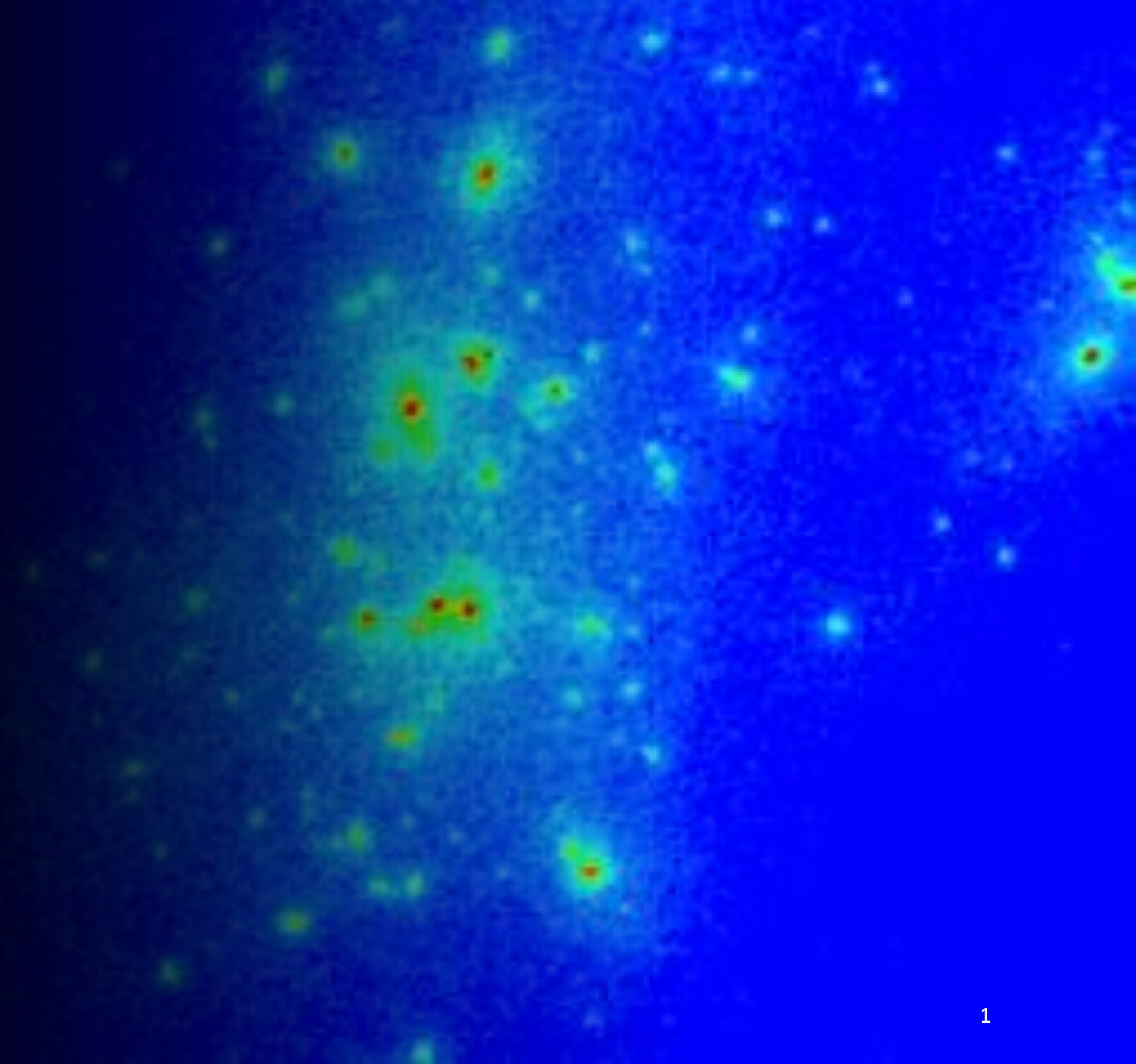


Cannibal domination and small scale structure

arxiv:2008.04311 and arxiv: 2106.09041

-Pranjal Ralegankar
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

So what is a cannibal?

- In Standard Model plasma: once T falls below the mass of a particle, the particle annihilates into lighter particles.

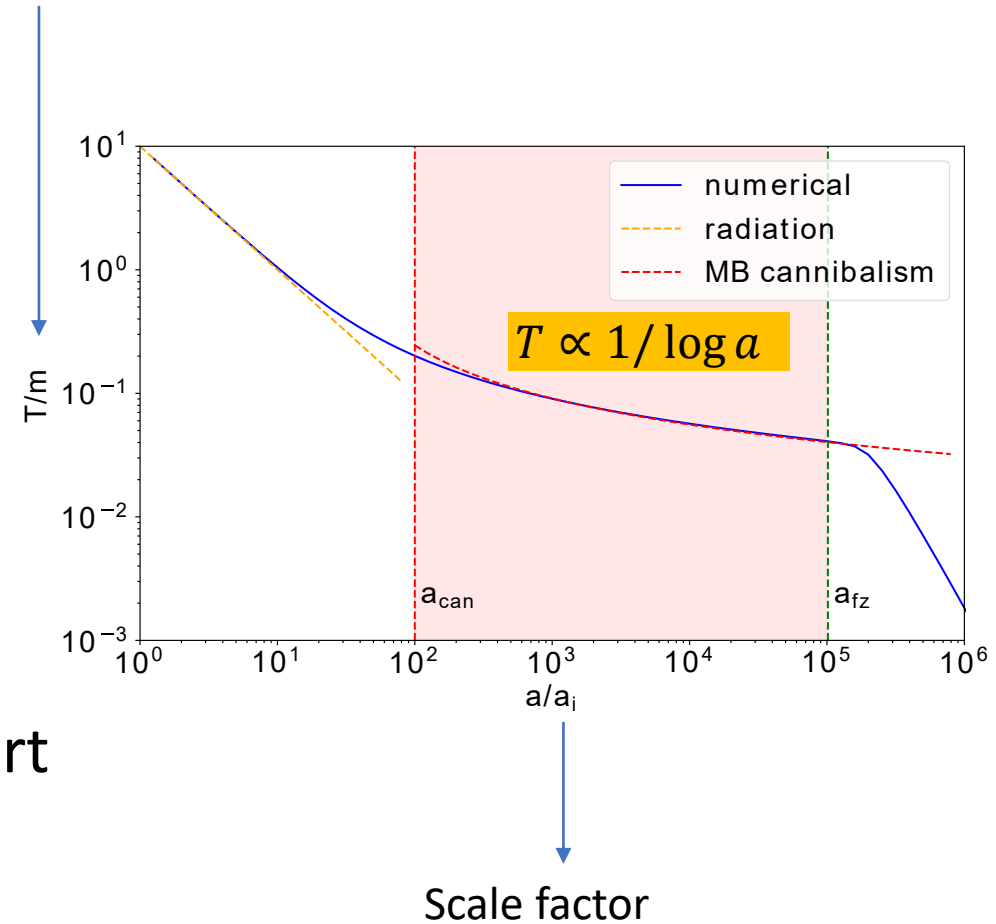
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 1. lightest particle has a mass
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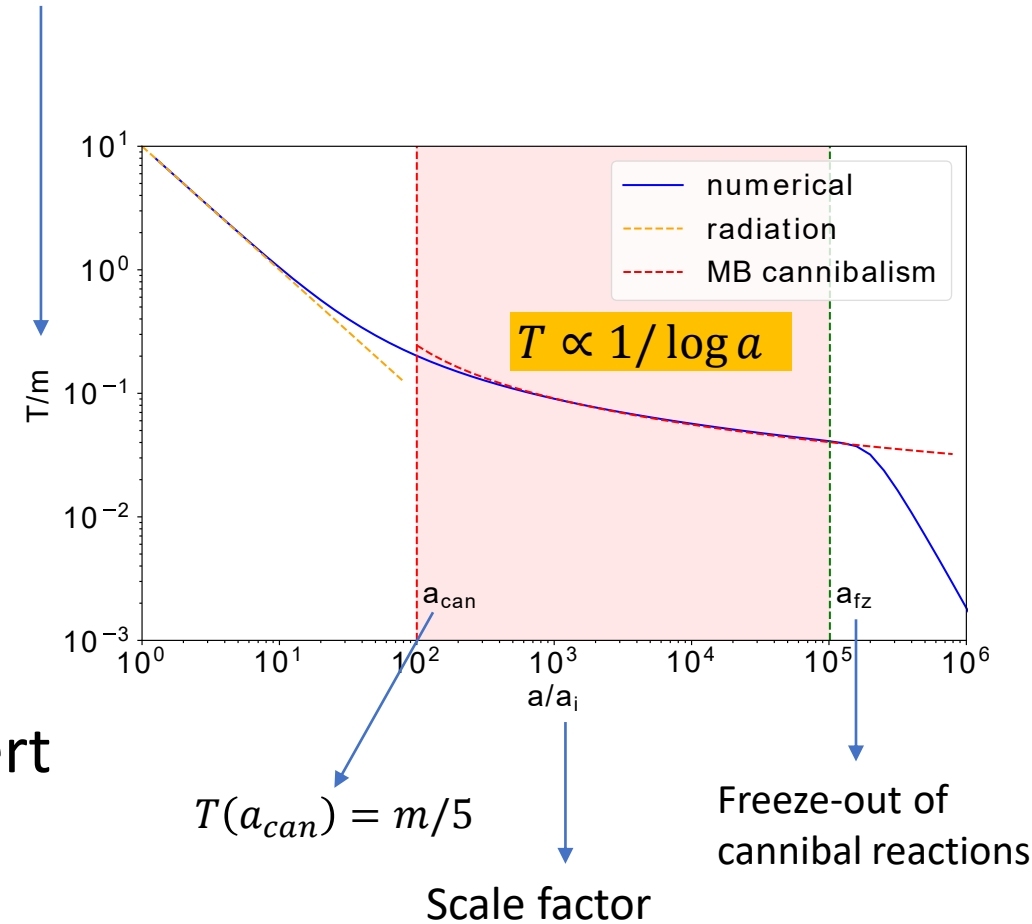
Temperature of cannibal with respect to its mass



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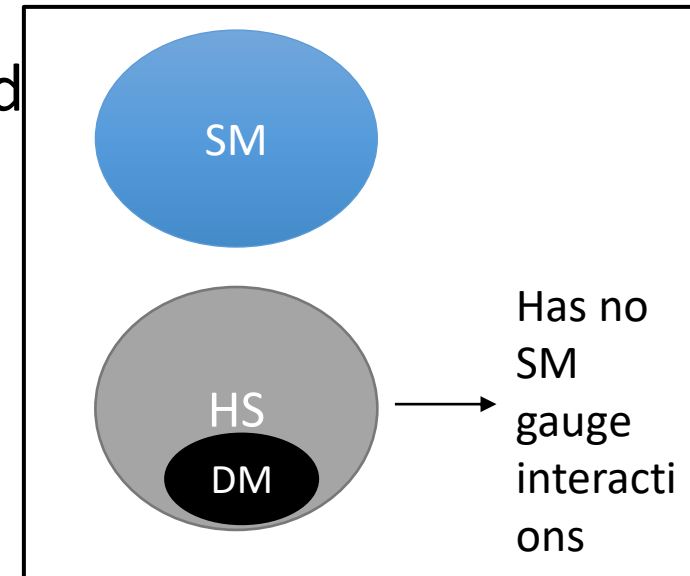


Cannibals are realized naturally in hidden sector models.

- Require: decoupled sector + mass gap + number-changing self interactions

Cannibals are realized naturally in hidden sector models.

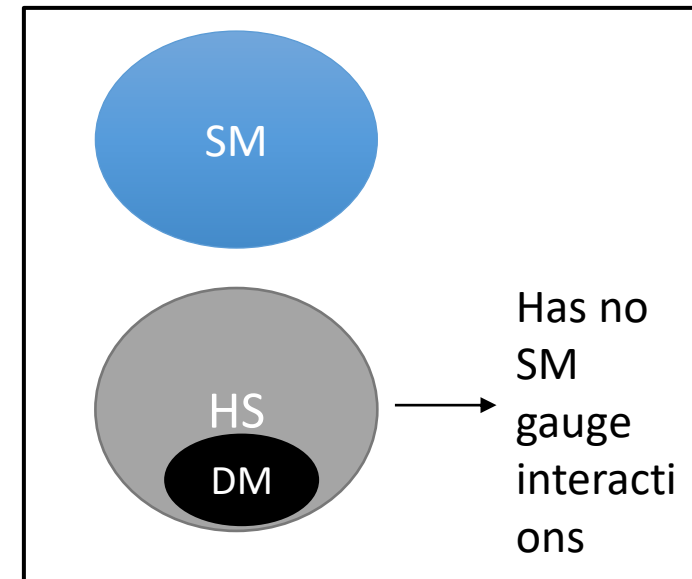
- Require: **decoupled sector** + mass gap + number-changing self interactions
- Hidden sector (HS) theories are well motivated to explain dark matter (DM):



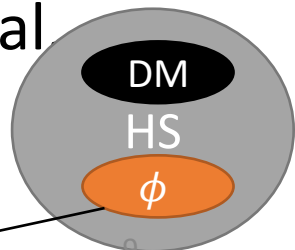
Cannibals are realized naturally in hidden sector models.

- Require: decoupled sector + mass gap + number-changing self interactions

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



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



Early matter dominated era as cosmological probe of Hidden sector theories

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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?

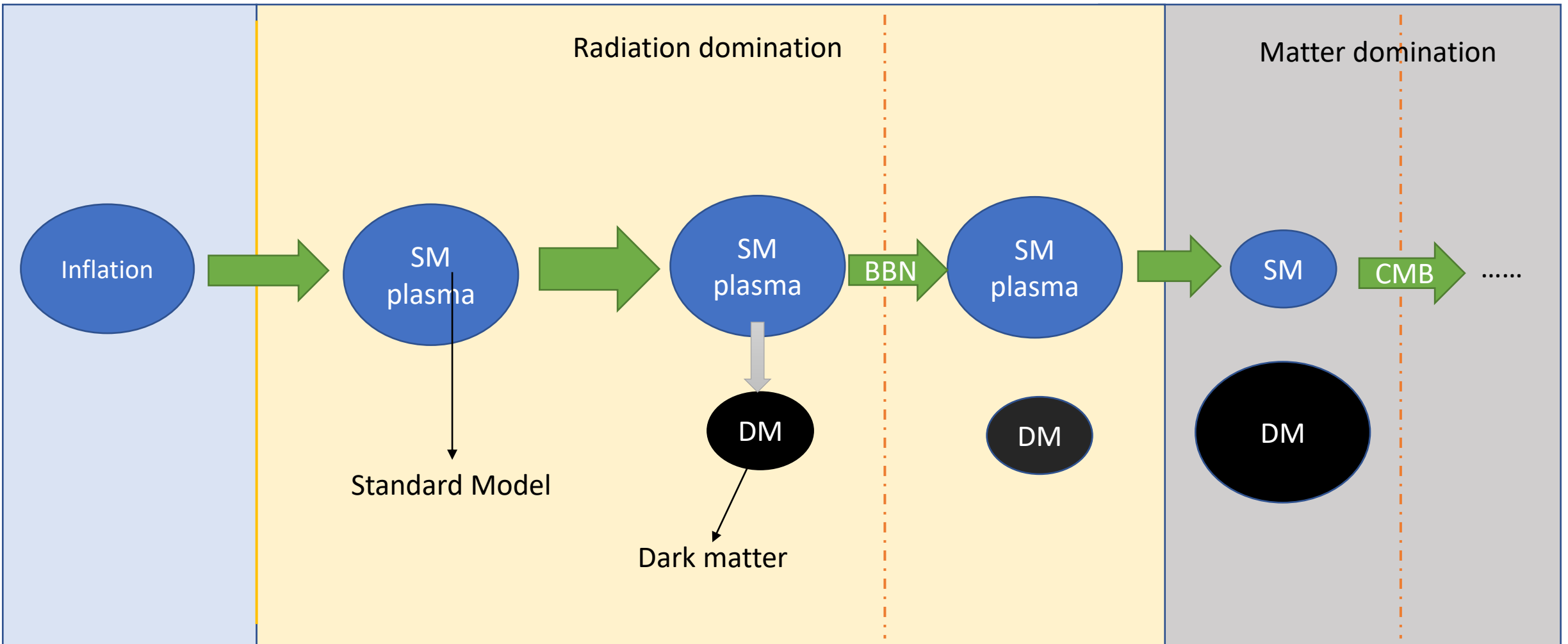
The questions we answer:

1. Link cannibal particle parameters with key matter power spectrum features
2. Estimate the kind of micro-halos produced using *linear theory*

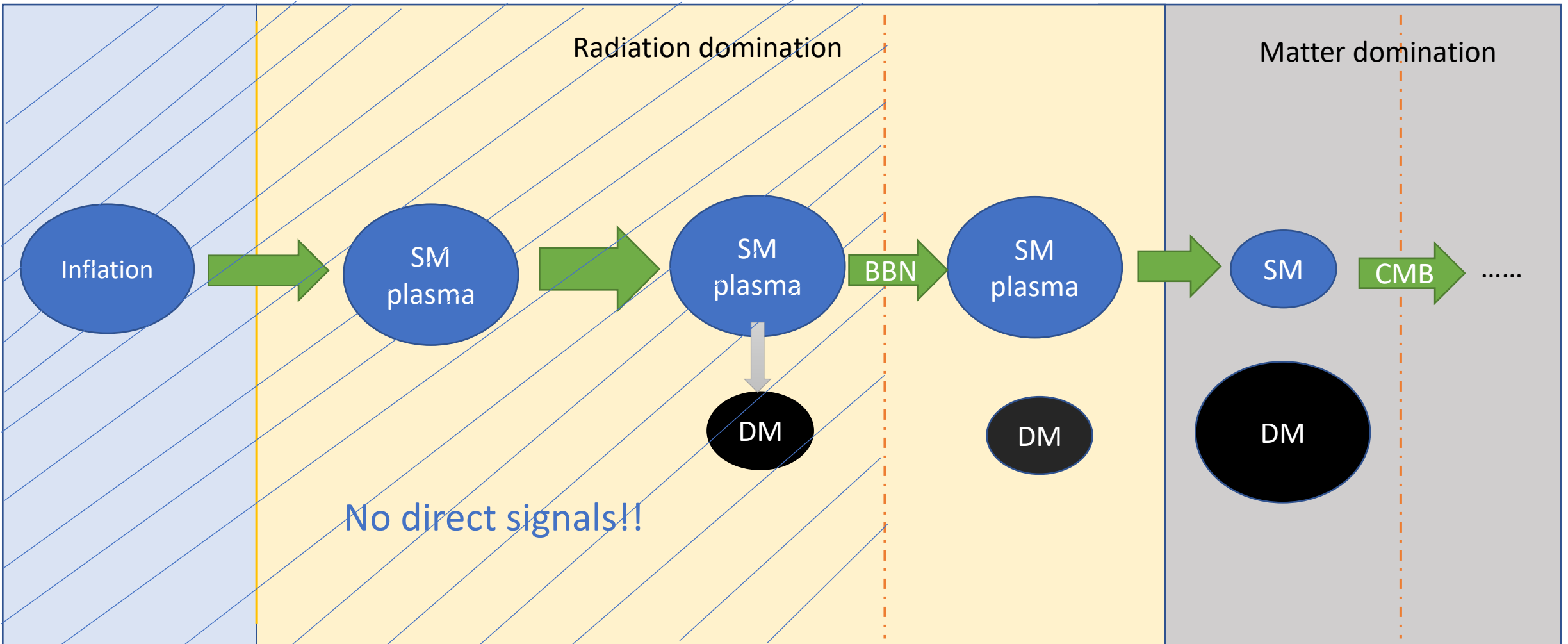
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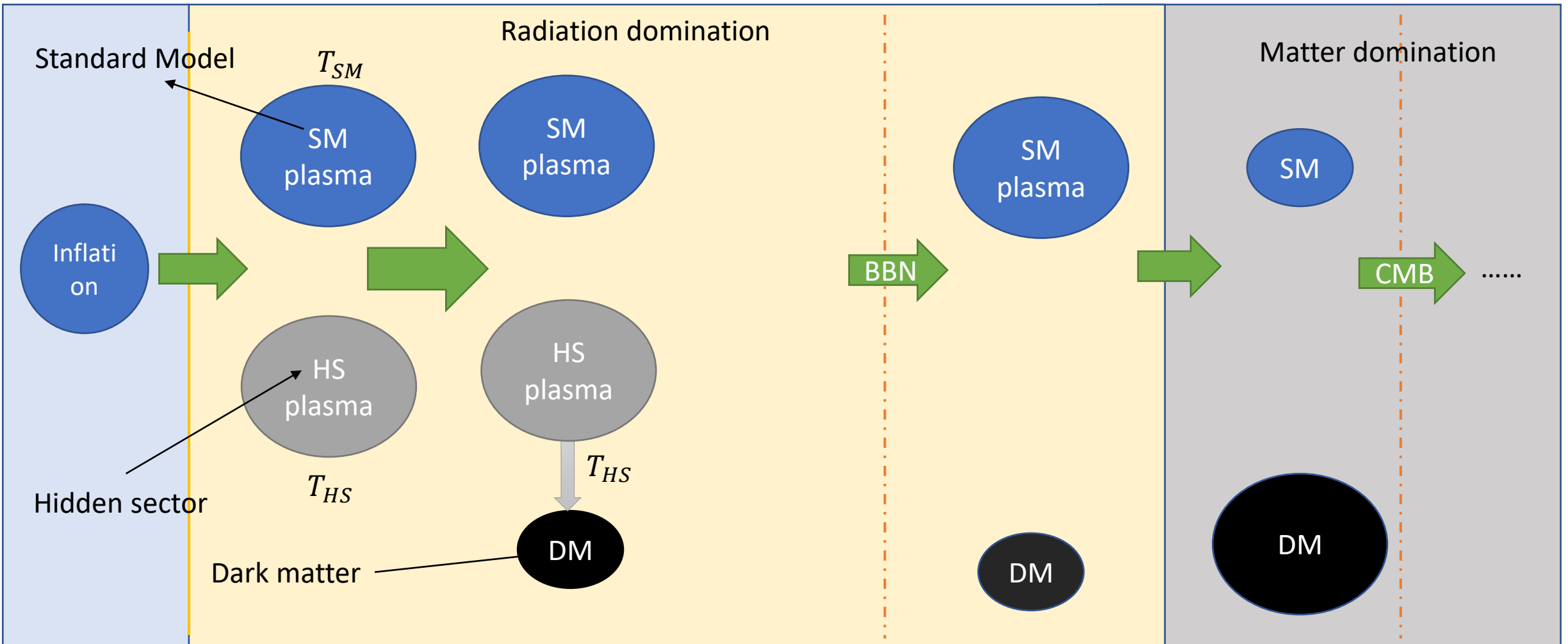
Vanilla Λ CDM cosmology



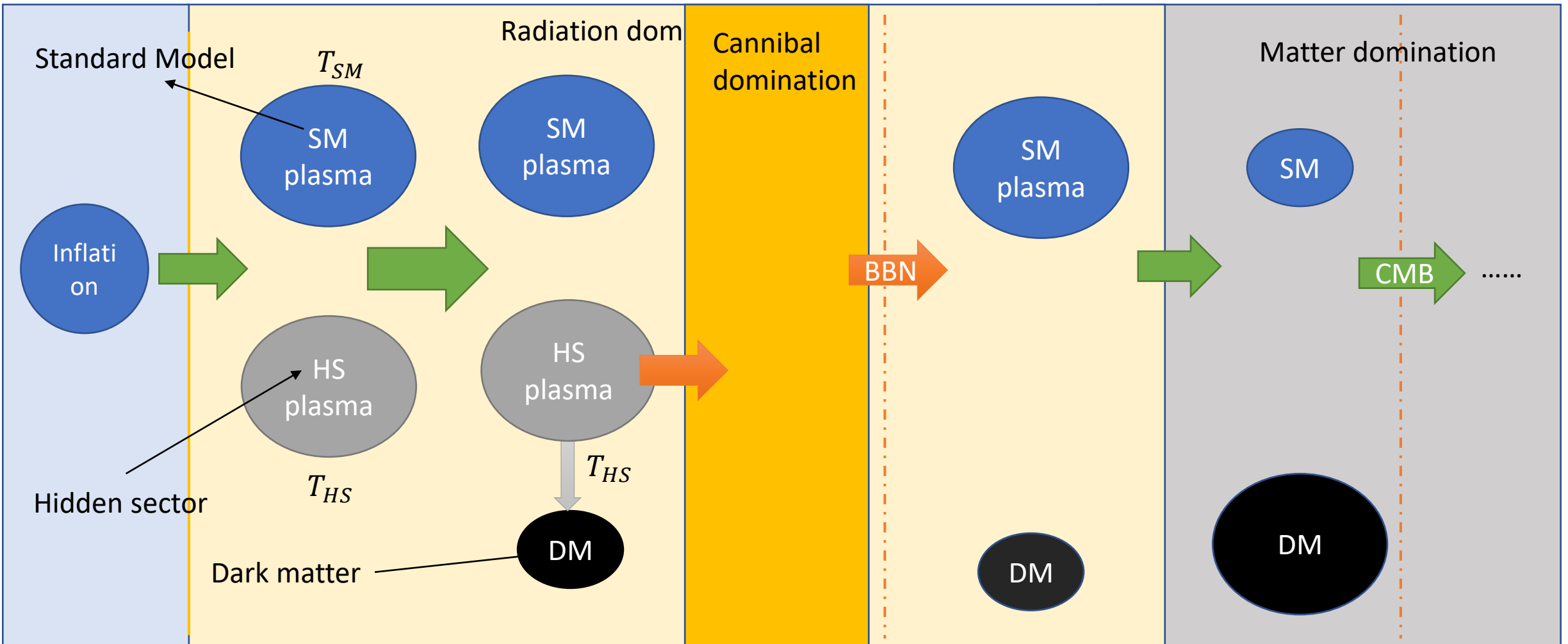
Anything can occur before BBN



Hidden sector cosmology



Hidden sector cosmology with cannibal domination

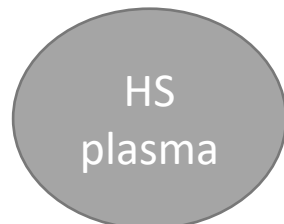
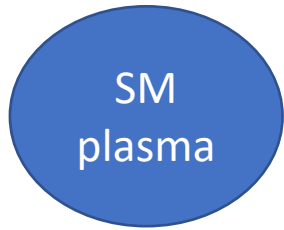


