3. Phenomenology of WIMPs

Consider effective interaction of DM:

1. annihilation

\[ \text{DM} \rightarrow \text{SM} \]

2. scattering

\[ \text{SM} \rightarrow \text{SM} \]

3. production

\[ \text{DM} \rightarrow \text{DM} \]

Corresponding search strategies:

1. Indirect detection
2. Direct detection
3. Collider searches

3.1 Indirect detection

Central prediction for WIMPs:

\[ \langle 0 \rangle \sim 3 \cdot 10^{-26} \text{ cm}^3/\text{s} \]

Annihilations become inefficient after freeze-out (\( M \) too small)

Can become important again after structure formation (\( M \) grows rapidly)

Observables in the present Universe?
Need to know

1. Distribution of DM in astrophysical objects

2. Types and energies of particles produced by annihilations
   - $\gamma$-rays
   - neutrinos
   - positrons
   - anti-protons

3. Probability for particles to reach the Earth
   - Easy for $\gamma s + 2^2s$ (no deflection or absorption)
   - Hard for charged particles (complicated propagation)

3.1.1 Gamma-rays

$$\frac{dN}{dt \, dA \, dE} = P \cdot J$$

\[ \text{differential particle flux} \quad \text{particle physics} \]
P: Spectrum of $\gamma$-rays produced at interaction point

$\Rightarrow$ Depends on

- relative contribution of different final states $f$:
  
  $BR_f$ (branching fraction)

- spectrum of $\gamma$-rays produced by final state $f$:

  \[
  \frac{dN_f}{dE_\gamma}
  \]

Examples:

1) $xx \rightarrow \gamma \gamma$

   $E_{\gamma} = m_x$

   $\Rightarrow \frac{dN_f}{dE_\gamma} = \delta(E_{\gamma} - m_x)$

2) $xx \rightarrow e^+e^-$

   Final state radiation

   $\Rightarrow \frac{dN_f}{dE_\gamma} \sim \frac{x}{\pi} \frac{1}{E_{\gamma}}$
3) \( xx \rightarrow q\bar{q} \)

Hadrornization:

\( q\bar{q} \rightarrow (p, \bar{p}, \pi^+, \pi^-, \eta, \eta', \ldots) \)

Calculation of \( \frac{dN_f}{dE_f} \) with dedicated codes (Pythia, ...)

\[
P = \frac{<\sigma v>}{2m_x^2} \sum_f \frac{BR_f}{p} \frac{dN_f}{dE_f}
\]

\[v_x^2 = \frac{1}{m_x^2} \approx S_x^2\]

\[J(d\Omega) = \int d\Omega \int_0^\infty dl \; d\Omega \; s_x^2(l)\]

Where to look?

\[\rightarrow \text{Maximize } J\text{-factor}\]

\[\rightarrow \text{Minimize backgrounds}\]
Obvious target: Galactic centre
  
  \( \rightarrow \)

  Very close, large DM density
  \( \Rightarrow \) huge \( J \)-factor

  But: many astrophysical backgrounds
  \( \Rightarrow \) need modelling and subtraction

Interesting alternative: Galactic halo

Most promising target: dwarf galaxies

\( \rightarrow \)

Very few astrophysical backgrounds

\( \rightarrow \) \( J \)-factors small (and difficult to measure)

\( \Rightarrow \) Improved sensitivity by statistical combination ("stacking")

\( \Rightarrow \) Improvements by new discoveries
How to measure γ-rays?

