NEUTRINOS IN NUCLEAR PHYSICS

BJPJ

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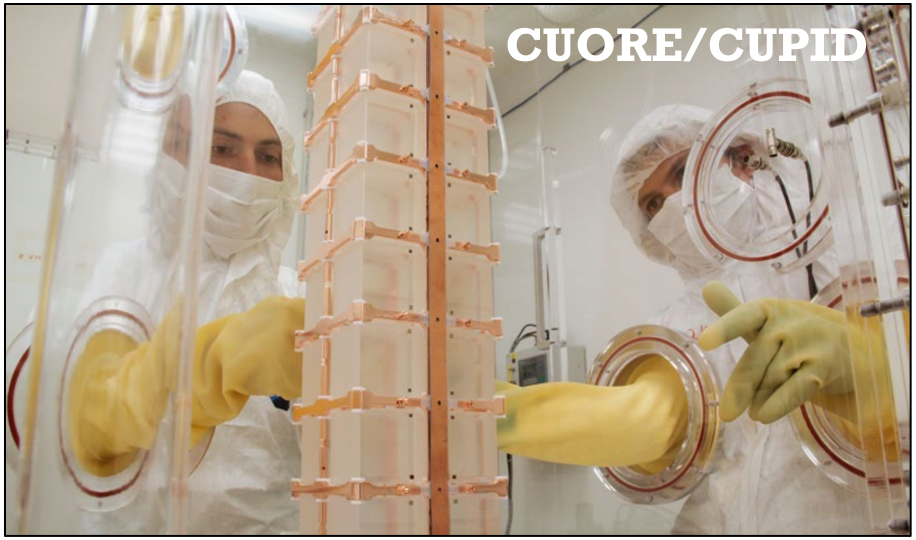
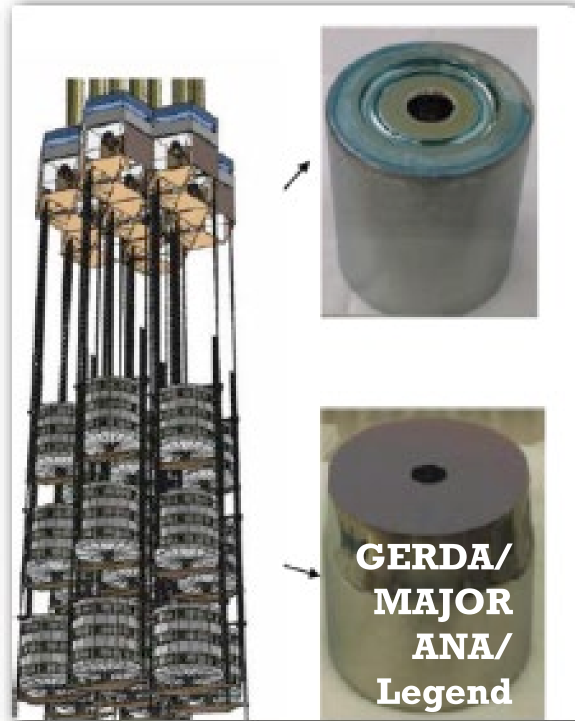
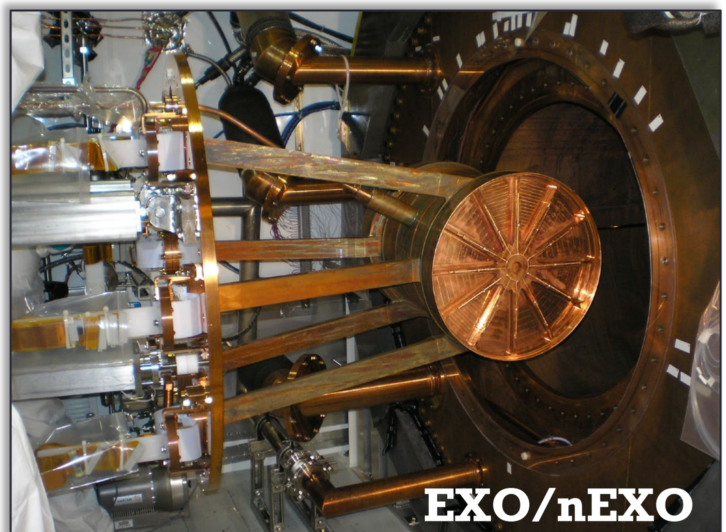
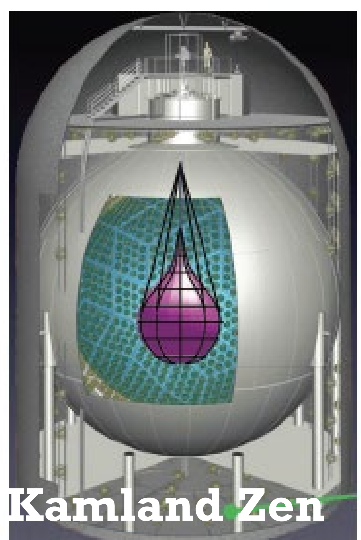
THE ZOO OF ONUBB SEARCHES





Many completely different technologies…



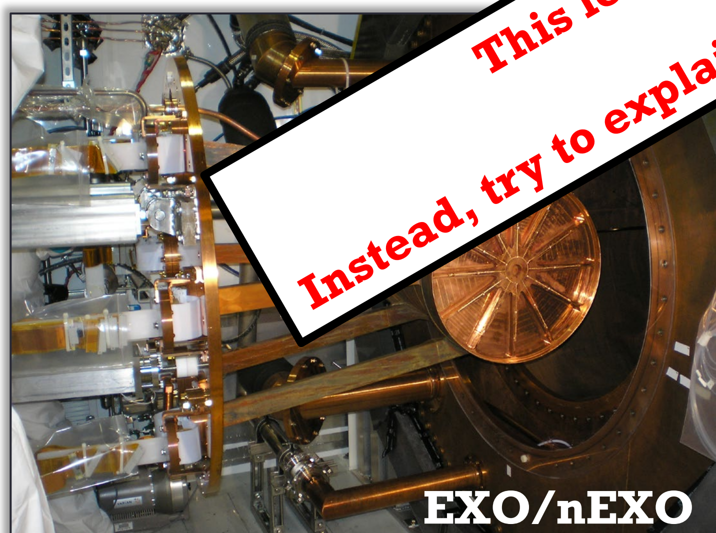


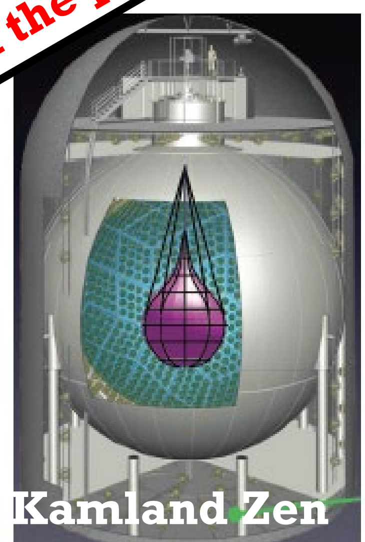
THE ZOO OF 0NUBB SEARCHES

Many completely different technologies…

This lecture, like life, is too short.

Instead, try to explain the physics that connects them all





RELATIVISTIC QUANTUM MECHANICS

DIRAC EQUATION

Spin ½ fermions satisfy an equation of motion called the Dirac equation:

$$(i\gamma^\mu \partial_\mu - m)\,\Psi = 0$$

The Schrodinger Eq. of relativistic spin ½ fermions

The solution can be written as an object with four components called a Dirac spinor:

$$\Psi = \psi e^{ikx} \qquad \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

How much of this kind of particle is where

???

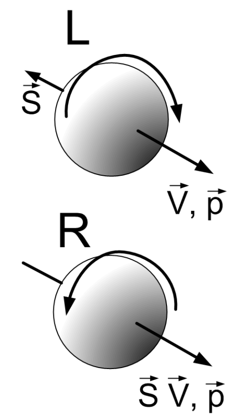
WHAT DO THE FOUR DEGREES OF FREEDOM OF THE DIRAC SPINOR MEAN?

- With a judicious choice of basis (Weyl):

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

Two left spinning things (ψ_1, ψ_2)

Two right spinning things (ψ_3, ψ_4)

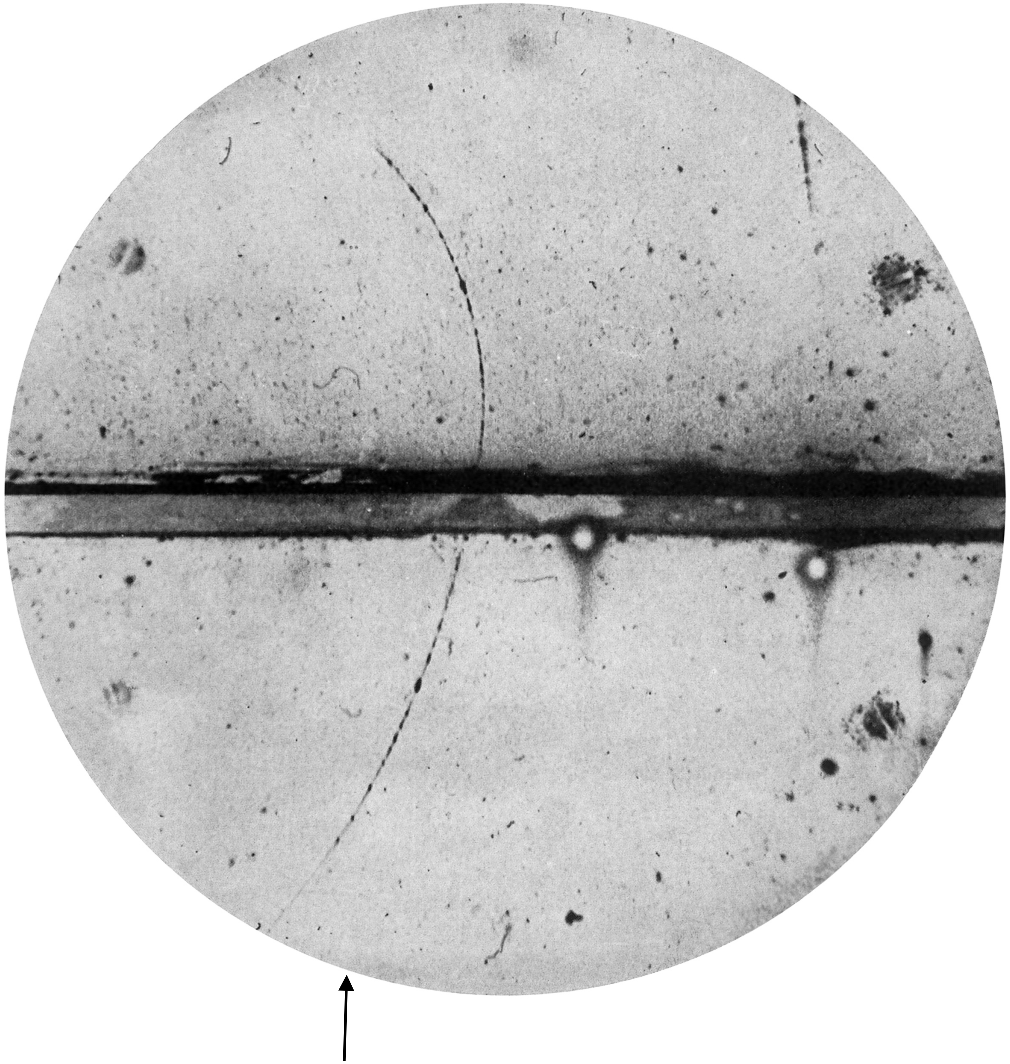


(when relativistic)

- Dirac spinor breaks into two components for a spin-up particle and two components for a spin-down particle.

- But why are there two kinds of field for each spin?

ANTIMATTER



First positron detection, 1932

- Each pair has a positive energy part and a negative energy part.
- The negative energy part represents antimatter.
  - →Matter moving backward in time, according to the Feynman Stueckelberg interpretation.

$$\Psi = \Psi_0 e^{-i E t / \hbar}$$

- The positron is the electrons antiparticle. It was predicted by Dirac (1928) before it was discovered by Anderson (1932).

NOT SO FAST!

Ettore Majorana

But, Ettore Majorana found a new class of solutions to Dirac's equation using only two degrees of freedom.

$$\psi = \left[\begin{array}{c} \omega \\ -i\sigma_2\omega^* \end{array} \right]$$

Four-component object built using some two-component

$$\omega = \left(\begin{array}{c} \omega_1 \\ \omega_2 \end{array} \right)$$

CHARGE CONJUGATION

$$\psi_c \equiv -i\gamma^2\psi^*$$

← Definition of charge conjugation operation: transform particles ←→ antiparticles

- For Majorana's solution:

$$\psi_c = \psi$$

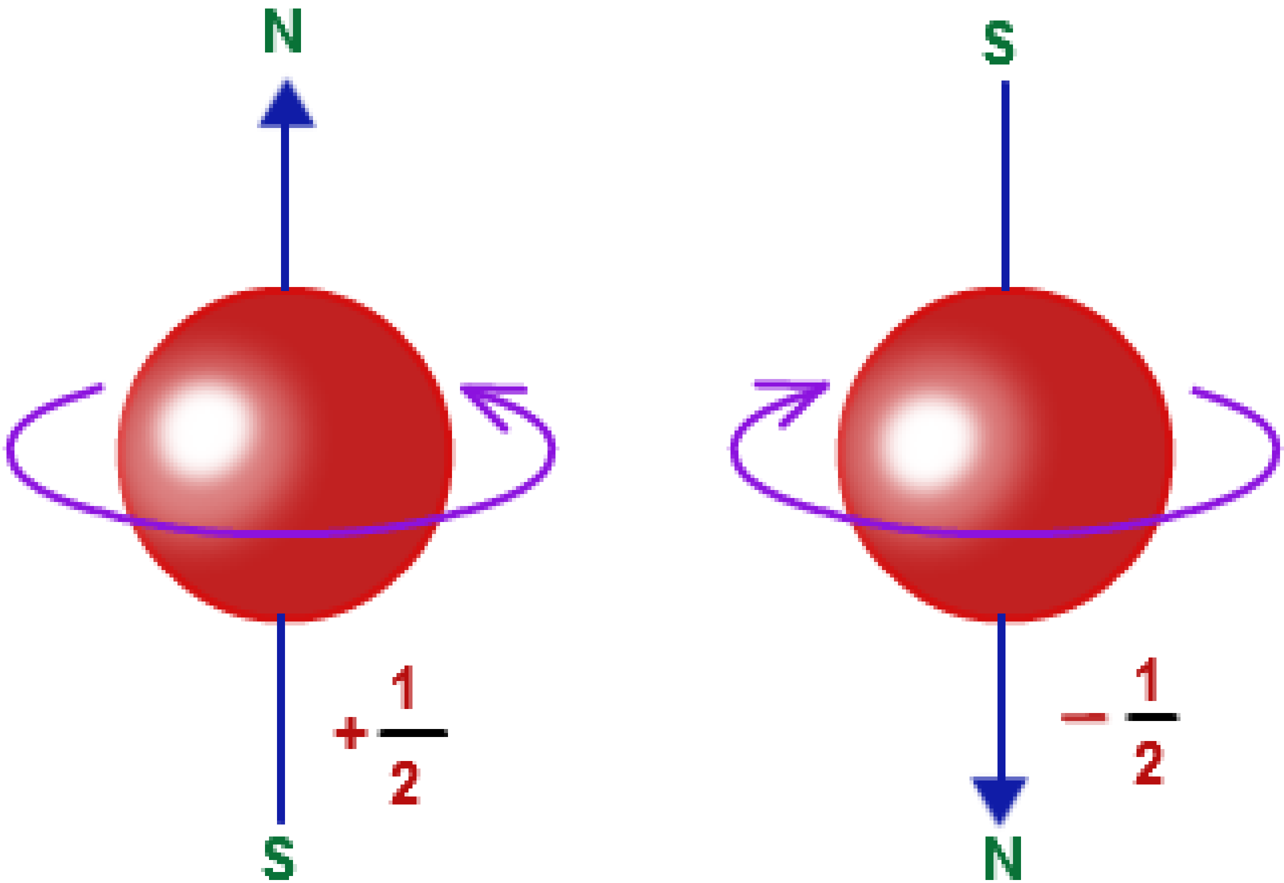
← **It's antiparticle is the particle!**
Two degrees of freedom correspond to left and right of a "particle-antiparticle-thing"

- Whereas for a general Dirac solution:

$$\psi_c \neq \psi$$

← **Distinct particle and antiparticle**
Four degrees of freedom correspond to left and right of particle and antiparticle.

IN SHORT, WHAT ARE MAJORANA FERMIONS:



We call it a particle
(behaves like matter)

We call it an antiparticle
(behaves like antimatter)

WHO CARES?

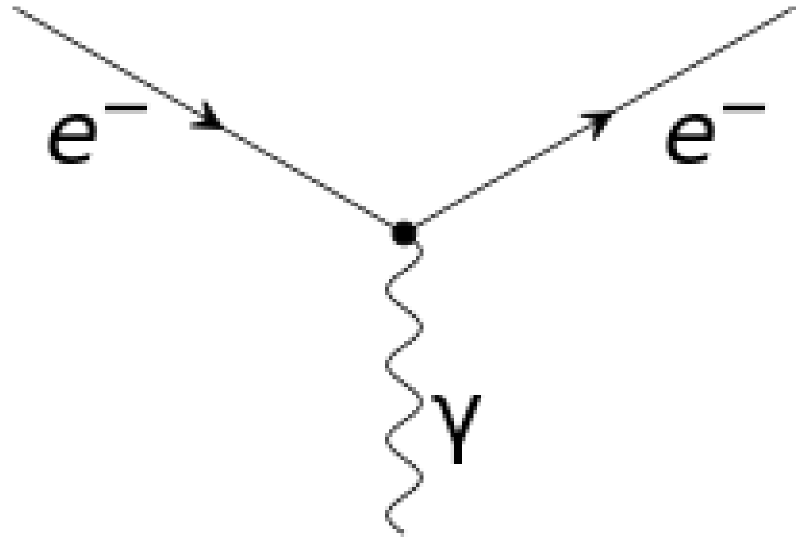
$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial+m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda)+\frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda)+(\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1-\gamma^5)u^\lambda_j)+(\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda)+\phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda)+i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ -$$
$$\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] +$$
$$igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

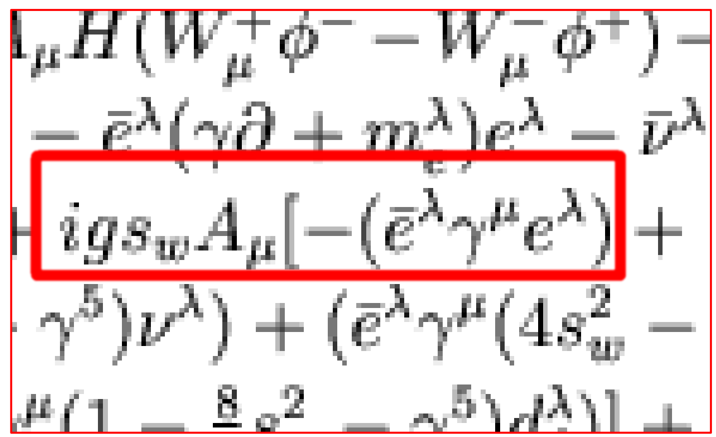
The standard model Lagrangian

Each term represents some interaction between quantum fields.

After quantizing the theory, this becomes an interaction between particles.

$$-\frac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu -$$
$$M^2W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$
$$\frac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ -$$
$$\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] +$$
$$igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$





- Mercifully, there is a recipe for writing down that Lagrangian.
- Write down all terms that are:
- **1) Consistent with the symmetries of nature**

Gauge invariance:

$$SU(3) \times SU(2)_L \times U(1)_Y$$

+ Lorentz invariance

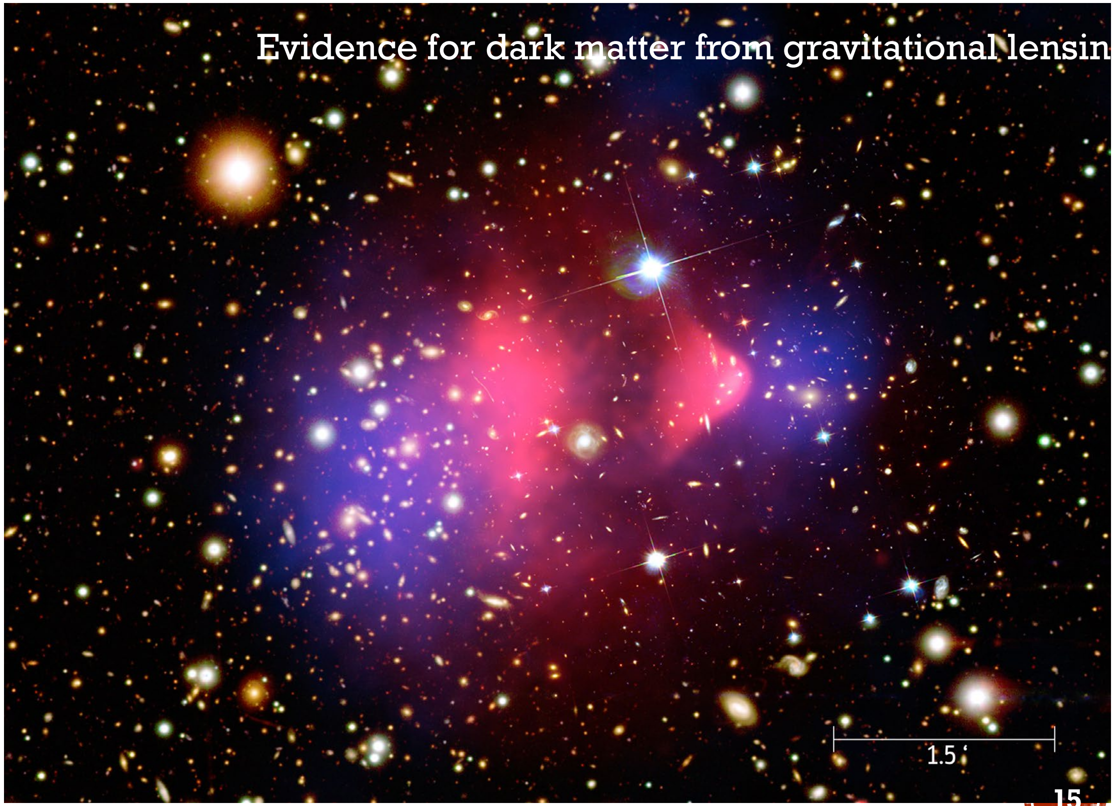
- **2) Renormalizible**

All appear in nature, except 1 mystery absentee (strong CPV).

IS THERE MORE?

- We've never seen a particle interaction not predicted by the SM. But we suspect there is new physics out there…
  - Dark matter
  - Hierarchy problem
  - Gauge unification
  - Etc…

- Lots of ideas:
  - SUSY
  - Extra dimensions
  - String theory
  - Lorentz violation
  - [your favorite theory]



- We believe that whatever the new physics is, it kicks in a high energies (that's why we build accelerators).

- Technically we say the SM is likely a "low energy effective theory".

At high energies:

COMPLETE THEORY, VALID AT ALL ENERGIES

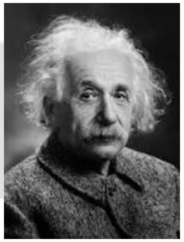
At low energies:

$$SU(3) \times SU(2)_L \times U(1)_Y$$

- As a point of reference, here is another low energy effective theory:

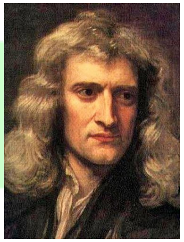
At high energies:

$$E = \sqrt{p^2 + m^2}$$



At low energies:

$$E \sim m + p^2/2m$$



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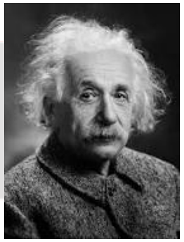
At high energies:

$$E = \sqrt{p^2 + m^2}$$



At low energies:

$$E \sim m + p^2/2m + p^4/8m^3 + \ldots$$

"dimension-4 correction"

And, we can test the high energy theory by confirming these corrections.

