Cannibal domination and small scale structure

arxiv:2008.04311 and to appear

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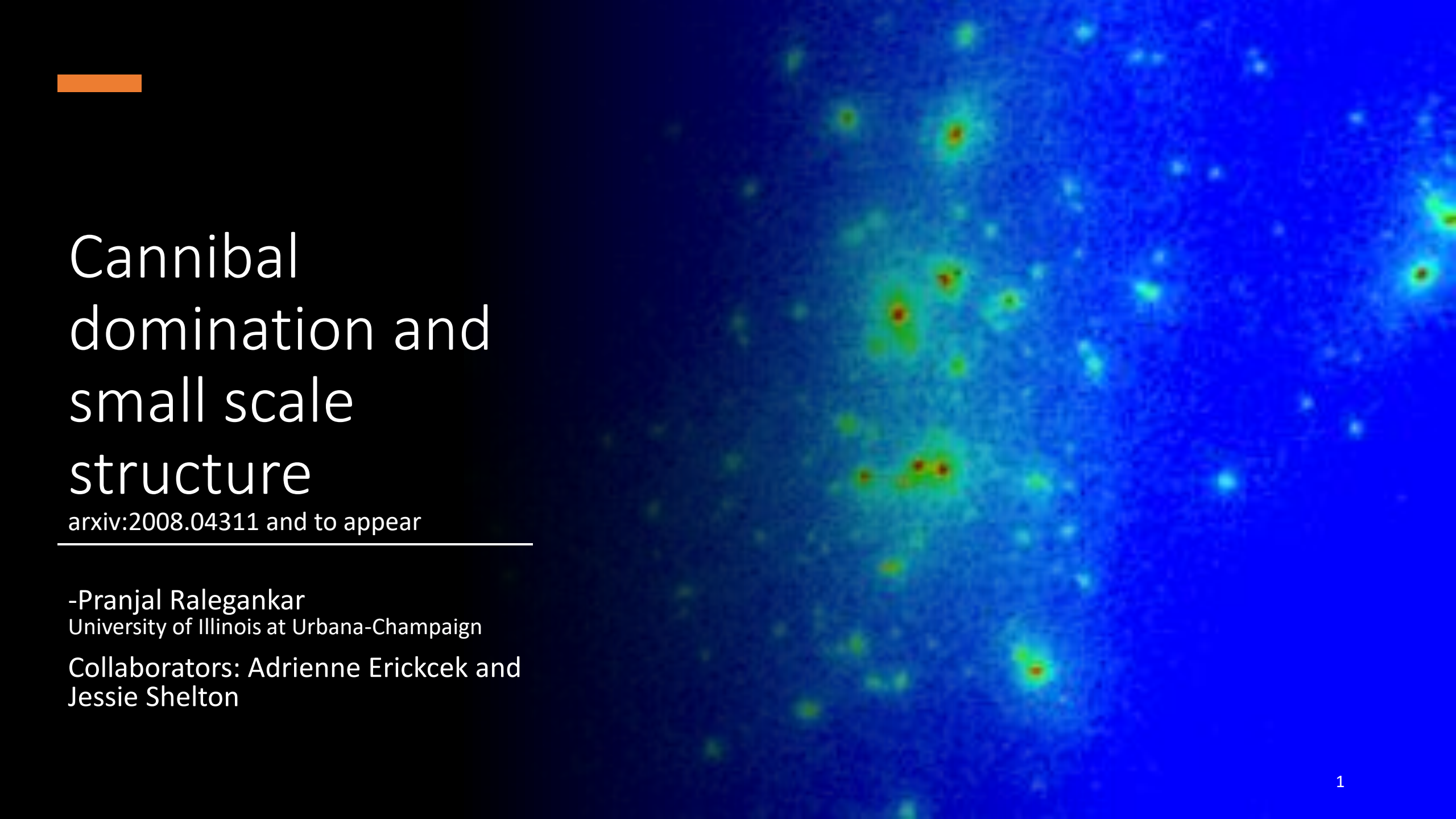
University of Illinois at Urbana-Champaign

Collaborators: Adrienne Erickcek and Jessie Shelton



Outline

- Motivation:
- Results
  - Background cosmology with cannibal domination
  - Impact on cosmological perturbations
  - Parameter space of interest
- Summary

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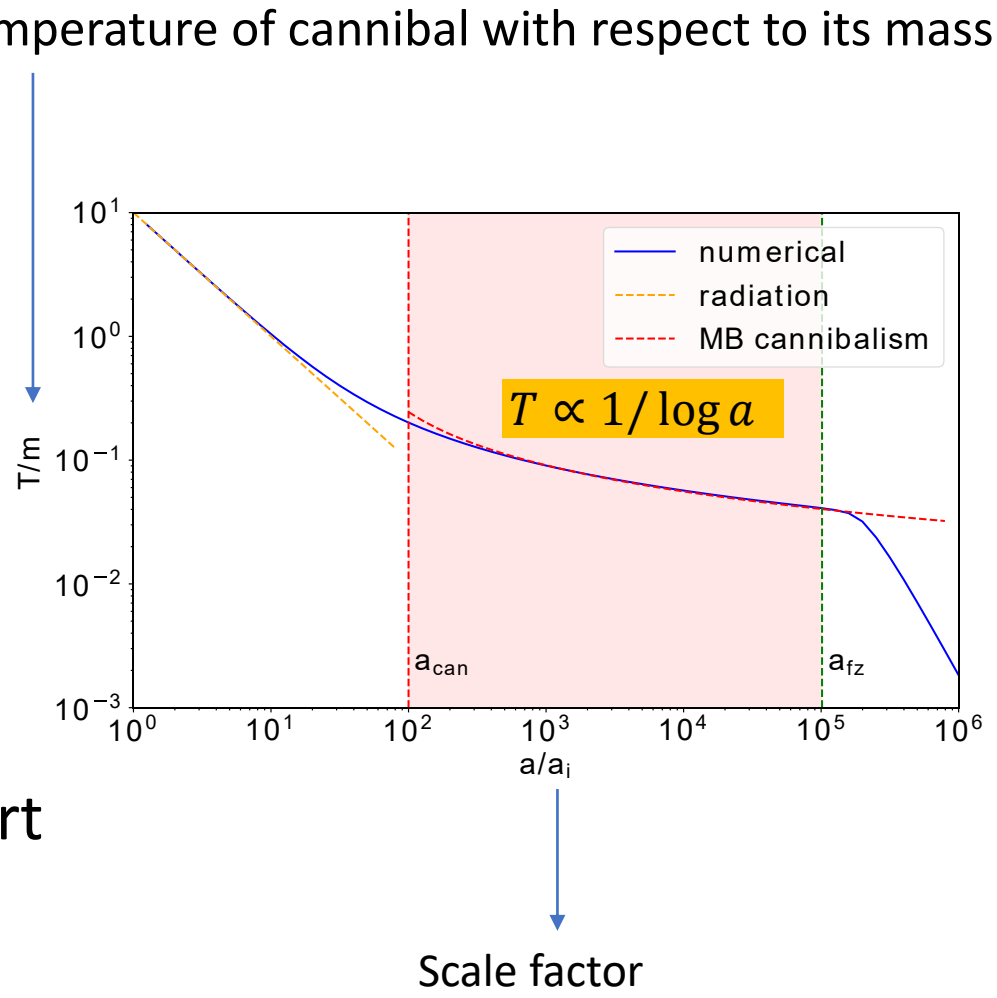

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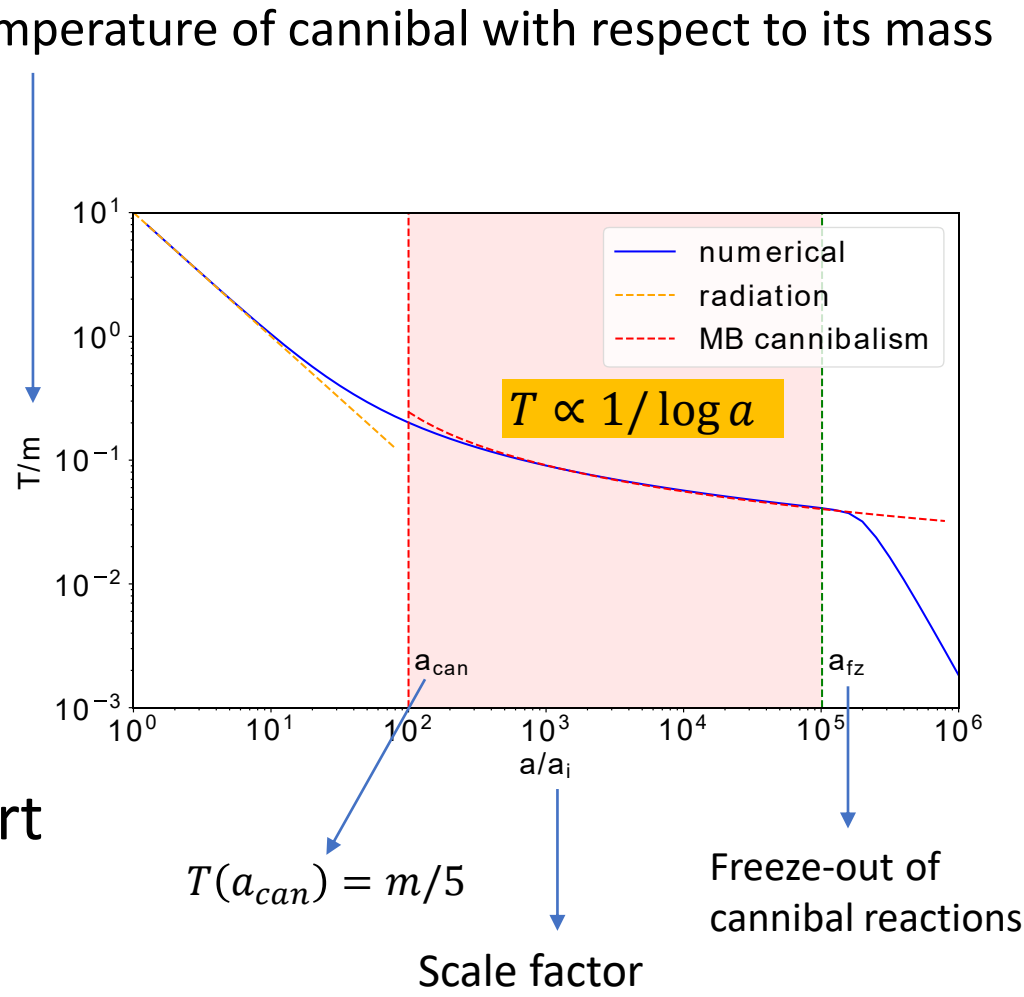

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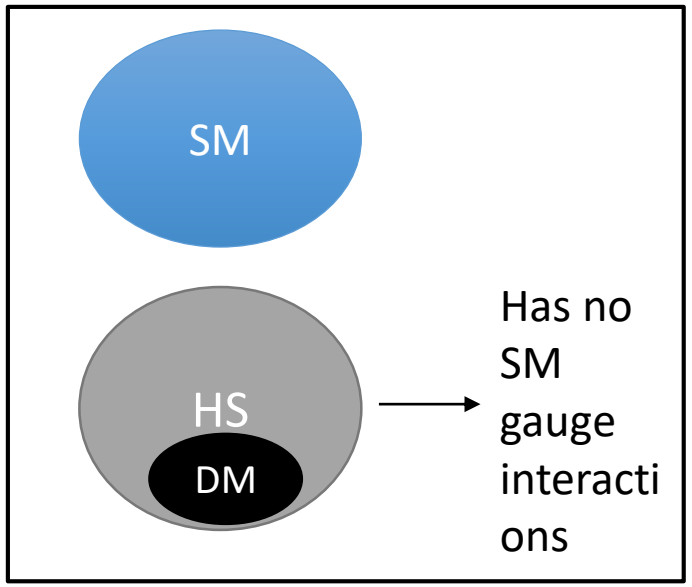
- Hidden sector (HS) theory are well motivated to explain dark matter (DM):



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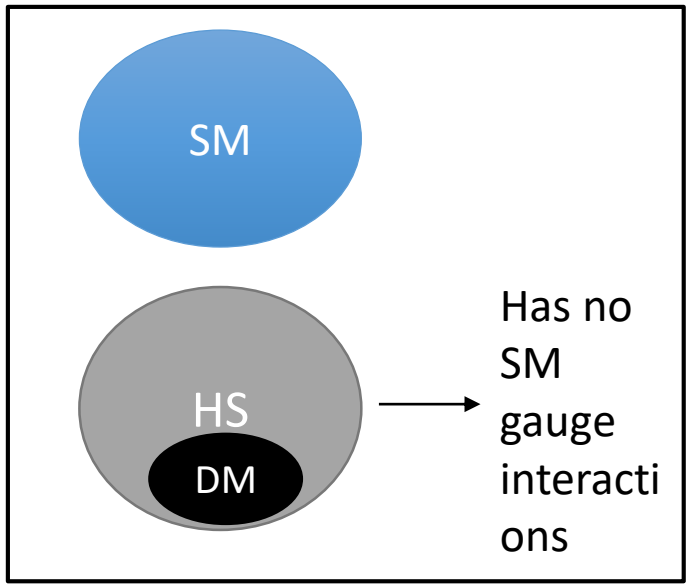
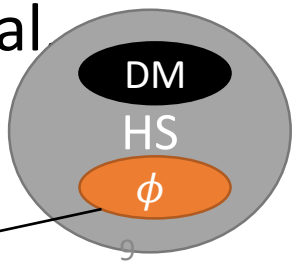


- The lightest particle in HS (not necessarily DM) can naturally be cannibal. Ex: glueballs, ϕ^4 scalar field, etc.



Arxiv: 1602.04219

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Early matter dominated era as cosmological probe of Hidden sector theories

- Hidden sector (HS) theories=> weak couplings with Standard Model => typically hard to probe in colliders.

- However, HS can be cosmologically probed through gravitational effect of lightest particle.
  - Can cause an ‘early matter dominated era’.
  - ‘Early matter dominated era’ can produce micro-halos of DM (arxiv:1106.0536)

What if HS leads to an early cannibal dominated era?

The questions we answer:

1. Link cannibal particle parameters with key matter power spectrum features

2. Estimate the kind of micro-halos produced using *linear theory*

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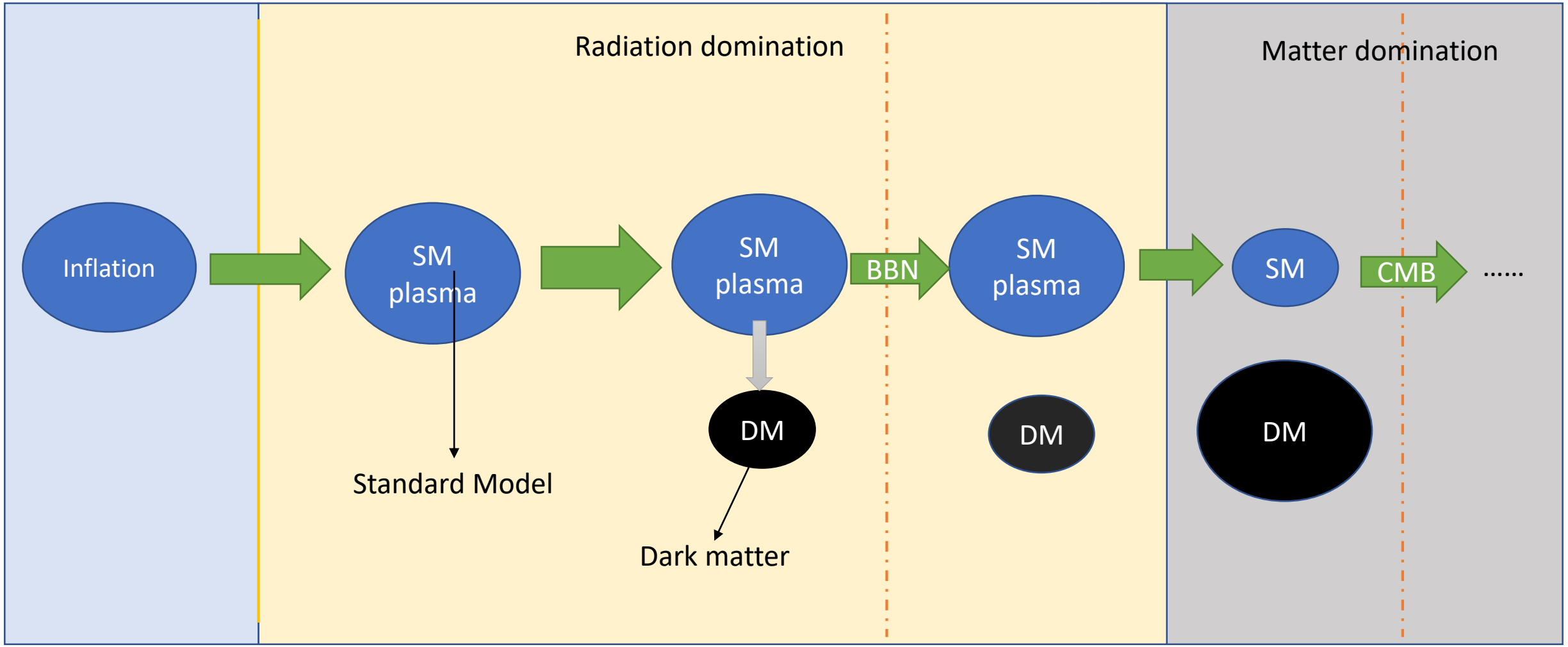
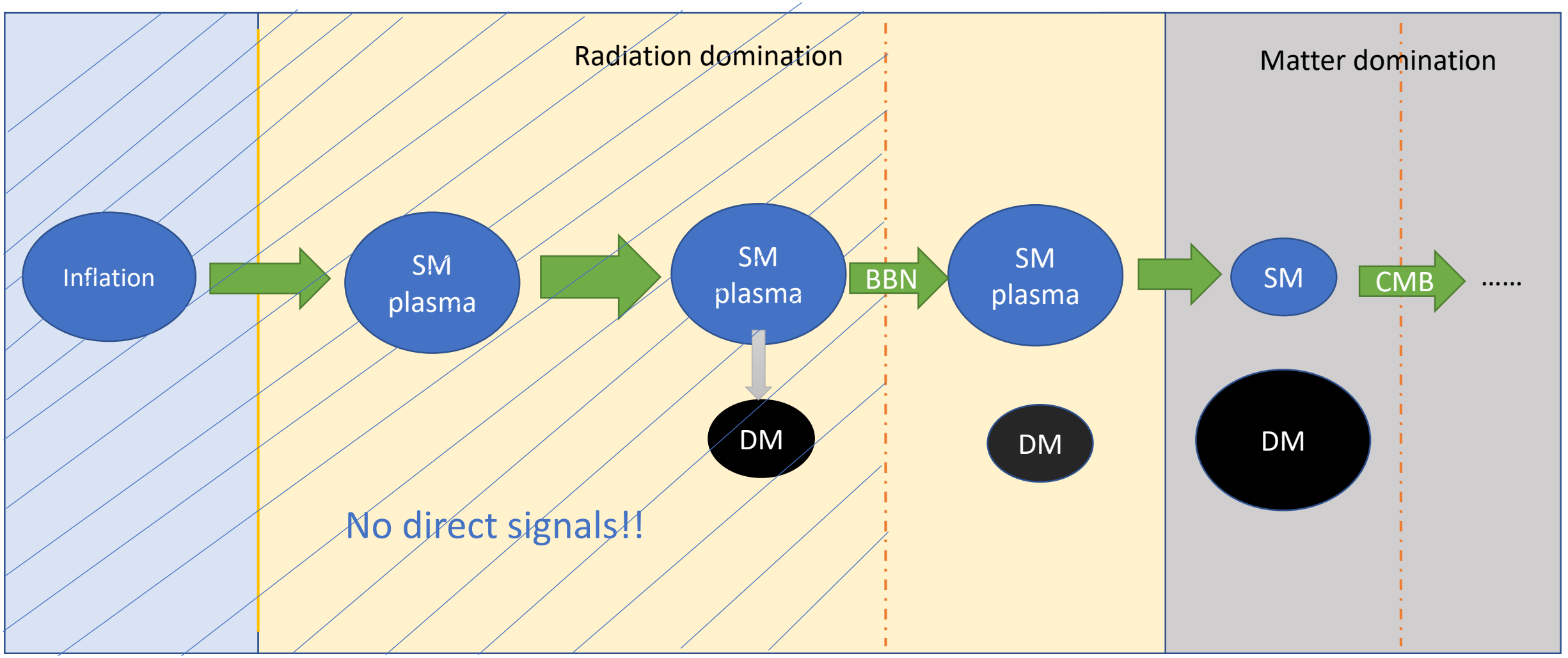
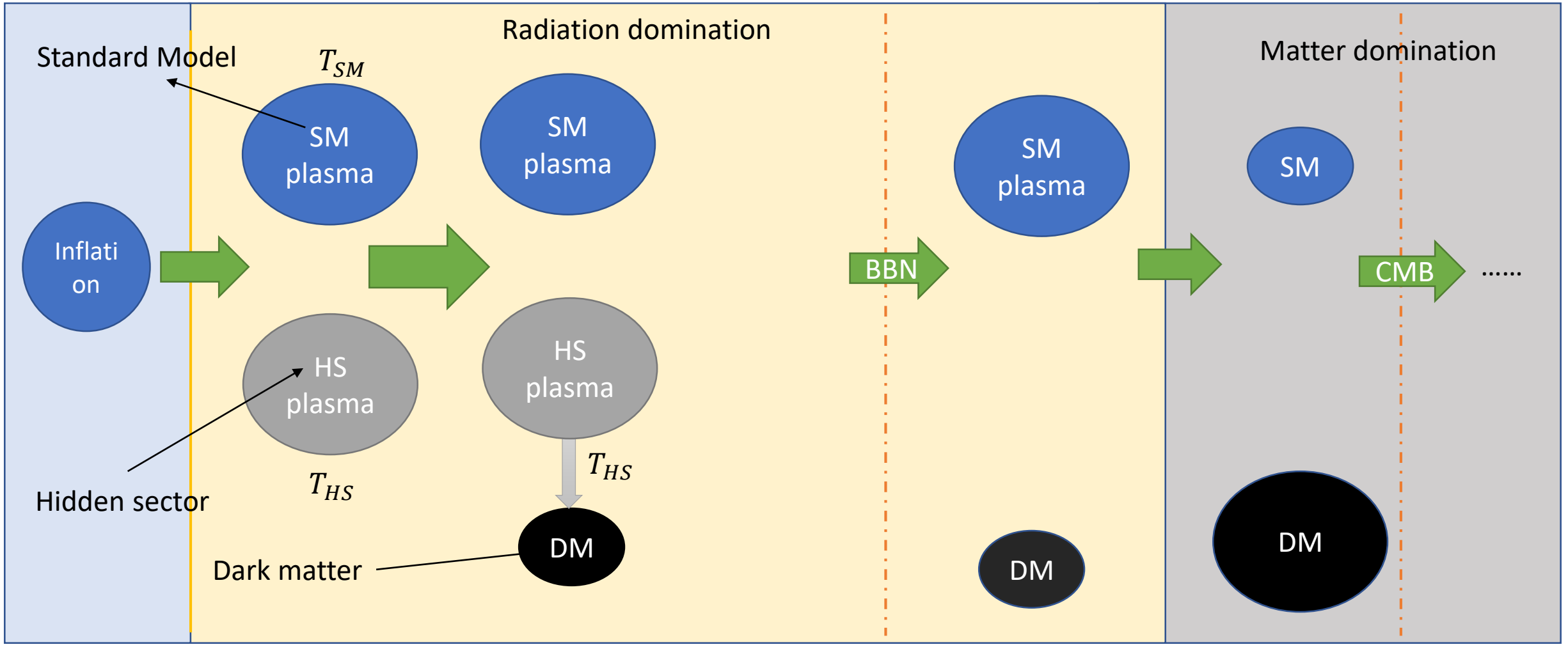
Vanilla ΛCDM cosmology



