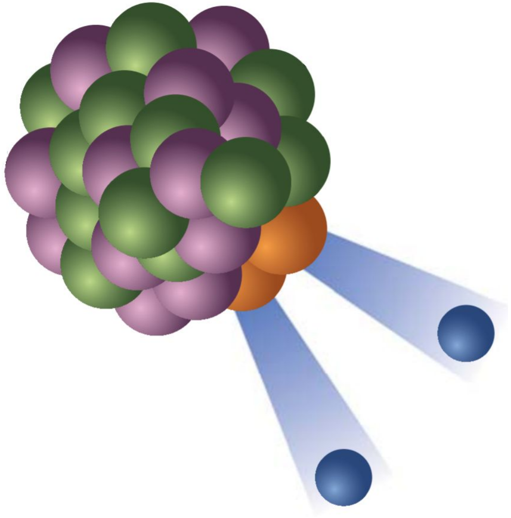
Toward the Discovery of Matter Creation with Neutrinoless $\beta\beta$ Decay



Matteo Agostini

STFC Ernest Rutherford Fellow at UCL

IoP 2022 - Joint APP/HEPP Conference

3- 6 April 2022, Rutherford Appleton Laboratory

UCL

UKRI Science and Technology Facilities Council

What is matter? What are its fundamental blocks?

According to the Standard Model

- particles / antiparticles symmetry
- energy ↔ 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)**

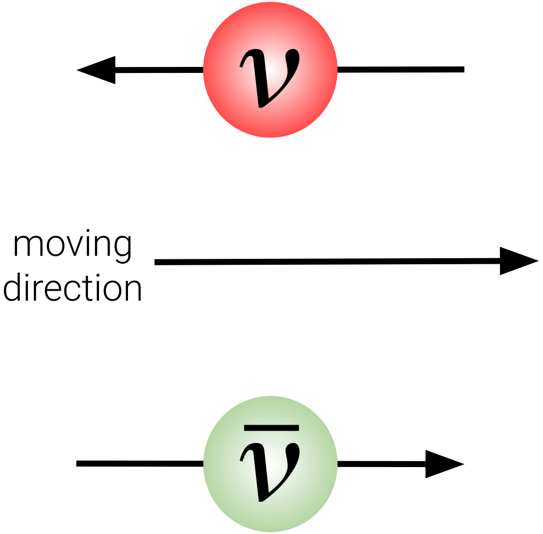
Matter			charge		Antimatter		
Quarks -> Baryons					Anti-Quarks -> Anti-Baryons		
u	c	t	+2/3	-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
d	s	b	-1/3	+1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
Leptons					Anti-Leptons		
e	μ	τ	-1	+1	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$
ν_e	ν_μ	ν_τ	0	0	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

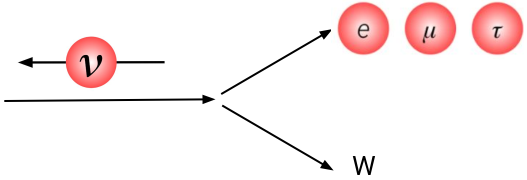
Which kind of processes can we look for?

What distinguishes particles from antiparticles?

What distinguishes neutrinos from antineutrinos?

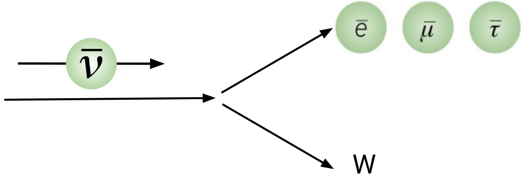
If they have no mass…





neutrinos move **antiparallel** to their spin

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



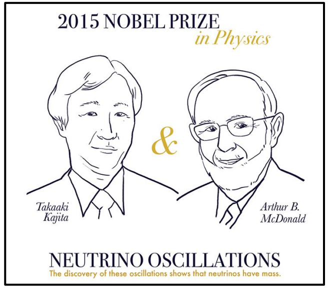
anti-neutrinos move **parallel** to their spin

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

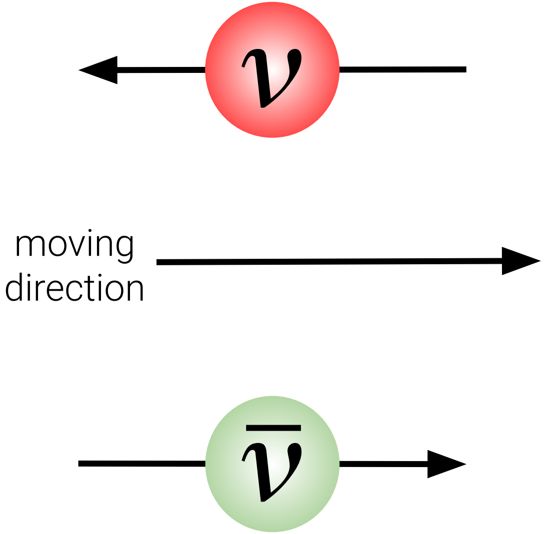
Dell'Oro, Marcocci, Viel and Vissani, Adv.High Energy Phys. 2016 (2016) 2162659

What distinguishes neutrinos from antineutrinos?

But neutrinos are massive!



See taks by Melissa Uchida and Stefan Söldner-Rembold



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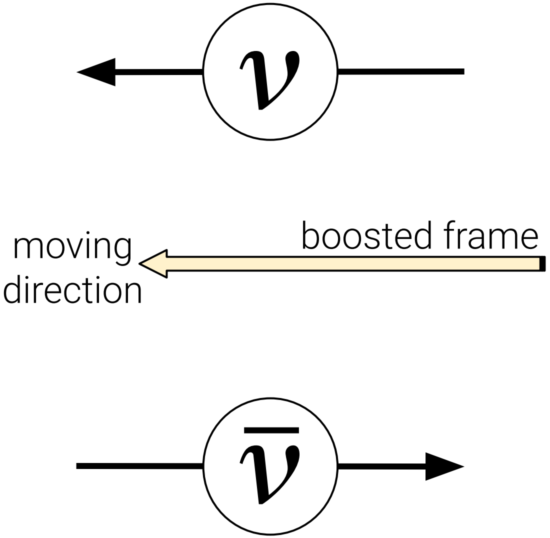
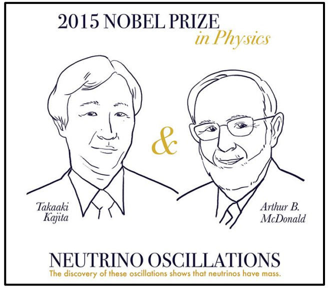


boosted frame

moving
direction



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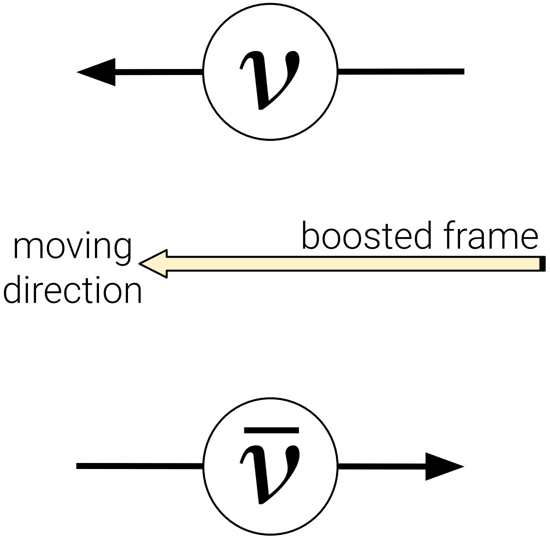
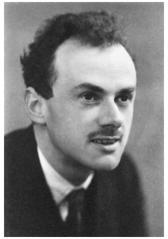
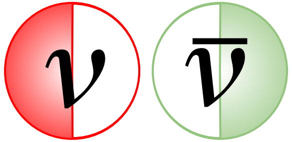
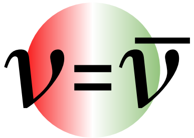




Dirac



Majorana



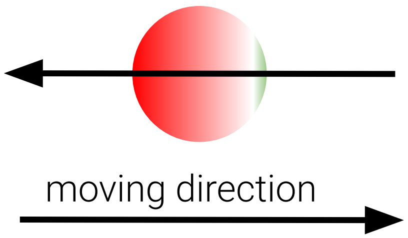
There are two new non-interacting “sterile” states….

