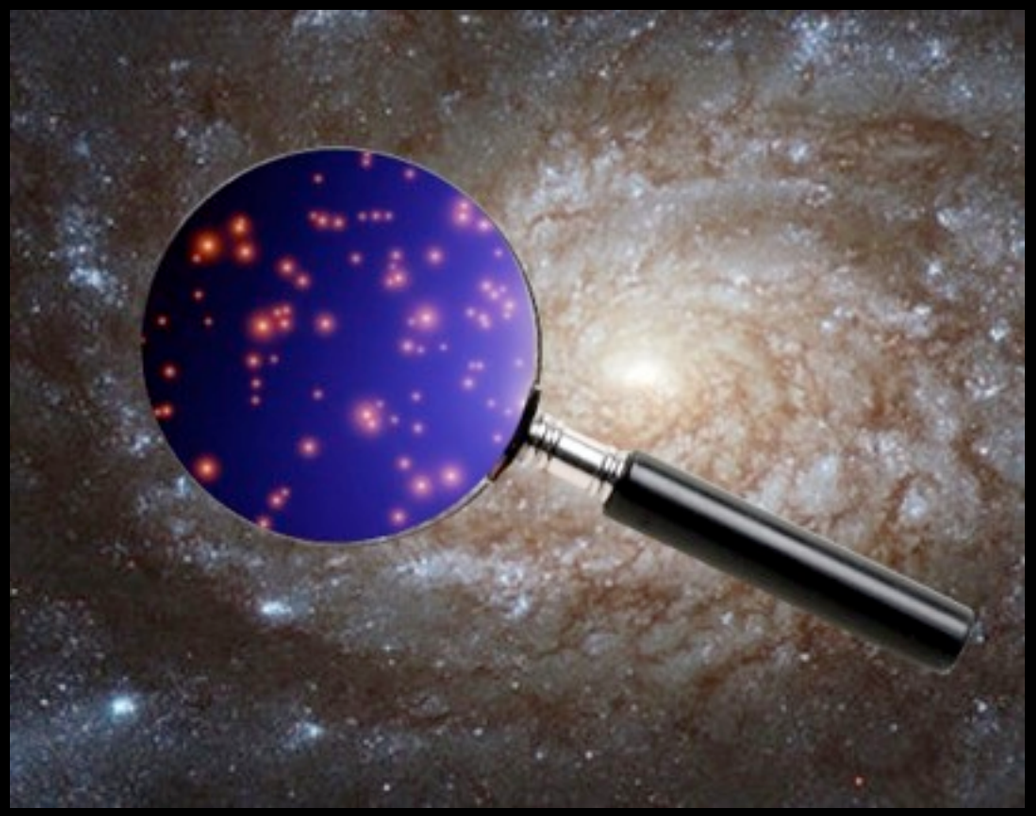
The Early Universe's Imprint on Dark Matter



Adrienne Erickcek
UNC Chapel Hill

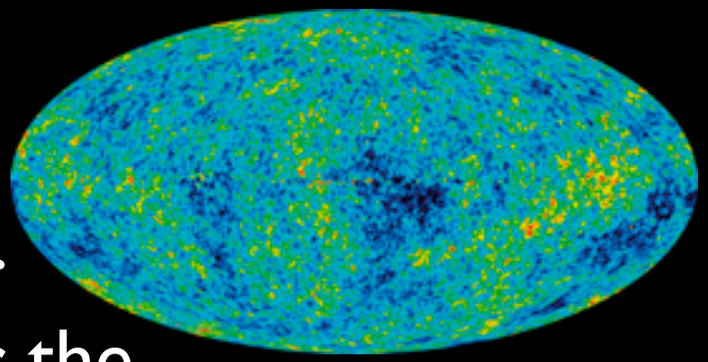
Towards Dark Matter Discovery
KICP, University of Chicago
April 13, 2018

What Happened Before BBN?

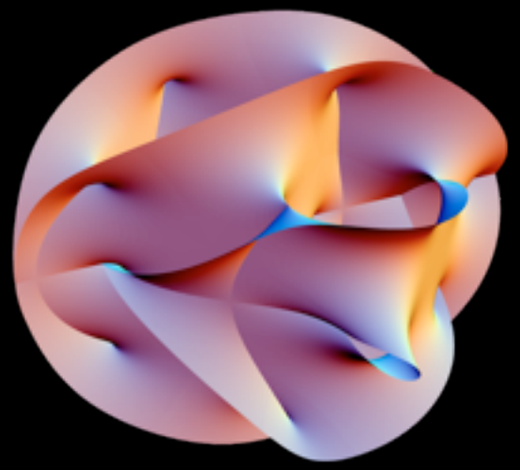
The (mostly) successful prediction of the primordial abundances of light elements is one of cosmology's crowning achievements.

- The elements produced during Big Bang Nucleosynthesis are our first direct 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.

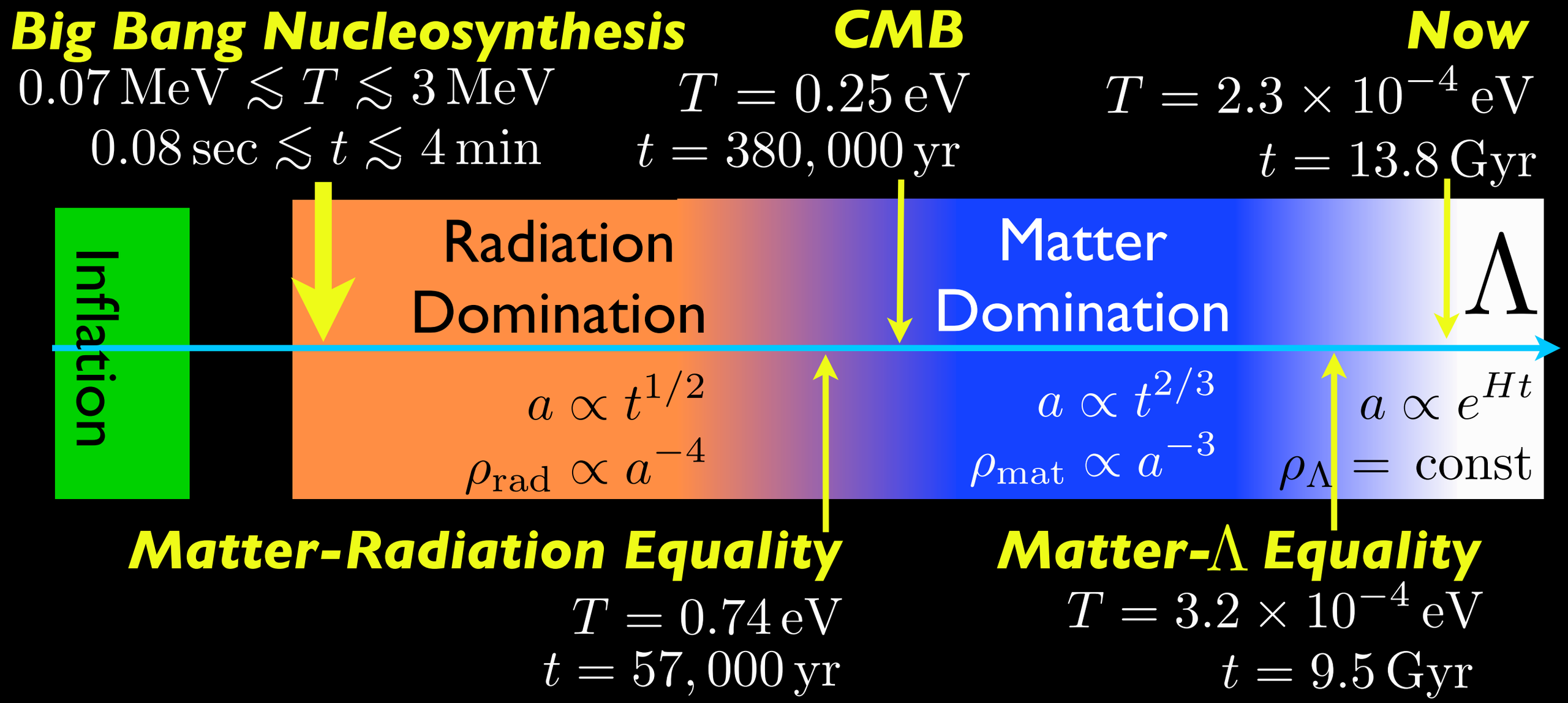


- Primordial density fluctuations point to inflation.
- During inflation, the Universe was scalar dominated.
- Other scalar fields may dominate the Universe after the inflaton decays.
- The string moduli problem: scalars with gravitational couplings come to dominate the Universe before BBN.

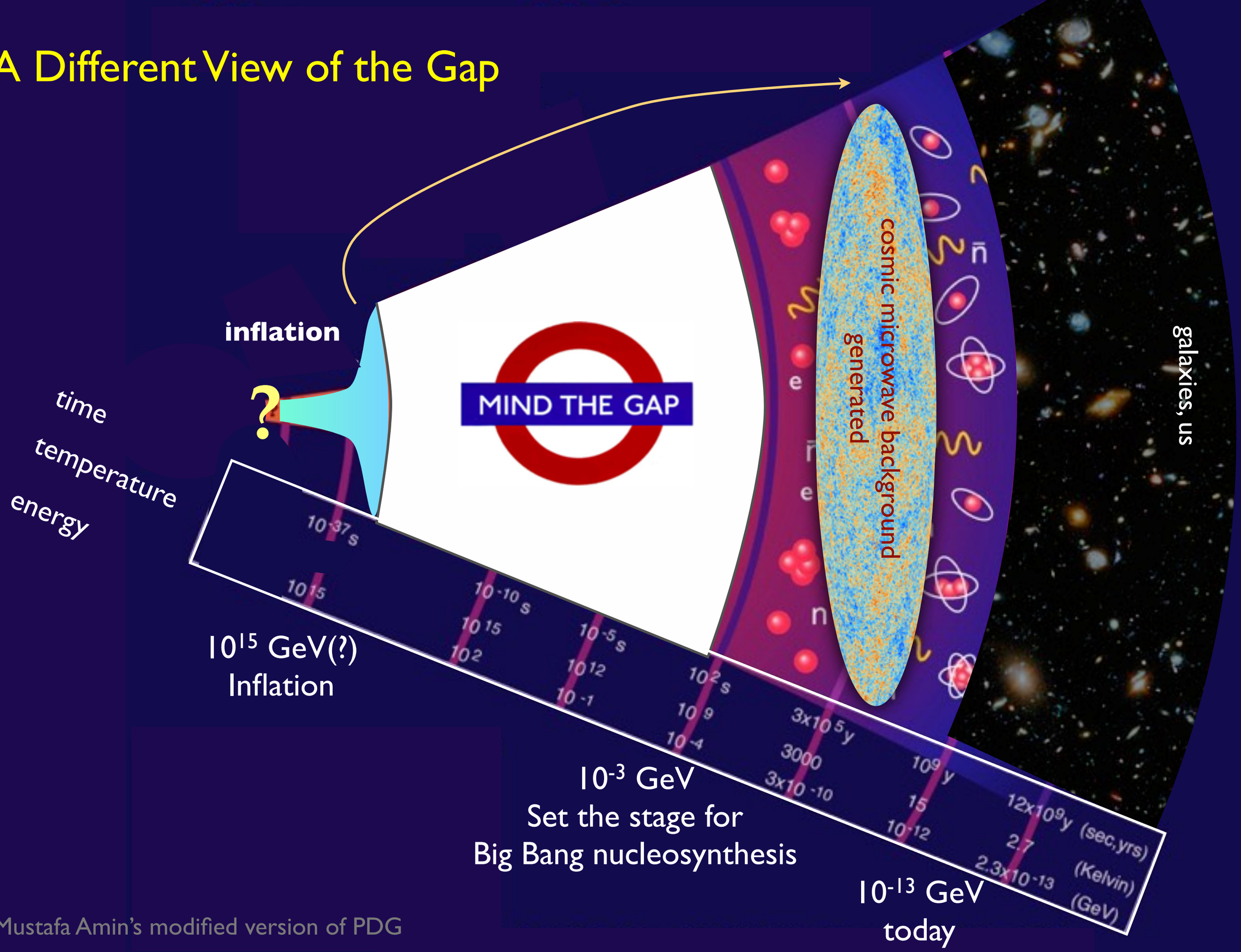


Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994
Acharya, Kumar, Bobkov, Kane, Shao, Watson 2008
Acharya, Kumar, Kane, Watson 2009
Recent Summary: Kane, Sinha, Watson 1502.07746

Cosmic Timeline



A Different View of the Gap

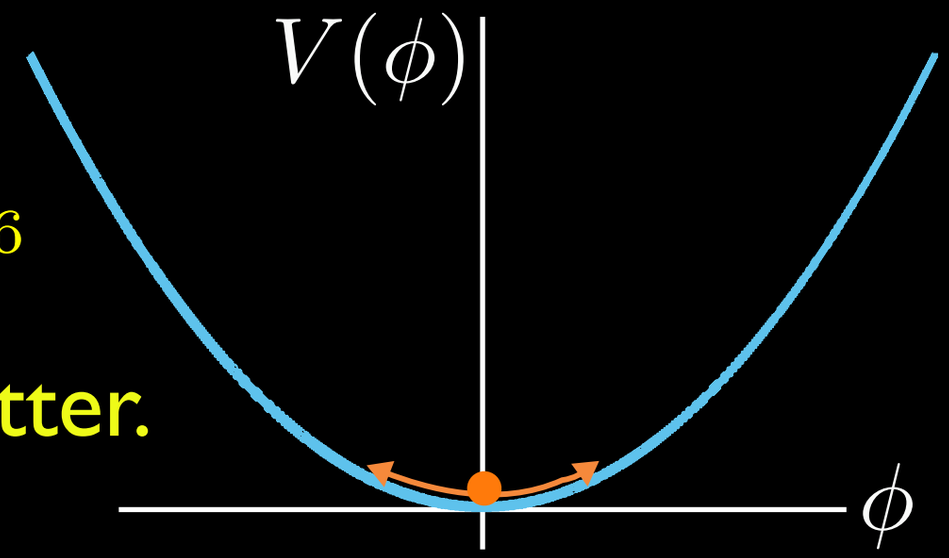


Mustafa Amin's modified version of PDG

Evolution of the pre-BBN Universe

The Universe was once dominated by a scalar field

- the inflaton
- string moduli



Fast-rolling scalar: $\rho_\phi = P_\phi \Longrightarrow \rho_\phi \propto a^{-6}$

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

Other massive particles could come to dominate the Universe:

- axinos or gravitinos
- hidden sector particles/mediators

Eventually, the scalar/particle decays into radiation, reheating the Universe.

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

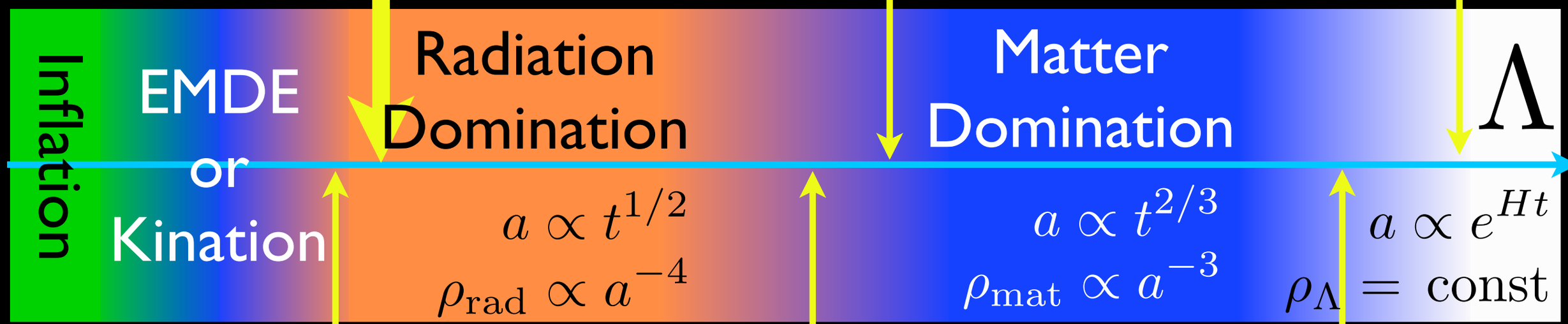
Ichikawa, Kawasaki, Takahashi 2005; 2007
de Bernardis, Pagano, Melchiorri 2008

Cosmic Timeline

BBN
$0.07\,\mathrm{MeV} \lesssim T \lesssim 3\,\mathrm{MeV}$
$0.08\,\mathrm{sec} \lesssim t \lesssim 4\,\mathrm{min}$

CMB
$T = 0.25\,\mathrm{eV}$
$t = 380,000\,\mathrm{yr}$

Now
$T = 2.3 \times 10^{-4}\,\mathrm{eV}$
$t = 13.8\,\mathrm{Gyr}$



Reheating
$T = ?$

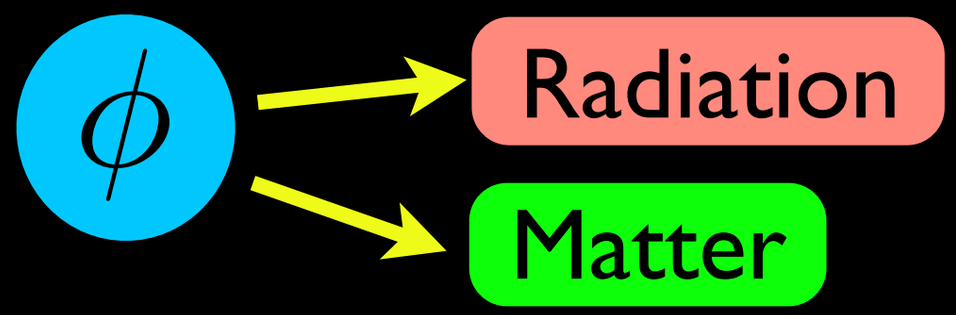
Matter-Radiation Equality
$T = 0.74\,\mathrm{eV}$
$t = 57,000\,\mathrm{yr}$

Matter-Λ Equality
$T = 3.2 \times 10^{-4}\,\mathrm{eV}$
$t = 9.5\,\mathrm{Gyr}$

Implications:

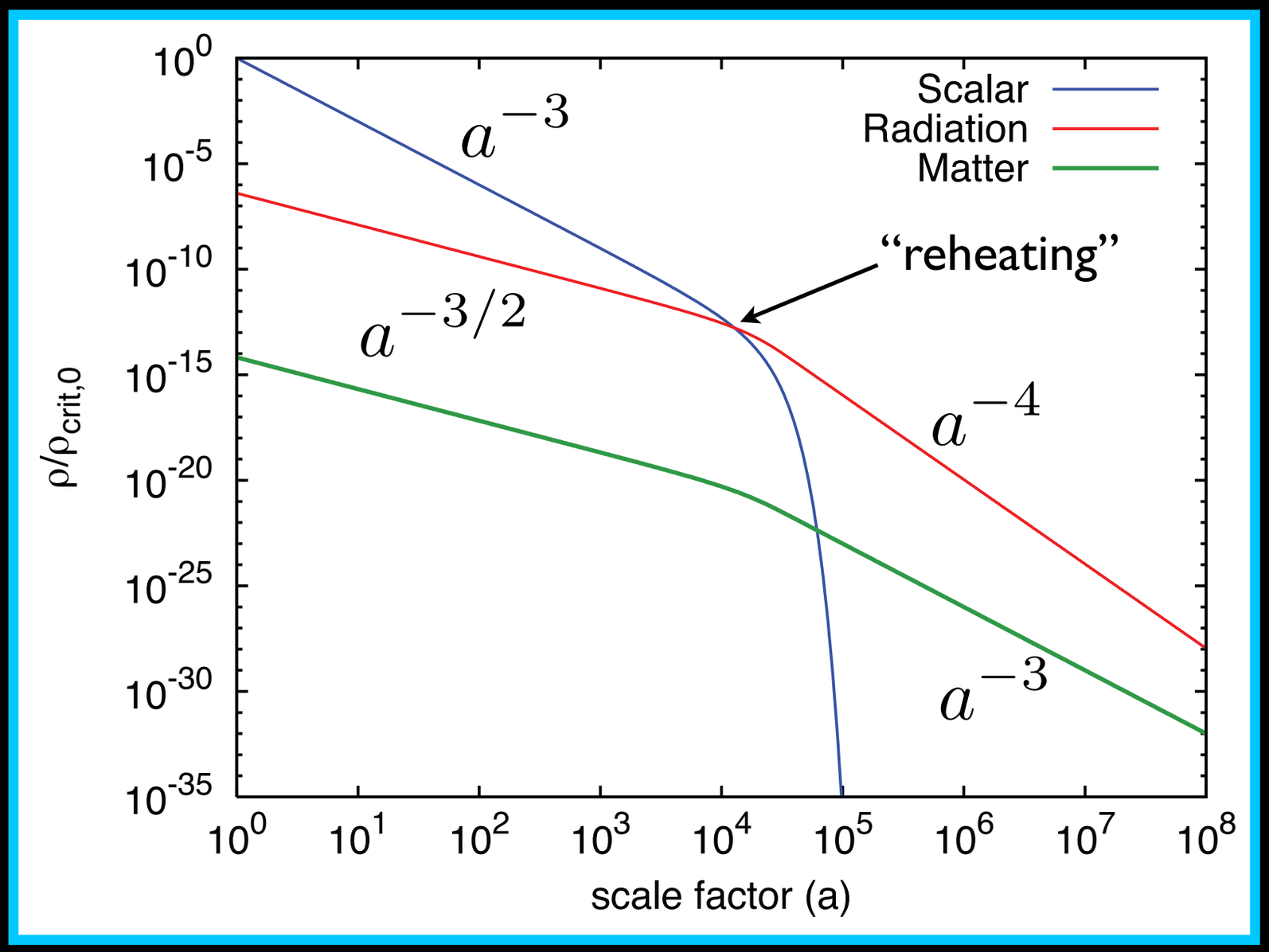
1. *Dark matter production*
2. *Early structure growth*

