Dark Matter detection

Carlos Muñoz

Meeting on Fundamental Cosmology
Santander, 17-19 June 2015
Evidence for DM at very different scales, since 1930’s:

- **Galaxies**: Rubin 1970’s
  - M33 rotation curve

- **Galaxy Clusters**: Zwicky 1933
- **Bullet Cluster**: Clowe et al. 2006
- **Filaments**: Dietrich et al. 2012

Carlos Muñoz
IFT UAM-CSIC

Dark Matter
Results from the Planck satellite,

\[ \Omega_{DM} h^2 \approx 0.12 \]

\[ \Omega_\text{b} h^2 \approx 0.022 \]

\[ \Omega_{DE} h^2 \approx 0.31 \]

confirm that about 85% of the matter in the Universe is dark
The only possible candidate for DM within the Standard Model of Particle Physics, the neutrino, is excluded.

Its mass seems to be too small, $m_\nu \sim \text{eV}$ to account for $\Omega_{\text{DM}} h^2 \approx 0.1$.

This kind of (hot) DM cannot reproduce correctly the observed structure in the Universe; galaxies would be too young.

This is a clear indication that we need to go beyond the standard model of particle physics.
We need a new particle with the following properties:

- **Stable or long-lived**  
  Produced after the Big Bang and still present today

- **Neutral**  
  Otherwise it would bind to nuclei and would be excluded from unsuccessful searches for exotic heavy isotopes

- **Reproduce the observed amount of dark matter**  
  \[ \Omega_{\text{DM}} h^2 \approx 0.1 \]

A particle with weak interactions and a mass \( \approx \text{GeV-TeV} \), the so called WIMP (Weakly Interacting Massive Particle), is able to reproduce this number.

In the early Universe, at some temperature the annihilation rate of DM WIMPs dropped below the expansion rate and their density has been the same since then, with:

\[ \Omega_{\text{WIMP}} h^2 \sim \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\sigma_{\text{ann}} V} \sim 0.1 \]

\[ \sigma_{\text{ann}} = \sigma_{\text{weak}} \]

\[ \sigma_{\text{ann}} v \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

thermal cross section

Carlos Muñoz  
IFT UAM-CSIC
The LHC could detect a new kind of particle

If we are able to measure the mass and interactions of the new particle, checking that $\Omega_{DM} h^2 \approx 0.1$, this would be a great success...

...but how can we be sure it is stable on cosmological scales?
A complete confirmation can only arise from experiments where the particle is detected as part of the galactic halo.

This can come from direct DM searches or indirect DM searches.
These three detection strategies are ideal because they allow exploring in a complete way many different particle dark matter models.

Besides, in the case of a redundant detection (in two or more different experiments) the combination of their data can provide good insight into the nature of the dark matter.
Underground Labs and indirect detection DM experiments around the world
through elastic scattering with nuclei in a detector is possible

\[ \rho_0 \sim 0.3 \text{ GeV/cm}^3 \]

\[ v_0 \sim 220 \text{ km/s} \]

\[ J \sim \rho_0 v_0 / m_{\text{WIMP}} \sim 10^4 \text{ WIMPs/cm}^2 \text{ s} \]

For \( \sigma_{\text{WIMP-nucleon}} \approx 10^{-8} - 10^{-6} \text{ pb} \) a material with nuclei composed of about 100 nucleons, i.e. \( m_N \sim 100 \text{ GeV} \)

\[ R \sim J \sigma_{\text{WIMP-nucleon}} / m_N \approx 10^{-2} - 1 \text{ events/kg day} \]

\[ E_{\text{WIMP}} \approx 1/2 (100 \text{ GeV/c}^2) (220 \text{ km/s})^2 \approx 25 \text{ keV} \]

energy produced by the recoiling nucleus can be measured through ionization, scintillation, heat \( \approx \text{few keV} \)

Carlos Muñoz
IFT UAM-CSIC

Dark Matter
10
DAMA experiment had 100 kg NaI crystals.

DAMA only measures scintillation light

\[ E_{\text{scintillation}} = Q \cdot E_{\text{recoil}} \]

\[ Q(\text{quenching factor}) = 0.3 \text{ for Na, 0.09 for I} \]

Annual modulation

DAMA/LIBRA

250 kg NaI crystal scintillators at Gran Sasso.

It does not strongly discriminate between WIMP scatters and background events.

Carlos Muñoz

IFT UAM-CSIC
WIMPs are expected to produce less or about $10^{-2}$ nuclear recoils/kg day with energies of few keV.

