

# Present and Future of Neutrinoless $\beta\beta$ Decays

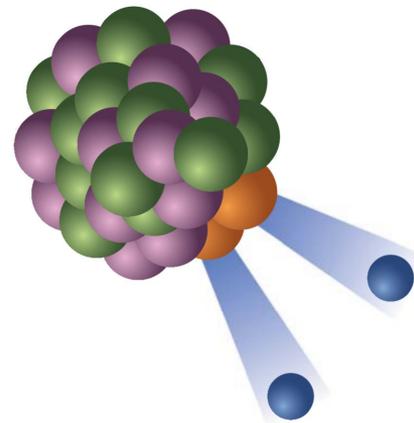
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Matteo Agostini

STFC Ernest Rutherford Fellow at UCL

Vulcano Workshop 2022

Elba, Sep 26 - Oct 1 2022



*Most of the material taken from  
MA, Benato, Detwiler, Menéndez and Vissani,  
arXiv:2202.01787*

# Present and Future of ~~Neutrinoless $\beta\beta$ Decays~~

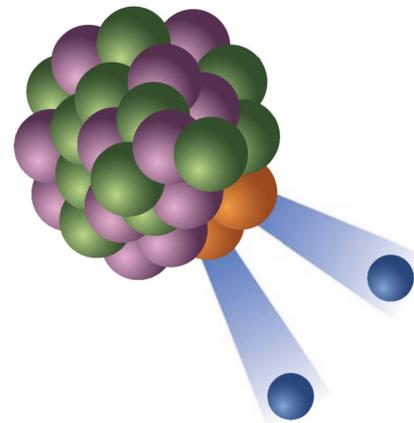
*matter-creation searches  
in nuclear decays*

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# Present and Future of ~~Neutrinoless $\beta\beta$ Decays~~

*and Majorana neutrinos*

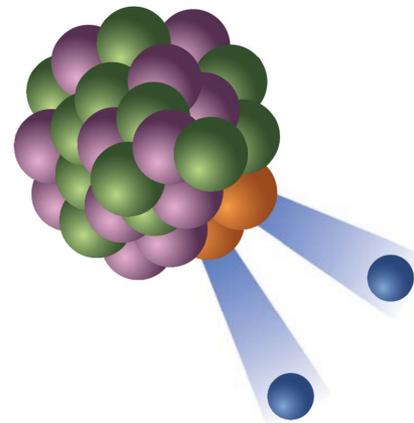
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# What is matter? What are its fundamental blocks?

According to the Standard Model

- particles / antiparticles symmetry
- energy  $\leftrightarrow$  particle + antiparticle
- still, our universe is dominated by Baryons

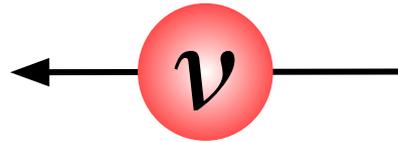
There must be processes altering

- $B = N_{\text{baryons}} - N_{\text{anti-baryons}}$
- $L = N_{\text{leptons}} - N_{\text{anti-leptons}}$
- **B-L (global symmetry of SM)**

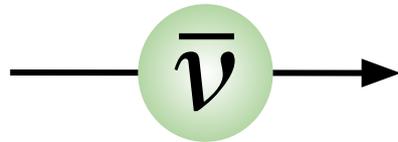
Matter			charge		Antimatter		
Quarks -> Baryons					Anti-Quarks -> Anti-Baryons		
u	c	t	+2/3	-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
d	s	b	-1/3	+1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
Leptons					Anti-Leptons		
e	$\mu$	$\tau$	-1	+1	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$
$\nu_e$	$\nu_\mu$	$\nu_\tau$	0	0	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

# What distinguishes neutrinos from antineutrinos?

If they have no mass...

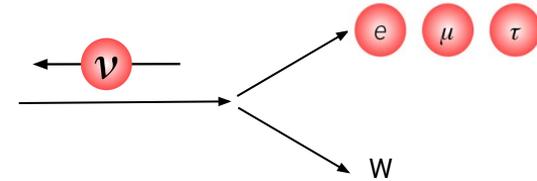


moving direction 



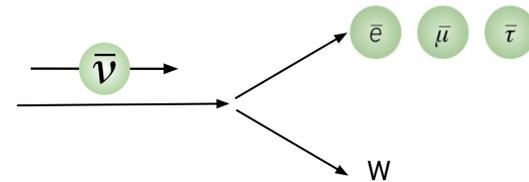
neutrinos move **antiparallel** to their spin

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



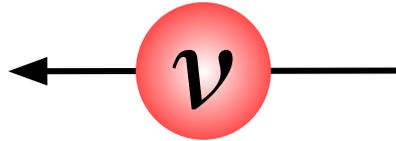
anti-neutrinos move **parallel** to their spin

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

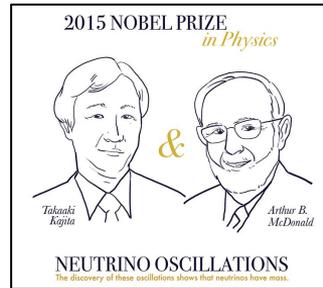
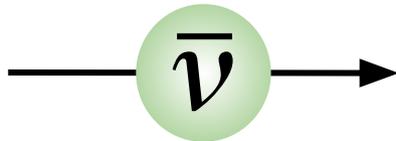


# What distinguishes neutrinos from antineutrinos?

But neutrinos are massive!

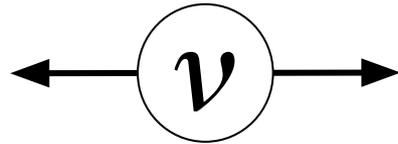


moving  
direction 

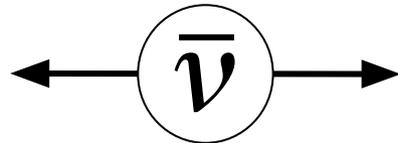
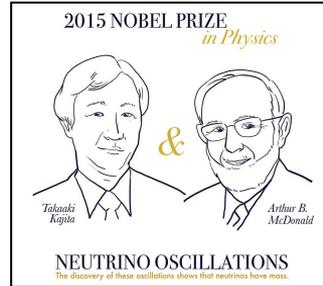


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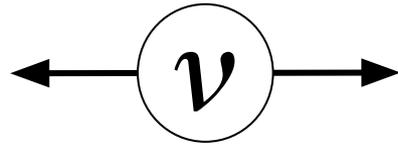


rest frame

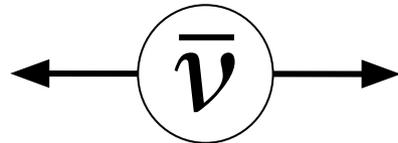


# What distinguishes neutrinos from antineutrinos?

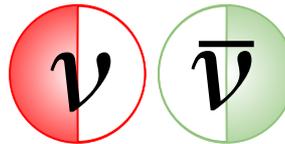
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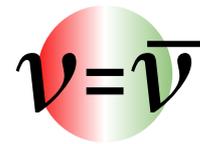
rest frame



Dirac



Majorana

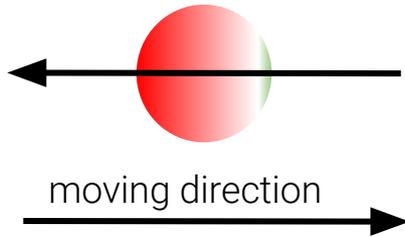


There are two new non-interacting “sterile” states...

...or the same object has both chiral states

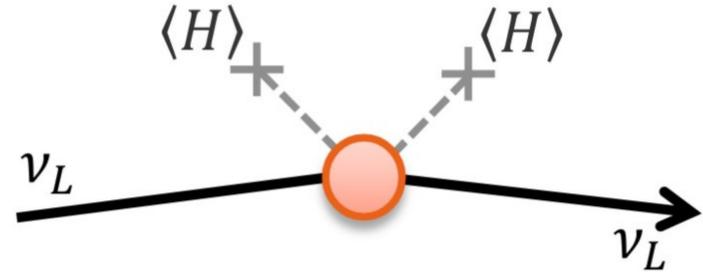
# Neutrino-antineutrino transformations

Majorana neutrinos can interact creating both matter and antimatter



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

Majorana masses

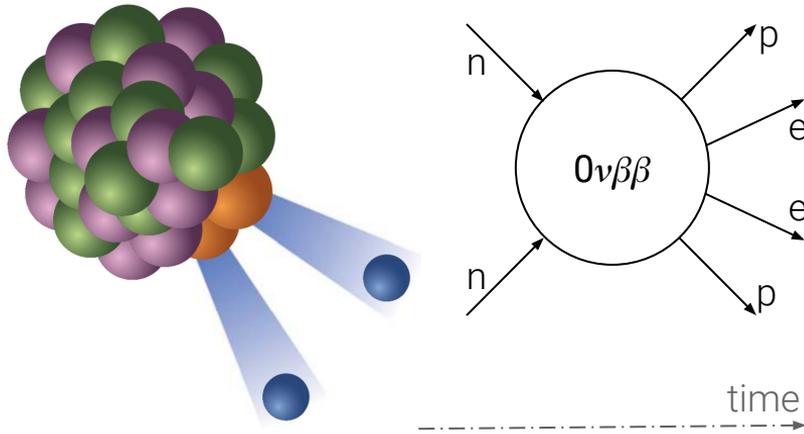


- variant of the Higgs mechanism
- no need for tiny Yukawa couplings
- neutrino tiny masses inversely proportional to those of heavy right-handed states

