Searching for Dark Matter
High and Low
• Dark Matter (DM) is the only theory that can explain the Universe on all scales at all times

• Very large body of evidence
  ○ Galaxy rotation curves
  ○ Galaxy clustering
  ○ Cluster collision
  ○ Large-scale structures
  ○ CMB fluctuations
  ○ Gravitational lensing

• Global fit of cosmological parameters:
  \( \Omega_\Lambda \approx 0.68 \), \( \Omega_{DM} \approx 0.27 \), \( \Omega_b \approx 0.05 \)
• Five times more DM than regular matter

• The discovery of DM will be one of the most important discoveries in modern physics

• Unfortunately, its detection has escaped us so far

• How to catch such a specter?
**Indirect Searches** search for DM where we know it exists: In the Universe

- Look at places where we expect particularly **large amounts of DM**, e.g:
  - Center of the Galaxy
  - Galaxies which are DM dominated
  - Objects with massive gravity like the sun

- So far **‘no smoking gun’** but some intriguing excesses

- **Galactic center** excess in γ-rays between 0.1 and 10 GeV from Fermi-Satellite data
  - Spherically symmetric within < 10° × 10° around the Galactic Center
  - Foreground modeling very difficult, open debate
Search Strategies

Earth

Satellite

Indirect

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SM
CMS DETECTOR
Total weight: 14,000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16 m² ~66M channels
Microstrips (80x180 μm) ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16 m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels
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Björn Penning
PSI Colloquium
If all evidence of DM is gravitational, why should we look for it at collider (particularly hadron)?

- Well motivated, ‘WIMP paradigm’ predicts particles approximate EW scale
- Complementarity: Collider have different strengths and uncertainties

But

- DM has to be kinematically accessible: ~1-1000 GeV
- We haven’t seen it yet
Search Strategies

Direct

LHC

Earth

Satellite

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- Detect DM as our solar system passes through the galactic halo
  - $v \sim 10^{-3} \text{ c}$
  - Kinetic energy $\sim 100 \text{ keV}$
- Detected by recoils off **ultra-sensitive detectors** deep underground
- Roughly 1 interaction per kg per year

\[
\frac{dR}{dE_R} = \frac{\rho_0}{m_N m_\chi} \int_{v_{\text{min}}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R) dv
\]

- Very stringent cleanliness and background rejection requirements
- **Variety of detection methods**
- Momentum transfer crucial
- Low mass difficult
- **LXe dual-phase TPCs** demonstrated best sensitivity
- **Dual phase TPC**, two signals
  - Prompt scintillation light (S1)
  - Prop. charge signal amplified in gas (S2)
- **Depth** \((z)\) from time difference between S1/S2 and light pattern provides \((x, y)\) **position**
- Allows to define a **fiducial volume**
- LXe is dense and **shelf-shielding**
- Ionization/excitation (charge/light) depends on $dE/dx$
- Signal ratio allows to **discriminate particles**
  - Electron scatter tend to produce **more charge**
  - Neutron scatter create **more light**
- Excellent discrimination of signal and most backgrounds: **99.5%** discrimination before statistical methods
- 10t LXe target mass
- Surrounded hermetically by veto detectors
- Operating since Christmas 2021
• The **Outer Detector** encloses hermetically the TPC

• Using Gadolinium based liquid scintillator (**Gd-LS**)

• OD views Gd-LS using 120 8”-PMTs, surrounded by reflector system and mechanical support in aggressive environment

• Capturing neutron created 7.9 MeV cascades of about 3-4γ

• About **doubles** the **fiducial volume**
- LZ is located at SURF 1 mile deep
- Historic (and future) place
- Permanent presence at SURF
Cosmic Rays

1 mi deep

Radioactive backgrounds
Need also to avoid all type of internal contaminants

- Use purest materials obtainable, screen all materials
- Build everything in clean room, reduce dust on surfaces to $O(\text{ng/cm}^2)$
- Keep circulating and purifying target material: aim Xenon contaminants to $O(0.015 \text{ ppt})$

