

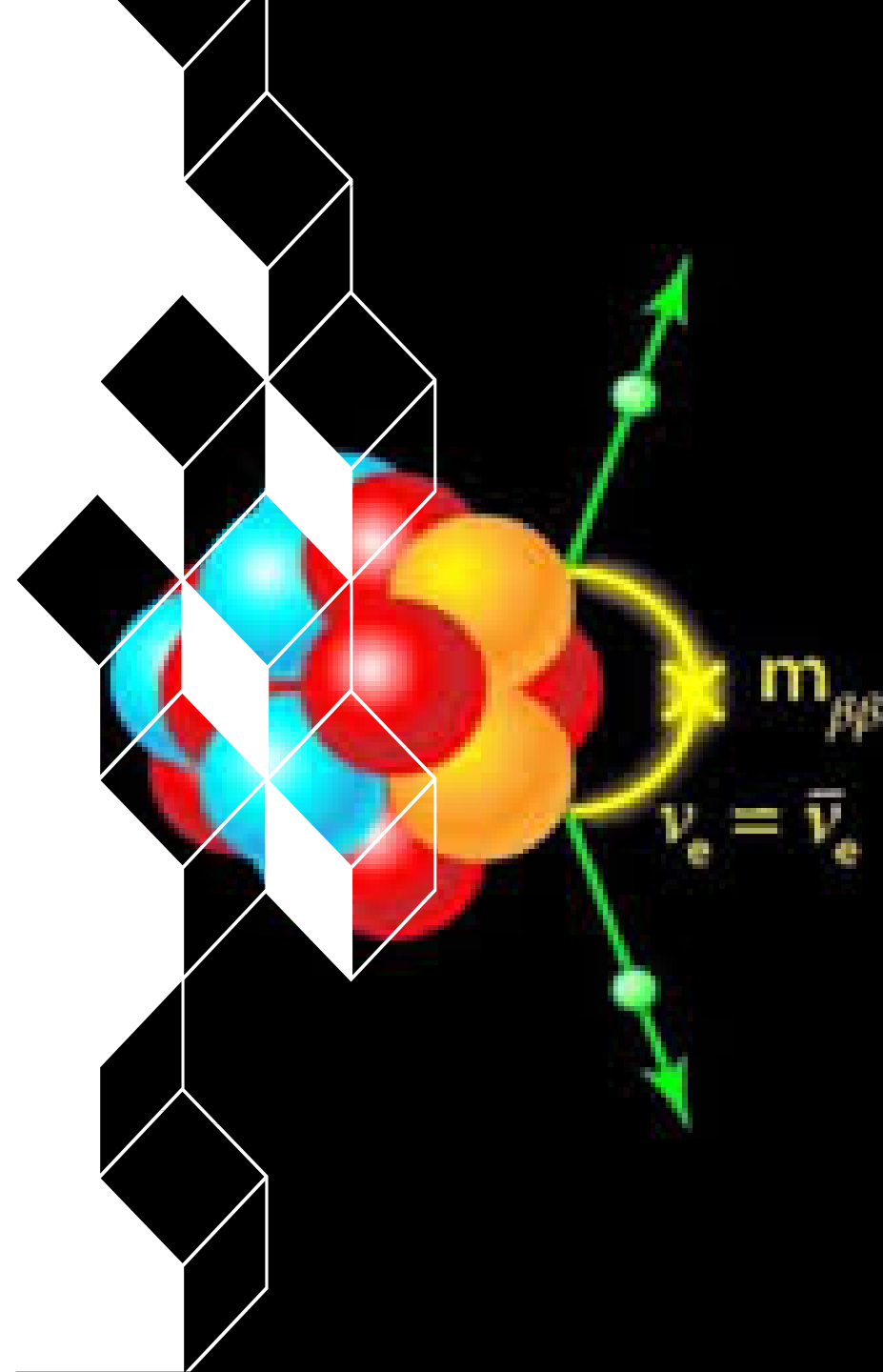


irfu



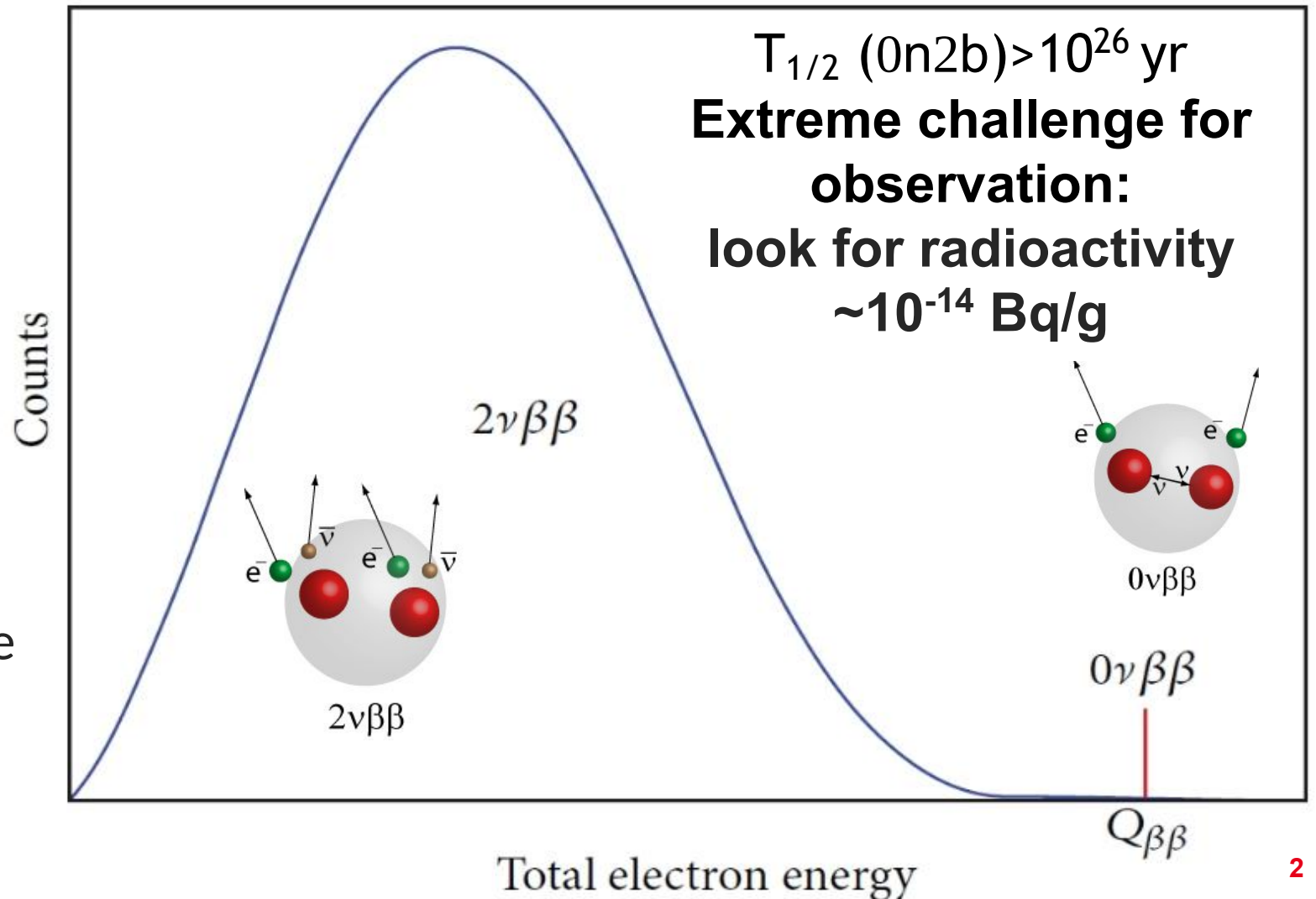
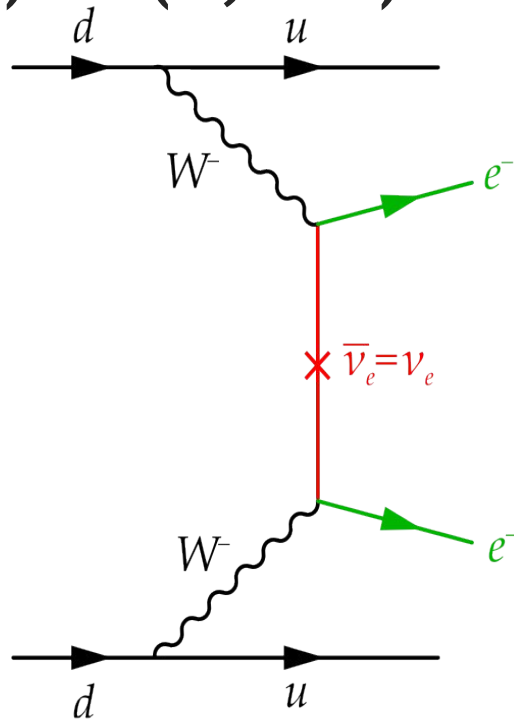
Neutrinoless double beta decay R&D projects: **BINGO** and **TINY** experiments

A. Zolotarova



Neutrinoless double beta decay

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



Determination of neutrino nature
 Total lepton number
 violation $\rightarrow$
 new physics beyond SM

0ν2β decay and neutrino masses

$$(T_{1/2}^{0\nu 2\beta})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

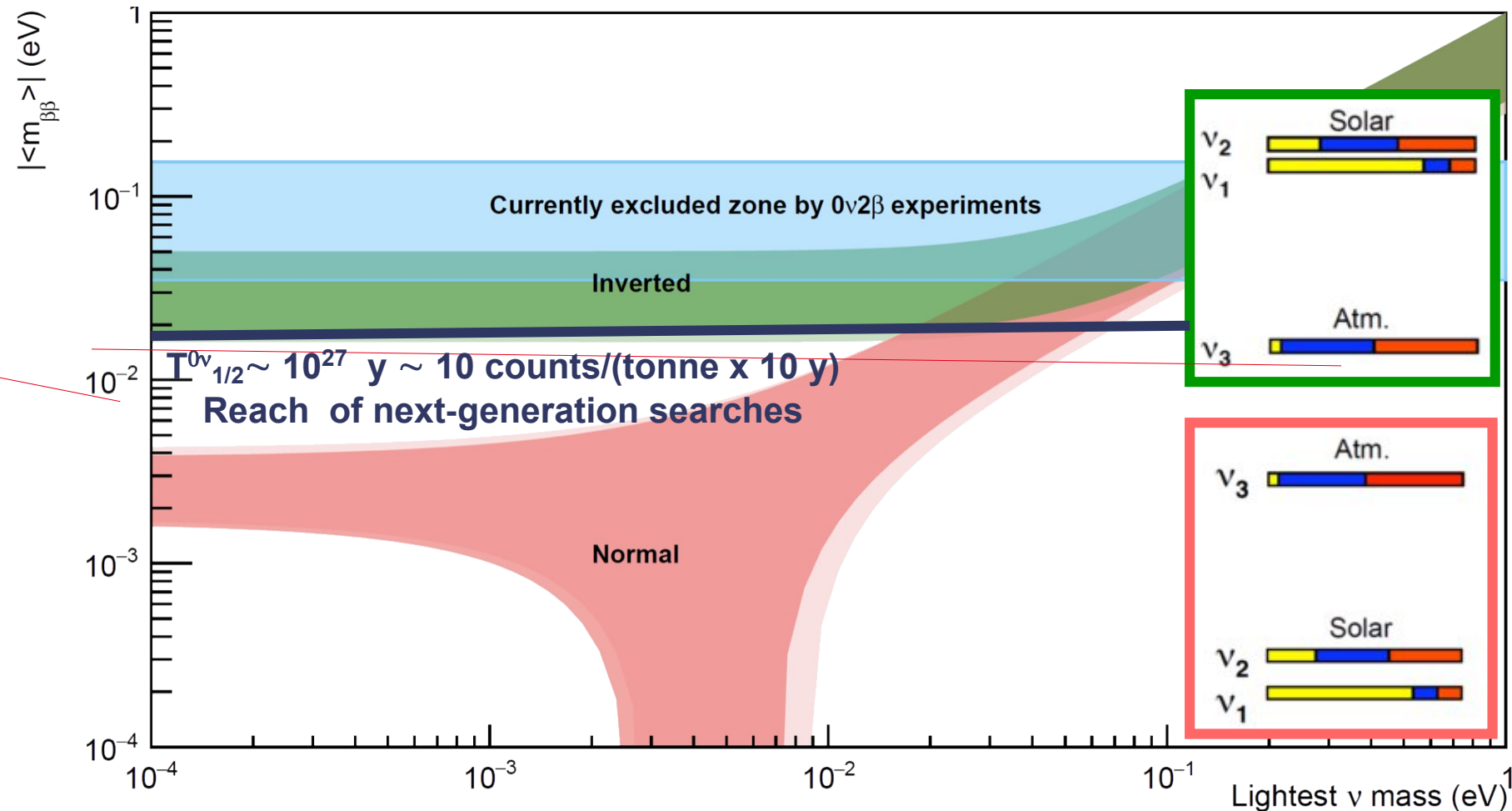
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}|$$

Experimental sensitivity :

$$T_{1/2}^{0\nu 2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

In case of $b \cdot \Delta E \cdot M \cdot t \ll 1$:

$$T_{1/2}^{0\nu 2\beta} \propto a \cdot \epsilon \cdot M \cdot t$$



0ν2β decay and neutrino masses

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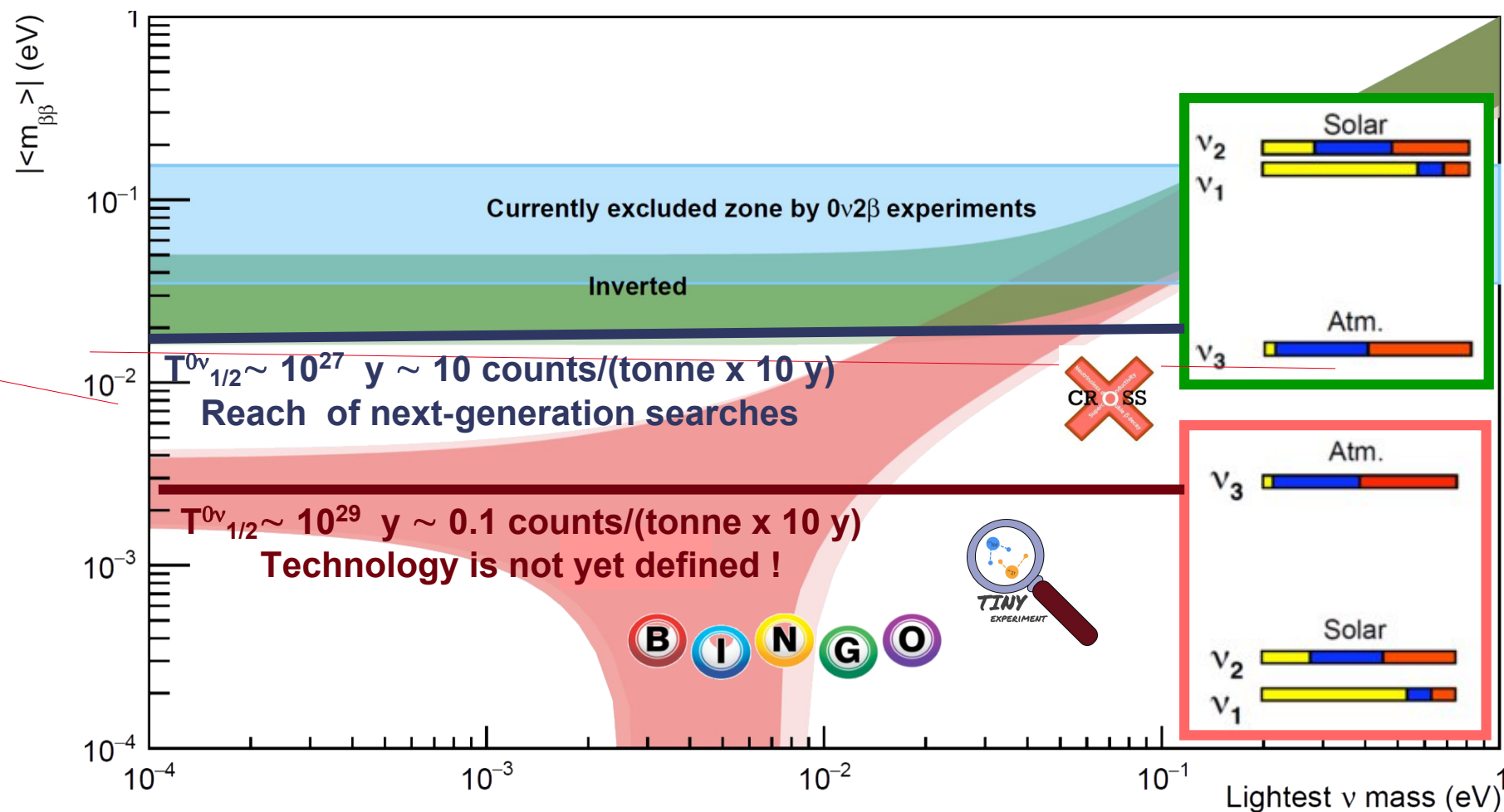
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$$T_{1/2}^{0\nu 2\beta} \propto a \cdot \epsilon \cdot M \cdot t$$



