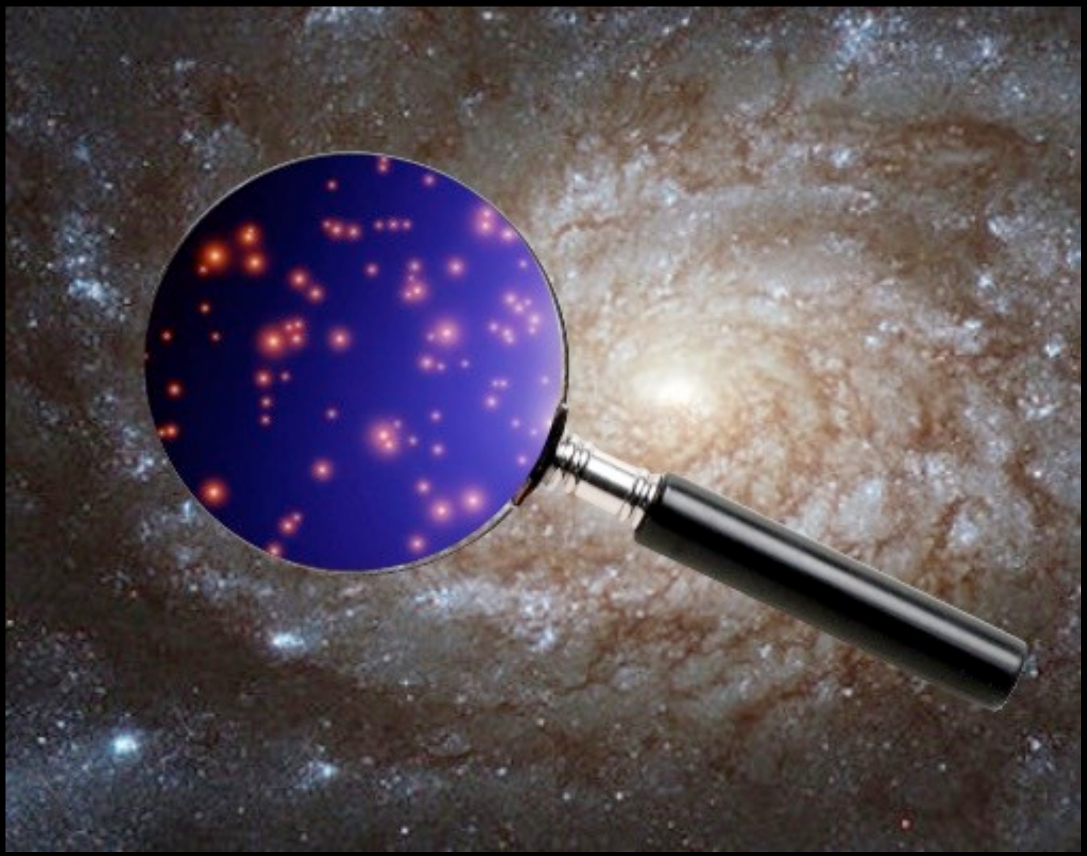
Probing the Early Universe with Dark Matter Annihilation

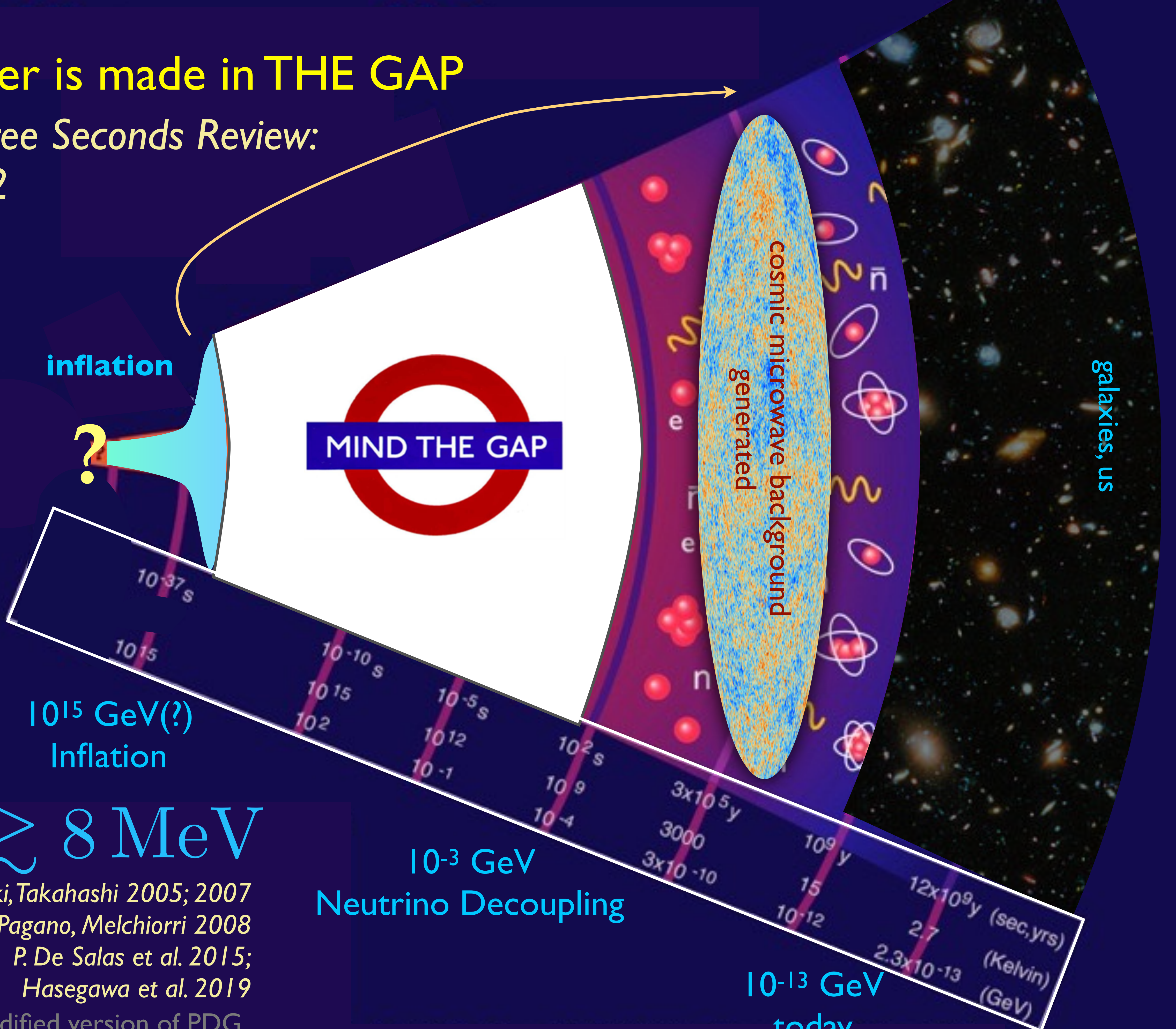


Adrienne Erickcek
UNC Chapel Hill

Collider, Dark Matter, and Neutrino Physics 2023
Mitchell Institute
May 16, 2023

Dark Matter is made in THE GAP

The First Three Seconds Review: 2006.16182



$$T_{\rm RH} \gtrsim 8\,{\rm MeV}$$

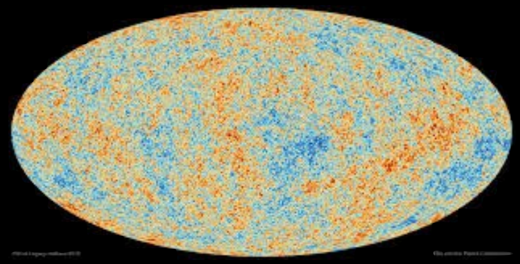
Ichikawa, Kawasaki, Takahashi 2005; 2007
de Bernardis, Pagano, Melchiorri 2008
P. De Salas et al. 2015;
Hasegawa et al. 2019

Mustafa Amin's modified version of PDG

What happened before BBN?

We have good reasons to think that the Universe was not radiation dominated at all times before neutrino decoupling.

- Primordial density fluctuations point to inflation. After inflation, the inflaton may have entered a fast-roll phase ($P \simeq \rho$; kination) or it may have oscillated ($P \simeq 0$; matter domination).



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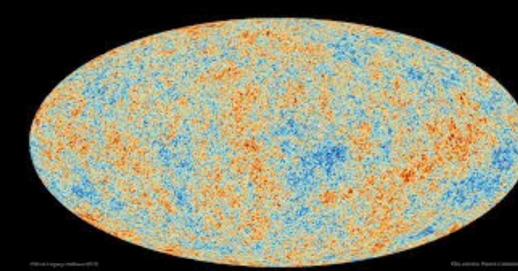
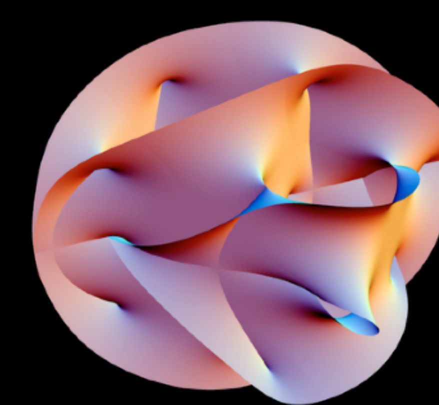


- Other scalar fields or particles may have come to dominate the Universe after inflation.
- The string moduli problem: oscillating scalar fields come to dominate the Universe before BBN.

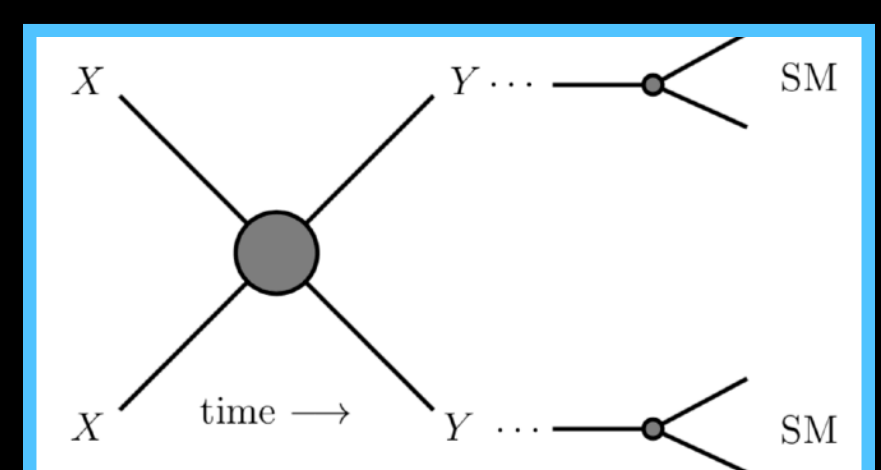


Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994
Acharya, Kumar, Bobkov, Kane, Shao, Watson 2008
Summary: Kane, Sinha, Watson 1502.07746

- String moduli can also generate periods of kination.

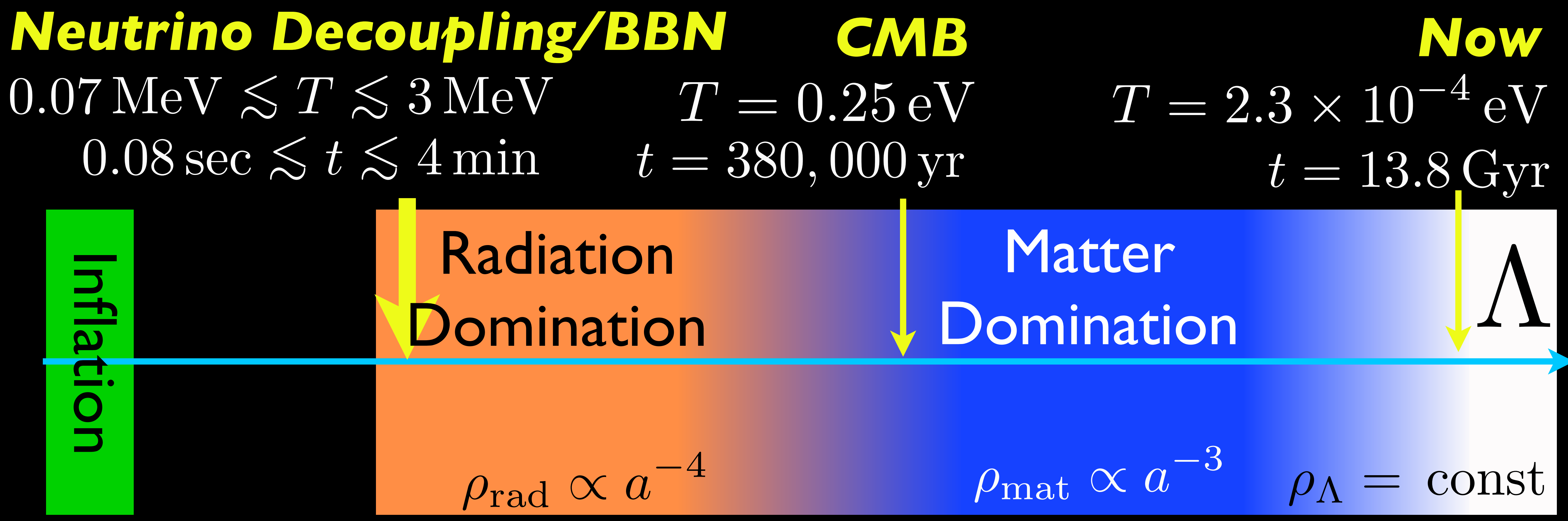
Conlon, Revello 2022
Apers, Conlon, Mosny, Revello 2023

- Hidden sector dark matter: massive mediators dominate the Universe.



