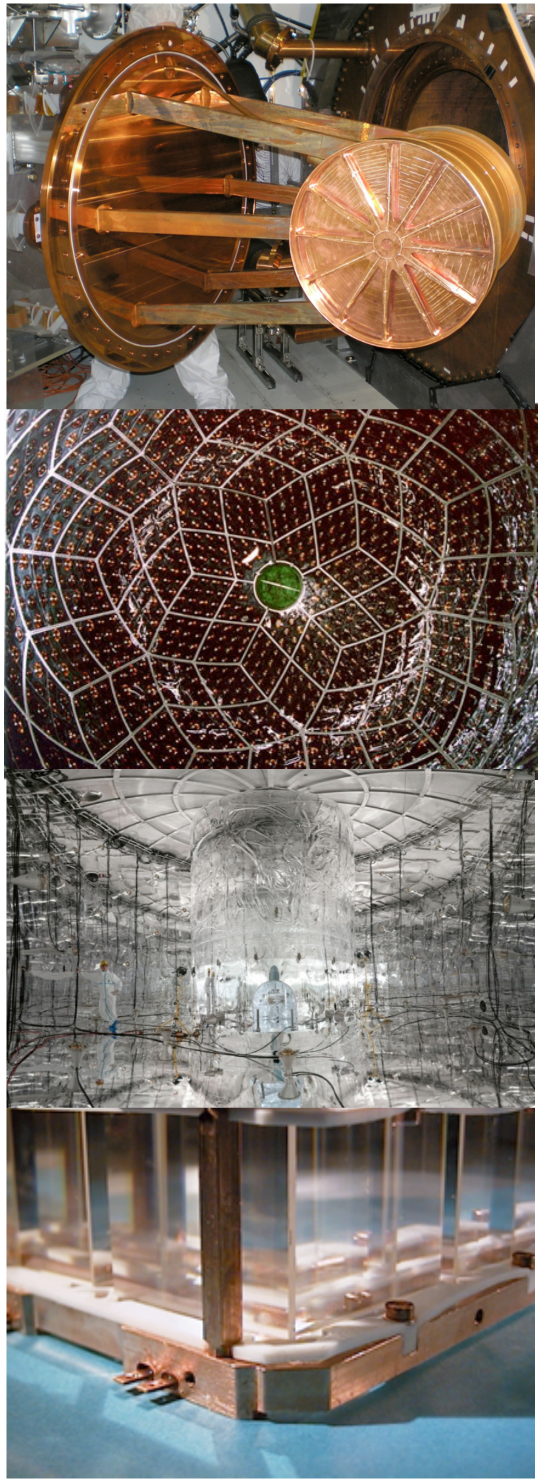
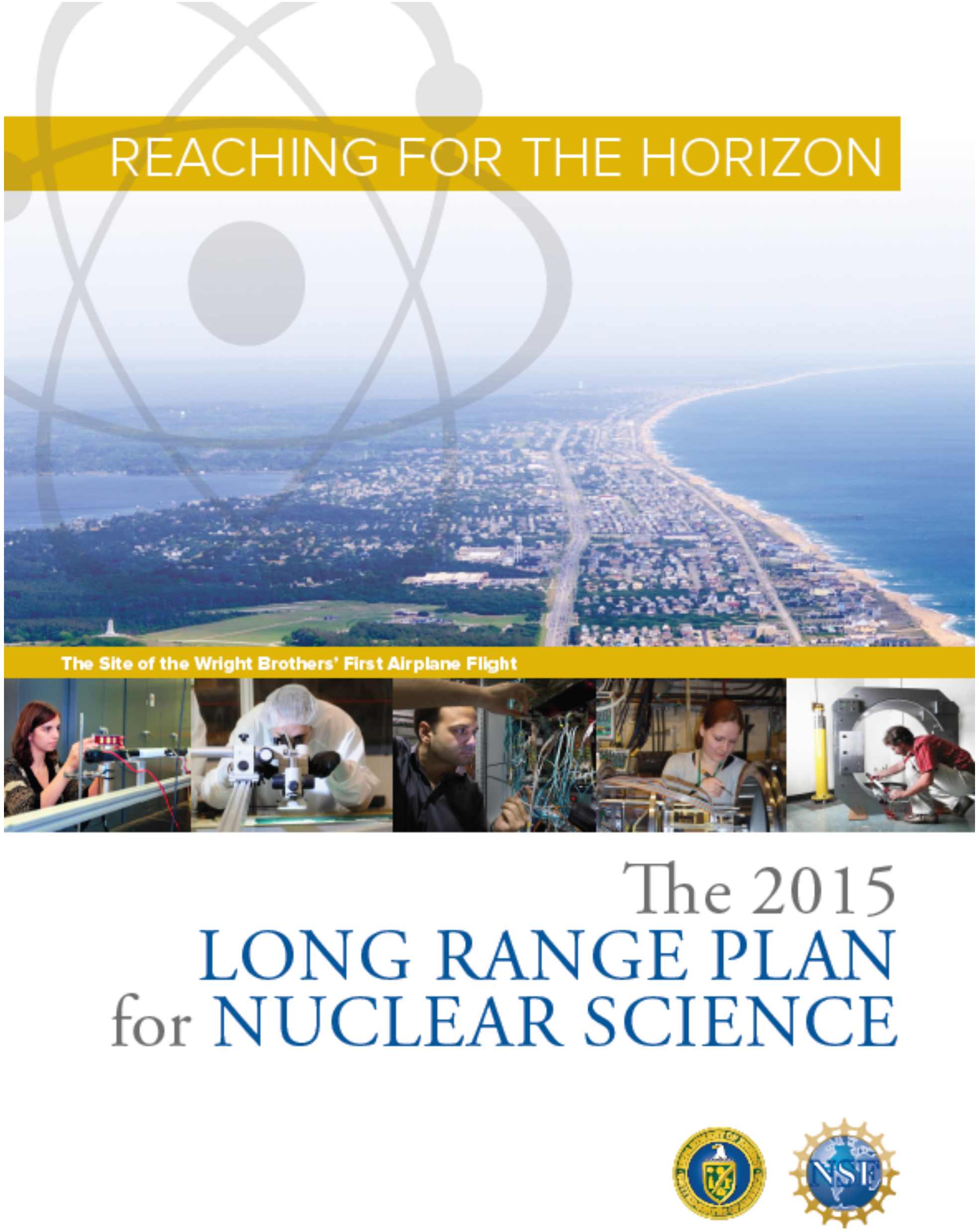


Double-Beta Decay: Part I
Phase Space, Matrix Elements and Experiments

Lindley Winslow
Massachusetts Institute of Technology



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

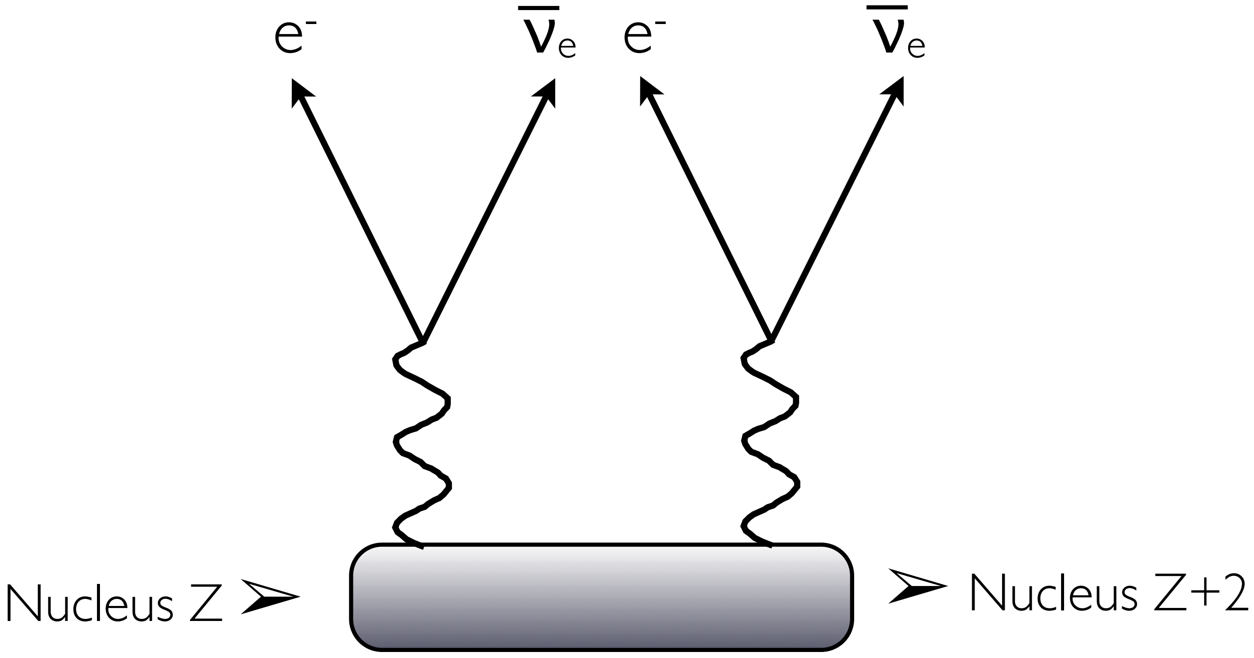
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

The 2015 Long Range Plan for Nuclear Science makes the ton-scale neutrinoless double-beta decay experiment the highest *new* priority.

What is Double-Beta Decay?

Two Neutrino Double Beta Decay:
The Standard Model Process

This process is completely allowed and the rate was first calculated by Maria Goeppert-Mayer in 1935.

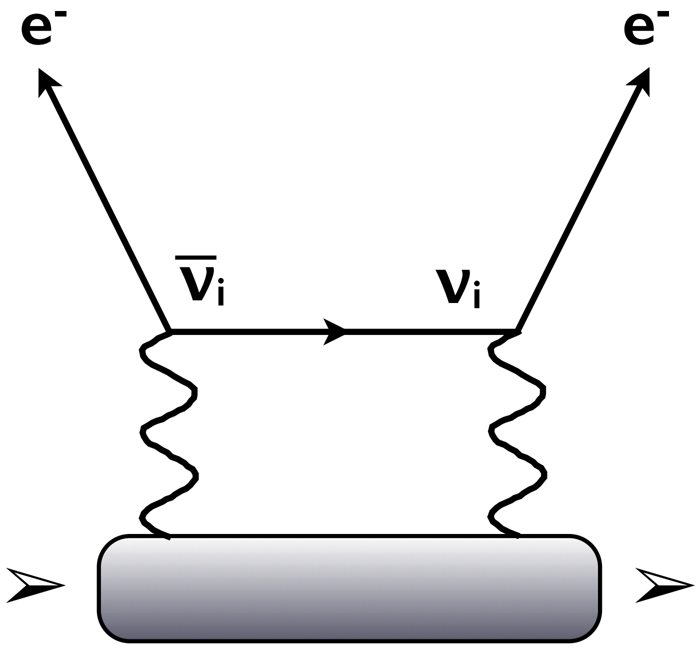


Nuclear Process

Phys. Rev. 48, 512-516 (1935)

Neutrinoless Double Beta Decay:
The New Physics

The observation of this process would prove that the neutrino is a Majorana particle i.e. its own anti-particle.

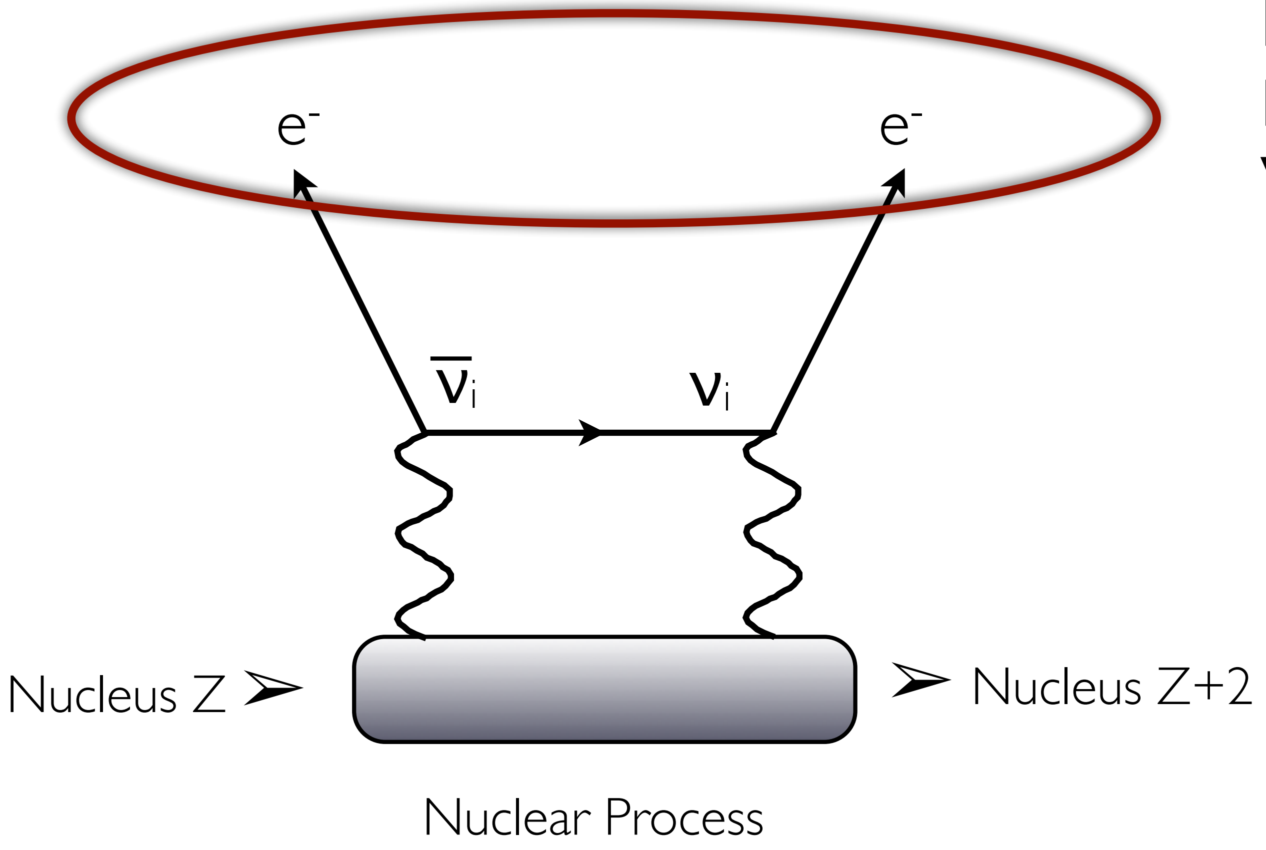


e^- e^-

$\bar{\nu}_i$ ν_i

Nucleus Z ➢ ➢ **Nucleus Z+2**

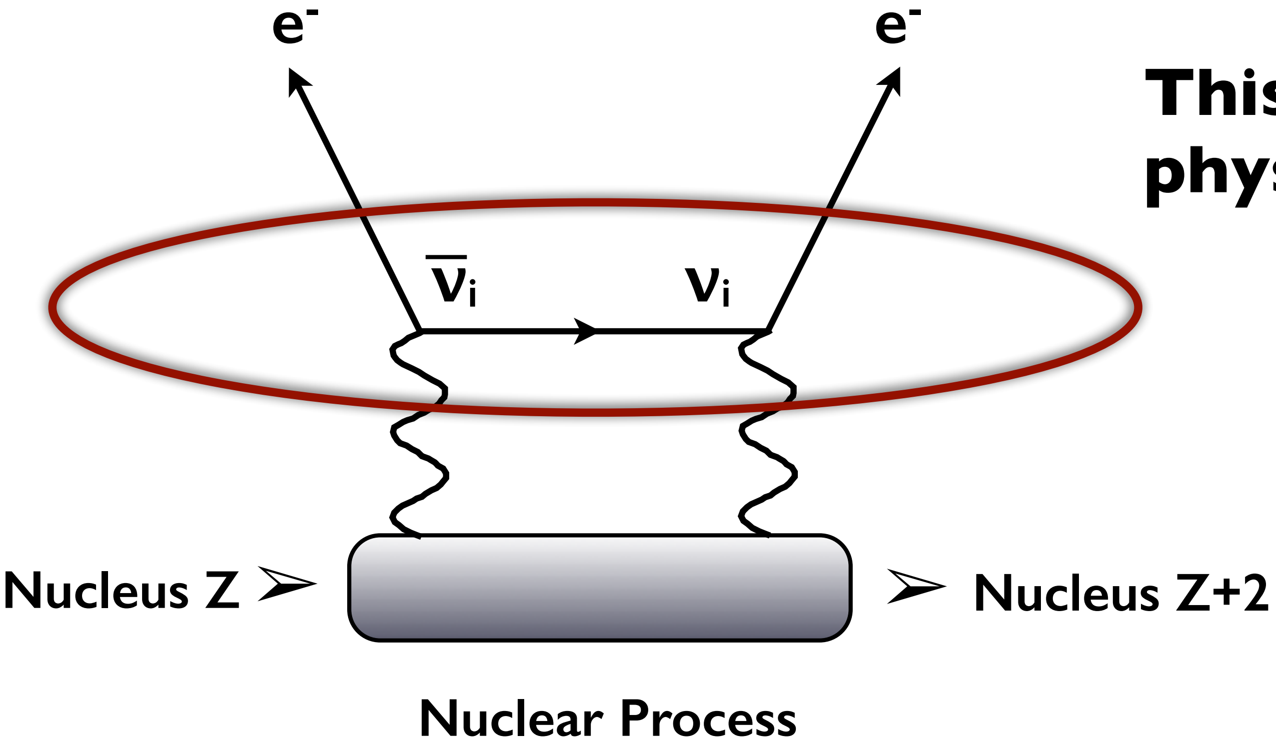
Nuclear Process



Lepton Number Violation!

Neutrinoless Double Beta Decay

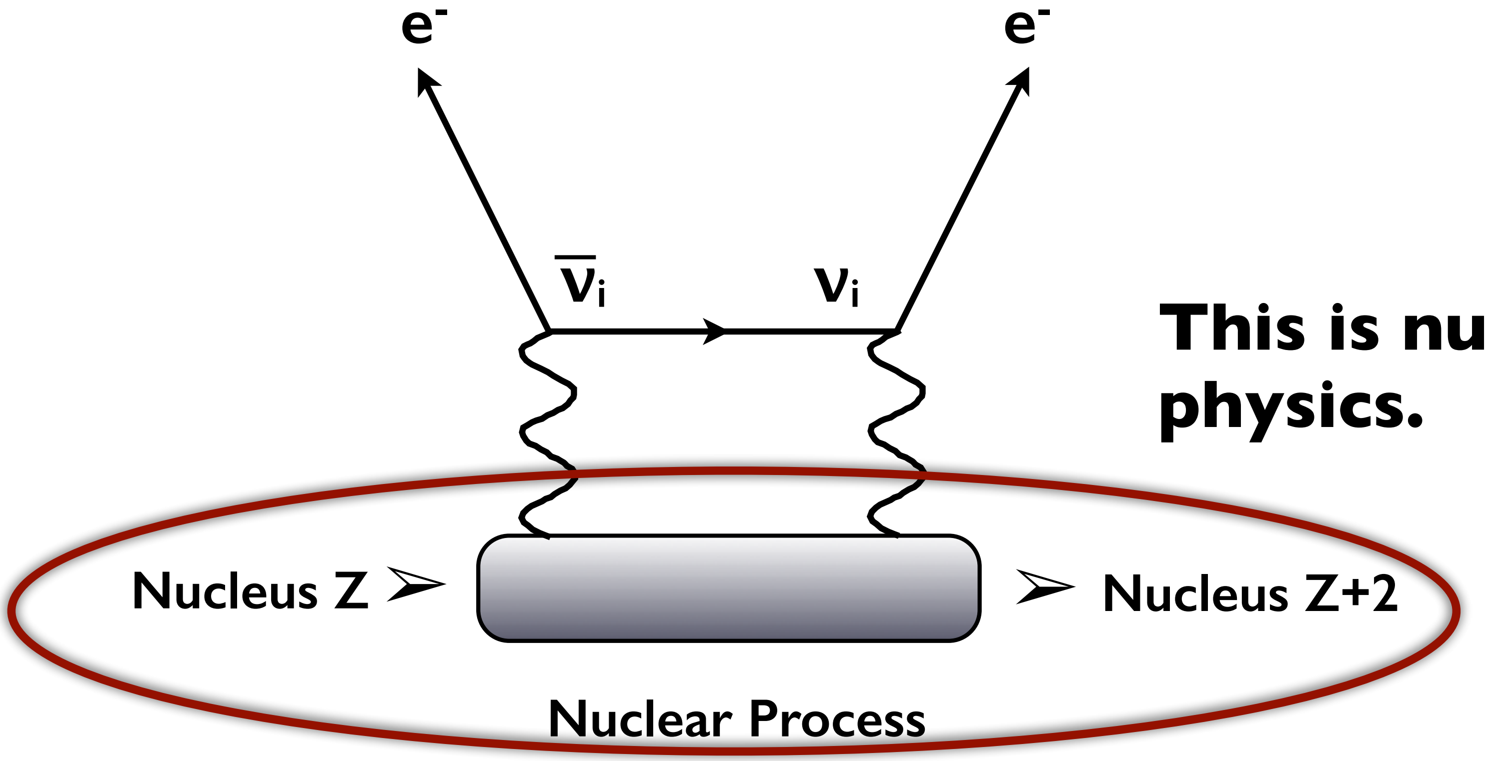
Light Majorana Neutrino Exchange (LMNE)



This is particle physics.

Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange (LMNE)



This is nuclear physics.

Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange (LMNE)

How do we measure this?

What is measured is a half-life...

The half-life of the neutrinoless decay via LMNE:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase space factor
This is a difficult calculation dependent on the decay mechanism.
Notice higher endpoint means faster rate.

What is measured is a half-life:

The half-life of the neutrinoless decay via LMNE:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Nuclear Matrix Element

This is a very difficult calculation with large errors and substantial variation between isotopes...motivates searches with multiple isotopes.

What is measured is a half-life:

The half-life of the neutrinoless decay via LMNE:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Effective Majorana Mass
of the neutrino

Electron Neutrino Mass:

This is what Joe Formaggio talked about!

$$m_{\nu_e}^2 = \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

Effective Majorana Mass:

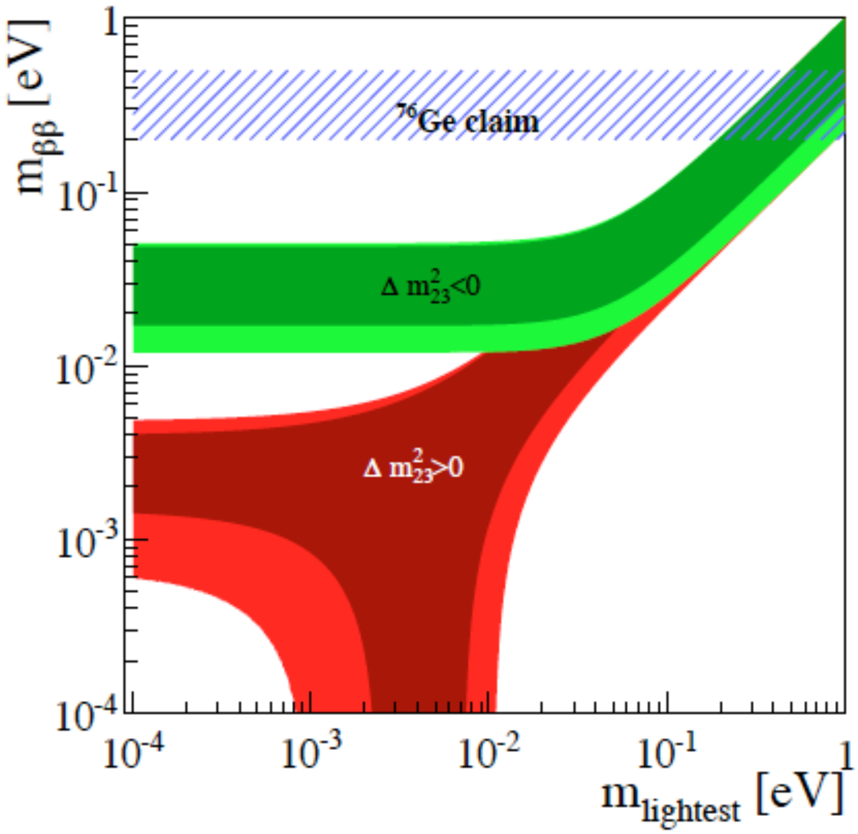
$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

Two more phases!

Double Beta Decay Parameter Space:
The Lobster Plots…

Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$



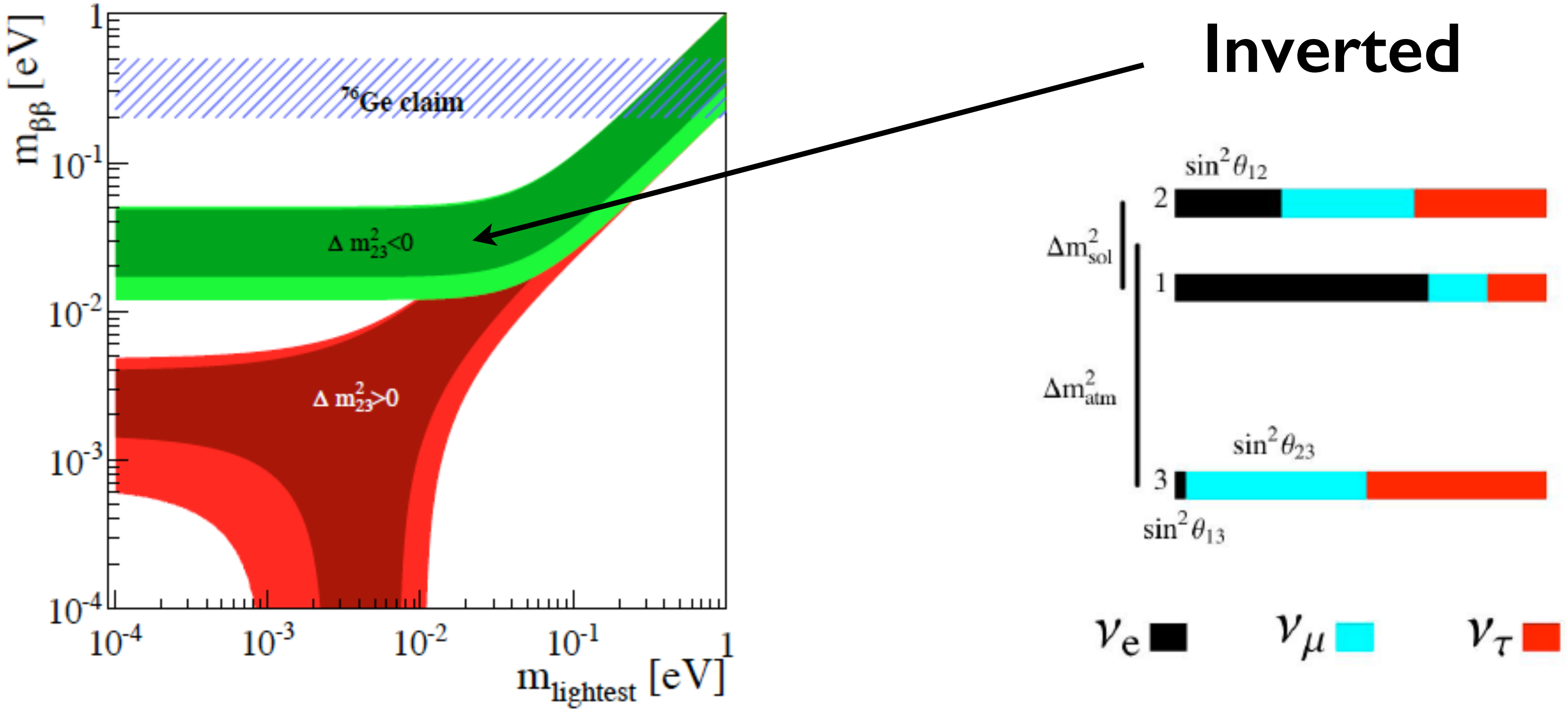
excluded

more sensitive experiments needed

As experiments become more sensitive they push down in this parameter space excluding larger masses.

Double Beta Decay Visualizing the Equations:

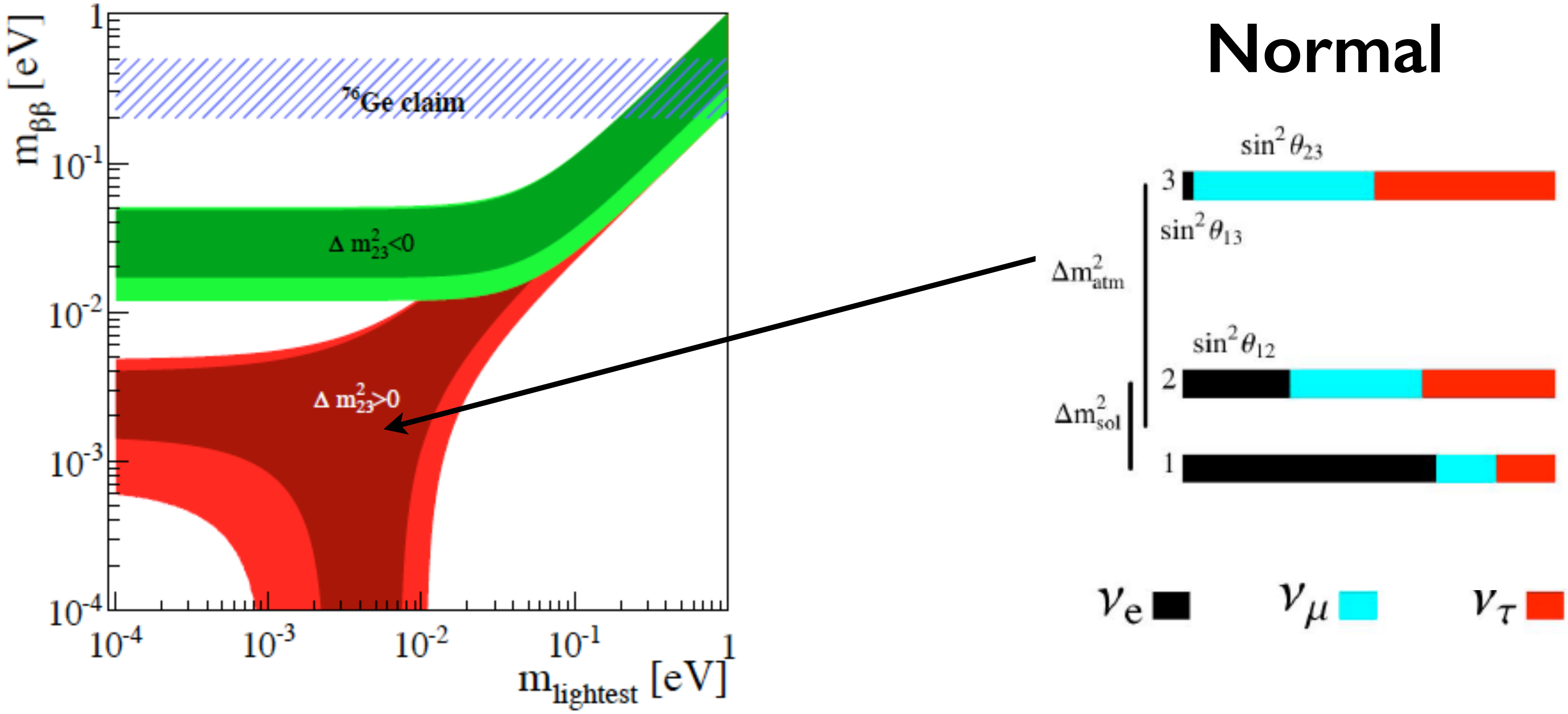
$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$



Inverted

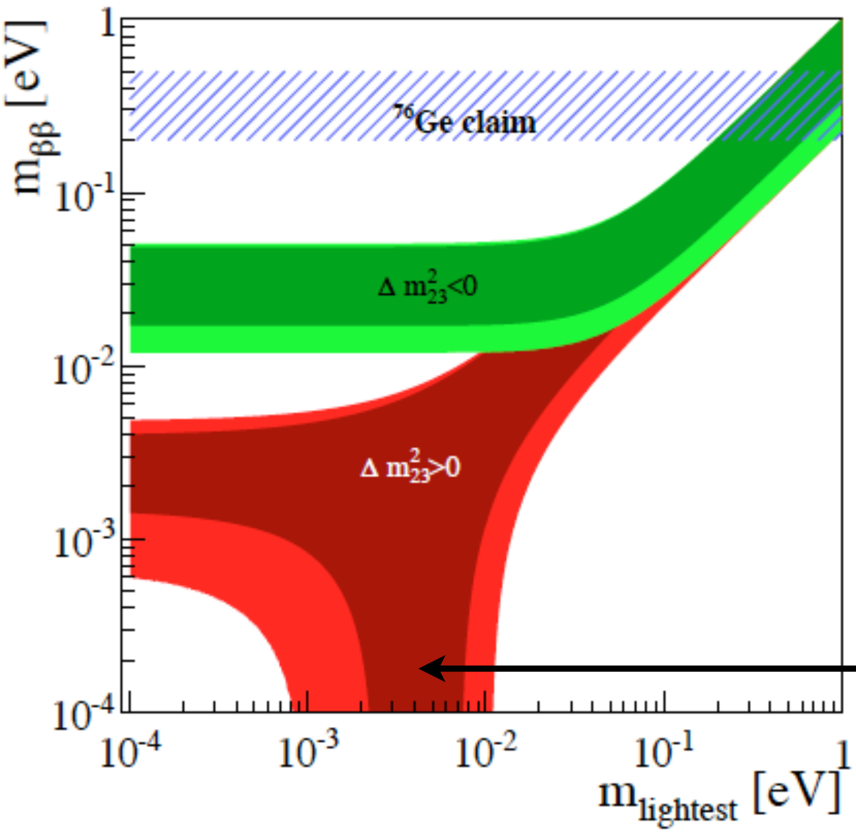
Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$



Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

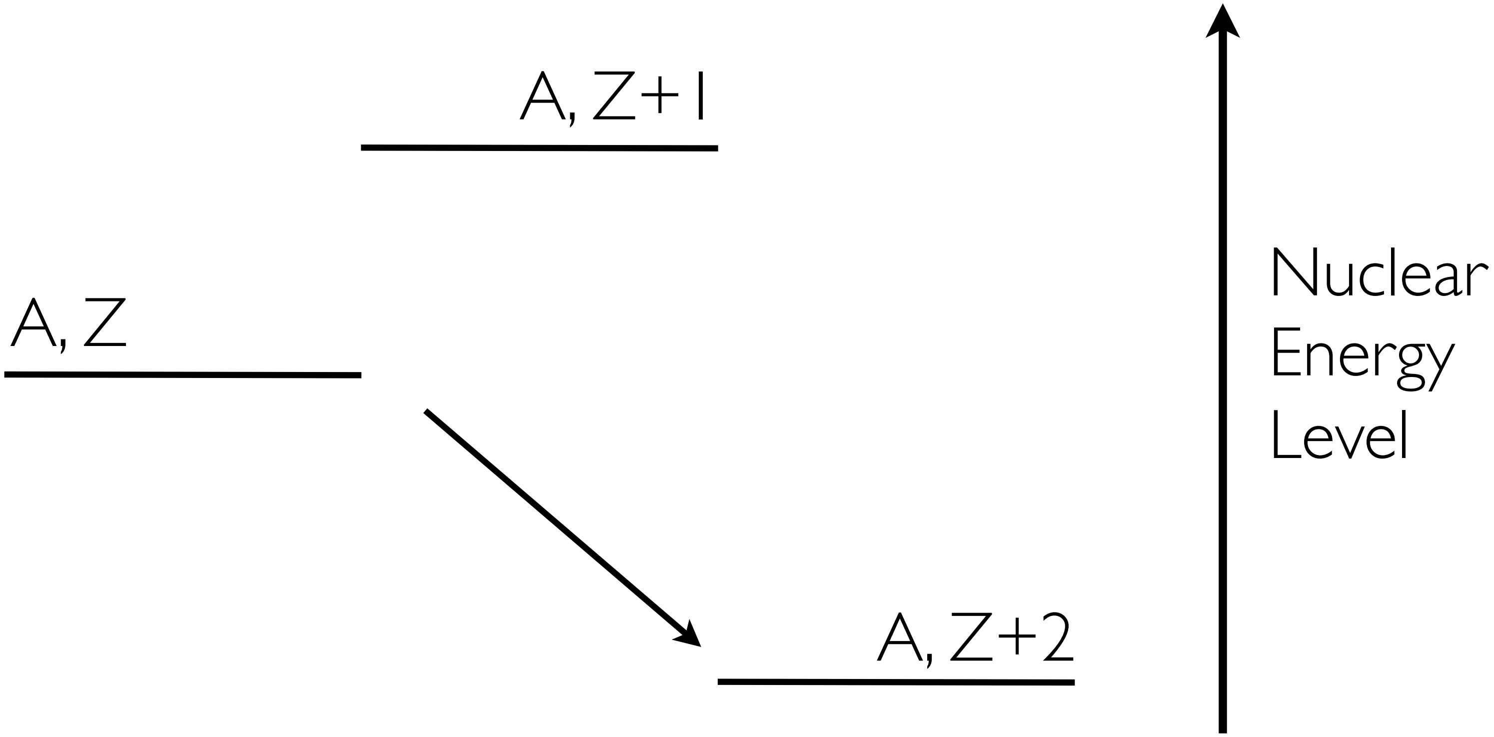


The dark part of the width of these bands is real and if nature is cruel there could be some very nasty interference.

What Nuclei?

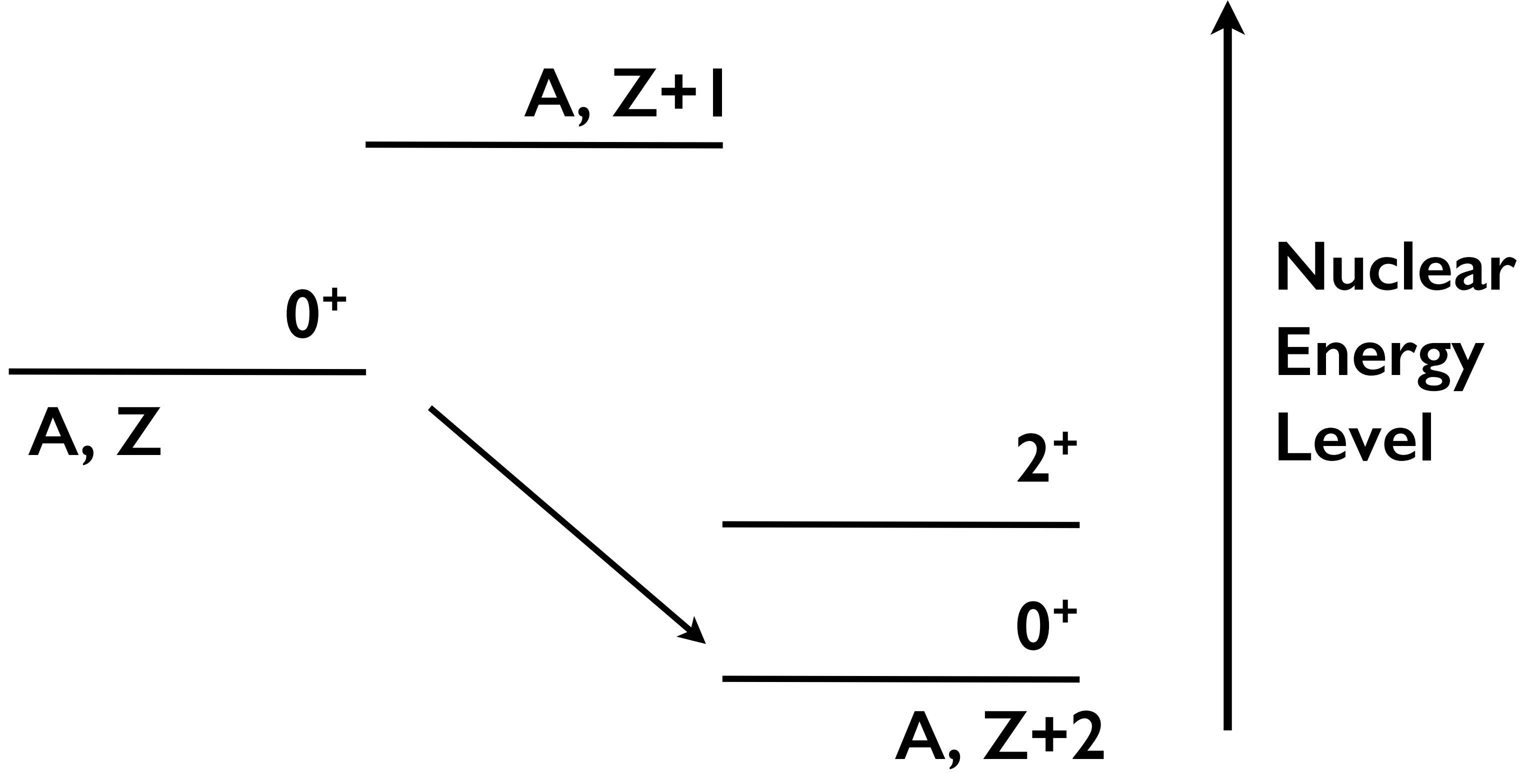
Double Beta Decay

Due to energy conservation some nuclei can't decay to their daughter nucleus, but can skip to their granddaughter nucleus.