…or the same object has both chiral states

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

Neutrino-antineutrino transformations

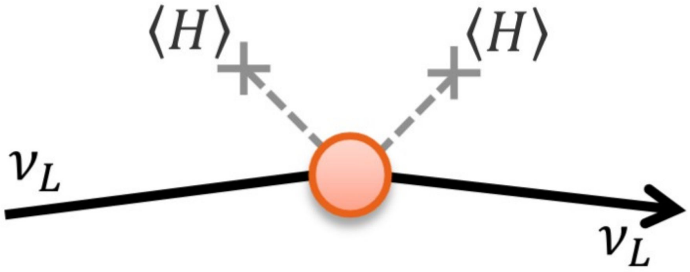
Majorana neutrinos can interact creating both matter and antimatter



- mechanisms to change **L** (and thus **B-L**)
- explain mystery of neutrino masses

  … and why there are so small

Majorana masses

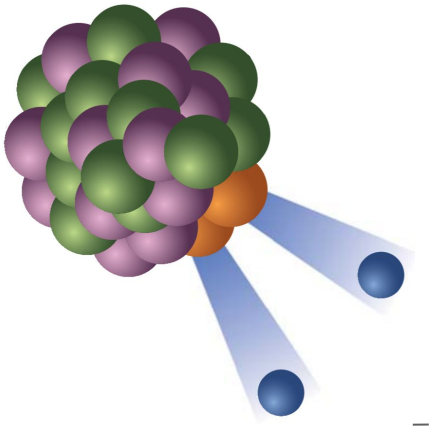


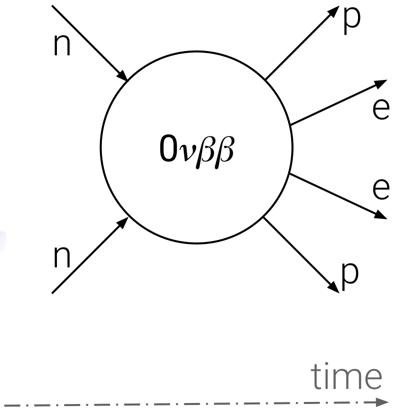
- variant of the Higgs mechanism
- no need for tiny Yukawa couplings
- neutrino tiny masses inversely proportional to those of heavy right-handed states

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

(A,Z) -> (A,Z+2) + 2

- 2 neutrons -> 2 protons (ΔB = 0)
- 2 electrons are emitted (ΔL = 2)





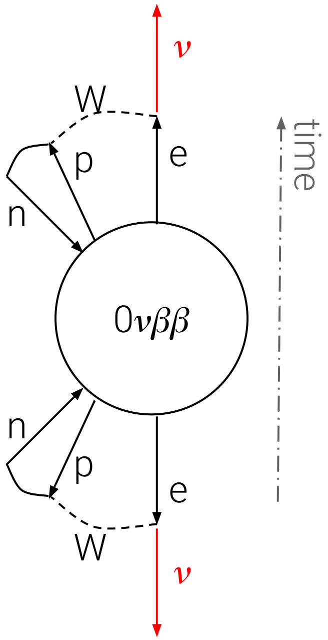
Direct violation of L and B-L

Same diagram

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

Schechter and Valle

1982



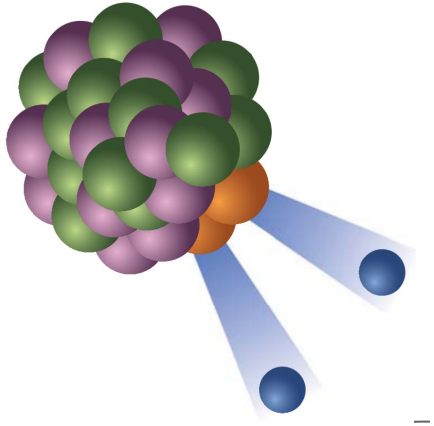
A tiny, but non-zero Majorana mass

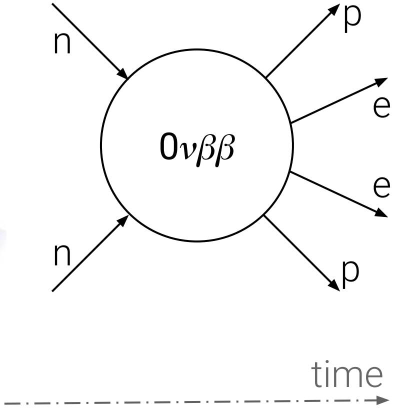
A portal to new physics beyond the SM

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

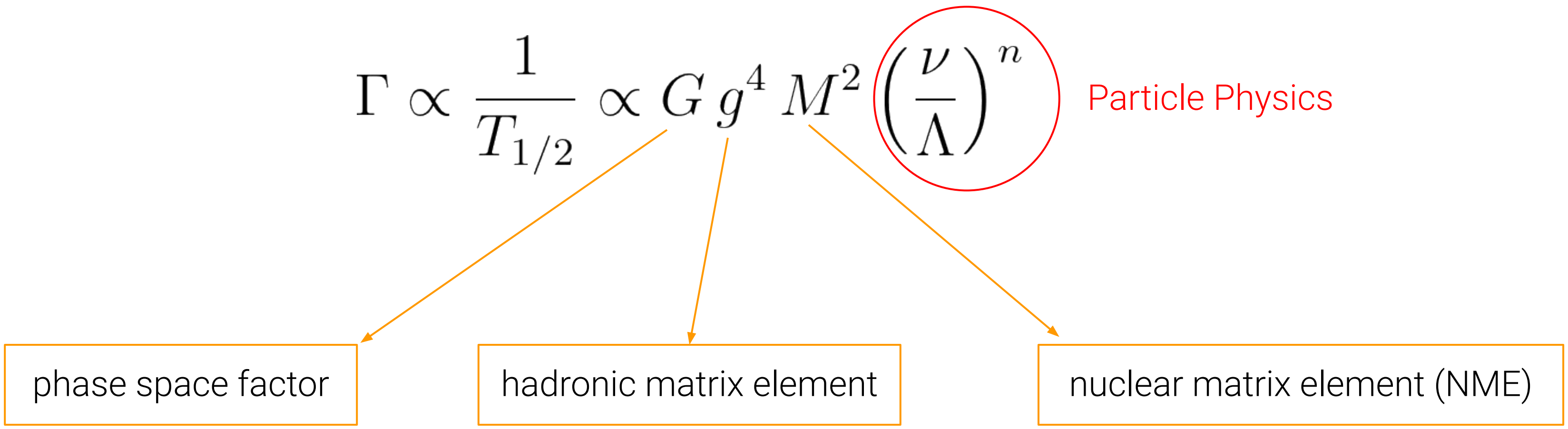
Particle Physics

Nuclear Physics





A portal to new physics beyond the SM



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

Particle Physics

Can be computed accurately

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

Requires calculations of :

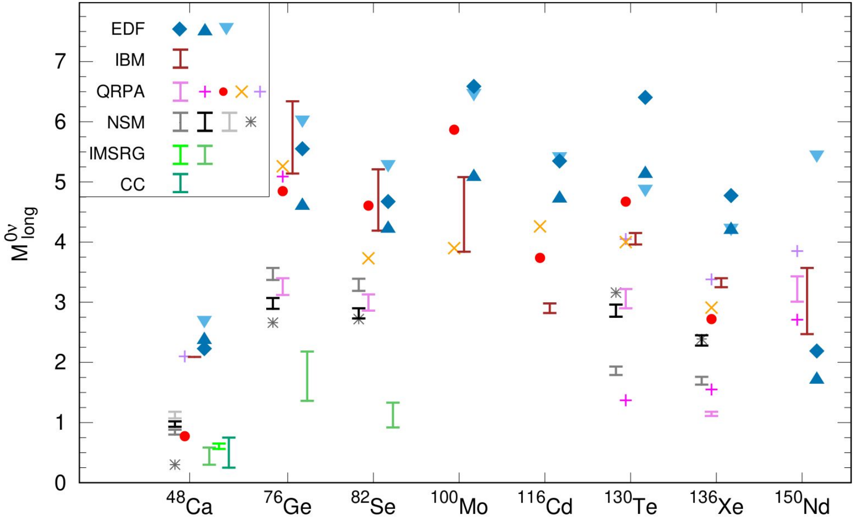
- wavefunction overlap between initial and final states
- lepton-nucleus interaction

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 matrix element (NME)



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

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A portal to new physics beyond the SM

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

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

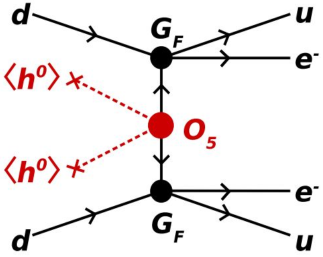
$$\Gamma \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Higgs vacuum expectation

energy scale of BSM

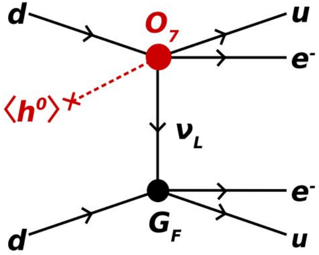
Dim 5: Weinberg Operator

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



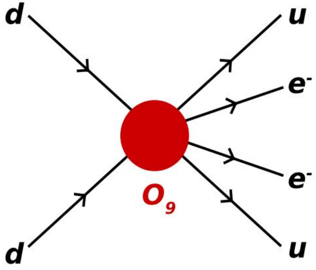
Dim 7

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



Dim 9

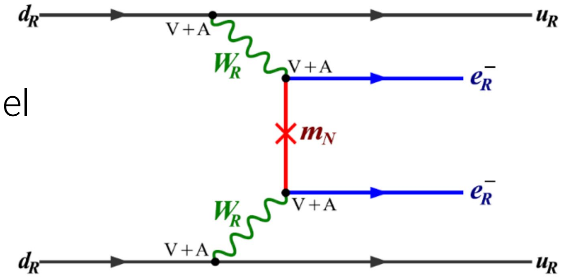
$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\Lambda}\right)^{10}$$



