Possible Dark Matter Masses

<table>
<thead>
<tr>
<th>Mass</th>
<th>Excluded by gravitational lensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-21}$ eV</td>
<td>wavelength doesn’t fit in galaxies</td>
</tr>
<tr>
<td>μeV</td>
<td></td>
</tr>
<tr>
<td>meV</td>
<td></td>
</tr>
<tr>
<td>eV</td>
<td></td>
</tr>
<tr>
<td>MeV</td>
<td></td>
</tr>
<tr>
<td>GeV</td>
<td></td>
</tr>
<tr>
<td>TeV</td>
<td></td>
</tr>
<tr>
<td>$M_{\text{Planck}}$</td>
<td></td>
</tr>
<tr>
<td>$M_{\text{solar}}$</td>
<td></td>
</tr>
</tbody>
</table>

80 orders of magnitude
Possible Dark Matter Masses

<table>
<thead>
<tr>
<th>Possible Dark Matter Masses</th>
<th>80 orders of magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-21} \text{eV}$</td>
<td>$\mu \text{eV}$ meV eV</td>
</tr>
<tr>
<td>$1/\text{year}$</td>
<td>$\text{optical}$</td>
</tr>
<tr>
<td>$\text{MeV GeV TeV}$</td>
<td>$M_{\text{Planck}}$ M_{\text{solar}}</td>
</tr>
<tr>
<td>bosonic / field</td>
<td>fermionic / particle</td>
</tr>
<tr>
<td>Axions</td>
<td>WIMPs</td>
</tr>
<tr>
<td>axion-like particles</td>
<td>thermal relics</td>
</tr>
</tbody>
</table>
# Possible Dark Matter Masses

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Units</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-21}$ eV</td>
<td>meV</td>
<td>Eöt-Wash, MAGIS, CASPER, DAMIC, CRESST-III, Sabre, XENON100</td>
</tr>
<tr>
<td>1/year</td>
<td></td>
<td>NEWS-G, XENON10, XMASS, Gaia, SuperCDMS, PICO, XENON1T, Deap3600</td>
</tr>
<tr>
<td>$\mu$eV</td>
<td></td>
<td>DAMIC, COSINE, LUX, SENSEI, LBECA, PandaX, DarkSide-50</td>
</tr>
<tr>
<td>80 orders of magnitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_{\text{Planck}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_{\text{solar}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_{\text{astro}}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Bosonic / Field**

<table>
<thead>
<tr>
<th>Bosonic / Field</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Eöt-Wash</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAGIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CASPER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DMRadio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABRACADABRA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADMX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAYSTAC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fermionic / Particle**

<table>
<thead>
<tr>
<th>Fermionic / Particle</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NEWS-G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XENON10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XMASS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRESST-III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sabre</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XENON100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAMIC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COSINE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SENSEI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBECA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PandaX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DarkSide-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SuperCDMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PICO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XENON1T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deap3600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF-He</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ColCen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XENONnT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LZ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DarkSide-20k</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Optical**

<table>
<thead>
<tr>
<th>Optical</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs/Al$_2$O$_3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gen3/DARWIN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DarkSide-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gen3/DARWIN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SuperCDMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PICO</td>
<td></td>
<td>XENON1T</td>
</tr>
<tr>
<td>Deap3600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ColCen</td>
<td></td>
<td>XENONnT</td>
</tr>
<tr>
<td>XENON1T</td>
<td></td>
<td>LZ</td>
</tr>
<tr>
<td>DarkSide-20k</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DarkSide-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XENON1T</td>
<td></td>
<td>LZ</td>
</tr>
<tr>
<td>Deap3600</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Think Big

Identify promising dark matter candidates independently of constraints due to current technology or funding
WIMP Direct Detection 101

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

- 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
  \[ E_{r,\text{max}} \sim \frac{p_X^2}{2m_N} \sim \frac{(100 \text{ GeV}/c^2 \times 10^{-3}c)^2}{2 \times 100 \text{ GeV}/c^2} = 50 \text{ keV} \]
WIMP Detection: Status

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

Rafael F. Lang: Xe
WIMP Detection: Status

Best limits all from xenon experiments

Low masses: fight threshold

High masses: number density decreases as mass density is fixed
Thermal Relics & WIMPs

Simple nonrelativistic scattering

Experiments are probing expected WIMP parameter space

Pushing experiments to probe deeper, lighter, and heavier

Rafael F. Lang: Xe
Dual-Phase TPC: e.g. XENON1T

3D position information
S2 hit pattern: $\delta r < 2 \text{ cm}$
drift time: $\delta z < 500 \mu \text{m}$
The Secret of Success

Redundant event information: can fight detector artefacts
(collect ~2.5MB per event)
Self-Shielding in Xenon

Reduce background with $\exp(-\text{diameter}/\lambda_\gamma)$
ER/NR Discrimination

Corrected S2 bottom [PE] vs Corrected S1 [PE]

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

$keV_{ee}$

$\beta,\gamma$

electronic recoils

$\beta,\gamma$

$e^-$
ER/NR Discrimination

Corrected S2 bottom [PE] vs Corrected S1 [PE]

