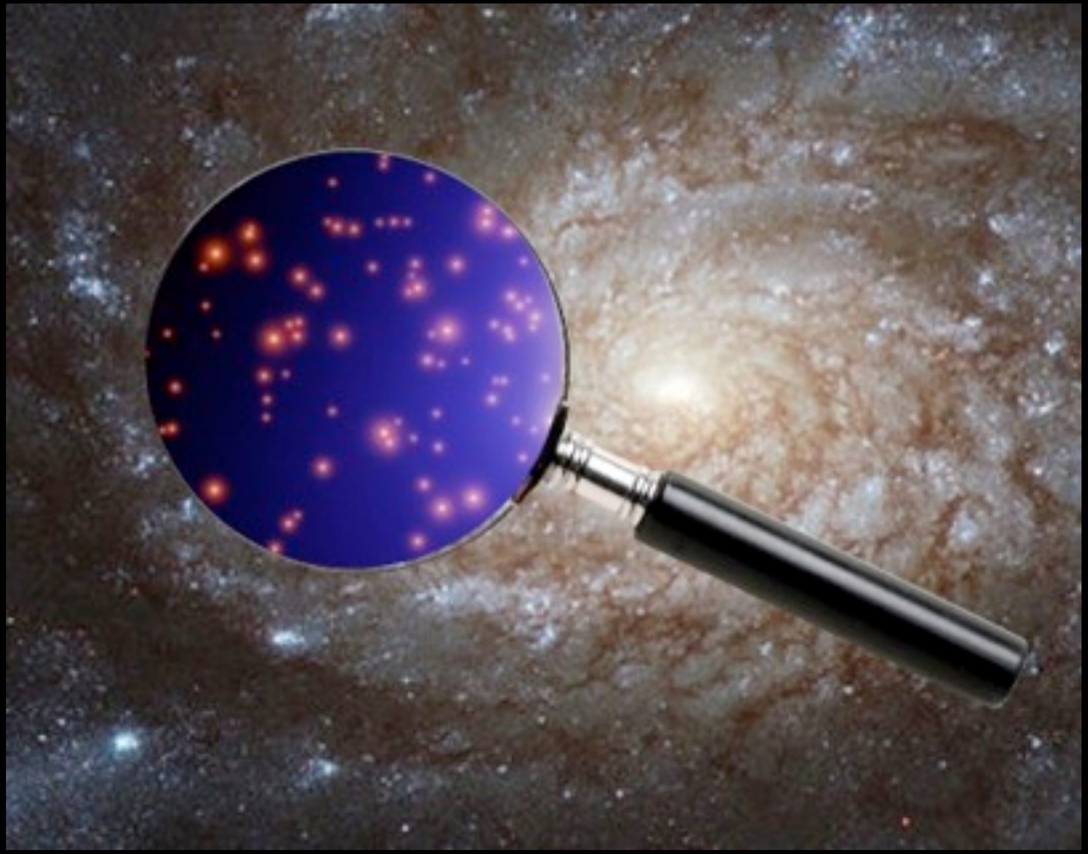
Using Microhalos to Probe the Universe's First Second



Adrienne Erickcek
UNC Chapel Hill

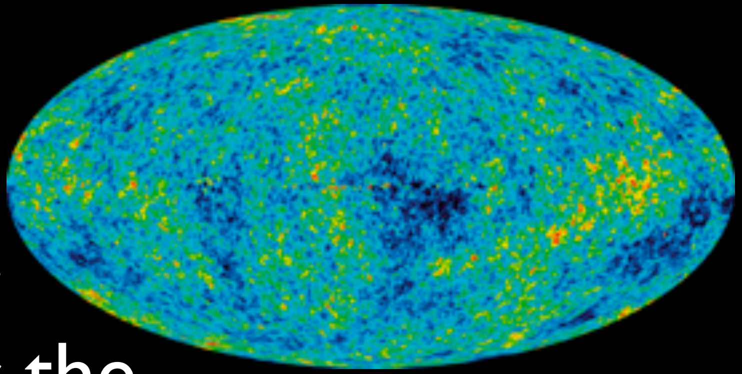
CIPANP
Palm Springs, CA
May 30, 2018

What happened before BBN?

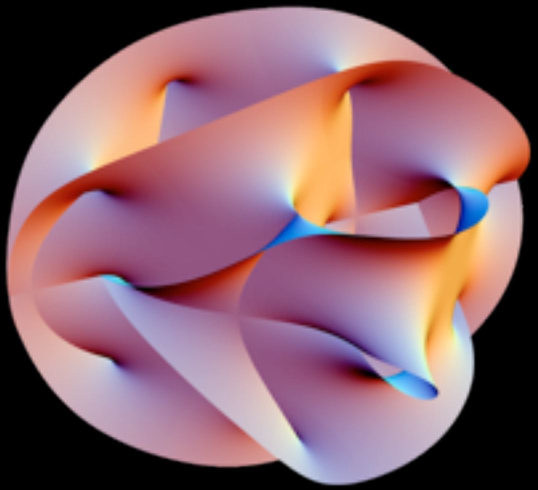
The (mostly) successful prediction of the primordial abundances of light elements is one of cosmology's crowning achievements.

- 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.

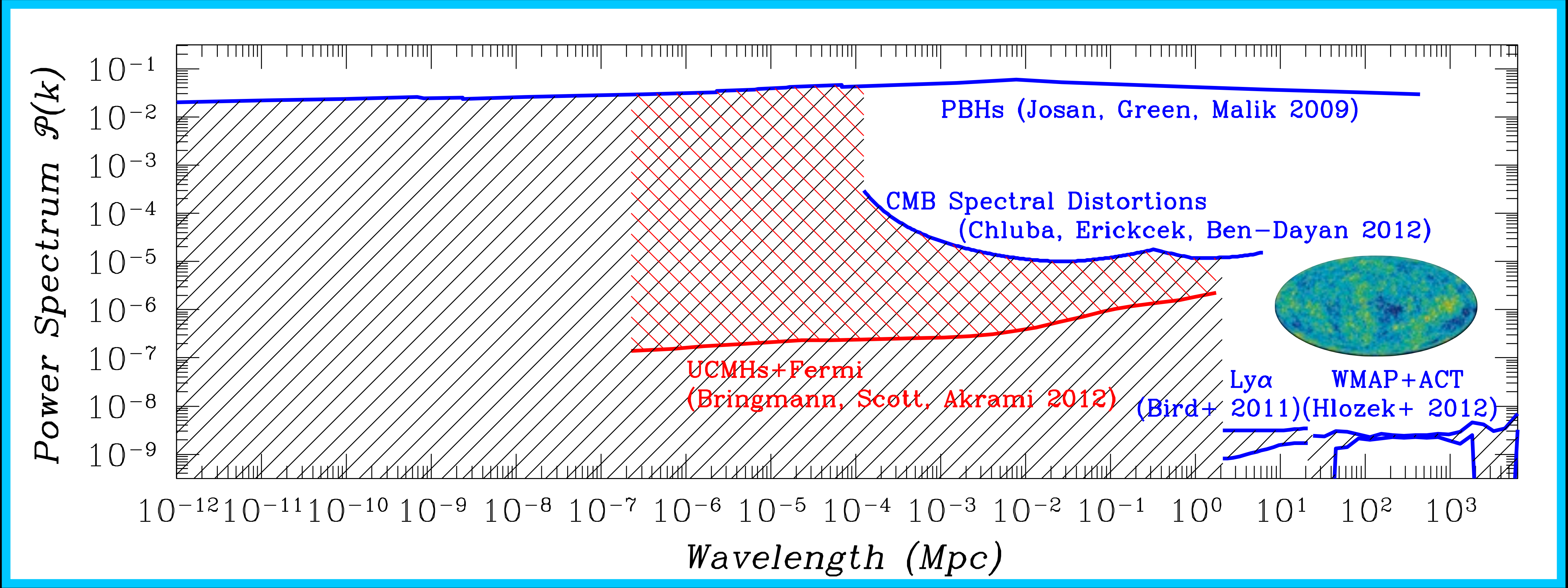


Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994

Acharya, Kumar, Bobkov, Kane, Shao, Watson 2008
Acharya, Kumar, Kane, Watson 2009
Giblin, Kane, Nesbit, Watson, Zhao 2017
Summary: Kane, Sinha, Watson 1502.07746

What do we know about inflation?

Observational probes of inflation are mostly limited to large scales.



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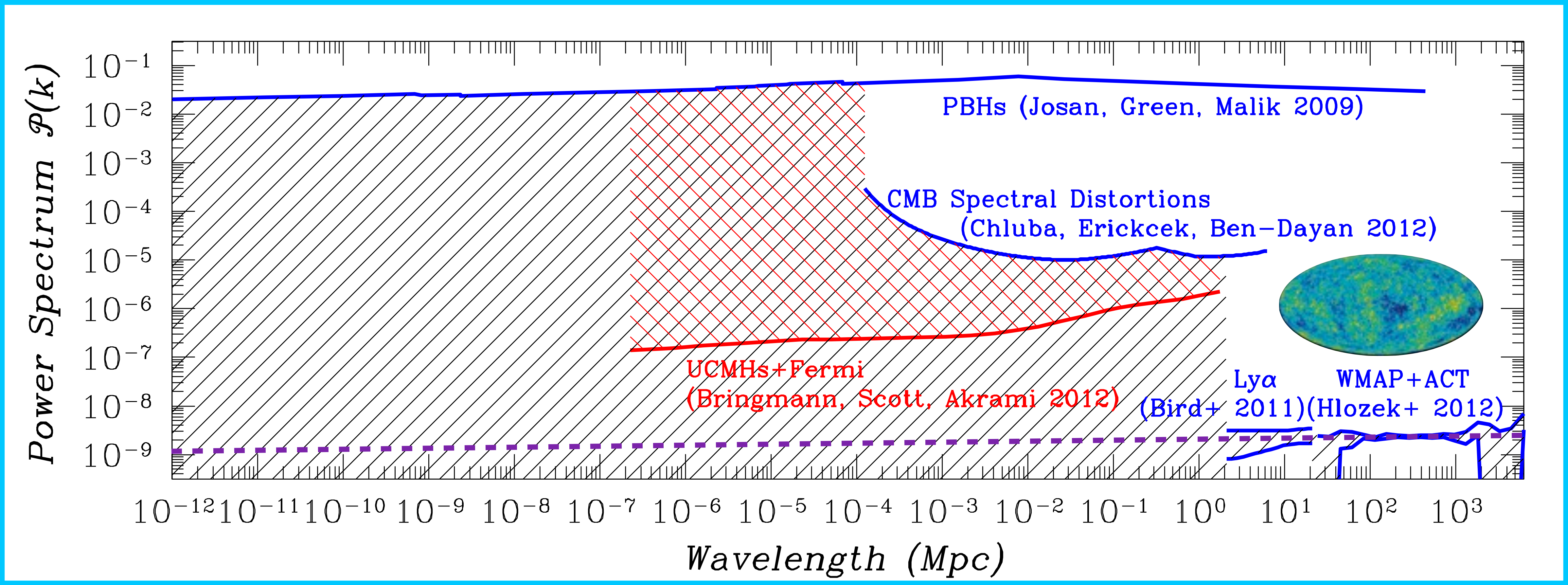

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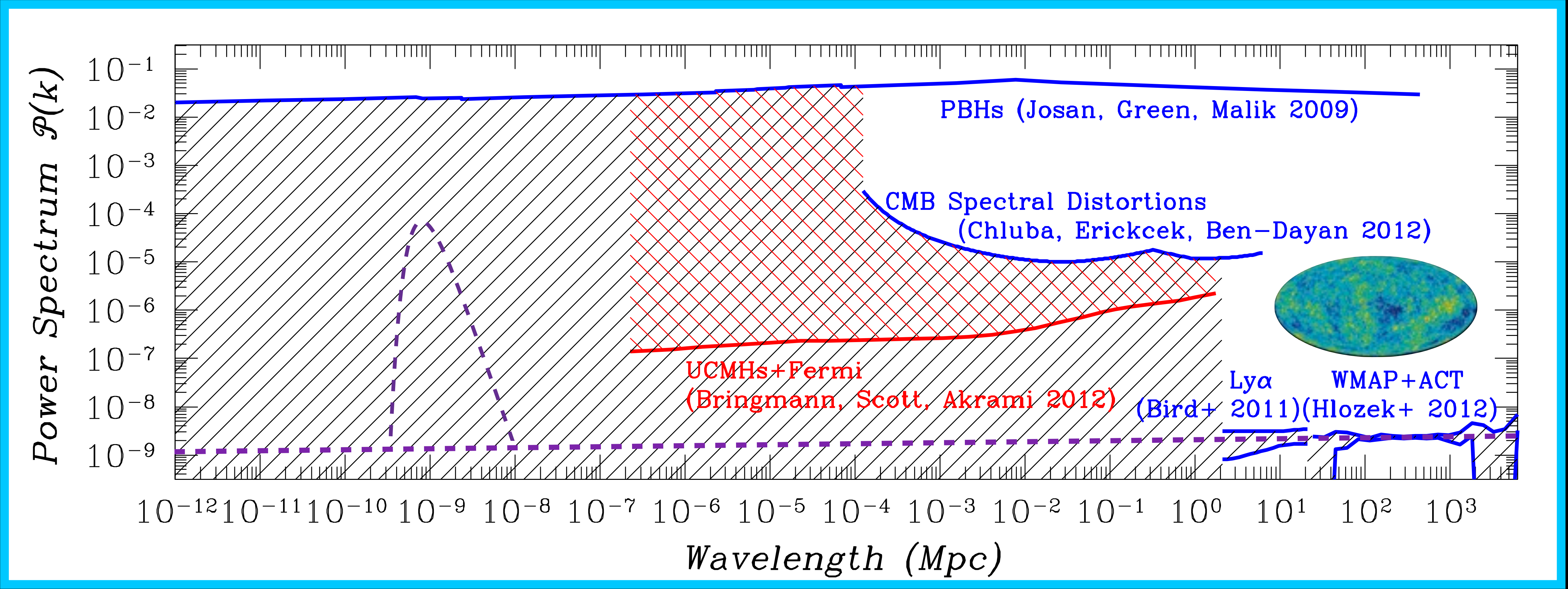

But surprises could be lurking on smaller scales.

- inflaton interactions: particle production or coupling to gauge fields
  Chung+ 2000; Barnaby+ 2009,2010; Barnaby+ 2011
- multi-stage and multi-field inflation with bends in inflaton trajectory
  Silk & Turner 1987; Adams+1997; Achucarro+ 2012
- any theory with a potential that gets flatter: running mass inflation
  Stewart 1997; Covi+1999; Covi & Lyth 1999
- hybrid models that use a "waterfall" field to end inflation
  Lyth 2011; Gong & Sasaki 2011; Bugaev & Klimai 2011; Guth & Sfakianakis 2012

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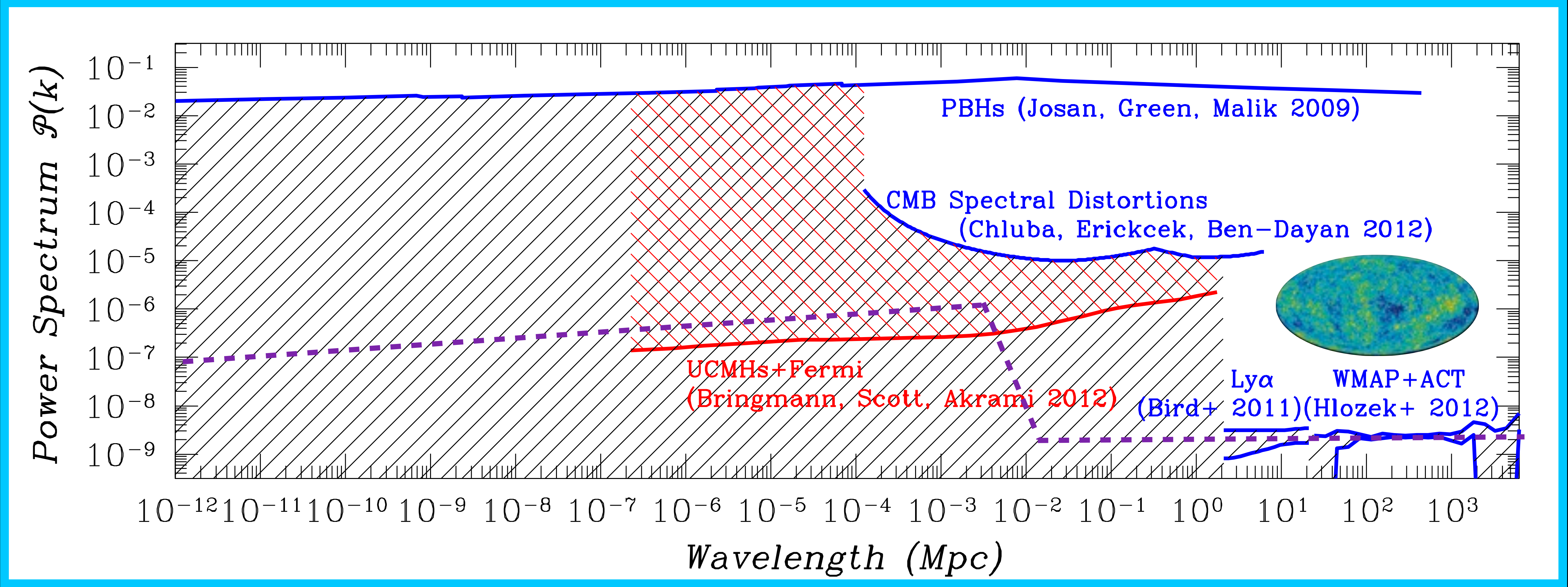

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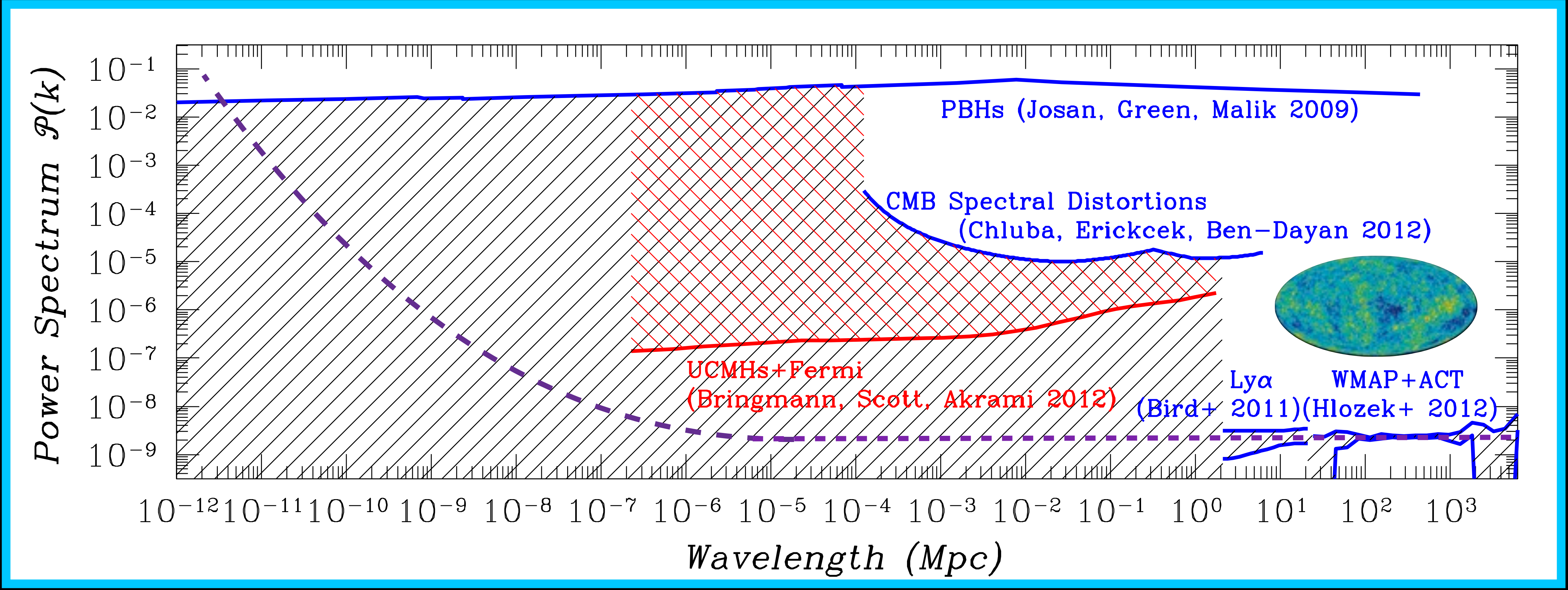

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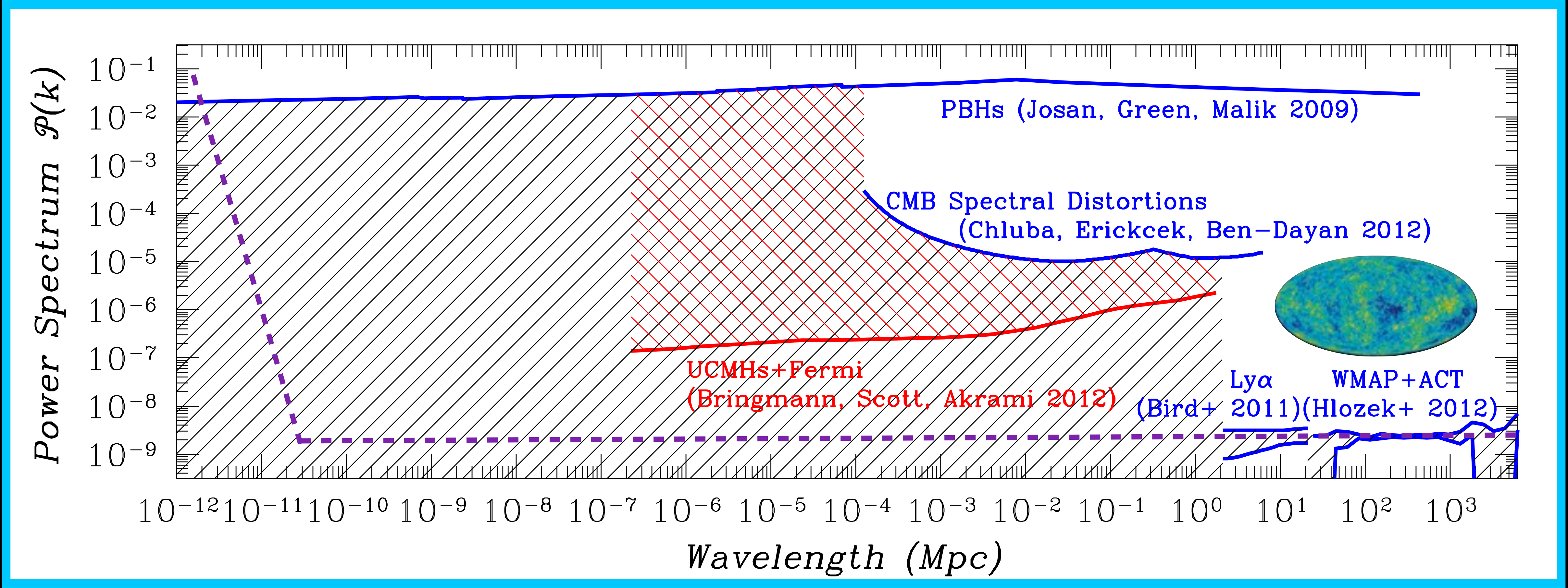

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Cosmic Timeline

Big Bang Nucleosynthesis

$0.07\,\mathrm{MeV} \lesssim T \lesssim 3\,\mathrm{MeV}$

$0.08\,\mathrm{sec} \lesssim t \lesssim 4\,\mathrm{min}$

CMB

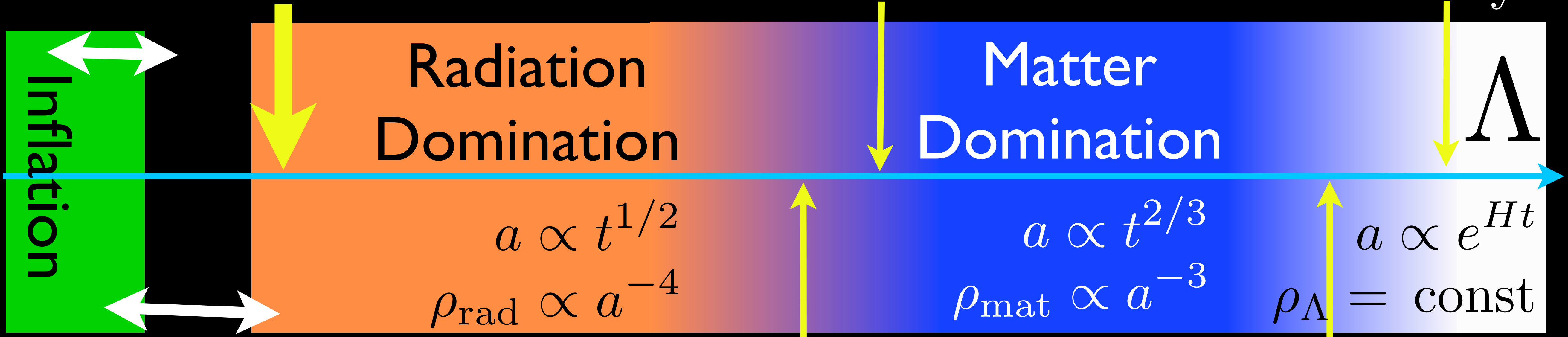
$T = 0.25\,\mathrm{eV}$

$t = 380,000\,\mathrm{yr}$

Now

$T = 2.3 \times 10^{-4}\,\mathrm{eV}$

$t = 13.8\,\mathrm{Gyr}$



Inflation

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$a \propto t^{1/2}$

$\rho_{\mathrm{rad}} \propto a^{-4}$

Matter Domination

$a \propto t^{2/3}$

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Λ

$a \propto e^{Ht}$

$\rho_{\Lambda} = \mathrm{const}$

Matter-Radiation Equality

$T = 0.74\,\mathrm{eV}$

$t = 57,000\,\mathrm{yr}$

Matter-Λ Equality

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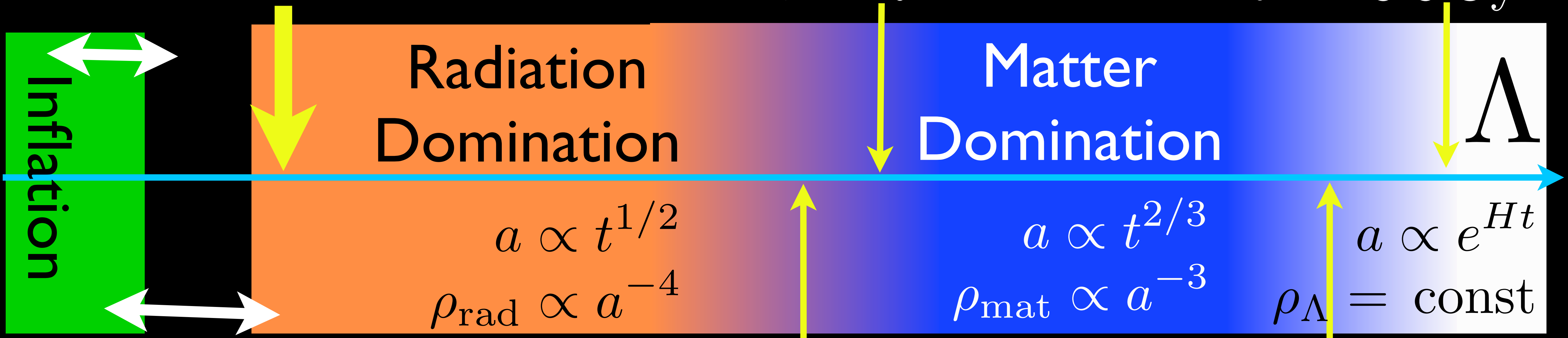
Cosmic Timeline



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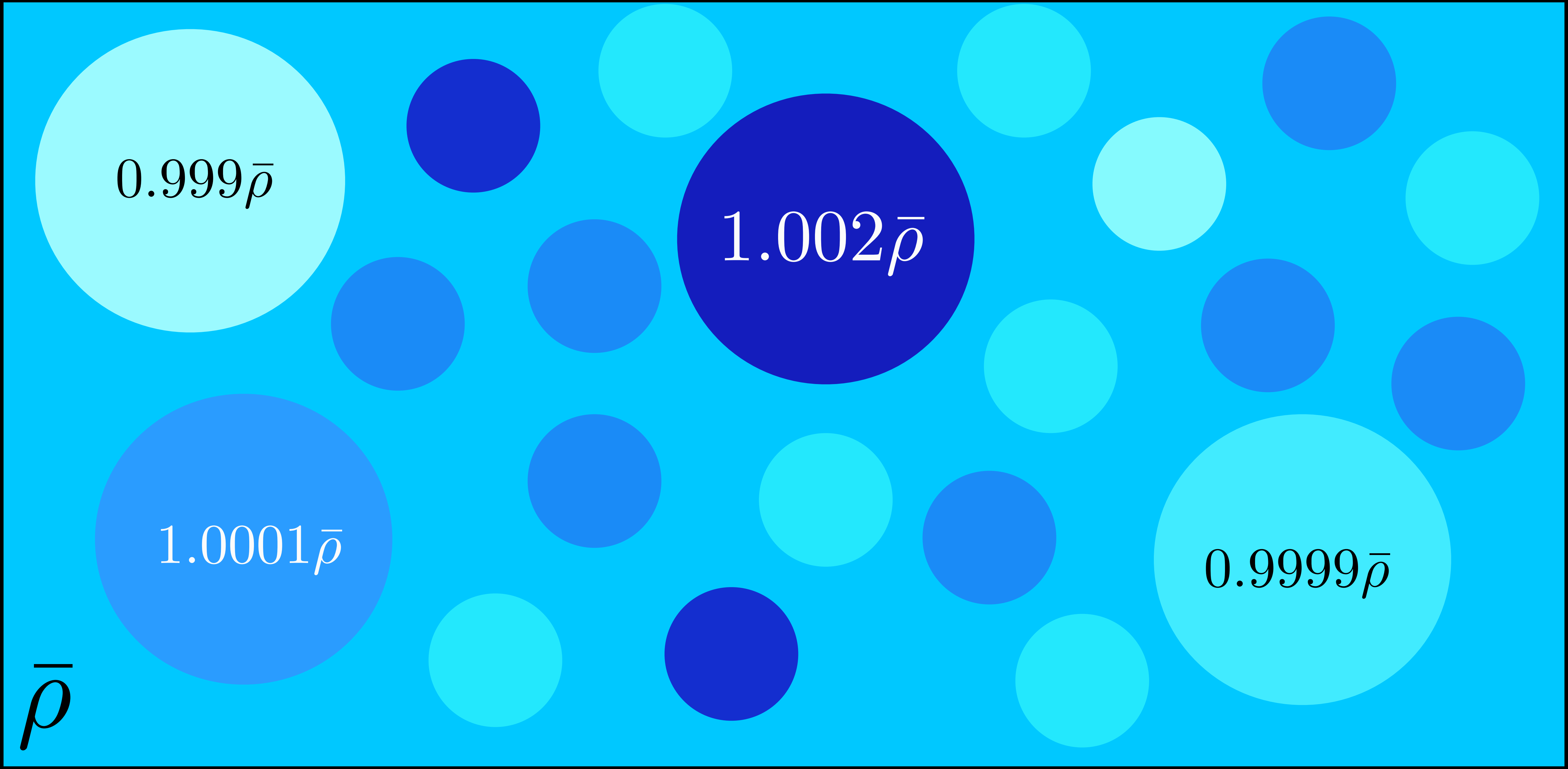
Idea I: Probing inflation with ultra-compact microhalos (UCMHs)

Idea II: Probing the pre-BBN thermal history with microhalos

UCMH Formation

If a region has an initial density $\rho > 1.001\bar{\rho}$, then all the dark matter in that region collapses at early times ($z \gtrsim 1000$) and forms an Ultra-Compact Minihalo.

