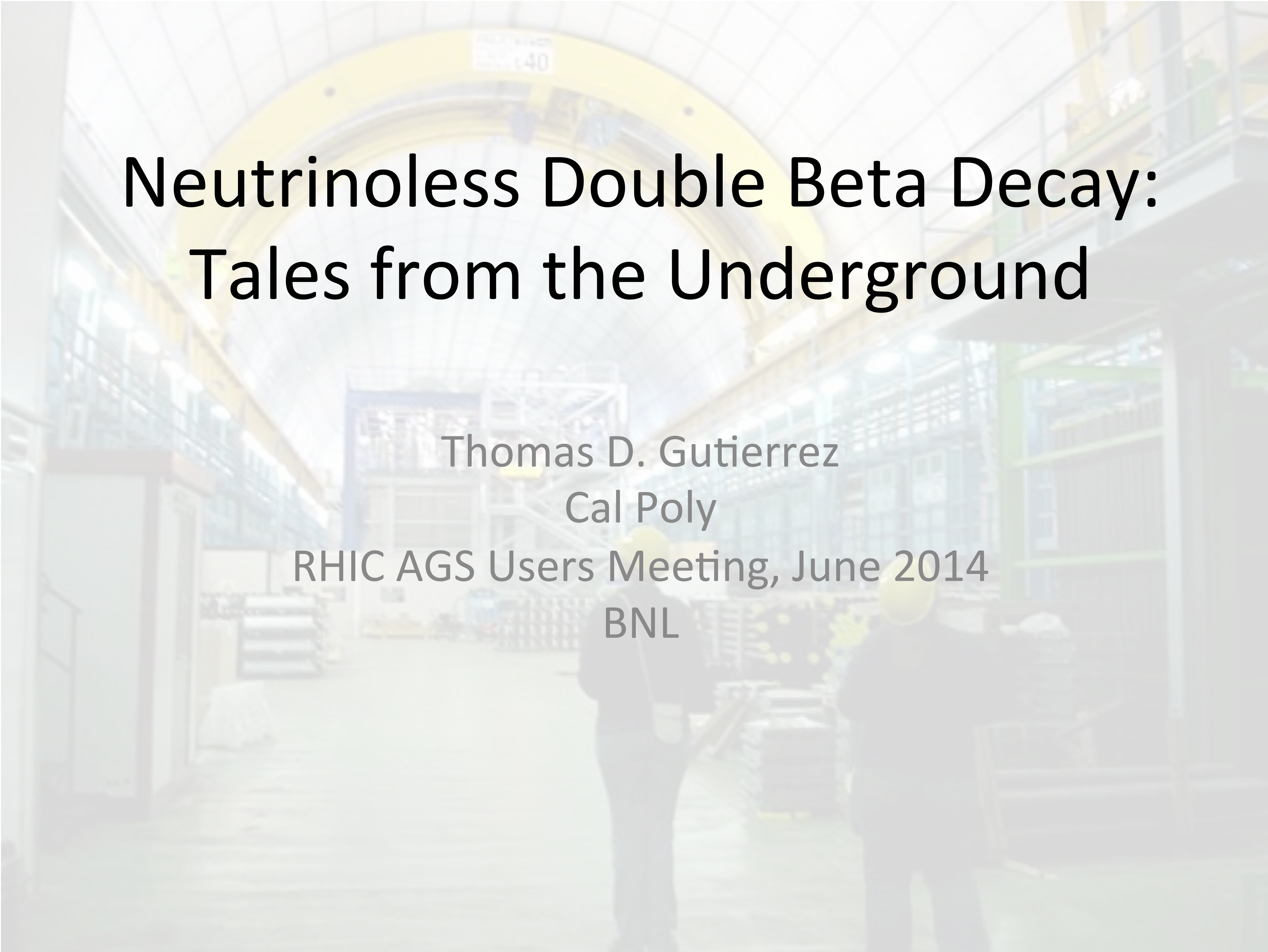

Neutrinoless Double Beta Decay: Tales from the Underground

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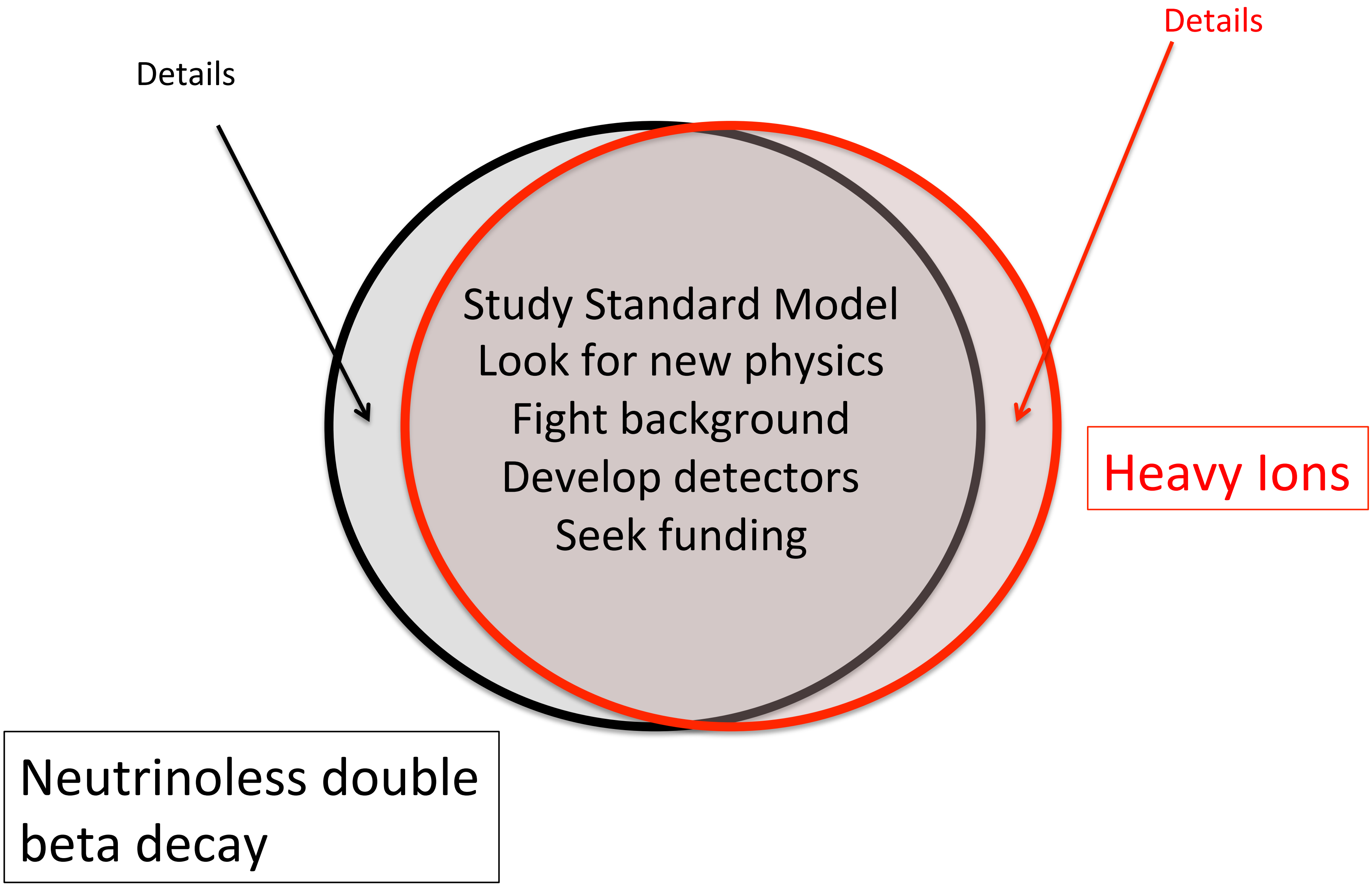
Cal Poly
RHIC AGS Users Meeting, June 2014
BNL

And now…
for something completely different

- Our fields are superficially different, hopefully stimulate discussions
- Neutrinos have (small) mass!
- What is the mass?
- Why is it small?
- What interactions generate its mass?
- Is the neutrino its own antiparticle?
- How to measure?
- Why do we care?


Details
Details
Study Standard Model
Look for new physics
Fight background
Develop detectors
Seek funding
Heavy Ions
Neutrinoless double beta decay

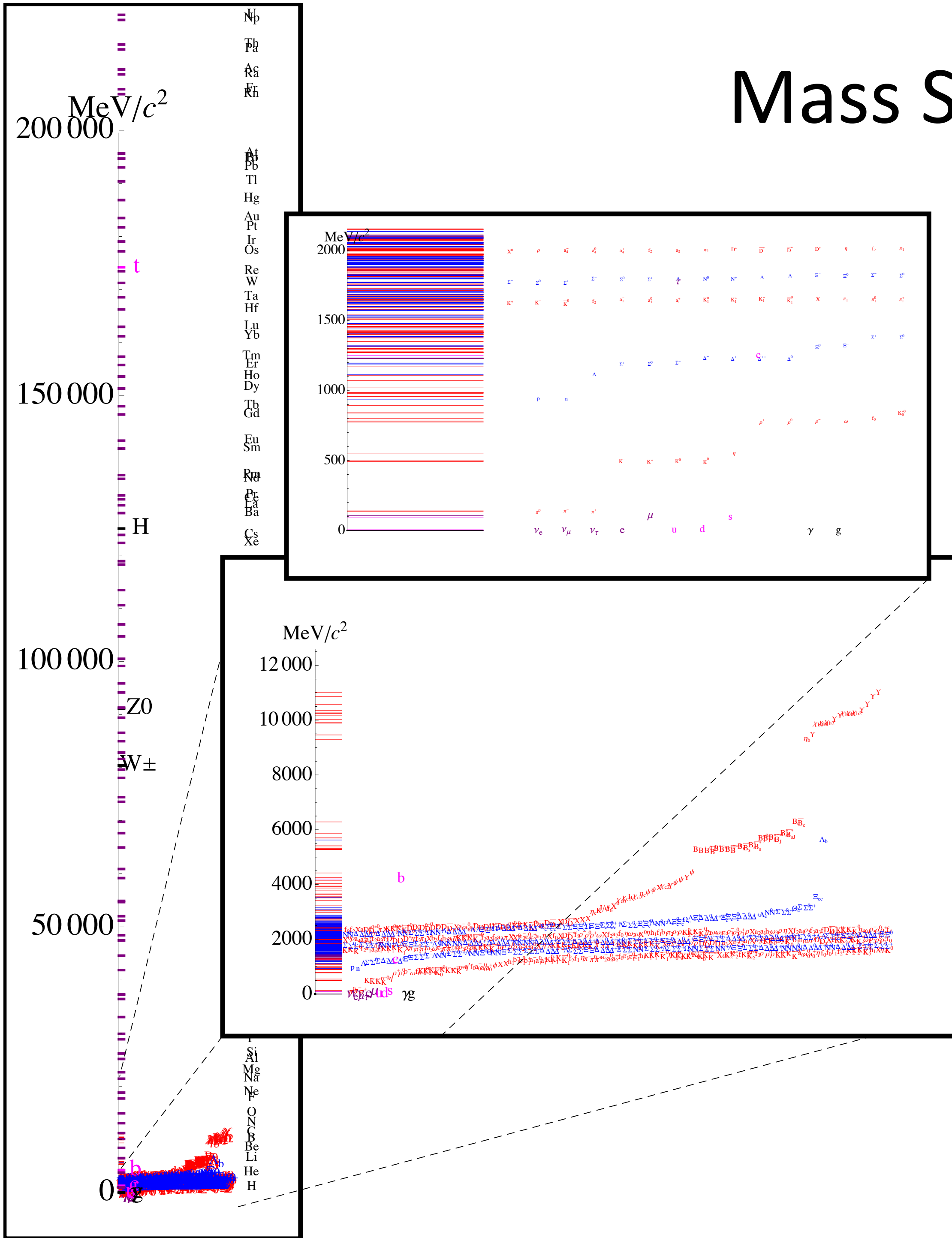
Standard Model Lagrangian: State of Our Vacuum, Our current business model

