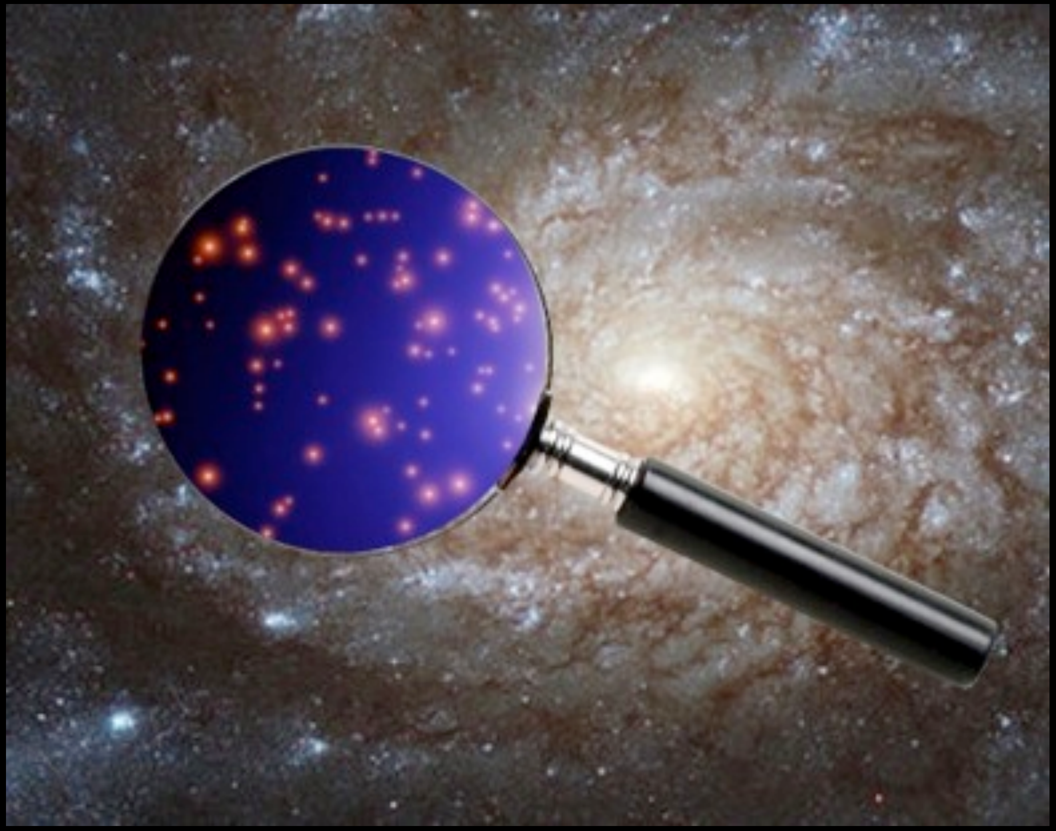
The Dark Matter Annihilation Boost from Low-Temperature Reheating



Adrienne Erickcek
UNC Chapel Hill

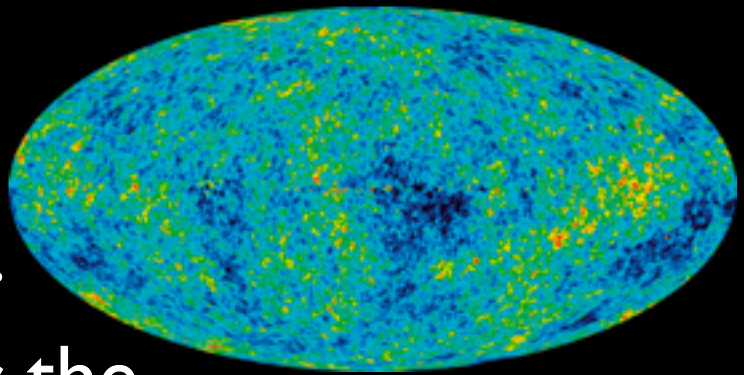
Mitchell Workshop on
Collider and Dark Matter Physics
May 21, 2015

What Happened Before BBN?

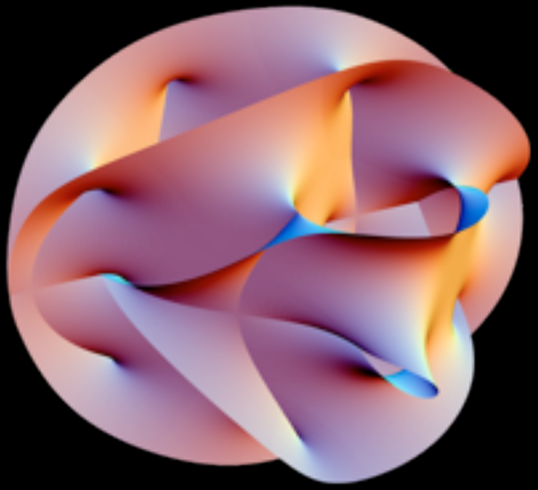
The (mostly) successful prediction of the primordial abundances of light elements is one of cosmology's crowning achievements.

- 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 moduli problem: scalars with gravitational couplings come to dominate the Universe before BBN.



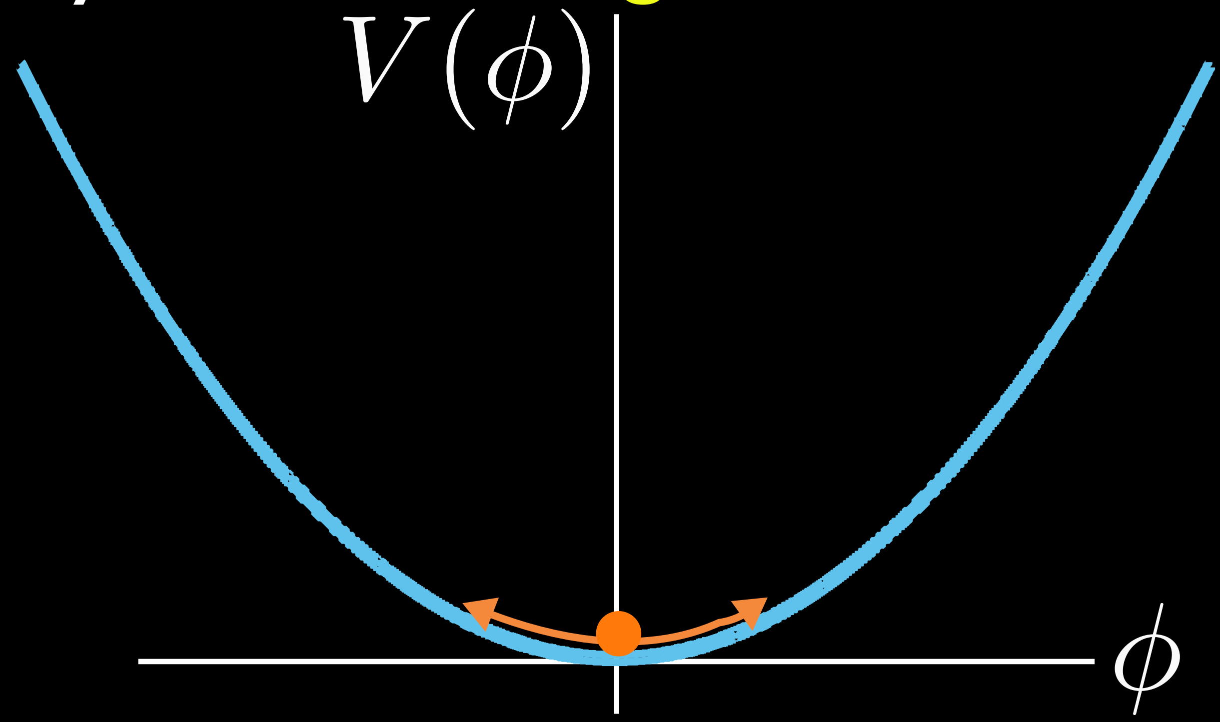
Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994

Acharya, Kumar, Bobkov, Kane, Shao, Watson 2008
Acharya, Kumar, Kane, Watson 2009
Recent Summary: Kane, Sinha, Watson 1502.07746

Scalar Domination after Inflation

The Universe was once dominated by an oscillating scalar field.

- reheating after inflation
- curvaton domination
- string moduli
- mediator domination *Hai-bo Yu's talk Zhang 2015*



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

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

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

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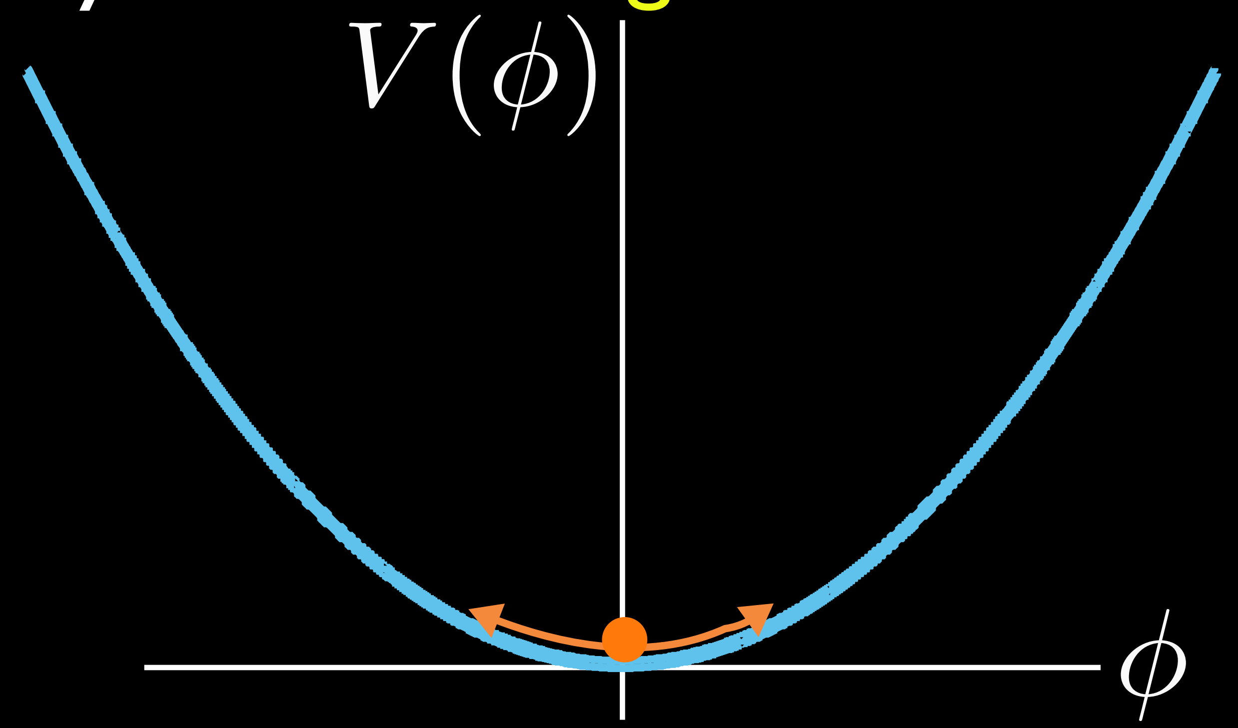
Hai-bo Yu's talk
Zhang 2015



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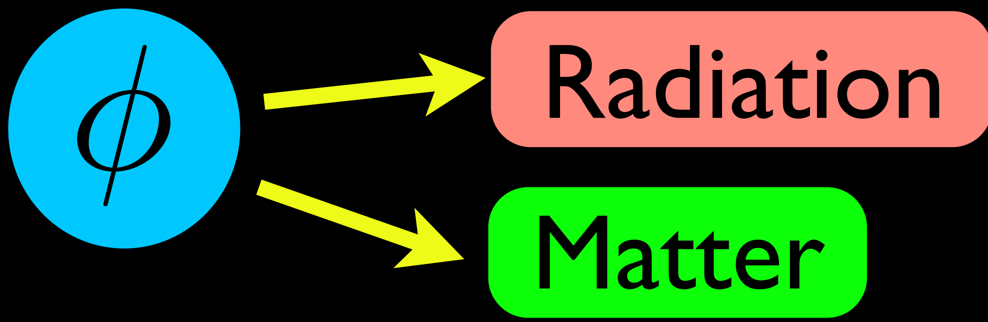
For $V \propto \phi^2$, oscillating scalar field $\simeq$ matter.

- 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

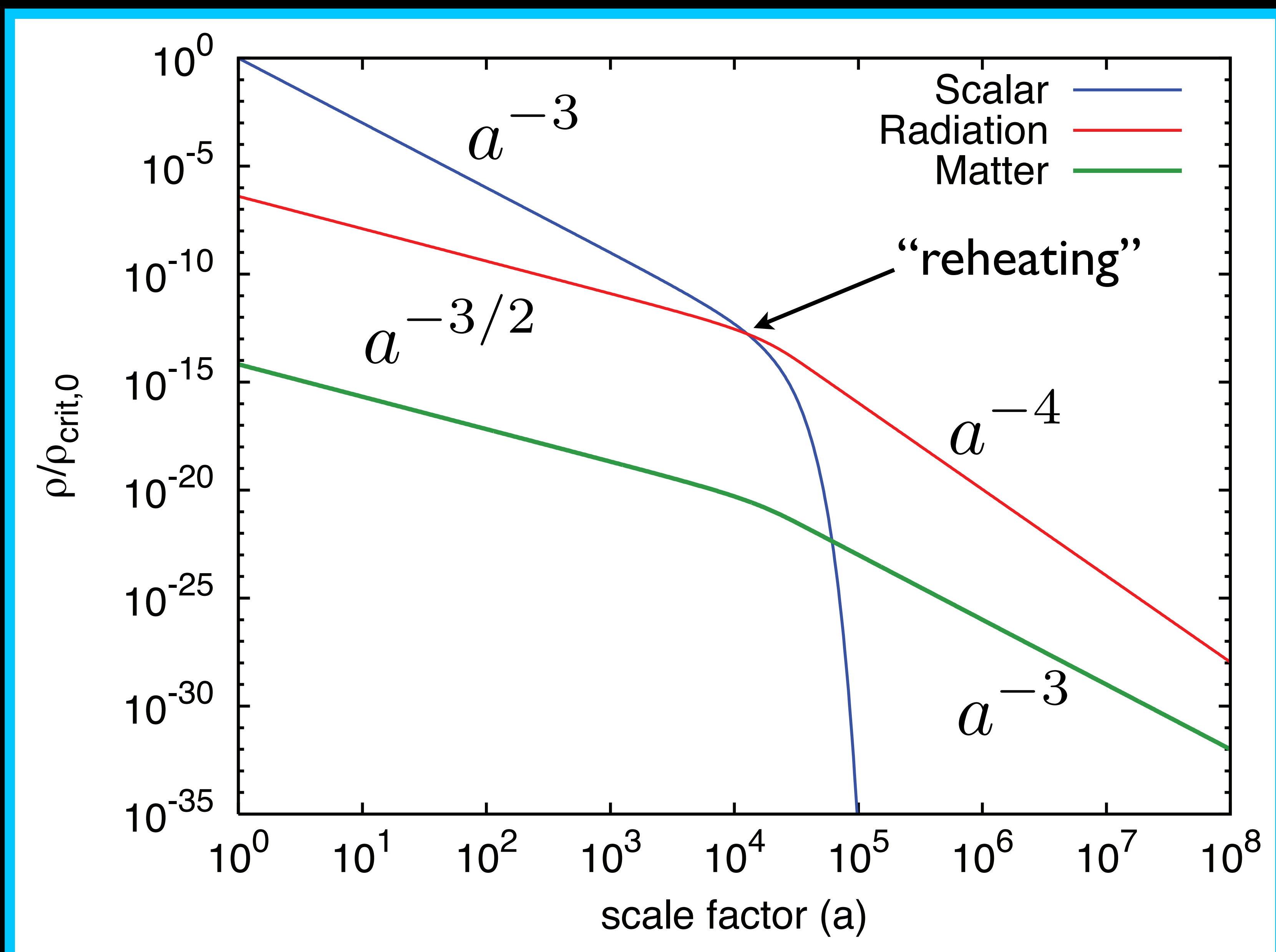
Dark matter may be produced during this early matter-dominated era!

DM Origin 1: Nonthermal



$$(1-f)\rho_\phi \longrightarrow \rho_{\rm rad}$$

$$f\rho_\phi \longrightarrow \rho_{\rm mat}$$



Branching ratio determines present-day dark matter density:

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

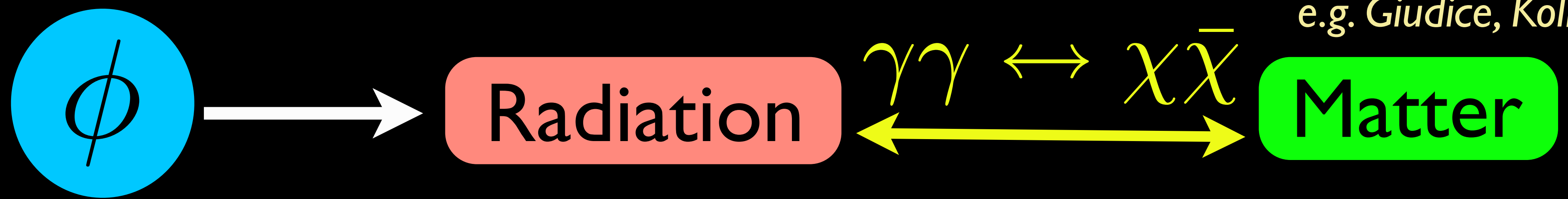
$$T_{\rm eq} = 0.75\,{\rm eV}$$

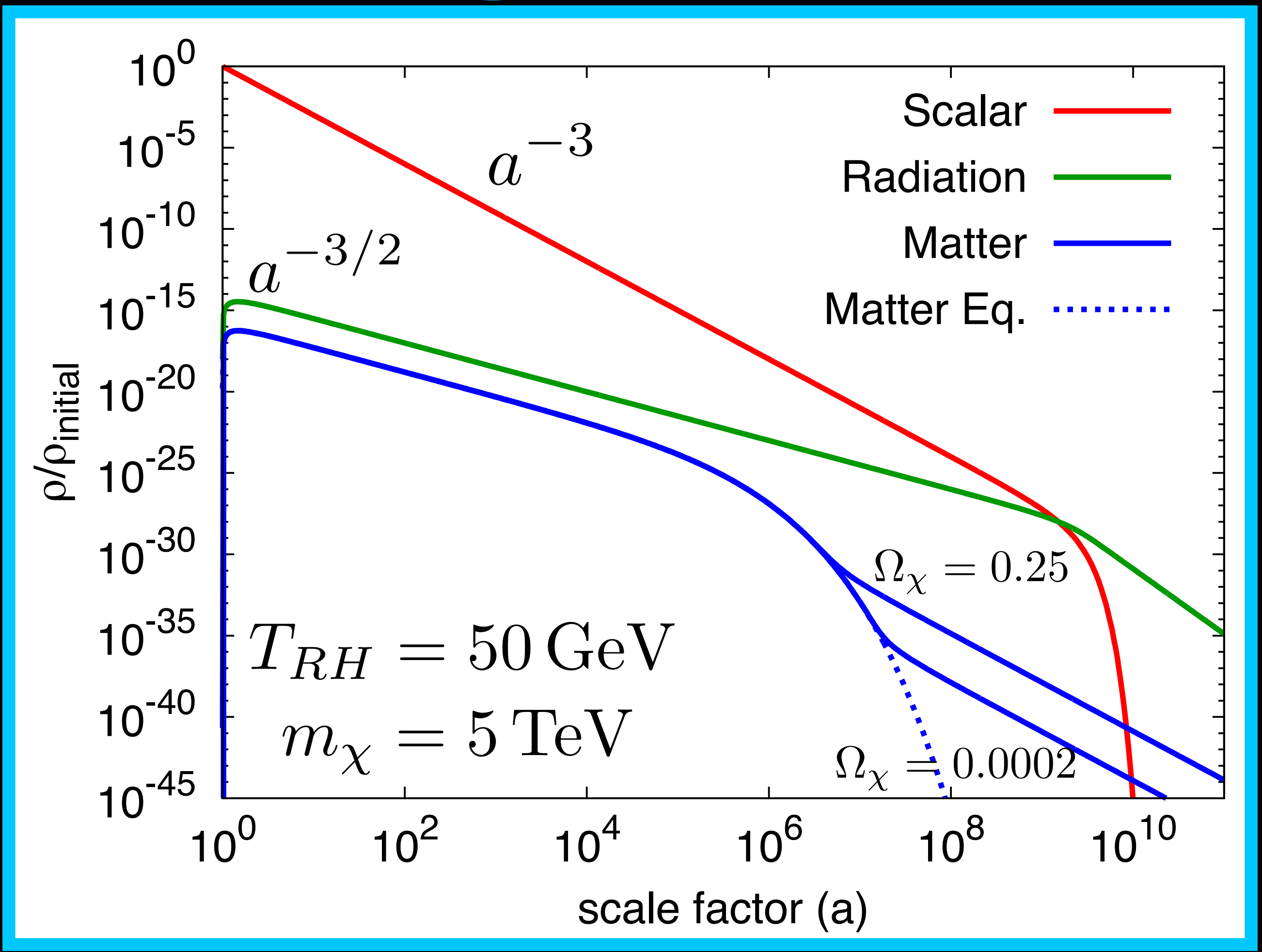
We need a very small branching ratio:

$$f < 10^{-7}$$

DM Origin 2: Thermal

e.g. Giudice, Kolb, Riotto 2001





Freeze-out: $\Omega_\chi \propto \dfrac{1}{\langle \sigma v \rangle}$

$$\langle \sigma v \rangle_{0.25} = 2 \times 10^{-29} \mathrm{cm}^3/\mathrm{s}$$

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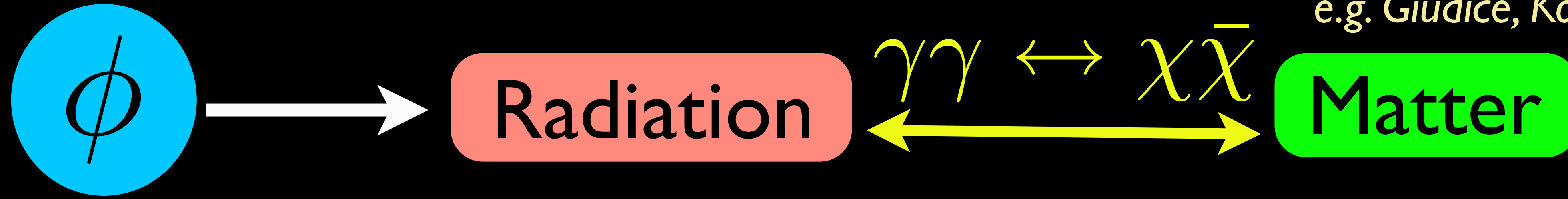