Ricotti & Gould 2009



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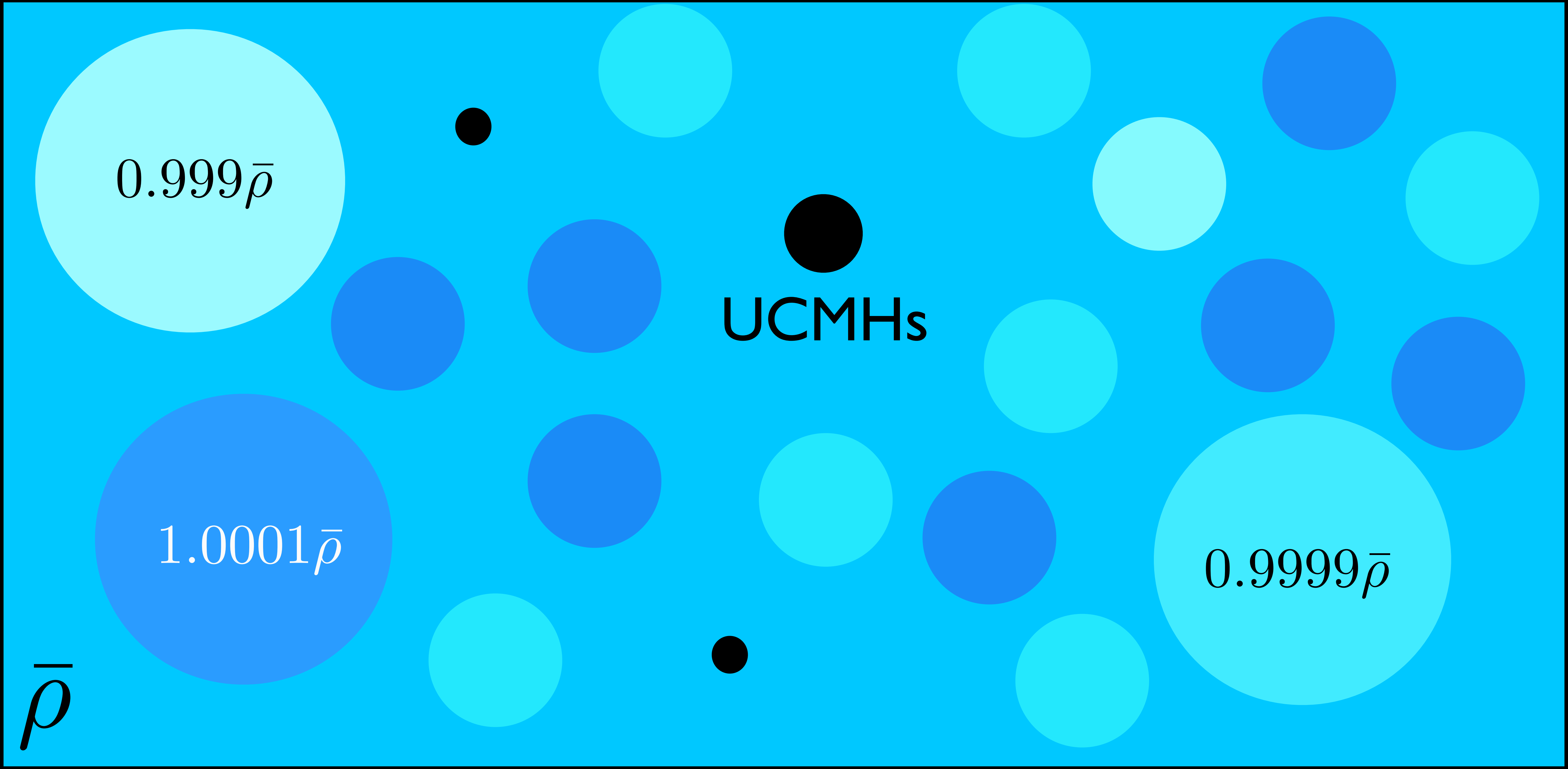
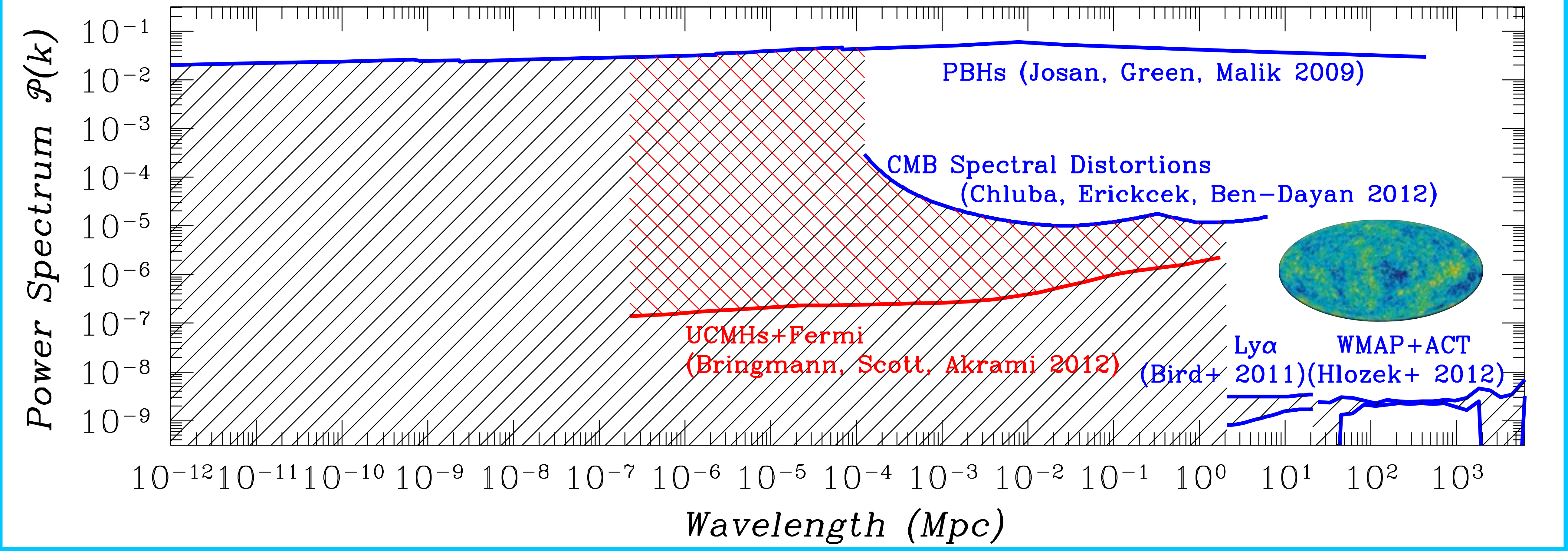


UCMHs Probe Power Spectrum

An upper bound on the **UCMH number density** leads to an upper bound on the **primordial power spectrum.**

Josan & Green 2010; Bringmann, Scott, Akrami 2012



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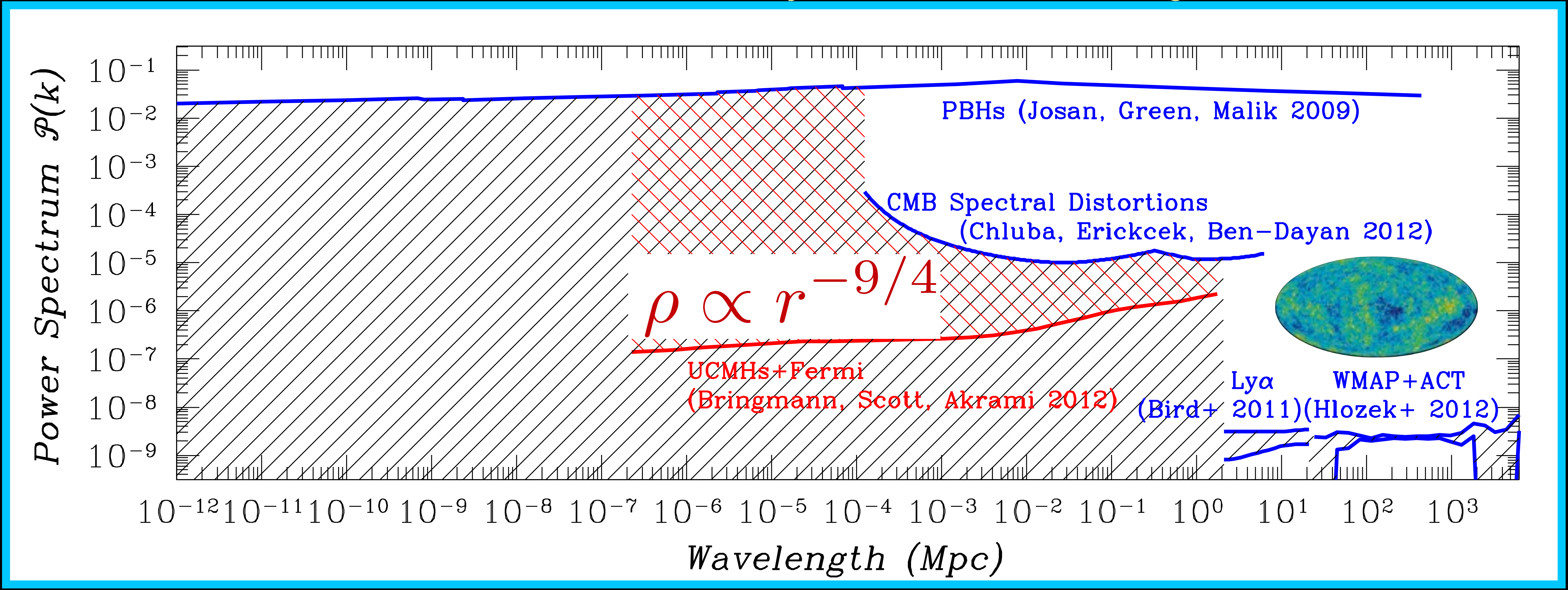
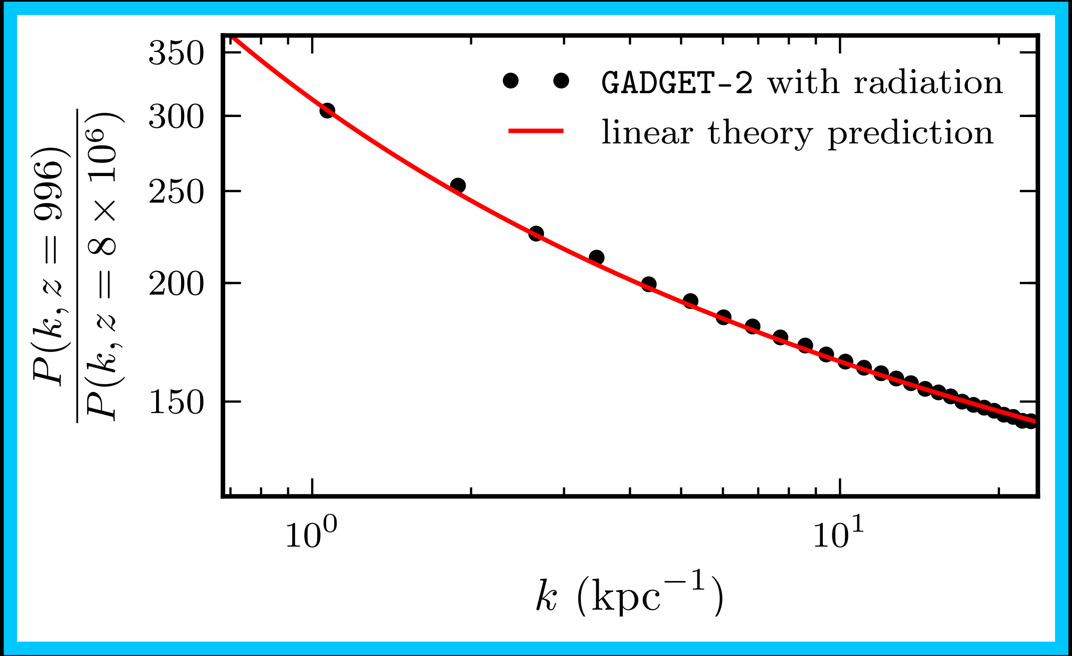


These bounds assume that UCMHs have a radial-infall density profile.

Simulations of UCMHs

***Sten Delos**, ALE, Bailey, Alvarez*
PRD 2018, 1712.05421
See also Gosenca+ 2017

1. Modify GadgetV2 to include smooth radiation component.



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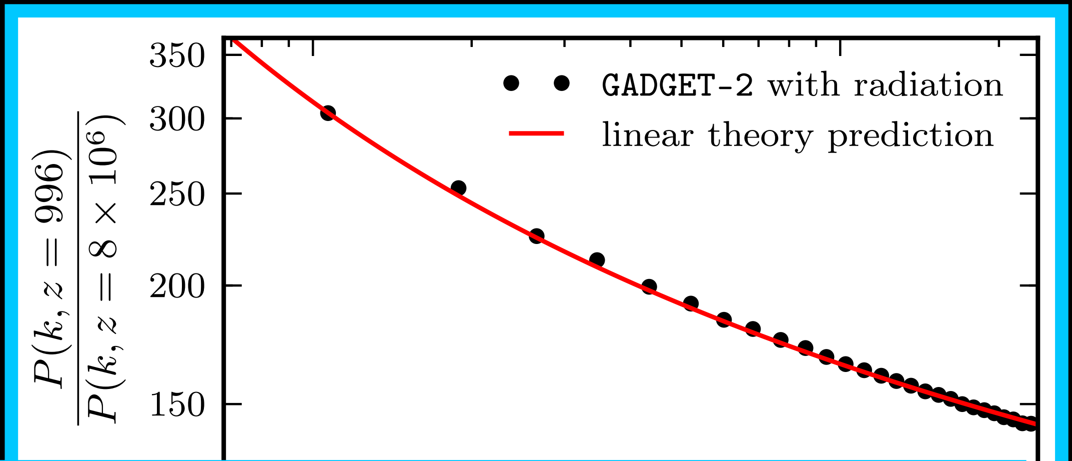

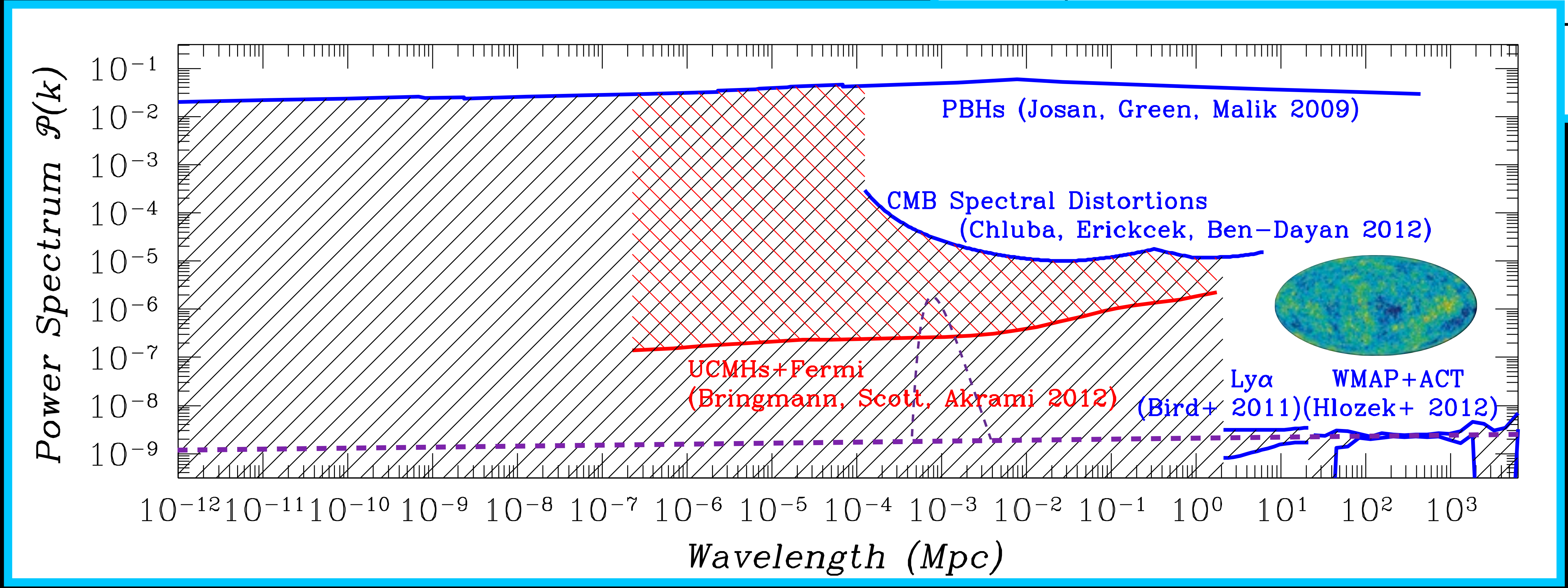

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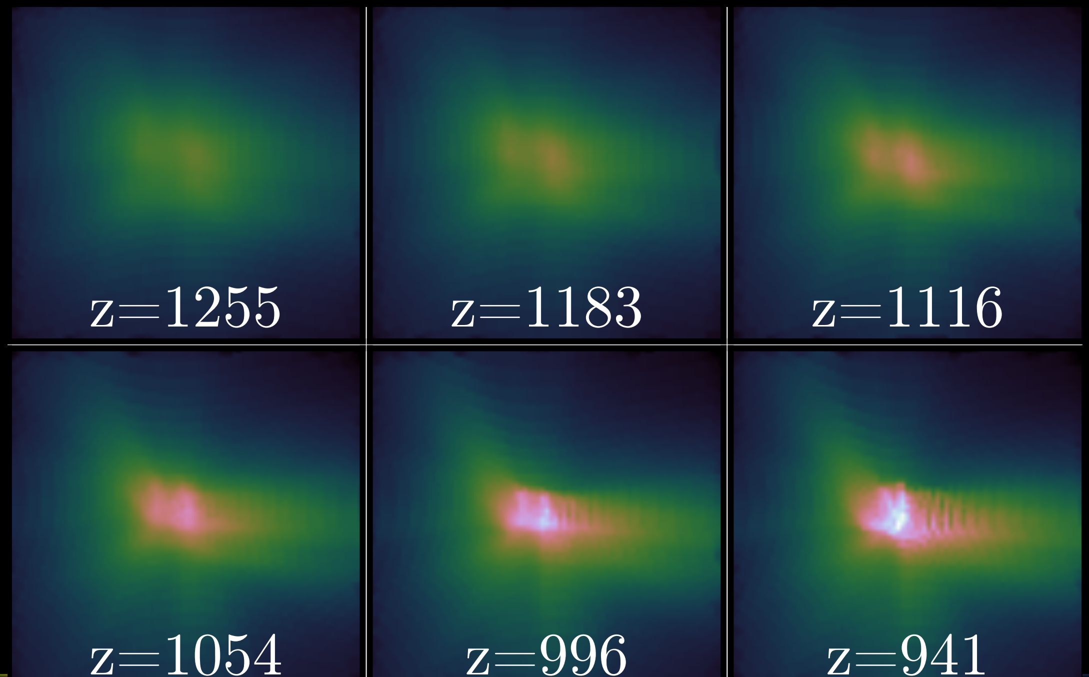
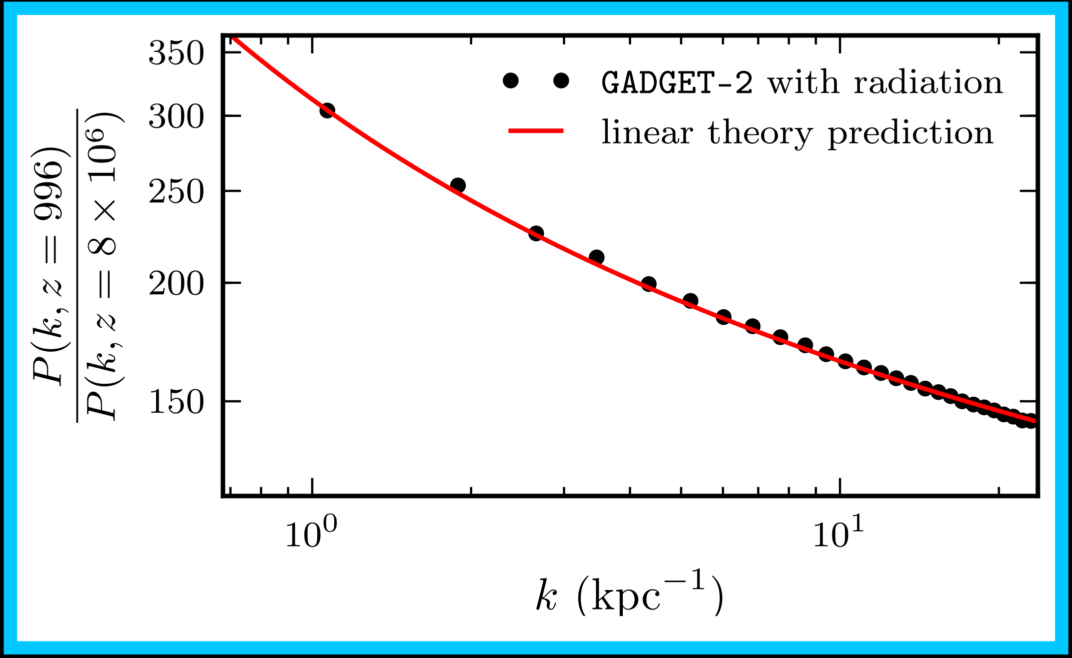
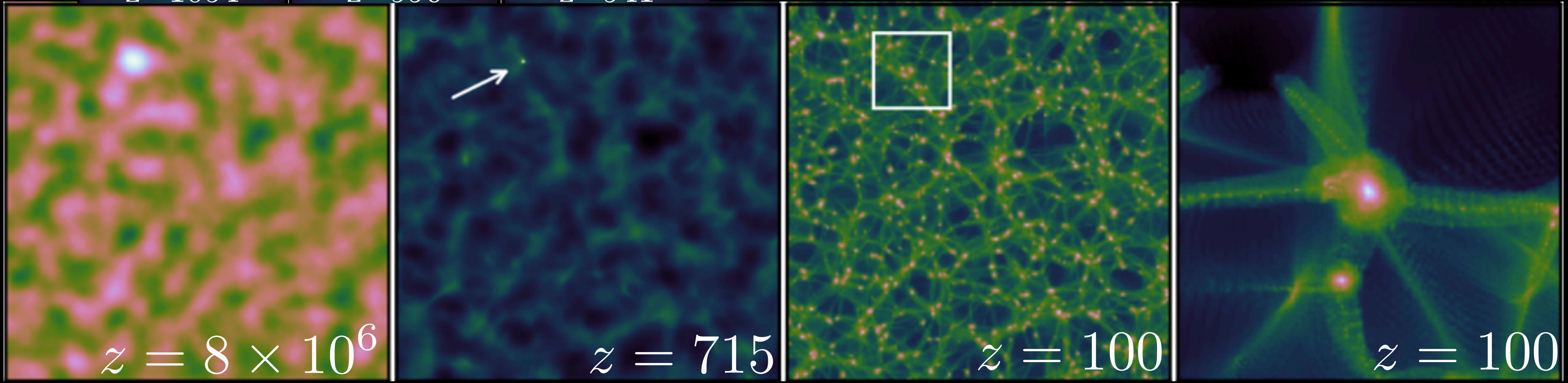
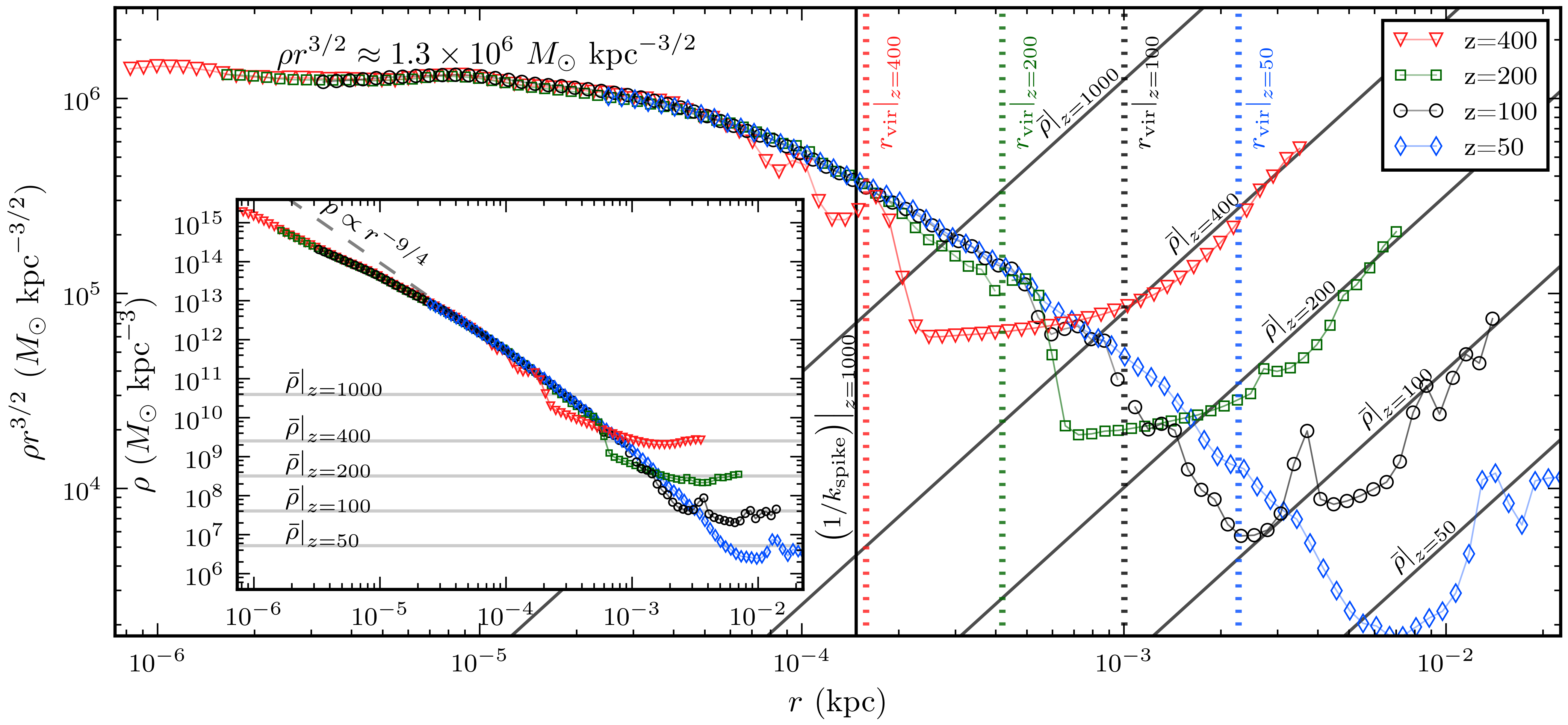
1. Modify GadgetV2 to include smooth radiation component.
2. Generate initial conditions from a power spectrum with a spike.
3. Make an UCMH!







