXiv:2203.08771)

- Decades of experience through many slow improvements
- More results still expected:
  - Background reduction through improved neutron tagging, refinement of intranuclear simulations, improvement of reconstruction techniques, search for novel decay channels

NOvA

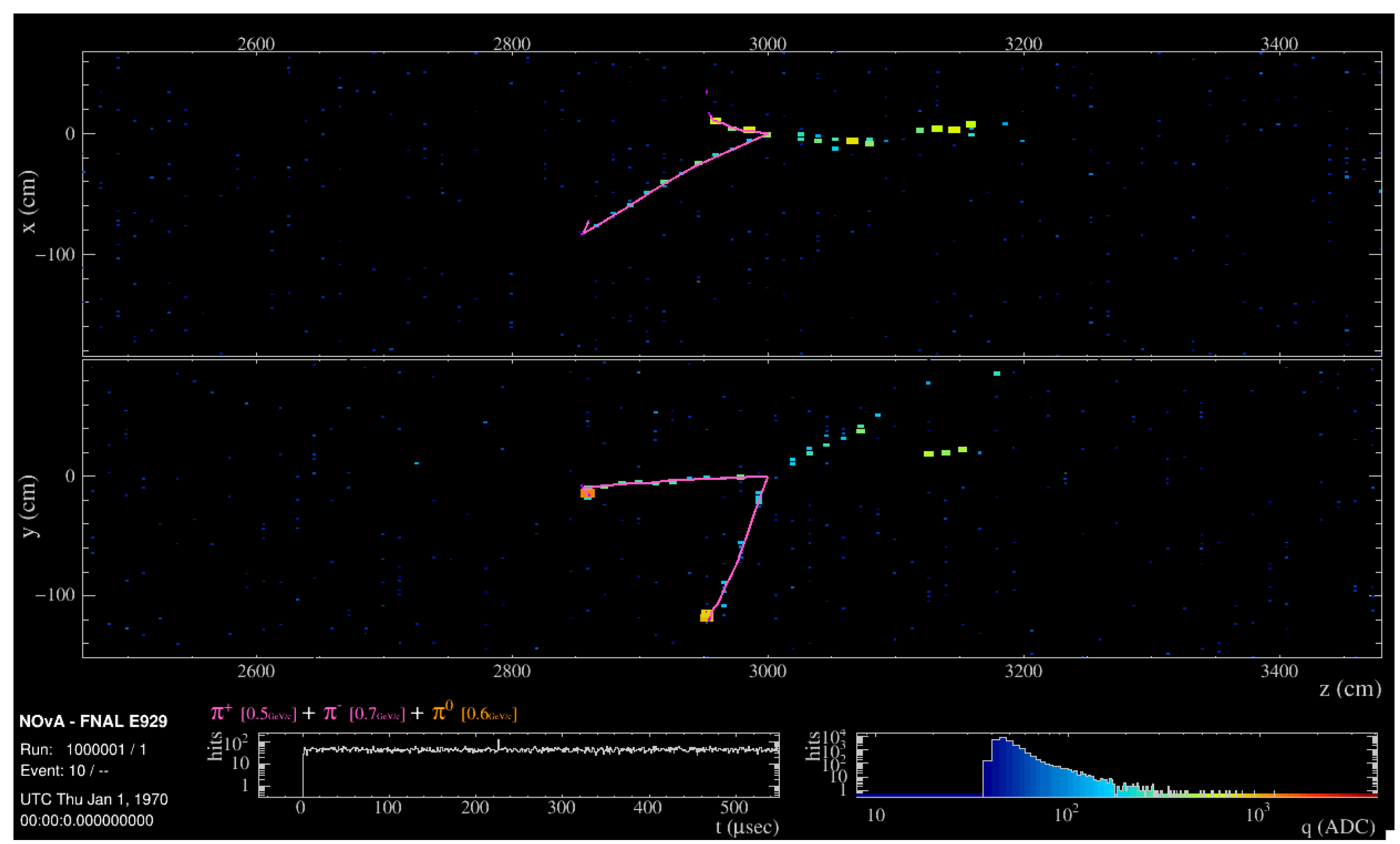
- NOvA is a long-baseline neutrino experiment:
  - 14 kton Far Detector in Minnesota
  - Sensitive to intranuclear $n - \bar{n}$ transformations

Annihilation with nearby neutron gives “pion-star” event



Example in NOvA

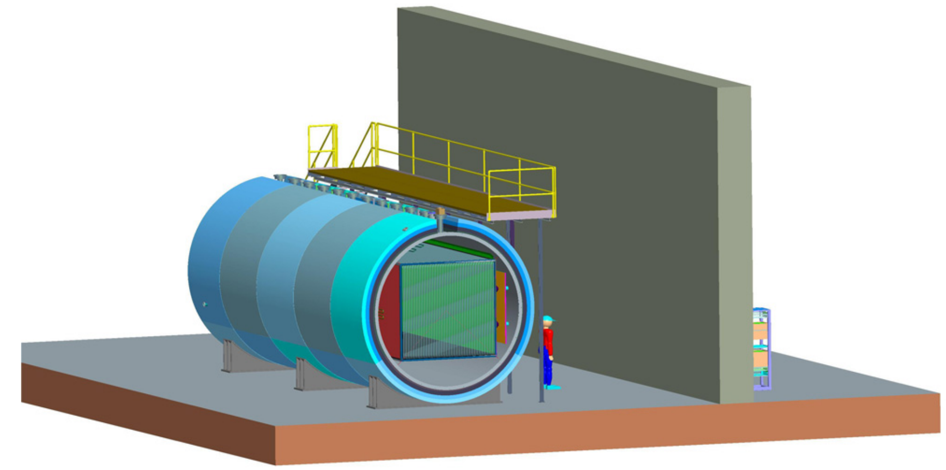
  - Pro: $n - \bar{n}$ suppression likely lower in C and Cl than in O
  - Con: shallow overburden
- Expect free neutron lifetime sensitivity $\gtrsim 10^8$ s (90% C.L.)

