LUX-ZEPLIN Overview and Status

Ricardo Cabrita
February 14, 2020
On behalf of the LIP Dark Matter Group

Dark Matter at LIP COimbra

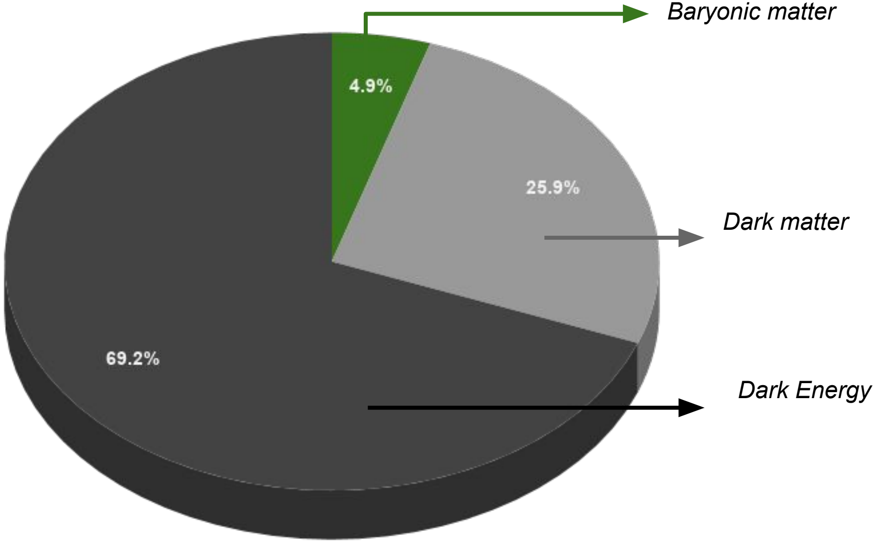
PI: Isabel Lopes

5 Master students
2 Phd students
6 Researchers

Left-to-right: Davide Porzio, Francisco Neves, Elias Asamar, Ricardo Cabrita, Fátima Alcaso, Andrey Solovov, Susana Castanheira, Paulo Braz, Vladimir Solovov, Guilherme Pereira, João Silva, Claudio Pascoal, Alexandre Lindote, Isabel Lopes

Looking for Dark Matter

Results from different sources (like Planck's CMB observations*) point to a Dark Matter density **~25%**



Among all the particles contained in the Standard Model of particle physics, none has the necessary properties to describe dark matter:

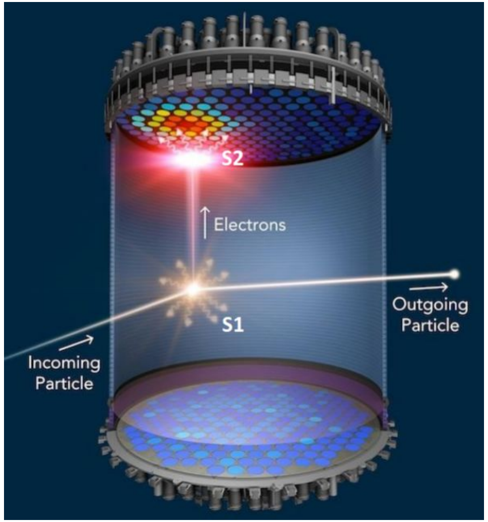
- a new type of elementary particle yet to be discovered is necessary.

The LZ detector employs 7 tonnes of liquid Xenon to look for such a particle!

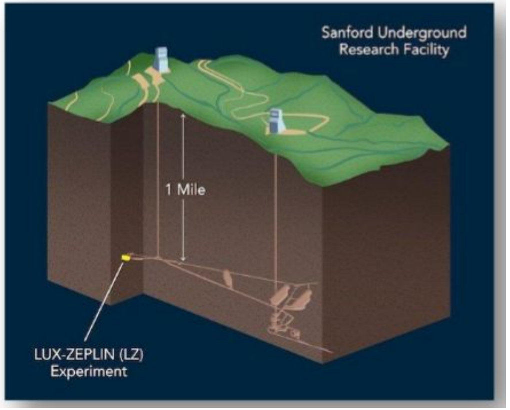
*Planck Collaboration, Planck 2018 results. VI. Cosmological parameters, 1807.06209

The LZ Detector

The core of the LZ Detector is a Xenon Double Phase Time Projection Chamber.



The detector is installed at Sanford Underground Research Facility (SURF), 1480 m underground in Homestake mine, Lead, South Dakota, USA.



For each particle interaction two optical signals are detected by the total of 494 PMTs organized in two arrays at the top and the bottom of the TPC:

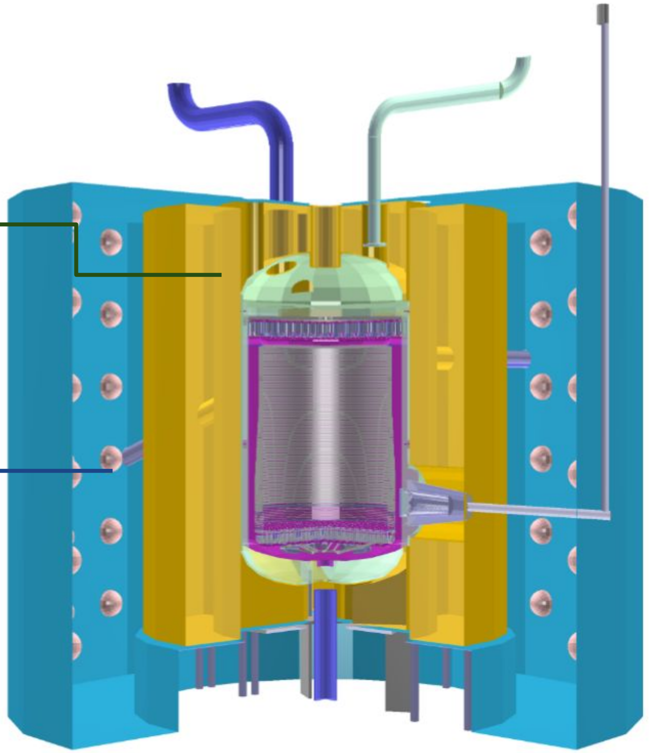
- Prompt scintillation in liquid phase - **S1**
- (delayed) electroluminescence in vapour phase - **S2**

3D position reconstruction, fiducialization and discrimination between nuclear and electron recoils are performed based on the analysis of S1 and S2 signals

The LZ Detector

Detector/Veto assembly like a "Russian Doll":

- The TPC sits inside the Inner Cryostat Vessel (ICV) surrounded by a liquid xenon skin 'layer' veto, which sits inside an Outer Cryostat Vessel (OCV).
- The OCV is surrounded by a liquid scintillator loaded with gadolinium inside an acrylic tank
- Everything sits in a water tank with 120 outer PMTs.



Water Cherenkov, passive liquid xenon Skin and liquid scintillator allow for neutron and gamma tagging:

Projected veto efficiency is*:

> 95% for neutrons
> 70% for gamma rays

*LUX-ZEPLIN Collaboration, The LUX-ZEPLIN (LZ) Experiment,, 1910.09124

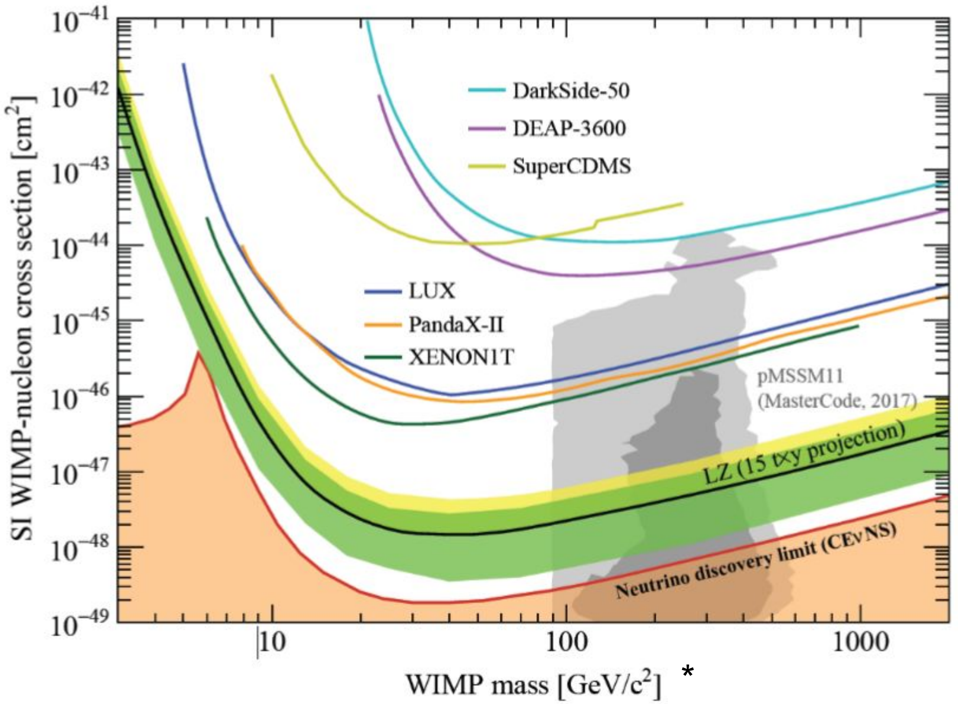
Background Sources

5.6 tonne fiducial, 1000 live-days
~1.5 - 6.5 keV, single scatters, no coincident veto signal

Background Source	ERs	NRs
Detector Components	9	0.12
Contaminants in the xenon — Rn, ^{85}Kr, ^{39}Ar	1200	—
Lab rock wall and Cosmogenics	5	0.06
Surface Contamination and Dust	40	0.28
Physics Backgrounds — ^{136}Xe 2β decay, neutrinos*	260	0.51
Total (after 99.5% ER discrimination and 50% NR efficiency)	**8**	

* not including ^{8}B and hep

Projected Sensitivity - Spin Independent



*

Best projected sensitivity for a WIMP mass of 40 GeV is 1.4×10^{-48} cm^2*.