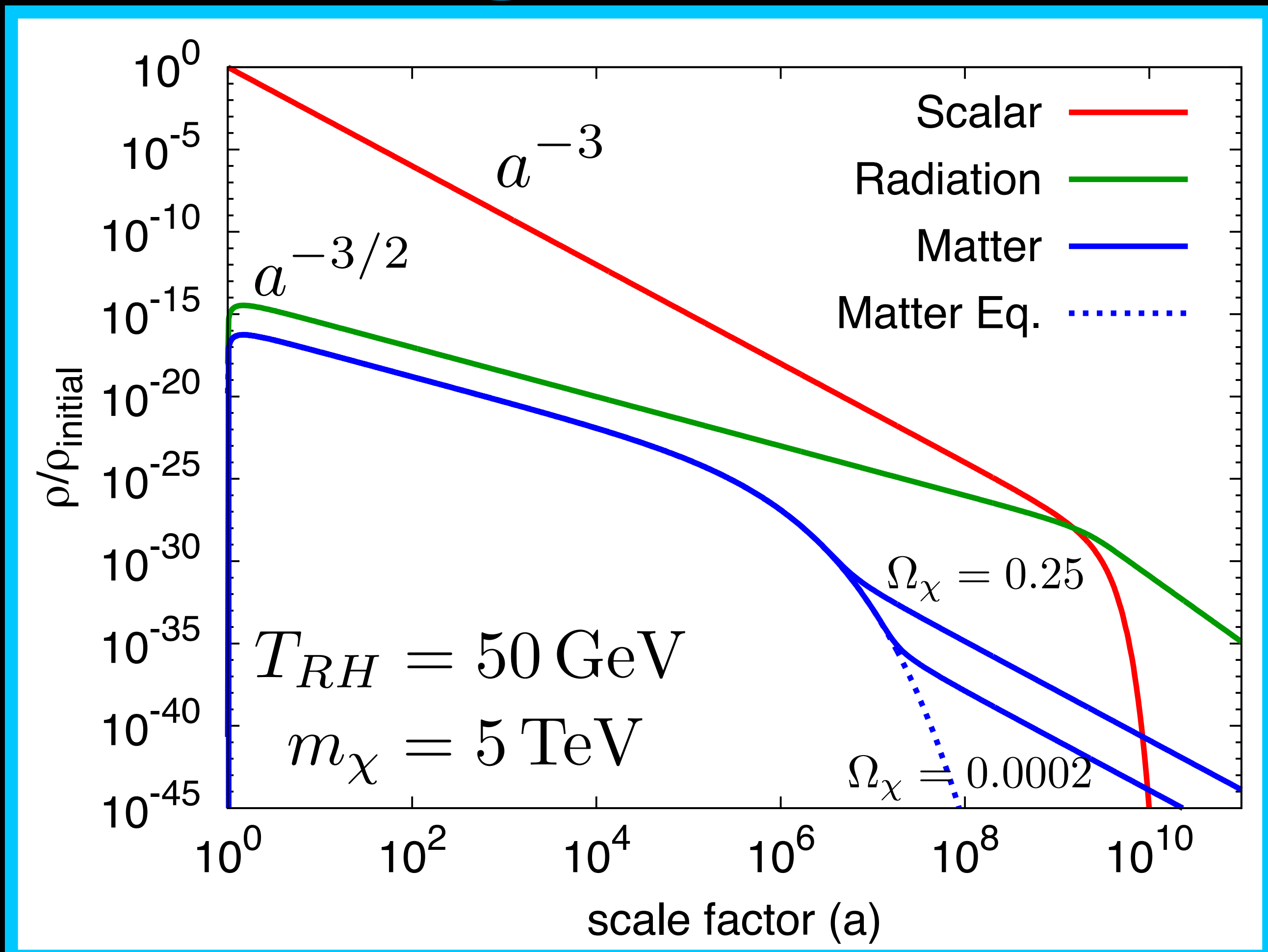

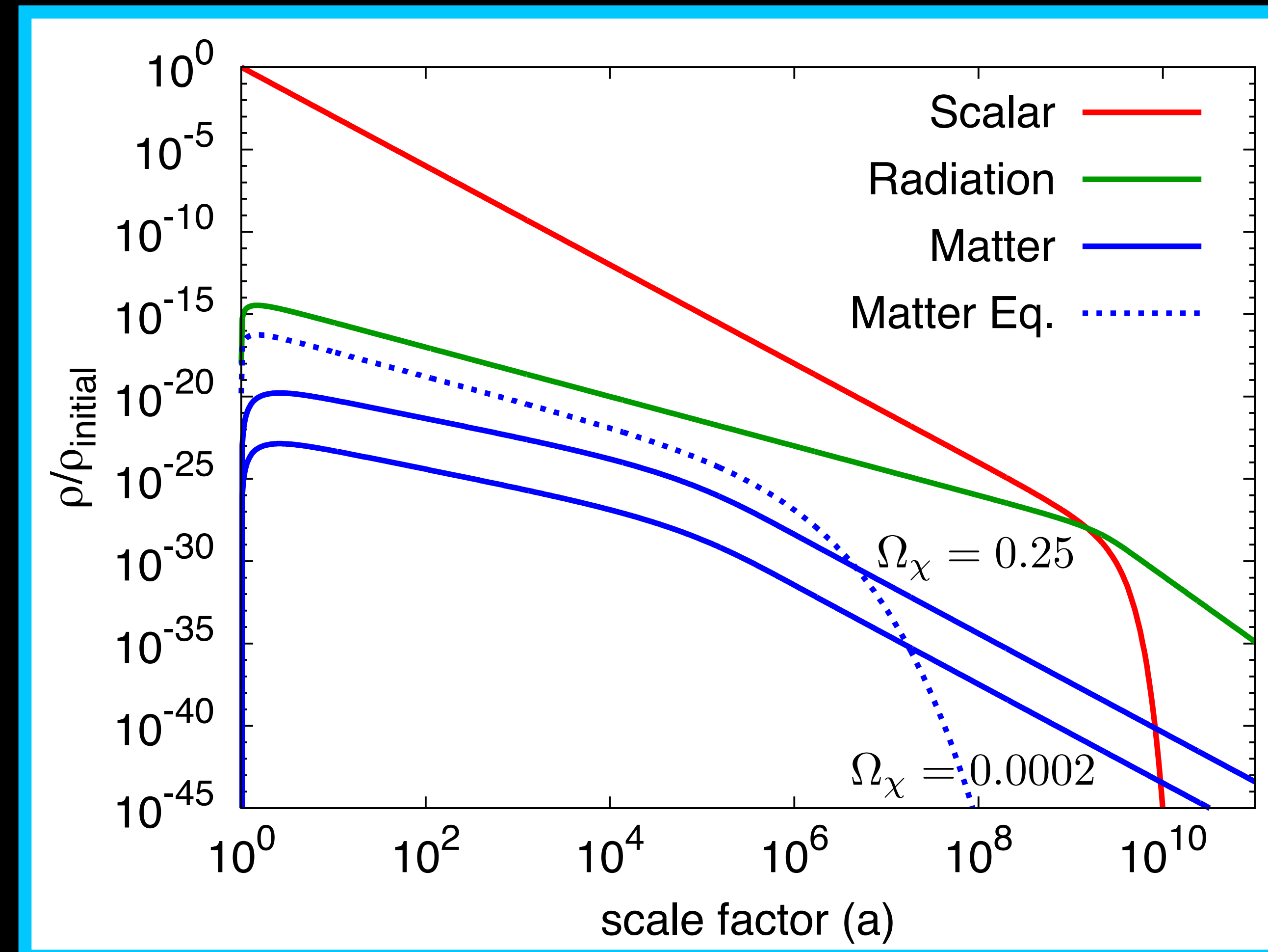

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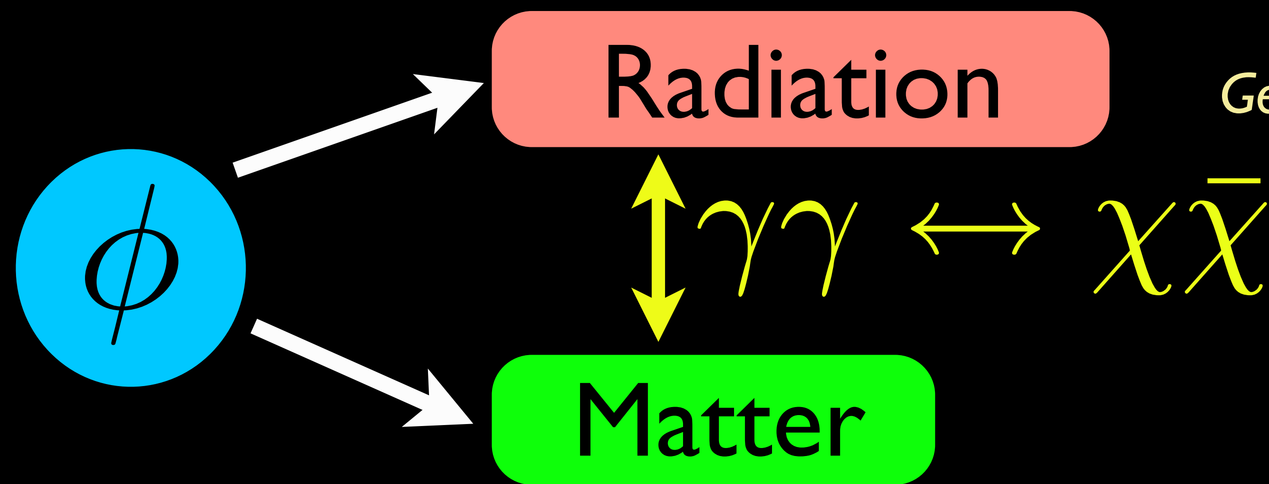
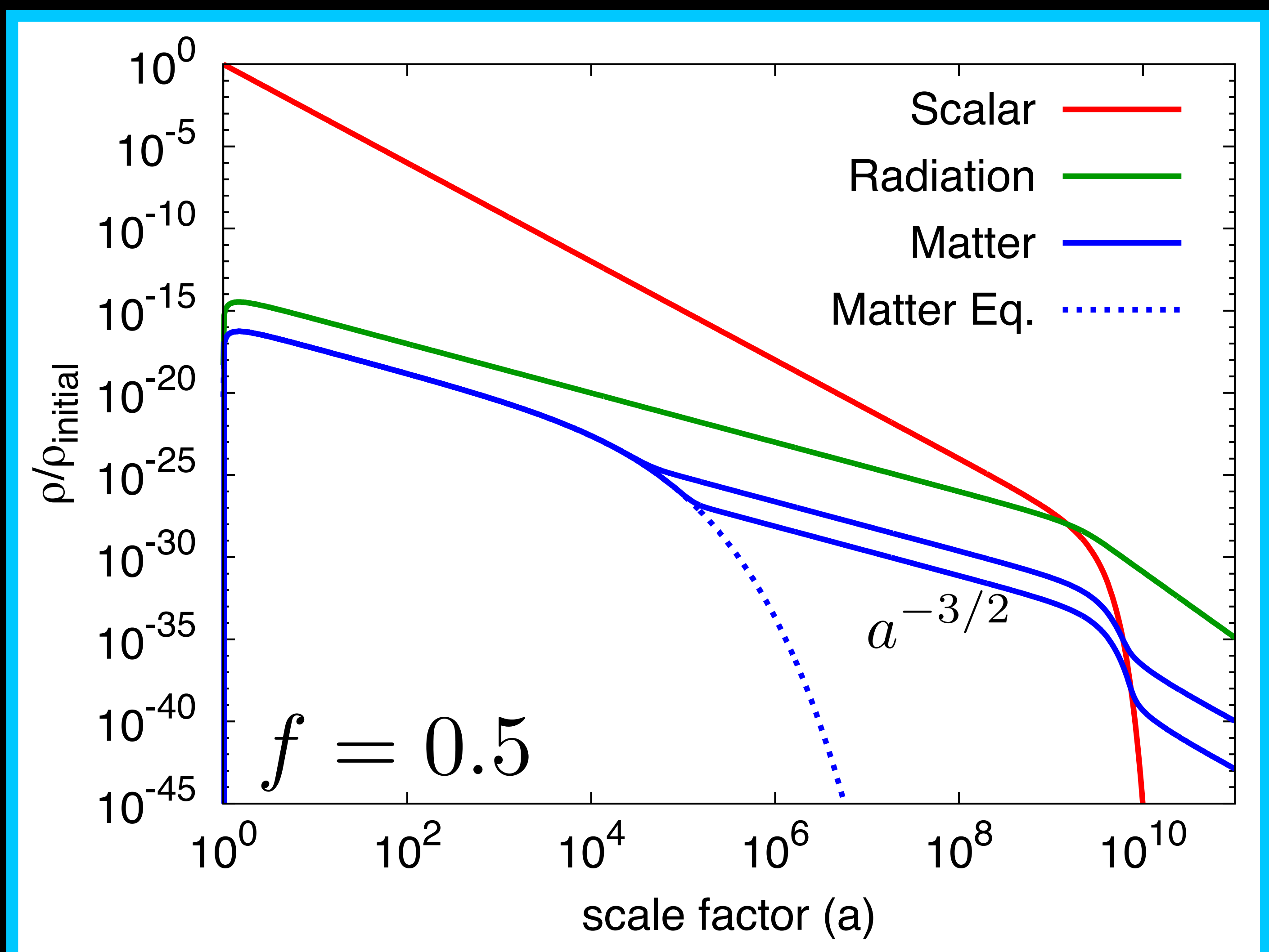
Freeze-in: $\Omega_\chi \propto \langle \sigma v \rangle$

$$\langle \sigma v \rangle_{0.25} = 9 \times 10^{-36} \mathrm{cm}^3/\mathrm{s}$$

DM Origin 3: Nonthermal with Annihilations

Gelmini, Gondolo 2006
Gelmini, Gondolo, Soldatenko, Yaguna 2006





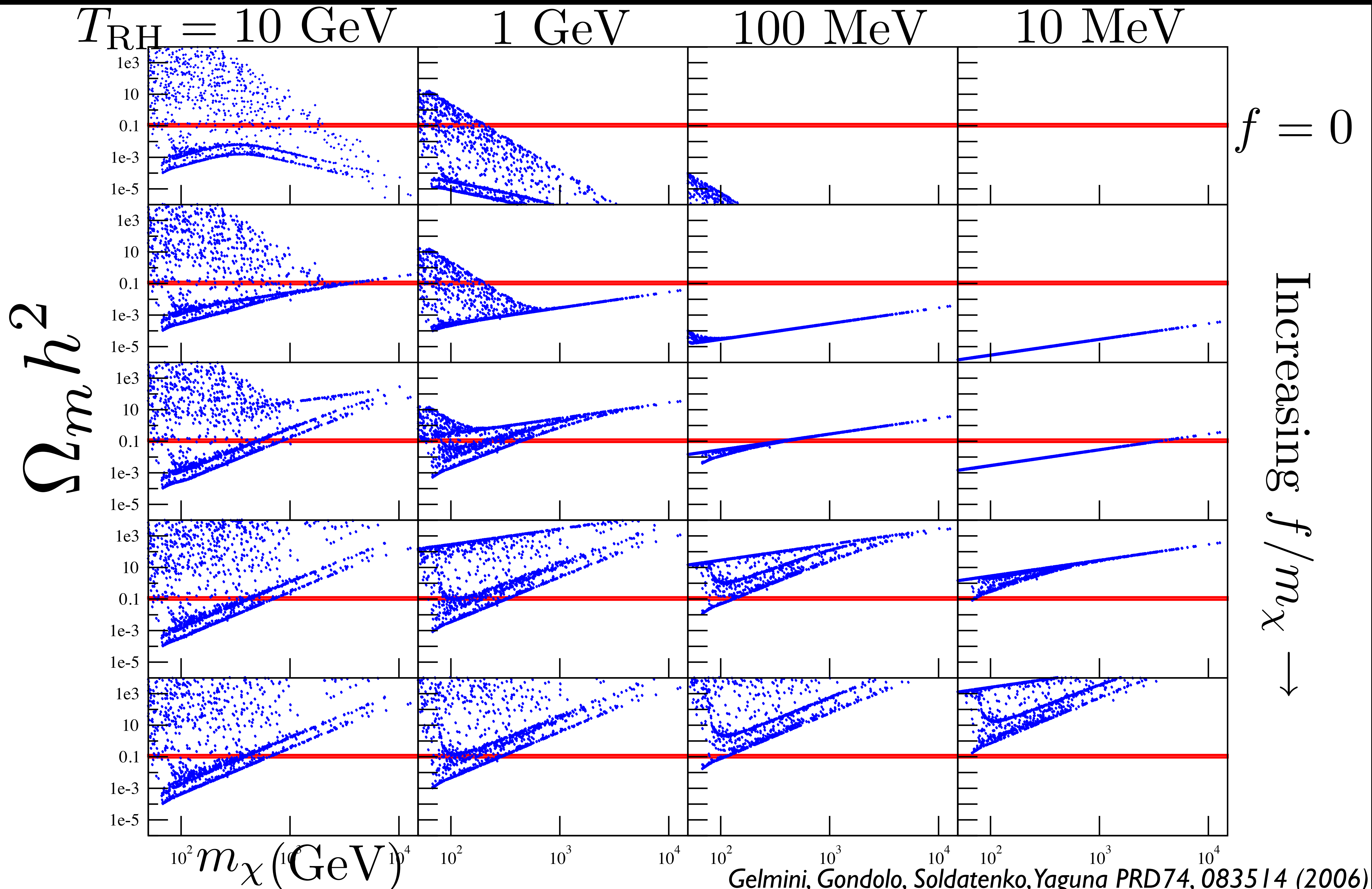
Branching ratio can be order unity: annihilations then destroy excess DM at reheating.

$$\text{Freeze-out: } \Omega_\chi \propto \frac{1}{\langle \sigma v \rangle}$$

This scenario requires a larger annihilation cross section:

$$\langle \sigma v \rangle_{0.25} \simeq \frac{m_\chi/20}{T_{\rm RH}} \times (3 \times 10^{-26} {\rm cm}^3/{\rm s})$$

From Miracle to Mess!



