Rare Processes and Precision Measurements Frontier
All-day virtual meeting — July 27, 2020

RPF04 — Baryon and Lepton Number Violating Processes
The experimental perspective

Andrea Pocar

University of Massachusetts, Amherst

the RPF04 team (https://snowmass21.org/rare/blv)

Co-conveners: Pavel Fileviez Perez (CWRU), Andrea Pocar (UMass Amherst)

- Theories for B and L number violation: P. Fileviez Perez (CWRU), M.B. Wise (Caltech)
- Neutrinoless double beta decays: V. Cirigliano (LANL), A. Pocar (UMass)
- B and L violation at colliders: R. Ruiz (Lovain), E. Thomson (UPenn)
- Proton decay: E. Kearns (Boston U.), S. Raby (Ohio St.)
- n-nbar oscillations: K. Babu (Oklahoma St.), L. Broussard (ORNL)
- More exotic L and B violating processes: S. Gardner (Kentucky), J. Heeck (Irvine)
- Connections to Cosmology: A. Long (Rice), C. Wagner (Chicago/ANL)

also on Slack: #rpf-04-blnv

the RPF04 activities (https://snowmass21.org/rare/blv)

Kickoff meeting:

BLV circa 2020 (July 6-8, 2020 – hosted by CWRU)
https://artsci.case.edu/blv2020/

All topical leaders, and others, presented for an excellent overview (theory, experiment, and their interplay)

All slides are posted on indico: day1, day 2, day 3

Most material shown here is detailed in those talks

Playbill

- BLV @ colliders
- Proton (and nucleon) decay
- Neutron-antineutron oscillation
- Neutrinoless double beta decay
- Exotic (less conventional) BLV

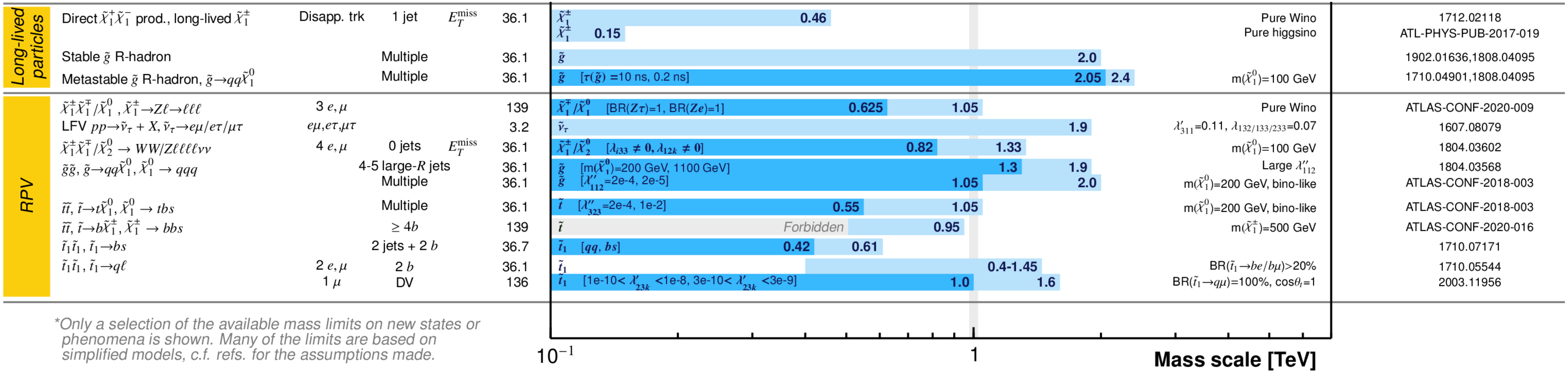
BLNV at colliders (SUSY)

(adapted from Evelyn Thomson)

- Review and discuss status of this field
  - R-parity violating (RPV) SUSY models evade the stringent limits from missing-energy-based searches, and remain excellent candidates for low-scale SUSY
  - Several recent searches by ATLAS and CMS with 2015-18 data
  - European strategy did not include any projections for RPV signatures
- Support Snowmass process, with letters of intent April 1 – August 31 2020
  - ➢ Development of RPV benchmarks and summary plots
  - ➢ Comparison of rare process measurements to collider reach
  - ➢ Coordinate with the Energy Frontier BSM model-specific explorations working group EF08

Possible topics

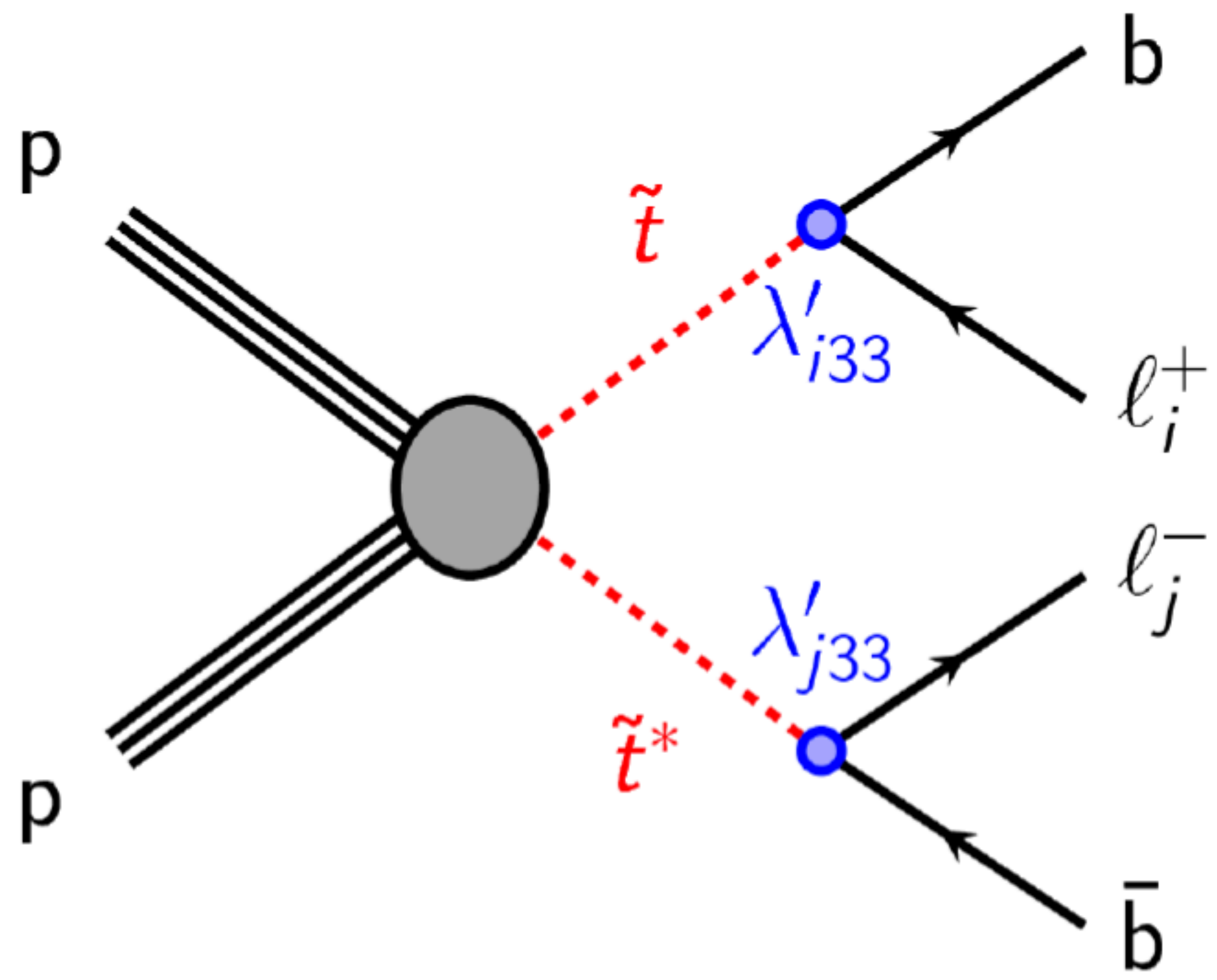
- RPV SUSY multijets
  - Gluino with LSP neutralino decay
- Low mass neutralino RPV decay
  - UDD to 3 jets
  - Trigger level analyses for low mass
- B-L MSSM
  - Wino LSP RPV decay
  - Bino LSP RPV decay
- Your ideas?



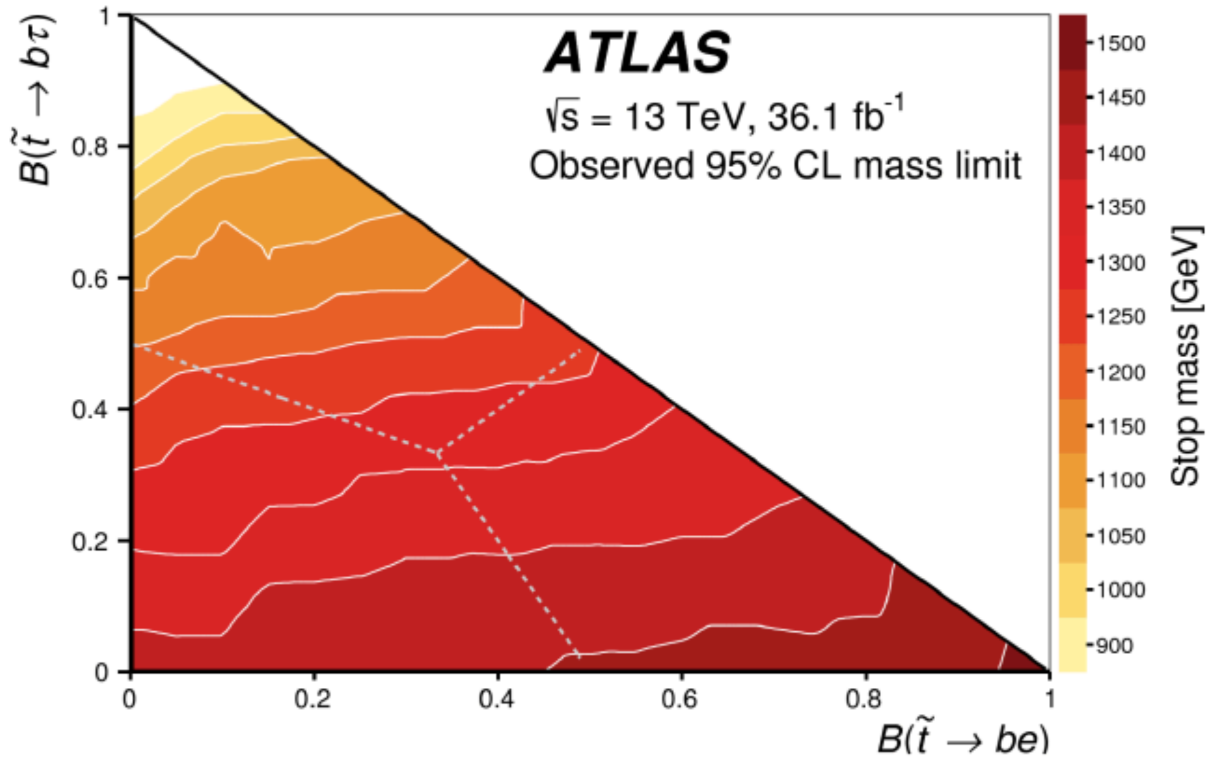
BLNV at colliders (SUSY example)

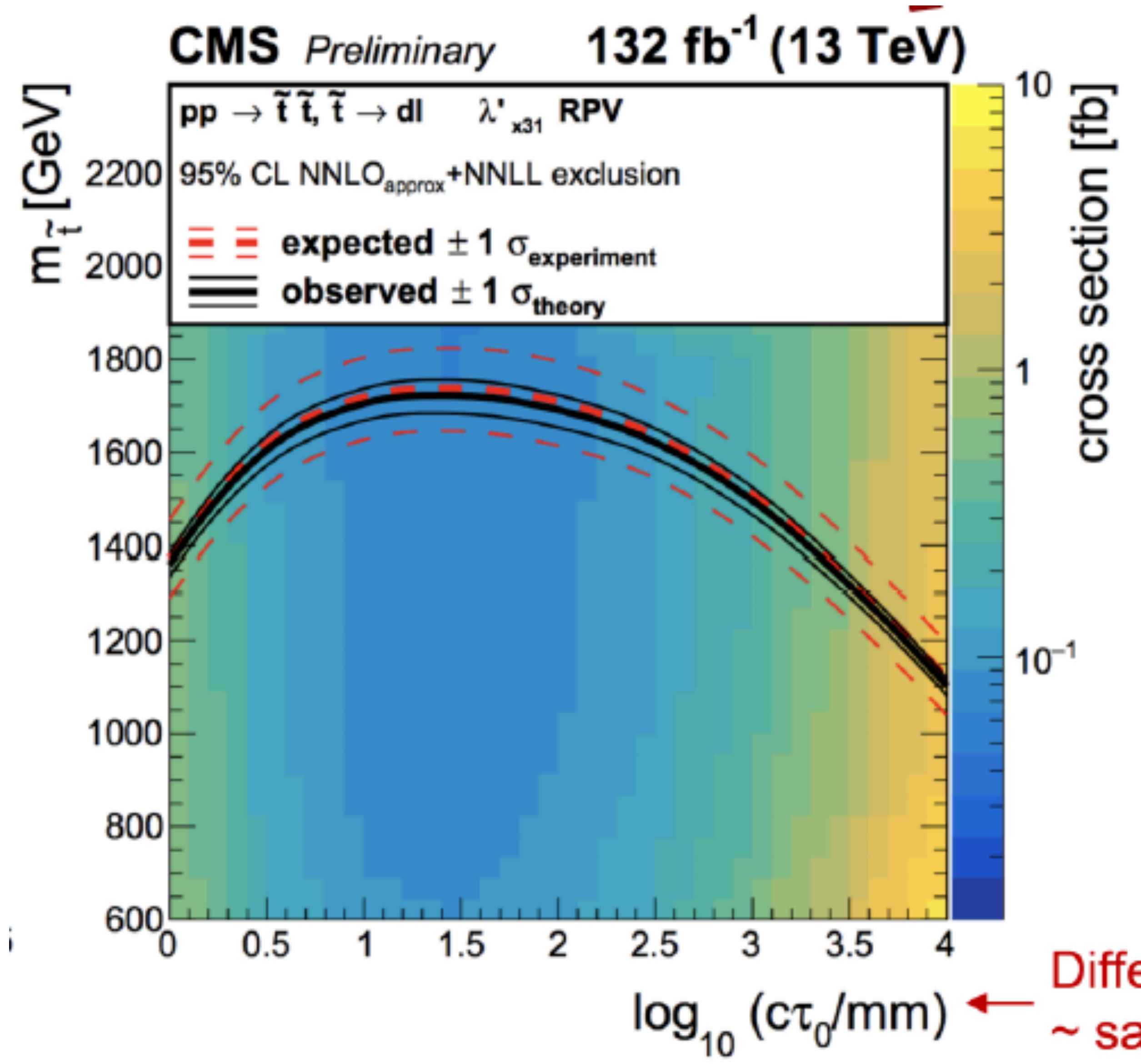
(adapted from Evelyn Thomson)

B-L MSSM scalar top



Leptoquark searches on the corners
100% to e, mu, tau





Different units
~ same range

Signature:

- Dijet systems matched to a displaced vertex.
  - Transverse displacements $r_{DV} \lesssim 55$ cm.
  - Before outer barrel of the silicon strip tracker.

Results:

- Expected 0.75 ± 0.44 (stat) $\pm$ 0.39 (syst).
- Observed 1 event with a DV with $r_{DV} = 26$ cm.
  - Close to a silicon strip layer (within ~1 cm).

- R-parity violating processes (B,L violation)

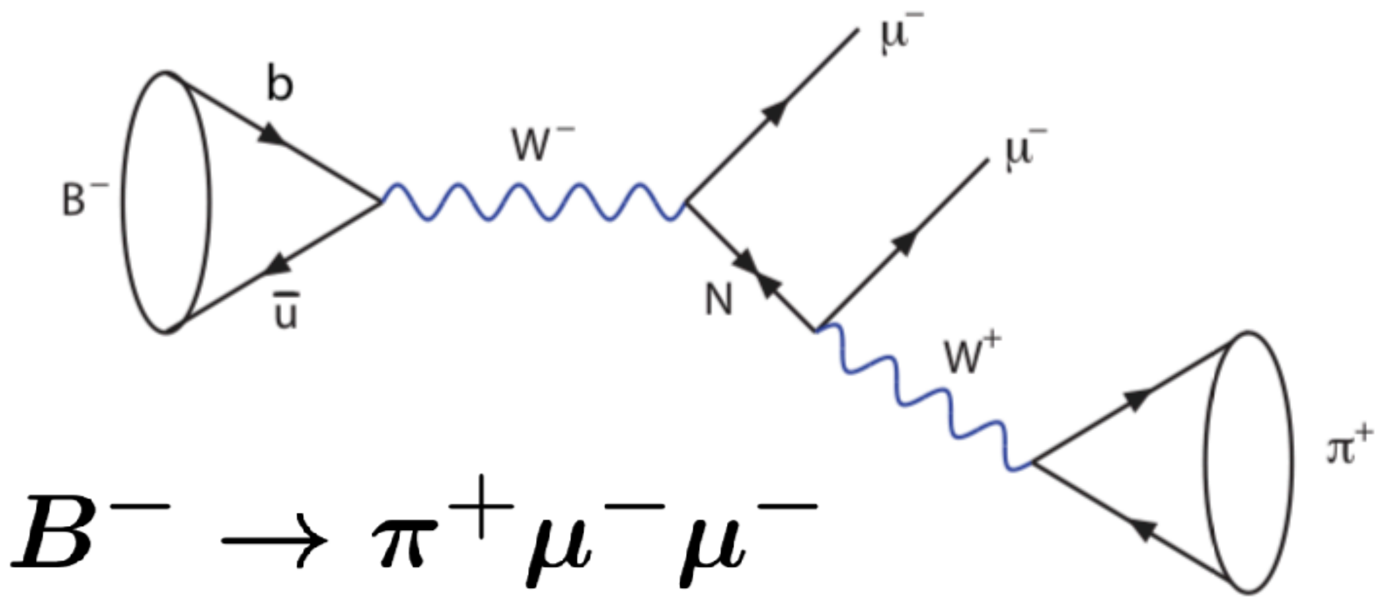
In this example:

- sensitivity to stop mass

Required tools (generally):

- particle ID
- jet reconstruction
- displaced vertices
- missing energy

BLNV at colliders (Majorana particles)



$$B^- \to \pi^+ \mu^- \mu^-$$

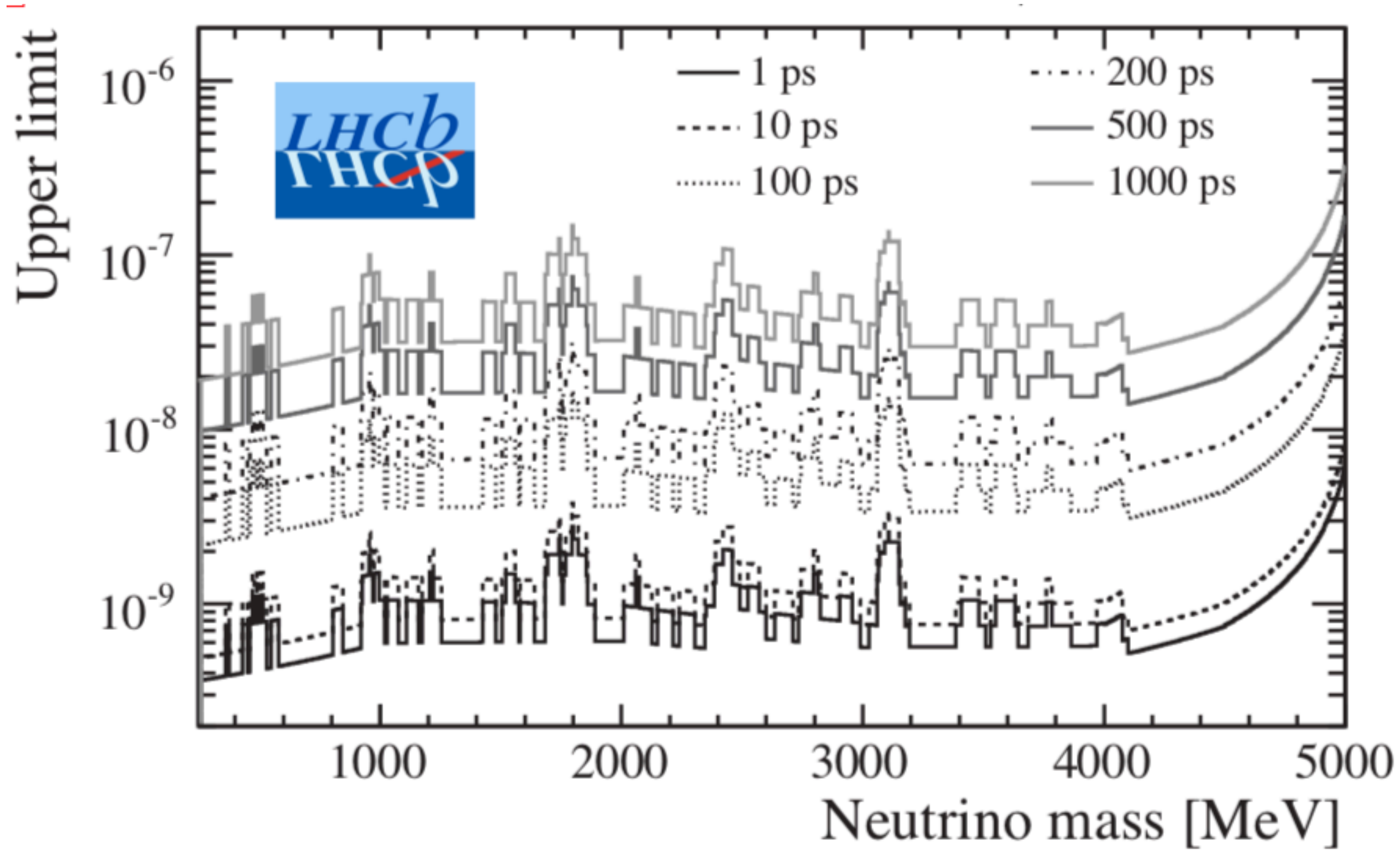
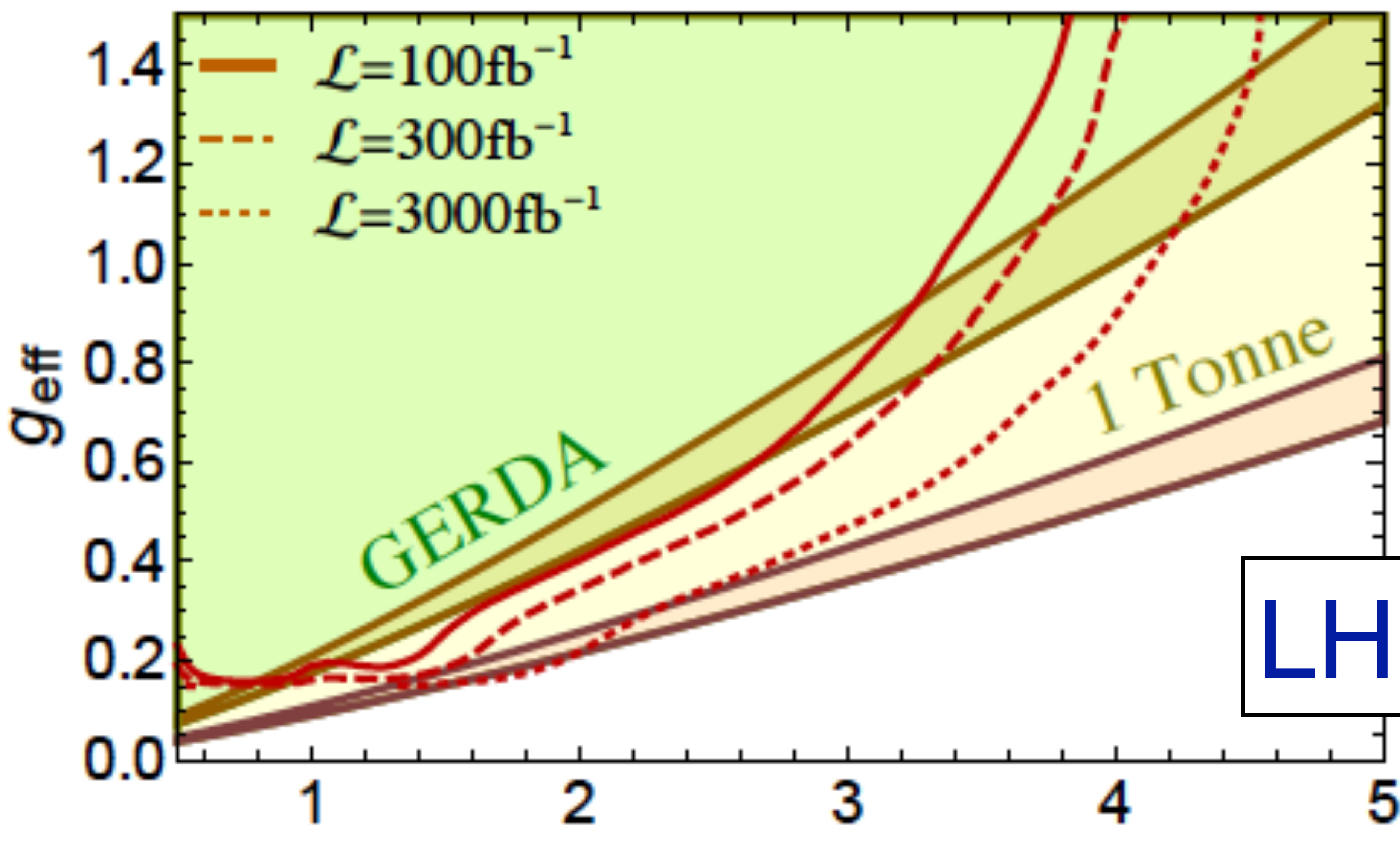


Figure 5: Upper limits on $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-)$ at 95% C.L. as a function of m_N, in 5 MeV intervals, for specific values of τ_N.