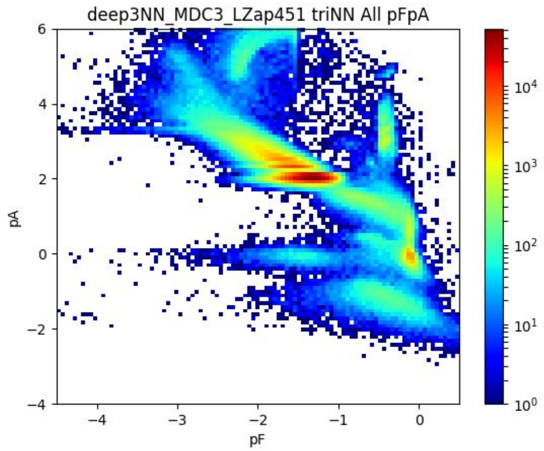
The current best limit is 4.1×10^{-47}cm^2 for a WIMP mass of 30 GeV from XENON1T**.

*LUX-ZEPLIN Collaboration, Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment, 1802.06039
**XENON Collaboration, Dark Matter Search Results from a One Tonne×Year Exposure of XENON1T, 1805.12562

Our roles in LZ

Data Analysis

Responsible for <u>raw pulse finder and classification</u> and <u>position reconstruction.</u>



Rare event searches

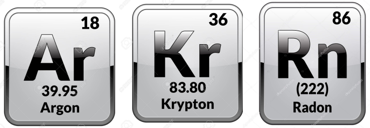
Coordinating the searches for the <u>neutrinoless double beta decay</u> of ^{136}Xe, the <u>double electron capture</u> of ^{124}Xe, and the <u>double beta decay</u> of ^{134}Xe

Coordinator:
Alexandre Lindote
Cláudio Silva
(until Nov 2019)

Background Model

Understanding and modelling backgrounds is extremely important to improve sensitivity.

Coordinator:
Alexandre Lindote
(until Oct 2019)



Our roles in LZ

Experiment Control

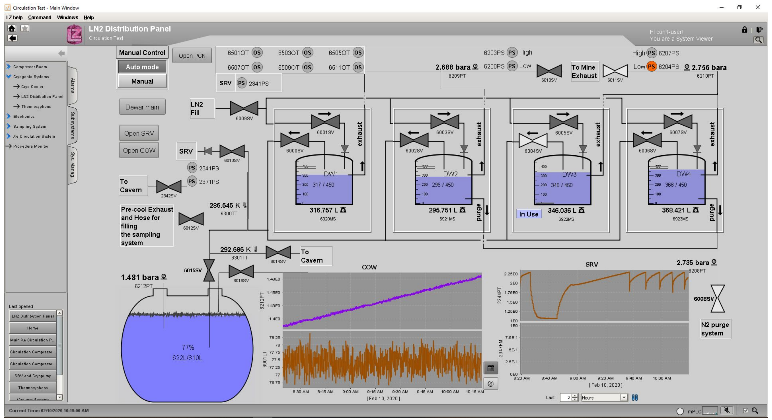
Responsible for implementing supervisory control and monitoring of the experiment, interfaces with major subsystems, GUI, alarms and automation

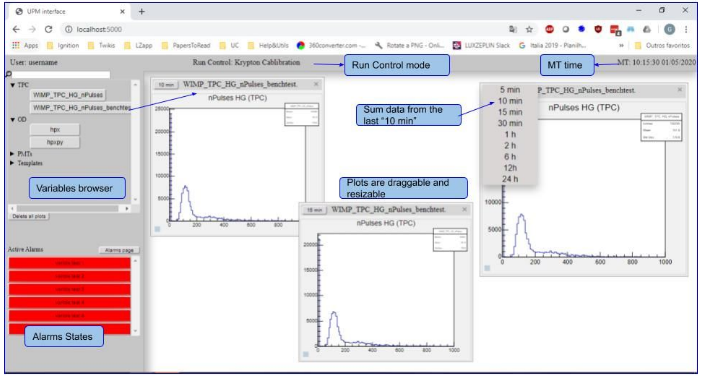
Coordinator: Vladimir Solovov

Underground Performance Monitor

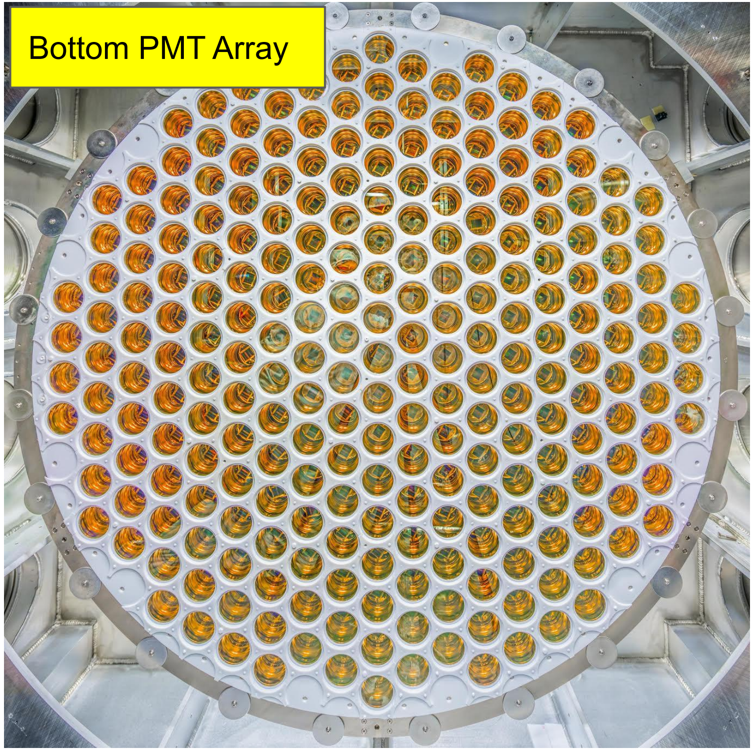
Responsible for developing a set of online tools for monitoring detector health and performance in real time.

Coordinator: Francisco Neves





Progress



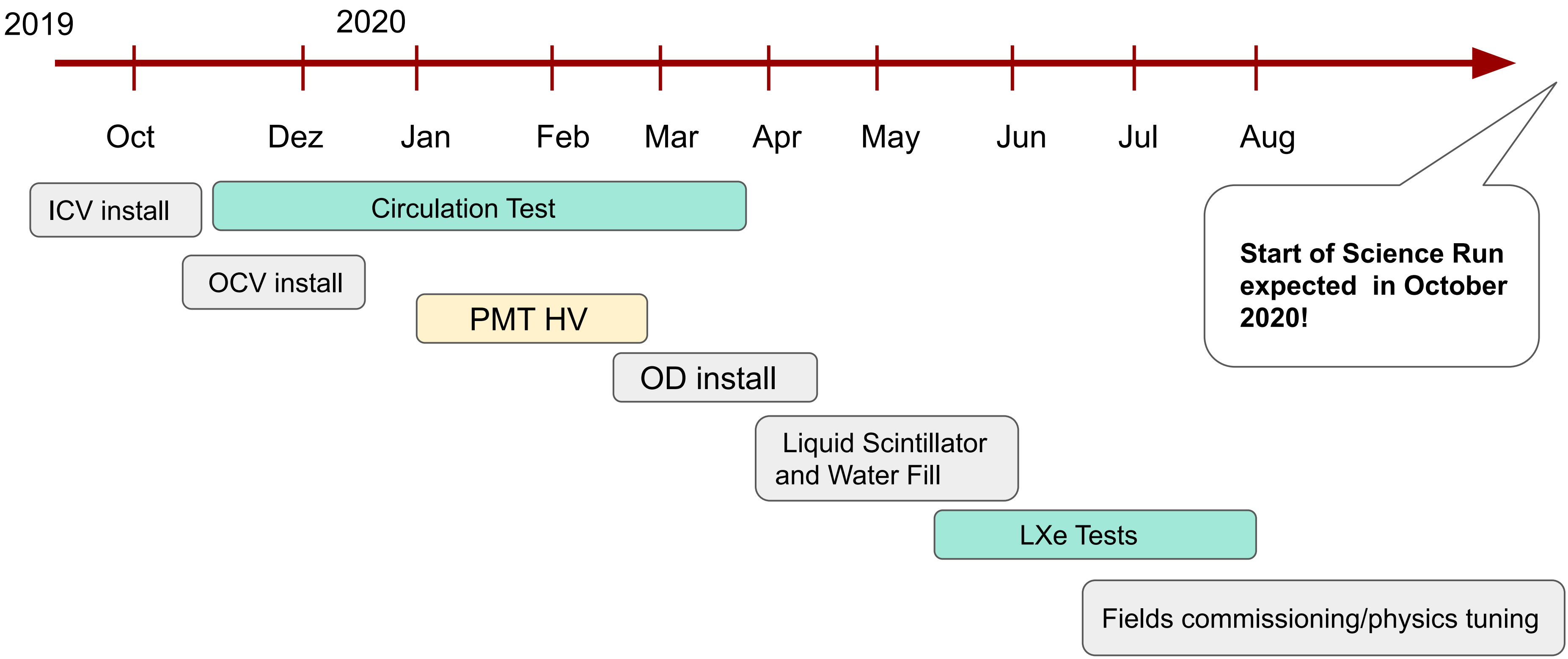
Progress

2019 2020

Oct | Dez | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug

ICV install

Progress


2019
2020
Oct
Dez
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
ICV install
Circulation Test
OCV install
PMT HV
OD install
Liquid Scintillator and Water Fill
LXe Tests
Fields commissioning/physics tuning
Start of Science Run expected in October 2020!

