Getting a Kick out of Xenon

Rafael F. Lang
Purdue University
rafael@purdue.edu
Oxford, May 2018
Spoiler Alert

We haven’t found Dark Matter yet.

Xenon-based experiments are probing our most popular models.

Creative new ideas cut across theory and experiment, bring discovery science back to universities.
Possible Dark Matter Masses

80 orders of magnitude

$10^{-21}$ eV  $\mu$eV  meV  eV  MeV  GeV  TeV  $M_{\text{Planck}}$  $M_{\text{solar}}$

wavelength

doesn’t fit

in galaxies

excluded by gravitational lensing
### Possible Dark Matter Masses

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-21}$ eV</td>
<td>1/year optical</td>
</tr>
<tr>
<td>µeV to meV</td>
<td>Fermionic / particle astro</td>
</tr>
<tr>
<td>MeV to GeV</td>
<td>Bosonic / field</td>
</tr>
<tr>
<td>TeV to M Planck</td>
<td></td>
</tr>
<tr>
<td>M Solar</td>
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**Axions**
- axion-like particles

**WIMPs**
- thermal relics

80 orders of magnitude
## Possible Dark Matter Masses

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- **bosonic / field**
- **fermionic / particle**
- **astro**

**Eöt-Wash**
- NEWS-G
- XENON10
- XMASS
- Gaia

**MAGIS**
- CRESST-II
- Sabre
- XENON100

**CASPEr**
- CRESST-III
- COSINE
- LUX

**DMRadio**
- DAMIC
- LBECa
- PandaX
- DarkSide-50

**ABRACADABRA**
- SENSEI
- PICO
- XENON1T
- Deap3600

**ADMX**
- SF-He
- SuperCDMS
- XENONnT
- LZ
- DarkSide-20k

**HAYSTAC**
- GaAs/Al_{2}O_{3}
- Gen3/DARWIN
- Argo
Available Mass Space

Dark Matter only has 80 orders of magnitude to hide
WIMP Direct Detection 101

- coherent scattering
  \[ \frac{\lambda_{\text{deBroglie}}}{2\pi} = \frac{\hbar}{p} = \frac{\hbar c}{mc^2 v/c} \sim \frac{197 \text{ MeV fm}}{100 \text{ GeV} \times 10^{-3}} \approx \text{fm} \approx r_{\text{nucleus}} \]

- rate prefers high-A (high-J) targets
  \[ N = n_{\text{target}} \Phi \sigma_{\chi,N} A^2 \quad \text{or} \quad \propto \sigma_{\chi,N} J(J + 1) \]

- recoil spectrum: falling exponential at low energies
  \[ E_{r,\text{max}} \sim \frac{p_X^2}{2m_N} \sim \left( \frac{100 \text{ GeV}/c^2 \times 10^{-3}c}{2 \times 100 \text{ GeV}/c^2} \right)^2 = 50 \text{ keV} \]
WIMP Detection: Target

Plot Cross Section versus WIMP mass

fill with your own prior

e.g. Z-mediation through a box, or Higgs-mediated, or Z-mediation at $10^{-10}$ abundance

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WIMP Detection: Status

Best limits all from xenon experiments

Low masses: fight threshold

High masses: number density decreases as mass density is fixed

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WIMP Detection

Simple non-relativistic scattering

Push deeper, lighter, and heavier
Dual-Phase TPC: e.g. XENON1T

3D position information
S2 hit pattern: $\delta r < 2\,\text{cm}$
drift time: $\delta z < 500\,\mu\text{m}$
Redundant event information: can fight detector artefacts
(collect ~2.5MB per event)
Self-Shielding in Xenon

Reduce background with \( \exp(-\text{diameter}/\lambda_\gamma) \)

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ER/NR Discrimination

(a) $^{220}\text{Rn}$ calibration

Corrected S1 [PE]

Corrected S2 bottom [PE]

keV$_{ee}$

$\beta,\gamma$

$\beta,\gamma$

e$^-$

electronic recoils
ER/NR Discrimination

Corrected S2 bottom [PE]

Corrected S1 [PE]

(b) $^{241}$AmBe calibration

$\text{keV}_{nr}$

$\text{keV}_{nr}$

$\text{electronic recoils}$

$\text{nuclear recoils}$

$\text{Xe}$

$n$

$n$
Dark Matter Search

First science data, 34 live days:

