Bundesministerium
für Bildung
und Forschung

SFB 1258 Neutrinos
Dark Matter
Messengers

Towards xenon-doped liquid argon for LEGEND

STUDENT TALK
12'+3'

Christoph Vogl* for the TUM LAr team
*TU-Munich, Germany

NBIA Summer School on Neutrinos, July 17-21 2023, Copenhagen

LEGEND Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Introduction

Neutrinoless ββ Decay is a powerful probe of fundamental neutrino physics and cosmology

If proven to exist, we know that

- Lepton number conservation is violated
- Neutrinos are Majorana particles

[J. Schechter and J. W. F. Valle, 10.1103/PhysRevD.25.2951.]

NEUTRINOLESS
DOUBLE BETA
DECAY

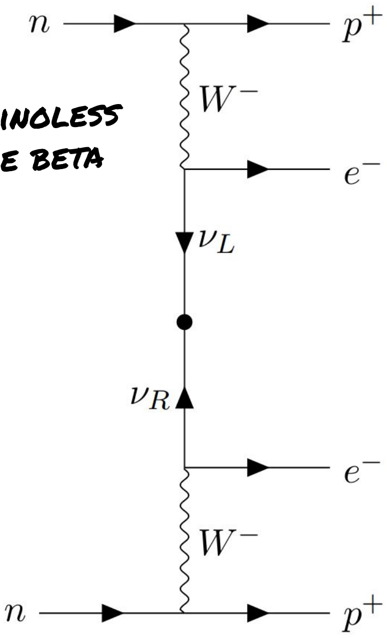


Fig.: Light Majorana neutrino exchange

Look for $0\nu\beta\beta$ where $2\nu\beta\beta$ happens, e.g. ^{136}Xe, ^{76}Ge

Strongest half-life limit on ^{76}Ge is 1.8 x 10^{26} yr, set by GERDA

[Phys. Rev. Lett. 125, 252502]

MUCH LONGER
THAN THE AGE OF
THE UNIVERSE!

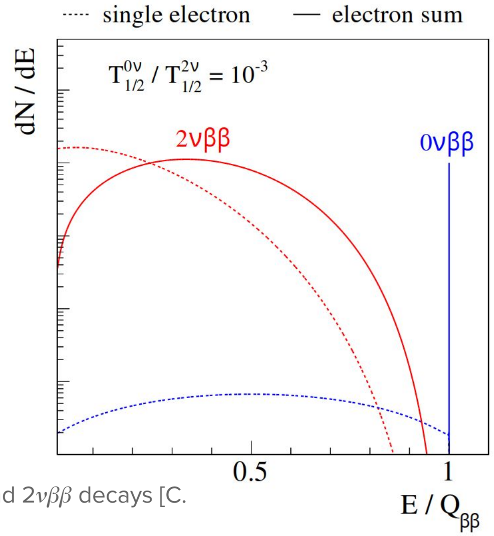
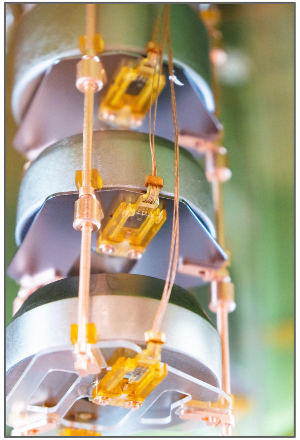
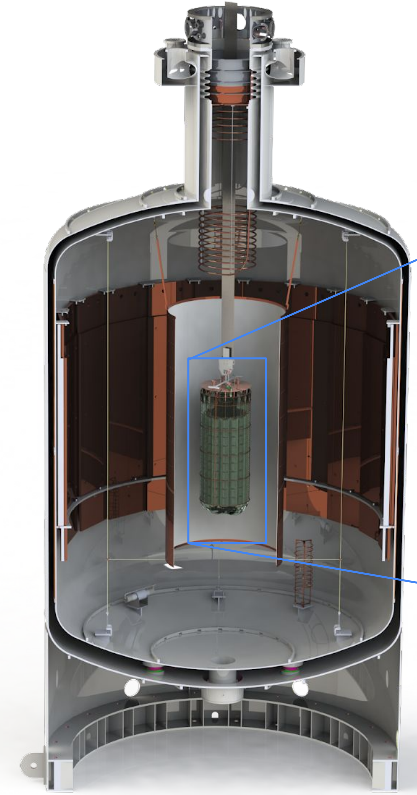


Fig.: Experimental signature of $0\nu\beta\beta$ and $2\nu\beta\beta$ decays [C. Wiesinger, PhD thesis, TUM, 2020]

LEGEND-200 builds upon the experience of GERDA and MAJORANA



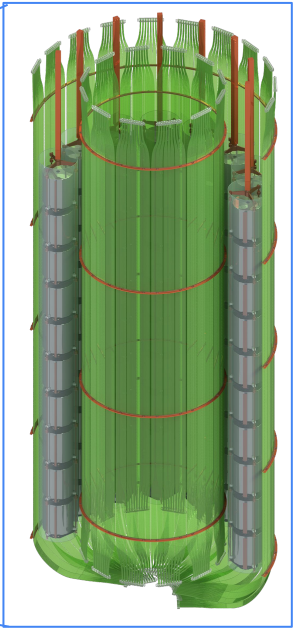
~200 kg of high-purity germanium detectors enriched in ^{76}Ge



64 m^3 liquid argon cryostat

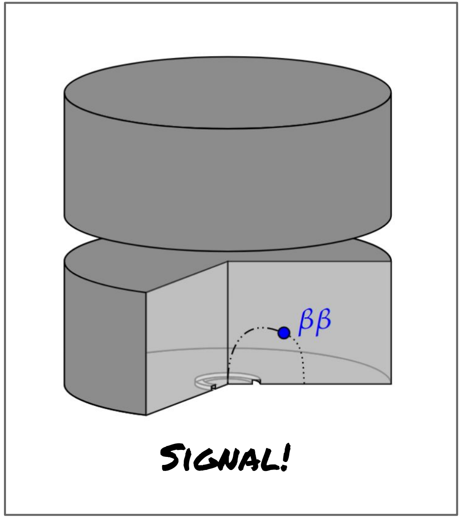
Wavelength-shifting and light guiding fibers connected to SiPMs

SCINTILLATION LIGHT IS READ OUT HERE

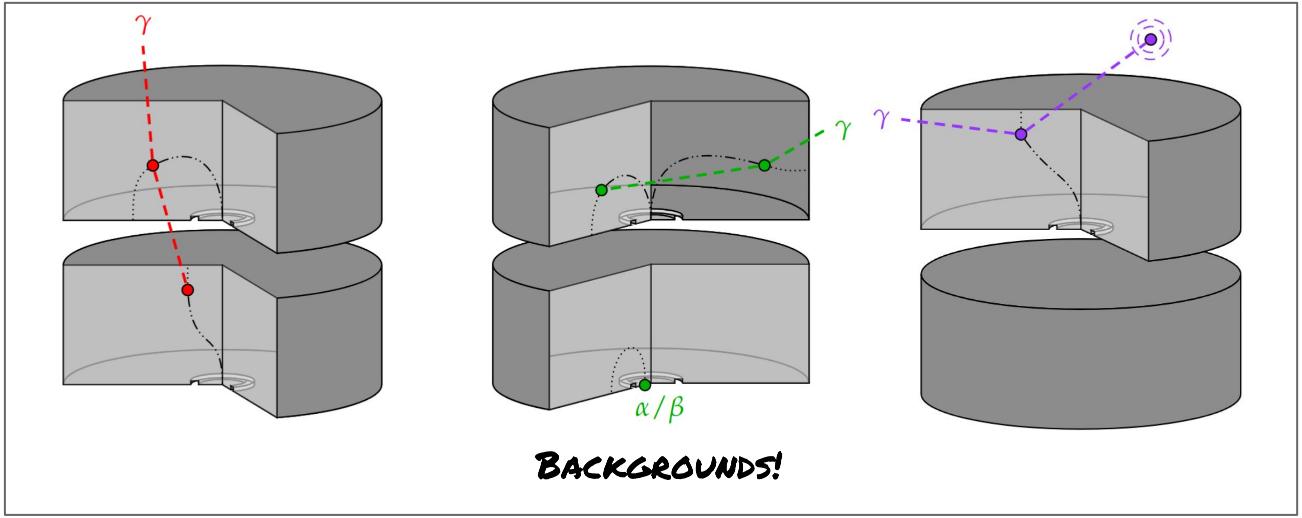


... AND HERE

Active background suppression in GERDA and LEGEND



[C. Wiesinger, PhD thesis, TUM, 2020]



Single-site, only one detector, and no LAr scintillation light → signal!

