Toward the Discovery of Matter Creation with Neutrinoless $\beta\beta$ Decay

Theory & Experiment

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LEGEND UK Open Workshop, 31/03/2022, UCL

Most of the material taken from
M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

UCL

UKRI Science and Technology Facilities Council

Why do we search for neutrinoless $\beta\beta$ Decay?

C:1. What are the fundamental particles and fields?	C:2. What are the fundamental laws and symmetries of physics?	C:3. What is the nature of space-time?
C:4. What is the nature of dark matter and dark energy?	C:5. How do quarks and gluons form hadrons?	C:6. What is the nature of nuclear matter?
C:7. Are there new phases of strongly interacting matter?	C:8. Why is there more matter than antimatter?	C:9. What will precision measurements of the Higgs boson reveal about the Universe?

What is matter? What are its fundamental blocks?

According to the Standard Model

- matter-antimatter symmetry
- energy ↔ particle + antiparticle
- still, our universe is dominated by particles

There must be processes altering

- $B = N_{baryons} - N_{anti\text{-}baryons}$
- $L = N_{leptons} - N_{anti\text{-}leptons}$
- **B - L**

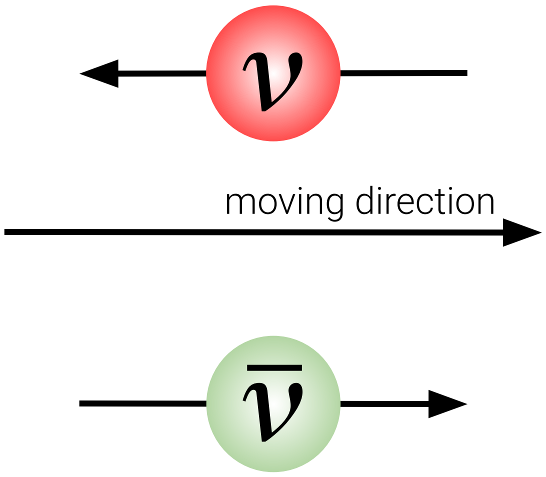
Matter			charge		Antimatter		
Quarks (B = +1/3, L=0)					Antiquarks (B = -1/3, L=0)		
u	c	t	+2/3	-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
d	s	b	-1/3	+1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
Leptons (B = 0, L=+1)					Antileptons (B = 0, L=-1)		
e	μ	τ	-1	+1	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$
ν_e	ν_μ	ν_τ	0	0	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

What distinguishes particles from antiparticles?

What distinguishes neutrinos from antineutrinos?

What distinguishes neutrinos from antineutrinos?

If they have no mass:
helicity = chirality



move antiparallel to its spin

left-handed chirality -> weakly-interact creating **particles**

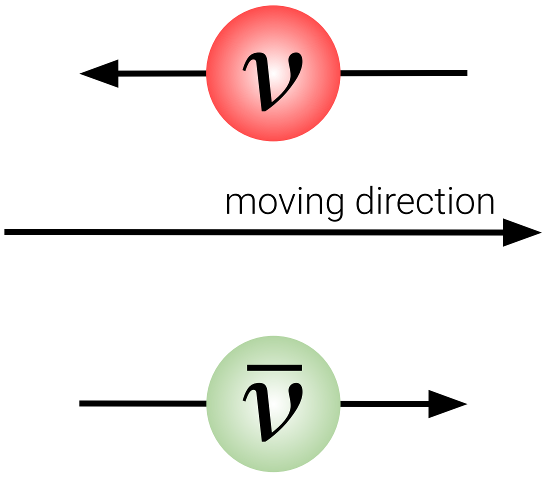
move parallel to its spin

right-handed chirality -> weakly-interact creating **antiparticles**

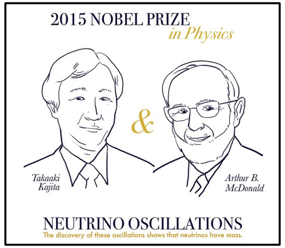
Dell'Oro, Marcocci, Viel and Vissani
Adv.High Energy Phys. 2016 (2016) 2162659

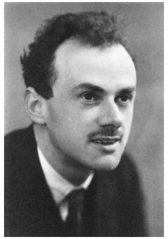
What distinguishes neutrinos from antineutrinos?

If they have no mass:
helicity = chirality

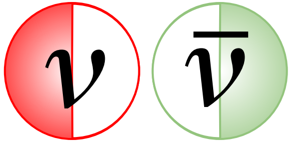


But neutrinos are massive!
In rest frame: helicity≠ chirality

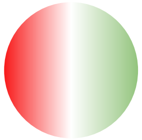




Dirac



Majorana



$\nu = \bar{\nu}$

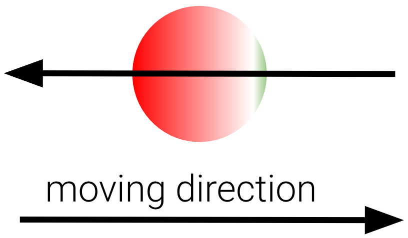
There are two "non-interacting" states….

…or a neutrino can always interact creating both matter & antimatter

Dell'Oro, Marcocci, Viel and Vissani
Adv.High Energy Phys. 2016 (2016) 2162659

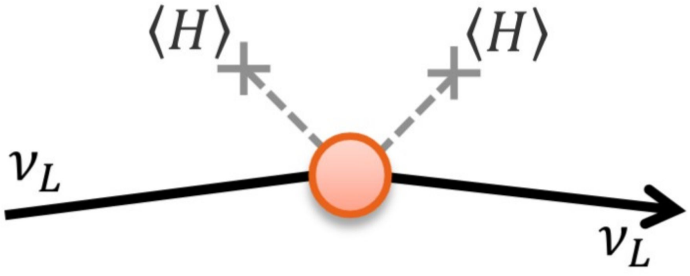
Neutrino-antineutrino transformations

If neutrinos are Majorana, both chiralities are always present



- mechanisms to change L (and thus B-L)
- explain mystery of neutrino masses
  … and why there are so small

Majorana masses



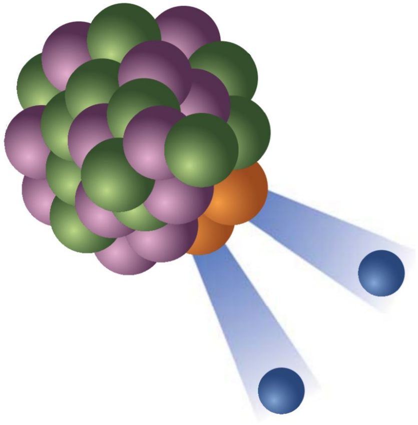
- not the Standard Higgs mechanism!
- no need for tiny Yukawa couplings
- see-saw models can explain tiny masses by introducing heavy right-handed states