18 free parameters, 61 <u>fundamental</u> particles

Paragon of human ingenuity; Not very pretty; Still many puzzles and enigmas

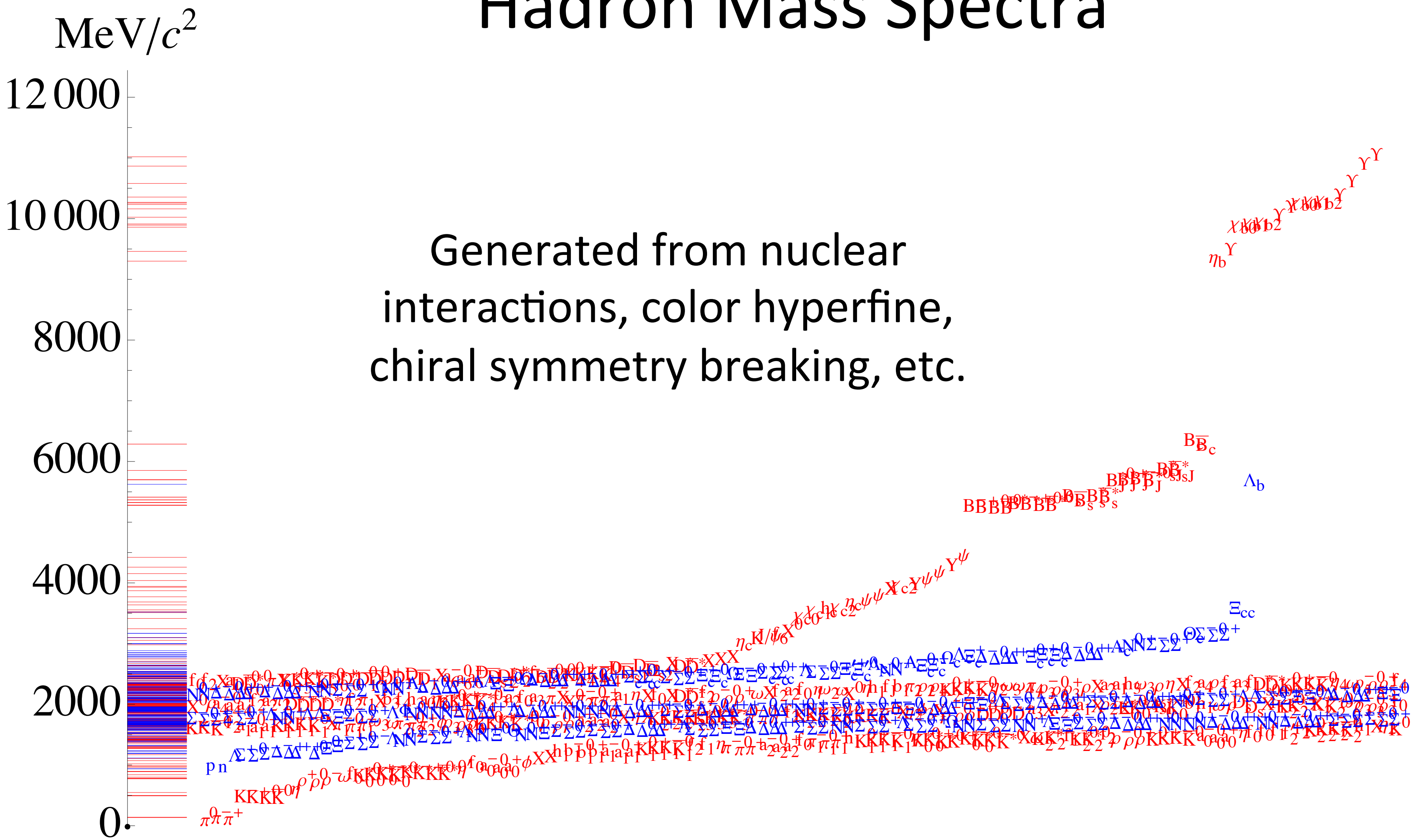
$$
\begin{aligned}
\mathcal{L}_{\rm SM} = {} & \frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \\
& \bar{G}^a\partial^2 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\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \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^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_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^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^5 e^\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^5 u^\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^2 Y + 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^-) +
\end{aligned}
$$

Mass Spectra



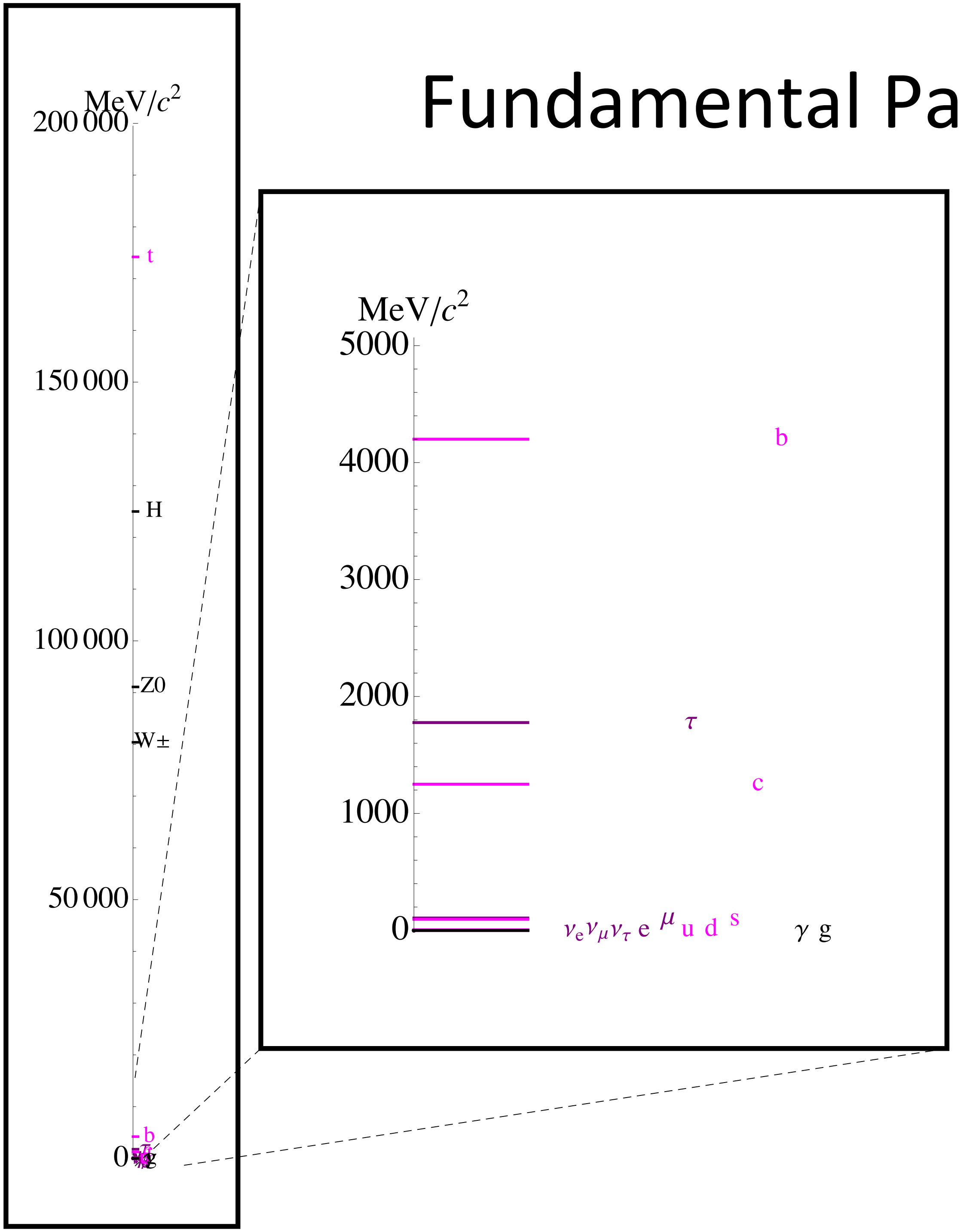
Mass is a measure of the energy content of a system; arises from interactions

Hadron Mass Spectra



Generated from nuclear interactions, color hyperfine, chiral symmetry breaking, etc.

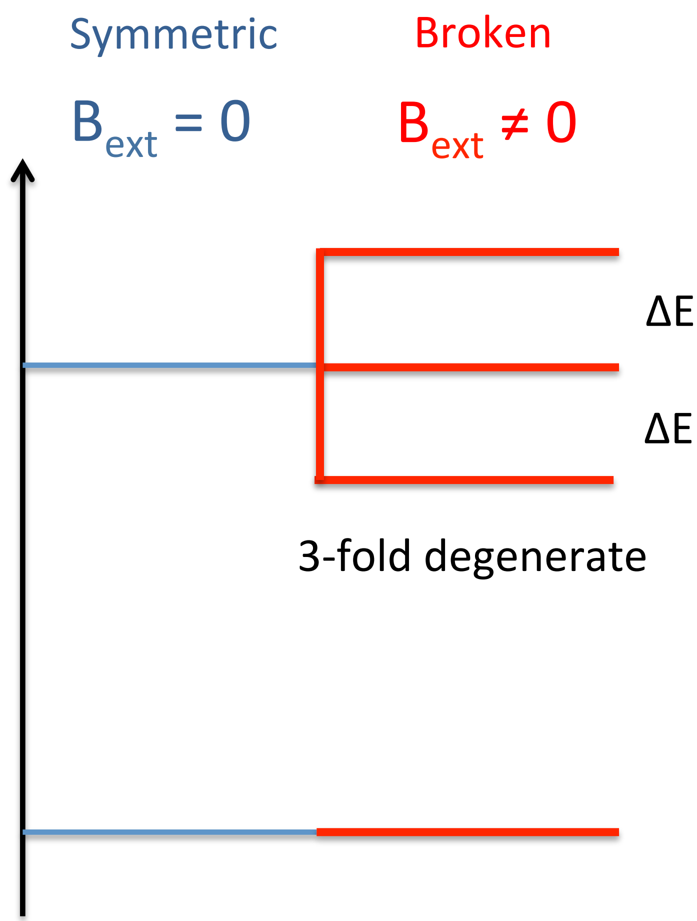
Fundamental Particle Spectra



Mass generated by
coupling to
Higgs vacuum
expectation value

$$\langle \Phi \rangle = 246\ \text{GeV}$$

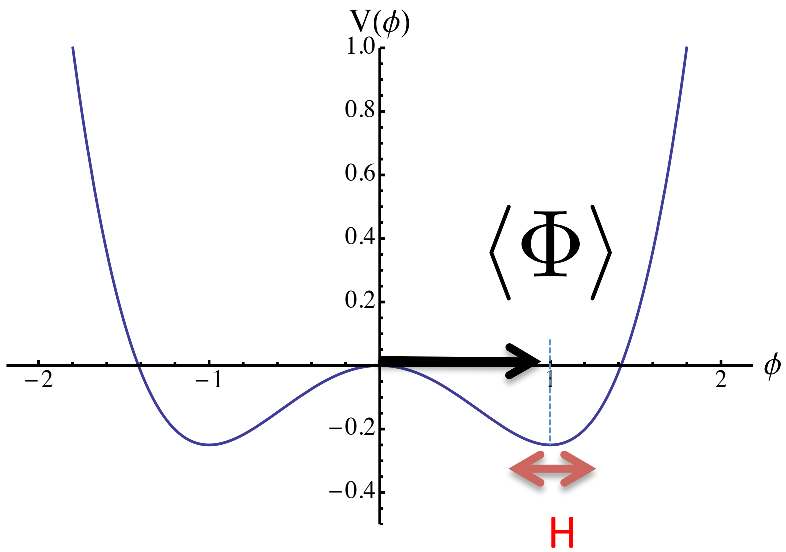
How Fields Impart Mass



- Case Study: Zeeman splitting
  - External (non spontaneous) field breaks internal degeneracy
  - Literally changes mass of affected states
  - Details of splitting contained in the physics of the coupling

$$\Delta E = -\vec{\mu} \cdot \vec{B}_{\text{ext}} = \frac{e\hbar}{2m_e} m_l B_z$$

Mass Generation



$$M \propto G\langle \Phi \rangle$$

$$\Delta E = -\vec{\mu} \cdot \vec{B}_{\text{ext}}$$

$$\langle \Phi \rangle = 246 \text{ GeV}$$

Your Recently Acquired Vacuum State!