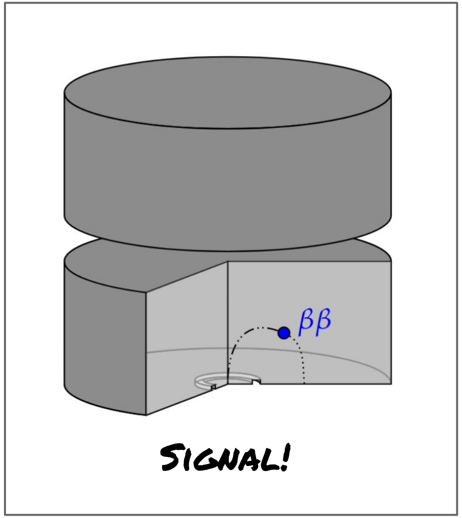
Multiple detectors → Ge anticoincidence cut

Multiple compton scattering and α or β backgrounds → pulse shape discrimination

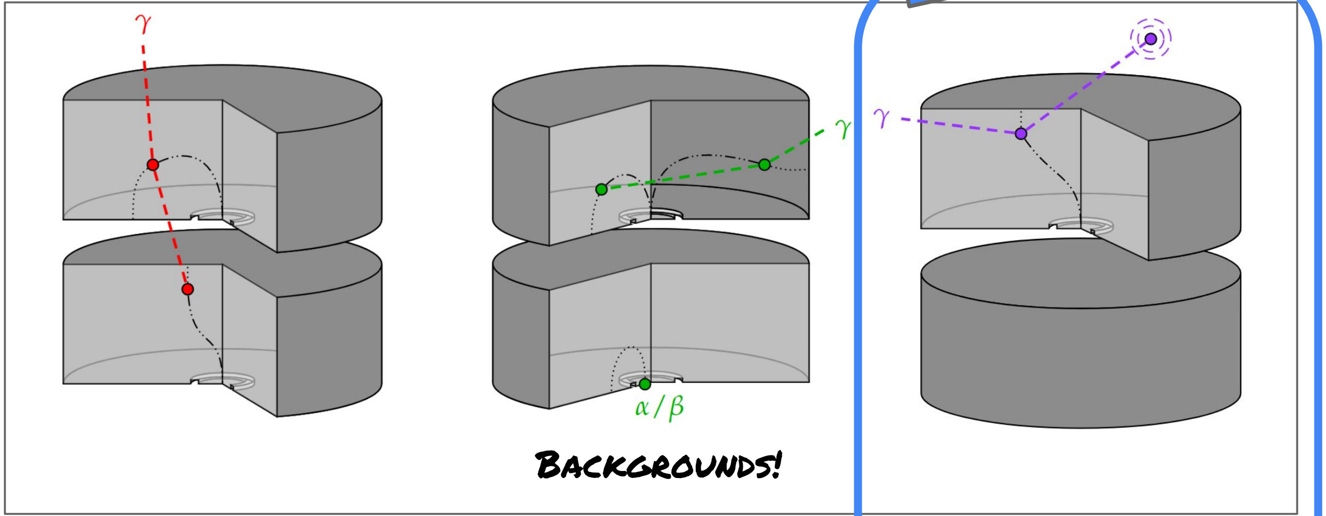
External γ background → LAr active shield

Active background suppression in GERDA LEGEND

Important for this talk!



[C. Wiesinger, PhD thesis, TUM, 2020]



Single-site, only one detector, and no LAr scintillation light → signal!

Multiple detectors → Ge anticoincidence cut

Multiple compton scattering and α or β backgrounds → pulse shape discrimination

External γ background → LAr active shield

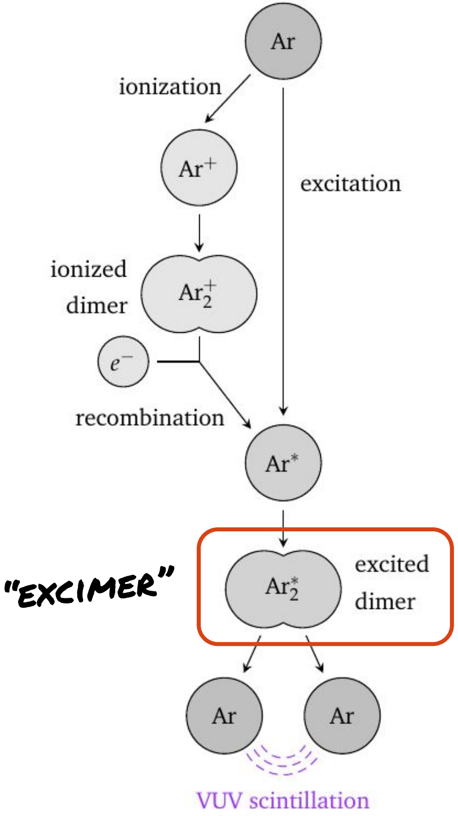
The scintillation process of LAr relies on excited argon dimer (excimer) formation

Either **ionization** & recombination, or **direct excitation** or Ar atom

In both cases argon excimers Ar^*_2 form at the end

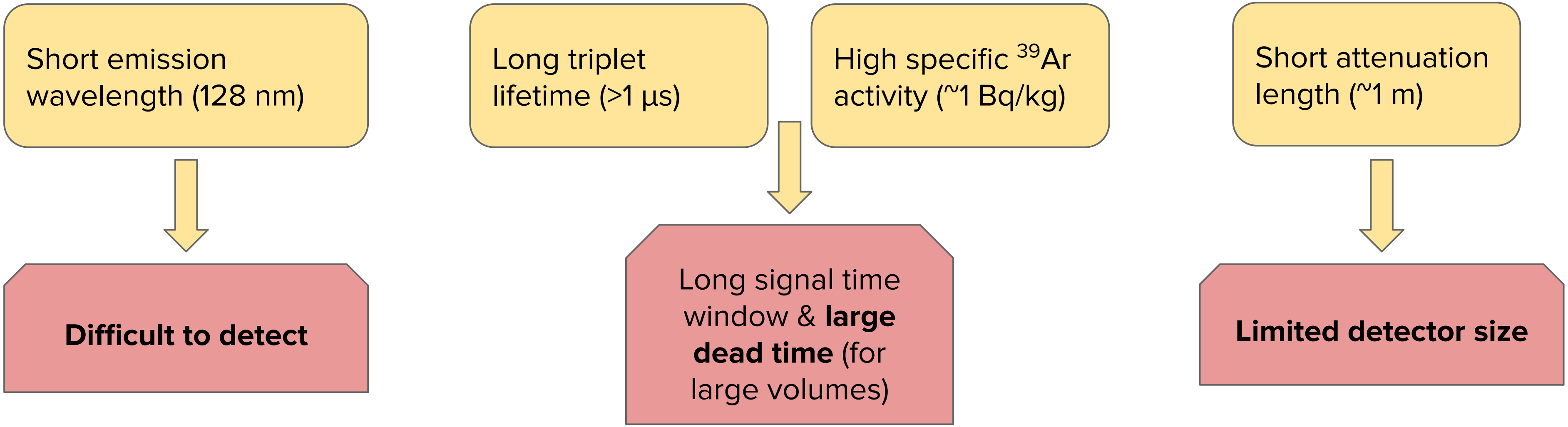
Ar_2^* has unstable **singlet** & metastable **triplet** state

Singlet lifetime 5-10 ns
Triplet lifetime **1.3-1.6 µs**



[C. Wiesinger, PhD thesis, TUM, 2020]

Pure LAr scintillation comes with some inconveniences



Short emission wavelength (128 nm)

