Detecting the undetectable

Technologies and challenges in rare-event searches

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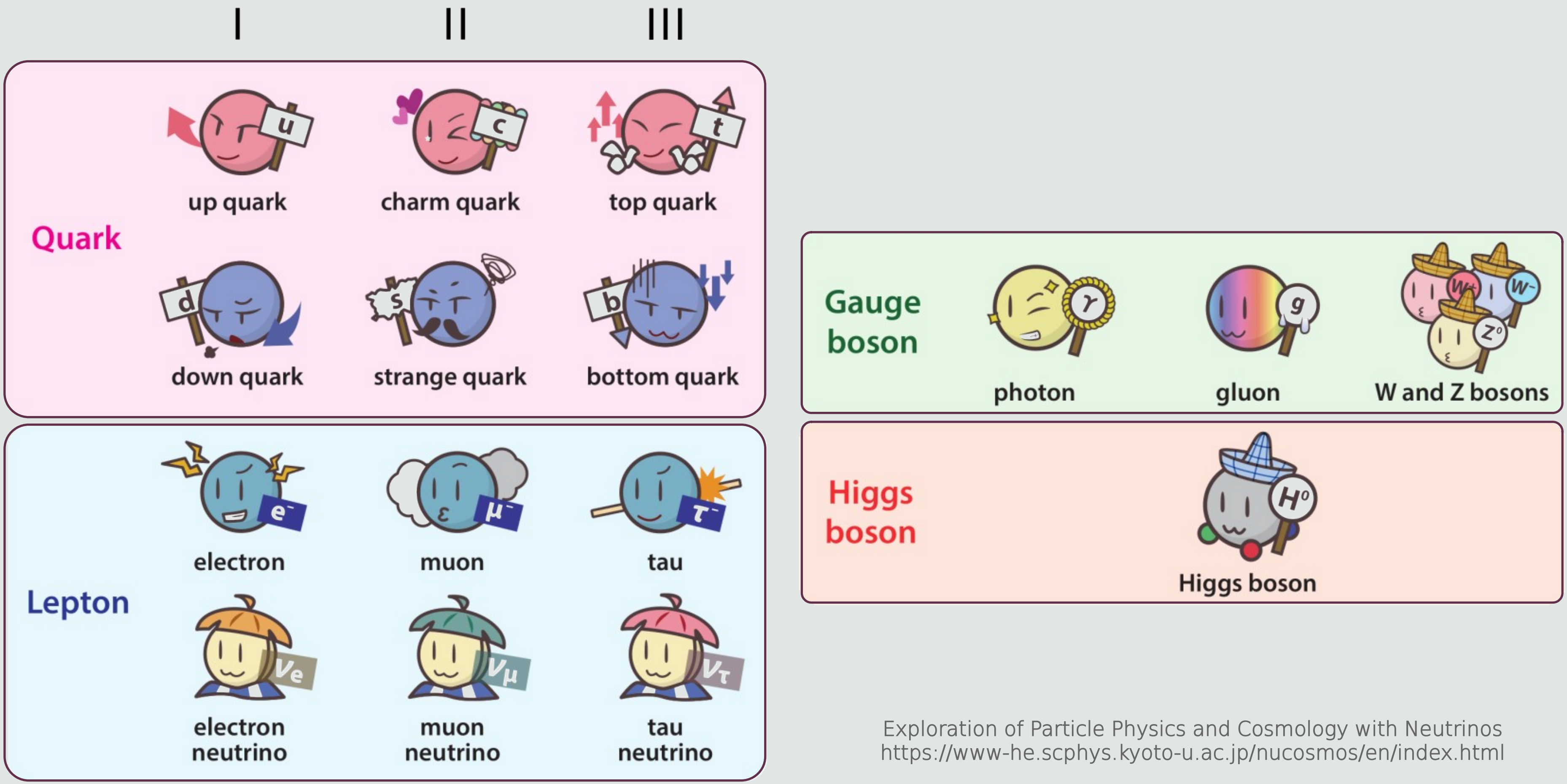
LPSC

LPSC GRENOBLE | MODANE

LAPP seminar 28/11/25

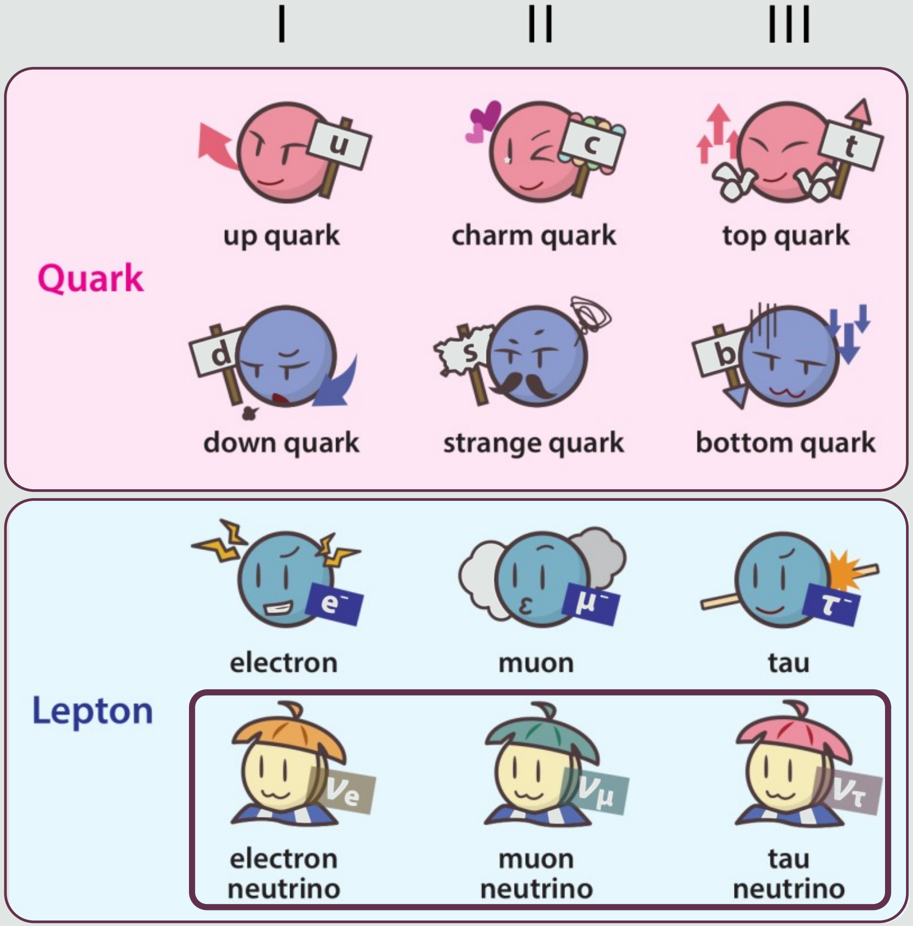
UGA Université Grenoble Alpes

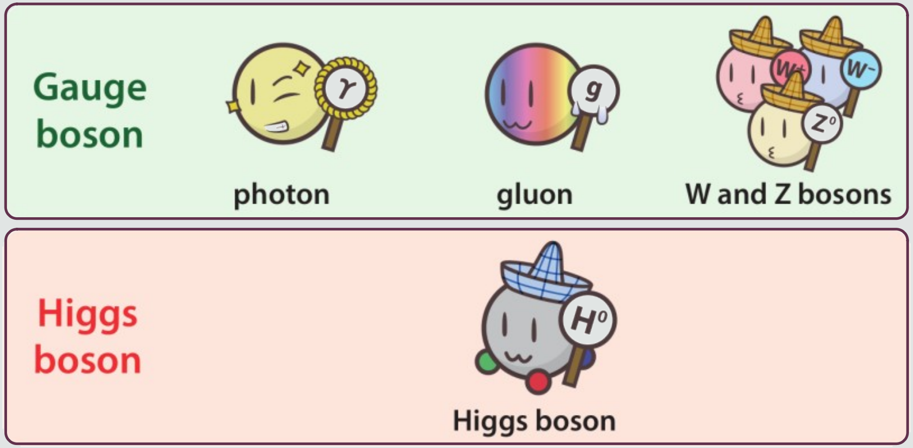
Let's start with some basics



Exploration of Particle Physics and Cosmology with Neutrinos
https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/index.html

Let’s start with some basics





Exploration of Particle Physics and Cosmology with Neutrinos
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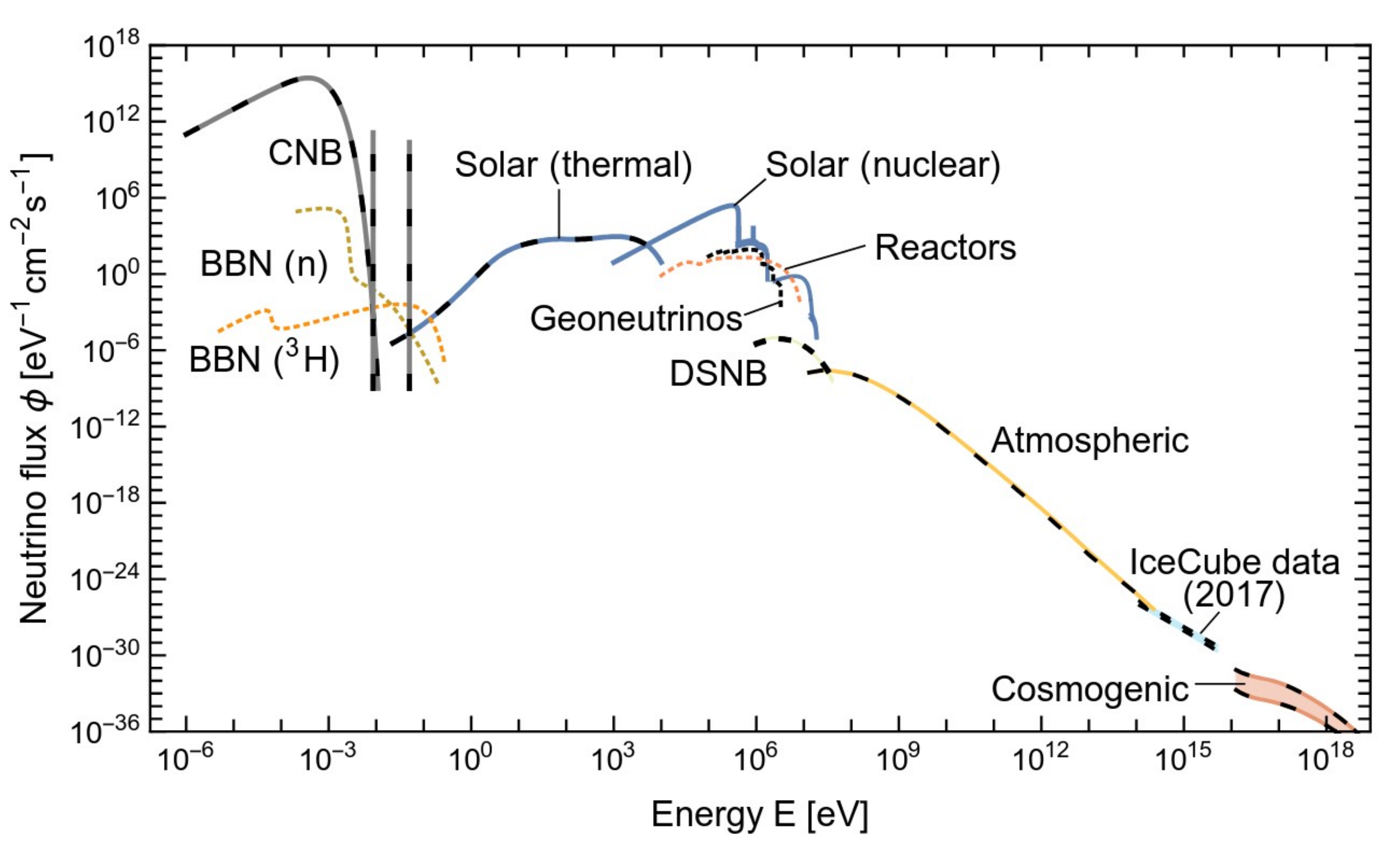
The neutrino physics field

Neutrino physics spans a vast energy range, from sub-MeV (for solar / geoneutrinos) up to multi-GeV or TeV (for atmospheric, astrophysical, accelerator neutrinos), depending on the source.

From doi.org/10.1103/RevModPhys.92.045006

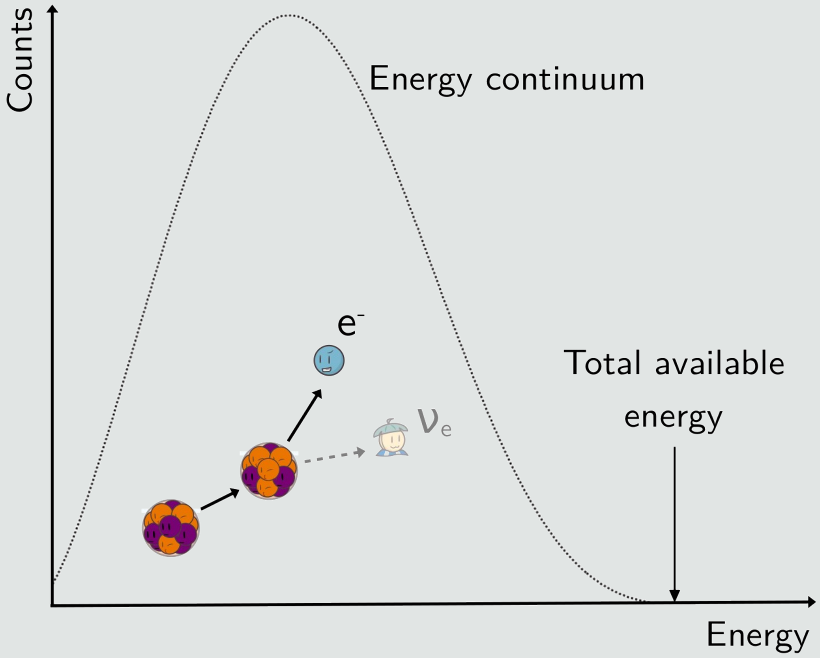


A bit of history

The discovery of neutrino

H.Becquerel (1896):
Discovery of radioactivity
1900: **β decay**

Lise Meitner (1911):
Beta energy spectrum
Only electron observed
Non conservation of total energy



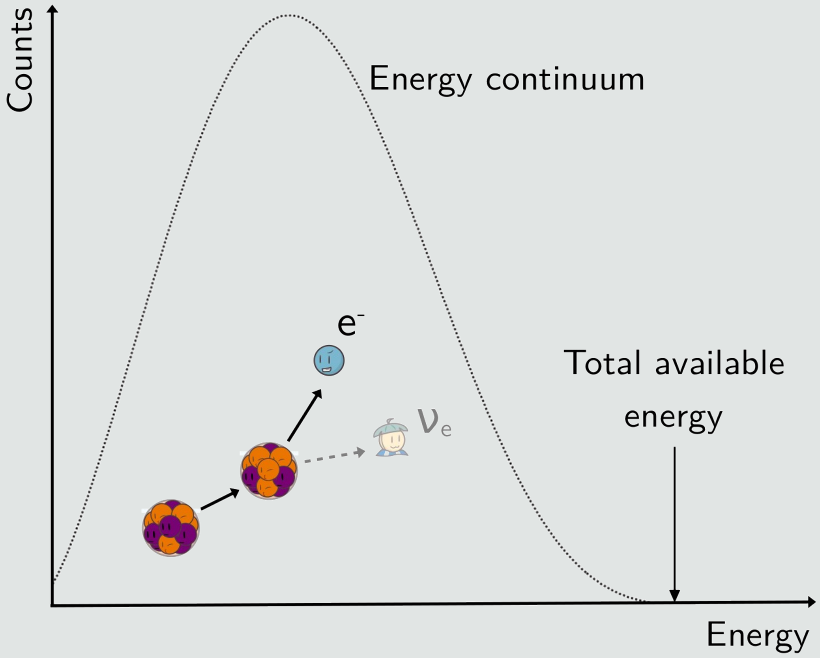
Drawings: courtesy of Cwiosna Roques

A bit of history

The discovery of neutrino

W.Pauli (1930):
Solution to conserve total energy
"**Neutrino**": small interaction probability, neutral, spin 1/2, small or null mass

E.Fermi (1934):
Effective theory
Foundation stone of weak interaction



Drawings: courtesy of Cwiosna Roques

Neutrinos are some special creatures...

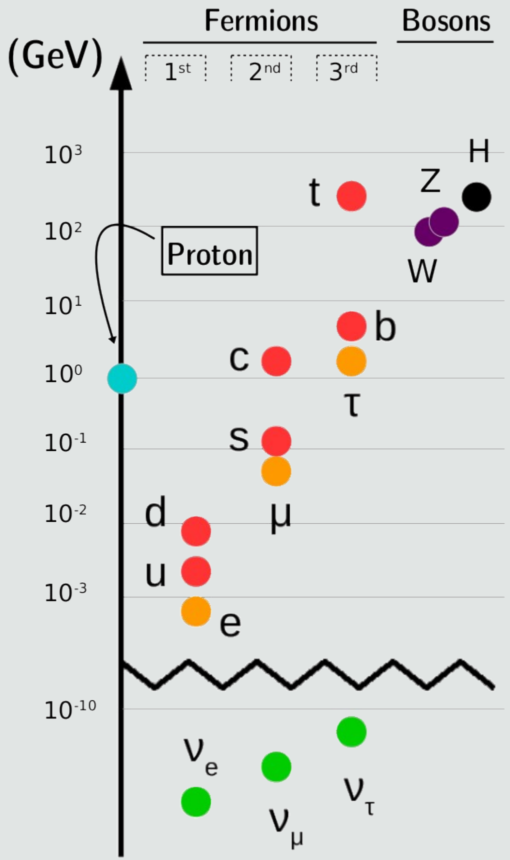
Flavor eigenstates ≠ mass eigenstates

Oscillation probability (2 flavors):

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

↳ $\neq 0$ → Non-zero neutrino masses and mixing

Solar neutrinos:
$\Delta m^2_{21} \approx 7.4 \times 10^{-5}\,\mathrm{eV}^2$
Atmospheric neutrinos:
$|\Delta m^2_{31}| \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$



The nature of neutrinos: Dirac or Majorana?

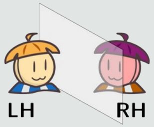
“Dirac” neutrinos

Neutrino & antineutrino **distinct particles**

As other fermions: mass → **Higgs** mechanism:

$$\mathcal{L}_{\nu}^{\mathrm{Dirac}} = -\frac{v}{\sqrt{2}}\overline{\nu}_L Y^{\nu} \nu_R + \mathrm{h.c.}$$

→ Need to **extend** the SM with ν_R



“Majorana” neutrinos

The neutrino is its **own antiparticle**

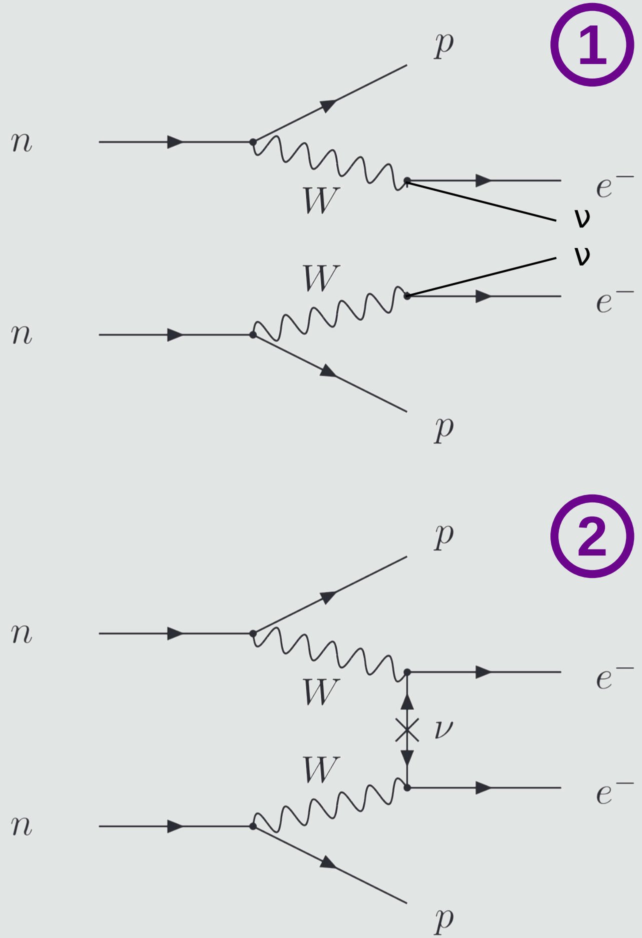
Majorana mass term in the Lagrangian

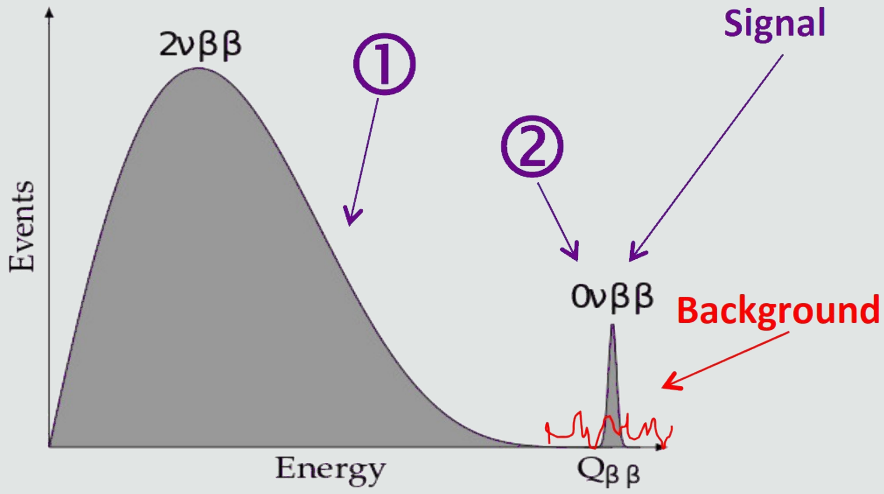
$$\mathcal{L}_{\nu}^{\mathrm{Majorana}} = \frac{1}{2} m_{\nu} \overline{\nu}_{\mathrm{L}}^{c} \nu_{\mathrm{L}} + \mathrm{h.c.}$$

- **Lepton Number Violation** (LNV) ΔL=2
- **Seesaw** mechanisms: smallness of neutrino masses

Probe: Neutrinoless double beta decay (0νββ)

Neutrinoless double beta decay (0νββ)





Best sensitivities on $T^{0\nu}_{1/2} > 10^{24\text{-}26}$ years

$T^{0v}_{1/2} > 10^{24}$ y ⟶ Hard

↓

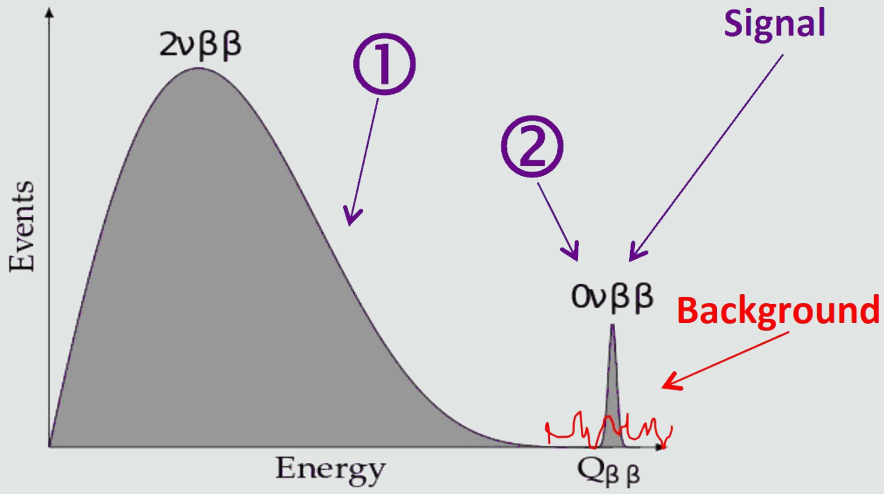
$T^{0v}_{1/2} > 10^{25}$ y ⟶ Harder

↓

$T^{0v}_{1/2} > 10^{26}$ y ⟶ Even harder

Neutrinoless double beta decay (0νββ)

Isotope	Q [keV]	nat. abund. [%]
^{48}Ca	4273.7	0.187
^{76}Ge	2039.1	7.8
^{82}Se	2995.5	9.2
^{96}Zr	3347.7	2.8
^{100}Mo	3035.0	9.6
^{110}Pd	2004.0	11.8
^{116}Cd	2809.1	7.6
^{124}Sn	2287.7	5.6
^{130}Te	2530.3	34.5
^{136}Xe	2461.9	8.9
^{150}Nd	3367.3	5.6



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↓

$T^{0\nu}_{1/2} > 10^{26}$ y → Even harder

The sensitivity of an experiment to 0νββ decay

Sensitivity in exclusion to **half-life**

Signal detection efficiency

ββ isotope mass

Acquisition time

$$T_{1/2}^{0\nu\beta\beta} > \frac{\ln 2 \times N_a \times a}{W} \times \frac{\varepsilon_{0\nu} \times M \times t}{N_{excl}}$$

