Double Beta Decay II: How to Look for $0\nu\beta\beta$

Julieta Gruszko

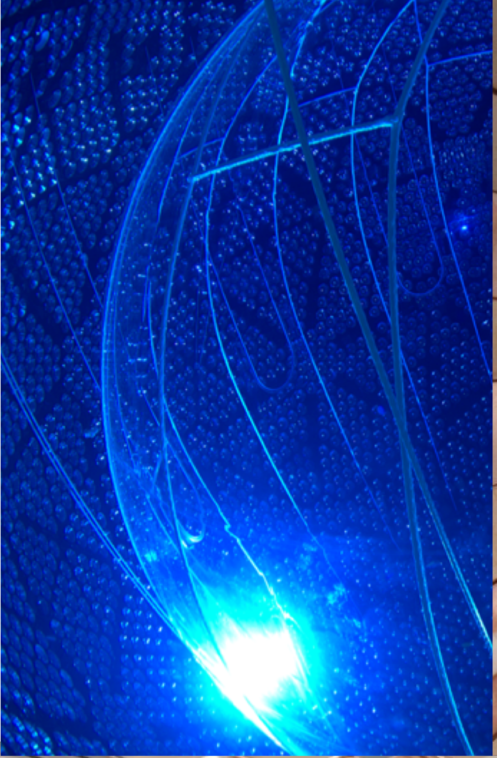
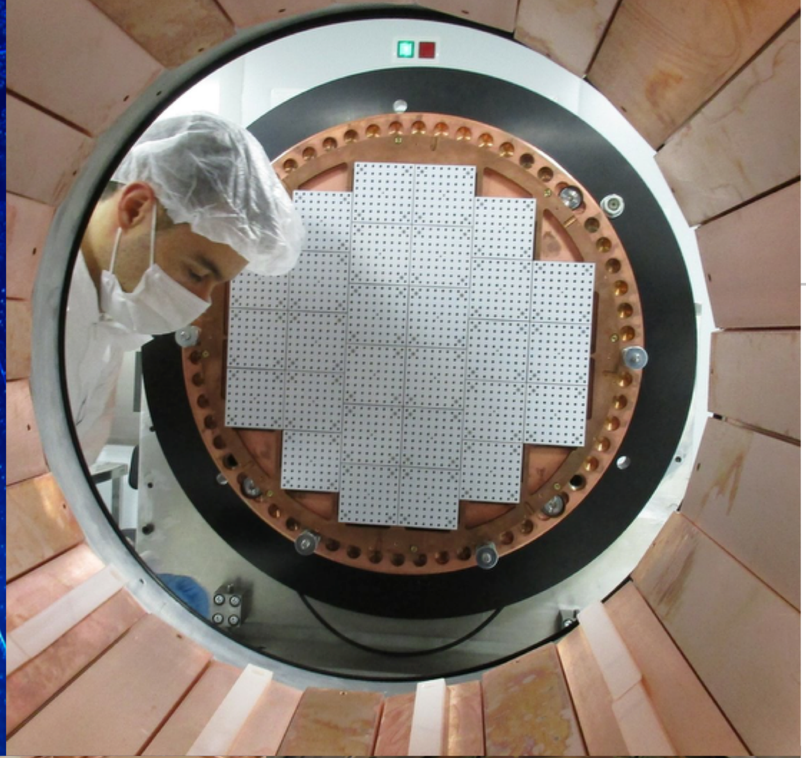
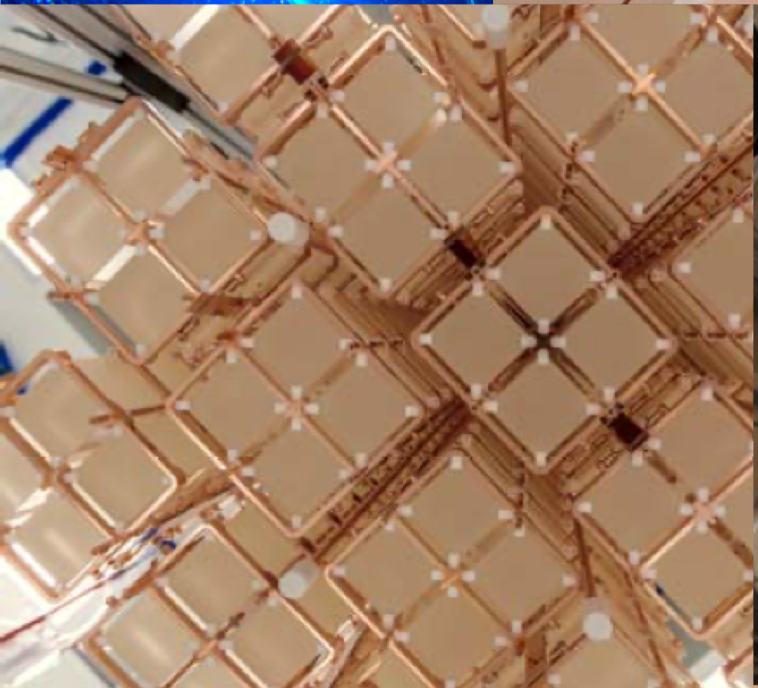
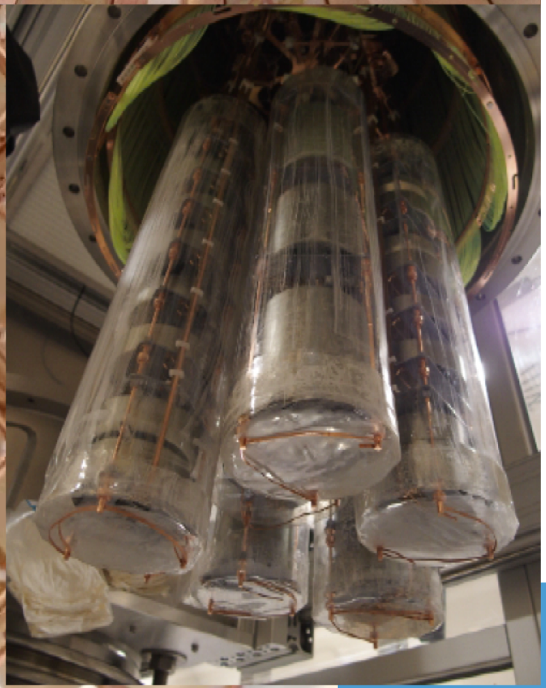
National Nuclear Physics Summer School

July 14, 2022

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Reminder from Yesterday

- Neutrinos are the only SM particles that could be Majorana fermions
- Majorana neutrinos could explain why the neutrino mass is small but non-zero, and the origin of the matter/anti-matter asymmetry
- There are many models that predict Majorana neutrinos
- If neutrinos are Majorana, $0\nu\beta\beta$ **may** occur; if $0\nu\beta\beta$ is observed, the neutrino **must** have a non-zero Majorana mass component

Outline

- Wednesday: Why look for 0νββ?
- Thursday: How to look for 0νββ

  Calculating the Rate of 0νββ:
  - Revisiting the 0νββ decay rate
  - Mean-field calculation methods
  - EFT, Lattice, and Ab-Initio methods

  Designing a 0νββ Search:
  - The 0νββ Parameter Space
  - Discovery, Sensitivity, and Backgrounds
  - Designing the Ideal Experiment
- Friday: The State of the Field

Calculating the 0vββ Decay Rate

The Light Majorana Neutrino Exchange 0νββ Rate

- Some highlights from the calculation…

$$H = \left(\sqrt{2}G_F\,|V_{ud}|\right)^2 \left[\bar{e}_L\gamma_\mu(1-\gamma_5)\nu_L\right]\left[-\bar{\nu}_L^c\gamma_\mu(1-\gamma_5)e_L^c\right]\left[\bar{p}\gamma^\mu(1-g_A\gamma_5)n\right]\left[\bar{p}\gamma^\mu(1-g_A\gamma_5)n\right]$$

2nd order weak decay

W boson couples u to d

Leptonic vertices

Hadronic currents (turn neutrons into protons)

"Fudge factor" to account for multi-nucleon interactions

*Again, see B. Jones's "The Physics of Neutrinoless Double Beta Decay: A Primer" for the details: 2108.09364

The Light Majorana Neutrino Exchange 0νββ Rate

- Replacing leptonic vertices with a neutrino propagator:

$$\mathcal{M} = -2G_F^2 |V_{ud}|^2 \sum_n \int \frac{d^4k}{(2\pi)^4} \bar{u}(p_1) \frac{1-\gamma_5}{2} \gamma_\mu \frac{\not{k}_\nu + m}{k_\nu^2 - m^2} \gamma_\nu \frac{1-\gamma_5}{2} v(p_2) e^{i\vec{k}_\nu . r} \times$$

$$\langle N_i | J^\mu | n \rangle \langle n | J^\nu | N_f \rangle 2\pi\delta(k_\nu - E_{1i} + E_{1n} + \epsilon_1).$$

Hadronic part: N_i and N_f are initial and final nuclear wavefunctions, n is intermediate state

- This decomposes into leptonic and hadronic parts:

$$= -2G_F^2 |V_{ud}|^2 \sum_n L^n_{\mu\nu} H^{\mu\nu}_n .$$

The Light Majorana Neutrino Exchange 0νββ Rate

- The leptonic part can be evaluated. After some manipulation:

$$L_n^{\mu\nu} = m_\nu \eta^{\mu\nu} \int \frac{d^4k}{(2\pi)^4} \frac{1}{(E_{1i} - E_n - E_1)^2 - \epsilon_\nu^2} \bar{u}(p_1) \frac{1 - \gamma_5}{2} v(p_2) e^{i\vec{k}_\nu . r} .$$

The Light Majorana Neutrino Exchange 0νββ Rate

- We'd like to eliminate the sum over intermediate states:

$$\mathcal{M} = -2G_F^2\,|V_{ud}|^2 \sum_n \int \frac{d^4k}{(2\pi)^4}\bar{u}(p_1)\frac{1-\gamma_5}{2}\gamma_\mu\frac{\not{k}_\nu + m}{k_\nu^2 - m^2}\gamma_\nu\frac{1-\gamma_5}{2}v(p_2)e^{i\vec{k}_\nu . r} \times \langle N_i|J^\mu|n\rangle\langle n|J^\nu|N_f\rangle 2\pi\delta(k_\nu - E_{1i} + E_{1n} + \epsilon_1).$$

- It's customary to use the "closure approximation": all the intermediate states E_n have approximately the mean intermediate state energy $\langle E_n \rangle$
- The closure approximation is pretty good for 0νββ, where the virtual neutrino can carry any momentum, but less good for 2νββ, where the intermediate states are truncated at lower energy

The Light Majorana Neutrino Exchange 0νββ Rate

- Using the closure approximation:

$$\sum_n \frac{\langle N_f|J_1|n\rangle\langle n|J_2|N_i\rangle}{(E_i - E_n - E_\eta - E_\nu)} \rightarrow \frac{\langle N_f|J_1\left(\sum_n |n\rangle\langle n|\right)J_2|N_i\rangle}{(E_i - \langle E_n\rangle - E_\eta - E_\nu)} \rightarrow \frac{\langle N_f|J_1 J_2|N_i\rangle}{(E_i - \langle E_n\rangle - E_\eta - E_\nu)}$$

$$M = -2G_F^2\,|V_{ud}|^2 \sum_n L^n_{\mu\nu} H_n^{\mu\nu} \rightarrow -2G_F^2\,|V_{ud}|^2\, L_{\mu\nu} H^{\mu\nu}$$

- Adding over spins and neutrino mass states and squaring:

$$= 4G_F^2\,|V_{ud}|^4\, H^\mu_\mu H^\rho_\rho 2p_1.p_2 \left[\frac{1}{4\pi}F(r)\right]^2 m^2_{\beta\beta}. \qquad F(r) = \frac{1}{4\pi^2}\sum_{\eta=1}^{2}\int d^3k_\nu \frac{e^{ik_\nu r}}{(-\epsilon_\nu)(E_i - \langle E_n\rangle - E_\eta - E_\nu)}.$$

The Light Majorana Neutrino Exchange 0νββ Rate

- So the full decay rate is:

$$\frac{d\Gamma}{d\cos\theta\, dE_1} = \left\{ \frac{G_F^4\, |V_{ud}|^4}{16\pi^5} E_1 E_2 |\vec{p}_1||\vec{p}_2| \left(1 - \frac{\vec{p}_1 . \vec{p}_2}{E_1 E_2}\right) \right\} \left\{ H_\mu^\mu H_\rho^\rho \left[\frac{1}{4\pi} F(r) \right]^2 \right\} \left\{ m_{\beta\beta}^2 \right\} .$$

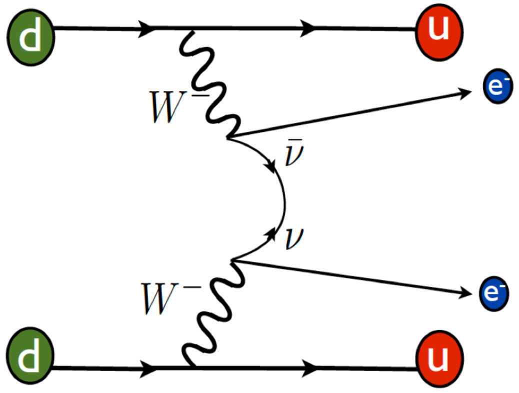
Phase space factor ($G^{0\nu}$)
Can be calculated exactly

Matrix element (M)

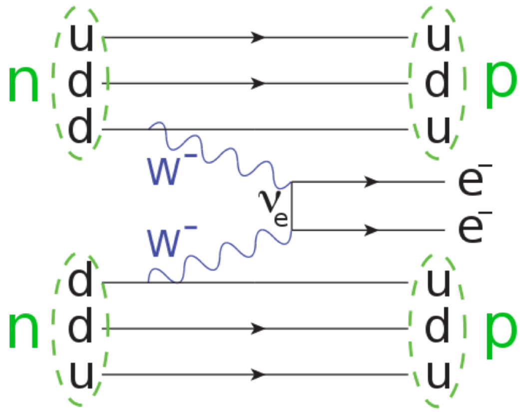
Effective Majorana mass ($m_{\beta\beta}$), known up to unknown neutrino physics

