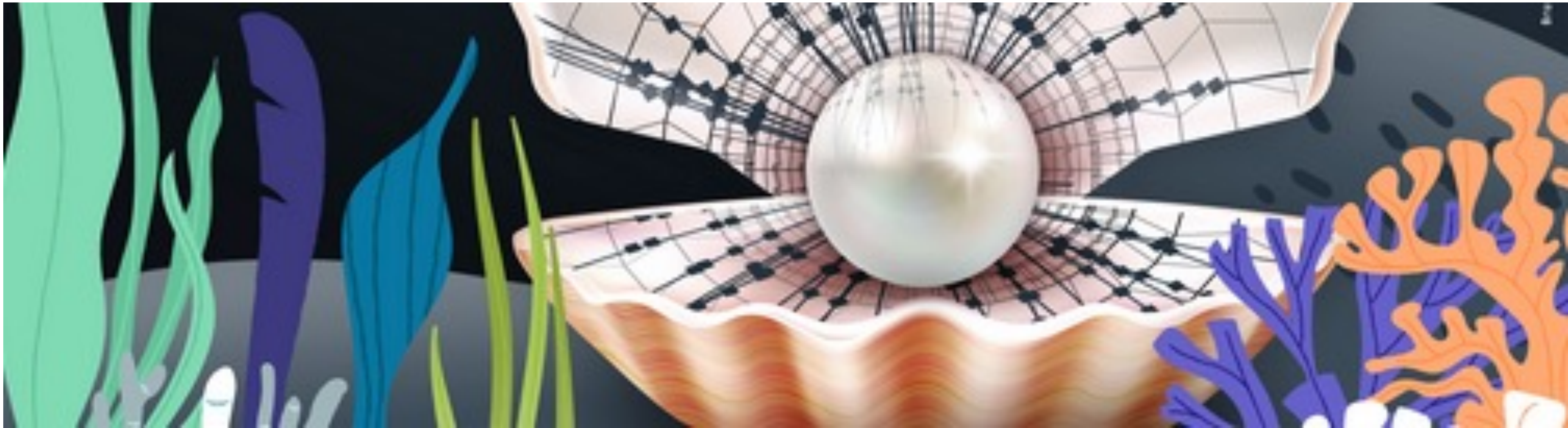
Sonder la nouvelle physique via la désintégration double béta sans émission de neutrino

Yoann KERMAÏDIC

Journée SFP – évènements rares
LPNHE - Paris

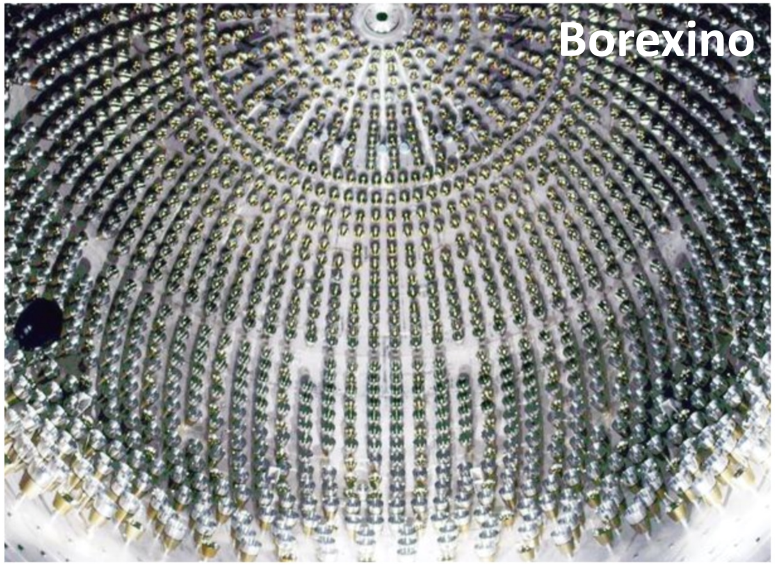
31 mars 2022

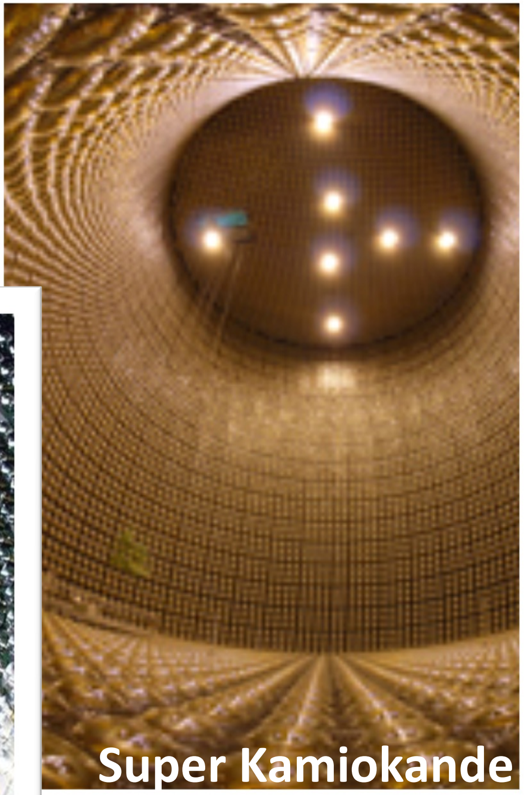


Neutrinos meet rarity

- **1st neutrino discovered in 1956 / ν_τ neutrino in 2000!**

- **Interaction cross-section extremely feeble**
  - Massive detectors ($\gtrsim 1000$ t.)
  - (Very) long measurement time ($\gg 1$ yr including upgrade)
  - Intense flux (nuclear, accelerator, sun, …)





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- **Since 1998, only sector with new physics signature in laboratory**
  - Neutrino flavor oscillation = massive neutrinos not predicted by the SM
  - 20 years after this discovery : no fundamental explanation / mass still not measured

- **Neutrino mass measurement**
  - Sensitivity $\times 500$ in 70 years
  - **status : last upper limit $m_\nu < 0.8\ \mathrm{eV}/c^2$ @90% C.L. (Feb. 2022)!**

[Nature Physics]

Rich measurement program

- **PMNS mixing matrix measurement:**
  - 2 major experiments running to probe $\not{CP}_\nu$: T2K & NOvA
  - + DUNE & Hyper-Kamiokande will take over for a non ambiguous measurement
  - ➢ **status : all matrix elements have been measured but the CP phase and mass ordering**

- **Sterile(s) neutrino(s) near nuclear reactors**
  - STEREO PROSPECT Precision Oscillation and Spectrum Experiment SoLid …
  - ➢ **status : reactor anomaly hypothesis largely excluded but other discrepancies remains**

- **Coherent elastic neutrino - nuclei scattering**
  - COHERENT SNS CONUS nucleus EXPERIMENT RICOCHET …
  - ➢ **status : discovered in 2017 near CsI detectors, plans for more precise measurements**

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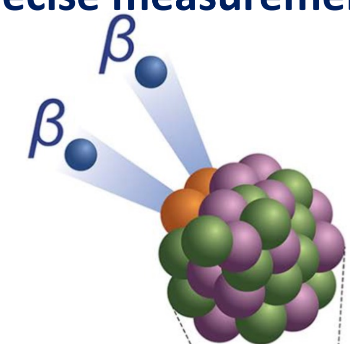
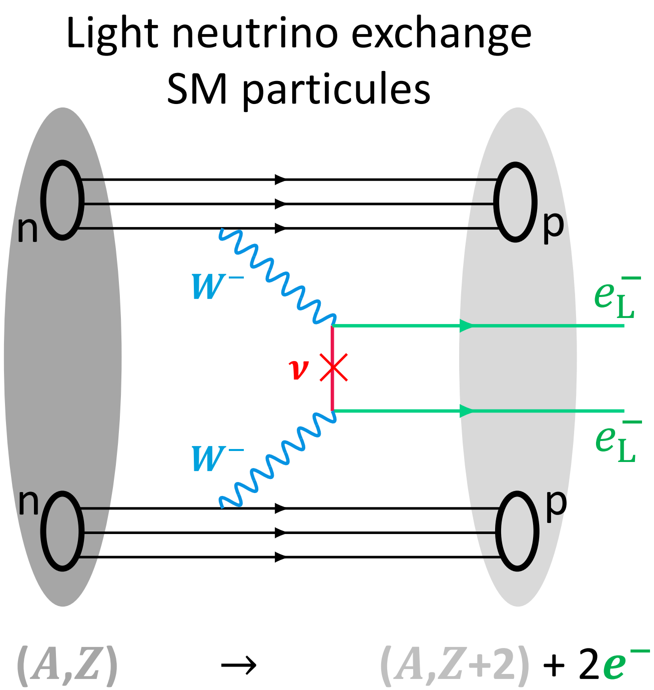
- **Nature of neutrinos**
  - Neutrinoless double-beta decay
  - ➢ **status : escape detection for … 70 years**



« Light neutrino exchange »



$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \, G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$T_{1/2}^{0\nu}$	experimentally probed half-life
g_A	axial vector coupling cnst = 1.25(?)
$M^{0\nu}$	nuclear matrix element (NME)
$G^{0\nu}$	phase space factor
m_e	electron mass

- Attractive: Minimal model without requiring new particles (mediator = active ν + SM bosons)

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right| \qquad \Sigma = \sum_{i=1}^{3} m_i \qquad m_\beta = \sqrt{\left|\sum_{i=1}^{3} U_{ei}^2 m_i^2\right|}$$

U = PMNS matrix [NuFit]

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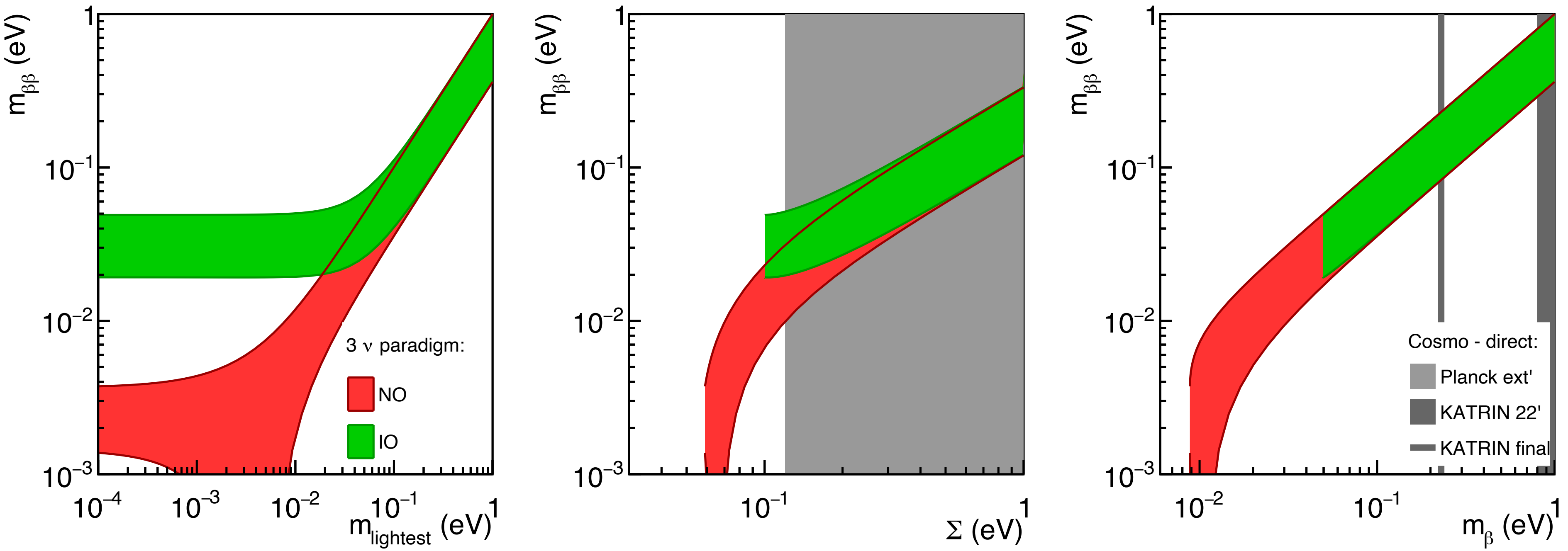

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U = PMNS matrix [NuFit]

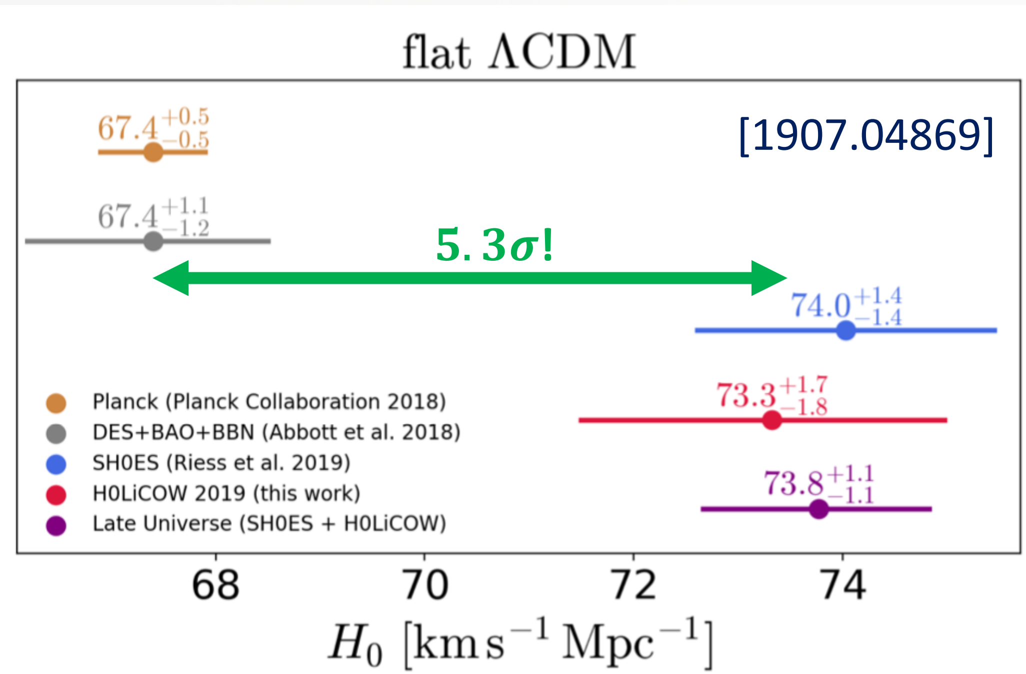
- Direct relationship with the cosmological neutrino mass sum and direct mass measurement
- Rich complementarity in case of non-zero measurement in one of the channels