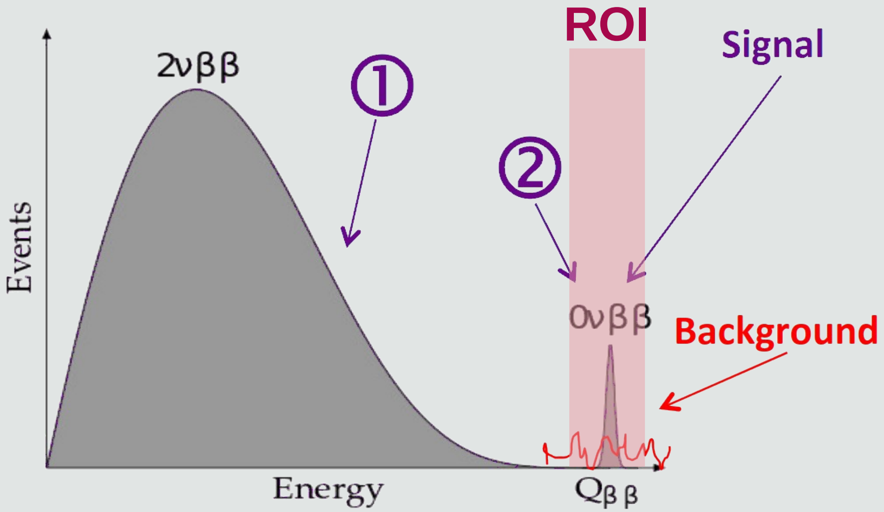
Upper limit on signal count
Number of **excluded** signal events
→ **Depends on number of background events**

Background-free → $T_{1/2} \propto \sqrt{M \times t}$

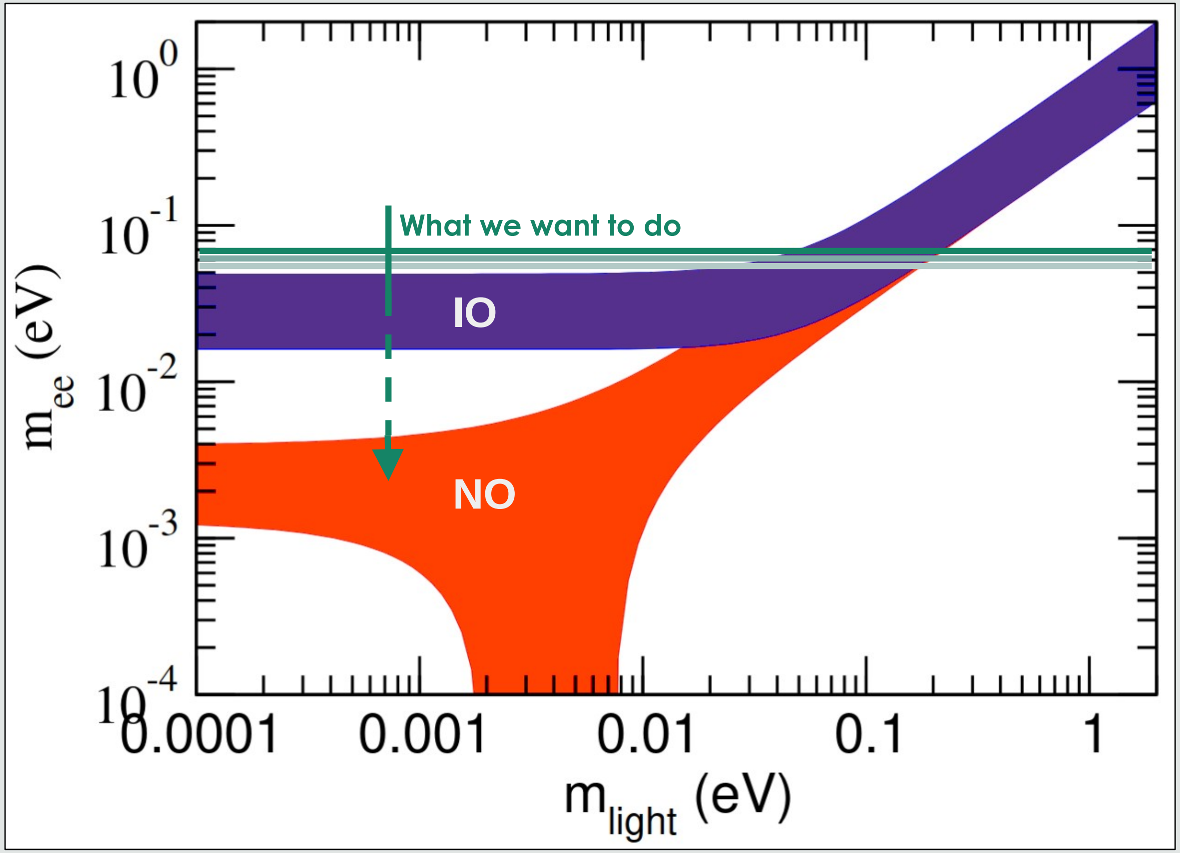
Background-limited → $T_{1/2} \propto M \times t$

Improve sensitivity by

- increasing exposure
- improving efficiency
- increasing isotopic abundance
- **reducing background index in ROI**
- narrowing ROI ΔE



The sensitivity of an experiment to 0vββ decay



DOI: 10.1103/PhysRevD.110.030001

Effective Majorana **mass**:

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

Mixing matrix elements

Neutrino masses

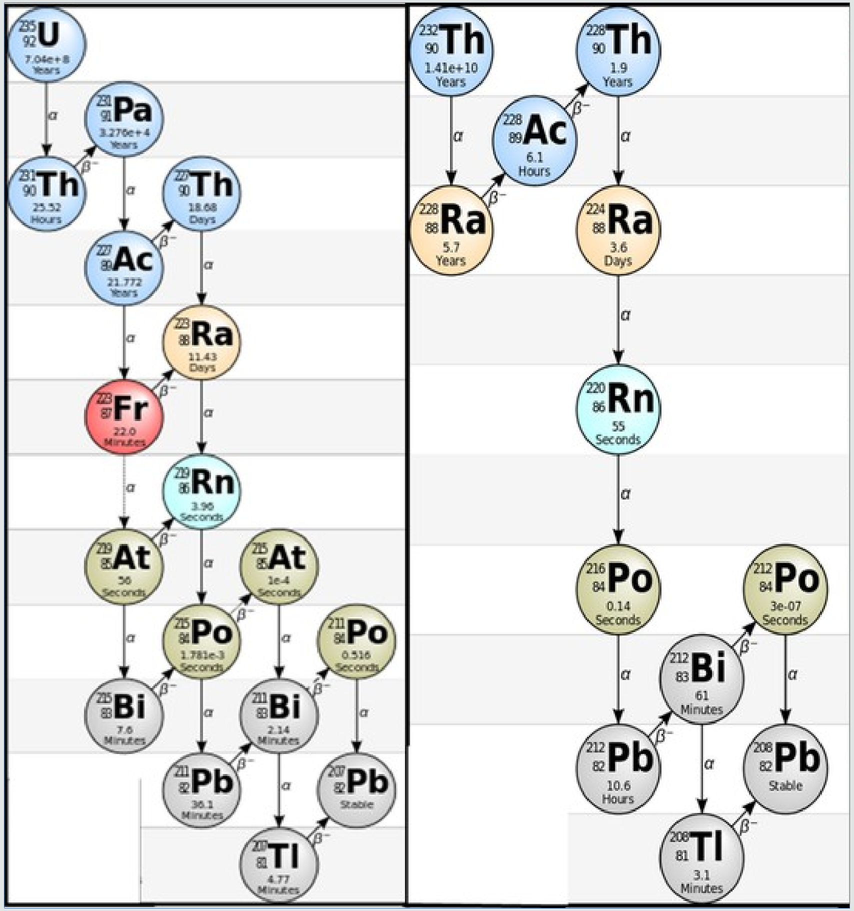
0vββ decay **half-life**:

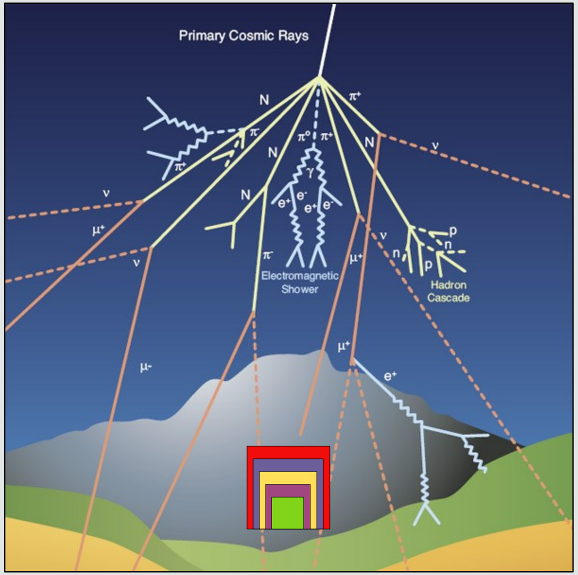
$$T_{1/2}^{0\nu} = \frac{m_e^2}{G^{0\nu}\,|M^{0\nu}|^2\, m_{\beta\beta}^2}$$

Phase space factor

Nuclear matrix elements

Many sources of background





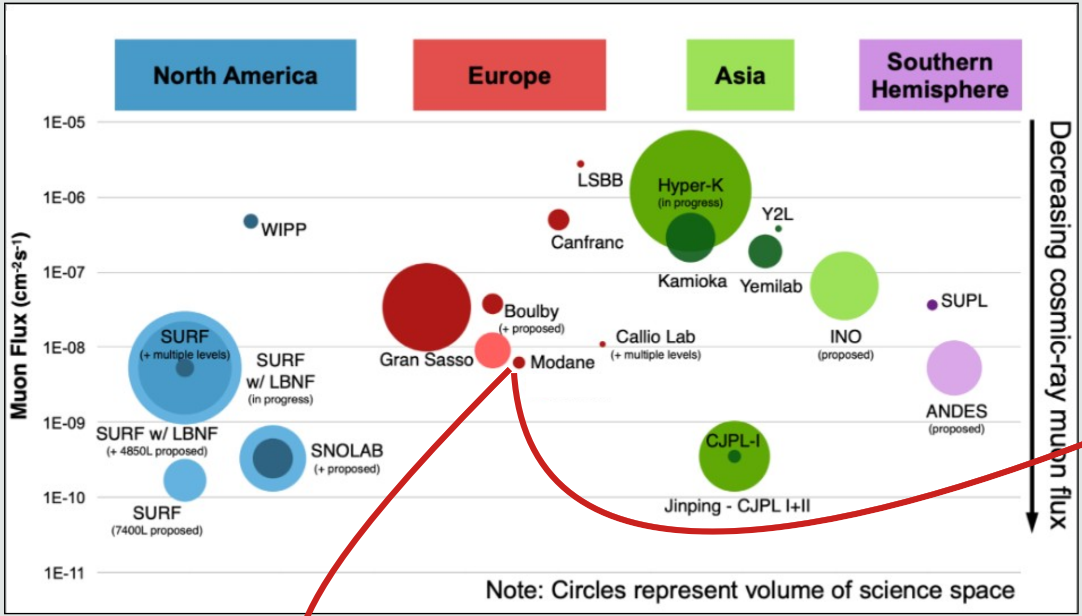
- Deep **underground** → shield from cosmic rays
- Active and passive **shieldings**
- **Anti-radon** techniques
- **Radiopure** materials

} **Natural radioactivity** (^{238}U, ^{232}Th, ^{40}K)

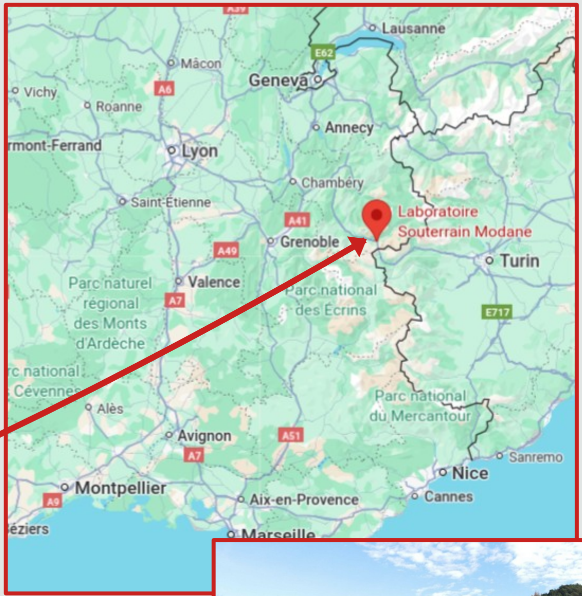
- Track past material exposure to cosmic rays
- Many other things **depending on technology**

Going underground to lower cosmic ray flux

Underground facilities provide unique environments for particle/astroparticle & multidisciplinary research with main feature being the **overburden protection from cosmic-ray muons**

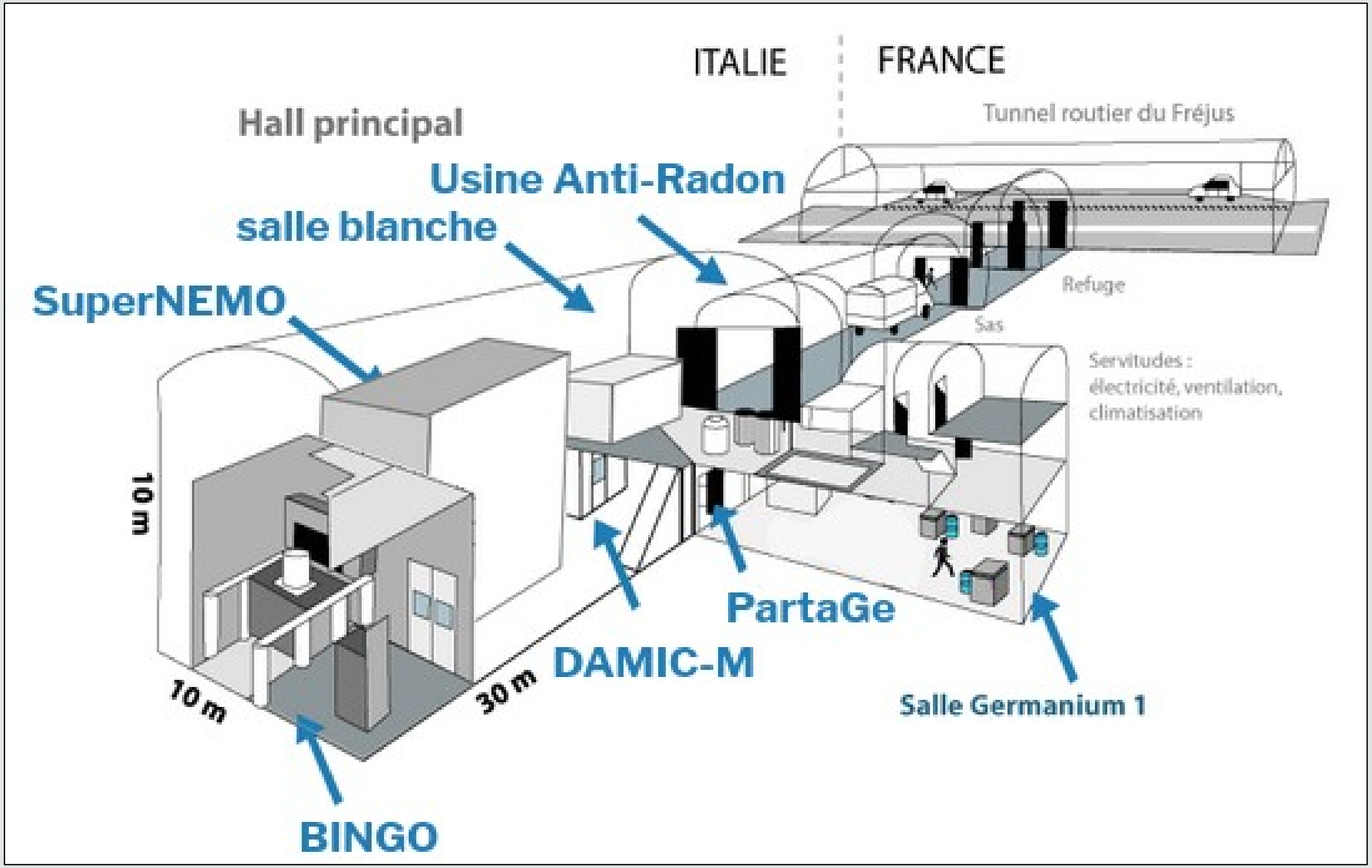


LSM underground lab



- **Deepest site in Europe** dedicated to astroparticle, nuclear & particle physics
- **4800 meter water equivalent (m.w.e)**: muon flux reduced by >10^6 relative to surface
- Flexible access (hall accessible to trucks up to 9m);
- Natural radioactivity due to radon of about 10-15 Bq/m^3

Laboratoire Souterrain de Modane



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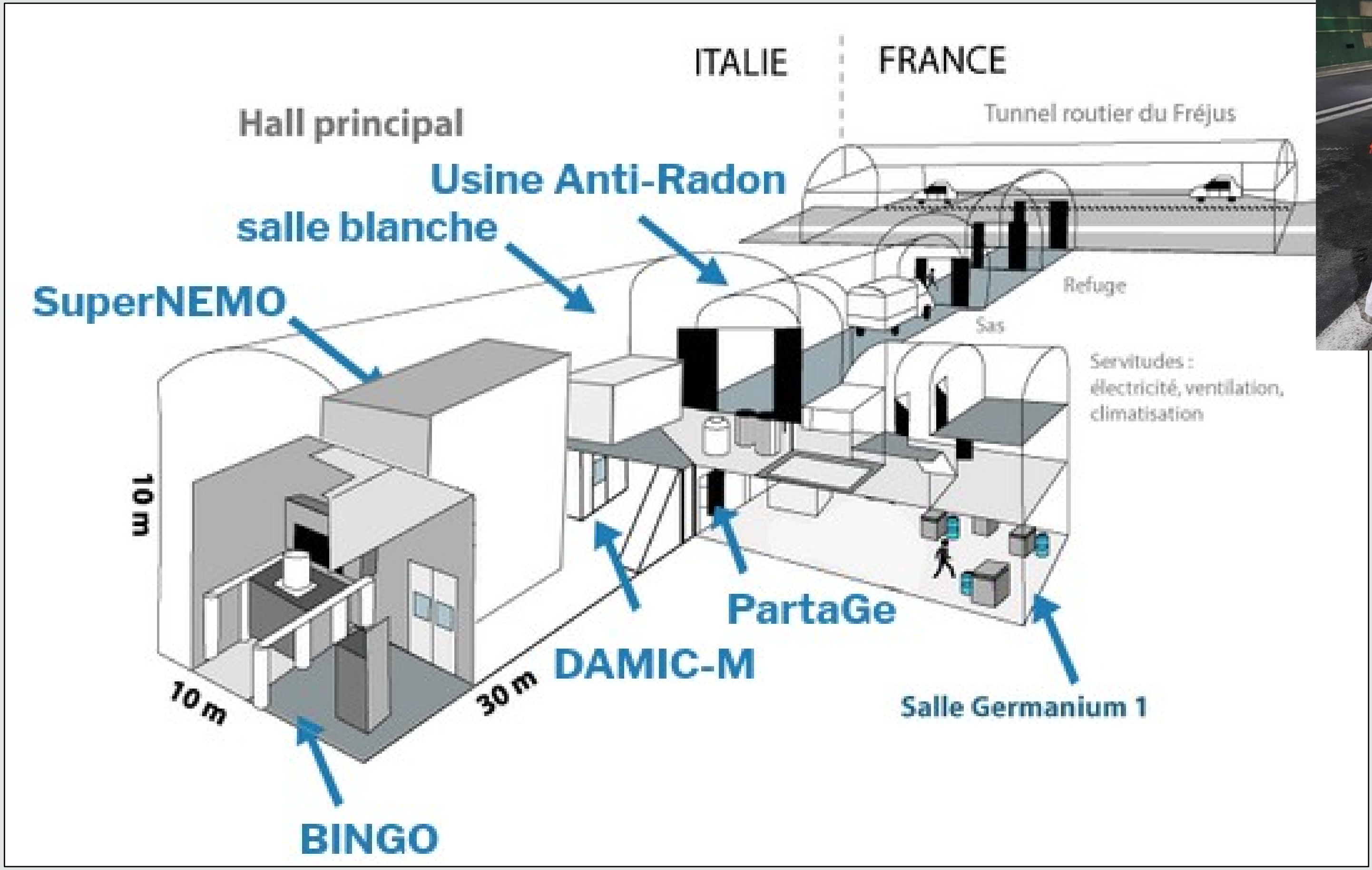
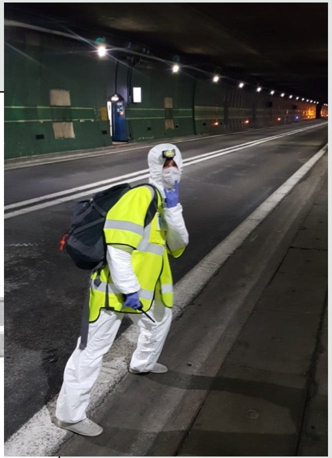
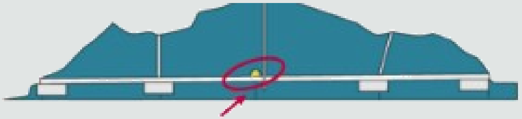




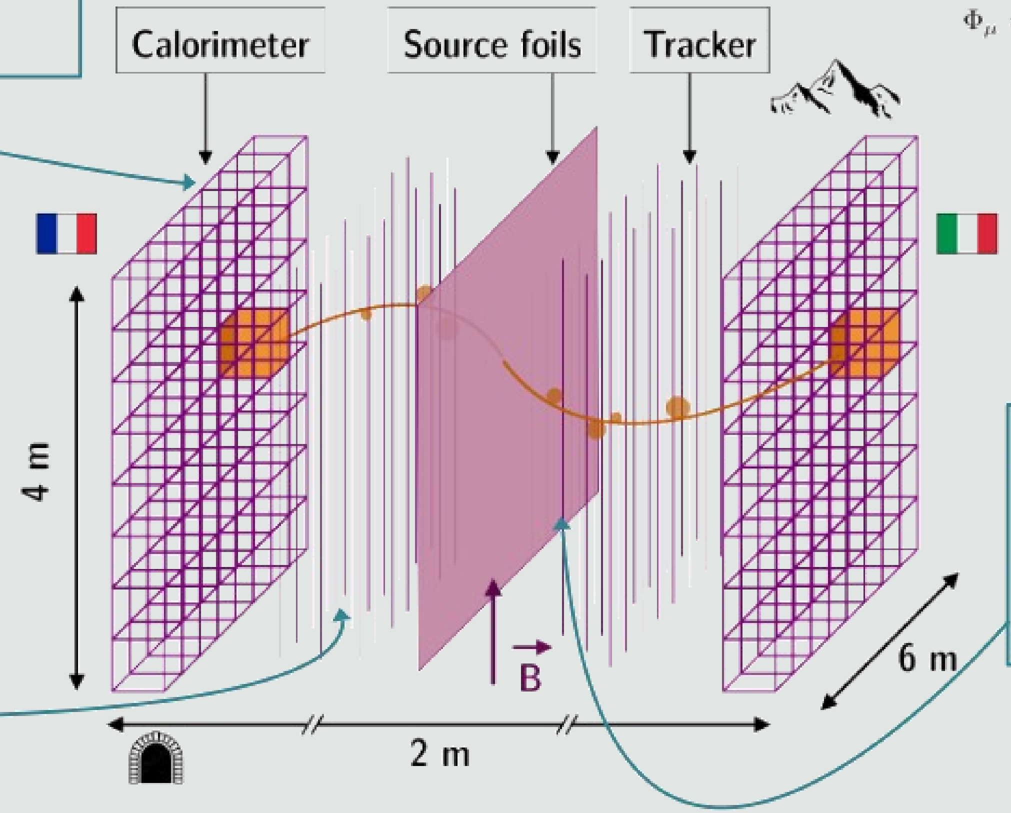
Tracker-calorimeter technology

The SuperNEMO demonstrator

The SuperNEMO demonstrator



Segmented in optical modules
Measure individual particles' energies and times of flight

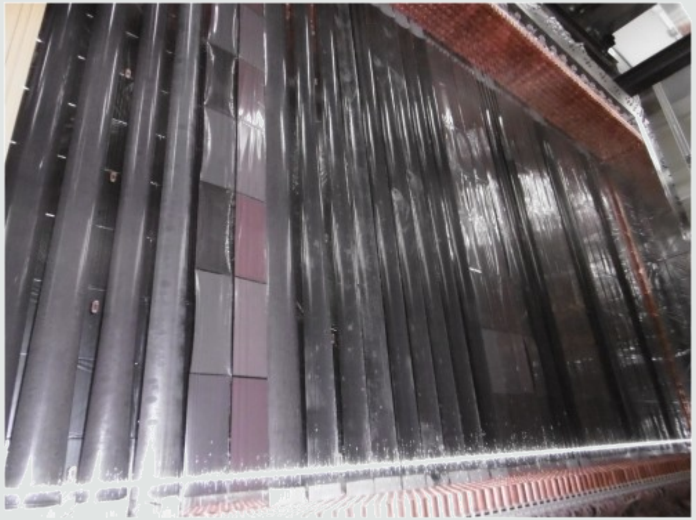


25 G from copper coil
Bend charged particles trajectories

Wire chamber
Particles' track reconstruction and identification

ββ isotope
~100 μm thickness for the electrons to escape from it

The SuperNEMO demonstrator



Source

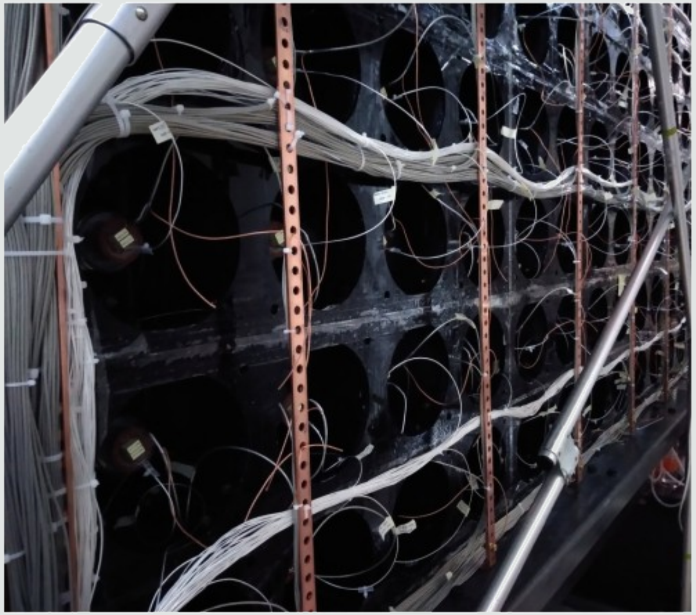
^{82}Se isotope: 6.11 kg

Transition energy $Q_{\beta\beta}$ = 2.99 MeV

Tracker

4 sections

2034 cells



Calorimeter

712 optical modules (OMs)

