7. Asymmetric DM

7.1 Motivation

Focus so far: How to explain $\Omega_{DM} h^2 = 0.12$

But what about $\Omega_B h^2 \sim 0.02$?

How do baryons obtain their abundance ?

Naive freeze-out calculation: $\langle \sigma v \rangle \sim \frac{1}{m_\pi^2}$

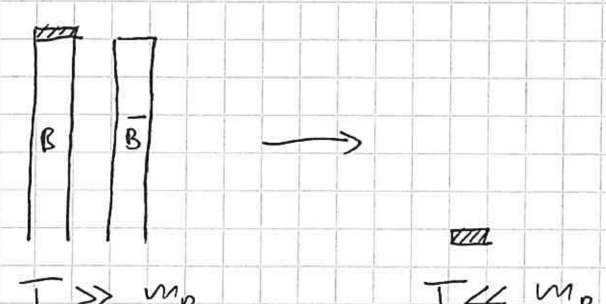
$\Rightarrow \Omega_B h^2 \sim 10^{-10} \rightarrow$ very wrong !

Also: Universe contains only baryons but no anti-baryons (no observable $p\bar{p}$ annihilations)

Solution: Initial baryon asymmetry

For $T \gg m_p$: $\eta_B = \frac{n_B - n_{\bar{B}}}{s} \sim 10^{-10}$

For $T \ll m_p$: Symmetric component annihilates away



$T \gg m_p$ $\qquad$ $T \ll m_p$

$\Rightarrow \Omega_B = \eta_B \cdot s_0 \cdot \rho_c^0 \cdot m_p \sim 5\%$

Next puzzle: Why is $\Omega_B \approx \Omega_{DM}$?

↳ Great coincidence for all the production mechanisms discussed so far

⇒ Maybe DM also has an asymmetry ?

Assume $Y_{DM} = \frac{n_{DM} - n_{\overline{DM}}}{s} \approx Y_B$

$$\Rightarrow \Omega_{DM} = \Omega_B \cdot \frac{m_{DM}}{m_p}$$

If $m_{DM} \approx 5 \cdot m_p \Rightarrow \Omega_{DM} h^2 \sim 0.1$

↳ Asymmetric DM

How to create Y_B ?

Need to fulfil Sakharov conditions

1. Baryon number violation
2. Violation of C and CP

   ↳ Processes must produce more particles than anti-particles

3. Departure from thermal equilibrium

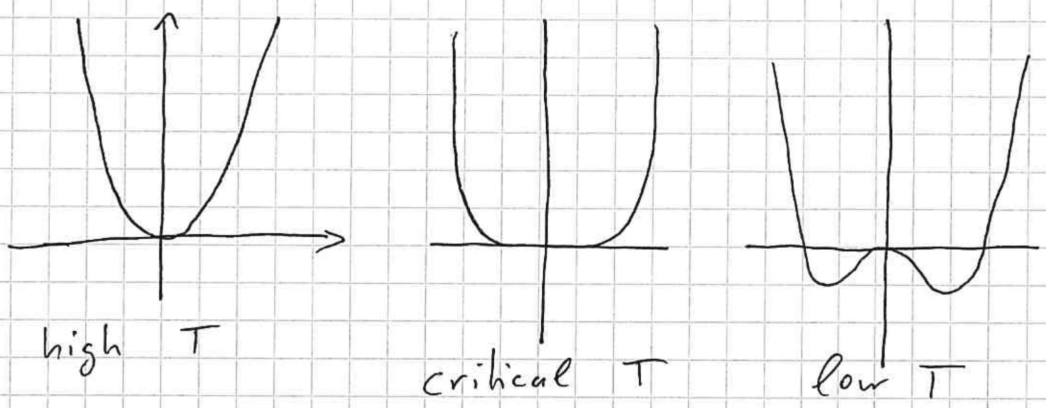
   ↳ Process and inverse ~~pro~~ process must have different rates

In SM these conditions are not fulfilled

↳ CP violation in weak interactions too small to create enough asymmetry

↳ No departure from thermal equilibrium

EW phase transition is a smooth cross-over



=> Need new physics to explain baryon asymmetry

- baryogenesis
- leptogenesis
- linked to DM production ?

