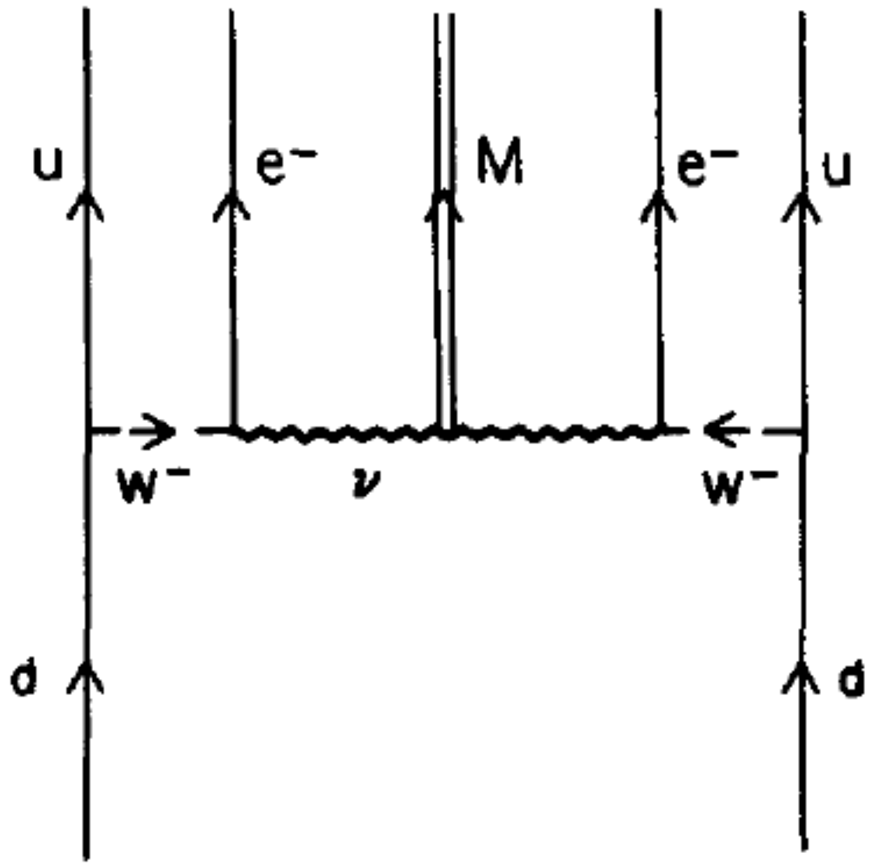
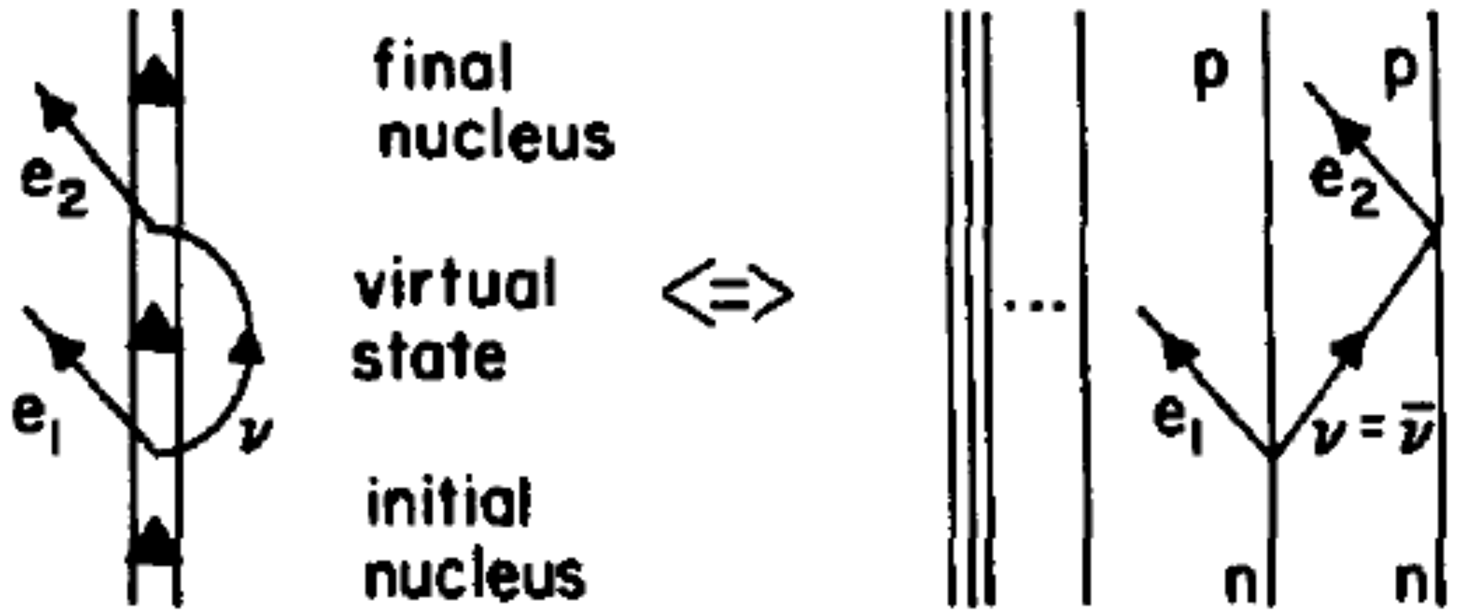
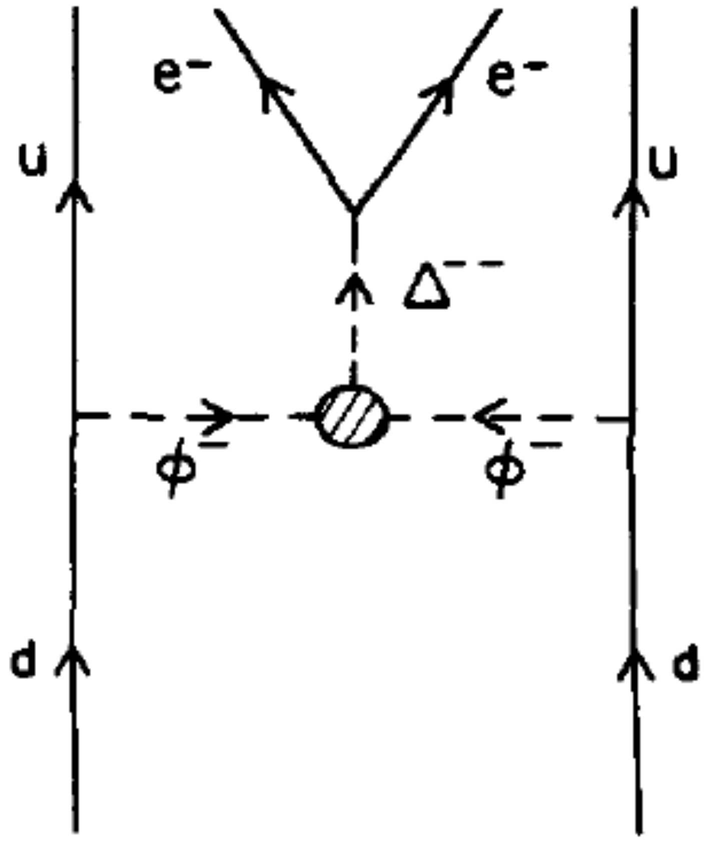
Testing Conservation Principles via Neutrinoless Double Beta Decay



Haxton and Stephenson, Prog. in Part. Nucl. Phys. **12** 409 (1984).



Haxton, Stephenson, and Strottman, PRL 47 153 1981



Haxton, Rosen, and Stephenson, PRD **26** 2360 (1982)

J.F. Wilkerson

Looking for ν physics on Earth and in the Cosmos
Wick Haxton Symposium
LBL, Berkeley, CA
January 7, 2020

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

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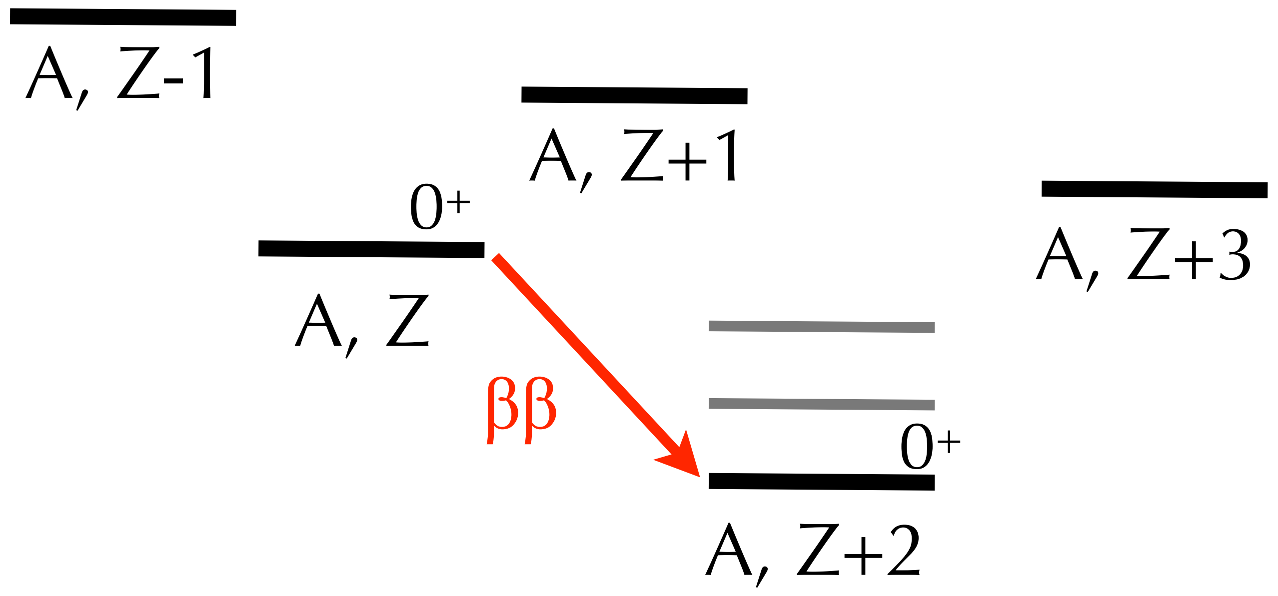
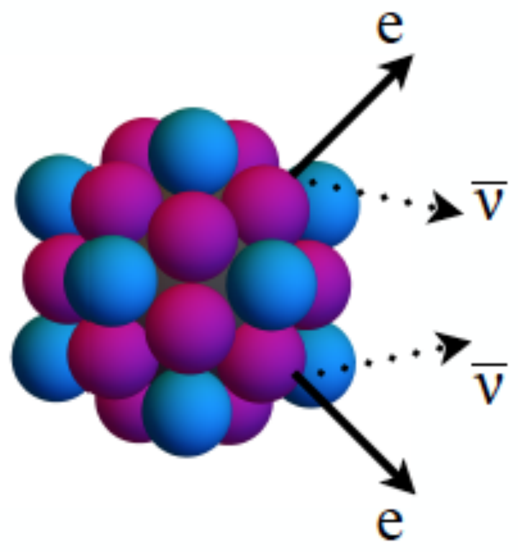
Double-Beta Decay (1930's)

2ν double-beta decay ($2\nu\beta\beta$): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + $\bar{\nu}$ + e^- + $\bar{\nu}$

Allowed second-order weak process

Maria Goeppert-Mayer (1935)





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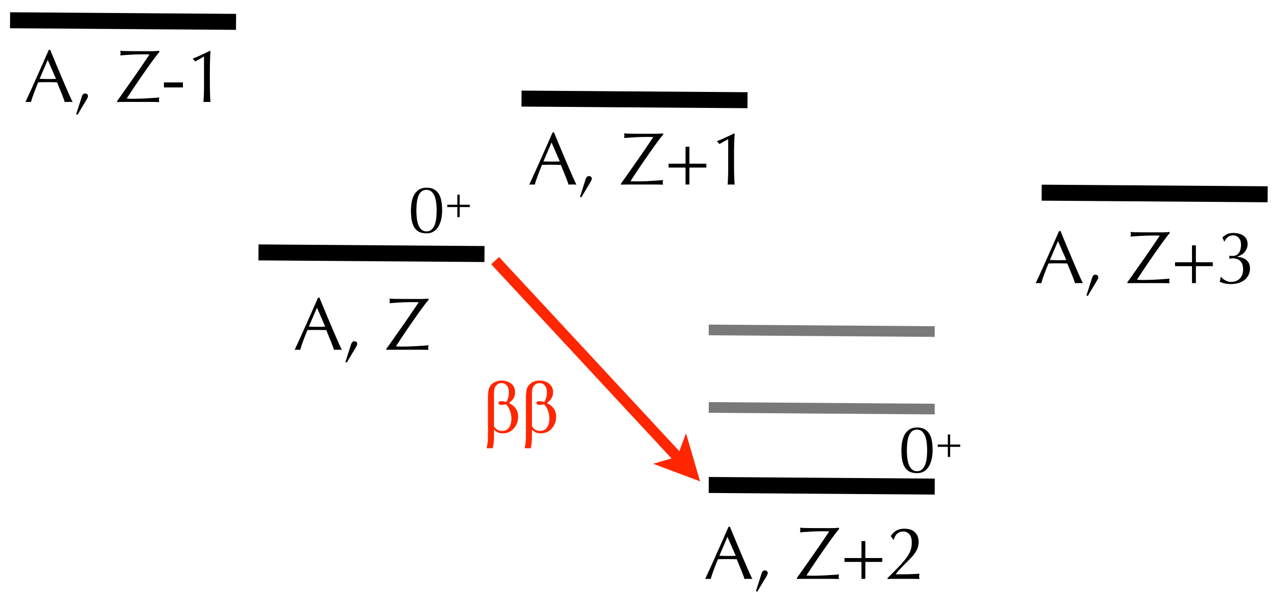

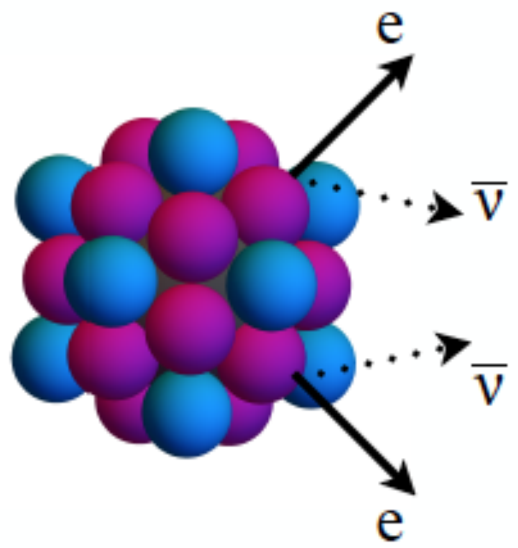

Ettore Majorana (1937) realized symmetry properties of Dirac's theory allowed the possibility for electrically neutral spin-1/2 fermions to be their own anti-particle

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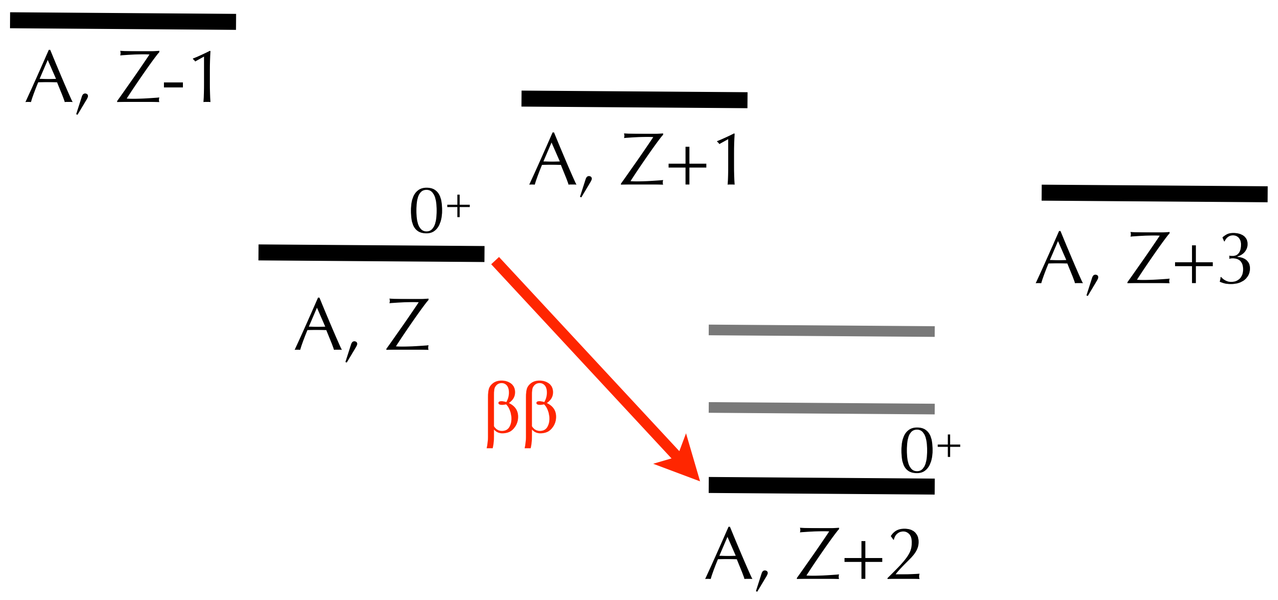

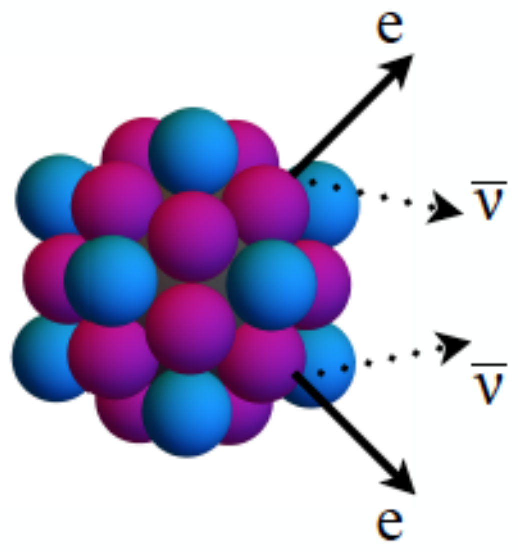

0ν double-beta decay ($0\nu\beta\beta$): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + e^-

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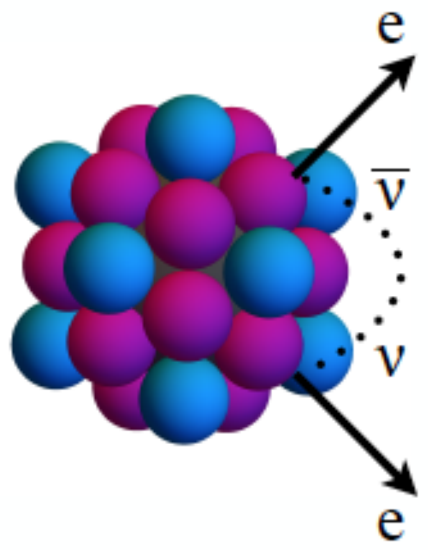

Racah (1937)

$$\mathbf{n} \rightarrow \mathbf{p} + e^- + \bar{\nu}$$

$$\nu + \mathbf{n} \rightarrow \mathbf{p} + e^-$$

Double-Beta Decay (1930's)

2ν double-beta decay ($2\nu\beta\beta$): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + $\bar{\nu}$ + e^- + $\bar{\nu}$