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:

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

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

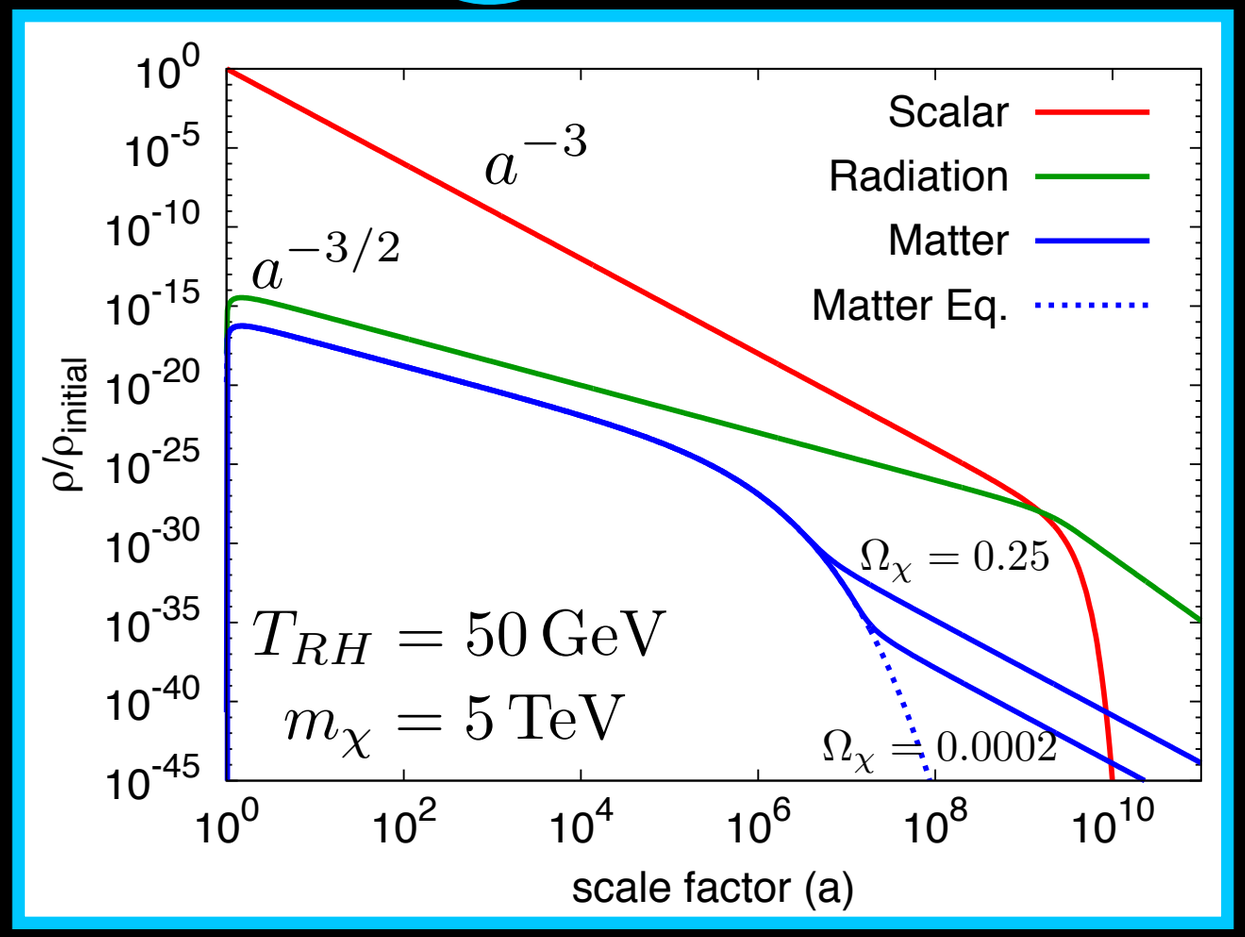
We need a very small branching ratio:

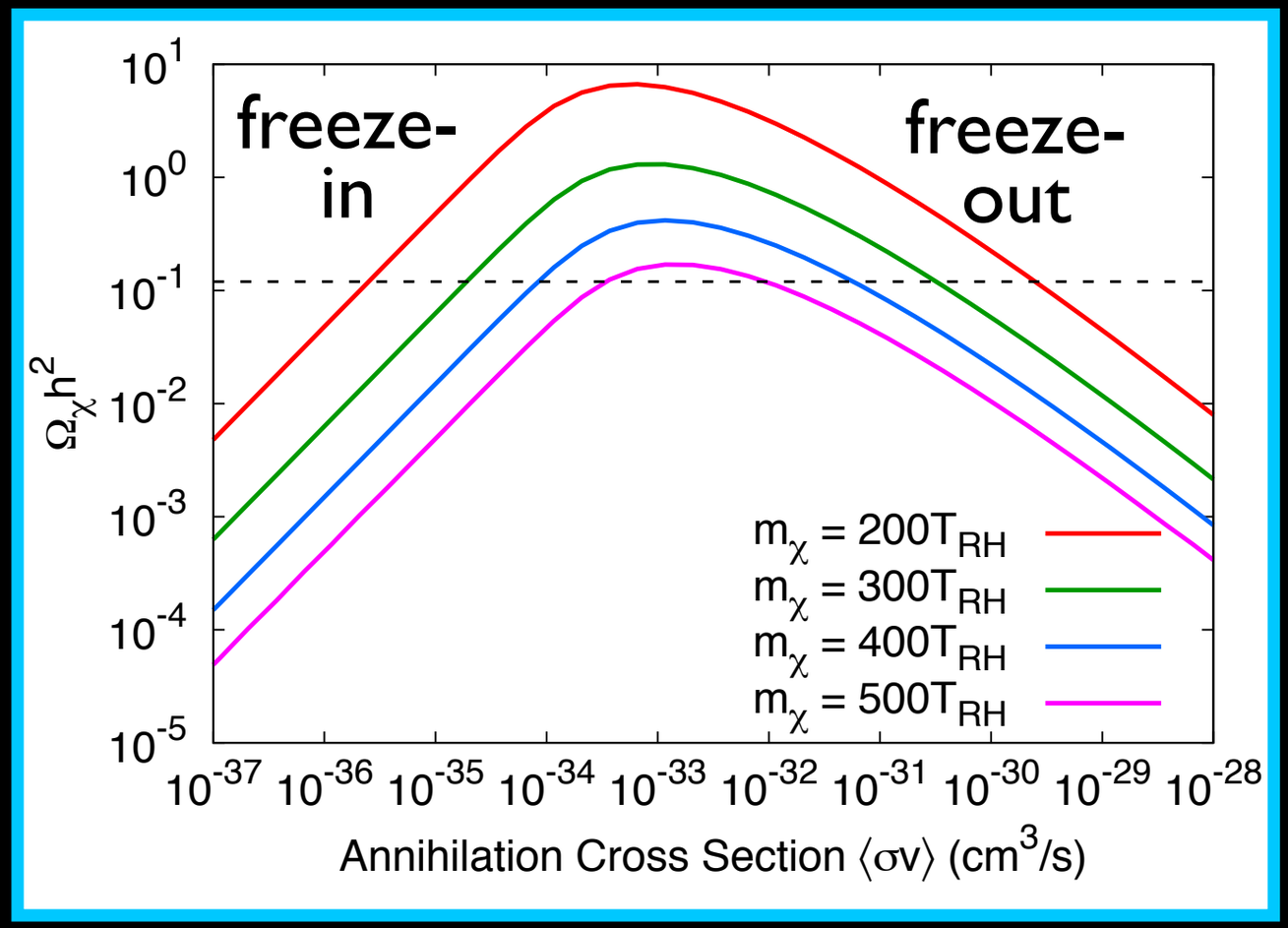
$$f < 10^{-7}$$

DM Origin 2: Thermal

Giudice, Kolb, Riotto 2001

$\phi \longrightarrow$ Radiation $\xleftrightarrow{\gamma\gamma \leftrightarrow \chi\bar{\chi}}$ Matter





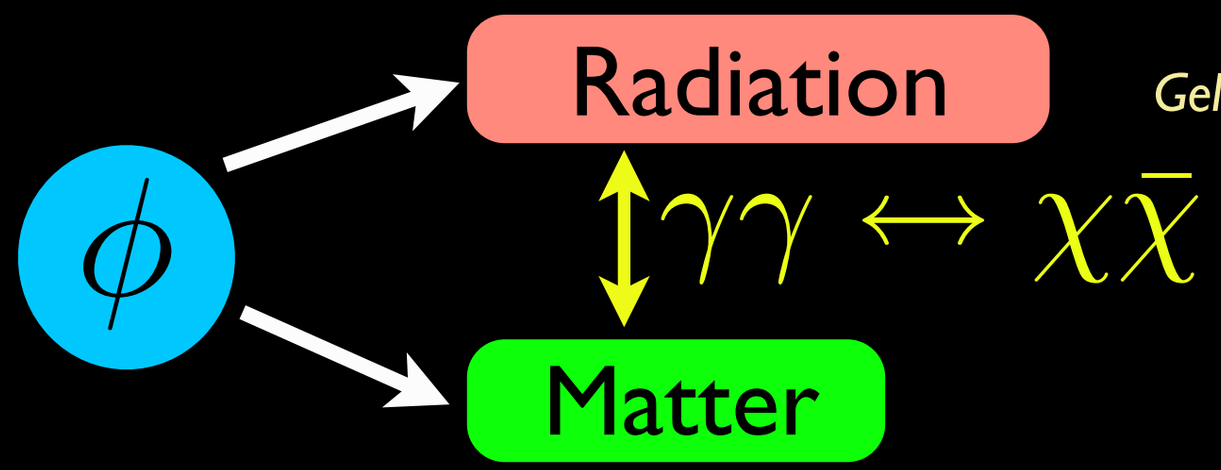
$$\langle \sigma v \rangle_{0.25} = 2 \times 10^{-29} \mathrm{cm}^3/\mathrm{s}$$

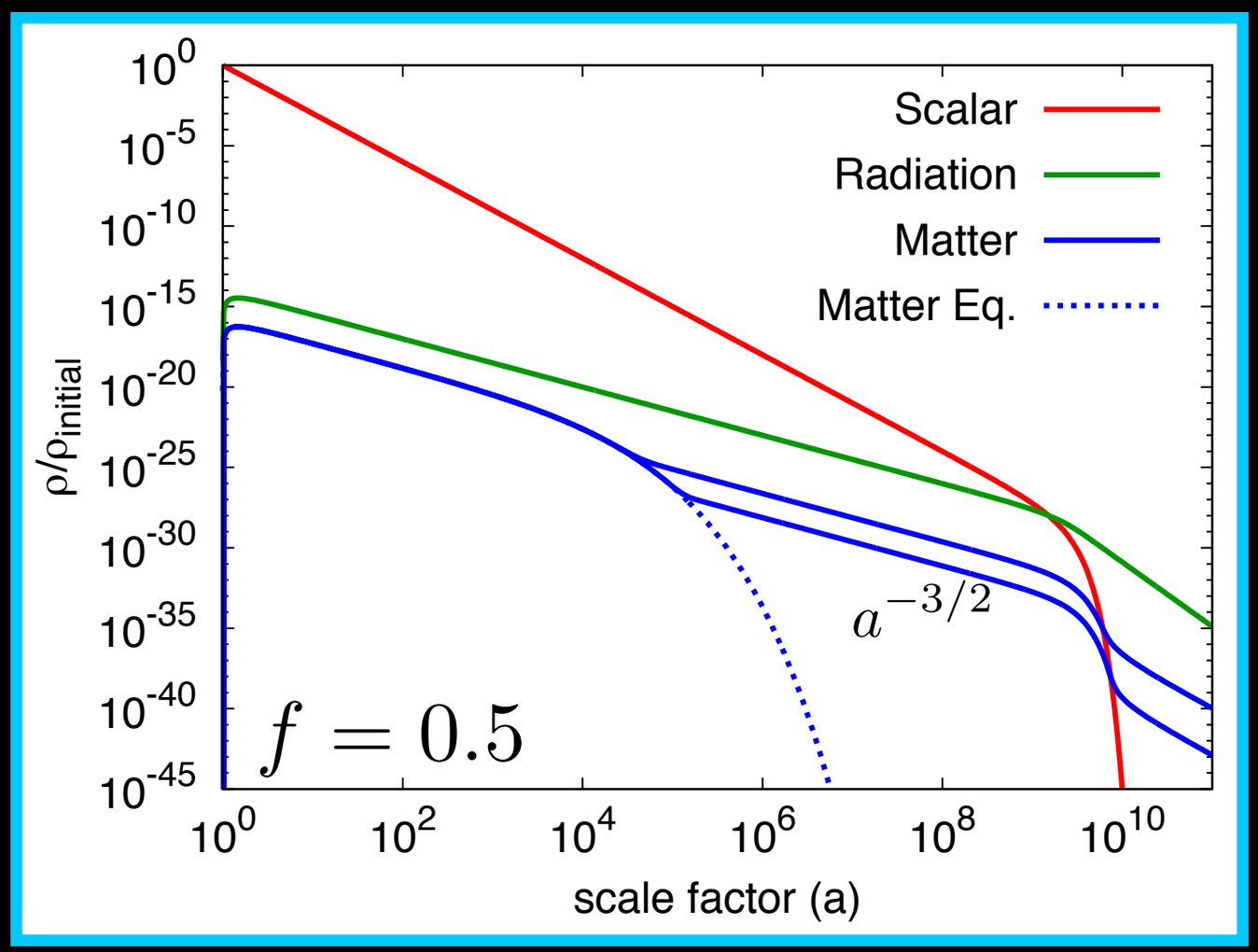
Freeze-out: $\Omega_\chi \propto \dfrac{1}{\langle \sigma v \rangle}$

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

DM Origin 3: Nonthermal with Annihilations

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





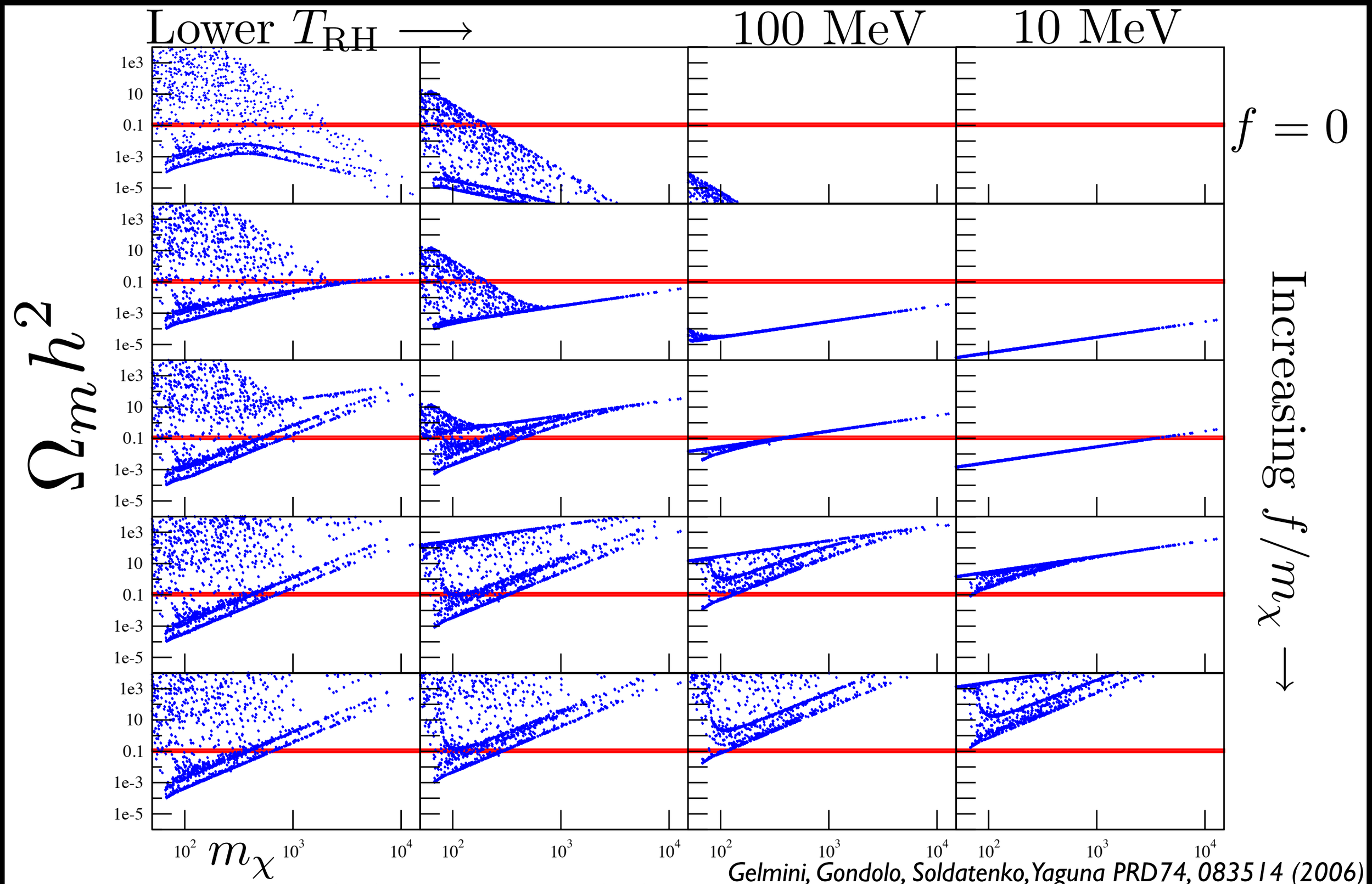
Branching ratio can be order unity: annihilations then destroy excess DM at reheating.

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

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!