LZ collaboration

1) Center for Underground Physics (South Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (Russia)
4) Imperial College London (UK)
5) STFC Rutherford Appleton Lab (UK)
6) University College London (UK)
7) University of Bristol (UK)
8) University of Edinburgh (UK)
9) University of Liverpool (UK)
10) University of Oxford (UK)
11) University of Sheffield (UK)
12) Black Hill State University (US)
13) Brookhaven National Lab (US)
14) Brown University (US)
15) Fermi National Accelerator Lab (US)
16) Lawrence Berkeley National Lab (US)
17) Lawrence Livermore National Lab (US)
18) Northwestern University (US)
19) Pennsylvania State University (US)
20) SLAC National Accelerator Lab (US)
21) South Dakota School of Mines and Technology (US)
22) South Dakota Science and Technology Authority (US)
23) Texas A&M University (US)
24) University at Albany (US)
25) University of Alabama (US)
26) University of California, Berkeley (US)
27) University of California, Davis (US)
28) University of California, Santa Barbara (US)
29) University of Maryland (US)
30) University of Massachusetts (US)
31) University of Michigan (US)
32) University of Rochester (US)
33) University of South Dakota (US)
34) University of Wisconsin – Madison (US)
35) Washington University in St. Louis (US)
36) Yale University (US)

Search for rare xenon decays and study of the Migdal effect in LZ

Paulo Braz| LIP Coimbra | February 14, 2020

Search for $0\nu\beta\beta$ decay of ^{136}Xe

Some isotopes are known to undergo two-neutrino double beta decay ($2\nu\beta\beta$) - e.g. ^{76}Ge, ^{130}Te, ^{136}Xe

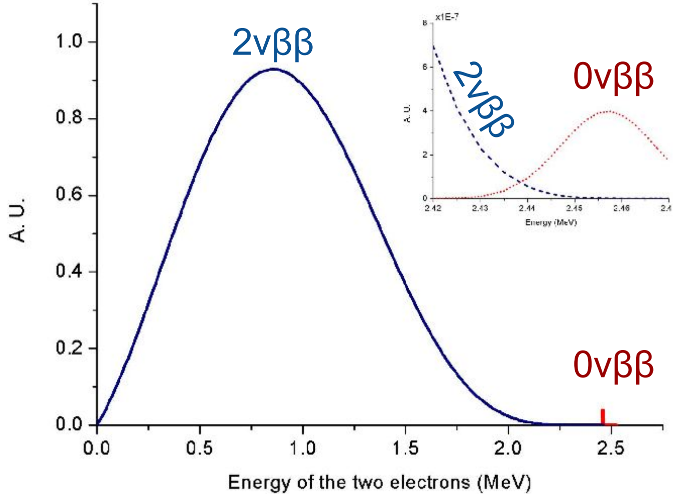
- The two neutrinos avoid detection.
- Observation of the summed energy of the two electrons.

If neutrinos are Majorana particles, a neutrinoless ($0\nu\beta\beta$) decay mode is possible - **not yet observed!**

- The two electrons will carry the total energy of the decay.

A detector can look for the $0\nu\beta\beta$ decay of a certain source by searching for an excess rate of events at the endpoint energy of the $2\nu\beta\beta$ decay spectrum.

Far-reaching implications: lepton number violation, neutrinos are Majorana particles, set absolute neutrino mass scale, possible insight on leptogenesis



$2\nu\beta\beta$ already observed in ^{136}Xe

$Q_{\beta\beta} = 2{,}457.83 \pm 0.37$ keV

$T_{1/2}(2\nu) = 2.11 \pm 0.04 \pm 0.21 \times 10^{21}$ yr
EXO-200 (PRL 107 212501, 2011)

$T_{1/2}(2\nu) = 2.38 \pm 0.02 \pm 0.14 \times 10^{21}$ yr
KamLAND-Zen (PRC 85 045504, 2012)

Search for 0νββ decay of ^{136}Xe

LZ features ~**623 kg** of ^{136}Xe in the active region without enrichment.

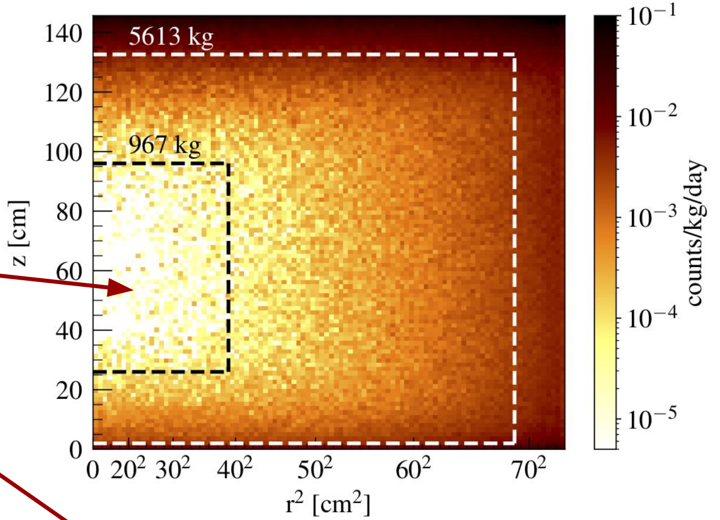
- 1 t control volume for BG characterization.
- 5.6 t fiducial volume for PLR analysis.

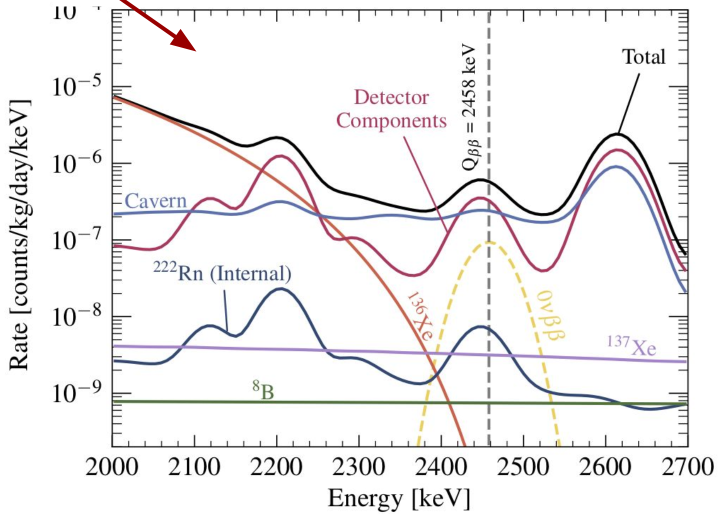
Main backgrounds by source at $Q_{\beta\beta}$

- **2448 keV** gamma line from ^{214}Bi (^{238}U chain)
- **2615 keV** gamma line from ^{208}Tl (^{232}Th chain)
- “Naked” beta from ^{214}Bi (internal ^{222}Rn)
- Beta decay from muon-induced ^{137}Xe
- 2νββ decay of ^{136}Xe
- Elastic scattering of solar neutrinos from ^{8}B chain

Item	Counts from ^{238}U	Counts from ^{232}Th	Total Counts
Det. components subtotal	21.0	2.32	23.3
Cavern walls	3.21	8.41	11.6
Neutron-induced ^{137}Xe	-	-	0.28*
Internal ^{222}Rn	-	-	0.45*
^{136}Xe $2\nu\beta\beta$	-	-	0.01†
^{8}B solar neutrinos	-	-	0.03
Total	24.2	10.7	35.6

In 1000 days on the inner 1 t volume and within 1% of $Q_{\beta\beta}$



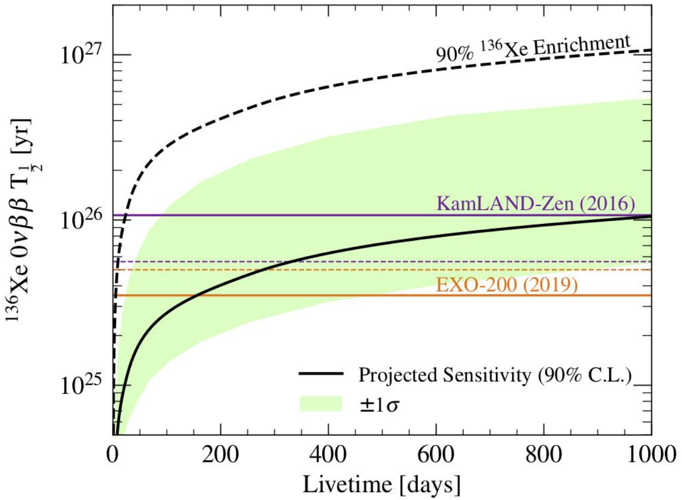


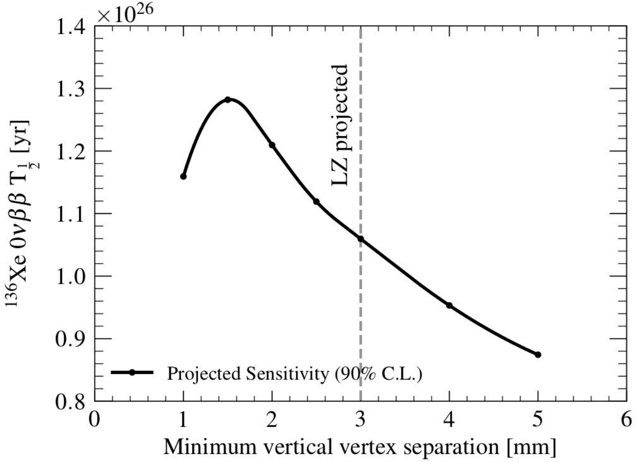
Search for $0\nu\beta\beta$ decay of ^{136}Xe

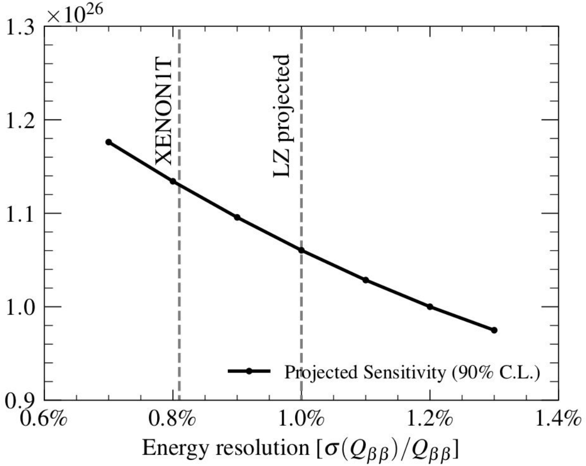
Sensitivity projection:

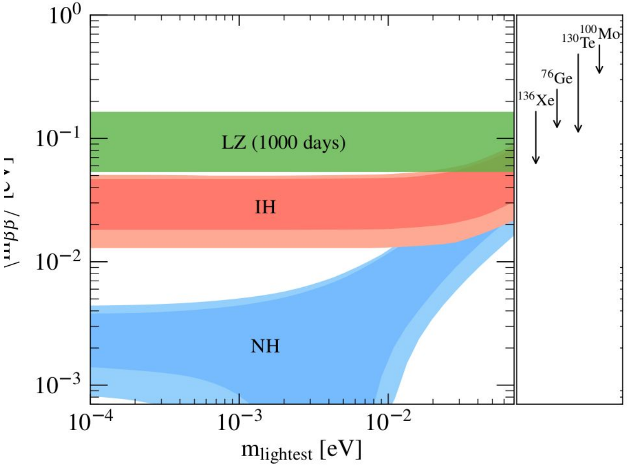
- LZ can reach **1.06×10^{26} years after 1000 live days** (comparable to the current KamLAND-Zen result)

