Filtered dark matter from droplet-forming first order phase transitions

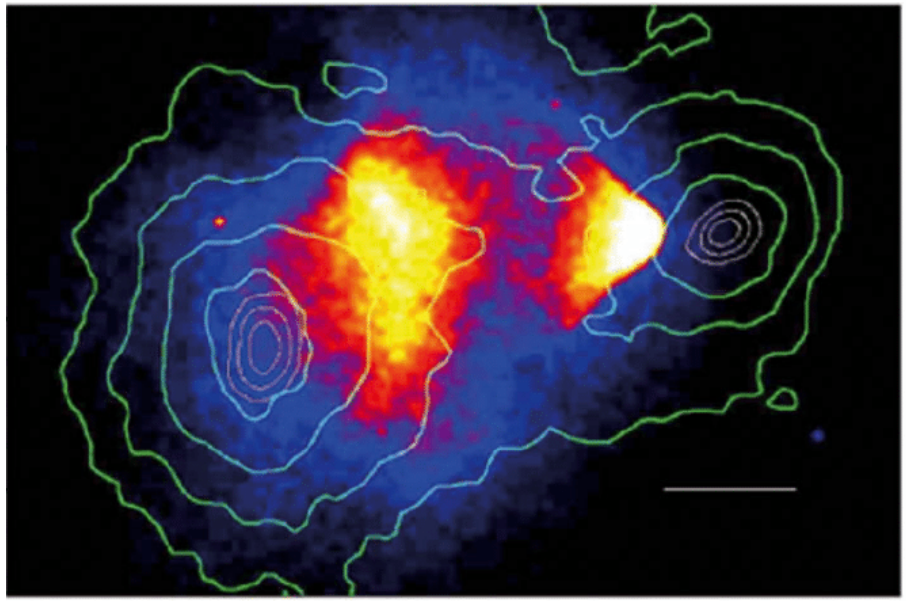
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22.10.2026

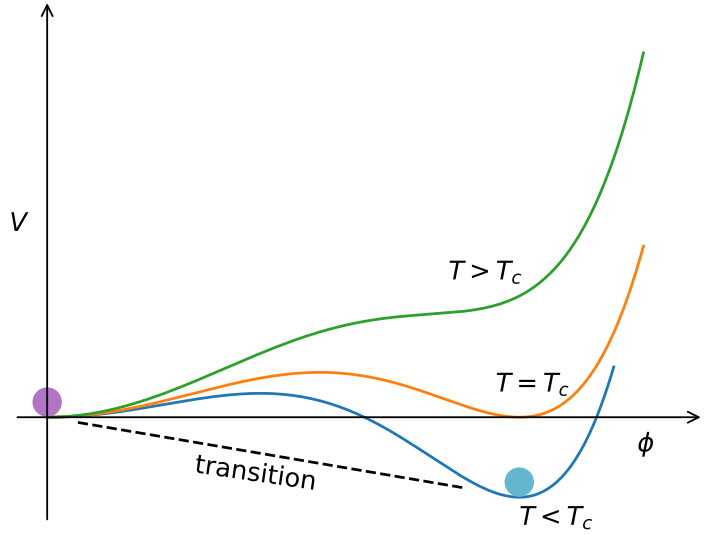
Motivation

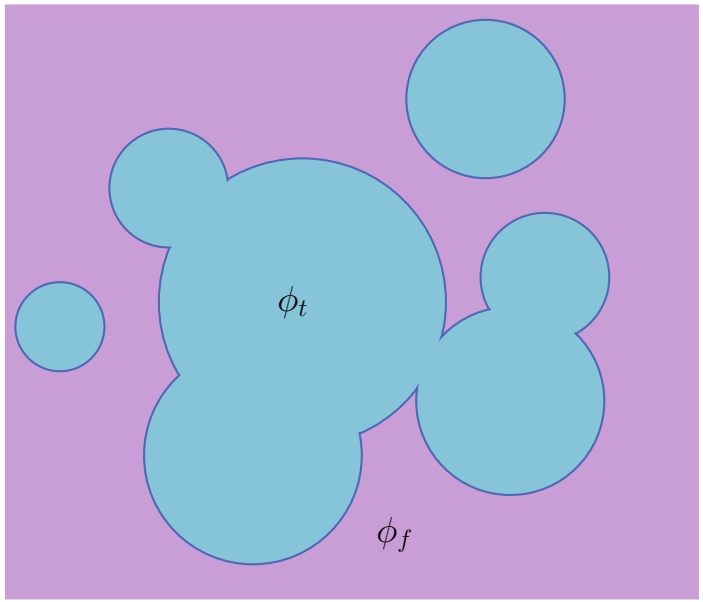
- Dark matter produced by thermal decoupling in the early universe
- Phase transitions in the early universe
  - Could affect DM freeze-out
  - Primordial gravitational waves as indirect probes for DM
- Filtered DM
  - Enables a large range of possible DM masses



Early universe 1st order phase transitions

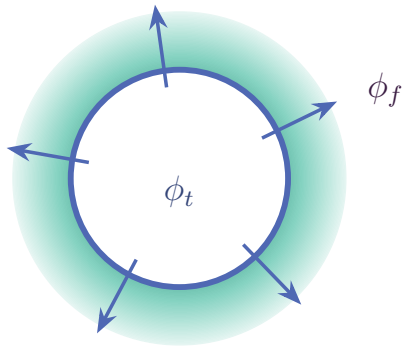
- Symmetry breaking transformations in the early universe
  - GUT, electroweak, QCD, dark sector...
- Detectable (or constrained) by gravitational waves
- Universe cools down
- Phases separated by a potential barrier
- Bubbles nucleate, then expand and collide with each other