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

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

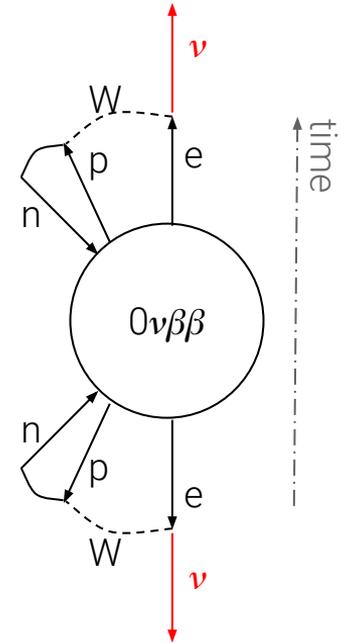
- 2 neutrons  $\rightarrow$  2 protons ( $\Delta B = 0$ )
- 2 electrons are emitted ( $\Delta L = 2$ )



Direct violation of L and B-L

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

*Schechter and Valle*  
1982

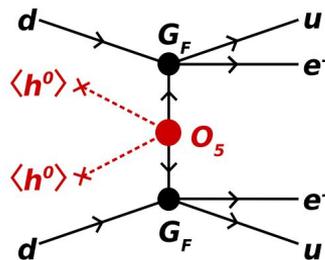


A tiny, but non-zero Majorana mass

# A generic search for ultrahigh-energy BSM physics

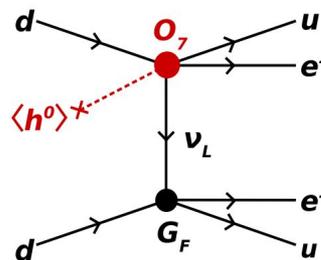
Dim 5: Weinberg Operator

$$P \propto \left(\frac{\nu}{\Lambda}\right)^2 \quad \text{with} \quad \frac{\nu}{\Lambda} \propto m_{\beta\beta}$$



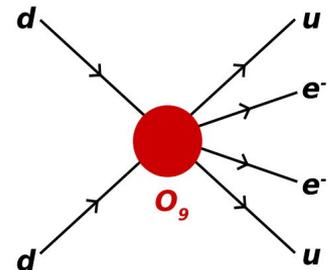
Dim 7

$$P \propto \left(\frac{\nu}{\Lambda}\right)^6$$



Dim 9

$$P \propto \left(\frac{\nu}{\Lambda}\right)^{10}$$



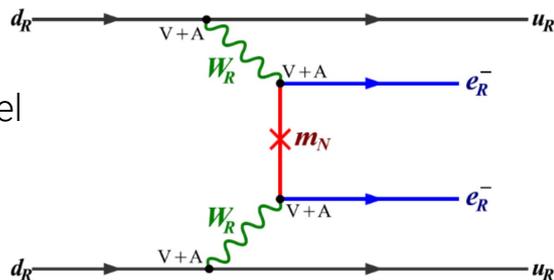
Cirigliano et al., JHEP 12, 097 (2018)

Deppisch, Graf, Iachello and Kotila  
Phys.Rev.D 102 (2020) 9, 095016

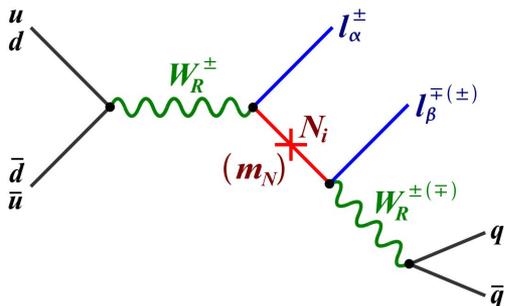
# A generic search for ultrahigh-energy BSM physics

Example: left-right symmetry

$0\nu\beta\beta$  decay channel  
(dim 9 operator)



Strong synergy between  $0\nu\beta\beta$  decay, cosmic neutrinos and colliders



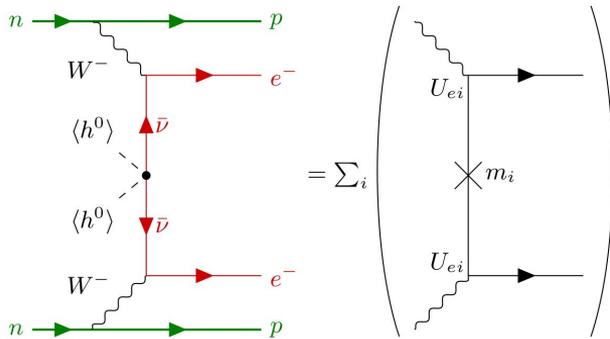
Same as dilepton signature at LHC

Deppisch, Graf, Iachello and Kotila  
*Phys.Rev.D* 102 (2020) 9, 095016



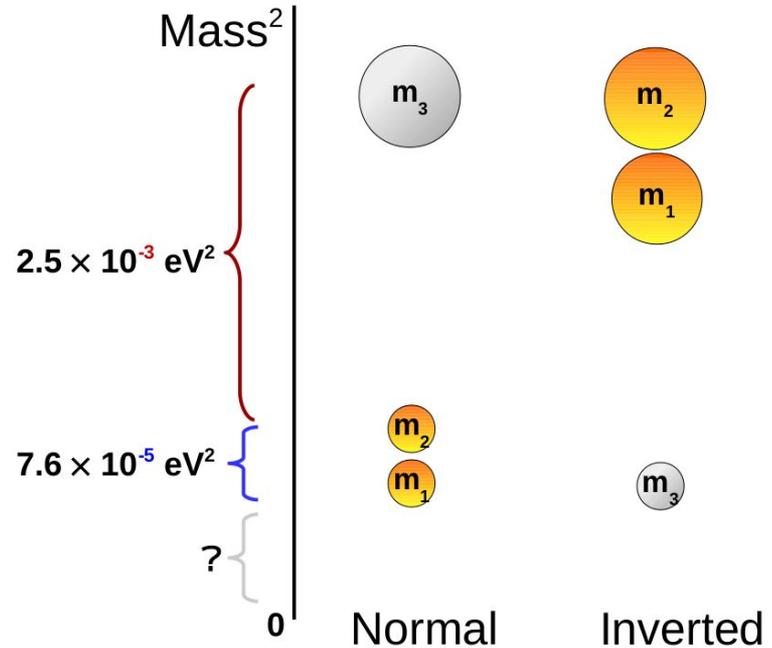
# Light Majorana neutrino exchange

$$P \propto \left(\frac{\nu}{\Lambda}\right)^2 \quad \text{with} \quad \frac{\nu}{\Lambda} \propto m_{\beta\beta}$$



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

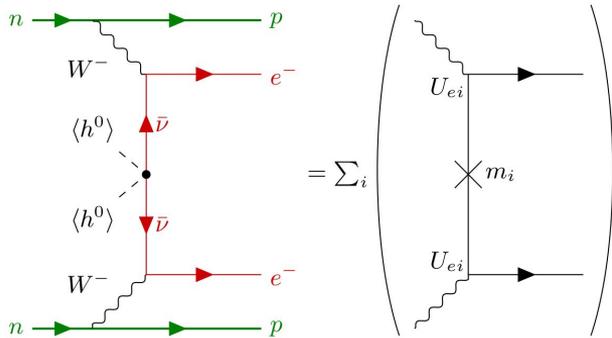
$$= \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i2\alpha} + s_{13}^2 m_3 e^{i2\beta} \right|$$



[from hyper-k.org]

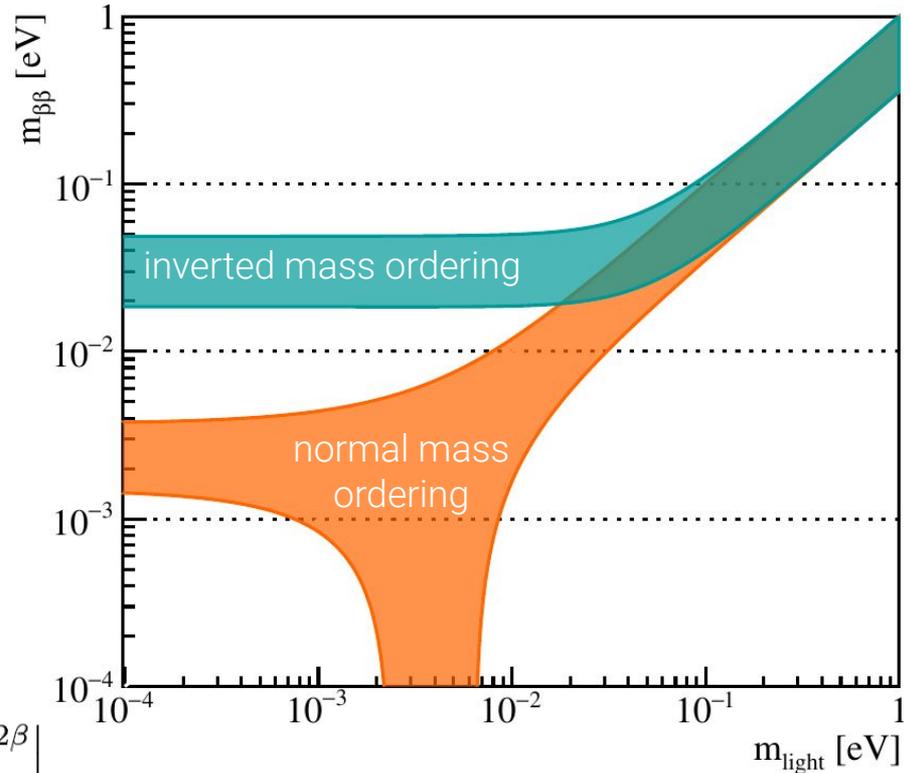
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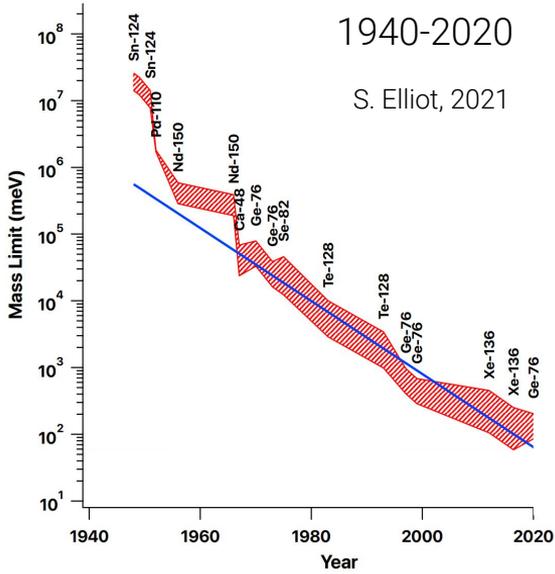