- Considering **1% energy resolution** and **single scatter separation of 3 mm in depth**
  - conservative estimates (XENON1T claims 0.86% E-res)









Search for 0νββ decay of ^{136}Xe

LZ sensitivity paper is now on arXiv and submitted to Physical Review C

Corresponding author: P. Brás

Projected sensitivity of the LUX-ZEPLIN experiment to the $0\nu\beta\beta$ decay of ^{136}Xe

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Projected Sensitivity of the LUX-ZEPLIN Experiment to the $0\nu\beta\beta$ Decay of ^{136}Xe

LZ Collaboration (D.S. Akerib (SLAC & KIPAC, Menlo Park) *et al.*) Show all 192 authors

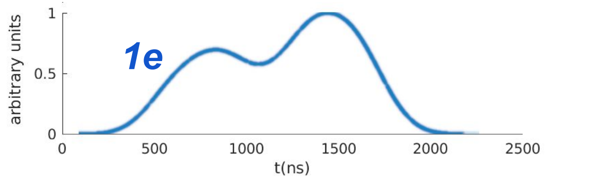
Dec 9, 2019 - 13 pages

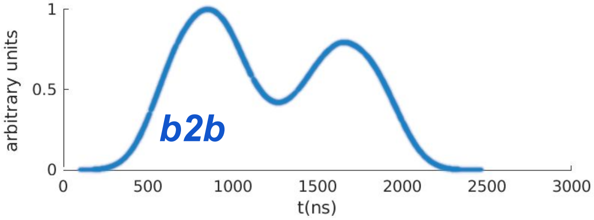
FERMILAB-PUB-19-635-AE
e-Print: arXiv:1912.04248 [nucl-ex] | PDF
Experiment: LZ

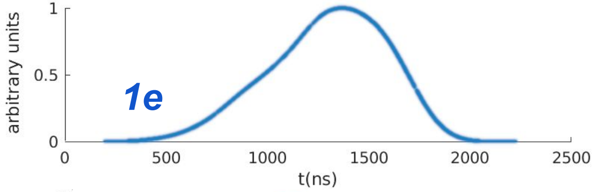
Abstract (arXiv)
The LUX-ZEPLIN (LZ) experiment will enable a neutrinoless double beta decay search in parallel to the main science goal of discovering dark matter particle interactions. We report the expected LZ sensitivity to ^{136}Xe neutrinoless double beta decay, taking advantage of the significant (> 600 kg) ^{136}Xe mass contained within the active volume of LZ without isotopic enrichment. After 1000 live-days, the median exclusion sensitivity to the half-life of ^{136}Xe is projected to be 1.06×10^{26} years (90% confidence level), similar to existing constraints. We also report the expected sensitivity of a possible subsequent dedicated exposure using 90% enrichment with ^{136}Xe at 1.06×10^{27} years.

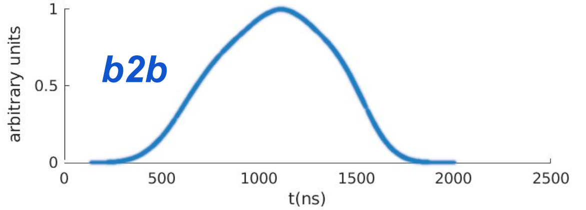
ML in the search for $0\nu\beta\beta$ decay of ^{136}Xe

- Explore Machine Learning classification for background discrimination:
  - Single (1e) VS double (b2b) tracks
  - using the waveform only for now (Z)
  - later include XY position reconstruction information
- Tested algorithms (after parametrization of the pulses):
  - kNN, RBF SVM, Gaussian proc., Random forest









Results for ideal conditions

Y,1,0 kNN

actual label \ predicted label	1e	b2b
1e	75%	25%
b2b	45%	55%

N,1,1 RBF SVM

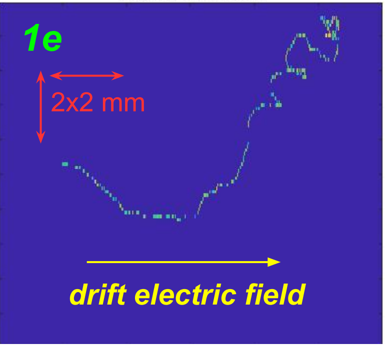
actual label \ predicted label	1e	b2b
1e	91%	9%
b2b	19%	81%

N,2,0 G. proc.

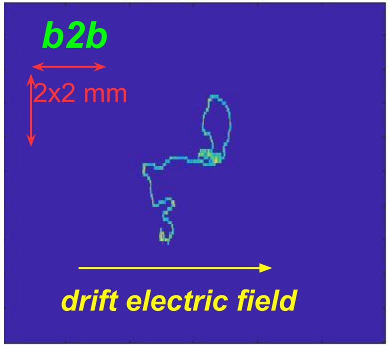
actual label \ predicted label	1e	b2b
1e	82%	18%
b2b	10%	90%

N,1,0 R. frst.

actual label \ predicted label	1e	b2b
1e	77%	23%
b2b	26%	74%



Background



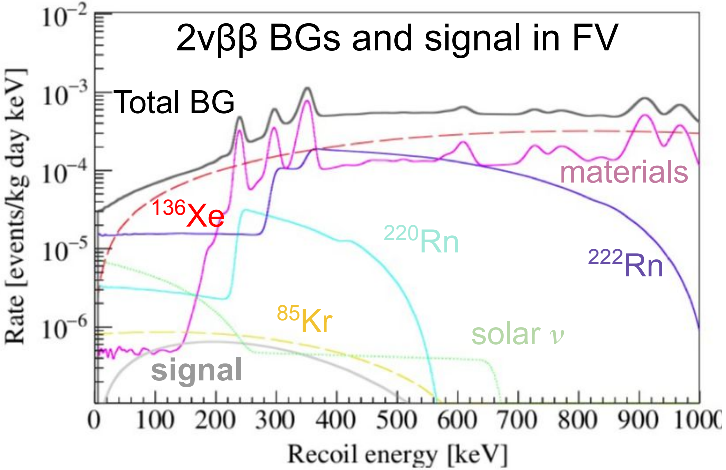
Signal

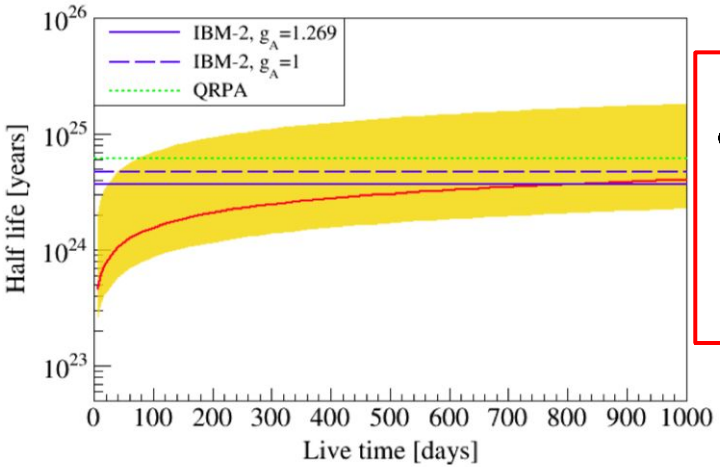
$2\nu\beta\beta$ and $0\nu\beta\beta$ decays in ^{134}Xe

Sensitivity paper in internal collaboration review
E. Asamar, S. Pal corresponding authors

- ^{134}Xe can also decay via $2\nu\beta\beta$ decay (**not yet observed!**) and $0\nu\beta\beta$
  - Q_{value} = 826 keV → lower Q implies longer half-lives (compared to ^{136}Xe)
- Theoretical predictions for $2\nu\beta\beta$: (3.7 – 6.1) × 10^{24} yr
  - current best $2\nu\beta\beta$ experimental limit is > 8.7×10^{20} yr
  - for the $0\nu\beta\beta$ mode, LZ can reach 9.5×10^{24} yr (current limit is 10^{23} yr)
- ^{134}Xe and ^{136}Xe can be the first pair of isotopes of the same element for which $2\nu\beta\beta$ is experimentally confirmed, allowing validation of nuclear models

$2\nu\beta\beta$ decay from ^{136}Xe is the largest background



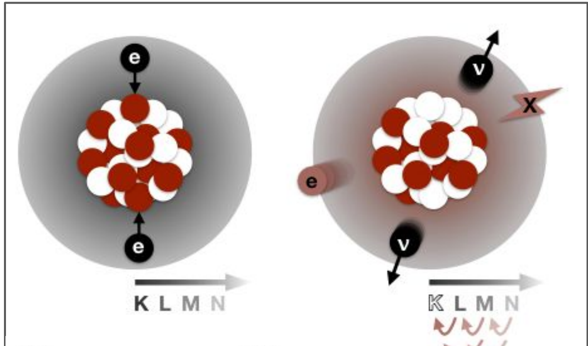


LZ can observe the longest decay ever in a laboratory

Double Electron Capture decay in ^{124}Xe

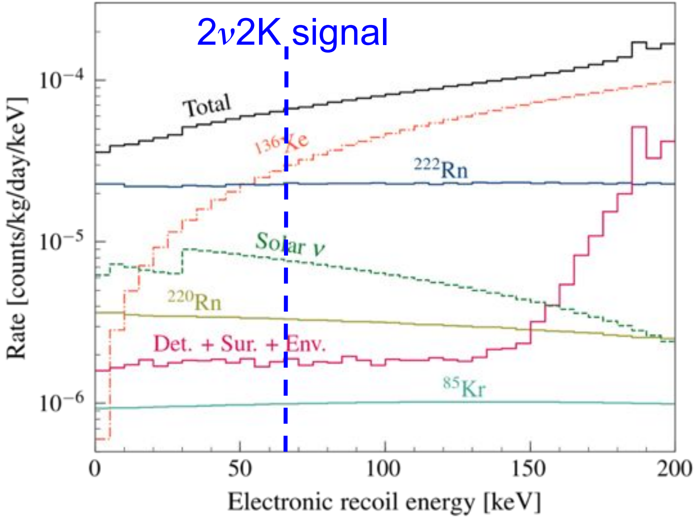
- Q_{value} = 2864 keV
  (highest amongst DEC candidate nuclei)
- 2ν2EC decay
  - Most likely the 2 electrons will be from the K-shell (2ν2K)
  - Signal is an energy peak around 64.5 keV
  - XENON1T reported observation with 4.4σ significance and 1.8×10^{22} yr half-life
  - LZ may be able to claim a discovery in under 3 months (>7σ)