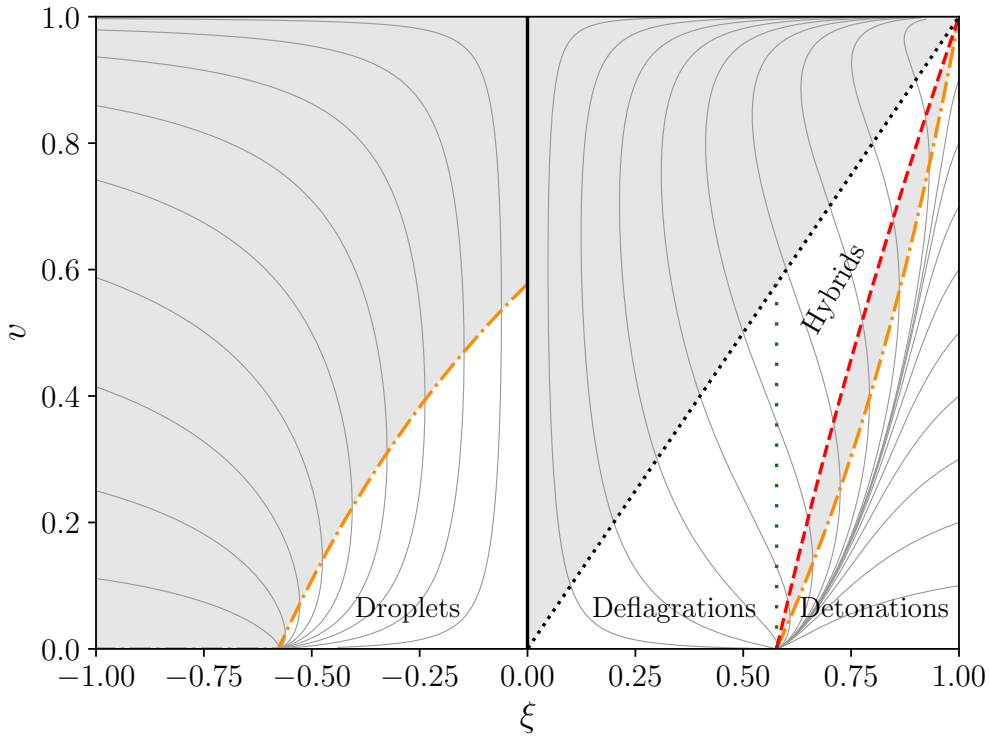




Bubbles in plasma - Deflagrations

- Friction from fluid slows the expansion
- Terminal wall velocity
- Long living droplets of symmetric phase





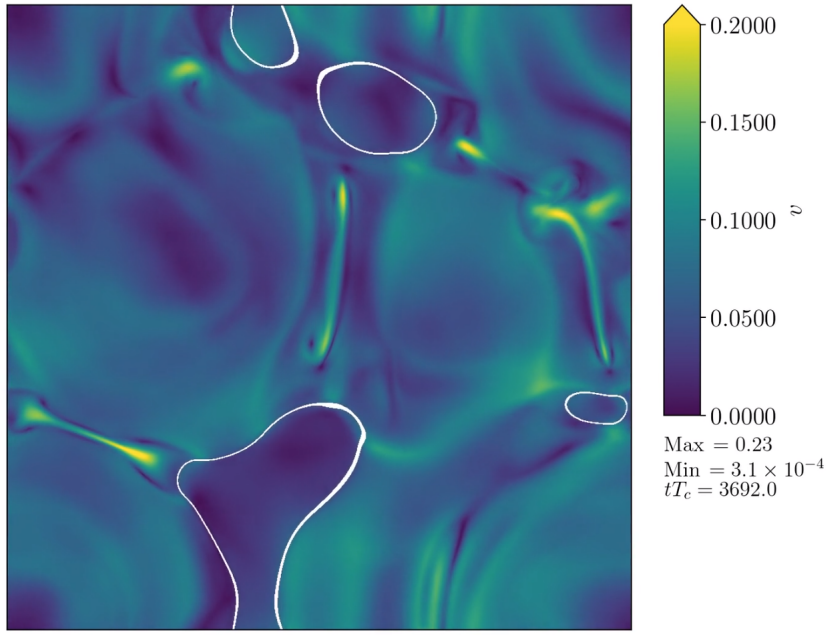
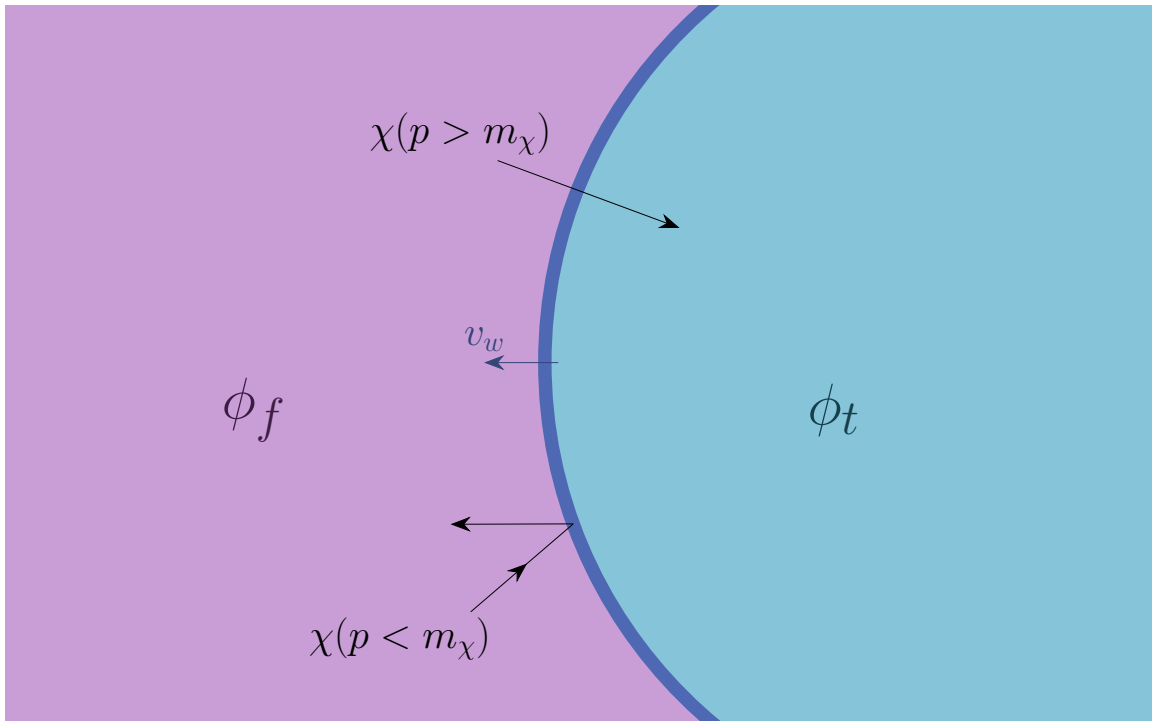


