Title: What Dark Matter Microhalos Can Tell us About Reheating

Date: Sep 22, 2011 04:20 PM

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Abstract: The expansion history of the Universe before big bang nucleosynthesis is unknown; in many models, the Universe was effectively matter-dominated between the end of inflation and the onset of radiation domination. I will show how an early matter-dominated era leaves an imprint on the small-scale matter power spectrum. This imprint depends on the origin of dark matter. If dark matter originates from the radiation bath after reheating, then small-scale density perturbations are suppressed, leading to a cut-off in the matter power spectrum. Conversely, small-scale density perturbations are significantly enhanced if the dark matter was created nonthermally during reheating. These enhanced perturbations trigger the formation of numerous dark matter microhalos during the cosmic dark ages. The abundance of dark matter microhalos is therefore a new window on the Universe before nucleosynthesis.

What Dark Matter Microhalos can tell us about Reheating

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University of British Columbia

arXiv: 1106.0536
Phys. Rev D in press

Unravelling Dark Matter at PI
September 22-24, 2011

Overview

Motivation and a simple model for reheating

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

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?

Microhalos from reheating

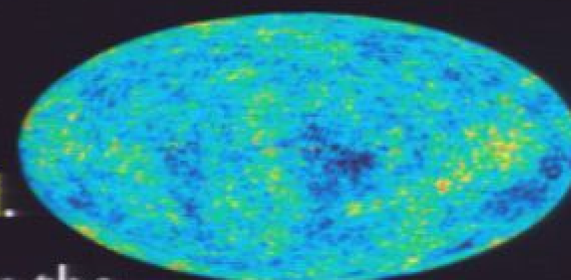
What substructures should we be looking for?

What Happened Before BBN?

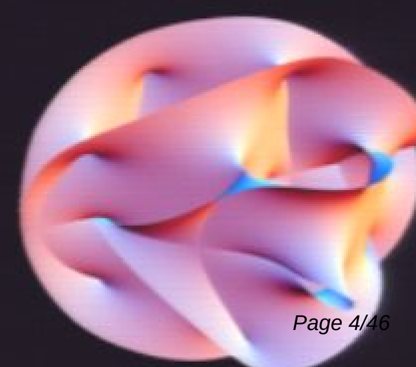
he (mostly) successful prediction of the primordial abundances of ght elements is one of cosmology's crowning achievements.

- 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.

ut we have good reasons to think that the Universe was not adiation dominated before BBN!



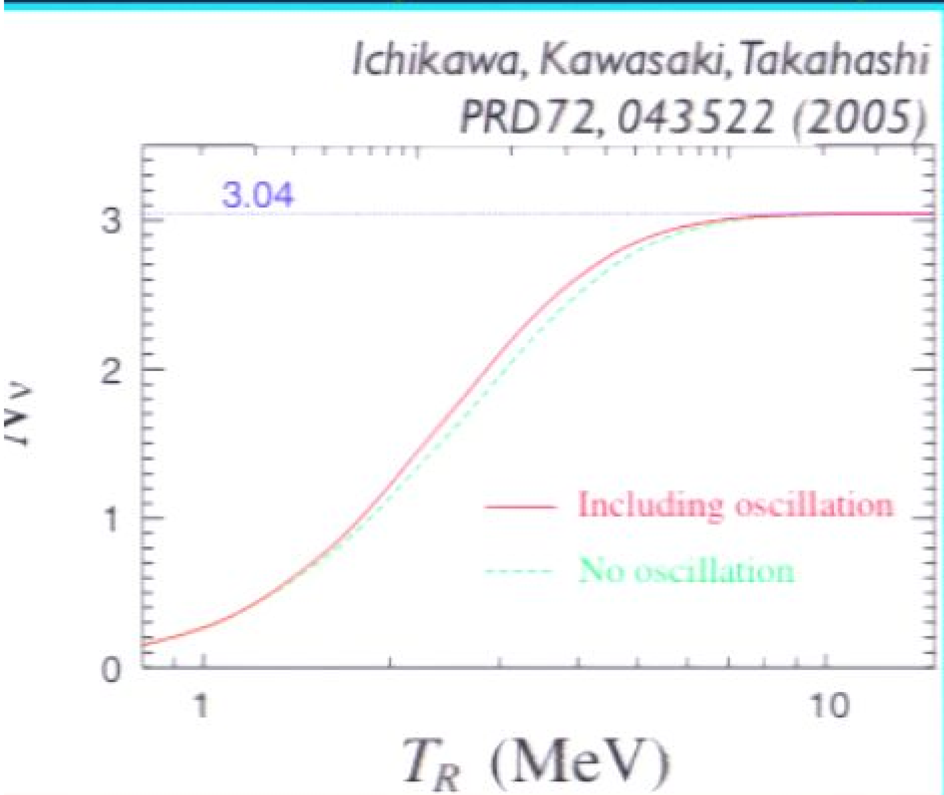
- Primordial density fluctuations point to inflation.
- During inflation, the Universe was scalar dominated.
- Other scalar fields may dominate the Universe after the inflaton decays.
- The string moduli problem: scalars with gravitational couplings come to dominate the Universe before BBN.

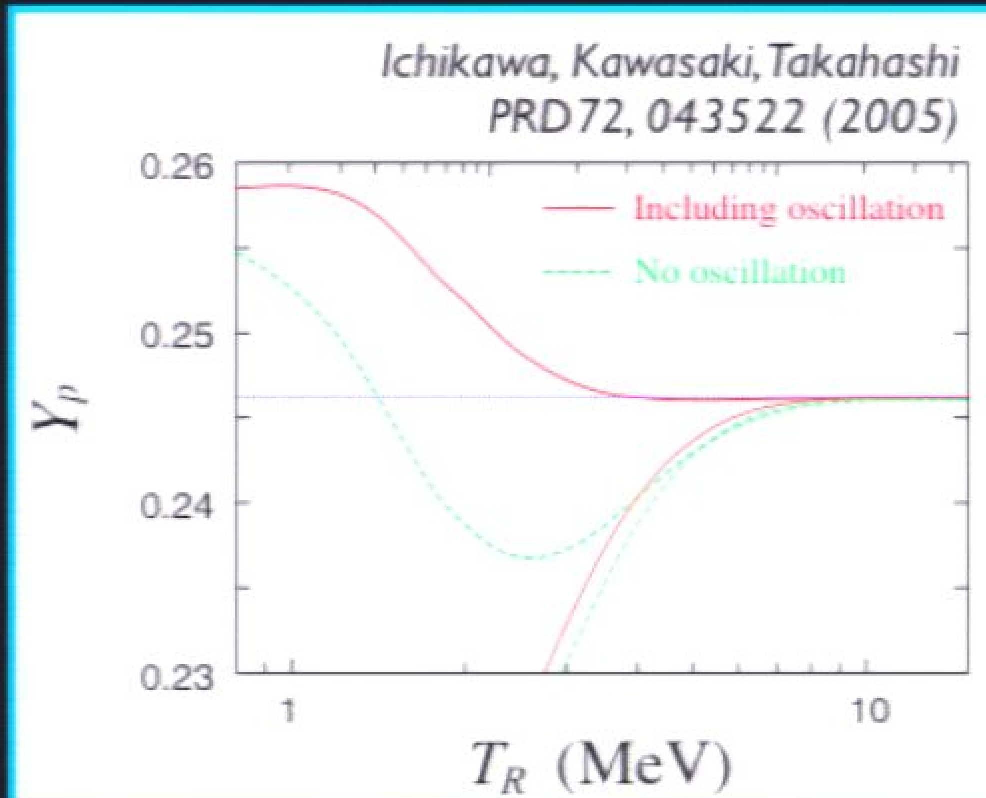


Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994
Acharya, Kane, Kuflik 2010

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

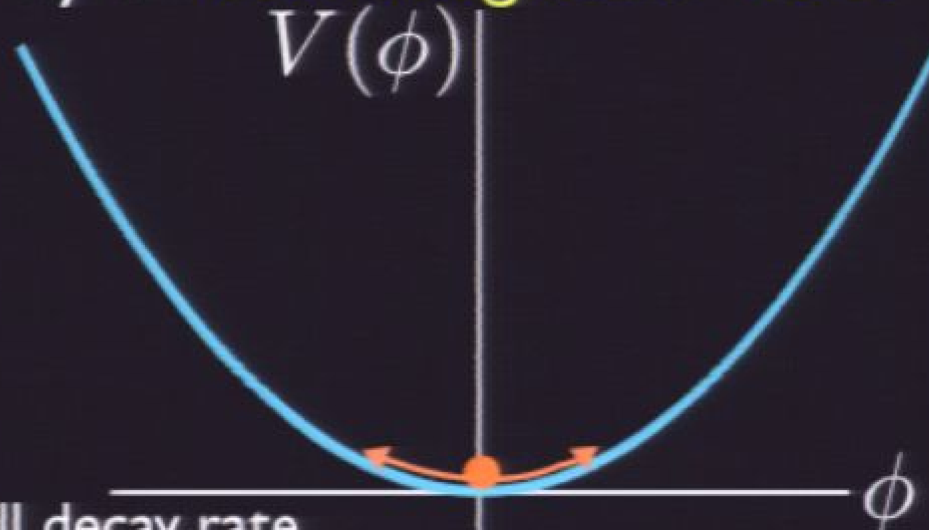
$$T_{\rm RH} \gtrsim 3\ {\rm MeV}$$

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

Scalar Domination after Inflation

he Universe was once dominated by an oscillating scalar field.

- reheating after inflation
- curvaton domination
- string moduli



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- assume perturbative decay; requires small decay rate
- scalar decays can also produce dark matter
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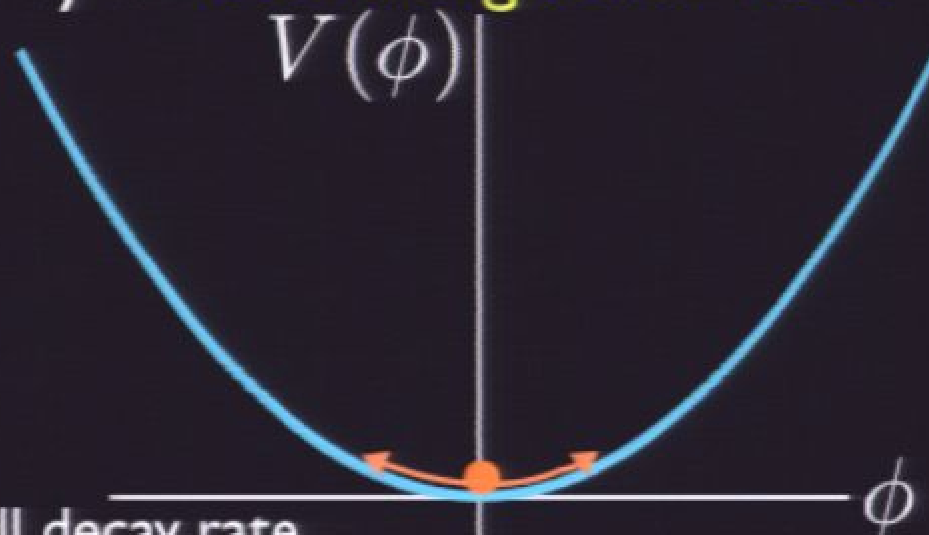

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r $V \propto \phi^2$, oscillating scalar field $\simeq$ matter.

- 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

hat happens to these perturbations after reheating?

Scalar Field Decay

$$\rho_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

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

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

Scalar Field Decay

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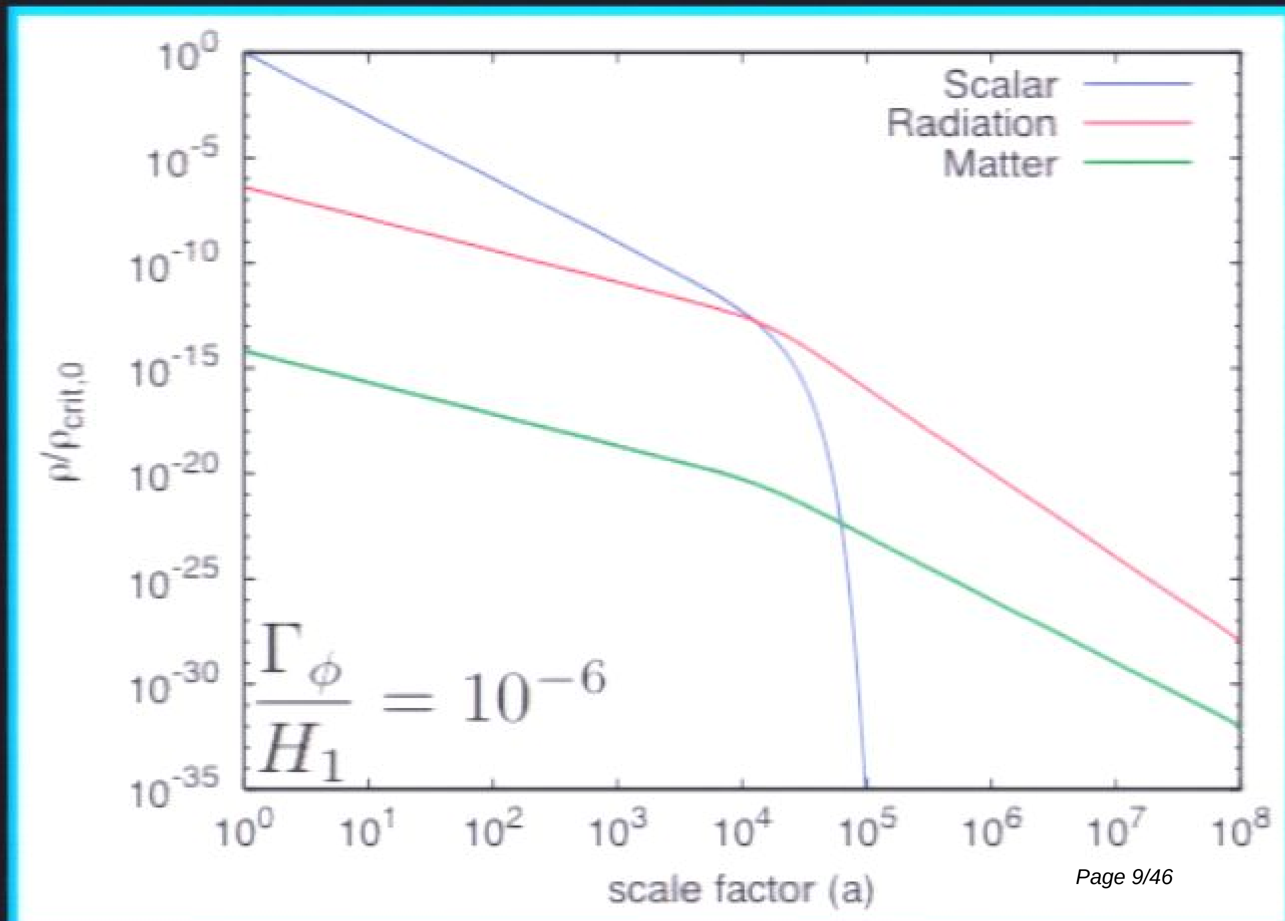
Matter-Radiation Equality

