Status and Perspectives of Direct Dark Matter Detection

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Evidence for Dark Matter

Cluster dynamics

Dwarf galaxies

Cluster gas in x-rays

Gravitation lenses

Bigbang nucleosynthesis

Galactic radiation curves

Cosmic 3K background rad.

Structure formation

Cluster collisions

Evidence for Dark Matter

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Evidence for Dark Matter

an impressive variety of arguments:
GR-dynamic, GR-static, radiation, …

vastly different scales and times: galactic to cosmology

something going beyond

- Standard Model of particle physics \( \Rightarrow \) BSM
- General Relativity (GR) & standard cosmology
Competing Dark Matter Directions

Gravity

Something wrong with GR?

Einstein Field Equations:
1) From line element: metric, Bianchi identities, Riemann tensor, Ricci scalar
2) Hilbert-Einstein action → variation → field equations

\[ l_{HE} = \frac{1}{2\kappa} \int d^4 x \sqrt{-g} [R + \mathcal{L}_m]. \]

\[ G_{\mu\nu} = \kappa T_{\mu\nu}. \]

Credit: J. Chagoya
Competing Dark Matter Directions

Particles

DM candidates should
- have no EM interaction
- not couple to QCD
- may have weak interaction
- must couple to gravity
- must not spoil things:
  - BBN
  - ...
- must not be excluded:
  - LHC, $\nu$-experiments,
    DM searches, ...

➤ solve known problems
➤ convincing extensions
(not probabilistic)
# Competing Dark Matter Directions

## Gravity
- **MOND**
  - a simple one scale modification
  - → fails badly
- **Other**
  - more elaborate GR modifications
  - or
  - a suitable population (mass, number) of black holes

## Particles
- **BSM physics**
  - motivated by SM problems
  - + WIMPs (neutralinos)
  - + axions
  - + sterile $\nu$’s
  - - ...
- **Correct thermal abundance**
  - + WIMPs
  - - dark photons
  - - ALPs
  - ? other new particles

**WIMPs combine both aspects in an attractive way: BSM + abundance**
The cosmic Matter Balance

- Dark matter: 26.8%
- Dark energy: 68.3%
- Chemical elements: (not H & He) 0.025%
- Neutrinos = CvB: 0.17%
- Stars: 0.8%
- H & He: gas 4%
- Radiation: 0.005%
- Radiations: 0.005%

Questions:
- Only one component?
- New particles or gravity?
- Which new particles?
- Connections to other topics?
- …
The WIMP Miracle

• Inflation ➔ many e-folds
• Reheating ➔ all particle types produced
• Evolution of original plasma by:
  - expansion (dilution)
  - decays
  - interactions ➔ conversion processes

Evolution of original DM density:
➔ Boltzmann equation

\[ \frac{dn_X}{dt} + 3H(T)n_X = -\langle \sigma v \rangle (n_X^2 - n_{X,eq}^2) \]

Remarkable coincidence:
• Correct (cold) DM abundance
  ➔ WIMP masses O(10-1000 GeV)
• SM hierarchy problem
  ➔ TeV BSM physics
  ➔ BSM motivated DM candidates
➔ Automatically ~ correct abundance
Hunting WIMPS in different Ways

known Standard Model (SM) particles interact with WIMPs: assumptions…

indirect detection

FERMI, PAMELA, AMS, HESS, IceCube, CTA, HAWC…
- astronomical uncertainties...
- signal without doubt from DM?

WIMP wind: 220km/s from Cygnus
⇒ see the DM in the Universe

colliders

- may detect new particles
- is it DM (lifetime, abundance)?

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DM particles do not interact via electromagnetic interaction

➤ no DM tracks in a detector

DM particles carry energy & momentum

➤ missing energy

two approaches at colliders for DM search:

1) direct production of DM particles

annihilation of standard model particles into a pair of DM particles

2) indirect production of DM particles

search for dedicated decay chains with DM-like particles using a dedicated model (e.g. SUSY)

Drawbacks:
- a signal does not guarantee a long life-time
- unrelated to DM density in the Universe
EFT Interpretation

For $q \ll $ mediator mass $M_{\text{med}}$

$\rightarrow$ Interaction described by $M^*$ and $m_{\text{DM}}$

- type of interaction $\rightarrow$ different operators

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M^2} \bar{\chi}\chi q\bar{q}$</td>
</tr>
<tr>
<td>D5</td>
<td>$qq$</td>
<td>vector</td>
<td>$\frac{1}{M^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$</td>
</tr>
<tr>
<td>D8</td>
<td>$qq$</td>
<td>axial-vector</td>
<td>$\frac{1}{M^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu q$</td>
</tr>
<tr>
<td>D9</td>
<td>$qq$</td>
<td>tensor</td>
<td>$\frac{1}{M^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$</td>
</tr>
<tr>
<td>D11</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4M^4} \bar{\chi} \chi \alpha_s (G^8_{\mu\nu})^2$</td>
</tr>
</tbody>
</table>

most common:

- D1, D5, D11 spin independent (SI), D8, D9 = SD

Mediator induces also SM $\rightarrow$ SM processes

$\rightarrow$ LHC sets limits on $g_{\text{SM}}^2/M^2_{\text{med}}$ (mod. $m_{\text{DM}}$)

$\rightarrow$ Unless $g_{\text{SM}}$ is tiny TeV-ish limits on $M_{\text{med}}$.