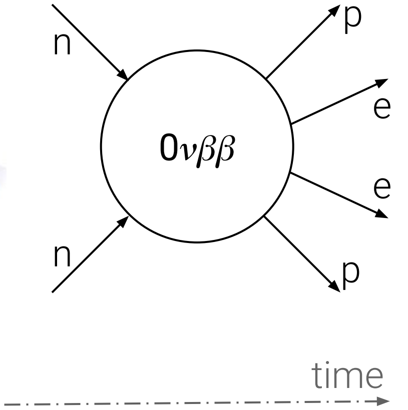
The test: neutrinoless $\beta\beta$ decay ($0\nu\beta\beta$)

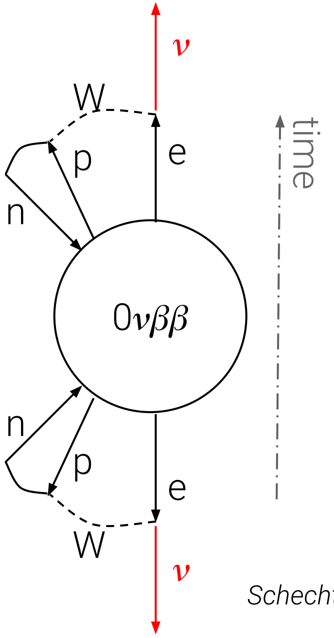
- (A,Z) -> (A,Z+2) + 2
- 2 neutrons -> 2 into two protons (ΔB = 0)
- 2 electrons are emitted (ΔL = 2)
- direct violation of L and B-L

Same diagram creates $\boldsymbol{\nu \leftrightarrow \bar{\nu}}$

A tiny, but non-zero Majorana mass







Schechter and Valle, 1982

A portal to new physics beyond the SM

$$\Gamma \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Particle Physics

Nuclear Physics

A portal to new physics beyond the SM

$$\Gamma \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Higgs vacuum expectation

energy scale of BSM

phase space factor

hadronic matrix element

nuclear matrix element (NME)

A portal to new physics beyond the SM

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Higgs vacuum expectation

energy scale of BSM

phase space factor

hadronic matrix element

nuclear matrix element (NME)

Can be computed accurately

(even if sometime ***g*** is used to incorporate biases in NME calculations)

Requires calculations of :

- wavefunction overlap between initial and final states
- lepton-nucleus interaction

$$\langle \text{Final} \,|\, \mathcal{L}_{\text{leptons}-\text{nucleons}} \,|\, \text{Initial} \rangle = \langle \text{Final} \,|\, \int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Initial} \rangle$$

Deppisch, Graf, Iachello and Kotila, PRD 102 (2020) 9, 095016

A portal to new physics beyond the SM

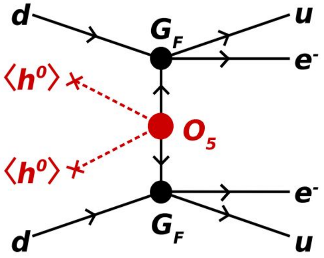
$$\Gamma \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Higgs vacuum expectation

energy scale of BSM

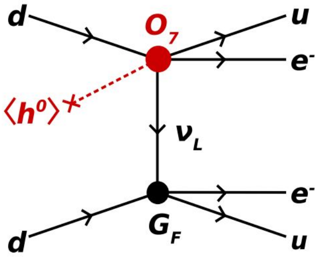
Dim 5: Weinberg Operator

$$\frac{1}{T_{1/2}} \propto \left(\frac{\nu}{\Lambda}\right)^2 \text{with } \frac{\nu}{\Lambda} = \frac{m_{\beta\beta}}{m_e}$$



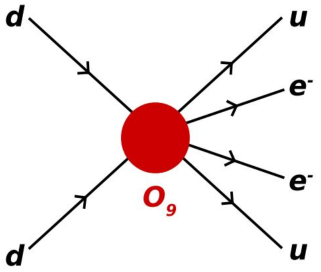
Dim 7

$$\frac{1}{T_{1/2}} \propto \left(\frac{\nu}{\Lambda}\right)^6$$

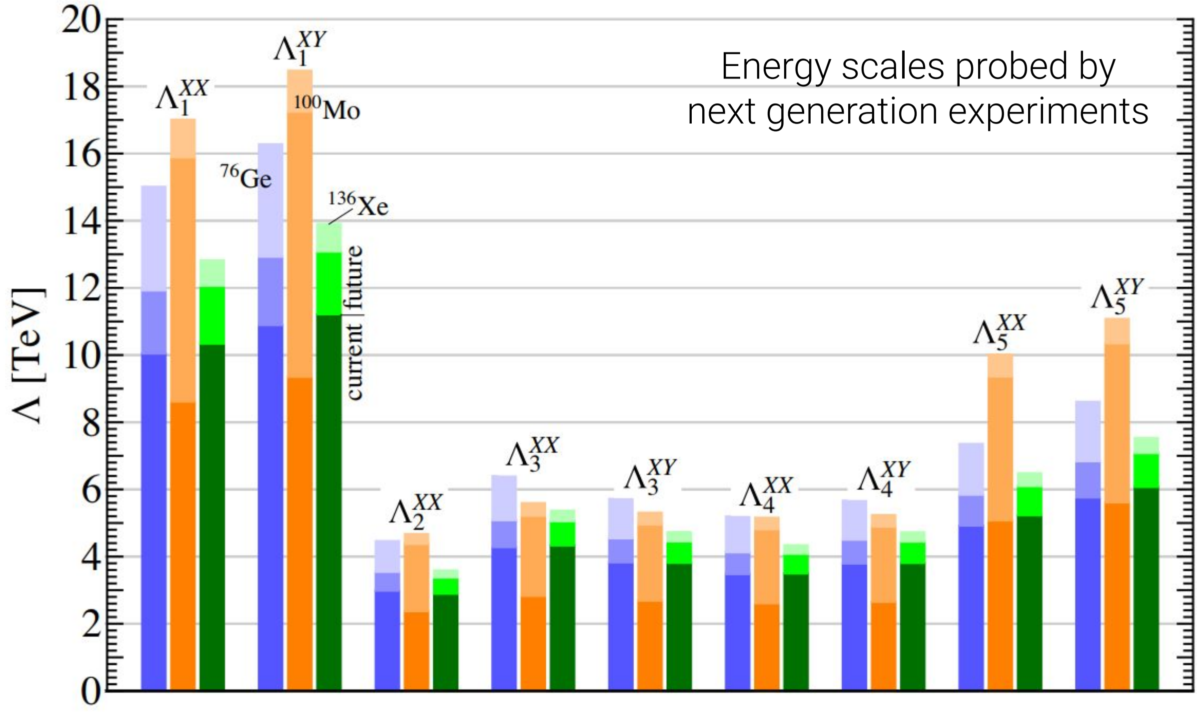


Dim 9

$$\frac{1}{T_{1/2}} \propto \left(\frac{\nu}{\Lambda}\right)^{10}$$



A generic search for ultrahigh-energy BSM physics



Deppish, Graf, Iachello and Kotila
PRD 102 (2020) 9, 095016

Complementary to current and future accelerators

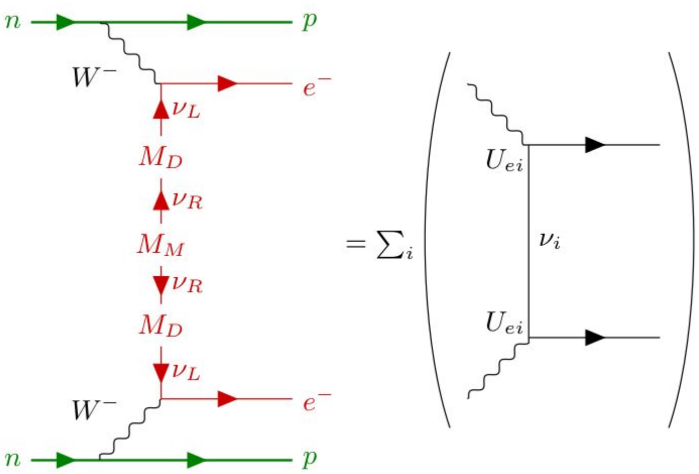
$T_{1/2}$ is proportional to the energy scale, similarly to the collision energy