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

What about density perturbations?

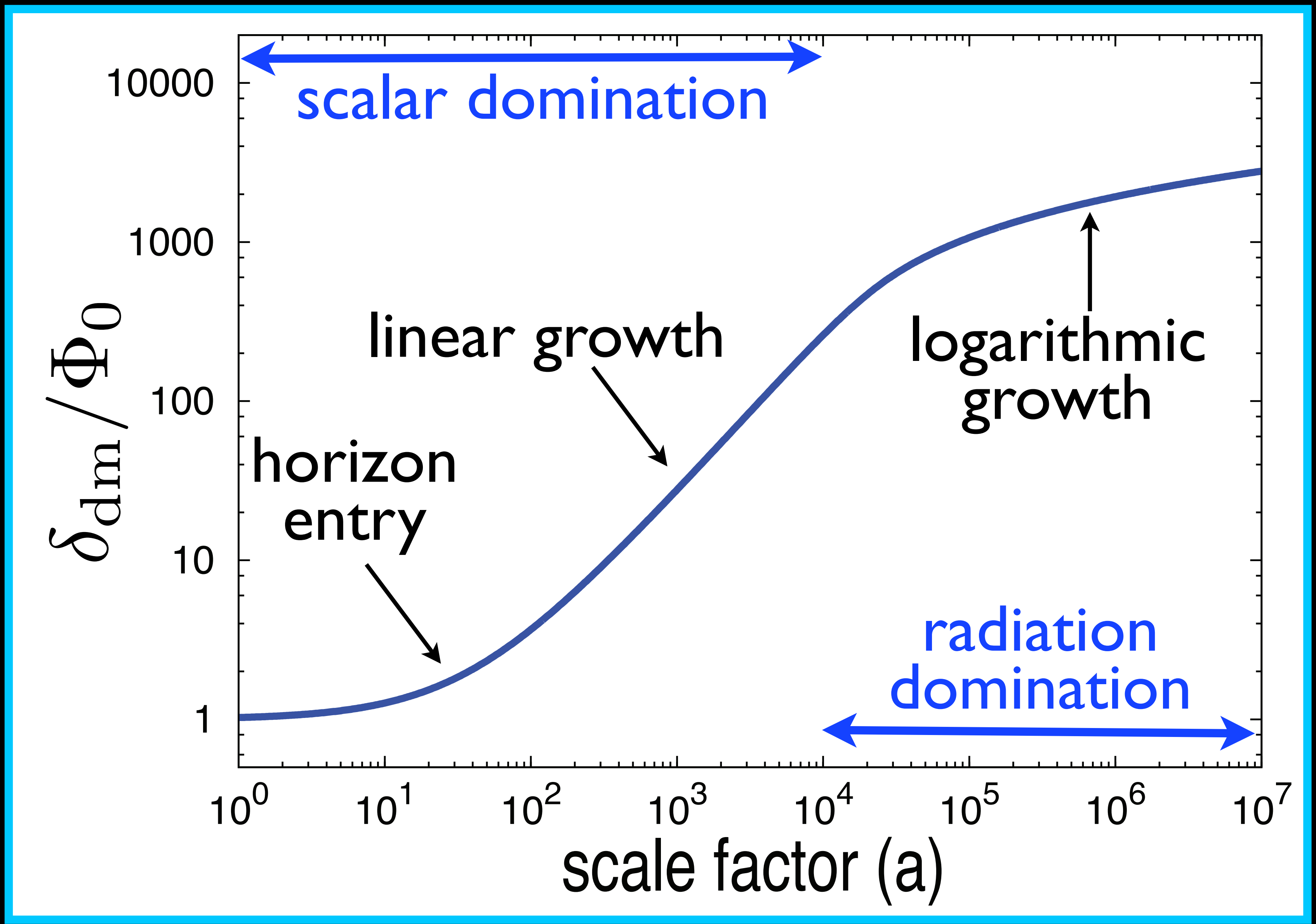
Nonthermal Dark Matter:
ALE & Sigurdson, Phys. Rev D 84, 083503 (2011)

Nonthermal Dark Matter with Annihilations:
Fan, Ozsoy, Watson, Phys. Rev. D 90, 043536 (2014)

Thermal Dark Matter:
ALE 1504.03335

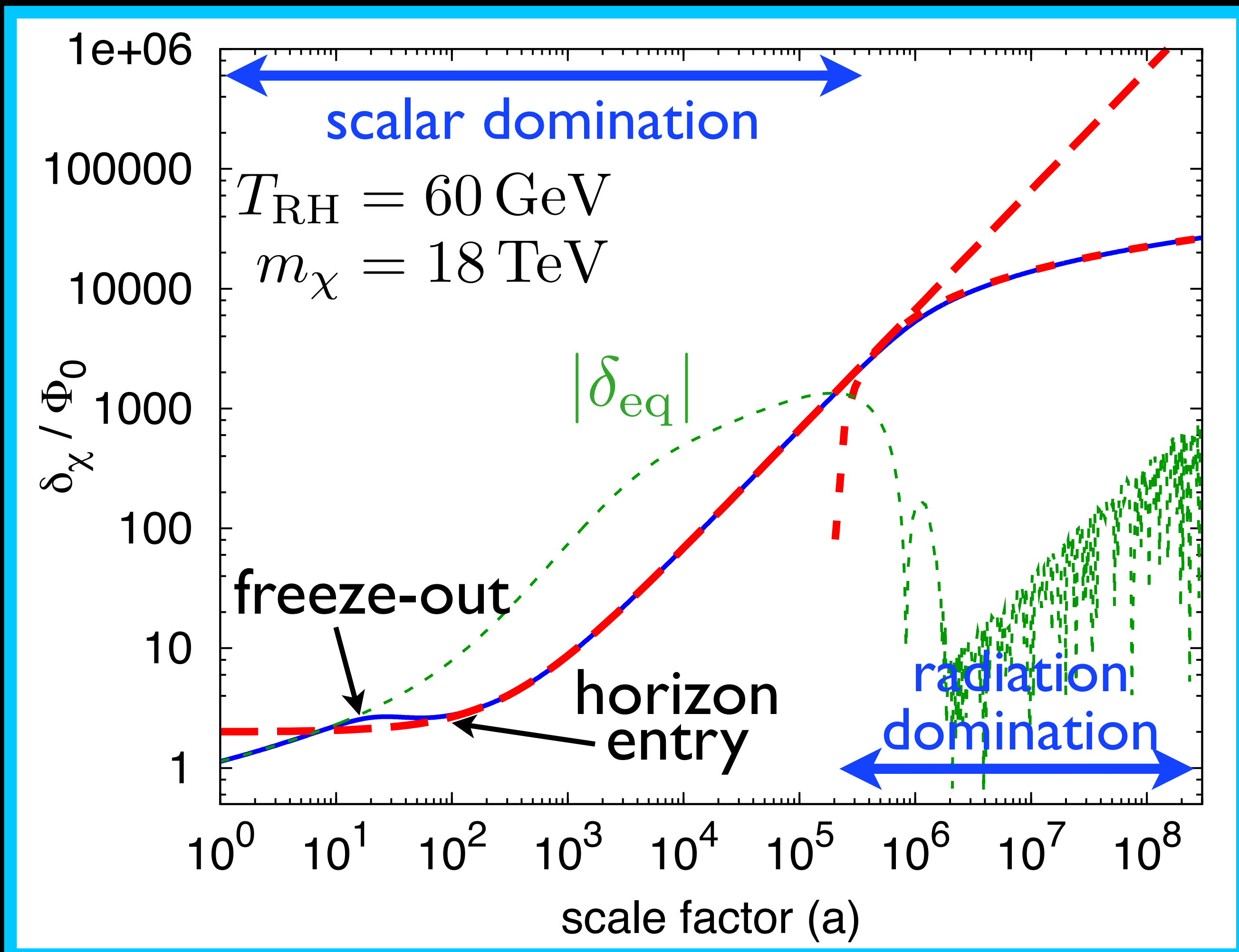
The Nonthermal Matter Perturbation

Evolution of the Matter Density Perturbation

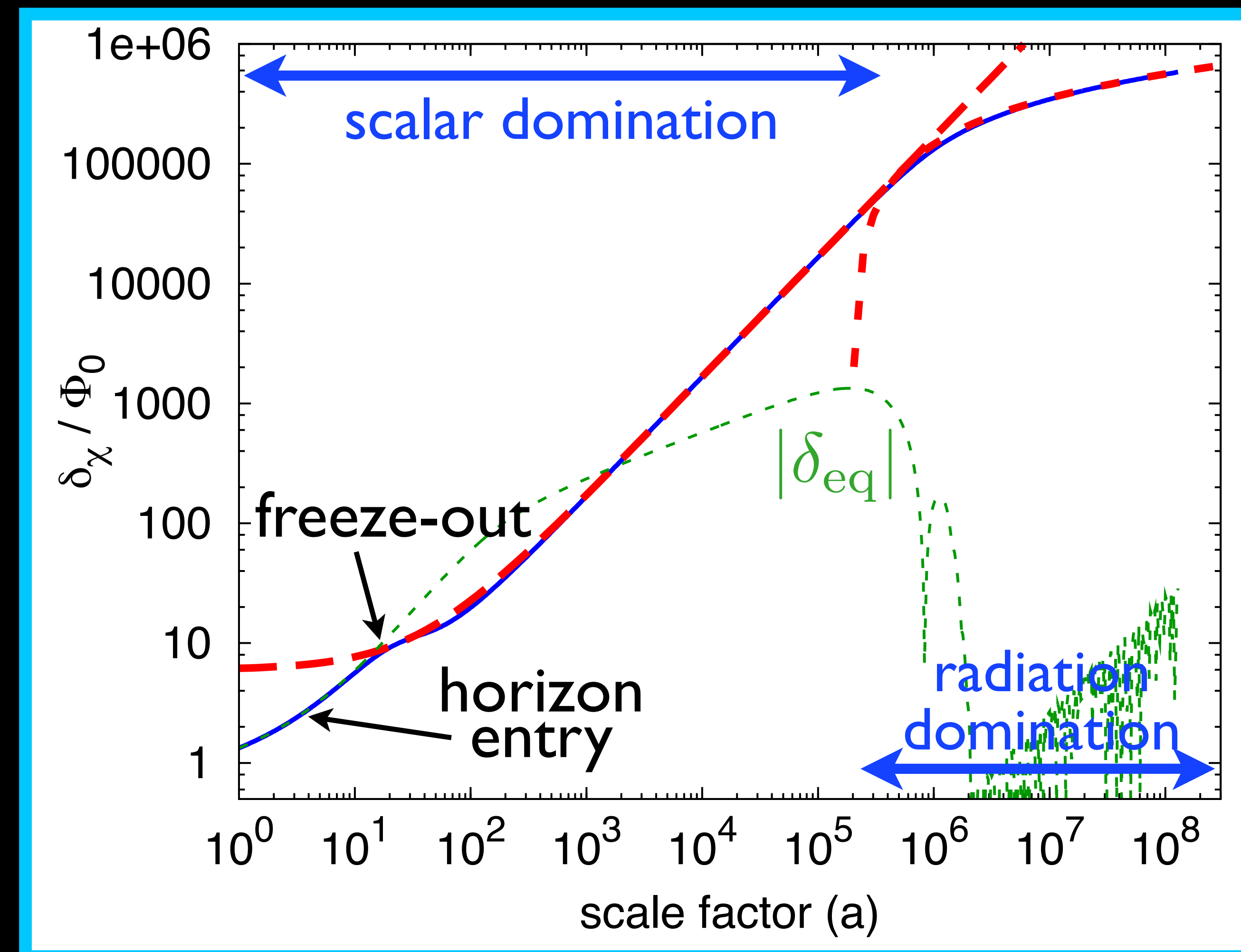


- dark matter produced in scalar decays
- the dark matter perturbation is sensitive only to the background expansion

The Thermal Matter Perturbation



$k/k_{\rm RH} = 74$



$k/k_{\rm RH} = 370$

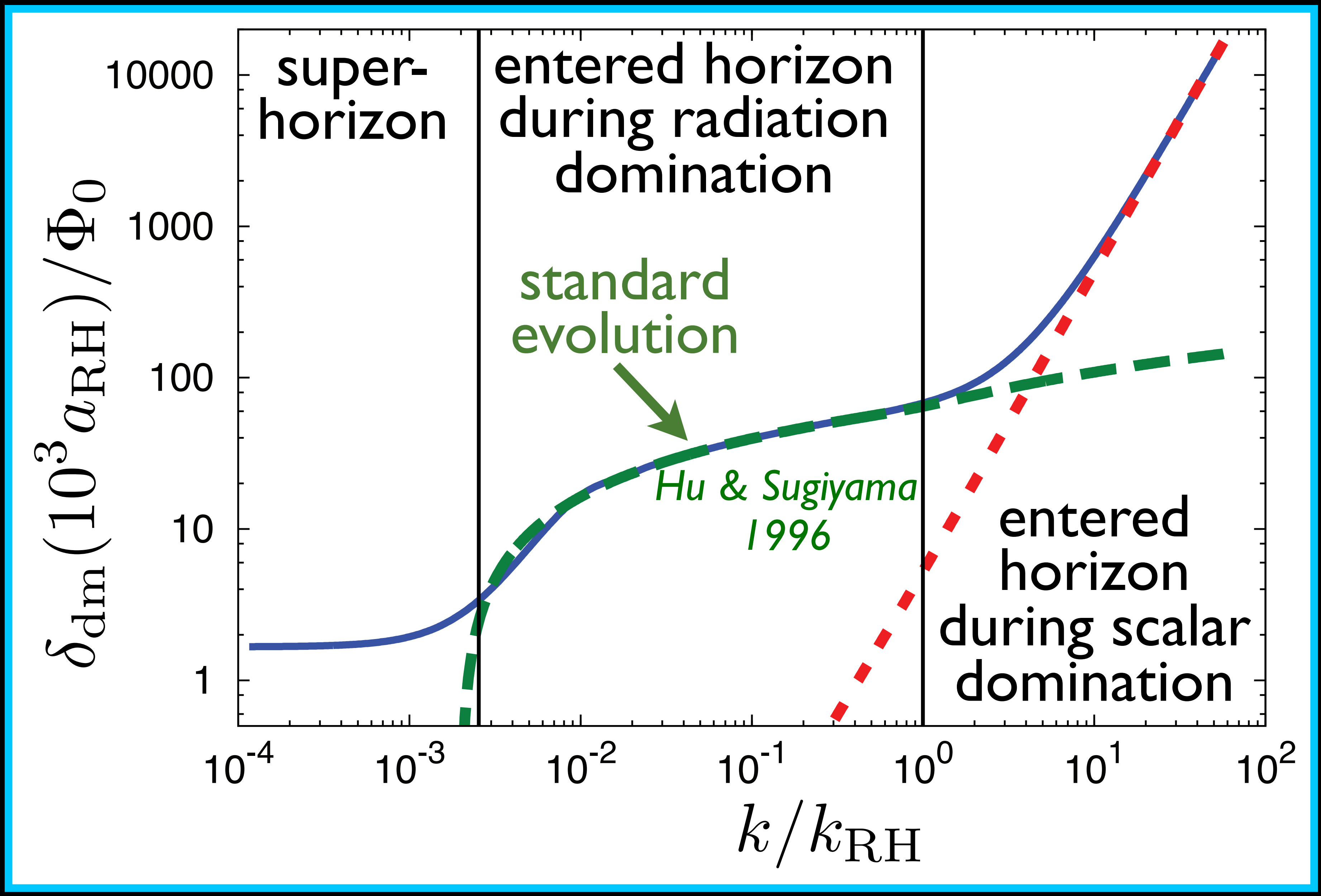
Before freeze-out: $\delta_\chi = \delta_{\rm eq} = \frac{1}{4}\left(\frac{3}{2} + \frac{m_\chi}{T}\right)\delta_\gamma$

After freeze-out and horizon entry: linear growth

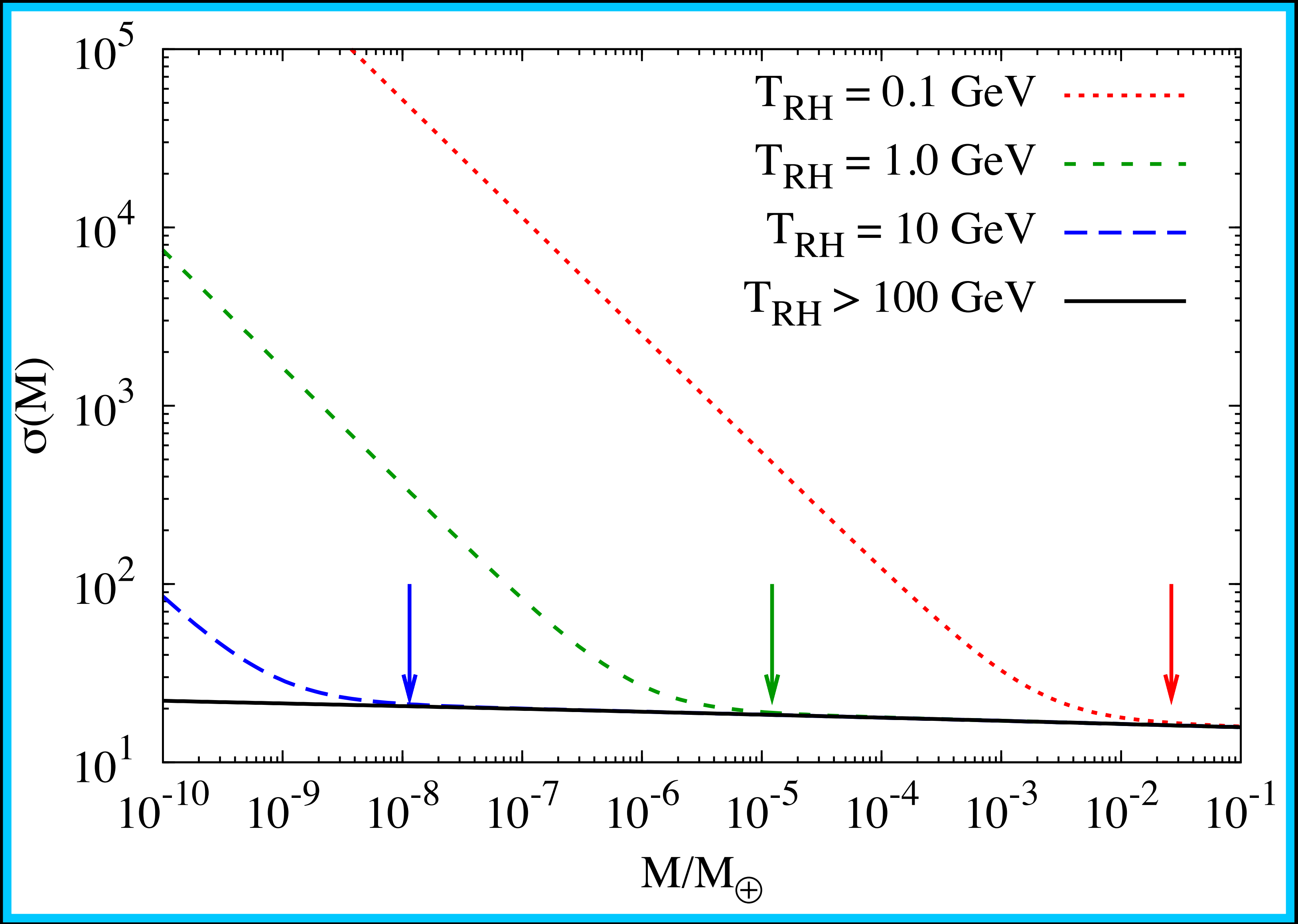
After reheating: logarithmic growth, same as nonthermal case