Closing of the detector : November 2018

The SuperNEMO demonstrator @LSM

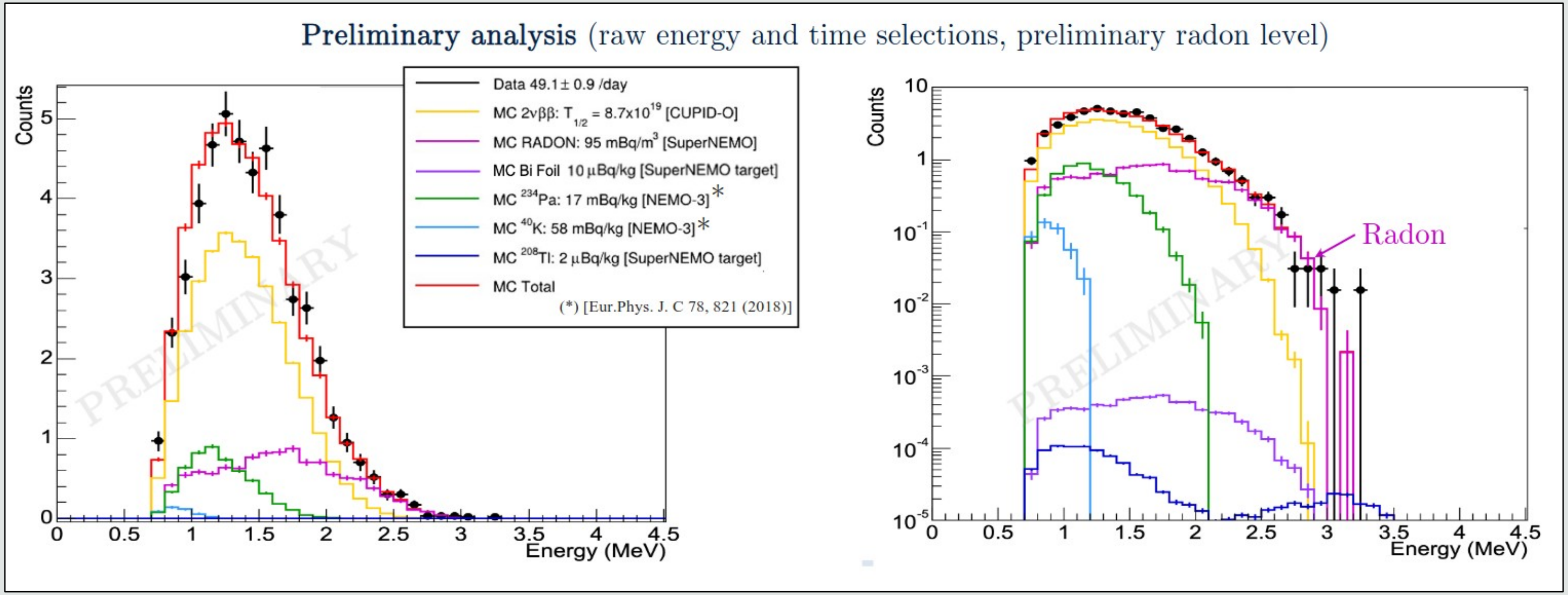
During my PhD (~2019)

+ de-radonized air from LSM beginning of october

Now

The SuperNEMO demonstrator @LSM

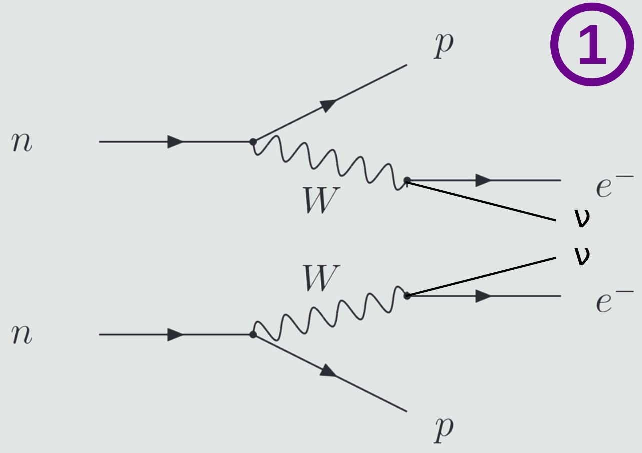
Start of data acquisition with the complete detector on April 10, 2025
2.37 kg.y exposure (radon-limited phase)

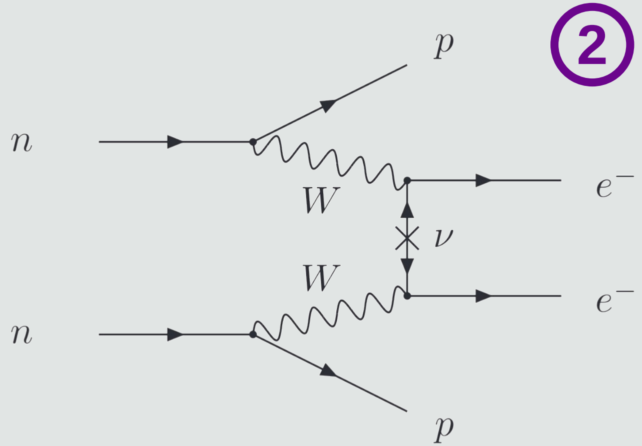


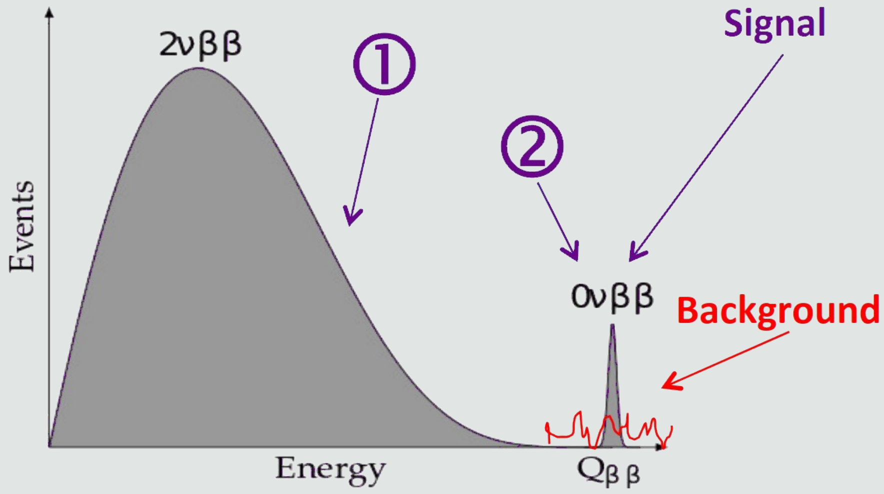
Slides presented at IN2P3 CS oct. 2025 by Christine Marquet

- Whole energy distribution dominated by the expected 2νββ decay shape with no events above 3.4 MeV
- Above 2 MeV: Radon dominates (expected without LSM radon-free air facility)

Neutrinoless double beta decay (0νββ)

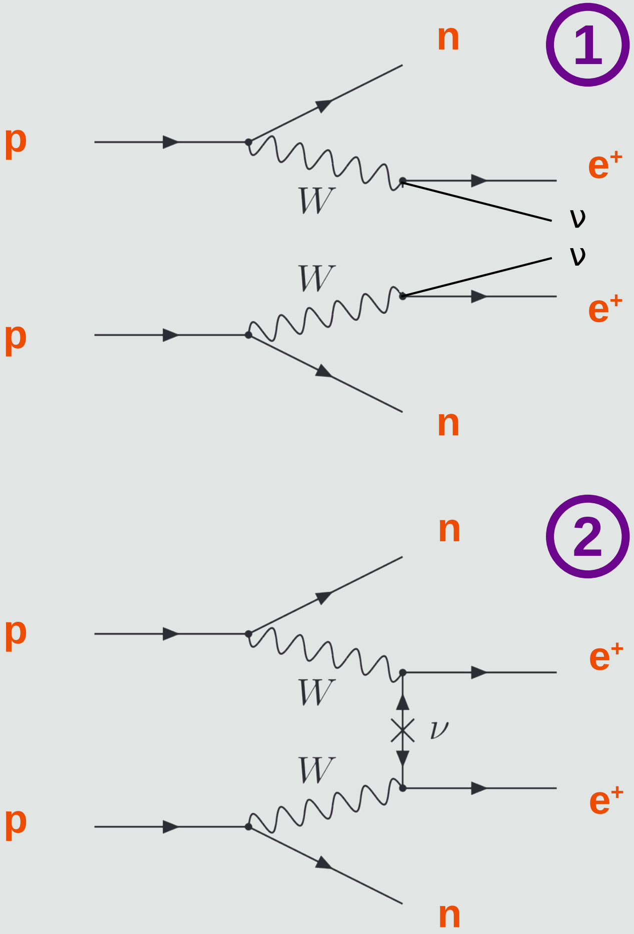


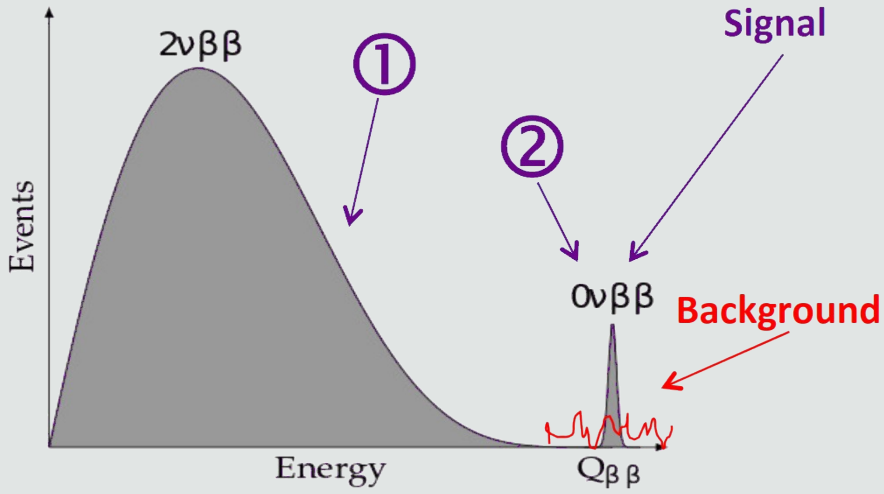




Best sensitivities on $T^{0\nu}_{1/2} > 10^{24\text{-}26}$ years

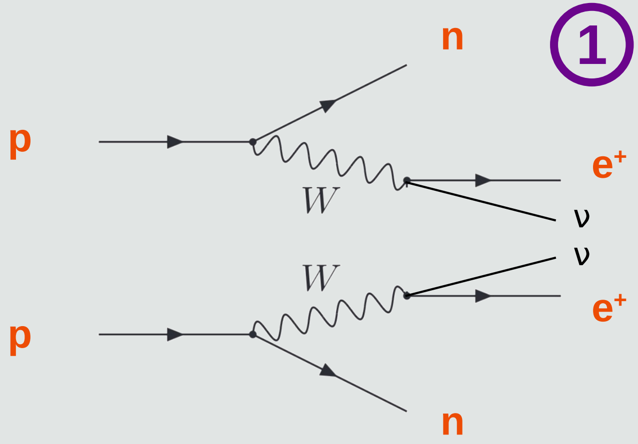
Neutrinoless double beta **plus** decay (0νββ⁺⁺)

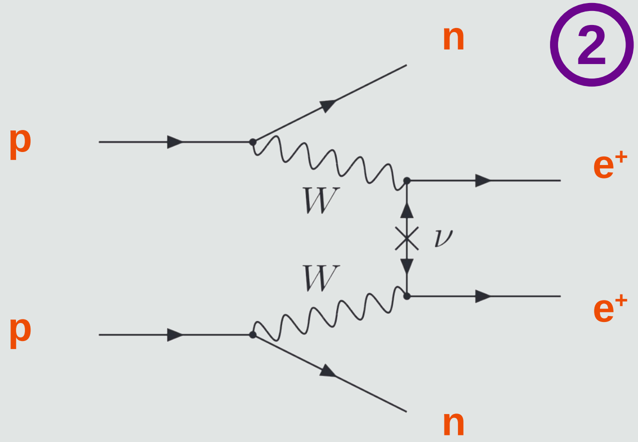


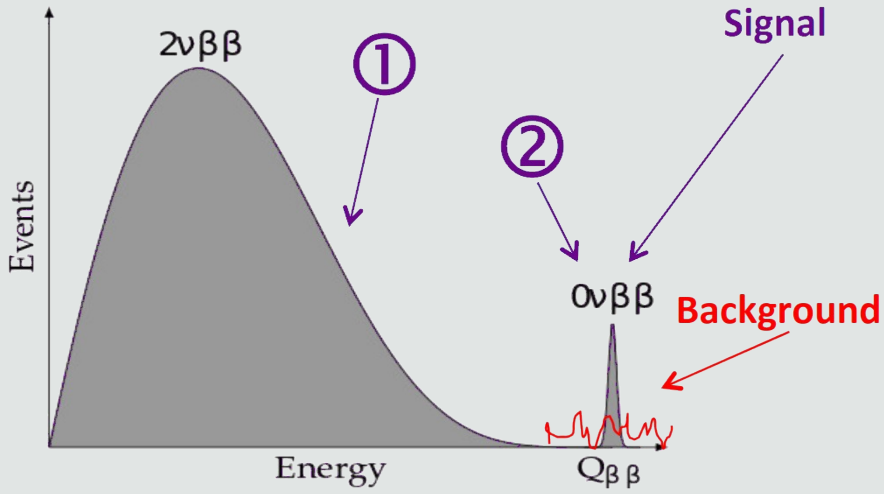


- Suppressed decay probabilities
- Less favorable Q-values
- Low natural abundances of nuclei
- Challenging signatures

Neutrinoless double beta **plus** decay ($0\nu\beta\beta^{++}$)







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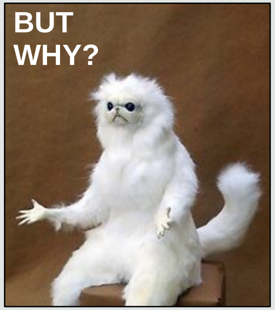
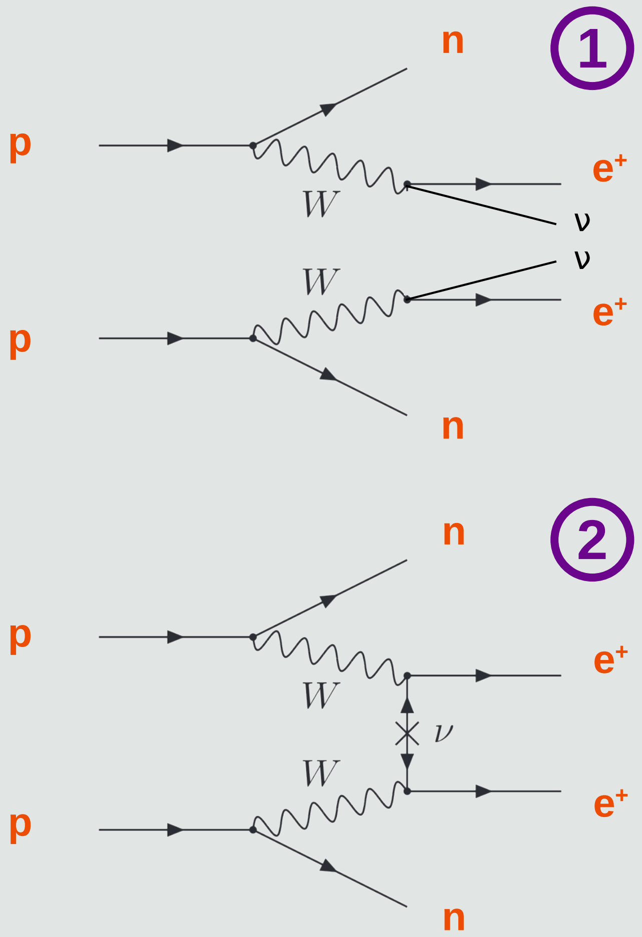
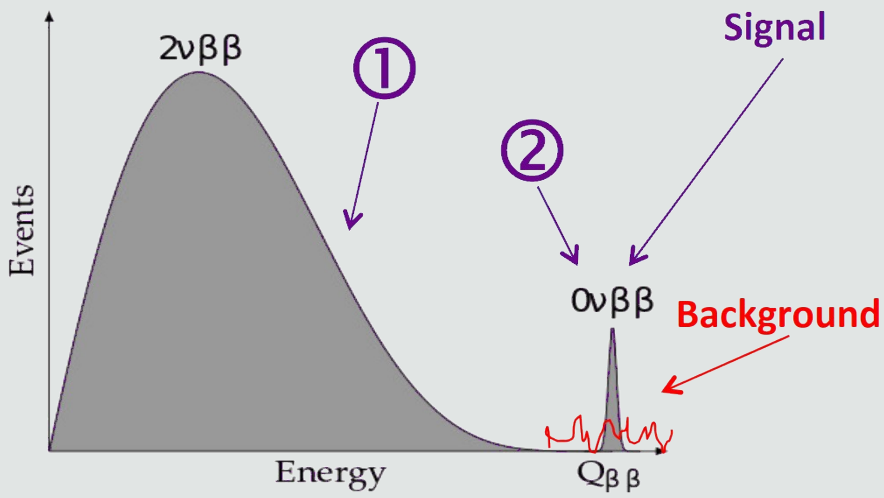


Neutrinoless double beta **plus** decay (0νββ^{++})





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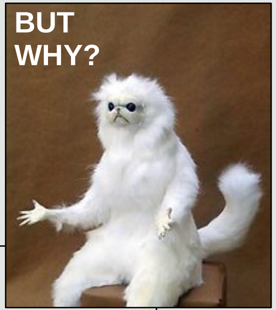

- Studies of nuclear structure models
- Valuable constraints on theoretical models
  → deeper understanding of underlying nuclear physics

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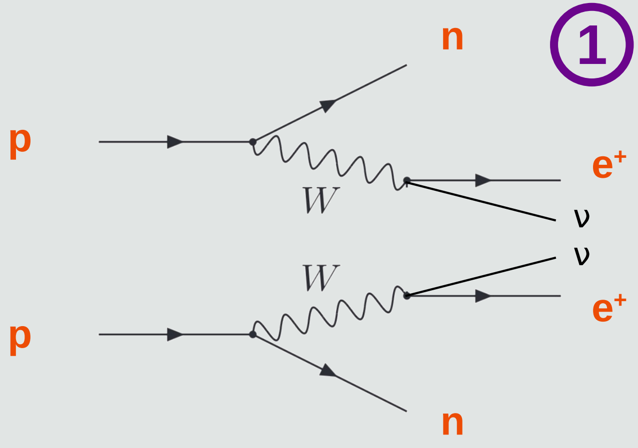

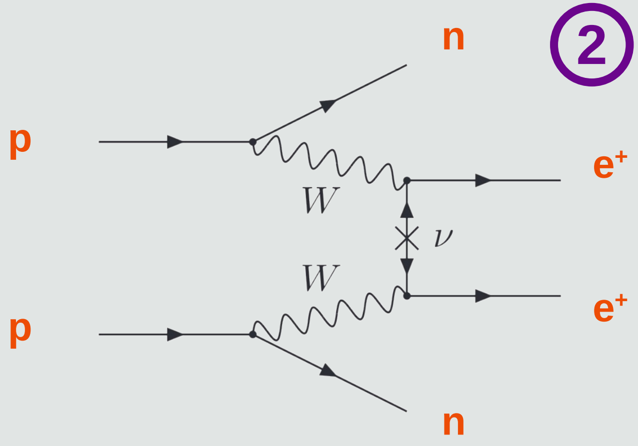

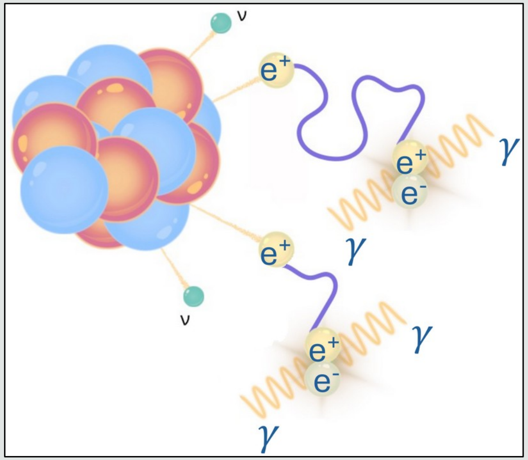

Courtesy of S.Schoppmann

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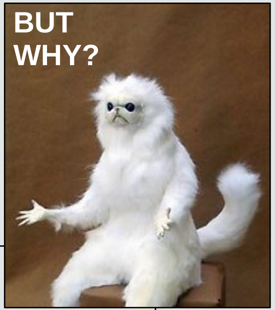

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Newest developments in liquid scintillators

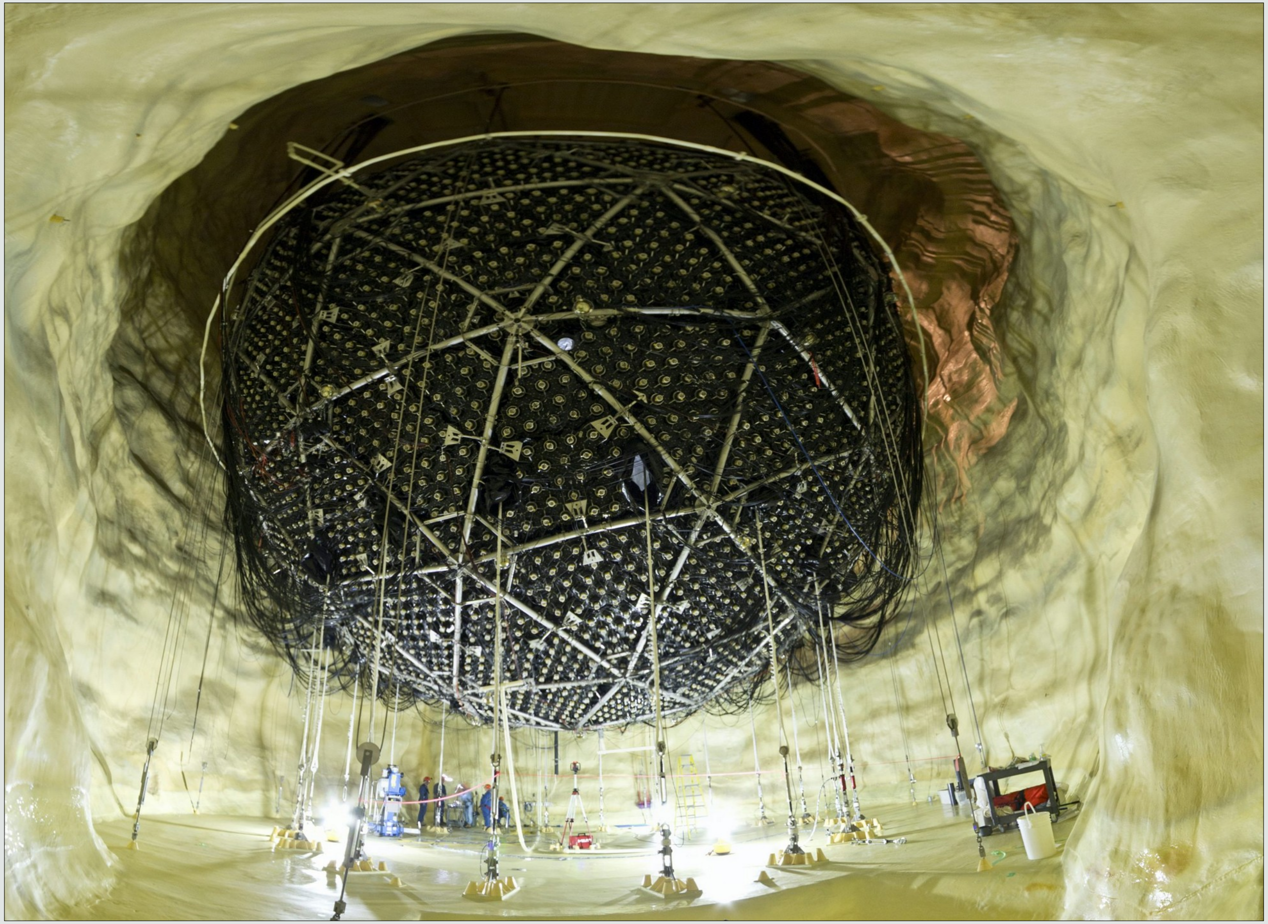
The NuDoubt^{++} detector

Newest developments in **liquid scintillators**

The NuDoubt^{++} detector

NuDoubt++

Transparent liquid scintillators

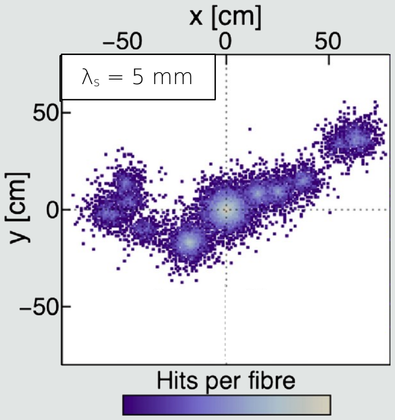


The SNO+ experiment

Exploring new detection technologies

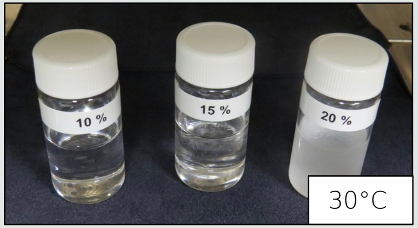
Opaque scintillator

Confine light around vertex



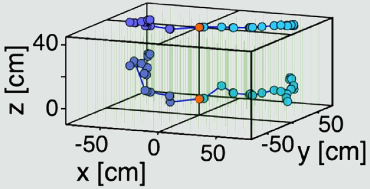
Simulation of e⁺ 1 MeV KE

First implementation of opaque scintillator: adding wax to LS (NoWaSH)