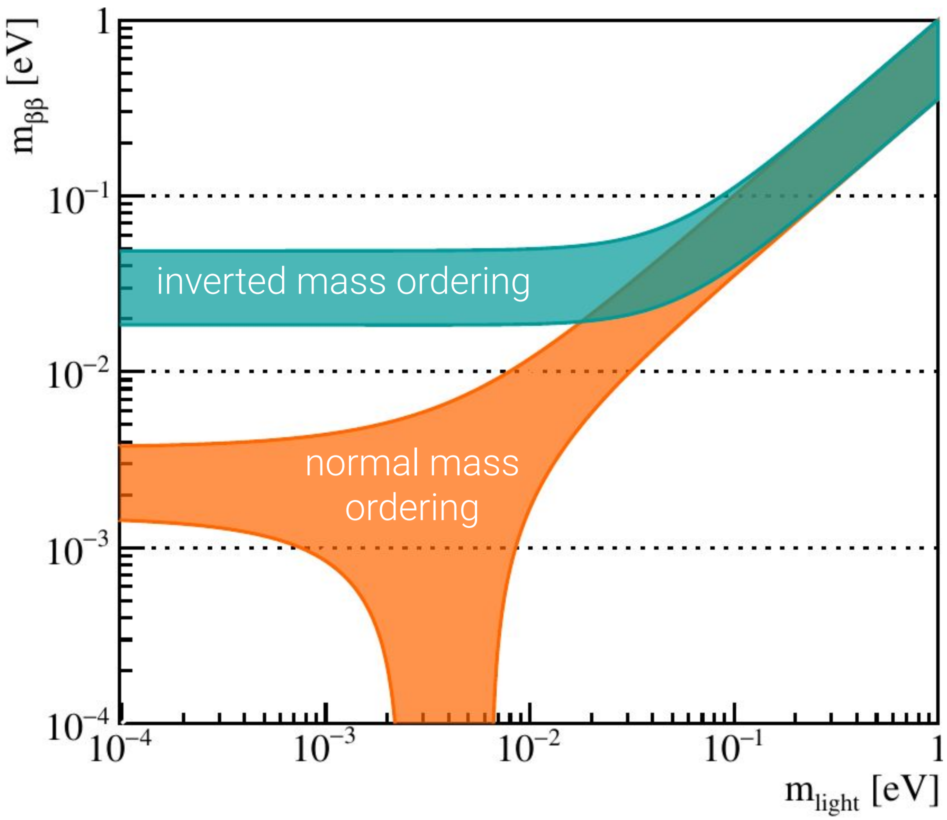
Generic search: a signal can manifest at any time

Light neutrino exchange - Propagator

Parameter connected to neutrino mixing probabilities, masses and complex phases

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



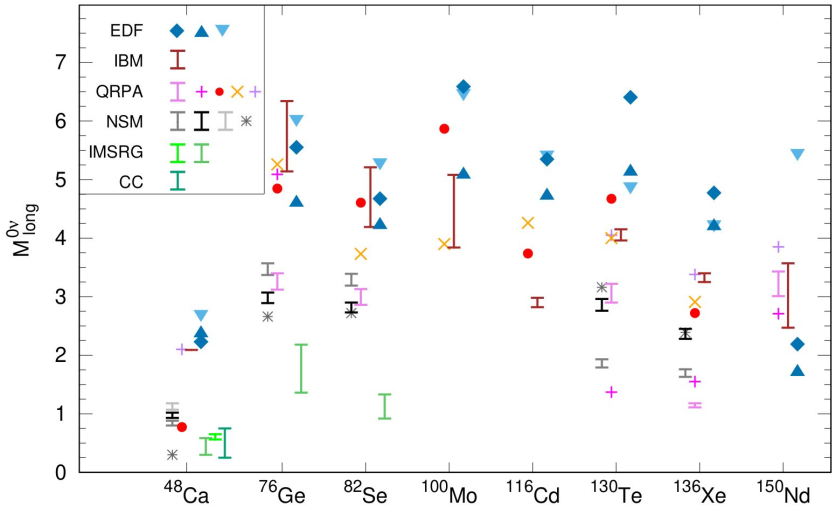


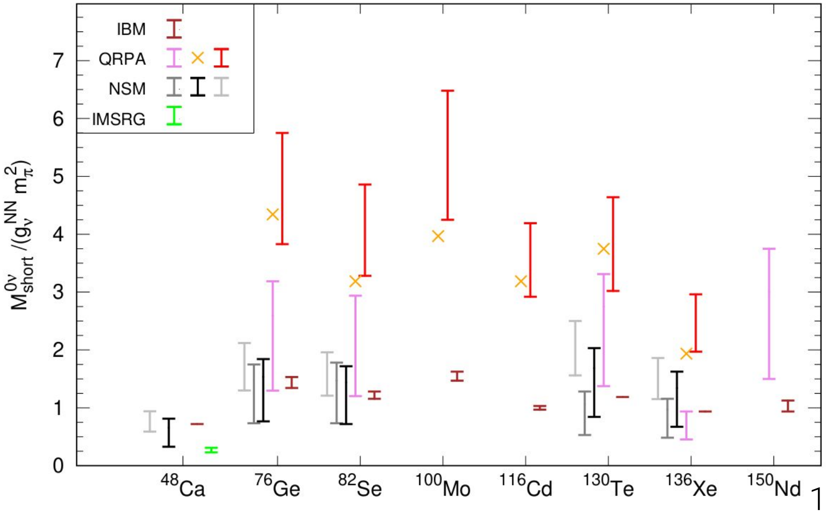
Light neutrino exchange
Nuclear Matrix Elements (NMEs)

$$\frac{1}{T_{1/2}} = G\, g_A^4 \left(M^{0\nu}_{\text{light}}\right)^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$$M^{0\nu}_{light} = M^{0\nu}_{long} + M^{0\nu}_{short}$$

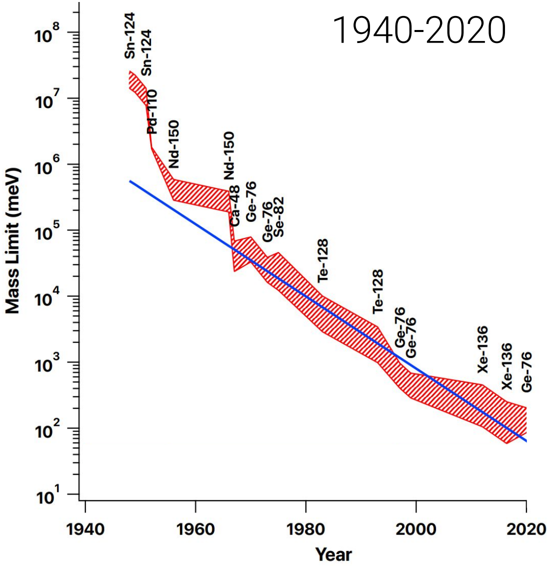
- “the worst e**N**e**M**i**Es**” for $0\nu\beta\beta$ decay hunters
- many-body methods: NSM, EDF, QRPA and IBM
- recently recognized new contact term due exchange of high-energy light neutrinos
- first ab-initio methods (fixing g_A issue?)