7.2 Phenomenology

Simple example: Consider a heavy particle ϕ that freezes out before decaying

→ departure from thermal equilibrium

Assume two decay modes

$$\phi \to p\bar{\psi} \quad \text{and} \quad \phi \to \bar{p}\psi$$

with different branching ratios
(need CP violation)

⇒ Create equal and opposite asymmetry in baryons and DM

Remaining challenge: Need to annihilate away symmetric comp.

⇒ $\langle \sigma v \rangle_{ADM} > \langle \sigma v \rangle_{WIMP}$

⇒ Strong interactions needed

Many ADM models assume new strong dynamics in the dark sector

⇒ confinement

⇒ bound state formation

Example: Mirror DM

Assume dark sector has exactly the same gauge group and particle content as SM
(dark protons, dark electrons, ...)

Problem 1: We measure Hubble rate during BBN & CMB

=> Strong constraint on new relativistic degrees of freedom

$$\Delta N_{eff} \lesssim 0.3$$

↑ extra neutrino species

=> Temperature of dark sector must be lower:

$$\Delta N_{eff} \sim \left(\frac{T_{DM}}{T_{SM}} \right)^4$$

Problem 2: DM behaves differently from visible matter

↳ no strong self-interactions

(Bullet Cluster: $\frac{\sigma_{SIDM}}{m_{DM}} \lesssim 1 \frac{cm^2}{g}$)

↳ no disk formation (need 3d DM halos)

=> Need efficient formation of dark hydrogen to reduce dissipation and scattering

Predictions: - No annihilation processes
=> no indirect detection signals

- Direct detection & collider searches very promising

- ADM can be captured and accumulated in stars
  - ↳ modified heat transfer (helioseismology)
  - ↳ black hole formation (destruction of neutron stars)