1 Banana = 15 Bq

- Bananas are actually somewhat radioactive due to potassium
  - 15Bq/Banana
- Our target activity in the Xe: 2 μBq/kg - 1/750,000 Bananas
- Cleaning, cleaning, cleaning, cleaning!
Those tanks look familiar…
Let's look at some Data!
An Event in the TPC

- Cartoon waveform:
• Cartoon waveform:

![Cartoon waveform]

• Actual waveform:

![Actual waveform]
• Backgrounds predominantly ERs, WIMPs produce NRs

• **ER band**: Tritiated methane (CH3T) injection, spatially homogeneous β source

• **NR band**: DD neutron generator (NR band), Monoenergetic 2.45 MeV neutrons
‘Naked’ $^{214}$Pb $\beta$-decays (no-$\gamma$) from Rn emanated in Xe are the main ER background.

Constrain $\beta$-decay rate by bracketing with Rn-chain $\alpha$-tagging & spectral fit of all internal BGs.

$^{222}$Rn activity within assay expectation.
● We actually observed more NR background than expected, successfully vetoed by the OD
• Event selections:
  ○ S1/S2 shape and topology selection
  ○ Veto detector, anti-coincidence
  ○ Fiducial Volume, ROI, single scatter cuts

• Selection criteria developed on non-WIMP ROI background & calibration data
• Rejection of live time with detector instabilities, high TPC pulse rates
• Key numbers:
  ○ 60 live days
  ○ 5.5 T of fiducial volume
- **Region-of-interest:**
  - $3 \text{ phd} < S1c < 80 \text{ phd}$, $S1$ coincidence $\geq 3$
  - $S2 > 600 \text{ phd} (6e^-)$, $S2c < 10^5 \text{ phd}$
- 335 events in final dataset
- 60 live days, $5.5 \pm 0.2$ tonne FV
LZ presently **world strongest result**
- LZ presently **world strongest result**

- Only **60 days out of a 1000 days** exposure published, considering extension to 2028
Modern LXe detectors are observatories for a wide range of physics processes.

**Sun**
- Solar pp neutrinos
- Solar Boron-8 neutrinos

**Supernova**
- Supernova neutrinos
- Multi-messenger

**Dark Matter**
- Dark photons
- Axion-like particles
- Planck mass

**WIMPs**
- Spin-independent
- Spin-dependent
- Sub-GeV

**Big Bang**
- Neutrinoless double beta decay
- Double electron capture

**Cosmic Rays**
- Atmospheric neutrinos
- Comics Muons
• MOU between LZ, XENON, DARWIN
• Had first meetings in Germany and LA
  ○ [https://xlzd.org/](https://xlzd.org/)
  ○ [White paper (2203.02309)](https://xlzd.org/)

Leading Xenon Researchers unite to build next-generation Dark Matter Detector

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

Low mass constraints much weaker

- We want to go lower & deeper!
\[ R = \sigma n_{\text{DM}} N_{\text{exp}} = \sigma \frac{\rho_{\text{DM}}}{m_{\text{DM}}} N_{\text{exp}} \]

Exposure: Rate scales inversely with dark matter mass

- Low mass constraints much weaker

- Compare ton scale LXe with gram scale low mass DM experiments
Lower mass searches require **light targets** and **very low energy thresholds**.
● Facing **new landscape**

● **Nuclear backgrounds**: Exists but less significant due to small ROI
  ○ γ down-scatter to low E, can also induce NR via Thomas-Delbrück
  ○ Epithermal **neutrons**

● **Novel backgrounds**:
  ○ Sensors sensitive to **smallest energies**
  ○ IR backgrounds, **parasitic power, phonons, vibrations, transition radiation** etc

● New **calibrations** necessary

● We know some of the challenges we’re facing, but some **cliffs** are probably still **hidden in the fog**
Low energy excess, observed in many experiments: SuperCDMS, Edelweiss, Nucleus, DAMIC, SENSEI etc

- Primary characteristic energy Scale: eV?
- Probably more than one origin
● What we need:
  ○ Low energy threshold
  ○ Scalable
  ○ Minimize backgrounds
  ○ Ability to discriminate and understand remaining and novel backgrounds
- **Tesseract**: Use different targets that probe different DM models and affected by different backgrounds

- **Energy sensitivity** is primary driver for low mass DM → need detectors with thresholds of 1-100 meV

