Search for WIMPs and sub-GeV dark matter particles using double-phase xenon detectors

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LIP

LZ

MultiDark
Multimessenger Approach for Dark Matter Detection

Seminário LIP, 5th of November 2020

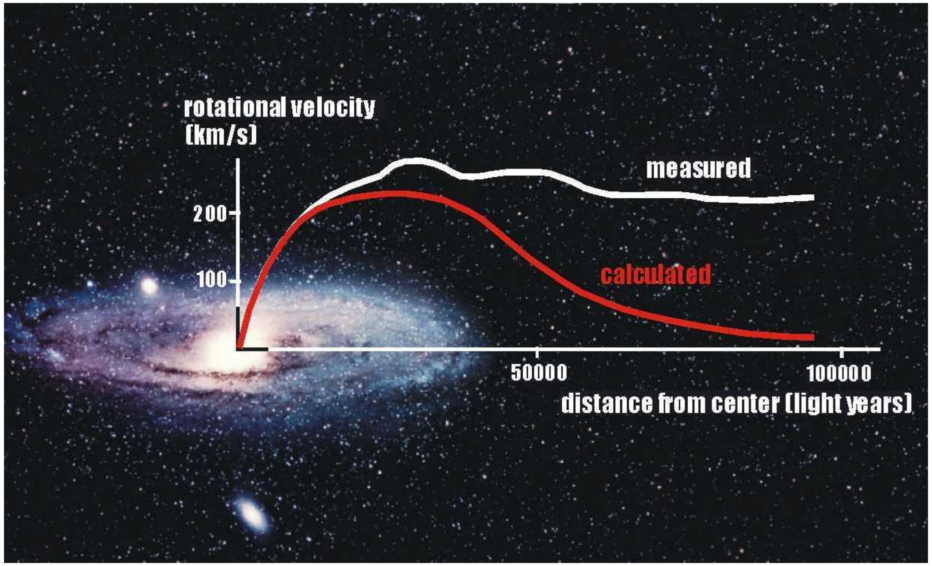
Overview

- Dark matter, direct detection
- Xe double-phase detectors
- LZ
- Migdal effect, MIGDAL experiment
- Future prospects and conclusions

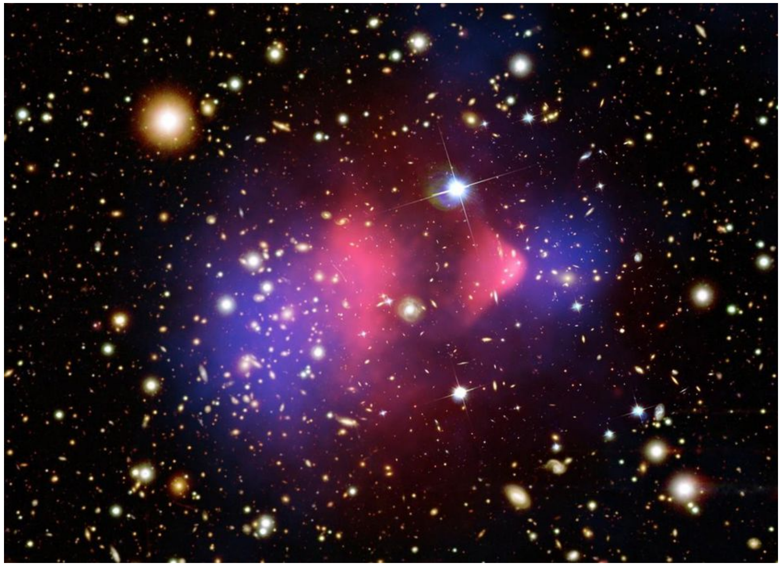
The dark matter problem

Dark matter (DM) is the simplest hypothesis to explain a large number of gravitational effects that are systematically observed over a wide range of astronomical scales

DM is a main component of the current cosmology model (ΛCDM), accounting for ~85% of the total mass content of the universe



~100 kpc scale



~10 Mpc scale

But we do not know what DM is made of

The dark matter problem

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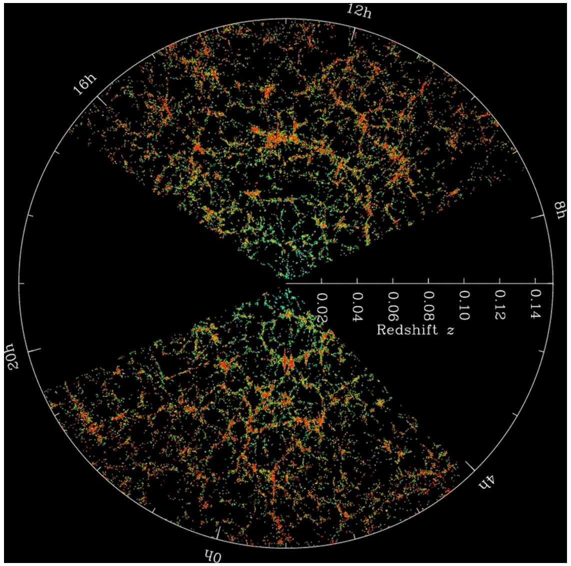
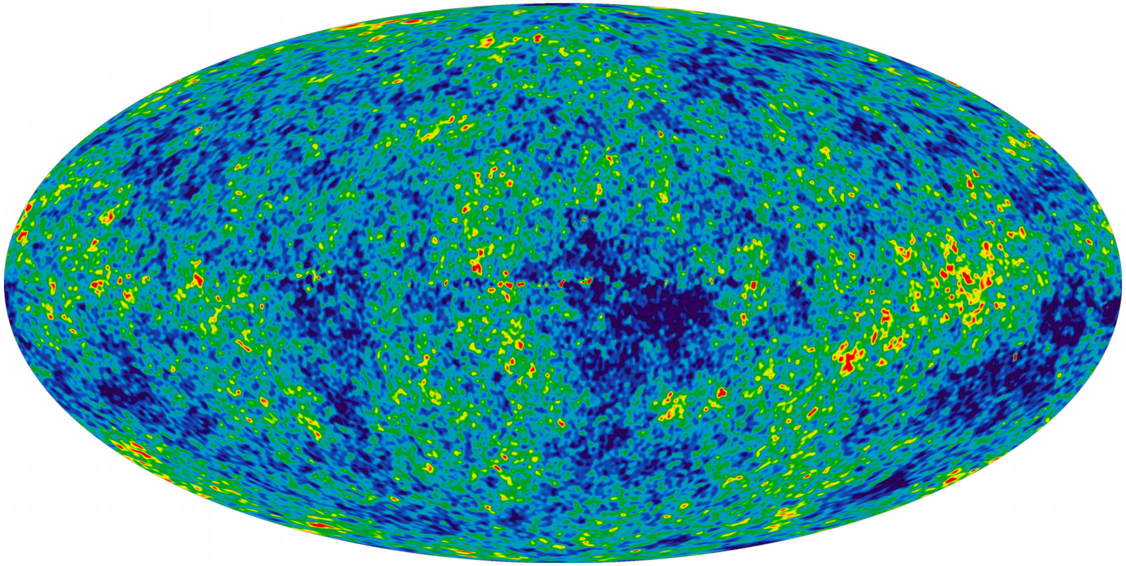


~1 Gpc scale



Entire universe

But we do not know what DM is made of

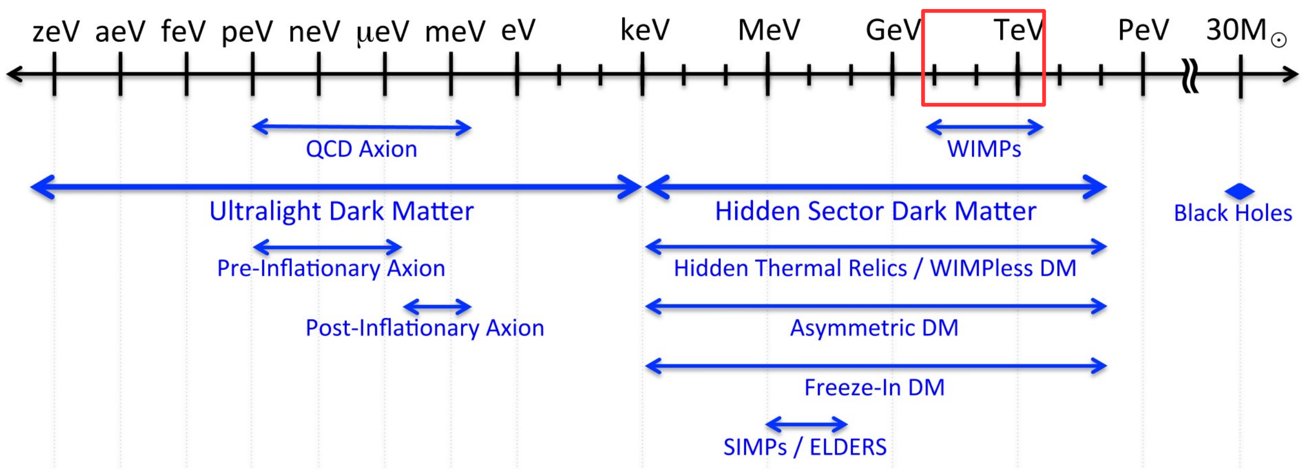
The dark matter problem

The observed effects imply that the basic constituents of DM must be electrically neutral, stable (or very long-lived) and non-relativistic

Standard Model (SM) particles cannot account for DM ⇒ New elementary particles?

Dark matter candidates

Astronomical observations do not constrain the mass of DM particles: wide range of candidates



Weakly-interacting massive particle (WIMP) hypothesis: explains amount of DM in the universe by assuming that it couples to ordinary matter through SM weak interaction

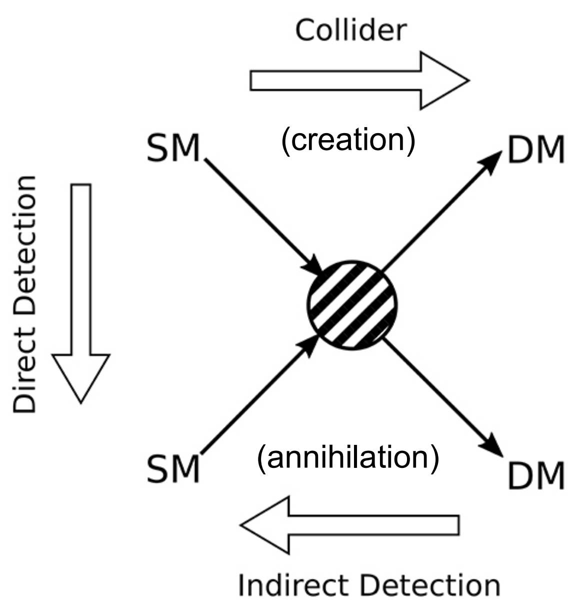
WIMP hypothesis motivates the search for DM particles in the GeV regime

In addition, several alternative DM production mechanisms (hidden sector freeze-out, asymmetric DM, freeze-in, etc) include sub-GeV candidates

WIMP search approaches

Three cases that exploit the coupling between WIMPs and ordinary matter:

- DM production at colliders: leading to excess of events with missing transverse energy
- DM annihilation in astronomical objects (indirect searches): leading to excess of astroparticle fluxes
- Direct searches: see next slide

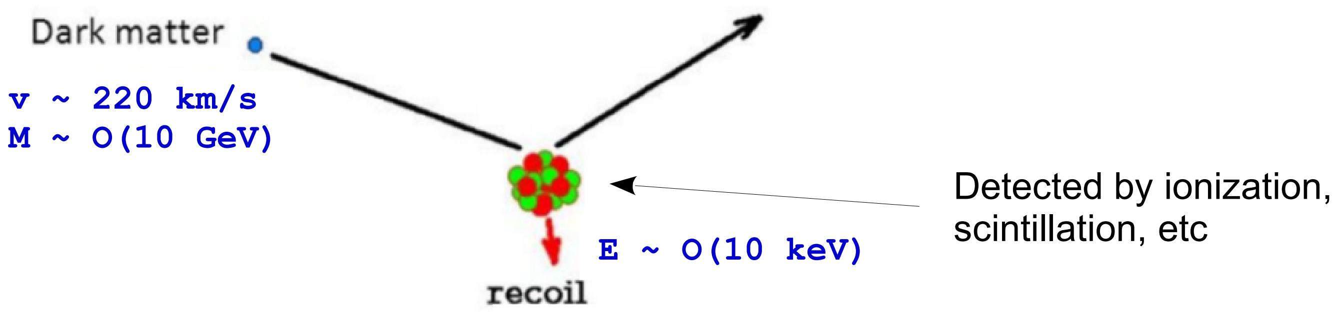


Direct WIMP searches

DM is distributed all over our galaxy ⇒ We expect some DM population at the Earth position

Direct searches: aim to detect an <u>excess of recoiling nuclei or electrons</u> (signal) occurring in a given volume (target), caused by interactions with galactic WIMPs