Zhang 2015
Berlin, Hooper, Krnjaic 2016
ALE, Ralegankar, Shelton 2021
Dror, Kuflik, Ng 2016
Dror, Kuflik, Melcher, Watson 2018

Cosmic Timeline



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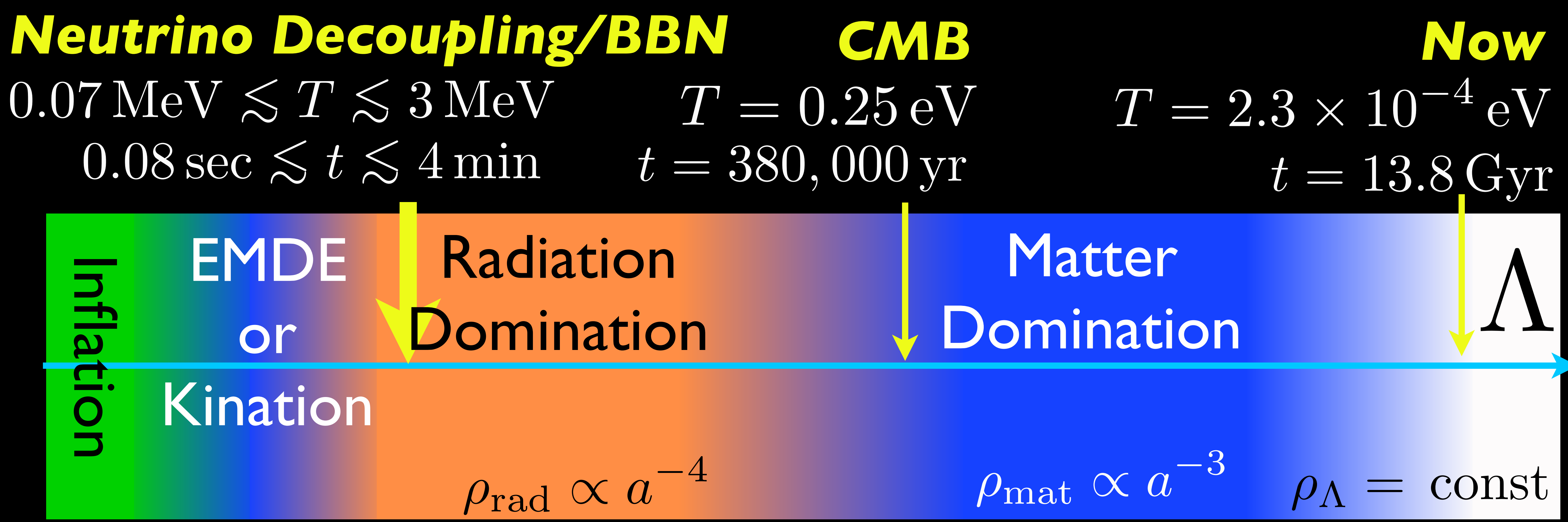


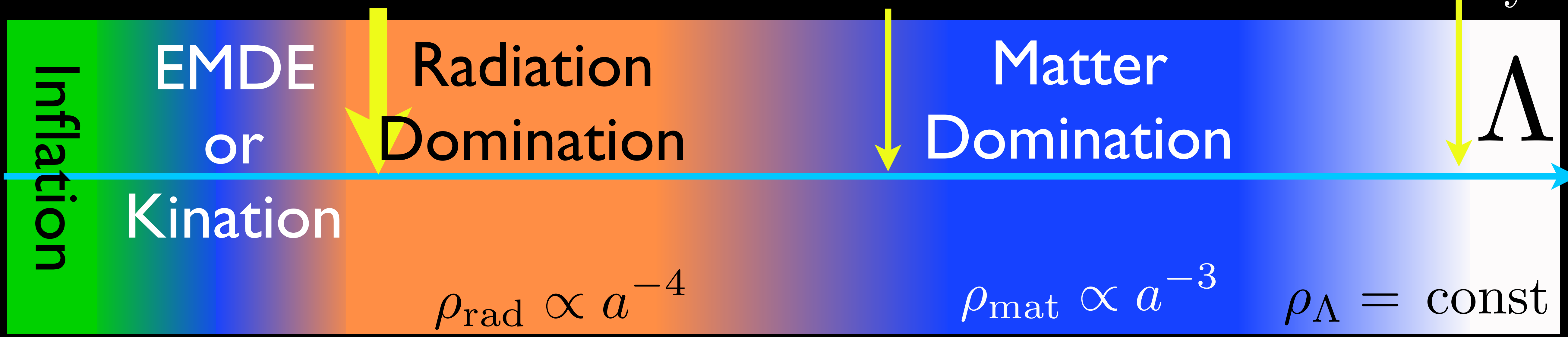
- An early matter-dominated era (EMDE):
  - Dominant component: $\rho \propto a^{-3}$
  - Ends when dominant component decays into relativistic particles.
- A period of kination:
  - Dominant component: $\rho \propto a^{-6}$
  - Ends when dominant component's energy density falls below radiation density (no entropy injection).

Cosmic Timeline

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



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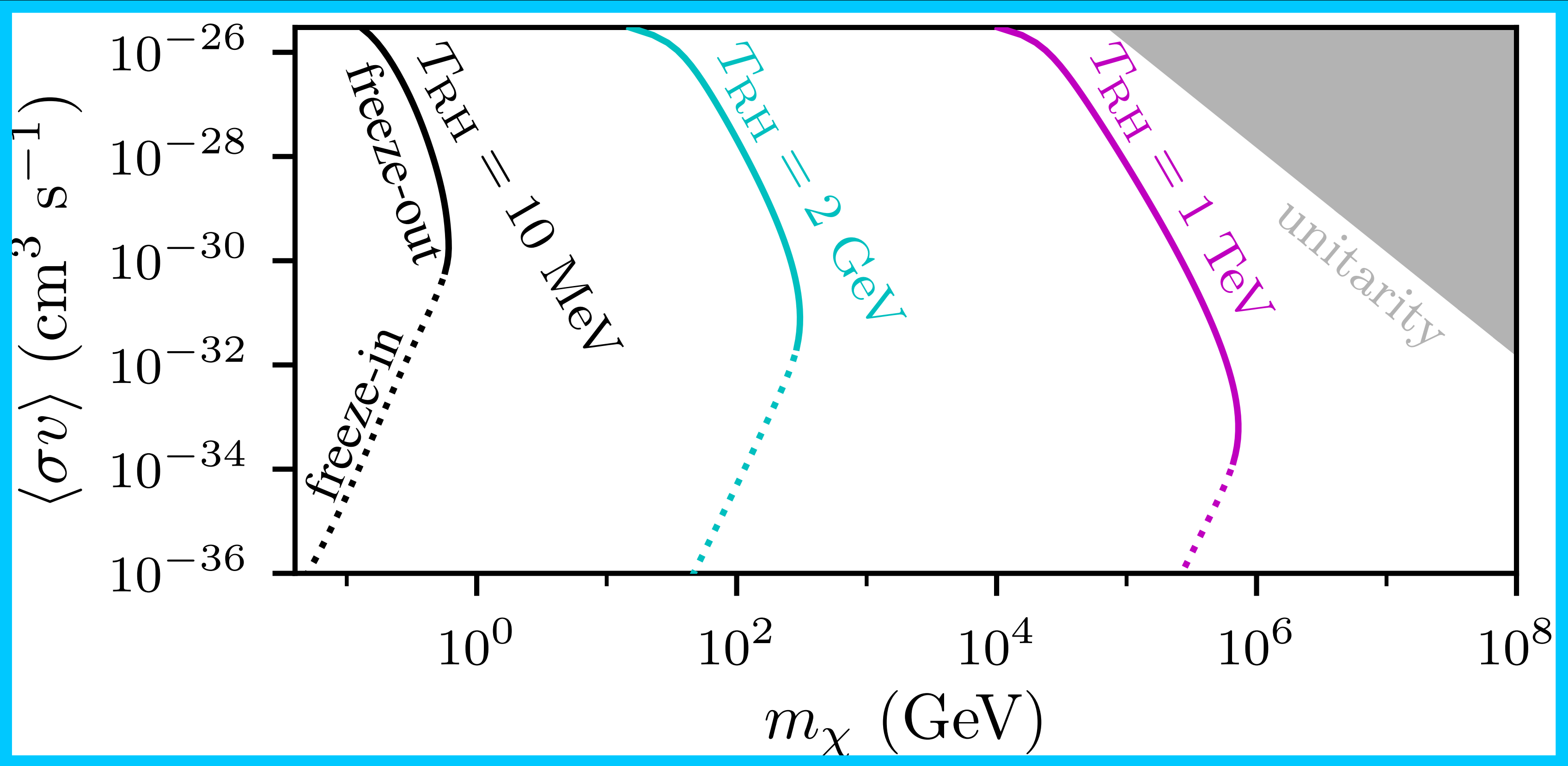
EMDE/Kination Implications:
1. Dark matter production
2. Early structure growth
3. Enhanced dark matter annihilation rates

Constraints on DM production before or during an Early Matter-Dominated Era (EMDE)

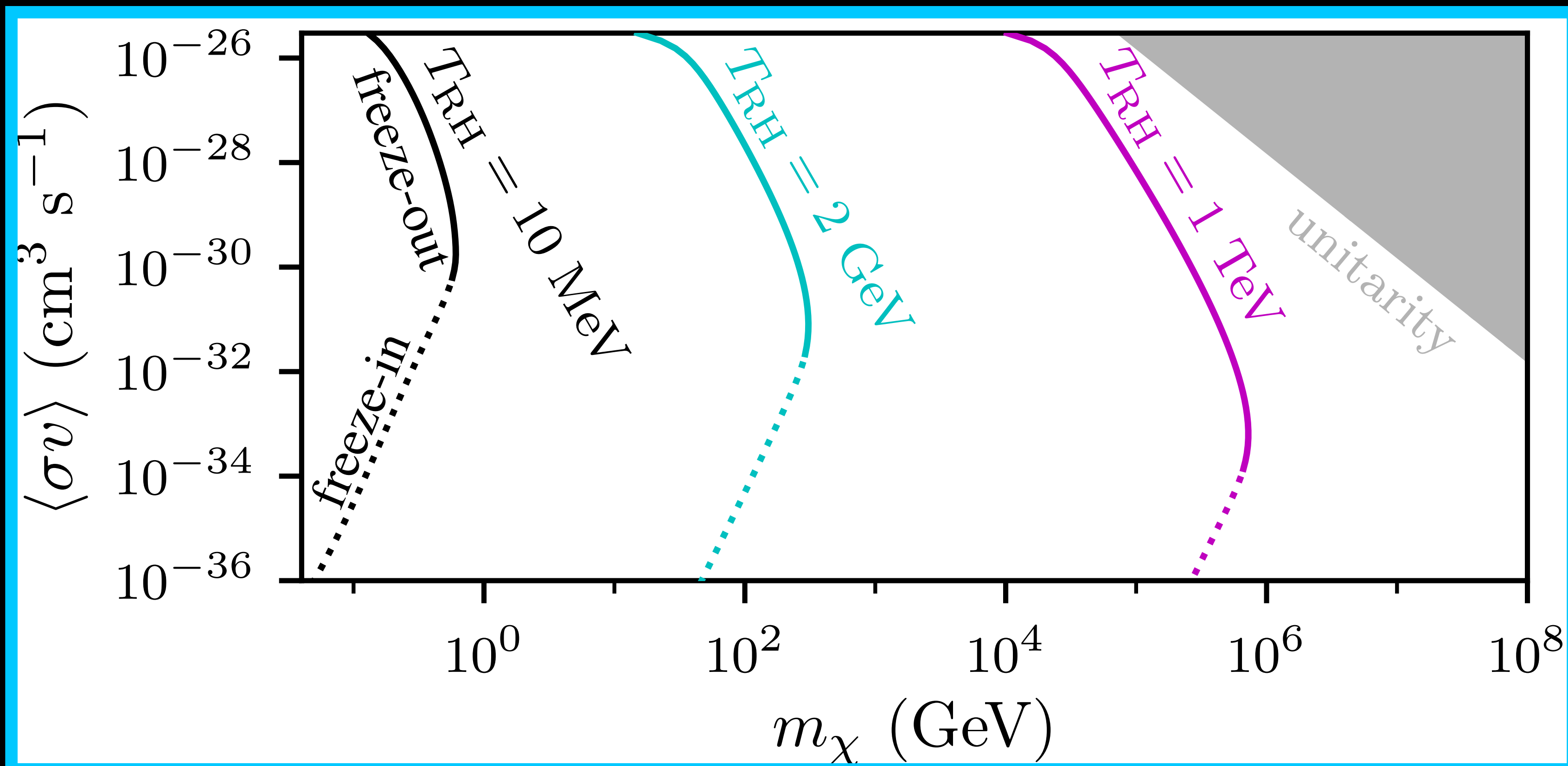
Thermal DM Production with an EMDE



Giudice, Kolb, Riotto 2001
ALE 2015
M. Sten Delos, Tim Linden, ALE 2019

The creation of new SM particles during the EMDE dilutes the DM abundance after freeze-out, so smaller annihilation cross sections are needed to match DM density.

