

Goals

- Understand in general terms how early-universe probes can constrain exotic energy injections (from dark matter or other sources)
- (with slides) Describe tools for detailed calculations

If DM annihilates or decays to SM particles, steady trickle of energy from $\text{DM} \rightarrow \text{SM}$ over all cosmic history.
Let us estimate the impact of this energy transfer for annihilation/decay (also relevant effects from scattering, oscillations).

Case 1: s-wave annihilation, DM is a thermal relic

Review: = no velocity dependence in $\langle \sigma v_{\text{rel}} \rangle$ for annihilation

as discussed earlier, freezeout occurs

$$\text{when } n \langle \sigma v \rangle \sim H \sim T^2 / m_{\text{Pl}}$$

After this the DM number density dilutes with the expansion of the universe, $n \propto 1/a^3$

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

$$= n \langle \sigma v_{\text{rel}} \rangle H^{-1} \xrightarrow{\text{Hubble time}}$$

probability of annihilation for a DM particle per unit time

$$= n \langle \sigma v_{\text{rel}} \rangle H^{-1}$$

$$\propto \frac{1}{a^3} \langle \sigma v_{\text{rel}} \rangle \cdot H^{-1} \text{ after freezeout}$$

$H \propto a^{-2}$ during radiation domination

$$\begin{array}{lll} \propto a^{-3/2} & \text{"} & \text{matter "} \\ \propto a^0 & \text{"} & \text{dark energy "} \end{array}$$

$\Rightarrow f_{\text{ann}} \approx 1$ at freezeout, for $\langle \text{cov}_{\text{rel}} \rangle$ constant we have

$\Rightarrow f \propto a^{-1}$ (rad. dom), $a^{-1.5}$ (matter dom.), a^{-3} (DE dom.)

Note: well after freezeout, $f_{\text{ann}} \ll 1$

We expect $T_{\text{freezeout}} \gtrsim 1 \text{ MeV}$ to avoid BBN limits

Matter-radiation equality (MRE): $T \sim 1 \text{ eV}$

\Rightarrow universe expands by $\gtrsim 6$ orders of magnitude from freezeout to MRE, f_{ann} drops by the same factor

Then from MRE to today (mostly matter domination, expansion by a factor of 3000), f_{ann} drops by another factor of $\sim 10^5$

\Rightarrow In regions of cosmological average density, expect $f_{\text{ann}} \lesssim 10^{-11}$ today

- no interesting depletion effect on DM density unless density is enhanced ~ 11 orders of magnitude above cosmological average value
- typically requires capture in/around compact objects (e.g. density near Earth is $\sim 4 \times 10^5$ higher than cosmological average).

So only a tiny fraction of DM annihilates significantly post-freezeout - but the energy transfer from that annihilation can still be significant.

Energy liberated by annihilation (for a cold relic) $\sim f_{\text{ann}} \chi$
(total mass in DM) $\sim 5 f_{\text{ann}} \text{ GeV} \times (\# \text{ of baryons})$

\Rightarrow energy per baryon $\sim (5 \text{ GeV})_{\text{ann}}$ per Hubble time

Since during radiation domination $f_{\text{ann}} \sim \frac{T}{T_f}$

(T_f = temperature at freezeout), \Rightarrow annihilation injects

$\sim \left(\frac{5 \text{ GeV}}{T_f}\right) T$ energy per baryon per Hubble time

\Rightarrow For $T_f \sim 5 \text{ GeV}$ ($m_{\text{DM}} \sim 100 \text{ GeV}$), enough power to double the kinetic energy of baryons

- even more power for DM that freezes out later

(Note this isn't what happens in practice, as the baryon temperature is tightly coupled to the CMB temperature down to $z \sim 150-200$ - CMB acts as a heat sink)

so e.g. at BBN, $T \sim 1 \text{ MeV}$, for 100 GeV DM with $T_f \sim 5 \text{ GeV}$ we are injecting $\sim 1 \text{ MeV}$ of energy per nucleon (comparable to n-p mass splitting, D binding energy) - potential to affect light element abundances. (see e.g. Jedamzik & Pospelov arXiv: 0906.2087)

At CMB epoch (shortly after matter-radiation equality, use rad. dom. scaling for estimate), $T \sim 0.2 \text{ eV}$,

$$\begin{aligned} \text{energy injected per baryon per Hubble time} &\sim (5 \text{ GeV}) \left(\frac{0.2 \text{ eV}}{T_f}\right) \\ &\sim 2 \times 10^{-2} \times 10 \text{ eV} \times (5 \text{ GeV}/T_f) \\ &\quad \downarrow \\ &\quad \sim \text{ionization energy of hydrogen} \end{aligned}$$

\Rightarrow for $T_f \sim 5 \text{ GeV}$ (100 GeV thermal relic), enough power to ionize 1-2% of all hydrogen; lighter DM (lower T_f) has a bigger effect

Ionization effects

- The CMB constrains extra ionization during/after recombination

- sensitive to changes of $O(10^{-3})$ in the ionization

fraction during the cosmic dark ages after recombination

⇒ if 100% of injected power went into ionization,
we should be able to test energy injections of
 $\sim 10^2 \text{ eV/baryon/Hubble time}$ at $T \sim 0.2 \text{ eV}$

Equating this rate to $(S \text{ GeV}) f_{\text{ann}}$, we should be able to
test $f_{\text{ann}} \sim \text{few} \times 10^{-12}$, or $T_f \sim 100 \text{ GeV}$

In reality, not all power goes into ionization, & we have
dropped several other $O(1)$ factors, so the actual
sensitivity is weaker.