But cosmic rays occur at >100 events/kg day with energies ~ keV-MeV and generate muon-induced neutrons producing nuclear recoils similar to those expected for WIMPs.

Experiments must be located in the deep underground to greatly reduced the rate of these background events.

In addition, neutrons are also generated by the environmental radioactivity, but also $\gamma$ rays and $\beta$ particles are generated producing electron recoils.

Combining two techniques of detection one can discriminate the electron recoils from nuclear recoils: heat + ionization, heat + scintillation, scintillation + ionization.

...everything above background might be a signal.
DIRECT DARK MATTER EXPERIMENTS

- DAMA/LIBRA (NaI)
- XMASS (Xe)
- KIMS (CsI)
- ANAIS (NaI)
- KIMS (NaI)
- DM-Ice (NaI)
- DEAP3600 (Ar)
- MiniCLEAN (Ar)
- CRESST (CaWO₄)
- EURECA (CaWO₄)
- CUORE (TeO₂)

- Superheated liquids (bubble)
  - PICASSO (C₄F₁₀)
  - SIMPLE (C₂ClF₅)
  - COUPP (CF₃I)/PICO

- Scintillation (light)
  - XENON100 (Xe)
  - ZEPLIN-III (Xe)
  - LUX (Xe)
  - LZ 7T (Xe)
  - XENON1T (Xe)
  - ArDM (Ar)
  - DarkSide (Ar)

- Phonon (heat)
  - CoGeNT (Ge)
  - CDEX (Ge)
  - TEXONO (Ge)
  - C-4 (Ge)
  - DRIFT (CS₂)
  - DM-TPC (CF₄)
  - NEWAGE (CF₄)
  - MIMAC (³He/CF₄)

- Ionization (charge)
  - CDMS (Ge, Si)
  - EDELWEISS-II (Ge)
  - SuperCDMS (Ge)
  - EURECA (Ge)

Present
Future
☆ DM hints
LUX: active 250 kg of liquid Xe (scintillation + ionization)
Sanford underground lab. South Dakota

CDMS II: 4.5 kg Ge + 1.2 kg Si (ionization + heat)
Soudan underground lab. Minnesota

But...what these results mean from the theoretical viewpoint?
Crucial Moment for Supersymmetry in 2015: LHC Run II 13 TeV

The spectrum of elementary particles is doubled with masses \( \approx 1000 \text{ GeV} \)

A rich phenomenology

Carlos Muñoz
IFT UAM-CSIC

Dark Matter
Neutralino in the MSSM (with R-parity conservation) is a WIMP

**Squark exchange**

Generally small (1<sup>st</sup>, 2<sup>nd</sup> gen. squarks are heavy)
Otherwise unconstrained from LHC

**Higgs exchange**

Leading contribution (increases with Higgsino component)
Constrained by the results on \( \text{BR}(h^0_{\text{SM}} \rightarrow \text{inv}) \)
Also affected by \( m_H = 126 \text{ GeV} \)

In view of the LHC constraints on SUSY, Higgs data, flavour physics observables, in the phenomenological MSSM (pMSSM) with 19 independent parameters, \( M_a, m_\alpha, A_\alpha, \tan \beta, \mu \), one obtains

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range (in GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tan \beta )</td>
<td>[1, 60]</td>
</tr>
<tr>
<td>( M_\alpha )</td>
<td>[50, 20000]</td>
</tr>
<tr>
<td>( M_1 )</td>
<td>[-30000, 3000]</td>
</tr>
<tr>
<td>( M_2 )</td>
<td>[-30000, 3000]</td>
</tr>
<tr>
<td>( M_3 )</td>
<td>[50, 3000]</td>
</tr>
<tr>
<td>( A_d = A_s = A_b )</td>
<td>[-10000, 10000]</td>
</tr>
<tr>
<td>( A_{\alpha} = A_{\beta} = A_{\tau} )</td>
<td>[-10000, 10000]</td>
</tr>
<tr>
<td>( \mu )</td>
<td>[-30000, 3000]</td>
</tr>
<tr>
<td>( M_{\tilde{t}<em>1} = M</em>{\tilde{H}_1} )</td>
<td>[0, 3000]</td>
</tr>
<tr>
<td>( M_{\tilde{t}<em>3} = M</em>{\tilde{H}_3} )</td>
<td>[0, 3000]</td>
</tr>
<tr>
<td>( M_{\tilde{g}} )</td>
<td>[0, 3000]</td>
</tr>
<tr>
<td>( M_{\tilde{b}<em>R} = M</em>{\tilde{b}_L} )</td>
<td>[0, 3000]</td>
</tr>
<tr>
<td>( M_{\tilde{b}_3} )</td>
<td>[0, 3000]</td>
</tr>
<tr>
<td>( M_{\tilde{b}_4} )</td>
<td>[0, 3000]</td>
</tr>
</tbody>
</table>

Table 1: pMSSM scan ranges.
For the relic density, the upper bound $\Omega_{\text{WIMP}} h^2 \sim 0.12$ is applied, allowing for the possibility of multiple DM componentes (neutralinos + axions and/or other candidates).