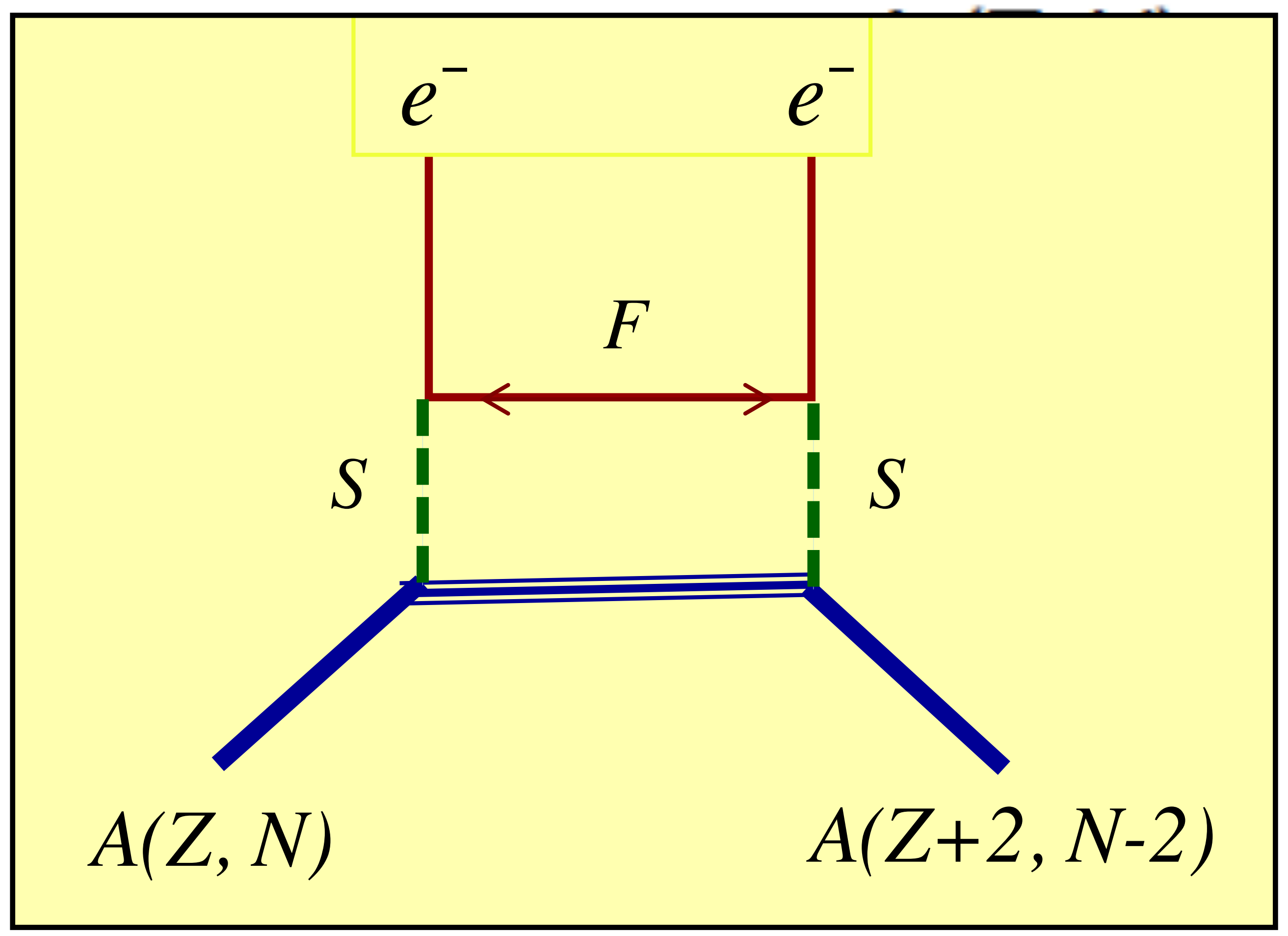
Phys. Rev. Lett. 112 (2014) 131802

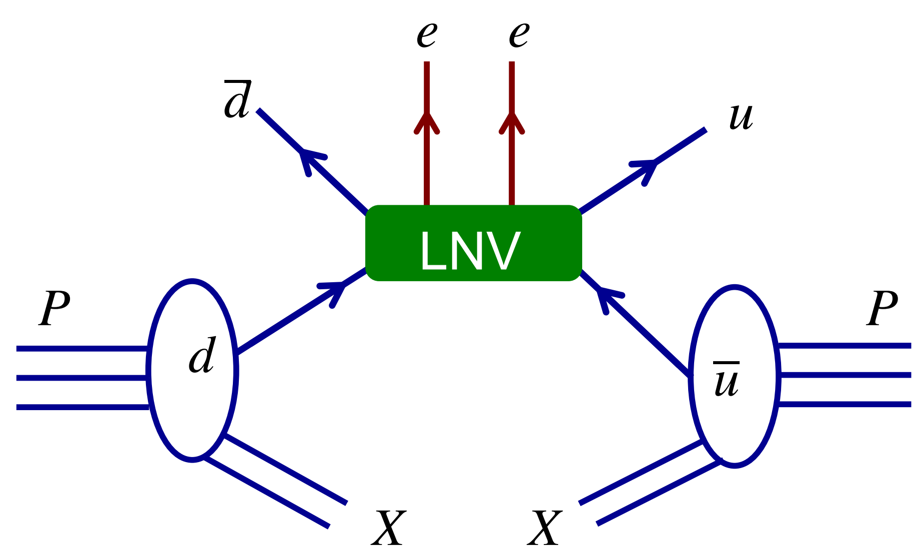
Benchmark Sensitivity: TeV LNV

T. Peng, M. Ramsey-Musolf, P. Winslow 1508.04444



LHC: ee jj

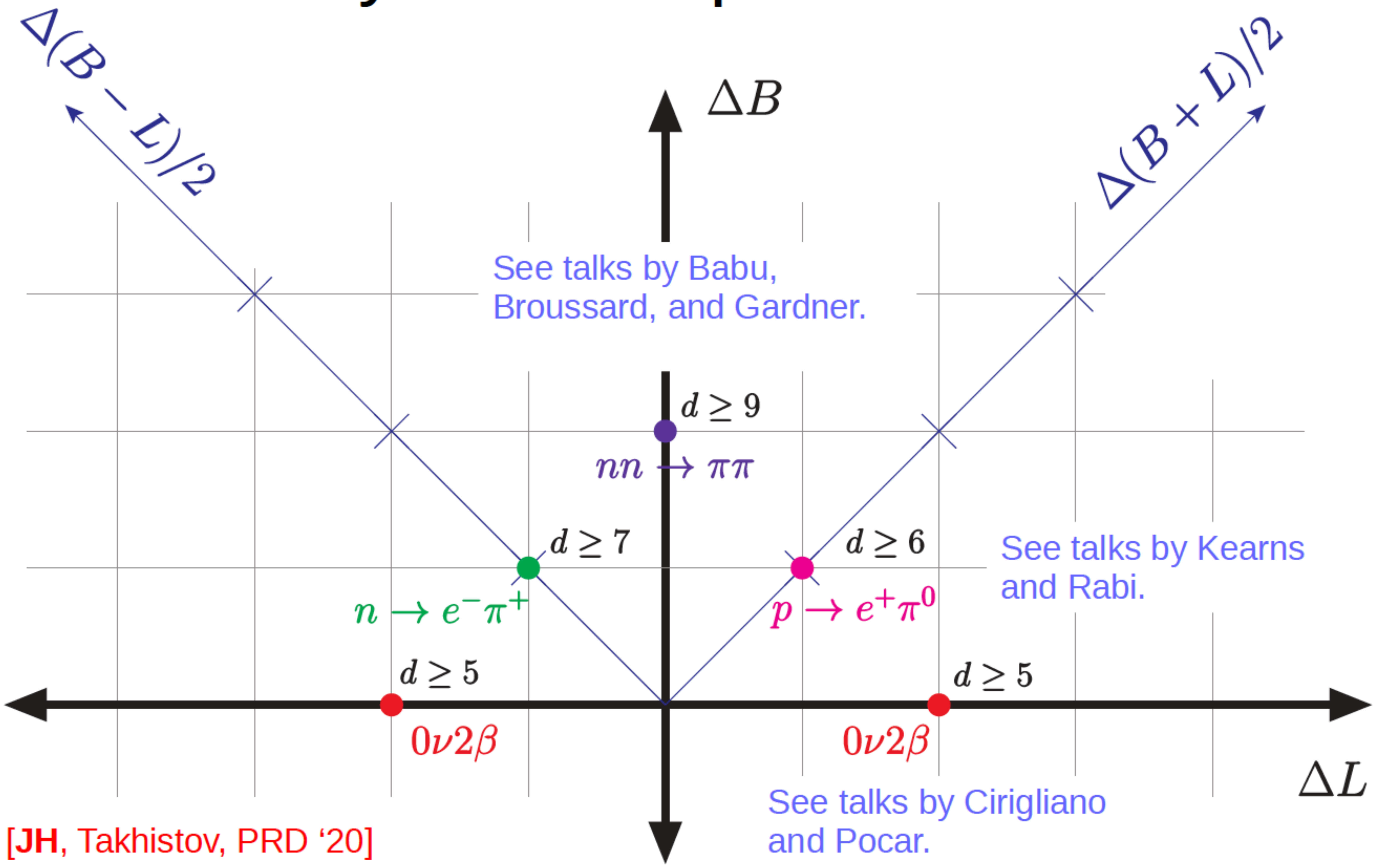




- m_{MIN} << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange

(from Julian Heeck, BLV ca. 2020)

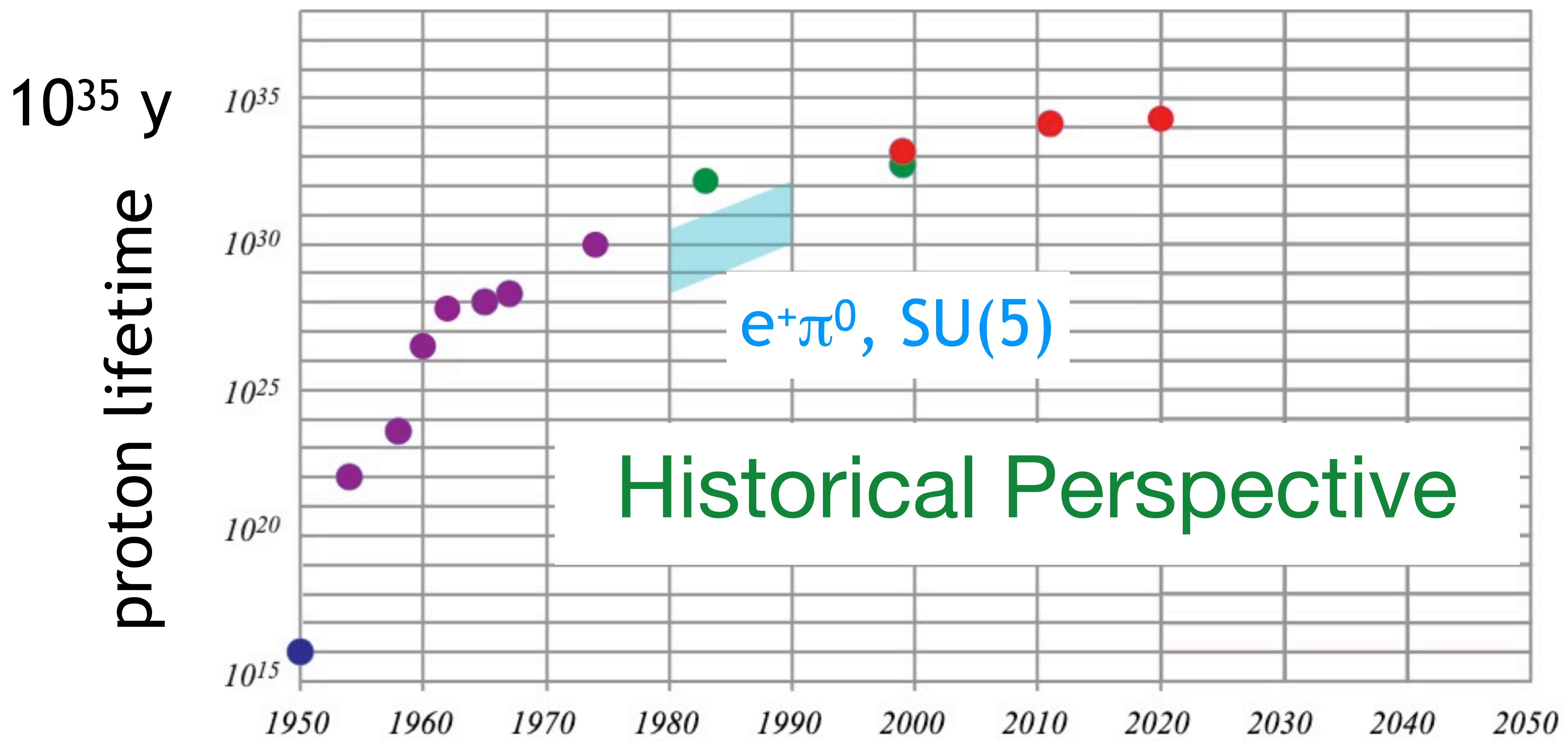
Baryon and lepton number



[**JH**, Takhistov, PRD '20]

Nucleon decay

(from Ed Kearns)



Scientific Perspective of Nucleon Decay

- Tests a fundamental, but unexplained conservation law:
  baryon number.
- Grand Unified Theories make specific predictions:
  decay modes, lifetimes, branching ratios.
- Probes scales forever inaccessible to accelerators.
- New force carrying particles.
- Deep connections with other fields:
  cosmology, inflation, BAU, neutrino mass.
- Even if no signal, limits are very constraining on theory.

Theoretical Outlook from Experimental Perspective

- Numerous and various models exist.
- Lifetime predictions are not precise — typically uncertain by 2-3 orders of magnitude.
- There are two favored and benchmark decay modes:
  $e^+\pi^0$ (gauge mediated) and νK^+ (SUSY D=5)
  good for water — good for LAr & Liq. Scint.
- There are other modes and processes:
  $\mu^+\pi^0$ (flipped), μ^+K^0 (SUSY), invisible modes, dinucleon decay, three-body modes, leptonic modes, B+L conserving modes ...

  Ideally, we wish to cover all possibilities
- Some theories suppress or exclude nucleon decay.

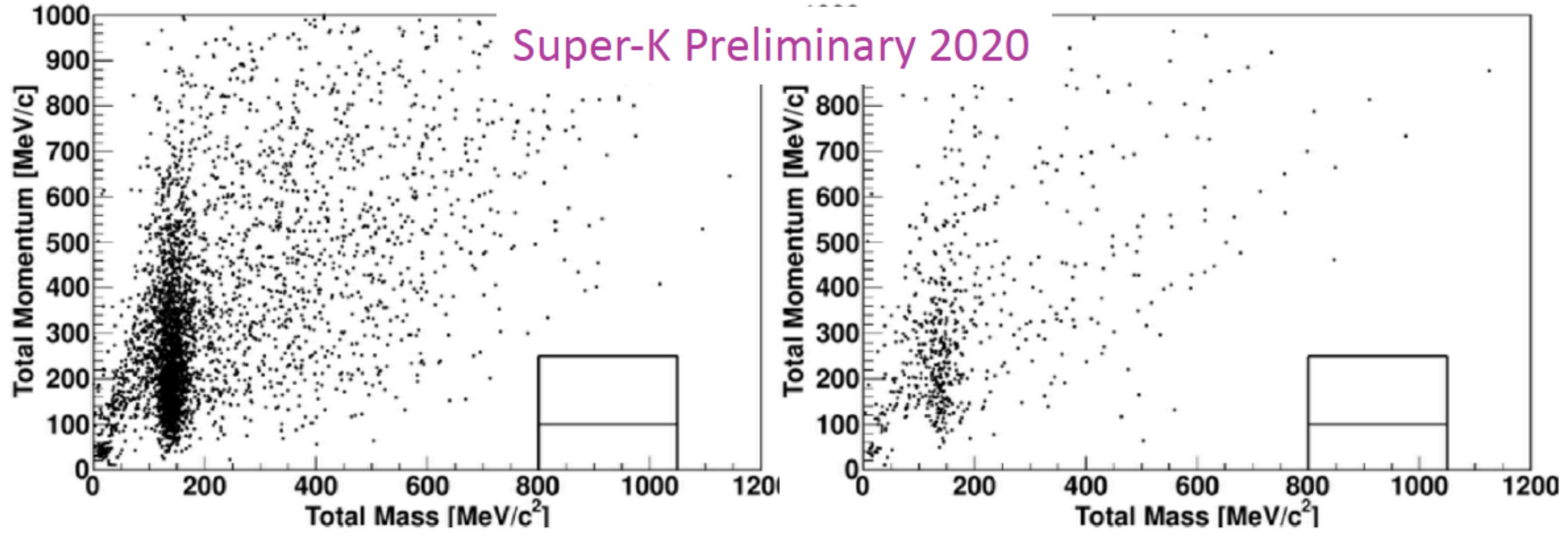
Nucleon decay (SuperK)

(from Ed Kearns)

Signal Efficiency (%)	SK-I	SK-II	SK-III	SK-IV w. n cap.	New 4.7 kton FV (SK I-IV)
100 < p_{net} < 200 MeV/c	21.0 ± 3.5	20.2 ± 3.2	21.1 ± 3.2	19.8 ± 3.3	15.5 ± 2.6
p_{net} < 100 MeV/c	19.9 ± 1.9	18.1 ± 1.8	20.3 ± 1.8	19.6 ± 1.6	10.3 ± 1.4

Background (evts/Mt y)	SK-I	SK-II	SK-III	SK-IV w. n cap.	New 4.7 kton FV (SK I-IV)
100 < p_{net} < 200 MeV/c	1.4 ± 0.6	2.2 ± 0.8	1.6 ± 0.6	1.0 ± 0.5	0.10 ± 0.05
p_{net} < 100 MeV/c	< 0.01	0.17 ± 0.14	< 0.01	< 0.01	0.01 ± 0.01

Super-K: 1996 – continuing



$$\tau/B(e^+\pi^0) > 2.4 \times 10^{34} \text{ years}$$

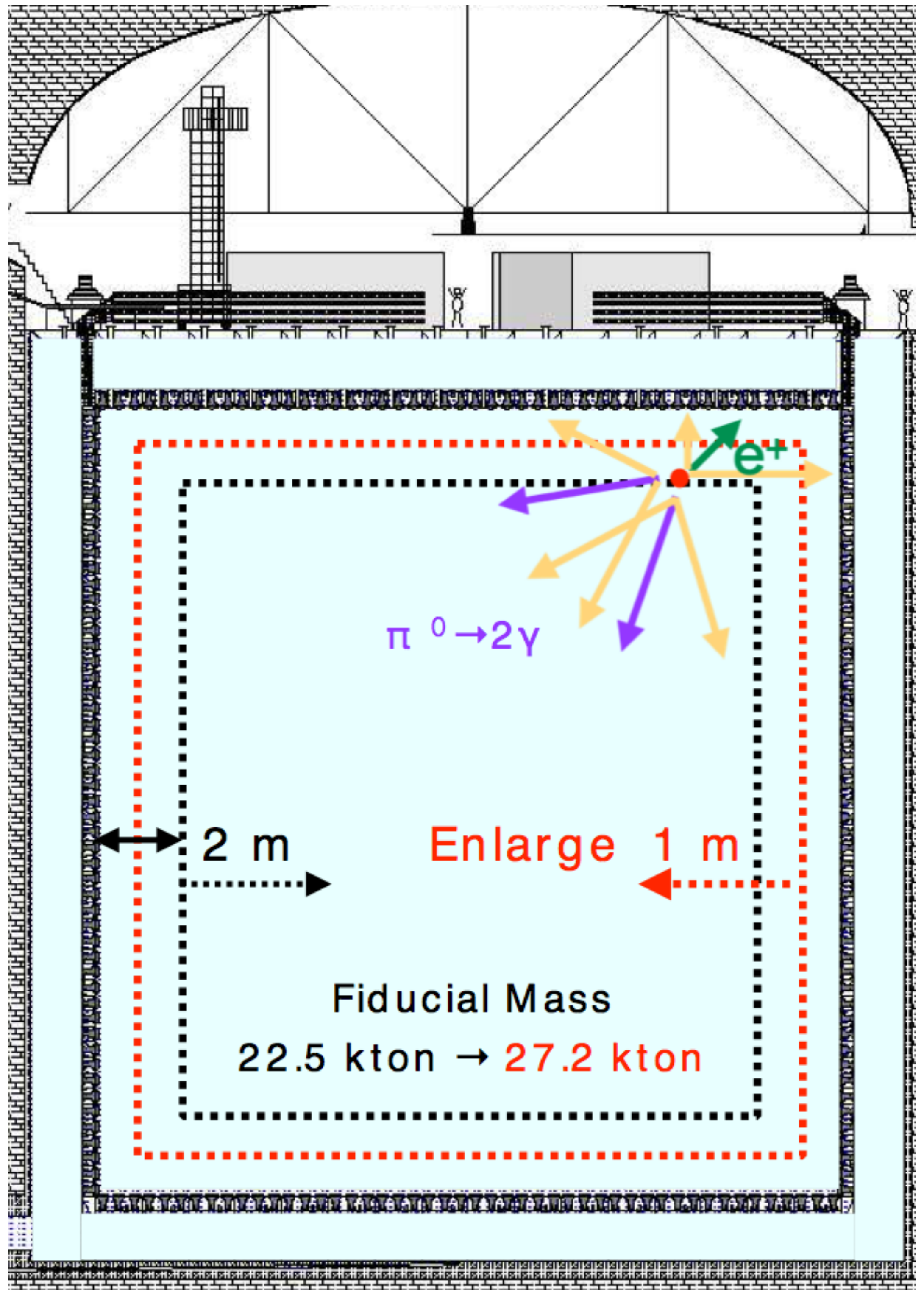
Published = 1.6e34

$$\tau/B(\mu^+\pi^0) > 1.6 \times 10^{34} \text{ years}$$

Published = 0.8e34
(1 candidate near upper box edge remains)

Nonstop effort since 2013:
Expanded fiducial volume
Neutron capture on H (25% eff.)
Two box search (free proton)
Improved reconstruction

2020: Add Gd for n-capture !