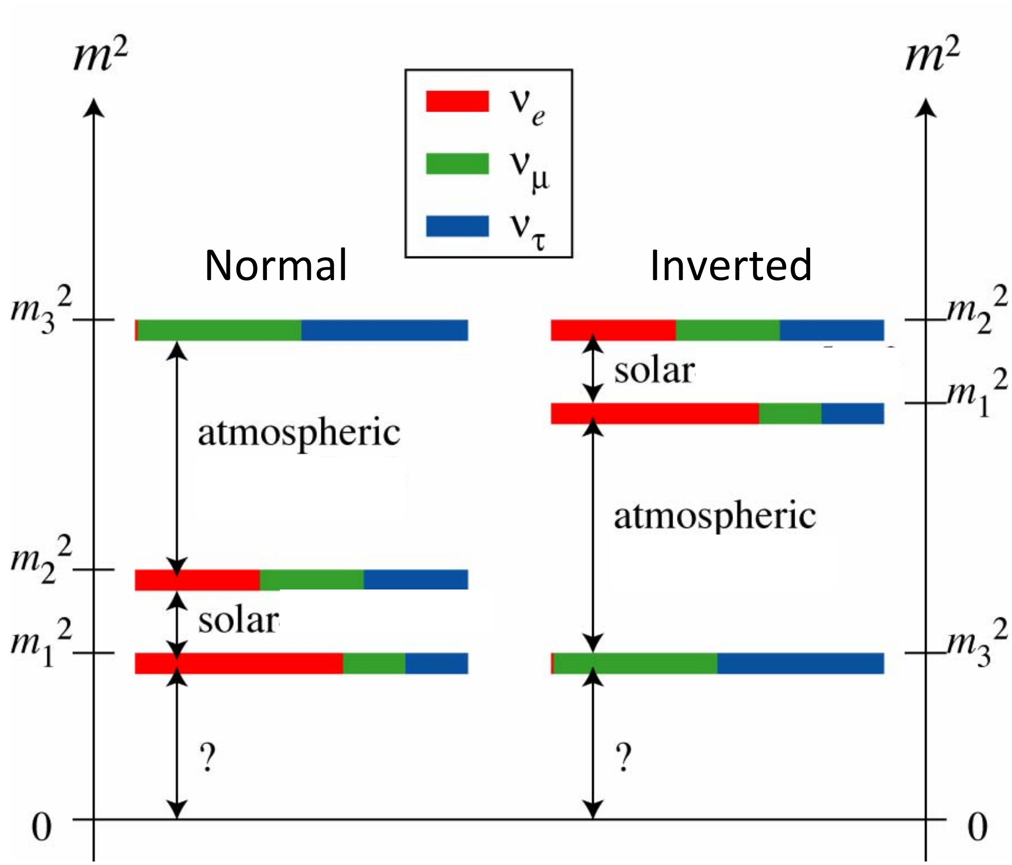
Each individual particle couples to the Higgs vacuum expectation value via unknown physics buried in G that gives the specific masses we observe

Neutrino Oscillations

- Neutrinos have mass
- Quantum mechanically coherent over astrophysical spacetime scales!
- Mass-flavor mixing: PMNS (similar to CKM in quark sector)

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$\begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ -c_{23}s_{12}s_{13}e^{i\delta} - s_{12}s_{23} & -c_{23}s_{12}s_{13}e^{i\delta} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\phi_2}{2}} & 0 \\ 0 & 0 & e^{i\frac{\phi_3}{2}} \end{pmatrix}$$



Flavor (weak) eigenstate

$$|\nu_e\rangle = a|\nu_1\rangle + b|\nu_2\rangle + c|\nu_3\rangle$$

Mass eigenstates; known time phasors
Individually stationary probability (QM)

$$\langle \nu_\mu(t)|\nu_e(0)\rangle \neq 0$$

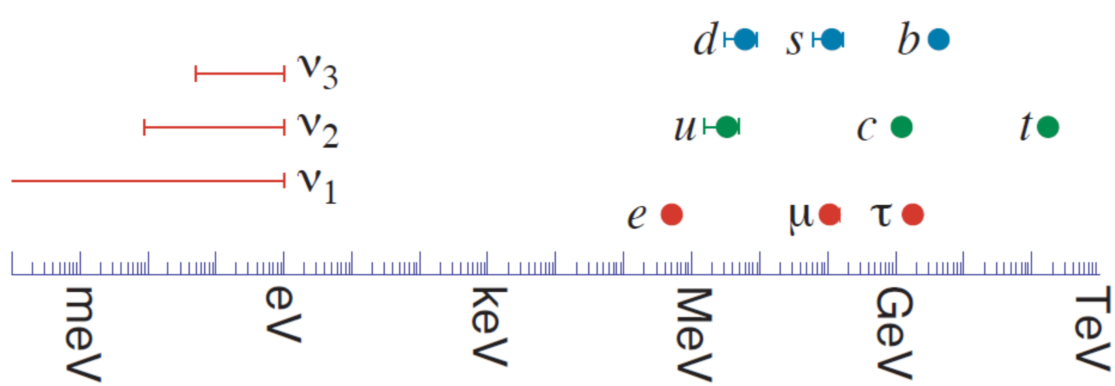
$$\Delta m^2_{\rm sol} = m_2^2 - m_1^2 \sim 7.54 \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{\rm atm} \sim 2.43 \times 10^{-3}\ \mathrm{eV}^2$$

$$\omega \propto \Delta(m^2)$$

Neutrino masses

- Very light compared to other leptons (and Higgs scale): “unnatural”
- Simplest: Mix chiral states for each flavor
- Dirac masses: from ordinary Higgs, chirality oscillations
- Majorana masses: violate lepton number



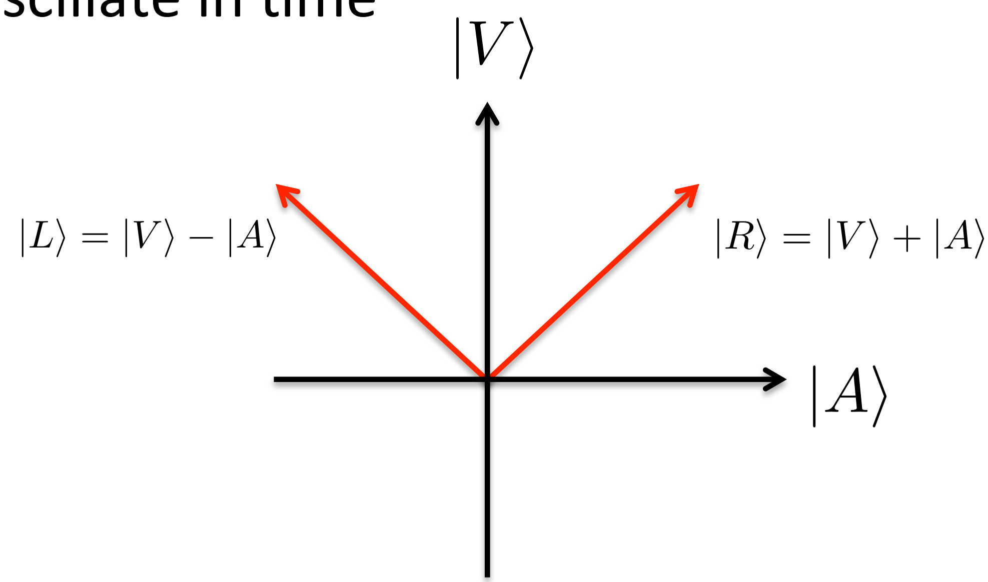
See Saw: Majorana Mass

- Heavy Majorana N and massless nu
- Physical states are mixes of these mass states that give rise to light neutrinos
- “Leptogenesis”: Decay of primordial N conserves B-L but can violate both; can help explain matter-dominated universe

$$M = \begin{pmatrix} M_L & M_D \\ M_D & M_R \end{pmatrix} \qquad M_\nu M_N = M_l^2$$

Chirality and Weak Vampirism

- Orthogonal/Complement to Parity (i.e. a spatial symmetry)
- The weak force maximally violates parity, couples only to L particles; Weak isospin is a weak (force) charge that is linked to chirality
- For massive particles (dirac masses), chirality is not a good Q#: will oscillate in time



Chiral Oscillations

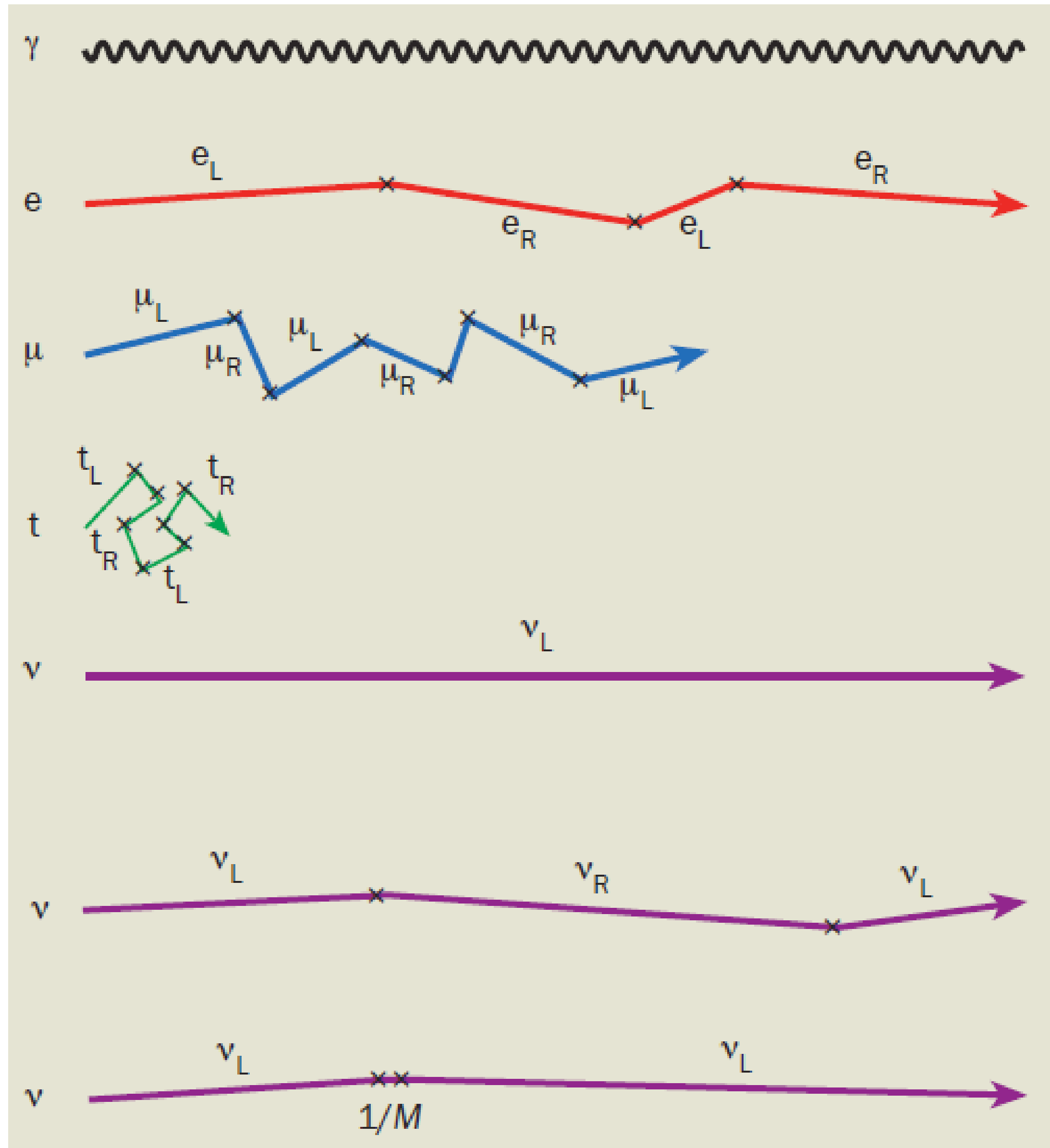
Charged leptons
Can only be Dirac

Neutrinos

Massless

Dirac mass

Majorana mass



Majorana Particles

- The neutrino could be its own antiparticle
- But isn't there beta decay and inverse beta decay? What about lepton number?
- Parity violation (Chirality) still allows this "loophole"
- Can have both Dirac and Majorana masses
- If mass is zero, Majorana/Dirac distinction is irrelevant