A generic search for ultrahigh-energy BSM physics

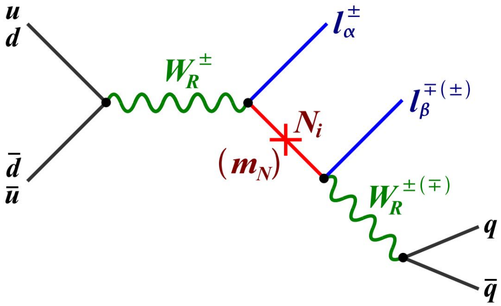
Example: left-right symmetry

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

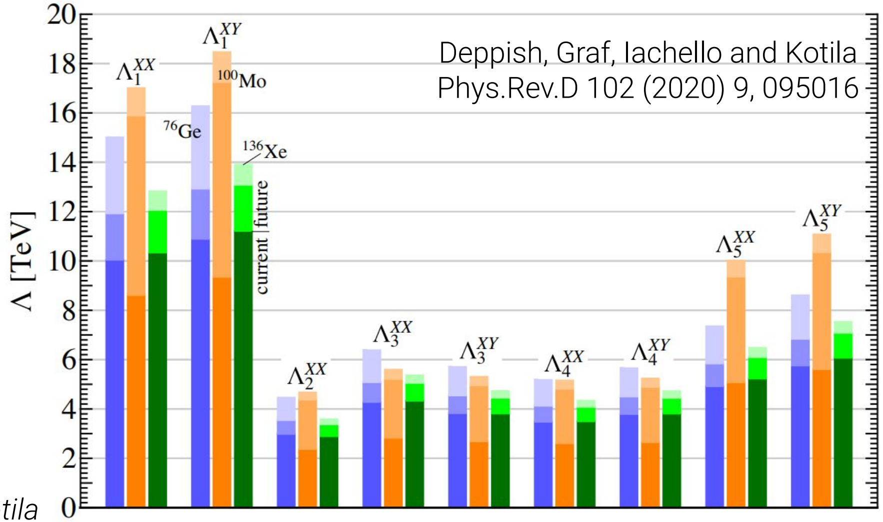


$0\nu\beta\beta$ and collider searches are complementary

$T_{1/2}$ is proportional to the energy scale, and a signal can manifest at any time!



Same as dilepton signature at LHC



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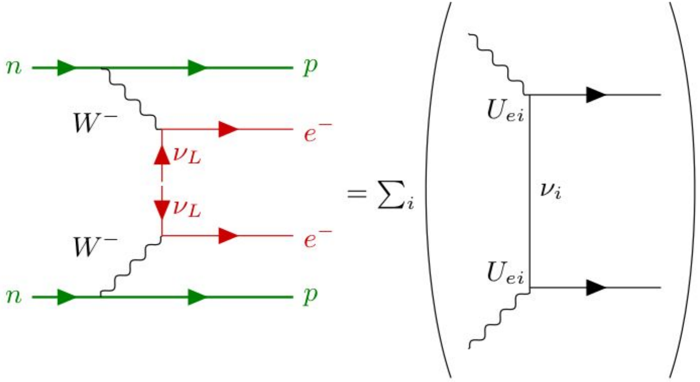
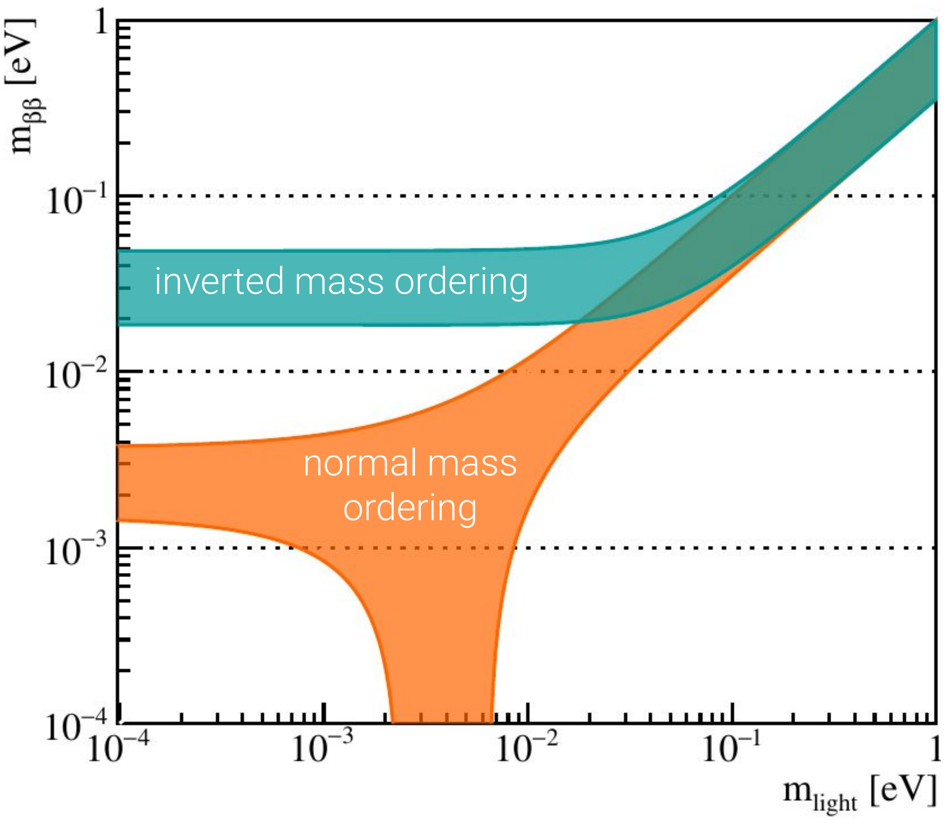
Light Majorana neutrino exchange

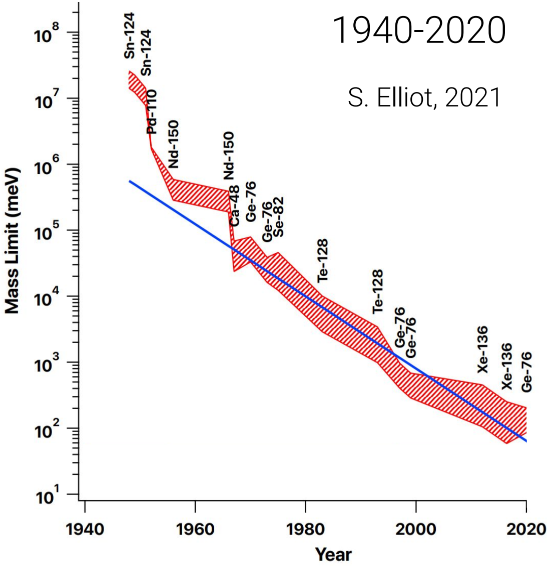
Parameter connected to neutrino mixing probabilities, masses and complex phases