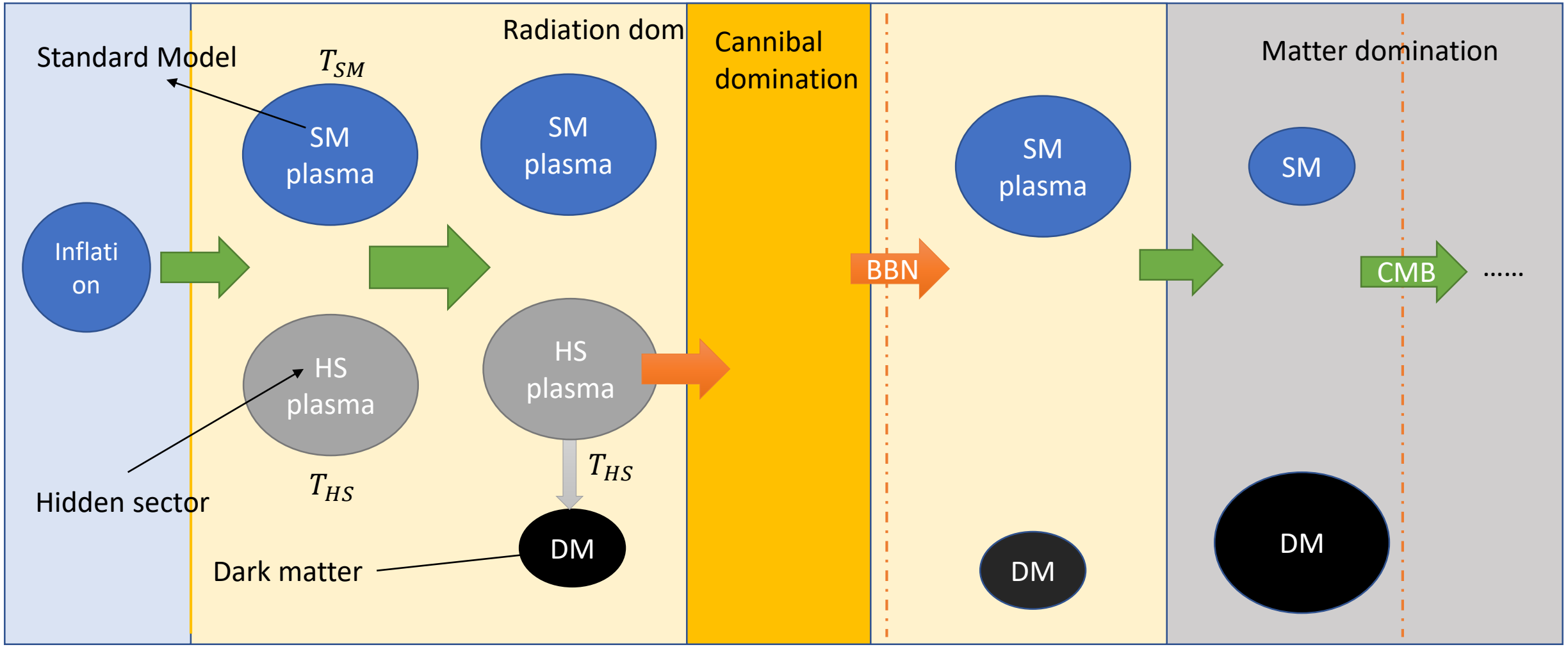
Anything can occur before BBN



Hidden sector cosmology



Hidden sector cosmology with cannibal domination



Cannibal can naturally cause an ‘early matter dominated era’

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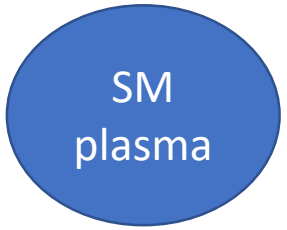
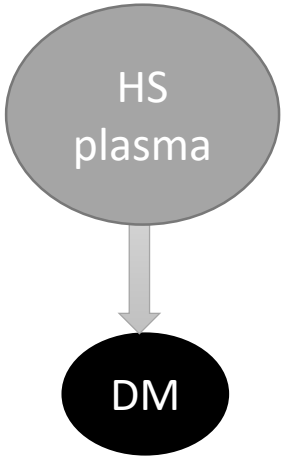
only lightest particle (cannibal) remains in the HS plasma





Standard cosmology

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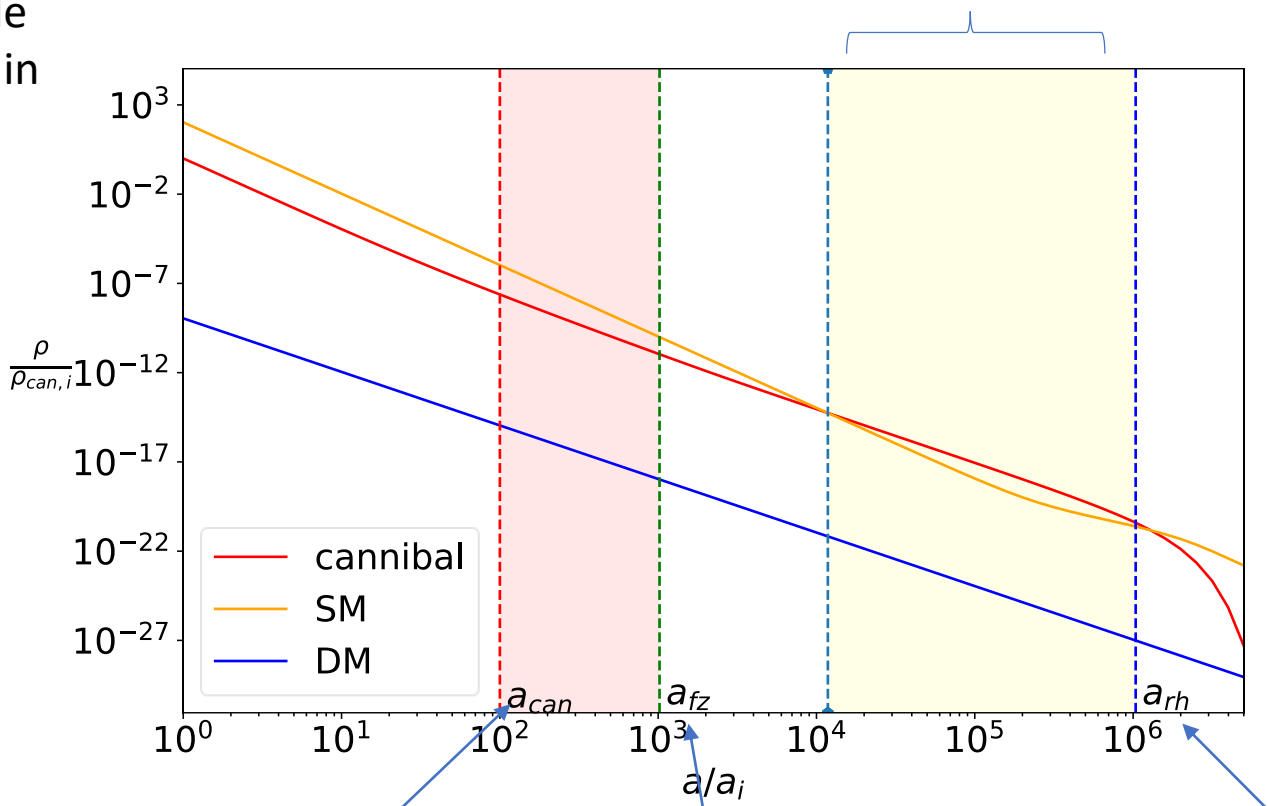
SM plasma

HS plasma

DM



BBN → Standard cosmology

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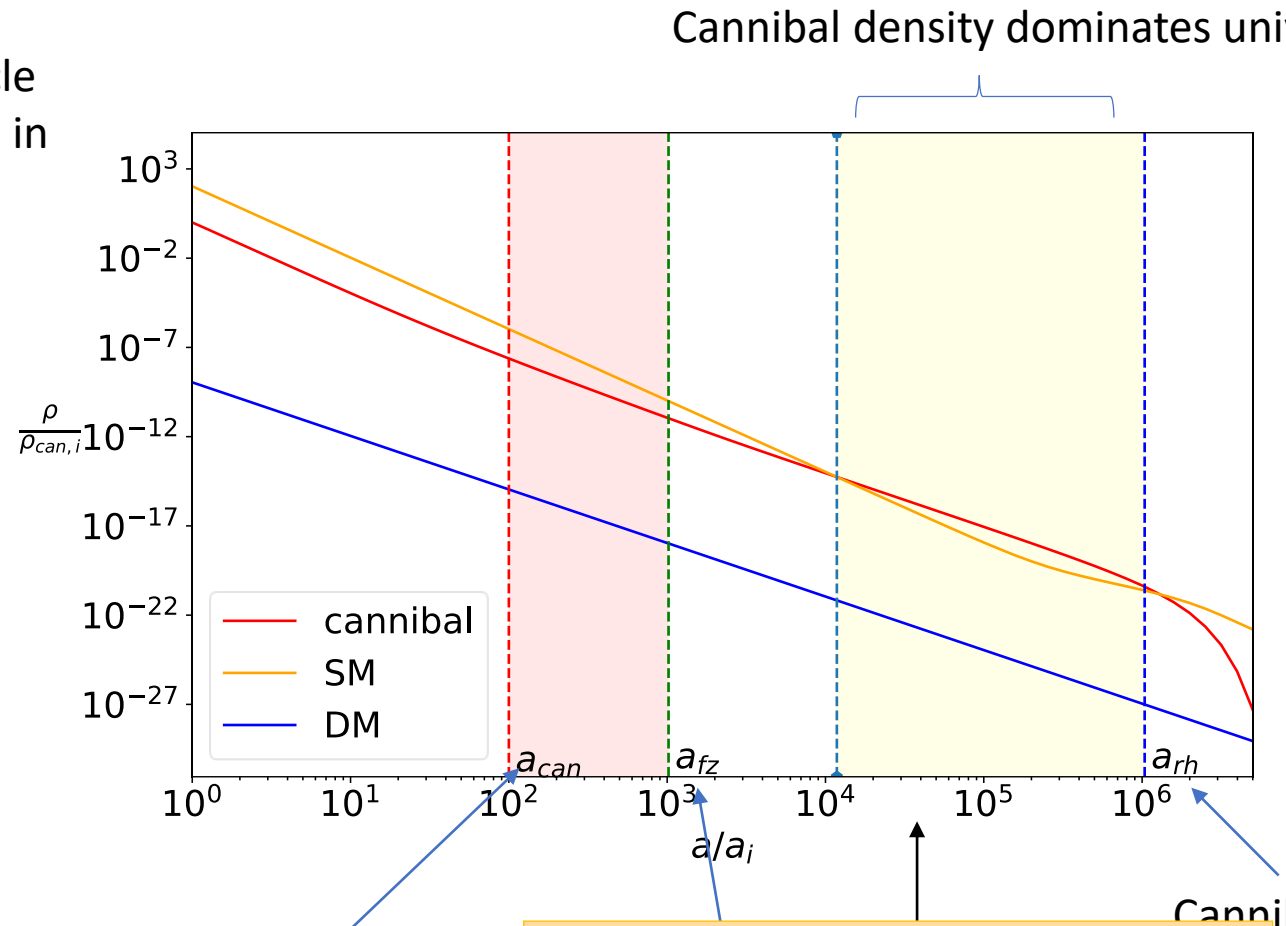
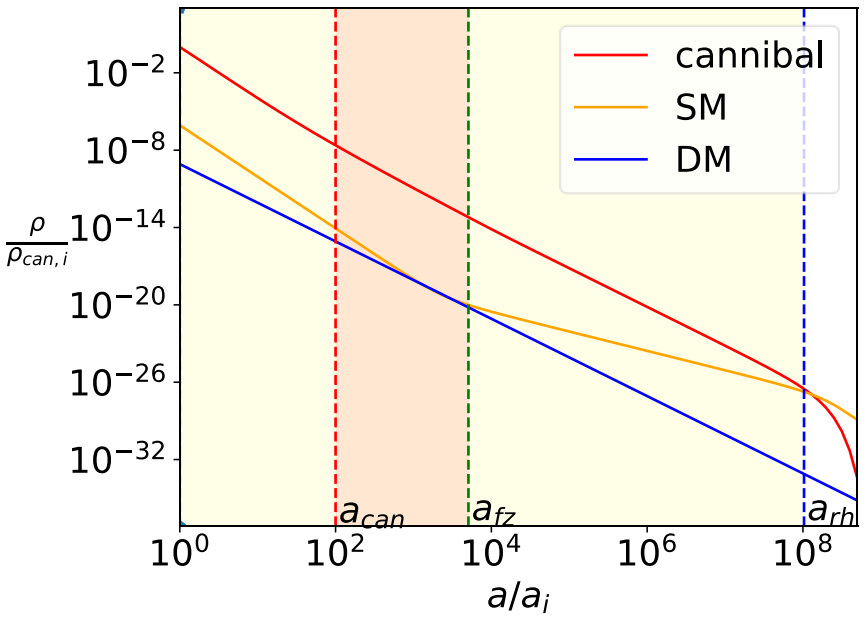


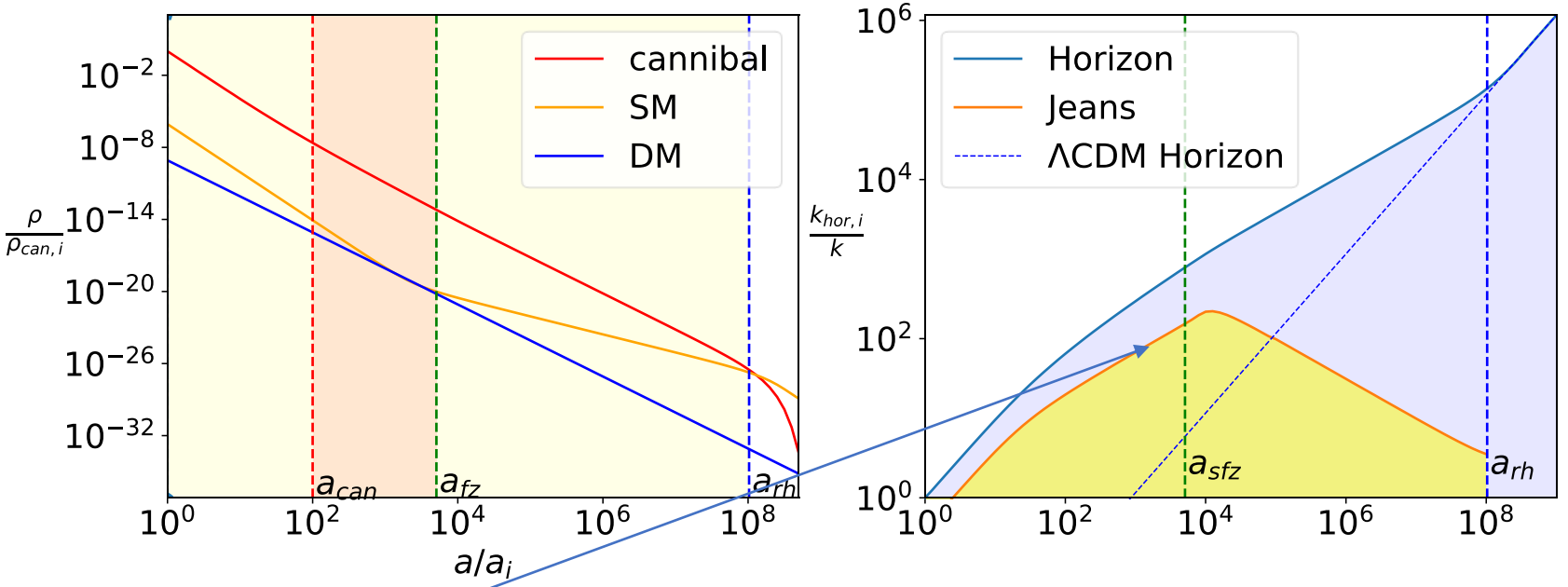
BBN

Standard cosmology

Perturbation evolution: Subdominant SM-energy density



Perturbation evolution: Cannibal Jeans length

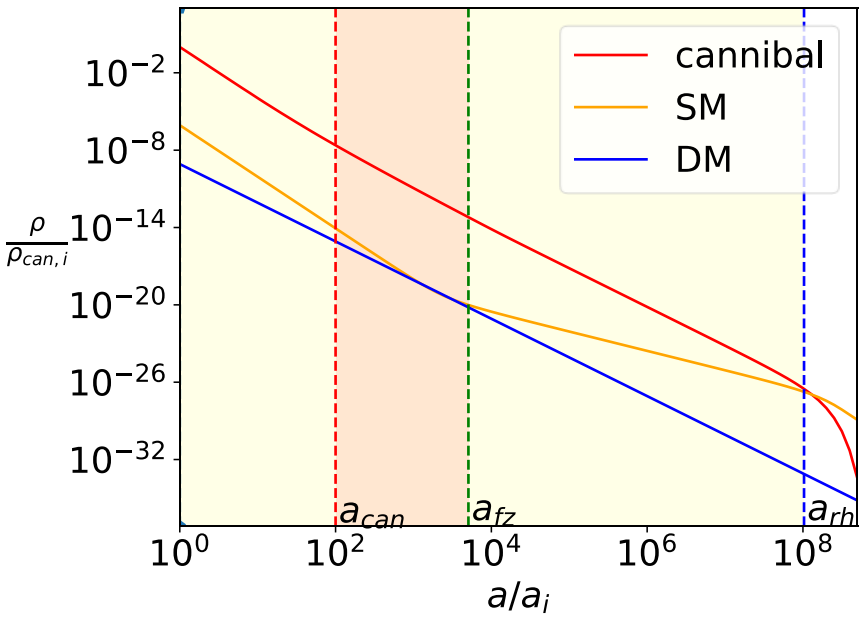


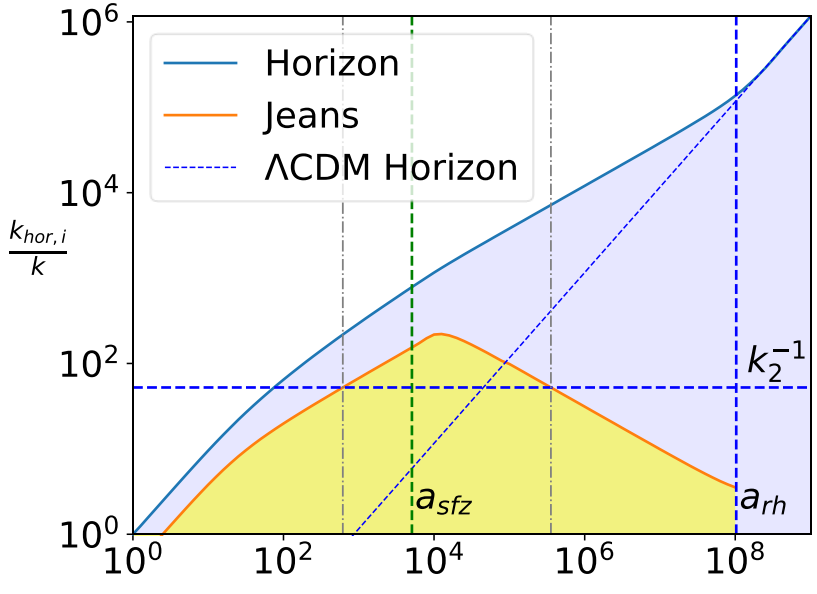
$$k_J^{-1} = \sqrt{\frac{2}{3(1+w_c)}}\frac{c_s}{aH}$$

Cannibal sound speed

Cannibal equation of state

Perturbation evolution: Oscillations within Jeans length





δ_c: Cannibal density perturbations

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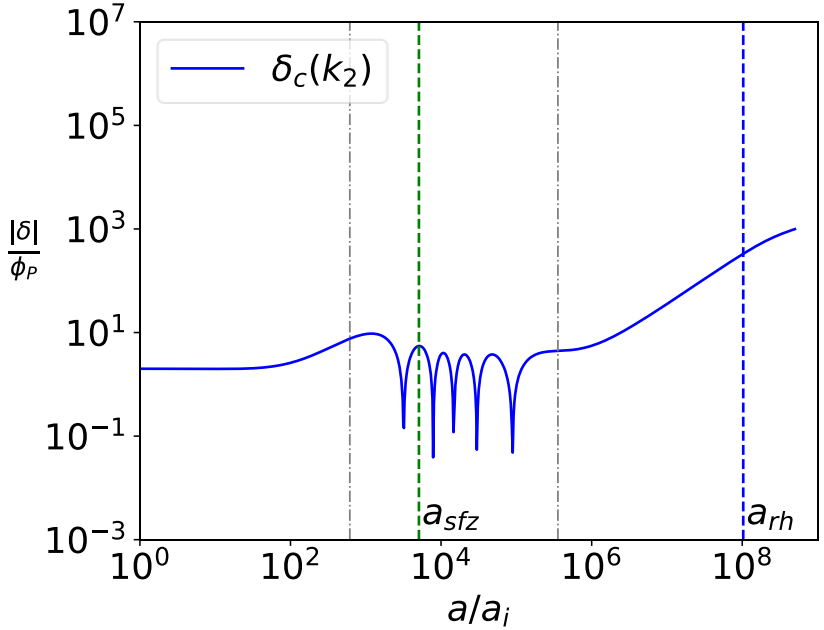