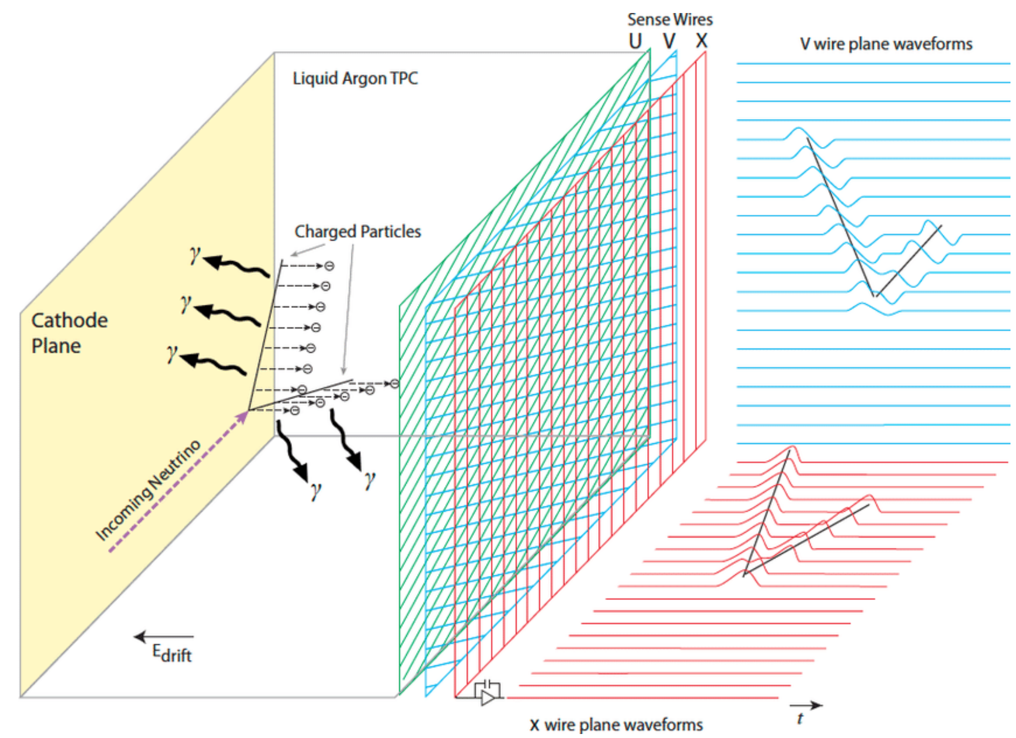


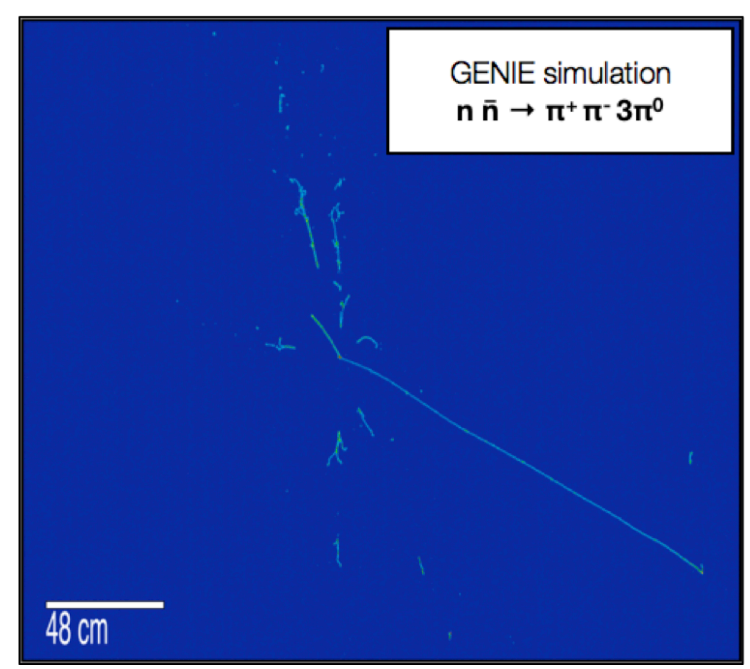
(event display from arXiv:2203.08771)

MicroBooNE

- MicroBooNE is part of Fermilab's short baseline neutrino program
  - 470 m from Booster Neutrino Beamline's target
  - 90 ton fiducial Liquid Argon Time Projection Chamber (LArTPC)
- Pros:
  - Excellent spatial and calorimetric resolution with LArTPC technology
- Cons:
  - Small size
  - Low overburden
- Analysis in progress:
  - Limit will not be competitive, but will demonstrate capabilities with LArTPC for first time





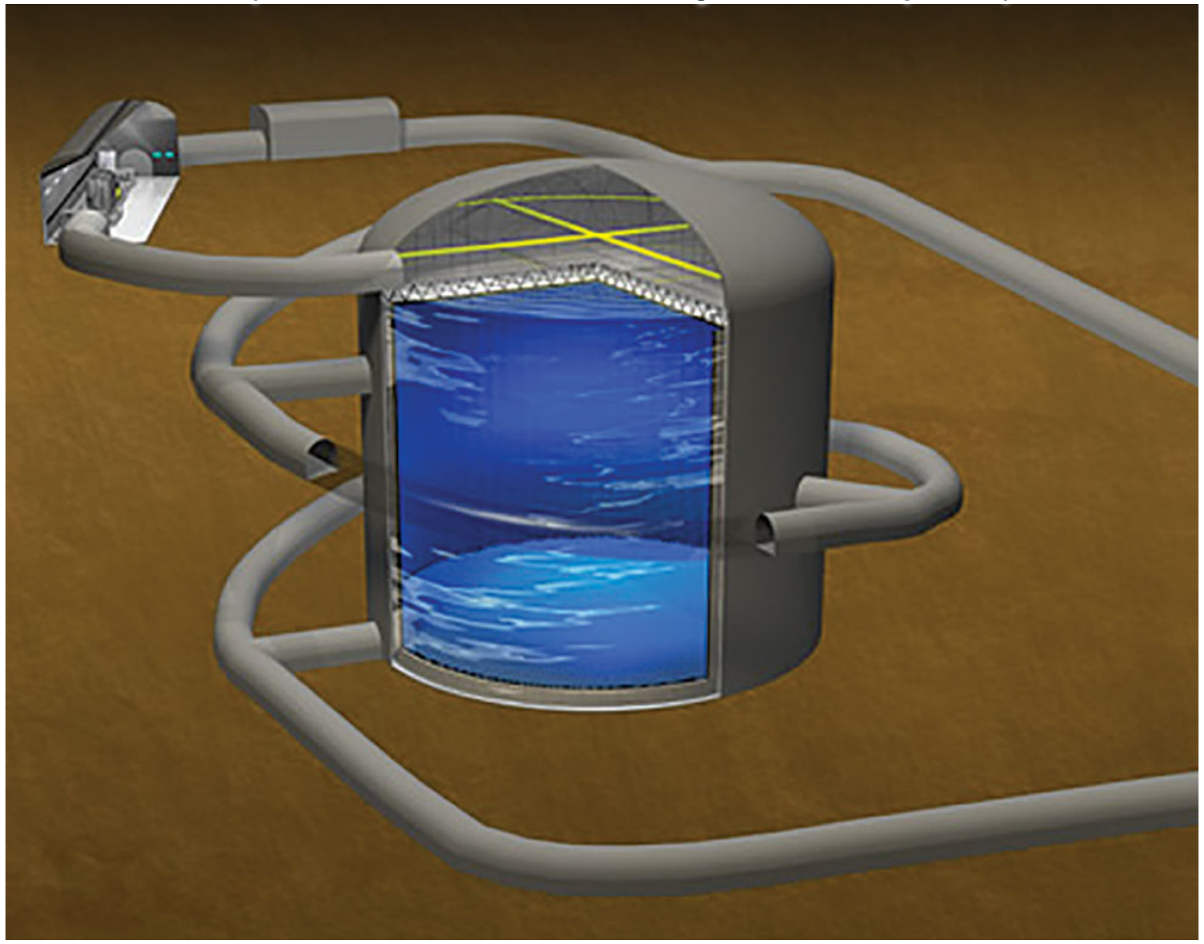


Next Generation Experiments

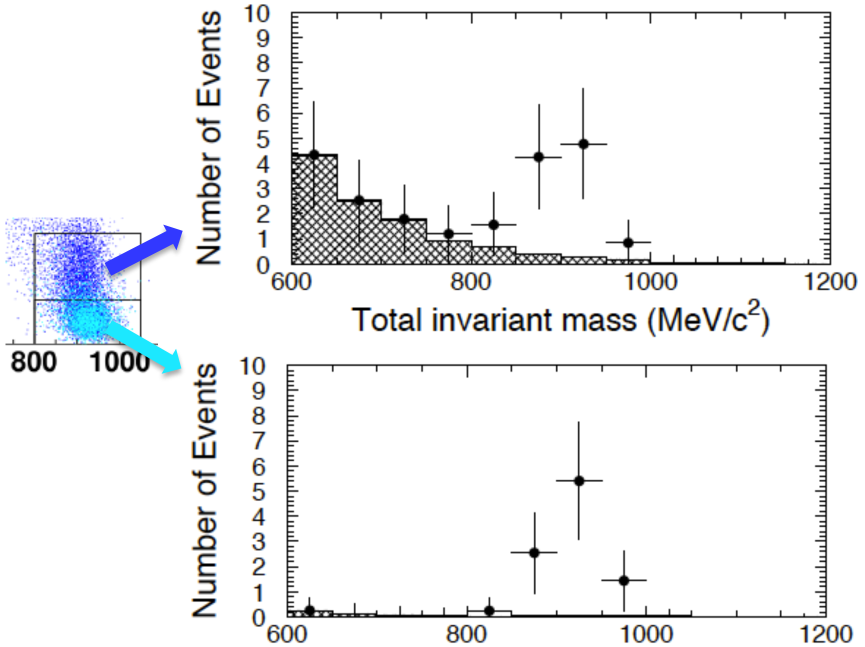
Hyper-Kamiokande

- Third generation nucleon decay + neutrino experiment
- Improvements with respect to SuperK:
  - **187 kton** fiducial water target (~8x more than SuperK)
  - PMTs with better detection efficiencies and timing resolution (both by factor of ~2)
    - Improved efficiency & background rejection
- Study natural neutrinos and 1.3 MW neutrino beam from upgraded JPARC accelerator
- Decay signals at SuperK limit would be “obvious” at HyperK ⟶
- Data taking to begin by ~2027

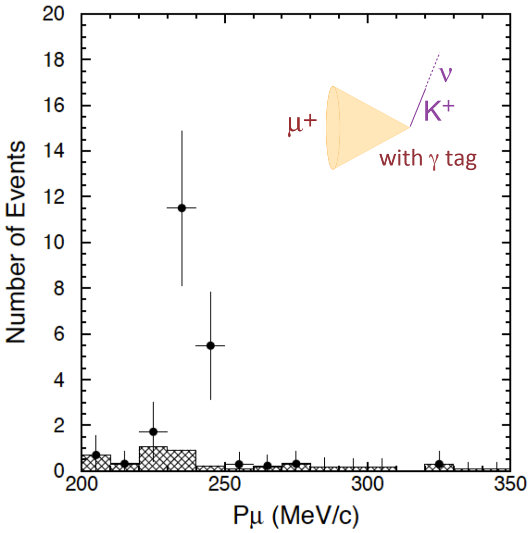
(location is 8 km away from SuperK)