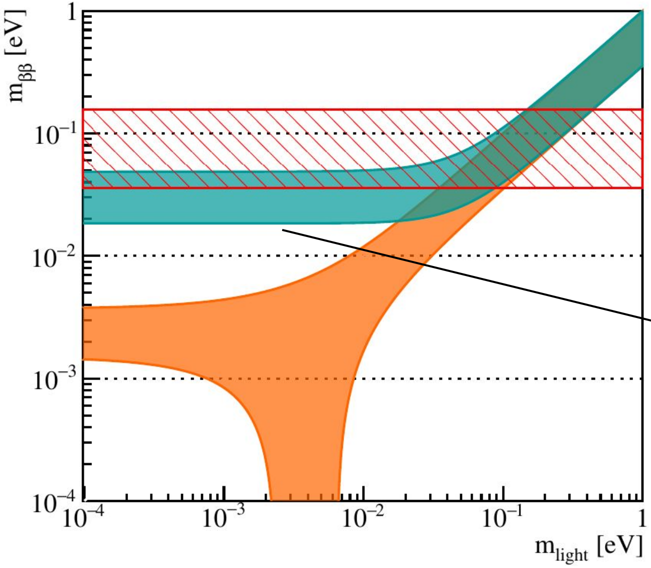
M.A., Benato, Detwiler, Menéndez and Vissani
arXiv:2202.01787

Discovery odds: **inverted** ordered neutrinos

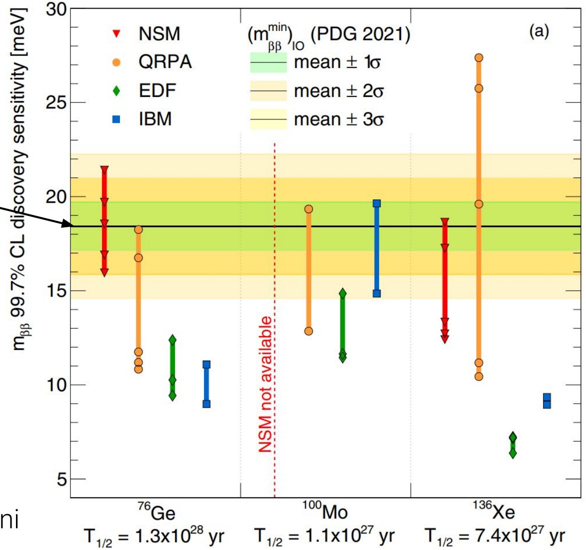


S. Elliot, 2021

Best Today
($T_{1/2}$ > 10^{26} yr)



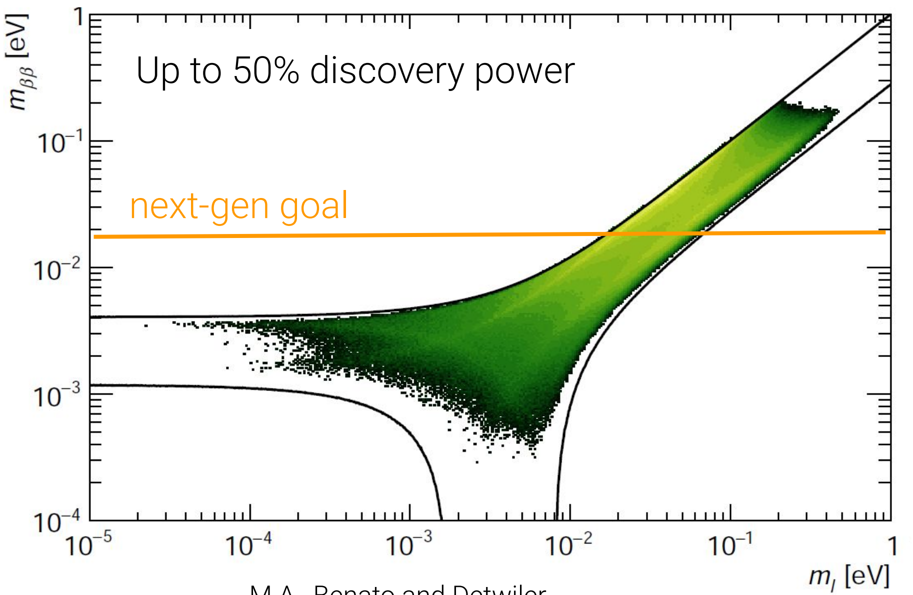
Best Nex Gen
($T_{1/2}$ > 10^{27} - 10^{28} yr)



M.A., Benato, Detwiler, Menéndez and Vissani
PRC 104, L042501

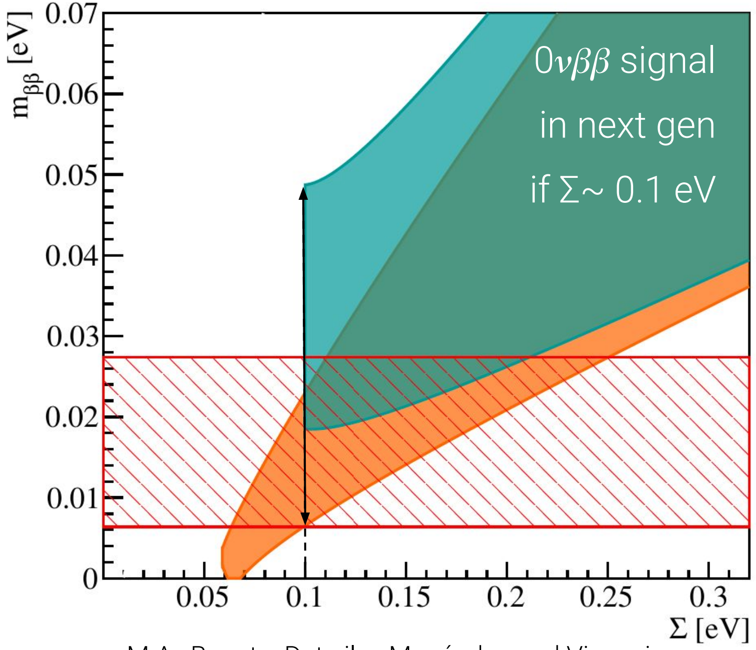
Discovery odds: **normal** ordered neutrinos

Not equiprobable parameter space: random phases favors large $m_{\beta\beta}$ values.