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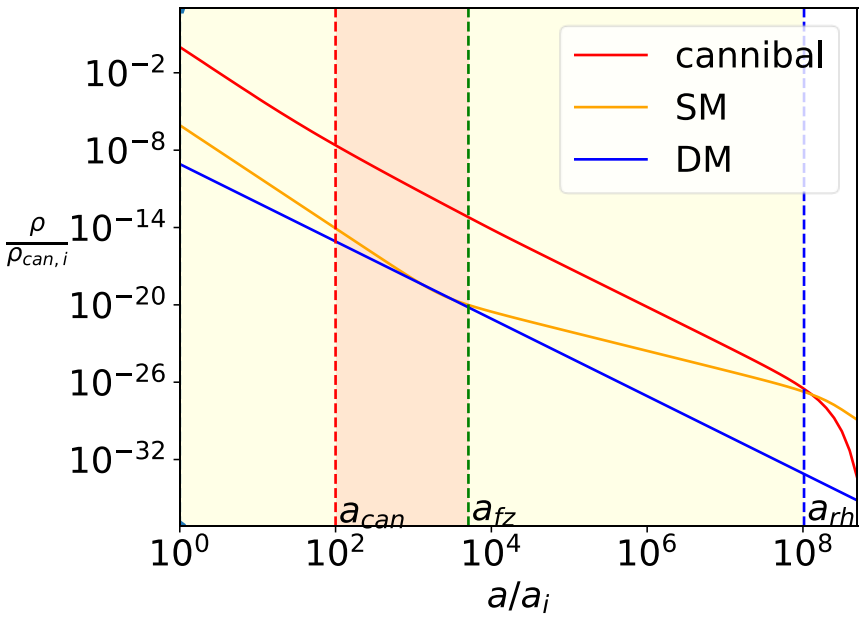

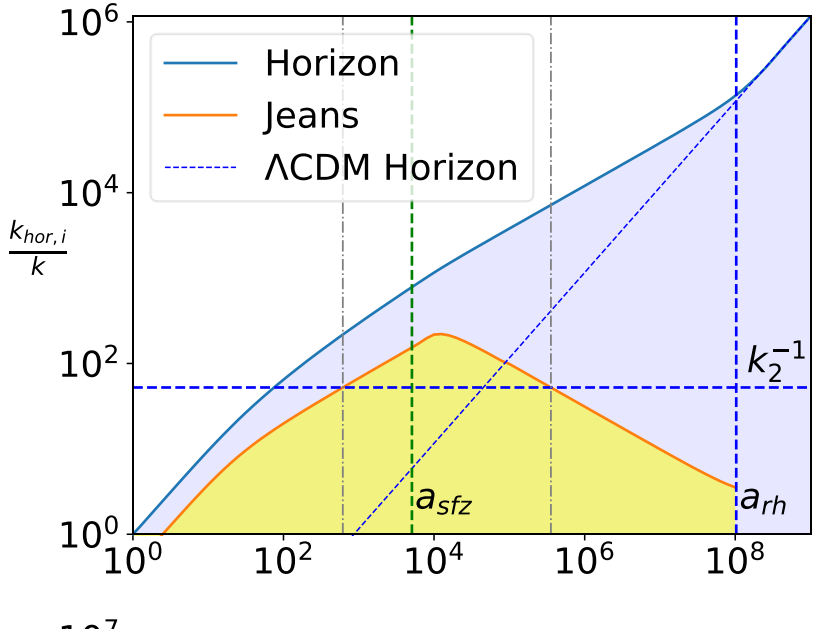

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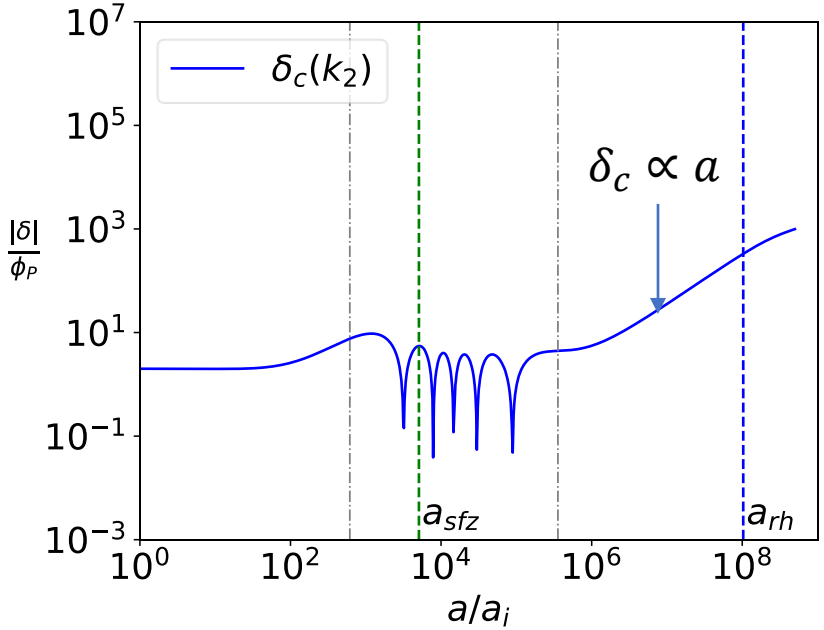
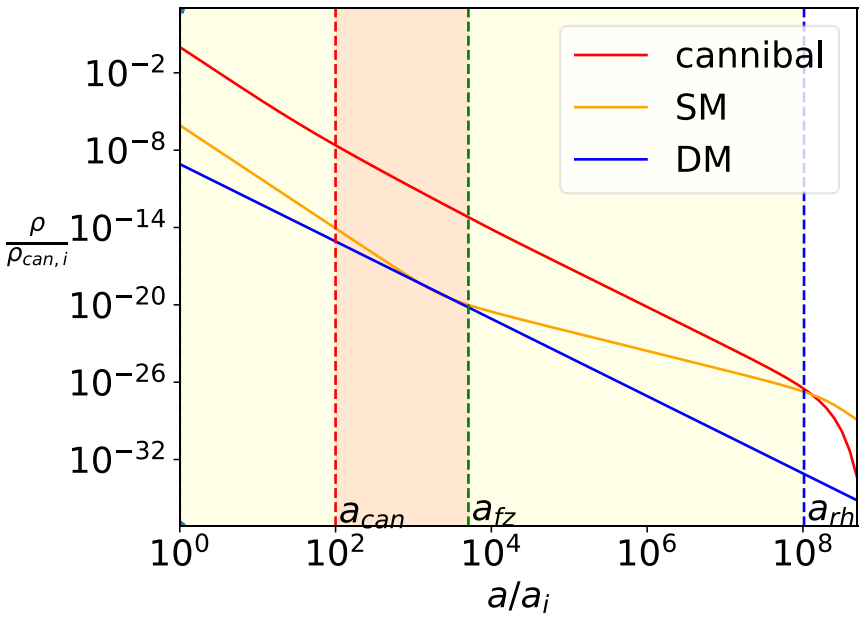
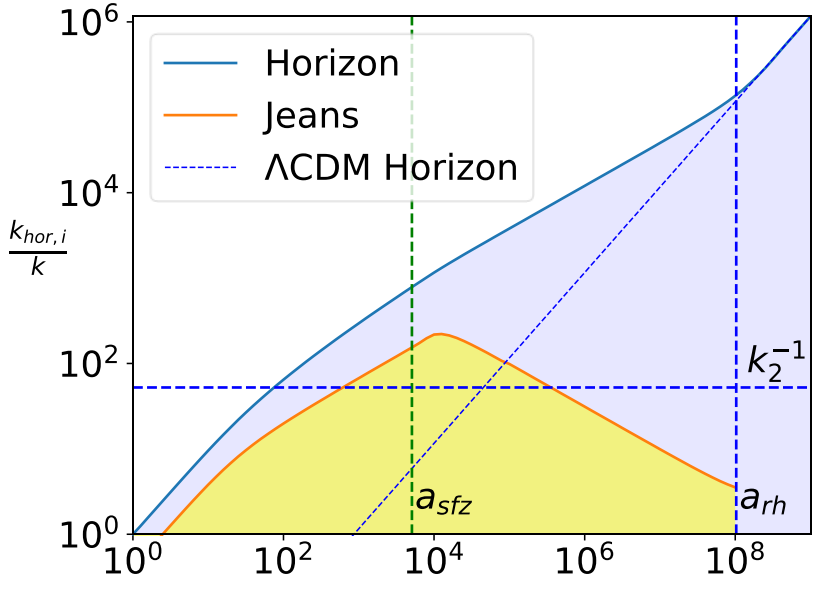


Perturbation evolution: DM falls into cannibal gravitational well





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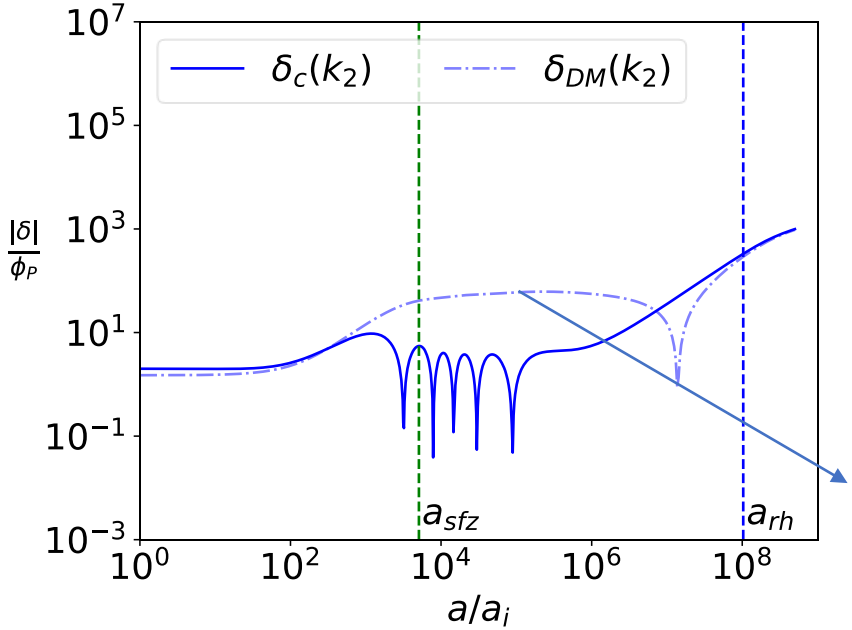
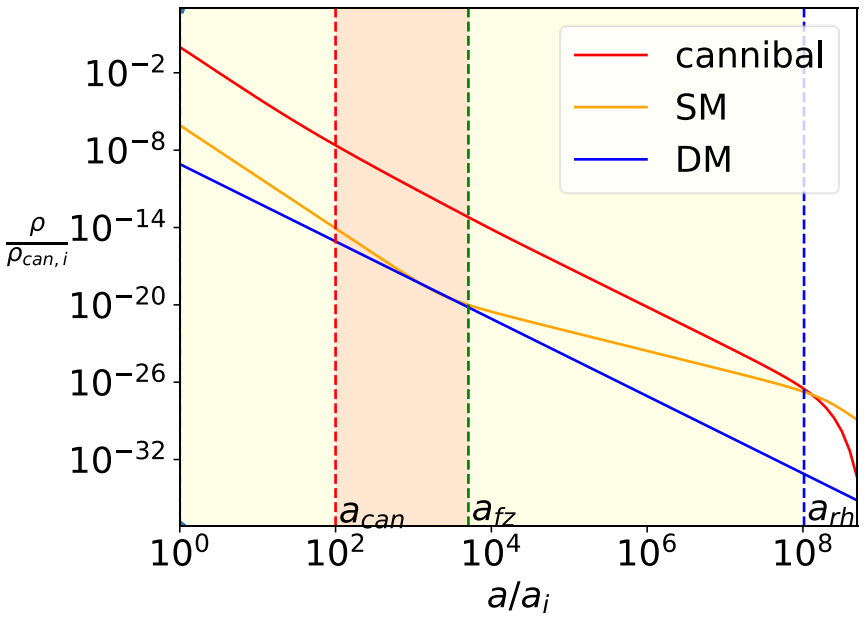
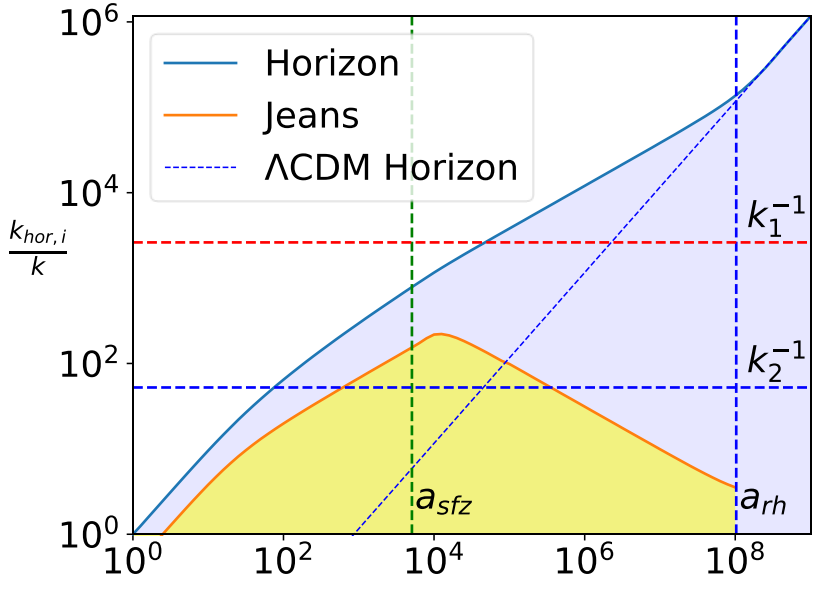


Stagnation while cannibal is oscillating

Perturbation evolution: Known EMDE evolution for modes entering horizon after cannibal freeze-out





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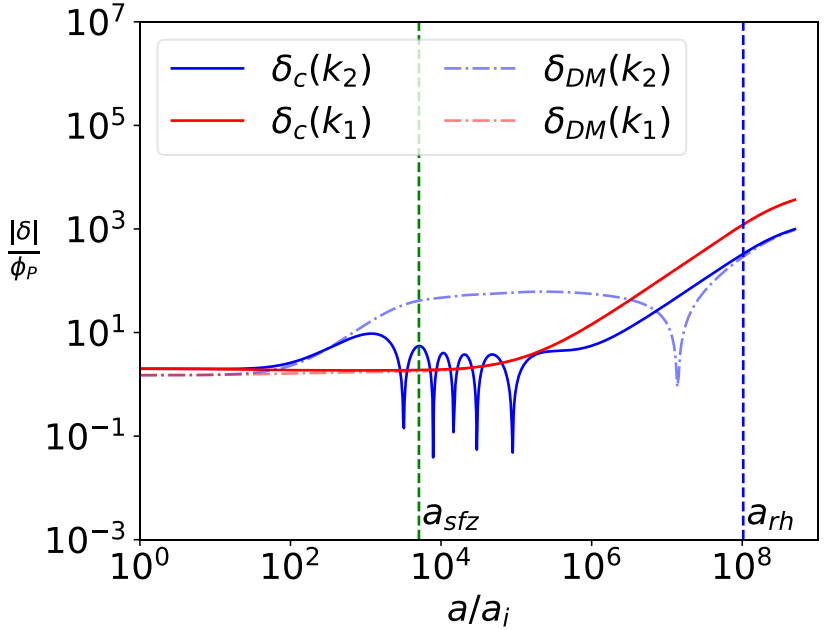
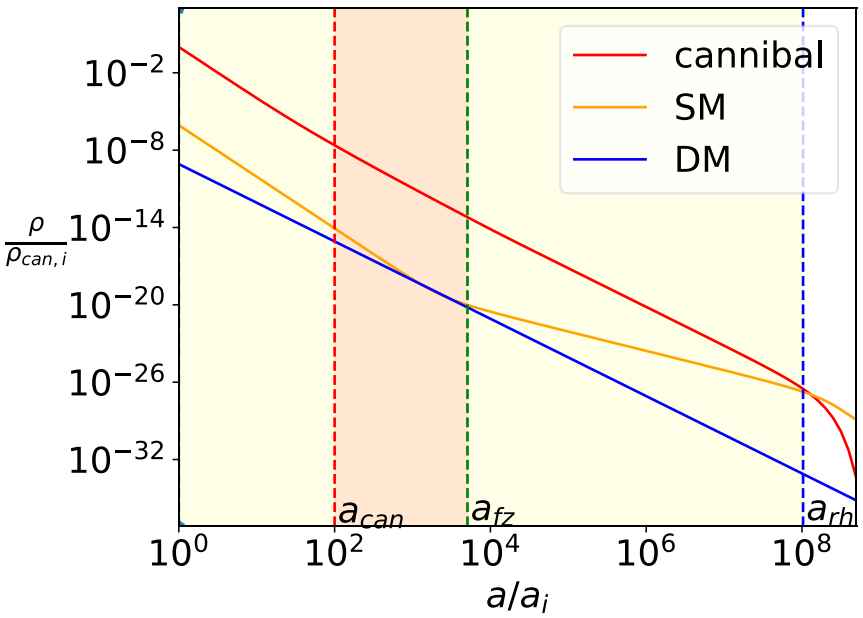
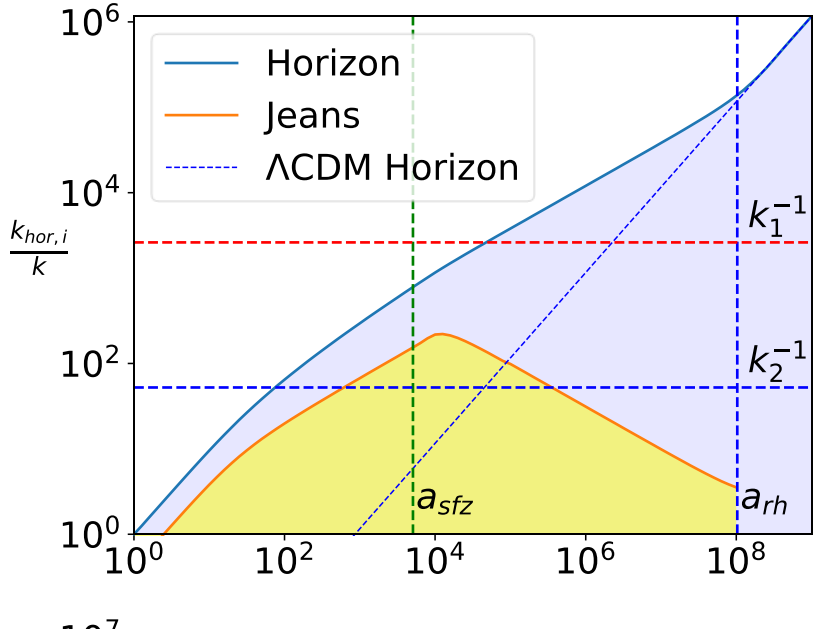
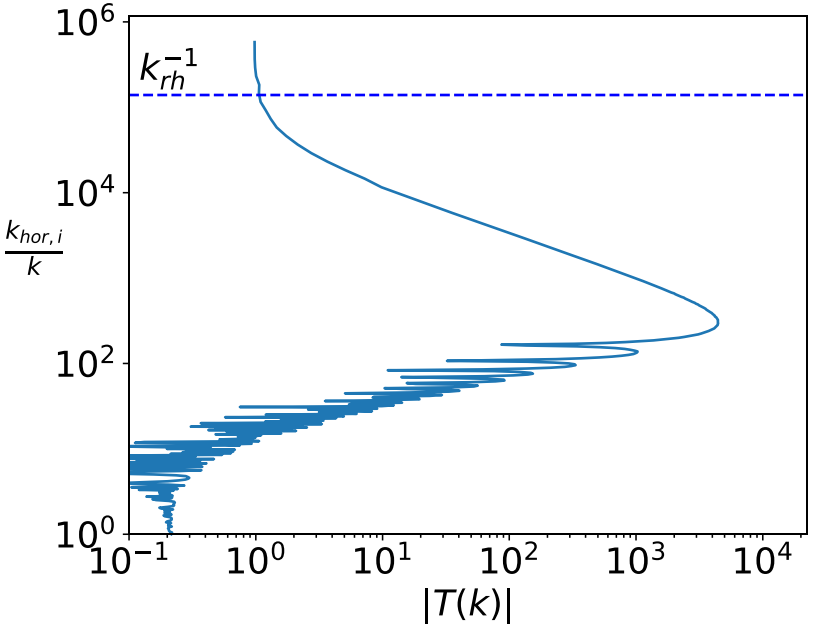


Perturbation evolution: Transfer function







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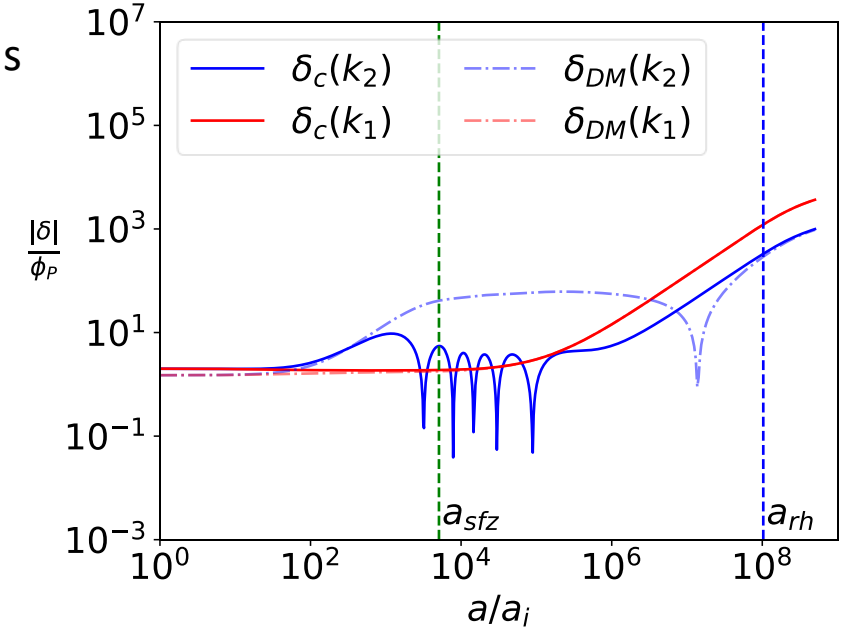
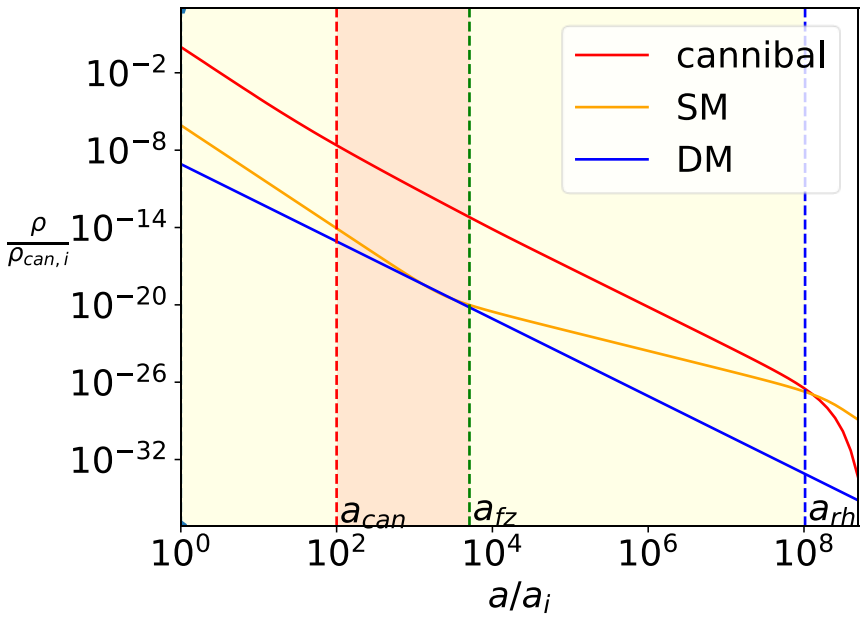
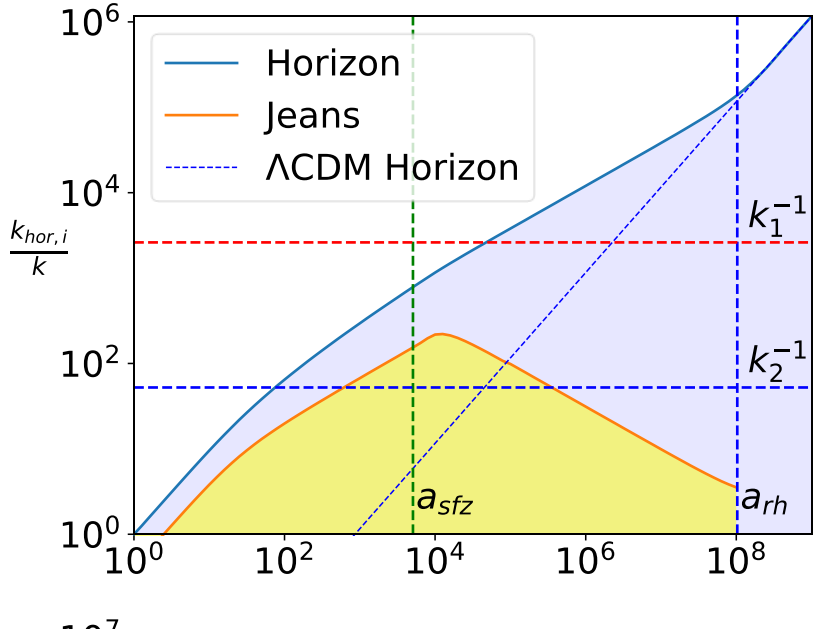