How to build a successful experiment?

$$G(Q,Z) \propto Q^5$$

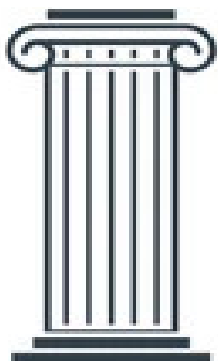
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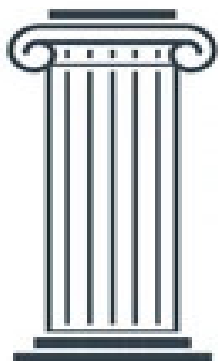
Background

zero bkg
“boosts”
the sensitivity



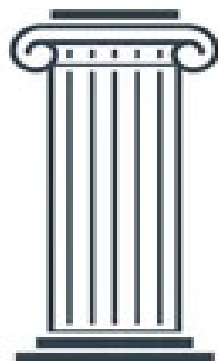
Exposure

Large masses
and a lot of
patience



Energy
resolution

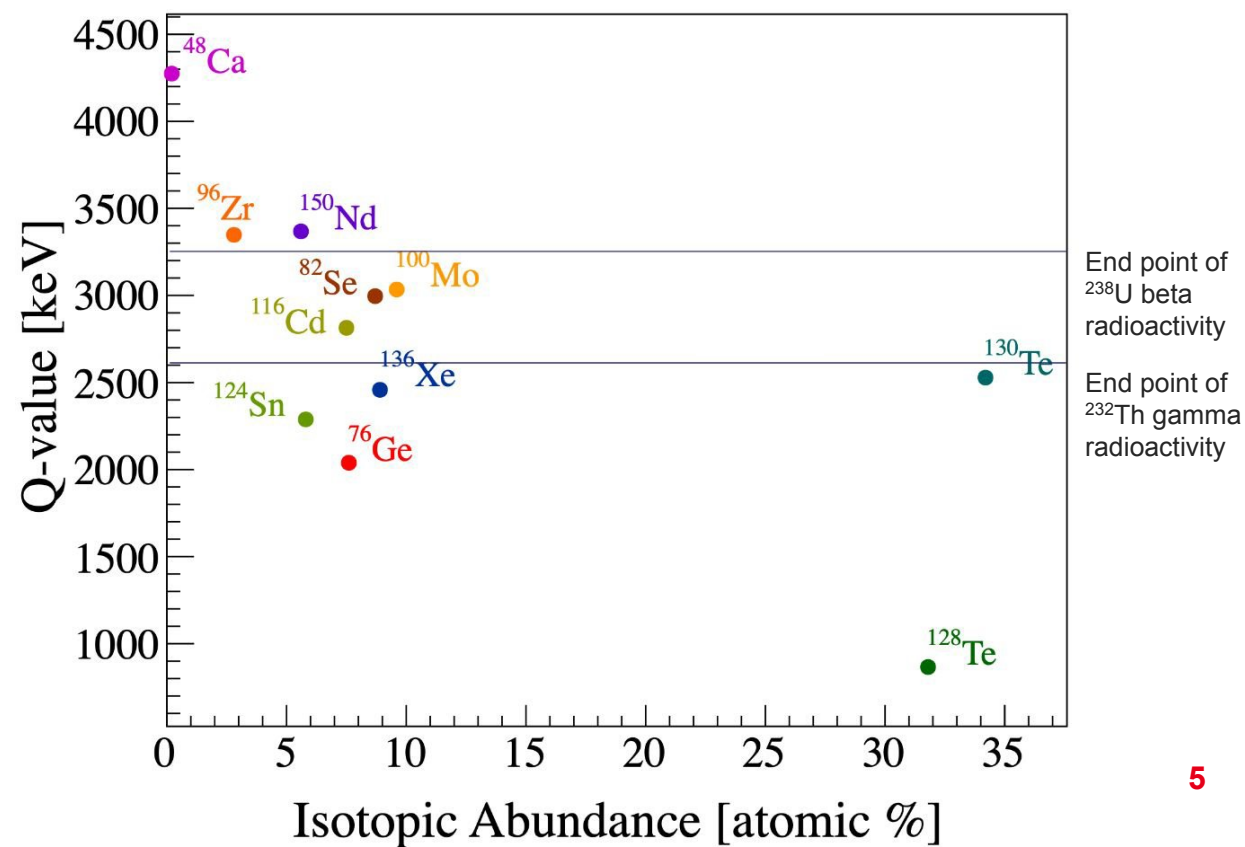
Better
resolution ->
narrower ROI



Isotope choice:

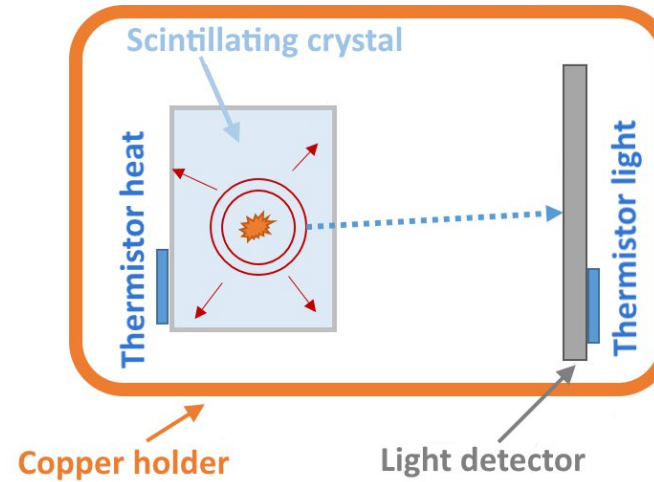
High $Q_{bb} \rightarrow$ lower background level
in ROI and higher $0\nu 2\beta$ decay rate

Large exposure - big mass: natural abundance
and possibility of enrichment are important

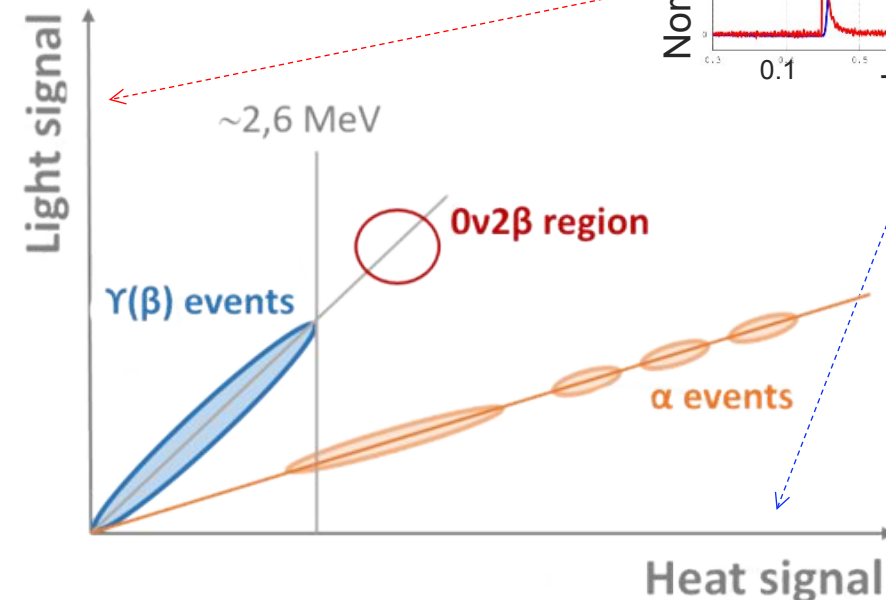
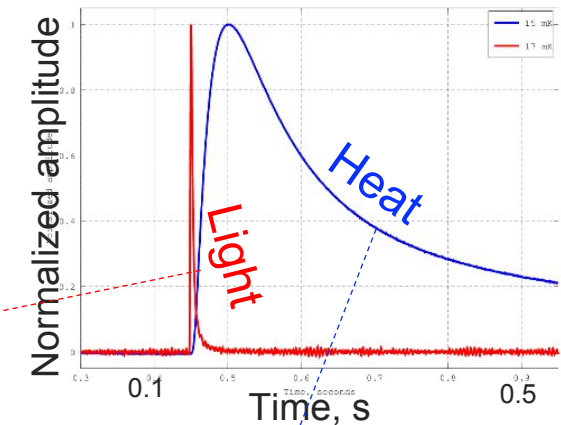


Bolometric technology

- Detectors measured at ~ 10 mK, the deposited energy is measured as a **temperature increase** in a crystal
- **Flexible composition:** dielectric crystals with low heat capacity
- **High detection efficiency** ($\sim 90\%$), ~ 5 keV FWHM ($\sim 0.2\%$) at the $Q_{\beta\beta}$
- **Particle discrimination using light or pulse-shape for α rejection**
- **Widely used for $0\nu 2\nu\beta$ searches:** CUORE, CUPID-Mo, CUPID-0, CUPID, AMoRe, R&D for other isotopes: ^{48}Ca , ^{82}Se , ^{100}Mo , ^{116}Cd , ^{130}Te - cryogenic detector technology confirmed
- **Scaling to ~ 1 ton detector confirmed by CUORE**

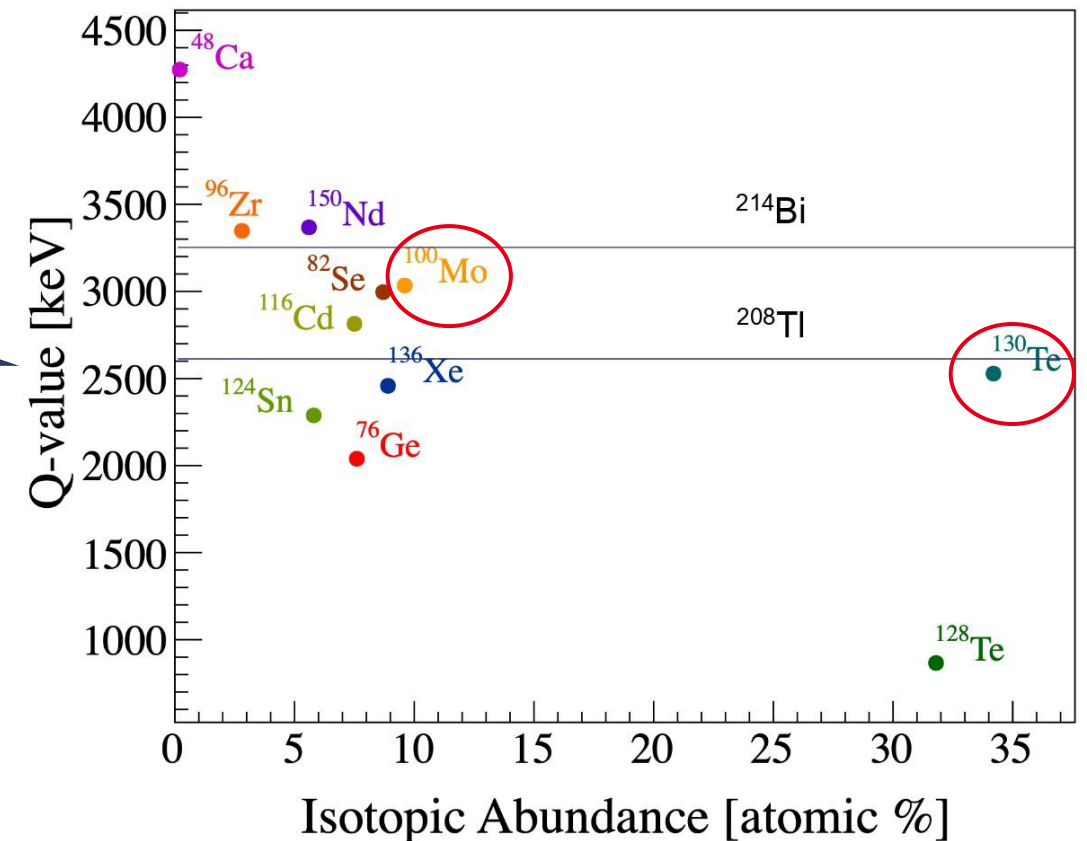
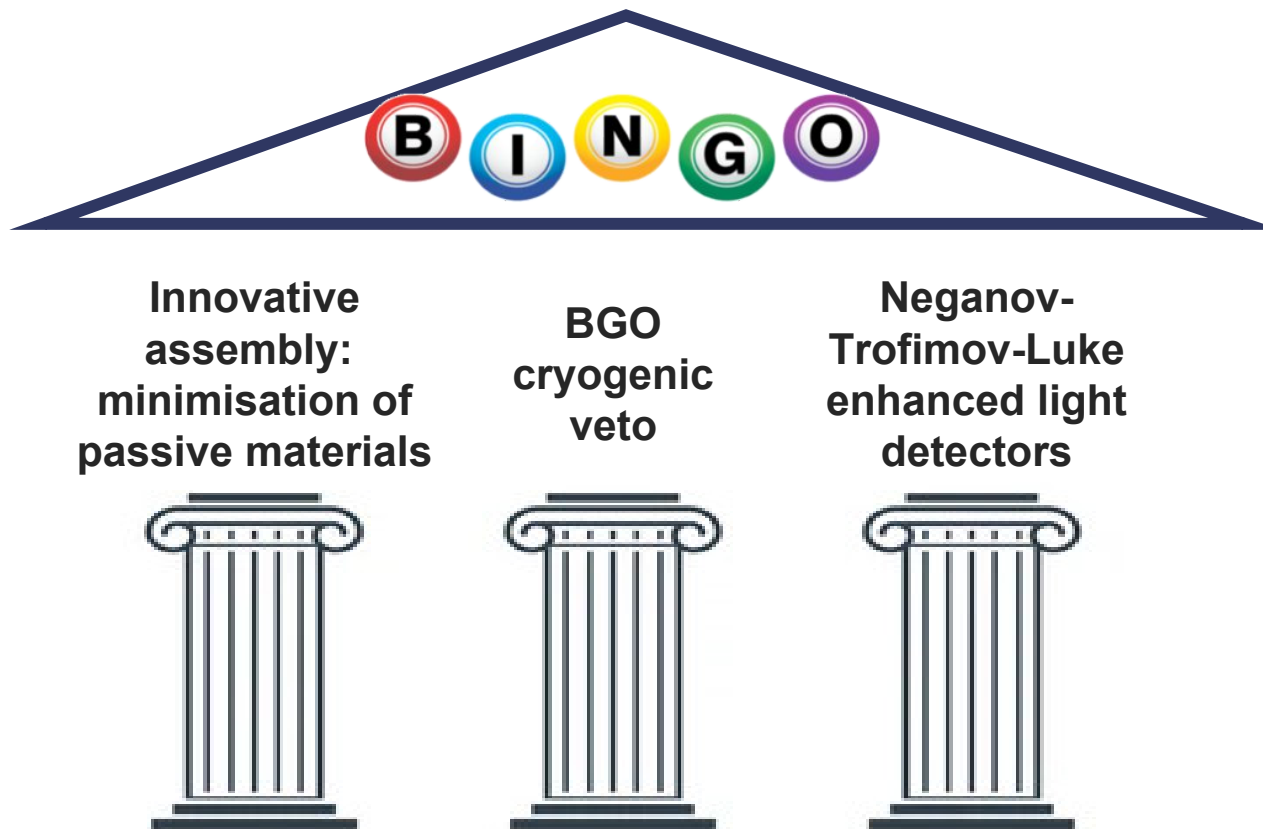