Thermal DM Production with an EMDE



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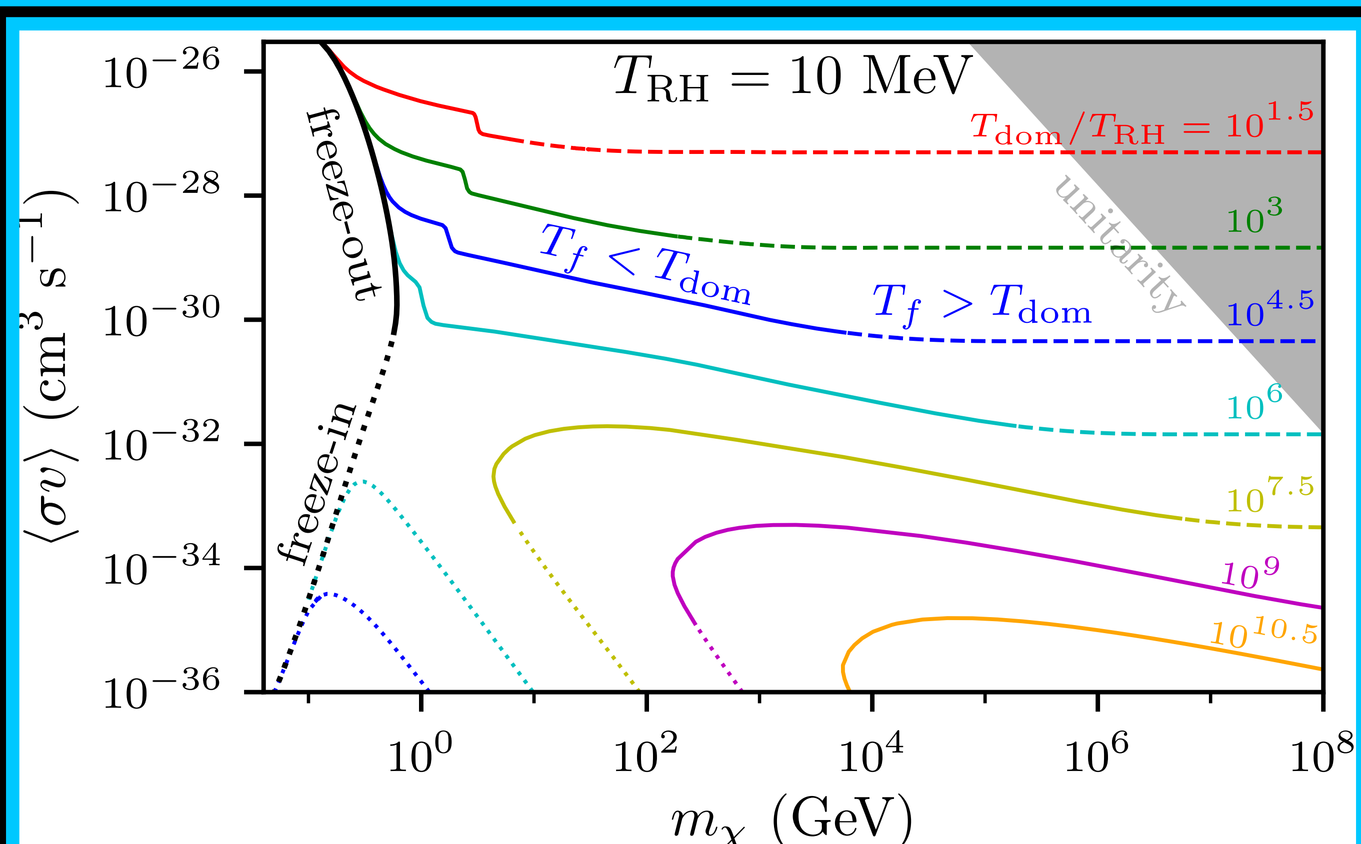

- A radiation-dominated era prior to the EMDE further widens the range of viable parameters.
- T_{dom} is the temperature at the start of the EMDE.

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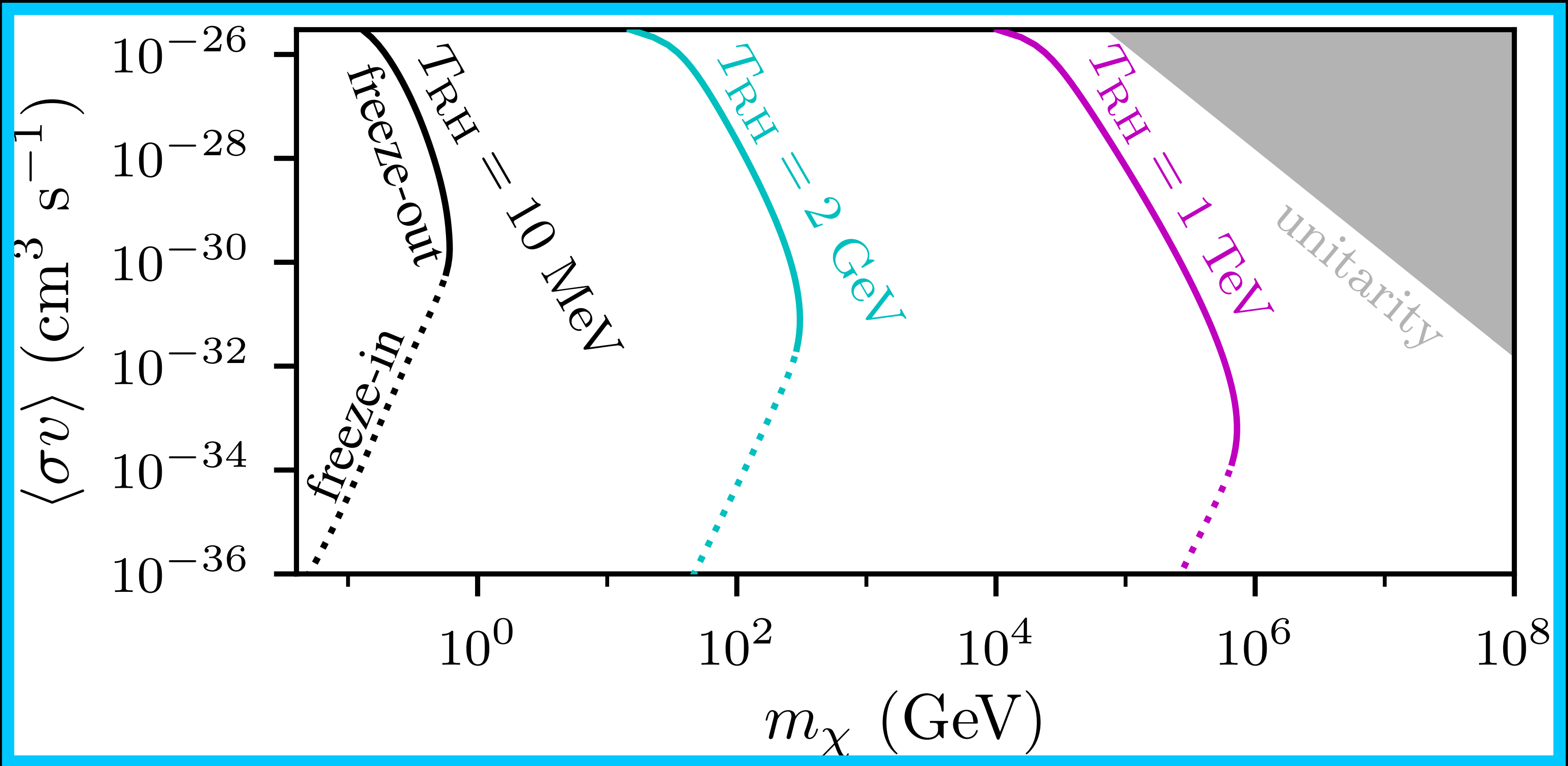

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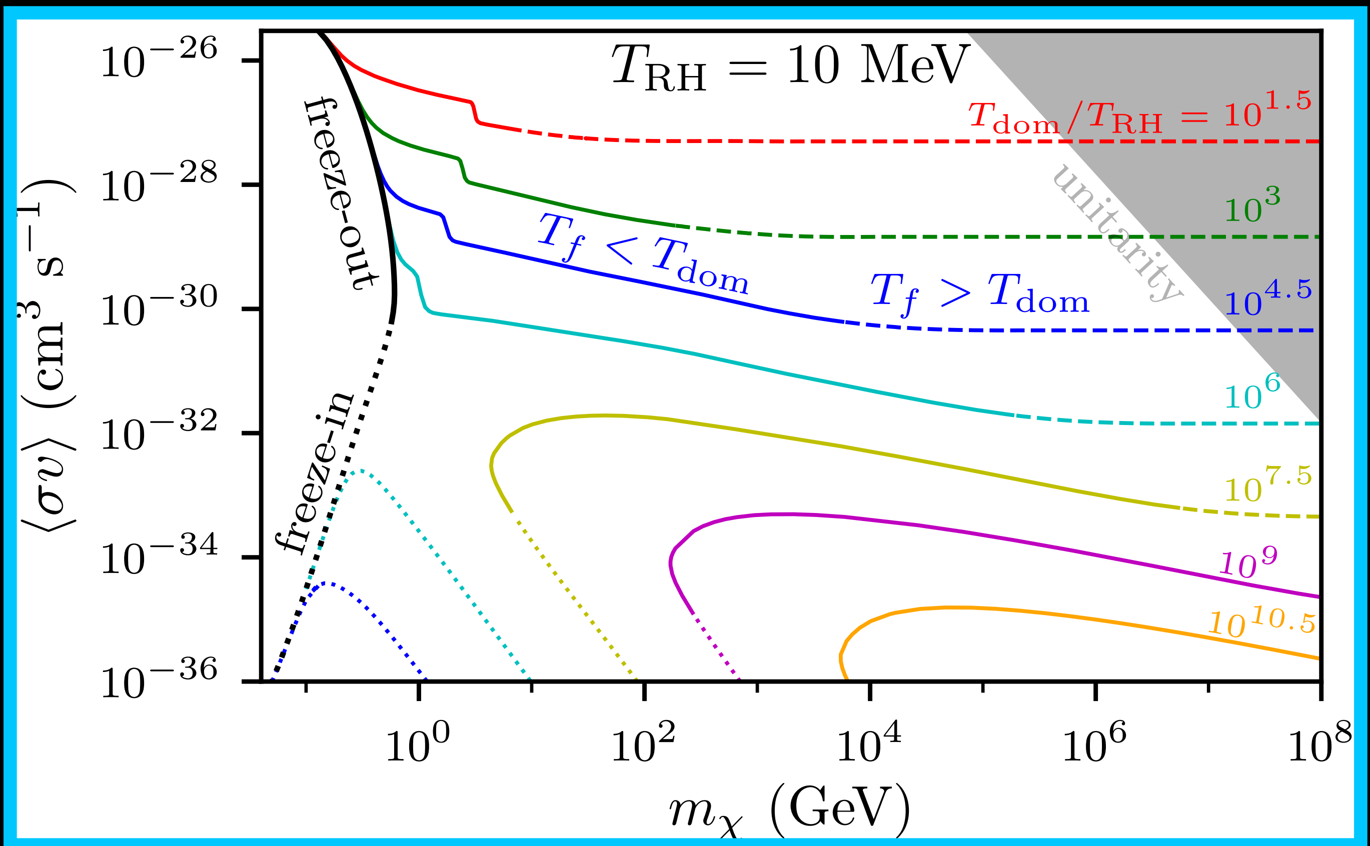

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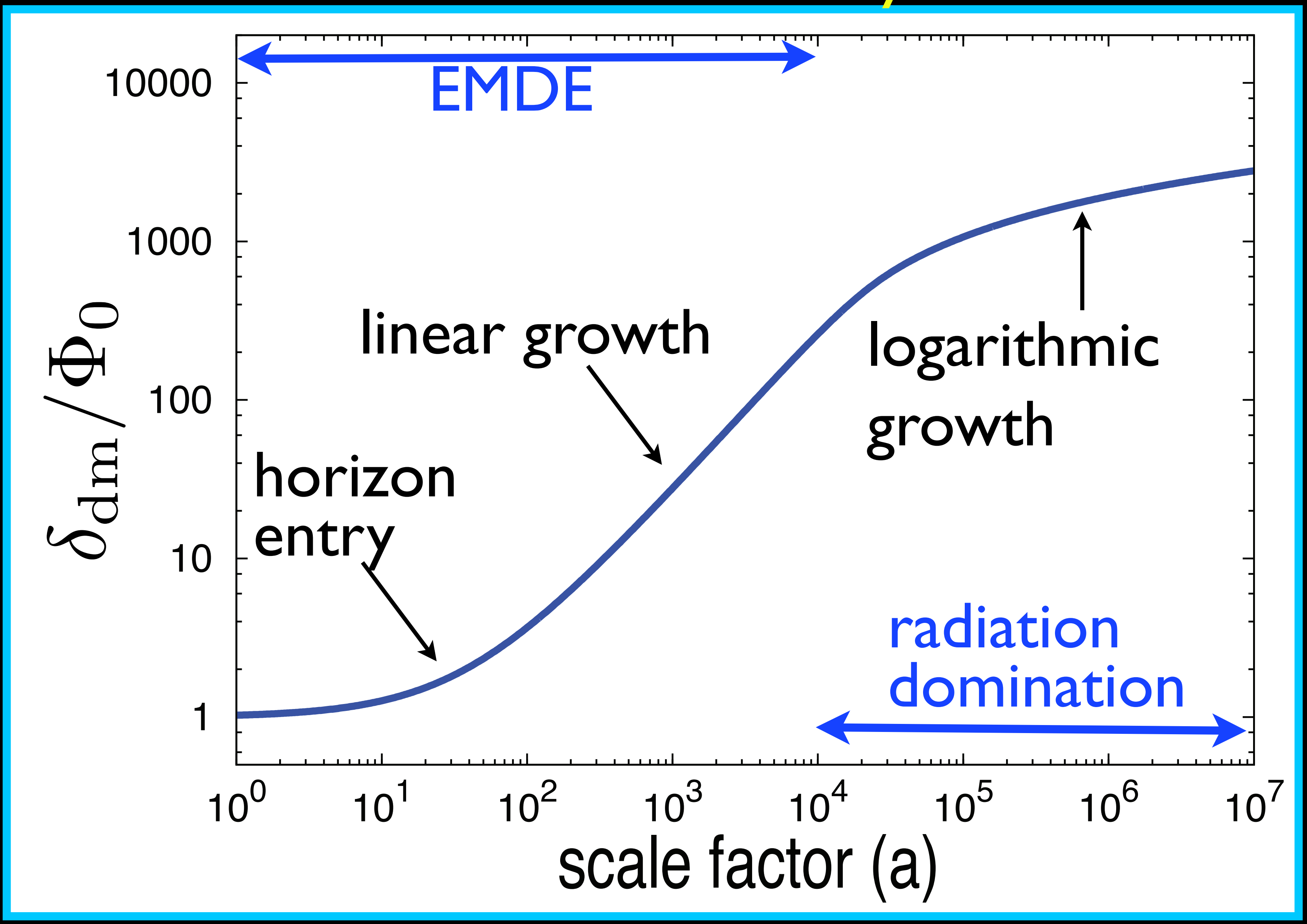
A nightmare scenario?