Double Beta Decay

More specifically, this happens only for even-even nuclei with spin and parity of the nucleus 0^+ and we typically look for the decay to the ground state also 0^+ although the decay to a 2^+ excited state is also possible.



Semi-Empirical Mass Formula

mass of a nucleus $m = Zm_p + Nm_n - \frac{E_B}{c^2}$

more bound
less mass
more stable

Binding Energy $$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} \pm \delta(A, Z)$$

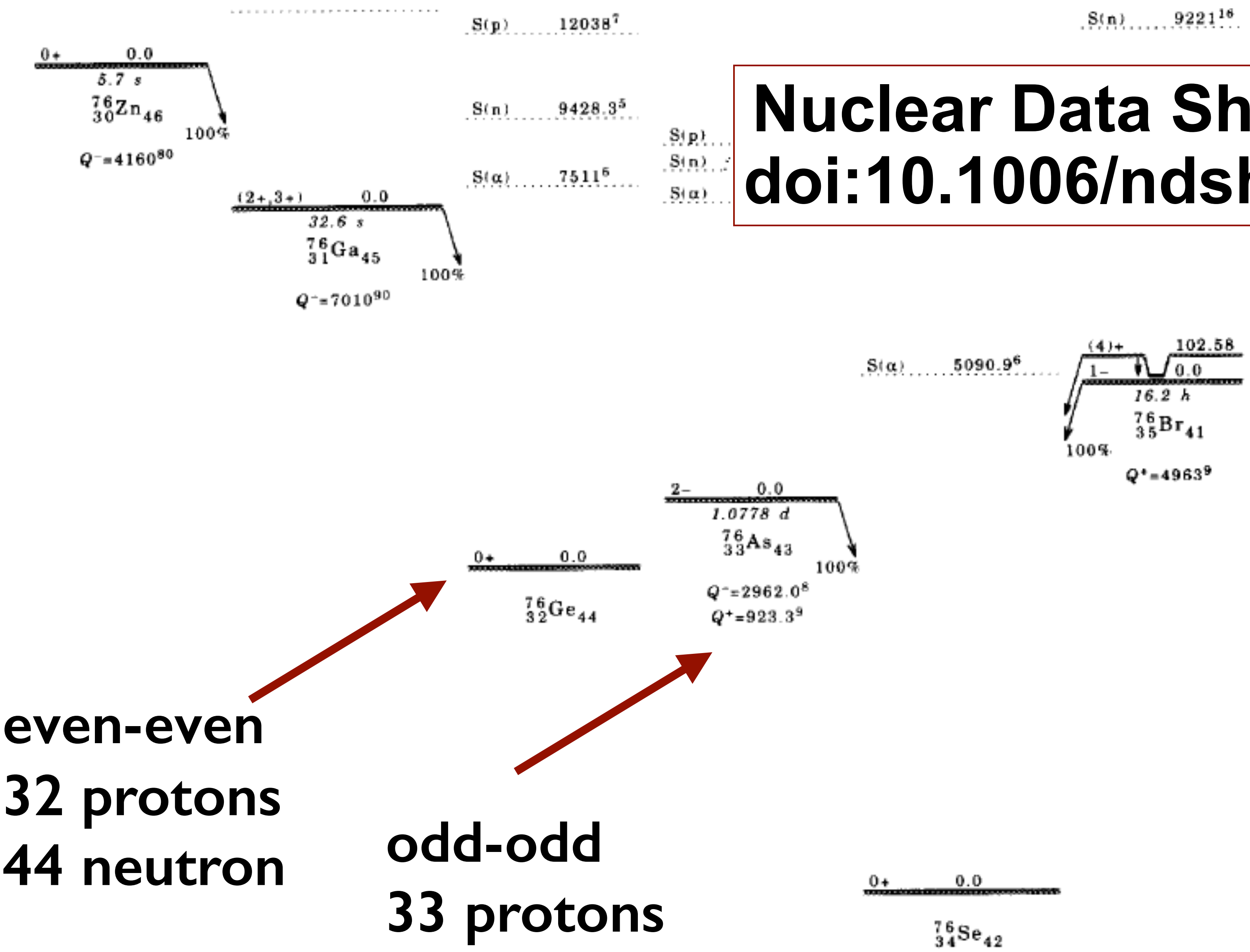
This is the pairing term

even-even nuclei
are most bound!

$$\delta(A, Z) = \begin{cases} +\delta_0 & Z, N \text{ even } (A \text{ even}) \\ 0 & A \text{ odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases}$$

**https://en.wikipedia.org/wiki/Semi-
empirical mass formula**

How does this play out?



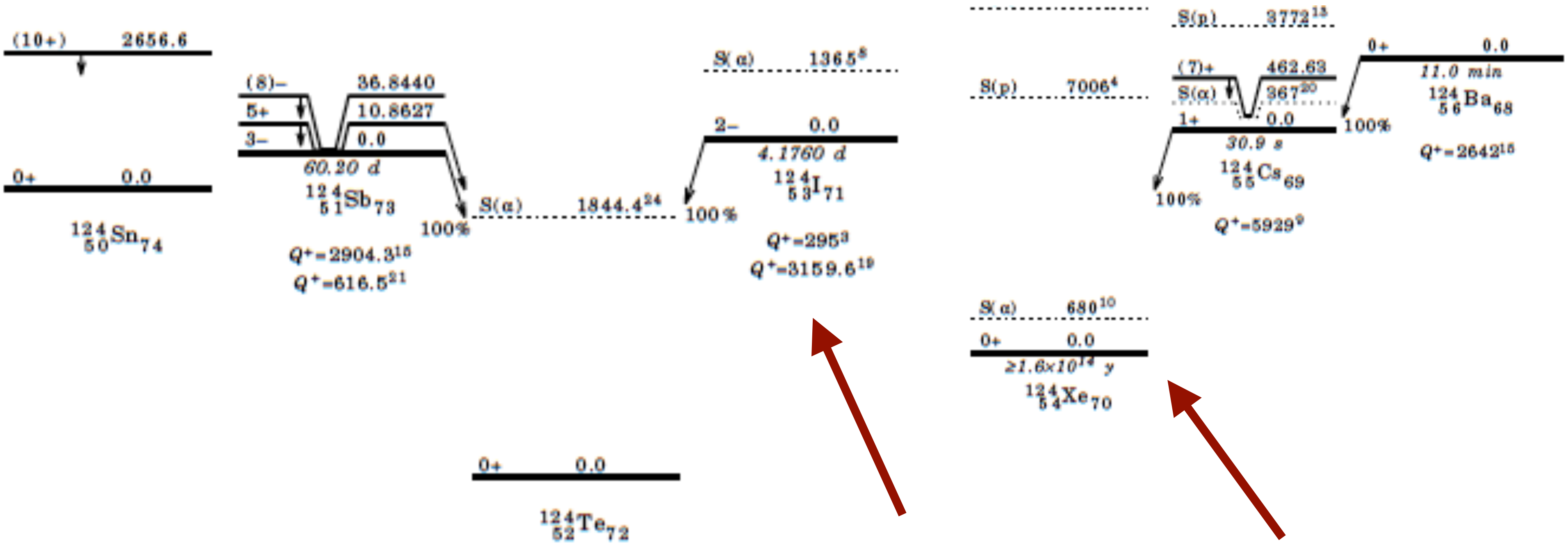
Nuclear Data Sheets A = 76
doi:10.1006/ndsh.1995.1005

even-even
32 protons
44 neutron

odd-odd
33 protons
43 neutron

And we can talk about Double-Positron Decay…

Nuclear Data Sheets A = 12
doi:10.1016/j.nds.2008.06.00



odd-odd
53 protons
71 neutron

even-even
54 protons
70 neutron

You don’t have to go through all the Isotopes, someone has done it…

https://www.dropbox.com/sh/vdr7xvndw6p1jpu/AADt3PAe2mBbMN4ACFI4XvDda?dl=0

http://tinyurl.com/jxx2nrc

Let’s take a second to look at the list.

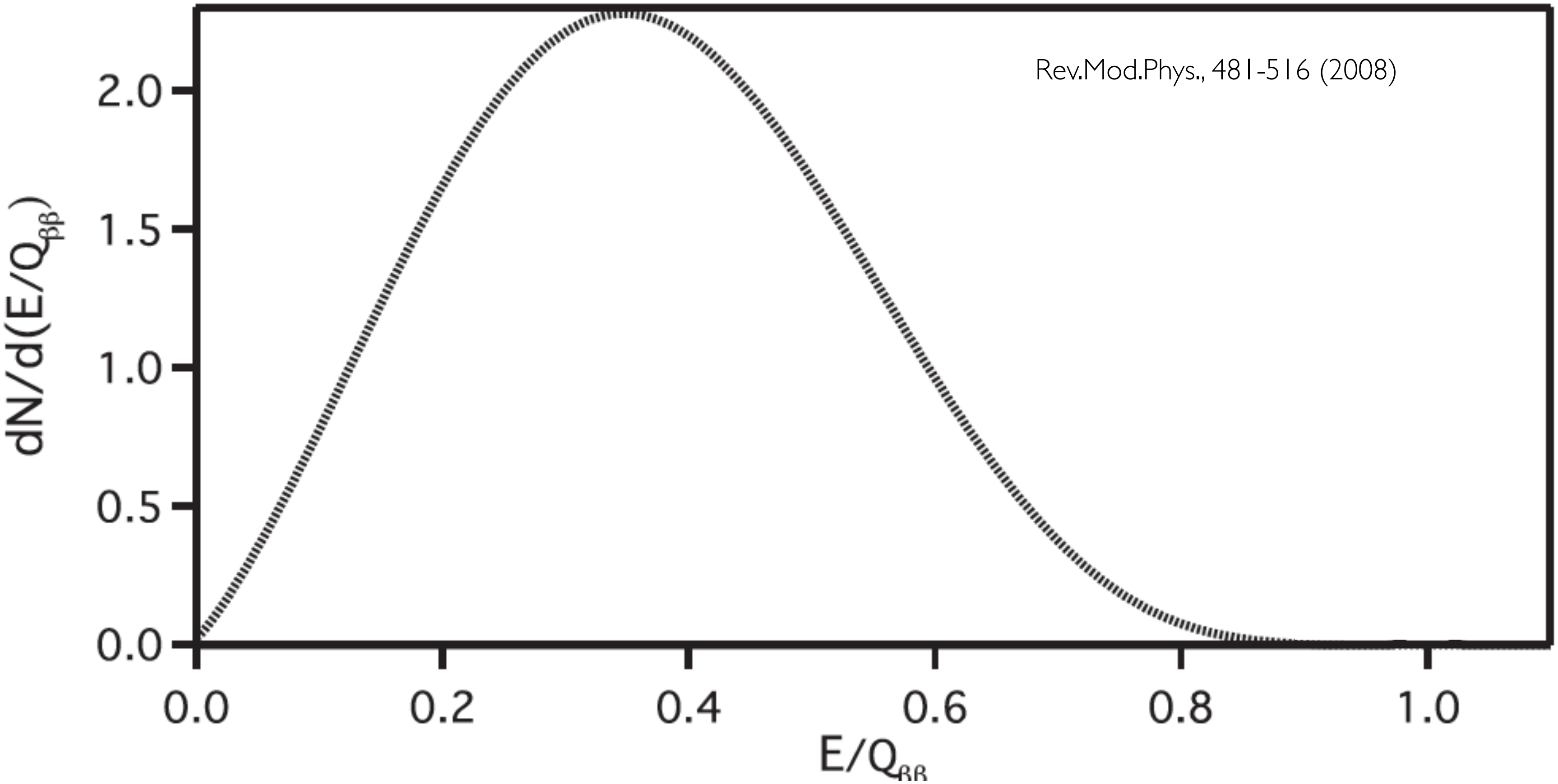
The highest endpoints end up being the best for experimental and phase space reasons…

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.527 MeV	34.5%
^{136}Xe	2.457 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%

What does the signal look like?

Two Neutrino Double Beta Decay

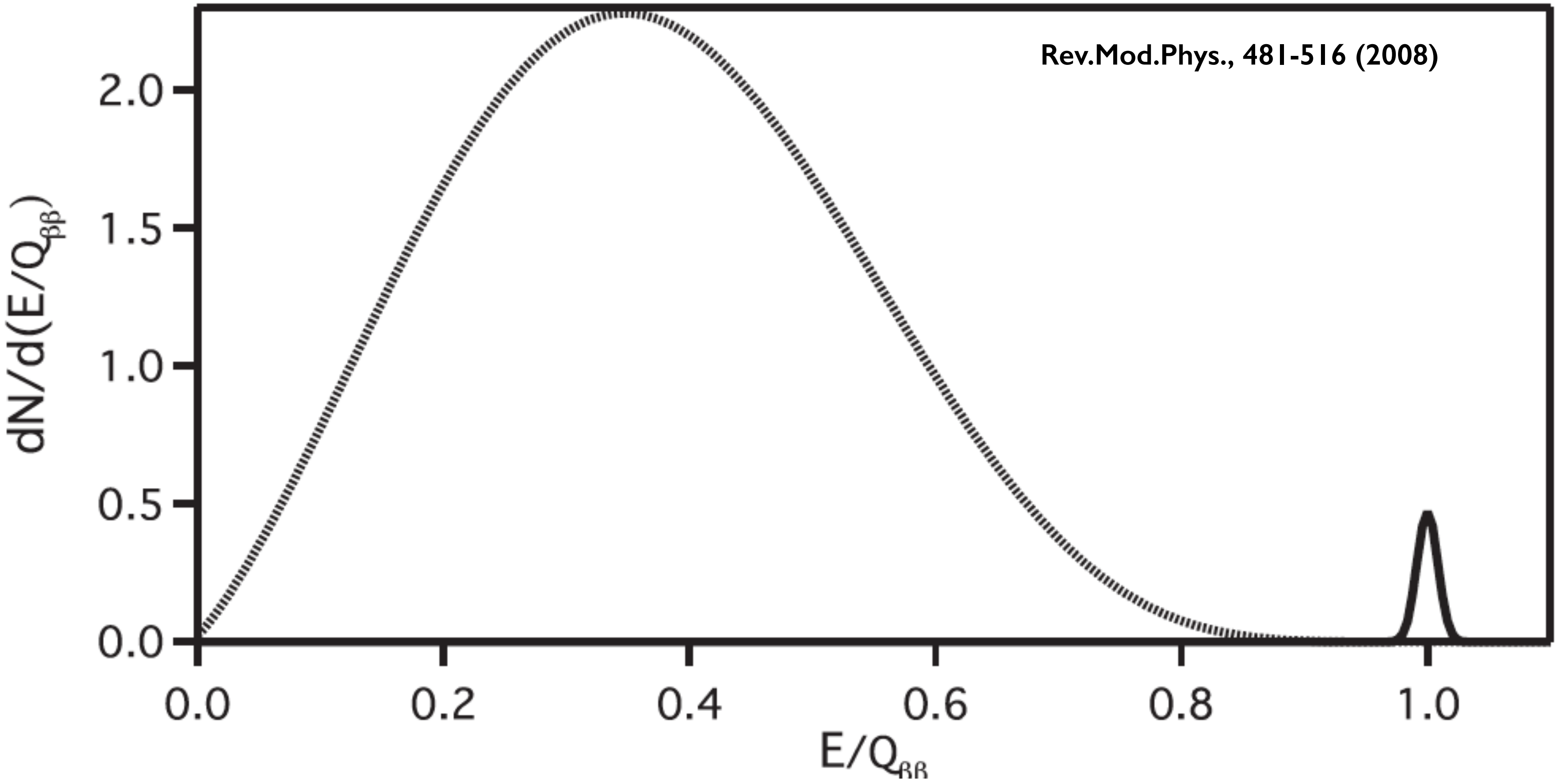
The sum of the electron energies gives a spectrum similar to the standard beta decay spectrum.



This has been observed and is the longest directly observed process!

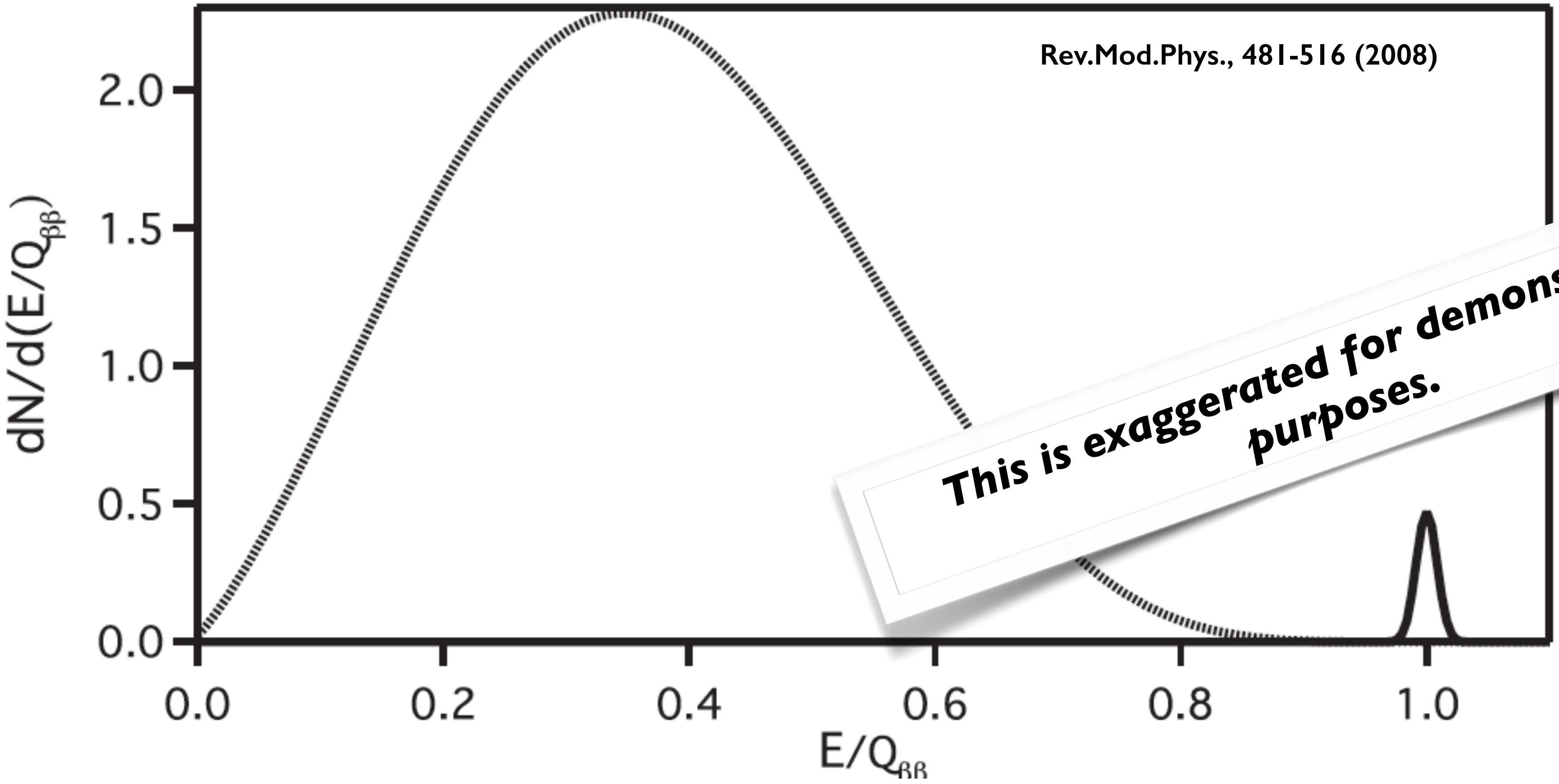
Neutrinoless Double Beta Decay

The sum of the electron energies gives a spike at the endpoint of the “neutrino-full” double beta decay.



Neutrinoless Double Beta Decay

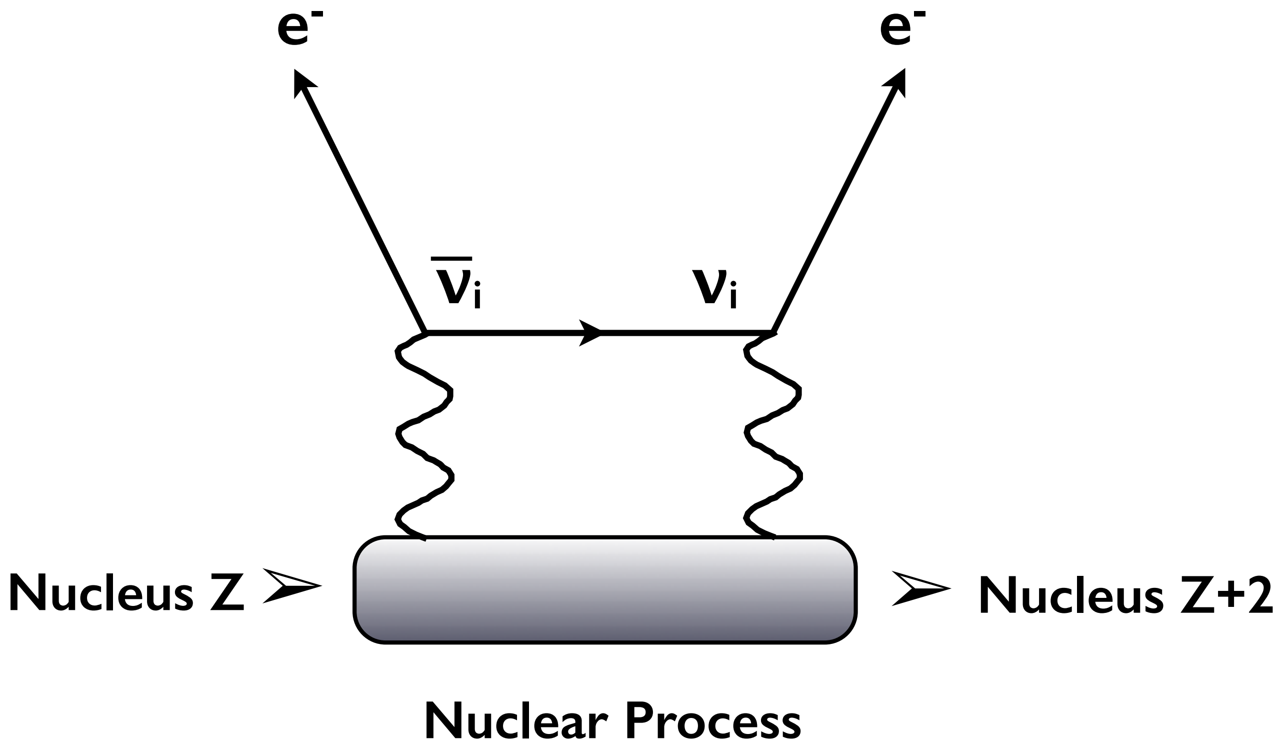
The sum of the electron energies gives a spike at the endpoint of the “neutrino-full” double beta decay.



Rev.Mod.Phys., 481-516 (2008)

This is exaggerated for demonstration purposes.

This is all true for the most straight forward mechanism:



Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange

Other Mechanisms

ATOMIC DATA AND NUCLEAR DATA TABLES **61**, 43–90 (1995)

Light Majorana neutrino exchange.

Right handed currents.

Single and double Majoron emission models.

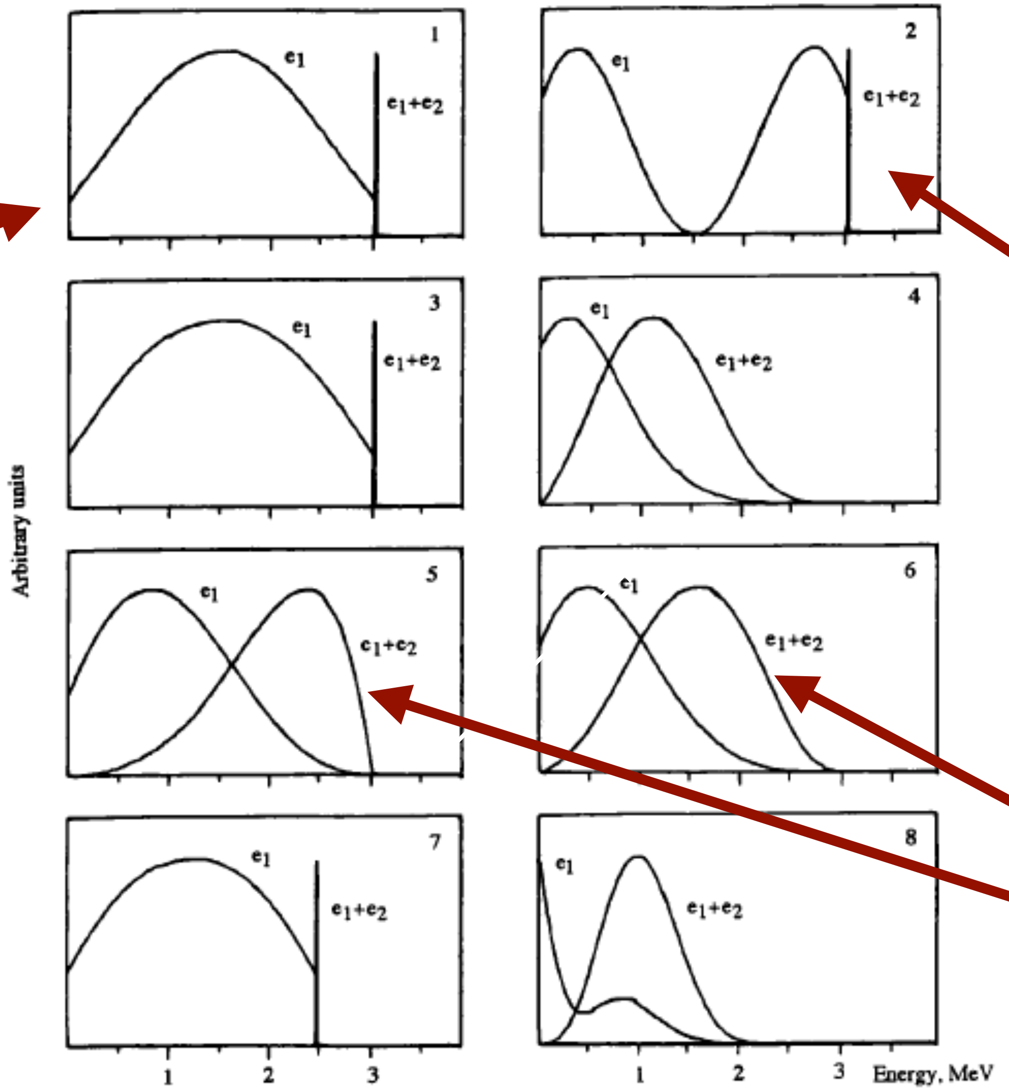
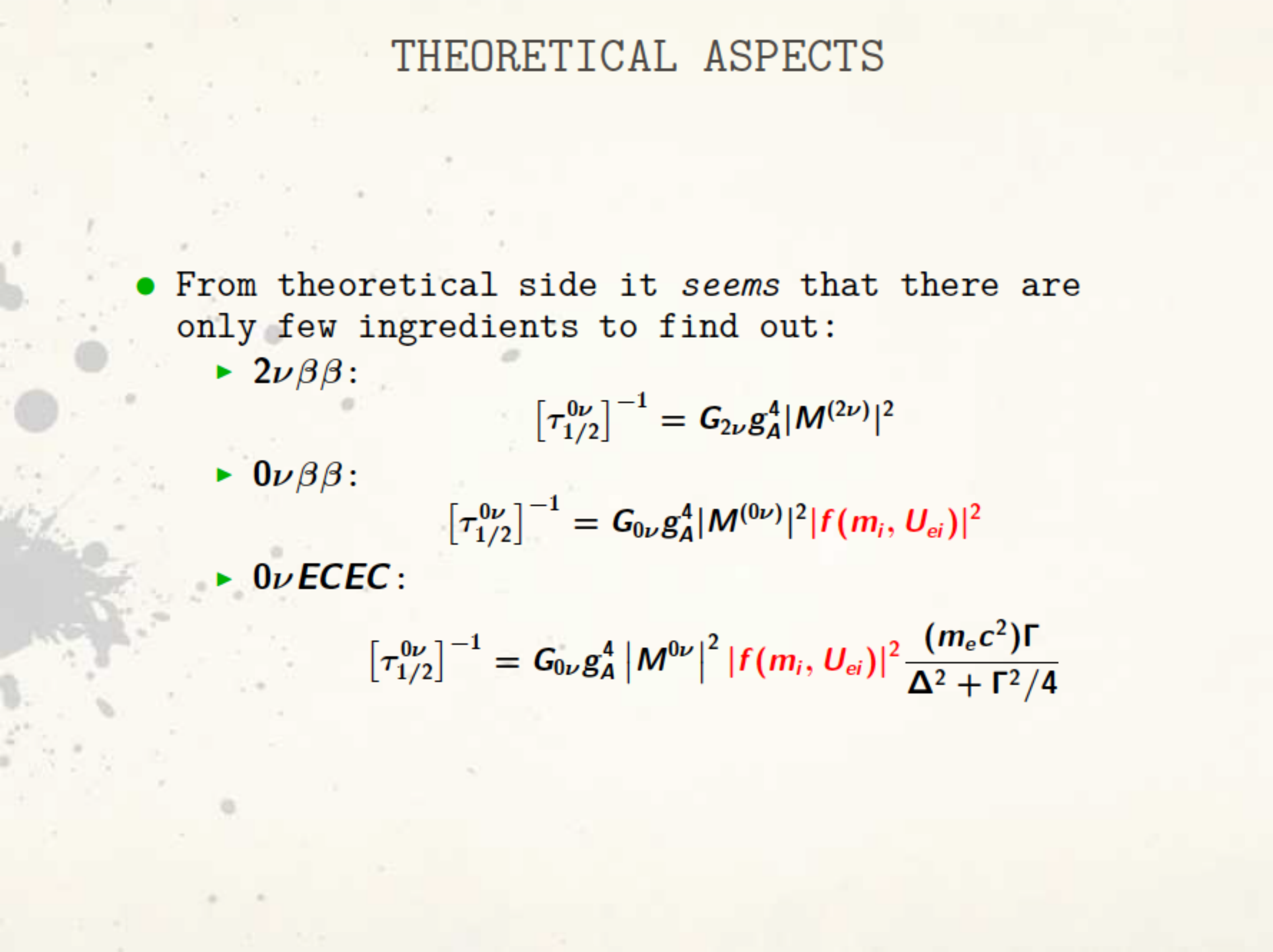


Figure 4. Theoretical distributions for the energy of a single electron (e_1) and for the sum of electron energies ($e_1 + e_2$) for ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV, $E(2^+)$ = 540 keV) for different modes and mechanisms of 2β decay: (1) $0\nu2\beta$ decay with neutrino mass, 0^+–0^+ transition, $2n$ mechanism; (2) $0\nu2\beta$ decay with right-handed currents, 0^+–0^+ transition, $2n$ mechanism; (3) $0\nu2\beta$ decay with right-handed currents, 0^+–0^+ transition, N^* mechanism; (4) $2\nu2\beta$ decay, 0^+–0^+ transition, $2n$ mechanism; (5) $0\nu2\beta$ decay with Majoron emission, 0^+–0^+ transition, $2n$ mechanism; (6) $0\nu2\beta$ decay with double Majoron emission, 0^+–0^+ transition, $2n$ mechanism; (7) $0\nu2\beta$ decay with right-handed currents, 0^+–2^+ transition, $2n$ mechanism; (8) $2\nu2\beta$ decay, 0^+–2^+ transition, $2n$ mechanism and N^* mechanism.

The nuclear physics changes based on the mechanism!

Let’s take a look at the nuclear physics.

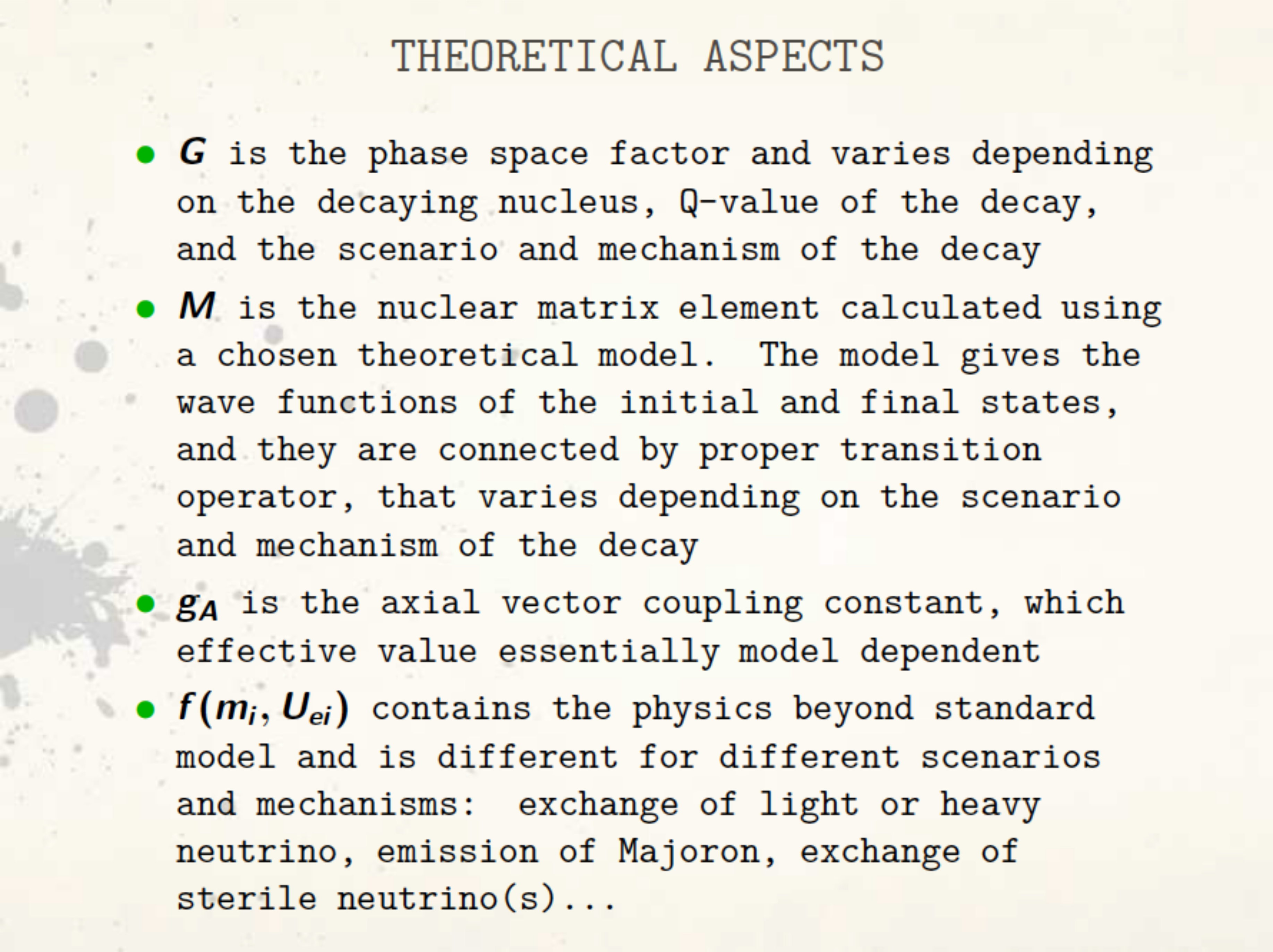
From Jenni Kotila.



THEORETICAL ASPECTS

- From theoretical side it *seems* that there are only few ingredients to find out:
  - $2\nu\beta\beta$:
    $$\left[\tau^{0\nu}_{1/2}\right]^{-1} = G_{2\nu} g_A^4 |M^{(2\nu)}|^2$$
  - $0\nu\beta\beta$:
    $$\left[\tau^{0\nu}_{1/2}\right]^{-1} = G_{0\nu} g_A^4 |M^{(0\nu)}|^2 |f(m_i, U_{ei})|^2$$
  - $0\nu ECEC$:
    $$\left[\tau^{0\nu}_{1/2}\right]^{-1} = G_{0\nu} g_A^4 \left|M^{0\nu}\right|^2 |f(m_i, U_{ei})|^2 \frac{(m_e c^2)\Gamma}{\Delta^2 + \Gamma^2/4}$$

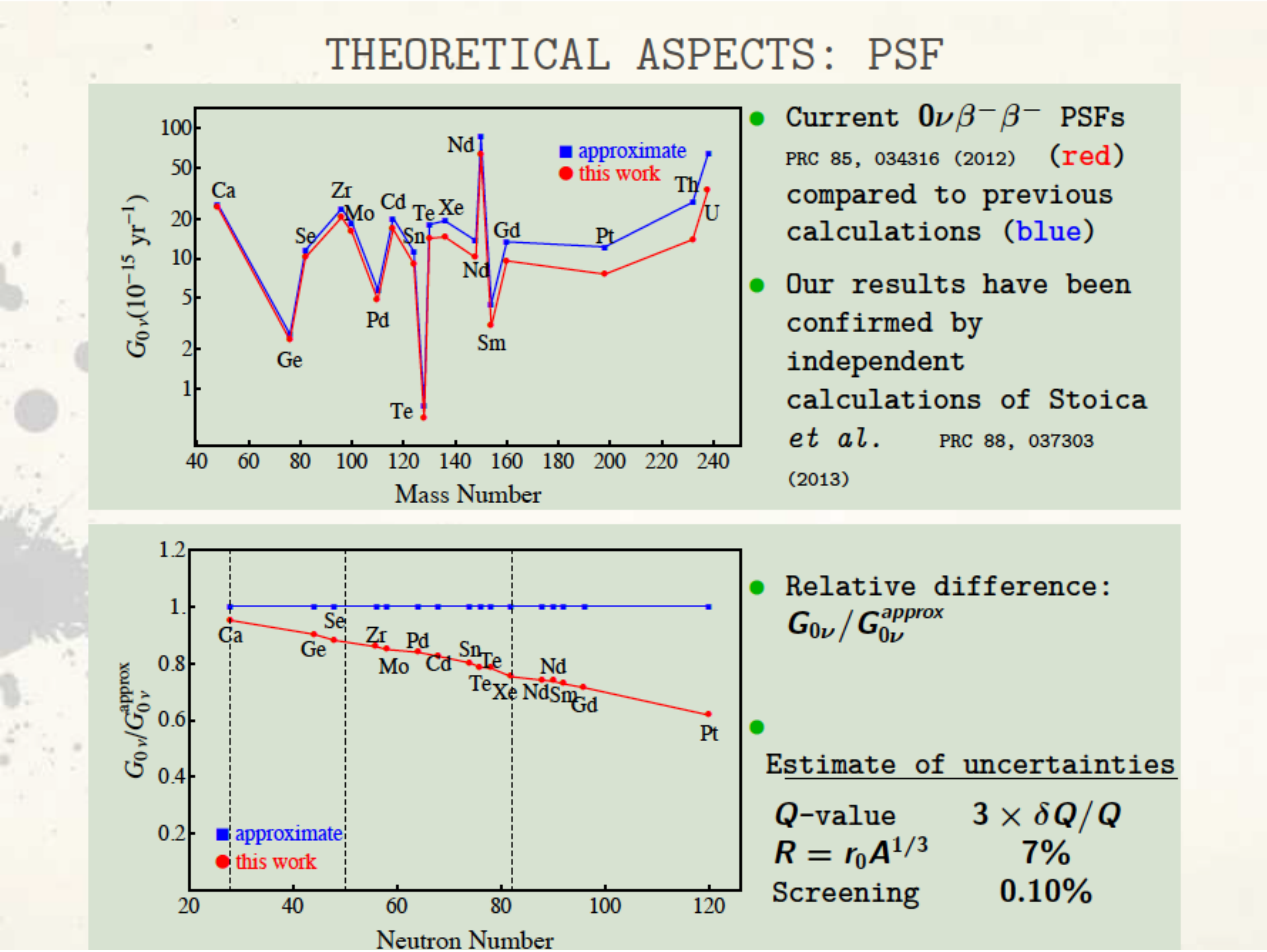
From Jenni Kotila.



