Neutrinoless Double Beta Decay

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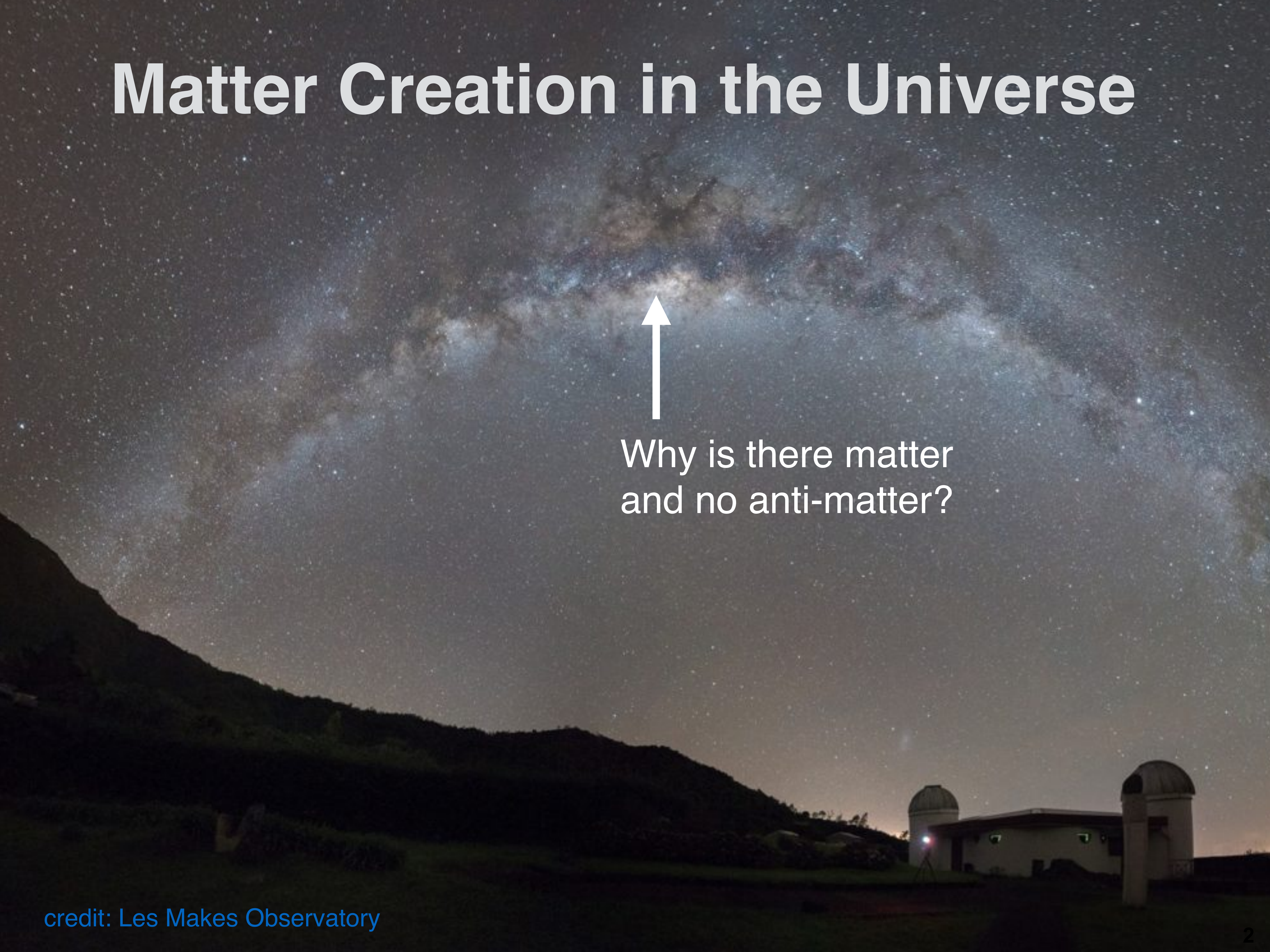
Matter Creation in the Universe



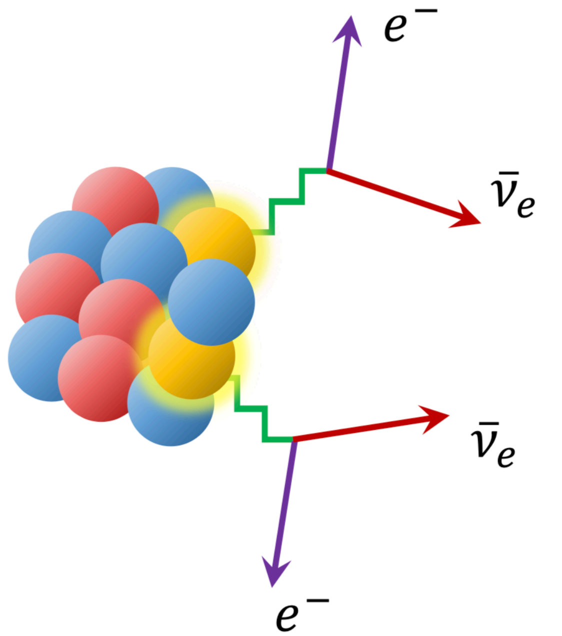
credit: Les Makes Observatory

Double beta decays:

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

$$0\nu\beta\beta : (Z, A) \rightarrow (Z + 2, A) + 2e^-$$

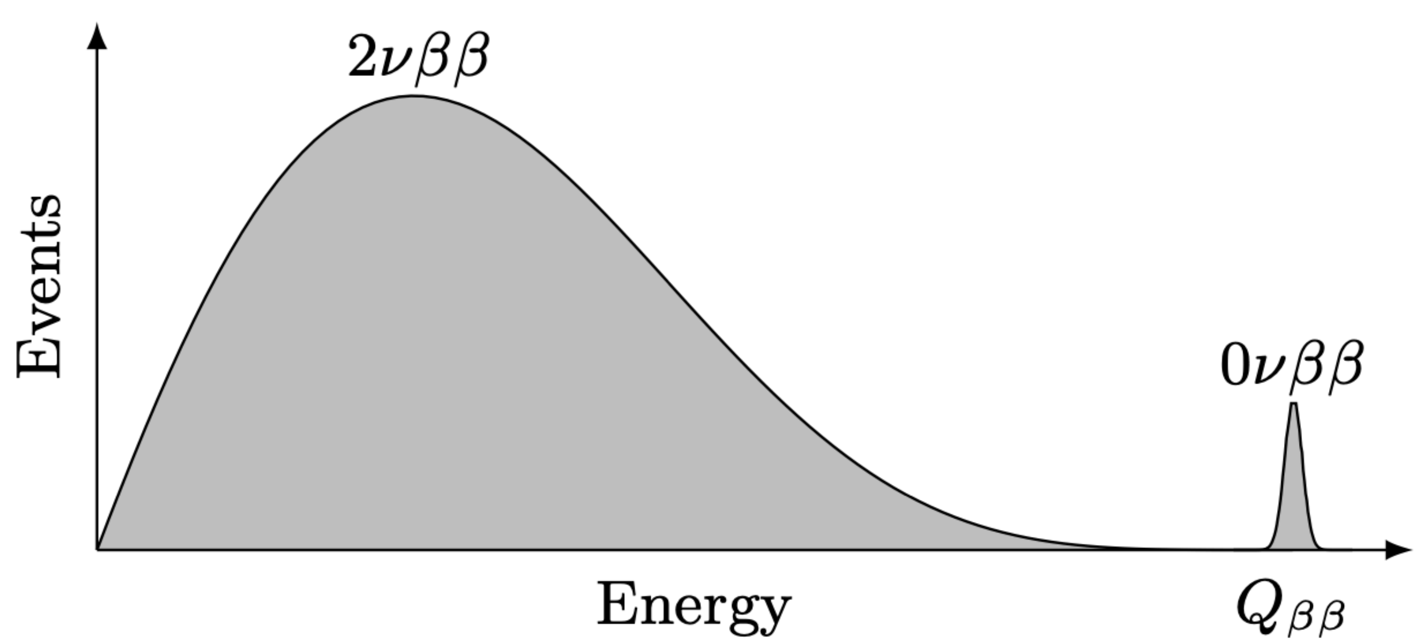
Matter is created
Lepton number not conserved: $\Delta L = 2$
Neutrinos are Majorana particles

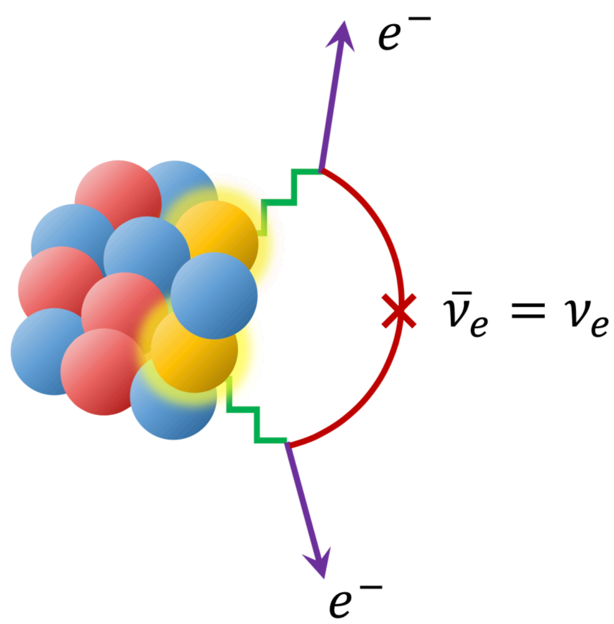


observed in 11 nuclei

Experimental signature:

- Peak search at Q-value
- Measure half-life of decay





undiscovered

Fundamental Symmetries

Accidental symmetries in Standard Model:

- B (baryon number)
- L_e, L_μ, L_τ (lepton flavors)
- $L = L_e + L_\mu + L_\tau$ (lepton number)

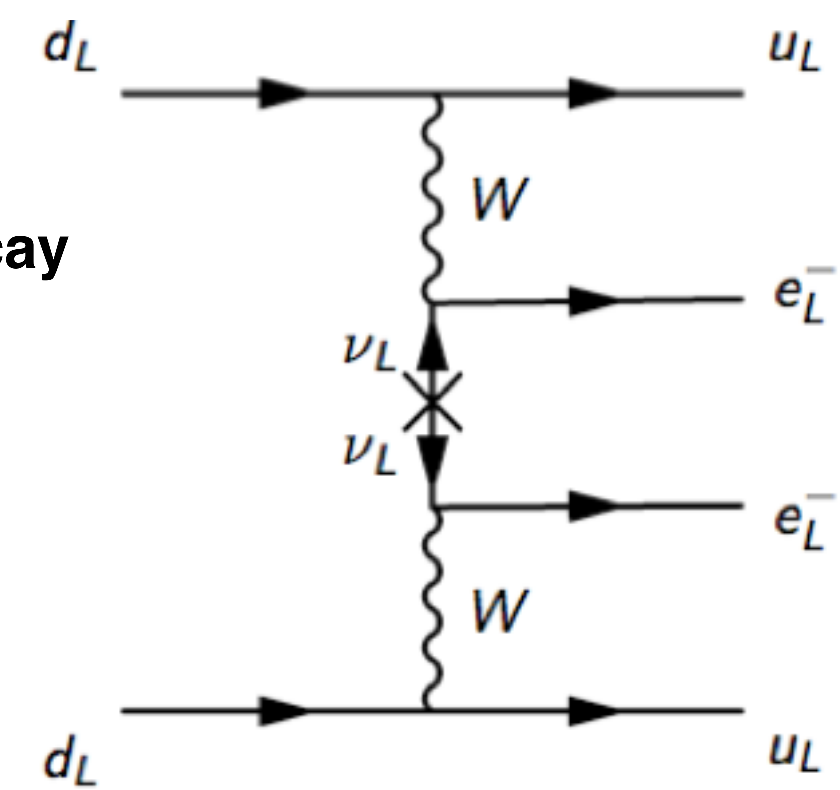
Exact global symmetries:

- $L_e - L_\mu$
- $L_\mu - L_\tau$
- B - L

- B — observed in universe but not in proton decay $p \rightarrow e^+ + \pi^0$
- $L_e - L_\mu$ — violation observed (e.g. T2K)
- $L_\mu - L_\tau$ — violation observed (e.g. OPERA)
- B - L — we don't know yet

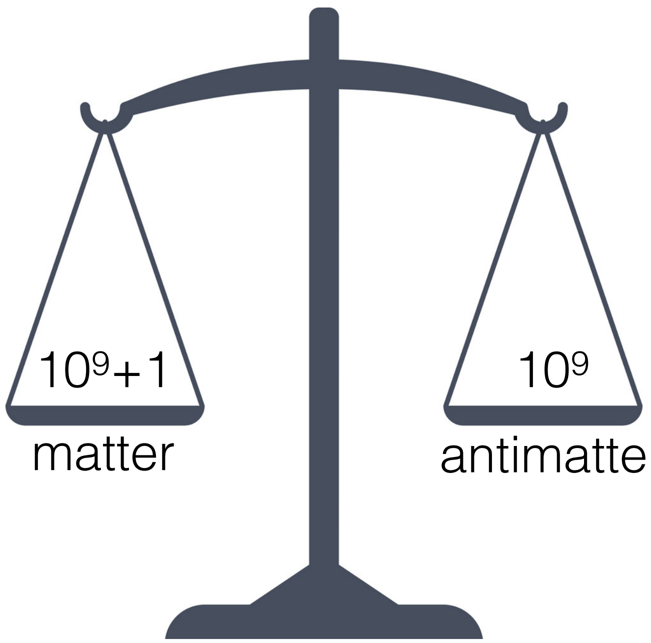
Neutrionless double beta decay (NLDBD, 0νββ)

- violates B-L
- BSM process
- creates matter



Why is there more matter than anti-matter in the Universe?