Figure: Simulation by D. Cutting

Filtered dark matter

ref. Baker, Kopp & Long, 2020

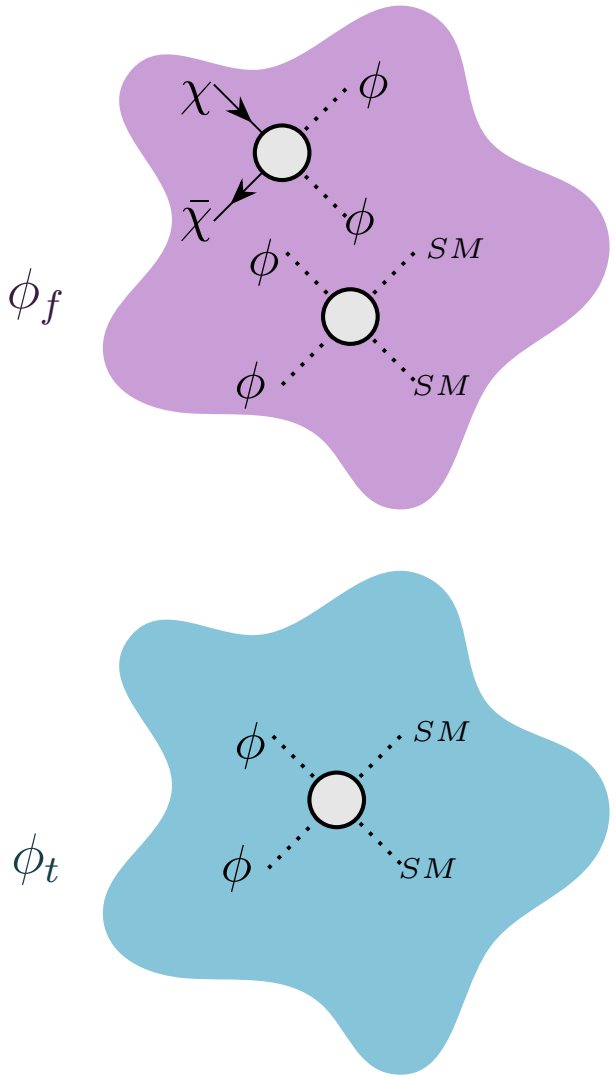
- Freeze-out brought about by 1st order phase transition
- Dark matter particles become massive when entering a bubble
- Some DM particles enter the bubble, others are reflected
- In the broken phase DM particles effectively stop interacting
  - Abundance frozen to the value of entered particles



Example model

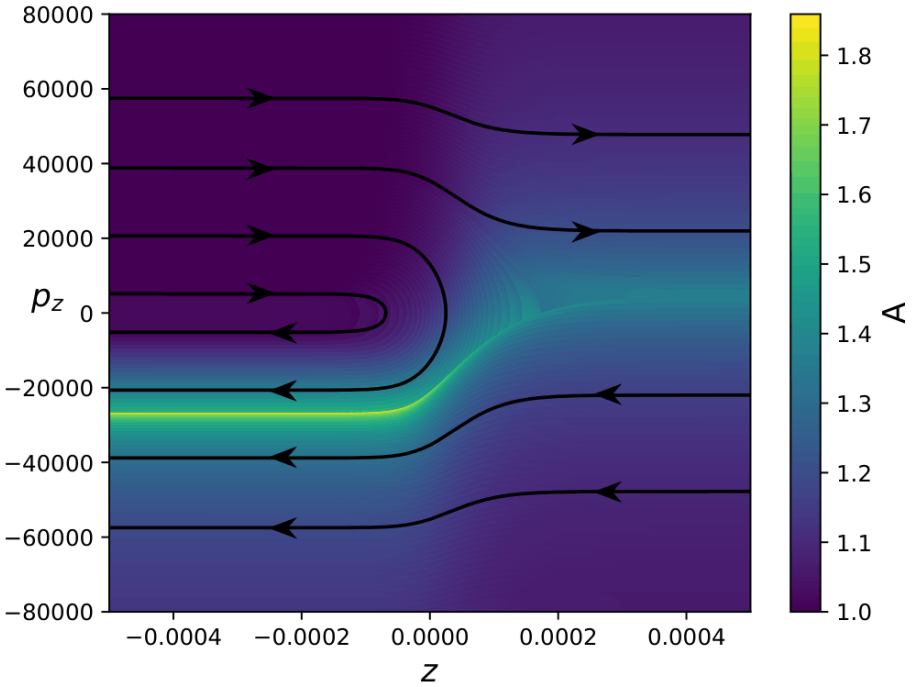
- Add to the standard model a scalar field ϕ and Dirac fermion χ, which is the dark matter
- Lagrangian containing $-y\phi\chi\bar{\chi} - V(\phi) - \mathcal{L}[\phi, \mathrm{SM}]$
- Potential $V(\phi)$ enables a 1st order phase transition
  Approximate the bubble wall

  and the DM mass as *tanh*
- Effect can be extended to other models



Methods

- Cross section calculations
- Boltzmann equation $\int \frac{dp_x dp_y}{(2\pi)^2} L[f_\chi] = \int \frac{dp_x dp_y}{(2\pi)^2} C[f_\chi]$ with L being the Liouville term and C containing the collision terms
- Ansatz $f_\chi = A(z,p) f_{eq}$
- Find DM relic abundance depending on dark matter mass, temperature, velocity of the plasma entering the bubble etc.