THEORETICAL ASPECTS

- G is the phase space factor and varies depending on the decaying nucleus, Q-value of the decay, and the scenario and mechanism of the decay
- M is the nuclear matrix element calculated using a chosen theoretical model. The model gives the wave functions of the initial and final states, and they are connected by proper transition operator, that varies depending on the scenario and mechanism of the decay
- g_A is the axial vector coupling constant, which effective value essentially model dependent
- $f(m_i, U_{ei})$ contains the physics beyond standard model and is different for different scenarios and mechanisms: exchange of light or heavy neutrino, emission of Majoron, exchange of sterile neutrino(s)...

From Jenni Kotila.



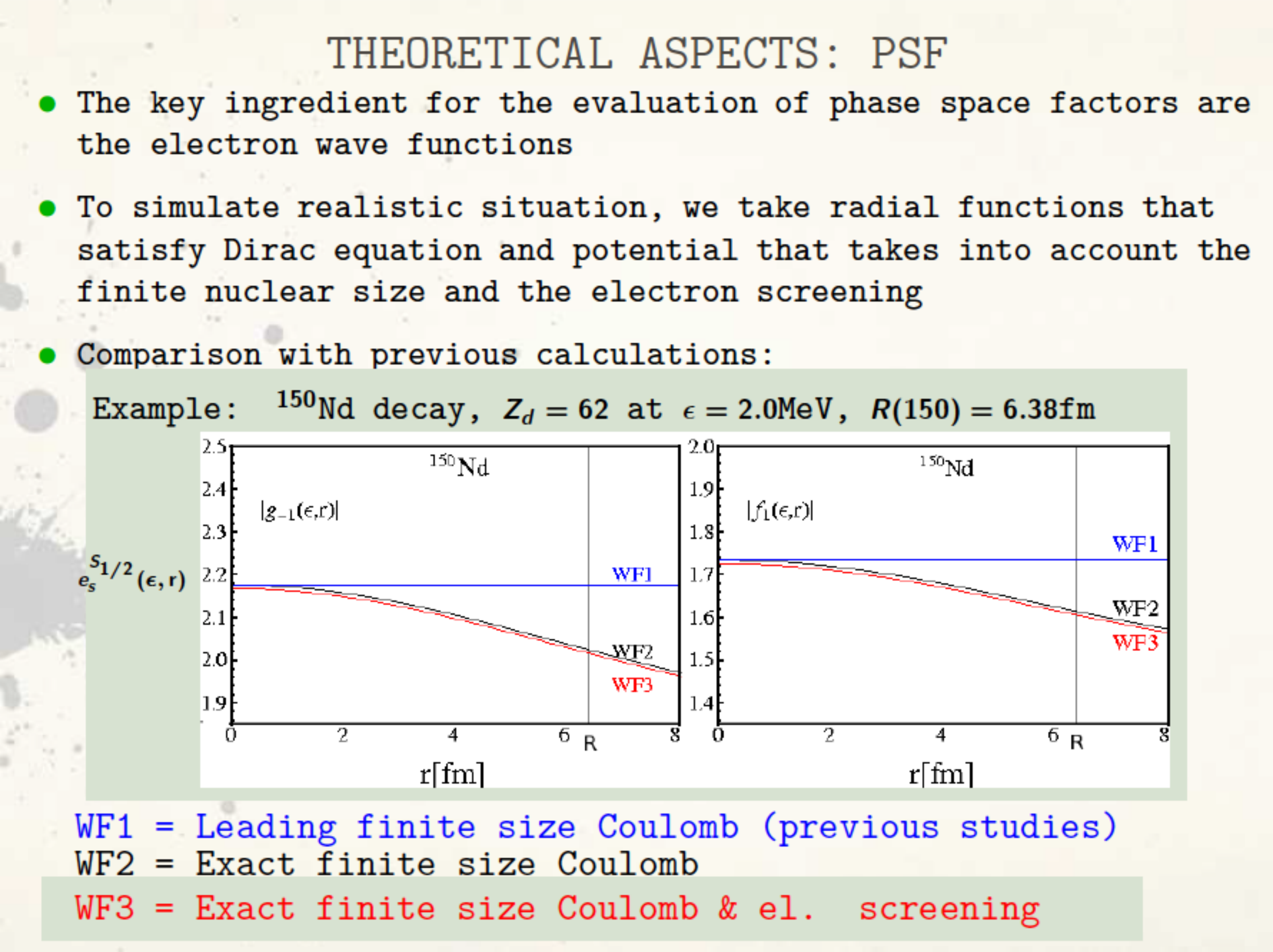
THEORETICAL ASPECTS: PSF

- Current $0\nu\beta^-\beta^-$ PSFs PRC 85, 034316 (2012) (red) compared to previous calculations (blue)
- Our results have been confirmed by independent calculations of Stoica *et al.* PRC 88, 037303 (2013)
- Relative difference: $G_{0\nu}/G_{0\nu}^{approx}$
-

Estimate of uncertainties

Q-value	$3\times\delta Q/Q$
$R=r_0A^{1/3}$	7%
Screening	0.10%

From Jenni Kotila.



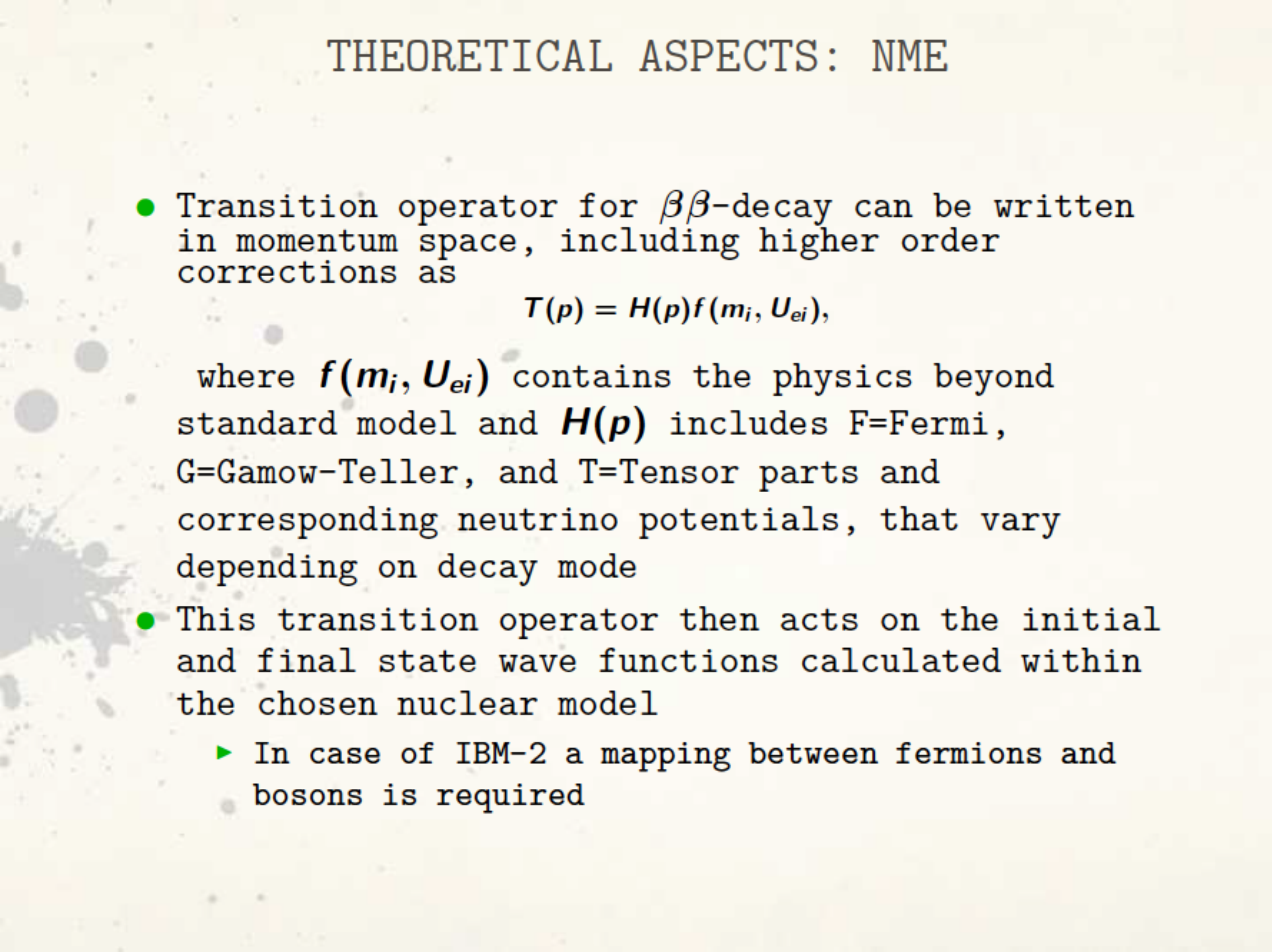
THEORETICAL ASPECTS: PSF

- The key ingredient for the evaluation of phase space factors are the electron wave functions
- To simulate realistic situation, we take radial functions that satisfy Dirac equation and potential that takes into account the finite nuclear size and the electron screening
- Comparison with previous calculations:

Example: ^{150}Nd decay, $Z_d = 62$ at $\epsilon = 2.0$MeV, $R(150) = 6.38$fm

WF1 = Leading finite size Coulomb (previous studies)
WF2 = Exact finite size Coulomb
WF3 = Exact finite size Coulomb & el. screening

From Jenni Kotila.



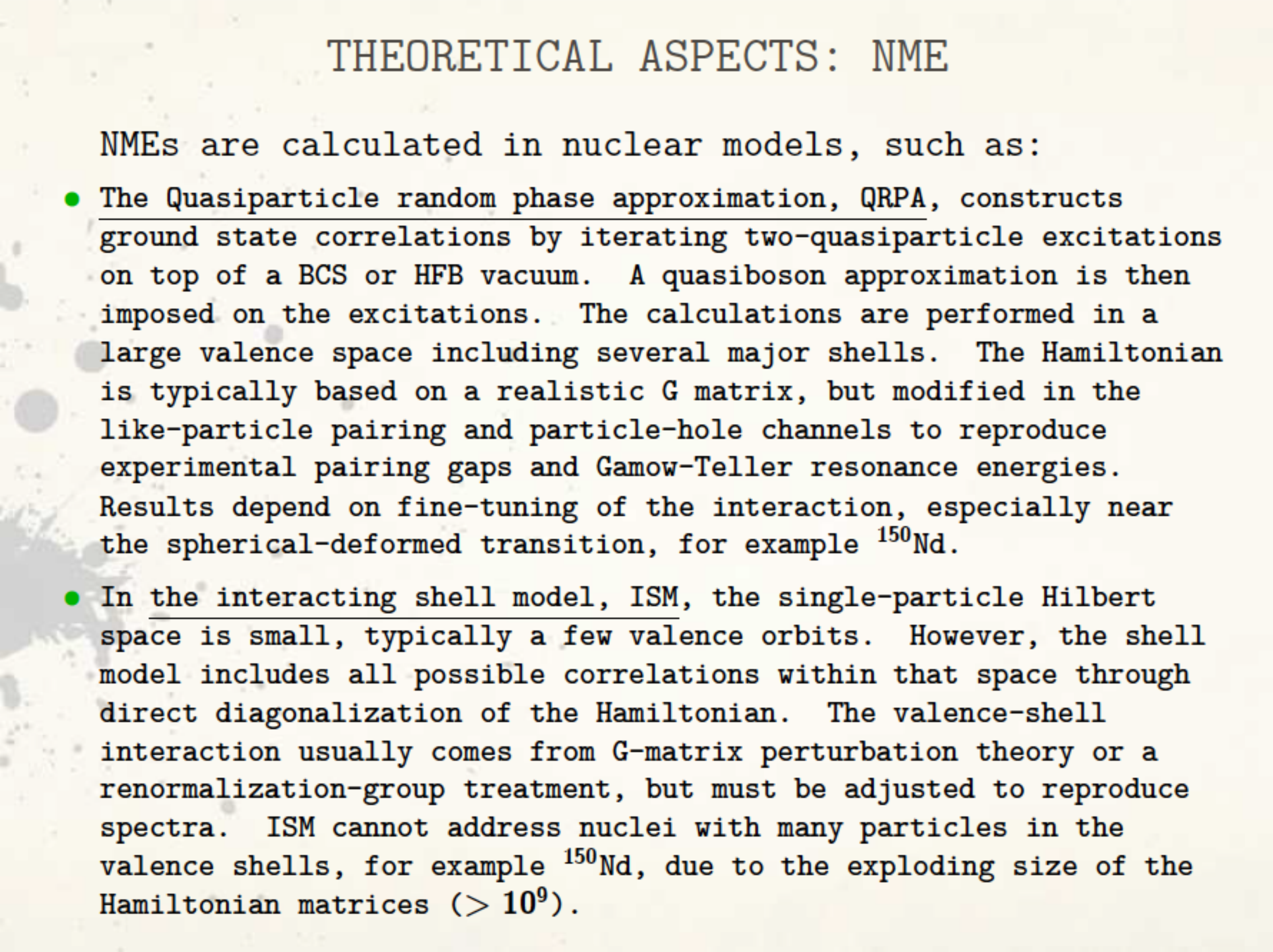
THEORETICAL ASPECTS: NME

- Transition operator for $\beta\beta$-decay can be written in momentum space, including higher order corrections as

$$T(p) = H(p) f(m_i, U_{ei}),$$

  where $f(m_i, U_{ei})$ contains the physics beyond standard model and $H(p)$ includes F=Fermi, G=Gamow-Teller, and T=Tensor parts and corresponding neutrino potentials, that vary depending on decay mode
- This transition operator then acts on the initial and final state wave functions calculated within the chosen nuclear model
  - In case of IBM-2 a mapping between fermions and bosons is required

From Jenni Kotila.

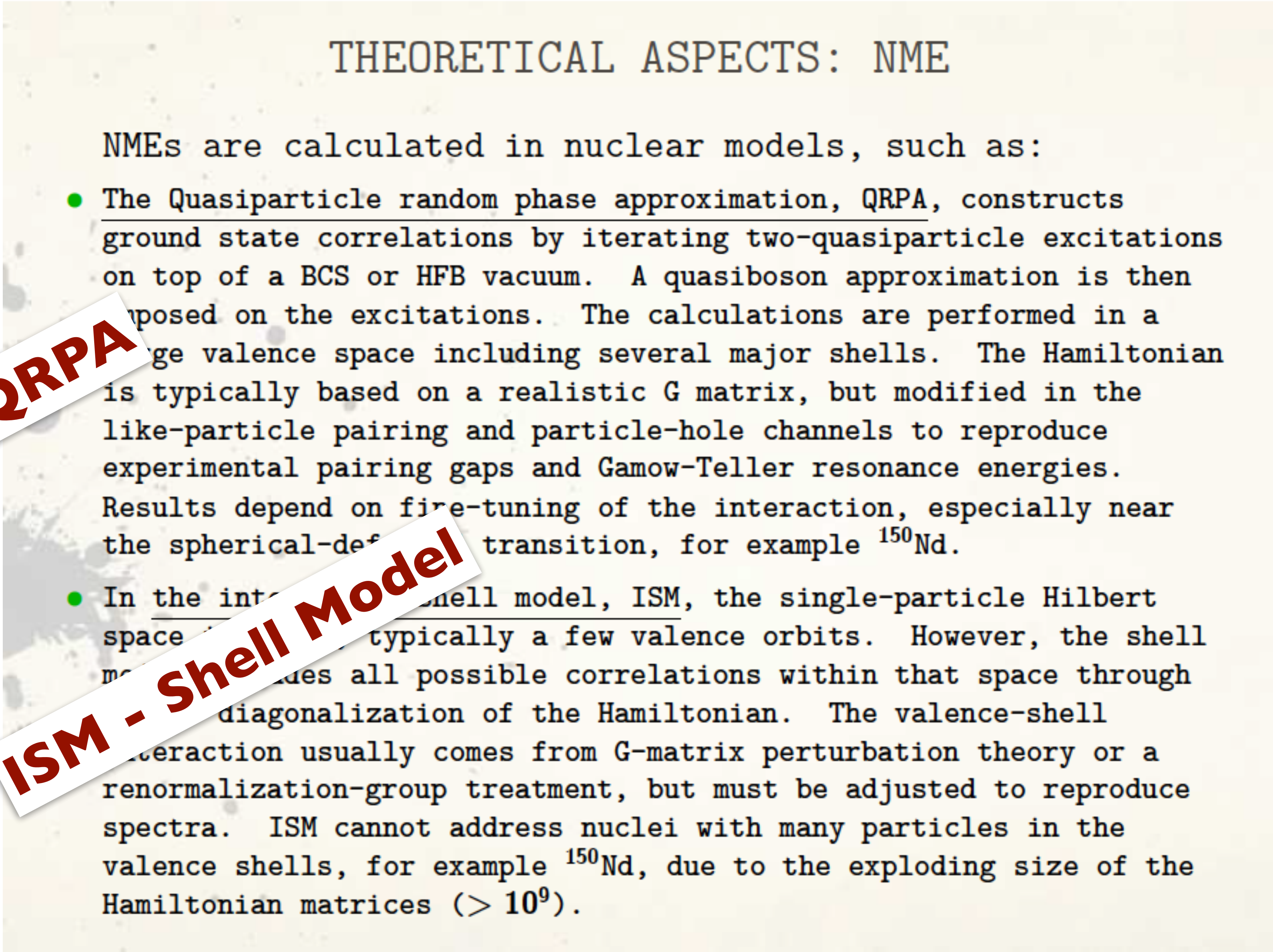


THEORETICAL ASPECTS: NME

NMEs are calculated in nuclear models, such as:

- The Quasiparticle random phase approximation, QRPA, constructs ground state correlations by iterating two-quasiparticle excitations on top of a BCS or HFB vacuum. A quasiboson approximation is then imposed on the excitations. The calculations are performed in a large valence space including several major shells. The Hamiltonian is typically based on a realistic G matrix, but modified in the like-particle pairing and particle-hole channels to reproduce experimental pairing gaps and Gamow-Teller resonance energies. Results depend on fine-tuning of the interaction, especially near the spherical-deformed transition, for example ^{150}Nd.
- In the interacting shell model, ISM, the single-particle Hilbert space is small, typically a few valence orbits. However, the shell model includes all possible correlations within that space through direct diagonalization of the Hamiltonian. The valence-shell interaction usually comes from G-matrix perturbation theory or a renormalization-group treatment, but must be adjusted to reproduce spectra. ISM cannot address nuclei with many particles in the valence shells, for example ^{150}Nd, due to the exploding size of the Hamiltonian matrices ($> 10^9$).

From Jenni Kotila.



THEORETICAL ASPECTS: NME

NMEs are calculated in nuclear models, such as:

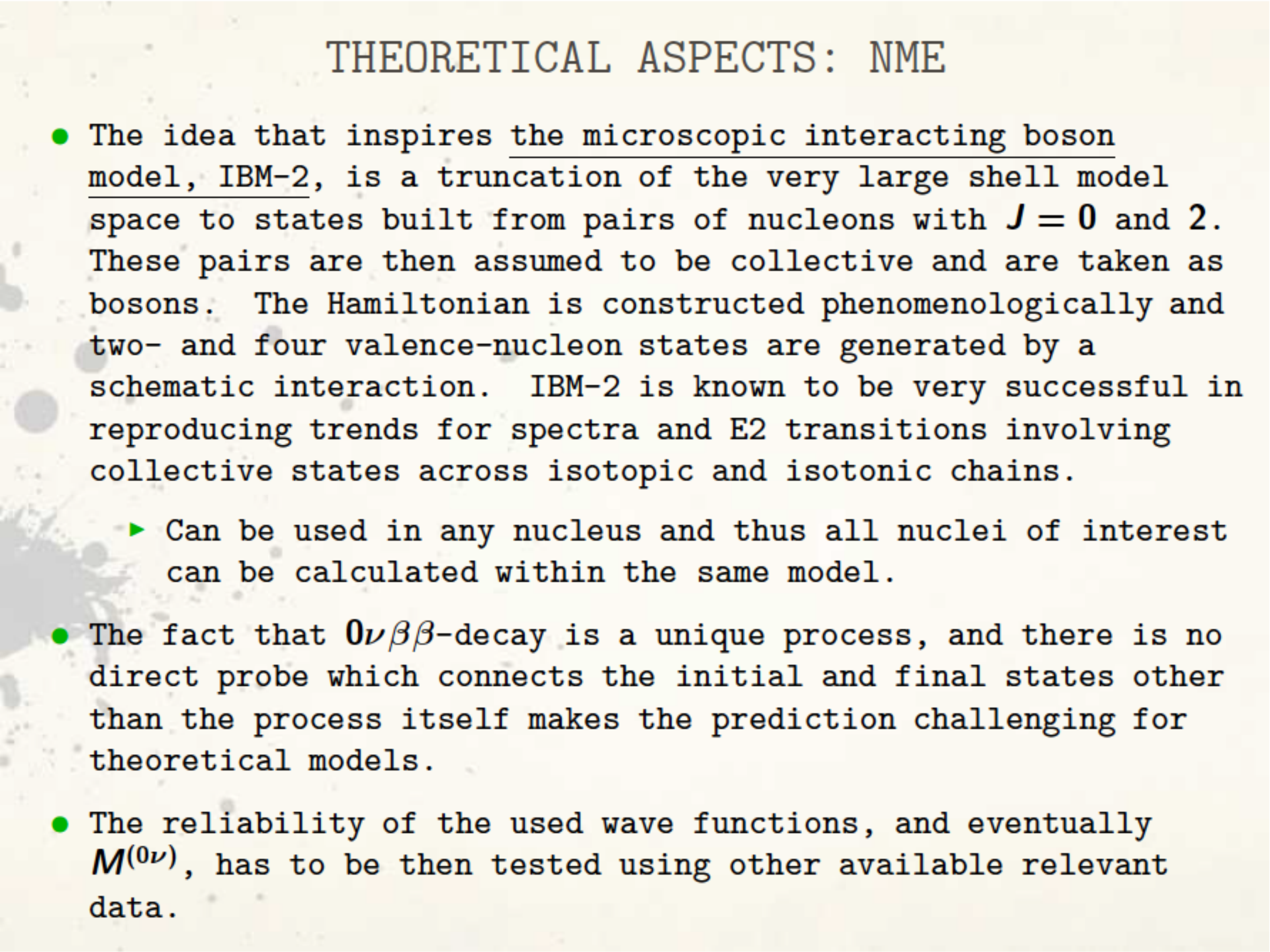
QRPA

- The Quasiparticle random phase approximation, QRPA, constructs ground state correlations by iterating two-quasiparticle excitations on top of a BCS or HFB vacuum. A quasiboson approximation is then posed on the excitations. The calculations are performed in a ge valence space including several major shells. The Hamiltonian is typically based on a realistic G matrix, but modified in the like-particle pairing and particle-hole channels to reproduce experimental pairing gaps and Gamow-Teller resonance energies. Results depend on fine-tuning of the interaction, especially near the spherical-def transition, for example ^{150}Nd.

ISM - Shell Model

- In the int shell model, ISM, the single-particle Hilbert space typically a few valence orbits. However, the shell m des all possible correlations within that space through diagonalization of the Hamiltonian. The valence-shell teraction usually comes from G-matrix perturbation theory or a renormalization-group treatment, but must be adjusted to reproduce spectra. ISM cannot address nuclei with many particles in the valence shells, for example ^{150}Nd, due to the exploding size of the Hamiltonian matrices ($> 10^9$).

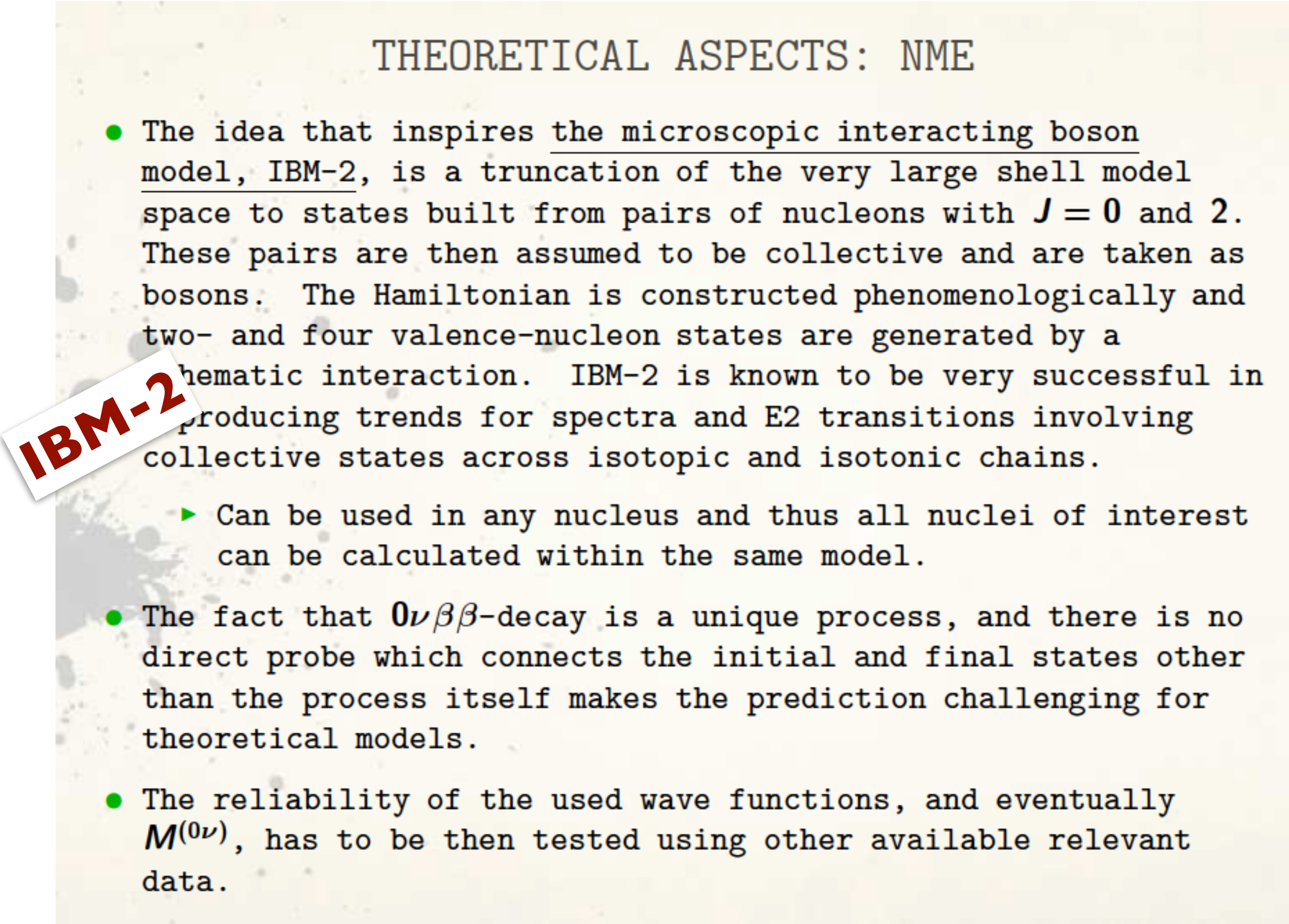
From Jenni Kotila.



THEORETICAL ASPECTS: NME

- The idea that inspires the microscopic interacting boson model, IBM-2, is a truncation of the very large shell model space to states built from pairs of nucleons with $J = 0$ and 2. These pairs are then assumed to be collective and are taken as bosons. The Hamiltonian is constructed phenomenologically and two- and four valence-nucleon states are generated by a schematic interaction. IBM-2 is known to be very successful in reproducing trends for spectra and E2 transitions involving collective states across isotopic and isotonic chains.
    - Can be used in any nucleus and thus all nuclei of interest can be calculated within the same model.
- The fact that $0\nu\beta\beta$-decay is a unique process, and there is no direct probe which connects the initial and final states other than the process itself makes the prediction challenging for theoretical models.
- The reliability of the used wave functions, and eventually $M^{(0\nu)}$, has to be then tested using other available relevant data.

From Jenni Kotila.

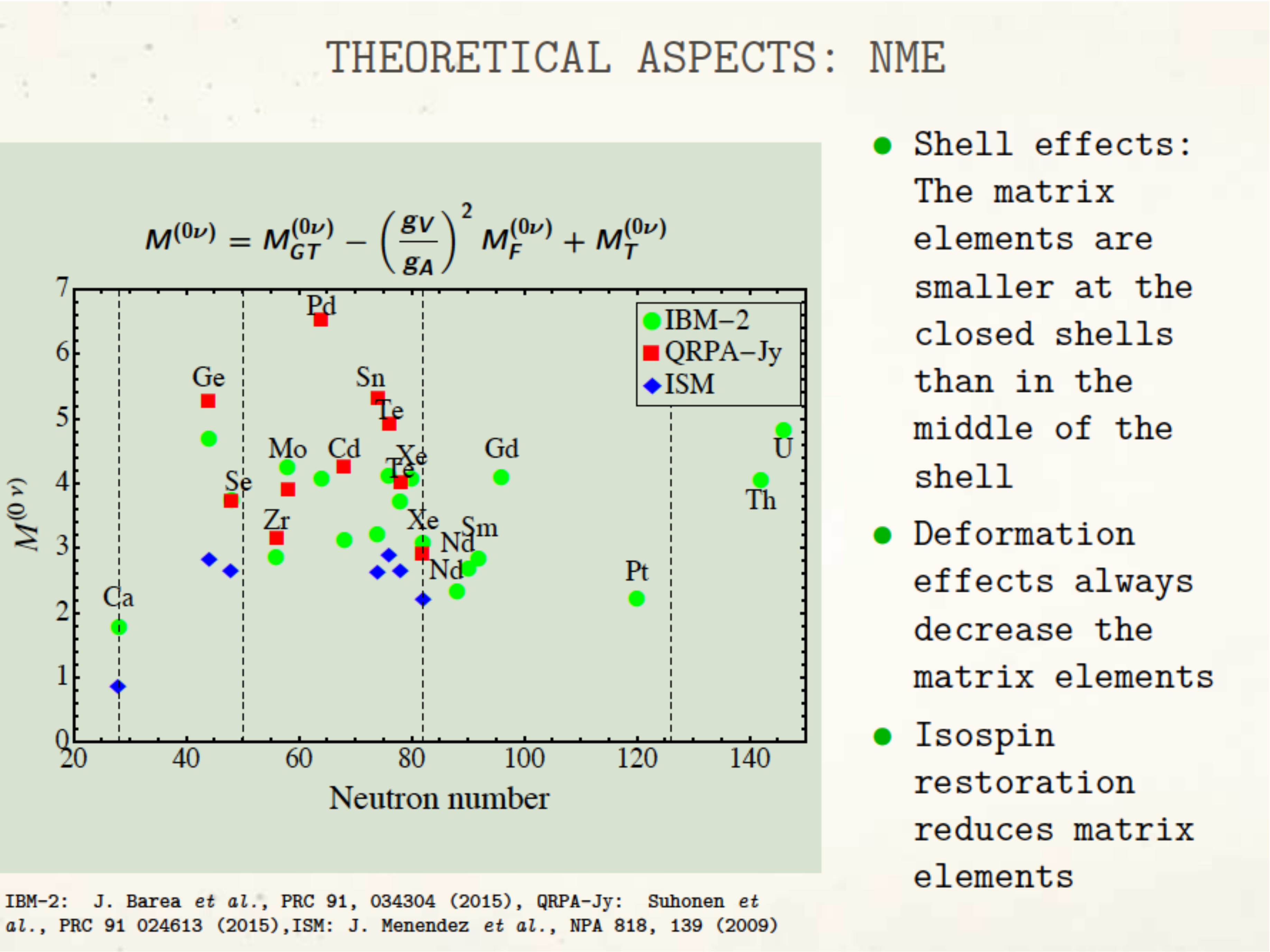


IBM-2

THEORETICAL ASPECTS: NME

- The idea that inspires the microscopic interacting boson model, IBM-2, is a truncation of the very large shell model space to states built from pairs of nucleons with $J = 0$ and 2. These pairs are then assumed to be collective and are taken as bosons. The Hamiltonian is constructed phenomenologically and two- and four valence-nucleon states are generated by a hematic interaction. IBM-2 is known to be very successful in producing trends for spectra and E2 transitions involving collective states across isotopic and isotonic chains.
    - Can be used in any nucleus and thus all nuclei of interest can be calculated within the same model.
- The fact that $0\nu\beta\beta$-decay is a unique process, and there is no direct probe which connects the initial and final states other than the process itself makes the prediction challenging for theoretical models.
- The reliability of the used wave functions, and eventually $M^{(0\nu)}$, has to be then tested using other available relevant data.

From Jenni Kotila.



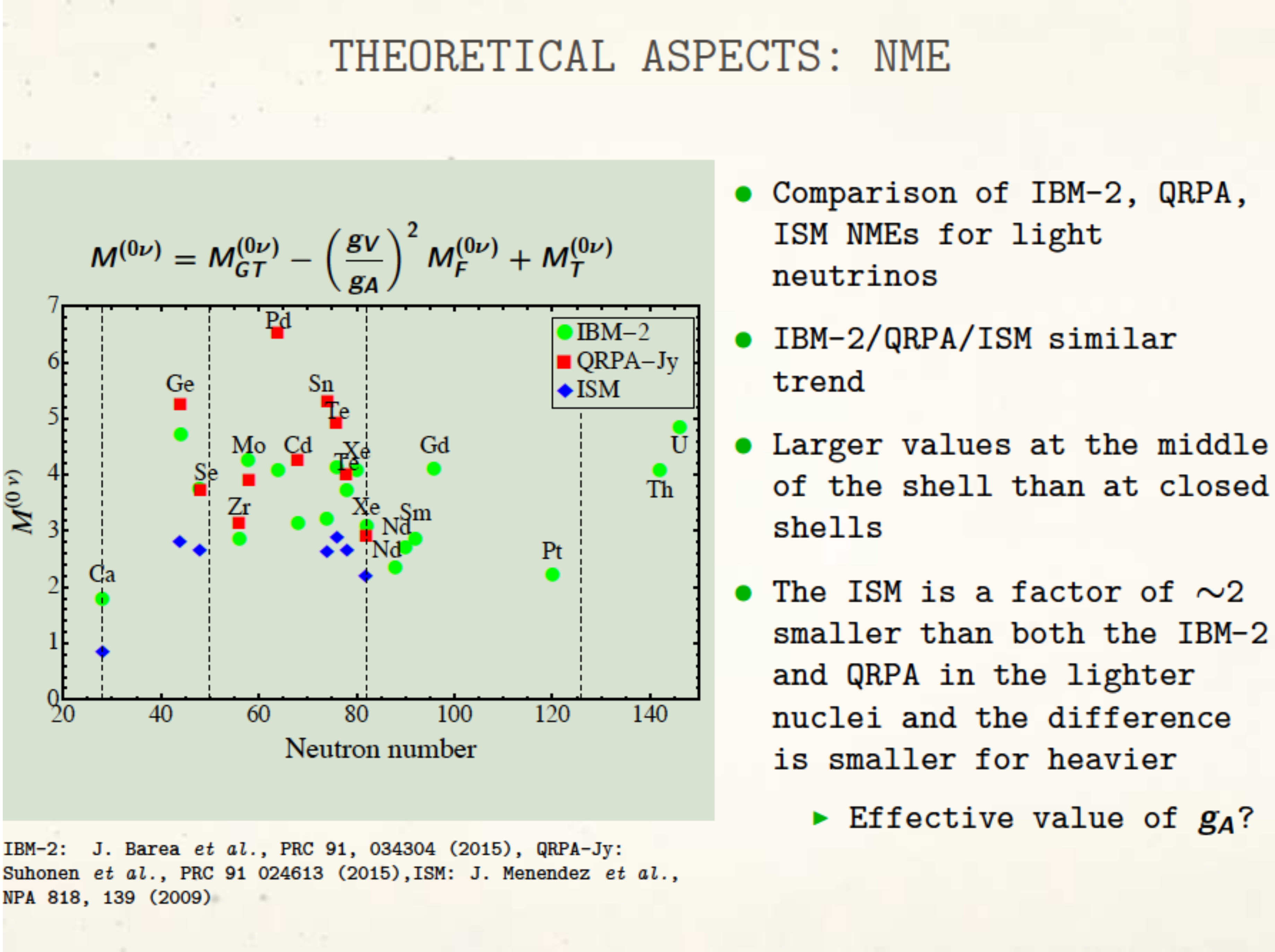
THEORETICAL ASPECTS: NME

$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$

- Shell effects: The matrix elements are smaller at the closed shells than in the middle of the shell
- Deformation effects always decrease the matrix elements
- Isospin restoration reduces matrix elements

IBM-2: J. Barea *et al.*, PRC 91, 034304 (2015), QRPA-Jy: Suhonen *et al.*, PRC 91 024613 (2015), ISM: J. Menendez *et al.*, NPA 818, 139 (2009)

From Jenni Kotila.



THEORETICAL ASPECTS: NME

$$M^{(0\nu)} = M^{(0\nu)}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{(0\nu)}_F + M^{(0\nu)}_T$$

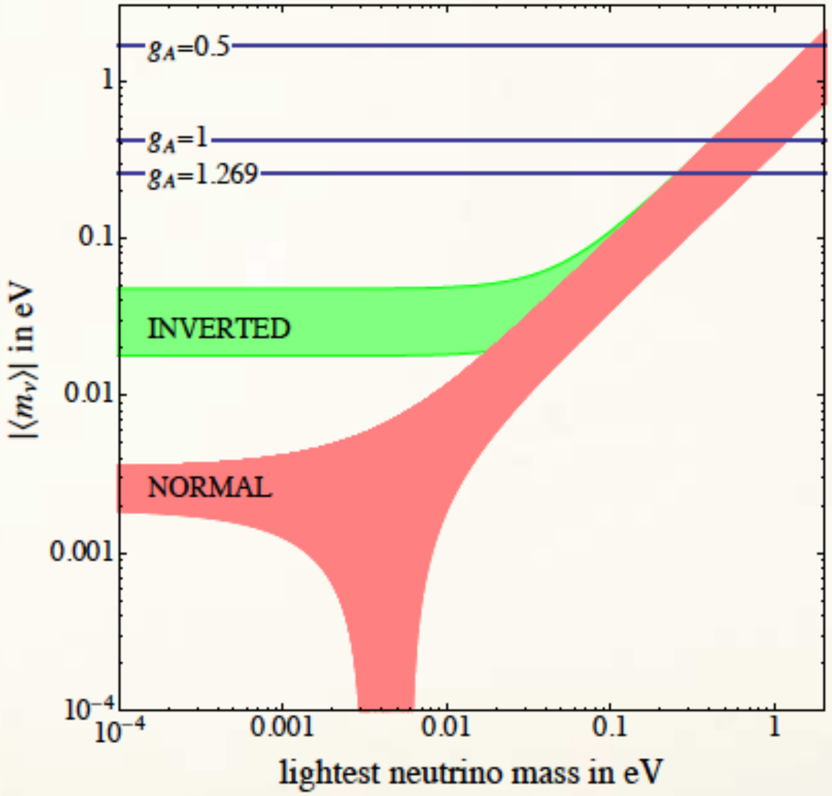
- Comparison of IBM-2, QRPA, ISM NMEs for light neutrinos
- IBM-2/QRPA/ISM similar trend
- Larger values at the middle of the shell than at closed shells
- The ISM is a factor of ∼2 smaller than both the IBM-2 and QRPA in the lighter nuclei and the difference is smaller for heavier
  - Effective value of g_A?