matter - antimatter asymmetry

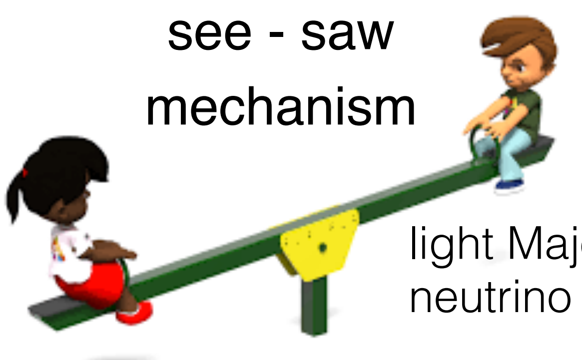


Baryon number asymmetry (B) observed today

B - observed in universe

L - hidden in CνB

see - saw mechanism



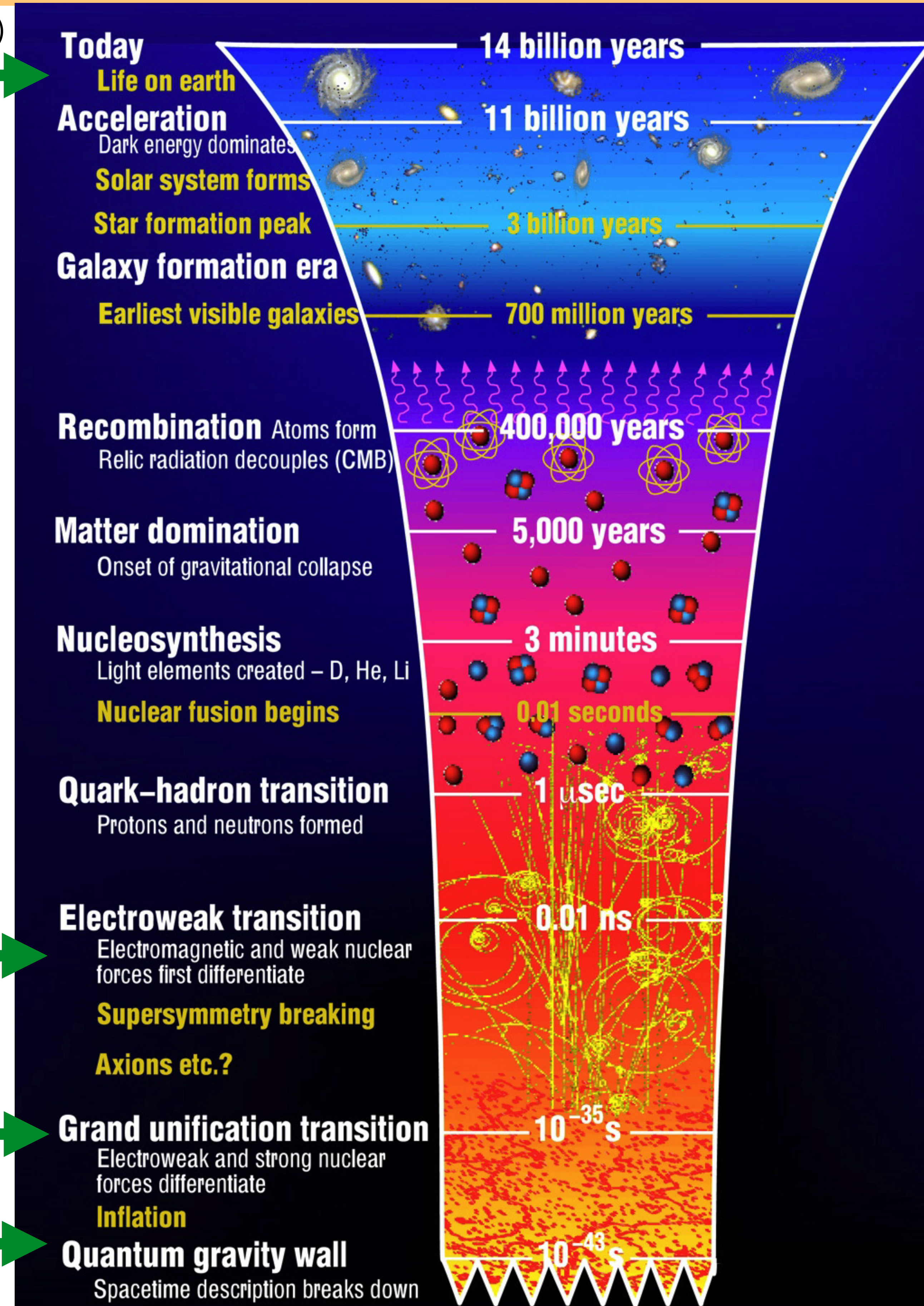
light Majorana neutrino

heavy Majorana neutrino

Lepton number asymmetry (L) transferred to Baryon number asymmetry (B), B-L conserved

Lepton number asymmetry (L) produced by decay of heavy ν

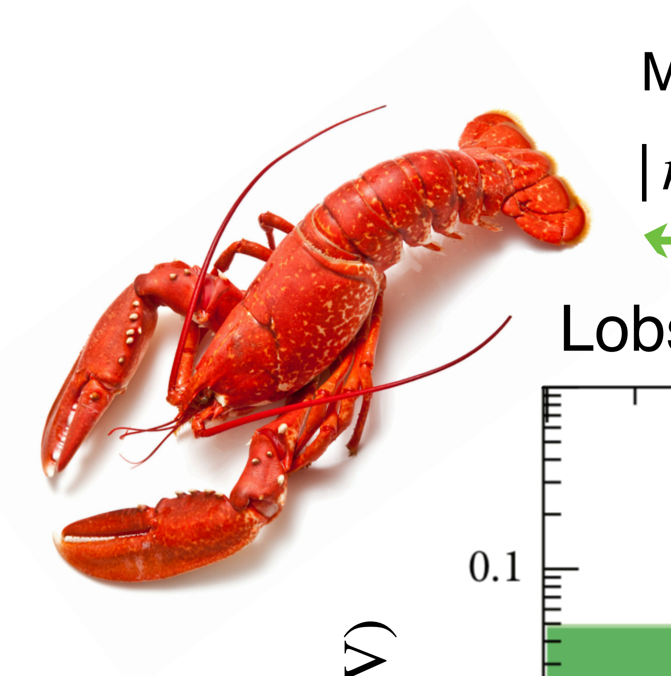
Matter and antimatter produced equally (L=0, B=0)



Standard Mechanism: Light Majorana Neutrino Exchange

$$\left(T_{1/2}\right)^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |m_{\beta\beta}|^2$$

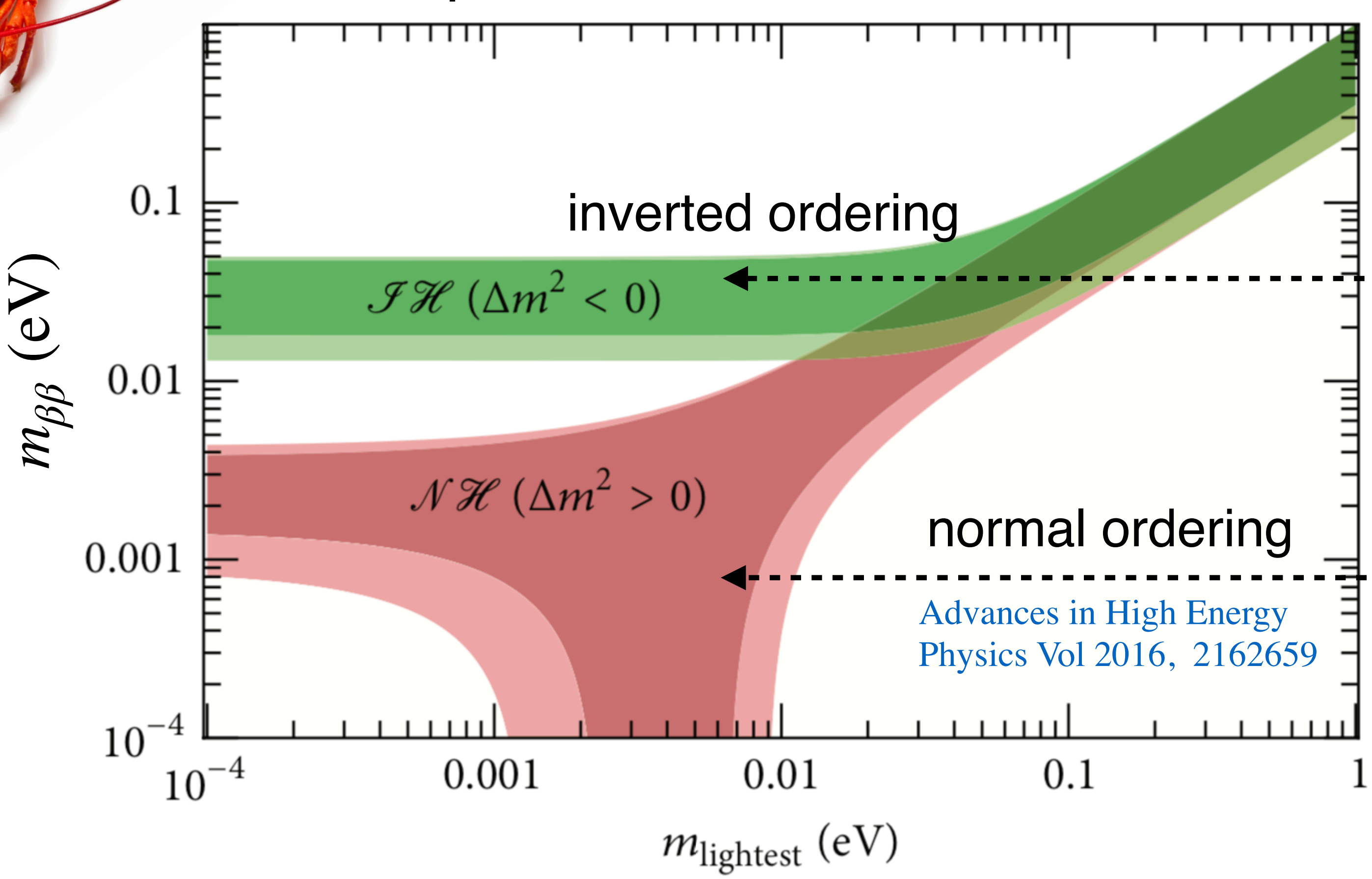
$\left(T_{1/2}\right)^{-1}$	$G^{0\nu}$	$\lvert M^{0\nu}\rvert^2$	$\lvert m_{\beta\beta}\rvert^2$
measured half-life	phase space factor	nuclear matrix element	effective Majorana neutrino mass
experiment	**atomic physics**	**nuclear physics**	**particle physics**

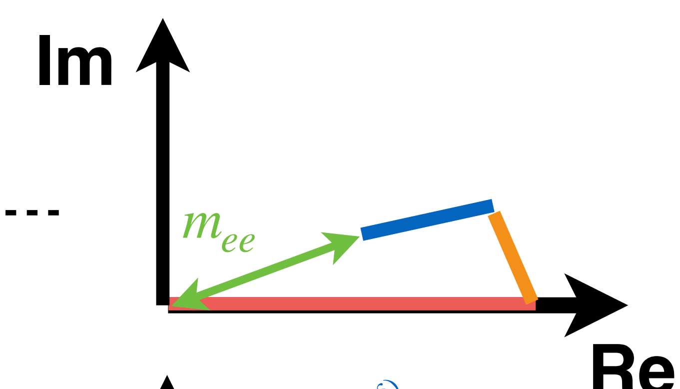


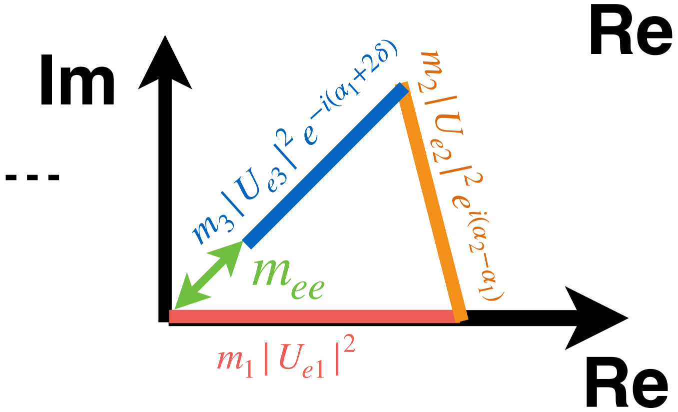
Mass of a virtual electron neutrino propagator:

$$|m_{\beta\beta}| = \left| m_1 |U_{ei}^2| + m_2 |U_{e2}^2| e^{i(\alpha_2-\alpha_1)} + m_3 |U_{e3}^2| e^{-i(\alpha_1+2\delta)} \right|$$