$$\nu_{\mathrm{L}}$$
$$\bar{\nu}_{\mathrm{R}}$$

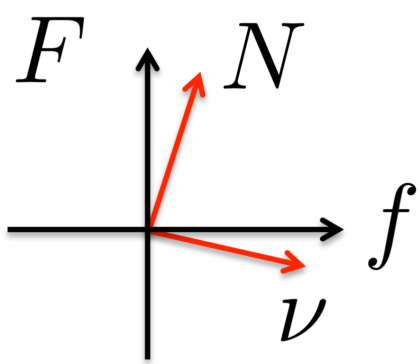
Dirac neutrinos
4 DOF, two are sterile

$$\begin{matrix} \nu_{\mathrm{L}} & \nu_{\mathrm{R}} \\ \bar{\nu}_{\mathrm{R}} & \bar{\nu}_{\mathrm{L}} \end{matrix}$$

$$\begin{matrix} \nu_{\mathrm{L}} \\ \bar{\nu}_{\mathrm{R}} \end{matrix}$$

Majorana neutrinos
4 DOF
2 Chiral doublets
One heavy (undetected)
One light (familiar)

$$\begin{matrix} \nu_{\mathrm{L}} \\ \bar{\nu}_{\mathrm{R}} \end{matrix}$$

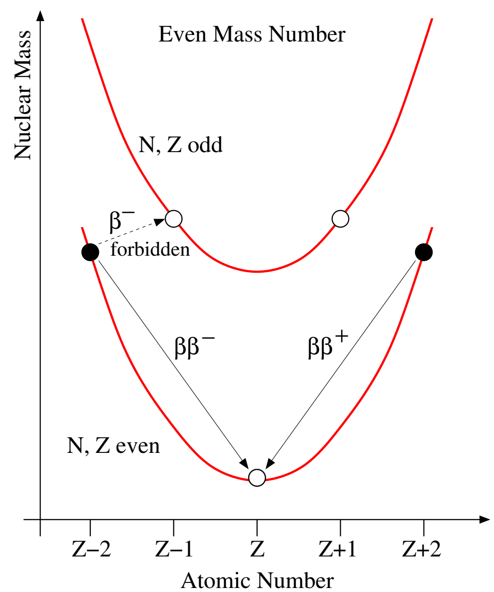


F, f are the physical states
N, nu are the mass states
Small rotation

Ordinary DBD

- Longest (rarest) half lives ever measured
  - 10^18 to 10^24 years

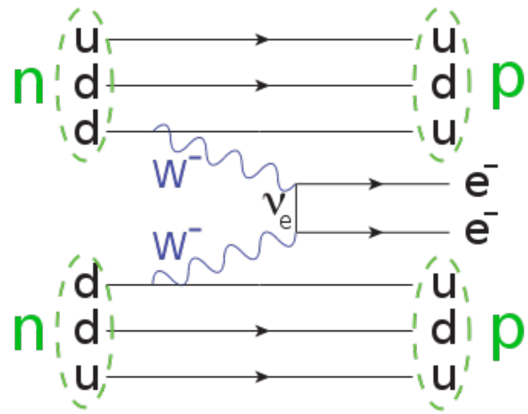
$$2\nu\beta\beta$$

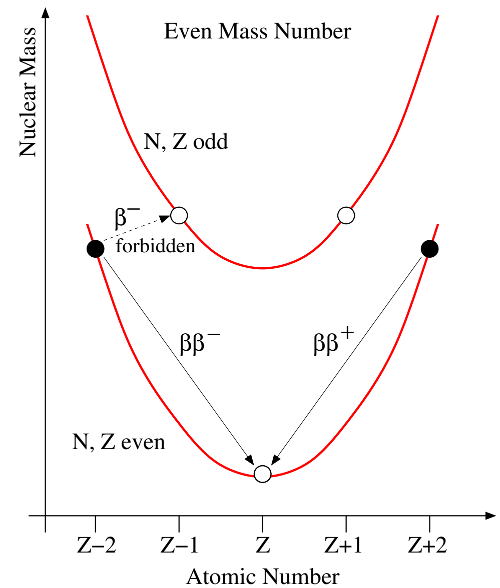


$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

Neutrinoless Double Beta Decay

$0\nu\beta\beta$





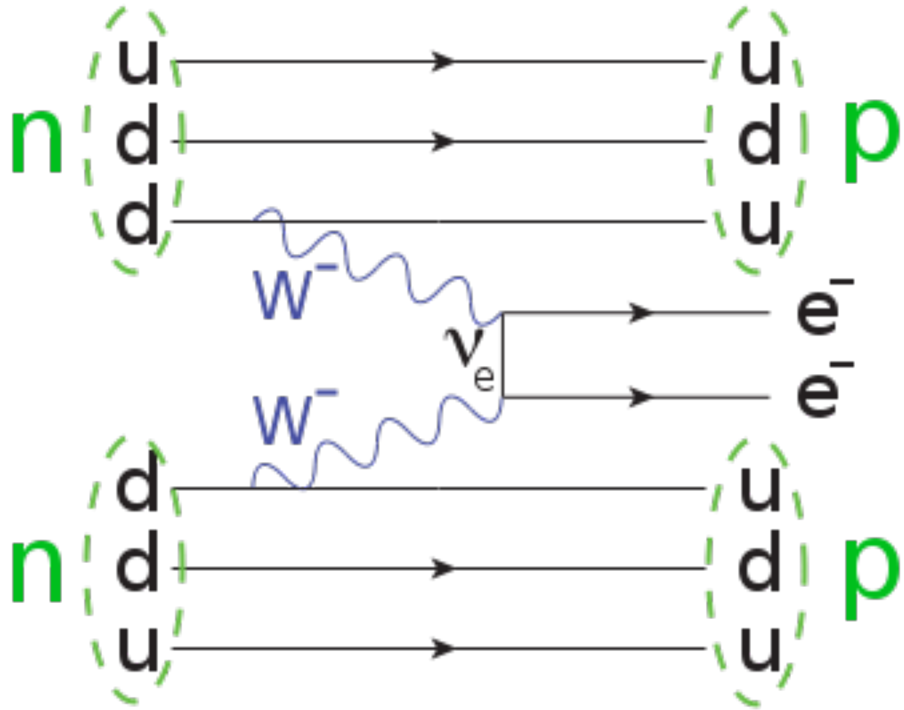
Decay detection indicates Majorana character of neutrino; violates lepton number; requires Massive neutrino

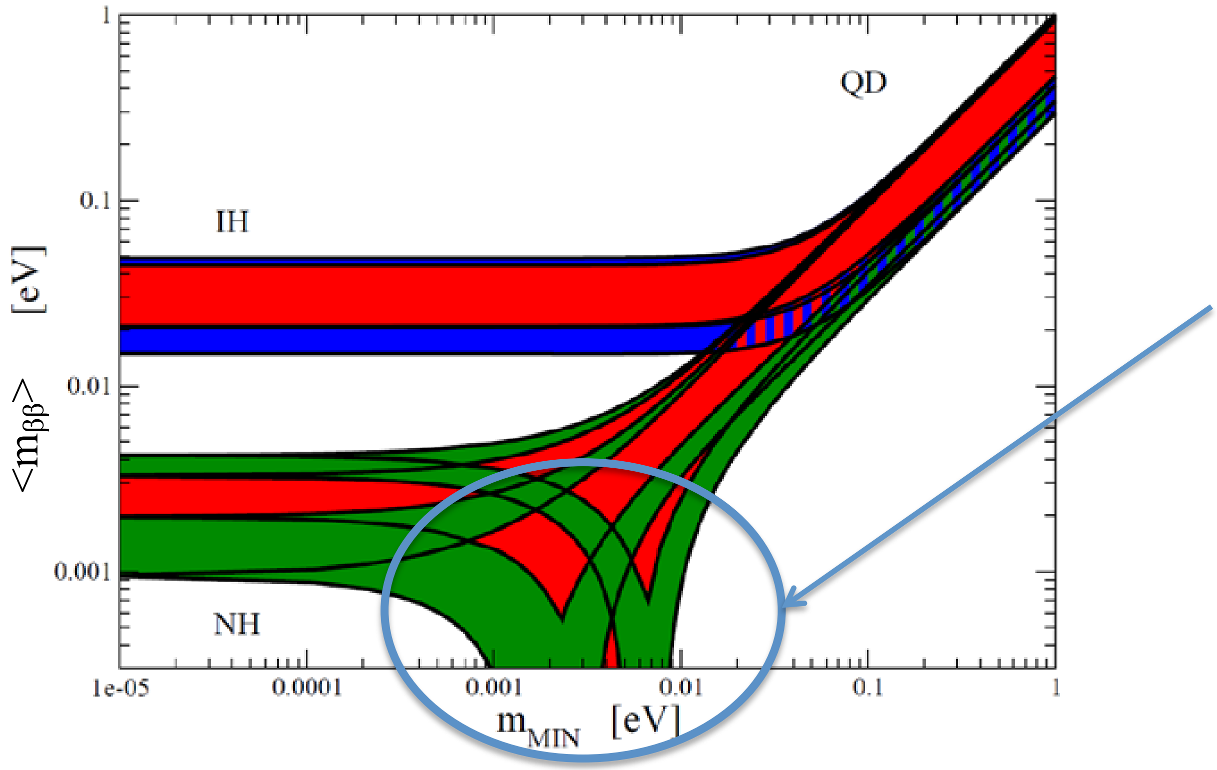
Virtual neutrino is absorbed with the "wrong" chirality after being emitted with the "correct" one

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$$

$$\Gamma^{0\nu} \propto G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ |\langle m_{\beta\beta}\rangle|^2$$

$0\nu\beta\beta$





Heartbreak region of normal hierarchy: Complex phases conspire to kill decay rate even though neutrino is a massive Majorana fermion; worry about it when we get there…

$$\Gamma^{0\nu} \propto G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ |\langle m_{\beta\beta}\rangle|^2$$

$$|\langle m_{\beta\beta}\rangle|_{\mathrm{N}} = |U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3|$$

$$|\langle m_{\beta\beta}\rangle|_{\mathrm{I}} = |U_{e3}^2 m_1 + U_{e2}^2 m_2 + U_{e1}^2 m_3|$$