2ν2EC



$$^{124}Xe + 2e^- \rightarrow {}^{124}Te + 2\nu_e$$

LZ low energy background model



LUX limit paper on arXiv and submitted to PRC

3. arXiv:1912.02742 [pdf, other] nucl-ex physics.ins-det

Search for two neutrino double electron capture of ^{124}Xe and ^{126}Xe in the full exposure of the LUX detector

Authors: LUX Collaboration, D. S. Akerib, S. Alsum, H. M. Araújo, X. Bai, J. Balajthy, A. Baxter, E. P. Bernard, A. Bernstein, T. P. Biesiadzinski, E. M. Boulton, B. Boxer, P. Brás, S. Burdin, D. Byram, M. C. Carmona-Benitez, C. Chan, J. E. Cutter, L. de Viveiros, E. Druszkiewicz, A. Fan, S. Fiorucci, R. J. Gaitskell, C. Ghag, M. G. D. Gilchriese , et al. (74 additional authors not shown)

Abstract: Two-neutrino double electron capture is a process allowed in the Standard Model of Particle Physics. This rare decay has been observed in ^{78}Kr, ^{130}Ba and more recently in ^{124}Xe. In this publication we report on the search for this process in ^{124}Xe and ^{126}Xe using the full exposure of the Large Underground Xenon (LUX) experiment, in a total of of 27769.5~kg-days. No evidenc... ▽ More

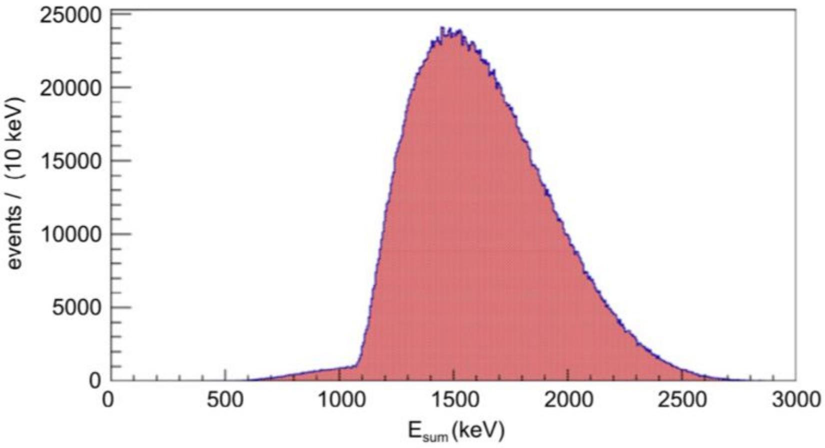
Submitted 5 December, 2019; **originally announced** December 2019.

Comments: 8 pages, 3 figures

Corresponding author: A. Lindote

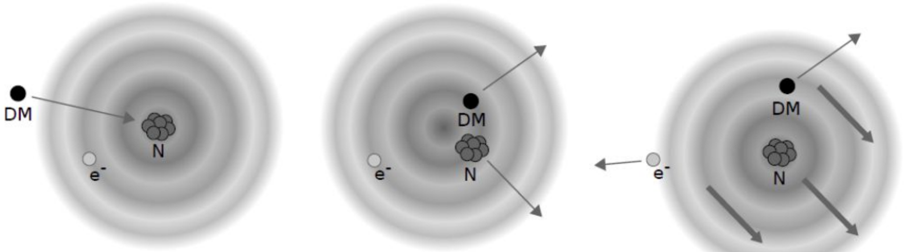
Other decays in ^{124}Xe

- The Q_{value} is high enough to open other decay channels
  - $2\nu\beta$+EC decay
    - ~10^{23} yr half-life expected
    - Can be the longest decay ever observed
    - Signature comes from the 511 keV gammas from the positron annihilation together with the β^+ spectrum
  - $2\nu2\beta$+ decay
    - Possible in only six nuclides
    - Expected half-life is ~10^{27} yr (too long for LZ)



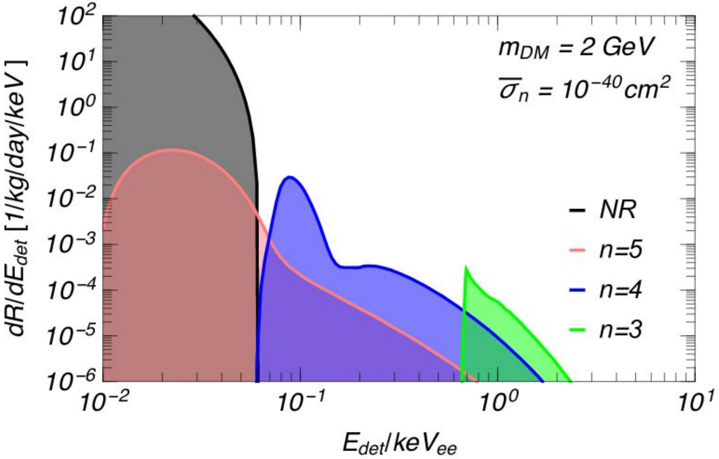
- 0ν2EC
  - An alternative channel to probe the nature of the neutrino and the mass hierarchy
  - If no neutrinos are emitted, the nucleus may emit a 2864 keV gamma
  - Expected half-lives are very long, but a possible resonance could make it detectable in LZ

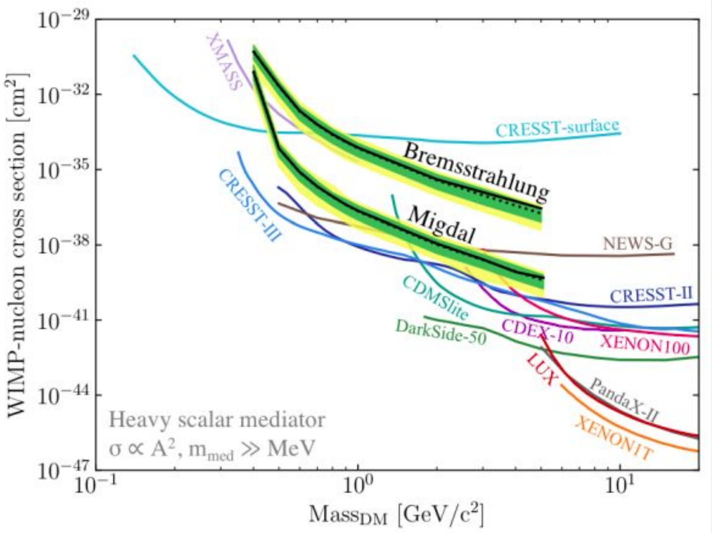
Studies on Migdal effect



$|\Phi_{ec}\rangle$ $\quad |\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$ $\quad \mathcal{P} = |\langle \Phi^*_{ec}|\Phi'_{ec}\rangle|^2$

- Energy of nuclear recoils from light WIMPs too low to observe in xenon detectors
- **Migdal effect:** electron emission by the disturbed atom following a nuclear recoil
- Allows Xe experiments to be competitive at low mass DM scales

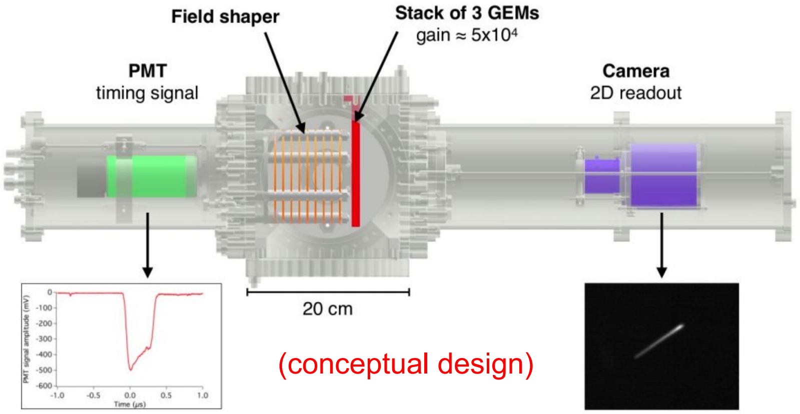




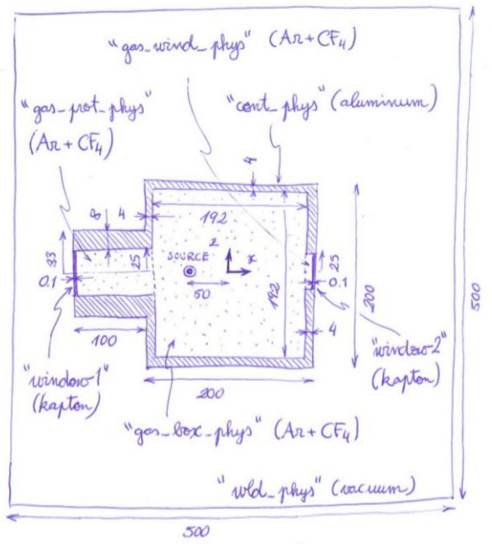
Studies on Migdal effect

Concept: use neutrons to induce Migdal effect in atoms of low-pressure scintillating gas

- Search for events with an electron track and a nuclear recoil with the same origin
- Collaboration between LIP, UK LZ groups (RAL, ICL) and CERN
- **LIP is contributing to design the shielding and to develop track reconstruction algorithms**



(conceptual design)



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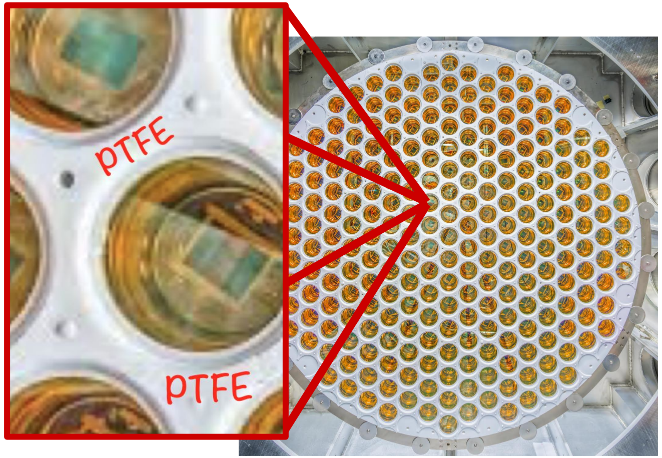
Measurement of optical properties of **PTFE**