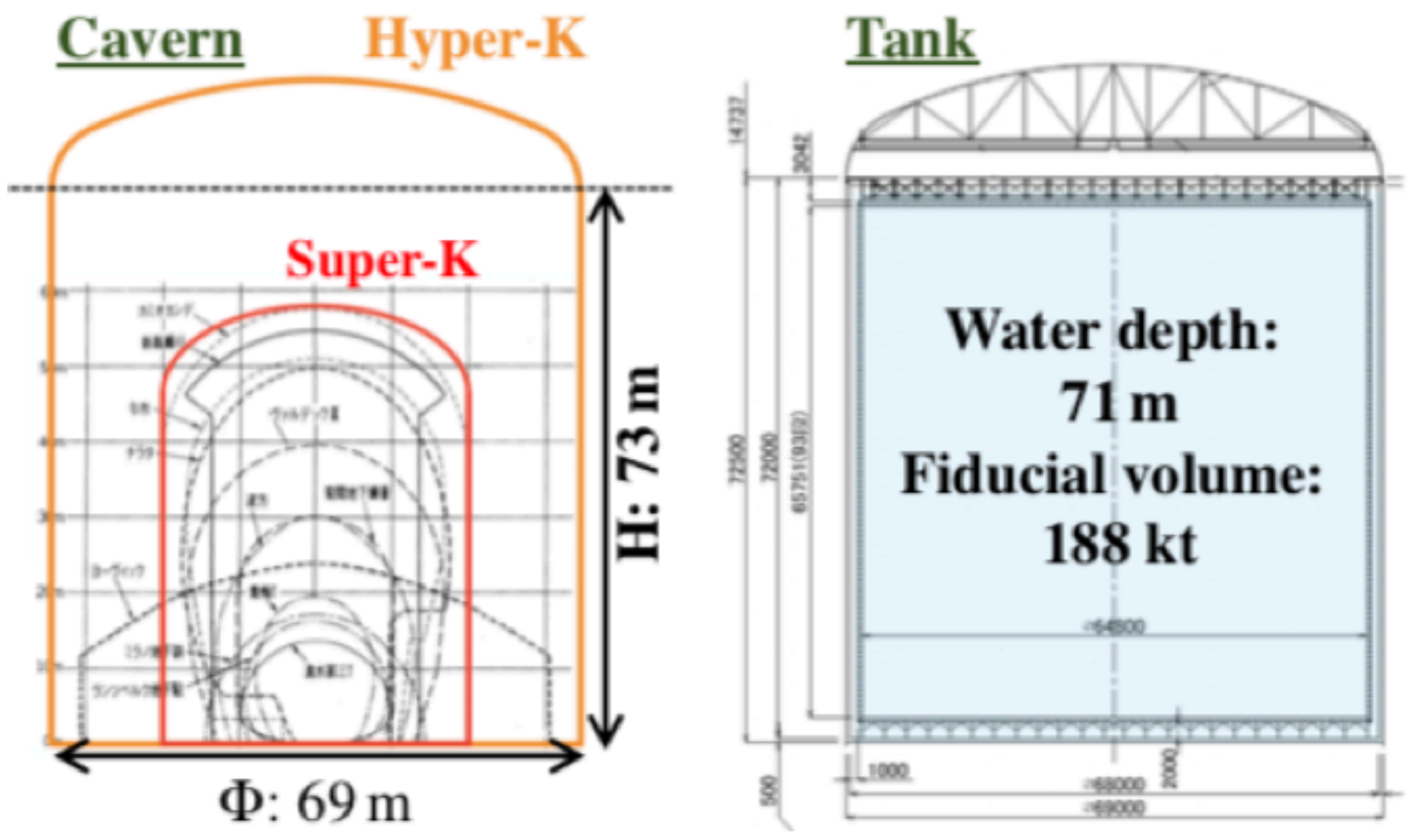


Nucleon decay (Hyper—Kamiokande)

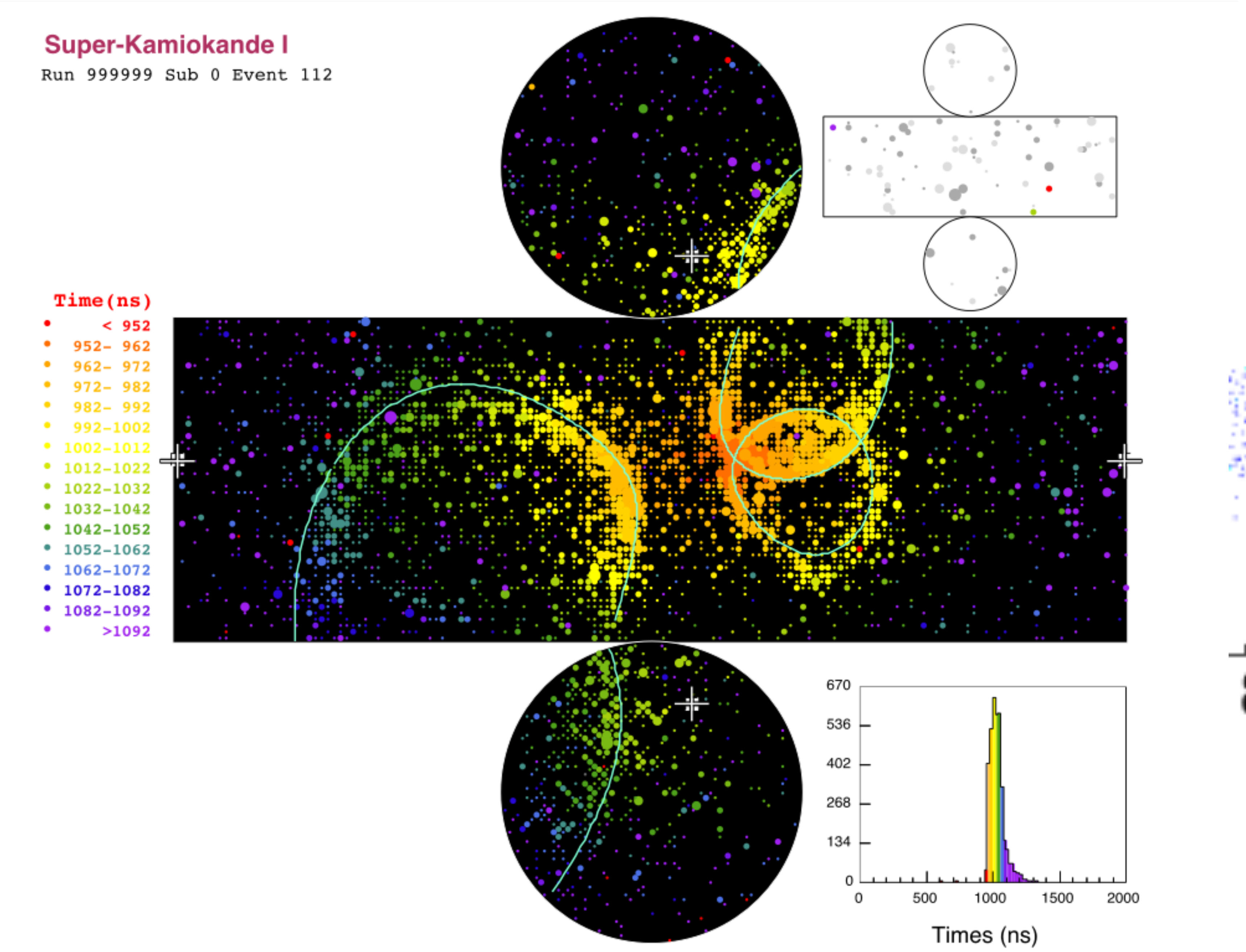
(from Ed Kearns)

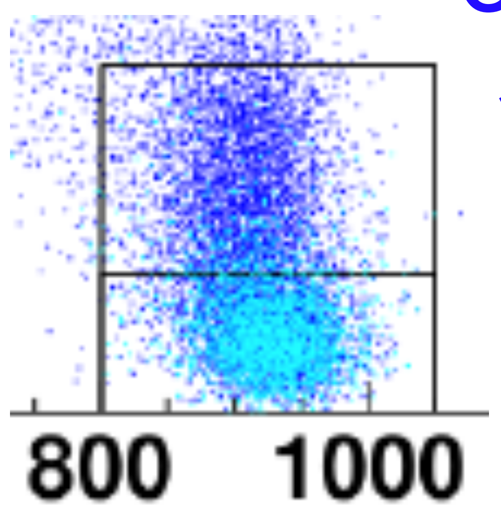
Hyper-K: 2027-

most massive – superior for $e^+\pi^0$
broad search capabilities
free proton advantage
kaons below Cherenkov threshold



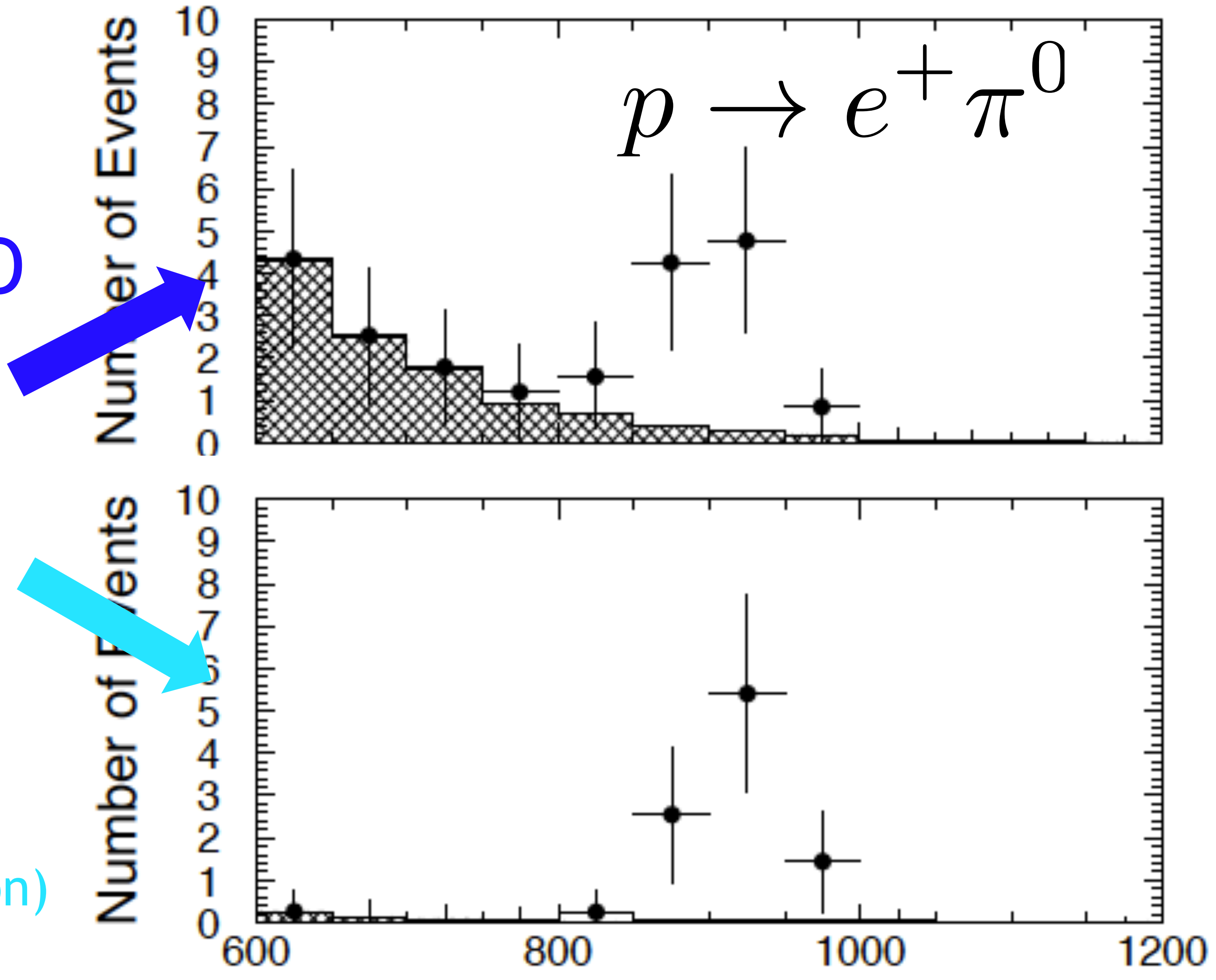
+ potential 2nd module,
maybe in S. Korea

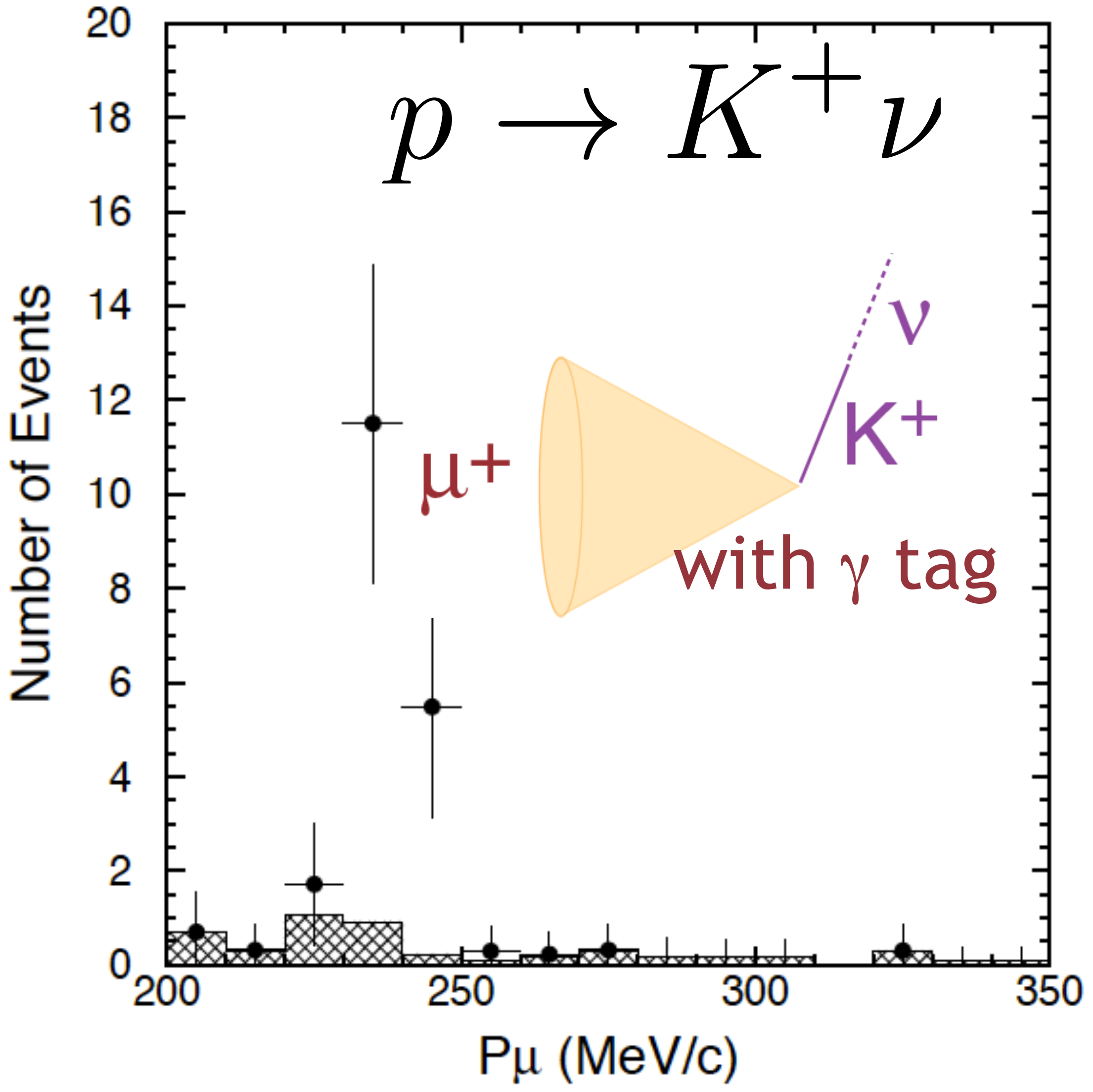




^{16}O

^{1}H (free Proton)

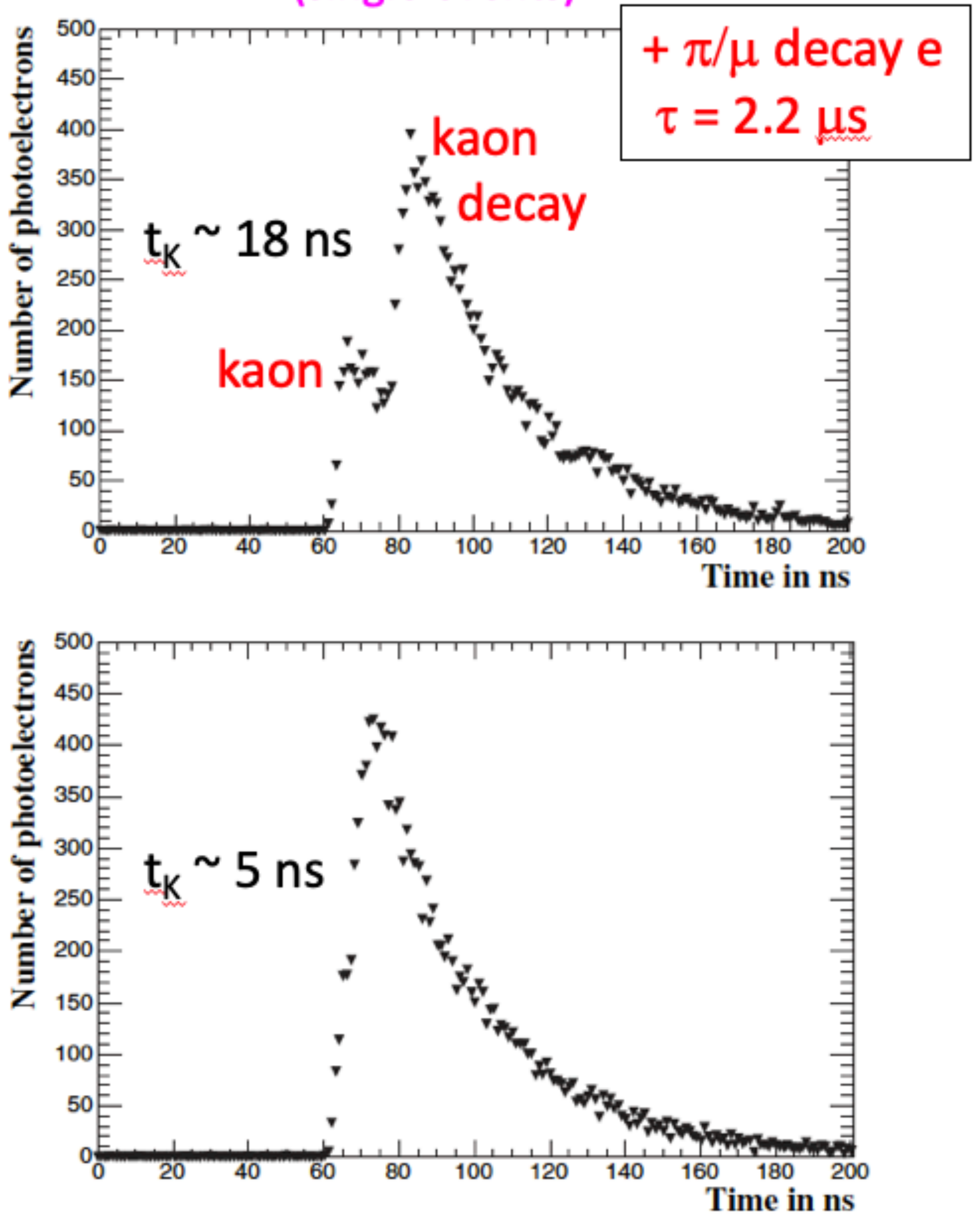




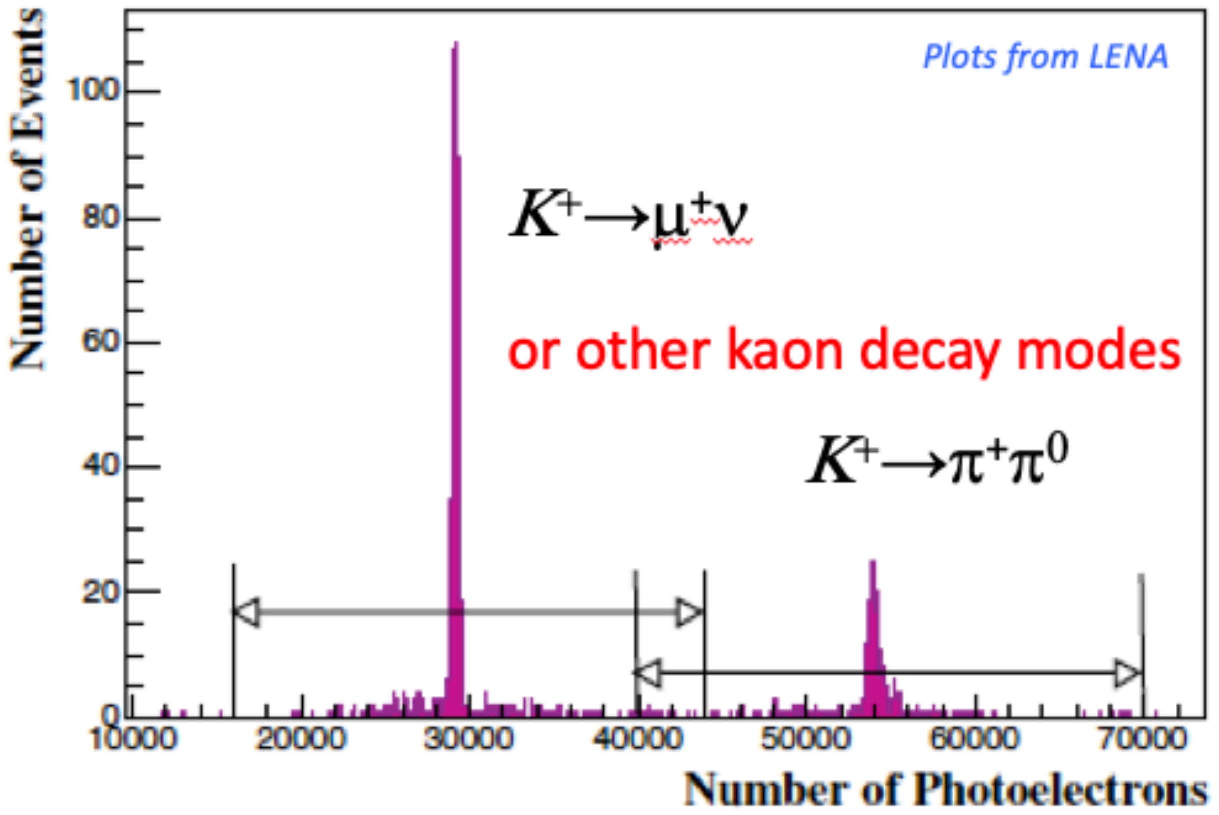
Nucleon decay (scintillator)

(from Ed Kearns)

Timing Response
(single events)