If SM is a low energy effective theory:

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \ldots$$

Standard model

Dimension-5 terms

Dimension-6 terms

Etc…

E_{new} > 10 TeV **Seems likely (LHC)**

E_{new} ~ 10^{13} TeV **Maybe? (GUT scale)**

If SM is a low energy effective theory:

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \ldots$$

- The only dimension-5 operator one can add obeying SM gauge symmetry:

$$\frac{L_1}{E_{new}} = y_{ij} \frac{\nu^i H \nu^j H}{E_{new}}$$

Weinberg 1979.

- This term does an important thing - it makes neutrinos Majorana particles, with mass suppressed by the new physics scale.

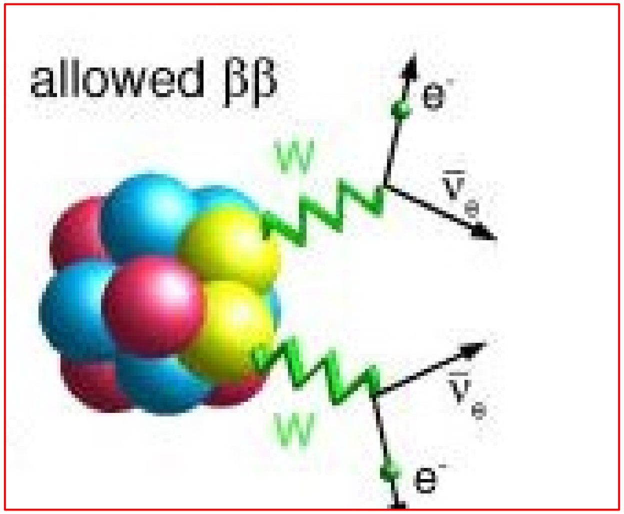
- And it makes the theory non-renormalizible – implying there must be something else at high scale.

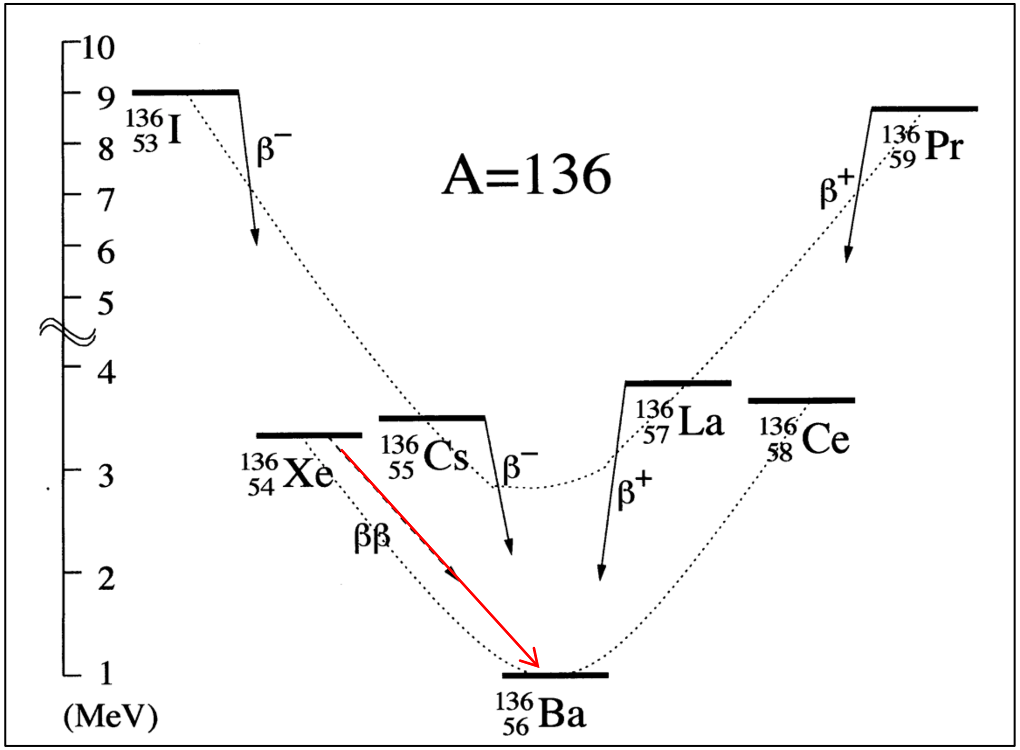
DOUBLE-BETA DECAY

A rare radioactive process, energetically allowed for some even-even nuclei where $m_{Z+1} > m_Z > m_{Z+2}$

$(Z,A) \rightarrow (Z+2,A) + e^-_1 + \underline{\nu}_1 + e^-_2 + \underline{\nu}_2$

Maria Goeppert Mayer





(NB: this decay mode has nothing to do with Majorana neutrinos, but we'll get back to them soon)

Direct Evidence for Two-Neutrino Double-Beta Decay in ^{82}Se

S. R. Elliott, A. A. Hahn, and M. K. Moe
Department of Physics, University of California, Irvine, Irvine, California 92717
(Received 31 August 1987)

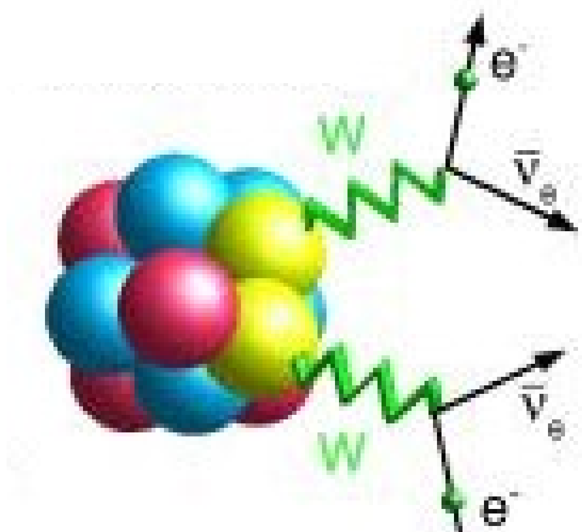
The two-neutrino mode of double-beta decay in ^{82}Se has been observed in a time-projection chamber at a half-life of $(1.1^{+0.8}_{-0.3})\times 10^{20}$ yr (68% confidence level). This result from direct counting confirms the earlier geochemical measurements and helps provide a standard by which to test the double-beta-decay matrix elements of nuclear theory. It is the rarest natural decay process ever observed directly in the laboratory.

PACS numbers: 23.40.Bw

Discovery of double beta decay

Observed in ^{82}Se, 52 years after prediction.

Half-life is ~10^{13} times age of Universe.



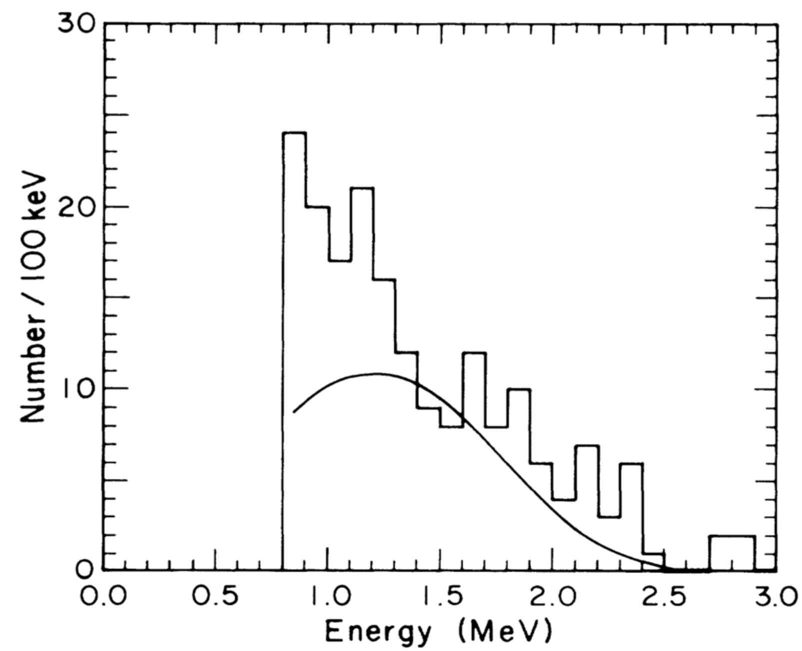
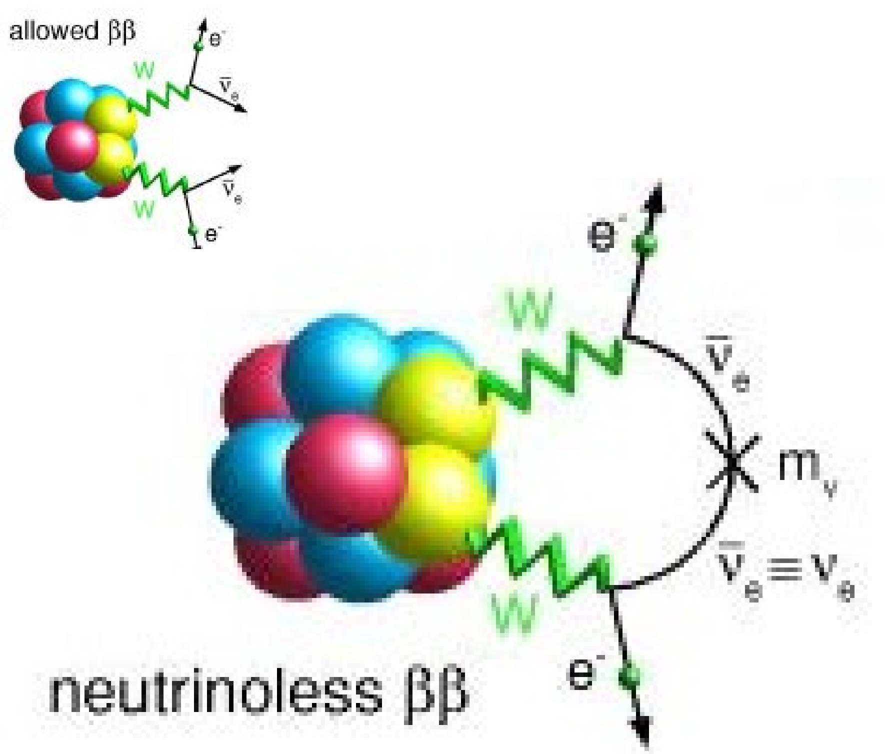


FIG. 1. The observed sum-energy spectrum of two-electron events. A threshold of 800 keV was imposed on the sum energy of the events, and a threshold of 150 keV was imposed on the single energy. The curve is the theoretical $\beta\beta(2\nu)$ sum-energy spectrum normalized to 1.1×10^{20} yr.

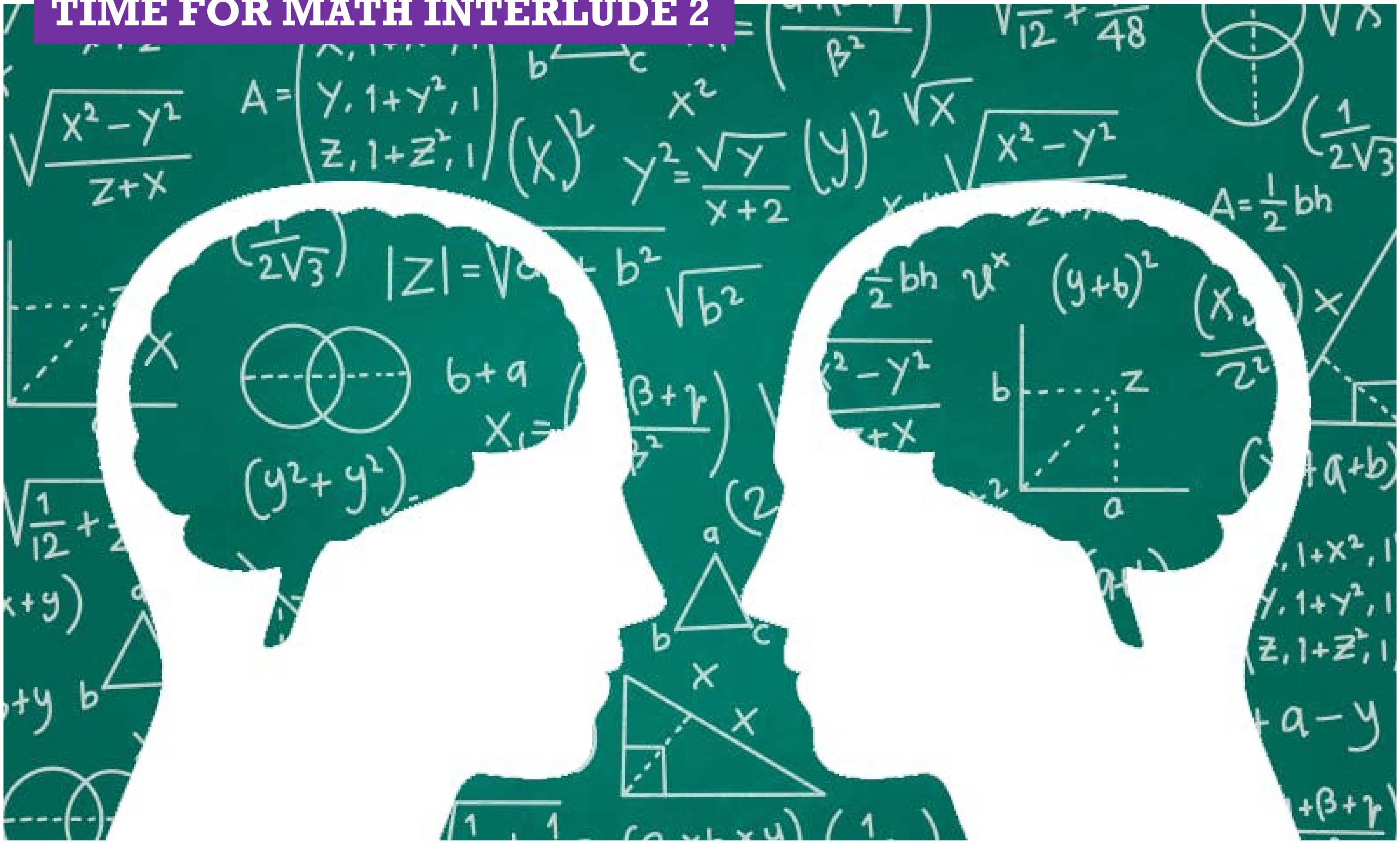
DOUBLE BETA WITH NO NEUTRINOS?



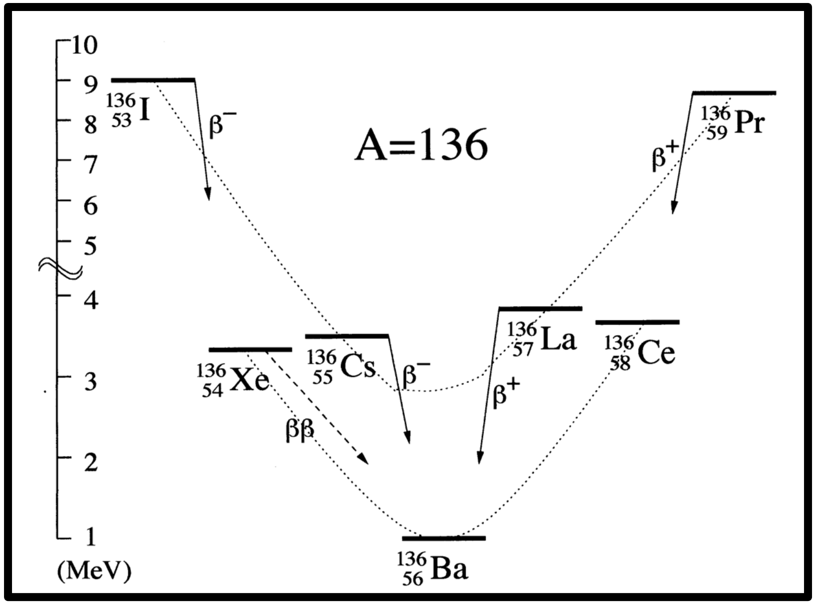
- This can only happen if the neutrino is its own antiparticle.
- Observation of double beta decay with no neutrinos would prove the neutrino to be a Majorana fermion.

How fast will this decay go? Lets find out!

TIME FOR MATH INTERLUDE 2



DOUBLE BETA ISOTOPES

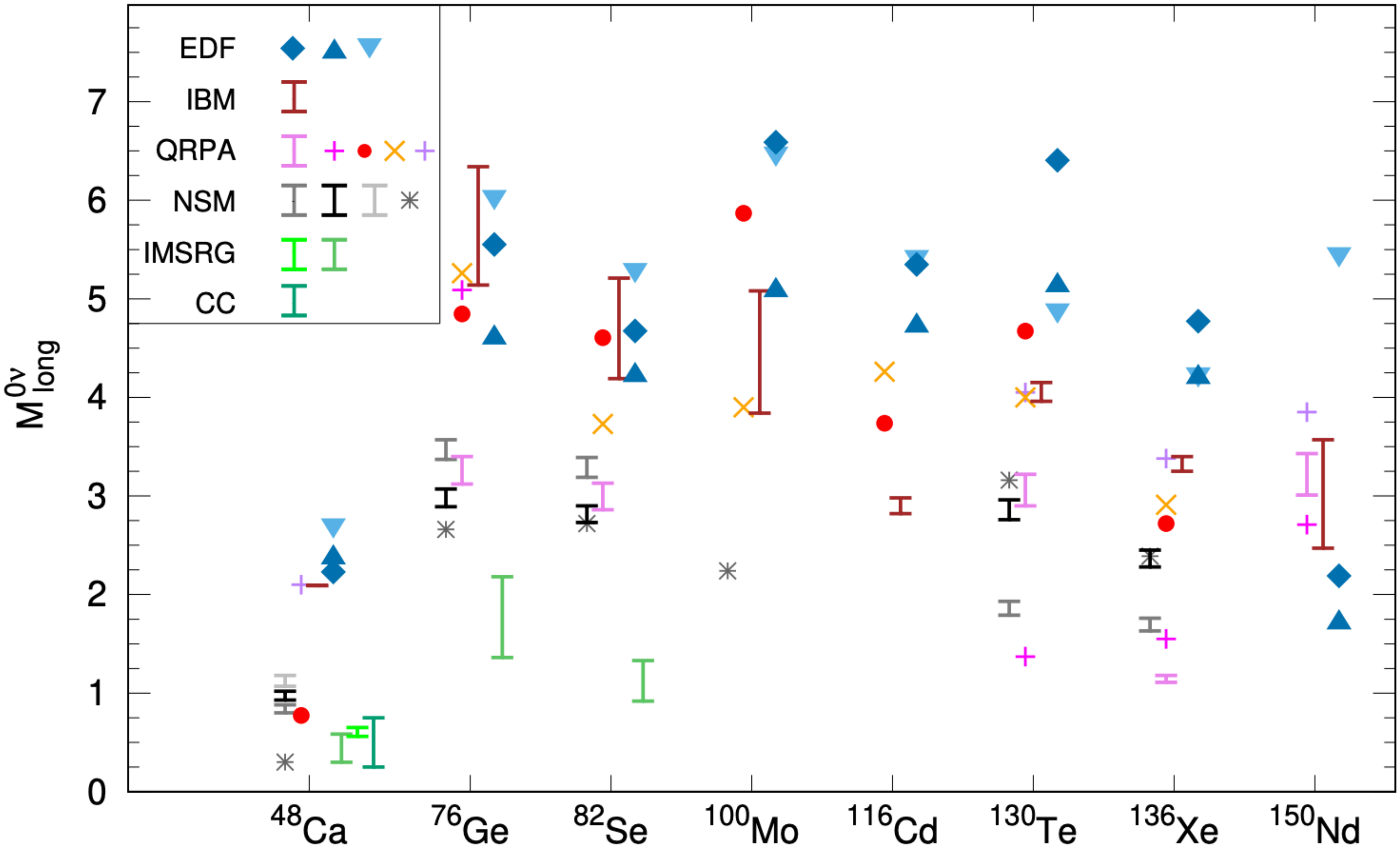


- Larger G → higher rate
- Helps if Q is above most background γ rays
- Abundance, cost, and ease of enrichment are also factors influencing isotope choice.

Phase space factor ↓ Energy of peak ↓ Natural abundance ↓

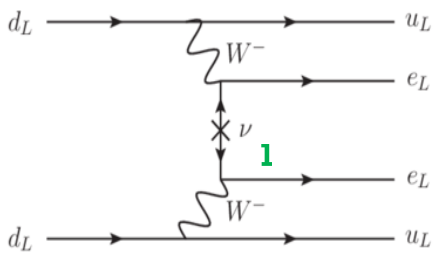
Isotope	$G^{0\nu}$ $(10^{-14}\ y^{-1})$	$Q_{\beta\beta}$ (keV)	Nat. ab. (%)
^{48}Ca	6.35	4273.7	0.187
^{76}Ge	0.623	2039.1	7.8
^{82}Se	2.70	2995.5	9.2
^{96}Zr	5.63	3347.7	2.8
^{100}Mo	4.36	3035.0	9.6
^{110}Pd	1.40	2004.0	11.8
^{116}Cd	4.62	2809.1	7.6
^{124}Sn	2.55	2287.7	5.6
^{130}Te	4.09	2530.3	34.5
^{136}Xe	4.31	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

NUCLEAR MATRIX ELEMENTS



Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

$\Gamma \propto \Big|$



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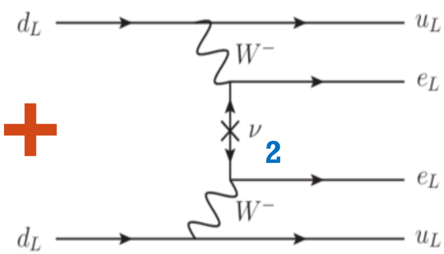

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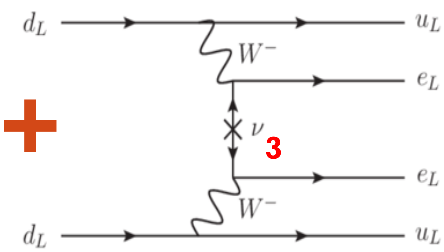
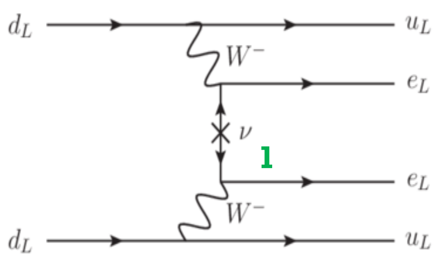
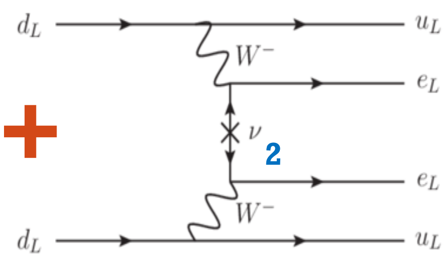
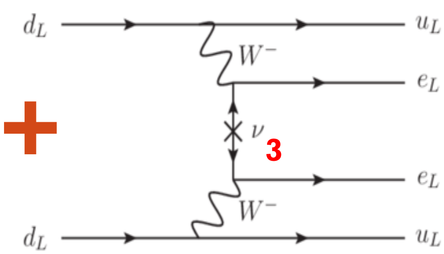


$\Big|^2$

$\Gamma \propto \Big|$ 

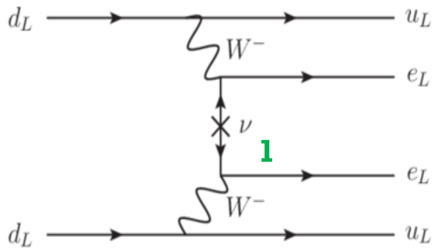
$+$ 

$+$ 

$\Big|^2$

$$= \left| (U_{e1})^2 m_1 + (U_{e2})^2 m_2 + (U_{e3})^2 m_3 \right|^2$$

$\Gamma \; \alpha \; \Bigg|$



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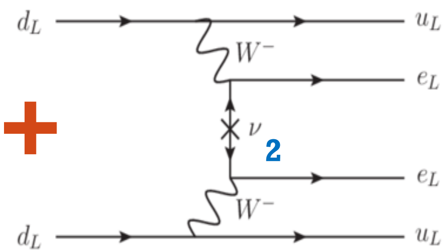