Davide Porzio| LIP Coimbra | February 14, 2020

Optical Properties of LZ

- Dark matter signal in LZ has a very **low energy threshold**
- Extremely important to **correctly model light collection** in the detector
- We need to describe **reflectance off** the **PTFE** wall of LZ with **high precision**
- **Building framework for optical measurements for particle physics**



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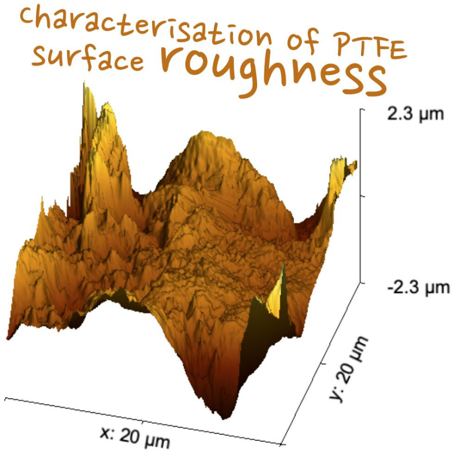

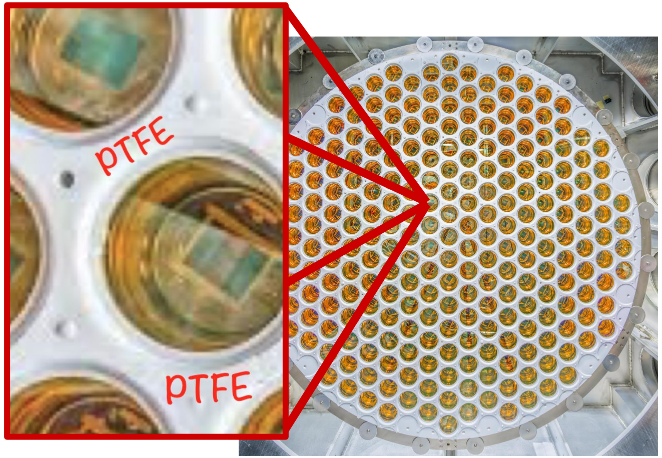

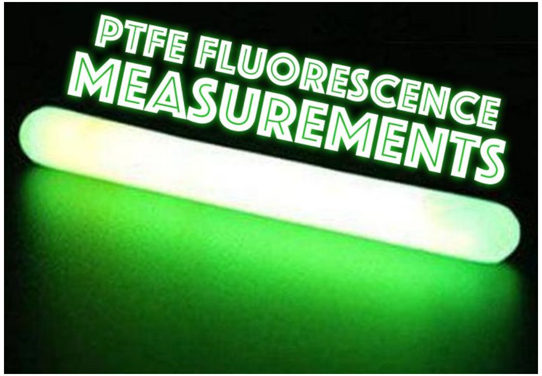

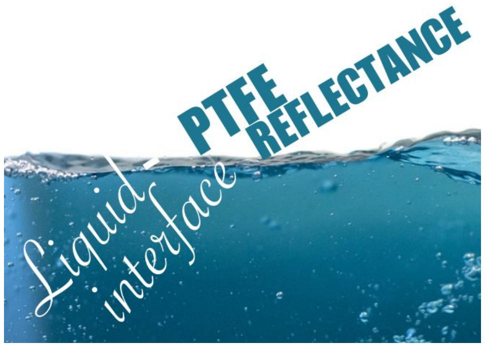

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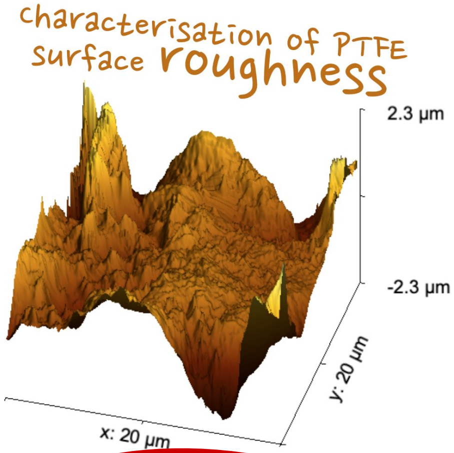
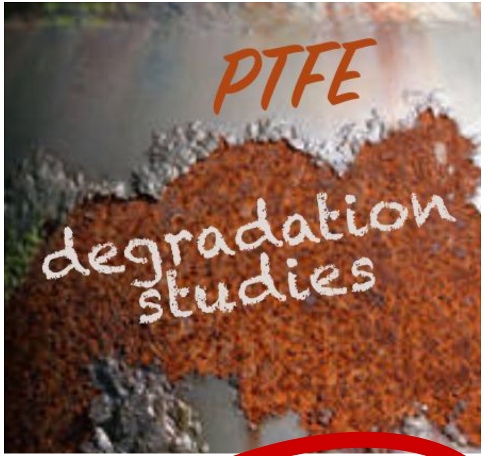
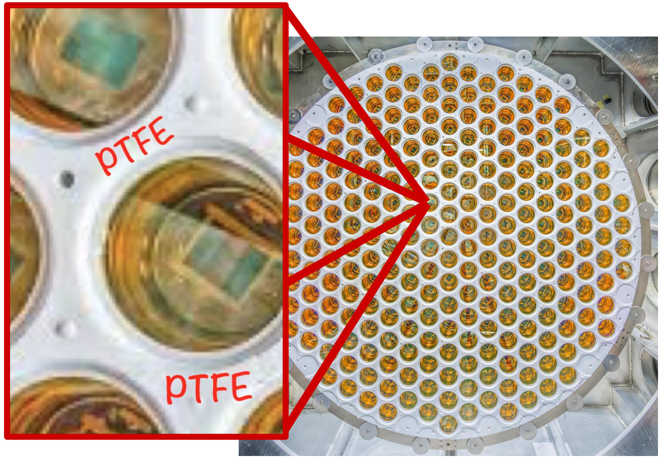
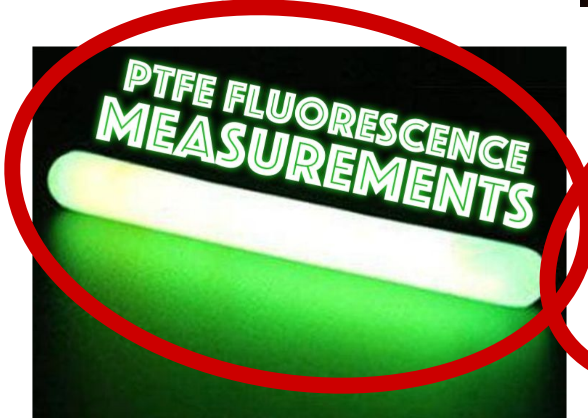






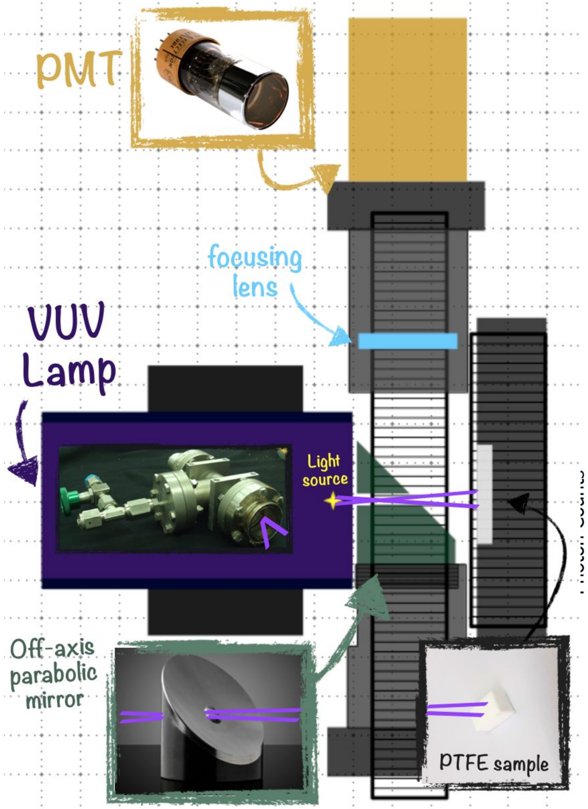


Fluorescence and Phosphorescence

- Volatile impurities from **hydrocarbons**, like toulene and naphthalene, can **contaminate** the highly-reflecting PTFE walls of the detector
- **Absorption** of **UV light** by the contaminants is responsible for **fluorescence spectra**
- **Delayed light emission** off the PTFE walls can be a source of **background**

Fluorescence and Phosphorescence

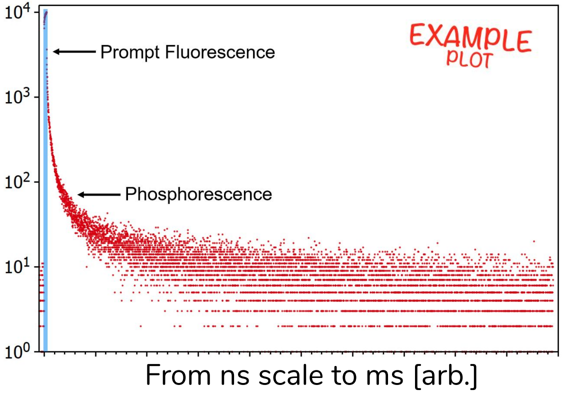
- Measuring **single photons** from fluorescence and phosphorescence
- Current setup makes use of an **off-axis parabolic mirror** with through hole to direct VUV light on PTFE sample and collect **emitted spectrum** onto **PMT**
- Alternative setup for different *timing scales*
- Use of **cooling systems** for **temperature dependence** studies