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



$p \to K^+\nu$



(from E. Kearns, Snowmass 2021 BLV workshop)

Hyper-Kamiokande

3σ discovery potential is 6×10^{34} yr

HyperK sensitivities to selected nucleon decay modes with 10 years of operation (20 years for dinucleon modes)

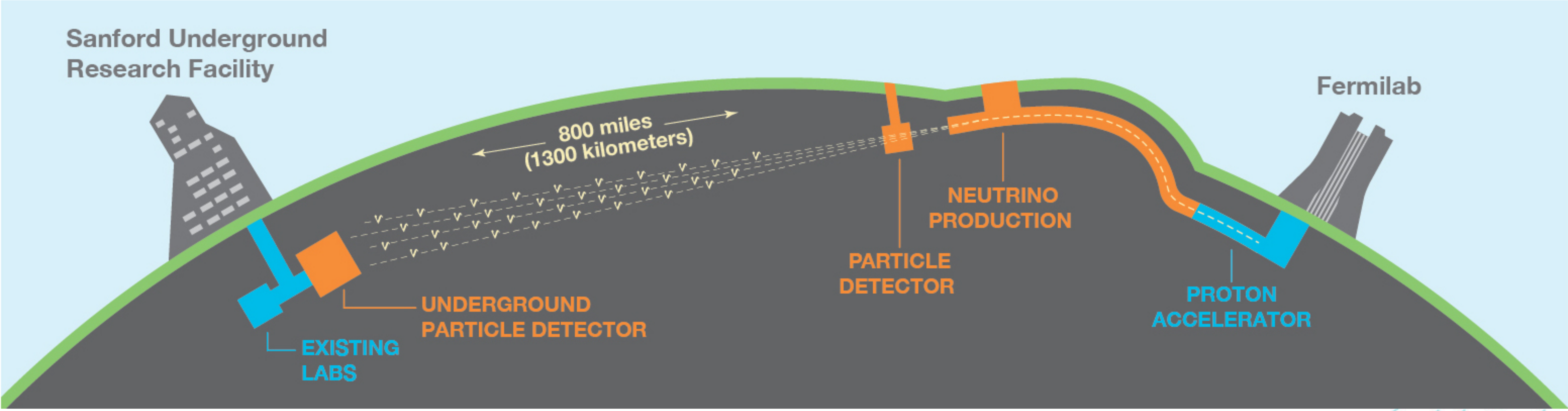
3σ discovery potential is 2×10^{34} yr

Mode	Sensitivity (90% CL) [years]	Mode	Sensitivity (90% CL) [years]
$p \to e^+\pi^0$	7.8×10^{34}	$p \to \overline{\nu}K^+$	3.2×10^{34}
$p \to \mu^+\pi^0$	7.7×10^{34}	$p \to \mu^+\eta^0$	4.9×10^{34}
$p \to e^+\rho^0$	0.63×10^{34}	$p \to \mu^+\rho^0$	0.22×10^{34}
$p \to e^+\nu\nu$	10.2×10^{32}	$p \to \mu^+\nu\nu$	10.7×10^{32}
$p \to e{+}X$	31.1×10^{32}	$p \to \mu^+X$	33.8×10^{32}
$np \to e^+\nu$	6.2×10^{32}	$np \to \mu^+\nu$	4.2×10^{32}
$np \to \tau^+\nu$	6.0×10^{32}	$n \to e^-K^+$	1.0×10^{34}

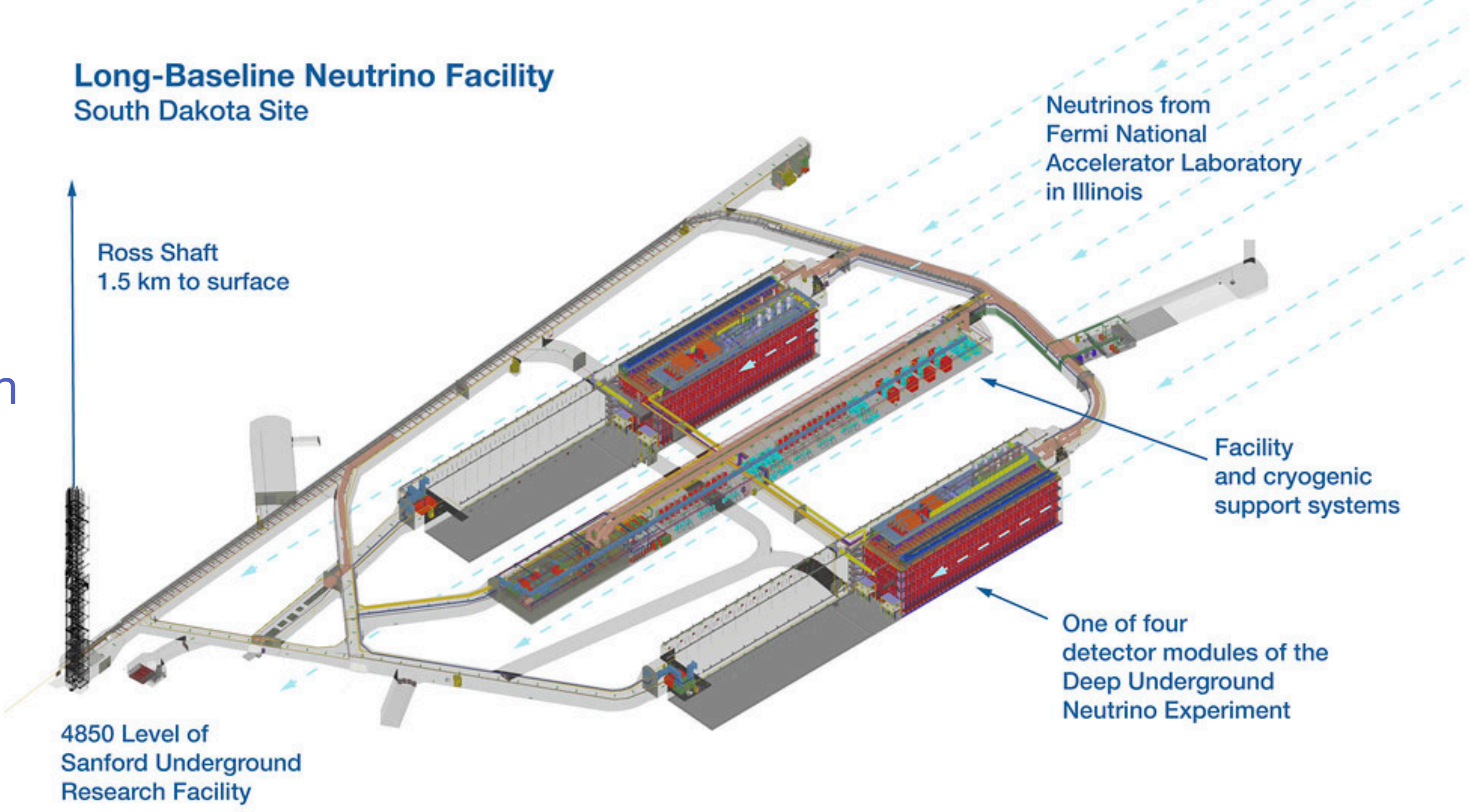
(table from arXiv:2203.08771)

- Improvement over Super Kamiokande limits all across the board
  - Only factor of ~few improvement for "partially invisible" modes (e.g. $p \to e^+\nu\nu$)
  - Could further reduce backgrounds through a variety of improvements, from from improved reconstruction algorithms to future gadolinium doping

DUNE



- The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline neutrino experiment
  - Modular Far Detector design with up to 40 kton total fiducial mass
    - 4th module under open study
  - 1.5 km deep
  - Study natural neutrinos and from 1.2 MW LBNF beam (upgradable to 2.4 MW)