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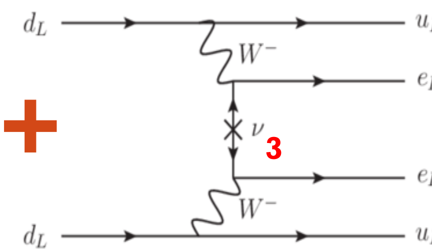
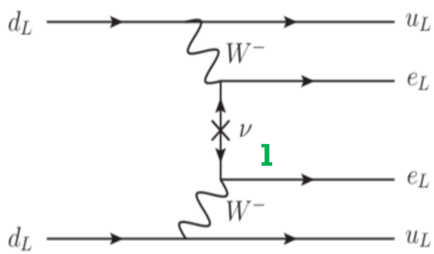


$\Bigg|^2$

$$= \left| (U_{e1})^2 m_1 + (U_{e2})^2 m_2 + (U_{e3})^2 m_3 \right|^2$$

$$= \left| c_{12}{}^2 c_{13}{}^2 e^{2i\alpha} m_1 + c_{12}{}^2 s_{12}{}^2 e^{2i\beta} m_2 + s_{13}{}^2 m_3 \right|^2$$

$\Gamma \propto$ $\Bigg|$



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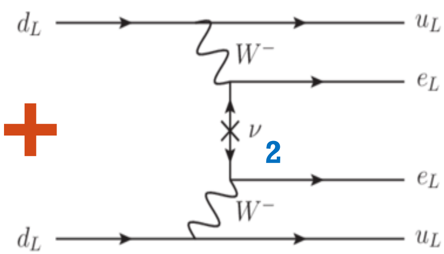

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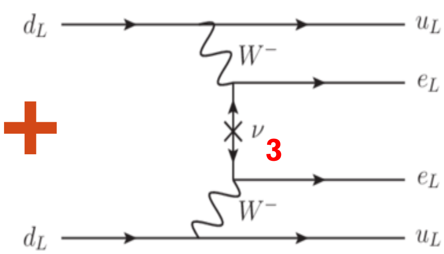
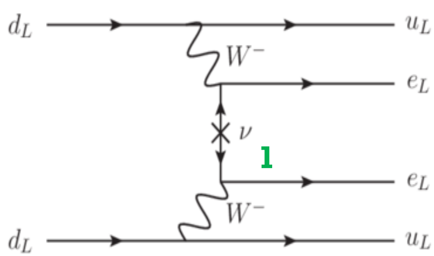


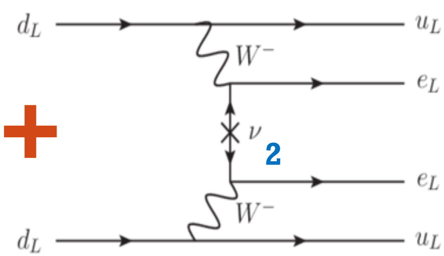
$\Bigg|^2$

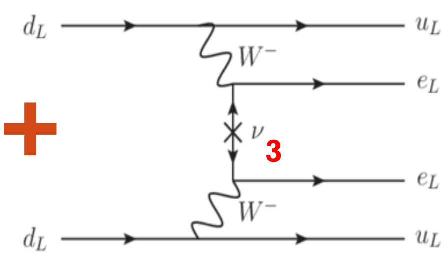
$$= \left| (U_{e1})^2 m_1 + (U_{e2})^2 m_2 + (U_{e3})^2 m_3 \right|^2$$

$$= \left| c_{12}{}^2 c_{13}{}^2 e^{2i\alpha} m_1 + c_{12}{}^2 s_{12}{}^2 e^{2i\beta} m_2 + s_{13}{}^2 m_3 \right|^2$$

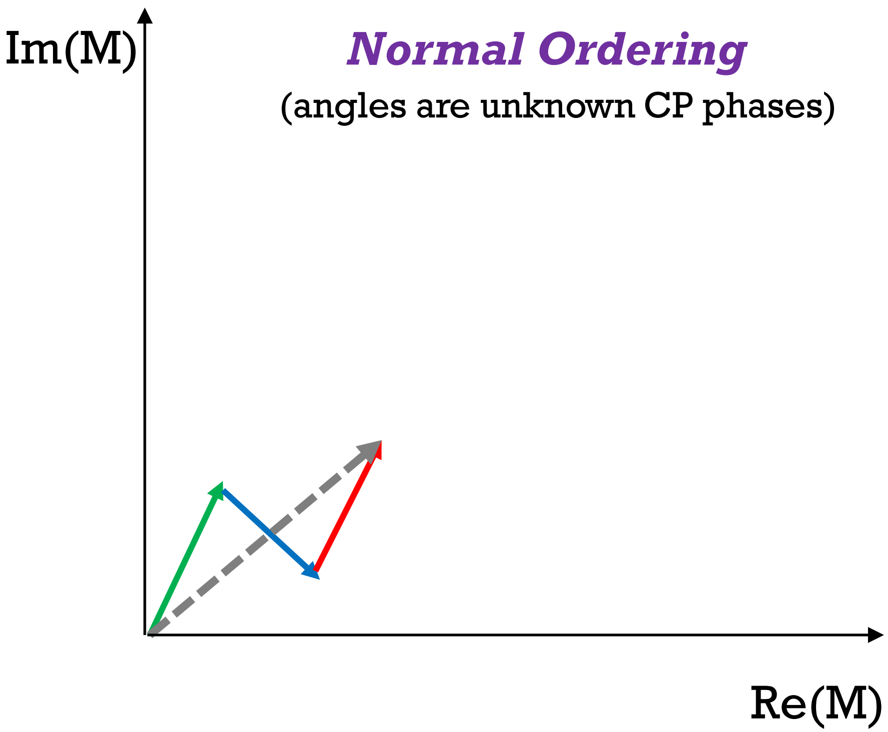
$$= \left| m_{\beta\beta} \right|^2$$

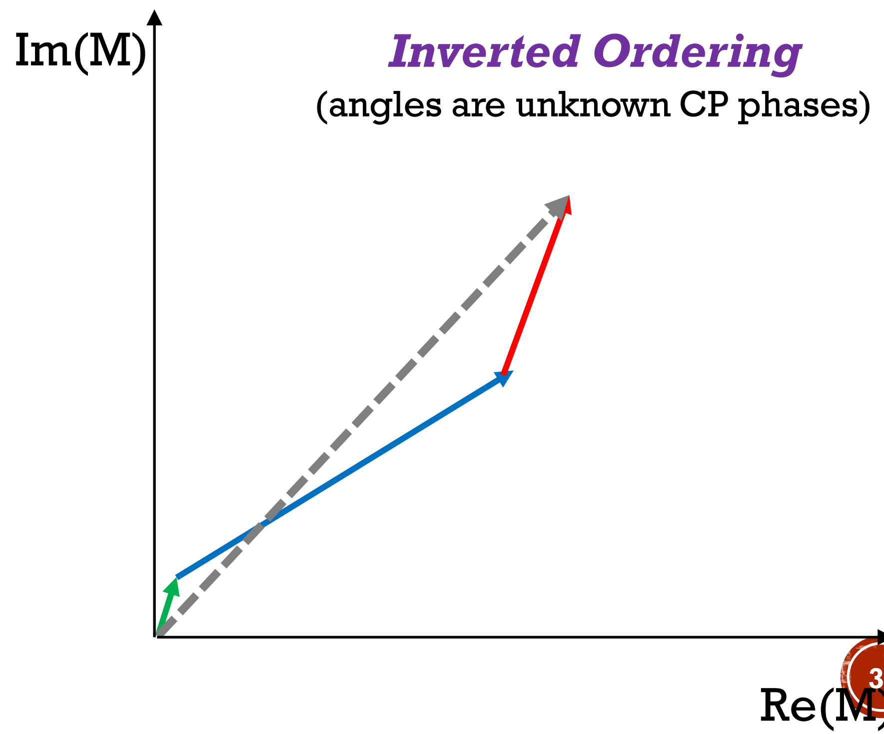
$\Gamma \propto \Big|$ 

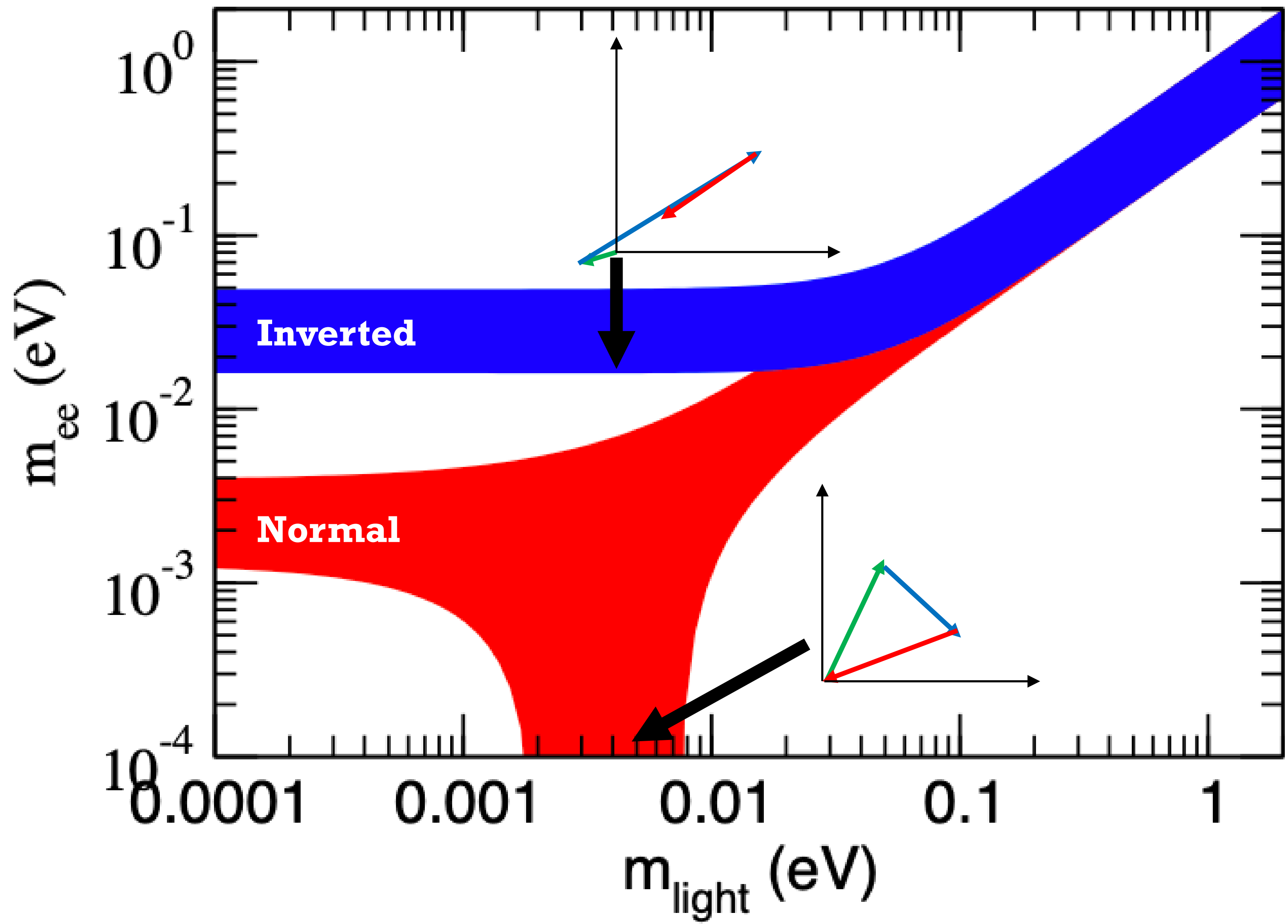
+ 

+ 

$\Big|^2$

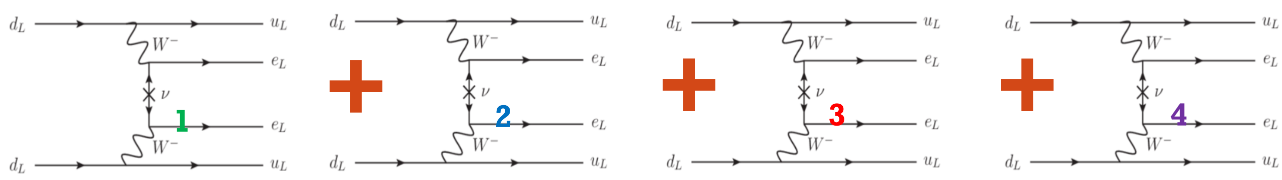


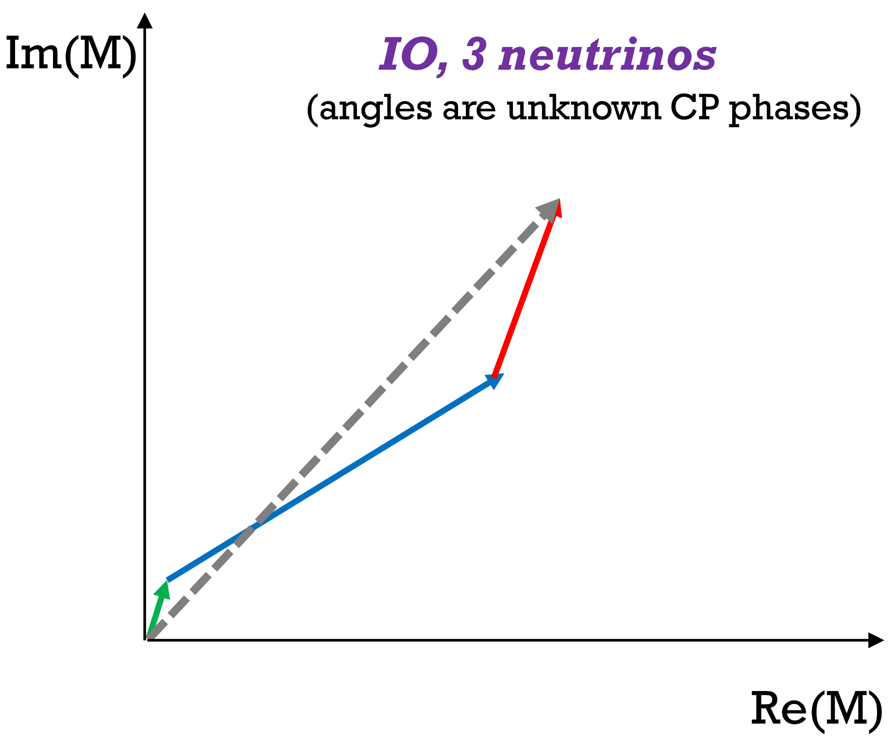


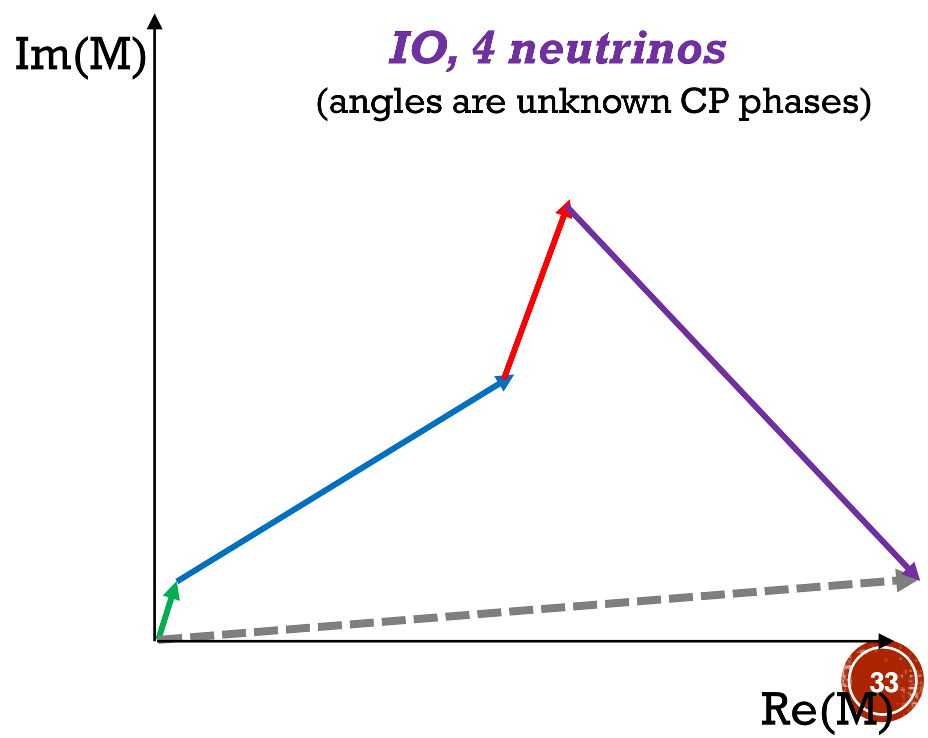


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
m_{ee} (eV)
Inverted
Normal
0.0001
0.001
0.01
0.1
1
m_{light} (eV)

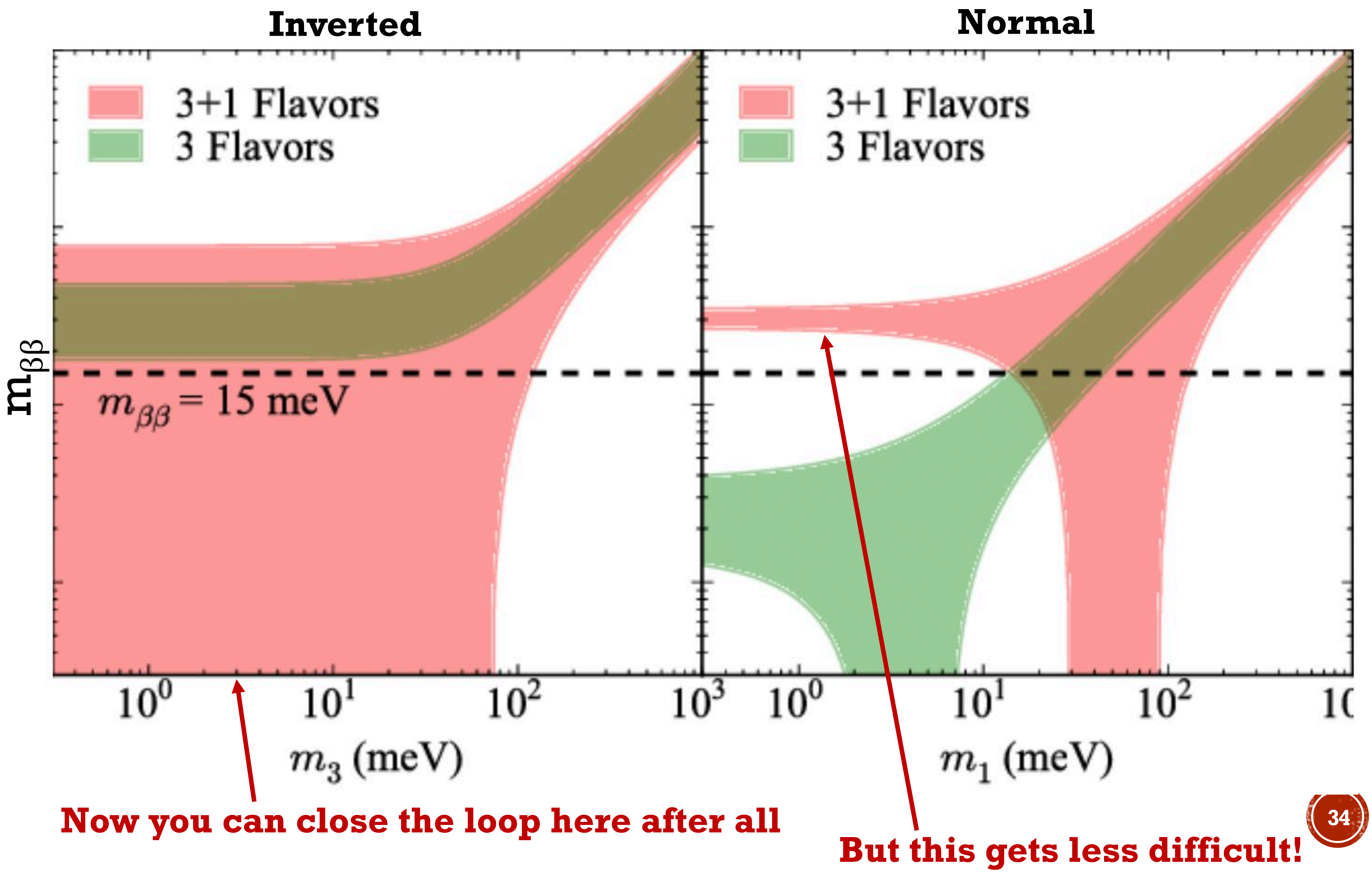
WHAT IF THERE ARE ADDITIONAL NEUTRINOS?

