Dark Matter search and the DAMIC experiment

Elodie Tiouchichine

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Evidence for dark matter I

- Since the 30's **rotation curves** of galaxies show **anomalous behavior** given the luminous mass

- Rotation curve of a typical spiral galaxy M 33 (yellow and blue points with error bars) and the predicted one from distribution of the visible matter (white dashed line).

- F. Zwicky (1933) problem in the Coma cluster mass distribution through motion of galaxies → The discrepancy between the two curves is accounted for by adding a **dark matter halo** surrounding the galaxy
Evidence for dark matter II

Weak gravitational lensing: The presence of mass alters the light direction.

At a statistical significance of $8\sigma$, it was found that the spatial offset of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law alone.

“At a statistical **significance of $8\sigma$**, it was found that the **spatial offset** of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law alone.”
Dark Matter properties

- **Cosmological parameters** constraint based on combined data from WMAP+eCMB+BAO+H0

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>WMAP data</th>
<th>Combined data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical baryon density</td>
<td>$\Omega_b h^2$</td>
<td>0.02256</td>
<td>0.02240</td>
</tr>
<tr>
<td>Physical cold dark matter density</td>
<td>$\Omega_c h^2$</td>
<td>0.1142</td>
<td>0.1146</td>
</tr>
<tr>
<td>Dark energy density ($w = -1$)</td>
<td>$\Omega_{\Lambda}$</td>
<td>0.7185</td>
<td>0.7181</td>
</tr>
<tr>
<td>Curvature perturbations, $k_0 = 0.002$ Mpc$^{-1}$</td>
<td>$10^9 A_L^2$</td>
<td>2.40</td>
<td>2.43</td>
</tr>
<tr>
<td>Scalar spectral index</td>
<td>$n_s$</td>
<td>0.9710</td>
<td>0.9646</td>
</tr>
<tr>
<td>Reionization optical depth</td>
<td>$\tau$</td>
<td>0.0851</td>
<td>0.0800</td>
</tr>
</tbody>
</table>

- Derived parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of the universe (Gyr)</td>
<td>$t_0$</td>
<td>13.76</td>
</tr>
<tr>
<td>Hubble parameter, $H_0 = 100h$ km/s/Mpc</td>
<td>$H_0$</td>
<td>69.7</td>
</tr>
<tr>
<td>Density fluctuations @ 8$h^{-1}$ Mpc</td>
<td>$\sigma_8$</td>
<td>0.820</td>
</tr>
<tr>
<td>Baryon density/critical density</td>
<td>$\Omega_b$</td>
<td>0.0464</td>
</tr>
<tr>
<td>Cold dark matter density/critical density</td>
<td>$\Omega_c$</td>
<td>0.235</td>
</tr>
<tr>
<td>Redshift of matter-radiation equality</td>
<td>$z_{eq}$</td>
<td>3273</td>
</tr>
<tr>
<td>Redshift of reionization</td>
<td>$z_{reion}$</td>
<td>10.36</td>
</tr>
</tbody>
</table>

- Dark matter compose 24% of our universe with the following features:
  - Dark: no EM interaction $\rightarrow$ no electric charge,
  - Small interaction with baryon,
  - Cold $\rightarrow$ non relativistic,
  - Stable (decay time much longer than universe age),
  - Distributed in big halo with spherical symmetry

- What dark matter is made of?
Dark matter candidates

➢ No candidate of dark matter in the standard model.

➢ **Relic particle** from our early universe
  ➢ During initial thermal equilibrium:
    \[ \chi \chi \leftrightarrow qq, ll \]
  ➢ When the universe started to cool down:
    \[ \chi \chi \rightarrow qq, ll, \text{until cool enough to keep stable amount of } \chi \]

> Weak Interacting Massive Particle is a class of stable particle with no electric charge, weakly interacting and with mass \( O(100 \text{ GeV}) \). WIMP emerge from few theories beyond the standard model like supersymmetry or universal extra dimensions...
WIMP's detection strategy I

- **Indirect detection**: Look for DM particles annihilation in cluster of galaxies.
- **Production in colliders**: Look for missing energy in the transverse plan.
- **Direct detection**: Look for WIMPs interaction with nuclei of detector.

From A. Molinario for EDIT School

![Diagram showing the relationship between WIMP detection strategies and processes.](Image)

- Thermal freeze-out (early Univ.)
- Indirect detection (now)
- Production at LHC
WIMP's detection strategy II

➢ Indirect detection: Look for DM particles annihilation in cluster of galaxies
➢ **Production in colliders:** Look for missing energy in the transverse plan
➢ Direct detection: Look for WIMPs interaction with nuclei of detector
WIMP's detection strategy III

- **Indirect detection**: Look for DM particles annihilation in cluster of galaxies
- **Production in colliders**: Look for missing energy in the transverse plan
- **Direct detection**: Look for WIMPs interaction with nuclei of detectors