Novel Opaque Scintillator for Neutrino Detection C. Buck et al., 2019

Readout with grid of **wavelength-shifting fibres & SiPMs**



Technology currently explored by **LiquidO** / AM-OTech / CLOUD

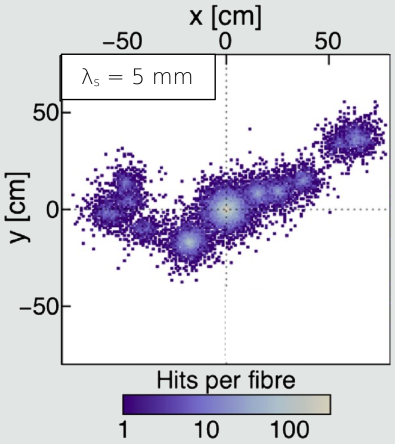
Advantages for 0νββ++

- **Good spacial resolution** (X,Y) → PID capabilities
- Tunable opacity

Exploring new detection technologies

Opaque scintillator

Confine light around vertex



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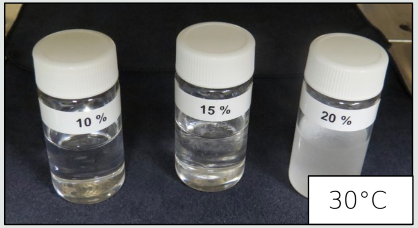

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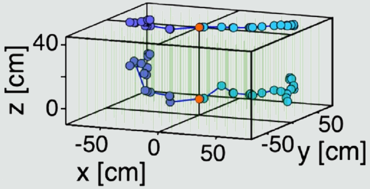

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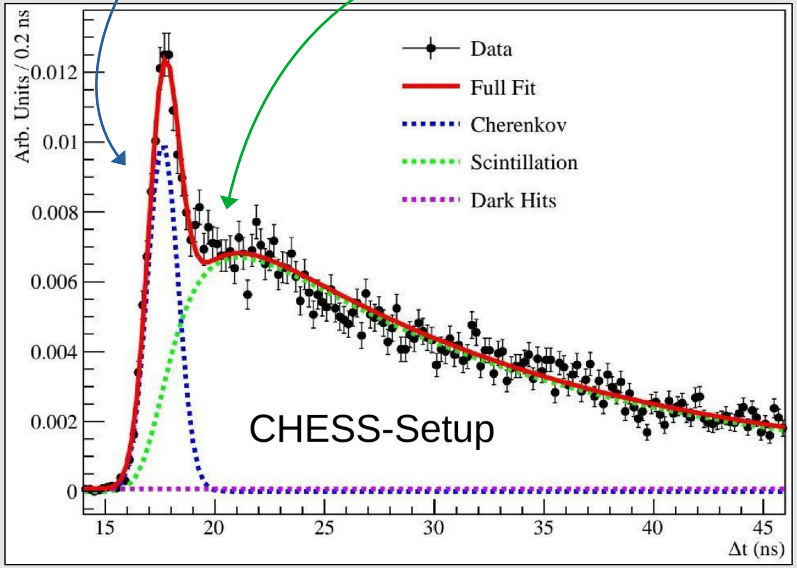
Slow scintillator

Separate Cherenkov and Scintillation light

Small Cherenkov peak visible in the beginning of light emission

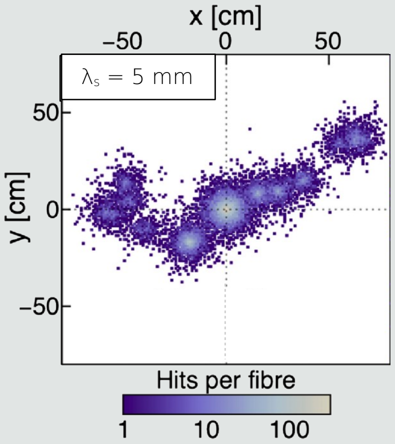
Scintillation light delayed in time (τ >10 ns)



Development of a Bi-solvent Liquid Scintillator with Slow Light Emission, H.Th.J. Steiger et al., 2024

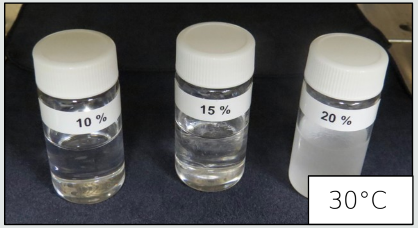
Exploring new detection technologies

Opaque scintillator
Confine light around vertex



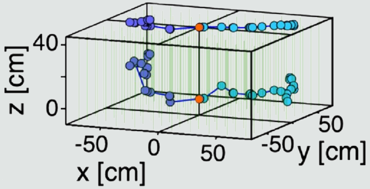
Simulation of e+ 1 MeV KE

First implementation of opaque scintillator: adding wax to LS (NoWaSH)



Novel Opaque Scintillator for Neutrino Detection C. Buck et al., 2019

Readout with grid of **wavelength-shifting fibres & SiPMs**



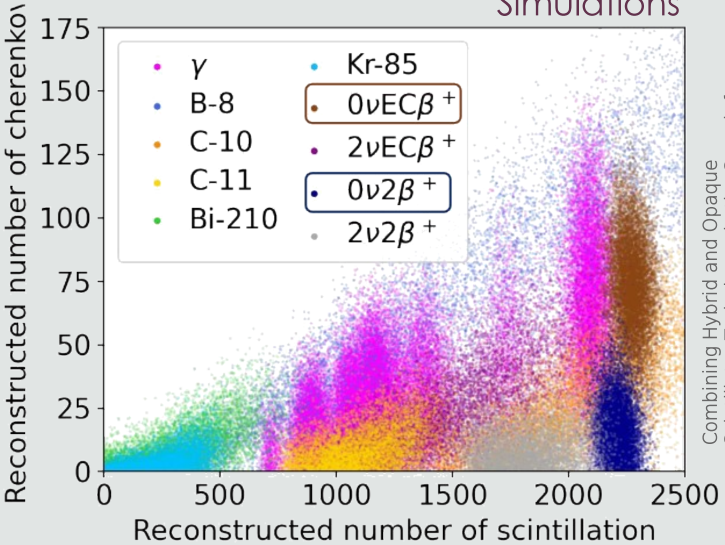
Technology currently explored by **LiquidO** / AM-OTech / CLOUD

Advantages for 0νββ++

- **Good spacial resolution** (X,Y) → PID capabilities
- Tunable opacity

Slow scintillator
Separate Cherenkov and Scintillation light

Simulations



Combining Hybrid and Opaque Scintillator Techniques in the Search for Double Beta Plus Decays, M. Böhles et al., 2025

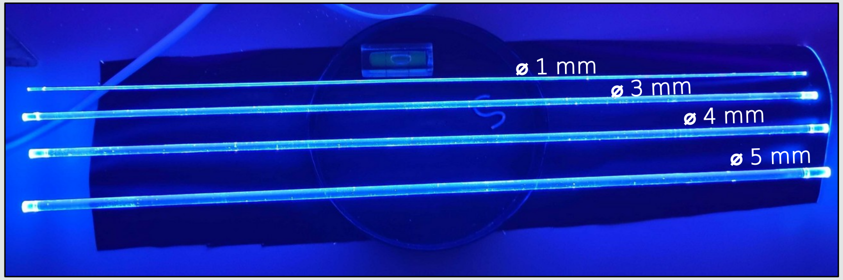
Advantages for 0νββ++

- **PID using Č/S ratio**
- **High scintillation LY** → good energy resolution
- Low energy threshold

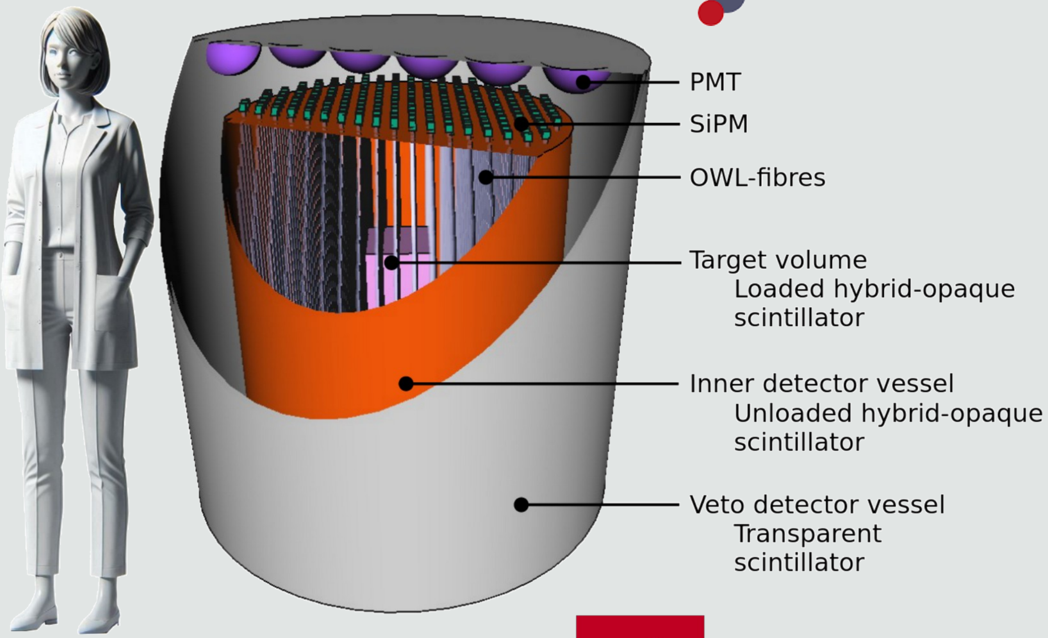
Exploring new detection technologies

- 50% **enriched** krypton-78 gas
- 5 bar **overpressure**
- 10 kg (scintillator Mass) in central fiducial vessel

First prototypes of polystyrene-based OWL-fibers



OWL = Optimised Wavelength-shifting fibres
PMMA fibers of ~mm diameter, coated with wavelength-shifting paint

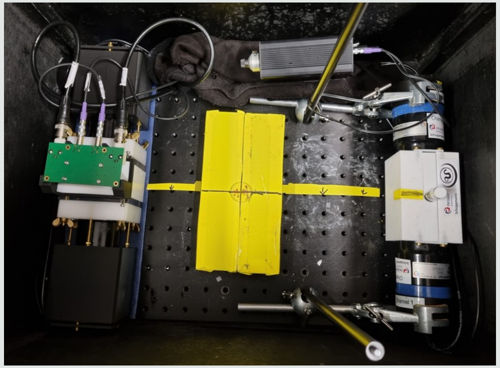


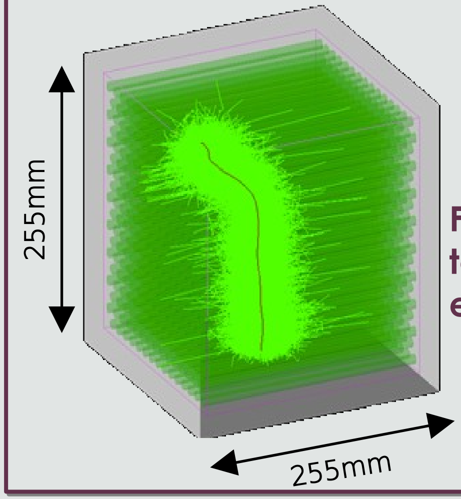
NuDoubt++

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Current operations for NuDoubt^{++}

Fiber/scintillator test bench

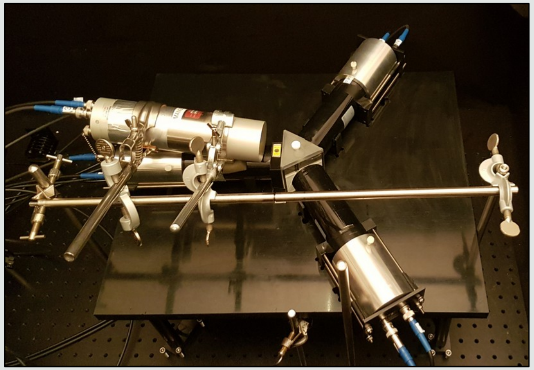




First prototype tested using an electron beam

Investigating gas loading with overpressure

Testing gas isotope composition with a proportional counter



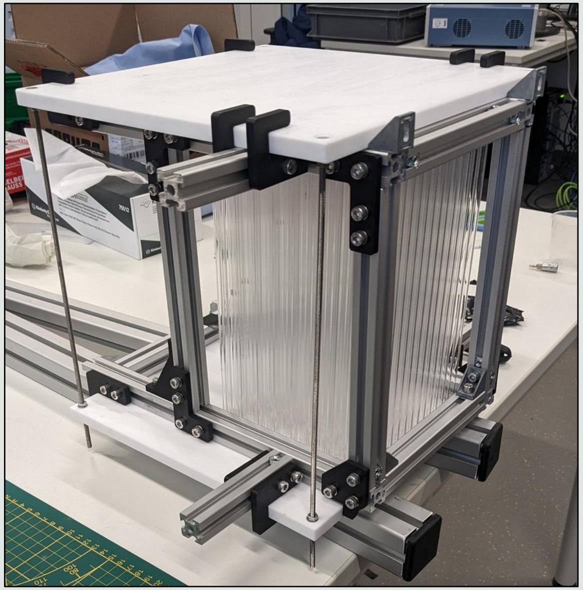
Studying Cherenkov-scintillation lights separation

PRiSMA^{++}

https://link.springer.com/article/10.1140/epjc/s10052-025-13847-1

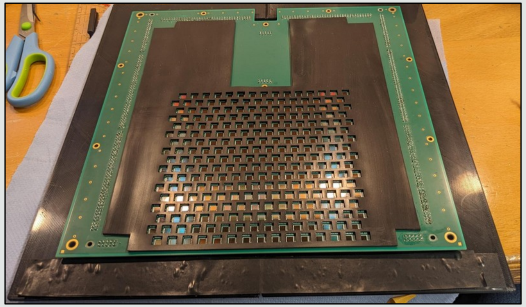
255 channels prototype @Mainz

OWL fibers mounted in prototype



Prototype mounted a electron beamline

SiPM plate



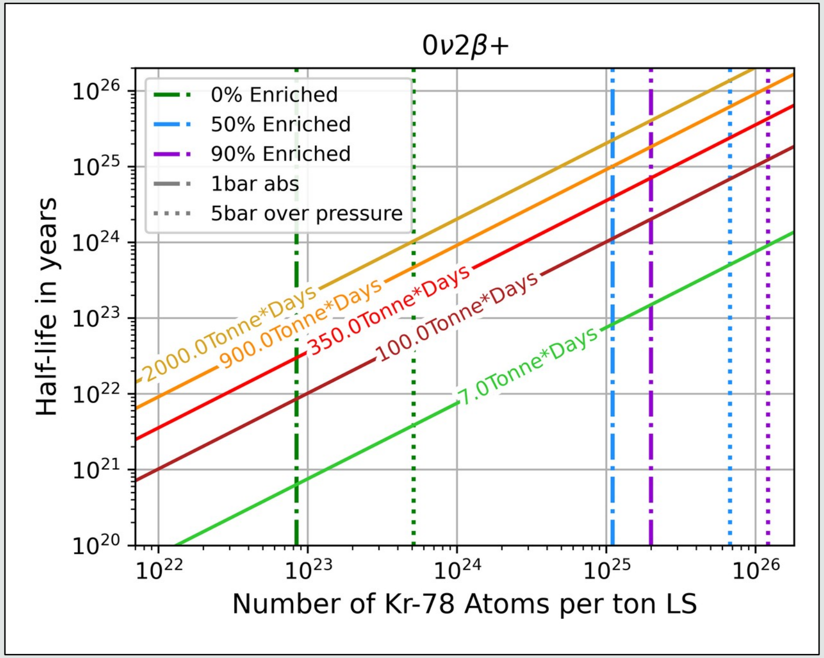
Expected sensitivity of NuDoubt^{++}

After **20kg.year** exposure (~1 year operation):

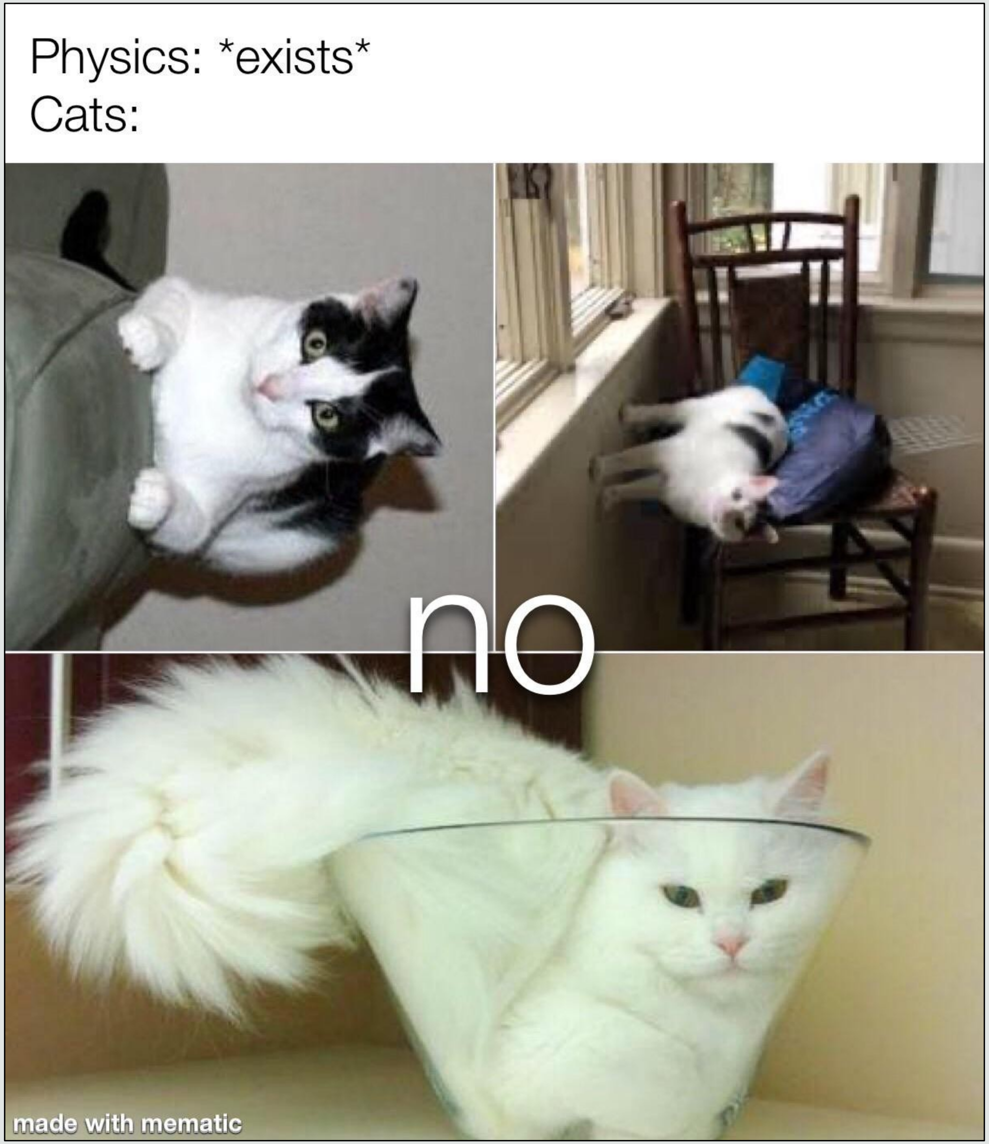
- Improvement of limits on neutrinoless modes by almost **3 orders of magnitude**

Assuming Gran Sasso overburden

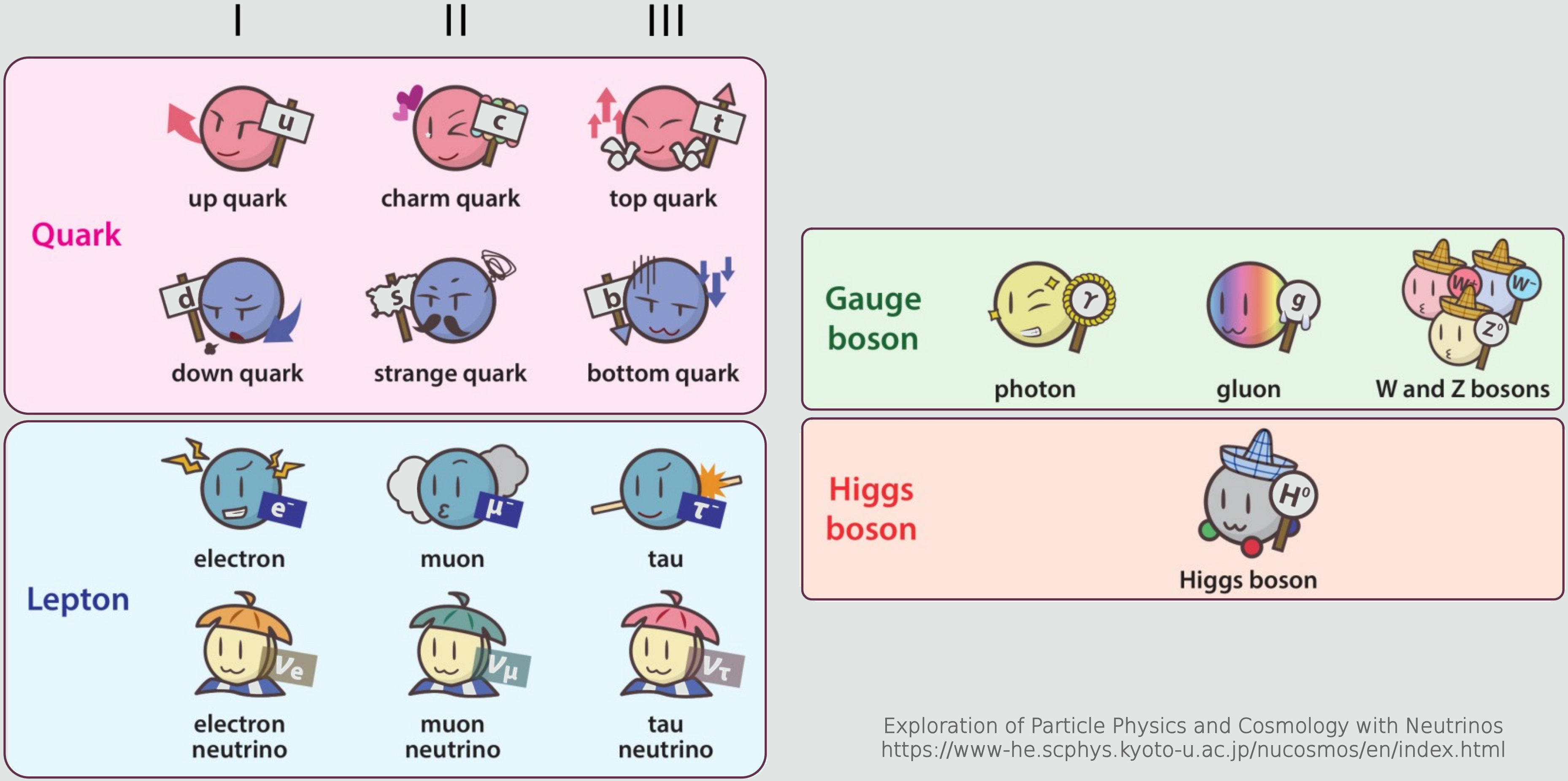
Expected 90% C.L. exclusion sensitivity



Starting to contact deep underground labs

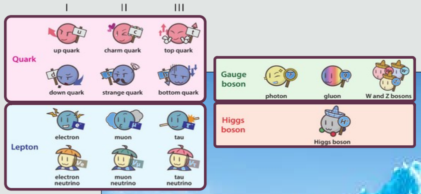

Physics: *exists*
Cats:
no
made with mematic

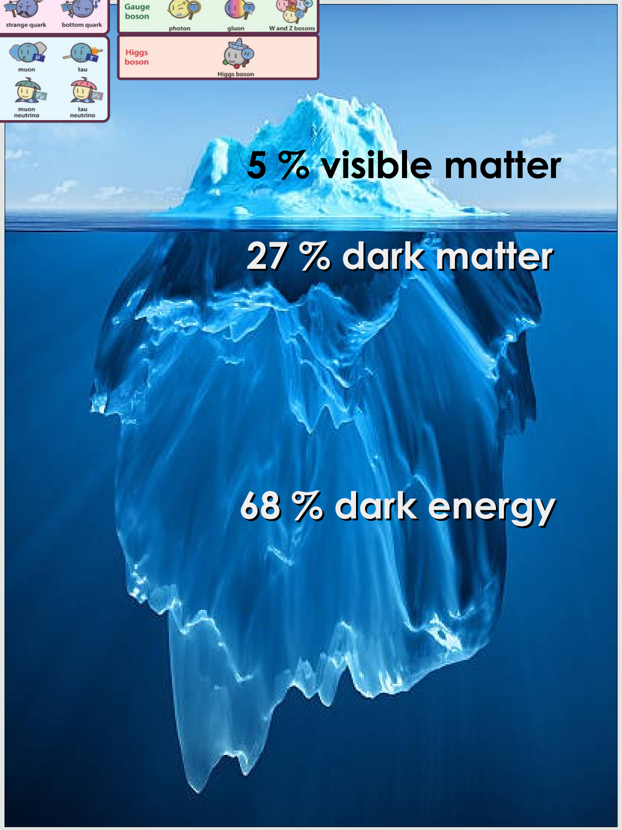
Remember the Standard Model



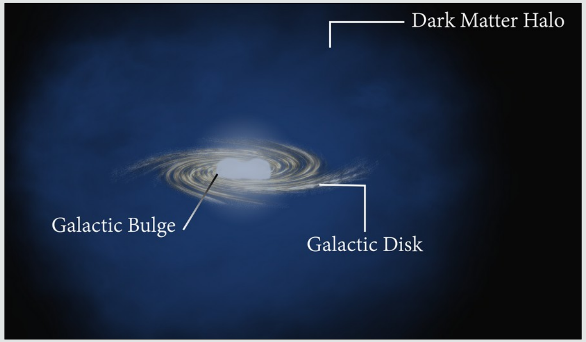
Exploration of Particle Physics and Cosmology with Neutrinos
https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/index.html