Phase space $\propto Q^5$

Nuclear matrix element

Effective neutrino mass

0ν-DBD rate

$$\Gamma^{0\nu} \propto G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ |\langle m_{\beta\beta}\rangle|^2$$

high Q candidates preferred

large phase space

Some candidates with various Q values

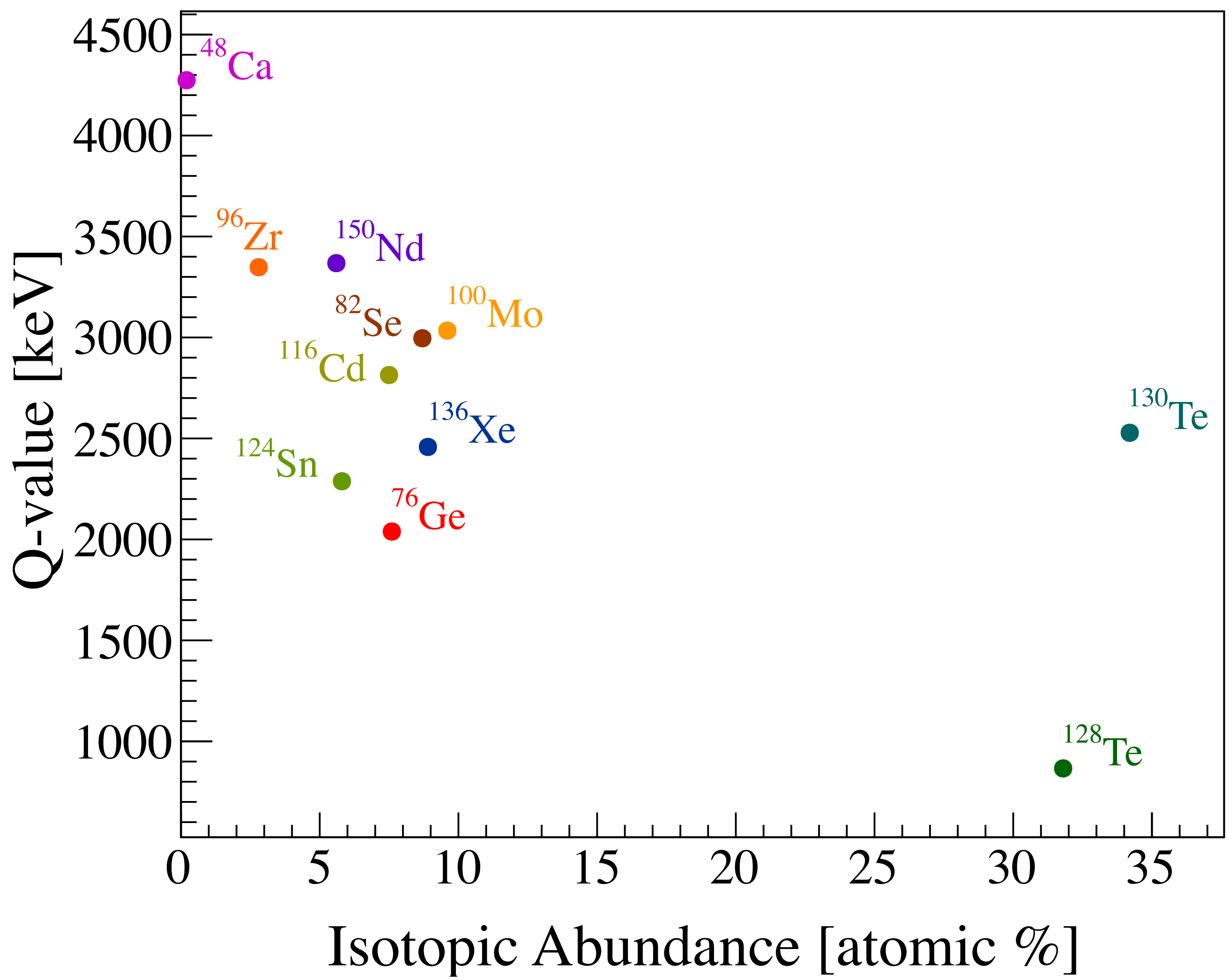
2039 keV (^{76}Ge)
2529 keV (^{130}Te)
4271 keV (^{48}Ca)

low background

^{238}U γ end at 2400 keV

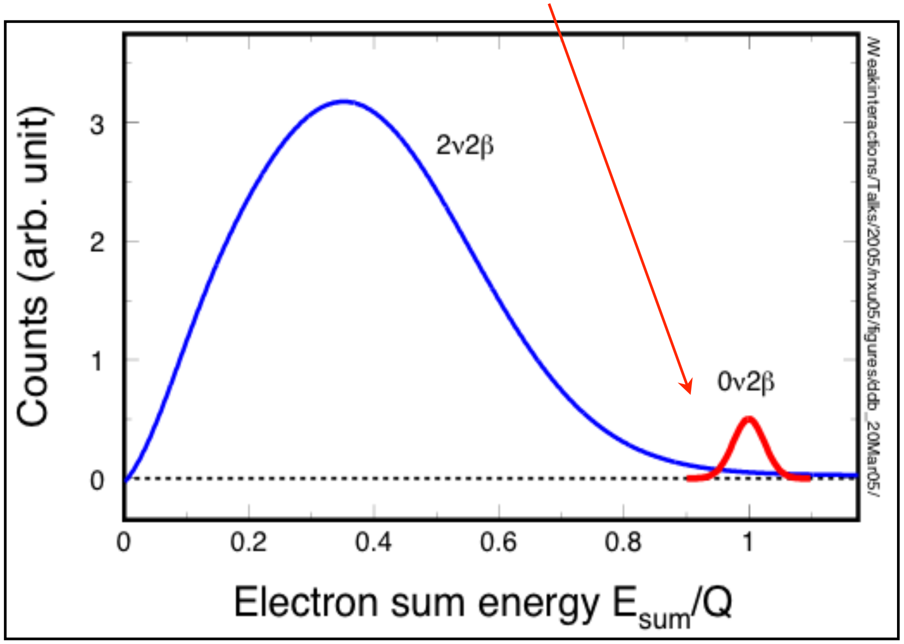
^{232}Th γ end at 2600 keV

Q values and abundances for Neutrinoless Double Beta Decay Candidates



Measurement Strategy

Smearing from energy resolution;
introduces background



$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

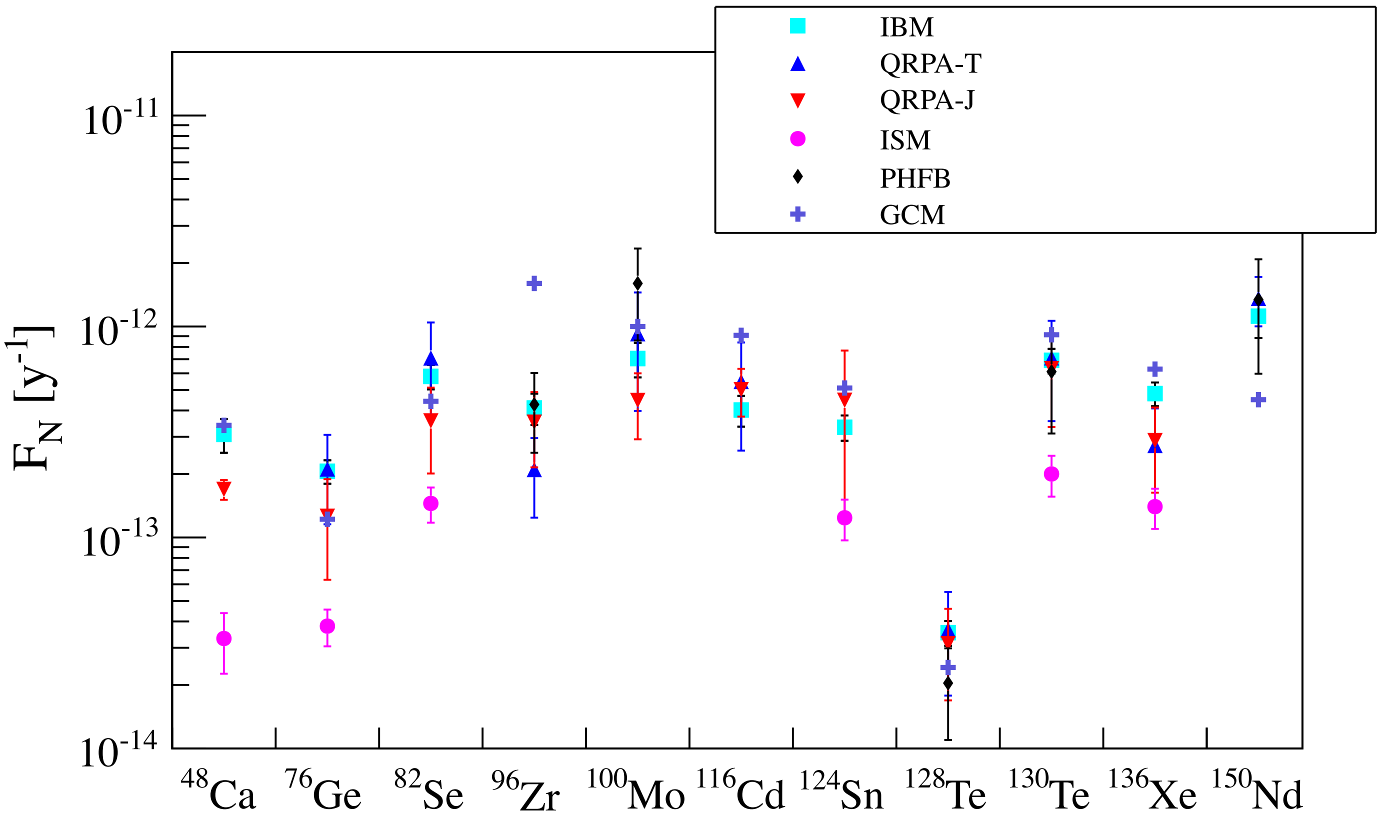
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

Each candidate isotope has a predicted Q value for the reaction

Strategy: Measure the two electron sum energy (and recoil):
The two neutrino mode will be a continuum
The zero neutrino mode will be a peak

Nuclear Figures of Merit for
Neutrinoless Double Beta Decay Candidates
Difficult to calculate; disturbingly very model dependent

$$F_N \equiv G^{0\nu}|M^{0\nu}|^2 \text{ years}^{-1}$$



Instantiation

- As a case study, look at CUORE technology and our strategy to find neutrinoless double beta decay
- Major industry in motion now and in the future
  - Many techniques, many isotopes
  - CUORE, Majorana, MD, Gerda, SuperNemo, EXO, EXO-200, NEXT, nEXO, Lucifer, and others

LNGS: Underground

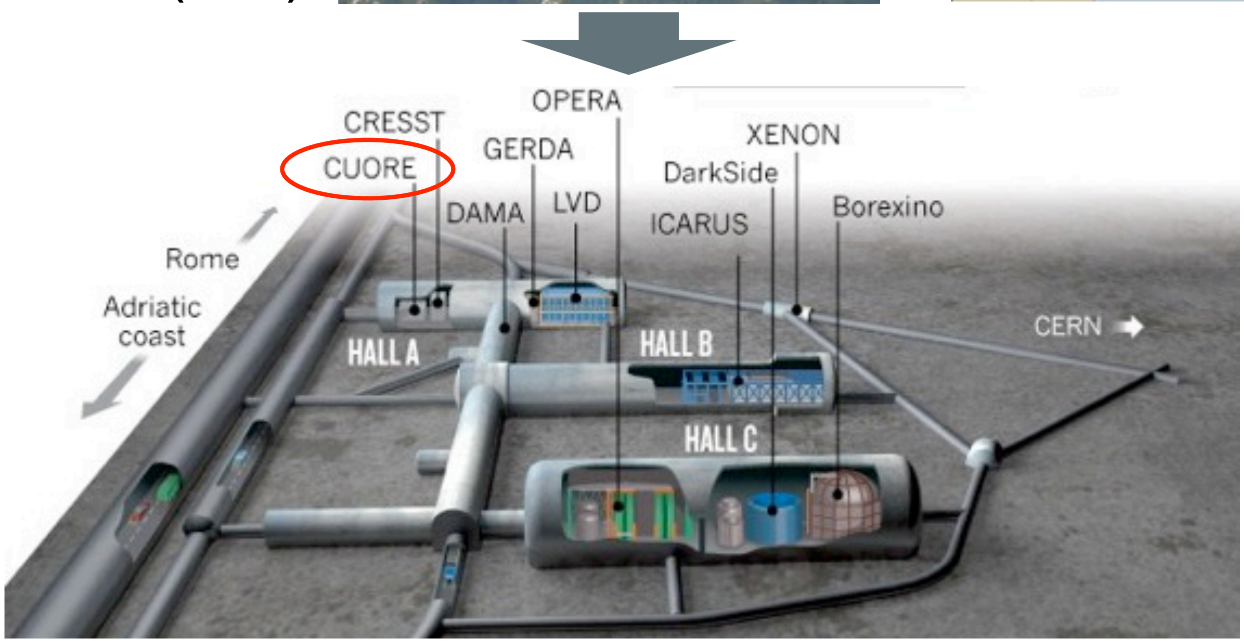
120 km from Rome

3650 m.w.e. deep

μs: 2.58×10^{-8}/(s cm^2)