$g_{\text{DM}} = 1$ is an assumption $\rightarrow$ could be tiny $\rightarrow$ weaker DM limits

*or* a full model $\rightarrow$ more signatures/effects & constraints
DM motivated Extensions have other Consequences

- More particles…
- All existing particles **produced in Big Bang** and later (decays, …)
- Some particles may be stable
- Very long-lived due to **small parameters → natural?**
- Effects of unstable states +/-
  - on the early Universe
  - on collider physics

**Warning:** Your DM model may affect many other known things!
Dark Matter at the LHC

• Generic signature

• Generic kinematics: weak dependence on WIMP mass for $m_{\text{DM}} \ll \text{beam energy}$

• Life is more complex…
  - many conceivable candidates
  - detection efficiencies, ...
    $\Rightarrow$ EFT or simplified models
    $=$parametrization – not always appropriate
  - $g_{\text{DM}} =$ assumptions *or* full model +...

• LHC:
  - can exclude a DM candidate
  - can establish a candidate
  - does not test if it is DM in Univ.: long lived? abundance?

light WIMPs $\mathcal{L} \Rightarrow$ timing

heavy WIMPS $\Rightarrow$ direct searches

$\leftrightarrow$ CRESST-III, SuperCDMS $\Rightarrow$ GeMMC

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Direct Detection: Billard with invisible Balls

- WIMPs scatter off atoms in a detector → detect the signal…
- Maximal momentum transfer → $M_{\text{WIMP}} \sim M_{\text{atom}}$
  Additionally: clean, transparent, high density, no free charges, → liquid Xenon (ca. -100 degree) ↔ rarest stable element

1) Maximize signal
   → big detector
2) Minimize background
   → extremely low radioactive background requirements
The WIMP Wind

- Solar system is about 8.5 kpc from galactic center
- Is pulled towards the Cygnus-Cluster $\sim 220$ km/s
  - flow of DM particles from Cygnus $\Rightarrow$ WIMP wind
The generic WIMP Cross-Section

- Quantum mechanics: wavelength $\lambda \sim 1/\text{mass}$
  - “size = area” of a particle: $\pi \lambda^2 = \pi/m^2$
  - cross section: area $\times$ coupling strength

$$\sigma \sim O(0.001-1.0)^2 \ g_2^2 \ \pi/m^2$$

- or tuning, symmetry, …

$$\leftrightarrow$$ abundance

- natural range for a 50GeV WIMP:
  $$\sigma \sim 10^{-42} \text{ to } 10^{-48} \text{ cm}^2$$

known amount of DM $\Rightarrow$ WIMP flux $\Rightarrow$ rate@direct.det.

$\Rightarrow$ we know size/sensitivity of a detector which can cover the most interesting natural WIMP space
The Players and their main Territory

solid state electron recoil
solid state nuclear recoil
liquid noble gas experiments

details not up to date

vanilla WIMP
Direct Detection Techniques (WIMPs)

- Detection of DM = see what the Universe is made of
  - WIMP wind (known flux) scatters on target atoms ➔ signal…
Detection methods: Crystals (NaI, Ge, Si), Cryogenic Detectors, Liquid Noble Gases

- CoGeNT, CDEX, Texono, Malbek, DAMIC
- XENON, LUX/LZ, ArDM, PandaX, Darkside, DARWIN
- DEAP3600, CLEAN, DAMA, KIMS, XMASS, DM-Ice, ANAIS, SABRE
- SuperCDMS EDELWEISS
- CRESST-I CUORE

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Tracking: DRIFT, DMTPC MIMAC NEWAGE

Superheated Liquids: COUPP PICO PICASSO SIMPLE
Converting WIMP Scattering into Signals

Light – ionization – heat: 3 examples

- semiconductors (Ge)
  → ionization → pulses
- crystals (e.g. CaWO₄)
  → heat + light
- liquid noble gases @TPC’s
  → light + ionization