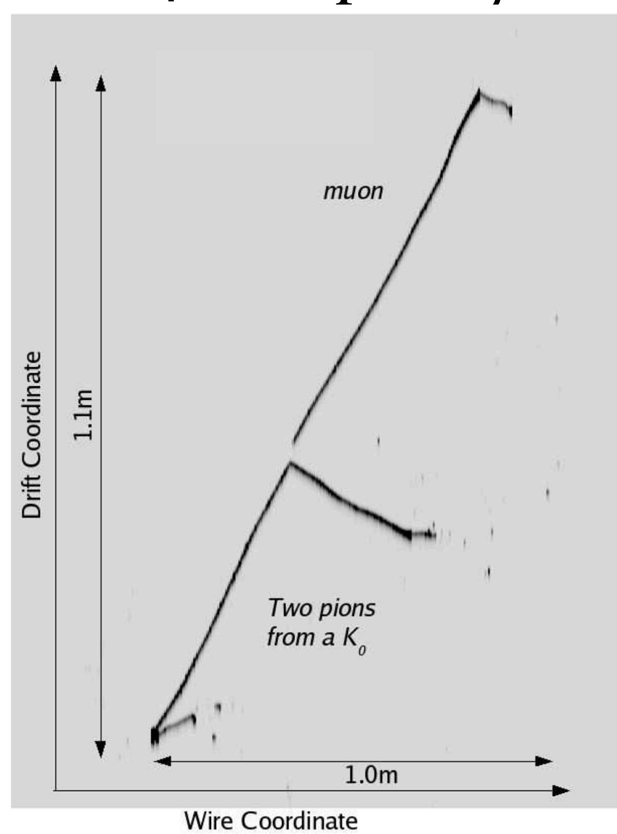
DUNE

- One of DUNE's main advantages: bubble-chamber-like detection capabilities with LArTPC technology
  - Ability to distinguish γ and e, low cosmic backgrounds, very low LAr ionization threshold for heavy charged particles, MeV-scale reach
- Provides an important advantages for certain channels
  - For example, modes with charged kaon in final state or with displaced vertices

Mode	Lifetime Sensitivity (90% C.L.)
$p \to e^+\pi^0$	$\sim 1.0 \times 10^{34}$ yr
$p \to \bar{\nu}K^+$	1.3×10^{34} yr
$n \to e^-K^+$	1.3×10^{34} yr
free $n - \bar{n}$	5.5×10^{8} s

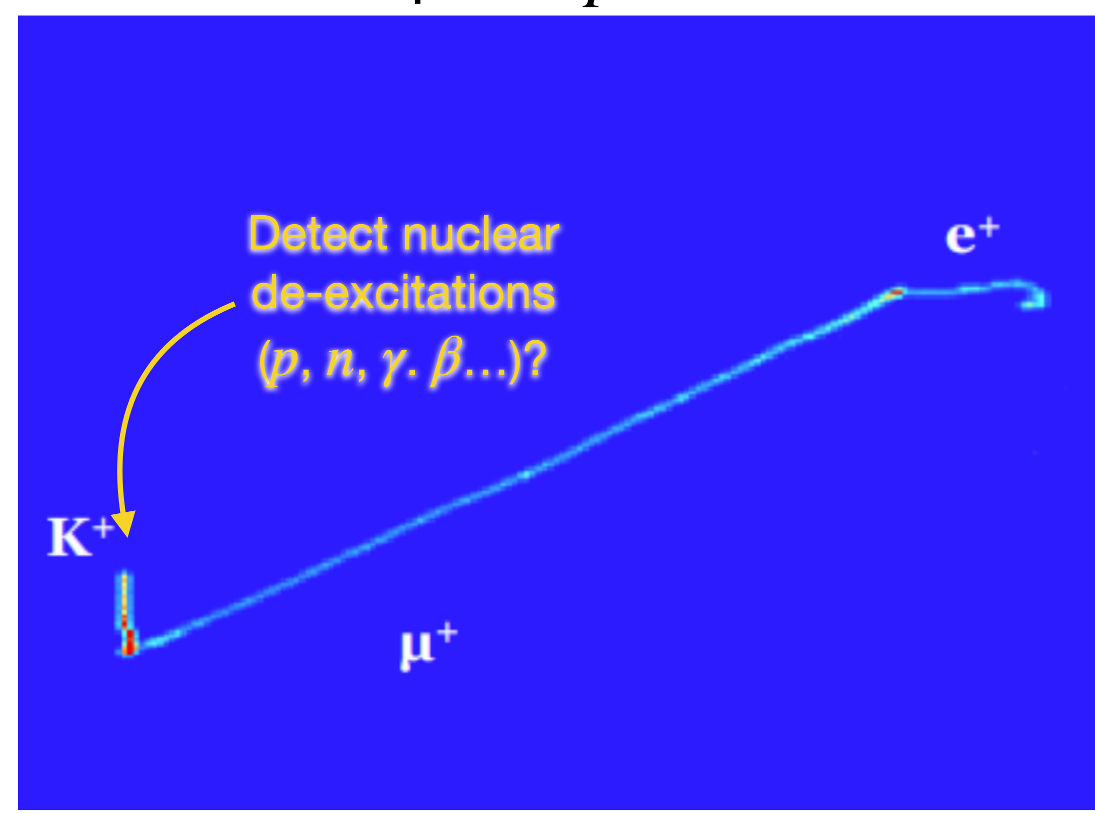
(selected estimates for 400 kt-yr exposure, arXiv:2203.08771)

Example of $p \to \mu^+K^0$



(from E. Kearns talk at Snowmass 2021 BLV workshop)