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



Discovery odds: **inverted** ordered neutrinos



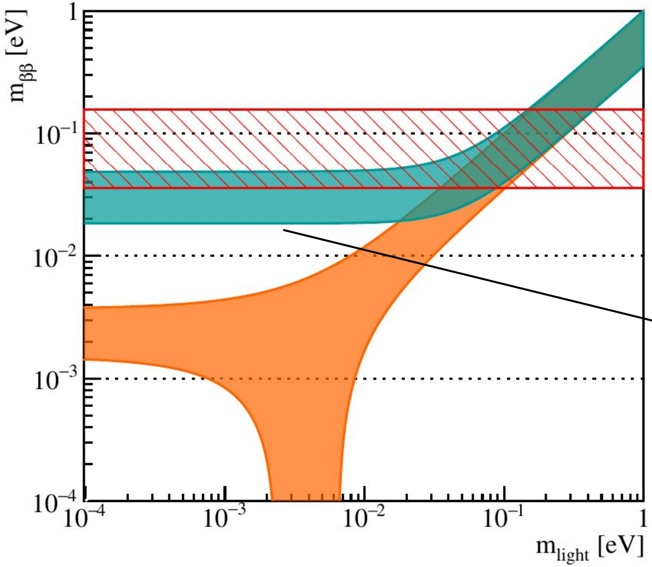
1940-2020

S. Elliot, 2021

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

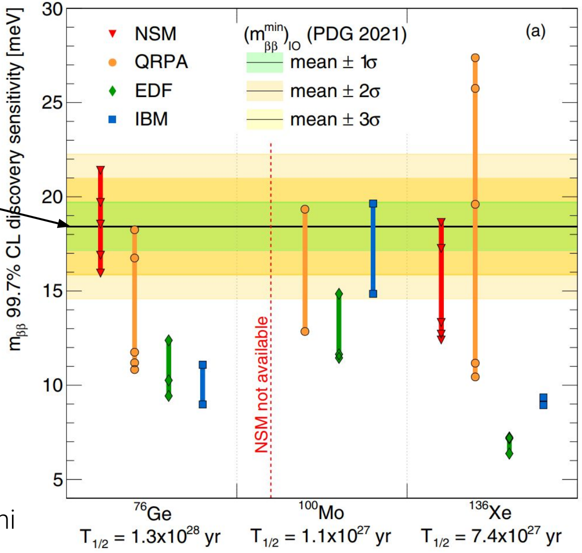
Best Today

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



Best Nex Gen

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

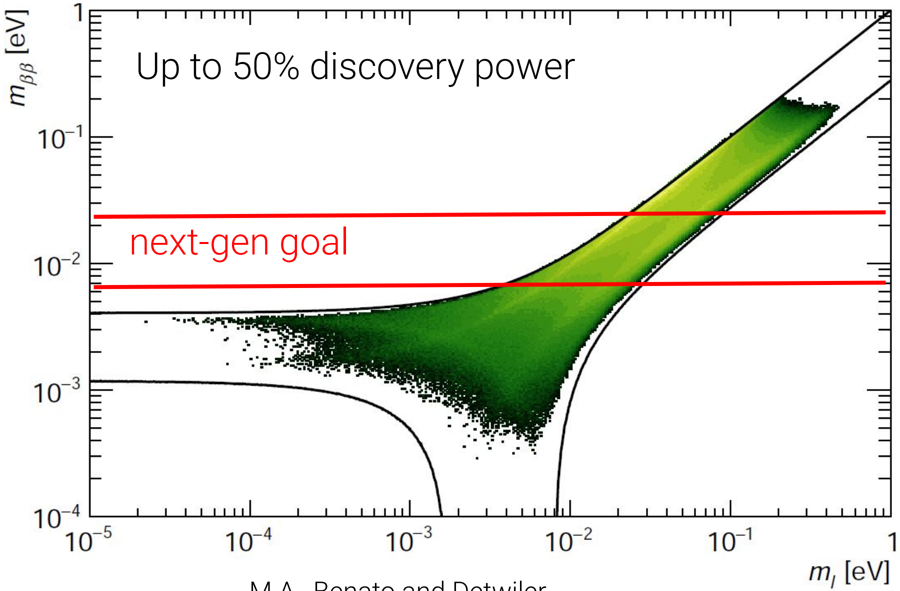


M.A., Benato, Detwiler, Menéndez and Vissani
PRC 104, L042501

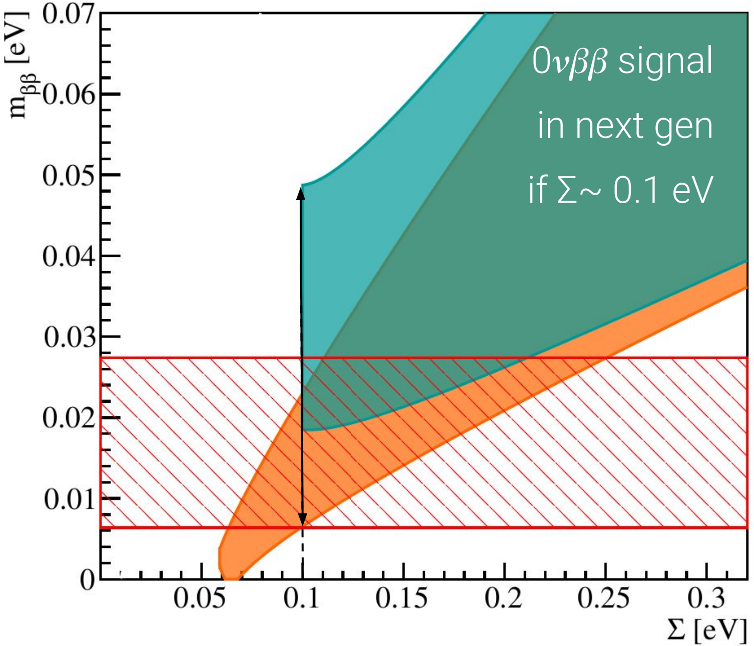
Discovery odds: **normal** ordered neutrinos

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

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



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



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How to build a $0\nu\beta\beta$ decay experiment?

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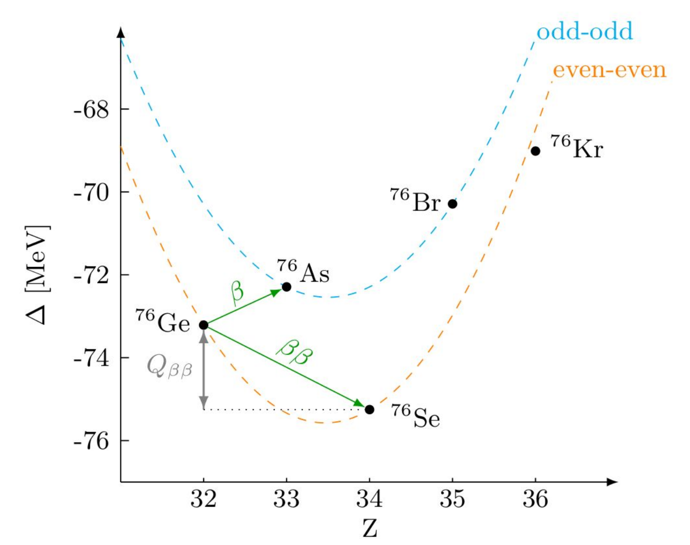
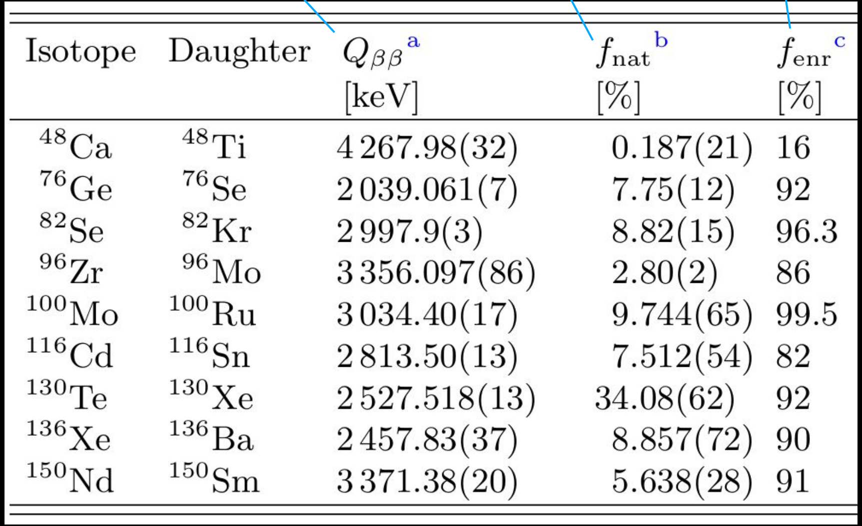
Step 1: Choose a $0\nu\beta\beta$-decay candidate isotope



Single β decay forbidden or strongly suppressed

$1/T_{1/2} \propto (Q_{\beta\beta})^5$ makes it cheaper lowers background



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

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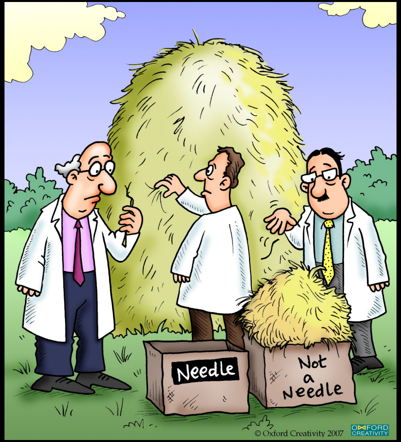
How to build a $0\nu\beta\beta$ decay experiment?

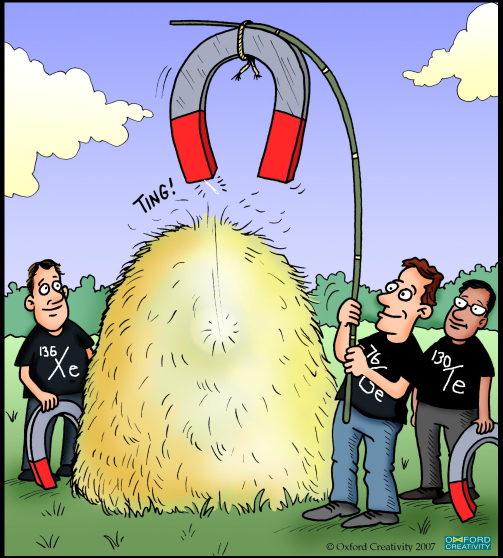
Step 1: Choose a $0\nu\beta\beta$-decay candidate isotope

Step 2: Develop a detection concept able to detect each single decay without false positives

Solid, liquid or gas target?

Ionization, scintillation, phonons, Cherenkov?





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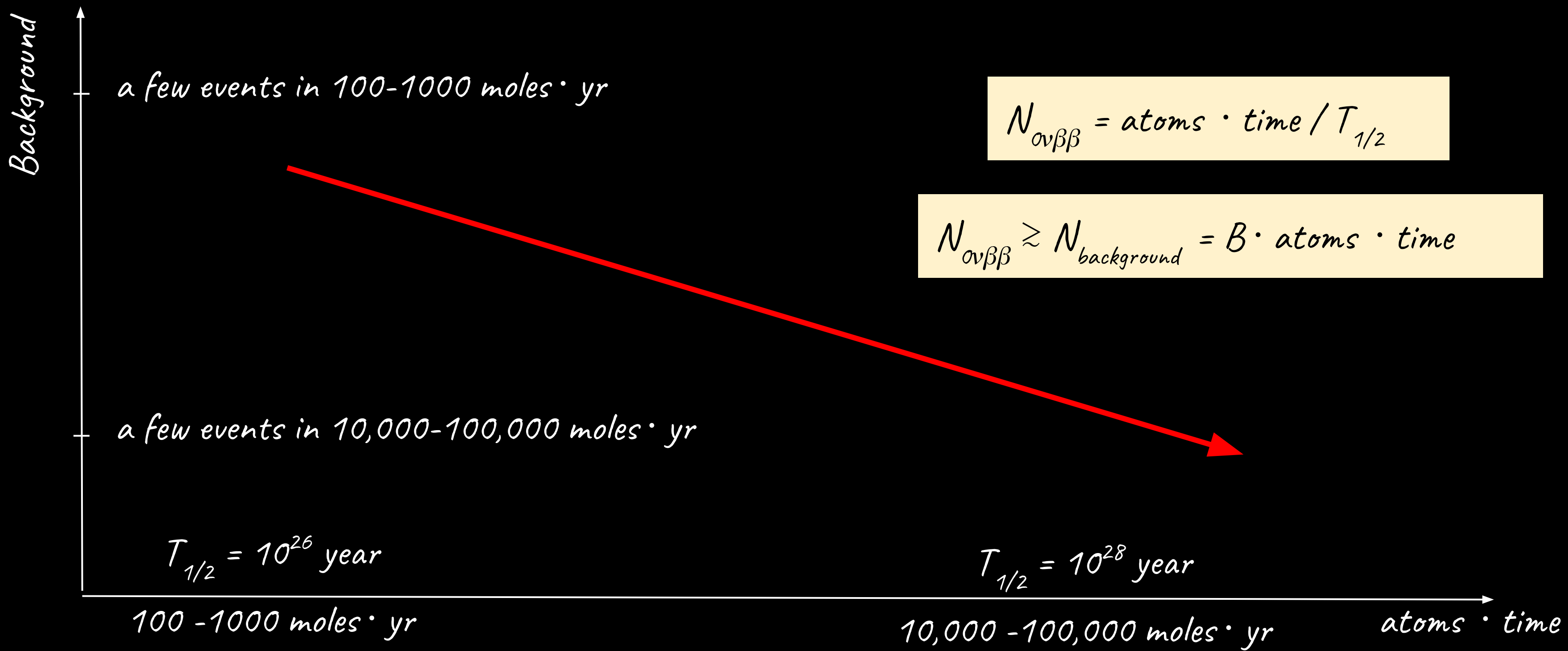
Step 1: Choose a $0\nu\beta\beta$-decay candidate isotope