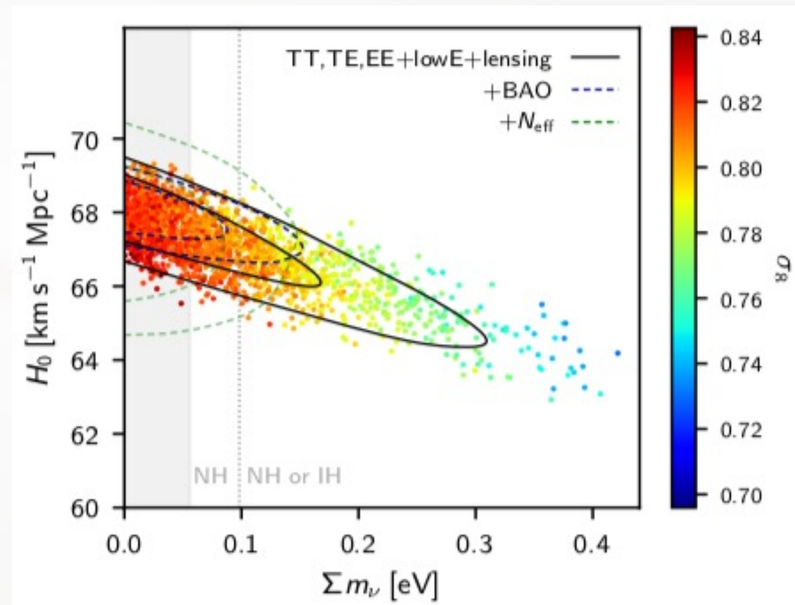
NB: Hubble constant “problem” shows some limitations

Cosmological detour : H_0 « problem »

- Strong correlation between sum of the neutrino masses and H_0
- Special workshop organized in July 2019 to review all the H_0 measurements:
“ **Tensions between the Early and the Late Universe”** http://online.kitp.ucsb.edu/online/enervac-c19/

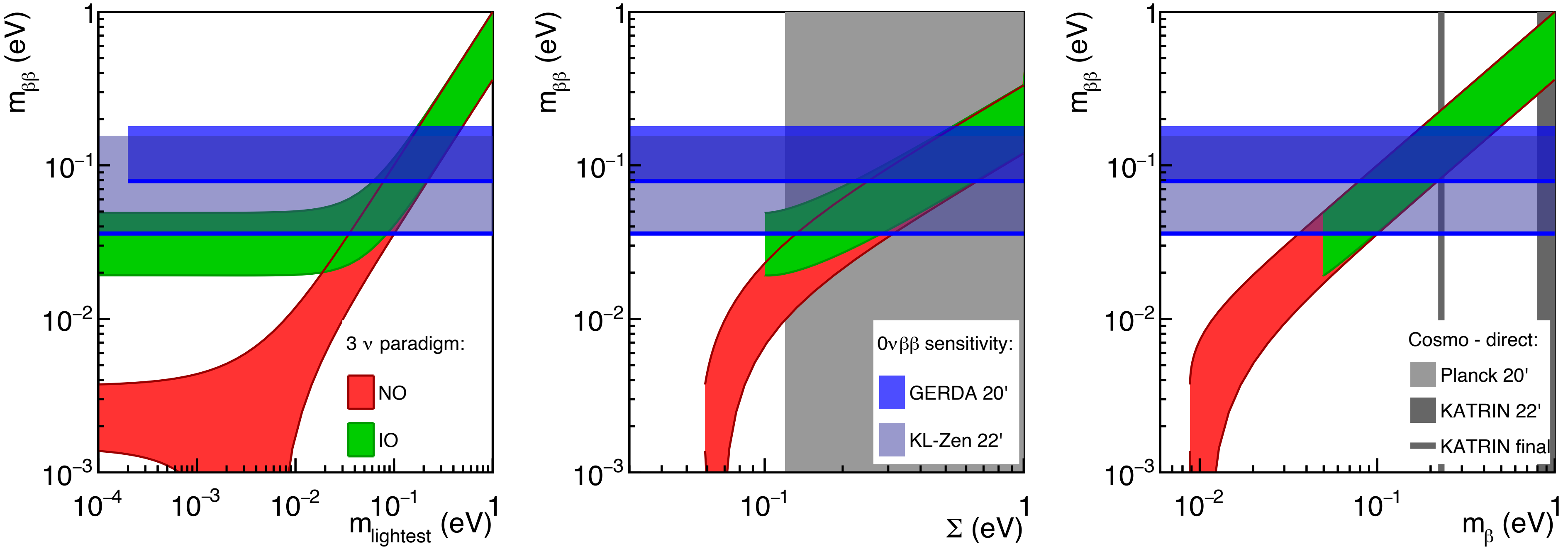
[Planck, 1807.06209]





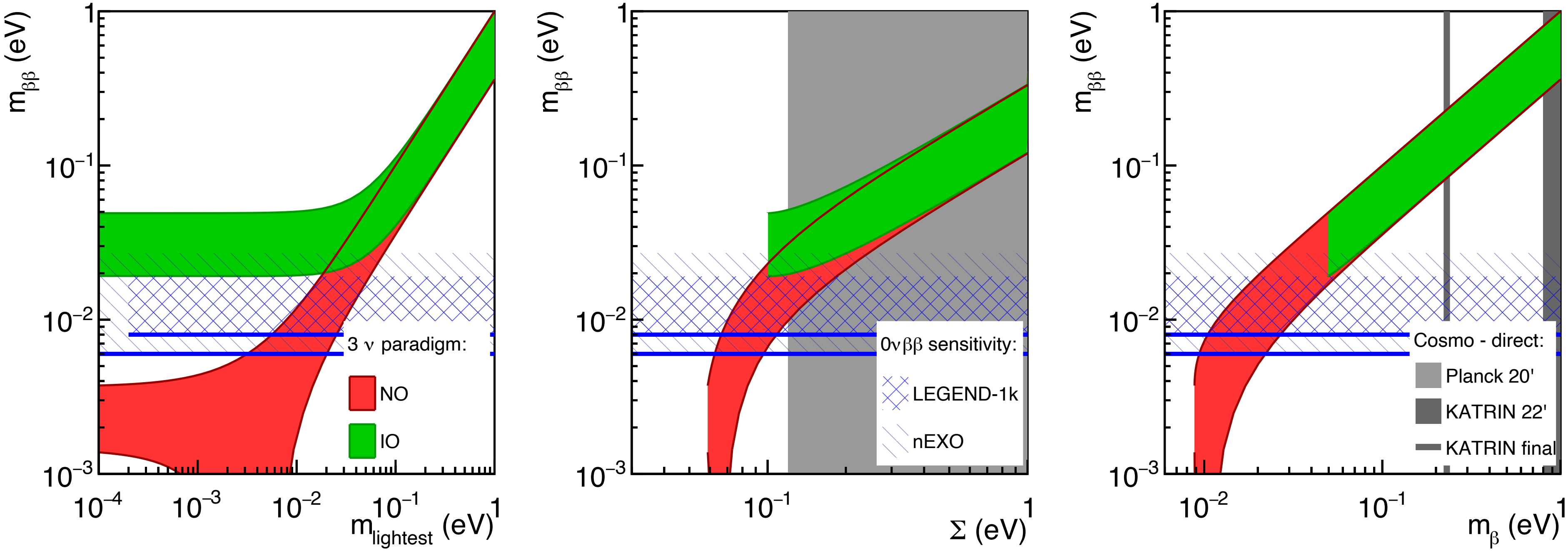
- We should remain aware of the models dependencies =)

« Light neutrino exchange »



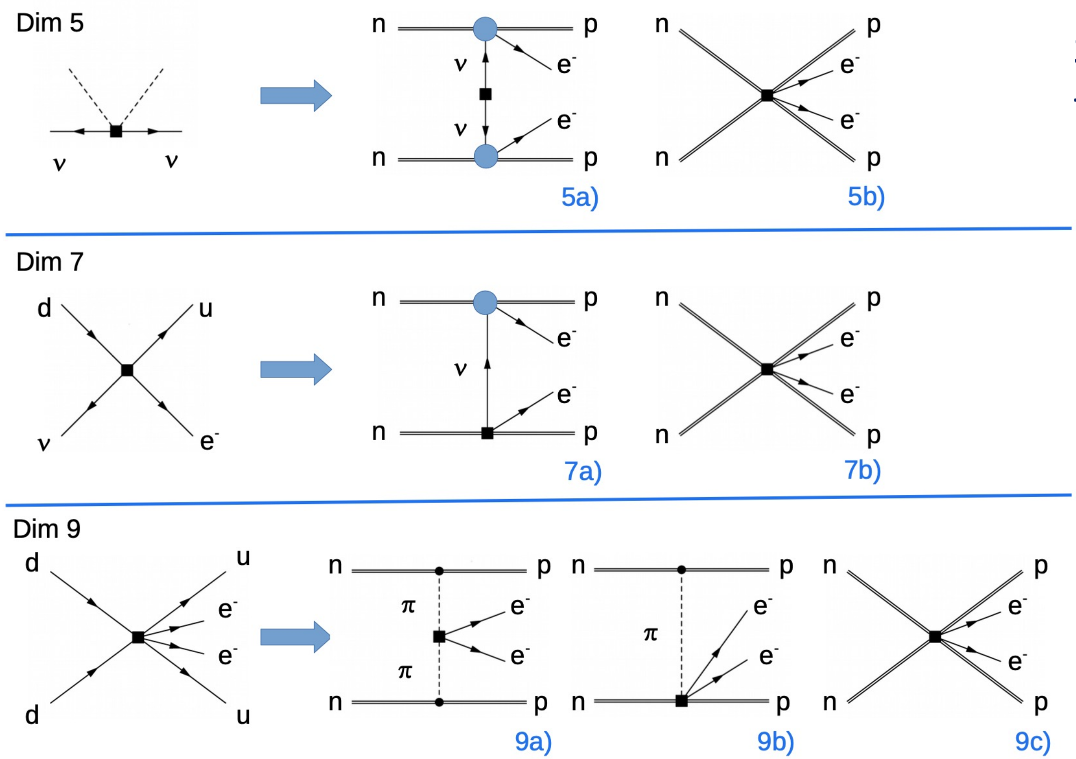
- The current situation on the $0\nu\beta\beta$ decay side
  - ➢ Start to cover the inverted ordering $m_{\beta\beta}$ band prediction

« Light neutrino exchange »



- Next gen $0\nu\beta\beta$ decay experiment reach
  - ➢ Entirely cover the inverted ordering $m_{\beta\beta}$ band prediction for most NMEs

Neutrinoless double beta decay - $0\nu\beta\beta$



See fresh review on theoretical tools [2203.12169]

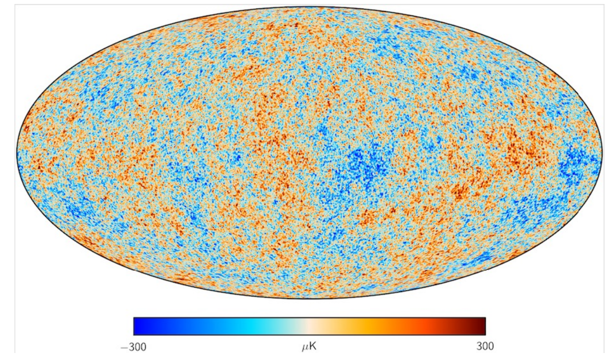
Such process:

- ✓ **violates the Lepton Number** by 2 units = New Physics! ($\mathcal{O}(5)$, $\mathcal{O}(\dots)$)
- ✓ determines the nature of neutrinos: **Majorana particle** $\boldsymbol{\nu = \bar{\nu}}$ [Valle – 1982]
- ✓ gives information on the ν mass via $m_{\beta\beta}$ (light neutrino exchange scenario)
- ✓ has never been observed so far

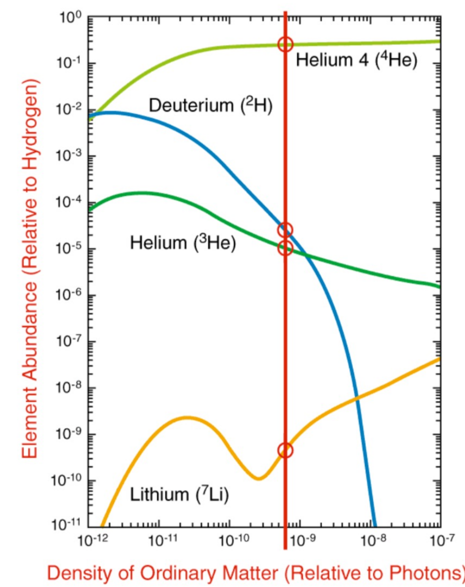
Understanding the matter-antimatter asymmetry of the Universe

Baryonic asymmetry of the Universe :

$$\eta_{\mathrm{CMB}} = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.12 \pm 0.06) \times 10^{-10}$$



- Sakharov criteria: [Sakharov, 1967]
  - *B̸, C̸, CP̸, int. out of equilibrium*
- Many theoretical scenarios including
  - ***High energy scale leptogenesis*** *(electroweak baryogenesis …)*
- Leptogenesis popular because ν is a unique particle
  - *Only left-handed, $\nu = \bar{\nu}$?, no electric charge*



Standard Model scenario	Beyond SM scenario
Baryogenesis **Excluded** - m_{H} too high / phase transition of 1st order - Too weak CPV $\boldsymbol{\eta \sim 10^{-26}}$	**Leptogenesis** **Plausible - to be falsified** - Enriched neutrino sector - CPV in the neutrino sector - **Majorana ν** - **Lepton Number Violation**

[Huet, 1994] [Fukugita, 1986]

Other new physics searches

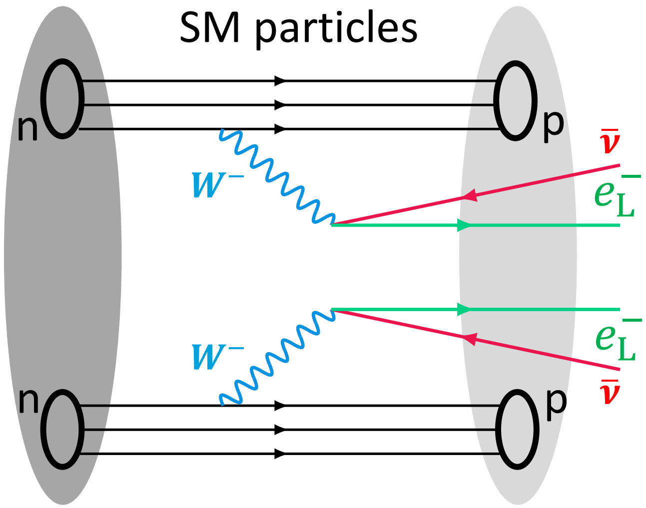
- **Next-gen provides ultra low background datasets with large exposure**