$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

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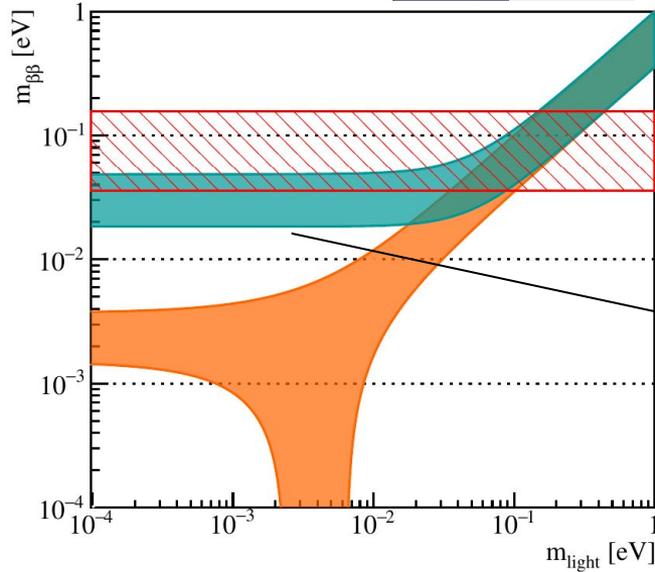


# Discovery odds: inverted neutrinos

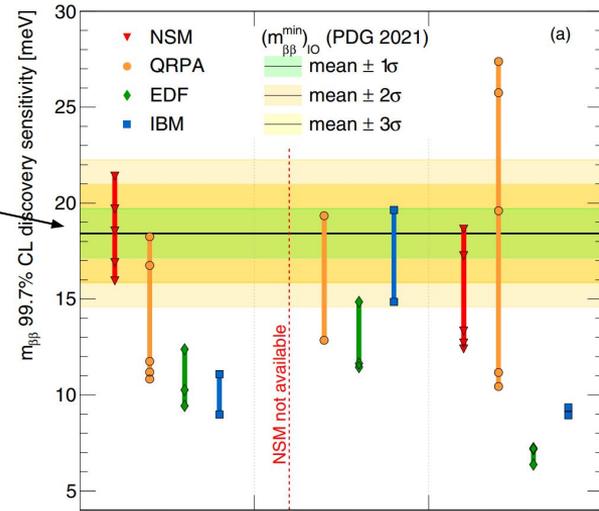


$$P \propto \frac{1}{T_{1/2}} \propto G g^4 M^2 \left( \frac{m_{\beta\beta}}{m_e} \right)^2$$

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

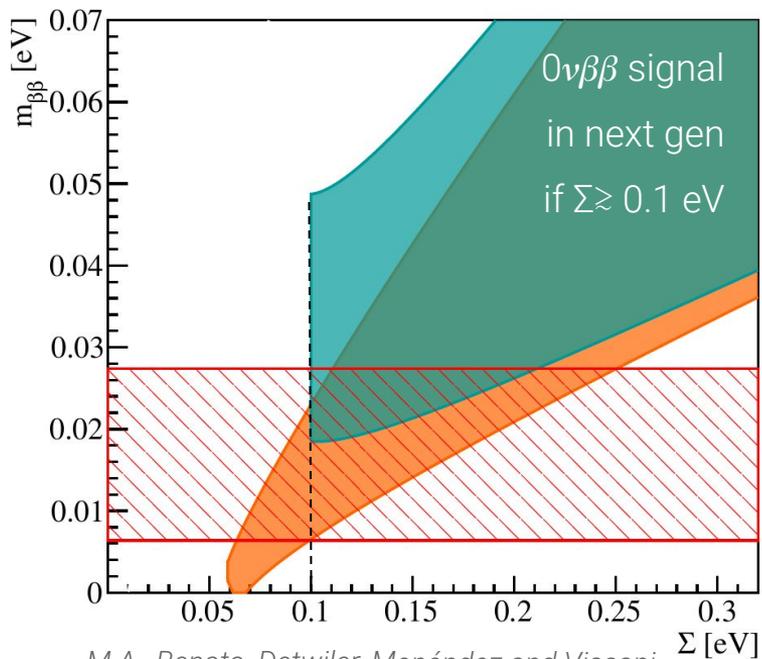
LEGEND



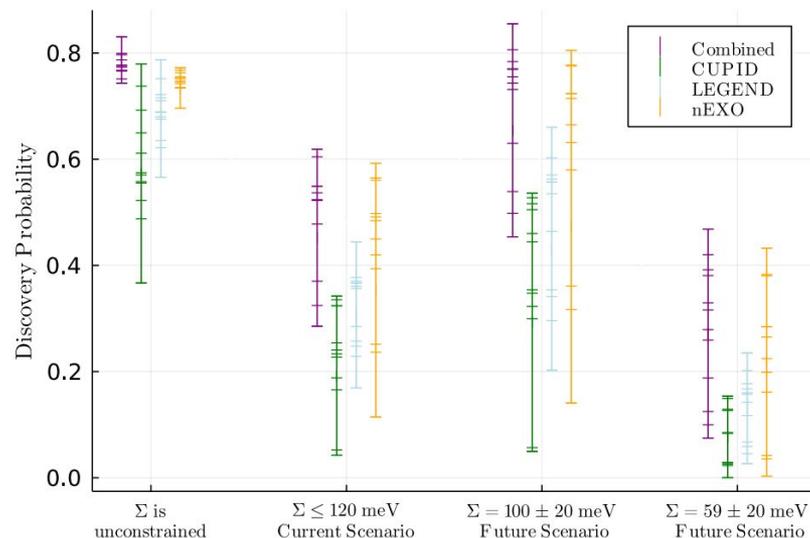
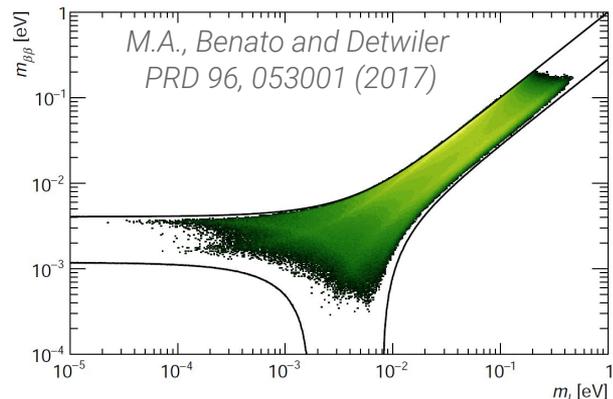
nEXO

# Discovery odds: normal neutrinos

Cosmology surveys (DESI/EUCLID) close to measure  $\Sigma = \sum_i m_i$



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

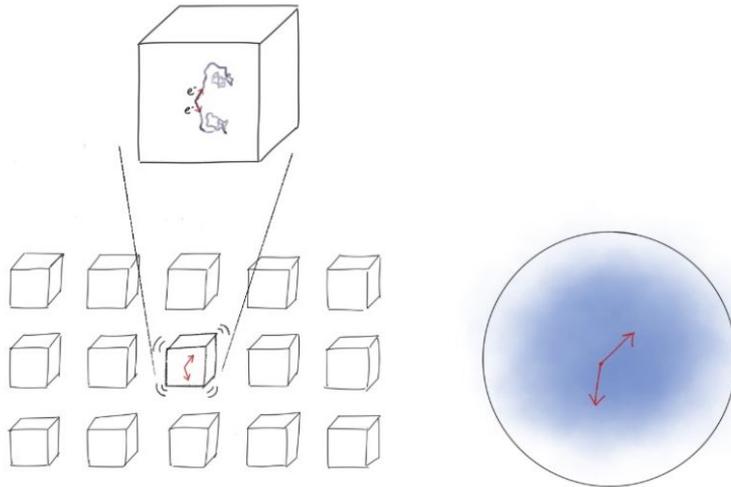


Ettengruber, M.A., Caldwell, Eller and Schulz 2208.09954

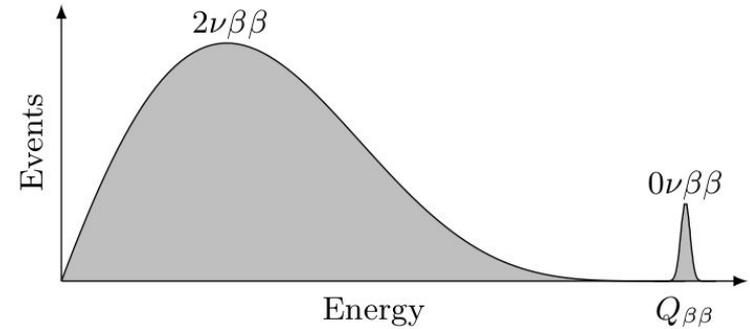
# Experiments

# Detection concepts

- calorimetric approach: source = detector
- solid state: pixelated detector
- liquid: monolithic self-shielding volume
- energy: primary and sufficient observable

