What Dark Matter Microhalos can tell us about Reheating

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Overview

I. Motivation and a simple model for reheating

What do we know about the Universe prior to Big Bang Nucleosynthesis?

II. The evolution of perturbations during reheating

What do the perturbations in the decay products "remember"?

How does reheating change the small-scale matter power spectrum?

III. Microhalos from reheating

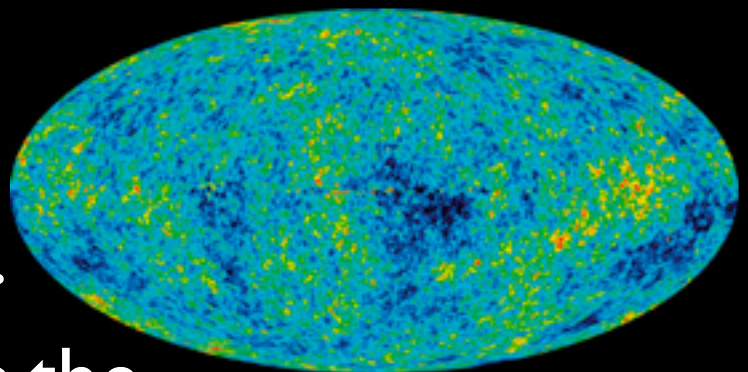
What substructures should we be looking for?

What Happened Before BBN?

The (mostly) successful prediction of the primordial abundances of light elements is one of cosmology's crowning achievements.

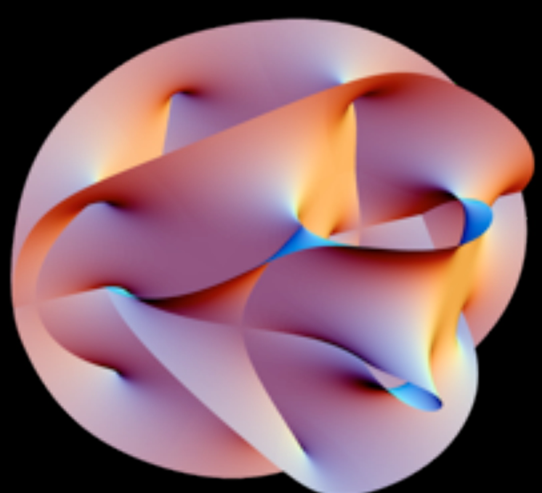
- The elements produced during Big Bang Nucleosynthesis are our first window on the Universe.
- They tell us that the Universe was radiation dominated during BBN.

But we have good reasons to think that the Universe was not radiation dominated before BBN!



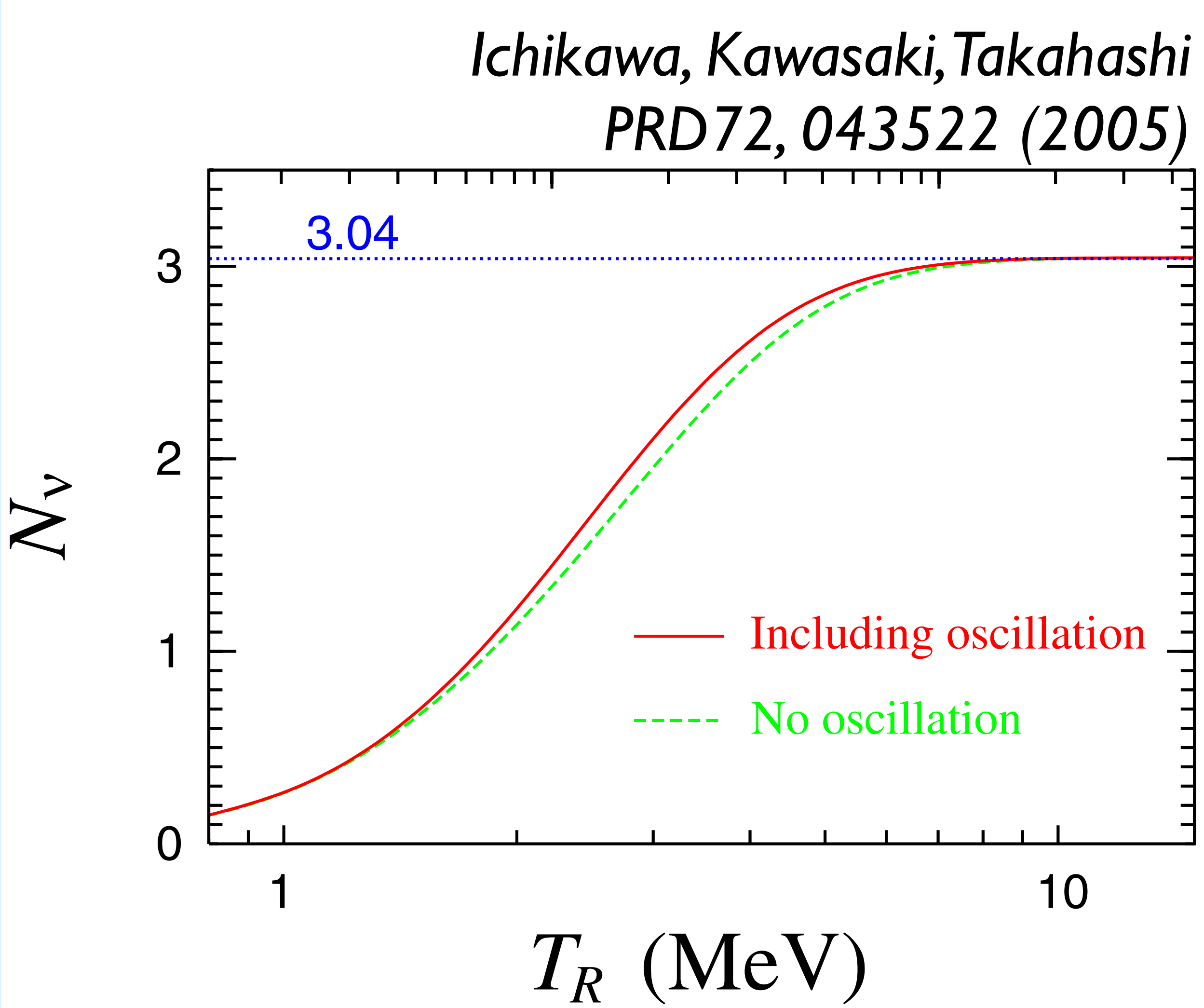
- Primordial density fluctuations point to inflation.
- During inflation, the Universe was scalar dominated.
- Other scalar fields may dominate the Universe after the inflaton decays.
- The string moduli problem: scalars with gravitational couplings come to dominate the Universe before BBN.

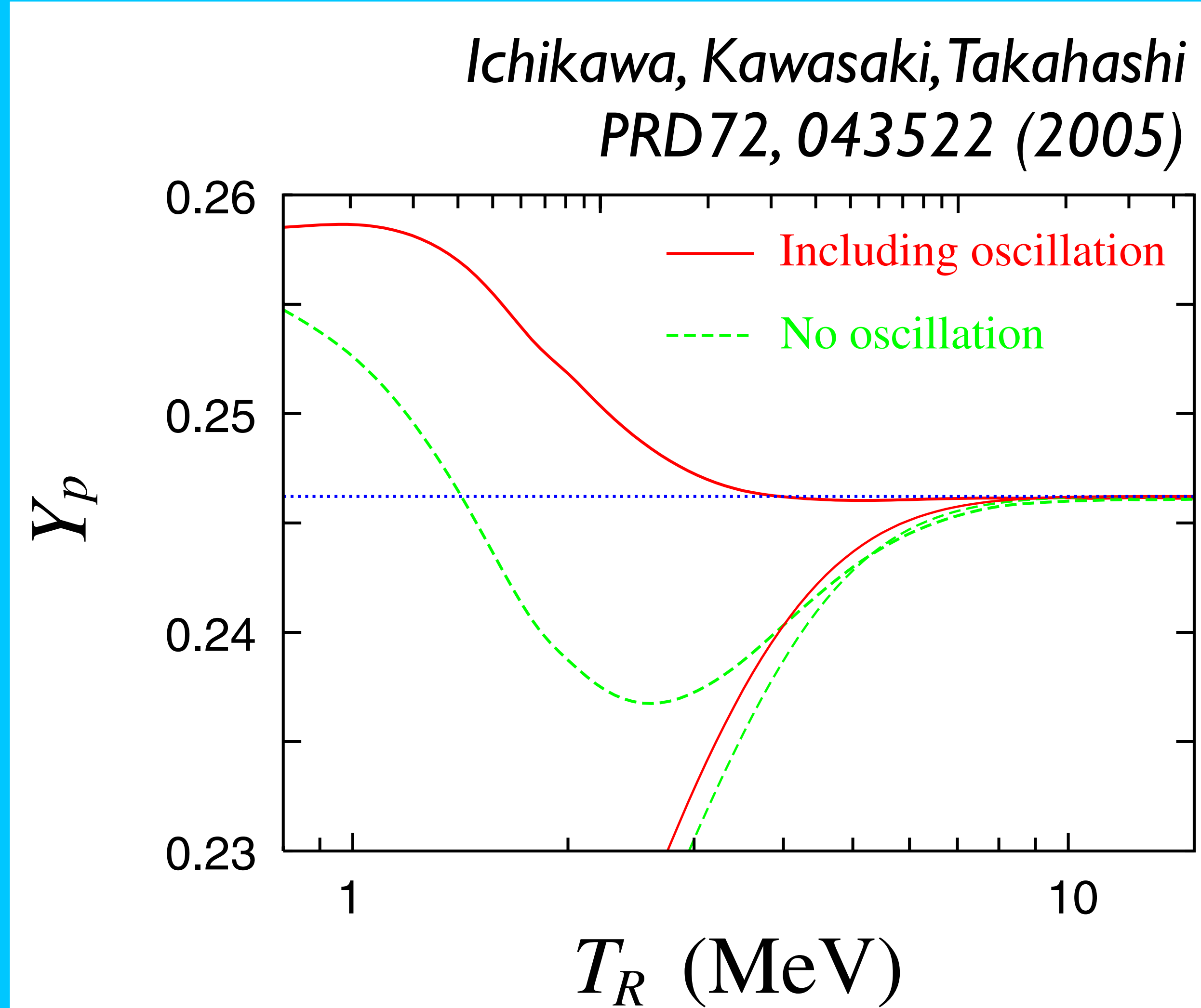
Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994
Acharya, Kane, Kuflik 2010



Don't Mess with BBN

Reheat Temperature = Temperature at Radiation Domination





Lowering the reheat temperature results in fewer neutrinos.

- slower expansion rate during BBN
- earlier neutron freeze-out; more helium
- earlier matter-radiation equality

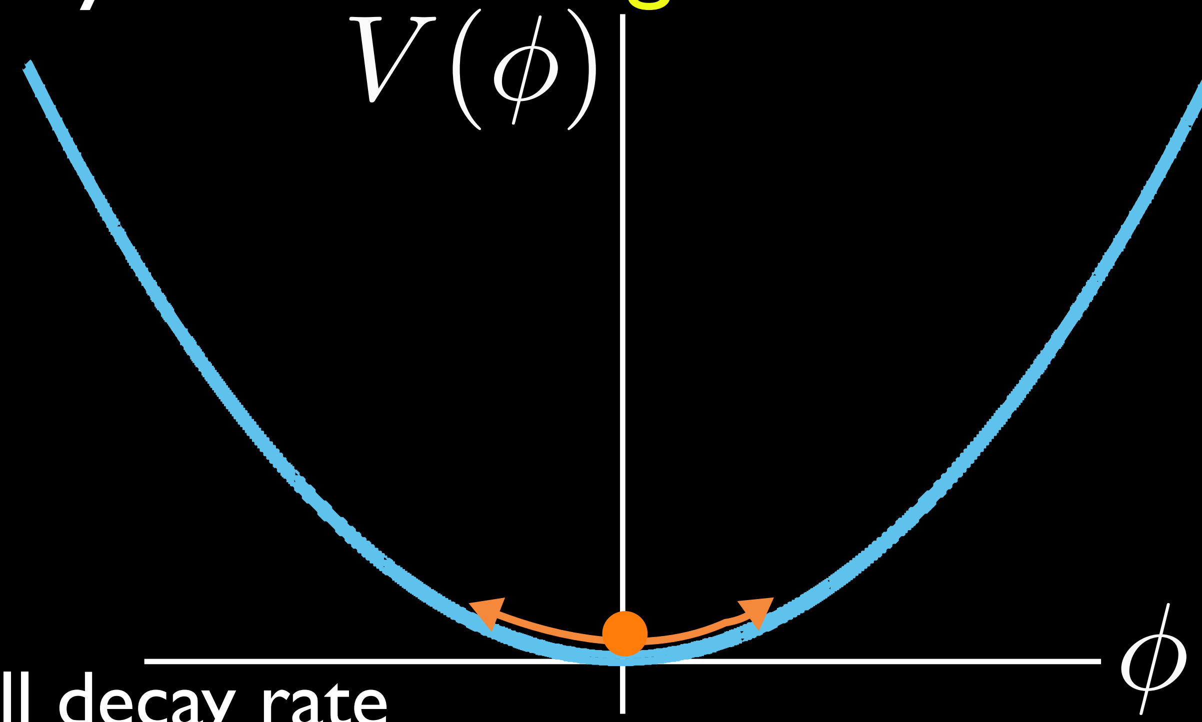
$$T_{\rm RH} \gtrsim 3 \text{ MeV}$$

Ichikawa, Kawasaki, Takahashi 2005; 2007
de Bernardis, Pagano, Melchiorri 2008

Scalar Domination after Inflation

The Universe was once dominated by an oscillating scalar field.

- reheating after inflation
- curvaton domination
- string moduli



Scalar domination ended when the scalar decayed into radiation, reheating the Universe.

- assume perturbative decay; requires small decay rate
- scalar decays can also produce dark matter
- unknown reheat temperature: $T_{\rm RH} \gtrsim 3 \ {\rm MeV}$

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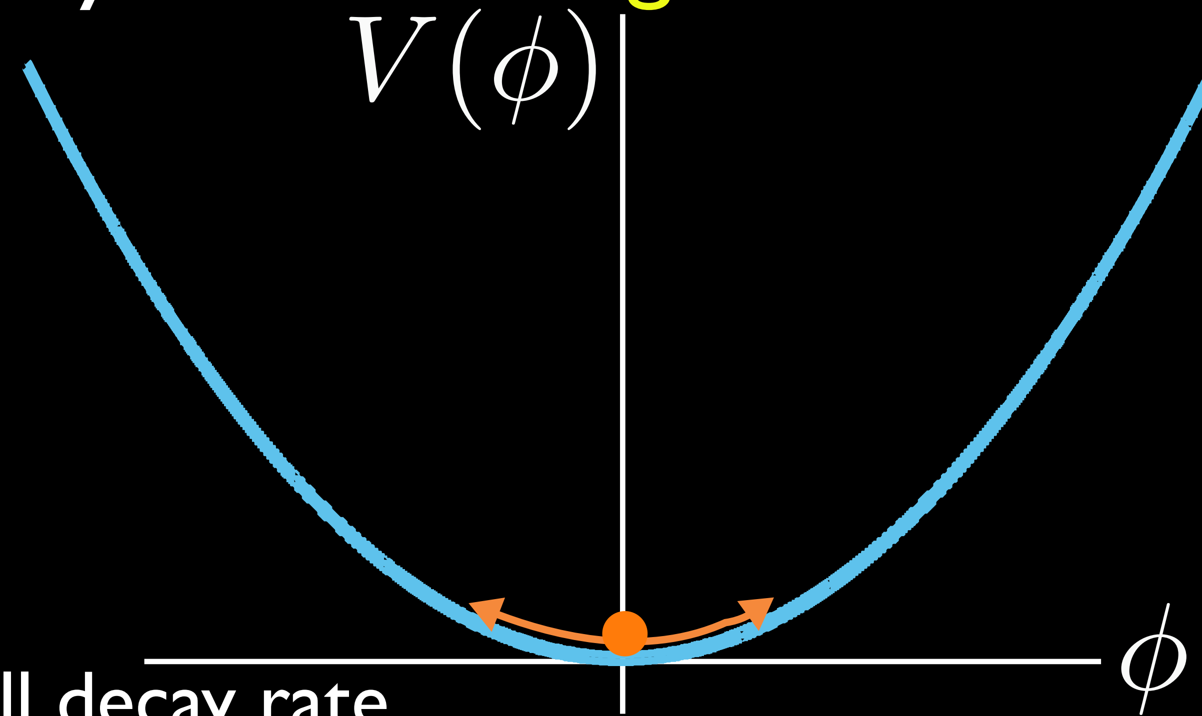

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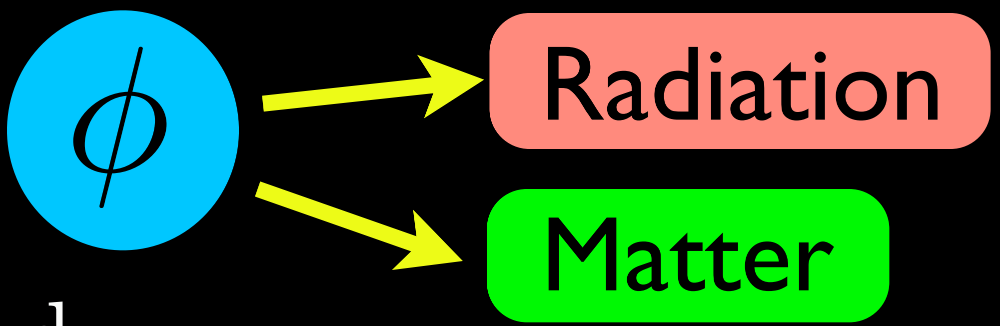
For $V \propto \phi^2$, oscillating scalar field $\simeq$matter.

- over many oscillations, average pressure is zero.
- density in scalar field evolves as $\rho_\phi \propto a^{-3}$
- scalar field density perturbations grow as $\delta_\phi \propto a$

Jedamzik, Lemoine, Martin 2010; Easther, Flauger, Gilmore 2010

What happens to these perturbations after reheating?

Scalar Field Decay

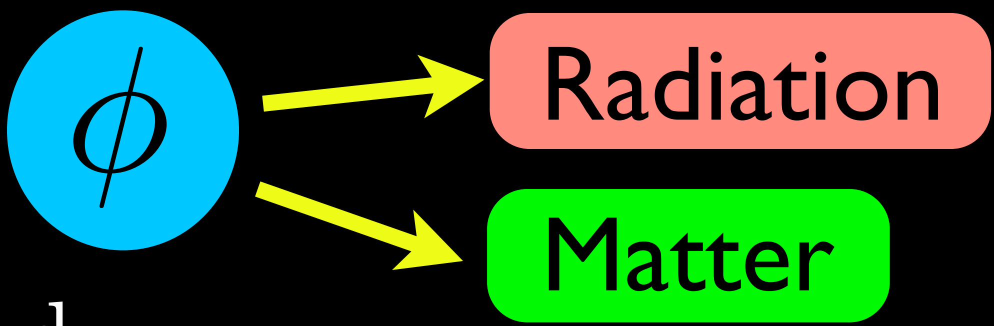


$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_r + 4H\rho_r = (1-f)\Gamma_\phi\rho_\phi$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{\mathrm{dm}} + 3H\rho_{\mathrm{dm}} = f\Gamma_\phi\rho_\phi$$