- **Can look for rare events:**
  - any shape distortion of the standard $2\nu\beta\beta$ decay spectrum
  - unknown very low rate gamma lines
  - unexpected time modulation in some rates

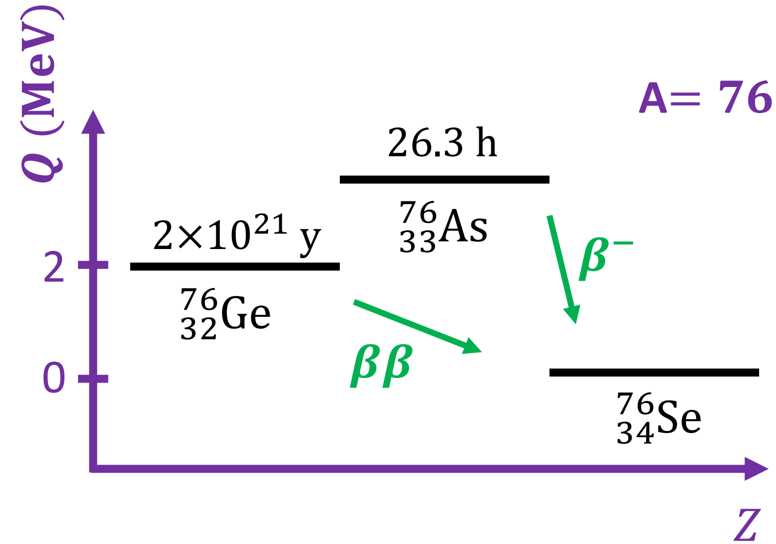
- **These can be caused by:**
  - violation of fundamental principles
    (Lorentz invariance, Pauli Exclusion Principle, CPT symmetry, …)
  - new particles (Sterile neutrinos, WIMPs, axions, …)
  - new interactions (B-violating tri-nucleon decay, charge violating electron decay, …)

See recent reference
in [2202.01787] review

Two neutrinos double beta decay - $2\nu\beta\beta$



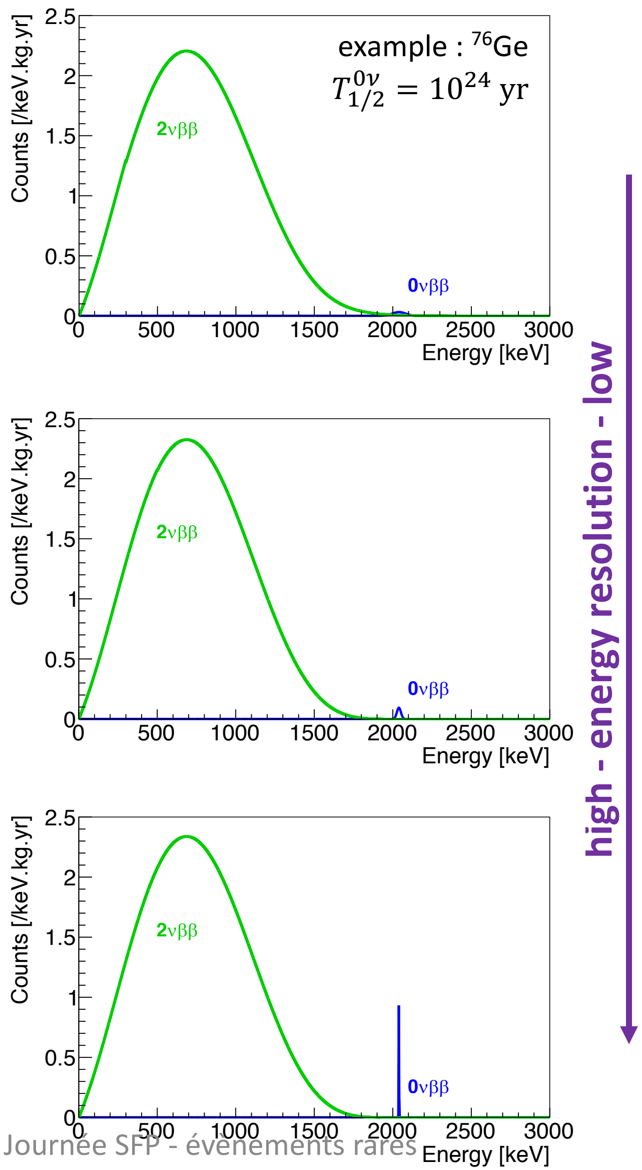
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$



Such process:

- ✓ energetically favored in some isotopes (^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe, …)
- ✓ is predicted by the SM [Goppert-Mayer – 1935]
- ✓ is measured experimentally

$0\nu\beta\beta$ decay experimental signature



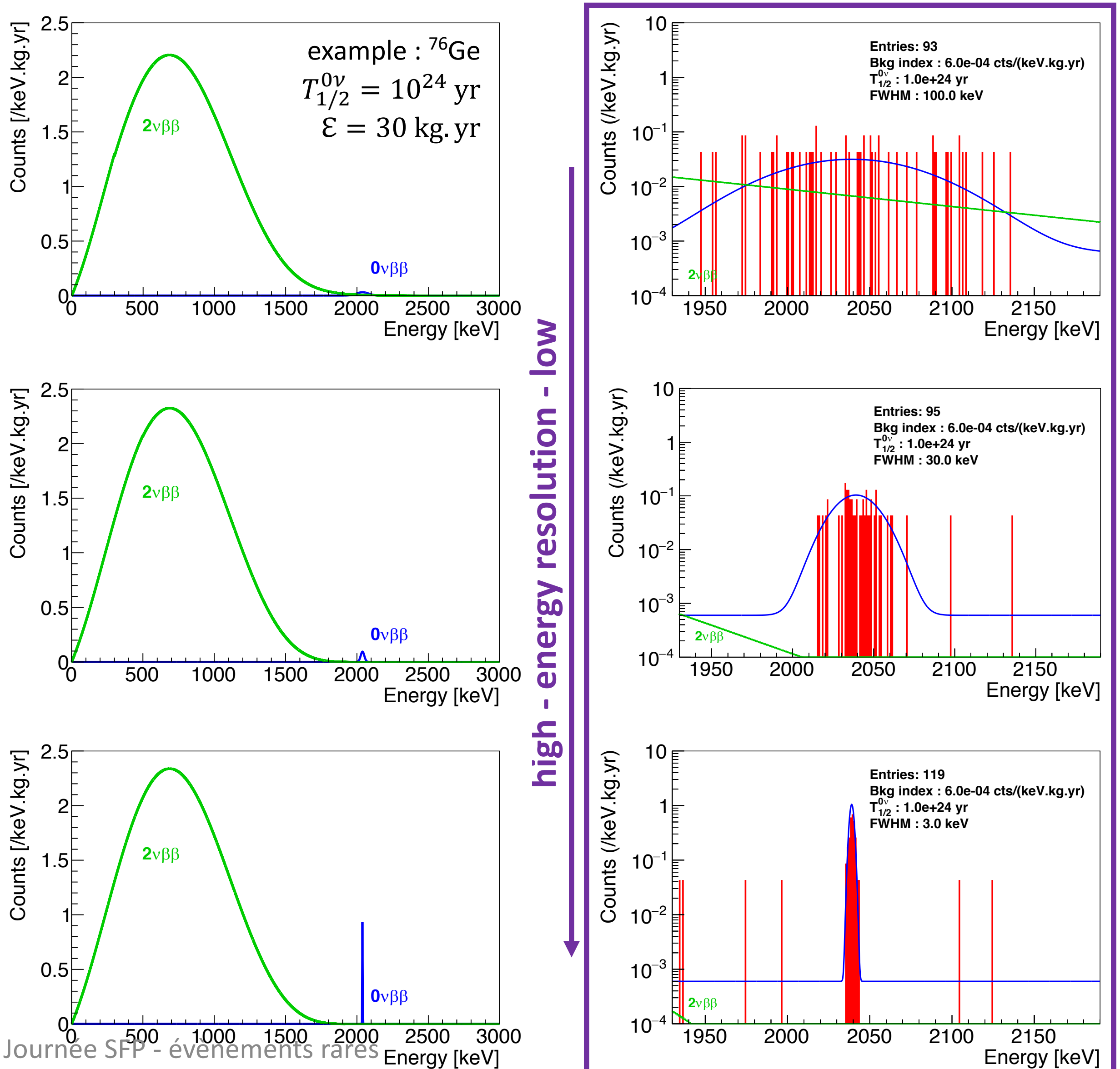
- $2\nu\beta\beta$ continuum + peak at $Q_{\beta\beta}$

- $T_{1/2}^{0\nu} = \ln 2 \, . \frac{N_A}{m_A} . \, \epsilon \, . \, \mathcal{E} \, . \frac{1}{N^S}$

- **Key points:**
  - Avogadro number: N_A
  - Efficiency [%] x exposure [kg.yr]: $\epsilon \, . \, \mathcal{E}$
  - Energy resolution [keV]
  - $\mathrm{BI} = \frac{N^B}{\mathcal{E} \, . \, \Delta E}$ [cts/(keV.kg.yr)]

- **Topology :**
  - Signal = *Single-Site Event (SSE)*
  - Background γ = *Multi-Site Event (MSE)*
    α/β = *Surface Event*

$0\nu\beta\beta$ decay experimental signature



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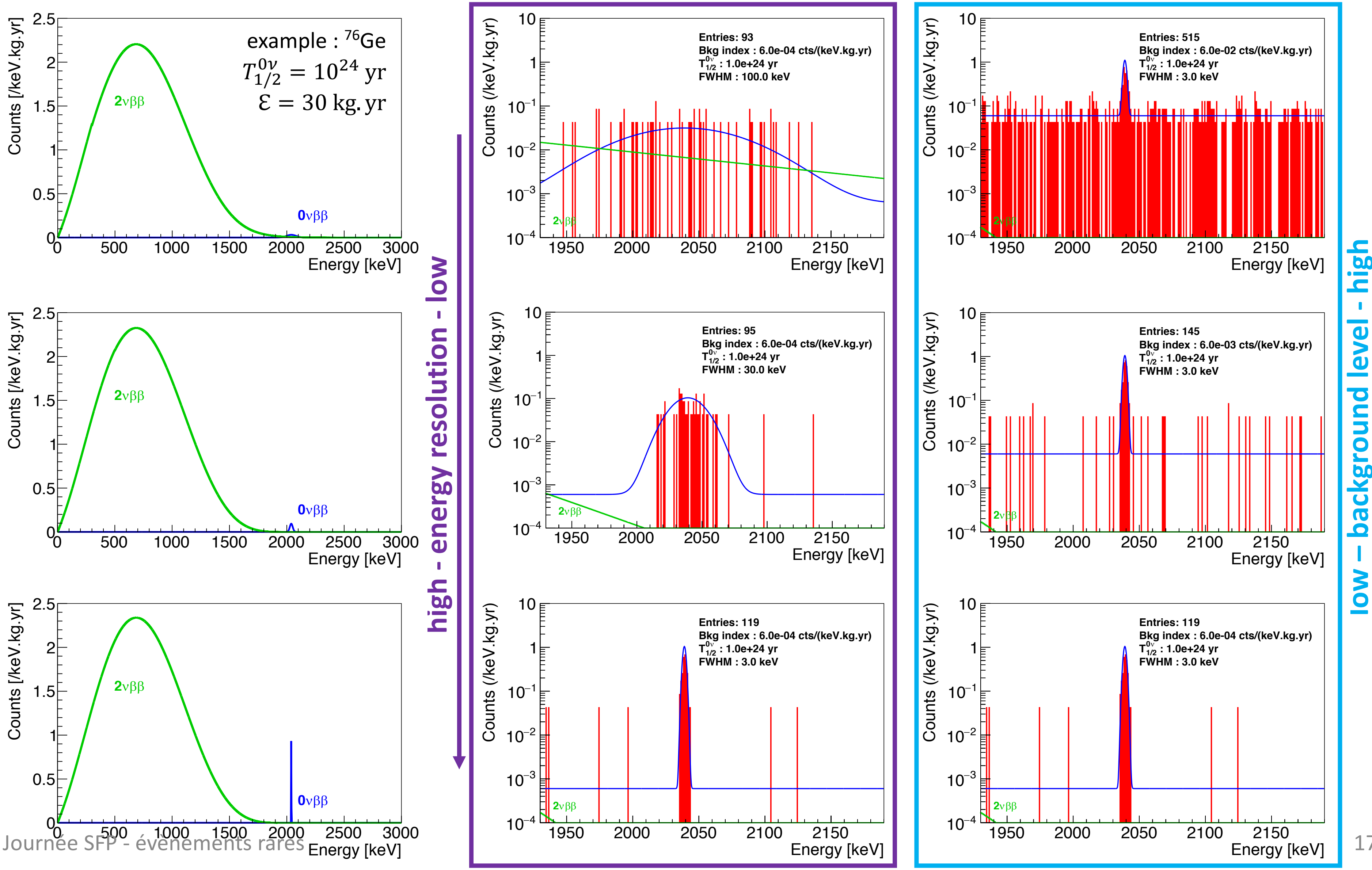

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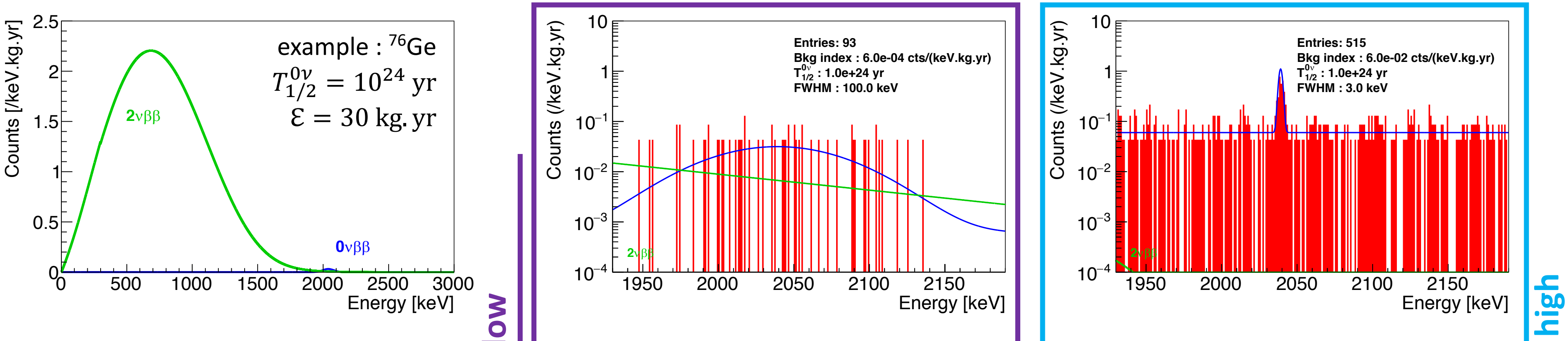