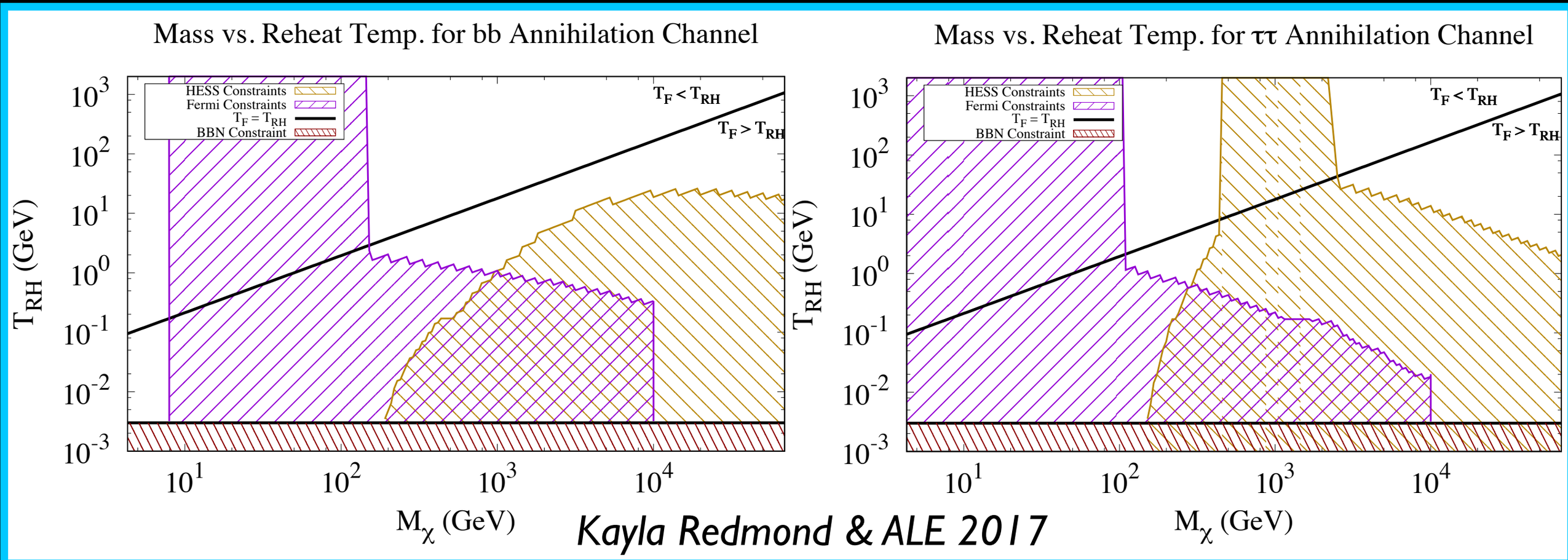


Gelmini, Gondolo, Soldatenko, Yaguna PRD74, 083514 (2006)

Probing Dark Matter Production

Kination: Universe dominated by a fast rolling scalar field $\rho_\phi \propto a^{-6}$

- faster expansion rate implies earlier freeze-out
- larger annihilation cross section needed to match observed abundance



Kayla Redmond & ALE 2017

But an early matter-dominated era (EMDE) requires smaller annihilation cross sections!

What hope do we have of probing these scenarios?

Microhalos from an EMDE

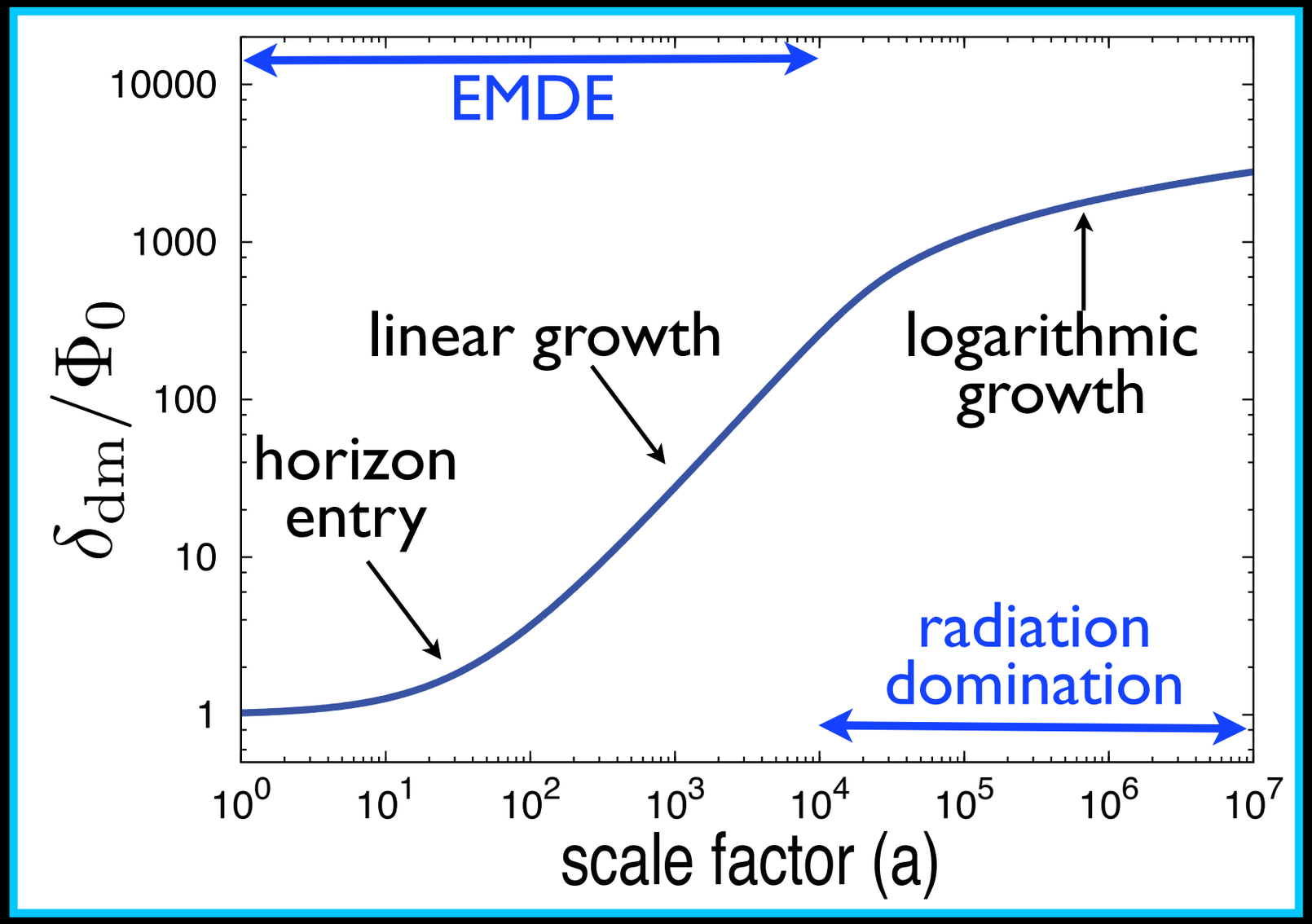
Nonthermal Dark Matter:
ALE & Sigurdson, Phys. Rev D 84, 083503 (2011)

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

Thermal Dark Matter:
ALE Phys. Rev. D 92, 103505 (2015)

The Dark Matter Perturbation

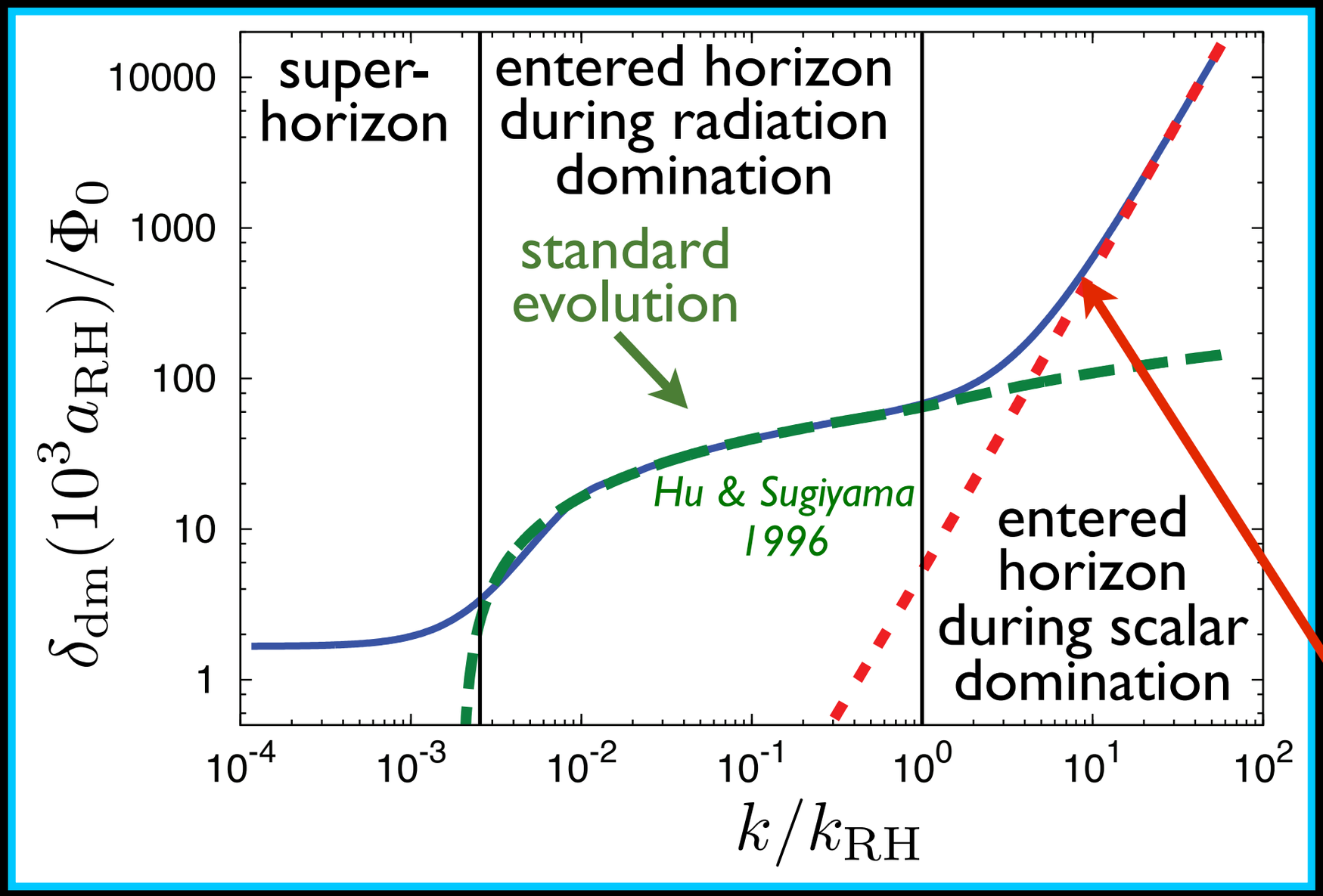
Evolution of the Matter Density Perturbation



- nonthermal dark matter immediately begins linear growth after horizon entry
- thermal DM is coupled to radiation prior to freeze-out, then grows linearly
- the amplitude of the perturbations during RD is the same for both thermal and nonthermal dark matter

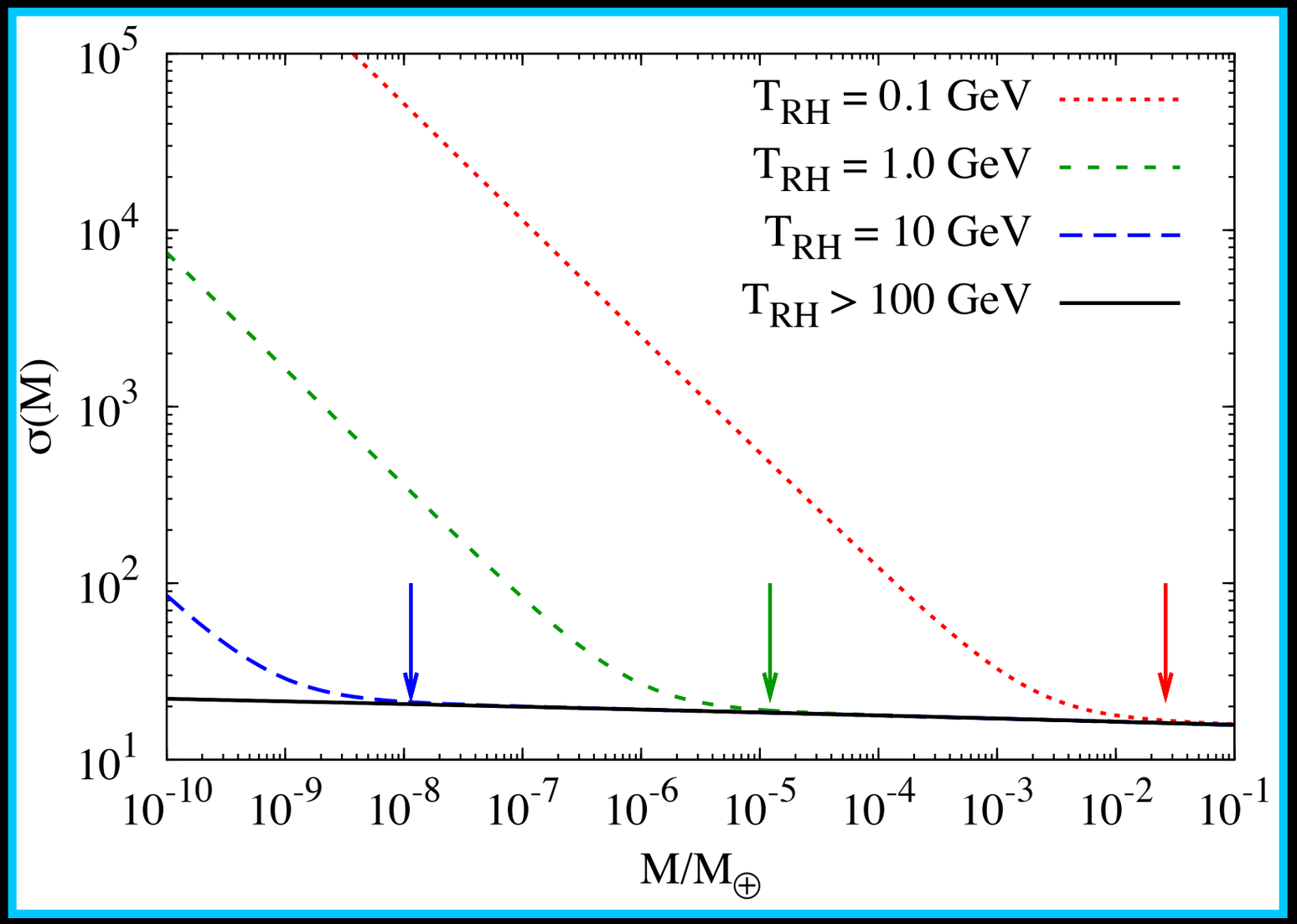
The Dark Matter Perturbation

The Matter Density Perturbation during Radiation Domination



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

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.

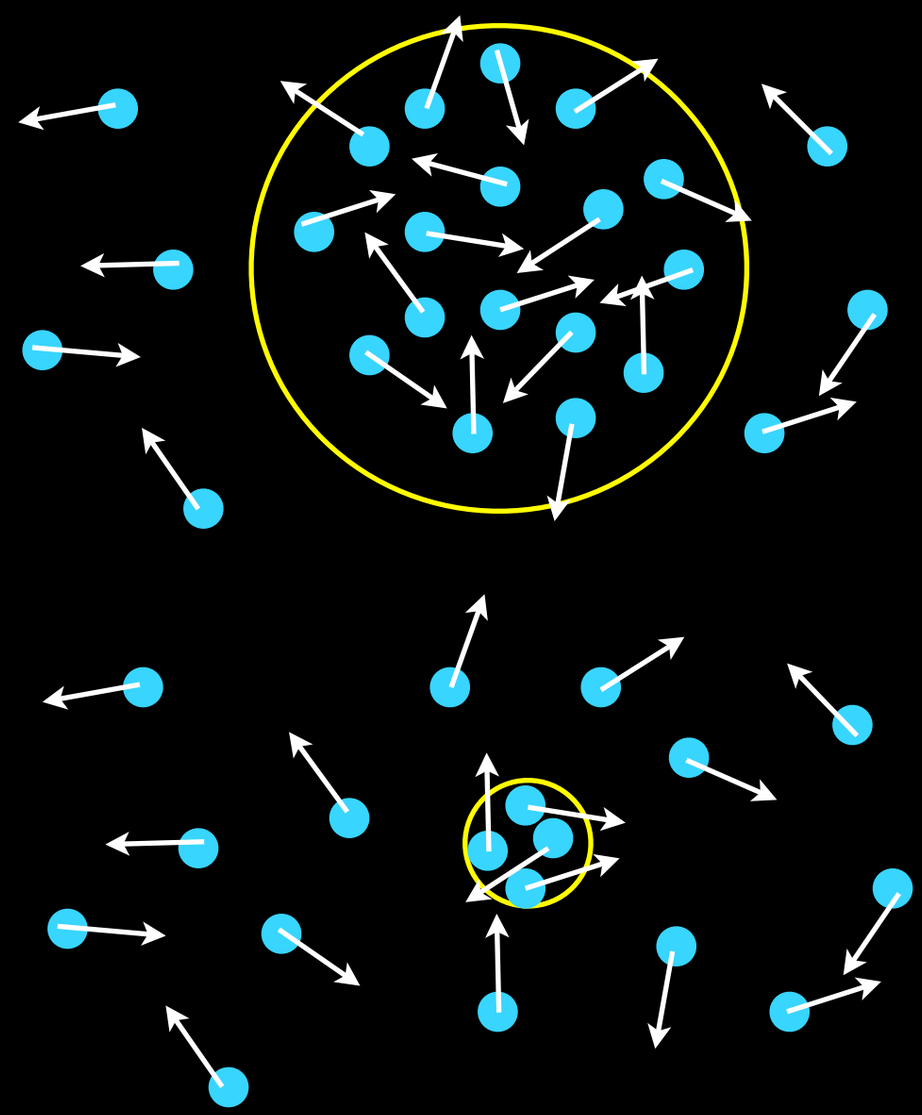
$$M_{\rm RH} \simeq 10^{-5}\, M_\oplus \left(\frac{1\,{\rm GeV}}{T_{\rm RH}}\right)^3$$

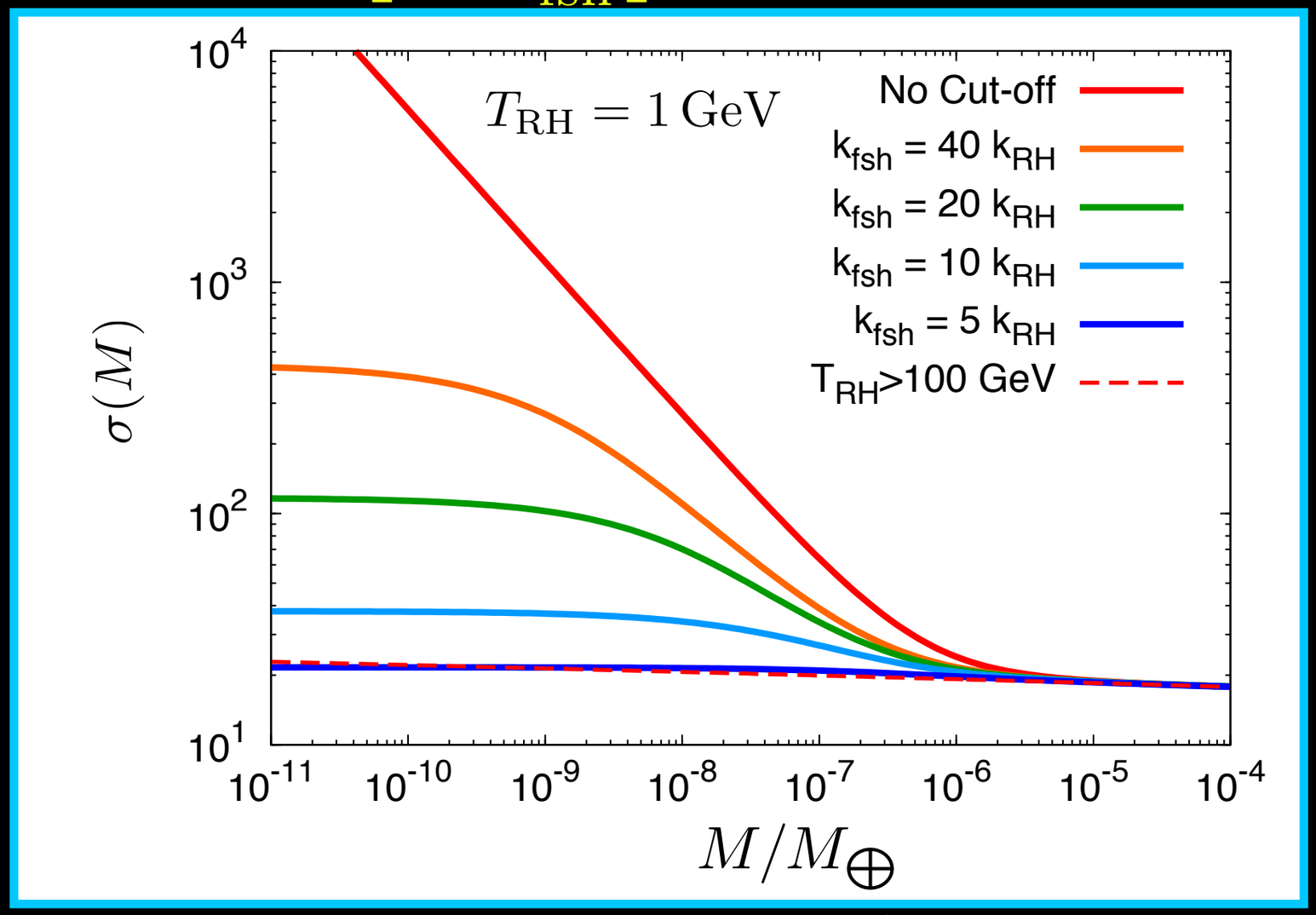
Microhalos!