Note that the target itself should have the ability to detect recoiling particles



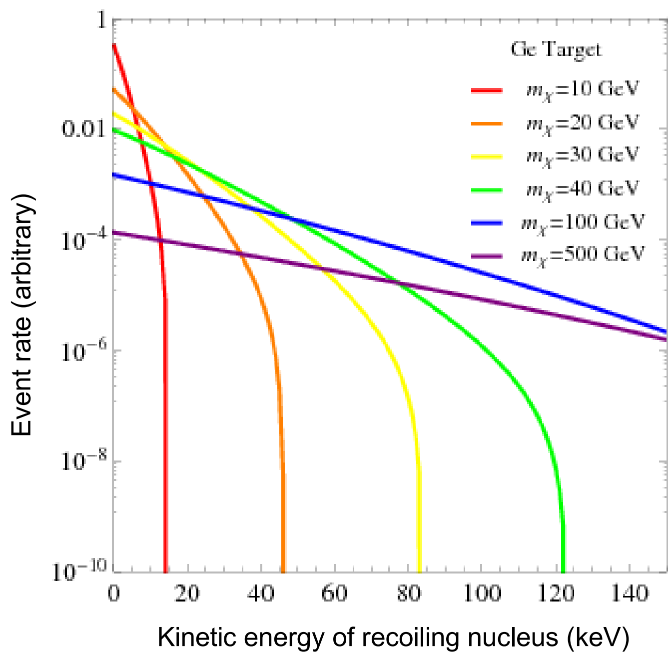
The greatest energy transfer occurs when M(target particle) = M(DM), therefore <u>recoiling nuclei</u> are preferred for direct WIMP searches

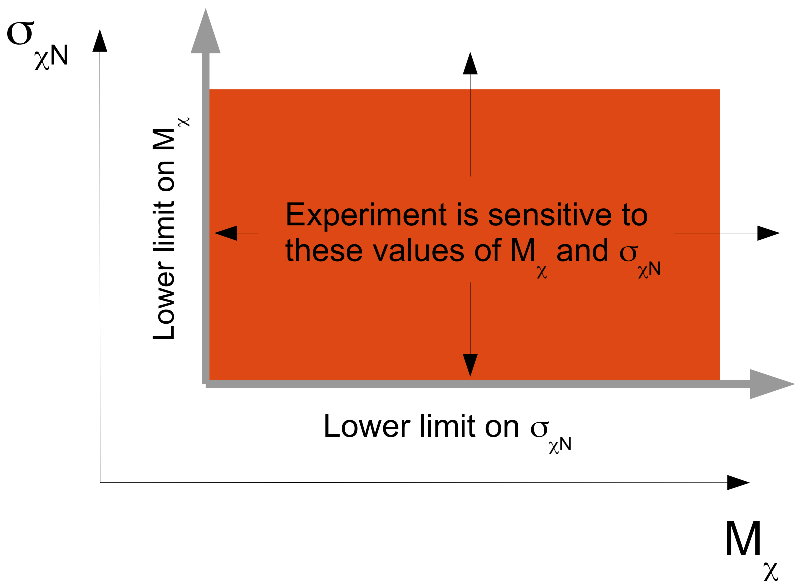
Direct WIMP searches

If assuming a given density and velocity distribution of galactic WIMPs at the Earth position, then signal depends only on WIMP mass (M_χ) and coupling to nucleons ($\sigma_{\chi N}$)

Therefore, results from direct searches allow to constrain M_χ and σ_χ

Sensitivity to M_χ depends on the energy threshold of the detector, and sensitivity to $\sigma_{\chi N}$ depends on the target mass, exposure time and background levels

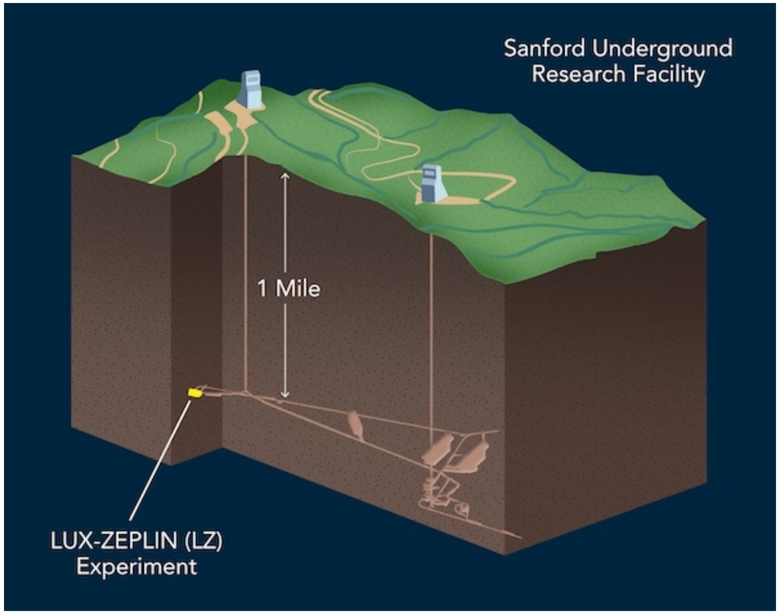


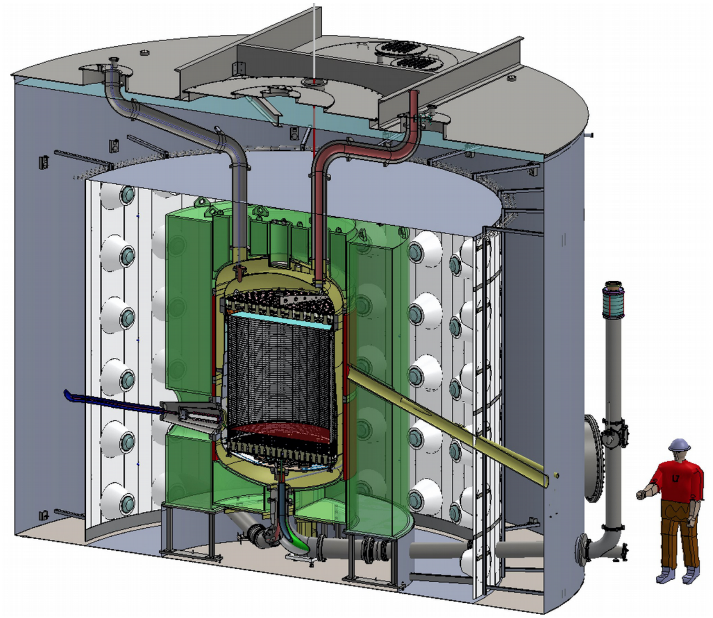


Direct WIMP searches

Signal consists of recoiling nuclei in the keV regime ⇒ Direct searches must reject background from environmental radiation (natural radioactivity+cosmic muons) by:

- Conducting experiments in underground laboratories
- Building shielding around the detector
- Using radiopure materials, and following strict cleanliness protocols



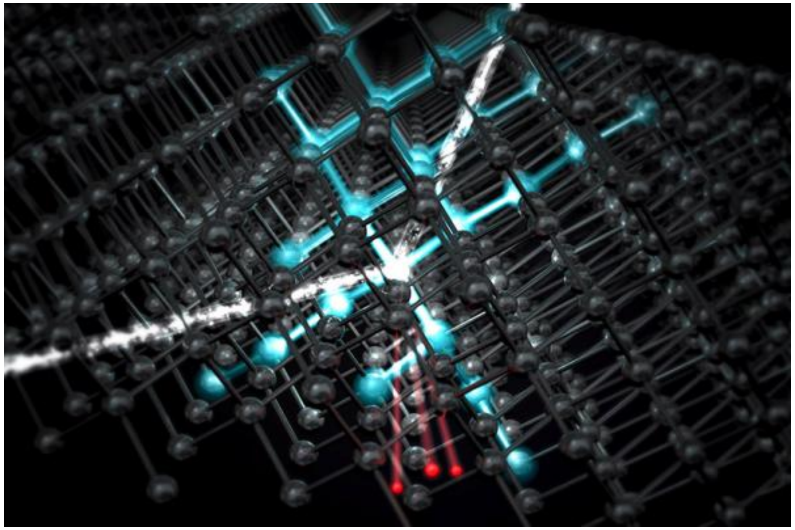


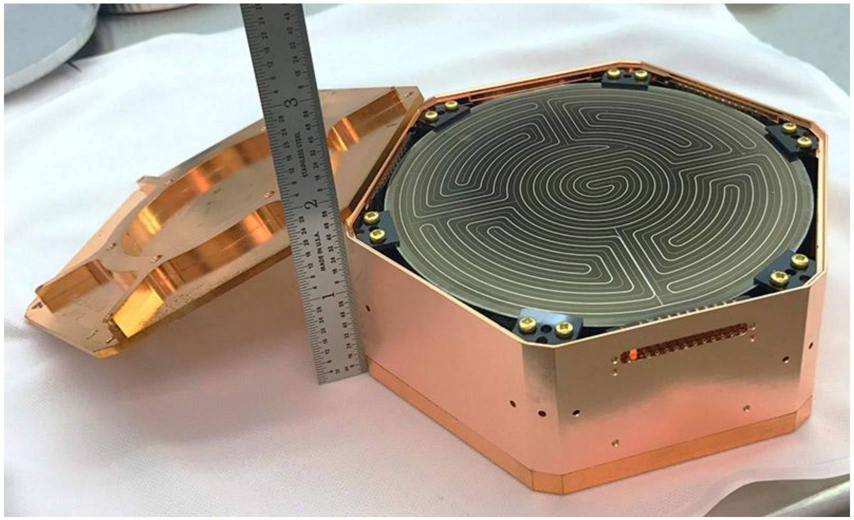
Direct WIMP searches

However a large <u>background of recoiling electrons</u> is still measured in direct WIMP searches ⇒ Need to discriminate recoiling nuclei from recoiling electrons (<u>particle-ID</u>)

Several experiments achieve particle-ID by <u>measuring two effects</u>:

- Phonons (quantized lattice vibrations)+ionization in semiconductors: CDMS (Ge, Si), EDELWEISS (Ge)
- Scintillation+ionization in noble elements: ZEPLIN, LUZ, LZ, XENON, PandaX (Xe), Darkside (Ar)

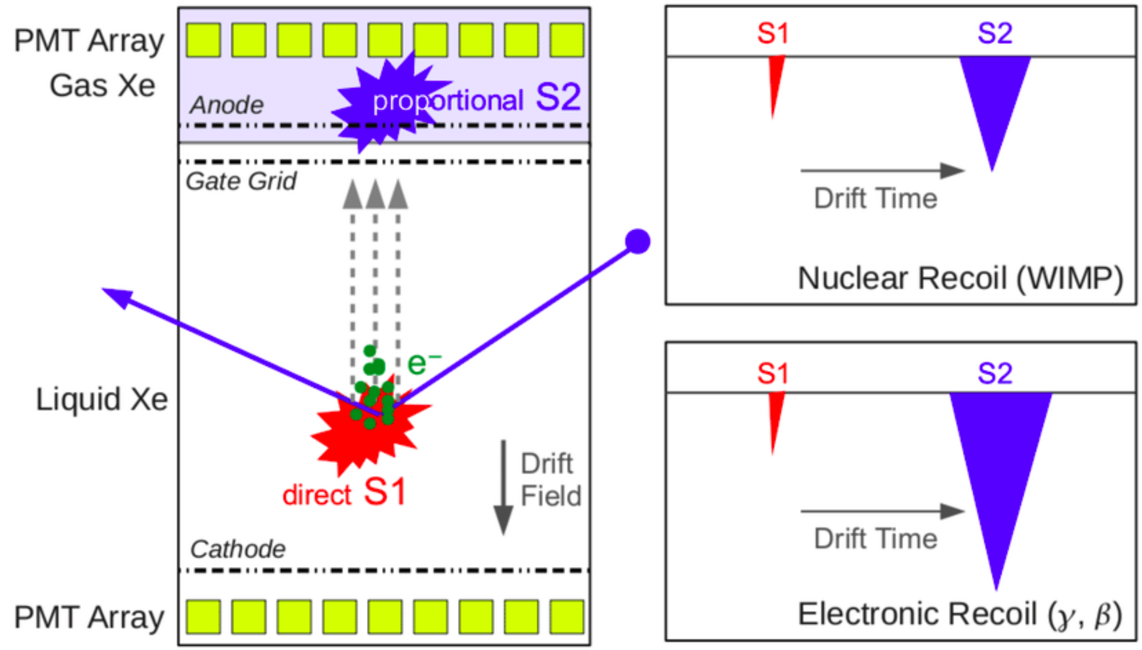




Double-phase xenon detectors

Double-phase xenon time projection chambers (TPCs) consist of:

- Large volume of liquid xenon (LXe), acting as target
- Thin layer of gaseous xenon above LXe
- Downwards electric field ⇒ Electrons drift upwards
- Top and bottom arrays of light detectors (PMTs)



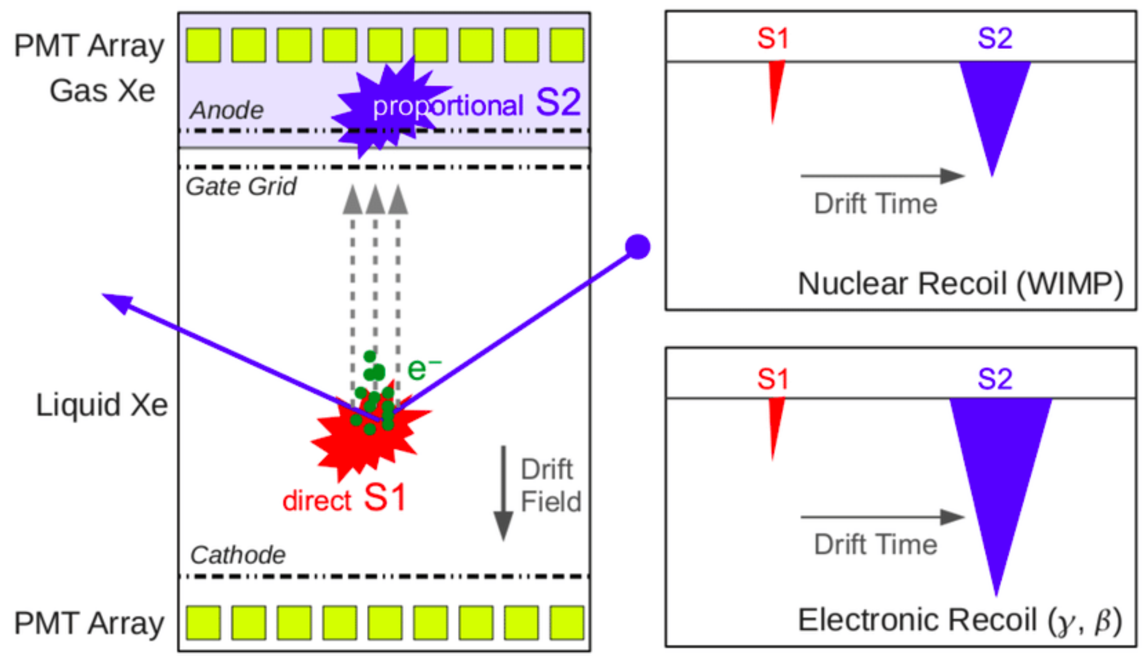
Double-phase xenon detectors

Energy deposited by a recoiling particle in LXe is split into scintillation and ionization

Scintillation produces prompt UV light (S1), while ionization drifts to gaseous phase and then produces proportional light by electroluminescence (S2)

Both S1 and S2 are detected by the PMT arrays

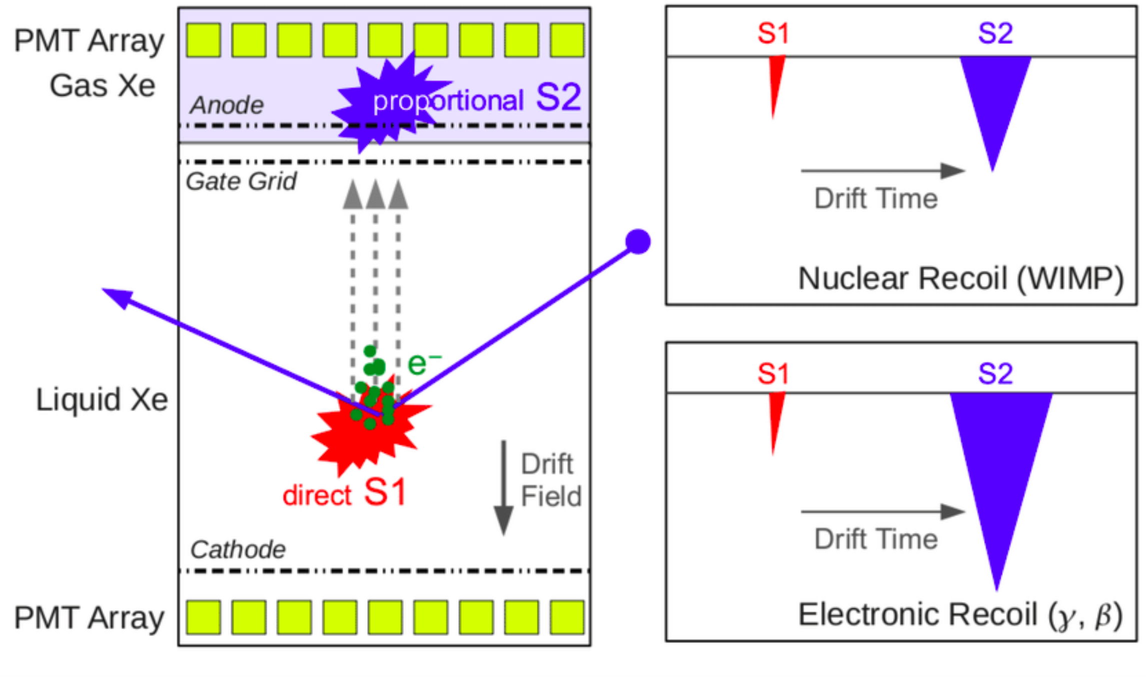
Energy threshold as low as ~3 keV for recoiling nuclei



Double-phase xenon detectors

Ionization/scintillation ratio depends on the recoiling particle ⇒ S2/S1 ratio allows to reject background from recoiling electrons

Time between S1 and S2 (drift time) allows precise measurement of the vertical position of interaction



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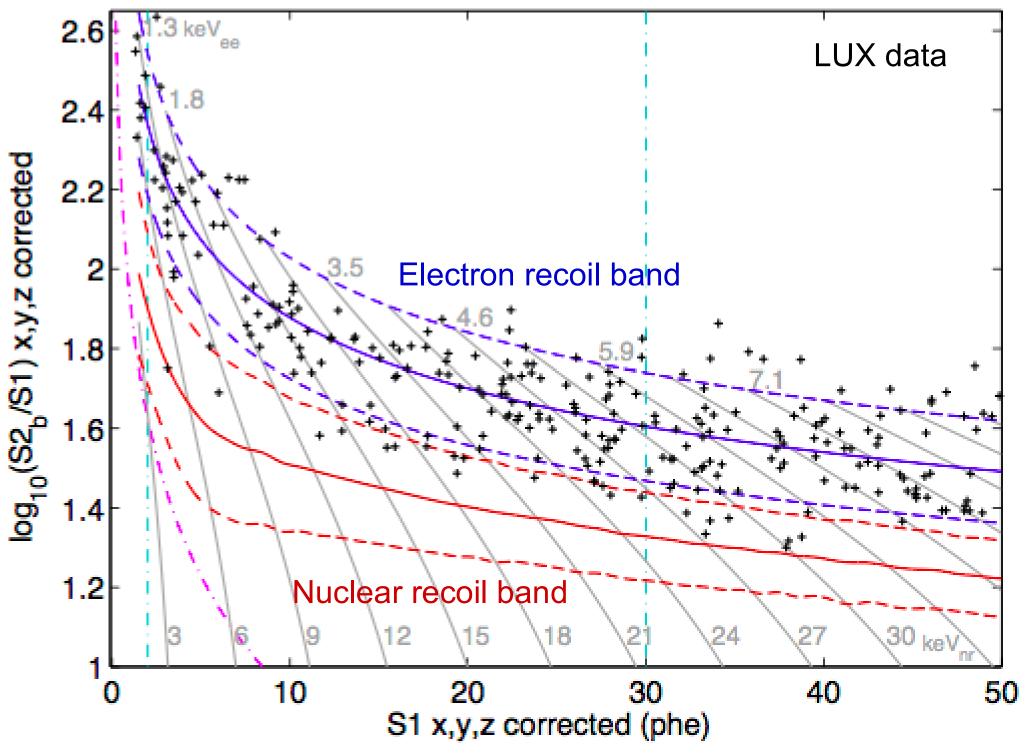
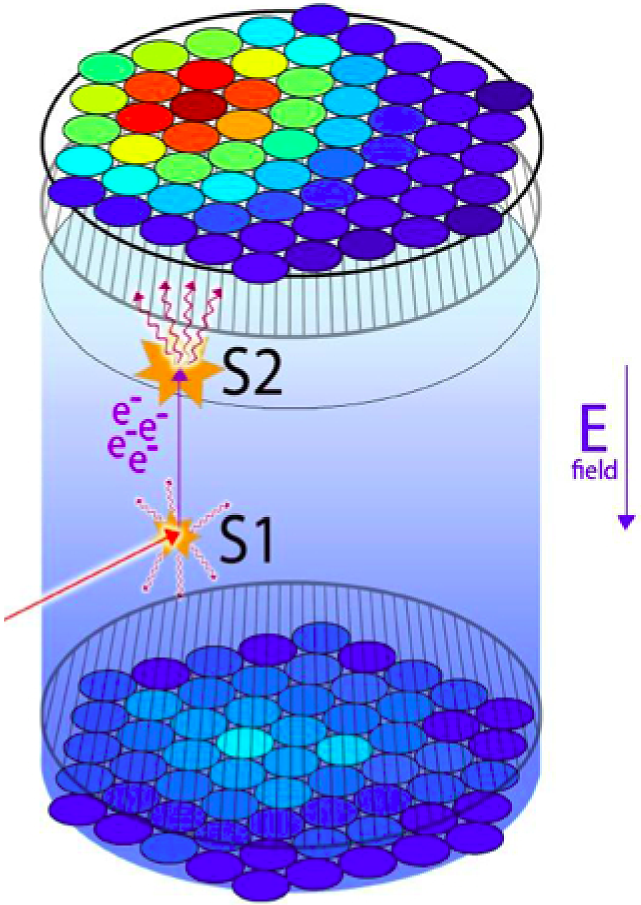


Double-phase xenon detectors

<u>Illumination pattern across PMTs</u> allows measurement of the <u>radial position</u> of interaction



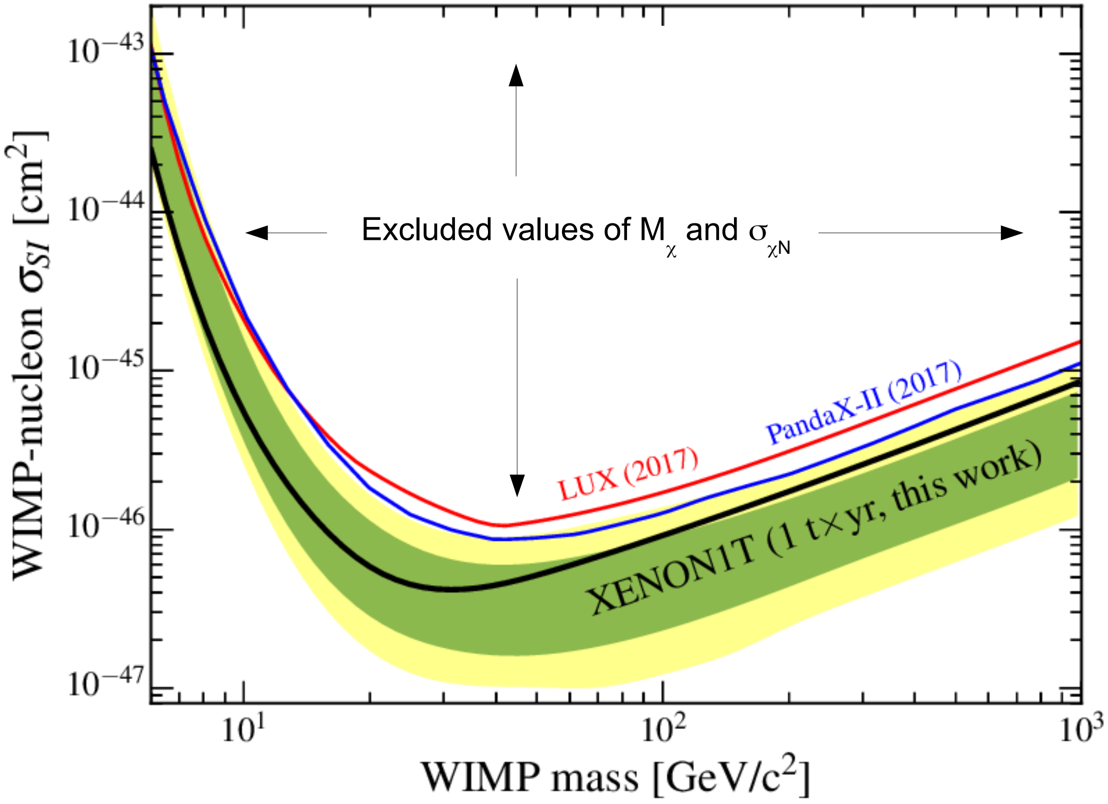
Double-phase xenon detectors

In summary, double-phase xenon TPCs allow to:

- Detect recoiling nuclei down to ~3 keV
- Discriminate recoiling nuclei from recoiling electrons
- Measure the position of interaction

Double-phase xenon detectors

Double-phase xenon detectors have achieved the best WIMP sensitivity to date

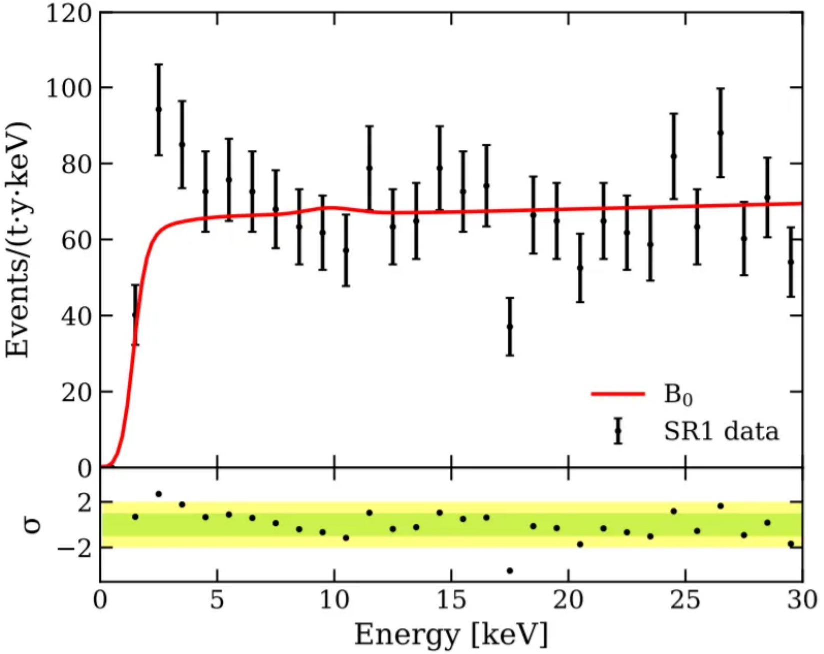


Double-phase xenon detectors

Besides, XENON1T recently reported an excess of recoiling electrons below ~5 keV

Possible explanations:

- New physics: solar axions, enhanced neutrino magnetic moment (both disfavoured by astrophysical constraints), dark photons, etc
- Unaccounted background: ^{37}Ar electron capture (X-ray line at 2.8 keV), or tritium beta decay (end point at 18.6 keV)



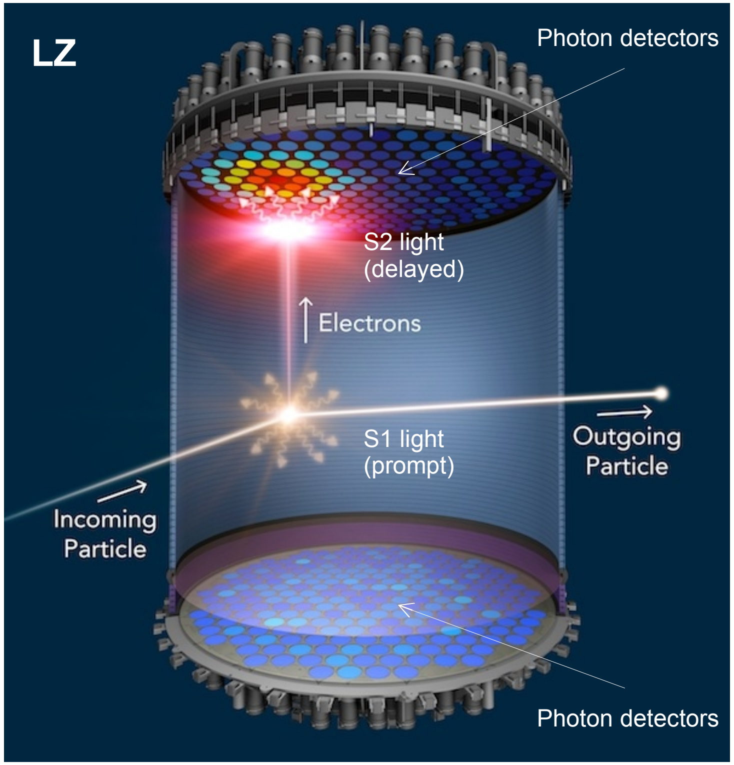
LUX-ZEPLIN (LZ) experiment

The LZ experiment

Second generation (G2) experiment, evolution of LUX and ZEPLIN experiments

Purpose: search for WIMPs beyond the current limits on σ_{XN} ⇒ Expected signal rate is lower than in previous experiments

Currently ending construction, planning to start Science Run 1 in spring 2021

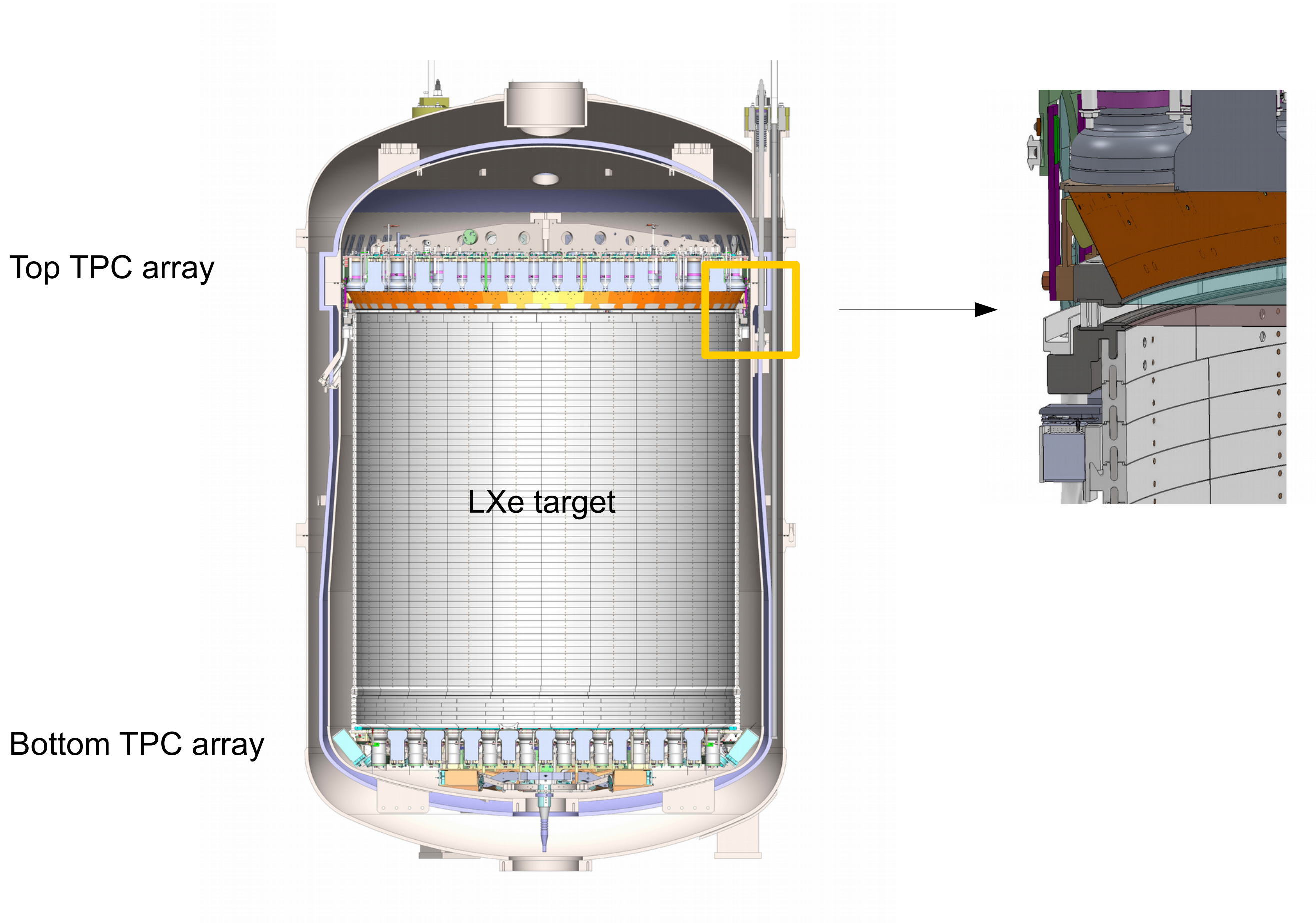


The LZ experiment

Height and diameter of TPC are both 1.46 m

TPC contains 7 tonnes of active LXe, viewed by 253 (top) and 241 (bottom) PMTs

Inner TPC surface is covered by highly reflective polytetrafluoroethylene (PTFE), measurements of PTFE reflectance in LXe were carried out at LIP-Coimbra

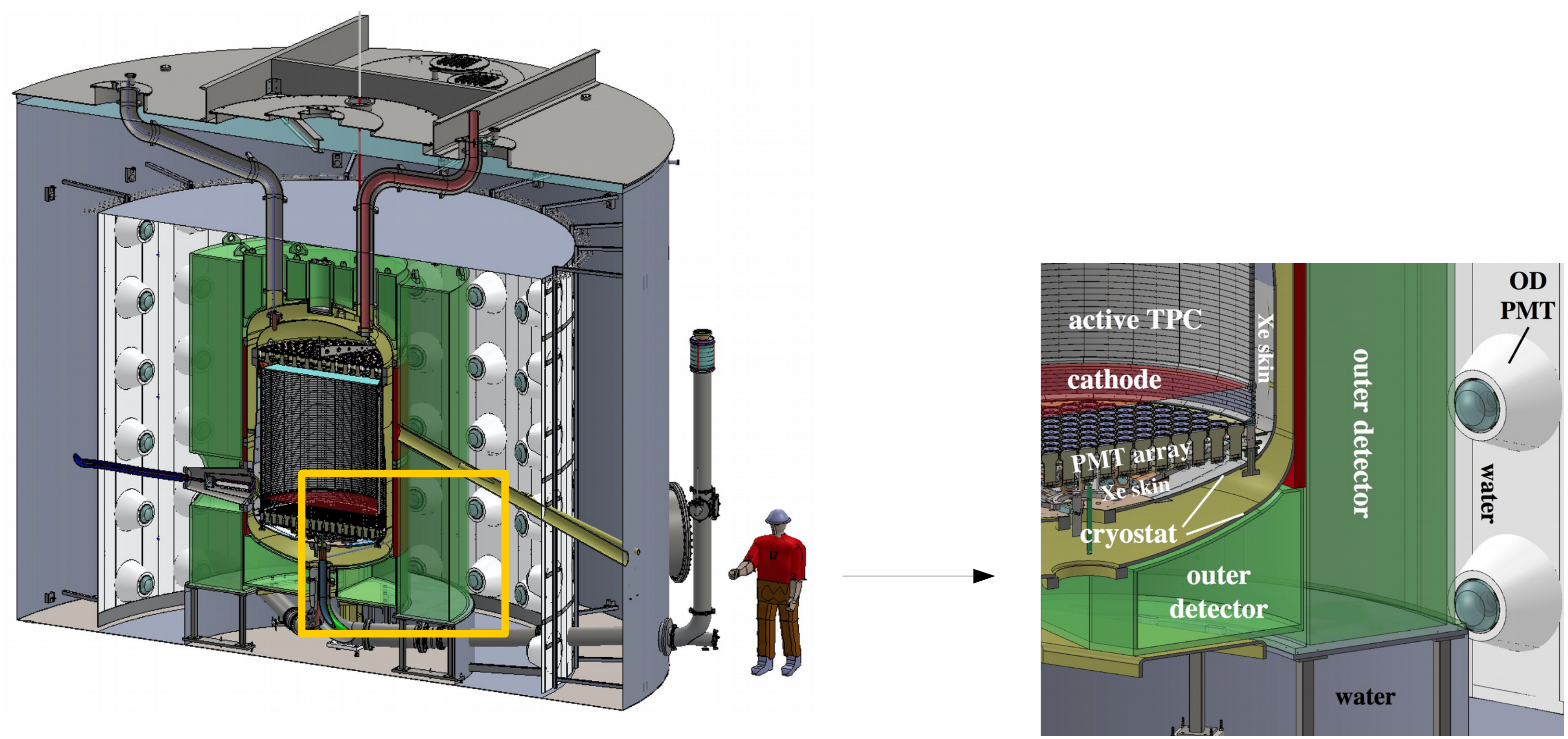


The LZ experiment

In order to achieve sensitivity to lower signal rates, a crucial requirement of LZ has been to increase background suppression with respect to previous experiments

To that purpose, LZ uses an active shielding: allows to identify background events by detecting additional scatters in a large volume around the target