Step 2: Develop a detection concept able to detect each single decay without false positives

$$N_{0\nu\beta\beta} = \text{atoms} \cdot \text{time} / T_{1/2}$$

Step 3: Make it big enough

How to build a $0\nu\beta\beta$ decay experiment?



Background

a few events in 100-1000 moles · yr

a few events in 10,000-100,000 moles · yr

$T_{1/2} = 10^{26}$ year

$T_{1/2} = 10^{28}$ year

100 -1000 moles · yr

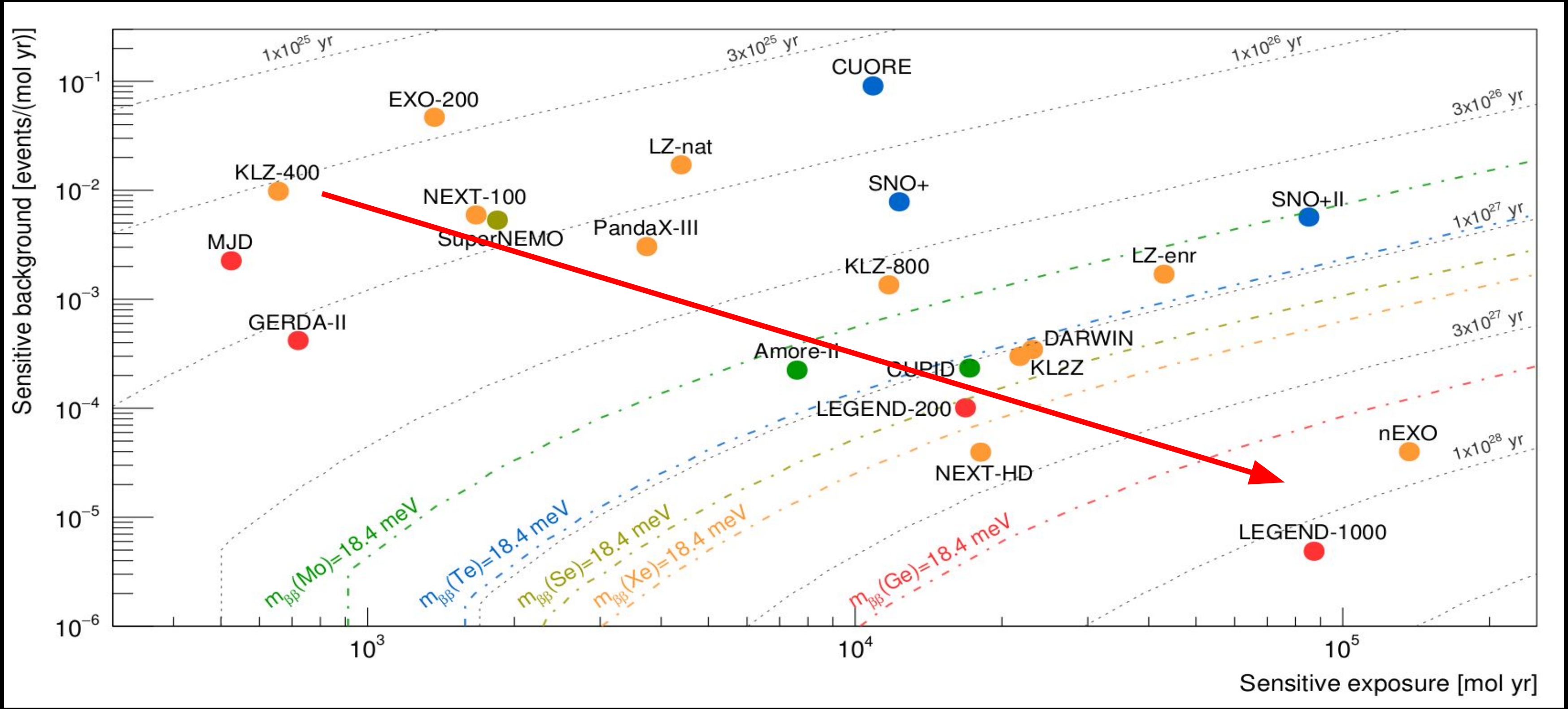
10,000 -100,000 moles · yr

atoms · time

$$N_{0\nu\beta\beta} = \text{atoms} \cdot \text{time} \,/\, T_{1/2}$$

$$N_{0\nu\beta\beta} \gtrsim N_{\text{background}} = B \cdot \text{atoms} \cdot \text{time}$$

Recent and future experiments



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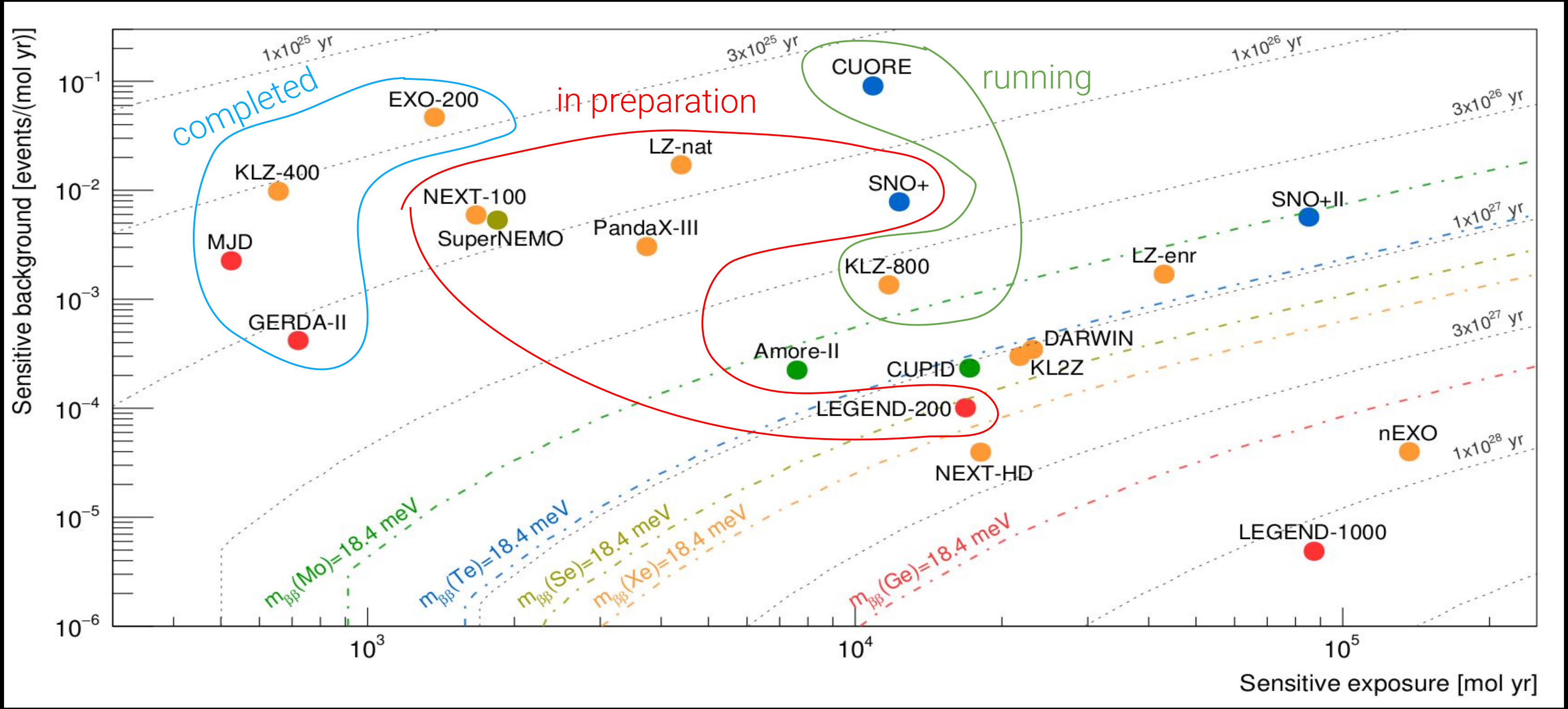