IBM-2: J. Barea *et al.*, PRC 91, 034304 (2015), QRPA-Jy: Suhonen *et al.*, PRC 91 024613 (2015),ISM: J. Menendez *et al.*, NPA 818, 139 (2009)

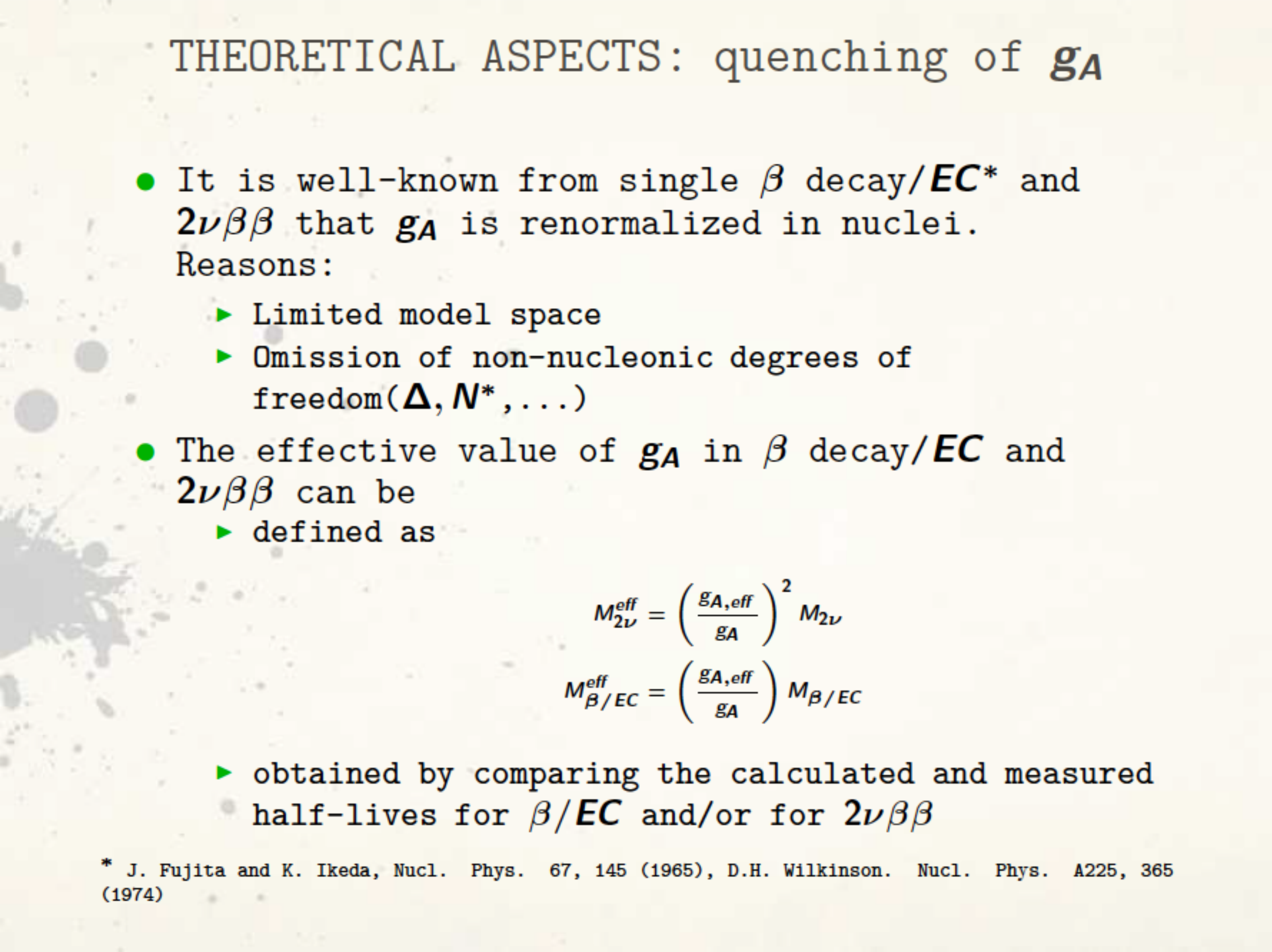
From Jenni Kotila.

THEORETICAL ASPECTS: quenching of g_A

- The question of effective value of g_A is still open. Three suggested scenarios are:
  - Free value: 1.269
  - Quark value: 1
  - Even stronger quenching: $g_{A,\mathit{eff}} < 1$



From Jenni Kotila.



THEORETICAL ASPECTS: quenching of g_A

- It is well-known from single β decay/EC* and $2\nu\beta\beta$ that g_A is renormalized in nuclei.
  Reasons:
  - Limited model space
  - Omission of non-nucleonic degrees of freedom($\Delta, N^*, \ldots$)
- The effective value of g_A in β decay/EC and $2\nu\beta\beta$ can be
  - defined as

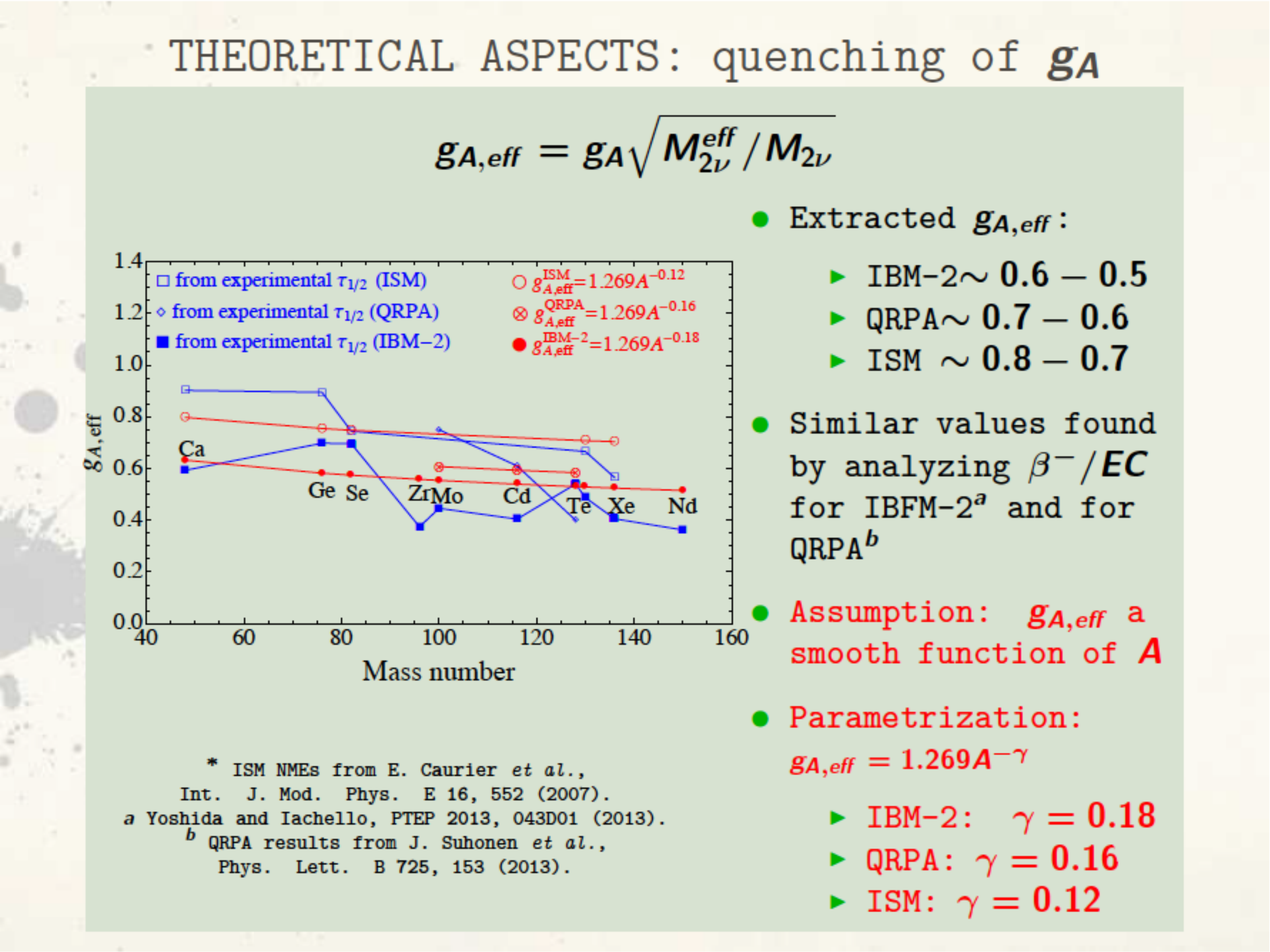
$$M_{2\nu}^{eff} = \left(\frac{g_{A,eff}}{g_A}\right)^2 M_{2\nu}$$

$$M_{\beta/EC}^{eff} = \left(\frac{g_{A,eff}}{g_A}\right) M_{\beta/EC}$$

  - obtained by comparing the calculated and measured half-lives for β/EC and/or for $2\nu\beta\beta$

* J. Fujita and K. Ikeda, Nucl. Phys. 67, 145 (1965), D.H. Wilkinson. Nucl. Phys. A225, 365 (1974)

From Jenni Kotila.



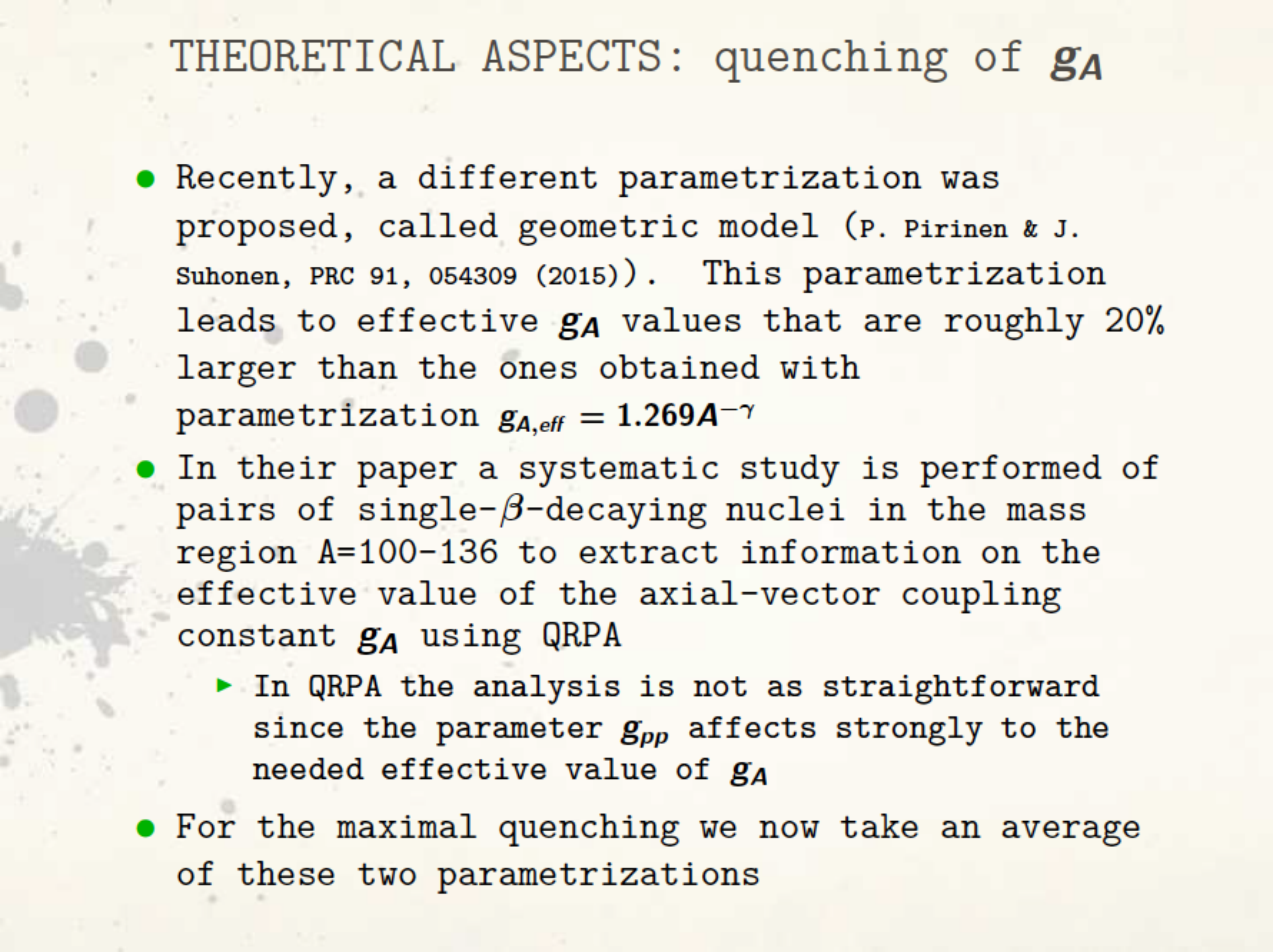
THEORETICAL ASPECTS: quenching of g_A

$$g_{A,eff} = g_A\sqrt{M_{2\nu}^{eff}/M_{2\nu}}$$

- Extracted $g_{A,eff}$:
  - IBM-2$\sim$ **0.6 – 0.5**
  - QRPA$\sim$ **0.7 – 0.6**
  - ISM $\sim$ **0.8 – 0.7**
- Similar values found by analyzing β^-/EC for IBFM-2^a and for QRPA^b
- Assumption: $g_{A,eff}$ a smooth function of A
- Parametrization: $g_{A,eff} = 1.269A^{-\gamma}$
  - IBM-2: $\gamma = 0.18$
  - QRPA: $\gamma = 0.16$
  - ISM: $\gamma = 0.12$

* ISM NMEs from E. Caurier *et al.*, Int. J. Mod. Phys. E 16, 552 (2007).
a Yoshida and Iachello, PTEP 2013, 043D01 (2013).
^{b} QRPA results from J. Suhonen *et al.*, Phys. Lett. B 725, 153 (2013).

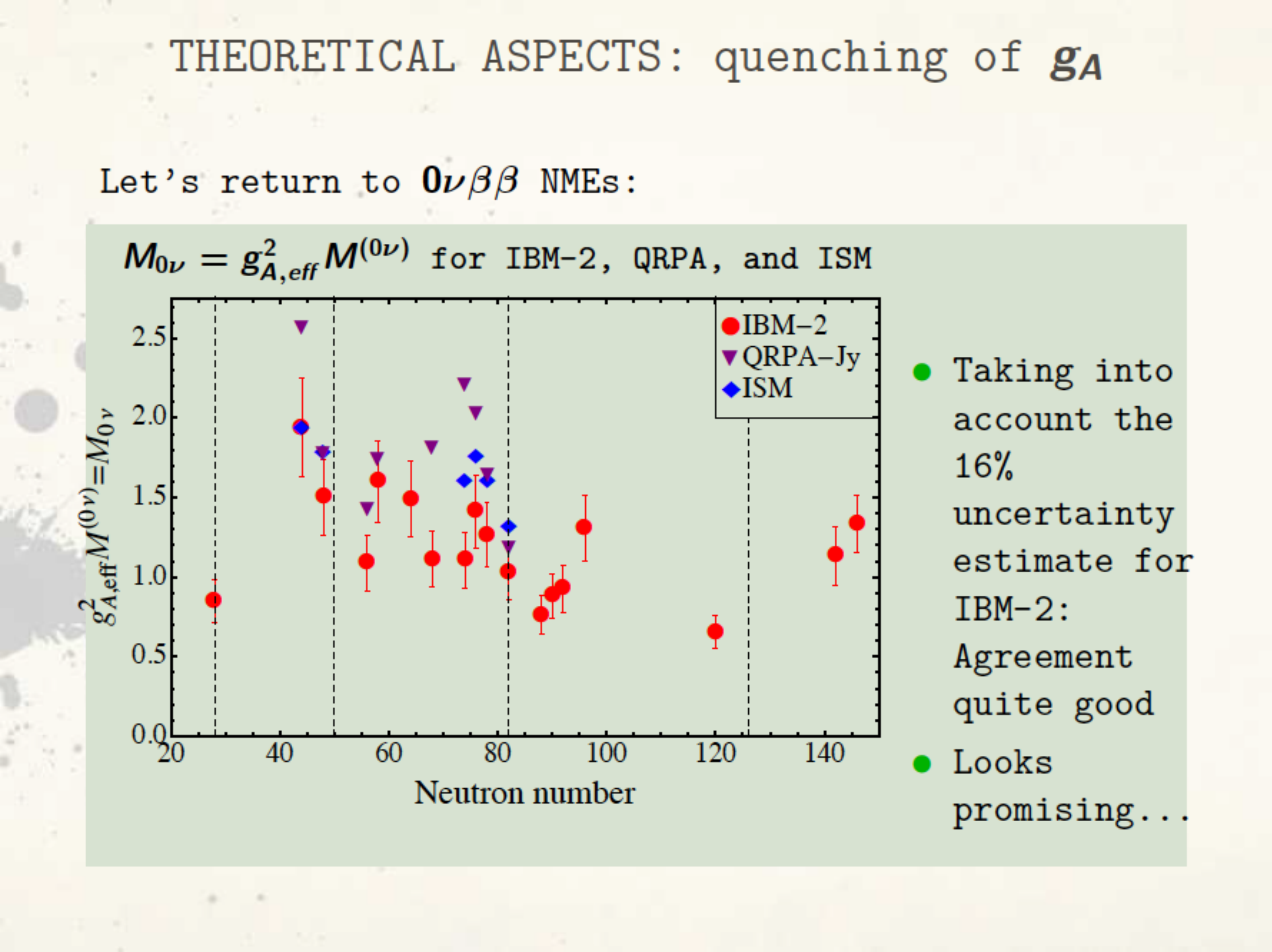
From Jenni Kotila.



THEORETICAL ASPECTS: quenching of g_A

- Recently, a different parametrization was proposed, called geometric model (P. Pirinen & J. Suhonen, PRC 91, 054309 (2015)). This parametrization leads to effective g_A values that are roughly 20% larger than the ones obtained with parametrization $g_{A,\mathrm{eff}} = 1.269A^{-\gamma}$
- In their paper a systematic study is performed of pairs of single-β-decaying nuclei in the mass region A=100-136 to extract information on the effective value of the axial-vector coupling constant g_A using QRPA
  - In QRPA the analysis is not as straightforward since the parameter g_{pp} affects strongly to the needed effective value of g_A
- For the maximal quenching we now take an average of these two parametrizations

From Jenni Kotila.



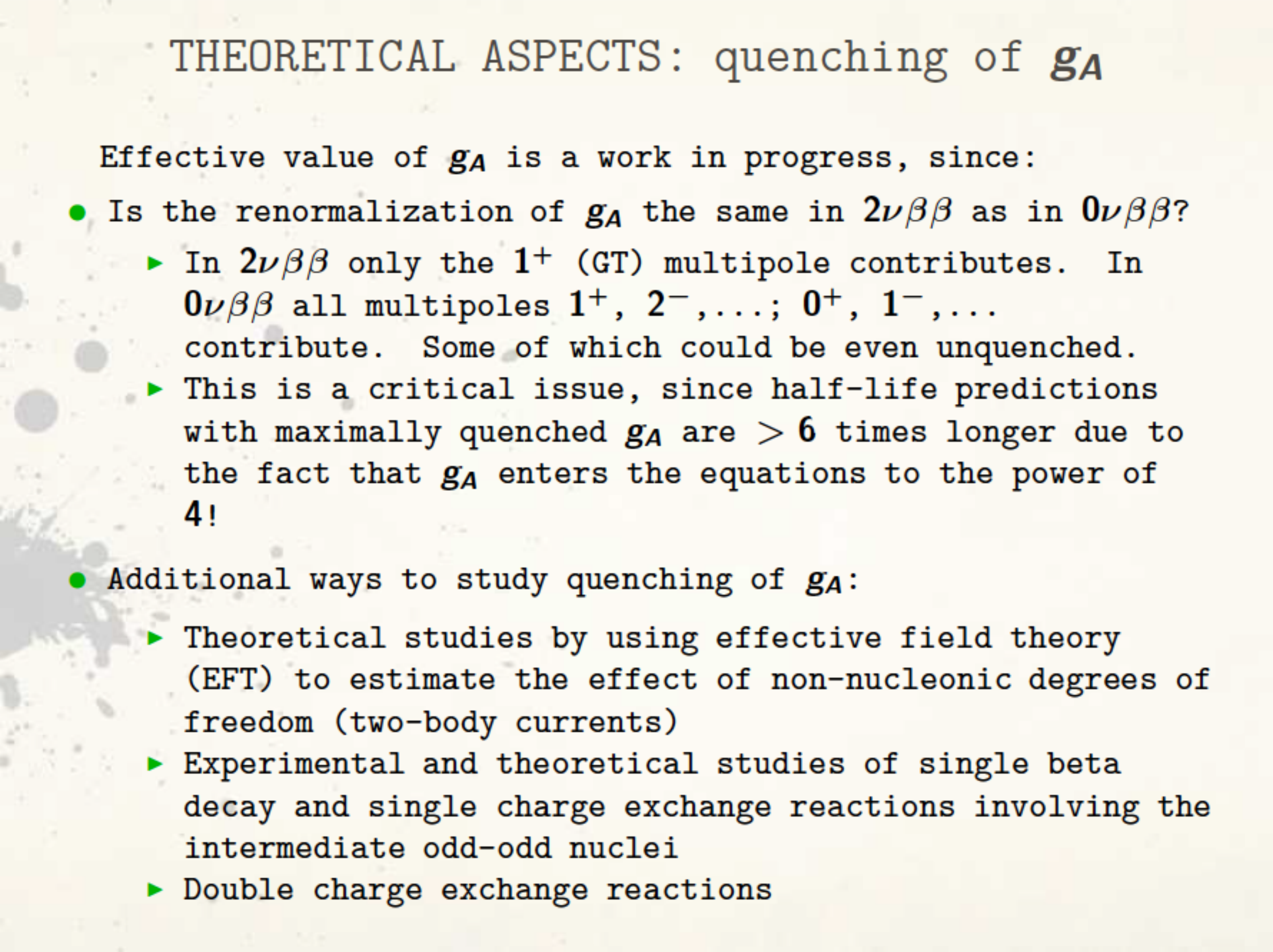
THEORETICAL ASPECTS: quenching of g_A

Let's return to $0\nu\beta\beta$ NMEs:

$M_{0\nu} = g^2_{A,eff} M^{(0\nu)}$ for IBM-2, QRPA, and ISM

- Taking into account the 16% uncertainty estimate for IBM-2: Agreement quite good
- Looks promising...

From Jenni Kotila.



THEORETICAL ASPECTS: quenching of g_A

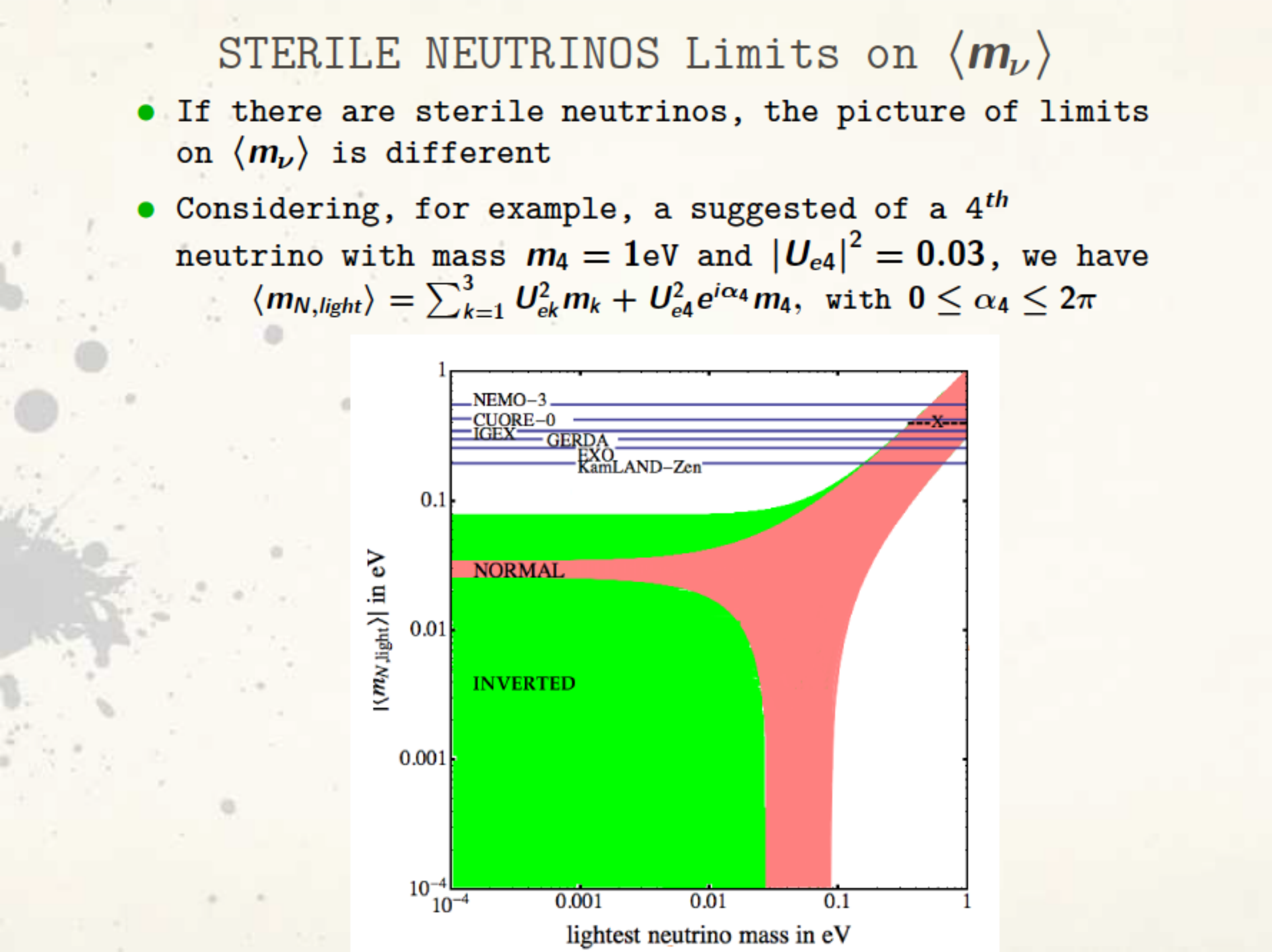
Effective value of g_A is a work in progress, since:

- Is the renormalization of g_A the same in $2\nu\beta\beta$ as in $0\nu\beta\beta$?
  - In $2\nu\beta\beta$ only the 1^+ (GT) multipole contributes. In $0\nu\beta\beta$ all multipoles 1^+, 2^-, ...; 0^+, 1^-, ... contribute. Some of which could be even unquenched.
  - This is a critical issue, since half-life predictions with maximally quenched g_A are > 6 times longer due to the fact that g_A enters the equations to the power of 4!
- Additional ways to study quenching of g_A:
  - Theoretical studies by using effective field theory (EFT) to estimate the effect of non-nucleonic degrees of freedom (two-body currents)
  - Experimental and theoretical studies of single beta decay and single charge exchange reactions involving the intermediate odd-odd nuclei
  - Double charge exchange reactions

This may seem a bit depressing…

and there is this….

From Jenni Kotila.

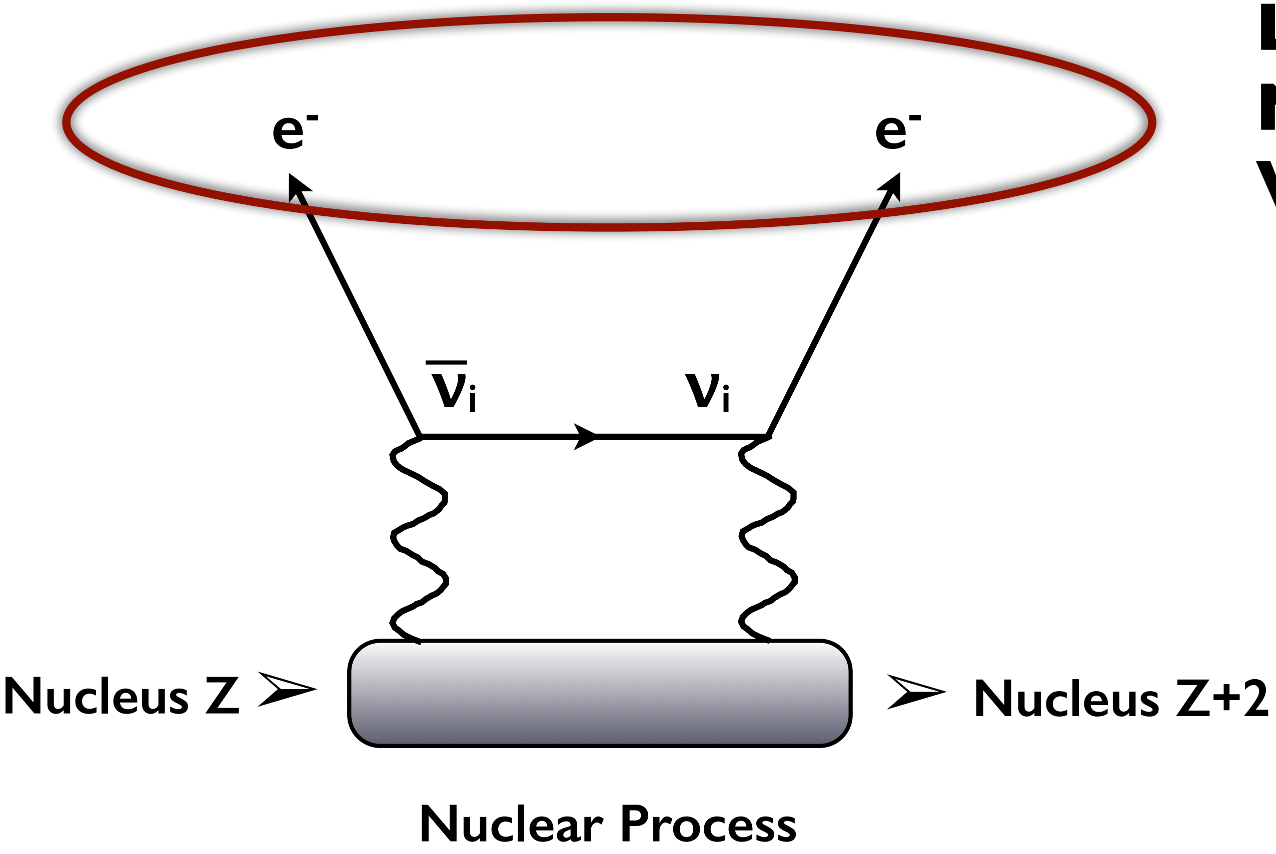


STERILE NEUTRINOS Limits on $\langle m_\nu \rangle$

- If there are sterile neutrinos, the picture of limits on $\langle m_\nu \rangle$ is different
- Considering, for example, a suggested of a 4^{th} neutrino with mass $m_4 = 1\text{eV}$ and $|U_{e4}|^2 = 0.03$, we have

$$\langle m_{N,light} \rangle = \sum_{k=1}^{3} U_{ek}^2 m_k + U_{e4}^2 e^{i\alpha_4} m_4, \text{ with } 0 \leq \alpha_4 \leq 2\pi$$

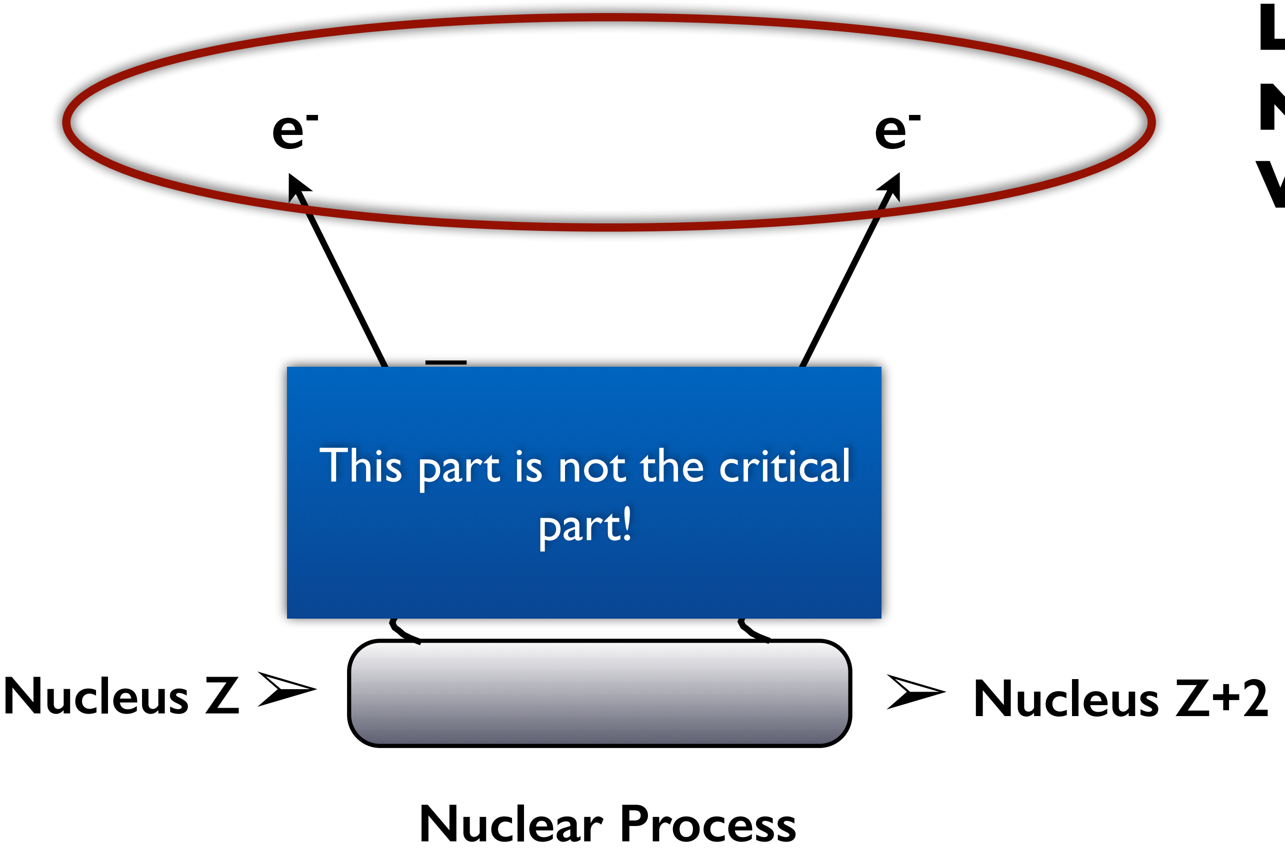
but remember what we are actually looking for….



Lepton Number Violation!

Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange (LMNE)



e^- e^-

Lepton Number Violation!

This part is not the critical part!

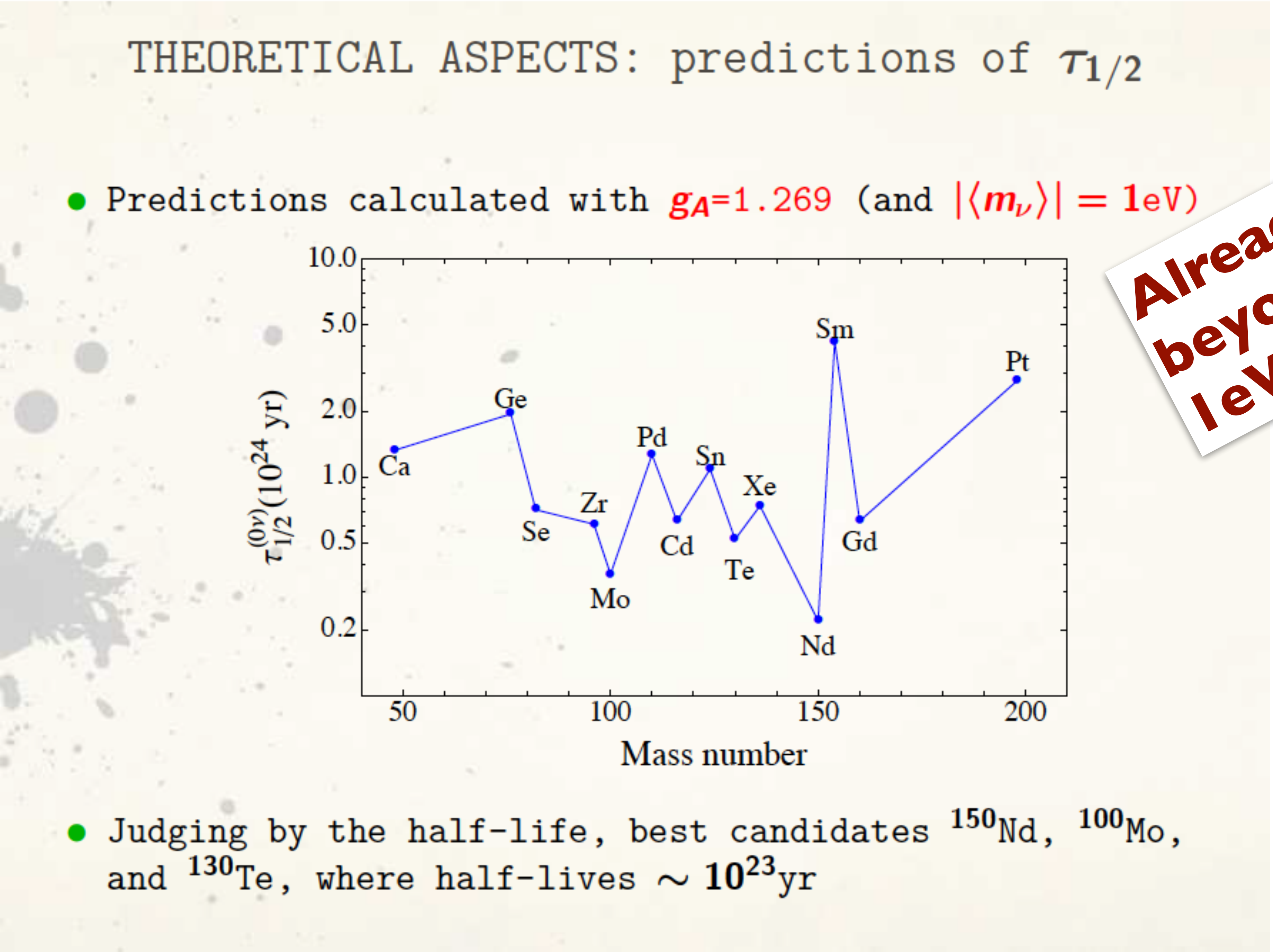
Nucleus Z ➢ ➢ Nucleus Z+2

Nuclear Process

Neutrinoless Double Beta Decay

Some predictions and other processes and mechanisms.

From Jenni Kotila.