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

Scale factor at decay

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

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



Scalar Field Decay

ϕ → Radiation

ϕ → Matter

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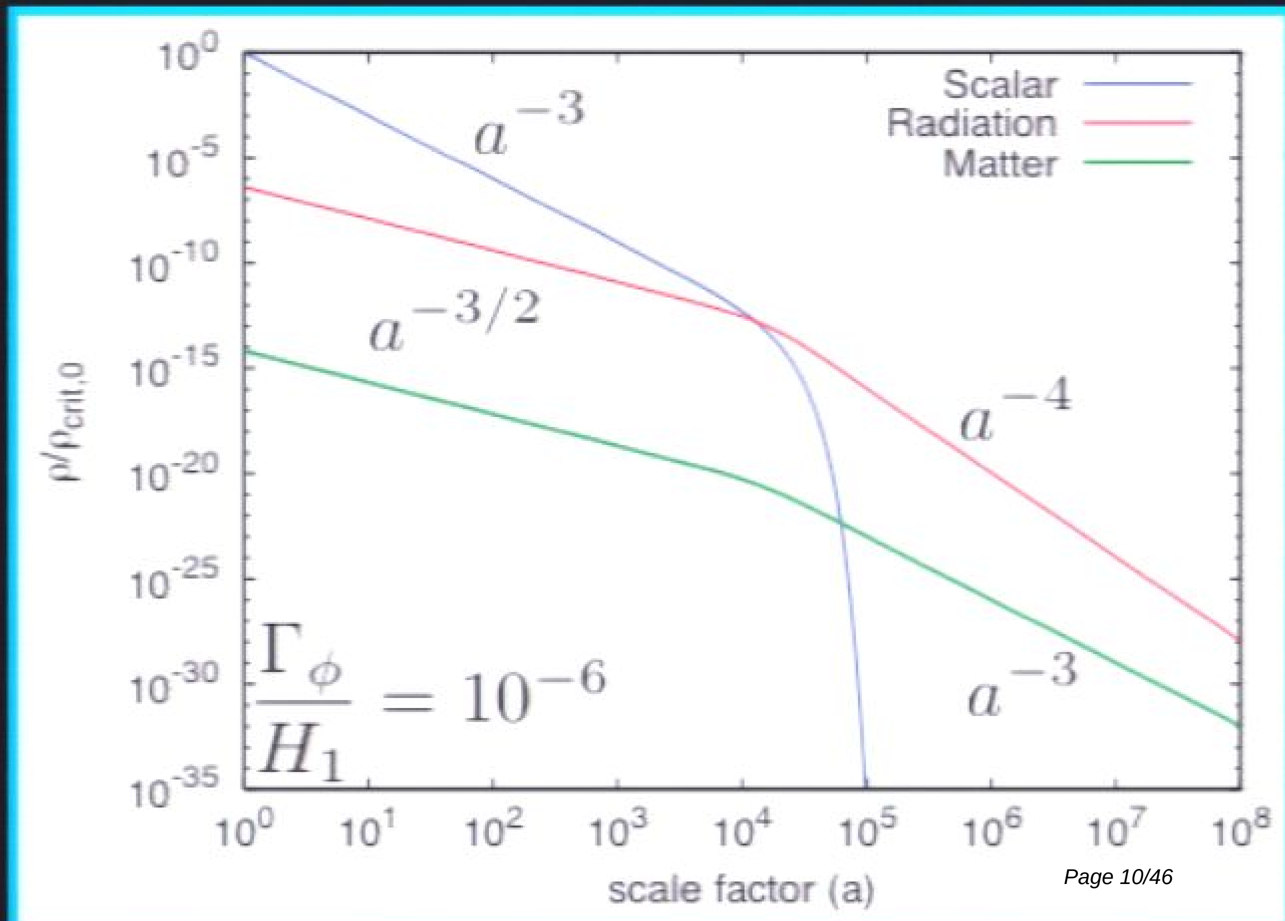
During Scalar Domination

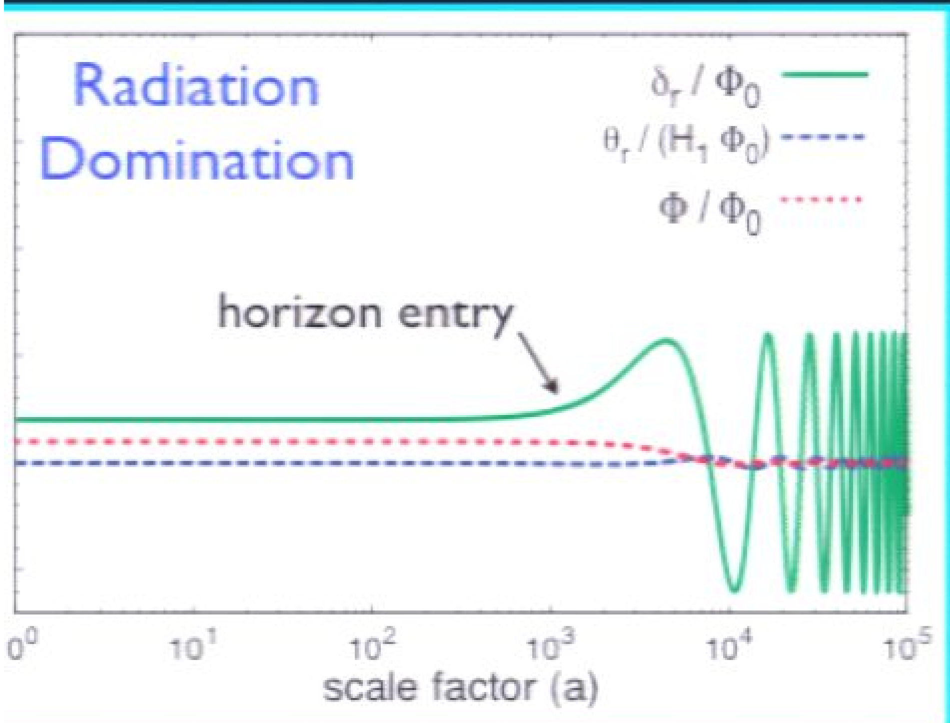
$$\rho_r \propto a^{-3/2}$$

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



Part II
Evolution of Perturbations during Reheating

The Radiation Perturbation



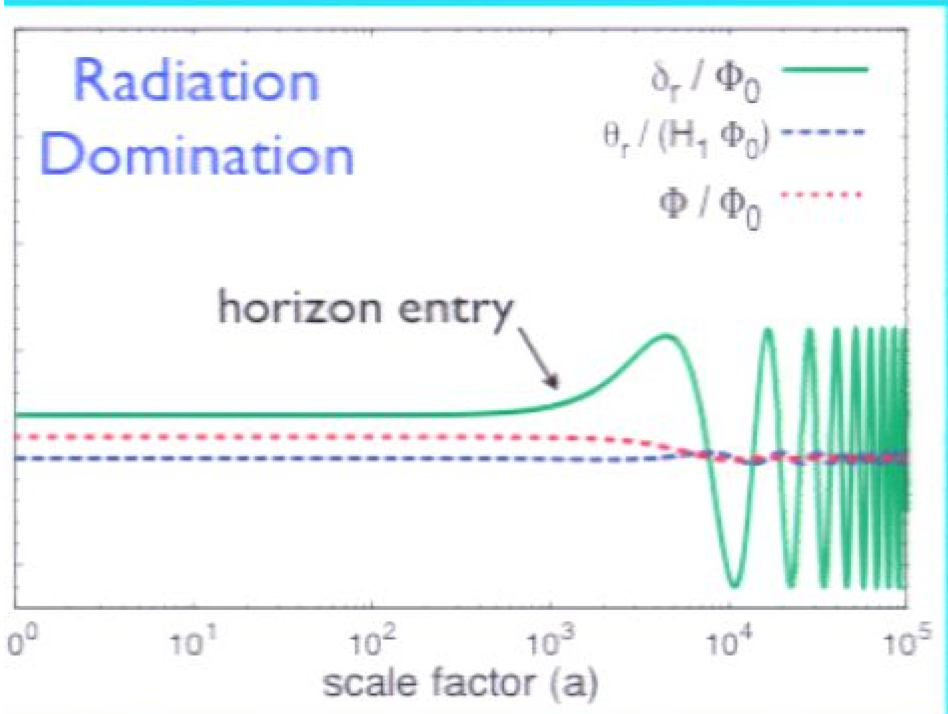
$$\dot{\delta}_r \simeq -\theta_r$$

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

During radiation domination, the radiation density perturbation oscillates.

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

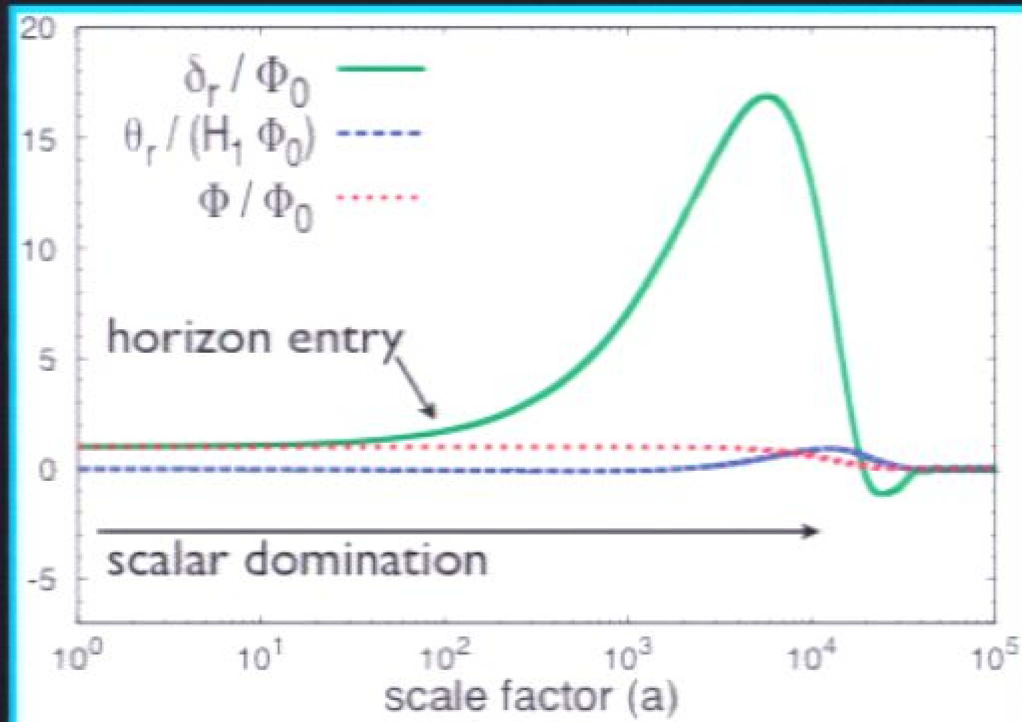
The Radiation Perturbation



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

Grows during scalar domination

Adding a period of scalar domination dramatically alters the evolution!



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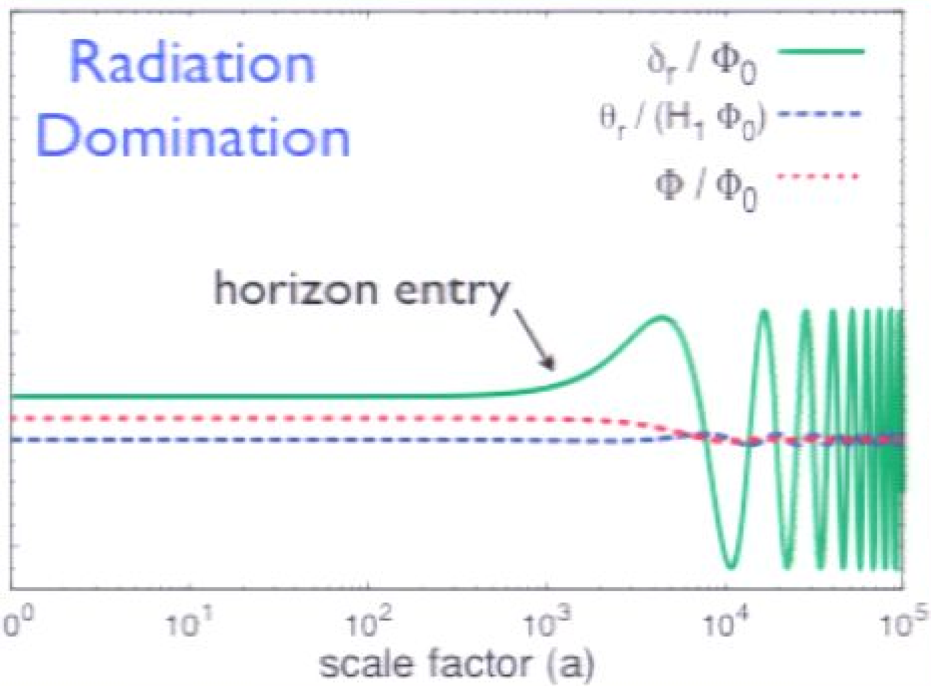

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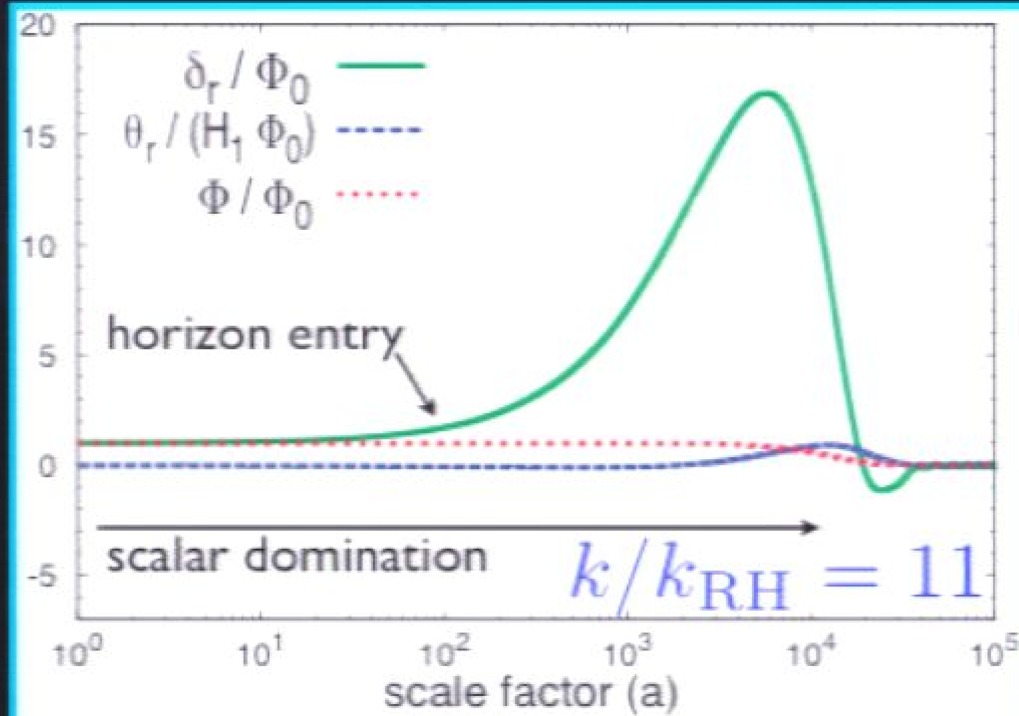
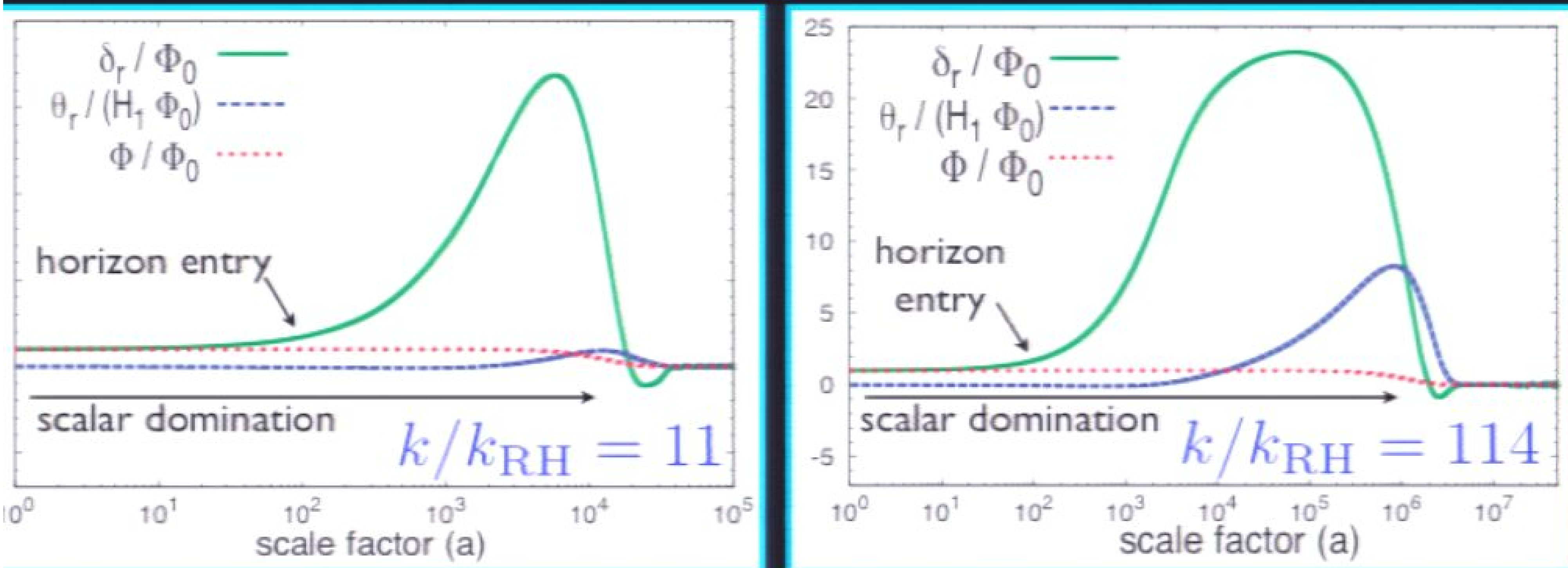


During radiation domination, the radiation density perturbation oscillates.