Remember the Standard Model





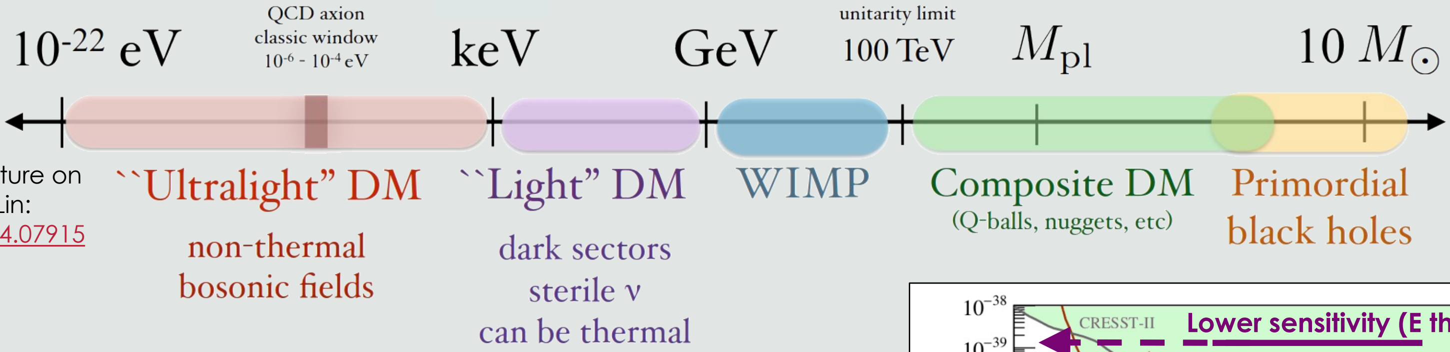
- **First evidence**: Galaxy cluster dynamics
  Fritz Zwicky (1933): **Coma cluster galaxies move too fast** → visible mass cannot explain gravitational binding
  → First hint of "missing mass"
- **Galactic rotation curves**
  Vera Rubin & Kent Ford: **Rotation curves of spiral galaxies stay flat at large radii** → need unseen mass extending far beyond the visible disk
- **Cosmic probes confirm DM**
  CMB anisotropies (WMAP, Planck), large-scale structure, gravitational lensing, BAO
  → Precisely fitted cosmology: ~26% of the Universe is dark matter
- **We still don't know what it is**
  No particle found yet → motivates **direct detection**, indirect detection, and collider searches



The mass scale of Dark Matter

Neutrino floor/fog: irreducible background from neutrino coherent scattering

If DM is elementary particle → **50 orders of magnitude in mass:**



Taken from a very nice lecture on DM direct detection by T. Lin: doi.org/10.48550/arXiv.1904.07915

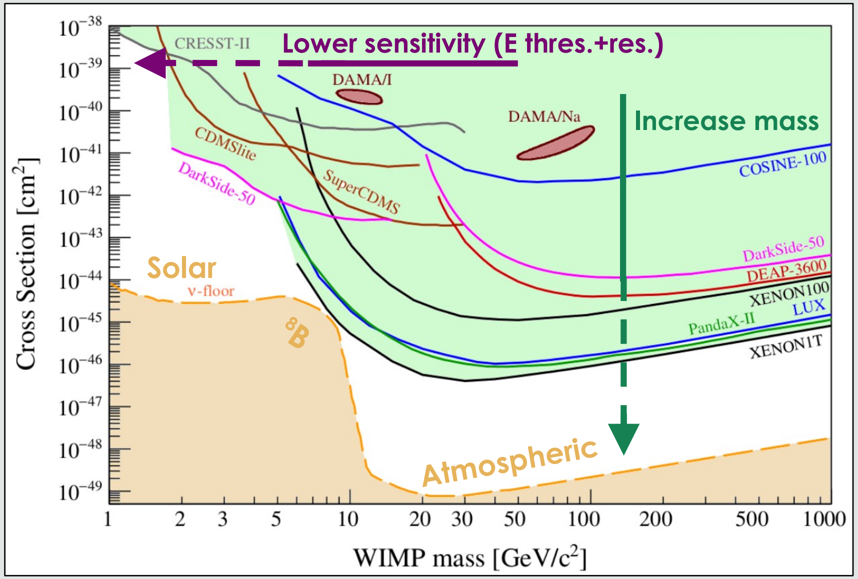
A lot of searches focus on

- **Axion** DM (μeV – meV)
- **WIMP** (GeV – TeV)

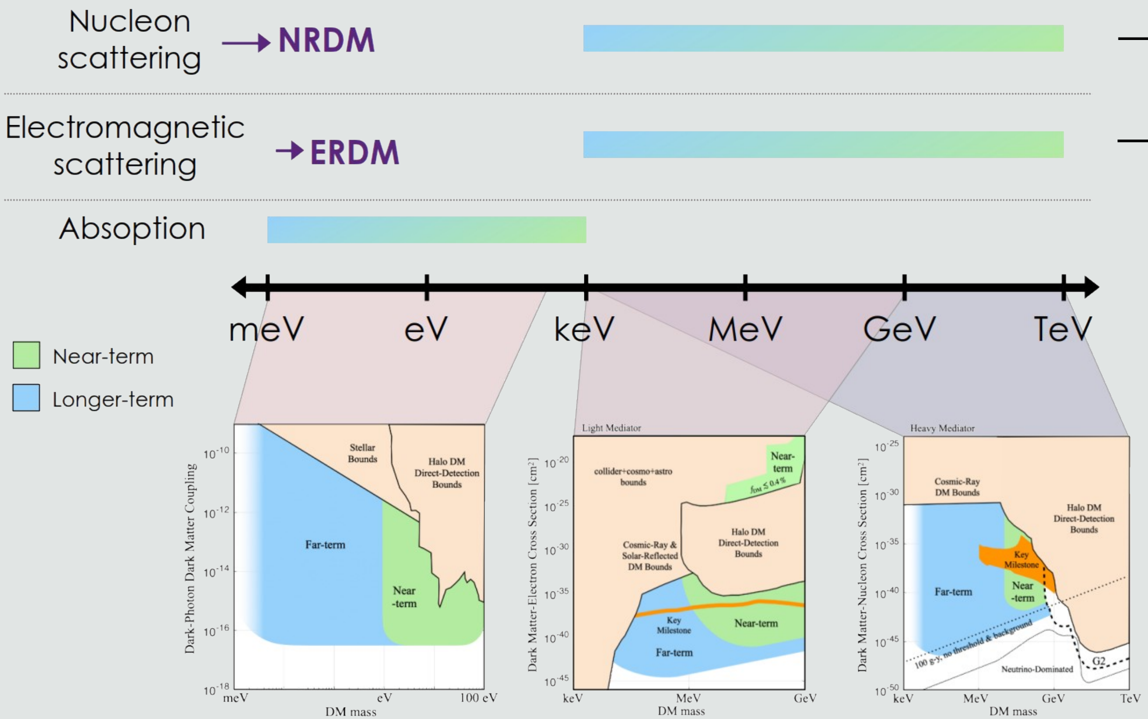
Both mass ranges for DM are highly motivated → Need to close the gap between those ranges

A lot of searches and improvements happen with nobles elements → approaching neutrino floor/fog

Once you've reached this bkg, very hard to go beyond (except with directionality)



Direct detection of DM particle



→ Elastic scattering : dark-matter particle scatters off a nucleus and transfers kinetic energy

→ Inelastic scattering: dark-matter particle interacts with a bound electron in the atom

All types of interactions DM can have with target material

- **Nuclear recoils** (NR): Nuclear interactions
  ex.: WIMP searches
- **Electronic recoils** (ER): electromagnetic interactions
  → favored for light DM
- **Absorption**: keeps all DM KE, released in detector

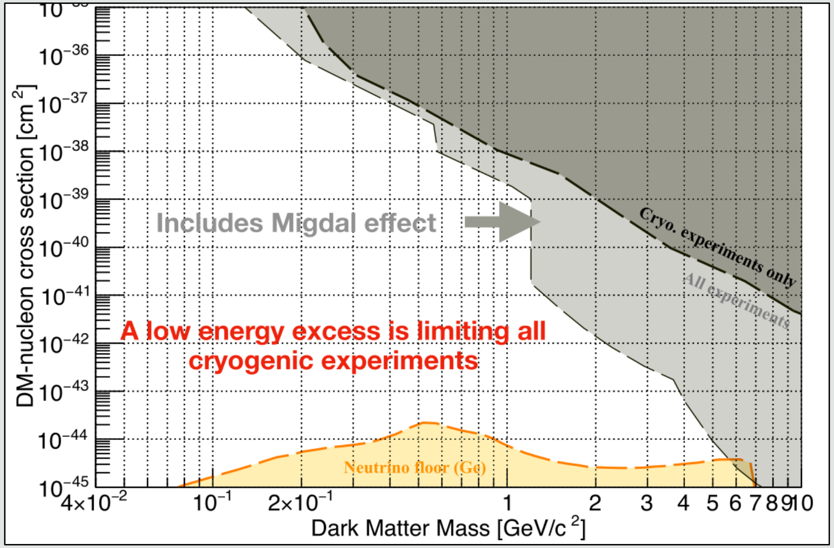
→ With all 3 interaction types: cover wide range from meV to TeV

Adapted from doi.org/10.1016/j.nuclphysb.2024.116465
Itself adapted from arxiv.org/pdf/2203.08297

Low-mass Nuclear Recoil DM

Migdal effect: after NR, you kick out electron
→ boosting signal

Exclusion limit for NRDM



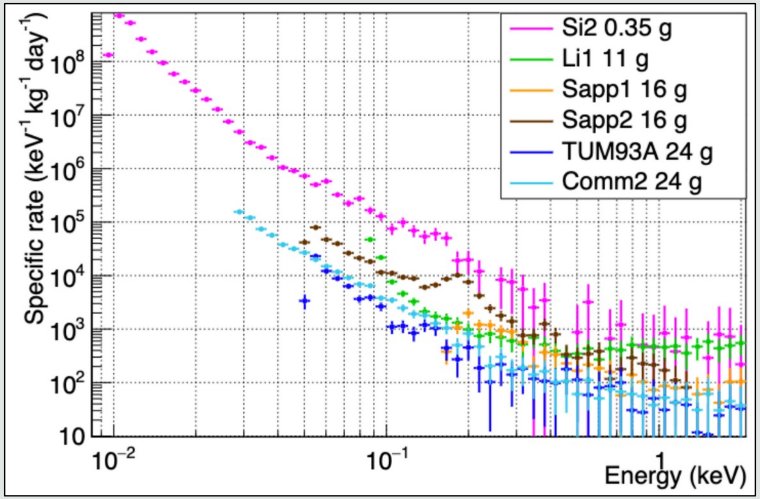
- Only cryogenic experiments are measuring NR energy scale with no assumption
- Many other experiments (mainly liquid Xe or Ar experiments) take into account some systematics making assumptions on ionization yields or include Migdal effect

Cryogenic experiments was believed to take the lead on low-mass DM search

But when lowering energy thresholds up to 1 eV, we see **Low Energy Excess (LEE)** limiting all cryogenic experiments below 1 GeV mass scale (CRESST, Edelweiss, SuperCDMS)

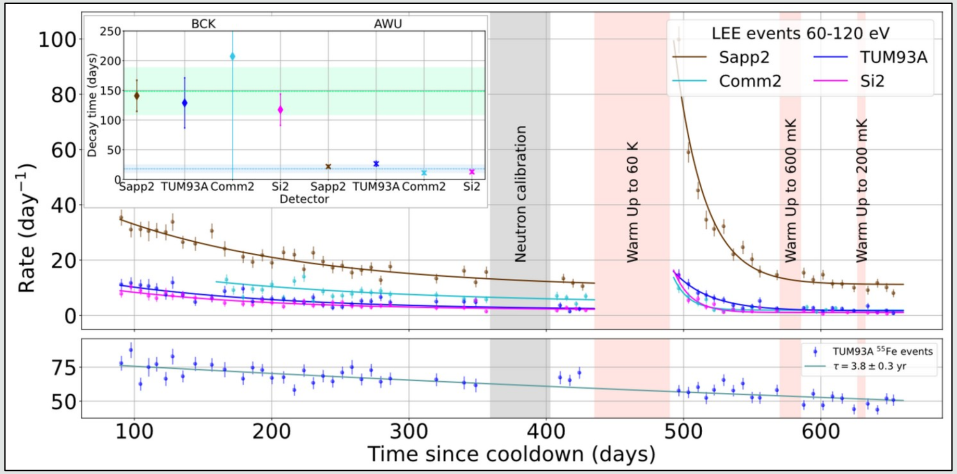
The Low Energy Excess

LEE or “Heat-only”



Rise in background rates below 1 keV → goes up to **10^8 DRU**
→ **Limiting DM sensitivity**

- **Seen by all cryogenic experiments** (+ quantum computing)
- **Time dependent** → warming up = “recharging” background
  Could happen in bulk of crystal or in sensor (to be answered)
- **Non-ionizing** (from Edelweiss)
  → can be rejected it if measuring **heat** (phonons) + **ionization**
- Independent of the site



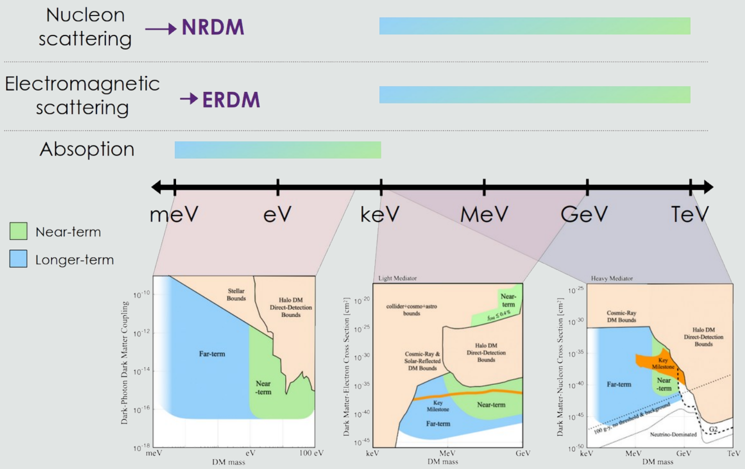
A multi-target experiment to search to low mass dark matter

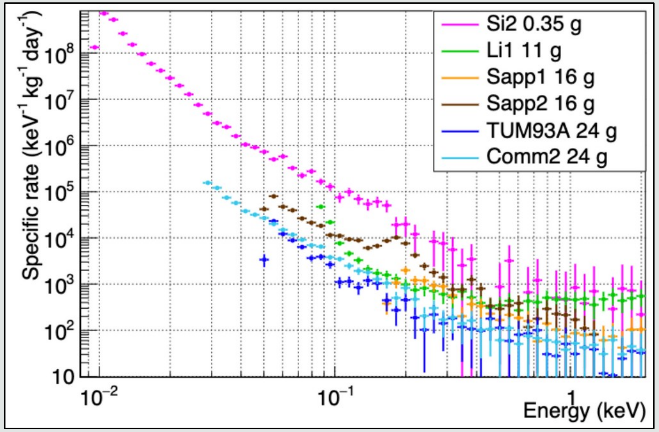
The TESSERACT experiment

TESSERACT

TESSERACT idea: have a broad search of DM

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets





Goal of TESSERACT

Extend DM search window from meV to GeV with **cryogenic detectors** with

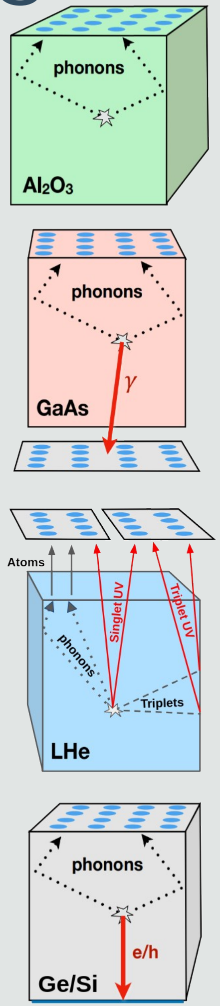
- Multiple target (complementarity)
- PID (important for background rejection, very hard without PID)
  → Depending on technology

LEE: drives design of TESSERACT

- Ultra low threshold
- Find origin of LEE + mitigate it
- + Develop technics to reject this background

The TESSERACT collaboration and technologies

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets



TESSERACT existing in U.S. since June 2020 for R&D development

→ 3 different technologies **using TES sensors** (Transition Edge Sensors): heat (phonon) sensors

- Polar crystals: sapphire (Al_2O_3)
- Gallium Arsenite (GaAs) → scintillation light + heat energy (as in CRESST)
- Liquid Helium target

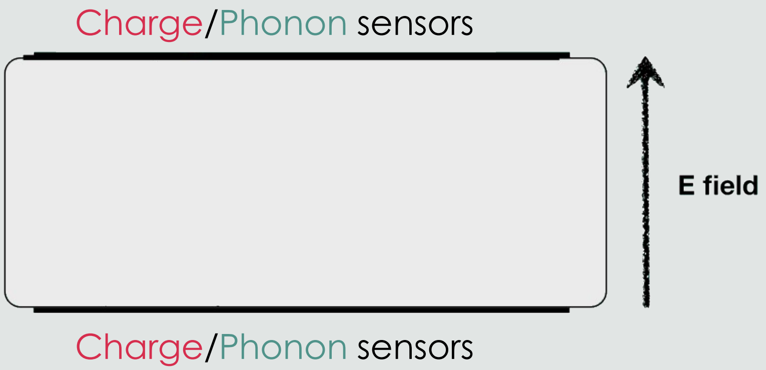
French part of collaboration benefits from Edelweiss / RICOCHET / CuPID with **low-background bolometer expertize**

- Add **Germanium bolometers** to TESSERACT technologies
- **Installation at LSM**

→ **TES4DM project**

Ge/Si bolometers

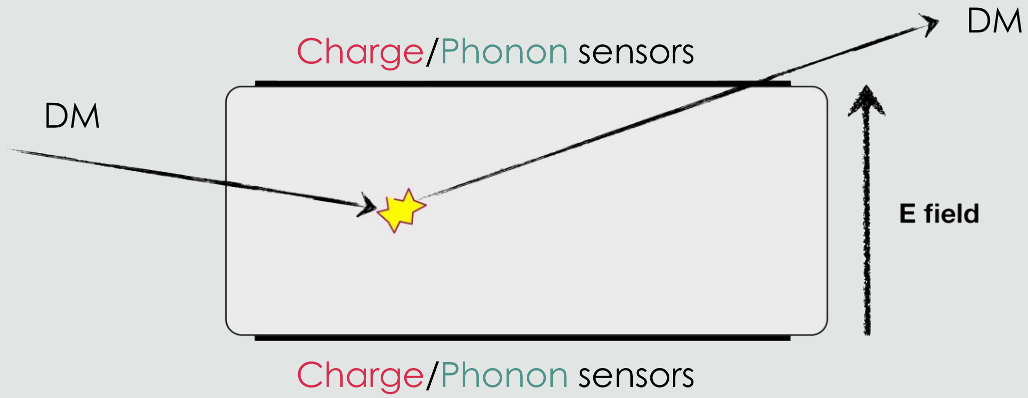
Phonons are **collective excitations** of the atoms in a solid or liquid
→ simplest example: sound waves in a medium



Ge/Si bolometers

Phonons are **collective excitations** of the atoms in a solid or liquid
→ simplest example: sound waves in a medium

1. Particle interacts in crystal
   There are **charge** and **phonon** sensors on both sides allowing to apply electric field



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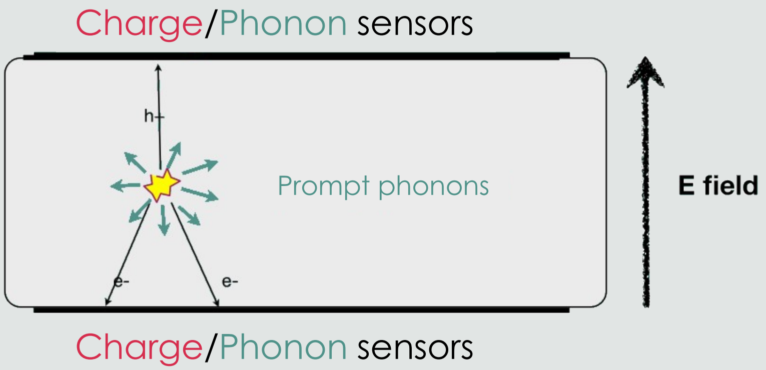
2. After interaction → emission of

- prompt phonons **coming from recoil** energy
- + ionization creating electron-hole pairs



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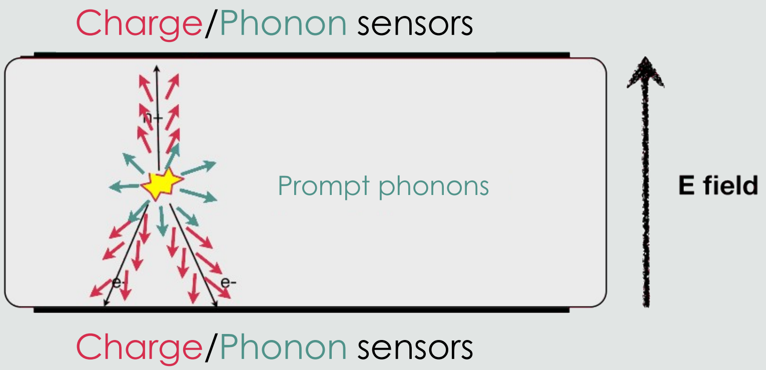
  → e-h pairs will drift across electric field
  → will generate additional phonons (like Joules effect) called "Neganov-Luke-Trovimov phonons"



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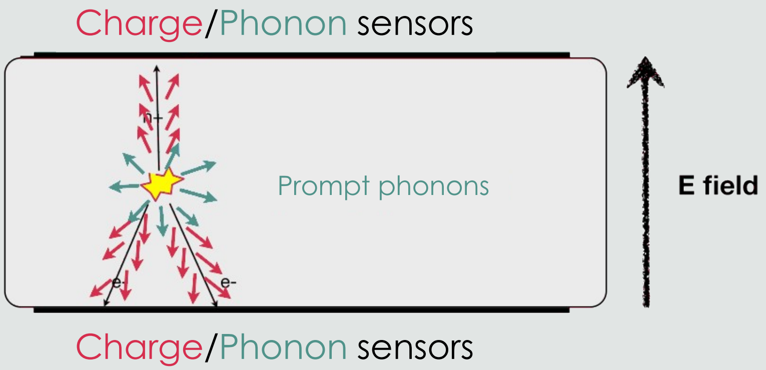
$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\,eV} E_{ion} \Delta V$$

Measuring both **phonons (heat)** and **ionization**
→ can recover total energy, **model independent**

If increase Voltage, you boost NTL (Luke) contribution
→ "NTL" **signal amplification**



The TES sensors

Phonons are **collective excitations** of the atoms in a solid or liquid
→ simplest example: sound waves in a medium

A Cooper pair is a pair of fermions
bound together at low temperatures

Used in DM for some time (CRESST → TES, Edelweiss → NTD)