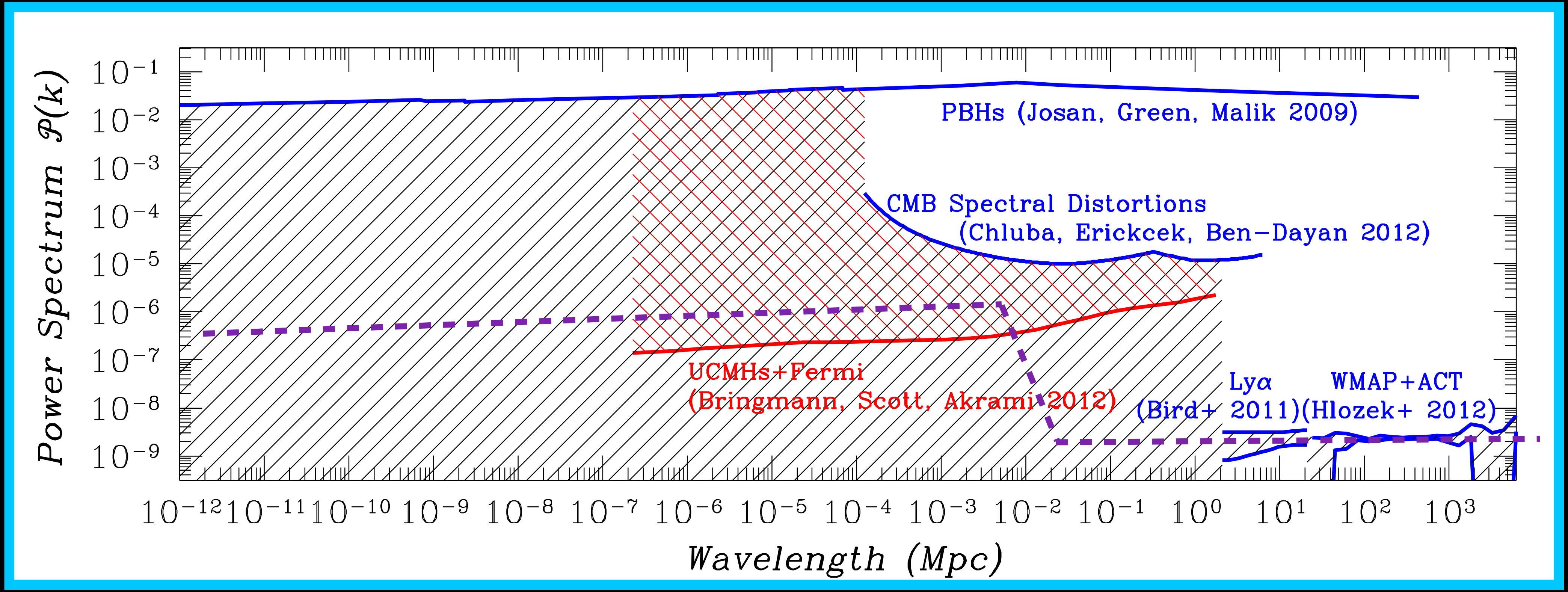
UCMH Density Profiles: Spike

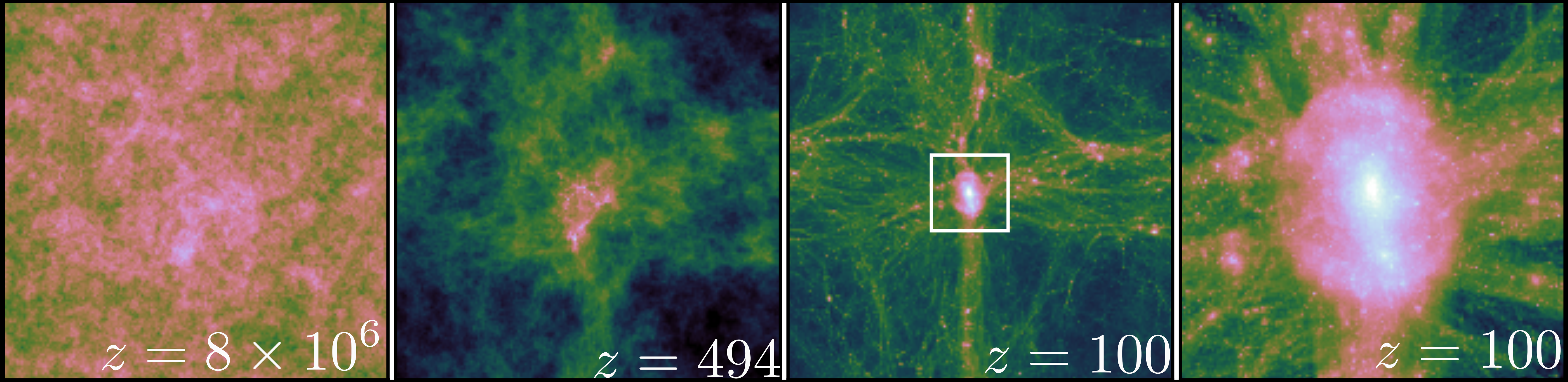


- Nine simulated UCMHs
- All have similar density profiles: $\rho = \dfrac{\rho_s}{(r/r_s)^{1.5}(1+r/r_s)^{1.5}}$
- Stable with redshift, unless there's a merger....

UCMH Density Profiles: Plateau

We also formed UCMHs using a plateau feature





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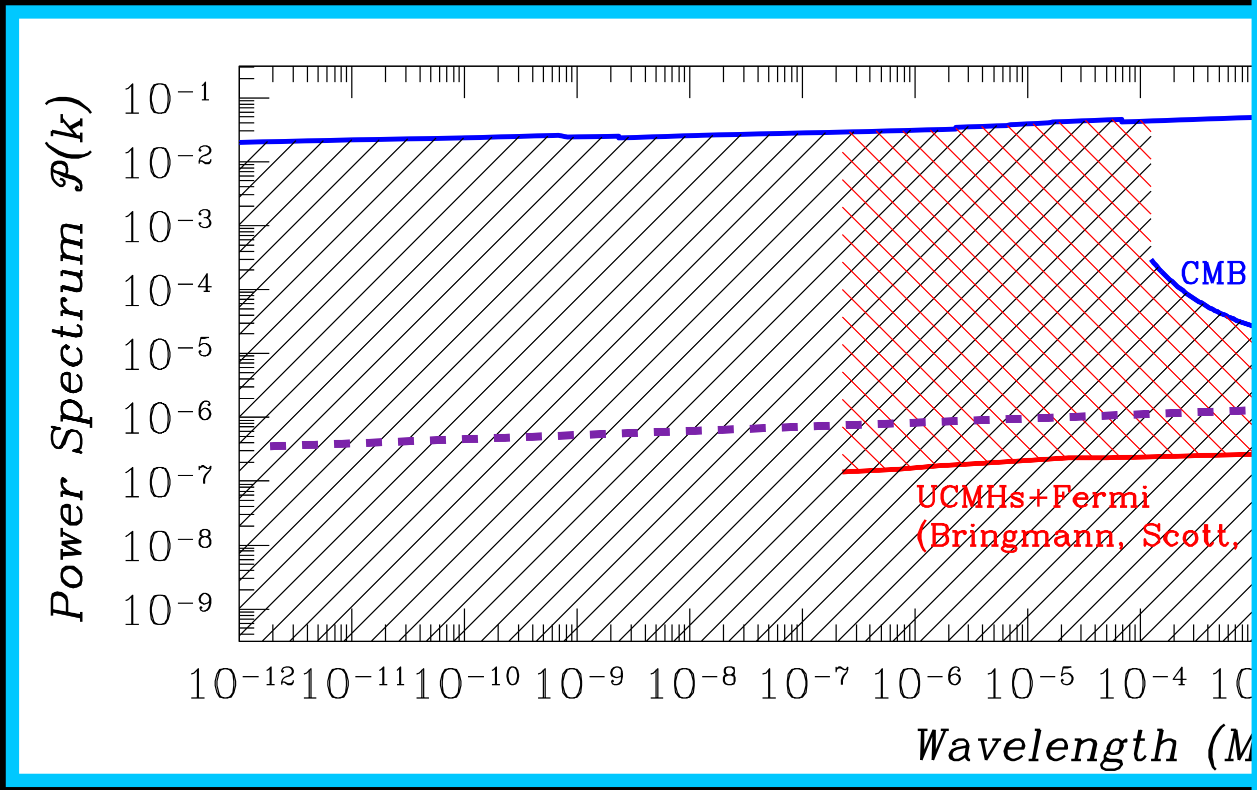
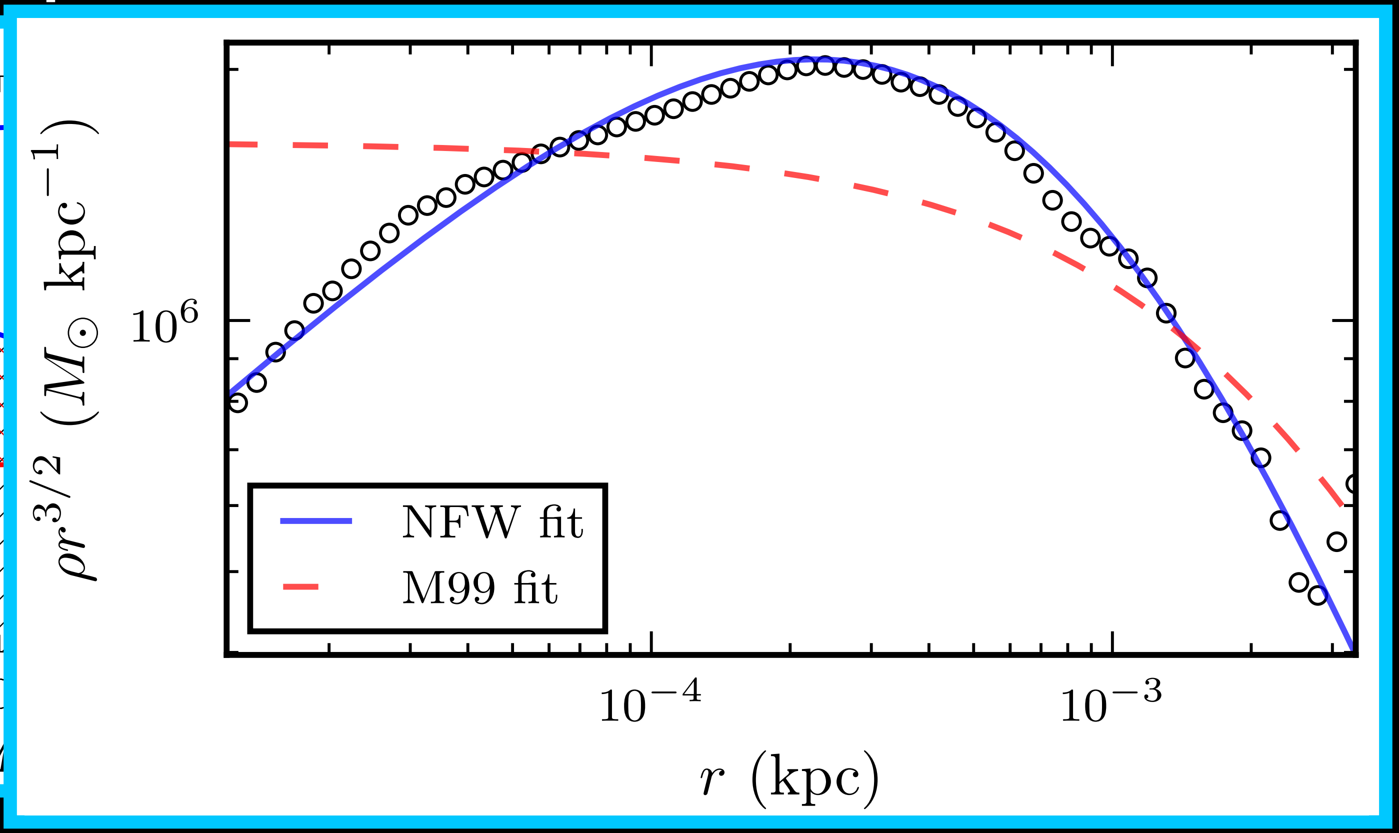
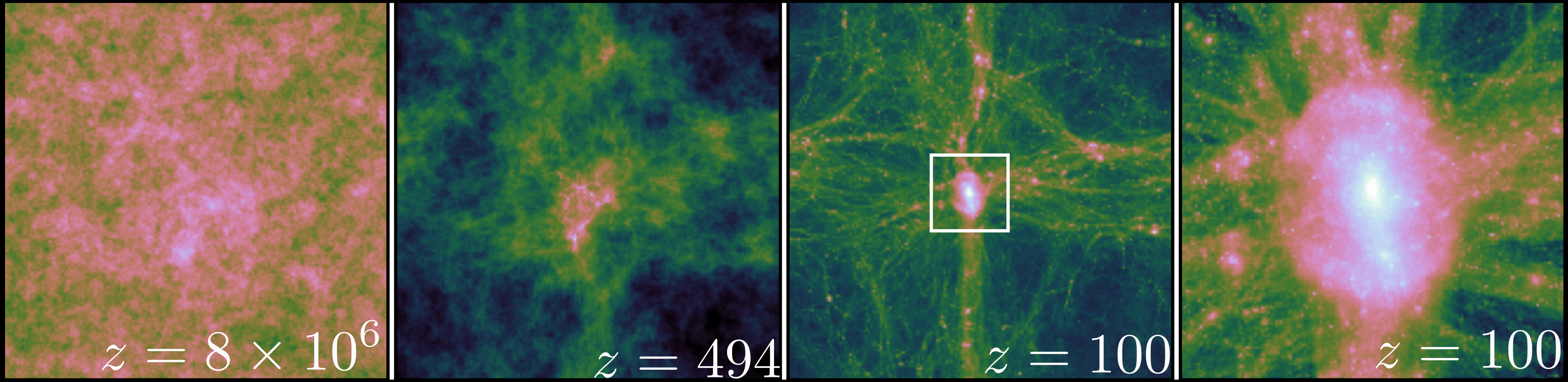




and these UCMHs have NFW proflies!



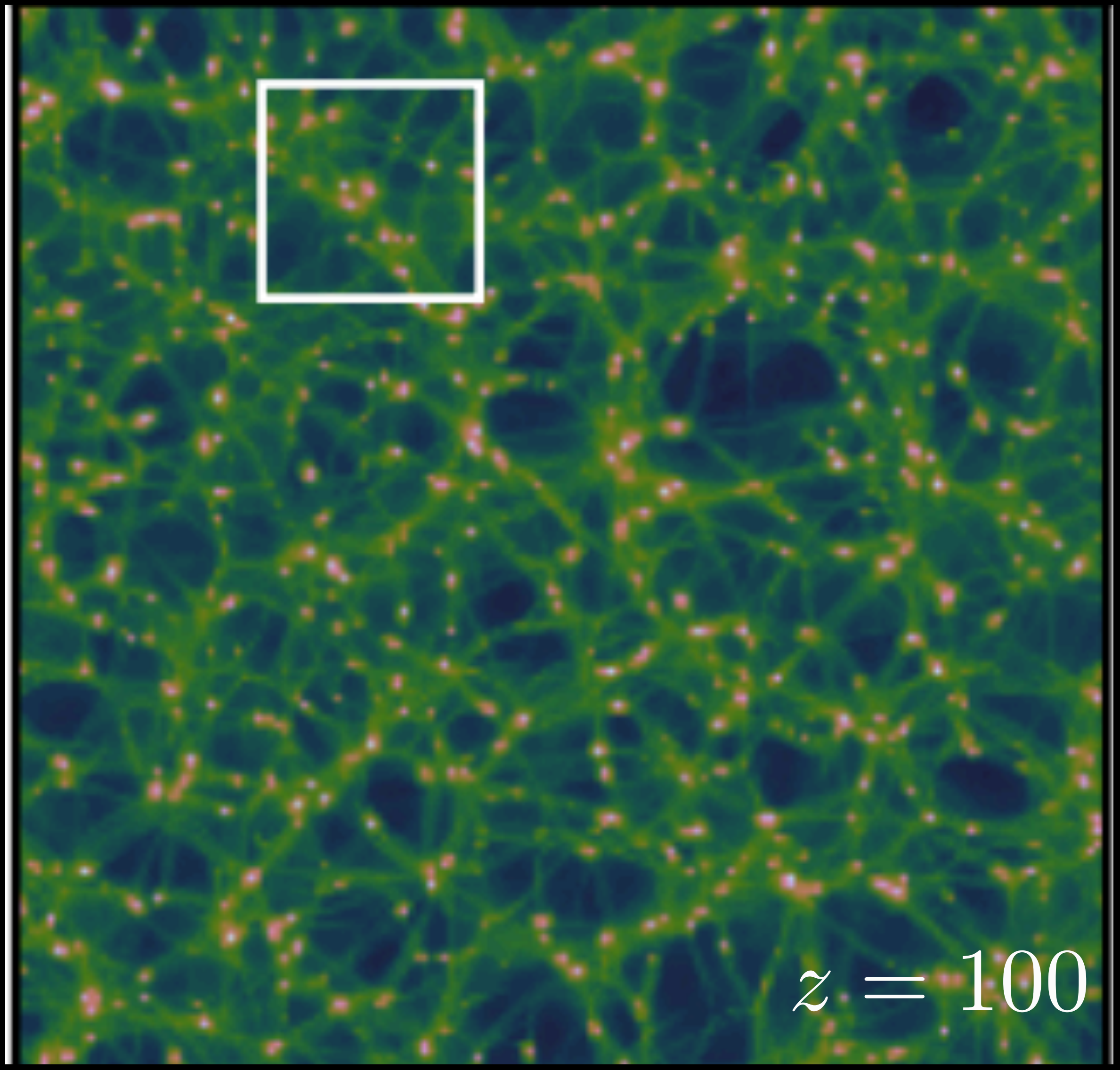
UCMHs: Summary and Outlook

- UCMHs that form from spikes in the primordial power spectrum have Moore profiles ($\rho \propto r^{-1.5}$), while plateaus in the primordial power spectrum generate UCMHs with NFW profiles ($\rho \propto r^{-1}$).

- The dark matter annihilation rate within the UCMHs is reduced by a factor of 200, which reduces upper bound on UCMH abundance by 3000.

- But we have so many more halos to consider...

***Sten Delos**, ALE, Bailey, Alvarez*
coming soon



STAY TUNED

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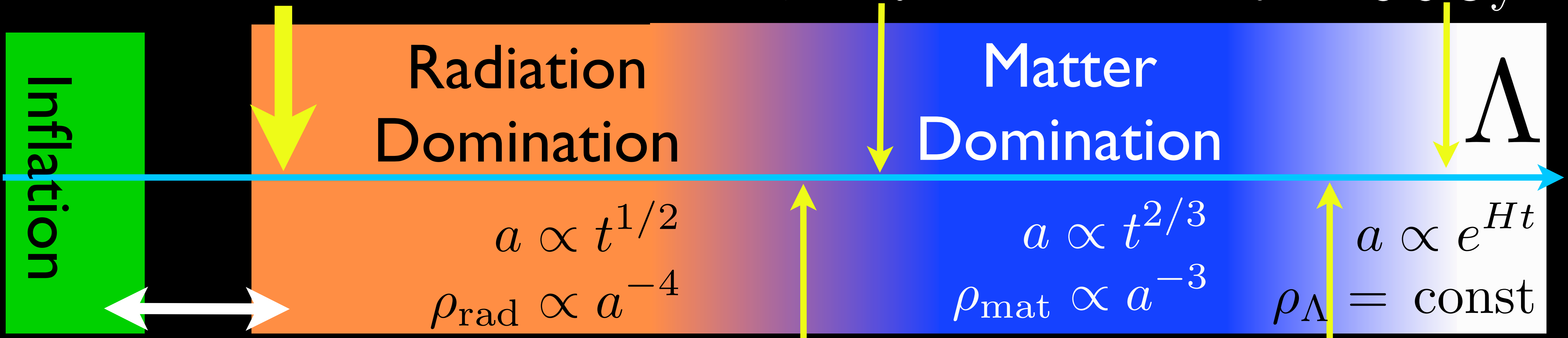

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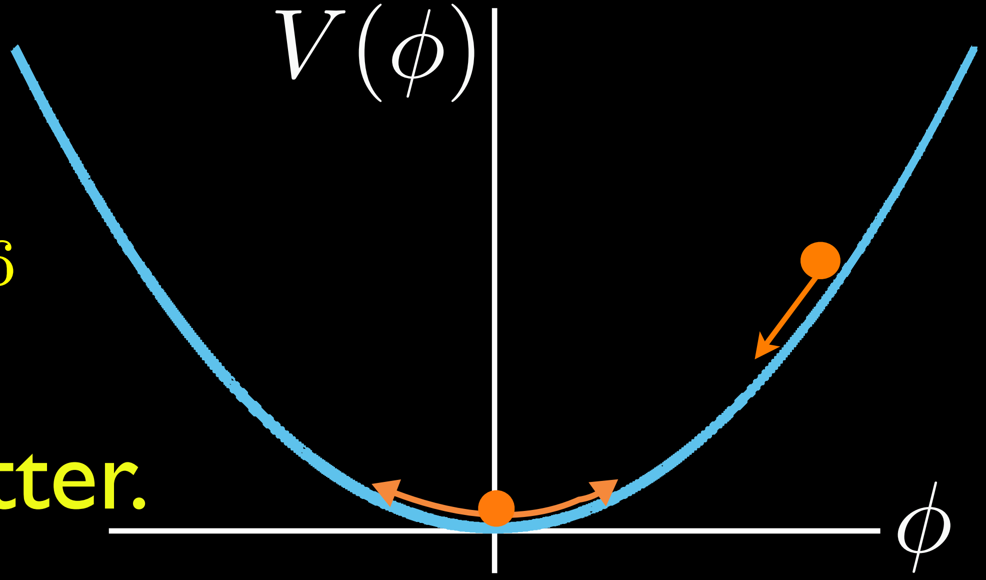
Evolution of the pre-BBN Universe

The Universe was once dominated by a scalar field

- the inflaton
- string moduli



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

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

- over many oscillations, average pressure is zero.
- scalar field energy density evolves as $\rho_\phi \propto a^{-3}$
- or we could form oscillons, which are effectively massive particles

Other massive particles could come to dominate the Universe:

- axinos or gravitinos
- hidden sector particles *e.g. Dror, Kuflik, Melcher, Watson 2018*
  Berlin, Hooper, Krnjaic 2016

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

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

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

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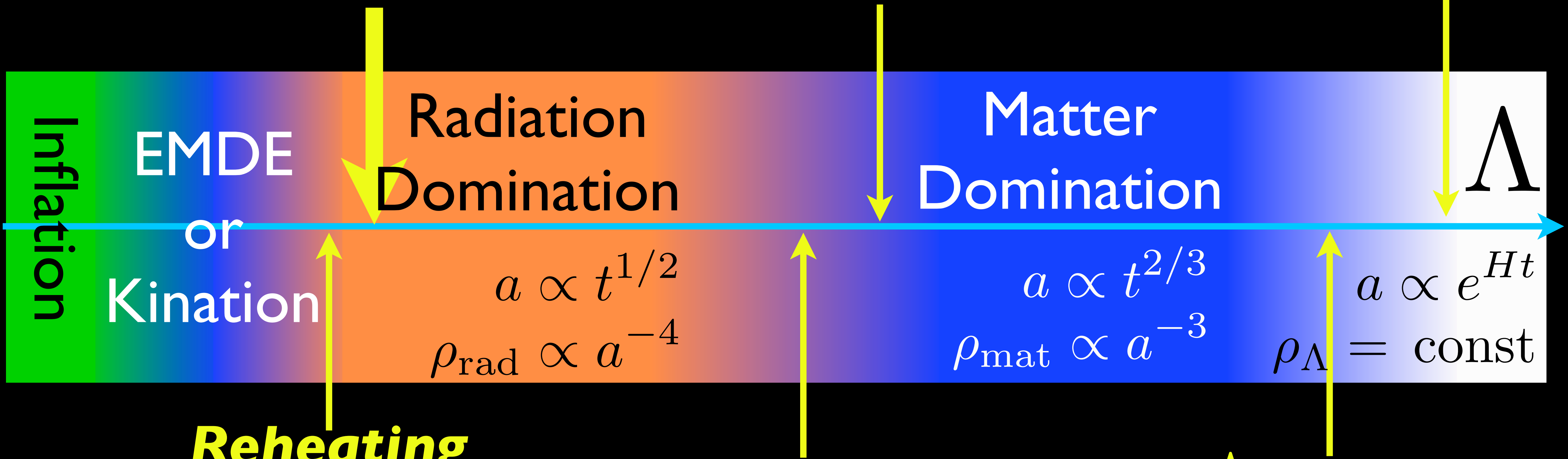

Inflation

EMDE or Kination

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Reheating

$T = ?$

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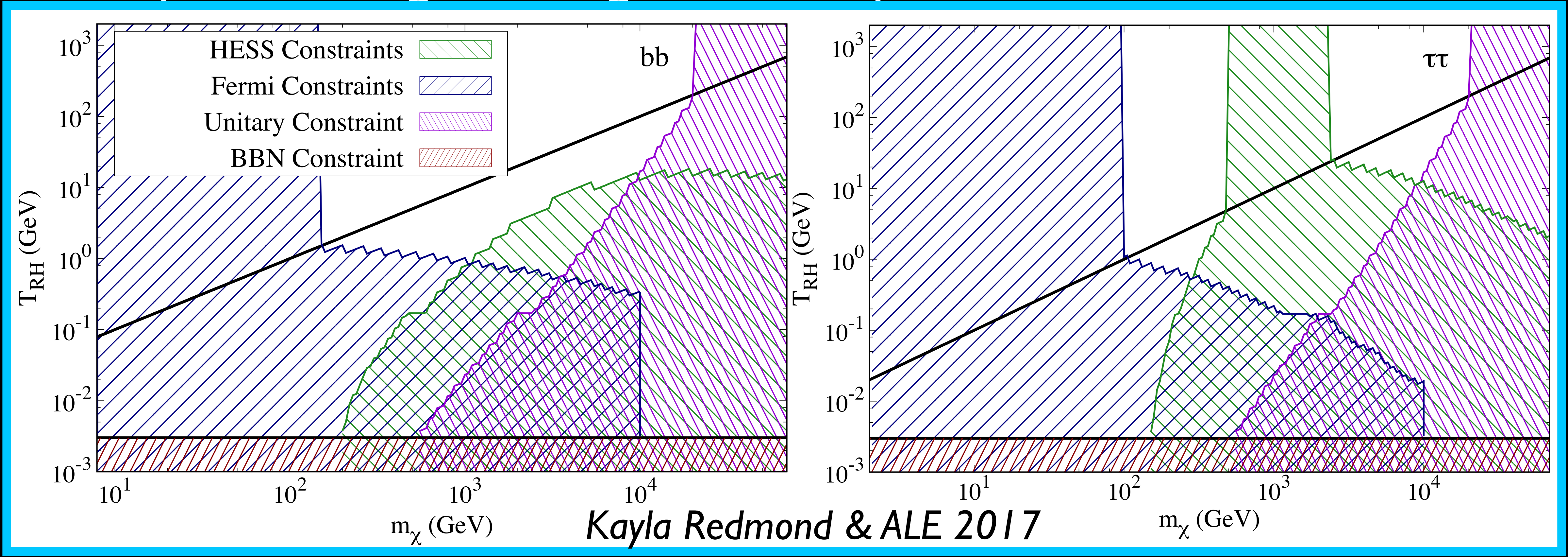
Probing Dark Matter Production