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

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

The Radiation Perturbation

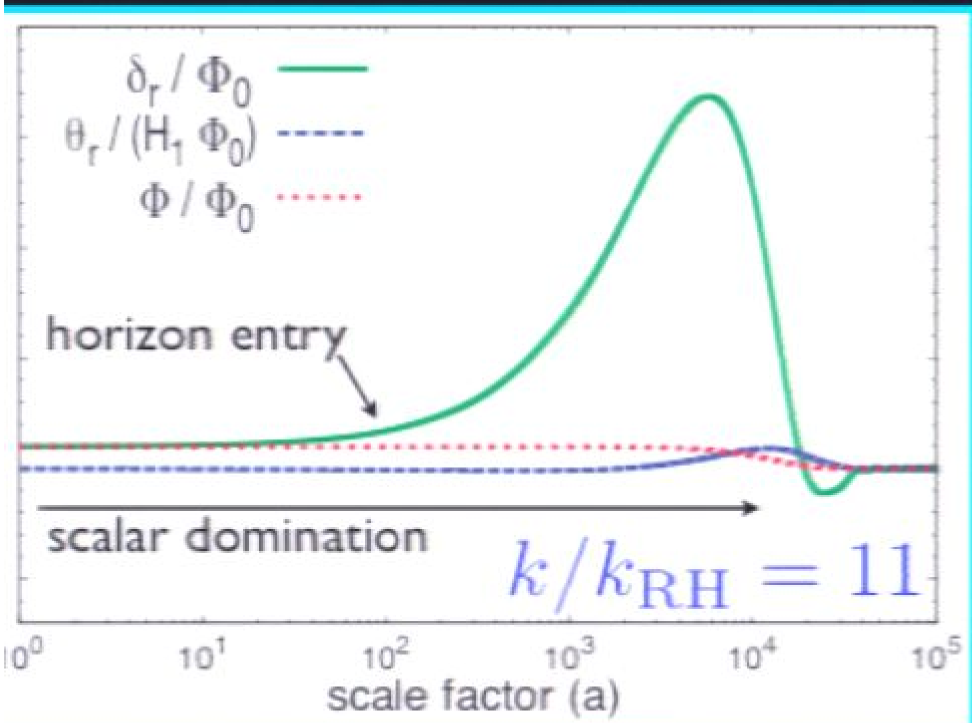


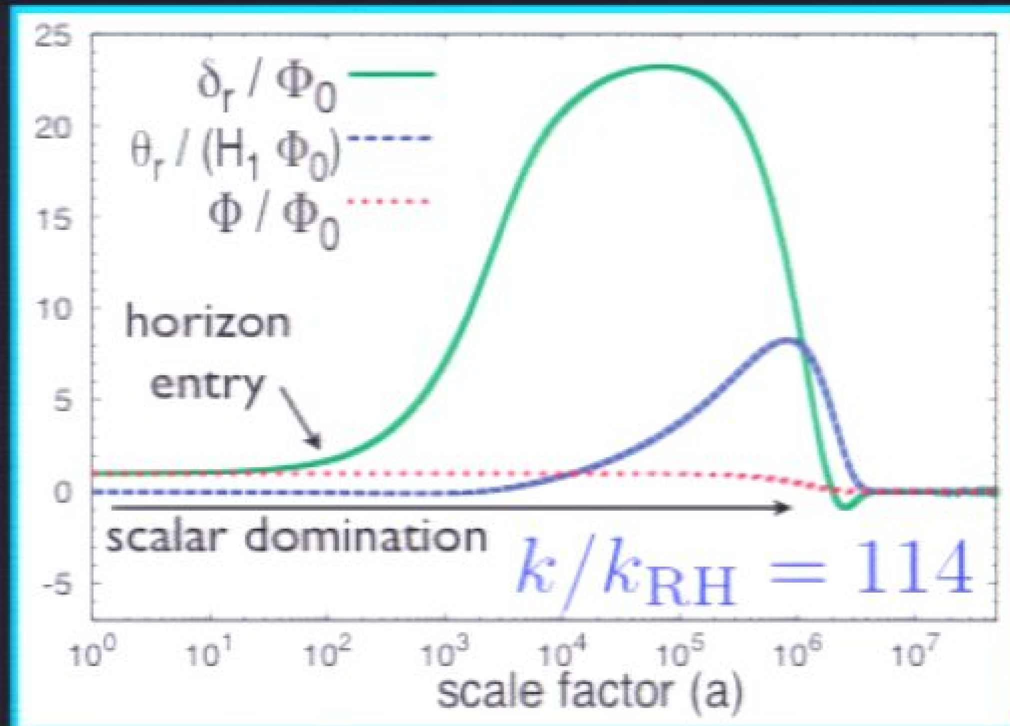
$\delta_{\rm max} = 0.085\Phi_0$ $\delta_{\rm max} = 0.0007\Phi_0$

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

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

The Radiation Perturbation





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

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

$T_r \lesssim 10^{-3}$ $\quad k/k_{\rm RH} \gtrsim 20$

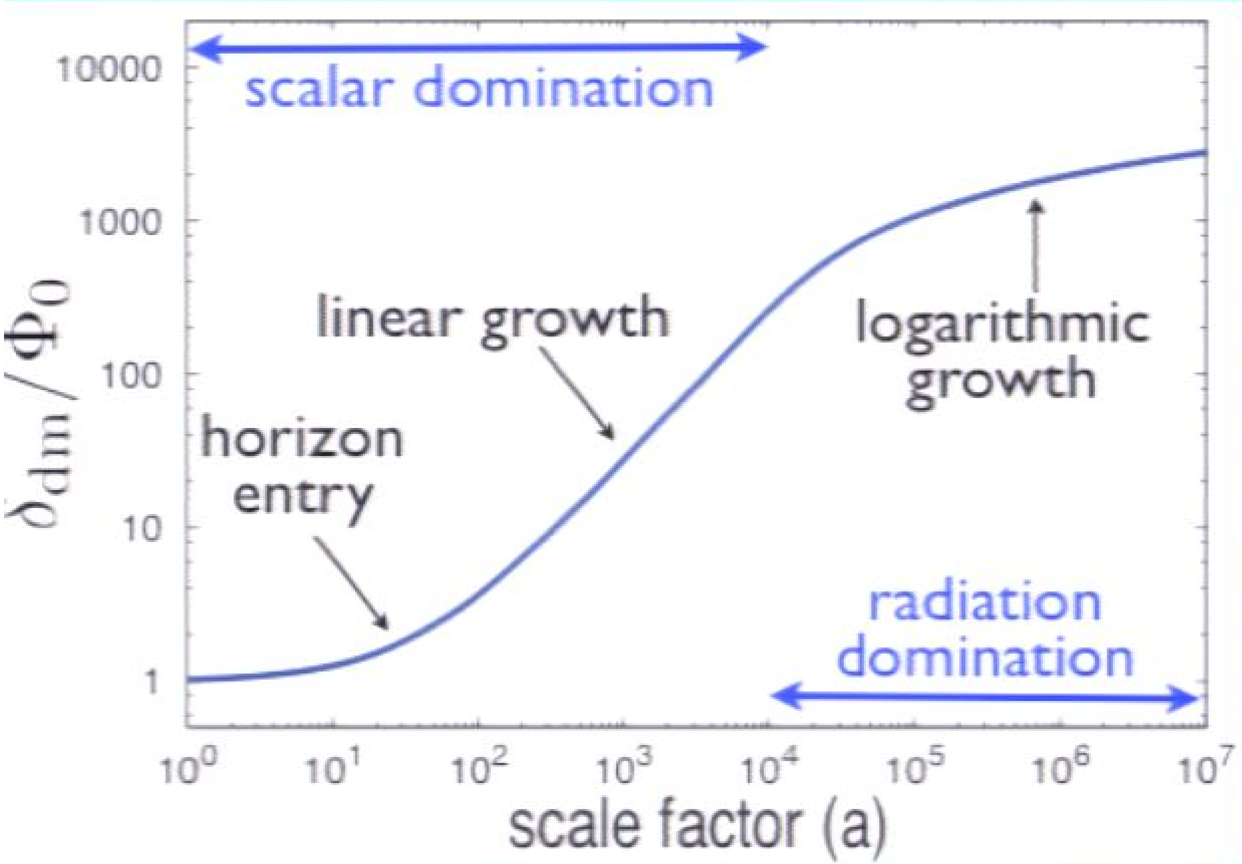
$T_r \simeq 1.5$ $\quad 2 \lesssim k/k_{\rm RH} \lesssim 4$

$T_r = 10/9$ $\quad k/k_{\rm RH} \lesssim 0.1$

Suppression if dark matter couples to radiation after reheating.

The Matter Perturbation

volution of the Matter Density Perturbation



dark matter produced in scalar decays
the dark matter perturbation is sensitive
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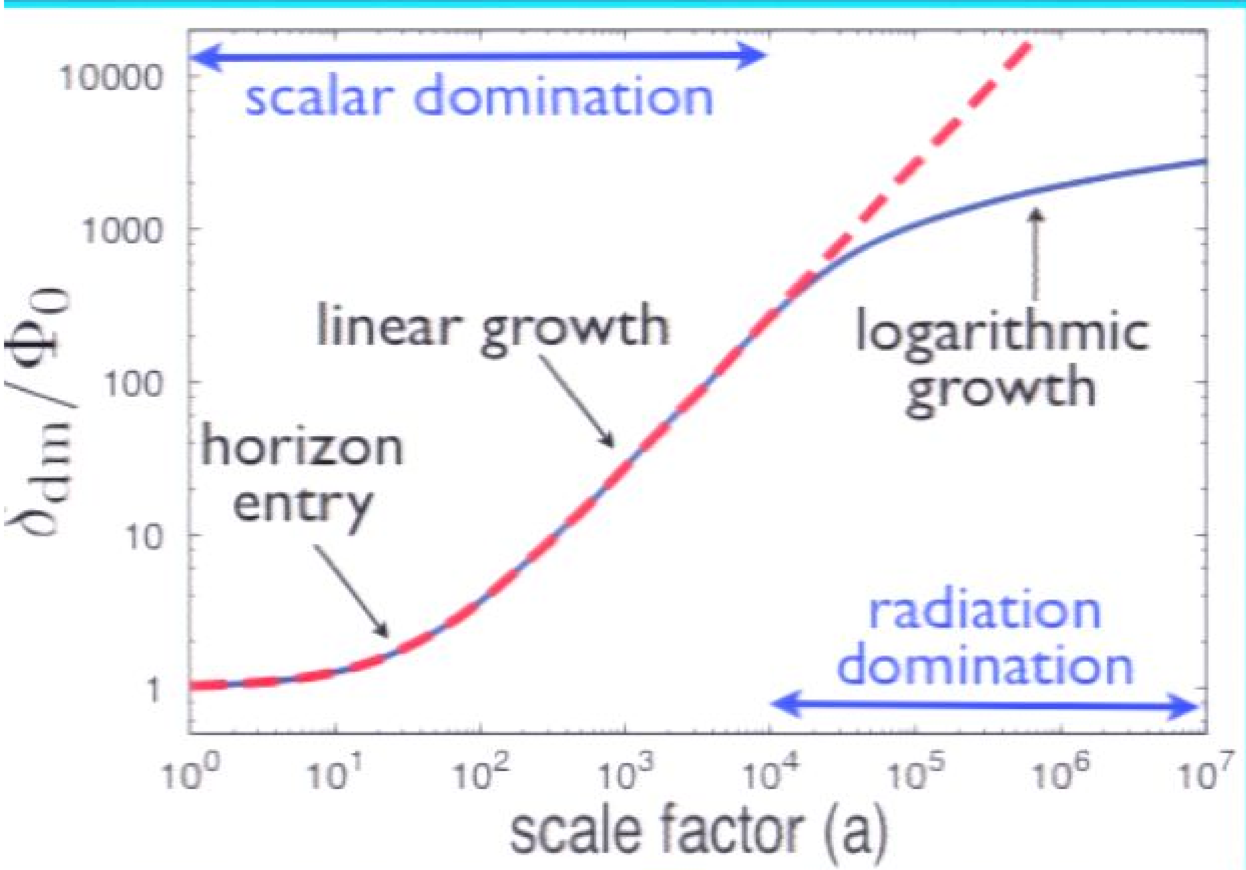

During Scalar Domination:

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

linear growth

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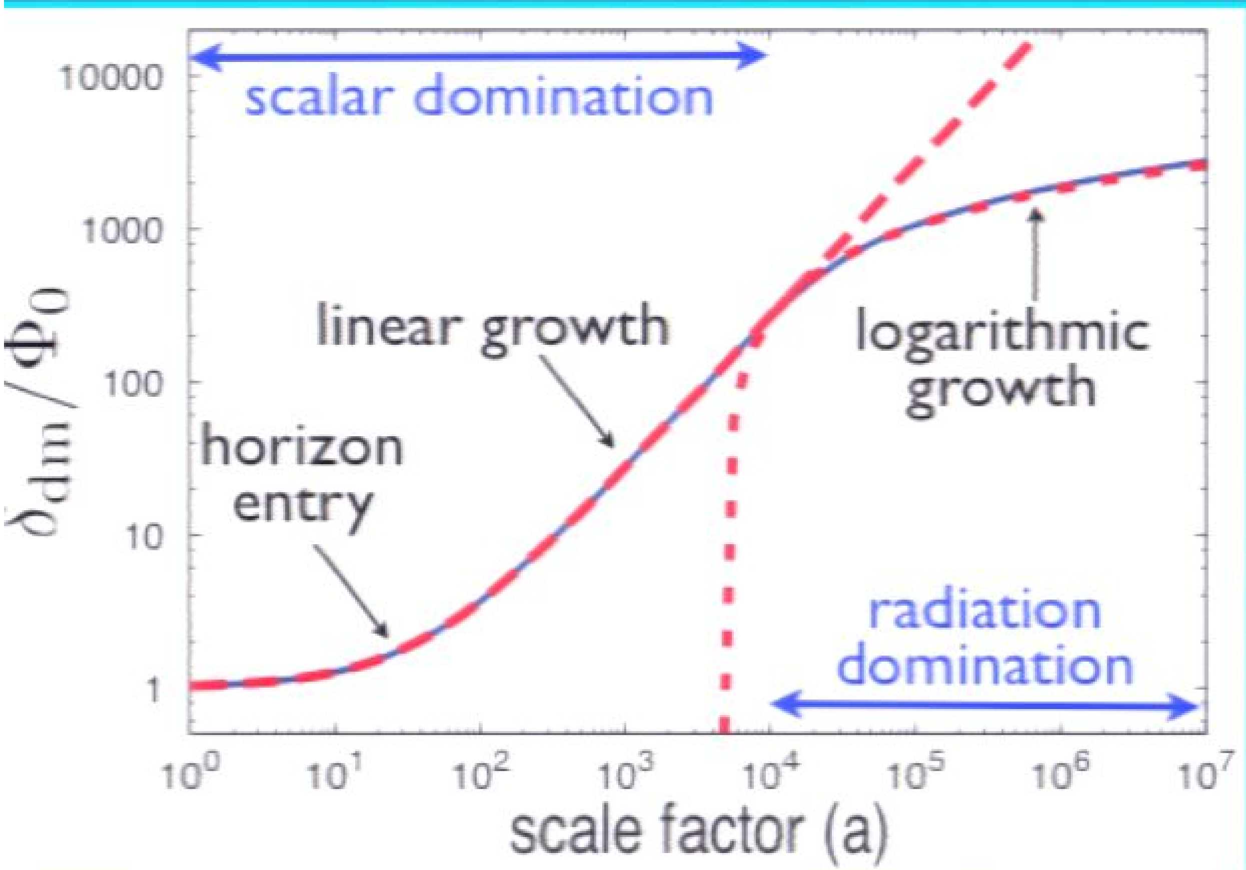


During Scalar Domination:

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

linear growth

After reheating:

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

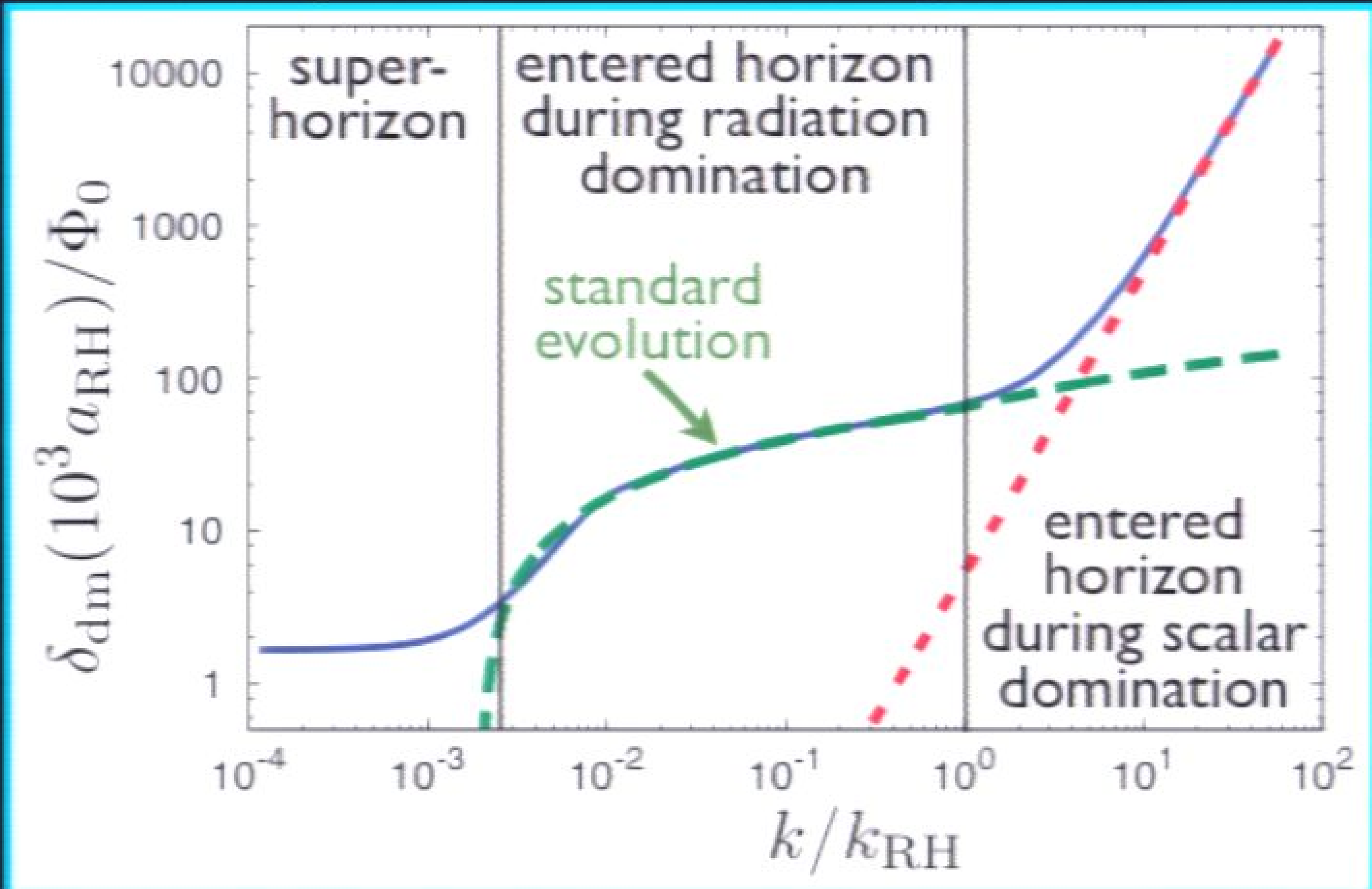
dark matter produced in scalar decays the dark matter perturbation is sensitive only to the background expansion

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

logarithmic growth

The Matter Perturbation

The Matter Density Perturbation during Radiation Domination

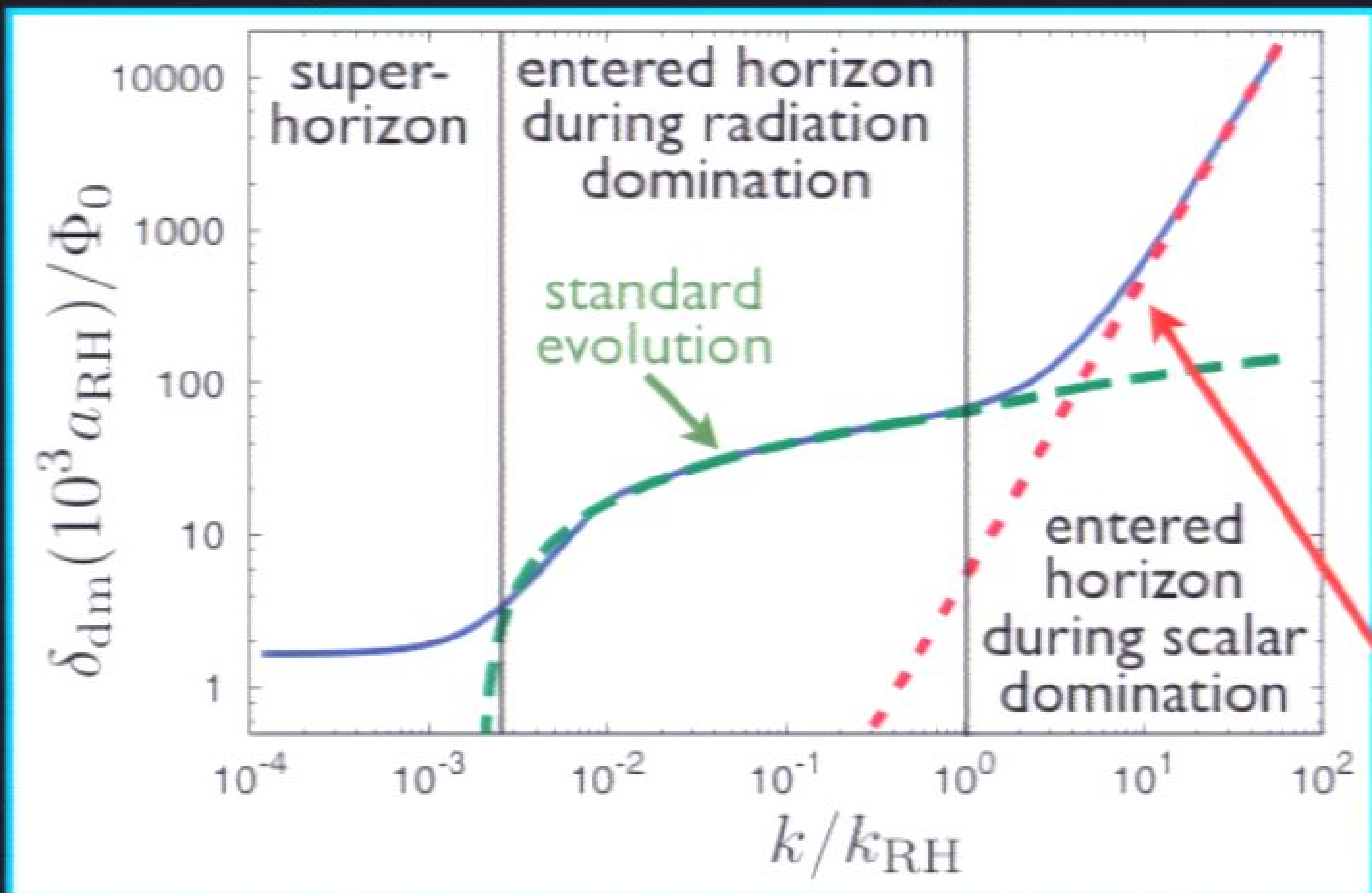


Superhorizon modes evolve at reheating: $\Phi \rightarrow (10/9)\Phi_0$

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

The Matter Perturbation

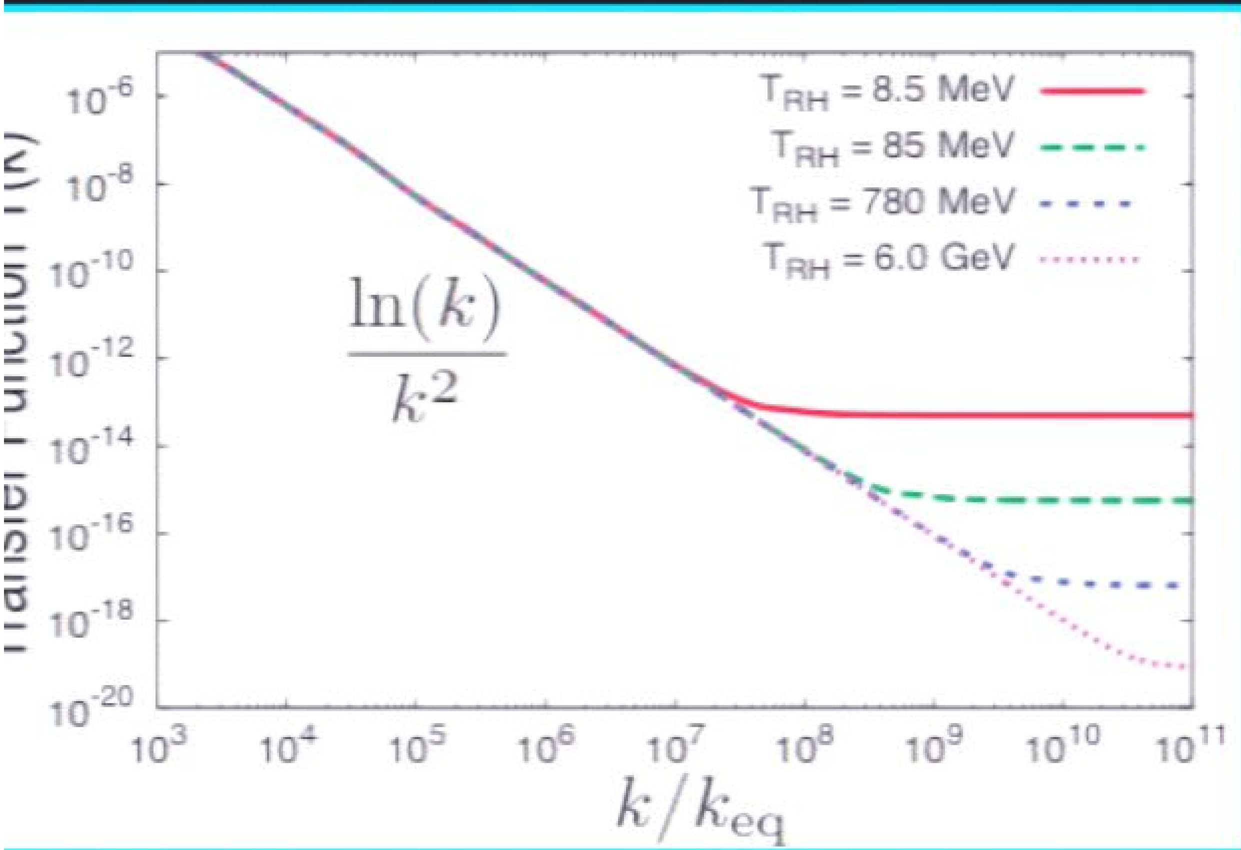
The Matter Density Perturbation during Radiation Domination



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

The Matter Transfer Function

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



ubhorizon 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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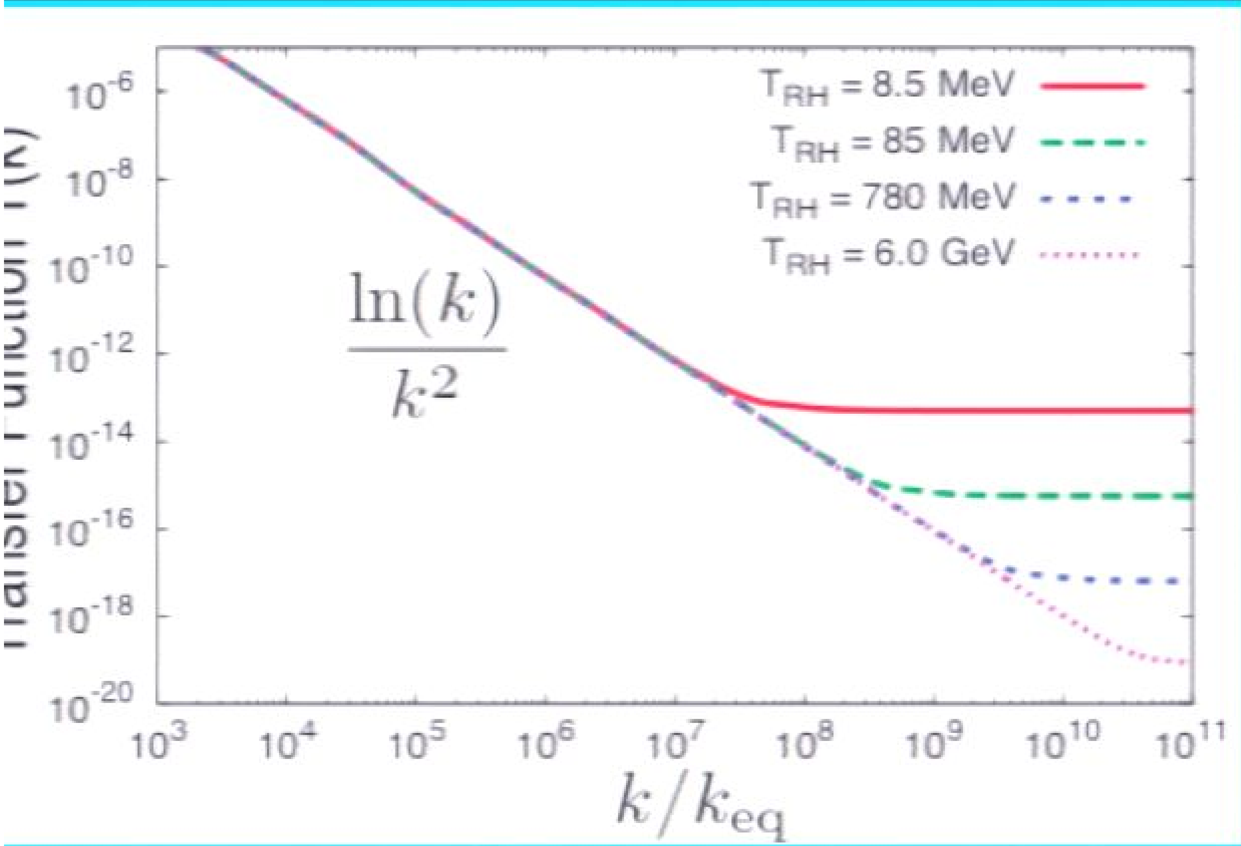

For modes that enter the horizon during scalar domination ($k > k_{\rm RH}$):