Scalar Field Decay



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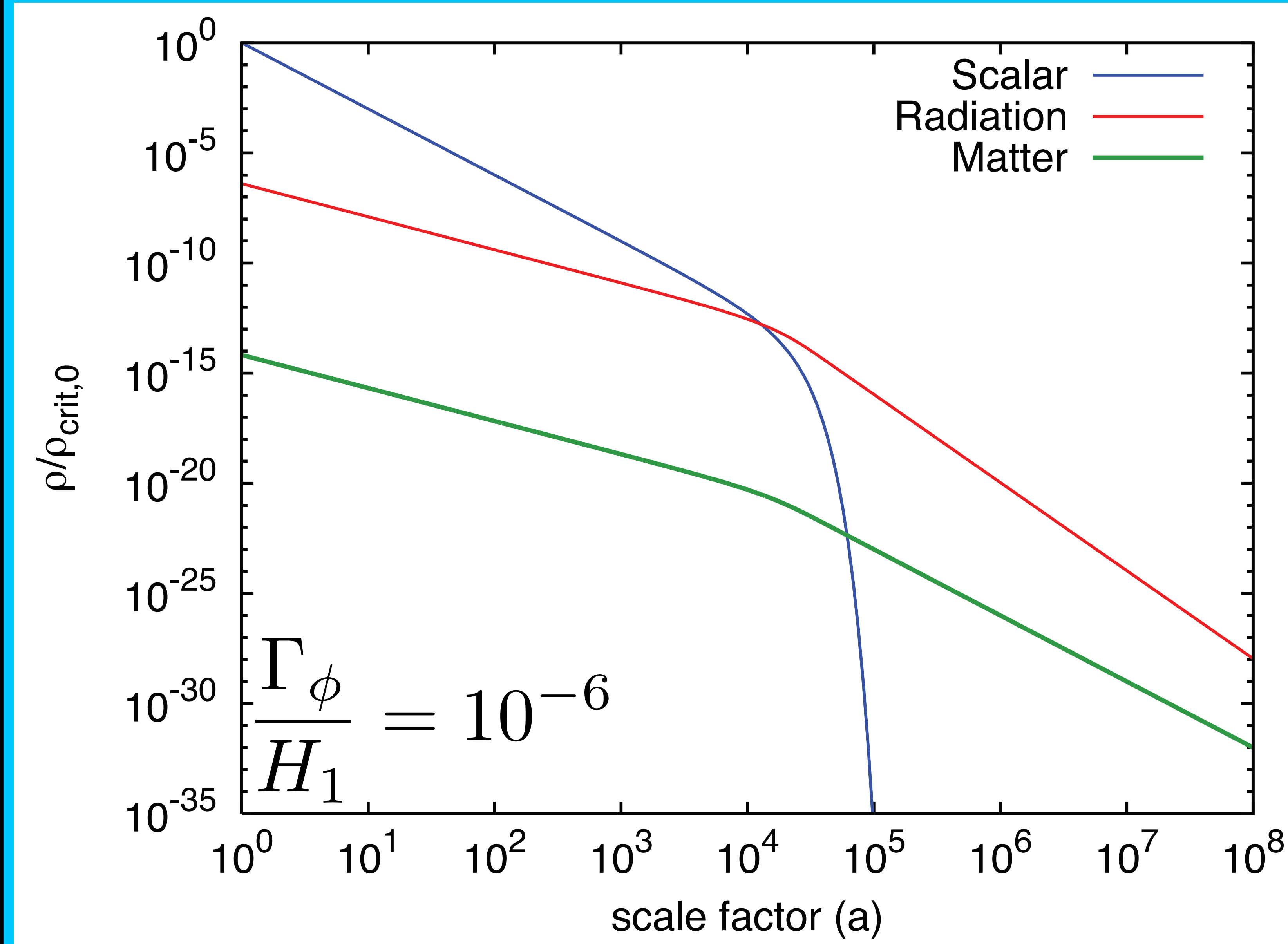
- Matter-Radiation Equality

$$f \simeq 0.43(T_{\rm eq}/T_{\rm RH})$$

- Scale factor at decay

$$H(a=1) \equiv H_1$$

$$a_{\rm RH} \simeq \left(\frac{\Gamma_\phi}{H_1}\right)^{-2/3}$$



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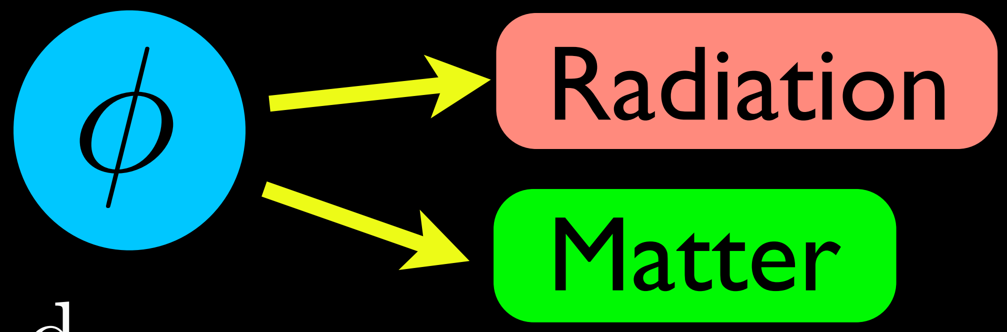

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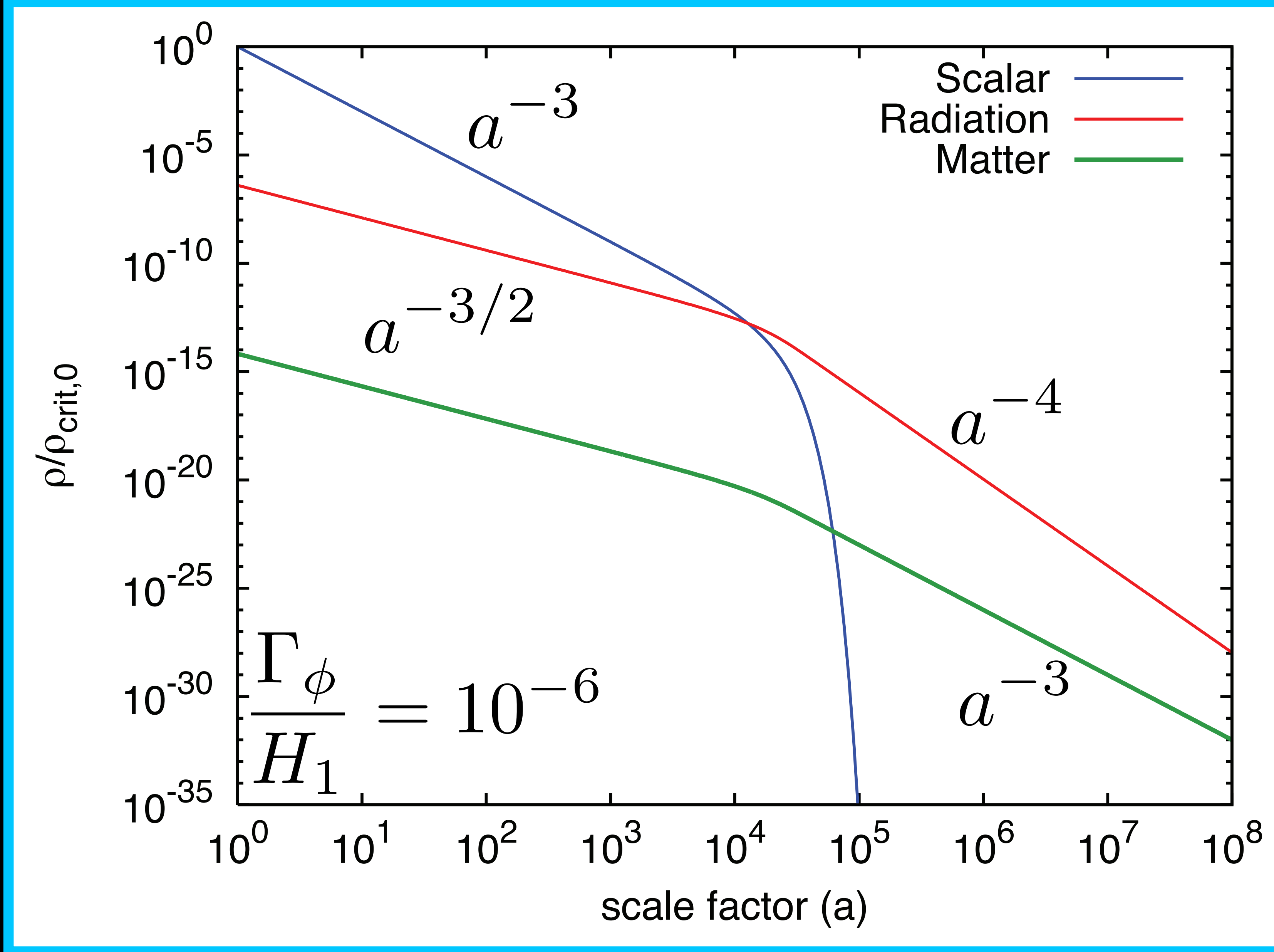
- During Scalar Domination

$$\rho_r \propto a^{-3/2}$$

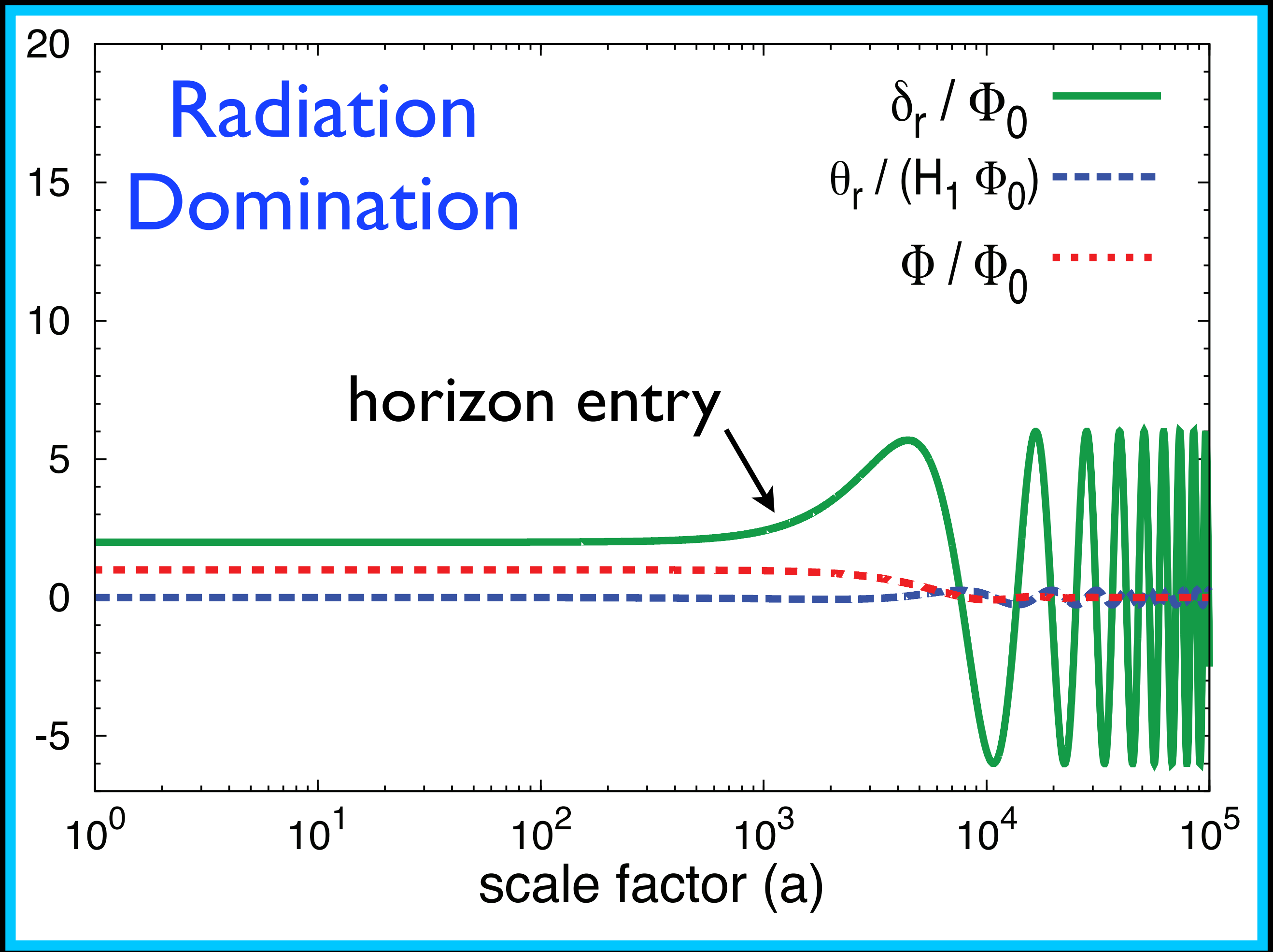
$$T \propto a^{-3/8}$$



Part II

Evolution of Perturbations during Reheating

The Radiation Perturbation

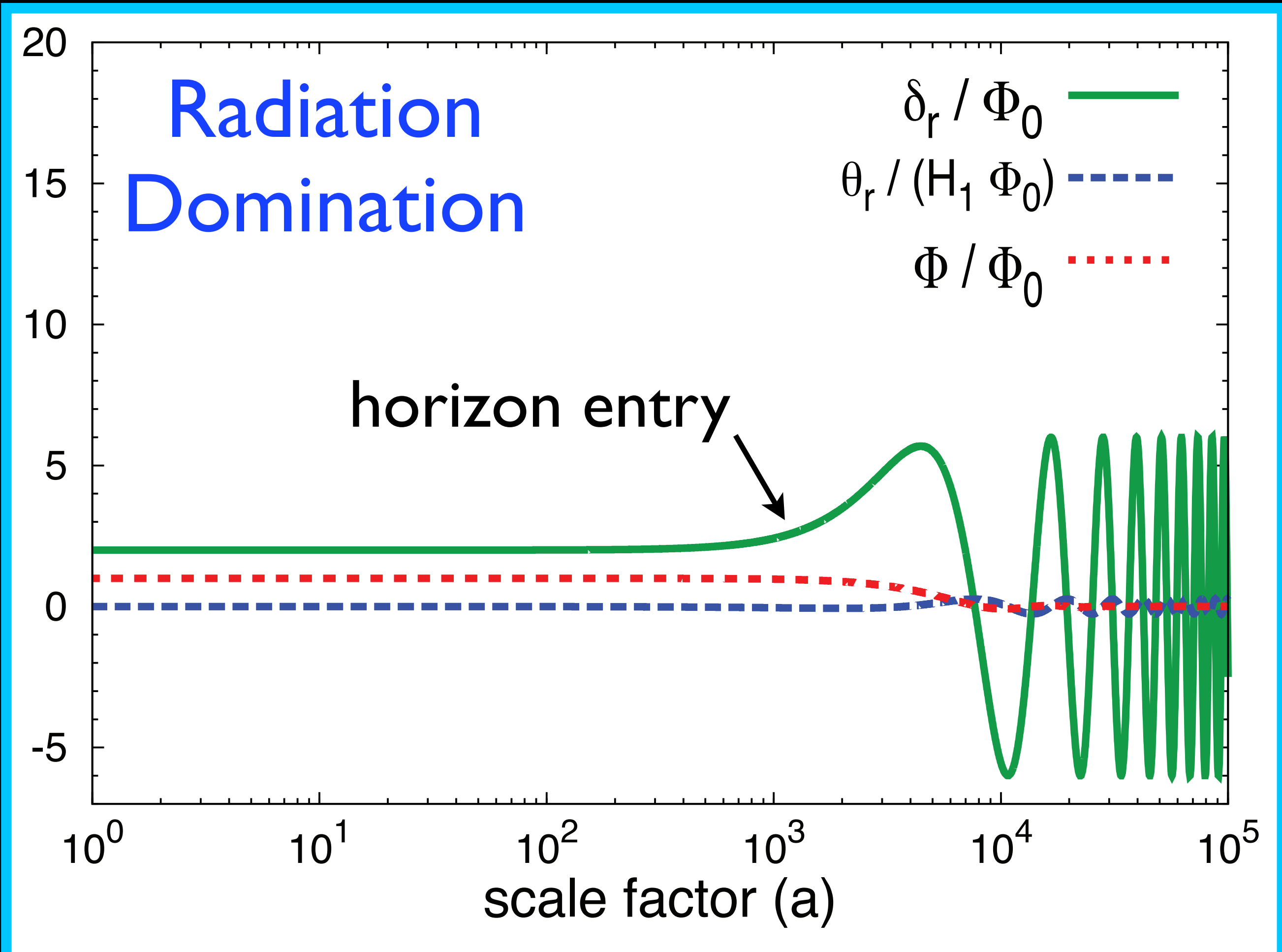


$$\dot{\delta}_r \simeq -\theta_r$$
$$\dot{\theta}_r \simeq k^2 \delta_r$$

During radiation domination, the radiation density perturbation oscillates.

$$\delta_{\max} = 6\Phi_0$$

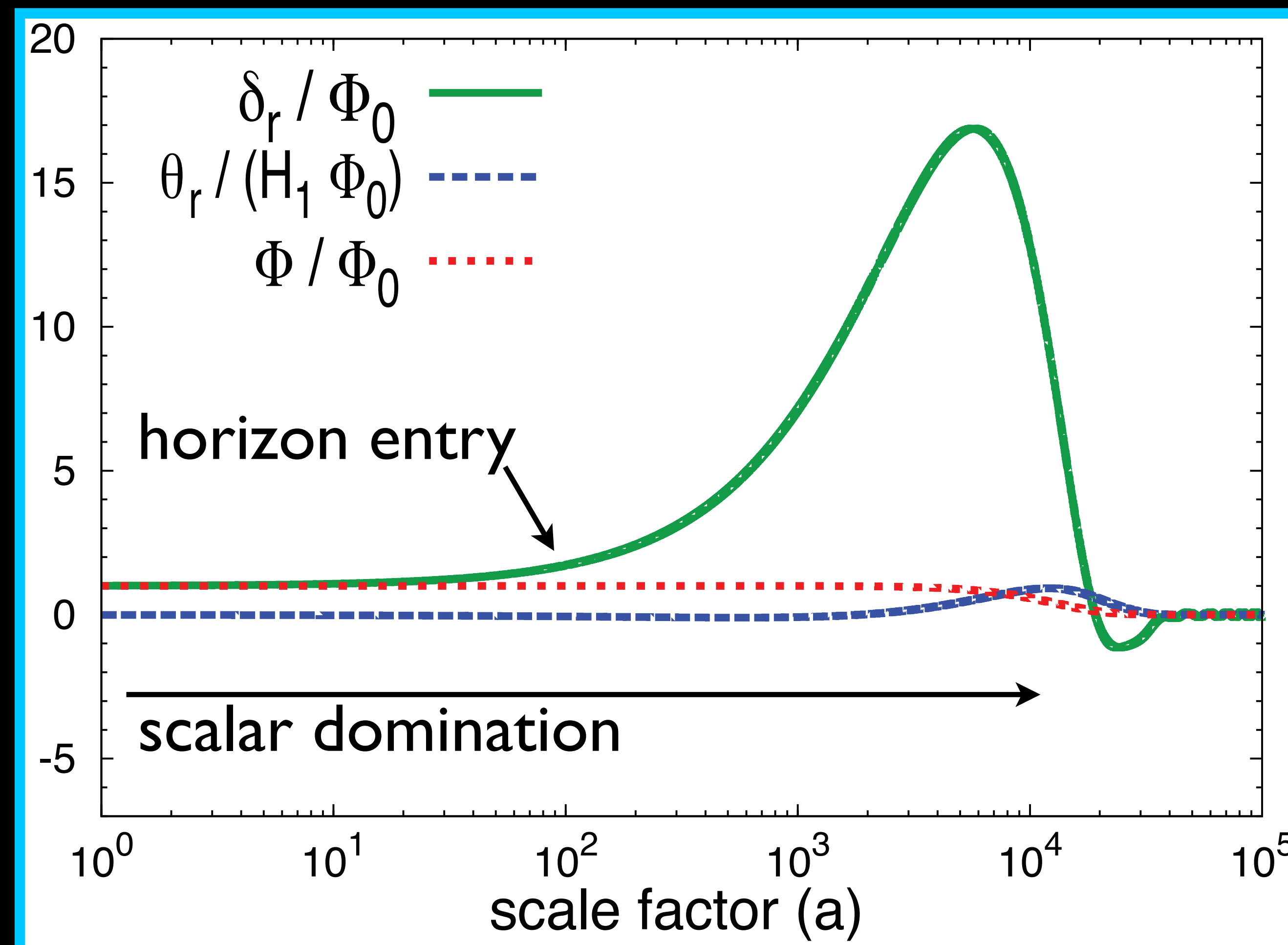
The Radiation Perturbation



$$\dot{\delta}_r \simeq -\theta_r + \mathcal{S}(\delta_\phi)$$
$$\dot{\theta}_r \simeq k^2 \delta_r + \mathcal{S}(\theta_\phi)$$

Grows during scalar domination

Adding a period of scalar domination dramatically alters the evolution!