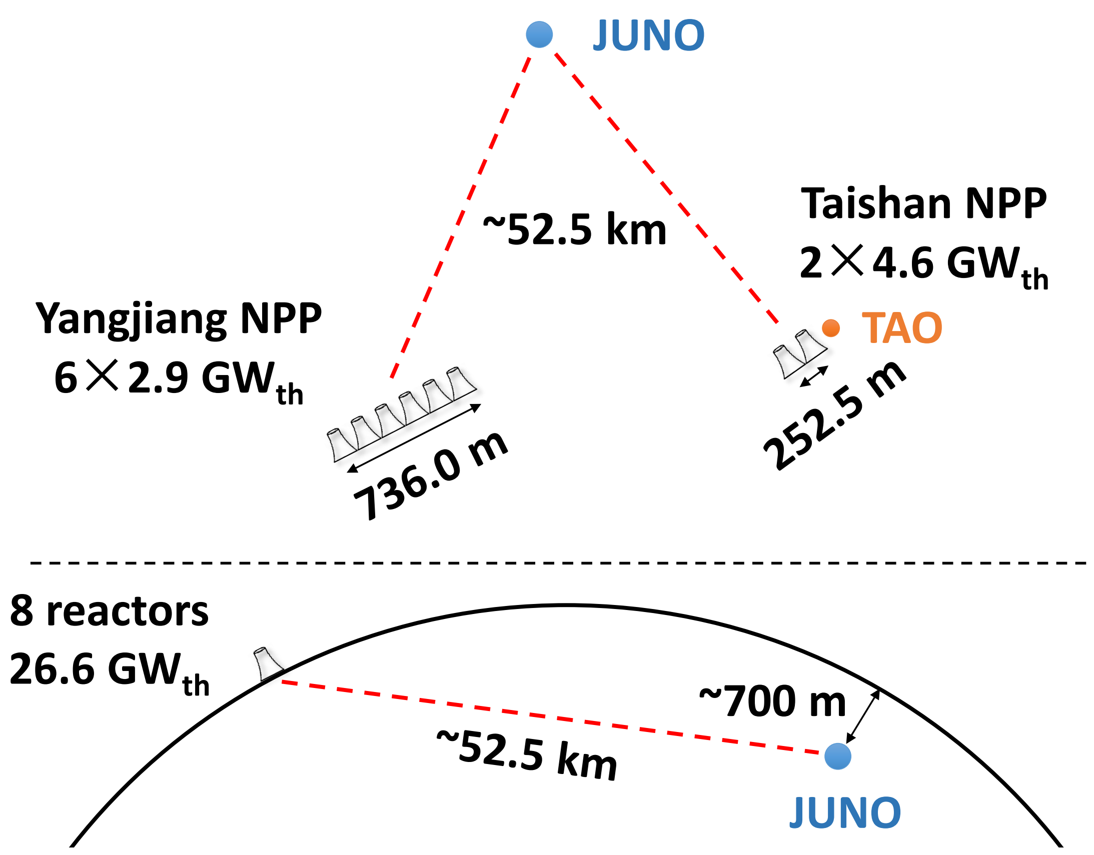
Example of $p \to \bar{\nu}K^+$

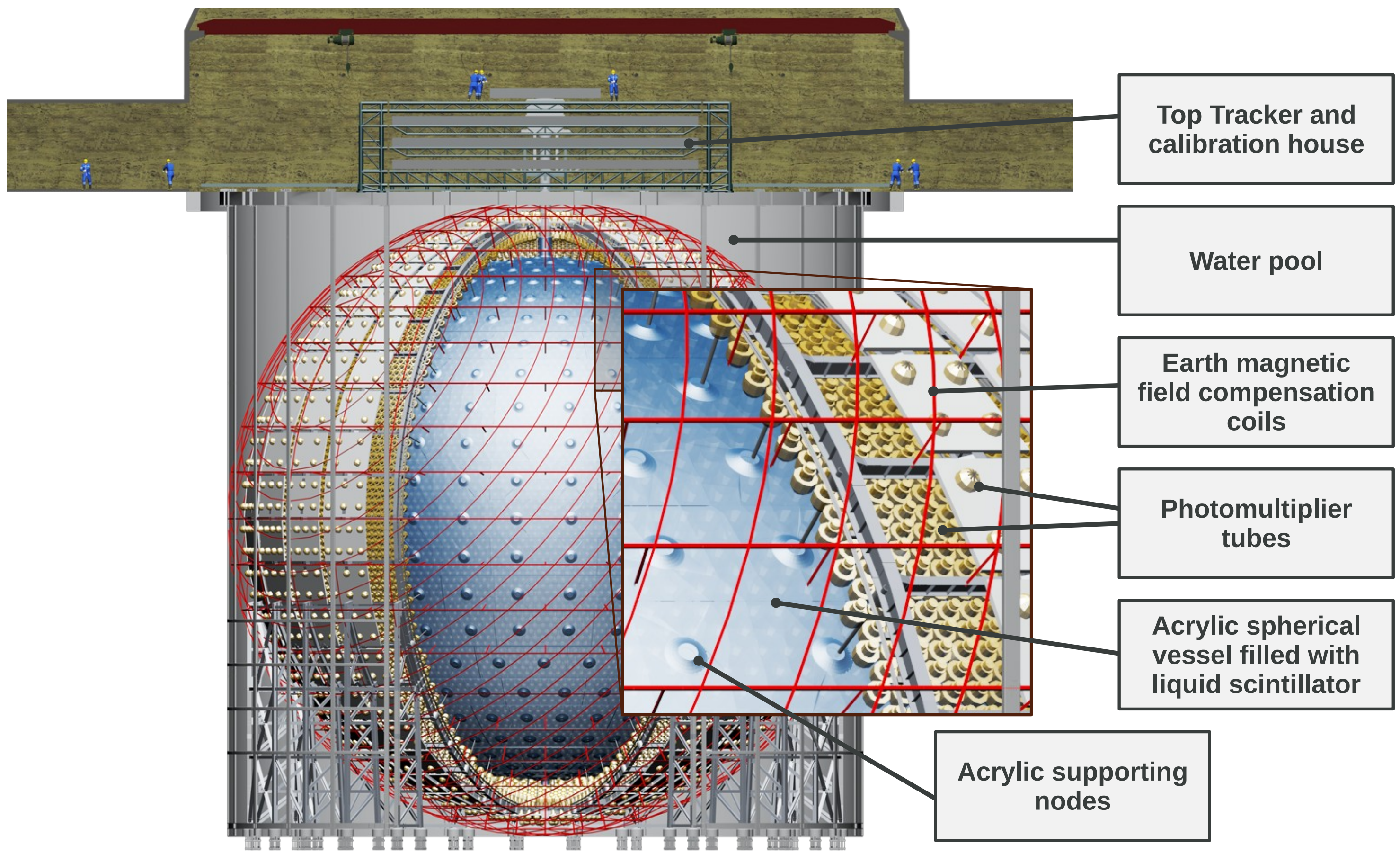


(adapted from FERMILAB-CONF-18-679-ND)

JUNO

- The Jiangmen Underground Neutrino Observatory is a multi-purpose experiment under construction in China
  - ~52.5 km from eight nuclear reactors
  - ~650 m overburden

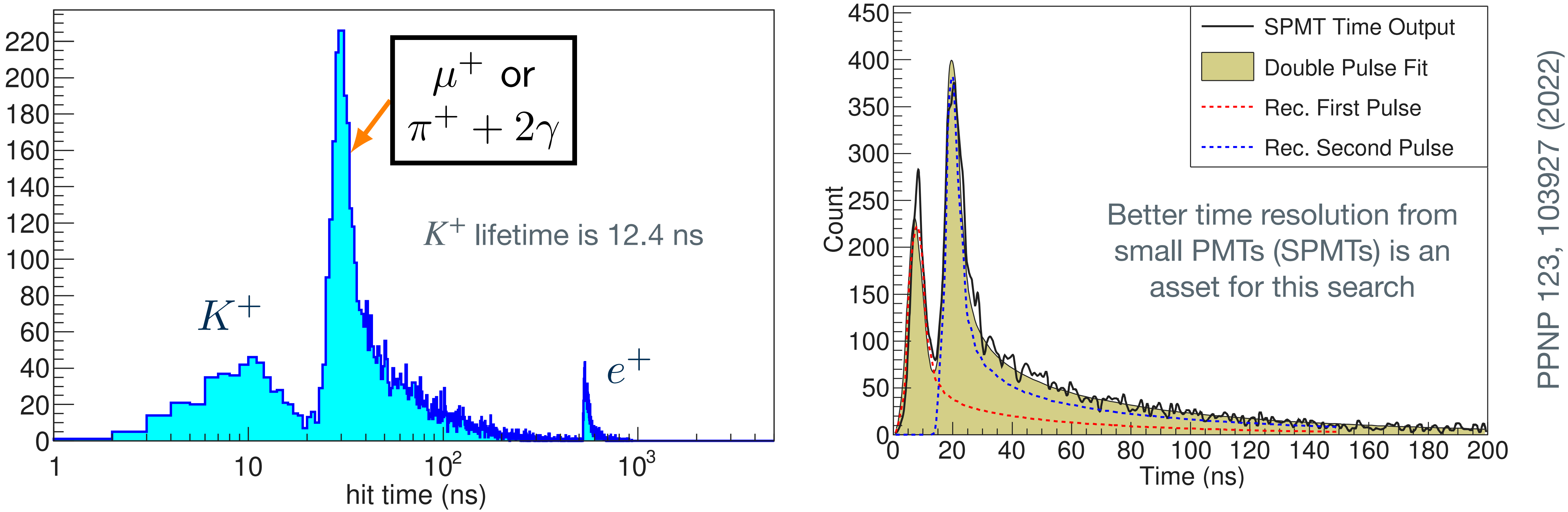




- **20 kton** liquid scintillator target surrounded by 17,612 20-inch PMTs and 25,600 3-inch PMTs (>76% photocathode coverage)
- Unprecedented energy resolution of 3% at 1 MeV for a detector of this type

JUNO

- Liquid scintillator detectors is ideal for $p \to \bar{\nu} K^+$ mode
  - K^+ below threshold in Cherenkov detectors
  - Detectable threefold coincidence, which is a powerful handle against backgrounds:

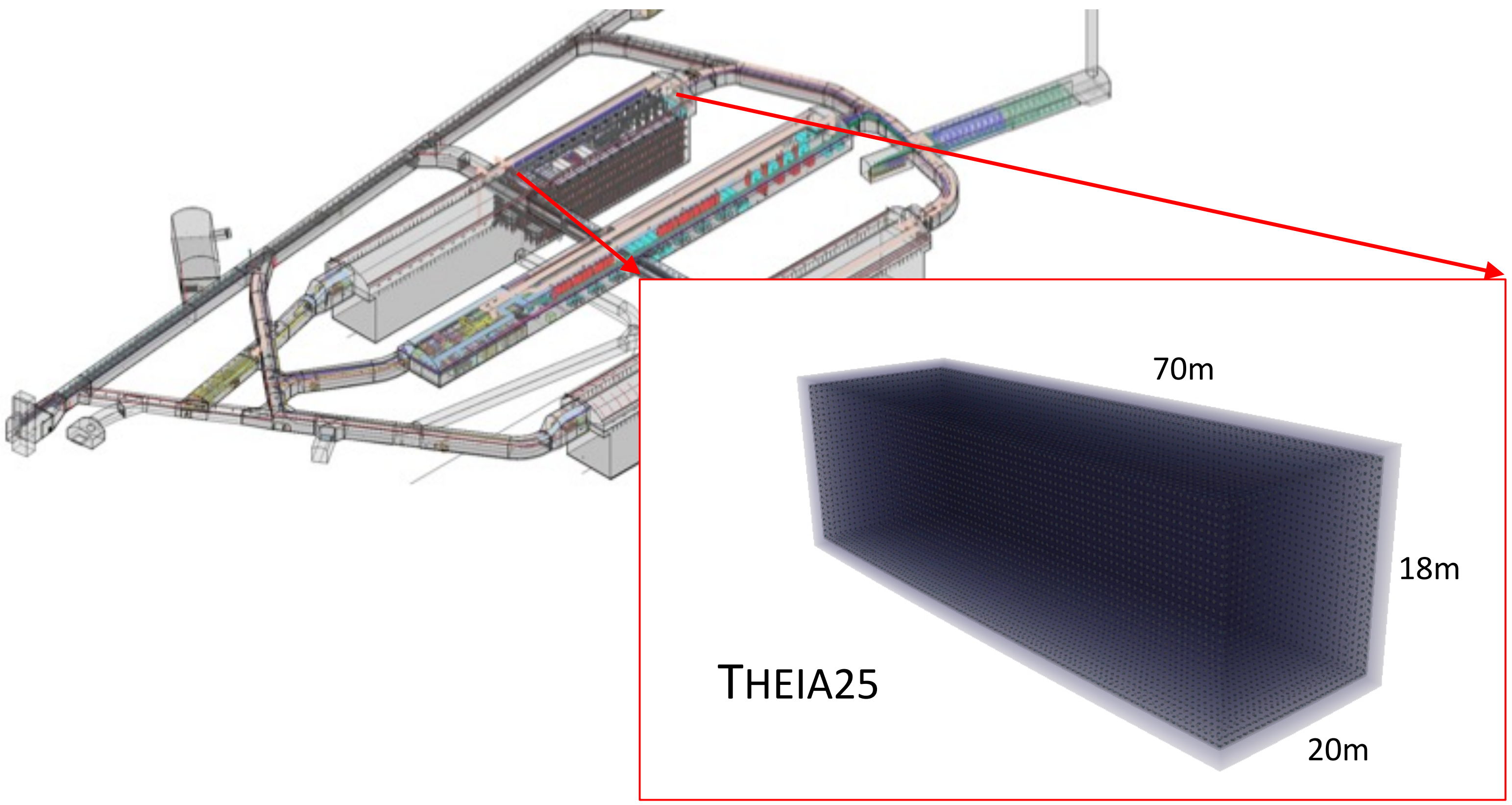


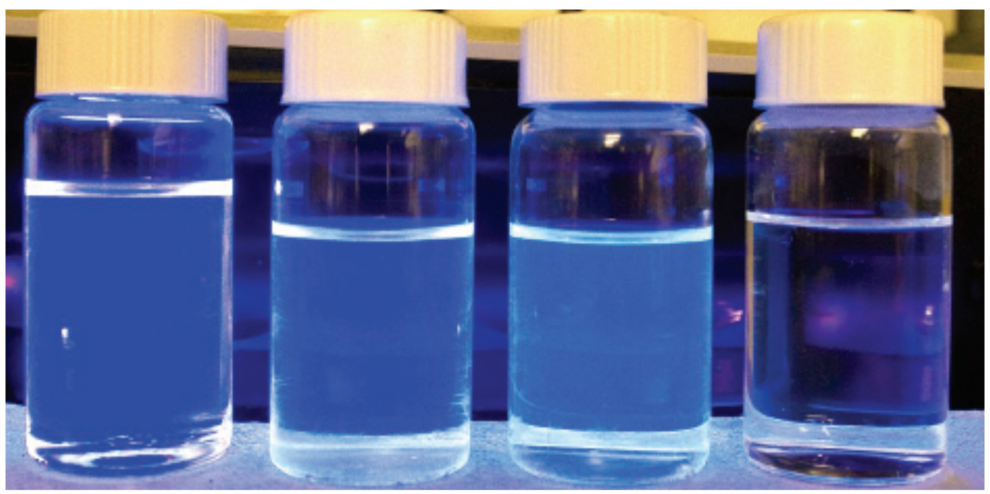
  - Latest estimate of 90% C.L. sensitivity with 10 years of data: 8.34×10^{33} yr
  - Proof-of-principle done by KamLAND in 2015 (limit of 5.4×10^{32} yr)
- Also expect good performance for invisible mode $n \to 3\nu$
  - Detect de-excitation of the nucleus (see PRD 96, 101802 (2006) and PRD 92, 102004 (2004))
  - Sensitivity under evaluation

THEIA

- THEIA is a hybrid Cherenkov + scintillator detector concept relying on two technological advances:
  - Water-based Liquid Scintillator (WbLS)
  - Fast detectors with chromatic separation

Get directionality and particle ID from Cherenkov detectors with superior energy resolution and low threshold afforded by scintillation light