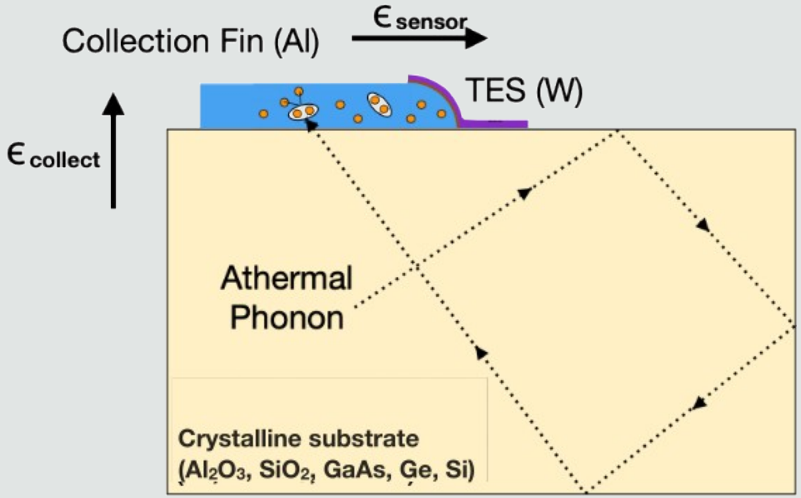
Principle:

- Interaction in target material, generating athermal **phonons** bouncing around in crystal
- Some phonons trapped in Collection Fin (Al) (Cooper pairs), **breaking the Cooper pairs**
- **Creates quasi-particles**, then drifting to TES sensor
- Quasi-particles absorption → **measurement of heat**

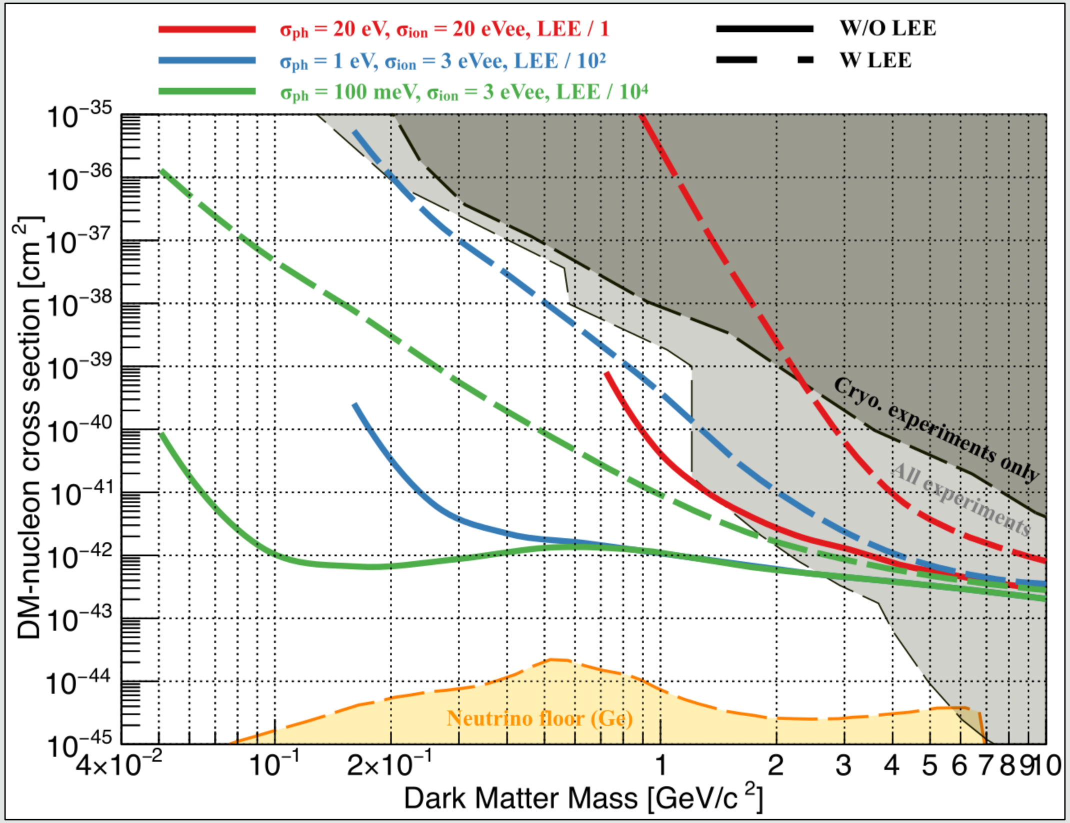
$$\sigma_E \propto V_{det}^{1/2} T_c^3$$

Energy threshold decreases with detector mass

Energy threshold decreases very quickly with critical temperature

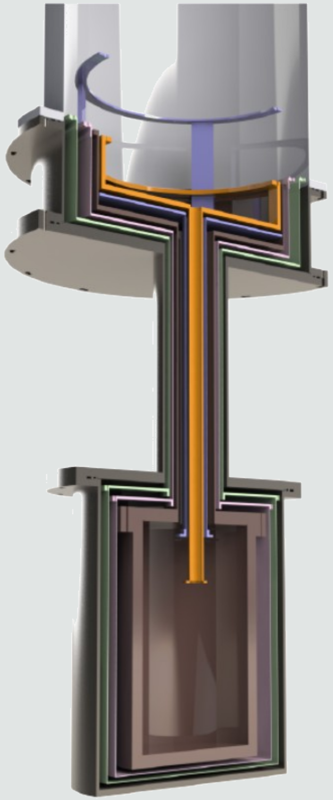


Germanium bolometers in TESSERACT



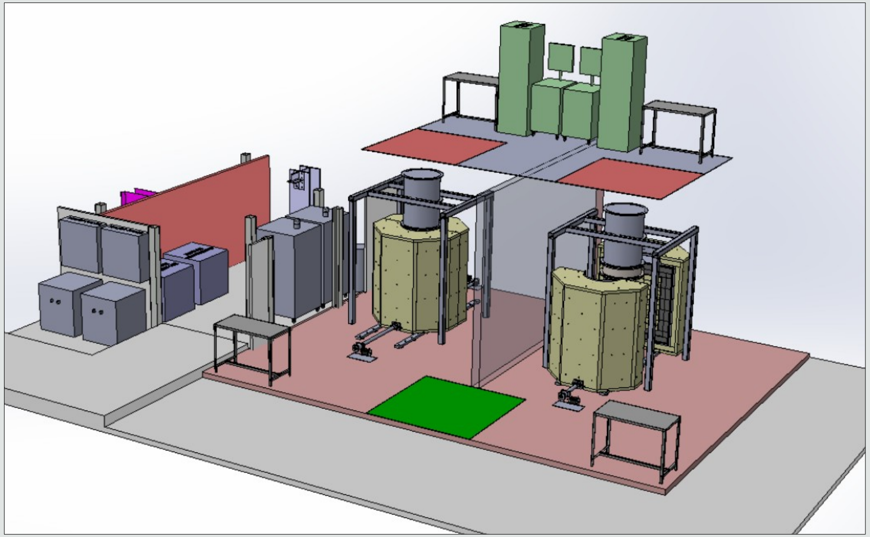
Ge bolometers (LV) technology in TESSERACT will allow to vastly extend NRDM searches down to 100 MeV with **particle ID** and **LEE** rejection in a region of the parameter space inaccessible to non-cryogenic experiments

The TES4DM project



TESSERACT@LSM = 2 (cryostats+shielding) at LSM, **one** is paid by **TES4DM** (French contribution)

Preliminary
(& without clean rooms displayed)



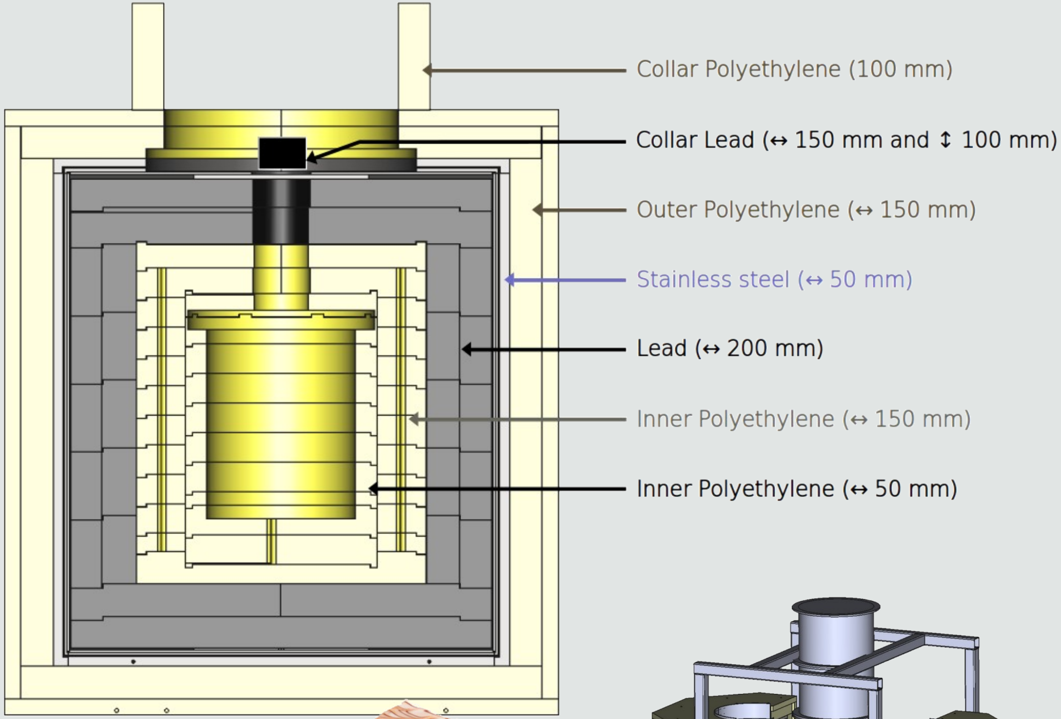
A lot of challenges

- **Vibrations**: movement at nm scale
- **Electromagnetic interferences**
- **Cryogenic** performances **<10 mK**
- **Ultra-low radioactivity**: **<1 event/kg/day**

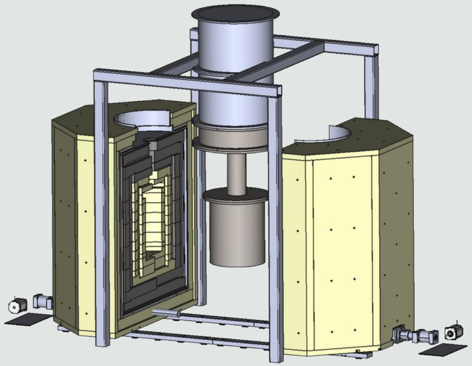
The TES4DM project: timeline

- Tender process ongoing for **cryostat**, should be finalized by the **end of 2025**
- Tender process for **shielding** will start early **2026**
- **Commissioning at LPSC** before integration at LSM
- **Installation at LSM planned for 2028**

The conception of the shielding for TESSERACT

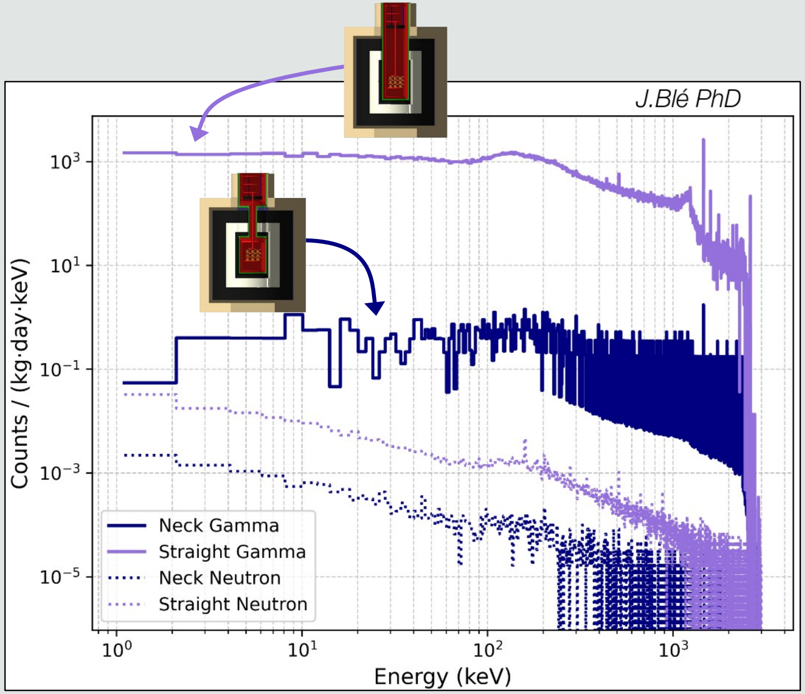


~20 T of 



Work with U.S. and Zurich on design
A lot of G4 simulations ongoing

- Material of internal layer
- Radiopurity needed for different layers

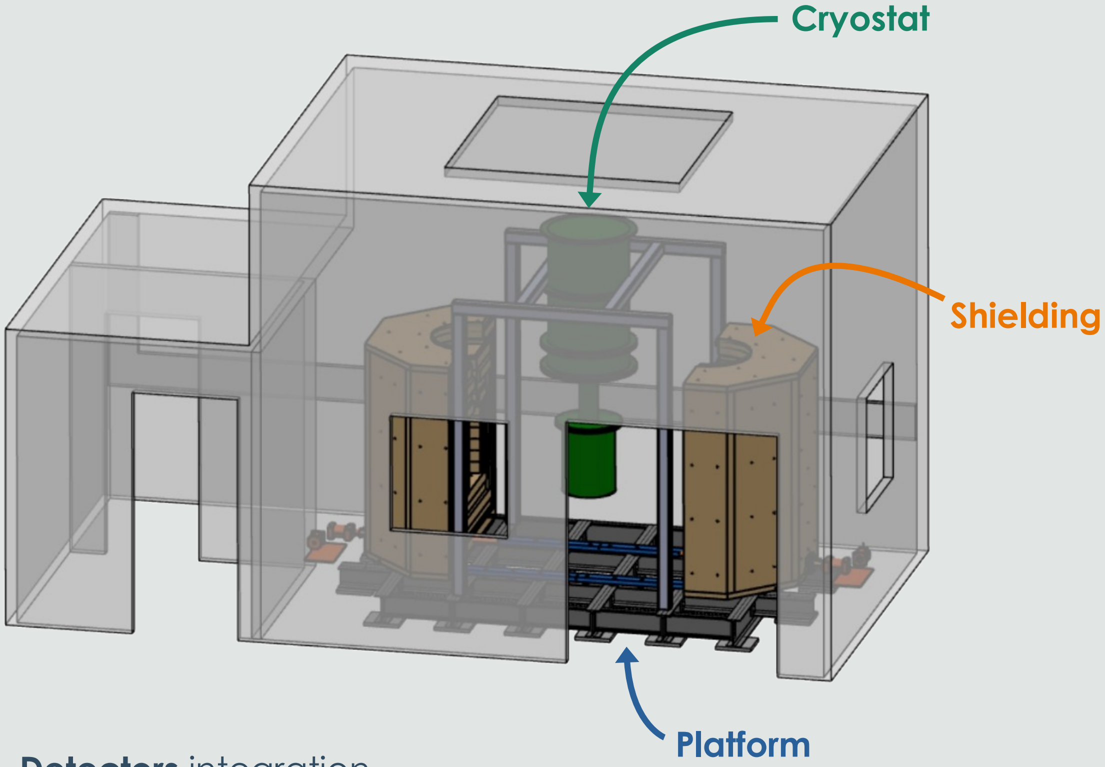


The TES4DM project: timeline

Commissioning at LPSC

Platform, **shielding**, and **cryostat** integration

- Installations
- Procedure drafting
- Commissioning



Detectors integration

- Installations
- Repetition of maneuvers
- Drafting of procedures
- Commissioning
- Performance validation

Which message to take home?

- Not that easy to detect particles/processes that may not exist
- We have to consider a lot of parameters
  - Some are common to several fields
  - Some are specific
- A lot of technologies, some are shared between Neutrino and Dark Matter physics fields

Both fields have a lot in common! (GDR DUPhy)

Which message to take home?

- Not that easy to detect particles/processes that may not exist
- We have to consider a lot of paramaters
  - Some are common to several fields
  - Some are specific
- A lot of technologies, some are shared between Neutrino and Dark Matter physics fields

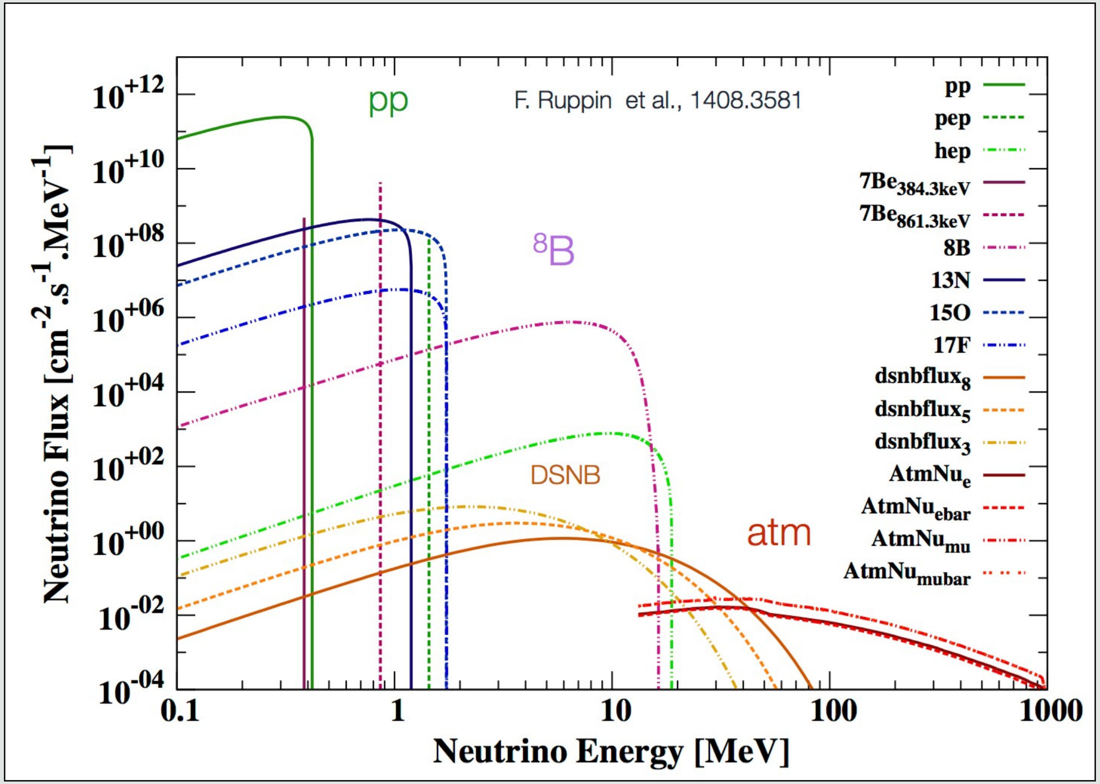
Both fields have a lot in common! (GDR DUPhy)

- OR Maybe we should do like cats and do not care too much about physics...

THANK YOU

Backup

Neutrino spectrum



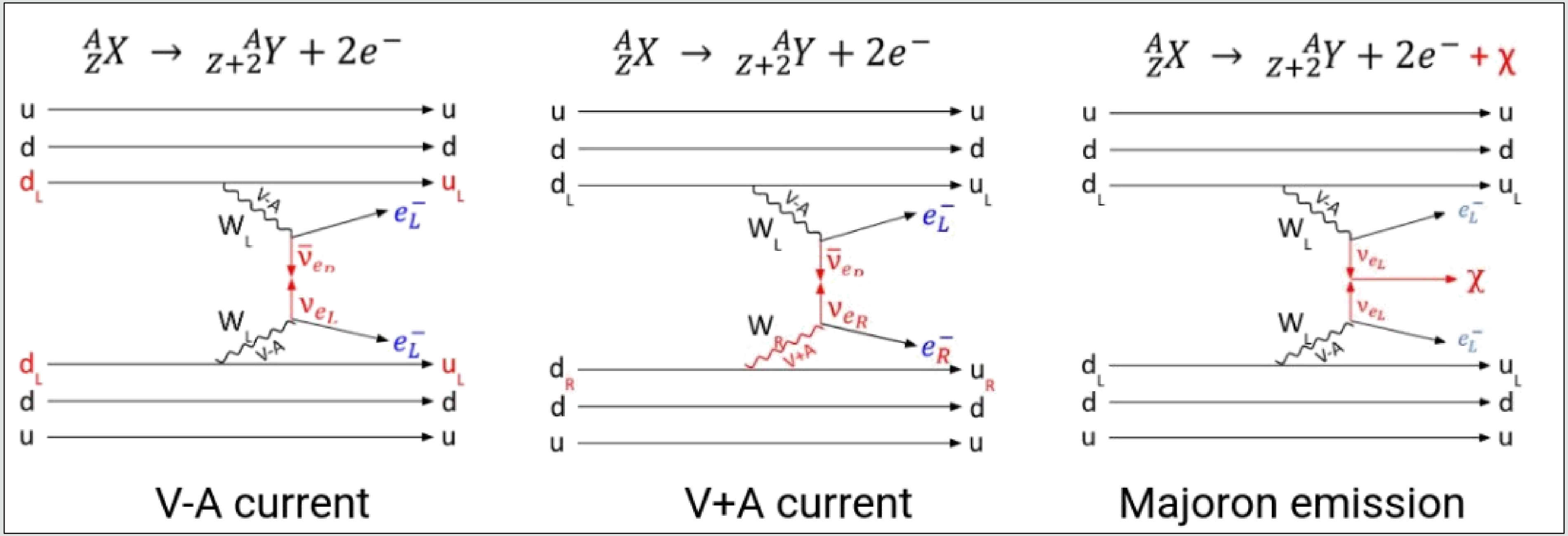
- Cosmic rays & cosmogenic activation of detector materials
- Natural radioactivity (^{238}U, ^{232}Th, ^{40}K): γ, e$^-$, n, α, β

Ultimately:

- neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)

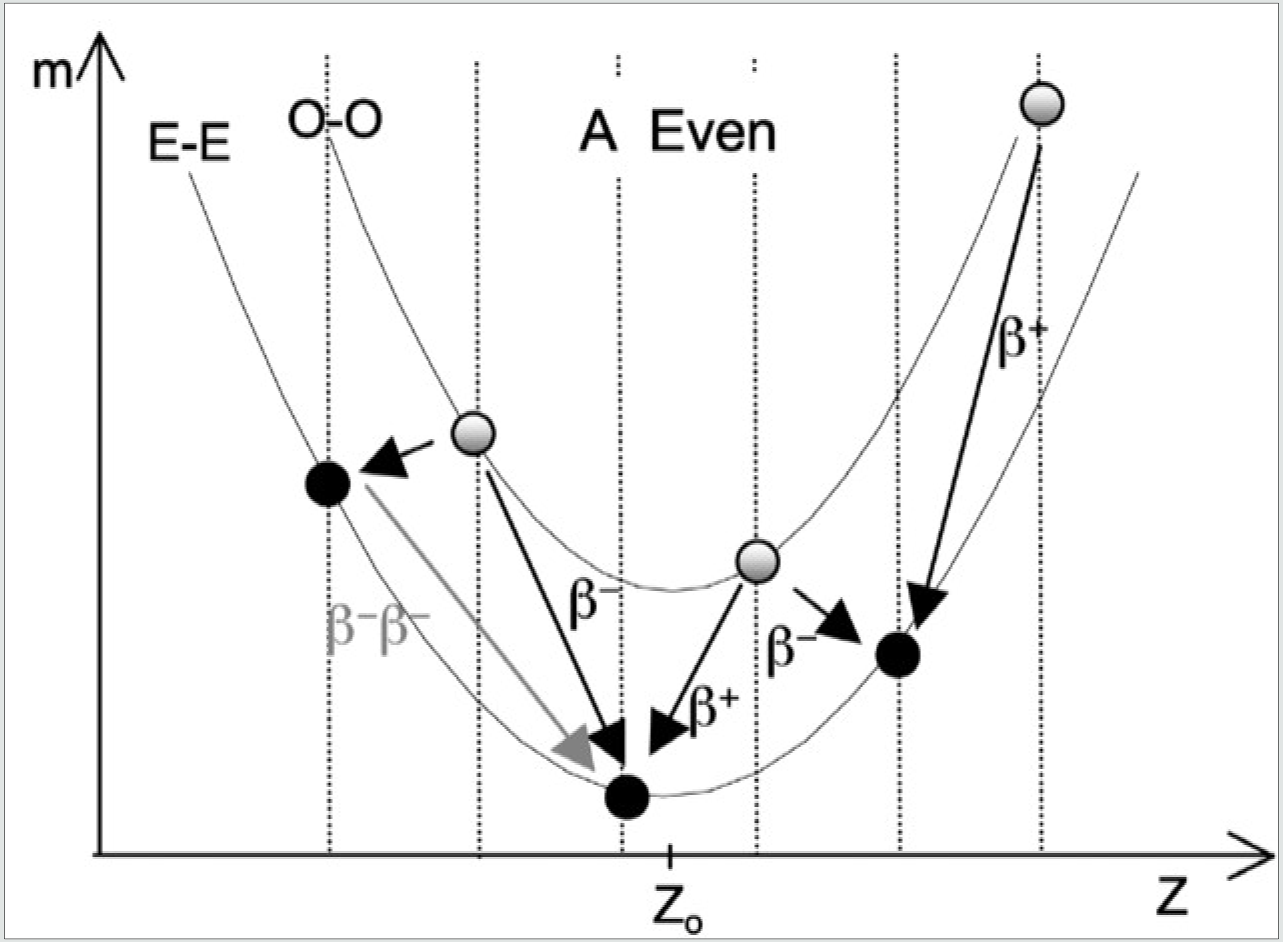
Neutrinoless double beta decays

Many different models result in neutrinoless decay modes:



...