Similar results for neutralinos or sneutrinos in the NMSSM are expected.

Future experiments will explore large regions of the parameter space.
INDIRECT DETECTION

An excess of **positrons** for energies larger than 10 GeV has been detected by PAMELA (2008), Fermi-LAT (2010) and AMS (2013).

Possible astrophysical explanations:

1. Contributions of $e^-$ and $e^+$ from Monogem or Geminga pulsar or a sum of Milky Way pulsar population, assuming different distance, age and energetic of the pulsars.
2. Super Nova Remnants

Problems with the WIMP ($\sim$1 TeV) explanation:

- No antiproton excess is observed
- Data implies $\sigma_{\text{ann}} v \sim 10^{-23}$ cm$^3$ s$^{-1}$, but this would produce $\Omega h^2 \sim \frac{3 \times 10^{-27} \text{ cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} << 0.1$
- Otherwise boost factors, ranging $10^2 - 10^4$, provided by clumpiness in the DM distribution, are needed.

but the high energy positrons mainly come from a region within few kpc from the Sun (those far away lose their energies during the propagation), where boost factors > 10 are not expected.
an excess of gamma rays could be a signature of DM annihilations

An interesting possibility could be to search for DM around the Galactic Center where the density is very large

on behalf of the Fermi-LAT:
Morselli, Vitale, 0912.3828
Morselli, Cañadas, Vitale 1012.2292
analized the inner galaxy region

But conventional astrophysics in the galactic center is not well understood. An excess might be due to the modeling of the diffuse emission, unresolved sources, etc.
Assuming an excess, and that the DM density in the inner galaxy is $\rho(r) \sim \rho_0 / r^\gamma$, one can deduce possible DM examples reproducing the observations

$$\Phi_\gamma(E_\gamma, \psi) = \frac{1}{2} \langle \sigma_{\text{ann}} v \rangle \sum_i \frac{dN_i}{dE_\gamma} B_i \int_{l.o.s.} \rho^2 \, dl,$$

The spectrum of the excess peaks at 1-3 GeV, and is well fit by 31-40 GeV DM particle annihilating to $\gamma \sim 1.1 - 1.3$

$$\sigma_{\text{ann}}V \sim 1.4 - 2.0 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

Carlos Muñoz
IFT UAM-CSIC

Hooper, Goodenough, 1010.2751
Hooper, Linden, 1110.0006
Abazajian, Canac, Horiuchi, Kaplinghat, 1402.4090
Daylan, Finkbeiner, Hooper, Linden et al., 1402.6703
Calore, Cholis, Weniger, 1409.0042
Local Group **dwarf spheroidal galaxies** (dSph) are attractive targets because:
- they are nearby
- largely dark matter dominated systems
- relatively free from gamma-ray emission from other astrophysical sources

6-years of **Fermi-LAT** data. No excess from a combined analysis of 15 dSph

![Image](image.png)

**FIG. 2.** Comparison of constraints on the DM annihilation cross section for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels from this work with previously published constraints from LAT analysis of the Milky Way halo (3$\sigma$ limit) \cite{33}, 112 hours of observations of the Galactic Center with H.E.S.S. \cite{34}, and 157.9 hours of observations of Segue 1 with MAGIC \cite{35}. Closed contours and the marker with error bars show the best-fit cross section and mass from several interpretations of the Galactic center excess \cite{16-19}.

Constraints lie below the canonical termal relic cross section for DM of mass $\lesssim 100$ GeV annihilating via $b\bar{b}$ channel and $\tau^+\tau^-$ channel
In general the final state will be a combination of the final states shown here e.g., in SUSY, the neutralino annihilation modes are 70% \( bb \) - 30% \( \tau \tau \) for a Bino DM, and 100% \( W^+W^- \) for a Wino DM.