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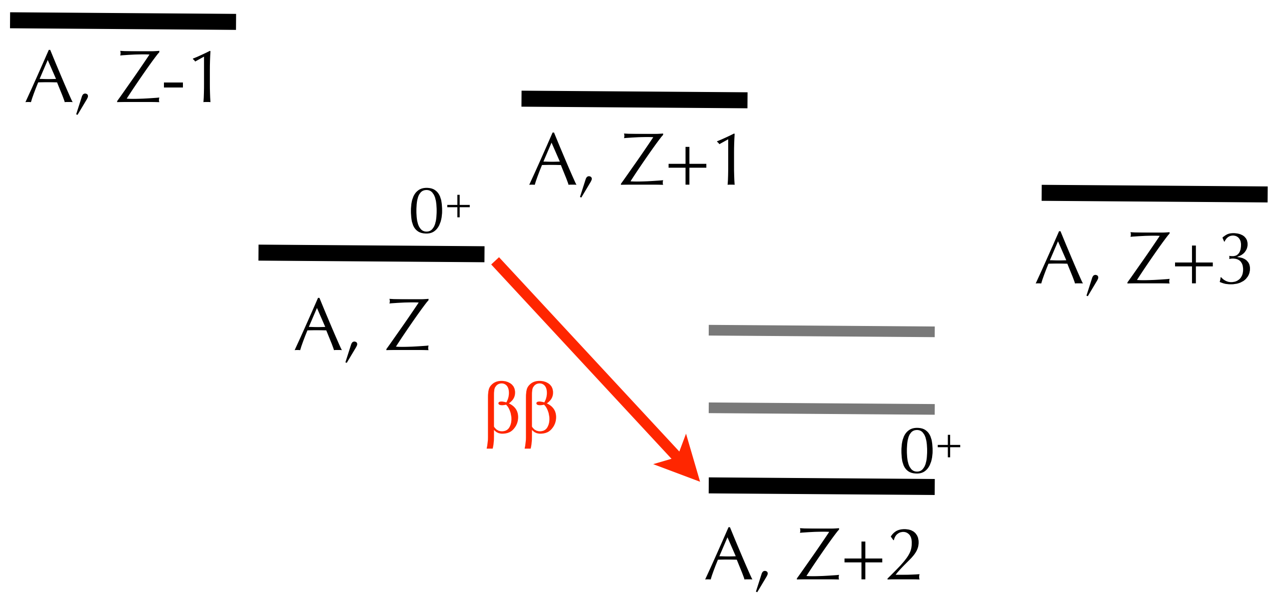
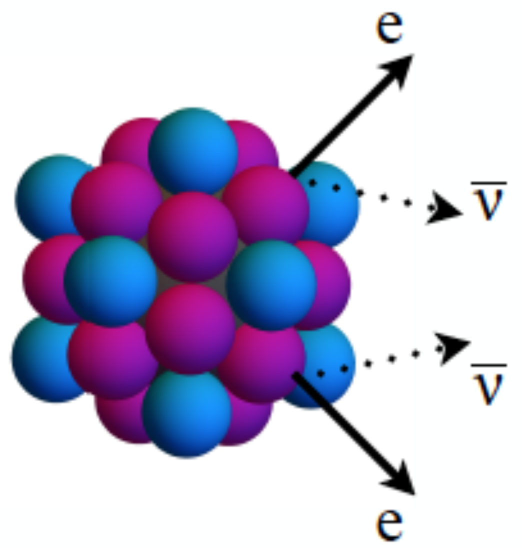
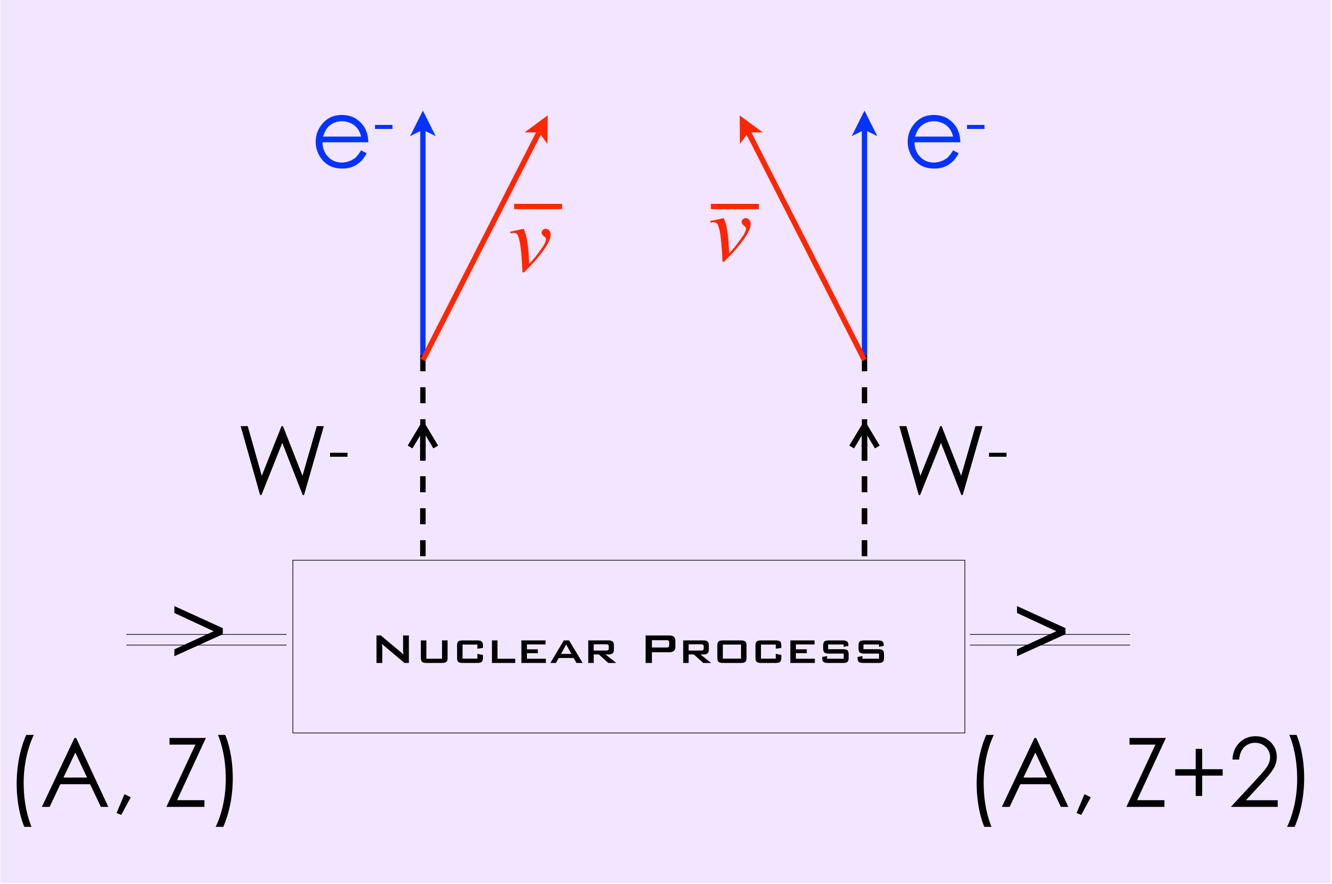
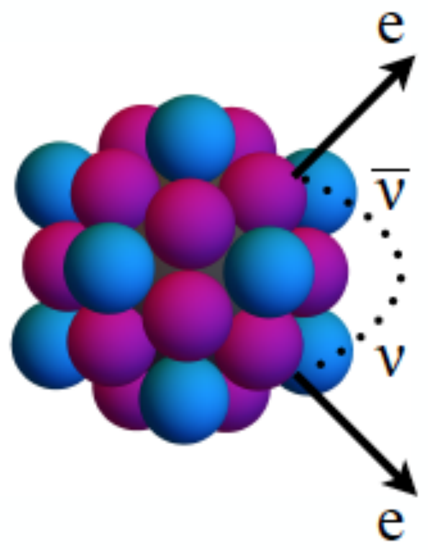






0ν double-beta decay ($0\nu\beta\beta$): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + e^-

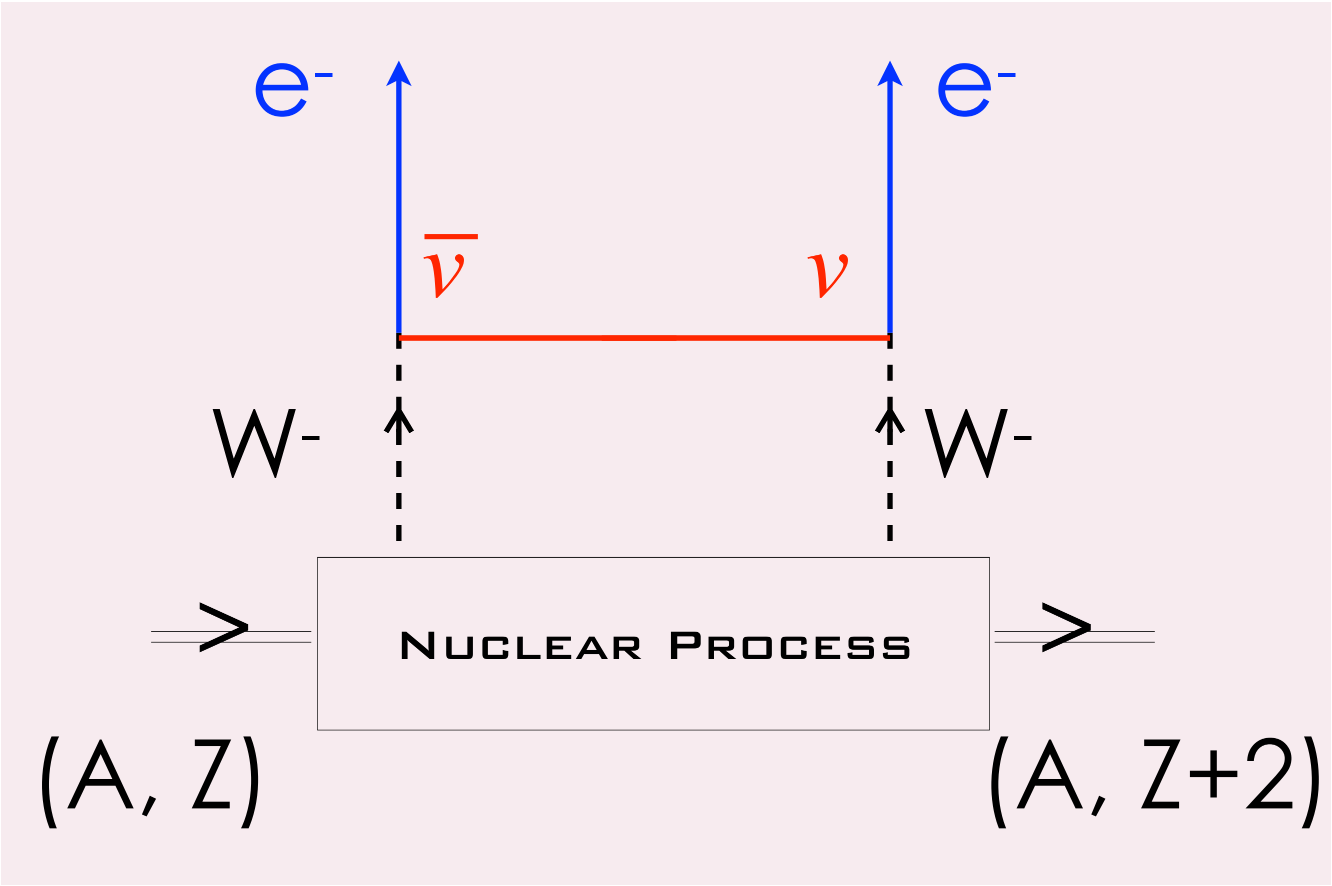
Ettore Majorana (1937) realized symmetry properties of Dirac's theory allowed the possibility for electrically neutral spin-1/2 fermions to be their own anti-particle



Racah (1937)

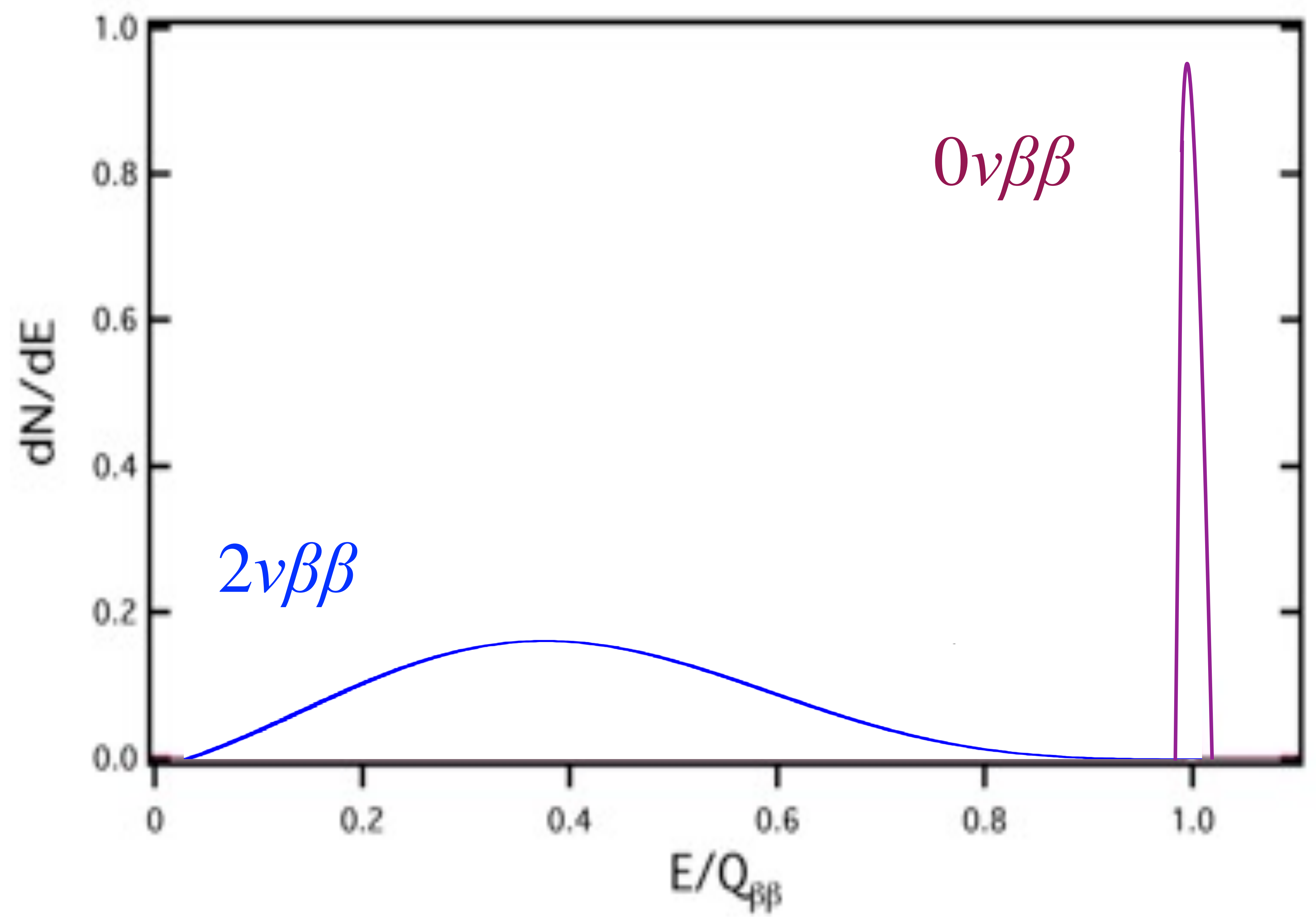
$$n \rightarrow p + e^- + \bar{\nu}$$

$$\nu + n \rightarrow p + e^-$$



0νββ Signature and Searches (before 1957)

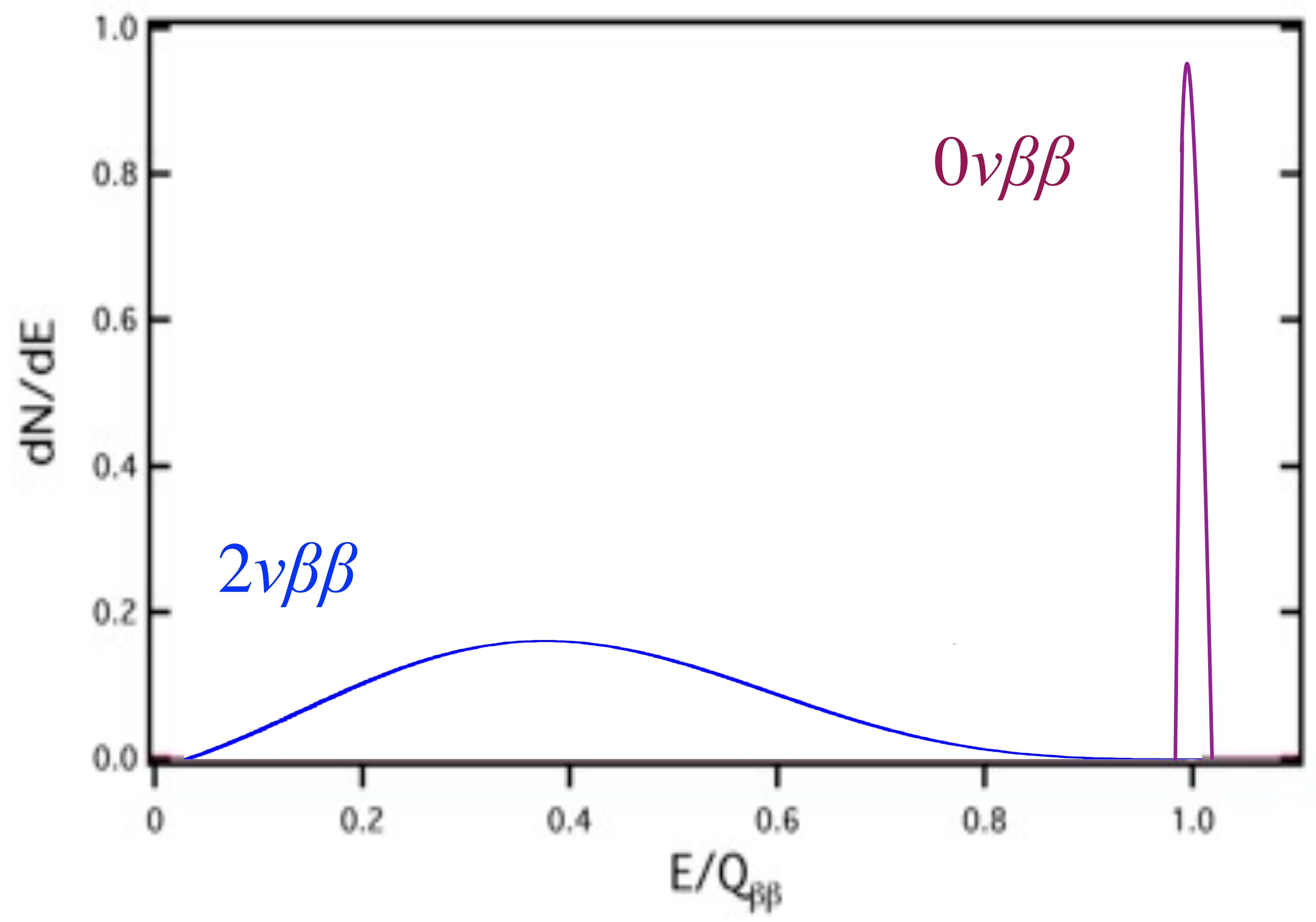
Theory



- 0νββ significantly favored, 10^5 - 10^6, over 2νββ based on decay phase-space
- Observation of 2νββ with no 0νββ thought to rule out Majorana neutrinos.