Structure Growth during an EMDE

Evolution of the Matter Density Perturbation



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

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

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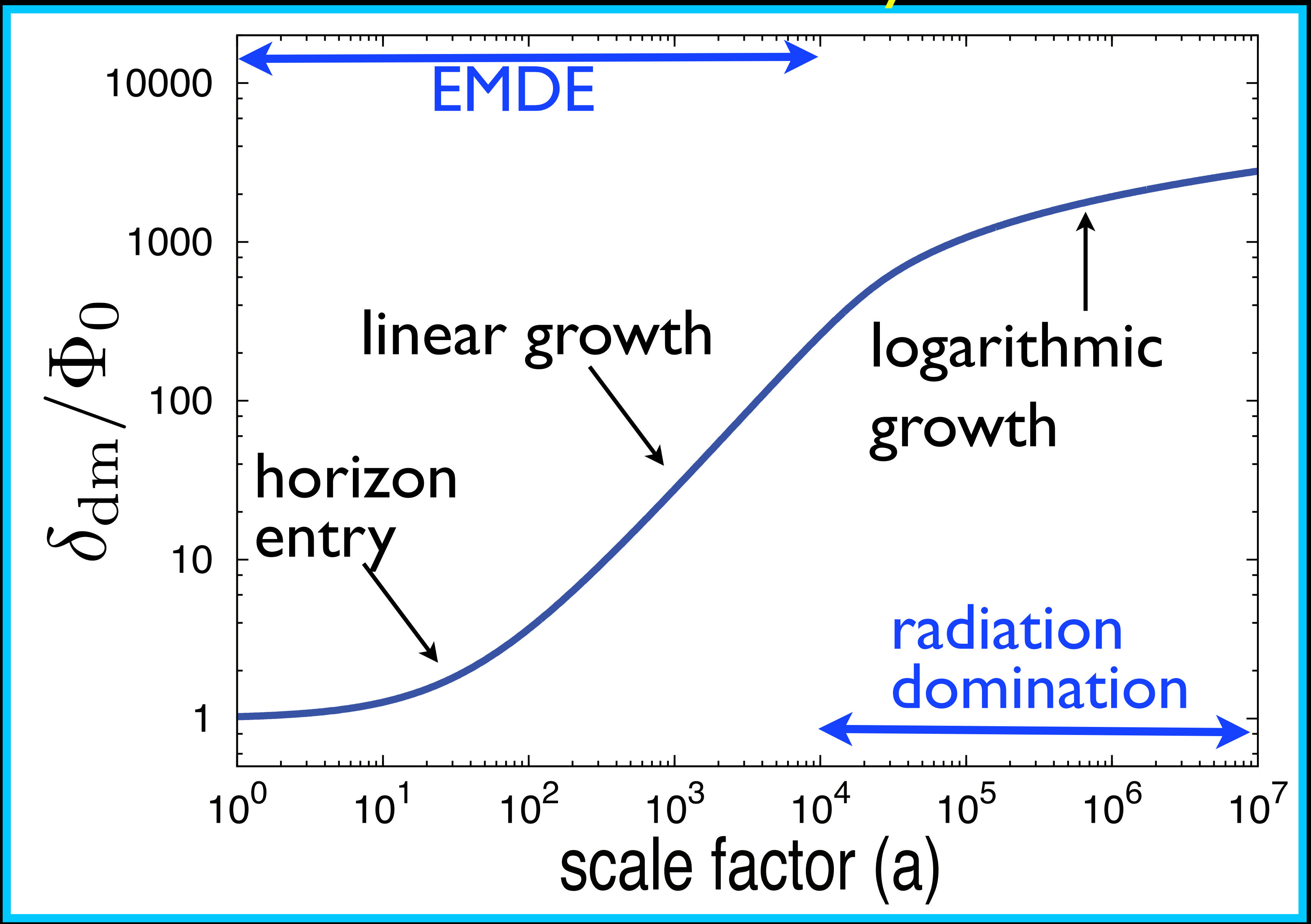

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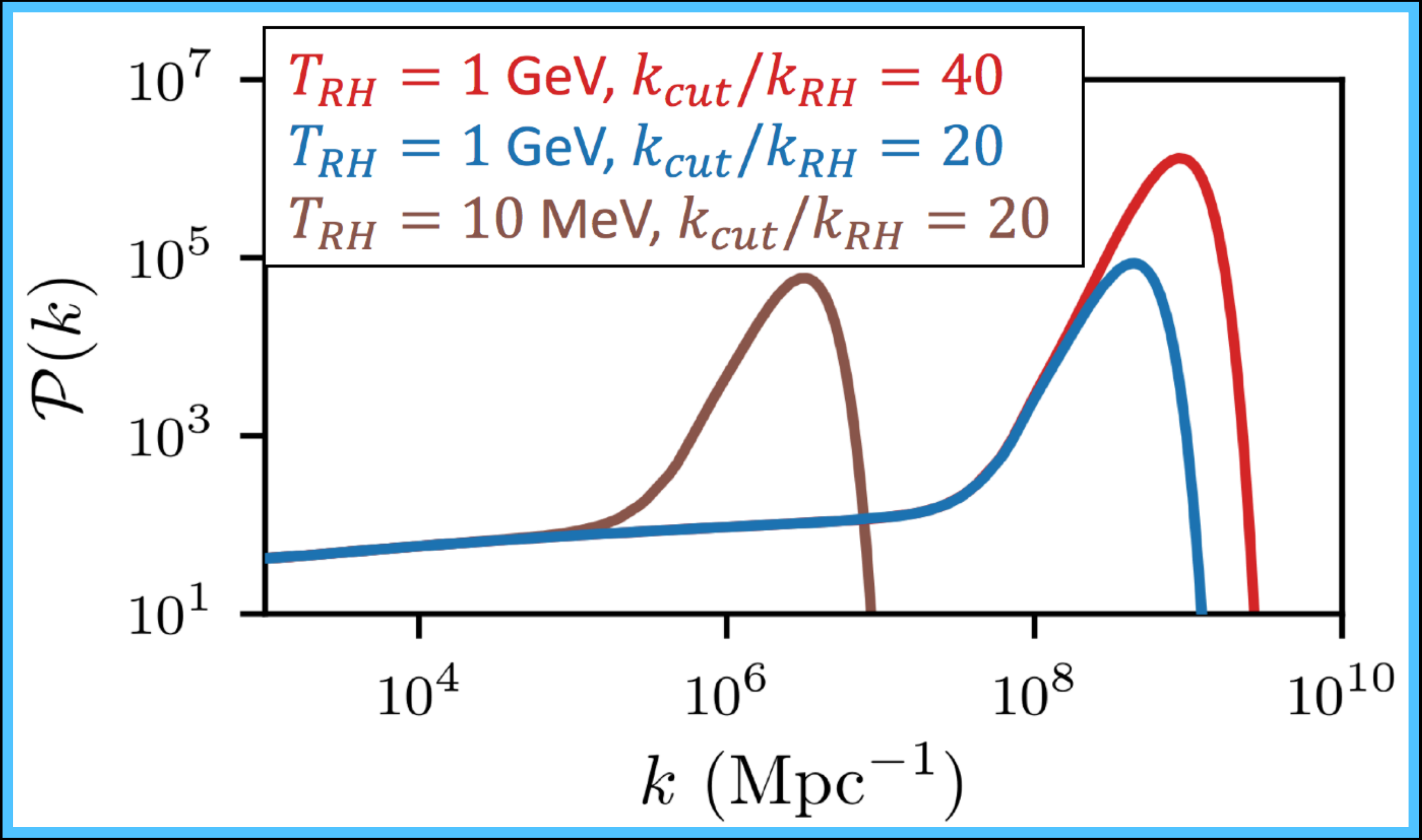
$$M_{\rm RH} \simeq 10^{-5}\, M_\oplus \left(\frac{1\,{\rm GeV}}{T_{\rm RH}}\right)^3$$

Microhalos!

The Small-Scale Cut-off

The small-scale cut-off in the matter power spectrum determines the mass and formation time of the first halos.



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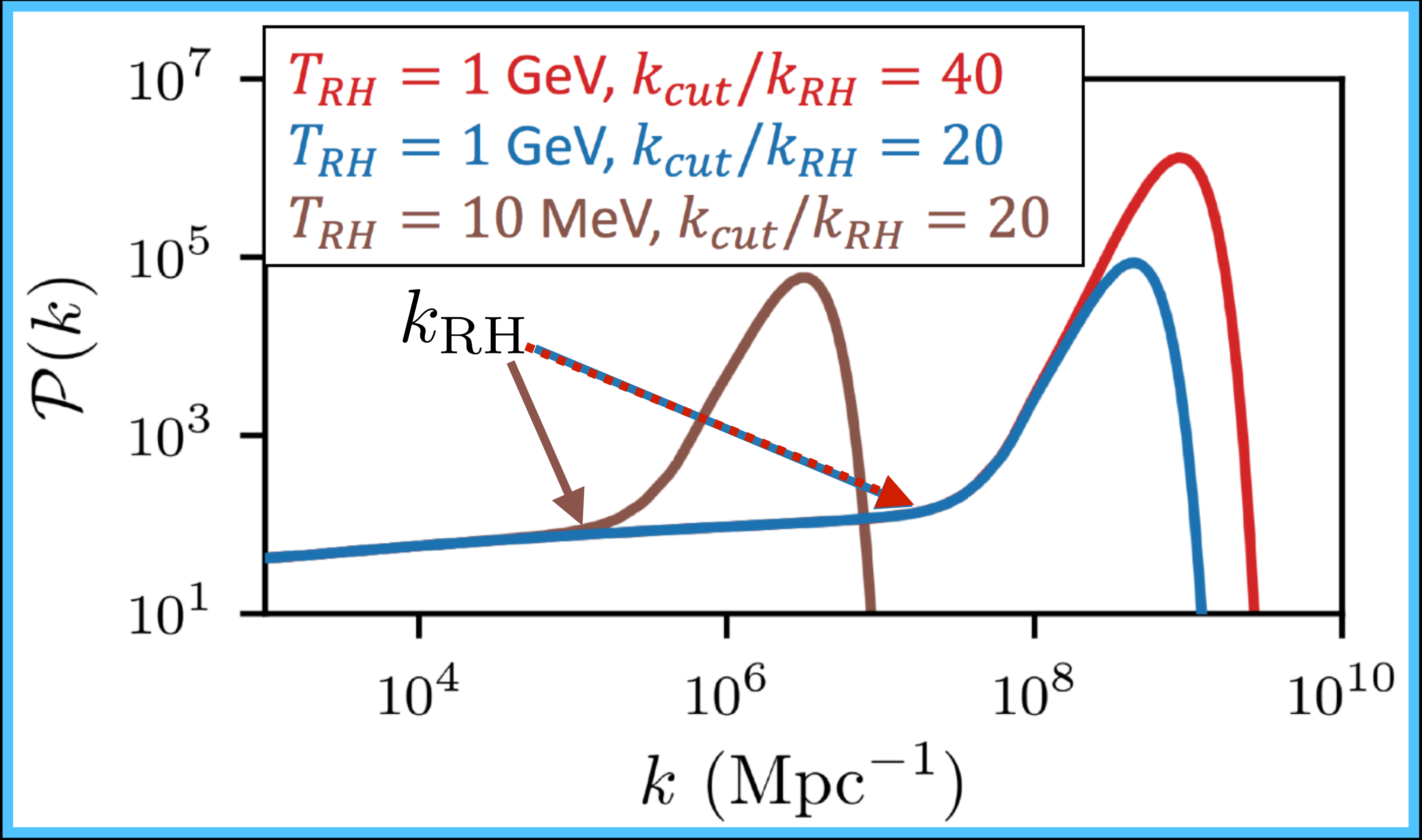