$\Gamma \propto \Big|$  $\Big|^2$



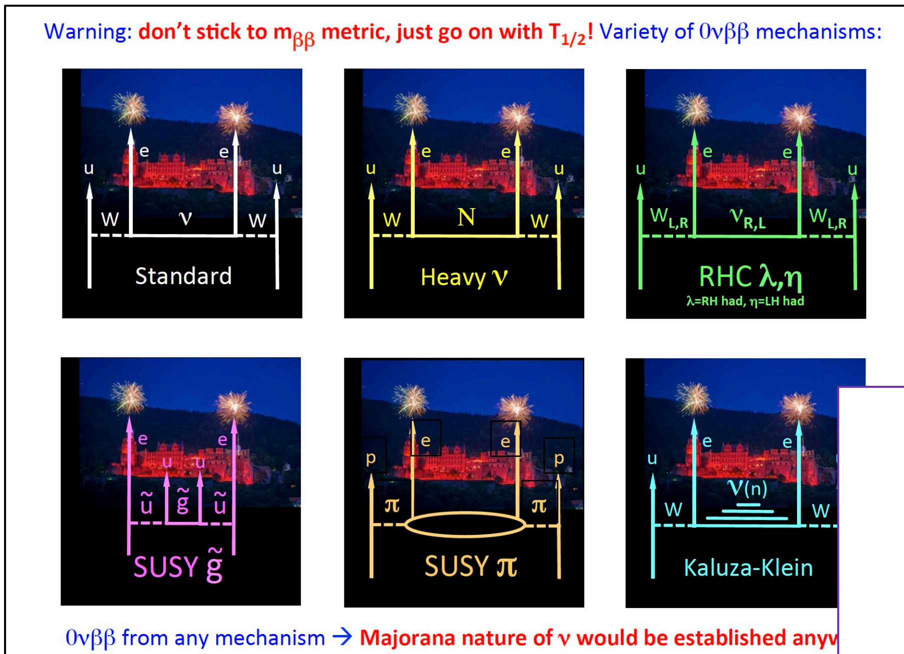


WITH A STERILE NEUTRINO:



If SM is a low energy effective theory:

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \ldots$$



You can also get it from up here

https://arxiv.org/pdf/1708.09390.pdf

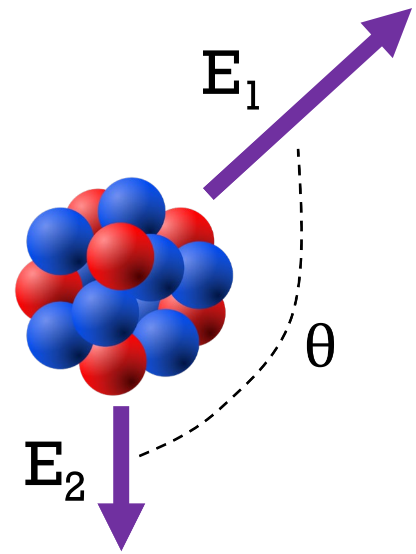
BSM theory with lepton number violation at high energy makes SM Wilson coefficients in the EFT expansion

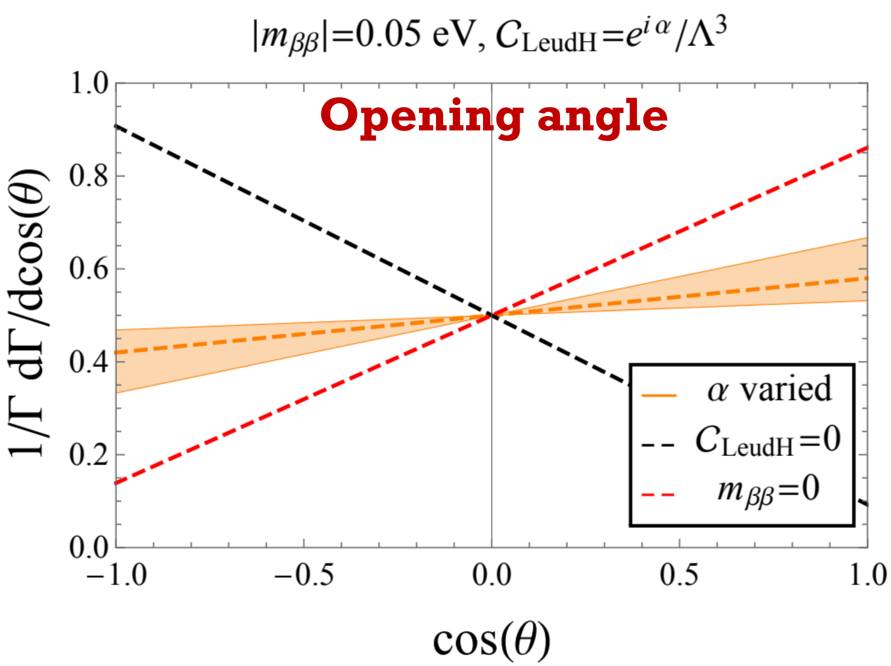
Neutrinoless double beta decay in chiral effective field theory: lepton number violation at dimension seven

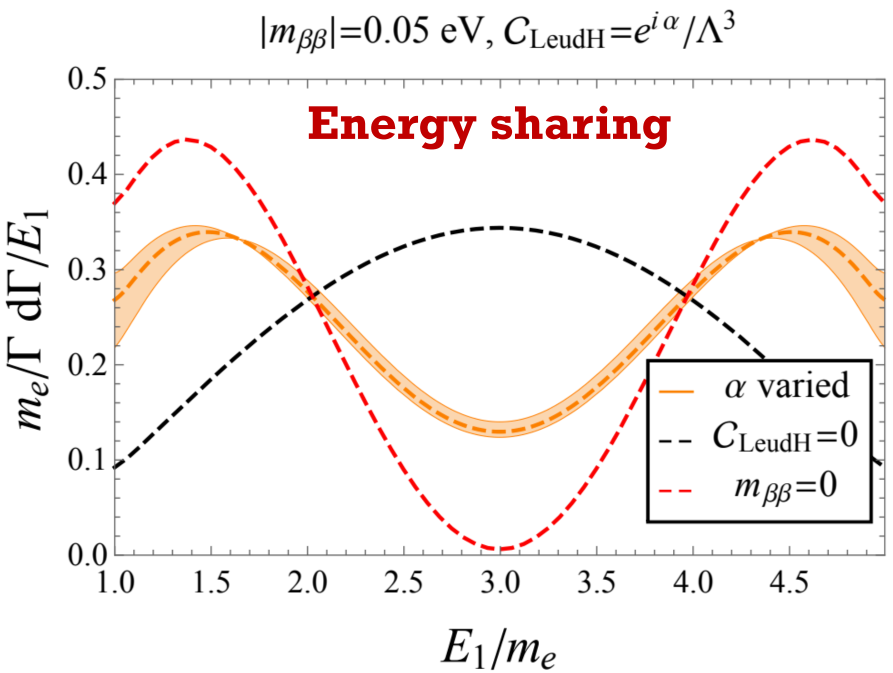
V. Cirigliano[a], W. Dekens[a,b], J. de Vries[c], M. L. Graesser[a], and E. Mereghetti[a]

So really we need to consider 0nubb as a discovery search – just hit the longest half lives possible!

- Given a high energy model, the kinematics of the final electrons can be predicted.
- If 0nubb is seen, measuring the opening angle and energy sharing could illuminate the mechanism.







CURRENT WORLD HEAVYWEIGHT CHAMPION

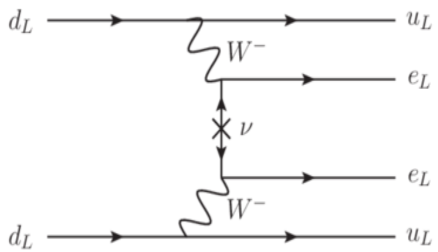
WWE world heavyweight champion

Seth "Freakin" Rollins

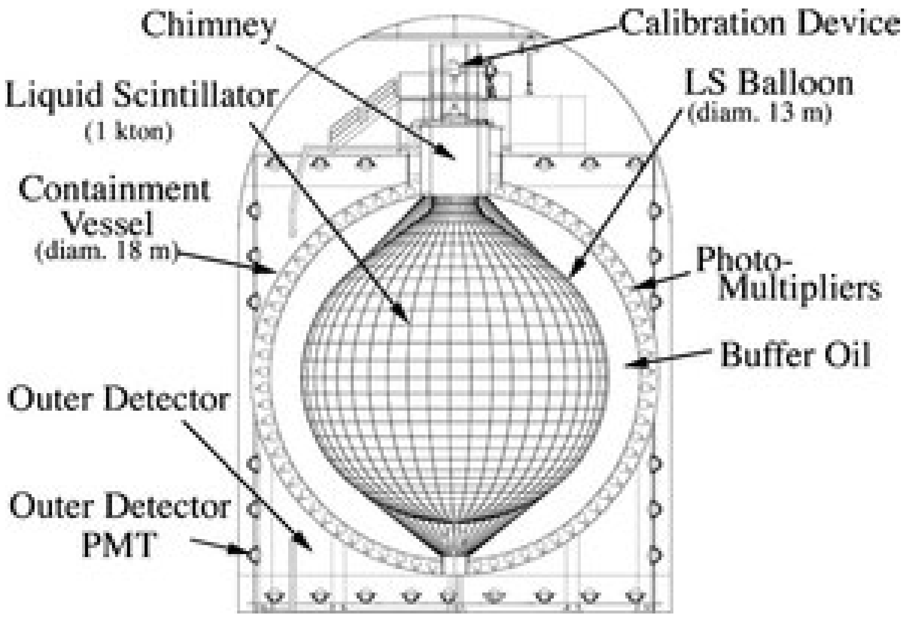
CURRENT WORLD HEAVYWEIGHT CHAMPION

WWE world heavyweight champion

Seth "Freakin" Rollins



0nubb world heavyweight chamption



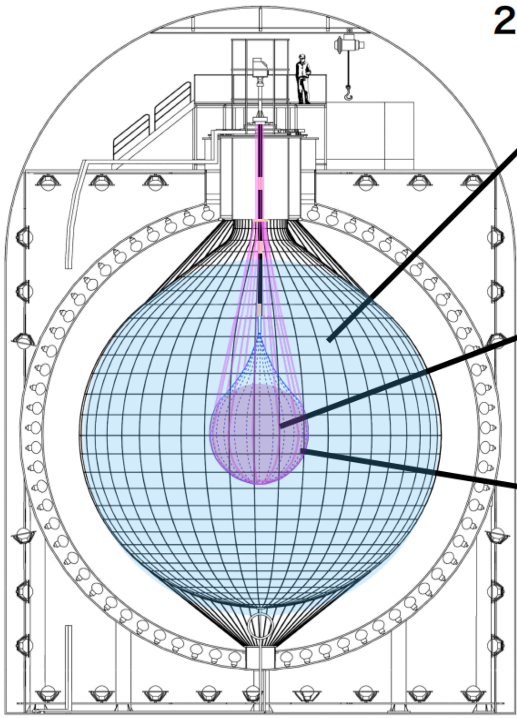
Kamland "Freakin" Zen

From Neutrino2024

KamLAND-Zen

Zero Neutrino Double Beta

Kamioka underground KamLAND detector



2-type of liquid scintillator

1000-ton pure liquid scintillator

U, Th < 10^{-17} g/g

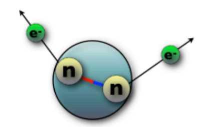
745 kg Xe-loaded liquid scintillator (91% enrichment)

inner balloon (IB)

2002− KamLAND

reactor, geo, solar neutrino observation

2011− KamLAND-Zen



double beta decay measurement ($0\nu\beta\beta$ search)

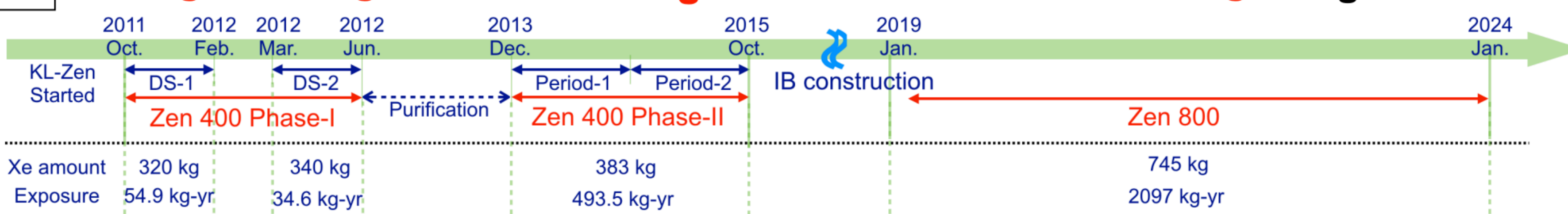
2019− Xe increase, cleaner balloon

big and pure : no background from external gamma-rays

purification of LS, replacement of mini-balloon are possible

→ **high scalability**

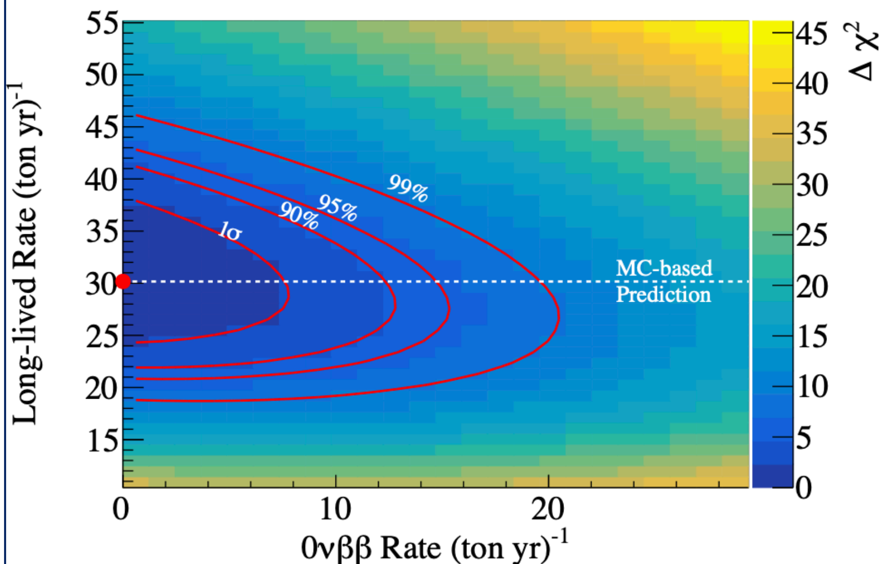
Xe **320 kg** **340 kg** **383 kg** **745 kg** **largest ^{136}Xe !!**

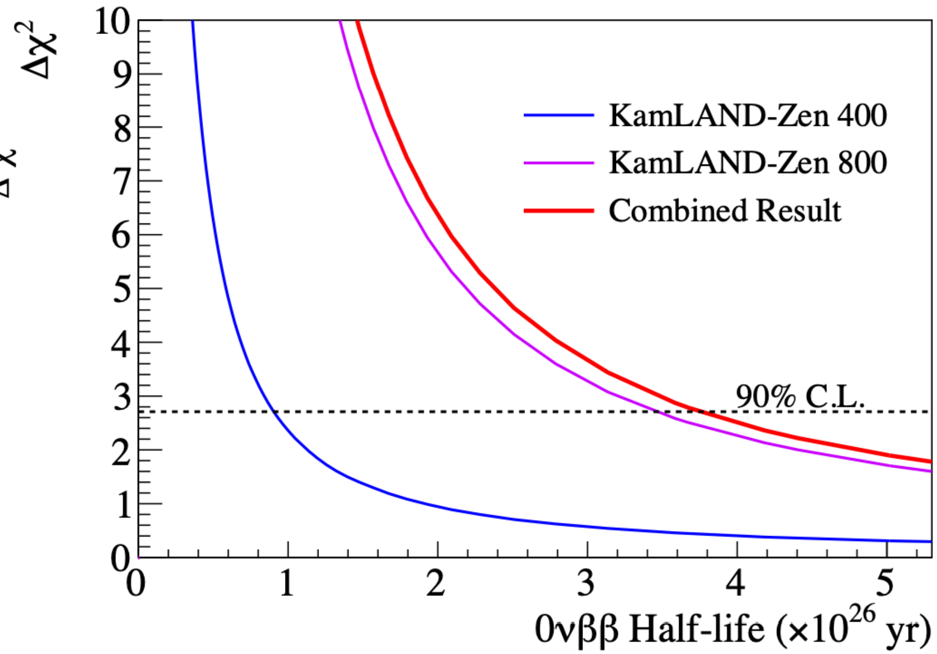


News from Neutrino2024:

^{136}Xe $0\nu\beta\beta$ Decay Half-life

(0ν rate, Long-lived BG rate)





Long-lived BG rate in 2.35-2.70 MeV = 30.2 ± 4.5 events/Xe-ton/yr

(MC prediction = 30.0 ± 2.2 events/Xe-ton/yr)

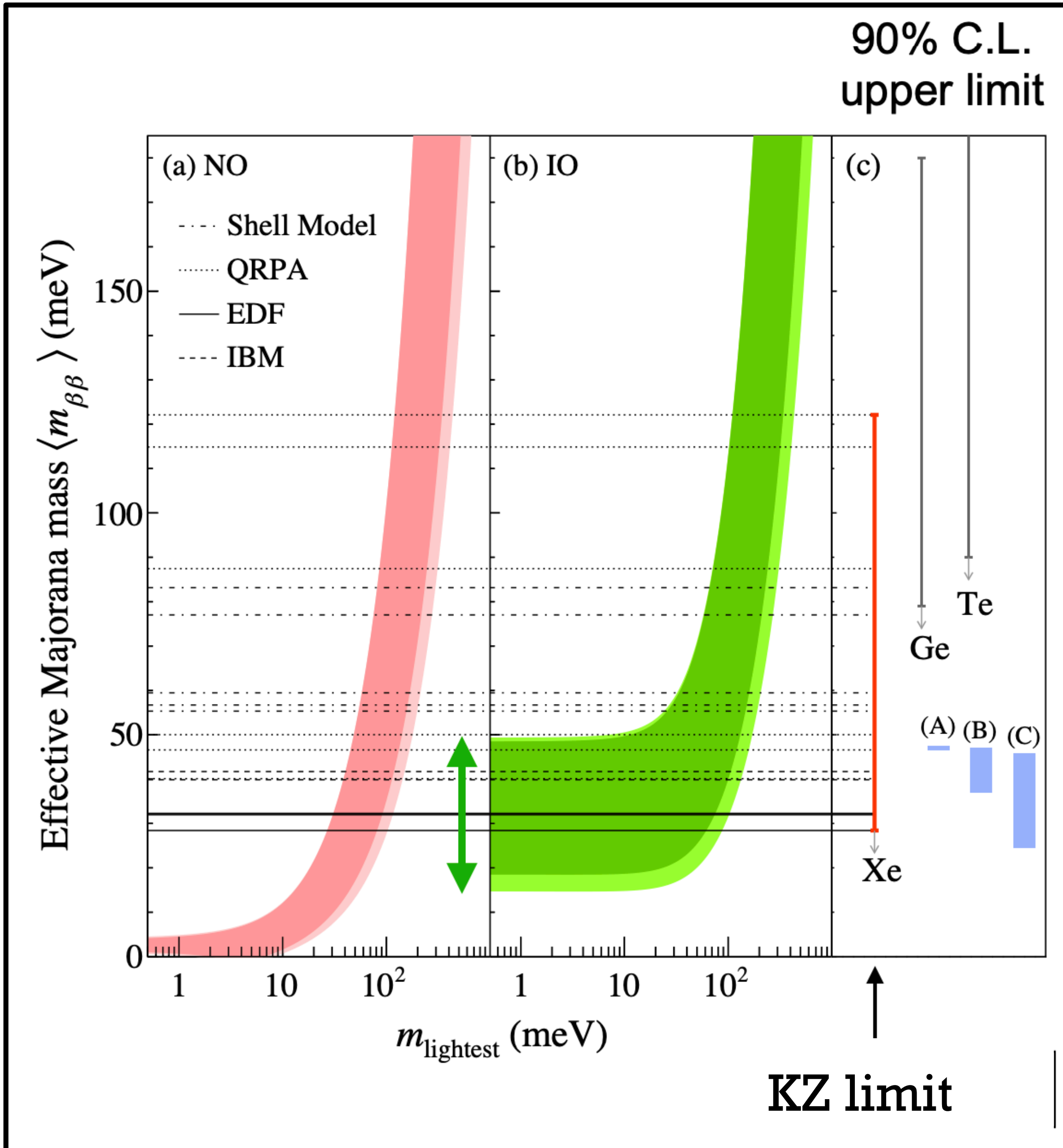
Long-lived BG rate was measured

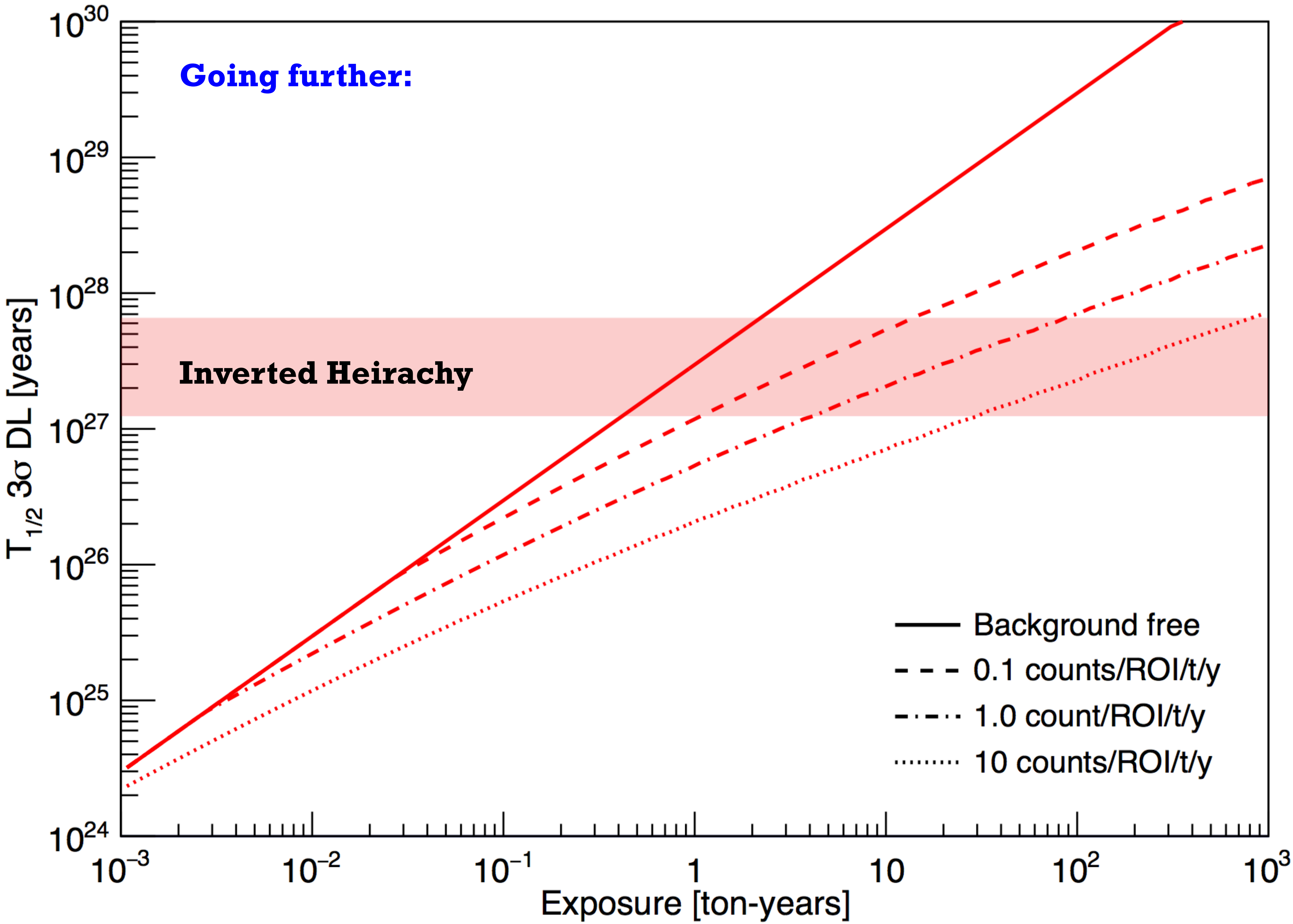
Half-life limit at 90% C.L.

Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
Zen 800	$T^{0\nu}_{1/2} > 3.4 \times 10^{26}$ yr
Combined	$T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr

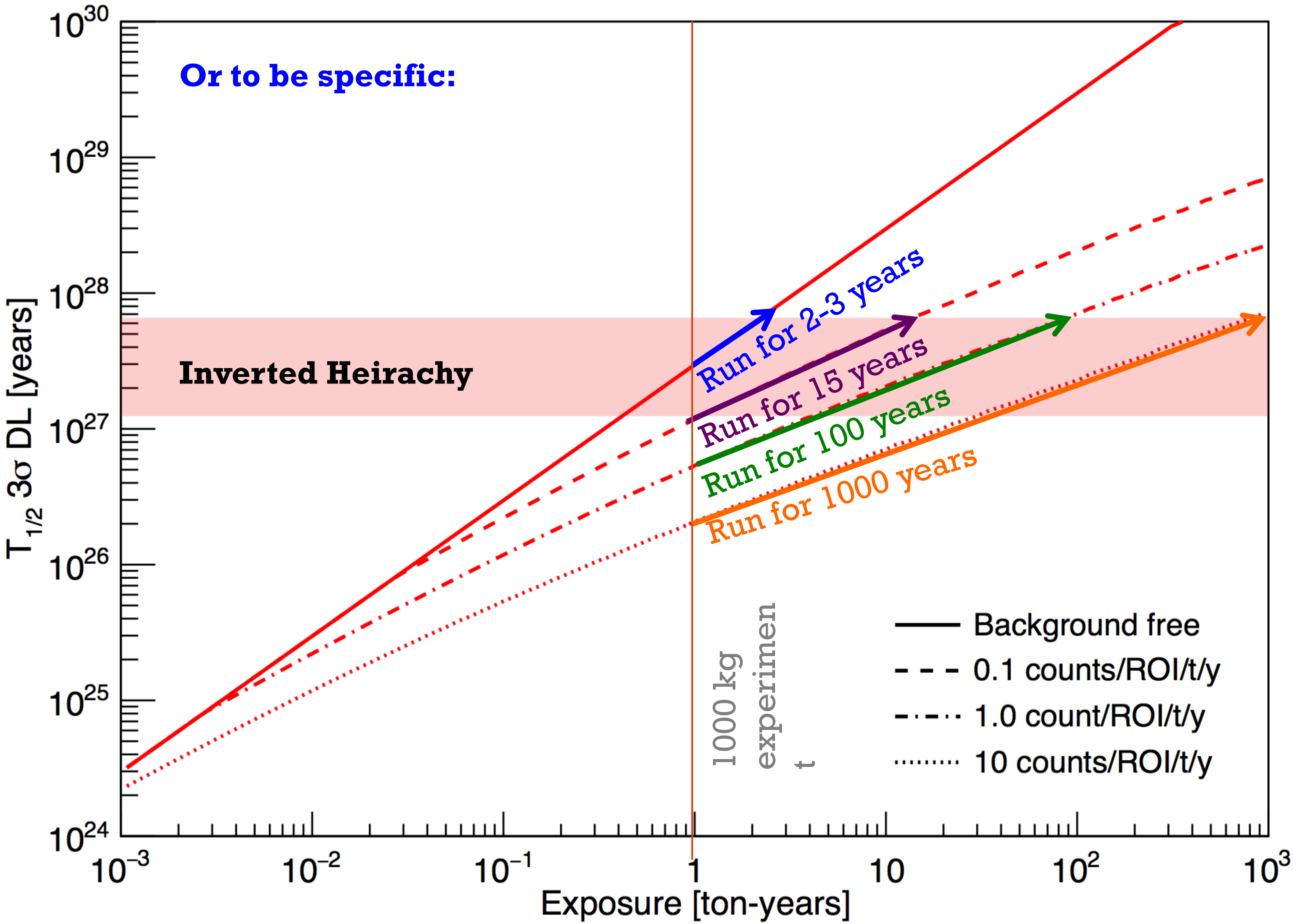
Limits on ^{136}Xe half-life are improved (~1.7 times better than previous)

CURRENT LIMITS





Going further:
Inverted Heirachy
$T_{1/2}$ 3σ DL [years]
Exposure [ton-years]
Background free
0.1 counts/ROI/t/y
1.0 count/ROI/t/y
10 counts/ROI/t/y
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{30}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}


Or to be specific:
Inverted Heirachy
Run for 2-3 years
Run for 15 years
Run for 100 years
Run for 1000 years
1000 kg experiment
Background free
0.1 counts/ROI/t/y
1.0 count/ROI/t/y
10 counts/ROI/t/y
$T_{1/2}$ 3σ DL [years]
Exposure [ton-years]
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{30}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}

Where are the backgrounds from?