- WIMPs, SI & SD!
- iDM and other EFT
- GeV DM
Ample Science from "Background"

First science data, 34 live days:

- leptophilic/axial-vector WIMPs, MeV DM
- Migdal & Bremsstrahlung
- inelastic scatter, miDM
- ALPs, dark photons, SuperWIMPs, solar axions, luminous DM, mirror DM
- sterile $\nu$
- DEC on $^{124}$Xe

- WIMPs, SI & SD!
- iDM and other EFT
- GeV DM

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Migdal Effect

Scatter inelastically off entire atom

Eject Auger electron at higher energy, at expense of lower rate

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Liquid TPCs

Technology of choice for WIMPs: monolithic, scalable, cheap, redundant event information.
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Uhmm... We can take pretty pictures too?
Excellent Data Taking & Stability

279 live days of dark matter data on tape:

- ScienceRun0
- ScienceRun1
XENON1T Science Run 1

recently unblinded

unsalted last week

public this month

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Very Near Future

Scattering Cross Section in $\text{cm}^2$

WIMP Mass in GeV/$c^2$

ruled out

PandaX, LUX, XENON1T 2017

XENON1T

ruled out

WIMP Mass in GeV/$c^2$

XENON1T with improved sensitivity soon
overall, $2\nu2\beta$ important ($t_{1/2} \sim 10^{21}$ years!)

$^{222}\text{Rn}$ a technological challenge

some sensitivity at low energies to $\text{pp}$ solar $\nu$
Veto Dominant $^{222}\text{Rn}$ Background

map convection, match decay chain, veto $^{214}\text{Pb}$

$^{214}\text{Po}$
164μs

$^{214}\text{Bi}$
20min

$^{214}\text{Pb}$
27min

$^{210}\text{Pb}$
22y

$^{222}\text{Rn}$
3.8d

$^{220}\text{Rn}$ in XENON100:

XENON1T Simulation
Upgrade: XENONnT

- Rapid upgrade:
  8t total
  6t active
  4t fiducial
  start 2019

- Re-use most sub-systems

- Xenon in hand,
  PMTs tested,
  fixing design
Near Future

Scattering Cross Section in cm$^2$

Ruled out

PandaX, LUX, XENON1T 2017

XENONnT, LZ

WIMP Mass in GeV/c$^2$

XENONnT and LZ start 2019

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XENON1T and Beyond

Results from 1 year with 1300kg coming anytime now

Starting 2019, XENONnT & LZ dig another order of magnitude deeper
Seriously, Neutrinos!

- BOREXINO, 17m, 280t
- Super-K, 40m, 50kt
- IceCube, 1km³, 1Gt
- XENON1T, 1m³, 2t

Low (keV) energies: coherent neutrino-nucleus scattering

\[ \sigma \propto A^2 \]
Simple scattering kinematics: degenerate in momentum → put on same plot
Solar $^8$B neutrinos ~2023

simulation: 1000 days LZ

electronic recoil background

dark matter nuclear recoils

$\sim 36$ $^8$B solar neutrino nuclear recoils
Supernova Neutrinos

few second burst $\nu_x + N \rightarrow \nu_x + N$

flavor-independent: complementary information

XENON1T sensitive across entire Milky Way:

![Graph showing detection significance vs. SN distance](image)
Measuring Neutrinos

Direct dark matter experiments become sensitive to solar and supernova neutrinos.
Direct Detection: Status

Scattering Cross Section in $\text{cm}^2$

- $10^{-42}$
- $10^{-43}$
- $10^{-44}$
- $10^{-45}$
- $10^{-46}$
- $10^{-47}$
- $10^{-48}$

WIMP Mass in GeV/c$^2$

- 1
- 3
- 10
- 30
- 100
- 300
- 1000
- 3000
- 10000

PandaX, LUX, XENON1T 2017

ruled out

Coherent Neutrino Signal

x1000

neutrino floor far, far away

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Direct Detection: Outlook

Ruled out

10^{-42} - 10^{-49} (Scattering Cross Section in cm^2)

1 - 10^5 (WIMP Mass in GeV/c^2)