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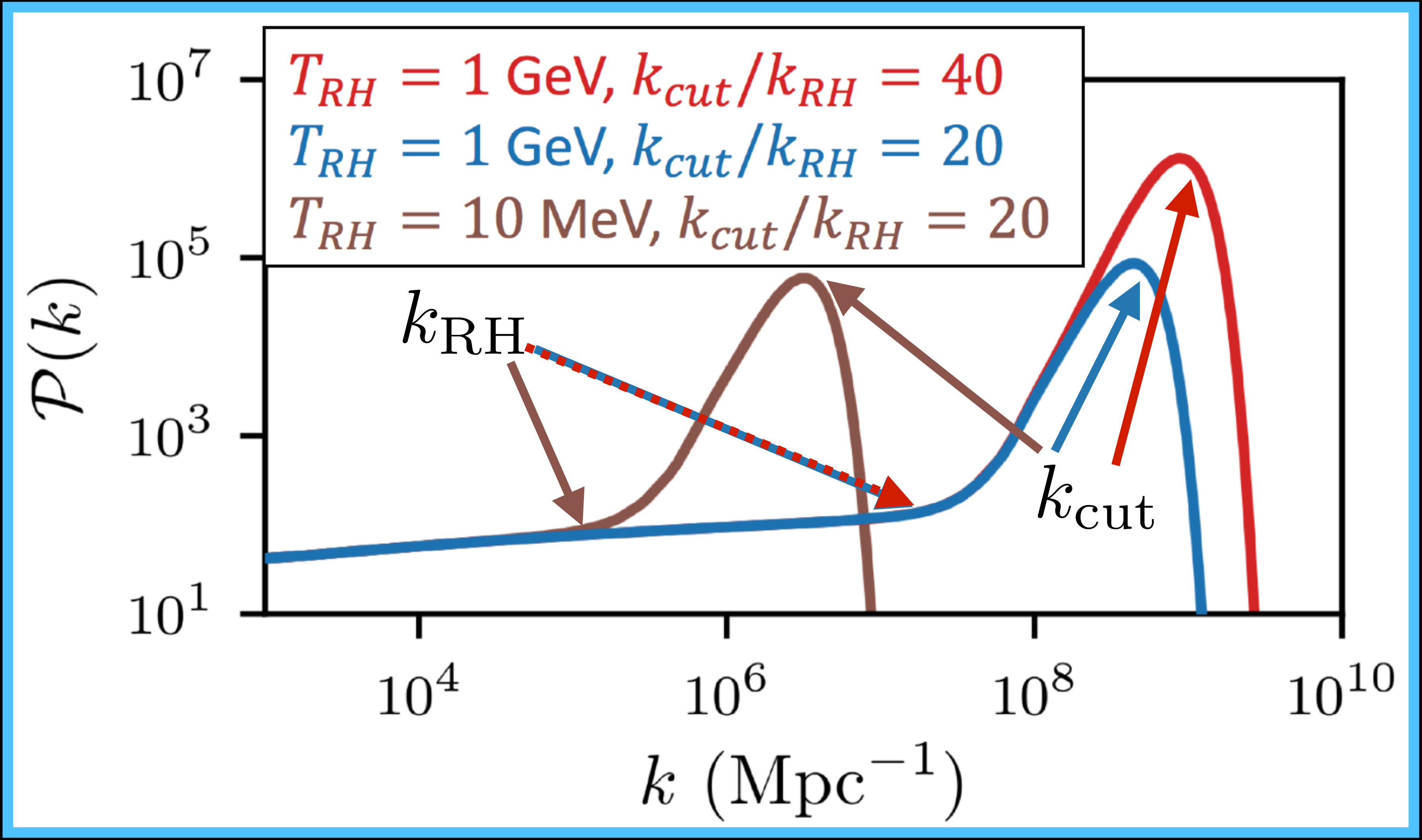

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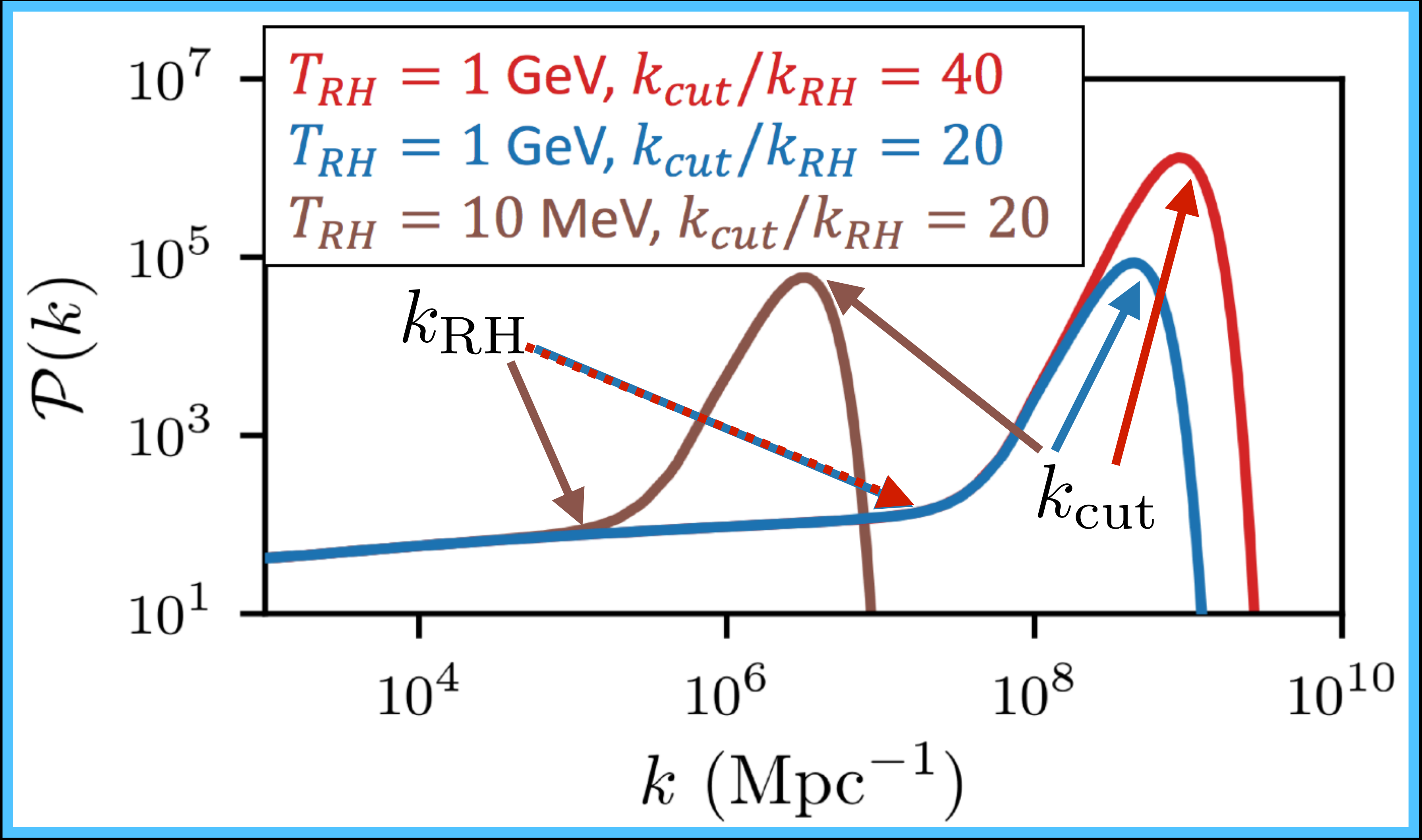
  ALE, Sinha, Watson 2016



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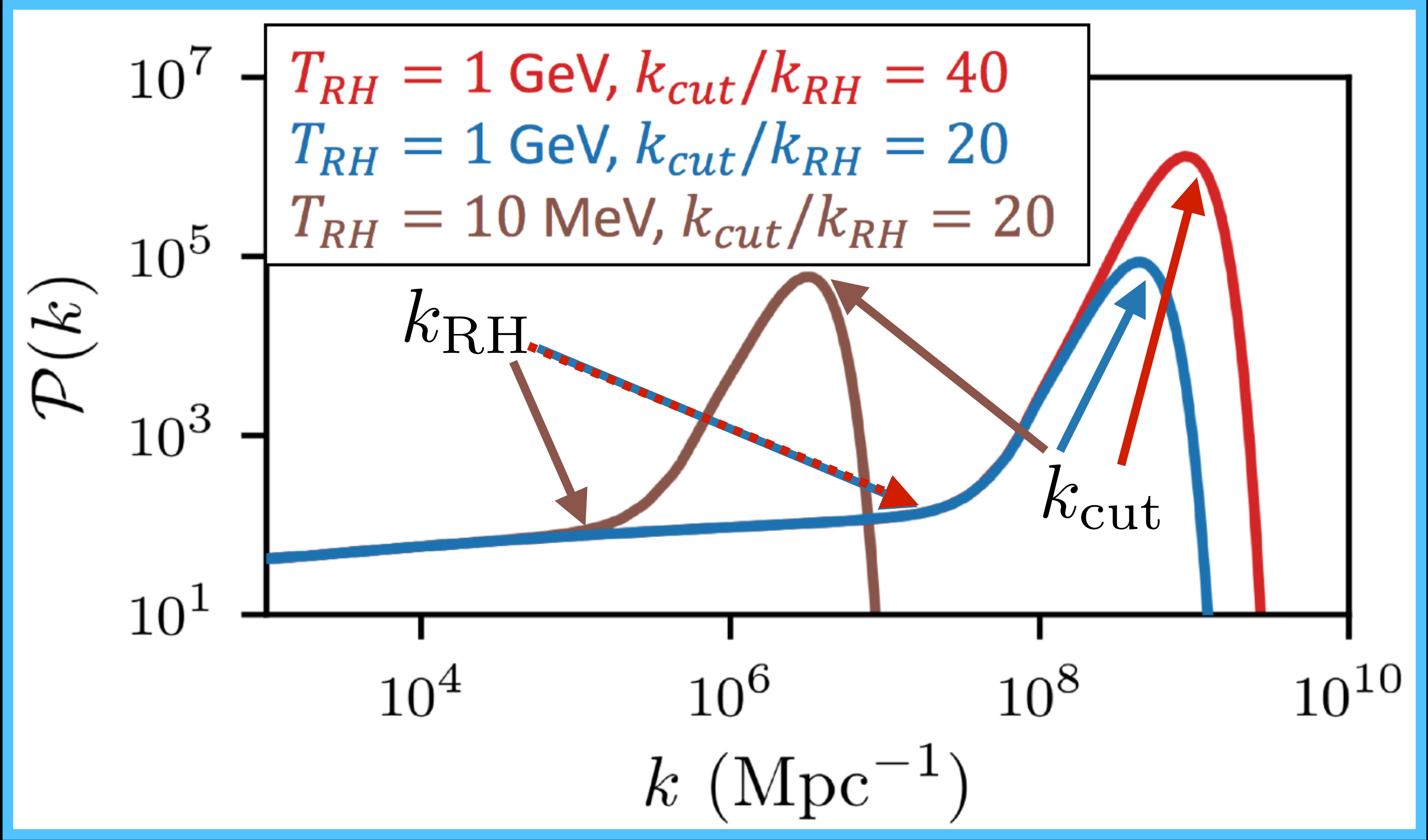
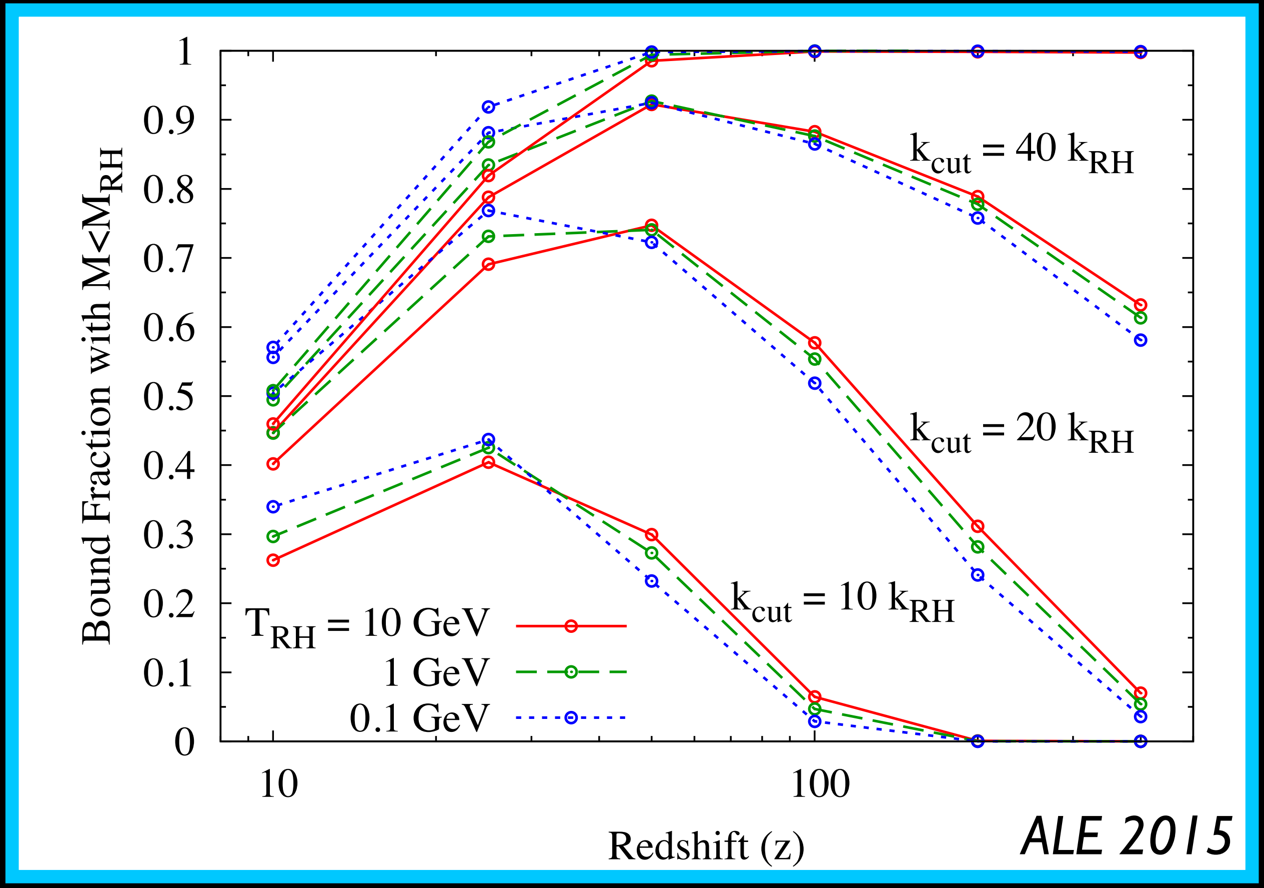


- Dark matter in a hidden sector is generally much colder, so the cut-off is set by other mechanisms.

The Microhalo Abundance

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.