M.A., Benato and Detwiler
PRD 96, 053001 (2017)

Cosmology surveys (DESI/EUCLID) will soon measure $\Sigma = \sum_i m_i$



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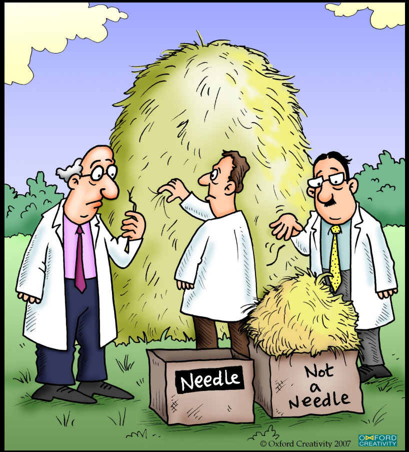
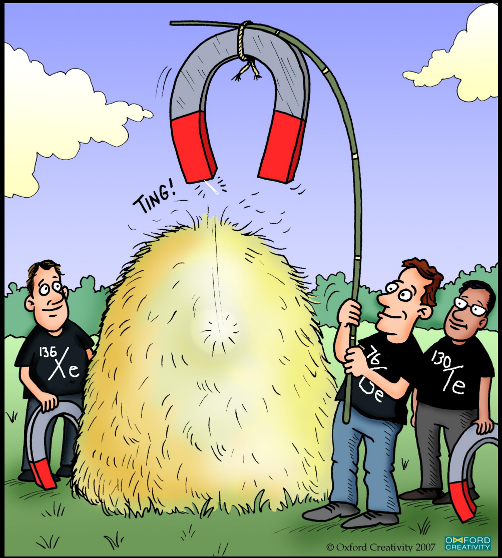
How to discover a decay with $T_{1/2}>10^{26}$ yr



1. observe hundreds moles of atoms per years
2. identify even a single decay!
3. full control on background processes able to mimic the signal



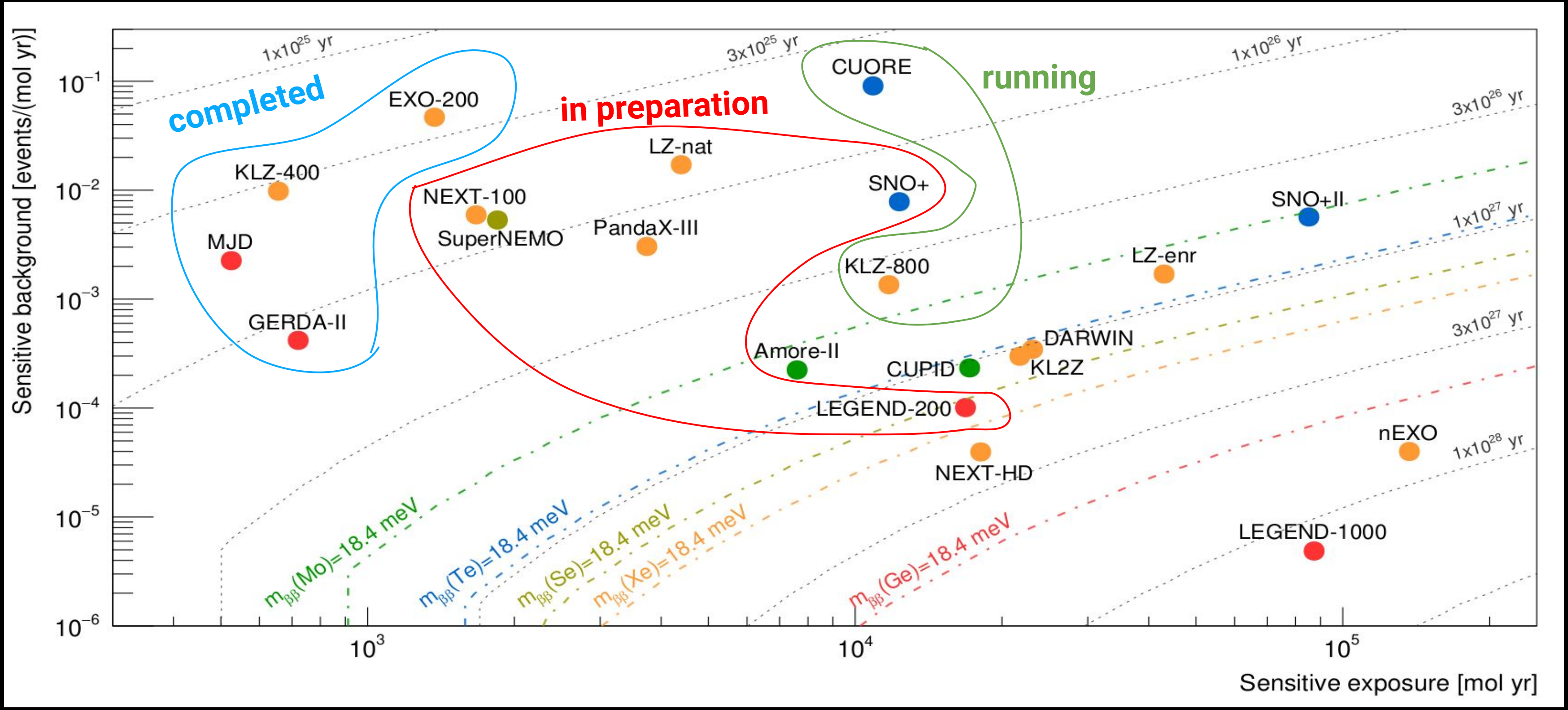
Key parameters: **exposure** $\mathcal{E}$ (mol yr) and **background** B (events/mol/yr)

$$N_{0\nu\beta\beta} = \frac{\ln 2 \cdot N_A \cdot \mathcal{E}}{m_a \cdot T_{1/2}} \quad \text{and} \quad N_{bkg} = \mathcal{B} \cdot \mathcal{E}$$

B=0: $T_{1/2}$ sensitivity ~ $\mathcal{E}$

B>0: $T_{1/2}$ sensitivity ~ sqrt($\mathcal{E}$/B)

Recent and future experiments



M.A., Benato, Detwiler, Menéndez and Vissani
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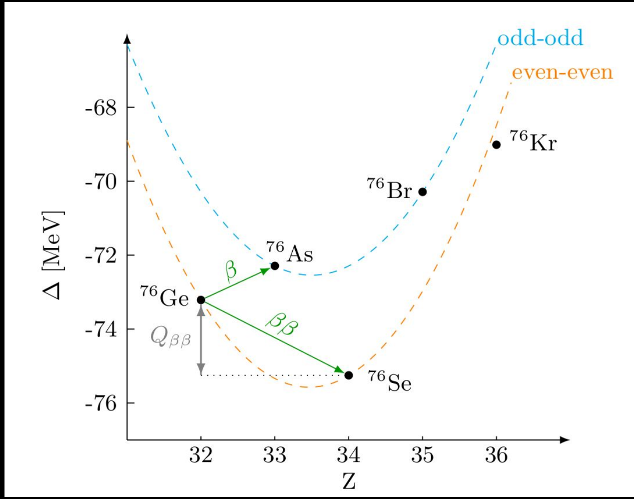
ββ decaying Isotopes