0νββ in Nuclei

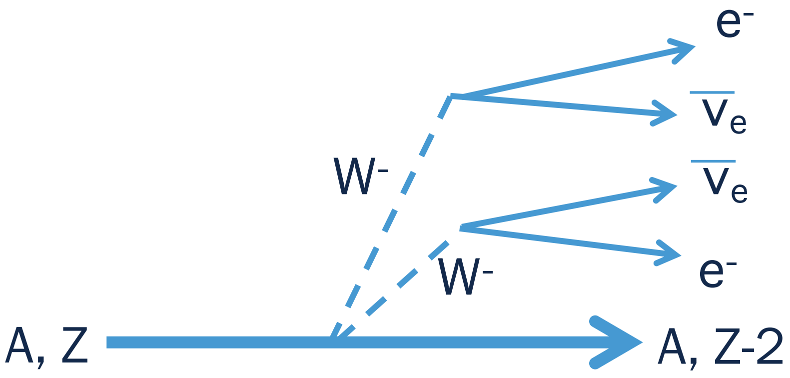
Not enough information…



…still not enough…



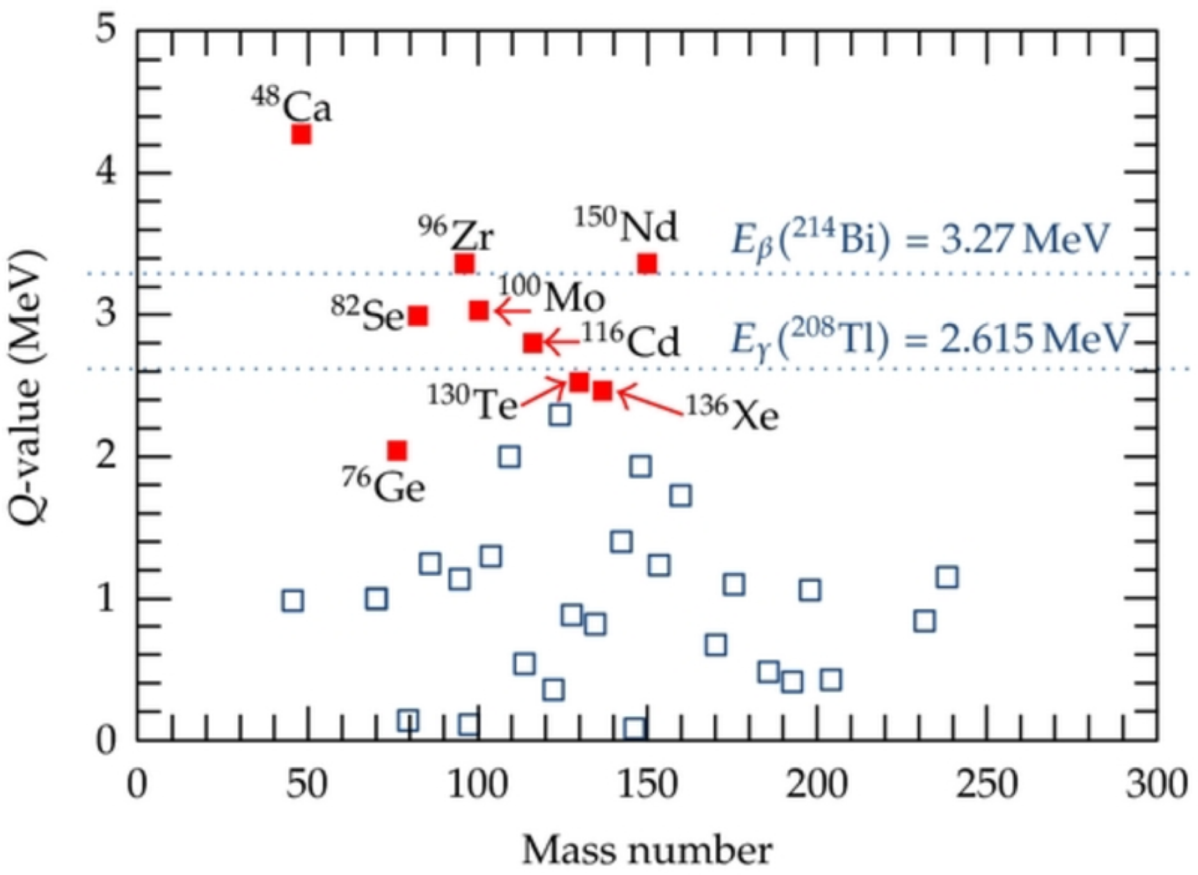
this is the diagram we actually care about, for some specific A, Z



- To calculate M exactly, we'd need the full wavefunction of the nucleus before and after the decay, $M \propto \langle N_f | J_1 J_2 | N_i \rangle$
- Nuclear effects are **highly significant** in determining the 0νββ rate!

Double-Beta Decay Isotopes

- 35 naturally-occurring isotopes are capable of double-beta decay; we've observed it in 14 of these
- The nuclei we care about are big! Calculating the full wavefunction is completely intractable.



Revisiting the 0νββ Rate

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

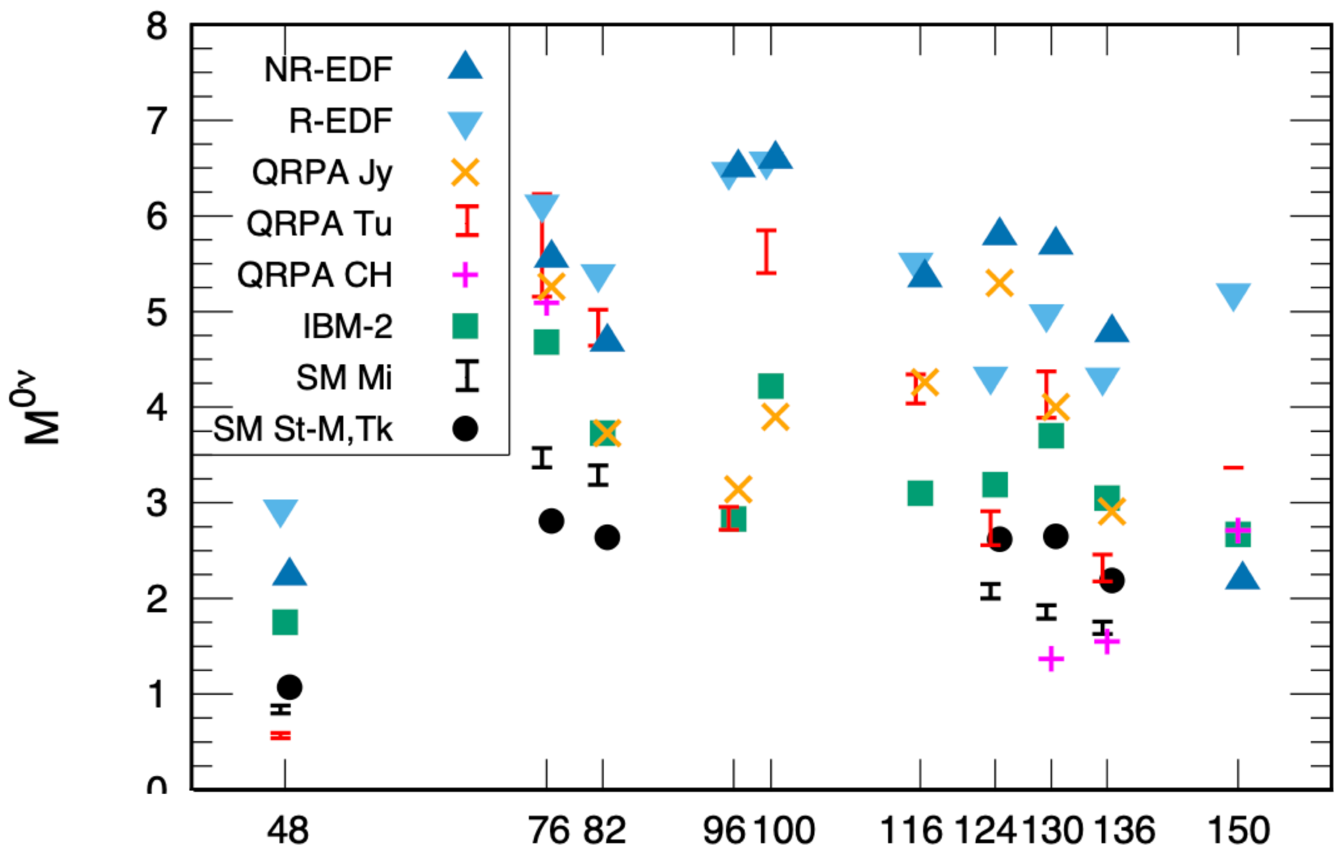
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\, g_A^4 \left(M_{0\nu} + \frac{g_\nu^{NN} m_\pi^2}{g_A^2} M_{0\nu}^{cont}\right)^2 m_{\beta\beta}^2$$

$$M_{0\nu} = M_{\rm GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_{\rm F}^{(0\nu)} + M_{\rm T}^{(0\nu)}.$$

- Weak current can be decomposed into Fermi (F), Gamow-Teller (GT) and Tensor (T) components
- The recently-discovered contact operator also contributes (more on this in a moment)
- In other 0νββ mechanisms, long-range and heavy neutrino matrix elements also become important

Matrix Element Calculations

- The matrix element calculations present a significant challenge
- Two main approaches:
  - Mean-field theory: make judicious approximations to solve some subsection of the problem, and treat the rest as a collective core
  - Ab-initio calculations: solve the many-body Schrödinger equation directly from 2 and 3-nucleon interactions



1610.06548

Calculating Matrix Elements: Mean-Field Methods

Mean-Field Methods

- There are many mean-field methods and variations on them
- I’ll address the two largest categories of methods: Shell Model and QRPA
- For a more detailed overview, see “Status and Future of Nuclear Matrix Elements for Neutrinoless Double-Beta Decay: A Review”, J. Engel and J. Menéndez, 1610.06548

Shell Model Matrix Element Calculations

- Commonly used to describe medium-mass and heavy nuclei
- Based on the idea that all the correlations between nucleons near the Fermi level are important for low-energy nuclear properties
- Restrict the dynamics to the valence space, containing only a subset of nucleons
- Use an effective nuclear interaction H_{eff}, tuning it to match 2 nucleon scattering data
- "Active" nucleons can only occupy a limited set of single-particle levels around the Fermi surface

The Shell Model: Strengths

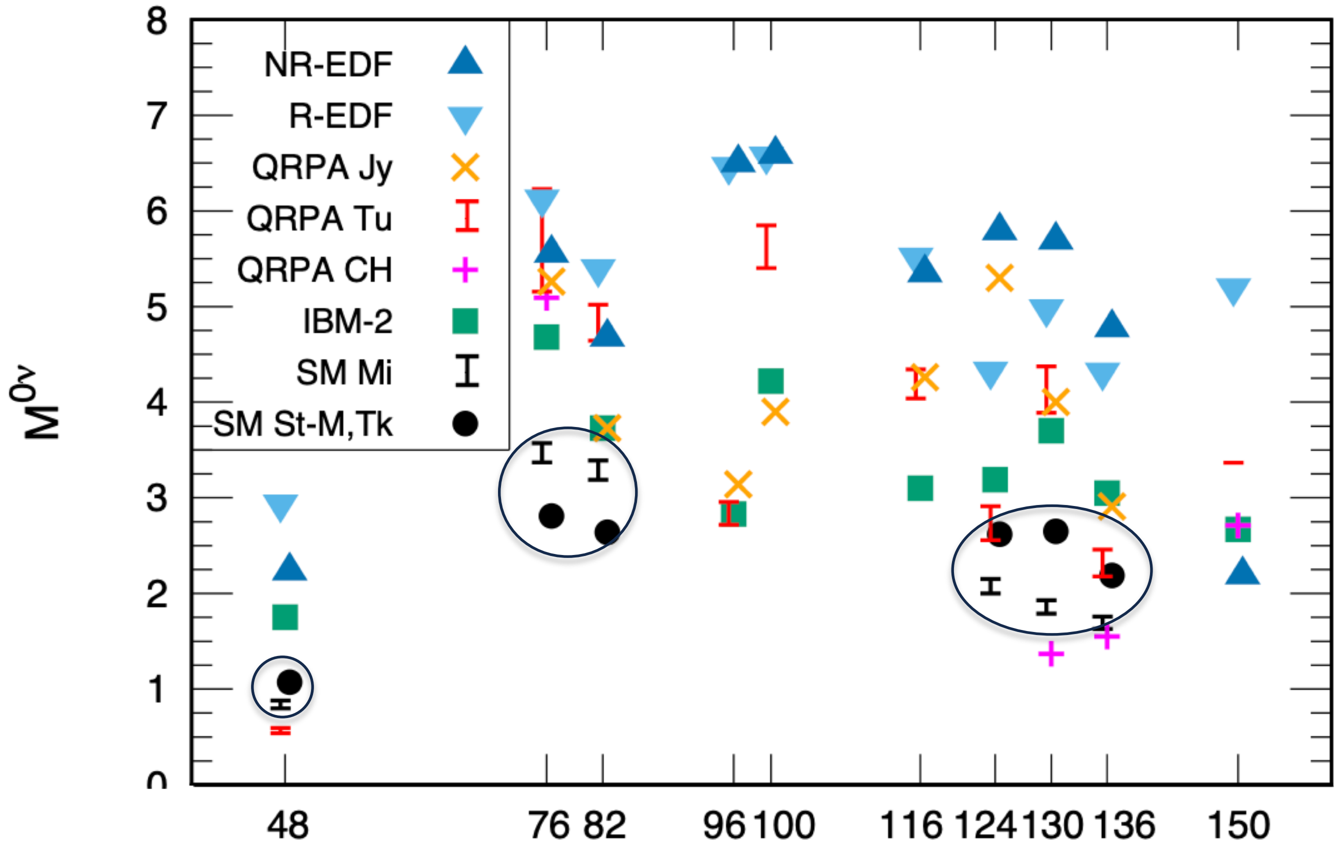
- Good at describing ground-state nuclear properties: masses, separation energies, charge radii
- Also good for low-lying excitation spectra, electric moments, and transitions
- Shell model states contain all correlations that come from coherent motion of the nucleons in the configuration/valence space

The Shell Model: Weaknesses

- Treating all the correlations means you can't handle many nucleons: most $0\nu\beta\beta$ calculations use 1 or 2 harmonic oscillator shells, each consisting of 4 or 5 single-particle orbitals
- This approach may struggle to capture two effects that are important for $0\nu\beta\beta$:
  - Pairing correlations
  - Spin-orbit interactions
- This approach can't be used for some nuclei: e.g. ^{100}Mo (though a first calculation recently appeared on arXiv)
- May be better of $2\nu\beta\beta$ than $0\nu\beta\beta$, but we have no way to check!

Shell Model Results

- To reproduce experimental single-β and 2νββ results, need to introduce "g_A quenching" – instead of using the bare nucleon value $g_a \cong 1.27$, reduce it by 20-30%
- No way to rigorously quantify uncertainty: one approach used is to compare results using different reasonable H_{eff}, leading to variations of 10-20%
- Shell model calculations tend to produce smaller values of M than other methods (larger half-life for a given $m_{\beta\beta}$)



1610.06548

The Quasiparticle Random Phase Approximation (QRPA) Method

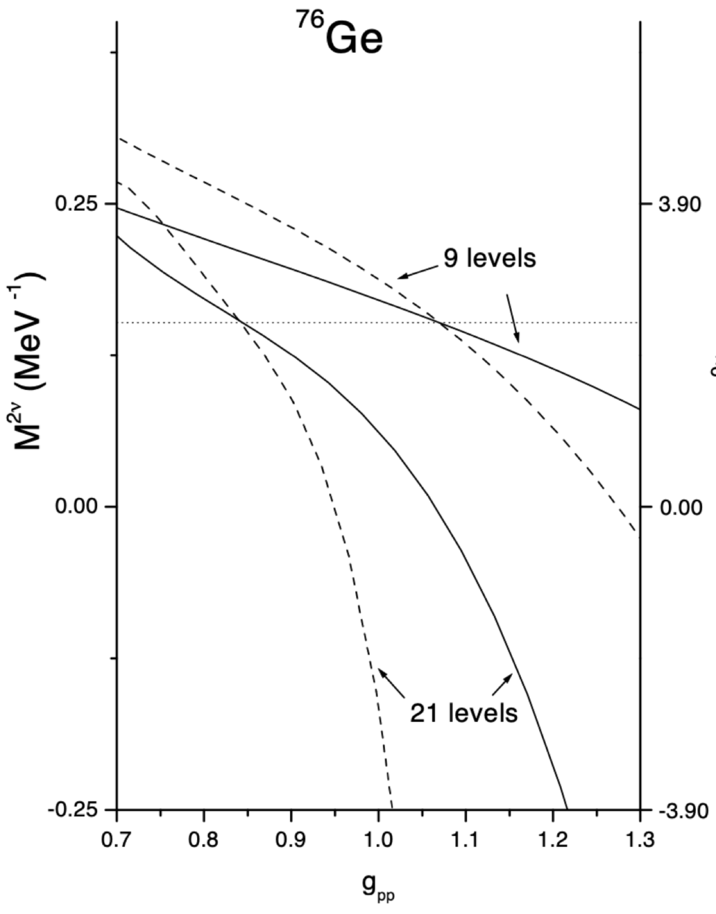
- Builds on the long-standing “Random Phase Approximation” technique, which allows you to find a set of one-particle, one-hole excitations that are the only states connected to the ground state through a one-body operator
- To use it for β and ββ decay, switch to states that change one neutron into one proton and add pairing by using 2-quasiparticle states
- For β decay, one application of QRPA gets you from initial to final states.
- For ββ decay, need to do QRPA twice: once from initial nucleus, once from final nucleus. You get 2 sets of intermediate states, and need to express one in terms of the other. This requires additional approximations.