Energy Response

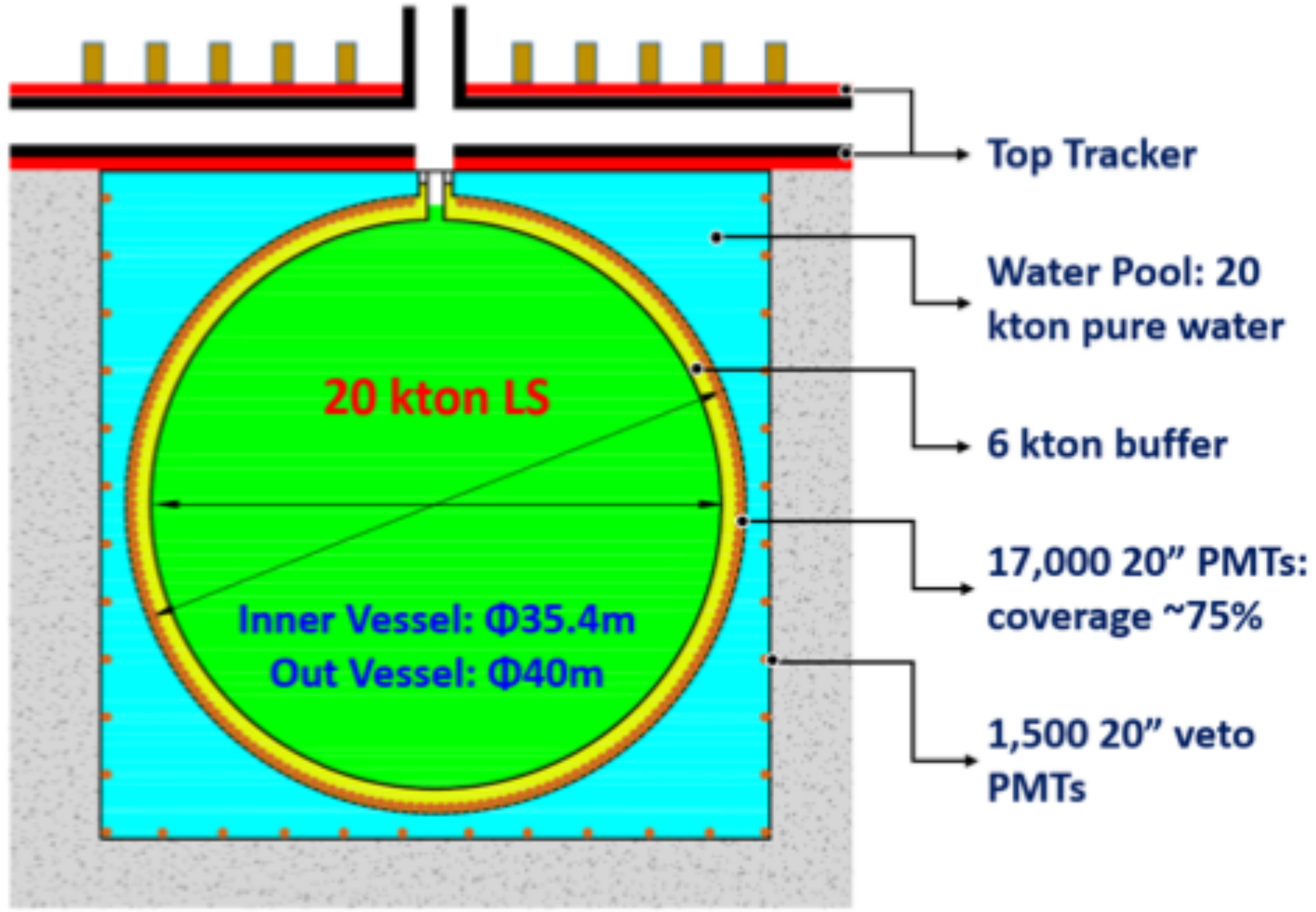


200 photoelectrons/MeV in LSc

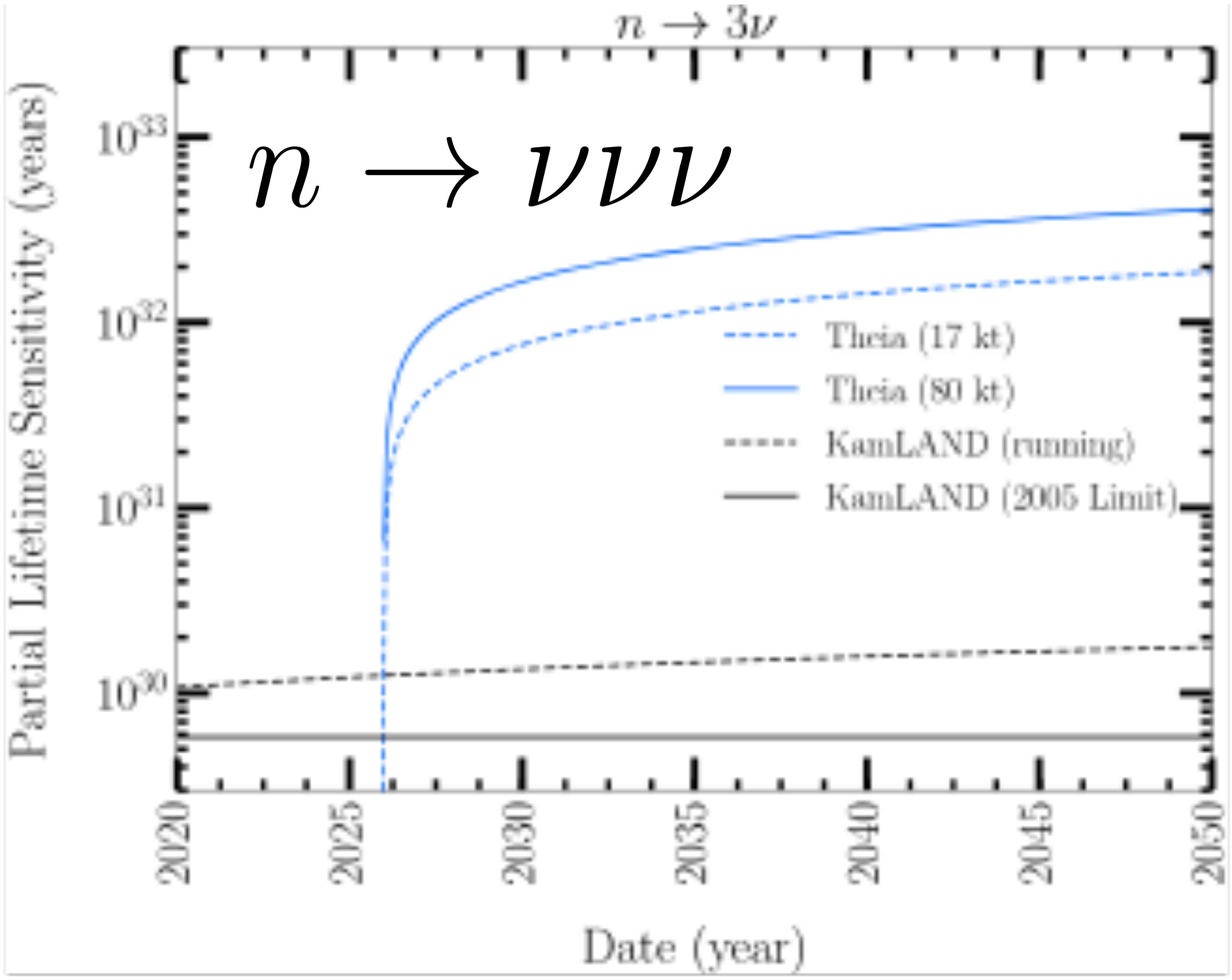
90 photoelectrons/MeV in WbLSc
(water-based liquid scintillator)

5 Cherenkov p.e./MeV in SK

JUNO: 2022



THEIA: 20??



Proof of principle: KamLAND
PRD 92, 052006 (2015)

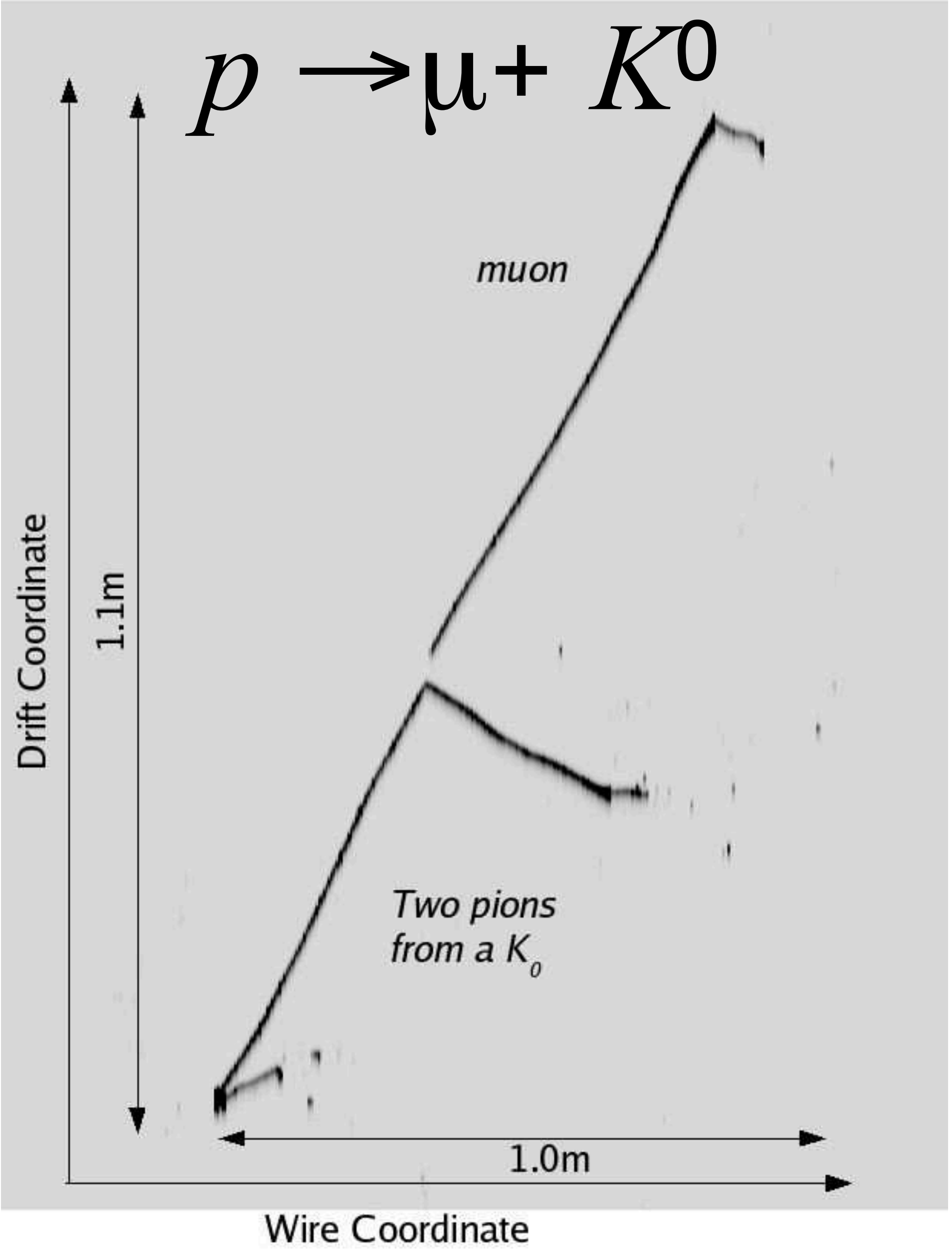
$$\frac{\tau}{B} > 5.4\times10^{32}\ \text{y}$$

Nucleon decay (DUNE)

(from Ed Kearns)

LArTPC Shines for Many Modes

- Modes with **charged kaon** in final state (SUSY)
- Modes with displaced vertices
- Multi-prong modes with no neutrino
- nnbar background rejection
  - No recoil proton allowed
  - No CC electron (or muon)



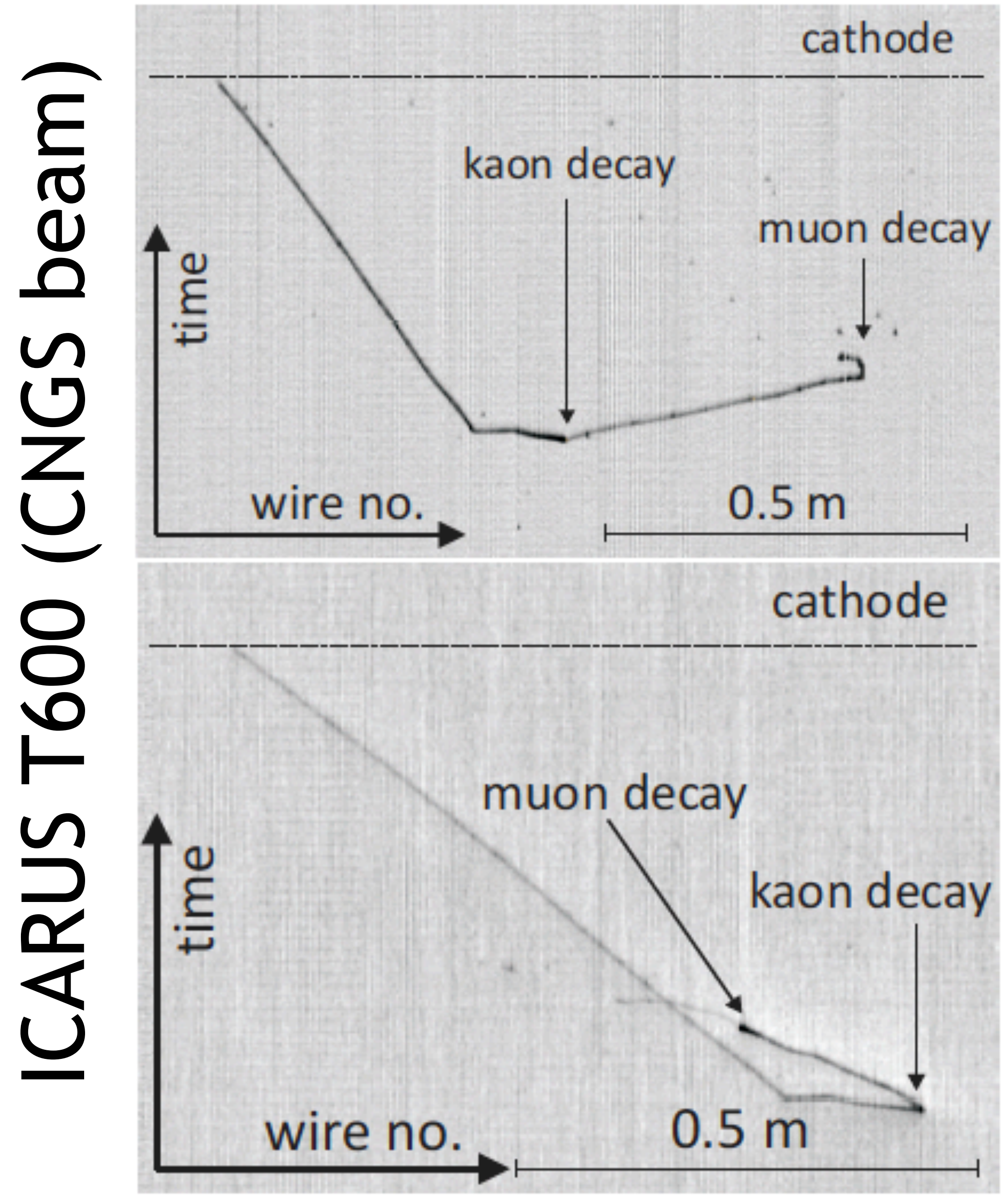
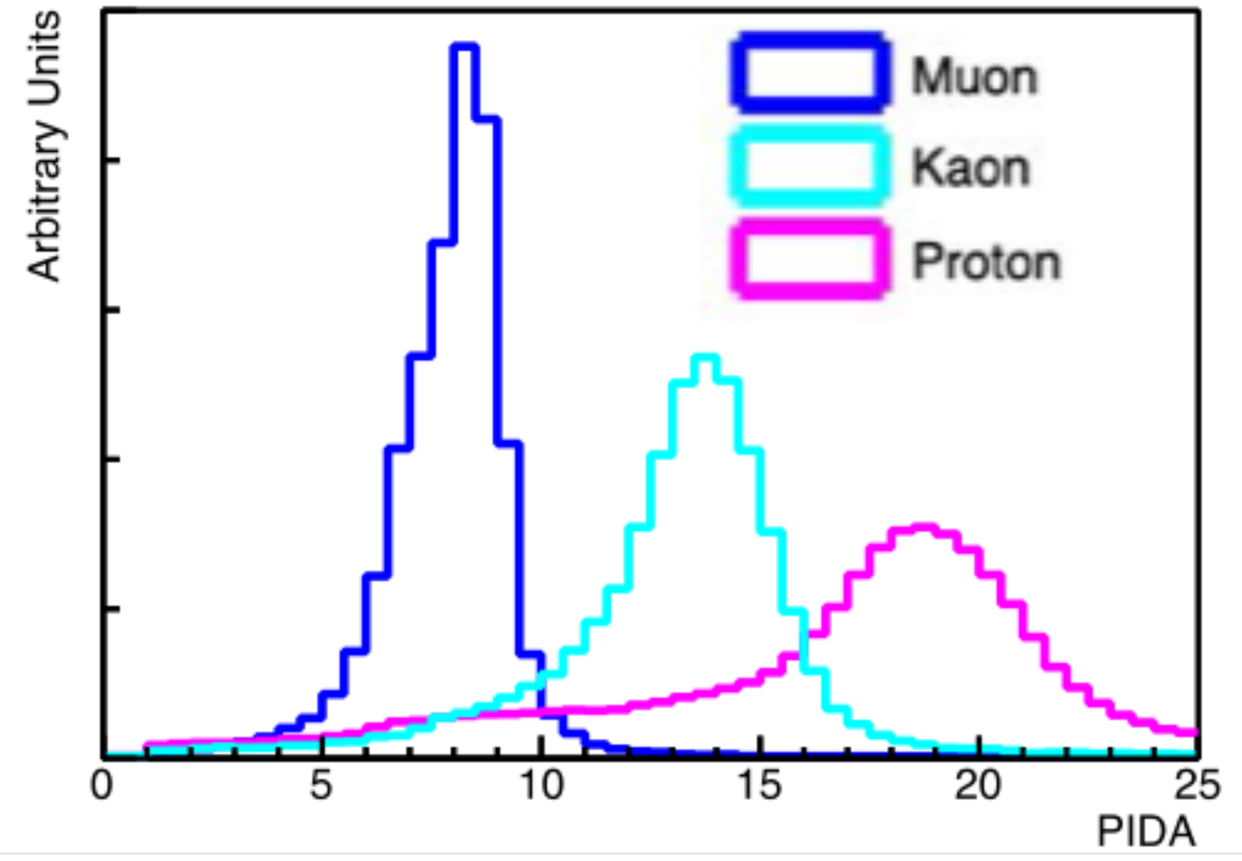


Figure 4.3: Event display for a decaying kaon candidate $K \rightarrow \mu\nu_\mu$ $\mu \rightarrow e\nu_e\nu_\mu$ in the ICARUS T600 detector observed in the CNGS data (K: 90 cm, 325 MeV; μ : 54 cm, 147 MeV; e : 13 cm, 27 MeV). The top figure shows the signal on the collection plane, and the bottom figure shows the signal on the second induction plane [102].

- Lepton + light meson likely no better than water due to nuclear absorption of the light meson.



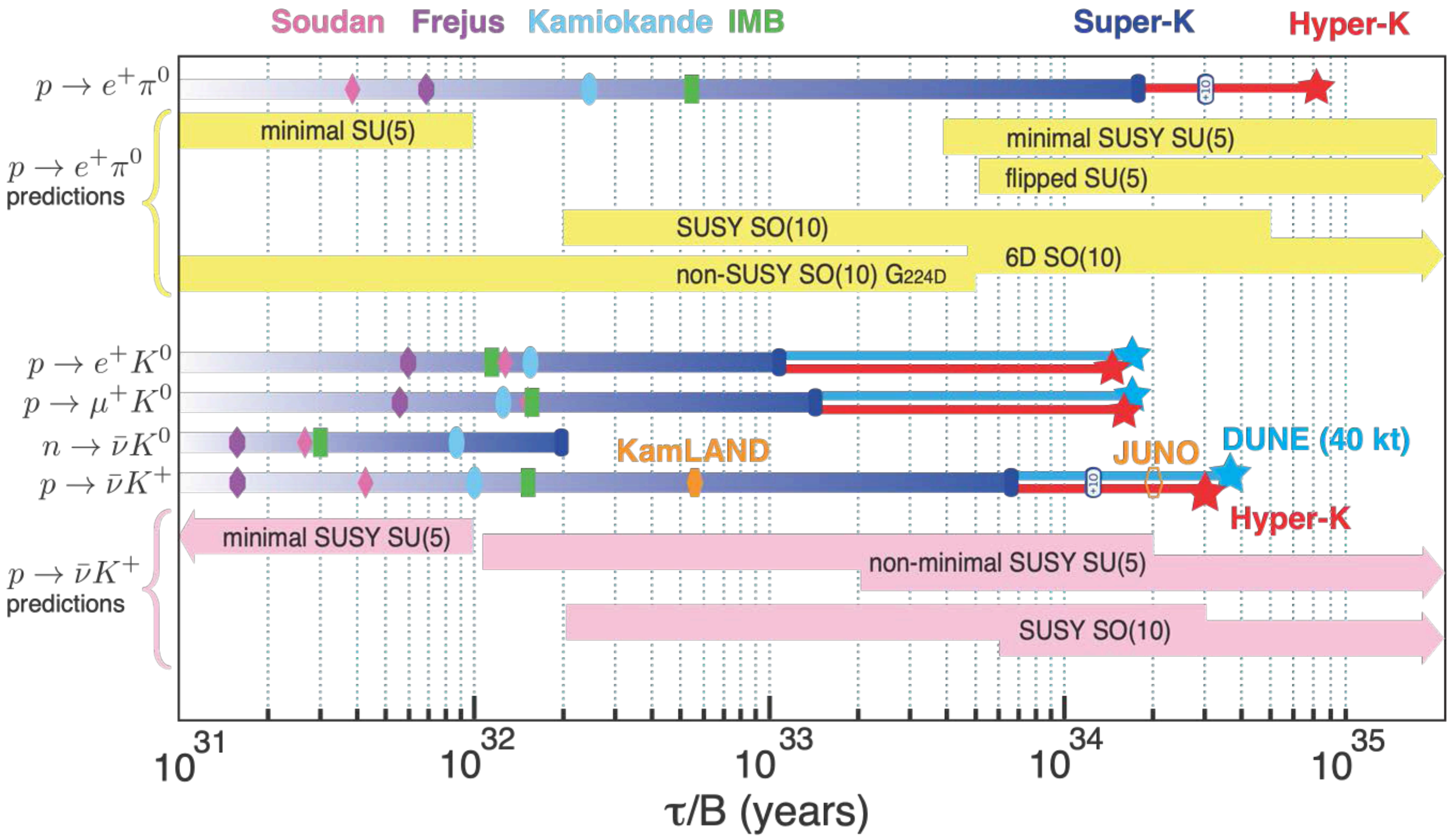
At this time, DUNE is taking the efficiency hit of 30%, with a background rate of 1/Mt y
(fully automated analysis, 10 y, 40 kt fiducial mass)

$$\tau/B(K^+\nu) > 1.3 \times 10^{34} \text{ years}$$

DUNE: 2026-

Summary

(from Ed Kearns)



current and next generation experiments are looking in theoretically motivated regions, even if they can't cover whole regions

Neutron – antineutron oscillation

(from Kaladi Babu)

- $n - \bar{n}$ oscillations violate baryon number by 2 units
- Time evolution of $n - \bar{n}$ system governed by:

$$\mathcal{M}_{\mathcal{B}} = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix}$$

$$\mathcal{L} = m_n \bar{n}\, n + \frac{\delta m}{2} n^T C\, n$$

- $n \to \bar{n}$ transition probability:

$$P(n \to \bar{n}) = \sin^2(2\theta)\sin^2(\Delta E t/2) e^{-\lambda t}$$

$$\Delta E \simeq 2|\vec{\mu_n}.\vec{B}|, \quad \tan(2\theta) = -\frac{\delta m}{\vec{\mu_n}.\vec{B}}$$

- Quasifree condition holds: $|\vec{\mu_n}.\vec{B}|t << 1$

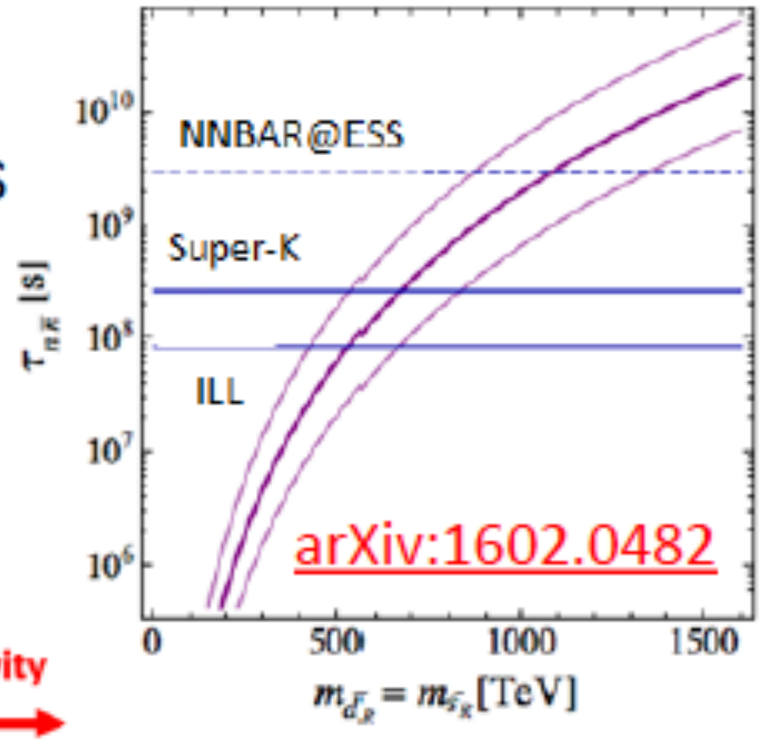
$$P(n \to \bar{n}) \simeq [(\delta m)t]^2 = [t/\tau_{n-\bar{n}}]^2$$

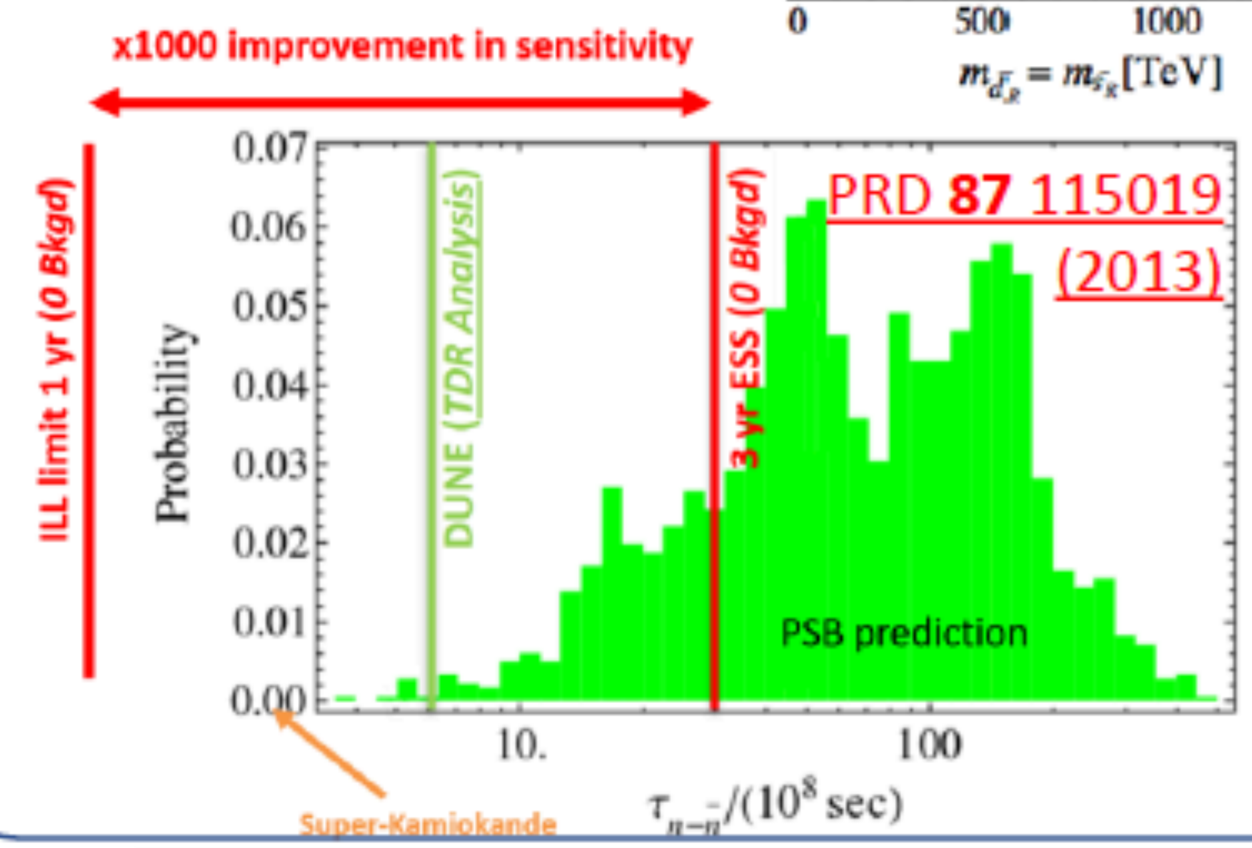
- Best limit on free neutron oscillation: $\tau_{n-\bar{n}} > 8.6 \times 10^7$ sec. Baldo-ceolin et. al., ILL (1994)