The Matter Perturbation

The Matter Density Perturbation during Radiation Domination



RMS Density Fluctuation



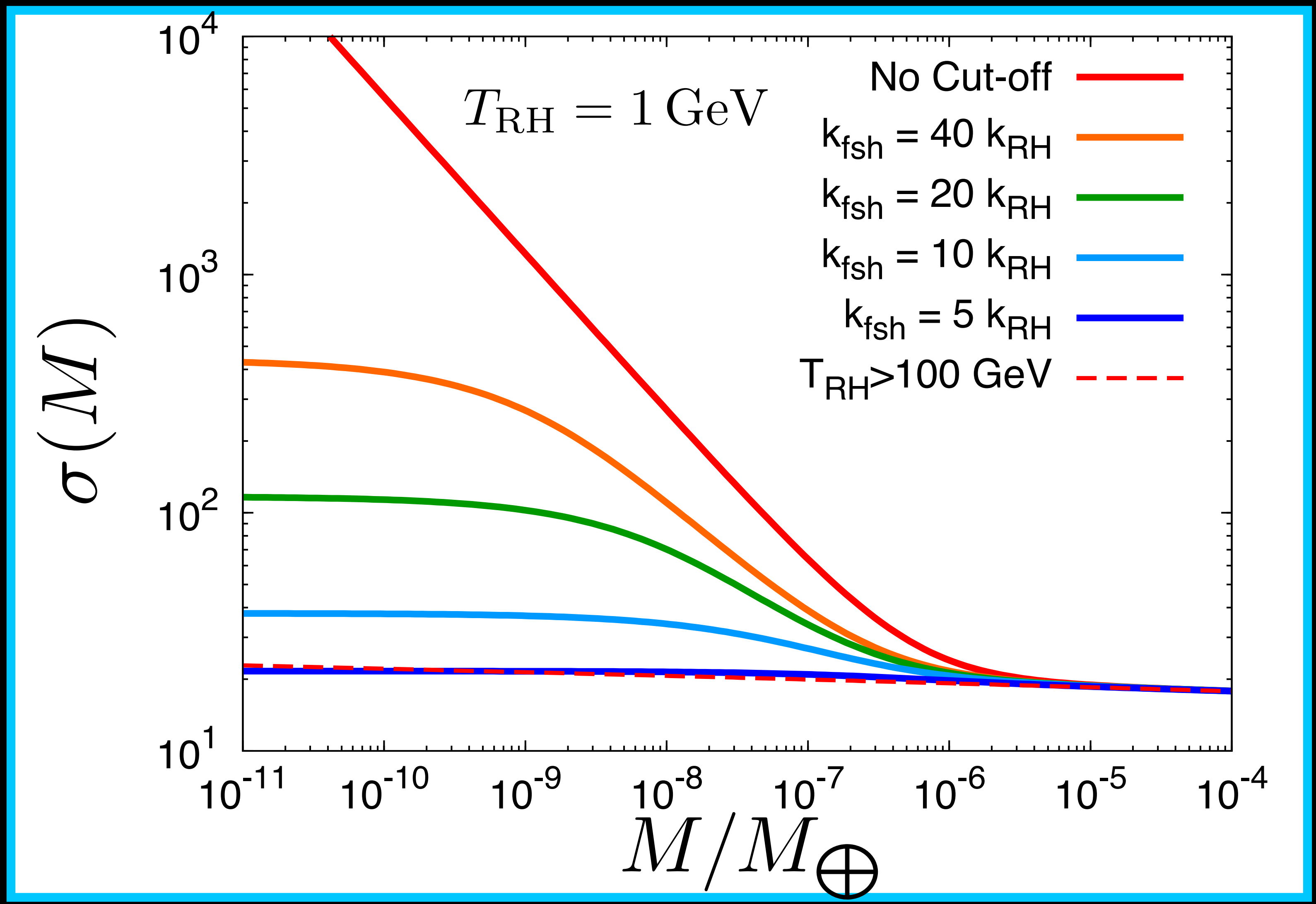
- Enhanced perturbation growth affects scales with $R \lesssim k_{\rm RH}^{-1}$
- Define $M_{\rm RH}$ to be mass within this comoving radius.

$$M_{\rm RH} \simeq 10^{-5}\, M_\oplus \left(\frac{1\,{\rm GeV}}{T_{\rm RH}}\right)^3$$

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

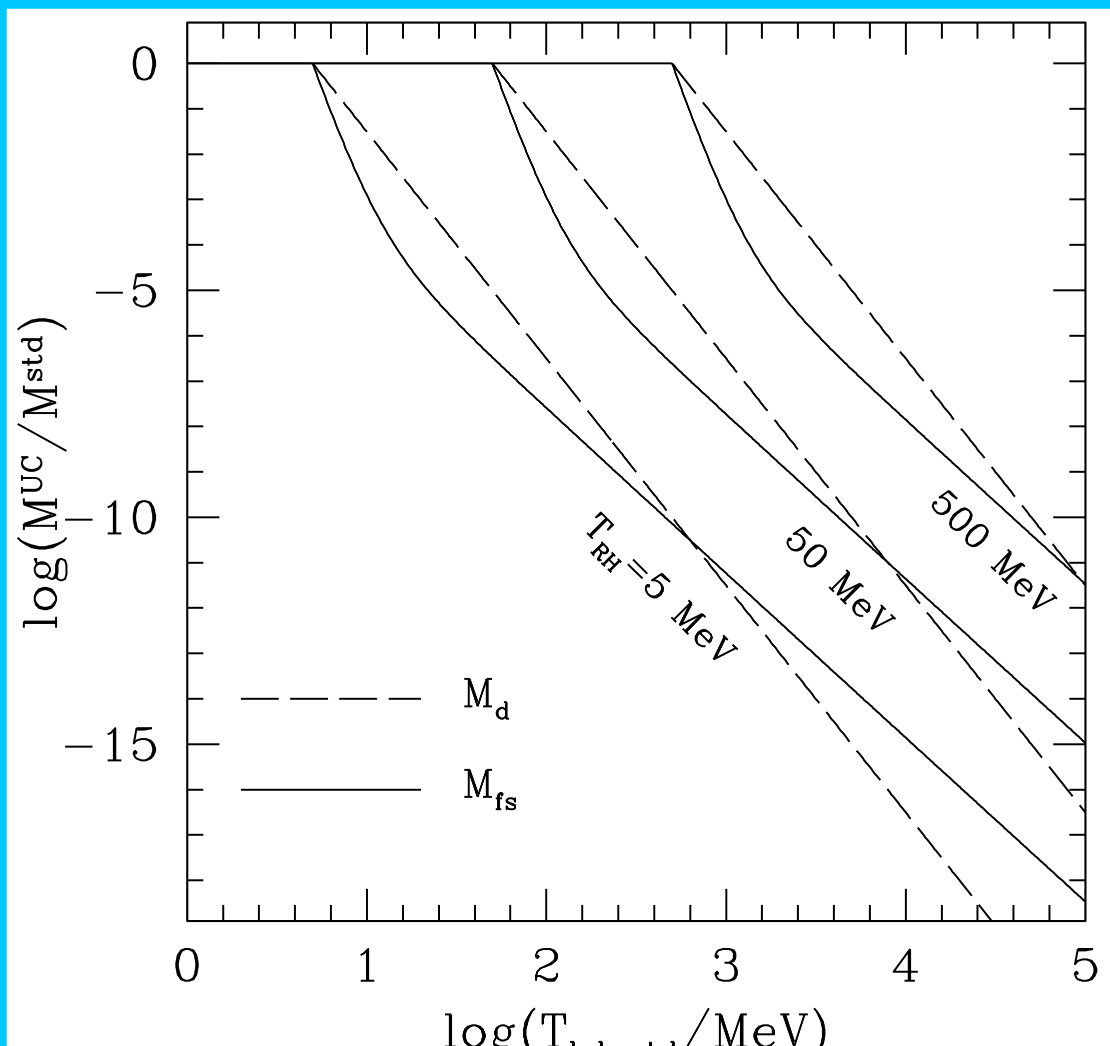


Structures grown during reheating only survive if $k_{\rm fsh}/k_{\rm RH} > 10$

Decoupling Prior to Reheating

Thermal dark matter is coupled to radiation, so we also have to worry about the power cut-off due to kinetic decoupling.

If dark matter kinetically decouples prior to reheating, then the minimum halo mass is dramatically reduced. *Gelmini & Gondolo 2008*



Gelmini & Gondolo 0803.2349

- decoupling happens at a higher temperature:

$$T_{\rm kd} = T_{\rm kdS}\left(\frac{T_{\rm kdS}}{T_{\rm RH}}\right)$$

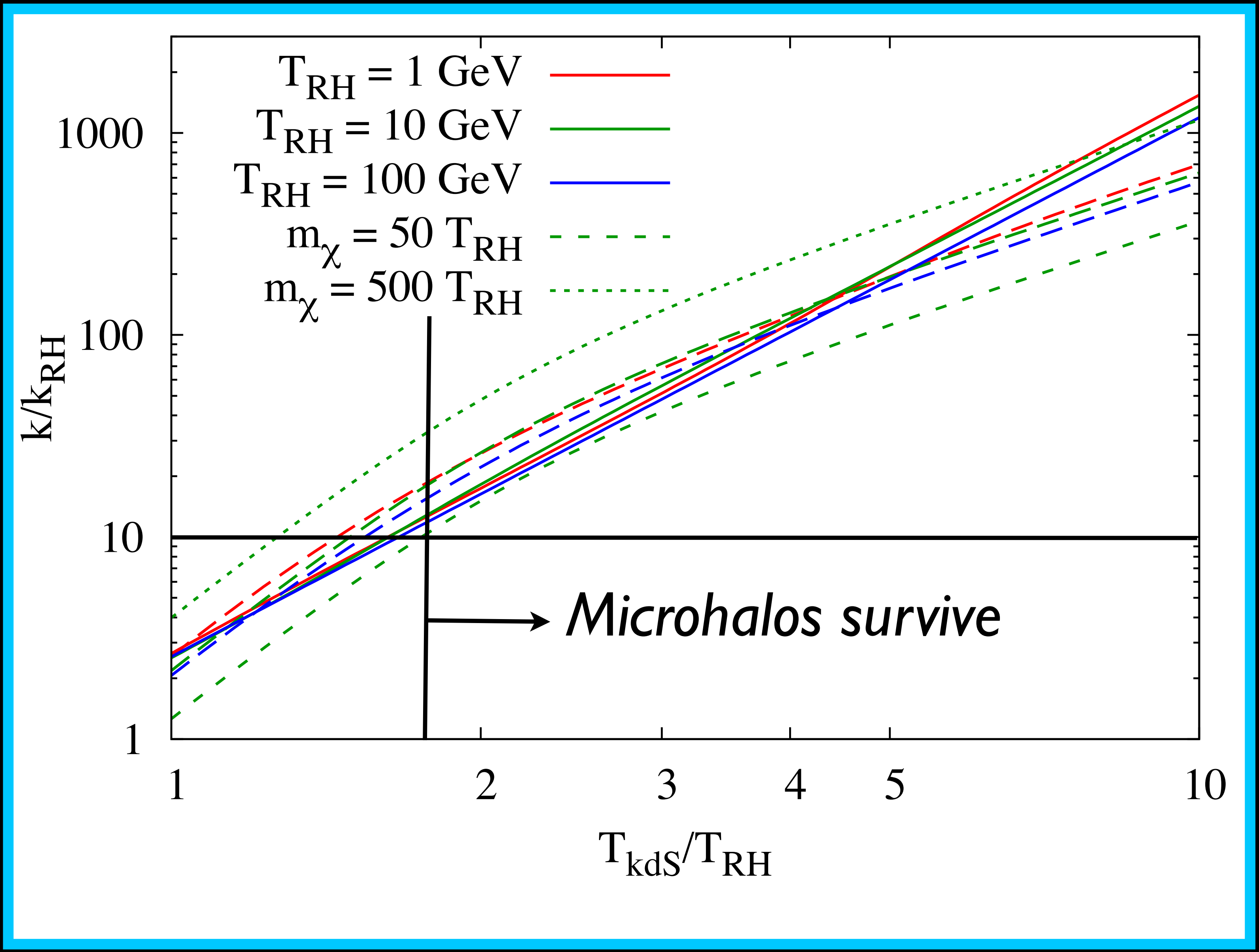
- velocities redshift away faster

$$v \propto a^{-1} \propto T^{8/3}$$

- horizon scales as $k \propto T^{4/3}$

Thermal Decoupling & Free-Streaming

Perturbations grown during reheating only survive if



$$k_{\rm cut}/k_{\rm RH} > 10$$

Thermal Decoupling & Free-Streaming

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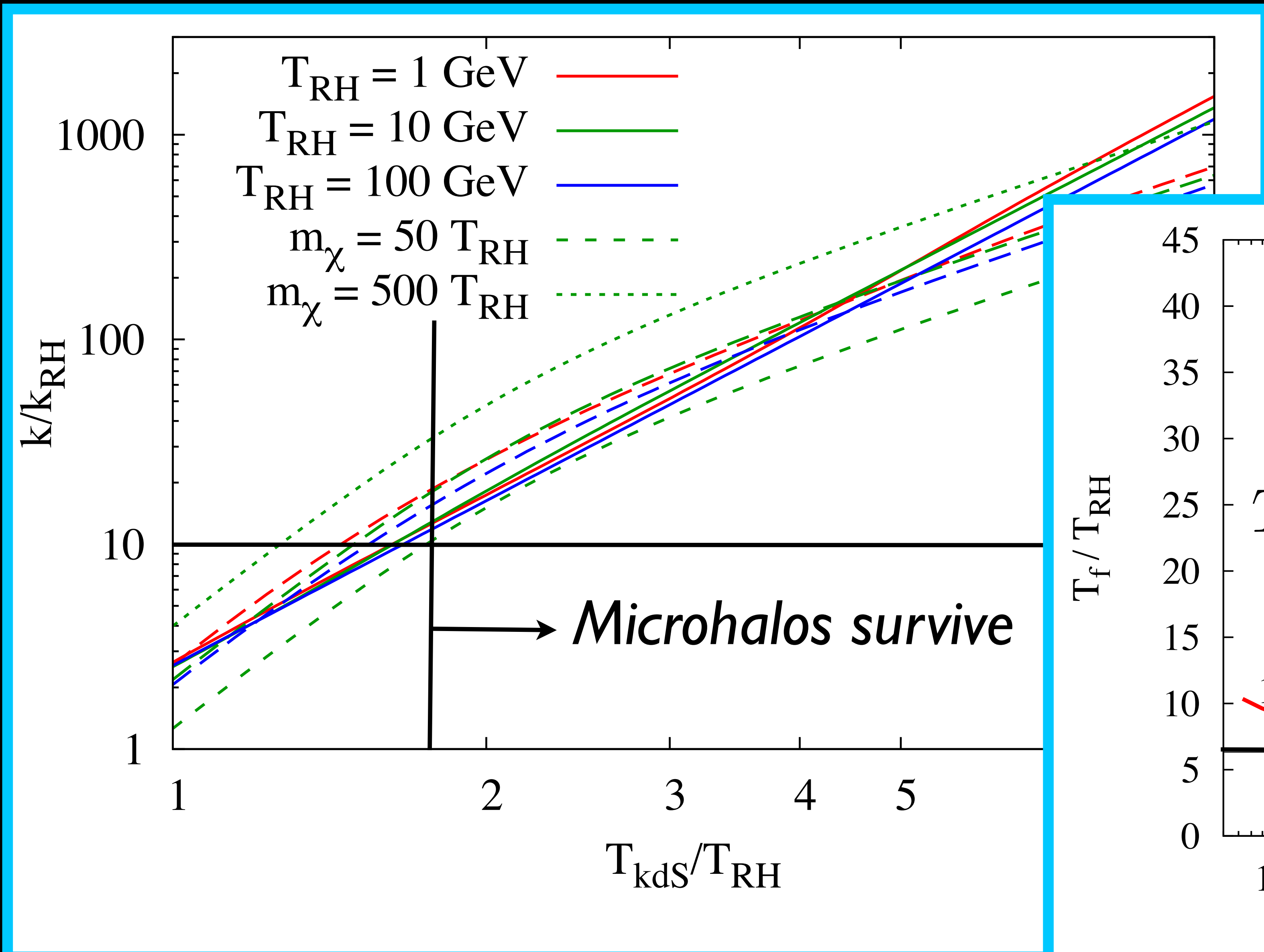

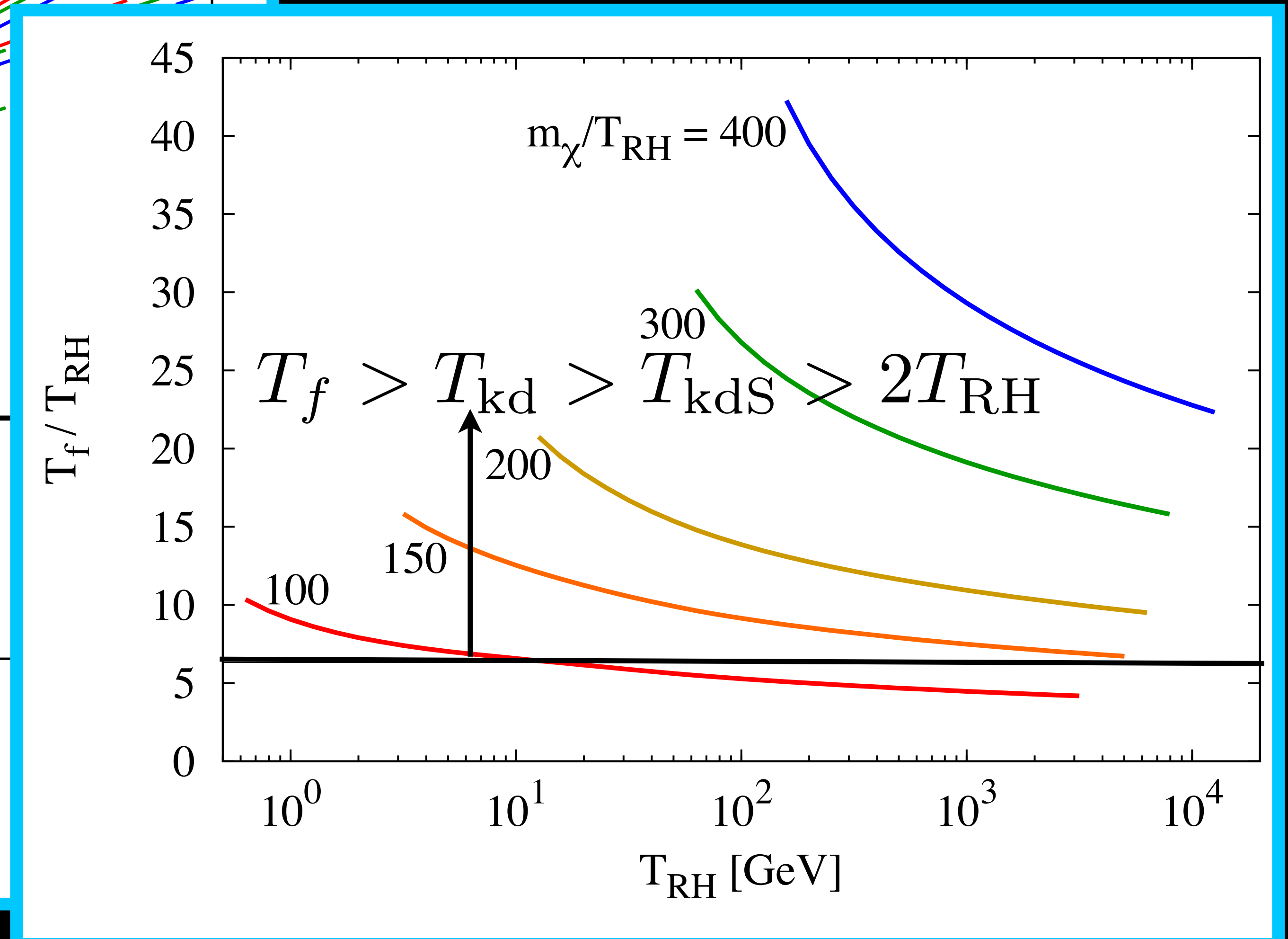

Demanding that DM freezes out before kinetically decoupling restricts the reheat temperature and the DM particle mass.