Also, the value of \( \sigma v \) in the Galactic halo might be smaller than \( 3 \times 10^{-26} \) cm\(^3\) s\(^{-1}\)

-e.g., in SUSY, in the early Universe coannihilation channels can also contribute to \( \sigma v \)

-Also, DM particles whose annihilation in the Early Universe is dominated by velocity dependent contributions would have a smaller value of \( \sigma v \) in the Galactic halo, where the DM velocity is much smaller, and can escape this constraint:

\[
\Omega h^2 \approx 3 \times 10^{-27} \text{ cm}^3 \text{s}^{-1} (\sigma v)^{-1} \approx 0.1
\]
**Gravitino as decaying dark matter**

In models where R-parity is broken, the neutralino or the sneutrino with very short lifetimes **cannot be used as candidates for (annihilating) DM**

The gravitino LSP also decays through the interaction gravitino-photon-photino ($\lambda$)

$$L_{\text{int}} = -\frac{i}{8M_{\text{pl}}} \bar{\psi}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda F_{\nu\rho},$$

Takayama, Yamaguchi, 2000

due to the photino-neutrino mixing

after sneutrinos develop VEVs, opening the channel

Nevertheless, it is supressed both by the Planck mass and the small R-parity breaking, thus the lifetime of the gravitino can be longer than the age of the Universe ($\sim 10^{17}$ s)

$$\tau_{3/2} = \Gamma^{-1}(\tilde{G} \rightarrow \gamma \nu) \approx 8.3 \times 10^{26} \text{ sec} \times \left(\frac{m_{3/2}^3}{1 \text{ GeV}}\right) \left(\frac{|U_{\gamma\nu}|^2}{7 \times 10^{-13}}\right)^{-1}.$$ 

Thus, the gravitino (superWIMP) can be a good (decaying) DM candidate
Since the gravitino decays into a photon and neutrino, the former produces a gamma-ray line at energies equal to $m_{3/2}/2$

**FERMI** might in principle detect these gamma rays

$$
\left[ \frac{E^2 \, dJ}{dE} \right]_{\text{halo}} = \frac{2E^2}{m_{3/2}} \frac{dN_{\gamma}}{dE} \frac{1}{8\pi \tau_{3/2}} \int_{\text{los}} \rho_{\text{halo}}(\vec{r}) \, d\vec{r},
$$

**μνSSM**

Lopez-Fogliani, C. M.,
PRL 97 (2006) 041801

As a consequence, values of the gravitino mass larger than about 10 GeV are disfavoured by *Fermi* LAT data

Carlos Muñoz
IFT UAM-CSIC

Choi, López-Fogliani, C.M., Ruiz de Austri, 0906.3681

Dark Matter
More recently, together with Fermi-LAT collaborators we performed the following search:

**Search for 100 MeV to 10 GeV \( \gamma \)-ray lines in the *Fermi*-LAT data and implications for gravitino dark matter in the \( \mu \nu \)SSM**


Category II paper:

- *Fermi*-LAT Collaboration: Albert, Bloom, Charles, Gómez-Vargas, Mazziotta, Morselli
- External authors: C. M., Grefe, Weniger
Applying these bounds to our model:

\[ \tau_{3/2} = \Gamma^{-1}(\tilde{G} \to \gamma \nu) \approx 8.3 \times 10^{26} \text{ sec} \times \left( \frac{m_{3/2}}{1 \text{GeV}} \right)^{-3} \left( \frac{|U_{\gamma\nu}|^2}{7 \times 10^{-13}} \right)^{-1}. \]

\( \mu \nu \text{SSM} \) gravitinos with masses larger than 4.8 (2.4) GeV or lifetimes smaller than 7.9 \( \times 10^{27} \) (1.3 \( \times 10^{28} \)) s are excluded as DM candidates.
CONCLUSIONS

- Evidence for the existence of Dark Matter
  
is overwhelming: galaxies, clusters, filaments, CMB, structure formation, ...
  
-about 85% of the matter of the Universe is dark

- Particle candidates for Dark Matter
  
-stable WIMPs like neutralino, sneutrino or Kaluza-Klein, scalar DM, fermion DM
  
decaying superWIMPs like gravitino or axion, ...

- Detection of the Dark Matter
  
-There are impressive experimental efforts by many collaborations around the world:
    DAMA/LIBRA, CoGeNT, CRESST, CDMS, XENON, LUX,..., Fermi, PAMELA, AMS, MAGIC, HESS,..., IceCube, ANTARES,...

Thus the present experimental situation is very exciting

And, besides, the LHC is back

So, stay tuned!
experiments
also
DM