Droplet wall velocity

- In the expansion stage the plasma velocity in the wall frame is v_+
- We assume that as long as the friction remains constant, the plasma velocity is the same in the droplet stage as in the expansion stage
  - $v_{w,d} = v_{+,d} = v_{+,b}$
  - Matches simulations and theoretical values very well

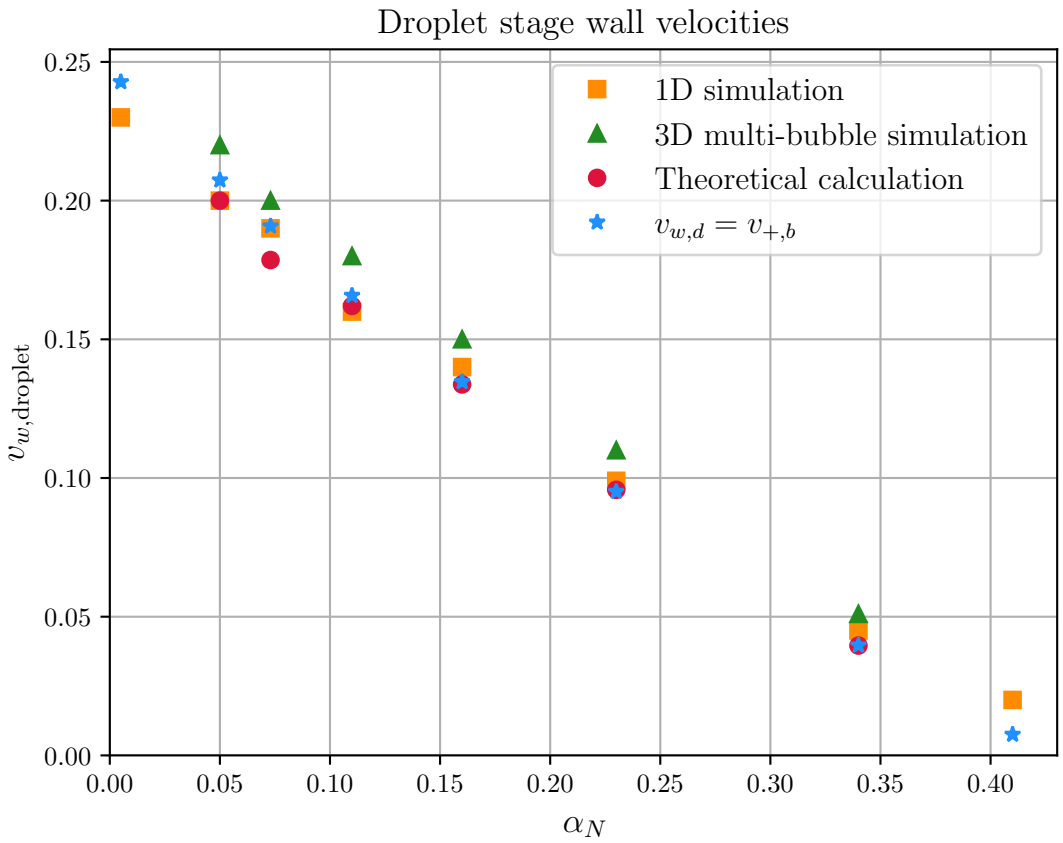
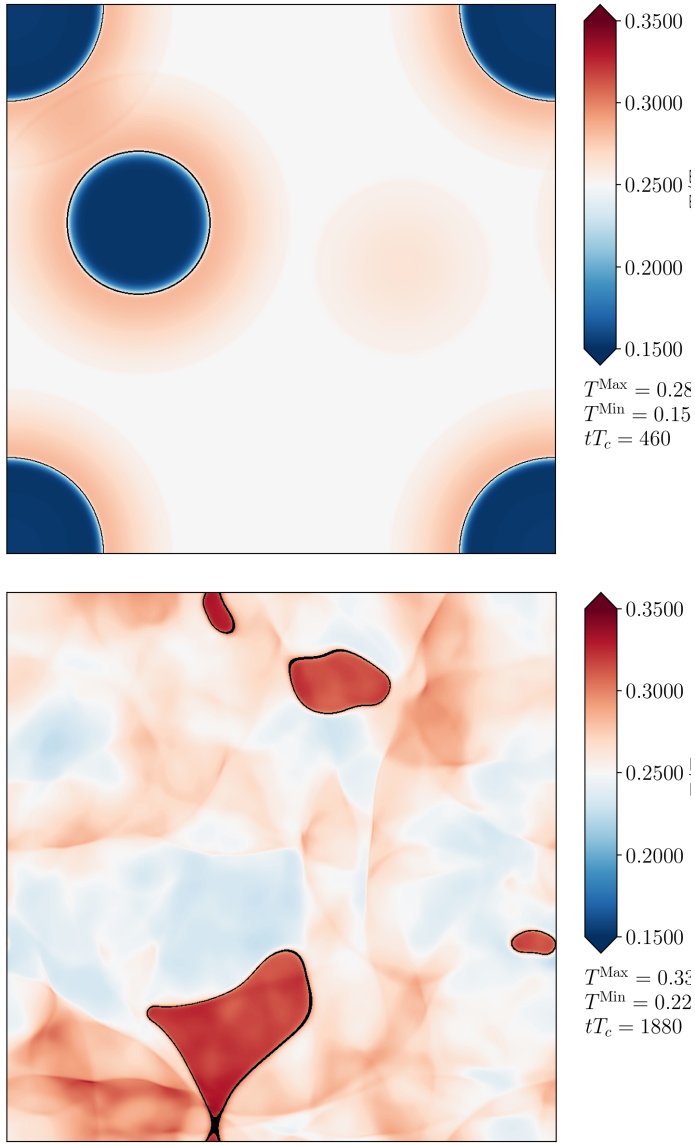