Cannibal can naturally cause an 'early matter dominated era'



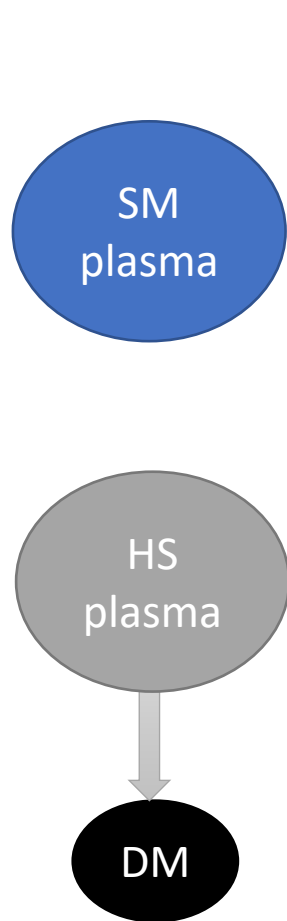
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only lightest particle
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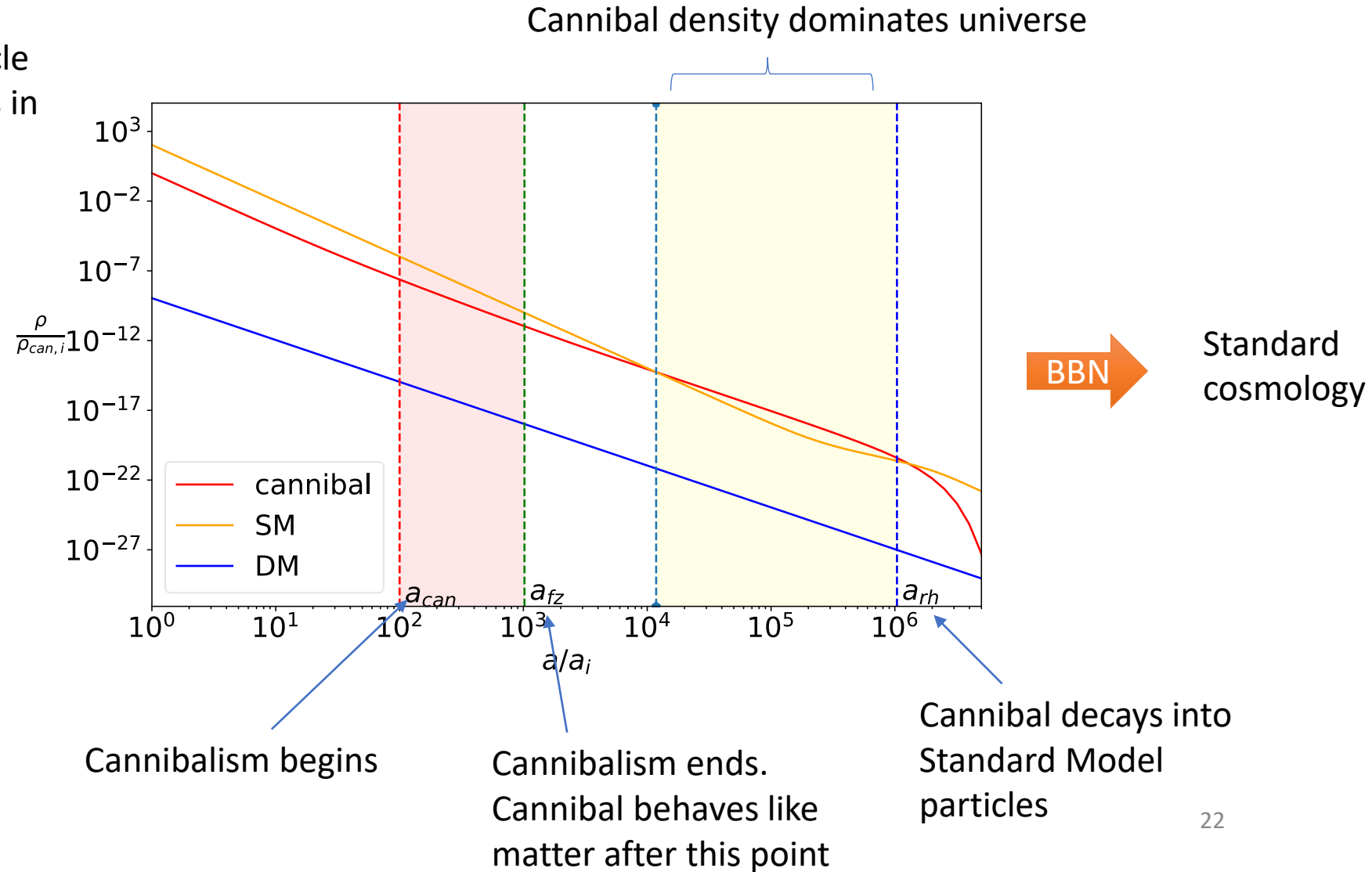


Standard
cosmology

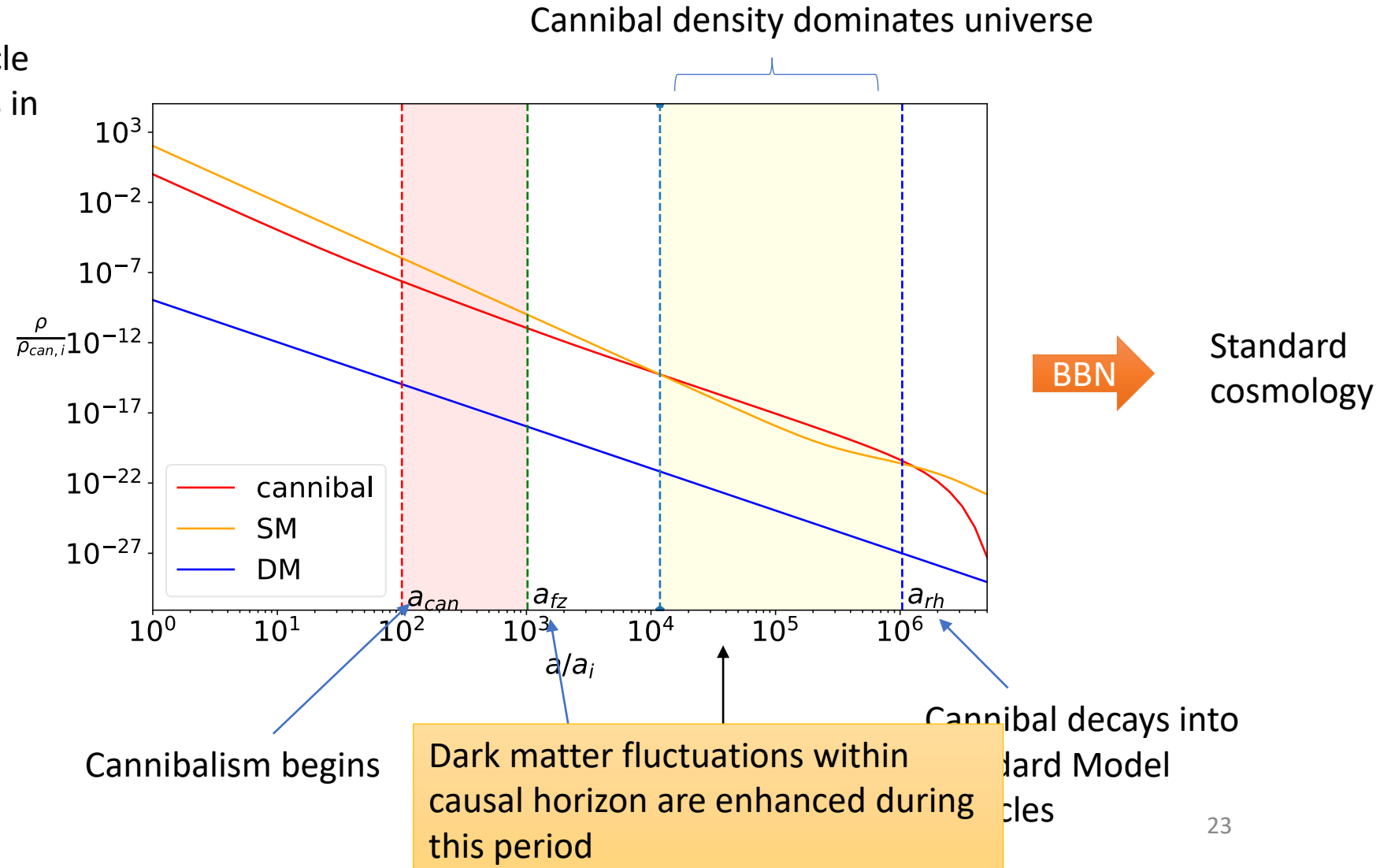
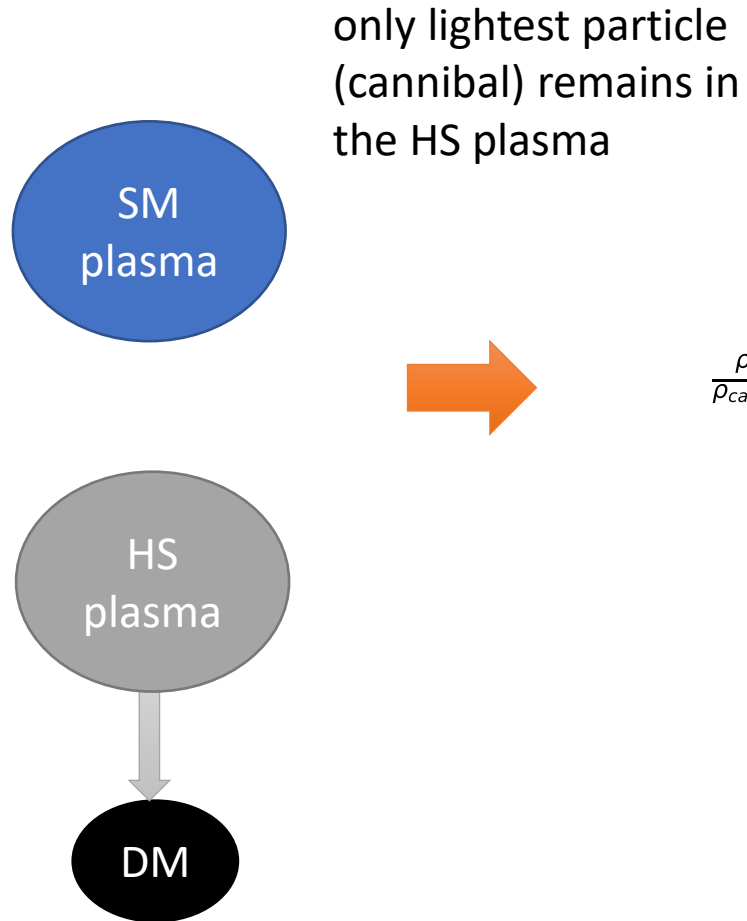
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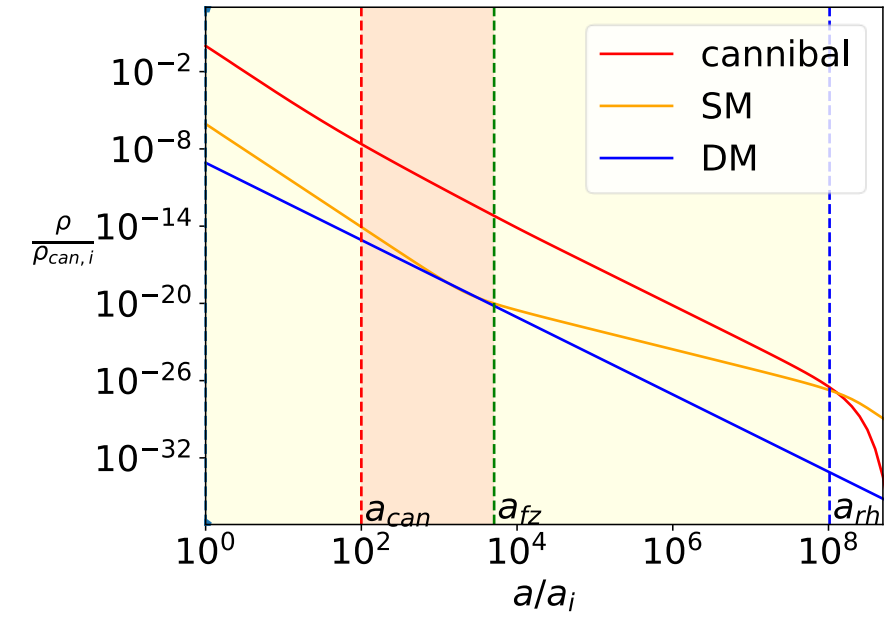
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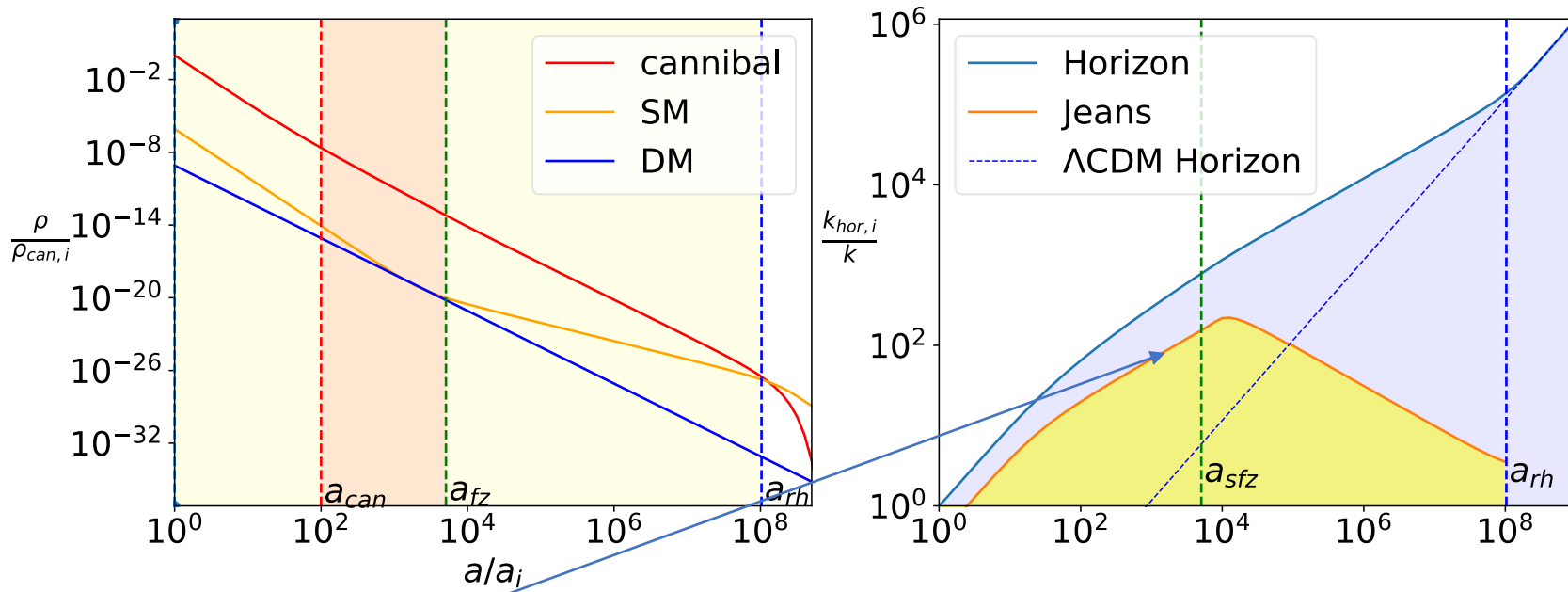
Cannibal can naturally cause an 'early matter dominated era'



Perturbation evolution: Subdominant SM-energy density



Perturbation evolution: Cannibal Jeans length

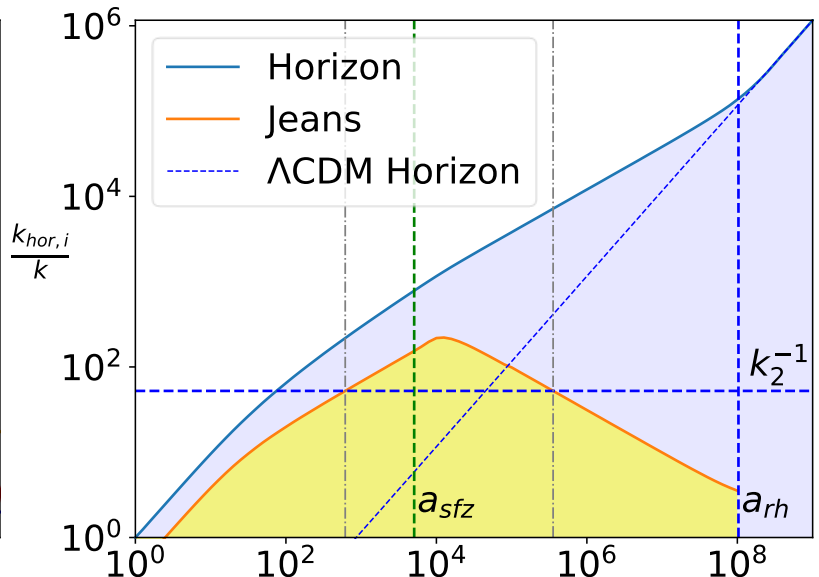
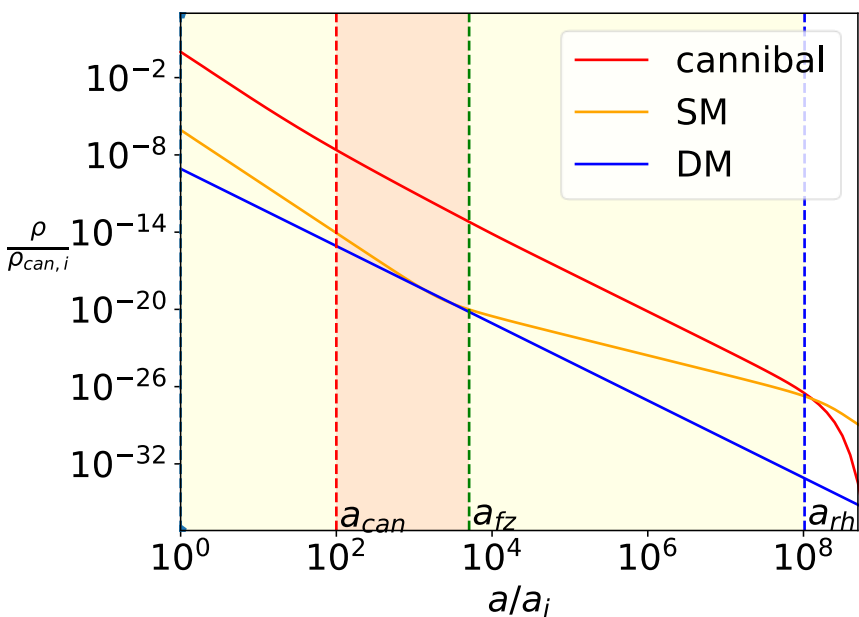


$$k_J^{-1} = \sqrt{\frac{2}{3(1+w_c)} \frac{c_s}{aH}}$$

Cannibal sound speed

Cannibal equation of state

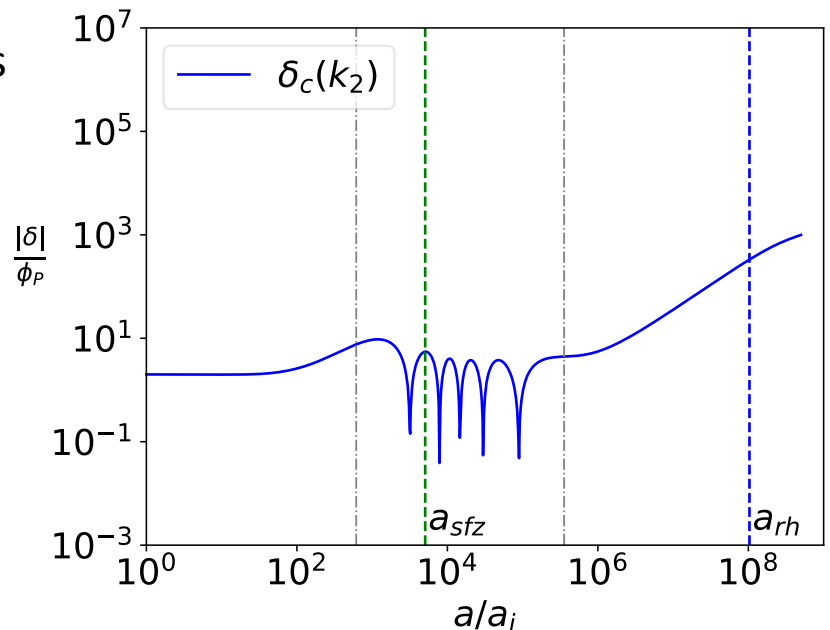
Perturbation evolution: Oscillations within Jeans length



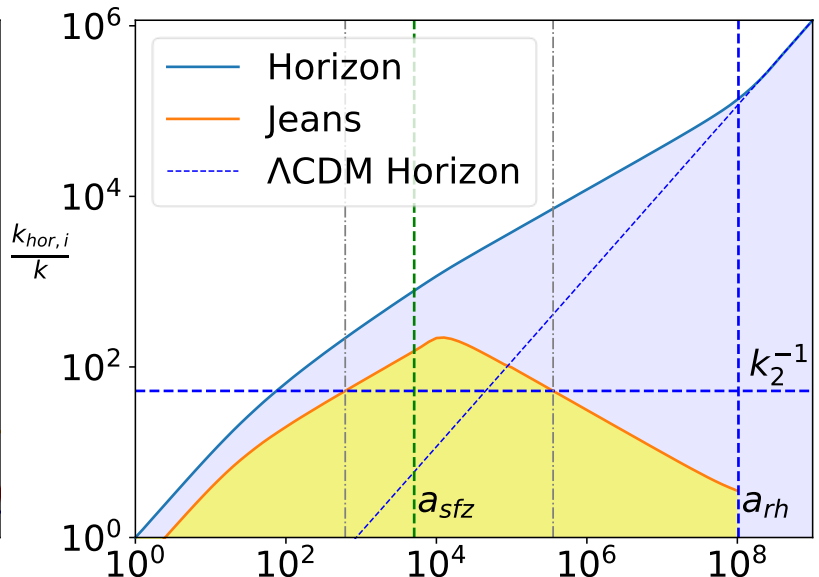
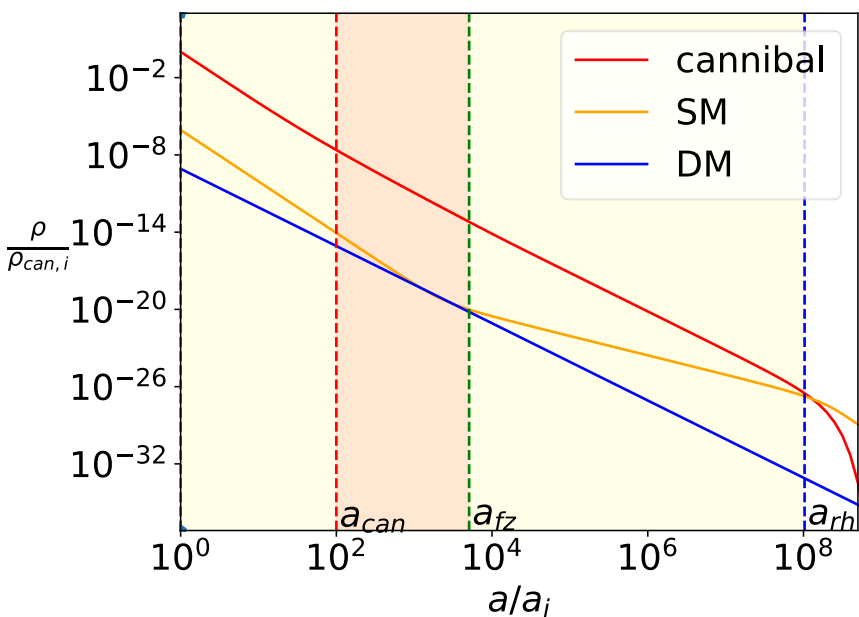
δ_c : Cannibal density perturbations