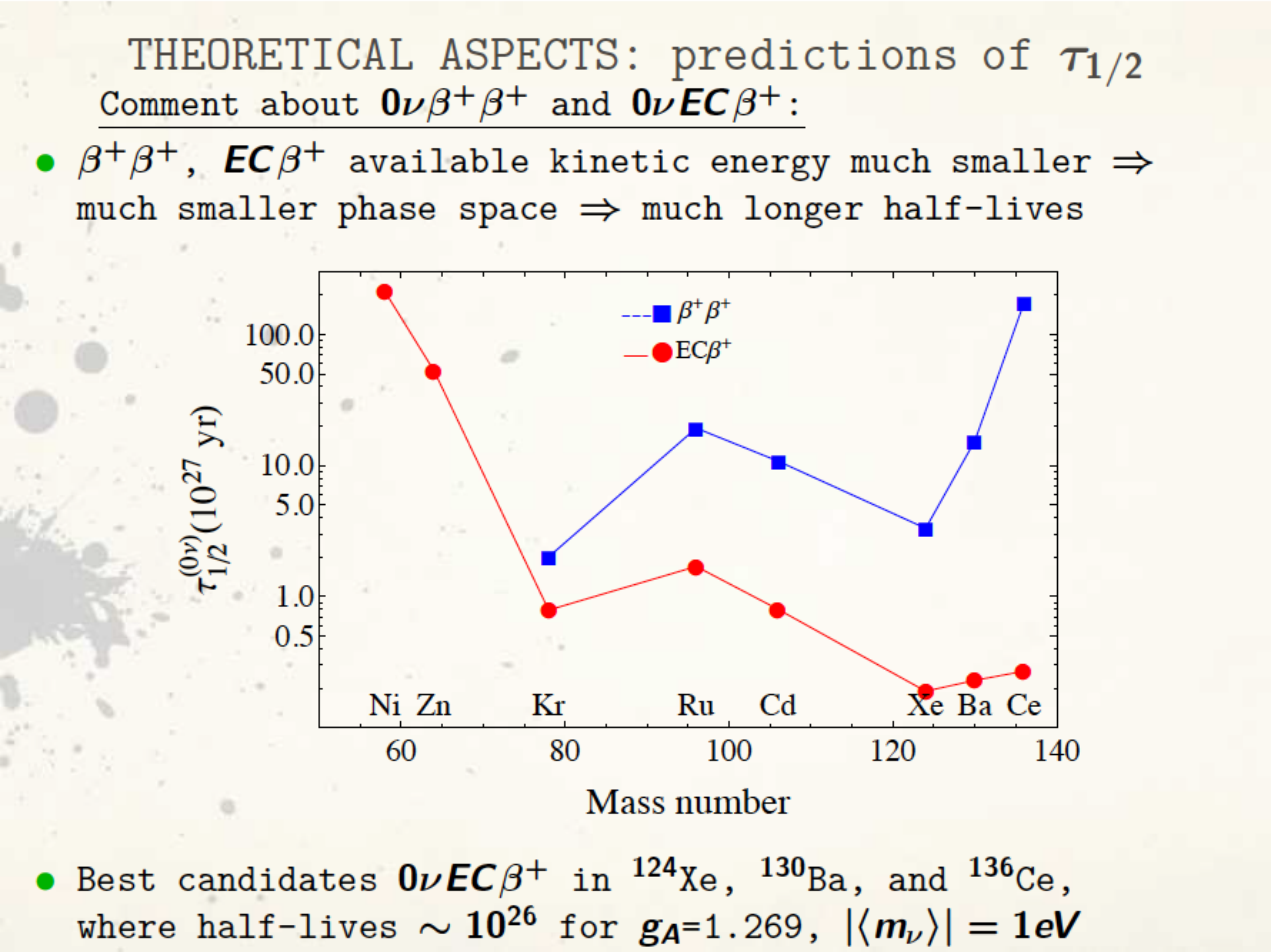
THEORETICAL ASPECTS: predictions of $\tau_{1/2}$

- Predictions calculated with g_A=1.269 (and $|\langle m_\nu \rangle| = 1$eV)

- Judging by the half-life, best candidates ^{150}Nd, ^{100}Mo, and ^{130}Te, where half-lives $\sim 10^{23}$yr

Already beyond 1eV

From Jenni Kotila.



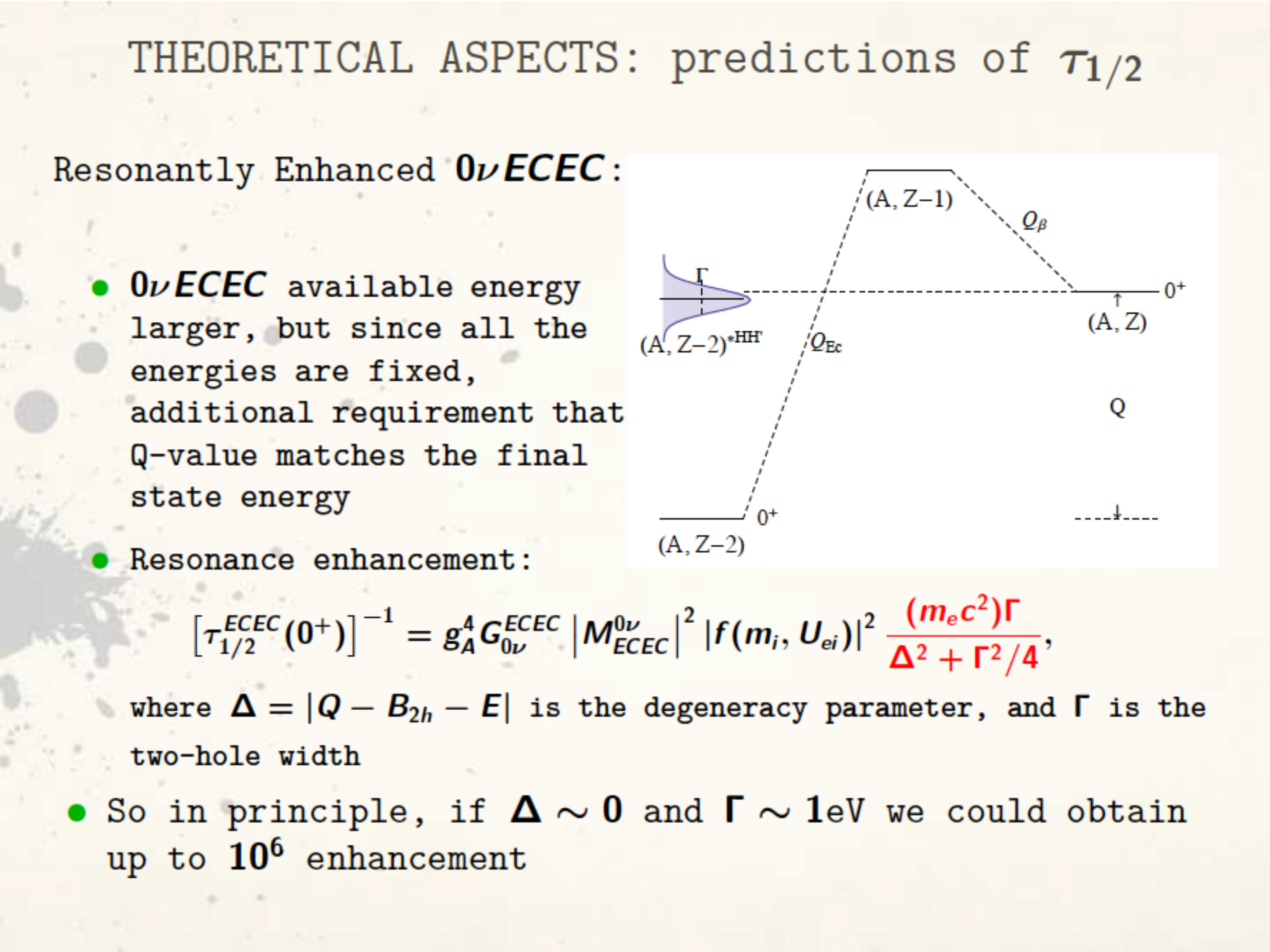
THEORETICAL ASPECTS: predictions of $\tau_{1/2}$

Comment about $\mathbf{0\nu\beta^+\beta^+}$ and $\mathbf{0\nu EC\beta^+}$:

- $\beta^+\beta^+$, $EC\beta^+$ available kinetic energy much smaller ⇒ much smaller phase space ⇒ much longer half-lives

- Best candidates $\mathbf{0\nu EC\beta^+}$ in ^{124}Xe, ^{130}Ba, and ^{136}Ce, where half-lives $\sim \mathbf{10^{26}}$ for g_A=1.269, $|\langle m_\nu \rangle| = 1eV$

From Jenni Kotila.



THEORETICAL ASPECTS: predictions of $\tau_{1/2}$

Resonantly Enhanced $0\nu ECEC$:

- $0\nu ECEC$ available energy larger, but since all the energies are fixed, additional requirement that Q-value matches the final state energy

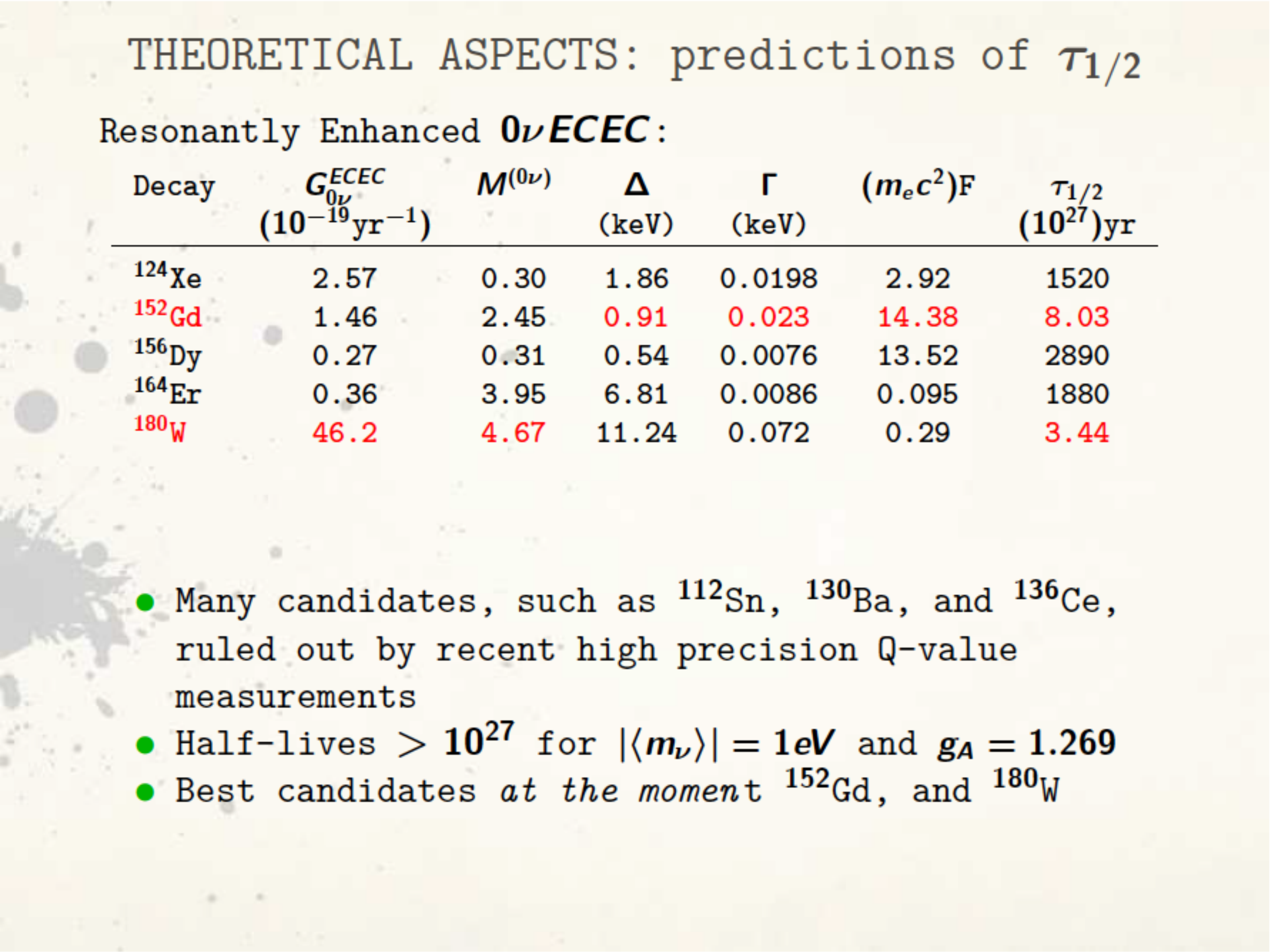
- Resonance enhancement:

$$\left[\tau_{1/2}^{ECEC}(0^+)\right]^{-1} = g_A^4 G_{0\nu}^{ECEC} \left|M_{ECEC}^{0\nu}\right|^2 \left|f(m_i, U_{ei})\right|^2 \frac{(m_e c^2)\Gamma}{\Delta^2 + \Gamma^2/4},$$

  where $\Delta = |Q - B_{2h} - E|$ is the degeneracy parameter, and Γ is the two-hole width

- So in principle, if $\Delta \sim 0$ and $\Gamma \sim 1$eV we could obtain up to 10^6 enhancement

From Jenni Kotila.



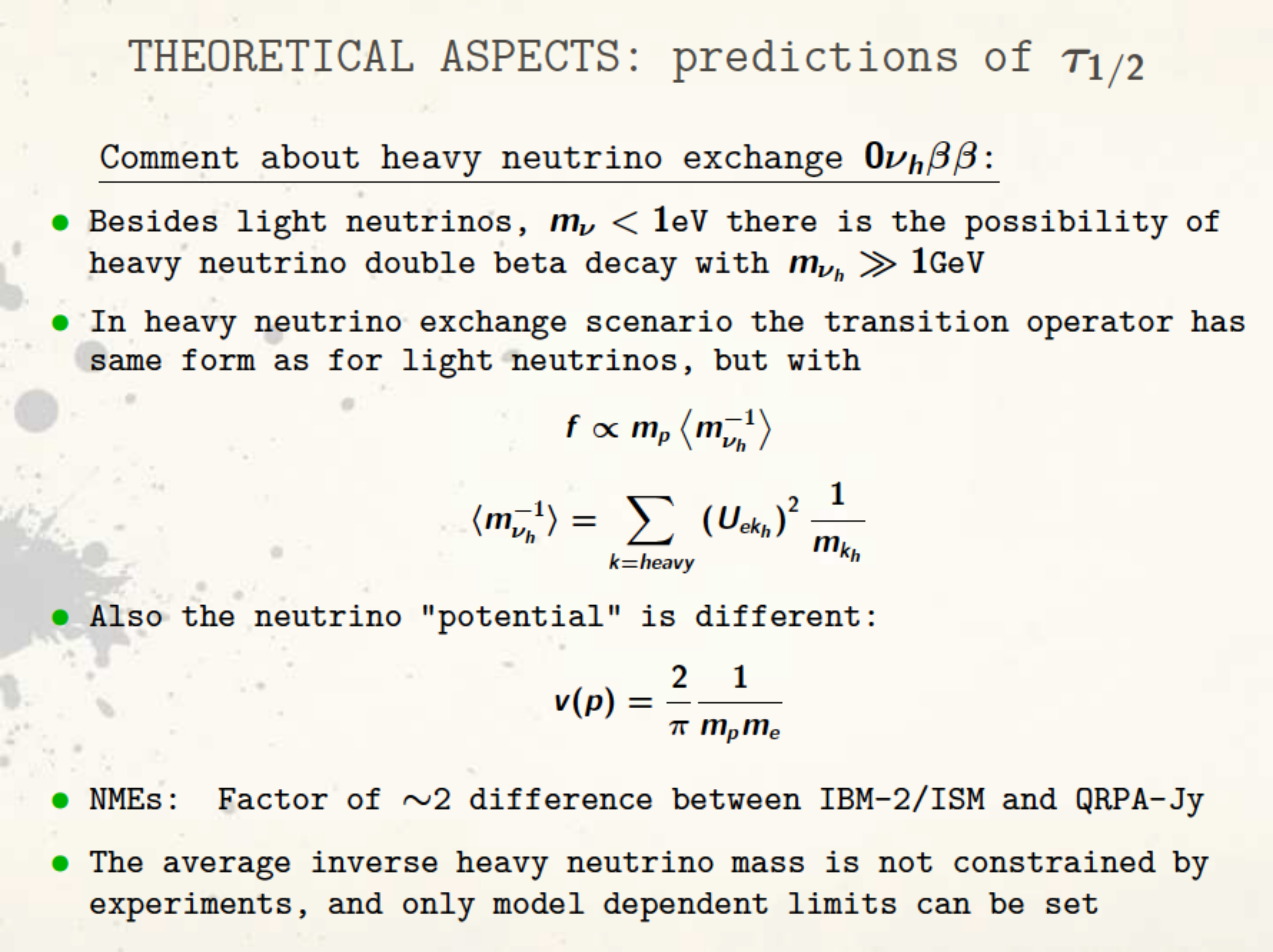
THEORETICAL ASPECTS: predictions of $\tau_{1/2}$

Resonantly Enhanced $\mathbf{0\nu ECEC}$:

Decay	$G_{0\nu}^{ECEC}$ $(10^{-19}\mathrm{yr}^{-1})$	$M^{(0\nu)}$	Δ (keV)	Γ (keV)	$(m_e c^2)$F	$\tau_{1/2}$ (10^{27})yr
^{124}Xe	2.57	0.30	1.86	0.0198	2.92	1520
^{152}Gd	1.46	2.45	0.91	0.023	14.38	8.03
^{156}Dy	0.27	0.31	0.54	0.0076	13.52	2890
^{164}Er	0.36	3.95	6.81	0.0086	0.095	1880
^{180}W	46.2	4.67	11.24	0.072	0.29	3.44

- Many candidates, such as ^{112}Sn, ^{130}Ba, and ^{136}Ce, ruled out by recent high precision Q-value measurements
- Half-lives $> 10^{27}$ for $|\langle m_\nu \rangle| = 1eV$ and $g_A = 1.269$
- Best candidates *at the moment* ^{152}Gd, and ^{180}W

From Jenni Kotila.



THEORETICAL ASPECTS: predictions of $\tau_{1/2}$

Comment about heavy neutrino exchange $0\nu_h\beta\beta$:

- Besides light neutrinos, $m_\nu < 1$eV there is the possibility of heavy neutrino double beta decay with $m_{\nu_h} \gg 1$GeV
- In heavy neutrino exchange scenario the transition operator has same form as for light neutrinos, but with

$$f \propto m_p \left\langle m_{\nu_h}^{-1} \right\rangle$$

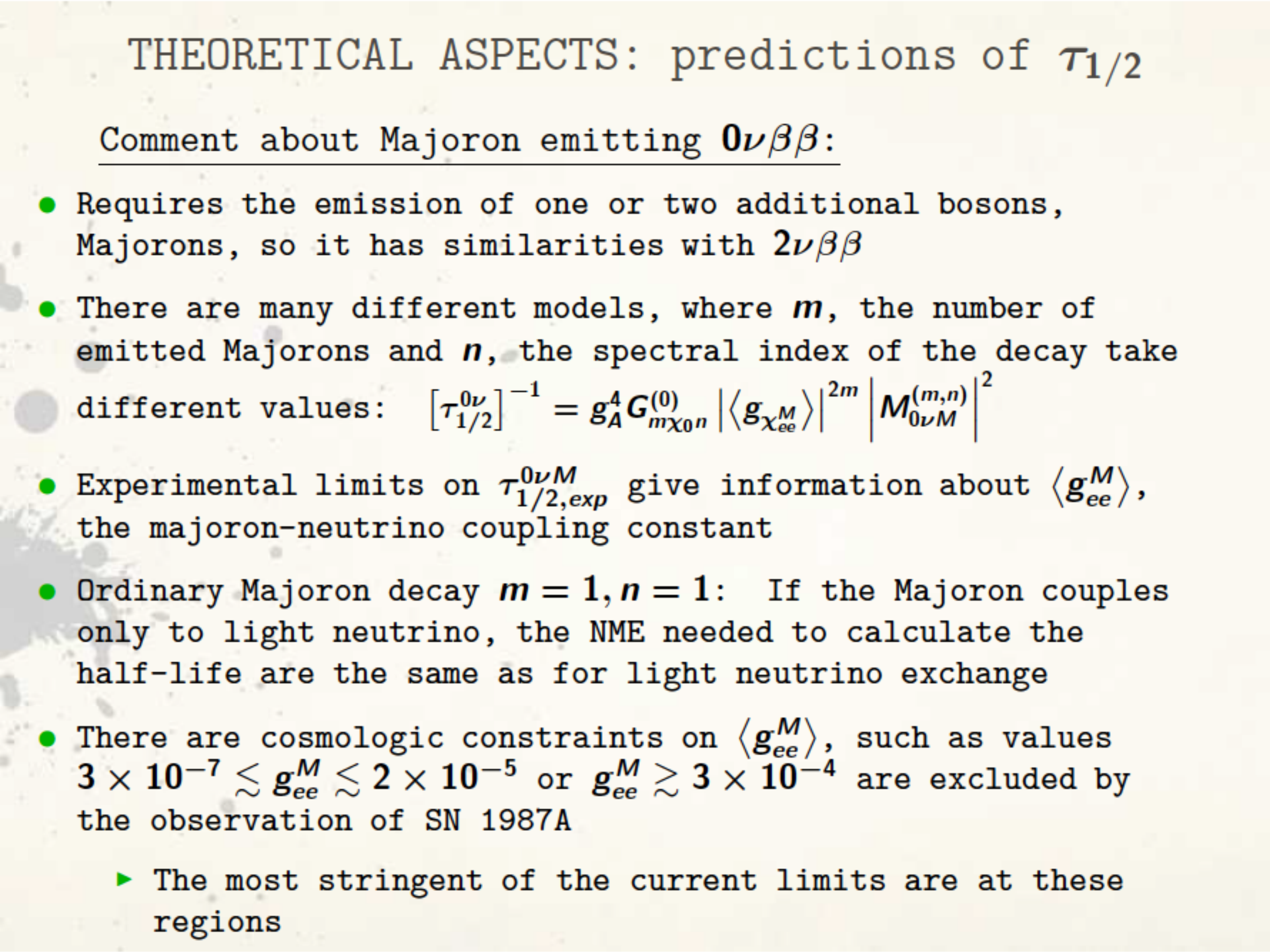
$$\langle m_{\nu_h}^{-1} \rangle = \sum_{k=heavy} \left(U_{ek_h}\right)^2 \frac{1}{m_{k_h}}$$

- Also the neutrino "potential" is different:

$$v(p) = \frac{2}{\pi} \frac{1}{m_p m_e}$$

- NMEs: Factor of ~2 difference between IBM-2/ISM and QRPA-Jy
- The average inverse heavy neutrino mass is not constrained by experiments, and only model dependent limits can be set

From Jenni Kotila.



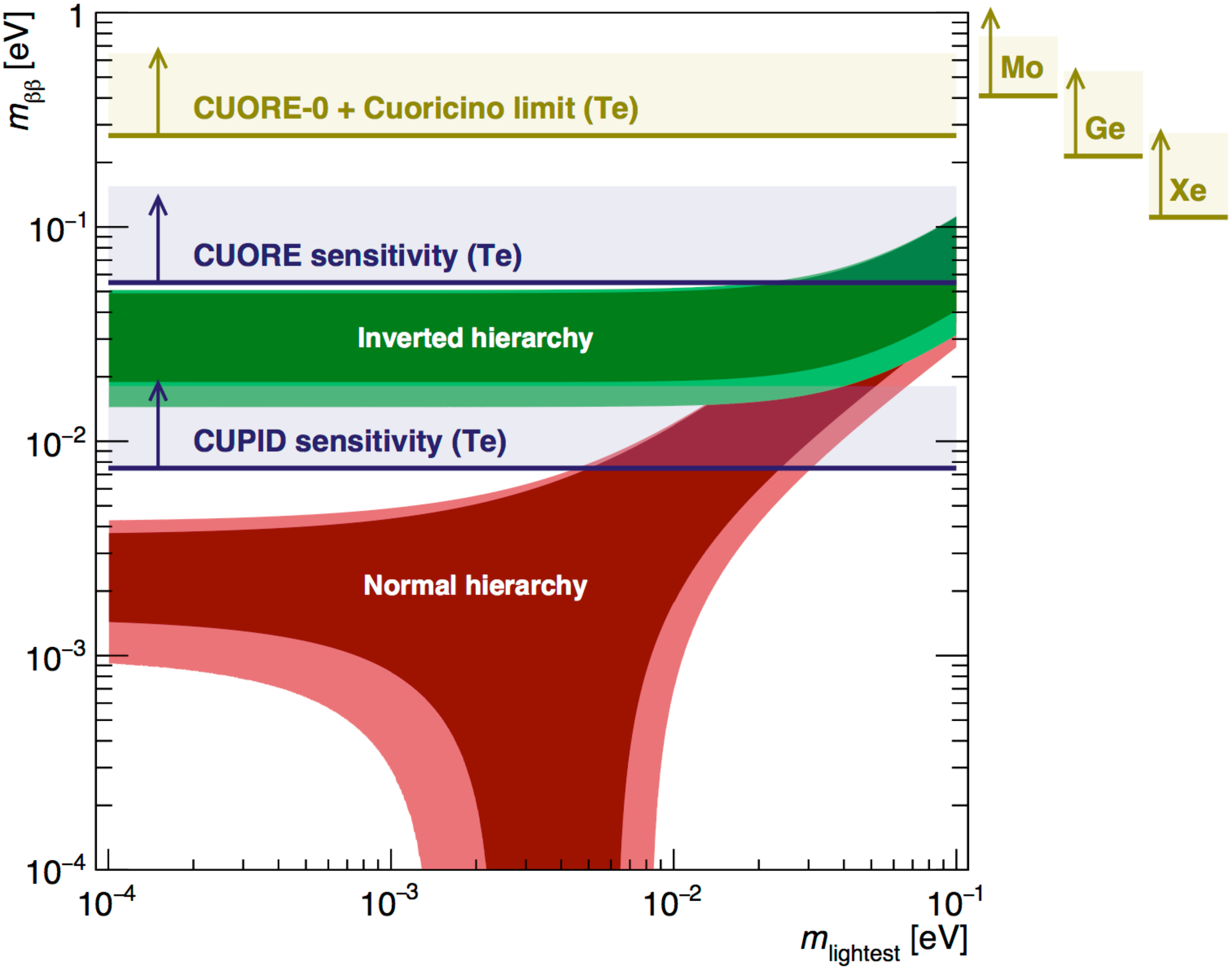
THEORETICAL ASPECTS: predictions of $\tau_{1/2}$

Comment about Majoron emitting $0\nu\beta\beta$:

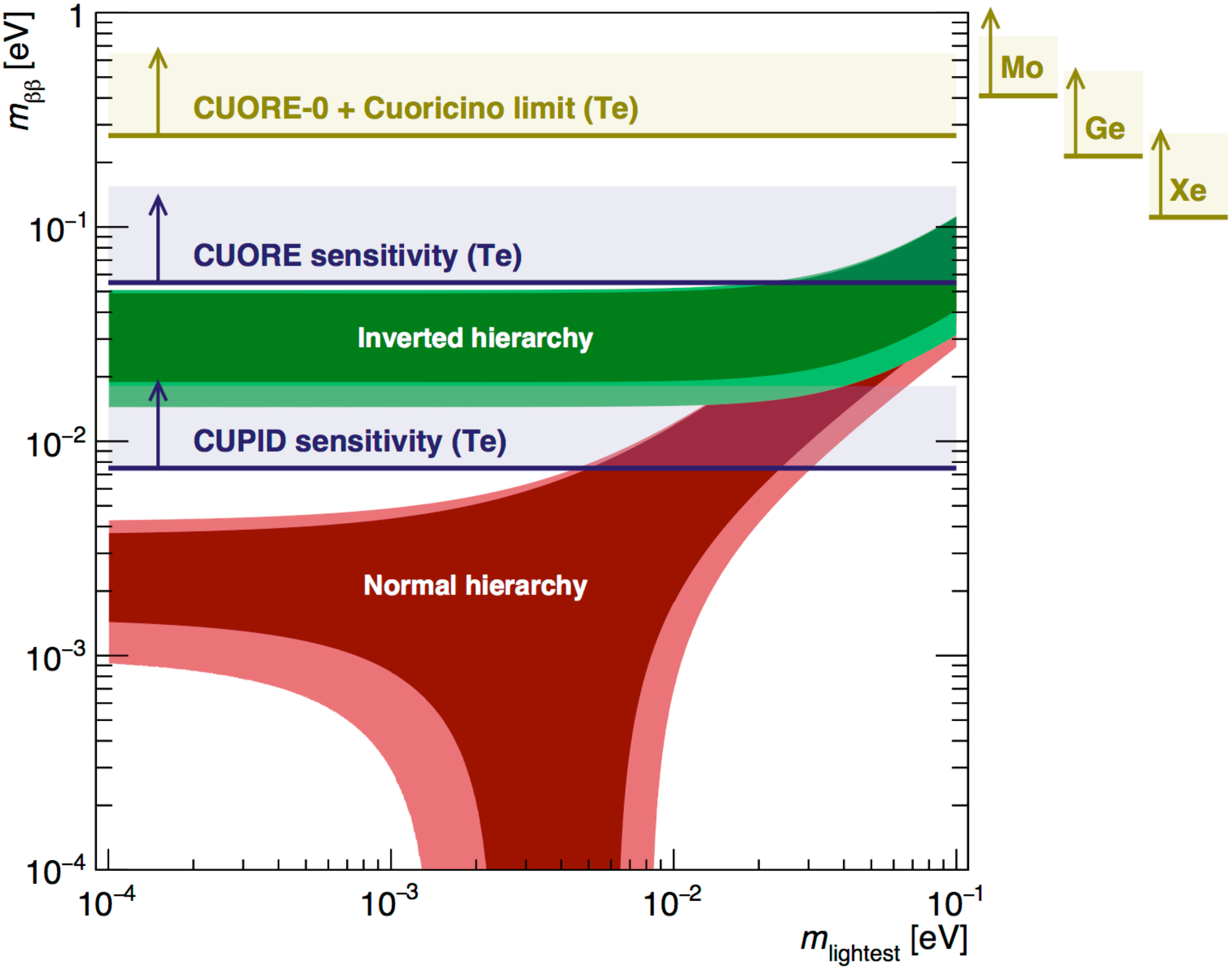
- Requires the emission of one or two additional bosons, Majorons, so it has similarities with $2\nu\beta\beta$
- There are many different models, where m, the number of emitted Majorons and n, the spectral index of the decay take different values: $\left[\tau_{1/2}^{0\nu}\right]^{-1} = g_A^4 G_{m\chi_0 n}^{(0)} \left|\langle g_{\chi_{ee}^M}\rangle\right|^{2m} \left|M_{0\nu M}^{(m,n)}\right|^2$
- Experimental limits on $\tau_{1/2,exp}^{0\nu M}$ give information about $\langle g_{ee}^M\rangle$, the majoron-neutrino coupling constant
- Ordinary Majoron decay $m = 1, n = 1$: If the Majoron couples only to light neutrino, the NME needed to calculate the half-life are the same as for light neutrino exchange
- There are cosmologic constraints on $\langle g_{ee}^M\rangle$, such as values $3 \times 10^{-7} \lesssim g_{ee}^M \lesssim 2 \times 10^{-5}$ or $g_{ee}^M \gtrsim 3 \times 10^{-4}$ are excluded by the observation of SN 1987A
    - The most stringent of the current limits are at these regions

What are experiments aiming for?

The goal is the inverted hierarchy:



But this is still a good goal…



Comparing Experiments' Sensitivity:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma} \left(\frac{\varepsilon a}{W} \right) \sqrt{\frac{Mt}{b\Delta(E)}}$$

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

How many sigma you would like to be able to measure.

Detector Efficiency

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\overset{\downarrow}{\varepsilon a}}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Isotopic abundance

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Molecular Weight

Exposure time

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Background rate

Total Mass

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16\times 10^{26}\ \text{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\underset{\nwarrow}{\Delta(E)}}}$$

Energy resolution
(Most important for separating
neutrinoless from two neutrino
double beta decay).

Rough Time Scales

^{14}C - 10^4 years

^{40}K - 10^9 years

^{232}Th - 10^{10} years

The Universe - 10^{10} years

Two Neutrino Double Beta - 10^{20} years

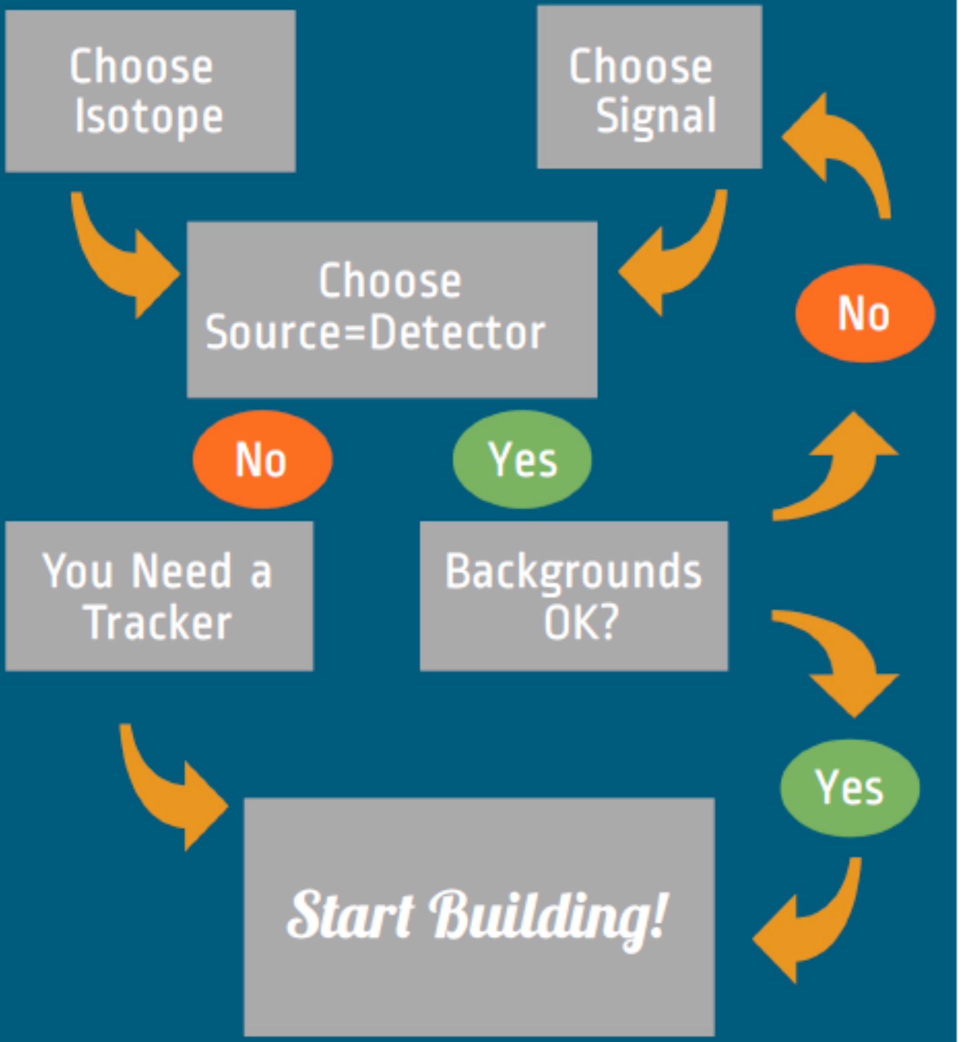
Neutrinoless Double Beta $>10^{26}$ years

Proton Decay $>10^{30}$ years

Let’s make a detector!

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.527 MeV	34.5%
^{136}Xe	2.457 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%

Design your own experiment



Choose Isotope

Choose Signal

Choose Source=Detector

No

Yes

No

You Need a Tracker

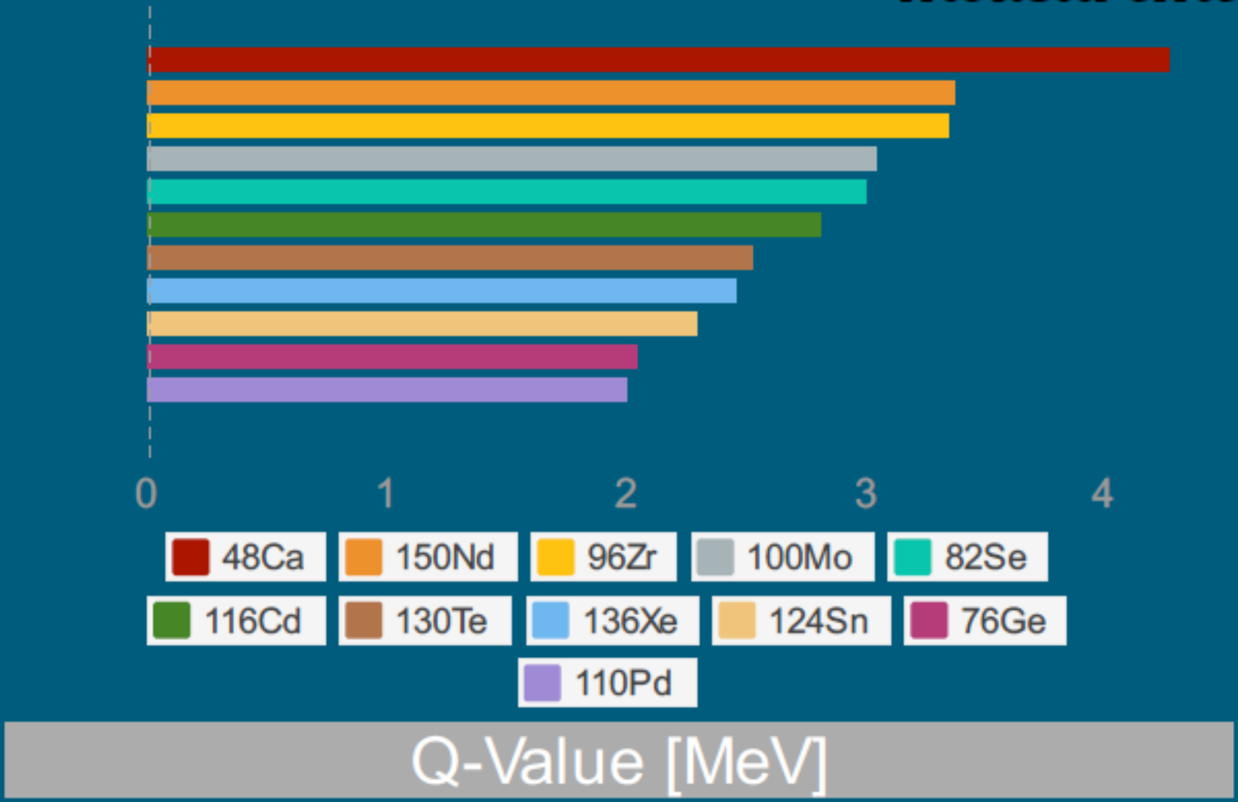
Backgrounds OK?

Yes

Start Building!