LXe TPCs
A / V scaling
The XENON Dark Matter Program

### The XENON program at Gran Sasso, Italy (3600 mwe)

<table>
<thead>
<tr>
<th></th>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T &amp; XENONnT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total (active) mass</strong></td>
<td>25 kg (14kg)</td>
<td>161 kg (62 kg)</td>
<td>3200 kg (2t) to ~8400 kg (5.9t)</td>
</tr>
<tr>
<td><strong>Drift length</strong></td>
<td>15 cm</td>
<td>30 cm</td>
<td>100 cm to 150 cm</td>
</tr>
<tr>
<td><strong>$\sigma_{SI}$ limit (@50 GeV/c^2</strong>)</td>
<td>$8.8 \times 10^{-44}$ cm²</td>
<td>$1.1 \times 10^{-45}$ cm²</td>
<td>$1.6 \times 10^{-47}$ cm² to $\sim 10^{-48}$ cm²</td>
</tr>
</tbody>
</table>

**XENONnT** prepared while XENON1T was running, switching gears.

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XENON1T @ LNGS

cryostat & TPC

water tank (veto)

crogenics & purification

distillation column

gas storage & handling

DAQ
Direct Dark Matter Detection

Background reduction ➔ extremely challenging:
- graded shielding
  - go deep underground
  - water
  - veto systems
- material selection
  - screening (γ, Rn, …)
  - distillation
- cryogenic distillation
- pulse shape analysis
- …

WIMPs ➔ nuclear recoils

Sun:
- Neutrinos
- Axions?
- ???

SM: too weak ➔ should not show up

Background reduction
- graded shielding
- material selection
- cryogenic distillation
- pulse shape analysis
- …
Dual Phase LXe TPC

- 16.0 kV

+ 4.5 kV
$z(dt) = v_{Drift} \cdot dt$

$v_{Drift} \approx 1.74 \text{ mm/\mu s}$
- reconstruct $x,y,z$

Next:
- fiducialize
- remove bg events
A WIMP scatters only once (if at all)
Distinguish: electronic recoils (ER) nuclear recoils (NR)
XENON1T: NR Search for WIMPs
XENON1T: Results on WIMPs

Most stringent result on SI scattering of WIMP Dark Matter down to 3 GeV/c² masses [PRL 121, 111302 + PRL 123, 251801]
$T = 1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}} \times 10^{22} \text{ yr}$

No rejection significance: $4.4\sigma$

- about one trillion times the age of the Universe
- longest half-life ever measured directly

Search for New Physics with ER Events

Phys. Rev. D 102, 072004

Large exposure:
0.65 tonne-years

Unprecedented low background:
76 ± 2 events/t/yr/keV

Low threshold:
1 keV$_{ee}$
Combine light and charge

\[ E = W \cdot (n_{ph} + n_e) \]
\[ = W \cdot \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \]

- detector constants \( g_1 \) and \( g_2 \)

- Anti-correlation between light and charge
  - checked with calibration sources
- Energy resolution < 5 % at 50 keV

\[ n_{ph} \quad n_e \]

\[ WIMPs, \textbf{X-rays}, \gamma \ (E < 200 \text{ keV}) \]
Data Selection ands Detection Efficiency

- **Science Run I**: Feb. 2017 - Feb. 2018 → 226.9 live days
- Fiducial volume: 1 tonne
- Energy range for single scatter events: [1,210] keV$_{ee}$
- Data quality cuts
- Include reconstruction efficiency & threshold at 10% detection efficiency
Distribution of Events

- [1 - 120] keV
- [1 - 7] keV
• $^{220}\text{Rn} (^{212}\text{Pb}, \beta\text{-decay})$ calibration data validates our model even below 1keV
• No threshold excess
• No large systematics
• Uses the same un-binned likelihood framework as in the main analysis
Background Model

Background prediction in [1,210] keV interval based on:
• knowledge from material screening and control measurements
• GEANT4 simulations smeared with detector effects
• 10 components

![Graph showing background prediction in keV interval](image)

**Internal (uniform in volume)**

- $^{214}\text{Pb}$ (main contribution)
- $^{85}\text{Kr}$ (distilled out)
- $^{136}\text{Xe}$, $^{124}\text{Xe}$ [Nature 568,532]
- $^{83m}\text{Kr}$ (calibration source issue)

**Neutron induced**

- $^{131m}\text{Xe}$, $^{133}\text{Xe}$, $^{125}\text{I}$

**Solar neutrinos**

**Materials** ←→ radio-essay & GEANT4

**Time-dependency**
The Result

- Exposure: 0.65 t*yr
- Single scatter events within [1,210] keV_{ee}
- Nice agreement at higher recoil energies