From A. Molinario for EDIT School
Direct detection: DM signature I

➢ Which DM?
WIMP trapped gravitationally in the galaxy assuming local
density of 0.3 GeV.cm\(^{-3}\) and halo velocity of 220 km/s.
Expected flux (\(M_{\text{WIMP}} \sim 100\) GeV) of 6.6\(\times 10^4\) cm\(^{-2}\). s\(^{-1}\)

➢ What is detected? Spectrum of nuclear recoil in detector
produced by the elastic scattering between DM and nuclei
of terrestrial detector

➢ Rates of event scales the atomic mass of nuclei target
Direct detection: DM signature II

- **Annual modulation of the recoil rate:**
  - Ruled by cosine function with period of one year,
  - Amplitude of modulation $\sim 2 - 10\%$,
  - Only in a specific range of energy,

- **Gives a clear signature**

Drukier, Freese, Spergel, PRD 33, 1986
Background and detector design

- **Background:**
  - Cosmic rays and cosmic activation of detector materials,
  - Natural radioactivity: $\beta$-decay, neutron, $\gamma$, $\alpha$.
  - Ultimately $\nu$-nucleus scattering

- **WIMP detector requirements:**
  - **Light target** (Si, Ar, Ge, Xe) and low energy threshold to detect **low mass** WIMP $O(1\text{keVr})$,
  - Shields detectors from cosmic rays putting detectors deep **underground**, 
  - Select **low radioactive** materials,
  - Space and Energy **resolution** to reject background.

![Relative Particle Flux at Underground Laboratories](image)
Experimental techniques

- Several approaches to detect nuclear: **temperature, scintillation, charge measurements**
- Some experiments **combine** techniques in order to improve electron/nuclear recoil discrimination
Experimental techniques

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From Laura Baudis at EDIT School
CRESST

Total of 10 kg of target detector

Phonon signal (heat) $\rightarrow$ deposited energy
Scintillation light $\rightarrow$ particle discrimination

Discrimination power $e/\gamma$

From F. Reindl's talk @ NDM 2015, Jyvaskyla
Experimental techniques

- Several approaches to detect nuclear: temperature, scintillation, charge measurements
- Some experiments combine techniques in order to improve electron/nuclear recoil discrimination
**XENON100**

Total of **100 kg** of target detector

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**XENON100** 62 kg Xenon target mass (161 kg total) started data taking in 2007, still running. Best WIMP exclusion limit at the time (2012) with 225 days long run.

**XENON1T** 1 ton Xenon fiducial volume (3 tons total) under construction. Water Cherenkov detector for. Start data taking by the end of this year.

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**Discrimination power**

**225 day x 34 kg**

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**arXiv:1207.5988**
Experimental techniques

- Several approaches to detect nuclear: temperature, scintillation, charge measurements
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From Laura Baudis at EDIT School
DAMA/NAI & DAMA/LIBRA results

➢ Array of radiopure sodium iodine (NaI) scintillating crystals coupled to low background photo-multipliers
➢ DAMA/NaI: completed 6 years of data taking in July 2002
➢ DAMA/LIBRA I: 7 years of data taking ended August 2013

Based on total exposure of 1.17 ton x year over 13 annual cycles, DAMA collaboration provides a model independent evidence of the presence of DM particles in the galactic halo at $8.9\sigma$ C.L.

Interpreted as WIMP with mass of 10 GeV and $\sigma = 10^{-40}$ cm$^2$

Results Challenged by other experiments
Status direct dark matter

Threshold & atomic mass

Detector size x time matter
DAMIC experiment detection strategy

- Uses silicon detector in order to probe the low mass WIMP region.
- Thick (675 μm) fully depleted CCDs are used as particle detectors.
- Contain typically 16 millions pixels (15 x 15 μm$^2$) operating at ~140 K.

Typical particle tracks in a segment of a DAMIC CCD.
- Signal WIMPs are expected to create diffusion limited hits.
Reach low energy threshold

- Electron / hole pairs created (~3.7 eV per pair) drift separately towards the gate / back of the CCD.
- **Charge accumulated over few hours** of exposure and moved to the readout electronics.

![Pixel energy distribution in an image](image)

- Only pixels with charge deposition above ~ $5\sigma_{\text{RMS}}$ are considered.
  
  → **very low nominal detection threshold** of ionizing energy to 50 eV$_{\text{ee}}$ corresponding roughly to a **nuclear recoil of 0.5 keV$_r$.**
Calibration

- CCD calibrated using external X-rays sources as $^{55}$Fe and $^{241}$Am.

- Excellent linearity and energy resolution.

- Not all nuclear recoil energy is transformed in ionization (phonon). Quenching factor is the ration between the ionization efficiency for nuclear recoil and electron recoils. In Si known down to 4 keV$_r$. DAMIC studies performed in order to measure this quantity for $E_{\text{recoil}} < 4$ keV$_r$. 