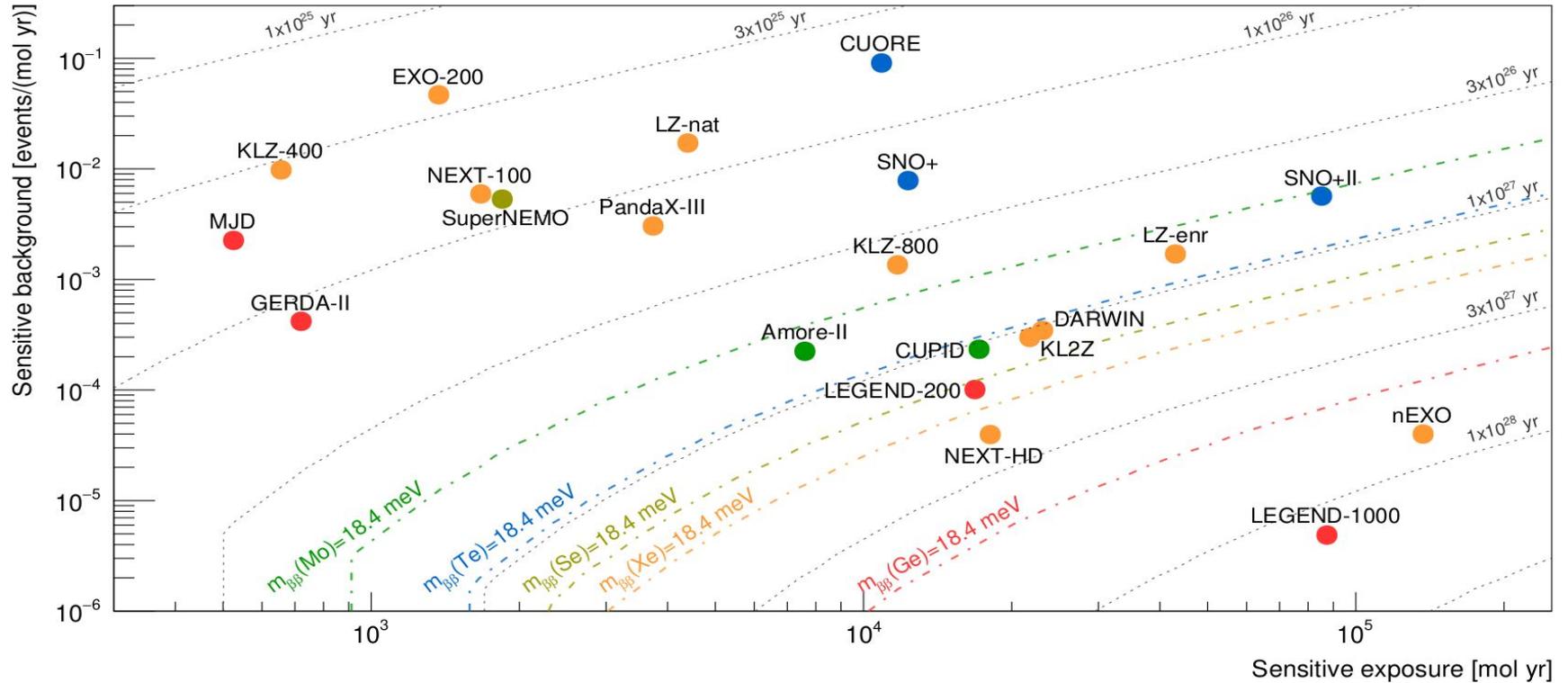


*arXiv:2202.01787 - Image courtesy of Laura Manenti*



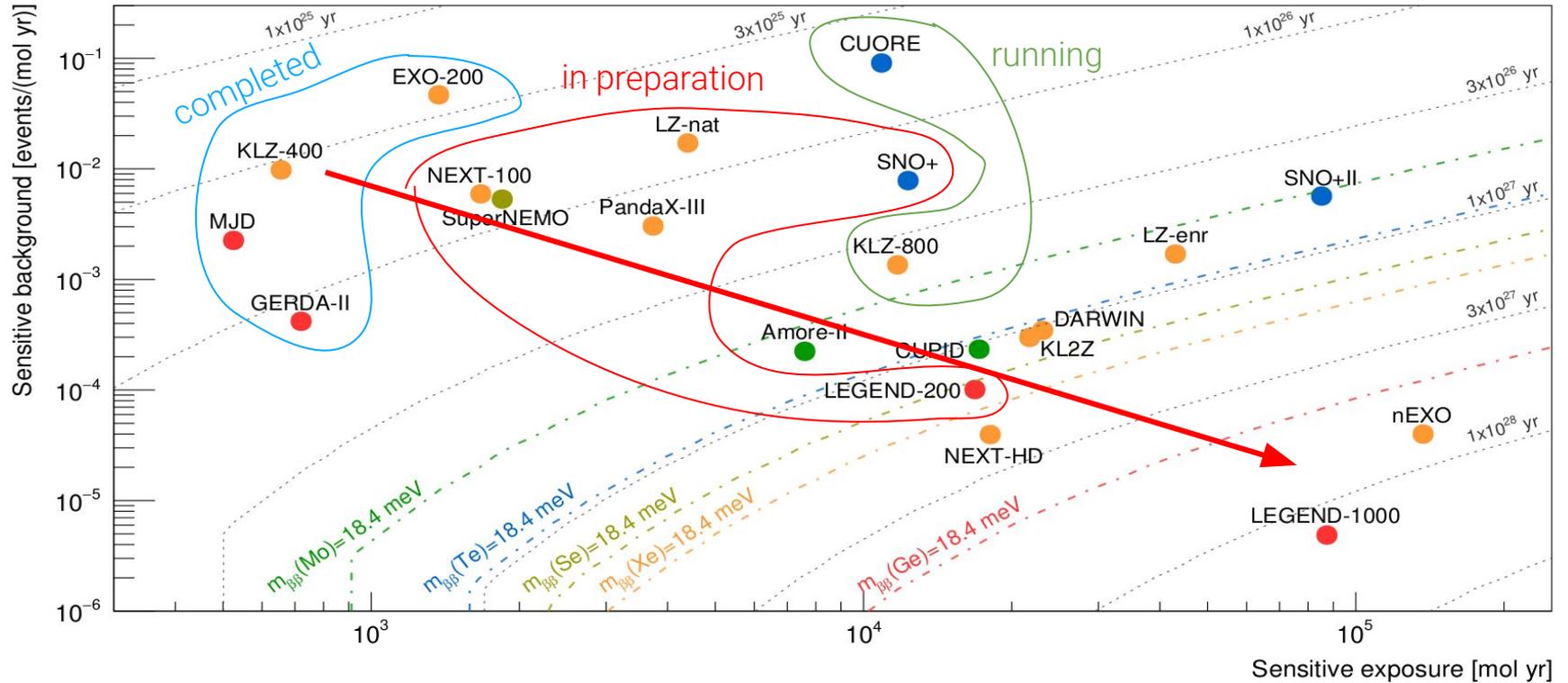
Isotope	Daughter	$Q_{\beta\beta}^a$ [keV]	$f_{\text{nat}}^b$ [%]	$f_{\text{enr}}^c$ [%]
$^{48}\text{Ca}$	$^{48}\text{Ti}$	4 267.98(32)	0.187(21)	16
$^{76}\text{Ge}$	$^{76}\text{Se}$	2 039.061(7)	7.75(12)	92
$^{82}\text{Se}$	$^{82}\text{Kr}$	2 997.9(3)	8.82(15)	96.3
$^{96}\text{Zr}$	$^{96}\text{Mo}$	3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

# Recent and future experiments



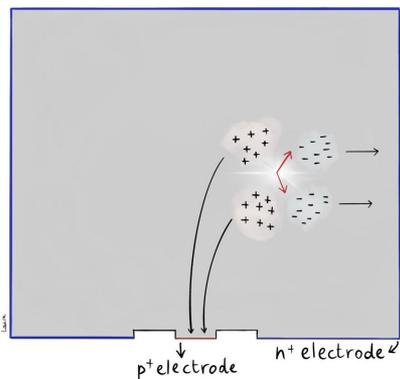
M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

# Recent and future experiments

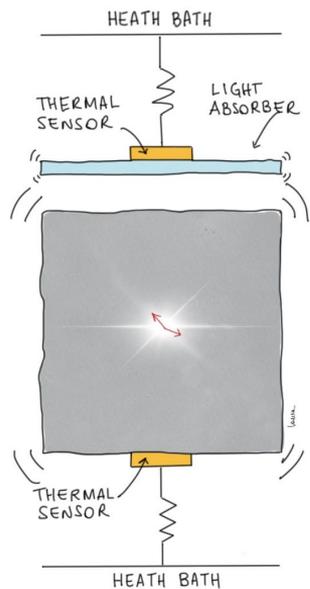


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

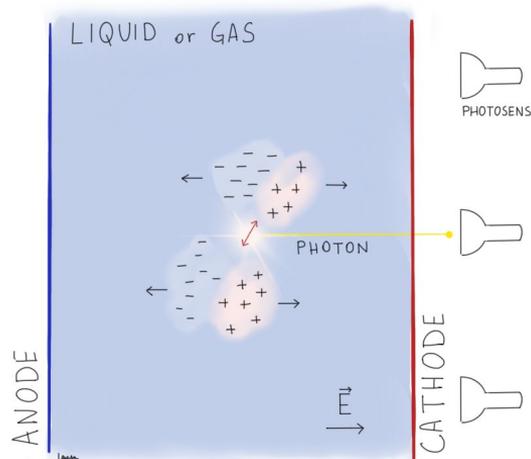
# The most sensitive technologies



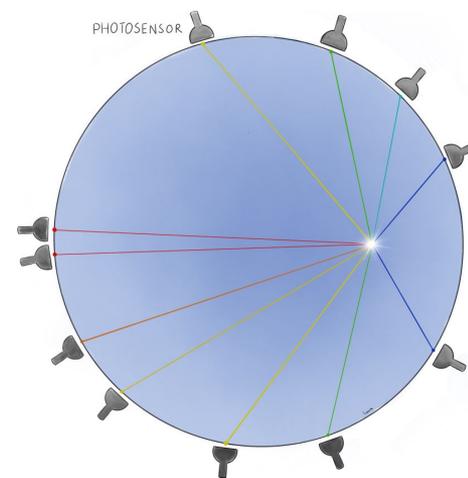
*Ge Semiconductor detectors ( $^{76}\text{Ge}$ )*