High sensitivity n — nbar oscillation searches are within reach

$n \to \bar{n}, n \to n'$: high precision probes of $\Delta B \neq 0, \Delta L = 0$ processes

- Features of theories of baryogenesis, dark matter, general models of BSM physics





Intranuclear searches in Super-K

- $\tau_{n\to\bar{n}} > 2.7 \times 10^8$ s PRD **91** 072006 (2015)
- Prelim. update: $\tau_{n\to\bar{n}} > 4.7 \times 10^8$ s L. Wan, Neutrino 2020

Last free neutron search at ILL

- $\tau_{n\to\bar{n}} > 0.86 \times 10^8$ s ZPhysC **63** 409 (1994)

NNBar at European Spallation Source can achieve sensitivity gain 1000 × ILL result arXiv:2006.04907 103 authors from 65 institutions

Brightness		≥ 1
Moderator Temperature	Colder neutron <TOF>, quadratic sensitivity	≥ 1
Moderator Area	Large aperture required	2
Angular Acceptance	2D = quadratic sensitivity	40
Length	∝ time, quadratic sensitivity	5
Run Time	ILL run = 1 year	3
Total gain vs ILL		≥ 1000

- Major tech. advances since ILL!
- ORNL-HIBEAM-NNBar staged program
- Large Beam Port for NNBar now constructed
- \$3M HighNESS project for moderator design underway

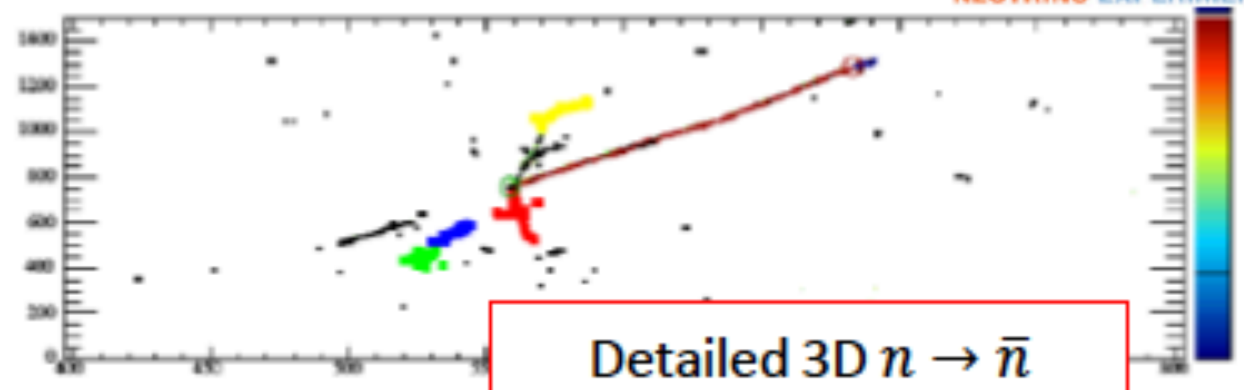
EUROPEAN SPALLATION SOURCE

3-5 year measurement: 10^{21} neutrons on target

DUNE could potentially break the background barrier of Super-K

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Lower kinetic energy threshold (e.g. protons), higher resolution, bubble chamber-like images, PID & dE/dx capabilities
- Expected reach: $\tau_{n\to\bar{n}} > 5.53 \times 10^8$ s arXiv:2002.03005



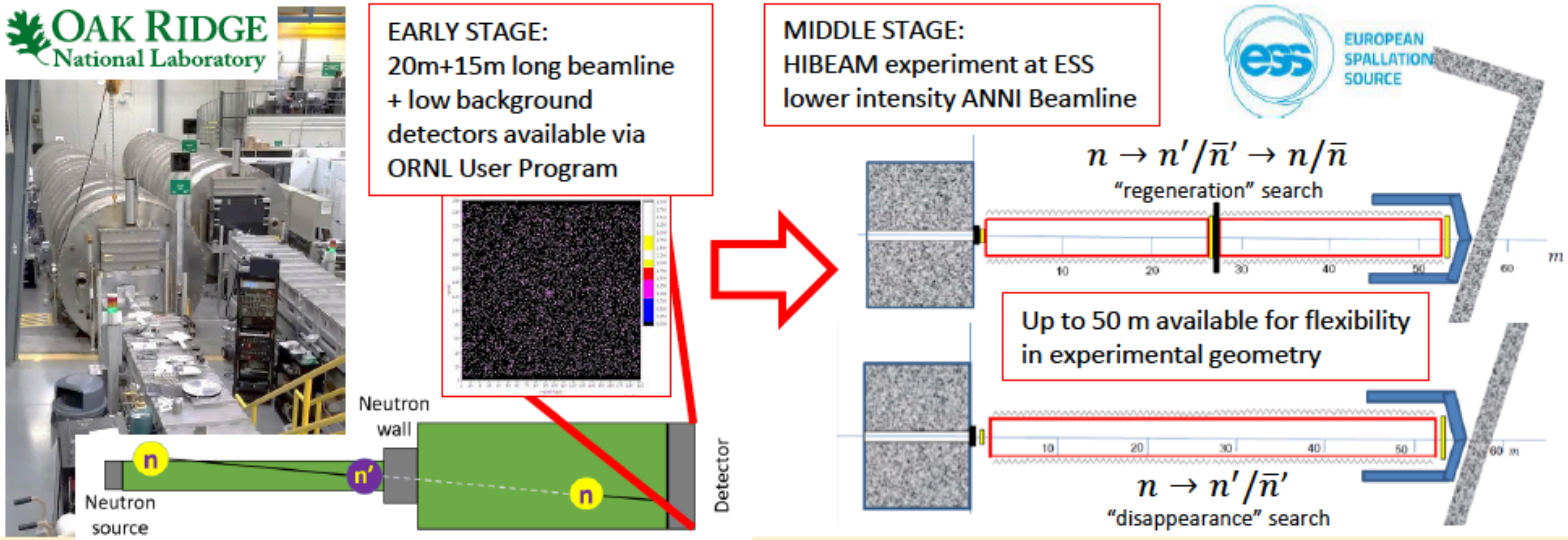
Detailed 3D $n \to \bar{n}$ reconstruction in DUNE

(from Leah Broussard, ORLN)

n – nbar: major opportunities in future experimental searches

(from Leah Broussard, ORLN)

- R&D path to NNBar underway by worldwide collaboration
  - Detector prototyping; improved neutronics; novel concepts ("phase non-reset" PRL **122** 221802 (2019)) to reduce complexity of experiment
- Staged program with complementary physics, including searches for $n \to n' \to n$, $n \to n' \to \bar{n}$ PRL **96** (2006) 081801; arXiv:2002.05609
  - Possible connection: 4σ neutron lifetime anomaly EPJC **79**, 484 (2019); MDPI Physics **1**, 271 (2019)
  - Possible mixing of sterile/antipartners offer opportunities for NNBar R&D
  - Use existing BES facilities at ORNL: first experiment completed & in analysis, next experiment beamtime awarded EPJ Web Conf **219**, 07002 (2019)
  - Improved sensitivities moving to ANNI/HIBEAM @ESS arXiv:2006.04907



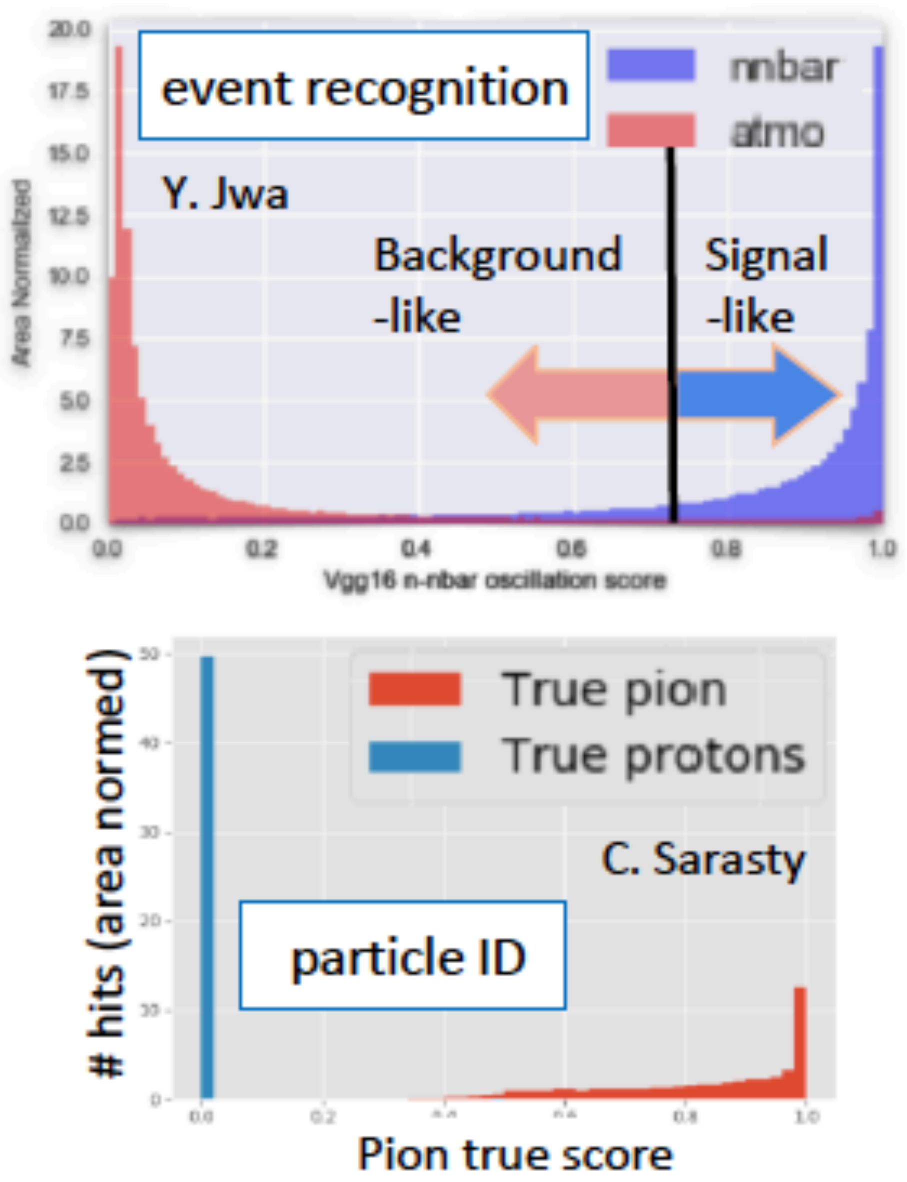
- Improvements in DUNE analysis can further enhance sensitivity
  - Signal and background modeling, background rejection, event reconstruction and event recognition; promising developments in particle identification

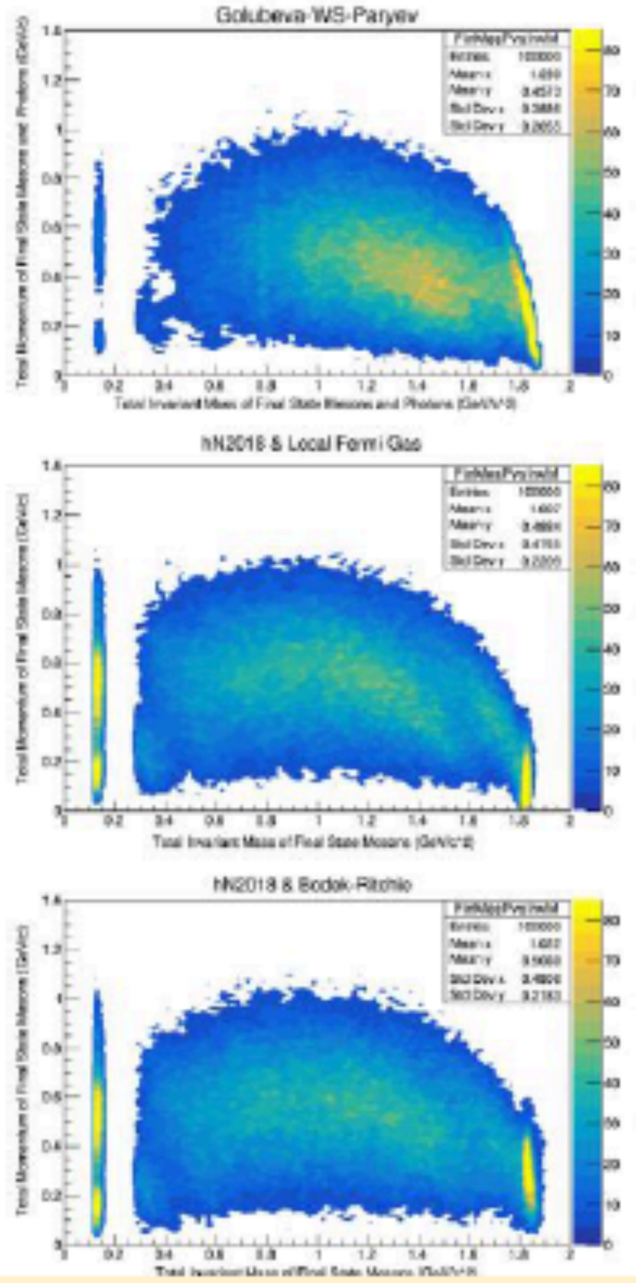
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Comparison of event generators in DUNE

PRD **101**, 036008 (2020)

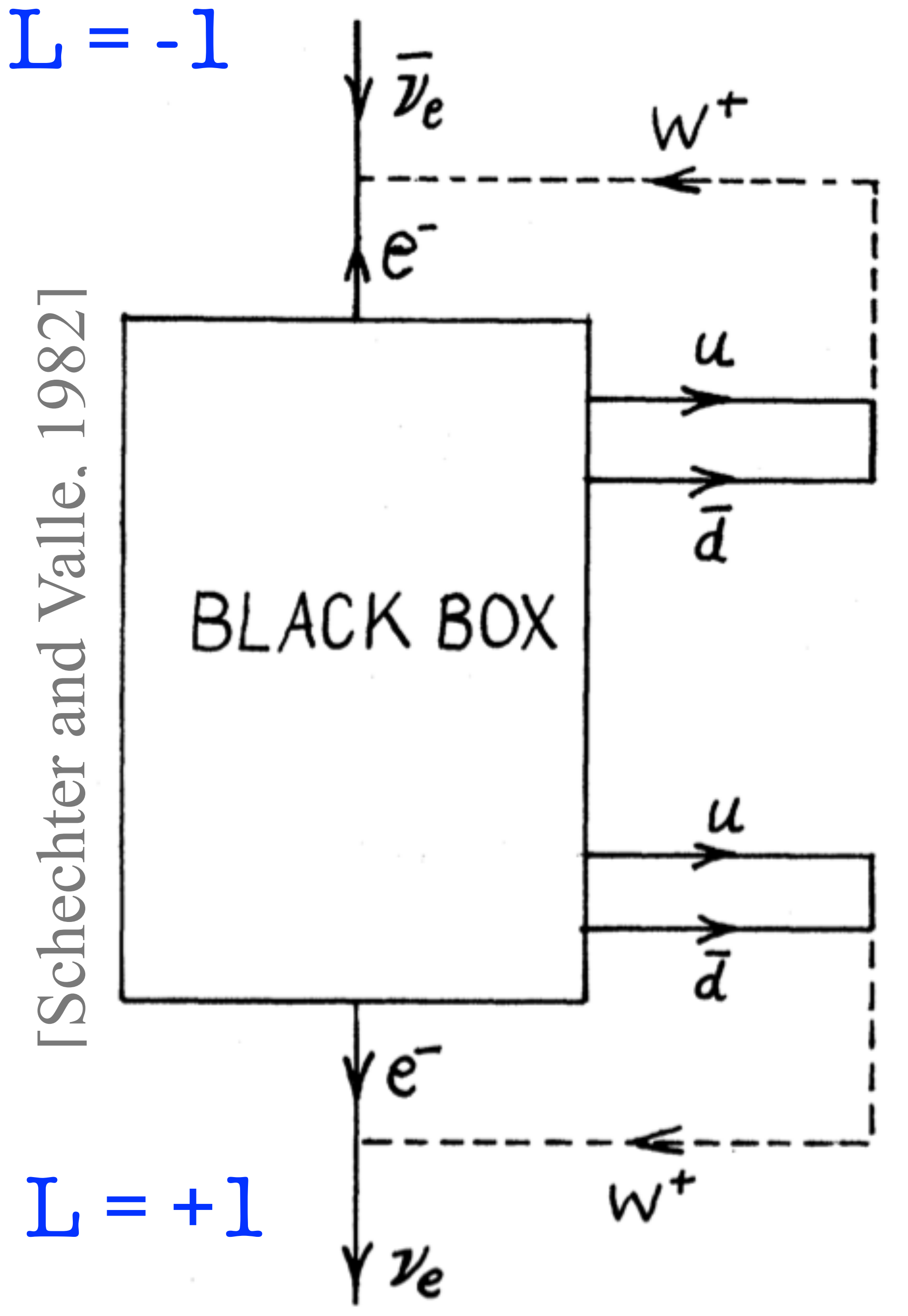
arXiv:2002.03005





Complementary physics: both intranuclear & free searches needed, especially if signal observed

Neutrinoless double beta decay



$$\Gamma^{0\nu} = G(Q,Z)\left|M(A,Z)\eta\right|^2$$

phase space factor:

$$G \sim G_F^4 g_A^4 m_e^5$$

nuclear matrix element (model dependent)

particle physics of the 'black box'

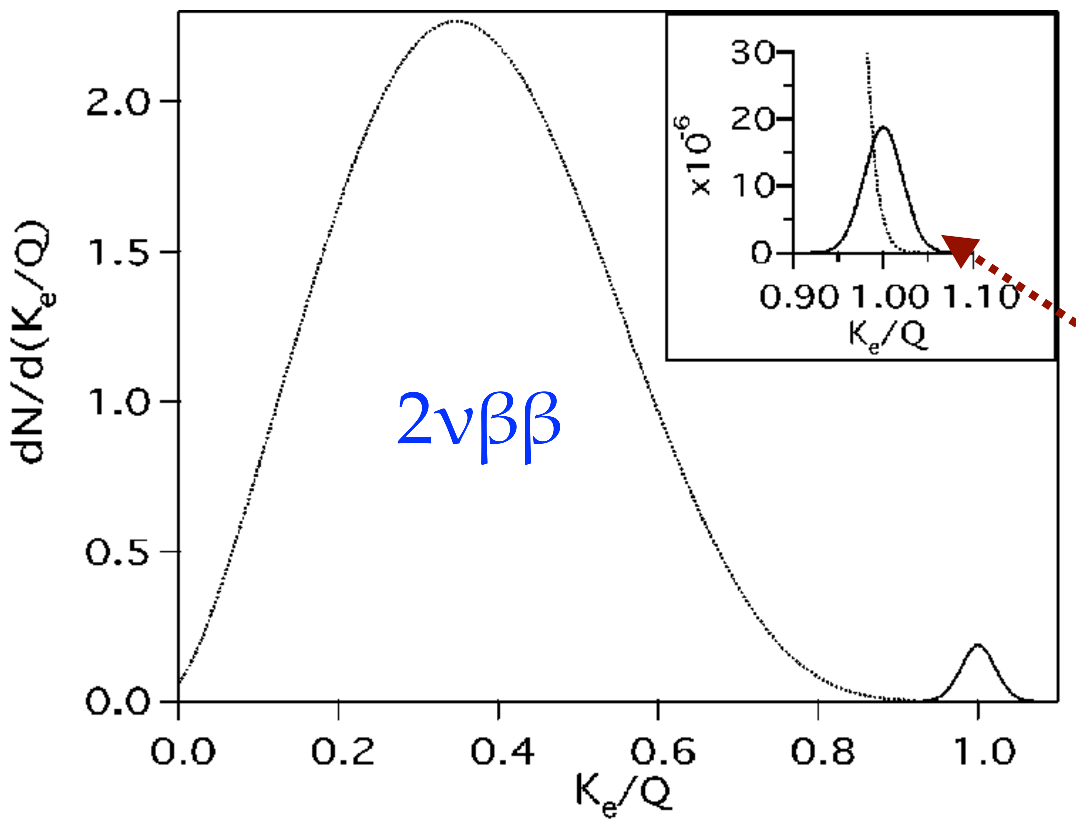
observation of 0νββ decay

- massive, Majorana neutrinos
- **lepton number violation ($\Delta L = 2$)**
- new mass creation mechanism
- new mass scale

0νββ rate

- absolute neutrino mass (model dependent)

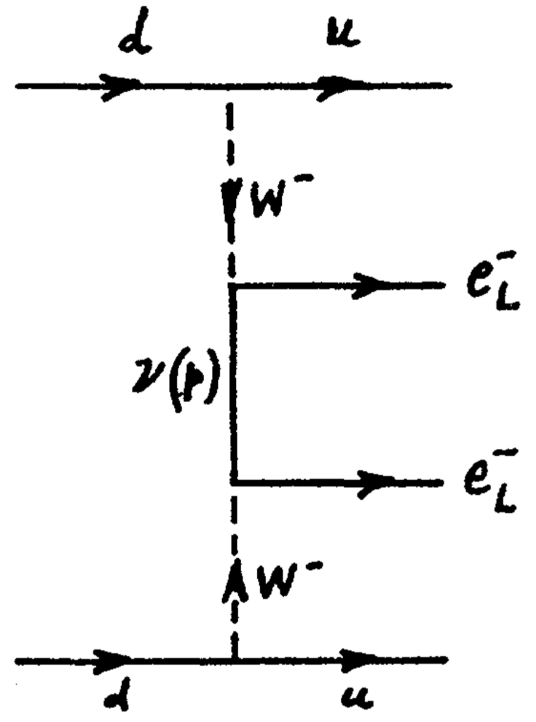
For virtual exchange of light Majorana neutrinos, the decay rate depends on an effective neutrino mass