Kination: Universe dominated by a fast rolling scalar field

- faster expansion rate at a given temperature implies earlier freeze-out
- larger annihilation cross section needed to match observed DM abundance
- already on the verge of being ruled out by HESS and Fermi observations



Kayla Redmond & ALE 2017

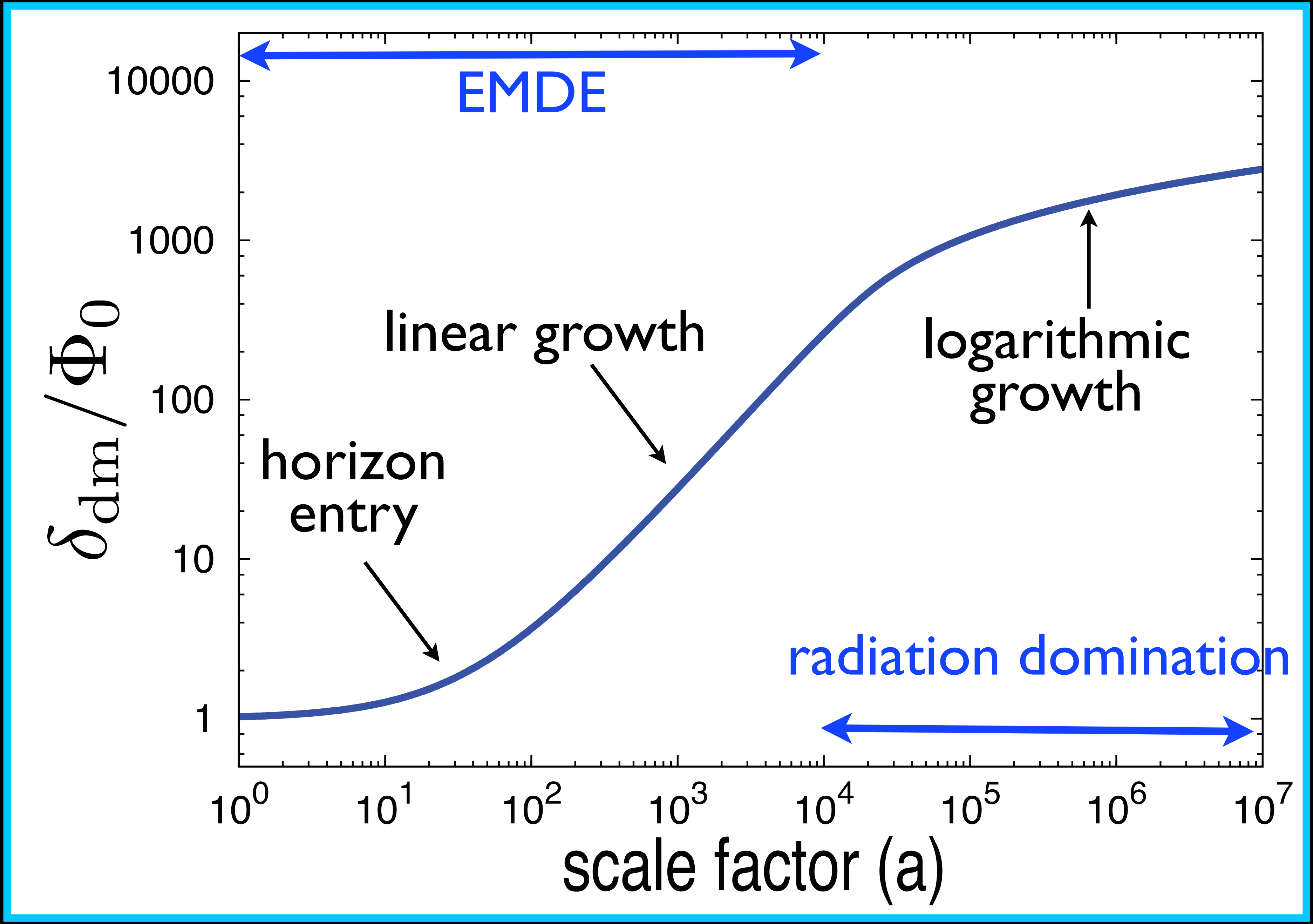
Thermal DM production during an early matter-dominated era (EMDE) requires much smaller annihilation cross sections!

Giudice, Kolb, Riotto 2001; Gelmini, Gondolo 2006; Gelmini, Gondolo, Soldatenko, Yaguna 2006, ALE 2015

What hope do we have of probing these scenarios?

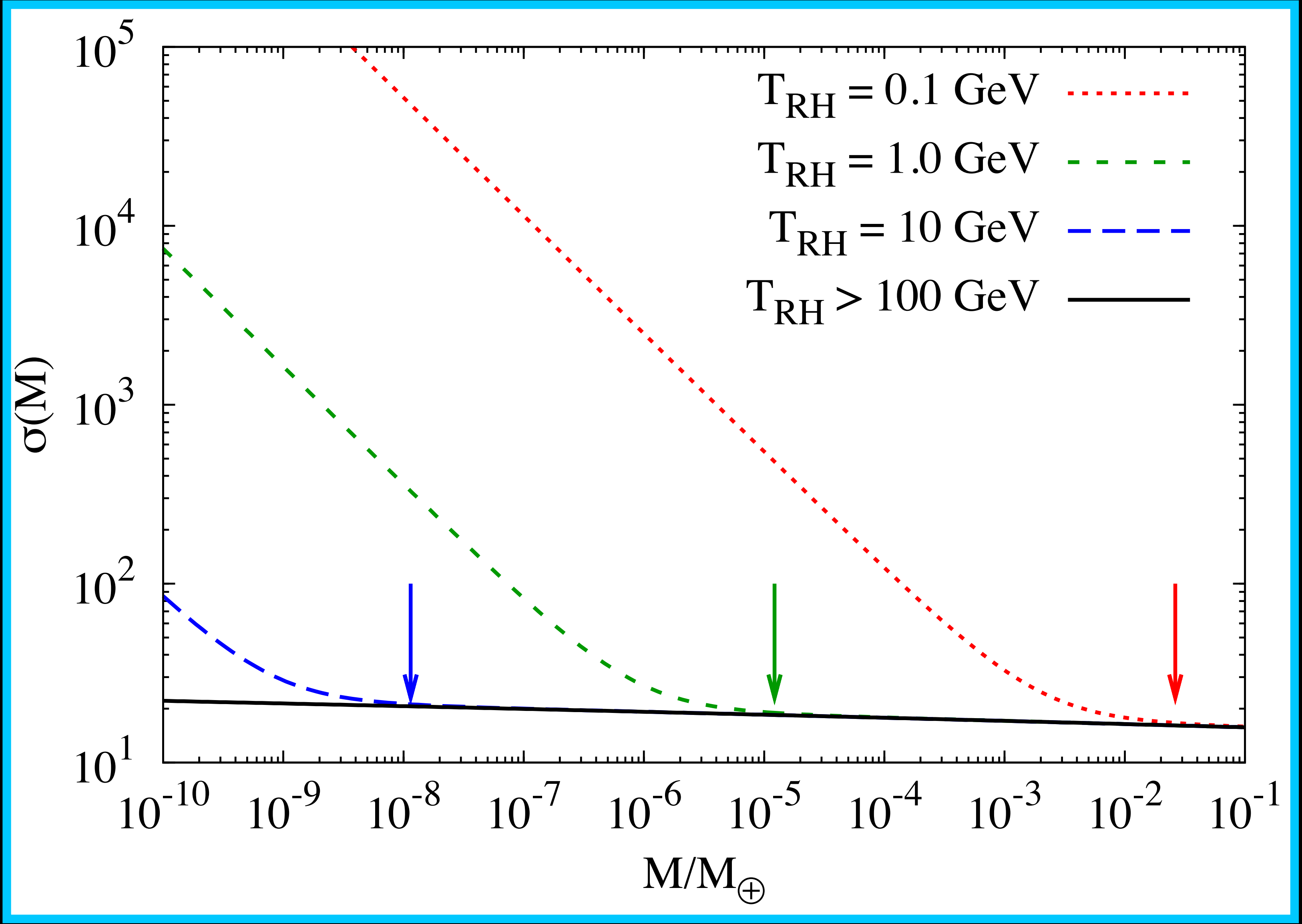
Structure Growth during an EMDE

Evolution of the Matter Density Perturbation



ALE & Sigurdson 2011; Fan, Ozsoy, Watson 2014; ALE 2015

RMS Density Fluctuation



- Enhanced perturbation growth affects subhorizon scales: $R \lesssim k_{\rm RH}^{-1}$

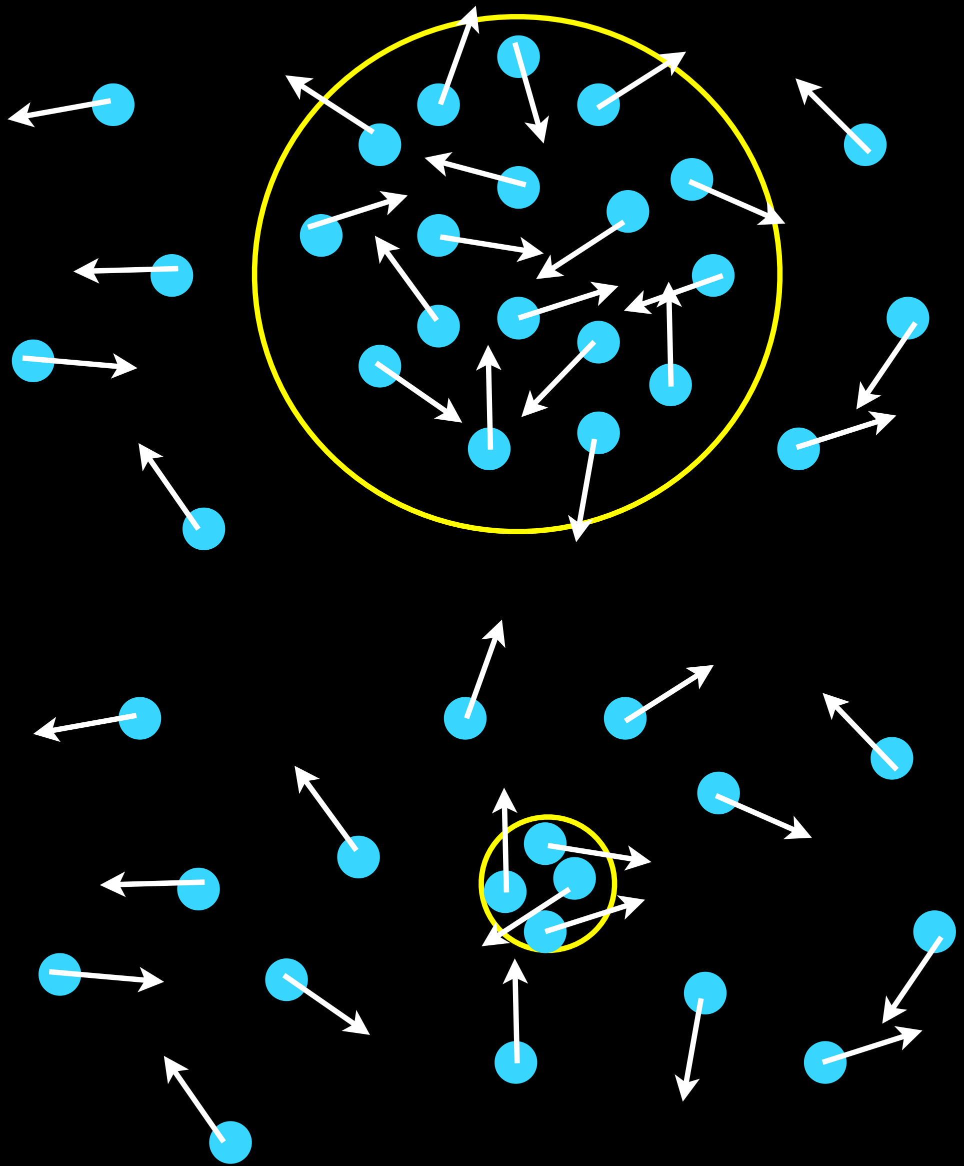
- Define $M_{\rm RH}$ to be mass within this comoving radius.

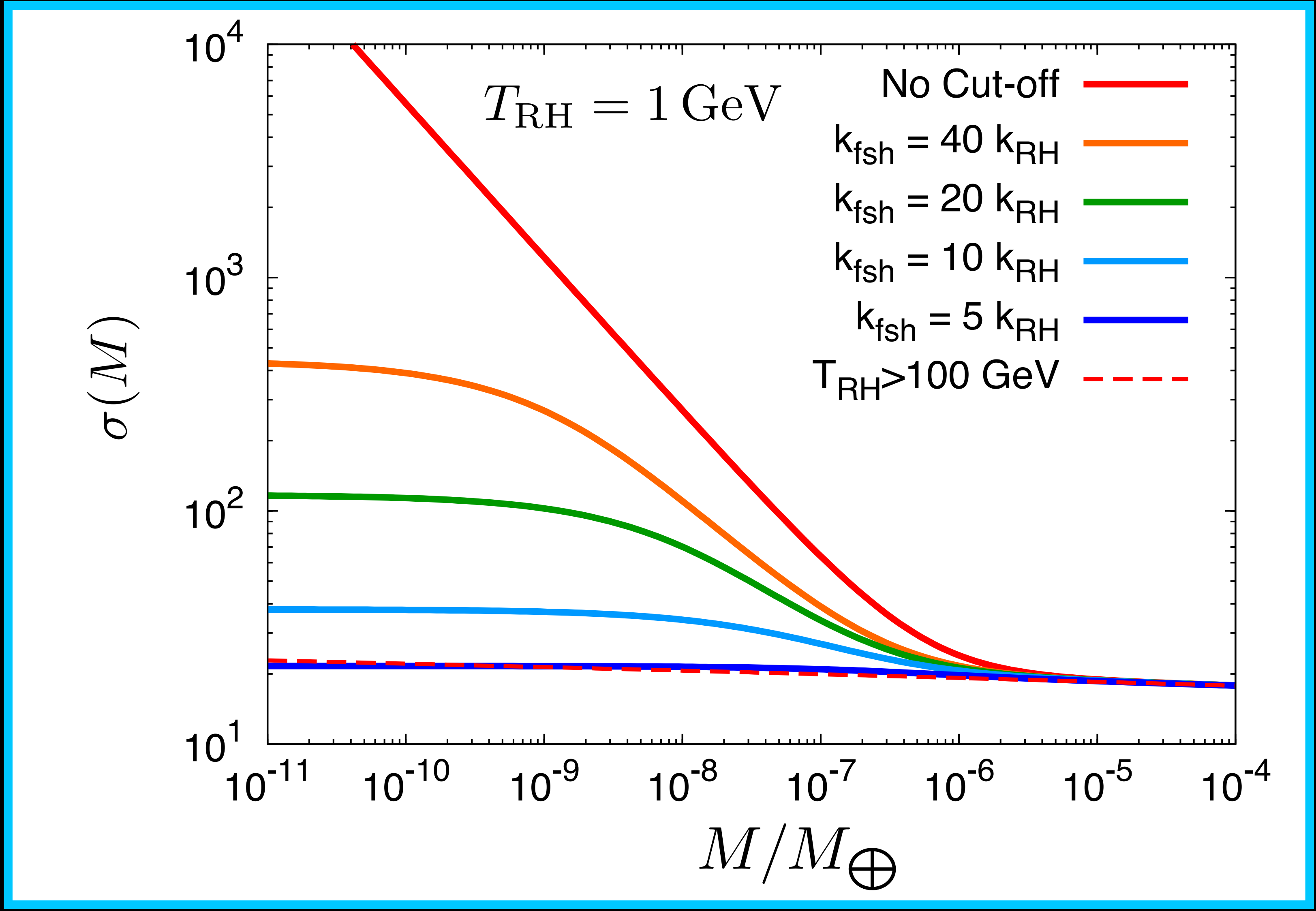
$$M_{\rm RH} \simeq 10^{-5}\, M_\oplus \left(\frac{1\,{\rm GeV}}{T_{\rm RH}}\right)^3$$

Microhalos!

Free-streaming

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

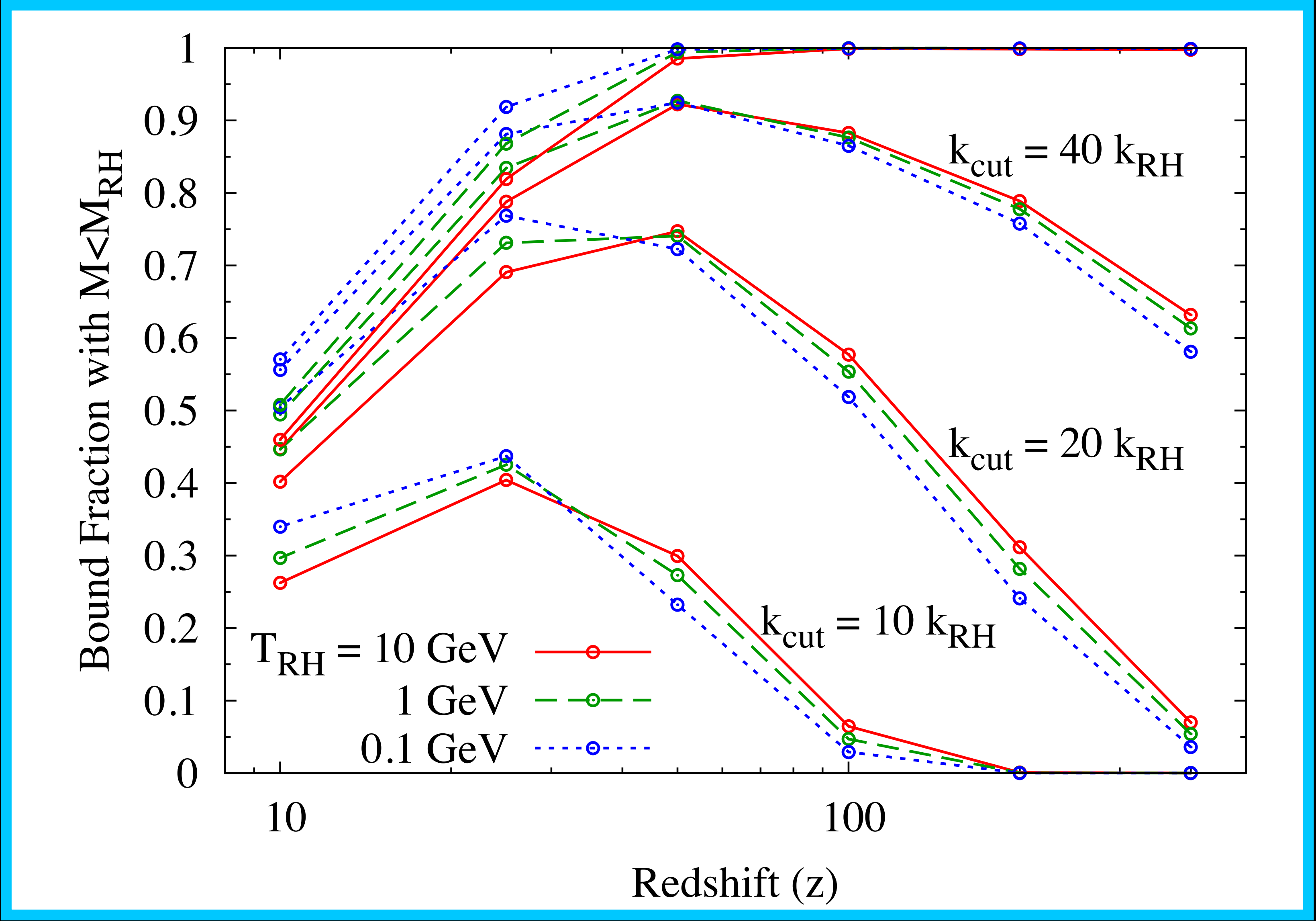




Structures grown during reheating only survive if $k_{\rm fsh}/k_{\rm RH} > 10$

The Microhalo Abundance

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.



ALE 2015

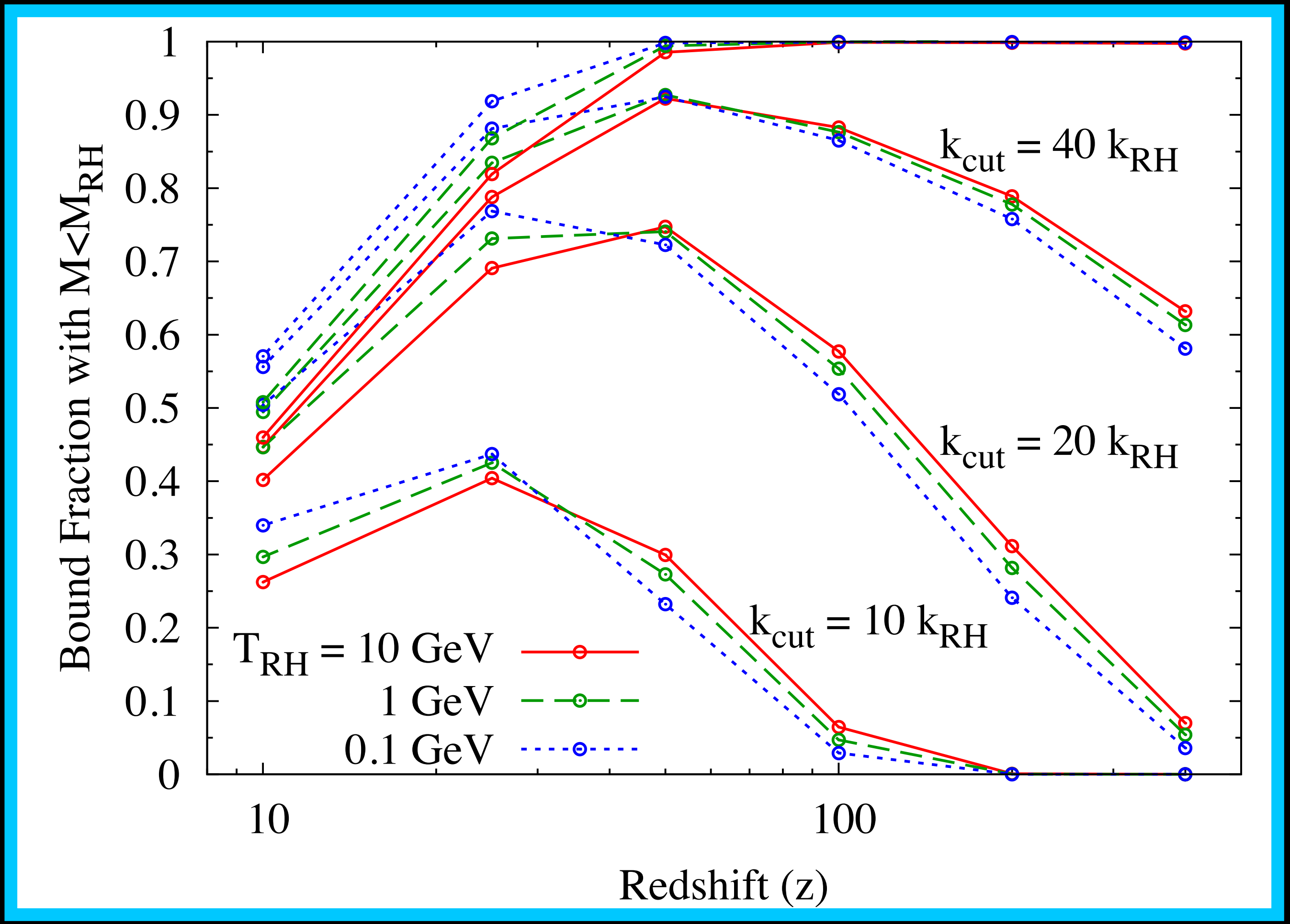
z	400	100	50
$k_{\rm fsh} = 40k_{\rm RH}$	0.6	0.9	0.9
$k_{\rm fsh} = 10k_{\rm RH}$	10^{-9}	0.05	0.3
Std.	0	10^{-4}	0.04

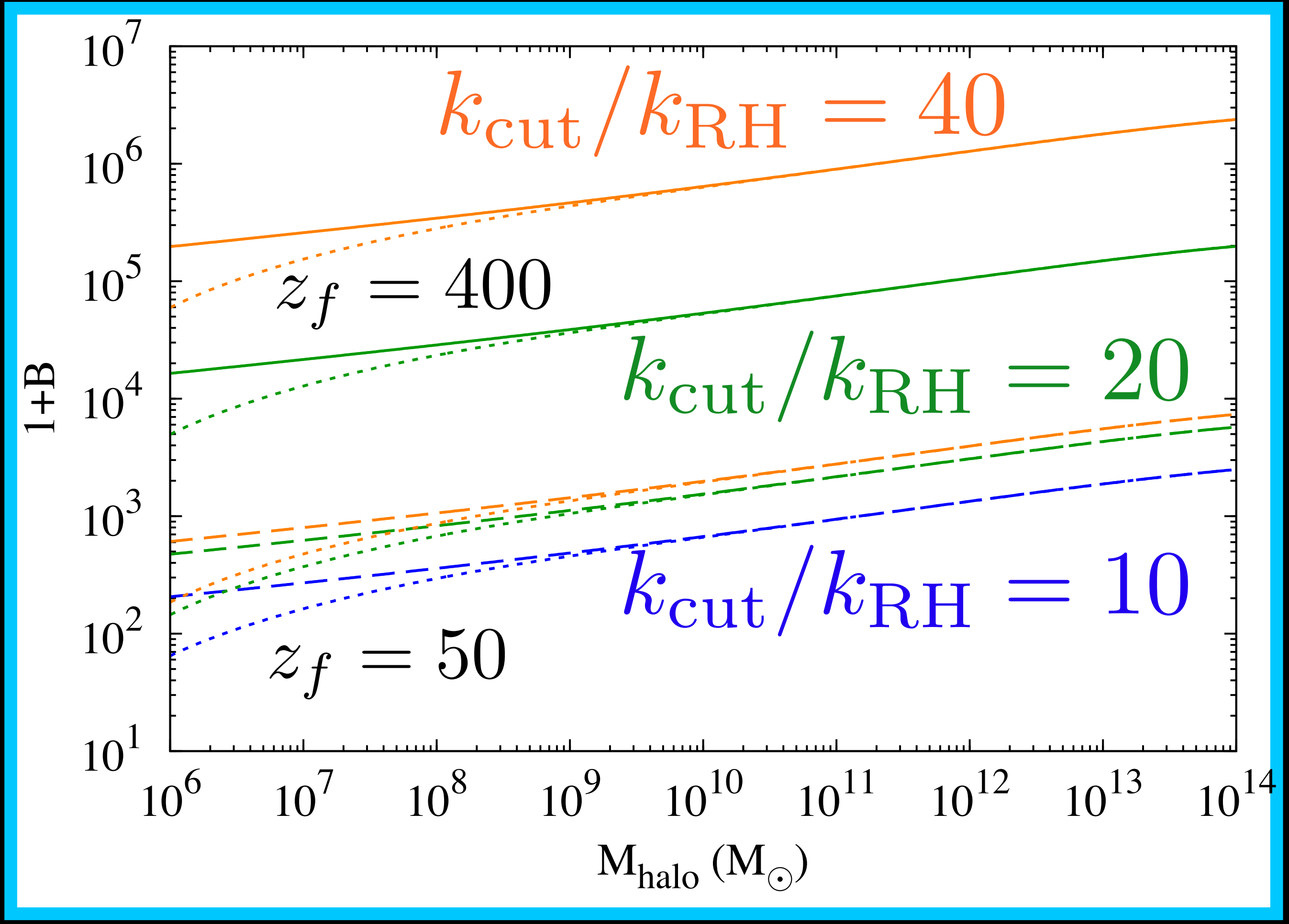
Estimating the Boost Factor

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

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

Estimating the Boost Factor

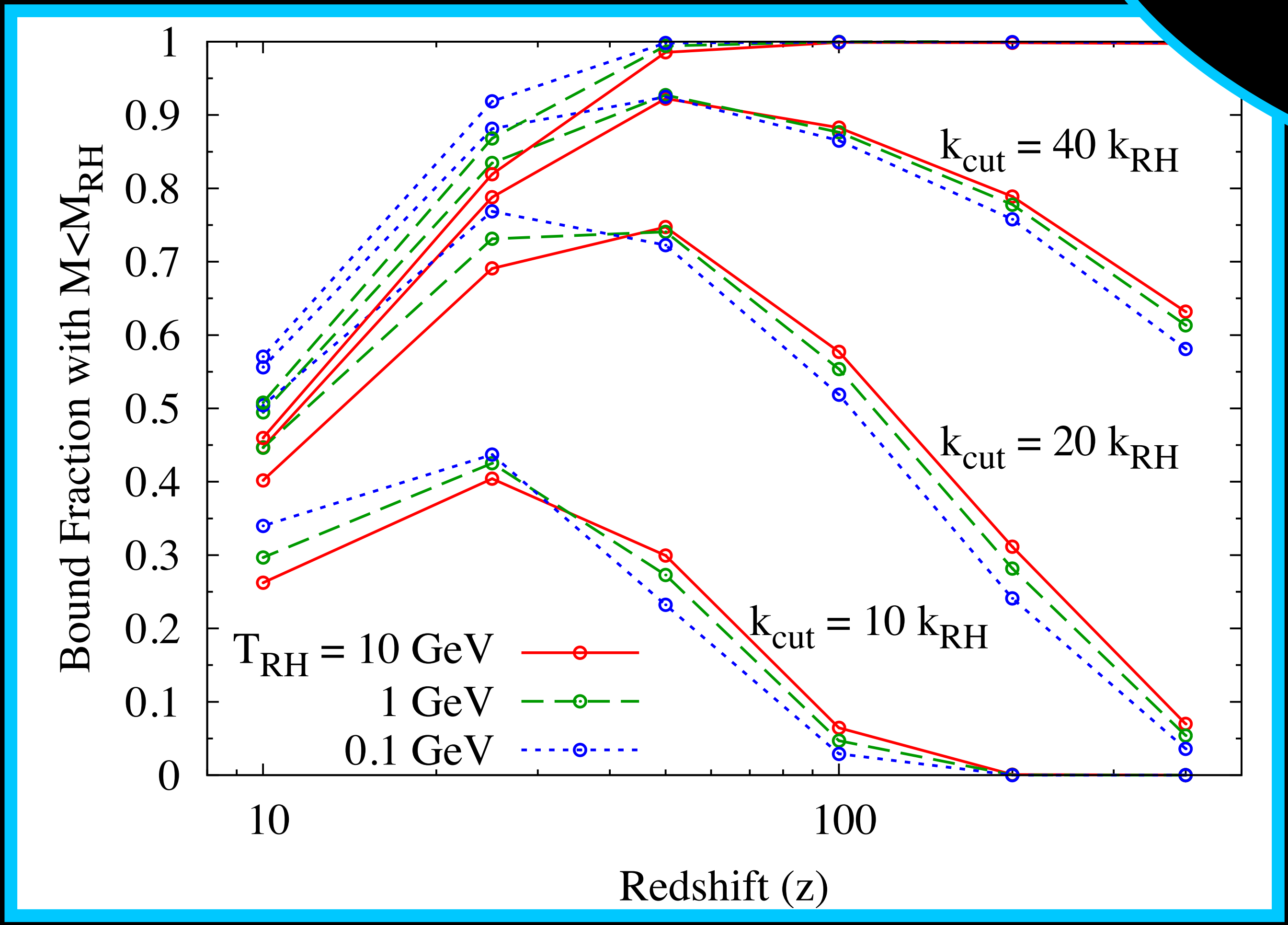
Dark matter annihilation rate: Γ $\frac{\langle \sigma v \rangle}{2} J$

