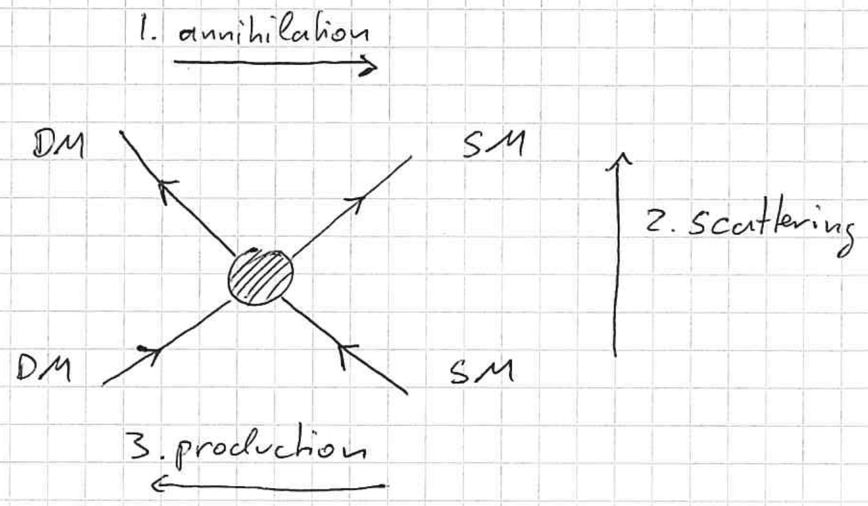
3. Phenomenology of WIMPs

Consider effective interaction of DM:



Corresponding search strategies:

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

3.1 Indirect detection

Central prediction for WIMPs:

$$\langle \sigma v \rangle \sim 3 \cdot 10^{-26} \, \mathrm{cm}^3/\mathrm{s}$$

Annihilations become inefficient after freeze-out (ρ too small)

Can become important again after structure formation (ρ grows rapidly)

Observable in the present Universe?

Need to know

1. Distribution of DM in astrophysical objects

2. Types and energies of particles produced by annihilations

   - γ-rays
   - neutrinos
   - positrons
   - anti-protons

3. Probability for particles to reach the Earth

   - Easy for γs + νs (no deflection or absorption)

   - Hard for charged particles (complicated propagation)

3.1.1 Gamma - rays

$$\underbrace{\frac{dR}{dt\, dA\, dE}}_{\text{differential particle flux}} = \underbrace{P}_{\text{particle physics}} \cdot \underbrace{J}_{\text{astrophysics}}$$

P: Spectrum of γ-rays produced at interaction point

↳ Depends on

- relative contribution of different final states f:

  BR_f (branching fraction)

- spectrum of γ-rays produced by final state f:

  $$\frac{dN_f}{dE_\gamma}$$

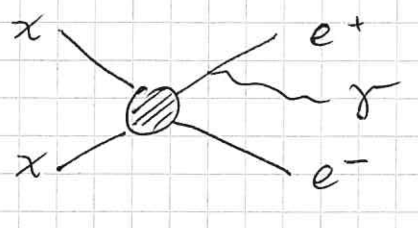
Examples: 1) $\chi\chi \to \gamma\gamma$

$$E_\gamma = m_\chi$$

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

2) $\chi\chi \to e^+e^-$

Final state radiation



$$\Rightarrow \frac{dN_f}{dE_\gamma} \sim \frac{\alpha}{\pi} \frac{1}{E_\gamma}$$

3) $\chi\chi \to q\bar{q}$

Hadronization:

$$q\bar{q} \to (p, \bar{p}, \pi^\pm, \pi^0, n, \bar{n}, \dots)$$
$$\hookrightarrow \gamma\gamma$$

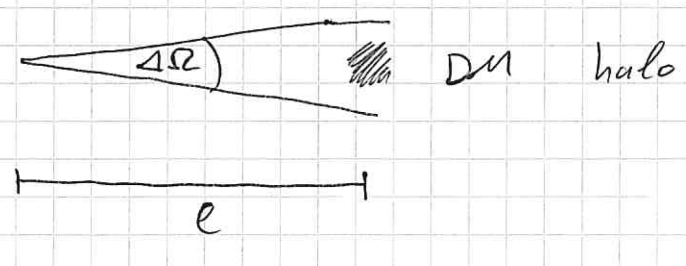
Calculation of $\frac{dN_f}{dE_\gamma}$ with dedicated codes (Pythia, ...)

$$P = \frac{\langle \sigma v \rangle}{2 m_\chi^2} \sum_f BR_f \frac{dN_f}{dE_\gamma}$$