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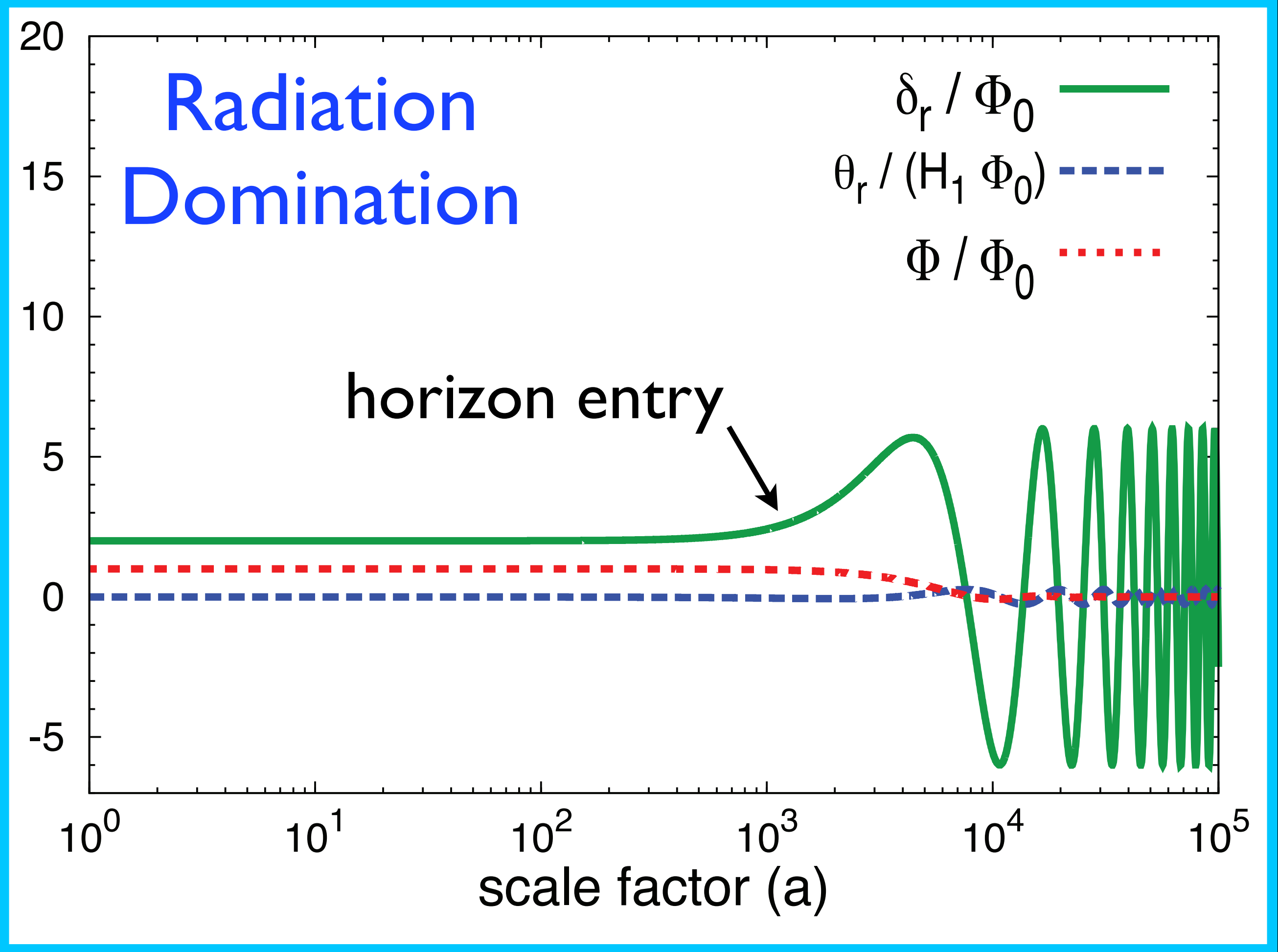

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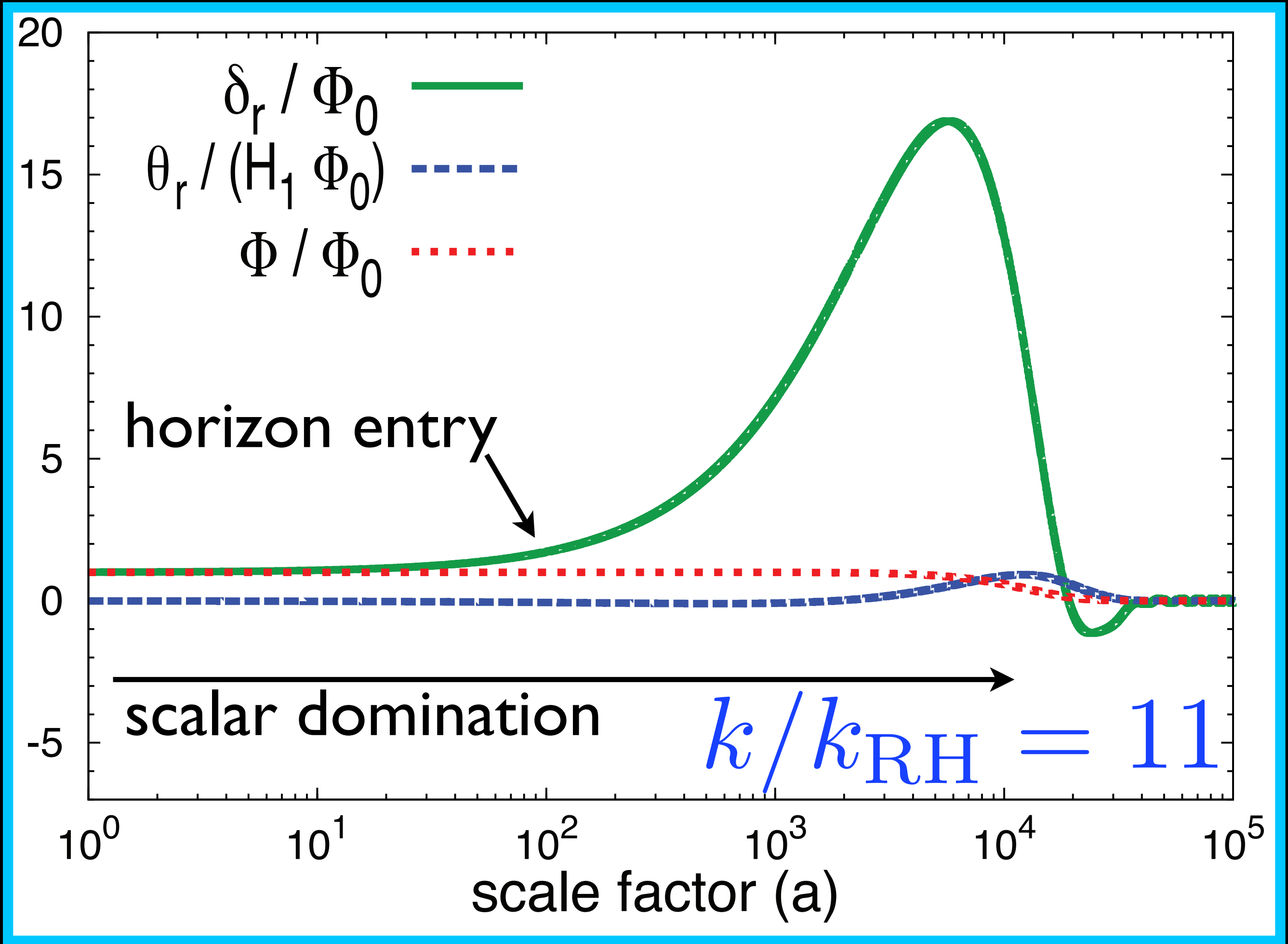
$$\delta_{\rm max} = 0.085\Phi_0 \text{ for } \frac{k}{k_{\rm RH}} = 11$$



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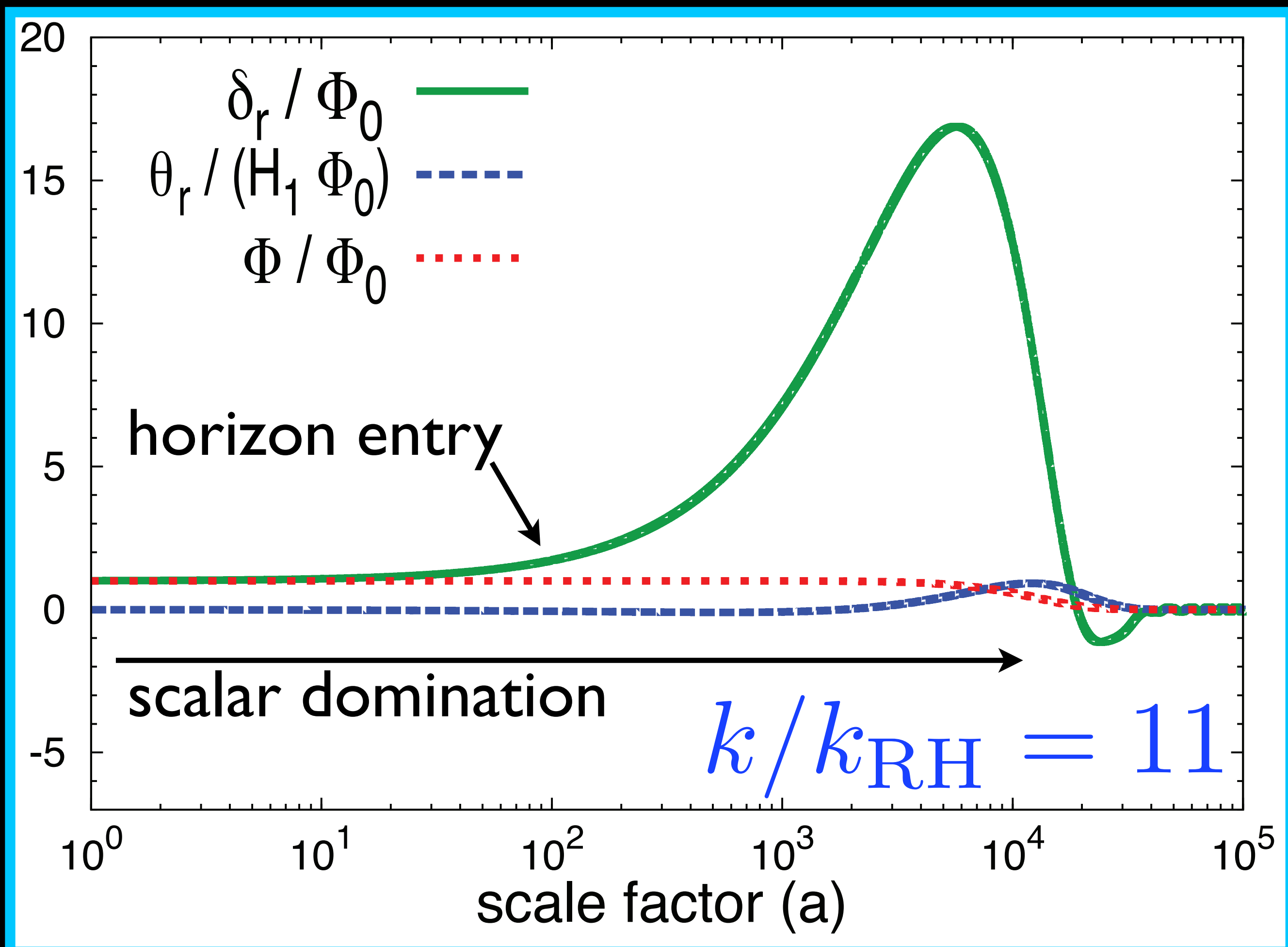
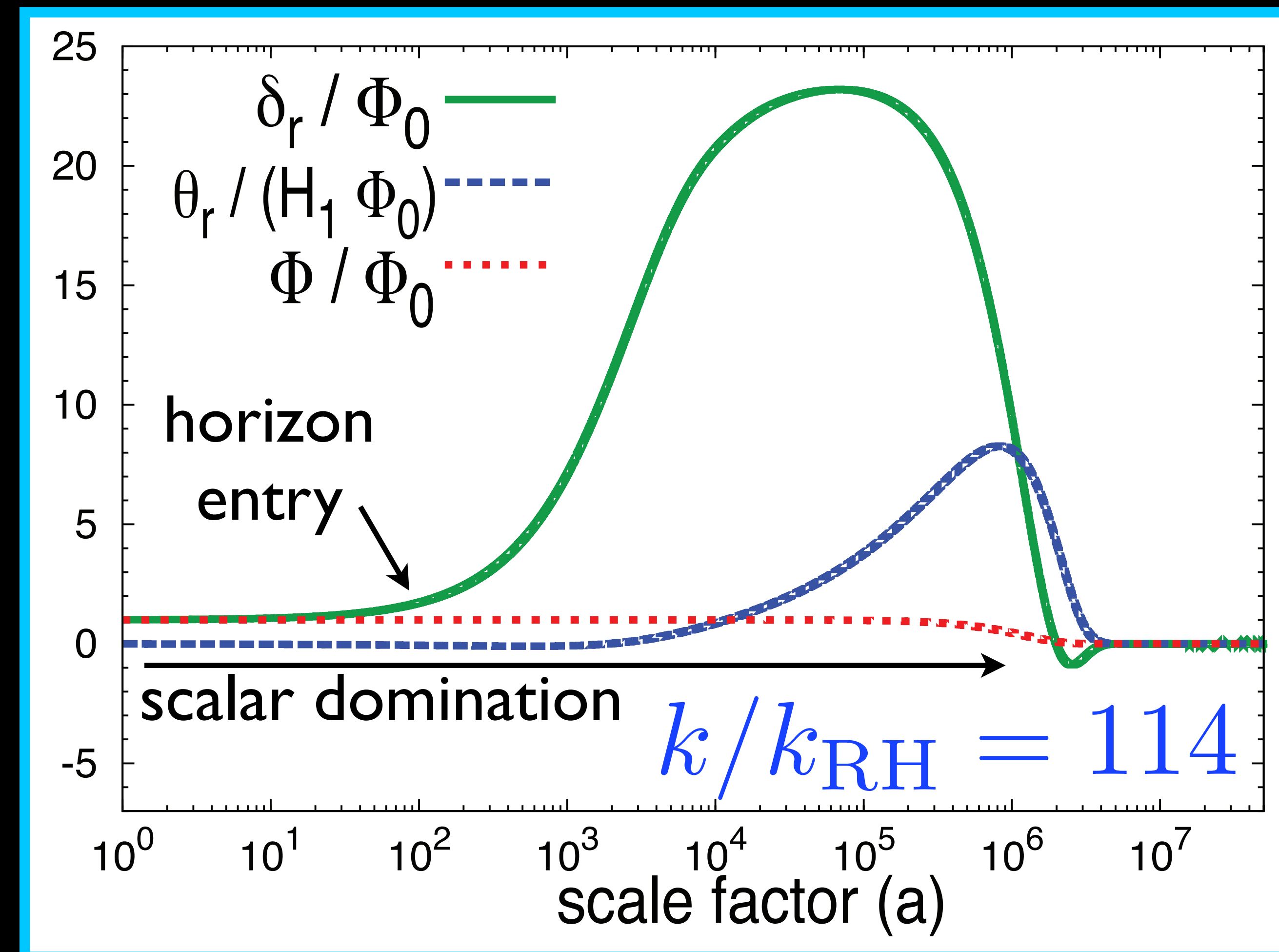


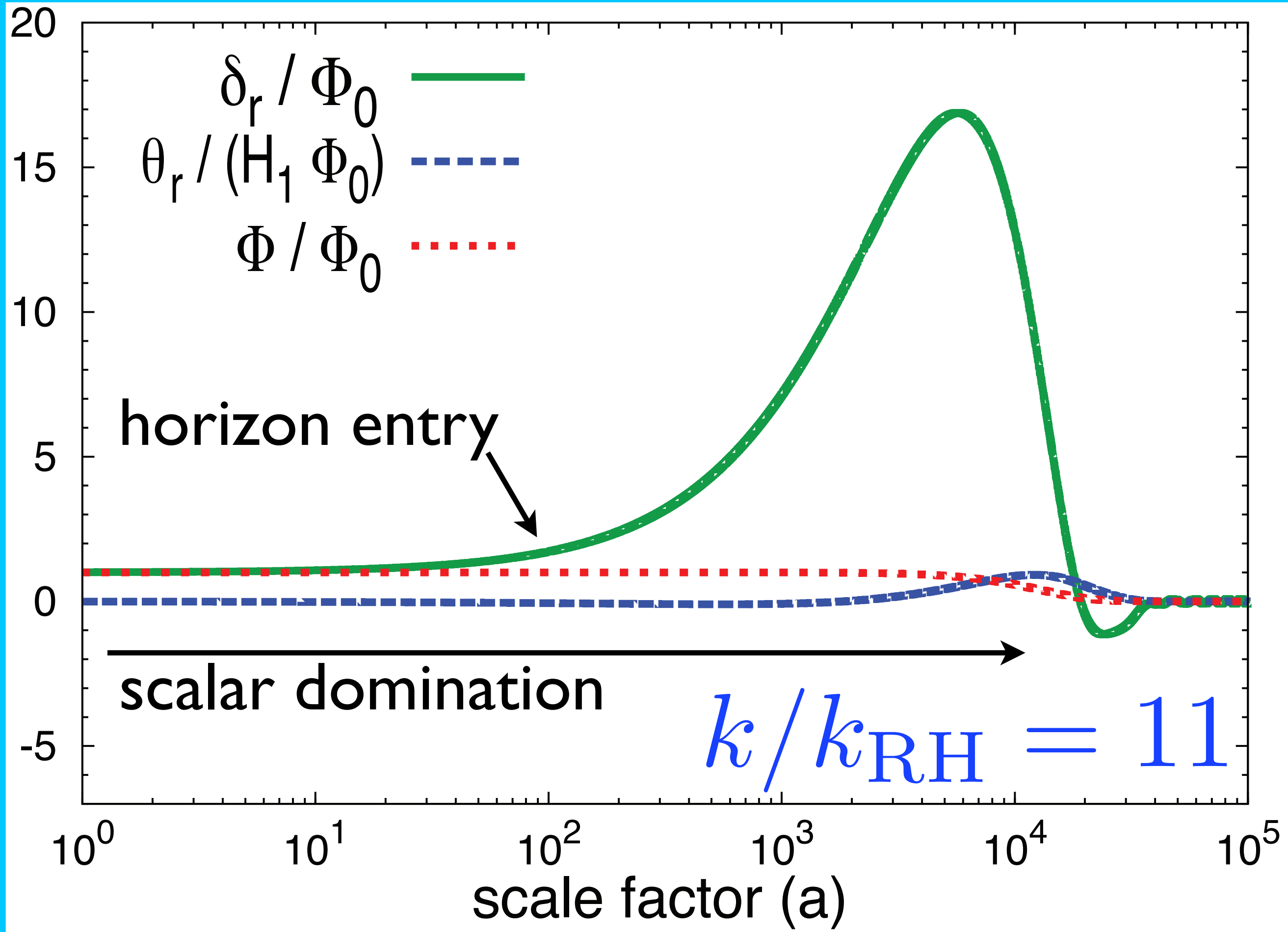


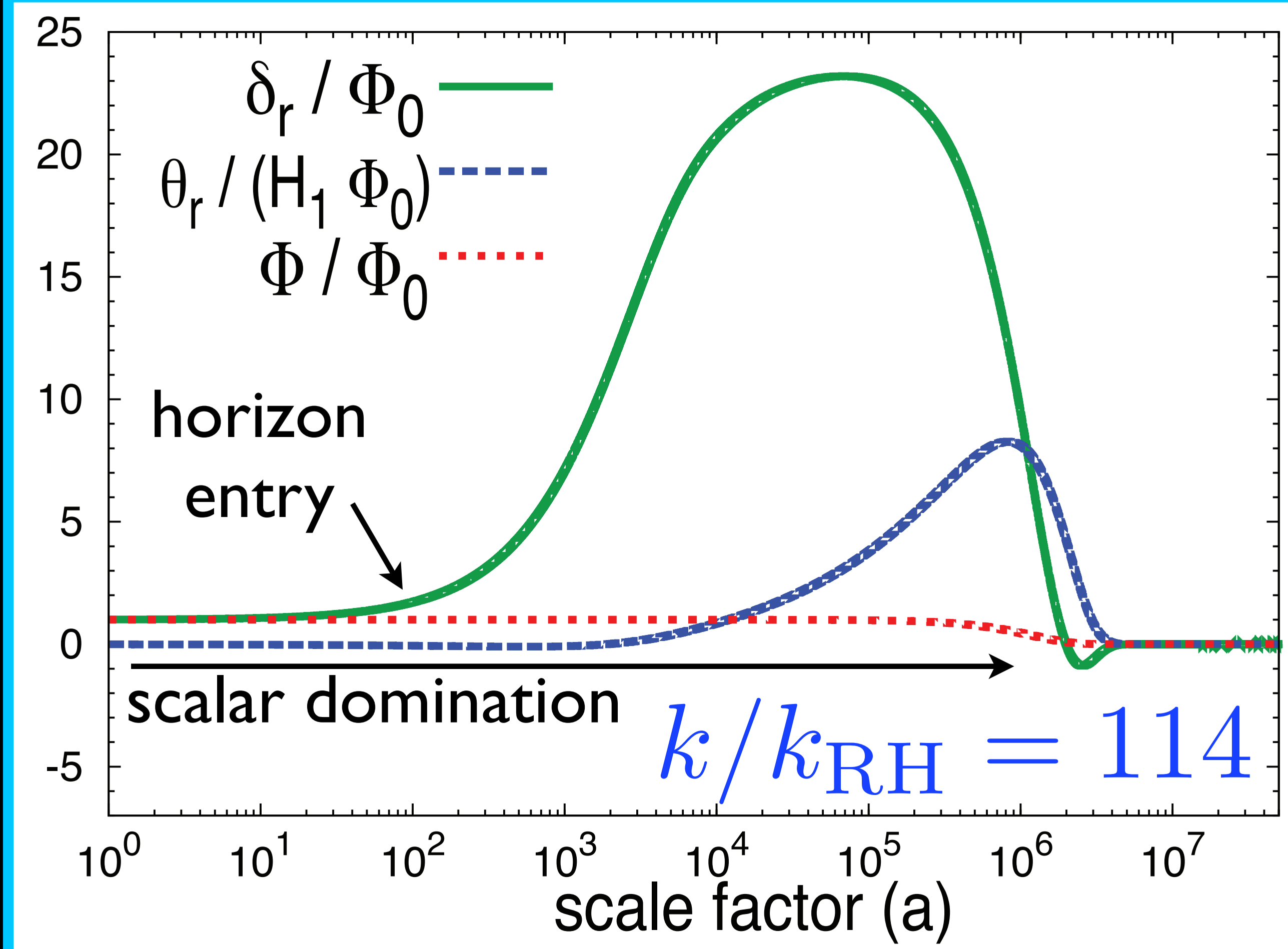
$\delta_{\rm max} = 0.085\Phi_0$ $\delta_{\rm max} = 0.0007\Phi_0$

$$\dot{\delta}_r \simeq -\theta_r + \mathcal{S}(\delta_\phi)$$
$$\dot{\theta}_r \simeq k^2\delta_r + \mathcal{S}(\theta_\phi)$$

The fluid velocity absorbs the effects of growth in the scalar perturbation.