⇒ Excess between 1-7 keV:
285 events observed
(232 ± 15) expected from best-fit

Explanation #1: 3.5σ fluctuation
- Good fit observed over most of the energy range
- Consistent with expectations
- Unbinned maximum likelihood fit profiling over nuisance parameters:

\[
\mathcal{L}(\mu_s, \mu_b, \theta) = \text{Poiss}(N|\mu_{tot}) \times \prod_i^{N} \left( \sum_j \frac{\mu_{b_j}}{\mu_{tot}} f_{b_j}(E_i, \theta) + \frac{\mu_s}{\mu_{tot}} f_s(E_i, \theta) \right) \times \prod_m C_{\mu_m}(\mu_{b_m}) \times \prod_n C_{\theta_n}(\theta_n),
\]

\[\mu_{tot} \equiv \sum_j \mu_{b_j} + \mu_s,\]

\[\Rightarrow (76 \pm 2) \text{ events / (t*y*keV)} \text{ in [1,30] keV window}\]

Lowest bg rate ever achieved in this energy range

**Explanation #2:**
Some unexpected new background?
Explanation #3: New Physics

- A signal from where?
- Sun:
  - neutrinos (exist, but CEνNS too small $\leftrightarrow$ neutrino floor)
  - some non-standard $\nu$ interaction with electrons
  - axions or ALPS produced in the sun

- DM density/flow
  - some new particle
  - not WIMPs
  - light and not hot DM? A new light boson?

- Diffuse background of invisible particles
  $\leftrightarrow$ consistency with other searches/limits

Many papers which try to explain the XENON1T result
$\Rightarrow$ mostly 3 main directions: Axions, $\nu$’s, light bosons
$\Rightarrow$ stay tuned: analysis of 1st run of XENONnT is on-going...
being prepared while XENON1T runs ➔ switching gears
Main changes for XENONnT

**Larger TPC**
- Total 8.4 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs

**Neutron veto**
- Inner region of existing muon veto
- optically separate
- 120 additional PMTs
- Gd in the water tank
- 0.5 % Gd$_2$(SO$_4$)$_3$

**222Rn distillation**
- Reduce Rn ($^{214}$Pb) from pipes, cables, cryogenic system
- New system, PoP in XENON1T

**LXe purification**
- Faster xenon cleaning
- 5 L/min LXe (2500 slpm)
- XENON1T ~ 100 slpm
• Turning on by 2022 with 1,000 initial live-days plan
• 10 tons total, 7 tons active, ~5.6 ton fiducial
• Unique triple veto
• GOALS: < 2 x 10^{-48} \text{ cm}^2, \text{ at 40 GeV} \sim 100 \text{ times better than LUX}

(Main Detector)
2-phase XeTPC
494 (131) TPC (Xe skin) PMTs
PandaX-4T at CJPL

- Drift region: $\Phi \sim 1.2\text{m}$, $H \sim 1.2\text{m}$
  - Xenon in sensitive region $\sim 4\text{ton}$
- Design goal:
  - High signal efficiency
  - Large and uniform electric field
  - Veto ability

- 2017-2018: Produce all components and test
- 2019-2020: On-site assembling and commissioning
- 2021-2022: Data-taking
- Eventual goal: $\sim 30\text{ t}$ at CJPL to reach neutrino floor sensitivity

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Overall Status and Plans

- XENONnT is analyzing data from 1\textsuperscript{st} science run \textrightarrow stay tuned!
- 2nd science run started
- LZ (similar size) is also operational \textrightarrow competition
- DARWIN (XENON + few more) \textrightarrow 50t target mass

- DARWIN-LZ-consortium:
  - merge expertise, ...

JCAP 11, 017 (2016)
www.darwin-observatory.org
tests the generic WIMP space ➔ find a WIMP or a paradigm change
➔ solar neutrino signal & CEνNS
➔ supernova neutrinos

neutrino phase
0νββ with $^{136}$Xe

8.9% natural abundance

$\Rightarrow$ 3.5 t $^{136}$Xe in 40t without enrichment!

$Q_{\beta\beta} = (2458.7 \pm 0.6)$ keV

Assume:
- 6t fiducial
- energy resolution at $Q_{\beta\beta} \sim 1$

Sensitivity @ 95% CL:
- 30 t*yr $\Rightarrow T_{1/2} > 5.6 \times 10^{26}$ yr
- 140 t*yr $\Rightarrow T_{1/2} > 8.5 \times 10^{27}$ yr

IMPORTANT: DARWIN might become a powerful, cost effective and time-wise competitive 0νββ experiment (no enrichment!)
LAr based TPCs

Darkside 20k @LNGS: 40 t LAr – see talk by A. Zoccoli

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

→ 300 t of underground argon

DS-20K @LNGS
ARGO @SNOLAB
Conclusions

• Direct detection of dark matter is essential for proving that it is made of particles
• Many candidates... ↔ spectrum of theoretical ideas
• WIMPs, axions, sterile ν’s appear best motivated ➔ find them or paradigms will change!
• Strong competition ➔ impressive sensitivity gain/time
• New results expected...
• Exciting longer term projects...
• Options for the discovery of other new physics (ν’s, ...)
  ➔ will remain an exciting field