- All targets read out using **Transition Edge Sensor (TES)** readouts, no E-field (no dark-currents)
Large collection area without the drawback of the heat capacity of a large sensor
  - Signal is degraded by low phonon collection efficiency

Readout of all targets identical except the substrate

More DM science doesn’t increase cost significantly!
- **Sapphire** ($\text{Al}_2\text{O}_3$): Many optical phonon modes that are kinematically well-matched to low-mass DM, high dark photon sensitivity

- **GaAs**: polar crystal, band gap matched well to low mass region. Reduce backgrounds via photons and phonons ratio/coincide

- **Superfluid helium** provides low mass NR sensitivity and multiple signal channels

- **All sensors operating** in demonstrator setups and are delivering physics

- **Novel & challenging backgrounds** due to femto and attoWatts sensitivity in TES

- **Advantage of Tesseract**: Ability to discriminate and characterize these backgrounds
- Targets relatively cheap, hence we consider several

- $\text{Al}_2\text{O}_3$ sensitivity across the board. One type of signal (phonon), multiple readouts to reduce instrumental background

- GaAs and superfluid helium: Advantages in background rejection: multiple signal channels and multipixel coincidence-based instrumental background rejection
• Measurement of $^4$He light yield of ER and NR and HeRALD proof of concept
• Good **agreement** with an **empirical model**
• High **NR light yield**, measurement of quantum evaporation gain
• Offers **ER/NR discrimination** via photon/roton ratio
- Two **identical detectors** (as possible)
  - One glued
  - One suspended from wire bonds
- **TES based readout** measures athermal phonon pulses in substrate
- Successful mitigation of mounting stress
  - **Two orders** of magnitude difference in rate  
    $\rightarrow$ stress is major source of LEE
- Investigating other sources: stress from sensor films, crystal and IR leakage
- See [arXiv:2208.02790](https://arxiv.org/abs/2208.02790)
- SbBe photoneutron + Fe shield
  - Fe transparent to neutron, serves as collimator and very efficient gamma shield
    - 124SbBe neutron energy: 23.47 keV
    - Fe n-transmission resonance: 24.54 keV
  - See arXiv:2302.03869

- Scattering of neutron of known energy, tag its scattering angle

- Large keV Neutron backing detector for low energy NR calibrations
  - See arXiv:2203.04896
- Developed a low background shield (1.2 DRU@1 keV) that can be opened to **swap detectors quickly**
  - Building prototype right now at Kamioka
- Experiment will be hosted in **Modane**, established the site and close collaboration with France last year
- Tesseract will **probe multiple unexplored DM parameter spaces** in a few years
- UZH will leads construction, operation and physics of Tesseract
- Data taking as early as **2026**
• **DM is out there** and will transform our understanding of the universe

• **LZ** has **60 out of 1000 days** of data published, many publications and potential discoveries soon

• **Tesseract demonstrated to work**, funded and growing, first physics results already published

• The field is being transformed right now:
  - **Xenon TPCs are the most sensitive detector** today
  - **Tesseract** will within a few years push sensitivities to yet **entirely unprobed energies**
  - **XLZD** preparing to **explore to the neutrino fog**

• These experiments will provide the **best sensitivity for dark matter for years to come**

• Continuous **interplay between hardware and physics** provides great training & opportunities
Backup
- Sub-Gev (low mass) DM barely explored
- DM masses in the **MeV regime** and cross sections approaching or below $10^{-40}$ cm$^2$ in reach
• Electron energy equiv. distribution, systematics are blue band
• Best fit with no WIMP signal
Best fit with zero WIMP events for all masses