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Cannibal sound speed (points to c_s)
 Cannibal equation of state (points to w_c)



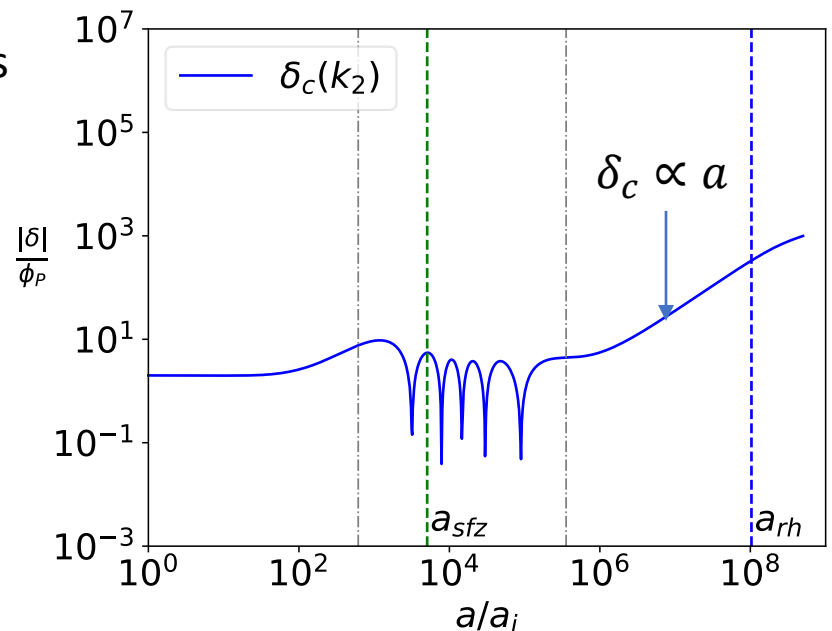
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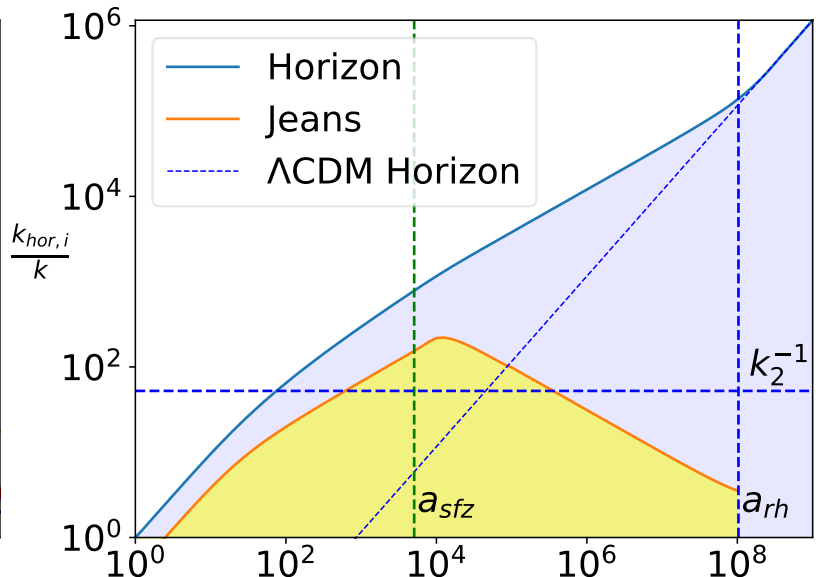
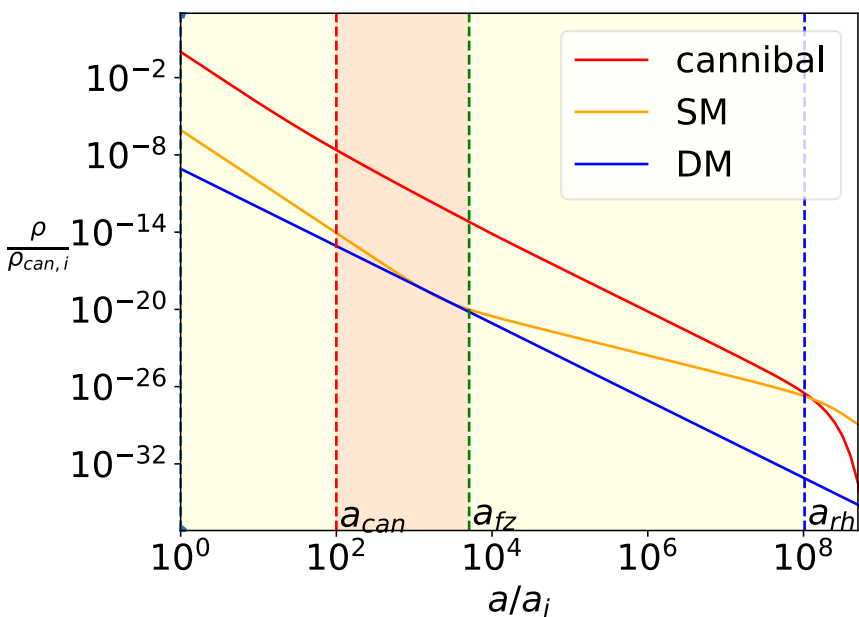
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Cannibal sound speed $\rightarrow c_s$
 Cannibal equation of state $\rightarrow 1+w_c$



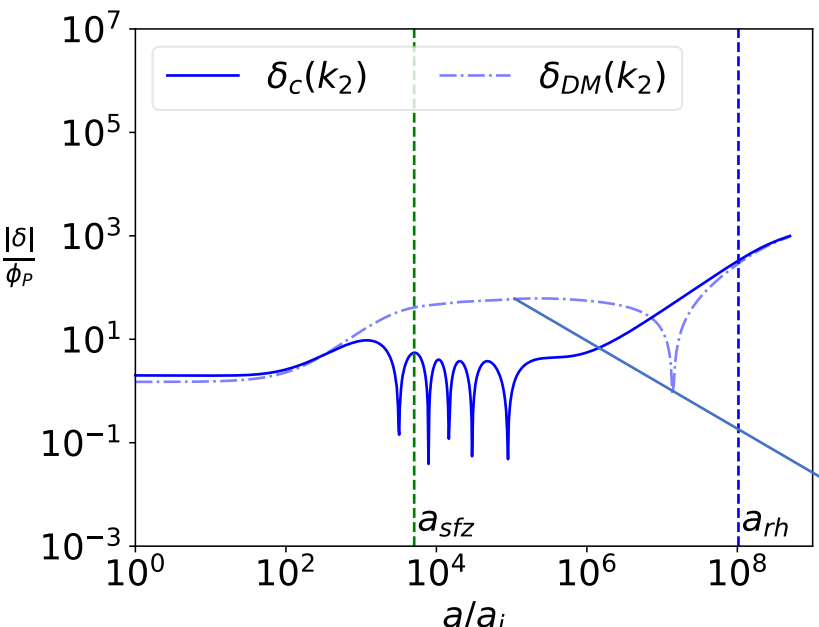
Perturbation evolution: DM falls into cannibal gravitational well



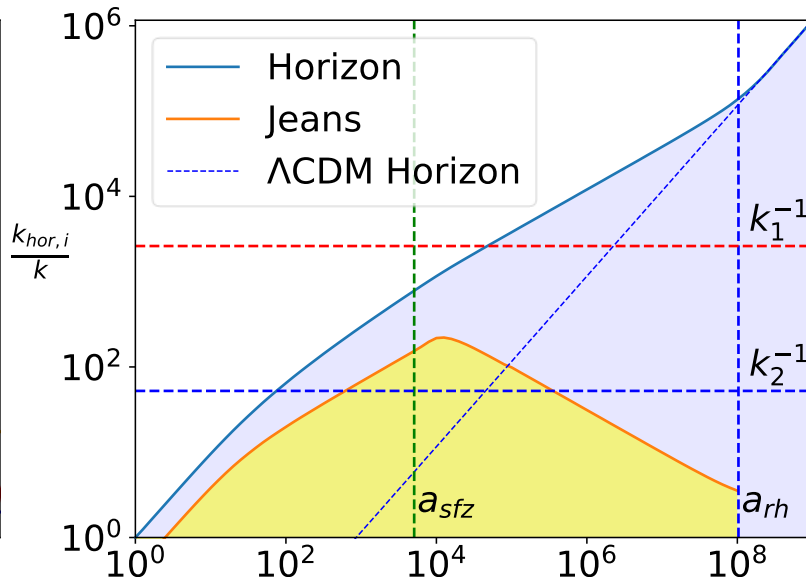
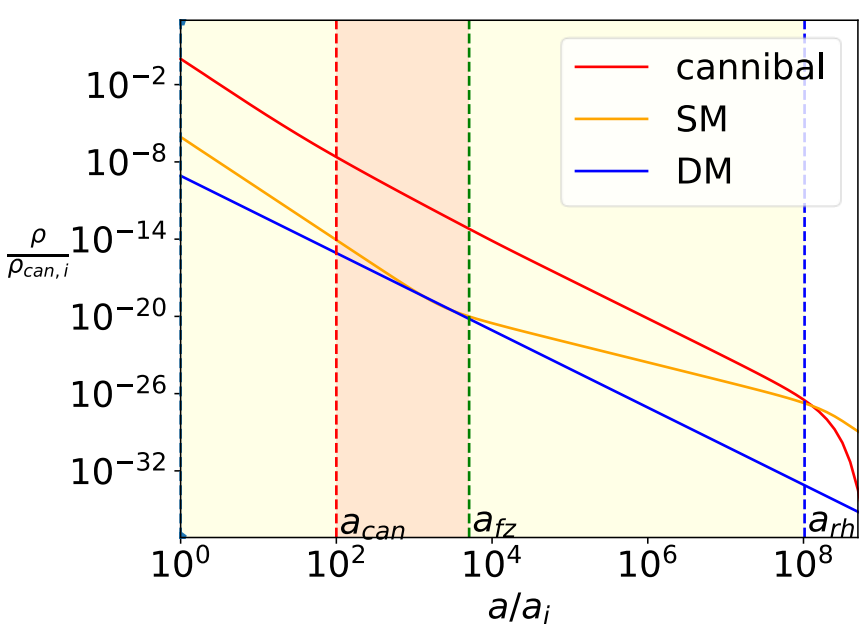
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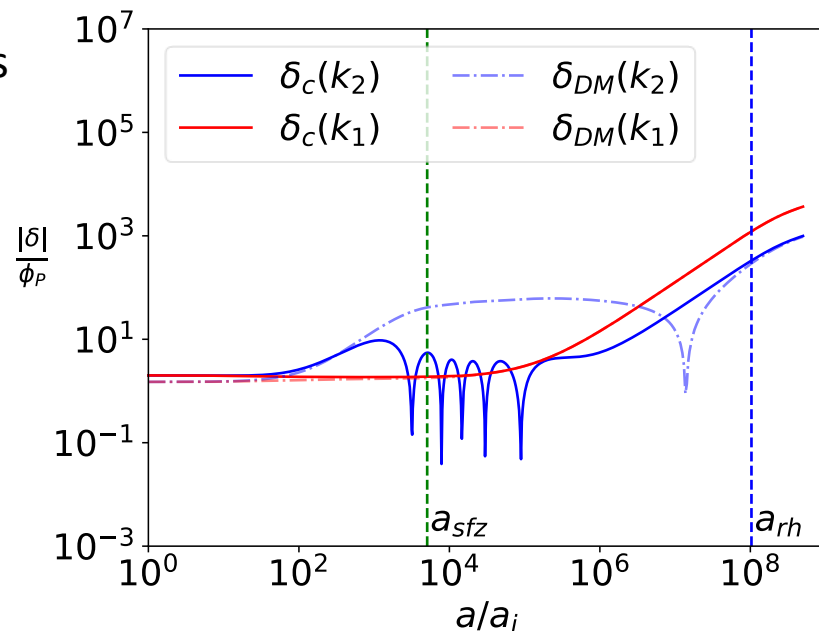
Perturbation evolution: Known EMDE evolution for modes entering horizon after cannibal freeze-out



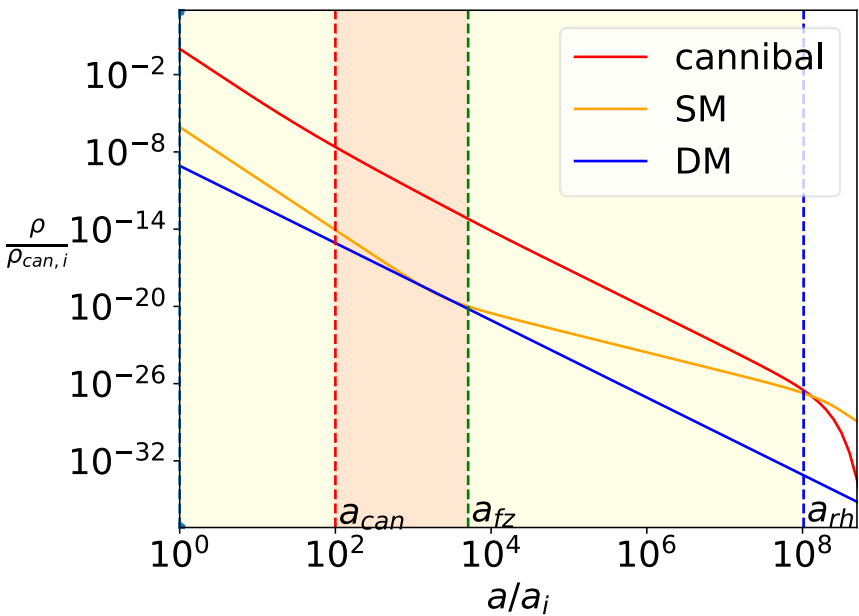
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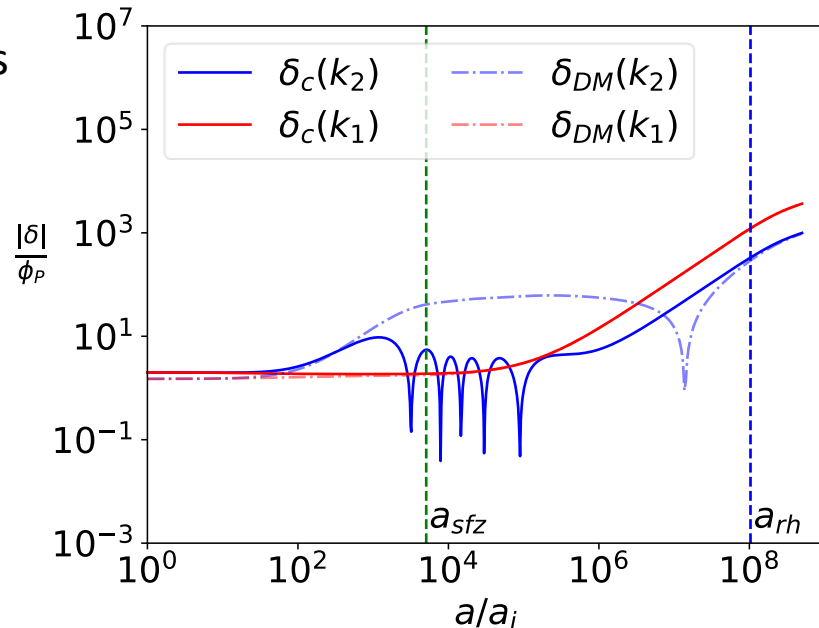
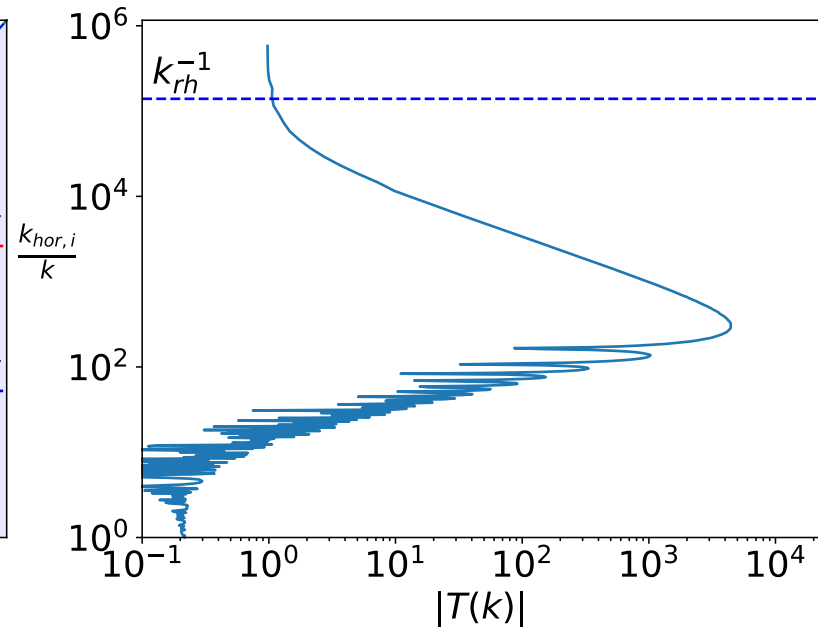
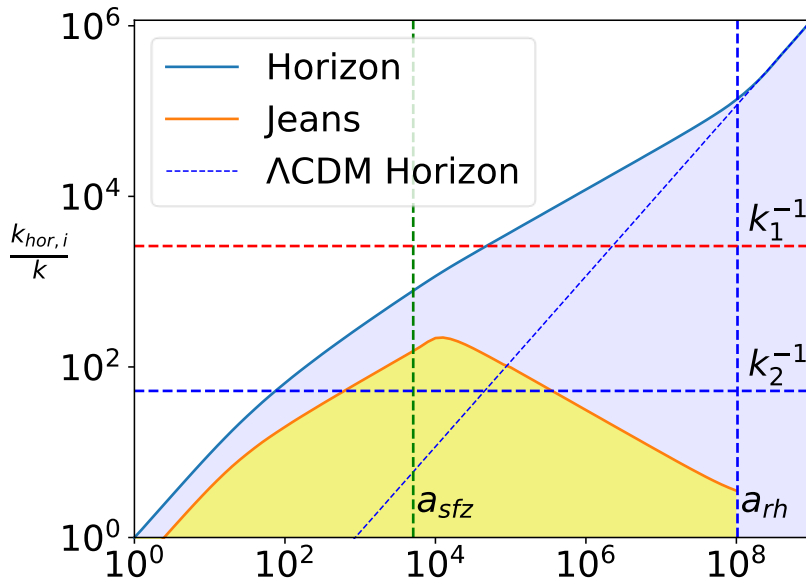
Perturbation evolution: Transfer function



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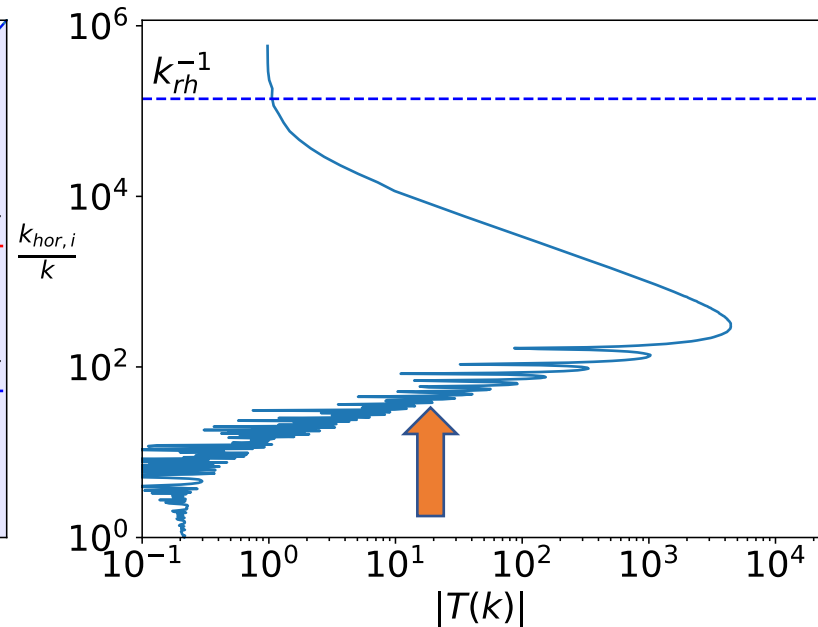
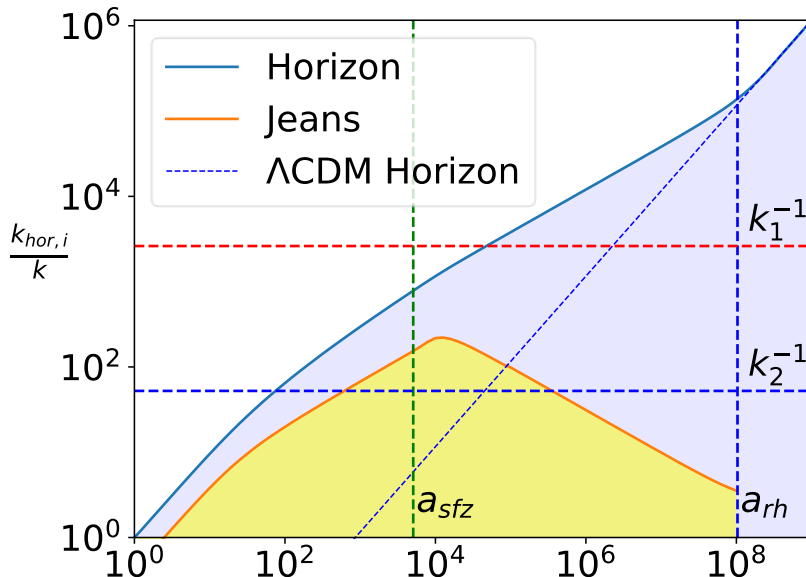
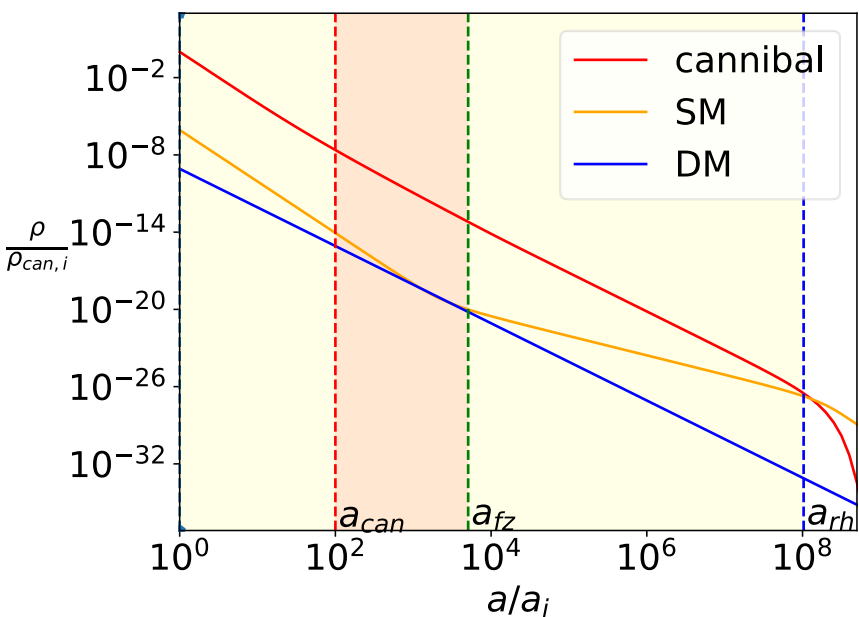
Cannibal sound speed
 Cannibal equation of state



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

DM perturbation in Λ CDM

Transfer function: Dark acoustic oscillations purely from gravitational couplings