Double beta decays



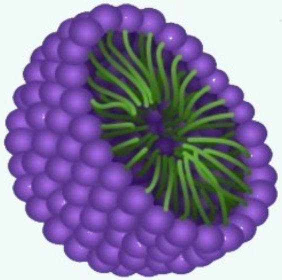
Simplified model of γ-ray flux in LSM

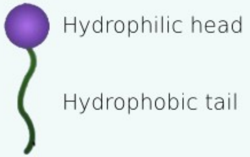
Isotope	γ-ray energy, keV	Flux, $cm^{-2}s^{-1}$
^{40}K	1461	0.1
^{208}Tl	2615	0.04
^{214}Bi	1764	0.05
	1600	0.026
	1300	0.041
	1120	0.046
	609	0.109
Total		0.411

Hybrid liquid scintillator

Separate Cherenkov and scintillation lights

Water-based approach:





Micelles suspended in water with surfactant interface (1-10% scintillator loading)

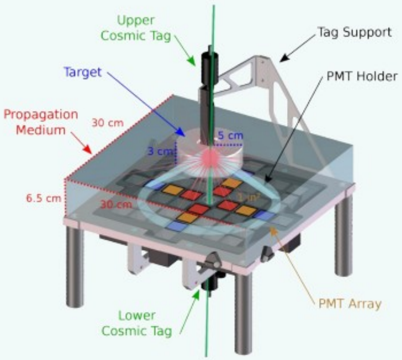
- Advantage: safe to handle
- Disadvantage: **low light yield**

Hybrid-slow approach: using slow solvents

Advantages:

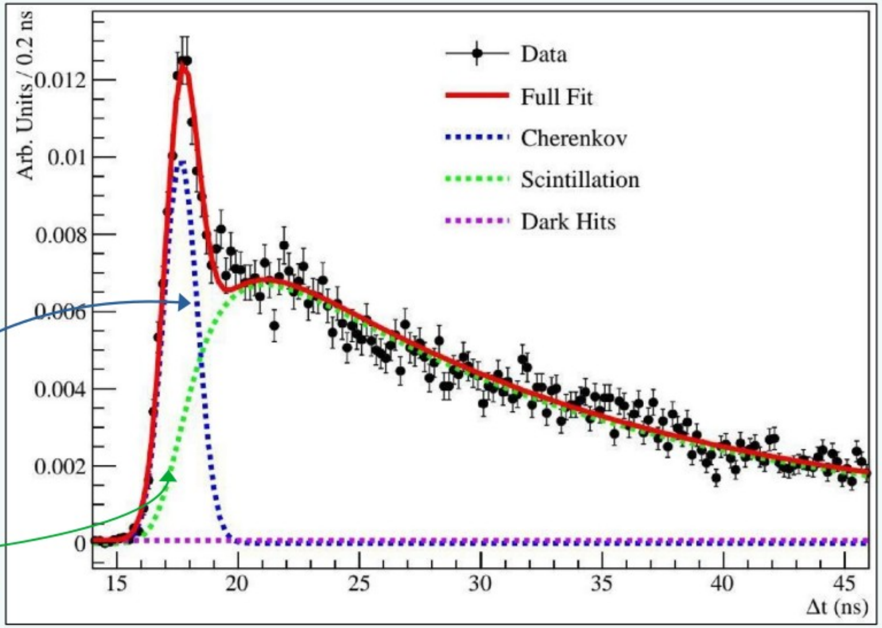
- **High scintillation LY** → good energy resolution
- Low energy threshold

CHESS Setup:



Small Cherenkov peak visible in the beginning of light emission

Scintillation light delayed in time (τ >10 ns)



Development of a Bi-solvent Liquid Scintillator with Slow Light Emission, H.Th.J. Steiger et al., 2024

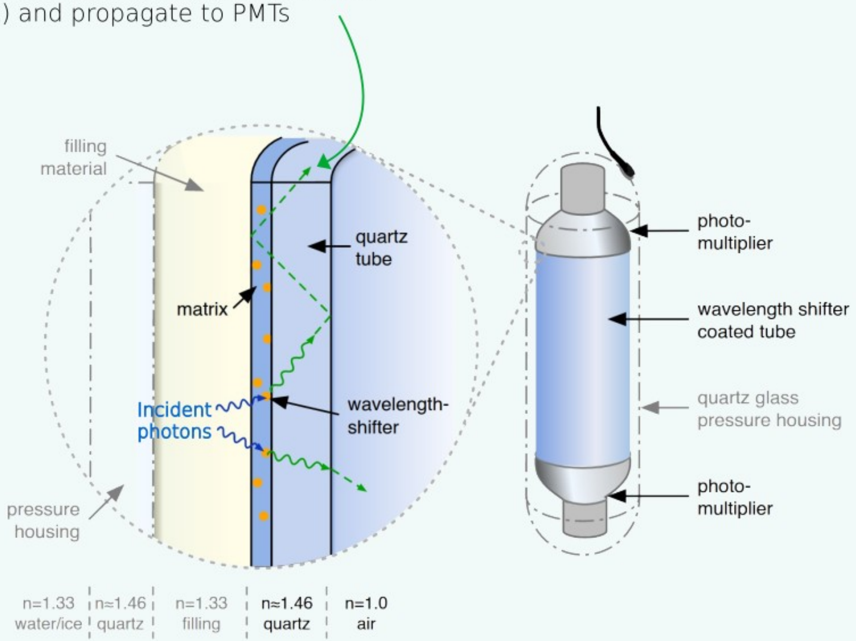
WOMs for IceCube Upgrade

Wavelength shifter only on surface of the tube

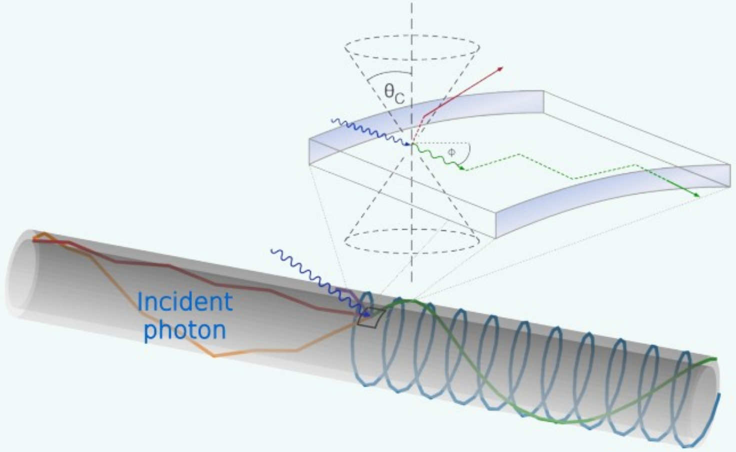
Goal: improve signal-to-noise ratio by maximizing light capture

Idea: decouple photosensitive area and cathode of PMT → Transparent tube + two PMTs at each end

Re-emitted optical photons can be captured by total internal reflection (TIR) and propagate to PMTs



These re-emitted photons can propagate with different paths in the coated tube:

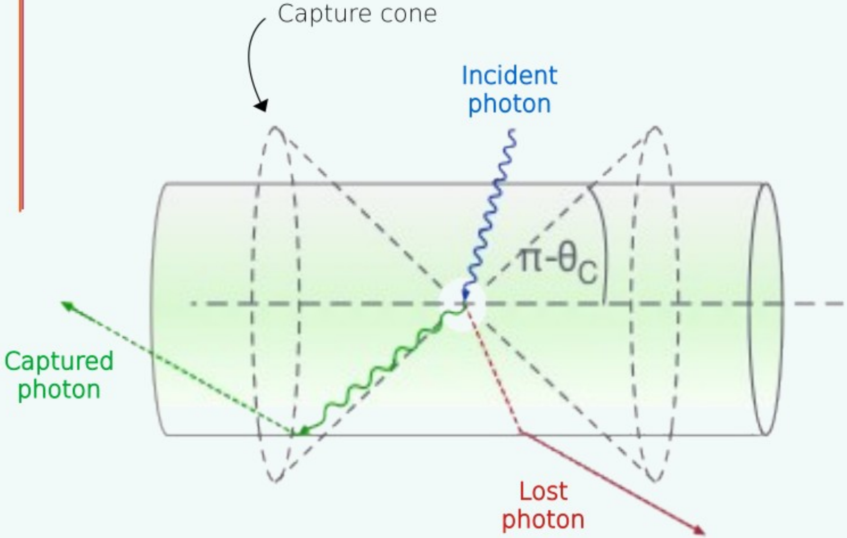


The Wavelength-Shifting Optical Module, B. Bastian-Querner et al., 2022

R&D on improved light readout

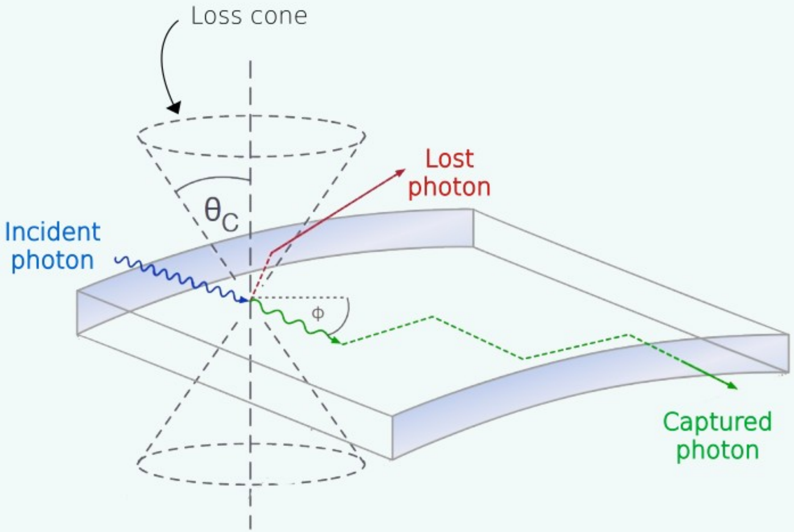
Commercial Wavelength-shifting fibers

For an incident photon in center of fiber:

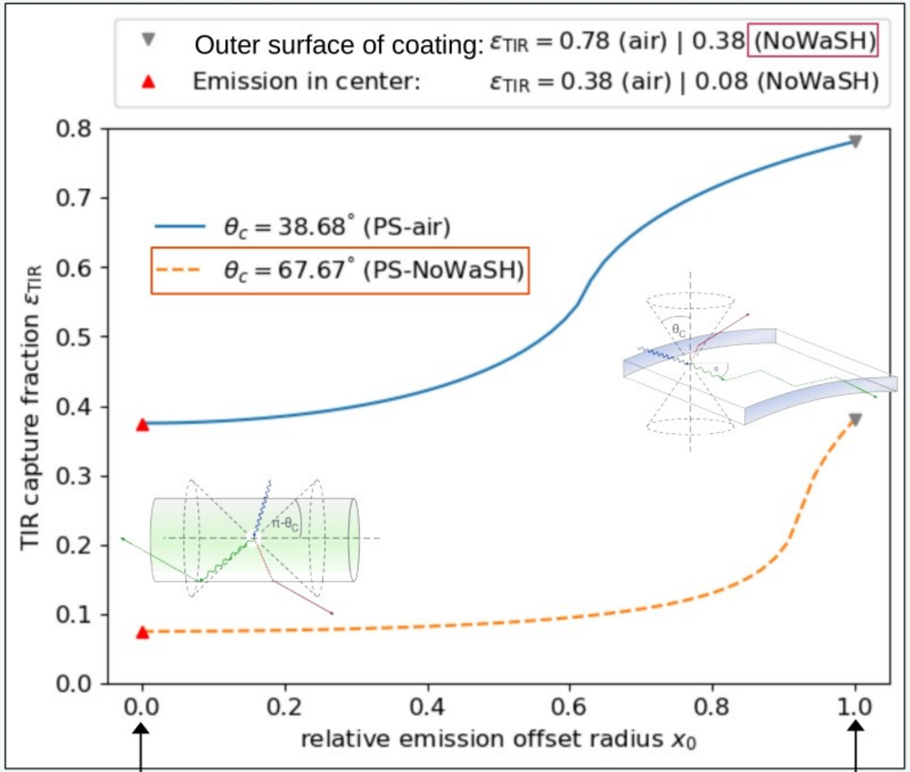


Modules developed for IceCube Upgrade

Incident photons on outer surface of fiber (tube) only



R&D on improved light readout



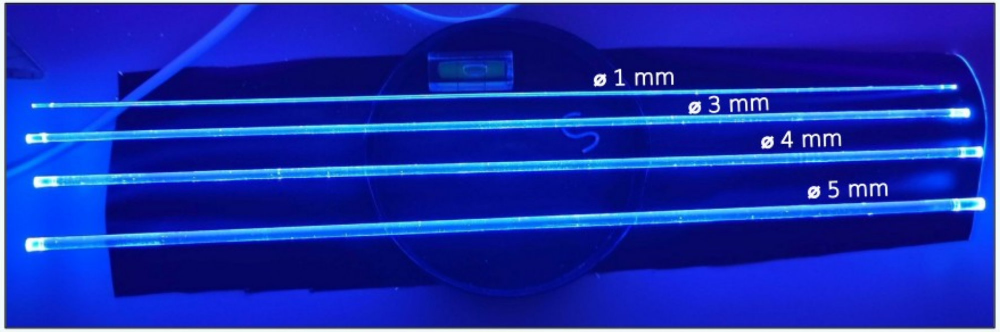
Center of fiber

$$x_0 = |\vec{r}|/R$$

Outer surface of fiber

Photons absorbed and emitted on outer **surface of fibre** have **higher chance** of being captured by total internal reflection (TIR)

First prototypes of polystyrene-based OWL-fibers



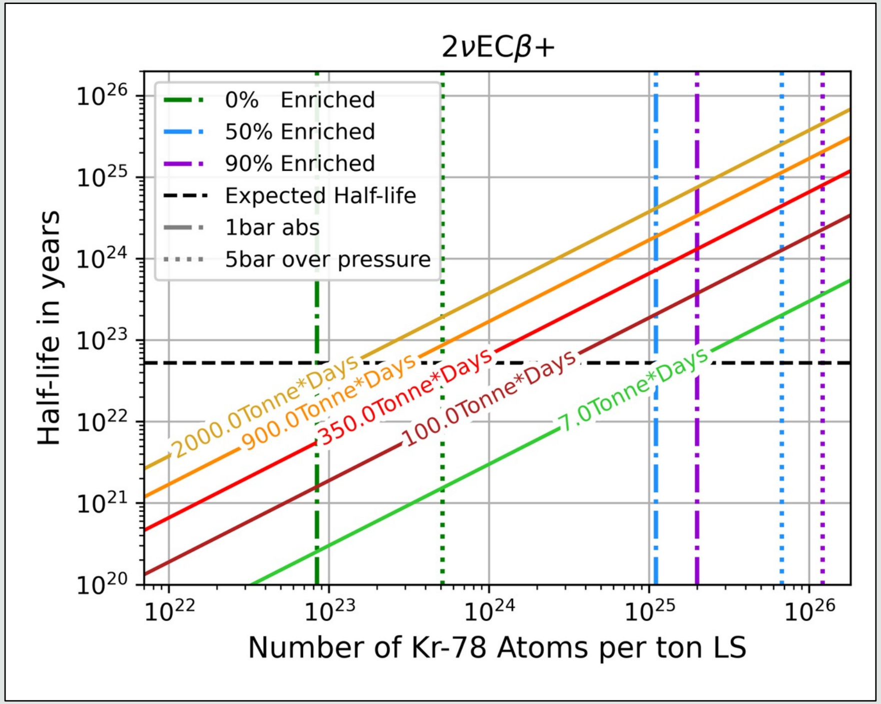
OWL = Optimised Wavelength-shifting fibres
PMMA fibers of ~mm diameter, coated with wavelength-shifting paint

Expected sensitivity of NuDoubt^{++}

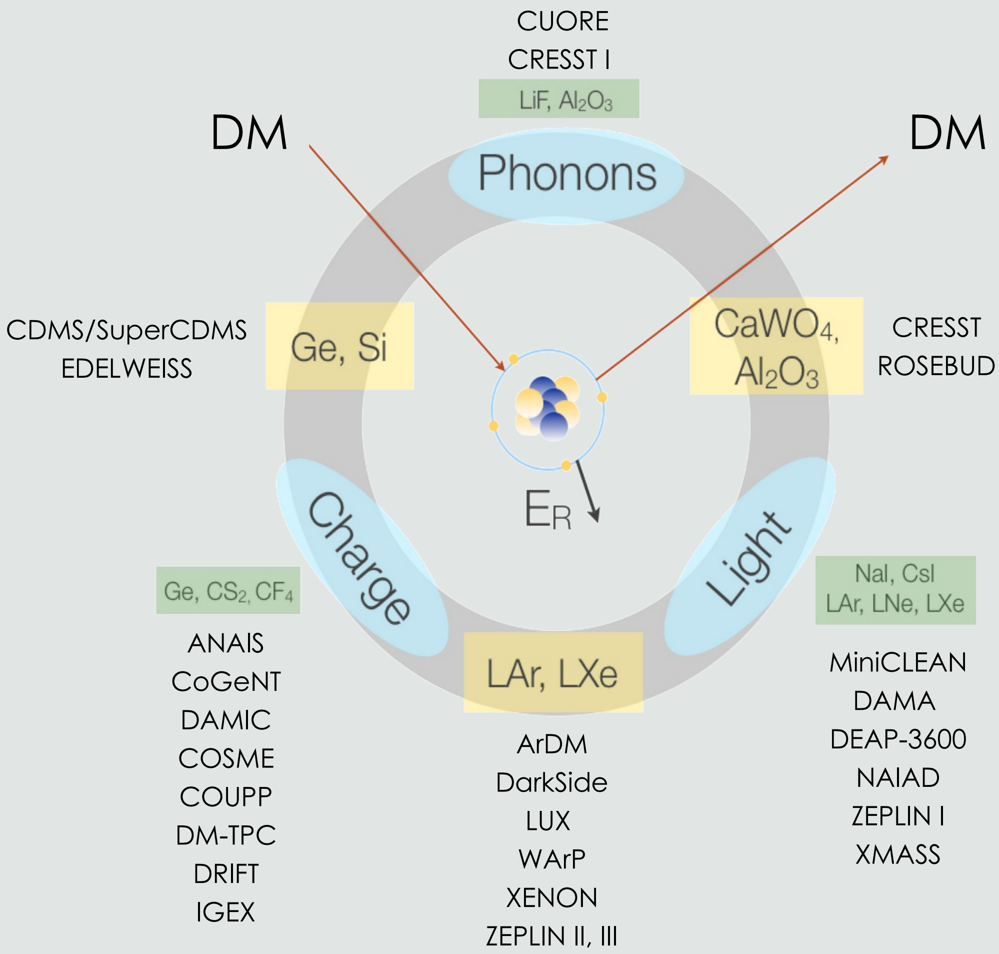
After **20kg.year** exposure (~1 year operation):
- First-time 5σ observation of SM modes 2νECβ+/2ν2β+

Assuming Gran Sasso overburden

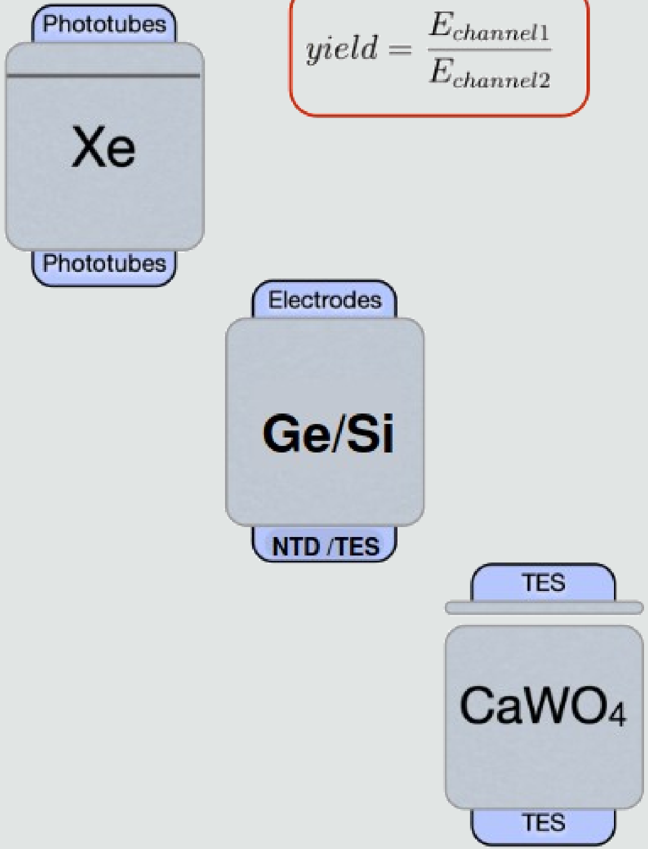
Expected 5σ observation sensitivity



Dark Matter direct detection

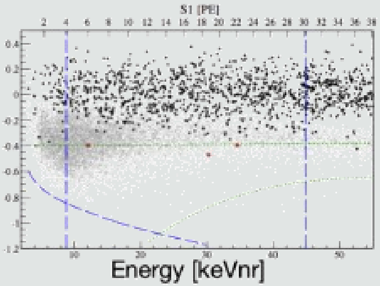


Dark Matter direct detection

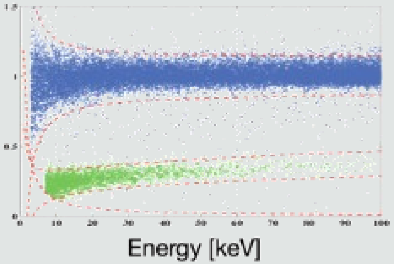


$$yield = \frac{E_{channel1}}{E_{channel2}}$$

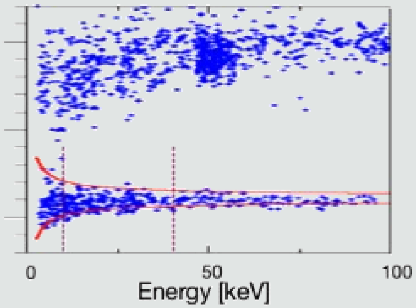
$\frac{\text{charge}}{\text{photons}}$



$\frac{\text{charge}}{\text{phonons}}$

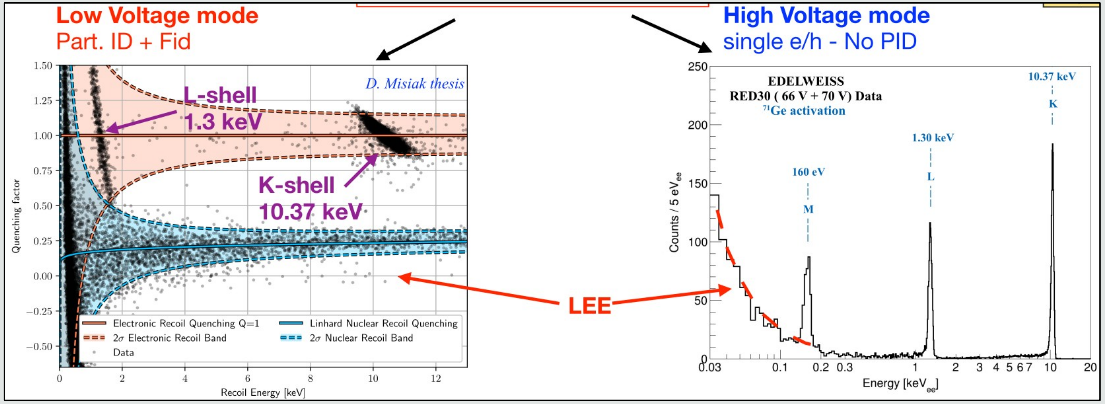


$\frac{\text{photons}}{\text{phonons}}$



Ge HV detector for TESSERACT

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\,eV} E_{ion}\Delta V$$



This technology was done in EDW, with 2 modes

- **Low Voltage** (LV) mode
- **High Voltage** (HV) mode

We see LEE in both cases

LV mode

- In orange: γ events centered around Q = 1 (due to calib)
- We see 1,3 keV and 10.37 keV lines from X-ray L- and K-lines from ^{71}Ge
- In blue: nuclear recoils

HV mode

Go to very low energy: observes K and L lines, but also M-shell line of ^{71}Ge (160 eV)

Ge HV detector for TESSERACT

→ Goal: enhance sensitivity to ERDM

- No PID
- Much lower threshold → ERDM

The scheme of electrodes gives ++ intense electric field near SSED (Superconducting Single Electron Detector) sensor

Most of Luke phonons at this location

SSED see burst of phonons coming from one electron → being able to tag one electron for an event

At 200 V (see CRYOSEL results)

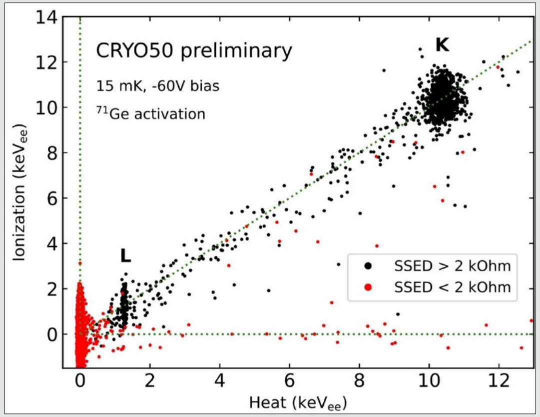
→ If you have single e-h sensitivity from heat (phonon) sensor
→ + this tagging from SSED