Choose an Isotope

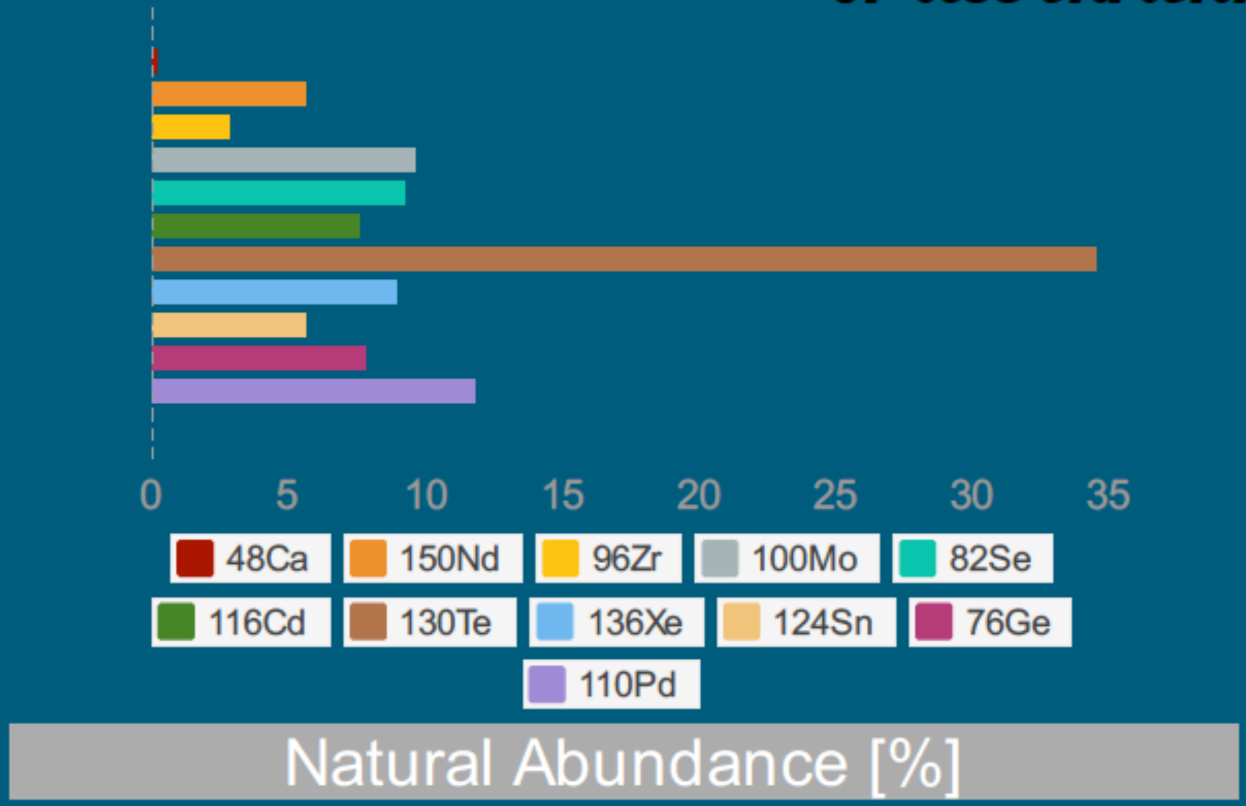
High Q-Value means a higher rate and an easier measurement!



PHYSICAL REVIEW D 87, 071301(R) (2013)

Choose an Isotope

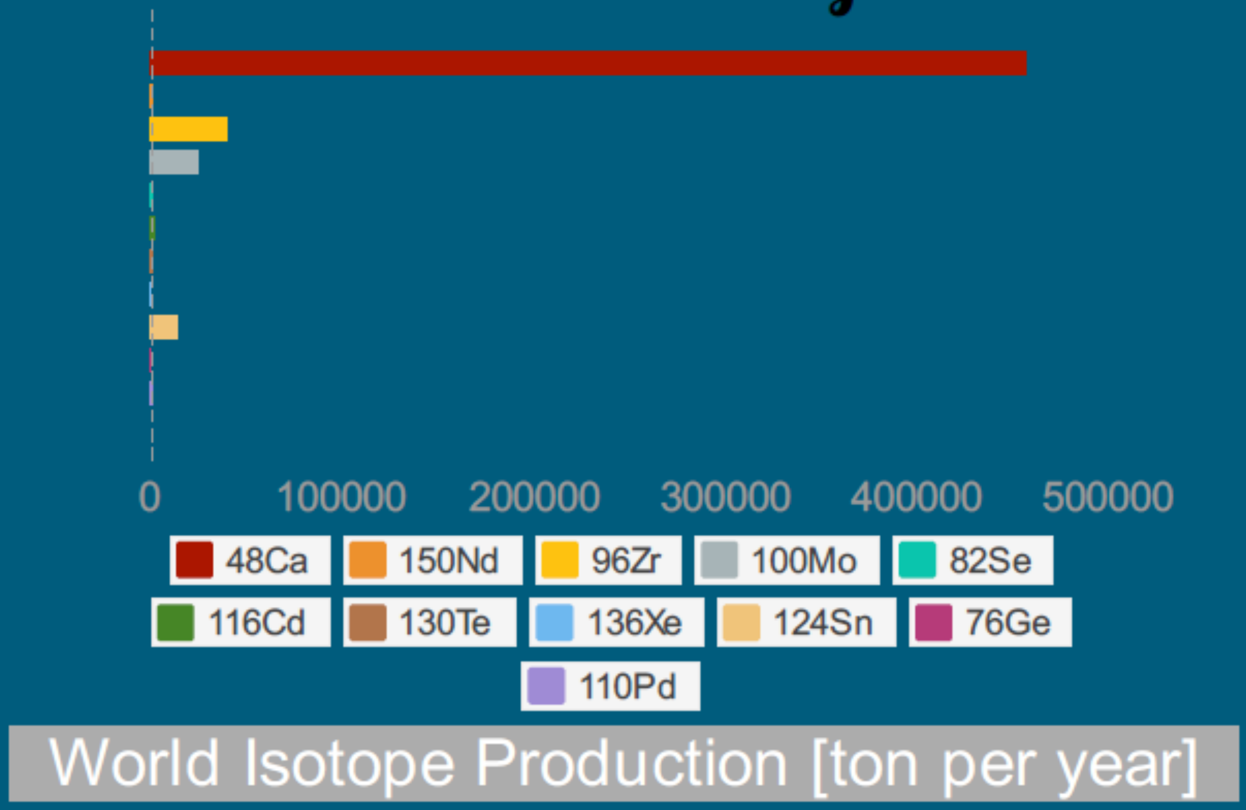
High natural abundance means a smaller detector or less enrichment!



PHYSICAL REVIEW D 87, 071301(R) (2013)

Choose an Isotope

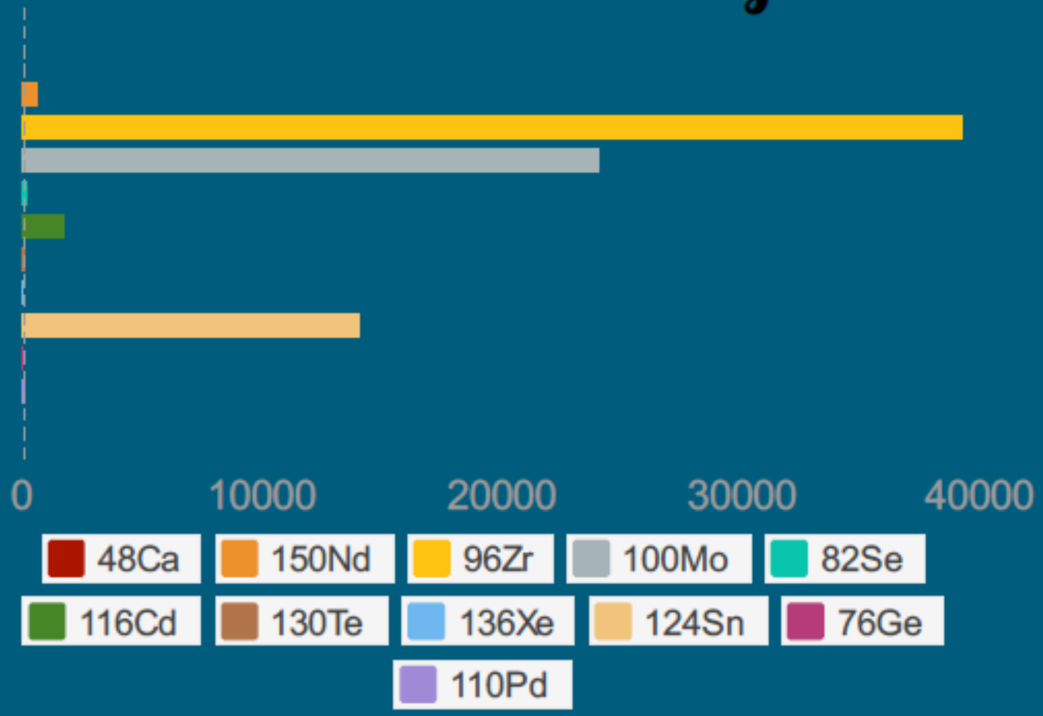
Highest Production



PHYSICAL REVIEW D 87, 071301(R) (2013)

Choose an Isotope

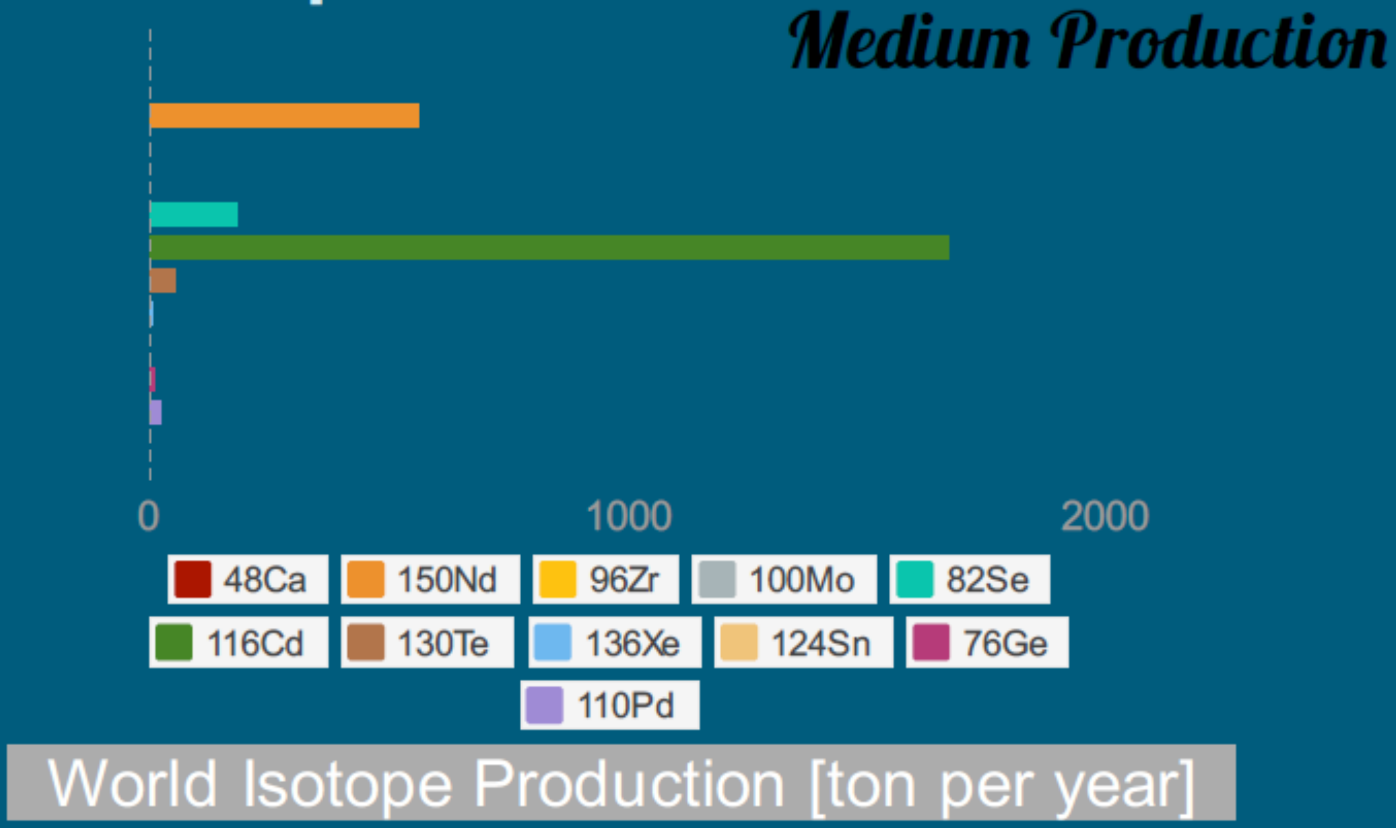
High Production



World Isotope Production [ton per year]

PHYSICAL REVIEW D 87, 071301(R) (2013)

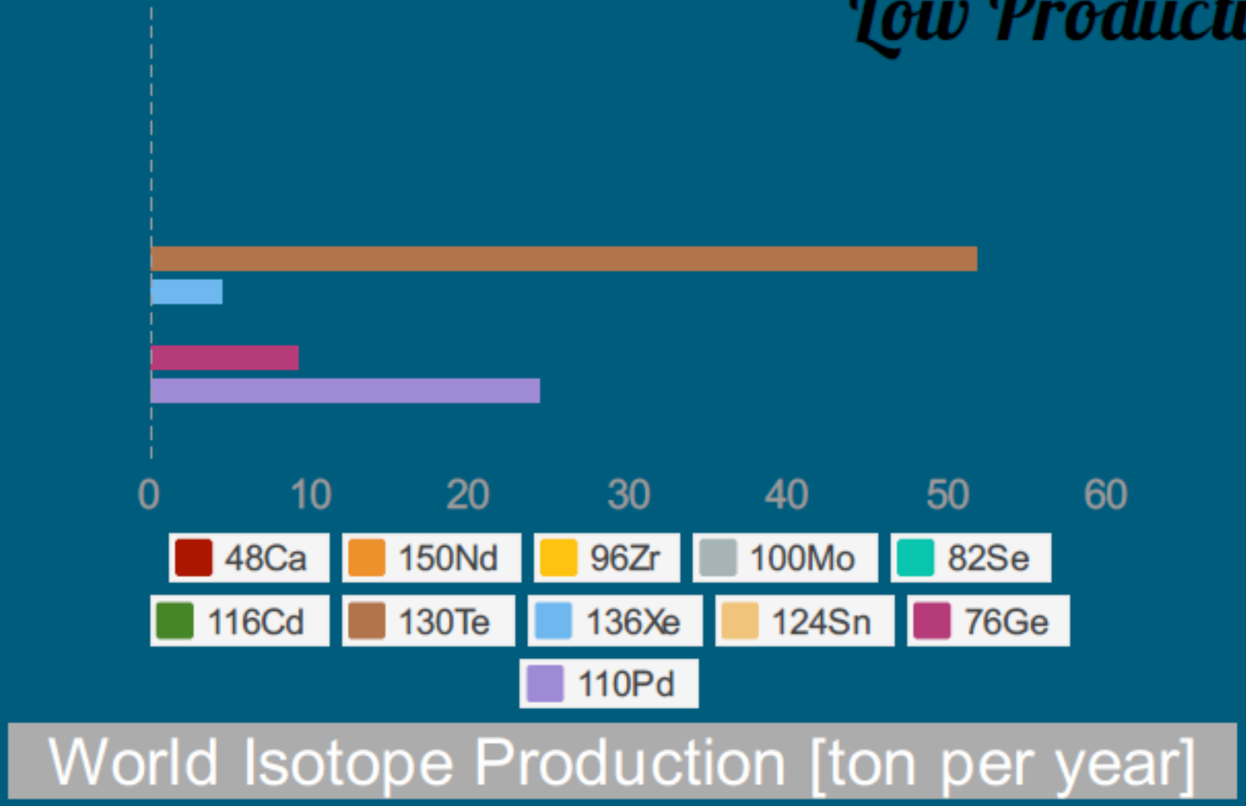
Choose an Isotope



PHYSICAL REVIEW D 87, 071301(R) (2013)

Choose an Isotope

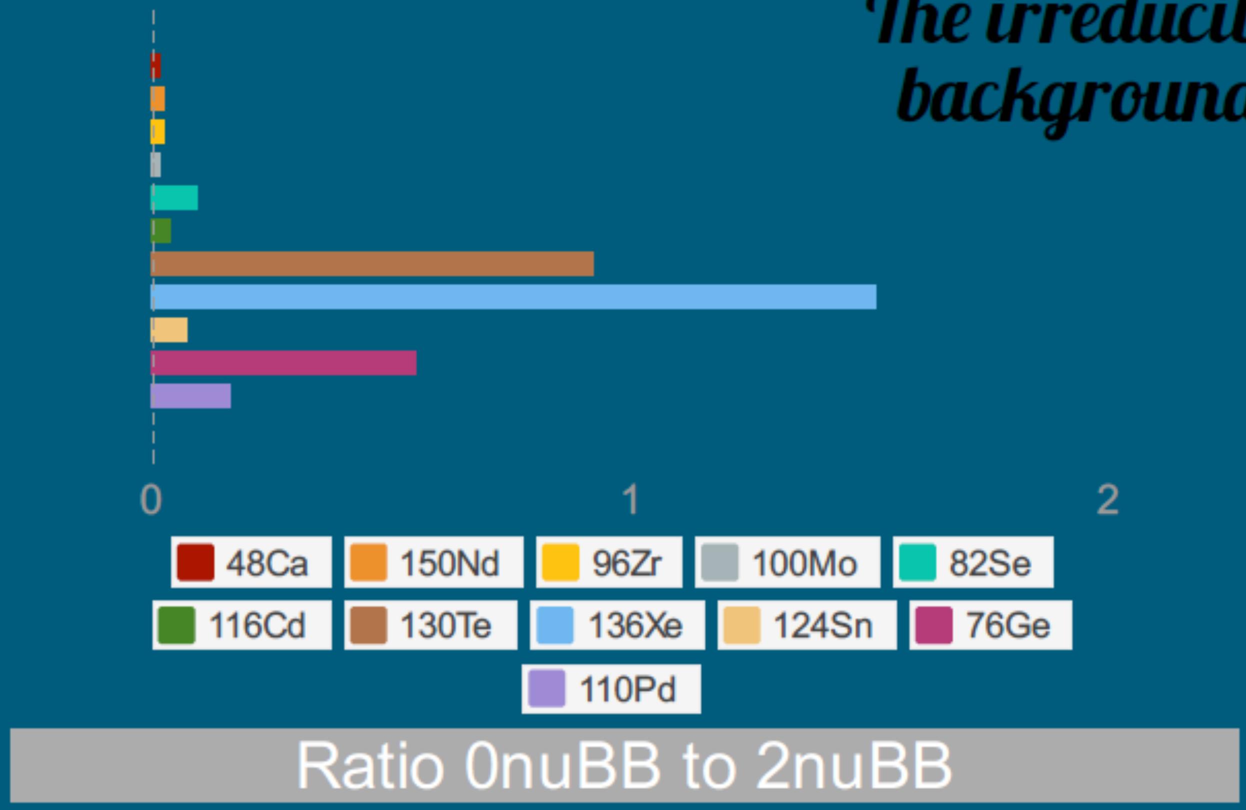
Low Production



PHYSICAL REVIEW D 87, 071301(R) (2013)

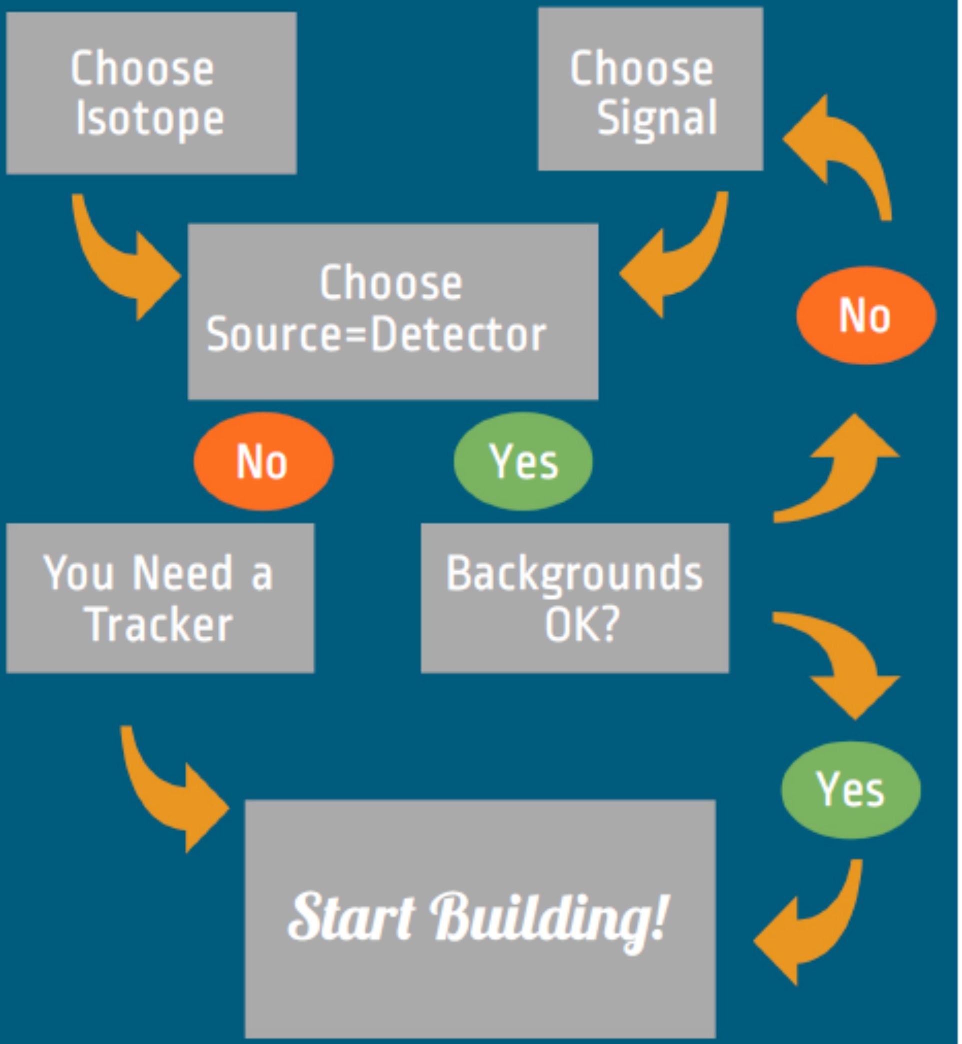
Choose an Isotope

The irreducible background!



PHYSICAL REVIEW D 87, 071301(R) (2013)

Design your own experiment



Choose Isotope

Choose Signal

Choose Source=Detector

No

Yes

You Need a Tracker

Backgrounds OK?

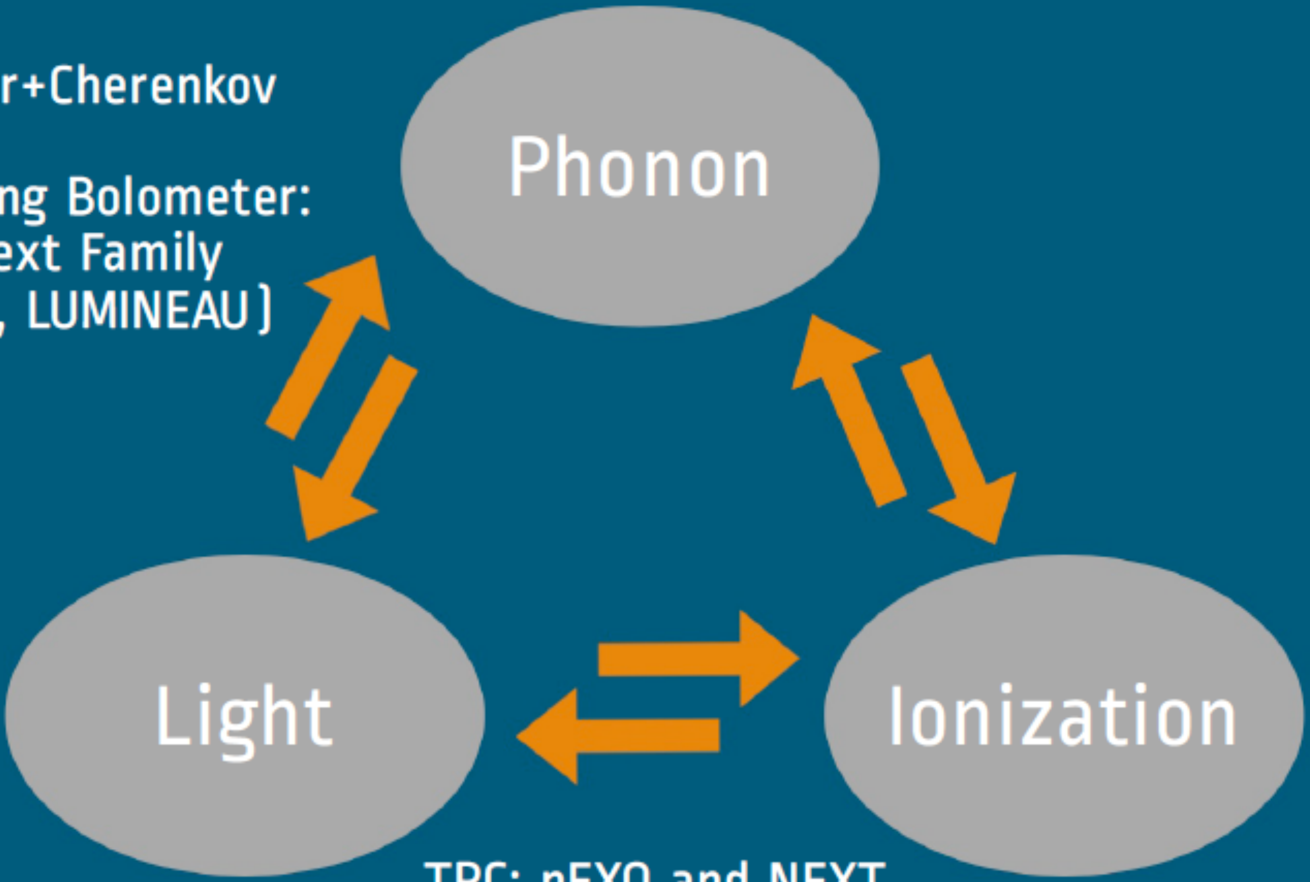
No

Yes

Start Building!

Choose a Signal:

A diagram that the direct dark matter experiments like to make.



CUORE

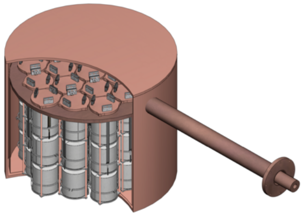
Bolometer+Cherenkov
or
Scintillating Bolometer:
CUORE-Next Family
[LUCIFER, LUMINEAU]
AmoRE

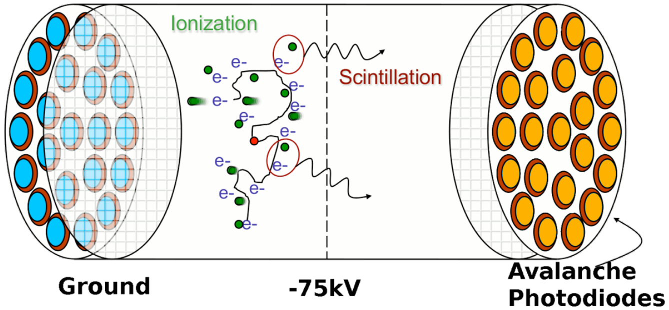
TPC: nEXO and NEXT

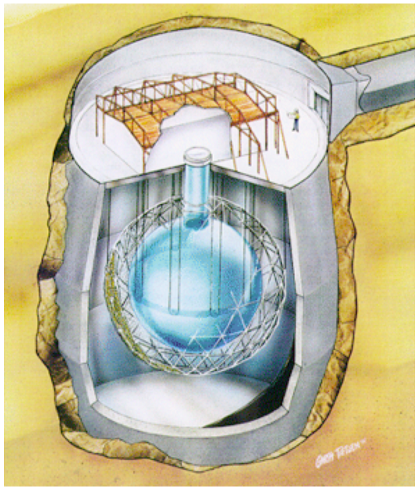
Liquid Scintillator:
KamLAND-Zen, SNO+
Scintillating Crystal:
CANDLES

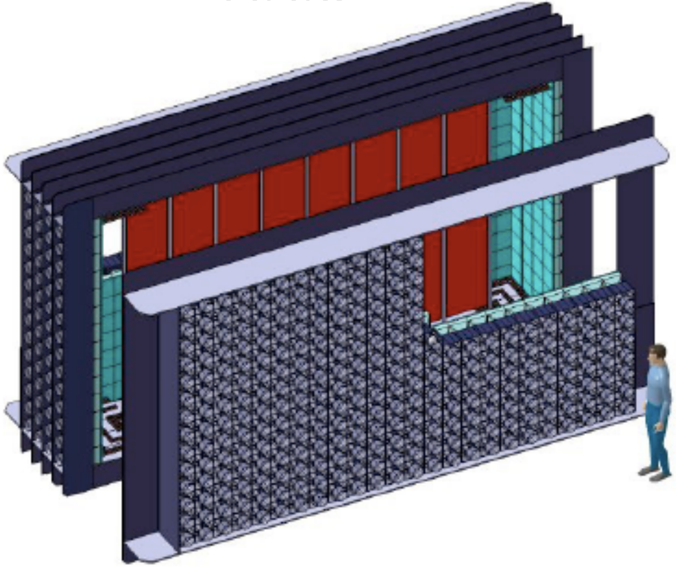
Semiconductor:
GERDA/Majorana
Tracking:
SuperNEMO, DCBA

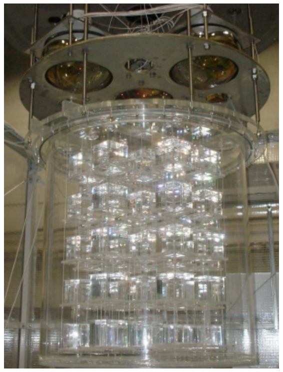
A lot of detector ideas:

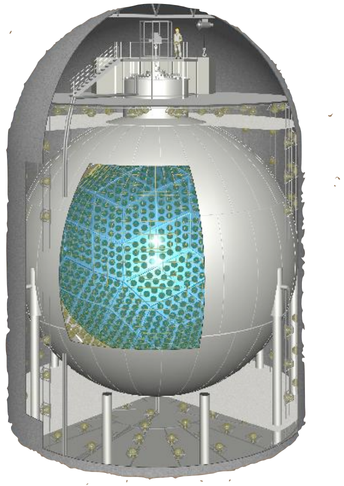


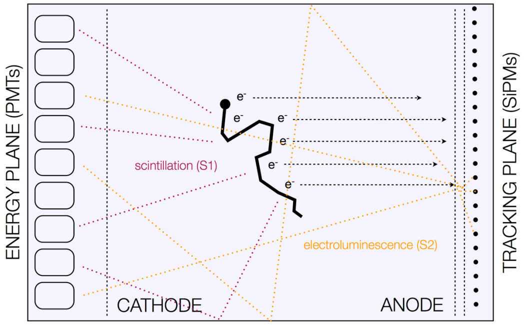


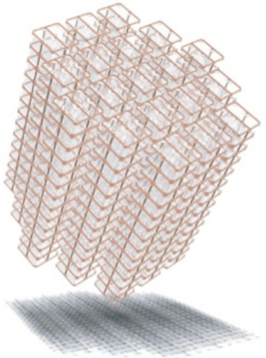




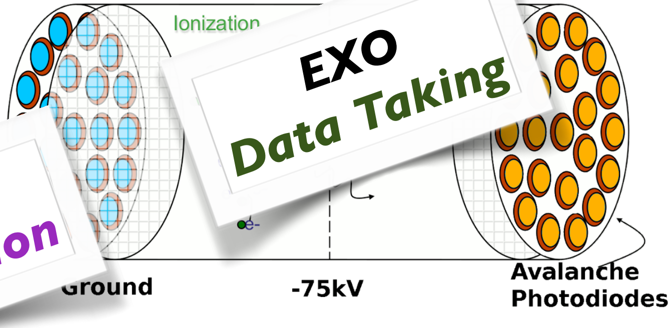




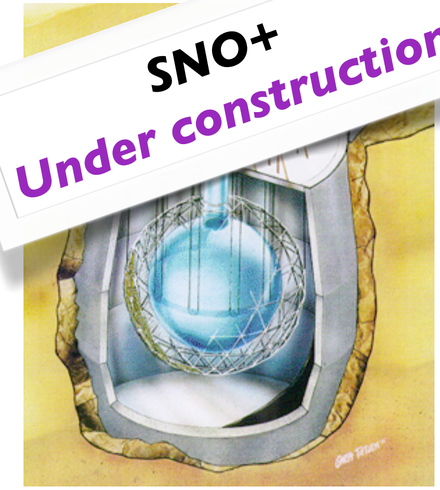




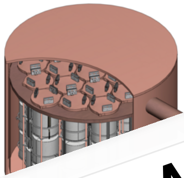
A lot of detector ideas:



EXO
Data Taking



SNO+
Under construction

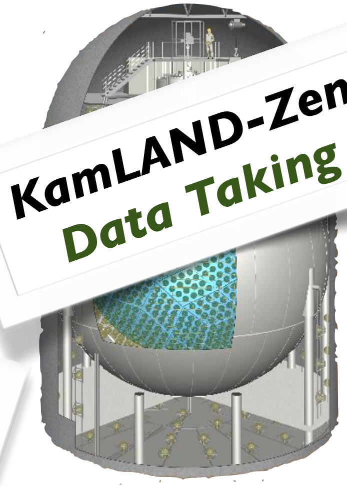


Majorana
Under construction

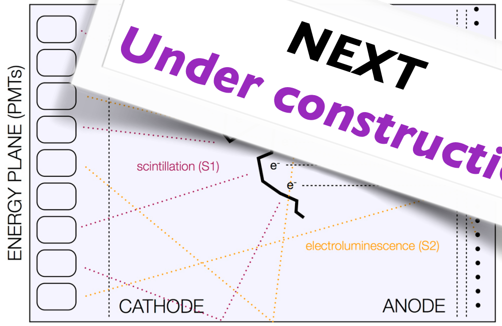
SuperNEMO
Under construction

GERDA
Data Taking

CANDLES
Complete



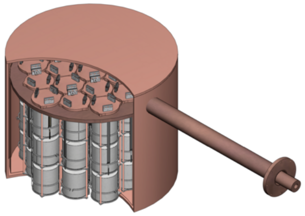
KamLAND-Zen
Data Taking

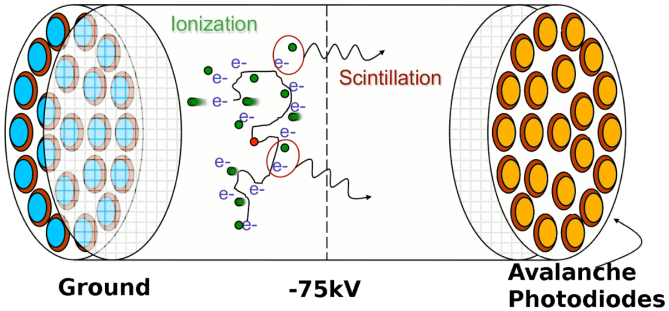


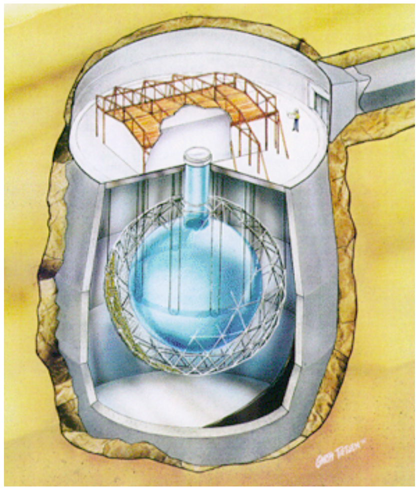
NEXT
Under construction

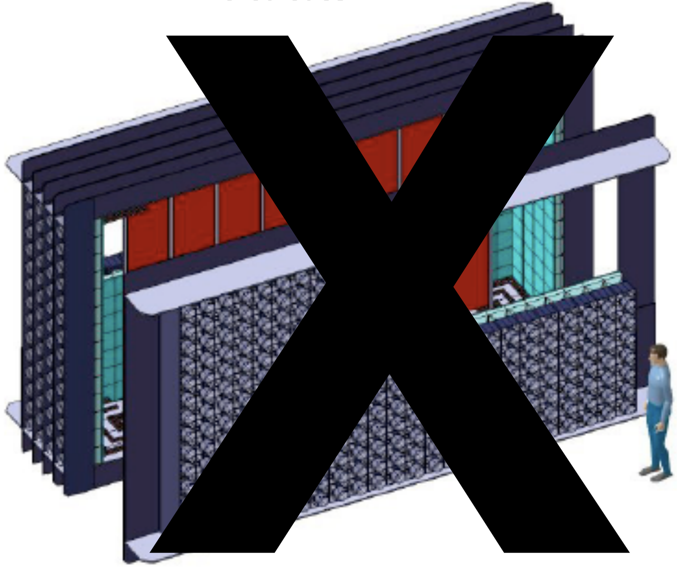
CUORE
Under construction

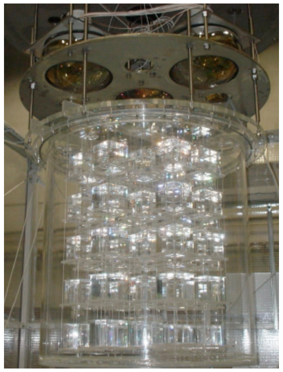
source = detector

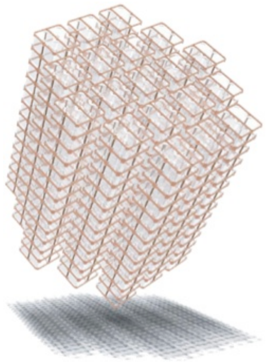


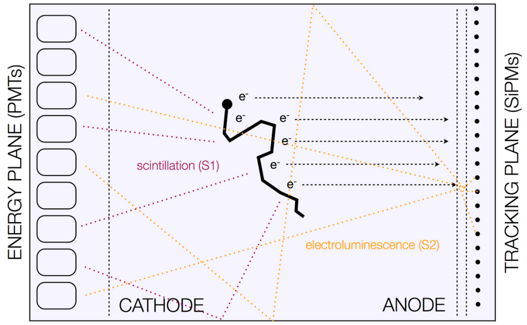


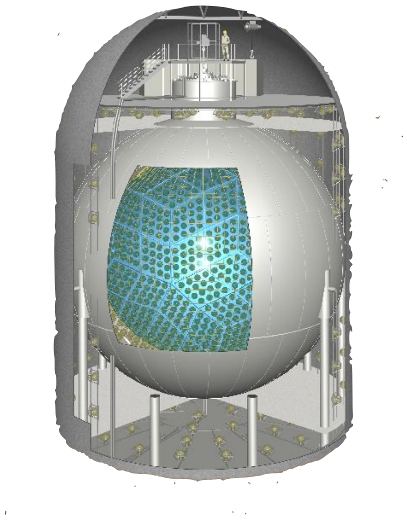




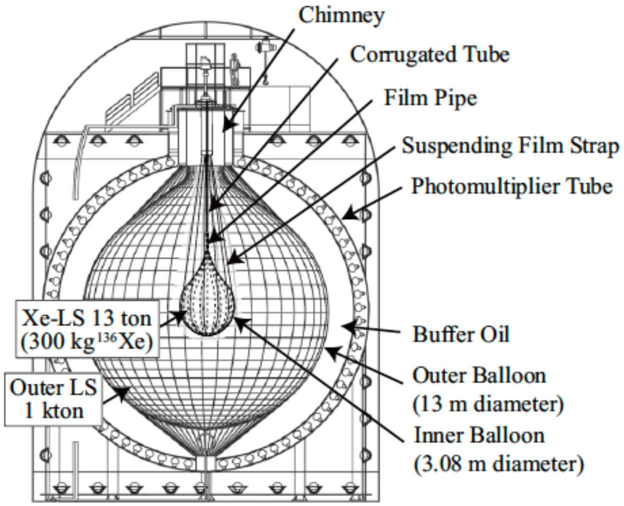






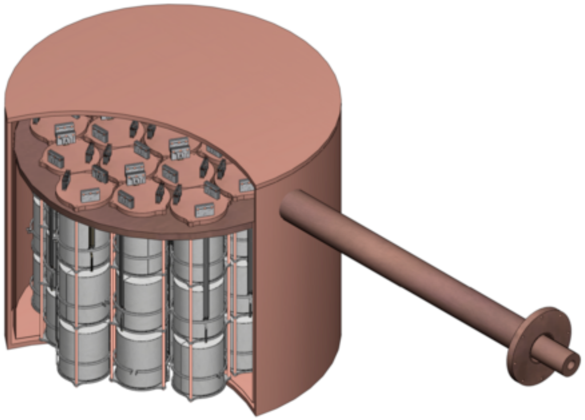


Good
at Size



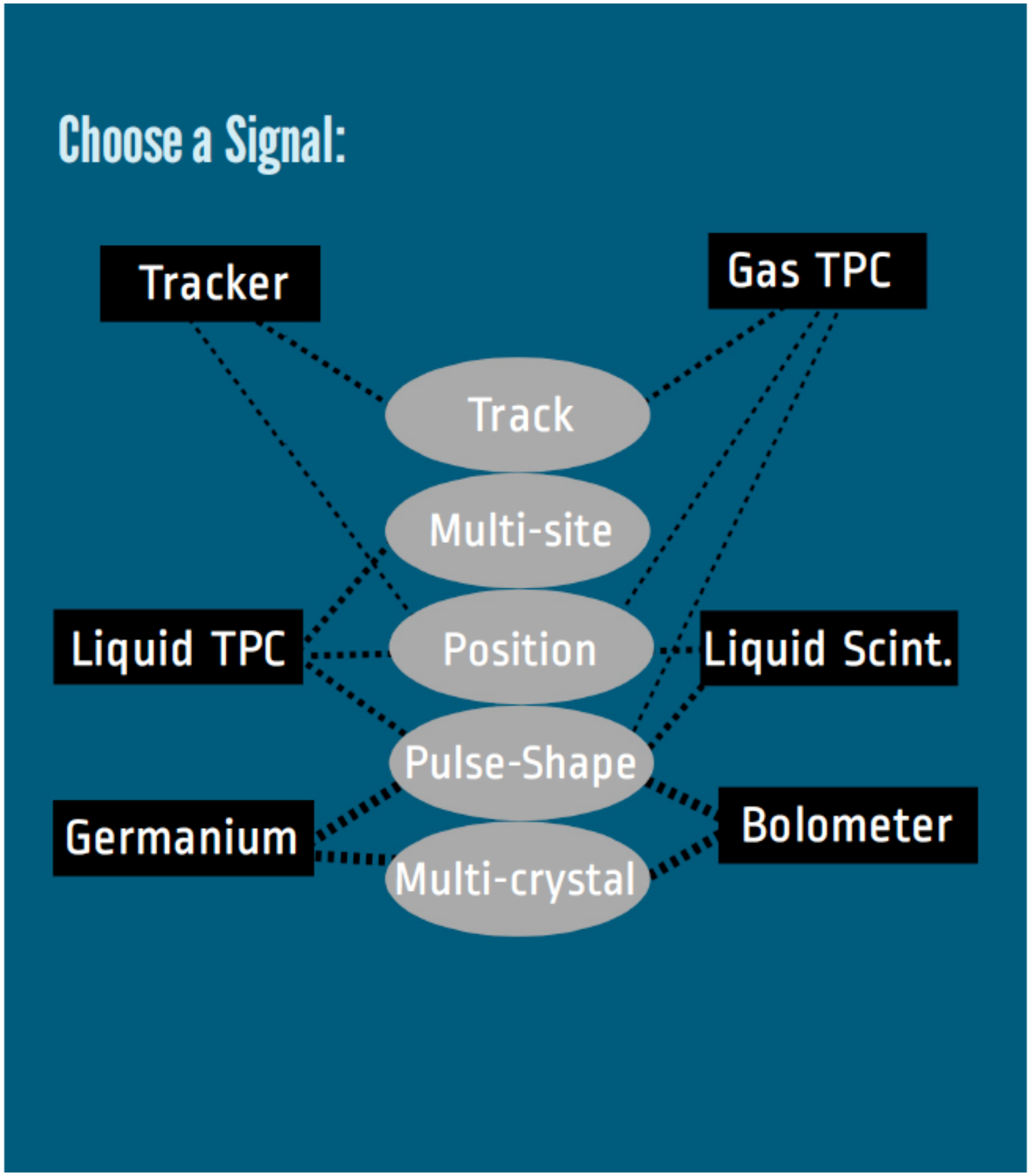
Bad Energy
Resolution

Good
Energy
Resolution

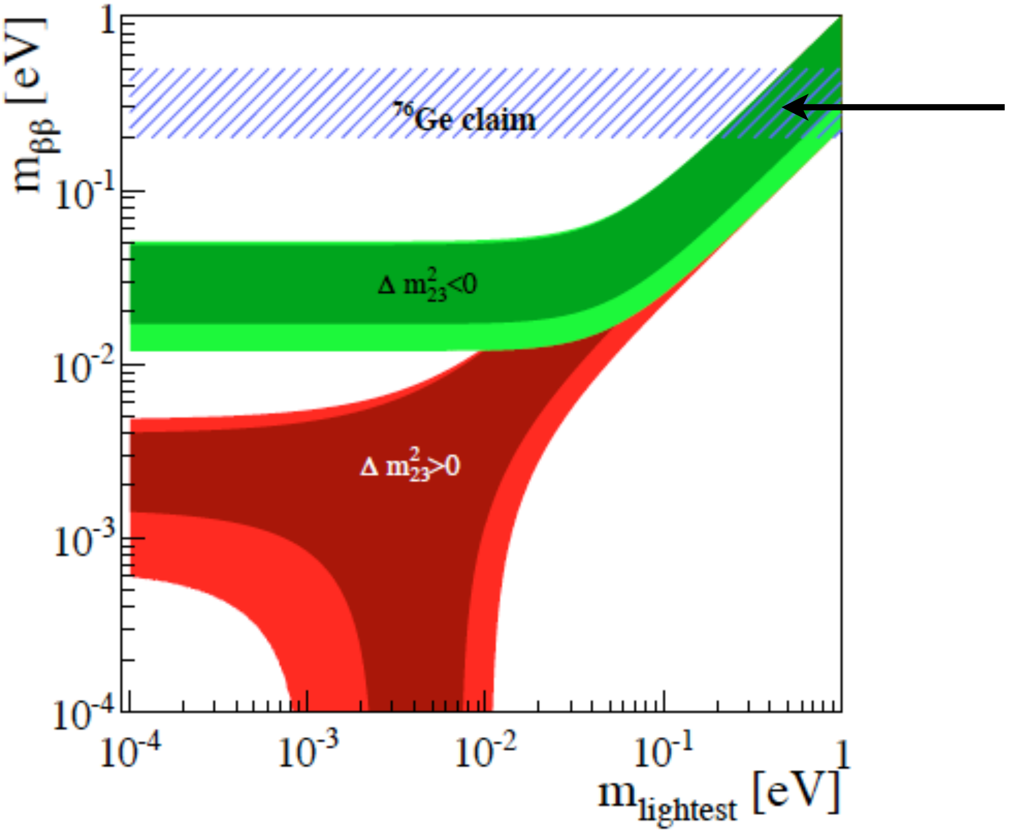


More Difficult
to make big.

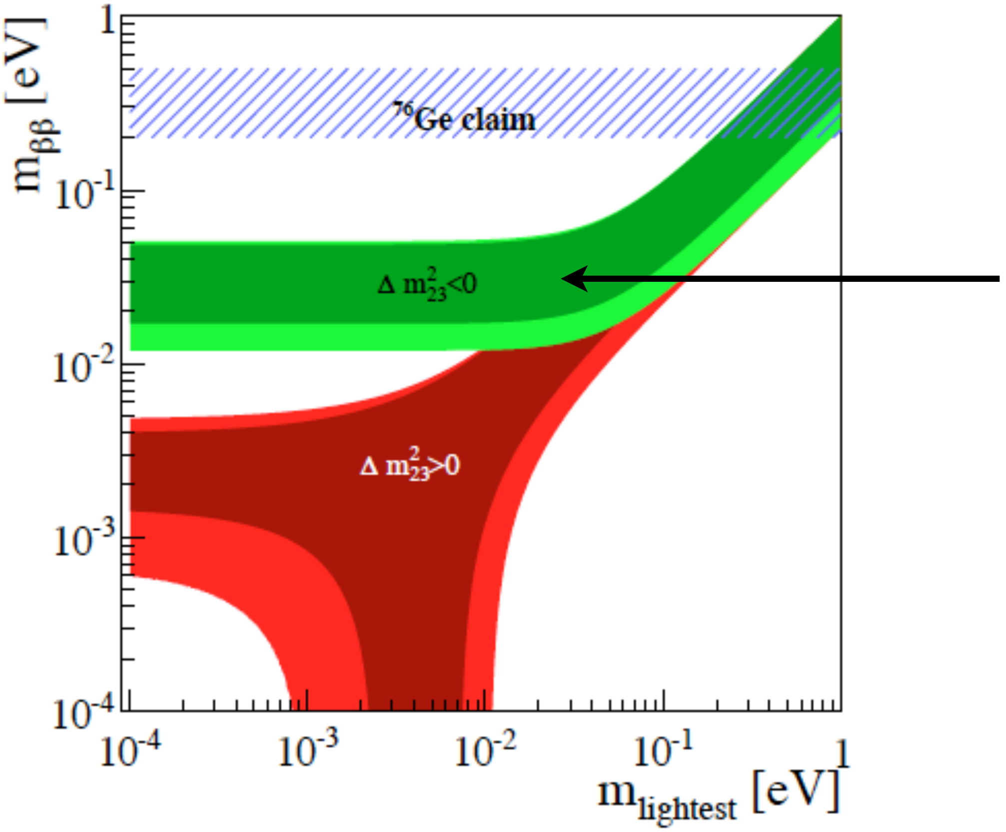
My attempt at a better diagram:



What has been happening lately…



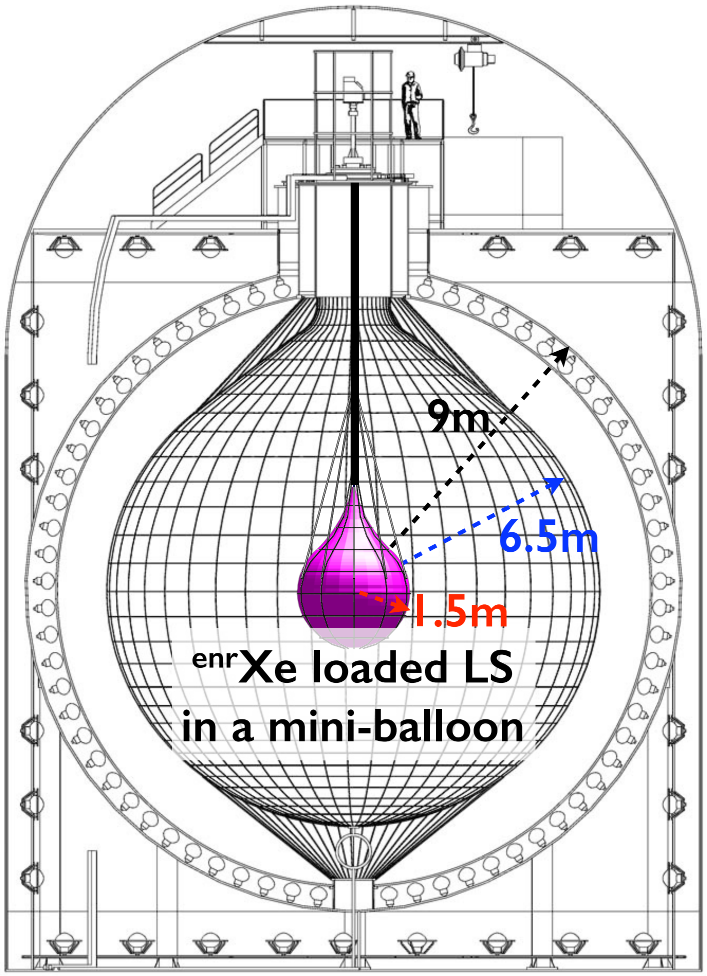
The last few years have focused on experiments sensitive to addressing this claim.



While trying to figure out what is needed for a definitive search over the parameter space corresponding to the inverted hierarchy.

KamLAND-Zen

Zero Neutrino
double beta decay search

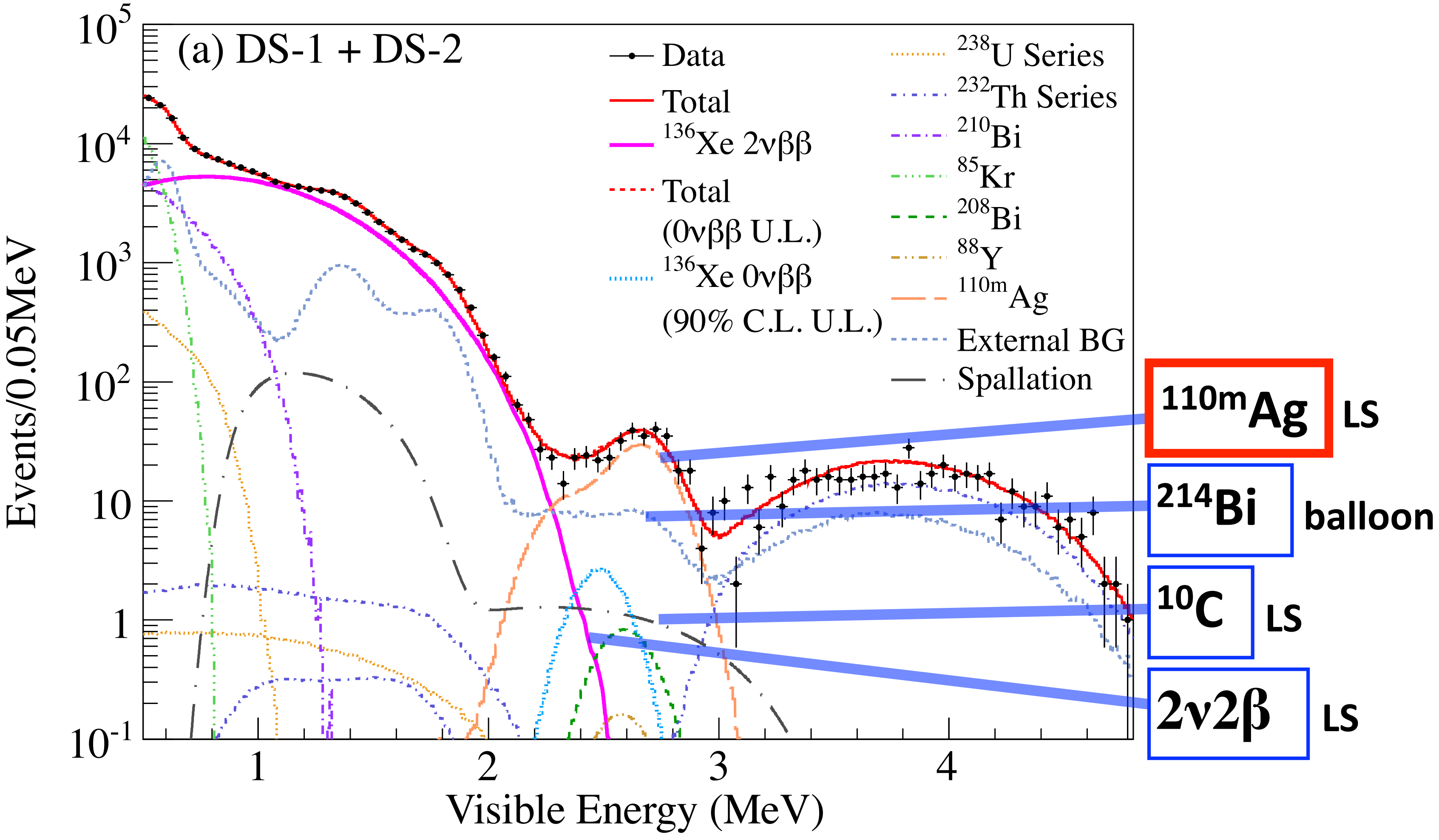


320kg 90% enriched ^{136}Xe installed for phase-1
and 380kg for phase-2

Advantages of using KamLAND:

- Running detector
  → relatively low cost and quick start
- Big and clean (1200m^3, U: 3.5x10^{-18} g/g, Th: 5.2x10^{-17})
  → negligible external gamma
  (Xe and mini-balloon need to be clean)
- Xe-LS can be purified and mini-balloon replaced relatively cheaply.
  → highly scalable (up to several tons of Xe)
- All energy from β, γ contained
  → BG identification relatively easy
- Anti-neutrino observation continues
  → geo-neutrino w/o Japanese reactors

KamLAND-Zen started in 2011:



^{110m}Ag LS

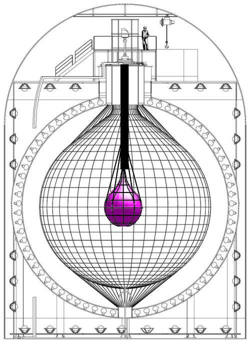
^{214}Bi balloon

^{10}C LS

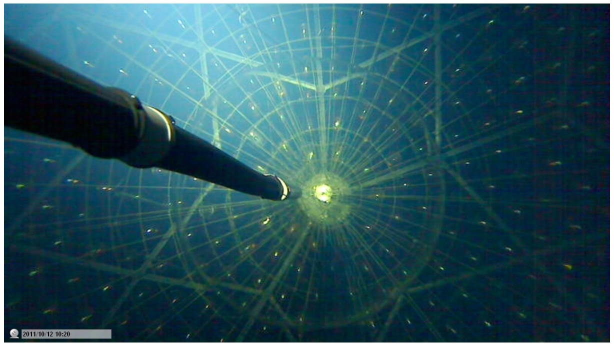
2ν2β LS

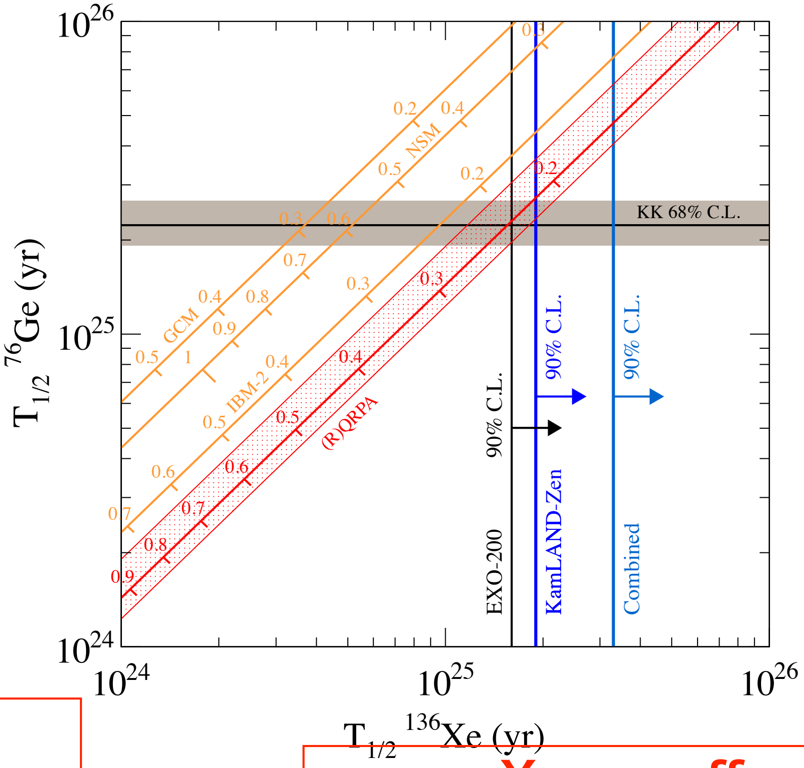
An Unexpected BG was found!

Published result w/ high silver rate (phase-1):



~320kg 90% enriched ^{136}Xe installed initially





Phys.Rev.Lett, 110, 062502 (2013)

so far the world best limit

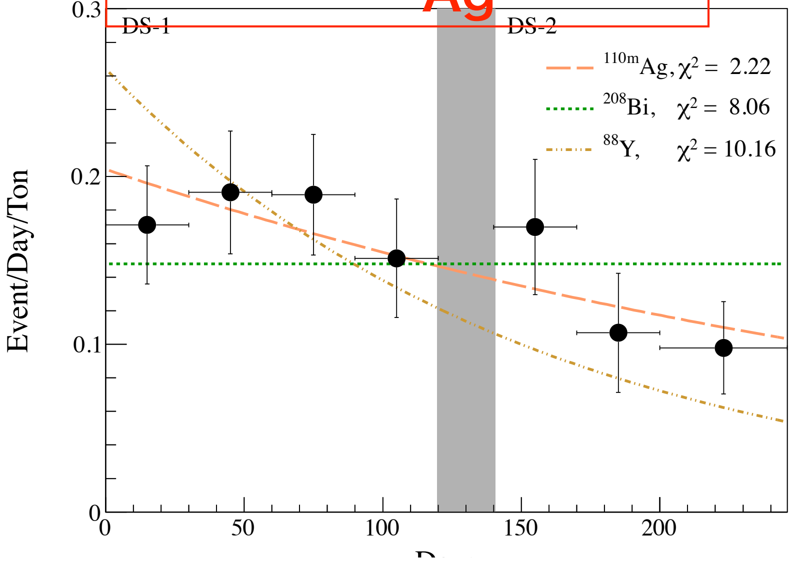
$T_{1/2} > 1.9 \times 10^{25}$ yrs (KL-Zen)

$\langle m_{\beta\beta} \rangle < 120 \sim 250\,\mathrm{meV}$

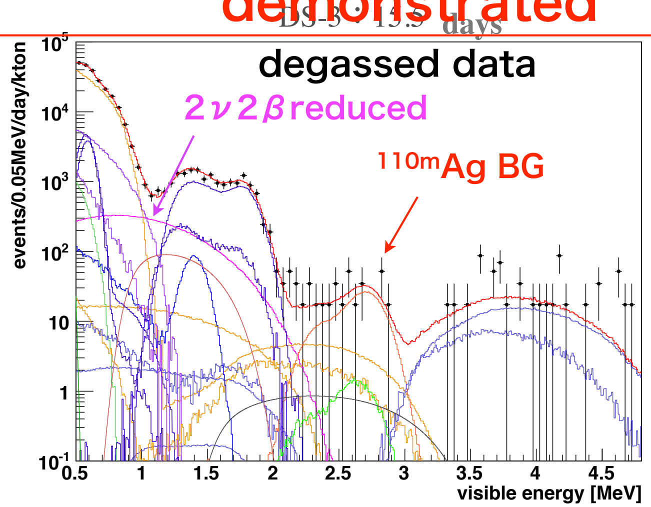
$> 3.4 \times 10^{25}$ yrs

KK-claim refuted at 97.5% CL

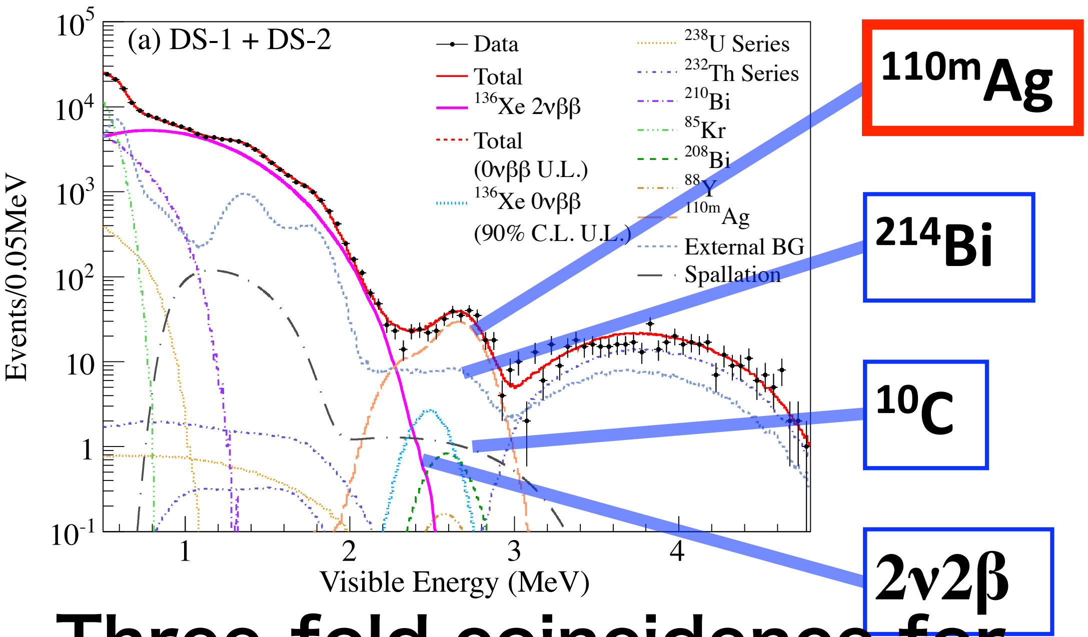
BG identified as ^{110m}Ag



Xe on-off measurement demonstrated



What can be done?



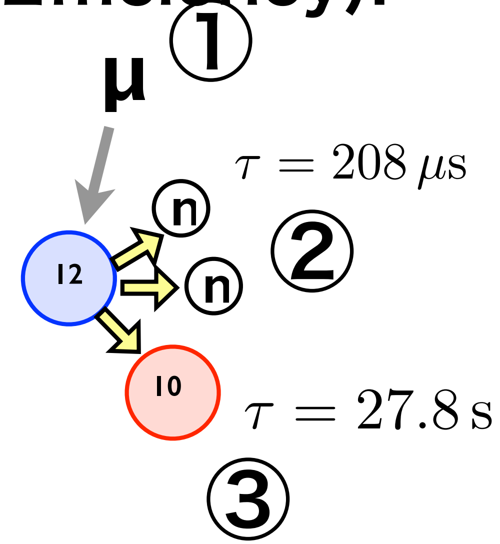
purification !!

fine binning of volume

triple fold coincidence

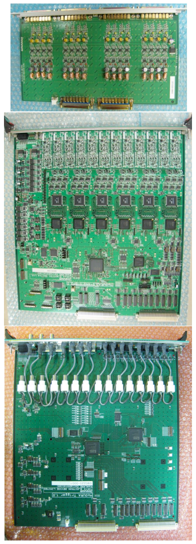
future upgrades

Three-fold coincidence for ^{10}C rejection (64% Efficiency):

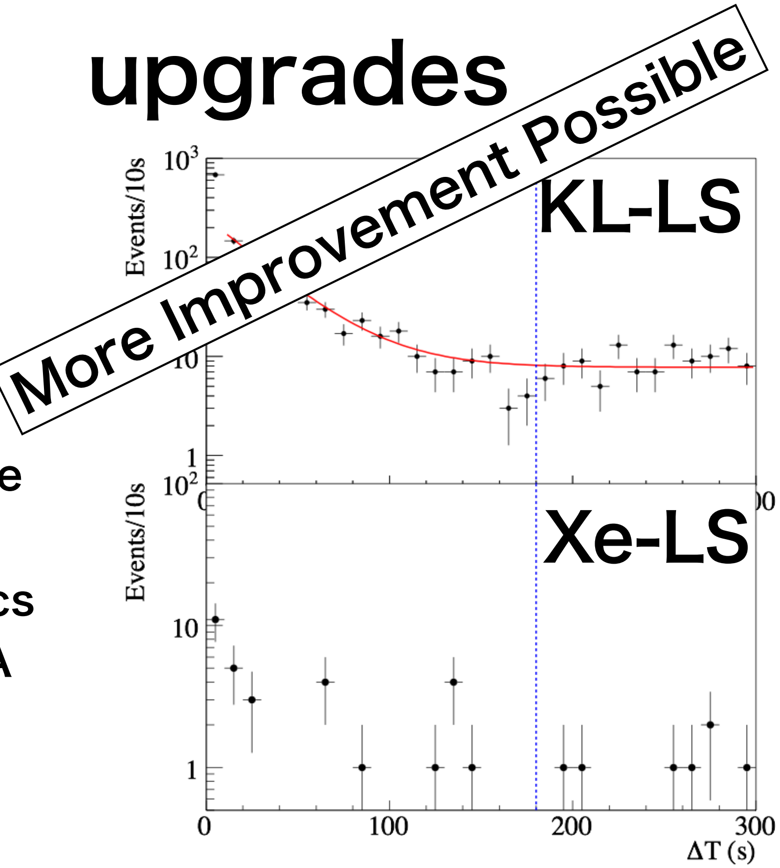


$\tau = 208\,\mu\mathrm{s}$

$\tau = 27.8\,\mathrm{s}$



dead time free electronics MoGURA

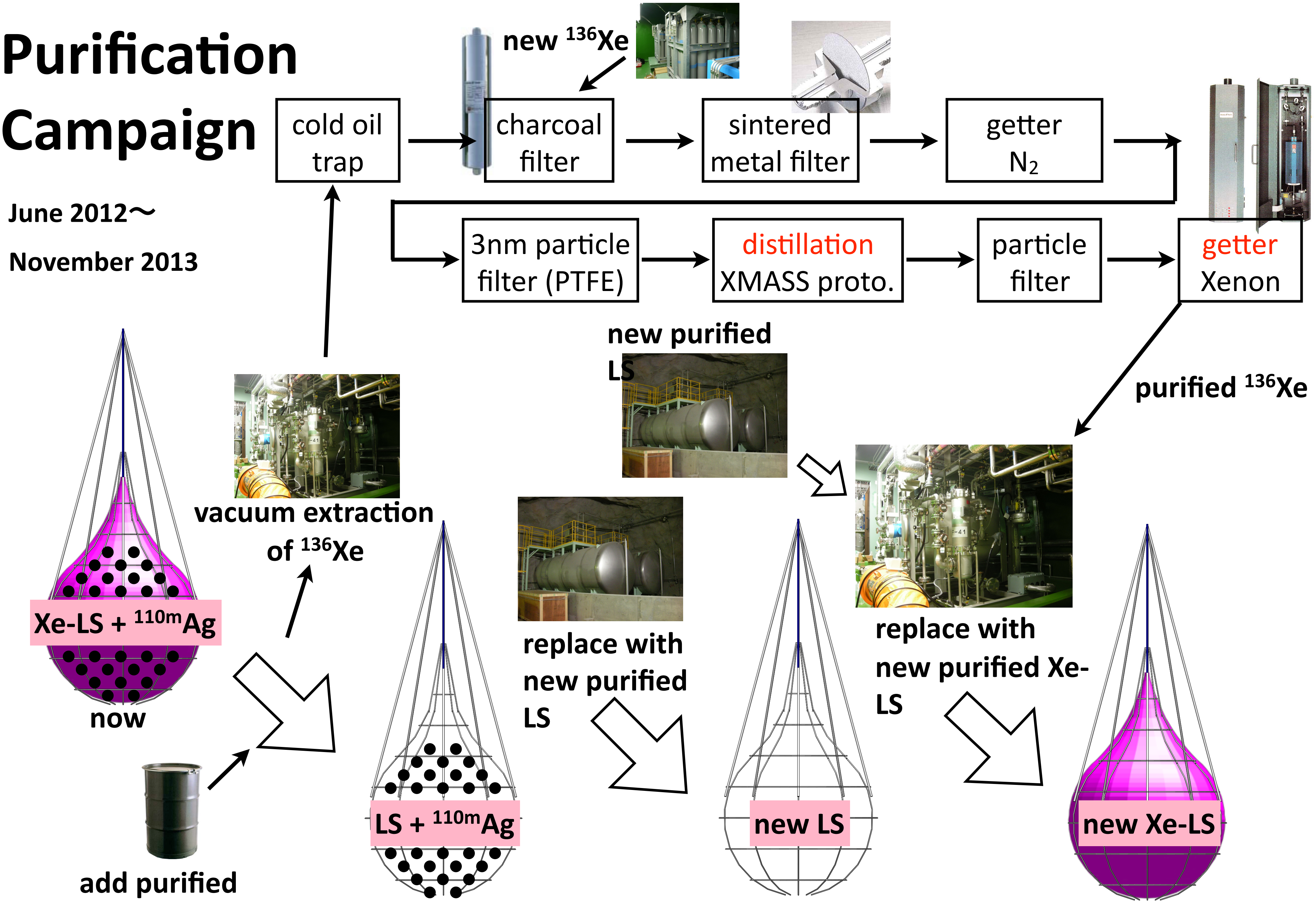


More Improvement Possible

Purification Campaign

June 2012〜

November 2013



cold oil trap → charcoal filter → sintered metal filter → getter N_2 → 3nm particle filter (PTFE) → distillation XMASS proto. → particle filter → getter Xenon

new ^{136}Xe

purified ^{136}Xe

vacuum extraction of ^{136}Xe

new purified LS

now

add purified PC for density adjustment

confirm ^{110m}Ag remains in LS

replace with new purified LS

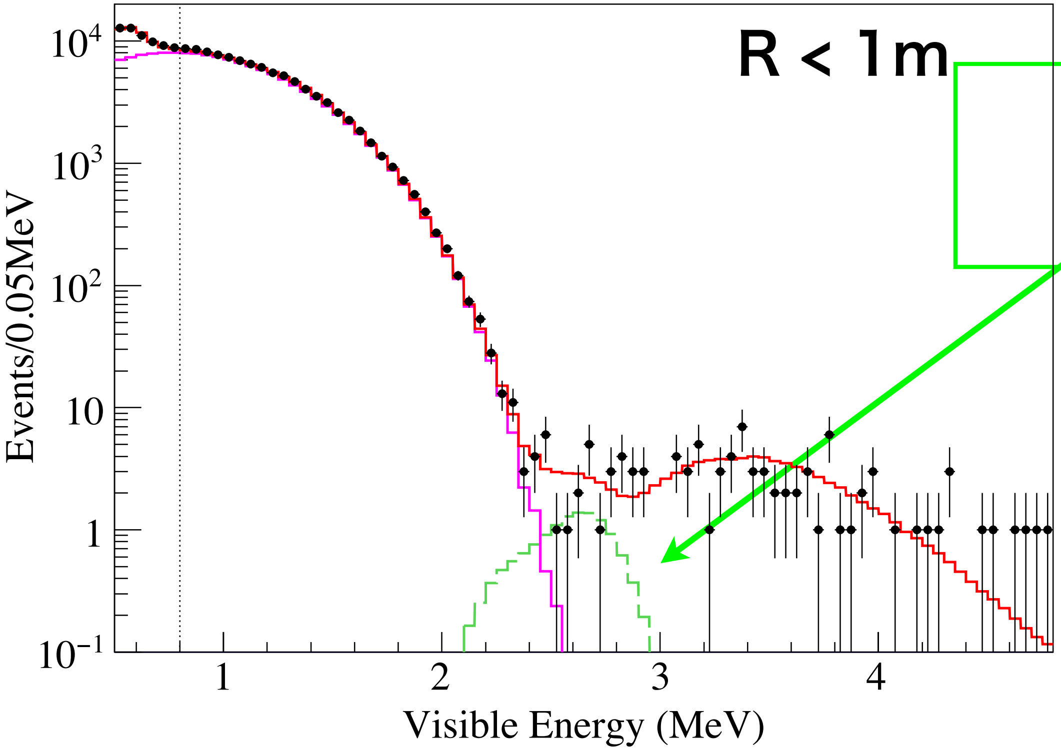
two times of distillation
confirm whole ^{110m}Ag drained

replace with new purified Xe-LS

~380kg Xe installed
aim: 1/100 reduction

Full phase-2 data-set

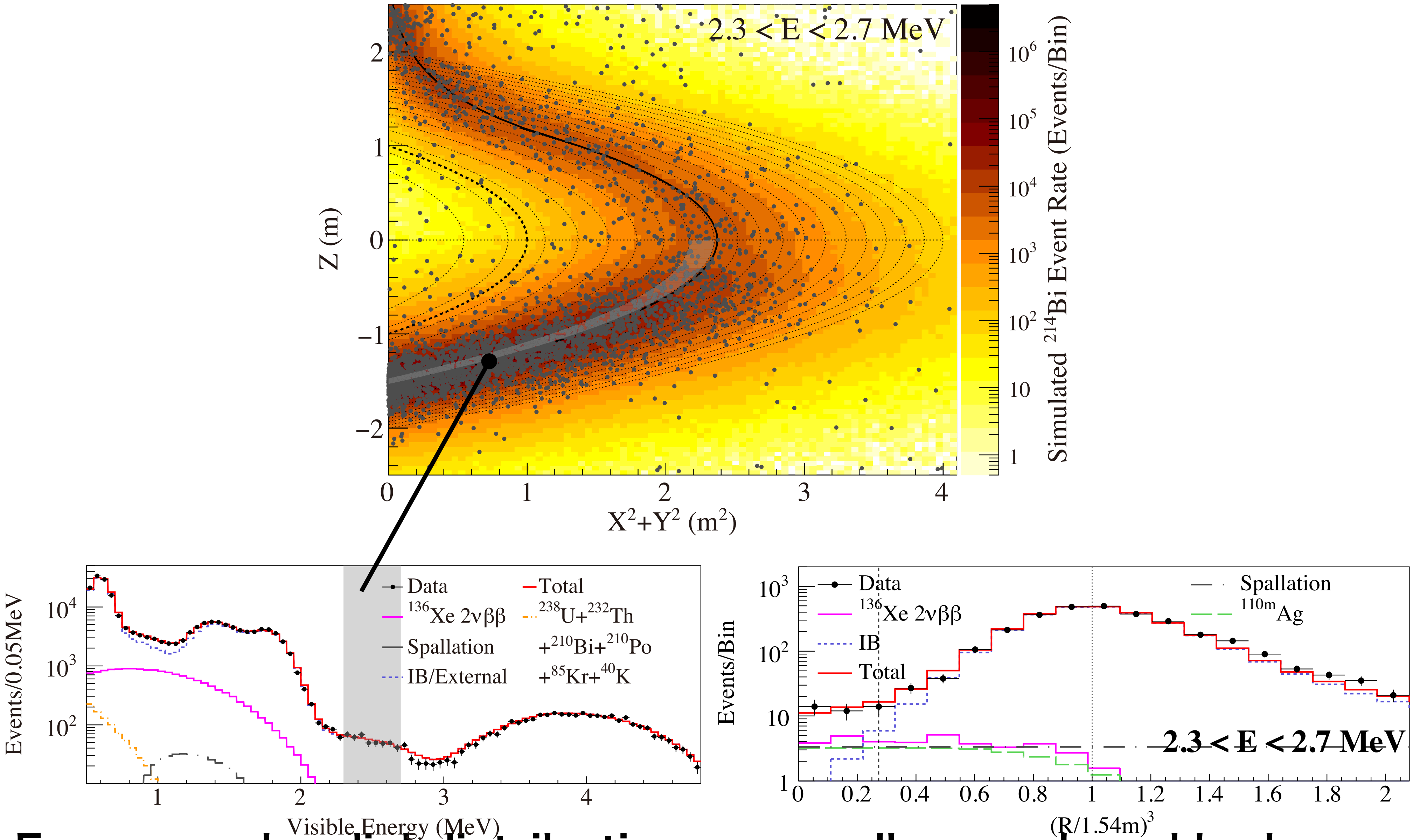
- After Purification
- December 2013 - October 2015
- Livetime 534.5 days, exposure 504 kg-yr
- For Reference: $T_{1/2}(^{110m}Ag)$ = 250 days.



^{110m}Ag still exists?

We might have scrubbed and dropped “dust” during extraction of the LS supply tube.