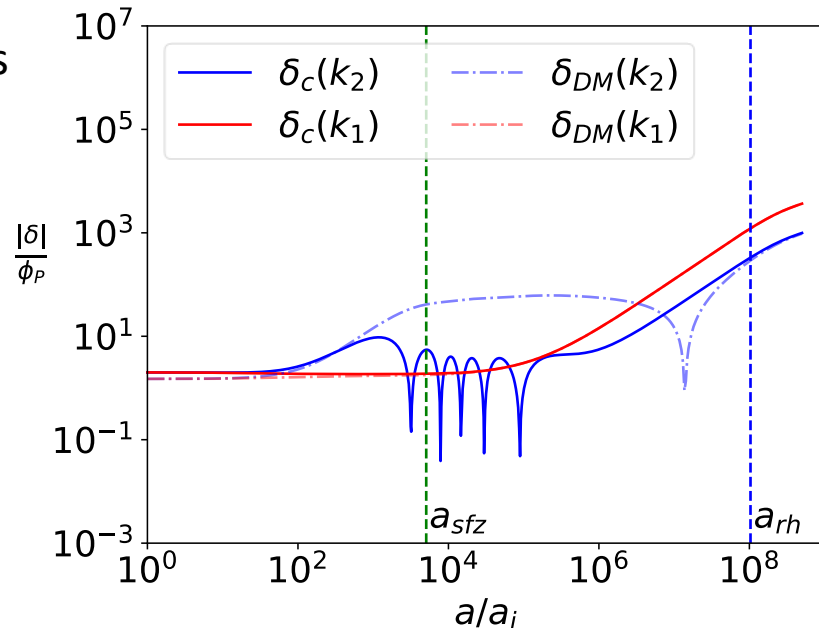


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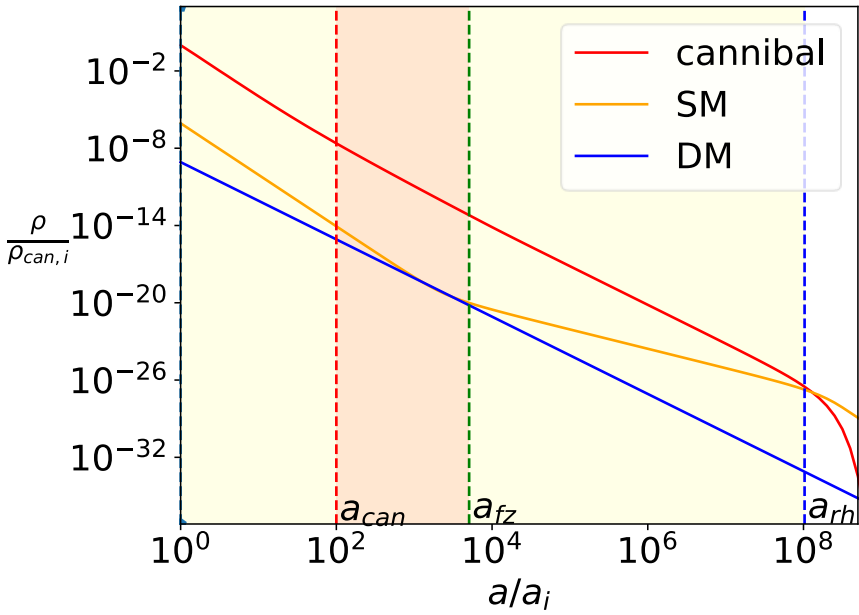
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DM perturbation in Λ CDM

Transfer function: Peak given by Jeans horizon

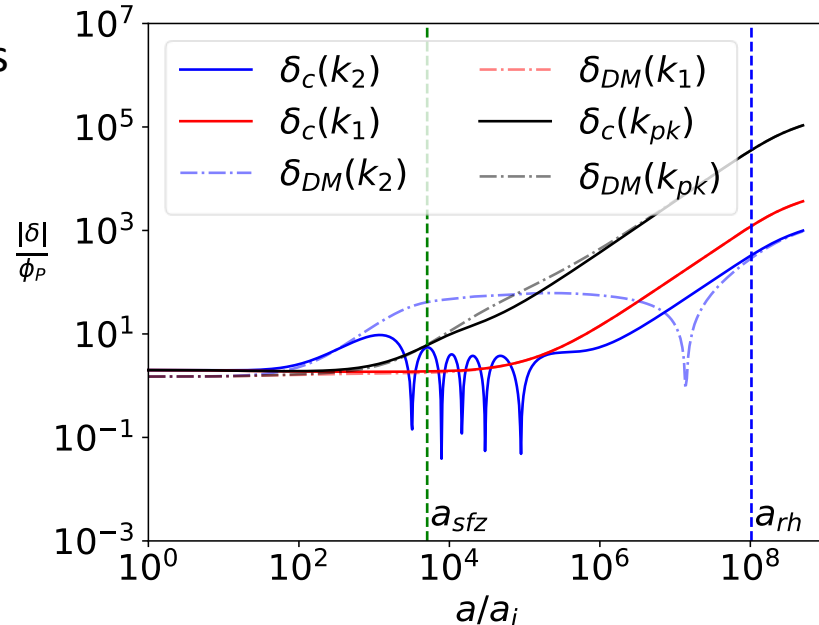
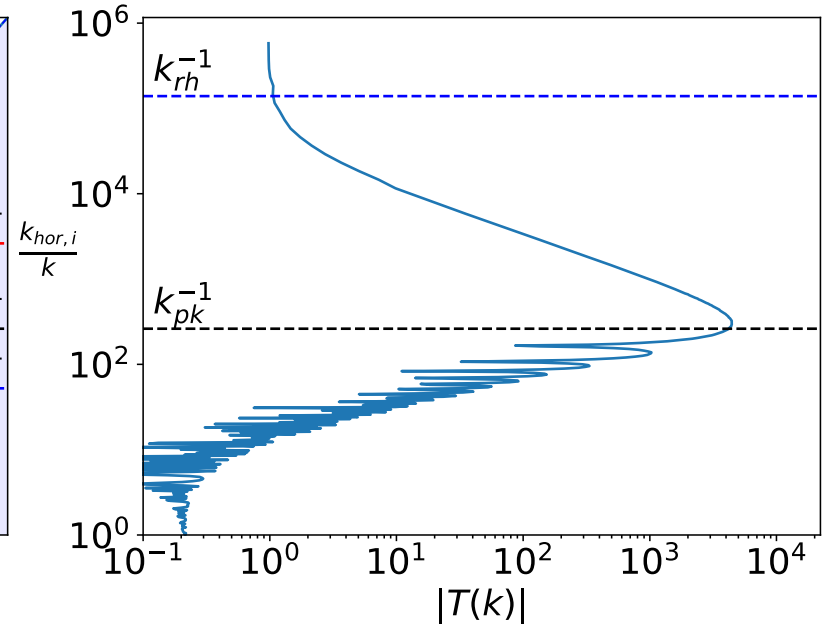
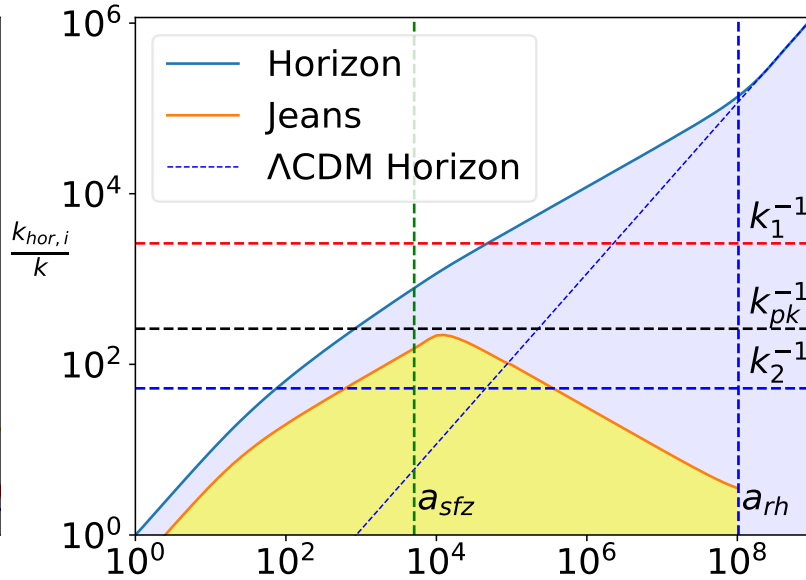


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Cannibal sound speed

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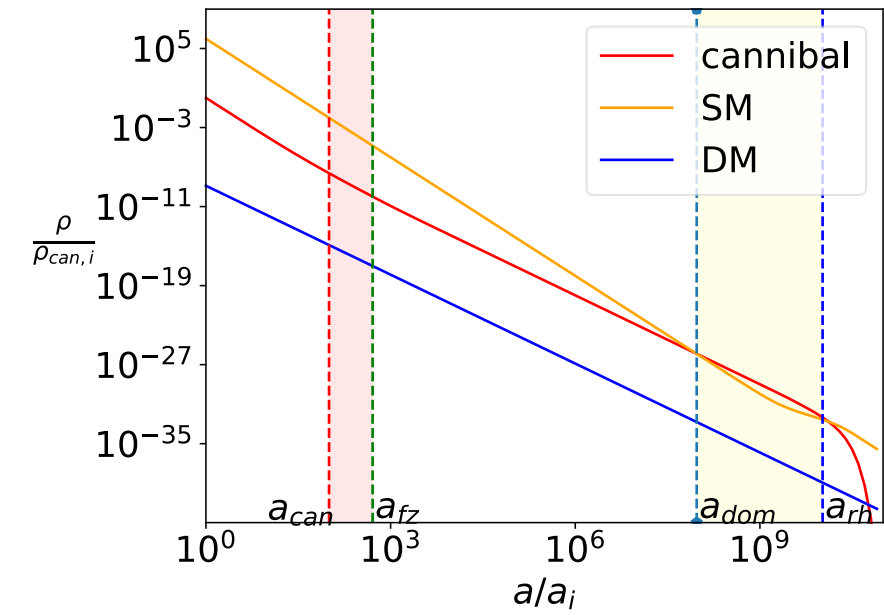
$$k_{pk}^{-1} \approx k_J^{-1}(2a_{fz})$$

(arxiv: 2008.04311)

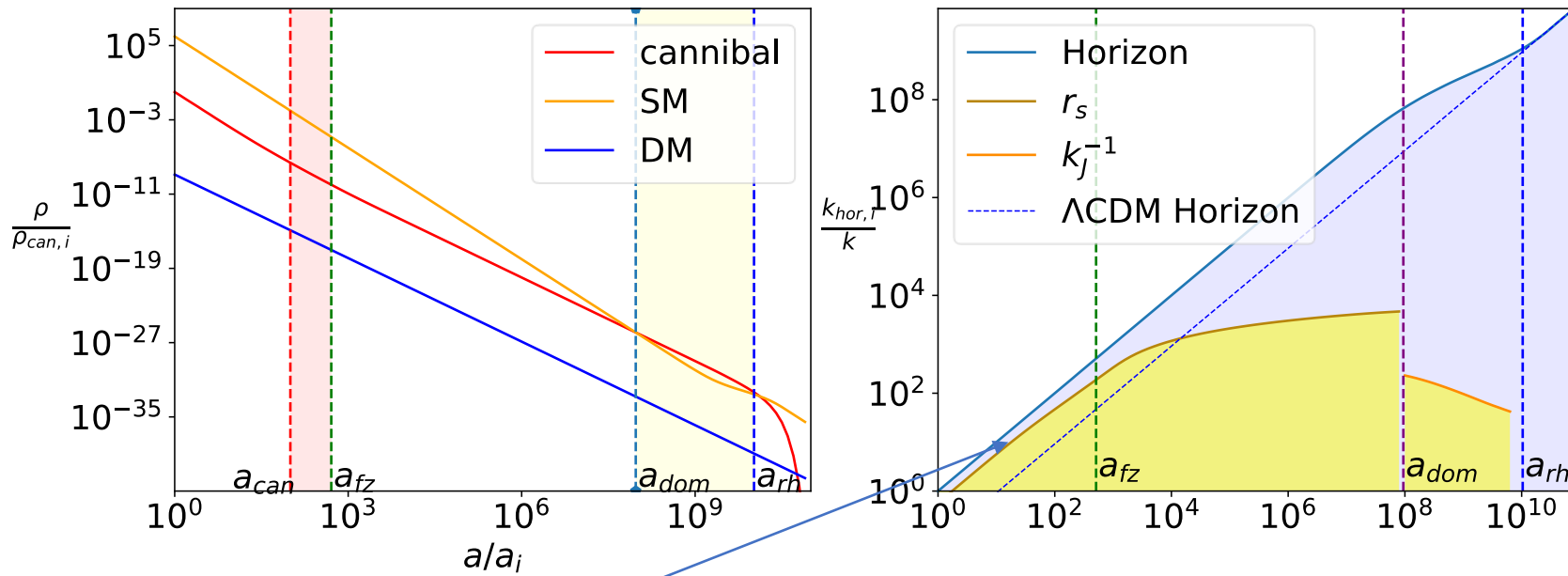
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DM perturbation in Λ CDM

Perturbation evolution: SM radiation domination during cannibal freeze-out



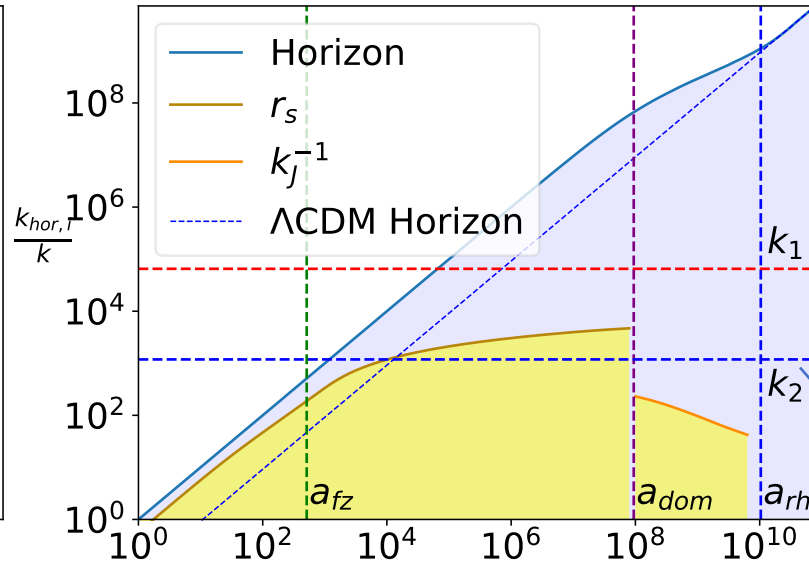
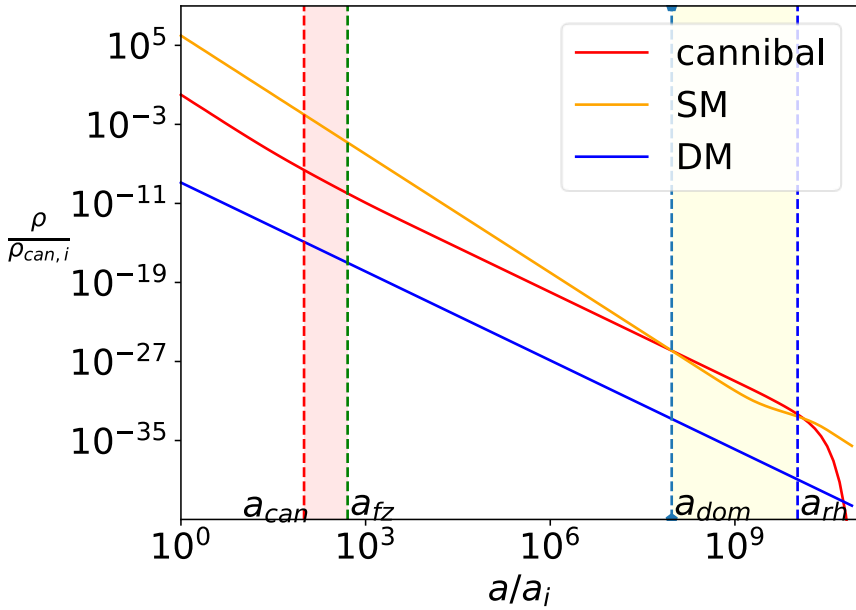
Perturbation evolution: SM radiation domination during cannibal freeze-out => relevant scale is sound horizon!



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

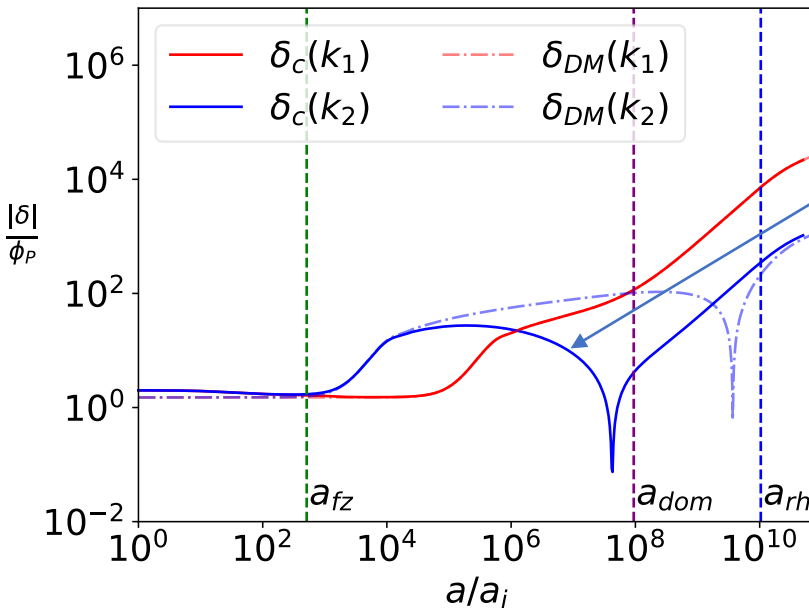
Cannibal sound speed

Perturbation evolution: oscillations within sound horizon



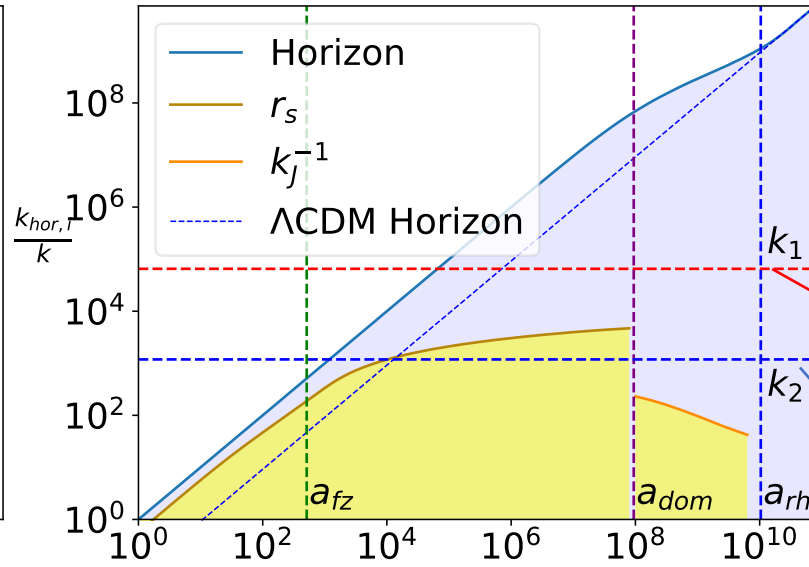
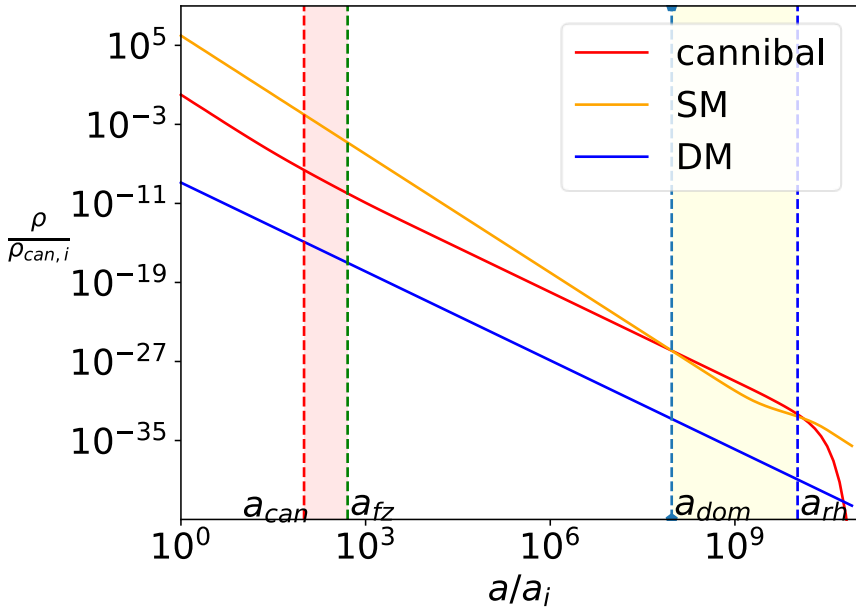
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Cannibal sound speed