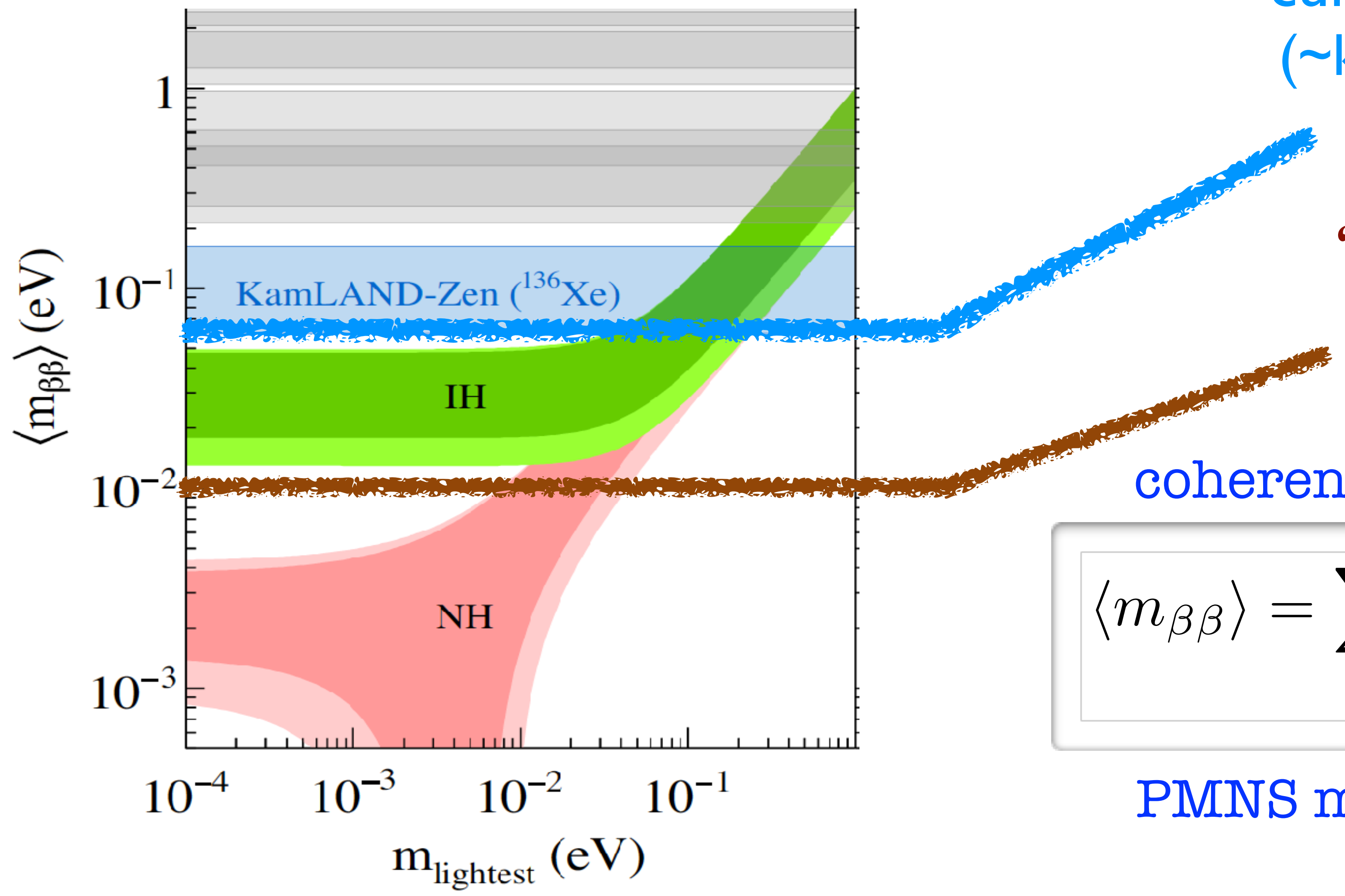
0νββ

new physics

proposed in 1937 by Racah + Furry



$$\eta \sim < m_{\beta\beta} >$$



current experiments (~kmole, $T_{1/2}$~10^{26} y)

"tonne-scale" ($T_{1/2}$~10^{28} y)

coherent superposition

$$\langle m_{\beta\beta}\rangle = \sum_j |U_{ej}|^2 e^{i\alpha_j} m_j$$

PMNS matrix

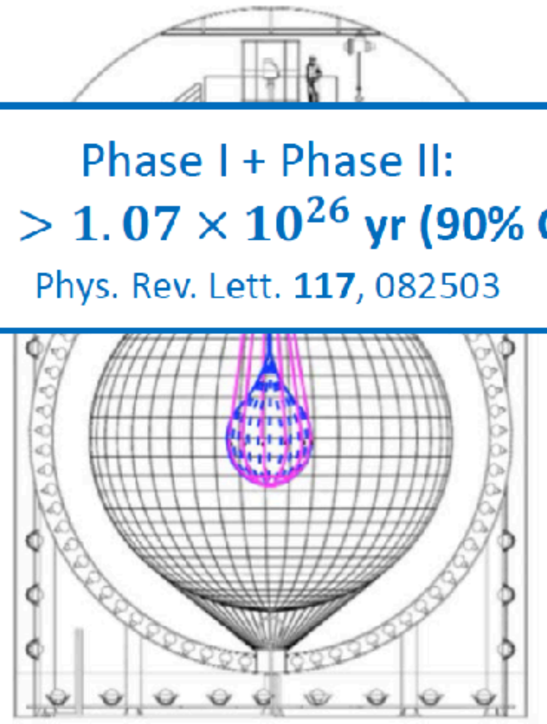
Majorana phases

Neutrinoless double beta decay (current status)

(sensitivity)	(lower limit)	isotope	exposure (kg · yr)	experiment	year	status
5.6 8.0	>10.7 >4	Xe-136	246.1	KamLAND-Zen (ph. I+II) KL-Zen 800	2016 2020	completed running
9 18	>11 >18	Ge-76	82.4 103.7	Gerda (phase I+II)	2019 2020	completed
4.8	>2.7	Ge-76	26	Majorana Demonstrator	2019	running
5.0	>3.5	Xe-136	234.1	EXO-200 (phase I+II)	2019	completed
1.7	>3.2	Te-130	372.5	Cuore (w/ Cuoricino)	2020	running
0.5 -	>0.35 >0.14	Se-82 Mo-100	5.29 2.17	Cupid-0 Cupid-Mo	2019 2020	completed running
		Te-130		SNO+		commissioning
		Xe-136		NEXT-100		construction

Past

Phase I + Phase II:
$T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)
Phys. Rev. Lett. **117**, 082503

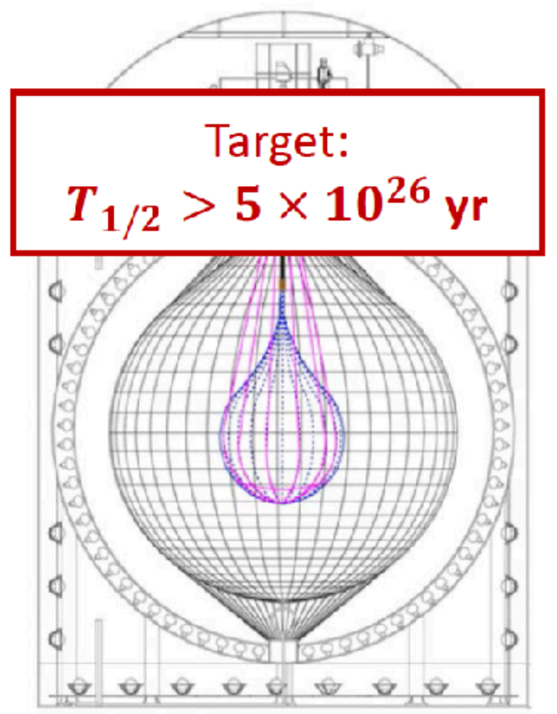


KamLAND-Zen 400

Mini-balloon Radius = 1.54 m
Xenon mass = 320 ~ 380 kg
2011 ~ 2015

Current

Target:
$T_{1/2} > 5 \times 10^{26}$ yr

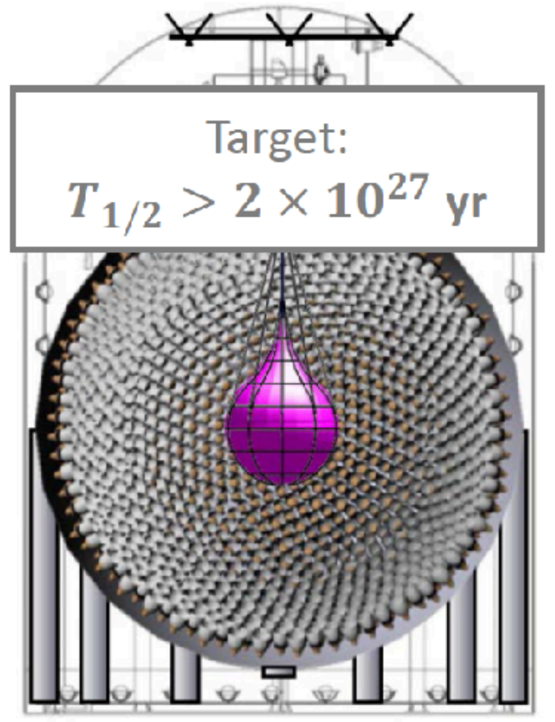


KamLAND-Zen 800

Mini-balloon Radius = 1.90 m
Xenon mass = 745 kg
Started January 2019

Future

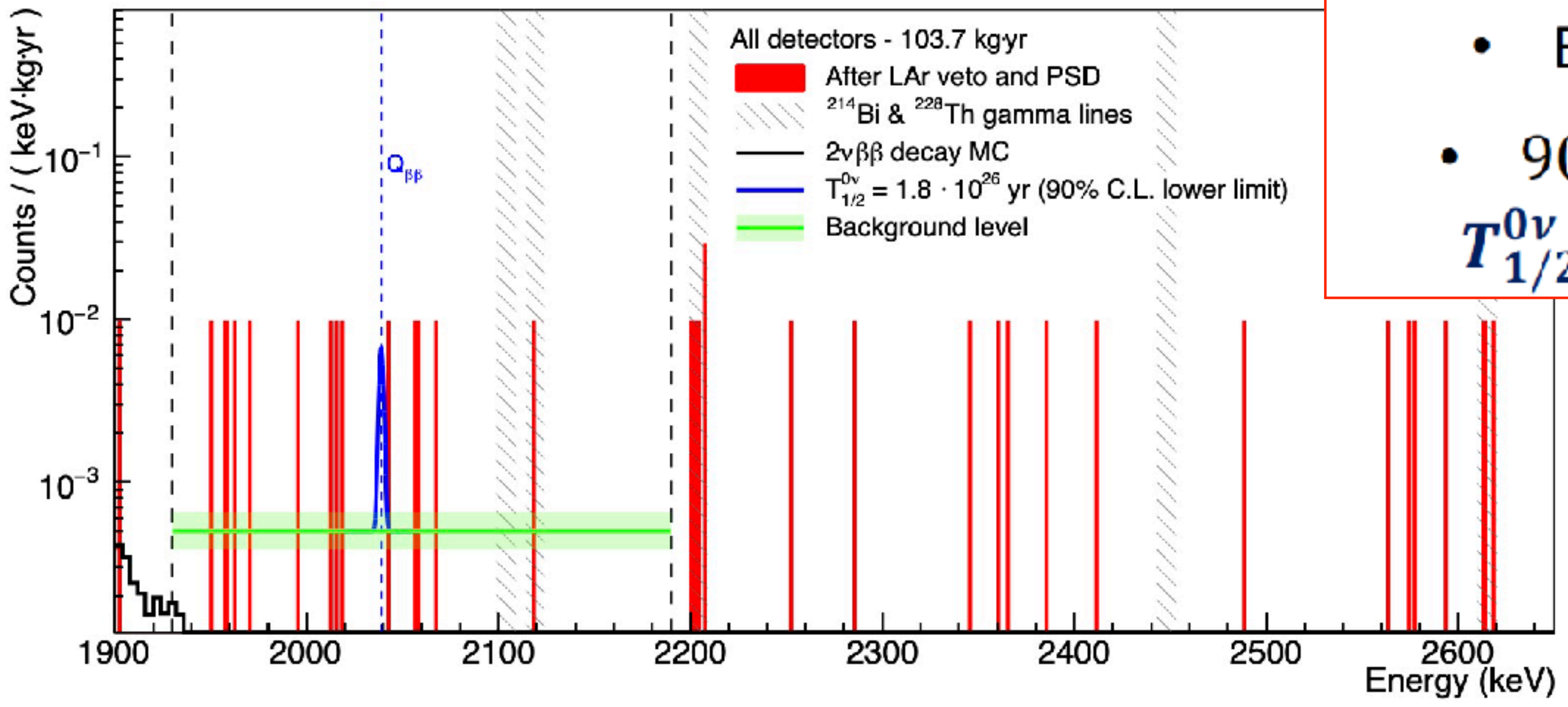
Target:
$T_{1/2} > 2 \times 10^{27}$ yr



KamLAND2-Zen

Xenon mass ~ 1 ton
× 5 increase in light collection
Scintillation balloon film

Gerda



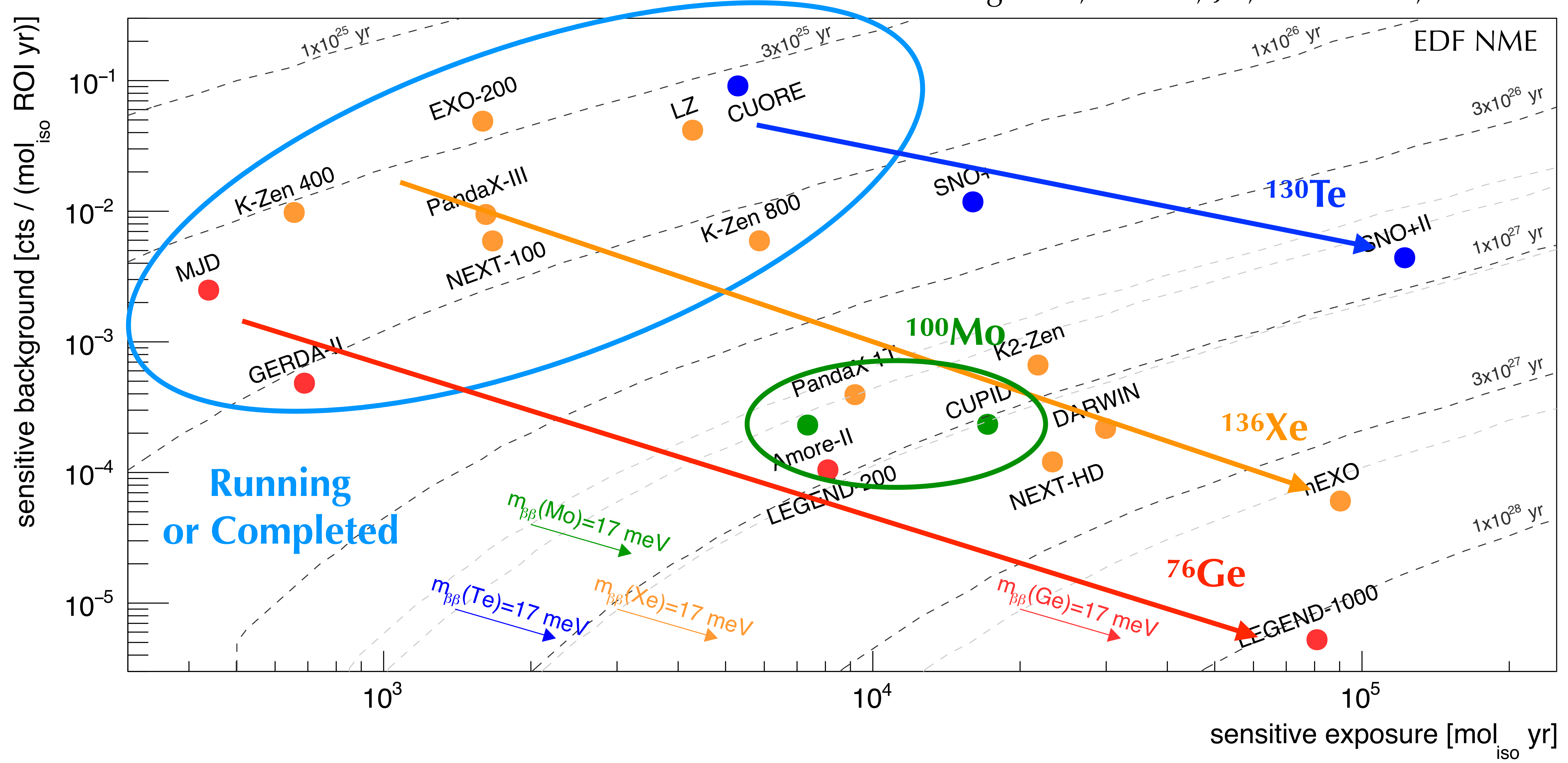
Frequentist analysis*:
Median sensitivity for limit setting:
1.8×10^{26} yr (90% C.L.)

- Best fit → no signal
- 90% C.L. lower limit: $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ yr

The tonne-scale program

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

Agostini, Benato, JD, Menendez, Vissani



"RECOMMENDATION II

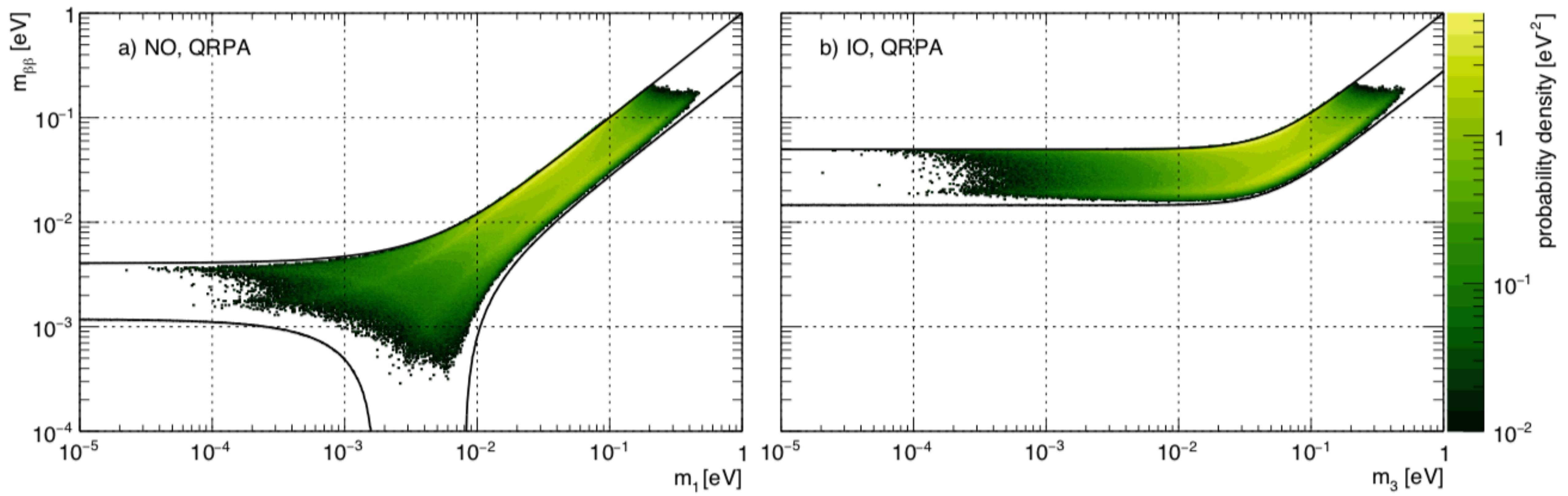
The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

Initiative B

"We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC."

The US DoE-NP has declared 'mission need' (CD0)



Discovery potential with:

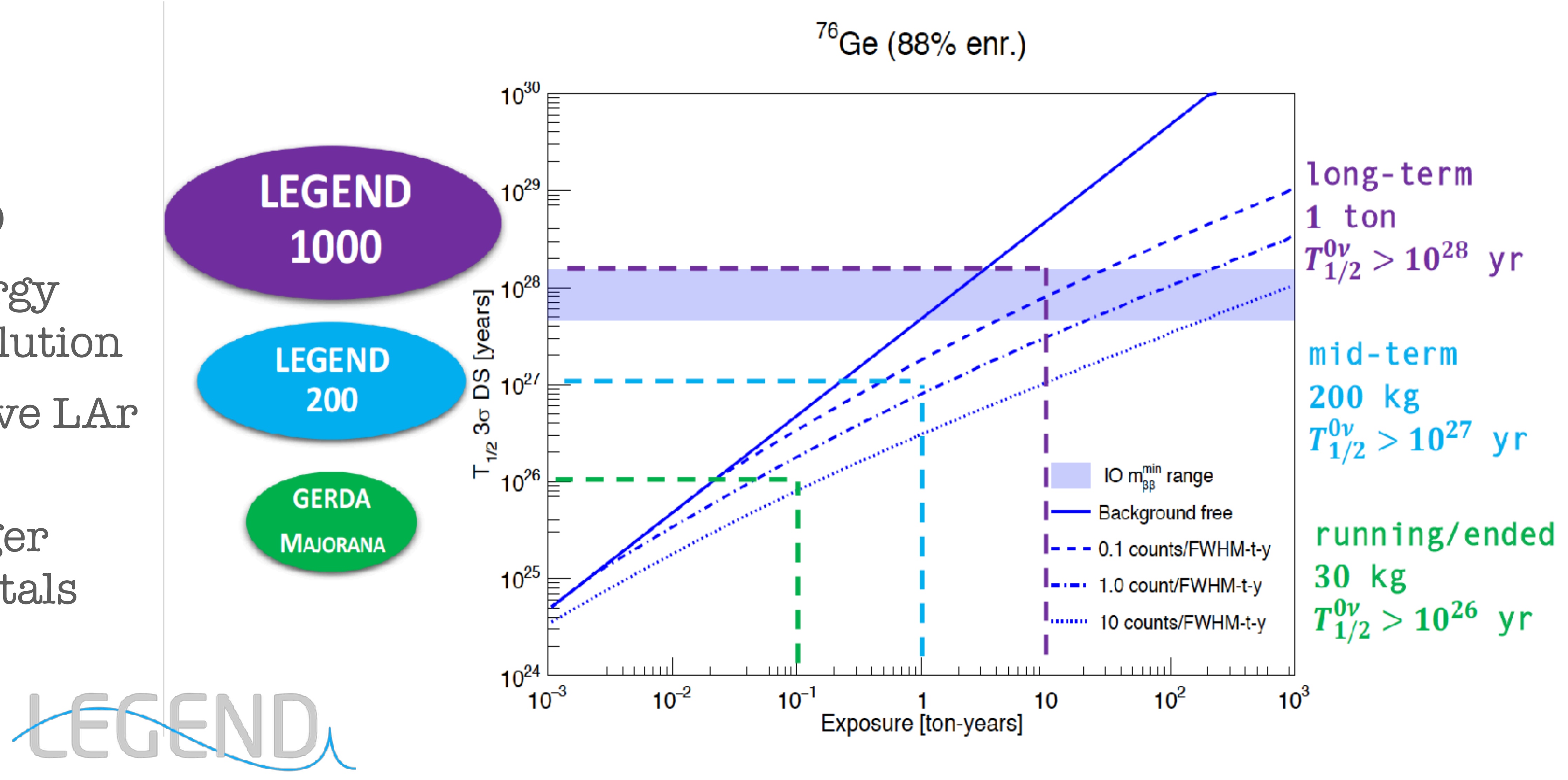
- assuming Type I seesaw
- free value of gA
- Bayesian analysis with flatly distributed priors for Majorana phases

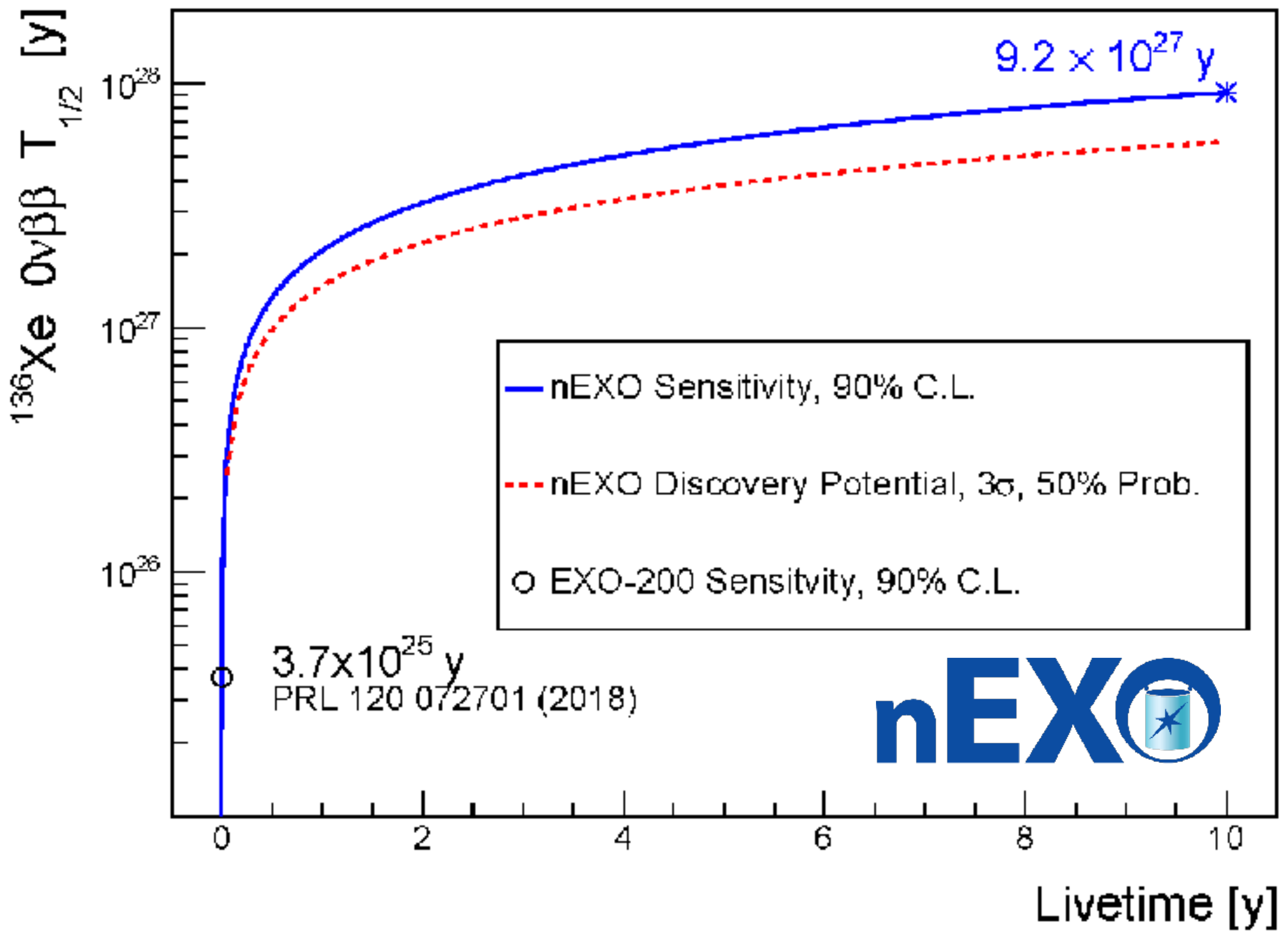
Agostini, Benato, Detwiler, PRD 96 (2017) 053001; also A. Caldwell et al., PRD 96 (2017) 073001)