*Cryogenic Calorimeters ( $^{100}\text{Mo}$ ,  $^{130}\text{Te}$ )*



*Xe Time Projection Chambers ( $^{136}\text{Xe}$ )*

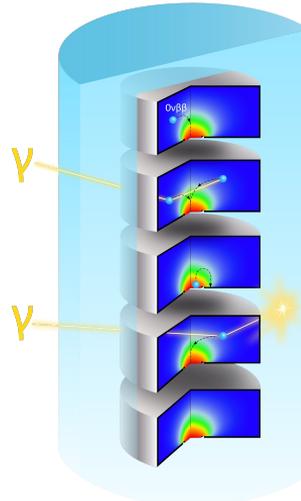
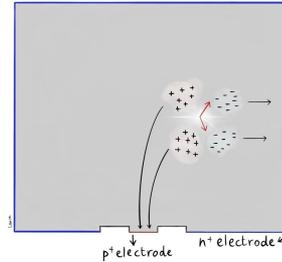


*Large Liquid scintillator detectors ( $^{130}\text{Te}$ ,  $^{136}\text{Xe}$ )*

# Ge semiconductor detectors

high-purity  $^{76}\text{Ge}$  detectors

- ionization and charge drift
- $< 0.1\%$  energy resolution
- event topology



liquid Ar detector

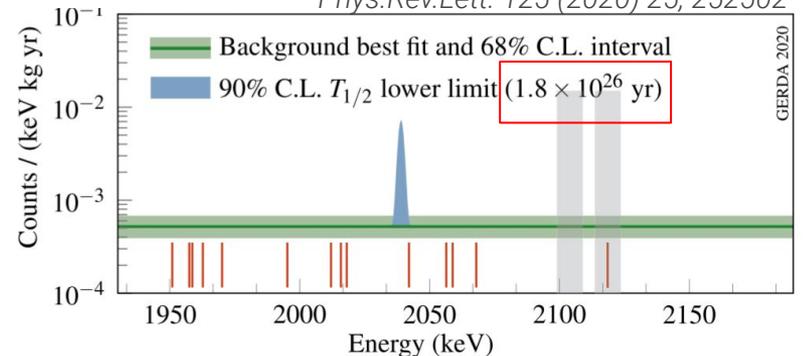
- shield and scintillation light



*Phys.Rev.Lett.* 125 (2020) 25, 252502

Staged approach:

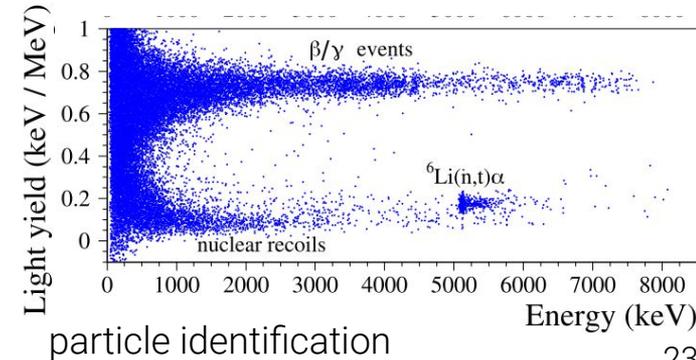
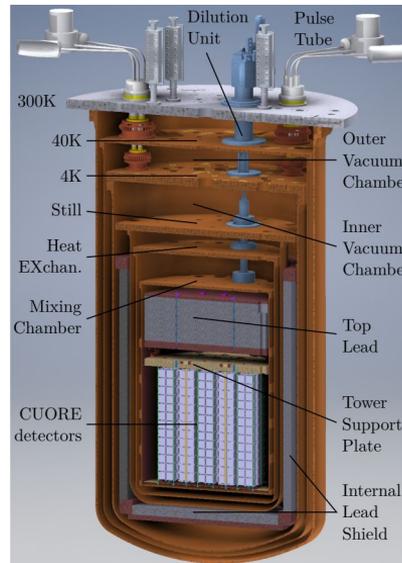
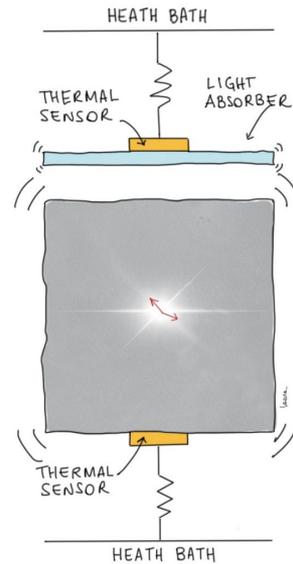
- **GERDA/MAJORANA** Demonstrator (40 kg)
- **LEGEND-200** under commissioning (200 kg)
- **LEGEND-1000** conceptual design in preparation (1 t)



# Cryogenic calorimeters

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

Experiment	Crystal	$m_{tot}$ [kg]	$f_{enr}$ [%]
CUORE	$^{nat}\text{TeO}_2$	742	34 <sup>a</sup>
CUPID-0	$\text{Zn}^{enr}\text{Se}$	9.65	96
CUPID-Mo	$\text{Li}_2^{enr}\text{MoO}_4$	4.16	97
CROSS	$\text{Li}_2^{enr}\text{MoO}_4$	8.96	98
CUPID	$\text{Li}_2^{enr}\text{MoO}_4$	472	$\geq 95$
AMoRE	$\text{Li}_2^{enr}\text{MoO}_4$	200	96



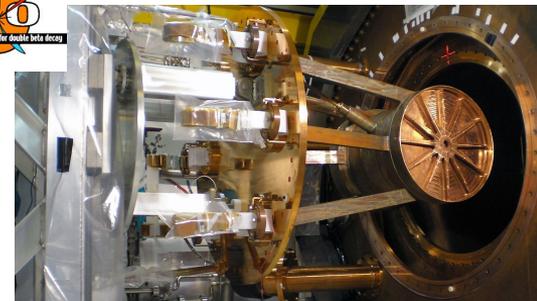
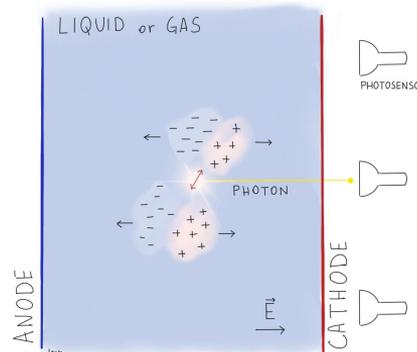
Nature 604 (2022) 7904, 53-58

$$T_{1/2}^{0\nu} > 2.2 \cdot 10^{25} \text{ yr}$$

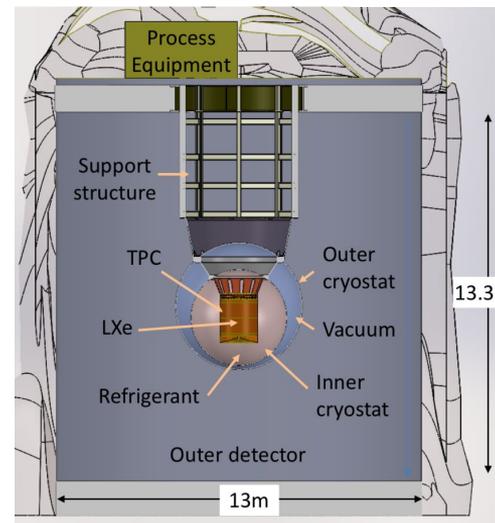
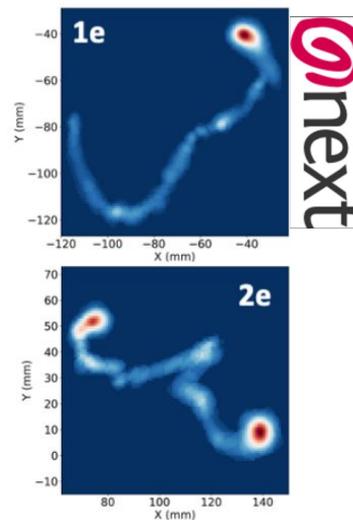
Matteo Agostini (UCL)

# Xe time projection chambers

- $^{136}\text{Xe}$  VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface,  $^{214}\text{Bi}$  and  $^{222}\text{Rn}$  remain problematic
- R&D to tag  $0\nu\beta\beta$  decay daughter isotope



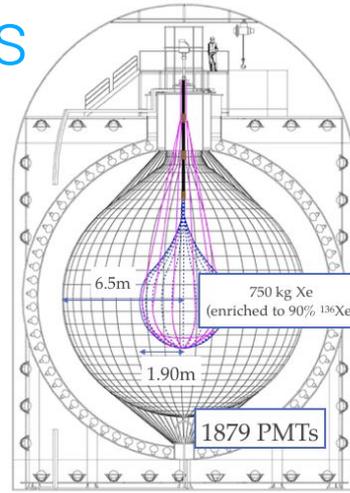
Experiment	$m_{tot}$ [kg]	$f_{enr.}$ [%]	Phase	Readout
EXO-200	161	81	liquid	LAPPDs + wires
nEXO	5109	90	liquid	electrode tiles + SiPM s
NEXT-100	97	90	gas	SiPMs + PMTs
NEXT-HD	1100	90	gas	SiPMs + PMTs
PandaX-III-200	200	90	gas	Micromegas
PandaX-III-1K	1000	90	gas	Micromegas
LZ-nat	7000	9	dual-phase	PMTs
LZ-enr	7000	90	dual-phase	PMTs
DARWIN	39 300	9	dual-phase	PMTs