QRPA: Strengths

- You can include many nucleons: most calculations include all the orbitals within 1 or 2 shells of the Fermi surface. Calculations including all the levels (with no inert core) are possible, though demanding.
- Can be used for all nuclei, regardless of shape
- Less reason to think that $0\nu\beta\beta$ calculation is worse-performing than $2\nu\beta\beta$ calculation

QRPA: Weaknesses

- Correlations are much more restricted, so the effective nucleon-nucleon interaction needs to be much more heavily modified
- Strengths of particle-hole and pairing interactions are often tuned independently to reproduce observables
  - Pairing interaction adjustment has a large effect on ββ matrix elements. Common practice is to force the 2νββ rate to match data.

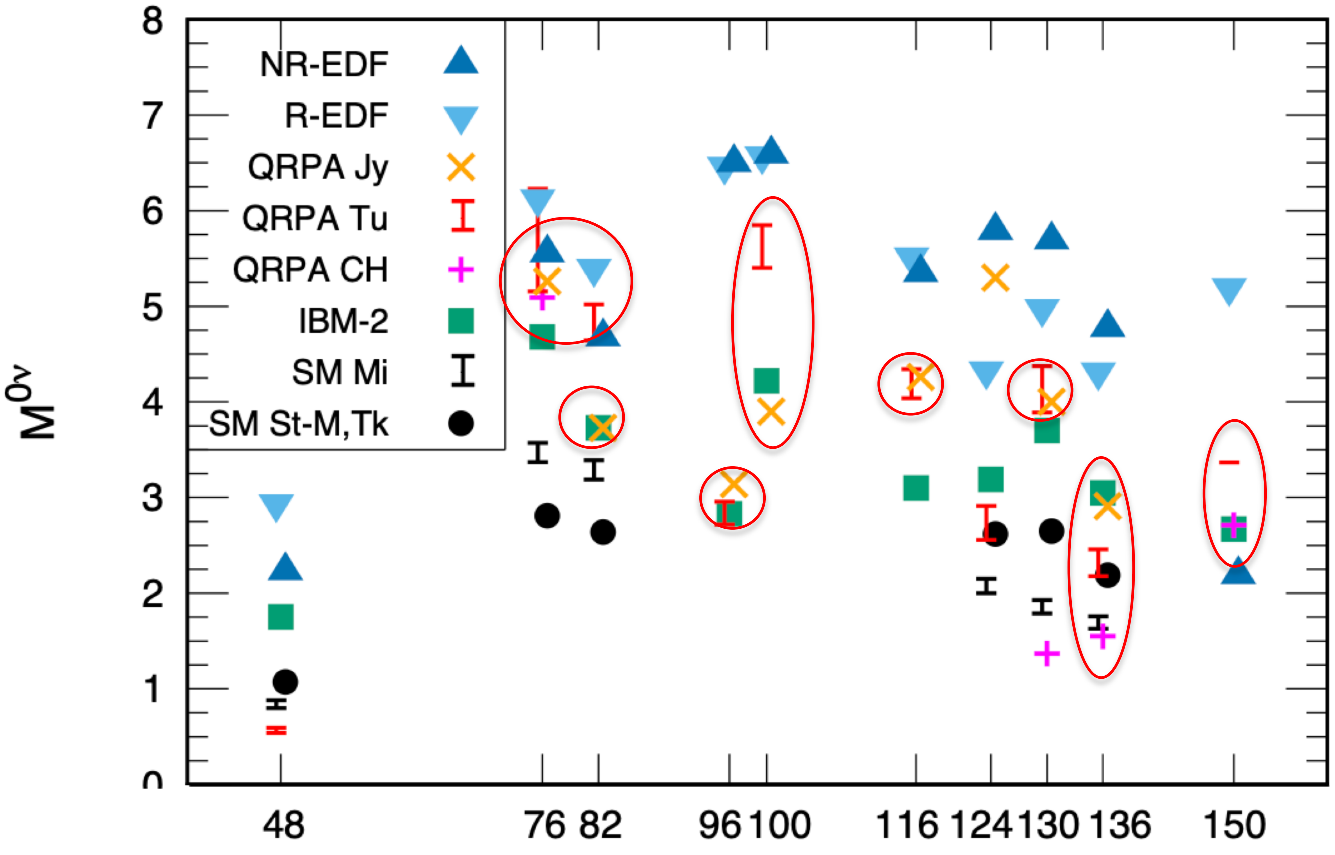


1610.06548

FIG. 6. Matrix elements $M^{2\nu}_{GT}$, (left scale, dashed lines) and $M^{0\nu}$, (right scale, solid lines) for the $2\nu\beta\beta$ and $0\nu\beta\beta$ decay of ^{76}Ge, as a function of the strength of the proton-neutron interaction g_{pp} for QRPA calculations in configuration spaces consisting of 9 and 21 single-particle orbitals. The dotted horizontal line is at the measured value of the $M^{2\nu}_{GT}$. Figure taken from Ref. [154].

QRPA Results

- Many variations on QRPA exist that try to fix the known issues (the pairing interaction problem in particular)
- QRPA matrix elements are almost uniformly larger than Shell Model elements
- More variation between QRPA calculations



1610.06548

Mean-Field Method Improvements

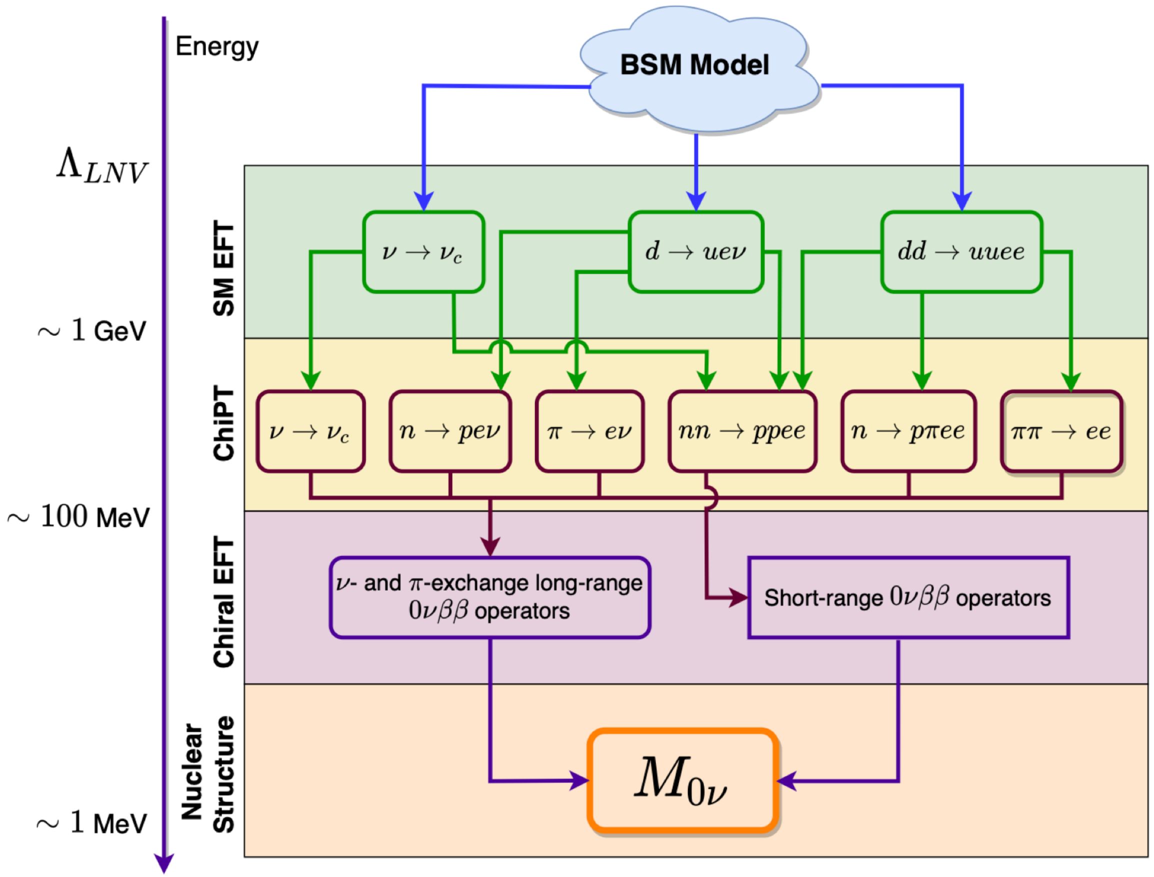
- Quite a bit of work has been done on trying to understand the model uncertainties of these methods:
  - Vary configuration spaces in Shell Model: strong effect on $2\nu\beta\beta$, smaller effect on $0\nu\beta\beta$
  - ”Turn off” correlations in Shell Model to match QRPA correlations: matrix elements grow
  - Use Shell Model to quantify which correlations are most important
- Ongoing work on improving mean-field methods:
  - Extending Shell Model configuration spaces: e.g. use MC sampling
  - Add more correlations to QRPA: e.g. add 4-quasiparticle excitations

Calculating Matrix Elements: Ab-Initio Methods

What Do We Mean by “Ab-initio”?

- “Ab-initio” = “from the beginning”
- Truly ab-initio calculations would have to solve QCD for quark and gluon degrees of freedom.
- The only way to do that is Lattice QCD; while there’s been a lot of progress, lattice methods aren’t going to get to 100-nucleon systems any time soon.
- What we mean:
  - Use nucleon degrees of freedom, including all nucleons
  - Use nuclear interactions and currents obtained from nucleon-nucleon scattering and properties of light nuclei (H, D, He)

How This Works



arXiv:2207.01085

How BSM physics shows up at the…

quark and gluon level

nucleon and pion level

nucleon-only level (pions accounted for in multi-nucleon operators)

nuclear level

What is χEFT? (AKA "Why are there pions everywhere?")

- In QCD vacuum, chiral symmetry is spontaneously broken, giving the pions a non-zero mass (if u and d quarks had the same mass, pions would be massless)
- Pions are much lighter than the other mesons
- Chiral perturbation theory is the "effective theory" for interacting pions.
- Uses the expansion parameter $\lambda_\chi = \frac{q}{\Lambda}$ or $\frac{m_\pi}{\Lambda}$, where Λ is the scale at which other hadrons can exist (~1 GeV)

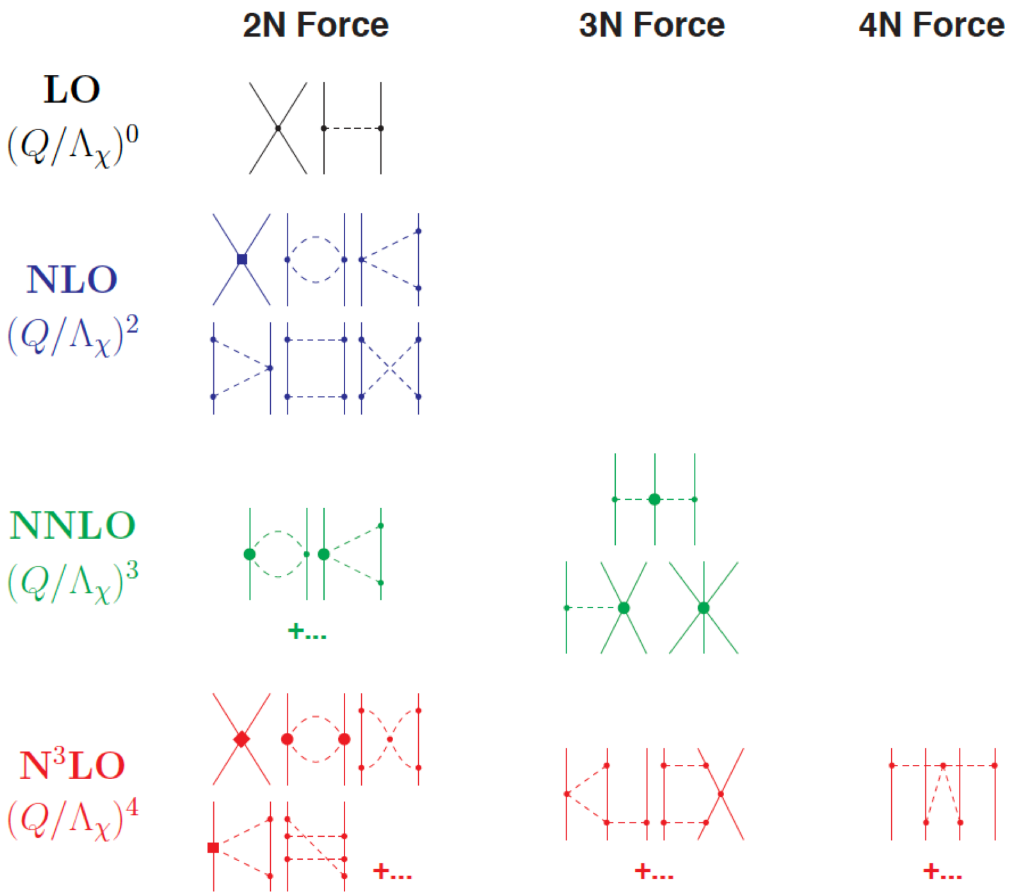
How to Use χEFT

- Gives a systematic expansion of two- and many-nucleon forces and consistent one-, two- and many-nucleon currents
- Once you have the interactions fixed, use a many-body method to calculate binding energies, spectra, decay rates, etc.
- A lot of the errors can be estimated and controlled from the power counting

χEFT Diagrams

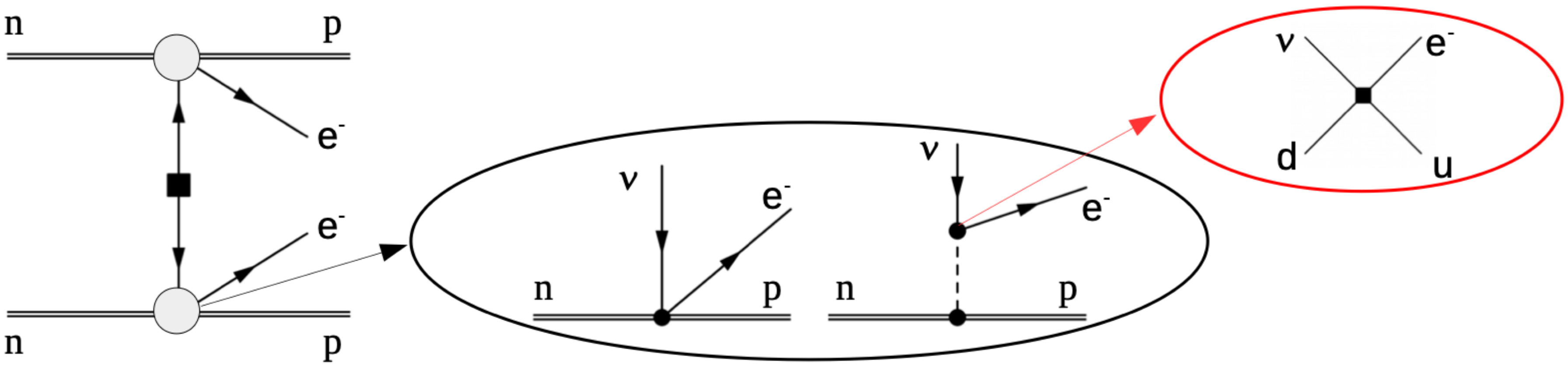
You can add nucleons to the mix, and study multi-nucleon forces