In addition, LZ has conducted an extensive and systematic screening program

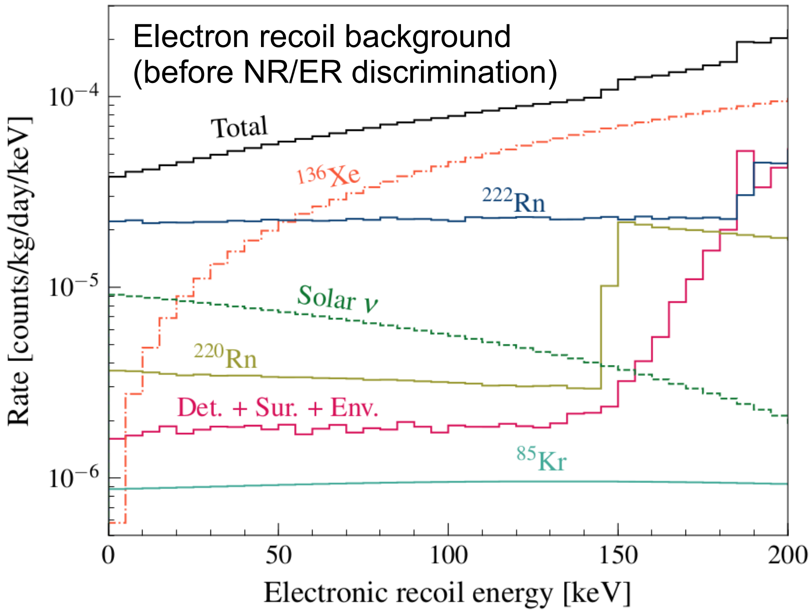


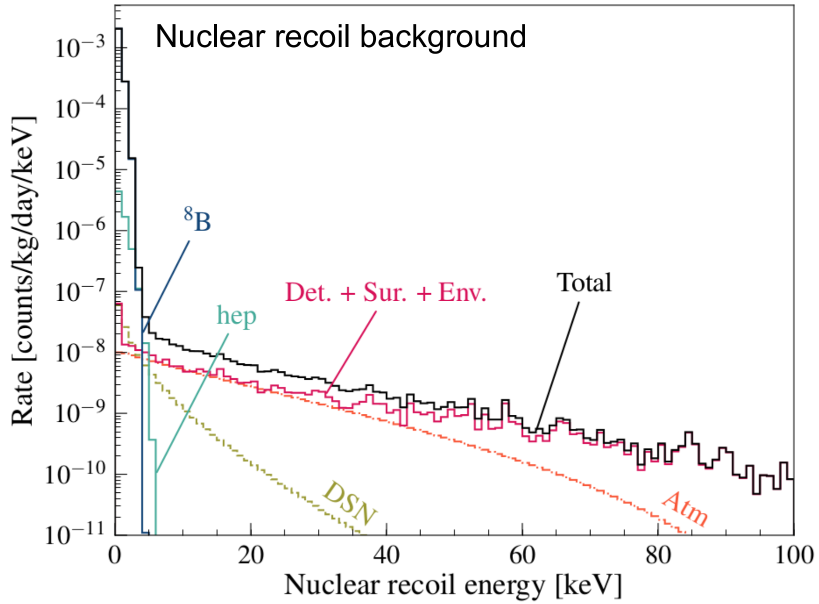
Backgrounds

After 1000 live days, LZ expects to have 6.5 background events passing the WIMP search selection

Most important background source is radon dispersed over the xenon target (4 events)

Recoiling nuclei from neutrons only account for 0.5 events



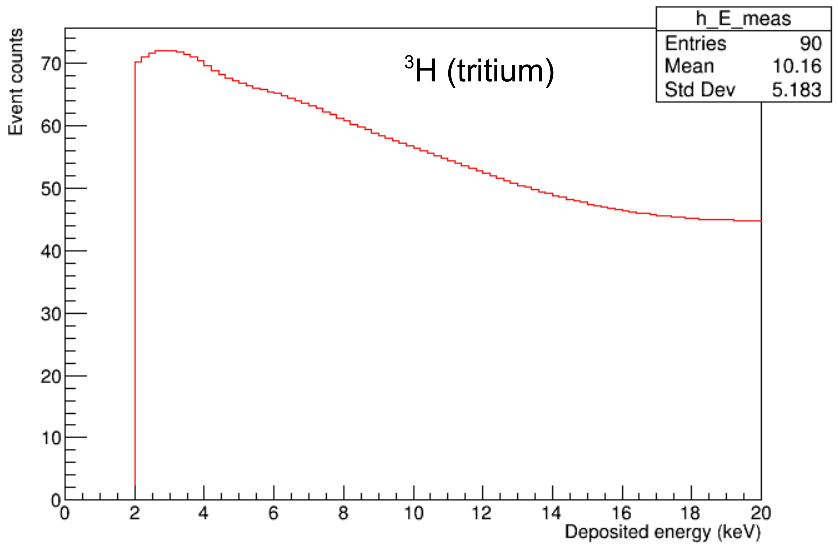


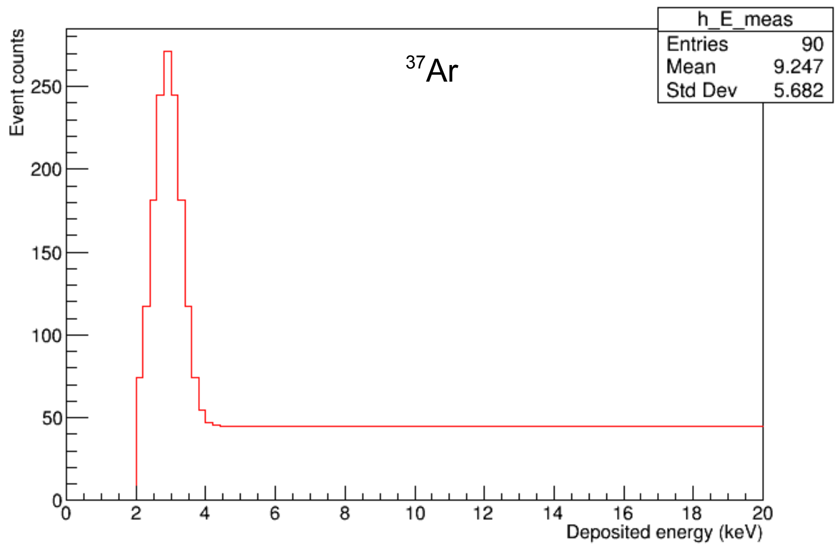
Backgrounds

^{3}H (tritium) beta decay and ^{37}Ar electron capture have not been considered in the LZ background model

XENON1T results showed that we might need to address such contributions

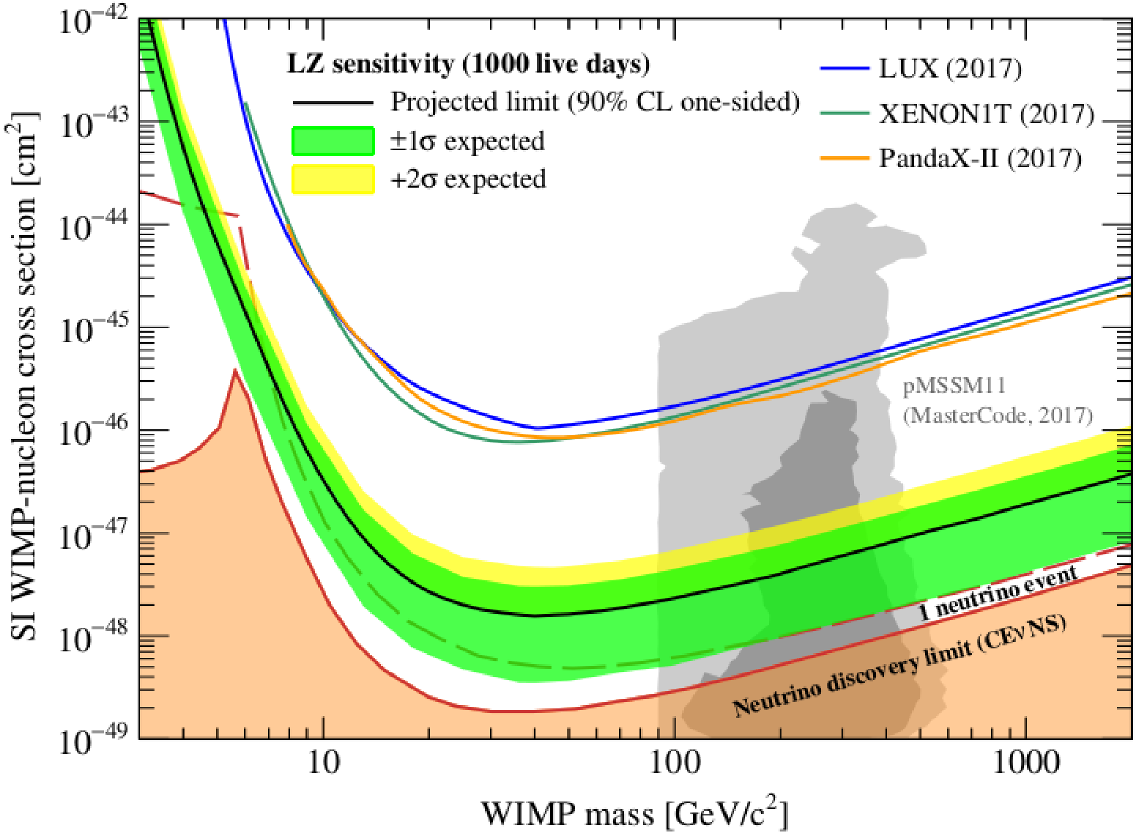
This year, one LIP summer internship has been dedicated to estimate the background from ^{3}H and ^{37}Ar in LZ, assuming the contamination levels that would explain the XENON1T excess





WIMP sensitivity

After 1000 live days, LZ expects to improve the existing limits by more than one order of magnitude



Complementary dark matter searches

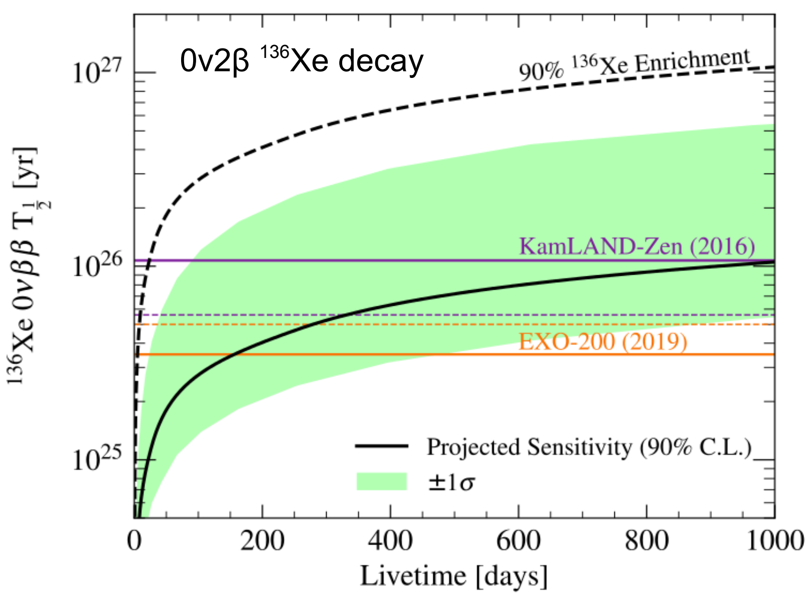
- WIMP search below nominal threshold: using S2 only
- Sub-GeV DM particles: Migdal effect or bremsstrahlung emission of recoiling nuclei
- Dark photons: search for excess of recoiling electrons at a definite energy

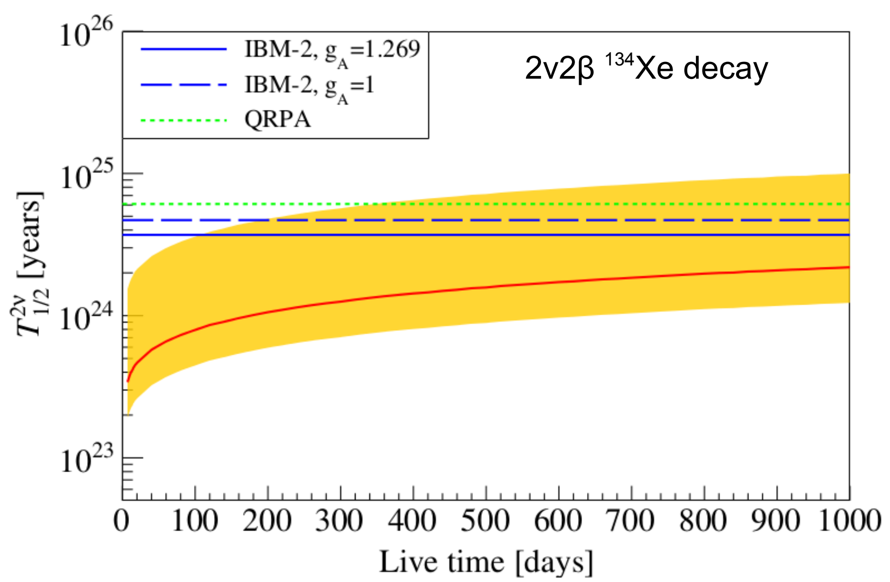
DM axions would deposit energy below the detector threshold, but solar axions would provide a measurable signal