$0\nu\beta\beta$ Signature and Searches (before 1957)

Theory

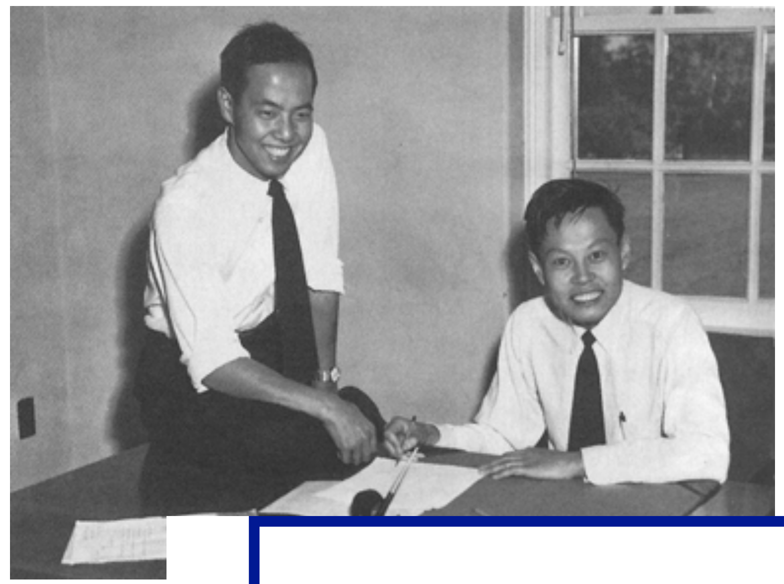


- $0\nu\beta\beta$ significantly favored, 10^5 - 10^6, over $2\nu\beta\beta$ based on decay phase-space
- Observation of $2\nu\beta\beta$ with no $0\nu\beta\beta$ thought to rule out Majorana neutrinos.

Searches

- First search in 1948, E.L. Fireman in ^{124}Sn
- Relatively sparse measurements (18 papers)
- Methods : coincidence counters, cloud chambers, photographic emulsions, one geochemical (^{130}Te)
- $\beta\beta$ positive $T_{1/2}$ claim from geochemical
  - ^{130}Te ~ 1.4×10^{21} y
- $0\nu\beta\beta$ positive $T_{1/2}$ claims from detectors
  - ^{48}Ca ~ 10^{17} y
  - ^{124}Sn ~ 10^{16} y
  - motivated additional measurements in both isotopes that ruled out claims.
- $0\nu\beta\beta$ most sensitive $T_{1/2}$ limits
  - ^{48}Ca $> 2 \times 10^{18}$ y
  - ^{124}Sn $> 1.5 \times 10^{17}$ y
  - ^{150}Nd $> 2.2 \times 10^{18}$ y

Parity Violation and ν helicity (1957)



PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

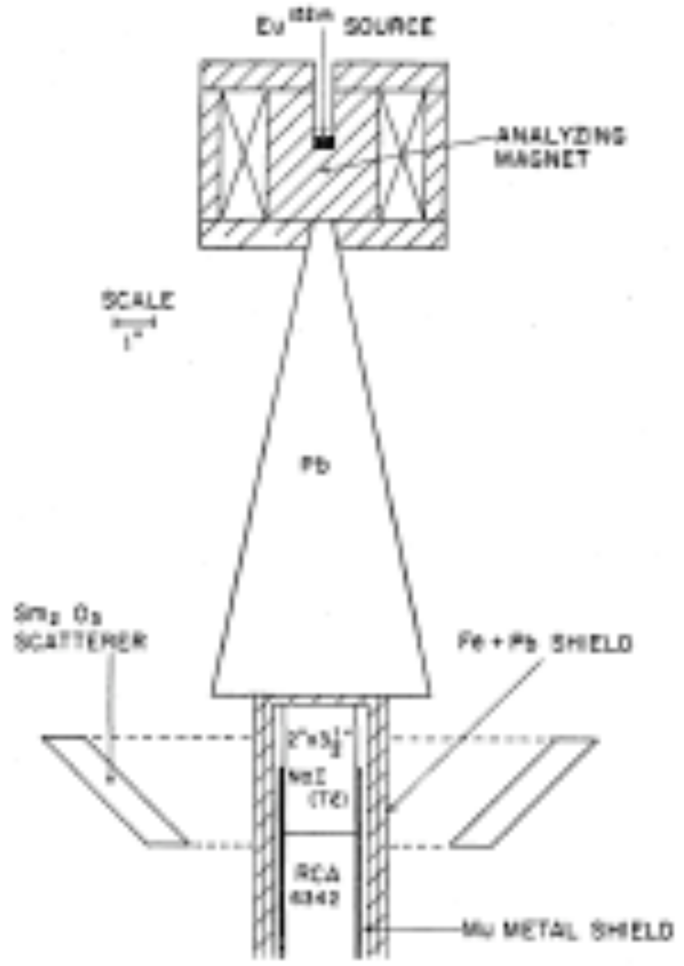
Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).



Experimental Test of Parity Conservation in Beta Decay*

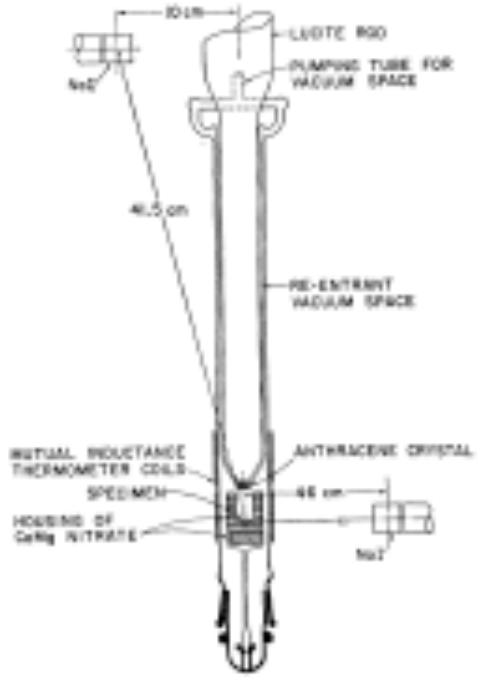
C. S. WU, *Columbia University, New York, New York*

AND

E. AMBLER, R. W. HAYWARD, D. D. HOPPES, AND R. P. HUDSON, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

IN a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation

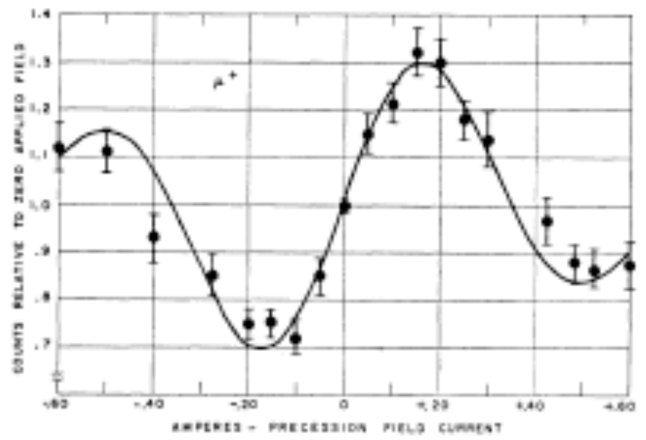


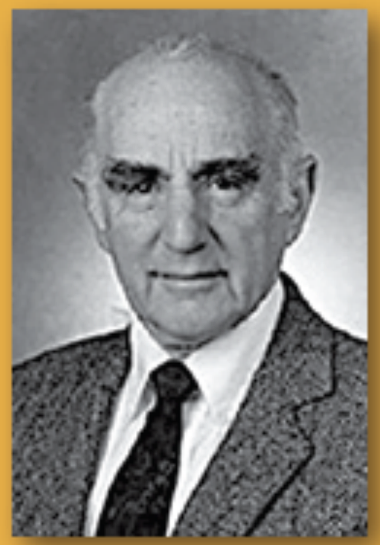
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)




Implications for ββ-decay (1959)

Primakoff and Rosen Rep. Prog. Phys. **22** 121 (1959)

$$H_{\mathrm{M}} = \sum_{\lambda} (\psi_{\mathrm{p}}{}^{\dagger}\, \Gamma^{(\lambda)}\, \psi_{\mathrm{n}})\, F_{\lambda}(\psi_{\mathrm{e}}{}^{\dagger}\, \Gamma^{(\lambda)}(1+\epsilon_{\lambda}\gamma_5)\,\phi_{\nu}) + \mathrm{h.c.}$$

- Initially considered most general, Lorentz invariant Hamiltonian -- included the possibility of both L-conserving and L-violating interactions, P-conserving and P-violating terms, along with potential contributions from S ,T, V, and A interactions.
- Assumed massless neutrino
- Recognized that with a "two-component" neutrino coupling (emitted in pure left or right handed helicity states) then no neutrinoless double-beta decay.
- Calculated both 2νββ and 0νββ-decay rates. For 0νββ assumed a predominately V-A and P-violating interaction, but also some amount of parity-conserving, lepton-violating scalar interaction. (Allowed by the existing experimental constraints.)
- Utilized closure method to account for the Nuclear Processes in calculating rates - nuclear structure, average separation between neutrons

Implications for ββ-decay (1959)

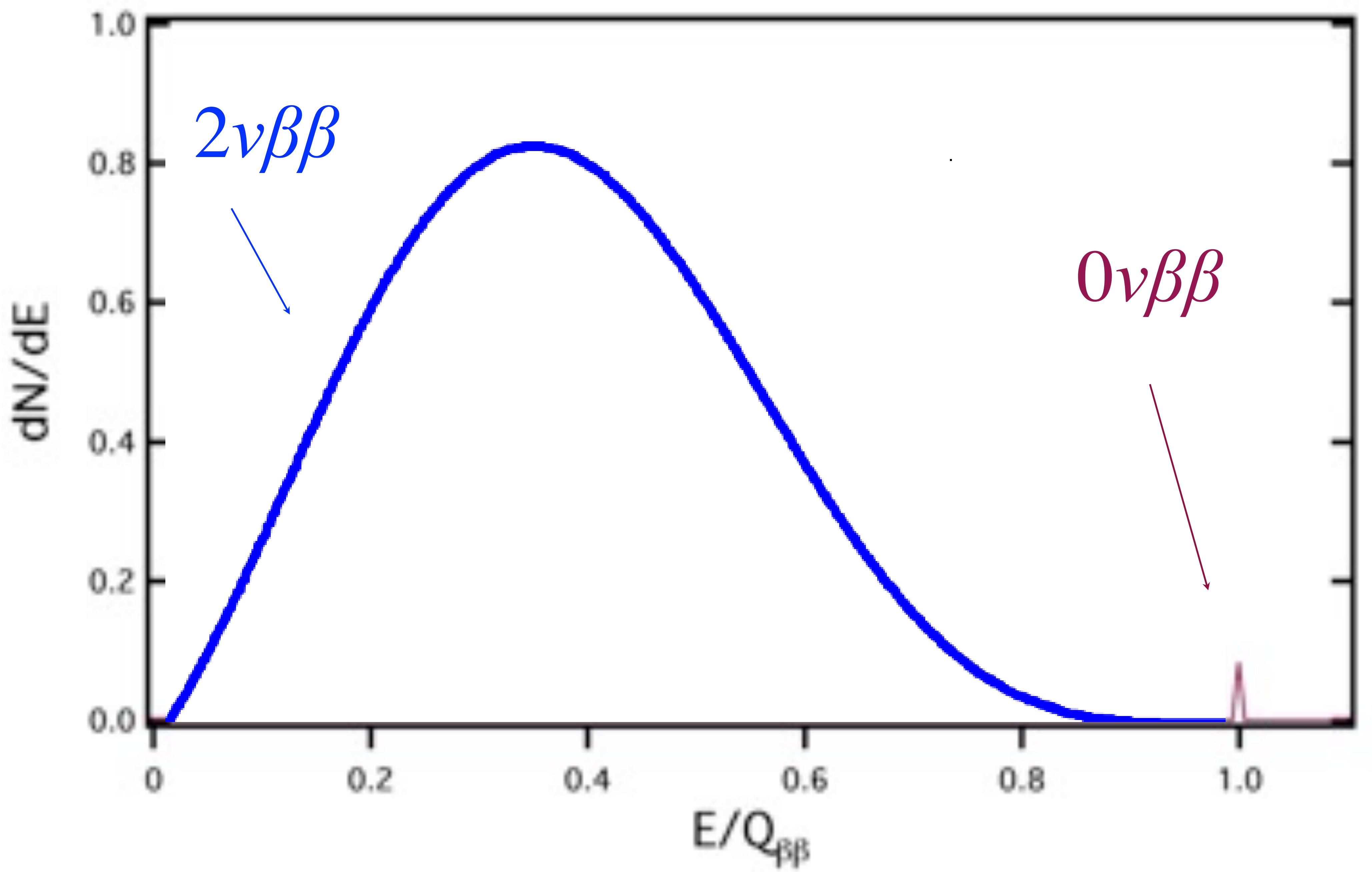
Primakoff and Rosen Rep. Prog. Phys. **22** 121 (1959)

Conclusions

- Observation of 2νββ tells one nothing about Dirac/Majorana nature of ν.
- Possible to have Majorana neutrinos, but a pure "two component" parity-violating interaction would not allow one to observe 0νββ.
- Calculated $T_{1/2}$ for 2νββ-decays on order of 10^{20} to 10^{22} years (with factor of 100 uncertainties)
- Calculated $T_{1/2}$ for 0νββ-decays on order of 10^{15} to 10^{16} years, with assumption that $|F_S/F_V|^2 \leq 1/3$. (assume non-zero scaler coupling constant)

0νββ Signature and Searches (1958-1980)

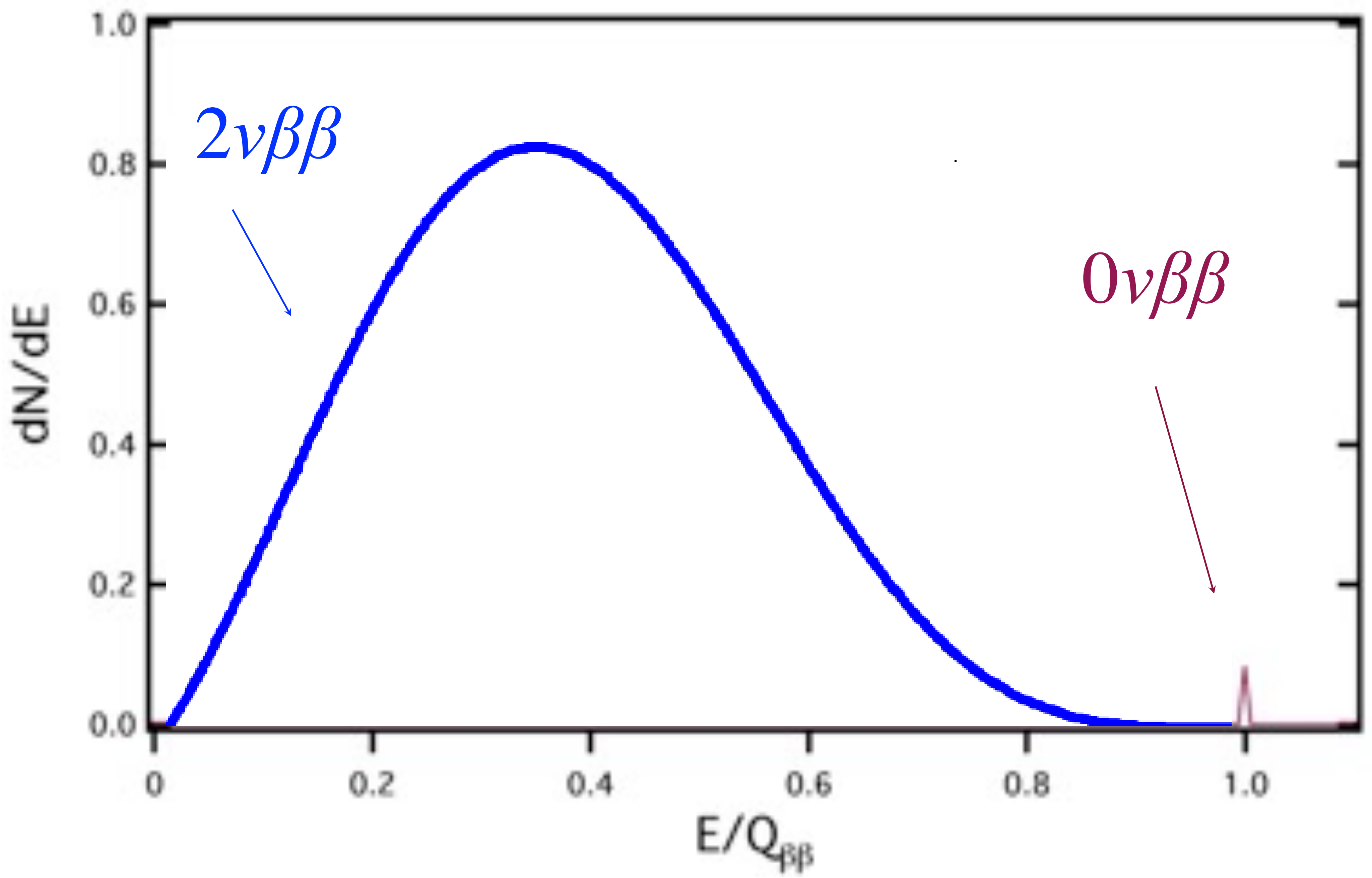
Theory



- "wrong-handed helicity" significantly suppresses 0νββ compared to 2νββ
- Observation of 2νββ does not provide information on Majorana nature of neutrinos.
- No strong experimental evidence for neutrinos to have non-zero mass.
- No strong theoretical justification for LNV.

$0\nu\beta\beta$ Signature and Searches (1958-1980)

Theory



- "wrong-handed helicity" significantly suppresses $0\nu\beta\beta$ compared to $2\nu\beta\beta$
- Observation of $2\nu\beta\beta$ does not provide information on Majorana nature of neutrinos.
- No strong experimental evidence for neutrinos to have non-zero mass.
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Searches

- Only a small group of experimentalist doing searches
- Geochemical measurements (15 papers)
  - ^{130}Te ~ 10^{21} y (and ratio of ^{130}Te/^{128}Te)
  - ^{82}Se ~ 10^{20} y
- Improved ^{48}Ca searches (7 papers, last paper 1970)
  - $0\nu\beta\beta > 2 \times 10^{21}$ y; $2\nu\beta\beta > 3.6 \times 10^{19}$
- ^{76}Ge searches with Ge(Li) (Fiorini 3 papers)
  - $0\nu\beta\beta > 5 \times 10^{21}$ y
- ^{82}Se searches (particle detectors)
  - $0\nu\beta\beta > 3.1 \times 10^{21}$ y (Cleveland 1975)
  - $2\nu\beta\beta > (1\pm0.4) \times 10^{19}$ y (Moe 1980)
- Other isotopes
  - ^{130}Te $0\nu\beta\beta > 1.2 \times 10^{21}$ y
  - ^{150}Nd $0\nu\beta\beta > 7 \times 10^{18}$ y; $2\nu\beta\beta > 5 \times 10^{18}$

Conservation Principles & New Expt. Results (early 1980s)

BARYON NUMBER AND LEPTON NUMBER CONSERVATION LAWS

Henry Primakoff
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

S. Peter Rosen
Department of Physics, Purdue University, West Lafayette, Indiana 47907

Ann. Rev. Nucl. Part. Sci. 1981. 31: 145–192

Recent years have witnessed a remarkable change of attitude among physicists toward baryon-number and lepton-number conservation. With the advent of the grand unified theories of strong, electromagnetic, and weak interactions (Langacker 1980, Ellis 1980), the old belief that baryon number and lepton number were exactly conserved has given way to a new belief that, because of the intrinsic structure of most grand unified theories, baryon-number and lepton-number conservation is only approximate. In part motivated by this new belief, active searches are now underway for baryon-number and lepton-number nonconserving processes such

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Estimation of the neutrino rest mass from measurements of the tritium β spectrum

V. A. Lyubimov, E. G. Novikov, V. Z. Nozik, E. F. Tret'yakov, V. S. Kozik, and N. F. Myasoedov

Institute of Theoretical and Experimental Physics
(Submitted 22 May 1981)
Zh. Eksp. Teor. Fiz. **81**, 1158–1181 (October 1981)

Measurements of the tritium β spectrum near the end point and the analysis of the results are described. In comparison with our earlier study [E. F. Tret'yakov *et al.*, Bull. Acad. Sci. USSR, Phys. Ser. **40**, No. 10, p. 1 (1976) and as reported at the Aachen 1976 Neutrino Conference (p. 663)], the statistical accuracy has been greatly improved and a more rigorous measurement technique has been used. All data obtained in the two studies have been analyzed. In determining the confidence interval for the antineutrino rest mass, the method of mathematical modeling is used. For the rest mass of $\bar{\nu}_e$ a lower limit is obtained for the first time: $14 \leq M_{\bar{\nu}_e} \leq 46$ eV. The value $E_0 = 18\,577 \pm 13$ eV is obtained for the energy of tritium β decay.