- $\text{var}(E) = 0.16 \times 3.62 \text{ eV} \times E$

- RMS = 30 eV (from noise)
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Soon contribution of LabDPR
DAMIC at SNOLAB

- Installed in November 2012, 2 km underground at SNOLAB in Canada.
- Series of changes at different levels → reduction of radioactive background by 3 orders of magnitude reaching \( \sim 5 \text{ kg}^{-1} \text{ day}^{-1} \text{ keV}_{ee}^{-1} \).
Results

Analysis performed on **data collected during 2014**, CCDs exposure:
- 36 days with two 2.2 g 500 μm thick CCDs and one 2.9 g 675 μm CCD
- 7 days with only one 675 μm thick CCD

Total exposure: 0.27 kg.day

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PRELIMINARY

**SUPERCDMS (2014)**

**DAMIC (2012)**

**DAMIC (2014)**

**CDMSII-Si (2013)**

**CDMSLite (2013)**

**DAMIC100 (2016)**

**LUX (2013)**

**CRESST (2014)**

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WIMP-nucleon cross-section / pb vs. WIMP mass / GeV c$^{-2}$
Results

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Towards DAMIC100

- Last year 2015, mostly dedicated to background study and detector commissioning
- Actual configuration of DAMIC: Upgrade from 8 Mpxels CCDs to 16Mpxels (5.9 g) → installation of 7 in April 2016.

DAMIC100 under installation and commissioning...
DAMIC100 expected sensitivity

90% CL

WIMP-nucleon cross-section [cm$^2$] vs. WIMP Mass [GeV c$^{-2}$]

- DAMIC 2015
  - 0.6 kg d
  - 30 dru
- DAMA/Na
  - 10 kg d
  - 5 dru
  - Dec 2016
- CRESST II 2015
  - 52 kg d
- CDMSlite
- SCDMS Ge light 877 kg d
- CDMS-Si 2013
- LUX 85d
- 350 kg d
  - 0.01 dru
  - 2019
Data analysis

➢ Typical data-taking procedure:
   ➢ Wait 30ks (8.3h) of exposure and read → Images used for physics analysis
   ➢ Wait few seconds and read → Images called blanks used during the noise treatment on the physics images
   ➢ Readout noise extracted for each CCDs on blank

➢ Two existing selection algorithms:
   ➢ Cluster seed selected when a pixel with $E > 4\sigma$.
   ➢ Fit each 7x7 window by “Signal + Noise” and “Noise” model, compute discriminant variable and cut → used in DAMIC official results
Signal definition

- WIMPs creates **diffusion limited tracks with ionization energy < 10 keV** produced by the Silicon nucleus recoil.
- Ionized charge diffuse as it is drifted → **spacial variance $\sigma$ proportional to the interaction depth.**
- Ionization charge from interactions on the back of the CCD travels more time before collection by the gate and are more diffused than the one coming from interactions on the surface.

![Diagram showing diffusion limited tracks and spacial variance](image)

**Extraction of $\sigma = f(z)$**

- $m: 0.302256$
- $b: 0.00171444$
Signal injection for efficiency measurement

- Simulation of an ideal CCD of 21 x 21 pixels generating events in energy range 50 – 800 eV:
  - Uniformly in the central pixel,
  - Spacial distribution of ionization electrons follows a 2D Gaussian with σ diffusion width,
  - 1000 events generated for each (E, σ) with σ: 0.4-1.2 pixels
- Readout noise: Gaussian of 6.0 eV per pixel

![Event Simulations](image)

- E: 100 eV, σ: 0.4
- E: 100 eV, σ: 0.8
- E: 100 eV, σ: 1.4
- Readout noise
**4σ algorithm performance**

- **Measured efficiency** of simulated signal injected on:
  - Ideal CCD simulation,
  - Blank (real data).

- As expected the **4σ algorithm** is more **efficient for signal on surface** of the CCD ($\sigma_{x,y}: 0.4$ pix) than on event deep in the CCD.

- **Discrepancies** between efficiencies measured on full simulated ccd and blank **due to non gaussian noise** contribution in blank.
Window seed algorithm

- In order to **improve the acceptance** in the critical low energy region and for the large diffused events we propose to selected seed when **sum of pixels energy in a window** > threshold.

- Free parameter to be studied:
  - Find optimal size of window
  - Threshold (fake read out noise rate)
Window seed algorithm

- Measured **fake rate on blank of ≠ window's size** vs threshold

- Measured **efficiencies**

- Important recovery of deep signal events going up to 60% at $E = 150$ eVee
Window seed algorithm

- Measured **fake rate on blank of ≠ window's size** vs threshold
  - Important recovery of deep signal events going up to 60% at \( E = 150 \text{ eVee} \)
  - No need to increase size of window above 4x4

- **Measure Efficiencies**

  - 1000 events injected, #fake: 712
Conclusions and future plans

- **CCDs** demonstrated they are **well adapted devices for dark matter search!**
- The reduced interacting material is compensated by the **low threshold**.
- After one year of operation at SNOLAB delivered the **best constraint limit on the WIMP XS below 5 GeV / c^2!**
- Since then the experiment have been constantly upgraded in order to improve the sensitivity.
- DAMIC100 is under installation, with already 8 CCD 4x4 of 5.9g each.
- LabDPR will contribute to the **nuclear recoil quenching factor measurement** in Si at low energy!
- Work ongoing in order to **improve selection efficiency** for events deep in the CCD