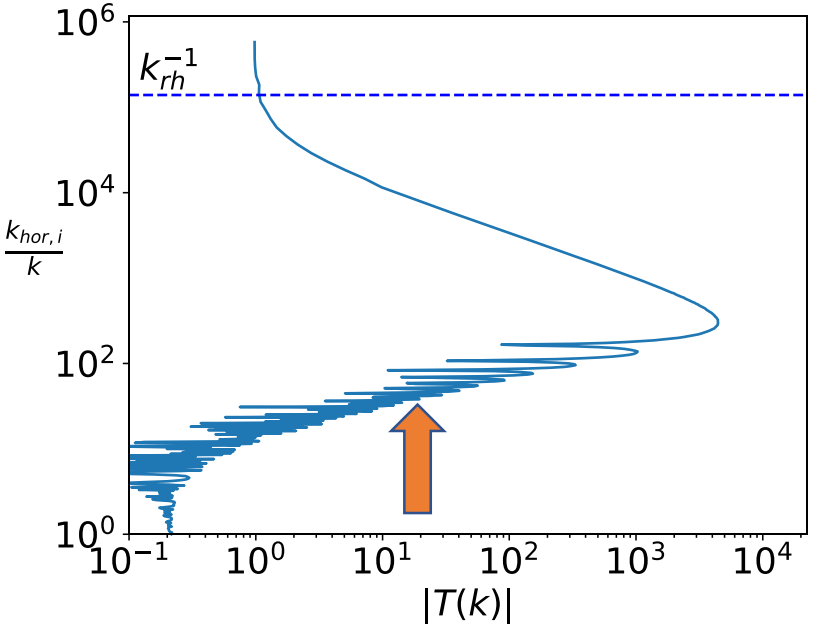
$$T(k) = \frac{\delta_{DM}(k,a)}{\delta_{DM,s}(k,a)} \quad a > a_{eq}$$

DM perturbation in ΛCDM

Transfer function: Dark acoustic oscillations purely from gravitational couplings







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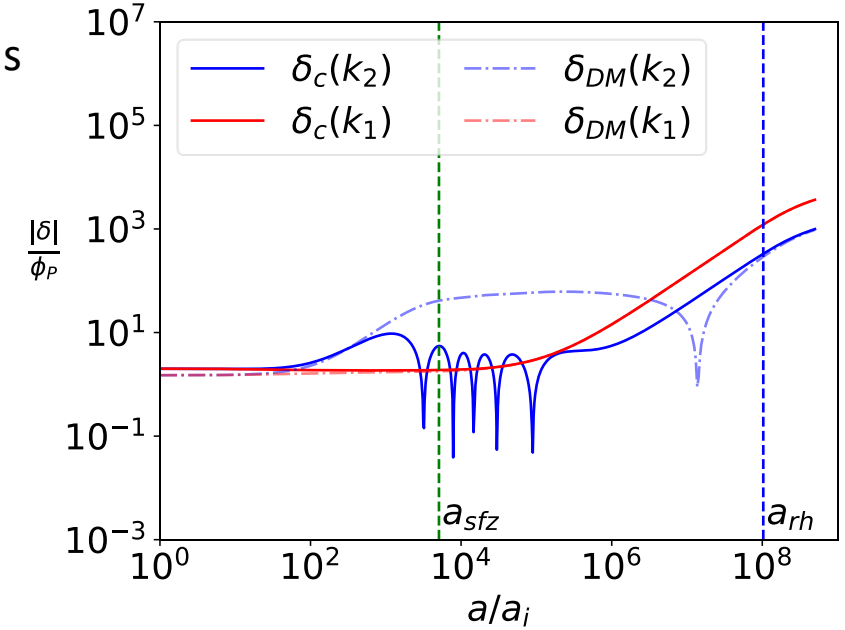

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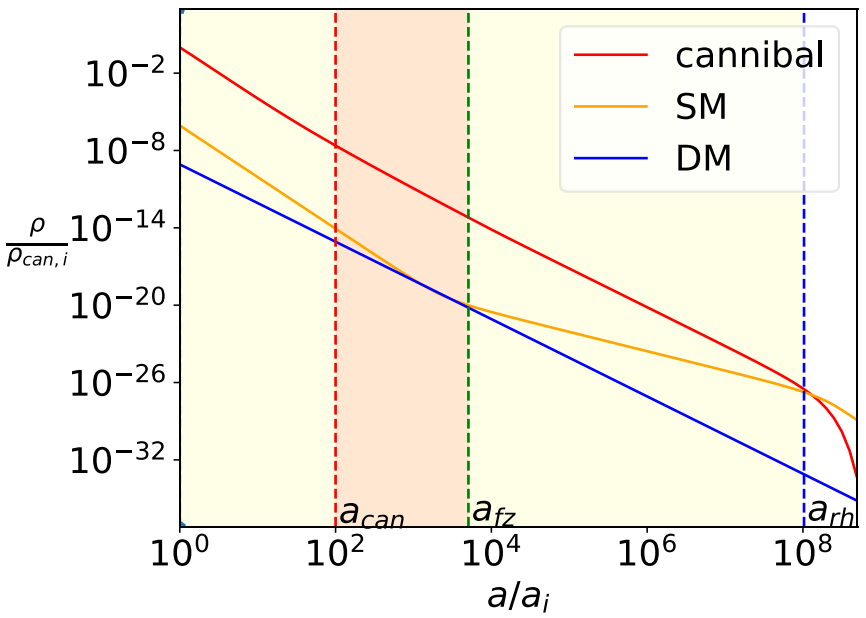
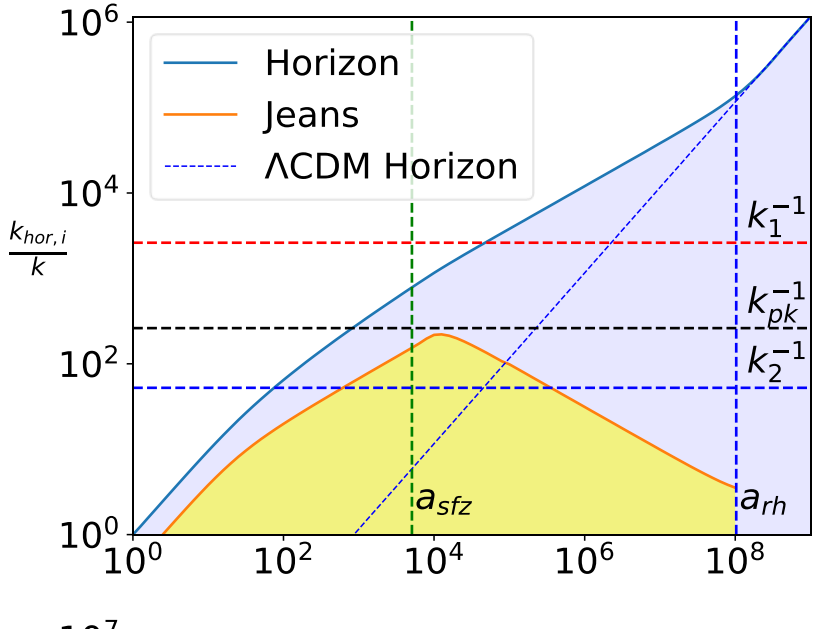
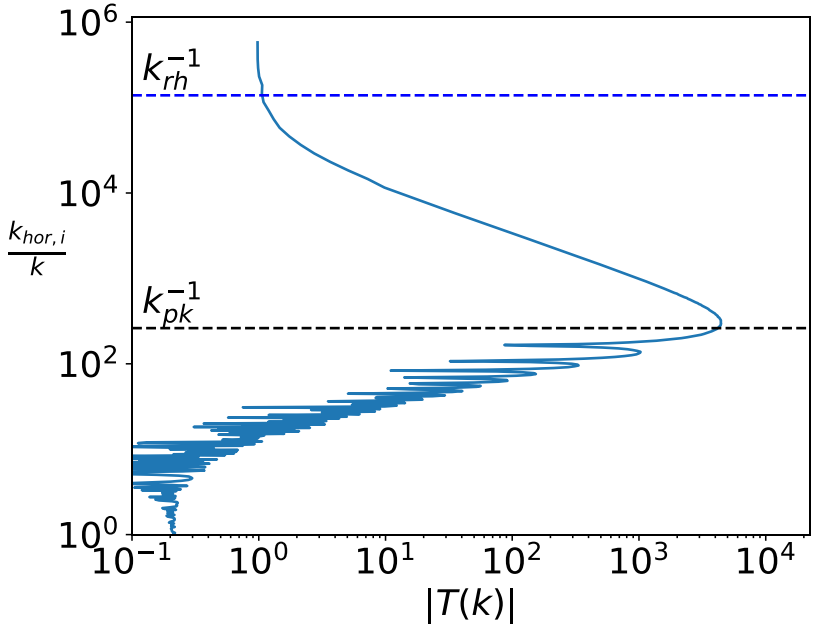
Transfer function: Peak given by Jeans horizon







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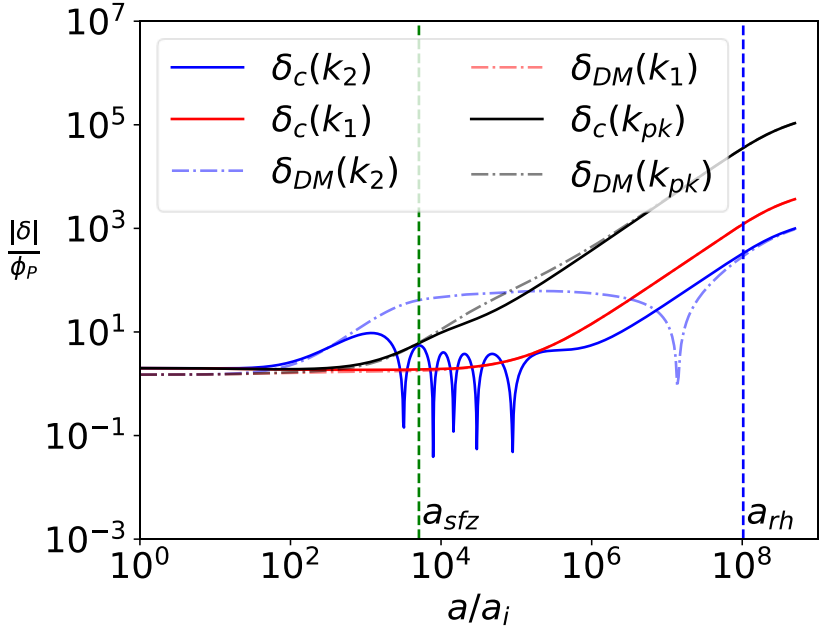

$$k_{pk}^{-1} \approx k_J^{-1}(2a_{fz})$$

(arxiv: 2008.04311)

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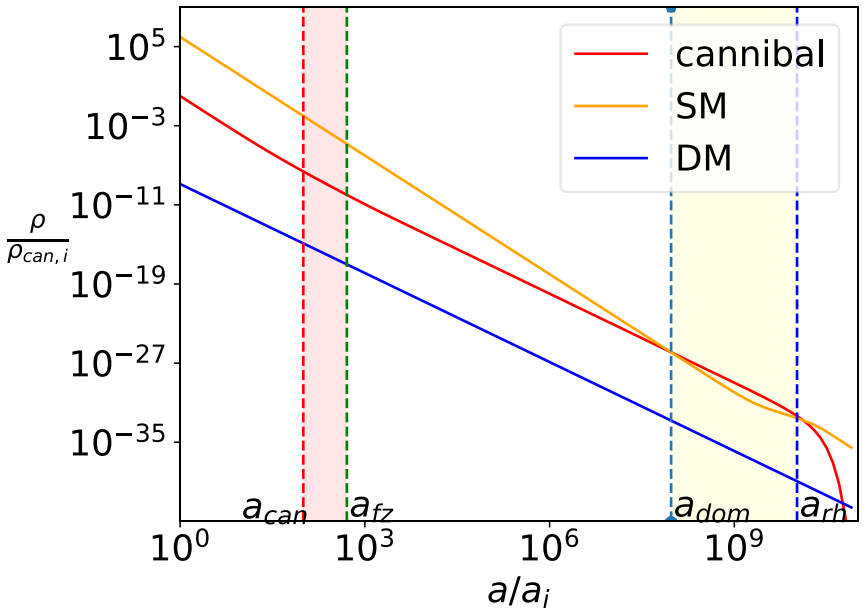
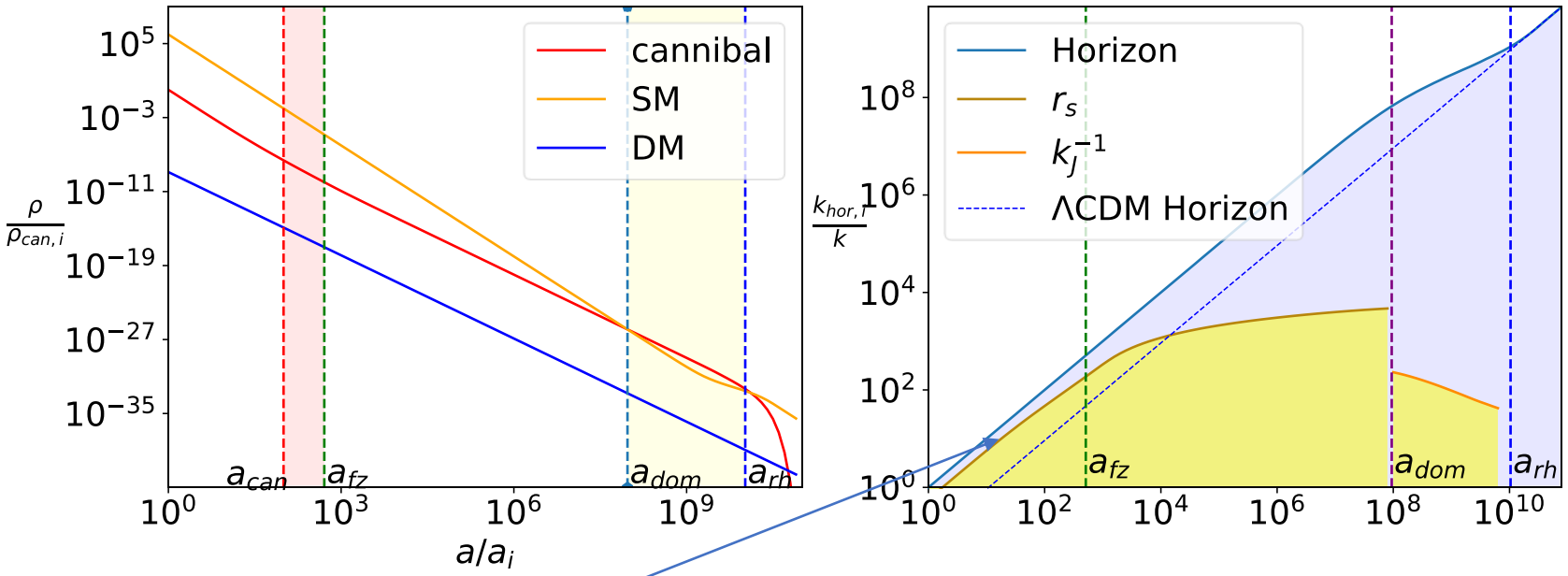
DM perturbation in ΛCDM

Perturbation evolution: SM radiation domination during cannibal freeze-out



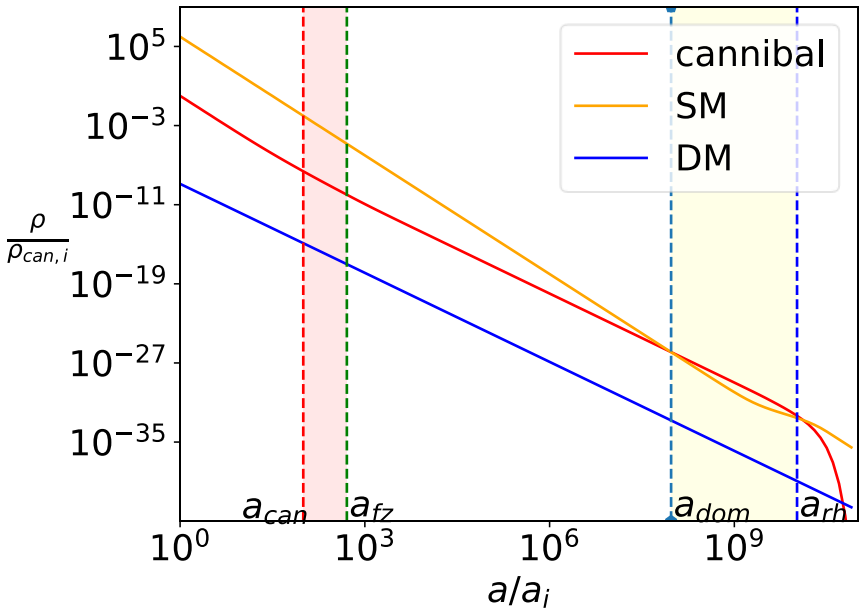
Perturbation evolution: SM radiation domination during cannibal freeze-out => relevant scale is sound horizon!

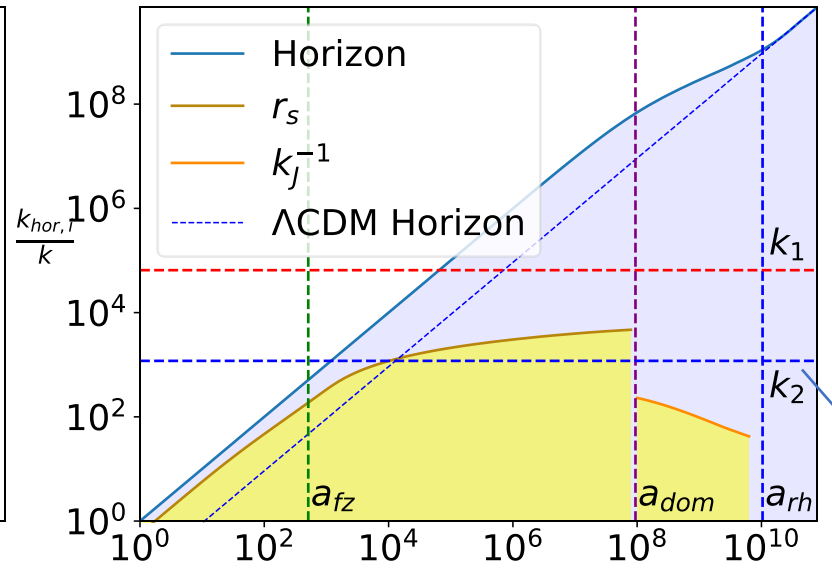


$$r_s = \int \frac{c_s}{aH} d\ln a$$

Cannibal sound speed

Perturbation evolution: oscillations within sound horizon





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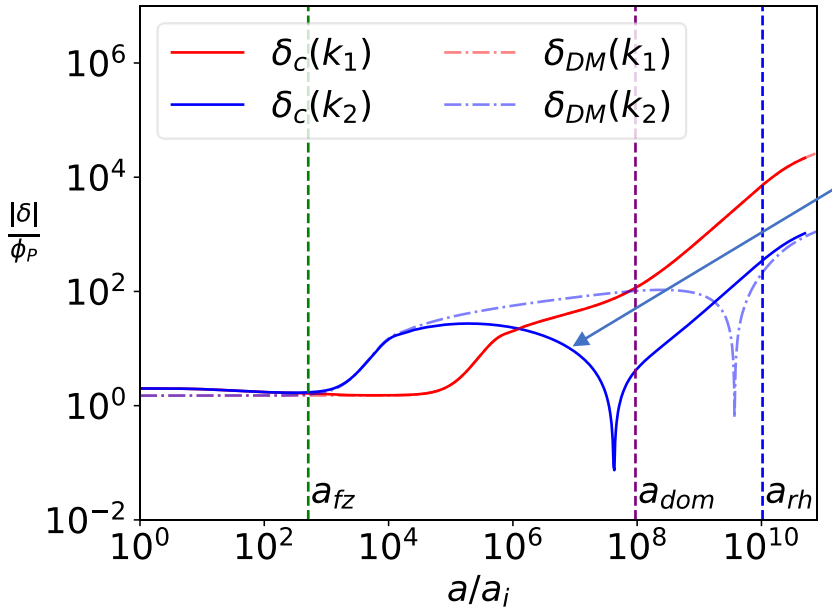
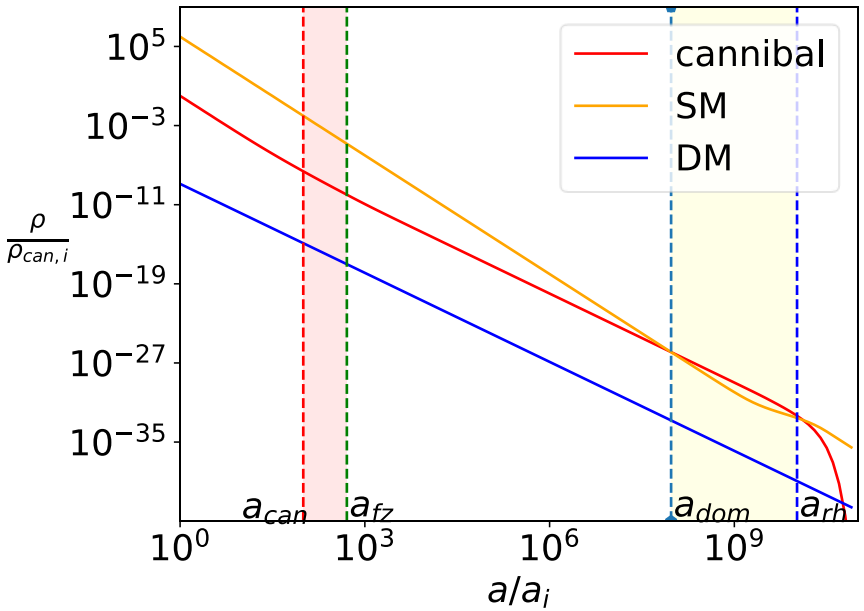
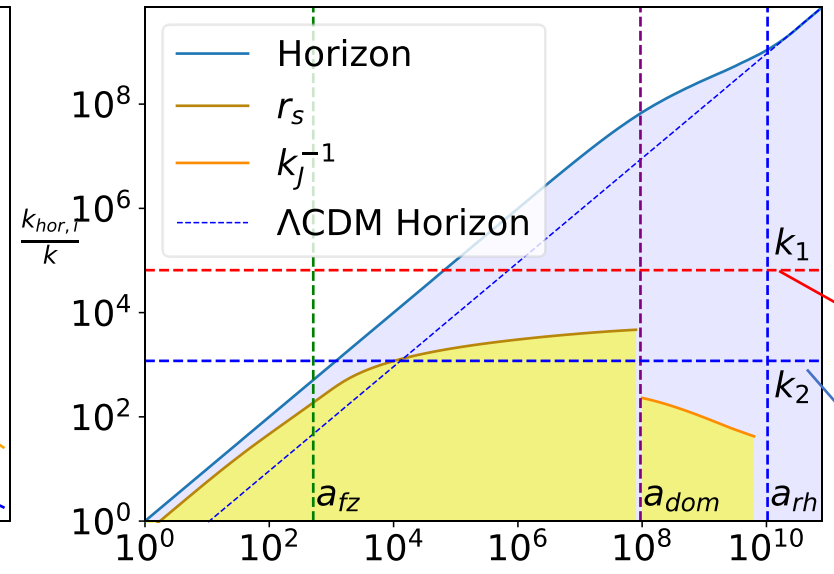
Cannibal sound speed