Two statistical notions scrutinized:

- sensitivity for limit setting (90% C.L.)
  « *limit on the signal strength assuming no signal* »

- 3σ discovery potential sensitivity
  « *minimal signal strength for which a discovery is expected with 3σ C.L.* »

see detailed discussion in: [1705.02996]

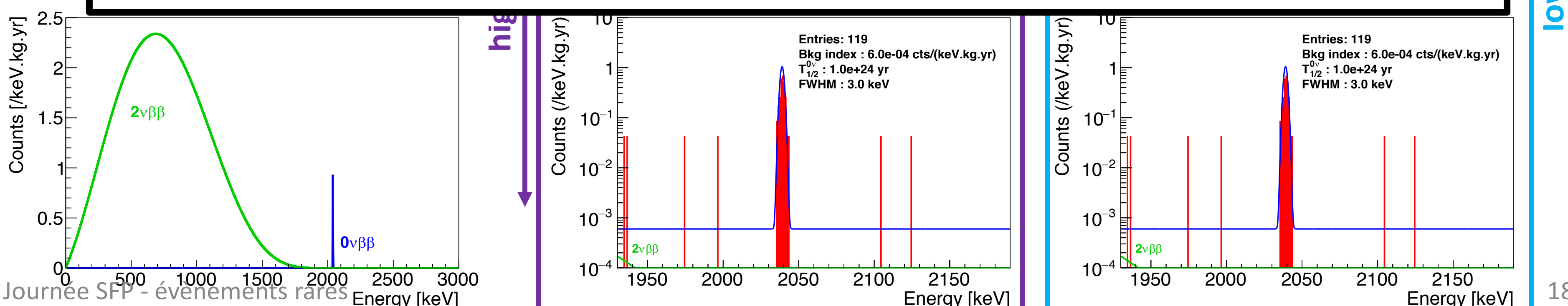
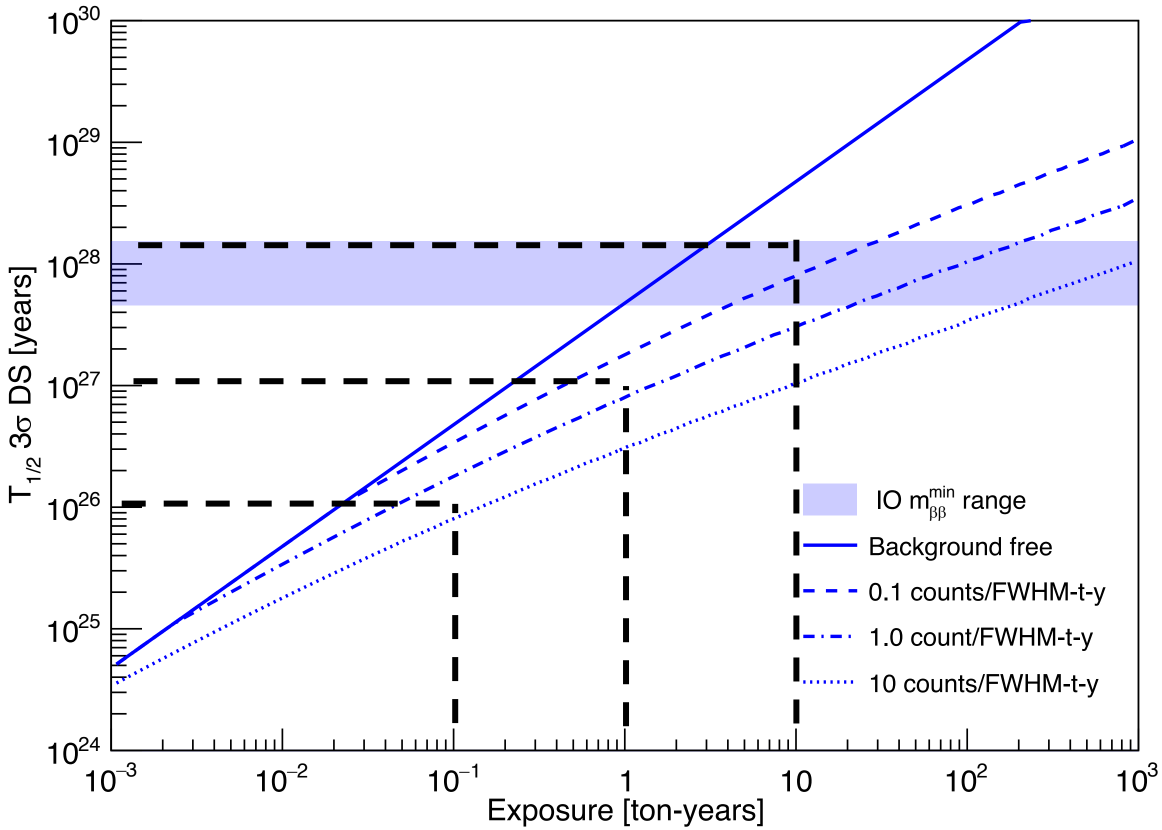


Figure of merit – discovery potential

« *minimal signal strength for which a discovery is expected with 3σ C.L.* »

see detailed discussion in: [1705.02996]

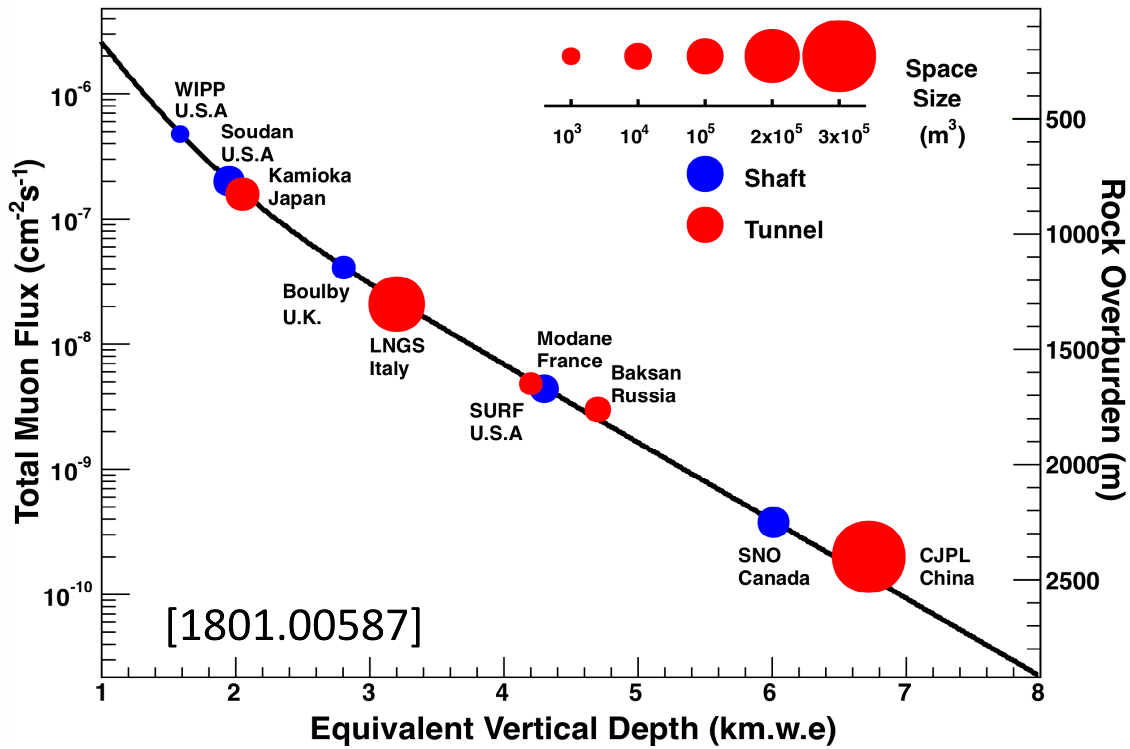
example : ^{76}Ge (88% enr.)



Defines the experimental design in terms of

- exposure (mass et duration)
- background goal (passive/active veto, detector design, analysis techniques)

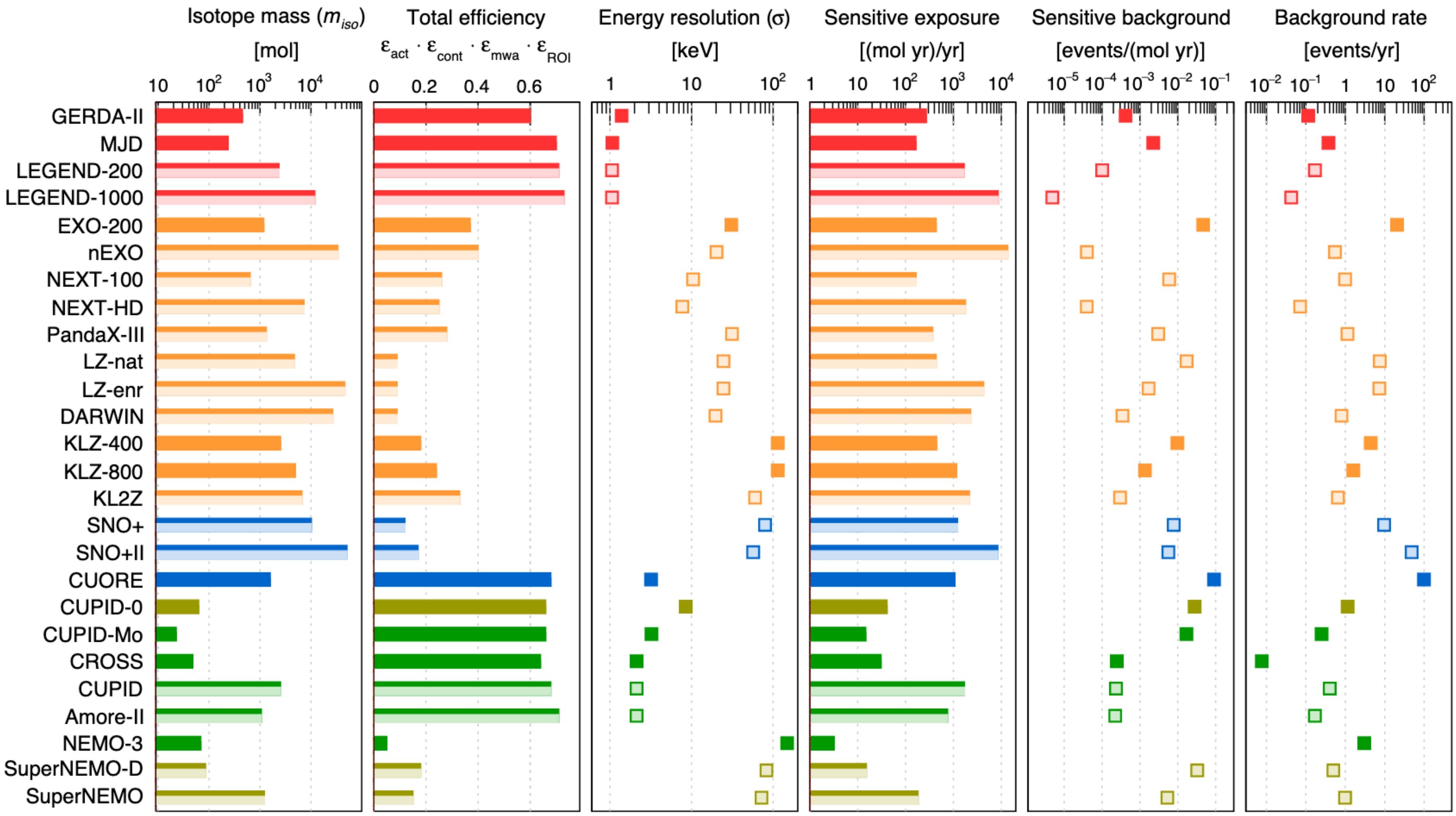
Underground laboratories worldwide



- Underground = passive background suppression for « free »
- Isotopic activation suppression (neutron capture– e.g. $^{76}\mathrm{Ge} + n \rightarrow {}^{77m}\mathrm{Ge} \rightarrow {}^{77}\mathrm{As}$ + **2.7 MeV**)
- Large experimental infrastructure required (shielding, cryostat, instrumentation)
- Size/depth/access compromise taken into account by the collaborations

The experimental landscape

See fresh exhaustive review [2202.01787]