Figure: 1D simulation data from [2204.03396], 3D simulation data from [1906.00480], theoretical calculation data from [2603.223977]

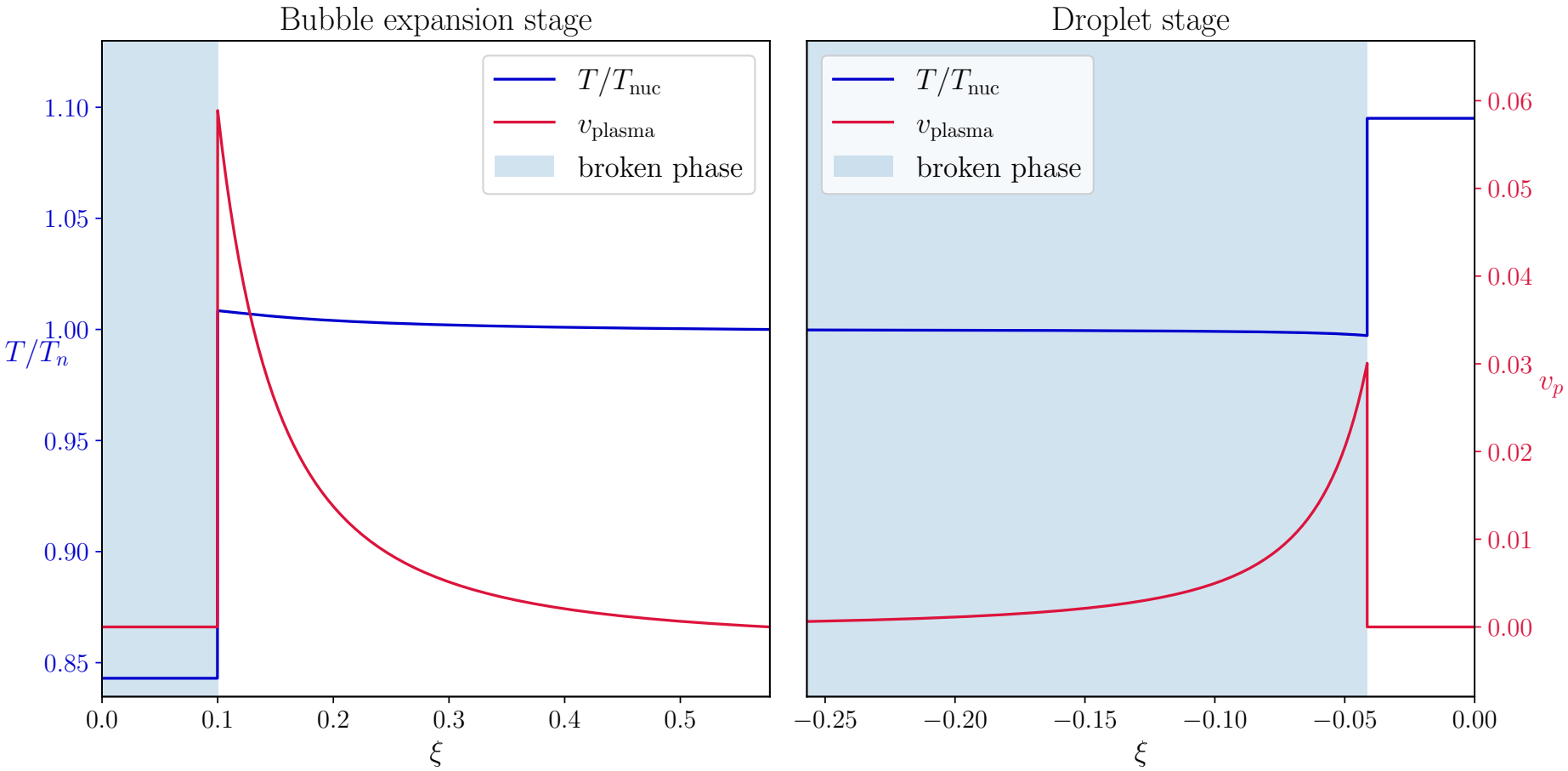
Droplet stage temperature

- Filtering is very sensitive to the temperatures in the system
- Need to set boundary condition for the temperature
  - Try to find and set T_b
- Previously
  - 2204.03396 used T_n motivated by simulations in 1906.00480
  - 2603.22397 calculated a T_0 with assuming that bubble reaches uniform temperature at droplet stage
- We choose $T_b = T_n$



