Direct + indirect detection of Dark Matter

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DM evidence in one slide
Machos

- Massive Compact Halo Objects might be the DM

- They can be seen by microlensing events of background stars

- Campaigns measuring these events have concluded that MACHOs cannot account for the DM in our Galaxy
A short reminder, we are looking for WIMPs...

Underground

Above ground

At the LHC
Galactic DM

- Our Galaxy is rotating at ~200 km/s at the Sun's orbit
- DM is “standing still”
- Hence, there is a “constant” flux of DM through Earth!

- Velocities are non-relativistic, $\beta \sim 10^{-3}$
- $\langle v_{DM}^2 \rangle = v_{SUN}^2$ (or close to it)
Principles of Direct Detection

• Movement with respect to the galactic frame imply DM flux,

\[ \Phi \approx 7.5 \times 10^4 \text{ particles/cm}^2/\text{sec} \quad \text{(for \sim 100 GeV particle)} \]

• DM recoils off a target material, leaving some energy in the form of:
  - Ionized electrons.
  - Scintillation light.
  - Heat/phonons.

• Signal is collected and the recoil energy is extracted.
Some thumb rules for the interaction

- Assuming an isothermal halo $\rho_{DM} \approx 0.3 \text{ GeV/cm}^3$
- Velocity of the sun around the Galaxy “rest frame” $v_0 \sim 230 \text{ km/s}$, escape velocity $\sim 550 \text{ km/s}$
- Recoil energy of a nucleus by elastic scattering:
  \[ E_{r,\text{max}} = \frac{p_x}{2m_N} \approx \frac{(100\text{ GeV/c}^2\times10^{-3}c)^2}{2\times100\text{ GeV/c}^2} \approx 50 \text{ keV} \Rightarrow \text{Low energy detectors} \]
- Coherent scattering
  \[ \frac{\lambda_{\text{DeBroglie}}}{2\pi} = \frac{\hbar}{p} \approx 1\text{fm} \approx r_{\text{nuc}} \Rightarrow \sigma_{SI} \propto A^2 \]
- Rate of interactions:
  \[ \Gamma = \Phi \sigma_{\chi,N} N_{\text{Detector}} A^2, \text{ for } \sigma_{\chi,N} = 10^{-45} \text{ cm}^2, m_\chi = 100 \text{ GeV} \]
  \[ \Gamma \sim 100 \text{ events/ton/yr} \]

Of course, reality is a bit more complicated...
Dark Matter Direct Detection

Goal: Observe WIMP interactions with some target material

Expected interaction rate

\[
\frac{dR}{dE_{NR}} \propto N \frac{\rho \chi}{2m_\chi \mu^2} \sigma_N |F^2(E_{NR})| \int_{v_{min}}^{v_{esc}} \frac{f(\vec{v})}{v} d^3v
\]

- Only those WIMPs with velocity above threshold will contribute to that energy
- For Spin Independent interactions the cross section is enhanced by a factor $A^2$ (coherent scattering)
Uncertainties in Velocity Distributions

- **Via Lactea**
  - $v_{esc} \sim 550$ km/s

- **Aquarius**
  - $v_{esc} \sim 565$ km/s

- **GHALO**
  - $v_{esc} \sim 433$ km/s

- **Ling et al.**
  - $v_{esc} \sim 520$ km/s

[Lisanti et al., 2010]
Minimum velocity

- Each combination of DM mass, target nucleus mass and detector threshold determines $v_{\text{min}}$, under which no recoil can be detected.

- As an example,

For Xe target and threshold of 5 keV:

- $M_\chi = 100$ GeV
- $M_\chi = 10$ GeV
Recoil Energy Spectrum

- Exponentially falling for simple scenarios, however there are complications.
- Exponential fall due to nucleus form-factor and velocity distribution
- Drop at low energy for inelastic scattering

\[ v_{\text{min}} = \frac{1}{\sqrt{2m_N E_R}} \left| \frac{m_N E_R}{\mu} + \delta \right|. \]
Dark matter and Earth dynamics: Annual modulation

- In general, the higher $v_{\text{min}}$, the stronger the relative modulation, but...