Typical signal: **0.1 mK/MeV**, converted to **0.1-0.2 mV/MeV**



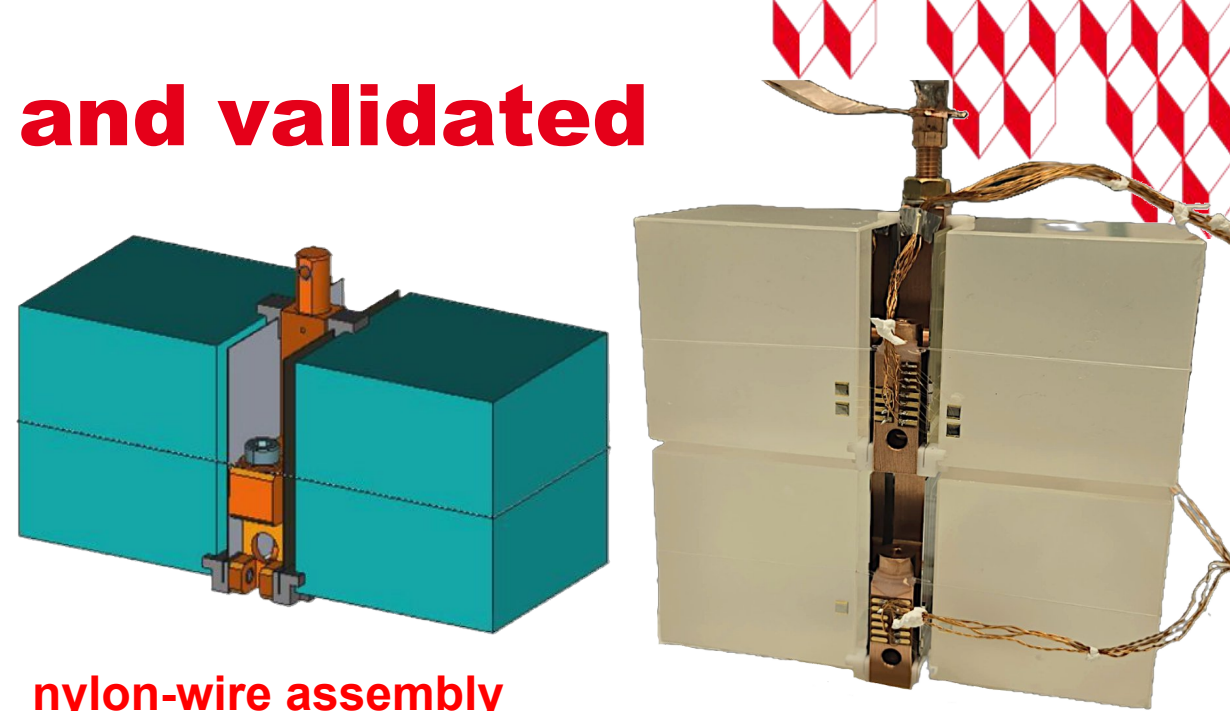
Bi-Isotope $0\nu\beta\beta$ Next Generation Observatory

- Use well-studied detectors: scintillating bolometers (TeO_2 and Li_2MoO_4)
- **Low radioactivity** for all the selected materials
- Address the **background mitigation** very thoroughly

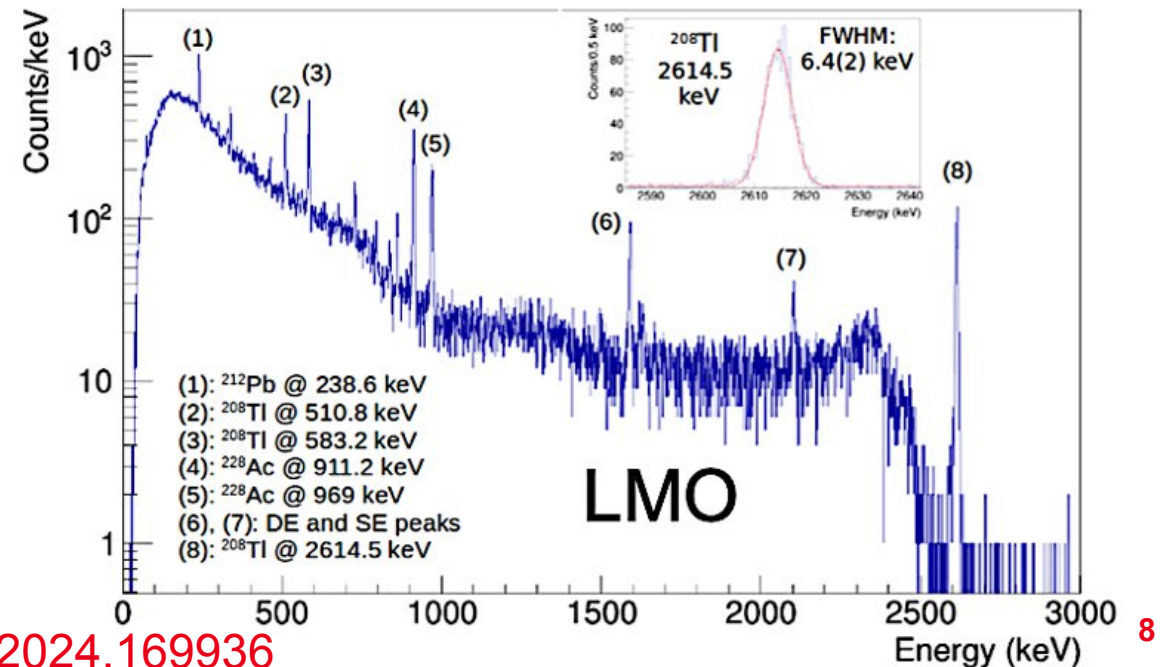
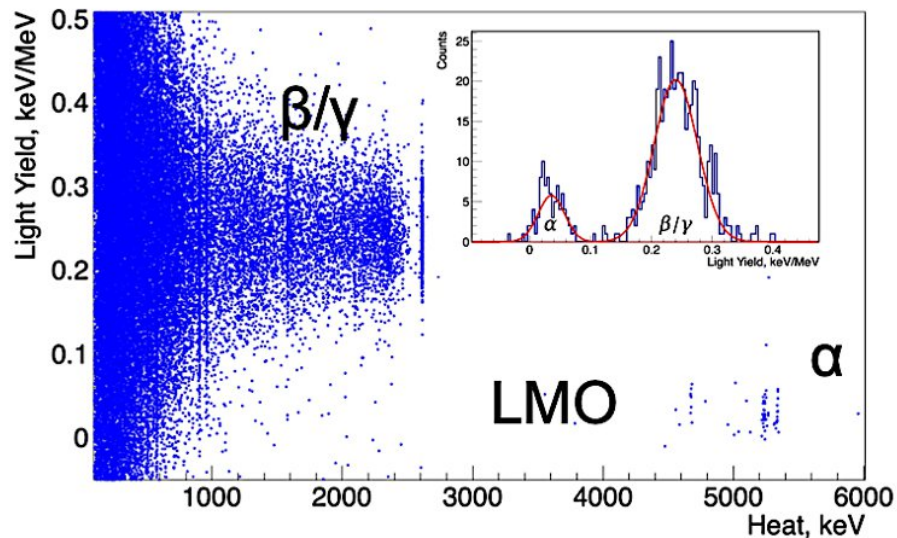


BINGO assembly : tested and validated

- Less passive materials
- Crystal sees almost nothing except LD surface
- Compact assembly
- No additional noise induced
- Li_2MoO_4 modules tested and validated:
- ~6keV FWHM at 2.6 MeV
- good discrimination between α and β/γ



nylon-wire assembly



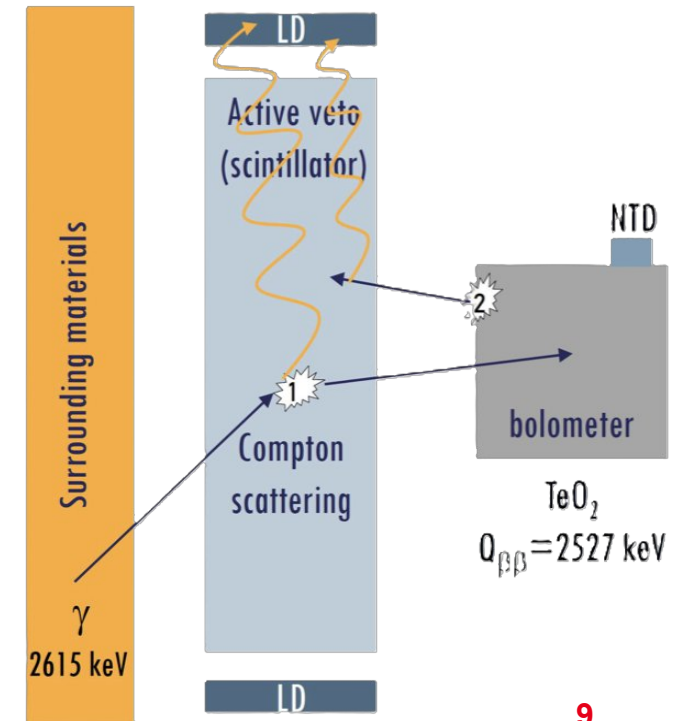
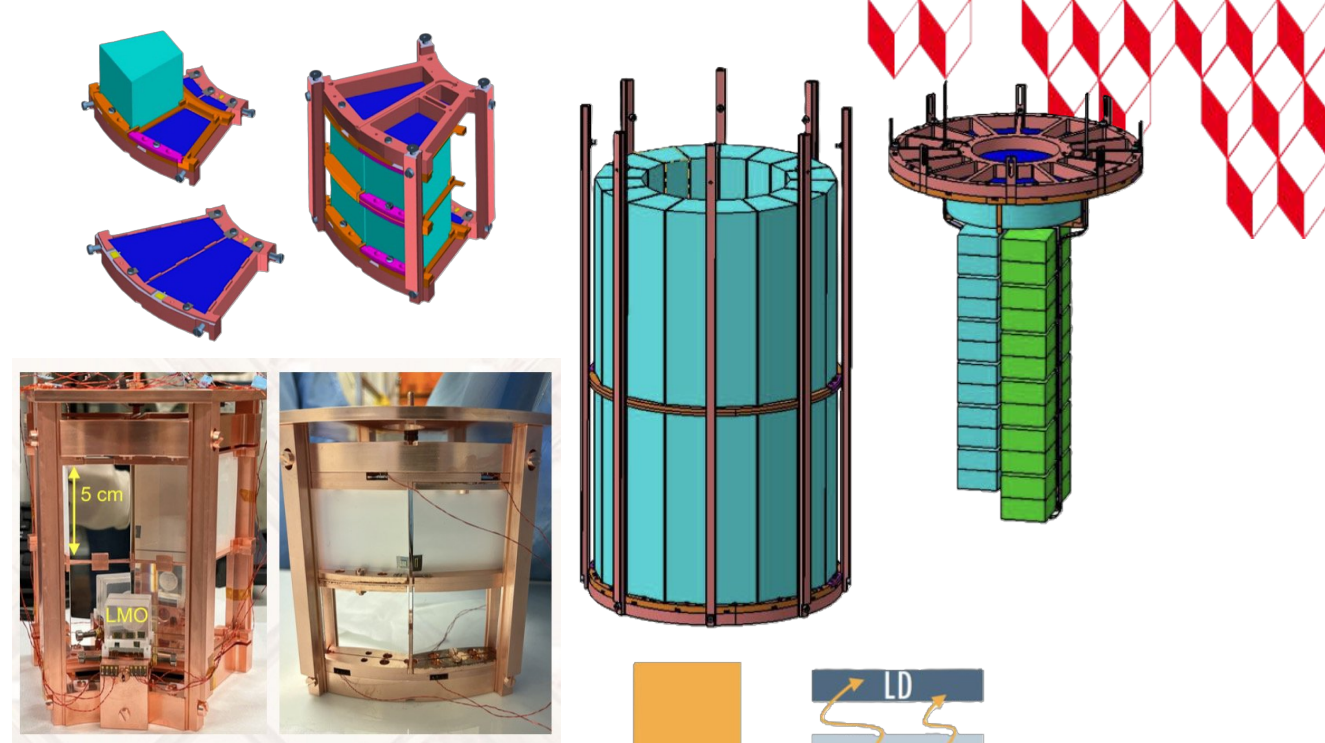
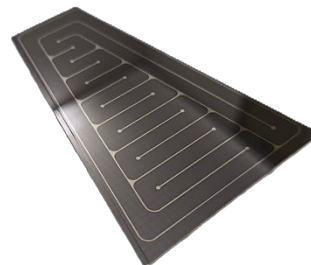
j.nima.2024.169936

Cryogenic veto

- Scintillators (BGO) with 4π coverage
- Cryogenic light detectors
- Suppression of external γ background
- Rejection of **surface contamination** events
- Aluminum coating on inner side, reflecting foil outside