Boost Factor:

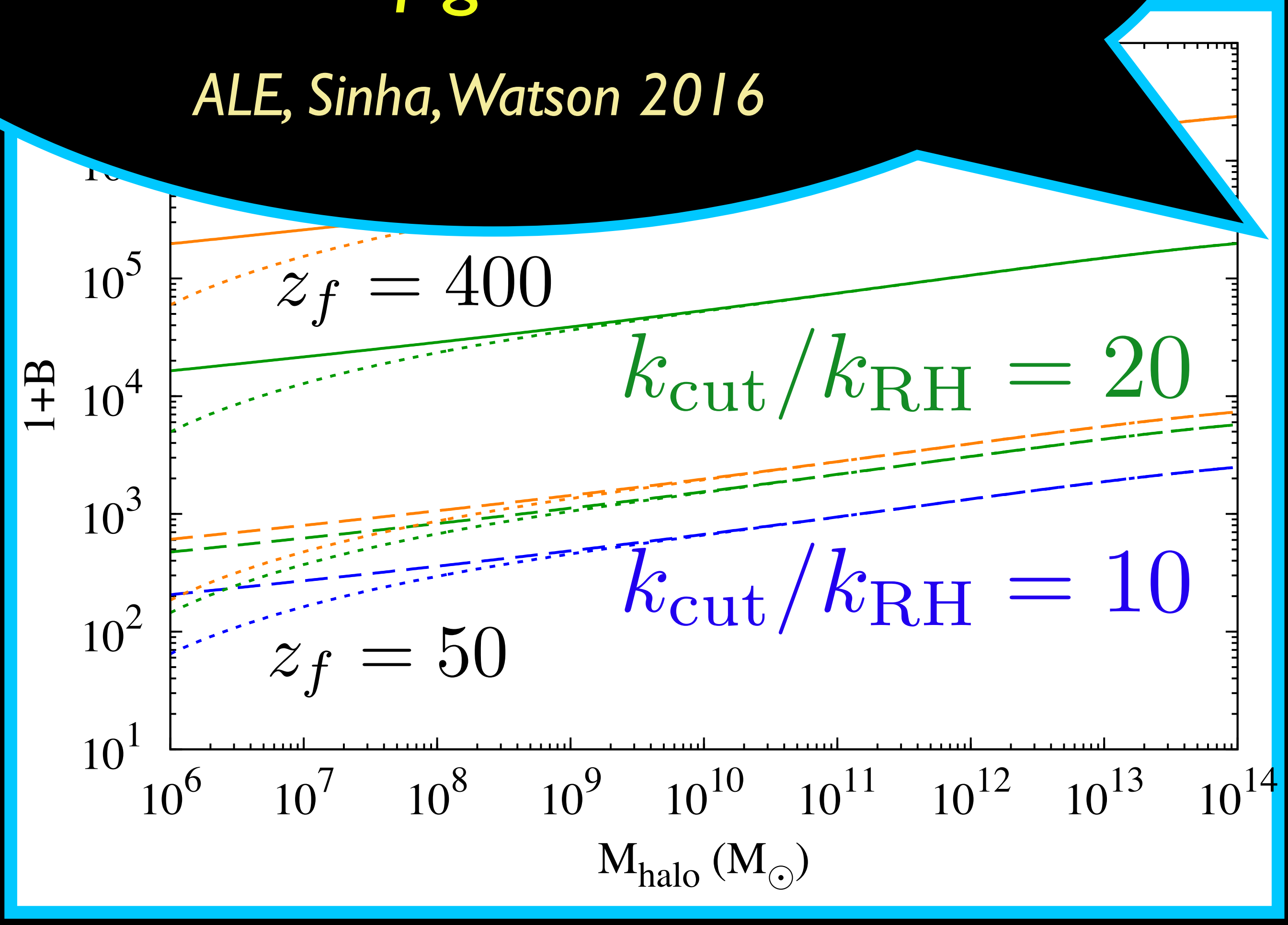
$$1 + B(M) \equiv \frac{J}{\int \bar{\rho}_\chi^2(r)\, 4\pi}$$

An EMDE could make an "isolated" bino a viable DM candidate with a detectable annihilation signature in dwarf galaxies.

ALE, Sinha, Watson 2016



ALE 2015



Boost from Microhalos

Estimating the Boost Factor

Dark matter annihilation rate: Γ … $\frac{\langle \sigma v \rangle}{\;} J$

Boost Factor:

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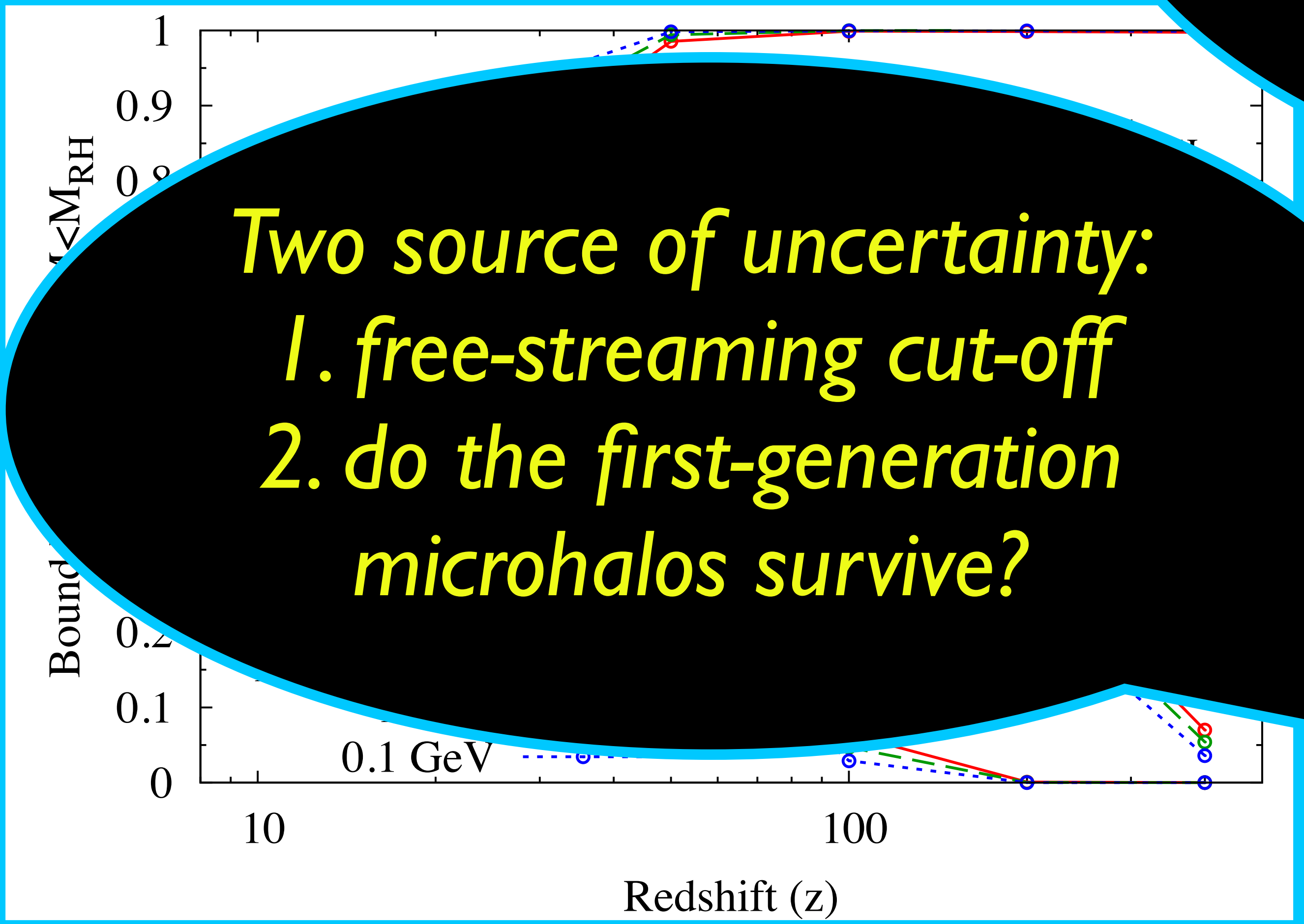
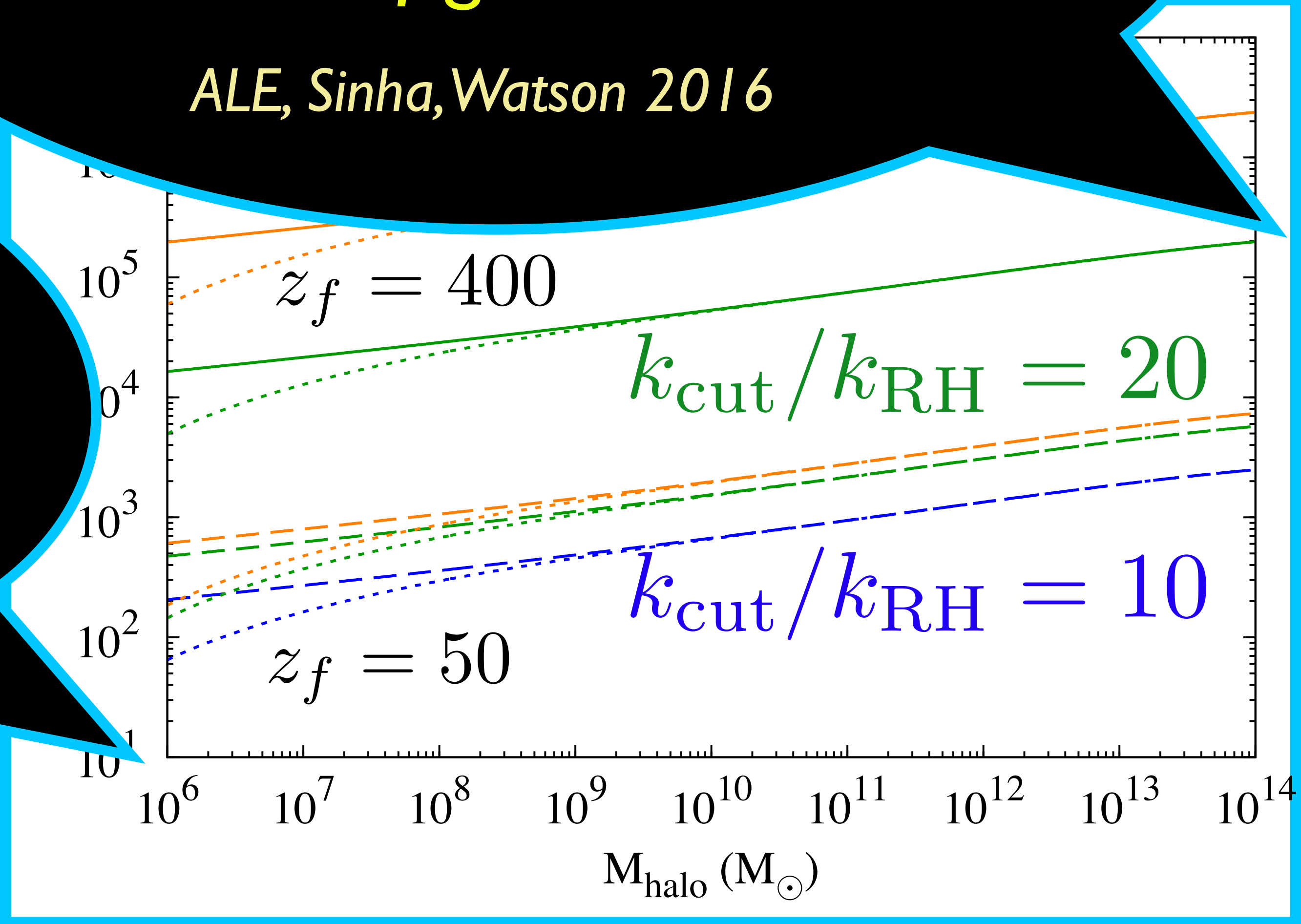


Two source of uncertainty:
1. free-streaming cut-off
2. do the first-generation microhalos survive?

ALE 2015



Boost from Microhalos

The DM temperature

Isaac Waldstein,
ALE, Cosmin Ilie
2017

To determine the free-streaming cut-off, we need the DM temperature.

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

momentum transfer rate

$$\gamma \propto T^6$$

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

expansion rate

- fully coupled:
  $\gamma \gg H \Rightarrow T_\chi \simeq T$
- fully decoupled:
  $\gamma \ll H \Rightarrow T_\chi \propto a^{-2}$

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Isaac Waldstein,
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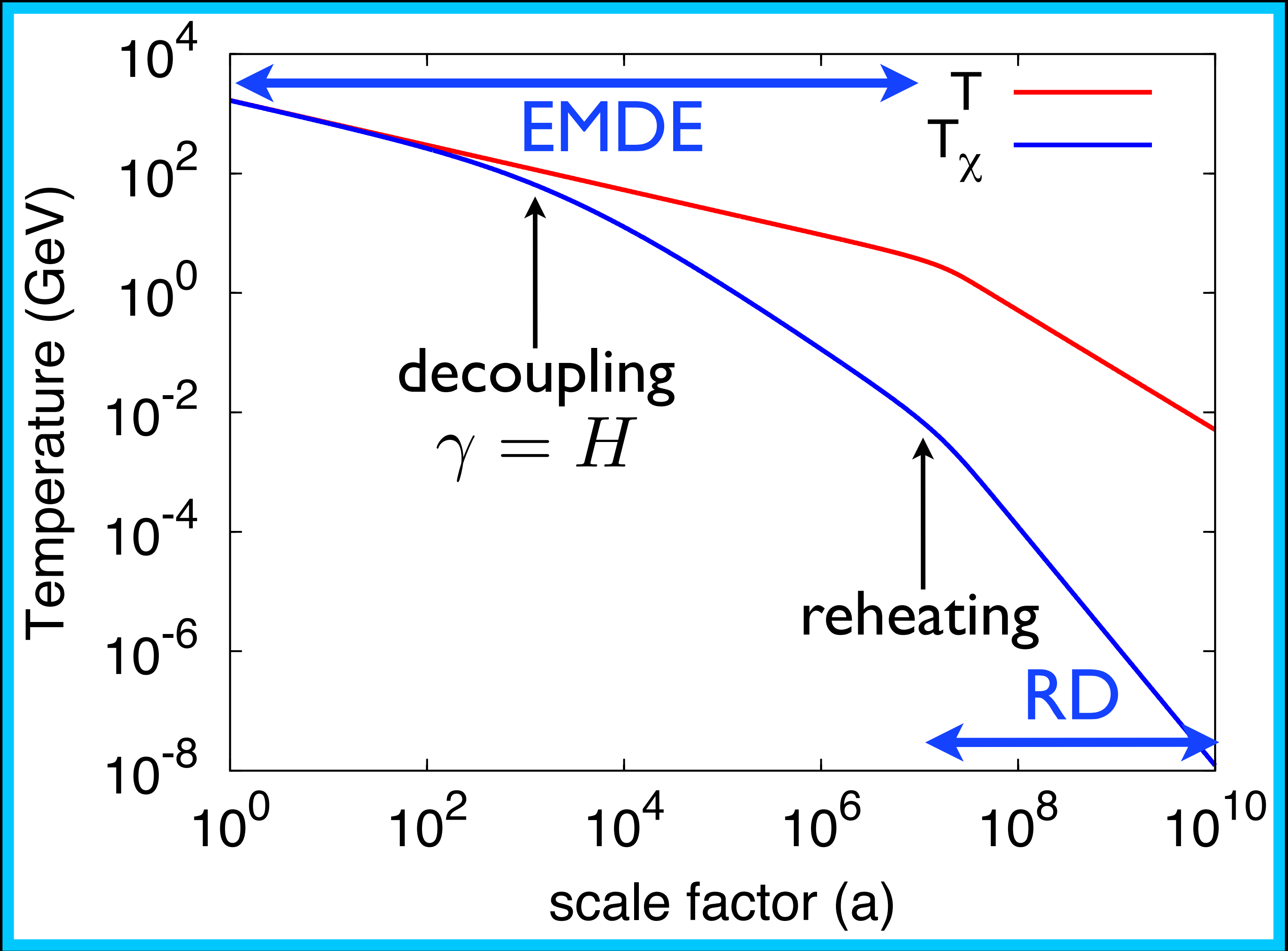

- fully coupled:
  $\gamma \gg H \Rightarrow T_\chi \simeq T$
- fully decoupled:
  $\gamma \ll H \Rightarrow T_\chi \propto a^{-2}$
- But during an EMDE
  $$\frac{\gamma}{H}T \propto \frac{T^6}{T^4}T \propto T^3 \propto a^{-9/8}$$
- quasi-decoupled: $T_\chi \propto a^{-9/8}$

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Isaac Waldstein,
ALE, Cosmin Ilie
2017

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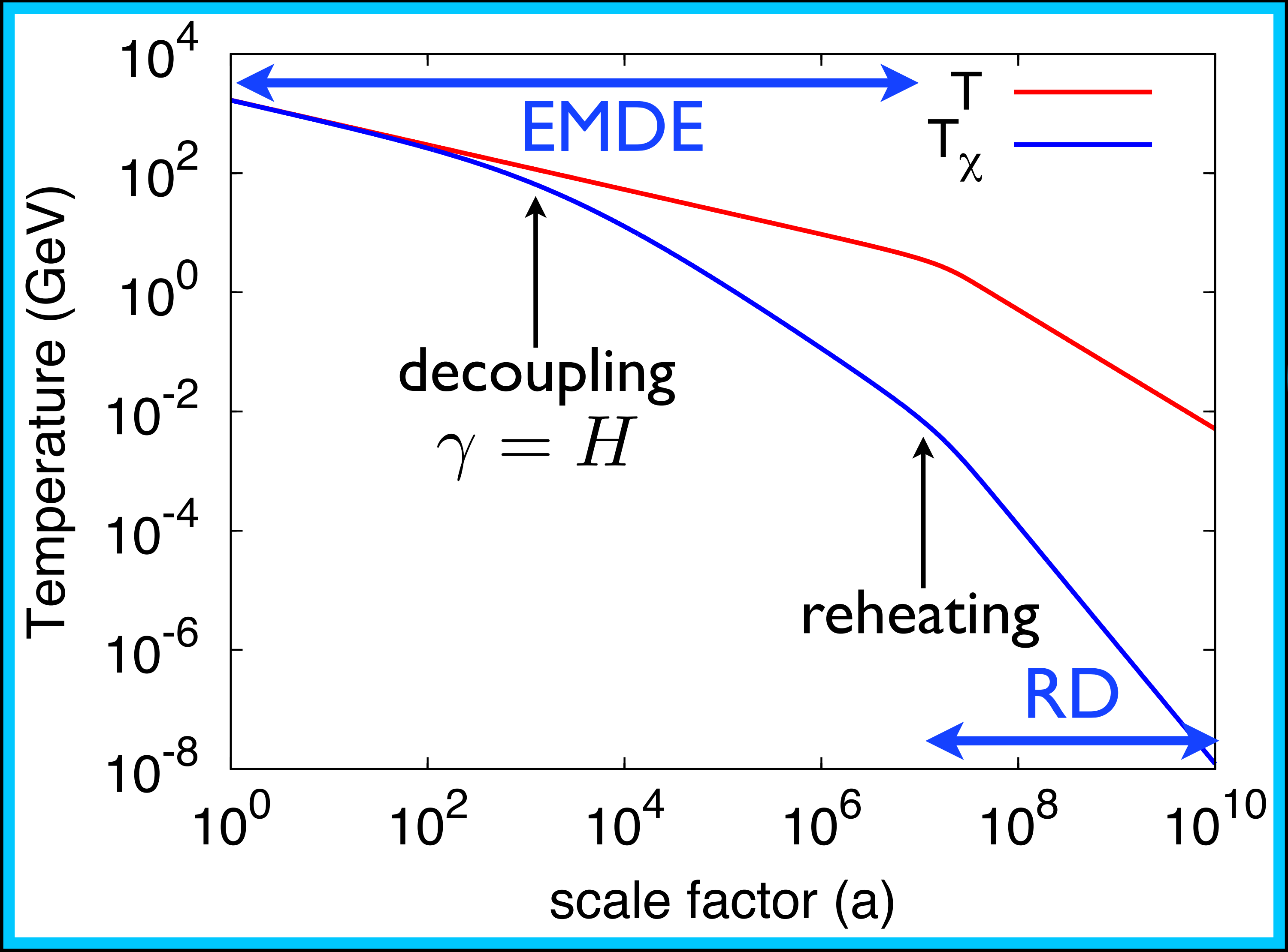


- fully co

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

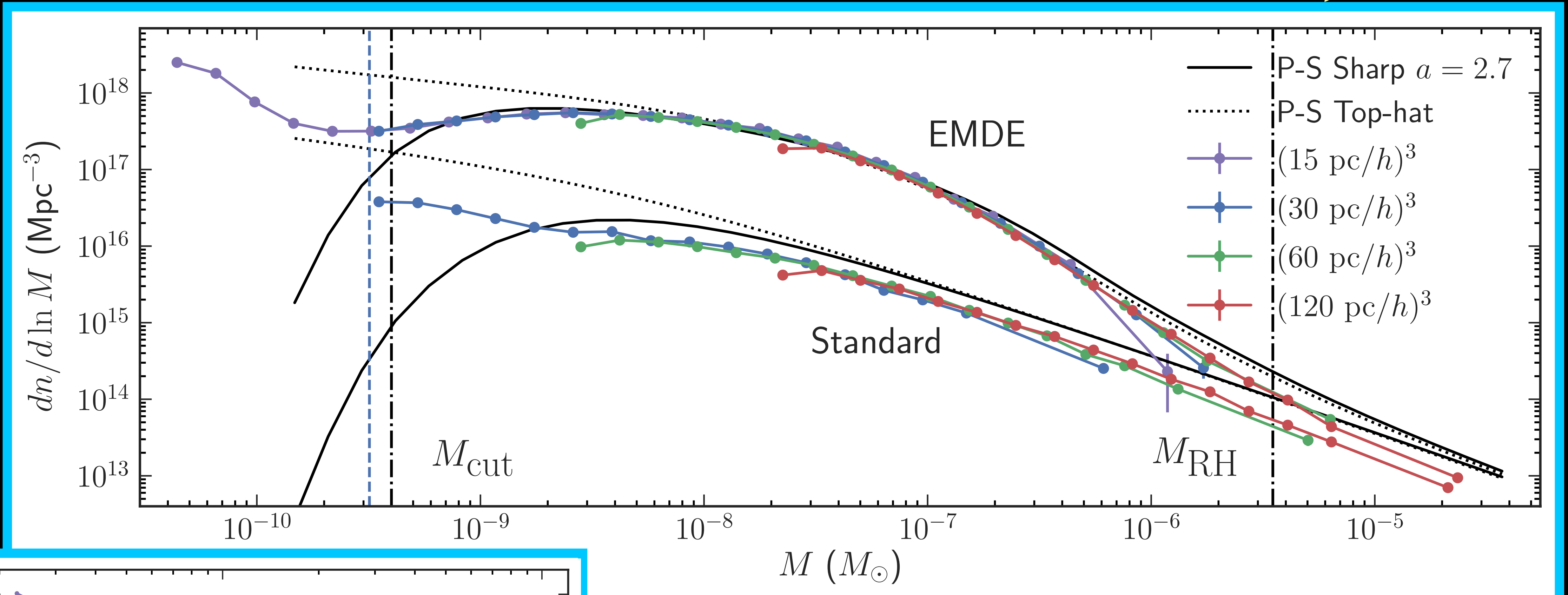
- Bu

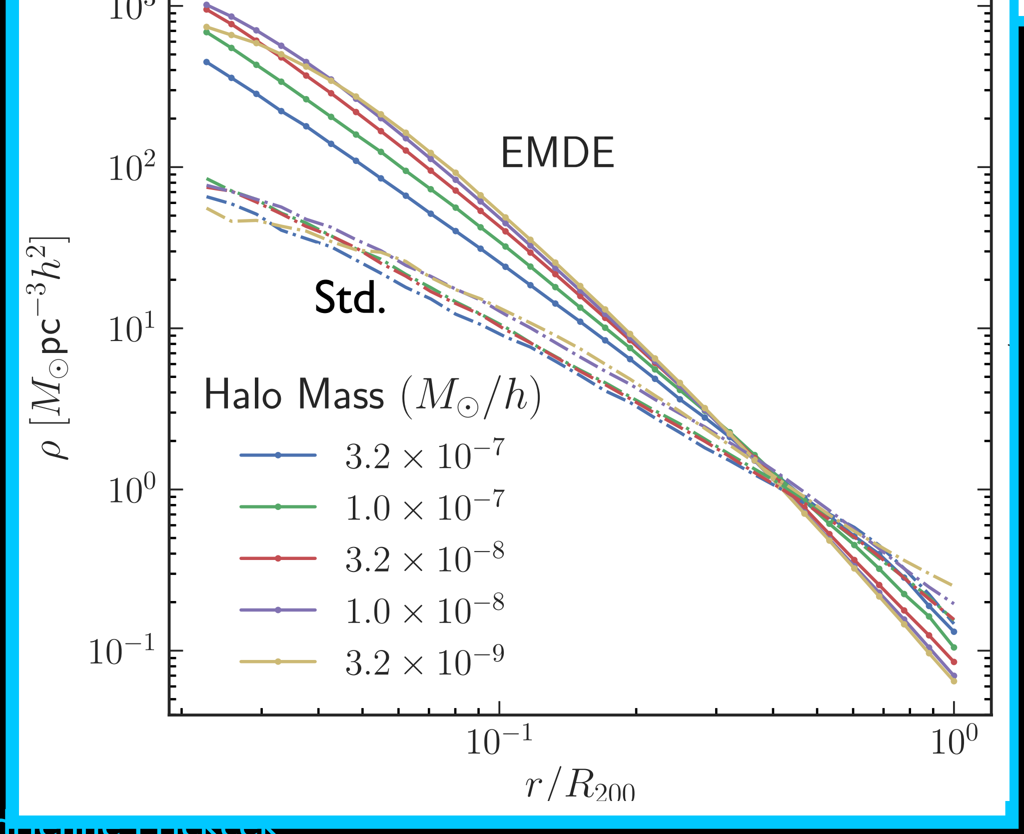
$$\frac{\gamma}{H}T \propto \frac{T^6}{T^4}T \propto T^3 \propto a^{-9/8}$$