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

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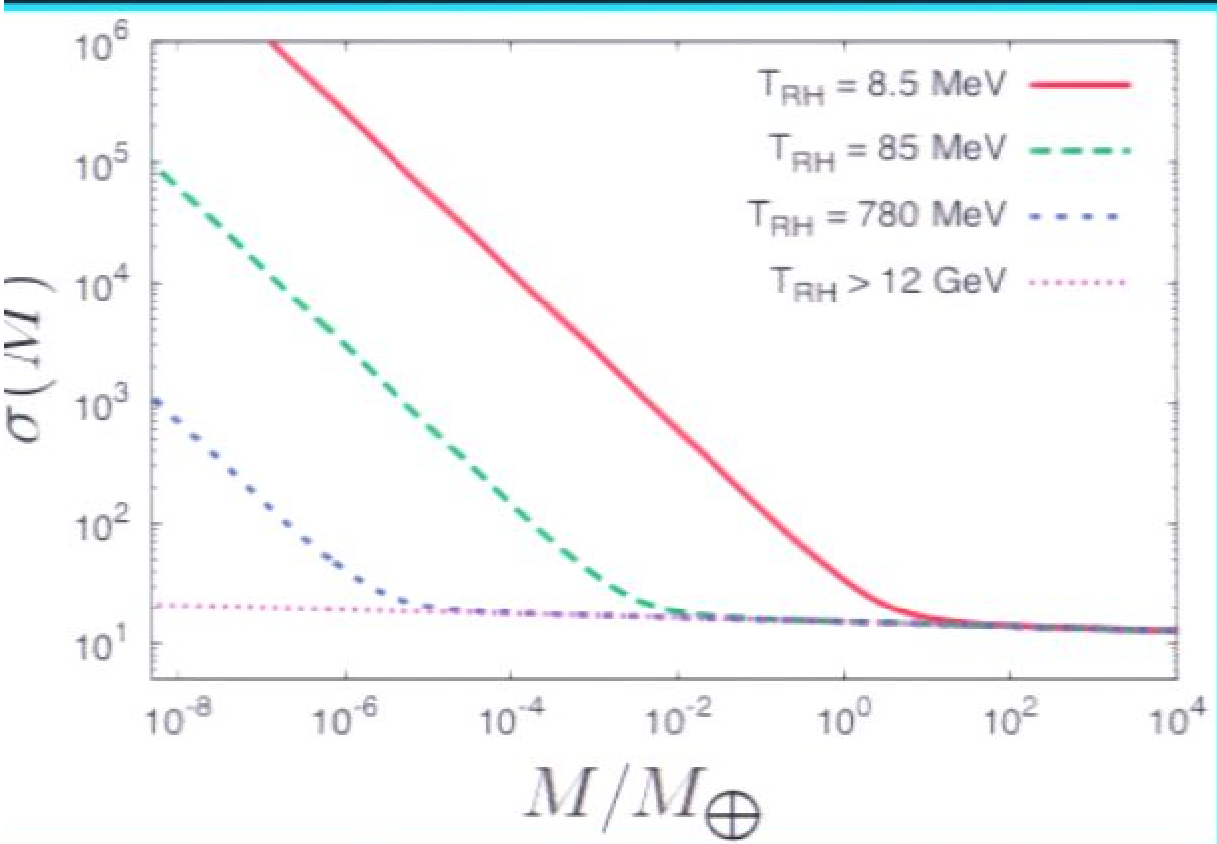
RMS Density Fluctuation



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

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

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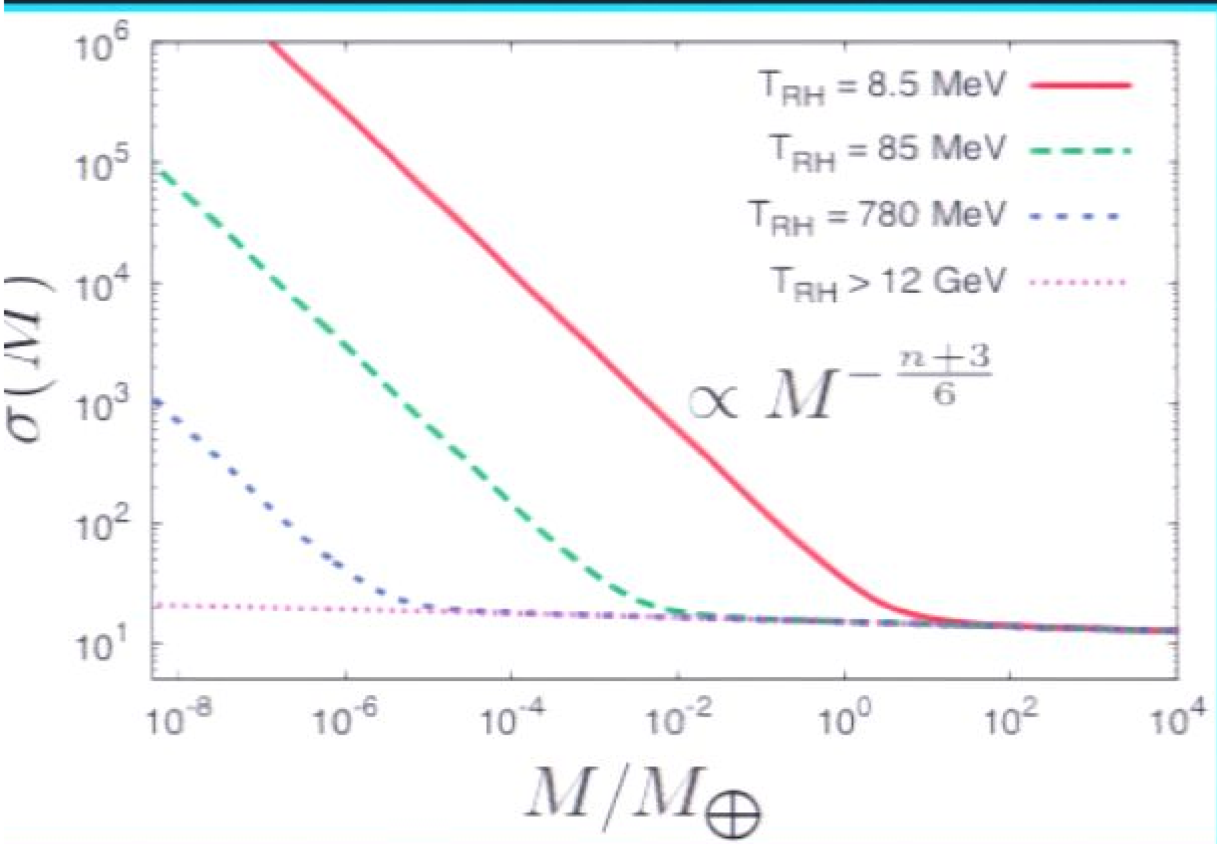

- Altered transfer function affects scales with $R \lesssim k_{\rm RH}^{-1}$
- Define $M_{\rm RH}$ to be mass within this comoving radius.
- For $k > k_{\rm RH}$, $P(k) \propto k^n$
- Since the power spectrum is a power law,

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

for

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

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

What about free-streaming?

ree-streaming will exponentially suppress power on
cales 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:

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

For range of reheat temperatures,

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

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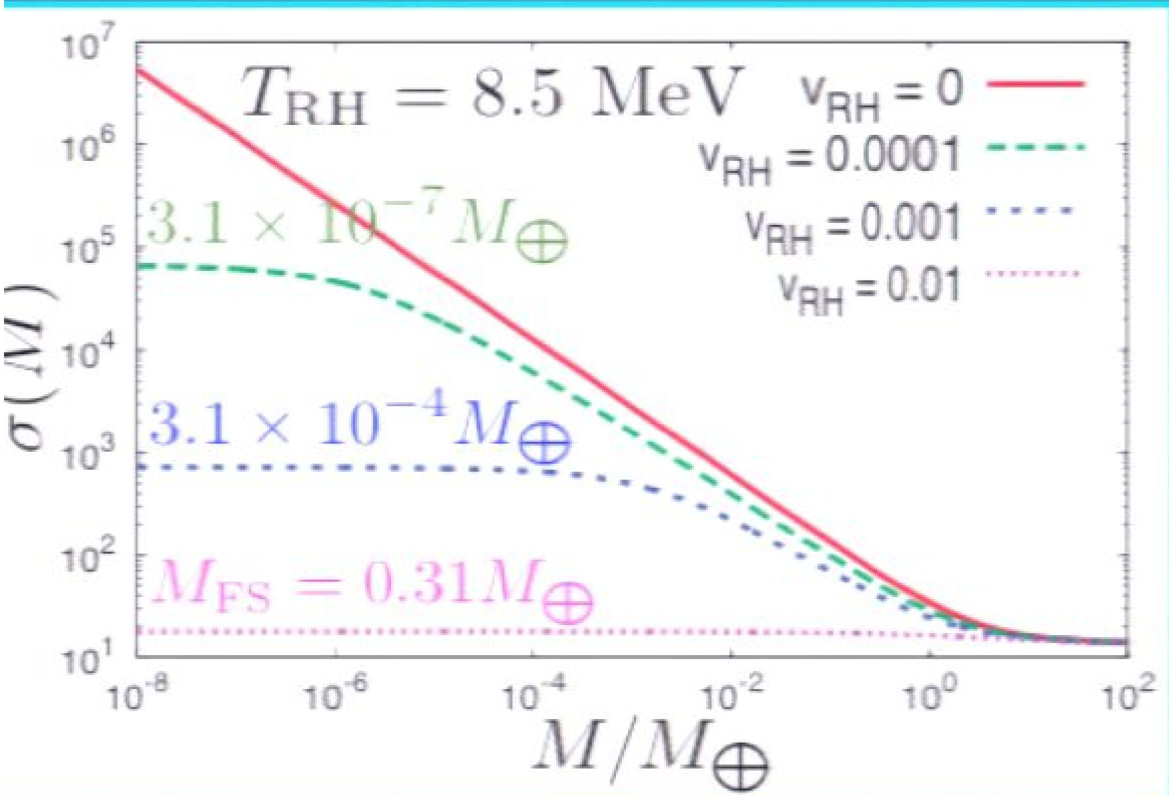

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Part III
Microhalos from Reheating

From Perturbations to Microhalos

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

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

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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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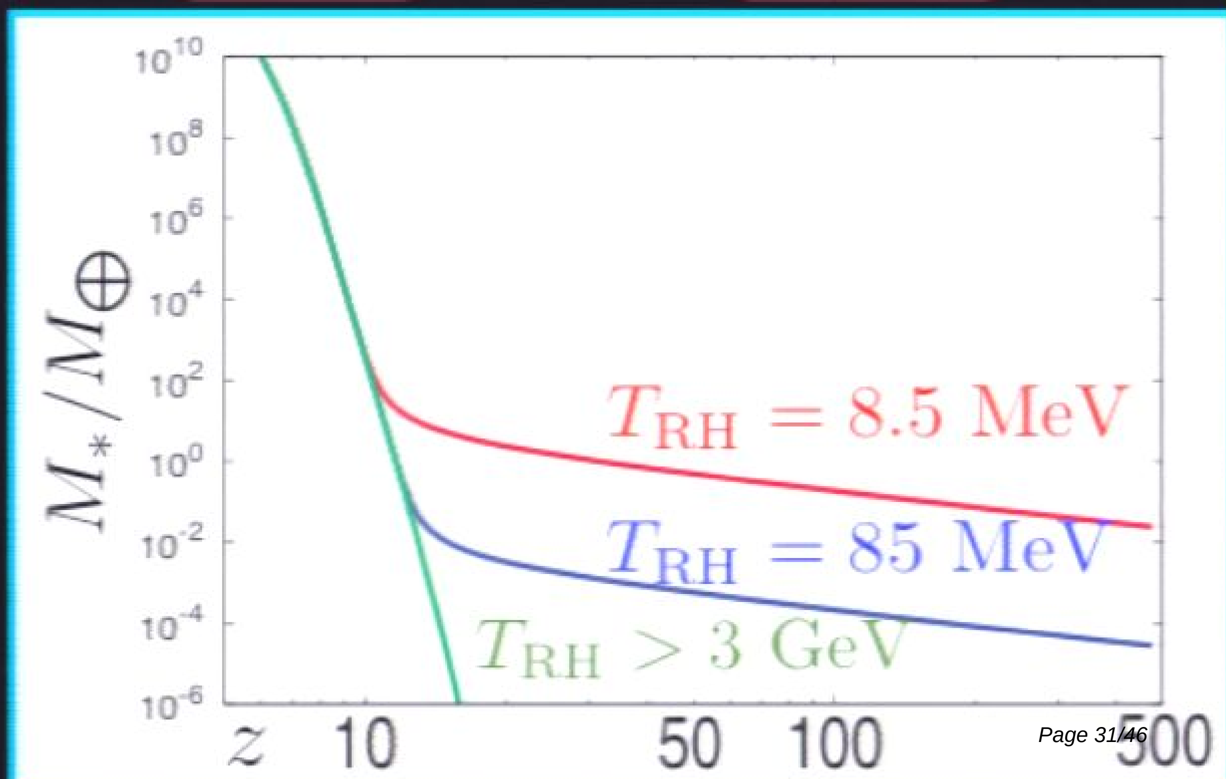
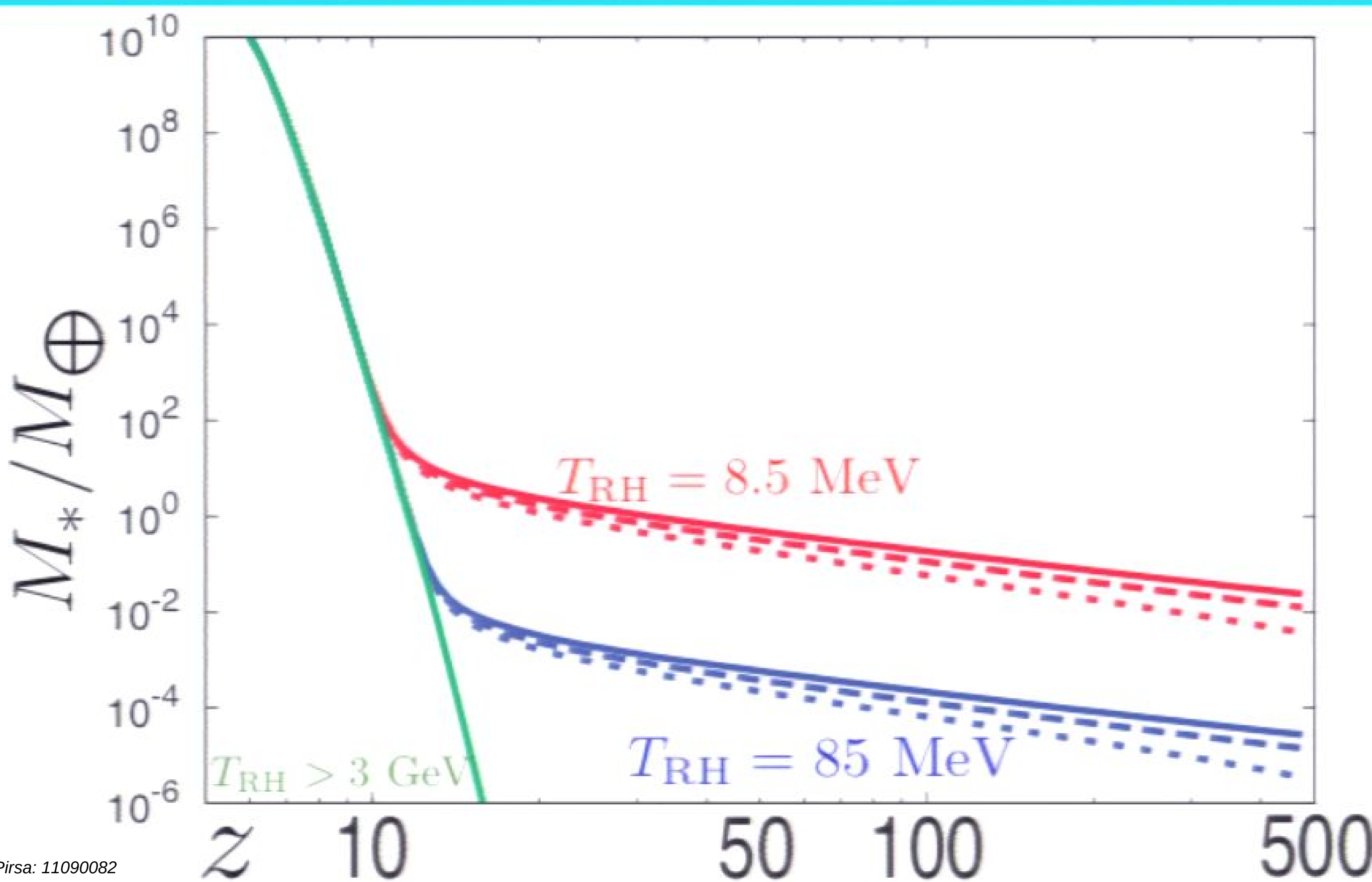