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected Events</th>
<th>Best Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ decays + Det. ER</td>
<td>218 ± 36</td>
<td>222 ± 16</td>
</tr>
<tr>
<td>$\nu$ ER</td>
<td>27.3 ± 1.6</td>
<td>27.3 ± 1.6</td>
</tr>
<tr>
<td>$^{127}$Xe</td>
<td>9.2 ± 0.8</td>
<td>9.3 ± 0.8</td>
</tr>
<tr>
<td>$^{124}$Xe</td>
<td>5.0 ± 1.4</td>
<td>5.2 ± 1.4</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>15.2 ± 2.4</td>
<td>15.3 ± 2.4</td>
</tr>
<tr>
<td>$^8$B CEvNS</td>
<td>0.15 ± 0.01</td>
<td>0.15 ± 0.01</td>
</tr>
<tr>
<td>Accidentals</td>
<td>1.2 ± 0.3</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>276 ± 36</td>
<td>281 ± 16</td>
</tr>
<tr>
<td>$^{37}$Ar</td>
<td>[0, 291]</td>
<td>52.1$^{+9.6}_{-8.9}$</td>
</tr>
<tr>
<td>Detector neutrons</td>
<td>0.0$^{+0.2}_{-0.2}$</td>
<td>0.0$^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>30 GeV/$c^2$ WIMP</td>
<td>–</td>
<td>0.0$^{+0.6}_{-0.6}$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>–</td>
<td>333 ± 17</td>
</tr>
</tbody>
</table>
Dissolved β-emitters:
- $^{214}$Pb ($^{222}$Rn daughter)
- $^{212}$Pb ($^{220}$Rn daughter)
- $^{85}$Kr
- $^{136}$Xe ($2\nu\beta\beta$)

Includes γ-emitters in detector materials:
- $^{238}$U chain, $^{232}$Th chain, $^{40}$K, $^{60}$Co

Total expected ER counts in ROI in first run: $276 + [0, 291]$ from $^{37}$Ar

Total expected NR counts in ROI in first run: 0.15

ER backgrounds: Dominated by $^{214}$Pb and $^{37}$Ar

Dissolved e-captures (mono-energetic x-ray/Auger cascades):
- $^{37}$Ar
- $^{127}$Xe
- $^{124}$Xe (double e-capture)

Solar neutrinos (ER):
- $pp + ^7Be + ^{13}$N

NR backgrounds:
- Neutron emission from spontaneous fission and ($\alpha$,n)
- $^8$B solar neutrinos

Accidental coincidence backgrounds

Flat-spectrum (in ROI) ERs

Includes γ-emitters in detector materials:
- $^{238}$U chain, $^{232}$Th chain, $^{40}$K, $^{60}$Co

Total expected ER counts in ROI in first run: $276 + [0, 291]$ from $^{37}$Ar

Total expected NR counts in ROI in first run: 0.15
- It took a few **hundred years**
- With the discovery of the **Higgs boson** the **Standard Model** has been completed
- However, this is just the **tip of the iceberg**

- **Atoms** 5%
- **Dark Matter** 27%
- **Dark Energy** 68%
We know exactly the speeds of orbiting objects, such as planets around the sun... or stars around the galactic center
Low NR E calibrations

- **SbBe photoneutron + Fe shield**
- Remarkable coincidence:
  - $^{124}$SbBe neutron energy: 23.47 keV
  - Fe n-transmission resonance: 24.54 keV
- Fe transparent to neutron, serves as collimator and very efficient gamma shield

- **Source built & works**
- Favorable n flux: $\sim$5 cm$^{-2}$s$^{-1}$
- Portable, ideal for CE$_{\nu}$NS and light DM experiments
- See arXiv:2302.03869
Recent Progress - Calibrations

- Developed a low energy neutron source
  - Scattering of neutron of known energy, tag its scattering angle
- Large arge keV Neutron backing detector for low energy NR calibrations
- $^6\text{Li} + \text{Scintillator} + \text{Reflector} + \text{WS fiber} + \text{SiPM}$
- Eff: 25% eff. & affordable
- See arXiv:2203.04896
Amplification of evaporation signal via Van der Waals acceleration

\[ ^4\text{He} \quad \text{vacuum} \quad \text{calorimeter} \]

- Phonon: \( \sim 1\text{meV} \)
- Atom: \( \sim 0.62\text{meV} \)
- Potential well: \( \sim 10\text{meV} \)
10 g of He
• Inner 5.5 tonne fiducial volume (FV) is lowest background and uniform

• **Skin and OD vetoes:**
  ○ Removes γ background
  ○ Tag neutron capture (main DM background)

• Provides in situ constraint on neutron BG:
  ○ $0^{+0.2}$ neutron events in SR1