9 potential isotopes:

- naturally abundant
- enrichment cost
- decay rate proportional to (Q-value)^5
- Favorable NME and phase space factors



Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]	f_{enr} [c] [%]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91

No "best" isotope

The possible detection techniques compensate for unfavorable parameters

Signal & Background

Tagging $0\nu\beta\beta$ decay events:

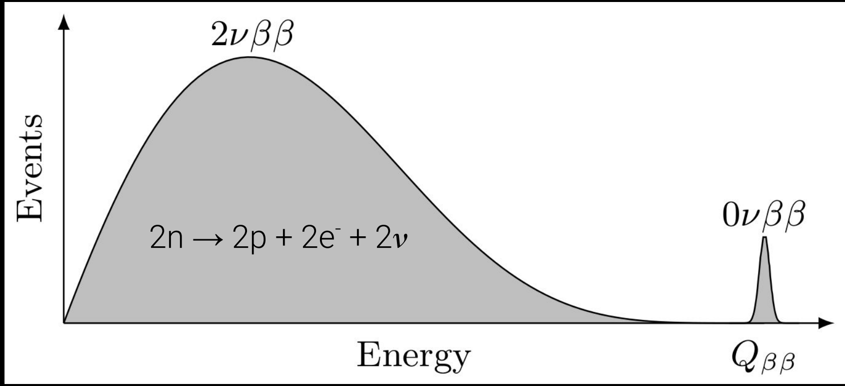
- two-electron summed energy = Q-value
- two-electron event topology
- (gamma-rays from de-excitation)
- (daughter isotope)

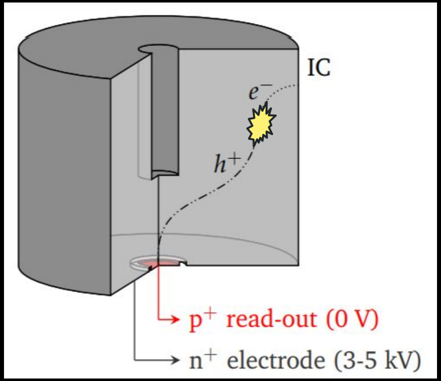
Backgrounds:

- cosmic-ray induced
- U/Th decay chains
- neutrons
- solar neutrinos
- 2vbb decay (only irreducible background)

Multivariate background discrimination:

- non uniform event rate in time or space
- spatially extended event topology
- particle identification
- energy (only way to mitigate 2vbb)



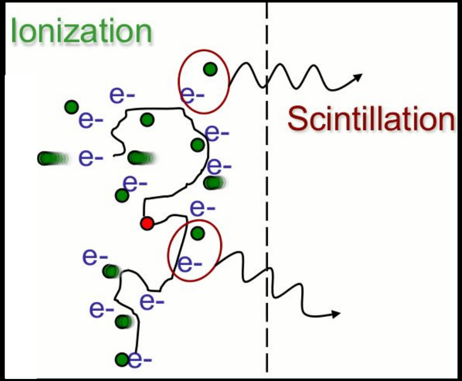


Ge Semiconductor detectors (^{76}Ge)

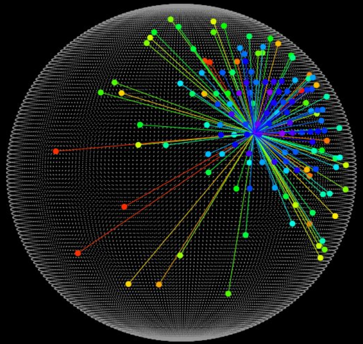
The longest-standing technology used for 0νbb-decay searches

Xe Time Projection Chambers (^{136}Xe)

Used for first real-time observation of 2νbb decay. At the forefront since then.



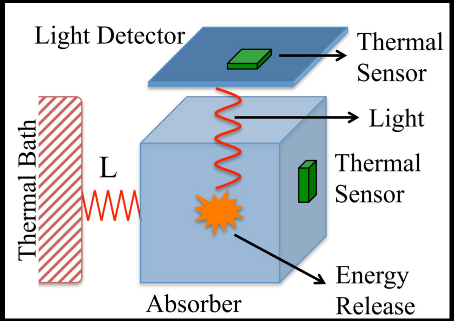
Large Liquid scintillator detectors (^{130}Te,^{136}Xe)



The most successful departure from the "source=detector" paradigm

Cryogenic Calorimeters (^{100}Mo, ^{130}Te)

The most versatile types of detectors for rare events searches

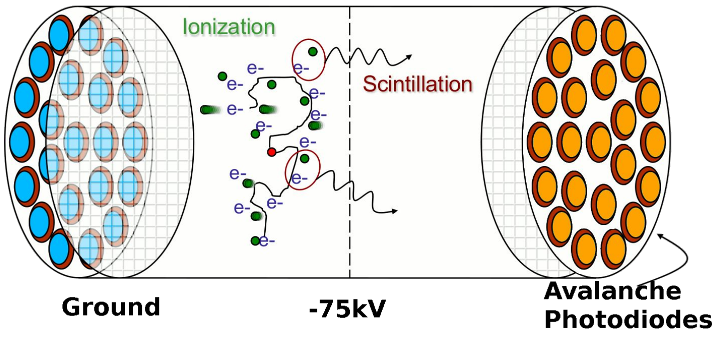


Xe time projection chambers

- Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface, ^{214}Bi and ^{222}Rn remain problematic
- R&D to tag $0\nu\beta\beta$ decay daughter isotope

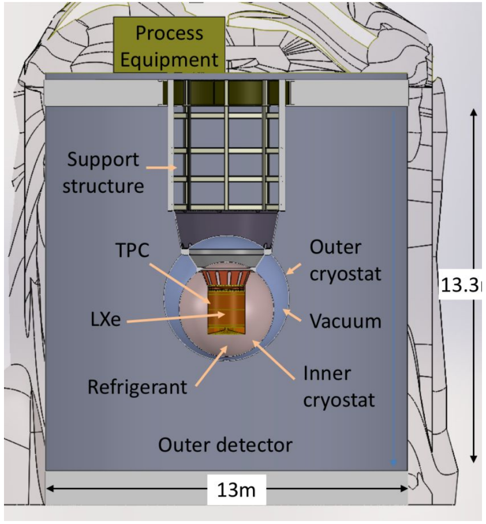
Experiment	m_{tot} [kg]	$f_{enr.}$ [%]	Phase	Readout
EXO-200	161	81	liquid	LAPPDs + wires
nEXO	5109	90	liquid	electrode tiles + SiPM s
NEXT-100	97	90	gas	SiPMs + PMTs
NEXT-HD	1100	90	gas	SiPMs + PMTs
PandaX-III-200	200	90	gas	Micromegas
PandaX-III-1K	1000	90	gas	Micromegas
LZ-nat	7 000	9	dual-phase	PMTs
LZ-enr	7 000	90	dual-phase	PMTs
DARWIN	39 300	9	dual-phase	PMTs