Long triplet lifetime (>1 µs)

High specific ^{39}Ar activity (~1 Bq/kg)

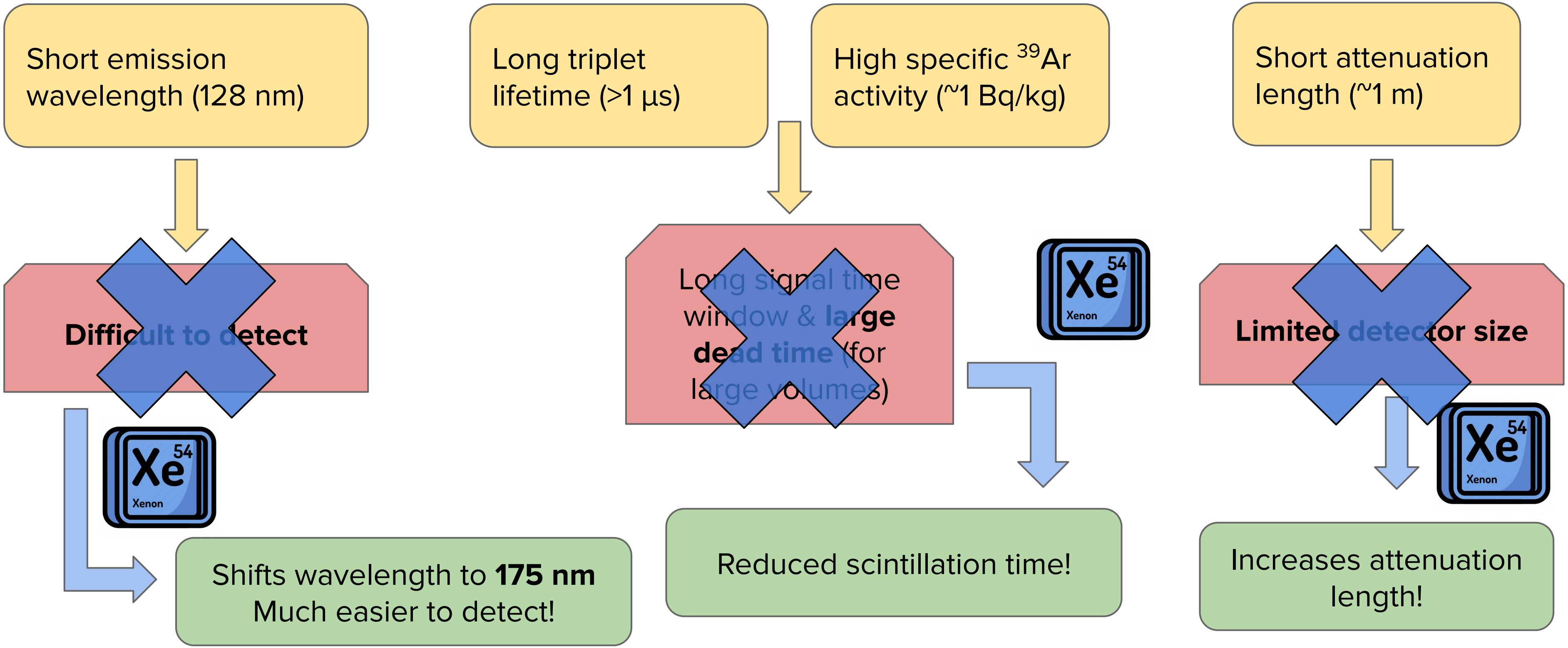
Short attenuation length (~1 m)

Difficult to detect

Long signal time window & **large dead time** (for large volumes)

Limited detector size

Xenon-doping addresses several problem of pure LAr scintillation



Short emission wavelength (128 nm)

~~**Difficult to detect**~~

Shifts wavelength to **175 nm**
Much easier to detect!

Long triplet lifetime (>1 µs)

High specific ^{39}Ar activity (~1 Bq/kg)

~~Long signal time window & **large dead time** (for large volumes)~~

Reduced scintillation time!

Short attenuation length (~1 m)

~~**Limited detector size**~~

Increases attenuation length!

XeDLAr scintillation measurements

XeDLAr scintillation is observed by a triggered SiPM array, LLAMA

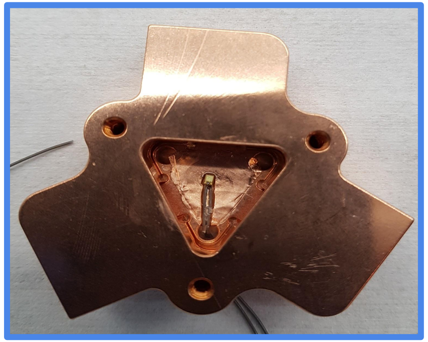
LLAMA measures **simultaneously**

- The photoelectron yield Y
- Effective triplet lifetime τ_3
- Effective attenuation length λ_{att}

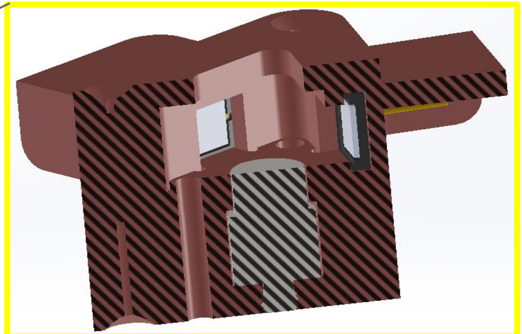
with 16 VUV sensitive SiPMs (Hamamatsu VUV4) located at different distances from the light source.

LLAMA: Legend Liquid Argon Monitoring Apparatus
[M. Schwarz et al., *ANIMMA 2021* (July 2021)]

85 CM TALL



An ^{241}Am source emitting 60 keV photons induces scintillation. The 3 source SiPMs **detect** the **light** at **~1 cm distance** from the interaction point



The xenon concentration is measured from the gaseous and liquid phases with IDEFIX

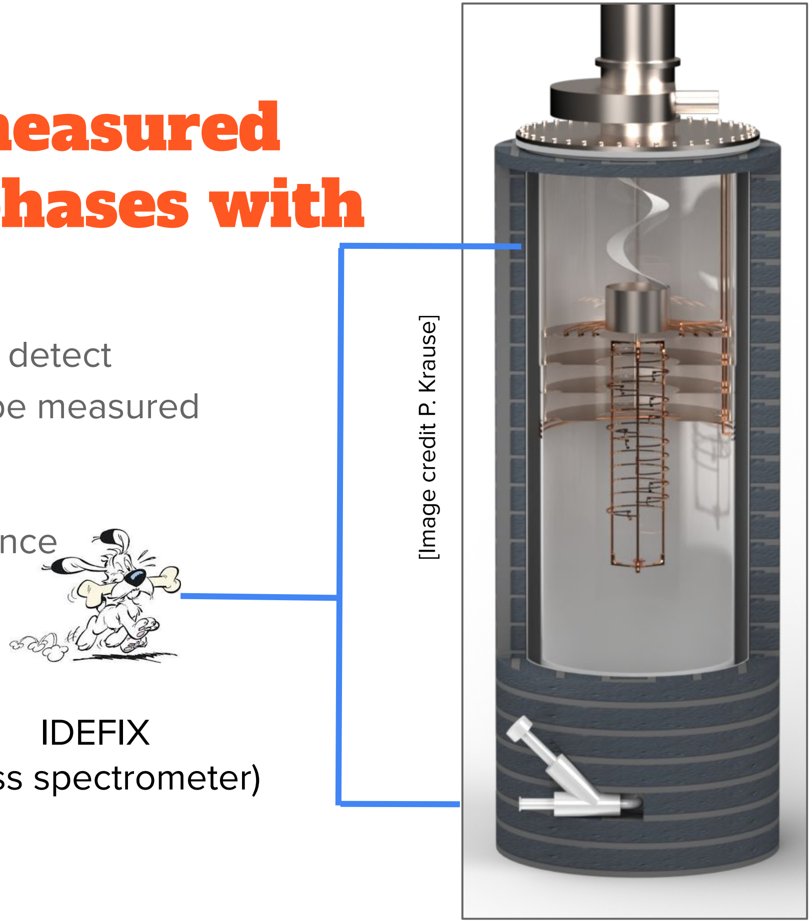
The Impurity DEtector For Investigation of Xenon (IDEFIX) can detect substances with masses less than 128 u (higher masses may be measured via higher order ionization).