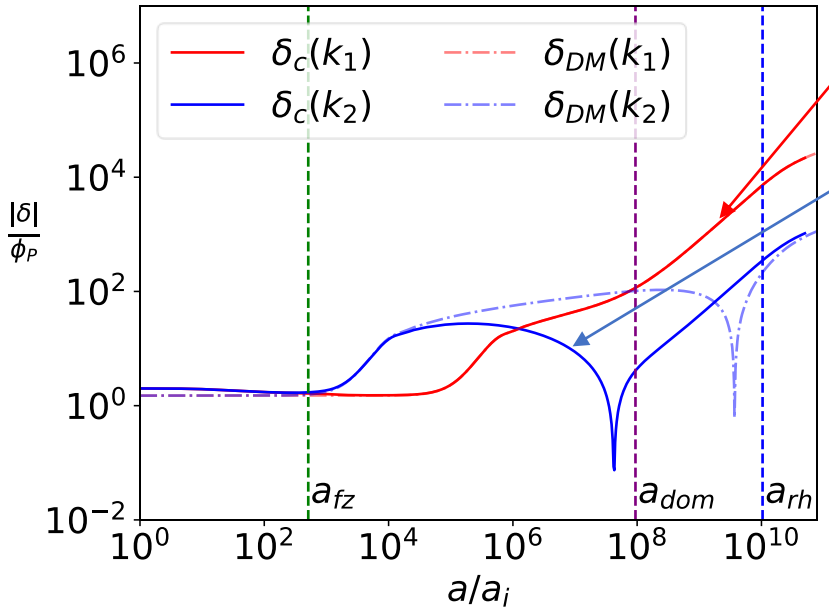


δ_c oscillates

Perturbation evolution: oscillations within sound horizon







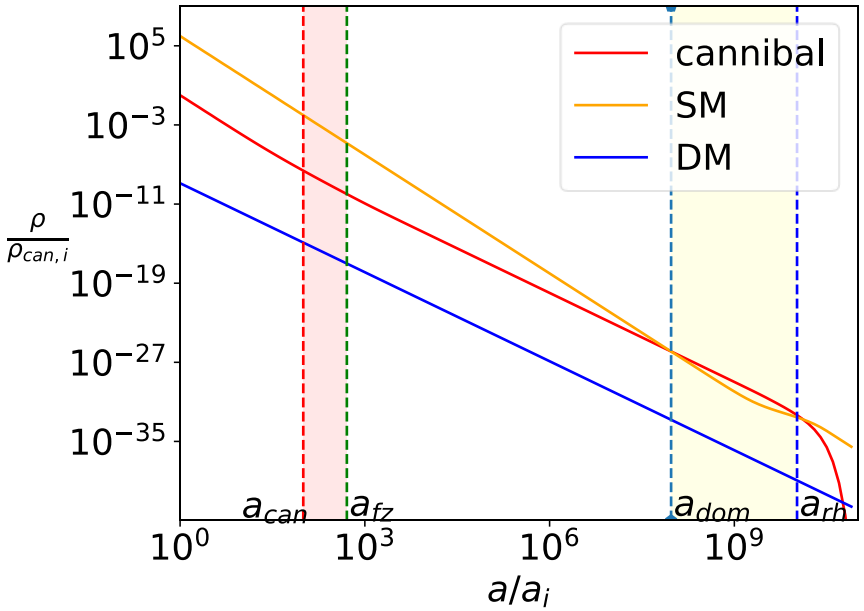
δ_c monotonically grows

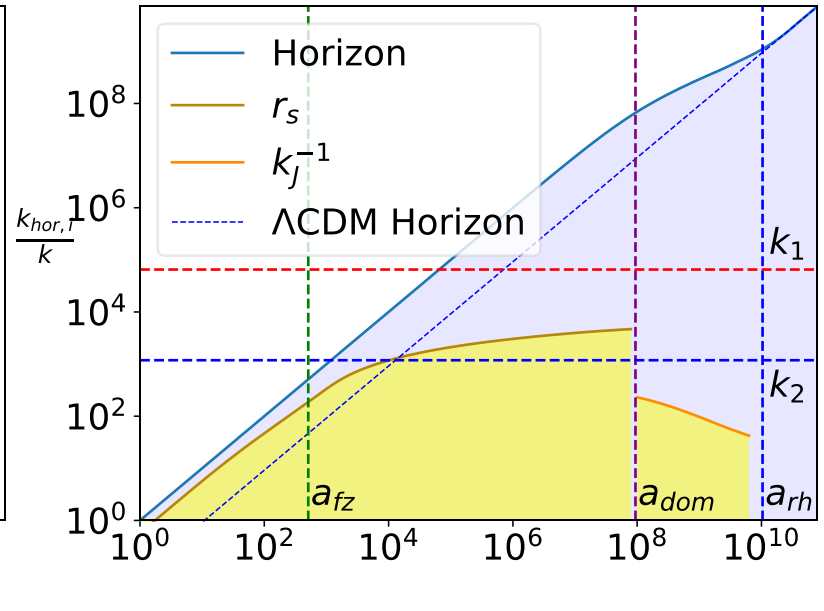
δ_c oscillates

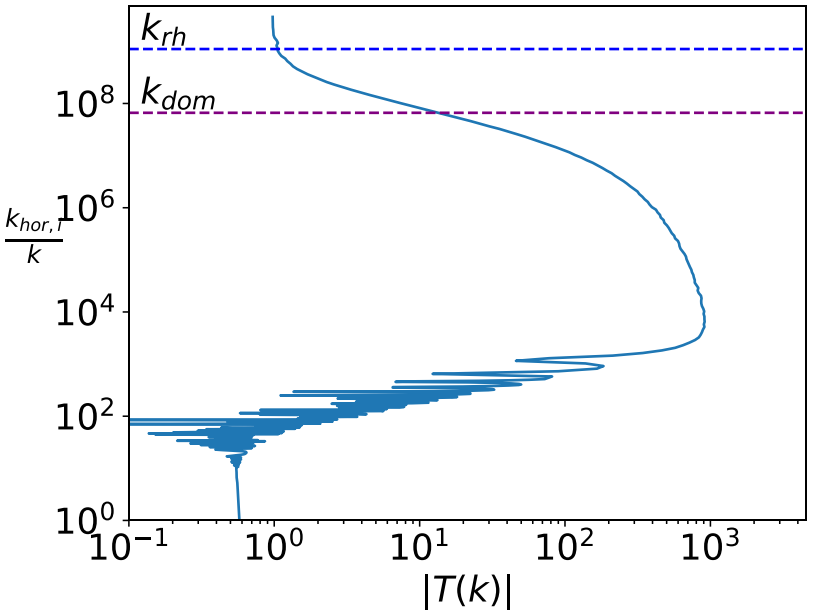
$$r_s = \int \frac{c_s}{aH} d\ln a$$

Cannibal sound speed

Perturbation evolution: Transfer function

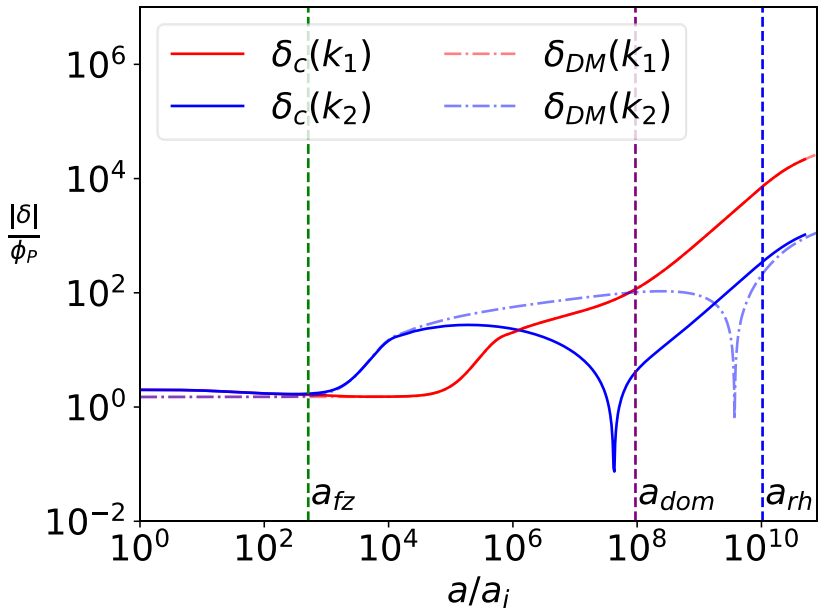






$$r_s = \int \frac{c_s}{aH} d\ln a$$

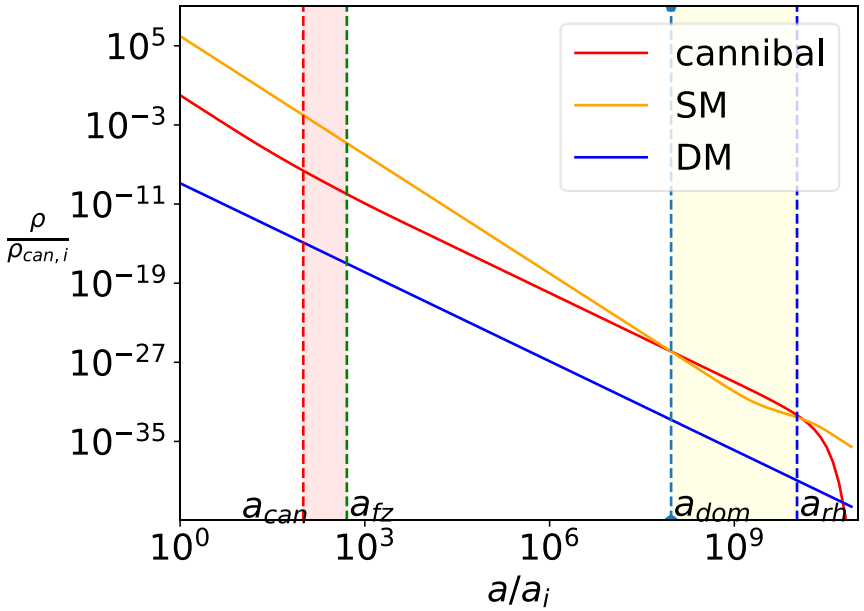
Cannibal sound speed

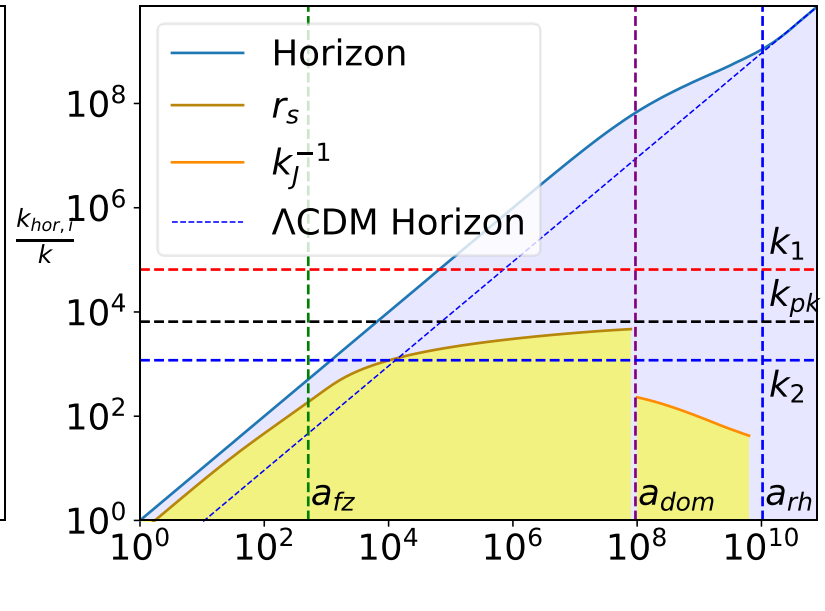


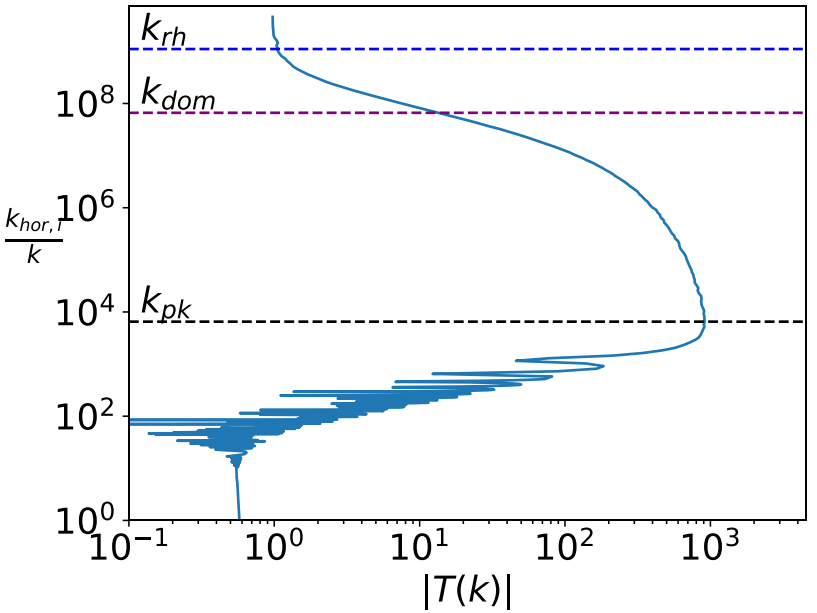
$$T(k) = \frac{\delta_{DM}(k,a)}{\delta_{DM,s}(k,a)} \quad a > a_{eq}$$

DM perturbation in ΛCDM

Transfer function: Peak given by sound horizon







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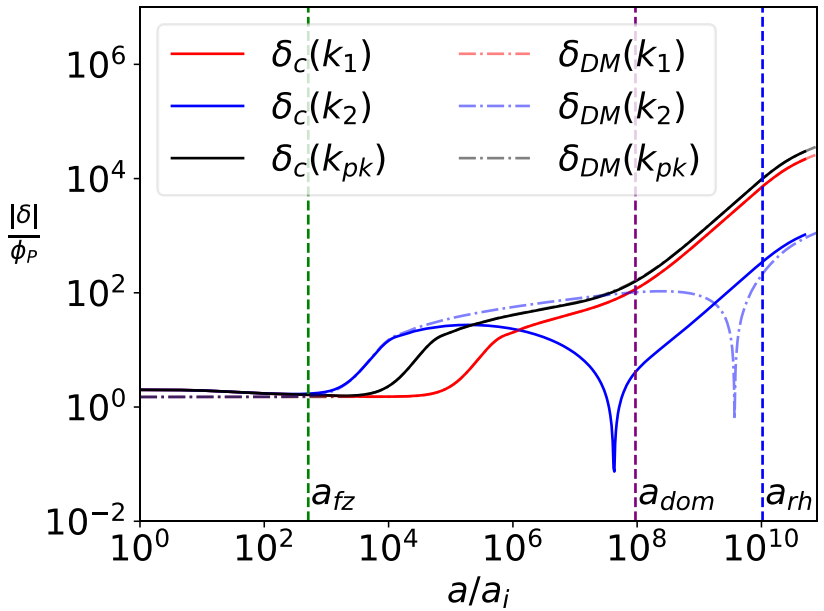


$$k_{pk}^{-1} \approx r_s(a_{dom})$$

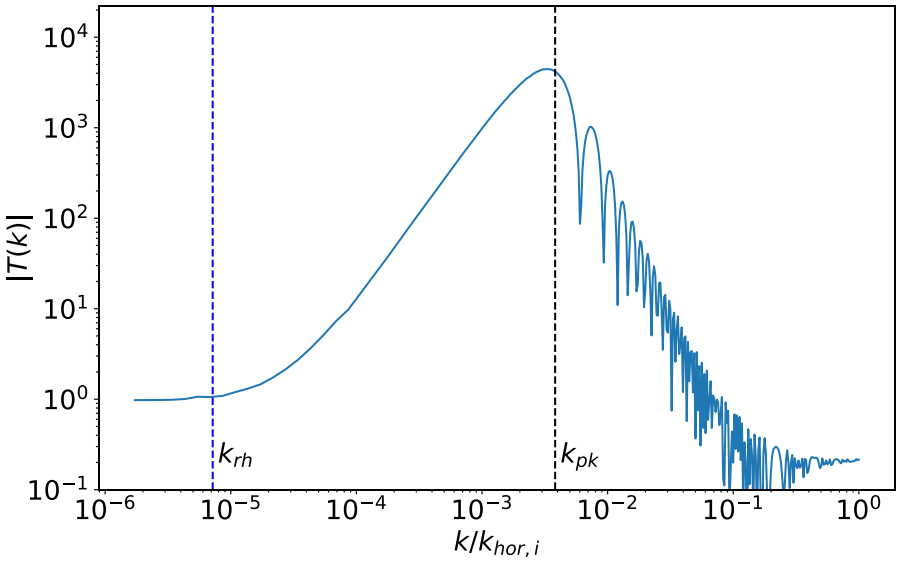
(arxiv: 2009.xxxx)

$$T(k) = \frac{\delta_{DM}(k,a)}{\delta_{DM,s}(k,a)} \quad a > a_{eq}$$

DM perturbation in ΛCDM

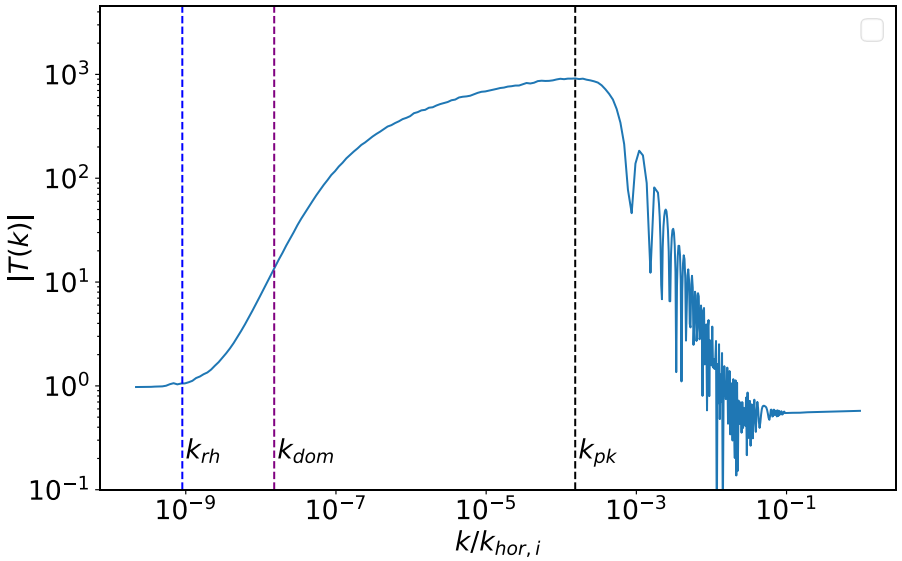
Two qualitatively different transfer functions