δ_c oscillates

Perturbation evolution: oscillations within sound horizon

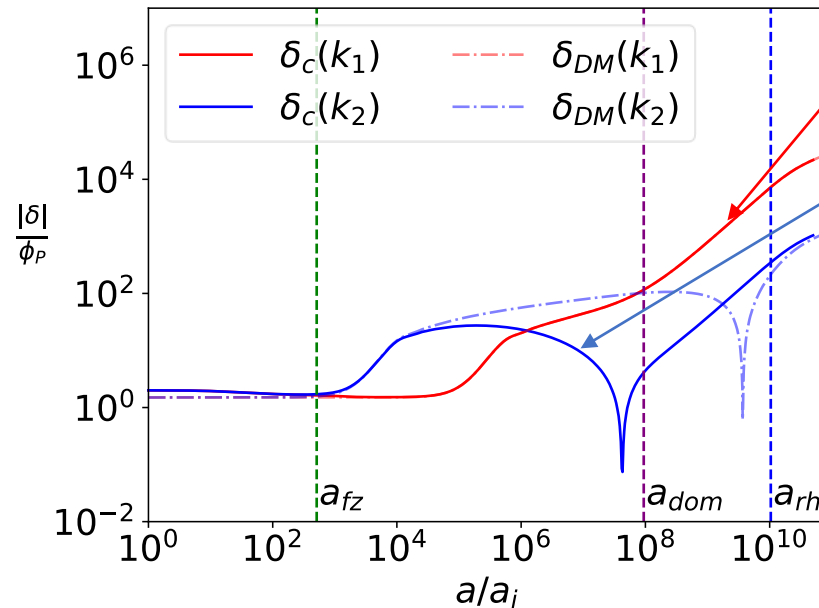


δ_c monotonically grows

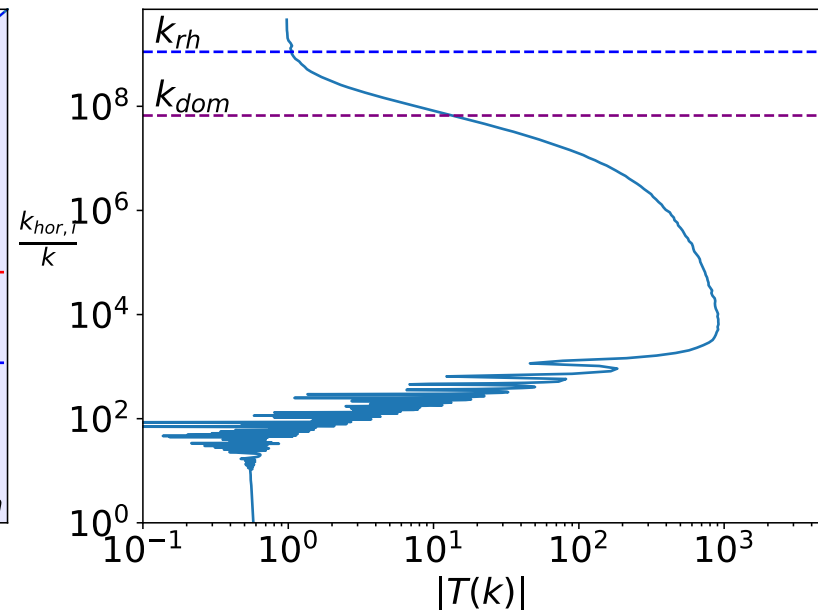
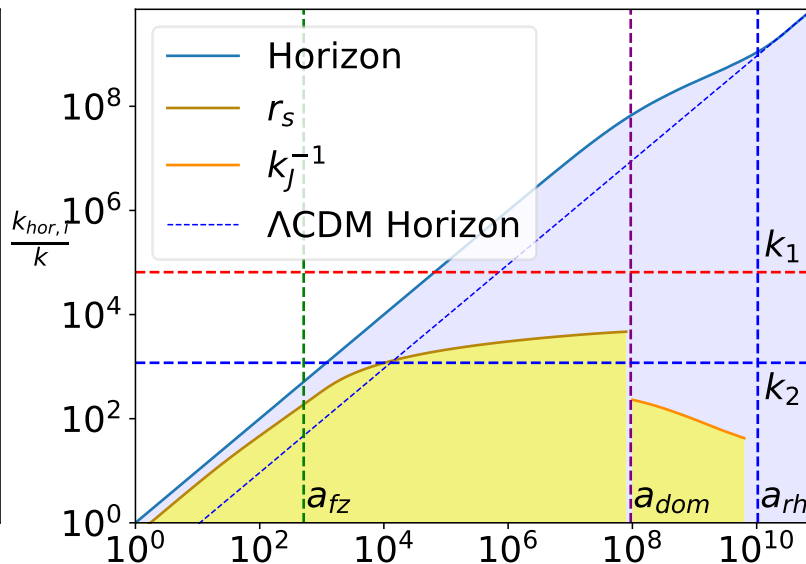
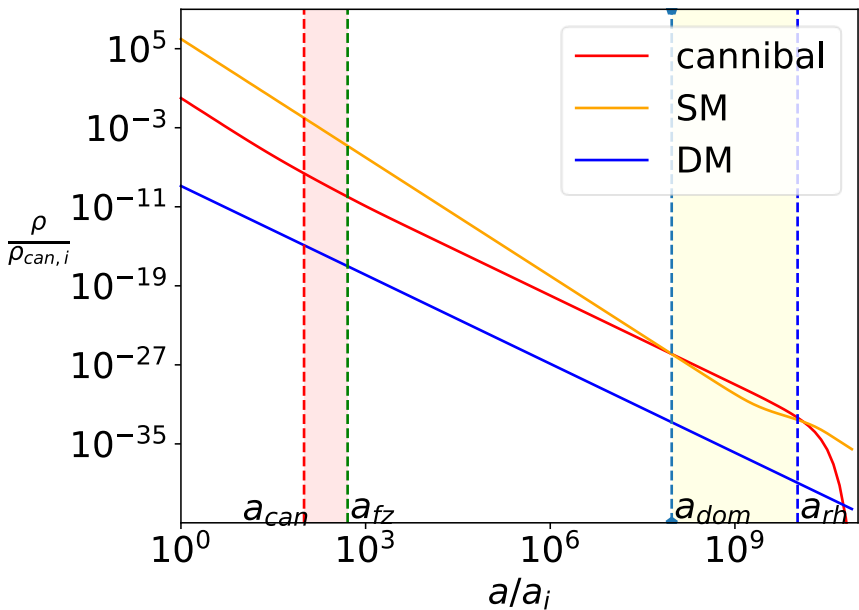
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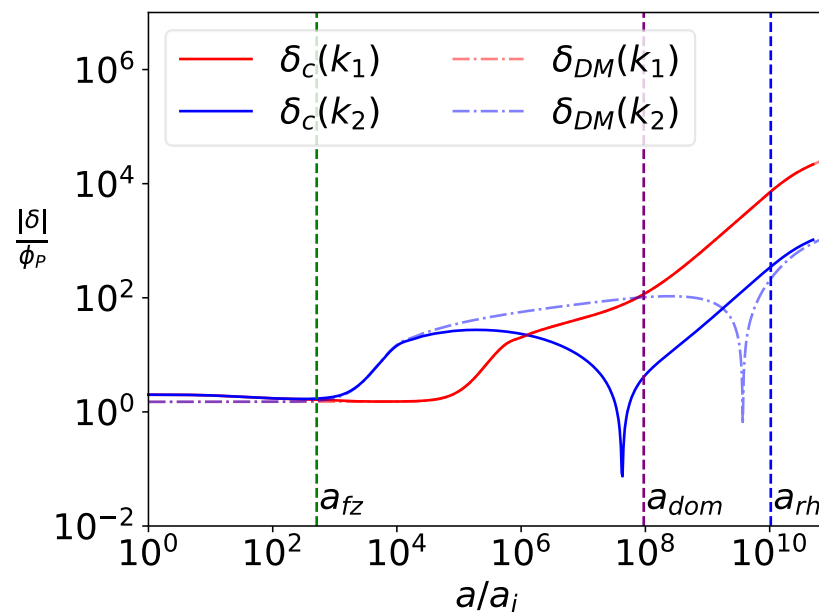


Perturbation evolution: Transfer function



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

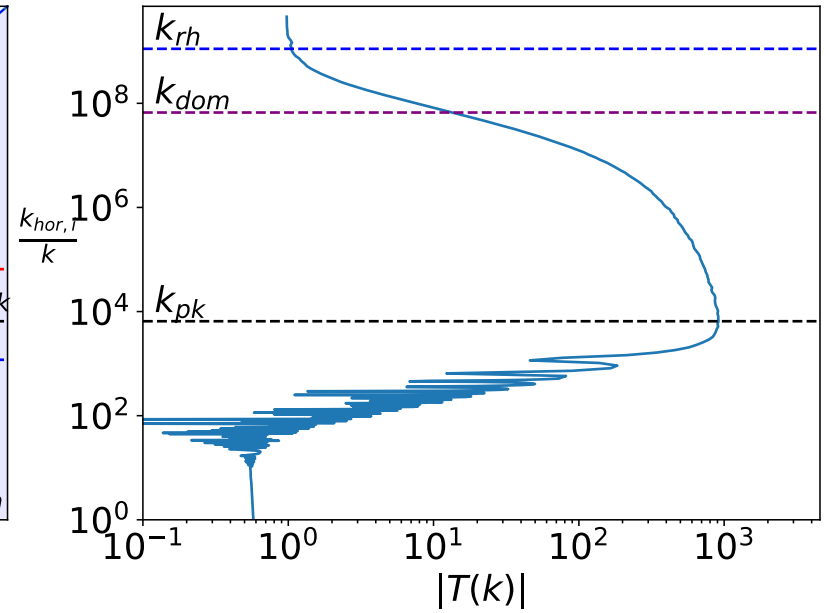
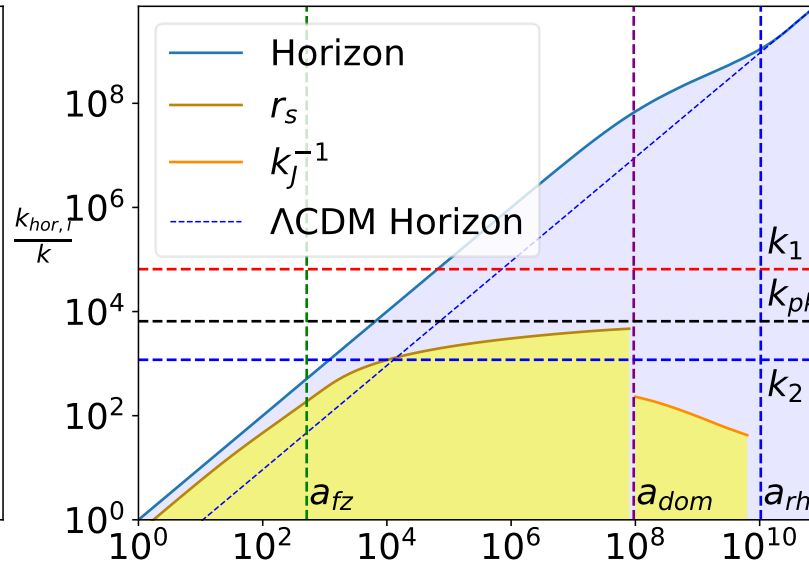
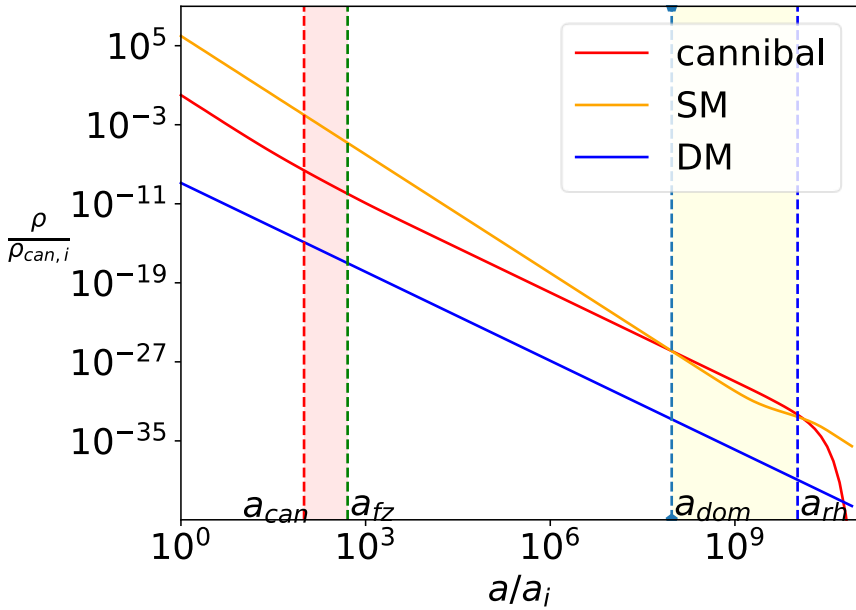
Cannibal sound speed



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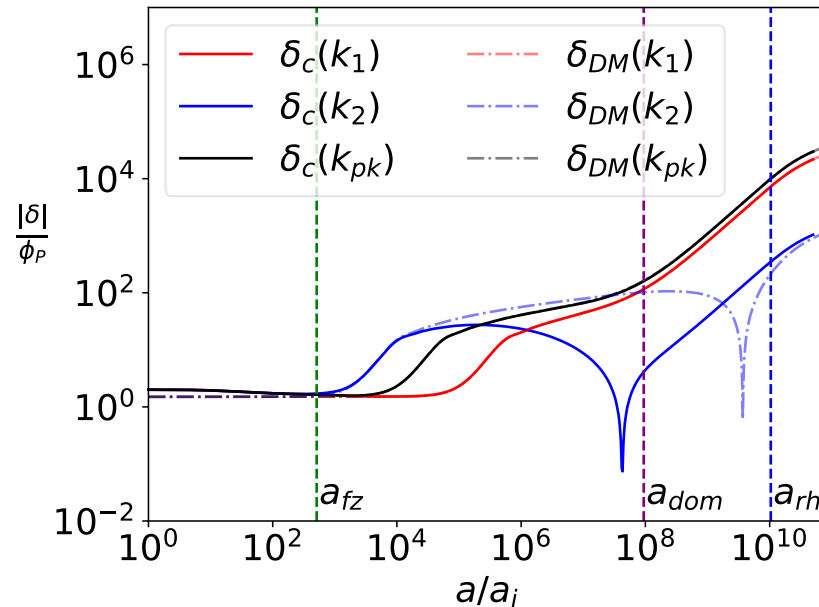
DM perturbation in Λ CDM

Transfer function: Peak given by sound horizon



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

Cannibal sound speed



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

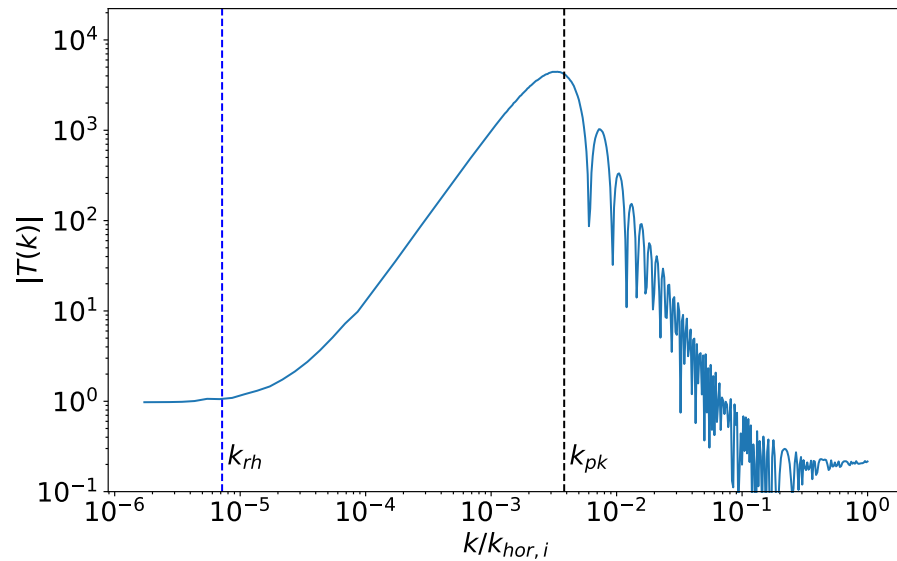
(arxiv: 2009.xxxx)

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DM perturbation in Λ CDM

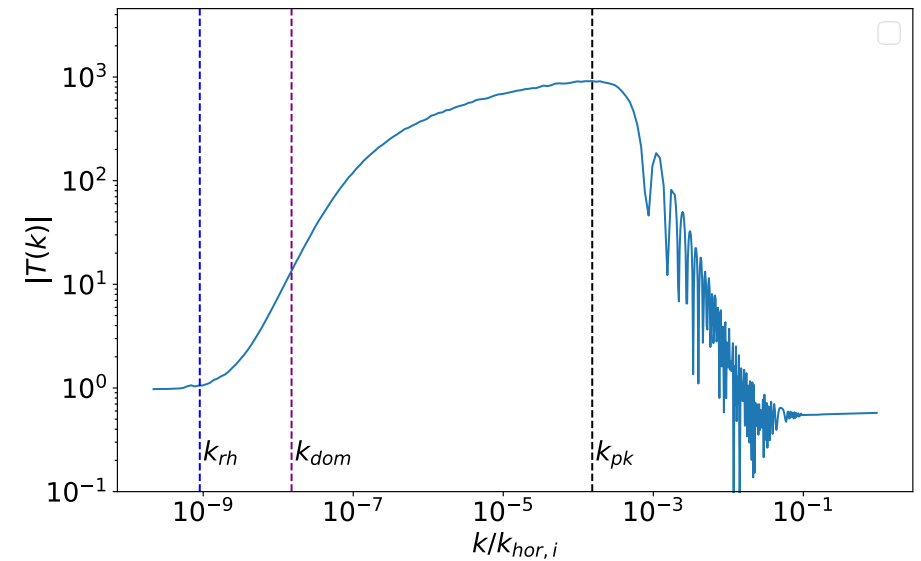
Two qualitatively different transfer functions

Cannibal dominated universe during freeze-out of cannibal reactions



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

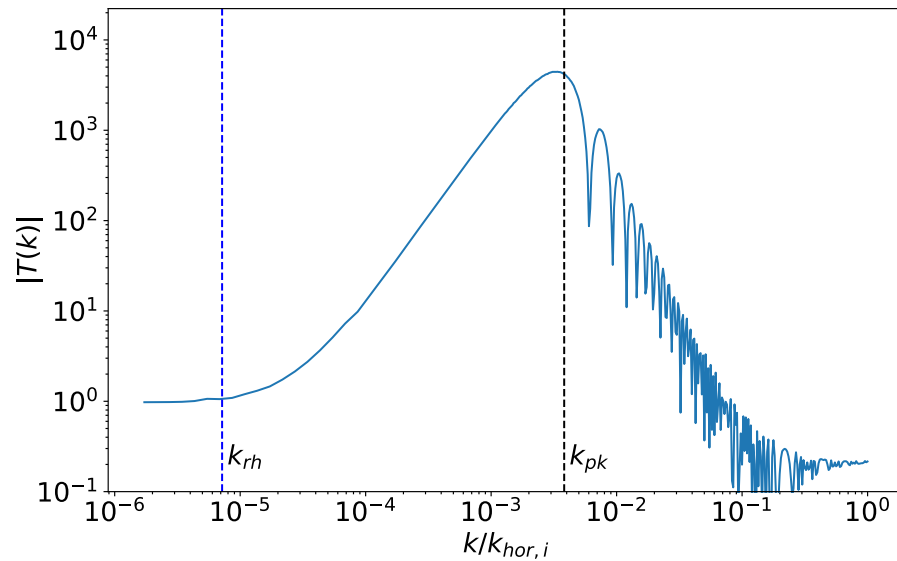
SM-radiation dominated universe during freeze-out of cannibal reactions



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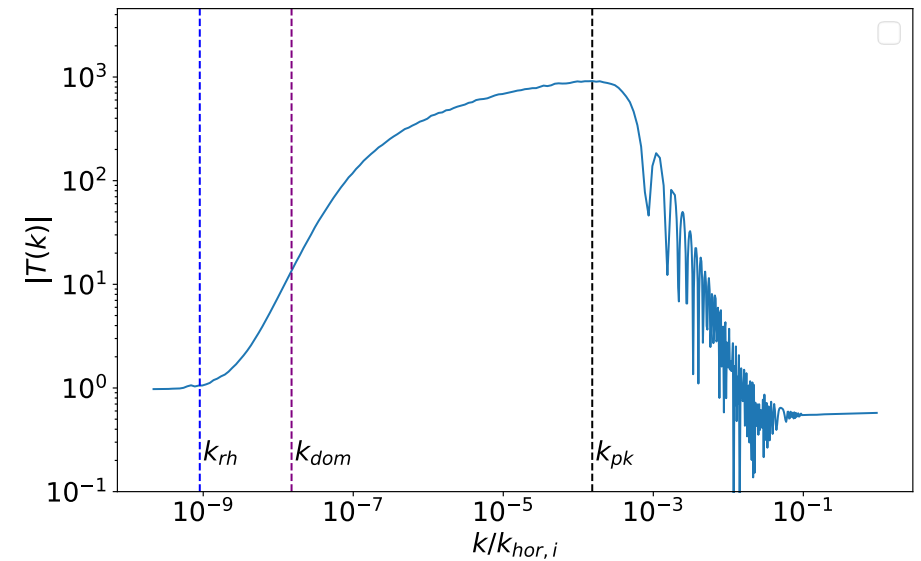
The cut-off in doth determined by cannibal self interactions

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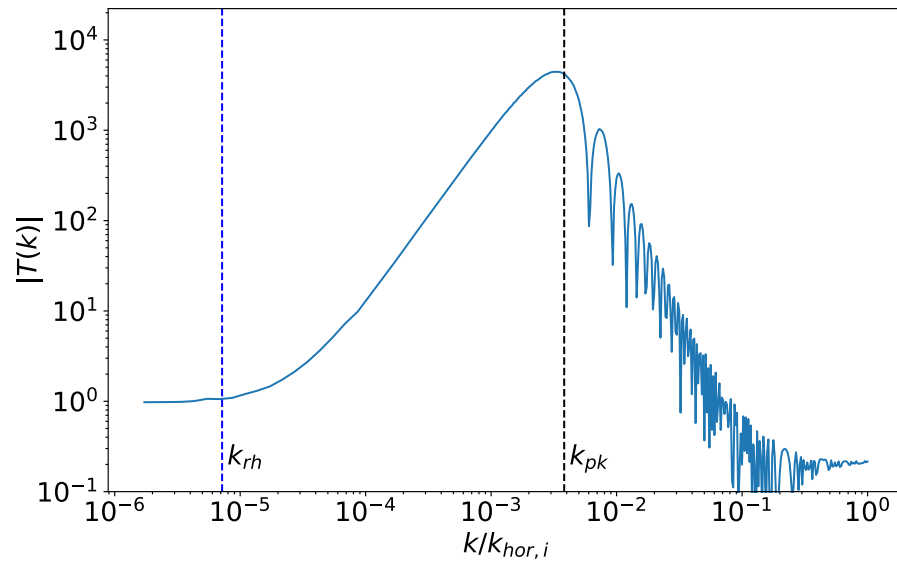


$$k_{pk}^{-1} \approx r_s(a_{dom})$$

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

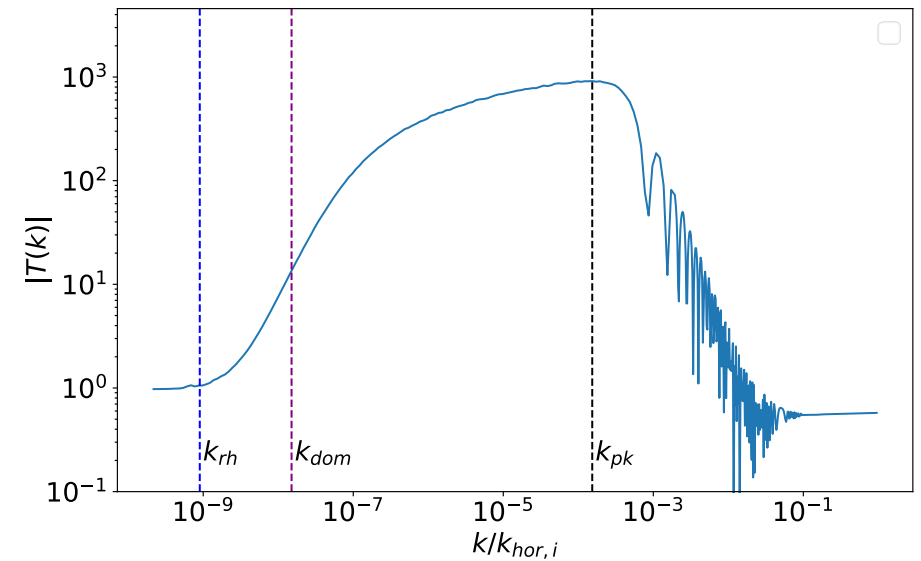
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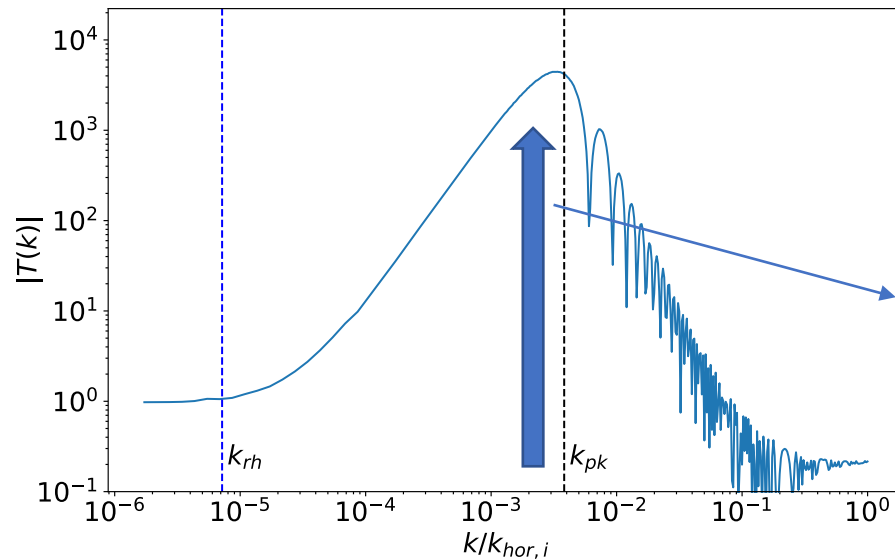


$$k_{pk}^{-1} \approx r_s(a_{dom})$$

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

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

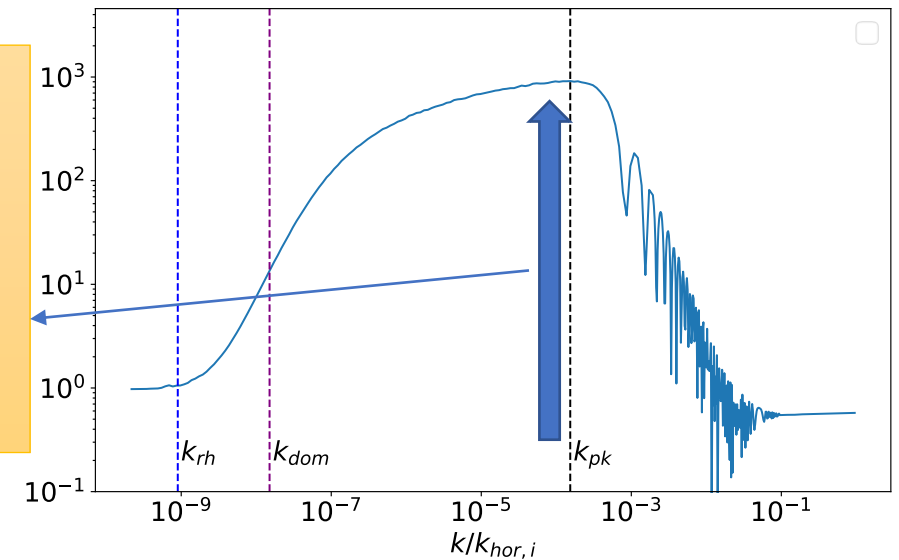
Cannibal dominated universe during freeze-out of cannibal reactions