Lobster plot







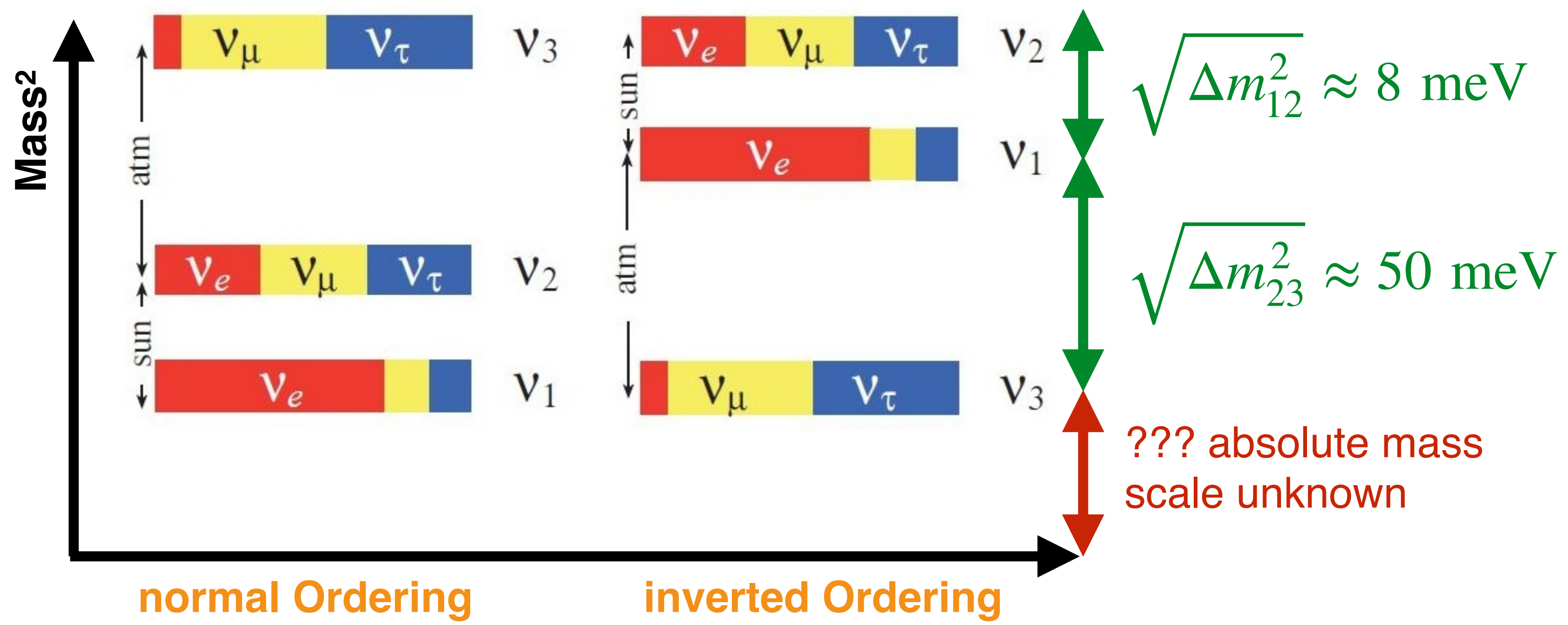
Neutrino Parameters

Neutrino mixing: PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

$$|\nu_{\text{flavor}}> = \sum_i U^*_{\alpha i} \cdot |\nu_{\text{mass}}>$$

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\Theta_{23} & s\Theta_{23} \\ 0 & -s\Theta_{23} & c\Theta_{23} \end{pmatrix} \begin{pmatrix} c\Theta_{13} & 0 & s\Theta_{13} \cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -s\Theta_{13} \cdot e^{-i\delta} & 0 & c\Theta_{13} \end{pmatrix} \begin{pmatrix} c\Theta_{12} & s\Theta_{12} & 0 \\ -s\Theta_{12} & c\Theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{pmatrix}$$

Neutrino masses:



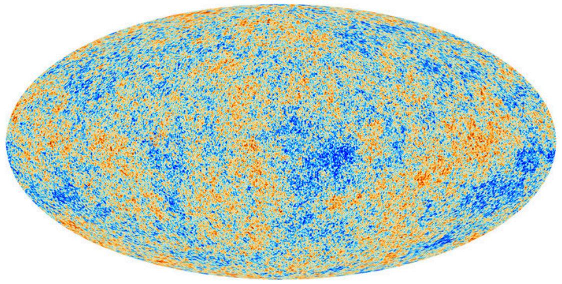
- Precision measurements with oscillation: $\Theta_{12}, \Theta_{13}, \Theta_{23}, \Delta m^2_{12}, \Delta m^2_{23}$
- Upcoming oscillation measurements (subdominant matter effects): CP phase $e^{i\delta}$, ordering $\text{sign}(\Delta m^2_{23})$
- Not accessible with oscillations: absolute mass scale, Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}, \alpha, \beta$)

Can be measured in neutrino mass and double beta decay experiments

Different Neutrino Mass Observables

β-**decay (kinematic)**
model independent

$$m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$$



cosmology
model dependent
- ΛCDM

$$m_\Sigma = \sum_i m_i$$

m_β — m_Σ — $m_{\beta\beta}$

mass eigenstate mixing

m_1 m_2 m_3

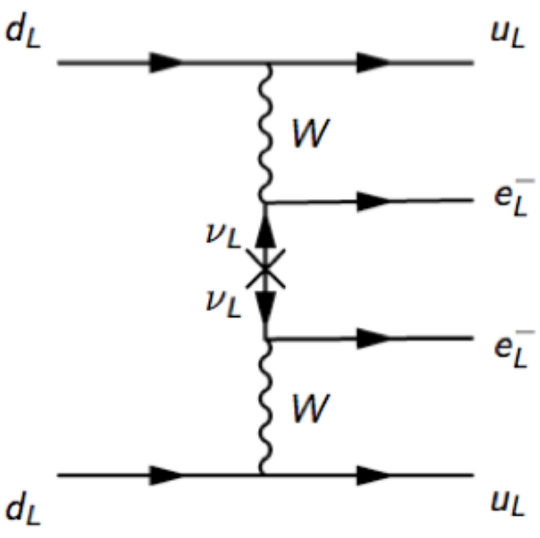
double beta decay
model dependent
- lepton number violation
- light Majorana neutrino exchange

$$m_{\beta\beta} = |\sum_i m_i U_{ei}^2|$$

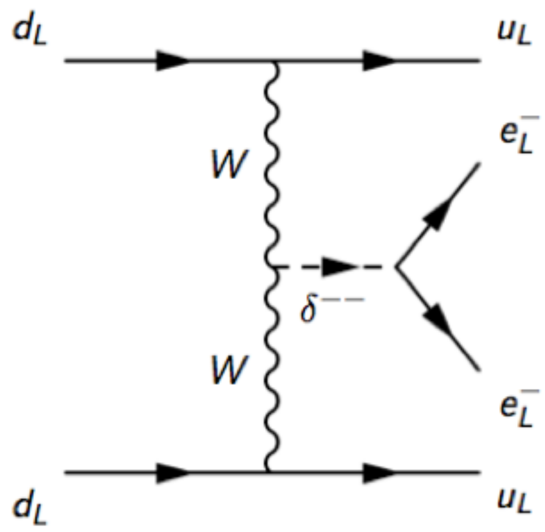
Other 0νββ Decay Mechanisms

Possible processes (not exhaustive)

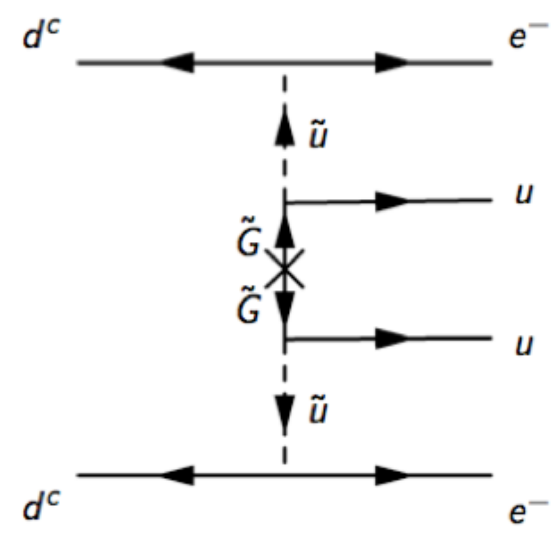
PRD 83, 113003 (2011)



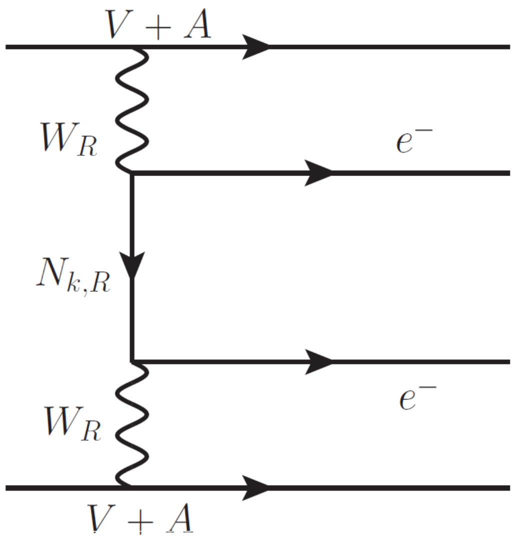
light Majorana



Higgs triplet



SUSY particle

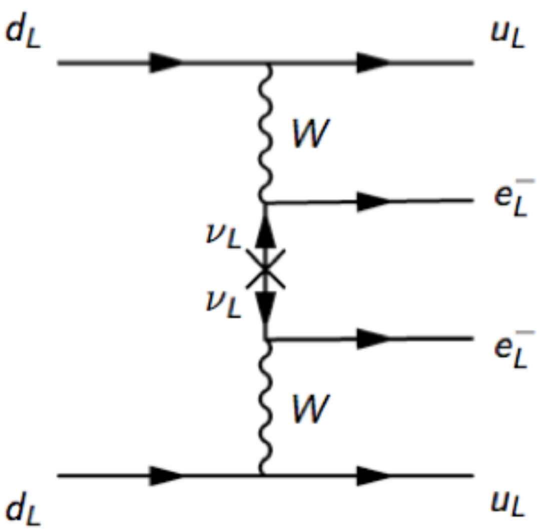


right handed currents

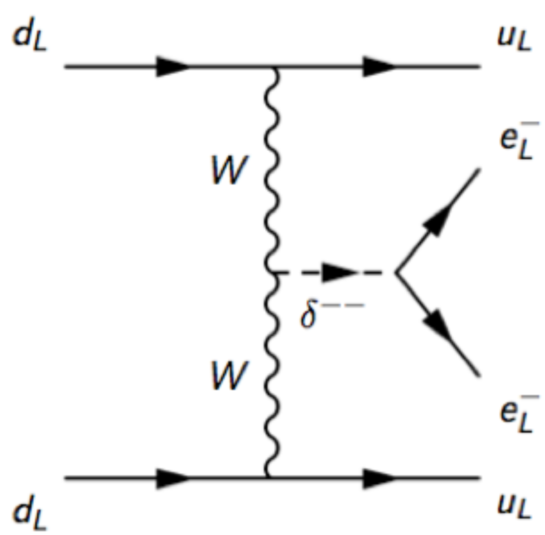
Other 0νββ Decay Mechanisms

Possible processes (not exhaustive)

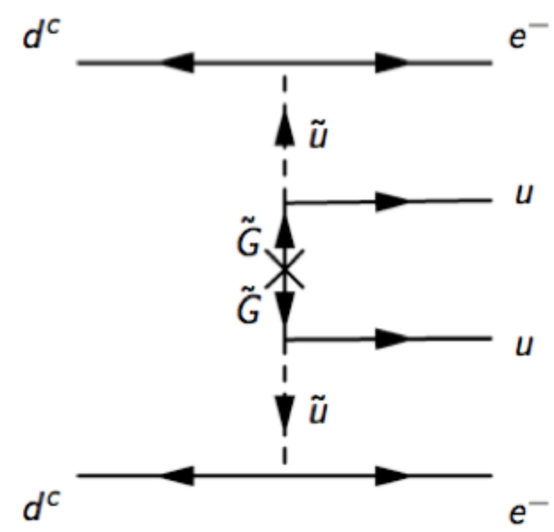
PRD 83, 113003 (2011)