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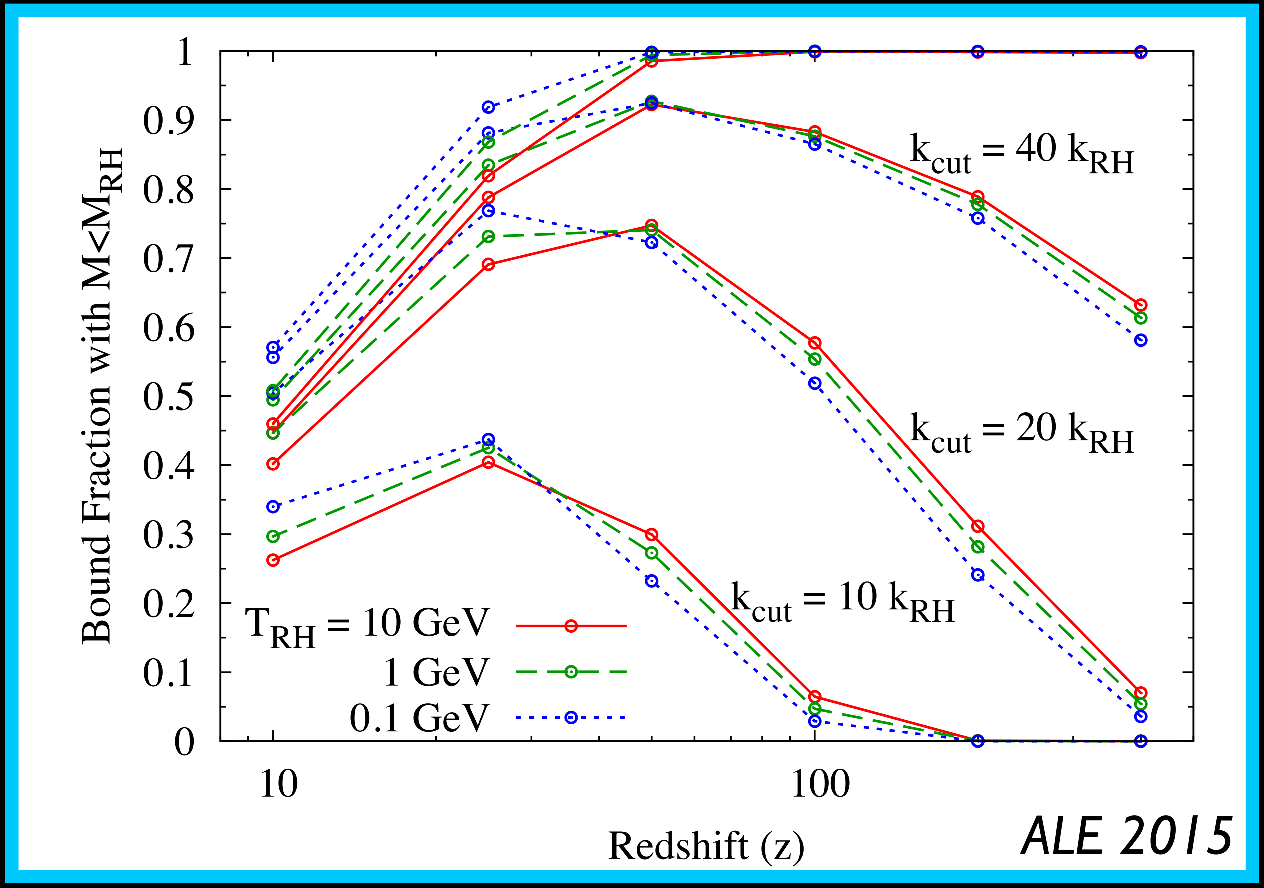

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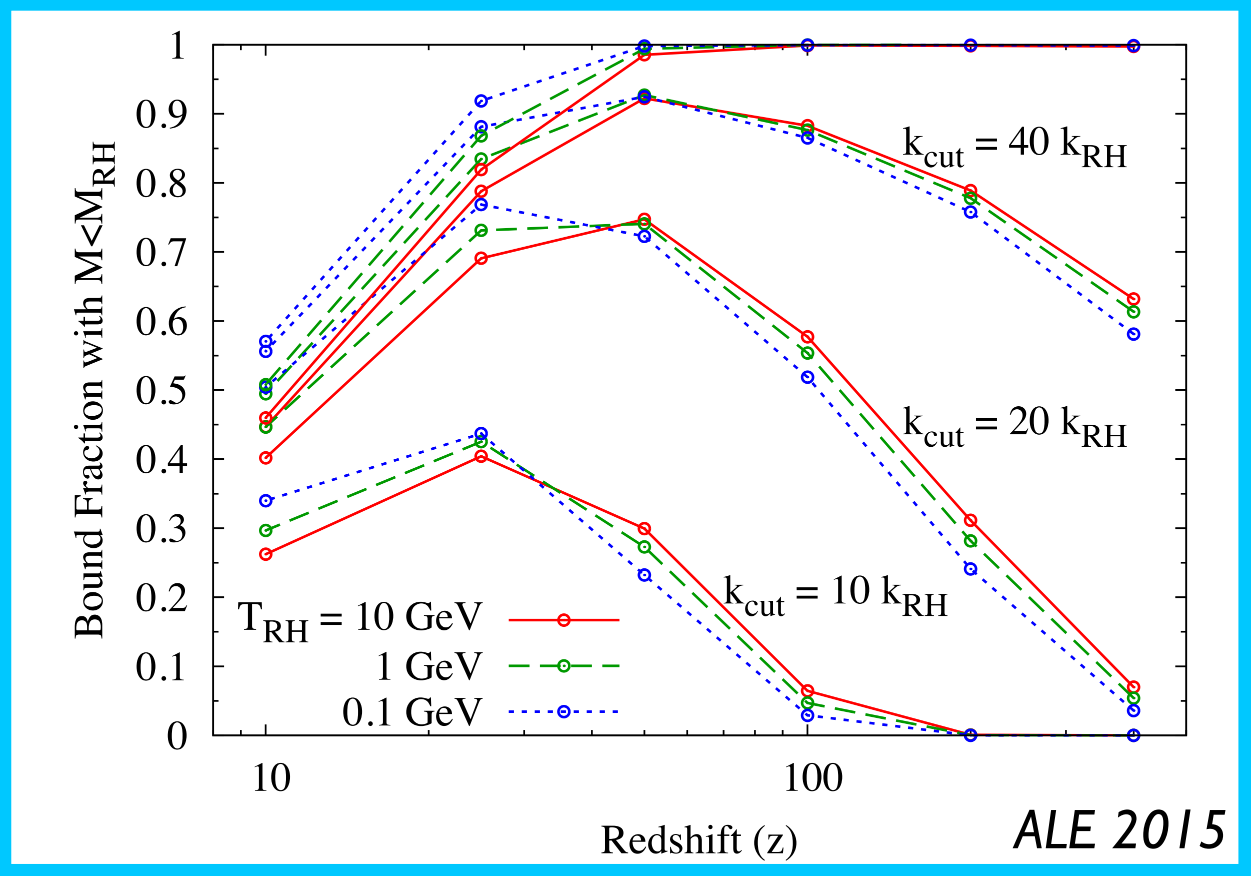

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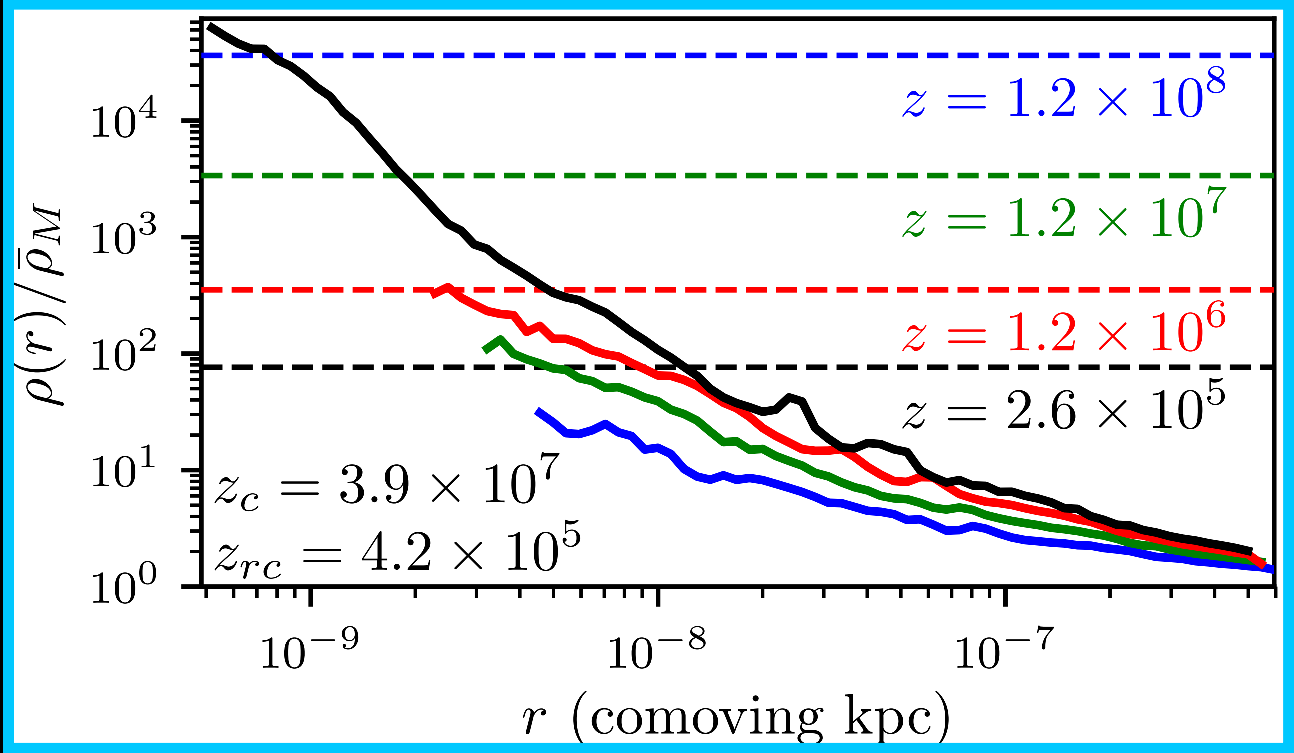
- With HS dark matter, we can form halos earlier, during radiation domination! *Blanco, Delos, ALE, Hooper 2019*



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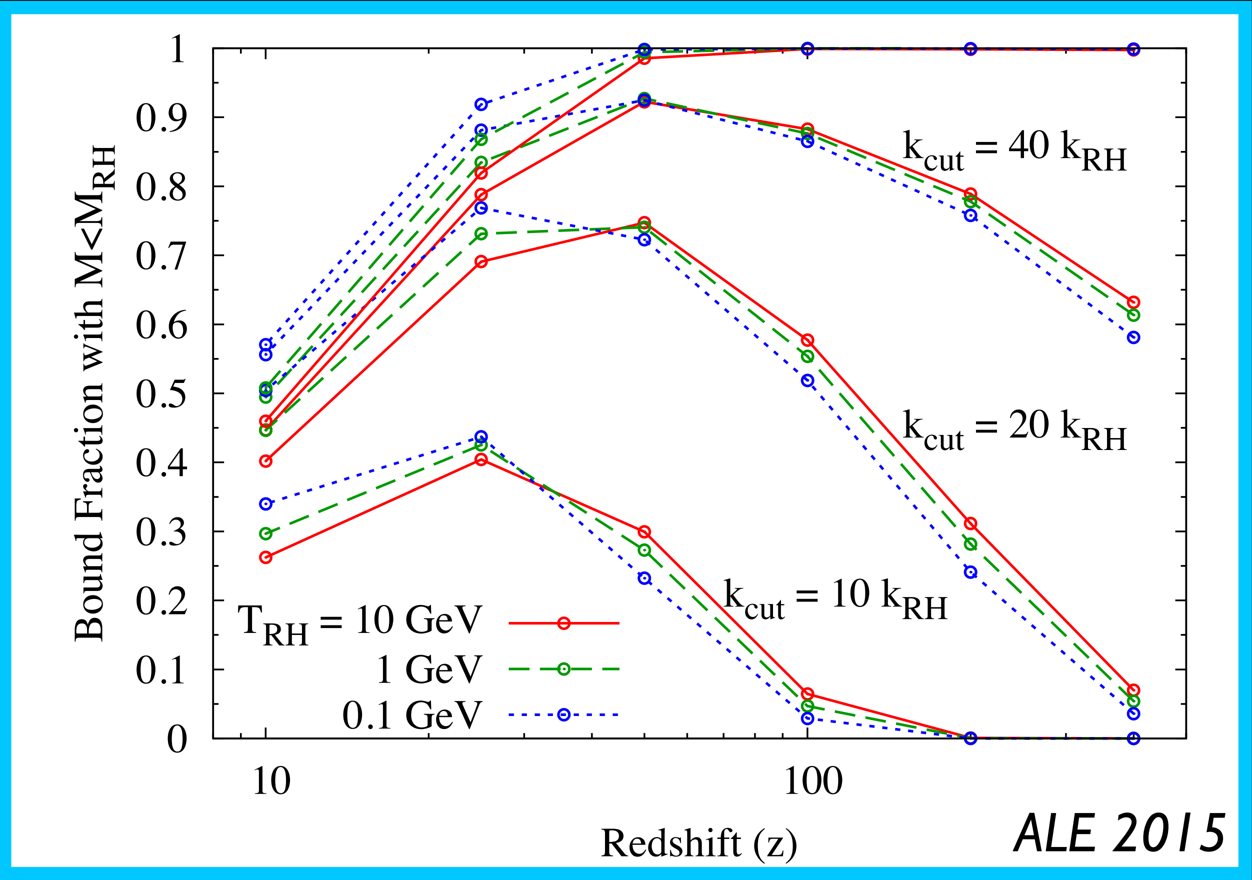