About 7% modulation on $\langle v \rangle$, can be much higher in signal
Dark Matter Direct Detection

- IONIZATION
  - CDMS I-II
  - superCDMS
  - EDELWEISS I-II
  - HPGe exp.
  - IGEX → GEDEON
  - GERDA
  - GENIUS
  - CoGeNT

- SCINTILLATION
  - ZEPLIN II-III
  - XMASS II
  - XENON
  - LUX
  - WARP,
  - ArDM
  - DarkSide

- Detector
  - HEAT
  - WIMP
  - SIMPLE
  - COUPP
  - PICO
  - CRESST -II
  - ROSEBUD
  - +time measurement
  - ZEPLIN I
  - CLEAN
  - DEAP
  - XMASS
  - DAMA / LIBRA
  - KIMS
Direct Detection Muon Background

We must seek shelter underground!
Looking for Dark Matter at Underground Labs

Techniques:
- Cryogenic (Ge, Si etc.)
- Solid Scintillator (NaI, CsI)
- Noble Liquids (LXe, LAr)
Direct Detection Progress

(Gross Masses kg)
DAMA – claimed detection

- Long standing measurement (first positive result in 1999).
- Uses NaI crystals (250 kg in second DAMA/LIBRA phase).
- No background/signal discrimination. Searches for annual modulation.
- Results in 0.87 ton-year of data, and 8.9σ evidence for modulation (13 cycles)! Phase is correct - peak at June 2 ± week.
CRESST II – detection and confusion

- Cryogenic calorimeter. Collects phonons and scintillation light.
- Target: CaWO$_4$
- First analysis:
  - 730 kg-days
  - Found 67 events
  - 4.2σ-4.7σ
- A new analysis:
  - 572 kg-days
  - Found 52 events.
  - 1.9σ-2.5σ
CoGeNT (Coherent Germanium Neutrino Technology)

- Germanium detector in Soudan Underground Lab. 0.5 keV threshold. No signal/background discrimination.


- Reported 442 live days on a 0.33kg Ge detector.

- CoGeNT's first release claimed an exponentially falling set of events, unexplained by background. Later an annual modulation was claimed.

- Latest results show decreased significance, but they are not discouraged!
CDMS: Cryogenic DM Search

- Uses Ge and Si detectors with two channels: Ionization and heat (on phase transition)
- Features background rejection, but still not background-free
- Lately analyzed data from 2006 in Si detectors and found 3 events, expecting 0.7
- Is it a claim???
The XENON project as an example

An international collaboration from 2002
Laboratori Nazionali del Gran Sasso (LNGS)

LNGS: 1.4km rock
(3700 mwe)
Two-Phase Xenon Detector

Time Projection Chamber = TPC

$\text{DM}$

$\text{Xe} \rightarrow \text{Xe}^*, \text{Xe}^+$
produces photons and electrons

Two types of signal:

$S_1$: prompt scintillation
$S_2$: proportional scintillation
(from ionization)
Two types of signal:

$S_1$: prompt scintillation

$S_2$: proportional scintillation (from ionization)
The XENON100 experiment

- PMT arrays
- Full TPC
- Radiation shield
Dual Phase TPC

3d Vertex Reconstruction

Signal/Background Discrimination

3d Vertex Reconstruction

Signal/Background Discrimination


PRL 107,13302 (2011)
Analysis Sequence

1) Start from all non-blind data

2) Basic quality and single scatter cuts

3) Energy threshold and FV cuts

4) Consistency cuts
(1.0 \pm 0.2) \text{ events expected}

\textbf{2 events observed}

\rightarrow 26.4\% \text{ probability that background fluctuated to 2 events}

\rightarrow \text{PL analysis cannot reject the background only hypothesis}

\textbf{No significant excess due to a signal seen in XENON100 data.}
Results of direct detection – limits for now