γs: ~0.73/(s cm^2)

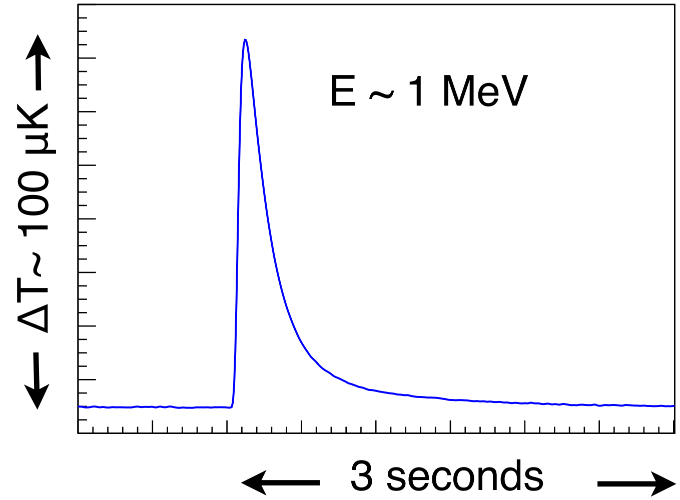
neutrons: 4×10^{-6} n/(s cm^2)



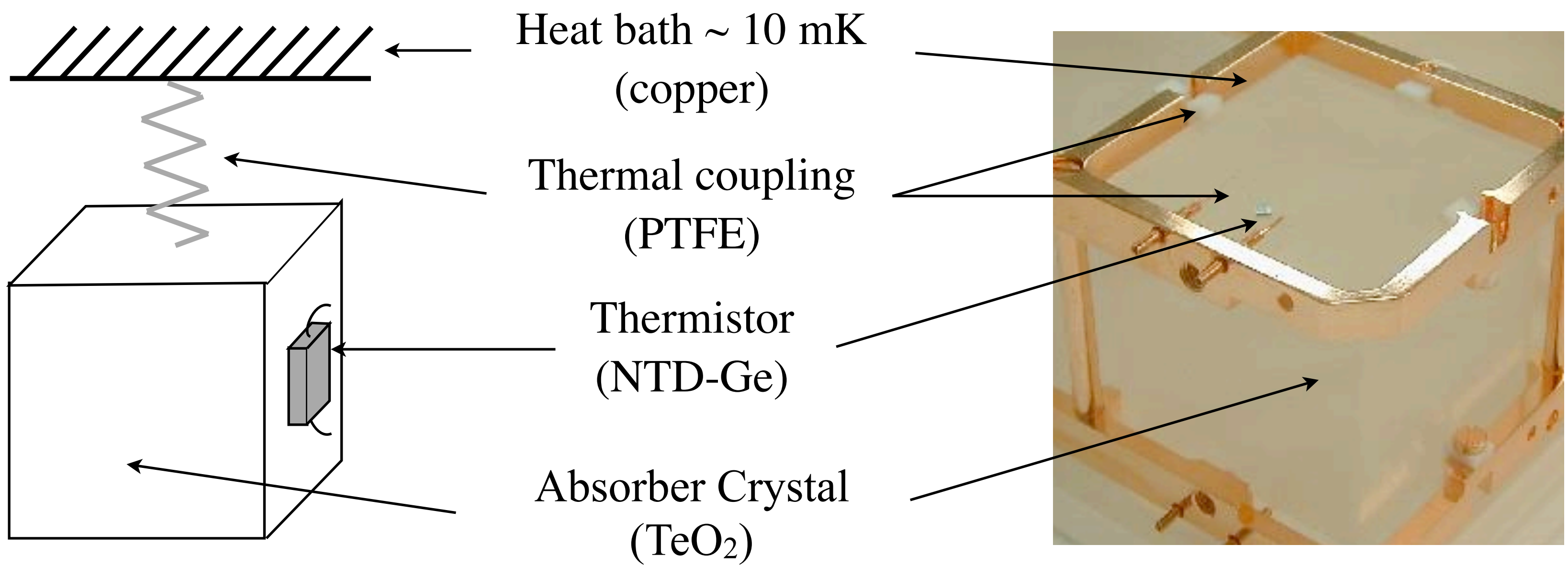
Source=Detector Cryogenic Bolometry

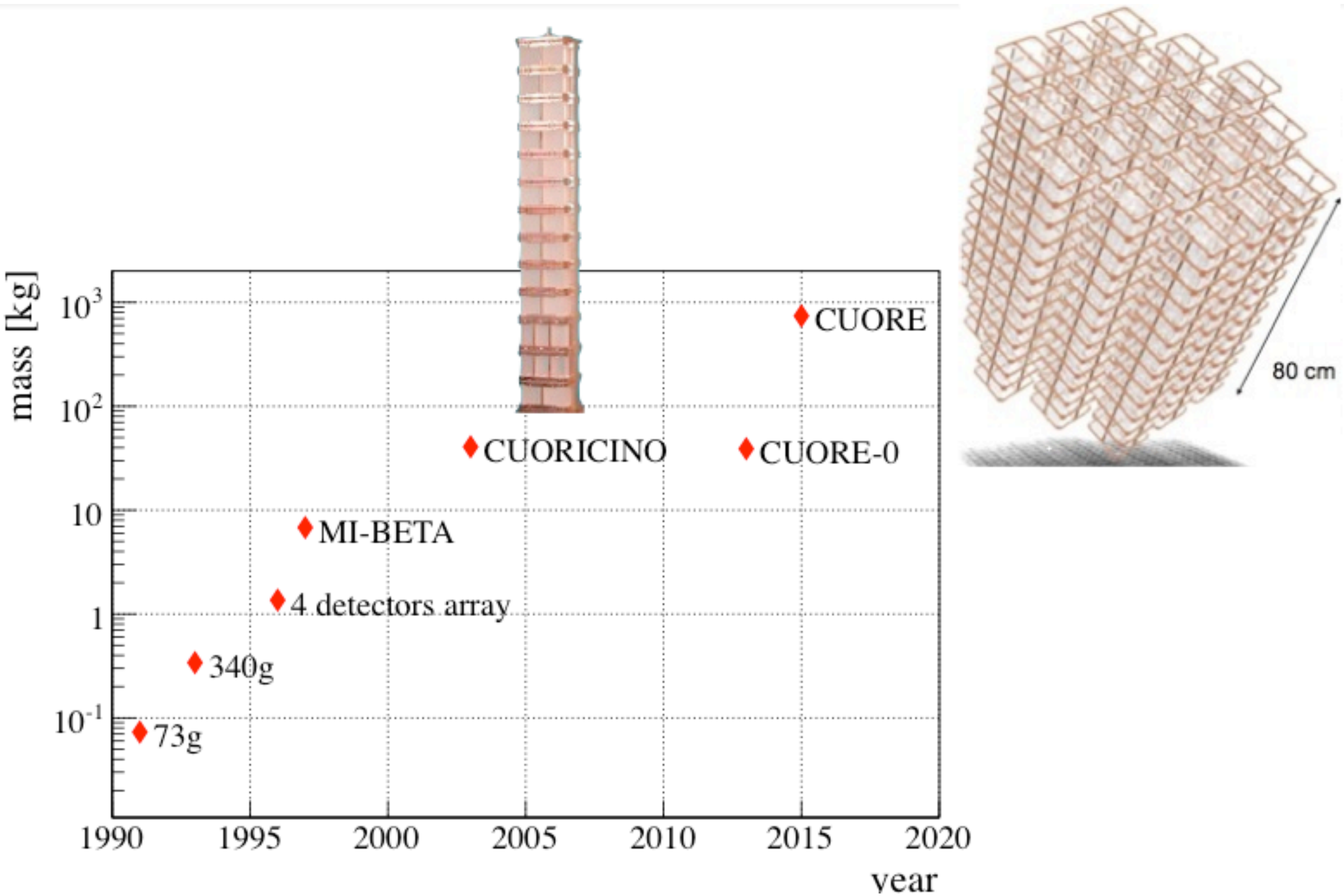
$$\Delta E = C\Delta T$$

$$C \sim T^3$$

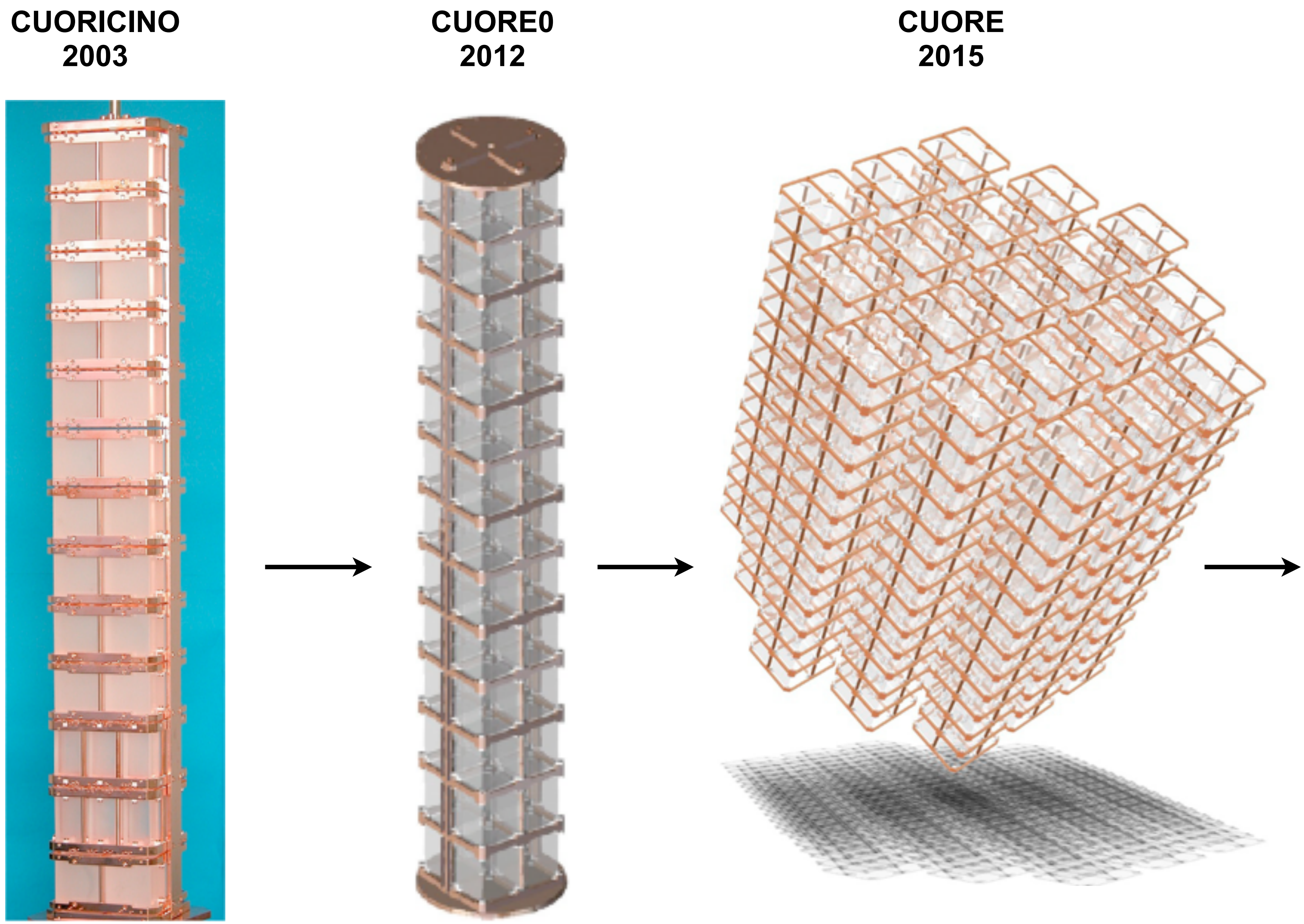


3-5 keV FWHM energy resolution

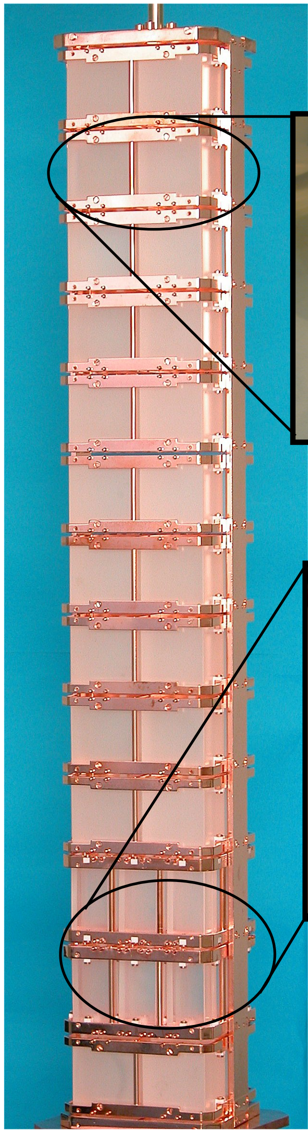




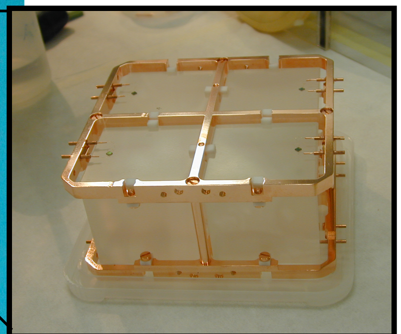
mass [kg]
10^3
10^2
10
1
10^{-1}
1990
1995
2000
2005
2010
2015
2020
year
CUORE
CUORICINO
CUORE-0
MI-BETA
4 detectors array
340g
73g
80 cm


CUORICINO
2003
CUORE0
2012
CUORE
2015

Cuoricino, the “little heart” of Gran Sasso

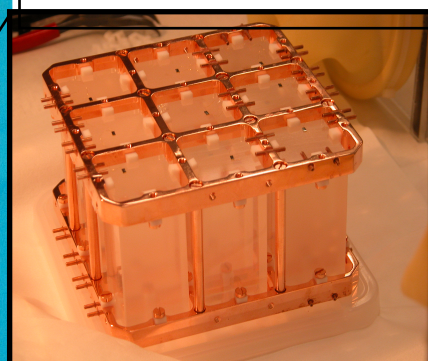


Cooled to 10mK with a powerful dilution refrigerator



11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 790 g
44 x 0.79 = 34.76 kg of TeO_2

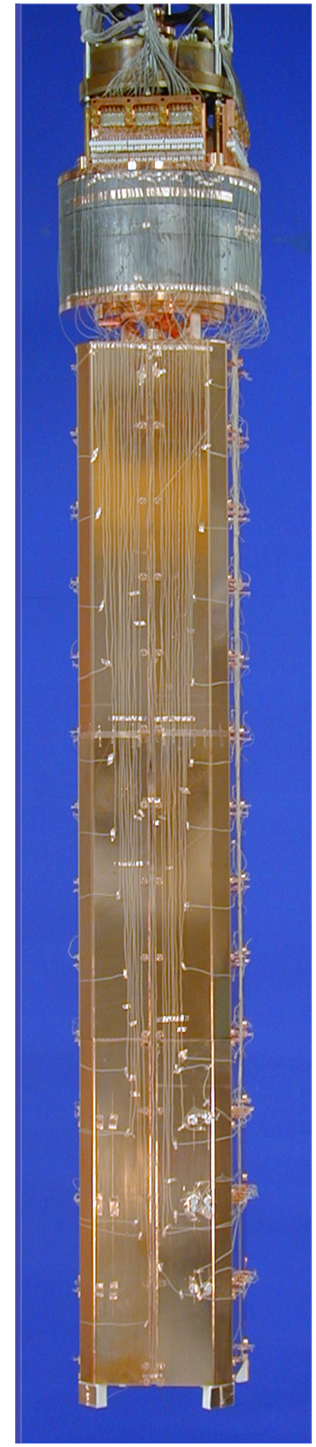