M_* Properties

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



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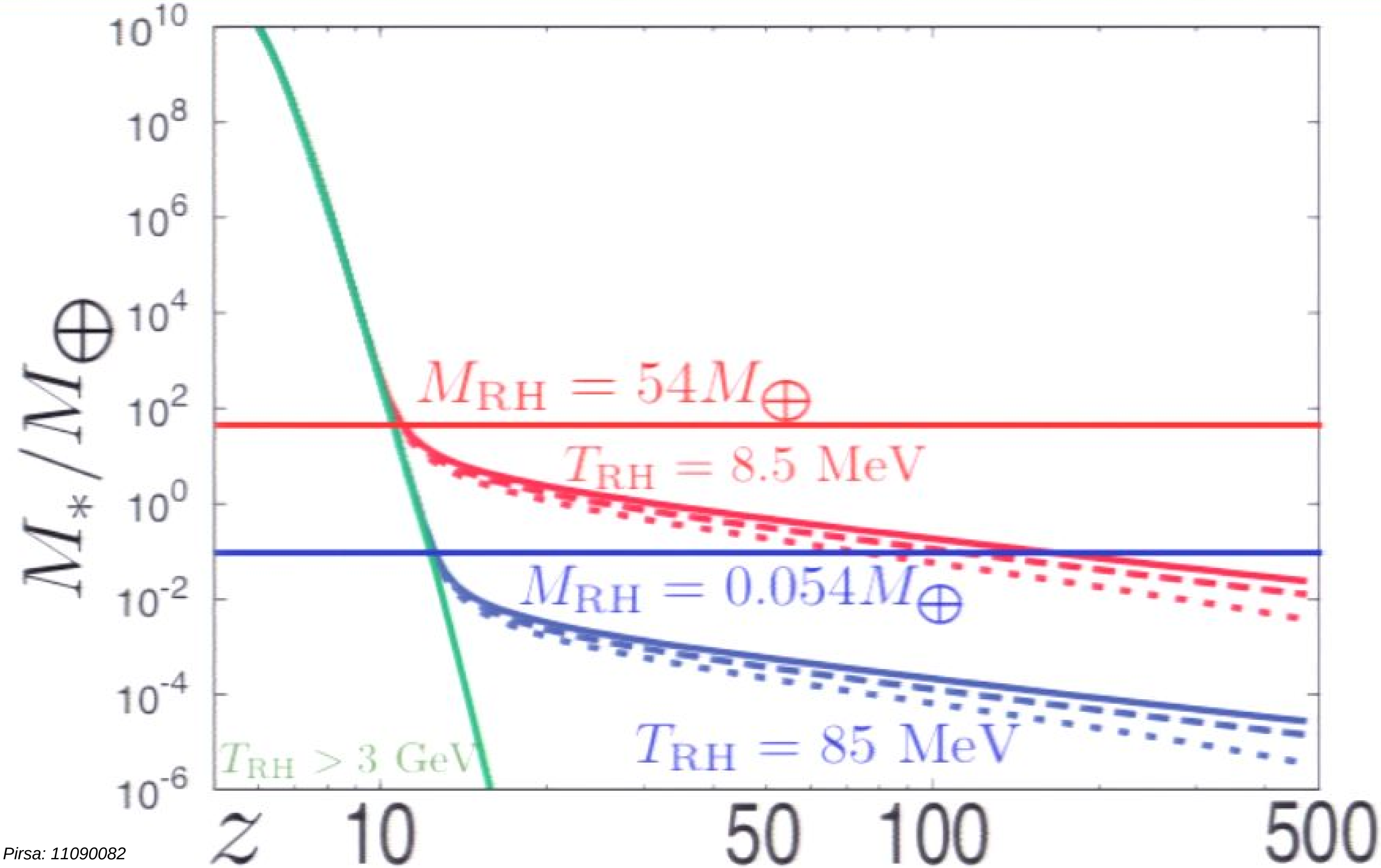

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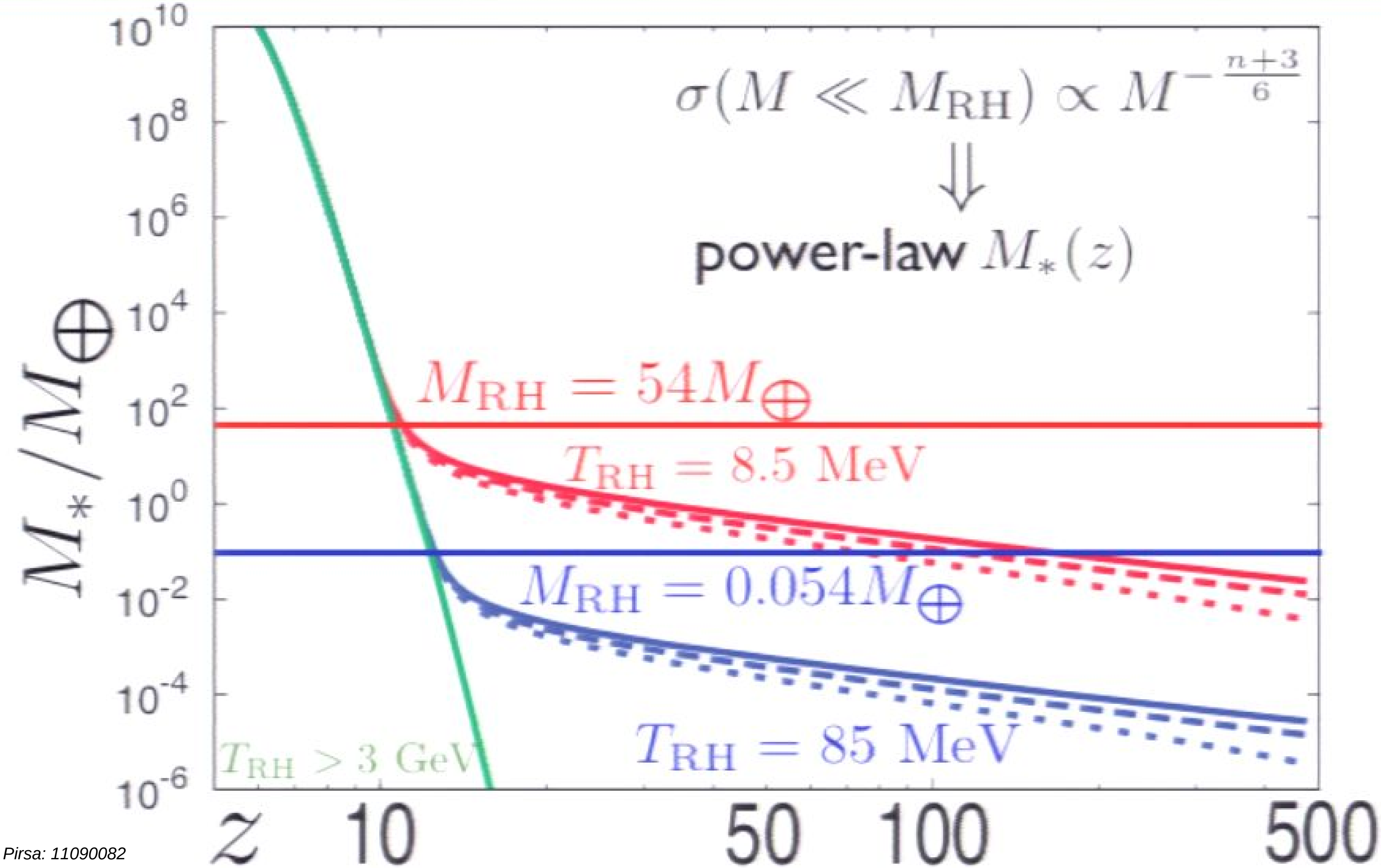

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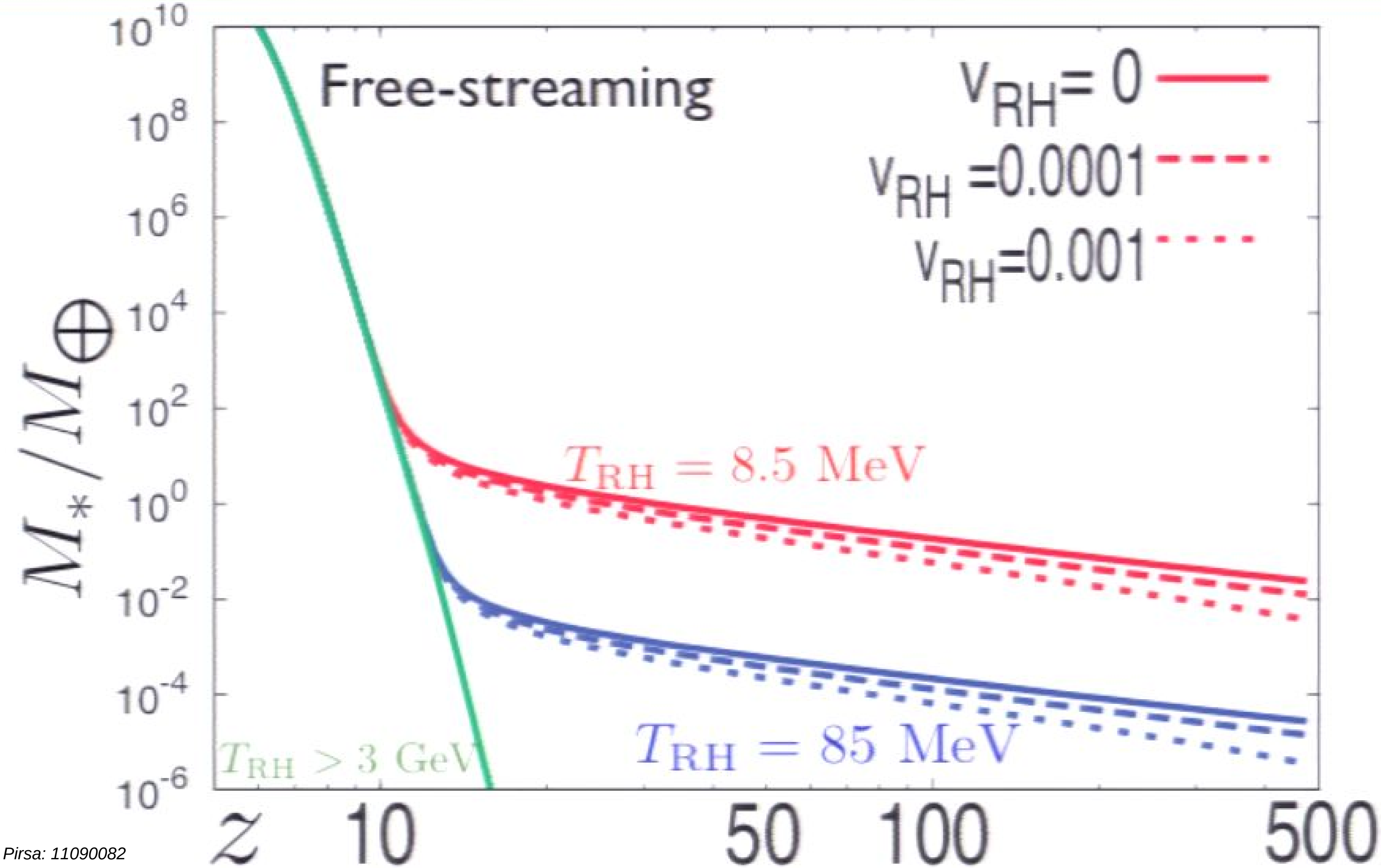

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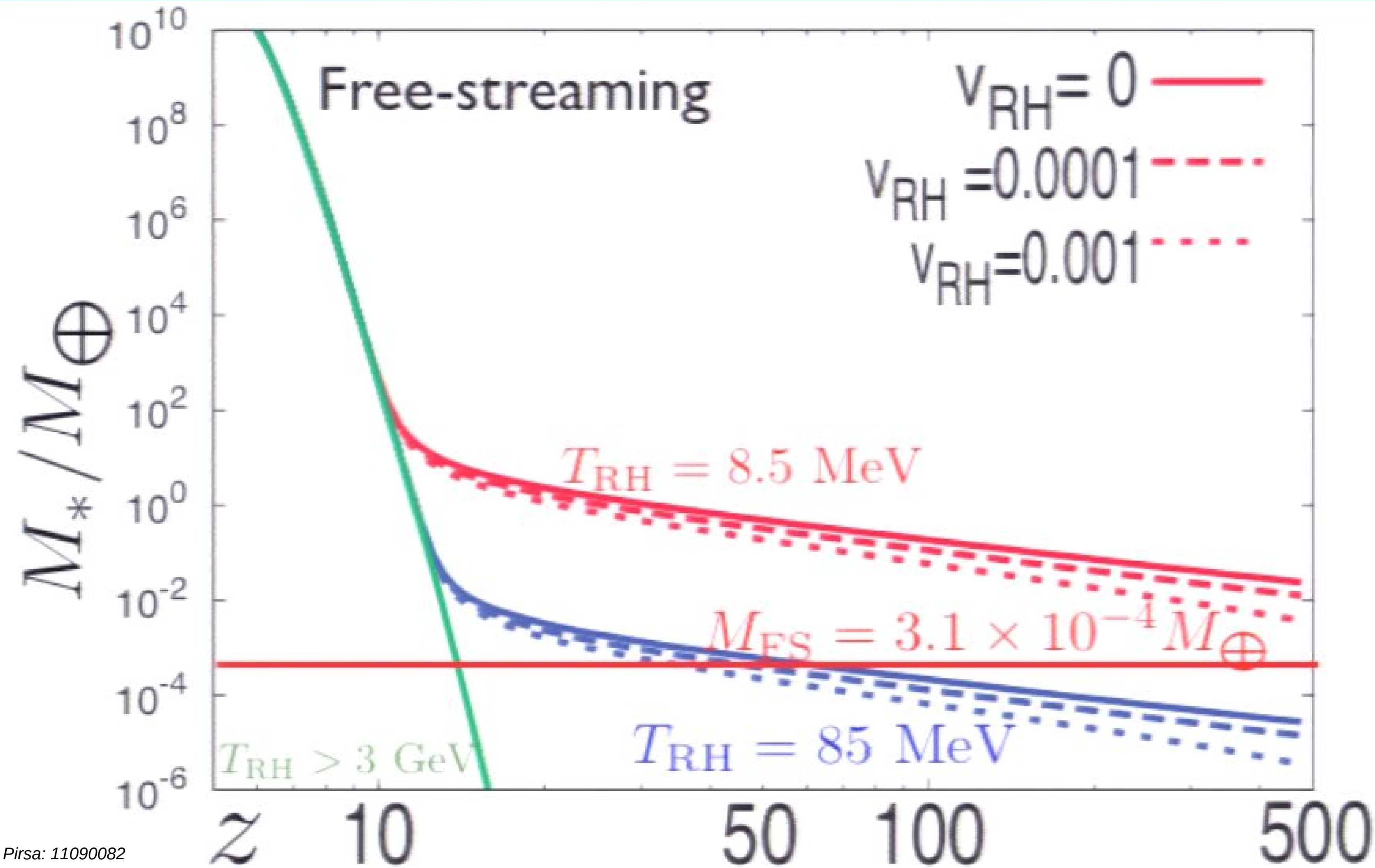

Microhalos at High Redshift

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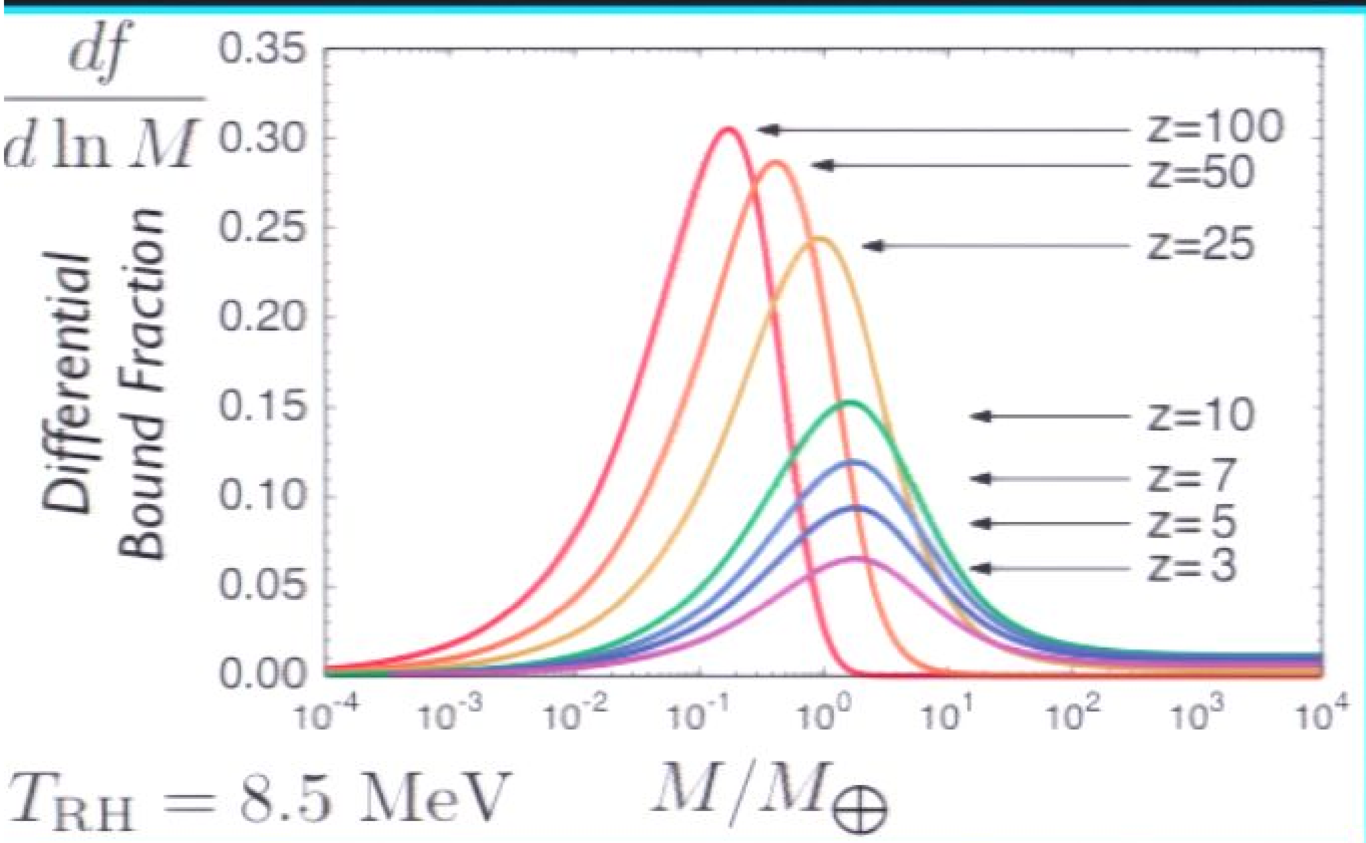