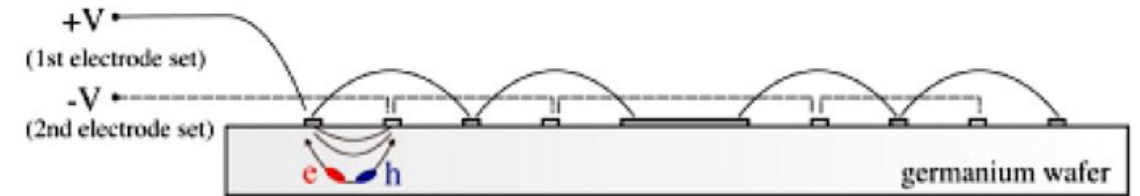
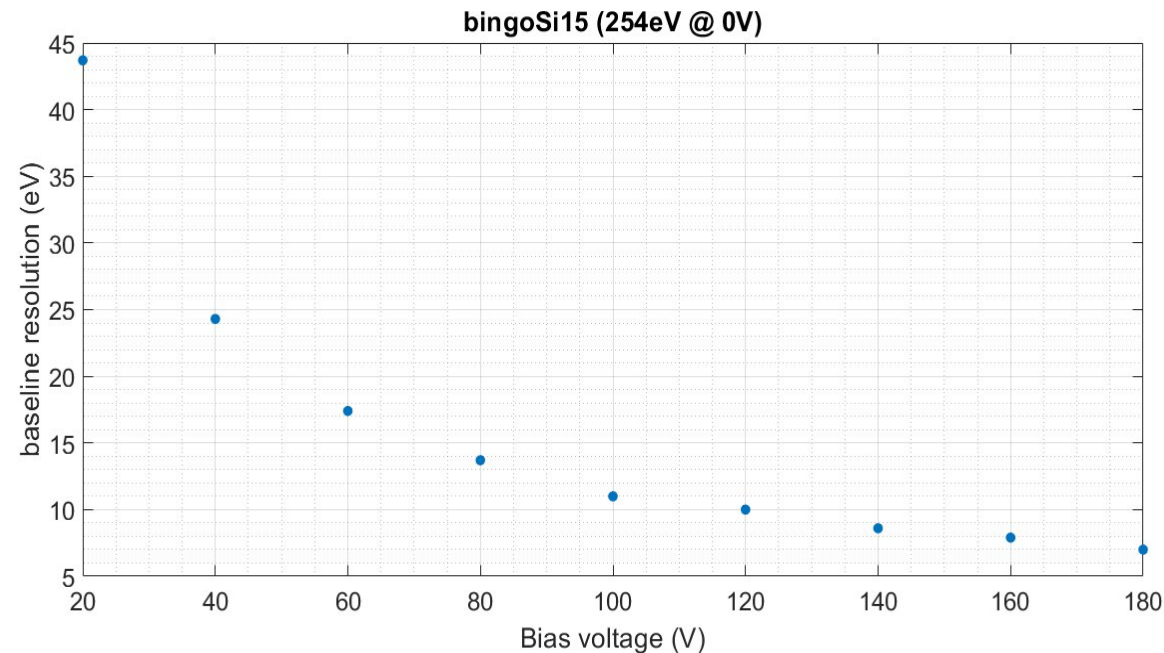
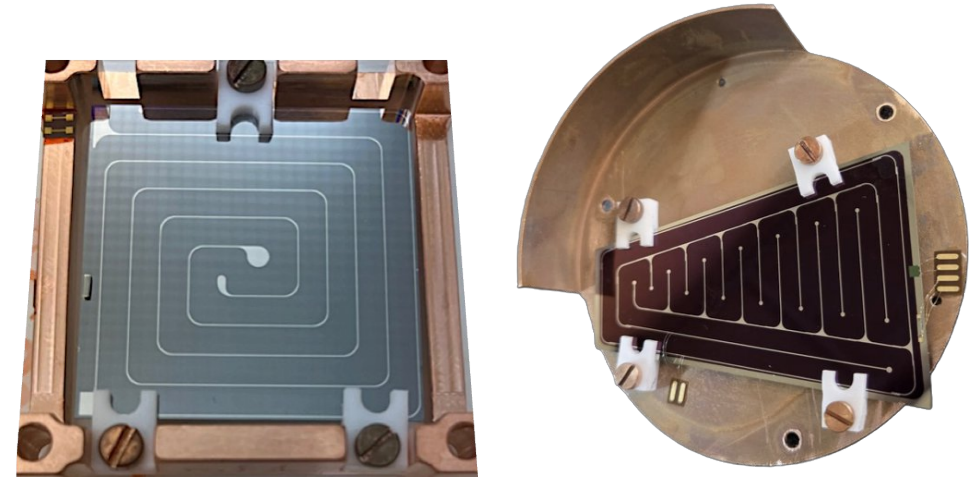
Preliminary test with smaller crystals :

- Mechanical structure validated
- Confirmed surface alpha tagging
- Article in preparation



NTL detectors

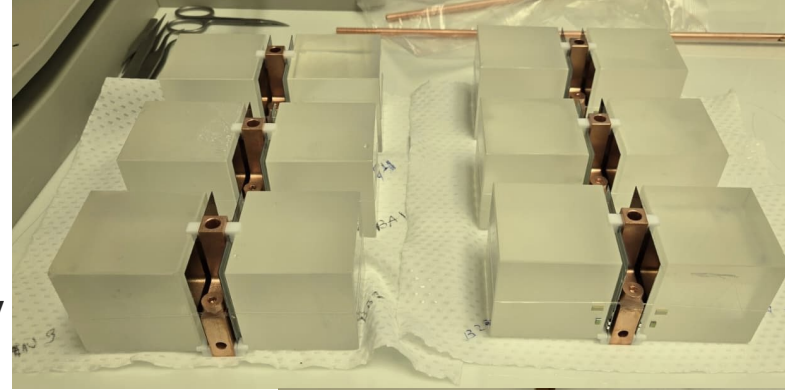
- Cherenkov light detection for TeO_2 crystals for **alpha rejection**
- Higher SNR to lower the cryogenic veto threshold
- **Pile-up rejection** for Li_2MoO_4 (high 2n2b rate)
 - at 0V: <100 eV RMS bsl resolution
 - at 50-150V NTL bias: **12 eV RMS** bsl resolution



Synergy with CROSS and CUPID for performance optimization

BINGO demonstrator

- Cryogenic facility at Modane underground laboratory
- Total demonstrator mass: 170 kg



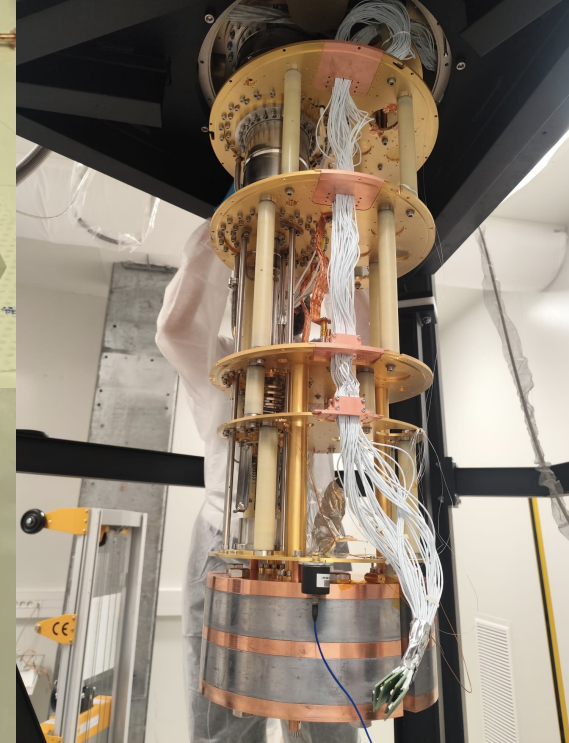
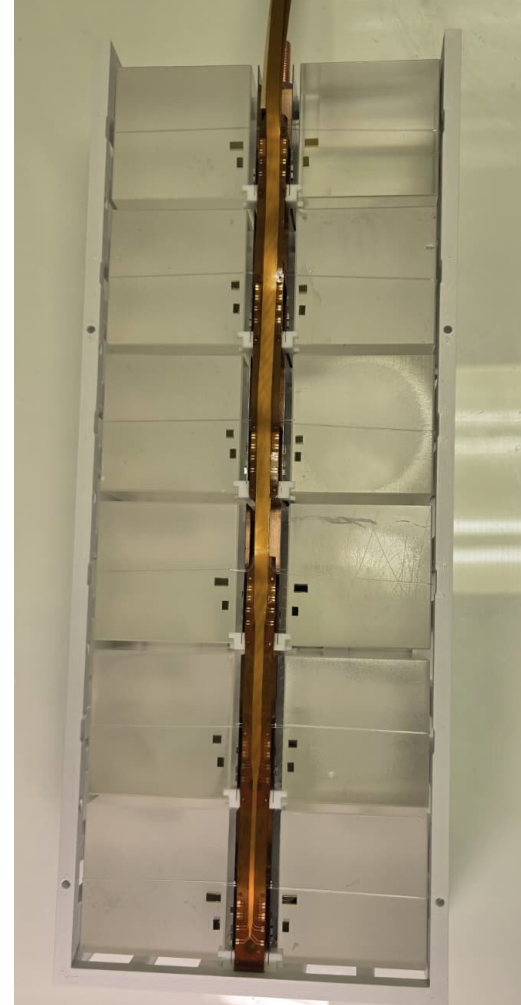
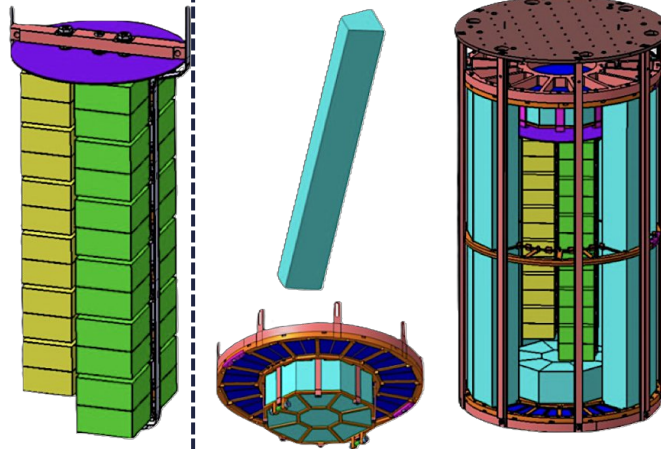
Towers

- 12 LMO (45x45x45 mm)
- 12 NTL square LD (45x45 mm)
- 12 TeO₂ (50x50x50 mm)
- 12 NTL square LD (50x50 mm)

Cryogenic veto

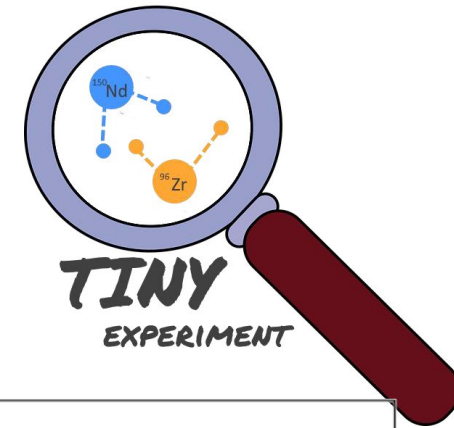
- 32 long trapezoidal BGO (23 cm)
- 32 NTL trapezoidal LD
- 16 short trapezoidal BGO (5 cm)
- 2 octagonal BGO

- Phase I:
installation this week !
- Main goals :
performance and
background model
validation
- Phase II : expected in 2027, upon BGO crystals reception



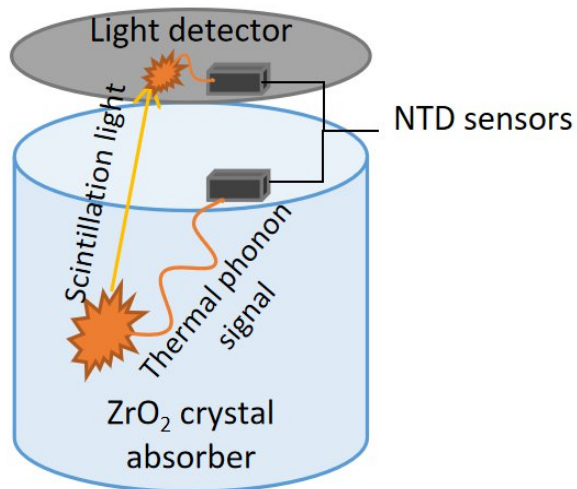
Two Isotopes for Neutrinoless double beta decay search

- Cryogenic detectors with ^{150}Nd and ^{96}Zr : high transition energy, but no developed technology for «source=detector» with high energy resolution yet



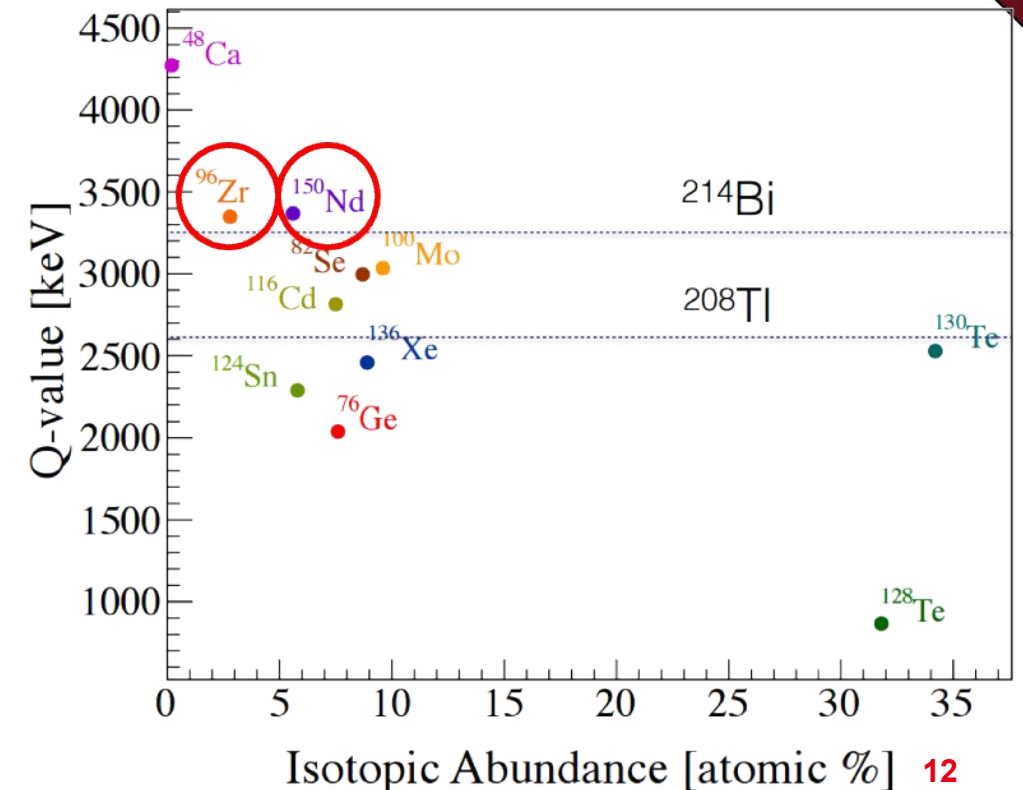
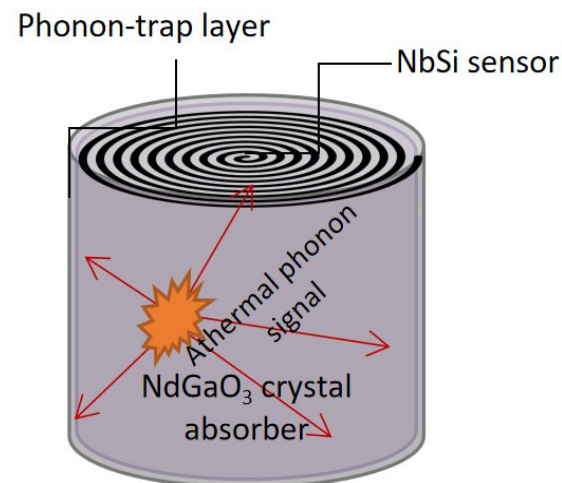
^{96}Zr

- Thermal phonon sensors
- PID through scintillation
- Selection of dielectric scintillating crystals