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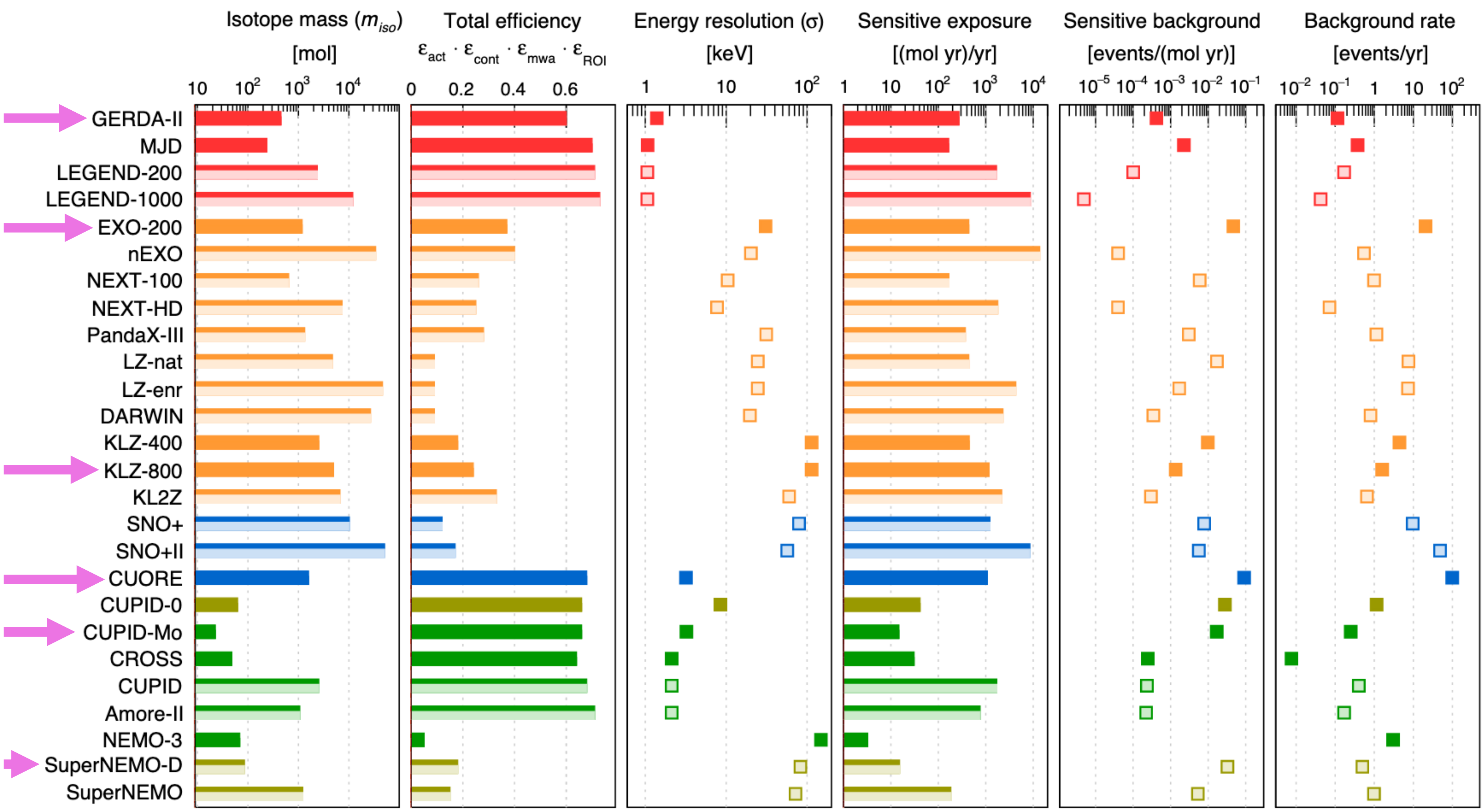
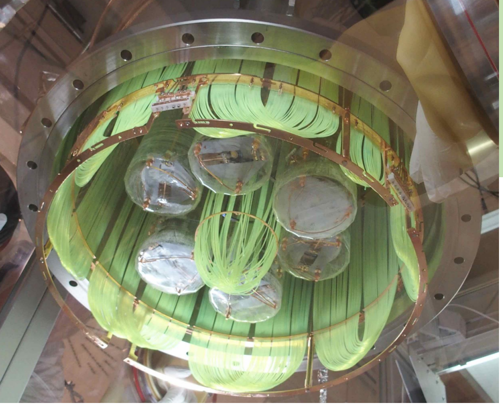
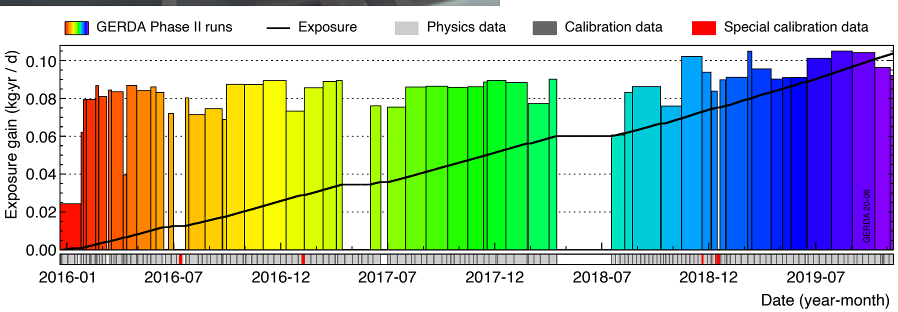


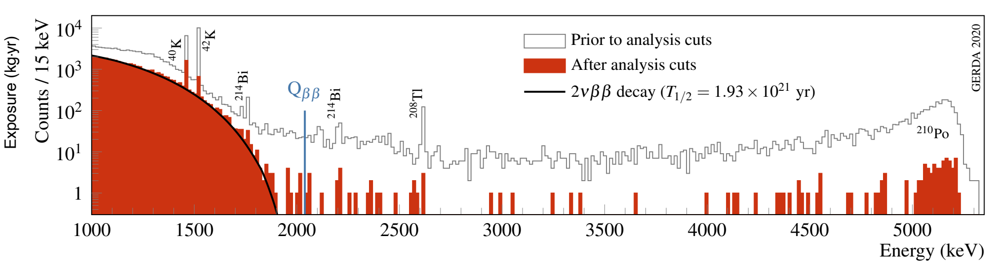
Détecteur semi-conducteur GERDA @ LNGS

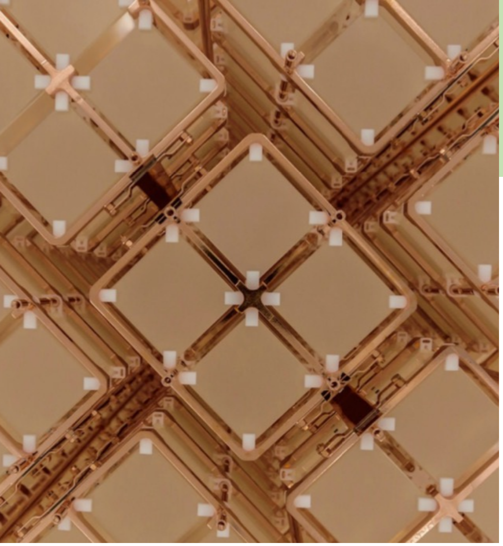
[PRL, 2020]



- ^{76}**Ge** $\boldsymbol{Q_{\beta\beta} = 2039}$ **keV** - $T_{1/2}^{2\nu} \sim 2 \times 10^{21}$ yr
- High detection efficiency de (detector = source)
- Enrichment up to 88% - active mass ~ 40 kg
- **New detector technology (0.7 kg → 3 kg /det.)**
- Excellent energy resolution : < 3 keV FWHM @ $Q_{\beta\beta}$
- **"Background-free"** experiment at final exposure (LAr veto + PSD)
- Sensitivity $T_{1/2}^{0\nu} > 10^{26}$ yr for the 1st time!
- Final exposure of 100 kg.yr reached in Nov. 2019
- $\boldsymbol{T_{1/2}^{0\nu} > 1.8 \times 10^{26}}$ **yr** $-$ $\boldsymbol{m_{\beta\beta} < [79 - 180]}$ **meV (90% C. L.)**
- **Successor : LEGEND**



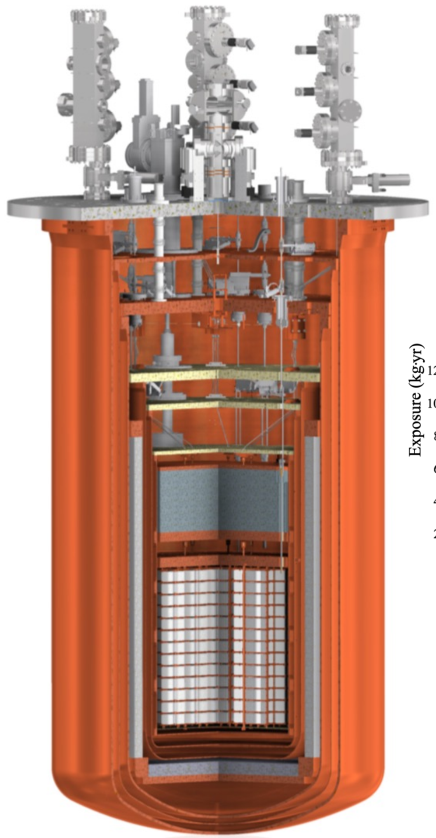


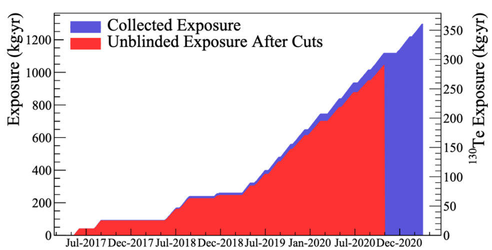


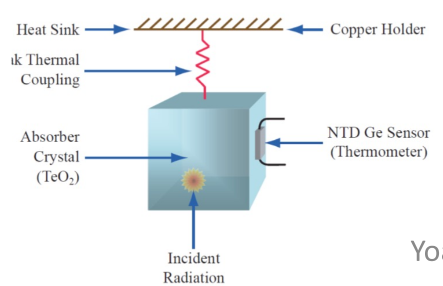
Bolometric detector CUORE @ LNGS

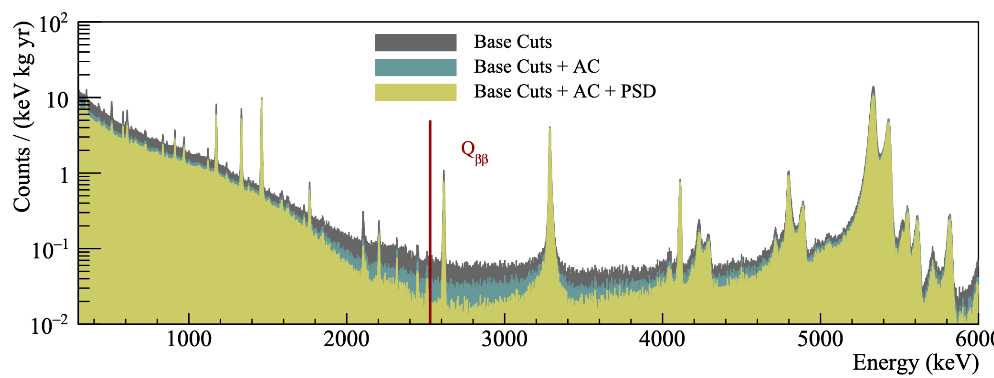
[2104.06906]

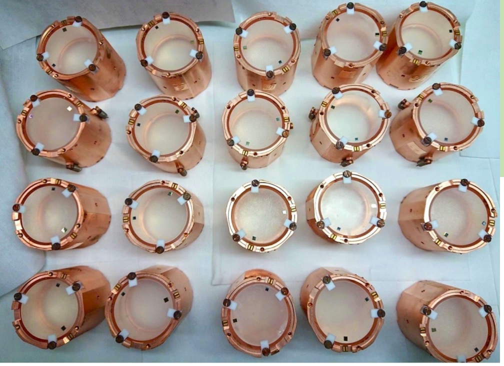
- **^{130}Te $Q_{\beta\beta} = 2528$ keV** - $T^{2\nu}_{1/2} \sim 8 \times 10^{20}$ yr
- 988 TeO_2 crystals with an active mass of 206 kg
- Natural abondance: 35% - no enrichment
- **Largest mK cryostat in the world**
- Very good energy resolution : 7.8 keV FWHM @ $Q_{\beta\beta}$
- $T^{0\nu}_{1/2} > 0.2 \times 10^{26}$ yr $- m_{\beta\beta} < [90 - 305]$ meV $(90\%$ C.L.$)$ **with 1038.4 kg.yr**
- **Stable operation of the cryostat demonstrated in 2021** continue the data taking while waiting for CUPID
- Problematic α/γ background → active veto needed (CUPID)

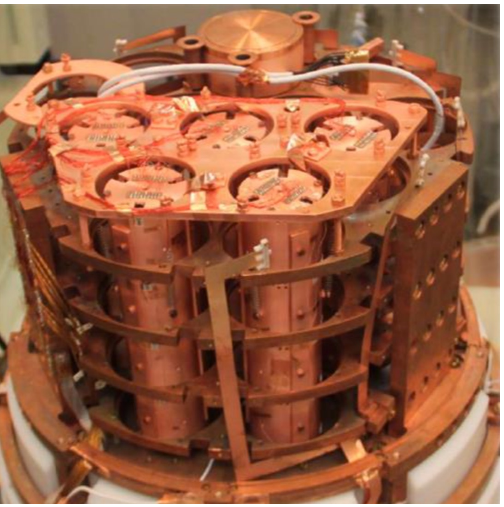








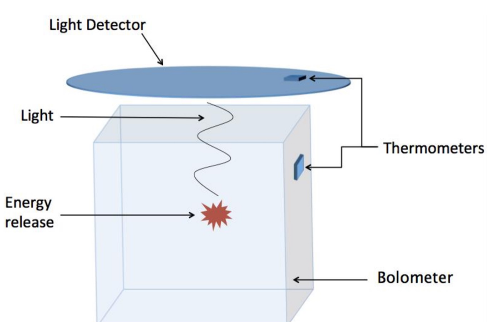


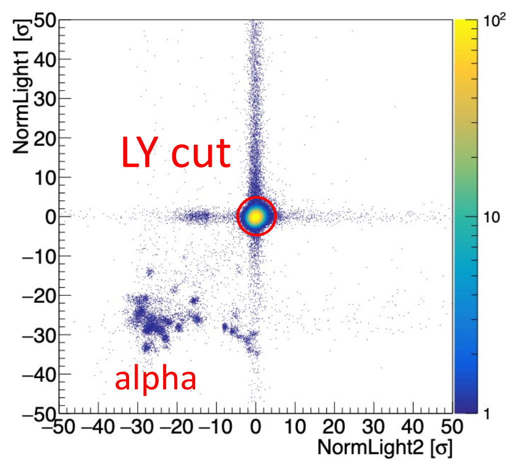


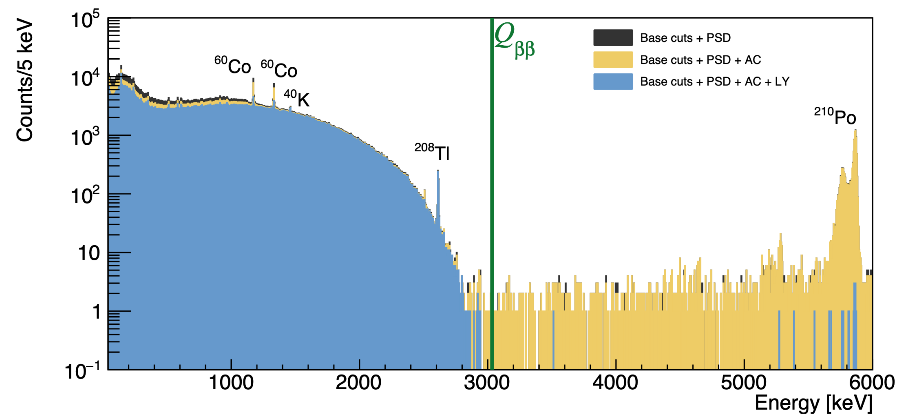
Bolometric detector CUPID-Mo @ LSM

[2202.08716]