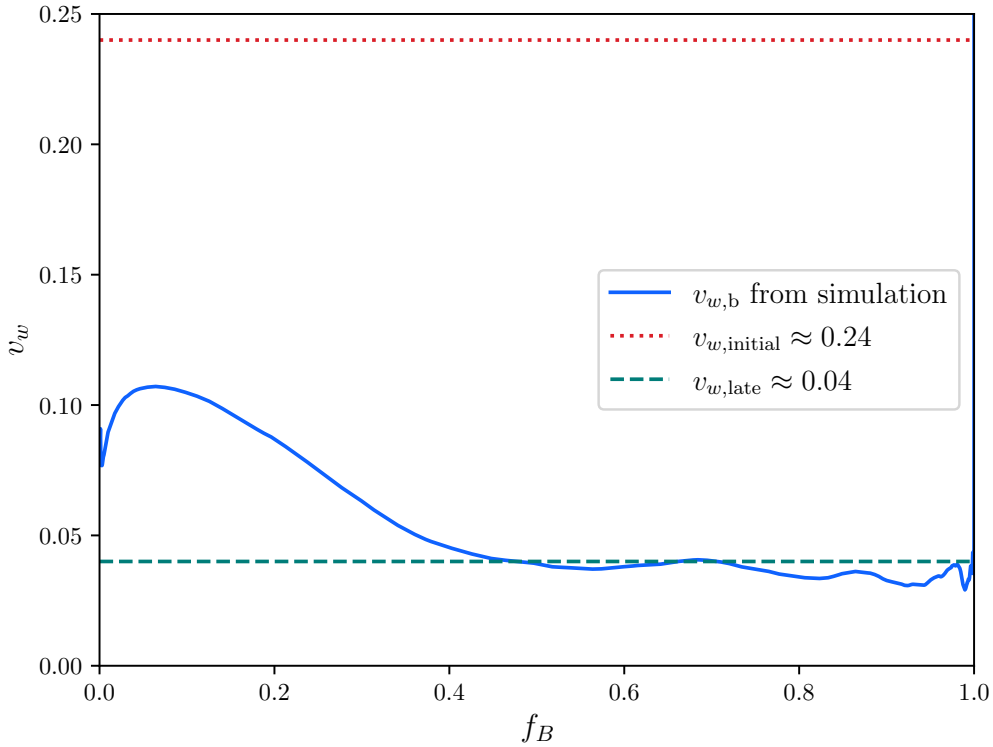
Expansion vs droplet stage

- Temperature and velocity profiles from PTtools
- DM production depends the temperatures just next to the phase border T_+ (symmetric phase) and T_- (broken phase)

