A dark path to long-lived particles

Part I : dark matter mystery

① Why do we believe it's a particle?

- Gravitational effects on galaxy scales (rotation curves) and on scales of galaxy clusters (lensing)
- Large Scale Structure of the Universe
- CMB
- Bullet Cluster
- Neutron stars merge (rules out viable modified gravity theories due to strong agreement with GR)

② Dark matter : what kind of beast is it?

We know:	We have no clue:
• It constitutes ~ 85% of matter in the Universe	• Other interactions?
• Interacts through gravity	• Mass, spin?
• If DM particles ever were relativistic - they should have slowed down early in the history of the Universe	• Several species?
• Electrically neutral (or has tiny charges)	
• Stable on cosmological scales	

DISCLAIMER: ① suggests that DM is a <u>macroscopic</u> on cosmological scales „particle". It can actually be huge and even baryonic!*

Examples: Massive compact halo objects (MACHOs),
Clouds of neutral gas, black holes...

However, there is not enough such objects (primordial black holes are still under consideration in a small area of parameter space)

<u>All these funny names:</u>

- Cold: Particles were created/decoupled non-relativistic (CDM)
- Warm: Particles were created/decoupled relativistic but became non-relativistic during radiation-dominated epoch. (WDM)
- Hot: Particles were created/decoupled relativistic and became non-relativistic in or around the matter-dominated epoch. (HDM)

<u>Why to care?</u> The „cusp-core/missing satellites/too big to fail" problems

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* In cosmology „baryonic" means everything that interacts strongly or electromagnetically, and is not photons.

All these problems have similar roots: it seems that there is fewer small-scale structures than predicted by CDM models.

Why making DM warm can help?

- CDM is pressureless ⇒ in the Early Universe structures of all scales can be formed, and they grow from small ones to the larger ones.

- WDM has nonzero pressure ⇒ Very small structures cannot be formed, minimal scales formed are set by the DM free-streaming length at that time. Smaller structures are to be created later on.

DISCLAIMER (again): the „problems" mentioned might originate from our incorrect models of baryonic matter in the corresponding objects, and no Warm dar matter wold be needed.

③ We need some assumptions:

- A1: DM interacts with the SM particles not only gravitationally.
- A2: Let's focus on CDM
- A3: DM used to be in equilibrium with the SM plasma, but decoupled later on (freeze-out). This process sets the DM relic abundance.

Part II: DM relic density. Boltzmann treatment.

① Intuitive picture

Expanding Universe: $ds^2 = -dt^2 + a(t)^2 \underset{\uparrow}{d\Sigma^2}$

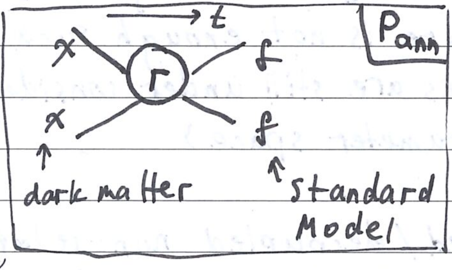
3-dim metric

Assume that DM particles can annihilate with the rate $\Gamma_{(t)}^{\text{comoving}}$:

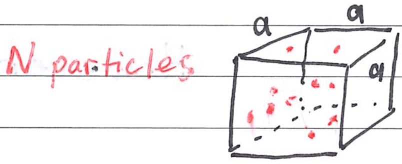
$$\boxed{\frac{dN}{dt} = -\Gamma_{(t)}^{\text{comoving}}}$$

$\Gamma_{(t)}^{\text{comoving}} = \Gamma(t)\, a^3(t)$

Hubble parameter $H = \frac{\dot a}{a}$



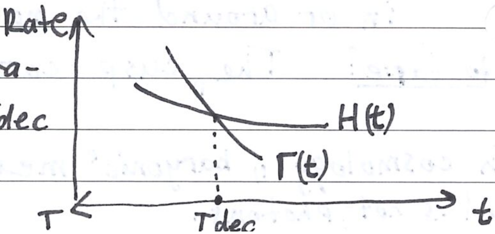
a volume with particles



No interaction: $N = na^3 = \text{const}$

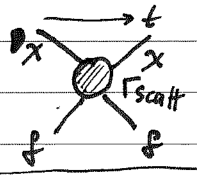
- If $\Gamma \gg H$ particles interact actively ⇒ they are in equilibrium
- If $\Gamma \ll H$ particles don't have enough time to find one another as the Universe expands too fast ⇒ they are out of equilibrium

If $\Gamma(t)$ decreases with time (increases with temperature T) faster than $H(T)$: $\exists\, T_{dec}$: [redacted] for $T < T_{dec}$ DM particles are out of equilibrium.



Remark : 2 types of equilibrium

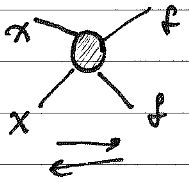
1) Kinetic (thermal) : A particle is in kinetic (thermal) equilibrium if it's distribution function is of an equilibrium shape (Bose-Einstein/ Fermi-Dirac).
Remains as long as scattering processes are active ($\Gamma_{scatt} >> H$)



=> particles have the same temperature T

2) Chemical : A process is in chemical equilibrium when it's rate is equal to the reverse one

Example :



$\Gamma(xx \to ff) = \Gamma(ff \to xx)$

A particle is out of chemical equilibrium when there is no process in which this particle takes part and that is in chemical equilibrium

- A4 : At the moment of decoupling Γ_{ann} is the only process that keeps DM in chemical equilibrium with plasma (so decoupling means loosing this equilibrium). Moreover, ~~throughout the following~~ DM is in thermal equilibrium with plasma during decoupling ($\Gamma_{scatt}(T_{dec}) >> \Gamma_{ann}(T_{dec})$)

Distribution function after kinetic decoupling :
In the approximation of instant decoupling and in case if there is no DM further interactions popping up, DM distribution function would keep it's shape in comoving coordinates. The only change would be redshifting of its momentum : $f(|\bar{p}|, t) = f_{decoupling}\left(\frac{a(t)}{a_{decoupling}}|\bar{p}|\right)$