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

EMDE Microhalo Simulations

Sheridan Green, ALE+ coming soon



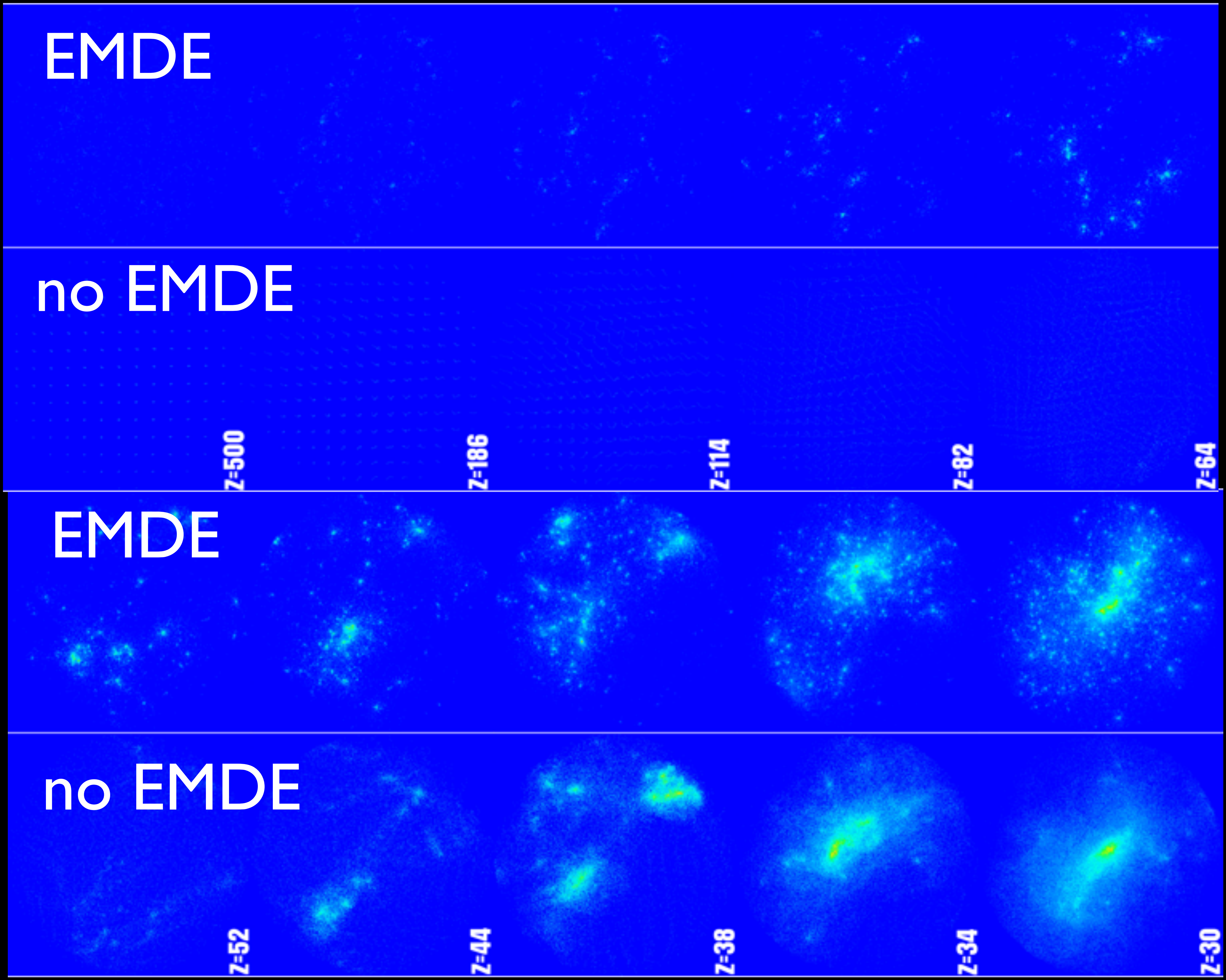


EMDE parameters:

$$T_{\mathrm{RH}} = 30\ \mathrm{MeV}$$

$$k_{\mathrm{cut}} = 20 k_{\mathrm{RH}}$$

EMDE Microhalo Simulations



EMDE

$$T_{\mathrm{RH}} = 30\ \mathrm{MeV}$$

$$k_{\mathrm{cut}} = 20 k_{\mathrm{RH}}$$

Sheridan Green, ALE+ coming soon

Boost Factor from Simulations

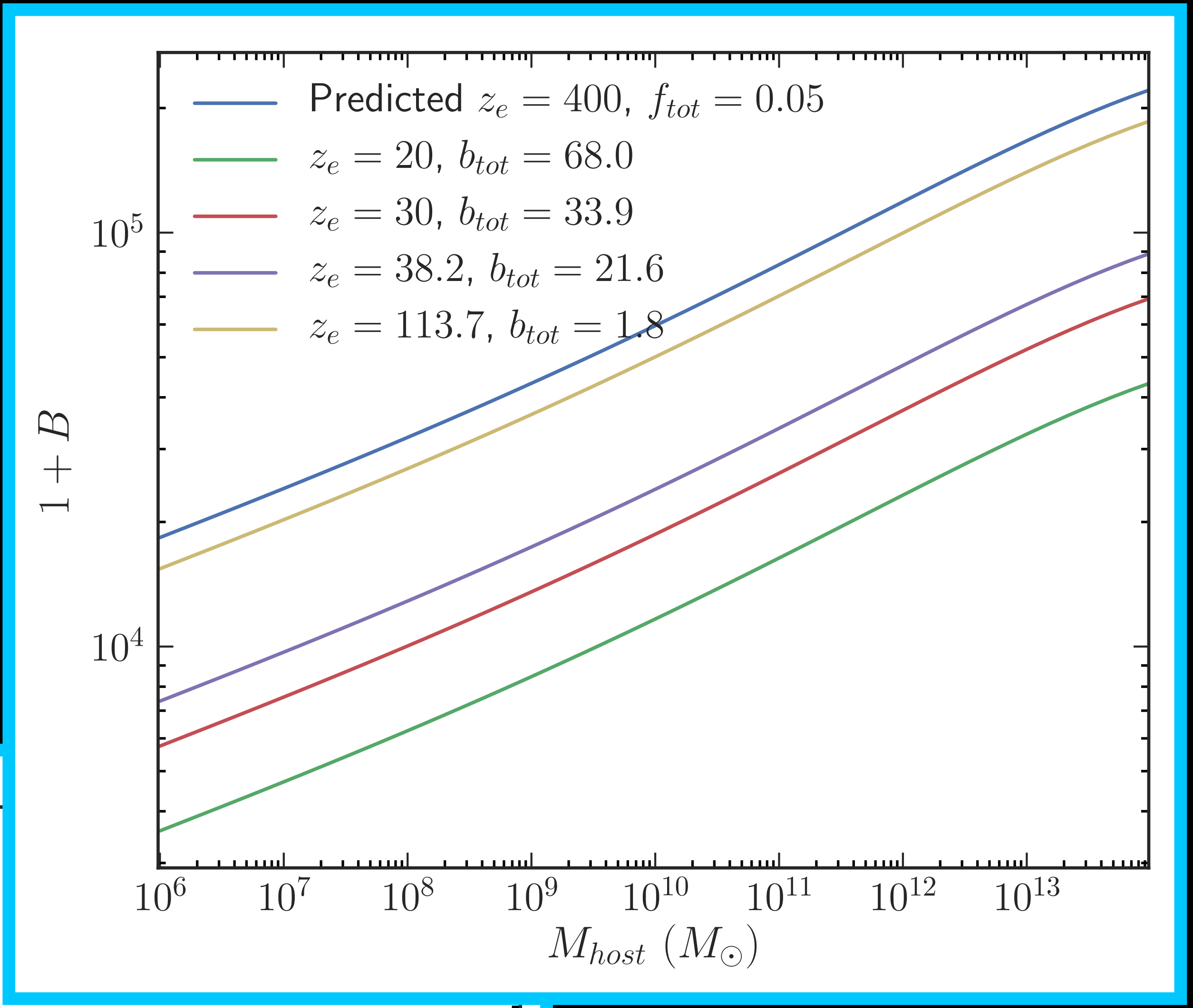
$$1 + B(M) \equiv \frac{J}{\int \bar{\rho}_\chi^2(r)\, 4\pi r^2 dr} \propto \frac{\rho(z_f)}{\rho_0 c_h^3} f_{\rm tot}(M < M_{\rm RH}, z_f)$$

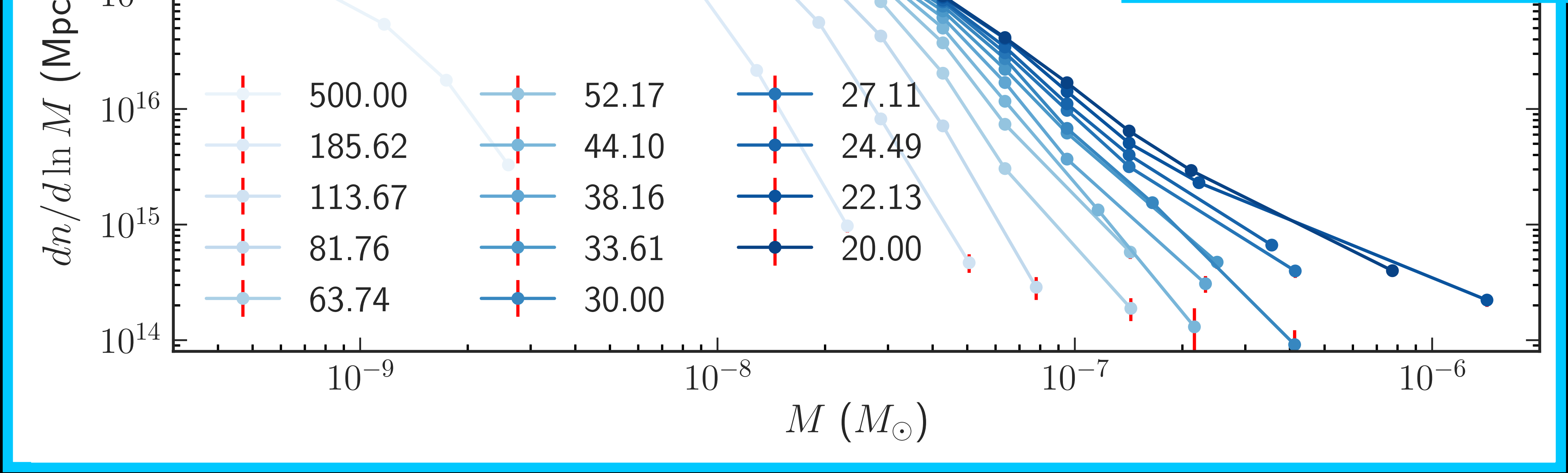
assumes all halos have same profile at z_f

include substructure:

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

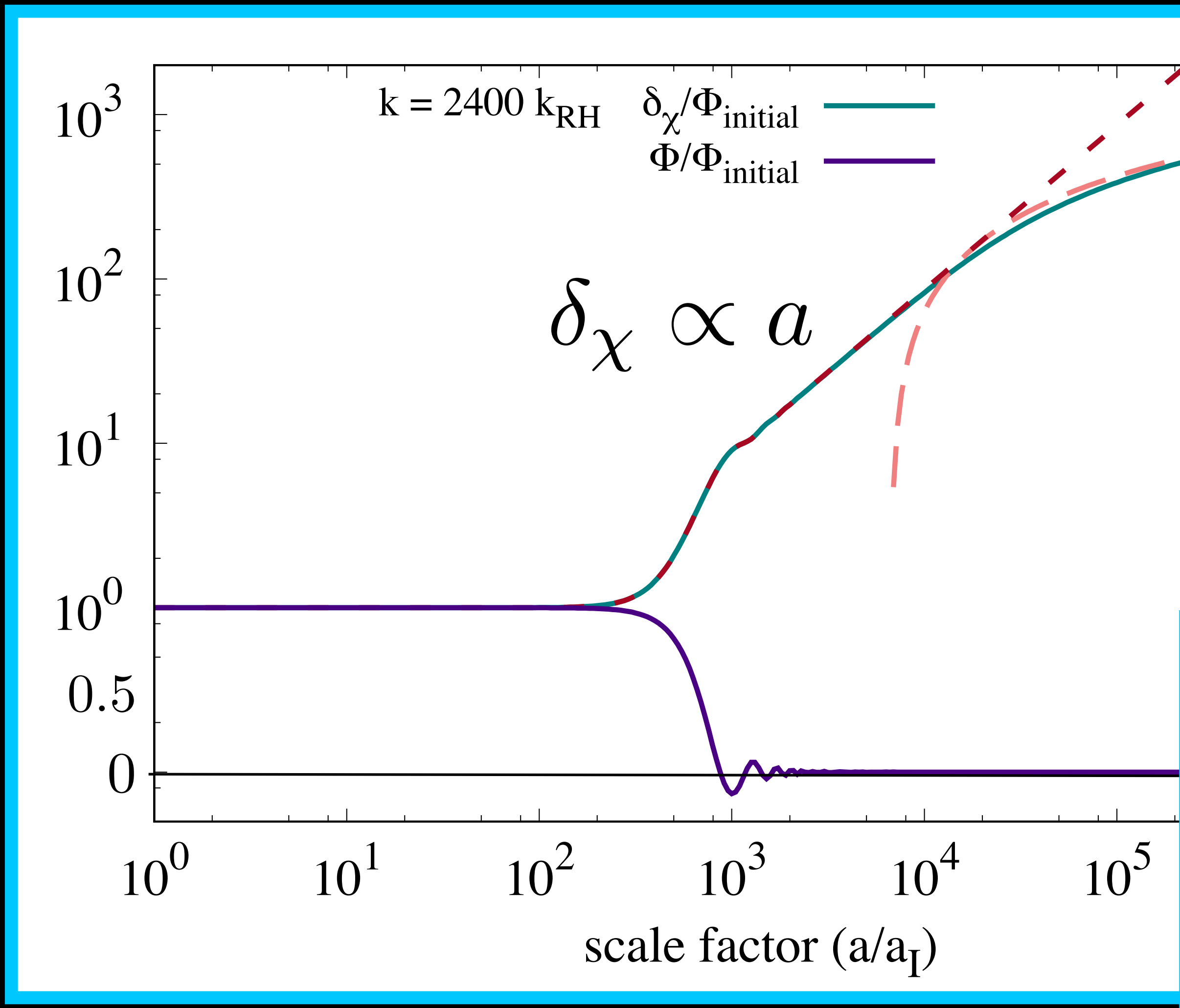
***Sheridan Green**, ALE+ coming soon*

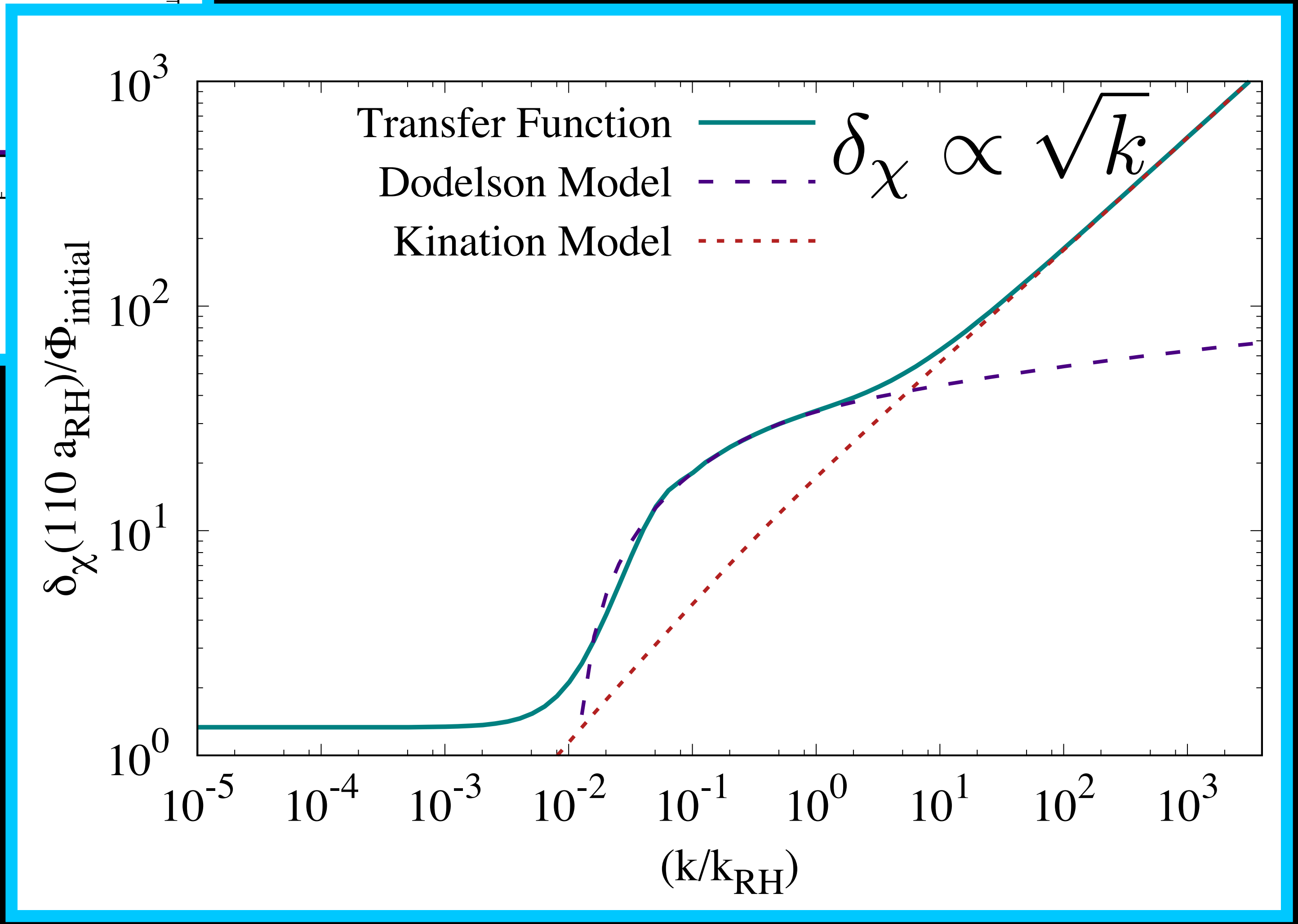




Perturbations during Kination

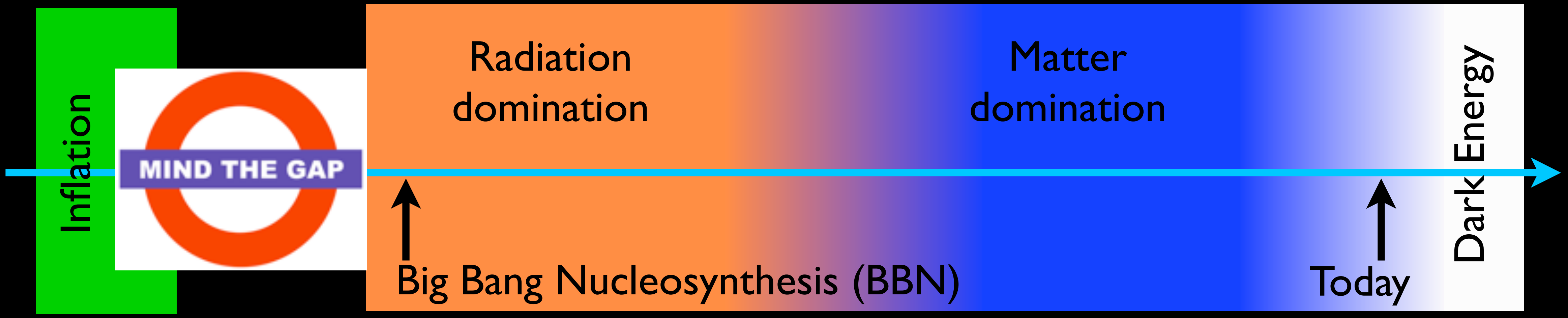
***Kayla Redmond**, Anthony Trezza,*
ALE coming soon





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

Summary: Mind the Gap after Inflation

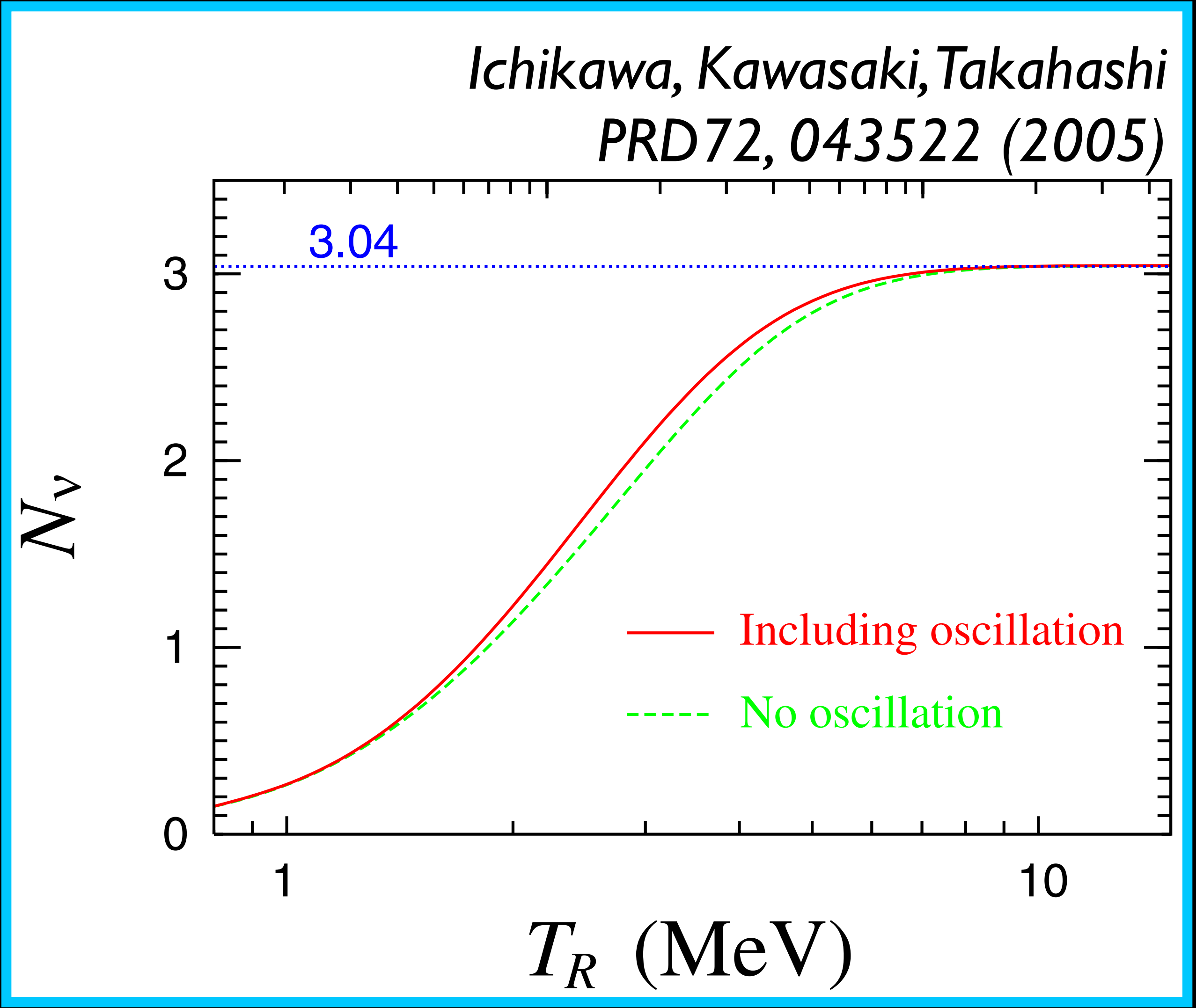


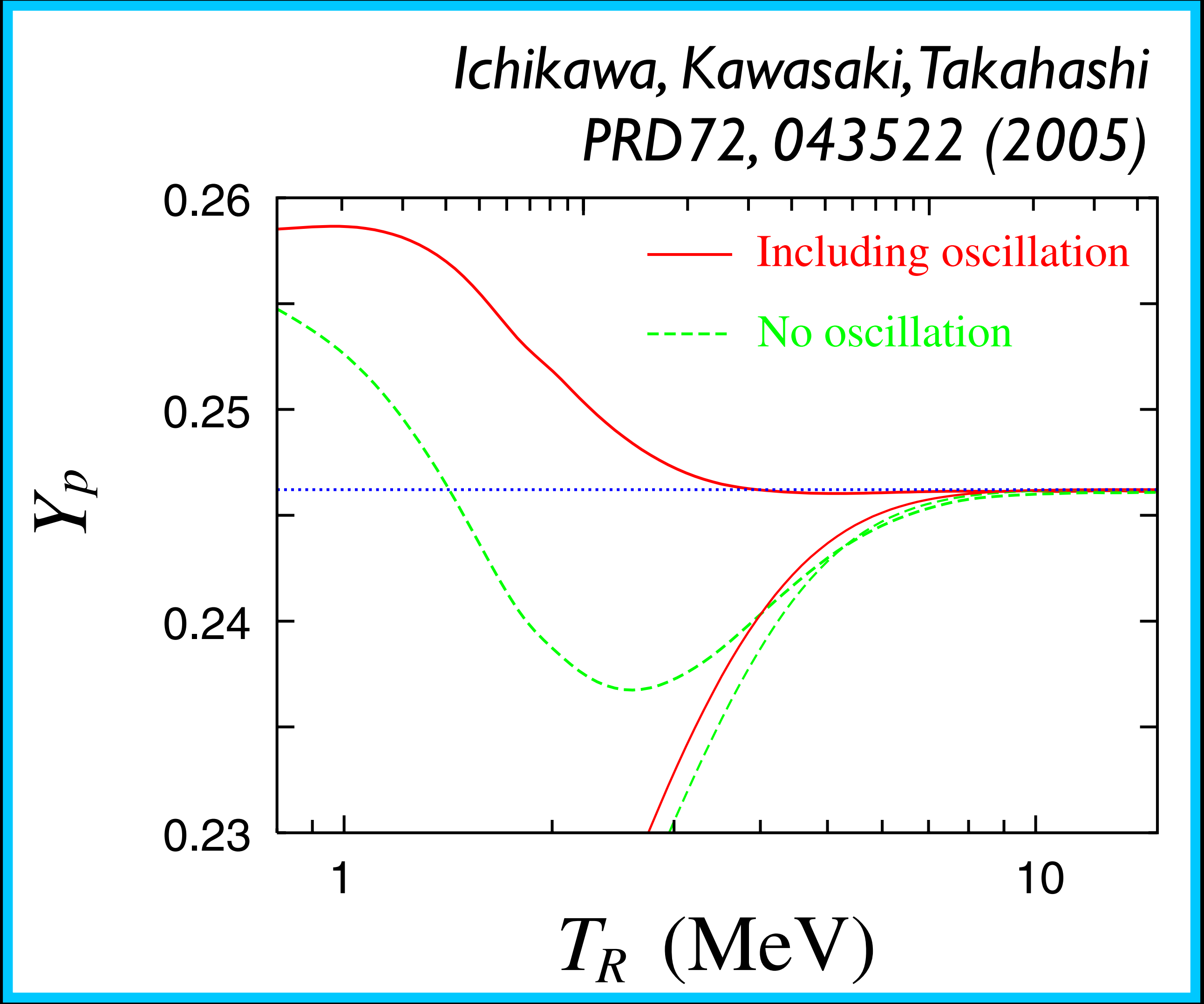
- There is a gap in the cosmological record between inflation and the onset of Big Bang nucleosynthesis: $10^{15}\ \mathrm{GeV} \gtrsim T \gtrsim 10^{-3}\ \mathrm{GeV}$
- Dark matter microhalos offer hope of probing the gap.
- Both kination and an early matter-dominated era (EMDE) enhance the growth 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 size of the smallest microhalos and if they survive to the present day.

