Plan

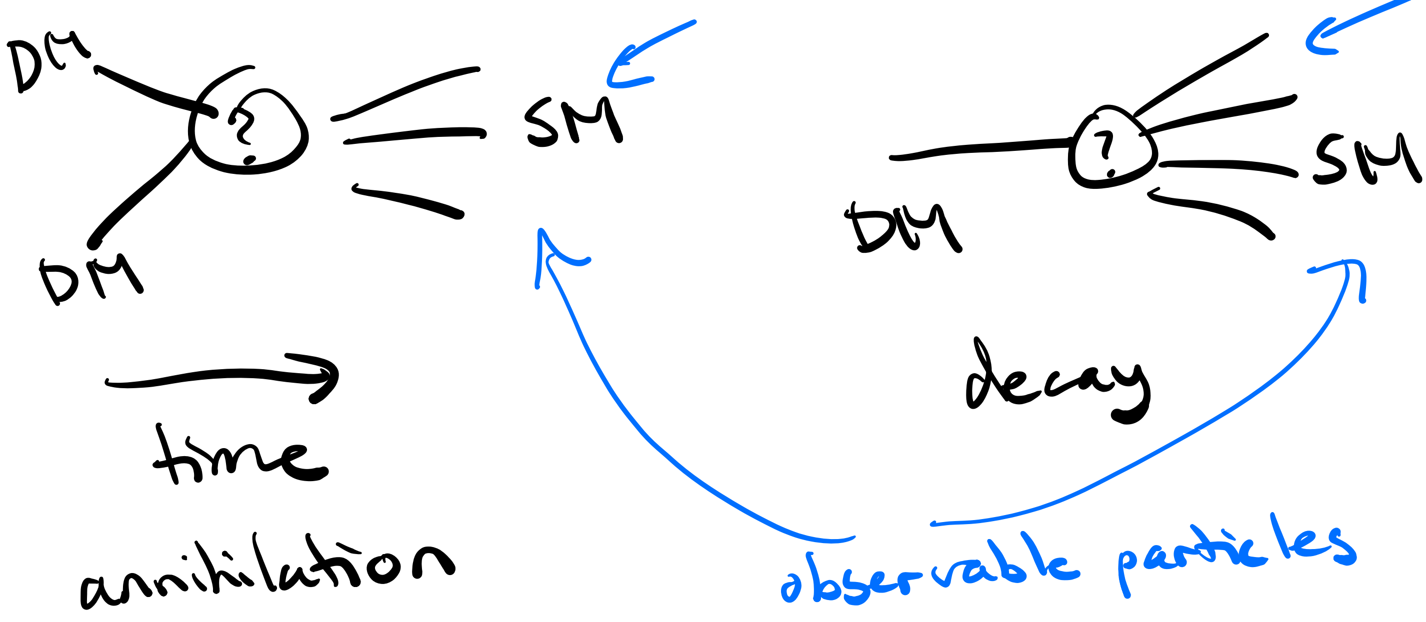
- Introduction (lecture 1-2)
  - Definition of indirect detection
  - Back-of-the-envelope estimates for signal strength & detectability over cosmic history
  - Dream/nightmare scenarios for indirect detection
- Tools for calculating signals (lectures 2-3)
  - Types of particles/spectra
  - Propagation effects
  - Directionality/J-factors
- Current status of the field (lectures 3-5)
  - Limits from a wide range of searches
  - Current anomalies & excesses
  - In-depth case study of one excess (if time permits)