Write $n_\chi^2 = \frac{1}{m_\chi^2} \cdot \rho_\chi^2$

particle physics | astrophysics

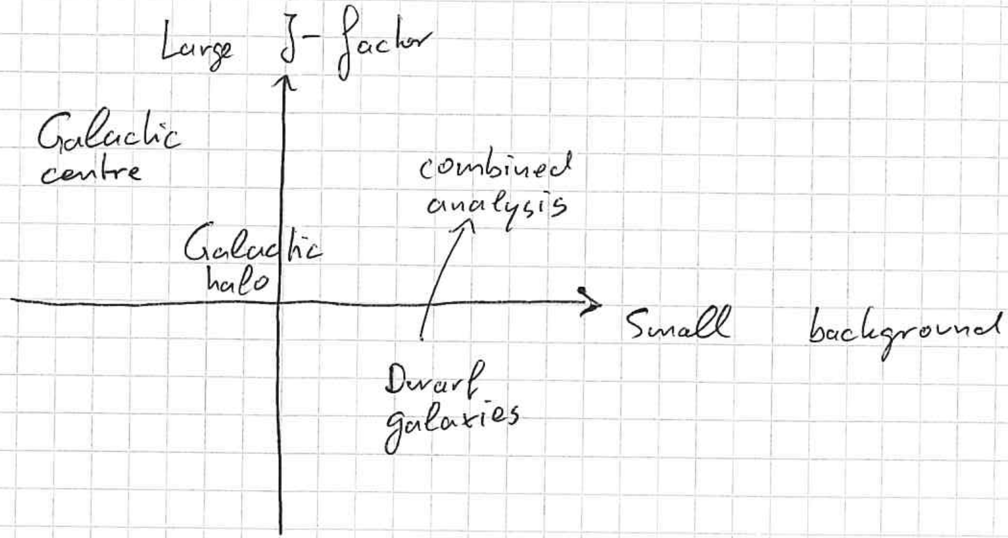
$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{l=0}^{\infty} dl \, d\Omega \; \rho_\chi^2(l)$$



Where to look?

→ Maximize J-factor

→ Minimize backgrounds



Obvious target: Galactic centre

↳ Very close, large DM density
⇒ huge J-factor

↳ But: many astrophysical backgrounds
⇒ need modelling and subtraction

Interesting alternative: Galactic halo

Most promising target: dwarf galaxies

↳ Very few astrophysical backgrounds

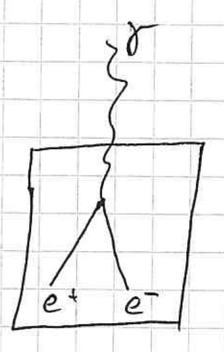
↳ J-factors small (and difficult to measure)

⇒ Improved sensitivity by statistical combination ("stacking")

⇒ Improvement by new discoveries

How to measure γ-rays ?

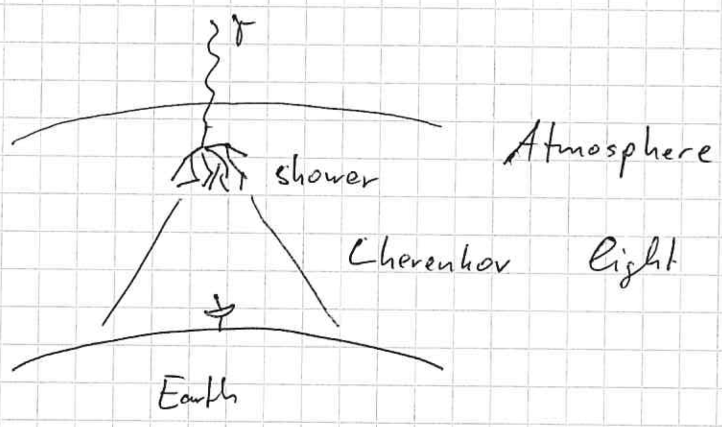
1) Satellites (example: Fermi-LAT)



} measure energy & momentum

$\Rightarrow$ Best sensitivity for $E_\gamma < 1\,\text{TeV}$

2) Imaging Air Cherenkov Telescopes



Examples: HESS, CTA (future)

$\Rightarrow$ Best sensitivity for $E_\gamma > 1\,\text{TeV}$

3.1.2 Charged cosmic rays

Primary target: Antimatter

↳ Not usually produced in (secondary) astrophysical processes

collisions with interstellar medium

↳ 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

⇒ Cannot trace back source (large backgrounds)

⇒ Only sensitive to local production

Example: TeV positrons lose energy within few kpc

⇒ Propagation models uncertain

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

⇒ Many uncertainties cancel out

Observation (PAMELA, AMS-02, ...): e^+ fraction rises above 10 GeV

⇒ Not expected from secondary production

⇒ Need primary sources (nearby)