(nb: these are pre-Neutrino2024 numbers)

TABLE I: Summary of the estimated and best-fit background contributions for the frequentist and Bayesian analyses in the energy region $2.35 < E < 2.70$ MeV within the 1.57-m-radius spherical volume. In total, 24 events were observed.

Background	Estimated	Best-fit Frequentist	Best-fit Bayesian
^{136}Xe $2\nu\beta\beta$	-	11.98	11.95
Residual radioactivity in Xe-LS			
^{238}U series	0.14 ± 0.04	0.14	0.09
^{232}Th series	-	0.84	0.87
External (Radioactivity in IB)			
^{238}U series	-	3.05	3.46
^{232}Th series	-	0.01	0.01
Neutrino interactions			
^{8}B solar ν e^- ES	1.65 ± 0.04	1.65	1.65
Spallation products			
Long-lived	7.75 ± 0.57 †	12.52	11.80
^{10}C	0.00 ± 0.05	0.00	0.00
^{6}He	0.20 ± 0.13	0.22	0.21
^{137}Xe	0.33 ± 0.28	0.34	0.34

† Estimation based on the spallation MC study. This event rate constraint is not applied to the spectrum fit.

Where are the backgrounds from?

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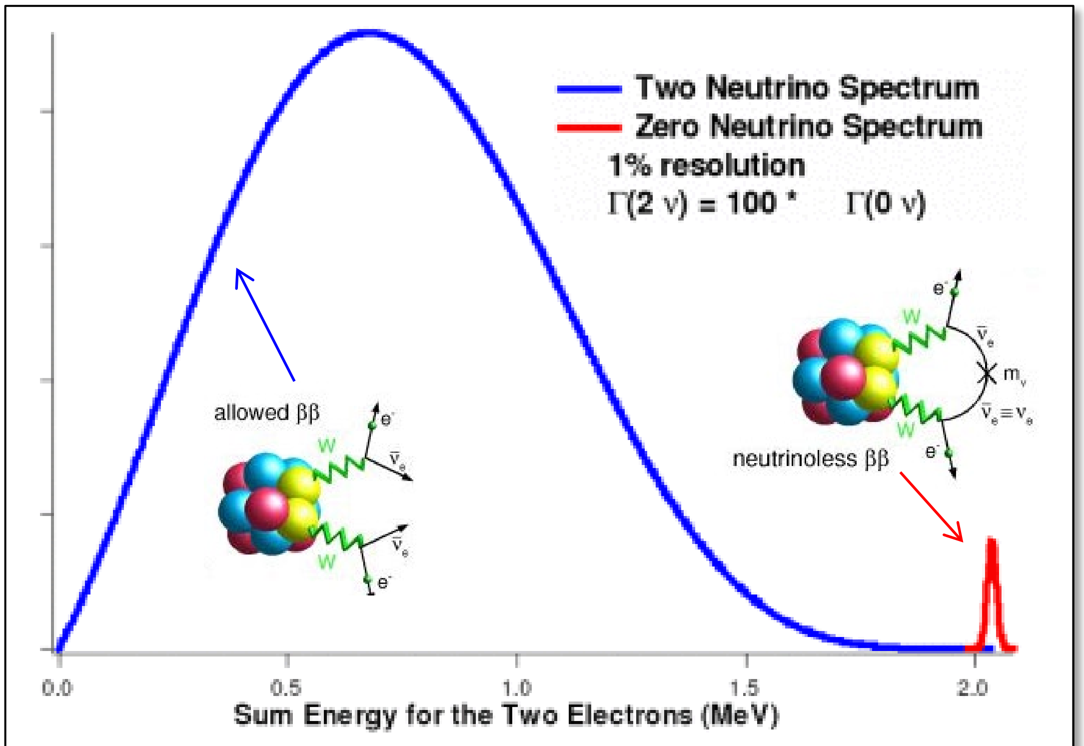
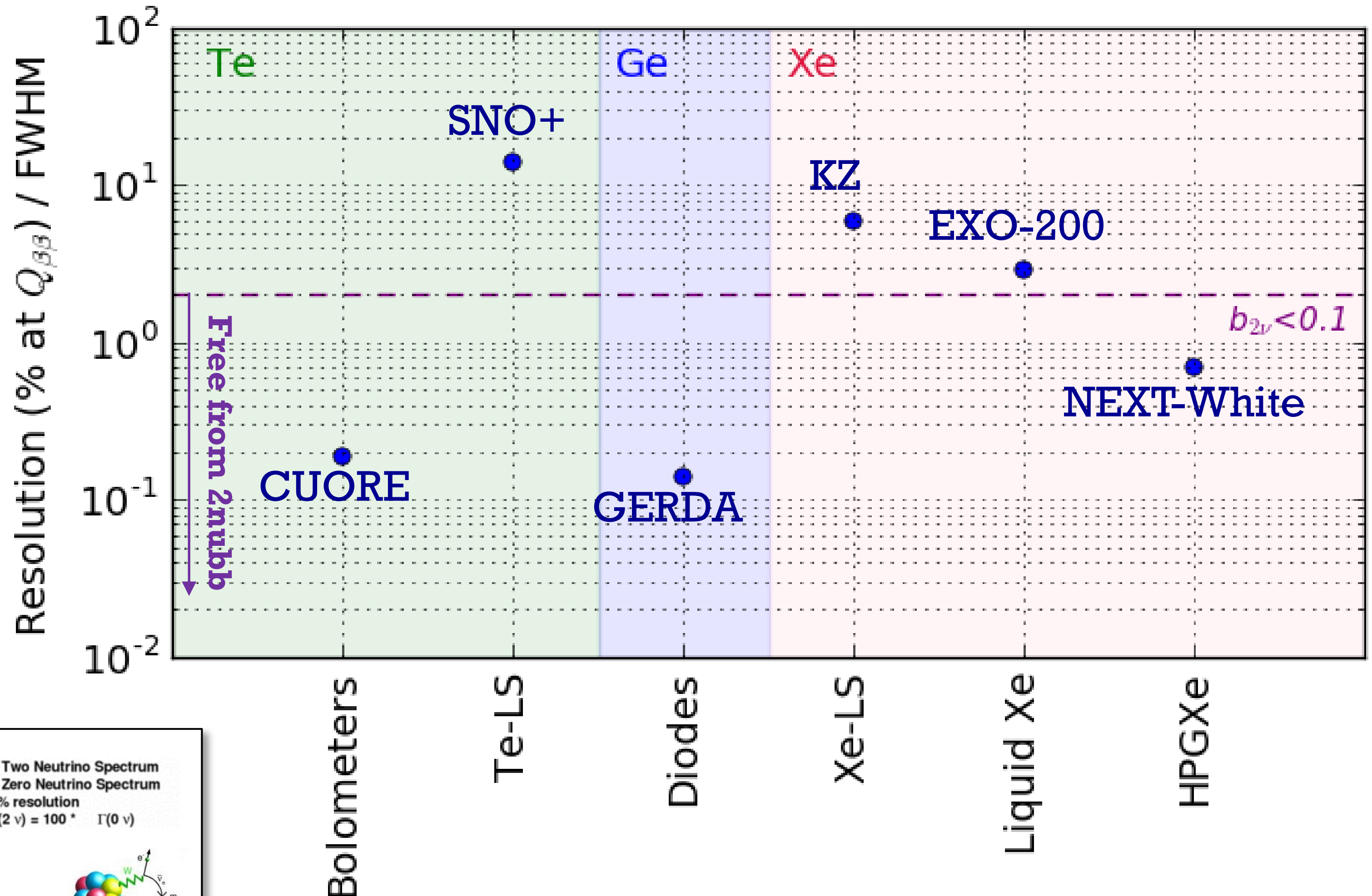
THE IDEAL EXPERIMENT:

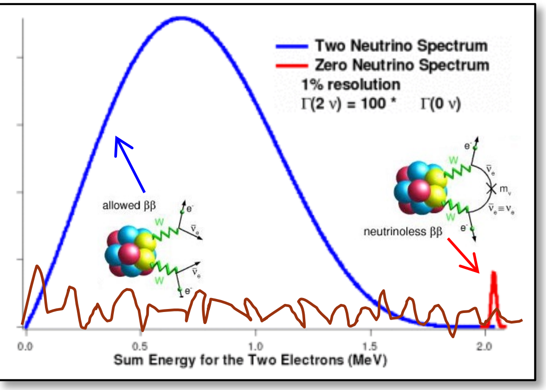


- ***MANDATORY:***
  - Resolution better than ~2% FWHM to fully reject two-neutrino mode

- ***Then just watch and wait…***

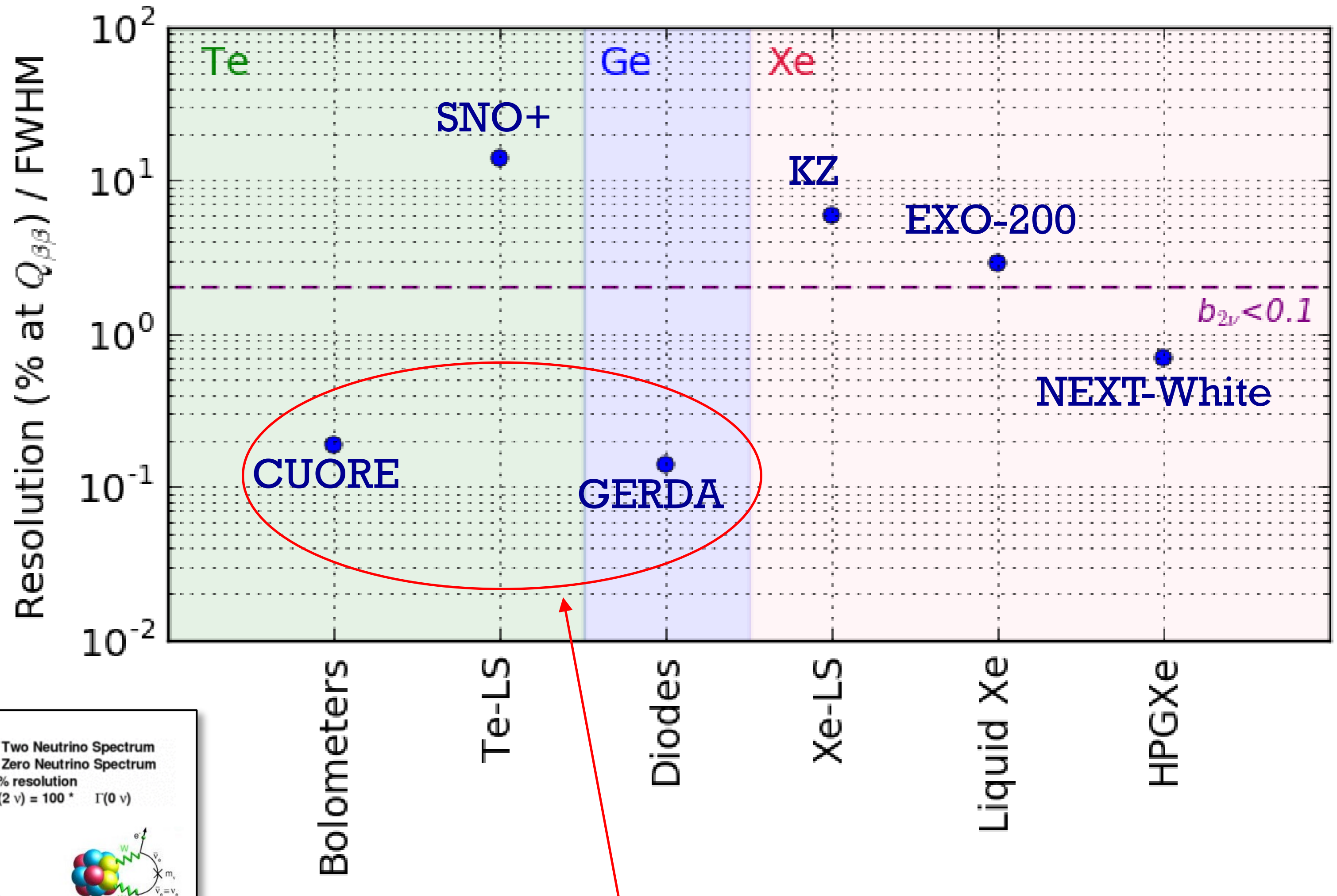
Measuring Energy

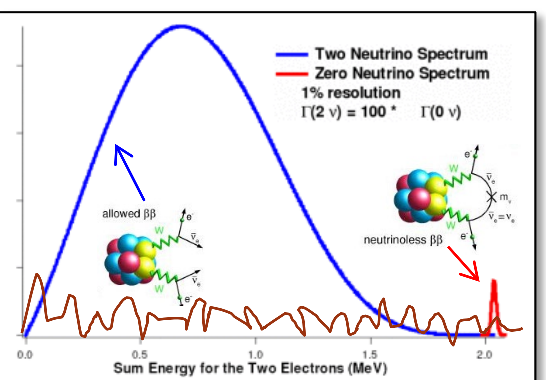




Once free from 2nubb, radioactive and cosmogenic backgrounds become dominant

Measuring Energy

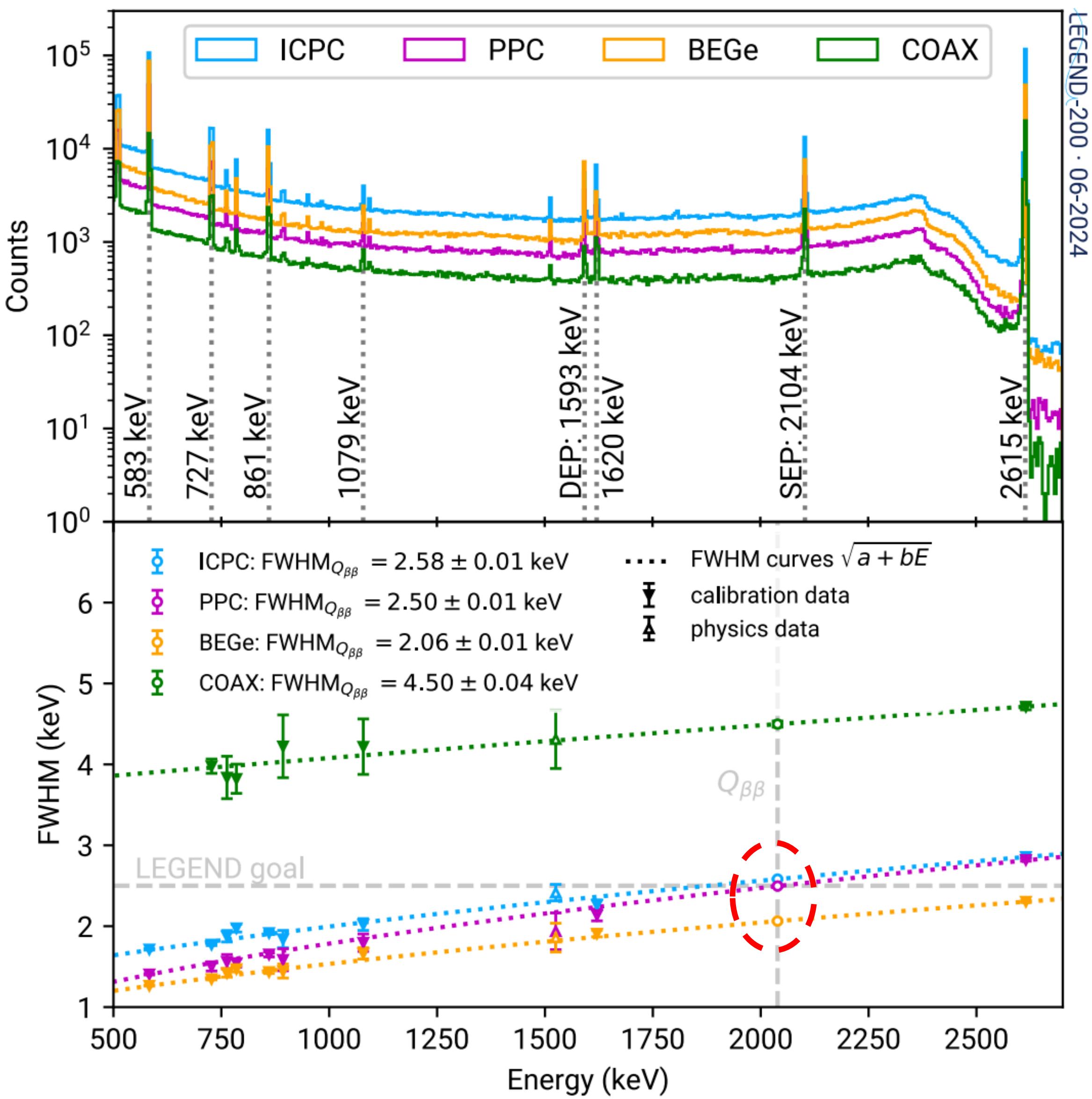




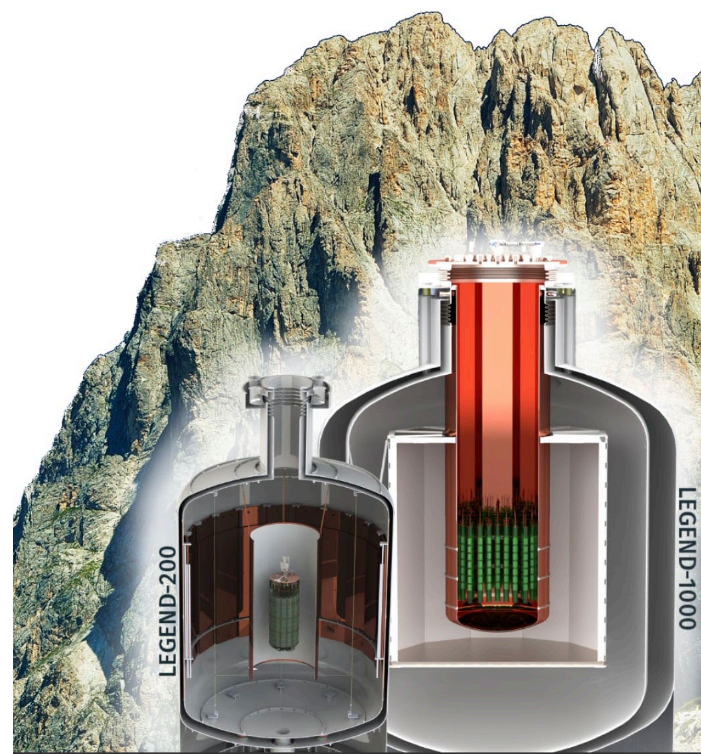
Solid state detectors are <u>amazing</u> for measuring energy.

LEGEND

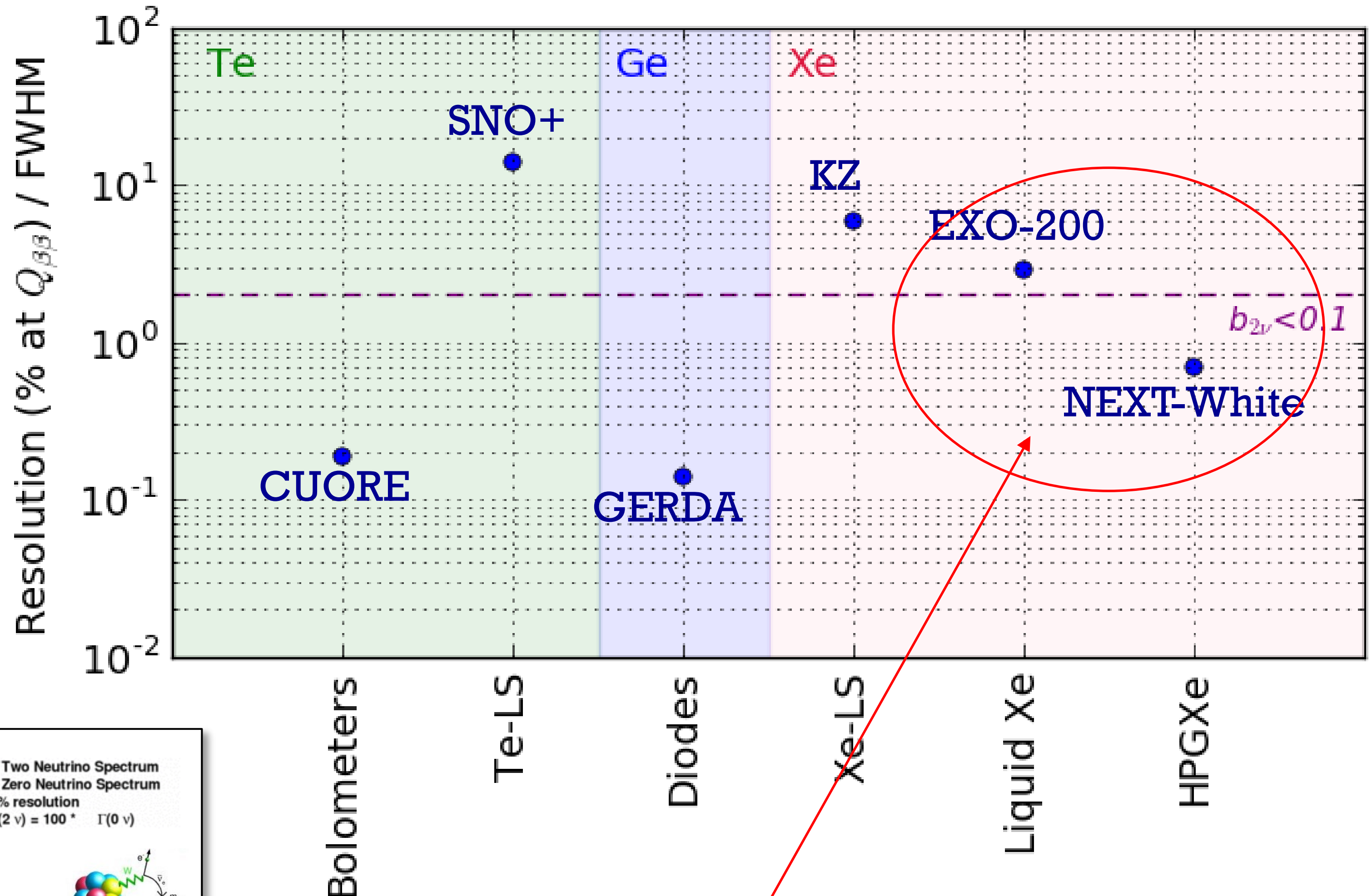
LEGEND200 backgrounds and energy resolutions:

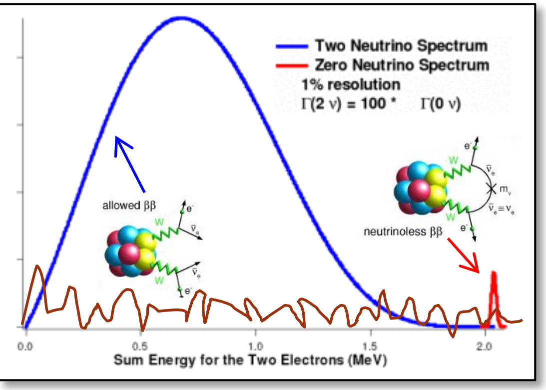


- 200kg, eventually 1000kg, of enriched ^{76}Ge crystals
- The king of excellent E resolution - *0.1%FWHM in the best crystals.*



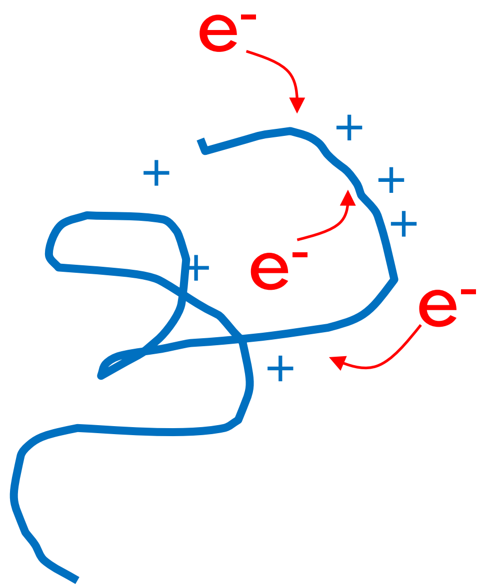
Measuring Energy





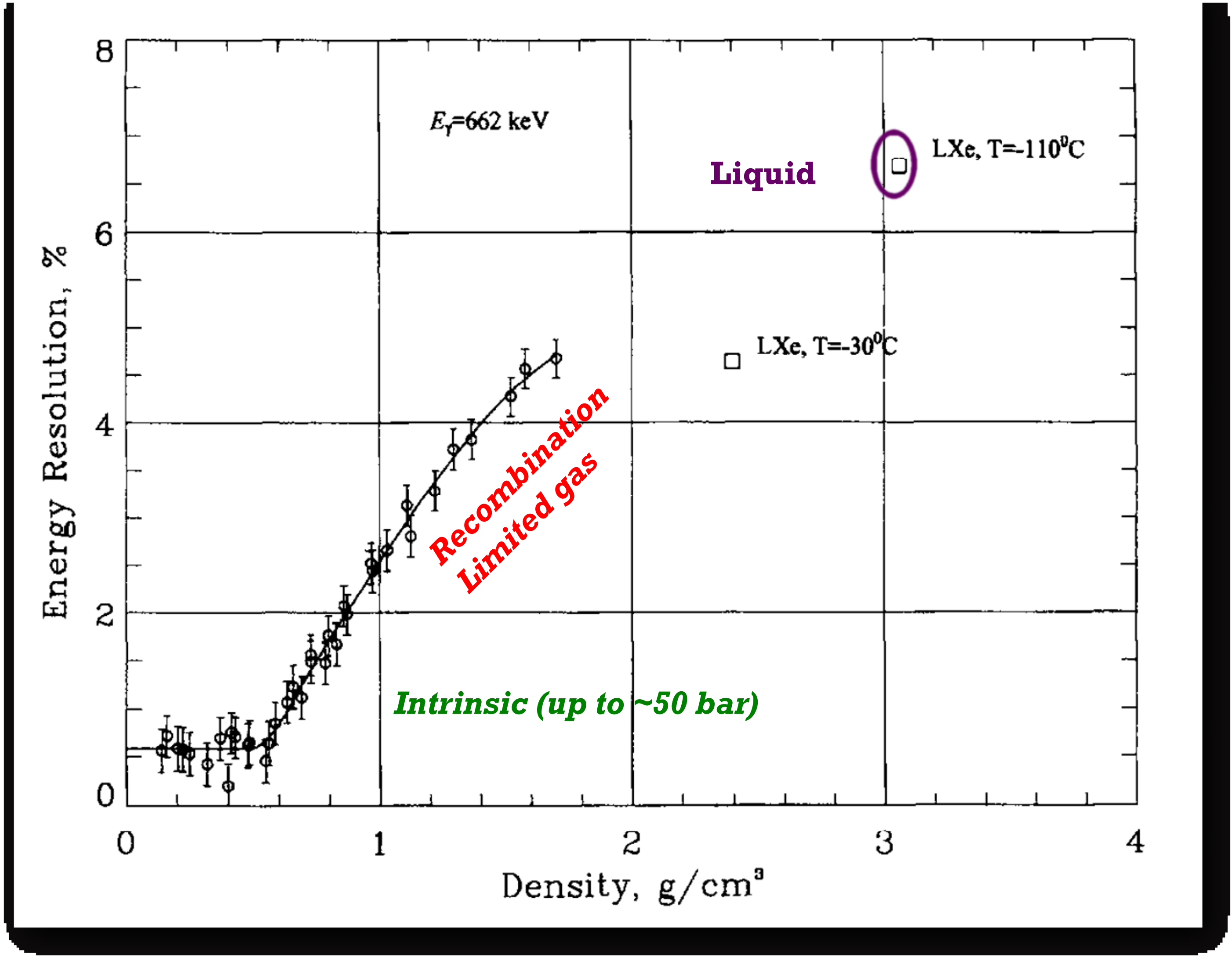
Xenon gas much better energy resolution than liquid Xe, why?

RECOMBINATION-LIMITED IONIZATION ENERGY RESOLUTION



Fluctuations in electron-ion recombination limit energy resolution for dense TPCs.

Every event is a random microscopic shape, so each loses different amounts of charge to recombination.



Where are the backgrounds from?

Radiogenics

Solar neutrinos(!)

Cosmogenics

These will limit all future experiments.

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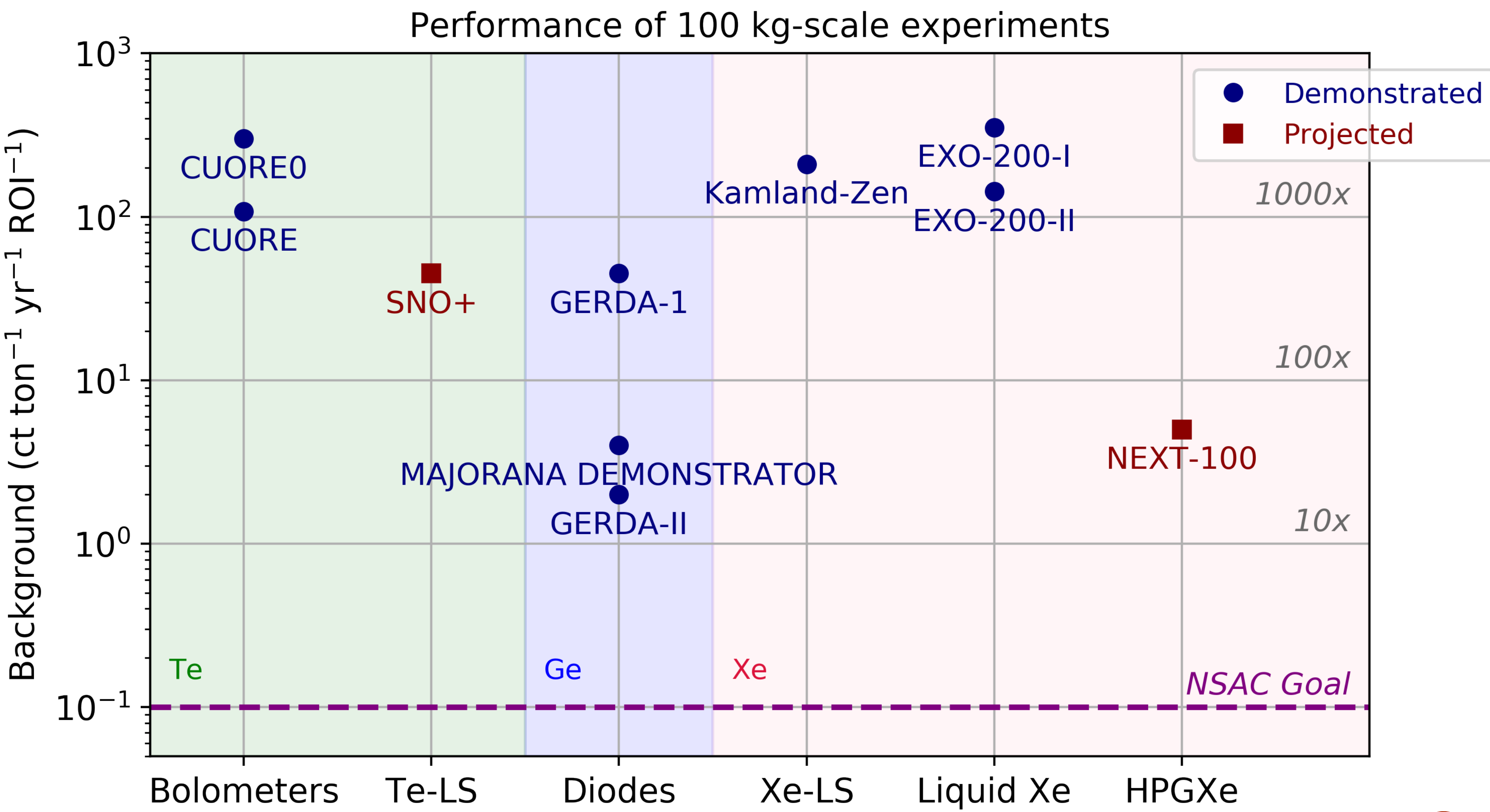
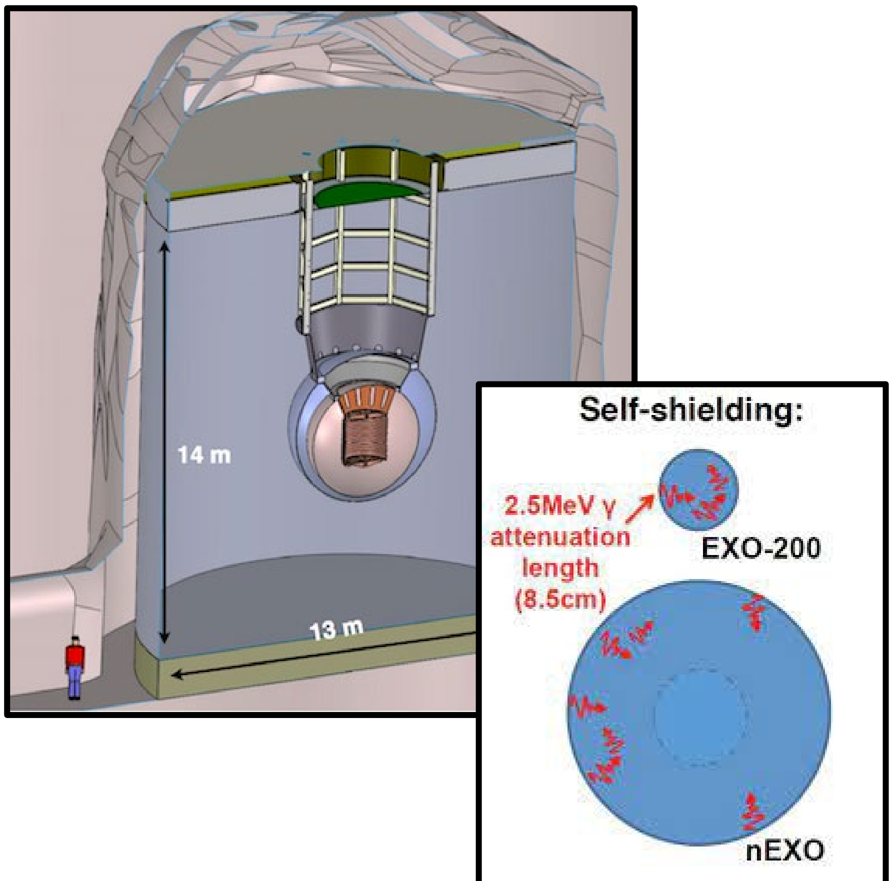
“100kg-class” experiments:



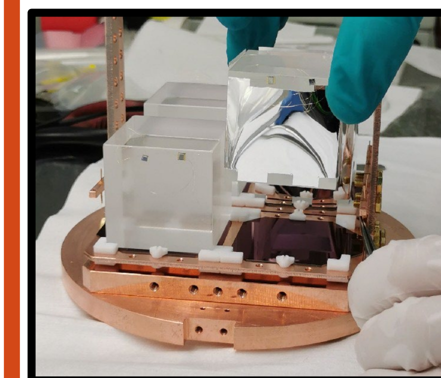
NEXO

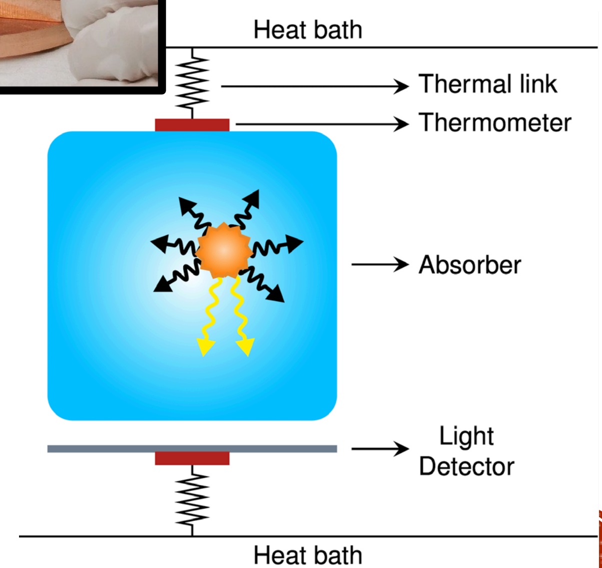
- Proposed ton-scale liquid xenon detector.
- Self-shielding of xenon from outer regions protects inner clean volume from backgrounds



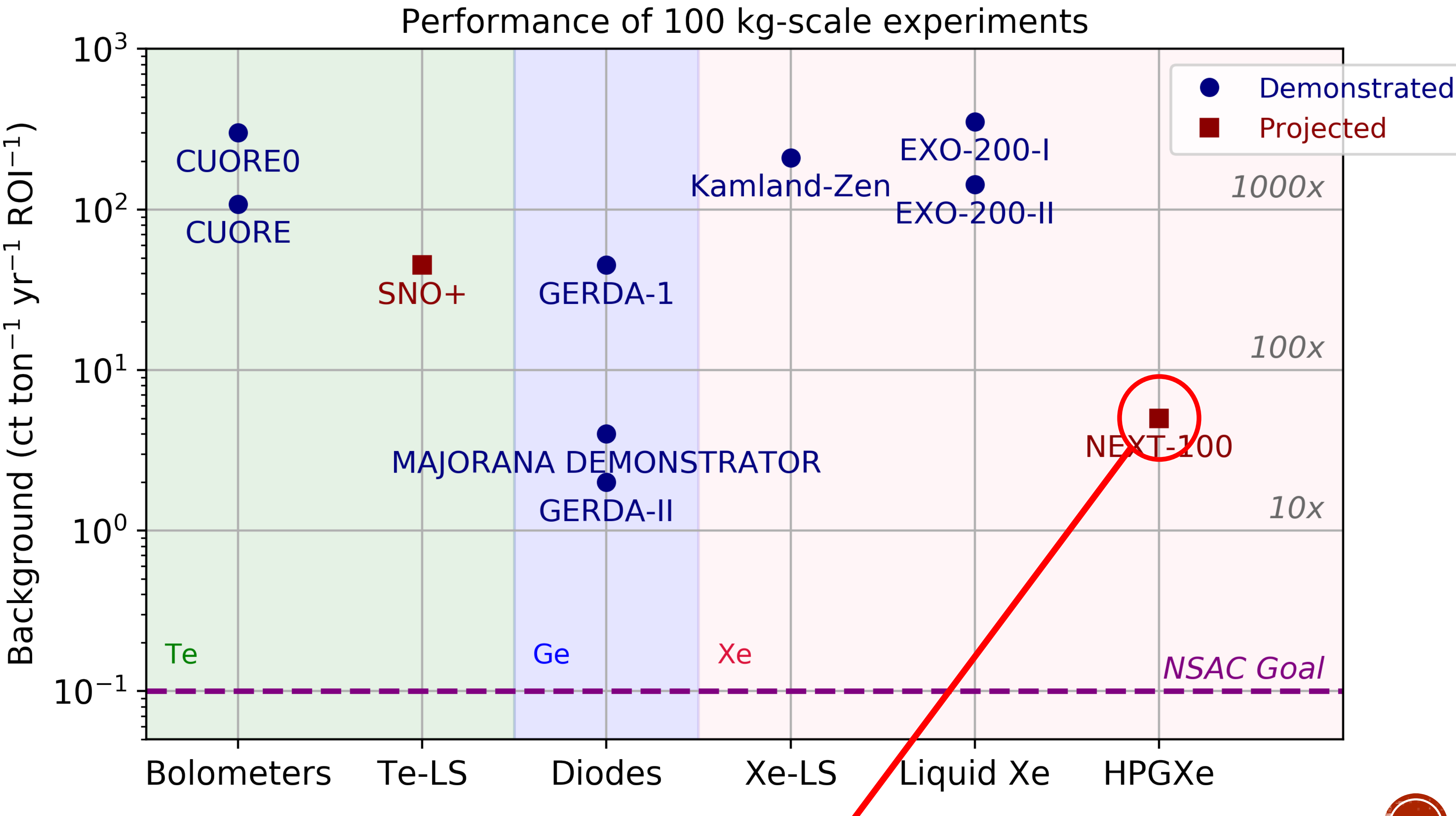
CUPID

- Cryogenic bolometers coupled to light sensors
- Precise calorimetry and optical handle on surface backgrounds advances on the CUORE approach.





"100kg-class" experiments:



I work on this one, so I'm going to tell you about it.

THE NEXT PROGRAM

- **Sequence of HPGXe TPCs, focused on achieving big, very low background xenon 0νββ detector**

→ NEXT-DBDM

(Berkeley, US)

→ NEXT-DEMO

(Valencia, Spain)

→ NEXT-White

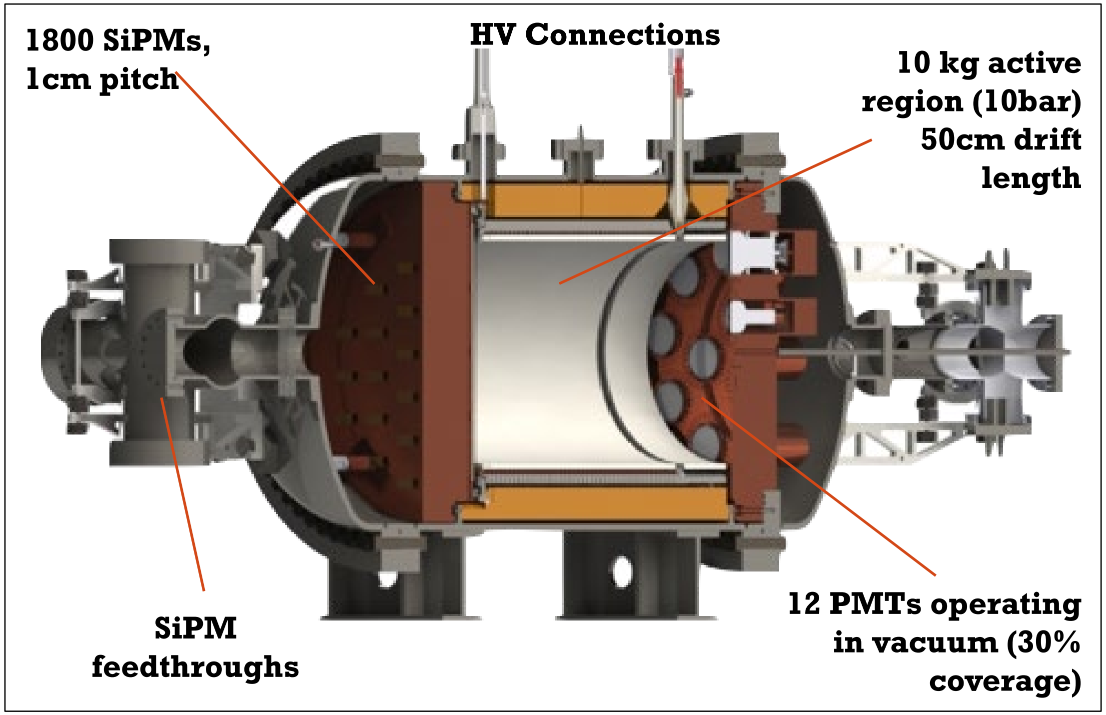
(Canfranc, Spain)

→ NEXT-100

(Canfranc, Spain)

R&D

→ N-Ton Scale

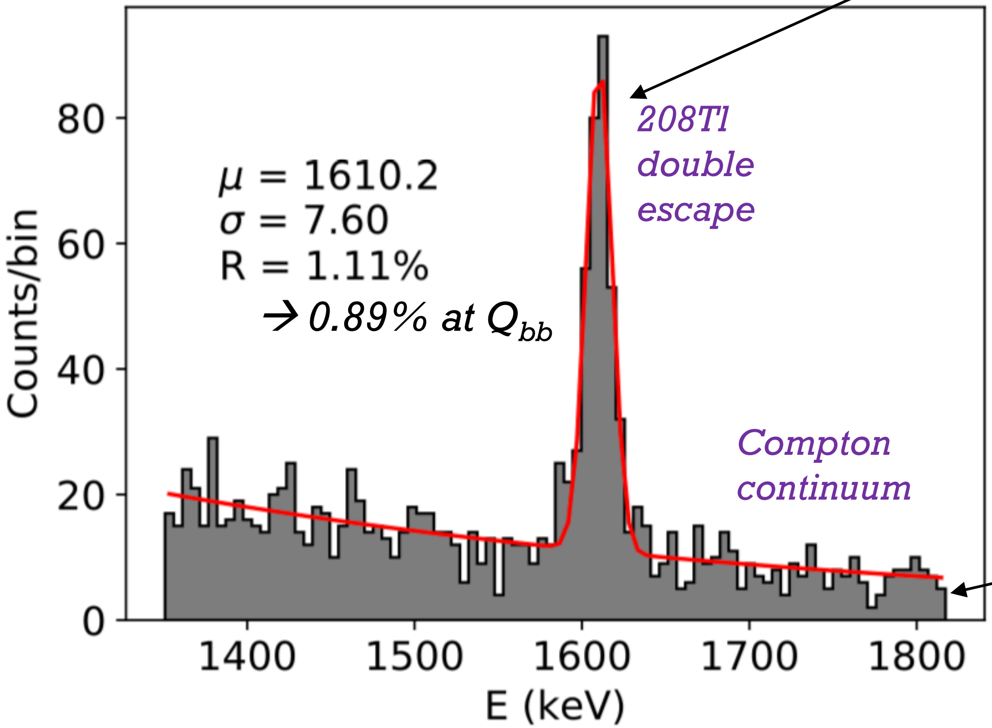


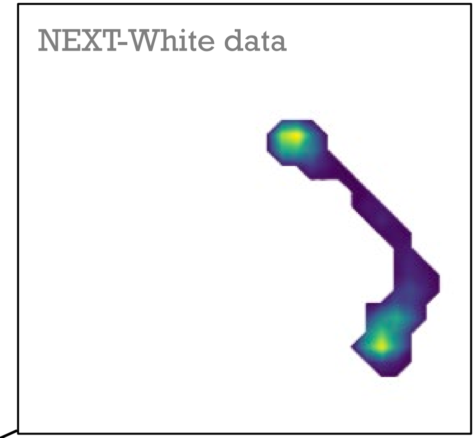
NEXT-White operating now
Full underground technology demonstrator @10kg scale

THE 208TL DOUBLE ESCAPE PEAK

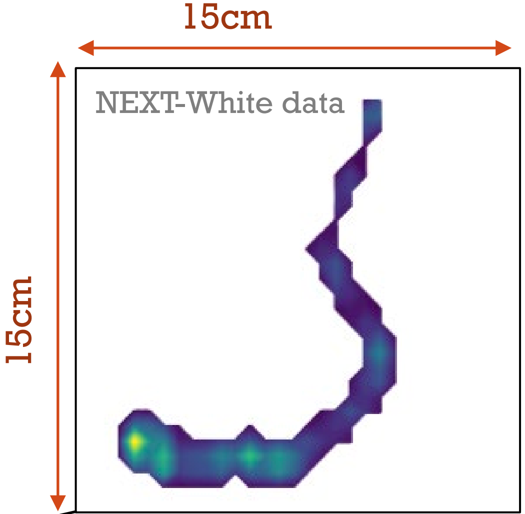
SM process that makes e+e- at a well-defined energy.