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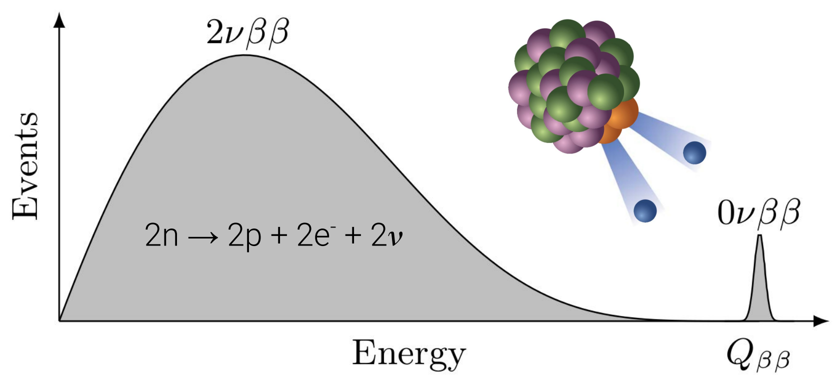
Signal & Background

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

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

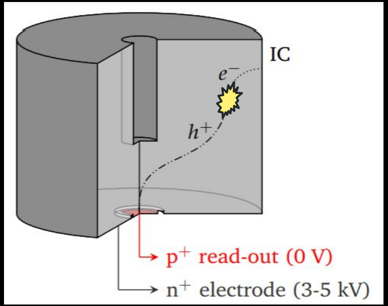


Backgrounds:

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

Mitigation

- underground laboratory
- material selection
- shielding strategy
- multivariate analysis
- energy tagging (only way to mitigate 2vbb)

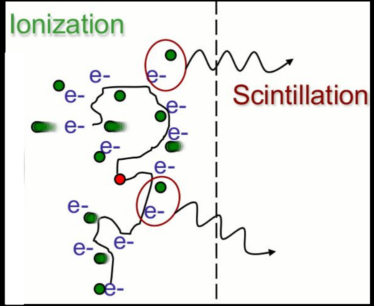


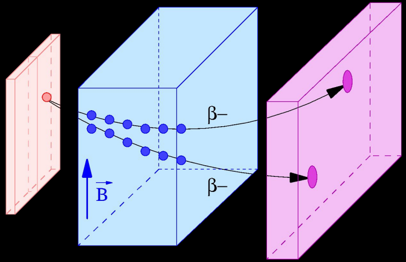
Ge Semiconductor detectors (^{76}Ge)

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

Xe Time Projection Chambers (^{136}Xe)

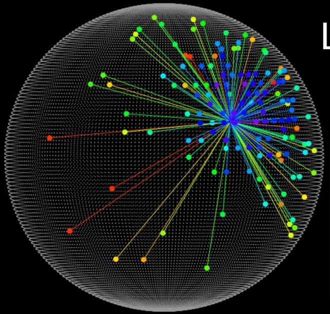
Used for first real-time observation of 2vbb decay. At the forefront since then.





Tracking Calorimeters (^{82}Se)

Only concept in which the source is decoupled from the detector

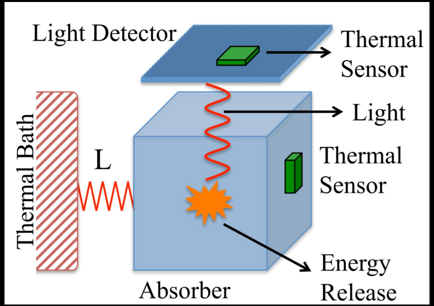


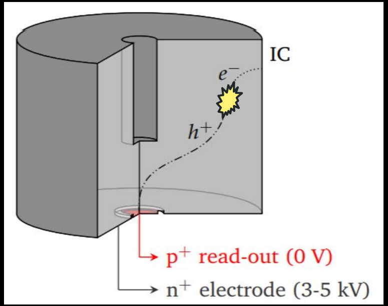
Large Liquid scintillator detectors (^{130}Te,^{136}Xe)

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



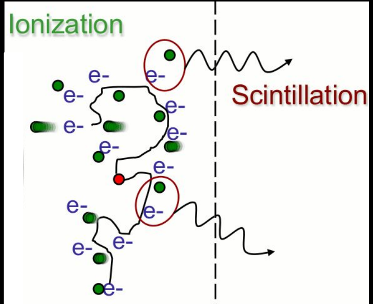


Ge Semiconductor detectors (^{76}Ge)

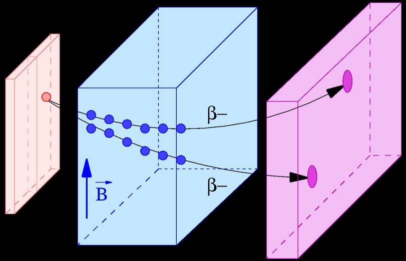
LEGEND

Xe Time Projection Chambers (^{136}Xe)

LZ

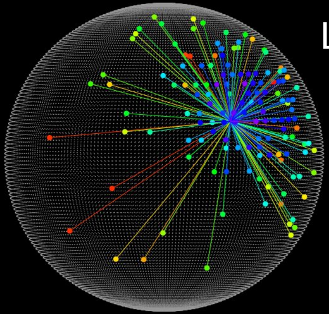


See talk by Kimberly Palladino



Tracking Calorimeters (^{82}Se)

supernemo collaboration



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

SNO+

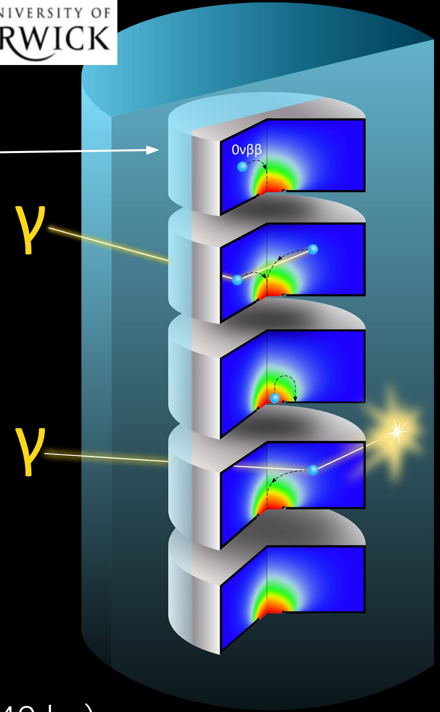
LEGEND

Lancaster University

UNIVERSITY OF LIVERPOOL

UCL

THE UNIVERSITY OF WARWICK



^{76}Ge semiconductor detectors

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

liquid Ar detector

- shield and scintillation light

Staged approach:

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

Leading experiment in:

- APPEC review
- DOE portfolio review
- North America & Europe summit

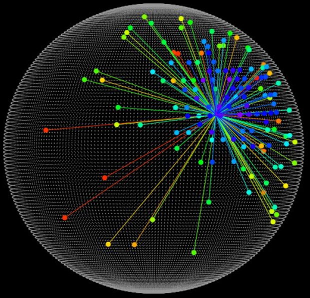
LEGEND-UK workshop (Mar 31): https://indico.legend-exp.org/event/751/

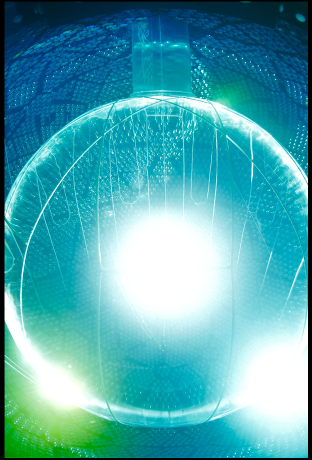
SNO+

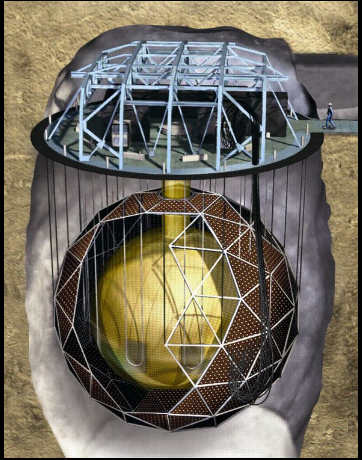
- scintillator loaded with target isotope
- scintillation photons detected by PMTs
- photon number and arrival time gives event energy and position
- clean, self-shielding, scalable

Phase I -> Phase II

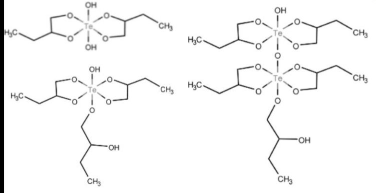
- loading with natural Te (high natural abundance of ^{130}Te → inexpensive)
- 0.5% Te-loading to start toward the end of next year (1.3 t)
- 3% or more Te-loading after initial demonstration of the method (> 7 t)