EXO-200 @ WIPP



nEXO @ SNOLAB

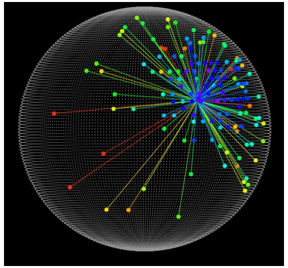
pCDR ready, world leading sensitivity



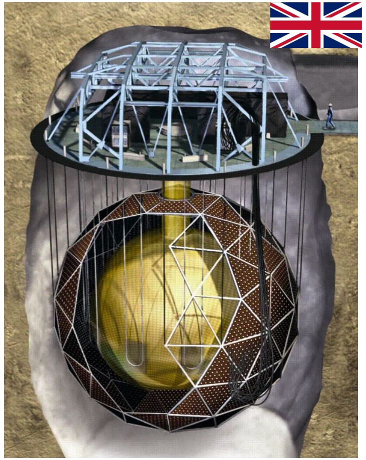
SNO+ @ SNOLAB

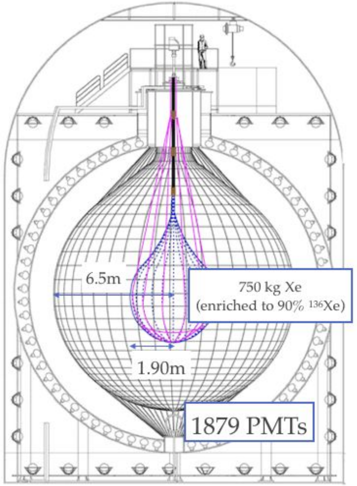
Large liquid scintillator detectors

- scintillator loaded with target isotope
- scintillation photons detected by PMTs
- photon number and arrival time gives event energy and position
- self-shielding and fiducialization



- 1.3 t of natural Te
- 0.5% loading
- filled with scintillator
- next Te loading
- next phase: 6.6 t of Te, 2.5% loading

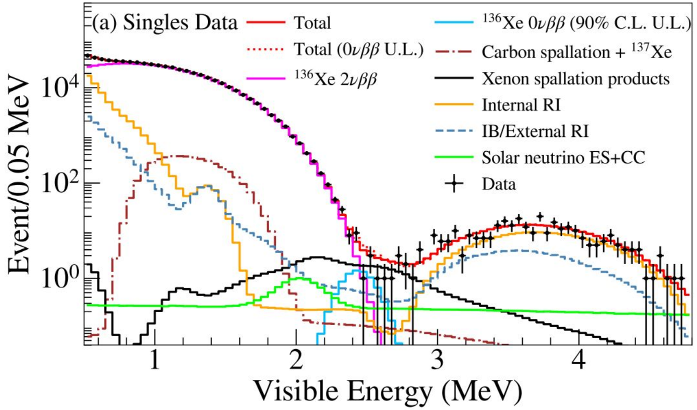




KamLAND-Zen-800 @Kamioka

- 750 kg of enriched Xe in nylon balloon
- backgrounds: 2vbb, cosmogenic, solar neutrinos, Bi on balloon
- next phase: improved resolution and purer scintillator

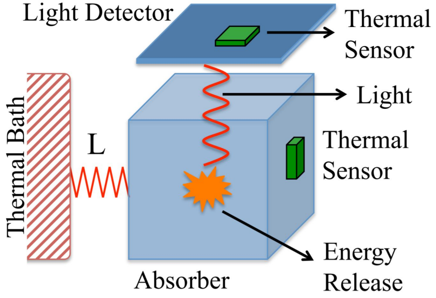
$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \text{yr at } 90\%\ \text{C.L.}$$



2203.02139

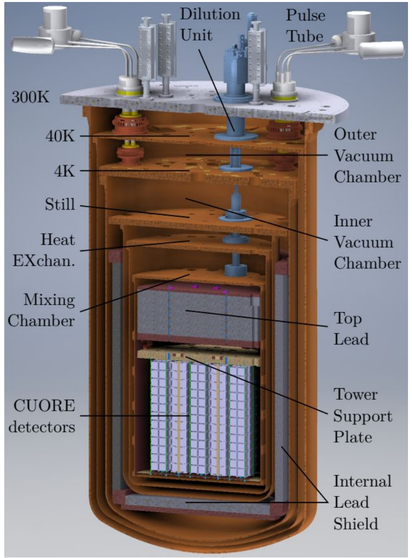
Cryogenic calorimeters

- temperature variation and scintillation light
- particle identification and good resolution
- array of isotopically enriched crystals operated at ~10 mK



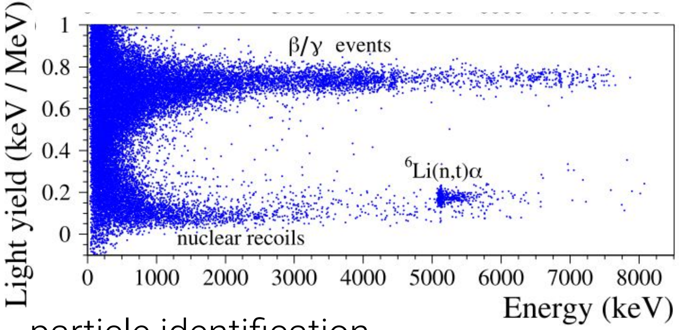
Experiment	Crystal	m_{tot} [kg]	f_{enr} [%]
CUORE	$^{nat}TeO_2$	742	34[a]
CUPID-0	$Zn^{enr}Se$	9.65	96
CUPID-Mo	$Li_2{}^{enr}MoO_4$	4.16	97
CROSS	$Li_2{}^{enr}MoO_4$	8.96	98
CUPID	$Li_2{}^{enr}MoO_4$	472	$\geq$95
AMoRE	$Li_2{}^{enr}MoO_4$	200	96