The sensitivity is 30 µL/L to 0.5 µL/L depending on the substance

Substance (mass)	Sensitivity [µL/L]
Nitrogen (28)	~ 30
Oxygen (32)	~ 0.5
Xenon (134)	**~ 0.8**

[M. Guevara, B.Sc. thesis, TUM, 2023]

µL/L = PPM BY VOLUME OR MOLE

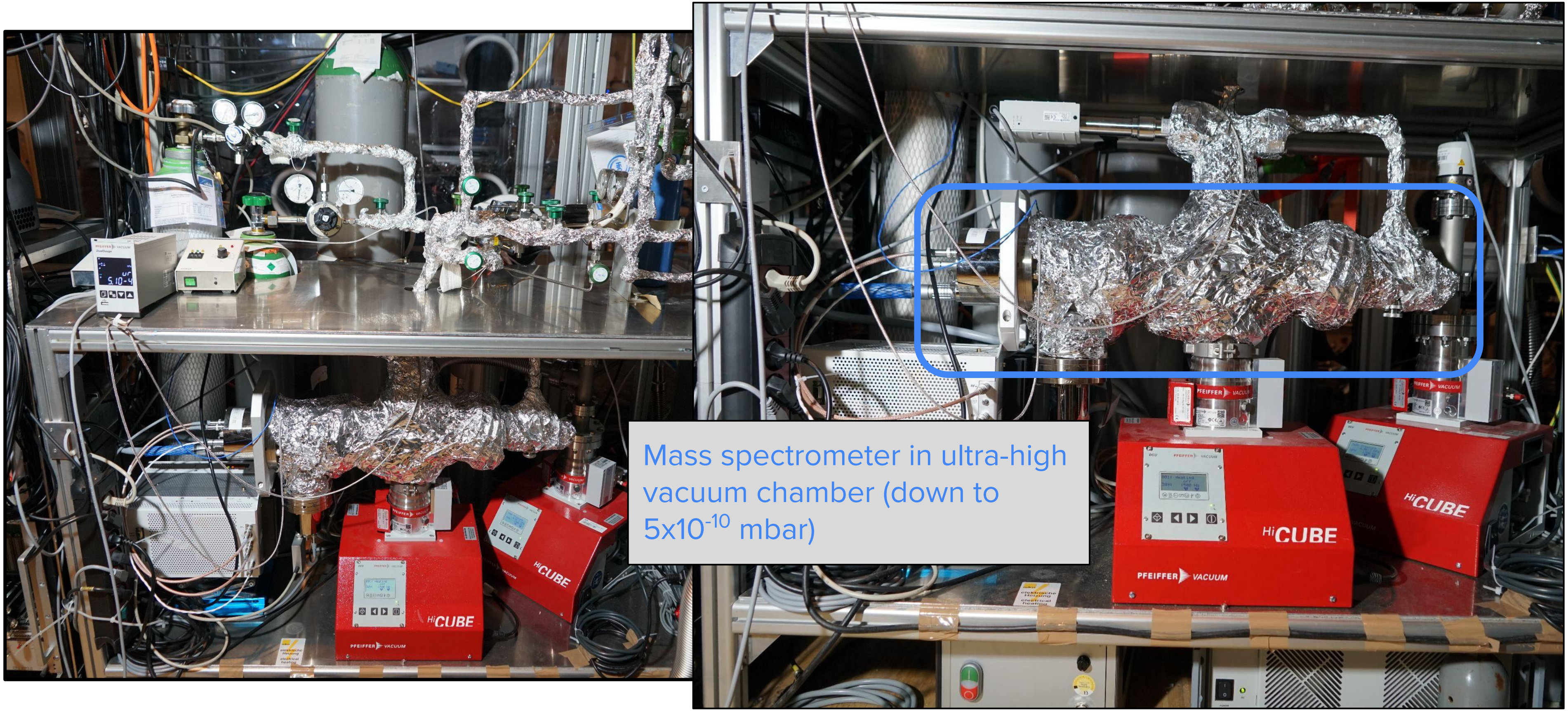


IDEFIX
(mass spectrometer)

[Image credit P. Krause]

SCARF
(1 ton (XeD)LAr cryostat

SCARF = SUBTERRANEAN CRYOGENIC ARGON FACILITY



Mass spectrometer in ultra-high vacuum chamber (down to 5×10^{-10} mbar)

Scintillation parameters for different Xe concentrations

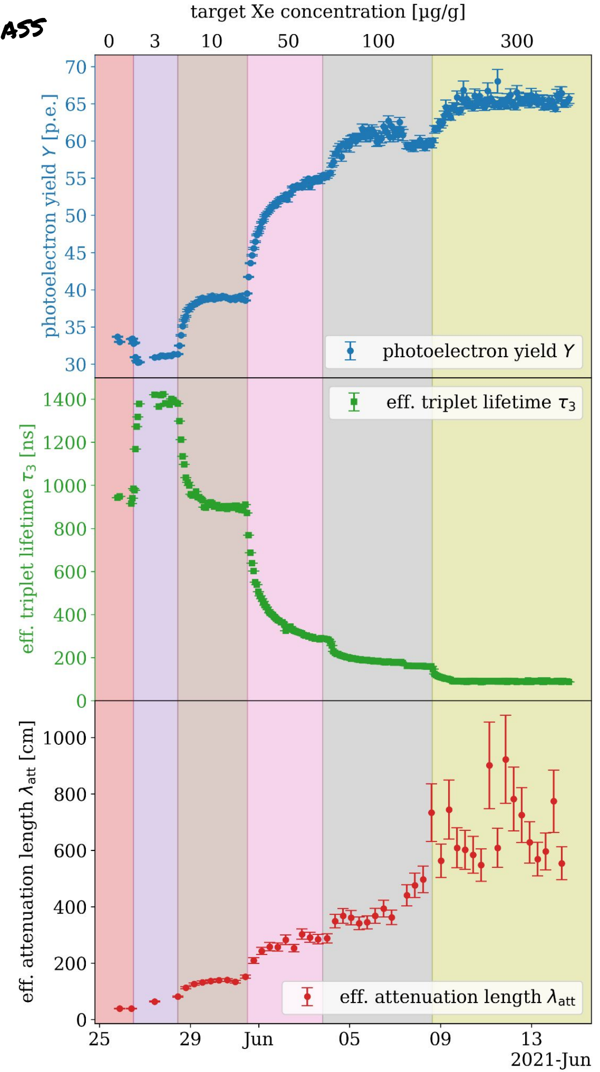
General trend:

- Increase of p.e. yield and eff. attenuation length due to increased PDE and undone impurity quenching
- Decrease of effective triplet lifetime

Surprising observation:

- Decrease of p.e. yield and increase of effective triplet (from ~900 ns) lifetime at 3 ppm Xe w.r.t. 0 ppm
- Could be due to energy transfer mechanism and long-lived intermediate state

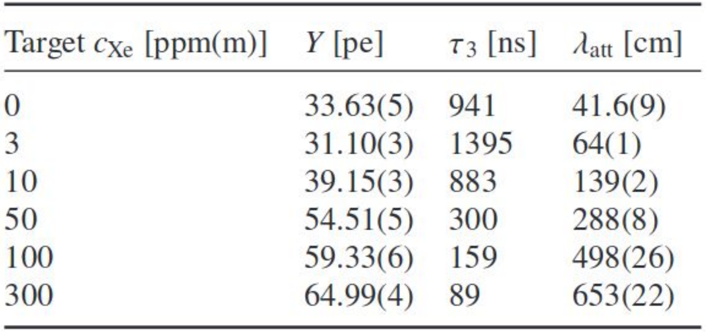
[C. Vogl *et al* 2022 *JINST* **17** C01031]