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

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.

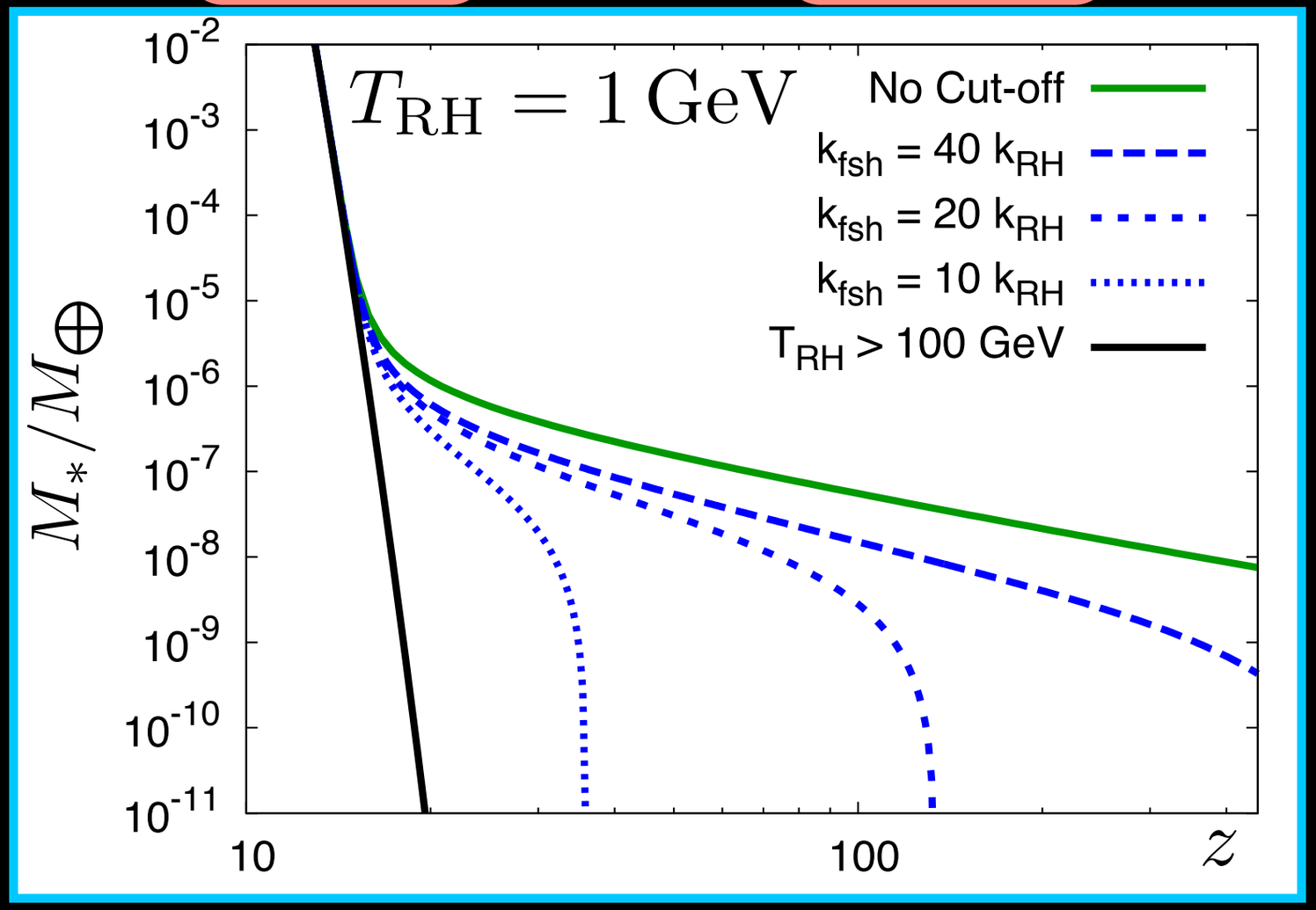
$$\frac{df}{d\ln M} = \sqrt{\frac{2}{\pi}} \left| \frac{d\ln\sigma}{d\ln M} \right| \frac{\delta_c}{\sigma(M,z)} \exp\left[-\frac{1}{2} \frac{\delta_c^2}{\sigma^2(M,z)} \right]$$

differential bound fraction

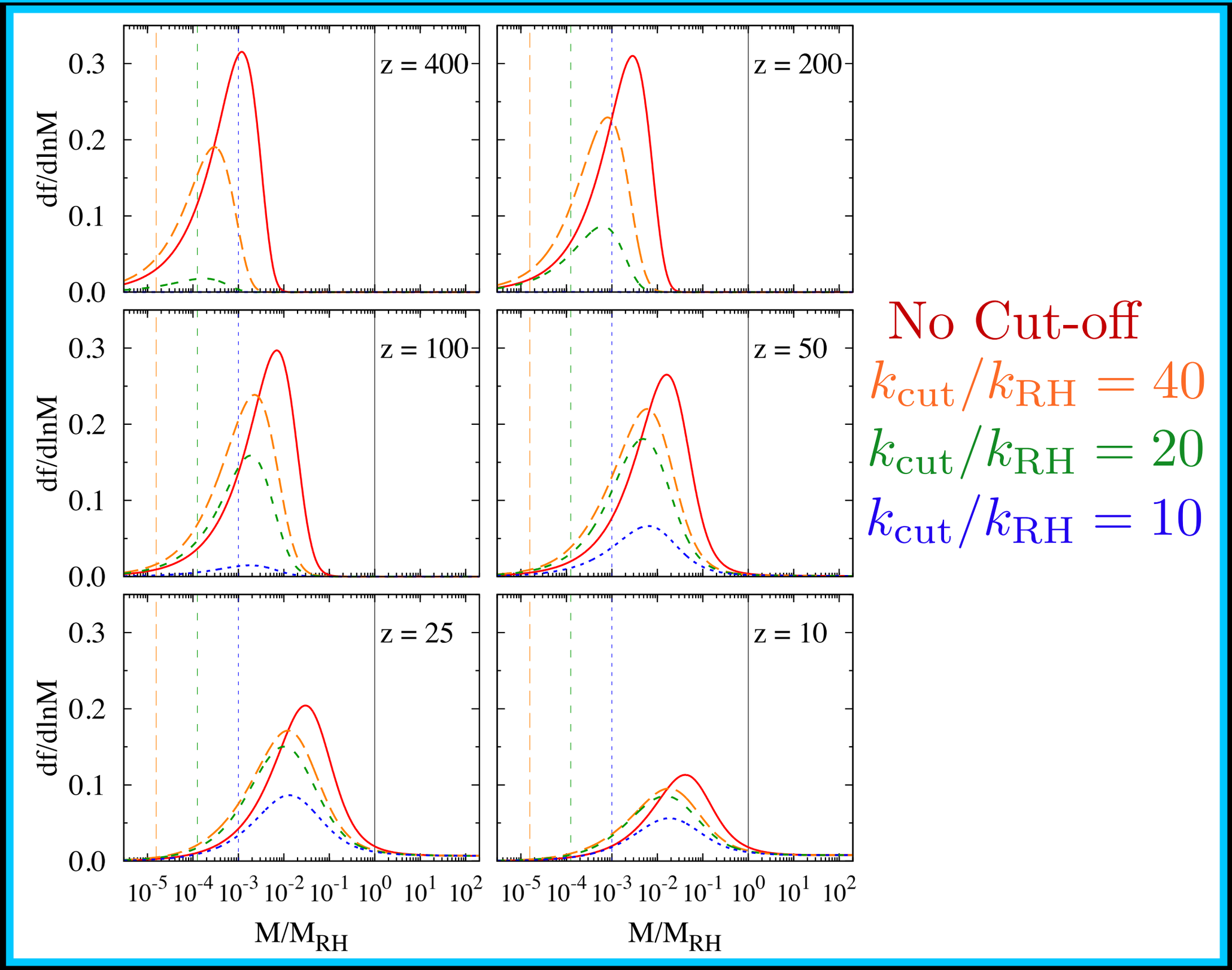
Key ratio: $\frac{\delta_c}{\sigma(M,z)}$

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

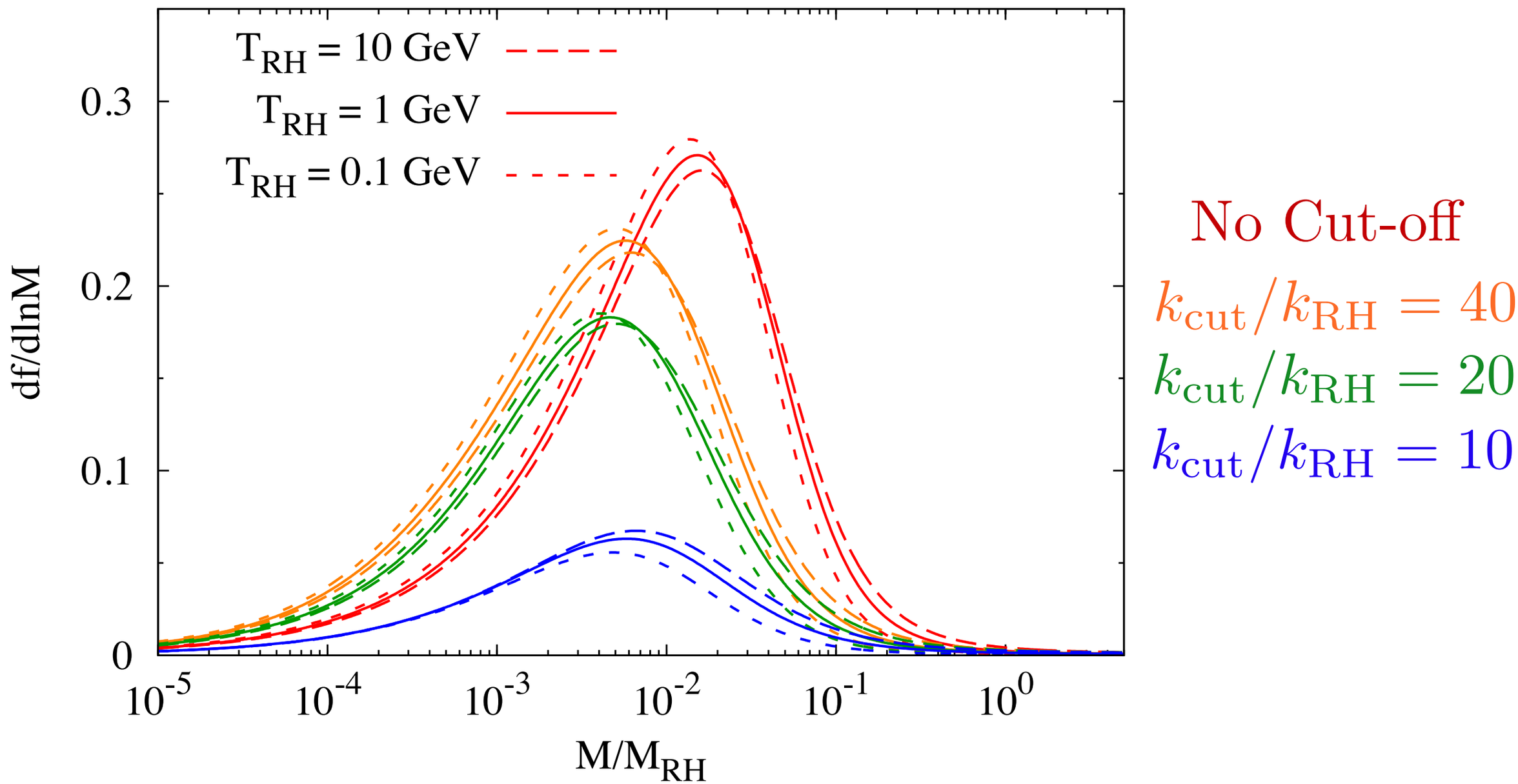
$$\sigma(M_*, z) = \delta_c$$



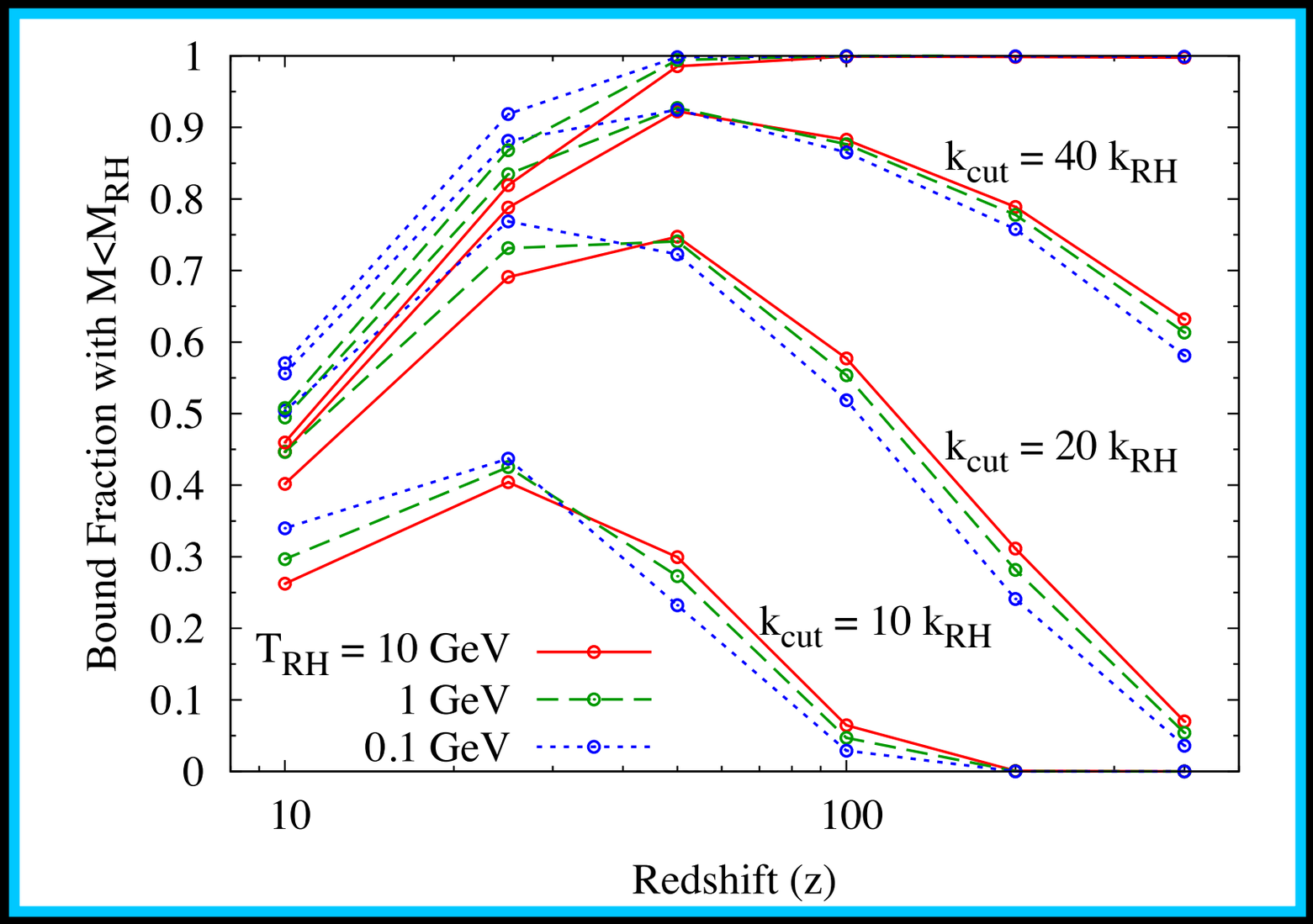
The Evolution of the Bound Fraction



Independent of Reheat Temperature



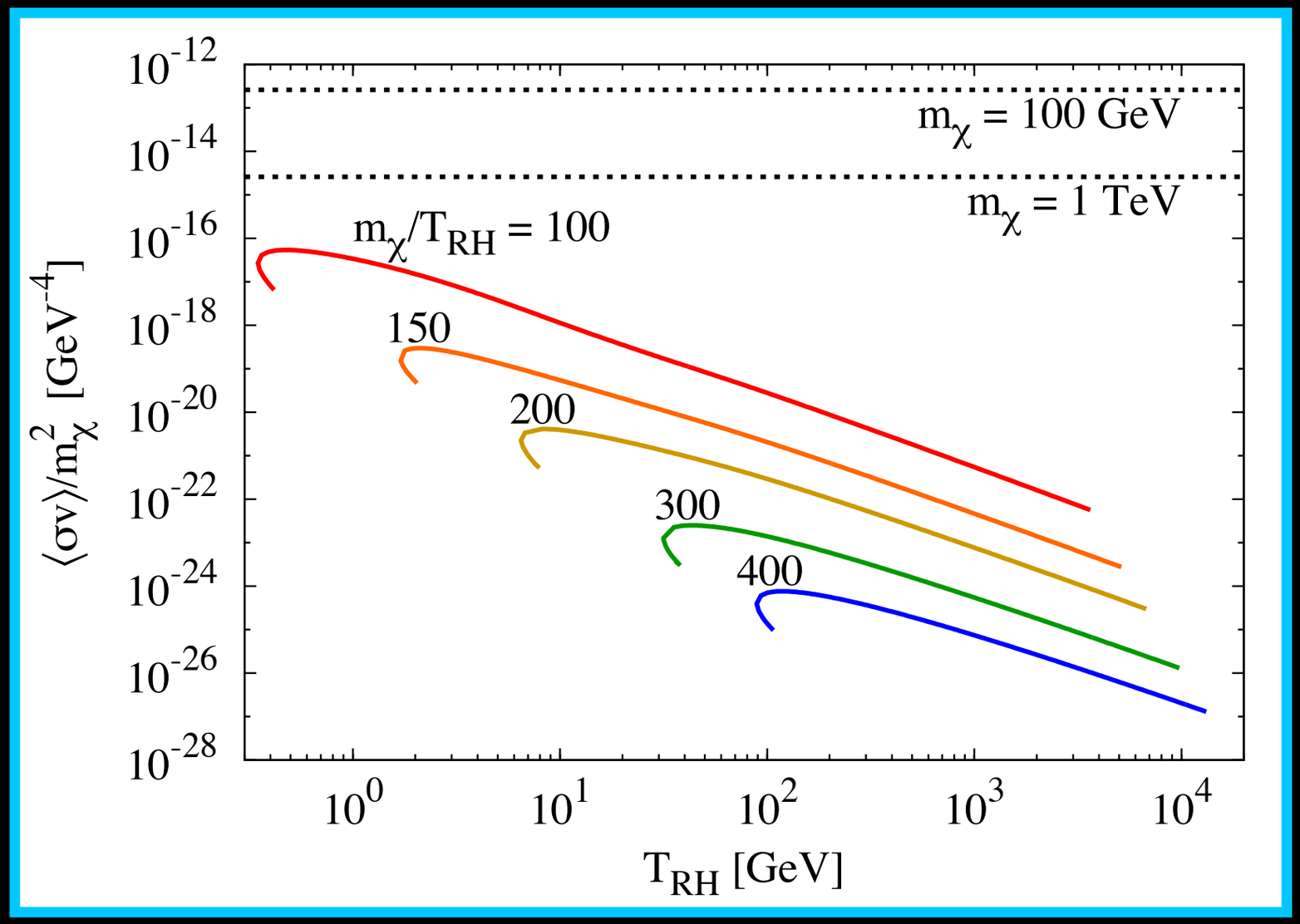
The Total Bound Fraction



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

The Annihilation Rate

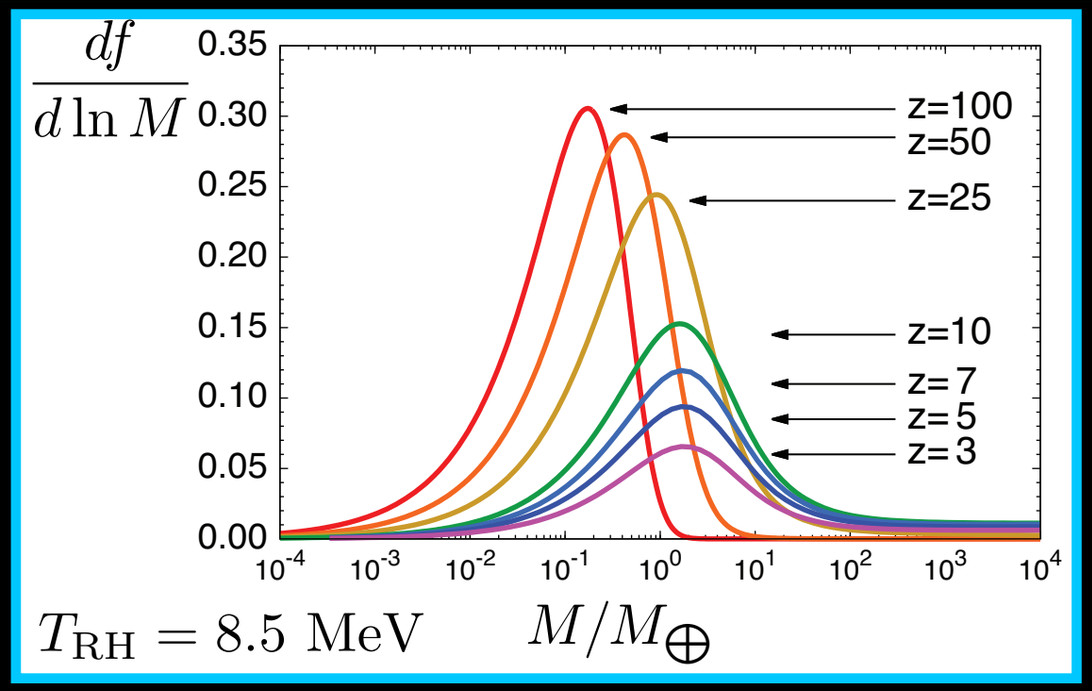
$$\frac{\Gamma_{\rm ann}}{\rm Volume} \propto \langle \sigma v \rangle n_\chi^2 \propto \frac{\langle \sigma v \rangle}{m_\chi^2} \rho_\chi^2$$



- The annihilation rate is highest for small dm masses and low reheat temperatures.
- The boost factor from enhanced substructure is critical for detection.