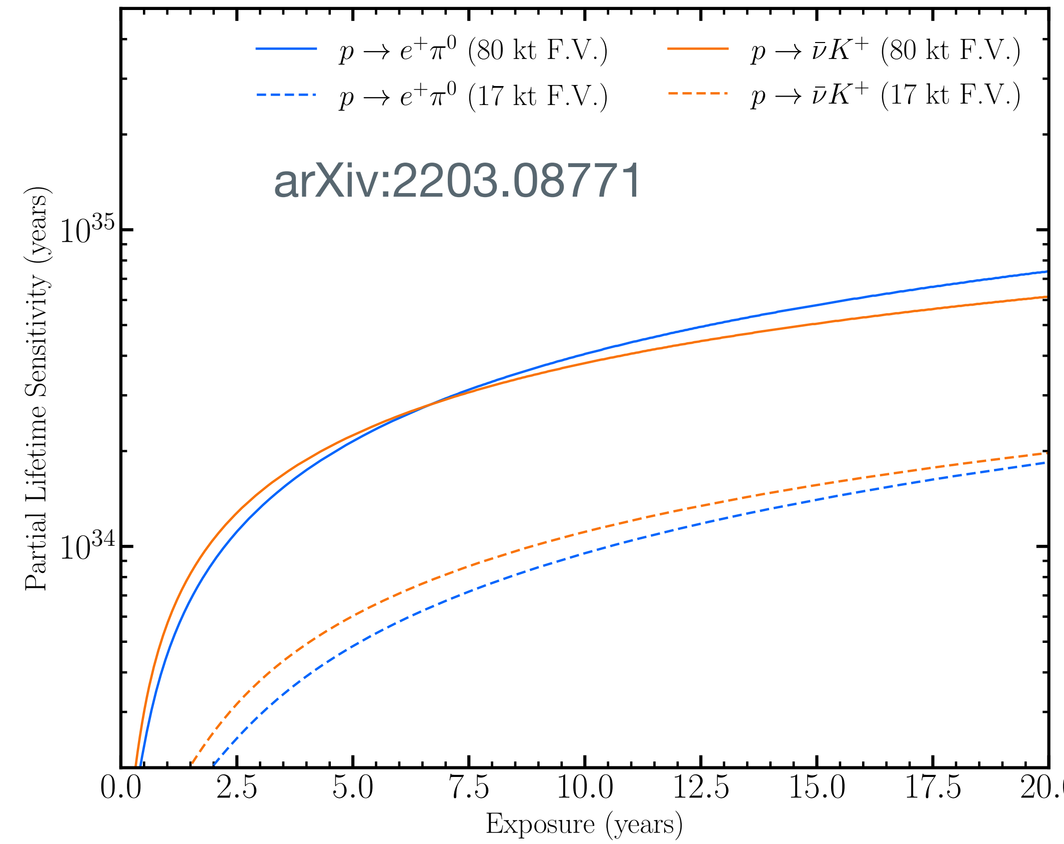


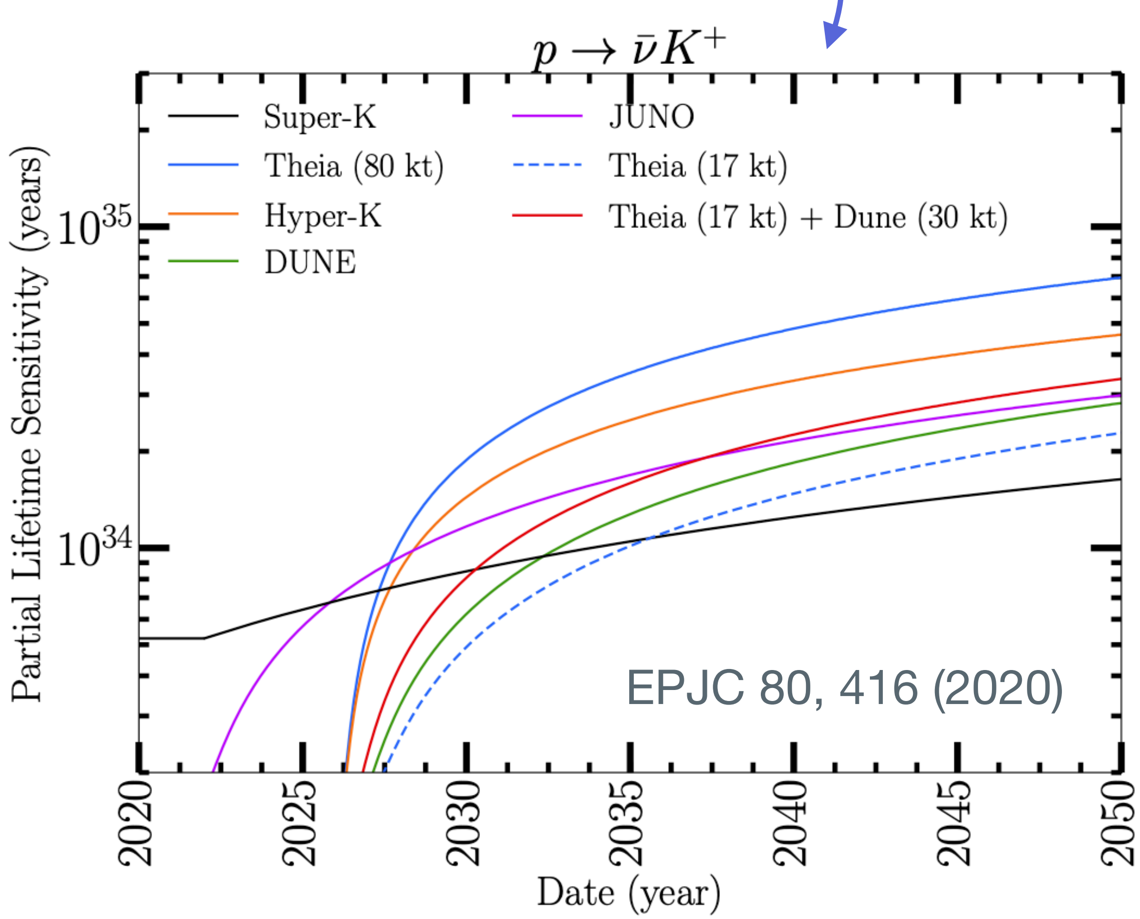
LS WbLS(1) WbLS(2) Water

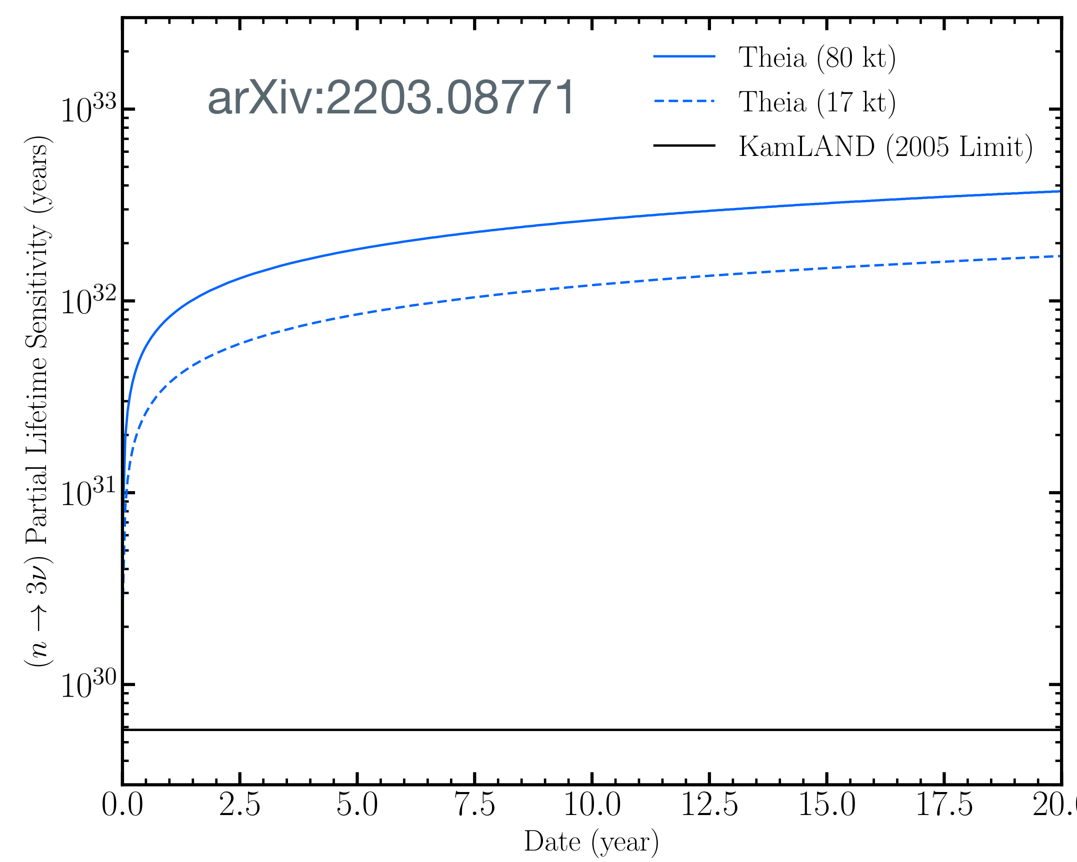
  - Better background rejection than conventional Cherekov detectors through improved neutron tagging, better resolution, and sensitivity to below-Cherenkov threshold charged particles
- Currently being considered as 4th module of DUNE (THEIA-25, 17 kton fiducial)
  - Also considering a 100 kton version called THEIA-100 with a broader program

THEIA

- Comparable or superior reach to other next-generation detectors:
  - Good sensitivity to invisible mode ($n \rightarrow 3\nu$) through de-excitation of ^{16}O nucleus
  - Worse performance for $p \rightarrow \bar{\nu}K^+$ compared to JUNO, but could be built to a larger scale





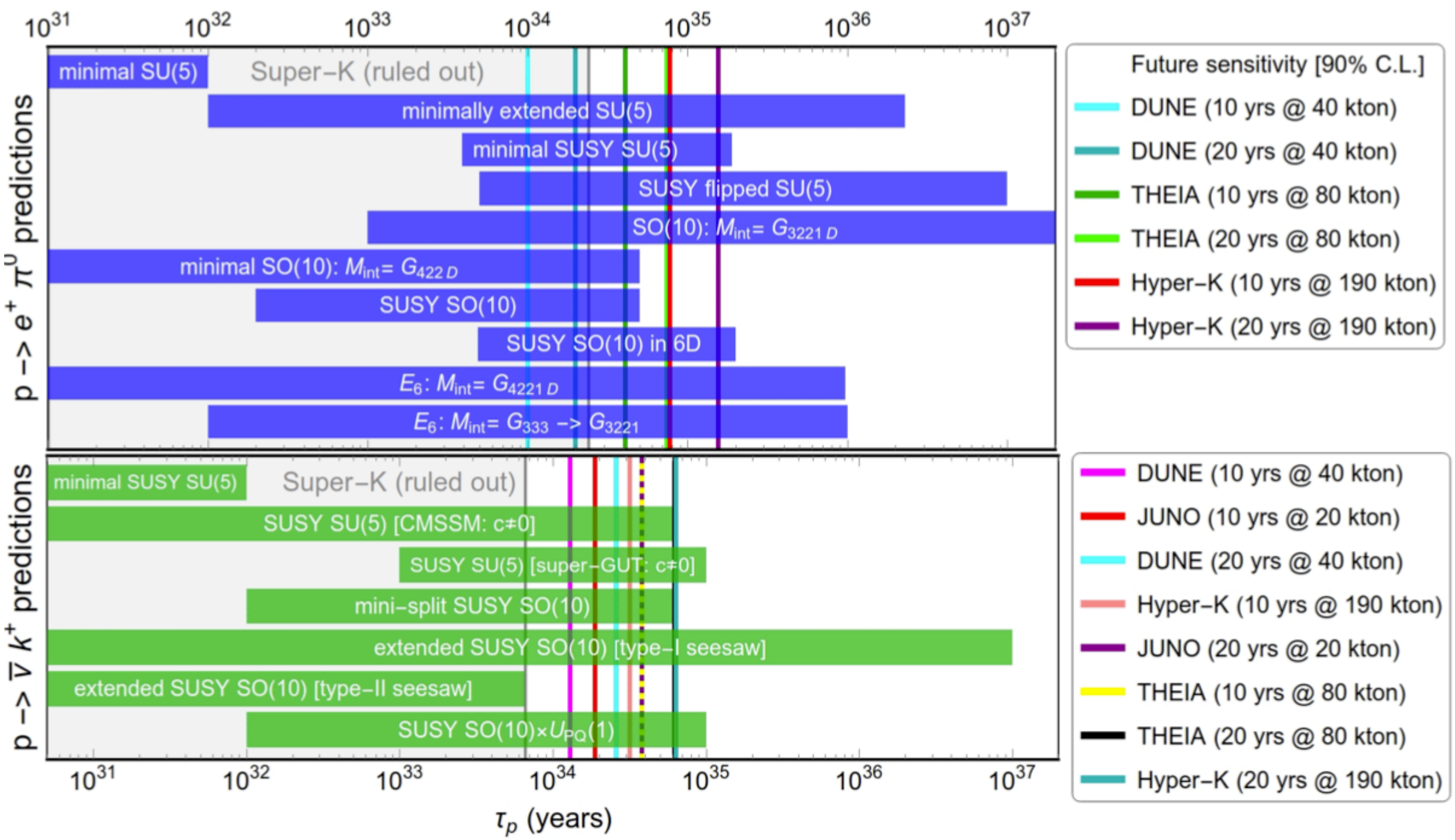


Summary & Conclusions

Summary & Conclusions

- Searching for BNV is a high-priority goal in particle physics
- Very strong synergy between neutrino physics & nucleon decay searches
  - Have covered a lot of ground in the last few decades
  - Next-generation experiments will extend our reach by up to 2 orders of magnitude