µG/G = PPM BY MASS

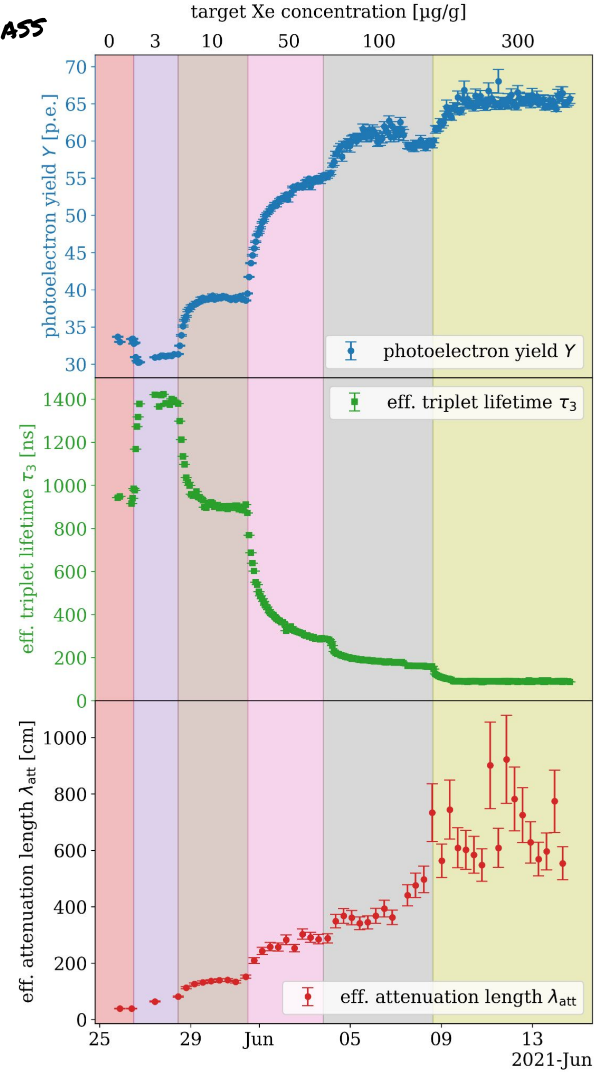
µG/G = PPM BY MASS

Scintillation parameters for different Xe concentrations



Target c_{Xe} [ppm(m)]	Y [pe]	τ_3 [ns]	λ_{att} [cm]
0	33.63(5)	941	41.6(9)
3	31.10(3)	1395	64(1)
10	39.15(3)	883	139(2)
50	54.51(5)	300	288(8)
100	59.33(6)	159	498(26)
300	64.99(4)	89	653(22)

Consolidation of stable phases



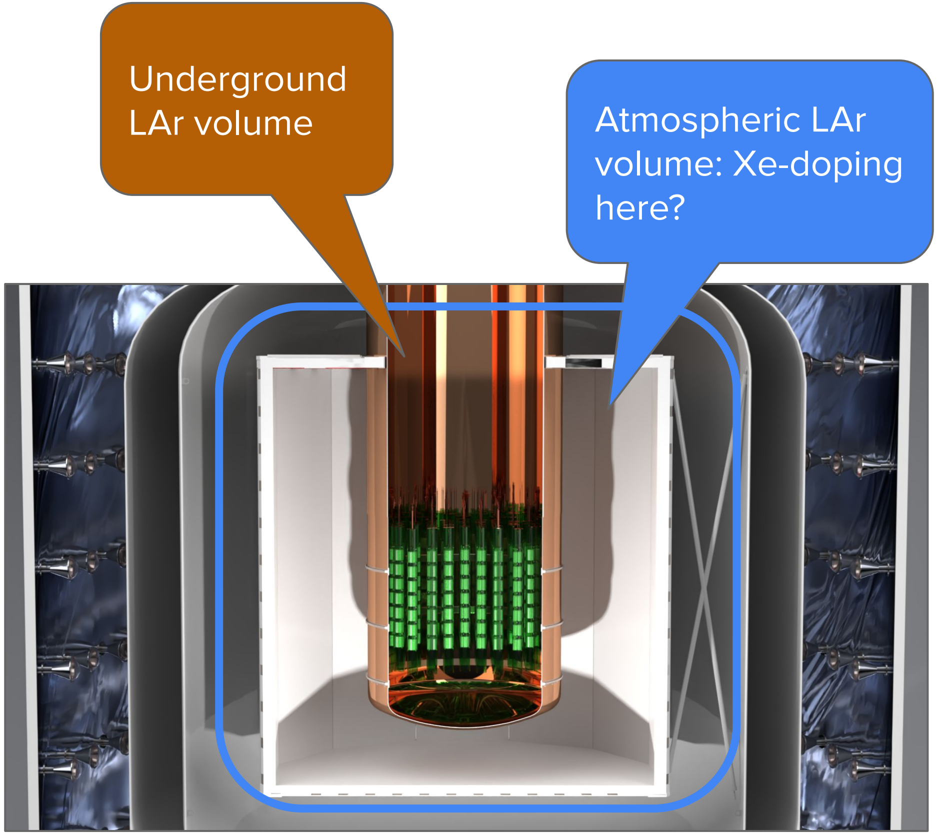
At 300 µg/g Xe in LAr the

- p.e. yield doubles
- effective triplet lifetime decreases to 90 ns
- effective attenuation length is > 6 m

[C. Vogl *et al* 2022 *JINST* **17** C01031]

Impact on LEGEND

- Currently: Xe-doping as an R&D project for LEGEND-1000
- Soon: Might get promoted to baseline design in the conceptual design report (CDR)
- If so, strong argument to test it already in LEGEND-200



Underground LAr volume

Atmospheric LAr volume: Xe-doping here?