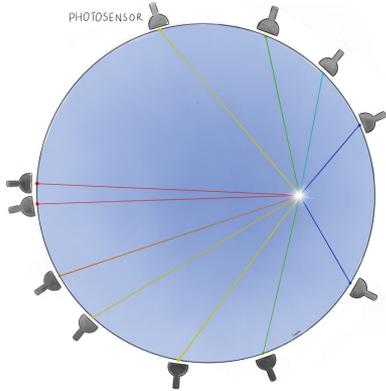
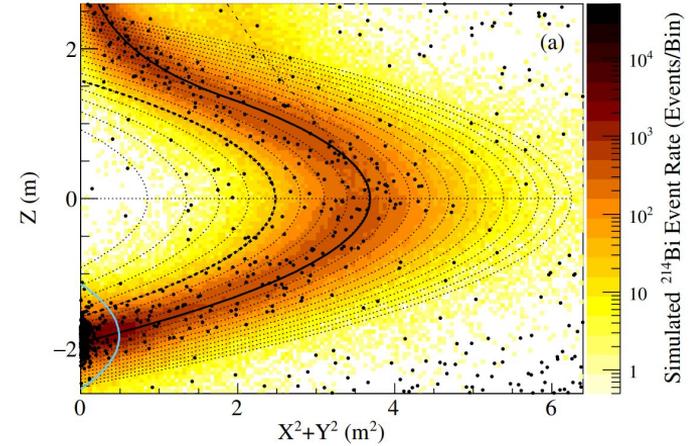
nEXO

# Large liquid scintillators

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



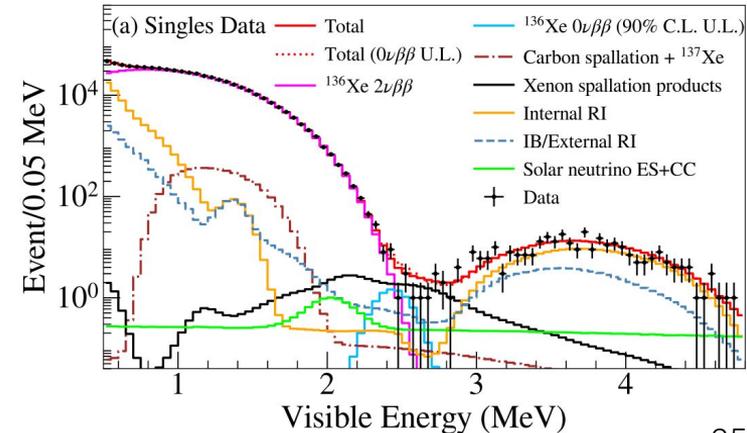
KZ collaboration, [2203.02139](#)



## KamLAND-Zen-800 @Kamioka

- 750 kg of enriched Xe in nylon balloon
- backgrounds:  $2\nu\beta\beta$ , cosmogenic, solar neutrinos,  $^{214}\text{Bi}$  on balloon
- next phase: improved resolution and purer scintillator

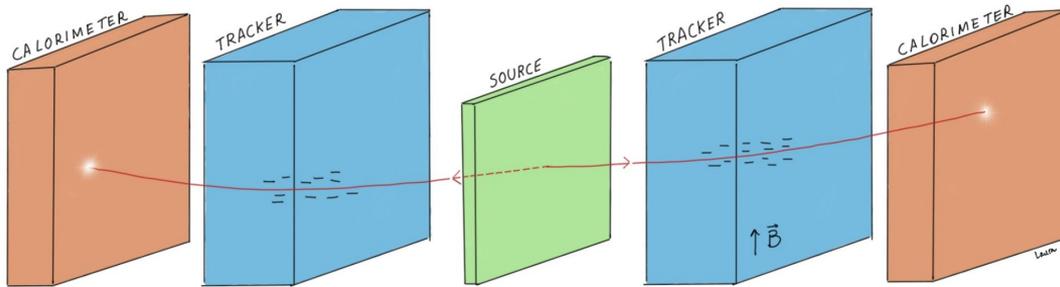
$$T_{1/2}^{0\nu} > 2.3 \times 10^{26} \text{ yr at 90\% C.L.}$$



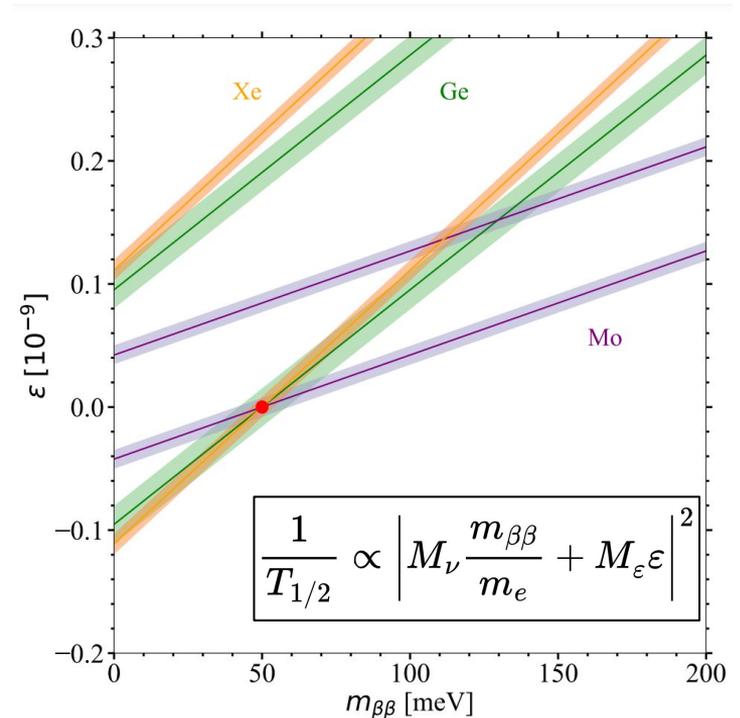
# Beyond a simple rate measurement

How to gain insight on the decay channel?

- measure the electron momenta  $\rightarrow$  angular distribution
- compare decay rate in different isotopes
- combined analysis of neutrino physics, including cosmology



arXiv:2202.01787 - Image courtesy of Laura Manenti



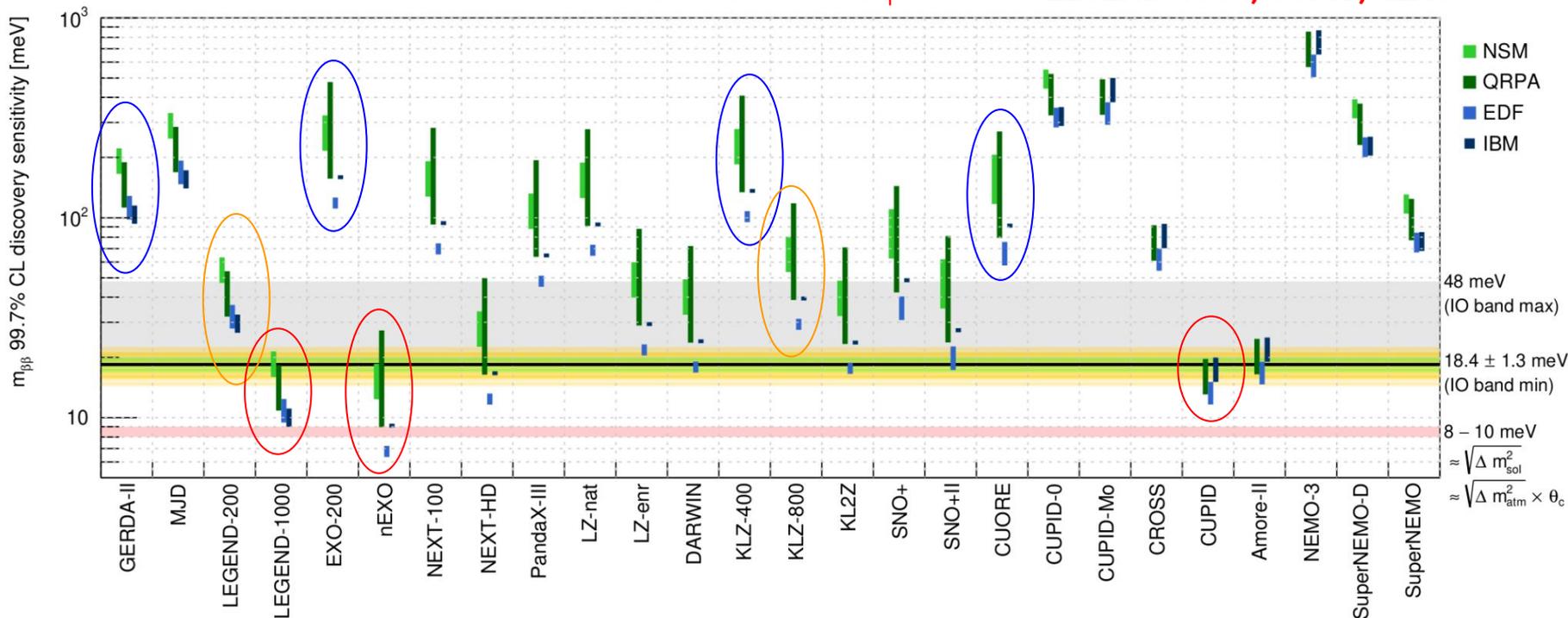
M.A., Deppisch and Van Goffrier  
In preparation