The Radiation Perturbation





Impact of Scalar Domination: $\Phi_0 \rightarrow T_r(k)\Phi_0$

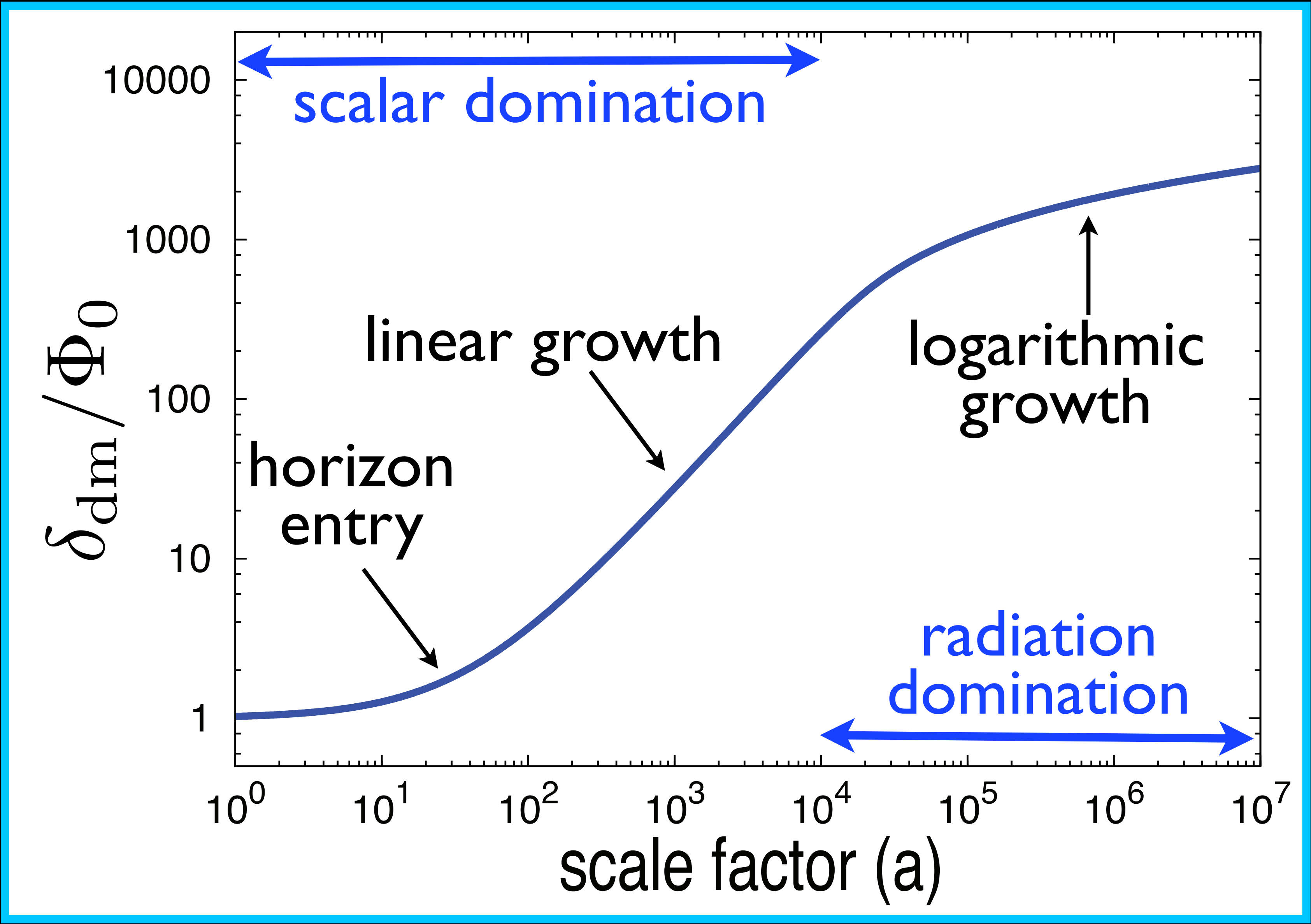
$$k_{\rm RH} = 35\ (T_{\rm RH}/3\,{\rm MeV})\ \ {\rm kpc}^{-1}$$

$T_r \lesssim 10^{-3}$	$k/k_{\rm RH} \gtrsim 20$
$T_r \simeq 1.5$	$2 \lesssim k/k_{\rm RH} \lesssim 4$
$T_r = 10/9$	$k/k_{\rm RH} \lesssim 0.1$

Suppression if dark matter couples to radiation after reheating.

The Matter Perturbation

Evolution of the Matter Density Perturbation



- dark matter produced in scalar decays
- the dark matter perturbation is sensitive only to the background expansion

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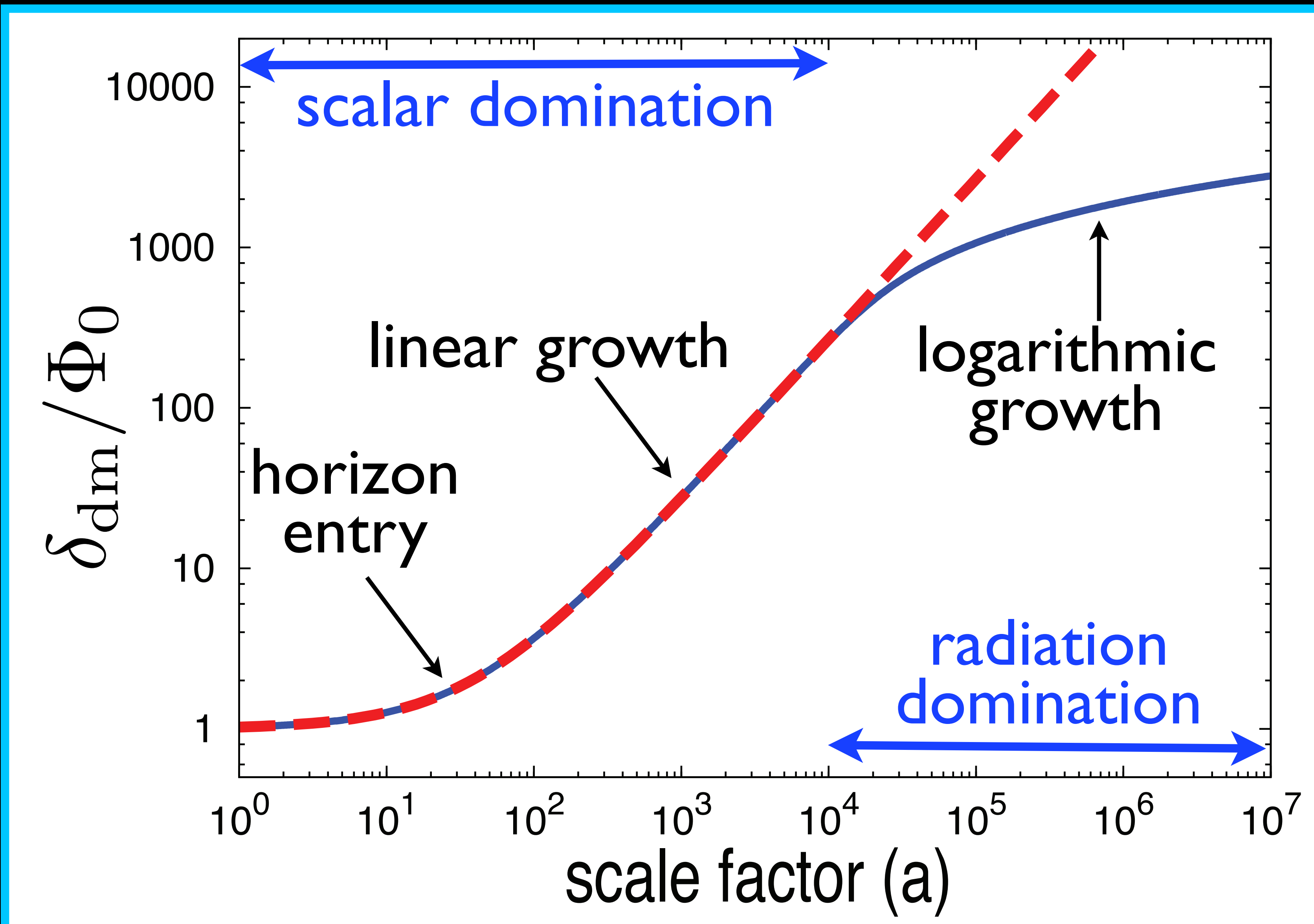

During Scalar Domination:

$$\delta_{\rm dm} = \Phi_0 \left(1 + \frac{2}{3}\frac{a}{a_{\rm hor}}\right)$$

linear growth

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The Matter Perturbation

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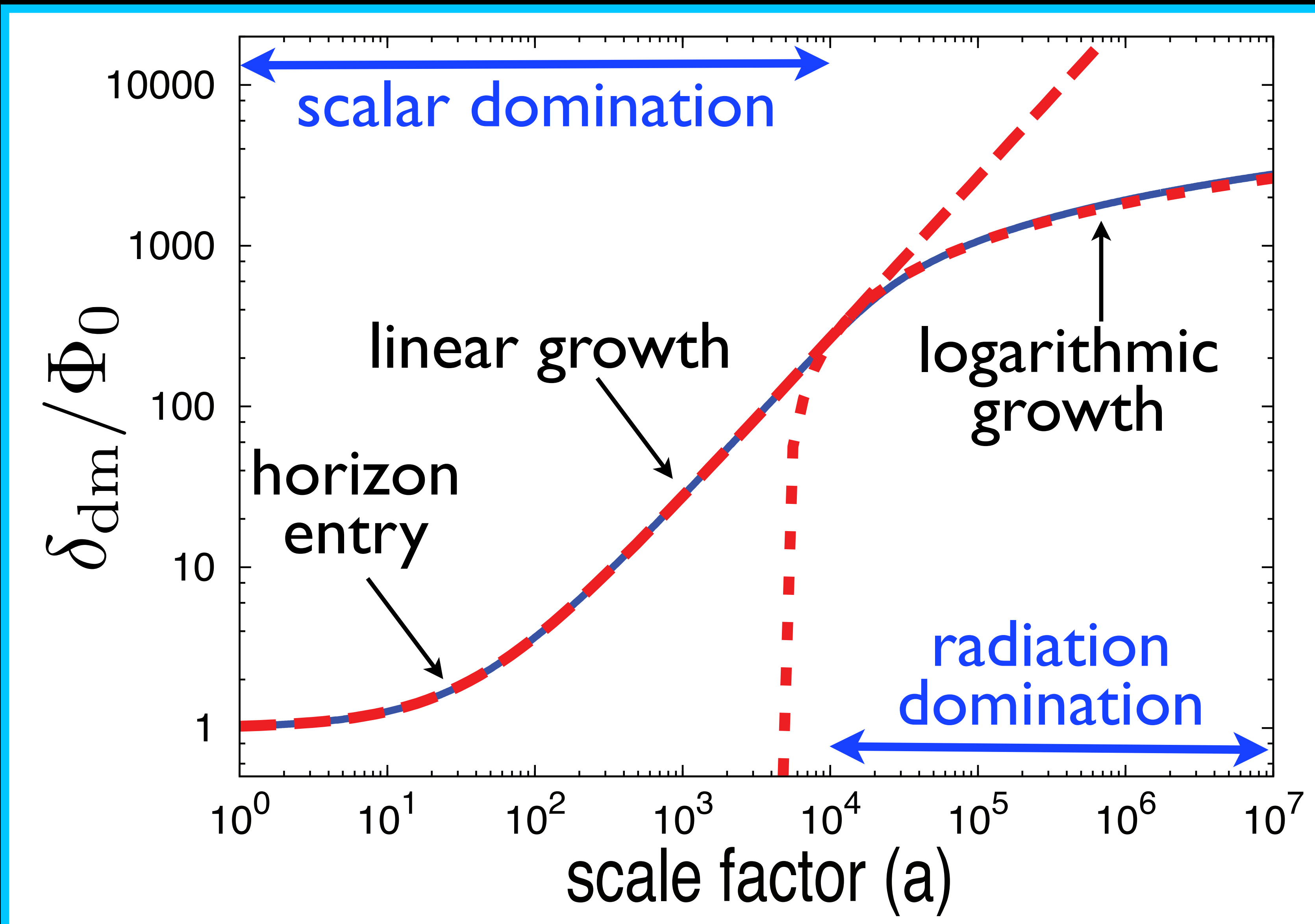

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linear growth

After reheating:

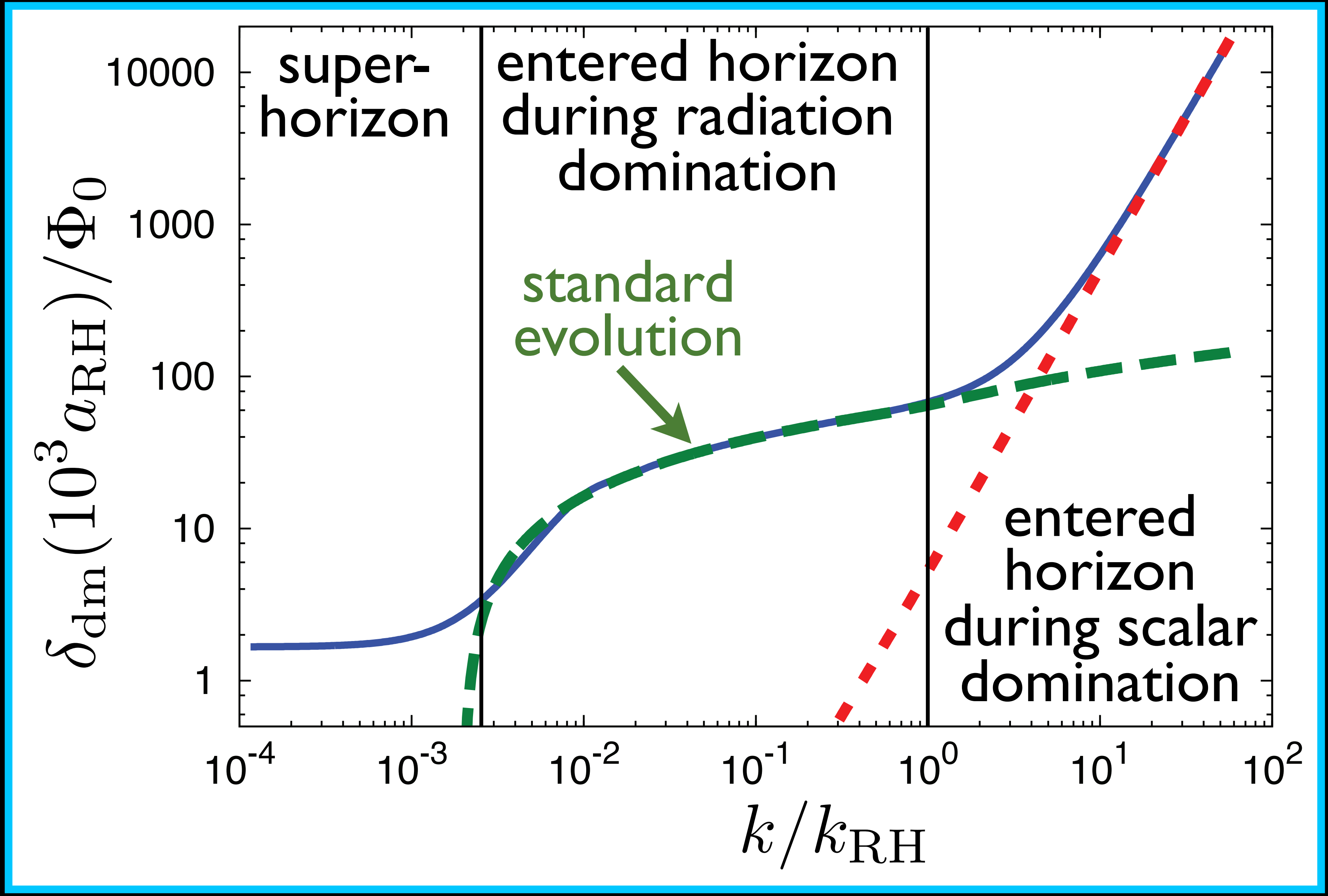
- During radiation domination, matter density perturbation grows logarithmically.
- Impose $a\delta'(a) = \text{const.}$ after reheating to get

$$\delta_{\rm dm} = \frac{2}{3}\Phi_0 \frac{a_{\rm RH}}{a_{\rm hor}}\left[1 + \ln\left(\frac{a}{a_{\rm RH}}\right)\right]$$

logarithmic growth

The Matter Perturbation

The Matter Density Perturbation during Radiation Domination

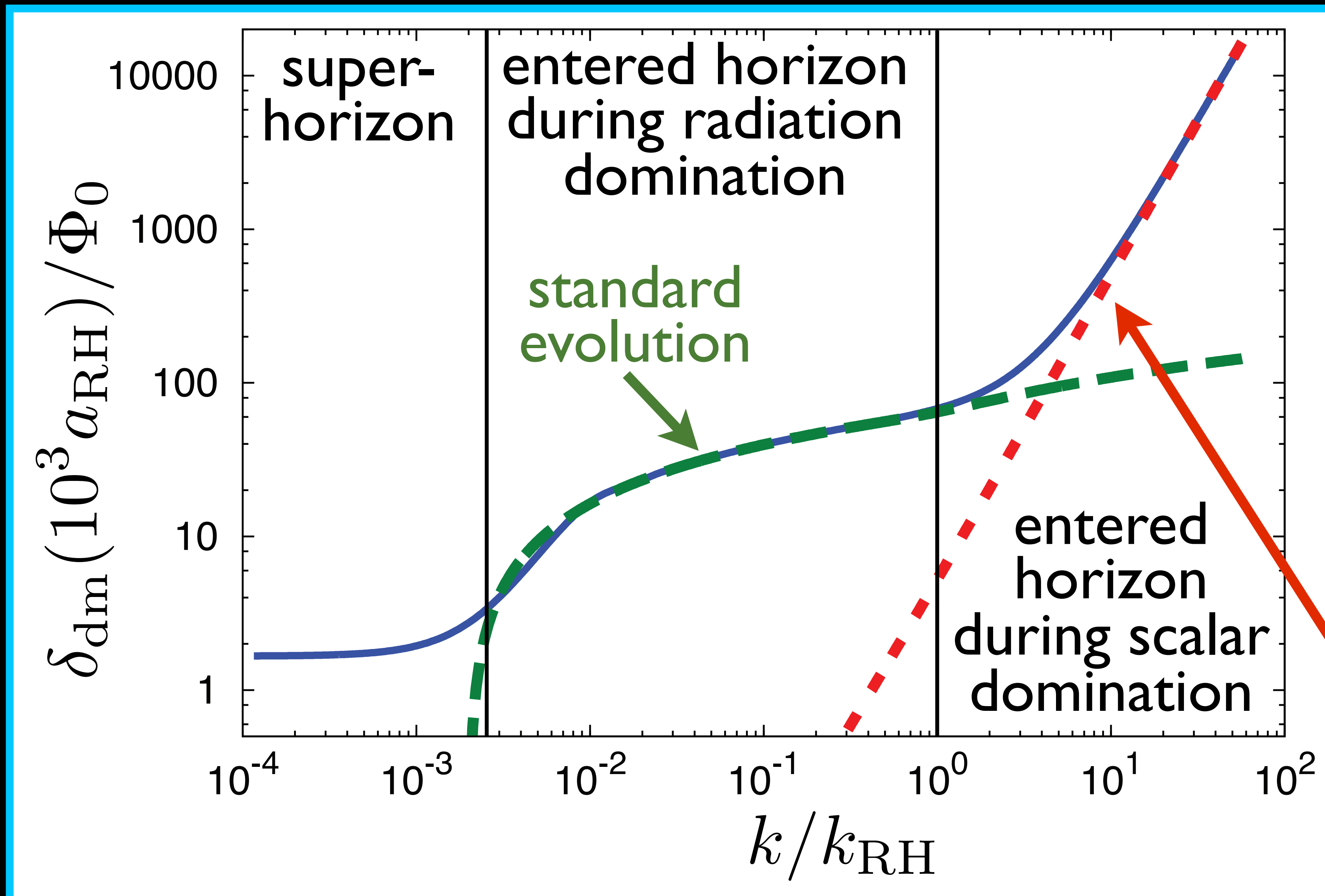


Superhorizon modes evolve at reheating: $\Phi \to (10/9)\Phi_0$

$$\delta_r \to 2\Phi = (20/9)\Phi_0 \quad \delta_{\rm dm} \to (5/3)\Phi_0 = (3/4)\delta_r$$

The Matter Perturbation

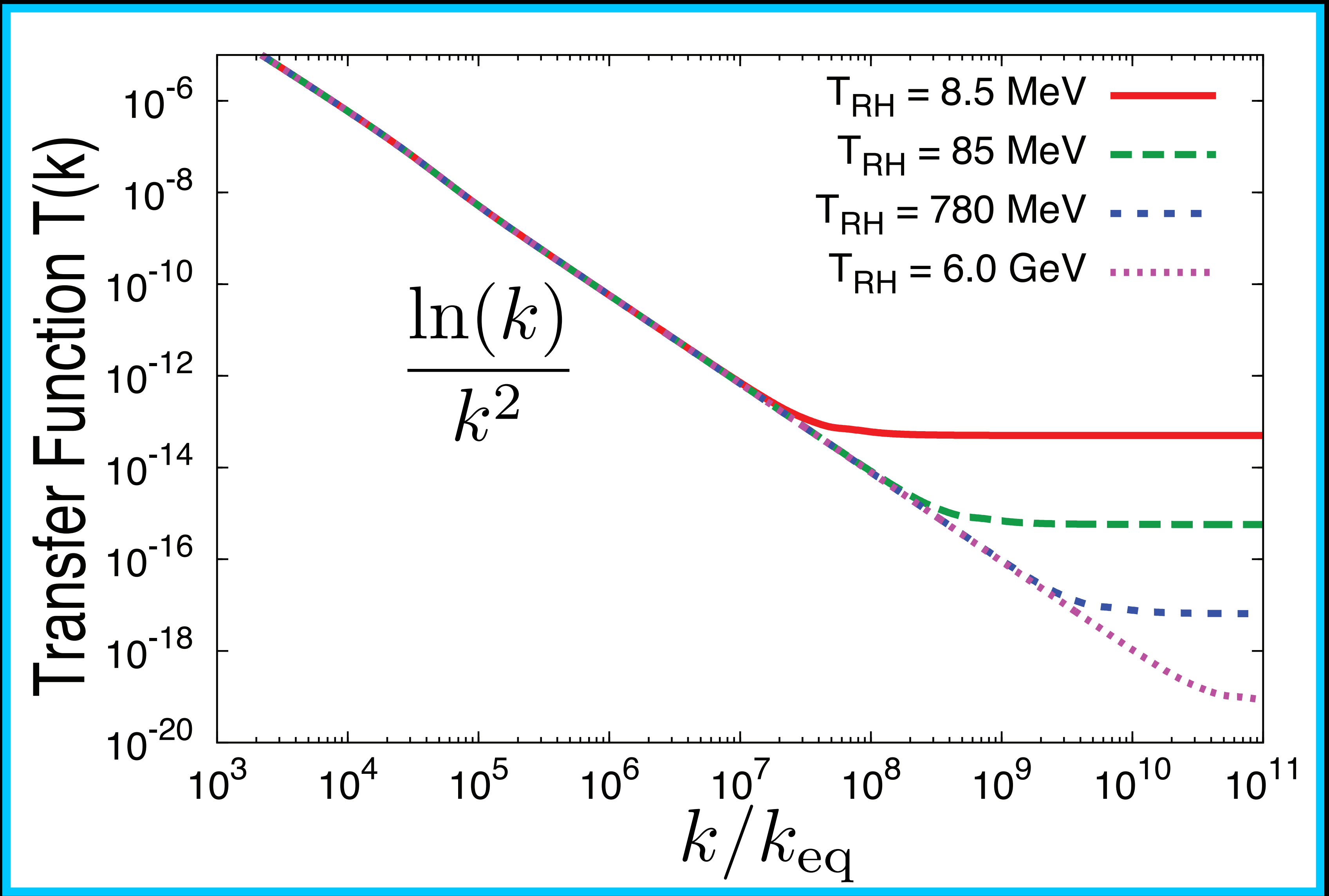
The Matter Density Perturbation during Radiation Domination



$$\delta_{\rm dm} \propto \frac{a_{\rm RH}}{a_{\rm hor}} \propto \frac{k^2}{k_{\rm RH}^2} \Longrightarrow \delta_{\rm dm} = \frac{2}{3}\Phi_0 \frac{k^2}{k_{\rm RH}^2}\left[1 + \ln\left(\frac{a}{a_{\rm RH}}\right)\right]$$