From Perturbations to Microhalos

To estimate the abundance of halos, we use 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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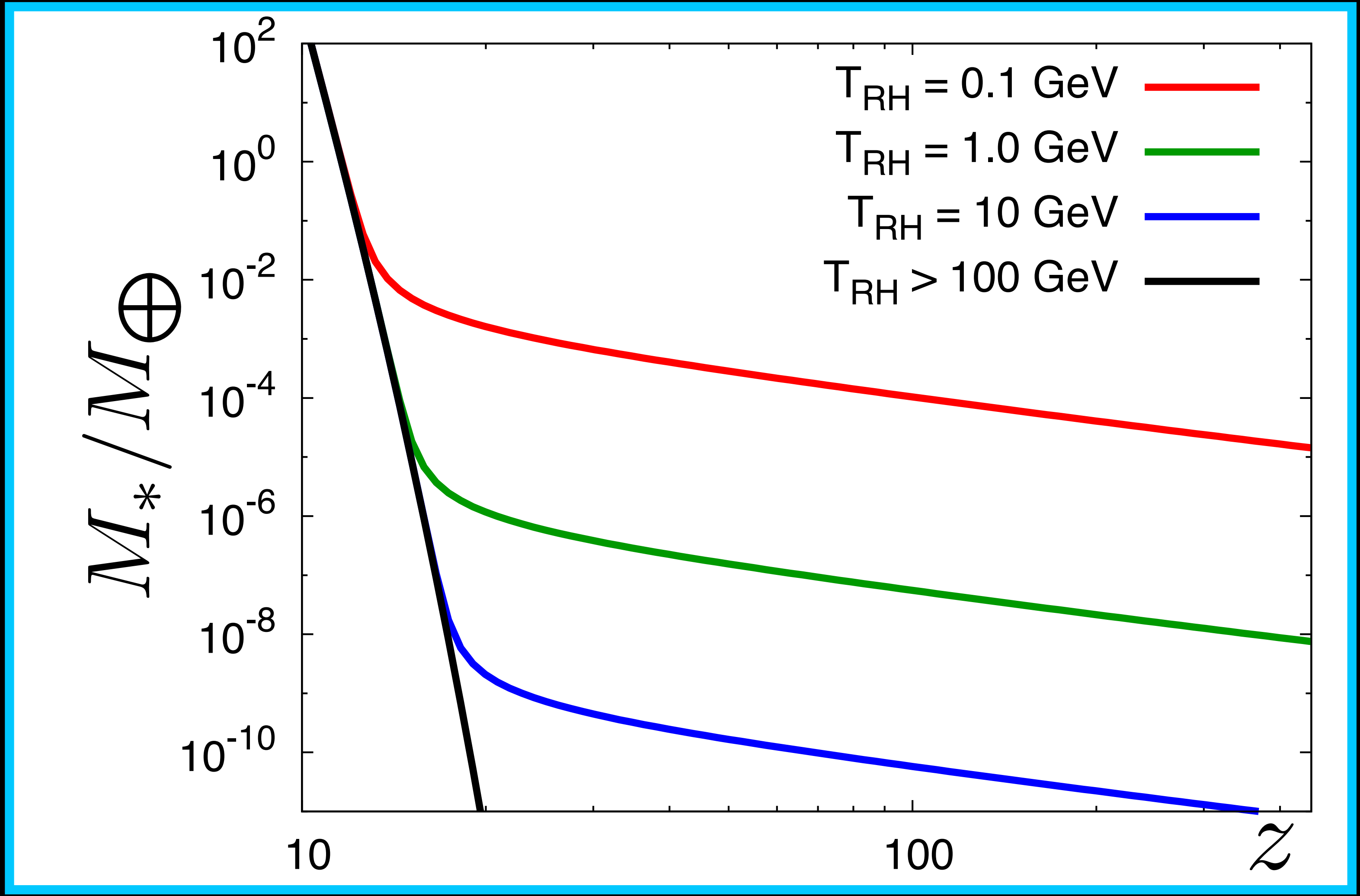
differential bound fraction

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

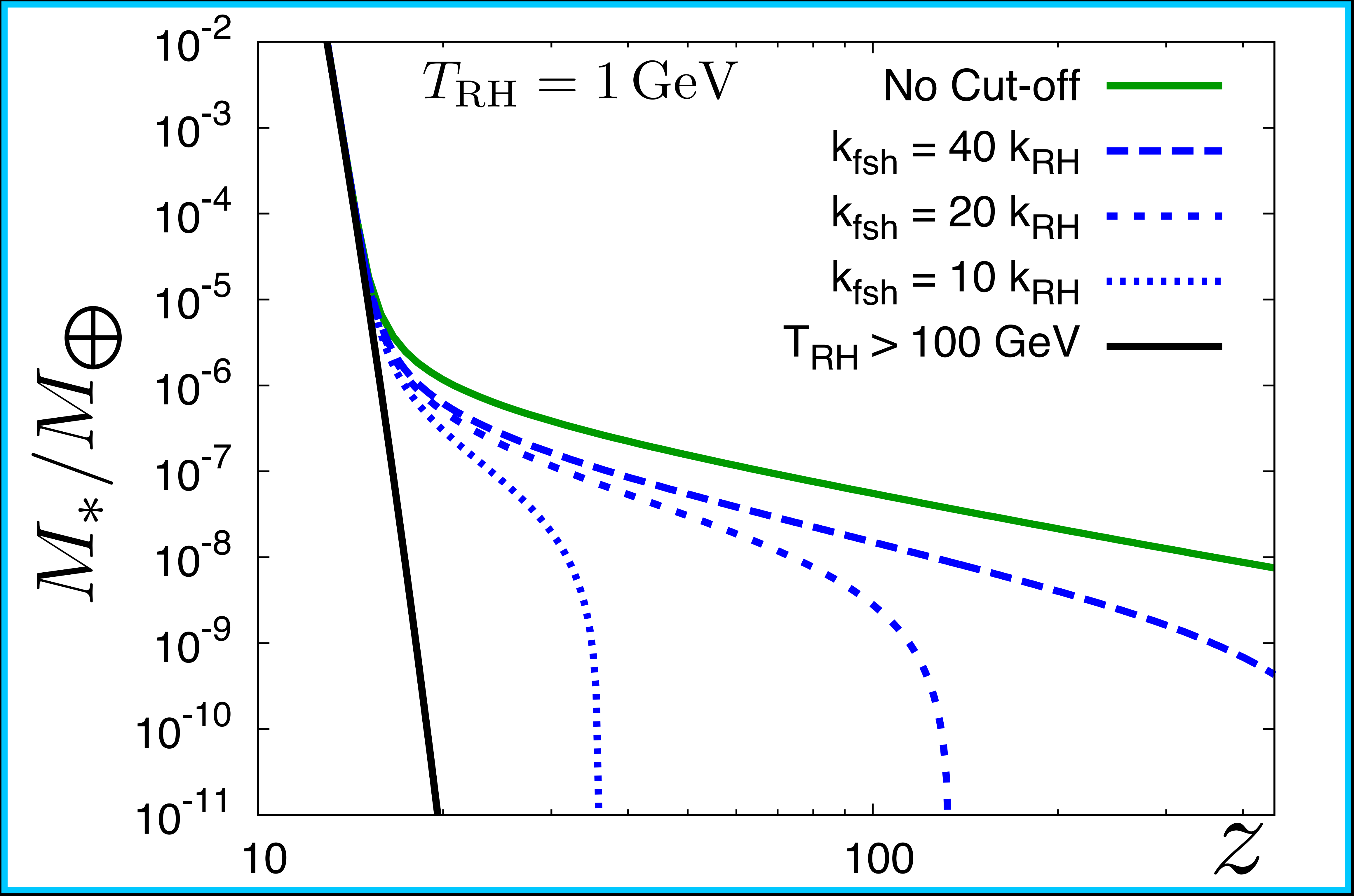
- Halos with $\sigma(M,z) < \delta_c$ are rare.
- Define $M_*(z)$ by

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

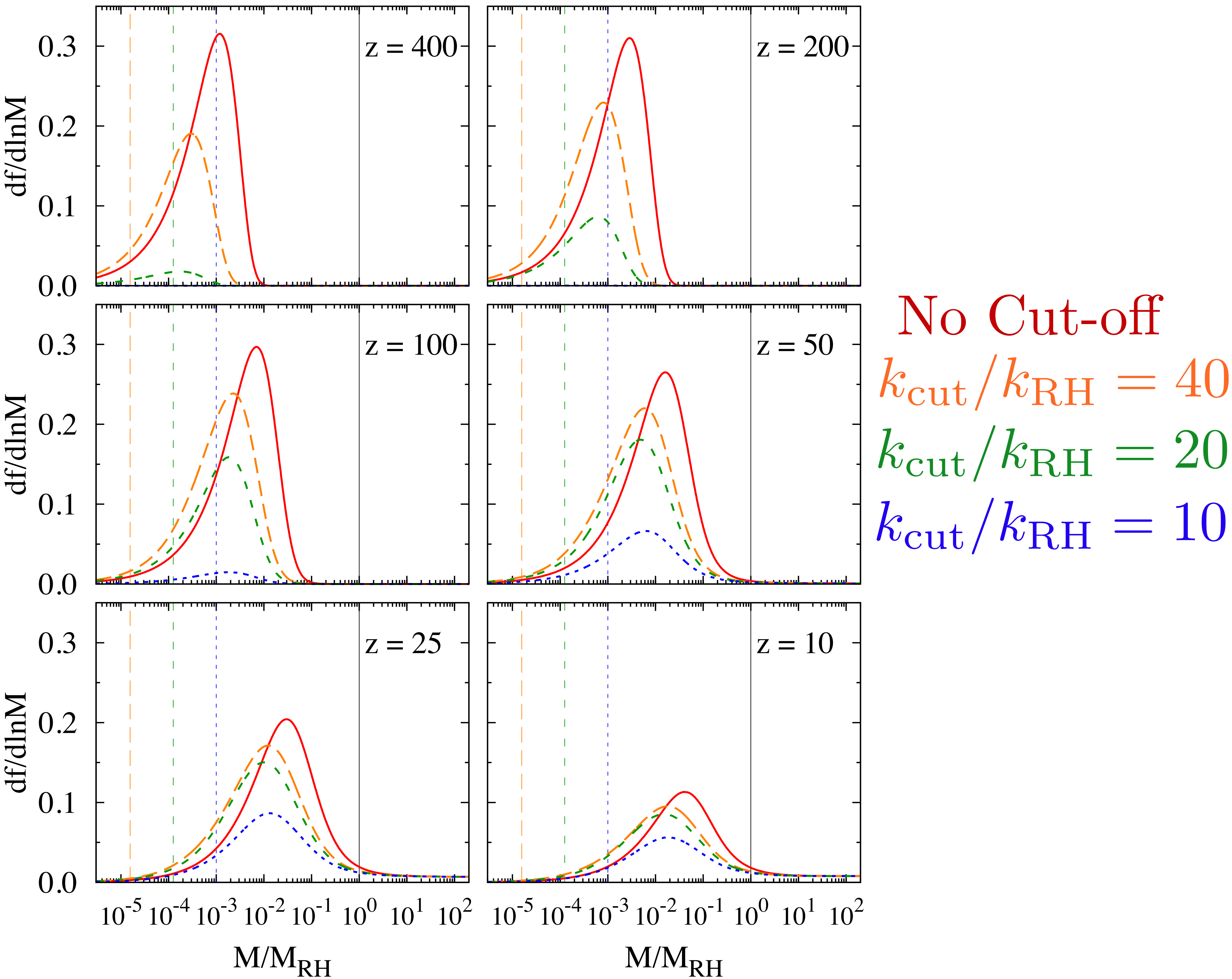


M_* Properties

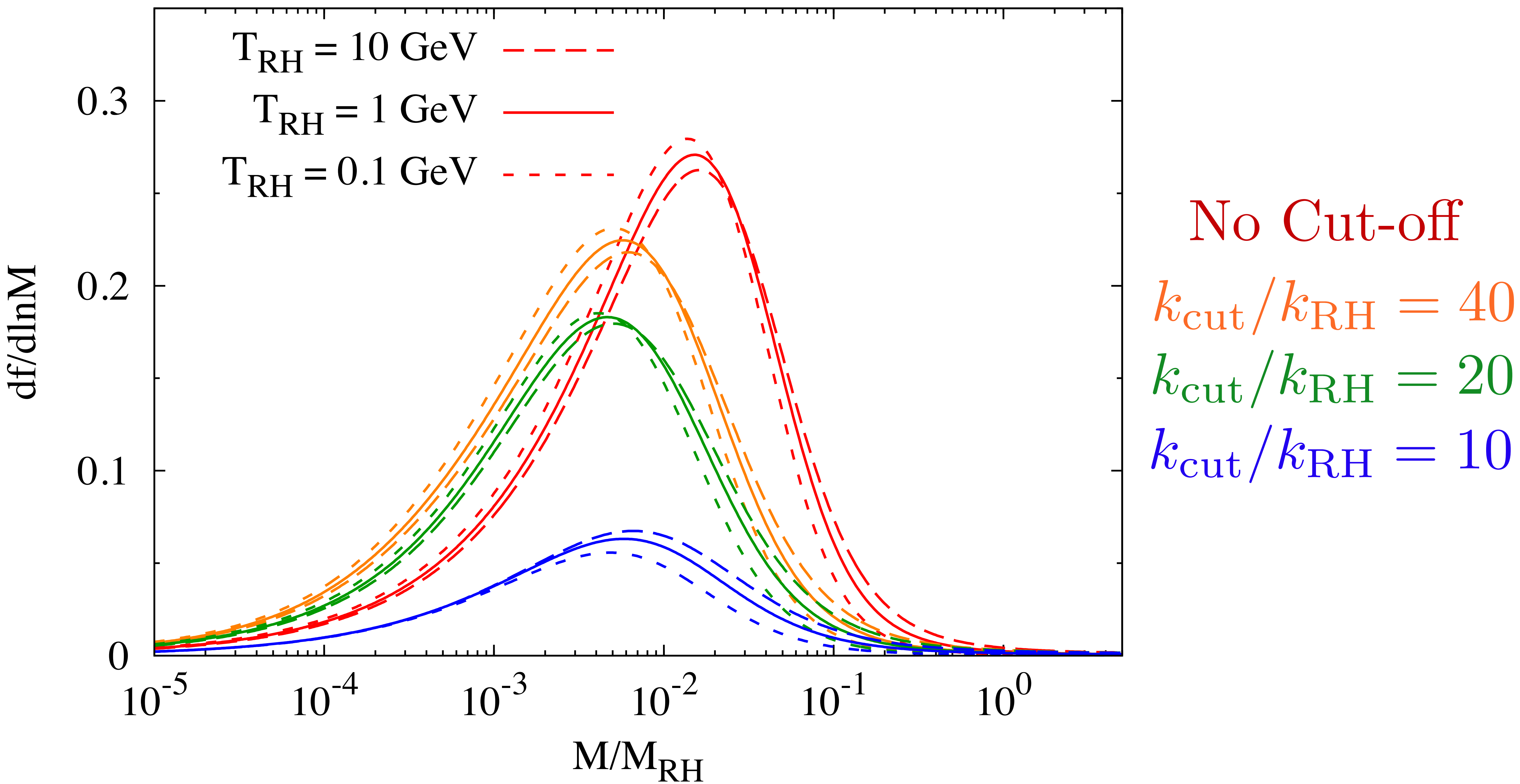
$M_*(z)$ is the largest halo that is common at a given redshift.