$14 < m_\nu < 46$ eV

Haxton, Stephenson, and Strottman (1981)

VOLUME 47, NUMBER 3 PHYSICAL REVIEW LETTERS 20 JULY 1981

Double Beta Decay and the Majorana Mass of the Electron Neutrino

W. C. Haxton
Department of Physics, Purdue University, West Lafayette, Indiana 47907,[(a)] *and Theory Division, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545*

and

G. J. Stephenson, Jr., and D. Strottman
Theory Division, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545
(Received 6 April 1981)

We have calculated the two-neutrino and no-neutrino, lepton-number-nonconserving double beta decay rates for ^{76}Ge and ^{82}Se. Our result for the two-neutrino decay of ^{82}Se is in agreement with a recent cloud-chamber measurement and thus in disagreement with the geochemical determination. We find that a constraint on the Majorana mass of the electron neutrino of $\langle m \rangle_\nu \gtrsim 15$ eV follows from the comparison of our calculations and the experimental limits on the neutrinoless decays of ^{76}Ge and ^{82}Se.

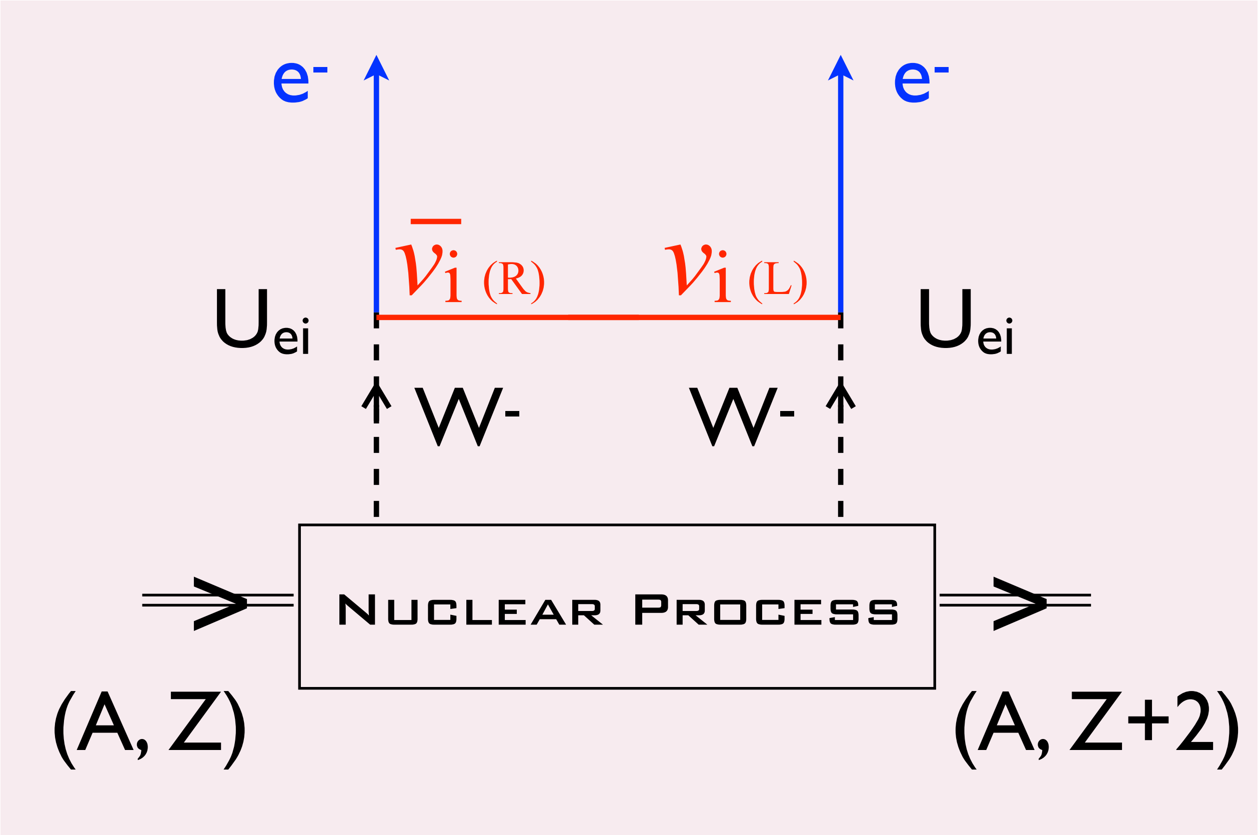
- Interest in searching for lepton number violation
- Recent Moe and Lowenthal 2νββ results for ^{82}Se
- Lubimov claims for non-zero m_ν and consequences for 0νββ

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

- Lepton violation via single massive Majorana field with LH and RH couplings
- Shell Model used to calculate NME
- Calculated of 2νββ and 0νββ decay rates
  - 2νββ rate for ^{82}Se in good agreement with Moe and Lowenthal
  - Experiments approaching sensitivity to 0νββ predicted for Lubimov claim

0νββ and lepton number violating interactions

Observable (decay rate) depends on nuclear processes & nature of lepton number violating interactions (η).



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}(\eta)\right|^2 \eta^2$$

$$\Downarrow$$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

- Phase space, $G_{0\nu}$ is calculable.
- Nuclear matrix elements (NME) require theory.
- Effective neutrino mass, $\langle m_{\beta\beta}\rangle$, depends directly on the assumed form of lepton number violating (LNV) interactions.

Haxton 0νββ related papers (early 1980s)

PHYSICAL REVIEW D VOLUME 25, NUMBER 9 1 MAY 1982

Lepton-number conservation and the double-β decay of ^{128}Te and ^{130}Te

W. C. Haxton
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545 and Department of Physics, Purdue University, West Lafayette, Indiana 47907

G. J. Stephenson, Jr. and D. Strottman
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 24 November 1981)

We consider the classic argument of Pontecorvo that the ratio of $\beta\beta$-decay half-lives for ^{130}Te and ^{128}Te may indicate violation of lepton number. We believe that the theoretical support for the assumption underlying this argument, equality of the nuclear matrix elements mediating the 2ν $\beta\beta$ decay of these isotopes, is weak due to a significant disparity between the calculated and geochemical absolute rates. If one ignores this inconsistency and attributes the breaking of the γ_5 invariance of the weak leptonic current to a Majorana mass, faithful treatment of the radial dependence of the 0ν-$\beta\beta$-decay operators yields $\langle m^{\mathrm{Maj}} \rangle_\nu \cong 10$ eV.

PHYSICAL REVIEW D VOLUME 26, NUMBER 7 1 OCTOBER 1982

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

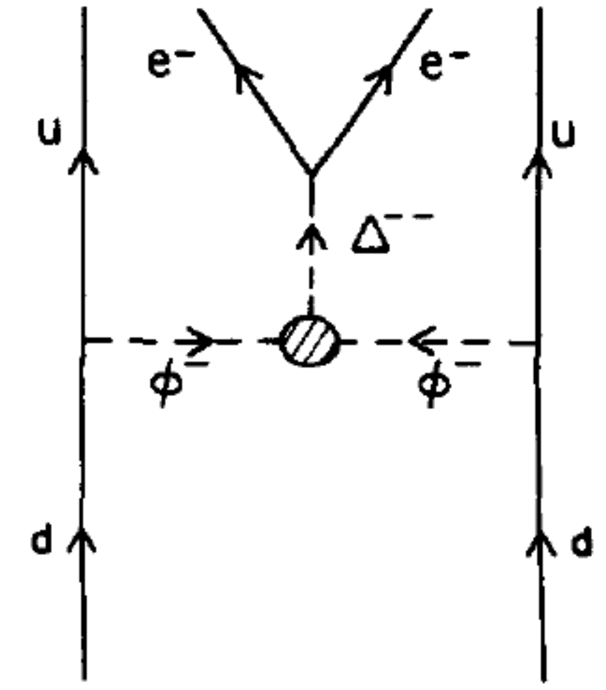
Higgs-boson-exchange contributions to neutrinoless double-β decay

W. C. Haxton
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545 and Physics Department, Purdue University, West Lafayette, Indiana 47907

S. P. Rosen
Physics Division, National Science Foundation, Washington, D.C. and Physics Department, Purdue University, West Lafayette, Indiana 47907

G. J. Stephenson, Jr.
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 17 May 1982)

We have calculated the contributions to the neutrinoless $\beta\beta$ decay ^{48}Ca(g.s.) $\rightarrow$ ^{48}Ti(g.s.) arising from the exchange of both Higgs scalars and Majorana neutrinos. We find, contrary to previous claims, that the Higgs-boson-exchange mechanism has no effect on the limits that can be placed on the masses and right-handed couplings of Majorana neutrinos. We also find that these limits are less stringent than those imposed by $\beta\beta$ decay experiments in several other nuclei.



RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 28, NUMBER 1 JULY 1983

Radiochemical tests of double beta decay

W. C. Haxton and G. A. Cowan
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Maurice Goldhaber
Brookhaven National Laboratory, Upton, New York 11973
(Received 17 February 1983)

We discuss the feasibility of radiochemical and geochemical measurements of the rates for two double beta decay reactions, ^{238}U $\rightarrow$ ^{238}Pu and ^{232}Th $\rightarrow$ ^{232}U, that produce unstable daughter nuclei.

Double beta decay, Haxton and Stephenson, 1984

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 12, 1984, Pages 409-479

Double beta decay ☆

W.C. Haxton [a, b], G.J. Stephenson Jr. [c]

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DOUBLE BETA DECAY*

W. C. HAXTON

Department of Physics, Princeton University, Princeton, NJ 08540 and
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.†

and

G. J. STEPHENSON, Jr.

Physics and Theoretical Divisions, Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.

CONTENTS

Double beta decay, Haxton and Stephenson, 1984

It has also long been recognized as a sensitive test of lepton number conservation, of the mass and charge conjugation properties of the electron neutrino, and of possible right-handed admixtures in the weak leptonic current. The new aspect in the study of $\beta\beta$ decay is the expectation arising from grand unified theories that many of the exact conservation laws of the standard electroweak model may be violated to some small degree.

An understanding of the nature and extent of these violations is likely essential to the formulation of a correct grand unified theory. It is our hope in this review to clarify the important role $\beta\beta$ decay is playing in testing lepton number conservation. It will become apparent that, to interpret such tests, important problems in both particle and nuclear physics must be addressed.

- Detailed derivations of decay rates for 2νββ and 0νββ (particle physics, SM, gauge theories).
- Success of Nuclear Matrix Element calculations pointed out the need for improved experimental 2νββ measurements.
- Explored 0νββ under various lepton violating process scenarios.
- Emphasized complementarity of neutrino mass, neutrino oscillation, and 0νββ experiments.
- Need for improved experimental measurements.

Haxton 0νββ related papers (1990's)

VOLUME 67, NUMBER 18 PHYSICAL REVIEW LETTERS 28 OCTOBER 1991

Double-Beta-Decay Mass Constraints on 17-keV Neutrinos

W. C. Haxton

Department of Physics, FM-15, University of Washington, Seattle, Washington 98195

(Received 18 July 1991)

Attempts to reconcile a 17-keV neutrino with constraints from astrophysics and double beta decay have led to model Majorana neutrino mass matrices with vanishing (or nearly vanishing) electron-electron components. A simple parametrization is presented of the higher-order mass effects on the intermediate-state propagator through which $0\nu\ \beta\beta$ decay can still occur. For light-mass eigenstates, the 0ν and 2ν rates are proportional, with the ratio depending on a weighted sum over mass eigenstates $\langle m_\nu^3 \rangle_{LL}^{Maj}$. Thus model $0\nu\ \beta\beta$ decay rates can be predicted with confidence.

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 46, NUMBER 6 DECEMBER 1992

Effective summation over intermediate states in double-beta decay

J. Engel

Bartol Research Institute, University of Delaware, Newark, Delaware 19716

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P. Vogel

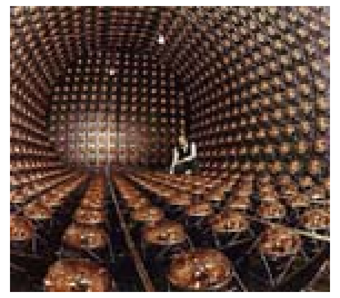
Physics Department, California Institute of Technology, Pasadena, California 91125

(Received 24 July 1992)

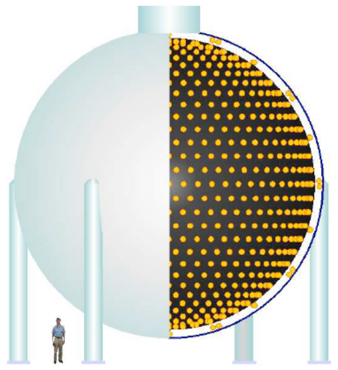
We consider two separate schemes for eliminating the explicit summation over states in the intermediate nucleus in double-beta decay. The first, known as the operator expansion method, has recently been applied in several calculations; we show in a variety of simple models that the method fails and isolate its weaknesses. We then describe an efficient technique for generating Green's function matrix elements, based on the Lanczos algorithm, and apply it to a full *fp*-shell calculation in ^{48}Ca. The method efficiently generates an exact (to within machine accuracy) result while the operator expansion method is again inaccurate.

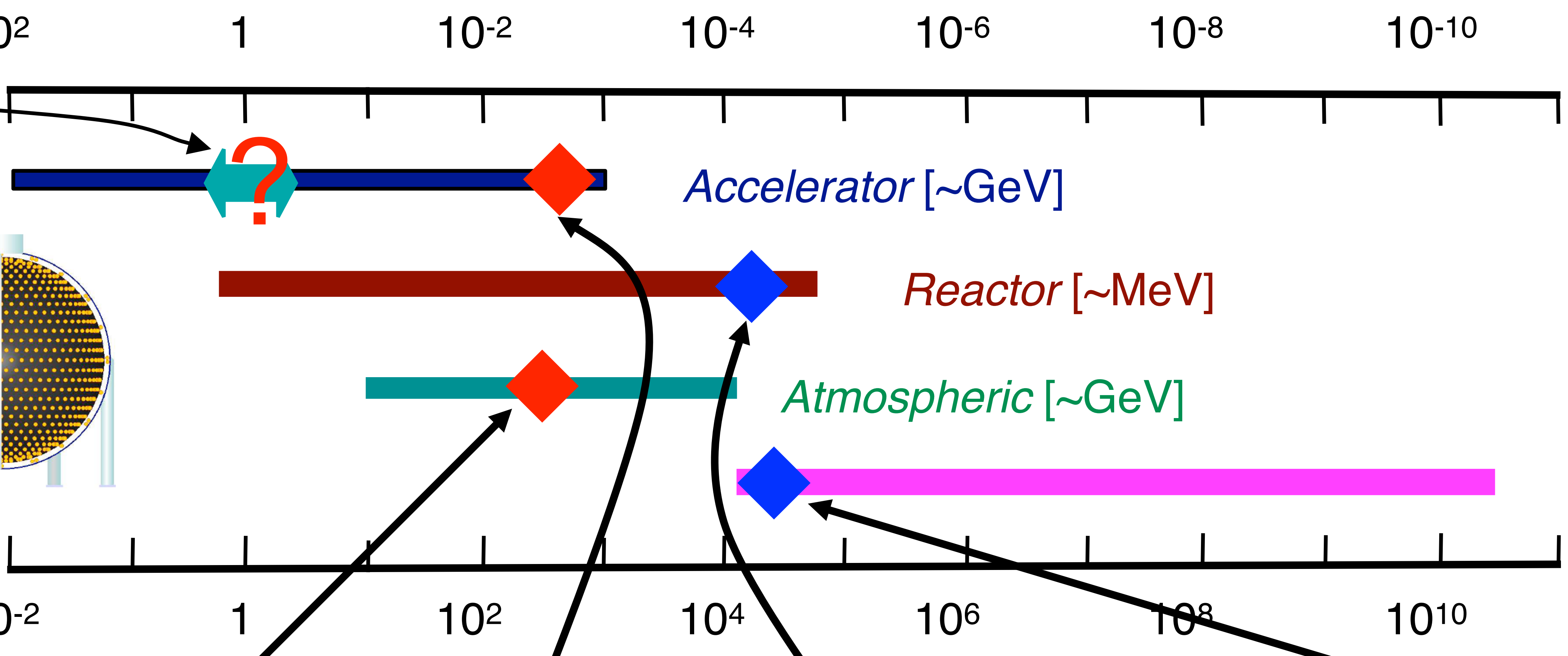
Expt. Observations of ν oscillations (mid 1990s - mid 2000s)

LSND



miniBoone



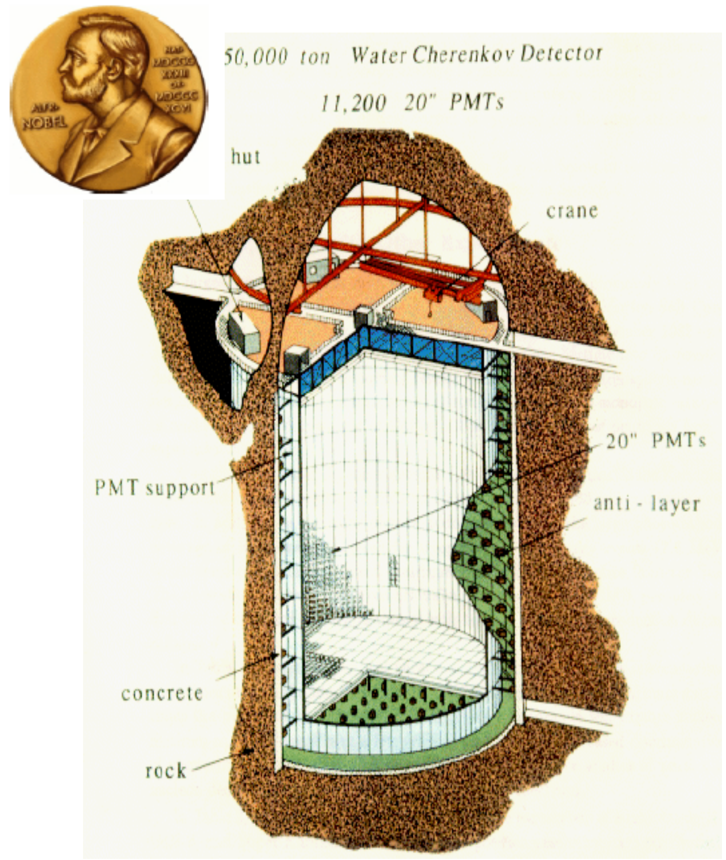


Δm^2
(eV^2)