^{150}Nd

- Athermal phonon sensors
- PID through PSD
- Proof-of-concept : magnetic cryogenic calorimeters

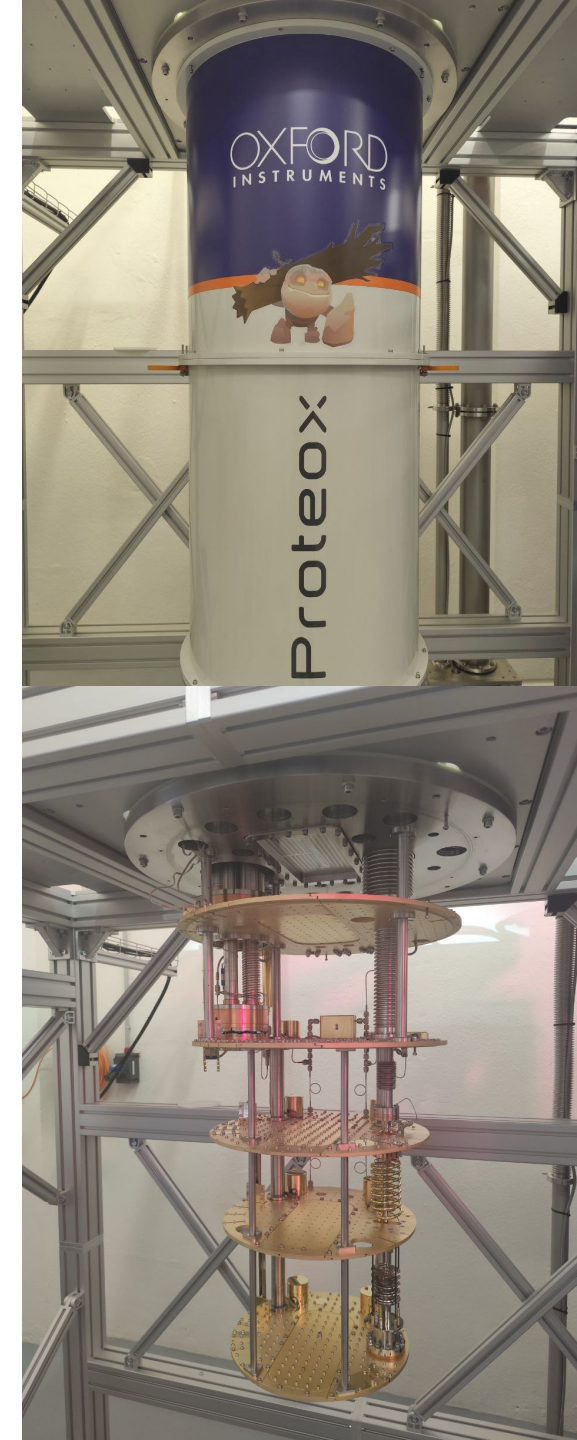


TINY cryogenic facility at CEA

- Proteo MX dilution unit cryostat installed in April 2025
- Experimental space (below MC):
Diameter = 36 cm, Height = 23 cm
- Cooling power: 12 μ W @20 mK, 450 mW @100 mK, 48 hours from 300K to 10 mK
- 1.5 ton lead shield

Base temperature <10mK Wired configuration

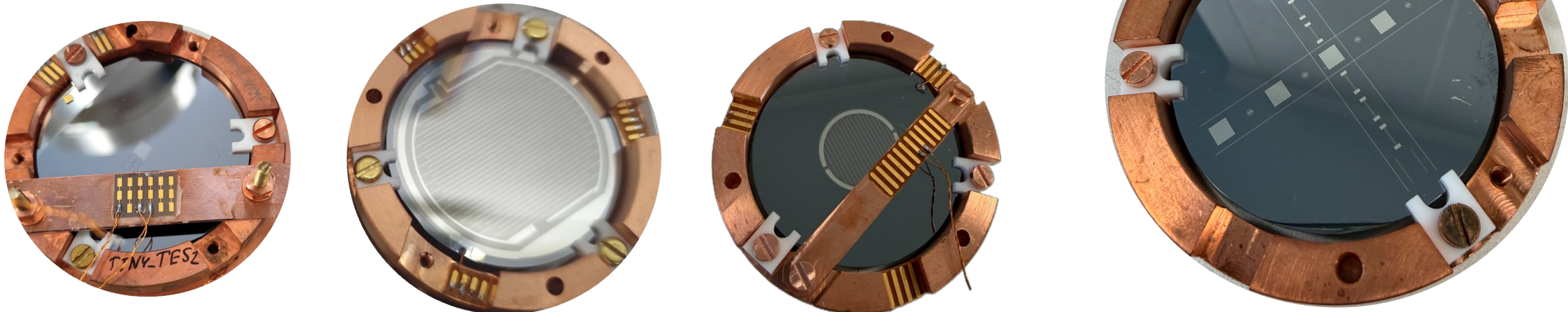
Parameter	Factory Acceptance Test (FAT)	Site Acceptance Test (SAT)
Mixing Chamber Temperature	8.681 mK	7.46 mK
Cold Plate Temperature	86.202 mK	80.18 mK
Still Plate Temperature	0.6461 K	0.627 K
PT2 Head/Plate Temperature	2.541 K / 2.6461 K	2.56 K / 2.71 K
PT1 Head/Plate Temperature	39.813 K / 42.595 K	40.30 K / 42.96 K
Electrical Power applied to Still	0 mW	0 mW
Condenser Pressure	25.32 KPa	24.8 KPa
Cooldown	32 h	41 h



Nd-based cryogenic calorimeters

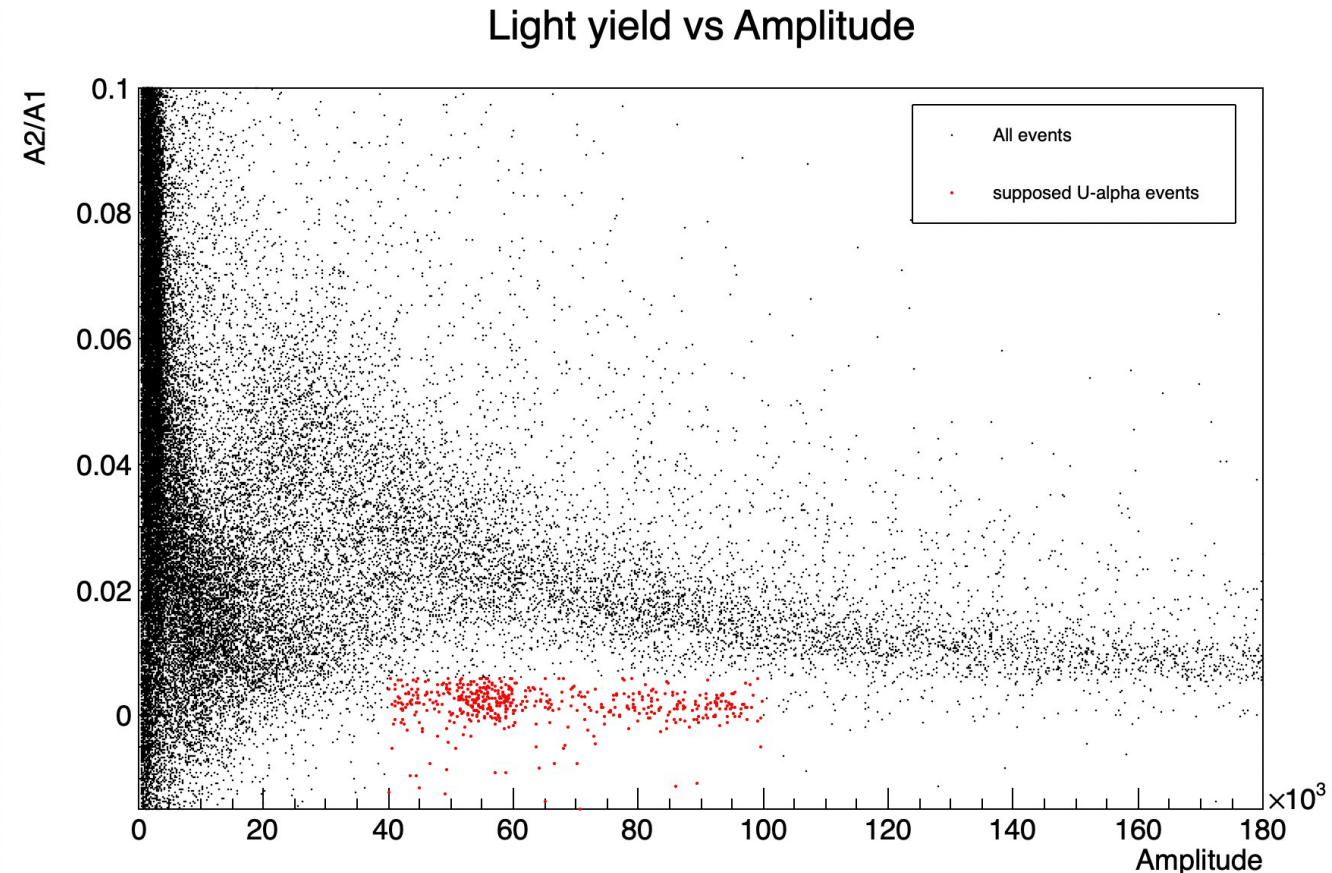
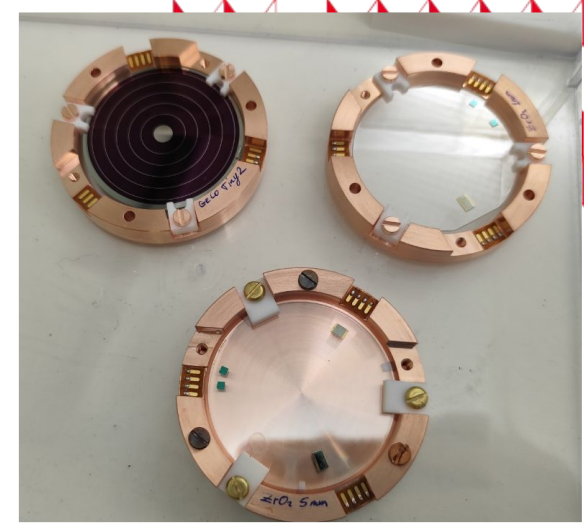


- Magnetic materials have high specific heat: Nd-based detectors do not work with NTD thermal sensors
- Phase 0: production and validation of **NbSi sensors** on Si wafers
- successfully used before in both TES and Anderson insulator regime in the past (<https://doi.org/10.1007/s10909-022-02899-2>, <http://doi.org/10.1007/s10909-008-9764-z>)
- Several geometries tested : performance do not meet the requirements yet
- Focus on reproducibility and film homogeneity studies



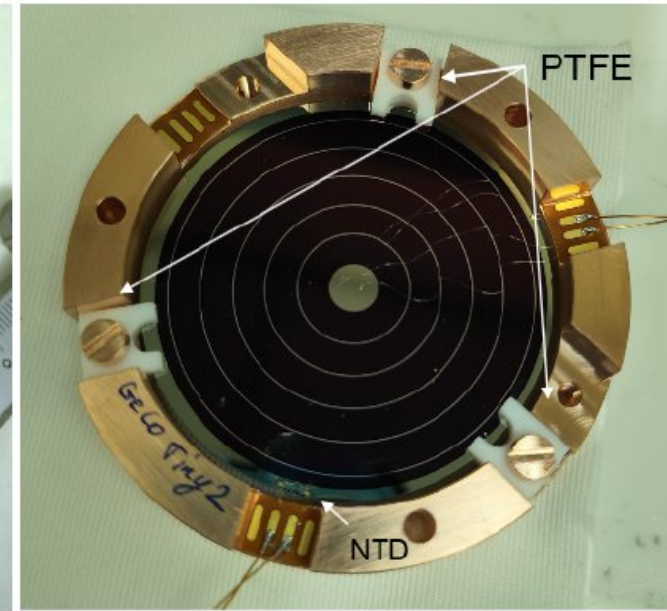
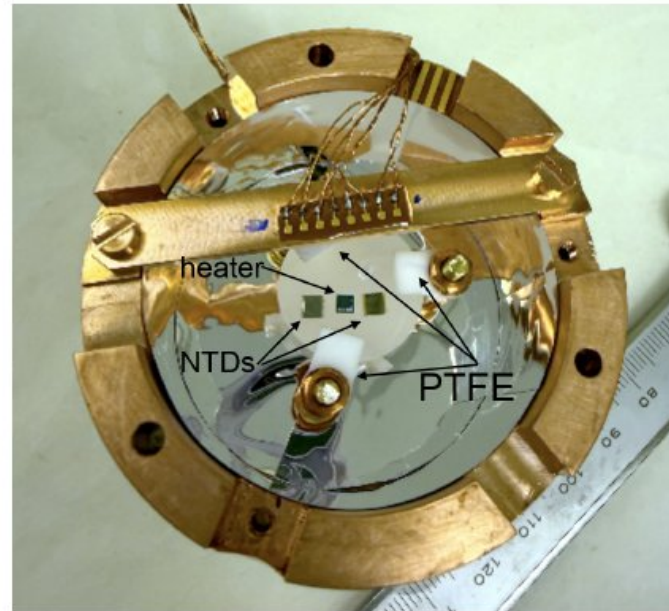
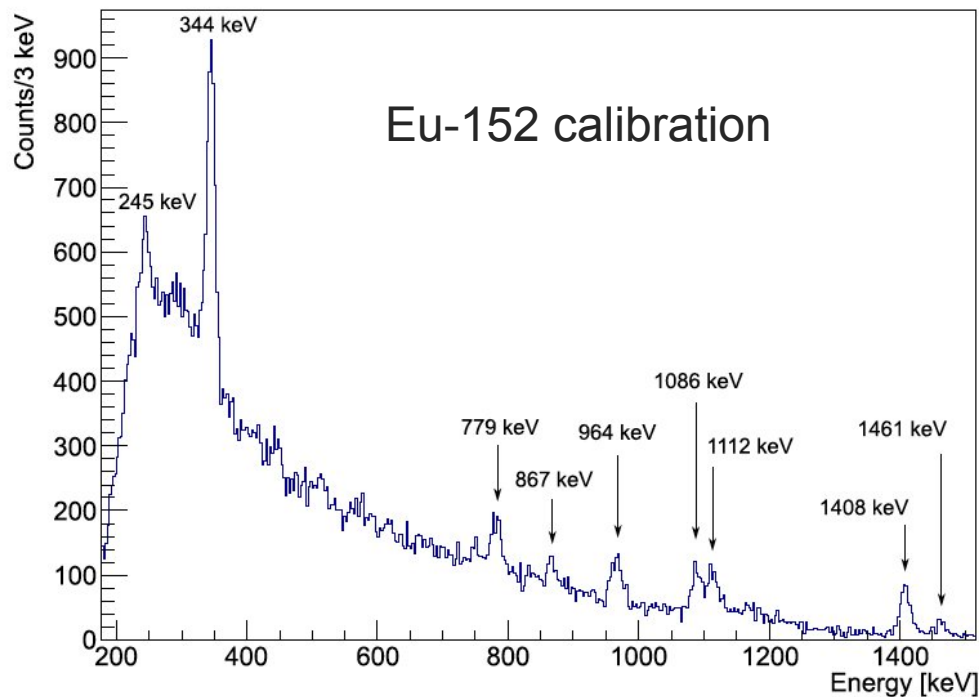
Zr-based cryogenic calorimeters