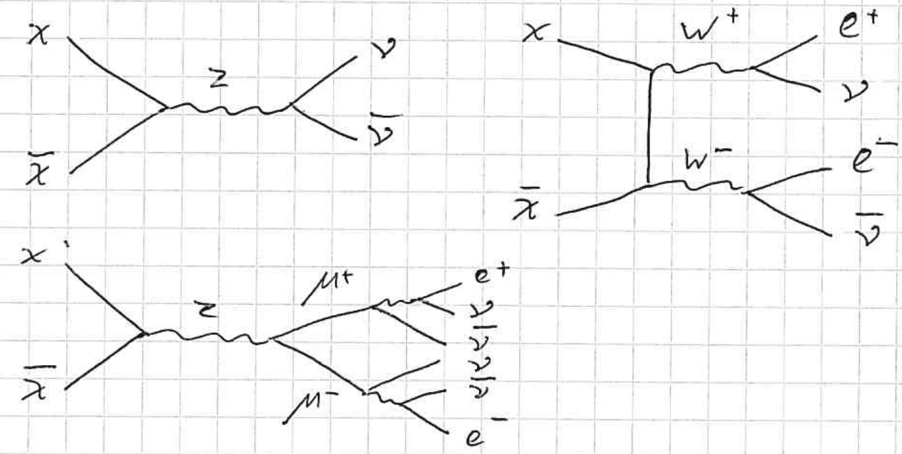
↳ Supernova remnants

↳ Pulsars

↳ Dark matter ?

3.1.3 Neutrinos

↳ Produced in many annihilation processes, e.g.

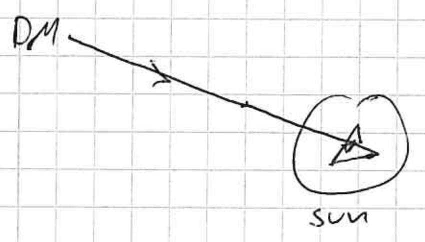


↳ Propagate freely from production point to detector (like γ-rays)

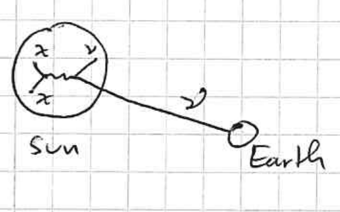
↳ Detection extremely challenging!

Unique advantage: Explore sources intransparent to γ-rays

Example: Solar capture



- DM particles can become gravitationally bound to the Sun
- Accumulation in solar center $\Rightarrow$ large density
- Neutrinos produced in DM annihilations can escape



$\Rightarrow$ Neutrino detectors like Super Kamiokande or Ice Cube can search for DM!

$\hookrightarrow$ 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

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

Justified if matrix element is velocity independent

$$\mathcal{M} \sim v^0 \Rightarrow |\mathcal{M}|^2 \sim v^0$$
$$\Rightarrow \sigma \sim \frac{1}{v} |\mathcal{M}|^2 \sim \frac{1}{v}$$
$$\Rightarrow \sigma v \sim v^0$$

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

$$\mathcal{M} \sim v \Rightarrow \sigma \sim v$$
$$\Rightarrow \sigma v \sim v^2 \quad \text{(p-wave)}$$

In this case

$$\underbrace{\langle \sigma v \rangle_{\text{today}}}_{v \sim 10^{-4} - 10^{-3}} \ll \underbrace{\langle \sigma v \rangle_{\text{freeze-out}}}_{v \sim 10^{-1}}$$

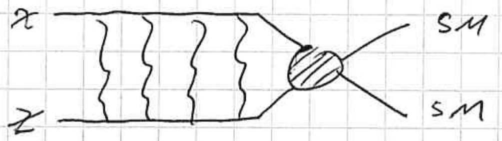
$\Rightarrow$ Indirect detection inefficient

Also possible to have

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

via the <u>Sommerfeld effect</u>

Idea: DM particles experience attractive force



$\Rightarrow$ enhanced annihilation at small velocities

$$\sigma v = \underset{\text{Sommerfeld factor}}{S(v)} \; \underset{\text{naive calculation}}{(\sigma v)_0}$$

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

$\Rightarrow$ Huge enhancement of indirect detect.

Example: To explain PAMELA excess with DM, one needs

$$\langle \sigma v \rangle \sim 10^{-24} \; cm^3/s$$

$\Rightarrow$ Can be compatible with freeze-out if

$(\sigma v)_0 \sim 3 \cdot 10^{-26} \; \frac{cm^3}{s}$ and $S(v) \sim 30$