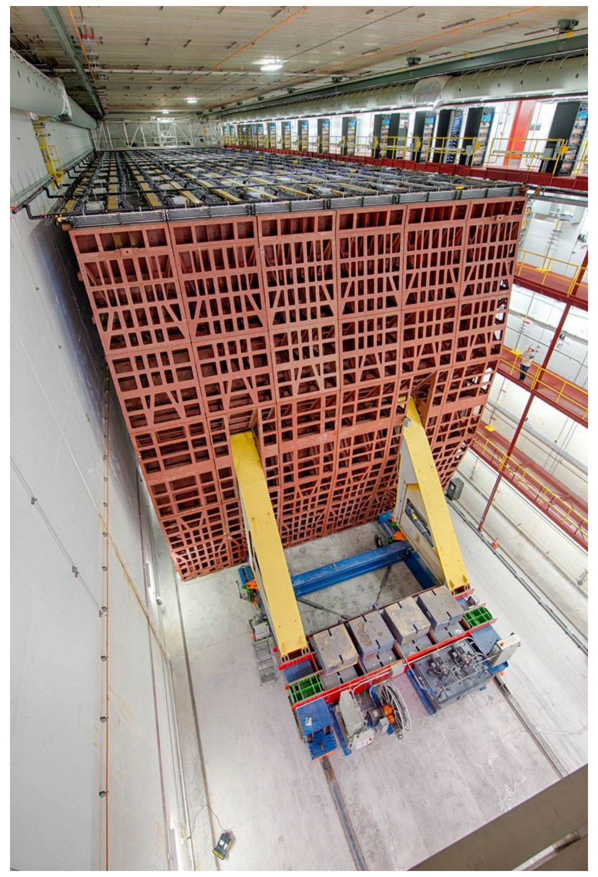
L/E
(km/GeV)

Solar ν's

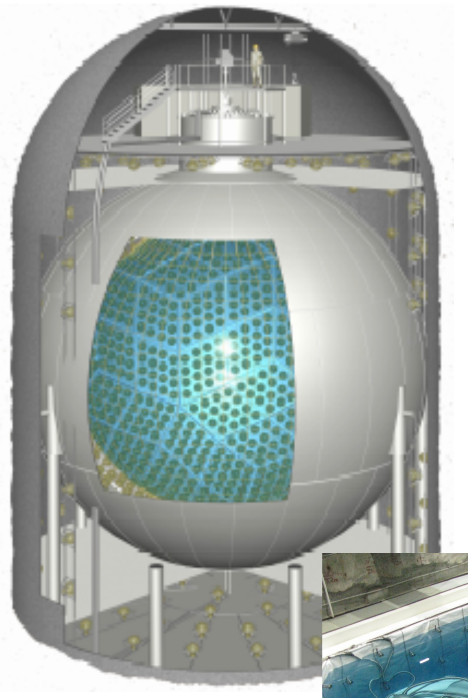
Atm. ν's
SuperKamiokande

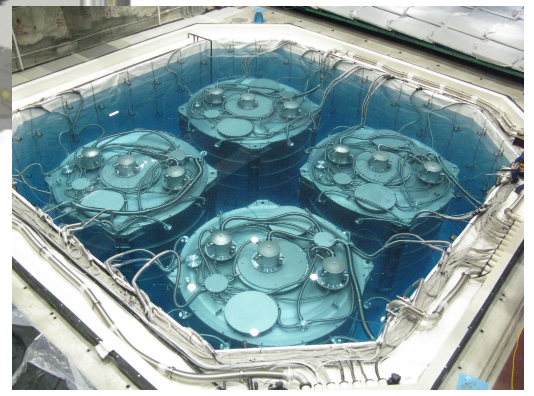


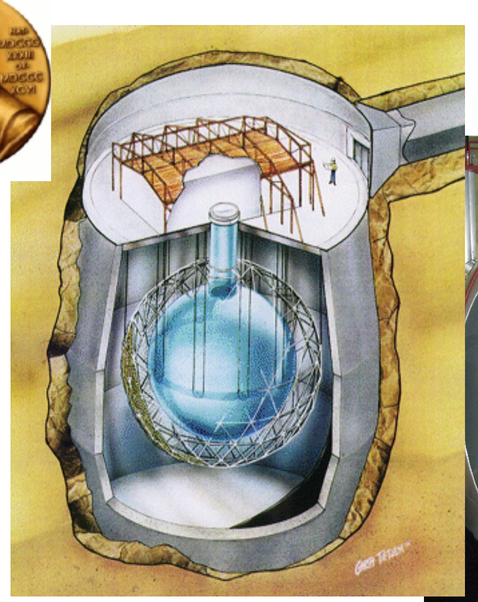
K2K, T2K,
MINOS, NOνA



KamLAND





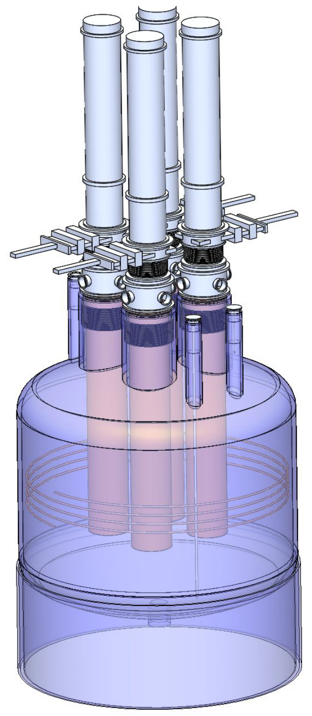


SNO, SuperK,
BOREXINO, Cl, Ga

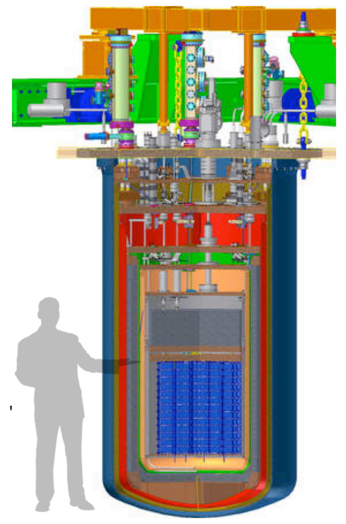
θ_{13} : SBL - Daya Bay, RENO,
Double Chooz

IceCube DeepCore, ANTARES

0νββ decay Experiments - Current Efforts



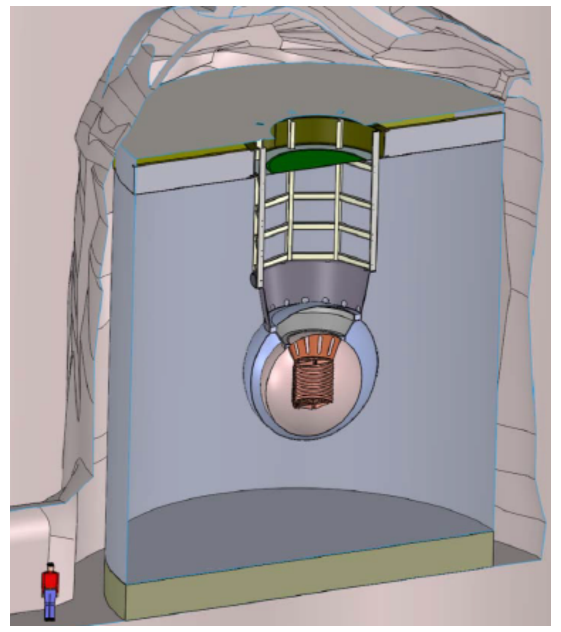
LEGEND



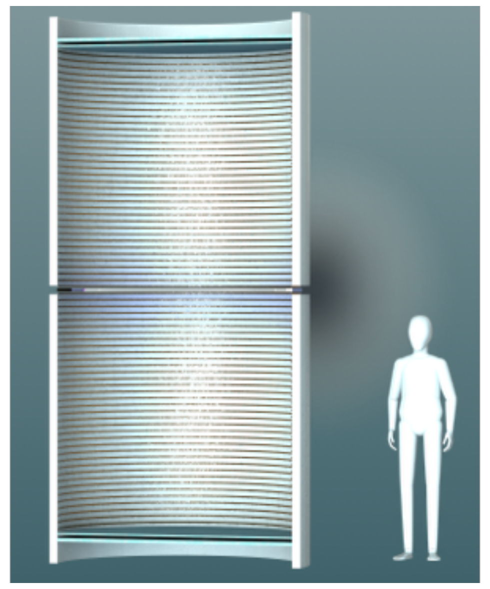
CUPID

KamLAND Zen

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
CUPID	Mo-100	Scint. Bolometer.	**~ ton**	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Complete
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - III	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D



nEXO



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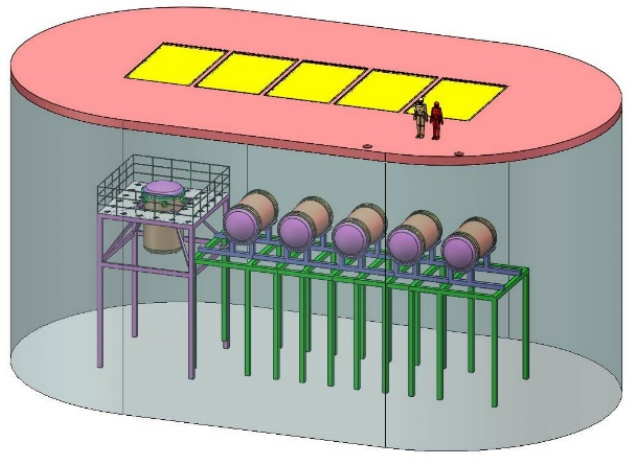
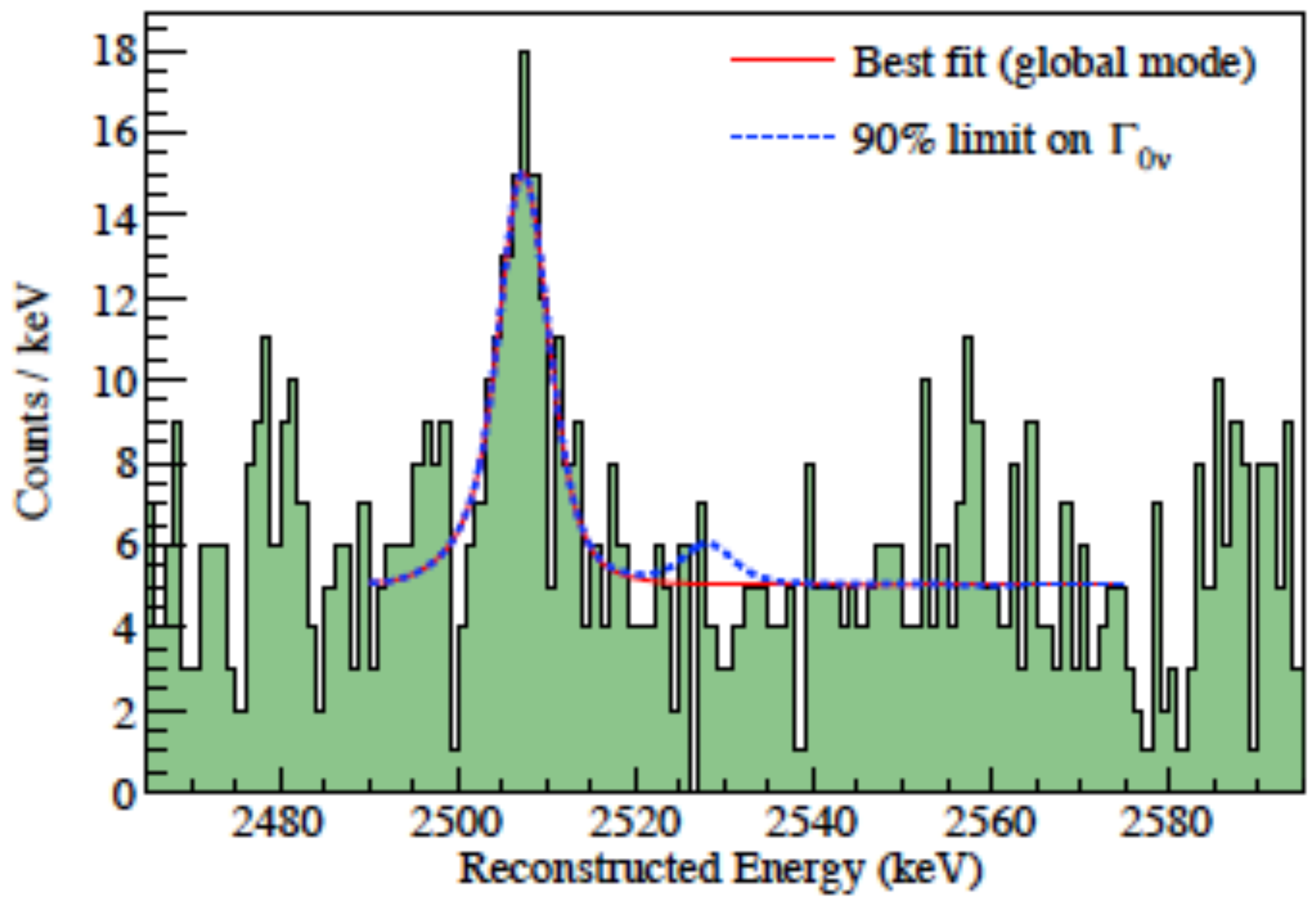


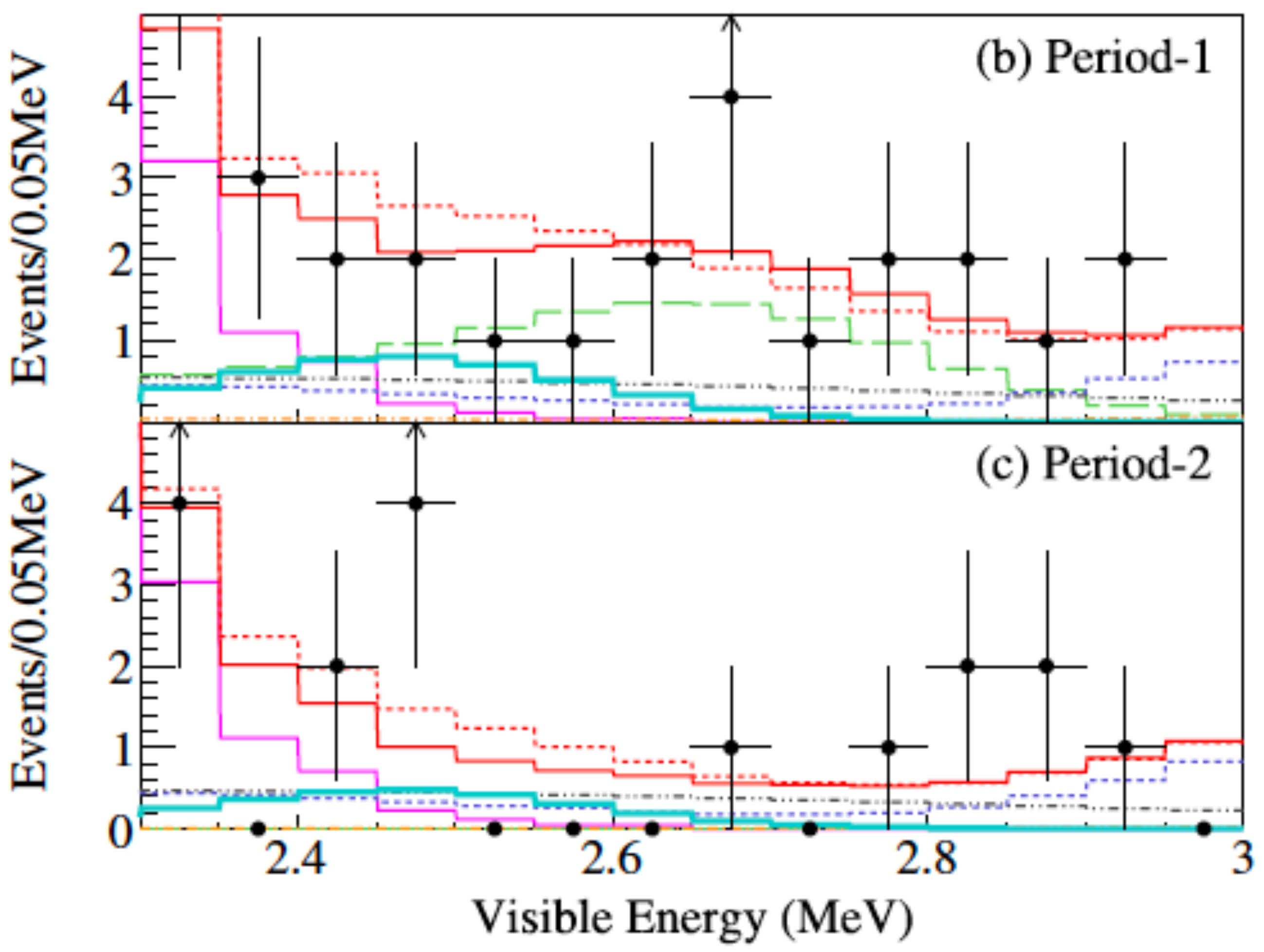
PandaX-III

0νββ Current Limits (no observation)