# Where are we heading?

The big 4 of last decade: **GERDA, EXO-200, KamLAND-Zen-400, CUORE**

The two that will dominate the next few years: **LEGEND-200, KamLAND-Zen-800**

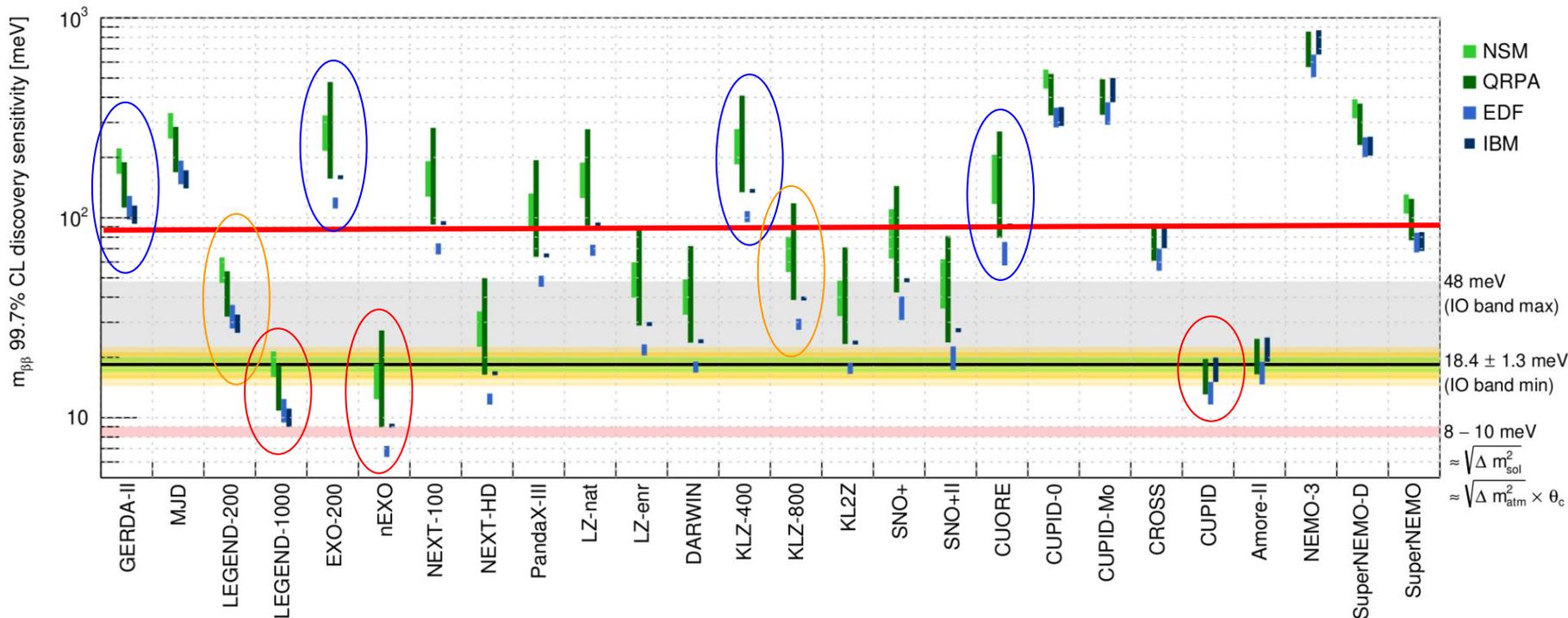
The ultimate 1-ton experiments: **LEGEND-1000, CUPID, nEXO**



# Where are we heading?

## Scenario 1: signal just beyond current limits

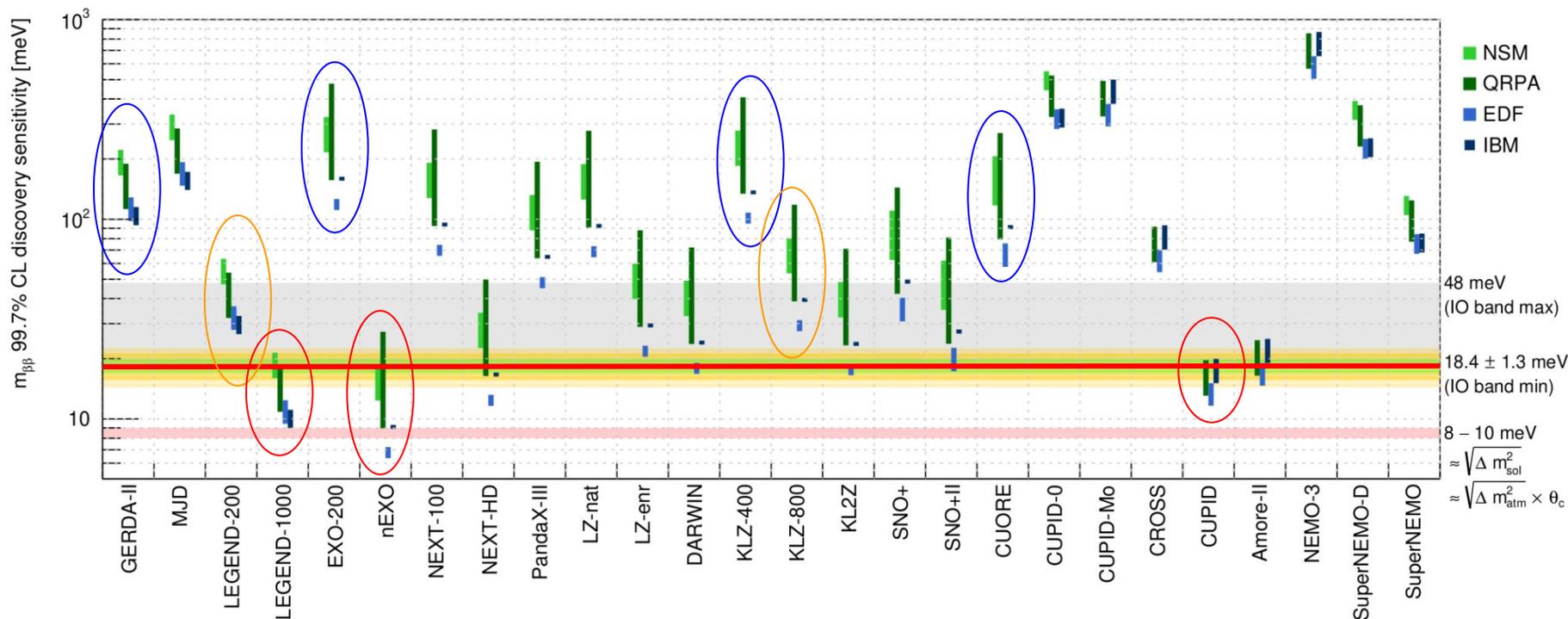
- experiments will discover it within a few years
- next-gen experiments will measure rate
- follow-up measurements of decay features



# Where are we heading?

Scenario 2: weakest signal for inverted ordered neutrinos

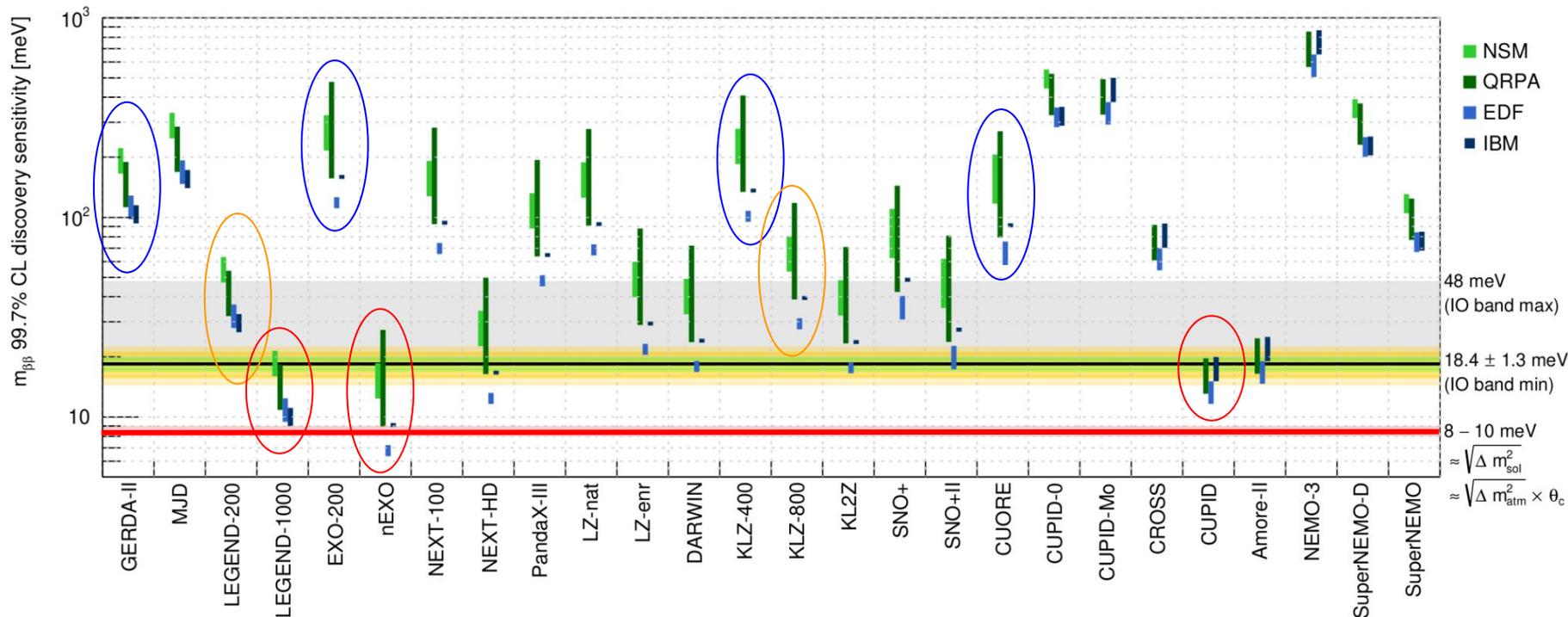
- need to wait next-gen experiments for a discovery
- need R&D to measure decay features



# Where are we heading?

## Scenario 3: signal even weaker or absent

- need R&D for a convincing discovery
- interplay with oscillation experiments and cosmology can still lead to theory breakthroughs



# Conclusions

$0\nu\beta\beta$  decay can lead to the **direct observation of B-L violation** at low-energy in a controlled **laboratory** environment