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

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

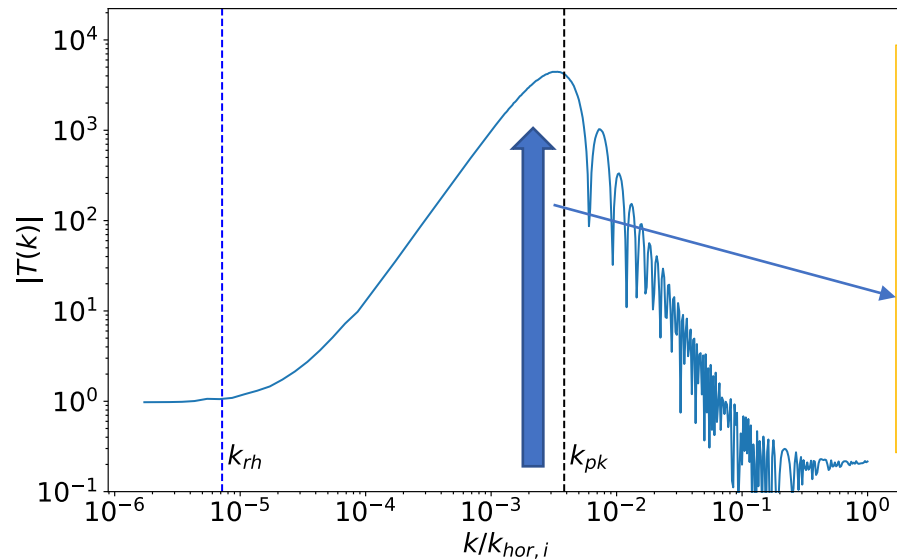
SM-radiation dominated universe during freeze-out of cannibal reactions



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

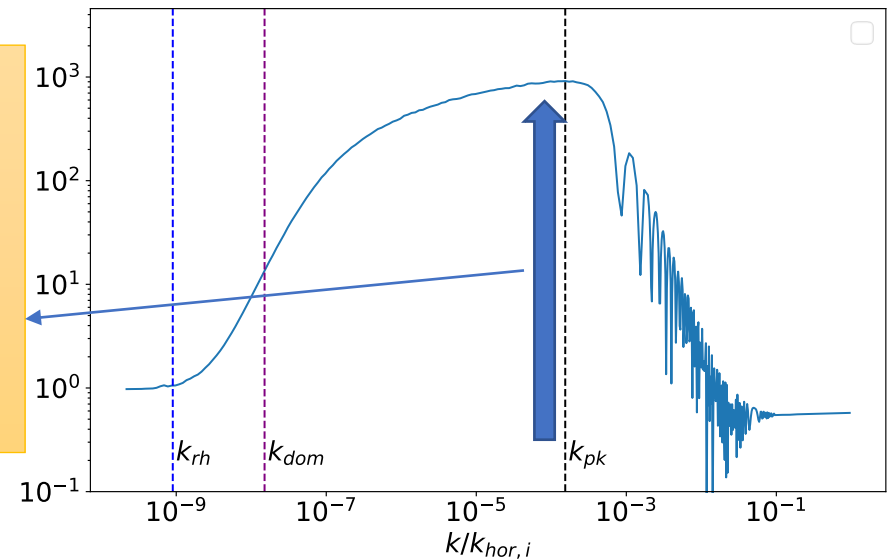
Peak enhancement of the transfer function determines key features of micro-halos

Cannibal dominated universe during freeze-out of cannibal reactions



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

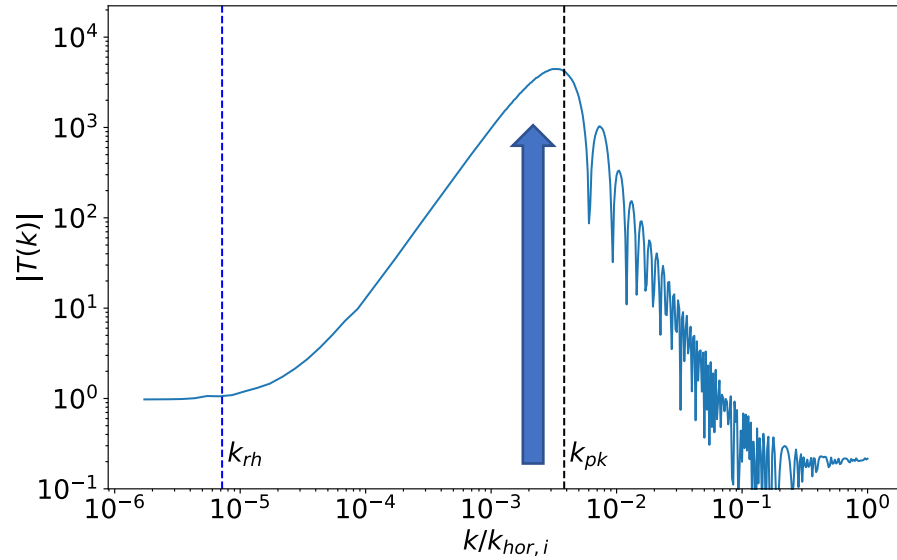
SM-radiation dominated universe during freeze-out of cannibal reactions



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

Cannibal parameters to key microhalo features

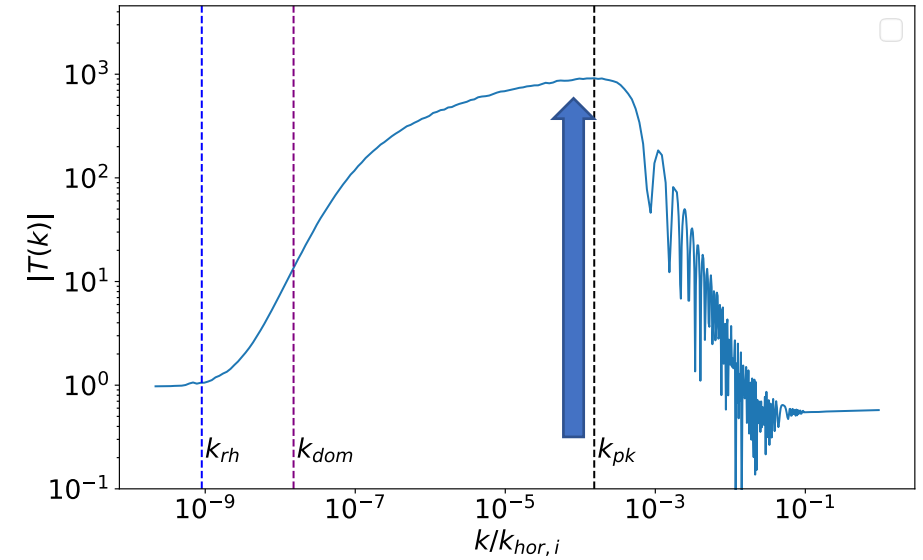
Cannibal dominated universe during freeze-out of cannibal reactions



$$M_{pk} \sim 10^{-11} \left(\frac{\alpha_c}{0.1} \right) \left(\frac{TeV}{m} \right)^{\frac{7}{3}} \left(\frac{10 MeV}{T_{rh}} \right)$$

$$T(k_{pk}) \sim 2 \times 10^3 \left(\frac{0.1}{\alpha_c} \right)^{\frac{2}{3}} \left(\frac{m}{TeV} \right)^{\frac{14}{9}} \left(\frac{10 MeV}{T_{rh}} \right)^{\frac{4}{3}}$$

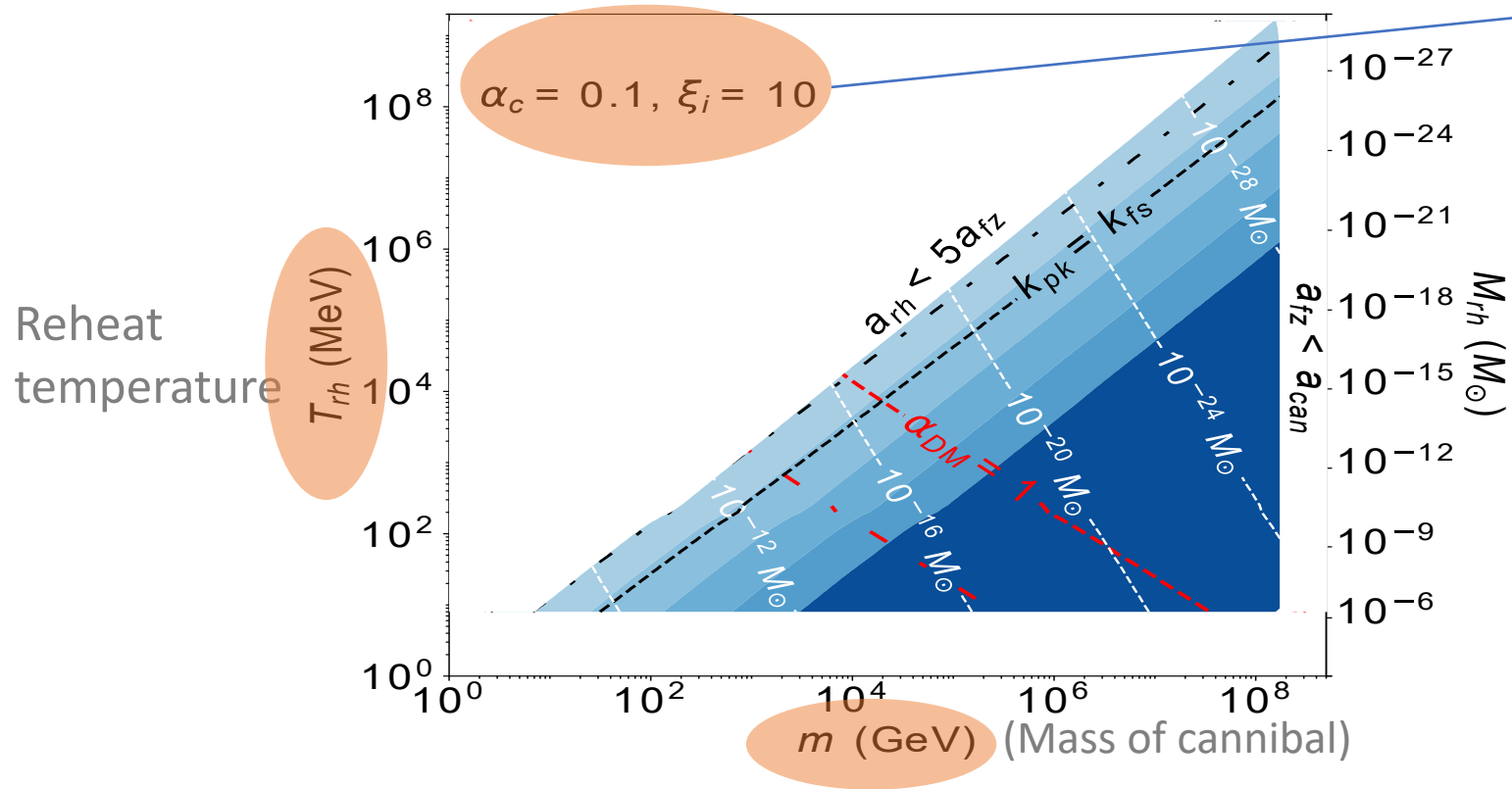
SM-radiation dominated universe during freeze-out of cannibal reactions



$$M_{pk} \sim 3 \times 10^{-13} \left(\frac{\alpha_c}{0.1} \right)^{\frac{9}{4}} \left(\frac{\xi_i}{0.4} \right)^{\frac{15}{2}} \left(\frac{TeV}{m} \right)^{\frac{7}{3}} \left(\frac{10 MeV}{T_{rh}} \right) \ln^{\frac{9}{2}}(..)$$

$$T(k_{pk}) \sim 2 \times 10^3 \left(\frac{\xi_i}{0.4} \right)^4 \left(\frac{m}{TeV} \right)^{\frac{4}{3}} \left(\frac{10 MeV}{T_{rh}} \right)^{\frac{4}{3}} \ln(..)$$

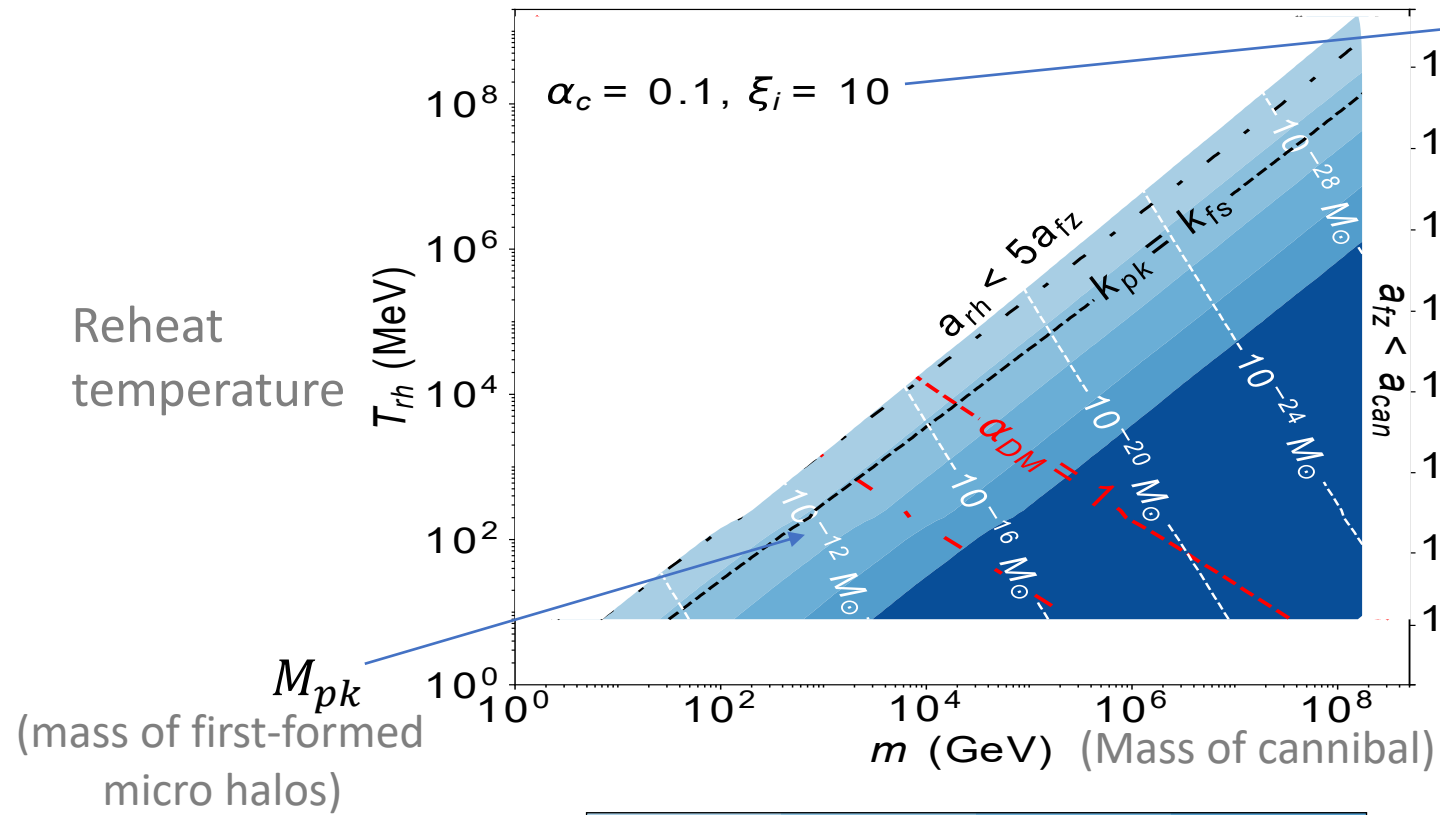
Parameter space of cannibal model: free parameters



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

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

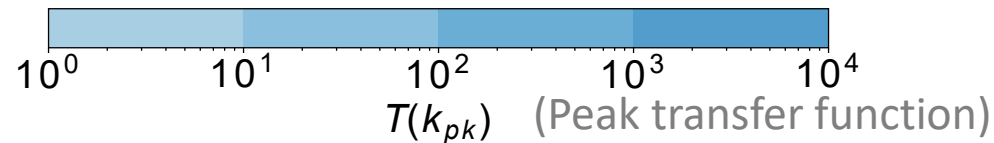
Parameter space of cannibal model: Type of microhalos



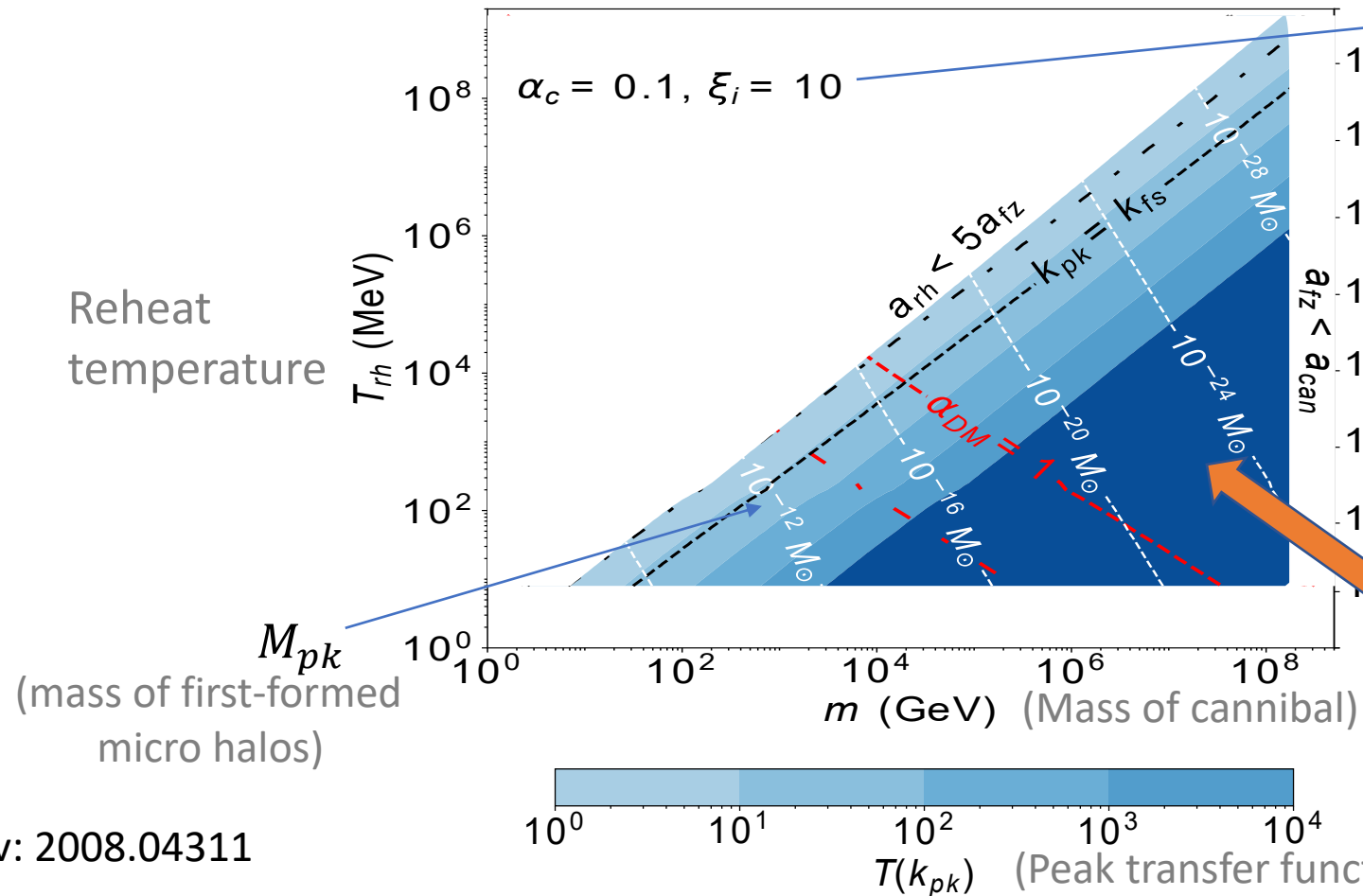
$$\langle \sigma v^2 \rangle_{can} = \frac{25\sqrt{5}\pi^2 \alpha_c^3}{5184 m^5}$$

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

arxiv: 2008.04311



Parameter space of cannibal model: microhalo evaporation

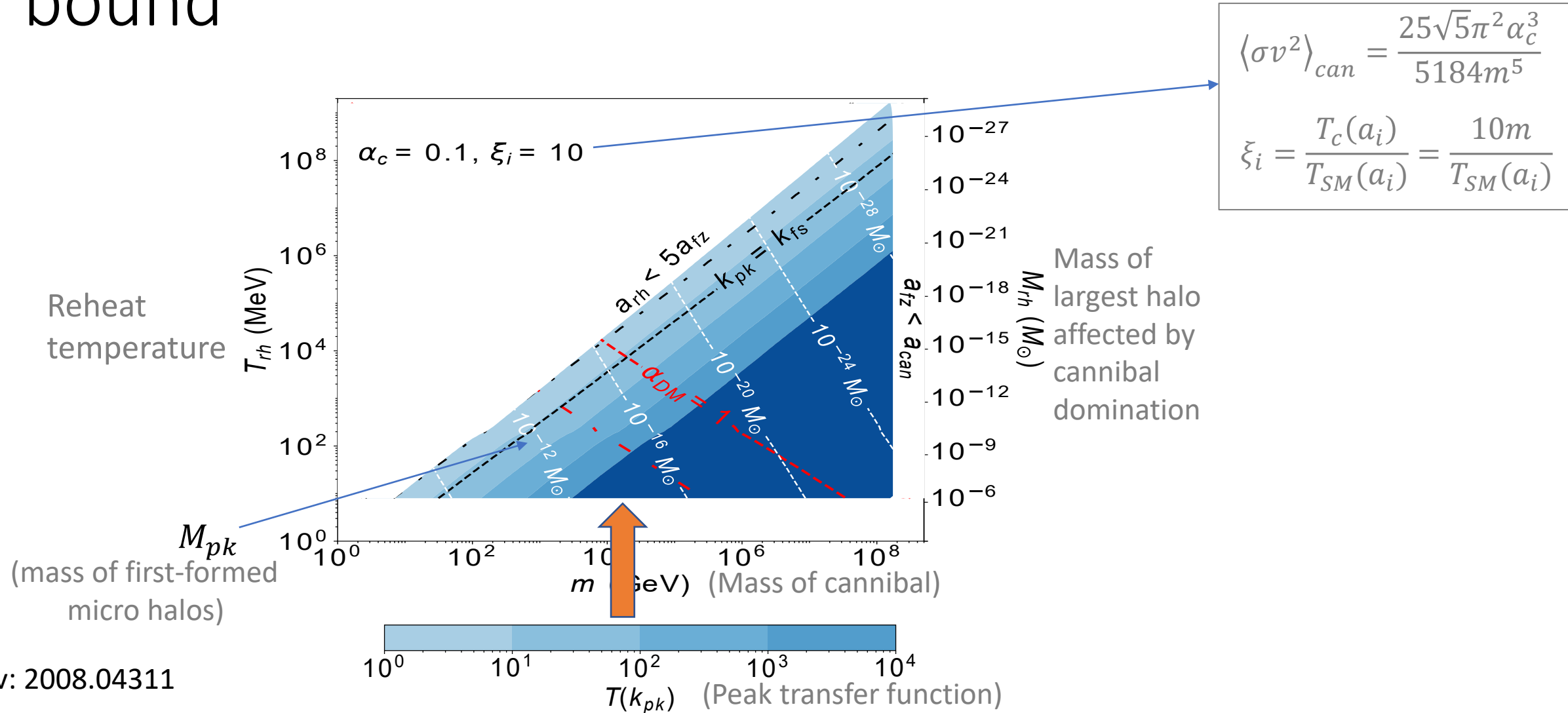


$$\langle \sigma v^2 \rangle_{can} = \frac{25\sqrt{5}\pi^2 \alpha_c^3}{5184 m^5}$$