Dashed = pions
Solid = nucleons



χEFT and Double-Beta Decay

Light Majorana ν exchange



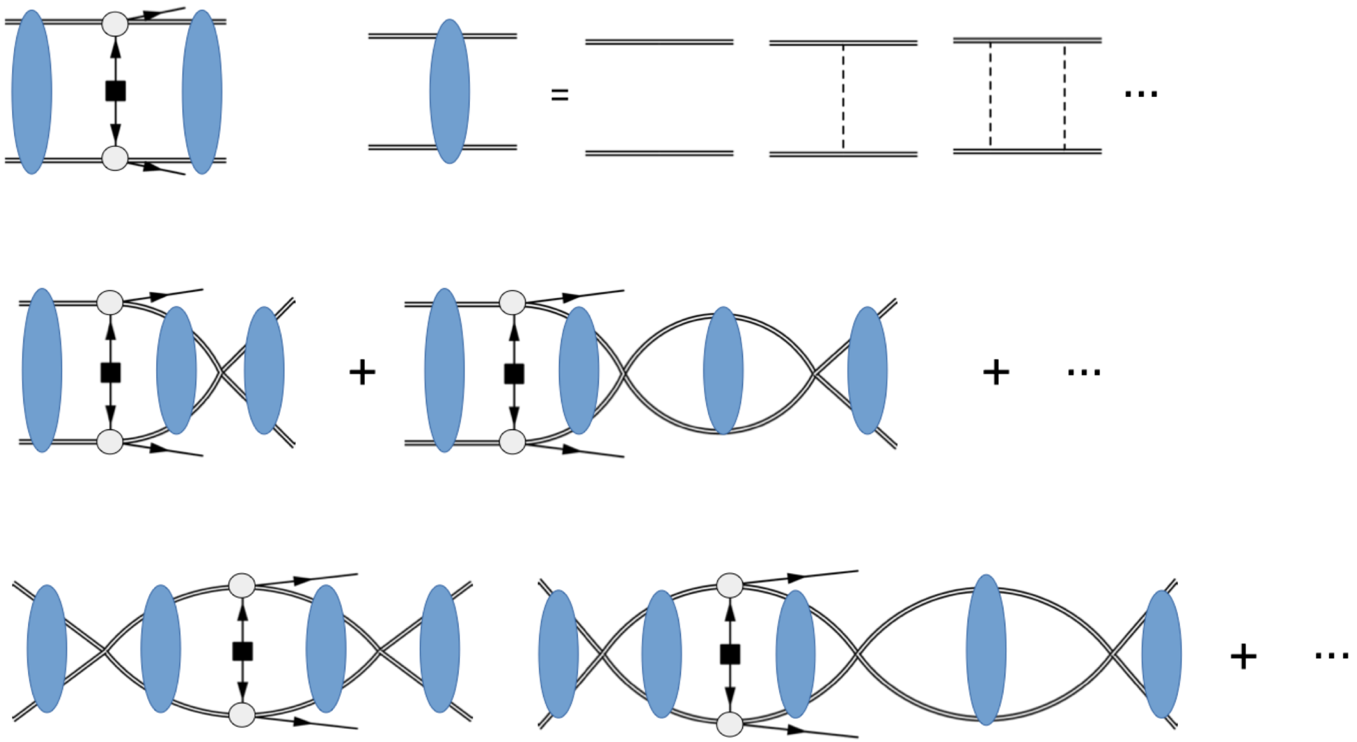
- long range ν-exchange, mediated by V, A 1-nucleon weak current
- Coulomb-like neutrino potential

$$V_\nu = G_F^2 m_{\beta\beta} \tau^{(1)+} \tau^{(2)+} \frac{1}{\mathbf{q}^2} \left\{ \mathbf{1}^{(a)} \times \mathbf{1}^{(b)} - \frac{2}{3} g_A^2 \boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} + \ldots \right\}.$$

F. Šimkovic *et al*, '99

χEFT and Double-Beta Decay

Adding NLO
and NNLO…

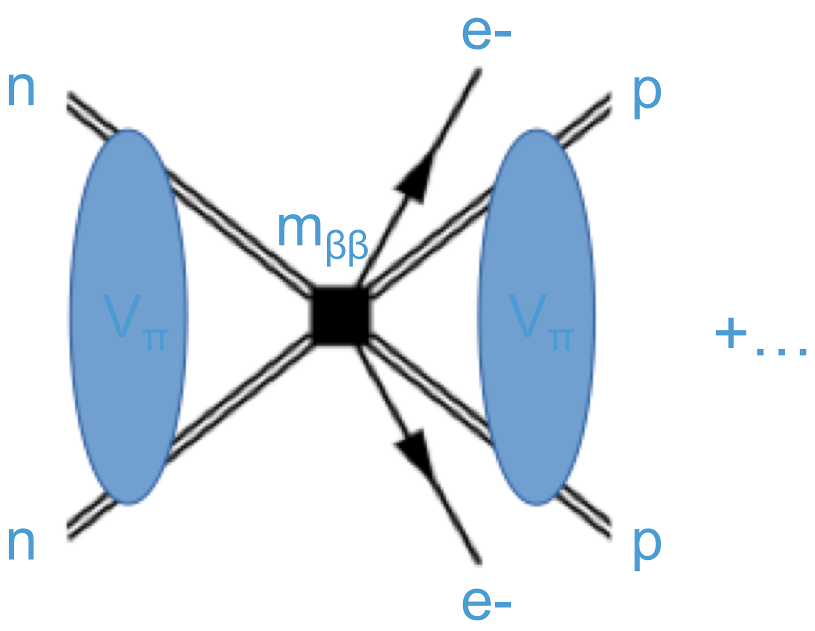


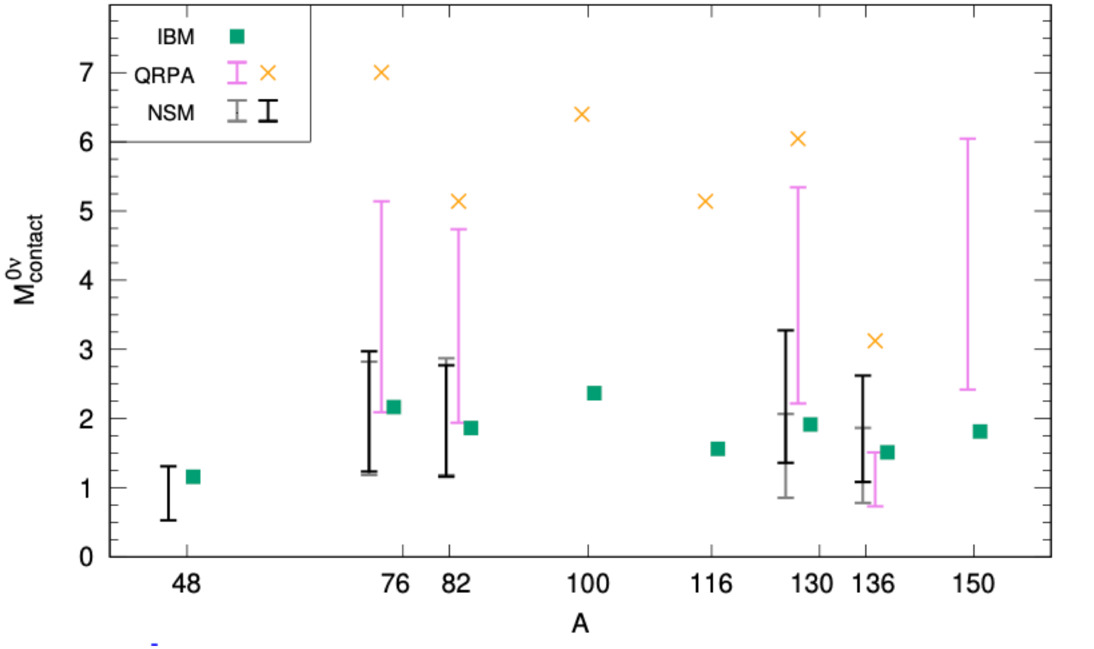
V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, EM, S. Pastore, U. van Kolck, ‘18

Successes of χEFT Approach: Contact Term

- In the last few years, a missing leading order contact term was identified using EFT methods
- Initial calculations indicate an enhancement of the 0νββ rate
- g_{NN} not known, needs to be measured or calculated with LQCD

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\, g_A^4 \left(M_{0\nu} + \frac{g_\nu^{NN} m_\pi^2}{g_A^2} M_{0\nu}^{cont} \right)^2 m_{\beta\beta}^2$$

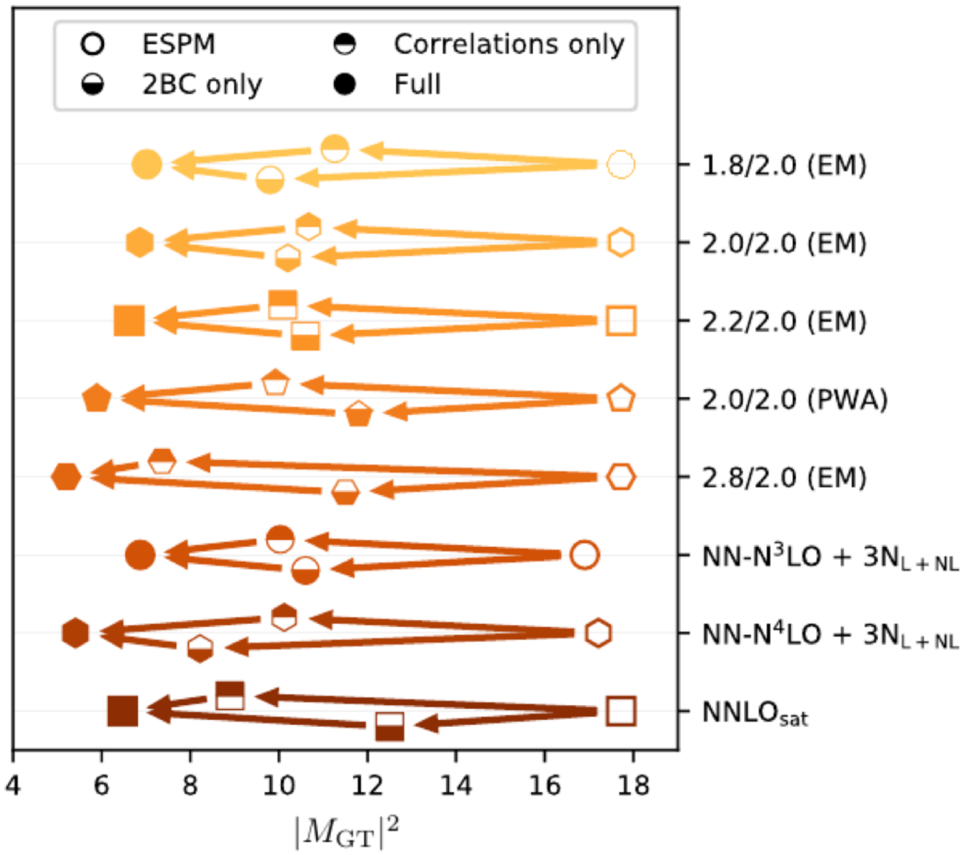




Courtesy of J. Menendez

Successes of χEFT Approach: "g_A quenching"

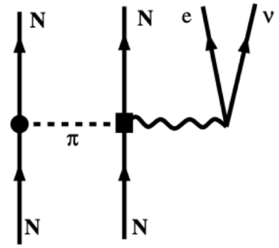
Which are main effects missing in conventional β-decay calculations?



Relatively similar and complementary impact of

- nuclear correlations
- meson-exchange currents

Gysbers et al.
Nature Phys. 15 428 (2019)



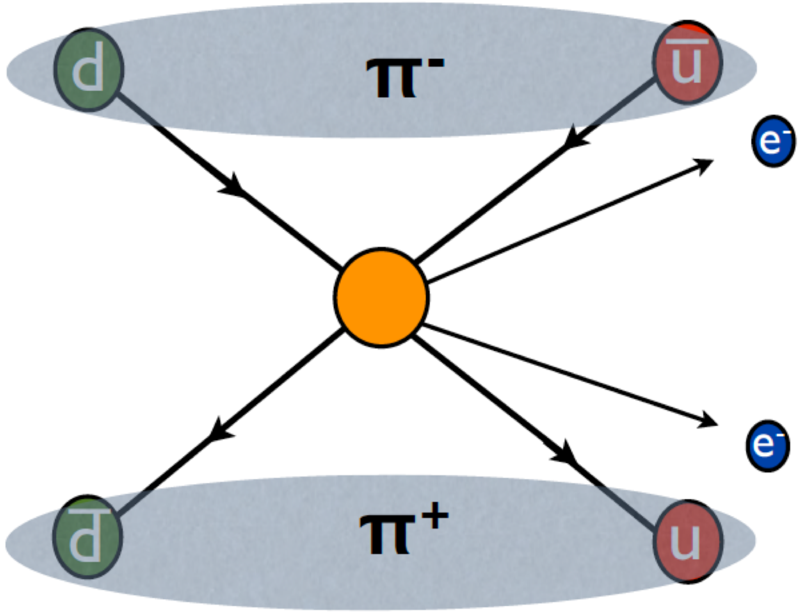
When you include correlations and meson exchange currents, the need for g_A quenching disappears

2-body currents appear to have a smaller effect in ββ decay than in β decay

Slide by J. Menendez

The Role of Lattice QCD

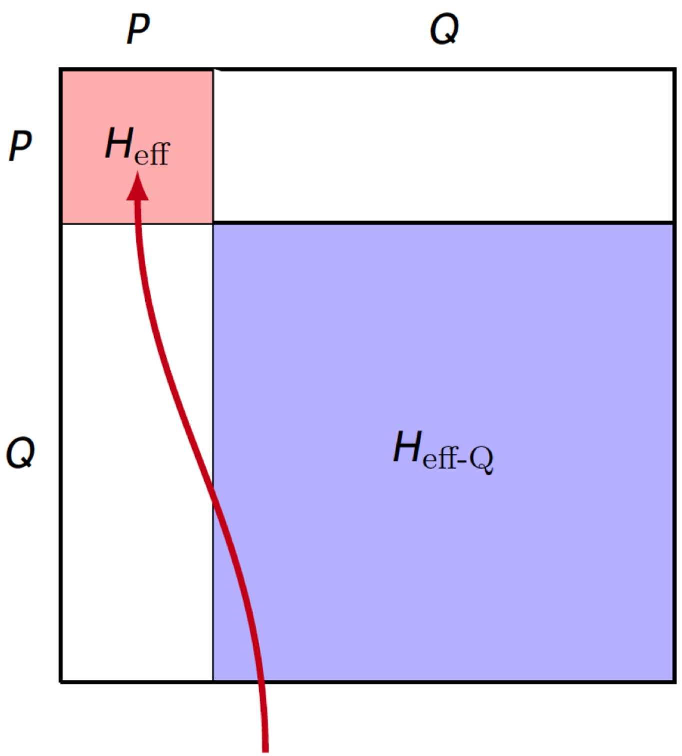
- Lattice QCD: quantize spacetime and calculate QCD directly (non-perturbative!)
- Currently, χEFT relies on low-energy constants that are determined experimentally– LQCD could calculate these directly
- Pionic matrix elements have been calculated for light neutrino exchange
- Working towards nn -> pp and on methods for constraining low-energy constants



Many-Body Methods

- Many approaches out there: coupled cluster, IM-GCM, VS-IMSRG, and more
- Many work by performing a unitary transformation to make the Hamiltonian easier to solve; often you solve just in a valence space
- These models are benchmarked to other approaches in light nuclei
- A nice overview can be found at [arXiv:2207.01085]

<u>Partition of Full Hilbert Space</u>



Shell model done here.