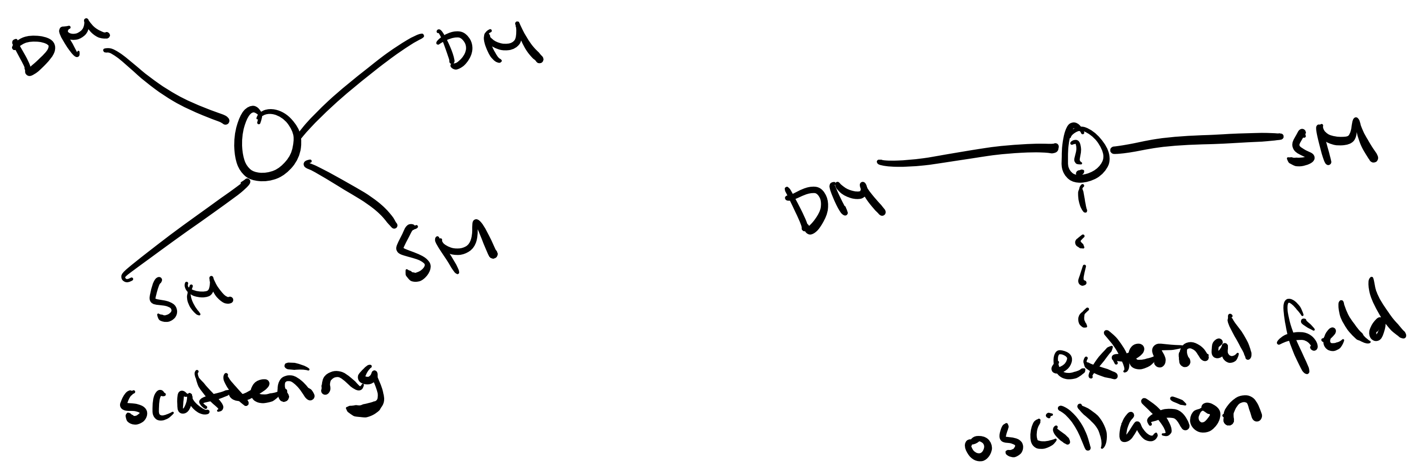
Goals

- Estimate indirect detection signals over history of cosmos
- Understand which models are dream/nightmare scenarios for ID

Indirect detection: identify signals of interactions between DM & SM

(occurring outside detector volume)





Advantages of ID

- Huge volume/time to integrate over
- Potential to test for new physics in conditions of temperature/density/fields not achievable on Earth
- Can take advantage of astrophysics observations

– Challenge: not controlled experiments, backgrounds often large/complex

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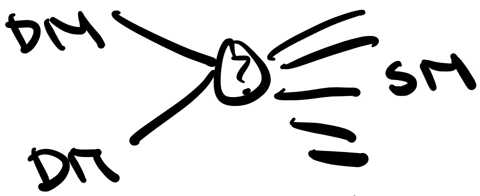
Estimate effects of annihilation/decay over cosmic history

Case 1: s-wave annihilation of a thermal relic DM

Review:



Freezeout: $n_f \langle \sigma v \rangle \sim H_f \sim \frac{T_f^2}{m_{PL}}$

assume constant

After freezeout, $n \propto 1/a^3$

Let $f_{ann} \equiv$ fraction of DM that annihilates over a Hubble time

$$\equiv n \langle \sigma v \rangle H^{-1}$$

Hubble time

probability a DM particle annihilates per unit time

$$\propto \frac{1}{a^3} \langle \sigma v \rangle H^{-1}$$

$$H \propto \begin{cases} a^{-2} & \text{during radiation domination} \\ a^{-3/2} & \text{" matter "} \\ a^{0} & \text{" dark energy "} \end{cases}$$

$f_{ann} \approx 1$ at freezeout

After freezeout

$$f_{ann} \propto \begin{cases} a^{-1} & \text{(rad. dom.)} \\ a^{-3/2} & \text{(matter dom.)} \\ a^{-3} & \text{(DE dom.)} \end{cases}$$

BBN: $T \sim$ MeV

Matter-radiation equality (MRE): $T \sim$ eV

Cosmic microwave background (CMB): $T \sim 0.2$ eV

Present day: $T \sim 2 \times 10^{-4}$ eV

$T_f \gtrsim 1$ MeV to avoid BBN problems

$f_{ann} \leq 10^{-6}$ at MRE

From MRE to today f_{ann} drops by about a factor of 10^5

$\Rightarrow$ f_{ann} today is very small even in regions of high density

Energy liberated by annihilation over a Hubble time per baryon:

$(5\text{ GeV})\, f_{ann}$

During rad. dom $f_{ann} \propto \frac{1}{a} \sim \frac{T}{T_f}$

$\left(\frac{5\text{ GeV}}{T_f}\right) T$

$\hookrightarrow O(1)$ for a 100 GeV WIMP

e.g at BBN is about 1 MeV per baryon per Hubble time

comparable to n-p mass splitting, D binding energy

(0906.2087)

For CMB, energy per baryon in a Hubble time

$$\sim \left(\frac{5\text{ GeV}}{T_f}\right) 0.2\text{ eV}$$

$$\sim 10\text{ eV} \times 2\times10^{-2} \times \left(\frac{5\text{ GeV}}{T_f}\right)$$

e.g 100 GeV DM can ionize 2% of hydrogen

- Planck can see perturbations to the ionization fraction of $O(10^{-3,4})$ well after recombination
- Potential for a very visible signal
- We should be able to test energy injections of 10^{-2} eV / baryon / Hubble time

Equate to (5 GeV) f_{ann}

i.e should be able to test $f_{ann} \sim$ few $\times 10^{-12}$

- Doing the calculation carefully, Planck can exclude $m_{DM} \lesssim 10$ GeV for thermal relic

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Temperature effects

- For $z \gtrsim 150$-200, baryons & photons are kept at the same temperature by scattering (photons more abundant by factor $\sim 10^{9}$-10^{10}, huge heat sink)
- For $z \lesssim 150$, however, possible to heat just baryons

- Baryons cool as $T \propto \frac{1}{a^2}$ after decoupling (as they are non-relativistic)
- Eventually photons from stars heat & ionize the gas - "reionization" - complete by $z \sim 6$

Early-universe temperature observations

- Ly-α: $z \sim 2-6$ (1808.04367, 2001.10018)

  $T_{gas} \sim 10^4\, K \sim 1\, eV$

- 21cm observations of hydrogen temperature pre-reionization - T_{gas} could be as low as $O(10)\, K$ $\sim 10^{-3}\, eV$

- Optimistically assume all energy $\rightarrow$ heating

  From Ly-α, we could see $(5\, GeV) f_{ann} \sim 1\, eV$

  $\Rightarrow f_{ann} \sim 2 \times 10^{-10}$ $\rightarrow$ probably not competitive w/ CMB

21cm: $(5\, GeV) f_{ann} \sim 10^{-3}\, eV$

$f_{ann} \sim 2 \times 10^{-13}$

Structure formation can boost relative to CMB - maybe competitive?

Case 2: decaying DM

$f_{dec} \equiv$ fraction of DM decaying in a Hubble time

assume constant

$= \Gamma H^{-1} = H^{-1}/\tau$

Energy injection/baryon in a Hubble time:

$5 \text{ GeV } f_{dec}$

$$f_{dec} \propto \begin{cases} a^2 & \text{- rad. dom.} \\ a^{1.5} & \text{- matter dom.} \\ a^0 & \text{- dark energy dom.} \end{cases}$$

Good to search at late times/low redshifts

CMB limits: $f_{dec} \approx \text{few} \times 10^{-12}$

$H^{-1} \sim 10^{14}\text{ s}$

$$\tau = \frac{1}{\Gamma} \sim \frac{H^{-1}}{f_{dec}} \sim 10^{25-26}\text{ s}$$

Temperature: Ly-α, $f_{dec} \sim 2 \times 10^{-10}$, $H^{-1} \sim 10^{16}\text{ s}$

$\tau \lesssim 10^{25-26}\text{ s}$ detectable

21 cm: $f_{dec} \sim 2 \times 10^{-13}$

$H^{-1} \sim 10^{15}\text{ s} \Rightarrow \tau \lesssim 10^{27-28}\text{ s}$ detectable