Bonus Slides

Don’t Mess with BBN

Reheat Temperature = Temperature at Radiation Domination





Lowering the reheat temperature results in fewer neutrinos.

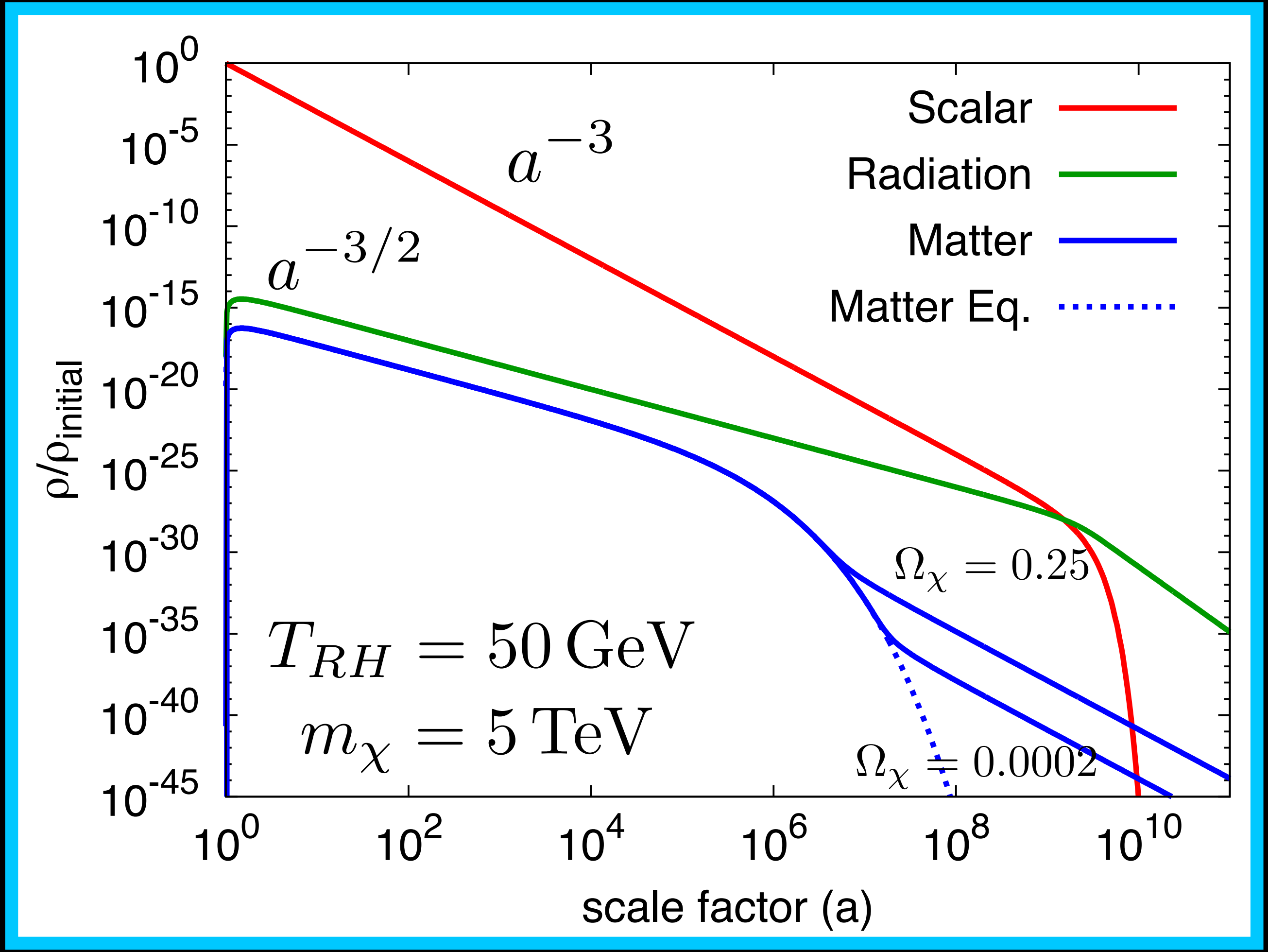
- slower expansion rate during BBN
- neutrino shortage gives earlier neutron freeze-out; more helium
- earlier matter-radiation equality affects CMB

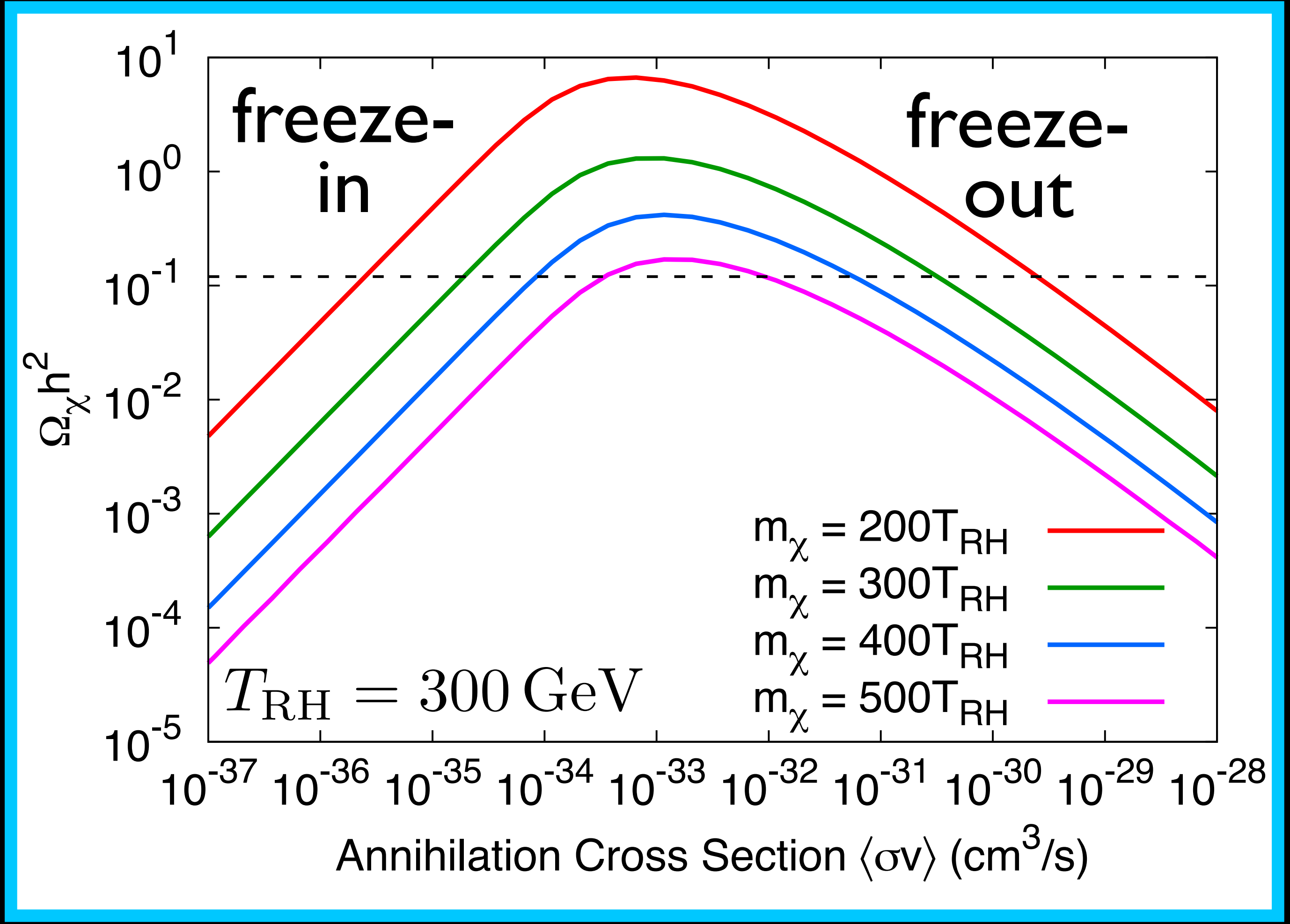
$$T_{\rm RH} \gtrsim 3 \text{ MeV}$$

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

DM Production during an EMDE

Giudice, Kolb, Riotto 2001; Gelmini, Gondolo 2006; Gelmini, Gondolo, Soldatenko, Yaguna 2006, ALE 2015

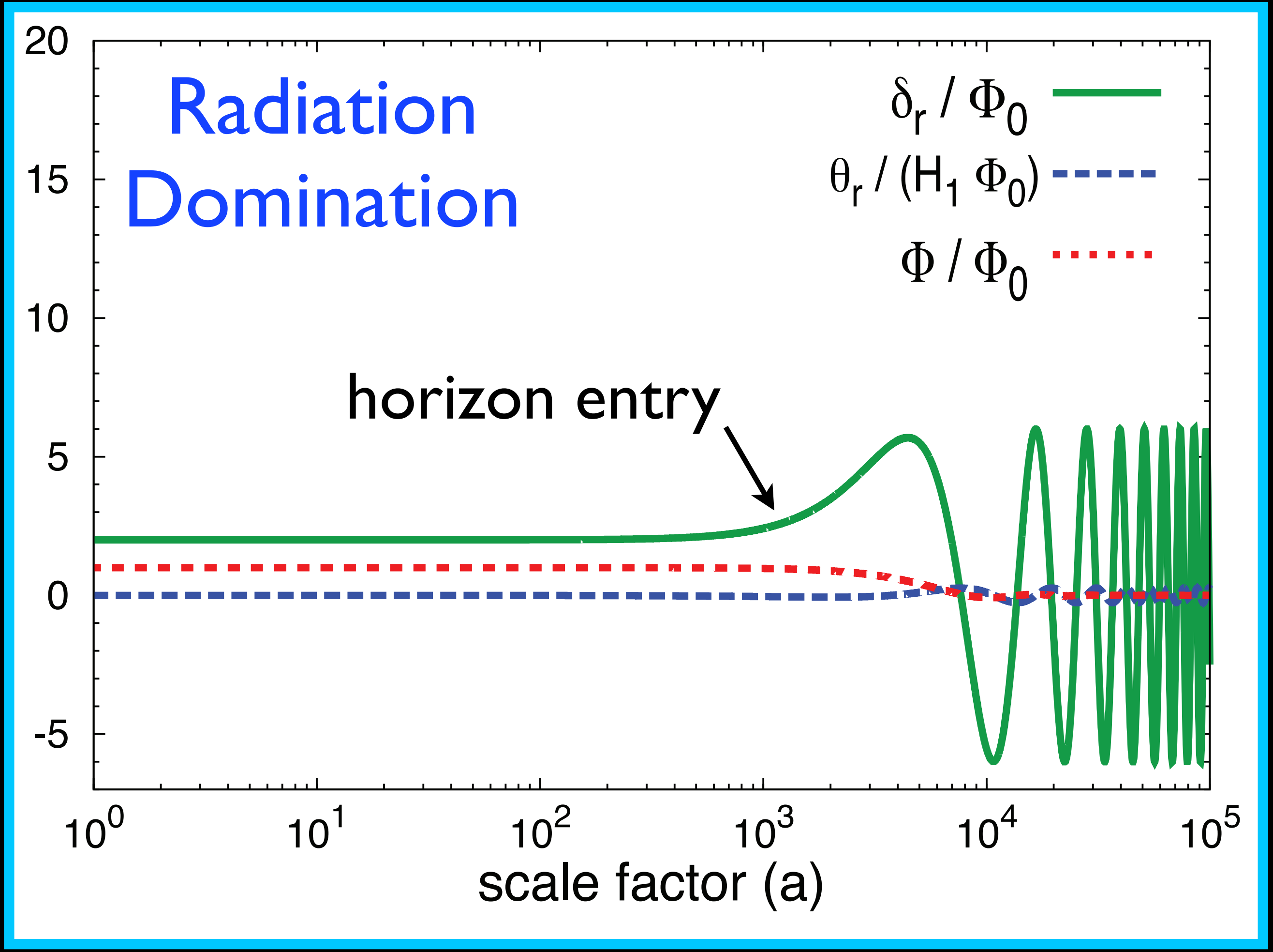




Thermal DM production during an early matter-dominated era (EMDE) requires much smaller annihilation cross sections!

What hope do we have of probing these scenarios?

The Radiation Perturbation



During radiation domination, the **radiation density perturbation oscillates.**

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

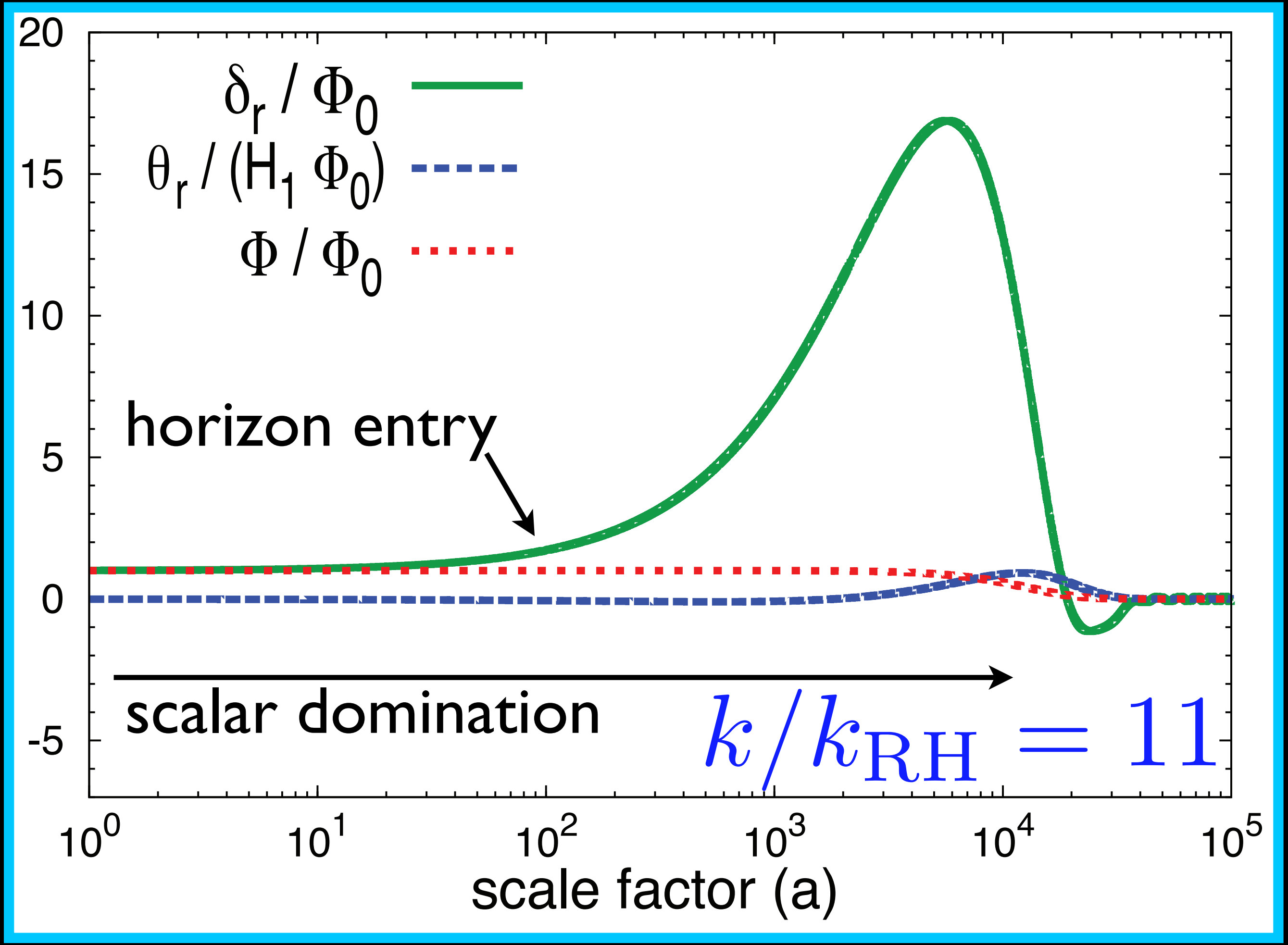
$$\delta_{\max} = 0.085\Phi_0 \text{ for } \frac{k}{k_{\rm RH}} = 11$$

$$\dot{\delta}_r \simeq -\theta_r + \mathcal{S}(\delta_\phi)$$

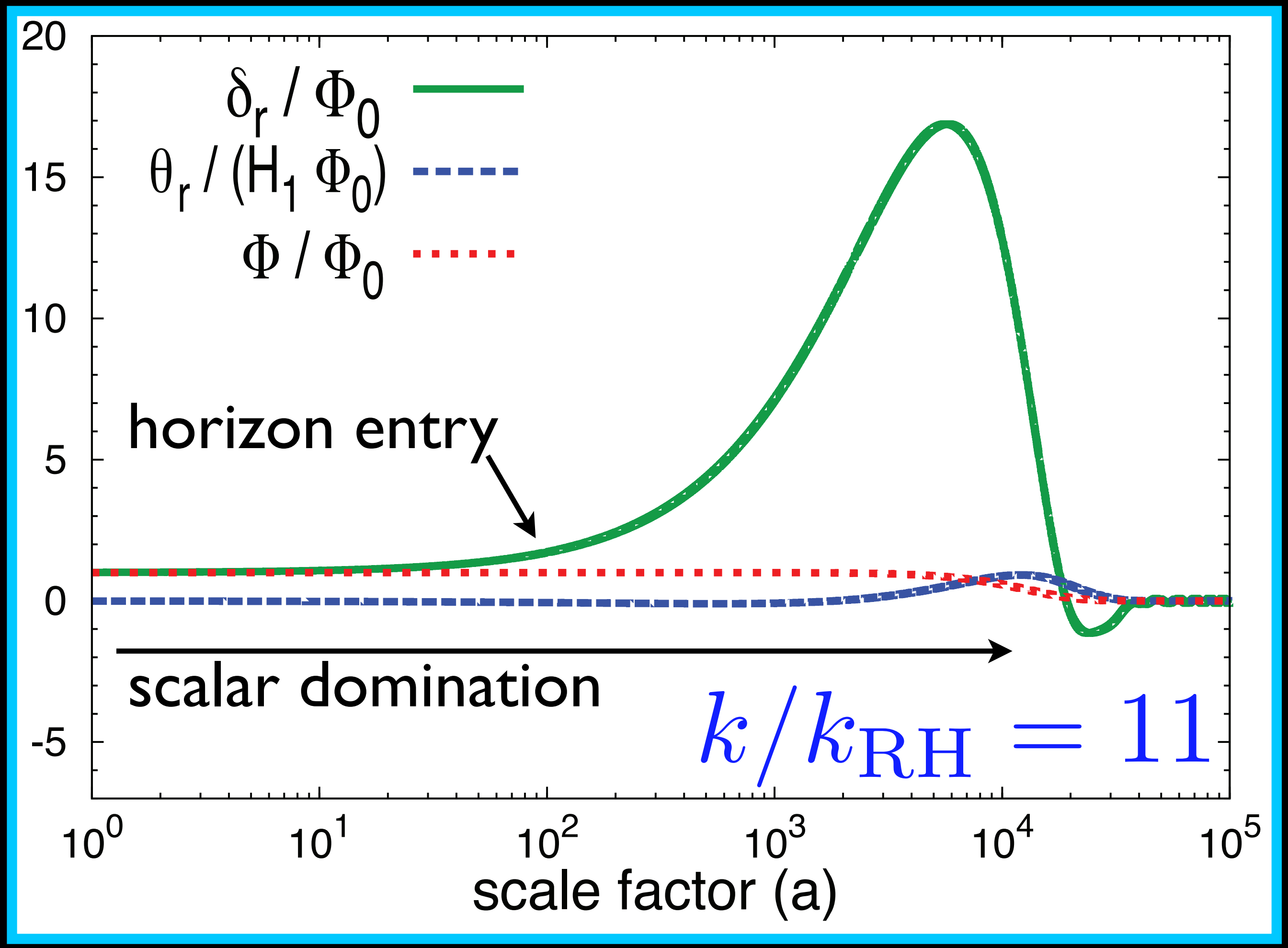
$$\dot{\theta}_r \simeq k^2 \delta_r + \mathcal{S}(\theta_\phi)$$

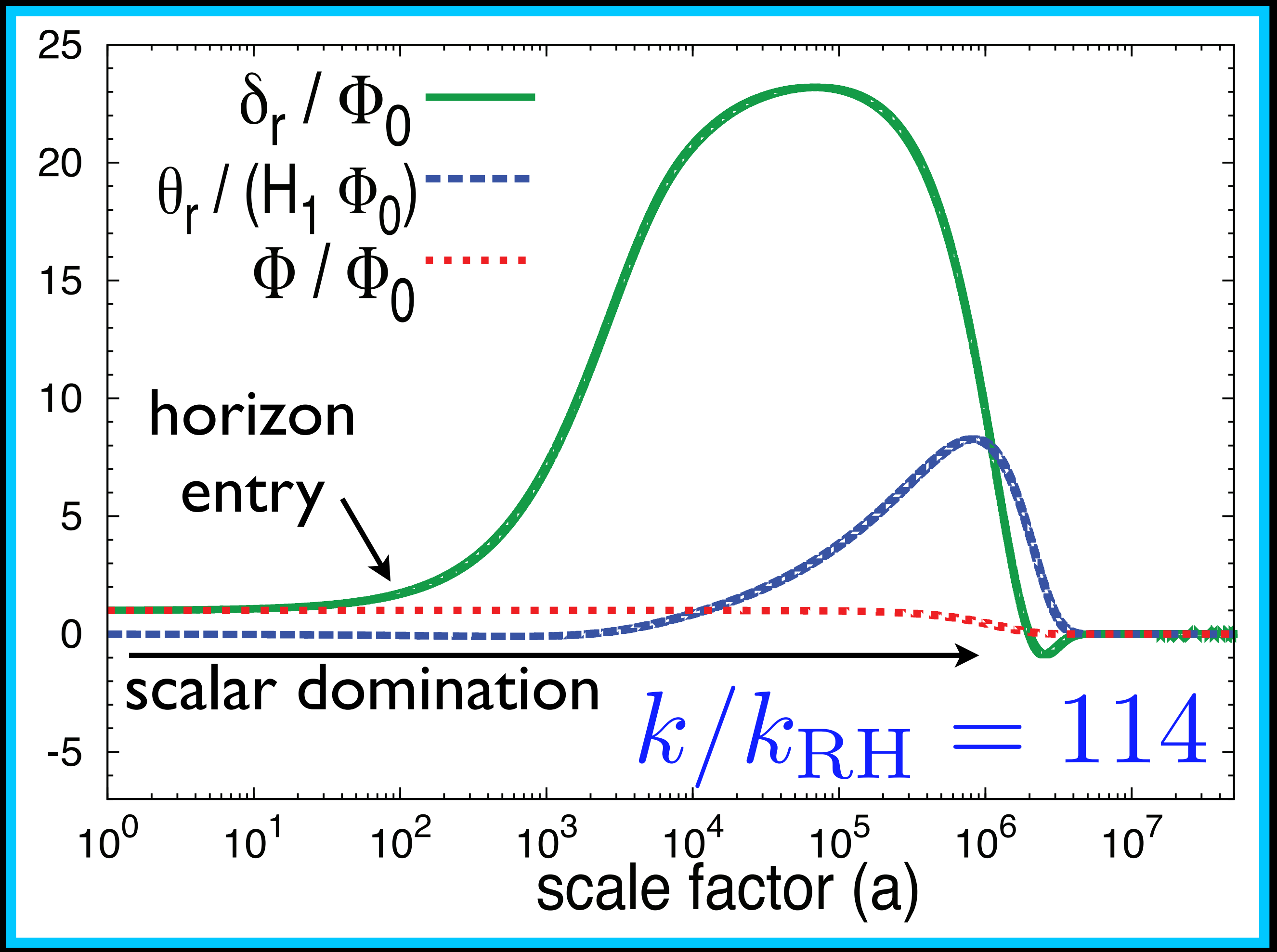
Grows during scalar domination

Adding a period of scalar domination dramatically alters the evolution!