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

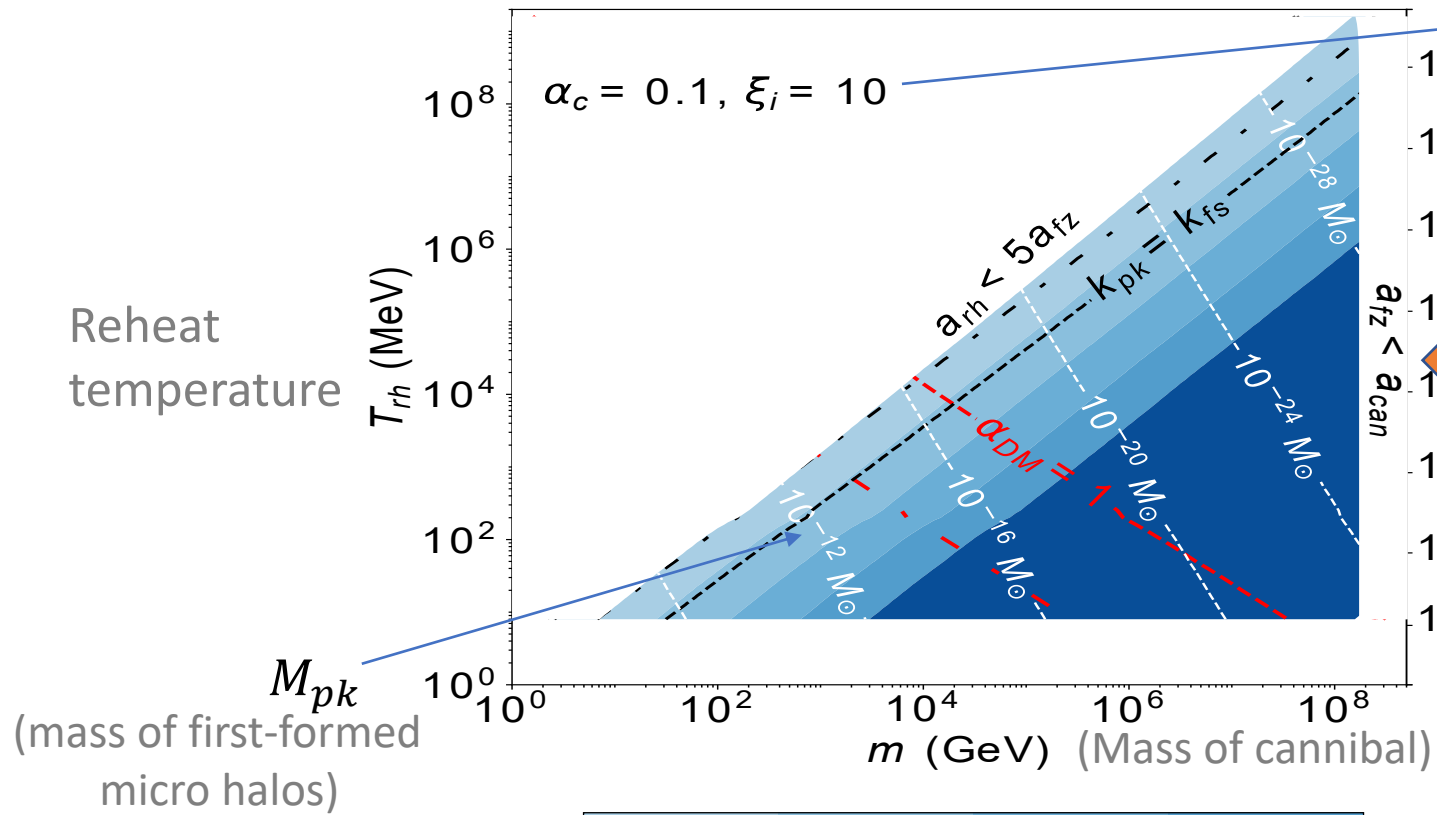
All enhancement in DM overdensity is erased

Parameter space of cannibal model: BBN bound



arxiv: 2008.04311

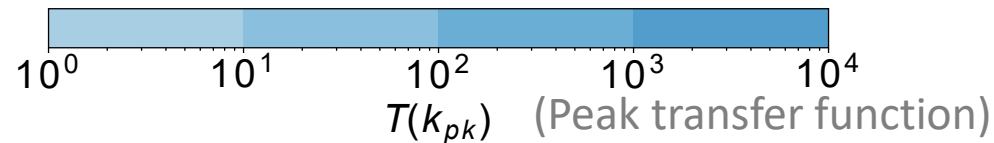
Parameter space of cannibal model: cannibalism bound



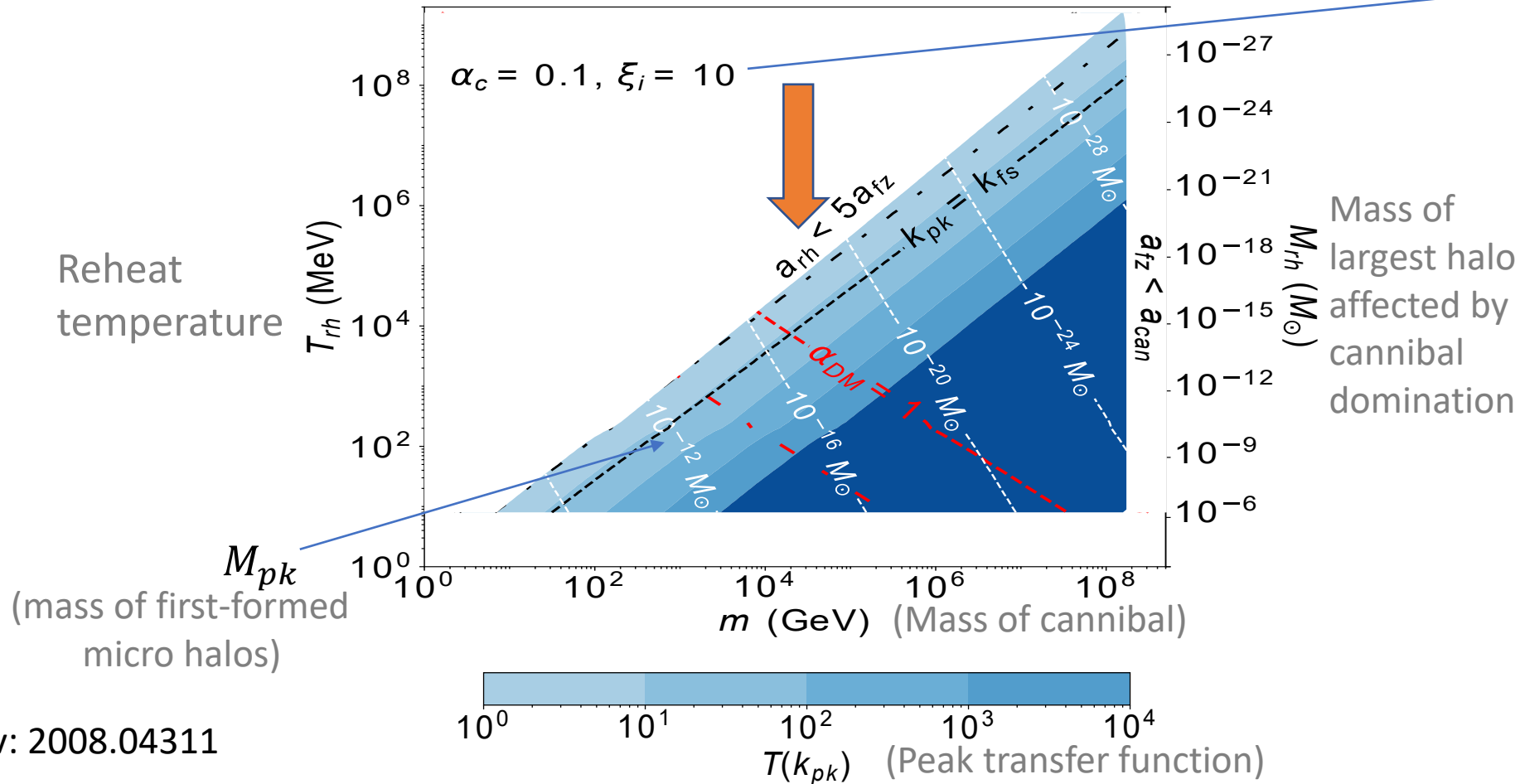
$$\langle \sigma v^2 \rangle_{can} = \frac{25\sqrt{5}\pi^2 \alpha_c^3}{5184m^5}$$

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

Mass of largest halo affected by cannibal domination



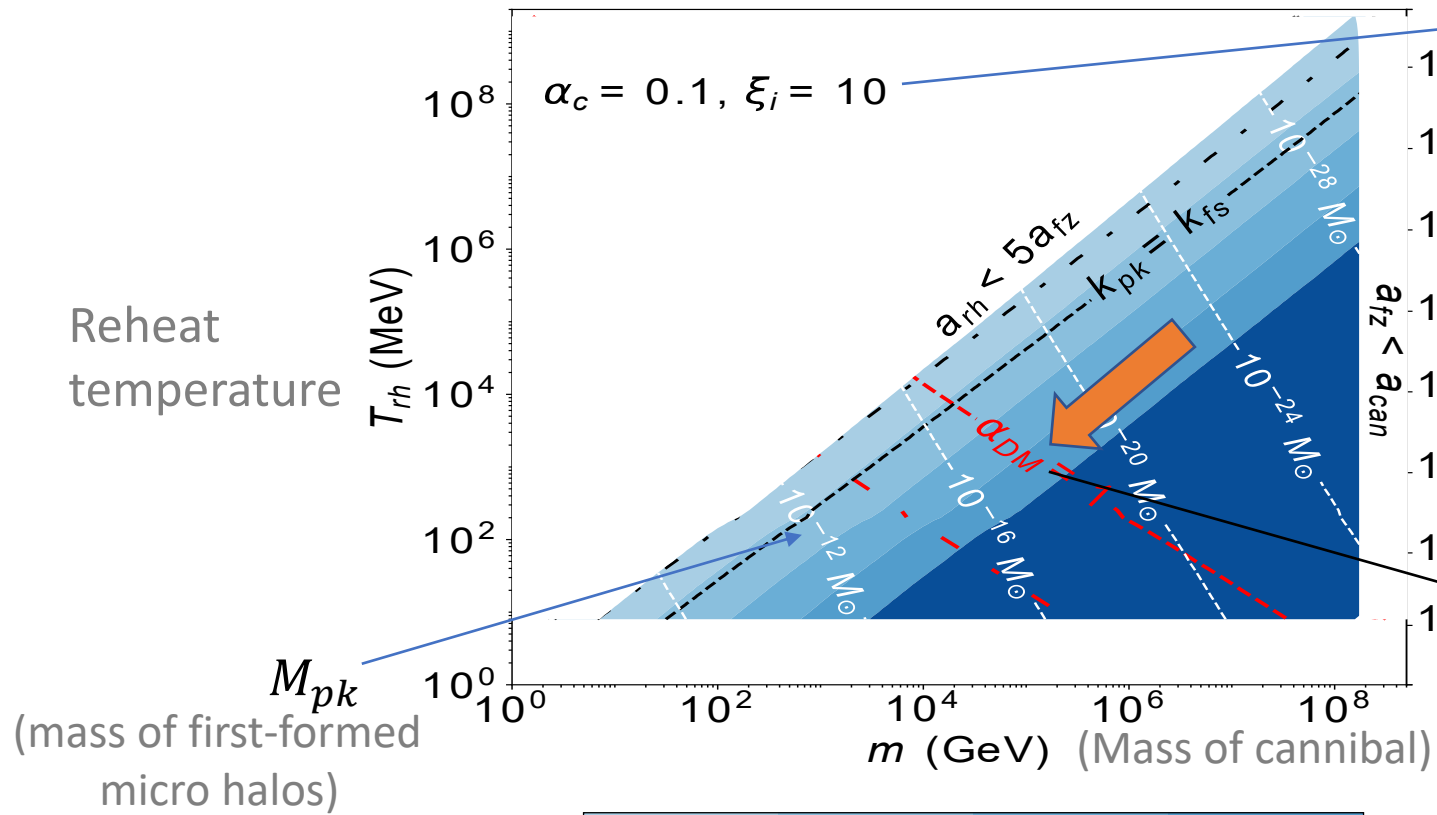
Parameter space of cannibal model: structure growth bound



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

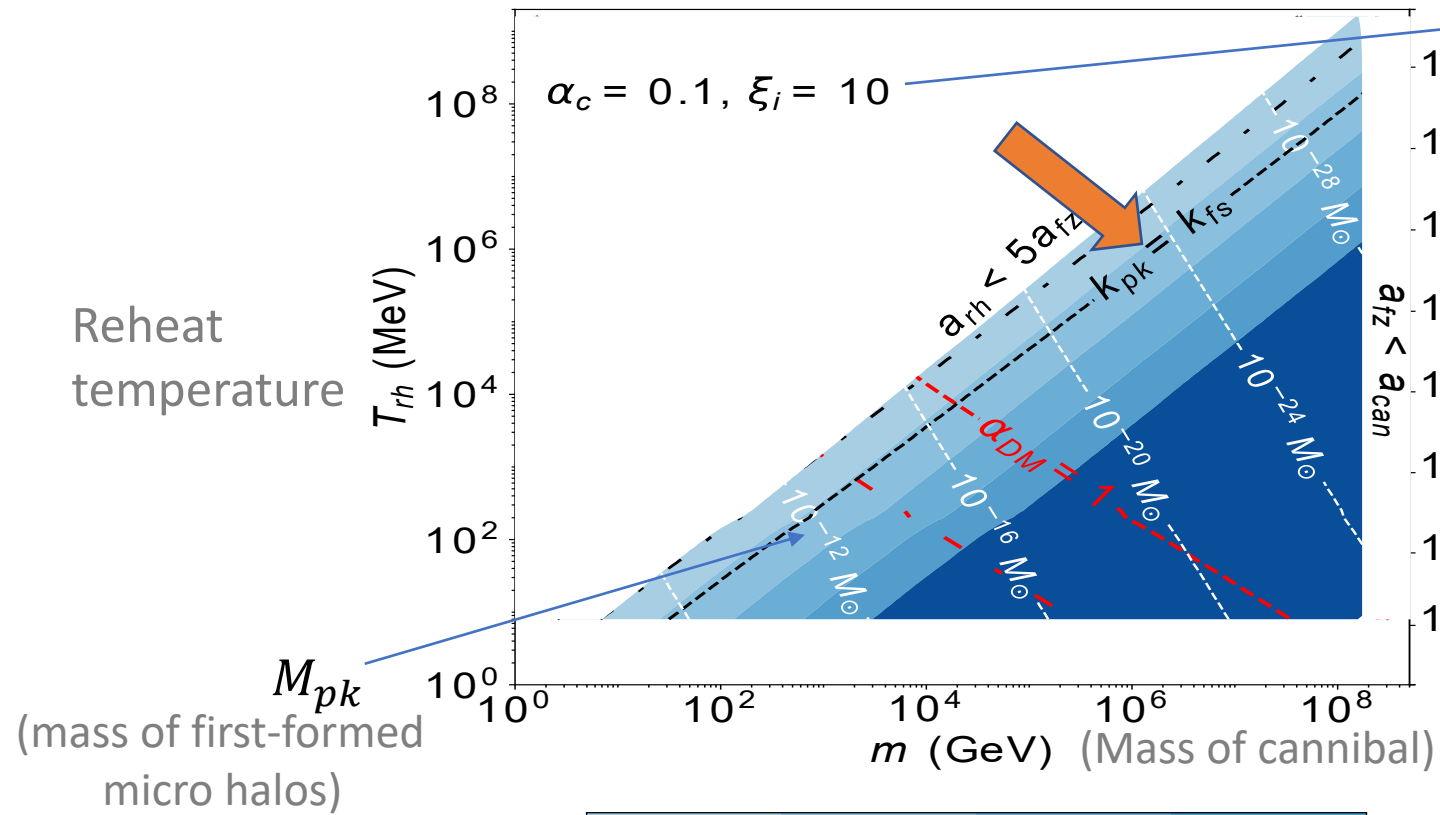
$$\xi_i = \frac{T_c(a_i)}{T_{SM}(a_i)} = \frac{10m}{T_{SM}(a_i)}$$

Parameter space of cannibal model: Unitarity limit if DM freezes out from HS bath



arxiv: 2008.04311

Parameter space of cannibal model: Post reheating DM free-streaming



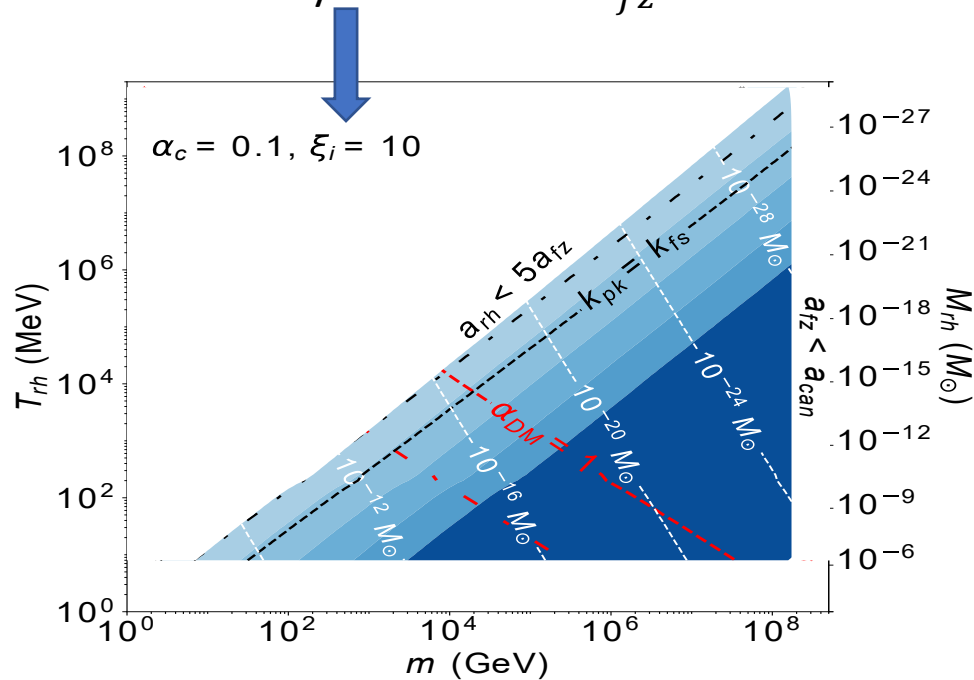
$$\langle \sigma v^2 \rangle_{can} = \frac{25\sqrt{5}\pi^2 \alpha_c^3}{5184 m^5}$$

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

Mass of largest halo affected by cannibal domination

Parameter space of cannibal model: Varying initial density

Cannibal density dominant at a_{fz}

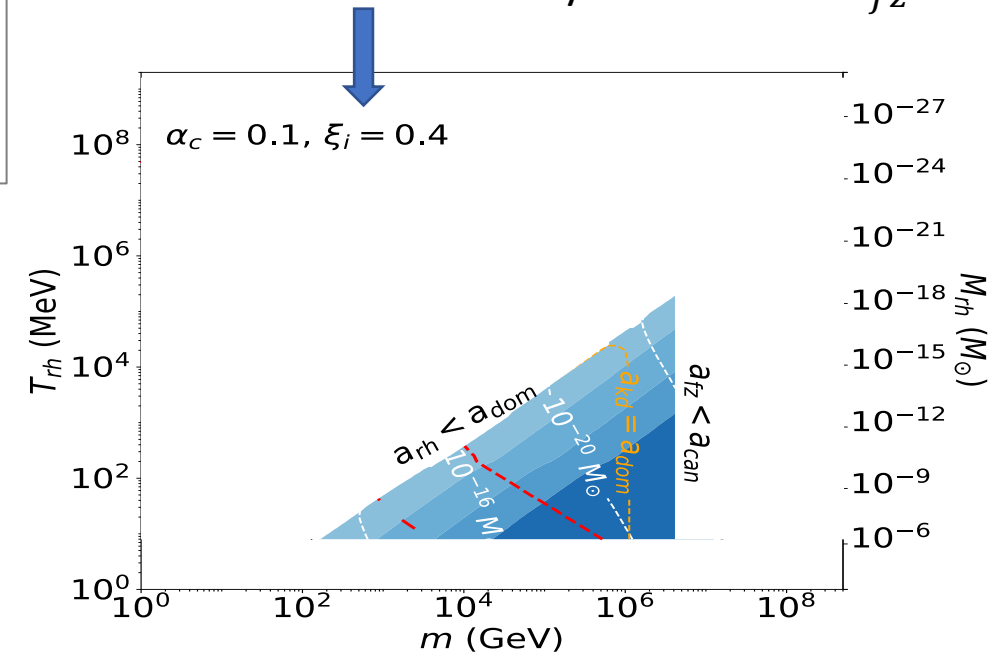


arxiv: 2008.04311

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

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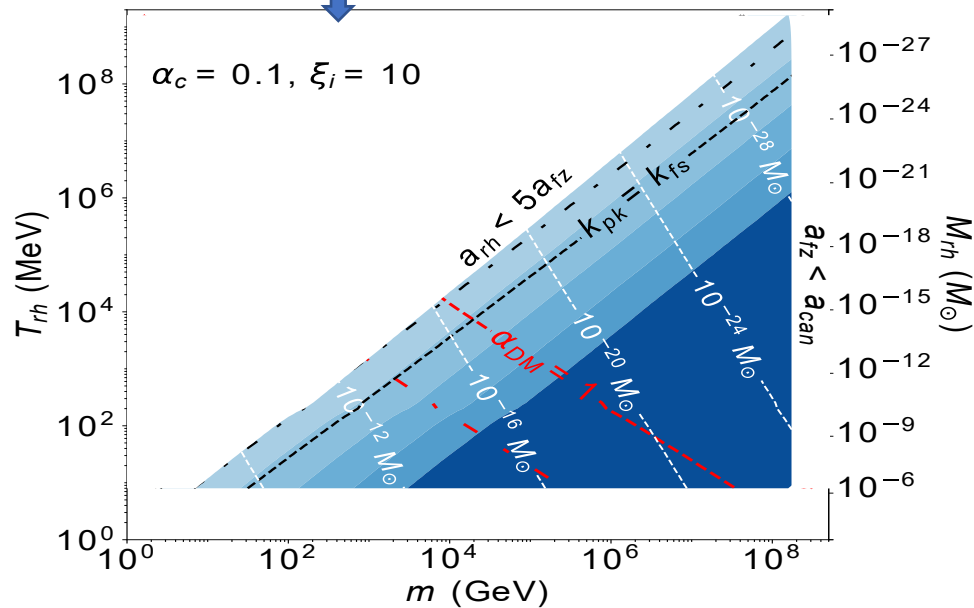
SM radiation density dominant at a_{fz}



arxiv: 2106.09041

Parameter space of cannibal model: cannibal domination bound

Cannibal density dominant at a_{fz}

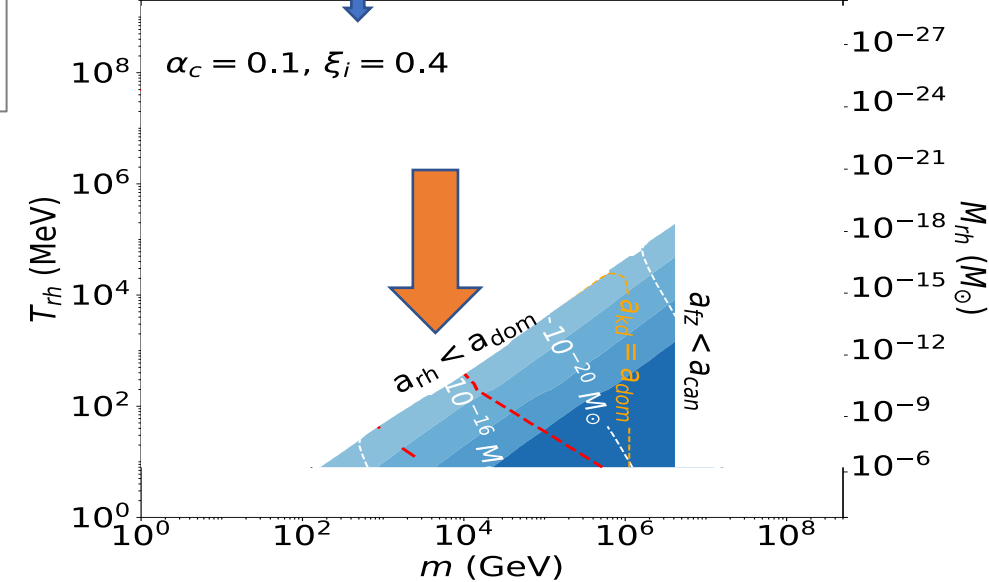


arxiv: 2008.04311

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

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

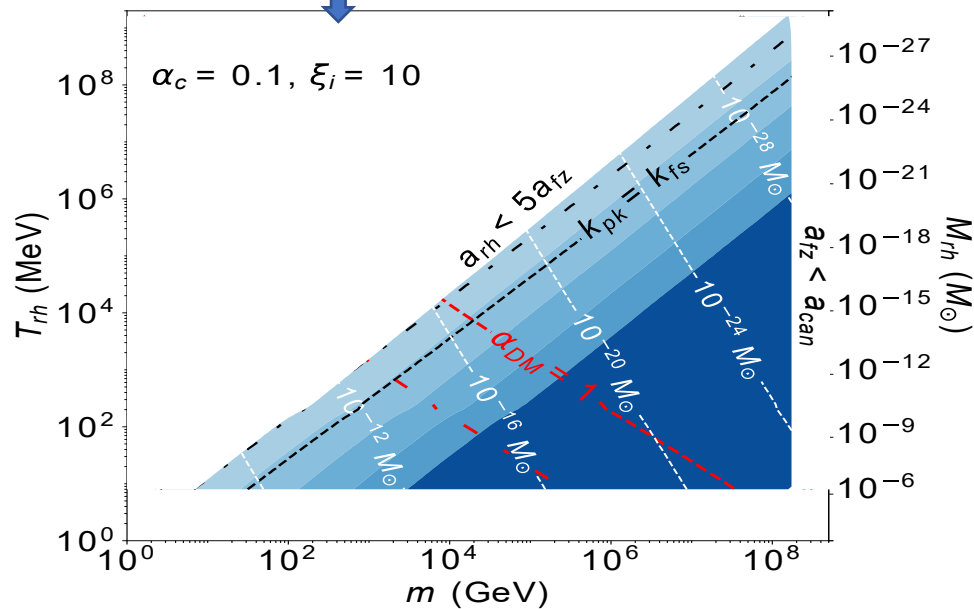
SM radiation density dominant at a_{fz}



arxiv: 2106.09041

Parameter space of cannibal model: cannibal free streaming

Cannibal density dominant at a_{fz}

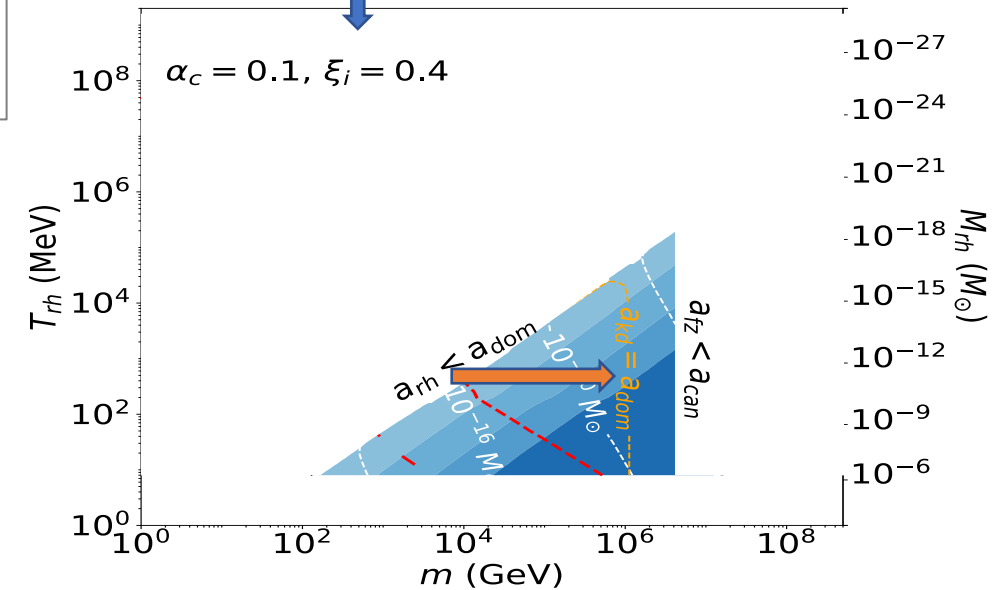


arxiv: 2008.04311

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

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SM radiation density dominant at a_{fz}