Encased in a cryostat, lead (+Roman) shield, nitrogen box, neutron shield, and Faraday cage



2 modules x 9 crystals each
crystal dimension: 3x3x6 cm^3
crystal mass: 330 g
18 x 0.33 = 5.94 kg of TeO_2

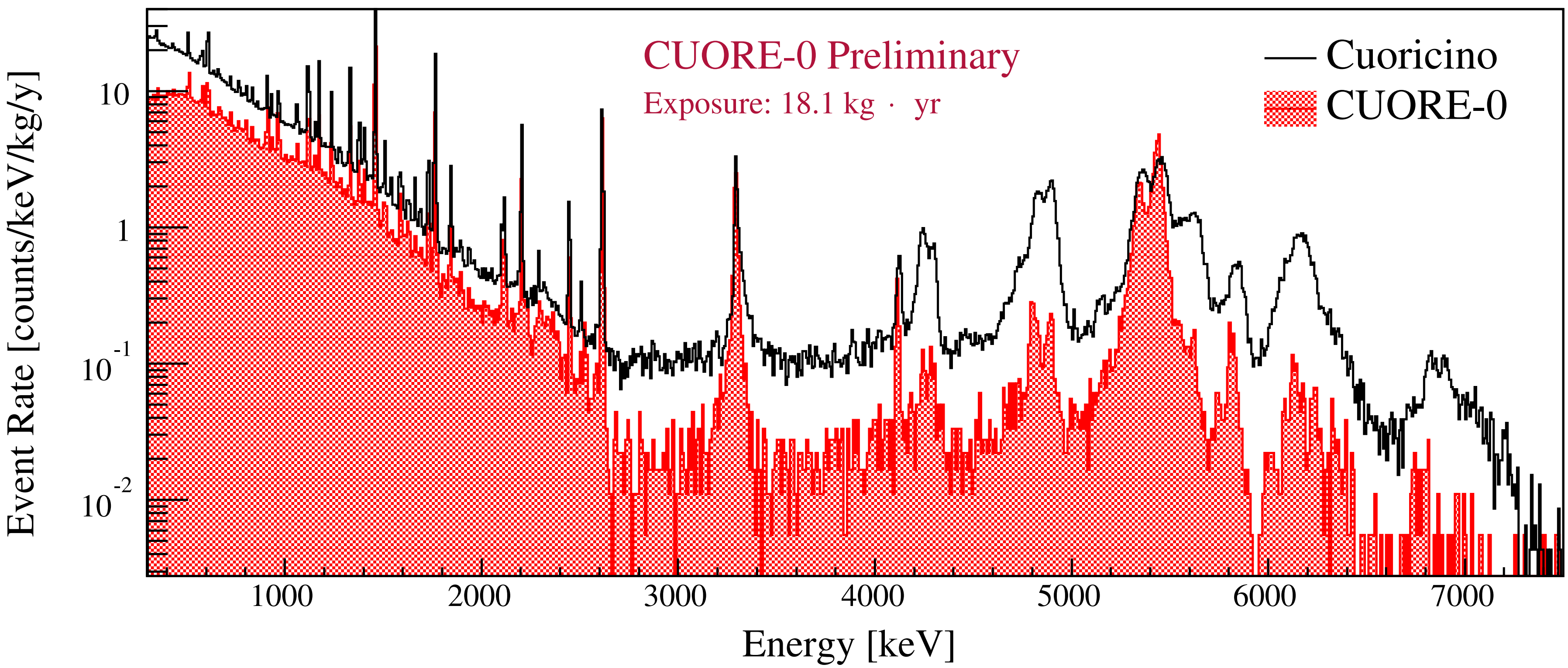
Total detector mass: 40.7 kg TeO_2 ⇒ **11.34 kg ^{130}Te**

$$T^{0\nu} > 2.8 \times 10^{24} \text{ years}$$



CUORE-0 has done its job

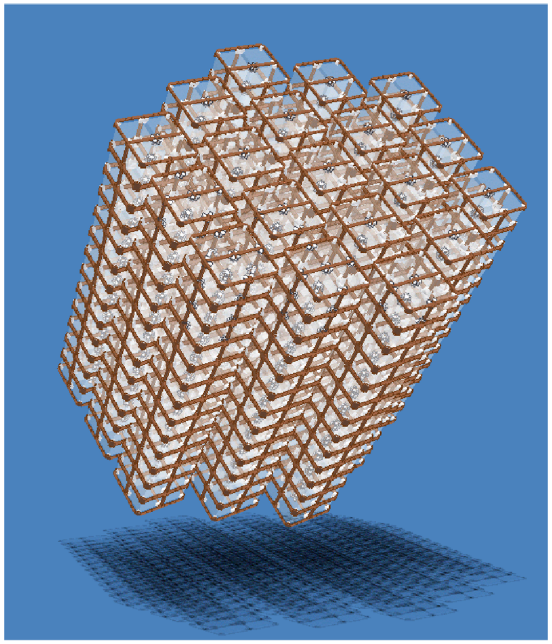
Running since 2013
Cuoricino-like tower with CUORE cleaning/R&D
0.02 counts/kg/keV/yr!
2700 to 3900 keV
(excluding 190Pt alpha line) at 3300



CUORE

Cryogenic Underground Observatory for Rare Events

- Array of 988 TeO_2 crystals
- 19 Cuoricino-like towers suspended in a cylindrical structure
- 13 levels of 4 5x5x5 cm^3 crystals (750g each)
- ^{130}Te: 33.8% isotope abundance
- 1st Data target: June 1, 2015