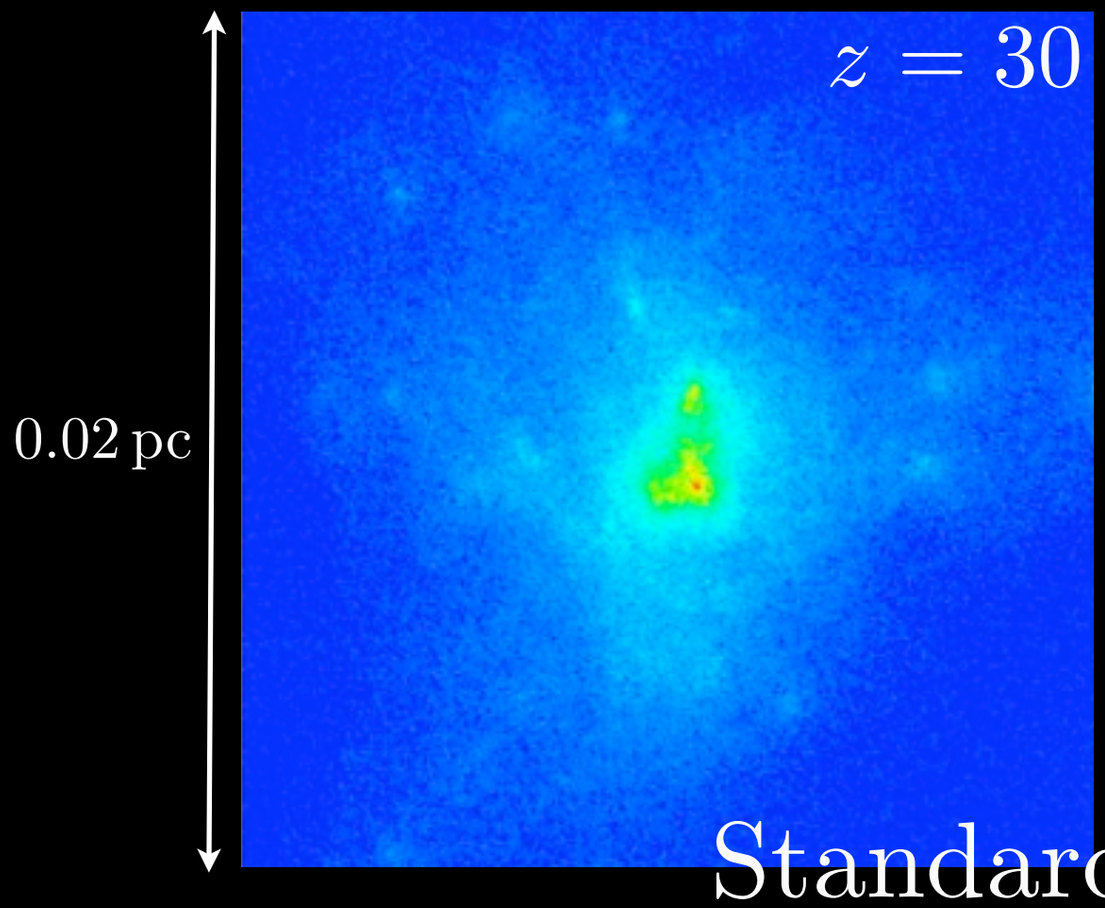
$$\left.\frac{\langle \sigma v \rangle}{m_\chi^2}\right|_{T_{\rm RH}\to\infty} = \frac{2.6\times 10^{-15}}{\rm GeV^4}\left(\frac{1\,\rm TeV}{m_\chi}\right)^2$$

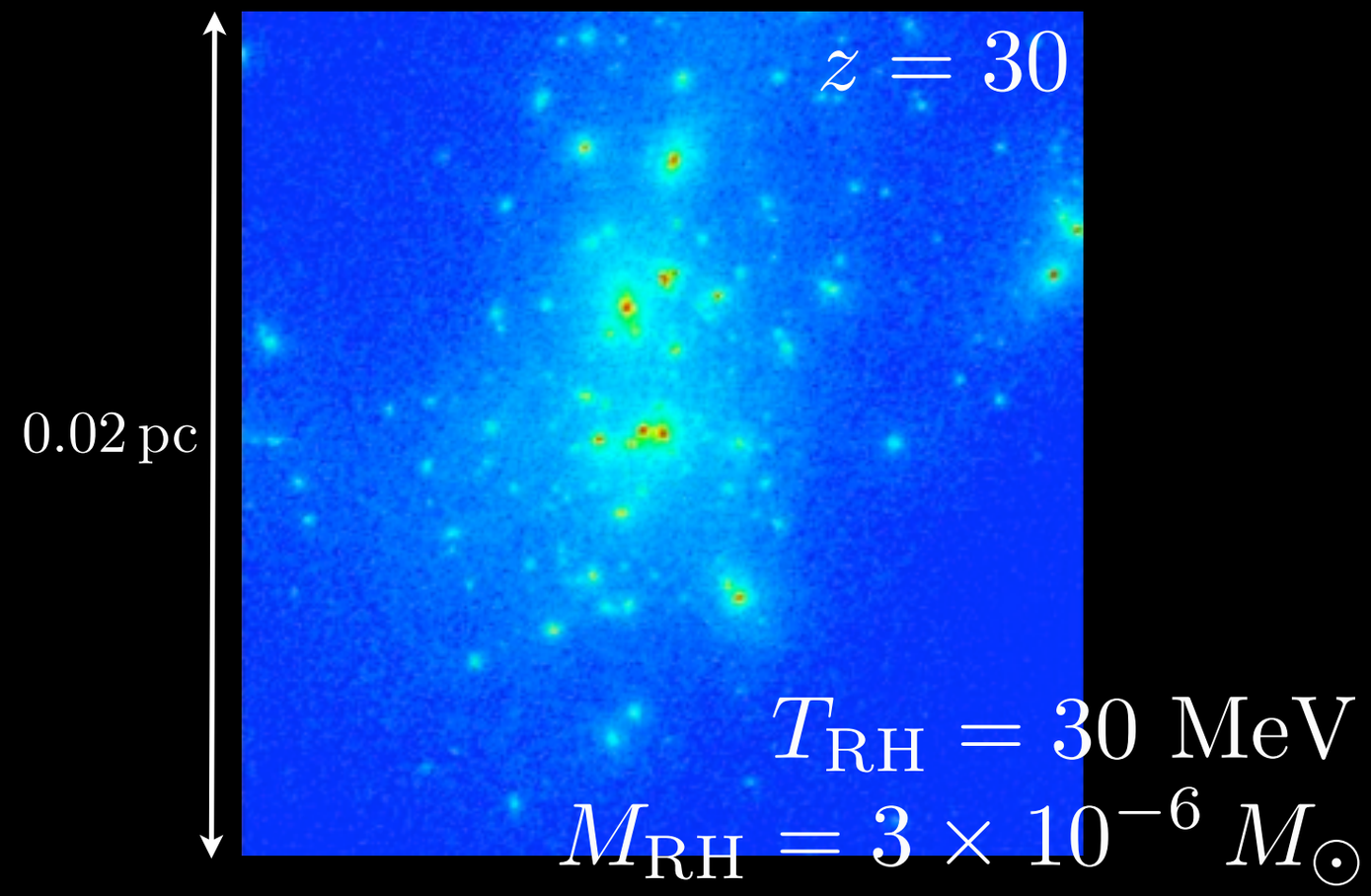
Towards the Boost Factor



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

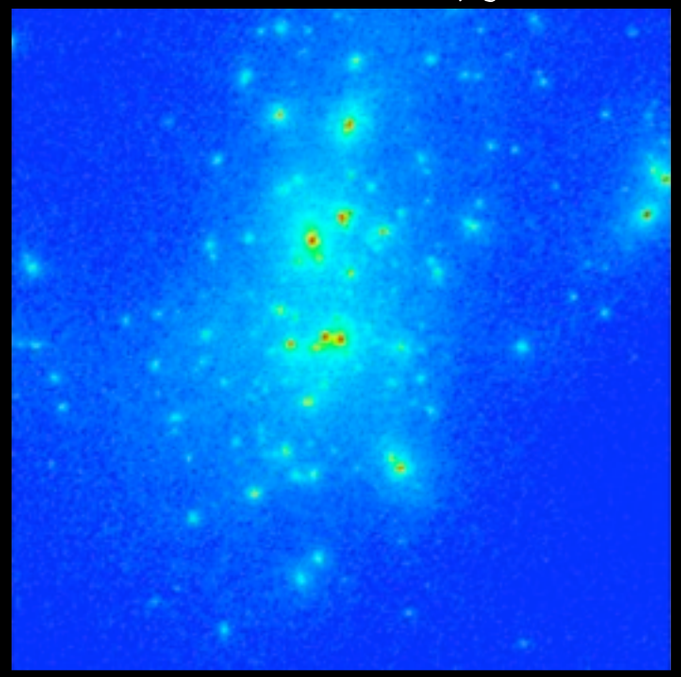
Dark matter annihilation rate: $\Gamma = \frac{\langle \sigma v \rangle}{2m_\chi^2} \int \rho^2(r) d^3r \equiv \frac{\langle \sigma v \rangle}{2m_\chi^2} J$

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:

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



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

Anderhalden & Diemand 2013
Ishiyama 2014

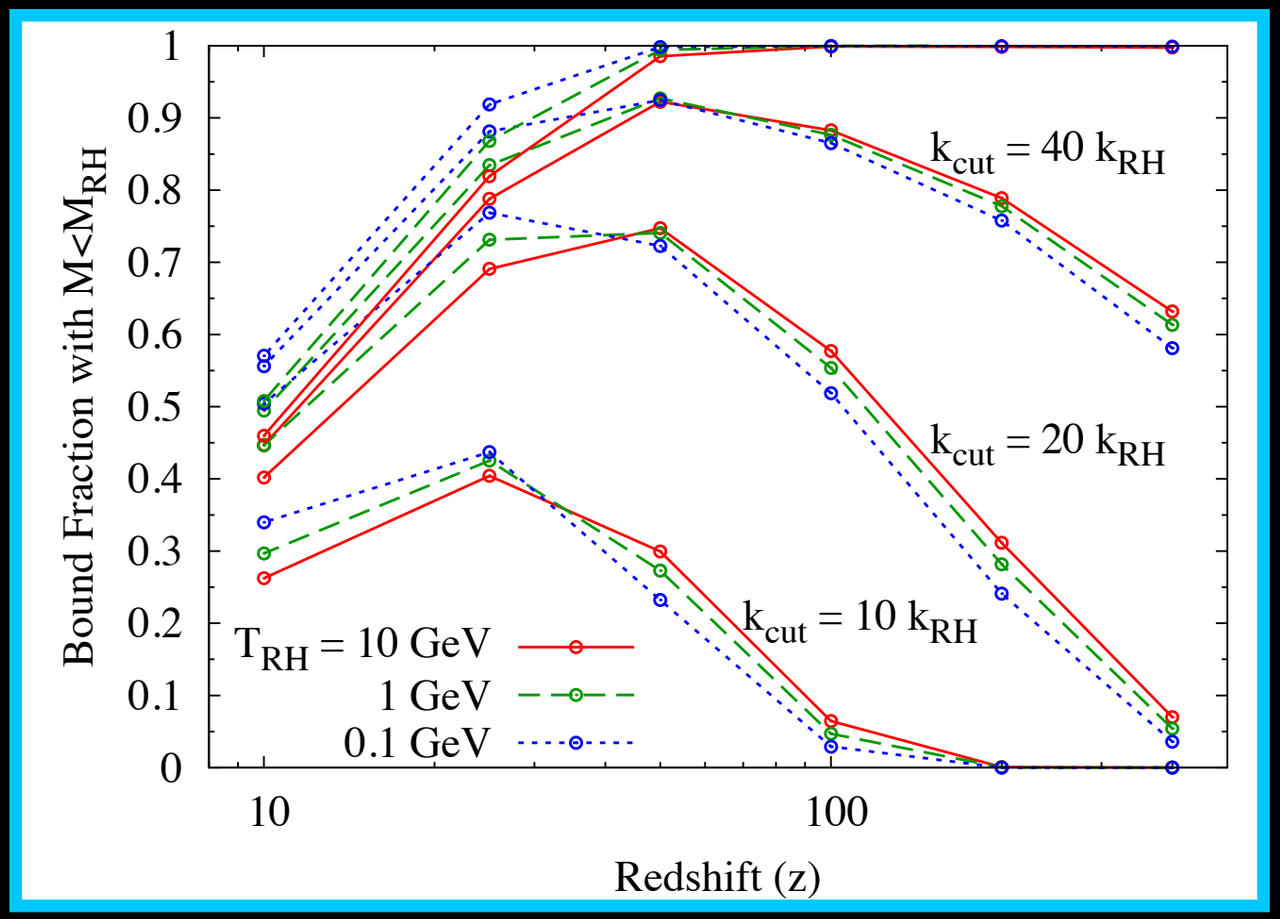
- early forming microhalos: $z_f \gtrsim 50$
- dense cores: $\bar{\rho}_{\rm micro}(r_s) > 2\bar{\rho}_{\rm halo}(r)$ for $r > 1\,{\rm kpc}$
- assume that microhalo centers survive outside of inner kpc: reduces number of microhalos by 1%.
- assume that microhalos are stripped to $r = r_s$: reduces $J_{\rm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

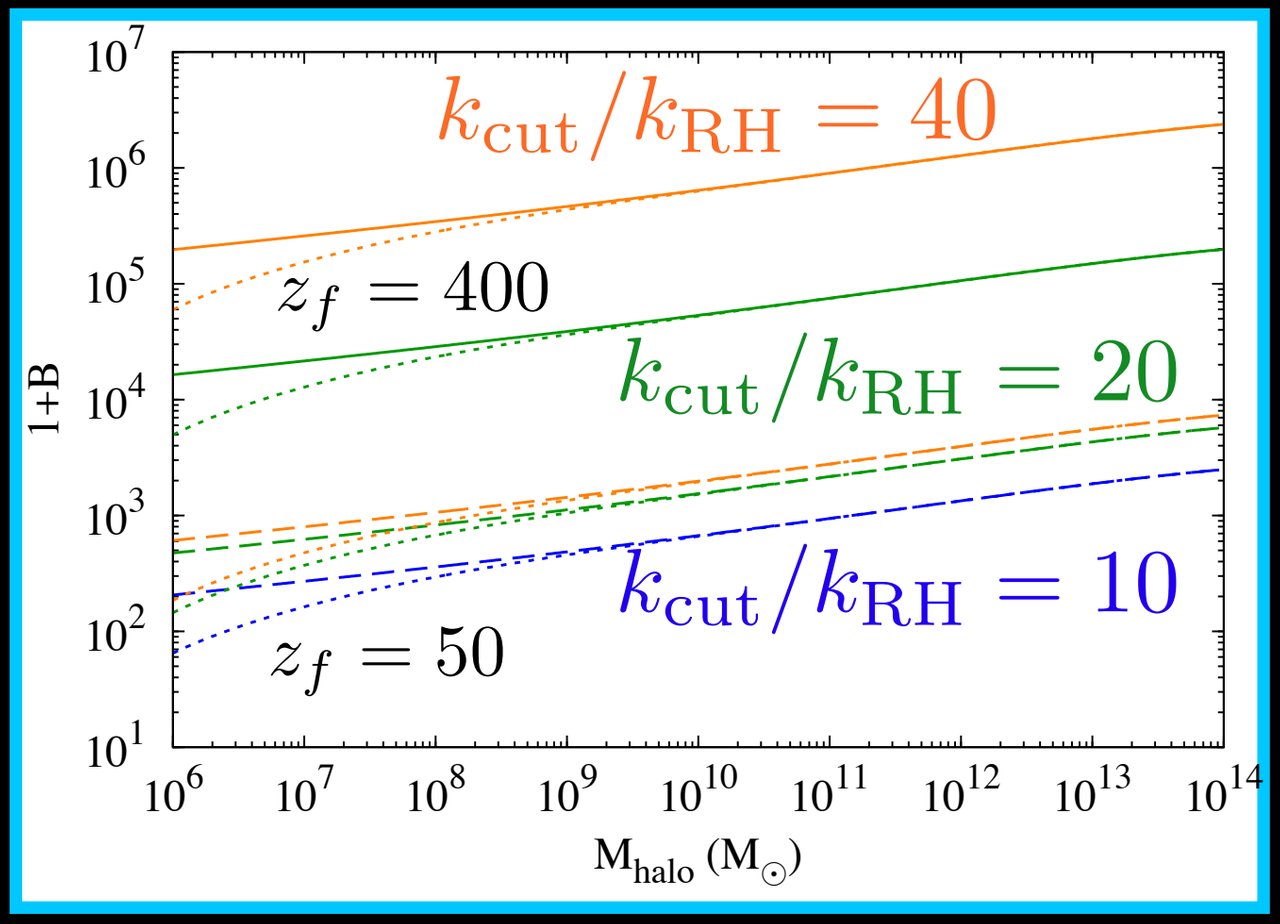
Estimating the Boost Factor II

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:

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



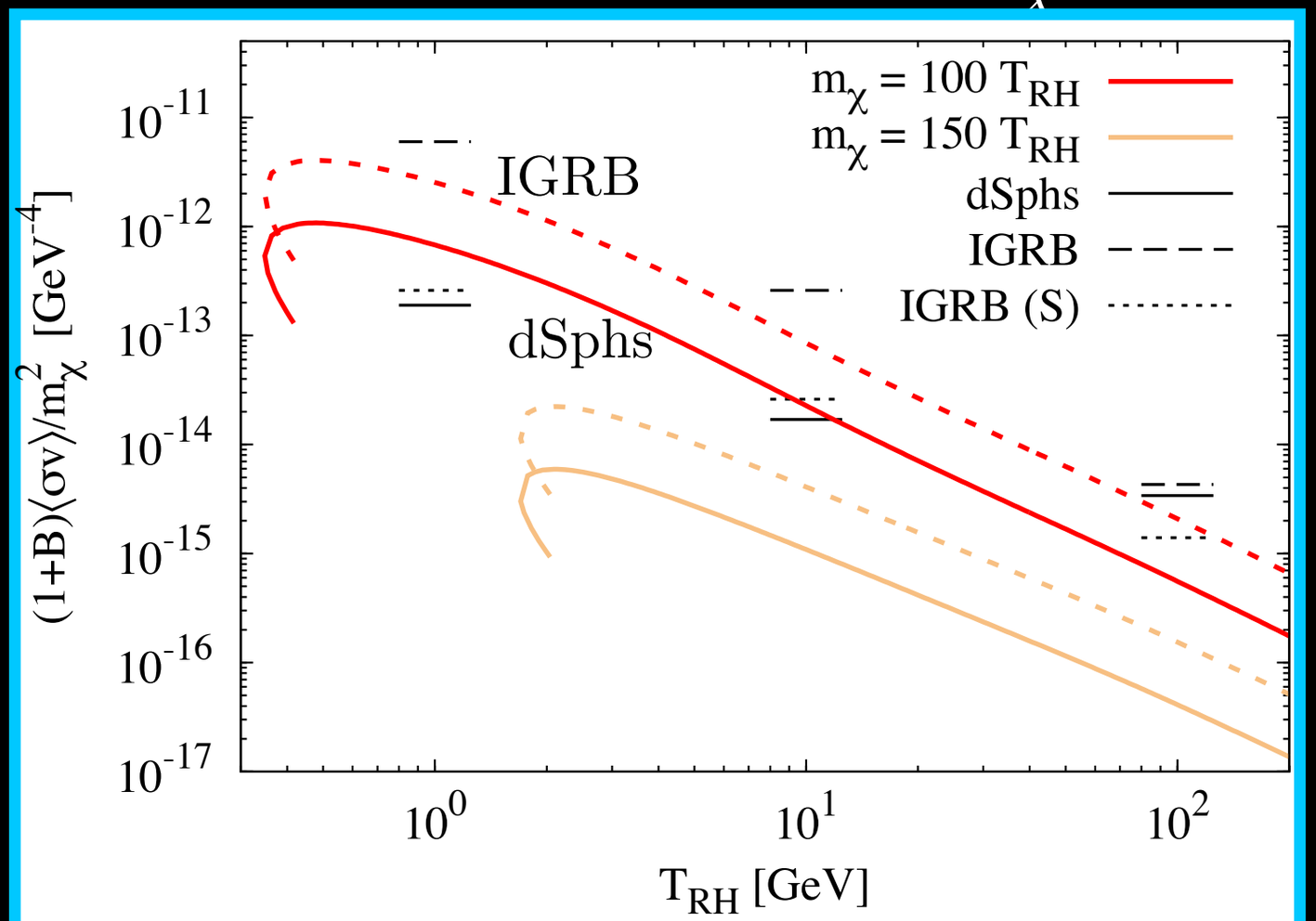


ALE 2015

Boost from Microhalos

Moving Toward Constraints

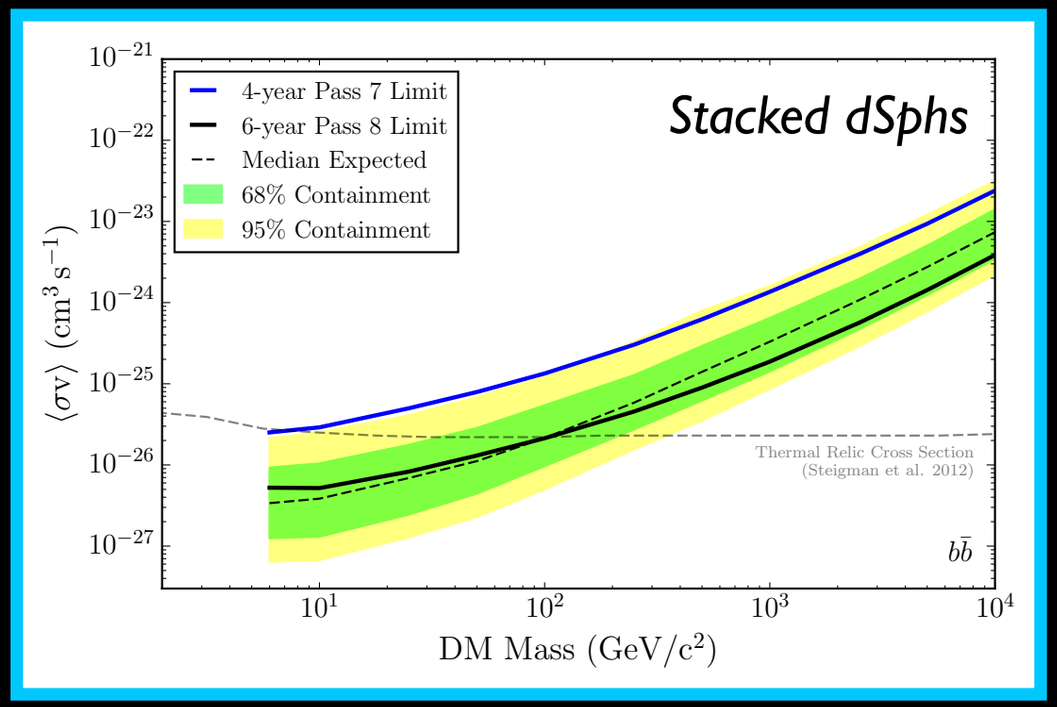
$$\frac{\Gamma_{\rm ann}}{\rm Volume} \propto \langle \sigma v \rangle n_\chi^2 \propto \frac{\langle \sigma v \rangle}{m_\chi^2} \rho_\chi^2$$



$$\text{IGRB: } B = 75,000 \quad k_{\rm cut} = 40 k_{\rm RH}$$

$$\text{dSphs: } B = 20,000 \quad k_{\rm cut} = 20 k_{\rm RH}$$

$$z_f = 400$$



Fermi-LAT Collaboration 2015

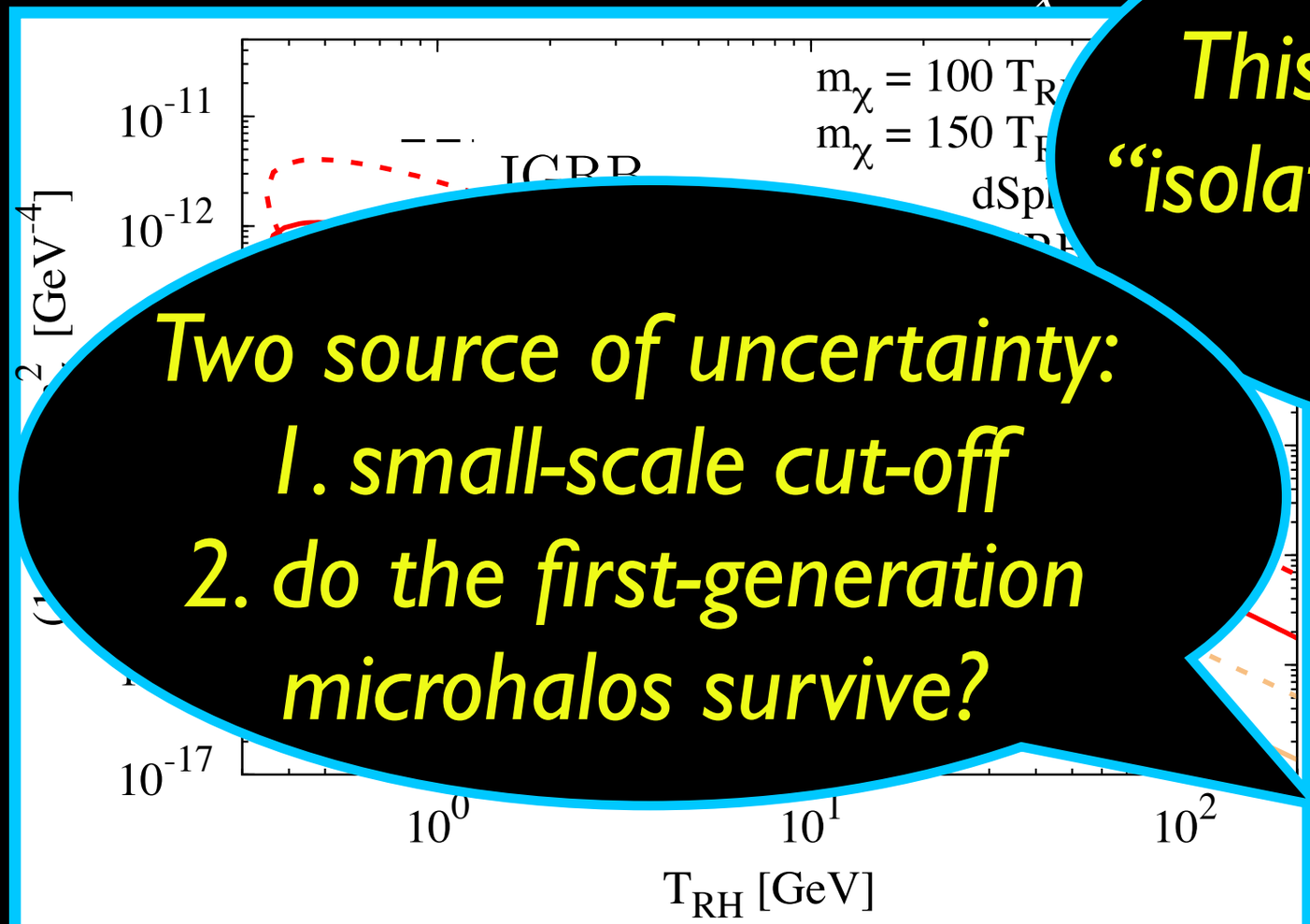
- Rough comparison

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

- dSphs: total boost for $10^6 M_\odot$ halo.
- IGRB: EMDE boost relative to standard boost.

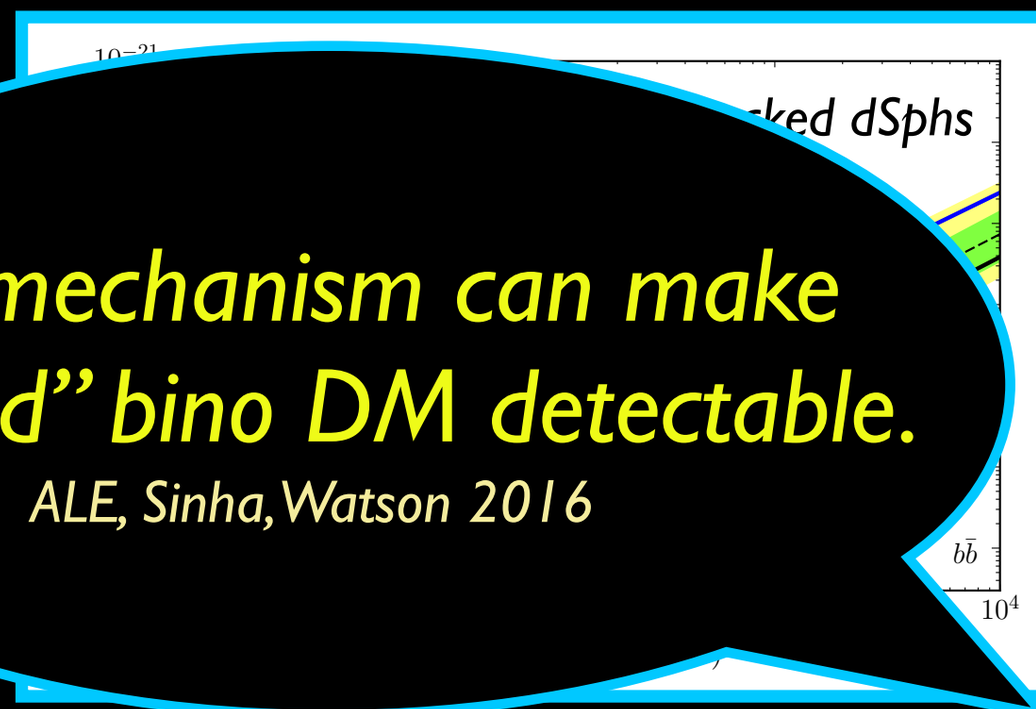
Moving Toward Constraints

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



Two source of uncertainty:
1. small-scale cut-off
2. do the first-generation microhalos survive?

$$\text{IGRB: } B = 75,000 \quad k_{\rm cut} = 40 k_{\rm RH}$$
$$\text{dSphs: } B = 20,000 \quad k_{\rm cut} = 20 k_{\rm RH}$$
$$z_f = 400$$



This mechanism can make "isolated" bino DM detectable.

ALE, Sinha, Watson 2016

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: total boost for $10^6 M_\odot$ halo.
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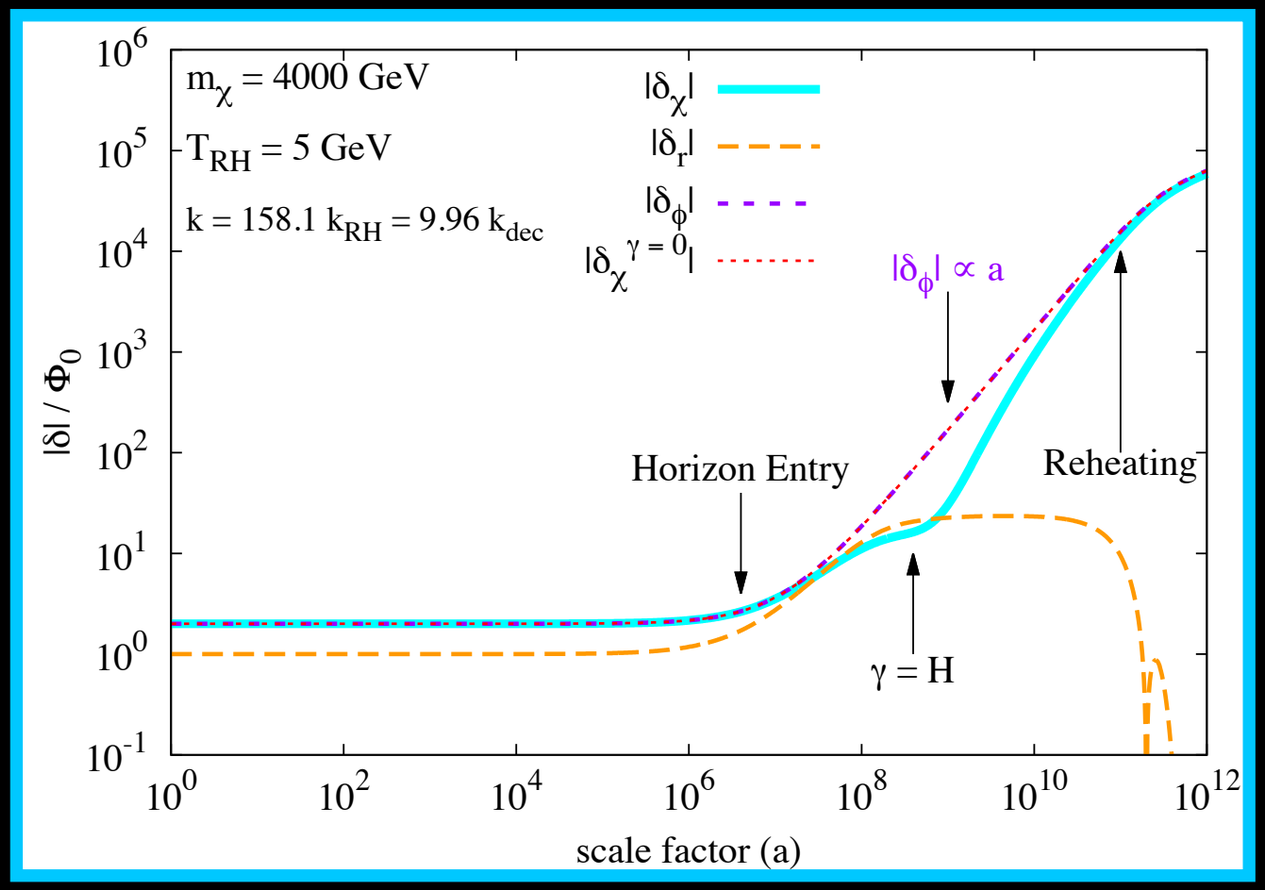
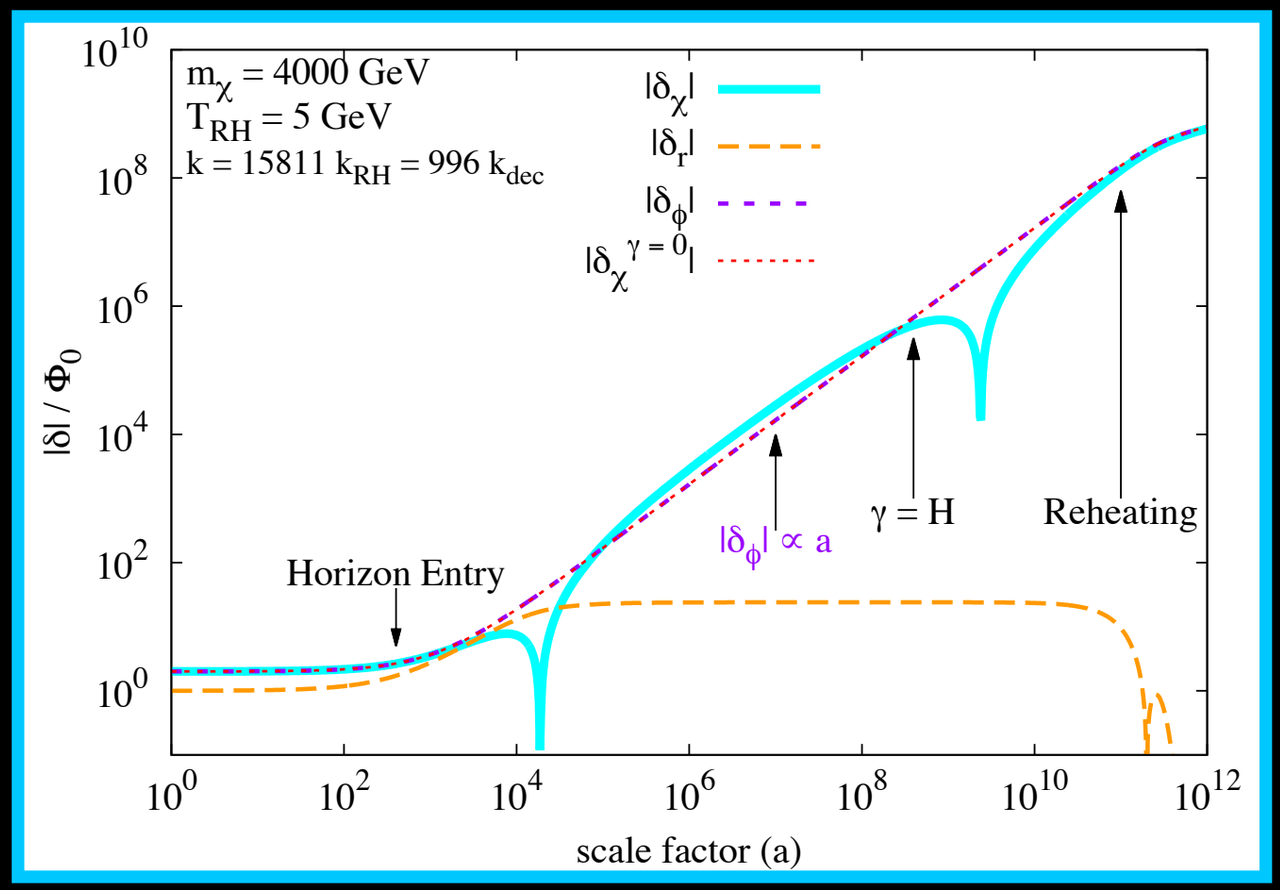
Kinetic Decoupling during an EMDE

Isaac Waldstein, ALE, Cosmin Ilie, coming soon

First potential source of a small-scale cut-off:
interactions between dark matter and relativistic particles





Interactions do not significantly suppress the perturbations,
even if the dark matter remains coupled to the relativistic particles
well into the EMDE...