- Doing these calculations carefully requires a detailed calculation of where the power goes (e.g ionization vs heating), but when this is done, the CMB excludes the simplest thermal relic scenario for $m_{\text{DM}} \lesssim 10 \text{ GeV}$, for all SM final states except neutrinos (Planck 2018 cosmological parameters paper)

Temperature effects

- Above $z \sim 150-200$, the baryon & photon temperatures are tightly coupled; injected heat is distributed among both species, primarily to photons (more abundant by a factor of $1/\eta$, $\eta = \text{baryon-to-photon ratio} = 6 \times 10^{-10}$)

⇒ change in temperature of the photon-baryon fluid is suppressed by a factor η , compared to the ΔT if only the baryons are heated

(For the same reason, distortions to the energy spectrum of the CMB from non-excluded DM annihilation models are typically at the $O(10^{-10})$ level)

Once the CMB & matter temperatures decouple, it is possible to heat the matter alone - much more feasible to see a signal.

The baryon temperature cools as $(1+z)^2 \propto \frac{1}{a^2}$ after decoupling, and remains cooler than the CMB until heated by stars during the "Cosmic Dawn" epoch.

Photons from stars both heat & rapidly ionize the universe - "reionization", ~completed by $z \sim 6$.

Early-universe temperature measurements:

- Lyman- α forest: redshifted Ly- α absorption lines tell us about the distribution + temperature of neutral hydrogen clouds after reionization, $z \sim 2-6$

Inferred temperatures are $\sim 10^4$ K ~ 1 eV

(e.g. Walter et al 1808.04367, Gaikwad et al 2001.10018)

CMB temperature $\sim 10^{-3}$ eV

- In the future, ^(confirmed) observations of a primordial 21cm absorption line could measure the gas temp. pre-reionization - could be as low as $0(10)$ K $\sim 10^{-3}$ eV.

(e.g. suppose decoupling from CMB occurs at

$z \sim 150$, then by $z \sim 15$ matter will be a factor of 10 cooler than the CMB. $T_{\text{CMB}}(z=15) \sim 50$ K, so expect matter temperature ~ 5 K.)

- Let us guess we could detect a DM annihilation/decay -induced temperature change of the same magnitude as the baseline temperature, over a Hubble time
 - Optimistically, suppose all energy goes into matter heating
Then we could detect $5 \text{ GeV fann} \sim 1 \text{ eV}$ from Ly- α , $5 \text{ GeV fann} \sim 10^{-3} \text{ eV}$ from 21 cm.
- Summarizing : expect to test energy injected/baryon over a Hubble time at the level of $\sim 10^{-2} \text{ eV}$ from CMB ($z \sim 1000$), $\sim 1 \text{ eV}$ from Ly- α ($z \sim 2-6$), $\sim 10^{-3} \text{ eV}$ from 21 cm ($z \sim 10-30$).

For decaying DM, energy injected/baryon over a Hubble time

$$\sim \underbrace{\Gamma H^{-1}}_{\substack{\text{fraction of DM} \\ \text{decaying}}} \times \underbrace{5 \text{ GeV}}_{\substack{\text{DM mass} \\ \text{/baryon}}}$$

$$(\text{CMB: } H^{-1} \sim 10^{14} \text{ s} \Rightarrow \text{test } \tau = \frac{10^{14} \text{ s} \times 5 \text{ GeV}}{10^{-2} \text{ eV}} \sim 10^{25} \text{ s})$$

$$(\text{Lyman-}\alpha: H^{-1} \sim 10^{16} \text{ s} \Rightarrow \text{test } \tau = \frac{10^{16} \text{ s} \times 5 \text{ GeV}}{1 \text{ eV}} \sim 10^{25} \text{ s})$$

$$(21 \text{ cm (future)}: H^{-1} \sim 10^{15} \text{ s} \Rightarrow \text{test } \tau = \frac{10^{15} \text{ s} \times 5 \text{ GeV}}{10^{-3} \text{ eV}} \sim 10^{27} \text{ s})$$

Note similar lifetime bounds of 10^{27-28} s can be set by direct (non-)observations of decay products from regions of high DM density.

Here we care only about total energy injection - can also constrain a sub component of DM decaying, or partial decay (e.g primordial black holes decaying via Hawking radiation).