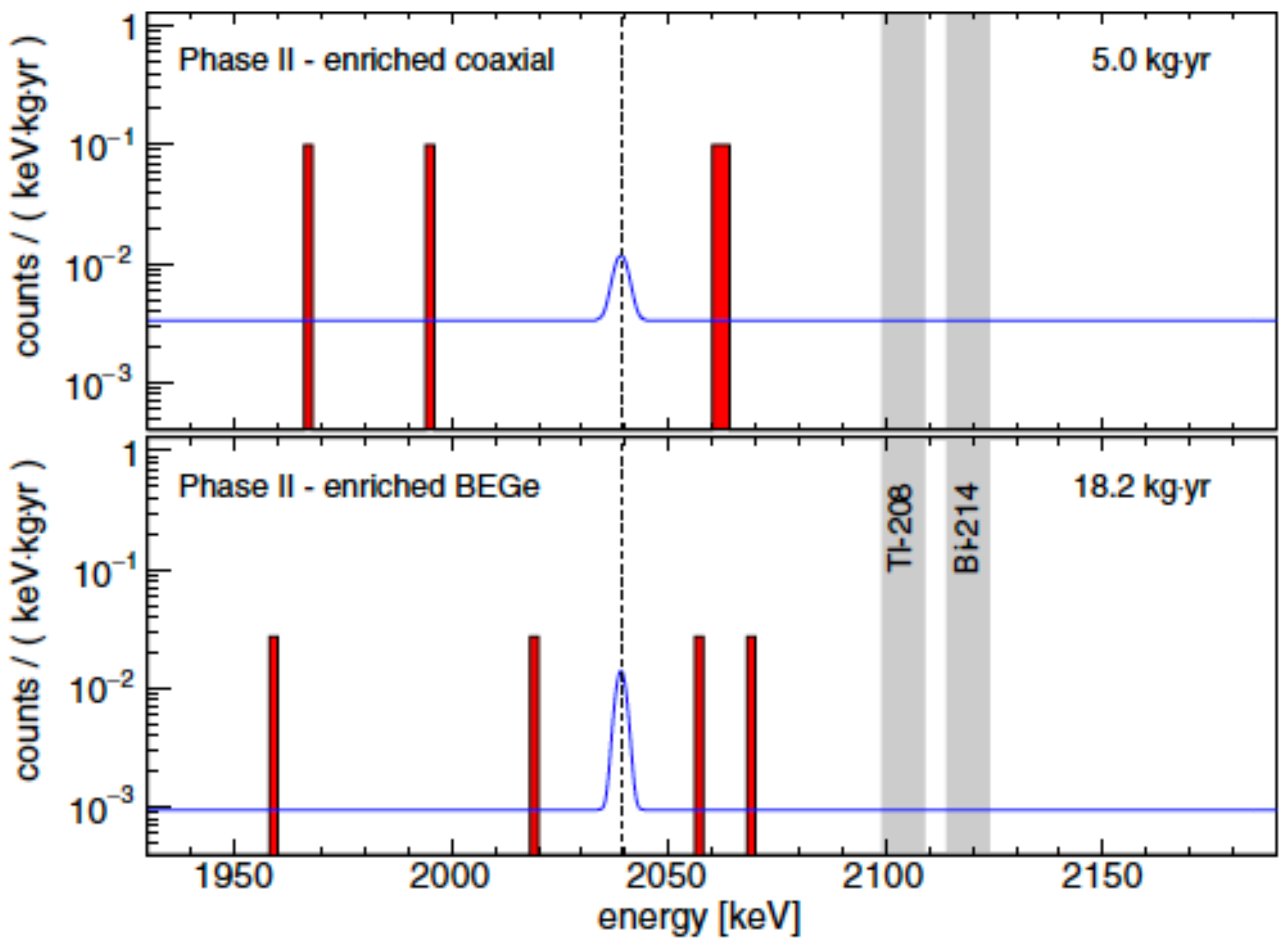
CUORE ^{130}Te



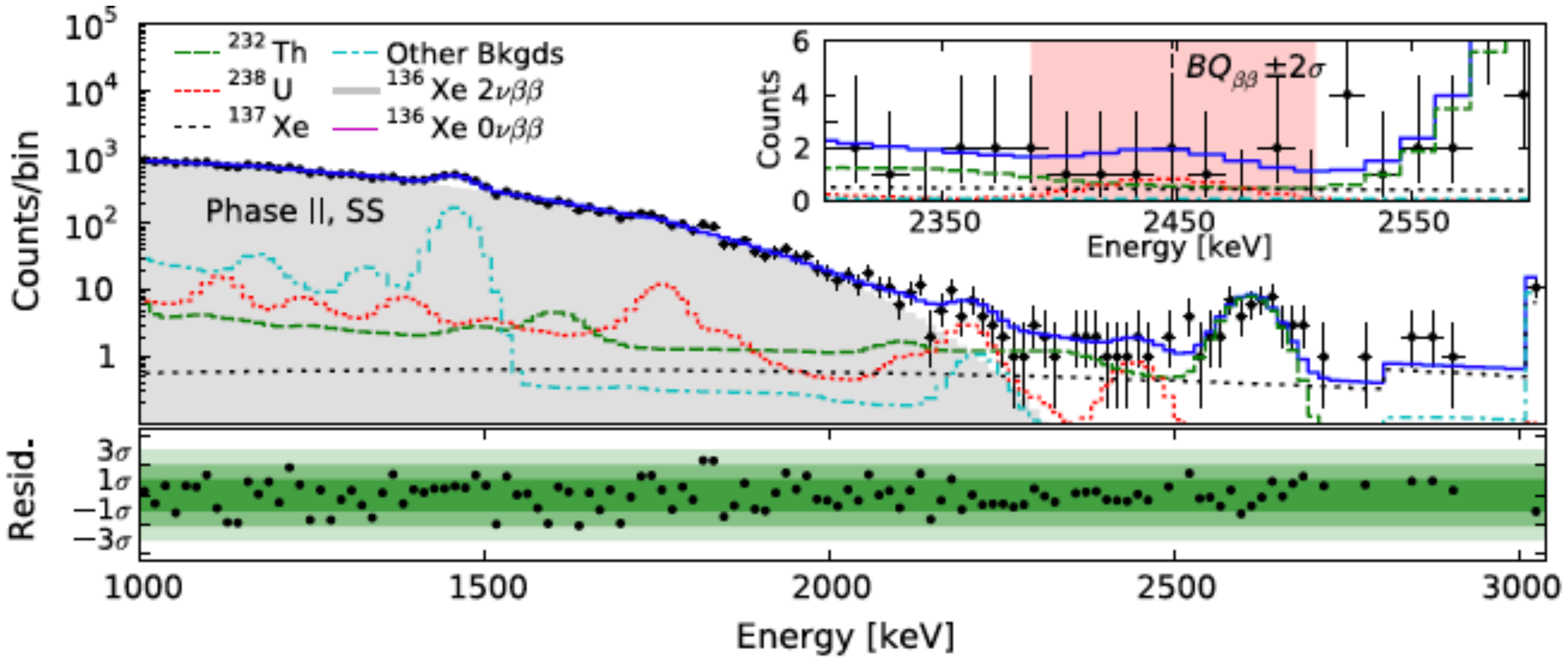
KamLAND Zen ^{136}Xe



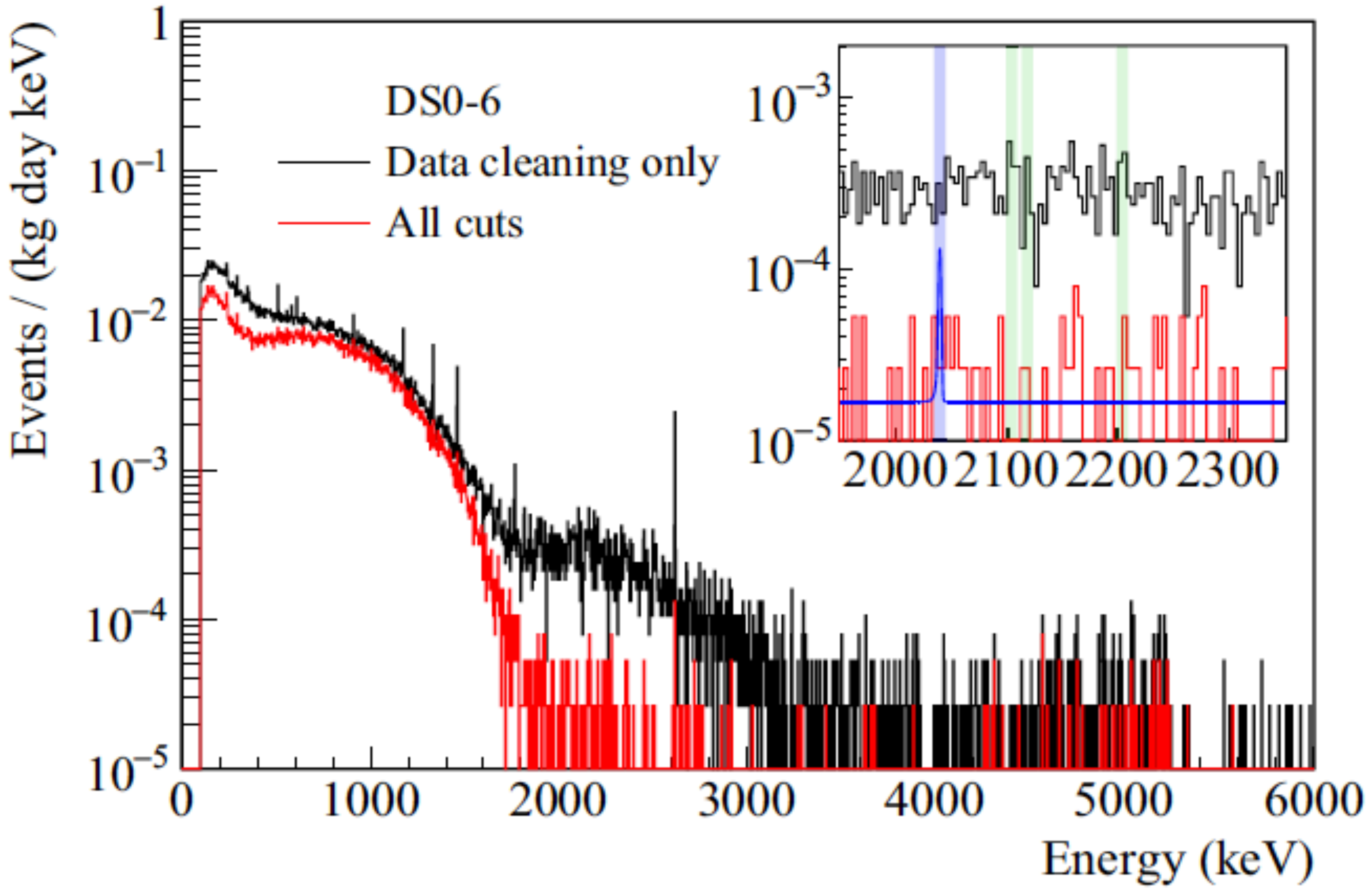
GERDA ^{76}Ge



EXO-200 ^{136}Xe



MAJORANA DEMONSTRATOR ^{76}Ge



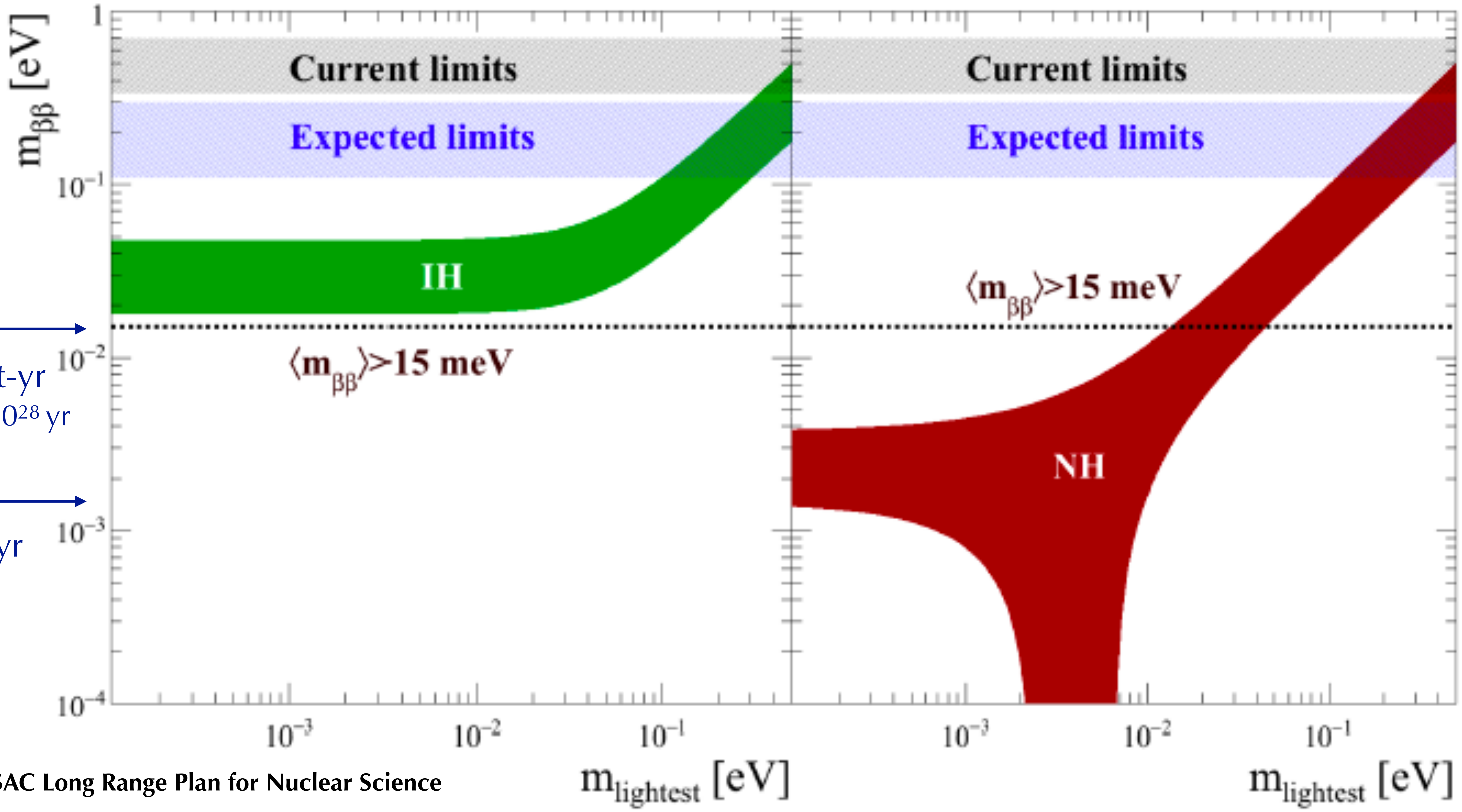
Searching for 0νββ Decay

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2 \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

10 t-yr
$T_{1/2} \sim 10^{28}$ yr

100 t-yr



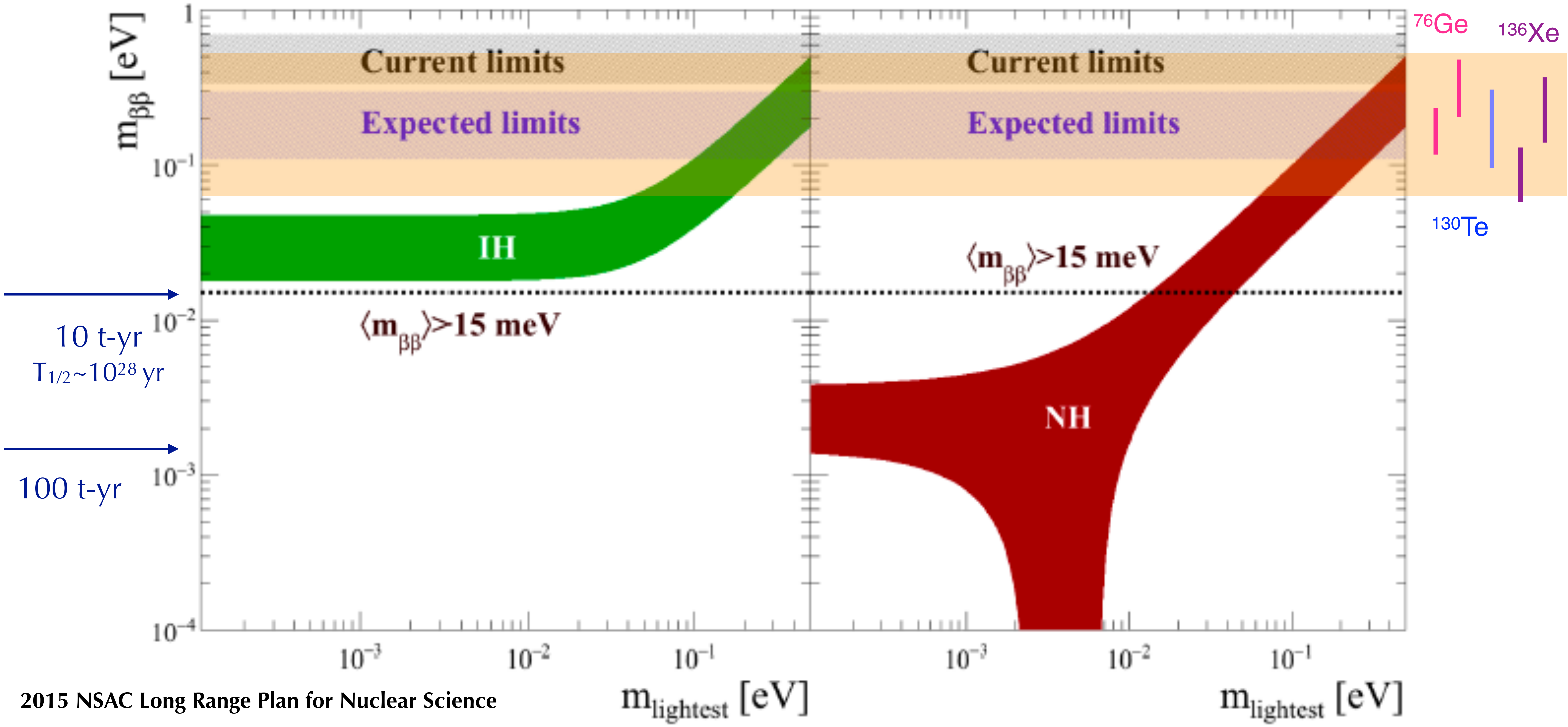
2015 NSAC Long Range Plan for Nuclear Science

Searching for 0νββ Decay

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



2015 NSAC Long Range Plan for Nuclear Science

NSAC 2015 Long Range Plan

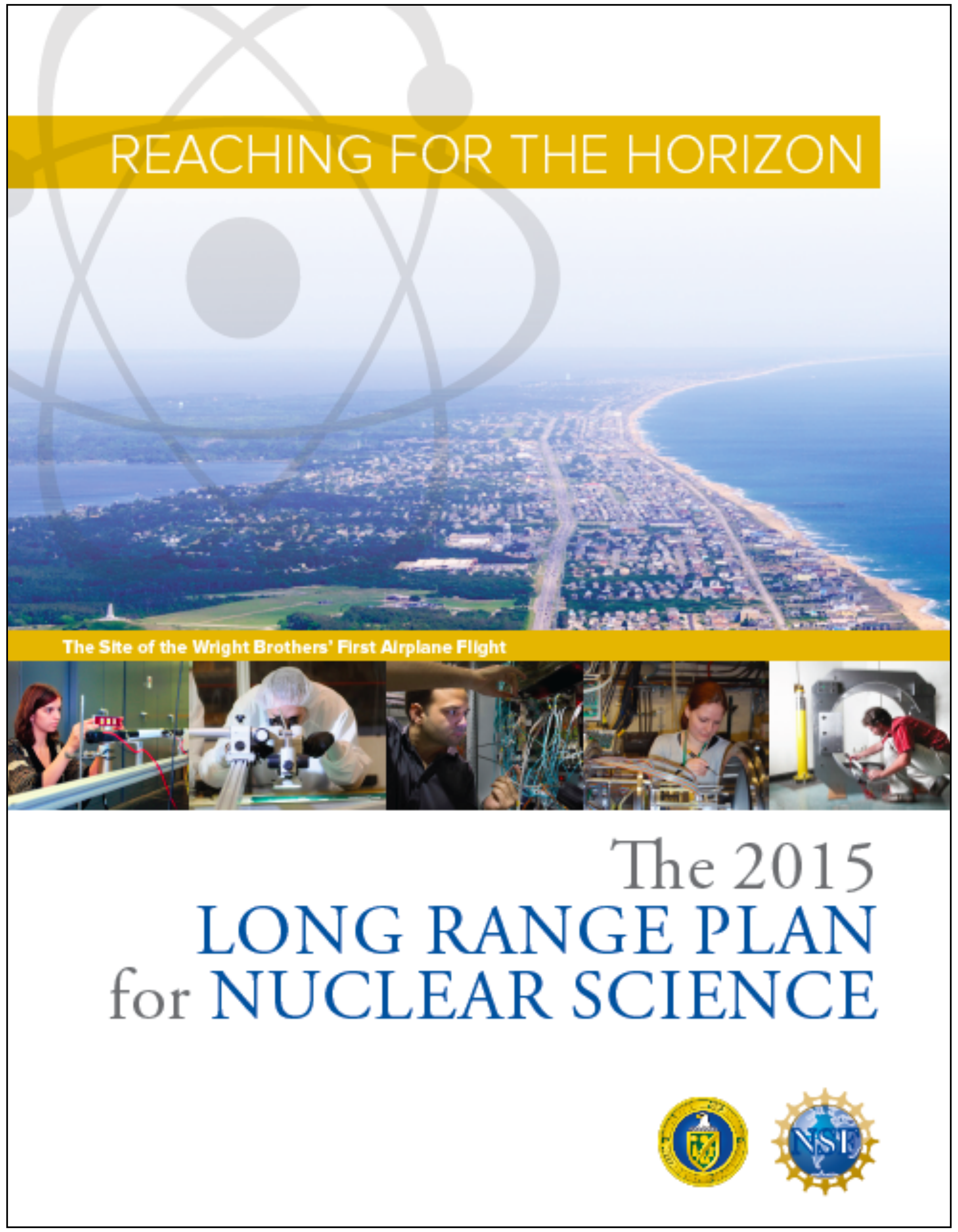
RECOMMENDATION II

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.