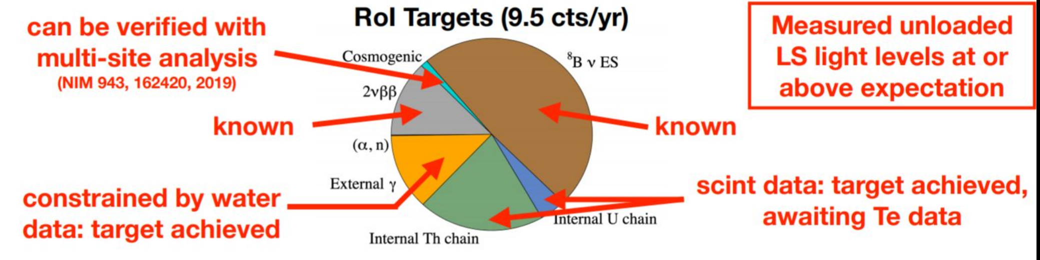






Diol Loading of ^{130}Te in Liquid Scintillator (also developed in UK)





can be verified with multi-site analysis (NIM 943, 162420, 2019)

known

constrained by water data: target achieved

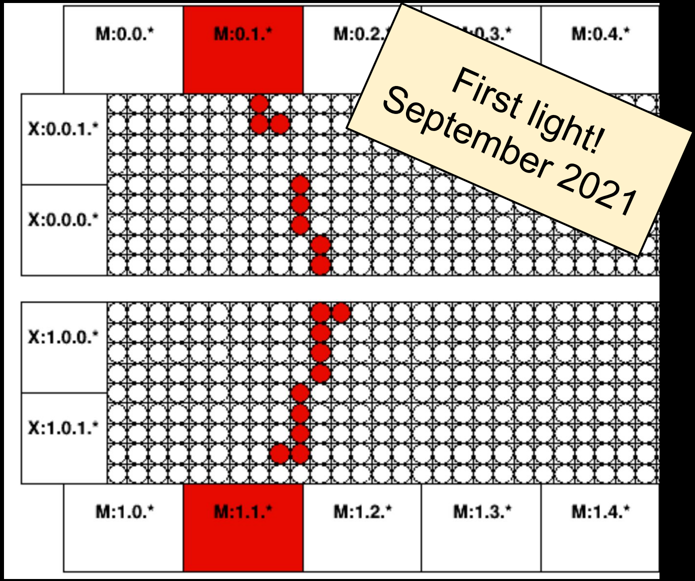
known

scint data: target achieved, awaiting Te data

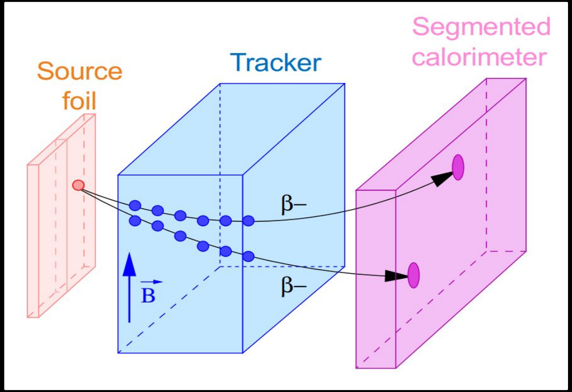
Measured unloaded LS light levels at or above expectation supernemo collaboration

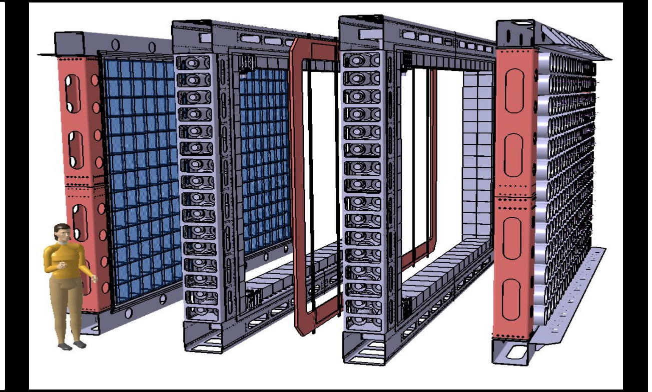
THE UNIVERSITY of EDINBURGH
Imperial College London
MANCHESTER 1824
THE UNIVERSITY OF WARWICK
UCL

- Can deploy any solid $\beta\beta$ isotope → SuperNEMO ^{82}Se
- Tracker and segmented calorimeter → particle ID: electron, γ, α
- Full $\beta\beta$ kinematics and topology → signal mechanism
- $2\nu\beta\beta$ physics programme → nuclear mechanisms

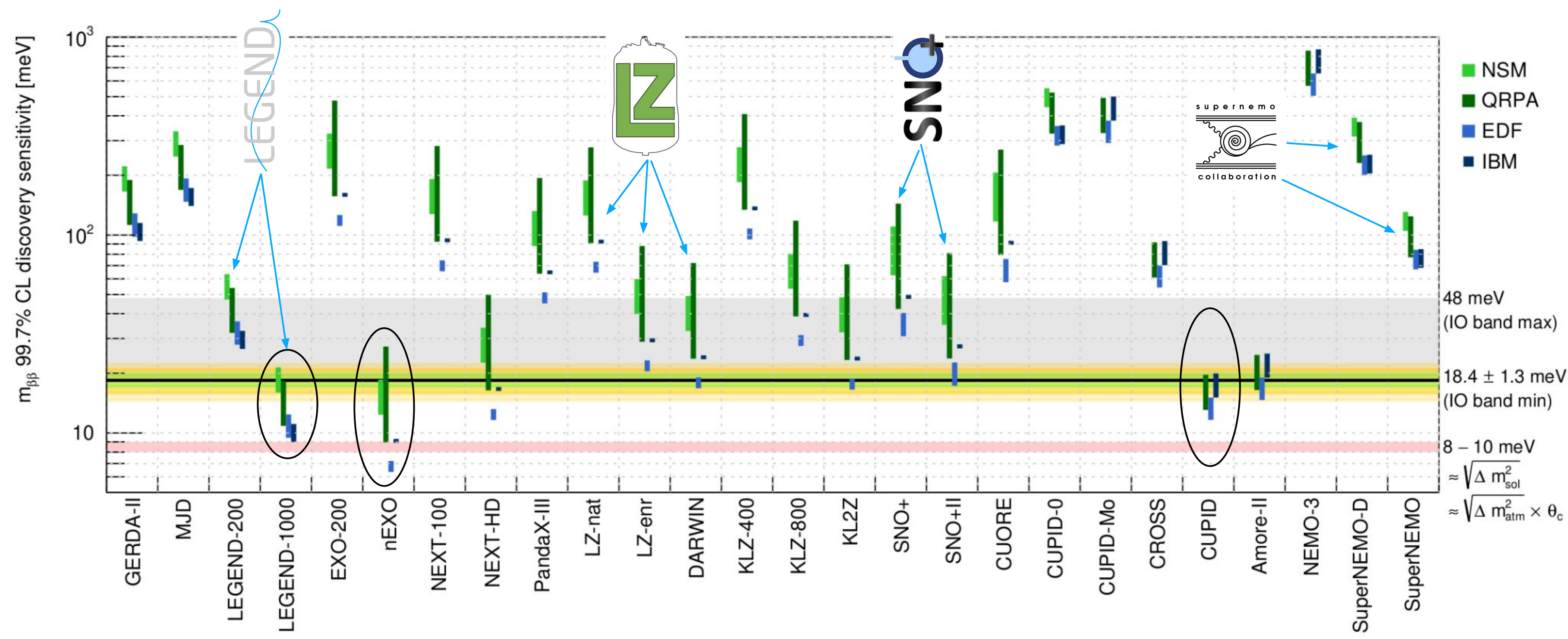


First light!
September 2021





Discovery power of the field

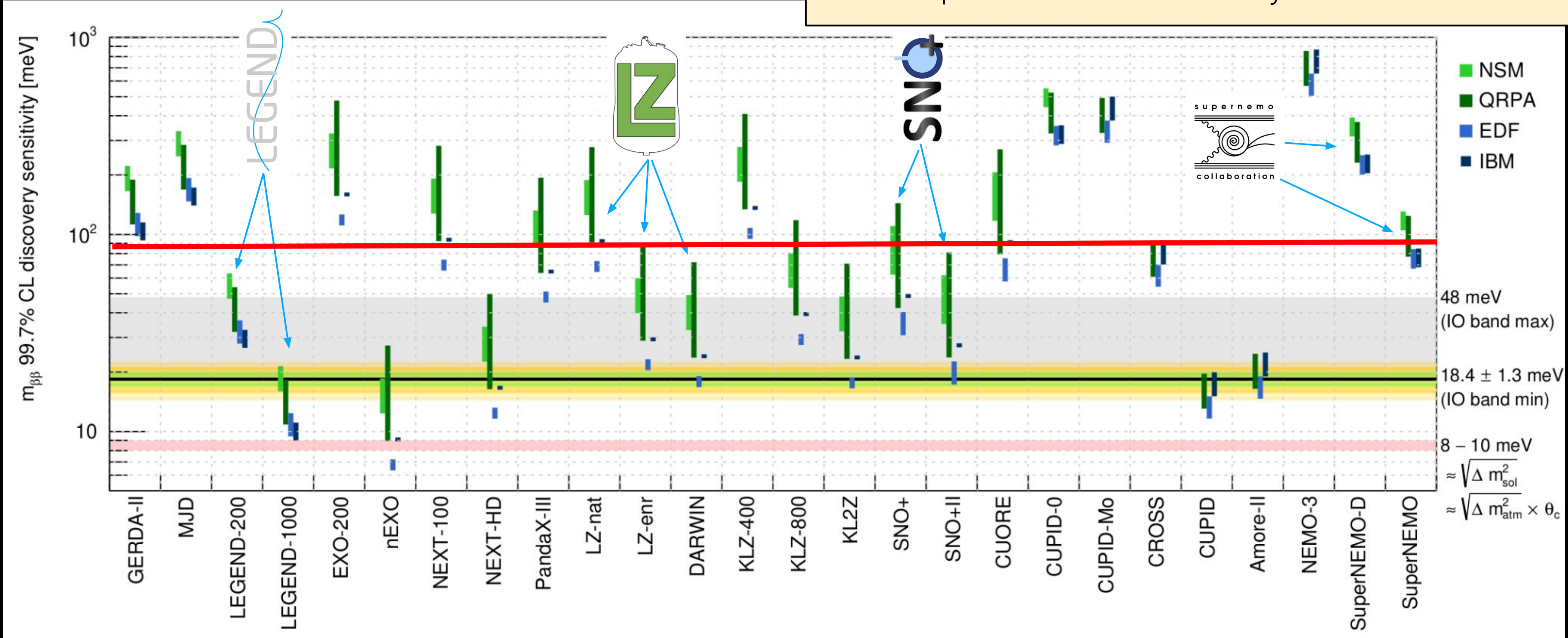


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 1: signal just beyond current limits