Neutrino and nuclear physics

The large target and low background levels of LZ allow to also conduct research on neutrino and nuclear physics:

- Coherent scattering of ^{8}B neutrinos on nuclei
- Neutrino magnetic moment
- Neutrinoless double beta decay and related processes: ^{136}Xe, ^{124}Xe, ^{134}Xe
- Very rare nuclear decays (half life longer than 10^{23} years): ^{124}Xe, ^{134}Xe

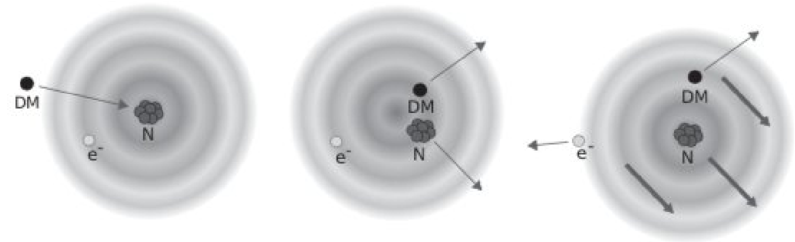




Migdal effect

The Migdal effect

Ionization mechanism proposed by A. B. Migdal in 1941: emission of an atomic electron when the respective nucleus suddenly acquires a given velocity



Concept: the electron eigenstates for the moving nucleus,

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

are not orthogonal to those for the initial nucleus at rest, therefore the transition probability between ground and ionized electron states,

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

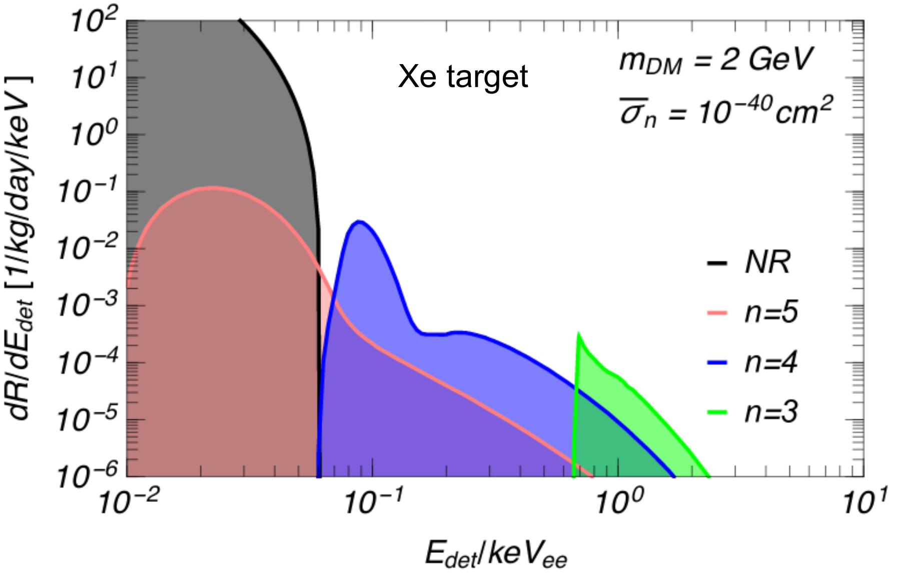
could be non-zero

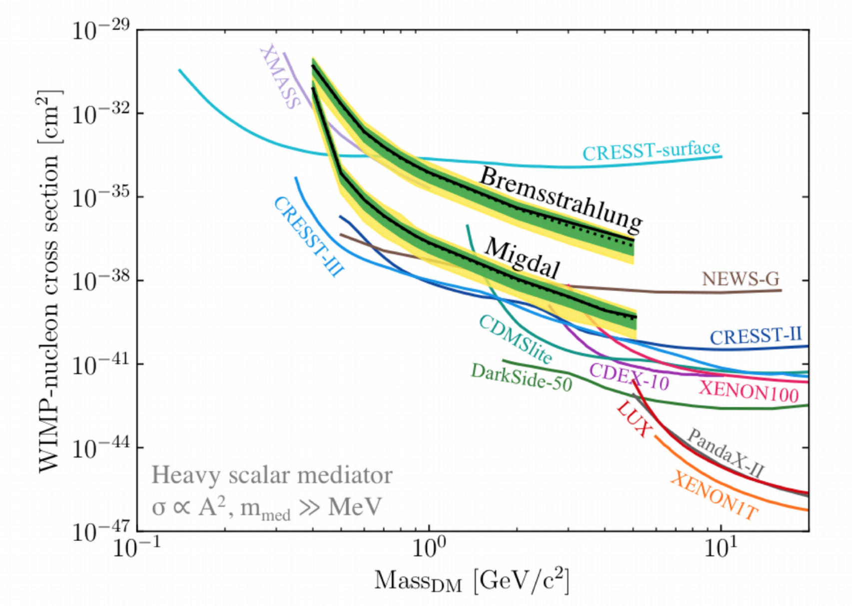
M. Ibe *et al.* have checked energy and momentum conservation in Migdal effect, in the context of direct DM searches

The Migdal effect

However, the Migdal effect has not been confirmed experimentally yet

Several direct detection experiments have calculated exclusion limits assuming that Migdal effect exists





Migdal effect would make xenon experiments competitive to search for sub-GeV DM particles: inelastic process, with recoiling electron in final state

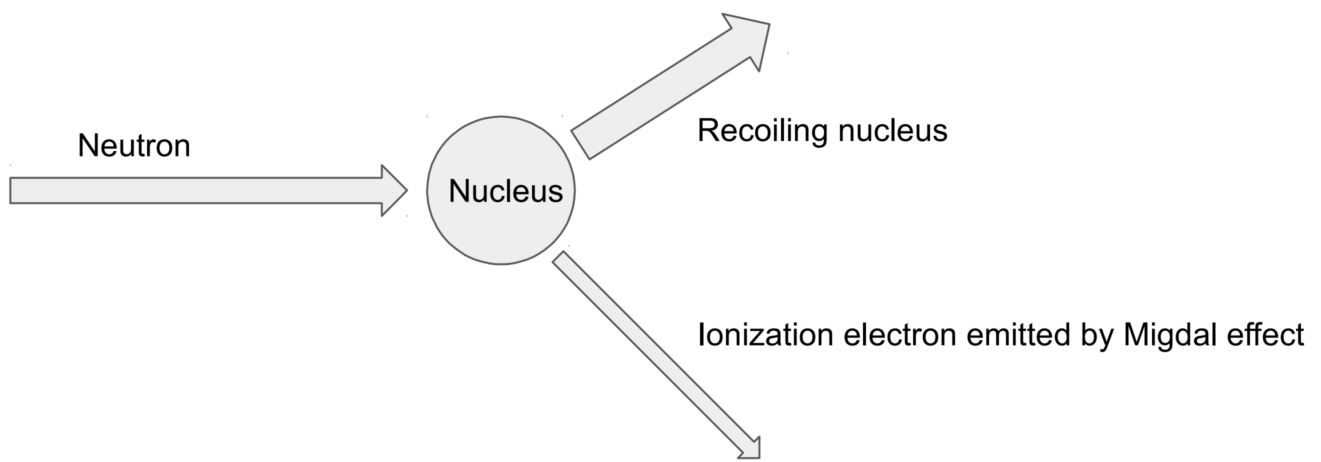
Experimental confirmation of Migdal effect

RAL (UK) is currently developing an experiment to confirm the Migdal effect, funded by STFC (Xenon Futures R&D project): MIGDAL experiment

Besides RAL, other collaborating institutes are Imperial College (UK), LIP and CERN (Switzerland)

Concept: use neutrons to induce Migdal effect in atoms of a gas target contained in a tracking detector

Therefore signal consists of two tracks that start from the same vertex: the recoiling nucleus and the Migdal ionization electron (~10 keV)

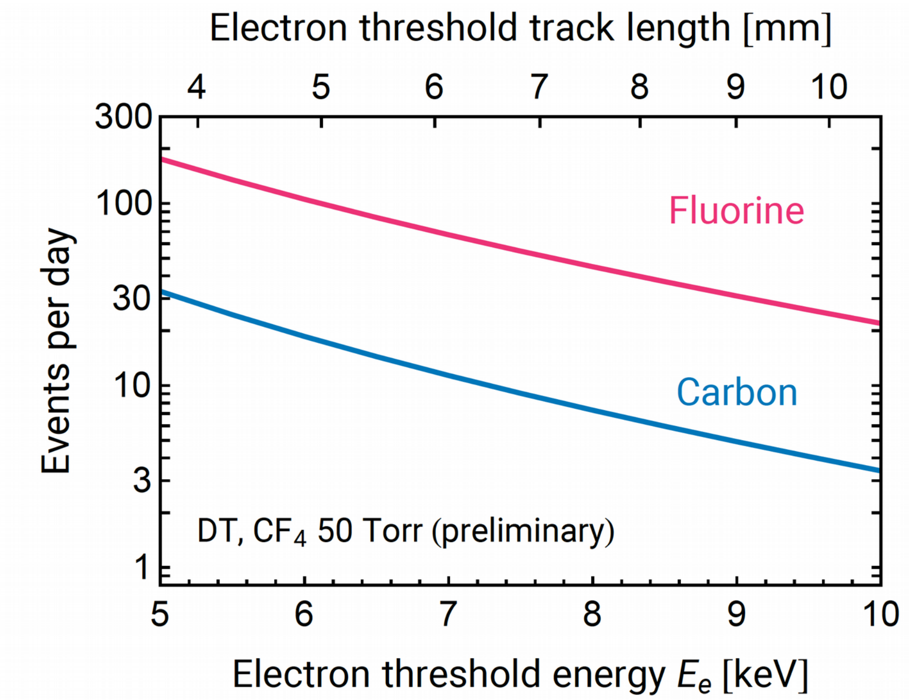


MIGDAL experiment

Neutron source: deuterium-tritium (DT) generator, producing 14.1 MeV neutrons at a rate of 10^{10} Hz

Target gas: carbon tetrafluoride (CF_4) at low pressure (50 torr) in order to have visible Migdal electron tracks

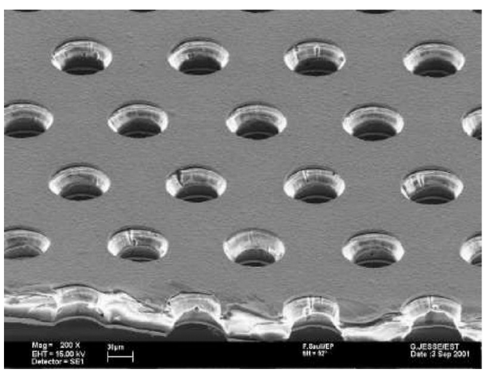
In a 10×10×5 cm^3 active volume the rate of neutron scatter events is ~60 Hz, and the predicted signal rate is ~200 events/day

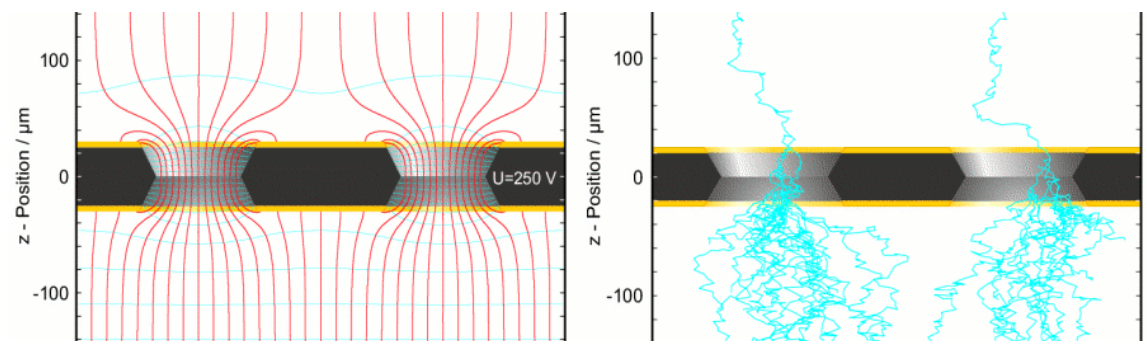


MIGDAL experiment

Tracking detector: optical time projection chamber (OTPC) that consist of:

- A cathode
- Two consecutive gaseous electron multipliers (GEMs)
- An indium tin oxide (ITO) anode
- A camera