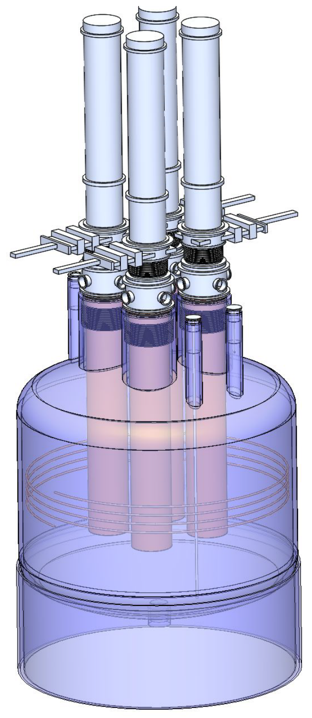
We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

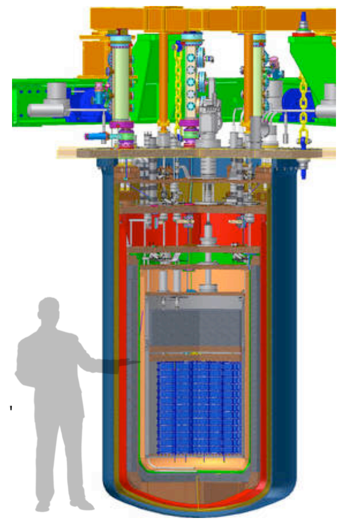
This recommendation flows out of the targeted investments of the third bullet in Recommendation I. It must be part of a broader program that includes U.S. participation in complementary experimental efforts leveraging international investments together with enhanced theoretical efforts to enable full realization of this opportunity.



$0\nu\beta\beta$ decay Experiments - Leading Efforts



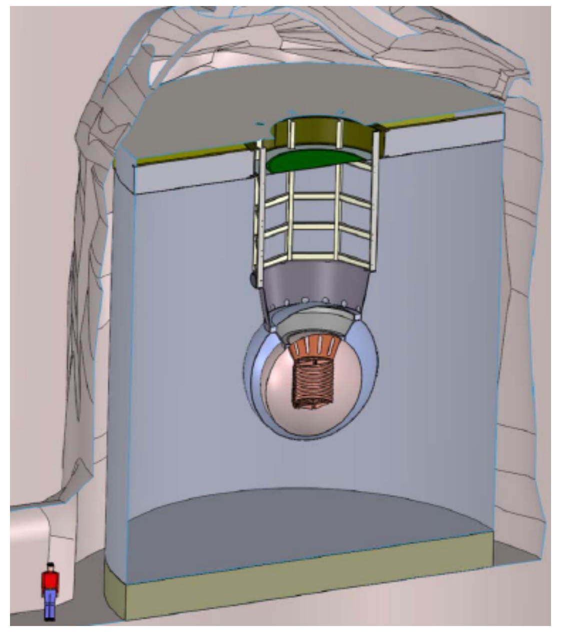
LEGEND



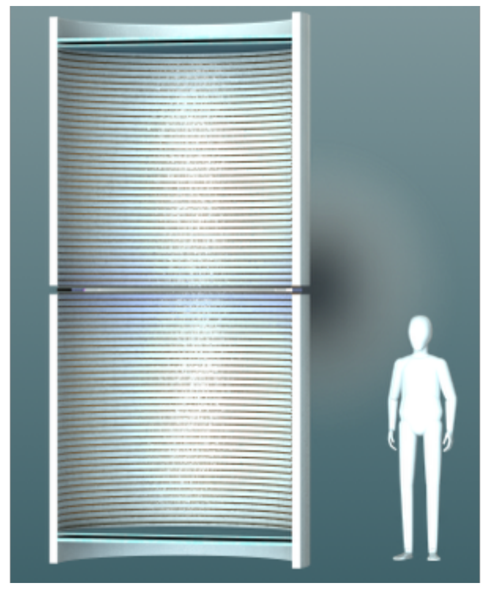
CUPID

KamLAND Zen

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	Const. LEGEND-200
CUPID	Mo-100	Mo-100 Scint. Bolometer	**~ ton**	R&D
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Constr./Commish
EXO200	Xe-136	Xe liquid TPC	79 kg	Complete
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**400, 800 kg**	Complete,
KamLAND2-Zen	Xe-136	Improved light coll, disc	**800 kg**	Operating
NEXT	Xe-136	High pressure Xe TPC	**~ton**	Oper. NEXT-100
PandaX - III	Xe-136	High pressure Xe TPC	**~ ton**	



nEXO



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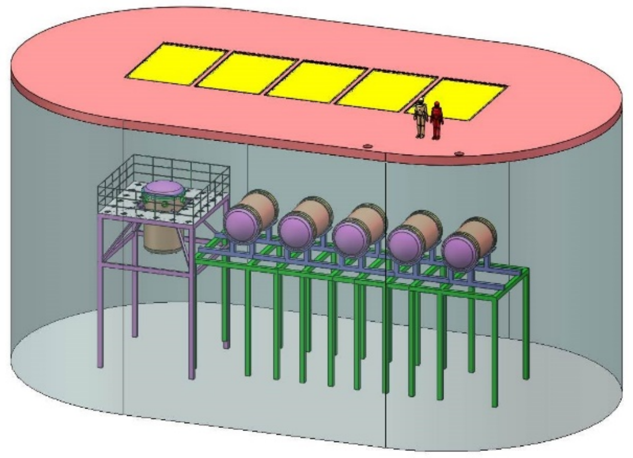
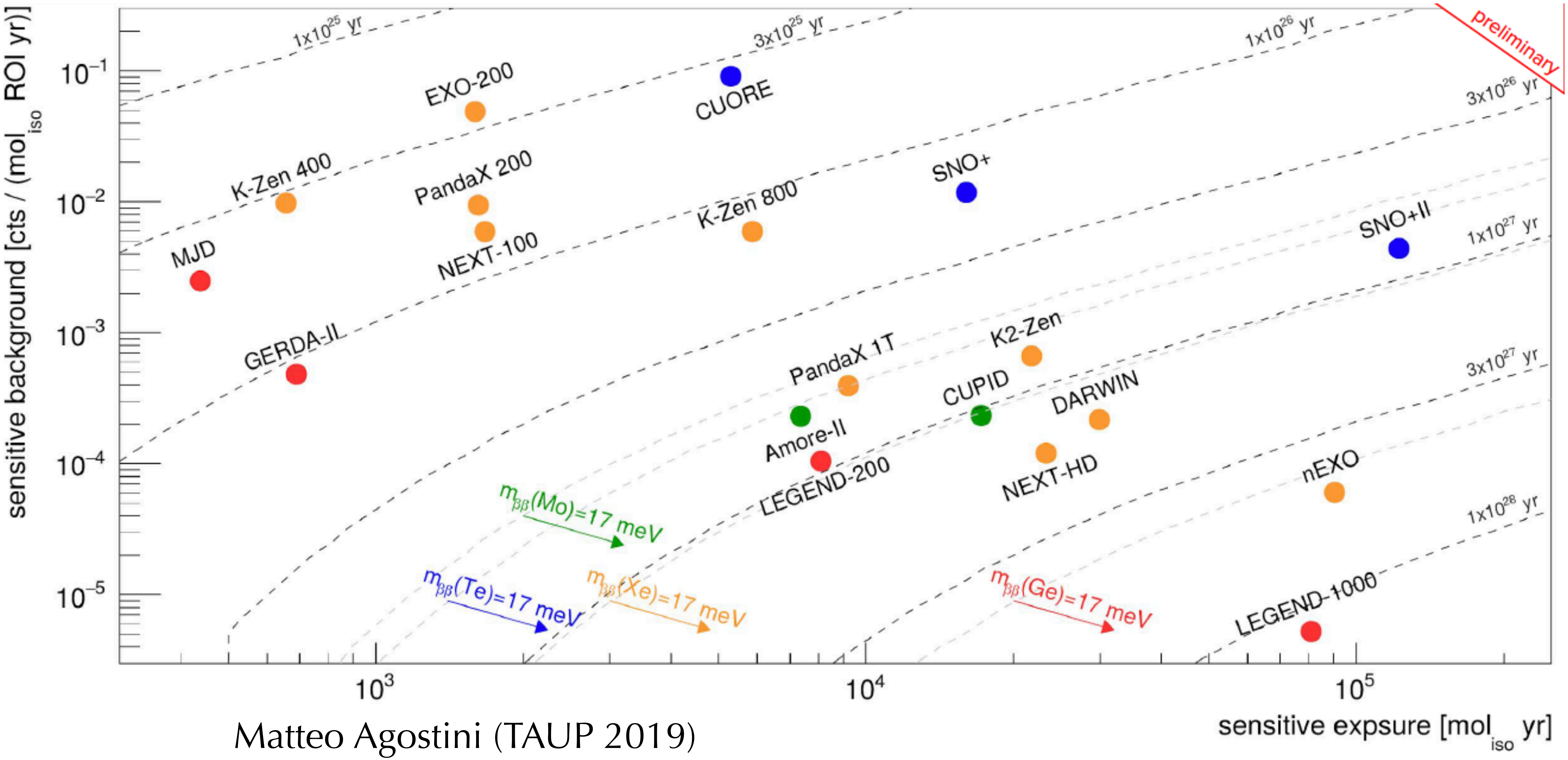


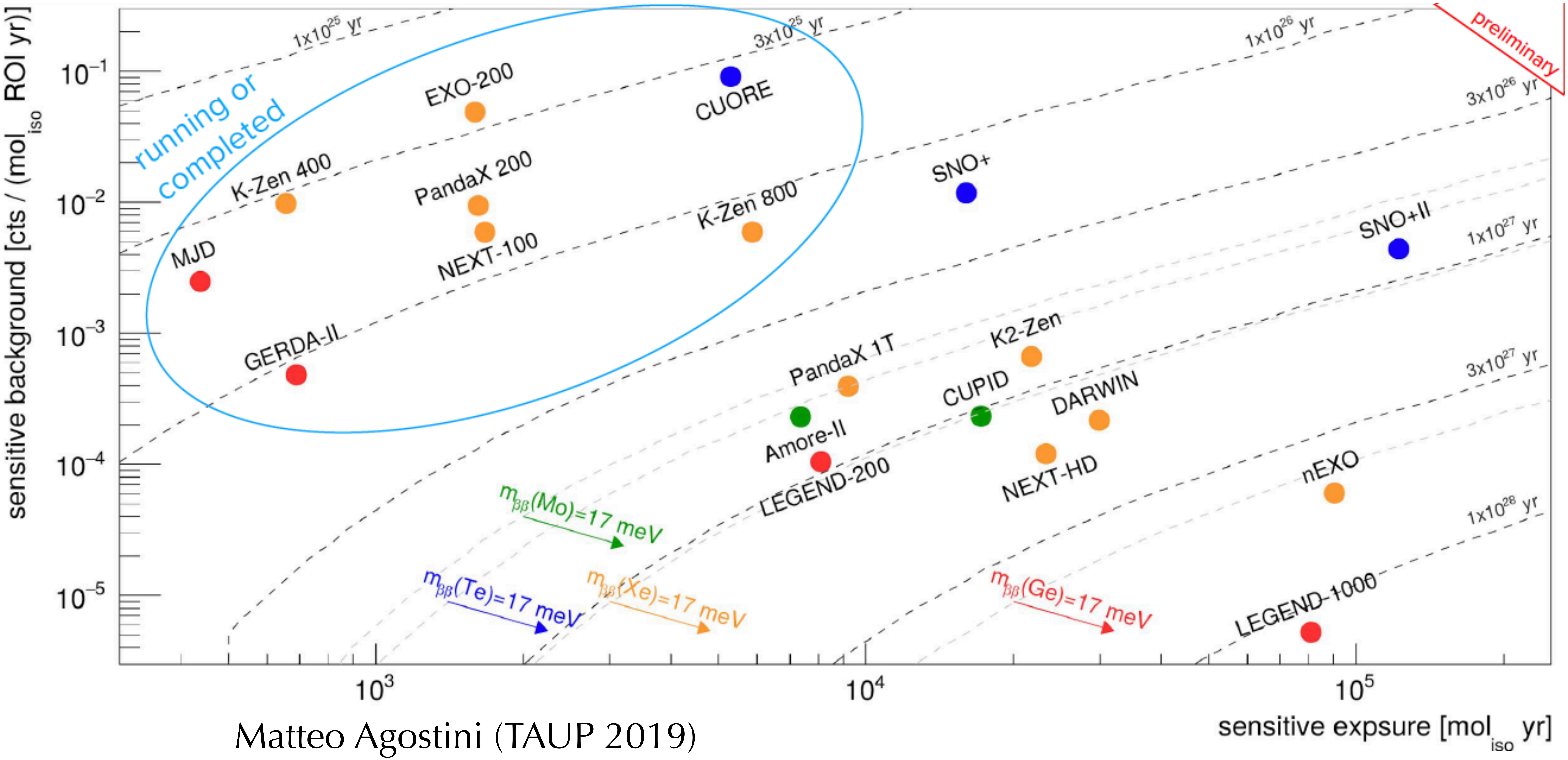
PandaX-III

0νββ Background and Sensitivity



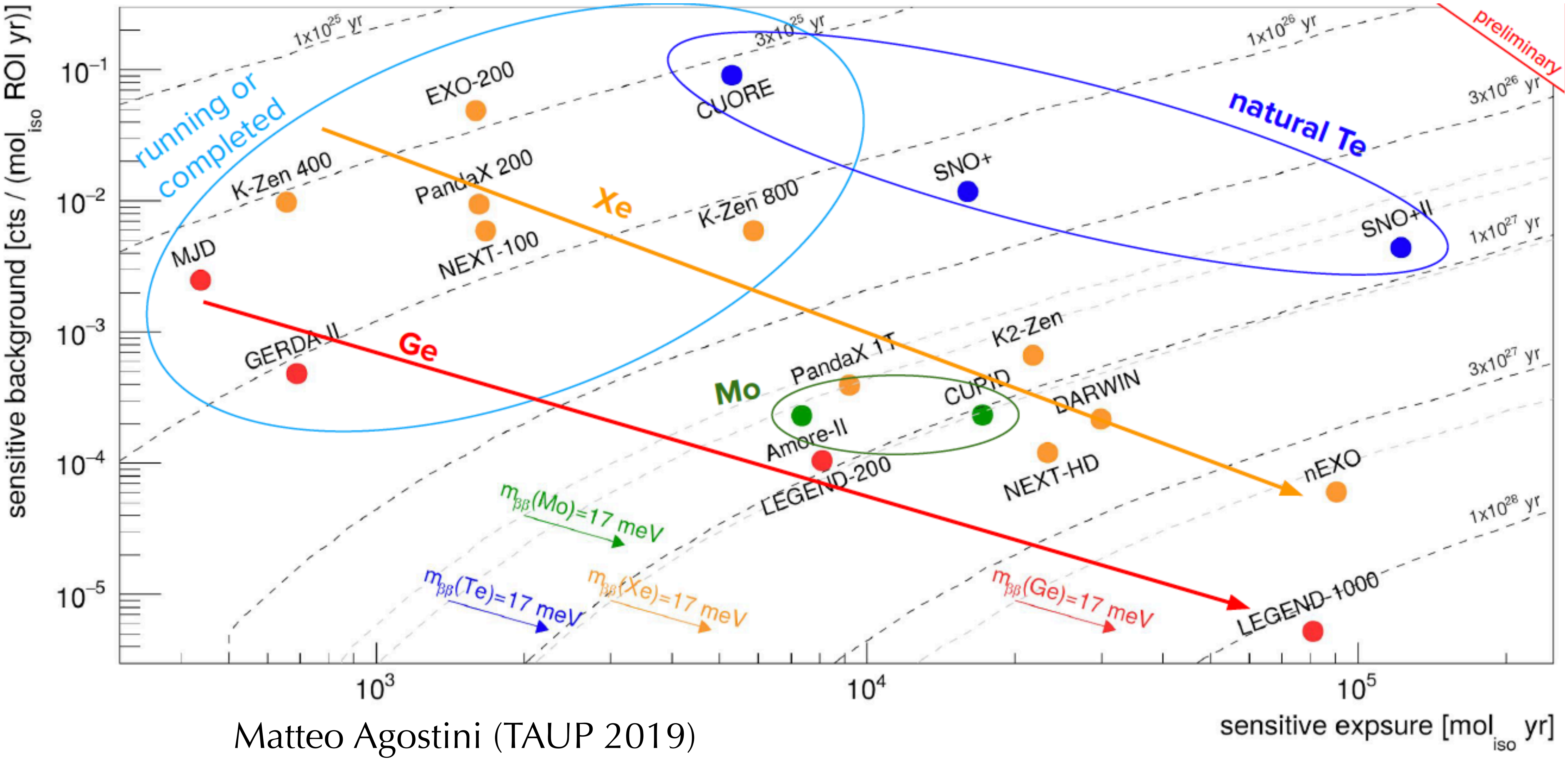
Matteo Agostini (TAUP 2019)

0νββ Background and Sensitivity



Matteo Agostini (TAUP 2019)

0νββ Background and Sensitivity

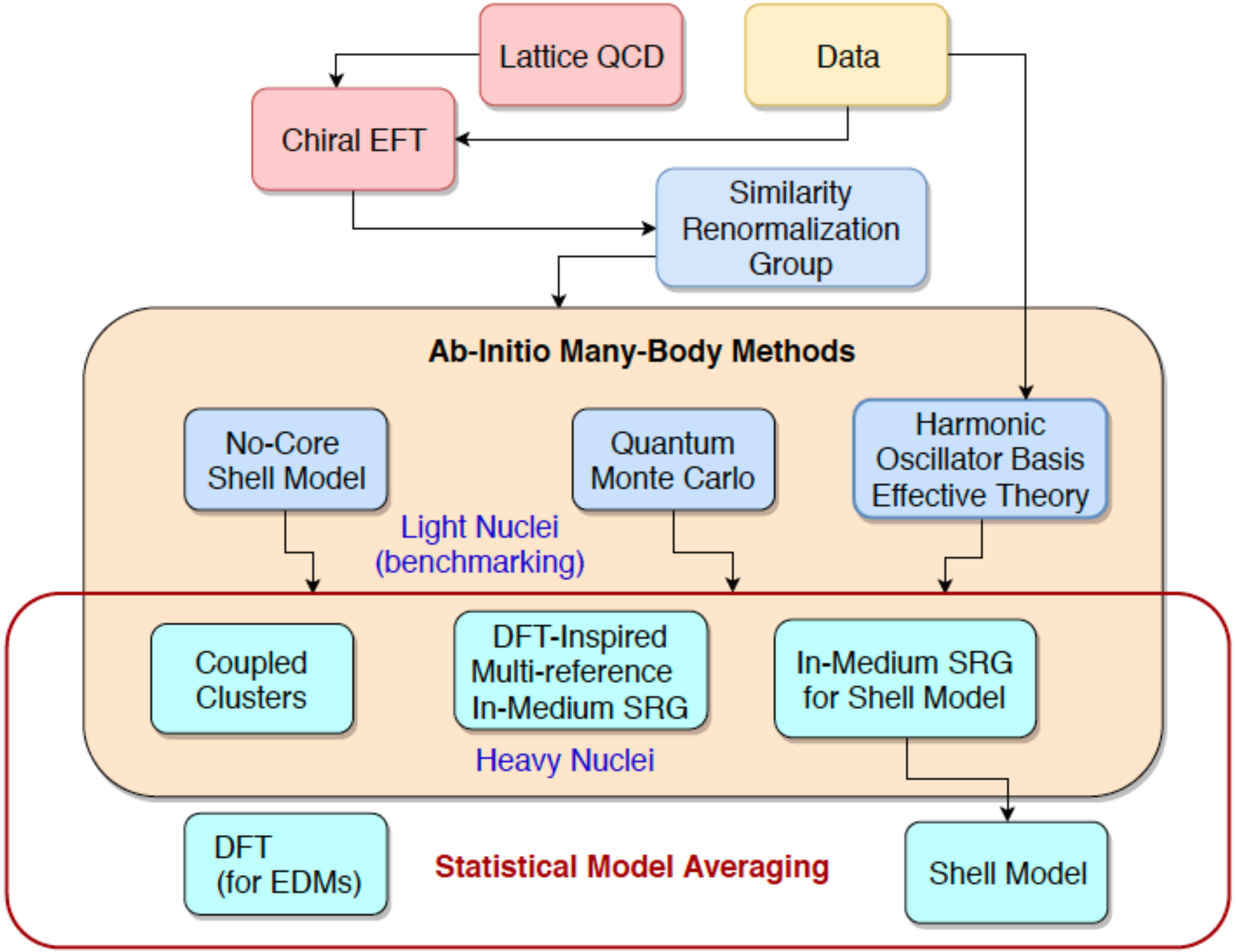


Matteo Agostini (TAUP 2019)