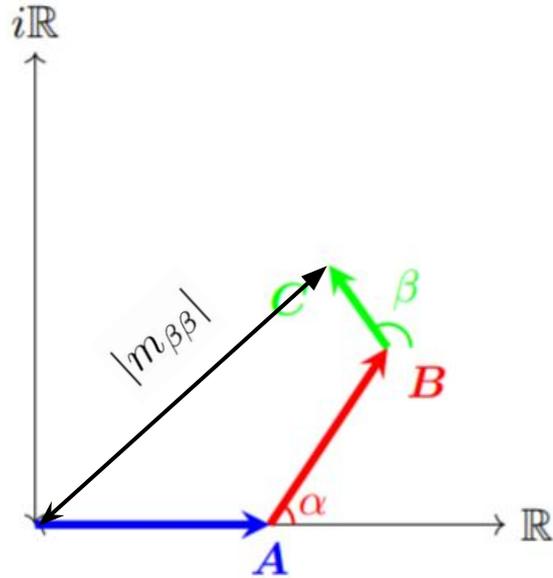
$0\nu\beta\beta$  decay is strongly linked to **L-violating Majorana** neutrinos

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

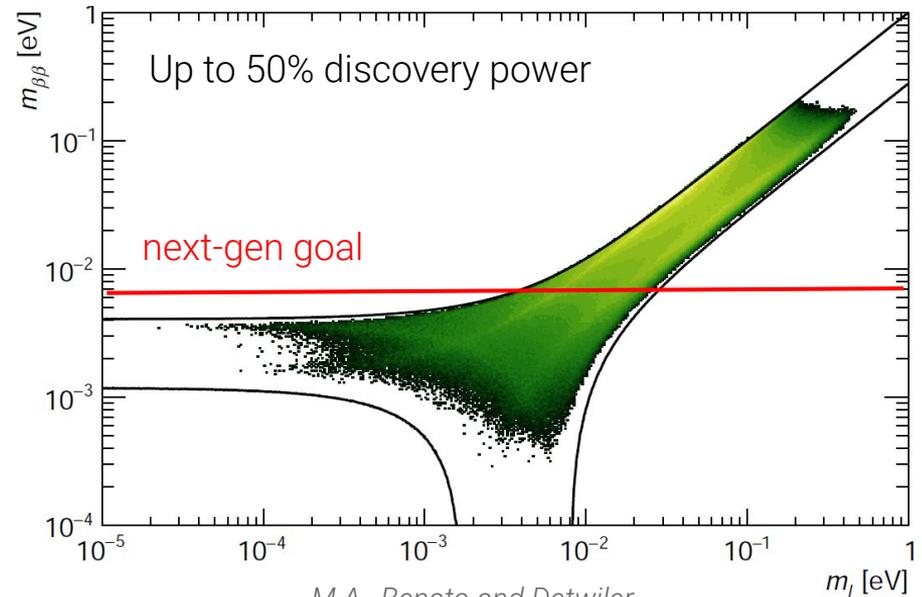
A worldwide, **multi-isotope** experimental program is exploring an exciting parameter space, where a signal can be around the corner

# Future discovery odds for normal ordered neutrinos

$$|m_{\beta\beta}| = \underbrace{(c_{12}^2 c_{13}^2 m_1)}_A + \underbrace{(s_{12}^2 c_{13}^2 m_2)}_B e^{i2\alpha} + \underbrace{(s_{13}^2 m_3)}_C e^{i2\beta}$$



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

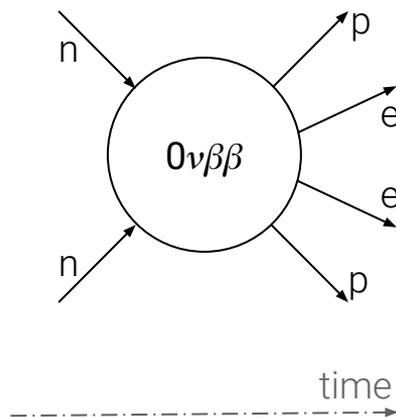
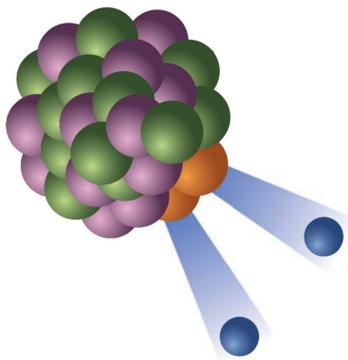


*M.A., Benato and Detwiler  
PRD 96, 053001 (2017)*

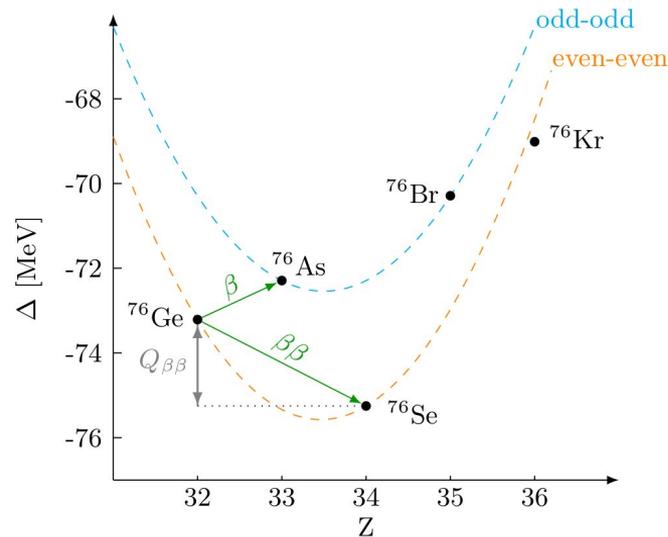
# What are we searching for?

Nuclear decay:  $(A, Z) \rightarrow (A, Z+2) + 2$

- 2 neutrons  $\rightarrow$  2 protons ( $\Delta B = 0$ )
- 2 electrons are emitted ( $\Delta L = 2$ )



Direct violation of L and B-L



Possible only for a few isotopes

# Signal & Background

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

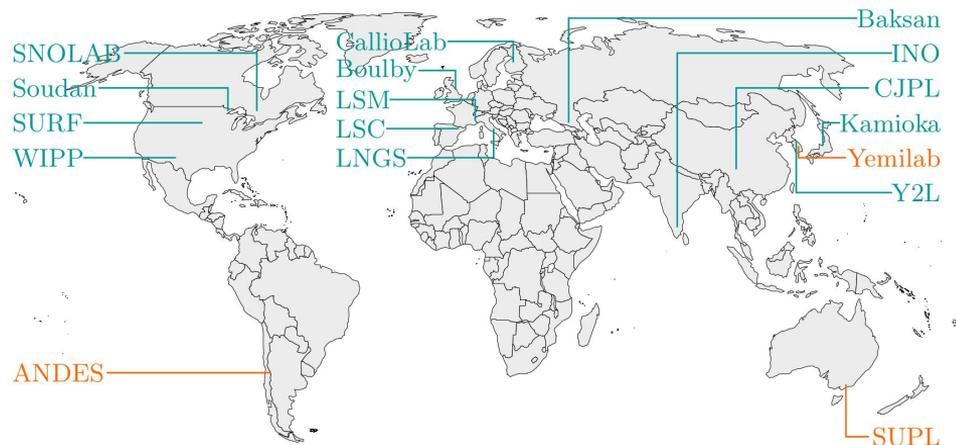
- two-electron summed energy = Q-value
- two-electron event topology
- (excited states/daughter isotope)

## Backgrounds:

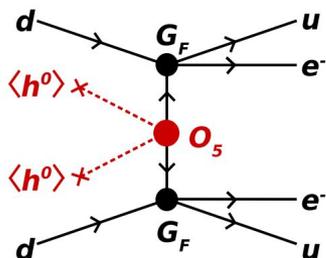
- cosmic-ray induced
- $^{238}\text{U}/^{232}\text{Th}$  decay chains
- neutrons
- solar neutrinos
- $2\nu\beta\beta$  decay (only irreducible background)

## Mitigation

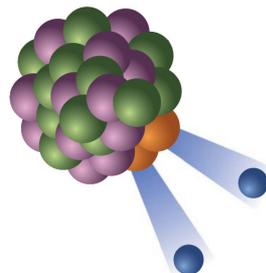
- underground laboratory
- material selection
- shielding strategy
- multivariate analysis
- energy tagging (only way to mitigate  $2\nu\beta\beta$ )



# How to connect the rate with particle physics?



$$P \propto \frac{1}{T_{1/2}} \propto G g^4 M^2 \left( \frac{m_{\beta\beta}}{m_e} \right)^2$$



phase space factor

hadronic matrix element

nuclear matrix element (NME)

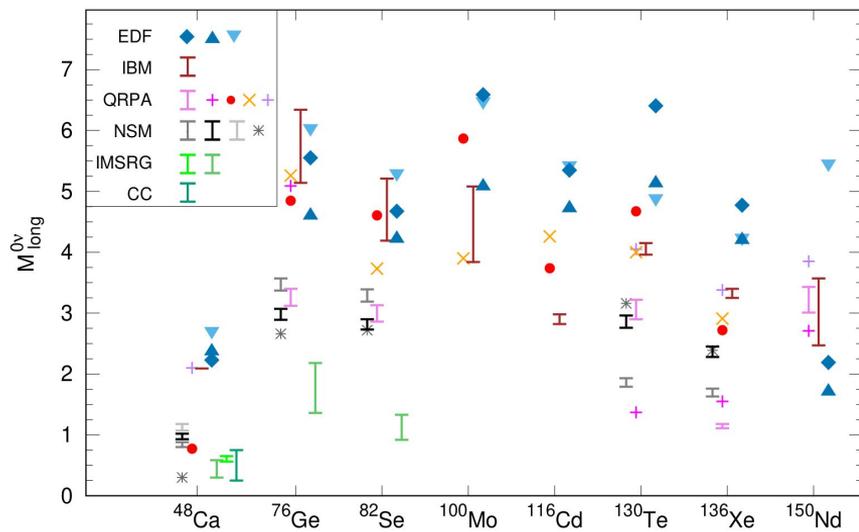
Can be computed accurately  
(even if sometime  $\mathbf{g}$  is used to  
incorporate biases in NME calculations)

Requires calculations of :

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

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