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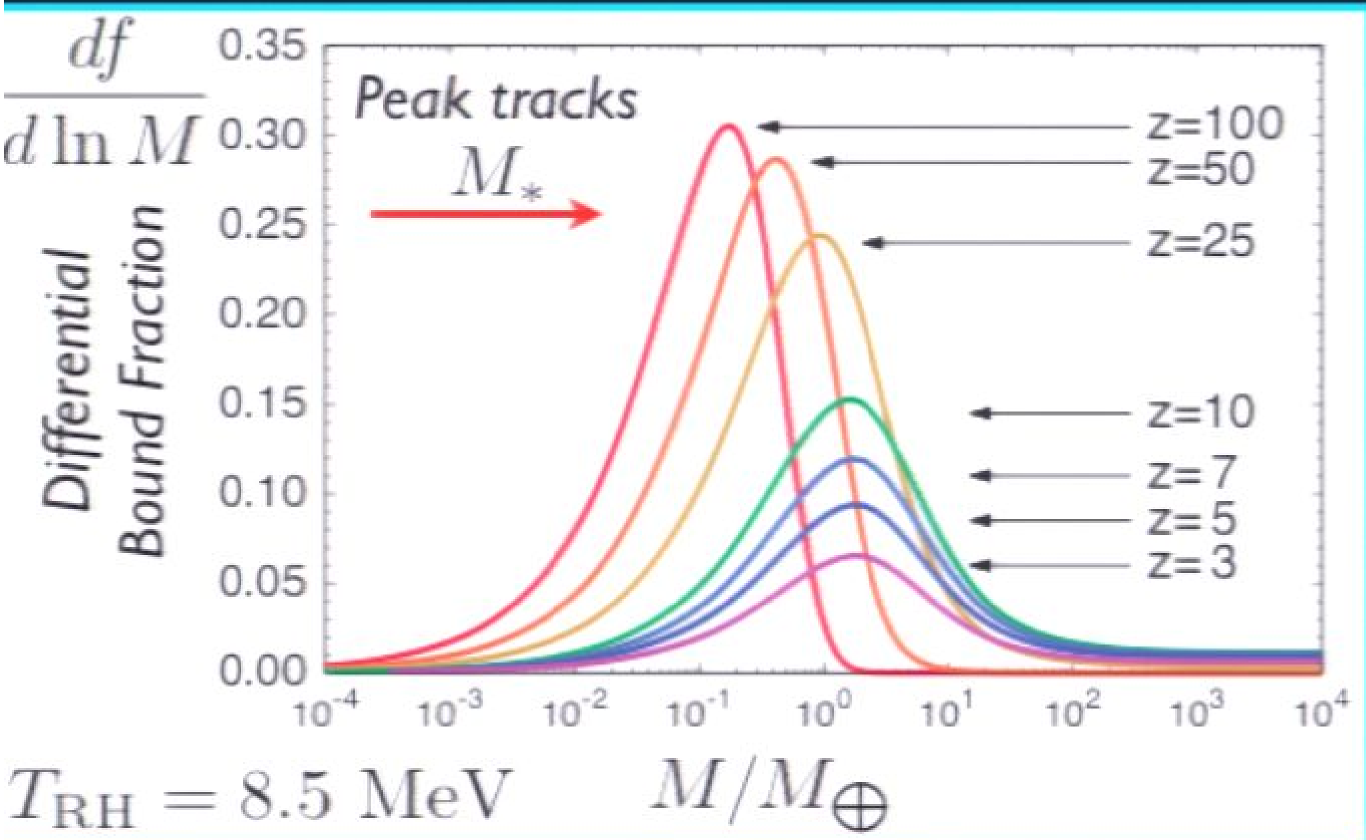

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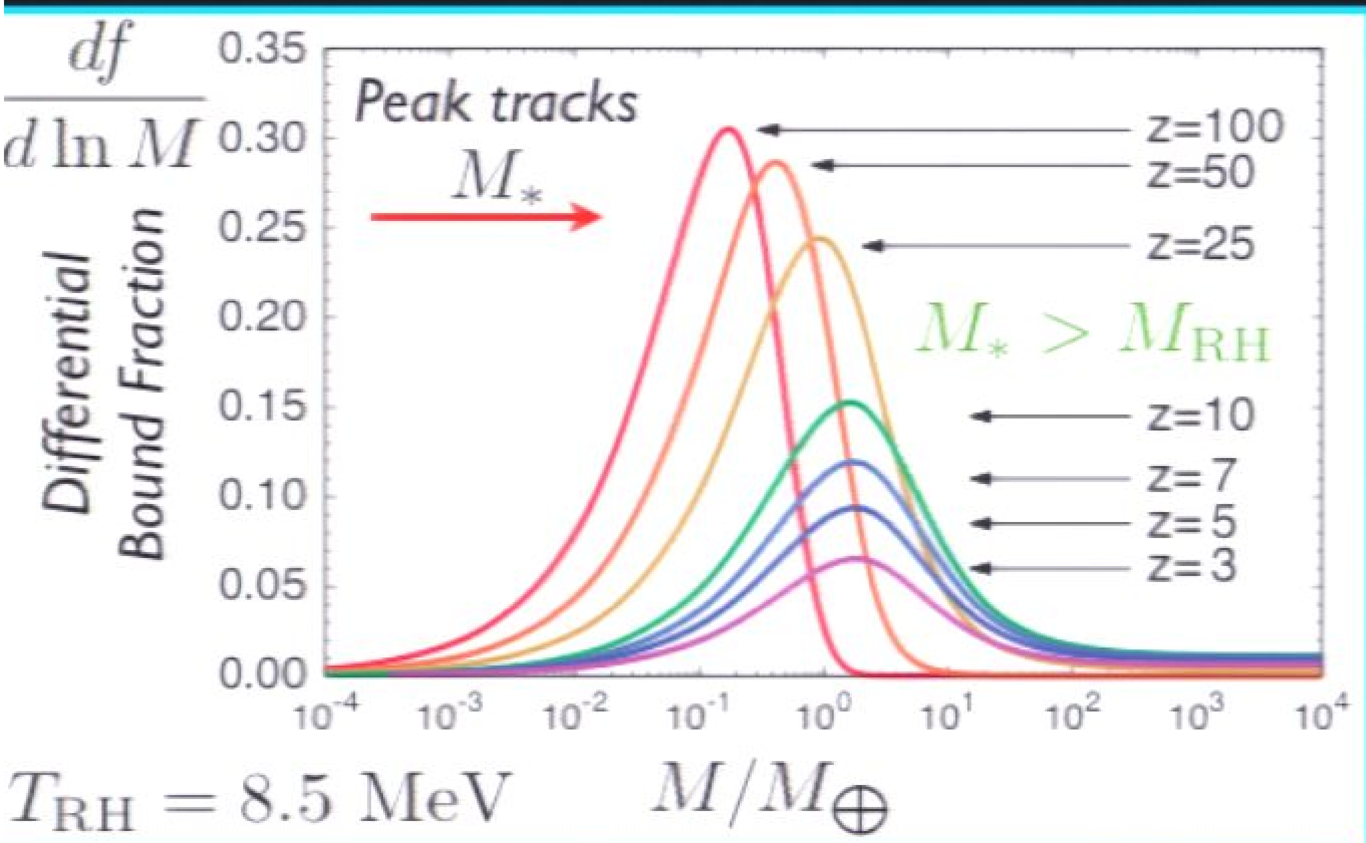

Fraction bound in halos with $M > 0.1\, M_\oplus$

z	Std	8.5 MeV
100	10^{-10}	0.49
50	10^{-3}	0.71
25	0.06	0.83

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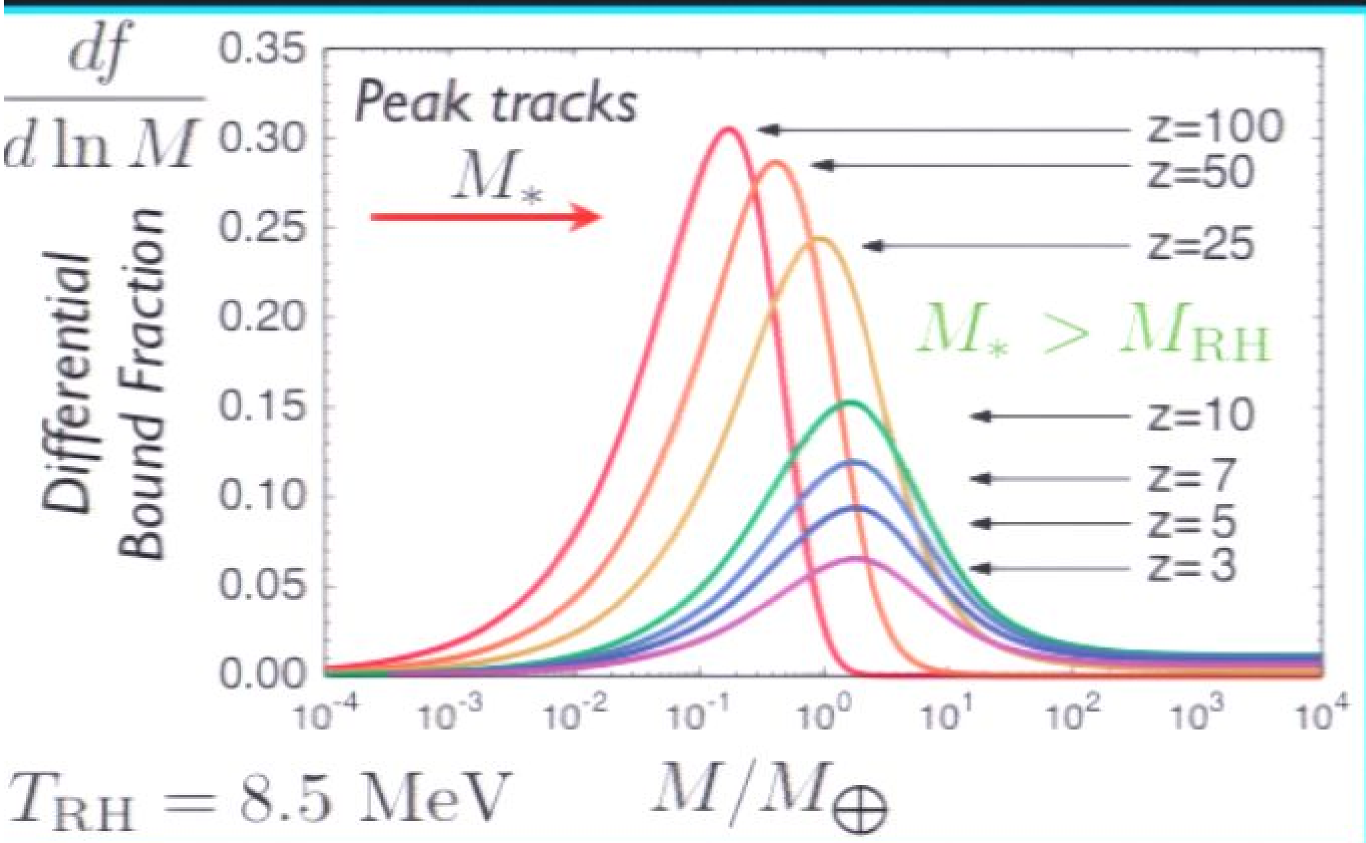
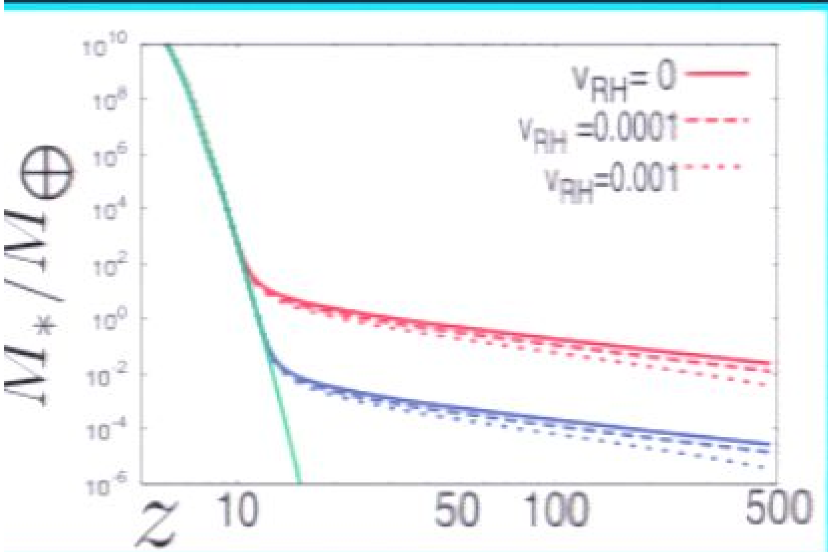


Fraction bound in halos with $M > 0.1\,M_\oplus$

z	Std	8.5 MeV
100	10^{-10}	0.49
50	10^{-3}	0.71
25	0.06	0.83

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

Microhalos with Free-Streaming

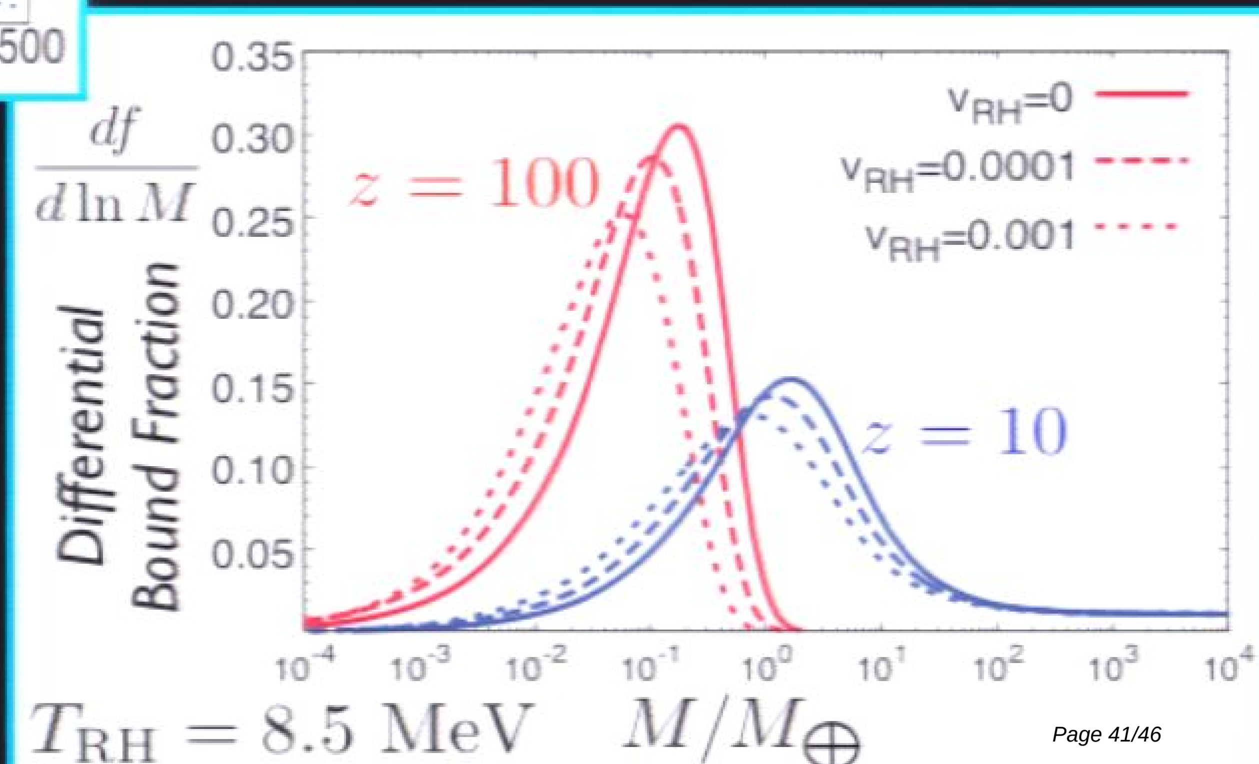


Giving the dark matter particles a small velocity at reheating slightly reduces M_* and $\left|\frac{d\ln\sigma}{d\ln M}\right|$.