1) Satellites (example: Fermi-LAT)

\[ \text{measure energy & momentum} \]

\[ \Rightarrow \text{Best sensitivity for } E_\gamma < 1 \text{ TeV} \]

2) Imaging Air Cherenkov Telescopes

\[ \text{shower} \]

\[ \text{Atmosphere} \]

\[ \text{Cherenkov Light} \]

\[ \text{Earth} \]

Examples: HESS, CTA (future)

\[ \Rightarrow \text{Best sensitivity for } E_\gamma > 1 \text{ TeV} \]

3.1.2 Charged cosmic rays

Primary target: Anti-matter

\[ \Rightarrow \text{Not usually produced in (secondary) astrophysical processes} \]

\[ \Rightarrow \text{An excess of anti-nuclei would be a clear signal of DM} \]
Challenge: Propagation

- Charged particles are deflected and lose energy through B-fields

- Need to solve diffusion equation + account for energy losses/reacceleration

  \[ \Rightarrow \text{Cannot trace back source (large backgrounds)} \]

- Only sensitive to local production

  \[ \Rightarrow \text{Example: TeV positrons lose energy within few kpc} \]

  \[ \Rightarrow \text{Propagation models uncertain} \]

  Important observable: \( e^+ \) fraction (i.e. \( e^+/e^- \) ratio)

  \[ \Rightarrow \text{Many uncertainties cancel out} \]

Observation (PAMELA, AMS-02, ...):

\[ e^+ \text{ fraction rises above 10 GeV} \]

\[ \Rightarrow \text{Not expected from secondary production} \]

- Need primary sources (nearby)

  \[ \Rightarrow \text{Supernova remnants} \]

  \[ \Rightarrow \text{Pulsars} \]

  \[ \Rightarrow \text{Dark matter} \]
3.1.3 Neutrinos

- Produced in many annihilation processes, e.g.

- Propagate freely from production point to detector (like γ-rays)

- Detection extremely challenging!

Unique advantage: Explore sources intransparent to γ-rays

Example: Solar capture

- DM particles can become gravitationally bound to the Sun
- Accumulation in solar center ⇒ large density
- Neutrinos produced in DM annihilations can escape
Neutrino detectors like Super Kamiokande or IceCube can search for DM!

Signal depends on $\langle \sigma v \rangle$ and on the capture rate (scattering cross section).

$\rightarrow$ next lecture

3.1.4 Velocity dependence

So far we assumed

$\langle \sigma v \rangle_{\text{freeze-out}} = \langle \sigma v \rangle_{\text{today}}$

Justified if matrix element is velocity independent

$M \sim v^0 \Rightarrow |M|^2 \sim v^0$

$\Rightarrow \sigma \sim \frac{1}{v} |M|^2 \sim \frac{1}{v}$

$\Rightarrow \sigma v \sim v^0$

For some models $M$ vanishes for $v \rightarrow 0$ (e.g. due to angular momentum conservation)

$M \sim v \Rightarrow \sigma \sim v$

$\Rightarrow \sigma v \sim v^2$ (p-wave)

In this case

$\langle \sigma v \rangle_{\text{today}} \ll \langle \sigma v \rangle_{\text{freeze-out}}$

$\Leftrightarrow v \sim 10^{-4} - 10^{-3}$

$\Leftrightarrow v \sim 10^{-1}$
Indirect detection inefficient

Also possible to have

\(<\sigma v>_{\text{today}} \gg <\sigma v>_{\text{freeze-out}}\)

via the Sommerfeld effect

Idea: DM particles experience attractive force

\[ \begin{array}{c}
\sigma \rightarrow \text{sm} \\
\xi \rightarrow \text{sm}
\end{array} \]

\(\Rightarrow\) enhanced annihilation at small velocities

\[ \sigma v = S(v) \left( \sigma v \right)_0 \]

Sommerfeld factor

Typically \(S(v) \sim \frac{1}{v}\)

\(\Rightarrow\) Huge enhancement of indirect detect.

Example: To explain PAMELA excess with DM, one needs

\(<\sigma v> \sim 10^{-24} \text{ cm}^3/\text{s}\)

\(\Rightarrow\) Can be compatible with freeze-out if

\(\left( \sigma v \right)_0 \sim 3 \cdot 10^{-26} \text{ cm}^3/\text{s}\) and \(S(v) \sim 30\)