Cannibal dominated universe during freeze-out of cannibal reactions



$$k_{pk}^{-1} \approx k_J^{-1}(2a_{fz})$$

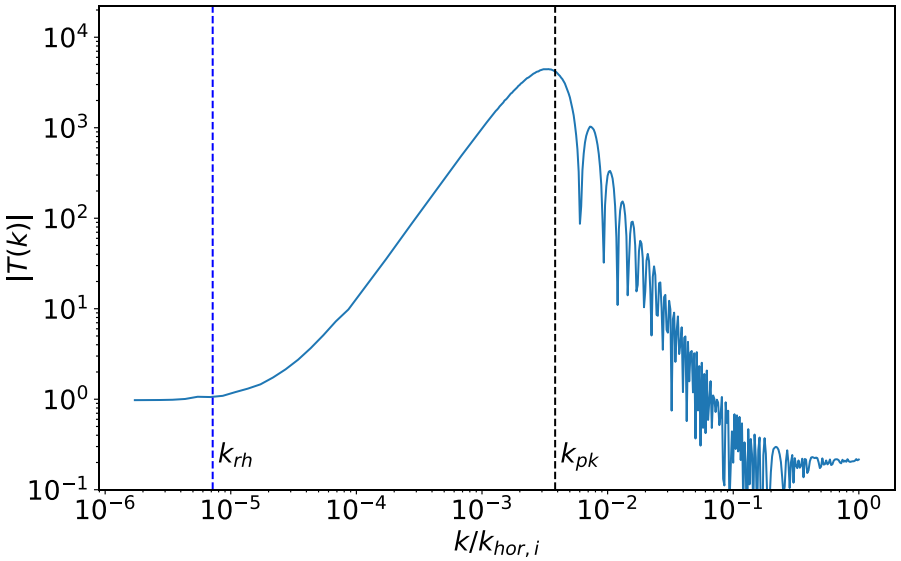
SM-radiation dominated universe during freeze-out of cannibal reactions



$$k_{pk}^{-1} \approx r_s(a_{dom})$$

The cut-off in doth determined by cannibal self interactions

Cannibal dominated universe during freeze-out of cannibal reactions



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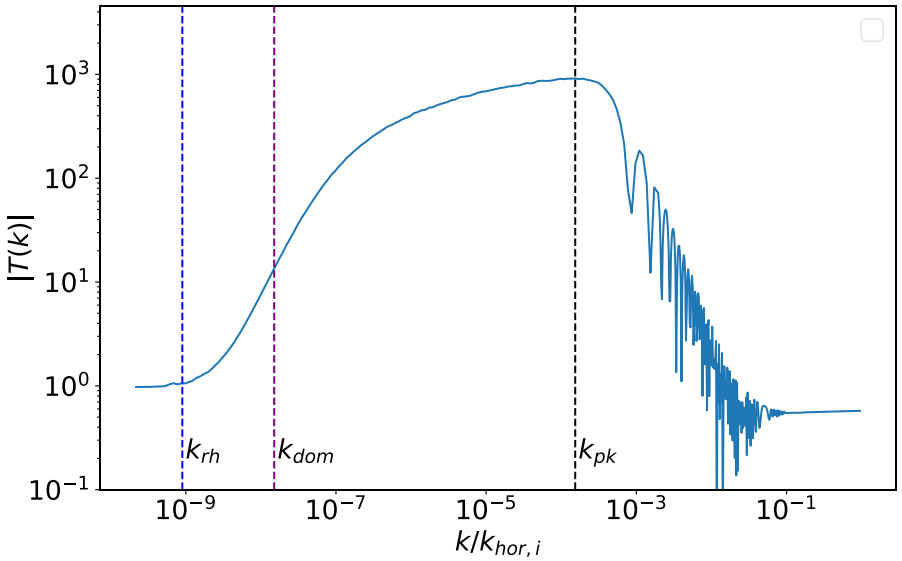

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$$\sim r_s(2a_{fz}) \ln\left(\frac{a_{dom}}{2a_{fz}}\right)$$

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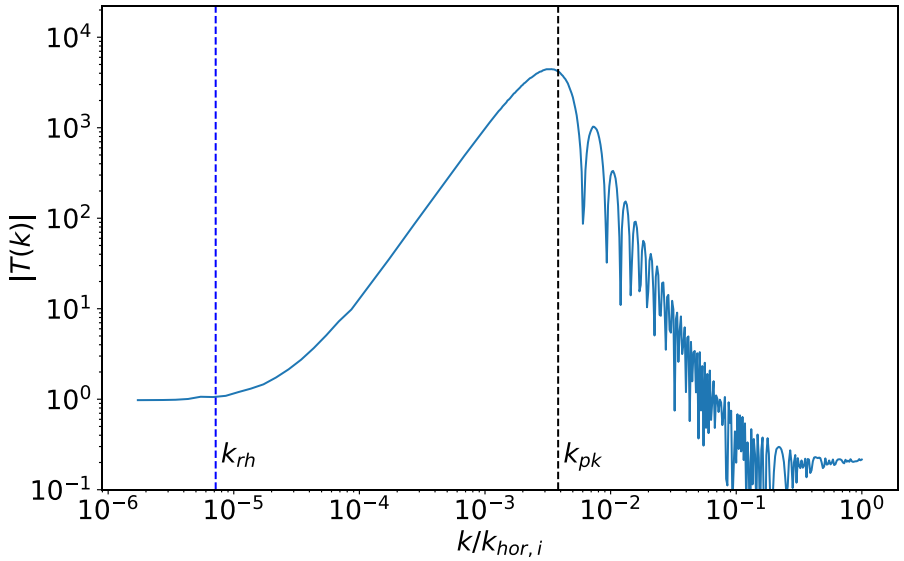

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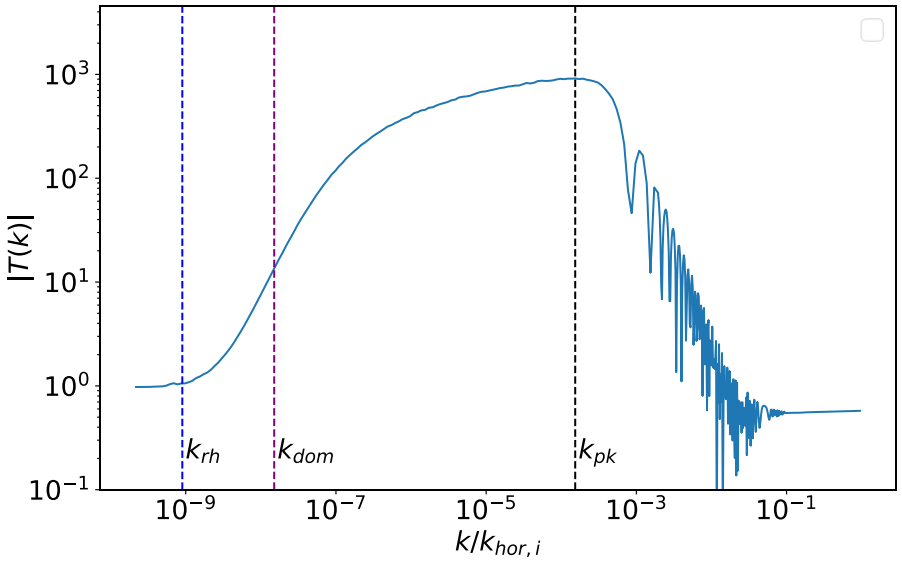

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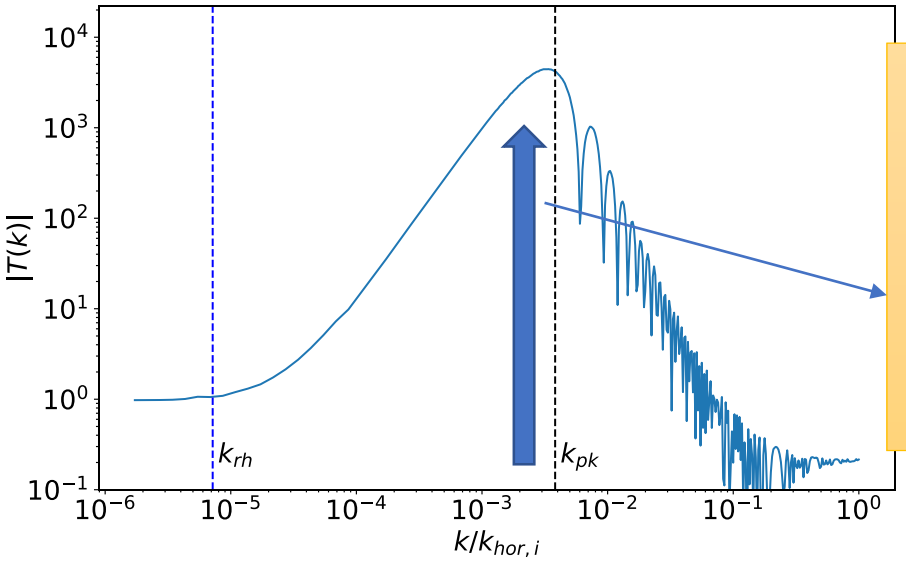
Peak enhancement of the transfer function determines key features of micro-halos

Cannibal dominated universe during freeze-out of cannibal reactions



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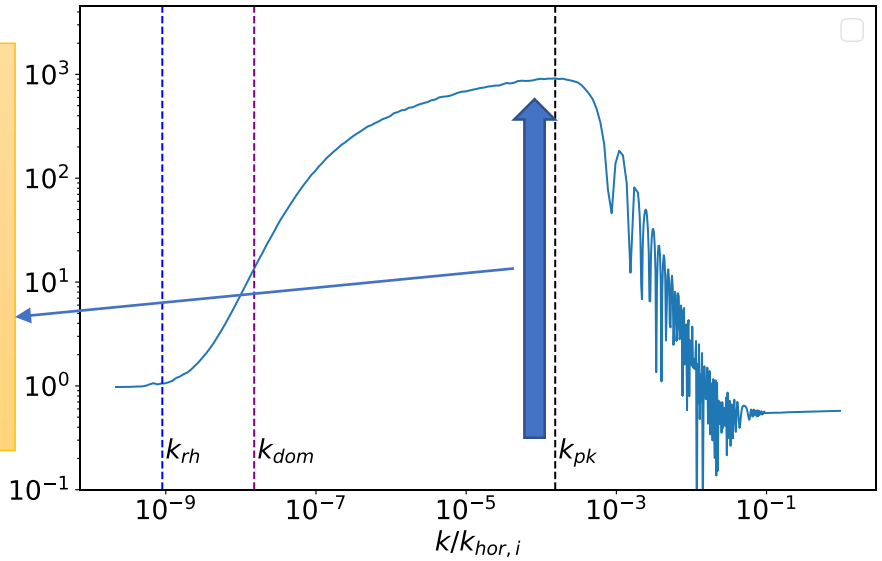
Enhanced DM fluctuations eventually become non-linear. Collapse to form micro-halos.

SM-radiation dominated universe during freeze-out of cannibal reactions



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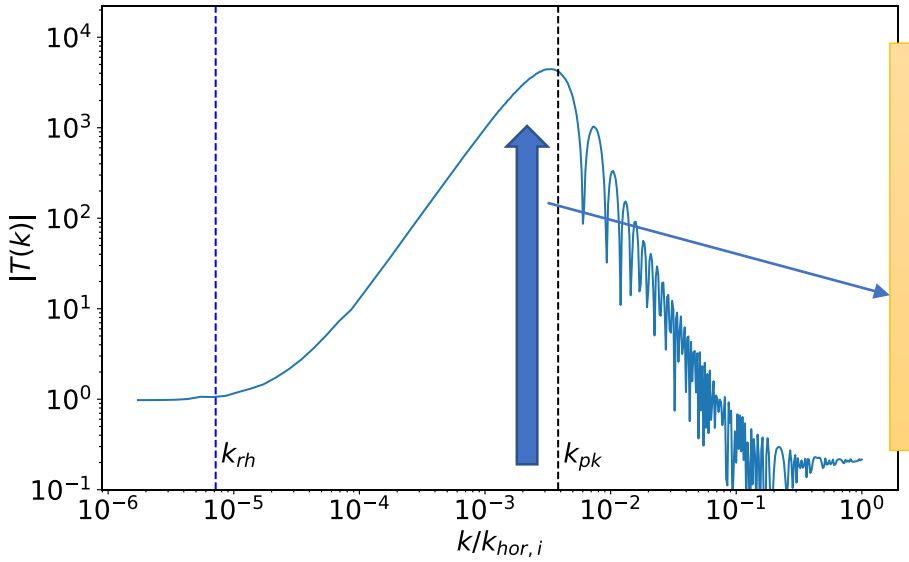

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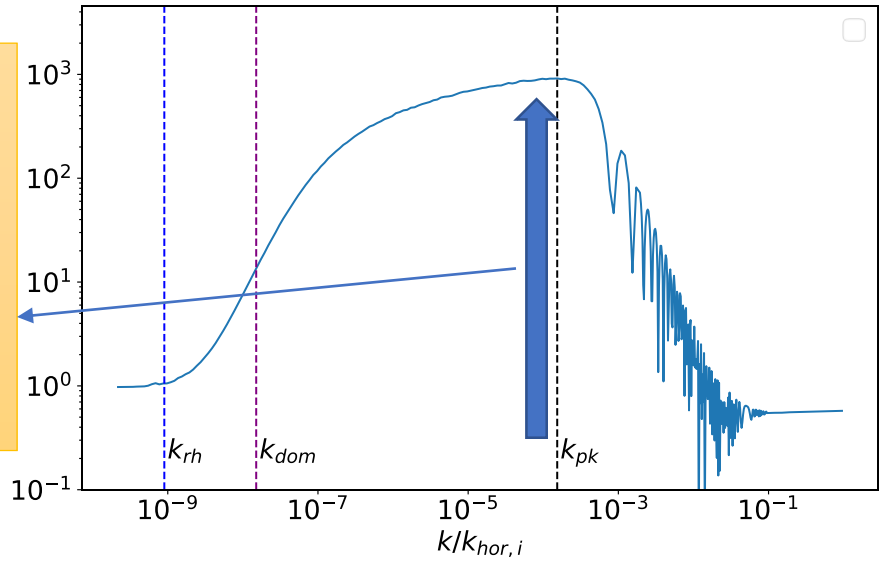

- k_{pk} determines the typical mass of micro halos: $M_{pk} \sim \frac{4\pi}{3}\rho_{DM}\left(k_{pk}^{-1}\right)^3$
- $T(k_{pk})$ determines the central density of micro-halos: Micro-halos are typically $\geq \left[T\left(k_{pk}\right)\right]^3$ times denser than standard micro-halos.

Type of micro-halos over parameter space of cannibal model

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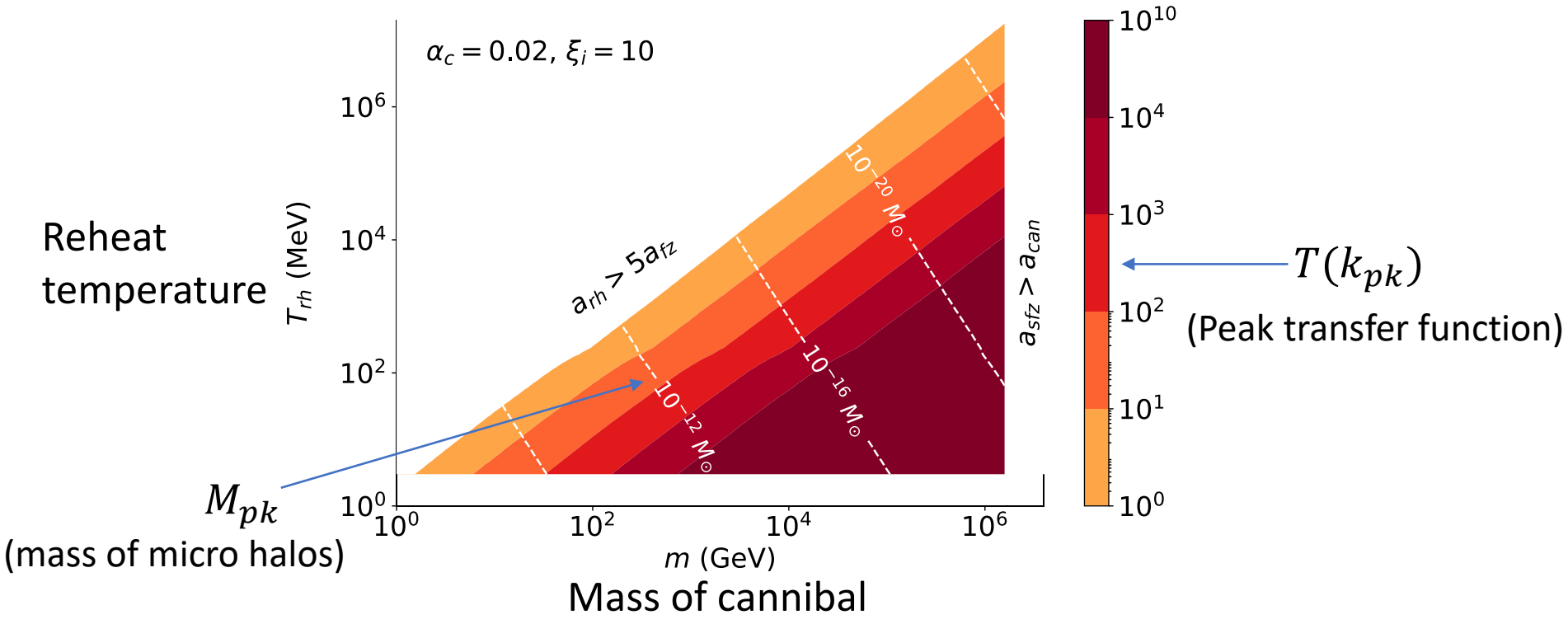
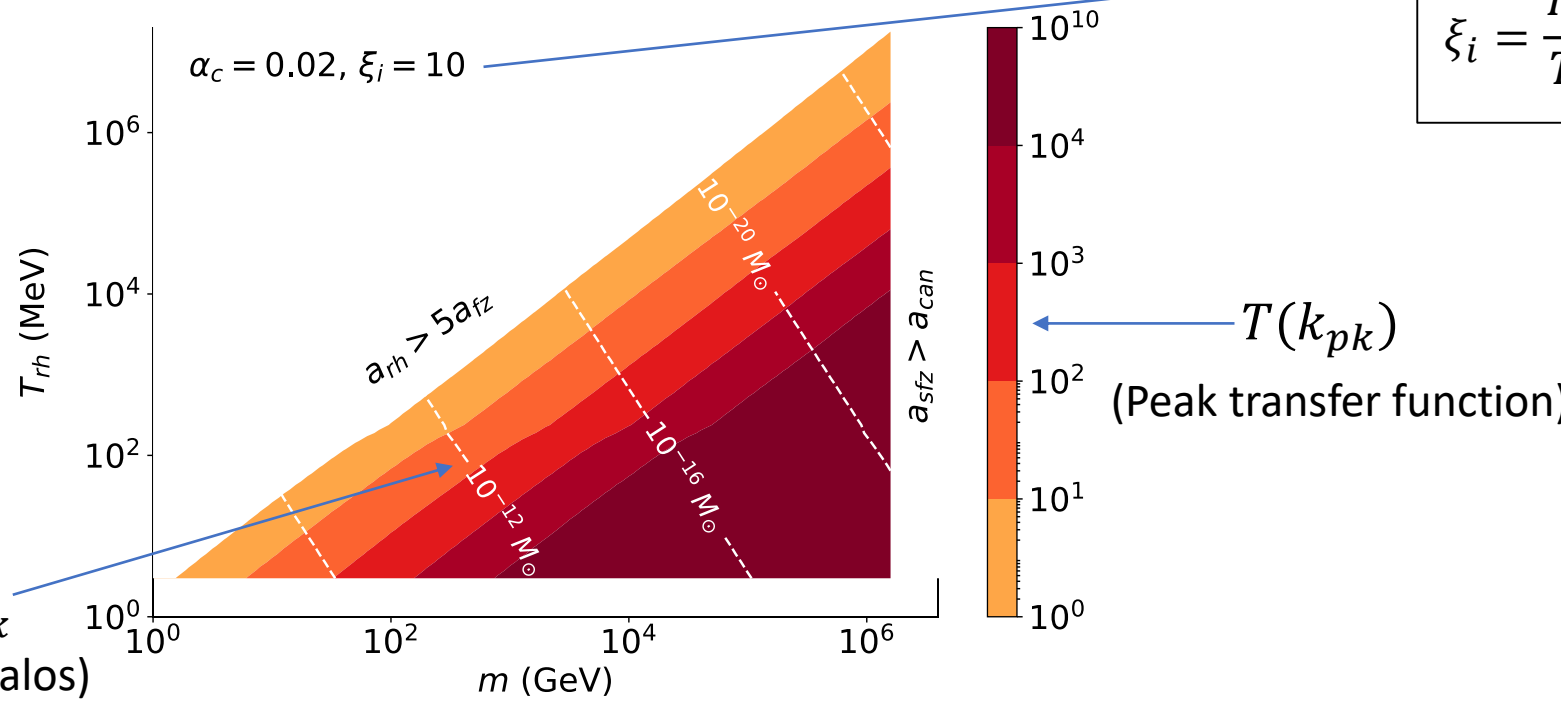


(arxiv: 2008.04311)

Type of micro-halos over parameter space of cannibal model

$$\langle \sigma v^2 \rangle_{can} = \frac{25\sqrt{5}\pi^2 \alpha_c^3}{5184 m^5}$$

$$\xi_i = \frac{T_{can}(a_i)}{T_{SM}(a_i)} = \frac{10m}{T_{SM}(a_i)}$$



Reheat temperature

$T(k_{pk})$

(Peak transfer function)

M_{pk}

(mass of micro halos)

Mass of cannibal

(arxiv: 2008.04311)

Type of micro-halos over parameter space of cannibal model: free-parameters

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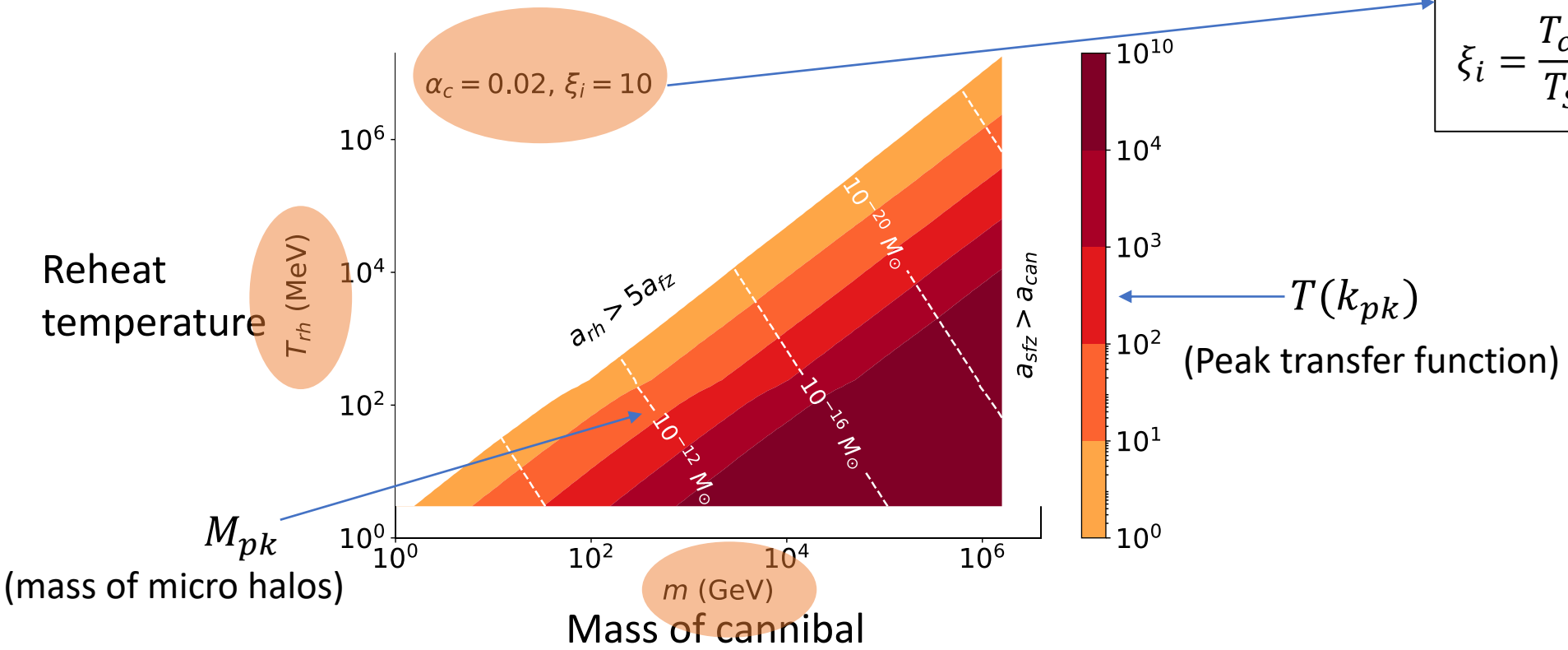