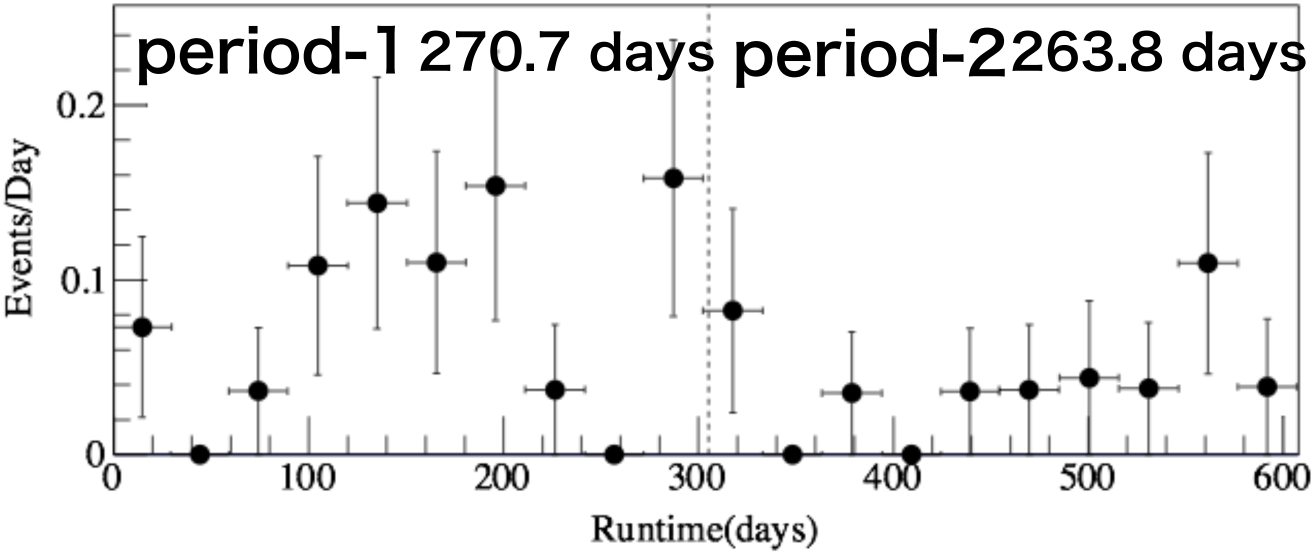
Analysis:
40 equal-volume bins



Energy and radial distributions are well-reproduced by known BGs.

Analysis:
2 Time Periods

2.3 < E < 2.7 MeV, R < 1 m

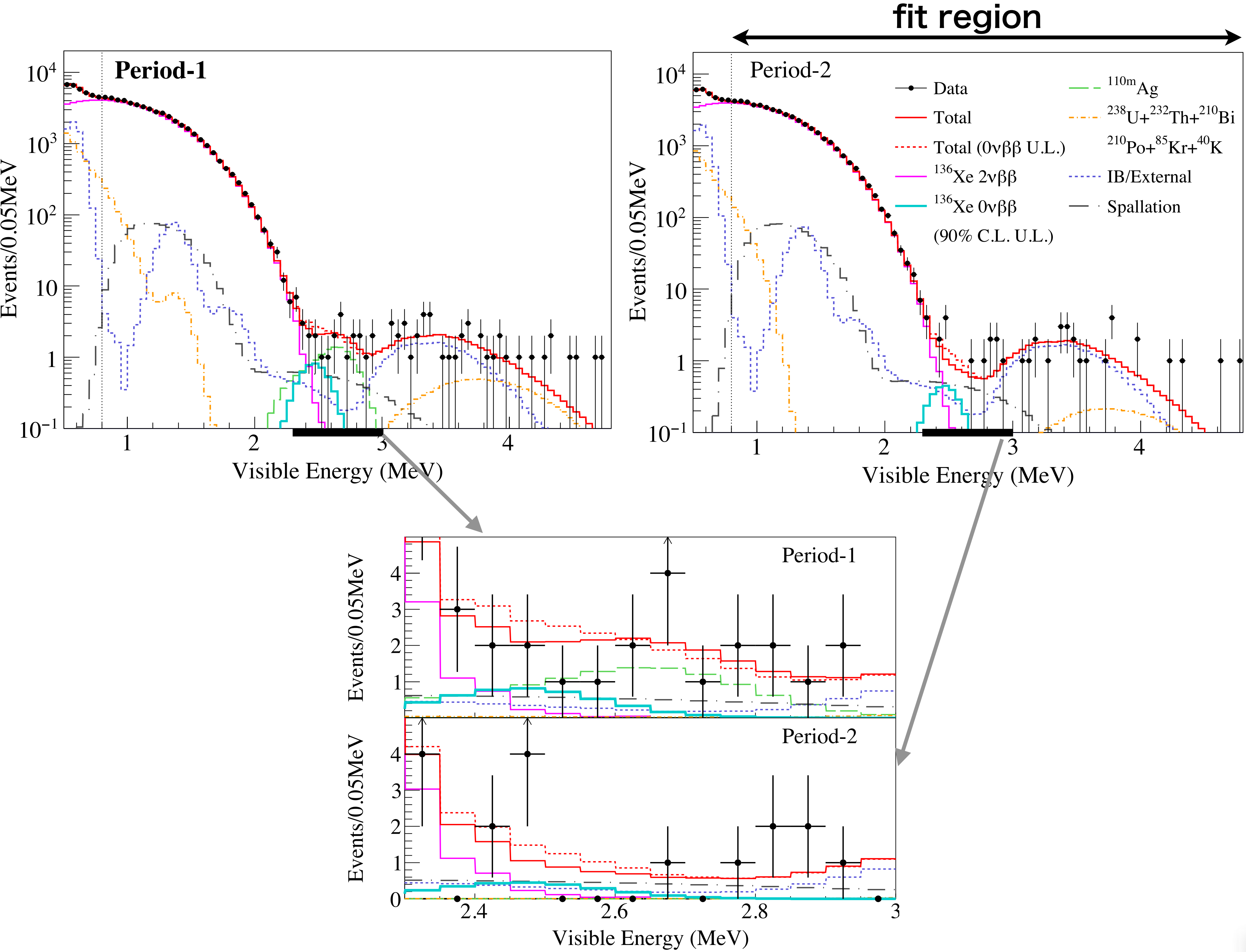


22 events

11 events

A hypothesis:
“Dust” sank !?

However,
only ~2σ
discrepancy
from the
simple decay


fit region

Period-1
Period-2
Data
Total
Total (0νββ U.L.)
^{136}Xe 2νββ
^{136}Xe 0νββ
(90% C.L. U.L.)
^{110m}Ag
^{238}U+^{232}Th+^{210}Bi
^{210}Po+^{85}Kr+^{40}K
IB/External
Spallation
Events/0.05MeV
Visible Energy (MeV)
10^{-1}
1
10
10^2
10^3
10^4
1
2
3
4
0
1
2
3
4
2.4
2.6
2.8
3

Event summary 2.3 < E < 2.7 MeV, R < 1 m

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.0	-	0.002
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.55	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.002	-	0.001
Spallation products				
^{10}C	2.7 ± 0.7	3.2	2.6 ± 0.7	2.7
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.9 ± 0.5	1.1	0.9 ± 0.5	0.8

Phase 2 - Results on $0\nu 2\beta$

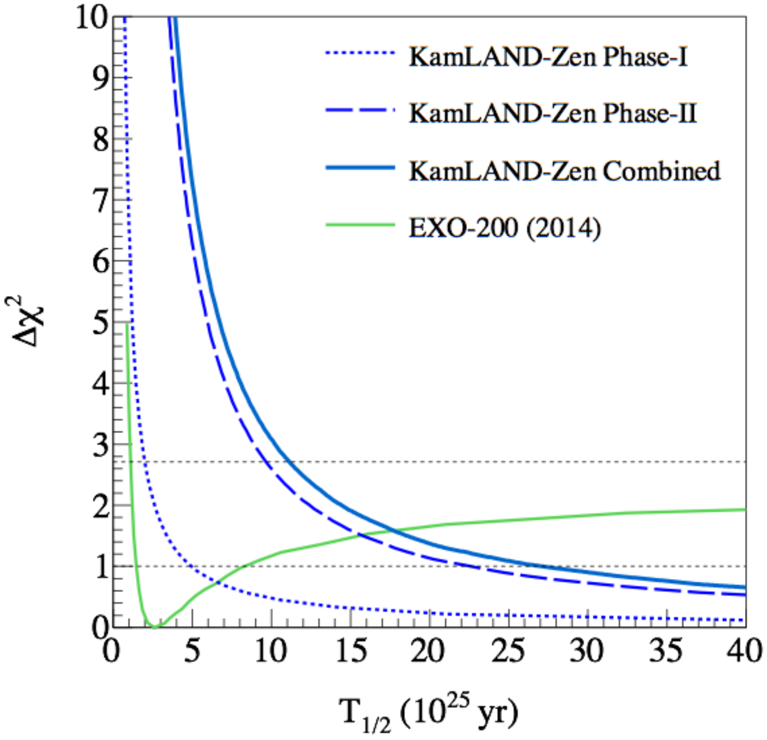
	period-1	period-2
livetime	270.7 days	263.8 days
^{136}Xe $0\nu 2\beta$ decay rate	< 5.6 /kton/day	< 3.2 /kton/day

combined < 2.4 /kton/day (90%C.L.)

^{136}Xe $0\nu 2\beta$ half-life > 9.6×10^{25} yr (90%C.L.)

sensitivity > 4.9×10^{25} yr (11% probability)

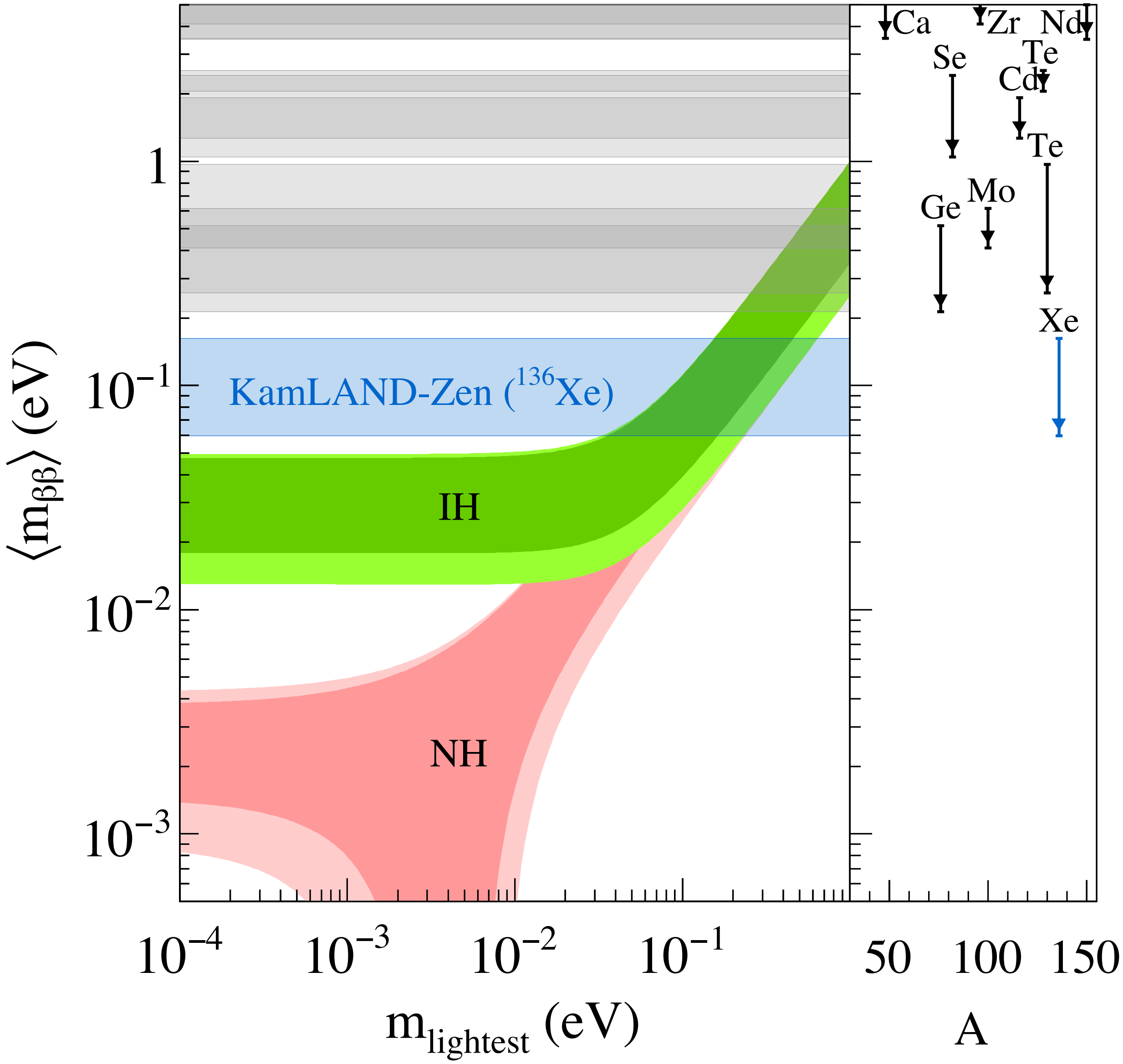
Phase-1 & 2 combined limit



!!!

$$T^{0\nu}_{1/2} > 1.1 \times 10^{26}\ \mathrm{yr}$$

$$\langle m_{\beta\beta} \rangle < (60 - 161)\ \mathrm{meV}$$



Big leap toward IH !!!

Summary

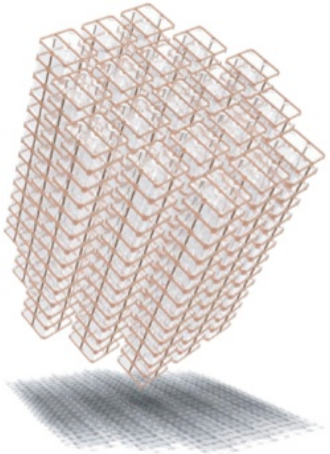
- New results from Phase-2 (534.5 days, 380 kg)
  - ^{110m}Ag has been successfully reduced.
  - improved analysis.
- Phase-1 & 2 combined result for $0\nu2\beta$ of ^{136}Xe

$$T^{0\nu}_{1/2} > 1.1 \times 10^{26}\ \mathrm{yr}$$

$$\langle m_{\beta\beta} \rangle < (60 - 161)\ \mathrm{meV}$$

- KamLAND-Zen 800 planned to start in this fall
  - 750 kg of enriched xenon will be installed.
  - Target sensitivity is below 50 meV.
- R&D for KamLAND2-Zen is going well.
  - Target sensitivity is below 20 meV.

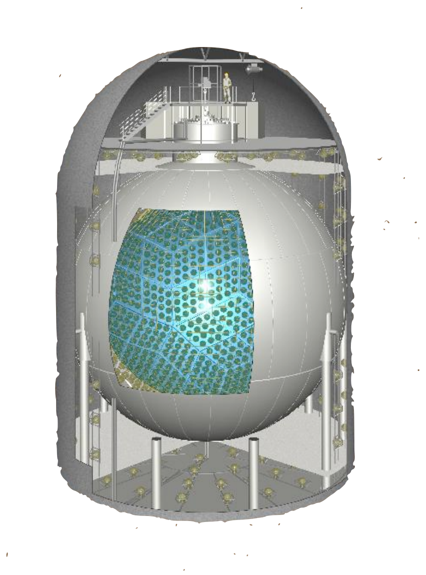
Good
Energy
Resolution



Bolometers

More Difficult
to make big.

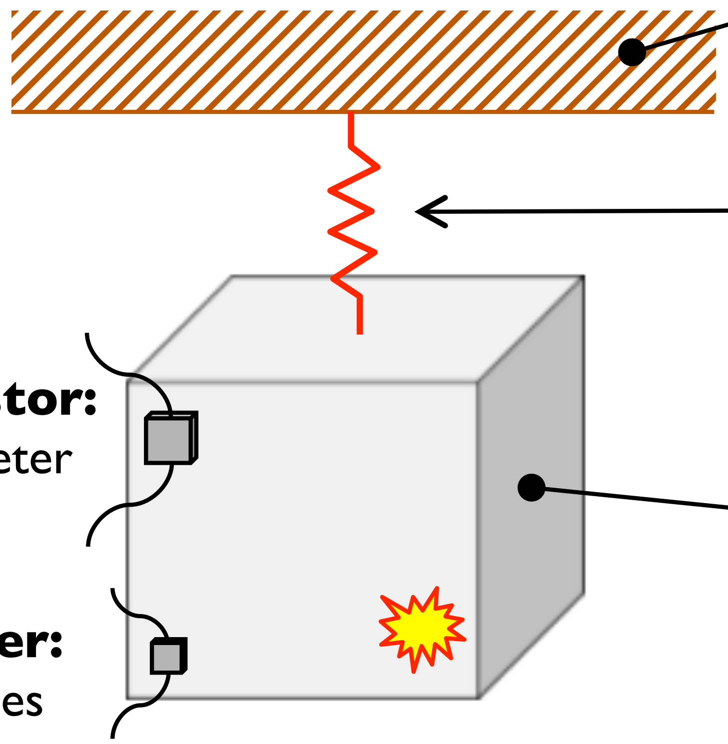
Good
at Size



Scintillator

Bad Energy
Resolution

How Bolometers work:



Copper frame:
10 mK heat sink

PTFE holders:
weak thermal coupling

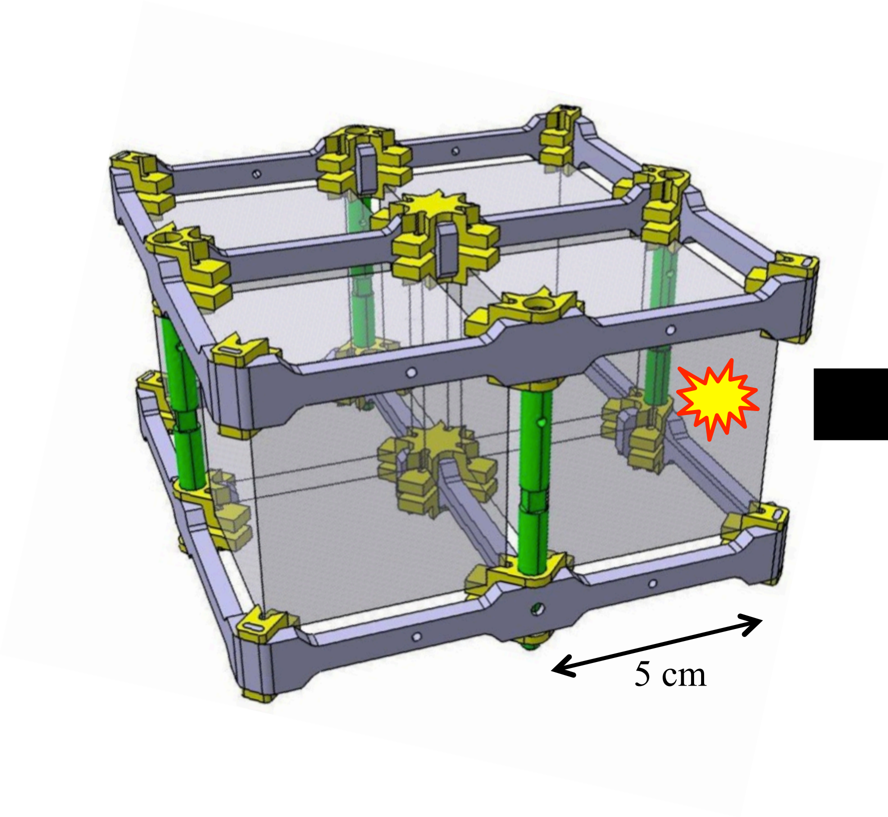
NTD Ge thermistor:
resistive thermometer

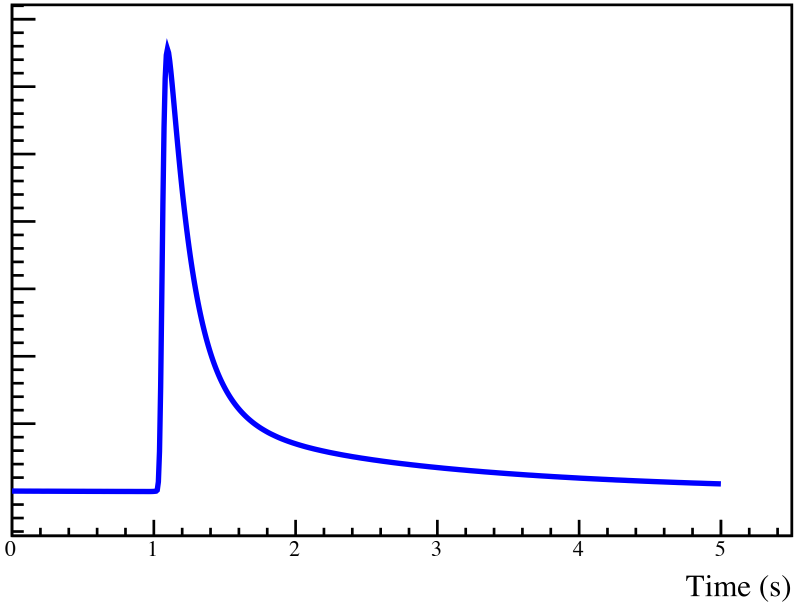
TeO_2 crystal:
energy absorber

Si joule heater:
reference pulses

Radiation:
energy deposit

The Signal:

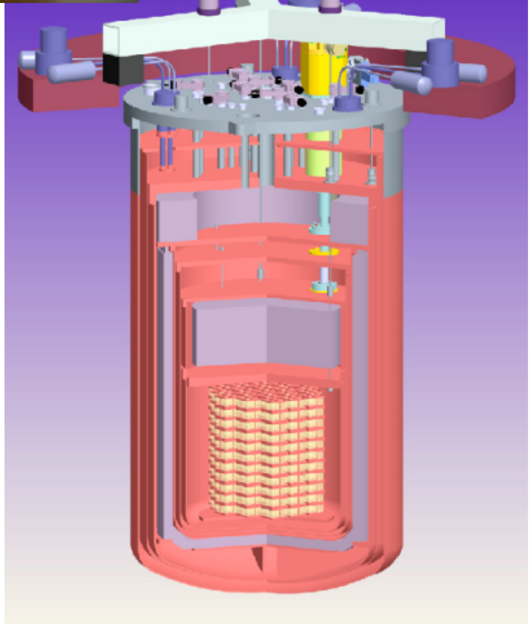


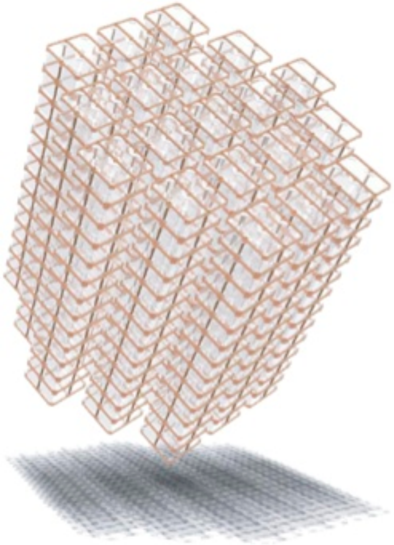


At T=10 mK, energy deposited inside a TeO_2 crystal by radiation produces a measurable rise in its temperature

Amplitude of temperature pulse is proportional to deposited energy

CUORE:
Cryogenic Underground Observatory for Rare E



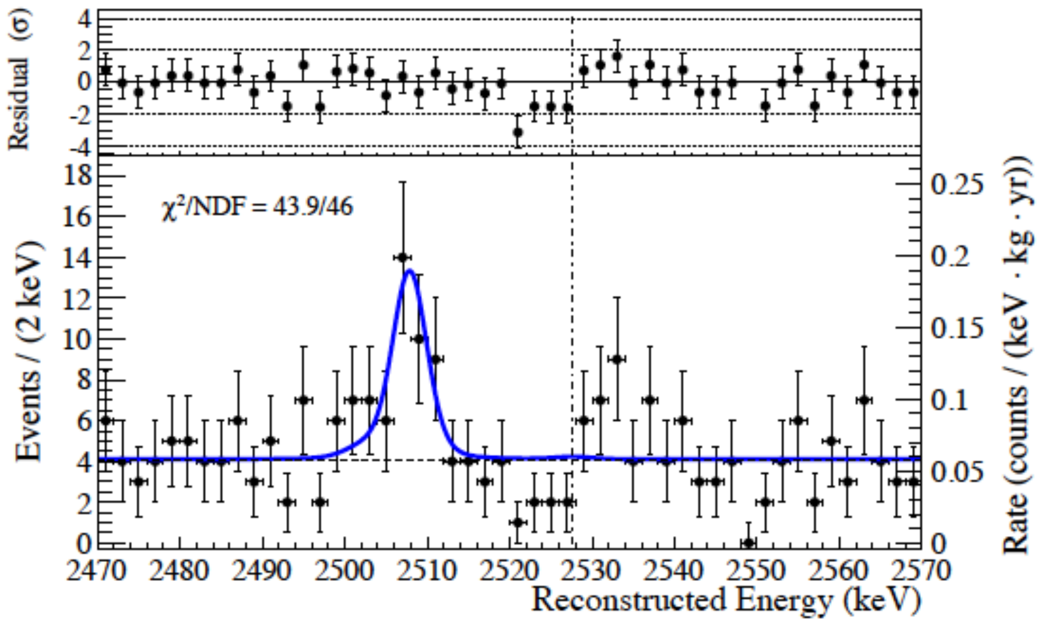


- 19 Towers, 988 TeO2 crystals operated as bolometers.
- We are the “Coldest cubic meter in the universe”.
- First data mid-2016, one of the most sensitive experiments for the next 5 years.

CUORE:
Cryogenic Underground Observatory for Rare E

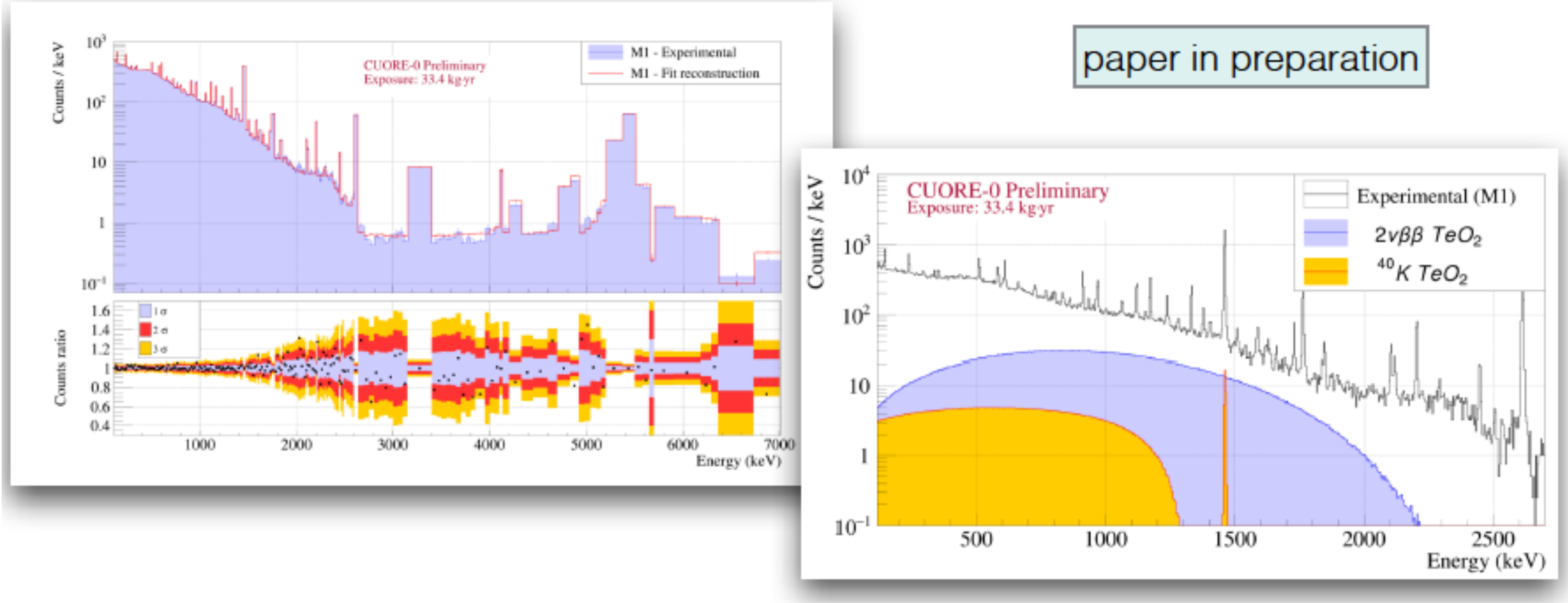
$$T^{0\nu}_{1/2} > 4.0 \times 10^{24}\ \mathrm{yr}$$

Phys.Rev.Lett. 115 (2015) 10, 102502



- First results from CUORE-0 (one CUORE-style tower operated in old cryostat).
- Shows CUORE will reach cleanliness goals.
- Long analysis paper just accepted at PRC.

Fit spectrum with 2νββ



paper in preparation

$$\text{CUORE-0: } T^{2\nu}_{1/2} = [8.2 \pm 0.2\ (\text{stat.}) \pm 0.6\ (\text{syst.})] \times 10^{20}\ \text{y}$$

$$\text{NEMO: } T^{2\nu}_{1/2} = [7.0 \pm 0.9\ (\text{stat.}) \pm 1.1\ (\text{syst.})] \times 10^{20}\ \text{y}$$

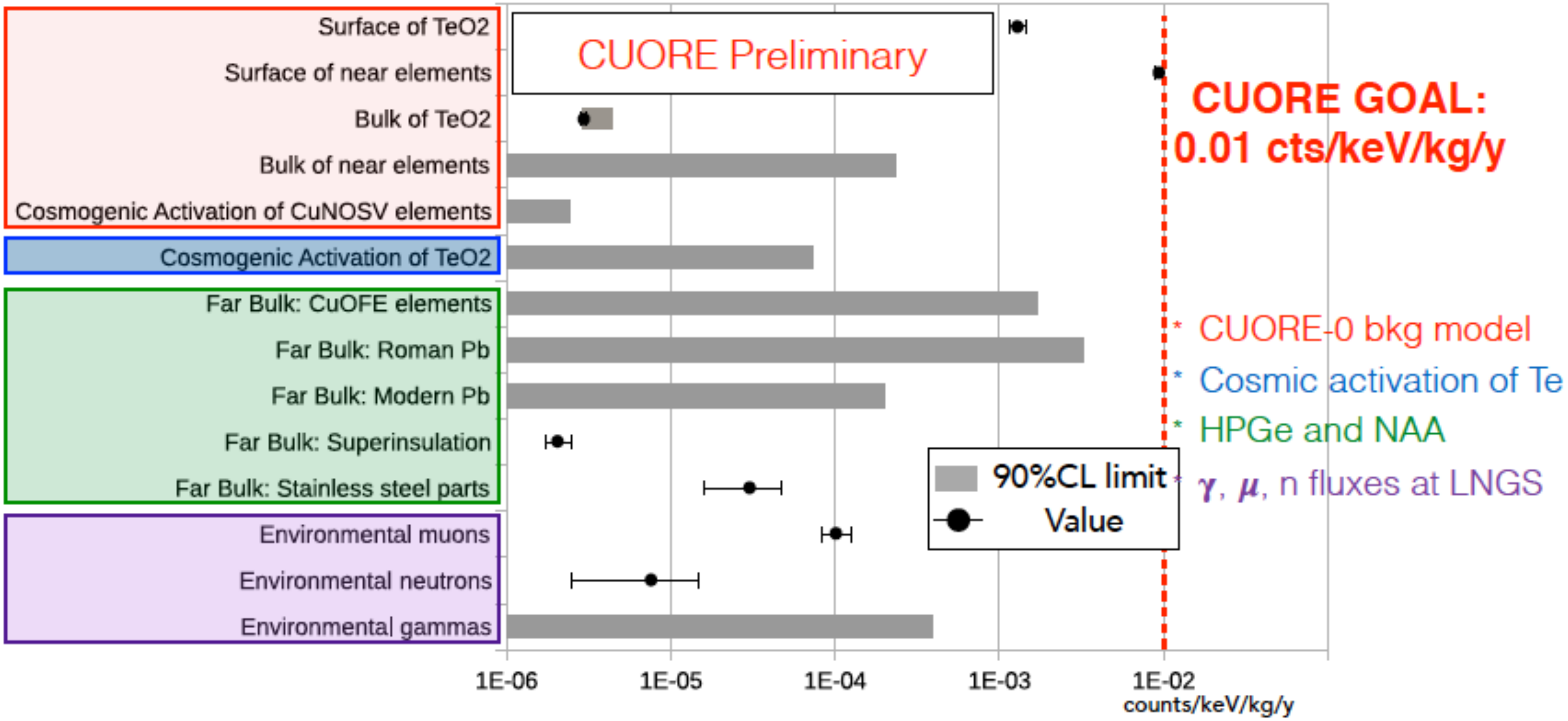
$$\text{MiDBD: } T^{2\nu}_{1/2} = [6.1 \pm 1.4\ (\text{stat.})\ {}^{+2.9}_{-3.5}\ (\text{syst.})] \times 10^{20}\ \text{y}$$

NEMO-3 Collaboration, Phys. Rev. Lett., 107, 062504 (2011).
C. Arnaboldi et al., Phys. Lett. B, 557, 167 (2003).

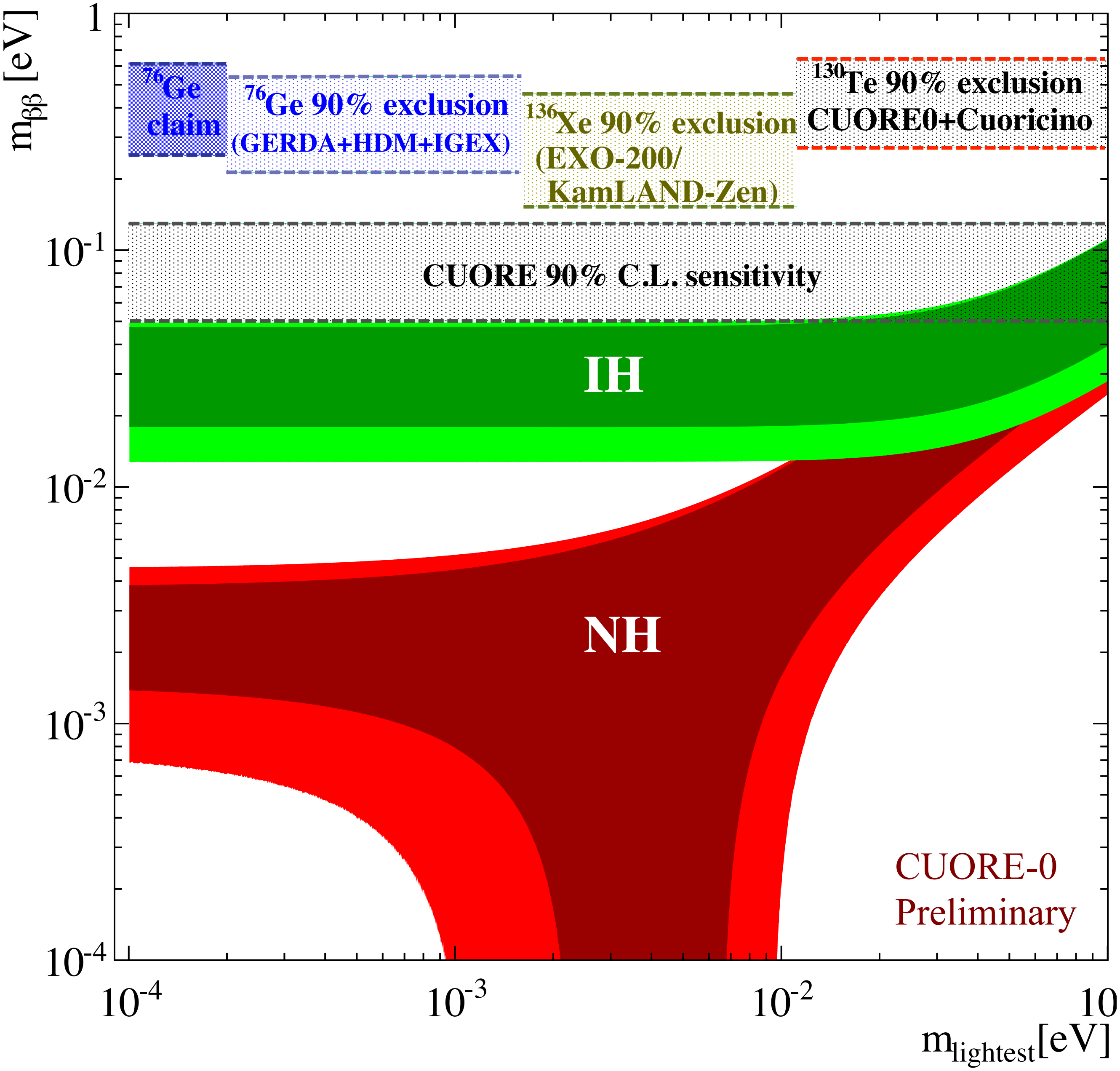
CUORE Background budget

paper in preparation

Geometry in the MC simulations was updated to the final CUORE design

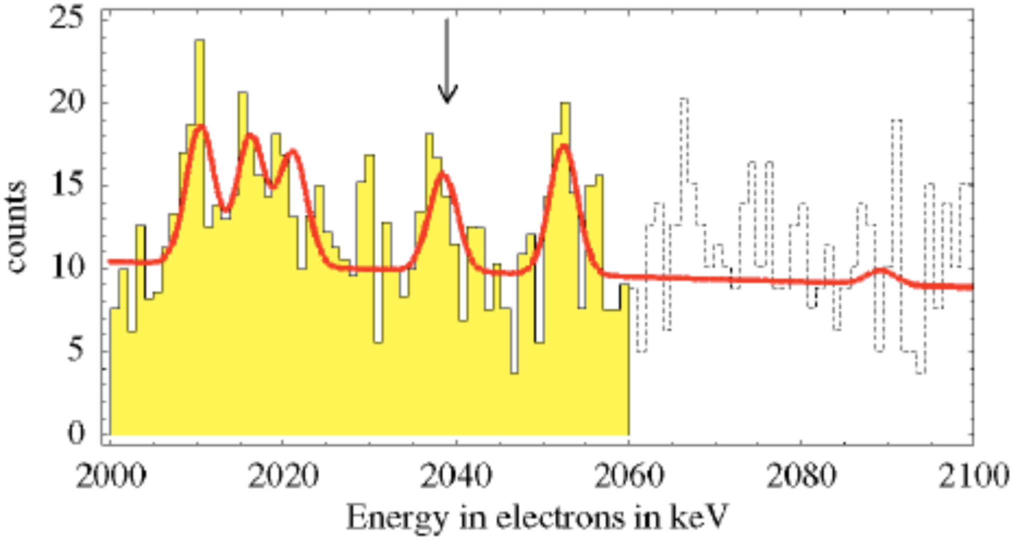


The Global Picture:

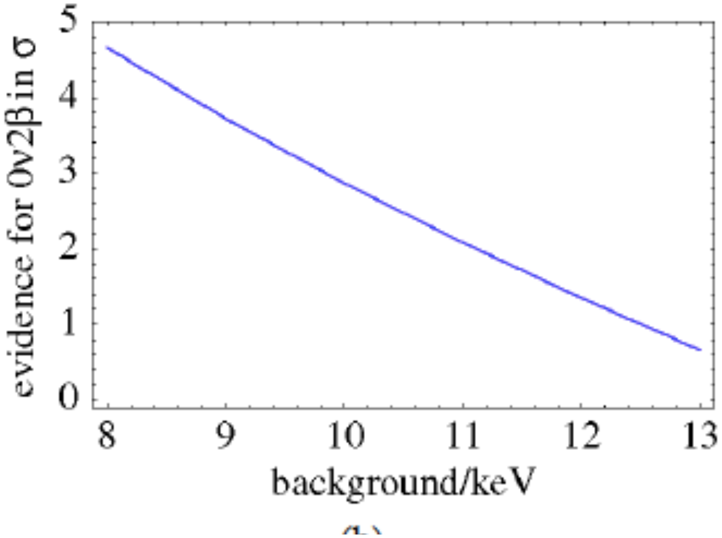


Bonus: A Signal?

Heidelberg-Moscow Experiment using ^{76}Ge......



From: Nuclear Physics B 726 (2005) 294–316



Final Analysis of the data using more advanced techniques makes the measurement almost background free.

Klapdor Kleingrothaus *et al.*, Mod. Phys. Lett. A **21** (2006) p 1547.