The objective is to obtain single photon counting

time-resolved fluorescence spectra

at different timing scales



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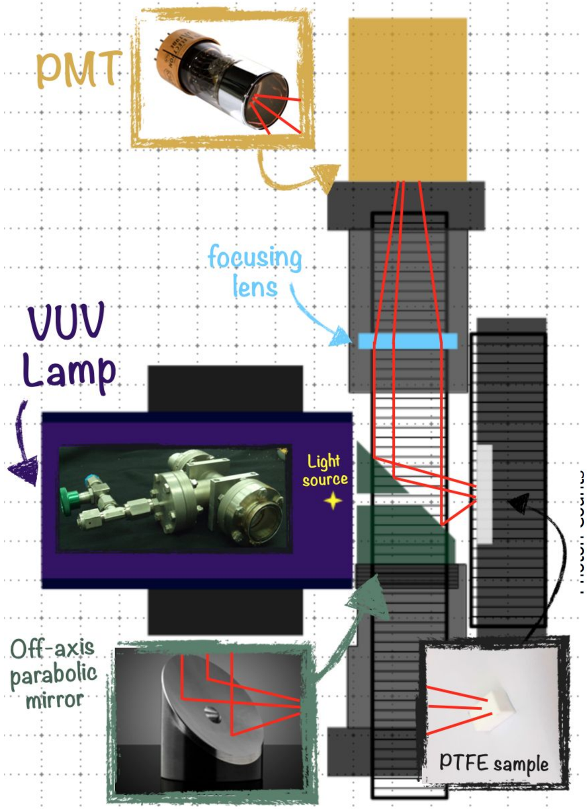

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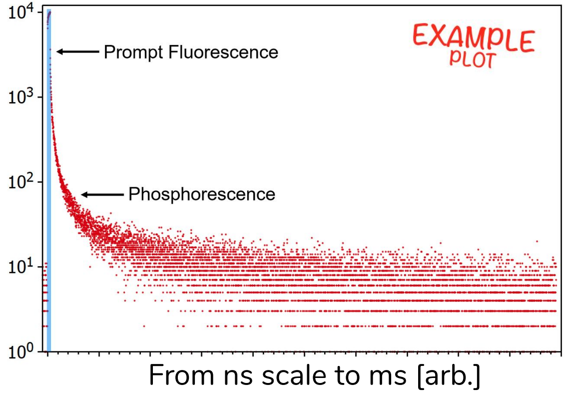
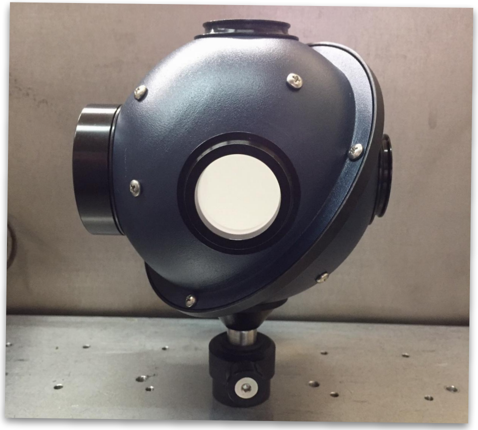
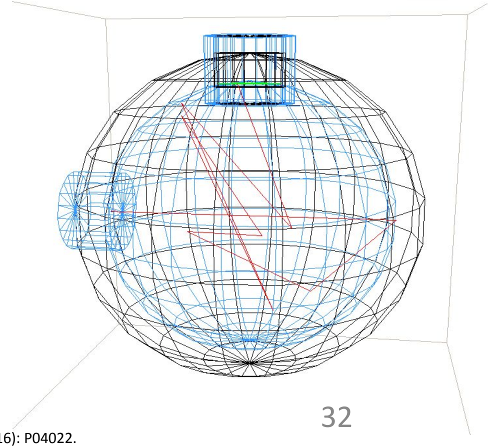


Reflectance in Liquids



- Strong **disagreement** between the reflectance observed in a **Gas-PTFE** interface (**R~70%**) and the reflectance observed in a **Liquid-PTFE** interface (**R>95%**)
- Study the diffuse reflectance in **liquid interface** using an **integrating sphere**:
  - Vary **wavelength** (LED matrix, 250 to 500nm)
  - Vary the **refractive index** of the first medium (Air, Water, Glycerine, ...) in a liquid interface
- Simulate the experiment in **ANTS2***, test various reflectance models against the results

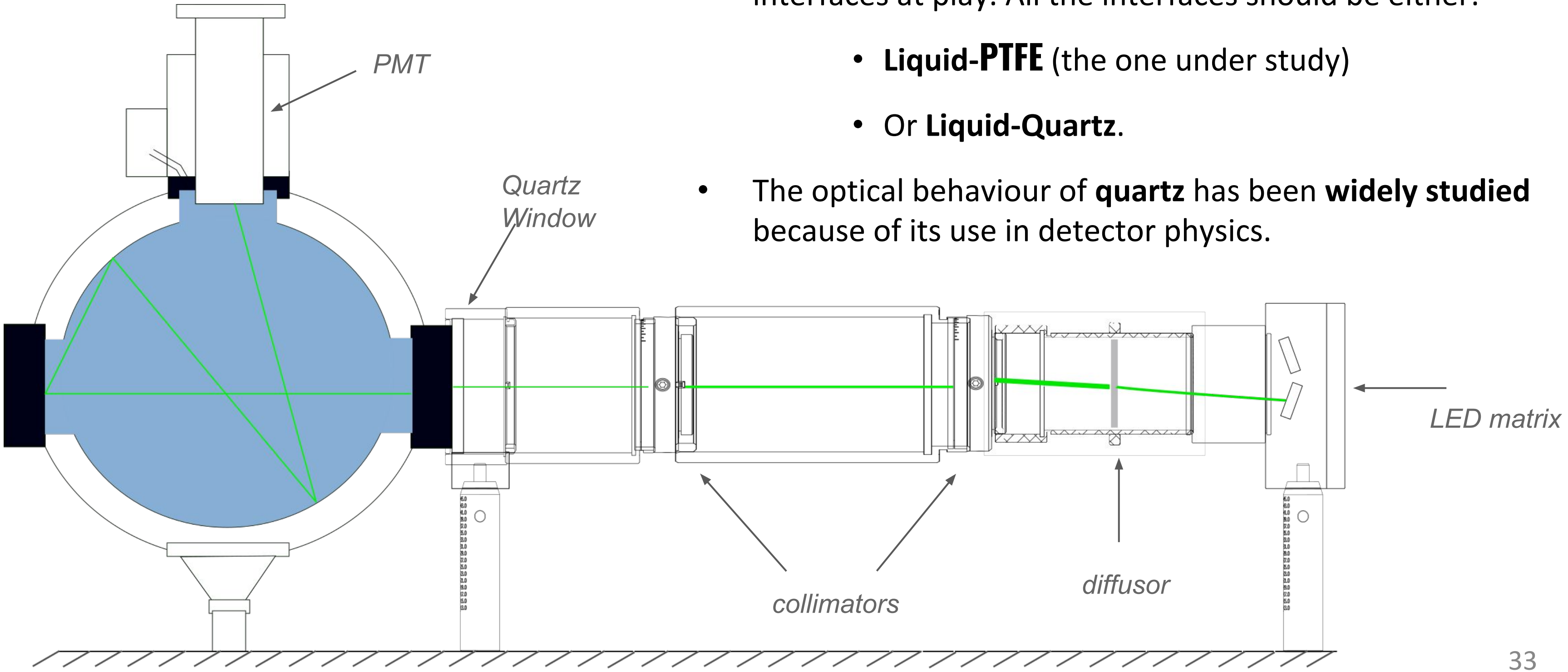
		λ (nm)	*255*			*450*	*700*
		μ (D)	n	k	α (cm-1)	n	n
Glycerin	$C_3H_5(OH)_3$	2.617	1.5532	0.0000	0.0000	1.4782	1.4700
Water (Ultra Pure)	H_2O	1.85	1.3604	3.15×10^{-8}	0.015523	1.3370	1.3310



*Morozov, A., V. Solovov, R. Martins, F. Neves, V. Domingos, and V. Chepel. "ANTS2 package: simulation and experimental data processing for Anger camera type detectors." *Journal of Instrumentation 11, no. 04* (2016): P04022.

Reflectance in Liquids

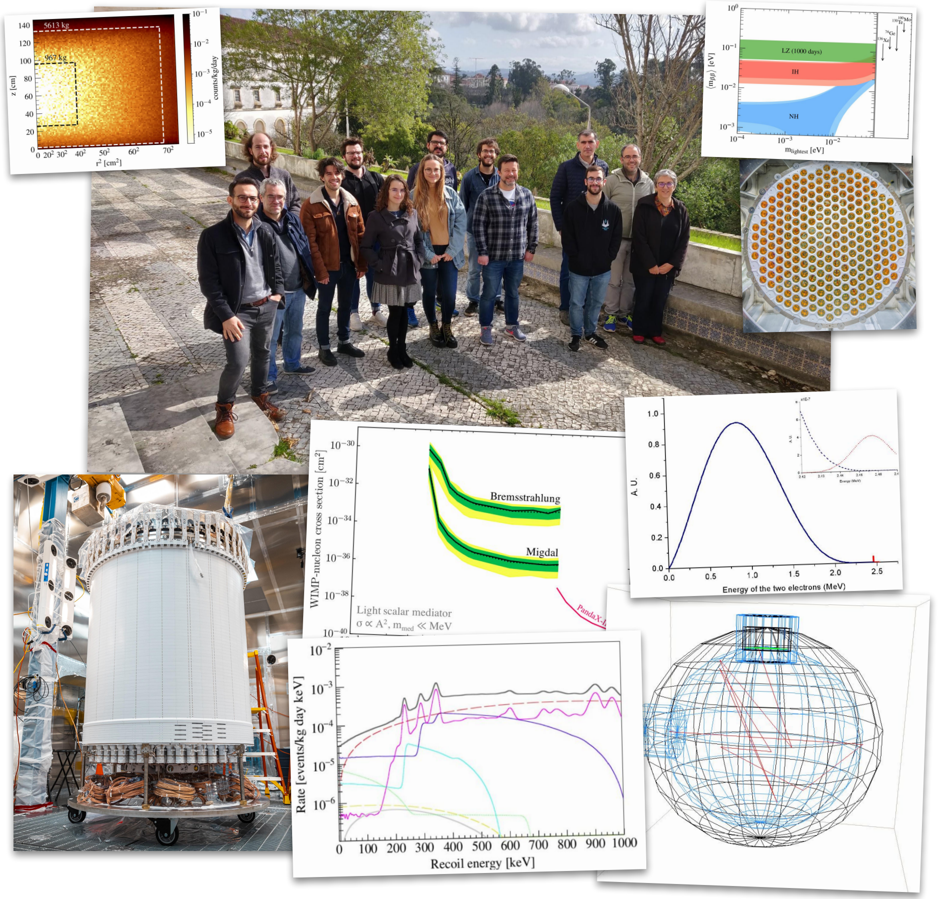
- For the simulations we need to know very well the optical interfaces at play. All the interfaces should be either:
  - **Liquid-PTFE** (the one under study)
  - Or **Liquid-Quartz**.
- The optical behaviour of **quartz** has been **widely studied** because of its use in detector physics.