PandaX, LUX, XENON1T 2017

Coherent Neutrino Signal

ruled out

x1000

x10

neutrino floor far, far away

strong program to improve factor 100
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neutrino floor far, far away

strong program to improve factor 100

current program leaves a WIMP gap
136Xe 0ν2β With nat Xe Target

136Xe → 136Ba + 2e⁻ (abundance 8.9%)
Requires large dynamic range of detector

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Physics with 60t LXe

Dark Matter:
- **spin-independent WIMPs**
- **spin-dependent WIMPs**
  - EFT couplings and inelastic WIMPs
  - GeV and MeV WIMPs (“S2-only”)
  - Planck mass dark matter
  - Migdal & Bremsstrahlung searches
  - Annual modulation searches
  - Magnetic Inelastic WIMPs
  - inelastic scattering
  - axial-vector coupling
  - Mirror & luminous DM
  - Axion-like particles
  - SuperWIMPs
  - Dark photons

Neutrinos:
- solar pp neutrinos
- coherent neutrino-nucleus scattering
- $^8$B solar neutrinos
- galactic supernovae
- neutrino oscillations
- sterile neutrinos
- neutrino magnetic moment
- $2\nu\beta\beta$ decay of $^{136}$Xe
- $0\nu\beta\beta$ decay of $^{136}$Xe
- double-EC on $^{124}$Xe

Other:
- solar axions
- fractionally charged particles
Not There Yet

Signal from atmospheric neutrinos far, far away

Need Generation-3 experiments to cover WIMP space
Extrapolating to High Masses

Which assumption breaks down?
Direct Detection at High Mass

![Graph showing cross-section vs. WIMP mass]

- Saturated Overburden Scattering
- DAMA
- XENONIT, WIMP 1-year
- XENONIT $\sigma_{\text{MFP}}$
- DARWIN $\sigma_{\text{MFP}}$
- DARWIN, WIMP 10-year
- DARWIN, WIMP 10-year flux limit
- XENONIT, 1-year flux limit
- DARWIN, 10-year flux limit
- Planck mass

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Probing Planck Mass

Generation-3 experiment can do it. Neutrino experiments too.
Extreme Low-Energy Sensitivity

Detect even individual electrons liberated anywhere in 2000kg of Xenon:

Build dedicated detector to tackle backgrounds and probe Dark Matter
Backgrounds: Photoionization

Xenon light 175nm=7eV
• Photoionizes metals & impurities

[Diagrams showing rate of small S2 signals vs. time difference and rate of small S2 signals vs. concentration of impurities]
Backgrounds: Extraction

Xenon light 175nm=7eV
- Photoionizes metals & impurities
- Delayed extraction:

![Graph showing signal strength over time with max drift at 0.3ms](image-url)
**LBEC A Project**

- Critical Xe expertise, multiple R&D setups
- Understand & reduce single $e^-$
- Build dedicated search

A. Bernstein, J. Xu, P. Sorensen, K. Ni, R. Essig, M. Fernandez-Serra, Rafael
Swiftly build dedicated, conventional xenon detector:

LBECA Project

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LBECa

Promising for fast results even below 10MeV

Bringing discovery-level science back to the universities
Much more than just a WIMP search

Dark Matter
- spin-independent WIMPs
- EFT couplings and inelastic WIMPs
- GeV and MeV WIMPs (“S2-only”)
- Magnetic Inelastic WIMPs
- inelastic scattering
- axial-vector coupling
- Mirror & luminous DM
- Axion-like particles
- SuperWIMPs
- Dark photons
- annual modulation searches

Astrophysics
- solar pp ν
- normalization of $^8$B solar rate
- galactic supernovae

Double-Beta
- 2ν and 0ν decay of $^{136}$Xe
- double-EC on $^{124}$Xe

Particle Physics
- coherent neutrino-nucleus scattering
- neutrino oscillations
- sterile neutrinos
- solar axions
- fractionally charged particles

Liquid Noble Physics
- light and charge yield
- properties of xenon
- radioactivity assays
- particle interaction modeling
- technology R&D for other applications
Conclusions

- Liquid Xe TPCs became versatile science machines
- Generation-3 detectors required to cover WIMPs
- Ample opportunities for creative phenomenology and impactful involvement in experiment