(table from arXiv:2203.08771)



- Stay tuned! A positive confirmed signal would make a profound impact on our understanding of the Universe

Backup

Summary Table

Modes (partial lifetime)	Current limit [90% CL] (10^{34} years)	Future Sensitivity [90% CL] (10^{34} years)
$\tau_p \; (p \to e^+\pi^0)$	Super-K: 2.4 [55]	Hyper-K (1900 kton-yrs): 7.8 [56] DUNE (400 kton-yrs): ~1.0 [57] THEIA (800 kton-yrs): 4.1
$\tau_p \; (p \to \mu^+\pi^0)$	Super-K: 1.6 [55]	Hyper-K (1900 kton-yrs): 7.7 [56]
$\tau_p \; (p \to \overline{\nu} K^+)$	Super-K: 0.66 [58]	Hyper-K (1900 kton-yrs): 3.2 [56] DUNE (400 kton-yrs): 1.3 [59] JUNO (200 kton-yrs): 1.9 [60] THEIA (800 kton-yrs) 3.8
$\tau_p \; (p \to \overline{\nu}\pi^+)$	Super-K: 0.039 [61]	–

(table from arXiv:2203.08771)

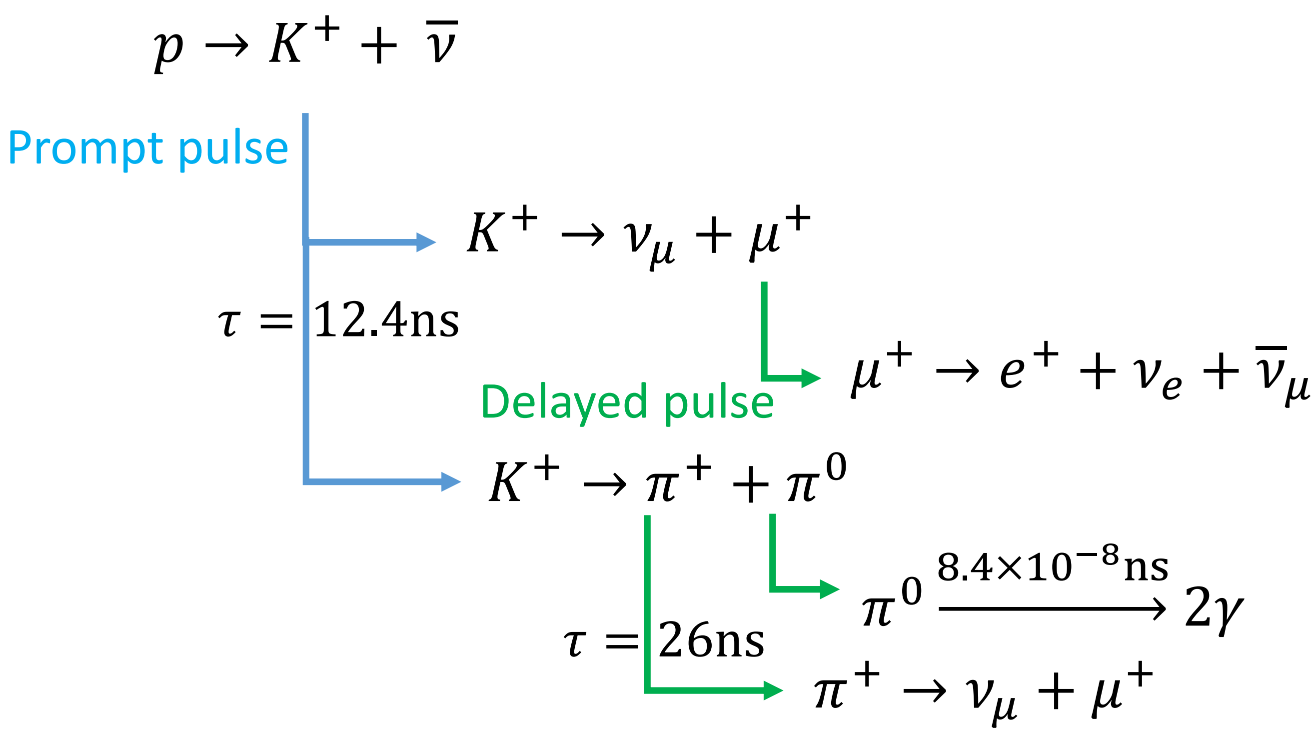
Water Cherenkov vs. LArTPC

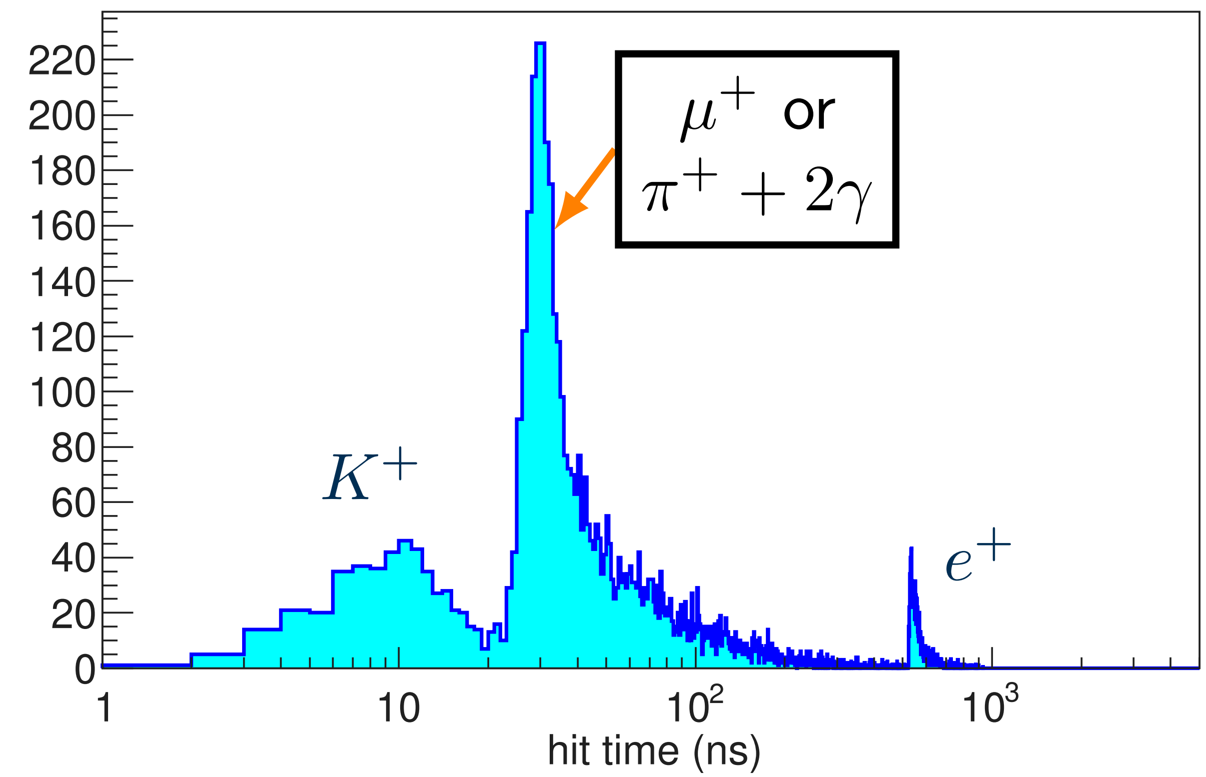
	Mode	Mega Water Ch.		Big LAr (generic, Bueno et al.)	
		Efficiency	BG Rate (/Mt y)	Efficiency	BG Rate (/Mt y)
B-L	$e^+\pi^0$	*38%*	*0.7*	45%	1
B-L	νK^+	*22.5%*	*1.6*	**97%**	**1**
B-L	$\mu^+ K^0$	*10%*	*5-10*	**47%**	**<2**
B+L	$\mu^- \pi^+ K^+$	?	?	**97%**	**1**
B+L	$e^- K^+$	10%	3	**96%**	**<2**
$\Delta B=2$	n nbar	12%	260	**?**	**?**

Rough and unofficial
SK efficiency & BG
or from HK Design Report

Work underway
to reevaluate these for DUNE
Using full reconstruction

Signatures of K^+: need for large liquid scintillator





- K^+ is below Cherenkov threshold in water, invisible. So is μ^+ from π^+.
  - Searching for μ^+ or $\pi^+ + 2\gamma$ alone has background.
- Liquid scintillator is ideal for identifying K^+.
  - Scintillation photons from mesons and muons with low kinetic energy.
- Investigated by Undagoitia et al. 2005 and realized by KamLAND 2015.