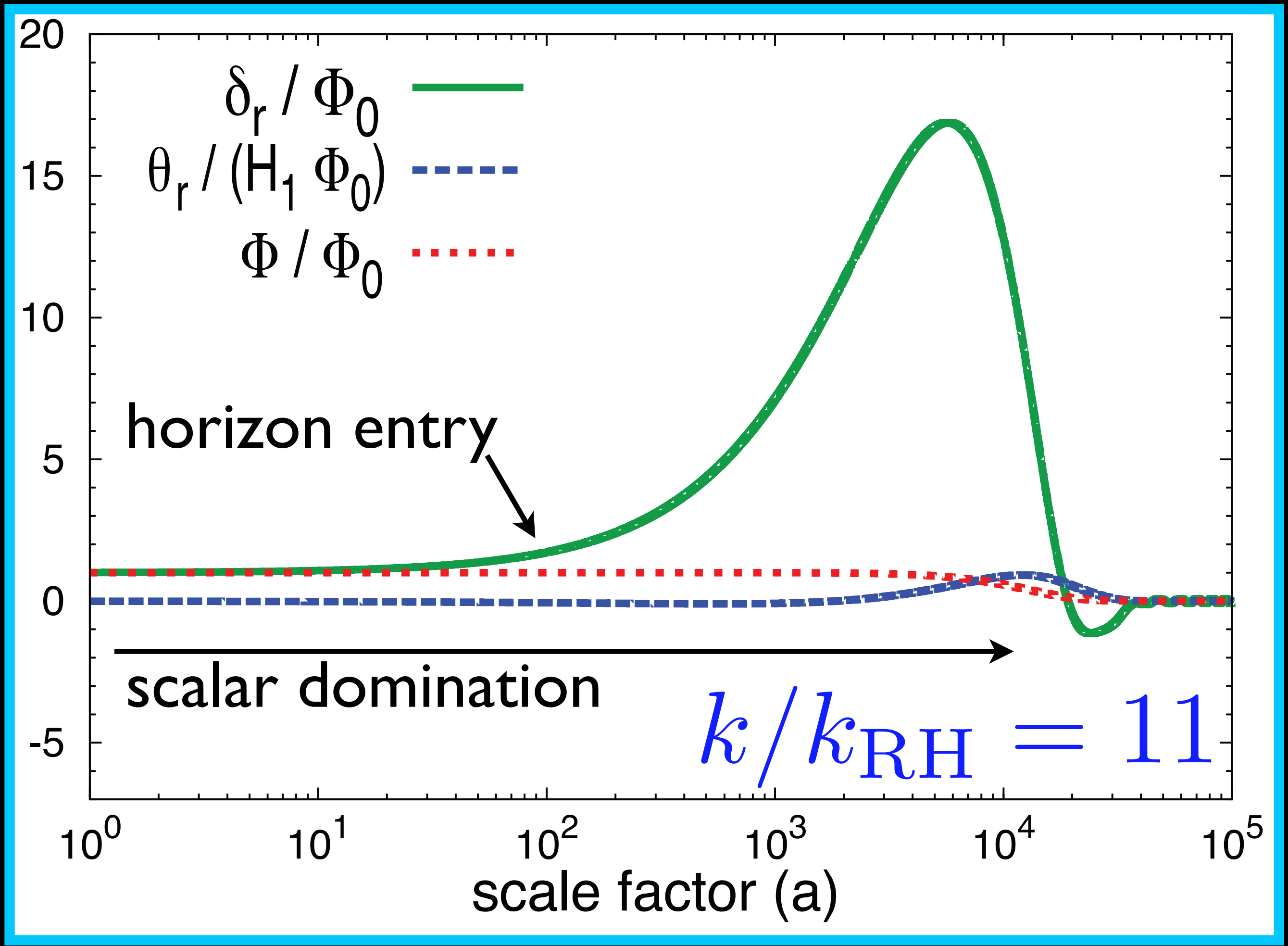


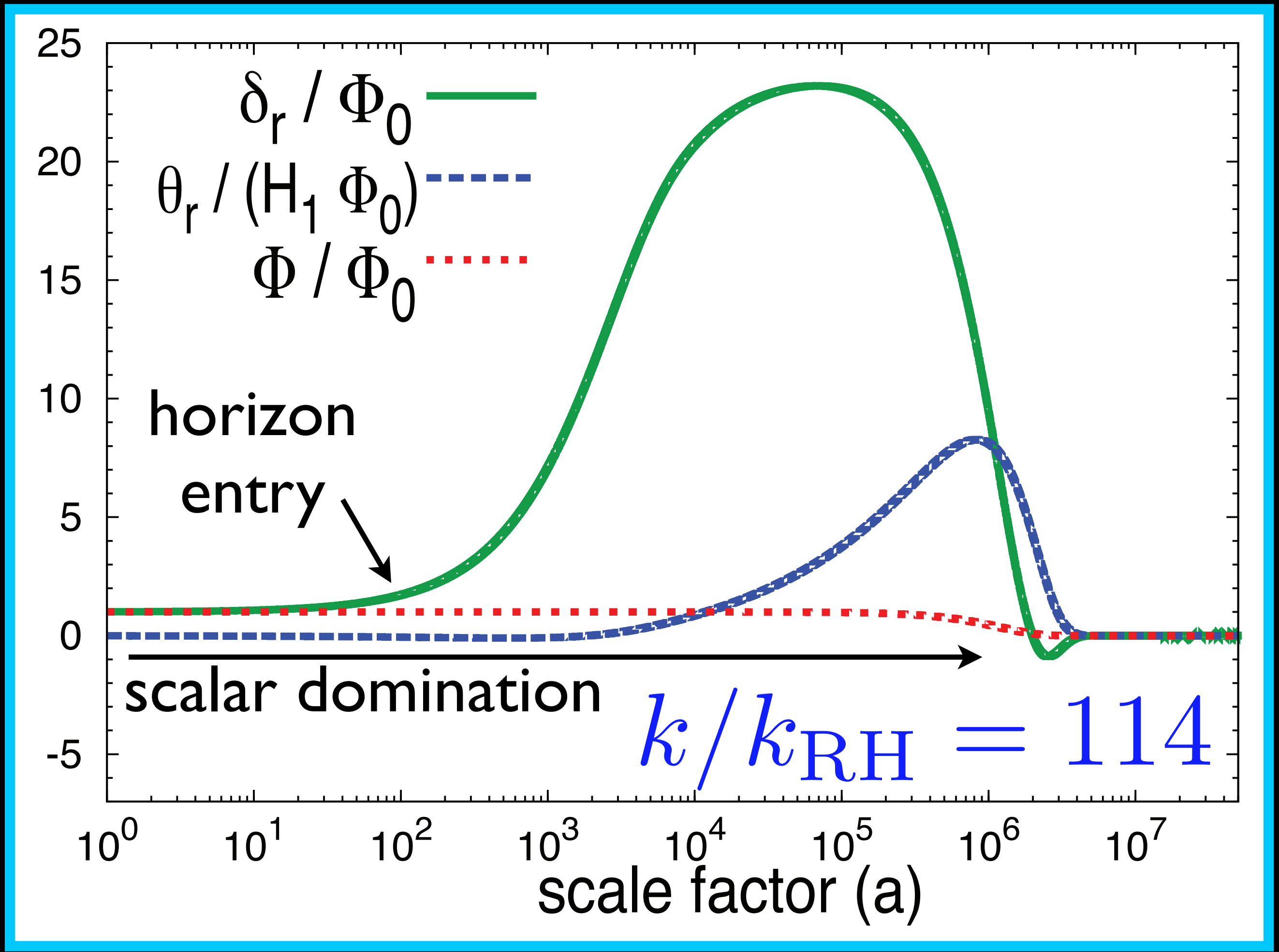
The Radiation Perturbation





The Radiation Perturbation





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

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

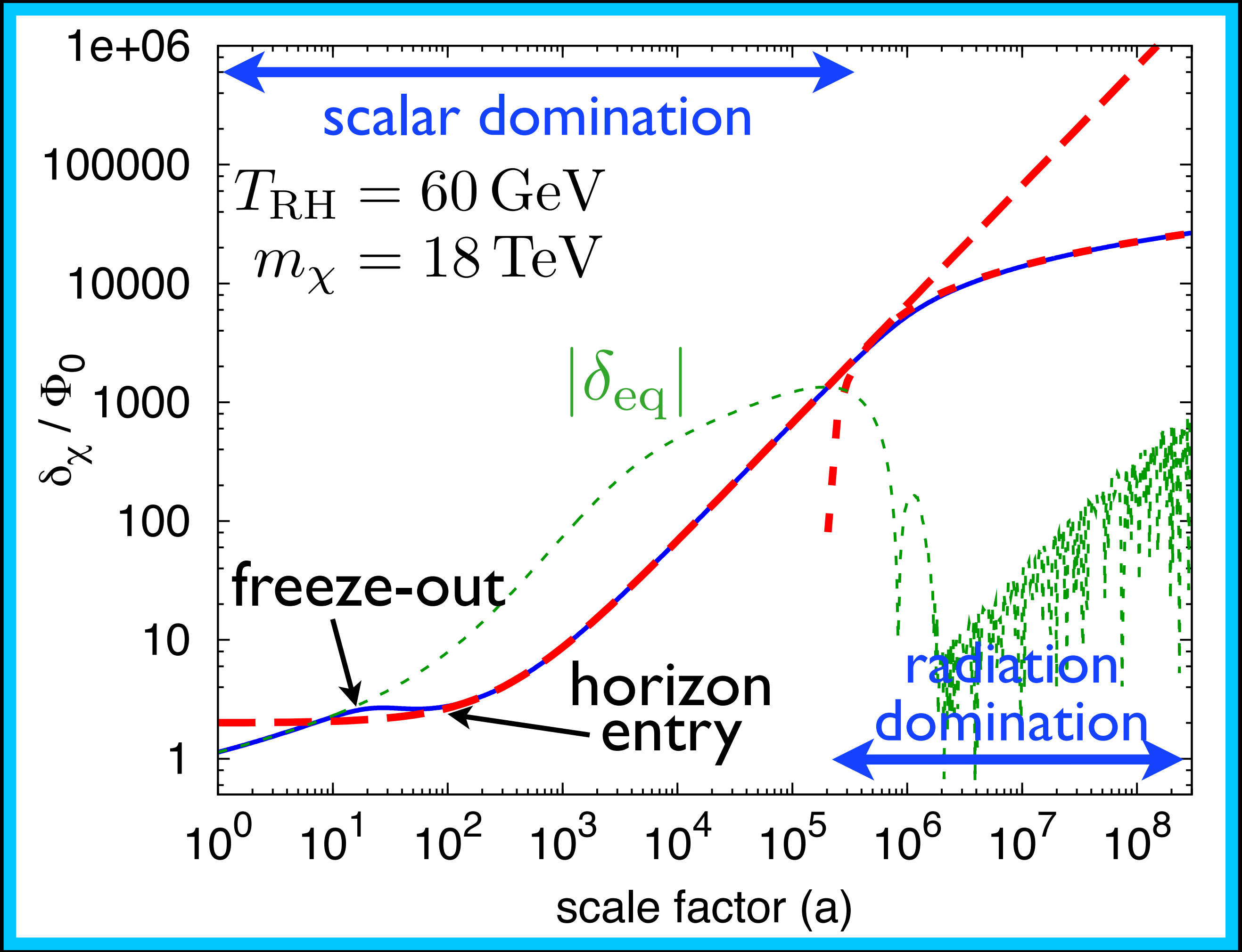
$T_r \lesssim 10^{-3}$ $k/k_{\rm RH} \gtrsim 20$

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

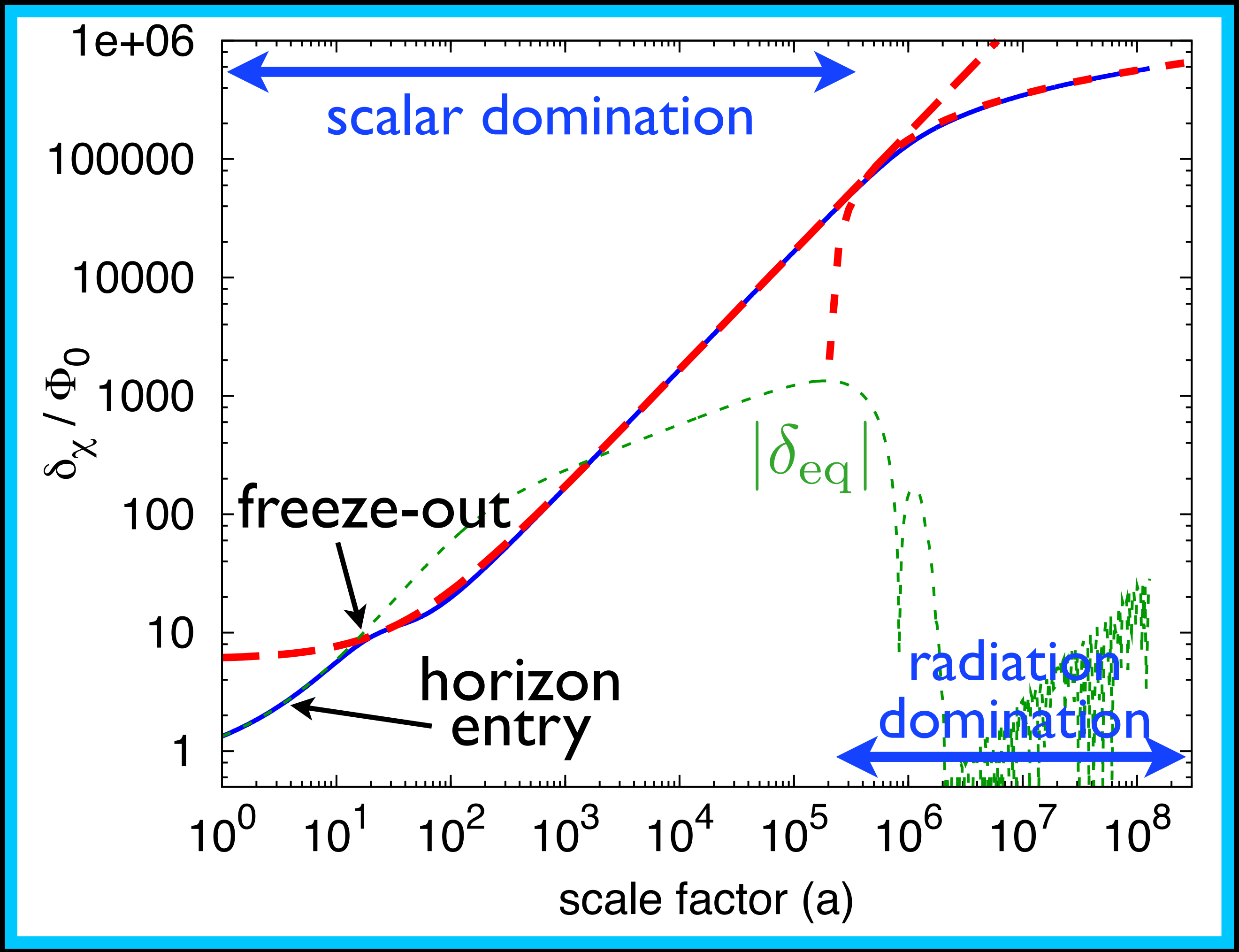
$T_r = 10/9$ $k/k_{\rm RH} \lesssim 0.1$

What impact does this have on the dark matter perturbations?

The Thermal Matter Perturbation



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



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

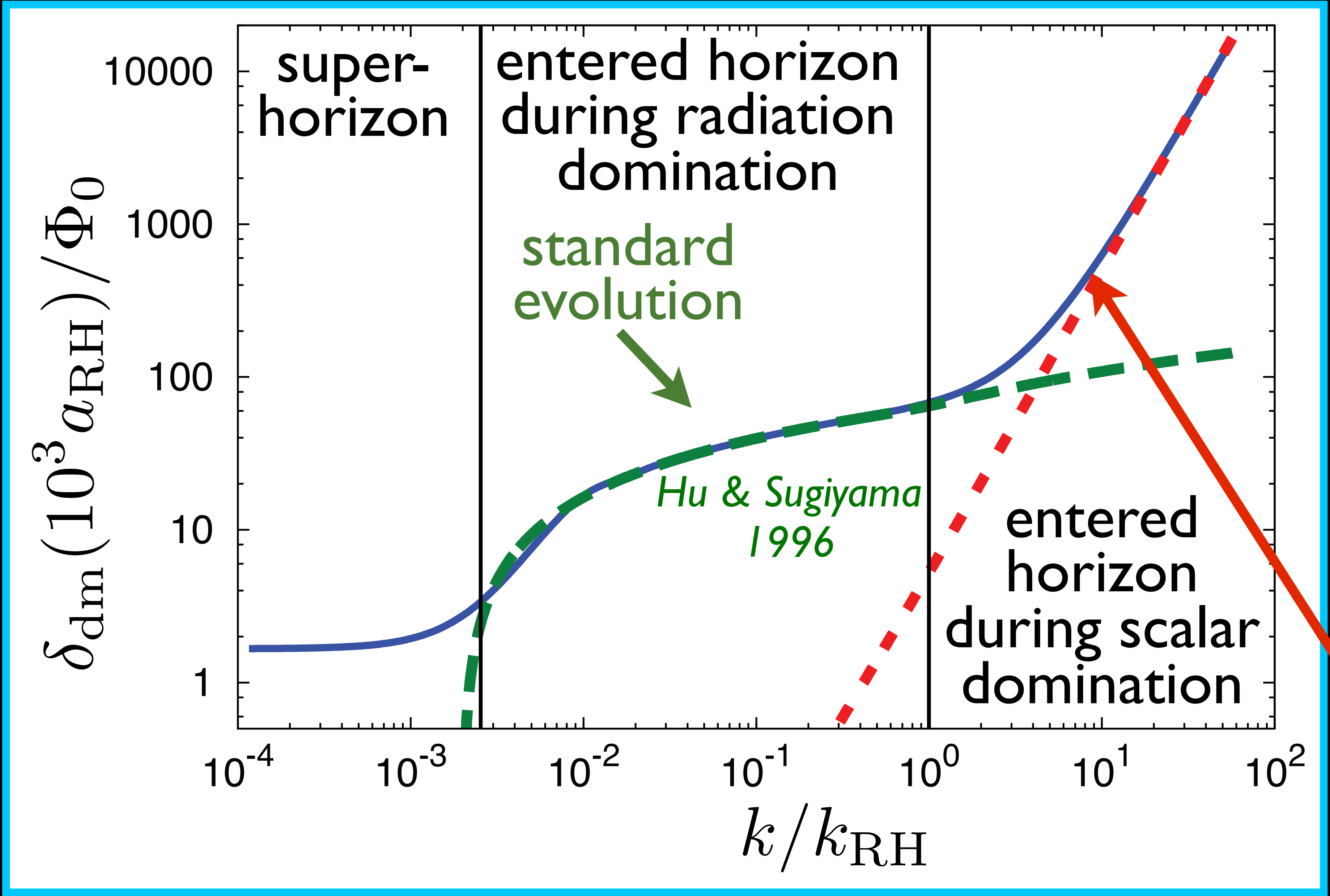
Before freeze-out: $\delta_\chi = \delta_{\rm eq} = \frac{1}{4}\left(\frac{3}{2} + \frac{m_\chi}{T}\right)\delta_\gamma$

After freeze-out: linear growth

After reheating: logarithmic growth, same as nonthermal case

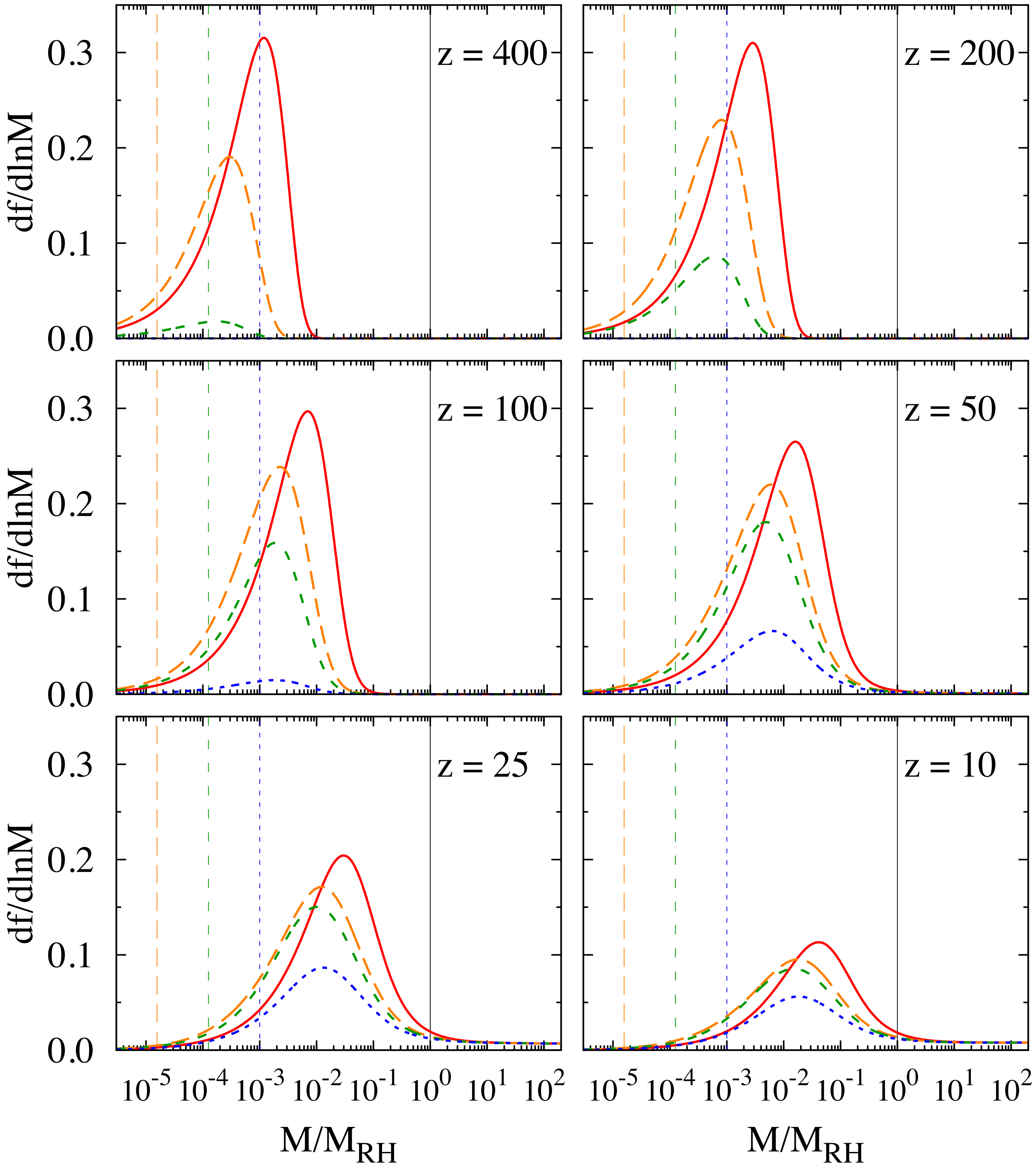
The Dark Matter Perturbation

The Matter Density Perturbation during Radiation Domination



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

The Evolution of the Bound Fraction



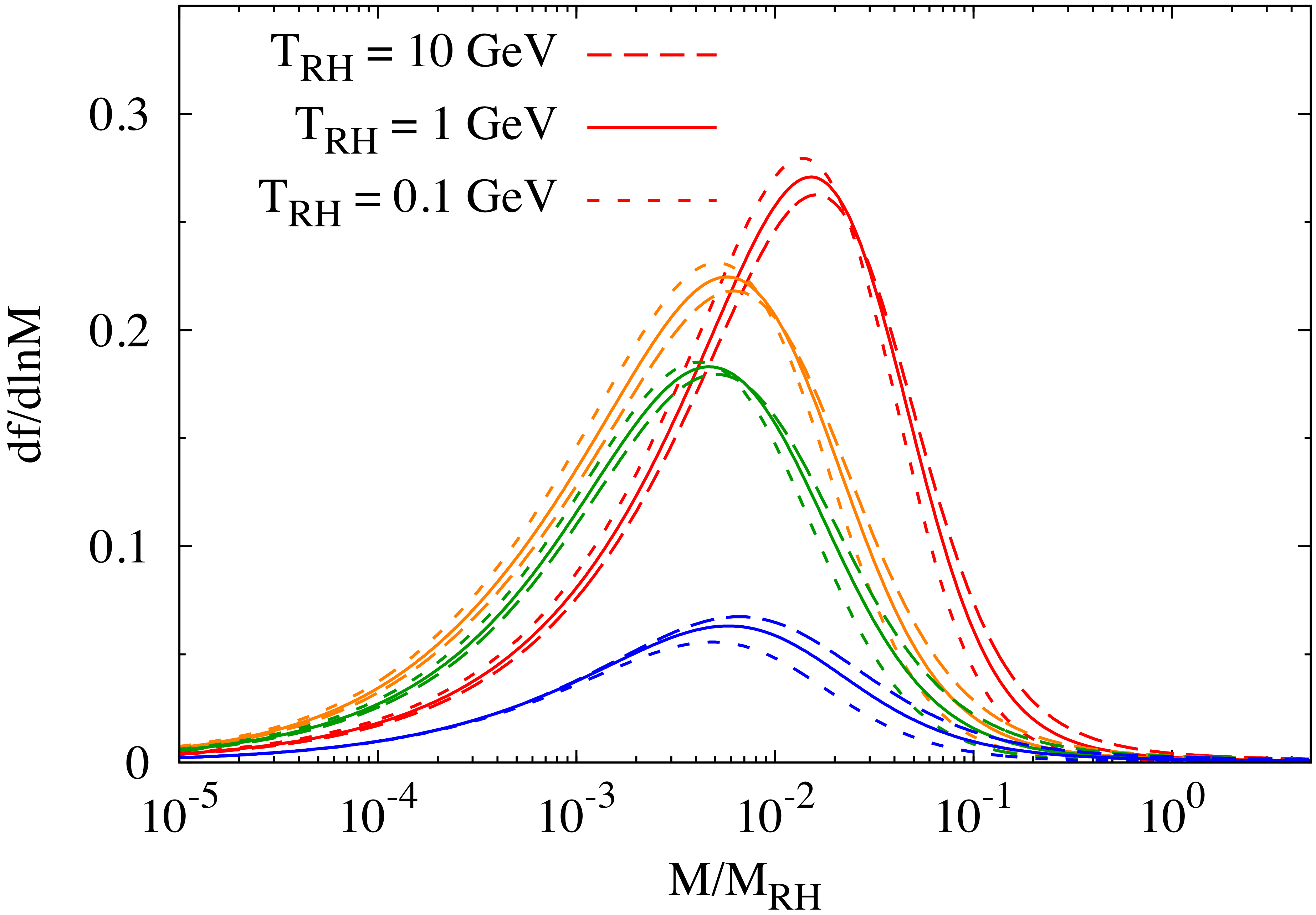
No Cut-off

$k_{\mathrm{cut}}/k_{\mathrm{RH}} = 40$

$k_{\mathrm{cut}}/k_{\mathrm{RH}} = 20$

$k_{\mathrm{cut}}/k_{\mathrm{RH}} = 10$

Independent of Reheat Temperature



No Cut-off

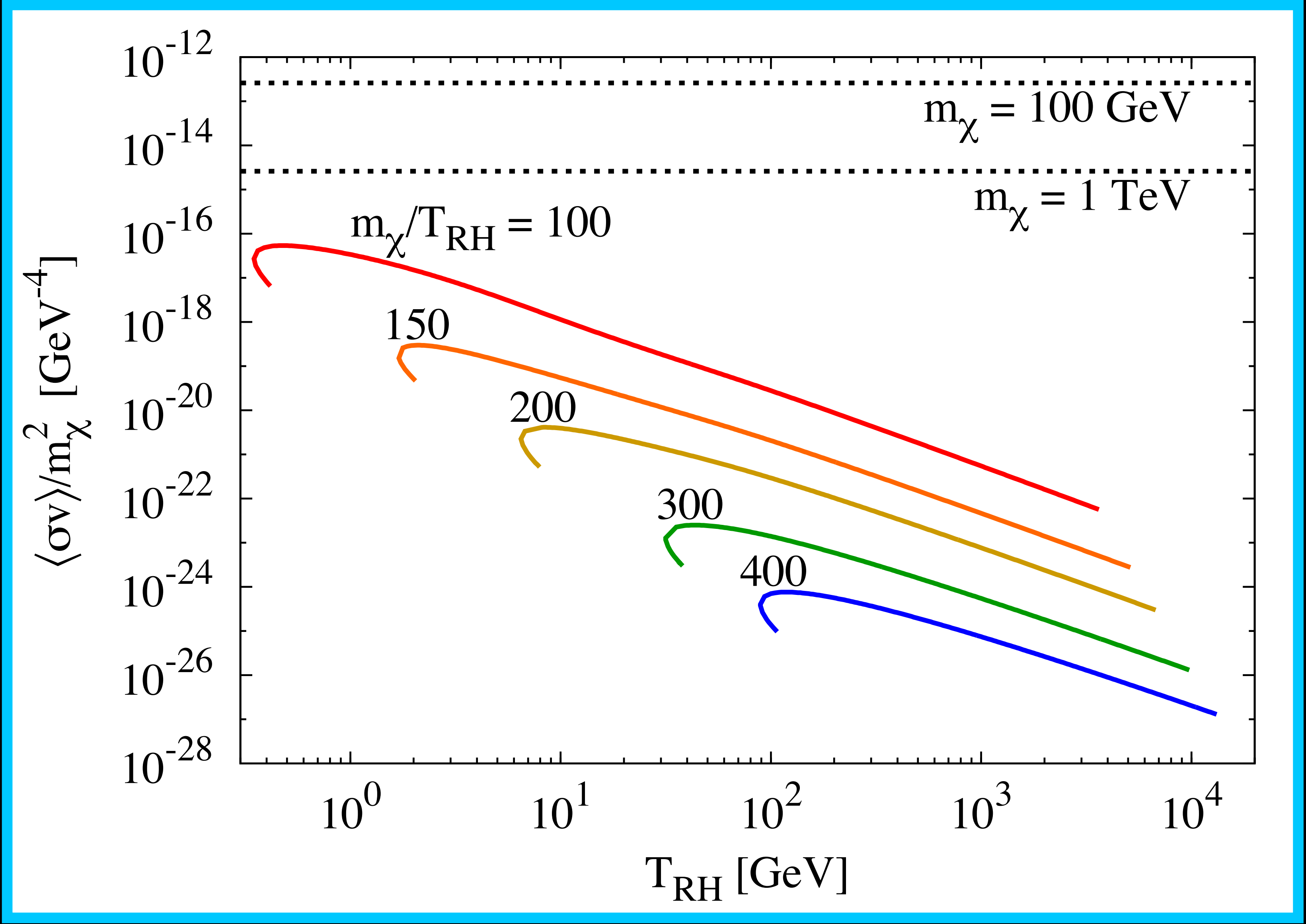
$k_{\rm cut}/k_{\rm RH} = 40$

$k_{\rm cut}/k_{\rm RH} = 20$

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

The Annihilation Rate

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



$$\left.\frac{\langle\sigma v\rangle}{m_\chi^2}\right|_{T_{\rm RH}\to\infty} = \frac{2.6\times10^{-15}}{\rm GeV^4}\left(\frac{1\,\rm TeV}{m_\chi}\right)^2$$

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

Estimating the Boost Factor

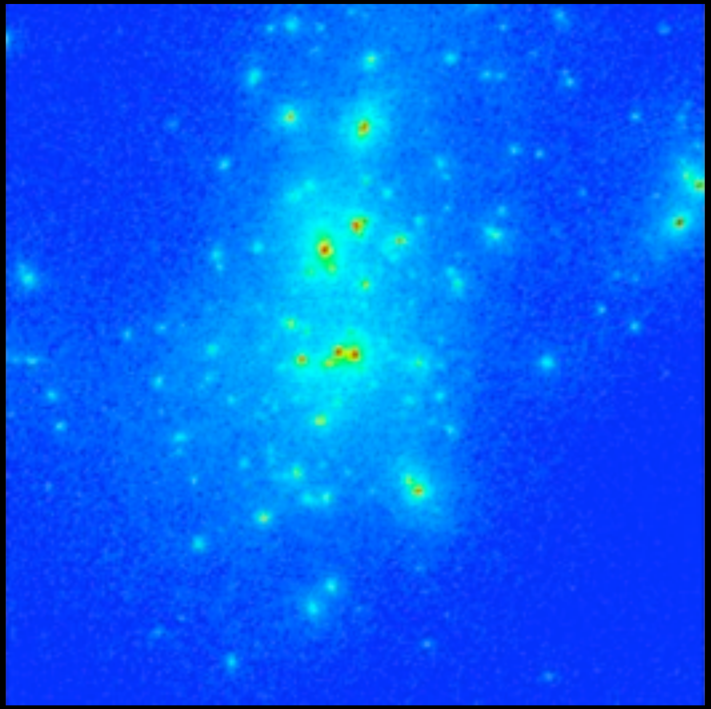
Dark matter annihilation rate: $\Gamma = \frac{\langle \sigma v \rangle}{2m_\chi^2} \int \rho^2(r) d^3 r \equiv \frac{\langle \sigma v \rangle}{2m_\chi^2} J$

Halo filled with microhalos:

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

Number of microhalos:

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



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

Anderhalden & Diemand 2013
Ishiyama 2014

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