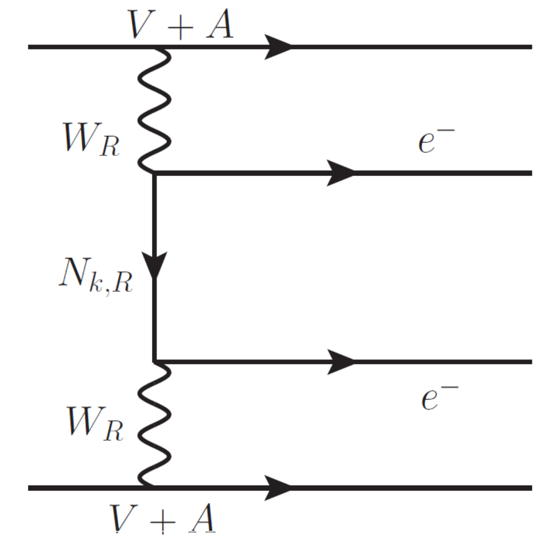
light Majorana



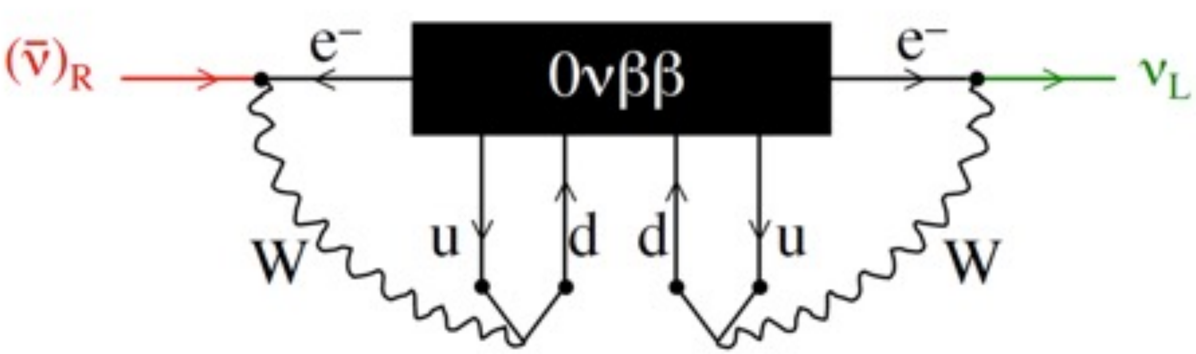
Higgs triplet



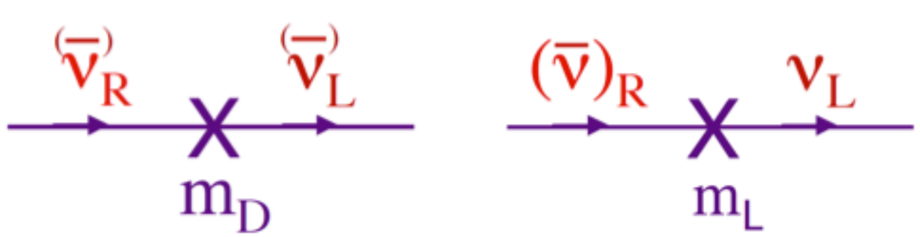
SUSY particle



right handed currents



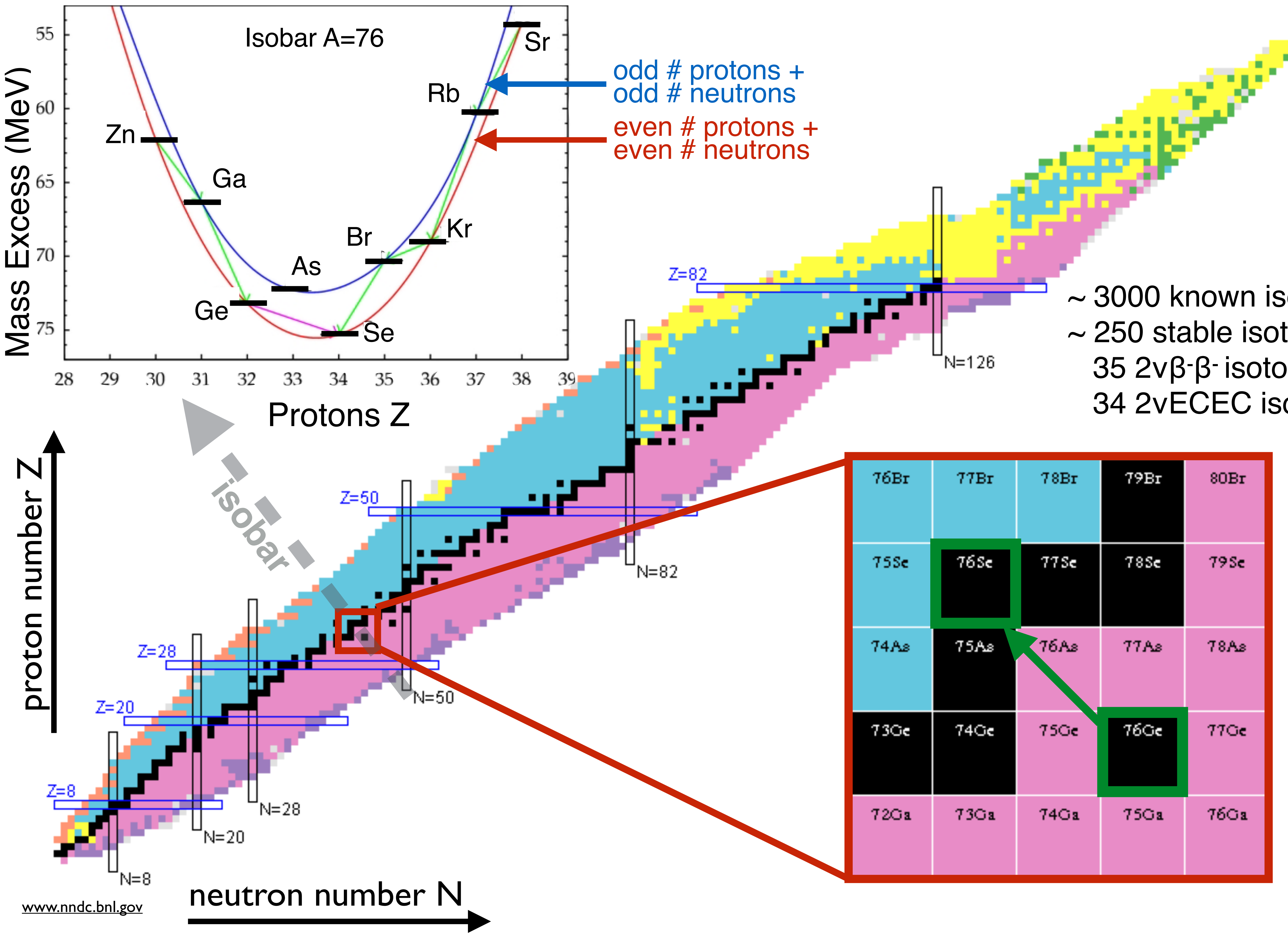
$$\mathcal{L} = m_D \bar{\nu}_R \nu_L + m_M \bar{\nu}_L \nu_L^c$$



Schechter-Valle theorem:

- If 0νββ exists, it can always be interpreted as a neutrino Majorana mass term PRD 25, 2951 (1982)
- Numerically this might be very small JHEP 1106:091 (2011)

Nuclear Physics: Double Beta Decay Isotopes



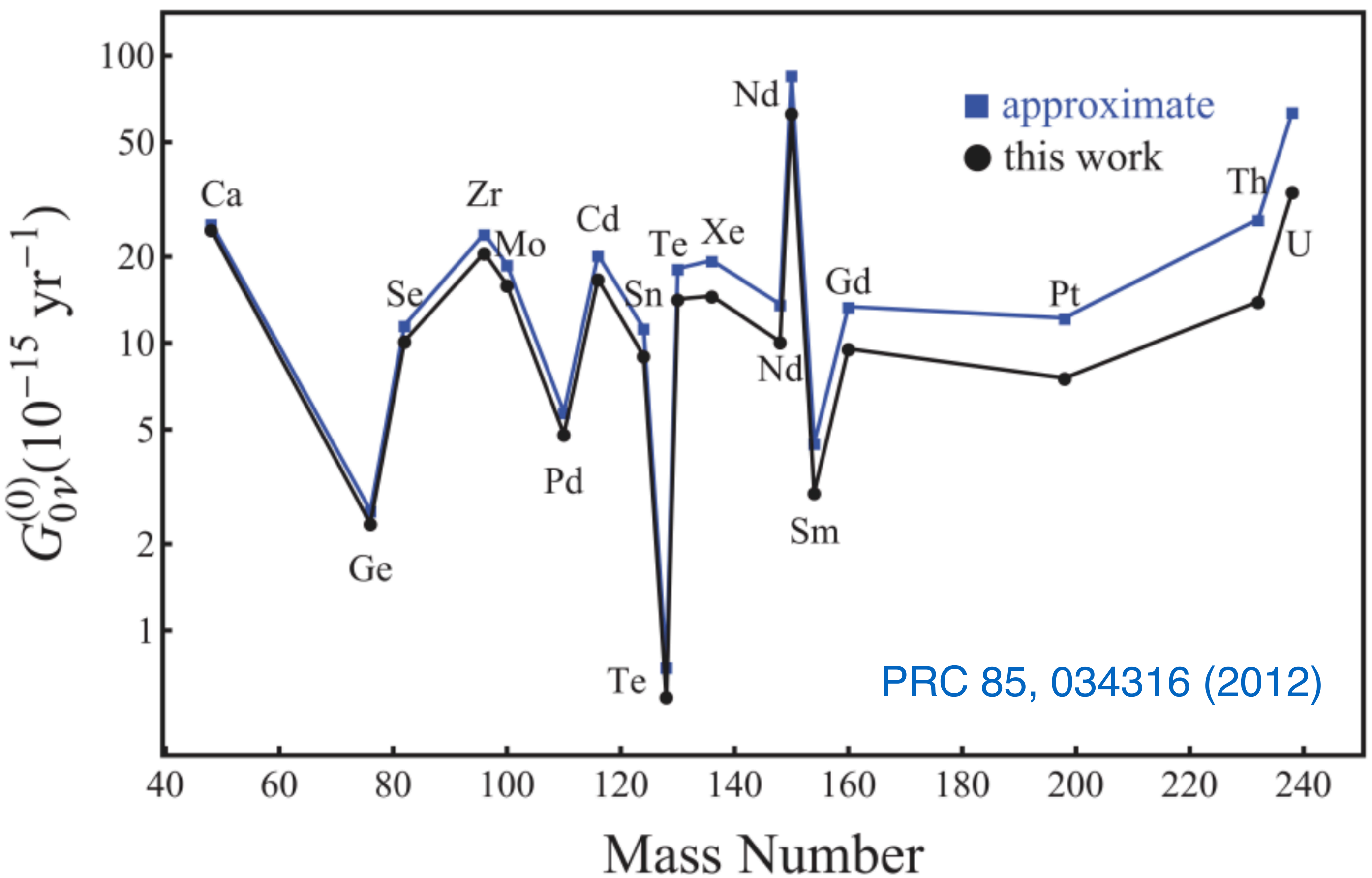
~ 3000 known isotopes
~ 250 stable isotopes
35 $2\nu\beta^-\beta^-$ isotopes
34 2vECEC isotopes

Nuclear Physics: Phase Space and Q-values

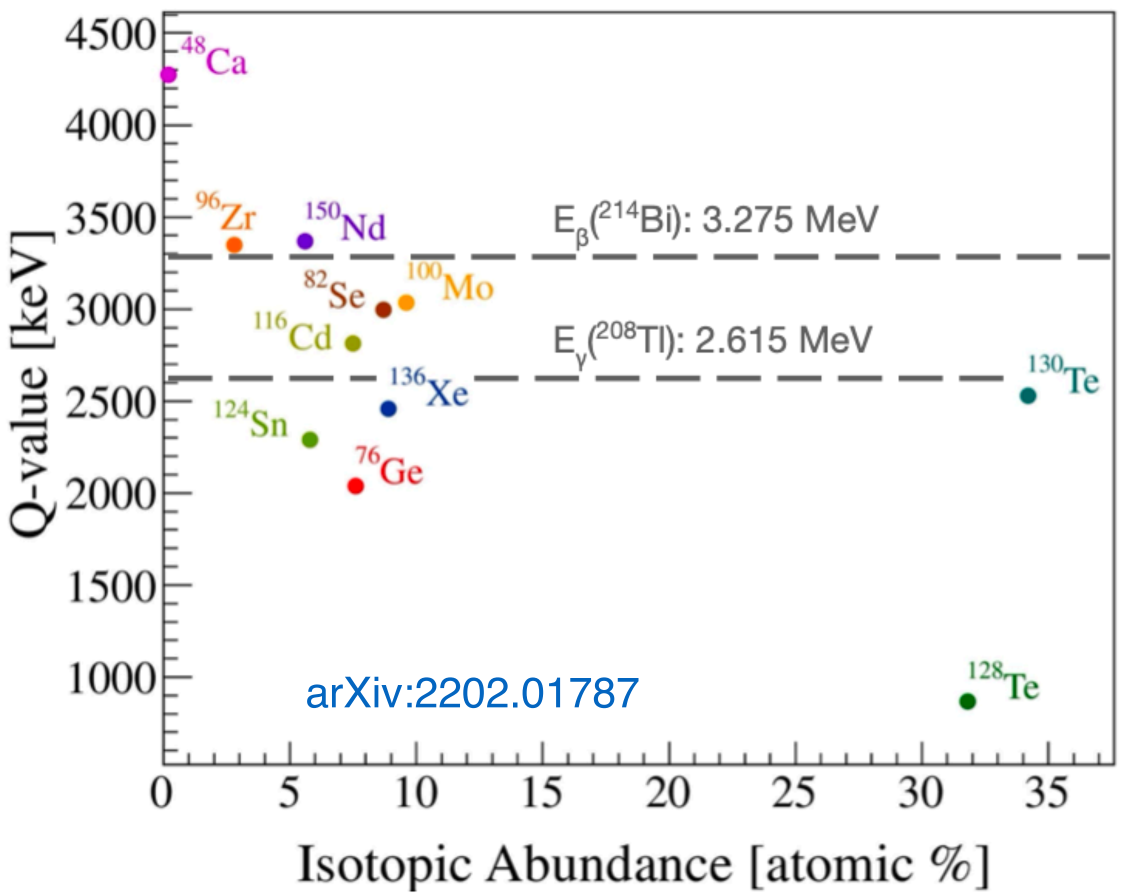
- Ingredients to connect measured half-life to neutrino mass

$$(T_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |m_{\beta\beta}|^2$$

Phase Space Factor ($G^{0\nu}$)