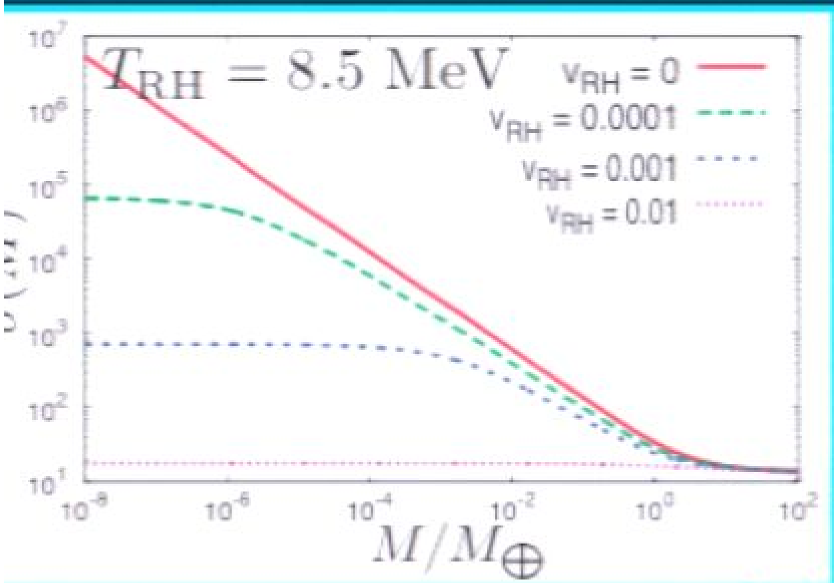
Consequently, free-streaming leads to microhalos that

- have smaller masses
- are less abundant

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



Microhalos with Free-Streaming



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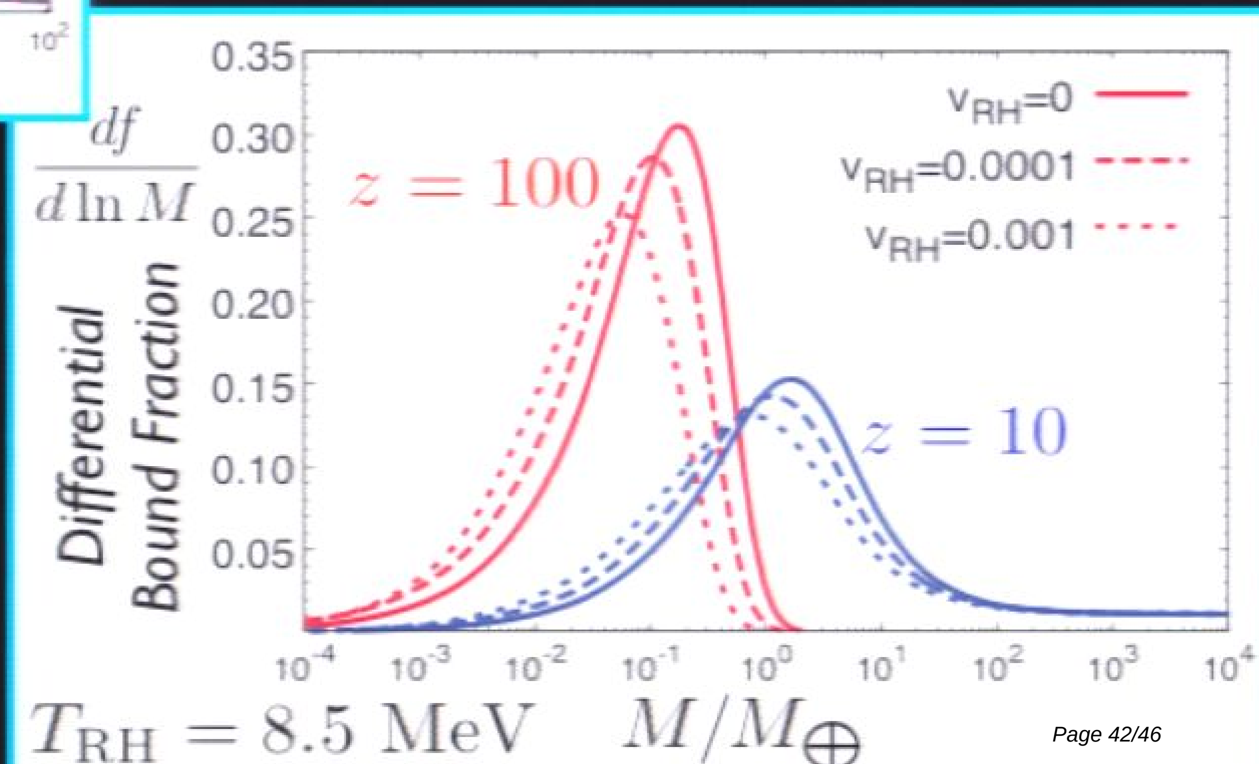
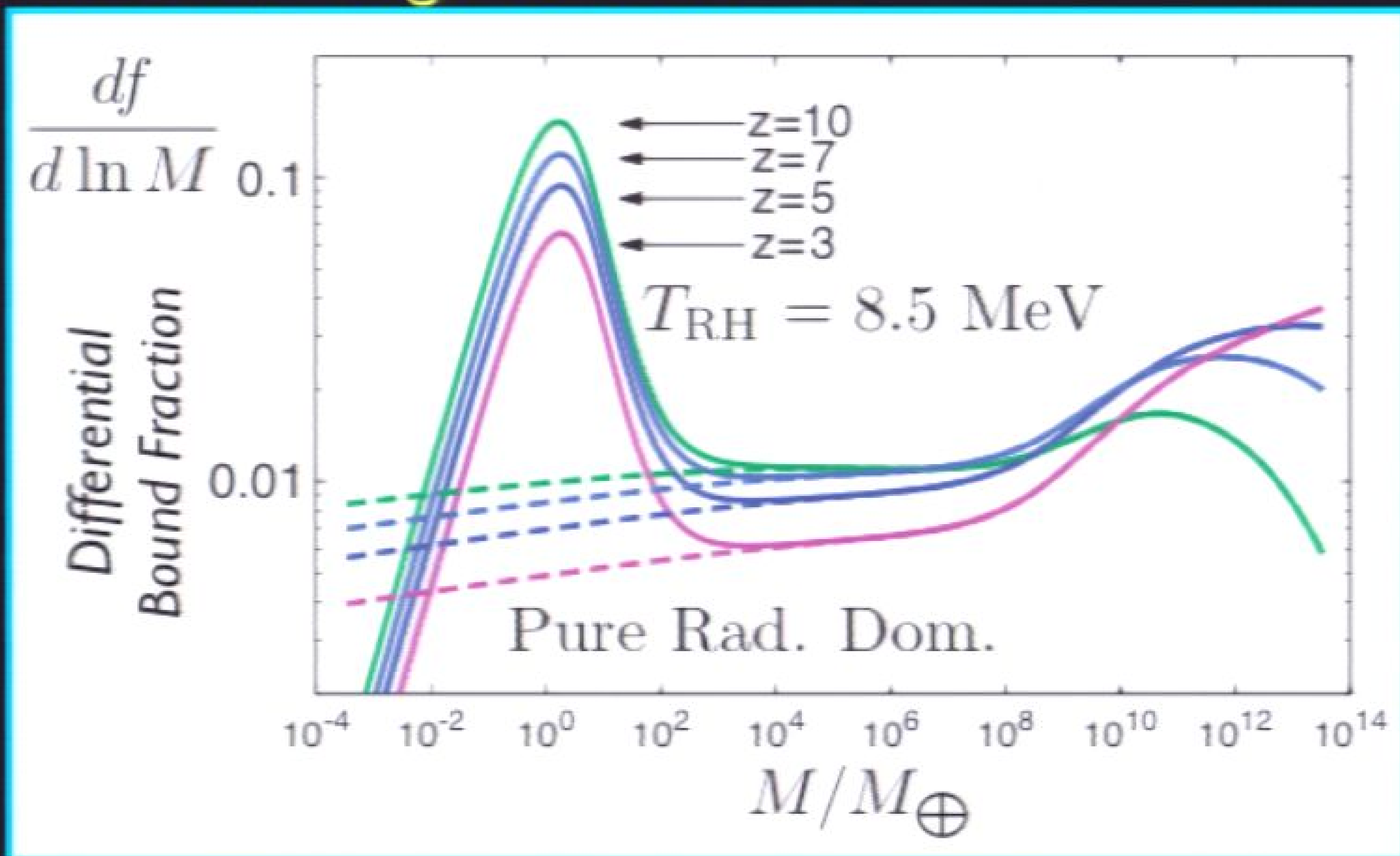


From Microhalos to Subhalos

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



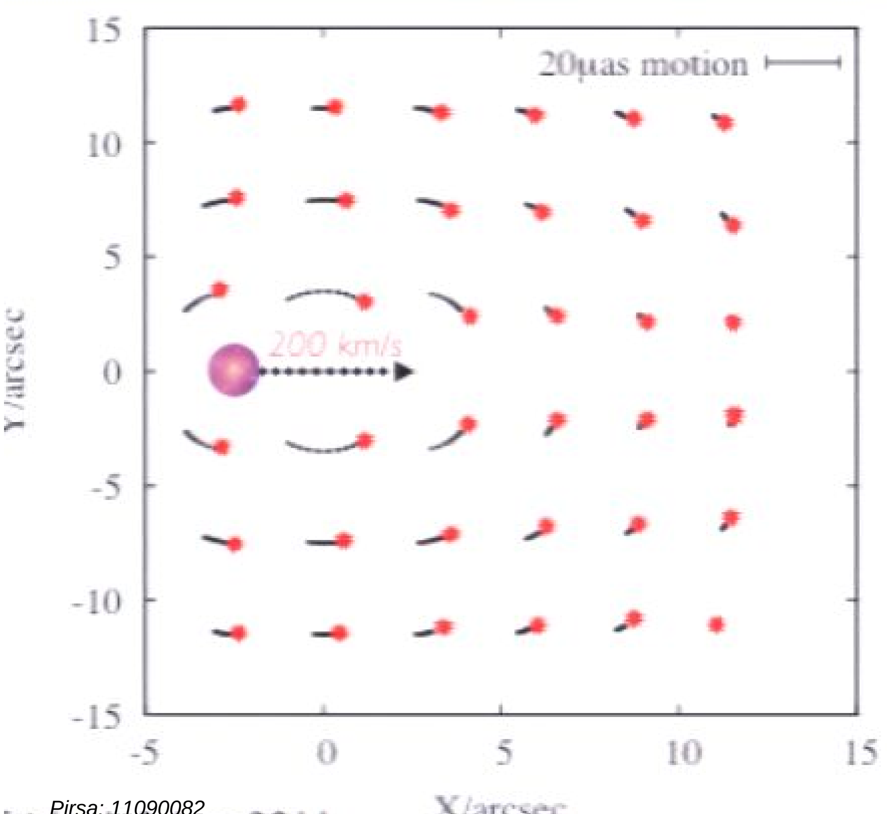
Since these microhalos formed at high redshift, they are far denser than standard microhalos and are more likely to survive.

Berezinsky, et al 2010

Detection Prospects

he only guaranteed signatures are gravitational.

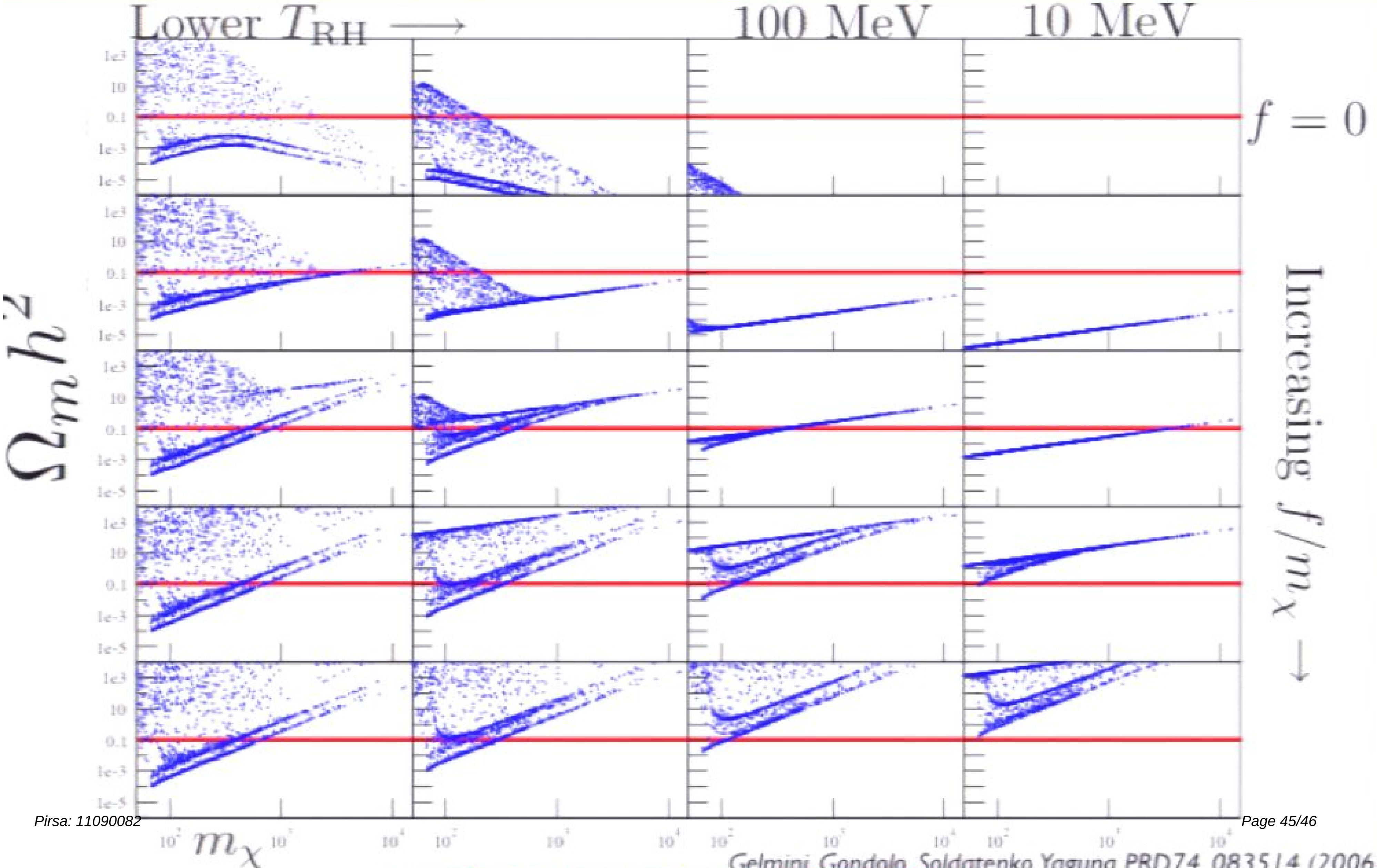
- Astrometric Microlensing *Erickcek & Law 2011*
- Pulsar Timing Residuals *Baghram, Afshordi, Zurek 2011*
- Photometric Microlensing *Ricotti & Gould 2009*



rickcek & Law 2011

If dark matter self-annihilates...

WIMP Dark Matter?



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

Summary: A New Window on Reheating

- erturbations that enter the horizon prior to reheating are ery 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.
- he enhancement in the dark matter power spectrum on mall 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