P = valence space
Q = the rest

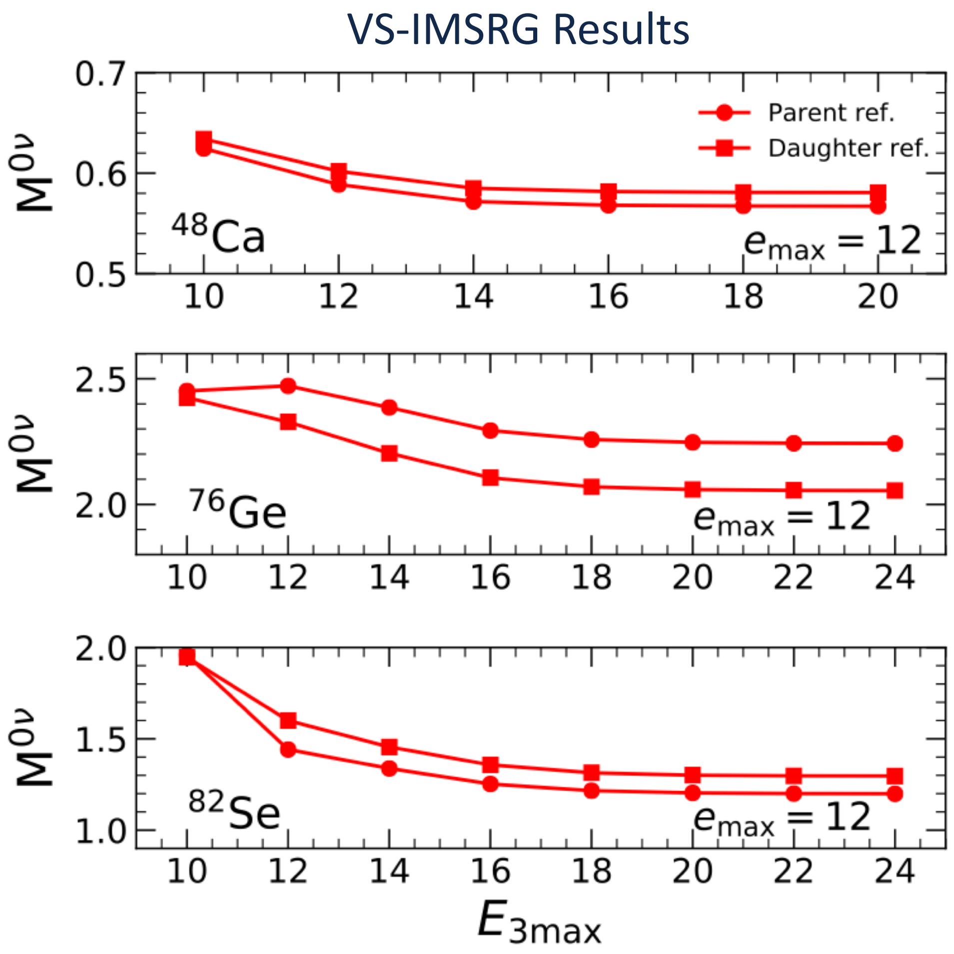
<u>Task:</u> Find unitary transformation to make H block-diagonal in P and Q, with H_{eff} in P reproducing d most important eigenvalues.

For transition operator $\hat{M}$, must apply same transformation to get $\hat{M}_{\text{eff}}$.

Courtesy of J. Engel

Ab-Initio Matrix Elements for 0νββ

- 3 methods have been able to calculate ^{48}Ca matrix elements
- 1 method has gone up to ^{76}Ge and ^{82}Se!
- More preliminary results for heavy nuclei are appearing at conferences
- After decades of work, the era of ab-initio matrix elements for 0νββ seems to be starting!
- Next focus: evaluating uncertainties in a consistent way (including uncertainties from many-body methods)

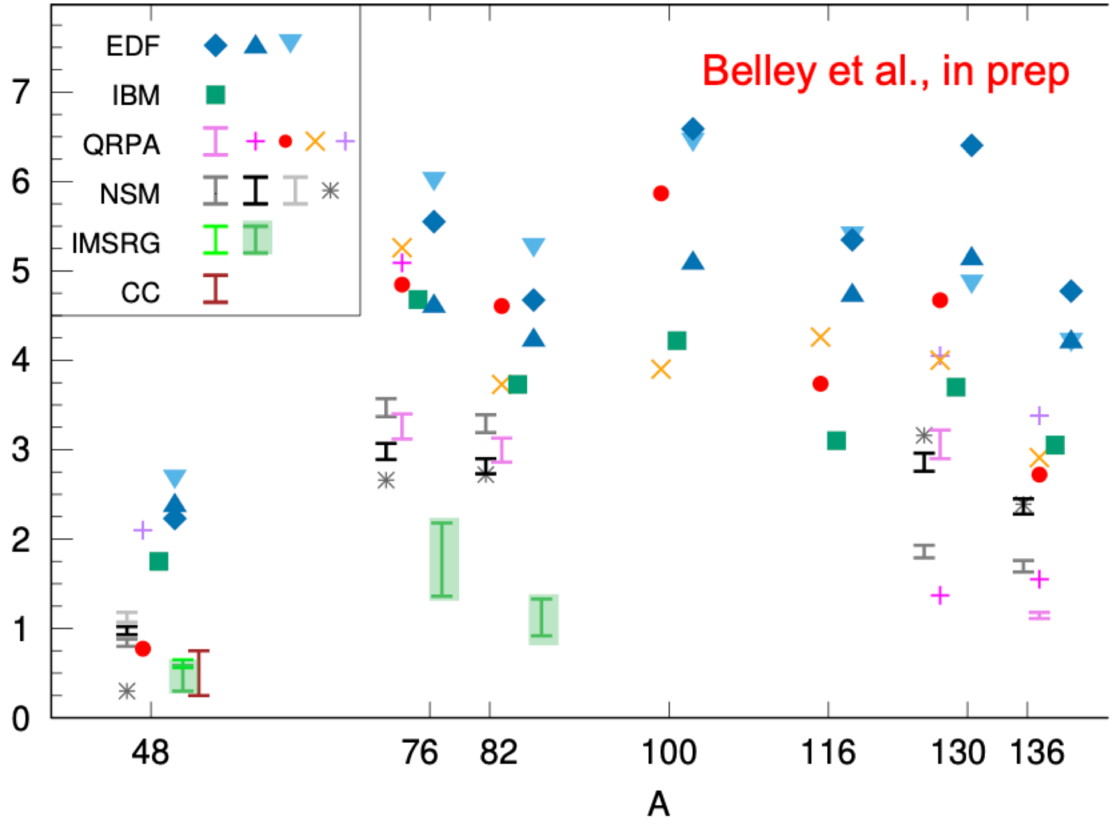


https://doi.org/10.1103/PhysRevLett.126.042502

Nuclear Matrix Elements: An Experimentalist's Perspective

- The bad news: ab-initio matrix elements seem to be small, making 0νββ searches more challenging
- The good news: we finally have an uncertainty associated with these values!
- As ab-initio calculations start to become a reality, we need to rethink how we treat uncertainties when quoting results
- How long should old calculations stick around?

Preliminary VS-IMSRG Results



Plot courtesy of J. Holt

The 0νββ Parameter Space

The "Probability of Discovery"

- What is the probability of discovering 0νββ in next-generation experiments?
- In a Bayesian framework, we can discuss the probability of discovering 0νββ (even if we don't know what $m_{\beta\beta}$ is)
- A couple of analyses exist that do this in the light Majorana neutrino exchange case. They make different assumptions for priors and get different results, which is instructive.
- We'll look at:
  1. "Discovery probability of next-generation double-β decay experiments," https://doi.org/10.1103/PhysRevD.96.053001
  2. "A Global Bayesian Analysis of Neutrino Mass Data," https://doi.org/10.1103/PhysRevD.96.073001

Parameterization

(1)

- Parameterization: $\{\Sigma m_\nu, \Delta m_{21}^2, \Delta m_{31}^2$ or $\Delta m_{23}^2, \theta_{12}, \theta_{13}, \alpha_{21}, (\alpha_{31} - \delta)\}$
- NO: use Δm_{31}^2 ; IO: use Δm_{23}^2
- Doesn't try to deal with matrix elements

(2)

- Parameterization: $m_{lightest}$, $\Delta m_{\odot}^2$, Δm_A^2, s^2_{12}, s^2_{13}, α_1, α_2, M
- $\Delta m_{\odot}^2 = \Delta m_{21}^2$;
- $\Delta m_A^2 = |m_3^2 - m_1^2|$
- M = matrix elements for the isotope in question

As we'll see, the choice of neutrino mass parameterization and prior has a major impact

Priors

Mixing angles and masses are constrained by experiment, so the priors used don't matter: NuFIT results included as part of the likelihood function

For Majorana phases, both use a flat prior from 0 to 2π

(1)

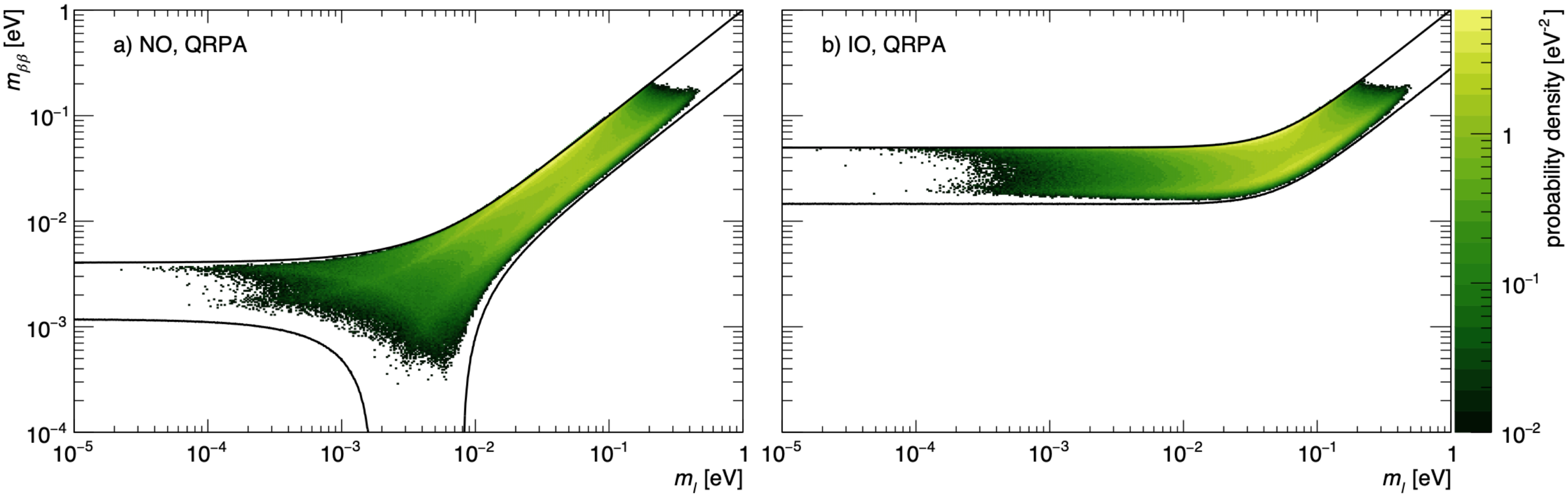
- Σm_ν: scale-invariant (logarithmic) prior
- Since Σm_ν can't be 0, you don't need to cut off the low end
- Also explicitly study the case where $m_{lightest} = 0$

(2)

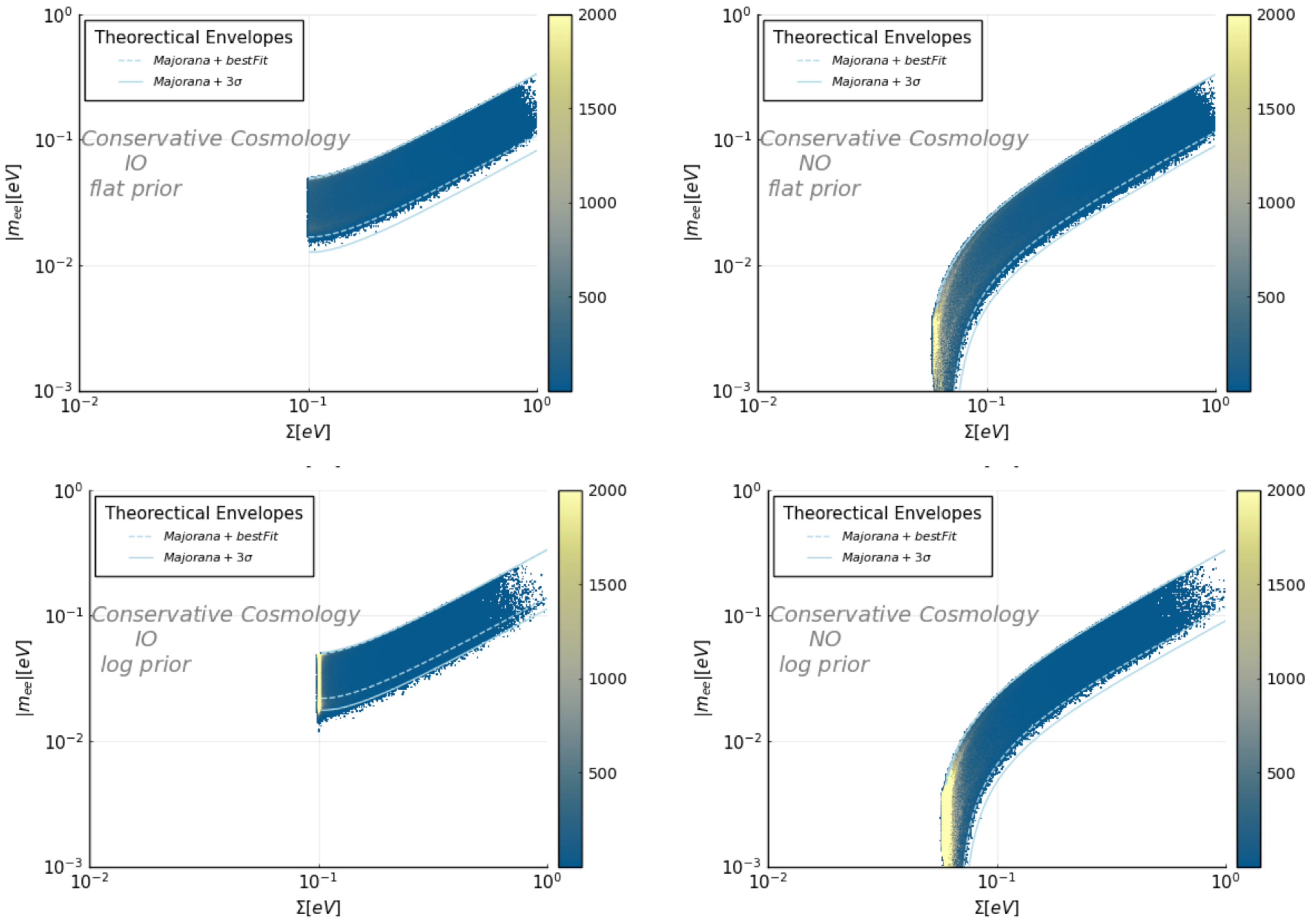
- NME priors: weight all calculations equally
- Two choices studied for $m_{lightest}$:
  - Flat: 90% of probability is at $m_{lightest} >$ 60 meV
  - Scale-invariant (logarithmic): 85% of probability is at $m_{lightest} <$ 60 meV
  - Both span {10^{-7}, 0.6 eV}

