The quest for Dark Matter

Nahuel Ferreiro Iachellini
Outline

1 Motivation
   - M33 Spiral Galaxy
   - The Bullet Cluster
   - CMB

2 Direct Detection
   - WIMPs
   - Interaction rate

3 Experimental Techniques
   - Charge-light
   - Phonon-charge
   - Phonon-light

4 CRESST
   - CRESST conventional design
   - CRESST installation
   - Event discrimination
The velocity distribution of visible matter does not follow the keplerian law $R^{-\frac{1}{2}}$. This mismatch can be solved accounting for additional (invisible) matter distributed in the galaxy.

Motivation for Dark Matter - The Bullet Cluster

Gravitational lensing is the light deflection caused by a mass distribution. This effect can be exploited to infer about the gravitational potential (green lines).
X-rays image shows the gaseous mass distribution, the dominant contribution among visible matter. Yet the two distributions overlay neither stars nor gravitational centers.

The CMB appears as a black body at 2.728K. Fluctuations of the temperature are present in the order of $100 \mu K$. These are originated by red-shift and probe the matter distribution some 13.7 billion years ago.

http://map.gsfc.nasa.gov
Starting (sad) point: we do not know dark matter! Despite the evidences for its existence we have no knowledge about its nature.

What we know:

- Roughly 25% of the Universe is made out of dark matter
- Dark matter needs to be cold in order to participate to structures formation
- Dark matter particles need to be stable, or at least the lightest particles

**WIMPs**: the Weakly Interactive Massive Particles are a class of particles which do not interact any stronger than the weak force. Created right after the Big Bang, these particles are believed to be thermally created and, as the universe cooled, their number was “frozen out”. Many theories predict WIMPs particles, i.e. Supersymmetry and its Lightest Super Partner. There are many other theories which involve new exotic particles which could account for dark matter (Axions, WIMPzillas, gravitino...)
Direct Detection - Interaction rate

\[ R = \Phi_\chi \cdot N_T \cdot \sigma \]

- \( R \) total count rate
- \( \Phi_\chi \) WIMPs flux
- \( N_T \) number of target nuclei
- \( \sigma \) cross-section
Direct Detection - Interaction rate

$R$ total count rate
$\Phi_\chi$ WIMPs flux
$N_T$ number of target nuclei
$\sigma$ cross-section
$v$ WIMPs velocity
$\rho_\chi$ WIMPs density
$m_\chi$ WIMPs mass
$E_R$ recoil energy
$m_N$ target nuclear mass

$$R = \Phi_\chi \cdot N_T \cdot \sigma$$

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} |v| f(v) \frac{d\sigma}{dE_R} d^3v$$
Direct Detection - Interaction rate

- $R$: total count rate
- $\Phi_\chi$: WIMPs flux
- $N_T$: number of target nuclei
- $\sigma$: cross-section
- $\nu$: WIMPs velocity
- $\rho_\chi$: WIMPs density
- $m_\chi$: WIMPs mass
- $E_R$: recoil energy
- $m_N$: target nuclear mass

Mathematical expression:

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} \left| \nu \right| f(\nu) \frac{d\sigma}{dE_R} d^3\nu$$

$$\frac{d\sigma}{dE_R} \propto \sigma_0 F^2(E_R) \quad \sigma_0 \propto A^2$$
Direct Detection - Interaction rate

- $R$ total count rate
- $\Phi_\chi$ WIMPs flux
- $N_T$ number of target nuclei
- $\sigma$ cross-section
- $v$ WIMPs velocity
- $\rho_\chi$ WIMPs density
- $m_\chi$ WIMPs mass
- $E_R$ recoil energy
- $m_N$ target nuclear mass

Let's put in some numbers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\chi$</td>
<td>100 GeV</td>
</tr>
<tr>
<td>$\rho_\chi$</td>
<td>0.3 GeV/cm$^3$</td>
</tr>
<tr>
<td>$\sigma_0$</td>
<td>$10^{-42}$ cm$^2$</td>
</tr>
<tr>
<td>$A$</td>
<td>$131$ ($Xe$)</td>
</tr>
<tr>
<td>$E_{th}$</td>
<td>40 keV</td>
</tr>
</tbody>
</table>

$E_{th} = 40$ keV $\Rightarrow R \approx 10^{-1}$ counts/kg/day
Direct Detection - Interaction rate

$R$ total count rate
$\Phi_\chi$ WIMPs flux
$N_T$ number of target nuclei
$\sigma$ cross-section
$\nu$ WIMPs velocity
$\rho_\chi$ WIMPs density
$m_\chi$ WIMPs mass
$E_R$ recoil energy
$m_N$ target nuclear mass

Let's put in some numbers

$$m_\chi = 100\,\text{GeV} \quad \rho_\chi = 0.3\,\text{GeV/cm}^3 \quad \sigma_0 = 10^{-42}\,\text{cm}^2$$

$$A = 131(\text{Xe}) \quad E_{th} = 40\,\text{keV} \implies R \approx 10^{-1}\,\text{counts/kg/day}$$
Two arrays of PMTs are faced to the LXe tank

Electric fields are applied across the liquid and gaseous phase

Read-out of charge (S2) and light (S1)

The ratio S2/S1 allows events identification
Germanium crystals are equipped with phonon and charge-ionization sensors.

- The phonon channel measures the event’s energy.
- The charge-to-phonon ratio allows events discrimination.
- A scintillating crystal (absorber) is operated at $\sim 15\text{mK}$
- Energy release within the absorber causes a temperature raise AND scintillation light emission
- The temperature raise is measured via Transition Edge Sensor
- A second detector, operated the same way as the absorber, is dedicated to the light measurement
CRESST - Conventional design

- ~ 300g crystal made out of CaWO₄
- Reflecting and scintillating housing to increase light collection AND veto events
- Light detector made out of Si (or Silicon on Sapphire). Sensible down to 5eV energies (few photons of blue light)
- The light-to-phonon ratio provides an event-by-event discrimination
CRESST - Conventional design

- Reflective bronze holding clamps
- W thermometer
- CaWO4 target crystal (300g)
- Light absorber
- W thermometer
- Reflective and scintillating foil
- Light detector
- Phonon detector
TES in CRESST are thin tungsten films
Their production is addressed to a transition temperature around 15mK
A stability control system keeps the temperature of the films in the middle of the transition
Particle events create phonons in the absorber, which are (partially) transmitted to the film
The temperature raise ($\sim \mu$K) translates to a resistance variation
CRESST - The installation

- CRESST is hosted at Laboratori Nazionali del Gran Sasso underground facility in Italy
- 3150m equivalent water of rocks shield against cosmic radiation
- The muon flux is reduced by six orders of magnitude
CRESST - The installation

- CRESST detectors are accommodated in a dilution refrigerator whose base temperature is below 10mK
- Several shields provide isolation from the environmental radioactivity
- Muon veto surrounds the installation
When a particle event occurs most of the energy is converted into phonons (phonon channel). The part converted into photons is measured by the light detector (light channel). Pulses amplitudes are proportional to the respective deposited energies.
The LY is a quantity specific for the kind of interaction happened in the absorber. It is conventionally set to 1 for $e^{-}/\gamma$ events.
Because of multi-target absorbers, WIMPs are expected to interact differently with different nuclei.
Thanks for your attention