LEGEND-1000 cryostat (single string design) © LEGEND collaboration

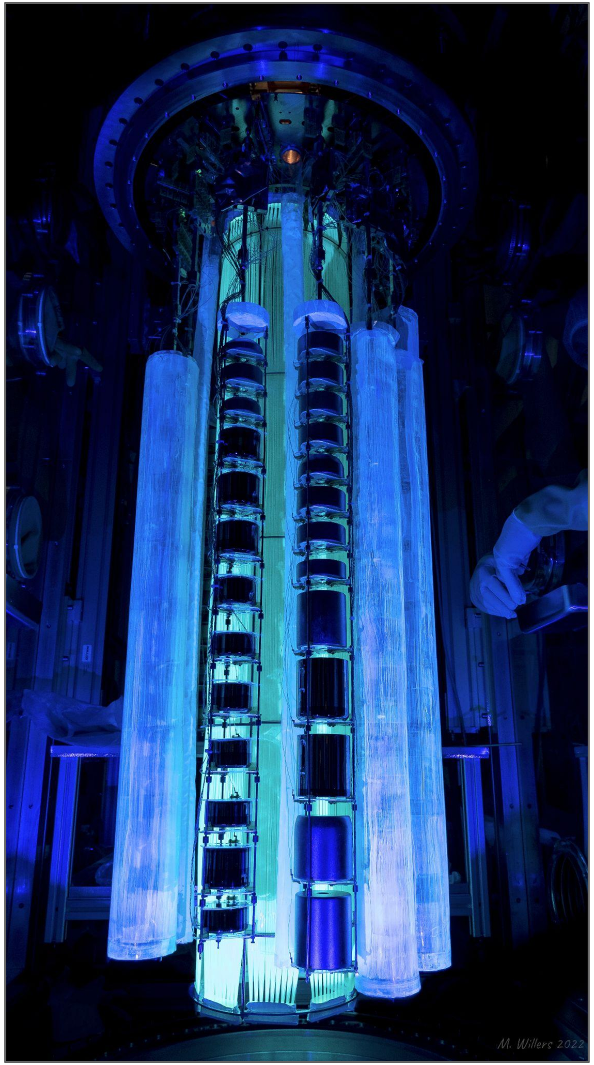
Summary

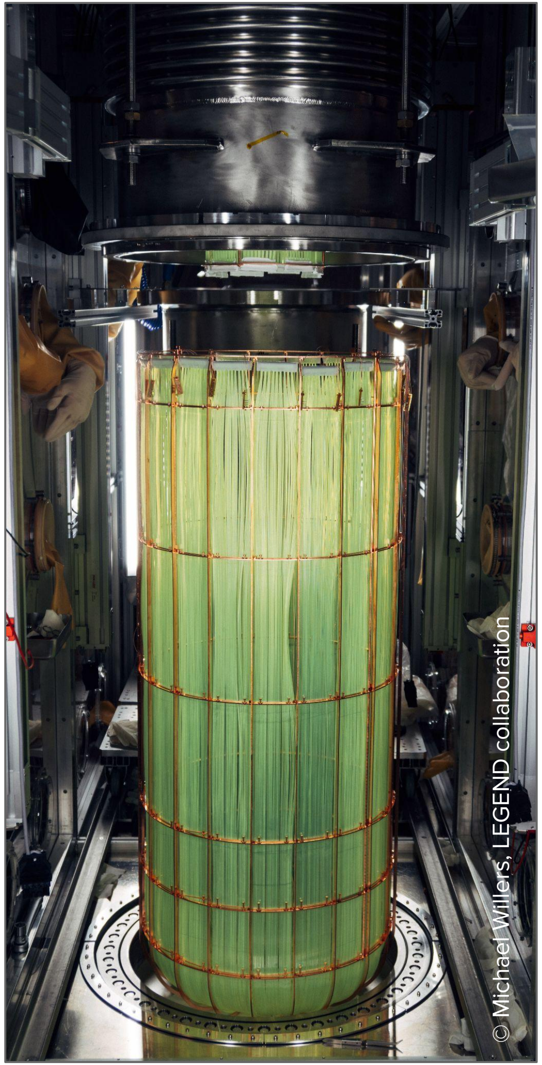
Active background suppression with LAr scintillation light read-out is important for LEGEND

LAr scintillation is great, and even better with xenon doping

LEGEND will further pursue R&D on XeDLAr and might adopt it as baseline design for L-1000

For more details, just ask ;)
After the school you can send me an email to christoph.vogl@tum.de

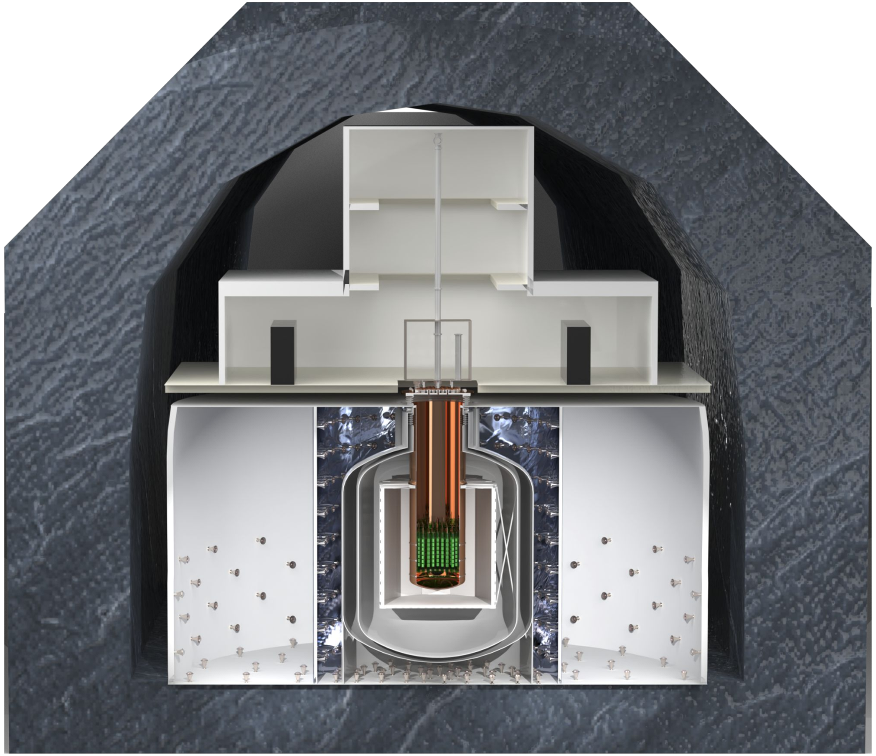




© Michael Willers, LEGEND collaboration

Backup

LEGEND-1000 is the next generation ^{76}Ge ββ experiment and features



1000 kg of enriched Ge detector mass

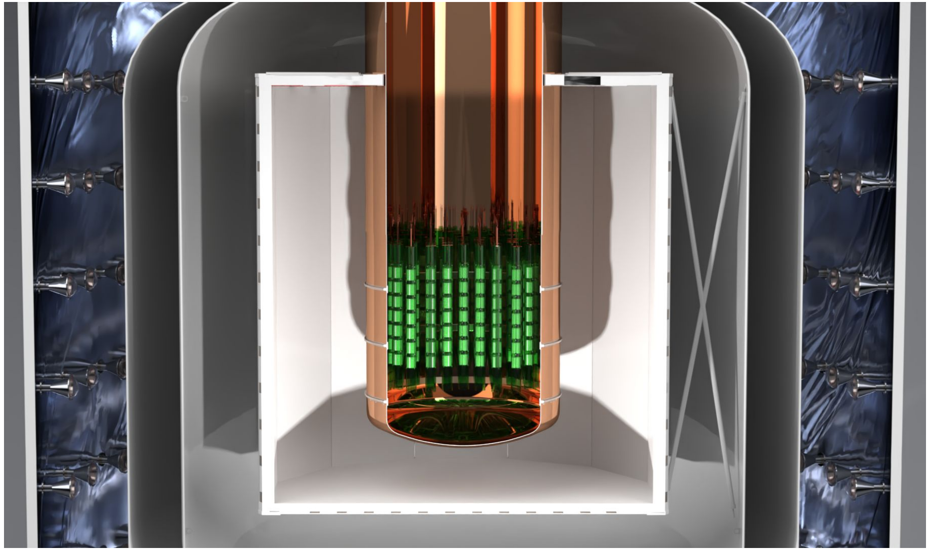
180 ton outer LAr mass (ALAr)

22 ton inner LAr mass (UGLAr) contained in ultra-clean copper tube

10^{28} yr discovery sensitivity for 10 t yr exposure and 9-21 meV $m_{\beta\beta}$ sensitivity fully covering inverted ordering

(10^{27} yr for L-200 for 1 t yr exposure and 30-40 meV $m_{\beta\beta}$ sensitivity)