- **^{100}Mo $Q_{\beta\beta} = 3035$ keV** - $T^{2\nu}_{1/2} \sim 7 \times 10^{18}$ yr
- **20 Li_2MoO_4 bolometers ran at 20 mK with improved radiopurity w.r.t. CUORE**
- Enrichment up to 97% - active mass ~ 4 kg
- **New veto technology: scintillating photons collection**
- Very good energy resolution: 7.4 keV FWHM @ $Q_{\beta\beta}$
- $\boldsymbol{T^{0\nu}_{1/2} > 0.02\times 10^{26}}$ **yr** $-$ $\boldsymbol{m_{\beta\beta} < [280 - 480]}$ **meV (90% C. L.)** with a final 1.5 kg.yr (481 days) exposure
- **Launching pad for CUPID (together with CUPID-0)**

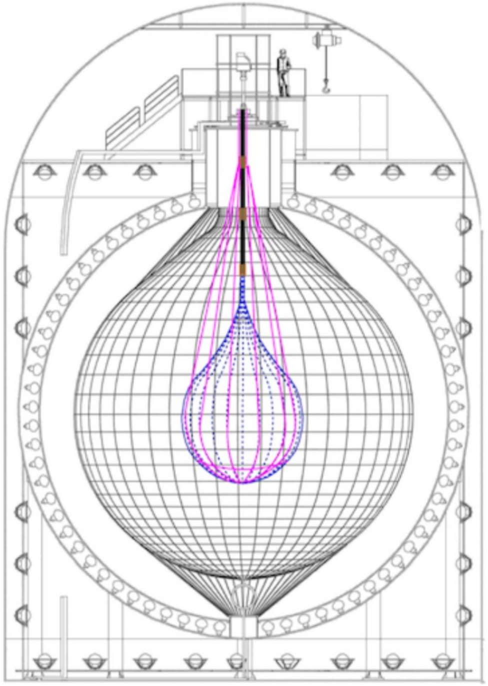






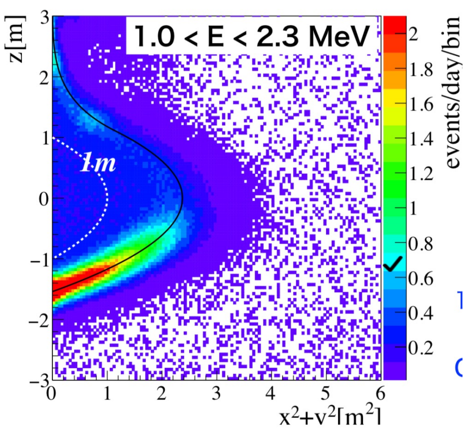
Liquid scintillator detector KamLAND-Zen @ Kamioka

[2203.02139]

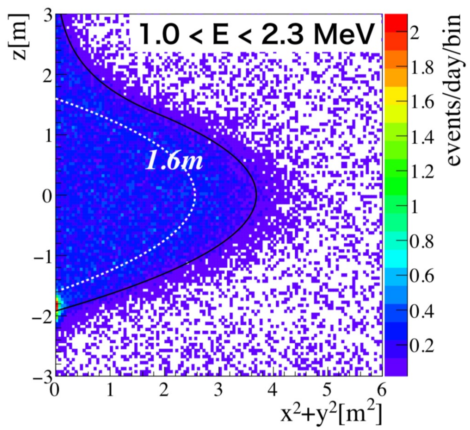


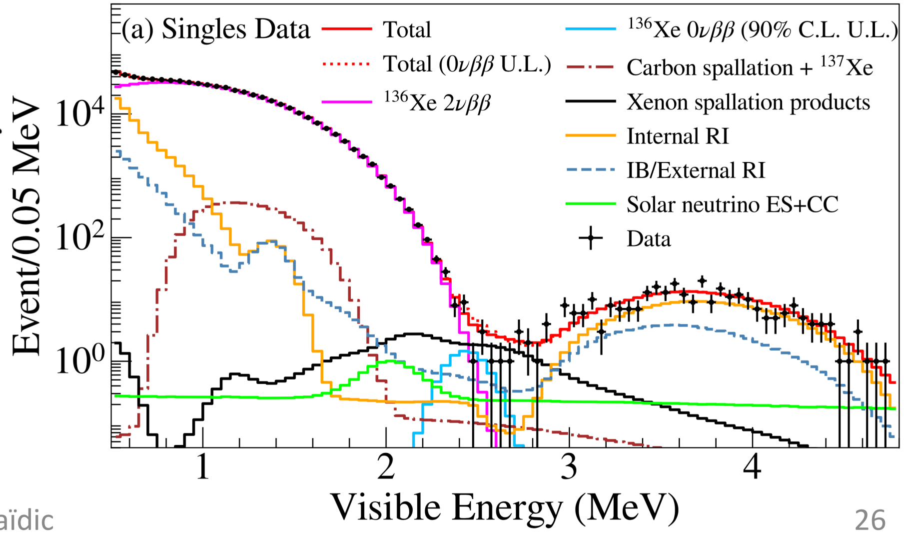
- **^{136}Xe $Q_{\beta\beta} = 2458$ keV** - $T_{1/2}^{2\nu} \sim 2 \times 10^{21}$ yr
- **Large LXe volume within a radiopure balloon immersed within a PMT instrumented liquid scintillator volume**
- Enrichment up to 91% - active mass ~ 745 kg
- **Balloon volume and mass increase x2 in 4 ans**
- post-Fukushima ^{110m}Ag contamination removed + overall bkg ÷10
- Low energy resolution: 250 keV FWHM @ $Q_{\beta\beta}$
- $\boldsymbol{T_{1/2}^{0\nu} > 2.3 \times 10^{26}}$ **yr –** $\boldsymbol{m_{\beta\beta} < [36 - 156]}$ **meV (90% C.L.) with 523.4 days exposure**

KamLAND-Zen 400 phaseII



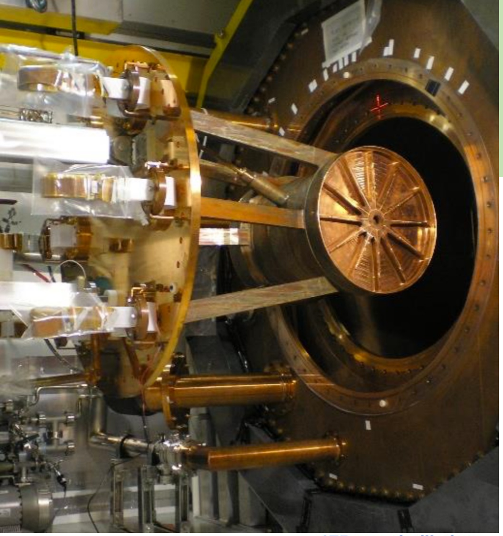
KamLAND-Zen 800

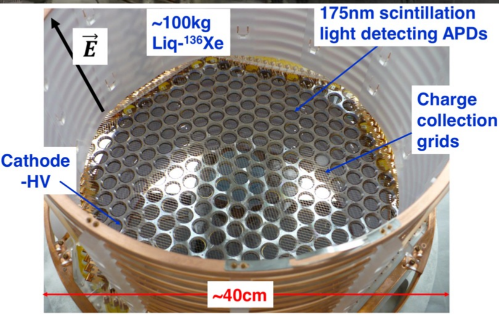




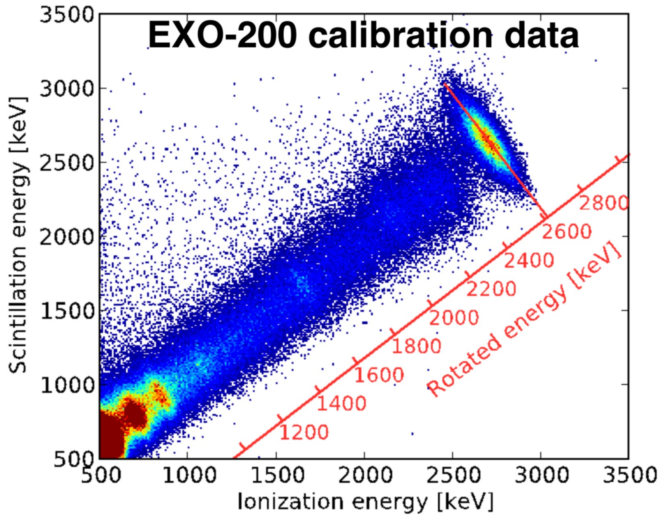
Liquid Xe TPC detector EXO-200 @ WIPP

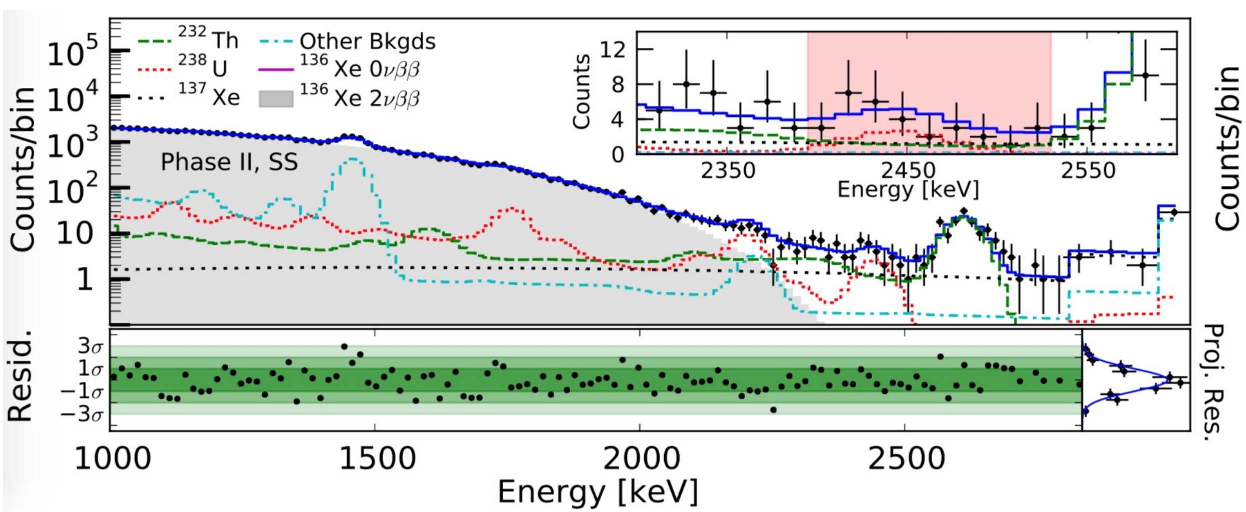
[PRL, 2019]

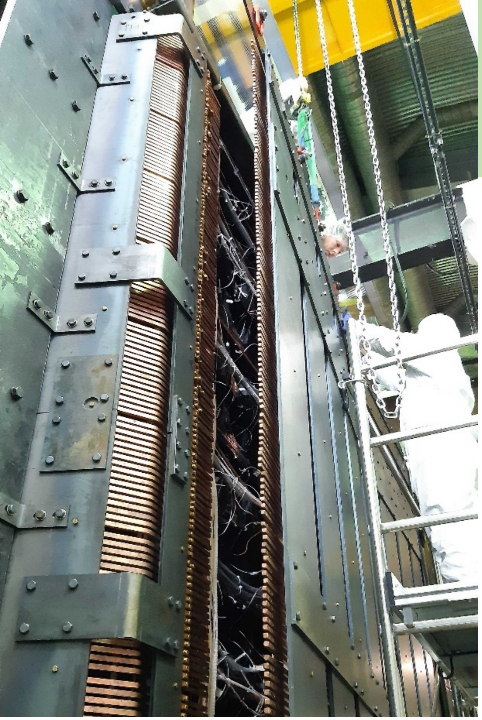




- ^{136}**Xe** $\boldsymbol{Q_{\beta\beta} = 2458}$ **keV** - $T^{2\nu}_{1/2} \sim 2 \times 10^{21}$ yr
- **LXe cylindrical *Time Projection Chamber***
- Enrichment up to 81% - active mass ~ 100 kg
- **Effective scintillation-ionisation correlation**
- Event reconstruction (x-y-z) + fiducialization for SSE vs MSE topology
- Low energy resolution: 60 keV FWHM @ $Q_{\beta\beta}$
- $\boldsymbol{T^{0\nu}_{1/2} > 0.4 \times 10^{26}}$ **yr –** $\boldsymbol{m_{\beta\beta} < [78 - 239]}$ **meV (90% C. L.)**

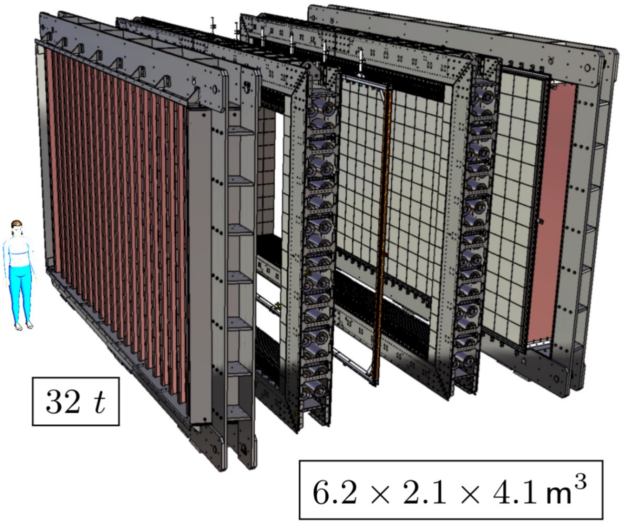


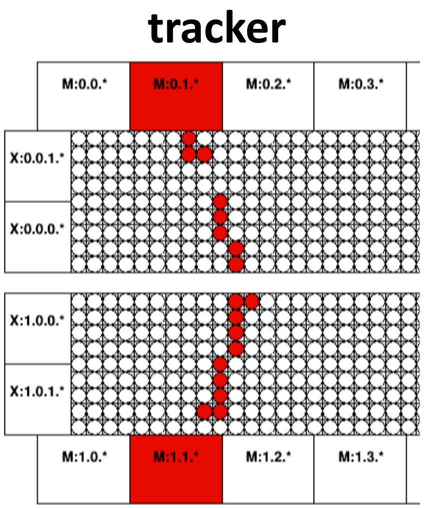


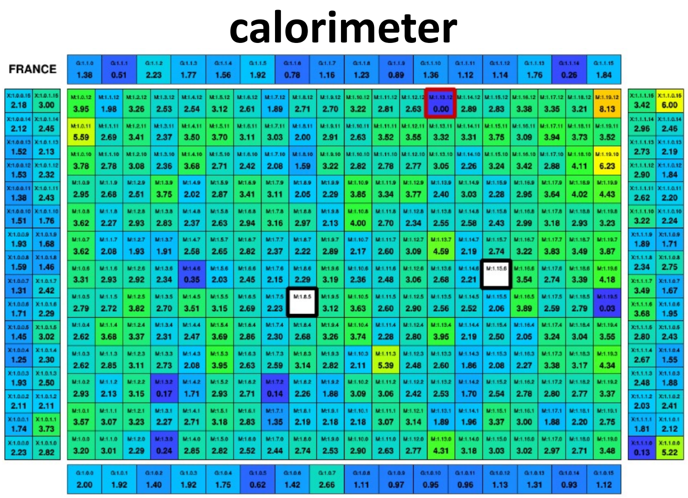


Tracker-calorimeter detector SuperNEMO @ LSM

- **Multi-isotope approach with thin foils**
- Important know-how in case of discovery by other experiments fine decay topology available (single electron spectrum/ang. dist.)
- Background mitigation by factor 30 w.r.t. NEMO-3
- Energy resolution : 8% @ 1 MeV
- Mass : 7 kg of ^{82}Se
- Demonstrator installation/commissioning at LSM
  - Traco-calo detector is operational
  - Background reduction setup (Ra, γ, n) to come in 22’