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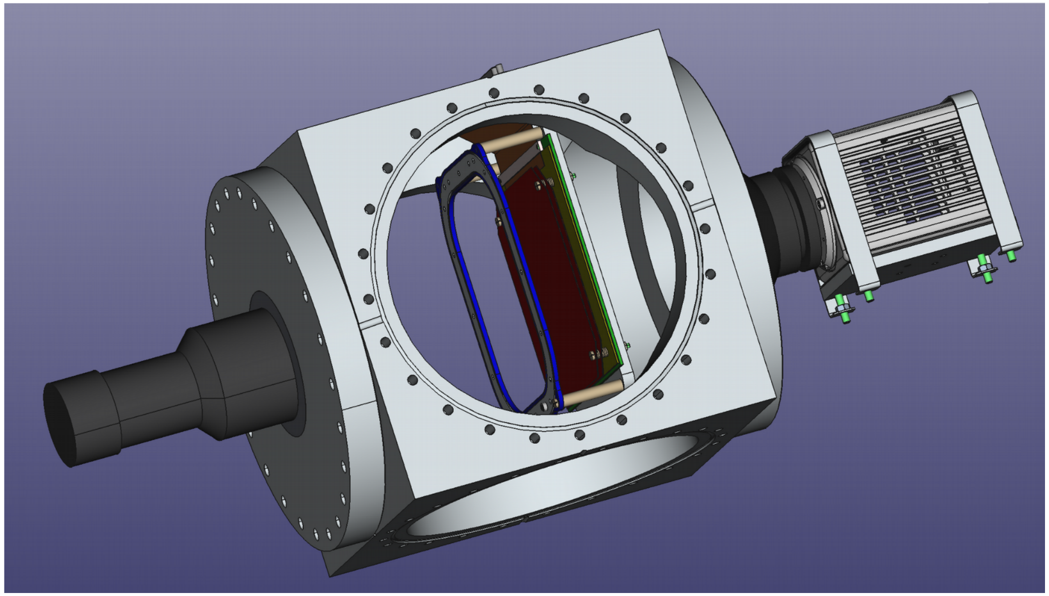

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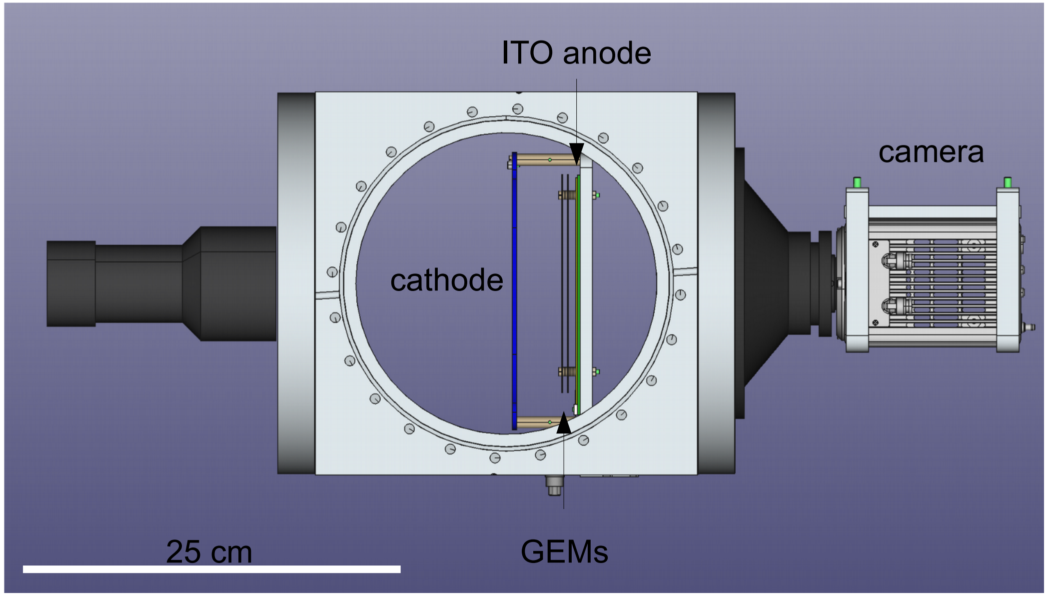
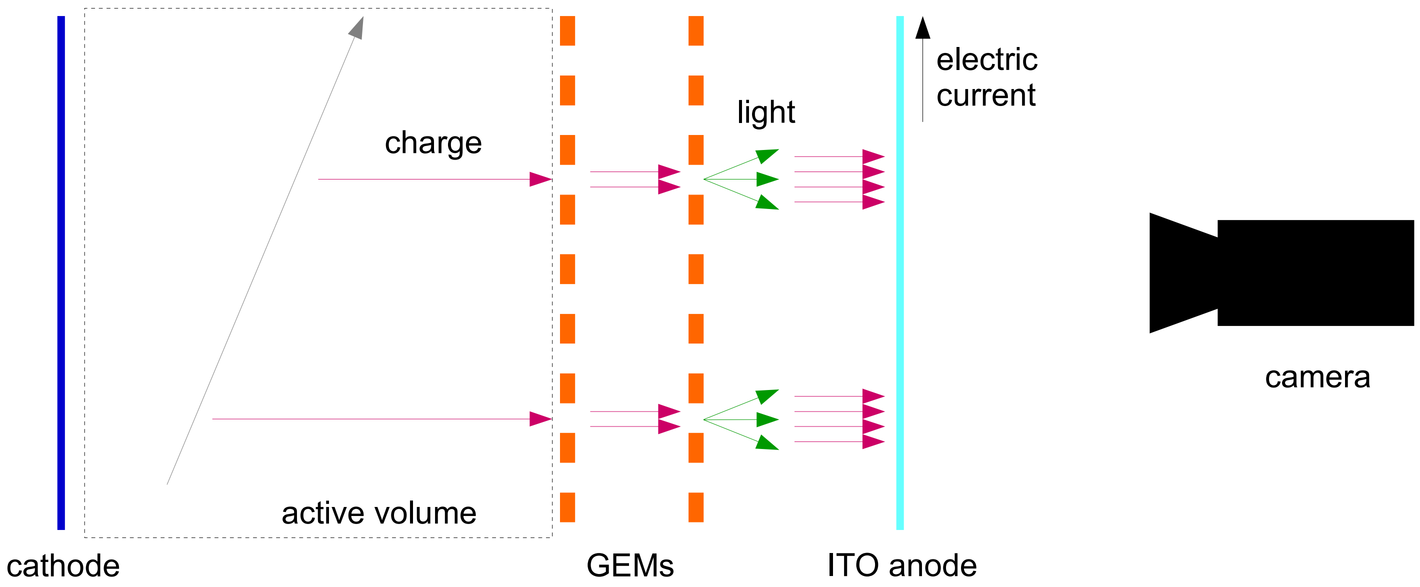


MIGDAL experiment

Particles produce ionization that drifts to GEMs, and then electron multiplication produces scintillation light from CF_4

Scintillation light is captured by the camera, and the amplified charge is collected at the ITO anode

The image from scintillation light is a 2D projection of the event tracks, while the timing of the charge collected at the ITO anode provides depth information



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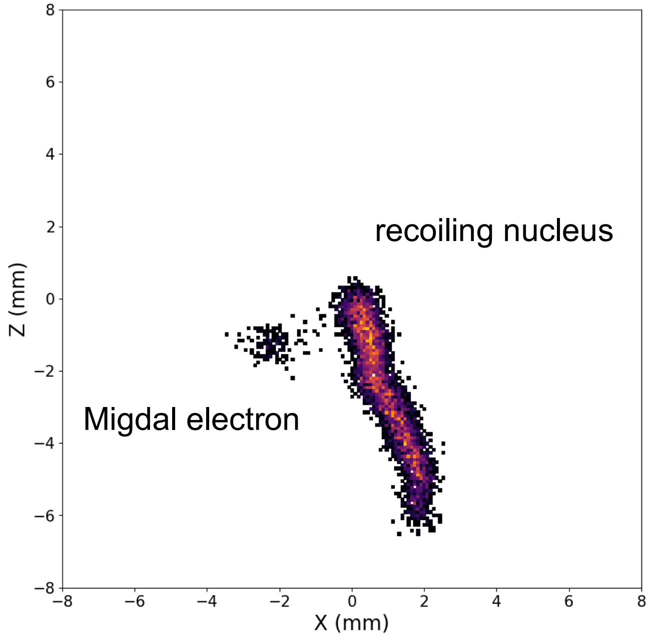
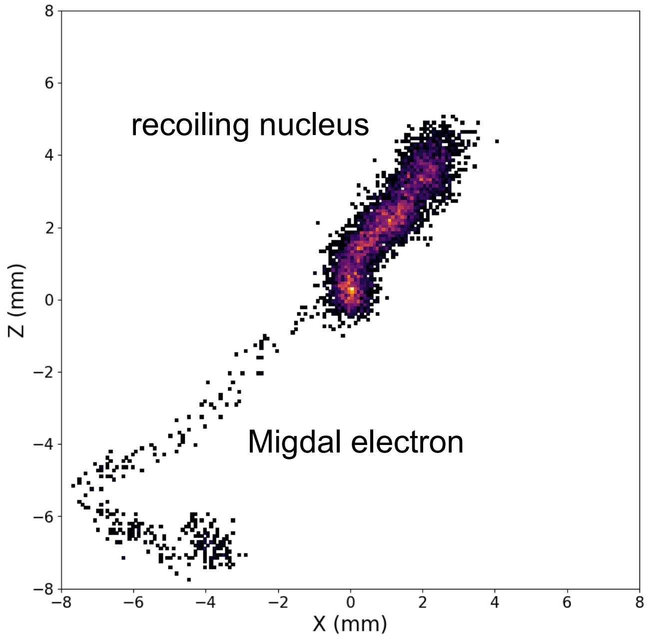




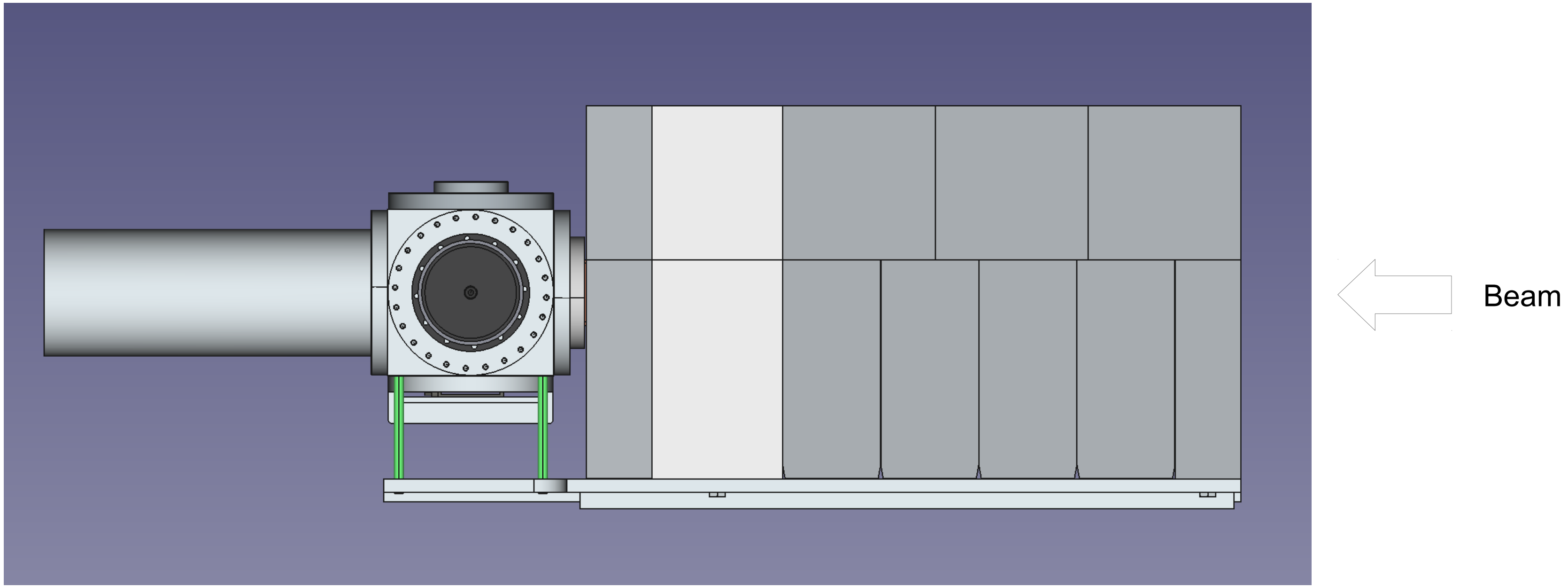
MIGDAL experiment

DT generator produces neutrons isotropically ⇒ Experiment requires setup to define a neutron beam focused on the active OTPC volume: front shield and collimator