Reheat temperature

M_{pk} (mass of micro halos)

Mass of cannibal

$T(k_{pk})$ (Peak transfer function)

(arxiv: 2008.04311)

Type of micro-halos over parameter space of cannibal model

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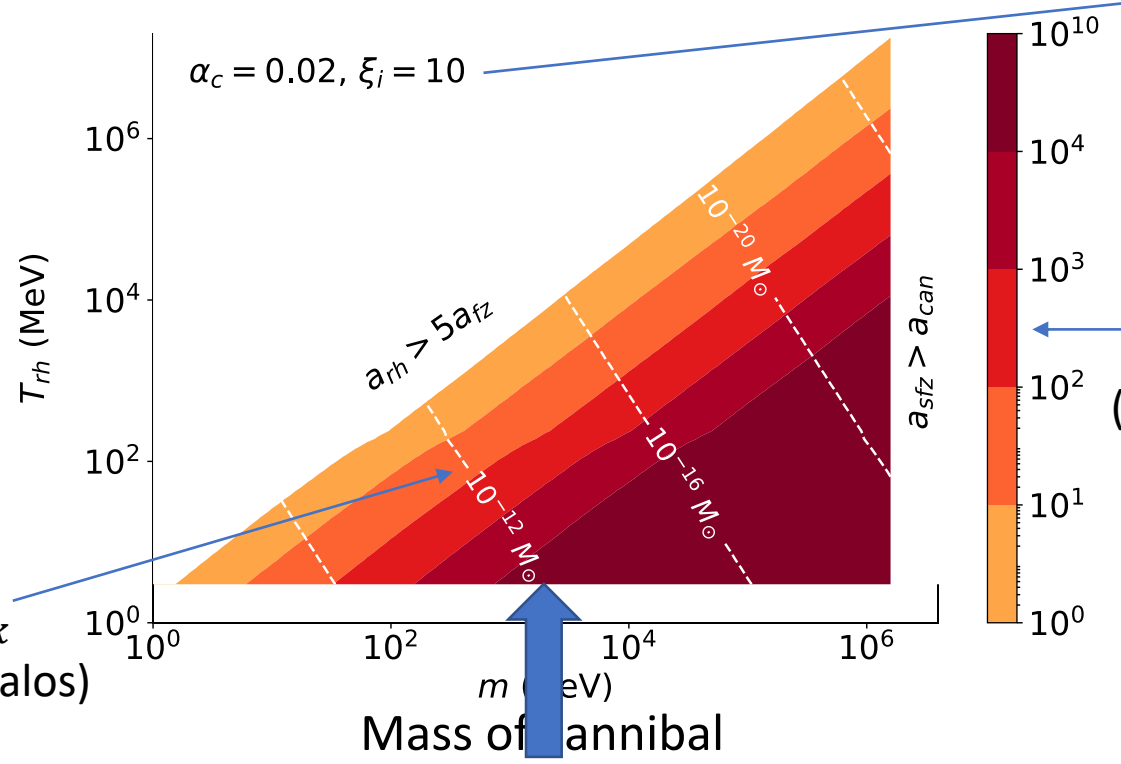

Reheat temperature

M_{pk} (mass of micro halos)

Mass of annibal

$T(k_{pk})$ (Peak transfer function)

(arxiv: 2008.04311)

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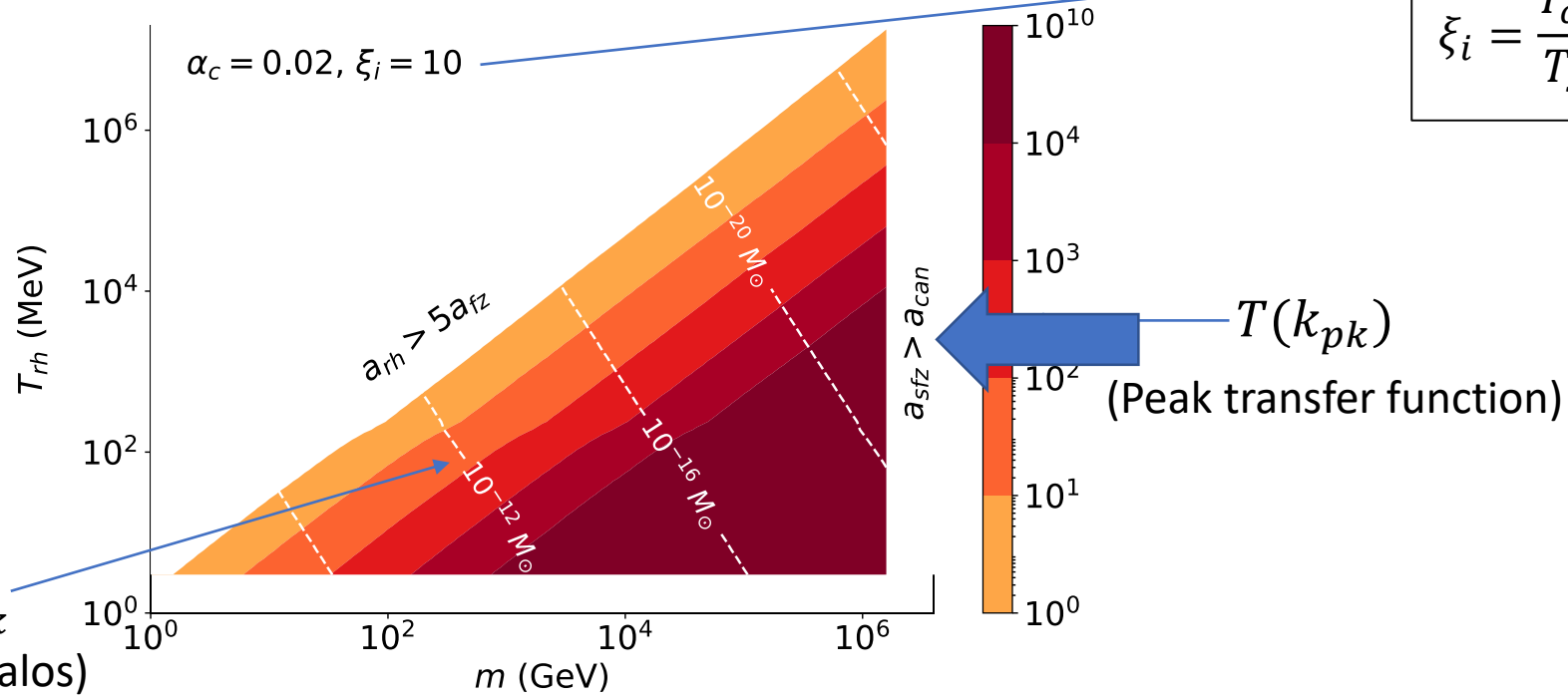

Reheat temperature

M_{pk} (mass of micro halos)

Mass of cannibal

$T(k_{pk})$ (Peak transfer function)

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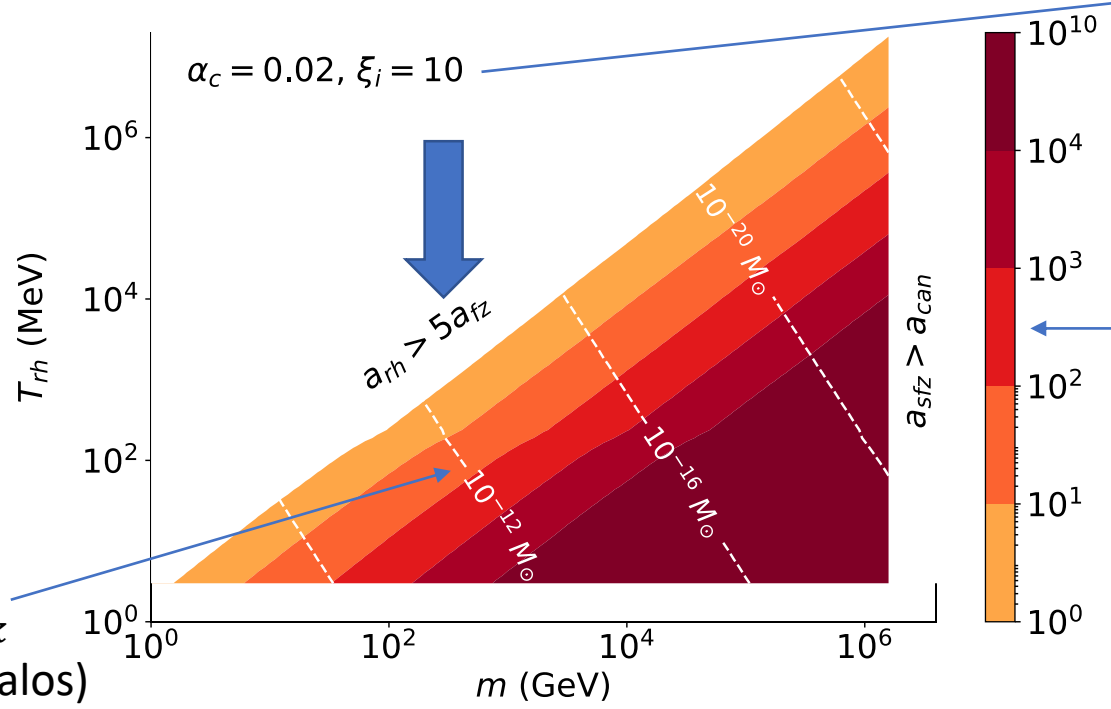

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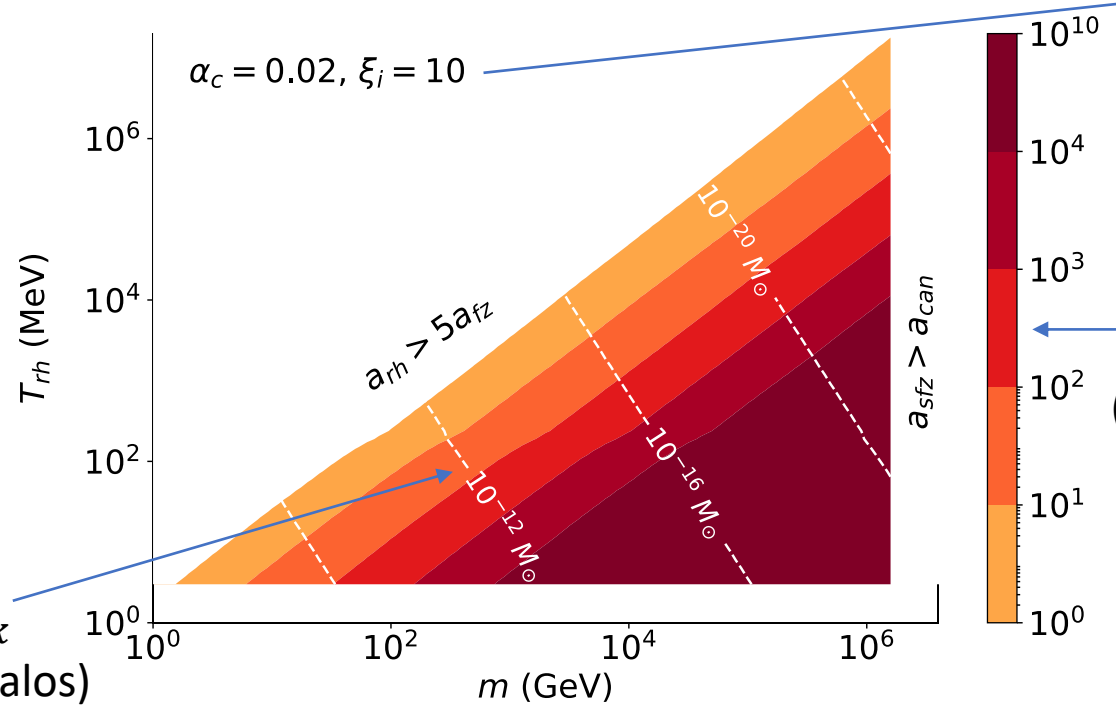

Reheat temperature

$T(k_{pk})$

(Peak transfer function)

M_{pk}

(mass of micro halos)

Mass of cannibal

$$M_{pk} \sim 10^{-12} \left(\frac{\alpha_c}{0.02}\right) \left(\frac{m}{TeV}\right)^{-\frac{7}{3}} \left(\frac{T_{rh}}{10\ MeV}\right)$$

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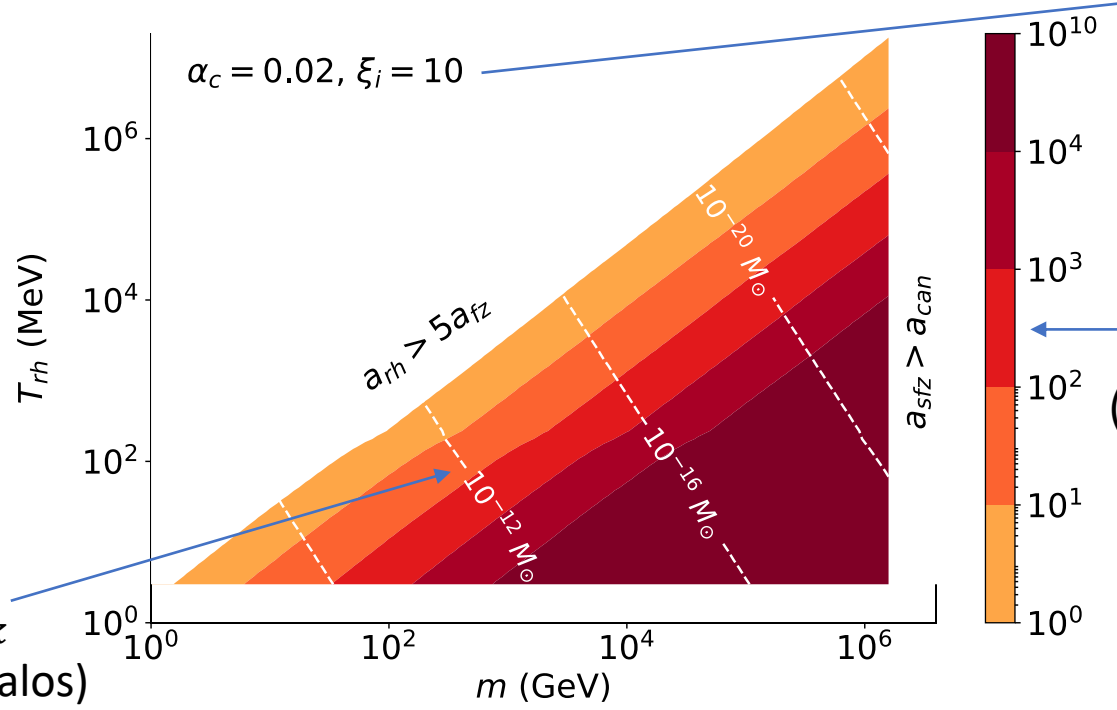

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Type of micro-halos over parameter space of cannibal model: varying initial density

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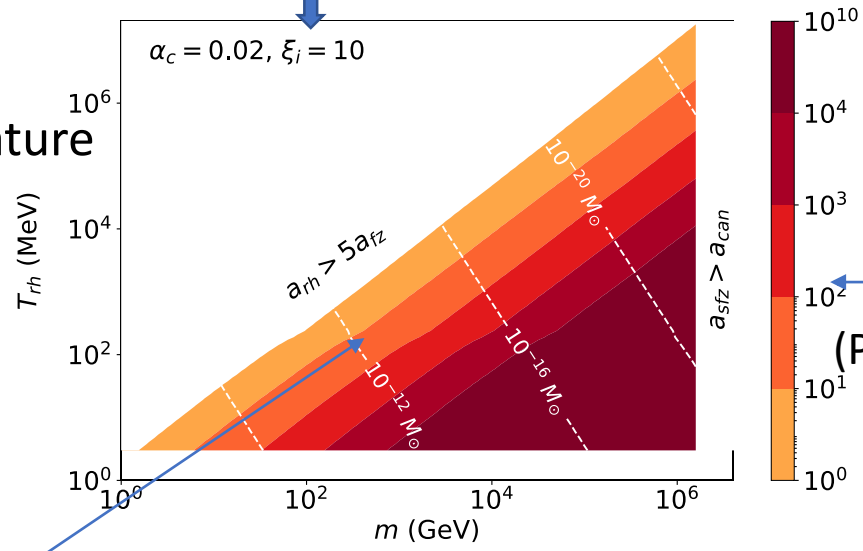
Cannibal density dominant at a_{fz}

SM radiation density dominant at a_{fz}

Reheat temperature



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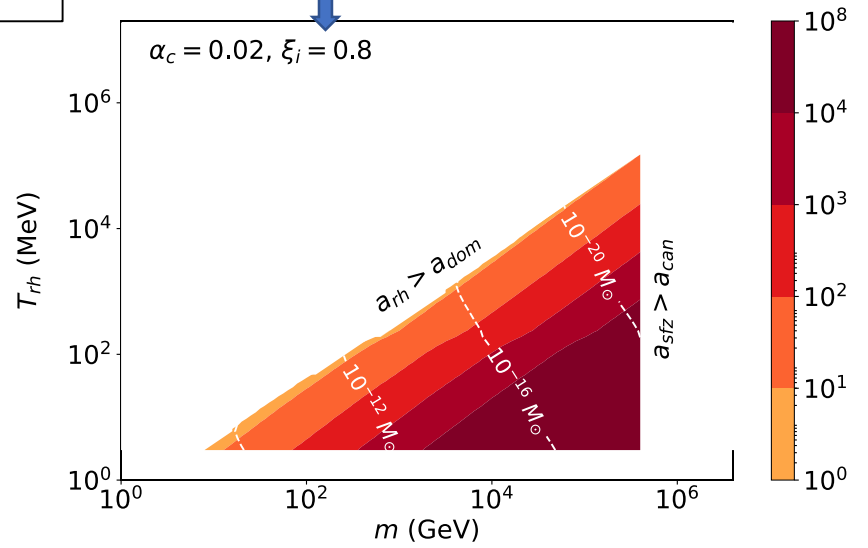
(Peak transfer function)



Mass of cannibal

M_{pk}

(mass of micro halos)

(arxiv: 2009.xxxx)

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Cannibal density dominant at a_{fz}

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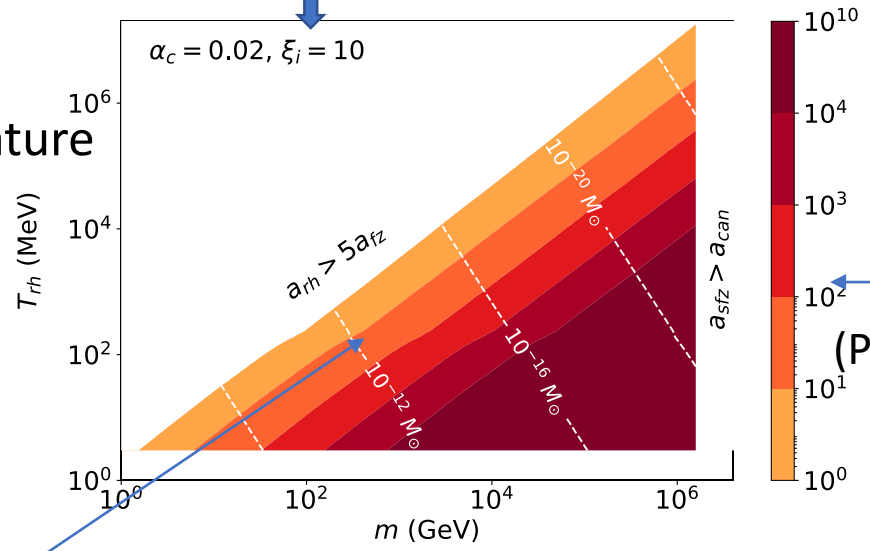
SM radiation density dominant at a_{fz}

Reheat temperature



$T(k_{pk})$

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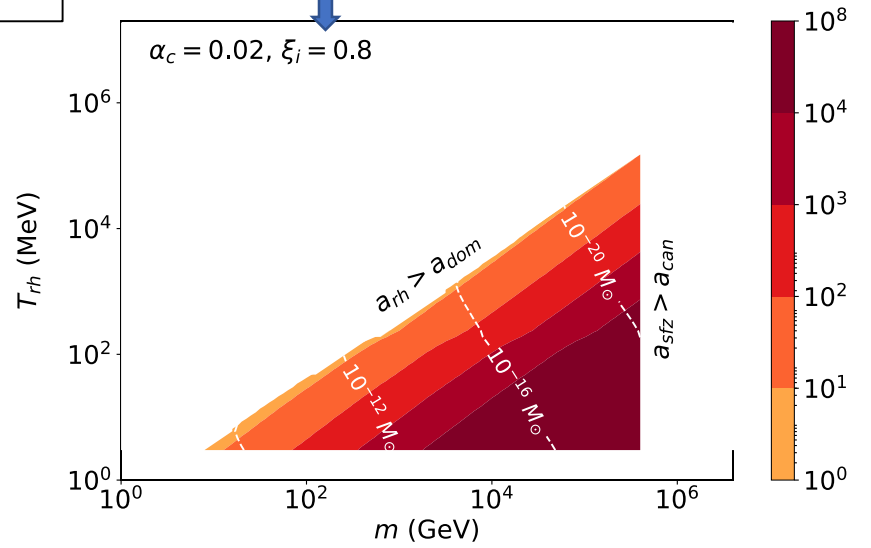

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(mass of micro halos)

(arxiv: 2009.xxxx)