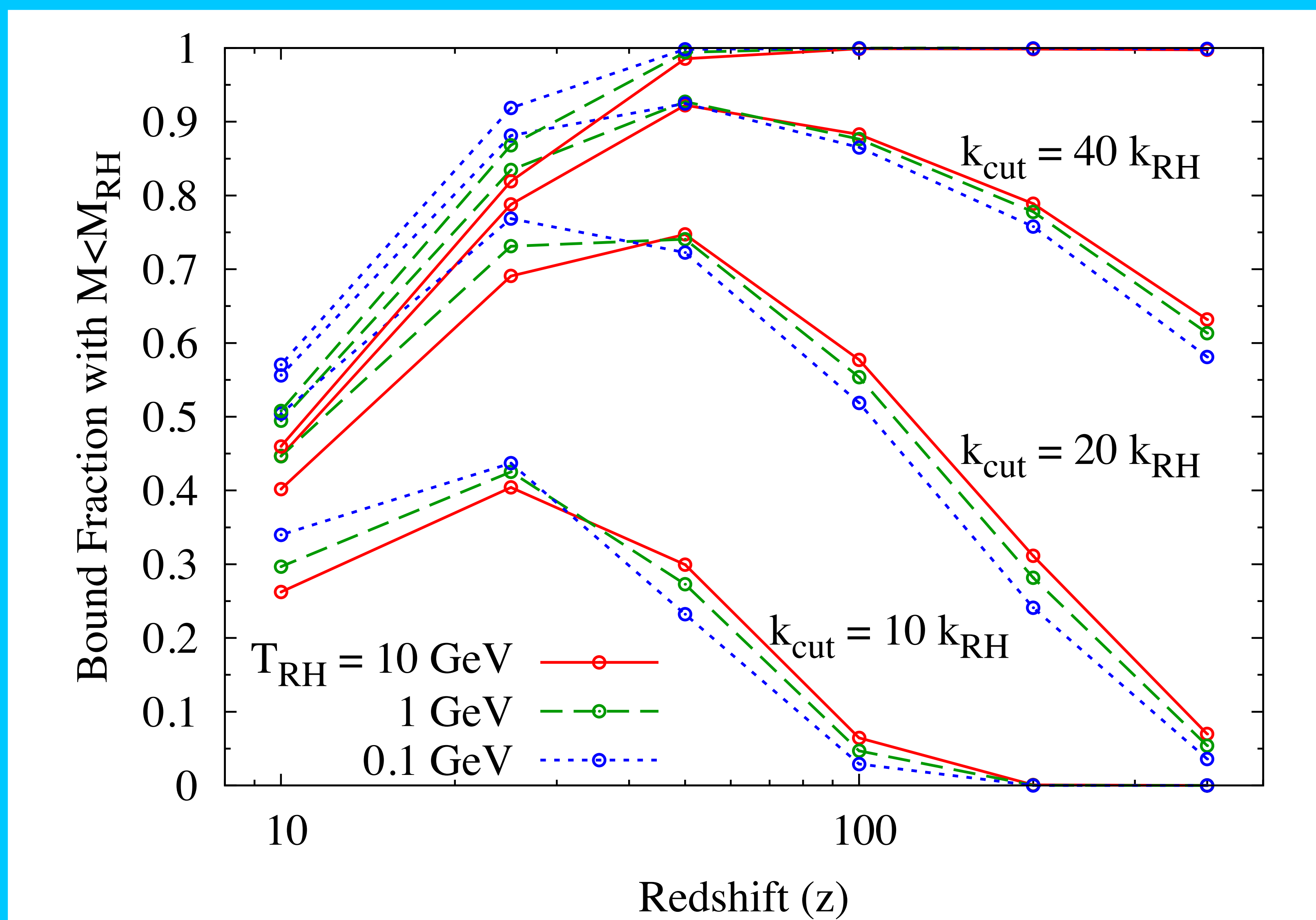
The Evolution of the Bound Fraction



Independent of Reheat Temperature



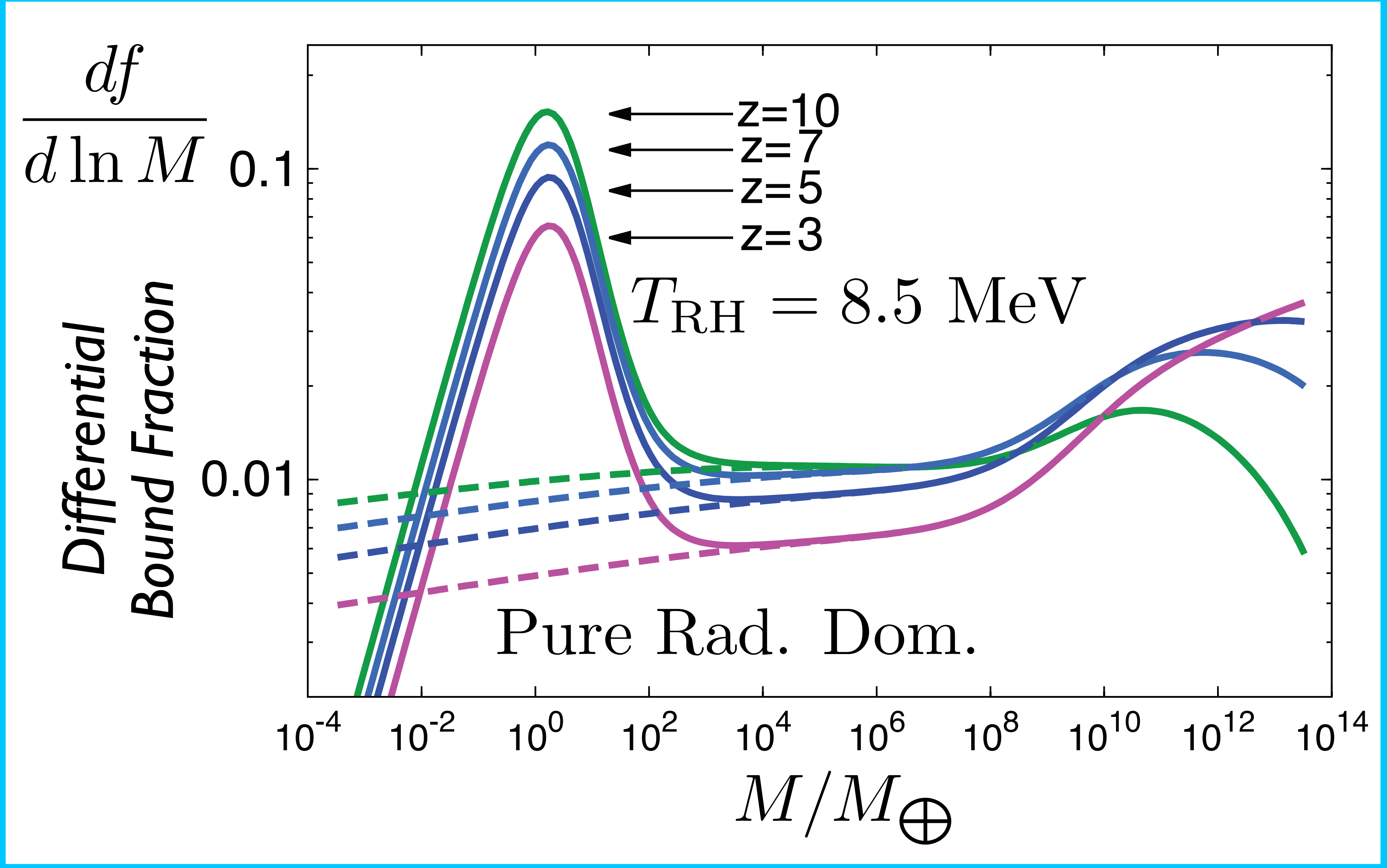
The Total Bound Fraction



z	400	100	50
$k_{fsh} = 40k_{RH}$	0.6	0.9	0.9
$k_{fsh} = 10k_{RH}$	10^{-9}	0.05	0.3
Std.	0	10^{-4}	0.04

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.



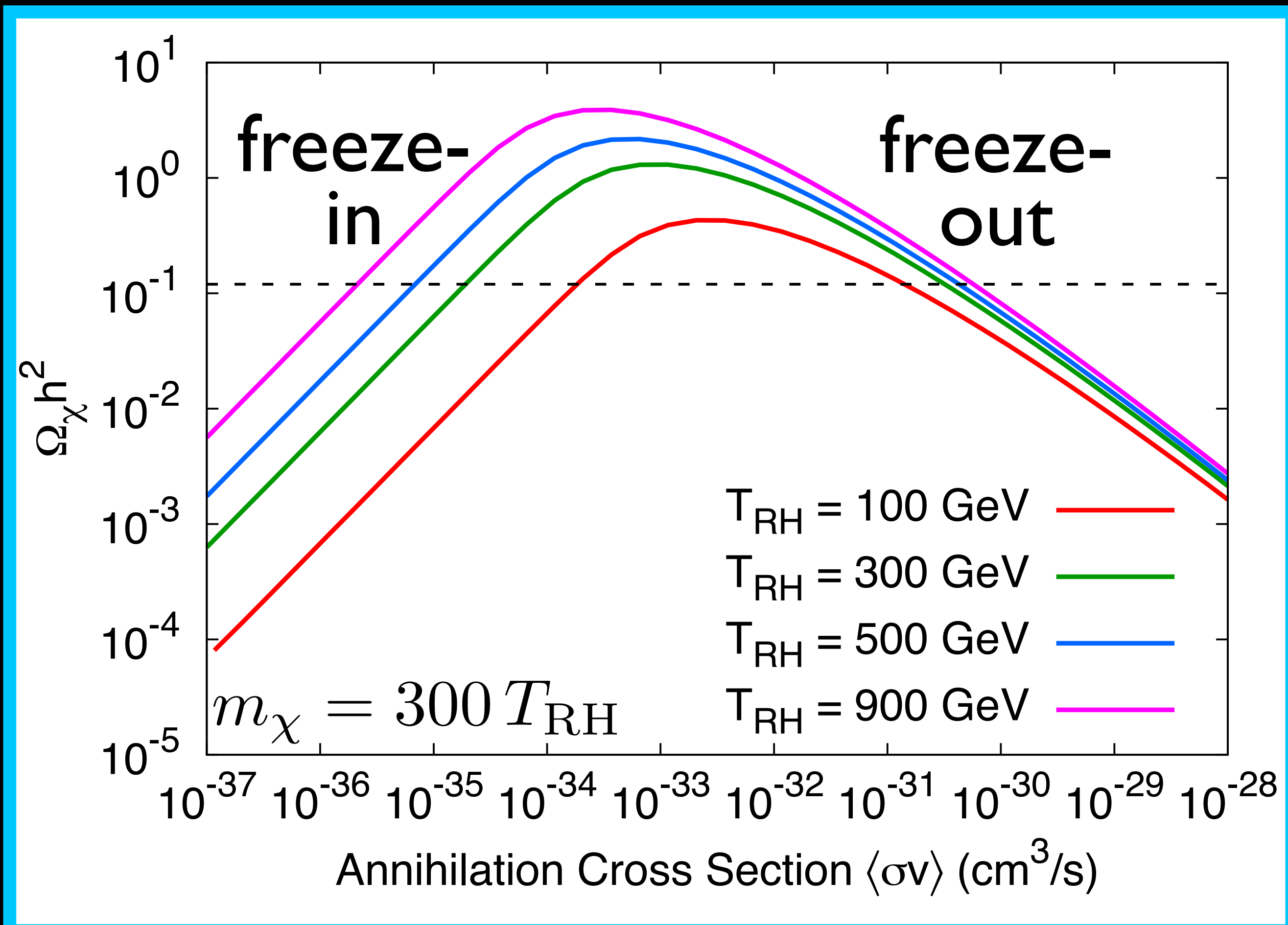
Since these microhalos formed at high redshift, they are far denser than standard microhalos and are more likely to survive.

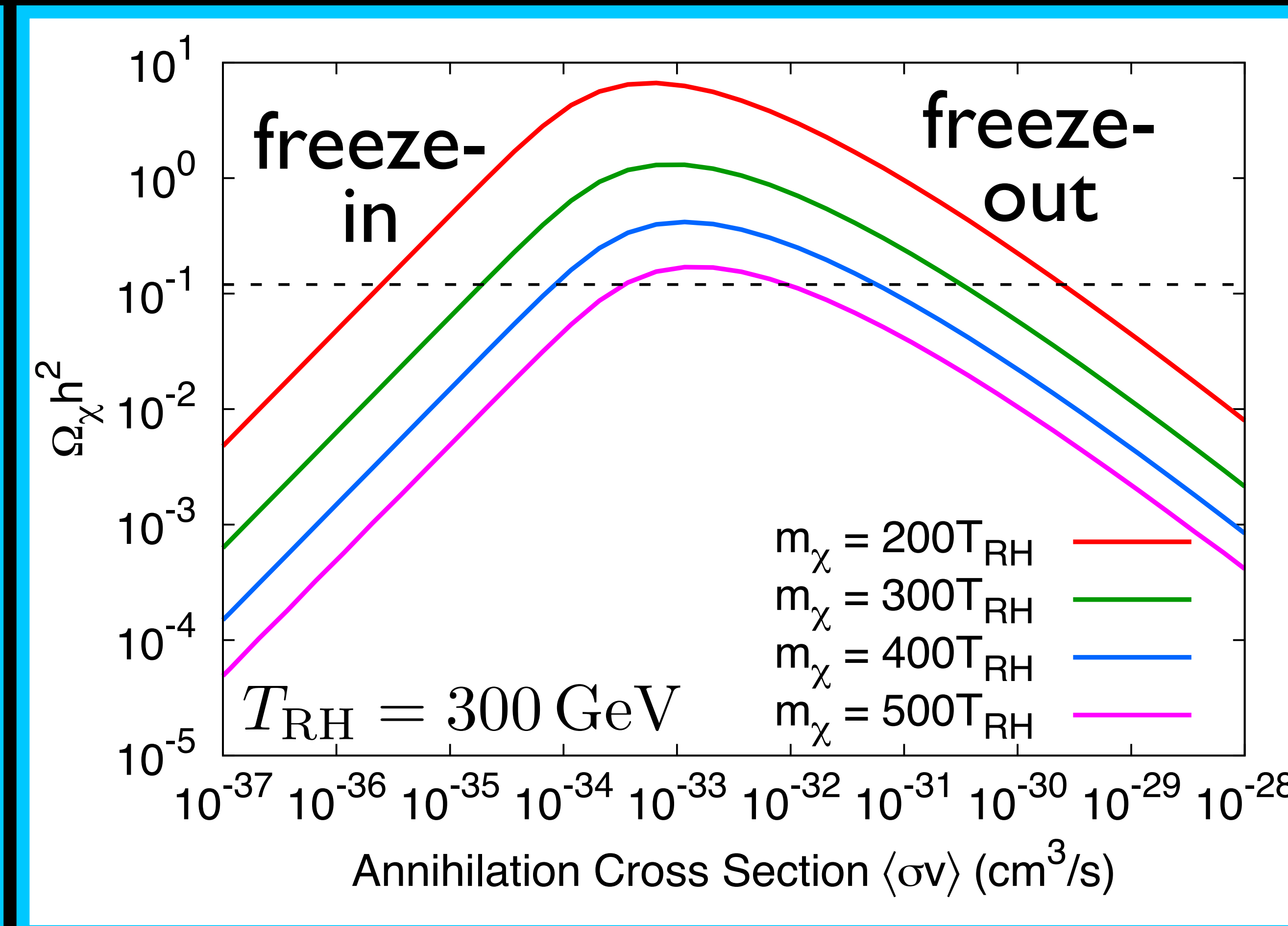
Berezinsky, et al. 2010

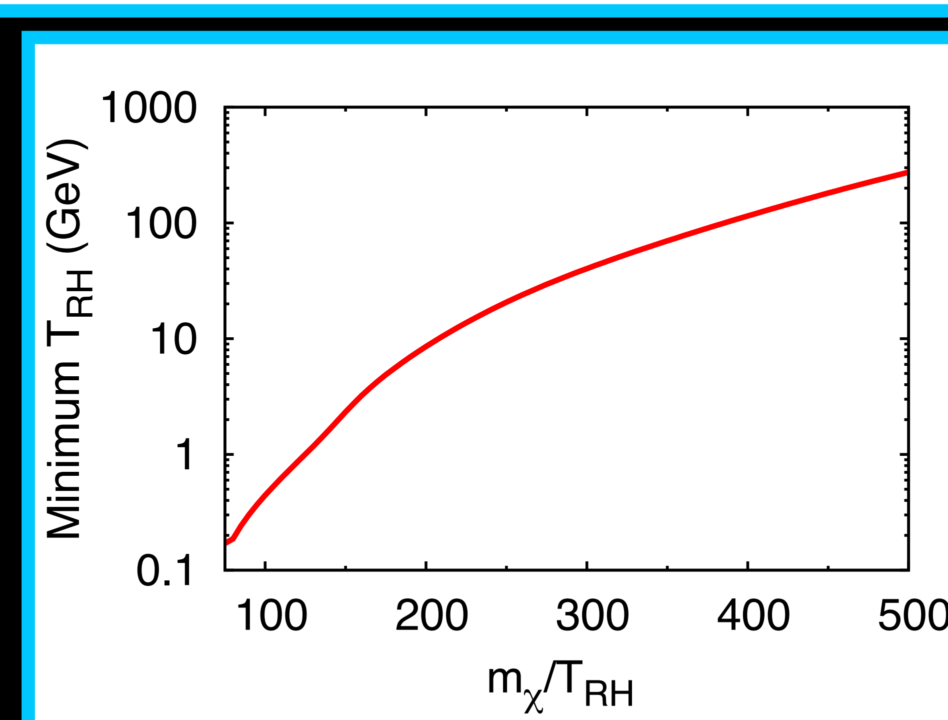
Annihilation Signatures

ALE 1504.03335

Annihilation Cross Sections



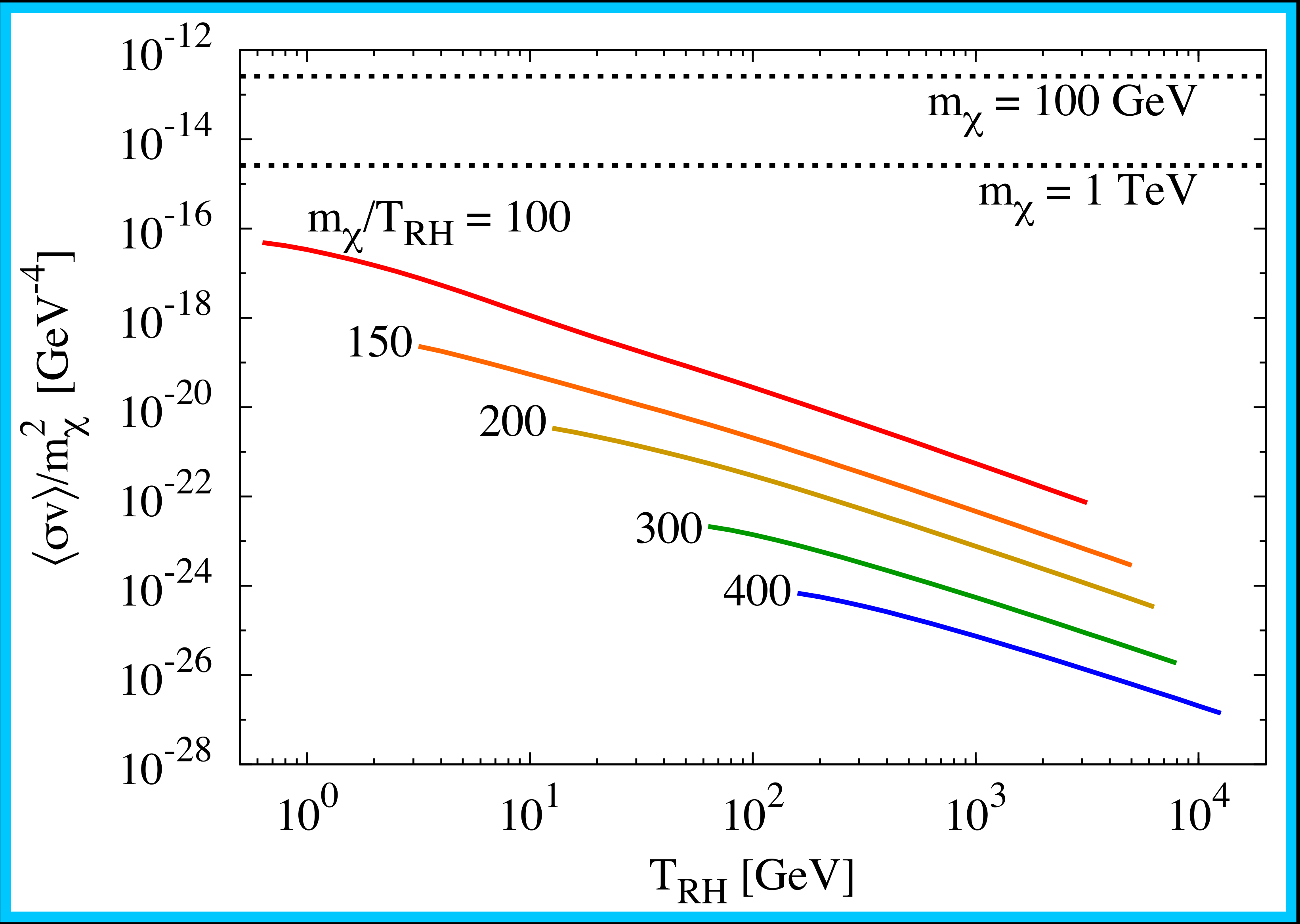




- Decreasing the reheat temperature or increasing the particle mass reduces the abundance.
- There is a minimum reheat temperature that can thermally produce $\Omega_\chi = 0.25$

The Annihilation Rate

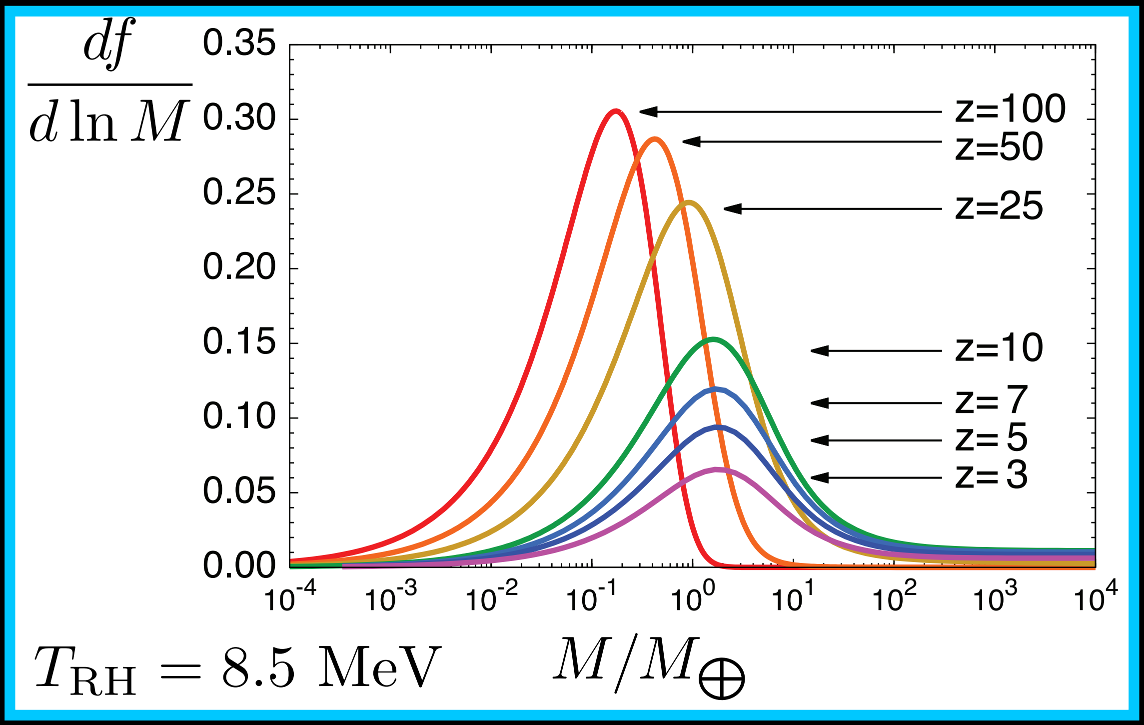
$$\frac{\Gamma_{\rm ann}}{\rm Volume} \propto \langle \sigma v \rangle n_\chi^2 \propto \frac{\langle \sigma v \rangle}{m_\chi^2} \rho_\chi^2$$



- The annihilation rate is highest for small dm masses and low reheat temperatures.
- To preserve microhalos, we need $T_{\rm kdS} \gtrsim 2T_{\rm RH}$
- The boost factor from enhanced substructure is critical for detection.