Optimization of front shield and collimator has been an important contribution from LIP-Coimbra

Front shield: 70 cm iron+20 cm borated polyethylene+10 cm lead

Collimator: double-trapezoid tunnel with copper walls



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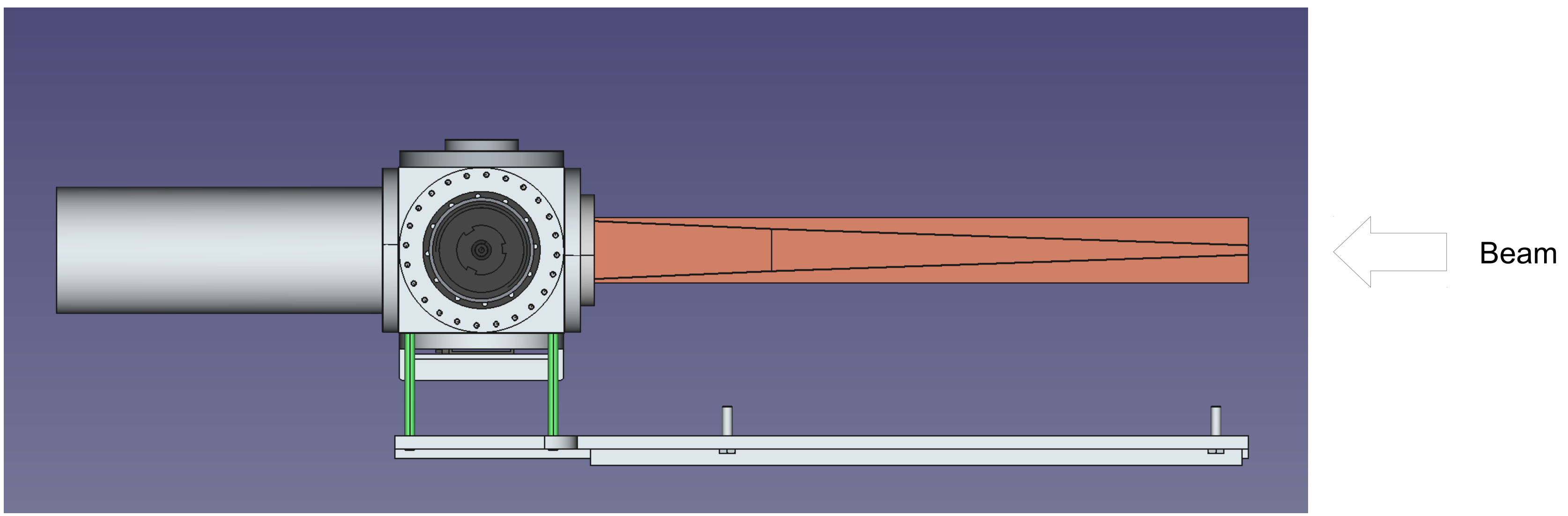

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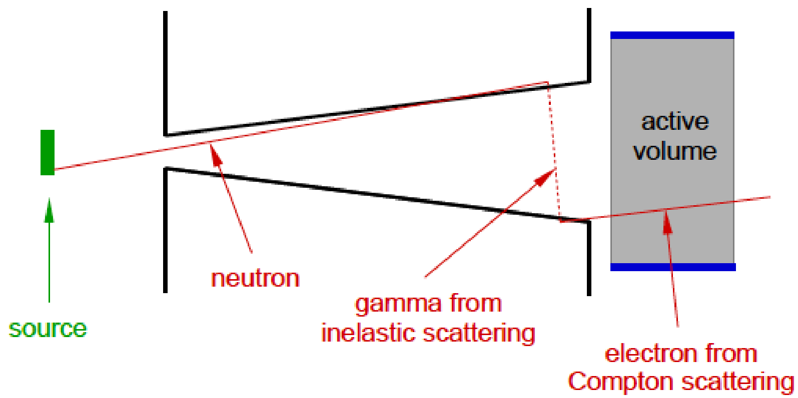
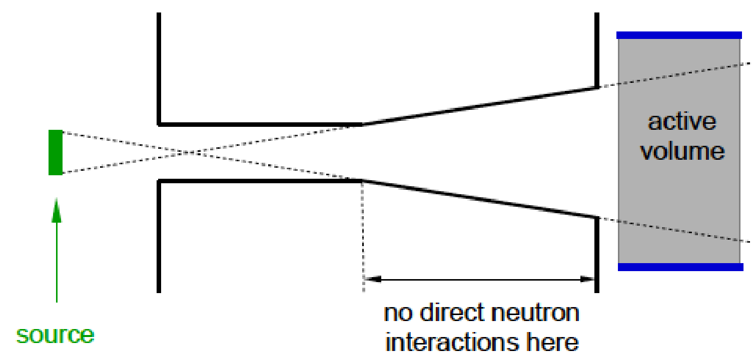
Simple trapezoidal collimator



Double-trapezoid collimator



MIGDAL experiment

Conducting an extensive study to identified potential sources of backgrounds

The only relevant background source identified to date is random track coincidences, estimating ~30 events/day

MIGDAL experiment expects to be able to confirm Migdal effect in CF_4 after ~1 month of data taking

Current status: starting construction, planning to operate before the end of 2021

If confirmed, Migdal effect will be also studied in argon and xenon (using Ar+CF_4 and Xe+CF_4 mixtures), and in a lower energy regime (using deuterium-deuterium neutrons)

Future prospects

Beyond G2 experiments

Double-phase xenon detector technology has the potential to continue leading direct dark matter searches after G2 experiments

Identified two main scientific objectives for a third generation (G3) xenon experiment:

- Extend sensitivity to $\sigma_{\chi N}$ down to the neutrino floor
- Consolidate the use of xenon detectors to search for sub-GeV DM

Proposed R&D to achieve these objectives is:

- Study the use of silicon photomultipliers (SiPMs) to improve detection of S1 and S2 light
- Improve the techniques to remove radon from LXe, that is expected to be dominant background source in LZ
- Confirm Migdal effect (discussed earlier)
- Study the feasibility of doping xenon with hydrogen to search for sub-GeV DM

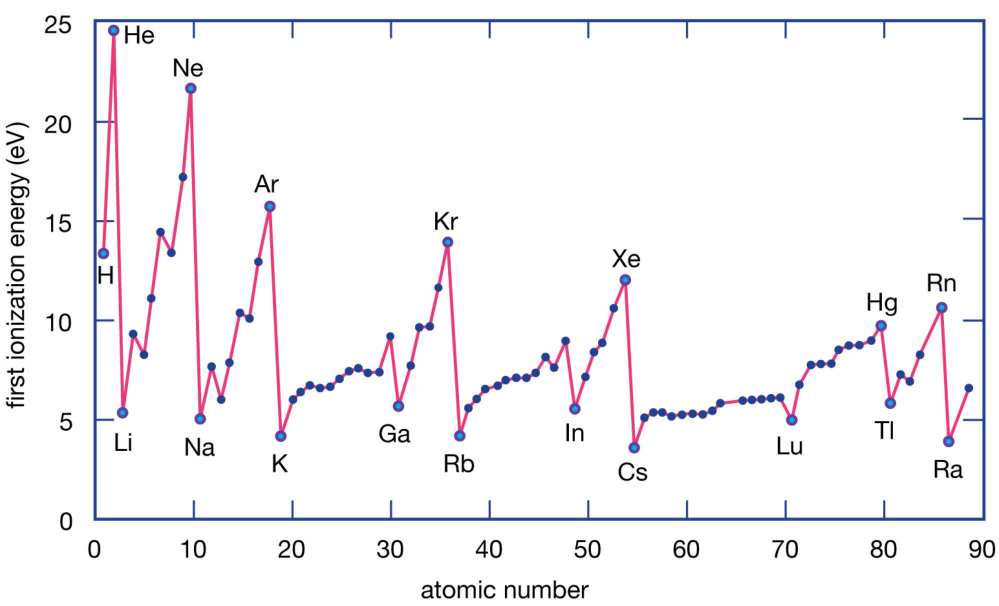
Hydrogen-doped xenon detectors

In a DM-nucleus interaction, a light nucleus receives more kinetic energy than a heavy one

Based on that, UCSB and Fermilab (US) have started R&D on detectors consisting of hydrogen gas diluted in LXe (HydroX project)

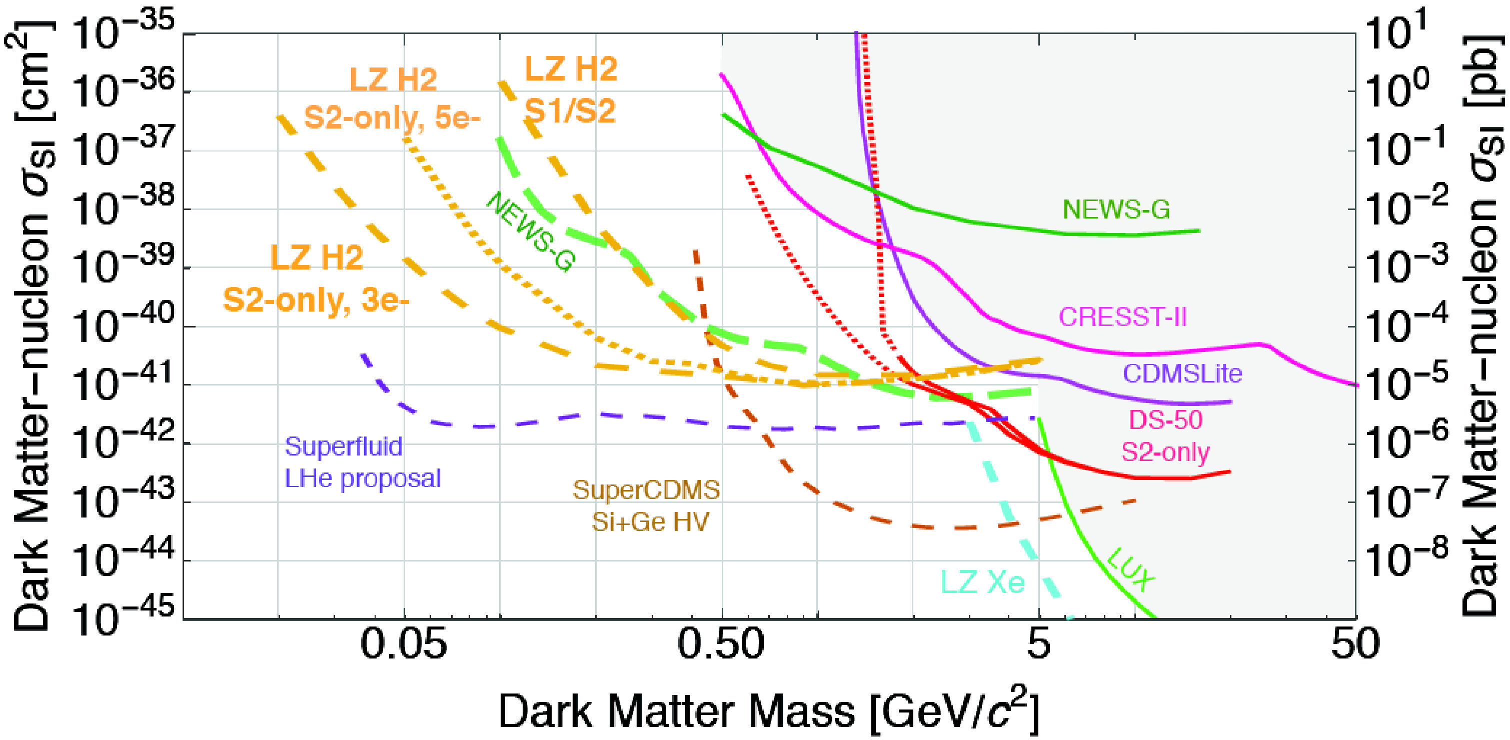
In this case, hydrogen gas acts as the target, and LXe acts as the detector medium

In this case, one advantage of xenon with respect to lighter noble gases is its low ionization energy (12.13 eV), that allows sensitivity to smaller values of M_X



Hydrogen-doped xenon detectors

If successful, this technology might be deployed in LZ after completing the scheduled science runs



Summary

- Double-phase xenon TPCs measure prompt scintillation light (S1) and delayed electroluminescence light from ionization (S2)
- Xenon experiments have achieved the best WIMP sensitivity to date
- LZ is a G2 experiment that will extend the search for WIMPs beyond the current limits on $\sigma_{\chi N}$
- Xenon experiments could be also competitive to search for sub-GeV DM if Migdal effect is confirmed
- Migdal effect: atomic ionization caused by a perturbed nucleus
- The MIGDAL experiment aims to observe the Migdal effect induced by neutrons, using a tracking detector
- Double-phase xenon TPC technology has the potential to continue leading direct dark matter searches after G2 experiment

Thank you for your attention