The Matter Transfer Function

Transfer function definition: $\delta_{\rm dm} \propto k^2 \Phi_0(k) T(k) D(a)$



Subhorizon modes at reheating: $\delta_{\rm dm} \propto k^2 \Phi_0 \Rightarrow T(k) = \text{const.}$

$$T(k) = \frac{3}{4}\left(\frac{k_{\rm eq}}{k_{\rm RH}}\right)^2 \ln\left[\frac{4\sqrt{2}}{e^2}\left(\frac{k_{\rm RH}}{k_{\rm eq}}\right)\right]$$

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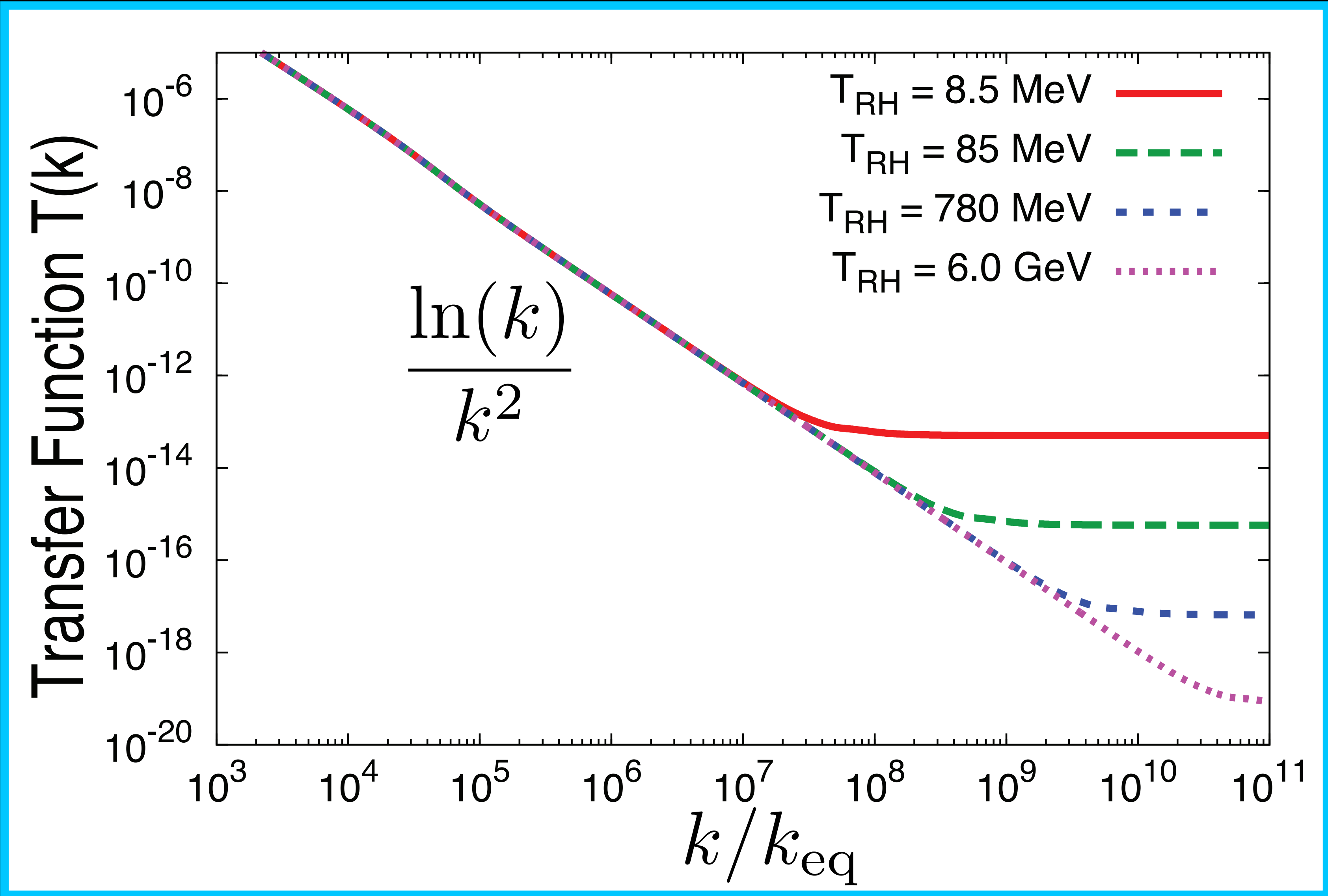

For modes that enter the horizon during scalar domination ($k > k_{\rm RH}$):

- Linear growth after horizon entry, except during radiation domination
- T(k) depends only on duration of radiation domination

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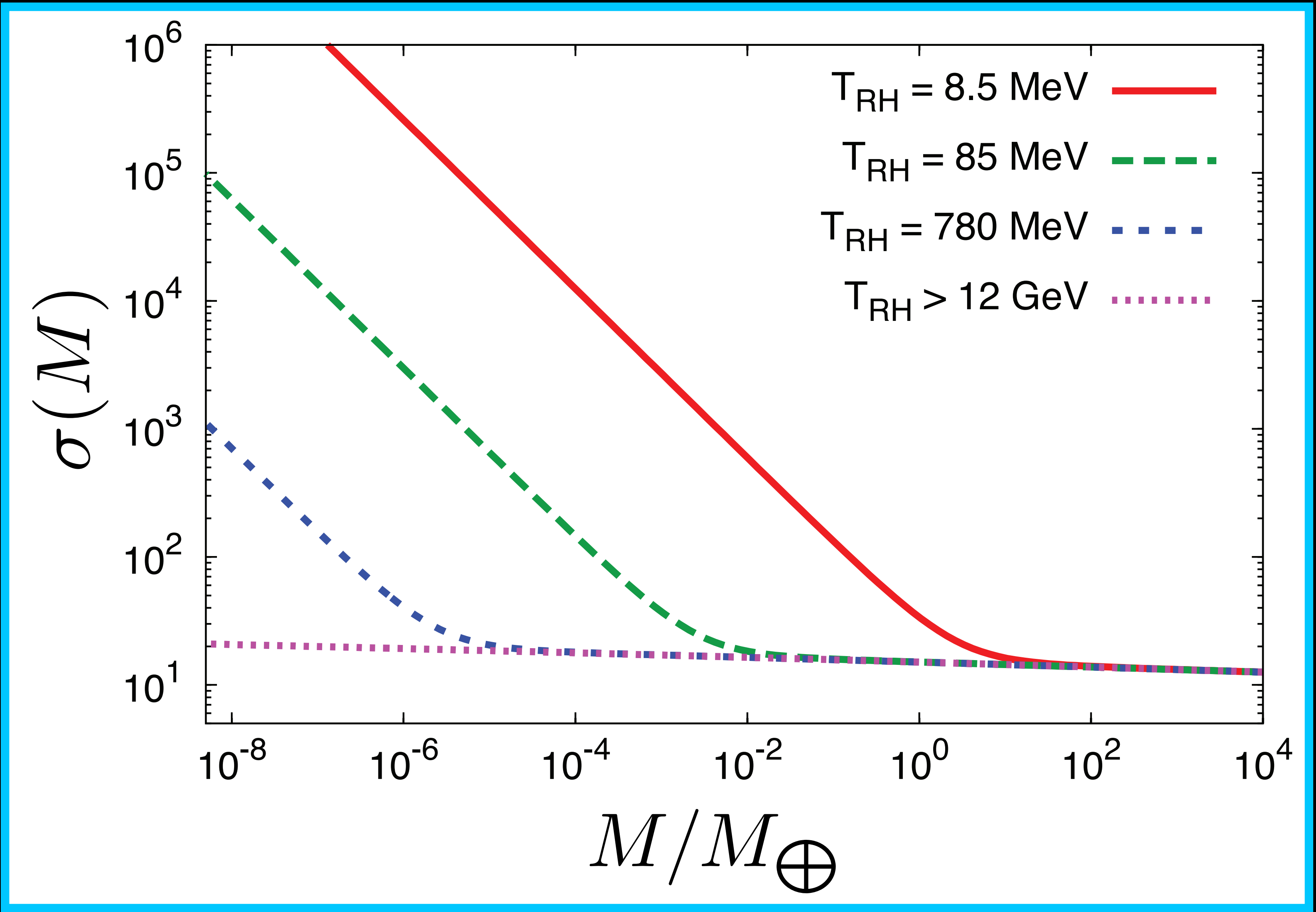
RMS Density Fluctuation



- Altered transfer function affects scales with $R \lesssim k_{\rm RH}^{-1}$
- Define $M_{\rm RH}$ to be mass within this comoving radius.

$$M_{\rm RH} \simeq 32.7 M_\oplus \left(\frac{10\,{\rm MeV}}{T_{\rm RH}}\right)^3$$

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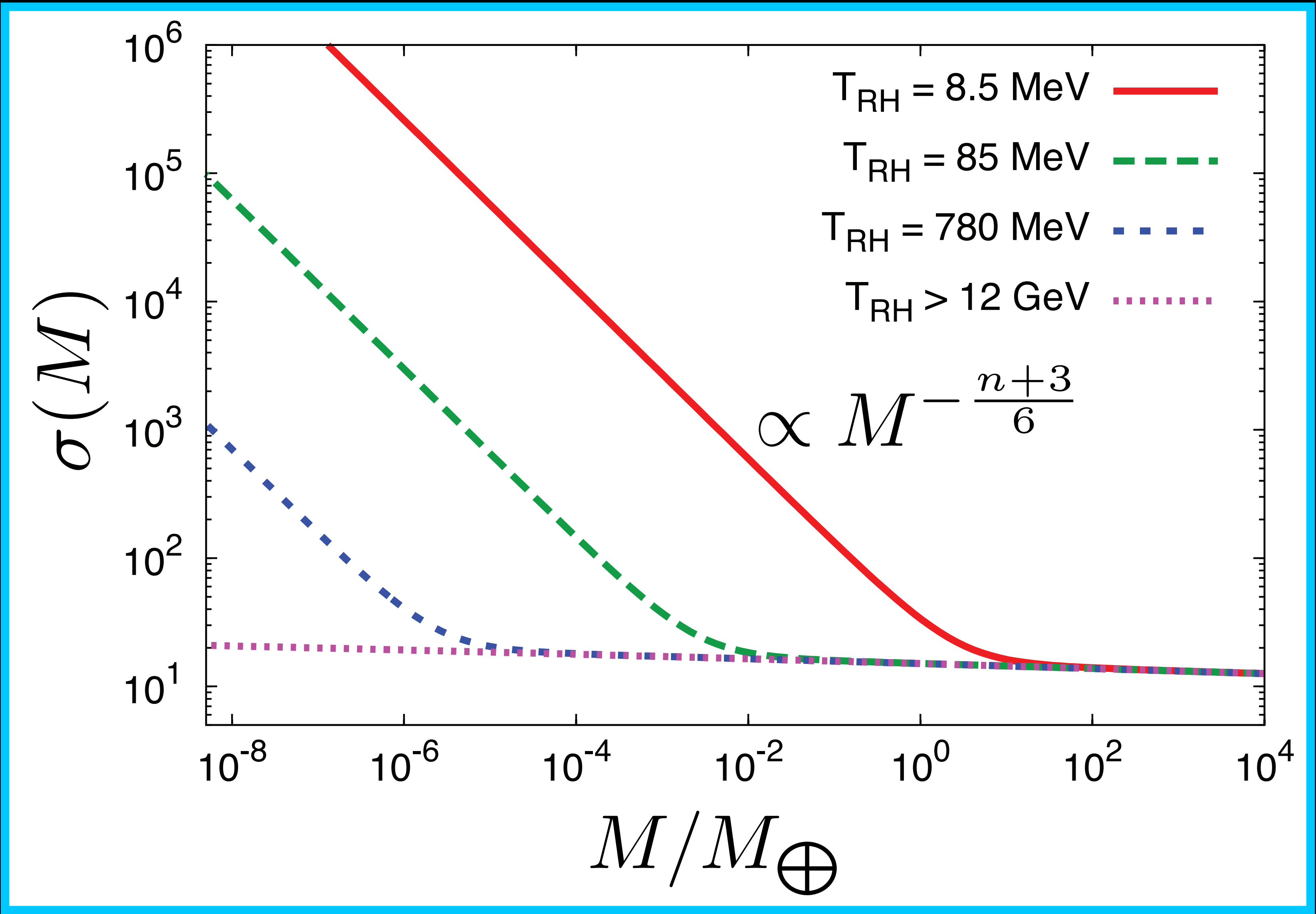

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- Altered transfer function affects scales with $R \lesssim k_{\rm RH}^{-1}$
- Define $M_{\rm RH}$ to be mass within this comoving radius.
- For $k > k_{\rm RH}$, $P(k) \propto k^n$
- Since the power spectrum is a power law,

$$\sigma(M) \propto M^{-\frac{n+3}{6}}$$

for

$$M < M_{\rm RH}$$

What about free-streaming?

Free-streaming will exponentially suppress power on scales smaller than the free-streaming horizon: $\lambda_{\rm fsh}(t) = \int_{t_{\rm RH}}^{t} \frac{\langle v \rangle}{a}\,{\rm d}t$

Modify transfer function: $T(k) = \exp\left[-\frac{k^2}{2k_{\rm fsh}^2}\right] T_0(k)$

Specify average particle velocity at reheating:

$$\langle v \rangle = \langle v_{\rm RH} \rangle \left(a_{\rm RH}/a\right)$$

For range of reheat temperatures,

$$\frac{k_{\rm RH}}{k_{\rm fsh}} \simeq \frac{\langle v_{\rm RH} \rangle}{0.06}$$

Structures grown during reheating only survive if $\langle v_{\rm RH} \rangle \lesssim 0.001c$

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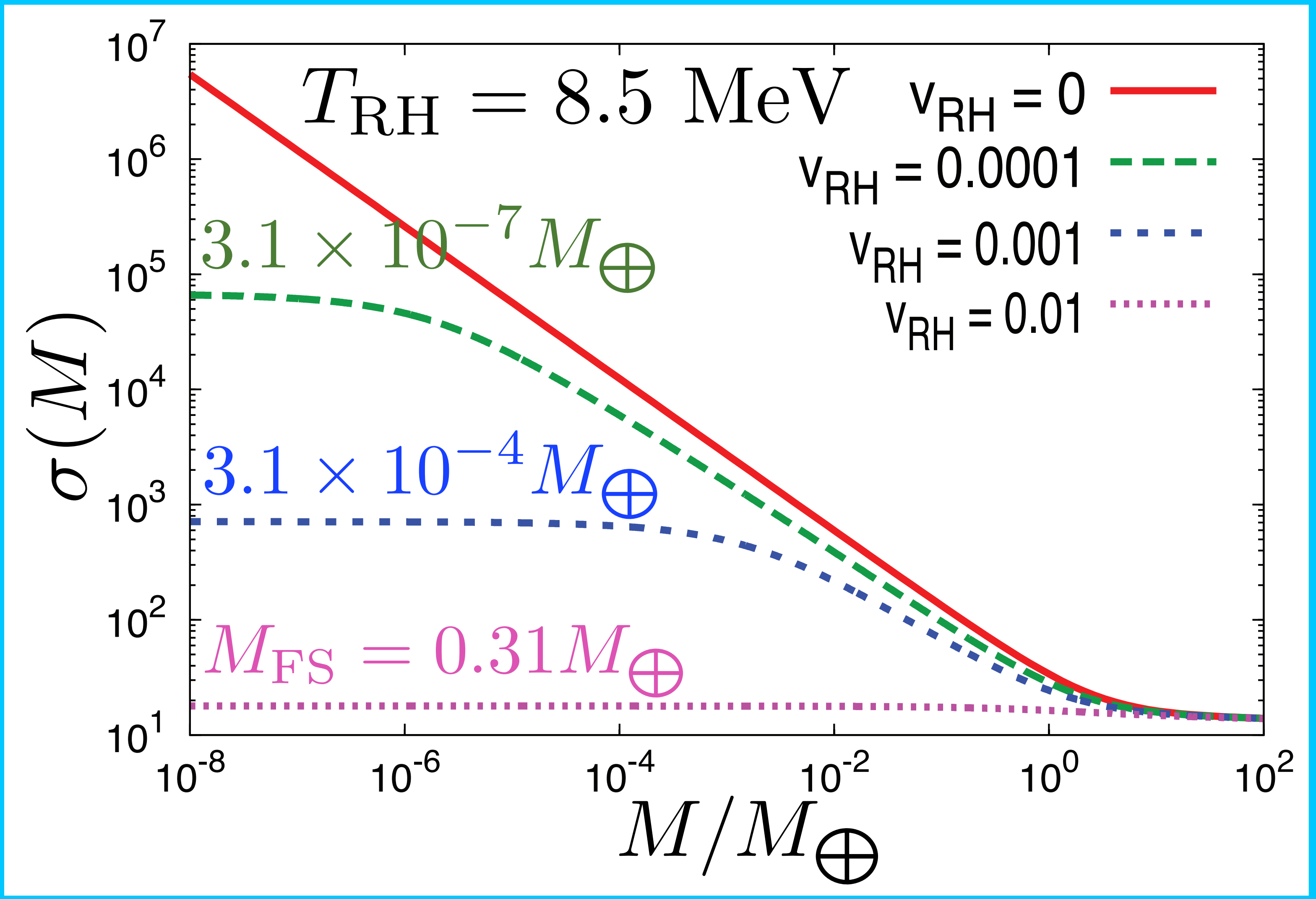

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Part III

Microhalos from Reheating

From Perturbations to Microhalos

To estimate the abundance of halos, we used the Press-Schechter mass function to calculate the fraction of dark matter contained in halos of mass M.

$$\frac{df}{d\ln M} = \sqrt{\frac{2}{\pi}} \left|\frac{d\ln\sigma}{d\ln M}\right| \frac{\delta_c}{\sigma(M,z)} \exp\left[-\frac{1}{2}\frac{\delta_c^2}{\sigma^2(M,z)}\right]$$

differential bound fraction

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Key ratio: $\frac{\delta_c}{\sigma(M,z)}$