We get to see energy resolution and topology all in one plot!





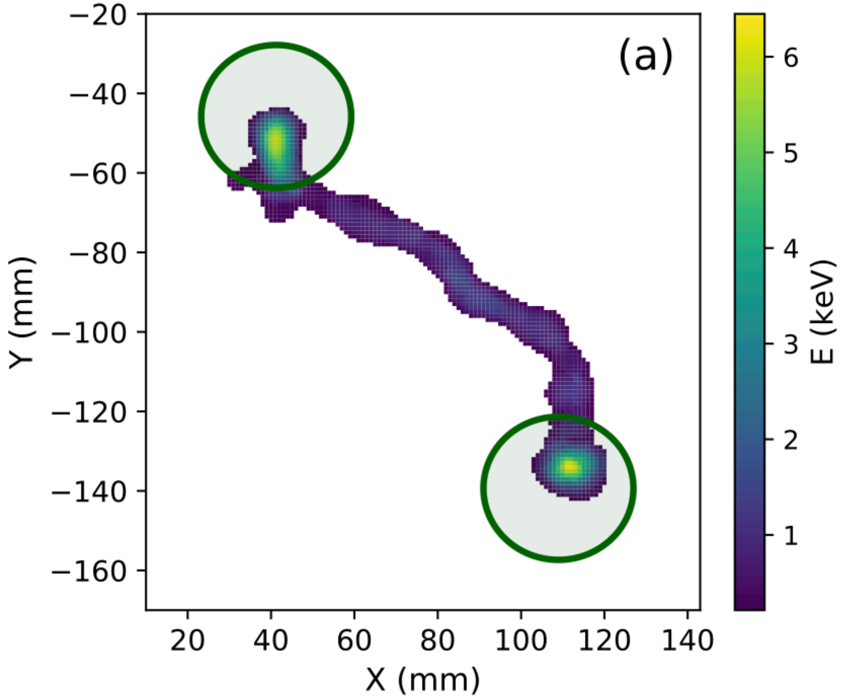
On double escape peak

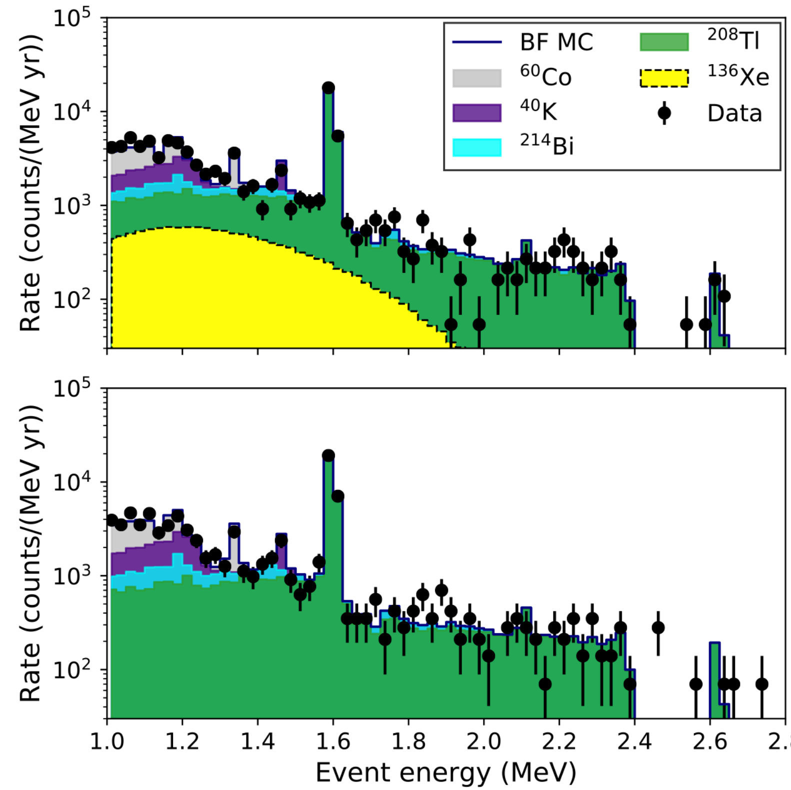


Off double escape peak

JHEP 2019, 52 (2019)

TWO-NEUTRINO DOUBLE BETA DECAY EVENTS





NEXT-White data

Topologically identified and away from double escape peaks

PHYSICAL REVIEW C

covering nuclear physics

Highlights Recent Accepted Collections Authors Referees Search Press About Editorial Team

Measurement of the ^{136}Xe two-neutrino double-β-decay half-life via direct background subtraction in NEXT

P. Novella *et al.* (NEXT Collaboration)

Phys. Rev. C **105**, 055501 – Published 10 May 2022

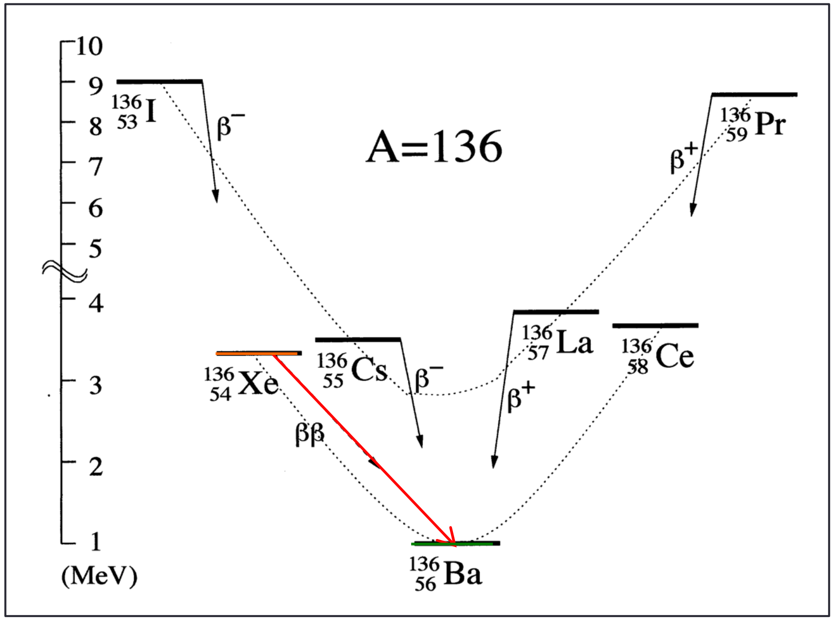
BARIUM TAGGING

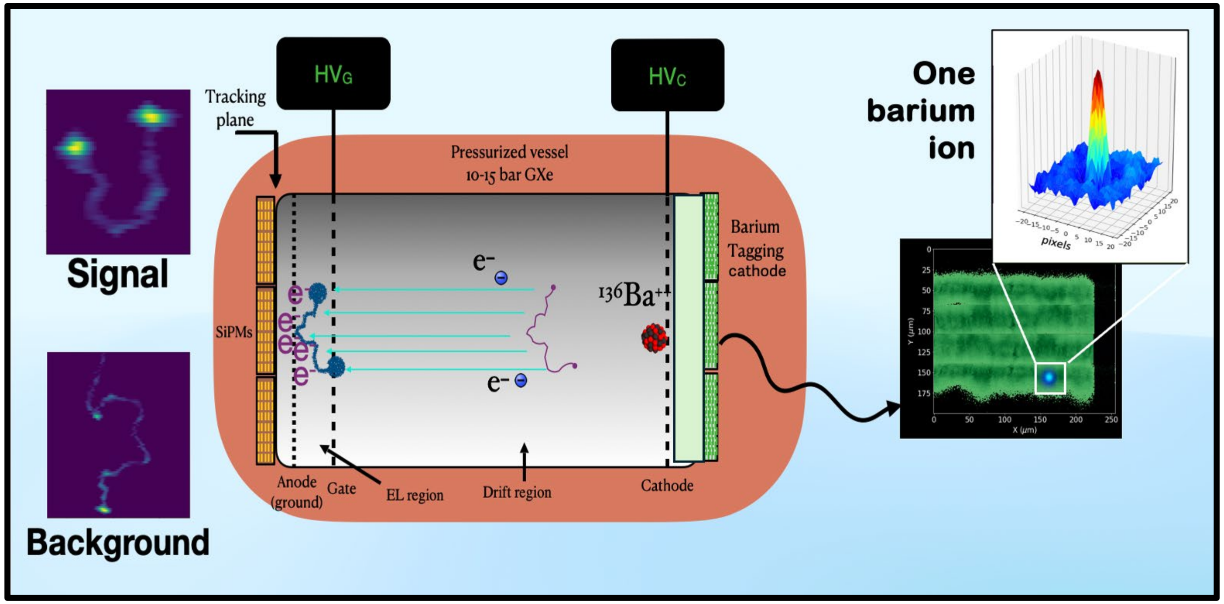
(My fave thing: forgive me for indulging ☺)

Barium ion is only produced in a true ββ decay, not in any other radioactive event→

Identification of Ba ion plus ~1% FWHM energy measurement would give a background-free experiment.

$^{136}Xe \rightarrow {}^{136}Ba + e + e$

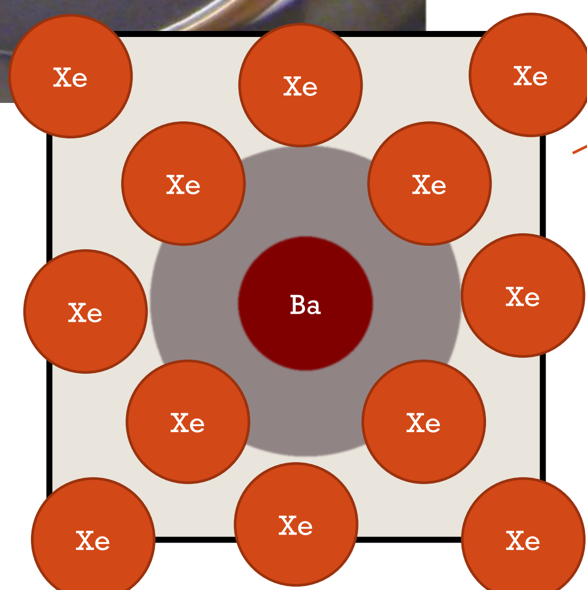




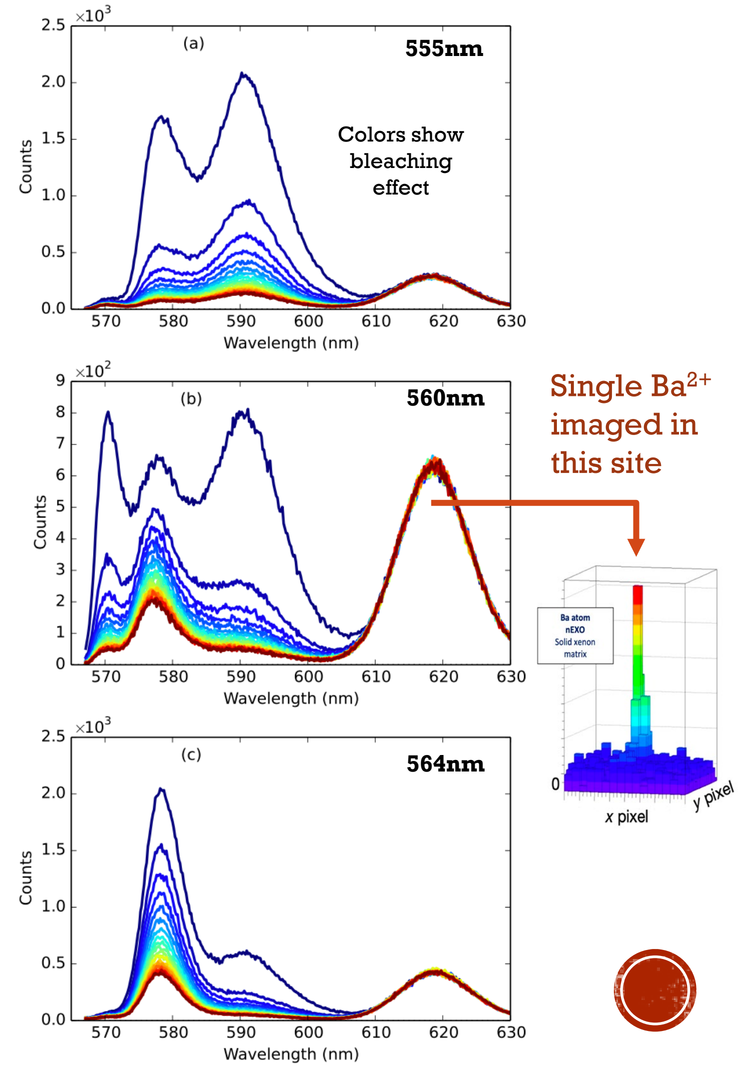
Is it plausible to detect an individual barium ion or atom in a ton of material, inside a working xenon TPC?

BA IMAGING IN XENON ICE

nEXO has developed methods of imaging Ba^{+} and Ba^{0} in carefully grown xenon ice.



Various types of defect sites



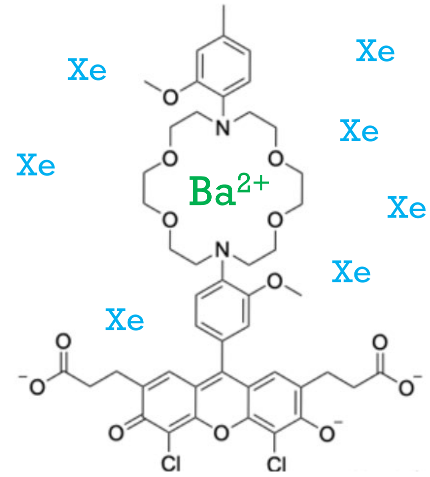
Single Ba^{2+} imaged in this site

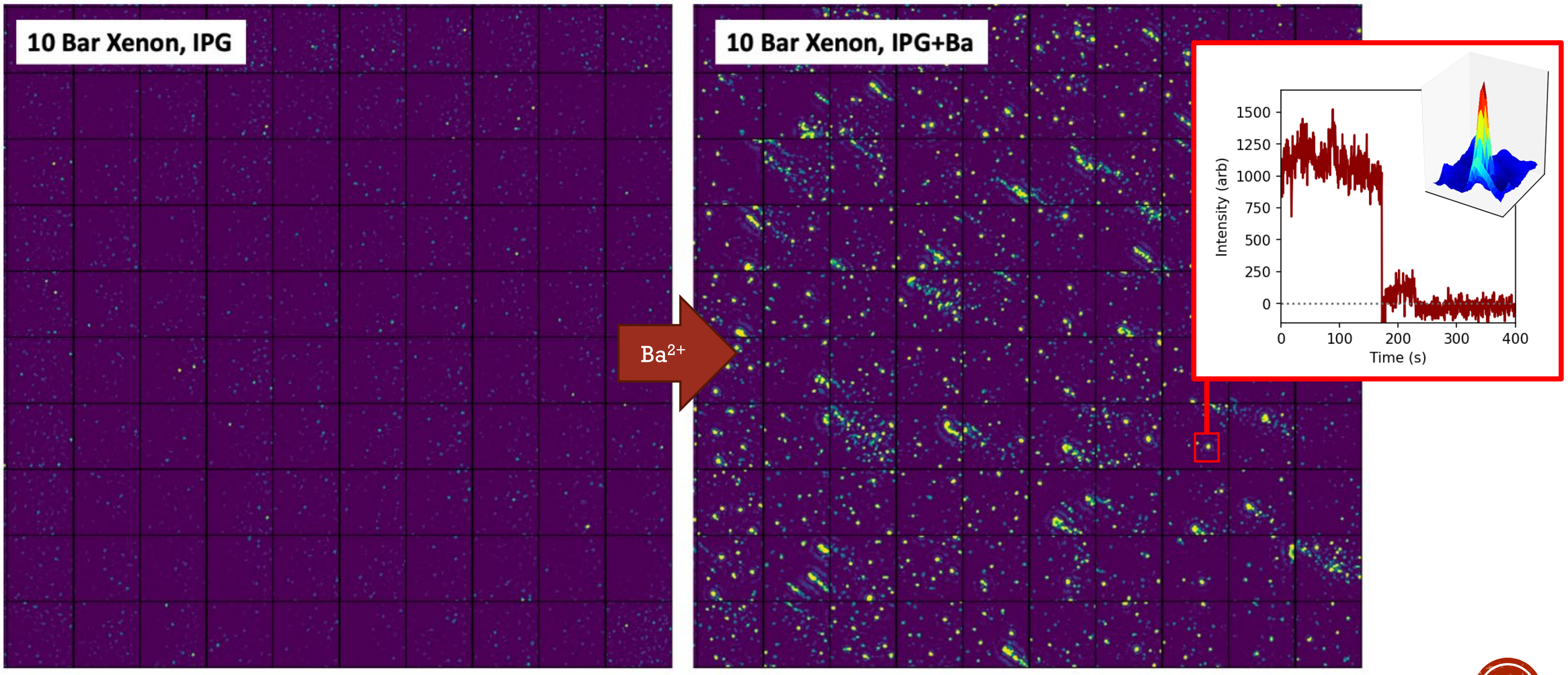
Individual Ba atoms imaged in frozen xenon matrices in vacuum

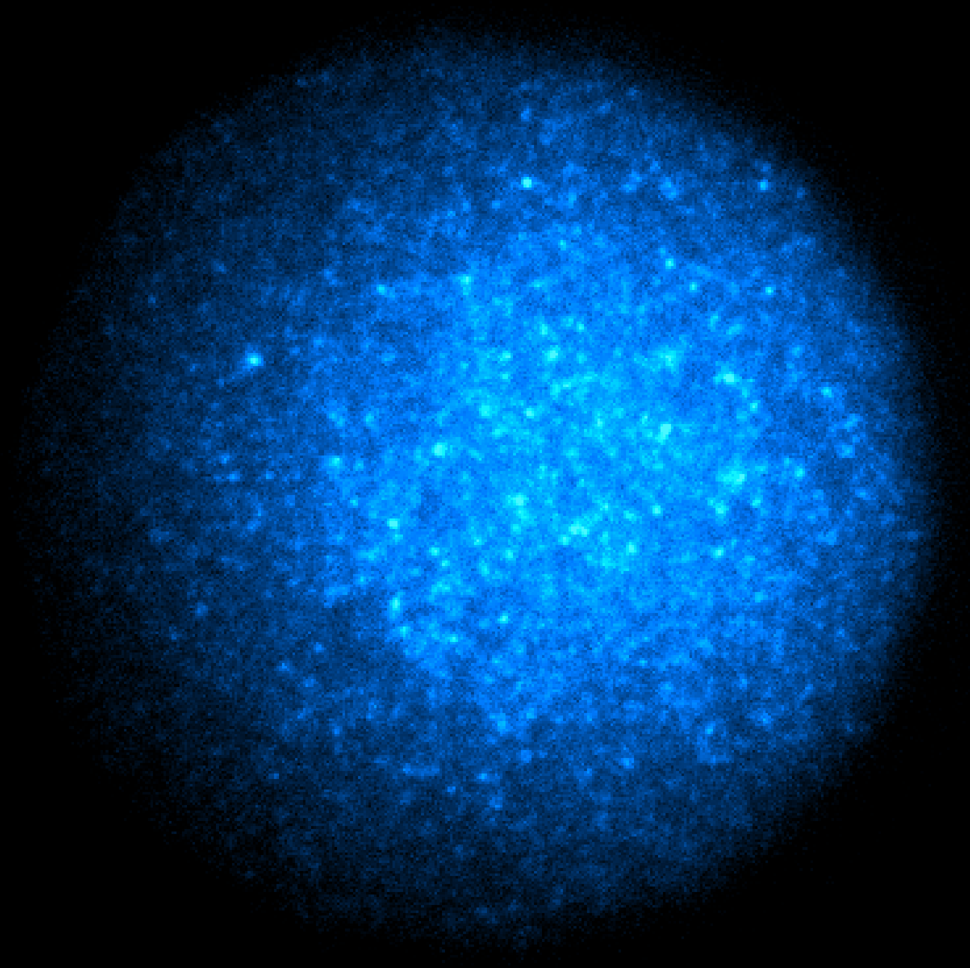
BA IMAGING IN XENON GAS

NEXT has built microscopy systems capable of imaging individual barium ions in high pressure xenon gas environments.

1mm x 1mm area can be scanned with single ion precision.