0ν DBD technology

LEGND

- Energy resolution
- Active LAr veto
- Larger crystals





nEXO

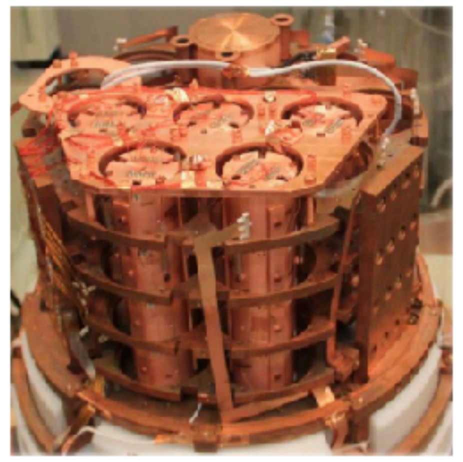
- Gamma-ray self-shielding measured bg
- Ionization and scintillation
- Inline purification

CUPID-Mo Li_2MoO_4 performance

CUPID

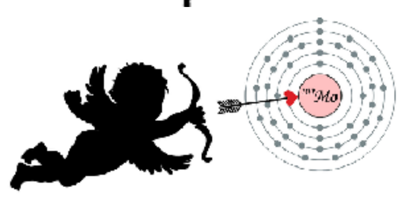
- Energy resolution
- Isotope flexibility
- Heat and scintillation (particle ID)

Discovery sensitivity (10 years):
$T_{1/2} > 1.1\text{x}10^{27}$ yr



Array of large of highly enriched $Li_2\,^{100}MoO_4$

Data confirms:
- α tagging performance
- Radiopurity of crystals
- Energy resolution



- Appealing prospect of >1 isotope with similar sensitivity
- LNV discovery machines (with Type-I See-Saw benchmark)
- Other programs:
  - SNO+: Tellurium in L-scintillator (10^{26}÷10^{27} years)
  - NEXT-HD (1 tonne Xe at 15 bar)

Beyond the tonne scale: new benchmarks (with Vincenzo C.)

with input from Michael Ramsey-Musolf

Experimental grand-challenges for the coming 2 decades

A. Cover the normal neutrino mass ordering down to the horizontal band, forgetting about the 'lobster claw' that drops down to zero. (New Benchmark #1)

B. Think beyond high-scale See-Saw. In particular, should tonne-scale experiments see candidate signal events:

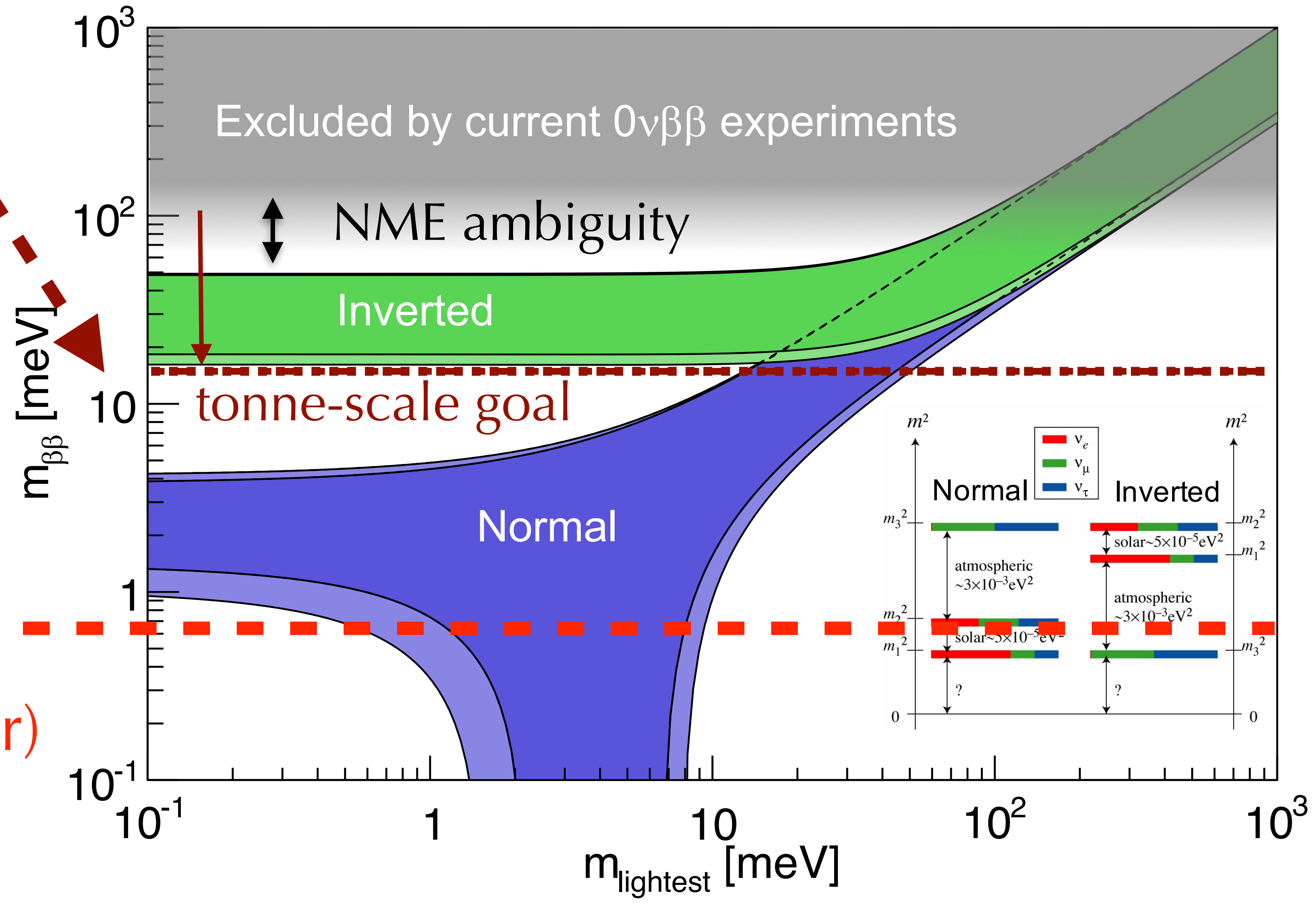
   a. Topology: single electron spectra and opening angle. Is measuring the electron polarization an option? Could 'recycle' the isotopes already in hand. (New Benchmark #2)

   b. Theoretical benchmarking: clearly define 'topological templates' that experiments could hope to distinguish amongst. These group into three separate classes of theories

   c. Multi-isotope program: cross-checking of theoretical models? (New Benchmark #3)

next precision benchmark (#2) ($T_{1/2}$ ~ 10^{28} yr)

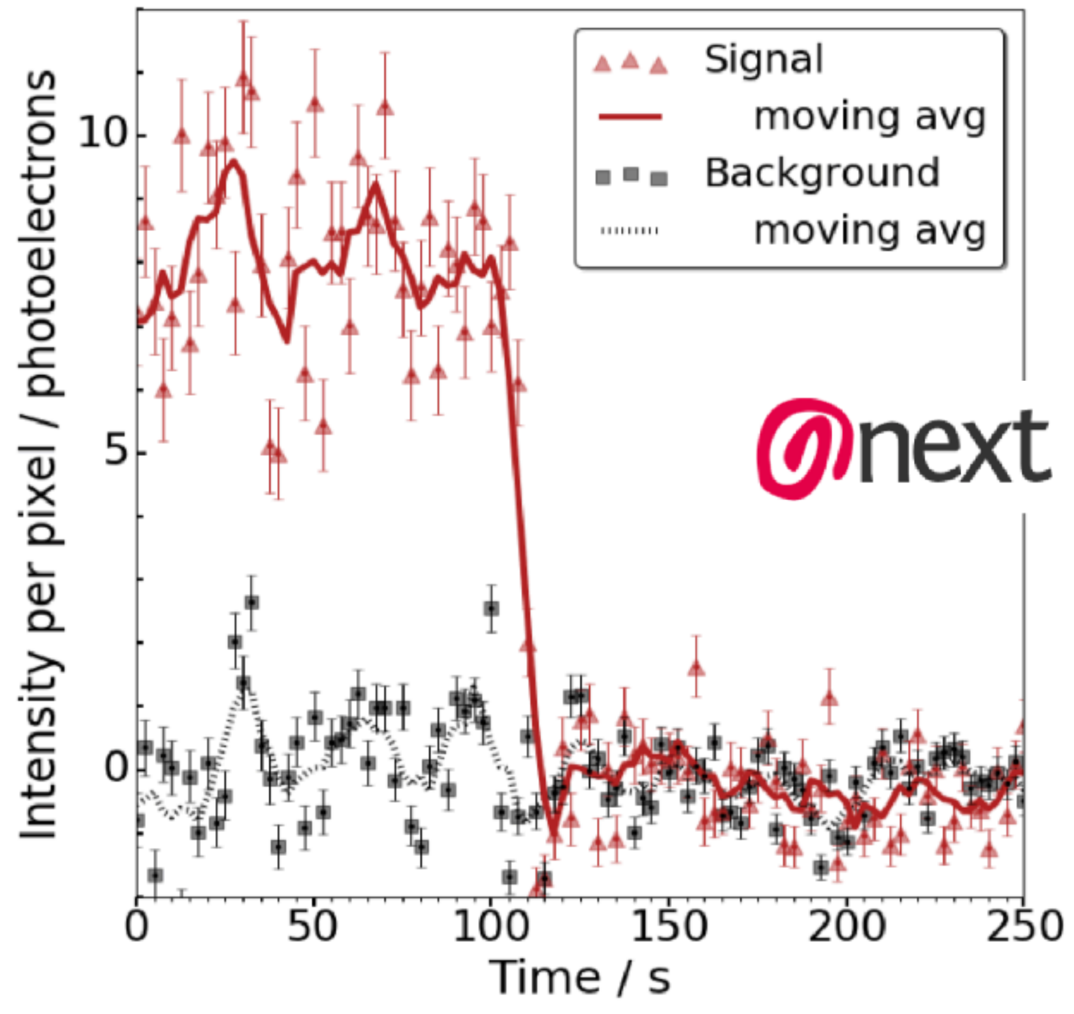
next discovery benchmark (#1) ($T_{1/2}$ ~ 10^{29}-10^{30} yr)



development of instrumentation is crucial

Beyond the tonne scale: how to do this?

- Huge (water-based?) scintillators (Te-130, no enrichment) (SNO+ --> THEIA)
- Layered amorphous ^{82}Se x-ray detectors readout by CMOS pixel arrays (industrial production, tracking, long-delay coincidences) (NEMO3/SuperNEMO —> Selena with Se-82)
- Large HPGas TPCS (Xe, SeH6 -- tracking/topology)
- Daughter ion/atom ID ("Ba-tagging" in Xe -- no gamma background)



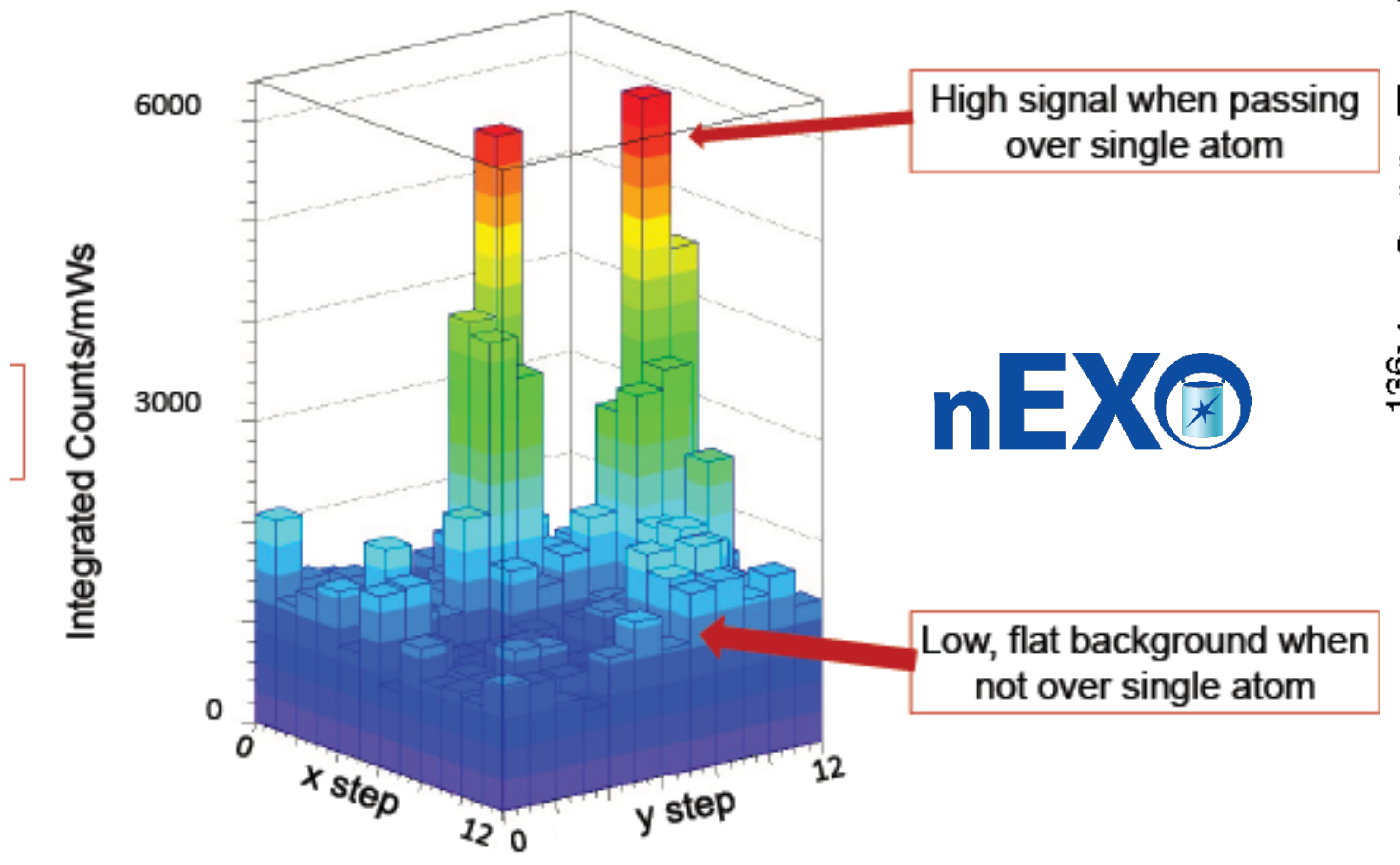
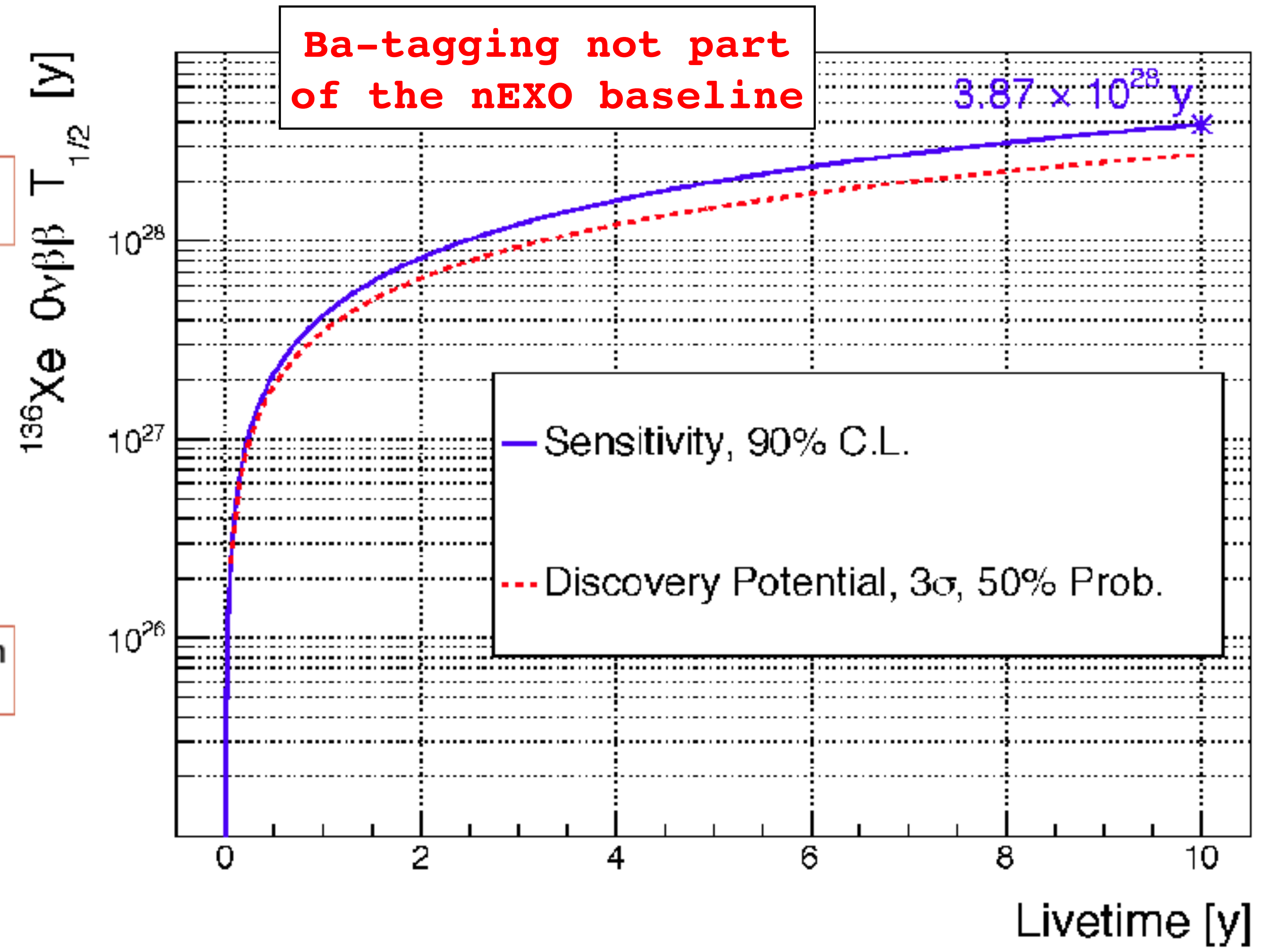


Image of two barium atoms in the single vacancy matrix site.[1]



Beyond the tonne scale: how to do this?

Aside from what isotope allows for the best future detector, the following instrumentation threads will be essential for the entire program

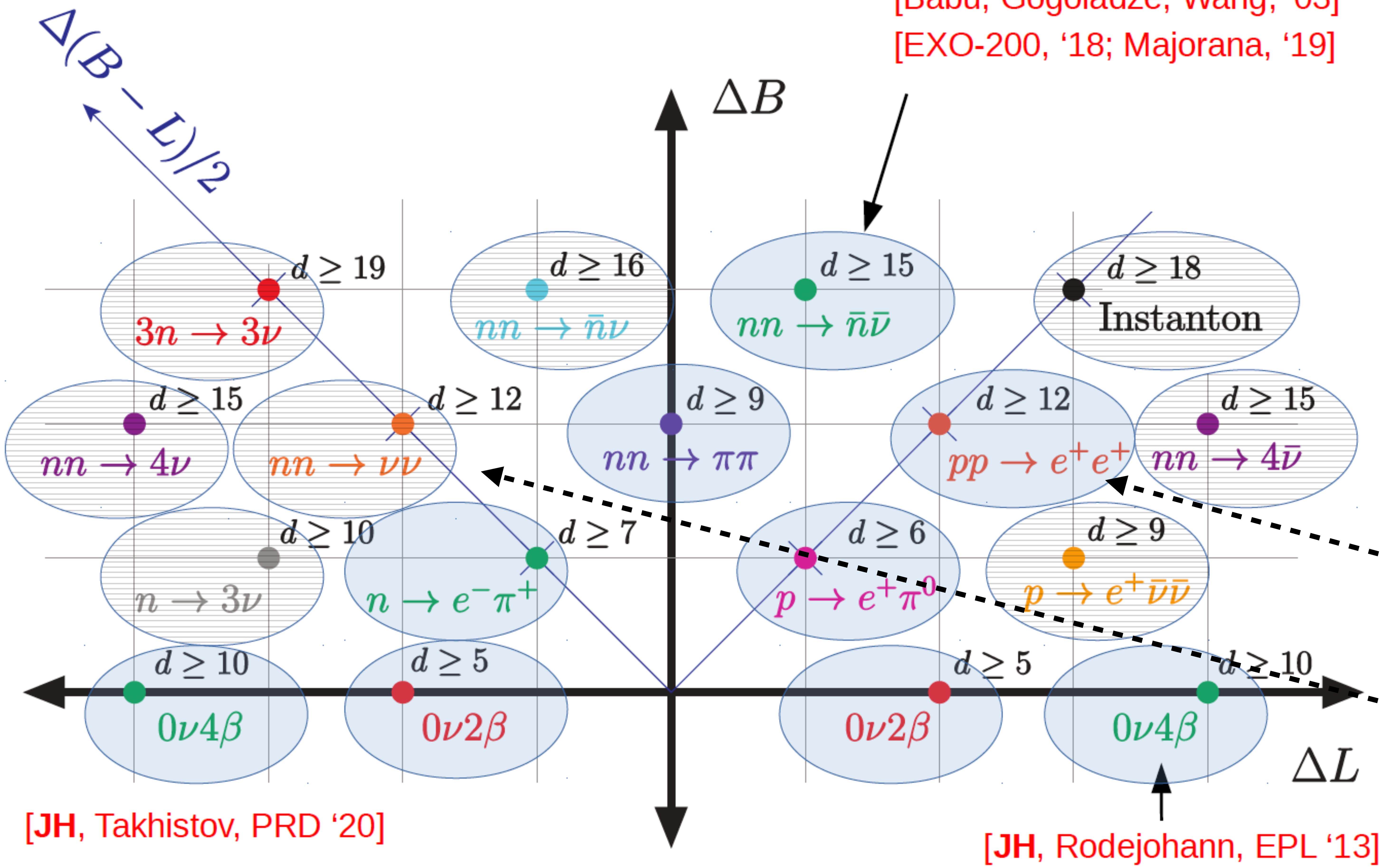
- massive procurement, storage, purification of isotopes and detector materials
- low-radioactivity screening
- materials selection
- control of radon-borne backgrounds
- control of cosmogenics
- low-mass, low-radioactivity, fast electronics
- deep learning techniques (fully exploit bg-discrimination capabilities of detectors)

BLNV exotica (adapted from Julian Heeck + Ed Kearns, BLV ca. 2020)

Recent limits: Older than 5 yr:

ppp $\to e^+\pi^+\pi^+$

[Babu, Gogoladze, Wang, '03]
[EXO-200, '18; Majorana, '19]



[JH, Takhistov, PRD '20]

[JH, Rodejohann, EPL '13]
[NEMO-3, PRL '17]