- Electronic recoils
- Nuclear recoils

\( \text{keV}_{\text{nr}} \)

(b) \( ^{241}\text{AmBe calibration} \)

**Rafael F. Lang: Xe**
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
Migdal Effect

Scatter inelastically

In Xenon: eject an Auger electron at higher energy at the expense of lower rate
Liquid TPCs

Technology of choice for WIMPs: monolithic, scalable, cheap, redundant event information
Excellent Data Taking & Stability

279 live days of dark matter data on tape:

Science Run 0  Science Run 1
XENON1T Science Run 1

recently unblinded

unsalted yesterday

public in weeks, not months
XENON1T with improved sensitivity soon
Rafael F. Lang: Xe

Upgrade: XENONnT

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

• Re-use most sub-systems

• Xenon in hand, PMTs tested, fixing design
XENON1T Background Spectrum

overall, $2\nu 2\beta$ dominant
($t_{1/2} \sim 10^{21}$ years!)

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

some sensitivity at low energies to $\text{pp}$ solar $\nu$

Rafael F. Lang: Xe
Veto Dominant $^{222}$Rn Background

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

$^{210}$Pb: 22y

$^{214}$Po: 164μs

$^{214}$Bi: 20min

$^{214}$Pb: 27min

$^{218}$Po: 3min

$^{220}$Rn in XENON100:

$^{222}$Rn: 3.8d

XENON1T Simulation

Rafael F. Lang: Xe
Near Future

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

- $10^{-42}$
- $10^{-43}$
- $10^{-44}$
- $10^{-45}$
- $10^{-46}$
- $10^{-47}$
- $10^{-48}$
- $10^{-49}$

WIMP Mass in GeV/c$^2$

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

XENONnT and LZ start 2019

PandaX, LUX, XENON1T 2017

ruled out

Rafael F. Lang: Xe
XENON1T Results

Results from 1 year with 1300kg should be coming anytime now

Another order of magnitude with XENONnT & LZ starting 2019

Rafael F. Lang: Xe
Neutrino-Nucleus Scattering

Simple scattering kinematics: degenerate in momentum

→ put on same plot

Rafael F. Lang: Xe
Direct Detection: Status

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

WIMP Mass in GeV/c$^2$

- $10^{-42}$
- $10^{-43}$
- $10^{-44}$
- $10^{-45}$
- $10^{-46}$
- $10^{-47}$
- $10^{-48}$
- $10^{-49}$
- $10^{-50}$

- $10^1$
- $10^3$
- $10^6$
- $10^{10}$
- $10^{30}$
- $10^{300}$
- $10^{3000}$
- $10^{30000}$

Coherent Neutrino Signal

ruled out

PandaX, LUX, XENON1T 2017

x1000

neutrino floor far, far away

Rafael F. Lang: Xe
Direct Detection: Outlook

Scattering Cross Section in cm$^2$

WIMP Mass in GeV/c$^2$

ruled out

PandaX, LUX, XENON1T 2017

XENONnT, LZ

Coherent Neutrino Signal

neutrino floor far, far away

strong program to improve factor 100

Rafael F. Lang: Xe
Require Generation-3 Detectors

neutrino floor far, far away

strong program to improve factor 100

current program leaves a WIMP gap
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
• $2\nu\beta\beta$ decay of $^{136}$Xe
• $0\nu\beta\beta$ decay of $^{136}$Xe
  • double-EC on $^{124}$Xe

Other:
• solar axions
• fractionally charged particles

Rafael F. Lang: Xe
Not There Yet

Becoming sensitive to solar and supernova neutrinos

Signal from atmospheric neutrinos far, far away

Need Generation-3 experiments to cover WIMP space

Rafael F. Lang: Xe
Direct Detection at High Mass

Planck mass

WIMP mass [GeV]

cross-section [cm$^2$]

$10^{-36}$

$10^{-33}$

$10^{-30}$

$10^{-27}$

$10^{-24}$

$10^{-21}$

Saturated Overburden Scattering

DAMA

XENON1T $\sigma_{M\text{IMP}}$

DARWIN $\sigma_{M\text{IMP}}$

XENON1T, WIMP 1-year

DARWIN, WIMP 10-year

XENON1T, WIMP 1-year flux limit

DARWIN, 10-year flux limit

$10^{13}$

$10^{15}$

$10^{17}$

$10^{19}$
Probing Planck Mass

Generation-3 experiment can do it. Neutrino experiments too.
Electron Scattering in Xenon

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
Backgrounds: Extraction

Xenon light $175\text{nm}=7\text{eV}$
- Photoionizes metals & impurities
- Delayed extraction:

$$\text{max drift} \quad 0.3\text{ms}$$
Swiftly build dedicated, conventional xenon detector:

**LBECA Reach**

A.Bernstein, J.Xu, P.Sorensen, K.Ni, R.Essig, M.Fernandez-Serra, Rafael

**heavy dark photon**

![Graph showing heavy dark photon reach]

**light dark photon**

![Graph showing light dark photon reach]
Conclusions

Liquid Xe TPCs became versatile science machines

Very stimulating interactions between theory and experiment:
Time of creative ideas in direct detection
Rafael F. Lang: Xe