- ZrO_2 first test: $\sim 8\%$ doping
- Arc and skull melting crystal growth (Germany)
- Coupled to NTL light detector:
Particle discrimination confirmed
- Strong position dependence for the pulse-shape: spectroscopic capability is not satisfactory
- To test again with athermal phonon sensors



Zr-based cryogenic calorimeters

- **Crystal** : Cs_2ZrCl_6 (CZC, 20 g, 16% of natZr) crystal with heater + 2 NTDs (thermal phonon sensors) + NTL LD
- Foil with U source facing the crystal for particle ID
- Good performance: sensitivity 90 nV/keV, bsl resolution 6.2 keV sigma



¹ PREPARED FOR SUBMISSION TO JINST

² **Zr-containing low-temperature detector for neutrinoless double-beta decay search in the TINY experiment**

⁴ P. Carniti,^{a,b} D. Cintas,^c A. Giuliani,^d C. Gotti,^{a,b} S.S. Nagorny,^{e,f} V.V. Nahorna,^g
⁵ C. Nones,^c G. Pessina,^{a,b} D.V. Poda,^d H. Khalife,^d B. Schmidt,^c D. Trotta,^{a,b} S. Vesce,^c
⁶ P.L. Wang,^g A. Zolotarova^{e,1}

⁷ ^aUniversità di Milano-Bicocca, 20126 Milano, Italy

⁸ INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy

⁹ IRFU, CEA, Université Paris-Saclay, 91191 Saclay, France

¹⁰ Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

¹¹ Gran Sasso Science Institute, Viale F. Crispi 7, I-67100 L'Aquila (AQ), Italy

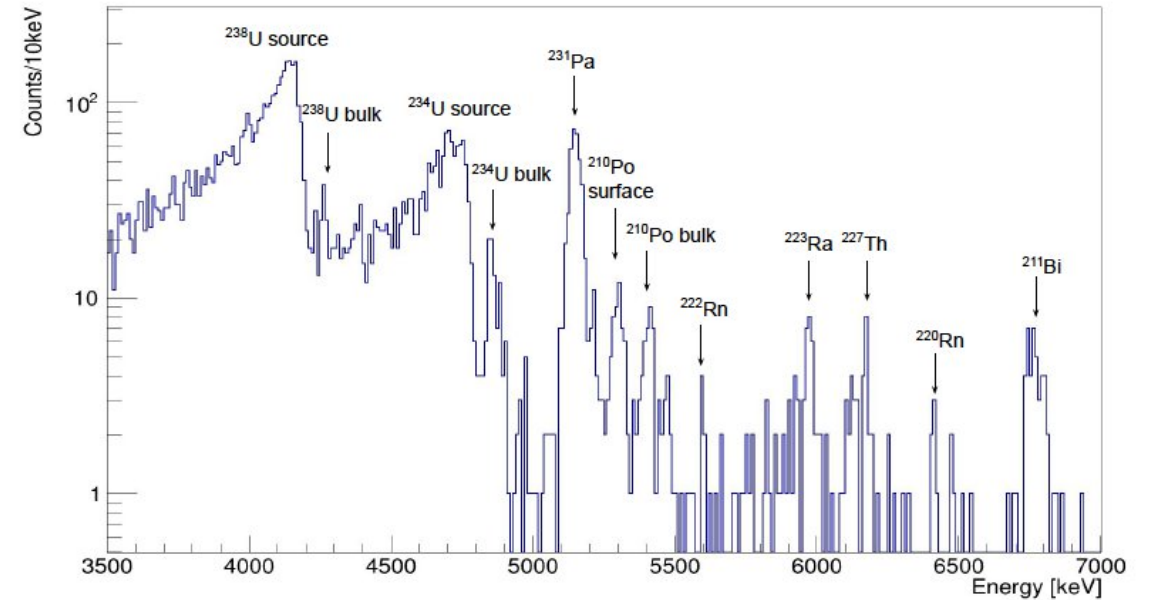
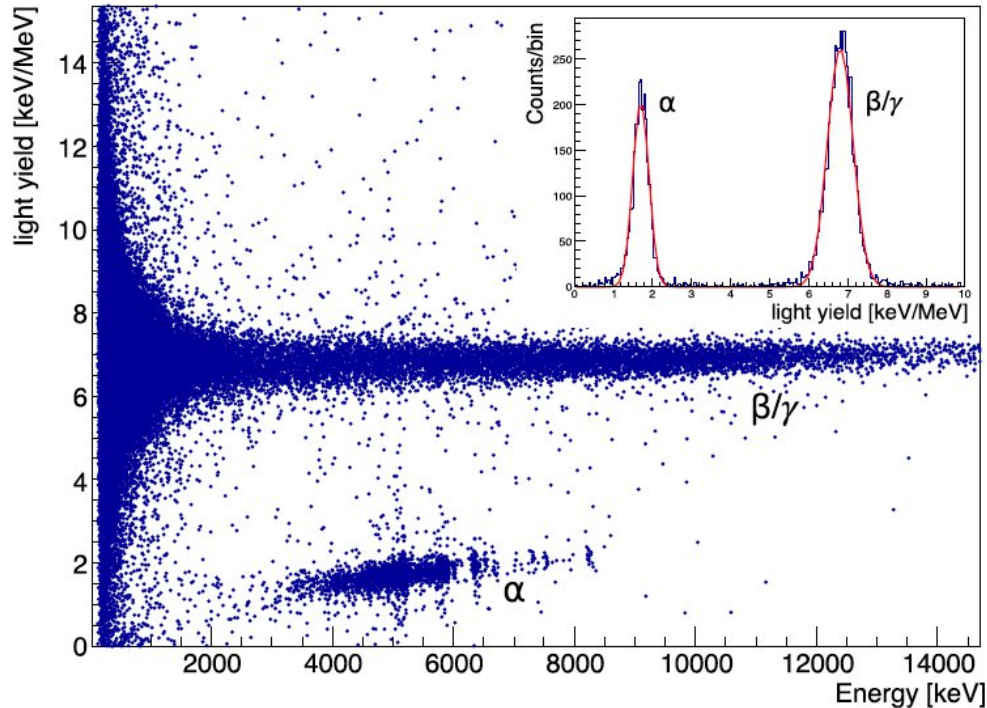
¹² INFN — Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, I-67100 Assergi (AQ), Italy

¹³ Department of Chemistry, Queen's University, Kingston, ON, K7L 3N6, Canada

¹⁴ E-mail: anastasiia.zolotarova@cea.fr

Zr-based cryogenic calorimeters

- Excellent scintillation : LY ~ 7 keV/MeV for β/γ , ~ 1.7 keV/MeV for α
- Excellent discrimination between α and β/γ , DP=13.4
- Alpha contamination evaluated
- Larger and higher purity crystals under production



1 PREPARED FOR SUBMISSION TO JINST

2 **Zr-containing low-temperature detector for neutrinoless**
3 **double-beta decay search in the TINY experiment**

4 P. Carniti,^{a,b} D. Cintas,^c A. Giuliani,^d C. Gotti,^{a,b} S.S. Nagorny,^{e,f} V.V. Nahorna,^g
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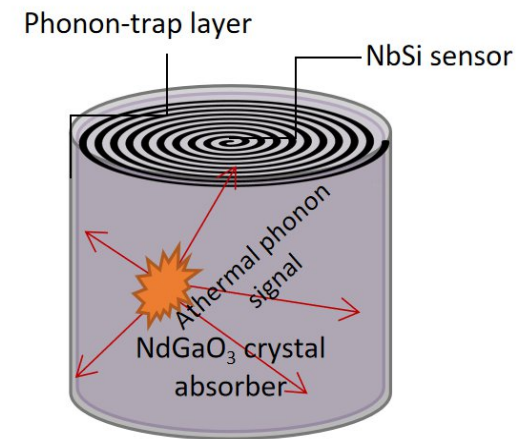
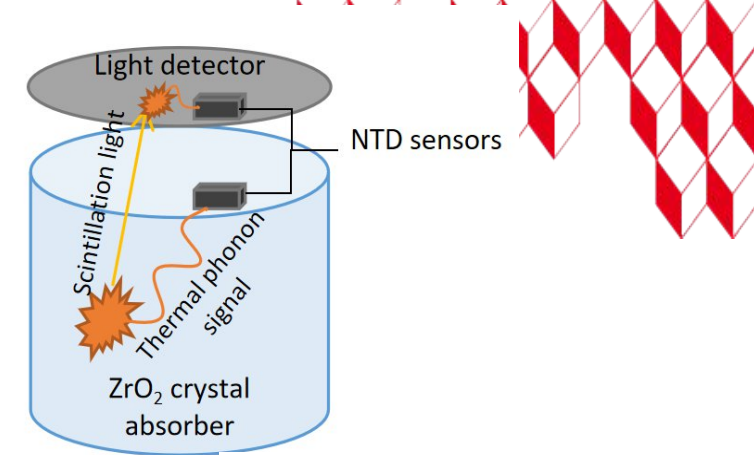
13 ^gDepartment of Chemistry, Queen's University, Kingston, ON, K7L 3N6, Canada

14 E-mail: anastasiia.zolotarova@cea.fr

TINY final demonstrator: projection

Baseline configuration: array of 10 crystals

- 5×400 g **enriched** Zr-based double read-out scintillating bolometers
- 5×400 g natural NdGaO_3 single read-out magnetic bolometers
- Precision measurement of $2\nu 2\beta$ spectra
- New limits in 1 year of measurements and background 10^{-3} cts/keV/kg/yr for both



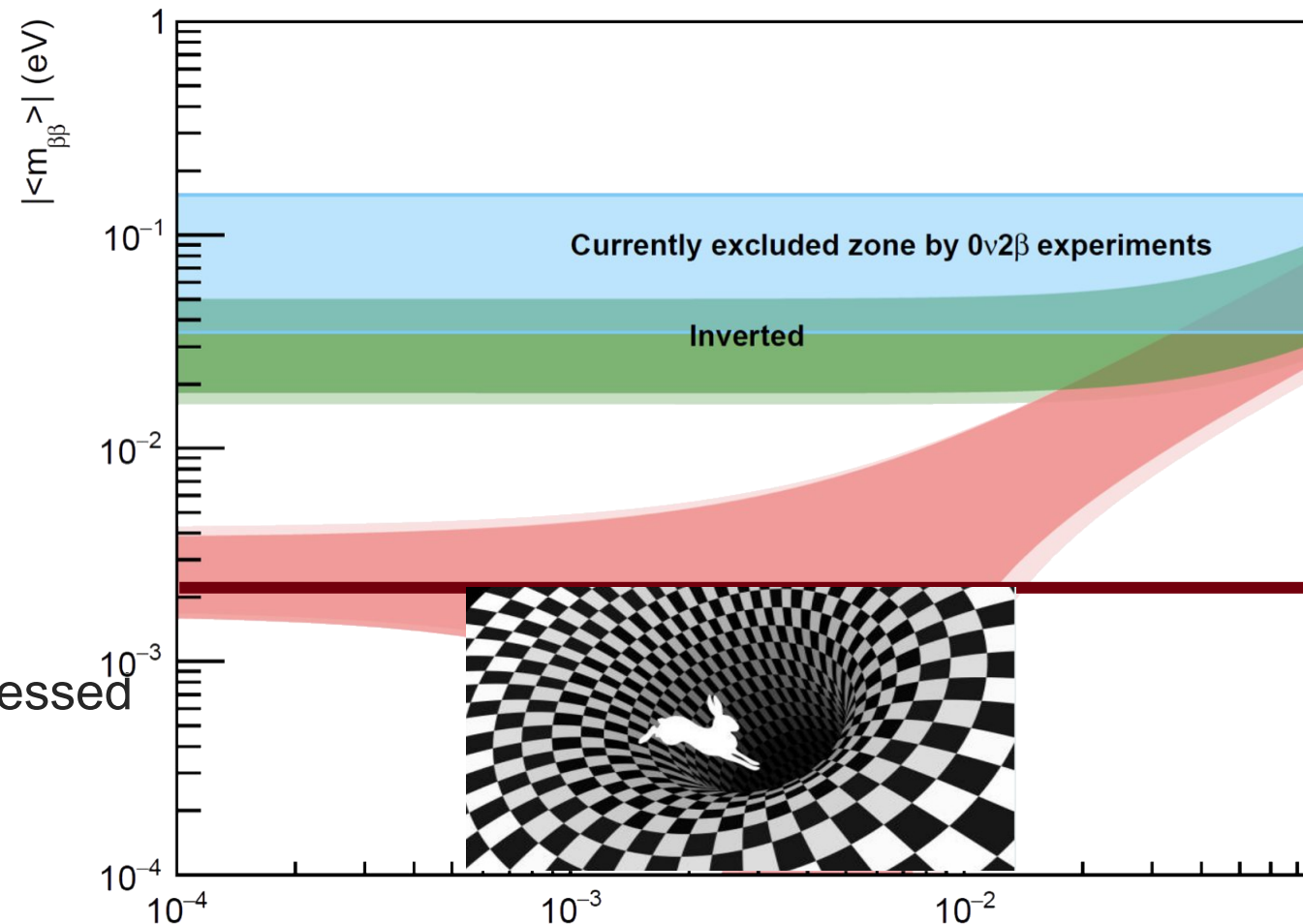
Isotope	NEMO-3		TINY	
	Exposure, kg×yr	Present limits, yr	Exposure, kg×yr	Present limits, yr
^{96}Zr	0.031	9.2×10^{21}	0.042	6×10^{22}
^{150}Nd	0.191	2×10^{22}	0.062	5.7×10^{22}

*J. Argyriades et. al., Measurement of the two neutrino double beta decay half-life of Zr-96 with the NEMO-3 detector, Nucl.Phys.A847:168-179 (2010)

J. Argyriades et al., Measurement of the double- β decay half-life of ^{150}Nd and search for neutrinoless decay modes with the NEMO-3 detector, Phys. Rev. C 80, 032501 (2009)