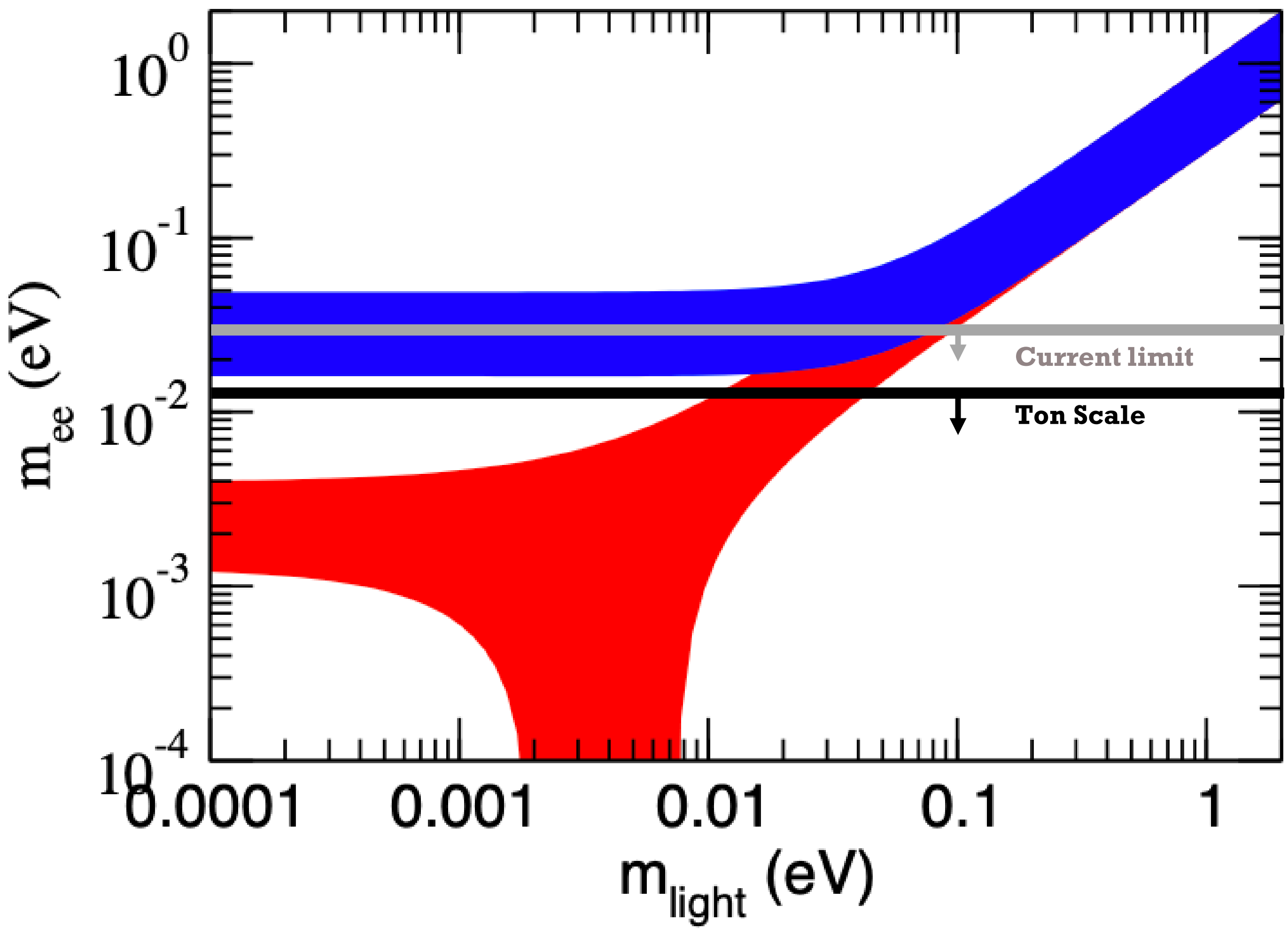






Single Ba^{2+} molecular complexes

THE TON SCALE

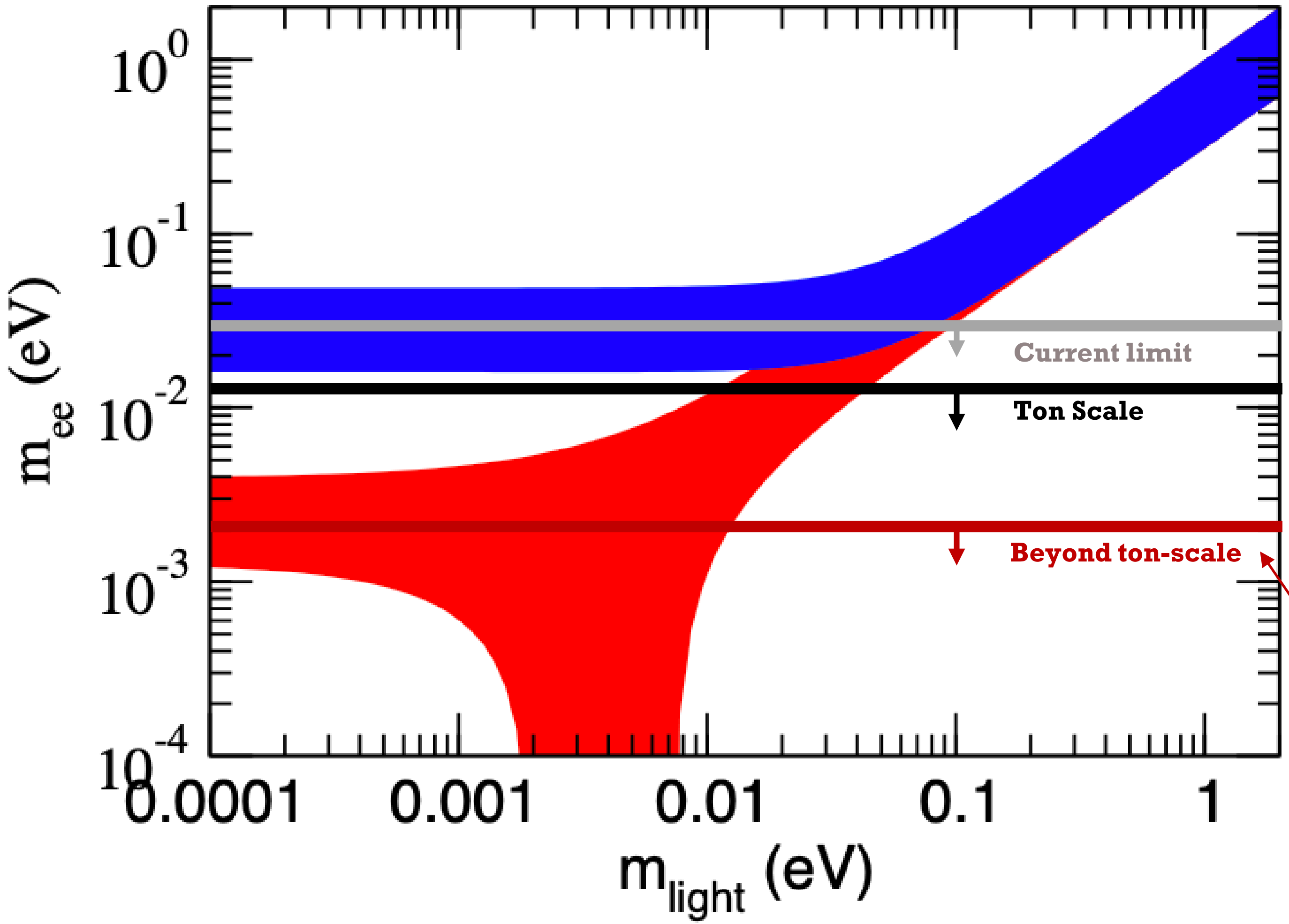


We need to do this with multiple isotopes and techniques

1016.05 kg | 1000.00 kg | 907.19 kg

NB: if you use these tons, the sensitivity will be better.

TOWARD NORMAL ORDERING



Can we ever do this?

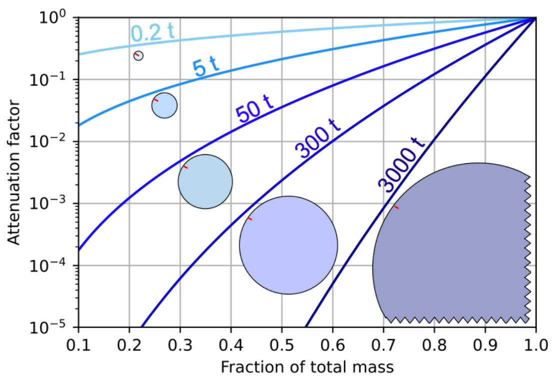
ISOTOPES

- Will need hundreds of tons of isotope. Current industrial production of any species is insufficient.
- There are difficulties with both **acquisition** of raw material and its **enrichment**.
- Some notable factoids:
  - **Tellurium:**
    Comes naturally enriched to 34%. So natural tellurium is the most viable for an unenriched experiment.
  - **Molybdenum:**
    New capacity for enrichment of Molybdenum in 100Mo for nuclear medicine is needed. 0nubb may be parasitic?
  - **Germanium:**
    Semiconductor industry enriches germanium already; 76Ge can in principle be extracted as byproduct?
  - **Xenon:**
    Atmospheric carbon capture technology based on metal organic frameworks has plausible extendibility to capture atmospheric Xe. Free from steel industry capacity limit?
- **Both enrichment R&D and new major facilities would be needed to produce isotope at the scale needed for a normal-ordering scale experiment.**

GIANT TPCS

Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches

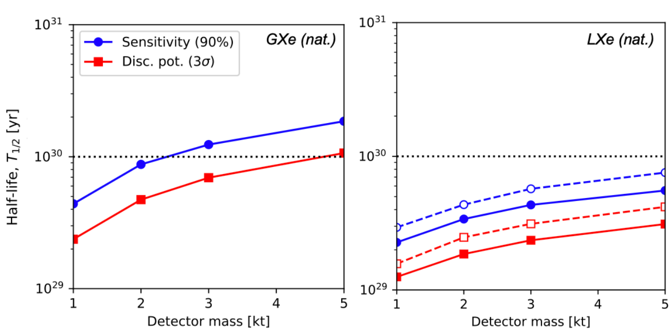
A. Avasthi,[1] T.W. Bowyer,[2] C. Bray,[3] T. Brunner,[4,5] N. Catarineu,[6] E. Church,[2] R. Guenette,[7] S.J. Haselschwardt,[8] J.C. Hayes,[2] M. Heffner,[6,*] S.A. Hertel,[9] P.H. Humble,[2] A. Jamil,[10] S.H. Kim,[6] R.F. Lang,[11] K.G. Leach,[3] B.G. Lenardo,[12] W.H. Lippincott,[13] A. Marino,[3] D.N. McKinsey,[14,8] E.H. Miller,[15,16] D.C. Moore,[10,†] B. Mong,[15] B. Monreal,[1] M.E. Monzani,[15,16] I. Olcina,[8,14] J.L. Orrell,[2] S. Pang,[6] A. Pocar,[9] P.C. Rowson,[15] R. Saldanha,[2] S. Sangiorgio,[6] C. Stanford,[7] and A. Visser[6]



← Radiogenics become totally irrelevant due to self shielding

Cosmogenics and solar neutrinos become a serious concern!

If energy resolution achievable at scale, with kiloton masses, normal ordering parameter space is accessible.



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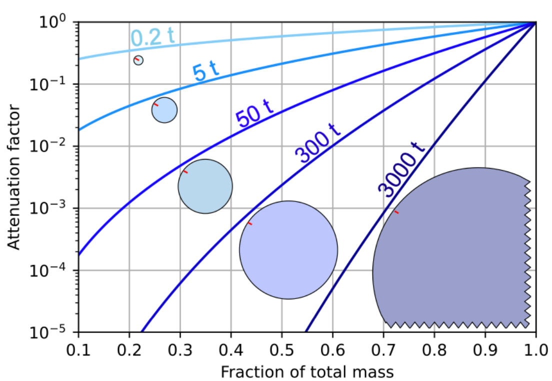

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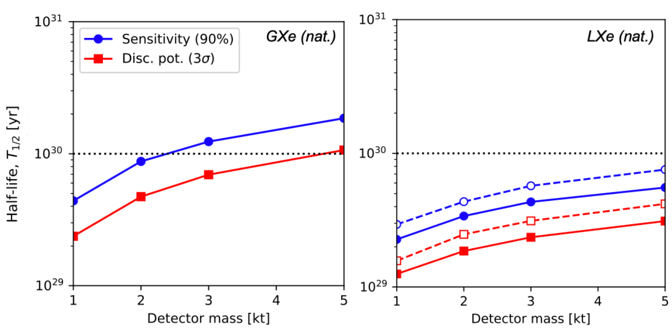
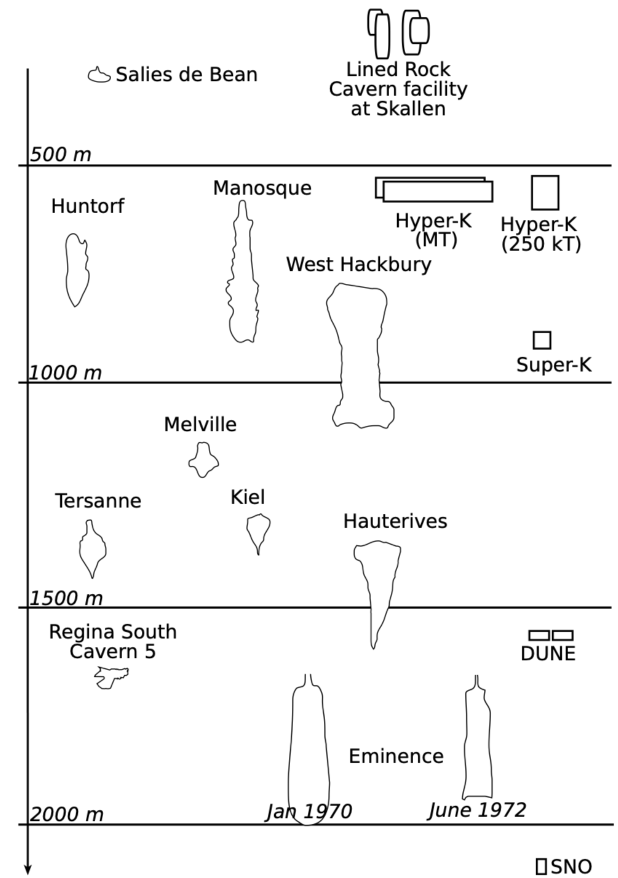


...in salt caverns?



High-pressure TPCs in pressurized caverns: opportunities in dark matter and neutrino physics

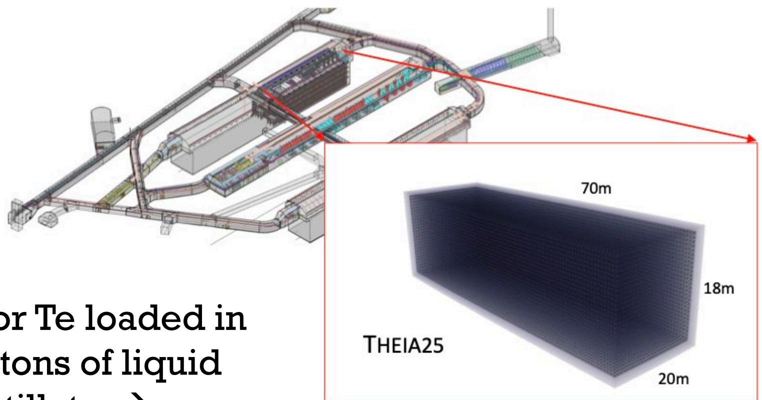
Author:
Benjamin Monreal (Case Western Reserve U.) [benjamin.monreal@case.edu]

ISOTOPE IN KTONS OF LIQUID SCINTILLATOR…

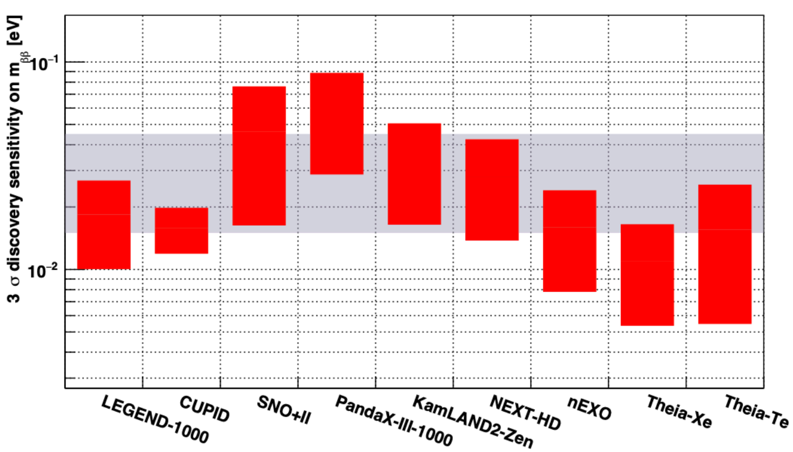
THEIA: Summary of physics program

Snowmass White Paper Submission

M. Askins,[1,2] Z. Bagdasarian,[1,2] N. Barros,[3,4,5] E.W. Beier,[3] A. Bernstein,[6] M. Böhles,[7] E. Blucher,[8]



Xe or Te loaded in kilotons of liquid scintillator→



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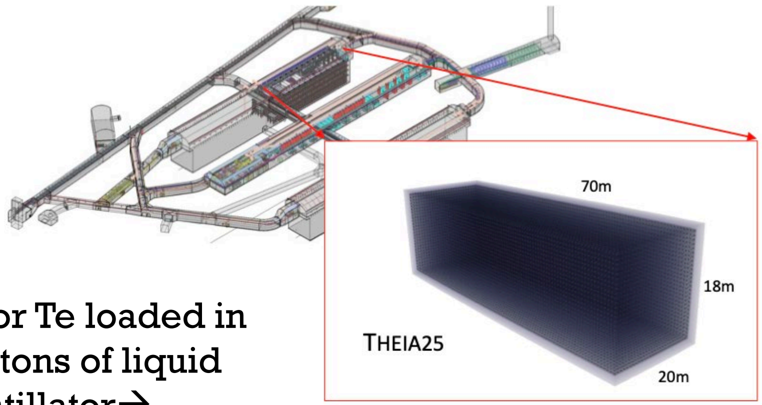

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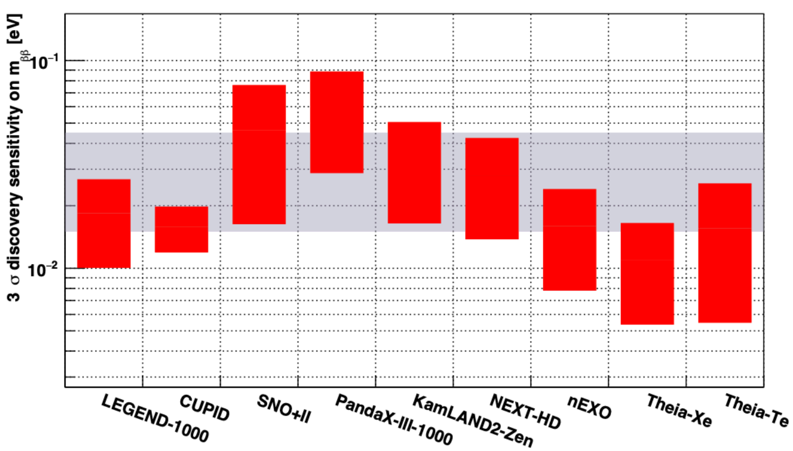
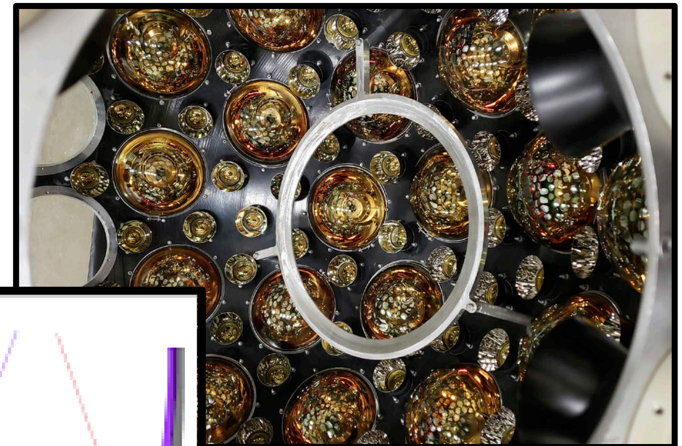
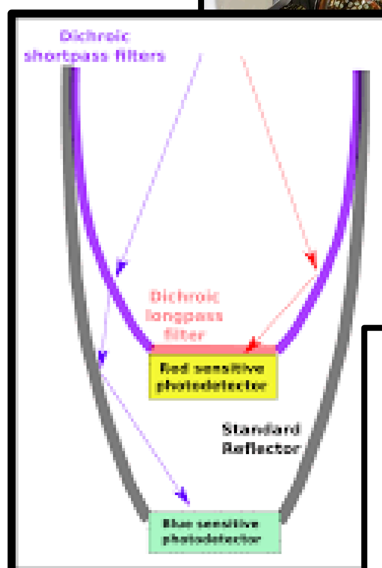


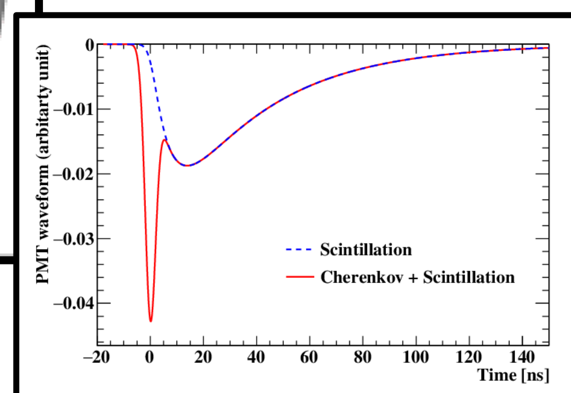
Much, much R&D…



Quantum dot doped liquid scintillator @NuDot



Dichroicon



Slow scintillator for Cerenkov separation

ISOTOPE IN KTONS LS, OR IN LIQUID ARGON?

Theia: Summary of physics program

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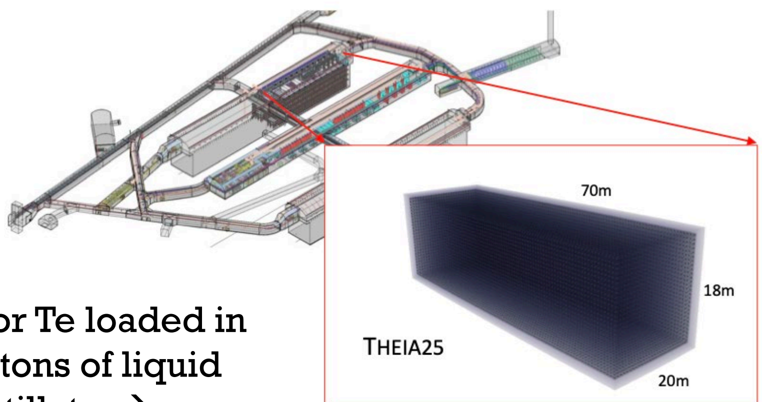
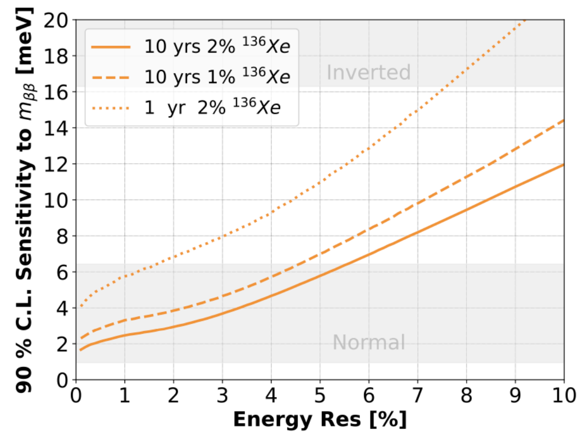
Xenon-Doped Liquid Argon TPCs as a Neutrinoless Double Beta Decay Platform

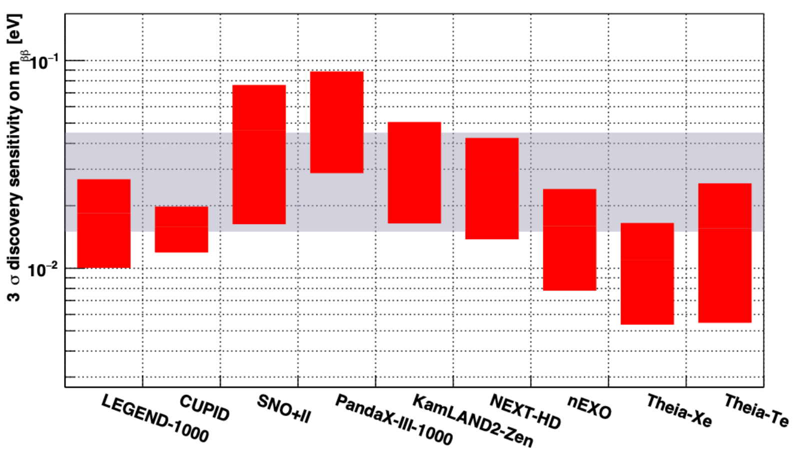
A. Mastbaum,[1] F. Psihas,[2] and J. Zennamo[2]
[1] Rutgers University, Piscataway, NJ, 08854, USA
[2] Fermi National Accelerator Laboratory (FNAL), Batavia, IL 60510, USA
(Dated: March 29, 2022)



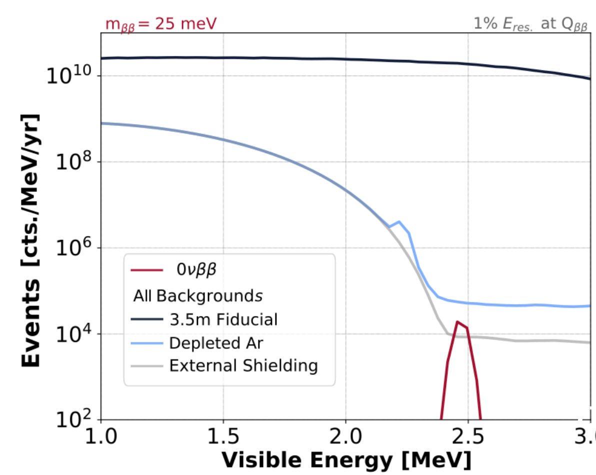
Xe or Te loaded in kilotons of liquid scintillator→



← Achieving this energy resolution in DUNE is an extreme challenge.



Argon also needs to be depleted to remove background from 42Ar →



CONCLUSIONS

- NDBD is the only sensitive known way to probe the Majorana nature of the neutrino.
- Experiments at the 100kg scale have demonstrated background indices in the range 2-200 ct/ton/ky/yr
- Ton-scale experiments plan to reduce backgrounds by 1.5-3 orders of magnitude relative 100kg phases and probe the inverted mass ordering range of parameter space.
- Beyond-ton-scale will require huge, ultra-low background detectors that we don't yet know how to build, but need to figure out!