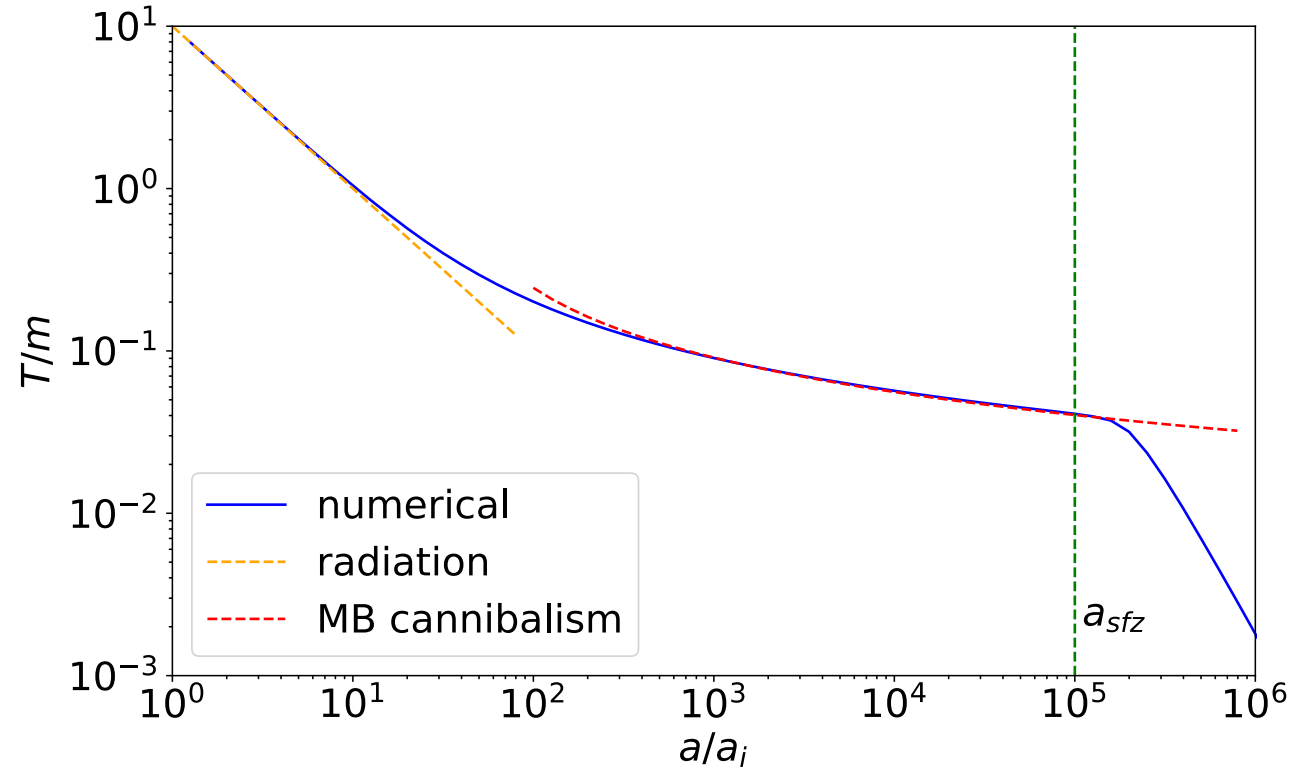


arxiv: 2106.09041

Summary

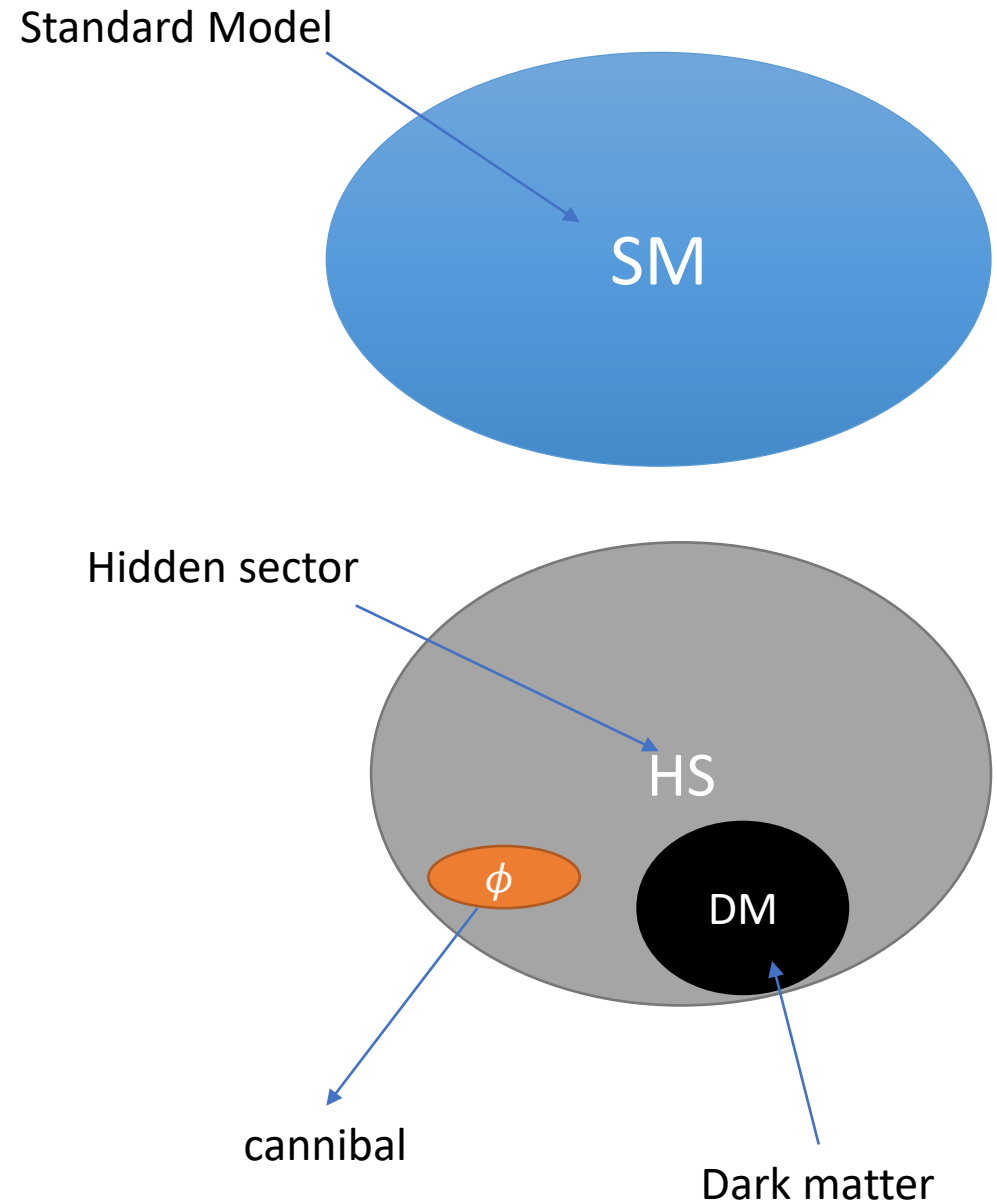
Summary

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



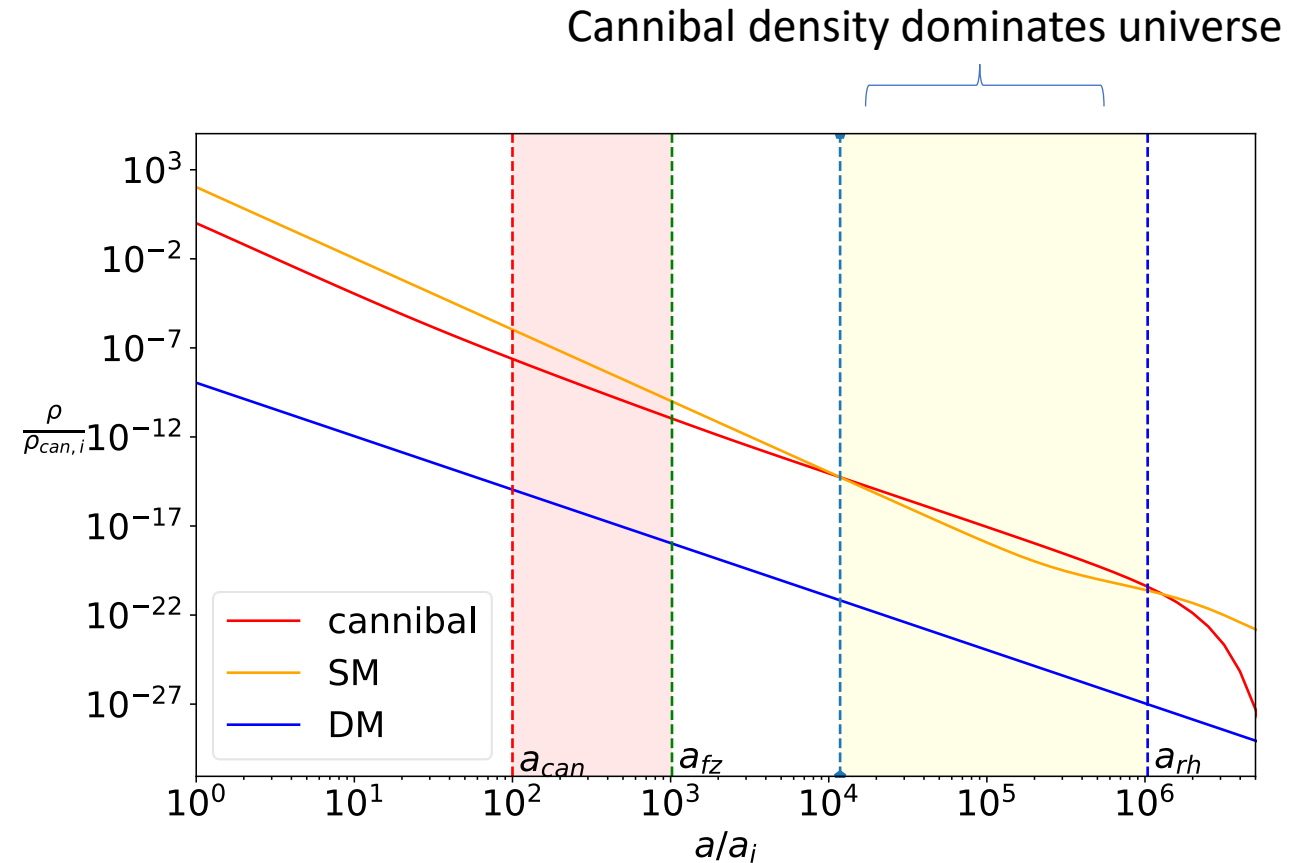
Summary

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



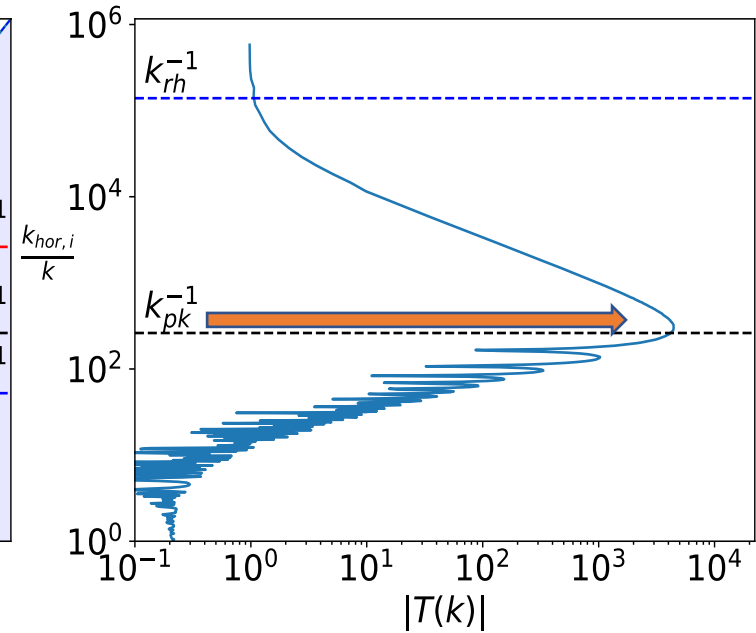
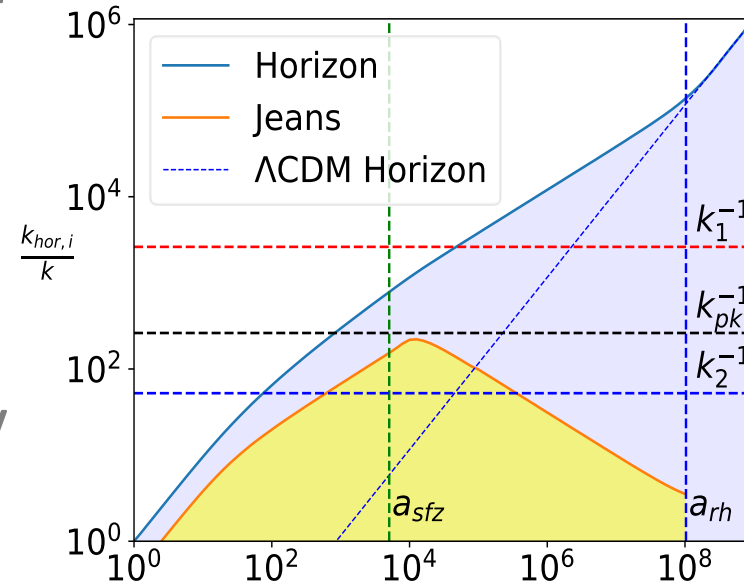
Summary

- Cannibal annihilates itself to convert rest mass energy to thermal energy
- Cannibal generically predicted in HS theories.
- Cannibal can lead to early matter domination.



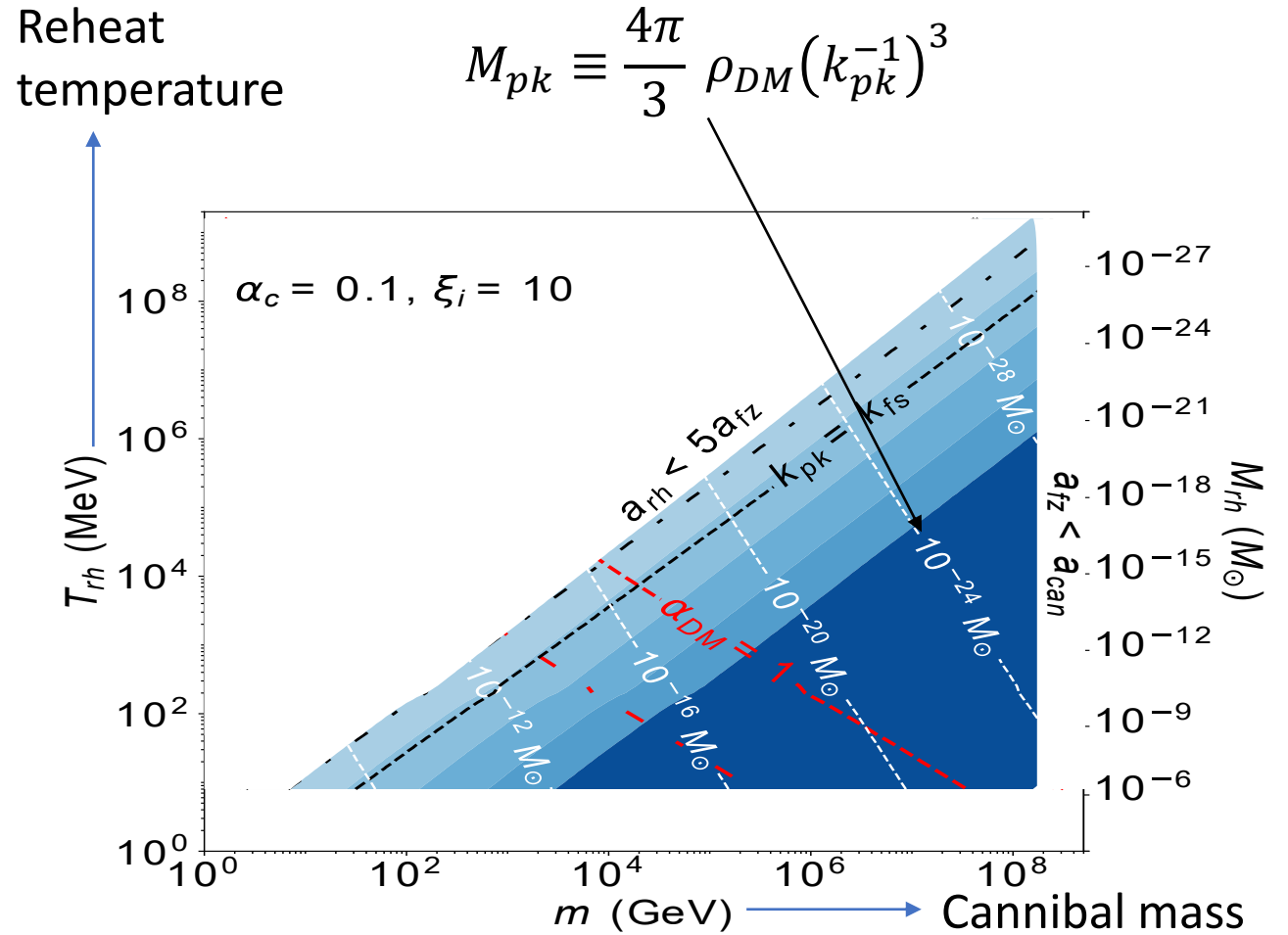
Summary

- Cannibal annihilates itself to convert rest mass energy to thermal energy
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- Cannibal can lead to early matter domination.
- Cannibal led matter domination: k_{pk} determined by a_{fz}



Summary

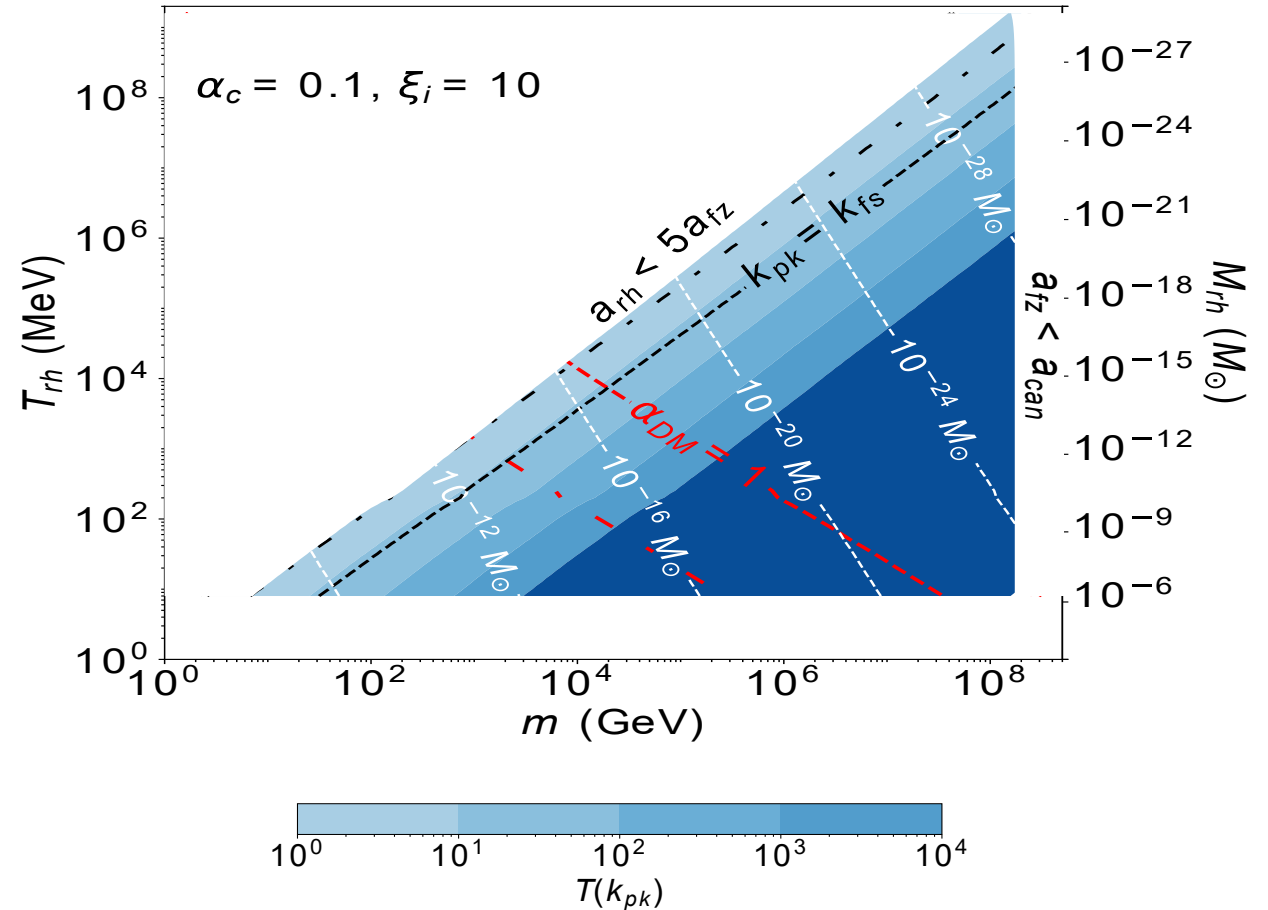
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- We provide map between particle parameters and key features of matter power spectrum



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

Summary

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Summary

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