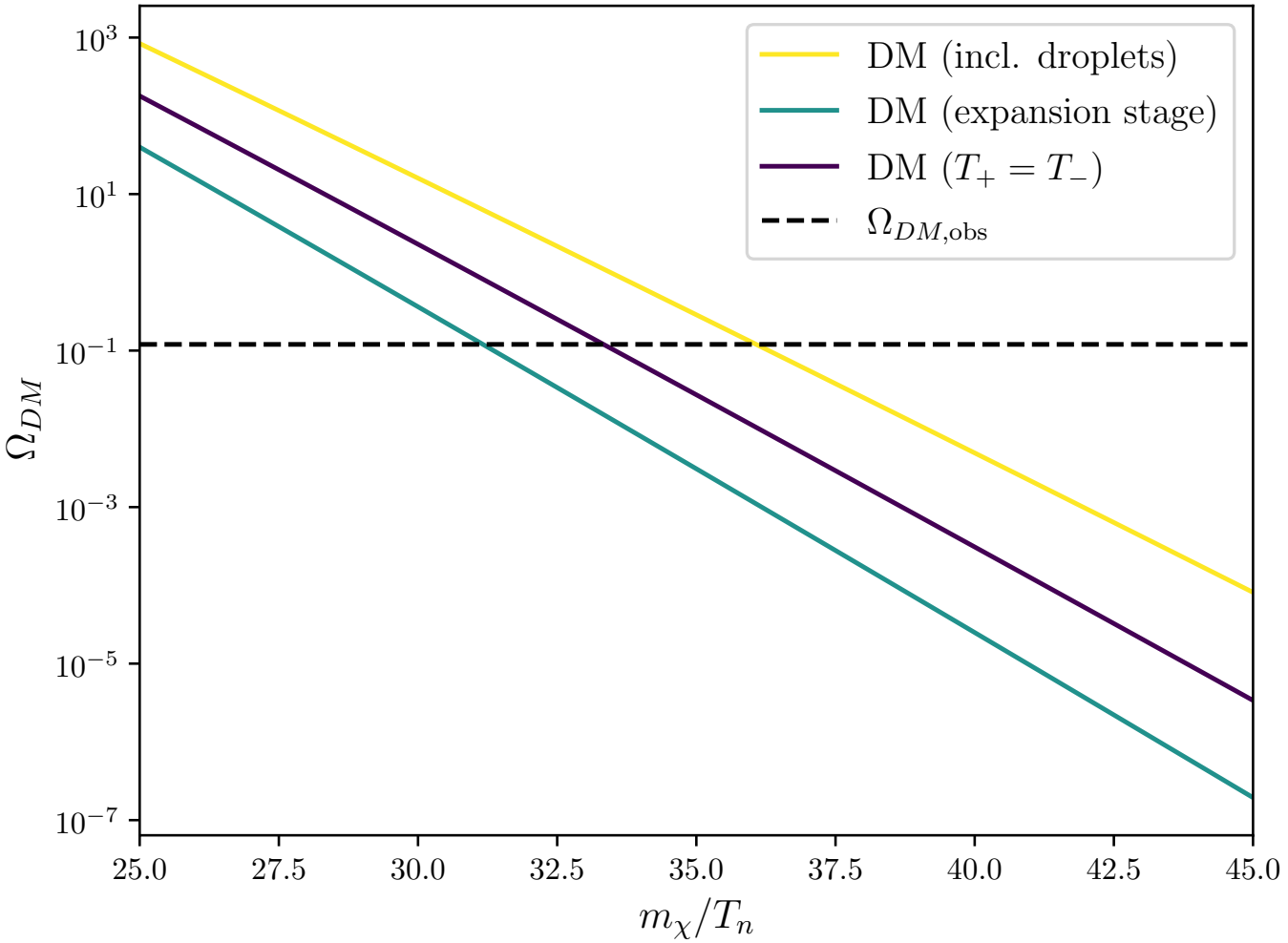


Total DM abundance from different stages

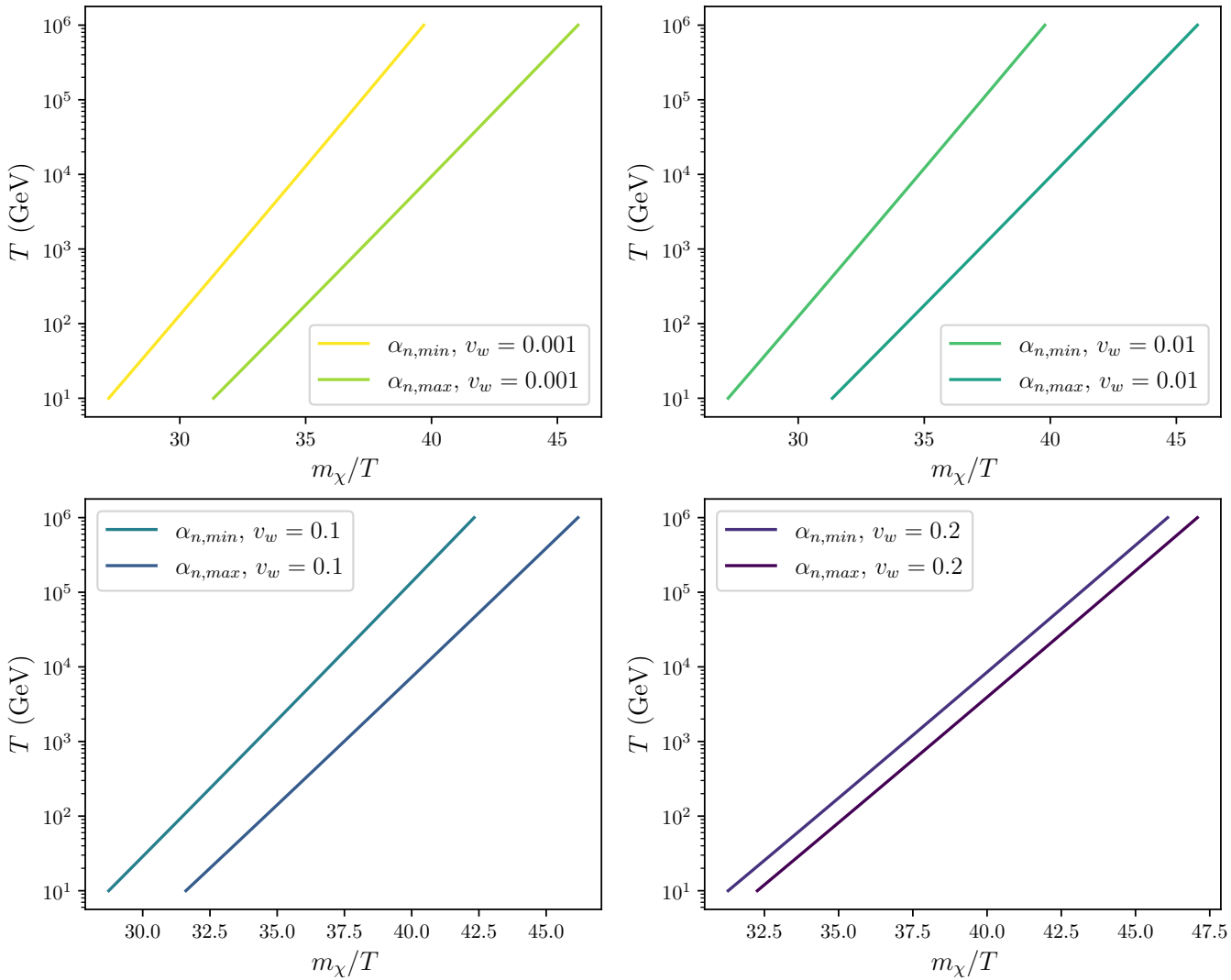
- We approximate the wall velocity as a step function
  - 50% of the universe experiences the low wall velocity
- Most DM produced at the droplet stage



