Lecture 1 (Part II)

Dark matter as a particle: importance of non-gravitational interactions

Outline:

- Thermal production of DM: the WIMP miracle
- Strategies for non-gravitational detection of WIMPs
  i) Indirect detection
  ii) Direct detection

(iii) Supersymmetry and cosmology, Feng, 2005, hep-ph/0405215,
(iv) Supersymmetric dark matter, Jungman, Kamionkowski and Griest, 1996, Physics Reports, 267, 195
(v) Galaxy formation and evolution, Mo, van den Bosch and White, Cambridge U. Press, 2010
Particle DM: WIMPs

- From the gravitational evidence of the existence of DM, we know that it has a global abundance of $\Omega \sim 0.23$, it doesn't produce electromagnetic radiation at a significant level and it should be compatible with a successful structure formation scenario.

- DM is mostly non-baryonic: CMB and abundance of light elements. The only possibility in the SM of Particle Physics is neutrinos, but given their low mass they would be incompatible with the hierarchical process of structure formation (“hot dark matter”, more on this in Lect. 4).

- Particle candidates arise in well-motivated extensions to the SM; among the different possibilities, the so-called WIMPs (Weakly Interacting Massive Particles) are the most studied.

- Most well-known example: the lightest neutralino. Naturally predicted by SUSY: a new symmetry in nature, for each particle in nature there is a “superpartner” with a spin differing by 1/2; since no superpartner has been observed this symmetry is broken allowing the superpartners to be more massive (in minimal models $\sim 1$TeV); gives a solution to the hierarchy problem. The LHC has constrained SUSY models (particularly the minimal one).

- There are 4 neutralinos: mass eigenstates (combinations) of the superpartners of the neutral gauge bosons of the theory: neutral Higgs, $Z^0$ and photon.

- The lightest one is typically the lightest SUSY particle (LSP), neutral, stable, with a mass of $\sim 100$GeV and is a Majorana fermion (its own antiparticle: it self-annihilates)
Thermal production of DM: the WIMP miracle

Relic Abundance (freeze-out approximation)
BLACKBOARD!
Thermal production of DM: the WIMP miracle (Summary)

- DM number density evolution given by the Boltzmann equation:
  \[ \frac{dn_\chi}{dt} + 3Hn_\chi = - \langle \sigma v \rangle \left( n_\chi^2 - (n_\chi^{EQ})^2 \right) \]

- At early times the solution follows closely the equilibrium solution.
- At a characteristic time \((\Gamma/H=1)\), the comoving number density “freezes-out”.

\[ \Omega_\chi = m_s Y(x=\infty) \sim \frac{10^{-10} \text{ GeV}^{-2}}{\langle \sigma_A v \rangle} \]

- If mass and self-annihilation cross section are set by the weak scale then we get the correct relic density:
  \[ m^2 \sim \langle \sigma_A v \rangle^{-1} \sim M_{\text{weak}}^2 \]

\[ \Omega_\chi \sim 0.1 \]  

Thermal cross-section (weak interactions):
\[ <\sigma v> \sim 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} \]

A different perspective: observed abundance constrains the DM annihilation cross section
Strategies for non-gravitational detection of WIMPs
Indirect detection: annihilation channels

Examples of Feynman diagrams for neutralinos (Jungman, Kamionkowski and Griest, 1996)

To $W$ bosons:

\[
\begin{align*}
\chi & \rightarrow Z \rightarrow W \chi \\
\chi & \rightarrow h, H \\
\end{align*}
\]

To fermions and photons

In general the number of Feynman diagrams for each final state is large, there are public numerical codes that perform these calculations (together with a precise computation of the relic density):

DarkSUSY (http://www.physto.se/~edsjo/darksusy/)
MicrOMEGAs (http://lapth.in2p3.fr/micromegas/)

For a generic theory that predicts WIMPS we have:

Gamma-rays

WIMP Dark Matter Particles $E_{CM}\sim 100$GeV

Neutrinos

+ a few $p\bar{p}$, $d\bar{d}$

Anti-matter

Fig. from Baltz et al. 2003
Indirect detection: annihilation rate

- The volume emissivity of a given annihilation by-product (energy of by-product produced per unit volume, time and energy range):

\[ \mathcal{E} = f_{\text{WIMP}} \rho_\chi^2 \quad f_{\text{WIMP}} = E \left( \frac{dN}{dE} \right)_{\text{SM}} \left( \frac{\langle \sigma v \rangle}{2m_\chi} \right) \]

- The density squared dependence is connected to the gravitational interactions of dark matter ("astrophysical factor"). The most natural places to look for annihilation are the regions with the highest DM densities: GC, nearby galaxies,...

- The properties of DM as a particle are in \( f_{\text{WIMP}} \), the by-product spectrum is particularly relevant (e.g. photons).