Credit: L. Simard

Experimental state of the art

See fresh exhaustive review [2202.01787]

Experiment	Isotope	Status	Lab	m_{iso} [mol]	ε_{act} [%]	ε_{cont} [%]	ε_{mva} [%]	σ [keV]	ROI [σ]	ε_{ROI} [%]	$\mathcal{E}$ $\left[\frac{mol\cdot yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{events}{mol\cdot yr}\right]$	λ_b $\left[\frac{events}{yr}\right]$	$T_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
High-purity Ge detectors (Sec. VI.B)															
GERDA-II	^{76}Ge	completed	LNGS	$4.5\cdot10^{2}$	88	91	79	1.4	-2,2	95	273	$4.2\cdot10^{-4}$	$1.1\cdot10^{-1}$	$1.2\cdot10^{26}$	93-222
MJD	^{76}Ge	completed	SURF	$2.4\cdot10^{2}$	90	91	89	1.1	-2,2	95	166	$2.3\cdot10^{-3}$	$3.7\cdot10^{-1}$	$5.5\cdot10^{25}$	140-334
LEGEND-200	^{76}Ge	construction	LNGS	$2.4\cdot10^{3}$	91	91	90	1.1	-2,2	95	1 684	$1.0\cdot10^{-4}$	$1.7\cdot10^{-1}$	$1.5\cdot10^{27}$	27-63
LEGEND-1000	^{76}Ge	proposed		$1.2\cdot10^{4}$	92	92	90	1.1	-2,2	95	8 736	$4.9\cdot10^{-6}$	$4.3\cdot10^{-2}$	$1.3\cdot10^{28}$	9-21
Xenon time projection chambers (Sec. VI.C)															
EXO-200	^{136}Xe	completed	WIPP	$1.2\cdot10^{3}$	46	100	84	31	-2,2	95	438	$4.7\cdot10^{-2}$	$2.1\cdot10^{+1}$	$2.4\cdot10^{25}$	111-477
nEXO	^{136}Xe	proposed	SNOLAB	$3.4\cdot10^{4}$	64	100	66	20	-2,2	95	13 700	$4.0\cdot10^{-5}$	$5.5\cdot10^{-1}$	$7.5\cdot10^{27}$	6-27
NEXT-100	^{136}Xe	construction	LSC	$6.4\cdot10^{2}$	88	76	49	10	-1.0,1.8	80	167	$5.9\cdot10^{-3}$	$9.9\cdot10^{-1}$	$7.0\cdot10^{25}$	66-281
NEXT-HD	^{136}Xe	proposed		$7.4\cdot10^{3}$	95	89	44	7.7	-0.5,1.7	65	1 809	$4.0\cdot10^{-5}$	$7.2\cdot10^{-2}$	$2.2\cdot10^{27}$	12-50
PandaX-III-200	^{136}Xe	construction	CJPL	$1.3\cdot10^{3}$	77	74	65	31	-1.2,1.2	76	374	$3.0\cdot10^{-3}$	$1.1\cdot10^{+0}$	$1.5\cdot10^{26}$	45-194
LZ-nat	^{136}Xe	construction	SURF	$4.7\cdot10^{3}$	14	100	80	25	-1.4,1.4	84	440	$1.7\cdot10^{-2}$	$7.5\cdot10^{+0}$	$7.2\cdot10^{25}$	64-277
LZ-enr	^{136}Xe	proposed	SURF	$4.6\cdot10^{4}$	14	100	80	25	-1.4,1.4	84	4302	$1.7\cdot10^{-3}$	$7.3\cdot10^{+0}$	$7.1\cdot10^{26}$	20-87
Darwin	^{136}Xe	proposed		$2.7\cdot10^{4}$	13	100	90	20	-1.2,1.2	76	2 312	$3.5\cdot10^{-4}$	$8.0\cdot10^{-1}$	$1.1\cdot10^{27}$	17-72
Large liquid scintillators (Sec. VI.D)															
KLZ-400	^{136}Xe	completed	Kamioka	$2.5\cdot10^{3}$	44	100	97	114	0,1.4	42	450	$9.9\cdot10^{-3}$	$4.4\cdot10^{+0}$	$3.3\cdot10^{25}$	95-408
KLZ-800	^{136}Xe	taking data	Kamioka	$5.0\cdot10^{3}$	58	100	97	114	0,1.4	42	1 173	$1.4\cdot10^{-3}$	$1.6\cdot10^{+0}$	$4.0\cdot10^{26}$	28-118
KL2Z	^{136}Xe	proposed	Kamioka	$6.7\cdot10^{3}$	80	100	97	60	0,1.4	42	2 176	$3.0\cdot10^{-4}$	$6.5\cdot10^{-1}$	$1.1\cdot10^{27}$	17-71
SNO+I	^{130}Te	construction	SNOLAB	$1.0\cdot10^{4}$	20	100	97	80	-0.5,1.5	62	1 232	$7.8\cdot10^{-3}$	$9.7\cdot10^{+0}$	$1.8\cdot10^{26}$	31-144
SNO+II	^{130}Te	proposed	SNOLAB	$5.1\cdot10^{4}$	27	100	97	57	-0.5,1.5	62	8 521	$5.7\cdot10^{-3}$	$4.8\cdot10^{+1}$	$5.7\cdot10^{26}$	17-81
Cryogenic calorimeters (Sec. VI.E)															
CUORE	^{130}Te	taking data	LNGS	$1.6\cdot10^{3}$	100	88	92	3.2	-1.4,1.4	84	1 088	$9.1\cdot10^{-2}$	$9.9\cdot10^{+1}$	$5.1\cdot10^{25}$	58-270
CUPID-0	^{82}Se	completed	LNGS	$6.2\cdot10^{1}$	100	81	86	8.5	-2,2	95	41	$2.8\cdot10^{-2}$	$1.2\cdot10^{+0}$	$4.4\cdot10^{24}$	283-551
CUPID-Mo	^{100}Mo	completed	LSM	$2.3\cdot10^{1}$	100	76	91	3.2	-2,2	95	15	$1.7\cdot10^{-2}$	$2.5\cdot10^{-1}$	$1.7\cdot10^{24}$	293-500
CROSS	^{100}Mo	construction	LSC	$4.8\cdot10^{1}$	100	75	90	2.1	-2,2	95	31	$2.5\cdot10^{-2}$	$7.6\cdot10^{-3}$	$4.9\cdot10^{25}$	54-93
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AMORE	^{100}Mo	proposed	Yemilab	$1.1\cdot10^{3}$	100	82	91	2.1	-2,2	95	760	$2.2\cdot10^{-4}$	$1.7\cdot10^{-1}$	$6.7\cdot10^{26}$	15-25
Tracking calorimeters (Sec. VI.F)															
NEMO-3	^{100}Mo	completed	LSM	$6.9\cdot10^{1}$	100	100	11	148	-1.6,1.1	42	3	$9.3\cdot10^{-1}$	$3.0\cdot10^{+0}$	$5.6\cdot10^{23}$	505-866
SuperNEMO-D	^{82}Se	construction	LSM	$8.5\cdot10^{1}$	100	100	28	83	-4.2,2.4	64	15	$2.1\cdot10^{-2}$	$5.0\cdot10^{-1}$	$8.6\cdot10^{24}$	201-391
SuperNEMO	^{82}Se	proposed	LSM	$1.2\cdot10^{3}$	100	100	28	72	-4.1,2.8	54	185	$5.4\cdot10^{-3}$	$9.8\cdot10^{-1}$	$7.8\cdot10^{25}$	67-131

Experimental state of the art

See fresh exhaustive review [2202.01787]

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Future of double-beta decay search

- Sensitivity goals: Cover $m_{\beta\beta} \sim 17$ meV (IH)

*$[\mathbf{cps/(FWHM.t.yr)}]$
** + KamLAND2-Zen + NEXT-HD

^{76}Ge :
GERDA + MAJORANA
→ **LEGEND**

200 kg in prep. @ LNGS
1000 kg lab. selection
LAr veto + mass /det.

BI* $< \mathbf{0.6} \,/ < \mathbf{0.1}$
$\boldsymbol{T^{0\nu}_{1/2}} > \mathbf{0.9 \,/\, 12 \times 10^{27}}$ **yr**
$\boldsymbol{m_{\beta\beta}} < \mathbf{[35-73]/[10-20]}$ **meV**

^{100}Mo :
CUORE + CUPID-0/Mo
→ **CUPID**

Defined isotope - 253 kg cristals
Validated light scint. technology
Reuse CUORE cryostat

BI* $< \mathbf{0.5}$
$\boldsymbol{T^{0\nu}_{1/2}} > \mathbf{1.1 \times 10^{27}}$ **yr**
$\boldsymbol{m_{\beta\beta}} < \mathbf{[12-20]}$ **meV**

^{136}Xe :**
EXO-200
→ **nEXO**

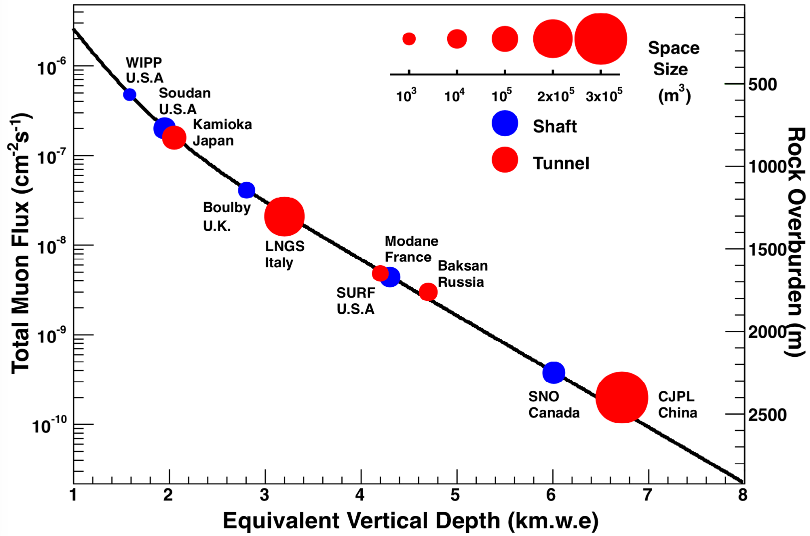
mass x25 = 5 tons LXe
SNOLAB – fiducial volume
Energy resolution 1%

BI* $< \mathbf{0.6}$
$\boldsymbol{T^{0\nu}_{1/2}} > \mathbf{9.2 \times 10^{27}}$ **yr**
$\boldsymbol{m_{\beta\beta}} < \mathbf{[6-17]}$ **meV**

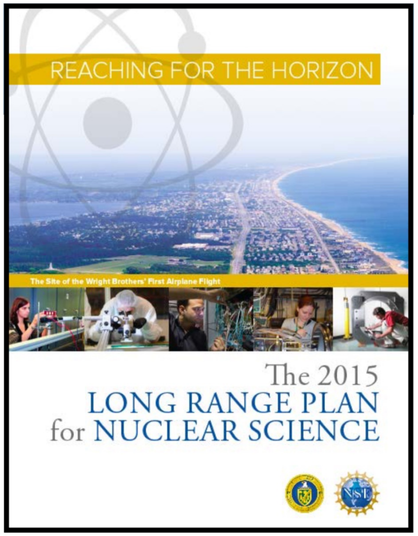
- Three major experiment in terms of mass/funding
  but many other alternative technology under development

Candidate underground labs

- **Europe:**
  - Feasibility studies of LEGEND-1000 at LNGS
  - LSC not deep enough
  - Not enough space at LSM
- **North America:**
  - Preference for SNOLAB in Canada (SURF not retained)
  - Active mine – new experimental hall dedicated to double-beta decay
- **China:**
  - Large hosting capacity at CJPL experimental hall built for CDEX (dark matter)



Selection process in the US



"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

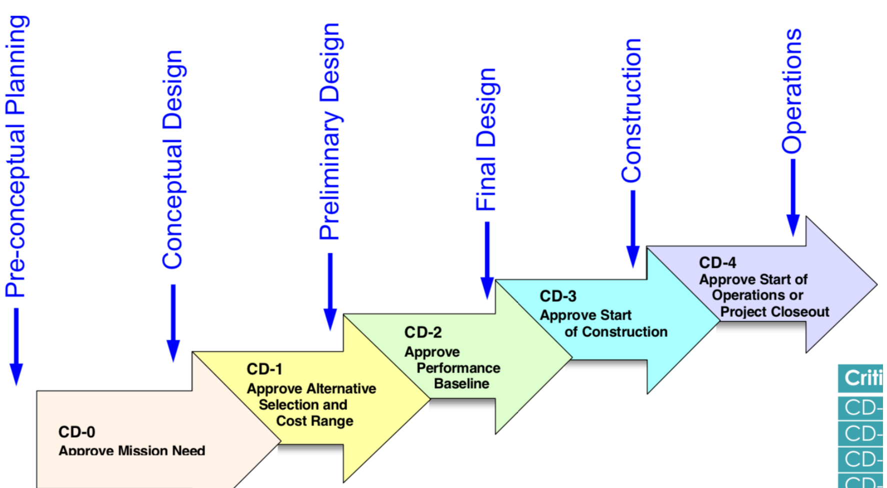


Figure 1. Critical Decision Flowchart

- **Three experiments seriously considered**
  - LEGEND-1k — ^{76}Ge – after LEGEND-200
  - nEXO — ^{136}Xe – after EXO-200
  - CUPID — ^{100}Mo – after CUORE
  - (?)