LEGEND-1000 single string design



© LEGEND collaboration

BSM opportunities for LEGEND-1000

From the pre-conceptual design report (pCDR), arXiv:2107.11462v1

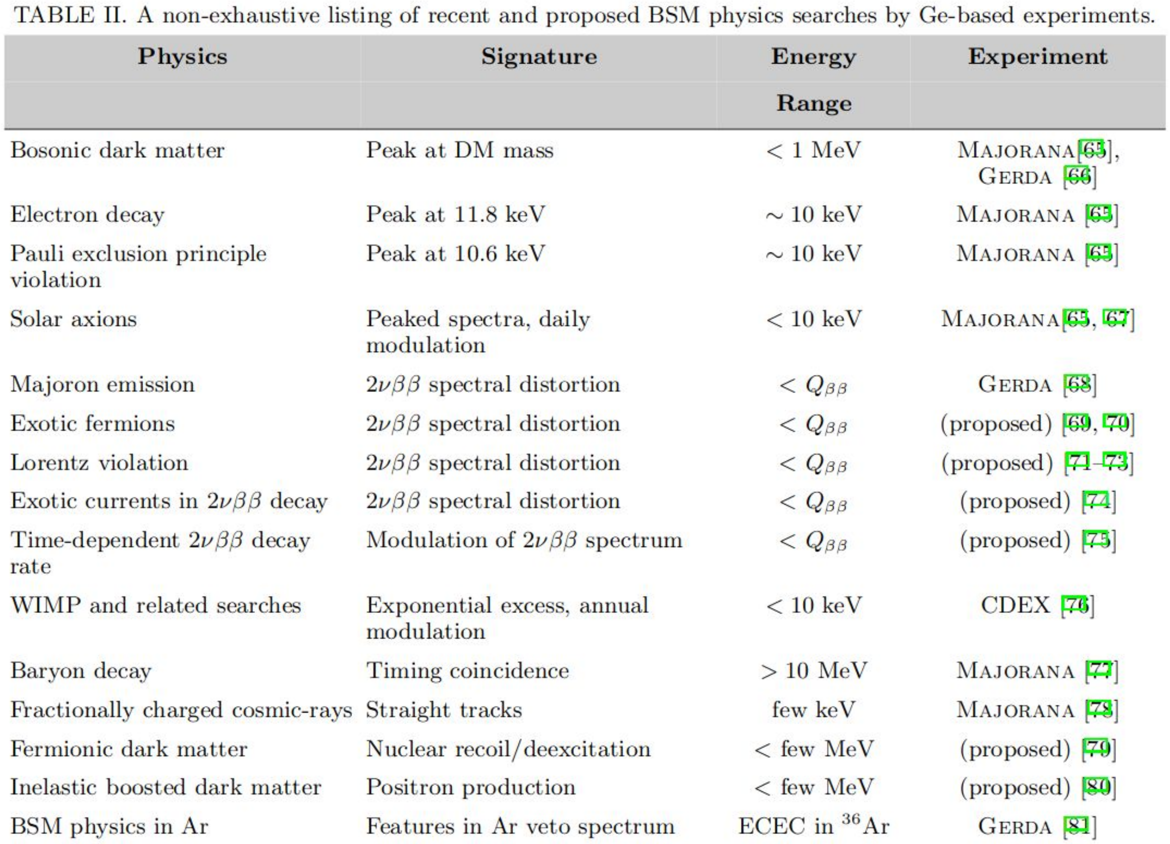


TABLE II. A non-exhaustive listing of recent and proposed BSM physics searches by Ge-based experiments.

Physics	Signature	Energy Range	Experiment
Bosonic dark matter	Peak at DM mass	< 1 MeV	Majorana[65], Gerda [66]
Electron decay	Peak at 11.8 keV	~ 10 keV	Majorana [65]
Pauli exclusion principle violation	Peak at 10.6 keV	~ 10 keV	Majorana [65]
Solar axions	Peaked spectra, daily modulation	< 10 keV	Majorana[65, 67]
Majoron emission	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	Gerda [68]
Exotic fermions	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [69, 70]
Lorentz violation	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [71–73]
Exotic currents in $2\nu\beta\beta$ decay	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [74]
Time-dependent $2\nu\beta\beta$ decay rate	Modulation of $2\nu\beta\beta$ spectrum	$< Q_{\beta\beta}$	(proposed) [75]
WIMP and related searches	Exponential excess, annual modulation	< 10 keV	CDEX [76]
Baryon decay	Timing coincidence	> 10 MeV	Majorana [77]
Fractionally charged cosmic-rays	Straight tracks	few keV	Majorana [78]
Fermionic dark matter	Nuclear recoil/deexcitation	$<$ few MeV	(proposed) [79]
Inelastic boosted dark matter	Positron production	$<$ few MeV	(proposed) [80]
BSM physics in Ar	Features in Ar veto spectrum	ECEC in ^{36}Ar	Gerda [81]

XeDLAr scintillation mechanism #1

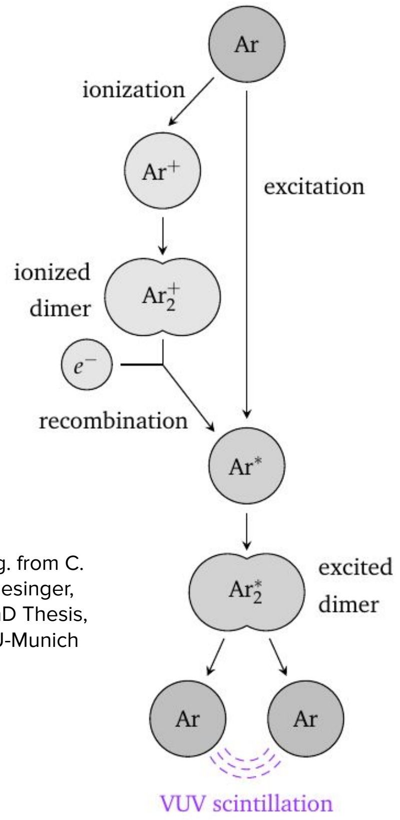


Fig. from C. Wiesinger, PhD Thesis, TU-Munich

The scintillation of XeDLAr relies first on the formation of Ar excimers via the usual pathway (left), and then on collisions:

$Ar_2^* + Xe \rightarrow Xe^* + Ar_2$

$Xe^* + Ar \rightarrow ArXe^*$

$ArXe^* + Xe \rightarrow Xe_2^* + Ar$

The reaction rate depends on the xenon concentration. At reasonable xenon concentrations (< 1000 ppm), mostly triplet state argon excimers are shifted.

Ar_2^*	4-10 ns singlet, 1.3-1.6 µs triplet	128 nm
$ArXe^*$	4.7 µs	149 nm
Xe_2^*	4 ns singlet, 22 ns triplet	175 nm

[Neumeier PhD thesis, G Nowak and J Fricke 1985 J. Phys. B: Atom. Mol. Phys. 18 1355, Soto-Oton: arXiv:2109.05858v1]

XeDLAr scintillation mechanism #2

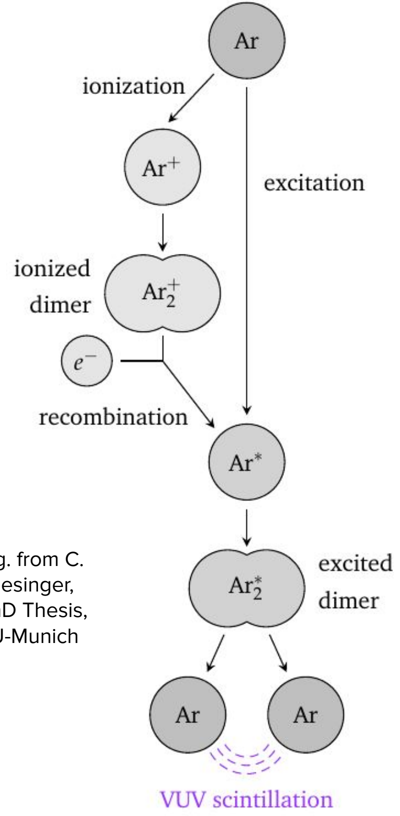


Fig. from C. Wiesinger, PhD Thesis, TU-Munich

Alternatively, xenon excimers can form starting with an initial photoexcitation by LAr scintillation light

$Xe + \gamma \rightarrow Xe^*$

$Xe^* + Ar \rightarrow ArXe^*$

$ArXe^* + Xe \rightarrow Xe_2^* + Ar$

Ar_2^*	4-10 ns singlet, 1.3-1.6 μs triplet	128 nm
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[Neumeier PhD thesis, G Nowak and J Fricke 1985 J. Phys. B: Atom. Mol. Phys. 18 1355, Soto-Oton: arXiv:2109.05858v1]

VUV4 SiPM PDE - Source of increase in p.e. yield?