- Halos with $\sigma(M,z) < \delta_c$ are rare.
- Define $M_*(z)$ by

$$\sigma(M_*,z) = \delta_c$$

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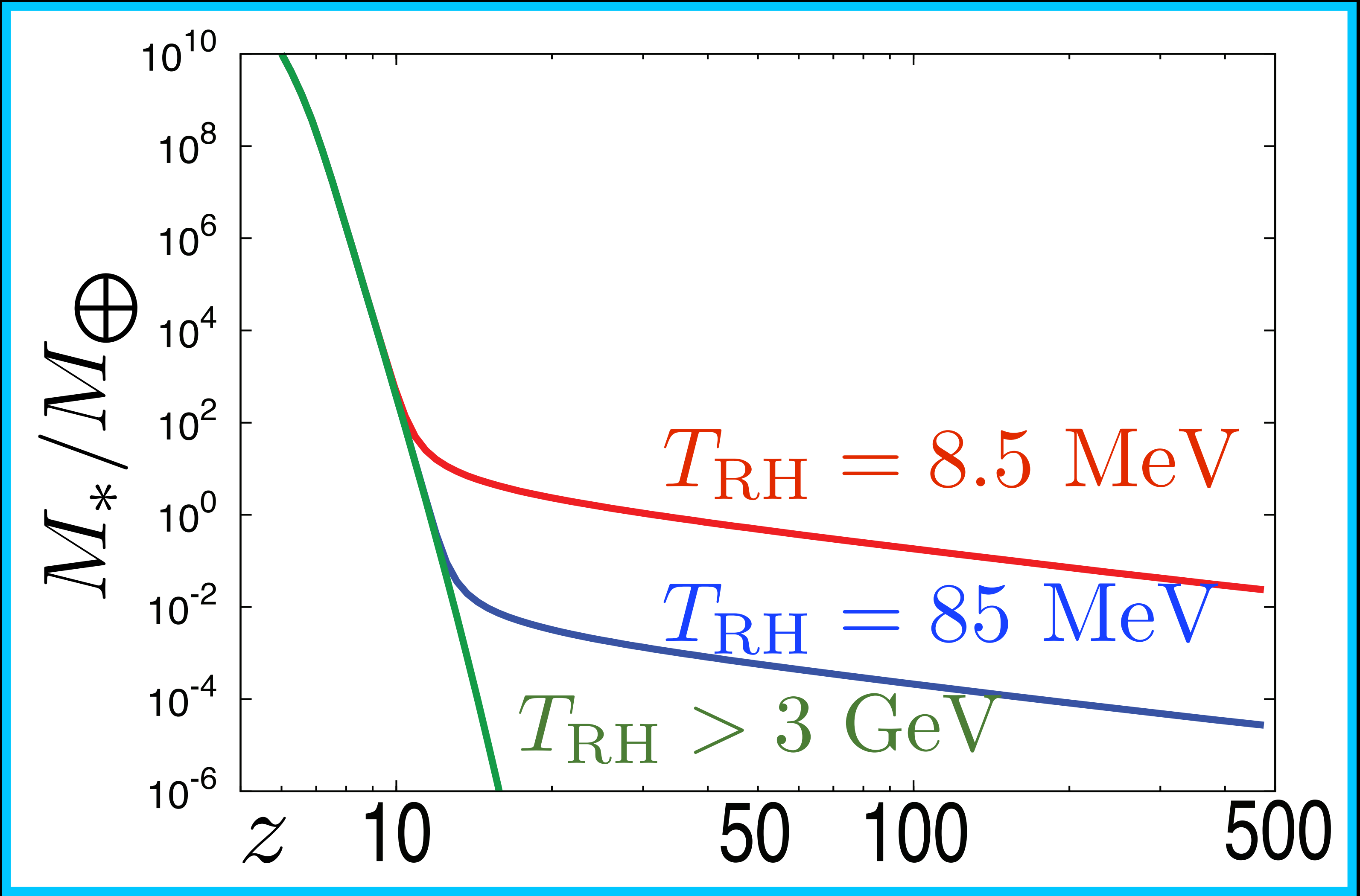
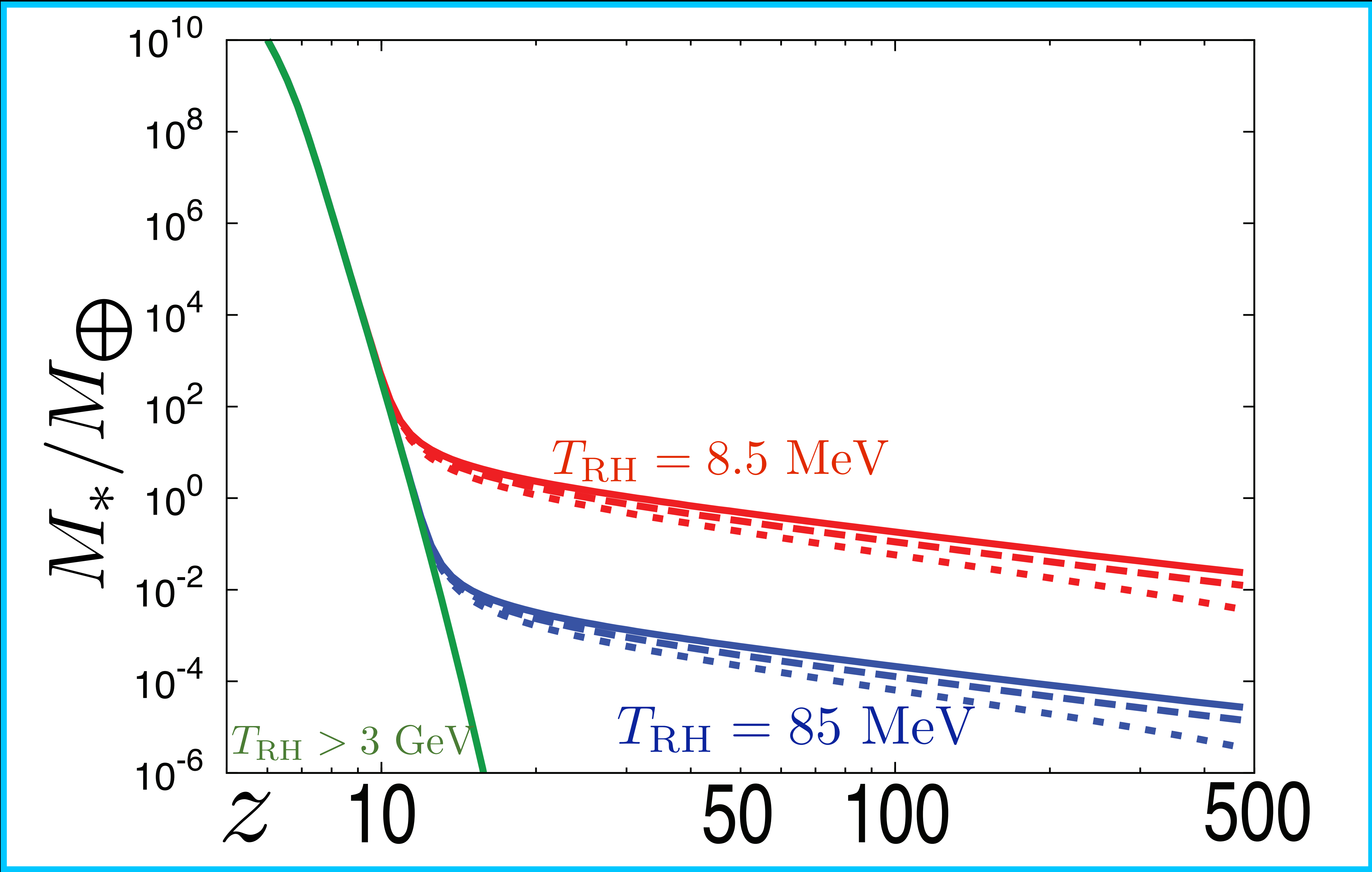


M_* Properties

$M_*(z)$ is the largest halo that is common at a given redshift.



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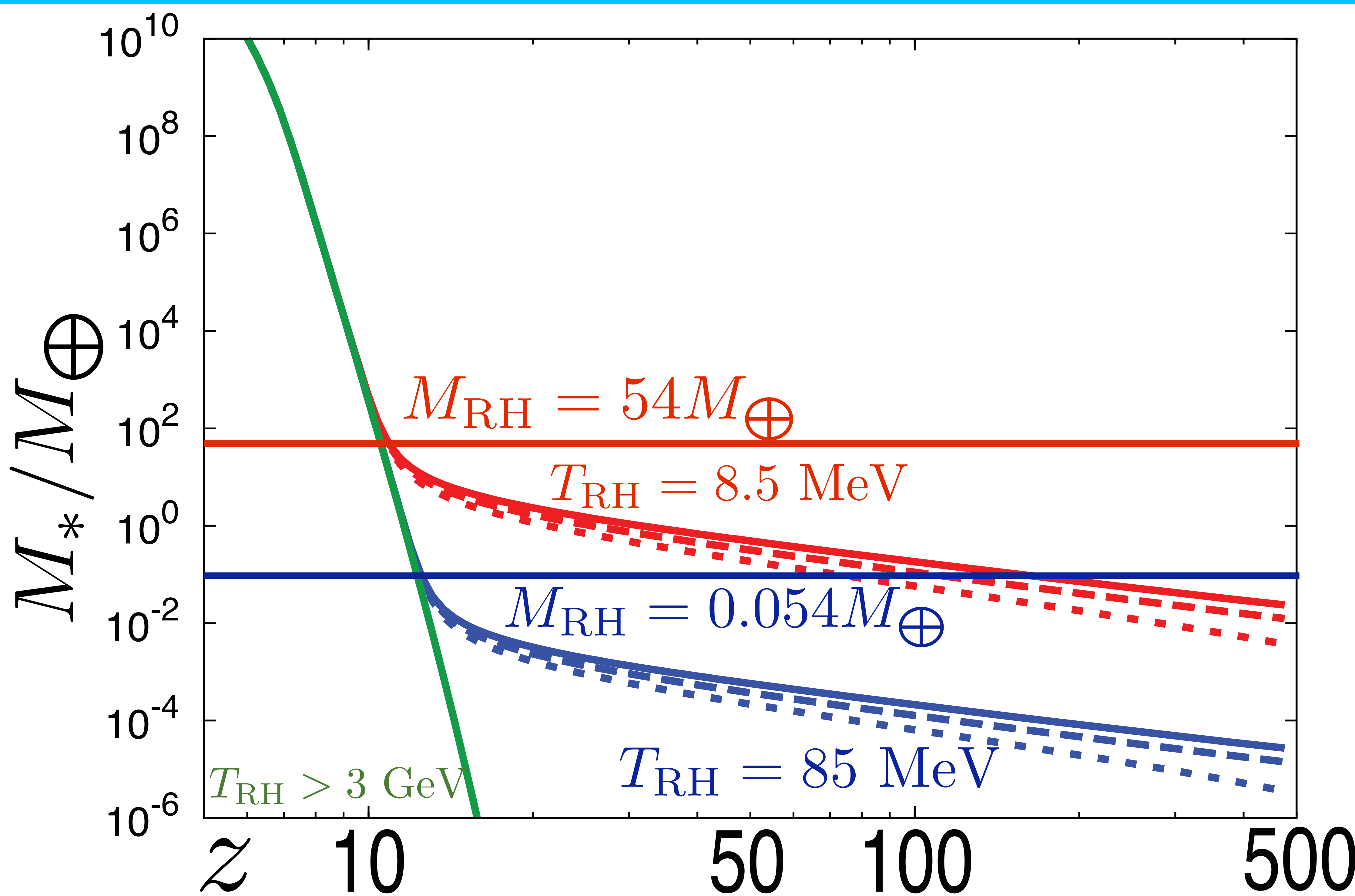

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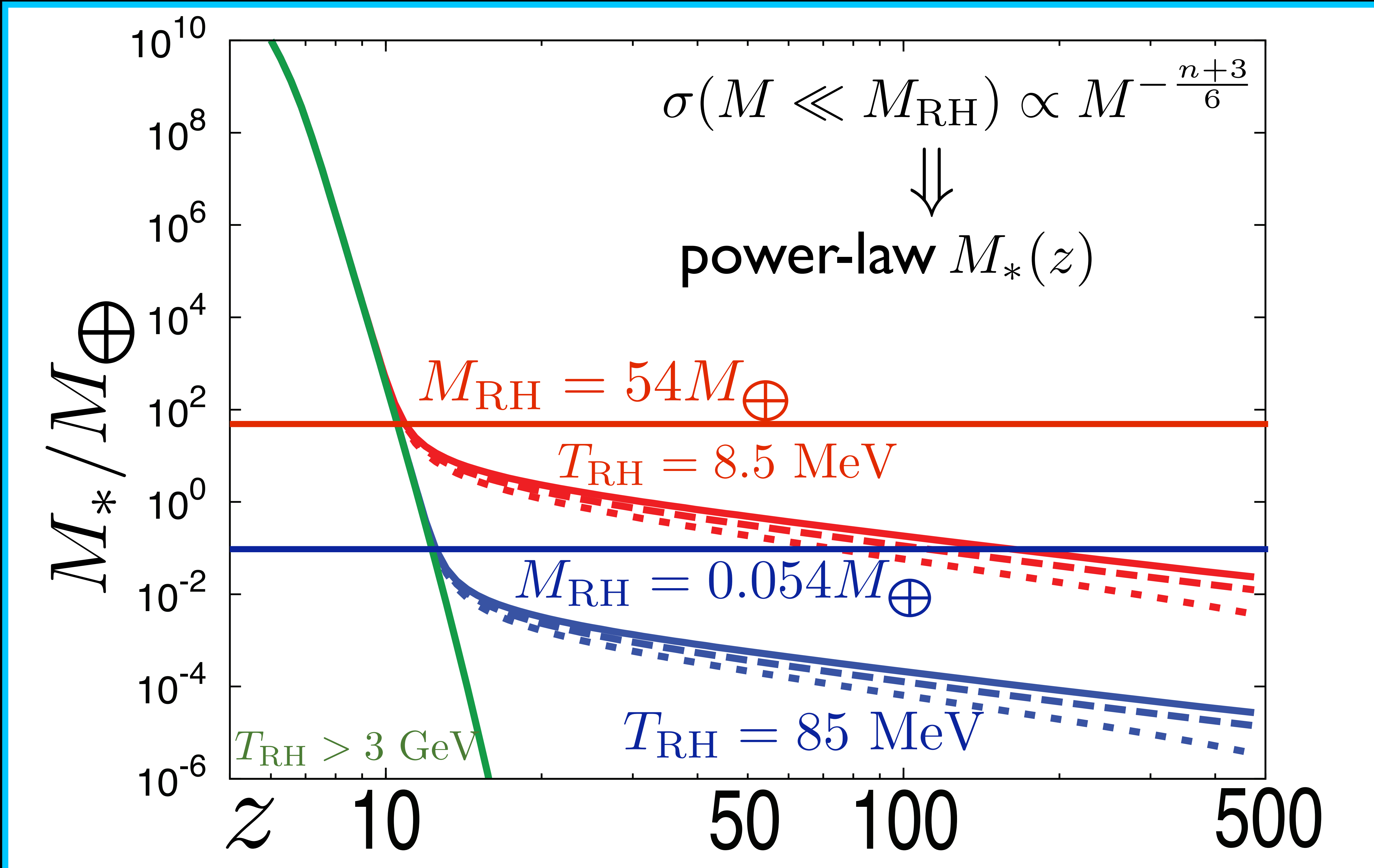

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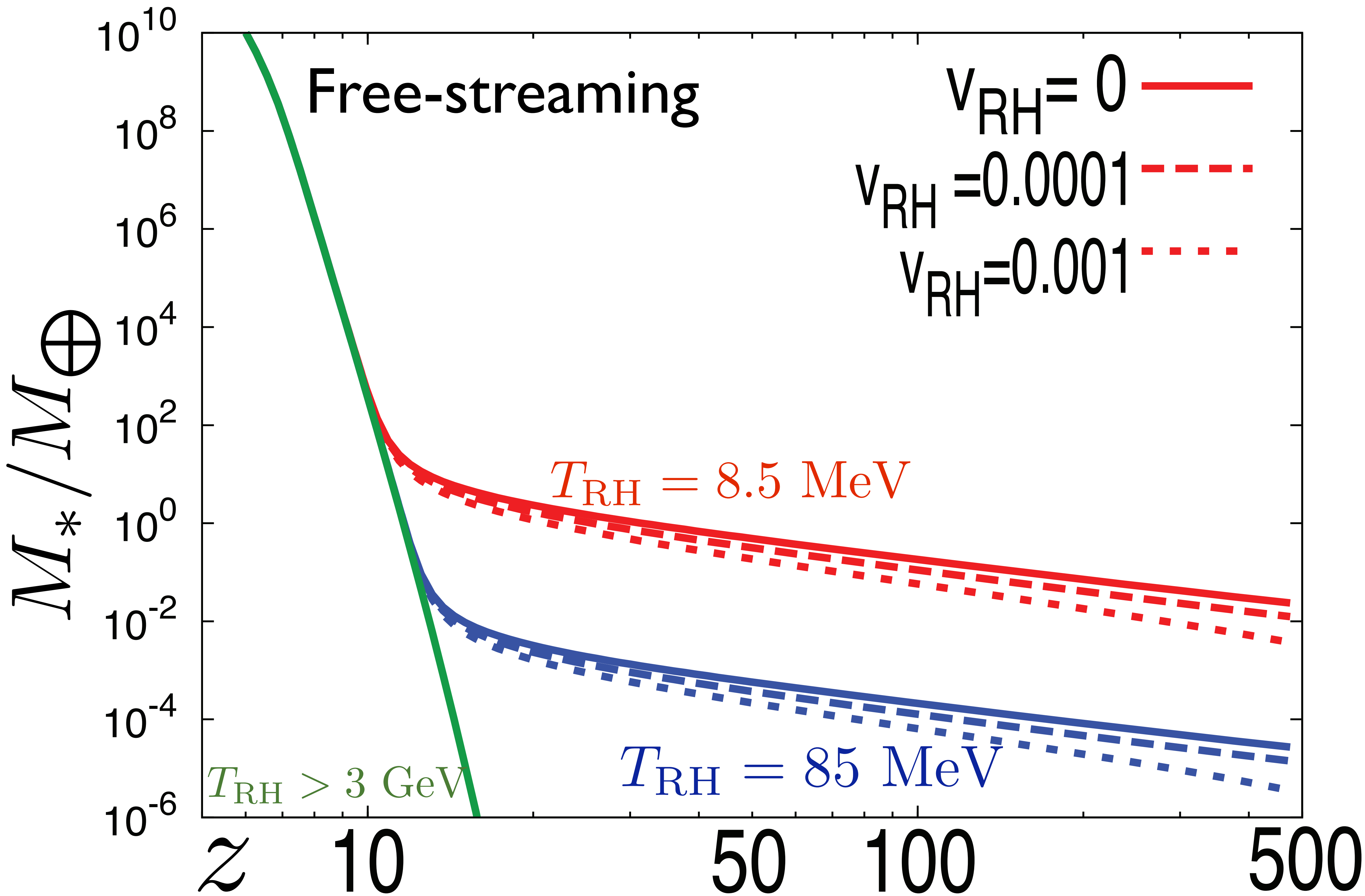

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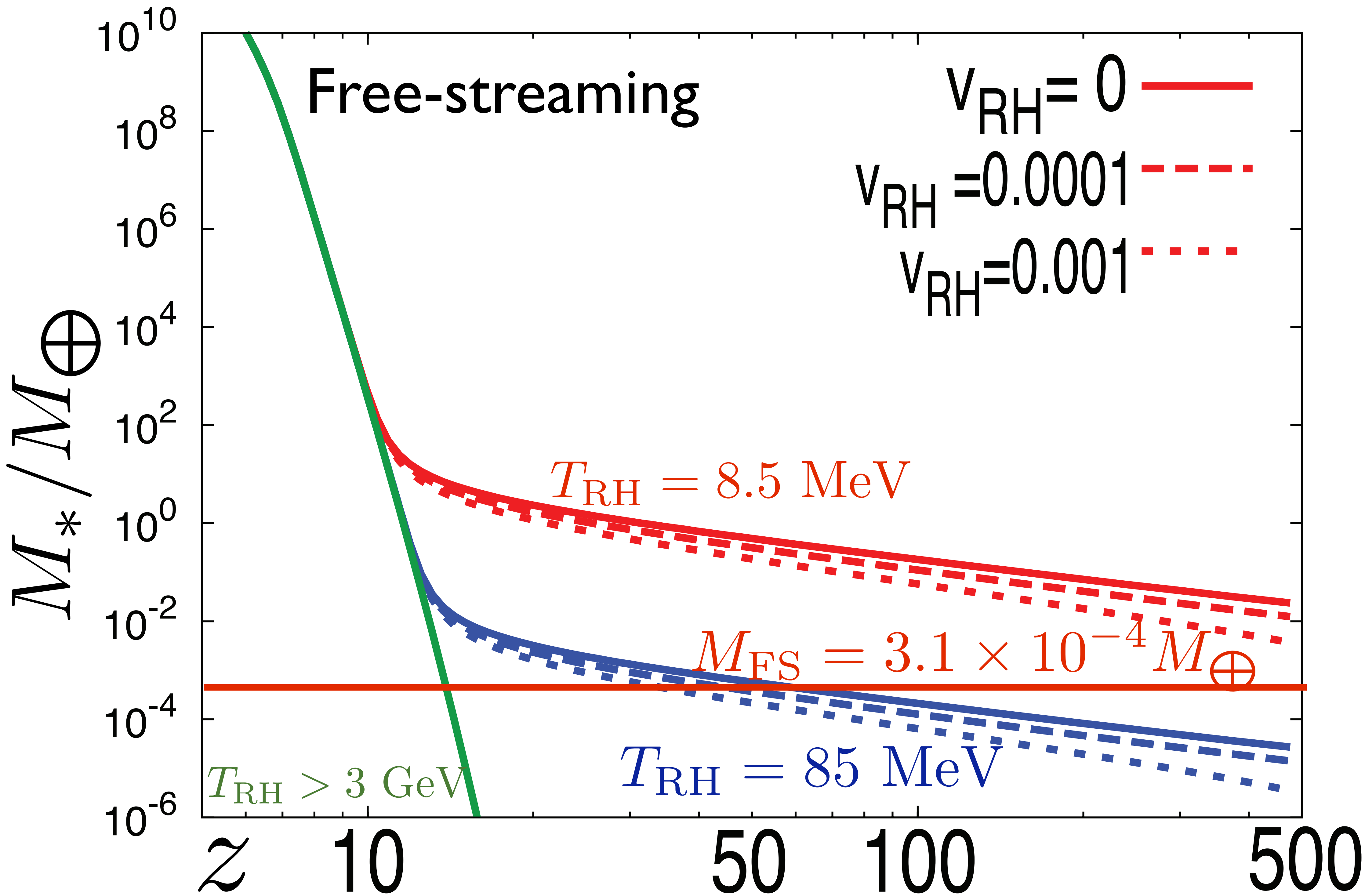