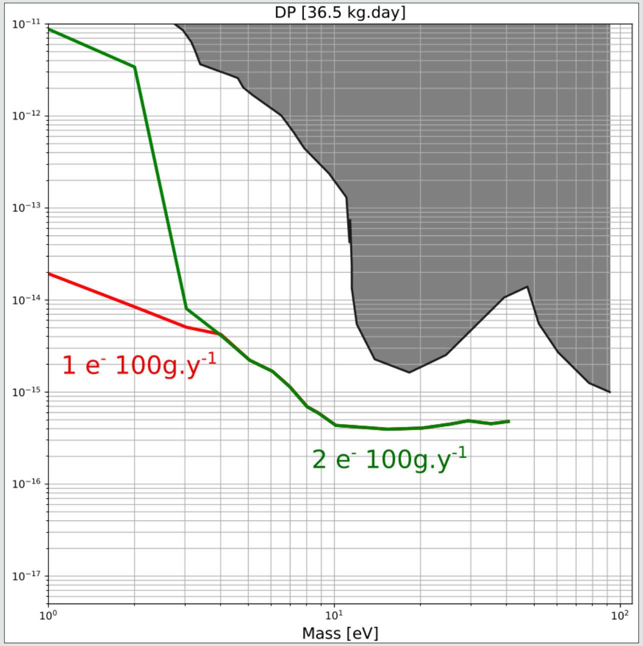
You reject all energy excess + very good single electron sensitivity

On top of that for TESSERACT:

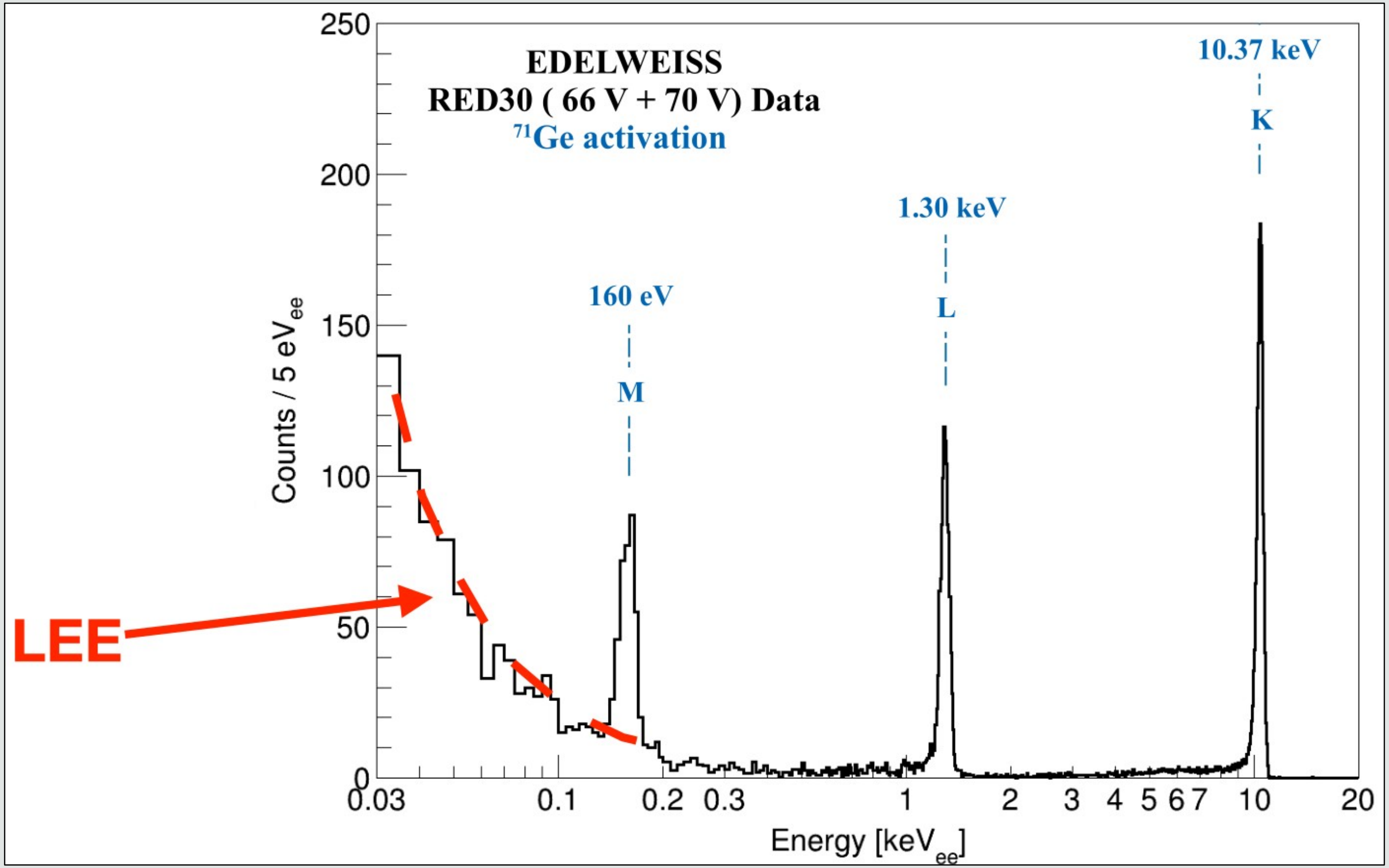
- Using TES for heat channel → sub-eV SSED energy threshold
- Very good control of IR bkg

→ very good sensitivities to ERDM processes with LEE discrimination

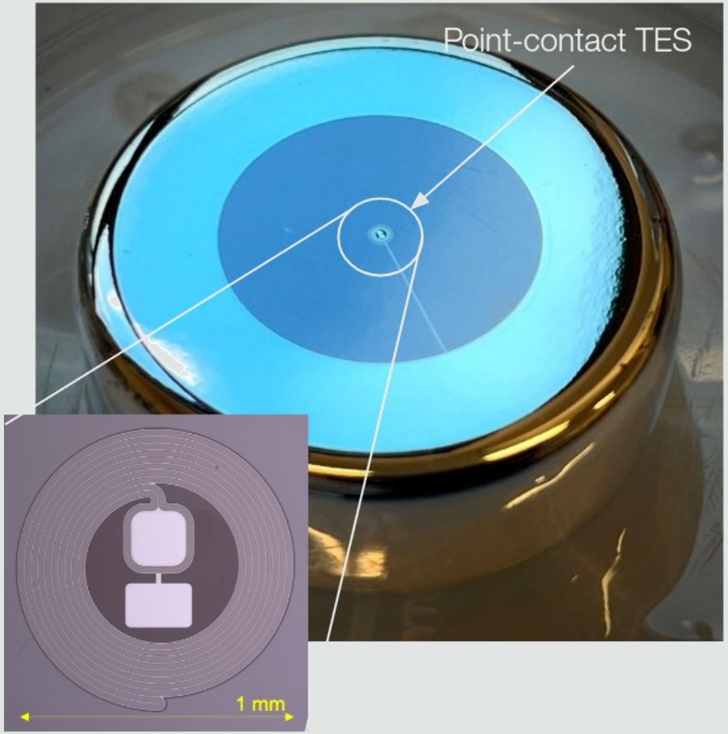


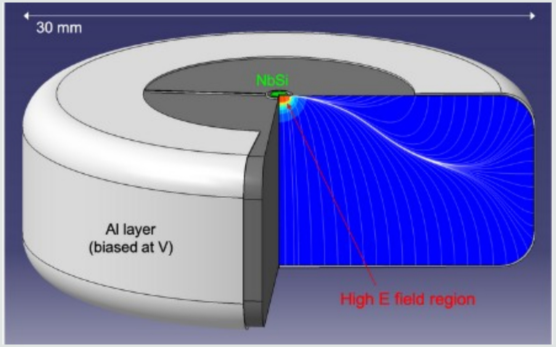


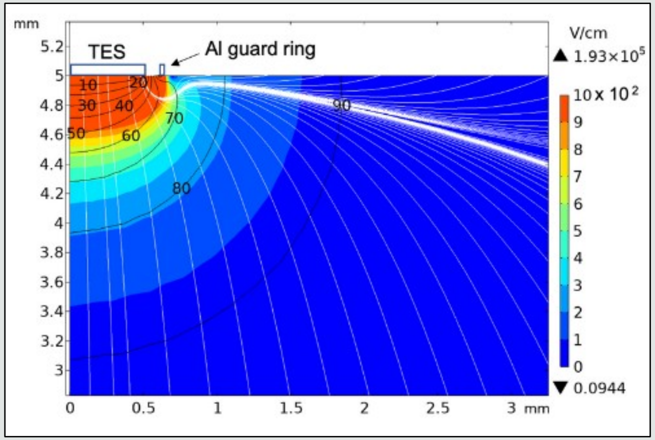
Ge HV detector for TESSERACT



Ge HV detector for TESSERACT



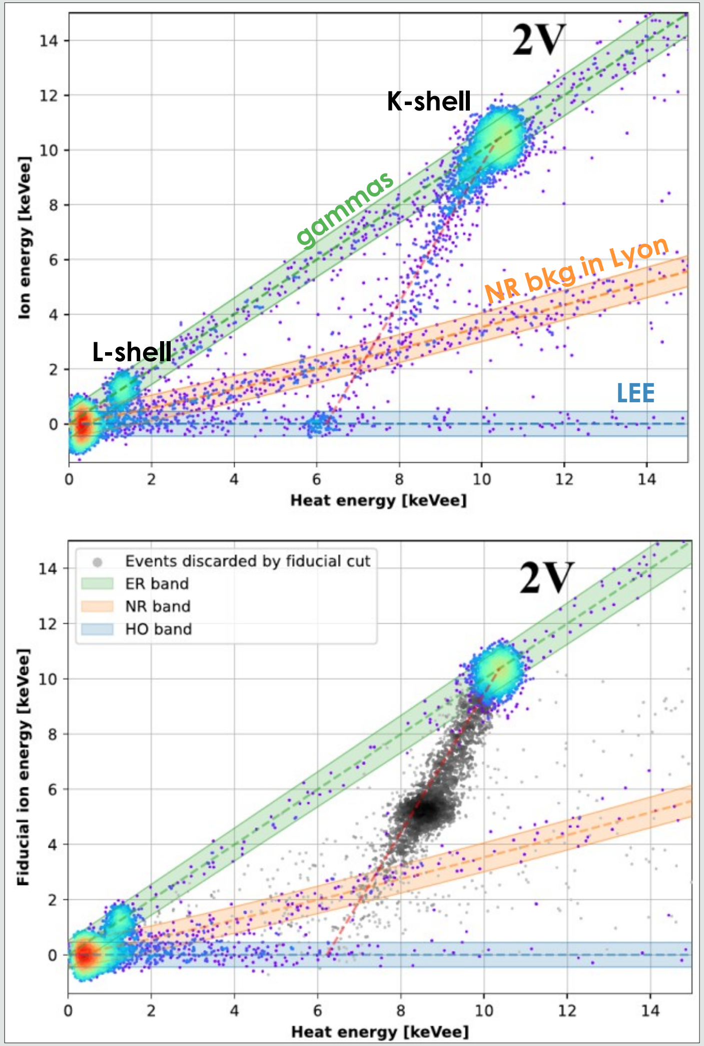




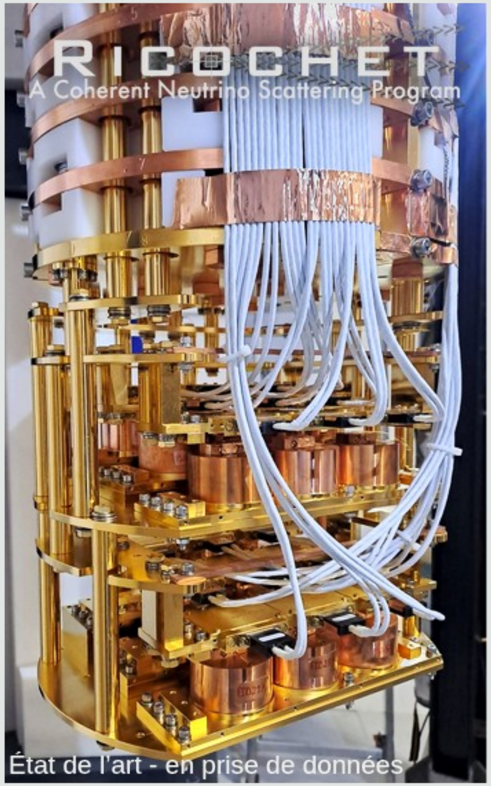
Ge LV detector for TESSERACT

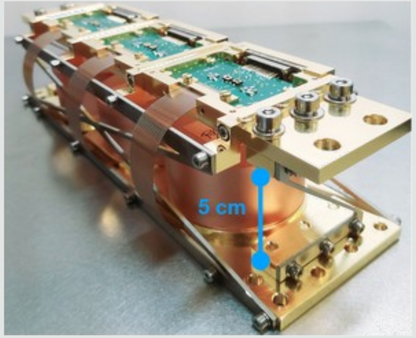
→ Goal: PID
Measure independently heat + ionization energy
Work at low voltage to avoid too many Luke phonons
Classic config: electrodes on both sides of crystal, measure ionization + heat energy
You see gamma population (K and L shell lines) + NR bkg in Lyon + LEE ("heat-only")

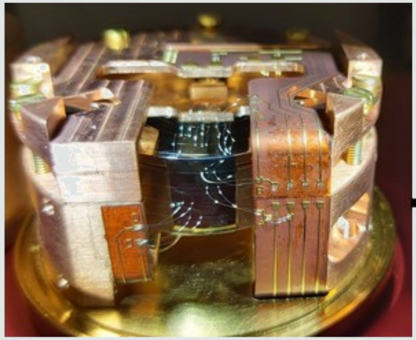
With FID electrode → rejecting surface events
Rejection surface bkg → proven by EDW



Ge LV detector for TESSERACT







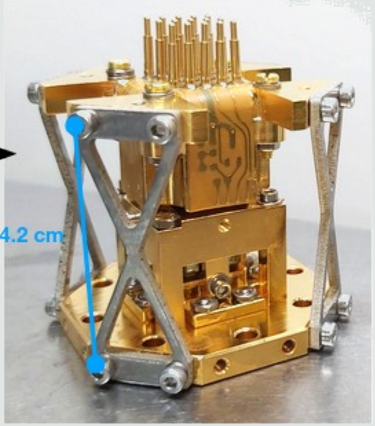
m 40 g
C_{det} 10 pF
C_{par} 40 pF
σ_{heat} 30 eVph
σ_{ion} 30 eVee

1ere étape - **Faisabilité**

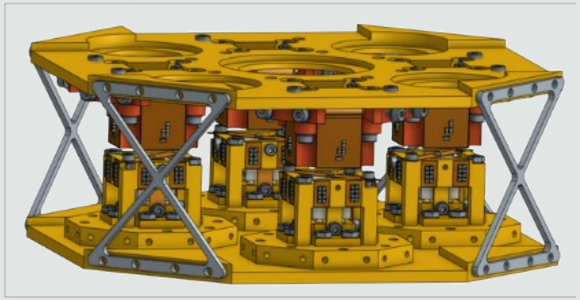
m 5 g
C_{det} 1 pF
C_{par} <10 pF
σ_{heat} 20 eVph
σ_{ion} 20 eVee

2eme étape - **Optimisation**

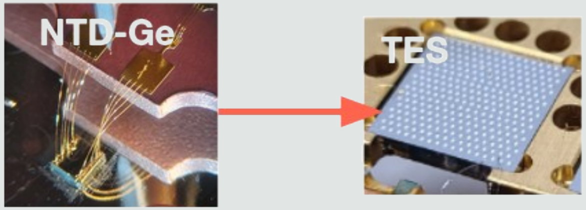
m 5 g
C_{det} 1 pF
C_{par} 1 pF
σ_{heat} 10 eVph
σ_{ion} 10 eVee



Technologie LV - **Forme finale**
Développement de la segmentation
4 x détecteur

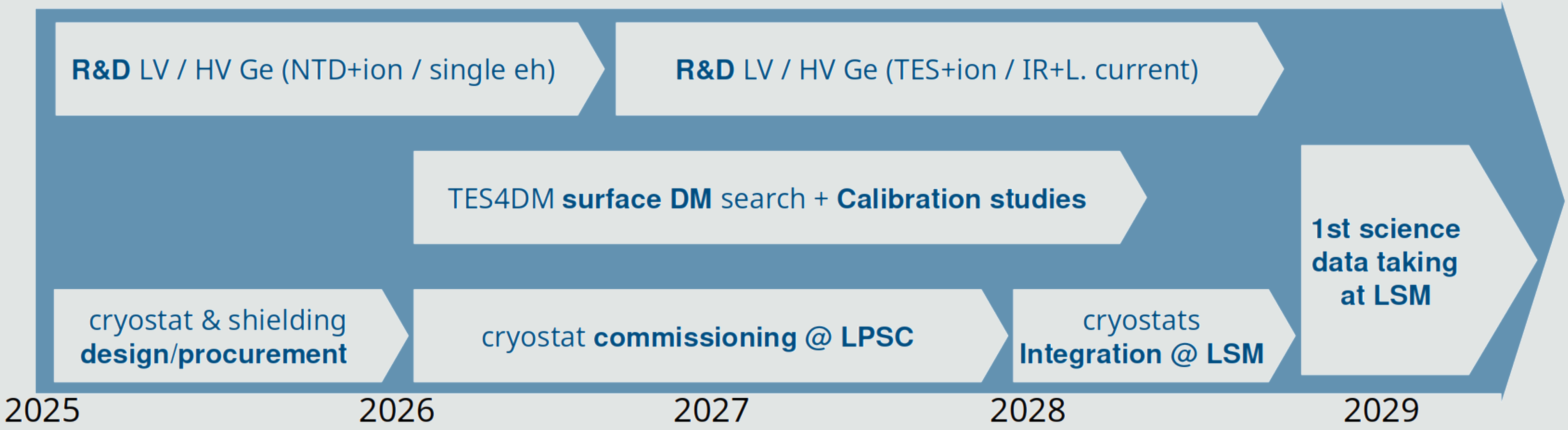


Transition technologique (LV-TES)



m 4x5 g
C_{det} 1 pF
C_{par} 1 pF
σ_{heat} 0.1 eVph
σ_{ion} 10 eVee

TESSERACT timeline with LV/HV

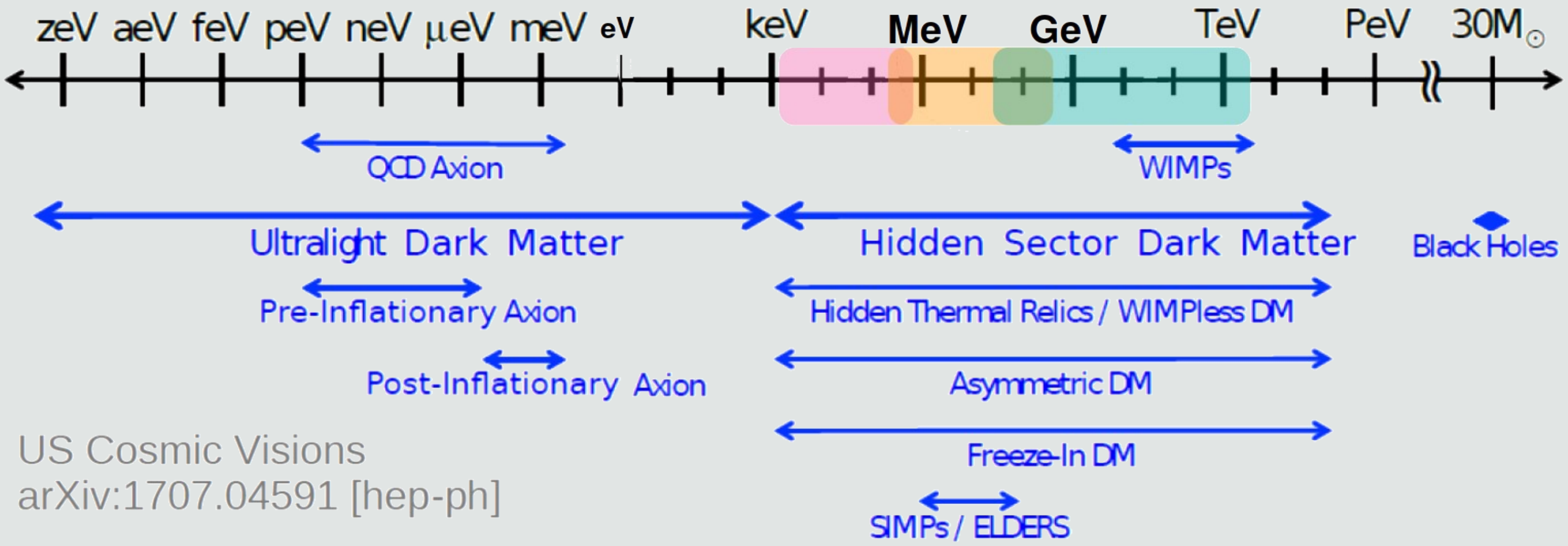


Summary of TESSERACT technologies

	Target	Search type	Mass range	LEE rejection	Particle ID
SPICE Polar crystals	Al_2O_3, SiO_2	ERDM	100 meV - MeV	Dual TES channel	None
SPICE Scintillator	GaAs	NRDM/ ERDM	eV - MeV MeV - GeV	Phonon/ photon coïncidence	Dual Phonon-photon readout
HeRALD LHe	He	NRDM	MeV - GeV	Multiple He4/photon detector	Pulse shape discriminatio n
Semicon. High V	**Ge, Si**	**ERDM**	**eV - MeV**	**SSED**	**None**
Semicon. Low V	**Ge, Si, C**	**NRDM**	**MeV - GeV**	**Phonon/ Ionization coincidence**	**Dual phonon-ionisation readout**

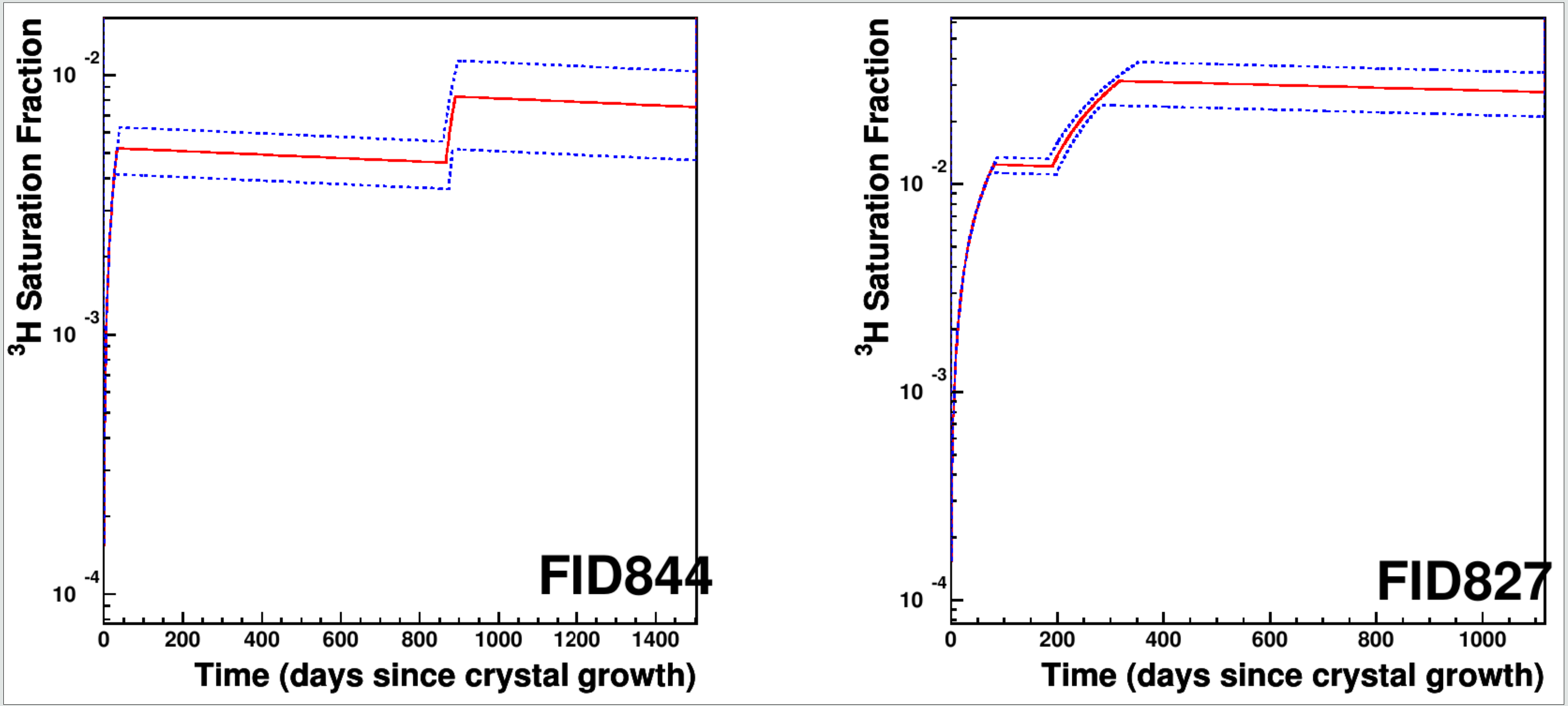
Dark matter candidates

DM-nucleus scattering (nucelar recoil)
DM-electron scattering (electron recoil)
Absorption (electron recoil)



US Cosmic Visions
arXiv:1707.04591 [hep-ph]

Cosmogenic activation of Edelweiss Ge crystals



From *Measurement of the cosmogenic activation of germanium detectors in EDELWEISS-III, 2016*