- Spin independent
- Spin dependent
Other NP searches as well

- Look for axion-electron interaction:

\[ \sigma_{\text{AE}} = \sigma_{\text{pe}}(E_A) \frac{g_{\text{AE}}^2}{\beta_A} \frac{3E_A^2}{16\pi \alpha_{\text{em}} m_e^2} \left(1 - \frac{\beta_A^{2/3}}{3}\right) \]

EDELWEISS best limit

Solar axions

Galactic axions and ALPs
LUX and others – today's frontier

370/250/118 kg, first results of 85 days

Expected improvement of almost X10!

Akerib et al PRL 112, 2013
The future: Aiming for size (?)
XENON1T/nT – our future
XENON1T at a glance

- Cryogenics and purification
- TPC
- Water Tank
- muon veto
- Storage and safety recovery
- Rn and Kr treatment
- DAC
XENON1T/nT

Expected to start running in 2015!
Plenty other experiments

DarkSide

miniCLEAN

DM-ice

XMASS
Ways to Detect Light DM

• The available energy is sufficient to induce inelastic atomic processes that would lead to visible signals.

• Three possibilities:

  Electron ionization

  Threshold: eV - 100’s eV
  DM-electron scattering

  Electronic excitation

  Threshold: eV - 100’s eV
  DM-electron scattering

  Molecular dissociation

  Threshold: ≥ few eV
  DM-nucleon scattering
Indirect detection

- There are many different methods to search indirectly for DM
- I will show a few, hopefully representative ones

CMB-Planck  AMS02  Fermi
Charged antimatter

• “Anomalous” amount or spectrum of antimatter can indicate decay or annihilation of DM

• In the past 6 years many efforts were given to positron production and propagation, following PAMELA:
AMS confirms and enhances

- It seems like there is a “bump” above the expected background
- Works naturally with heavy DM decay or annihilation
However...

- What do we understand about the astrophysics part?
- The models predicting the fluxes suffer serious systematic errors

It seems that still, the positron flux is consistent with what we know about “normal” astrophysics.
But there's still more

- AMS claim that antiproton flux is overabundant
- But including some account of astrophysical + experimental uncertainties....
Fermi looking at the galaxy

- Seems that there is an excess at a few GeV
- Astrophysics sources should not show this kind of spectrum
However, take a closer look

- The “bump” only appears after subtraction of backgrounds that are assumed to be known.

- Some of the backgrounds are taken from “templates”, which assume the galaxy has similarities away from the disc.

- Some works show that the significance is actually very low.

Calore, Cholis, Weniger 2014
Looking for annihilation

- Fermi limits from dwarf galaxies through annihilation to tau

![Graph showing thermal relic cross section](image)
Looking at the CMB

- There is more to the CMB, than running the stress-energy constituents in the Einstein equations.
- Thomson opacity determines where the photons we see last scattered
• Dark matter annihilation would inject energetic particles into the plasma with an efficiency prefactor $f$

• Ionize hydrogen $\rightarrow$ excess Thomson scattering

From Kfir Blum
Direct result from CMB

- Planck rules out s-wave thermal relic < 10 GeV
Other indirect paths

- Distortions in DM positioning $\rightarrow$ DM self interaction
- Effects on stellar structure from capture of DM
- Decay/annihilation in the Sun after capture (e.g. neutrinos)
- Other sources of gamma rays (dwarf galaxies, clusters)
- HE neutrinos
- Anomalies in ultra high energy cosmic rays
- Anomalies in precision measurements of time, gravity, dipole moment, isotopes...
- And more!
Summary

- Direct detection is proceeding fast, with each 6-12 month bringing a new leader. Current battle is over size – the bigger, the better

- “Anomalies” still surface, somehow don't yet stick

- Many indirect searches going on, anomalies appear and disappear

- The hope is that one of these will stick around!