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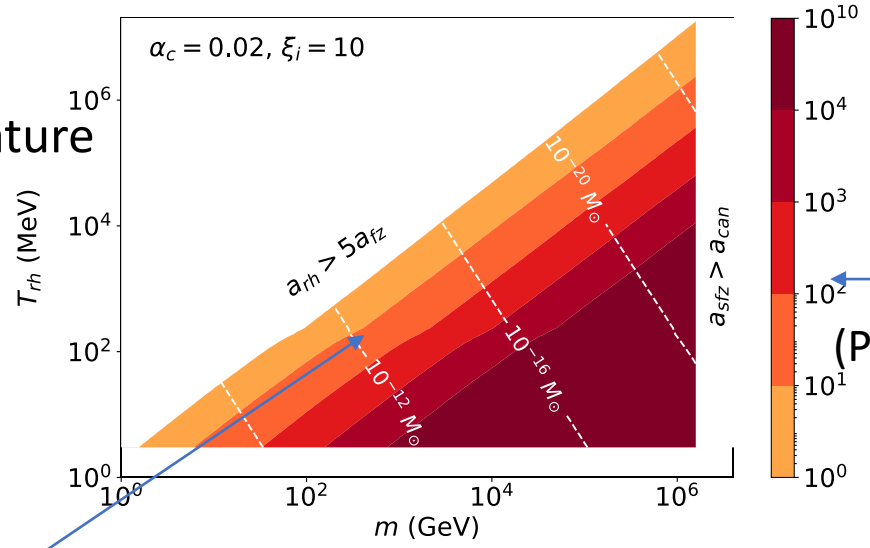
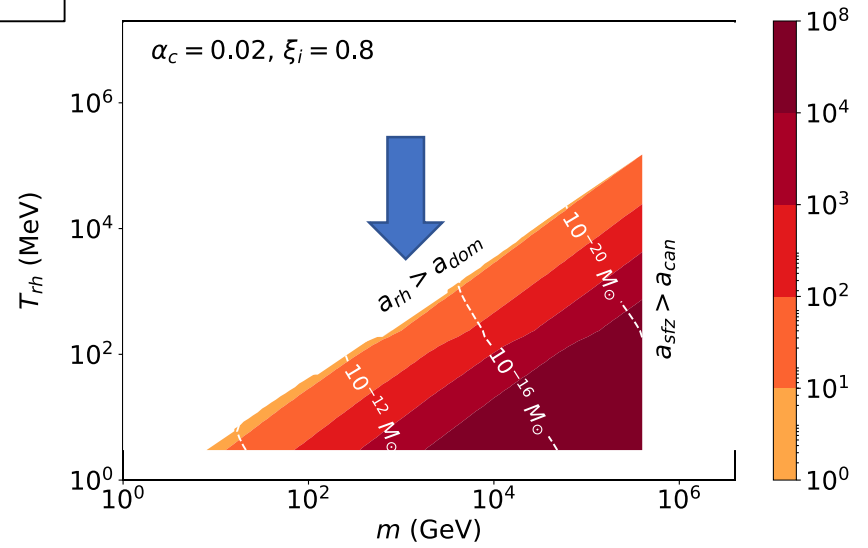


$T(k_{pk})$

(Peak transfer function)



Mass of cannibal

M_{pk}

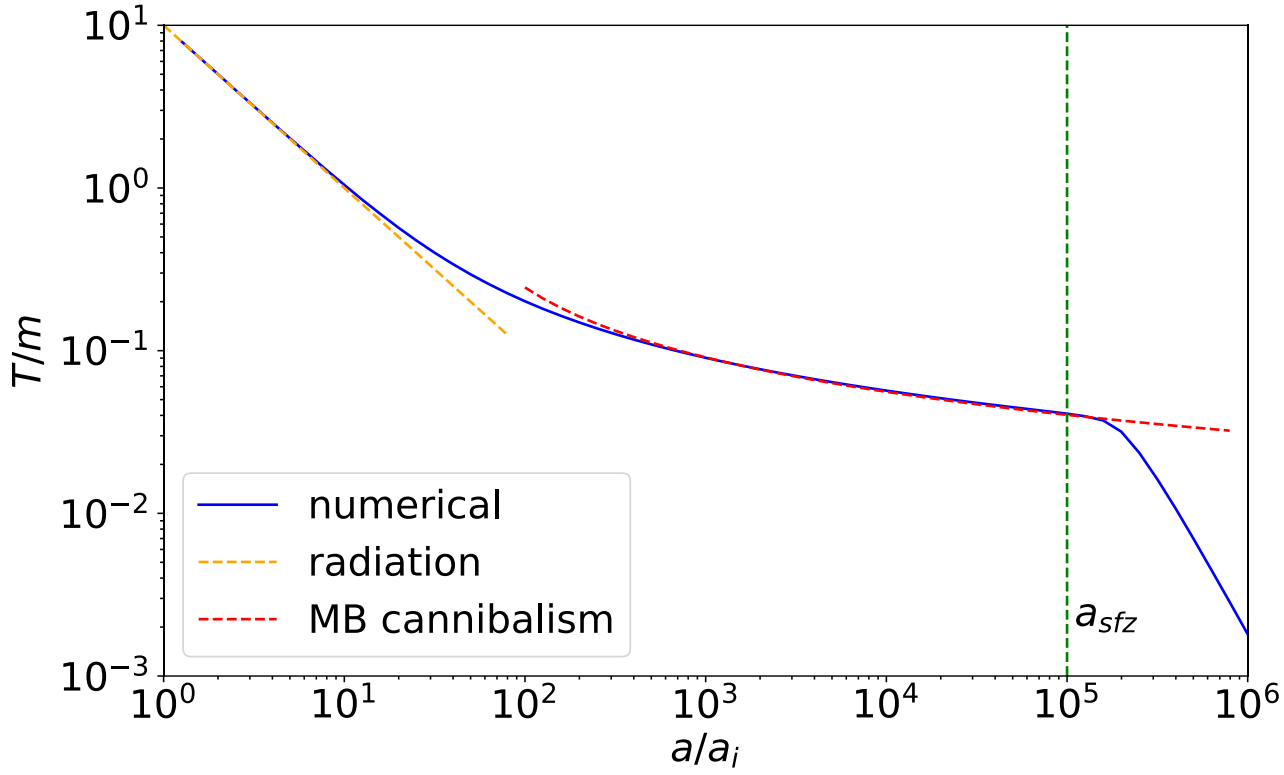
(mass of micro halos)

(arxiv: 2009.xxxx)

Summary

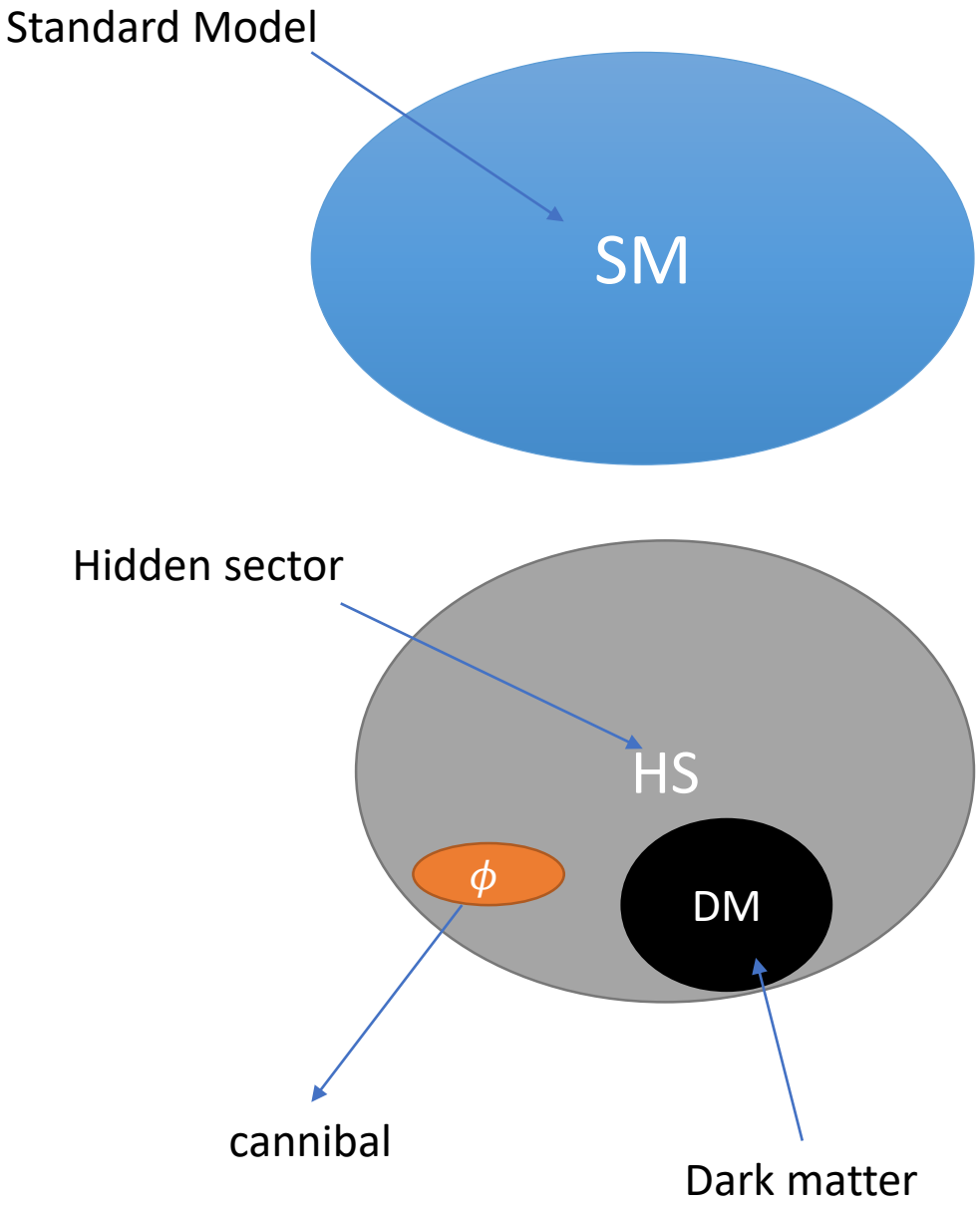
Summary

- Cannibal annihilates itself to convert rest mass energy to thermal energy



Summary

- Cannibal annihilates itself to convert rest mass energy to thermal energy
- Cannibal generically predicted in HS theories.



Summary

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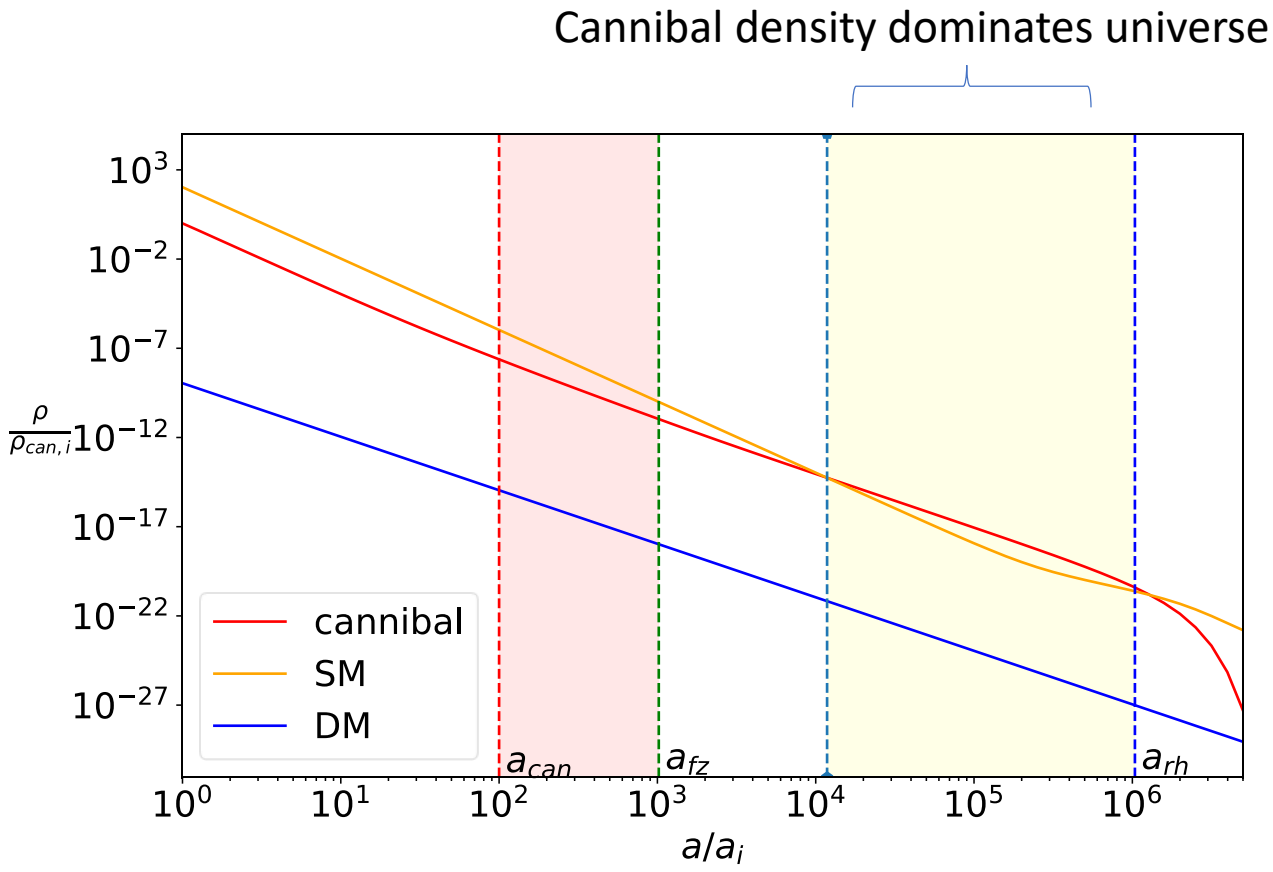
- Cannibal can lead to early matter domination.



Summary

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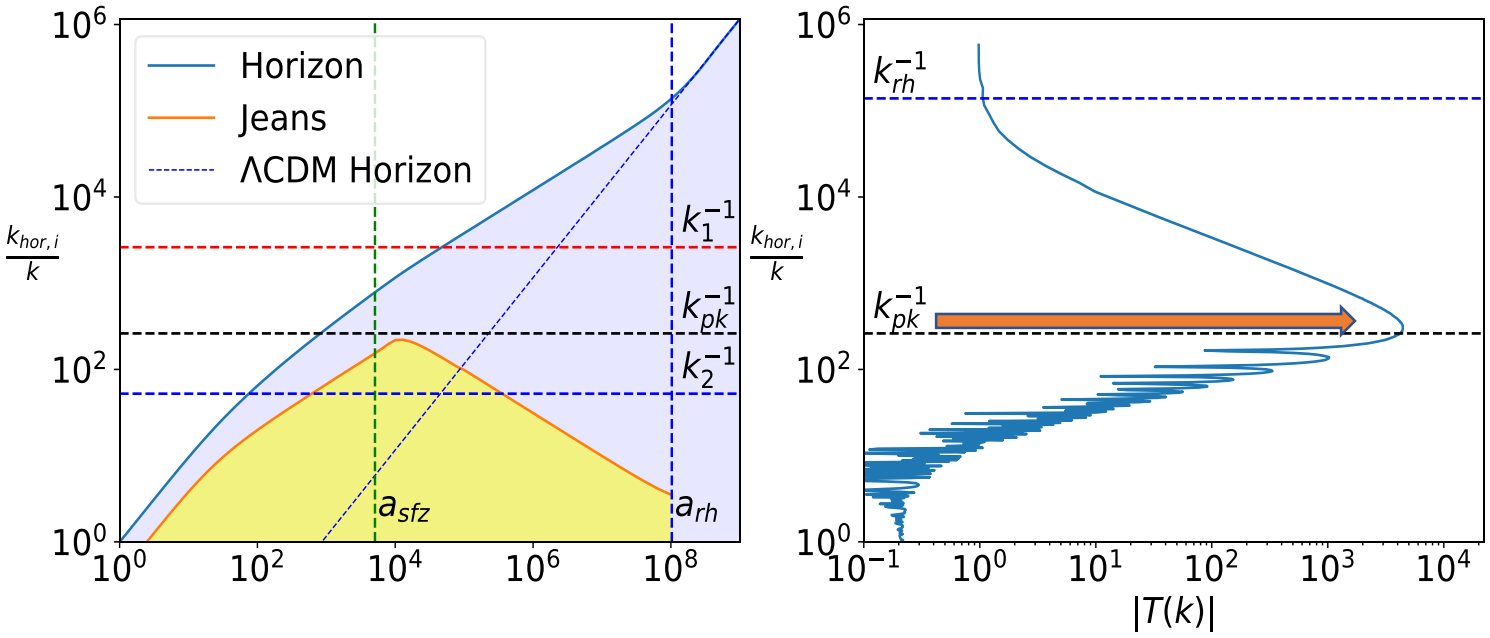

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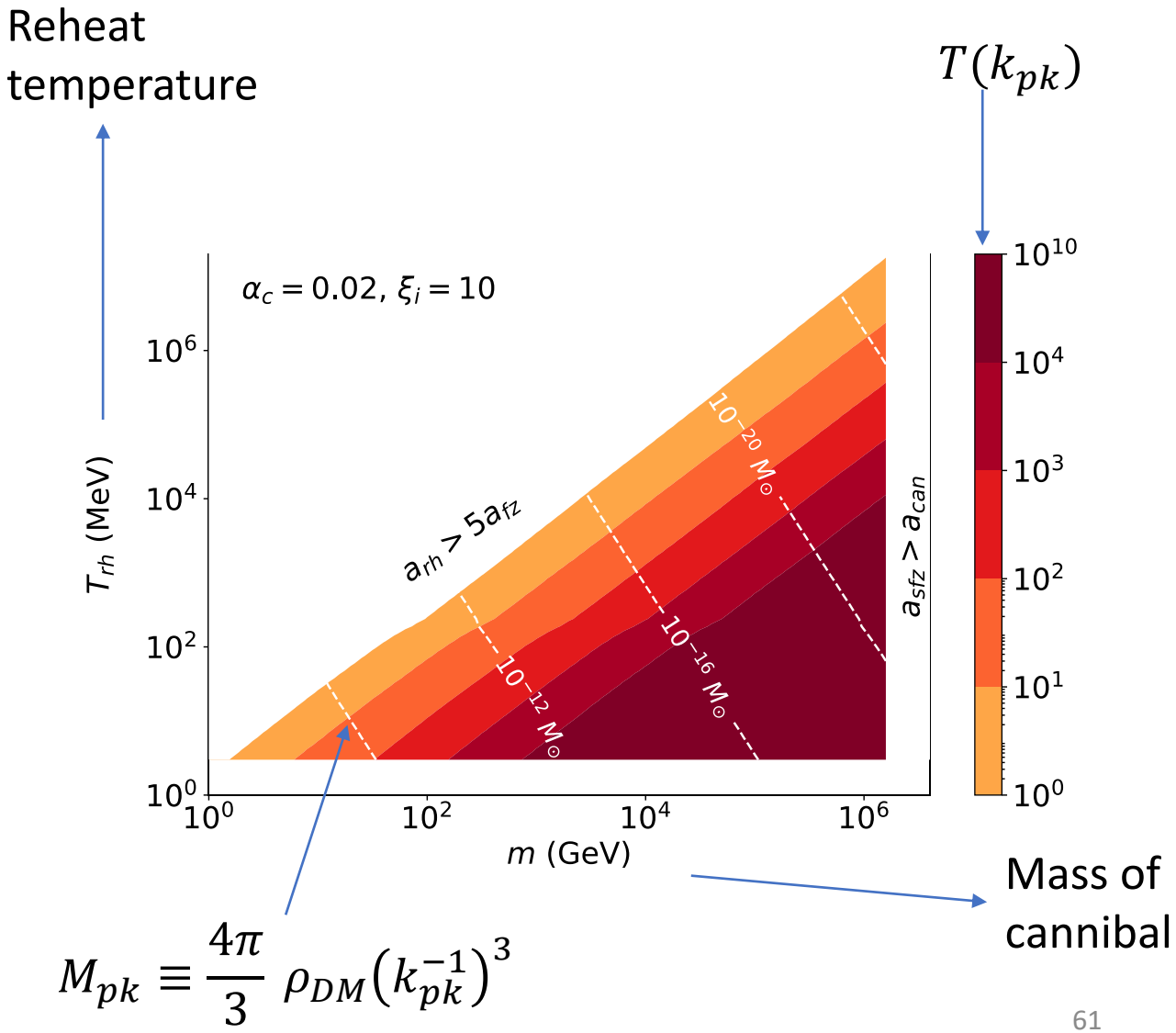
- We provide map between particle parameters and key features of matter power spectrum

Micro-halo density $\geq \left[T\left(k_{pk}\right)\right]^3$ times larger than density in standard micro-halos



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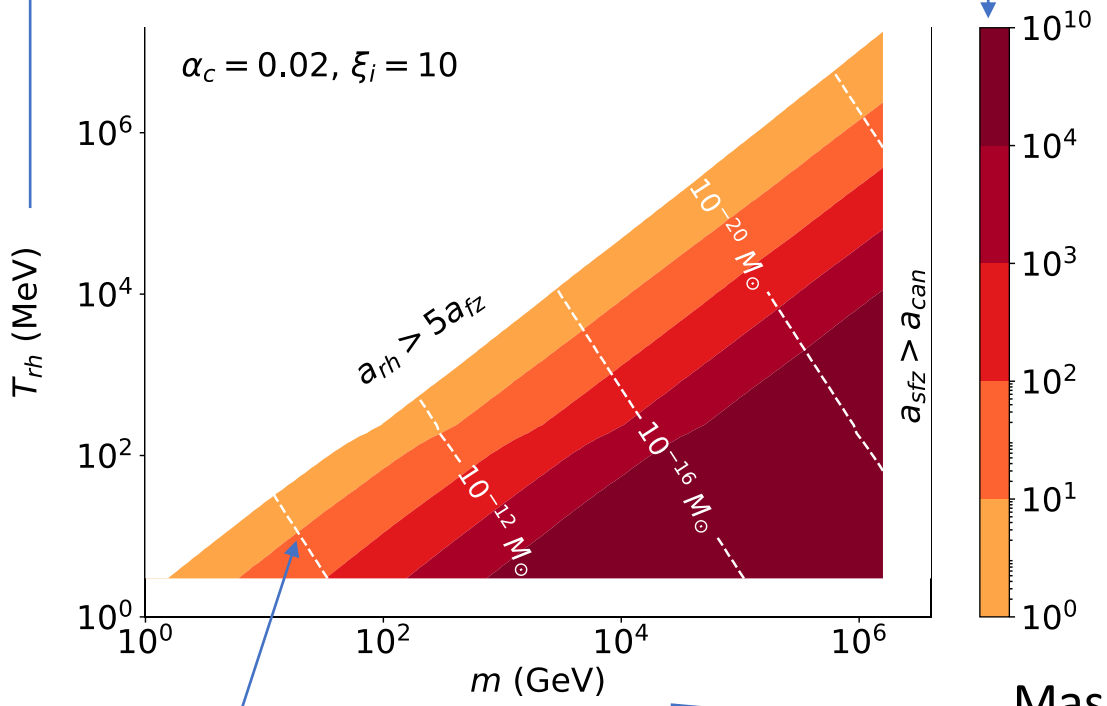
Reheat temperature

$T\left(k_{pk}\right)$



Mass of cannibal

$$M_{pk} \equiv \frac{4\pi}{3}\,\rho_{DM}\left(k_{pk}^{-1}\right)^3$$

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