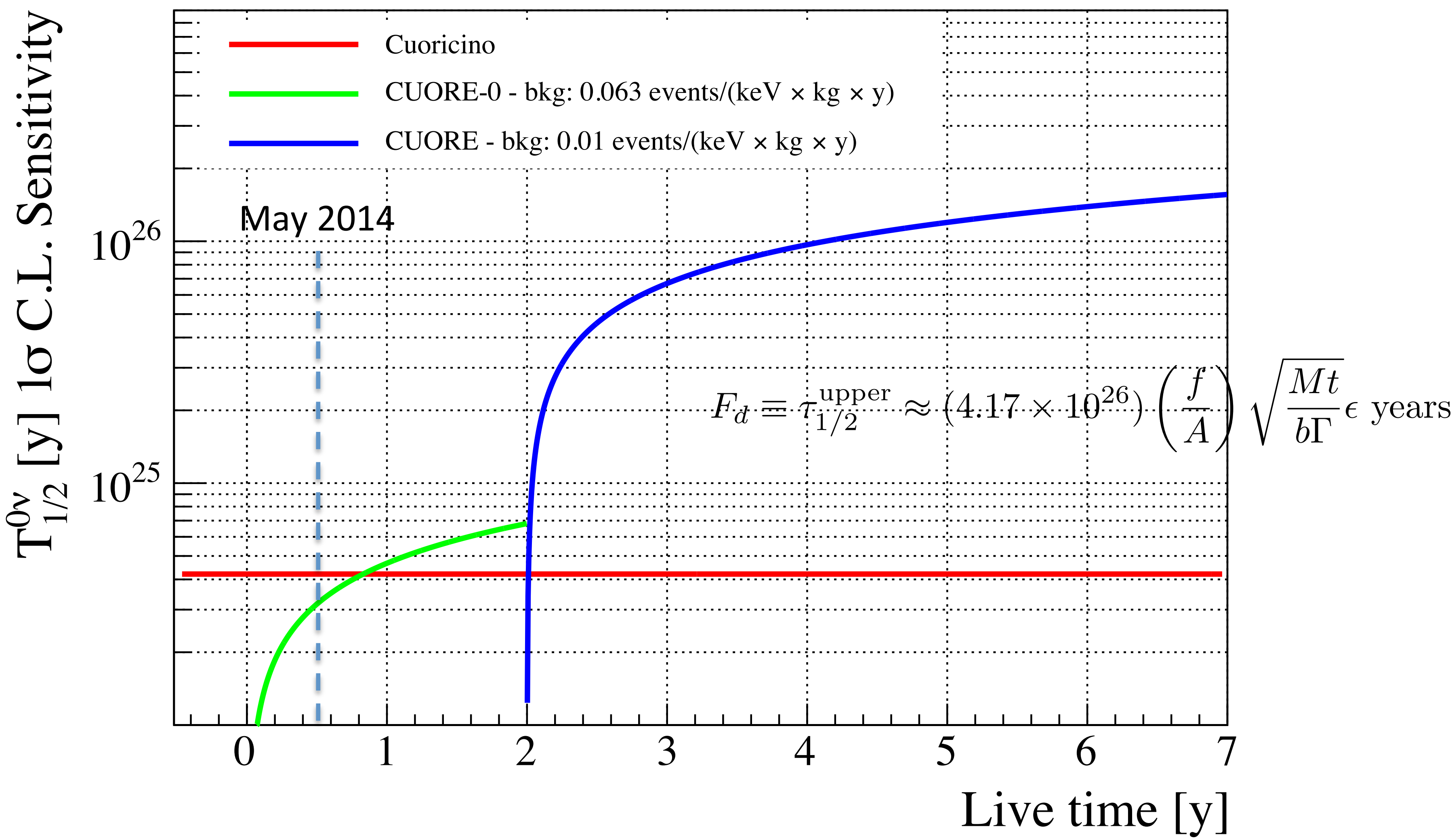
750 kg TeO_2 => 200 kg ^{130}Te

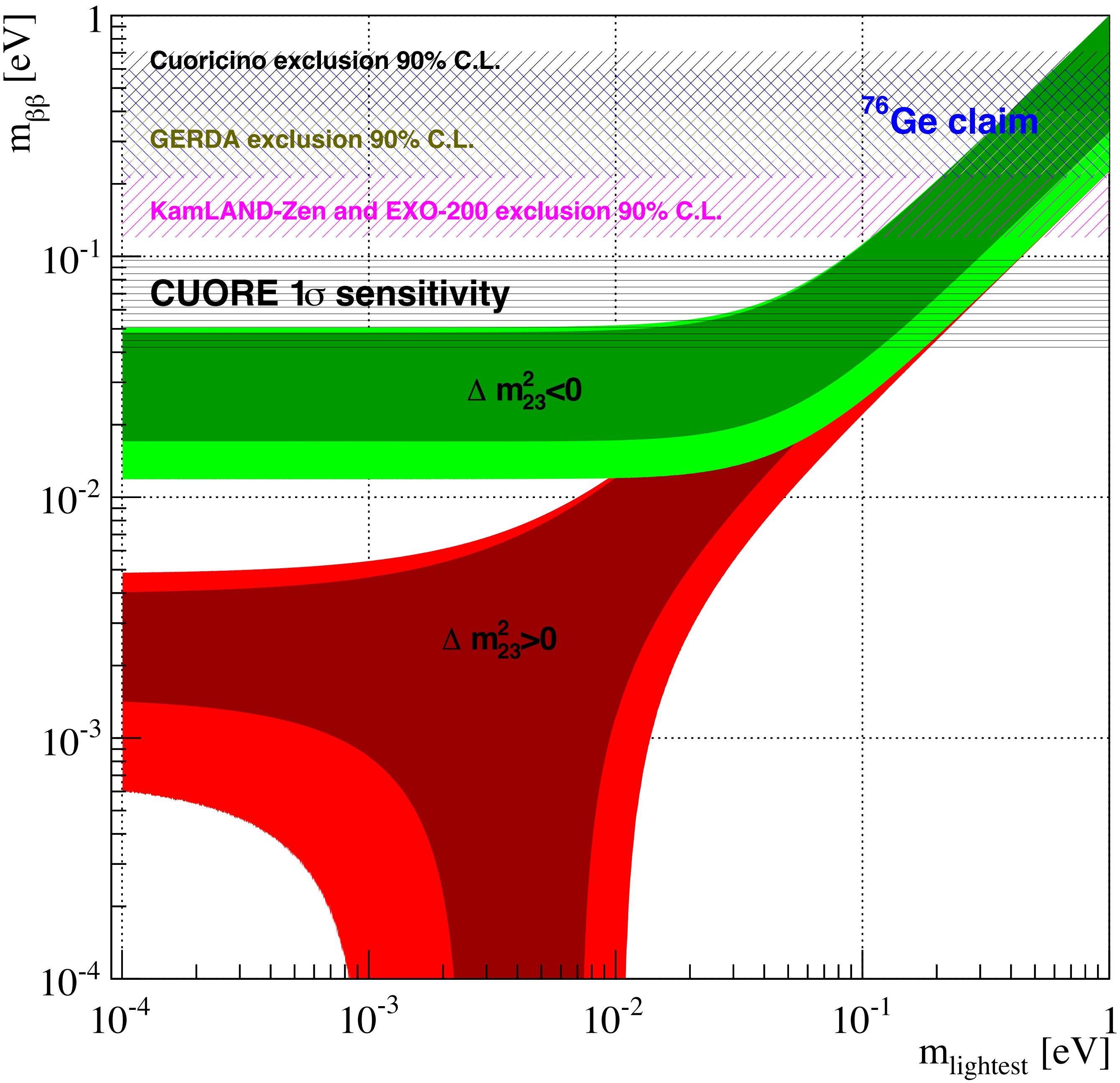
Acts as a single, highly segmented, detector;
Each crystal is a "pixel"

Currently under construction!

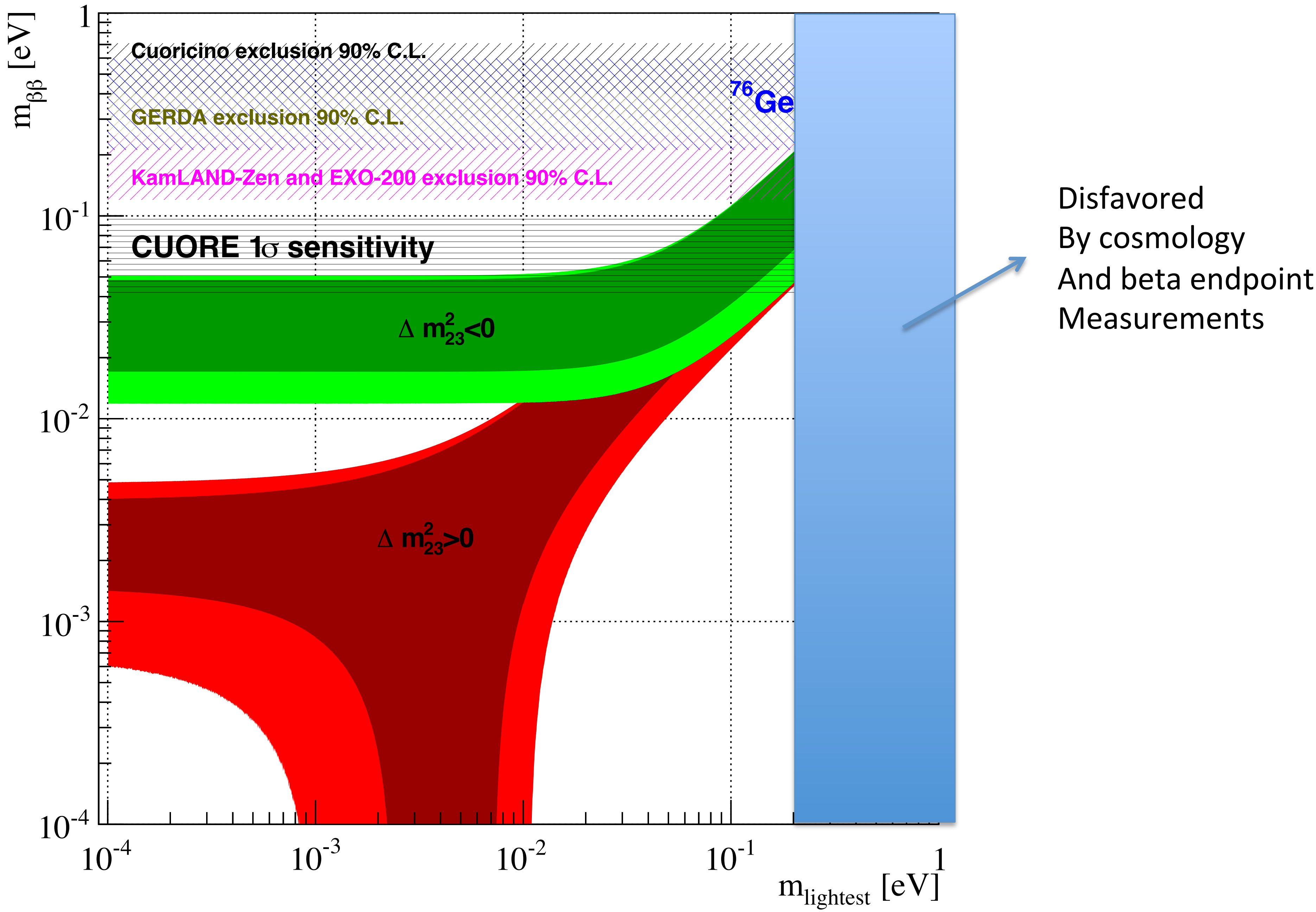
$$F_d \equiv \tau_{1/2}^{\mathrm{upper}} \approx (4.17 \times 10^{26}) \left(\frac{f}{A}\right) \sqrt{\frac{Mt}{b\Gamma}} \epsilon \text{ years}$$

Experimental sensitivity plot





- KK&K tension 76Ge claim
- EXO, Gerda, Kamland-Zen result



$m_{\beta\beta}$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Cuoricino exclusion 90% C.L.
GERDA exclusion 90% C.L.
KamLAND-Zen and EXO-200 exclusion 90% C.L.
^{76}Ge
CUORE 1σ sensitivity
$\Delta m^2_{23}<0$
$\Delta m^2_{23}>0$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$m_{lightest}$ [eV]
Disfavored
By cosmology
And beta endpoint
Measurements

Summary

?

- Exciting time for the field!
  - Is the neutrino its own antiparticle?
  - How to include neutrino mass in the standard model?
- On the cusp of discovery (or not!)
  - "Backwards science"; falsifiability is turned around: trying really hard to prove the null and falsify it by actually finding something
  - Science of staring at nothing…then something!
  - Late Stuart Freedman on rare event physics: if your detector is working perfectly, you turn it on, and nothing happens

Acknowledgements

- Would like to thank my CUORE and Cuoricino collaborators
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