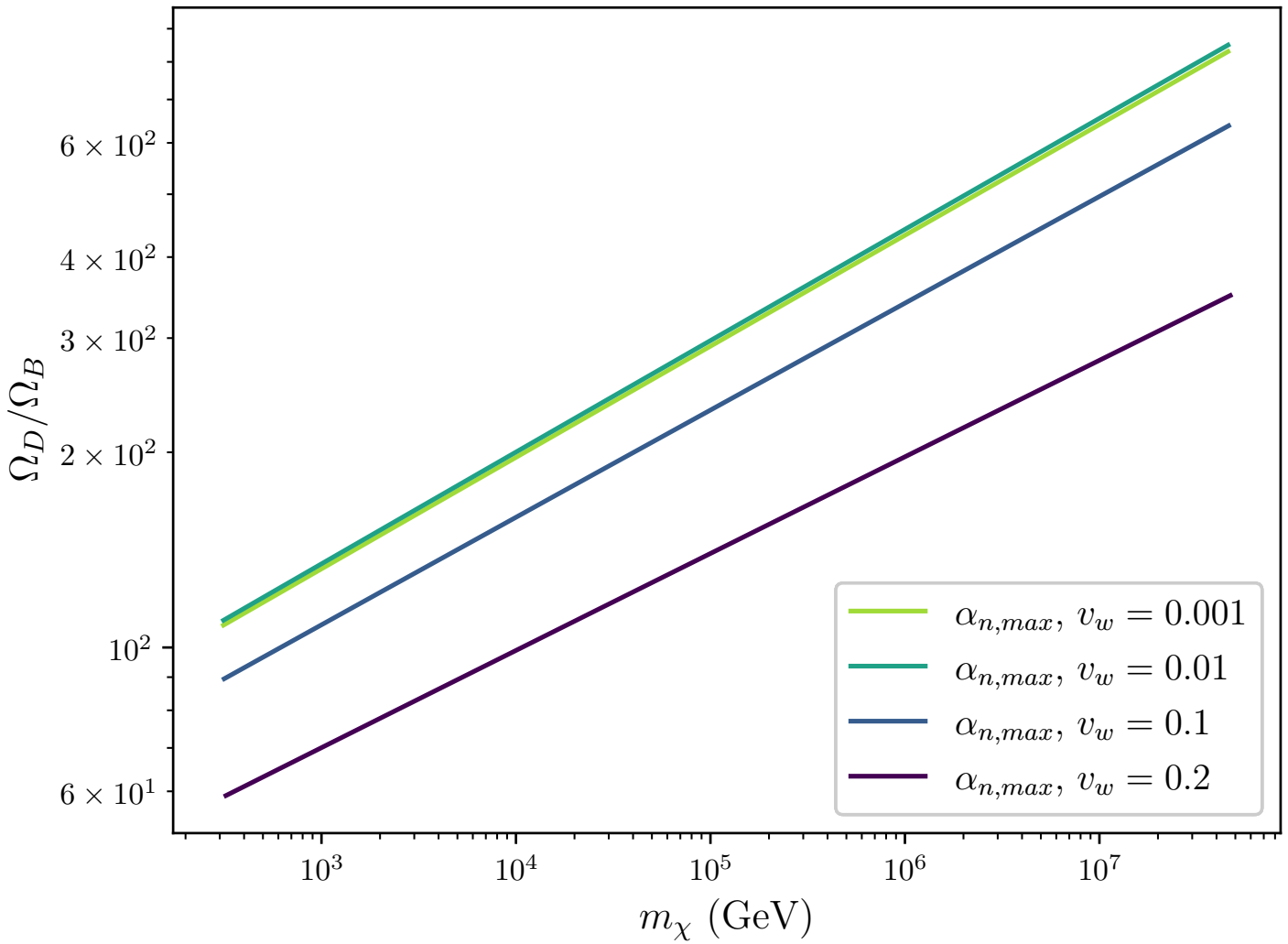
Produced DM


DM (incl. droplets)
DM (expansion stage)
DM ($T_+ = T_-$)
$\Omega_{DM,\mathrm{obs}}$
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
Ω_{DM}
25.0
27.5
30.0
32.5
35.0
37.5
40.0
42.5
45.0
m_χ/T_n

Scanning for the correct DM relic abundance

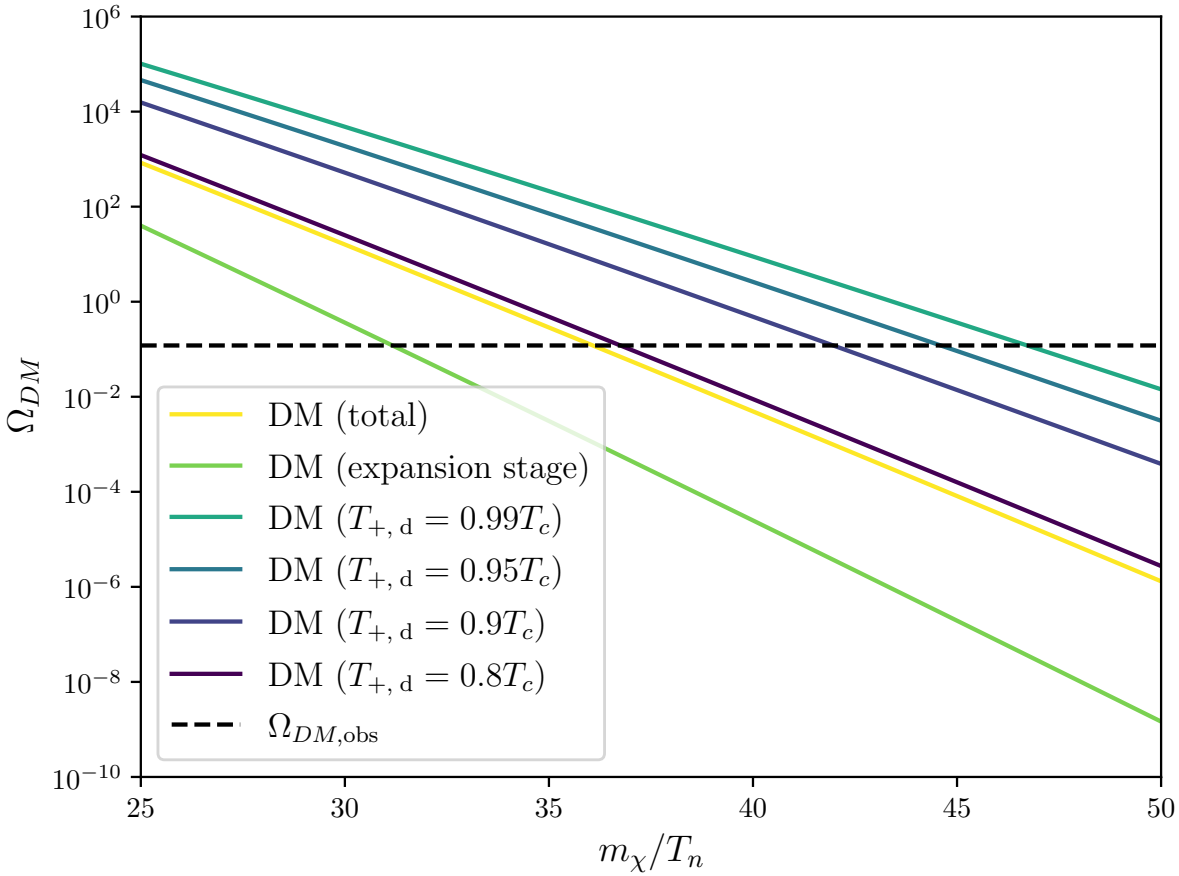


Difference between DM from droplet vs expansion stage



Effect of temperature fluctuations

- Due to the turbulence in the plasma some areas in the droplets may be more heated than others
- For example, the change $T_{+,d} = 0.9\,T_c$ corresponds to a 8% increase in temperature



Summary

- Phase transitions can affect the DM freeze-out via filtering
- For deflragration-type phase transitions we need to consider the early and late times separately
  - The wall velocity and the temperature profile are very important parameters
  - We can write the droplet stage wall velocity as $v_d = v_{+,b}$
- Although differences to the DM mass scales are small, taking the droplet stage into account can increase the total DM abundance
  - May result in isocurvature

Thank you!