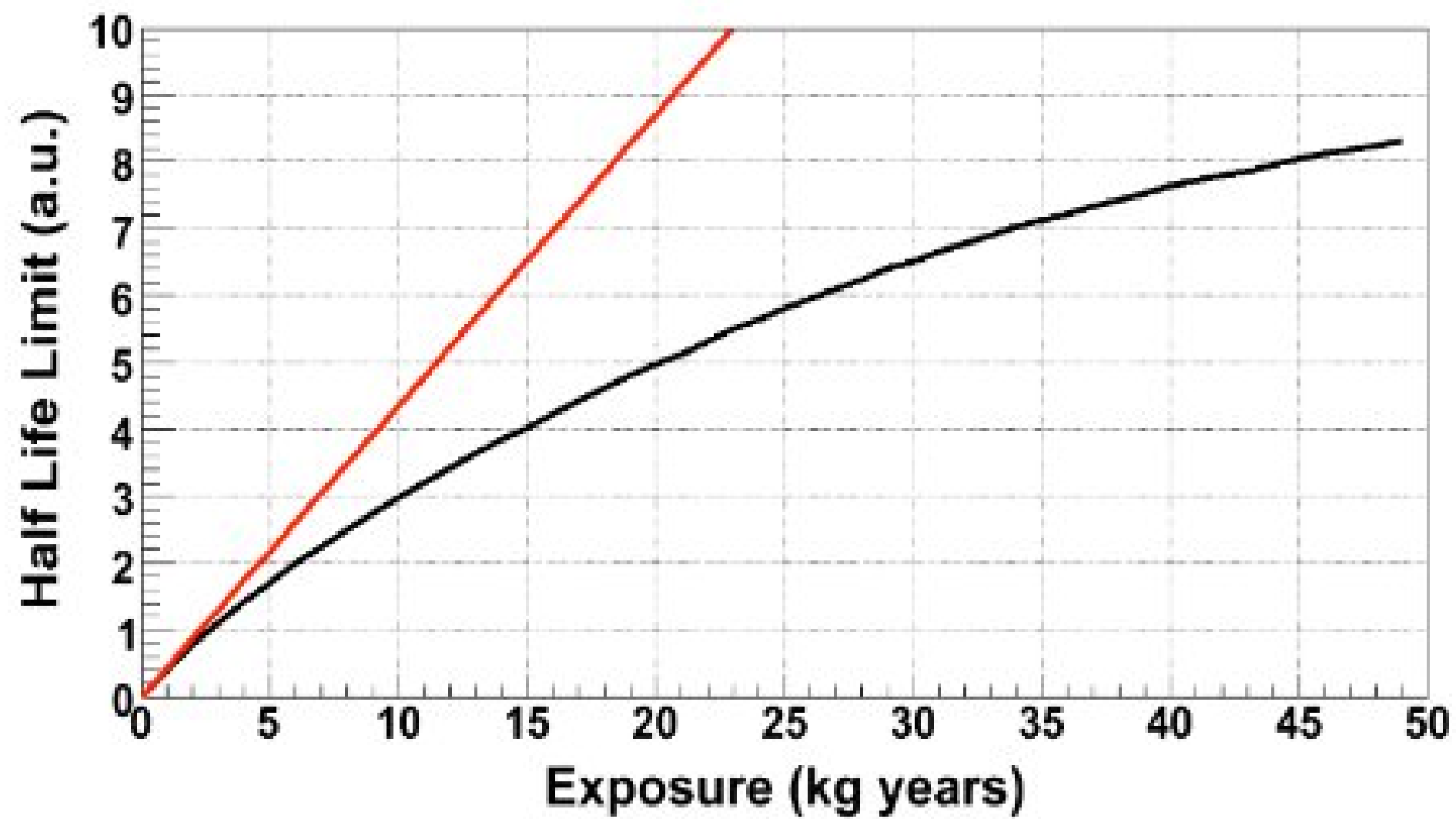
Conclusions

- We have to be ready to dive deep into normal hierarchy region of neutrino masses
- **BINGO** and **TINY** demonstrators aim to provide viable technology for higher sensitivities for next-next generation experiments
- **BINGO** :
 - **MINI-BINGO** demonstrator will be operational this autumn
 - Background index achievable:
 $b \sim 10^{-4}$ c/kg in 1 year of lifetime
- **TINY** :
 - Viable option with Zr-based crystal assessed
 - To confirm large crystals performance
 - Nd-based detectors : NbSi sensors to be validated



Backups

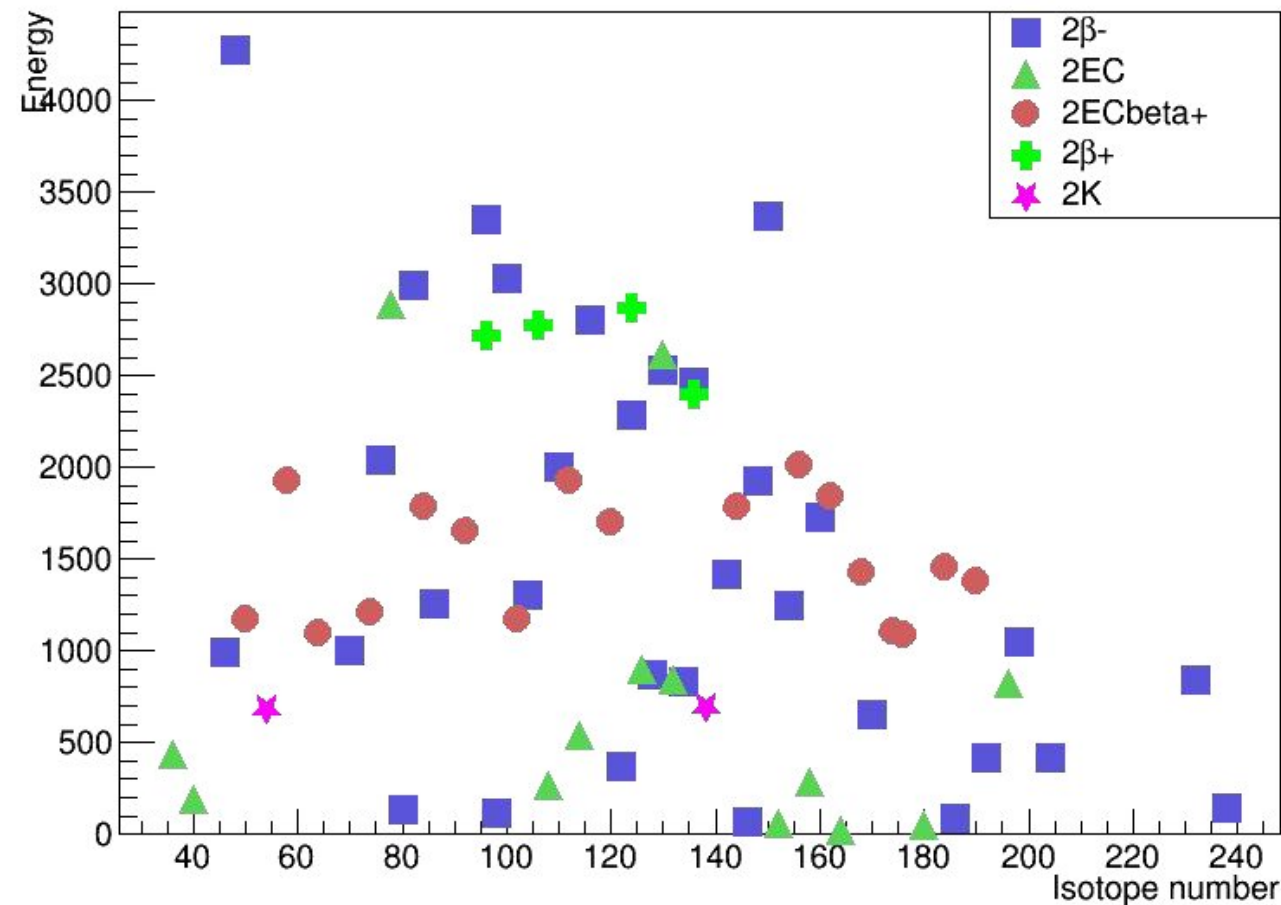




Double beta decay landscape

More than 70 isotopes can undergo certain mode of 2b decay

DBD isotopes



Simulations for BINGO

With a view to the mini-BINGO demonstrator, an intense background simulation work has started

Objectives:

- Calculate BI in the ROI considering known backgrounds
- Assess the experiment's sensitivity
- Reduce background by applying event selections across different detectors

Input of the simulation:

- Energy deposited in each detector within a time window
- Δt between energy deposits
- Multiplicity among detectors

Example of simulation: $1e9$ decays of K40
homogeneously distributed in BGOs

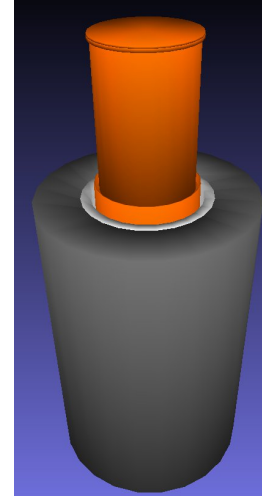
- Energy spectrum built for LMO and TeO2 crystals
- In **coincidence** and in **anticoincidence** with BGOs

90 % of simulations already done

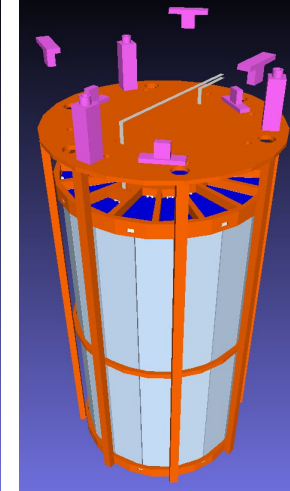
Next steps :

- Ragrupate bkg contributions originated in the same volume
- Build contribution spectra and assess BI

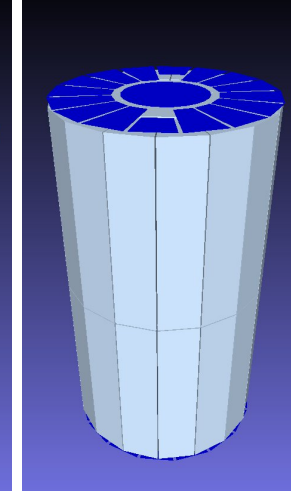
Cryostat+Shielding



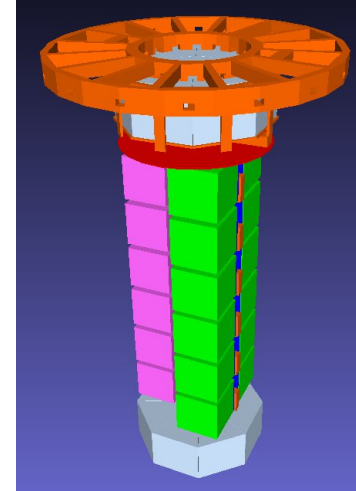
Housing



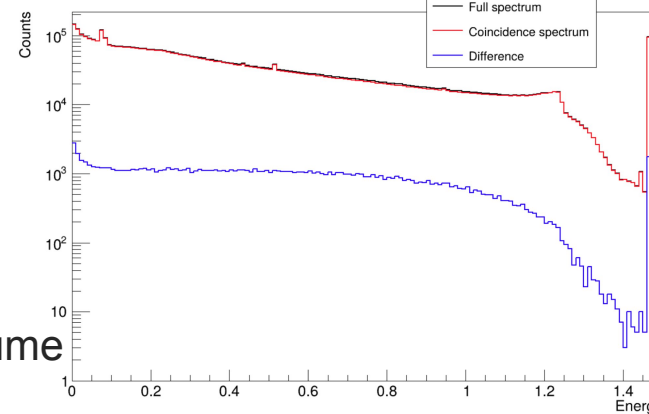
Veto



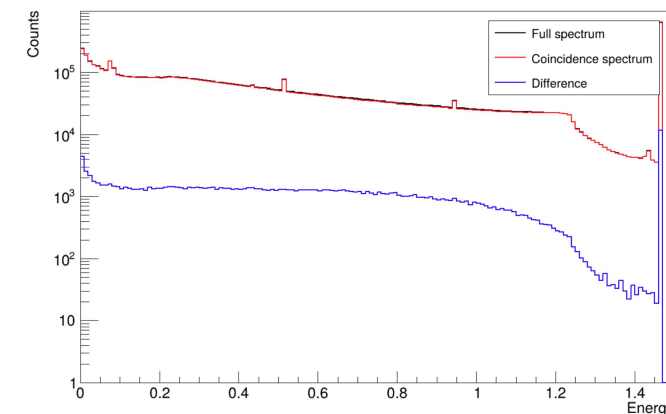
LMO/TO towers



Energy spectrum (LMOCrystal)



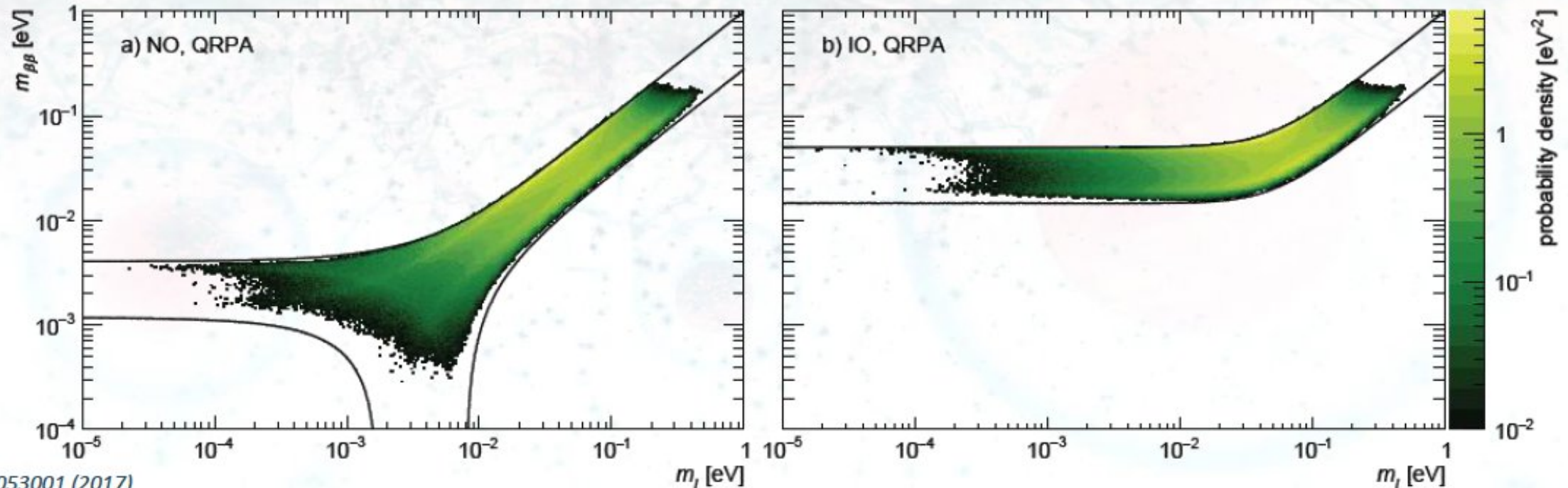
Energy spectrum (TeO2Crystal)



Probability of discovery: evaluation

- Global Bayesian analysis including neutrino oscillations, tritium, double beta decay, cosmology
- Ignorance of the scale of the parameters → Scale-invariant prior distributions
 - $\Sigma = m_1 + m_2 + m_3$, Δm_{ij}^2 : logarithmic
 - Angles and phases in PMNS matrix: flat