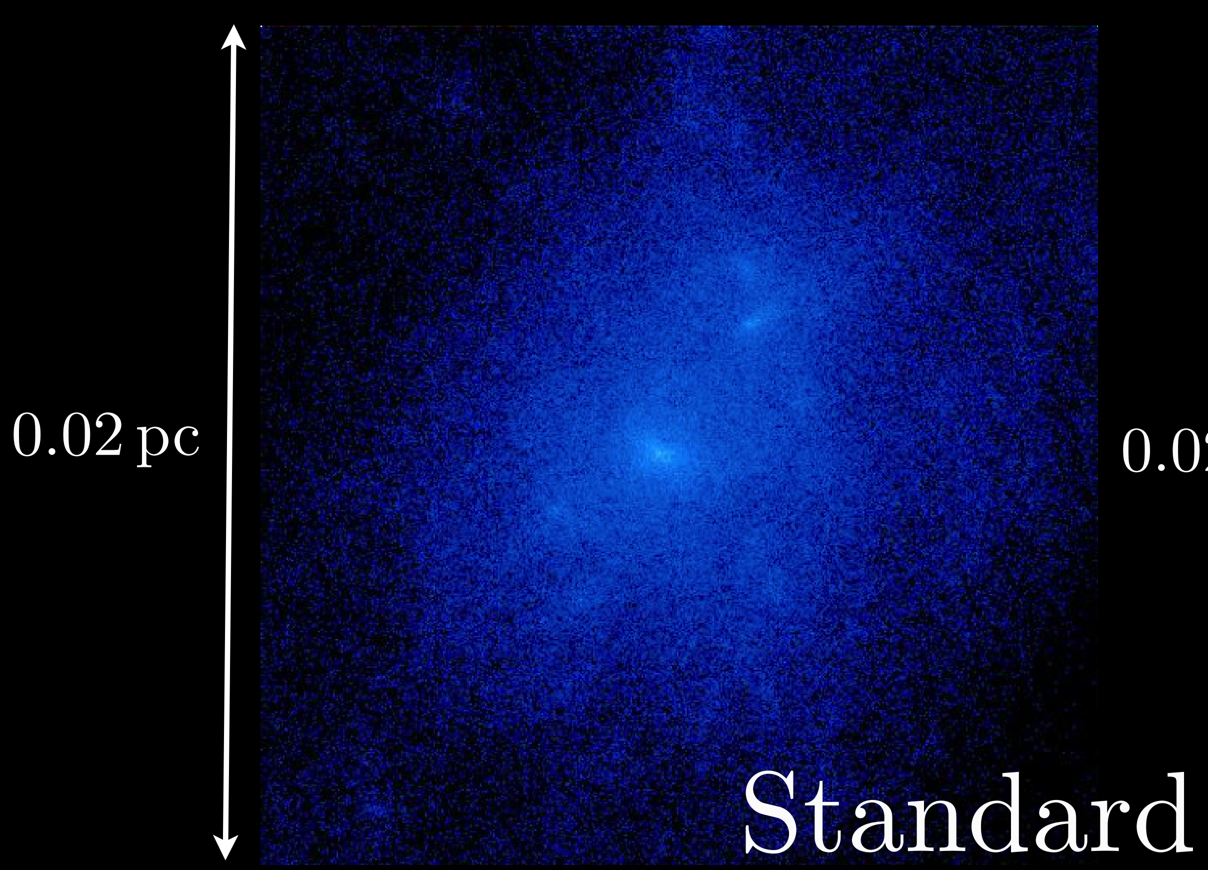
$$\left.\frac{\langle \sigma v \rangle}{m_\chi^2}\right|_{T_{\rm RH}\to\infty} = \frac{2.6 \times 10^{-15}}{\rm GeV^4} \left(\frac{1\,\rm TeV}{m_\chi}\right)^2$$

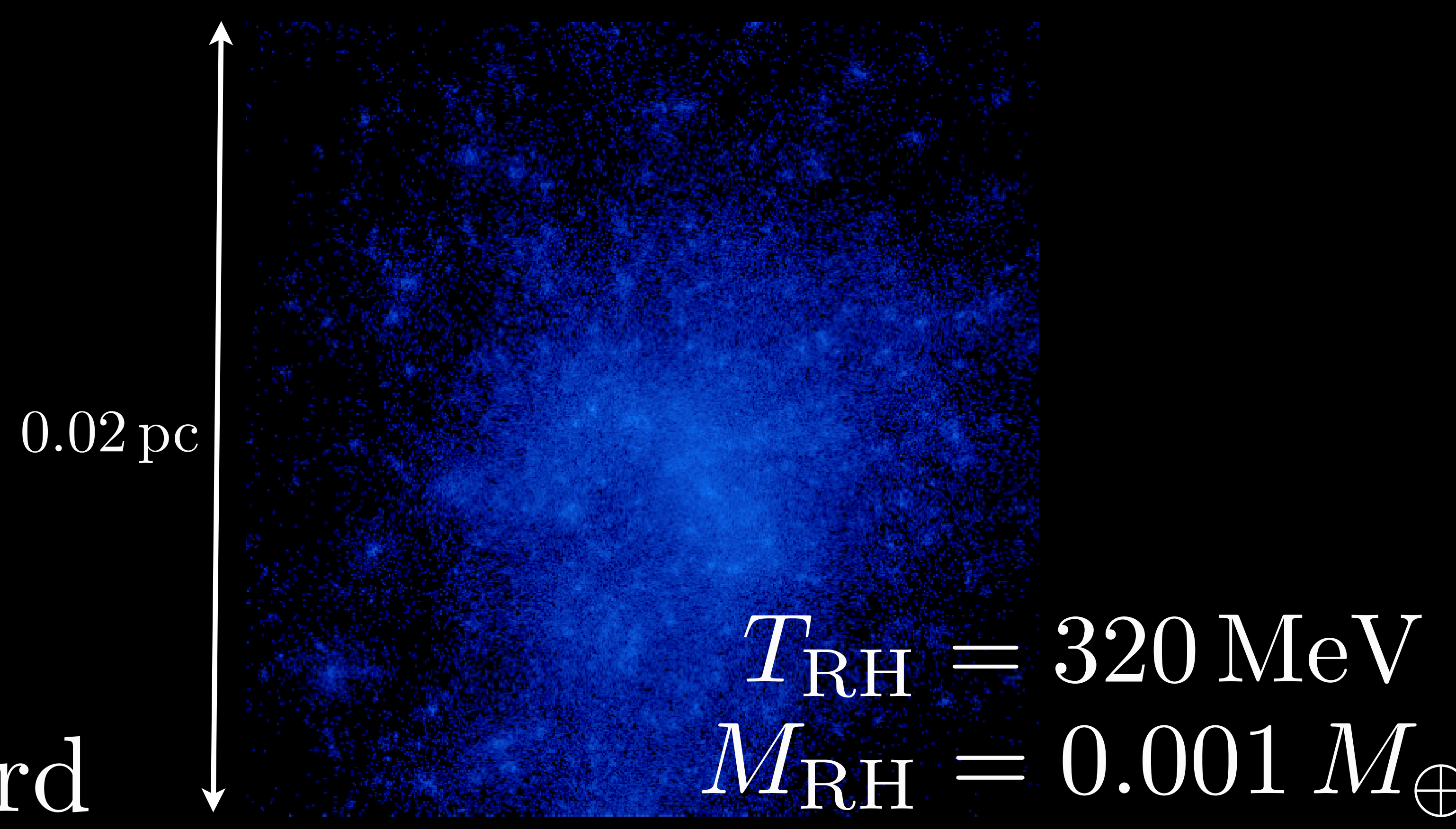
Towards the Boost Factor



The Press-Schechter formalism indicates that formation of the microhalos is strongly hierarchical: its microhalos all the way down.

Simulated Earth-mass microhalos



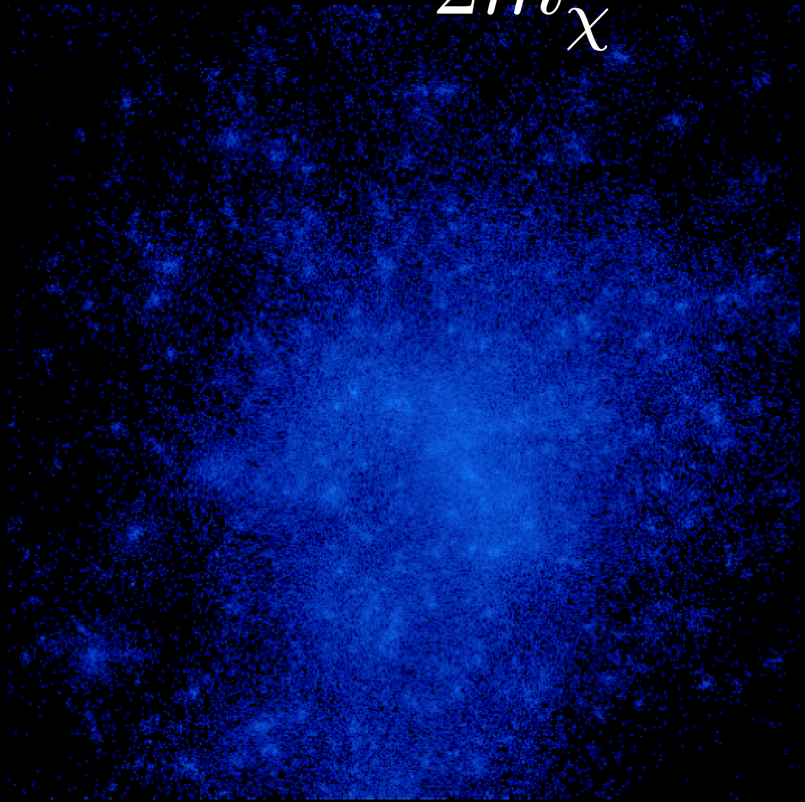


Estimating the Boost Factor

Dark matter annihilation rate: $\Gamma = \frac{\langle \sigma v \rangle}{2m_\chi^2} \int \rho^2(r) d^3r \equiv \frac{\langle \sigma v \rangle}{2m_\chi^2} J$

Halo filled with microhalos:

$$J = N J_{\rm micro} + 4\pi \int_0^R (1-f_0)^2 \rho_{\rm halo}^2(r)\, dr$$



Number of microhalos:

$$N = \int (\text{survival prob.}) \frac{M_{\rm halo}}{M} \frac{df}{d\ln M}\, d\ln M$$

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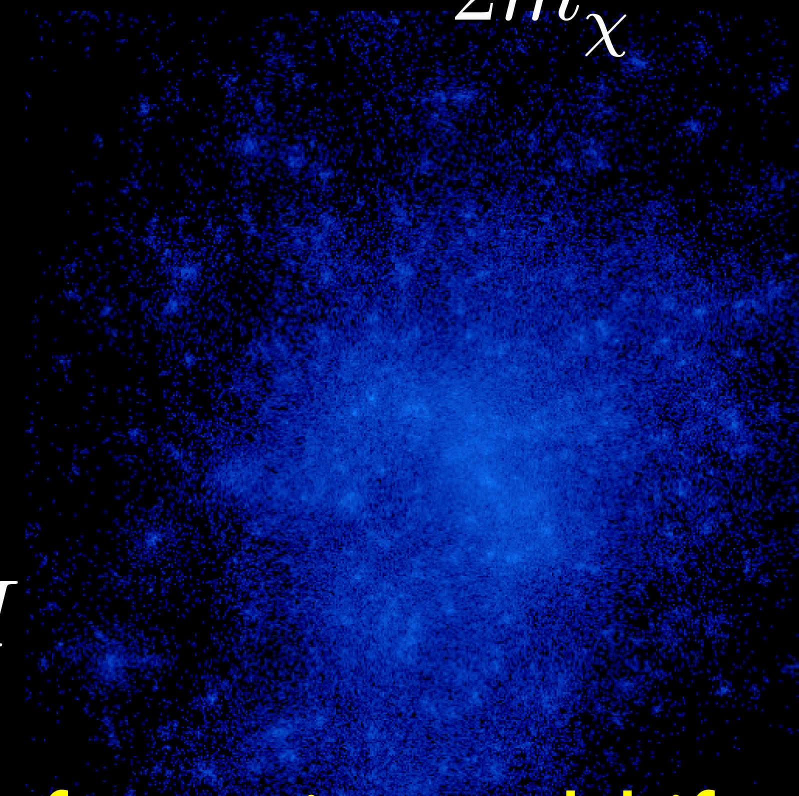


Assume microhalo NFW profile with c = 2 at formation redshift.

Anderhalden & Diemand 2013
Ishiyama 2014

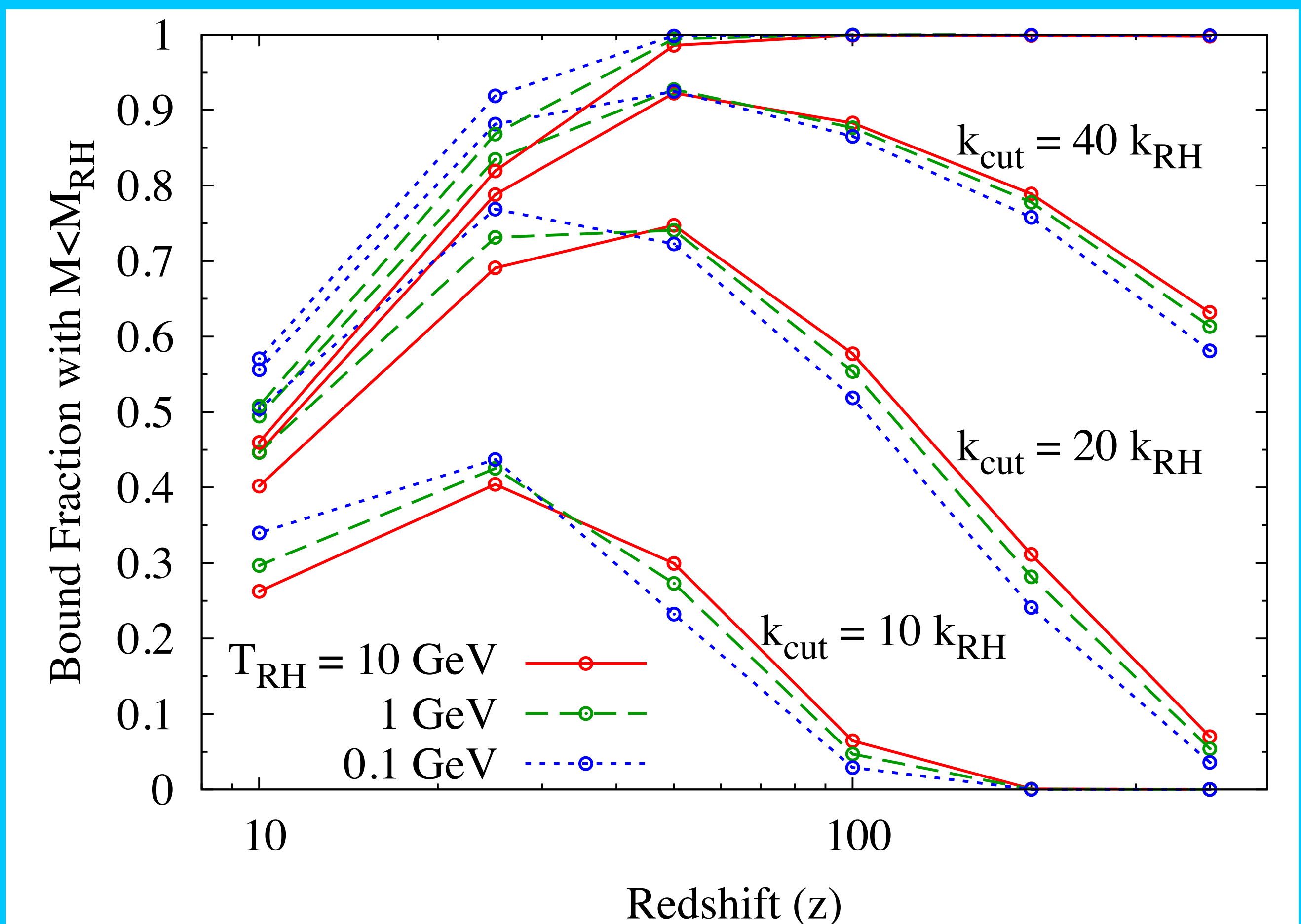
- early forming microhalos: $z_f \gtrsim 50$
- dense cores: $\bar{\rho}_{\mathrm{micro}}(r_s) > 2\bar{\rho}_{\mathrm{halo}}(r)$ for $r > 1\,\mathrm{kpc}$
- assume that microhalo centers survive outside of inner kpc: reduces number of microhalos by <1% in large halos
- assume that microhalos are stripped to $r = r_s$: reduces J_{micro} by <20%

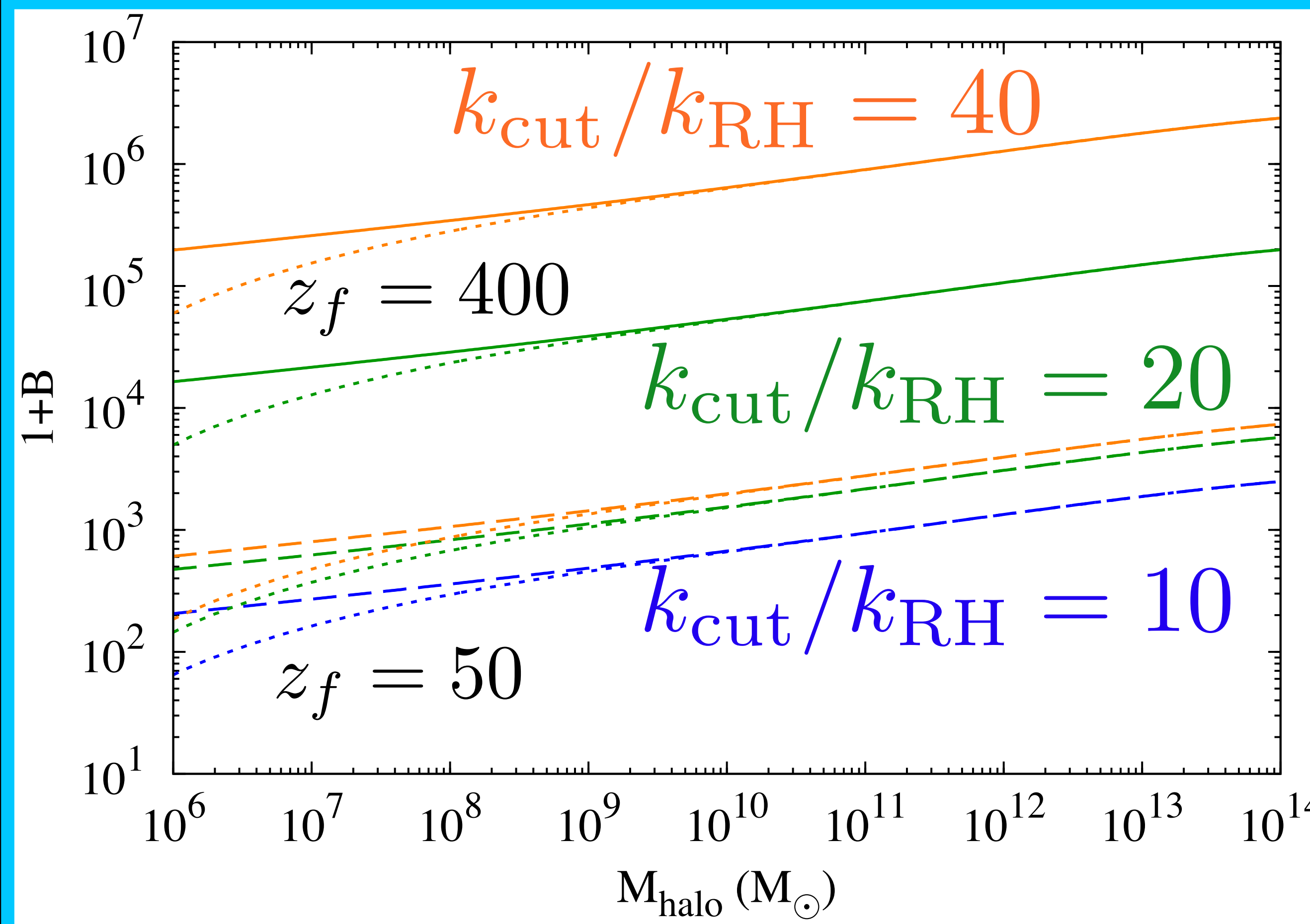
Estimating the Boost Factor II

Dark matter annihilation rate: $\Gamma = \frac{\langle \sigma v \rangle}{2m_\chi^2} \int \rho^2(r) d^3r \equiv \frac{\langle \sigma v \rangle}{2m_\chi^2} J$