Topical Nuclear Theory Collaboration for Double-Beta Decay and Fundamental Symmetries

Large theory collaboration with the goal to calculate nuclear matrix elements that:

1. Are more accurate
2. Carry a quantified uncertainty.



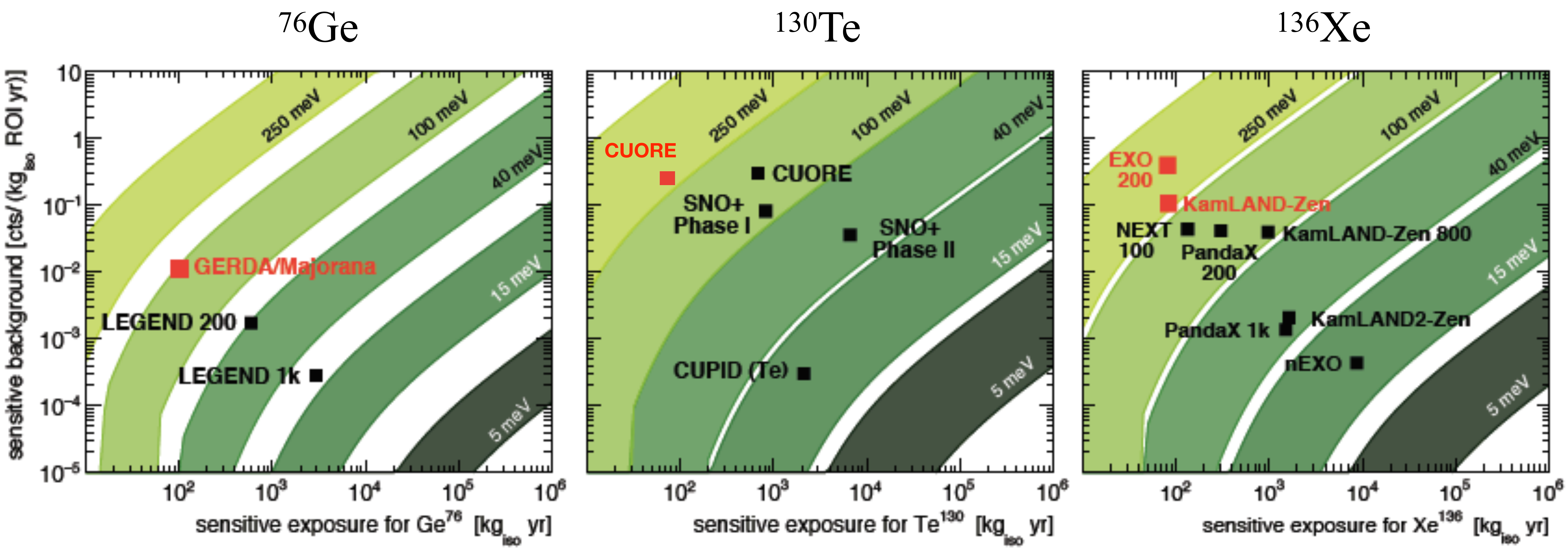
Jon Engel

Summary

- Wick and collaborators helped launch the $0\nu\beta\beta$ "modern era", utilizing expertise in particle and nuclear physics.
- Significant progress searching for $0\nu\beta\beta$.
  - Experiments have attained or are approaching sensitivities of $T_{1/2} > 10^{26}$ years, with substantially reduced backgrounds.
  - "Background free" measurements have been achieved as have detectors with masses >200 kg.
  - Theory progress should provide NME with realistic uncertainties and will likely reduce uncertainties associated with g_A .This will have a critical impact on understanding sensitivity and discovery potential
- The ability to discover $0\nu\beta\beta$ will require excellent energy resolution, low backgrounds ("background free") and large exposures (t-y) as well as observation by independent experiments, using different isotopes.
- $0\nu\beta\beta$ continues to be an exquisite method to test for lepton number violation and fundamental conservation laws.

0νββ Discovery Sensitivity and Future prospects

Discovery probability of next-generation neutrinoless double-beta decay experiments
Matteo Agostini, Giovanni Benato, and Jason Detwiler arXiv:1705.02996v1



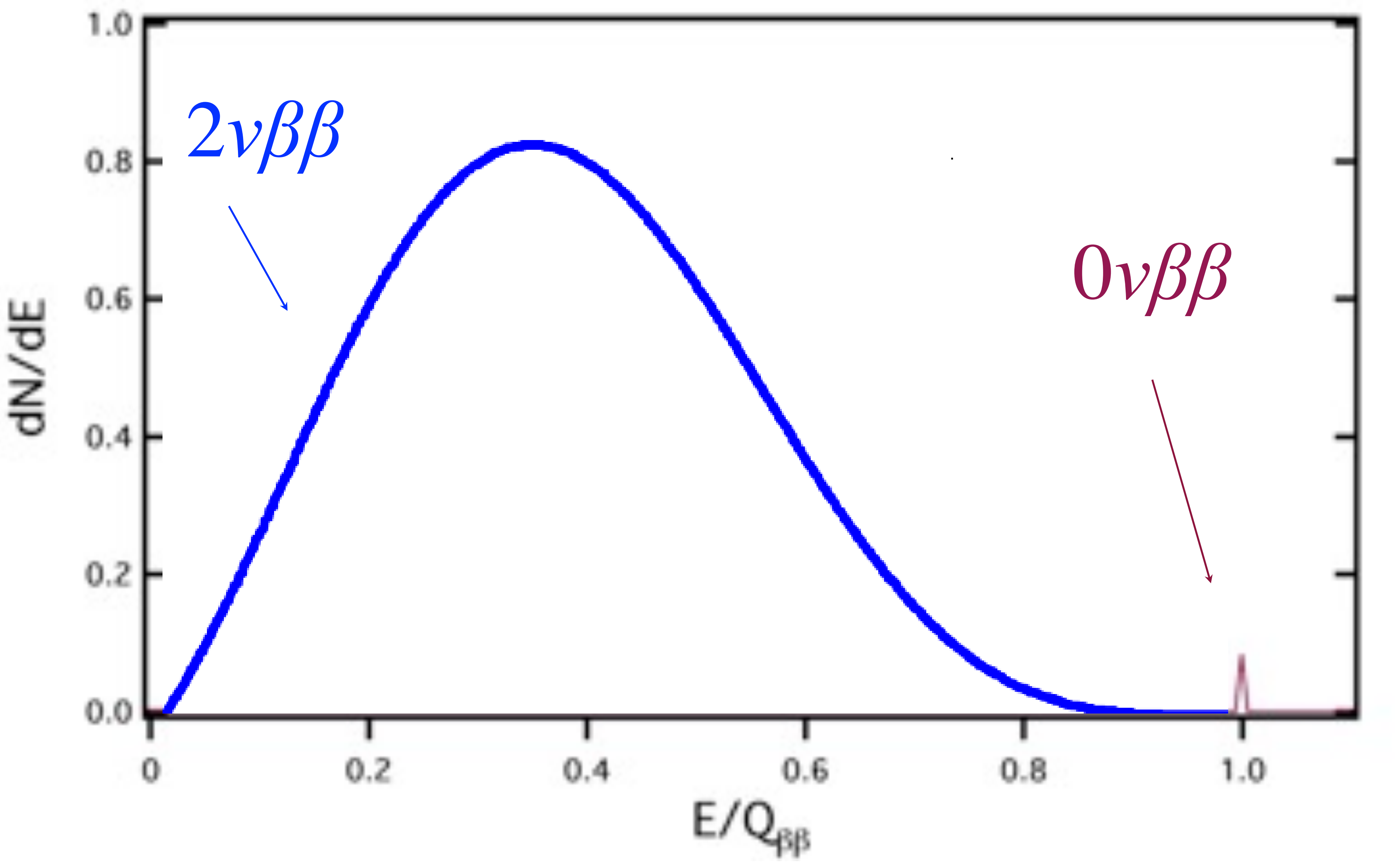
Red : Achieved Backgrounds; Black : Projected Backgrounds

Width of bands based on range of NME values

Experimental searches for 0νββ-decay

Most sensitive experiments to date using ^{76}Ge, ^{130}Te, and ^{136}Xe have attained results for $T_{1/2}$ approaching or > 10^{26} years.

With (source mass) × (exposure times) of 10 - 175 kg-years



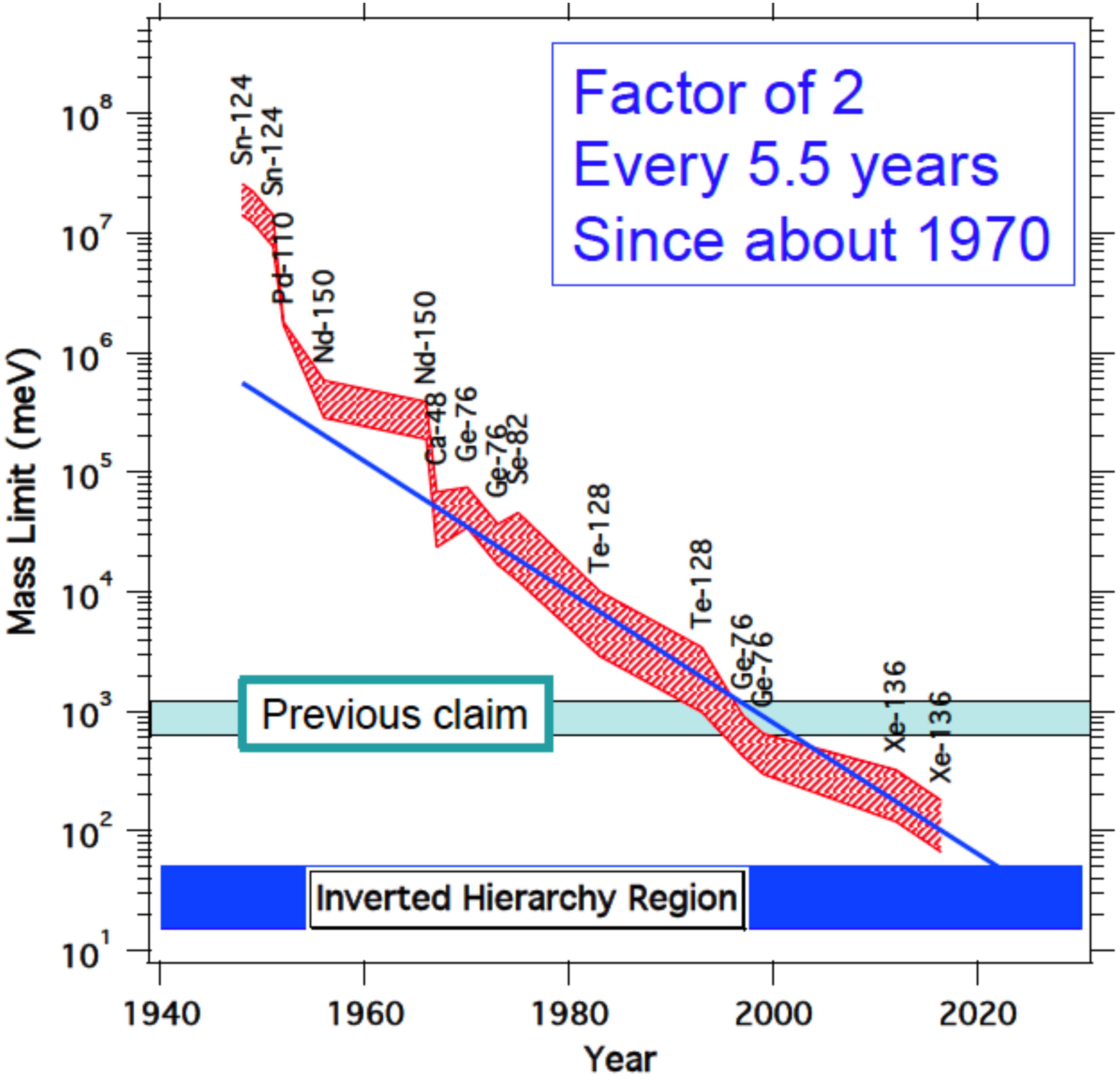
Covering IH region requires sensitivities of

0νββ $T_{1/2} \sim 10^{27}$- 10^{28} years

(2νββ $T_{1/2} \sim 10^{19}$ - 10^{21} years)

Half life (years)	~Signal (cnts/ton-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1
$>10^{29}$	0.05

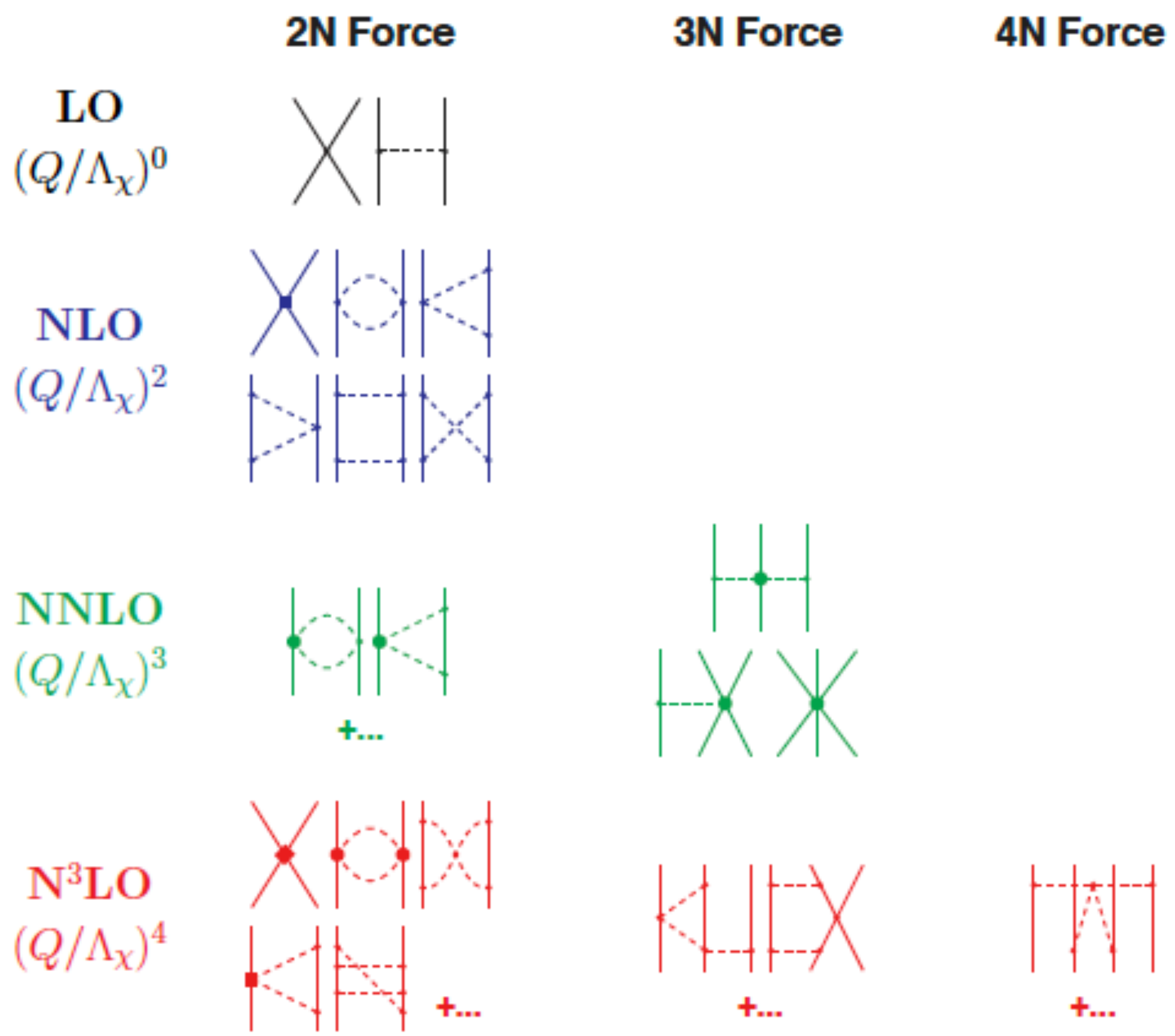
0νββ Historical Progress

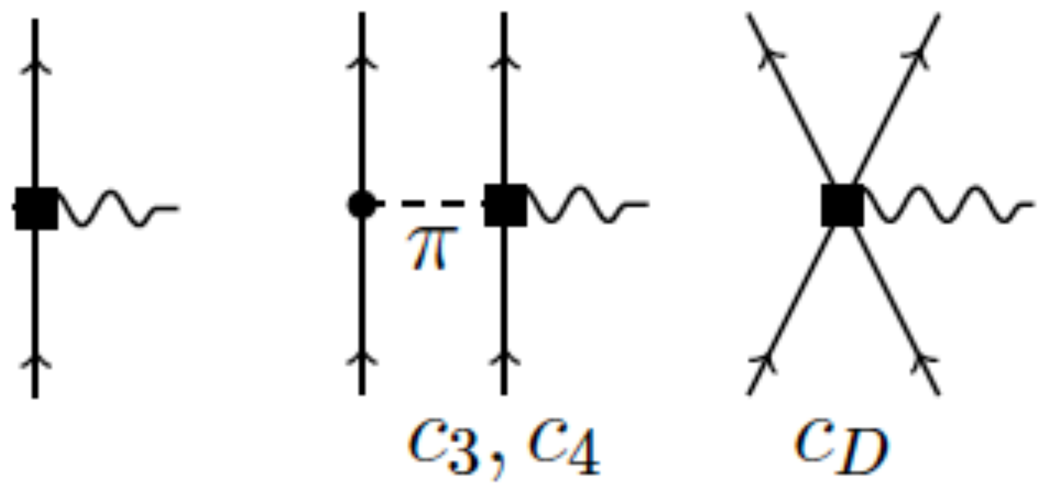


Steve Elliott

Progress with $0\nu\beta\beta$ Theory

Goal 2 requires a first-principles framework of interactions and currents: Chiral Effective Field Theory.





Comes with consistent weak current.

Cirigliano et al. recently found that we need new short-range operator, even when underlying mechanism is light-ν exchange. May increase uncertainty.

Along the way, have explained most of quenching in β decay, are currently exploring effects on ββ decay.