Microhalos at High Redshift

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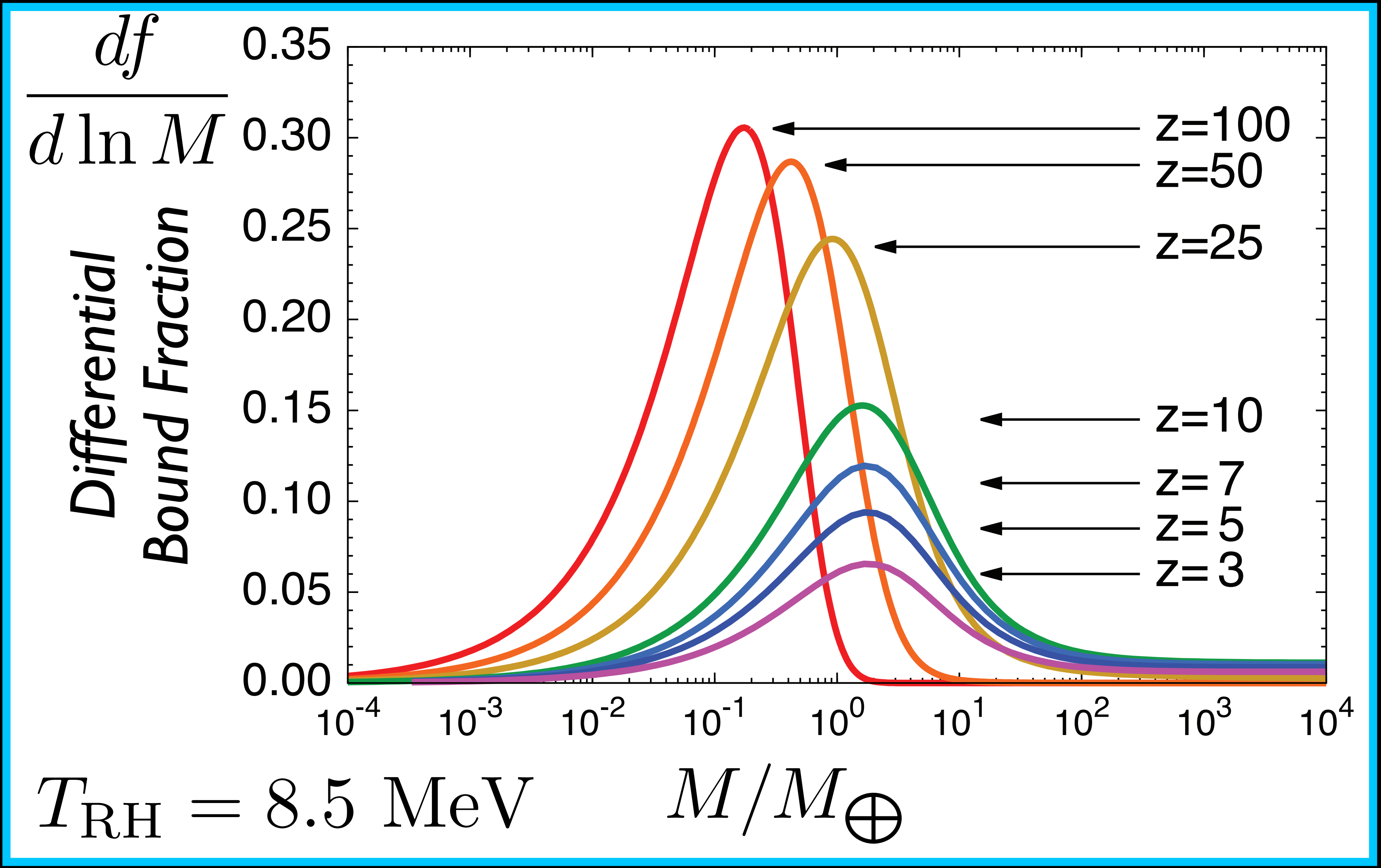

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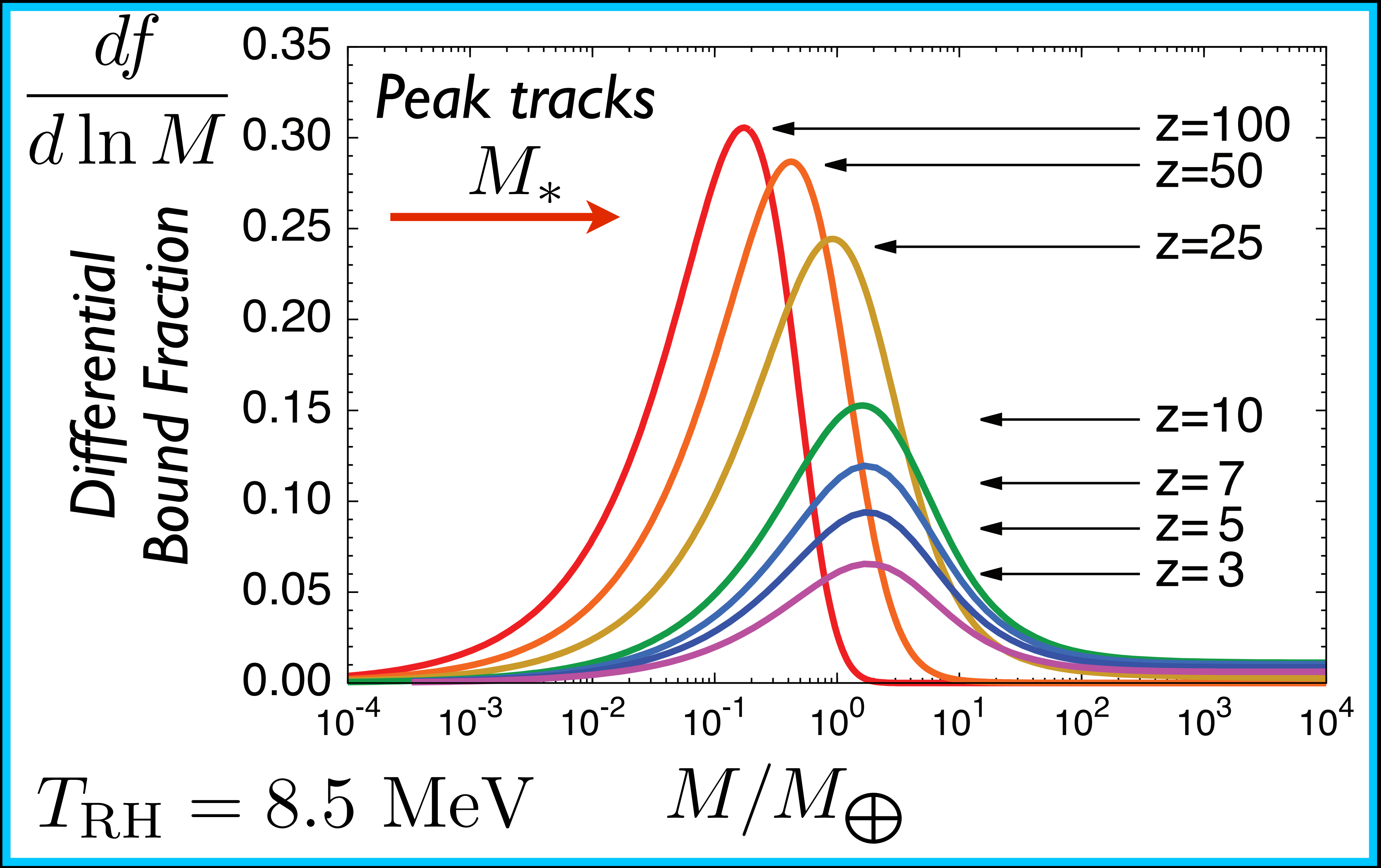

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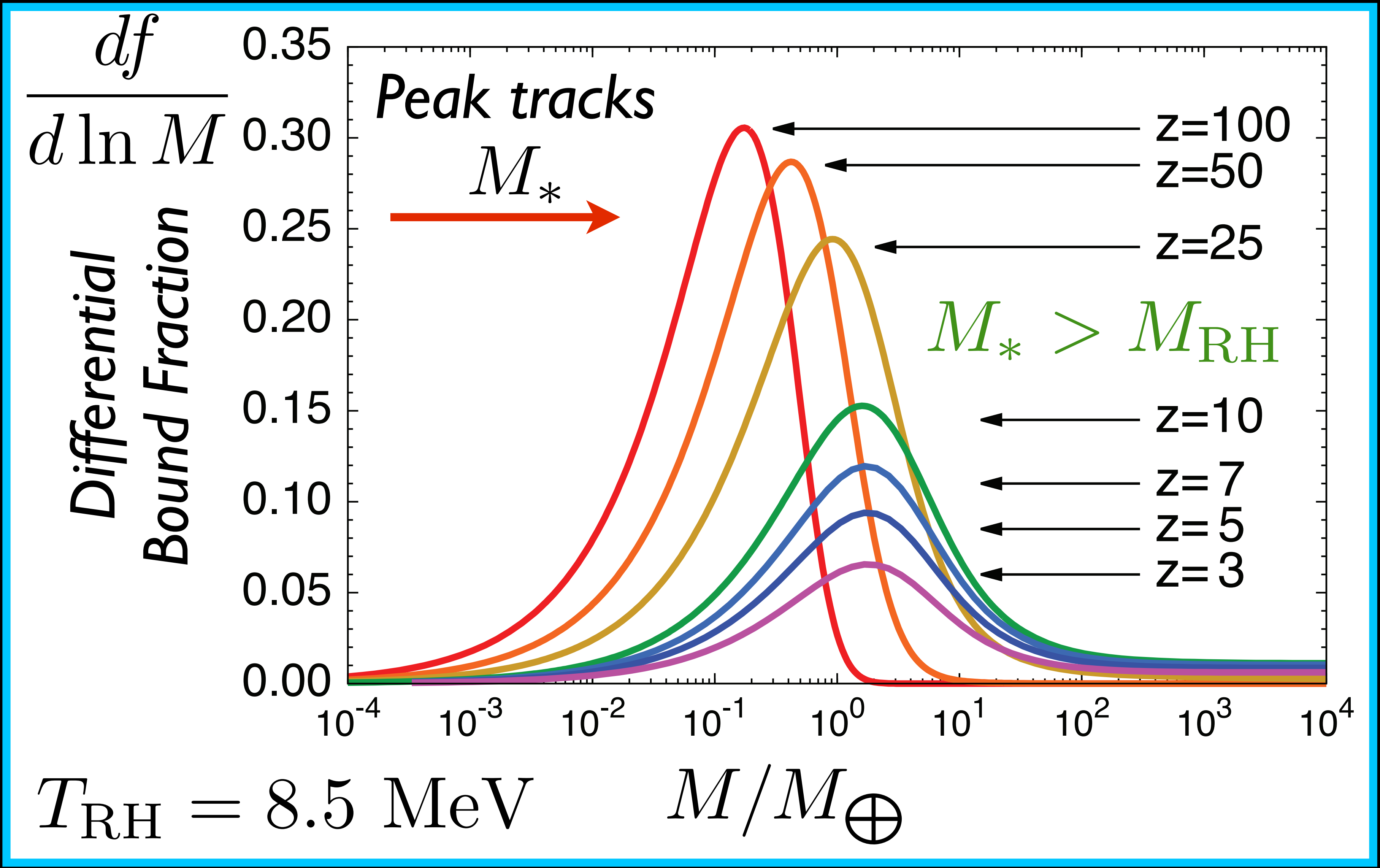
We used the Press-Schechter mass function to calculate the fraction of dark matter contained in halos of mass M.



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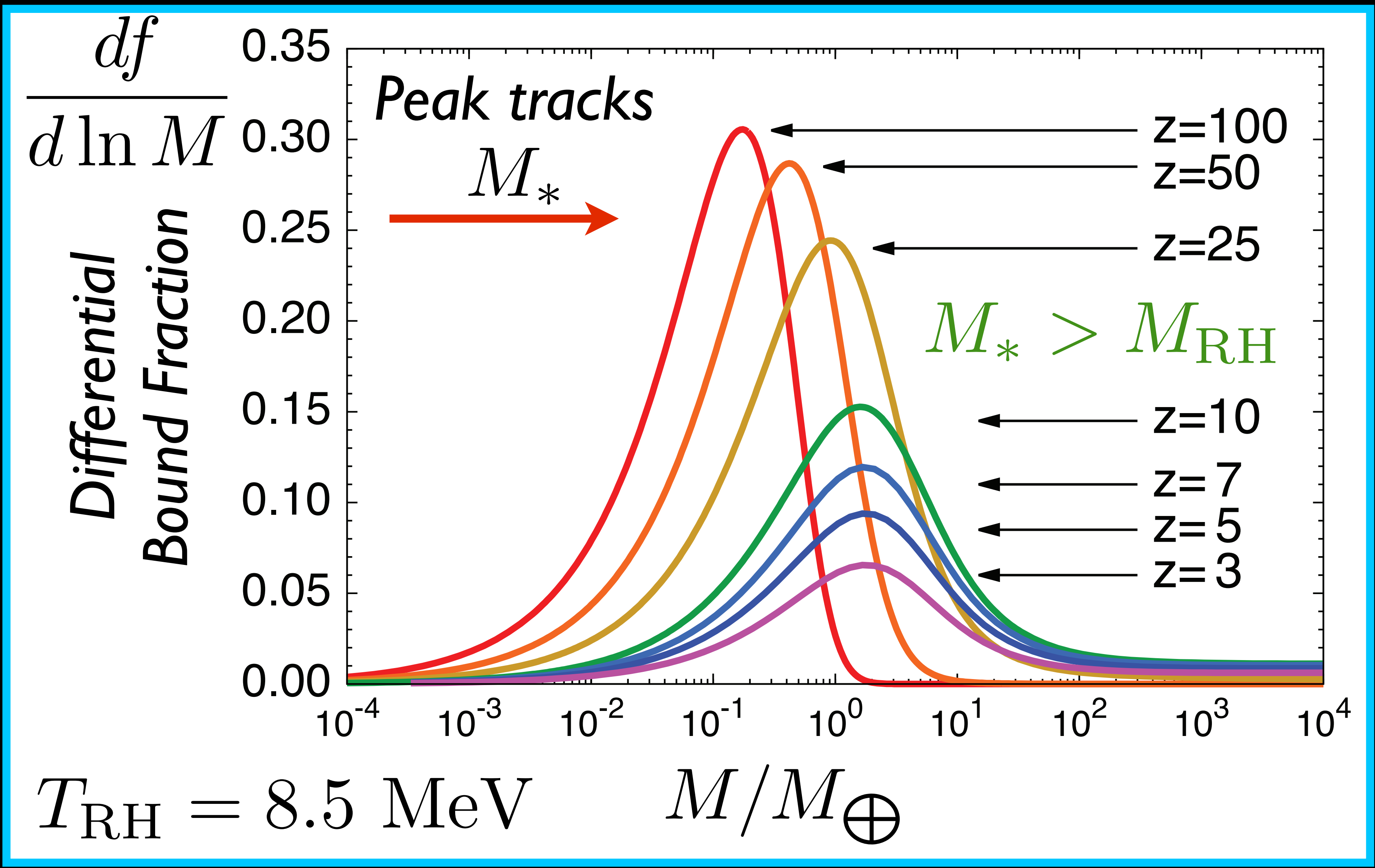

Fraction bound in halos with $M > 0.1\,M_\oplus$

z	Std	8.5 MeV
100	10^{-10}	0.49
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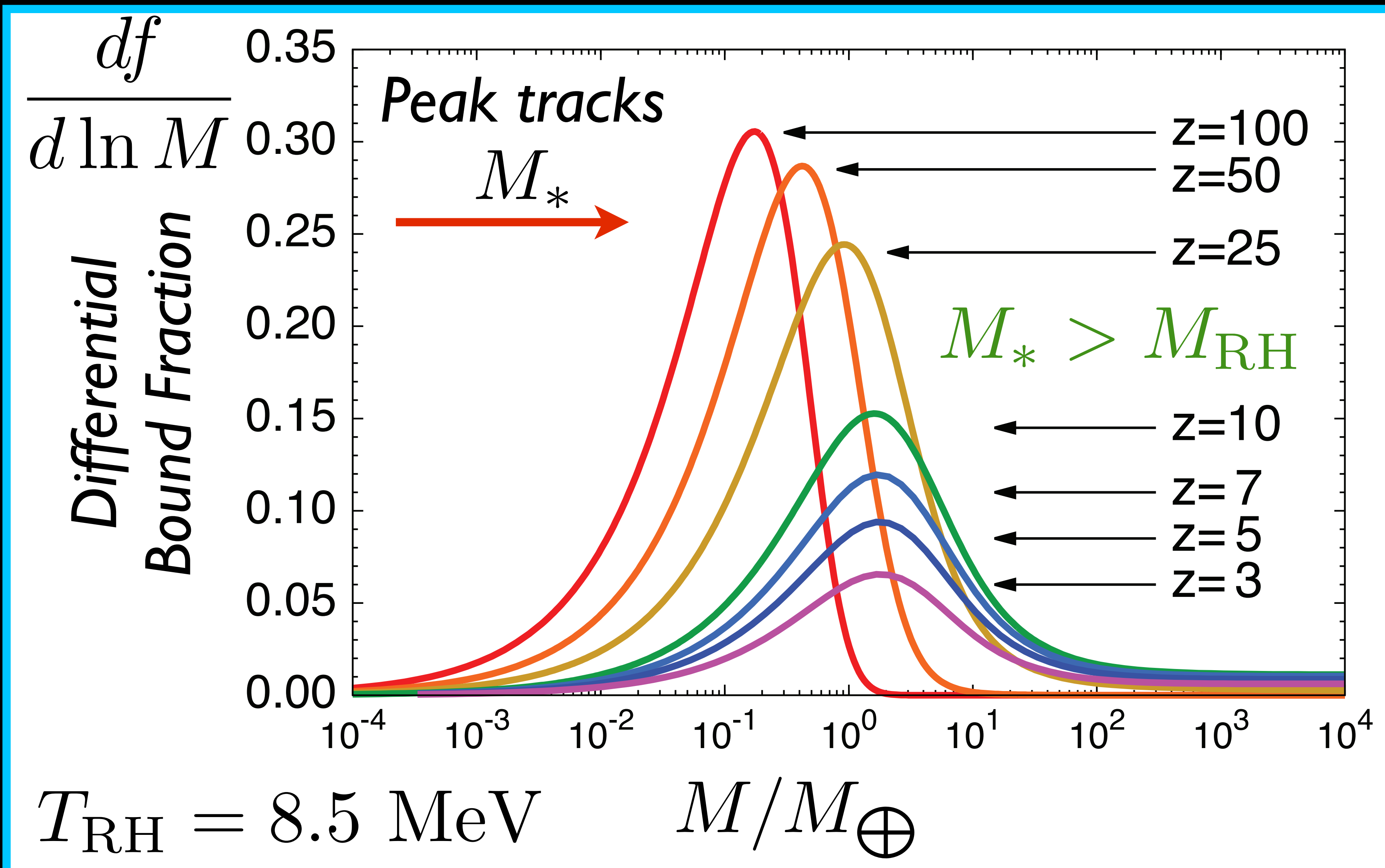

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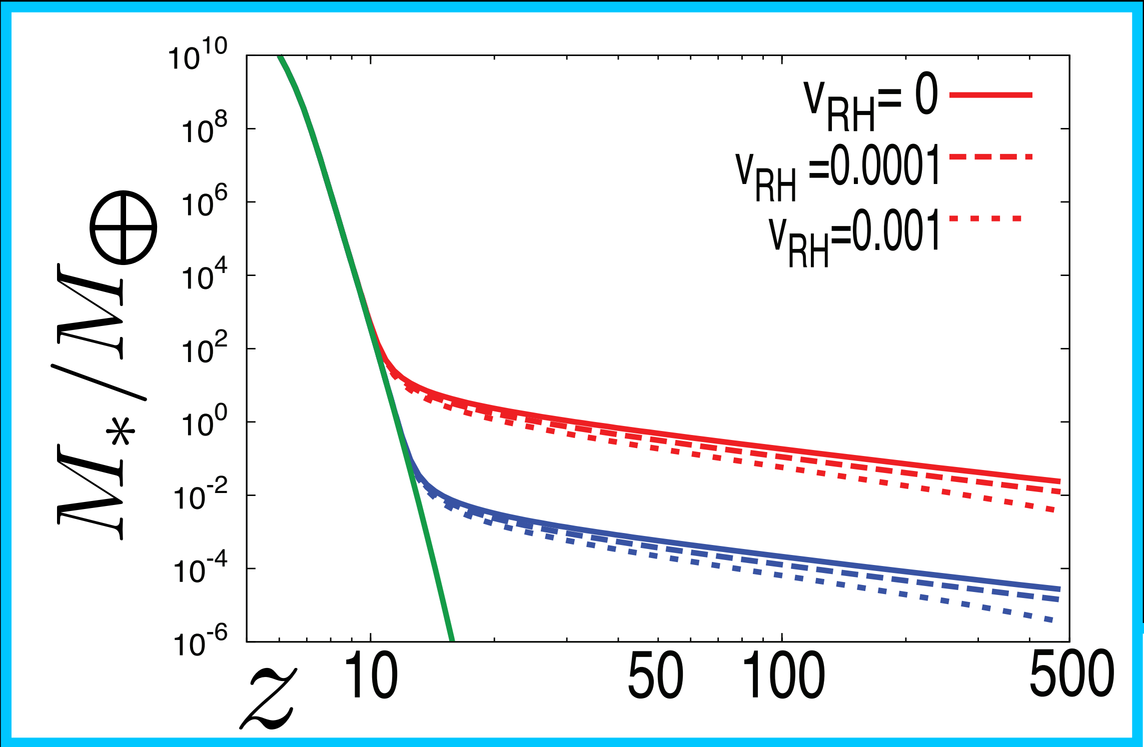
Most dark matter is bound into microhalos after $z = 100$!