8. Summary

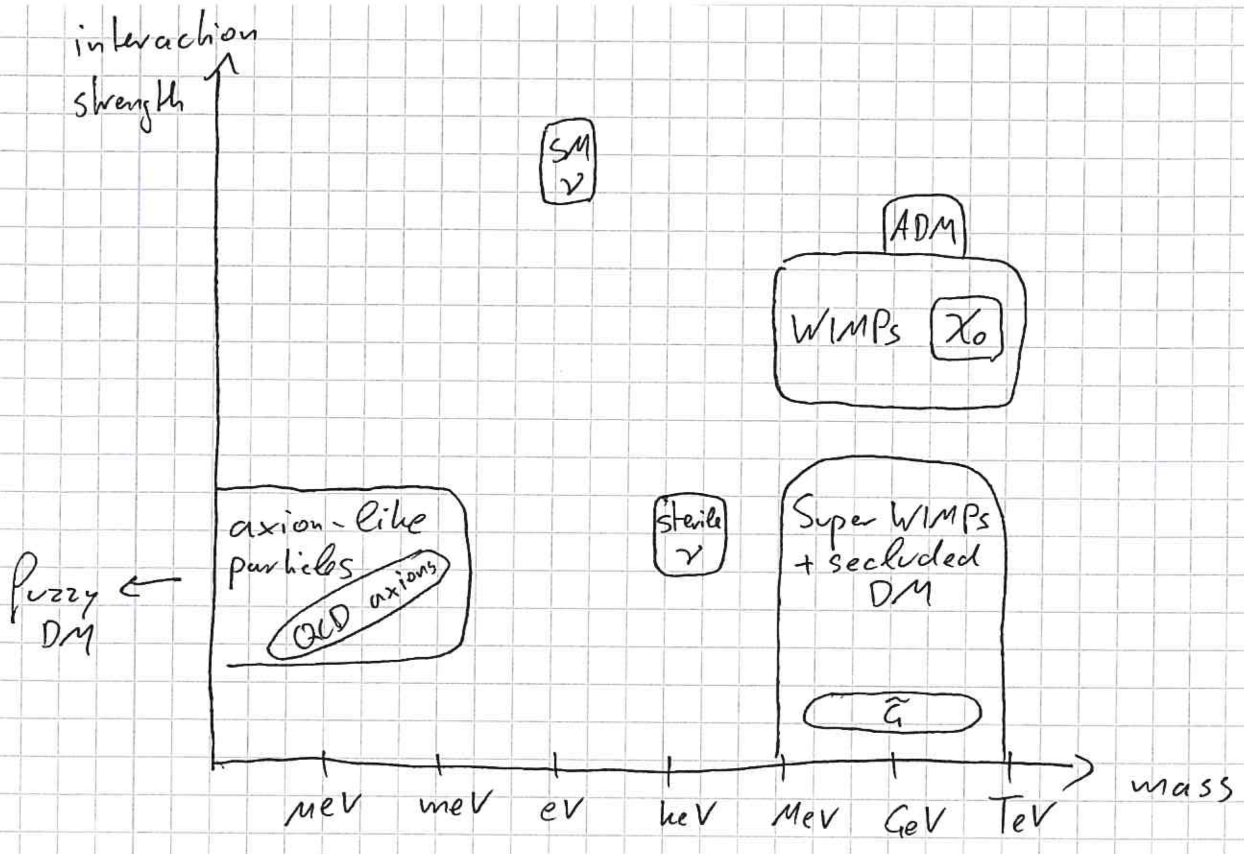
8.1 Overview of particle DM candidates

Theory motivations:

- Hierarchy problem (→ SUSY)
- Strong CP problem
- Neutrino masses
- Baryon asymmetry

Production mechanisms

- Freeze-out
- Freeze-in
- SuperWIMP mechanism
- Misalignment mechanism
- Topological defects
- Initial asymmetry



Search strategies:

- Direct detection (+ axion haloscopes)
- Indirect detection (annihilation, decay, conversion)
- Collider searches (+ LSW experiments)
- Astrophysical constraints (structure formation, stellar evolution)

↳ No clear signal yet but many hints!

8.2 What if DM is not a particle?

↳ Could be macroscopic objects ("MAssive Compact Halo Objects")

Most interesting possibility: black holes

⇒ Must have formed (long) before the beginning of BBN to satisfy constraints on Ω_B

↳ Primordial Black Holes (PBH)

Attractive scenario:

PBHs generated right after the end of inflation

↳ regions with high enough density never expand but immediately collapse into BH

⇒ Needs very non-standard inflation models

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} \sim 1$$

instead of $\delta \sim 10^{-5}$

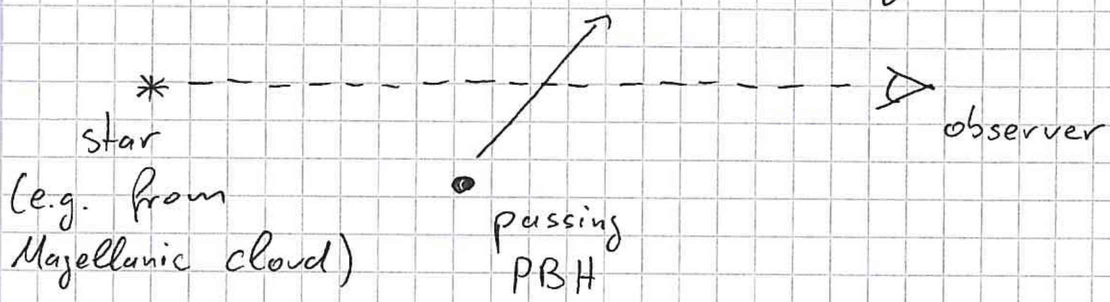
↳ Various working scenarios

PBHs subsequently merge to form more massive BHs

⇒ extended range of masses

Central prediction: DM is not smooth but "clumpy"

$\Rightarrow$ Look for microlensing



$\Rightarrow$ variation in brightness of star (not observed)

$\Rightarrow$ PBH cannot be all of DM for $10^{-14} M_\odot \lesssim M_{PBH} \lesssim 10 M_\odot$

Relatively weak constraints for

$M_{PBH} \sim 10 - 100 \; M_\odot$

↳ corresponds to mass range of BH mergers observed by LIGO

But PBH in this mass range are not fully dark

↳ accretion of gas

↳ conversion into radiation

↳ energy injection into plasma

$\Rightarrow$ Strong (but controversial) constraints