- **Support document**: « pCDR » (pre Conceptual Design Report)
  - LEGEND-1k : [2107.11462]
  - nEXO : [1805.11142]
  - CUPID : [1907.09376]

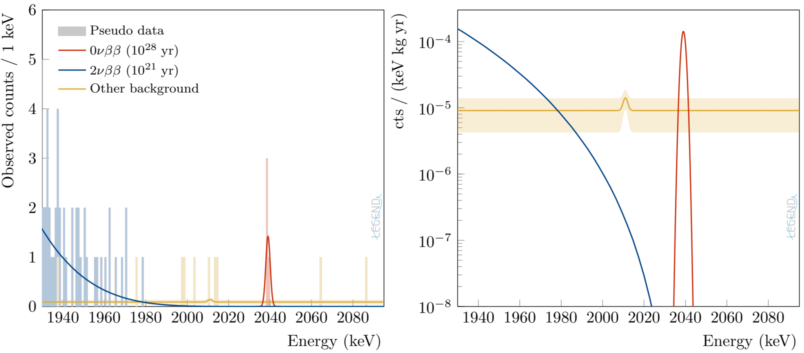
- **Budget**: Order of magnitude is ~[10-200] M$

- **Selection** : unknown date / strategy (interplay with EU funding strategy)

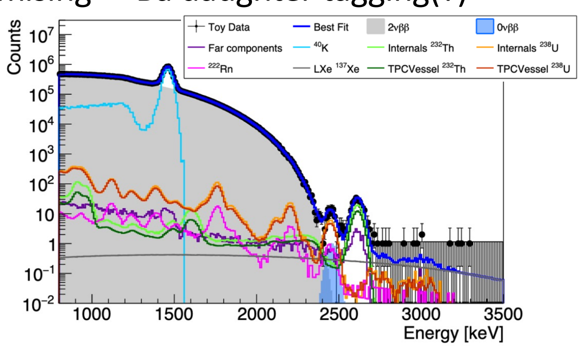
Sensitivity comparison with other isotopes

Strength of the LEGEND-1000 proposal:
- Quasi-background free at full exposure
- No known peaks near $Q_{\beta\beta}$

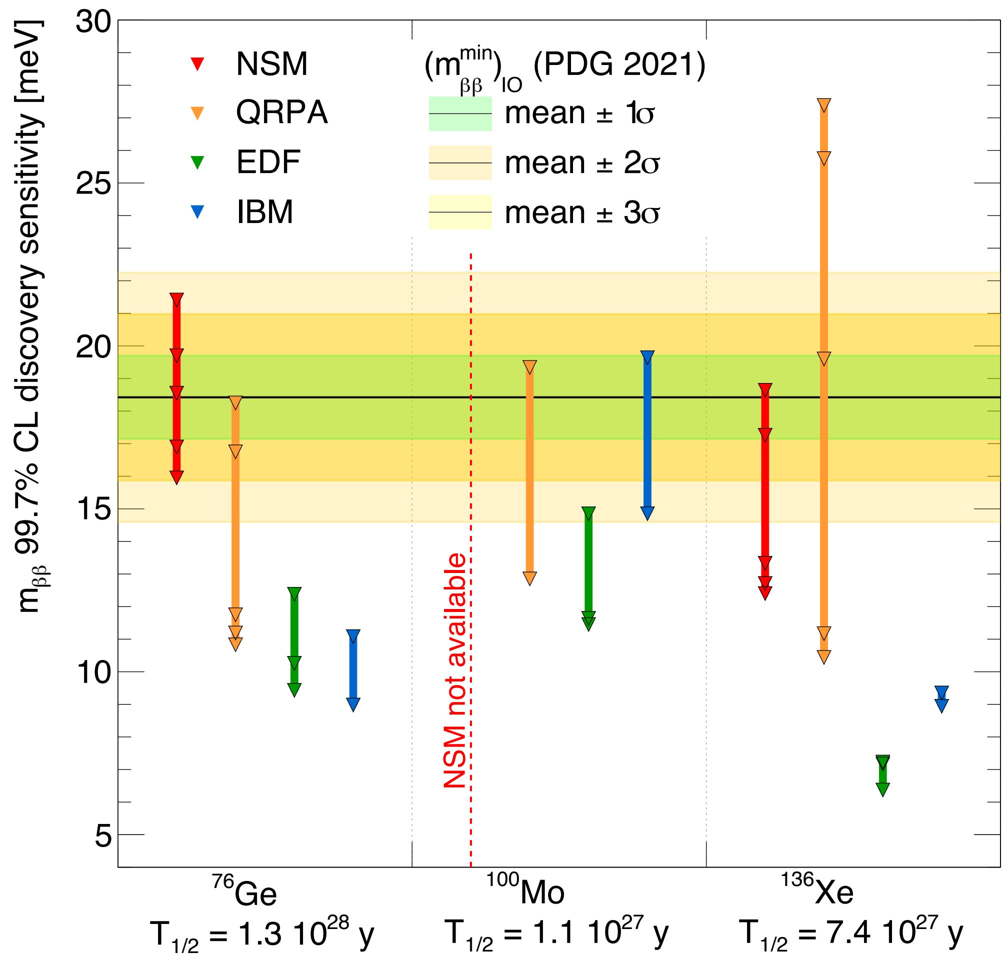
$m_{\beta\beta}$ inverted ordering band [2107.11462]



Strength of the nEXO proposal:
- Exposure (5 t) + fiducialization
- Promising ^{136}Ba daughter tagging(?)



Strength of the CUPID proposal:
- Existing cryogenic infrastructure
- Demonstrated bkg reduction technique w.r.t. CUORE



APPEC recommendations

[1910.04688]

APPEC : Astroparticle Physics European Consortium
Meeting on the 31 octobre 2019 dedicated to double-beta decay

Recommendation 1. The search for neutrinoless double beta decay is a top priority in particle and astroparticle physics.

Recommendation 2. A sustained and enhanced support of the European experimental programme is required to maintain the leadership in the field, exploiting the broad range of expertise and infrastructure and fostering existing and future international collaborations.

Recommendation 3. A multi-isotope program at the highest level of sensitivity should be supported in Europe in order to mitigate the risks and to extend the physics reach of a possible discovery.

Recommendation 4. A programme of R&D should be devised on the path towards the meV scale for the effective Majorana mass parameter.

Recommendation 5. The European underground laboratories should provide the required space and infrastructures for next generation double beta decay experiments and coordinate efforts in screening and prototyping.

Conclusions

- **The neutrino remains a golden channel to probe New Physics** despite its low interaction rate

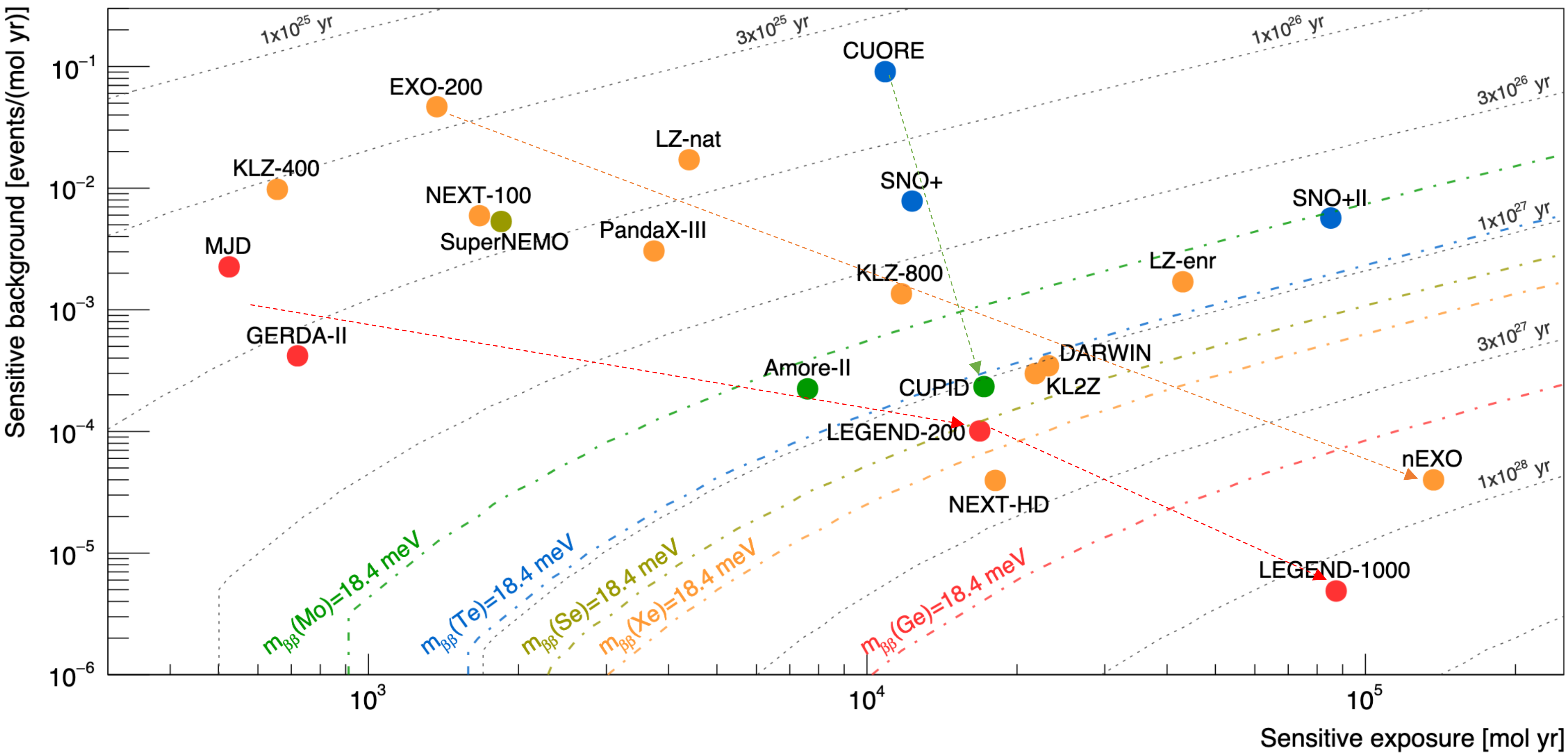
- **Neutrinoless double beta decay is in an exciting phase!**
  - ➢ Many highly sensitive experiments have recently delivered results
  - ➢ There is a roadmap to increase sensitivities by two order of magnitude on $T_{1/2}^{0\nu}$
    Future projects rely on different isotopes

- **The community is moving toward ton-scale projects**
  - ➢ with ultra-low background, high energy resolution
  - ➢ offering many possibility to probe rare events connected to new physics

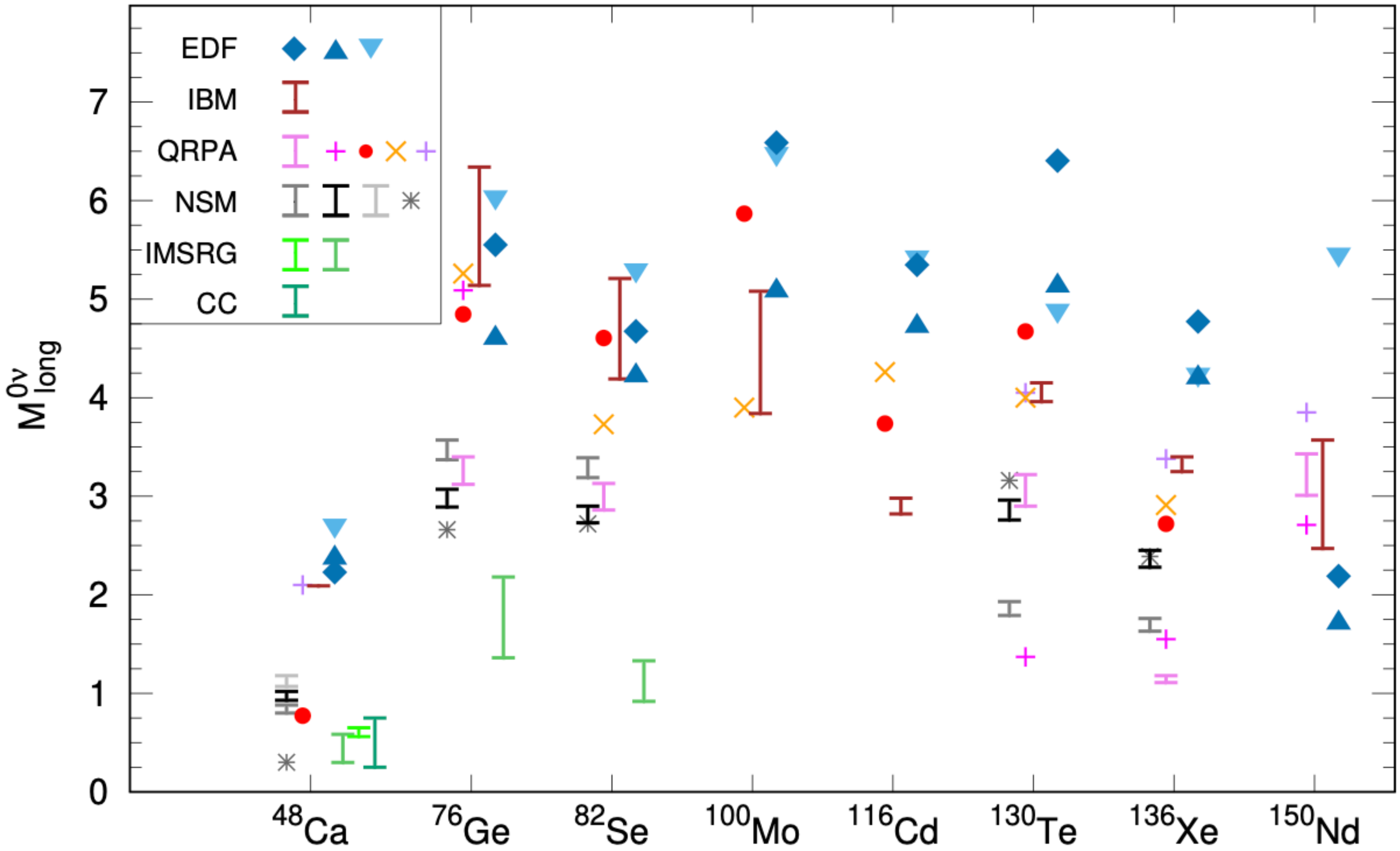
Technological risk evaluation

- **Large gap in exposure (horizontal axis)**
  = potential unknowns on the experiment functioning / long term robustness / …

- **Large gap on the background (vertical axis)**
  = potential unknowns on the radiopurity / ignored background components / …



Nuclear Matrix Element status



New NSM, IBM and QRPA calculations have been performed in 2020

Ab-initio (first principles) calculations now available for ^{76}Ge and ^{82}Se!