CUORE @ LNGS



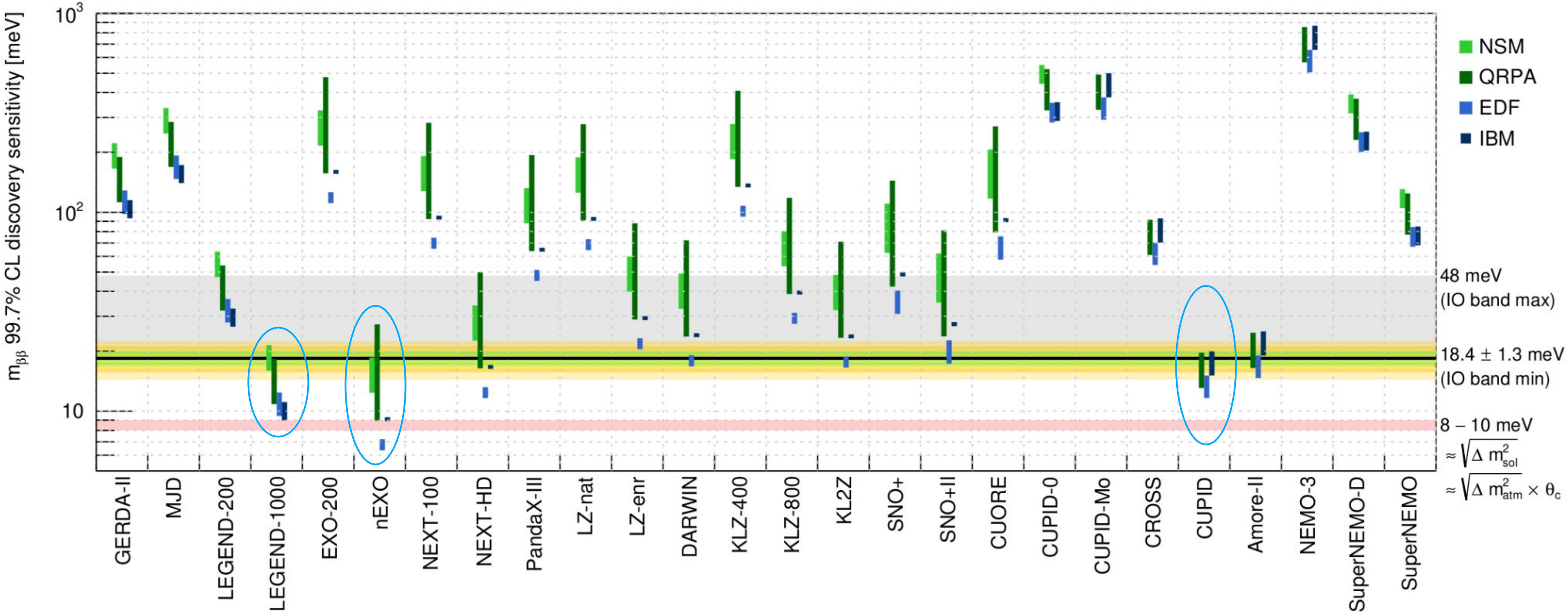
pCDR ready, world leading sensitivity

CUPID



particle identification

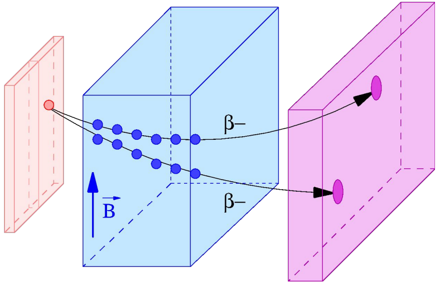
Discovery power of the field

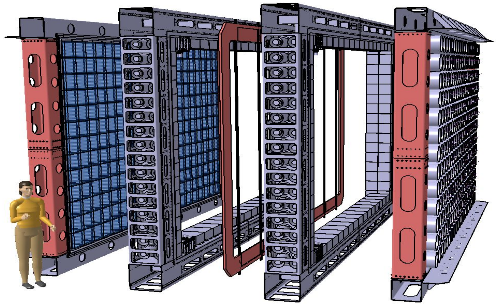


M.A., Benato, Detwiler, Menéndez and Vissani
arXiv:2202.01787

SuperNEMO Demonstrator @ Modan

Where are we heading?





Scenario 1: signal just beyond current limits

- L200, KZ-800, SNO+ discover it
- L1000, nEXO, CUPID measures rate
- superNEMO studies decay kinematic
- kinematic & multi-isotope data -> **decay mechanism**

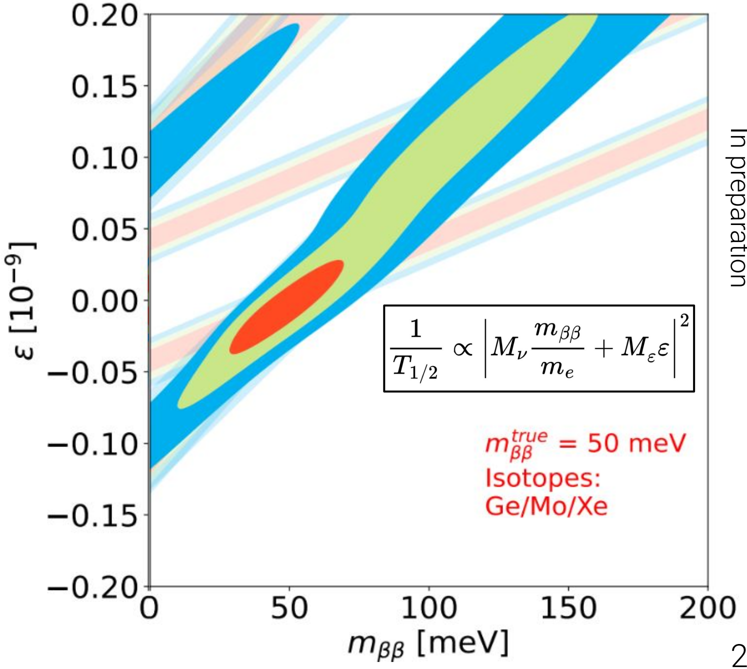
Scenario 2: weakest signal for inverted ordered neutrinos

- L1000, nEXO, CUPID discover it
- follow-up experiments needed to measure properties

Scenario 3: signal even weaker or absent

- need to design more sensitive experiments

Interplay with oscillation experiments and cosmology can also lead to theory breakthroughs

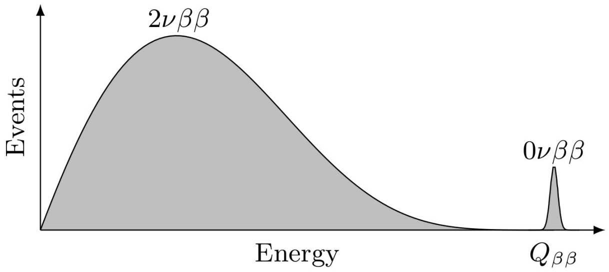


M.A., Deppisch and Van Goffrier
In preparation

Many other BSM discovery opportunities

Distorsions on 2vbb energy distribution

- massive & massless bosons (Majorons)
- violation of fundamental principles
  - Lorentz invariance
  - Pauli exclusion principle
  - CPT symmetry.
- exotic currents
- light exotic fermions (e.g. sterile neutrinos)
- Z_2-odd fermions or other dark matter candidates
- ....



Excess of events with specific energies or timing:

- B-violating tri-nucleon decay
- charge-violating electron decay
- WIMPS
- axions
- inelastic boosted dark matter
- fermionic dark matter
- fractional-charge
- lightly ionizing particles
- ...

Conclusions

The discovery of $0\nu\beta\beta$ decay would lead to a new “standard model”, with a new interpretation of the fundamental symmetries and the matter-antimatter concept

Advancements in nuclear theory are laying the groundwork to connect the nuclear decay with the underlying particle physics

A worldwide, multi-isotope experimental program is exploring an exciting parameter space, where a signal can be around the corner