Q-value of decay



- $G^{0\nu}$ scales with Q-value by E^5

- Experimentally lower background with higher Q-value

Nuclear Physics: Matrix Elements

- Ingredients to connect measured half-life to neutrino mass
- Difficult to describe nuclear system of O(100) nucleons

$$\left(T_{1/2}\right)^{-1} = G^{0\nu}\,|M^{0\nu}|^2\,|m_{\beta\beta}|^2$$

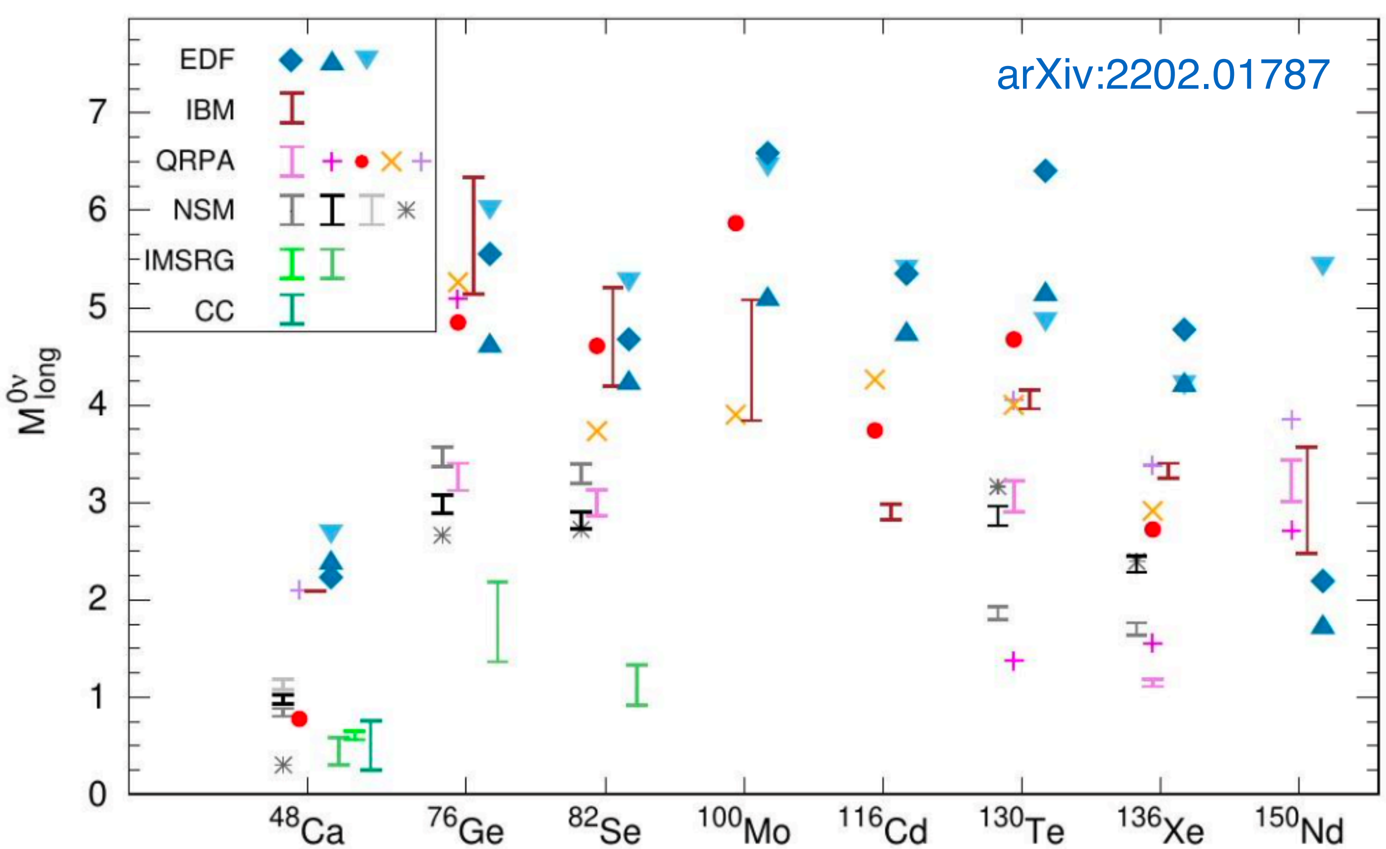
(1) Many body methods

- Approximation to few nucleons in nucleus
- x3 difference between models
- Overprediction of β-decay: ad-hoc quenching of g_A

(2) Ab-initio methods

- Treat explicitly all nucleons in nucleus interacting with realistic forces
- Computationally expensive
- Indicates that g_A quenching is problem in models

Nuclear Matrix Elements ($M^{0\nu}$)



- Large differences of $M^{0\nu}$ between nuclear models
- Enters with $\left(M^{0\nu}\right)^2$
- g_A enters with $(g_A)^4$
- No reliable nuclear models yet
- Active work in progress

Experimental Challenges

Sensitivity, background-free:

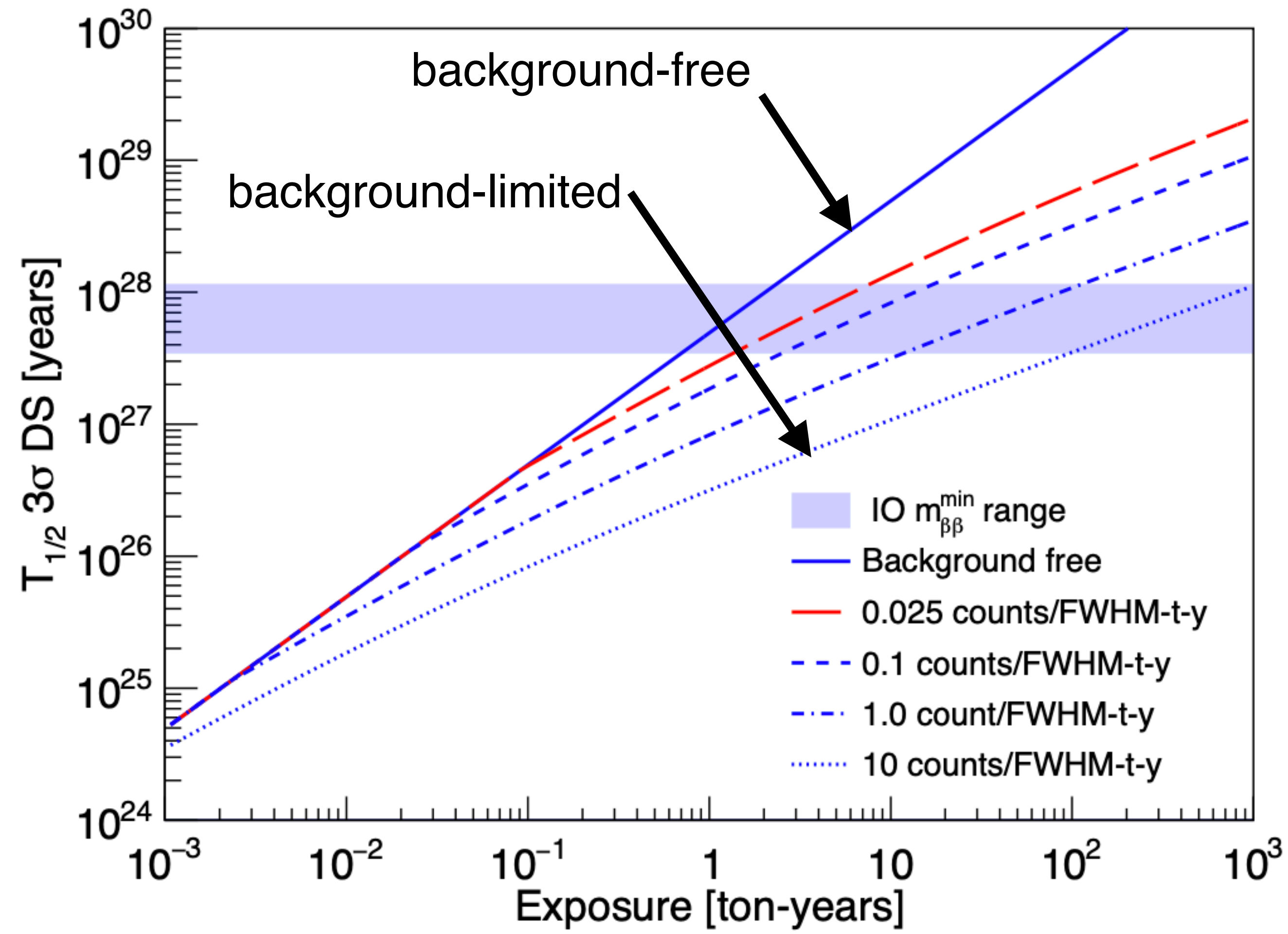
$$T_{1/2} \propto \text{efficiency} \cdot M \cdot T$$

Sensitivity, background-limited:

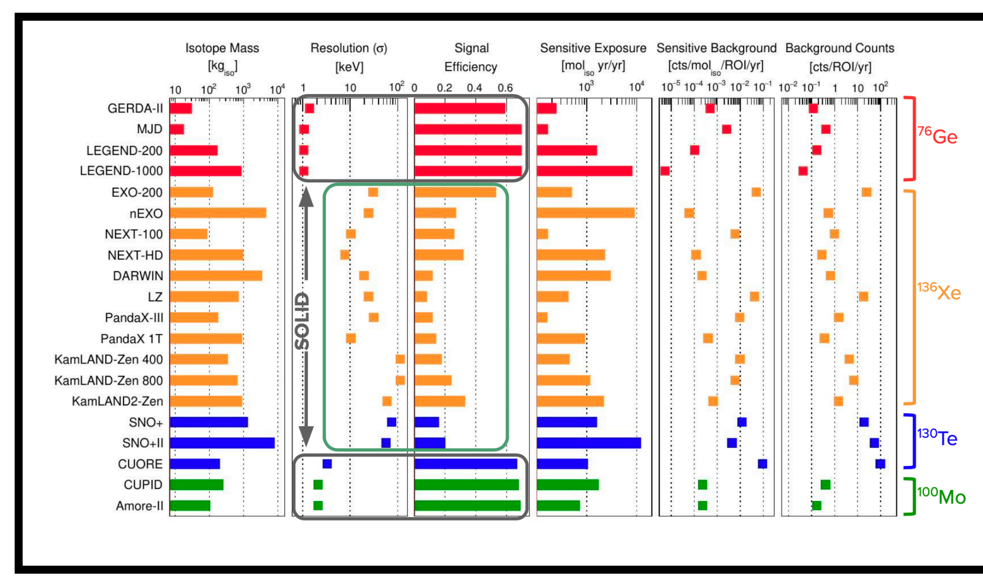
$$T_{1/2} \propto \text{efficiency} \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

Main experimental challenges:

- Reducing background
- Improve energy resolution
- Scale up mass



Long list of NLDBD experiments



arXiv:2202.01787

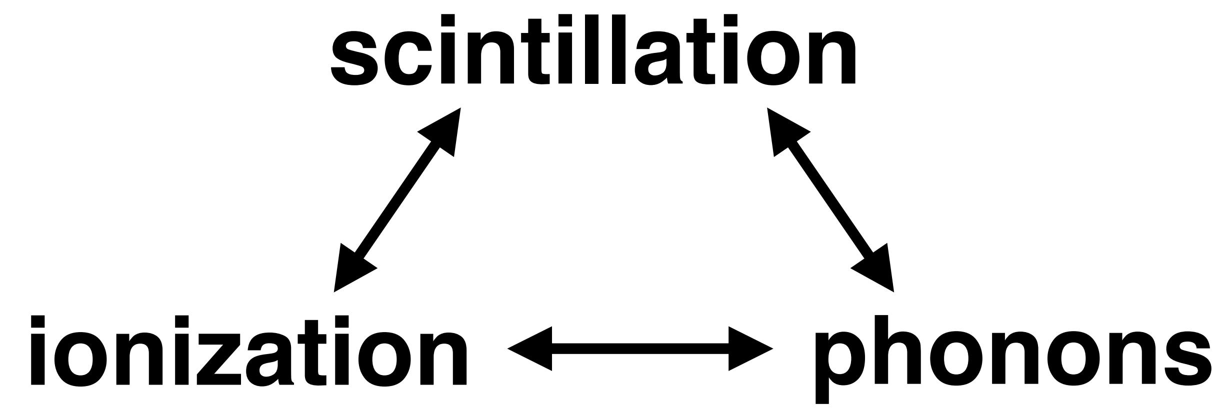
How to measure extremely long half-lives?

- ≈2x10[26] atoms in 20 kg Ge
- Expect ≈1 decay / yr
- Activity of <10[-12] Bq/g

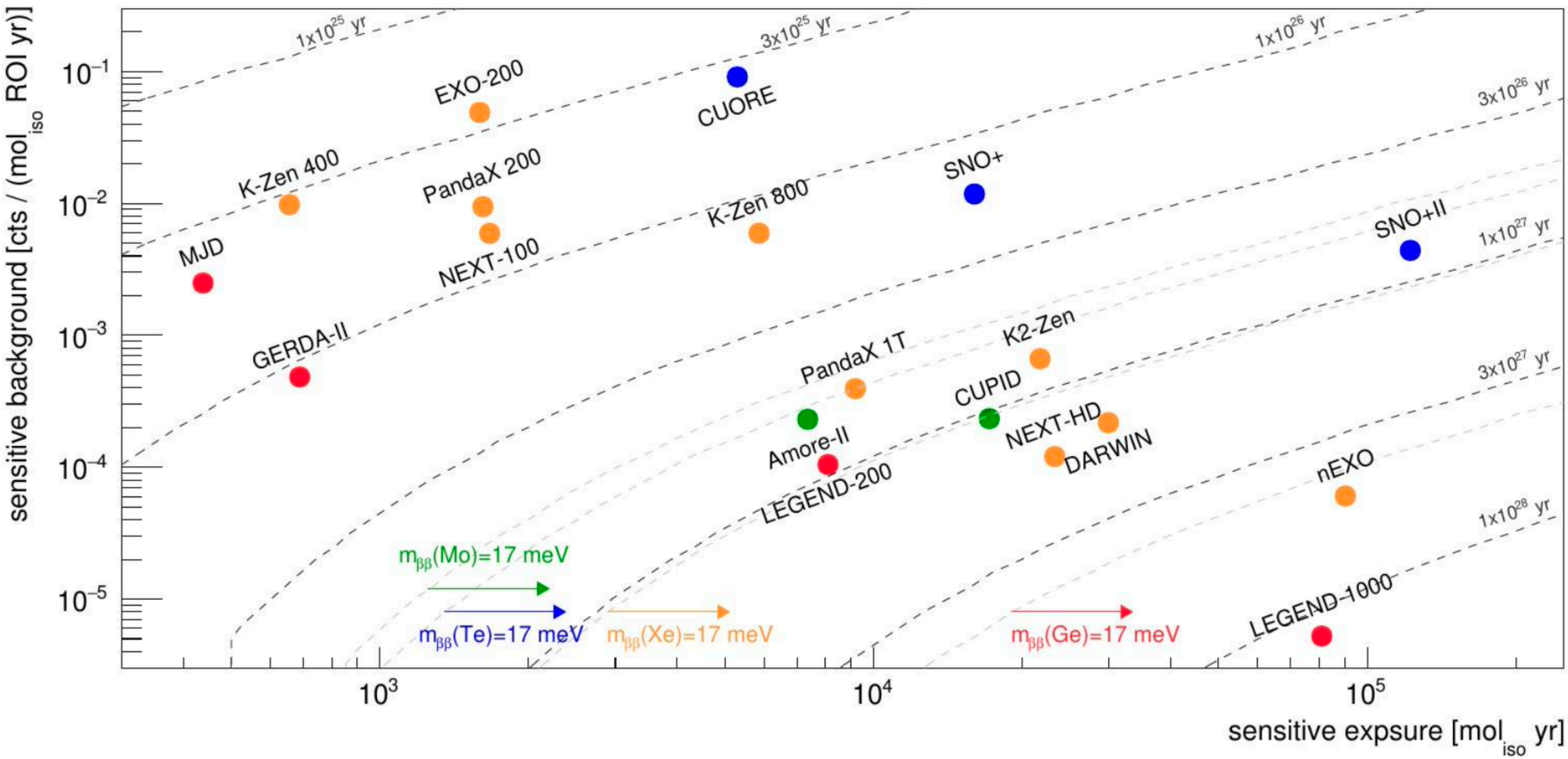
Banana equivalent 31 Bq/g

Sensitivity:

$$T_{1/2} \propto \text{efficiency} \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$