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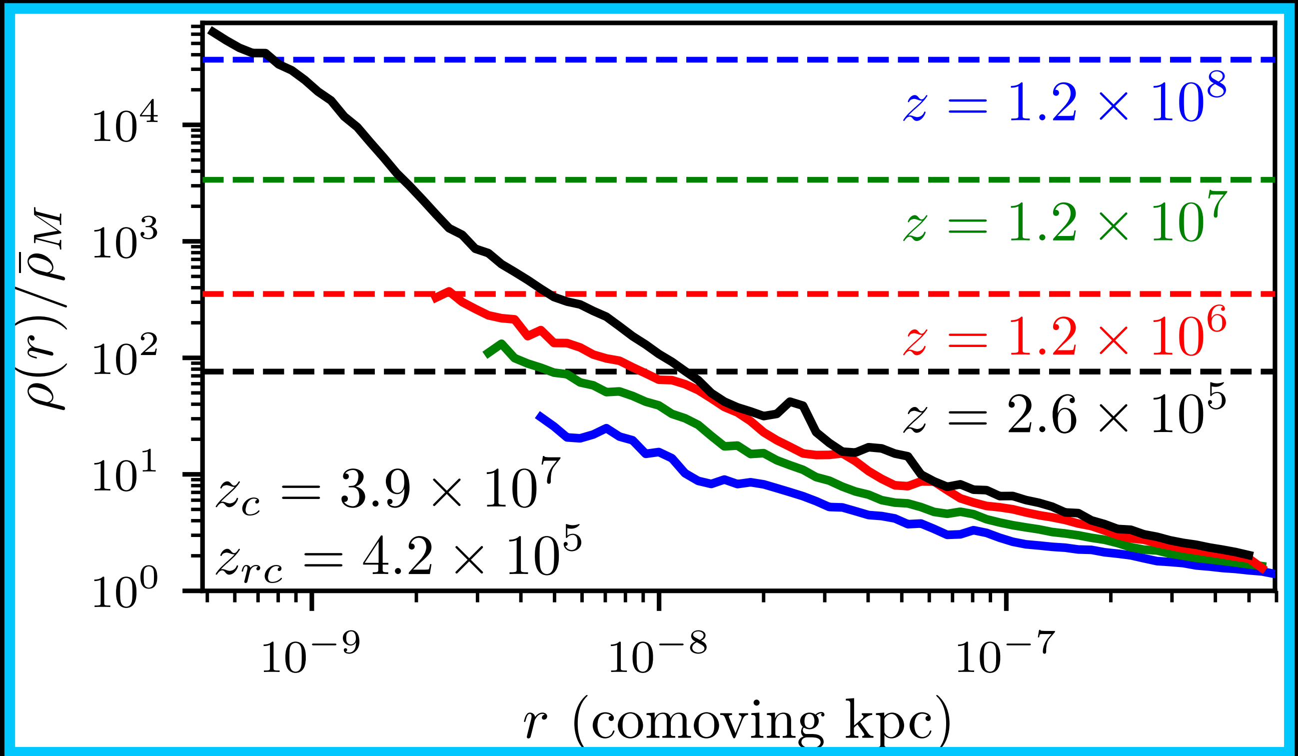
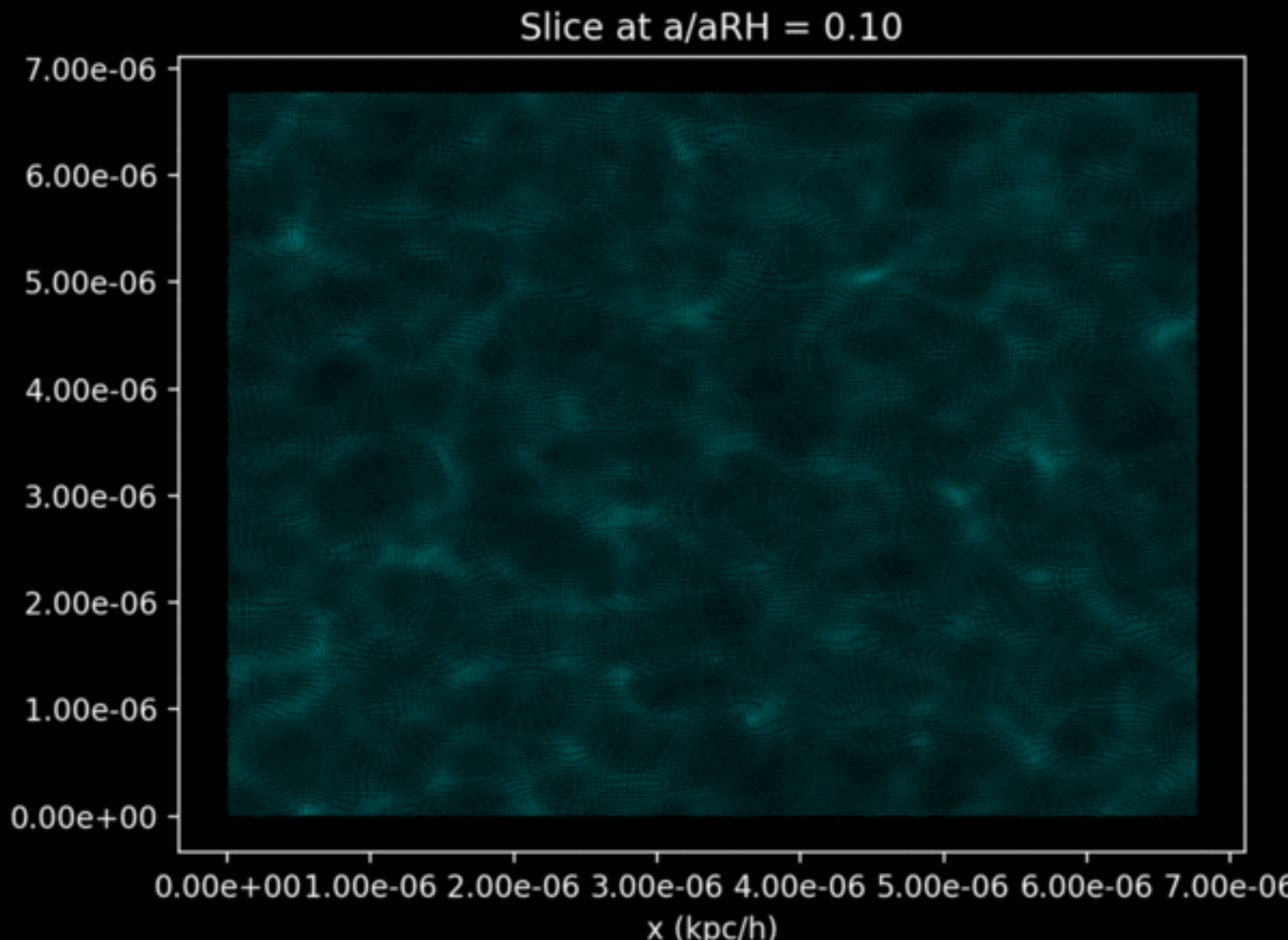


- Beware halo formation during the EMDE; it heats your dark matter!

Blanco, Delos, ALE, Hooper 2019
Barenboim, Blinov, Stebbins 2021

Gravitational Heating



Simulations by ***Himanish Ganjoo and M. Sten Delos***

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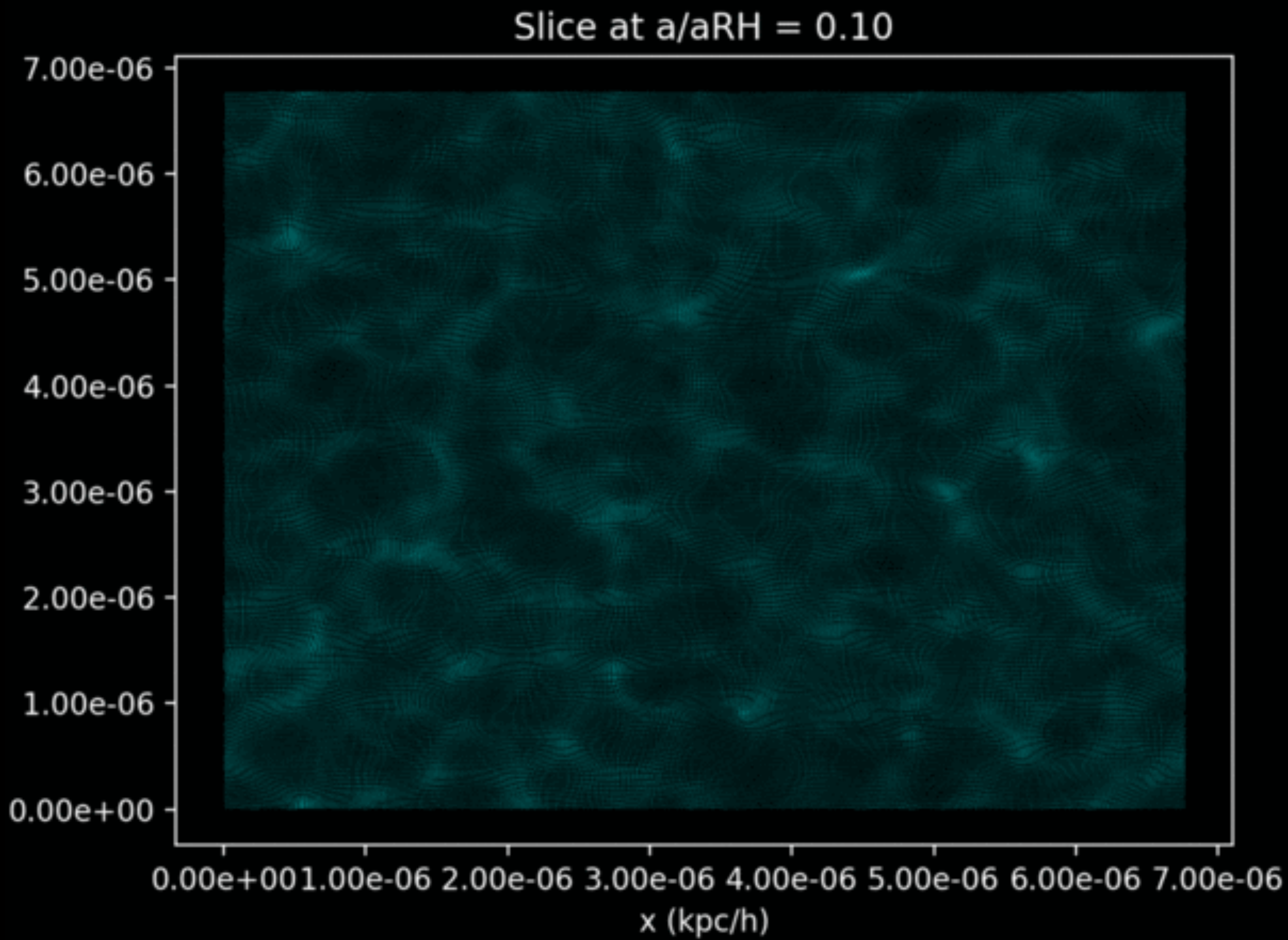

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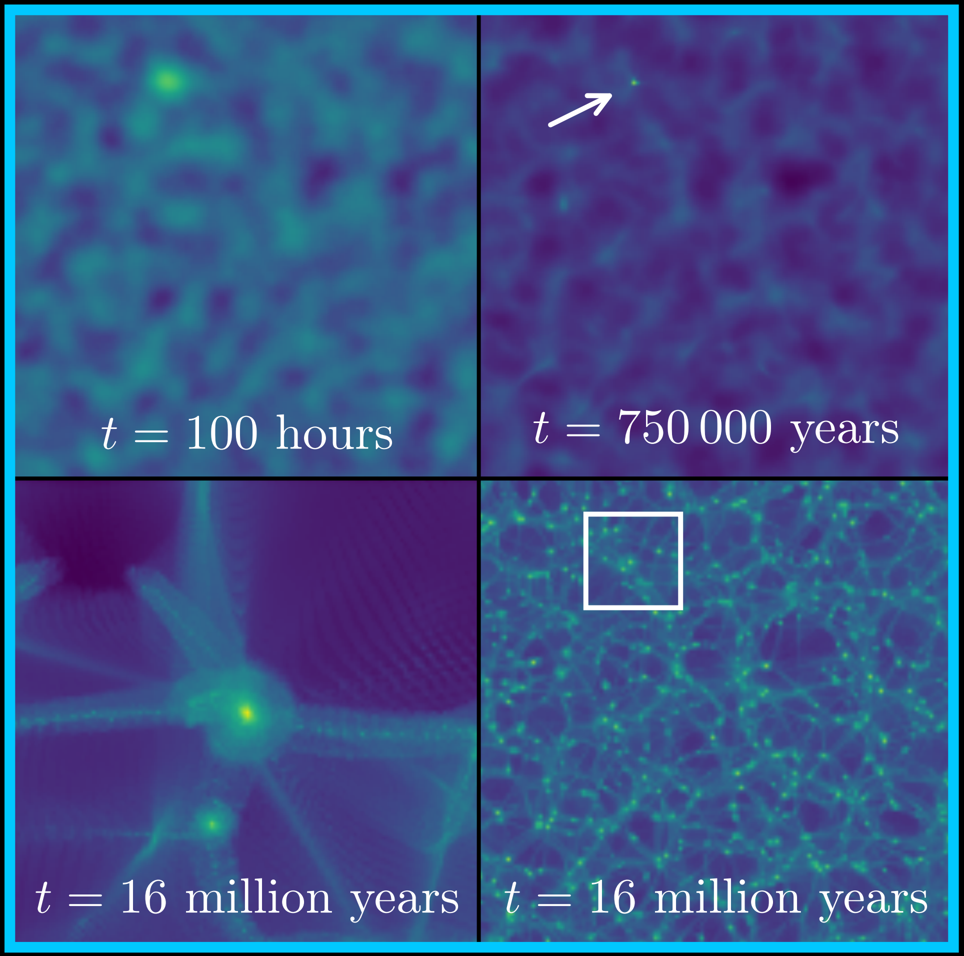
The Dark Matter Annihilation Rate

Microhalos increase the DM annihilation rate by increasing the boost factor:

$$B(z) \equiv \frac{\langle \rho_\chi^2 \rangle}{\bar{\rho}_\chi^2} = \frac{n_{\rm halo}\langle J \rangle}{\bar{\rho}_\chi^2}$$