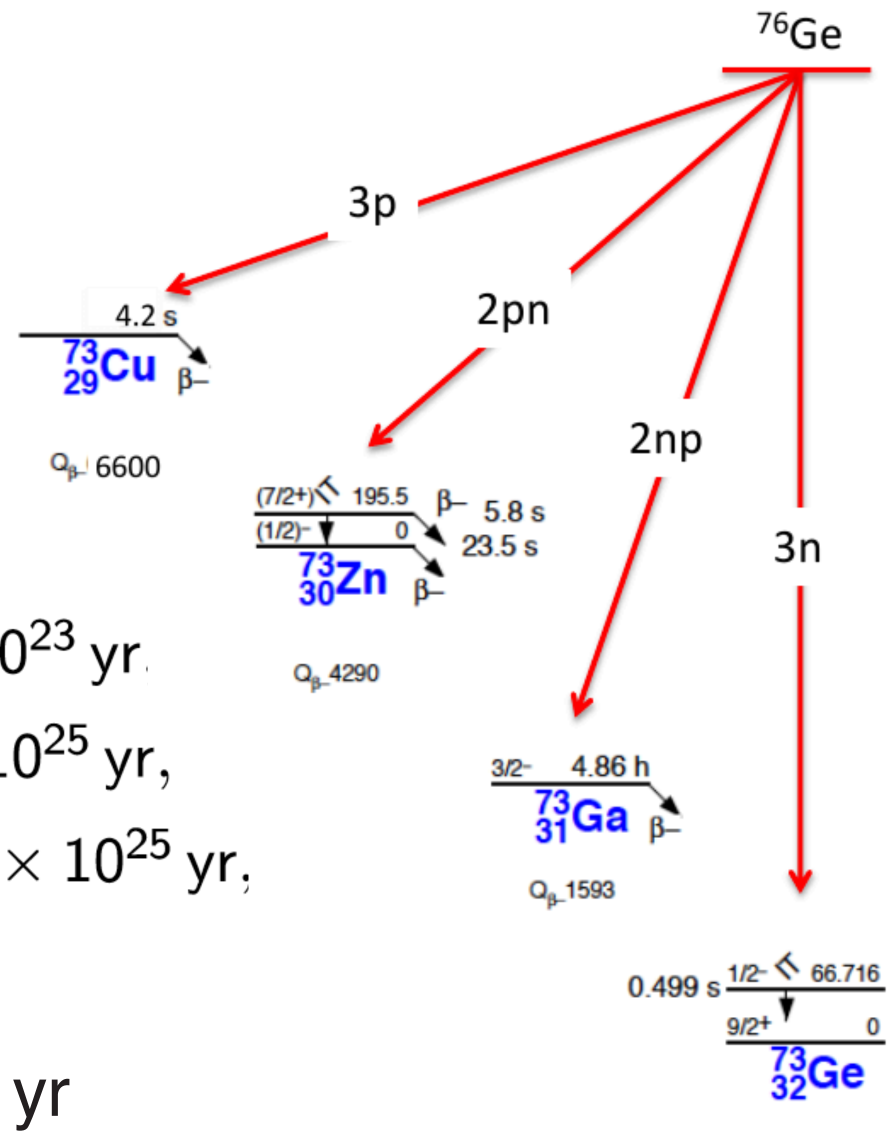
9

Majorana Demonstrator, PRD '19:

$\tau(^{73}\mathrm{Ge(pnn)} \to {}^{70}\mathrm{Ga}\, e^+\pi^0) > 7 \times 10^{23}$ yr

$\tau(^{76}\mathrm{Ge(ppn)} \to {}^{73}\mathrm{Zn}\, e^+\pi^+) > 5 \times 10^{25}$ yr,

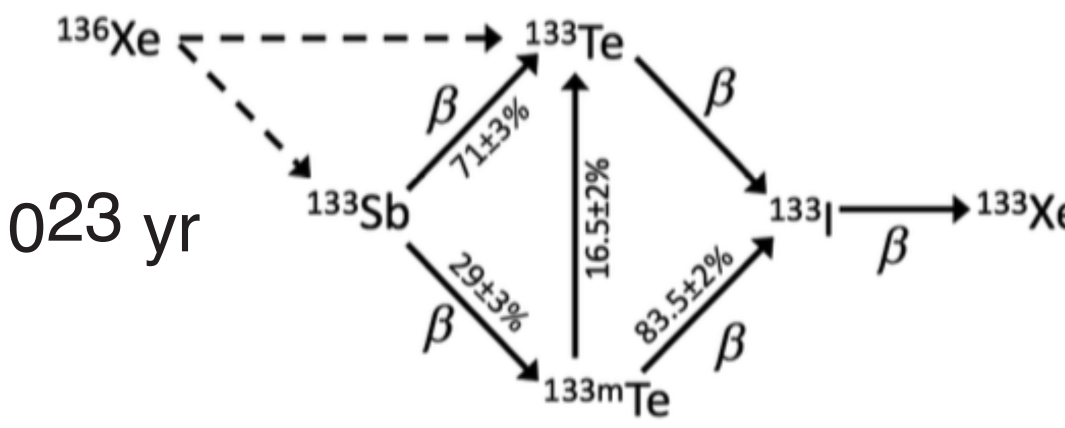
$\tau(^{76}\mathrm{Ge(ppp)} \to {}^{73}\mathrm{Cu}\, e^+\pi^+\pi^+) > 5 \times 10^{25}$ yr,



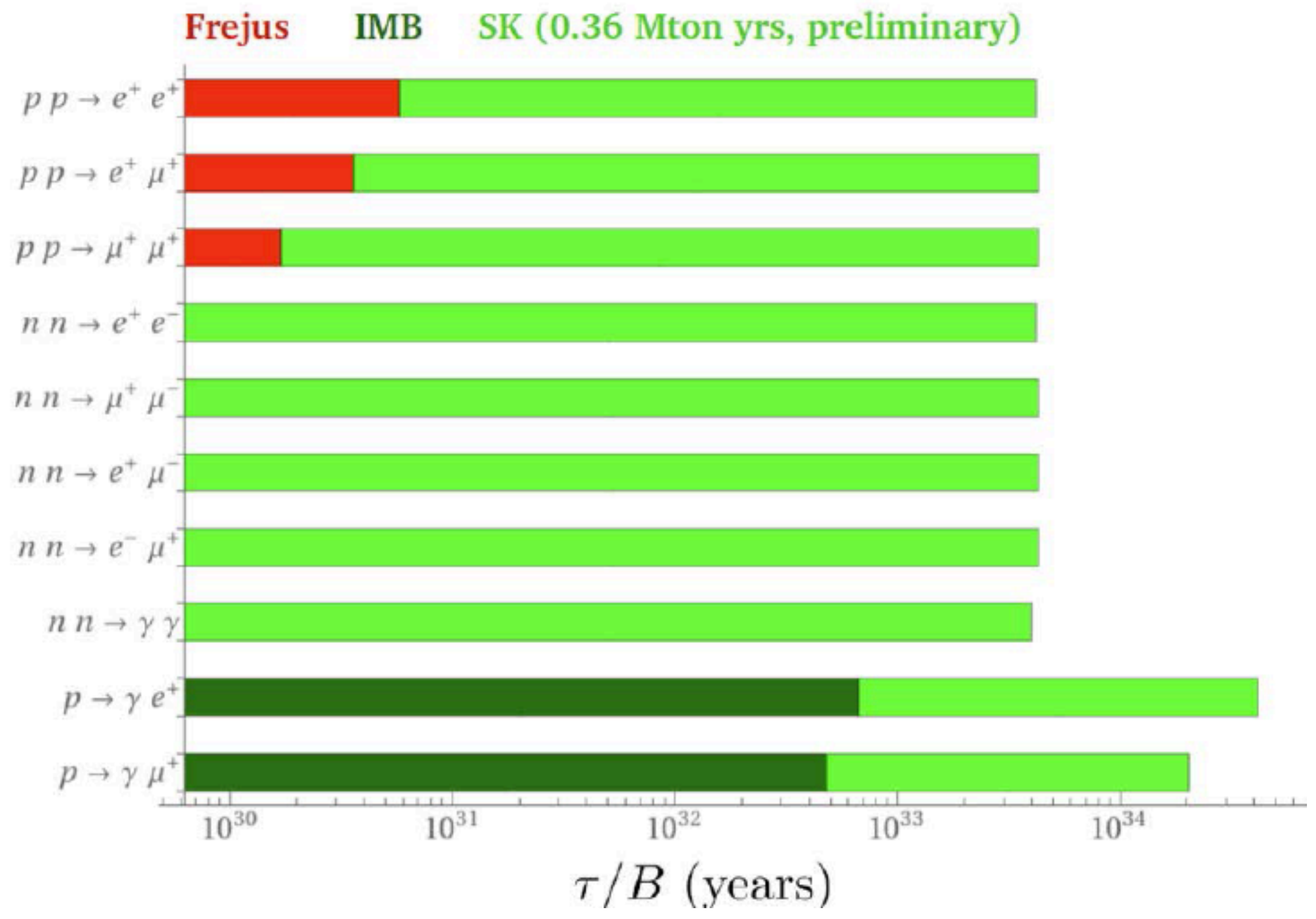
$> 1.9 \times 10^{23}$ yr

EXO-200, PRD '18:

$> 3.3 \times 10^{23}$ yr



https://arxiv.org/abs/1811.12430



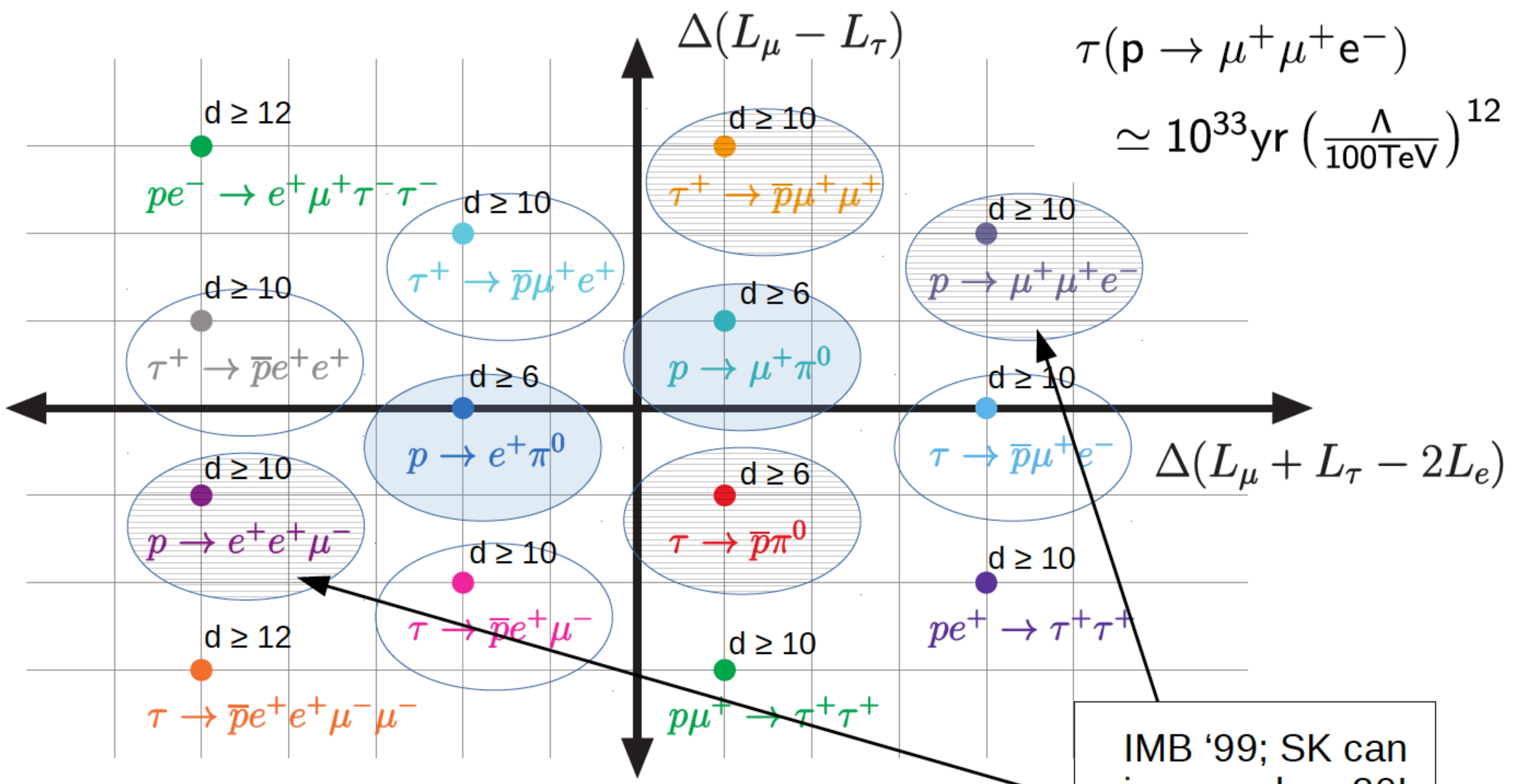
Need more (inclusive) searches!

BLNV exotica

(from Julian Heeck + Ed Kearns, BLV ca. 2020)

Currently being probed: Old results: Doable:

ΔB = ΔL = 1

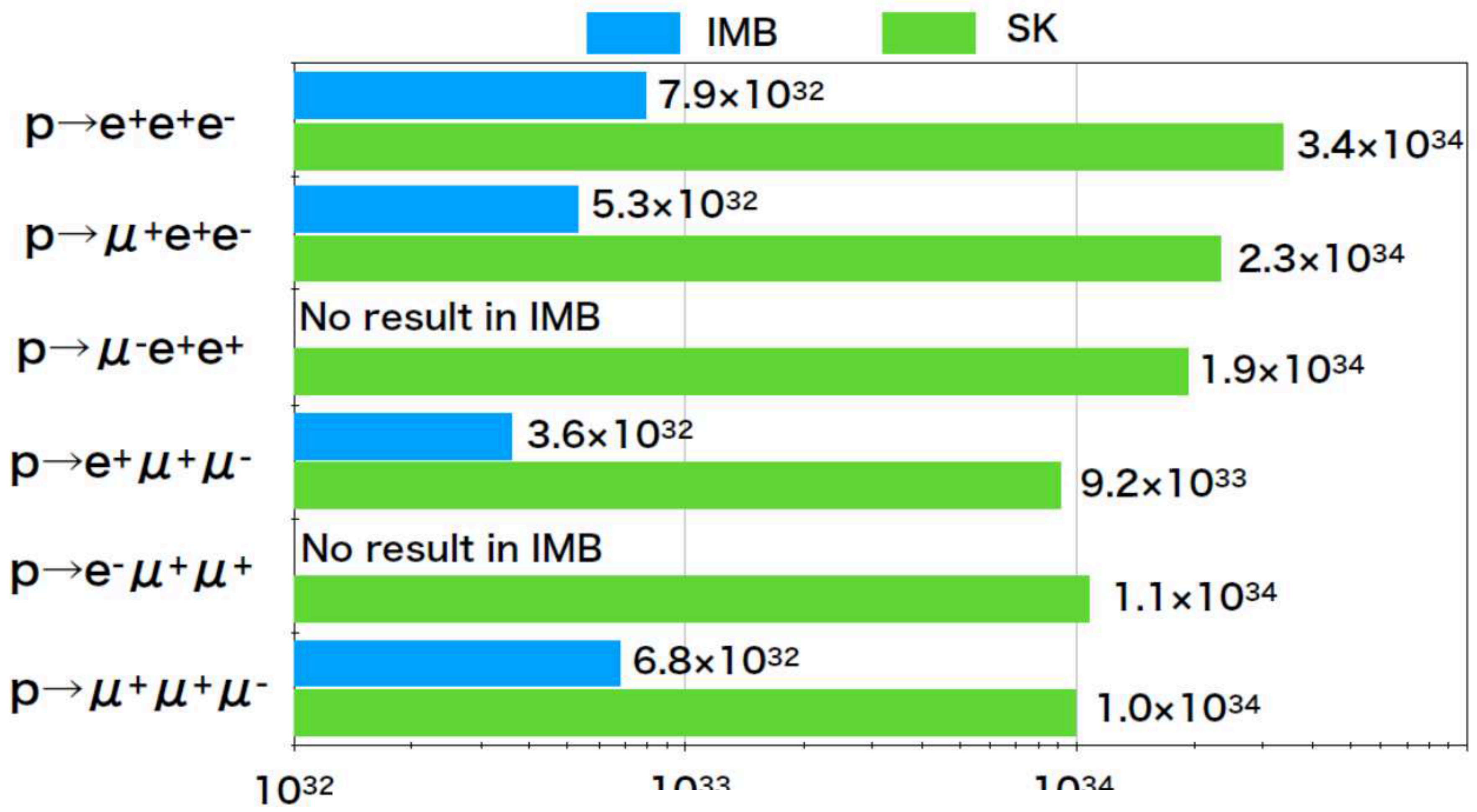


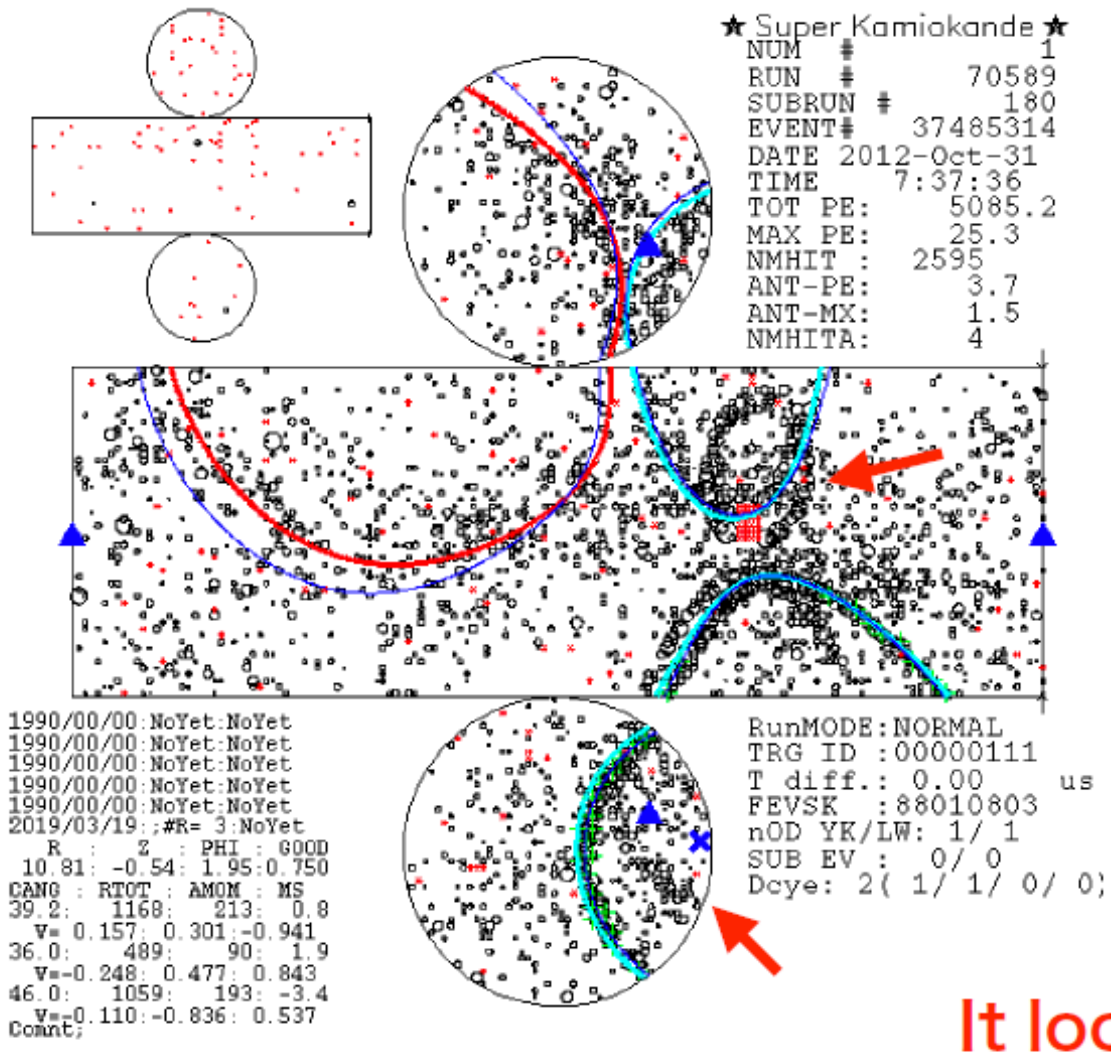
$$\tau(p \to \mu^+\mu^+e^-) \simeq 10^{33}\text{yr}\left(\frac{\Lambda}{100\text{TeV}}\right)^{12}$$

IMB '99; SK can improve by ~30!

[Hambye, **JH**, PRL '18]

Super-K searched for p → ℓℓℓ!





BLNV exotica

(from Susan Gardner and Julian Heeck)

Some Possibilities

In addition to $n - \bar{n}$ oscillations, we could consider…

$\Lambda - \bar{\Lambda}$ oscillations (or other flavorful transitions)
N or NN decays to various final (dark?) states
scattering-mediated $N\bar{N}$ transitions
such as $e^- p \to e^+ \bar{p}$ and $e^- p \to \bar{\nu}_e \bar{n}$
[SG & X. Yan, 2019]
and/or
collider searches for |ΔB|=|ΔL|=3 processes

In addition to 0ν ββ decay we could consider…

the role of light particle emission therein
|ΔL|=(or >) 2 processes also with μ or τ final states
muonium-antimuonium oscillations *(a 2-fer!)*

S. Gardner (w/ J. Heeck) “Exotic” Subgroup of RF04

Searches for exotic B and L violation

- Some recent limits on exotica: $p \to e^- \mu^+ \mu^+$ (SK), $ppn \to e^+ \pi^+$ (Majorana, EXO), $pp \to e^+ e^+$ (SK), 0ν4β (NEMO).
- Expect overall improvement on ΔB/ΔL with new detectors.
- Encourage *inclusive* searches to improve 40-yr-old limits!
  - E.g. $\Gamma^{-1}(\mathrm{N} \to \mathrm{e} + \mathrm{anything}) > 0.6 \times 10^{30}$ yr. [Learned++, ‘79]
  - Special case: invisible (multi-)neutron decay, e.g. $\Gamma^{-1}(\mathrm{n} \to \mathrm{neutrinos}) > 0.58 \times 10^{30}$ yr. [KamLAND, PRL ‘06]
  - Also probes ΔB > 1, light new physics, and dark matter! [Heeck, Takhistov, PRD ‘20]
- Different detectors *complementary*; encourage studies/LOI from SK/HK, DUNE, JUNO, 0νββ experiments on exotica.

Search under every lamppost!

Julian Heeck (w/ S. Gardner) "Exotic" Subgroup of RF04

Could one look for other LNV processes?

courtesy of Petr Vogel

Observing any of these processes would mean that the lepton number is not conserved, and that neutrinos are massive Majorana particles:

Neutrinoless ββ decay: $(Z,A) \to (Z\pm2,A) + 2e(^{\pm})$, $T_{1/2} > \sim10^{26}$ y
Muon conversion: $\mu^- + (Z,A) \to e^+ + (Z-2,A)$, BR $< 10^{-12}$
Anomalous kaon decays: $K^+ \to \pi^-\mu^+\mu^+$, BR $< 10^{-9}$

0νββ decay: $T_{1/2} > \sim10^{26}$ y —> BR $< 2\times10^{-5}$ (BR not a good metric)
μ conversion: BR $< 10^{-12}$ —> $T_{1/2} > 2.2\times10^{6}$ s (muon life time = 2.2 μs)
Kaon decays: BR $< 10^{-9}$ —> $T_{1/2} > 12$ s

Possible, currently impractical. A future opportunity?

the RPF04 activities (https://snowmass21.org/rare/blv)

DeltaB = 2 workshop (Aug. 3-6, 2020 — hosted by ACFI)
Particular focus on Snowmass 2021 LOI's
(https://www.physics.umass.edu/acfi/seminars-and-workshops/theoretical-innovations-for-future-experiments-regarding-baryon-number)

Relevant meetings are also held by:

- other topical groups within RPF (notable RPF-05, RPF-03)
- other Frontiers (Energy/BSM, Neutrino, Instrumentation)

Synergy with Neutrino Frontier (NF 05)

(courtesy of Lisa Kaufmann)

Relevant to neutrinoless double beta decay

- How can we realize the next generation of ultra-radio-pure materials?
- Can very large detectors be calibrated sufficiently well to achieve their goals?
- How are we approaching the increasing role of non-radiogenic backgrounds?
- How can a signal be confirmed if one is found (within the discovery experiment)?
- How can a signal be confirmed if one is found (beyond the discovery experiment)?
- Can the information content of events in existing technologies be further maximized?
- What does the path to the tens-of-ton scale look like (are any of the existing approaches suitable)?
- What are the issues associated with acquisition of target isotopes on large scales?
- In the event of (a) non-observation or (b) observation or (c) neither [a] nor [b], what happens next?
- Your thought-provoking questions here...

August 2020

- 19 Aug Mini Workshop: 0nubb Experiment II
- 12 Aug Mini Workshop: Neutrino Electromagnetic Properties
- 05 Aug Mini Workshop: 0nubb Experiment I

July 2020

- 22 Jul Mini Workshop: Nuclear theory of neutrinoless double-beta decay
- 15 Jul Mini Workshop: Particle theory of neutrinoless double-beta decay
- 08 Jul Mini Workshop: Direct Neutrino Mass Measurements

Agreement with the Neutrino Frontier (Lisa Kaufmann and Ben Jones) to avoid duplication and co-sponsor future events

Summary

- Searching for Baryon and Lepton number violation is a well-motivated, experimentally viable path to finding BSM physics
- In addition to probing fundamental symmetries of nature, BLV is at the core of understanding the matter dominance in the universe
- BLV searches are pursued with a variety of technologies and their sensitivity benefits from a broad net of instrumentation development:
    - high-energy and precision accelerators
    - neutron facilities
    - large neutrino and DBD detectors
    - detector development: light, charge, heat, timing, resolution, particle ID, spectroscopy, ion traps, engineered molecules, …
- New sensitivity regimes within reach of upcoming experimental programs
- Bold ideas exist for setting new medium/long-term milestones