Microhalos with Free-Streaming

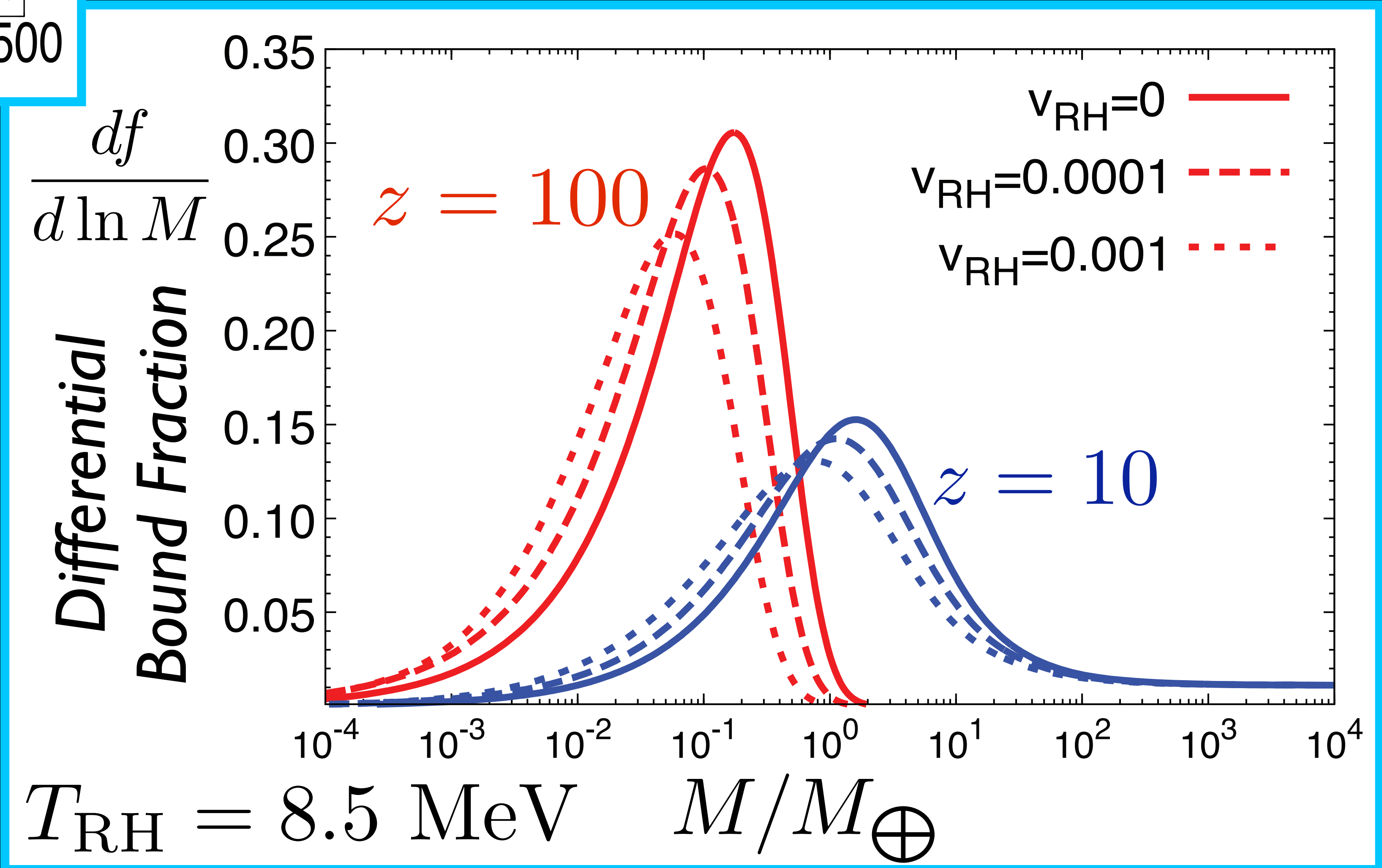


Giving the dark matter particles a small velocity at reheating slightly reduces M_* and $\left|\frac{d\ln\sigma}{d\ln M}\right|$.

Consequently, free-streaming leads to microhalos that

- have smaller masses
- are less abundant

$$\frac{df}{d\ln M} \propto \left|\frac{d\ln\sigma}{d\ln M}\right|$$



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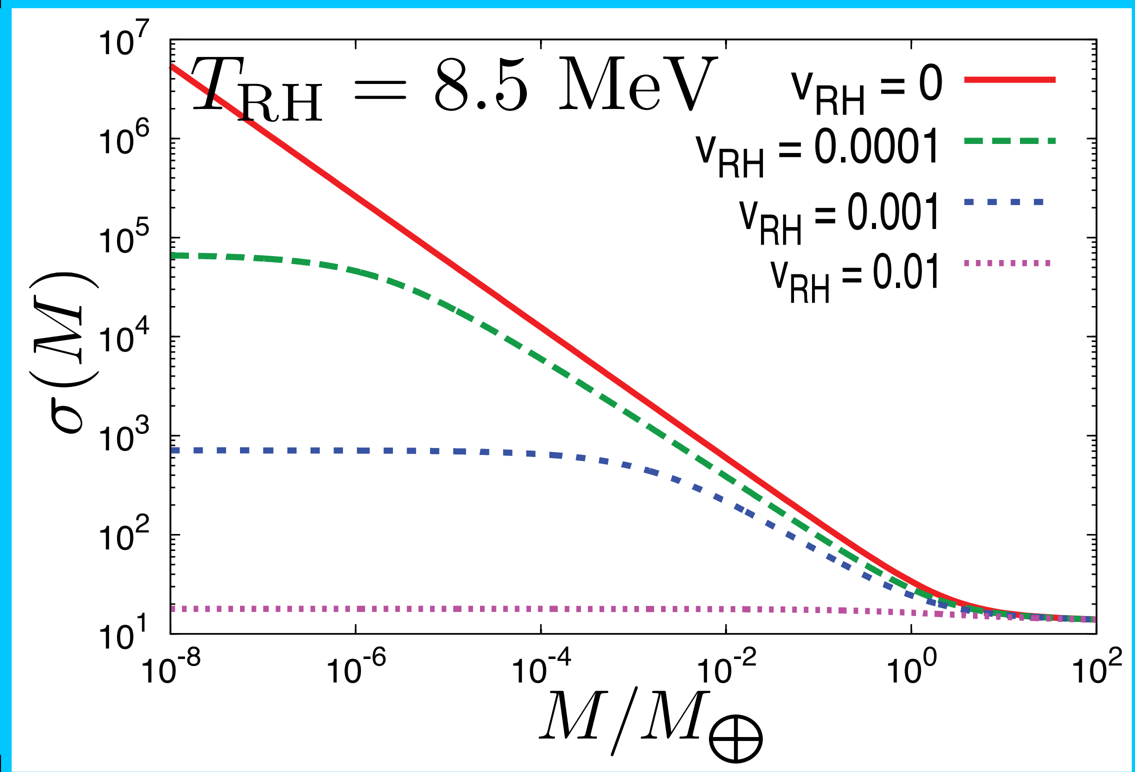

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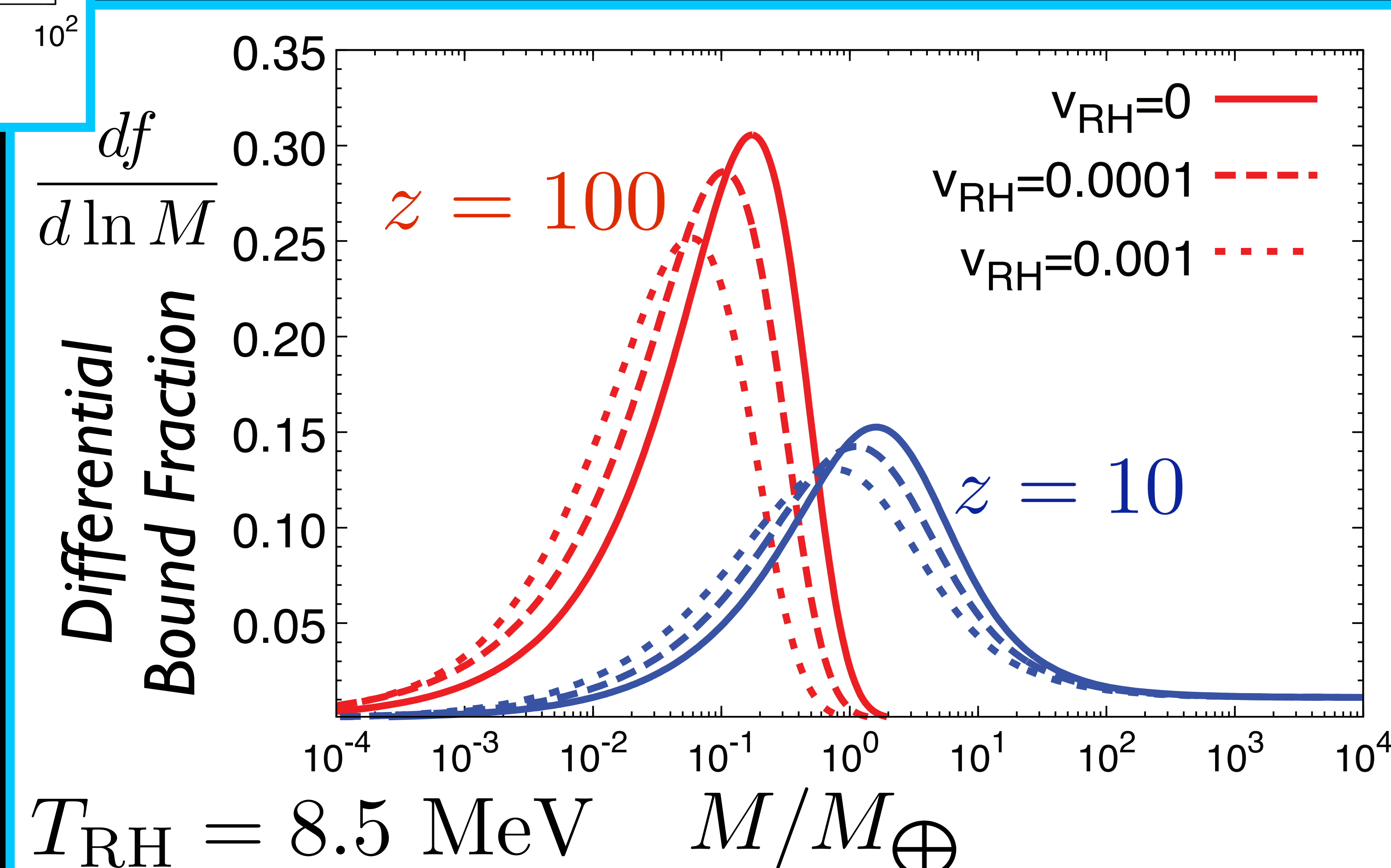
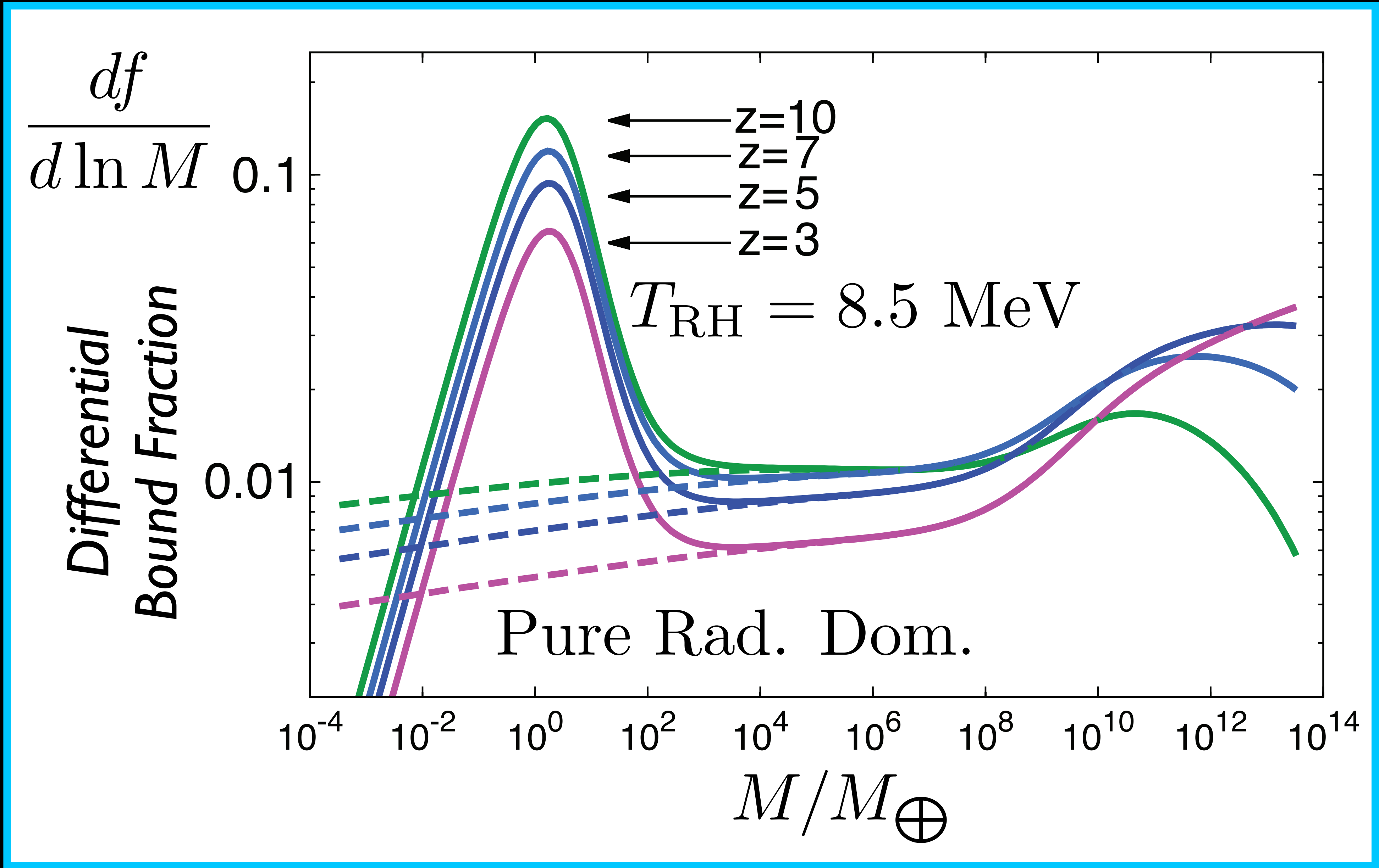


From Microhalos to Subhalos

After $M_* > M_{\rm RH}$, standard structure growth takes over, and larger-mass halos begin to form. The microhalos are absorbed.



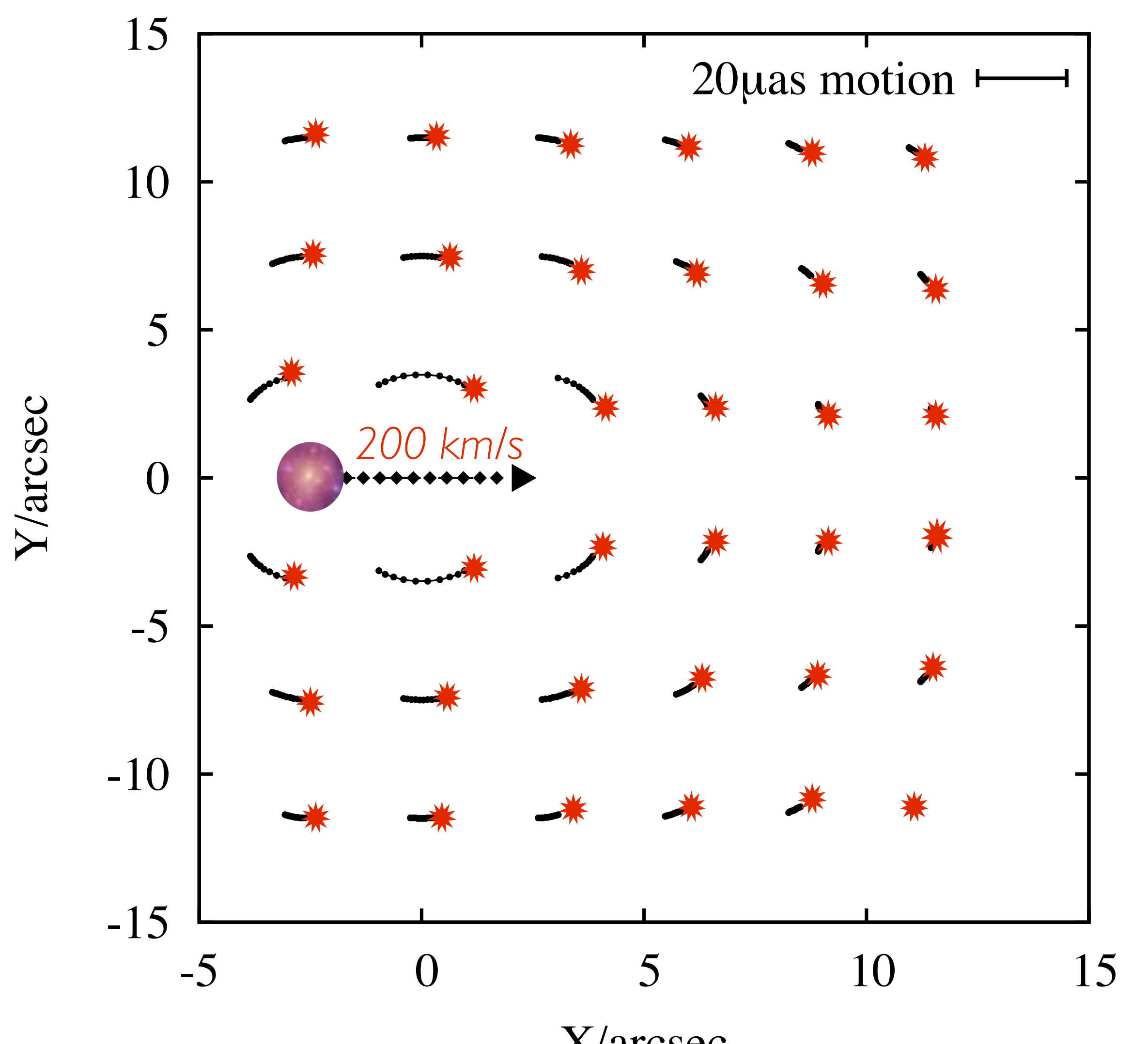
Since these microhalos formed at high redshift, they are far denser than standard microhalos and are more likely to survive.

Berezinsky, et al. 2010

Detection Prospects

The only guaranteed signatures are gravitational.

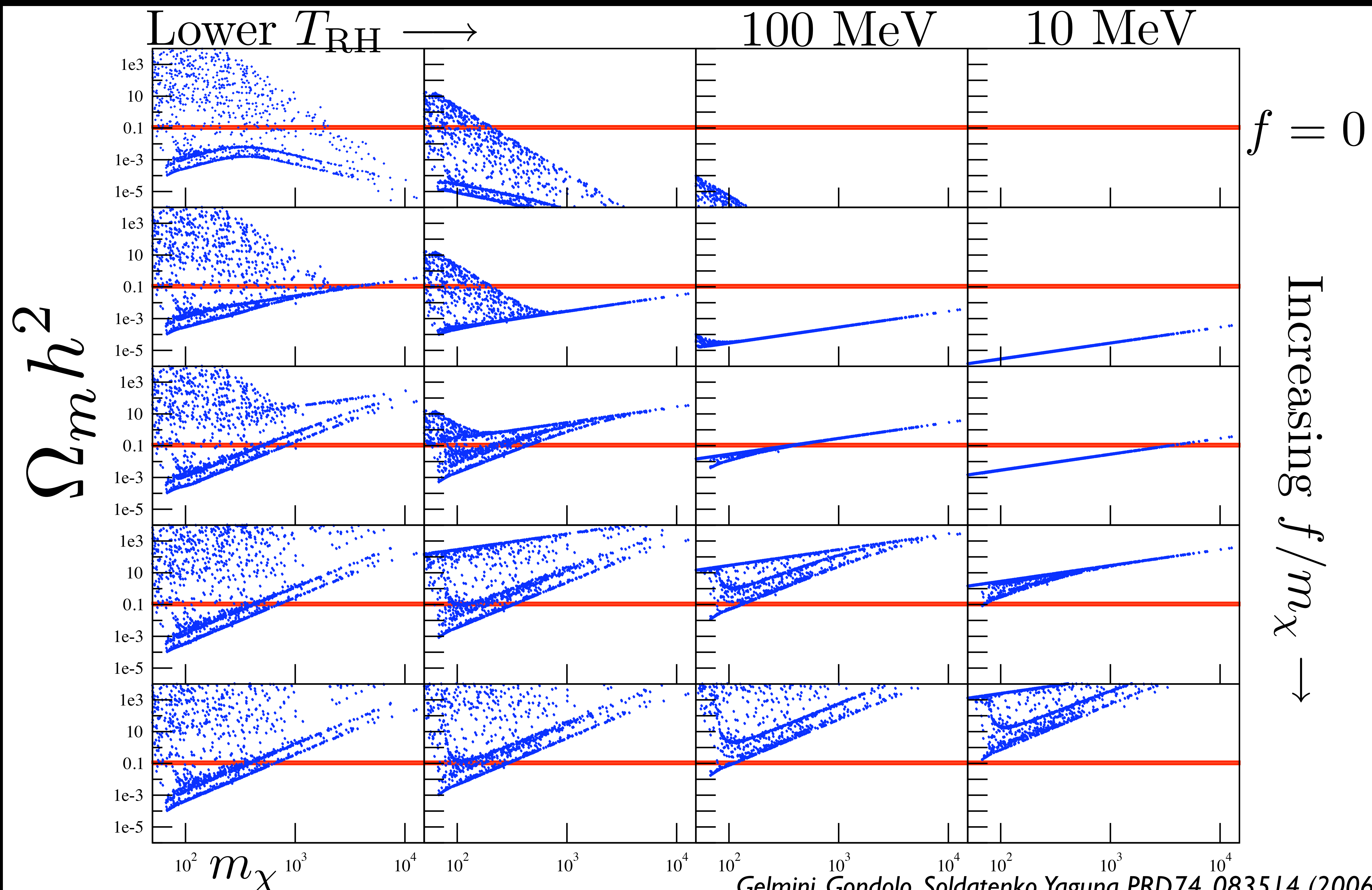
- Astrometric Microlensing — *Erickcek & Law 2011*
- Pulsar Timing Residuals — *Baghram, Afshordi, Zurek 2011*
- Photometric Microlensing — *Ricotti & Gould 2009*



Erickcek & Law 2011

If dark matter self-annihilates...

WIMP Dark Matter?



Gelmini, Gondolo, Soldatenko, Yaguna PRD74, 083514 (2006)

Summary: A New Window on Reheating

Perturbations that enter the horizon prior to reheating are very different from larger perturbations.

- The radiation perturbation on subhorizon scales is suppressed relative to superhorizon modes.
- If the scalar decays into cold dark matter, the matter directly inherits the scalar's enhanced inhomogeneity on subhorizon scales.

The enhancement in the dark matter power spectrum on small scales leads to an abundance of microhalos.

- At high redshift, half of the dark matter is bound into microhalos with masses smaller than the horizon mass at reheating.
- These microhalos might be detectable through gravitational lensing.
- Indirect detection can probe reheat history and origin of dark matter.

arXiv: 1106.0536

STAY TUNED