Kinetic Decoupling during an EMDE

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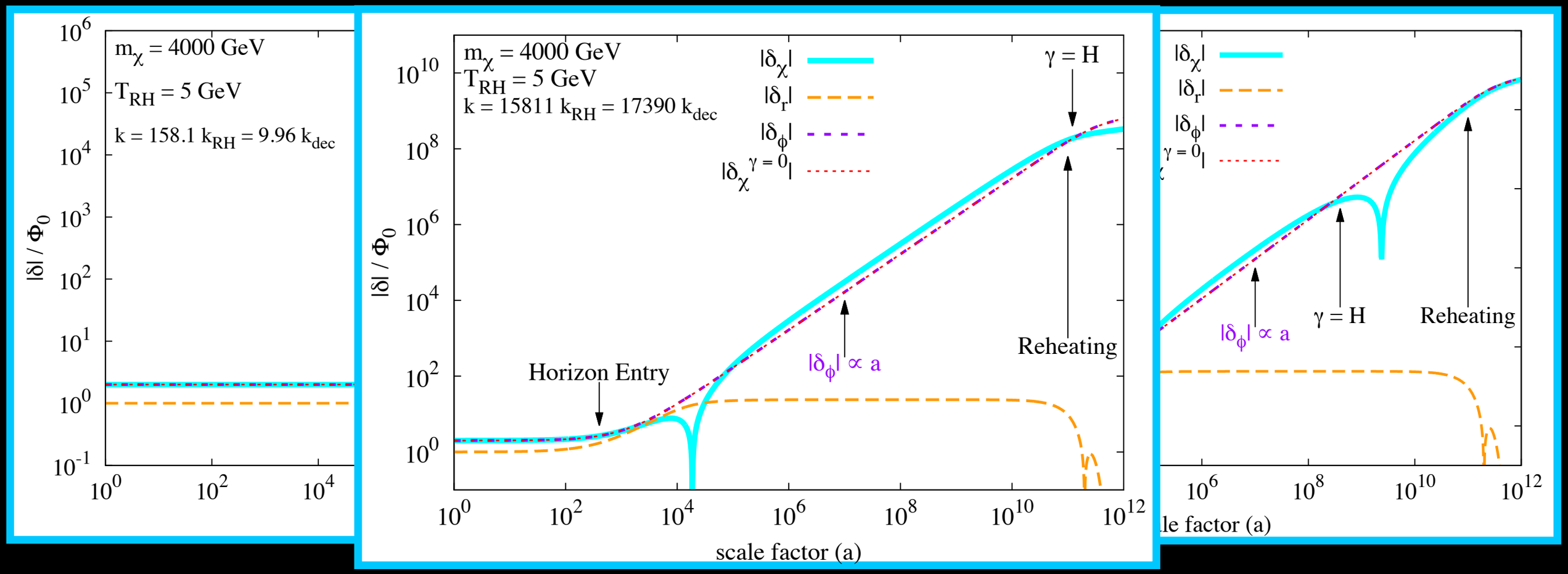
First potential source of a small-scale cut-off:
interactions between dark matter and relativistic particles



Interactions do not significantly suppress the perturbations,
even if the dark matter remains coupled to the relativistic particles
well into the EMDE... and even through reheating!

see also Choi, Gong, Shin 2015

The DM temperature

Isaac Waldstein, ALE, Cosmin Ilie 2017

What about free-streaming? We need the DM temperature.

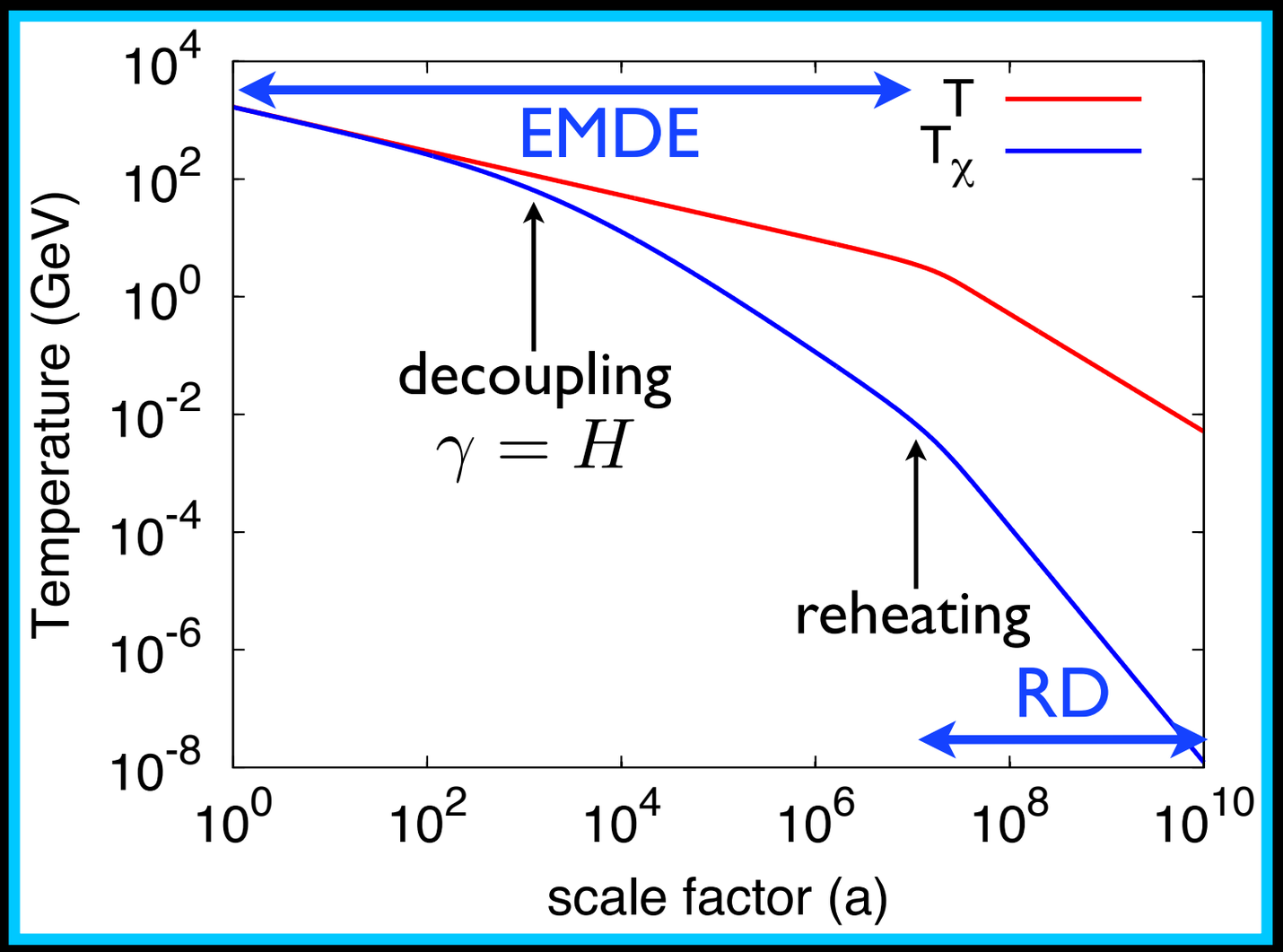
$$T_\chi \equiv \frac{2}{3}\left\langle \frac{|\vec{p}|^2}{2m_\chi} \right\rangle$$

$$a\frac{dT_\chi}{da} + 2T_\chi = -2\frac{\gamma}{H}(T_\chi - T)$$

momentum transfer rate

$$\gamma \propto T^6$$

expansion rate



- fully coupled:
  $\gamma \gg H \Rightarrow T_\chi \simeq T$
- fully decoupled:
  $\gamma \ll H \Rightarrow T_\chi \propto a^{-2}$
- But during an EMDE
  $$\frac{\gamma}{H}T \propto \frac{T^6}{T^4}T \propto T^3 \propto a^{-9/8}$$
- quasi-decoupled: $T_\chi \propto a^{-9/8}$

The DM temperature

Isaac Waldstein, ALE, Cosmin Ilie 2017

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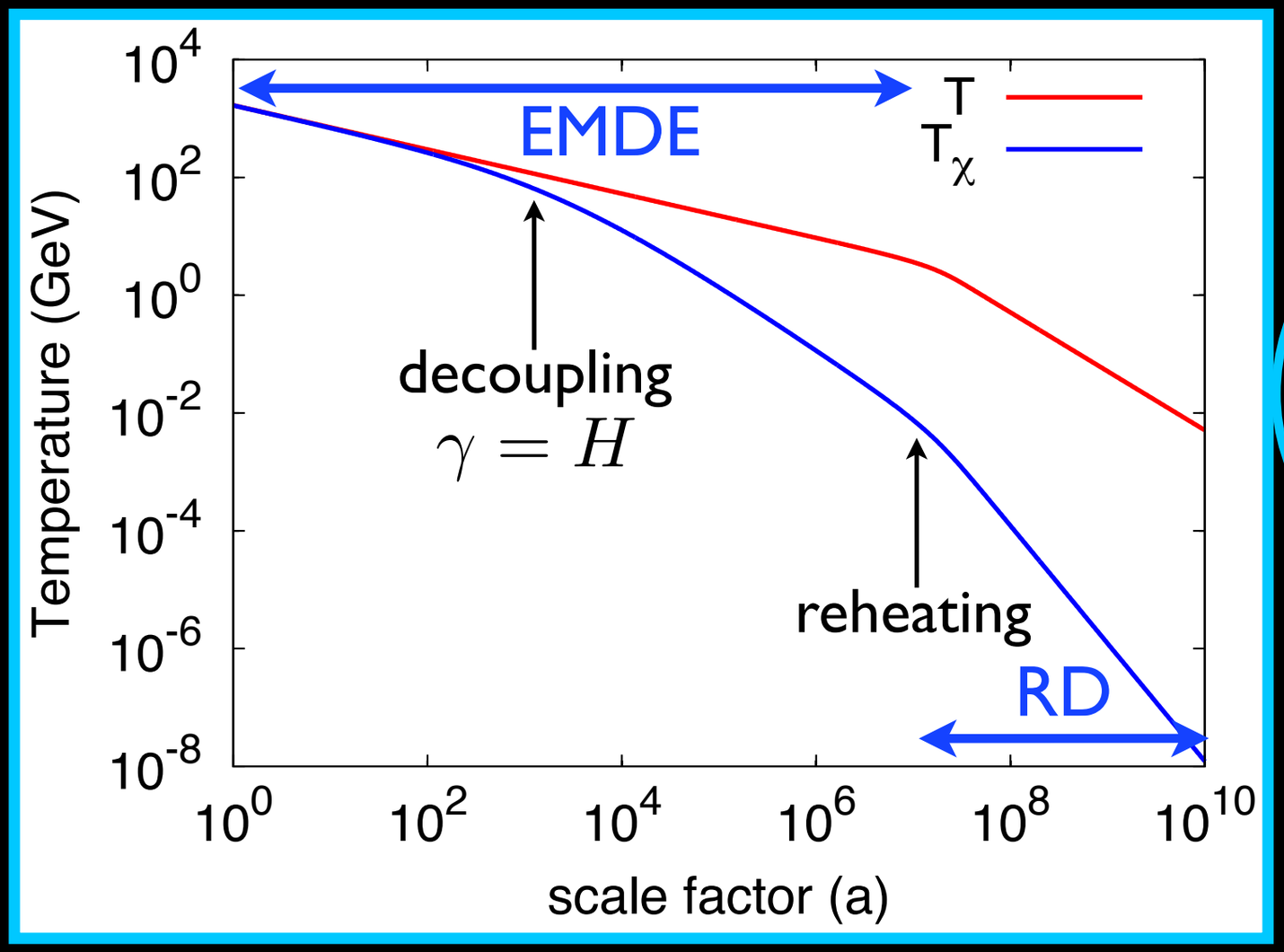


- fully coupled:

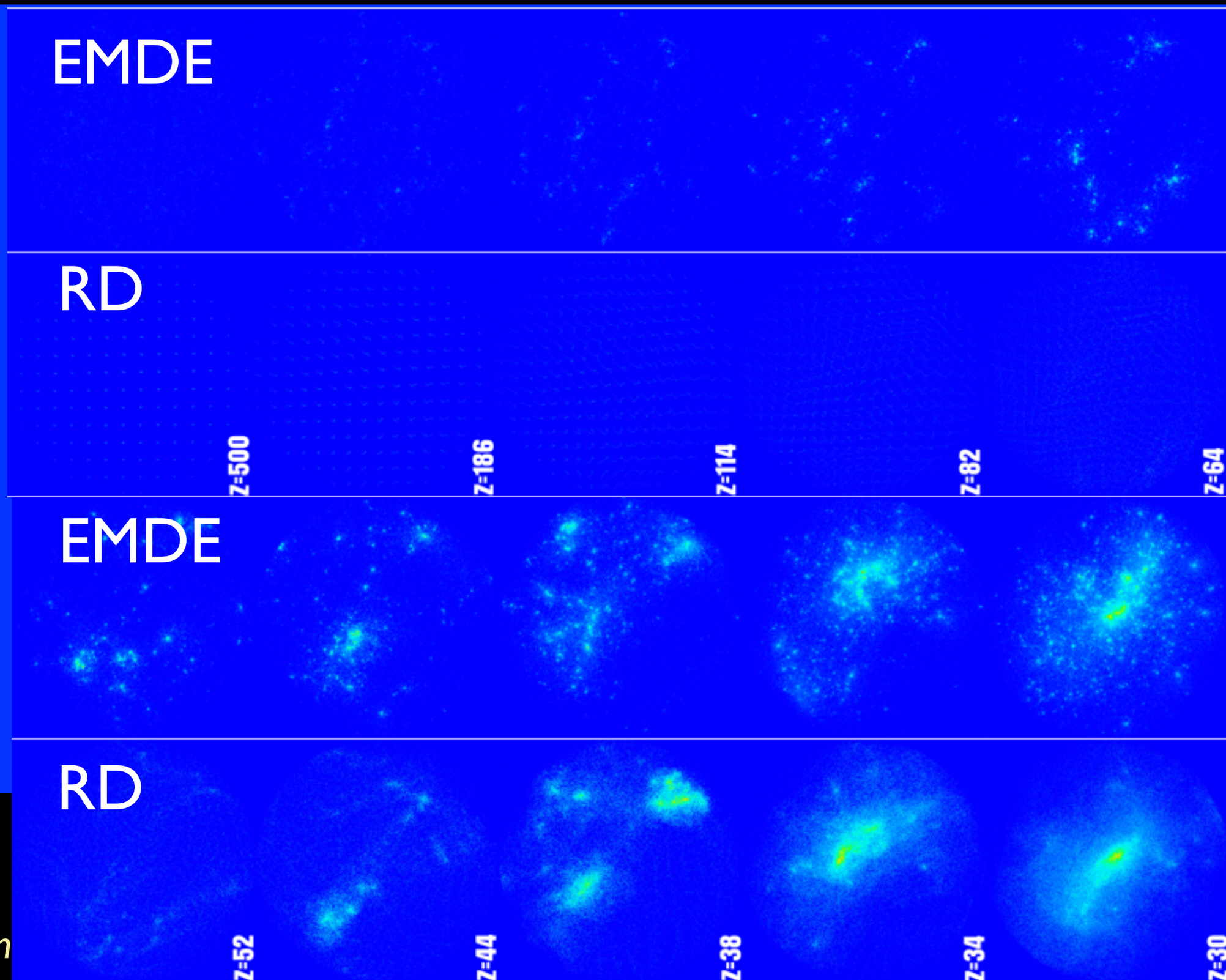
But what are the implications for free-streaming? It depends....

- B

$$\frac{\gamma}{H}T \propto \frac{T}{T^4}T \propto T^3 \propto a^{-9/8}$$

- quasi-decoupled: $T_\chi \propto a^{-9/8}$

Microhalo Simulations



E

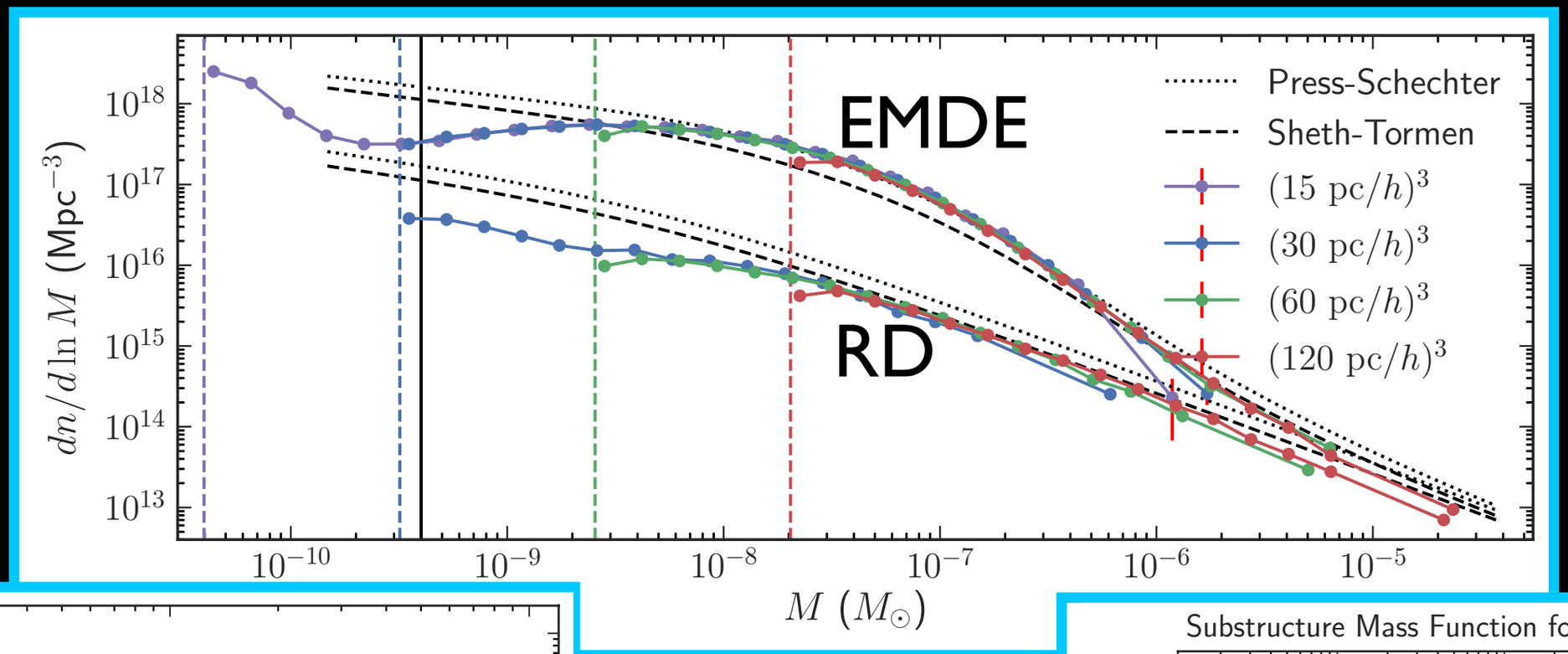
MeV

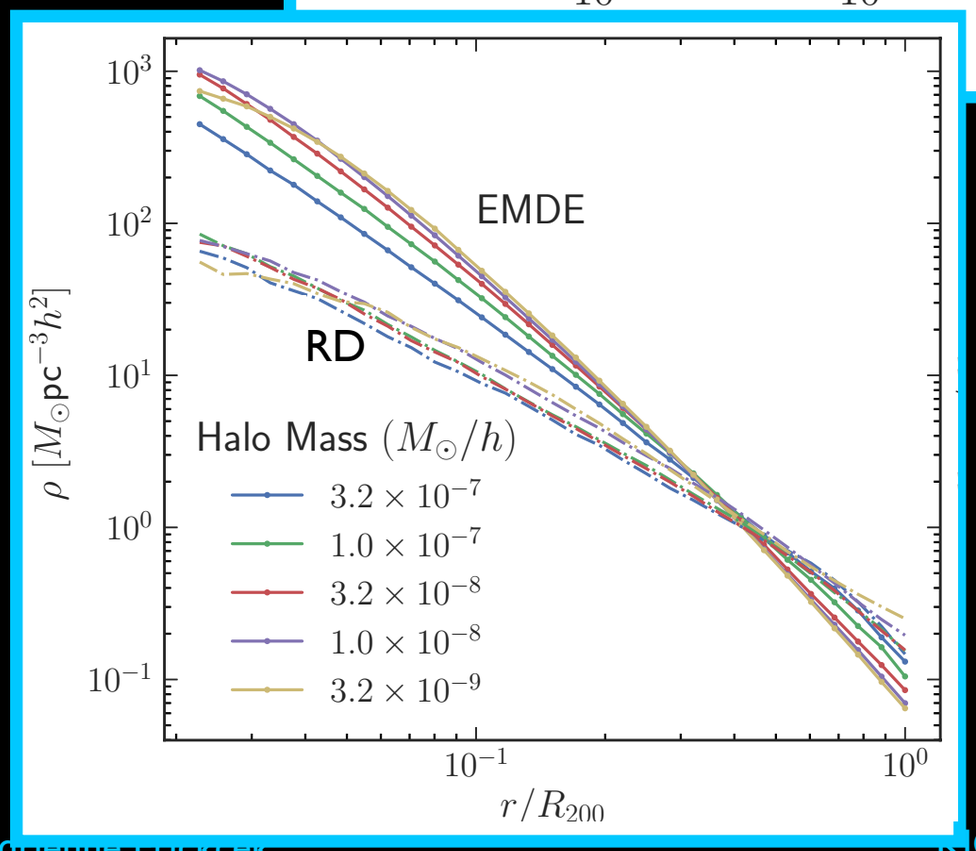
k_{RH}

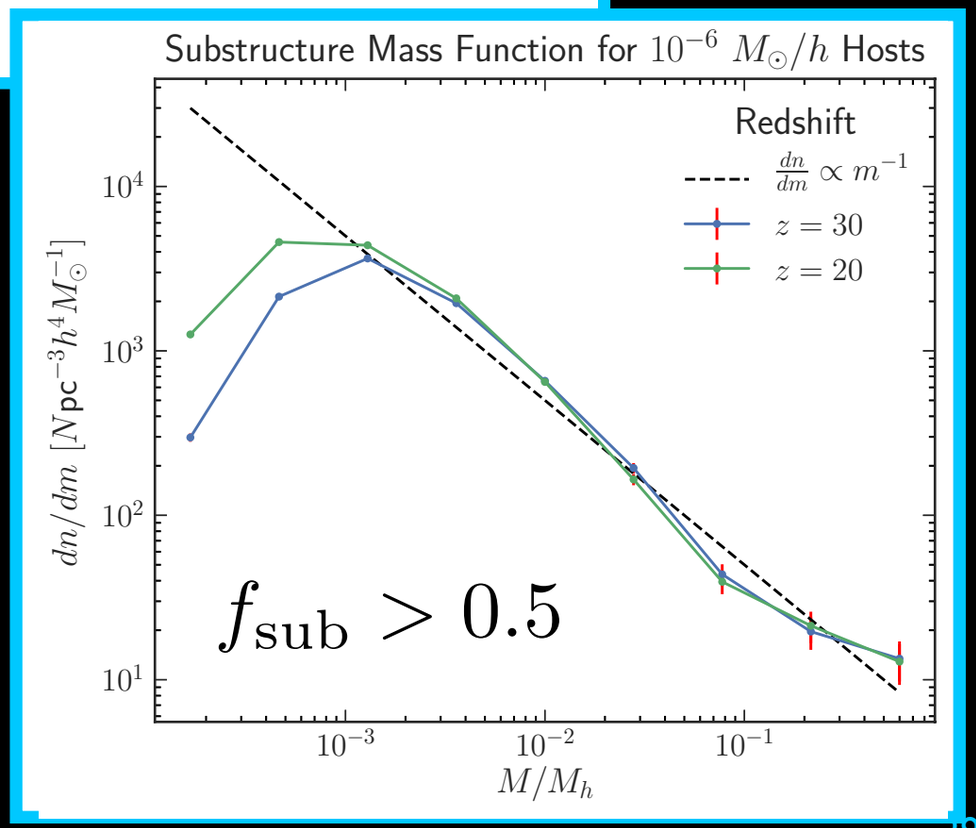
Sheridan

Simulation Results

Lots of microhalos with steep profiles and copious substructure.