$B \cdot \Delta E$



arXiv:2202.01787

$M \cdot T$

Liquid Scintillators: KamLAND-ZEN (^{136}Xe), SNO+ (^{130}Te)

Advantage LS: Large target mass, self-shielding, multi-purpose detectors

KamLAND-ZEN

@Kamioka, Japan

1 kt LS, ~1900 PMTs (~34% coverage)
91% enriched ^{136}Xe

KL-Zen 400
- 2011-2015
- 350 kg Xe
- $T_{1/2} > 1.1 \times 10^{26}$ yr
- $m_{\beta\beta} < 61 - 165$ meV

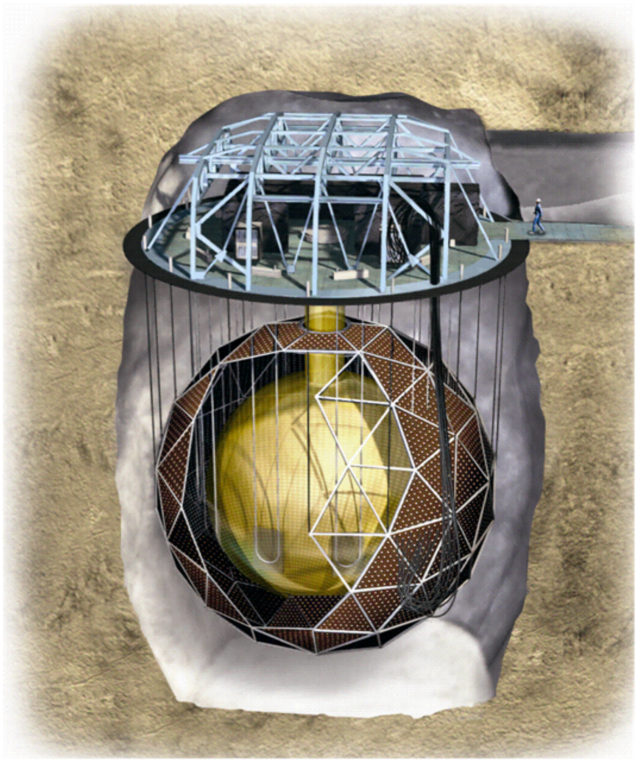
PRL 117, 082503 (2016)

KL-Zen 800
- since 2019
- 745 kg Xe
- $T_{1/2} > 2.3 \times 10^{26}$ yr
- $m_{\beta\beta} < 36 - 156$ meV

arXiv:2203.02139 (2022)

KamLAND 2 Zen (future)
- x5 light collection, scintillating balloon, new electronics
- 1 tonne Xe
- $T_{1/2} \sim 2 \times 10^{27}$ yr (goal)

SNO+



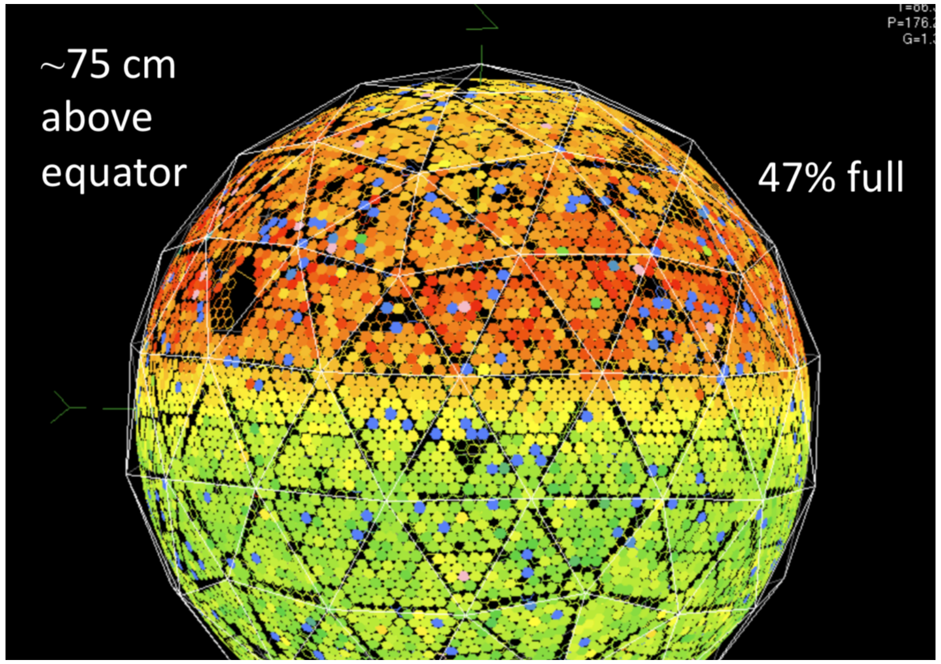
@SNOLAB, Canada

780 t LS, ~9300 PMTs (~50% coverage)
^{nat}Te (34% ^{130}Te)

Sensitivity for ^{nat}Te loading:
- 0.5%: $T_{1/2} \sim 2 \times 10^{26}$ yr (goal)
- 1.5%: $T_{1/2} \sim 4 \times 10^{26}$ yr (goal)
- 2.5%: $T_{1/2} \sim 1 \times 10^{27}$ yr (goal)

(0.5% loading ~1.3 t ^{130}Te)

filling with liquid scintillator

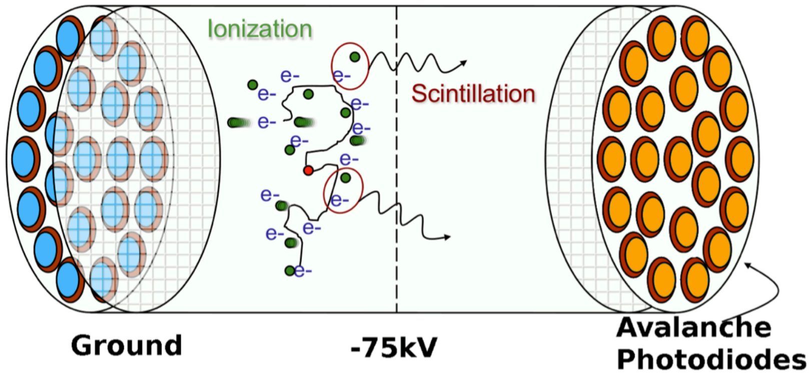


Xe TPCs: nEXO, NEXT, Darwin (^{136}Xe)

Advantage Xe TPC:
Self-shielding, Particle ID

LXe TPC single phase: EXO-200, nEXO

- signal: charge + scintillation light
- enriched ^{136}Xe (90%)



EXO-200 TPC @WIPP, USA

EXO-200

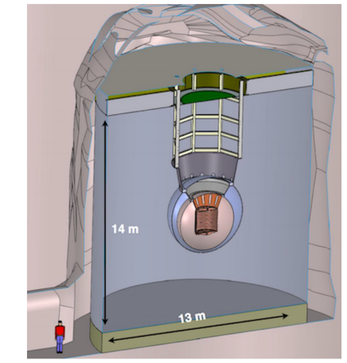
- 200 kg ^{enr}Xe
- $T_{1/2} > 3.5 \times 10^{25}$ yr (90% CL)
- $m_{\beta\beta} < 93$ - 286 meV

PRL 123, 161802 (2019)

nEXO

- 5 tonne ^{enr}Xe
- $T_{1/2} \sim 10^{28}$ yr (goal)
- $m_{\beta\beta} \sim 6$ - 18 meV (goal)

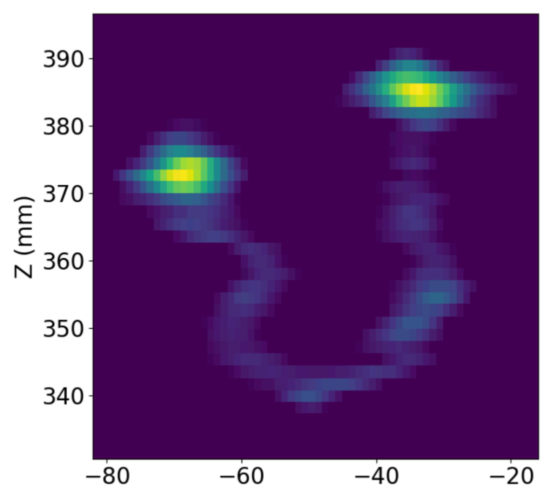
arXiv:1805.11142



@ SNOLAB

HPXeEL TPC: NEXT

NEXT-100 TPC @Canfranc, Spain



$\beta\beta$ topology ID

Experimental plans:
NEXT-White (5 kg)
NEXT-100 (100 kg)
NEXT-HD (1 t, ~10^{27} yr)
NEXT-BOLD (~10^{28} yr)

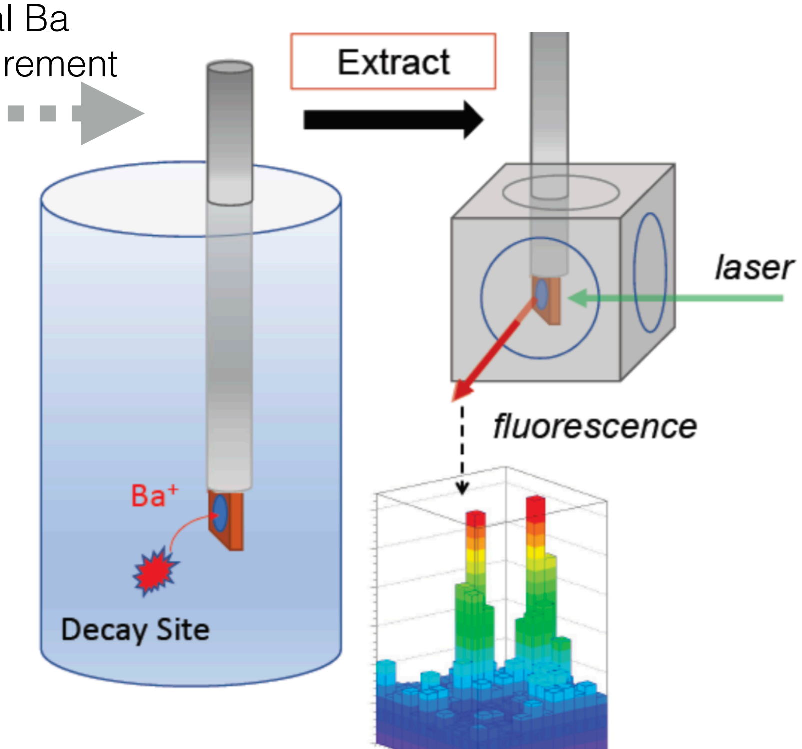
arXiv:1906.01743

Future potential: barium tagging

external Ba measurement

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$$

internal Ba measurement

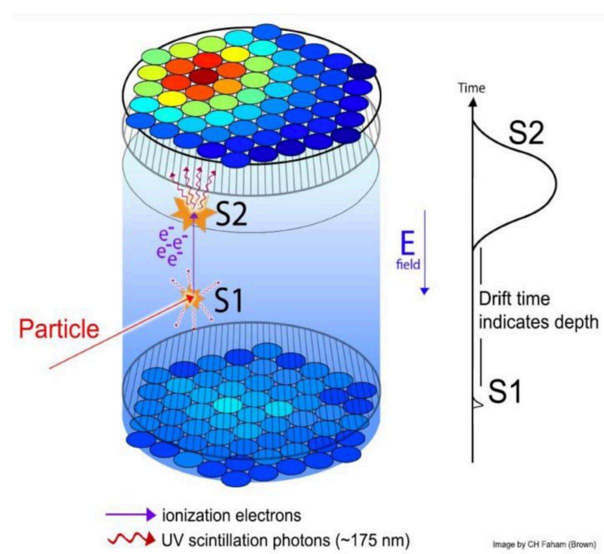


Nature 569, 203 (2019)

LXe TPC dual phase: Dark Matter detectors

- Xe WIMP detectors also sensitivity to $0\nu\beta\beta$ - decay
- Discovery of 2νECEC in ^{124}Xe (Xenon-1t)

Nature 568, 532 (2019)

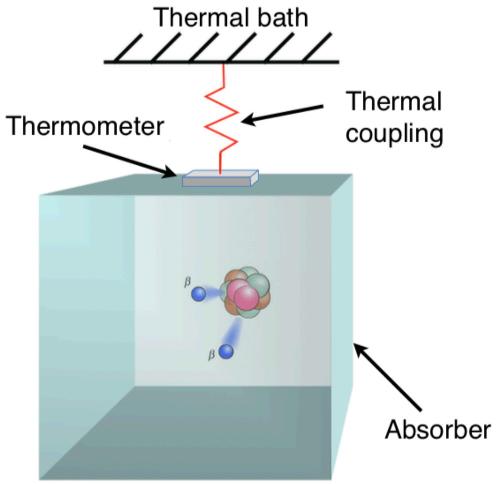


DARWIN:

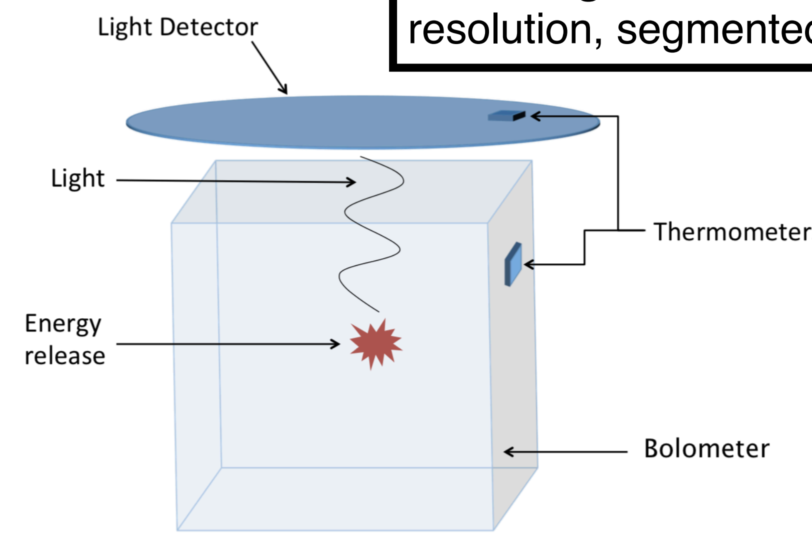
- 50 tonne ^{nat}Xe (9%),
- $T_{1/2} \sim 2.4 \times 10^{27}$ yr (goal)

arXiv:2003.13407

Bolometers: CUORE (^{130}Te), CUPID (^{100}Mo)



@LNGS, Italy



Advantage bolometers: Good resolution, segmented, flexible isotope

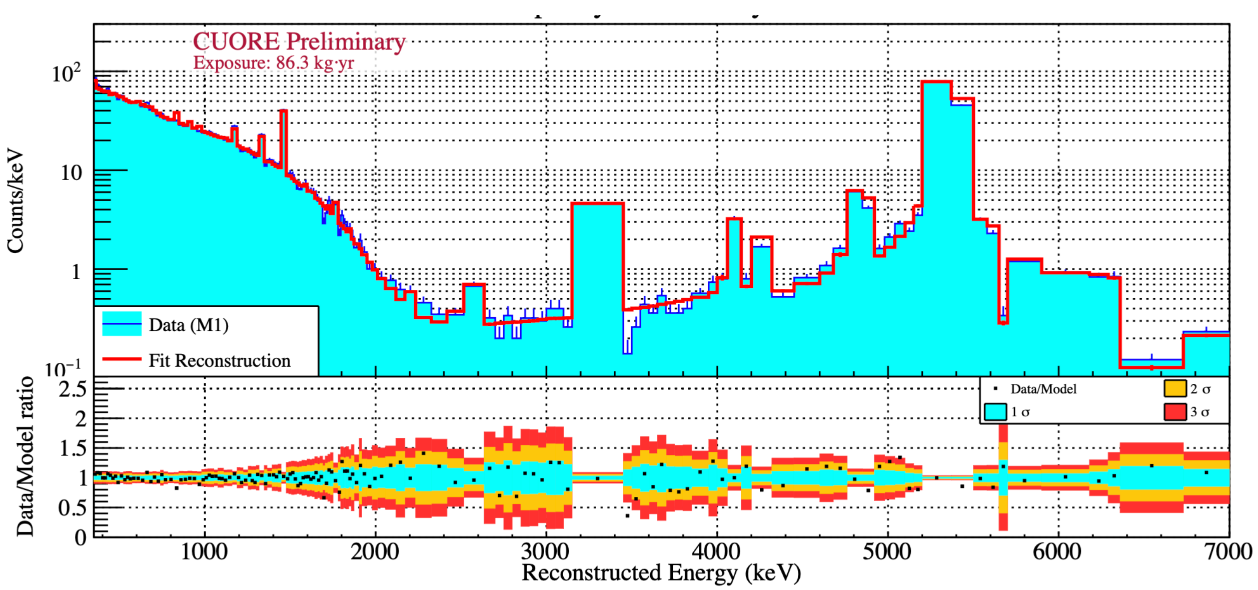
CUORE
- $^{nat}TeO_2$ crystals
- Heat
- $T_{1/2} > 2.2 \times 10^{25}$ yr (90% CI)
- $m_{\beta\beta} < 90$–305 meV

[Nature 604, 53 (2022)](#)

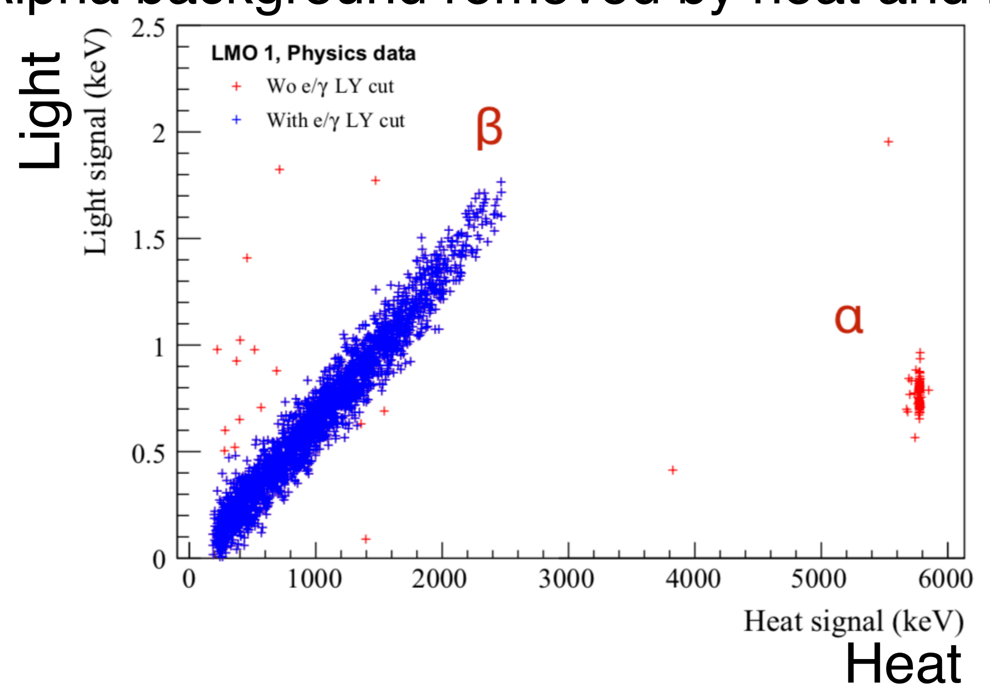
similar mass but major background reduction

CUPID
- $Li_2{}^{100}MoO_4$ crystals (enriched)
- Heat + light
- $T_{1/2} \sim 10^{27}$ yr (goal)
- $m_{\beta\beta} \sim 10$ - 20 meV (goal)

Background in CUORE dominated by alphas



Alpha background removed by heat and light



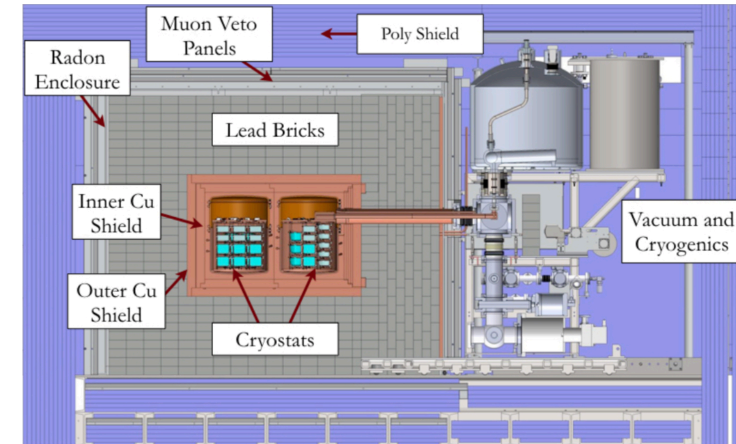
HPGe Detectors: GERDA, MJD, LEGEND (^{76}Ge)

Advantage HPGe:
Best resolution, segmented

@LNGS, Italy

GERDA
- HPGe in liquid argon
- Lowest background
- 44 kg ^{enr}Ge
- $T_{1/2} > 1.8 \times 10^{26}$ yr
- $m_{\beta\beta} < 80 - 182$ meV

Majorana Demonstrator
- HPGe in vacuum
- Best energy resolution
- 30 kg ^{enr}Ge
- $T_{1/2} > 8.3 \times 10^{25}$ yr
- $m_{\beta\beta} < 113–269$ meV

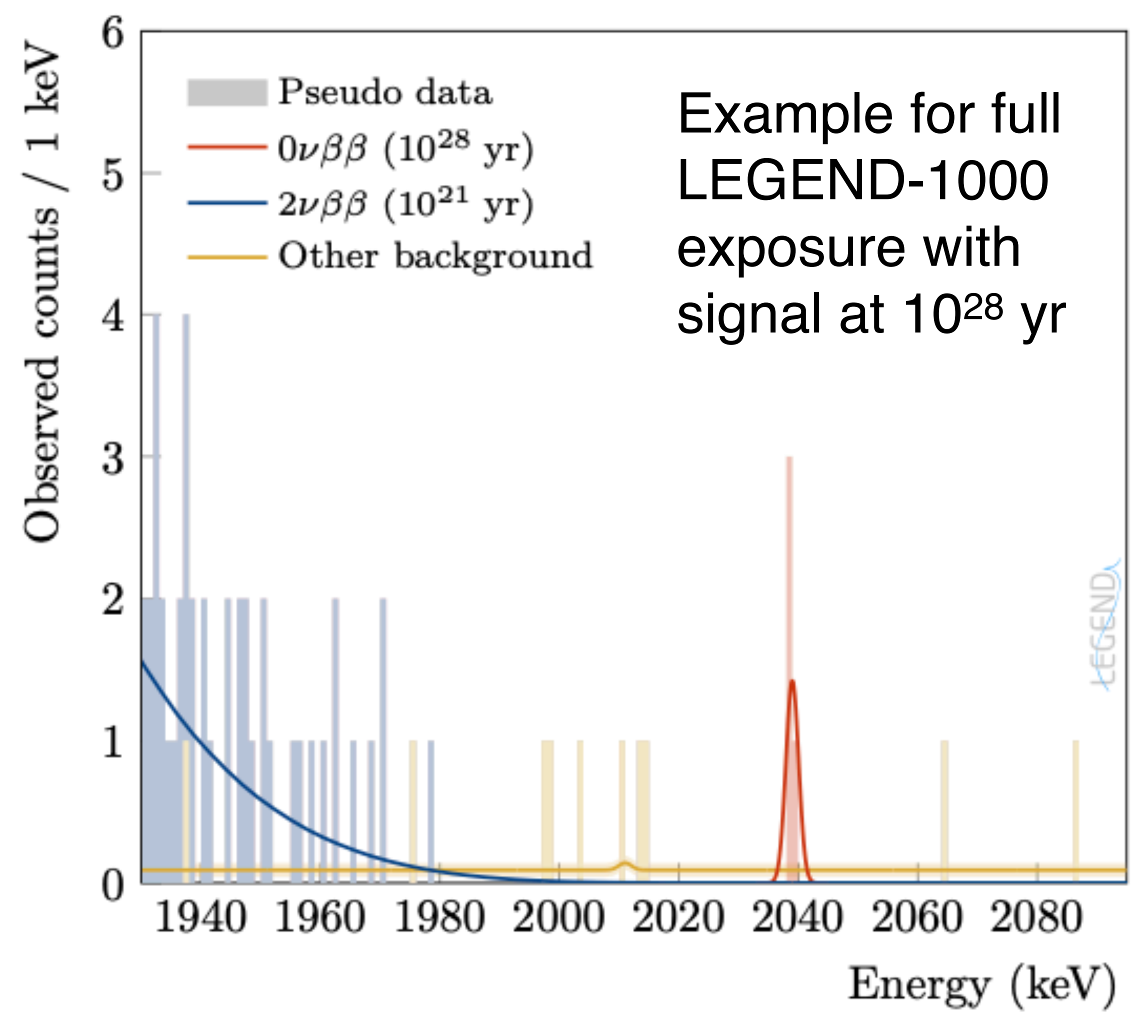


@SURF, USA

combining technology + new concepts

LEGEND-200
- Under commissioning in GERDA infrastructure
- $T_{1/2} \sim 10^{27}$ yr (goal)