These two papers also deal with cosmology-based neutrino mass limits differently, see publications for details

Results from (1)



Results from (2)

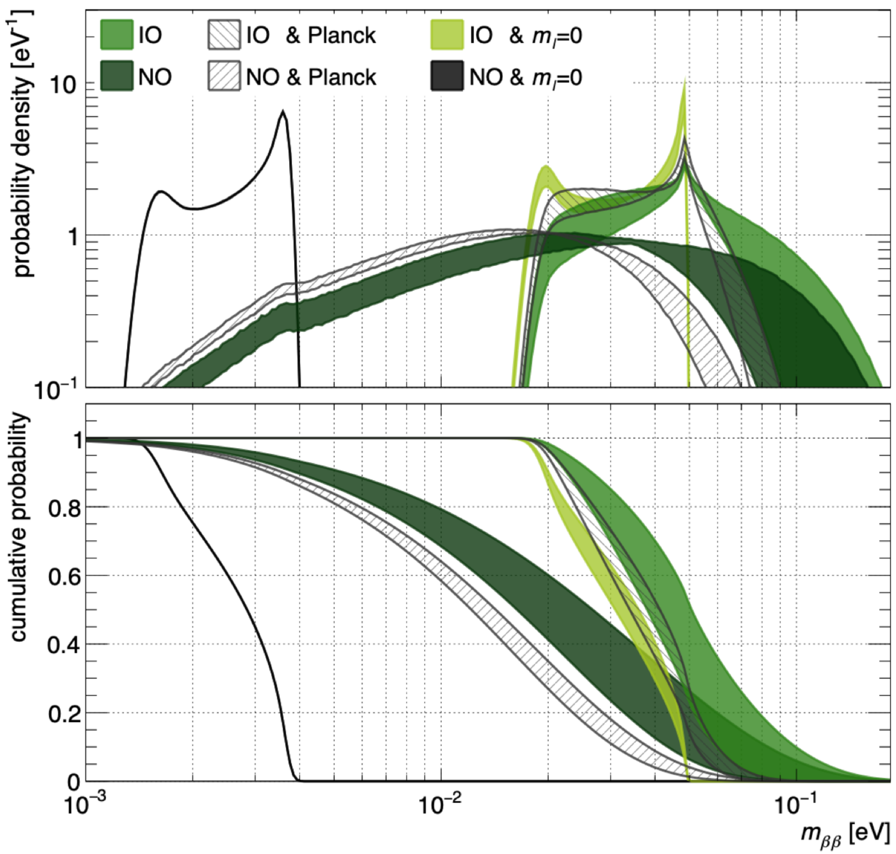


Discovery Probabilities from (1)

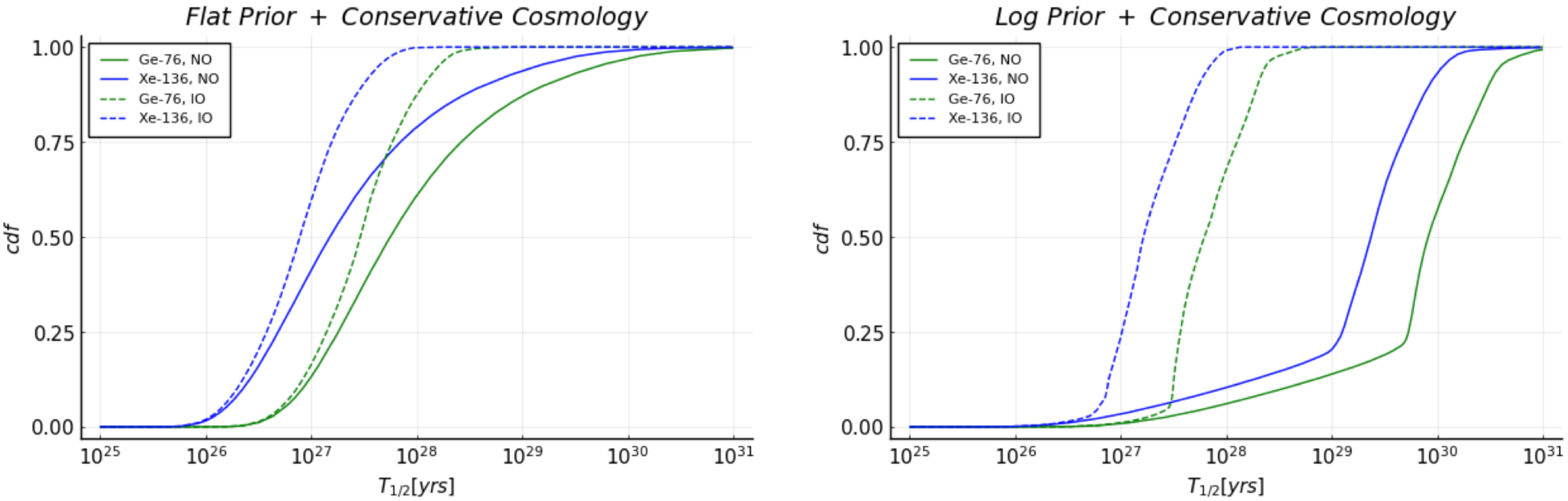
Take-aways:

Experiments that cover the IO region also cover 50% of the NO region, in this analysis

To cover 90% of NO region, need to reach $m_{\beta\beta}$~4 meV



Discovery Probabilities from (2)



"Covering the IO" ~ $T_{1/2} > 10^{28}$

In the flat prior case, the results are a bit different, but in the log prior, they're completely different

A Word of Caution

These analyses can be useful, and they're becoming more common, but you need to be careful about the parameterization and priors!

When you read something like this, think carefully about what aspect is setting the shape of the probability distribution.

E.g. another recent example analyzed the probability of NO vs IO, but the decision was actually being driven by the cosmological neutrino mass limits

The Take-Away

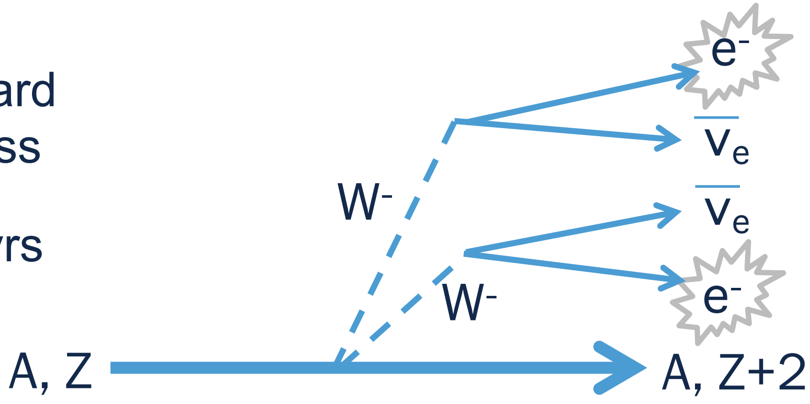
- Unless you're a pessimist about neutrino mass **and** neutrino hierarchy, the coming generation of experiments has a good chance of discovery $0\nu\beta\beta$, if it exists!
- Next, we'll talk about how to do that

Discovery, Sensitivity, and Backgrounds

The 0νββ Decay Signature

2νββ: Standard Model process

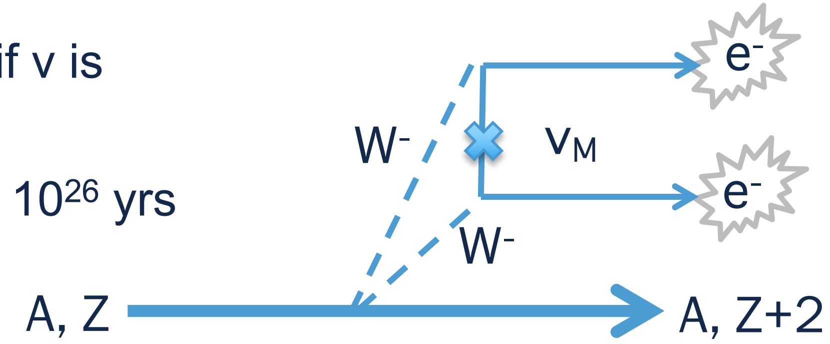
$T_{1/2} \sim 10^{20}$ yrs



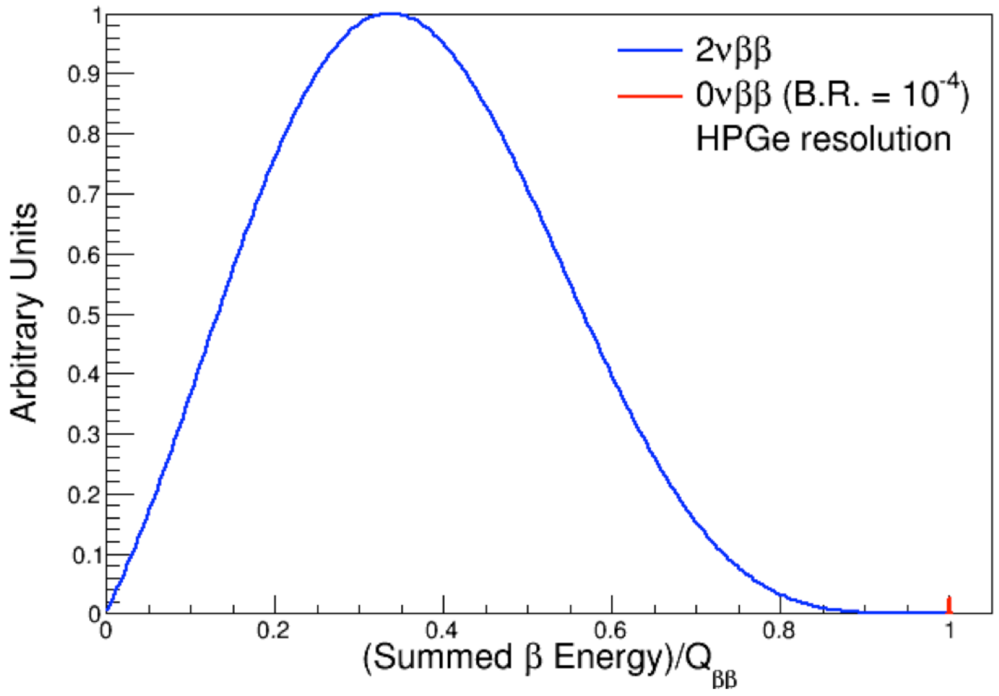
Missing energy

0νββ: Only if ν is Majorana

$T_{1/2} > 10^{25} – 10^{26}$ yrs



No missing energy

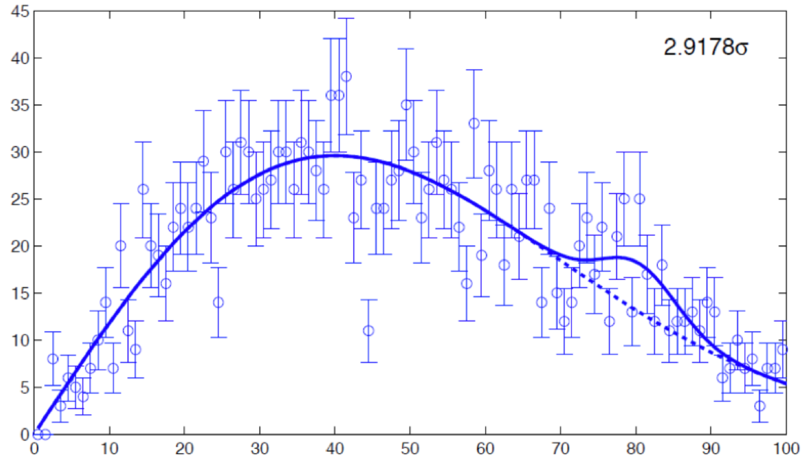


Discovery Threshold

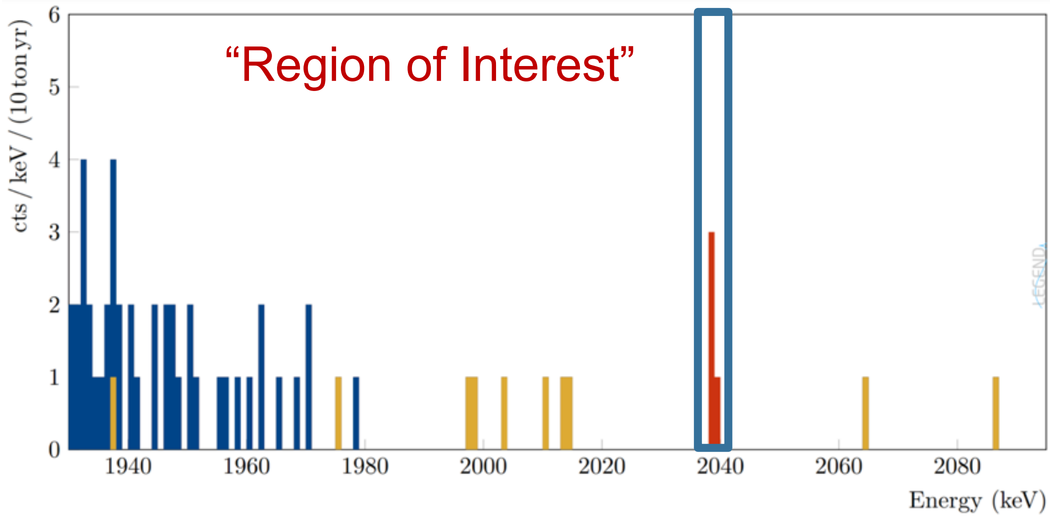
What does it mean to to discover something?