Boost Factor:

$$1 + B(M) \equiv \frac{J}{\int \bar{\rho}_\chi^2(r)\, 4\pi r^2 dr} \propto \frac{\rho(z_f)}{\rho_0 c_h^3} f_{\mathrm{tot}}(M < M_{\mathrm{RH}}, z_f)$$





Boost from Microhalos

Estimating the Boost Factor II

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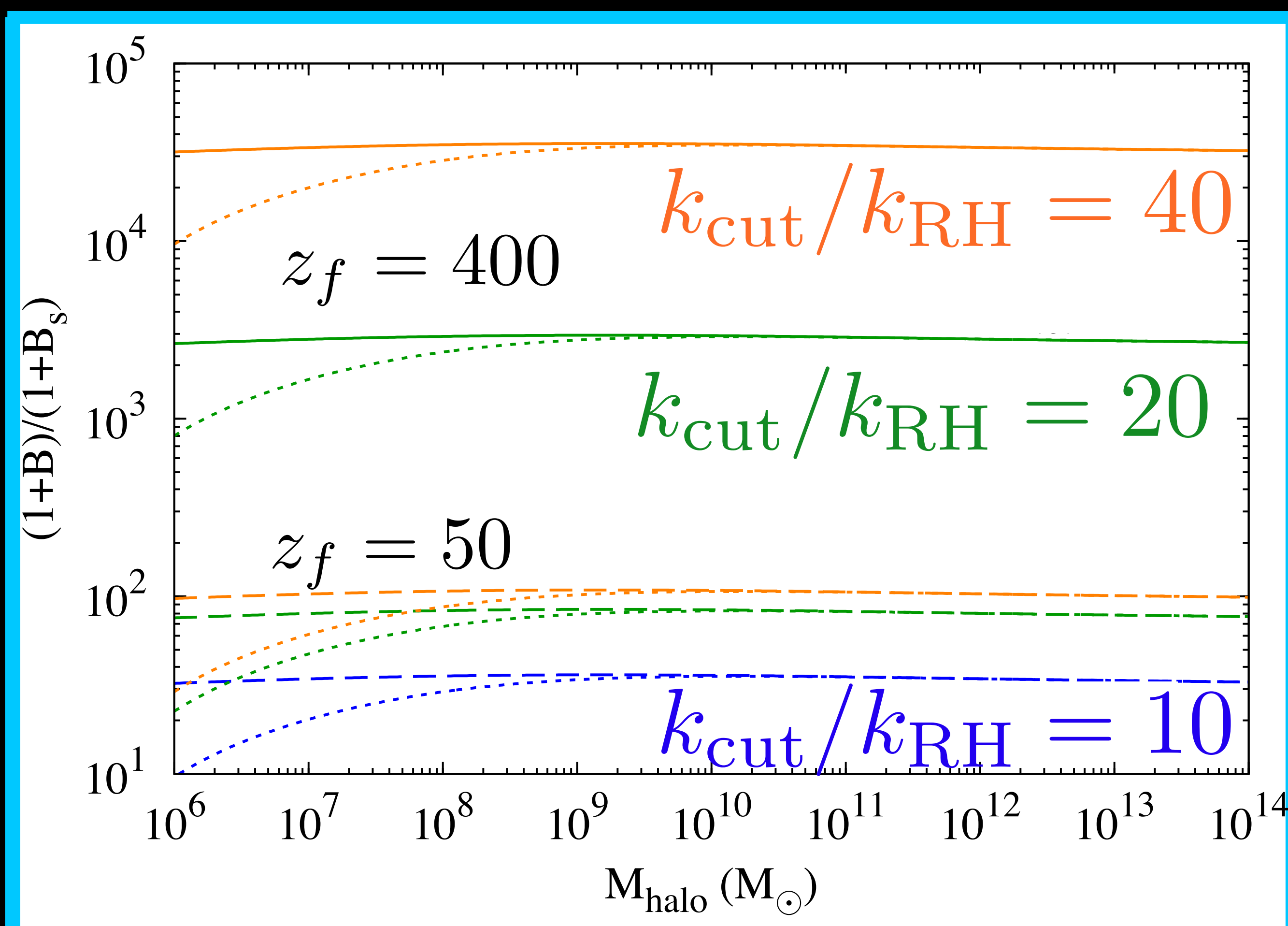
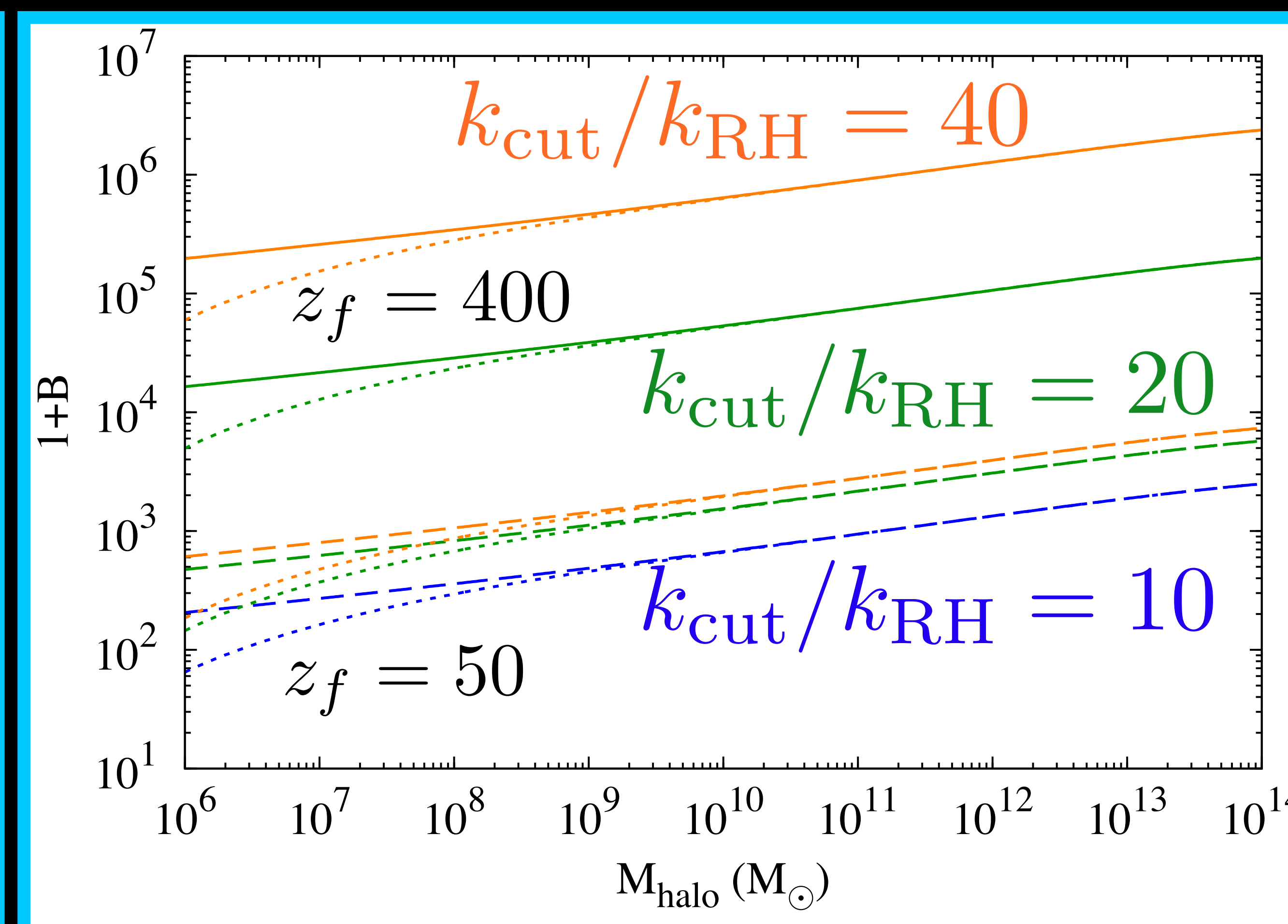


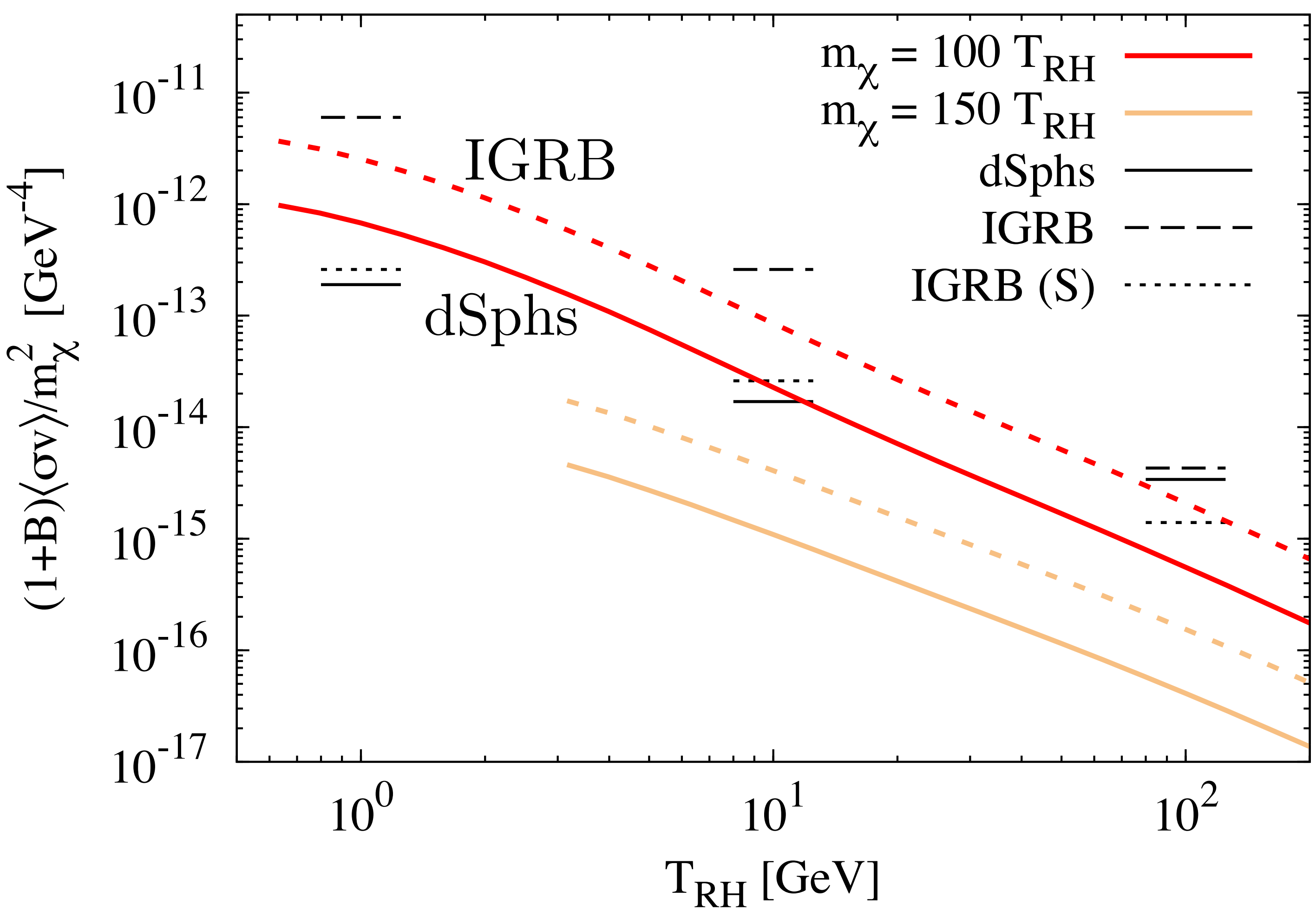


Relative Boost *(Sanchez-Conde & Prada 2014)*

Boost from Microhalos

Moving Toward Constraints

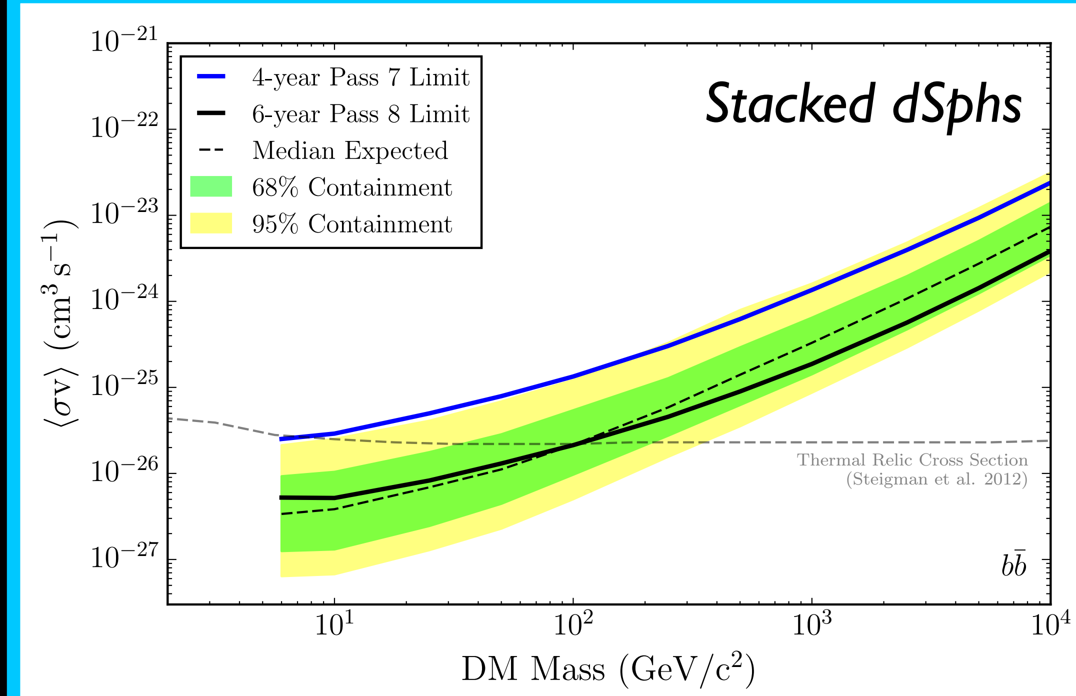
$$\frac{\Gamma_{\rm ann}}{\rm Volume} \propto \langle\sigma v\rangle n_\chi^2 \propto \frac{\langle\sigma v\rangle}{m_\chi^2}\rho_\chi^2$$



$$k_{\rm cut}/k_{\rm RH} = 40 \qquad z_f = 400$$

$$\text{IGRB: } B = 75,000$$

$$\text{dSphs: } B = 20,000$$



Fermi-LAT Collaboration 2015

- Rough comparison

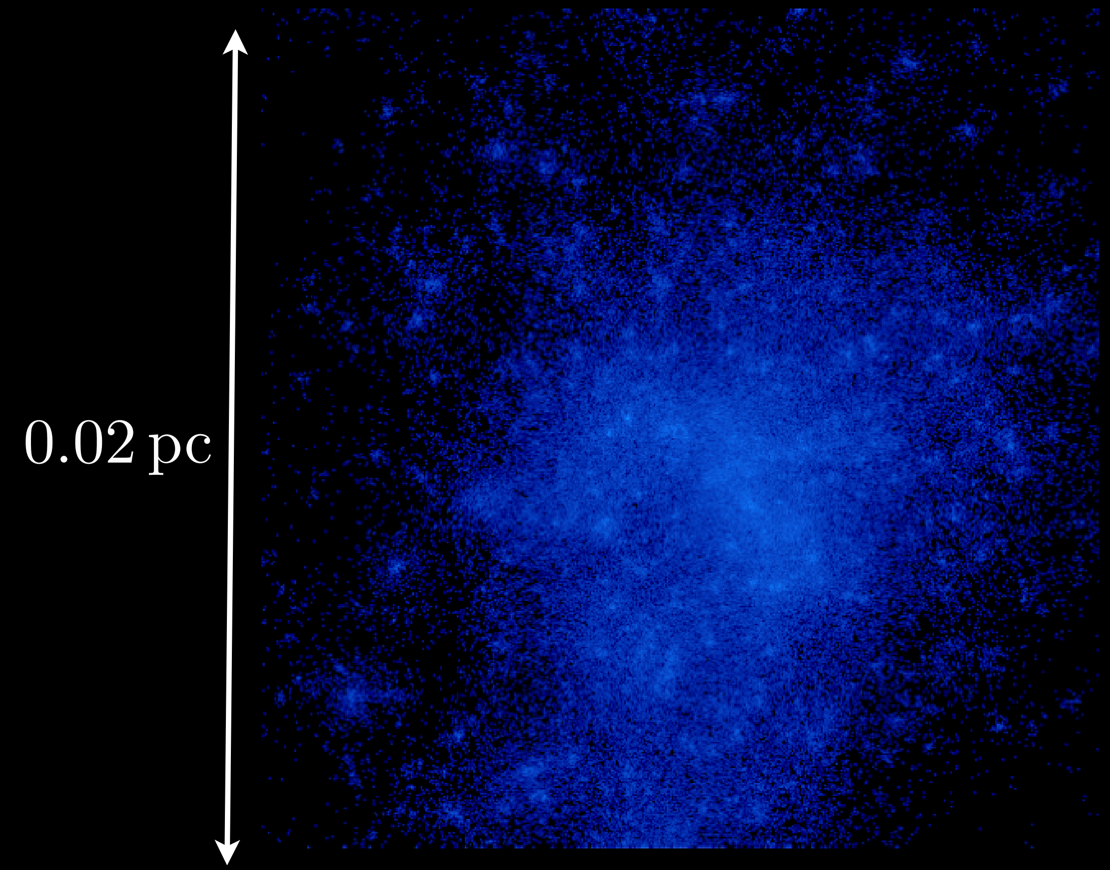
$$\left.\frac{\langle\sigma v\rangle}{m_\chi^2}\right|_{\rm obs} \quad \text{vs.} \quad (1+B)\left.\frac{\langle\sigma v\rangle}{m_\chi^2}\right|_{\Omega_{\rm M}=0.25}$$

- dSphs: ~0.1M in field of view, so reduce total boost by factor of 10.
- IGRB: EMDE boost relative to standard boost

Looking forward

Gamma-ray observations may already constrain scenarios with

- reheat temperatures $600\,\mathrm{MeV} \lesssim T_{\mathrm{RH}} \lesssim 10\,\mathrm{GeV}$
- particle masses $m_\chi \lesssim 100\,T_{\mathrm{RH}}$
- annihilation cross sections $\langle\sigma v\rangle \ll 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$
- decoupling temperatures $T_{\mathrm{kdS}} \gtrsim 2T_{\mathrm{RH}}$



What's next?

- specific WIMP candidates?
- microhalo density profiles?
- microhalos within microhalos?
- continue with simulations to get more accurate boost factor
- accurate small scale cut-off in light of radiation pert. growth
- full analysis of dSph boost factors

Summary: A New Window on Reheating

The relic abundance of dark matter and its perturbations depend on the thermal history of the early Universe.

- It's possible to get the observed relic abundance from a wide range of dark matter annihilation cross sections.
- If the scalar decays into cold dark matter or if the dark matter is a thermal relic, the dark matter perturbations on subhorizon scales grow linearly prior to reheating.

The enhancement in the dark matter power spectrum on small scales can enhance the abundance of microhalos.

- At high redshift, nearly all of the dark matter is bound into microhalos with masses smaller than the horizon mass at reheating if $T_{\mathrm{kdS}} \gtrsim 2T_{\mathrm{RH}}$
- Indirect detection may be able to probe the reheat history and the origin of dark matter, depending on the internal structure of the microhalos. *1504.03335*

STAY TUNED