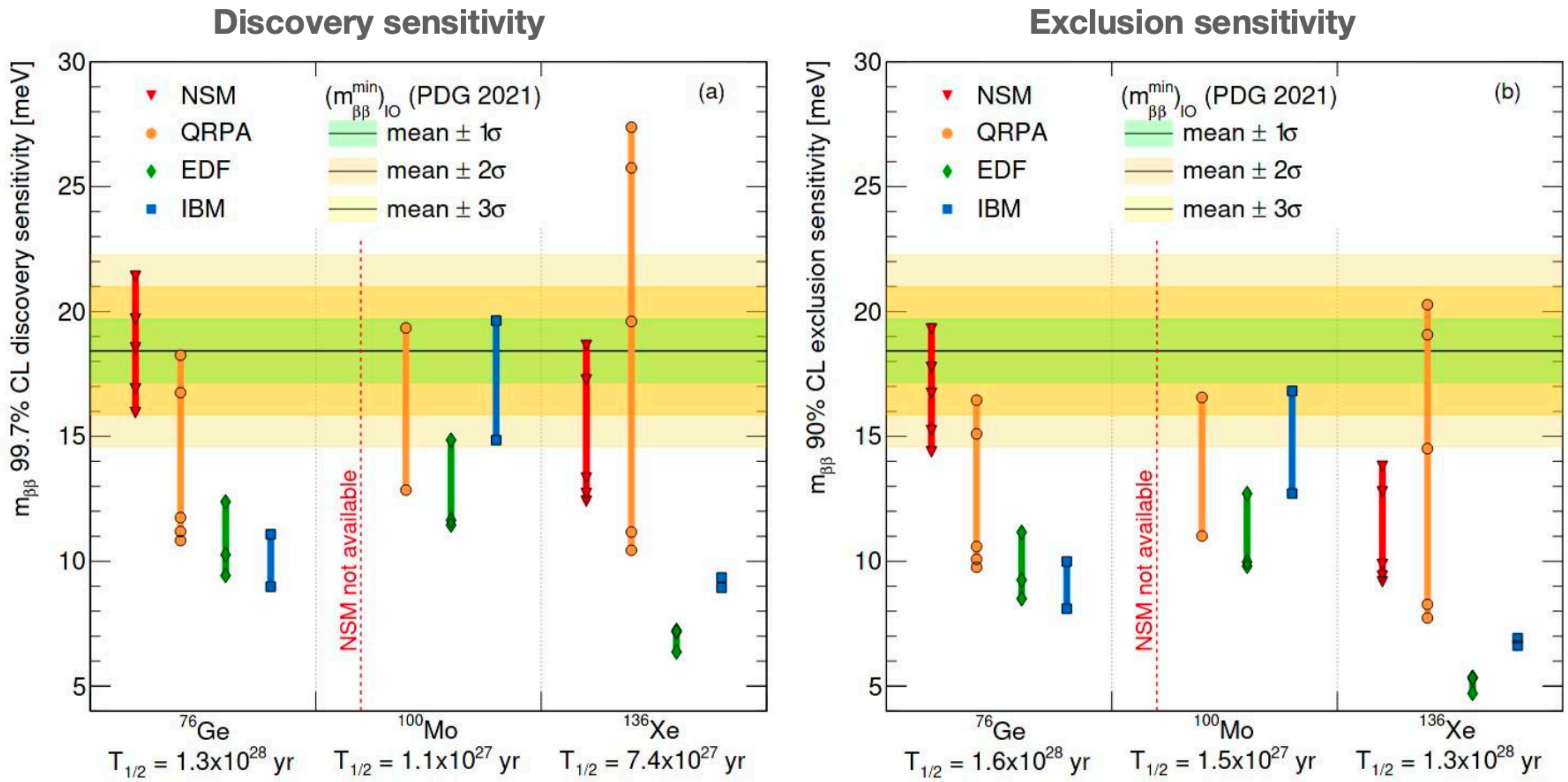
LEGEND-1000
- Tonne scale
- Underground argon
- $T_{1/2} \sim 10^{28}$ yr (goal)
- $m_{\beta\beta} \sim 10 - 20$ meV (goal)



Example for full LEGEND-1000 exposure with signal at 10^{28} yr

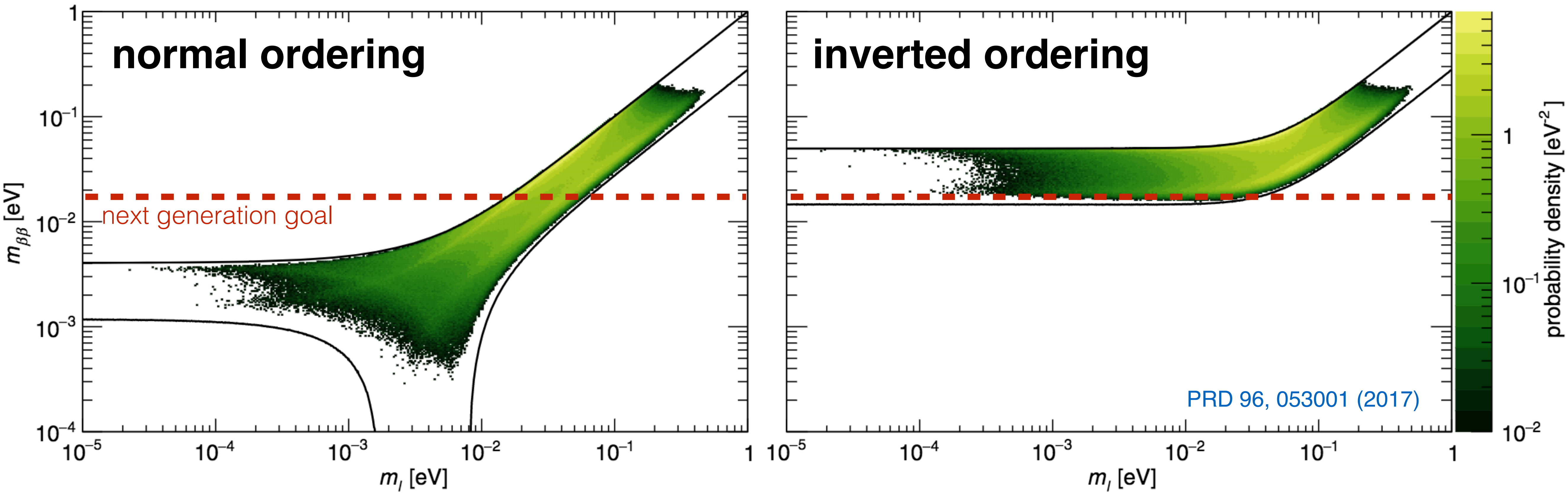
Conclusion I: Experimental status 2022

- Multitude of different detection techniques in different isotopes investigated in past decades
- 3 most promising techniques identified for “tonne-scale” NLDBD
  - Germanium detectors (^{76}Ge) - LEGEND-1000 arXiv:2107.11462
  - Liquid xenon TPC (^{136}Xe) - nEXO arXiv:1805.11142
  - Cryogenic bolometers (^{100}Mo) - CUPID arXiv:1907.09376
- Preparation for CD1 in 2023 - major funding imminent
- Data taking around 2030 for O(10 yr)



Conclusion II: What if Normal Ordering?

- Bayesian sampling of lobster plot (assuming flat priors on phases)



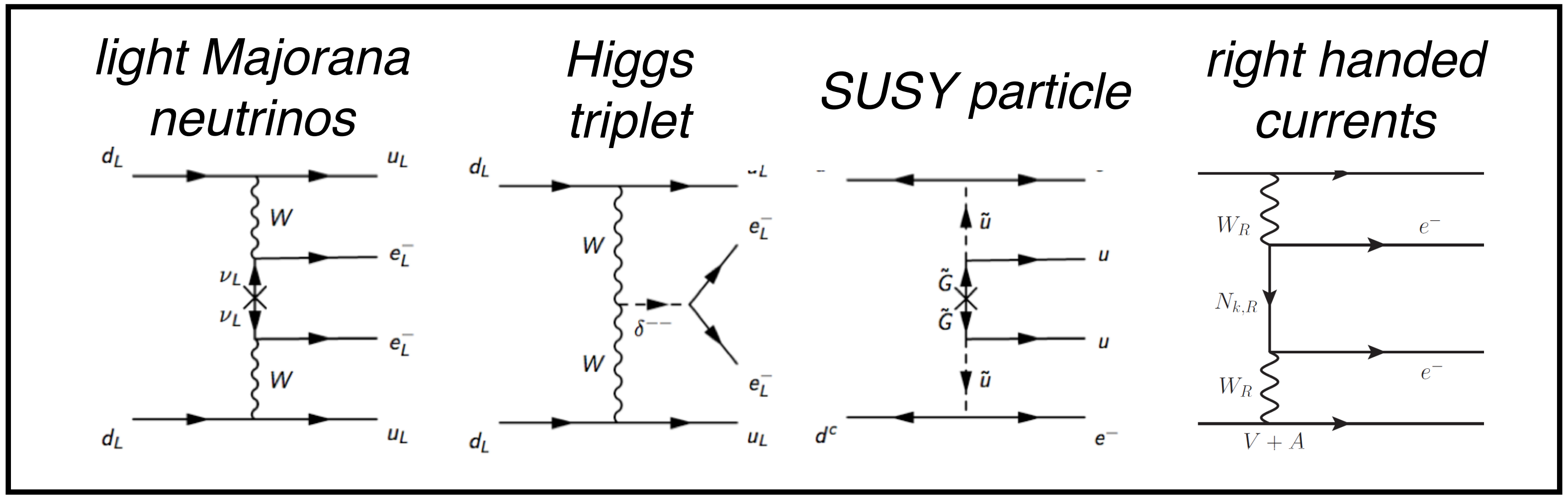
- Even if normal ordering is realized there is good chance of discovery!

Conclusion III: What if we discover NLDBD?

- Observed matter creation
- L and B-L are violated
- Neutrinos are Majorana particles

$$\left(T_{1/2}\right)^{-1} = G^{0\nu} \cdot \left| \sum_{\text{mech } i} M_i^{0\nu} \cdot \eta_i \right|^2$$

different dominant LNV mechanism?
coherent sum of multiple LNV mechanisms?

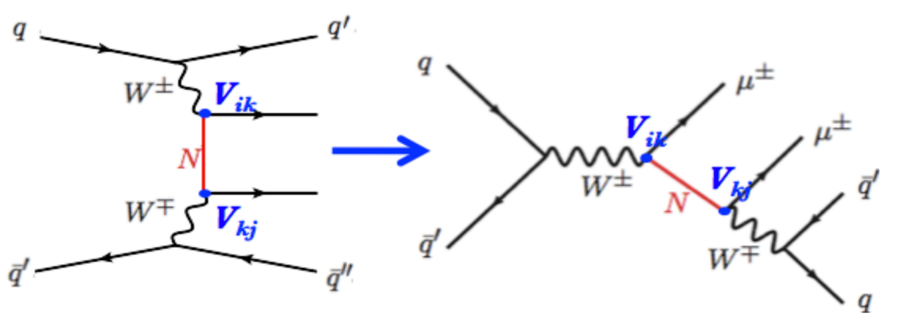


BUT: What is the mechanism?

- Disentangle mechanism with observation in multiple isotopes
- Very strong motivation for different 0νββ decay experiments / isotopes

Possible other signatures:

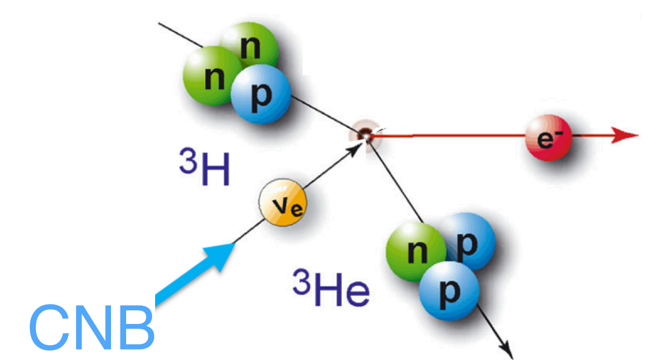
Same sign di-lepton di-jet searches



LNV with rare Kaon decay

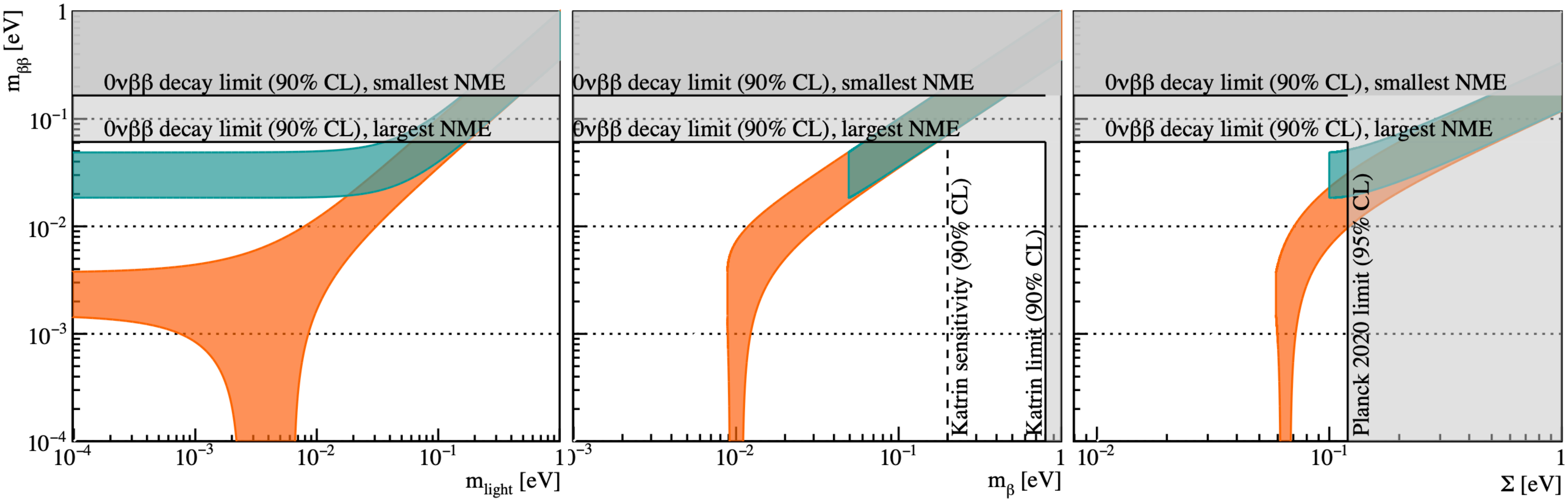
- $K^+ \rightarrow \pi^+ \nu\nu$
- $K_L \rightarrow \pi^0 \nu\nu$

Cosmic Neutrino Background



Backup

Neutrino Connection



arXiv:2202.01787