- HEP uses 5σ:
  - 1 in 10,000 chance of occurring randomly
  - Helps account for the fact that they don't know where the peak is ahead of time (the "look-elsewhere" effect)
- For 0νββ we know exactly where we need to look, so 3σ (1 in 740 random chance) is considered sufficient

Searching for new particle of unknown mass:

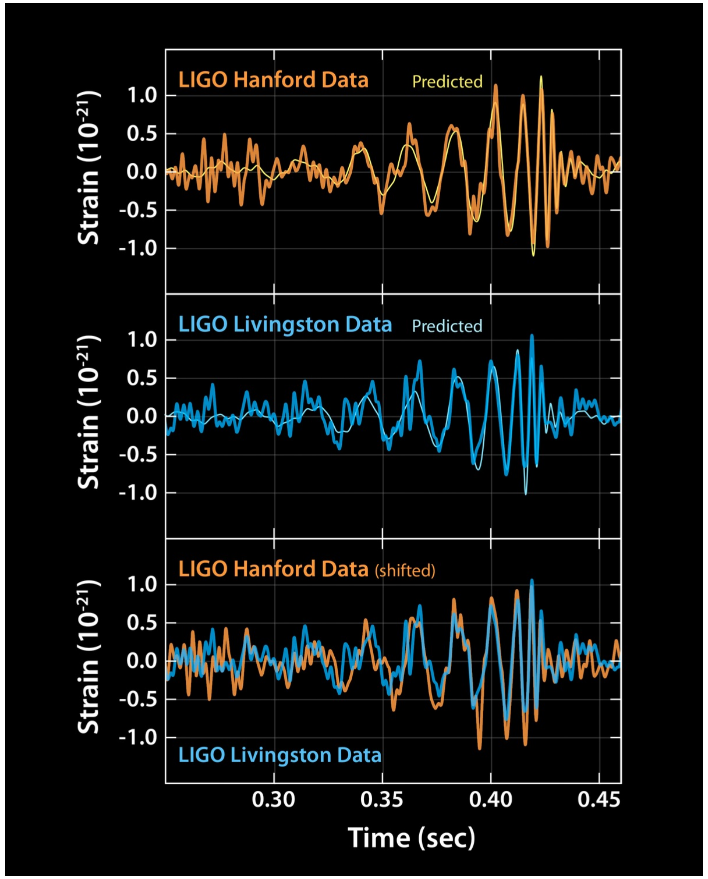


Searching for 0νββ:



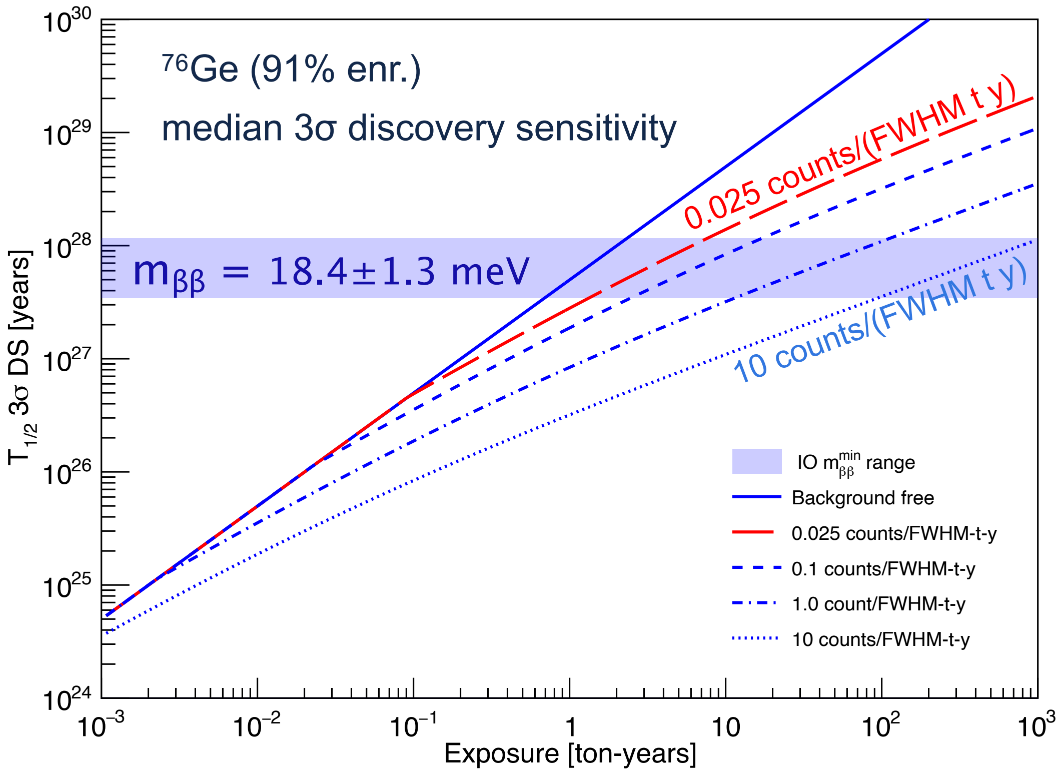
Background and Discovery

- Background-free: one event is enough for discovery!
  - Example: first LIGO event "signal-to-noise ratio" (SNR) was 24, making this a very-nearly-background-free search
  - Discovery potential grows linearly with exposure – measure for 2 days, you get twice as much signal, background stays at 0
- Background-limited: discovery potential grows as $\sqrt{\mathrm{Mt}}$
  - Toy example: suppose signal and background rate are both 1 event/day
    - Day 1: BG = 1 ± 1, S = 1
    - Day 2: BG = 2 ± 1.4, S = 2
    - Day 3: BG = 3 ± 1.7, S = 3

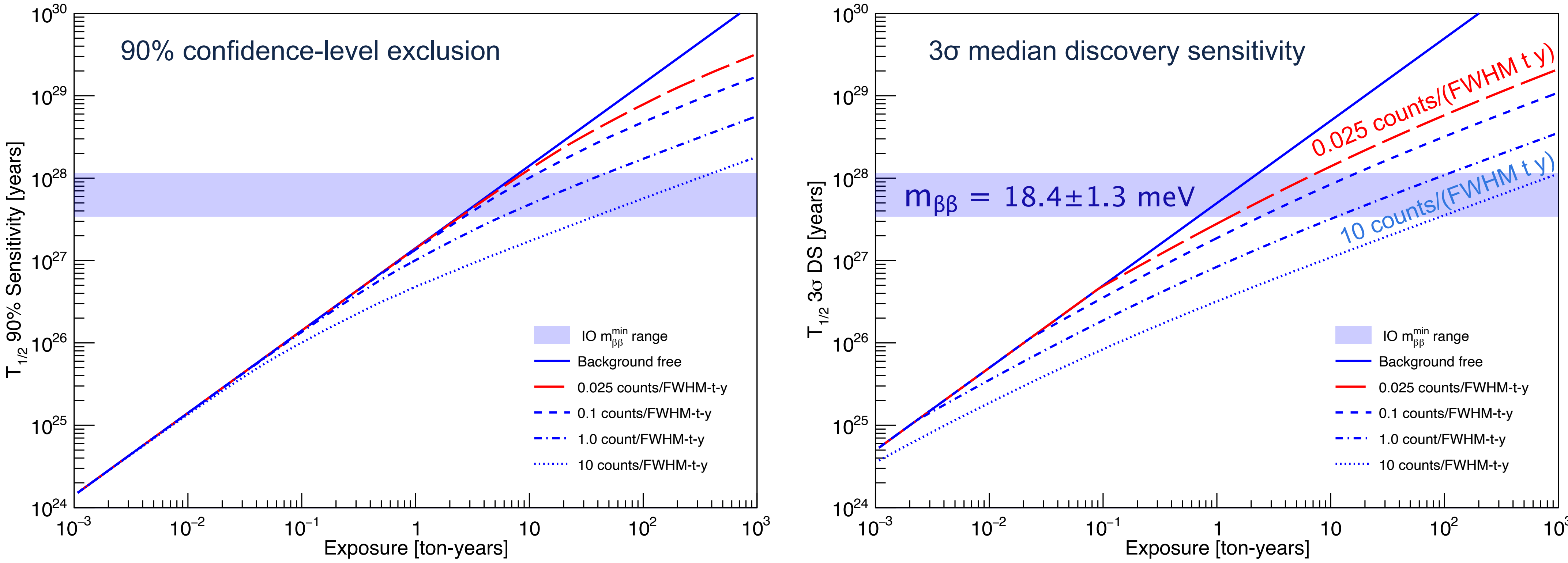


Quasi-Background-Free

- In between: quasi-background-free
  - Less than one background count expected in a 4σ Region of Interest (ROI) with the full exposure
- In this case, 3σ = 3 events in the full exposure
- Long half-lives mean you need large exposures. For 3-4 counts of 0νββ at…
  - 10^{26} years: 100 kg-years
  - 10^{27} years: 1 ton-year
  - 10^{28} years: 10 ton-years



Sensitivity vs. Discovery



Background demands are more stringent if you want to make a discovery

Designing the Ideal Experiment

Designing for Discovery

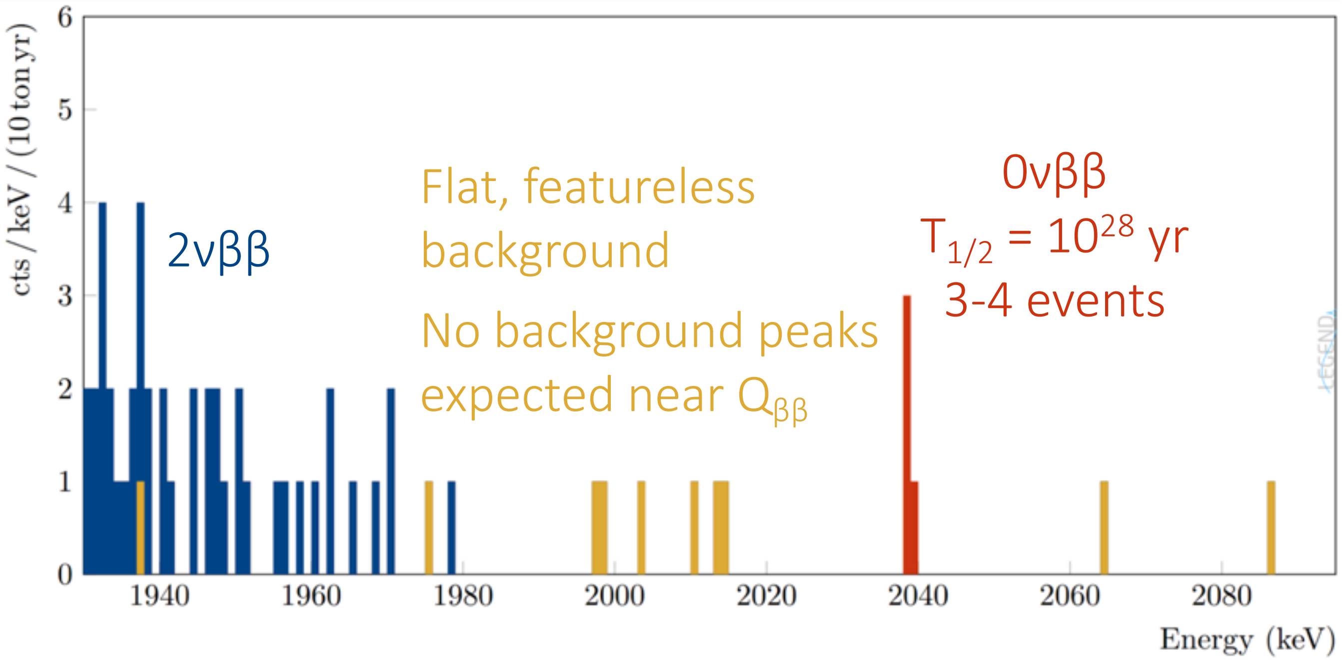
Need a good signal-to-background ratio to get statistical significance

- A very low background event rate
- The best possible energy resolution (makes ROI smaller)

Want to have low uncertainty on the background rate:

- Measure directly from data, instead of relying on background modeling

Simulated LEGEND-1000 example spectrum for $T_{1/2} = 10^{28}$ yrs, BI < 10^{-5} cts/keV kg yr, after cuts, from 10 years of data



< 10^{-6} 2νββ events leak into in $Q_{\beta\beta}\pm2\sigma$

≈0.1% FWHM energy resolution

Choosing an Isotope

How to choose?

- Q value: higher Q value, higher phase space; Q value above natural radioactivity lines reduces backgrounds
- Availability of large mass: inexpensive/abundant material is better
- Isotopic abundance/enrichment capability
- Ability to make a high-resolution and high-efficiency detector out of the material

Double-beta candidate	Q-value (MeV)	Phase space $G_{01}(y^{-1})$	Isotopic abundance (%)	Enrichable by centrifugation
^{48}Ca	4.27226 (404)	6.05×10^{-14}	0.187	No
^{76}Ge	2.03904 (16)	5.77×10^{-15}	7.8	Yes
^{82}Se	2.99512 (201)	2.48×10^{-14}	9.2	Yes
^{96}Zr	3.35037 (289)	5.02×10^{-14}	2.8	No
^{100}Mo	3.03440 (17)	3.89×10^{-14}	9.6	Yes
^{116}Cd	2.81350 (13)	4.08×10^{-14}	7.5	Yes
^{130}Te	2.52697 (23)	3.47×10^{-14}	33.8	Yes
^{136}Xe	2.45783 (37)	3.56×10^{-14}	8.9	Yes
^{150}Nd	3.37138 (20)	1.54×10^{-13}	5.6	No

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	^{48}Ca	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	^{48}Ca	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	^{76}Ge	Ge diodes in LAr	15 kg	Complete
GERDA II	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Complete
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
NEMO3	^{100}Mo/^{82}Se	Foils with tracking	6.9 kg/0.9 kg	Complete
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF6 high pressure gas TPC	50 kg	R&D
AMoRE	^{100}Mo	CaMoO4 bolometers (+ scint.)	5 kg	Construction
CUPID	^{100}Mo	Scintillating Bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE-0	^{130}Te	TeO_2 Bolometer	11 kg	Complete
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
SNO+ Phase II	^{130}Te	3% ^{nat}Te in liquid scint.	8 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scint.	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scint.	750 kg	Operating
KamLAND2-ZEN	^{136}Xe	2.7% in liquid scint.	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	Xe liquid TPC	3.5 tonnes	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DCBA	^{150}Nd	Nd foils & tracking chambers	30 kg	R&D

R&D | Construction | Operating | Complete

From J. Wilkerson

This table is a bit out of date, but it gives you an idea of the variety of isotopes and techniques in use

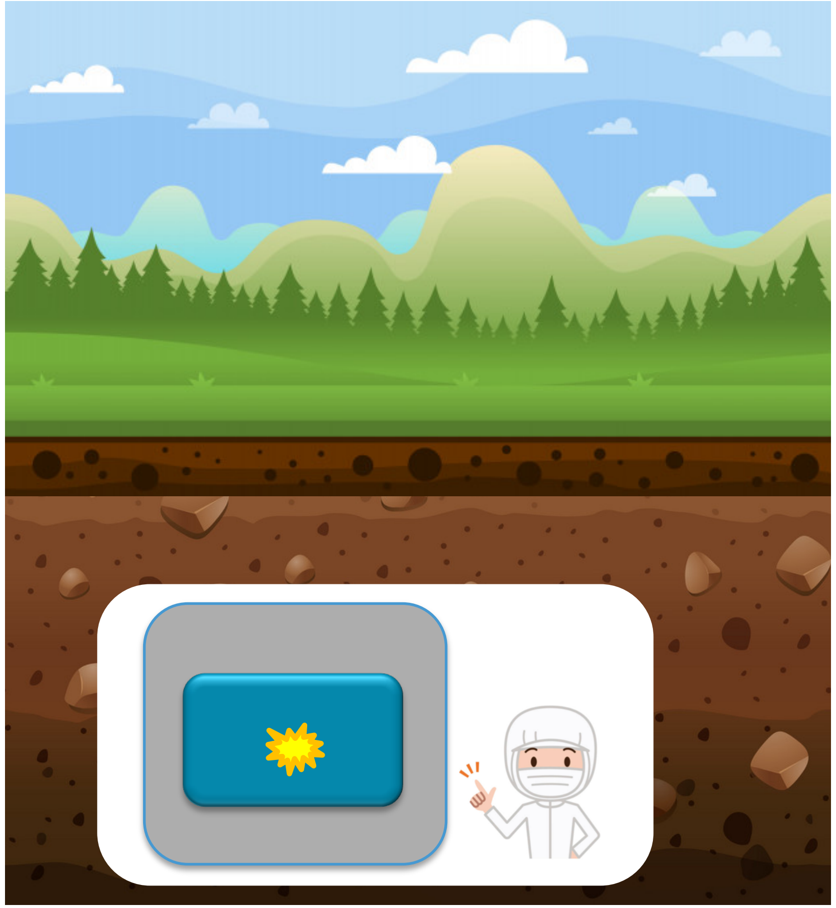
The Basic Idea

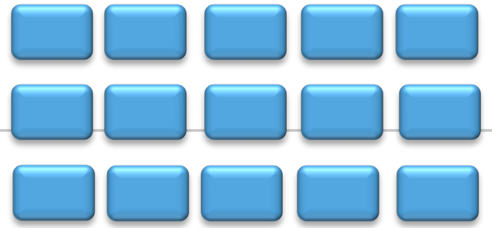
If I want to see 1 atom of $3x10^{24}$ decay (and be sure of what I saw), I need:

- Very high efficiency
- Very low rates of other kinds of events

This is hard, the world is very radioactive!