- L200, KZ-800, SNO+I discover it
- L1000, nEXO, CUPID, SNO+II measures rate
- SuperNEMO studies decay kinematic

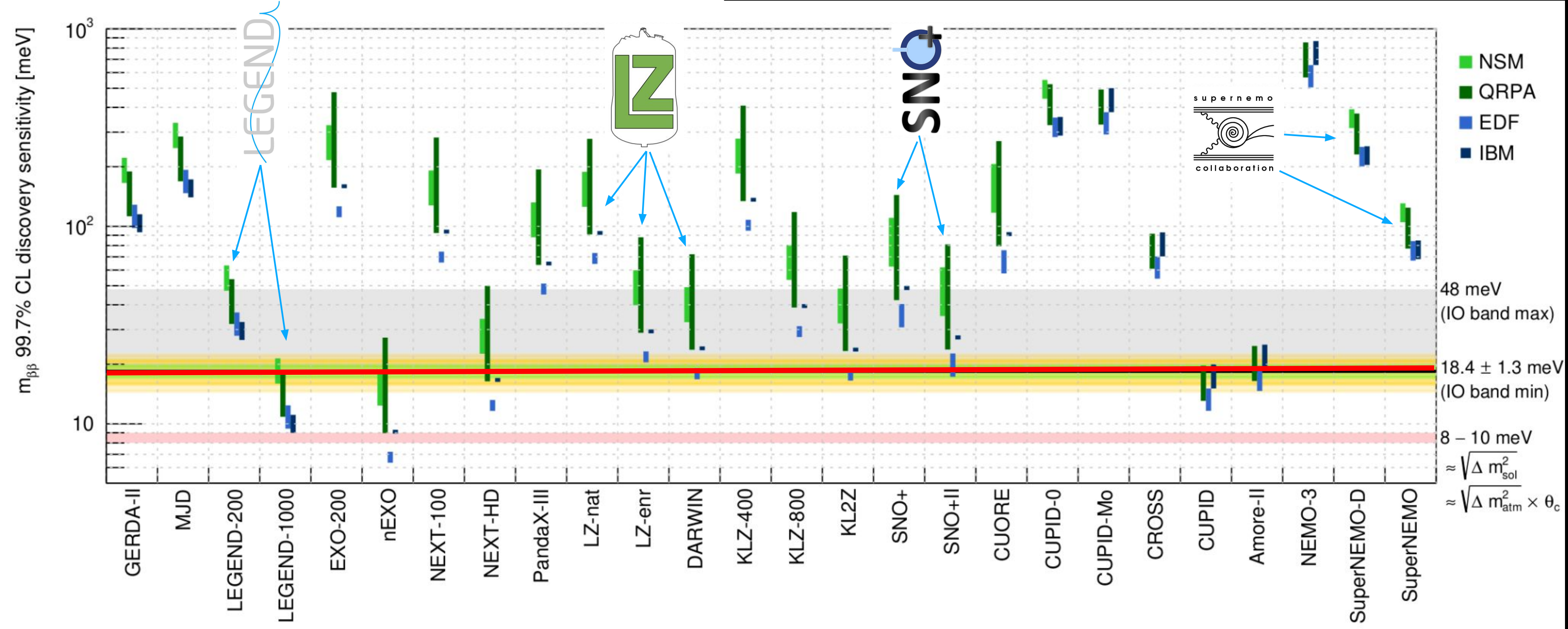


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 2: weakest signal for inverted ordered neutrinos

- L1000, nEXO, CUPID discover it
- follow-up experiments needed for precise measurements (SuperNEMO R&D?)

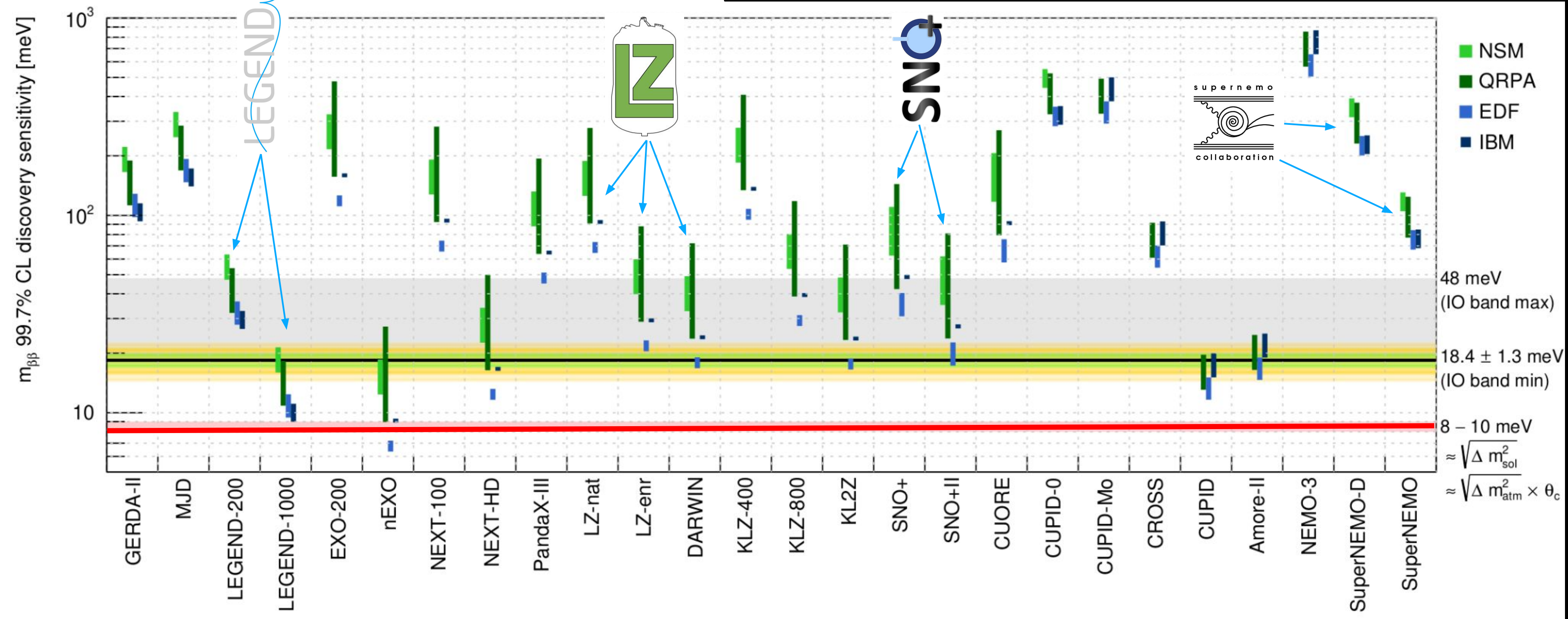


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 3: signal even weaker or absent

- need R&D, e.g. large scintillator detectors a la SNO+
- interplay with oscillation experiments and cosmology can also lead to theory breakthroughs



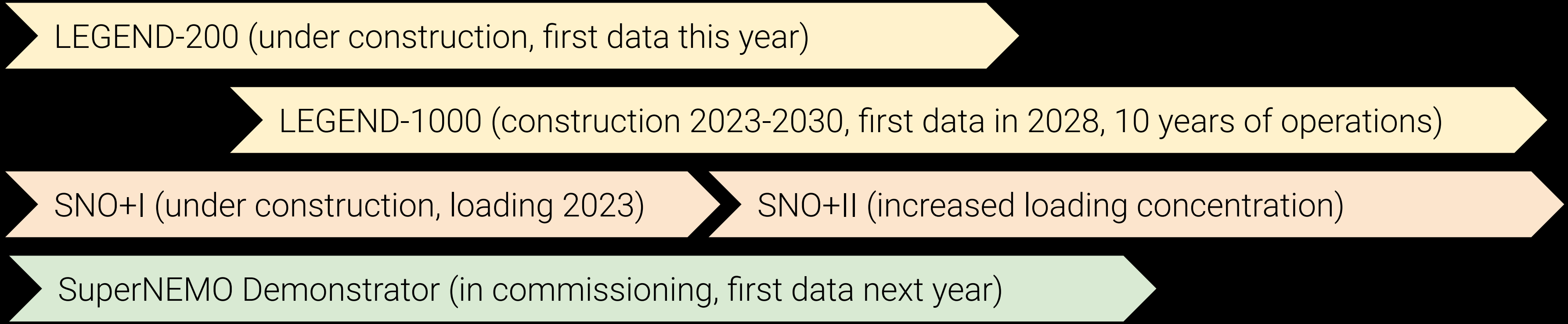
M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

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 of the concept of matter-antimatter

Advancements in nuclear and particle theory are laying the groundwork to connect future observations with underlying particle physics

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



LEGEND-200 (under construction, first data this year)

LEGEND-1000 (construction 2023-2030, first data in 2028, 10 years of operations)

SNO+I (under construction, loading 2023)

SNO+II (increased loading concentration)

SuperNEMO Demonstrator (in commissioning, first data next year)