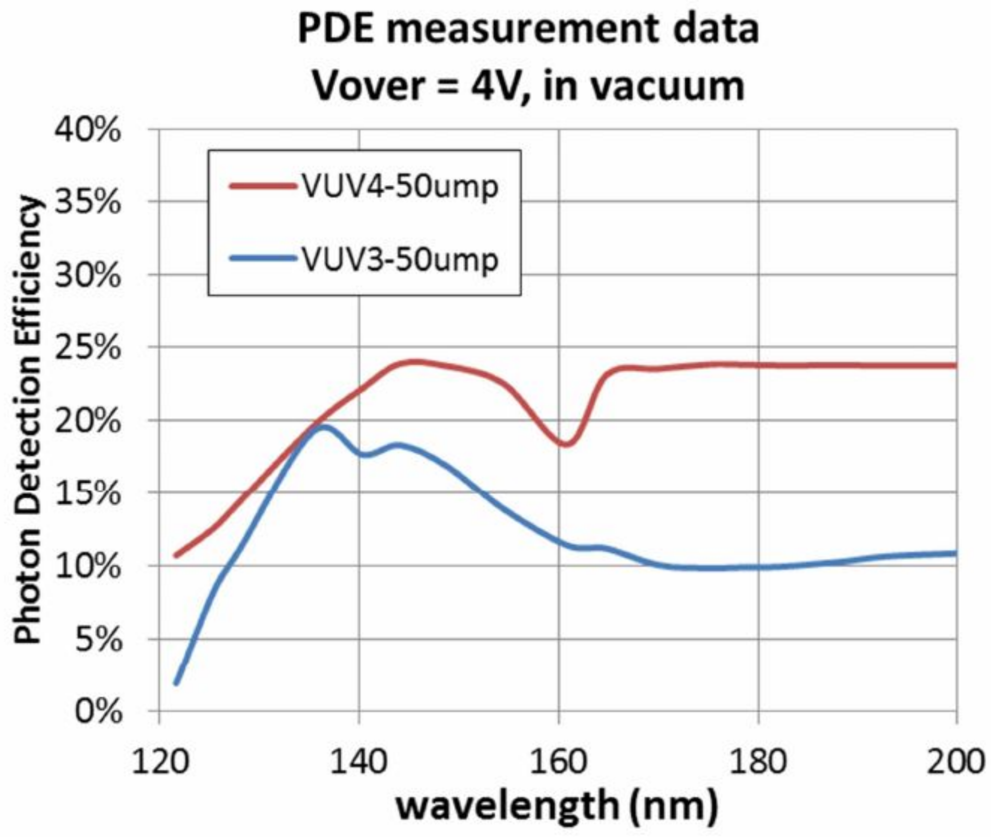
14% PDE at 128 nm (VUV4 in LLAMA)

24% PDE at 175 nm

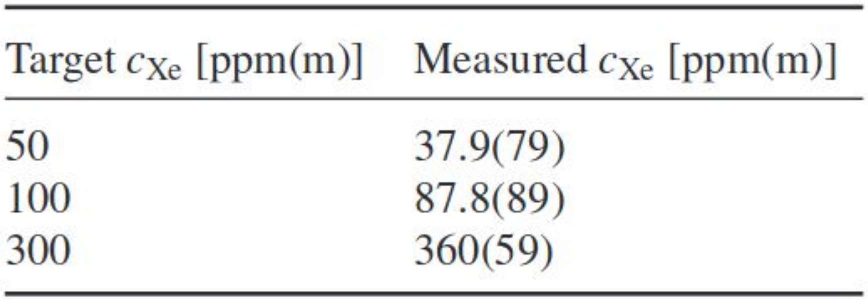
Assume perfect, monoenergetic shifting
➡ p.e. yield increase of factor of 1.6

Second effect: Recovery of quenched light. Initial p.e. yield reduced to ~80 % due to 0.3 ppm O_2.

➡ from 0.8 to 1.6 the increase is a factor of 2, compatible with observations



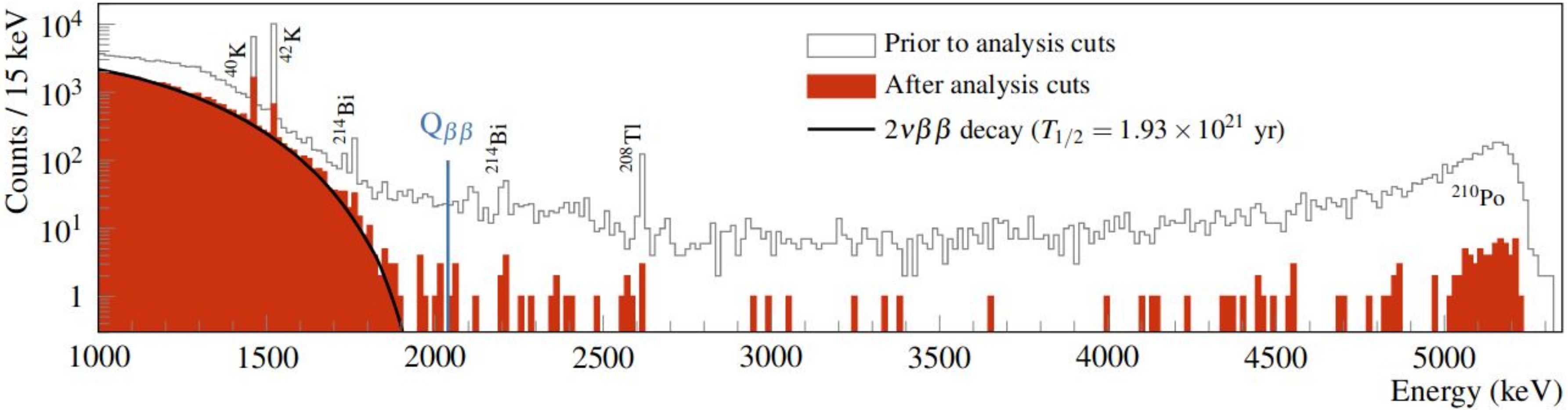
Successful injection of Xe into LAr



Target c_{Xe} [ppm(m)]	Measured c_{Xe} [ppm(m)]
50	37.9(79)
100	87.8(89)
300	360(59)

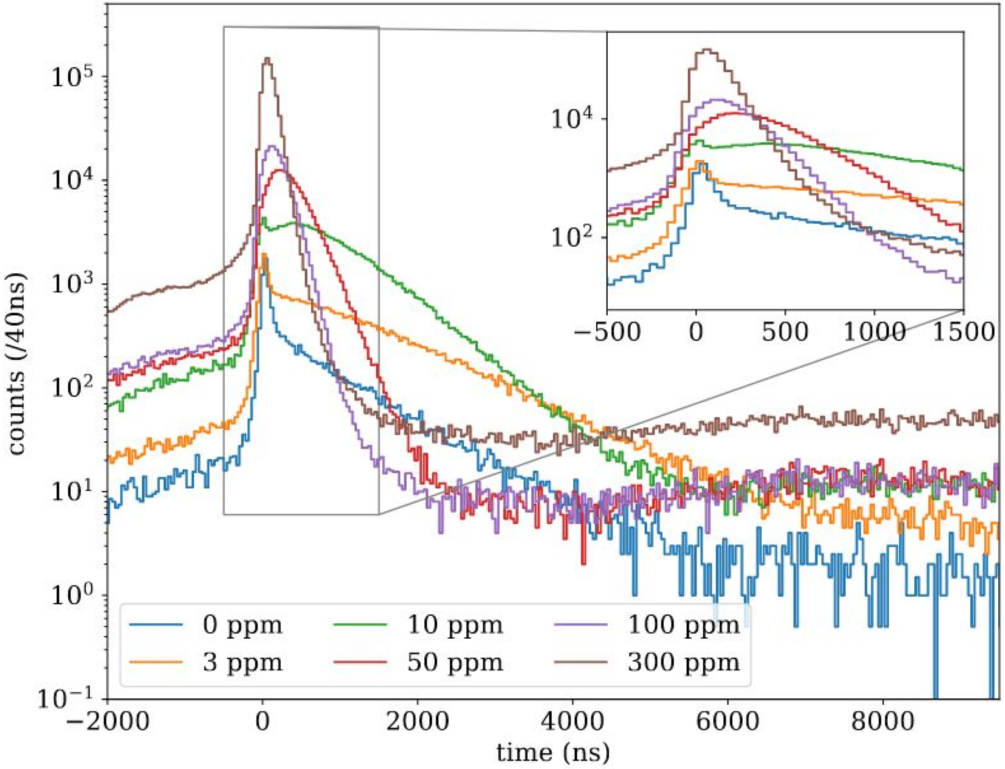
[C. Vogl *et al* 2022 *JINST* **17** C01031]

Energy distribution of GERDA phase II events



Phys. Rev. Lett. 125, 252502

XeDLAr scintillation time structure



Delayed hump in green (10 µg/g Xe in LAr) explained by Segreto's energy transfer model

[10.1103/PhysRevD.103.043001]

C. Vogl, M.Sc. thesis, TUM 2022
10.13140/RG.2.2.23118.54084