Conclusions

Exciting times as
LZ Science Run data taking is approaching!

- **LIP** undertaking many **critical tasks** for both the understanding and operation of the detector and the analysis of the data collected:
  - **Slow control** and **performance monitor** optimisation, crucial for smooth sailing of detector operation
  - **Background simulation**, **event reconstruction** and **data analysis** for rare event searches
  - Studies for **Migdal effect** - based searches, capable of extending LZ sensitivity to sub-GeV ranges.
  - R&D for better understanding and modelling of the **optical properties** of **PTFE**.



Conclusions

Exciting times a

LZ Sci

- **LIP** und
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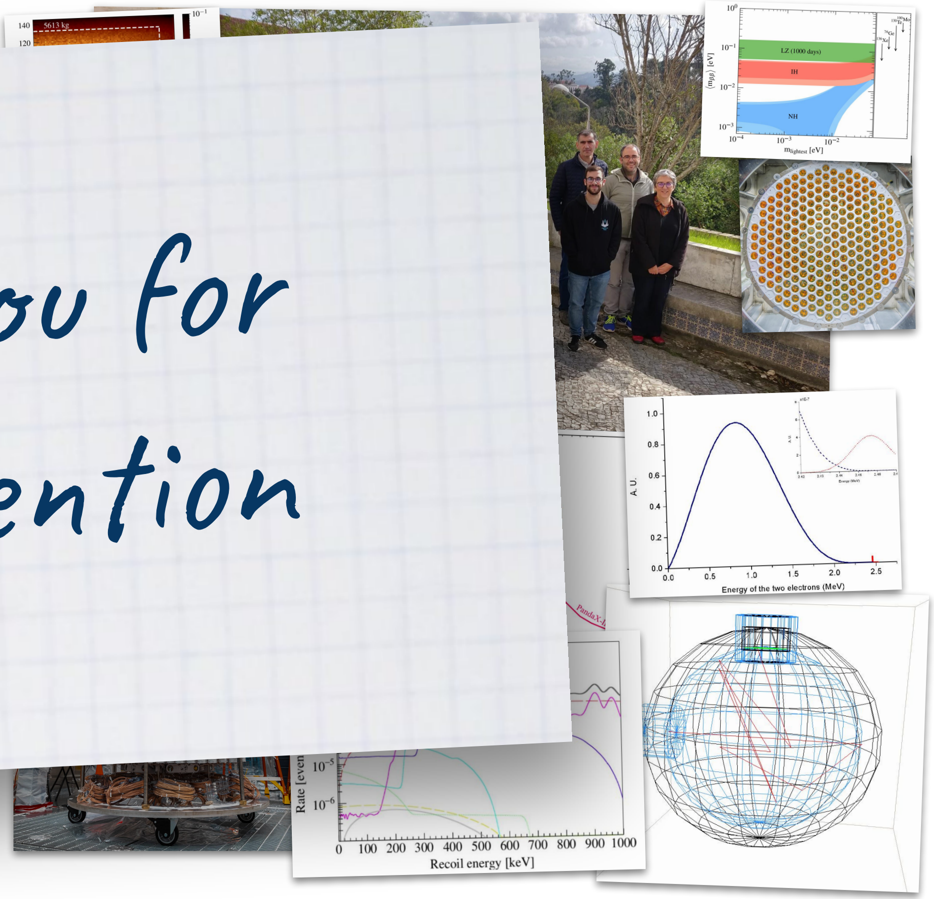
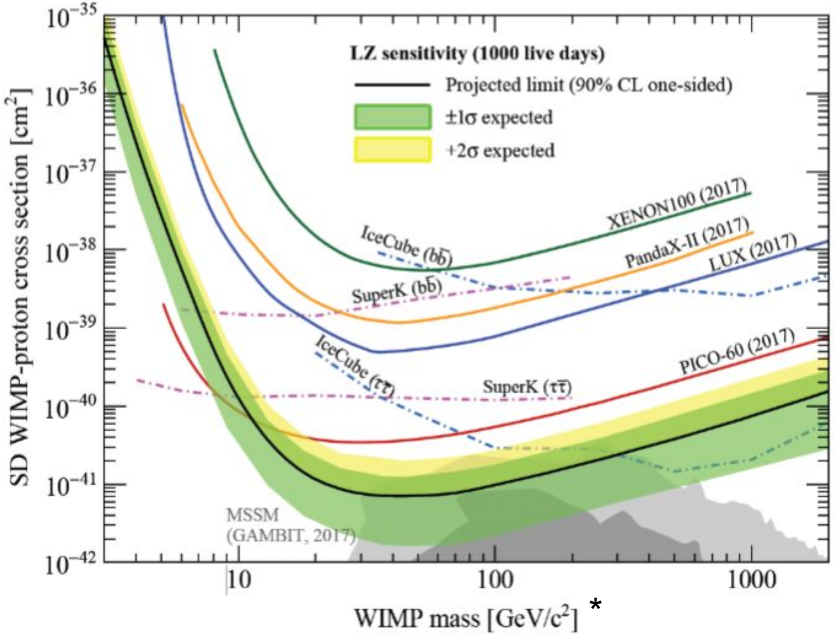
Thank you for your attention



Backup Slides

Expected Sensitivity - Spin Dependent



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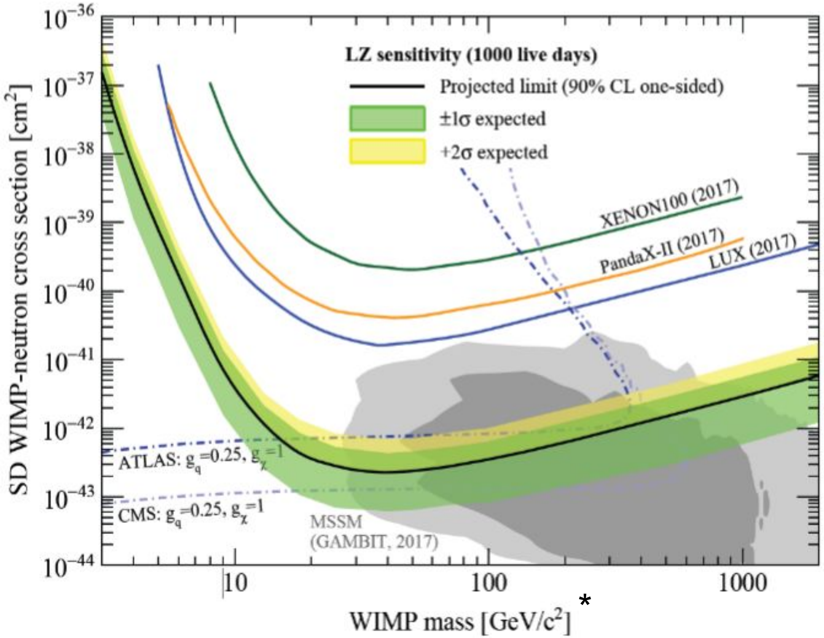
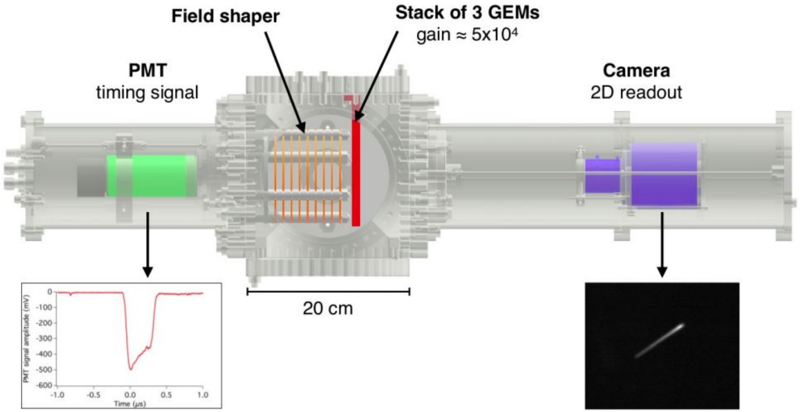


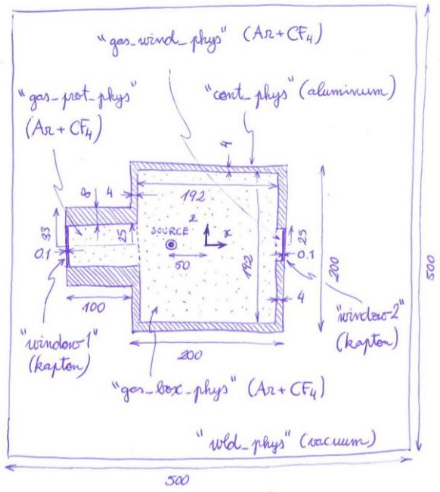
*

*LUX-ZEPLIN Collaboration, Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment, 1802.06039

Studies on Migdal effect

- An experiment is currently being developed at RAL (UK) to confirm the Migdal effect, so far funded by STFC (Xenon Futures R&D project)
- Besides RAL, other collaborating institutes are LIP, Imperial College and CERN
- Concept: use neutrons to induce Migdal effect in atoms of low-pressure scintillating gas, then search for events with an electron track and a nuclear track created at the same point
- The experiment was approved in October 2019, and it is currently being designed
- **LIP is contributing to design the shielding and to develop track reconstruction algorithms**

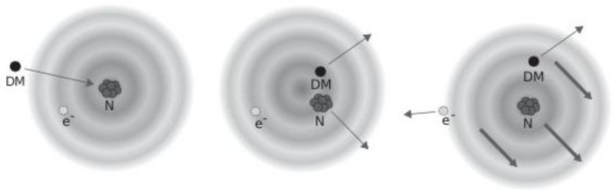




Studies on Migdal effect

- **Migdal effect:** ionization mechanism proposed by A. B. Migdal in 1941: electron emission by an atom, when the respective nucleus suddenly acquires a given velocity
- The electron eigenstates for the moving nucleus, $|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$ are not orthogonal to those for the nucleus at rest, i.e probability between ground and excited/ionized states, could be non-zero:

$$\mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$



Not yet confirmed experimentally

- Several exclusion limits are calculated assuming the Migdal effect (for comparison)
- Would allow Xe experiments to be competitive at sub-GeV DM scales: inelastic process, with recoiling electron in final state