Most Experiments





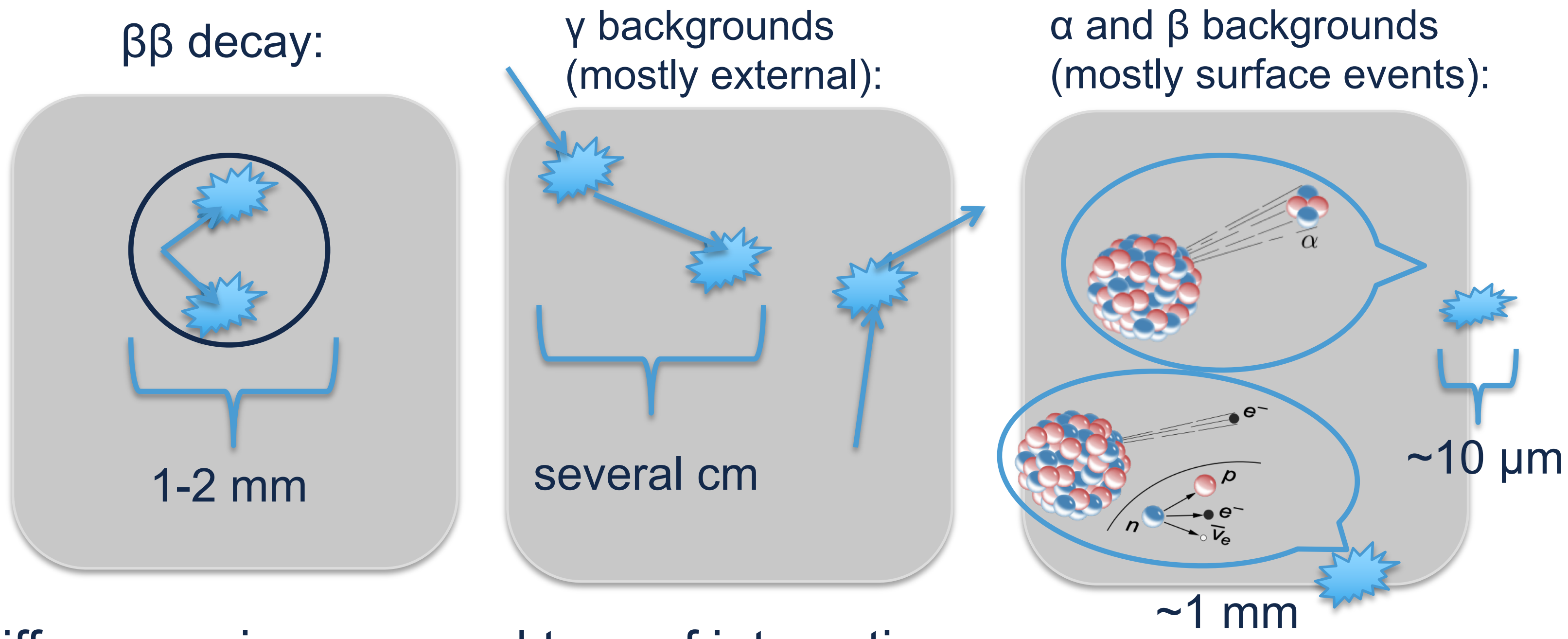
Granular Detectors

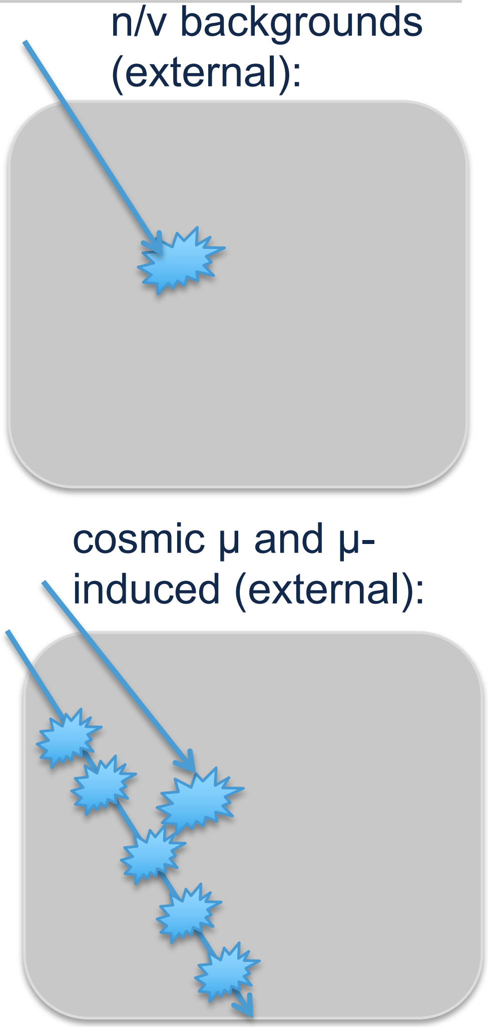
- Bolometers, crystal scintillators, semiconductors
- E.g. CUPID, LEGEND

Monolithic Detectors

- TPCs and liquid scintillator
- E.g. KamLAND-Zen, nEXO

Background Rejection





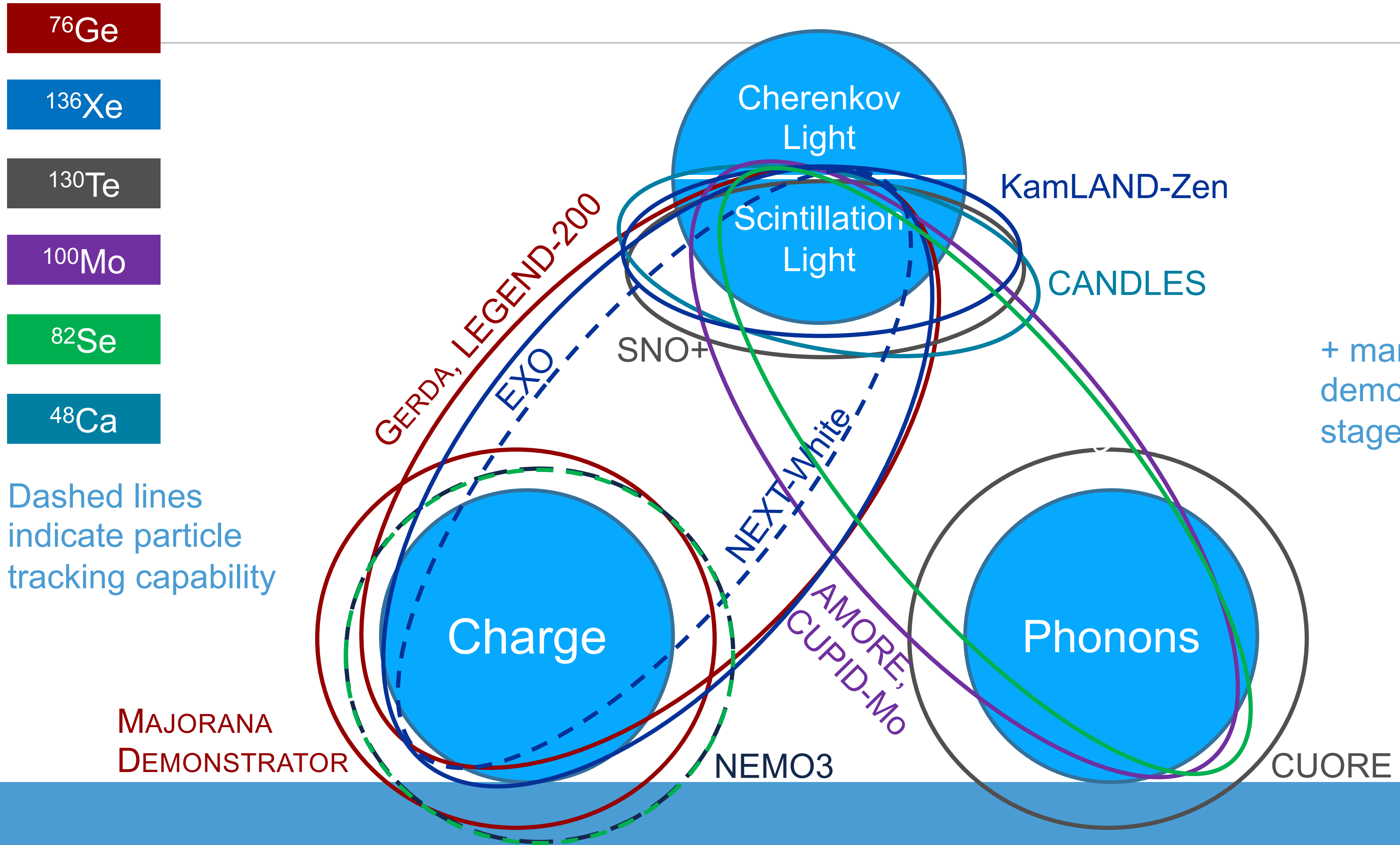
- Differences in range and type of interaction
- γ, β, and μ interact with electrons
- α, ν, and n scatter off of nuclei
- Certain background occur only near detector surface
- Cosmogenics leave long tracks or have multiple time-correlated events

Some Common Backgrounds

- Cosmogenic activation of materials
  - Store materials underground, build your experiment underground
  - Use coincidence signatures to reduce background
- Radon contamination and α backgrounds
  - Rn is emitted from rock underground, sticks to everything and has a long half-life (depending on where decay chain is broken)
  - Keep sensitive parts in Rn-reduced environment
- U and Th Decay Chains
  - Choose ultra-low background materials and keep them clean
  - Take advantage of self-shielding, active veto, and event topology to reduce backgrounds
- $2\nu\beta\beta$ Decay
  - Improved energy resolution reduces this background
  - Fast timing eliminates pile-up background

Photo: Enrico Sacchetti

Experimental Techniques: Current Generation

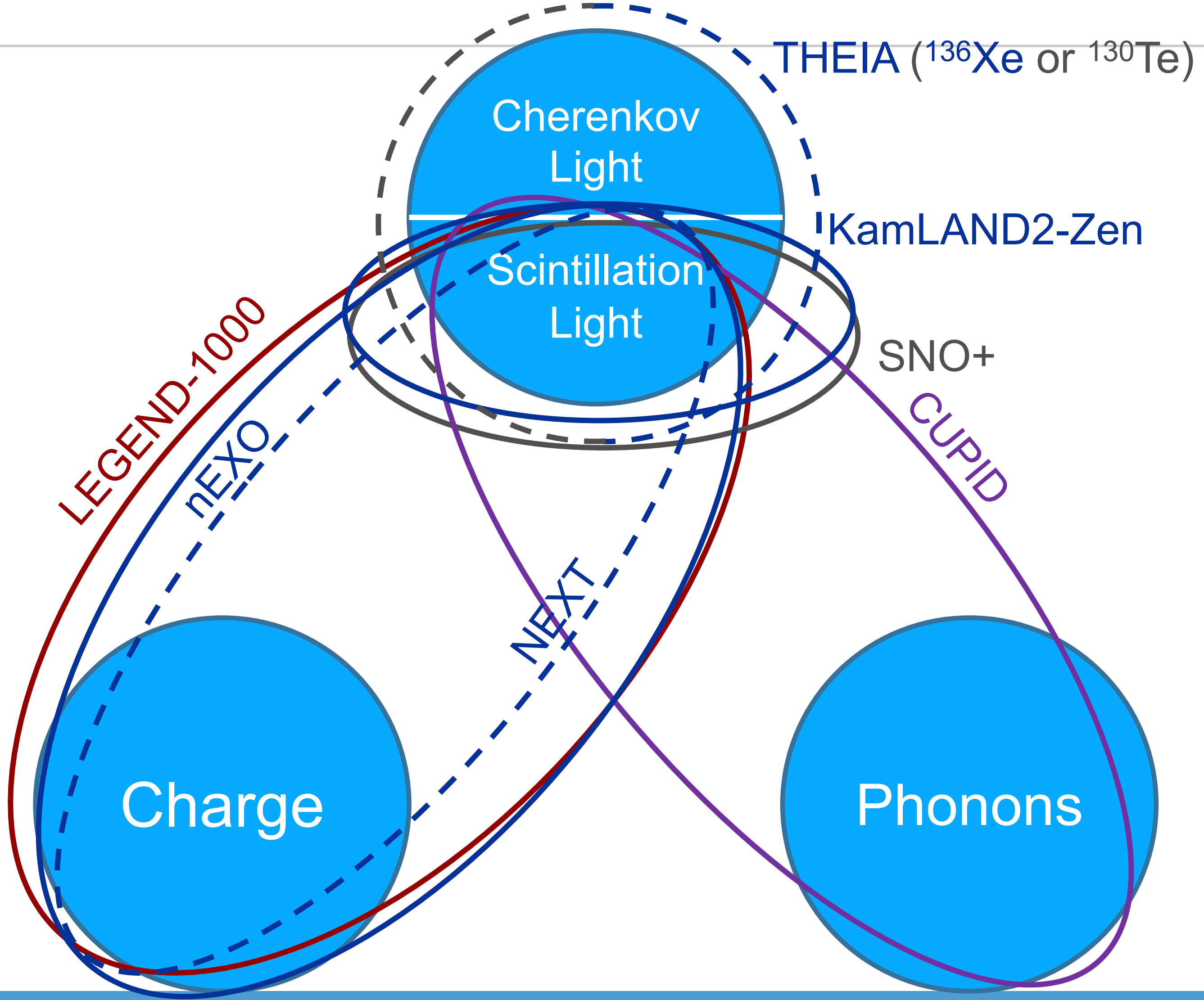


Dashed lines indicate particle tracking capability

+ many others in the demonstrator and R&D stages

Experimental Techniques: Ton Scale and Beyond

- ^{76}Ge
- ^{136}Xe
- ^{130}Te
- ^{100}Mo



Dashed lines indicate particle tracking/ direction capability

+ plans for daughter isotope tagging

Summary

- Calculating NMEs for 0νββ is challenging, but there's been very exciting progress in recent years, with more to come
- To discover 0νββ, we need very large experiments with very low backgrounds
- Tomorrow you'll hear more about many of these experiments