Fig. from Kuhlen 2010
Indirect detection strategies: gamma-rays

The **Fermi satellite** was launched in 2008 and has expanded our knowledge in gamma-ray astronomy ($20 \text{MeV} < E < 500 \text{ GeV};$ angular resolution $\sim 0.1 \text{deg above } 10 \text{GeV}$)

Recall that WIMPs have masses of $\sim 100 \text{GeV}$, so they are expected to produce photons in the gamma-ray energy range.
Indirect detection strategies: the richness of the gamma-ray sky

Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration
Indirect detection strategies: the richness of the gamma-ray sky

Ordinary astrophysical sources: **Galactic diffuse emission** (cosmic rays interacting with the interstellar medium and the interstellar radiation field)

- **Inverse Compton up-scattering**
- **Bremsstrahlung radiation**
- **Proton-proton collisions**

“Point” sources of gamma-rays:

**Blazars**: AGN with one of its jets pointing towards us (IC with background photons)

**Pulsars**: highly magnetized rotating neutron star (e.g. γ's from synchrotron radiation of accelerated charged particles)

**Supernova remnants**: electrons and protons accelerated to >TeV energies in the shock

Our limited knowledge of the different sources creates an uncertainty in DM searches!
DM annihilation constraints from gamma-ray observations

**MW satellites**

Good targets: low astrophysical background (DM-dominated systems M/L>100; low gas and stellar contents)

Uncertain DM distribution (incomplete phase-space information; see Lect. 3)

**Extragalactic gamma-ray background**

Integrated gamma-rays coming from DM structures along the line of sight (up to z~2)

Signal dominated by low-mass structures (devoid of stars/gas). Promising features in statistical properties of anisotropies

Uncertain abundance of low-mass structures (see Lect. 3)
DM annihilation constraints from gamma-ray observations

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Extragalactic gamma-ray background
DM annihilation signals? Cosmic Ray anomalies

Other CR “anomalies”:
- INTEGRAL/SPI 511 keV line (Weidenspointner et al. 2006)
- “WMAP Haze” (Dobler and Finkbeiner 2008)
- “Fermi Haze” (Dobler et al. 2010)
DM annihilation signals? Cosmic Ray anomalies

The case for DM annihilation

- WIMP annihilation can explain cosmic ray anomalies but: large cross section, ~100 times larger than the thermal relic value: $3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ (e.g. Bergström et al. 2009), possible in certain DM models that introduce a new force in the DM sector (see Lect. 4)
DM annihilation signals? Gamma-ray lines

~130 GeV gamma-ray line in the direction of the GC: Bringmann et al. 2012, Weniger 2012, Su and Finkbeiner 2012

Analysis of Fermi data (~4yrs), low photon statistics, residual = Map(120-140) – average Map(80-180)

Compatible with a ~130 WIMP annihilating into $\gamma\gamma$ and $\gamma Z$

Main issue with DM annihilation interpretation: region of emission is off-center (~200 pc); it might be possible through resonant interactions (gravitational) between DM particles and the Galactic bar (Kuhlen et. al 2012)
Direct detection

From Jungman, Kamionkowski and Griest 1996:

By crossing symmetry, the amplitude for WIMP annihilation to quarks is related to the amplitude for elastic scattering of WIMPs from quarks. Therefore, a WIMP that solves the dark-matter problem is generically expected to have some small, but non zero, coupling to nuclei (through the coupling to quarks). As a result, we expect there to be finite (although small) detection rates in generic models.

Crossing symmetry (typical example): Compton scattering and e+e- annihilation

“Local” WIMPs are expected to elastically scatter (momentum and kinetic energy are conserved) off nuclei in targets, producing nuclear recoil

\[ E_{\text{recoil}}^{\text{max}} = \frac{2m_X^2 m_N}{(m_X + m_N)^2} v^2 \]

\( \sim 10 \text{ keV for Xenon (A=54); } m_X \sim 100 \text{GeV; } v \sim 5 \times 10^{-4} c \) (150 km/s)

Scattering rate (number of scattering events per unit time per unit mass of detector):

\[ dN = d\rho_X (\sigma_{\text{scat}} \langle v \rangle)/m_N; \] WIMPs have a certain speed velocity distribution

\[
\frac{dN}{dE_r} = \frac{\sigma_0 \rho_X}{2 \mu^2 m_X} F^2(q) \int_{v_{\text{min}}}^{v_{\text{esc}}} \frac{f(v)}{v} dv
\]

\( \mu \) is the reduced mass

Threshold energy of the detector

uncertain local velocity distribution!
Direct detection: possible signals?

If the detector is at rest with respect to the galactic DM halo, and the WIMP speed distribution is Maxwellian with velocity dispersion $v_0 (R=N, m_r=\mu)$:

$$\frac{dR}{dE_r} \propto \exp \left( -\frac{m_N E_r}{2 m_r^2 v_0^2} \right)$$

No striking feature, exponential spectrum could be produced by different backgrounds

CoGeNT: “irreducible” background with exponential-like energy spectrum

keVee (keV electron equivalent) is used to quantify a measured signal from the detector in terms of the energy of an electron recoil that would be required to generate it

Annual modulation

Correct velocity distribution due to the relative motion of the Earth and the WIMPs wind

$$v_e = v_0 (1.05 + 0.07 \cos \omega t)$$

$$\omega = 2\pi / 1 \text{ year}$$

1 barn = $10^{-24}$ cm$^2$
pico = $10^{-12}$

CoGeNT collaboration, 2011
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Annual modulation

DAMA experiment reports an annual modulation signal at high significance

DAMA collaboration, Bernabei et al. 2008
Direct detection: current constraints the "zeptobarn" scale

The Xenon100 collaboration, 2012, arXiv:1207.5988