Boost Factor from Simulations

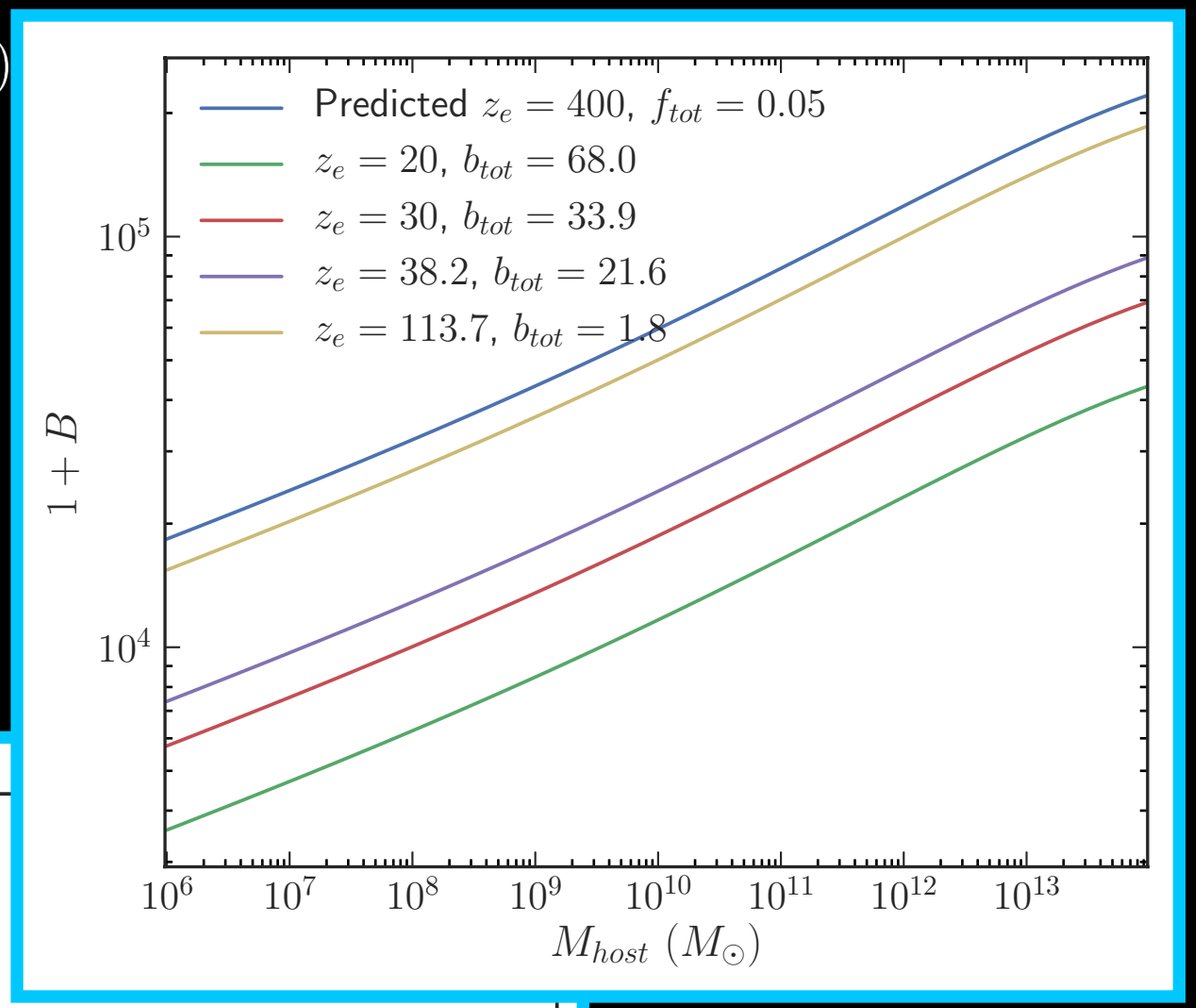
$$1 + B(M) \equiv \frac{J}{\int \bar{\rho}_\chi^2(r)\, 4\pi r^2 dr} \propto \frac{\rho(z_f)}{\rho_0 c_h^3} f_{\rm tot}(M < M_{\rm RH}, z_f)$$

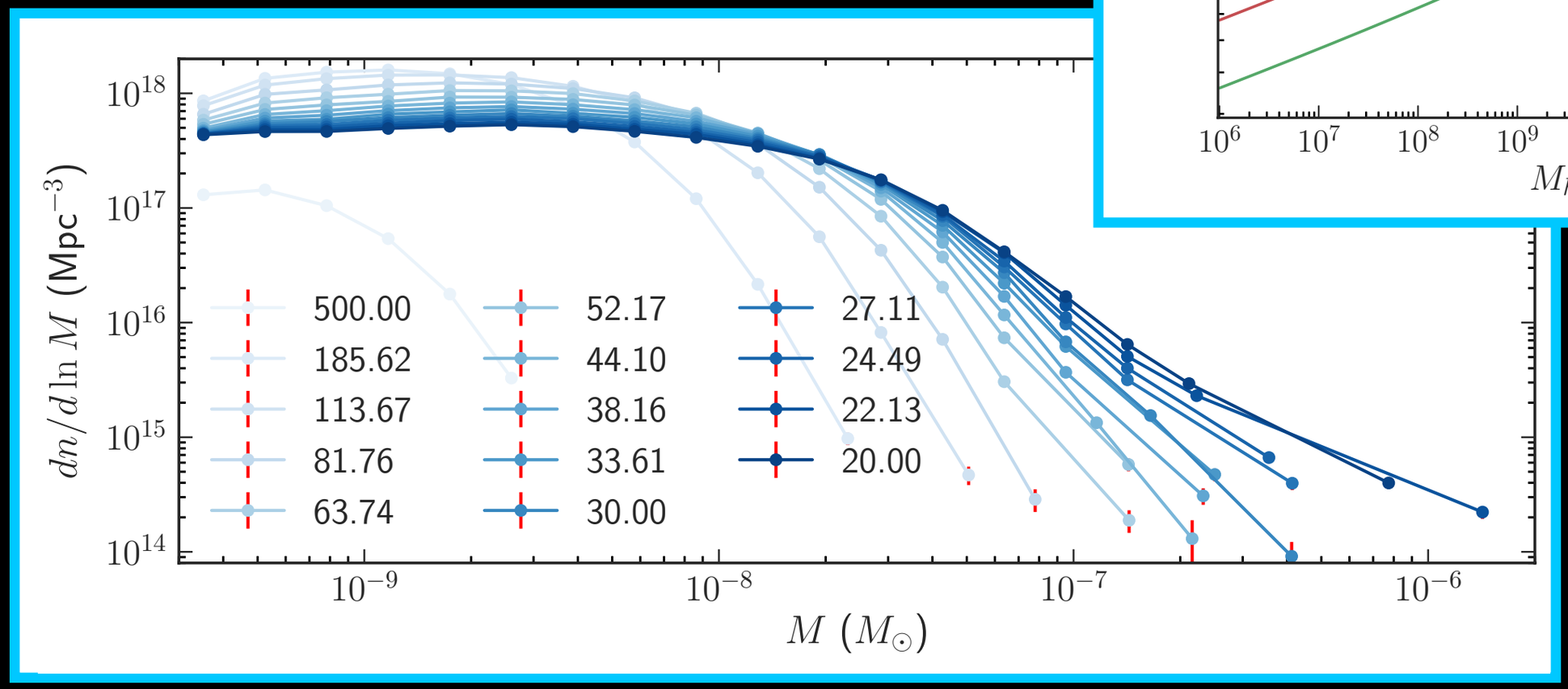
assumes all halos have same profile at z_f

include substructure:

$$f_{\rm tot} \rightarrow b_{\rm tot}$$

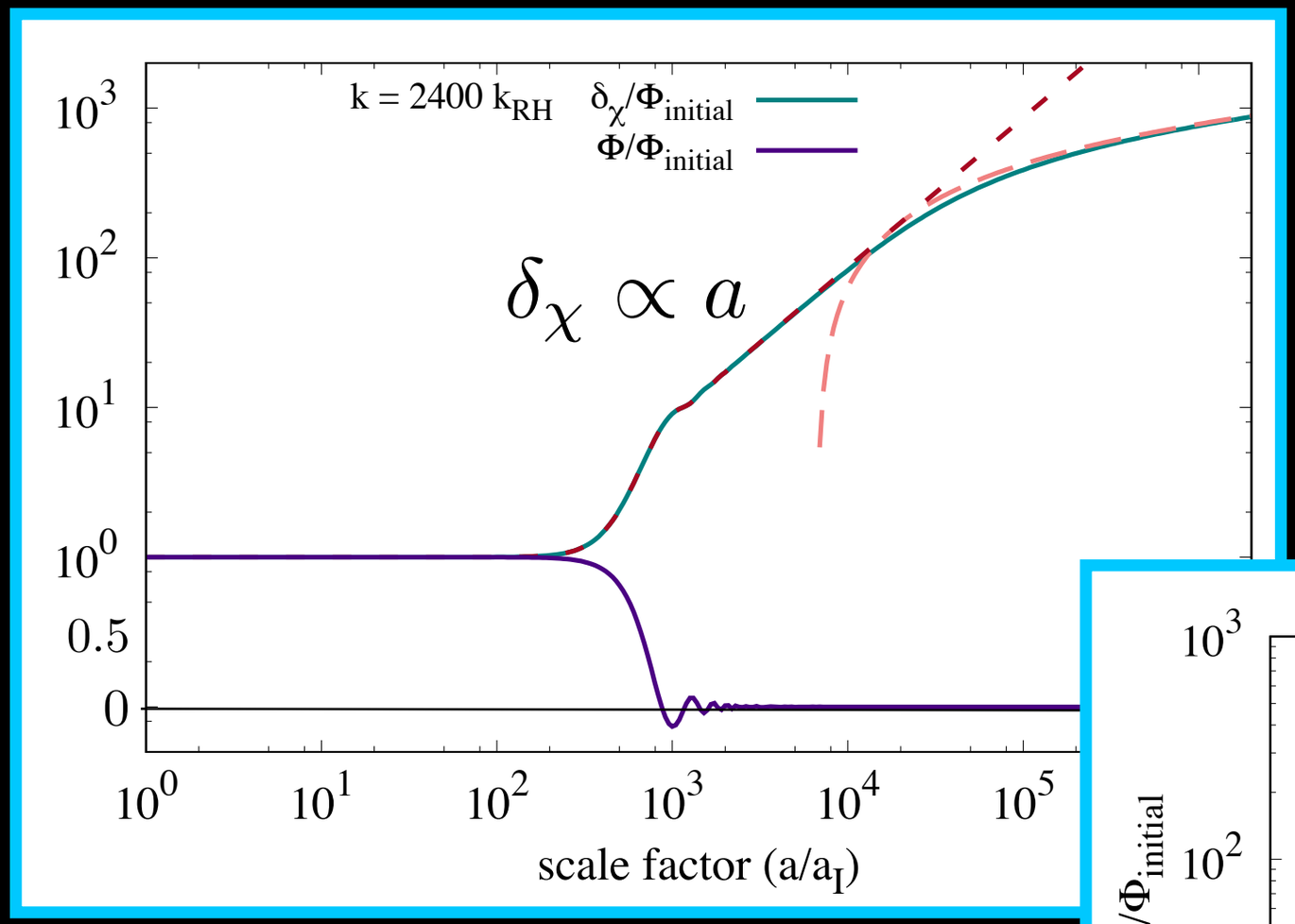
Sheridan Green, ALE+ coming soon

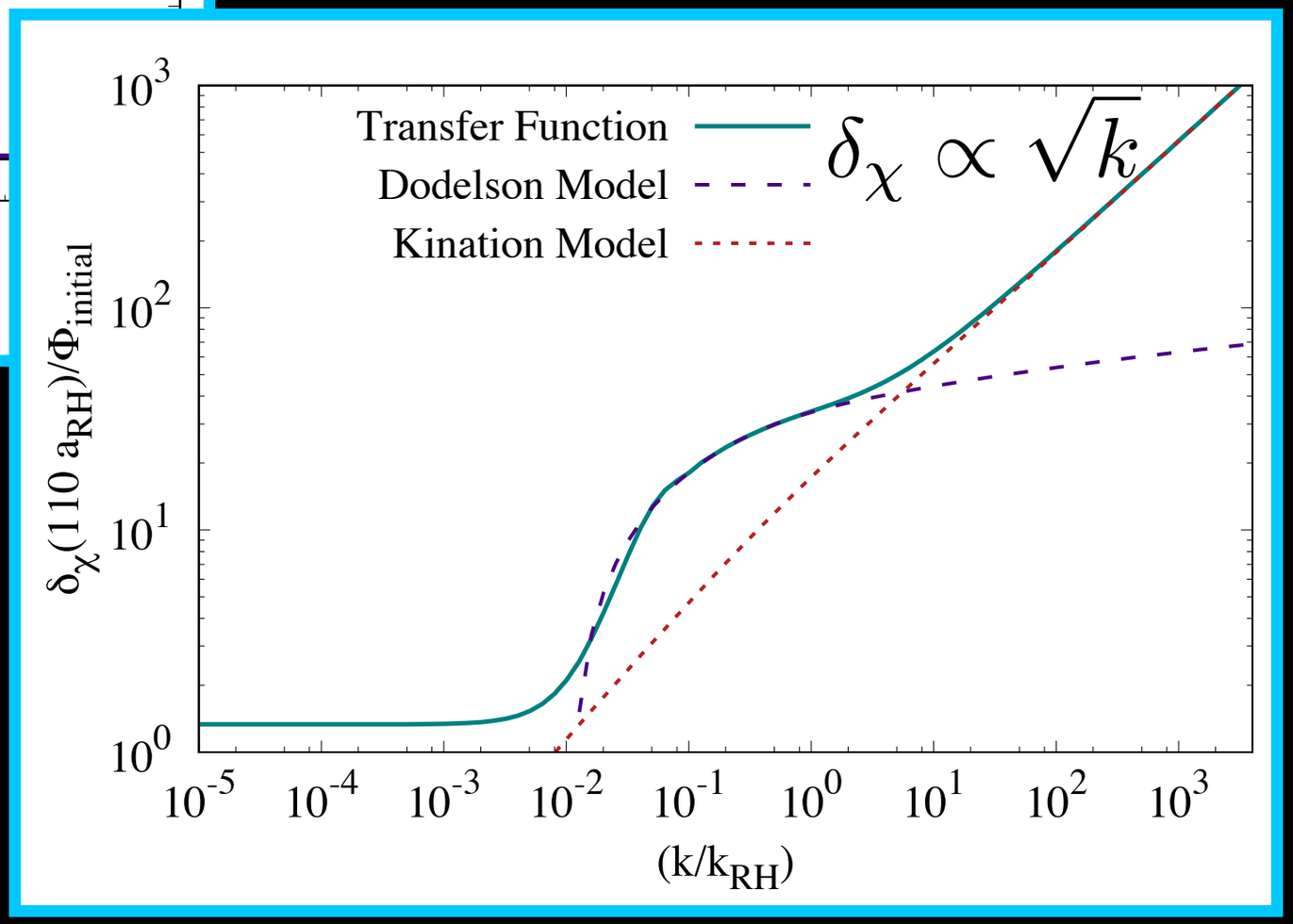




Perturbations during Kination

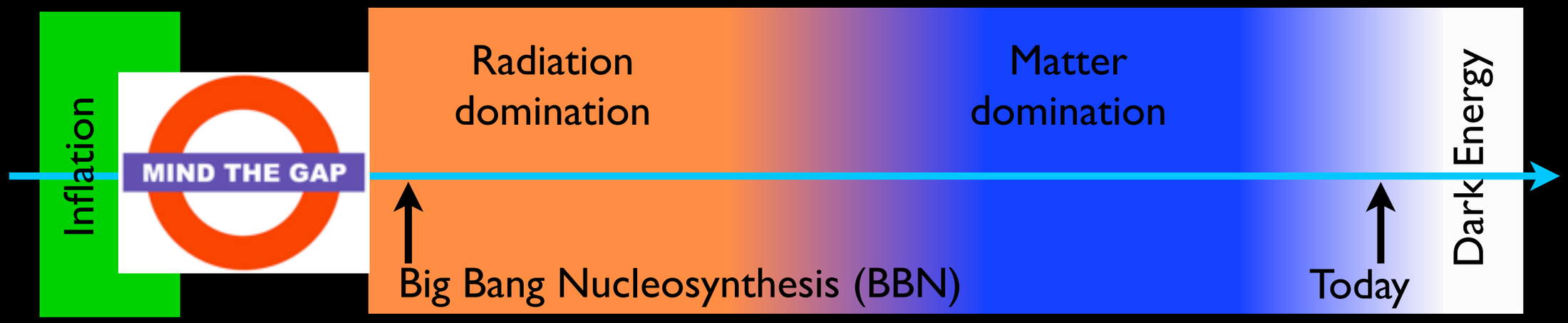
Kayla Redmond, ALE coming soon





$$\delta_\chi \propto \frac{a_{\rm RH}}{a_{\rm hor}} \propto \sqrt{\frac{k}{k_{\rm RH}}}$$

Summary: Mind the Gap after Inflation



- There is a gap in the cosmological record between inflation and the onset of Big Bang nucleosynthesis: $10^{15}\,\mathrm{GeV} \gtrsim T \gtrsim 10^{-3}\,\mathrm{GeV}$
- Dark matter microhalos offer hope of probing the gap.
- Both kination and an early matter-dominated era (EMDE) enhance the growth of sub-horizon density perturbations.
- The microhalos that form after an EMDE significantly boost the dark matter annihilation rate.
- We can use gamma-ray observations to probe the evolution of the early Universe, but first we have to determine the formation time of the smallest microhalos and if they survive to the present day.