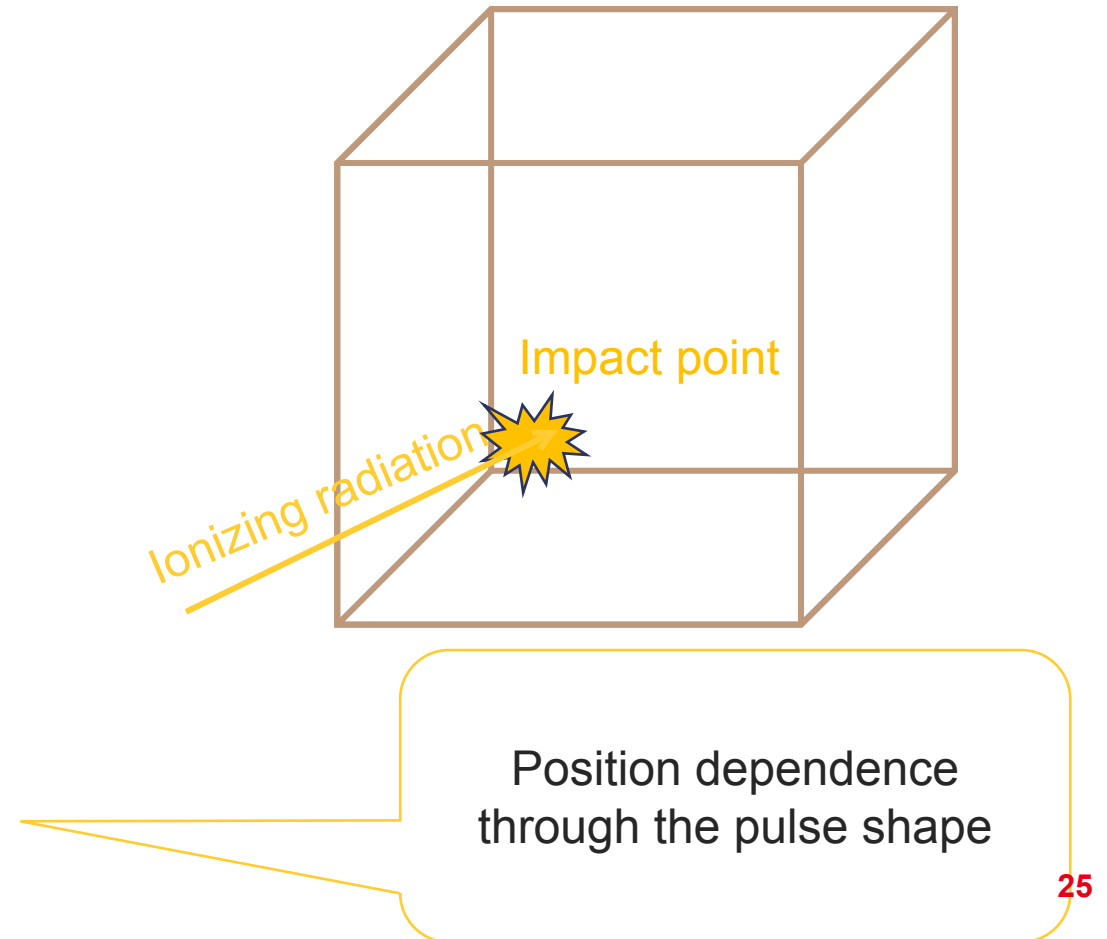
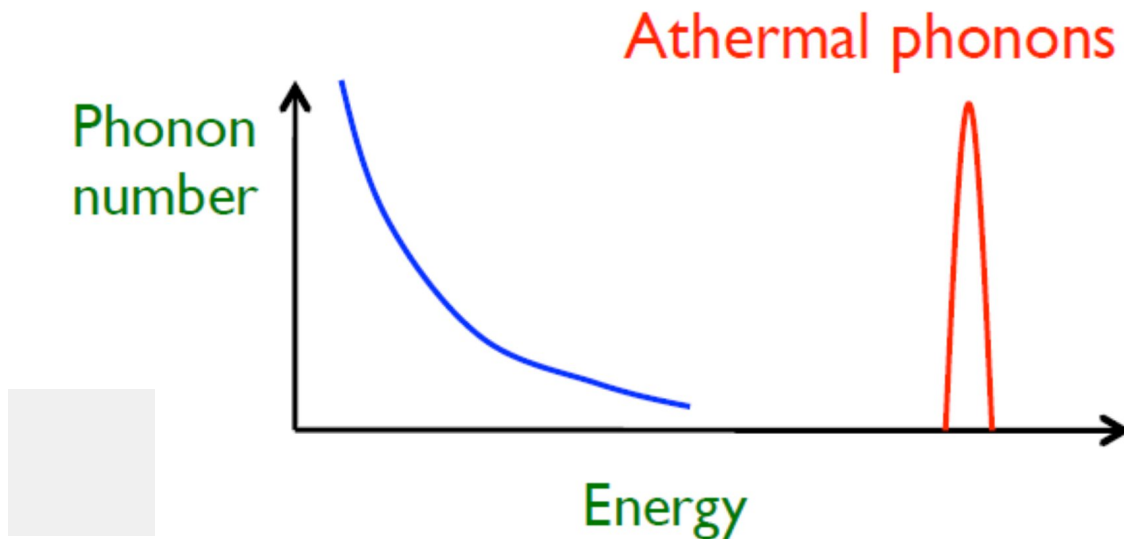
Marginalized posterior distributions of $m_{\beta\beta}$



Phonon propagation

Initial high-energy phonons:

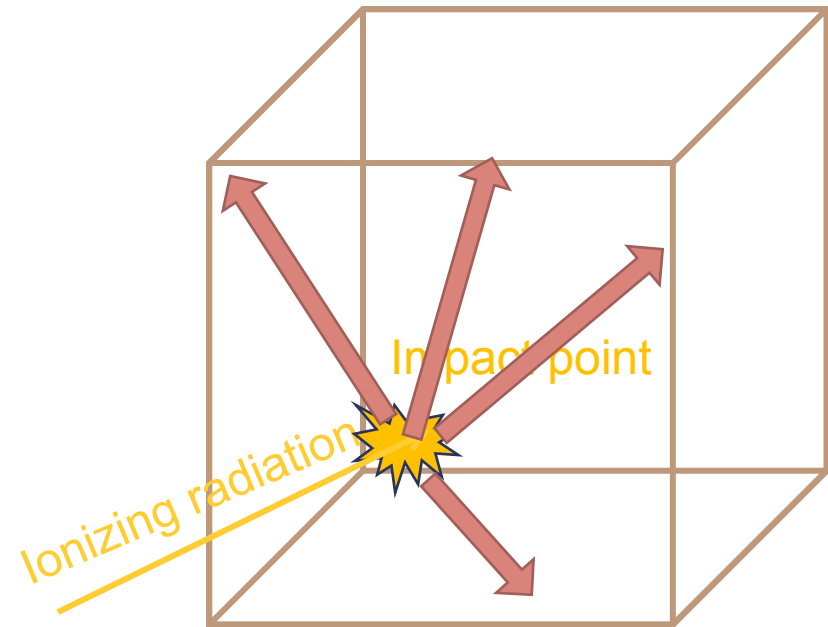
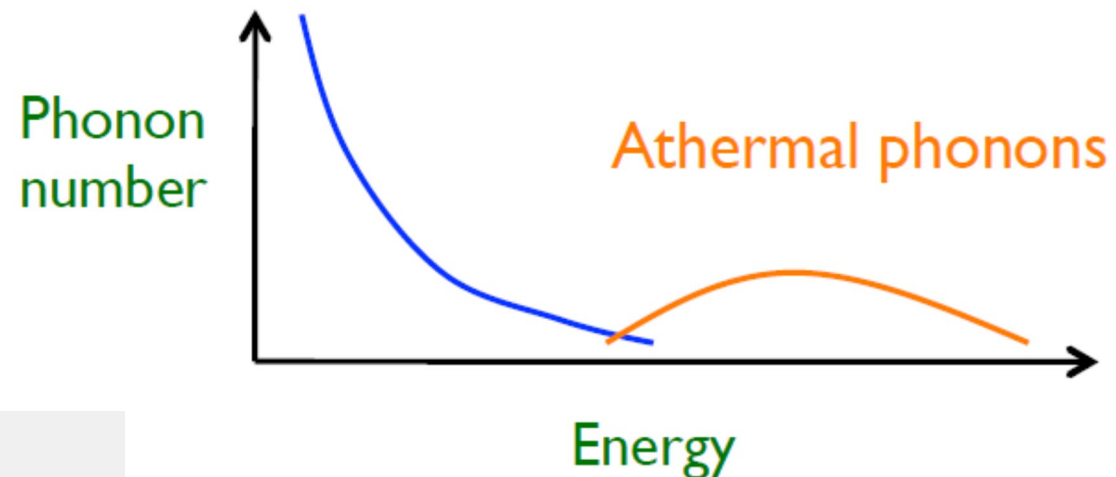
- Very short pathlength
- Degrade very quickly



Phonon propagation

Ballistic phonons

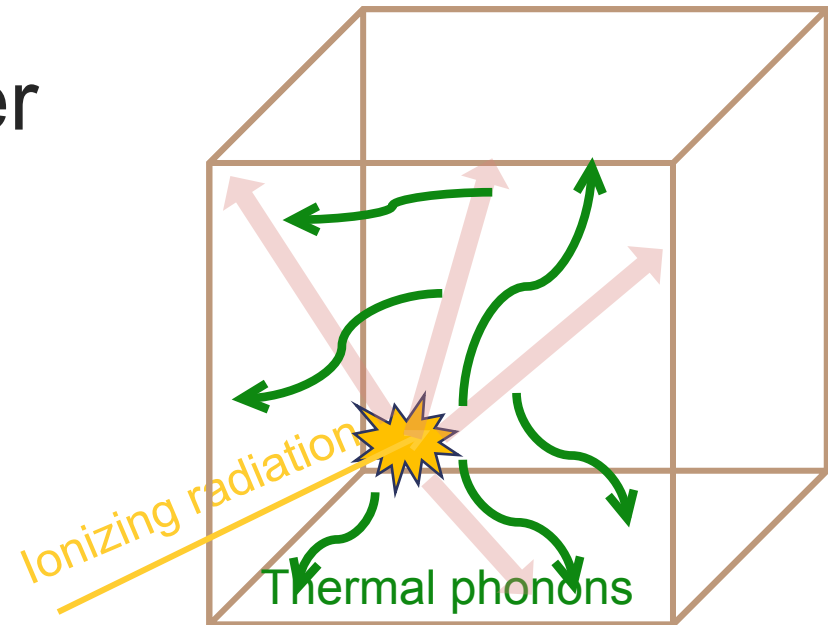
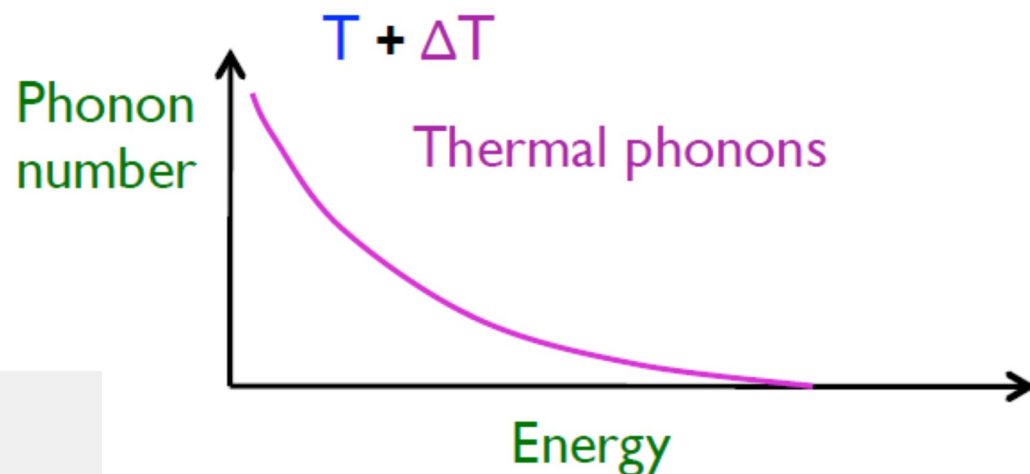
- Longer lifetime (ms)
- Path > detector size
- Degrade through scattering on surfaces (mostly)



Phonon propagation

Thermal phonons:

- Thermalization time = C/G
- Only energy is measured, all other features are washed out



Slow (~ms)
The most reliable energy
measurement

$0\nu2\beta$ decay rate

$$(T_{1/2}^{0\nu2\beta})^{-1} = G(Q,Z) g_A^4 |NME|^2 \langle m_{\beta\beta} \rangle^2$$

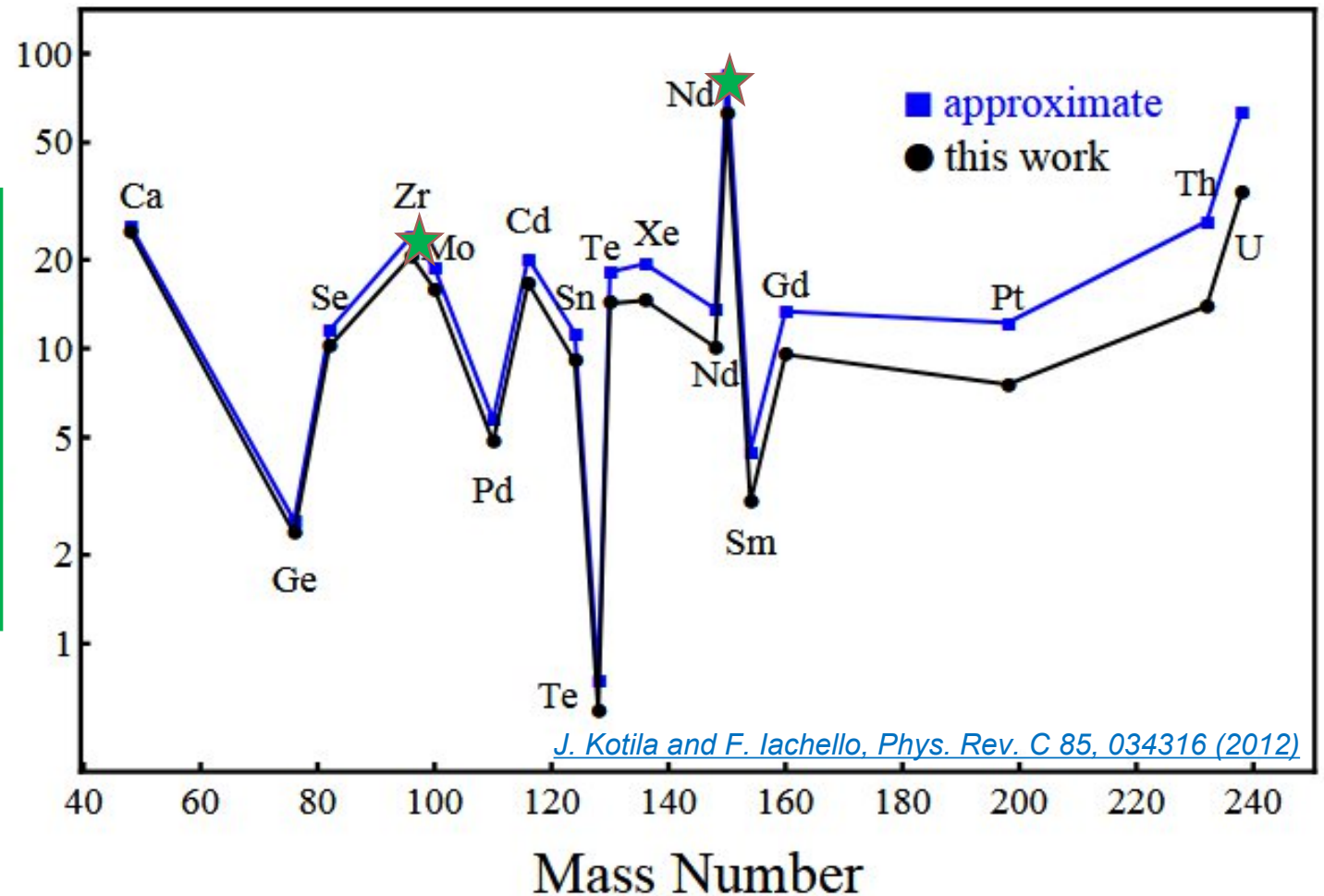
Observable

Phase space factor

Effective Majorana mass - the unknown

Process is allowed in 35 nuclei → **only few are interesting for experiments**

$G_{0\nu}^{(0)} (10^{-15} \text{ yr}^{-1})$



Enrichment of Zr-96

- Only russian company (ISOTOPE) so far provides the gas centrifugation enrichment: high yield, reasonable costs.
- Problematics: highly flammable gas, high cost of R&D to set up the production.
No other companies are interested in development of Zr enrichment without big investment and plans for large production so far.
- TINY demonstrator can confirm this need, in case of scaling of experiment to 100 kgs or more. But detector technology comes first in this case, to justify the investments.