Delos et al. 2017

- Use Peak-to-Halo (P2H) method to predict the central density profile of halos based on the properties of initial density peaks. *Delos, Bruff, ALE 2019*
- Use power spectrum to determine the abundance and properties of local maxima in the density field. *Bardeen, Bond, Kaiser, Szalay 1986*

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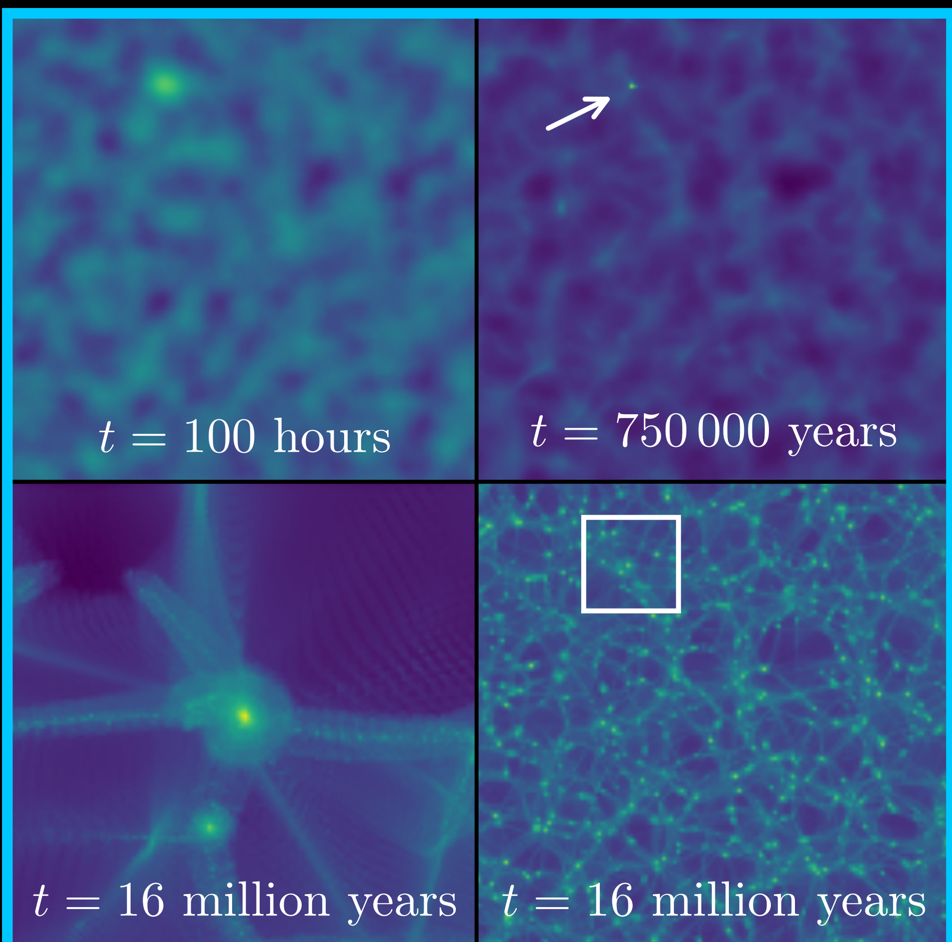

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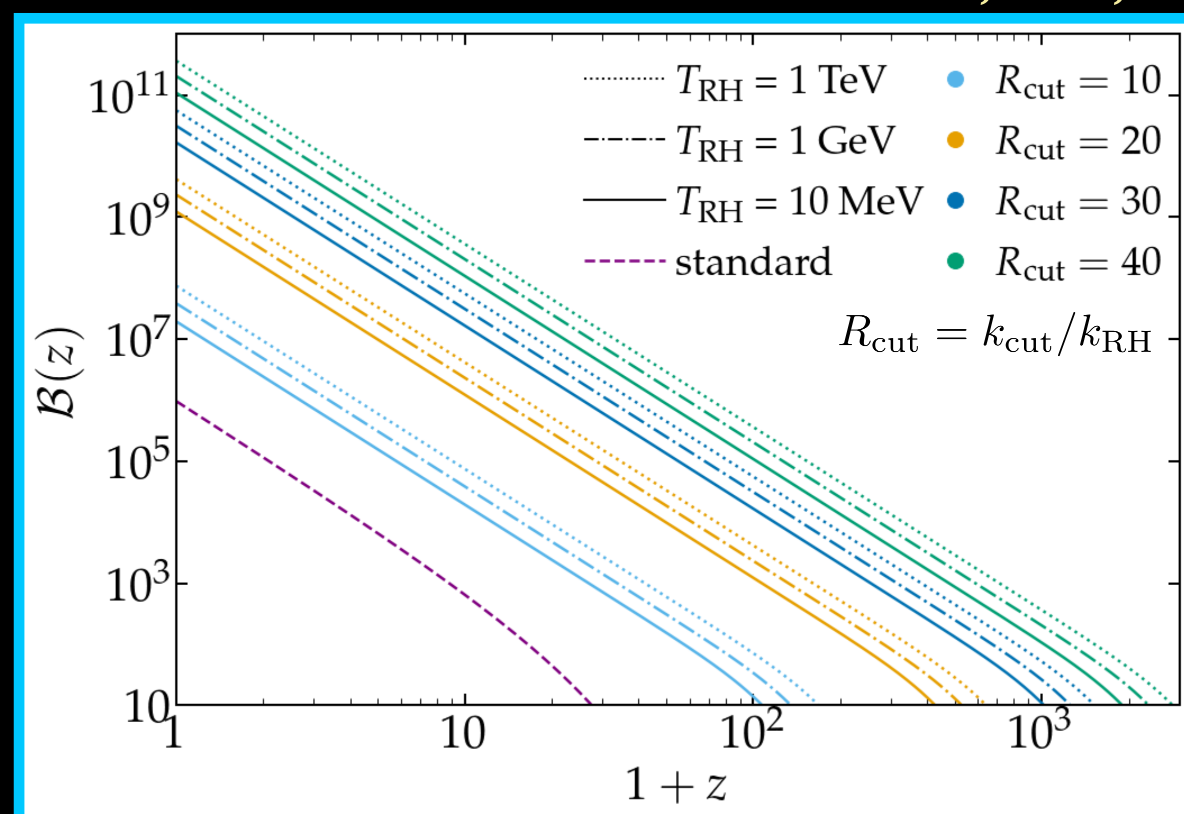
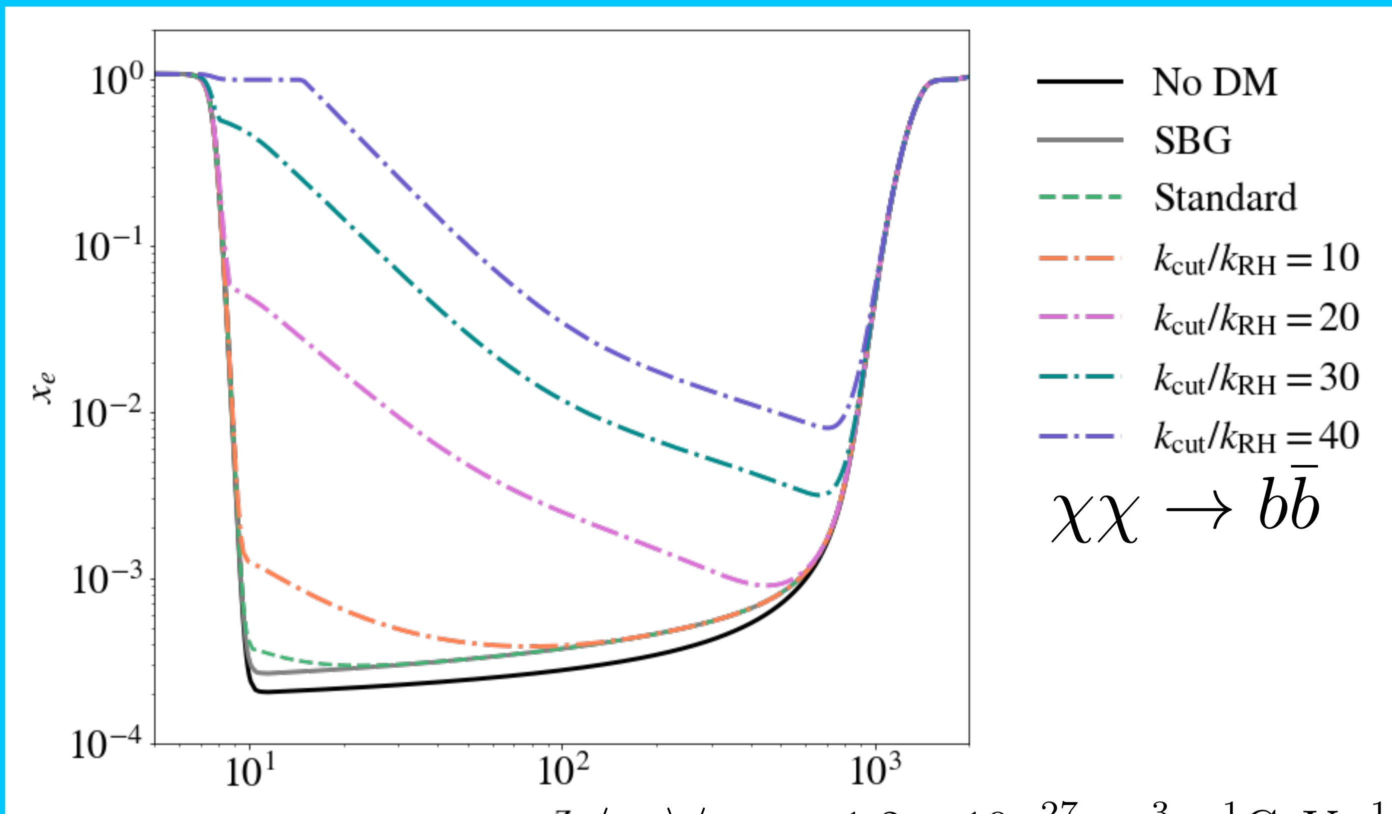
***Hwan Bae**, Delos, ALE, coming soon*

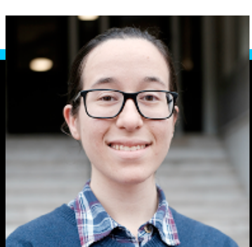


Observational Constraints

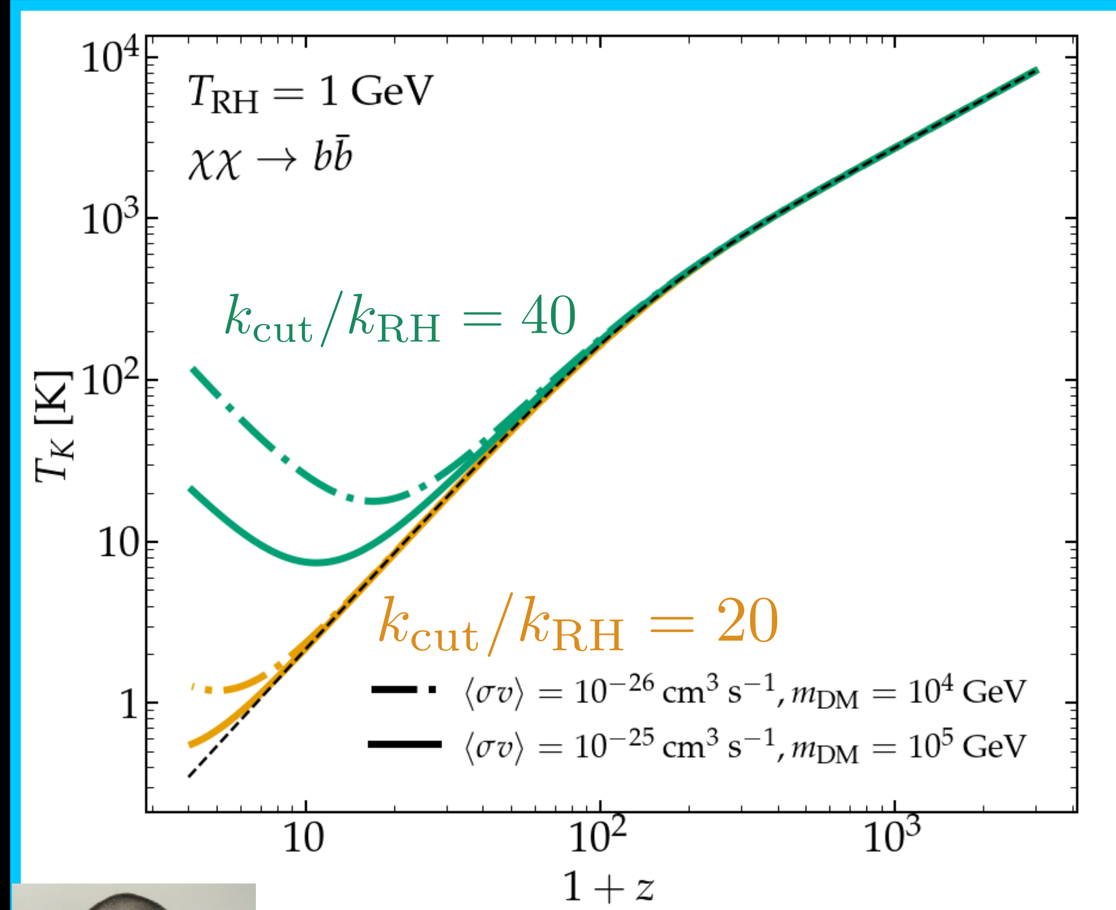
Energy released by DM annihilation affects the **ionization fraction** and **IGM temperature**. Can be constrained by CMB and 21cm absorption.



$\langle\sigma v\rangle/m_\chi = 1.2 \times 10^{-27}\ \mathrm{cm^3 s^{-1} GeV^{-1}}$



A. Turchaninova, Hwan Bae,
Poulin, ALE, coming soon



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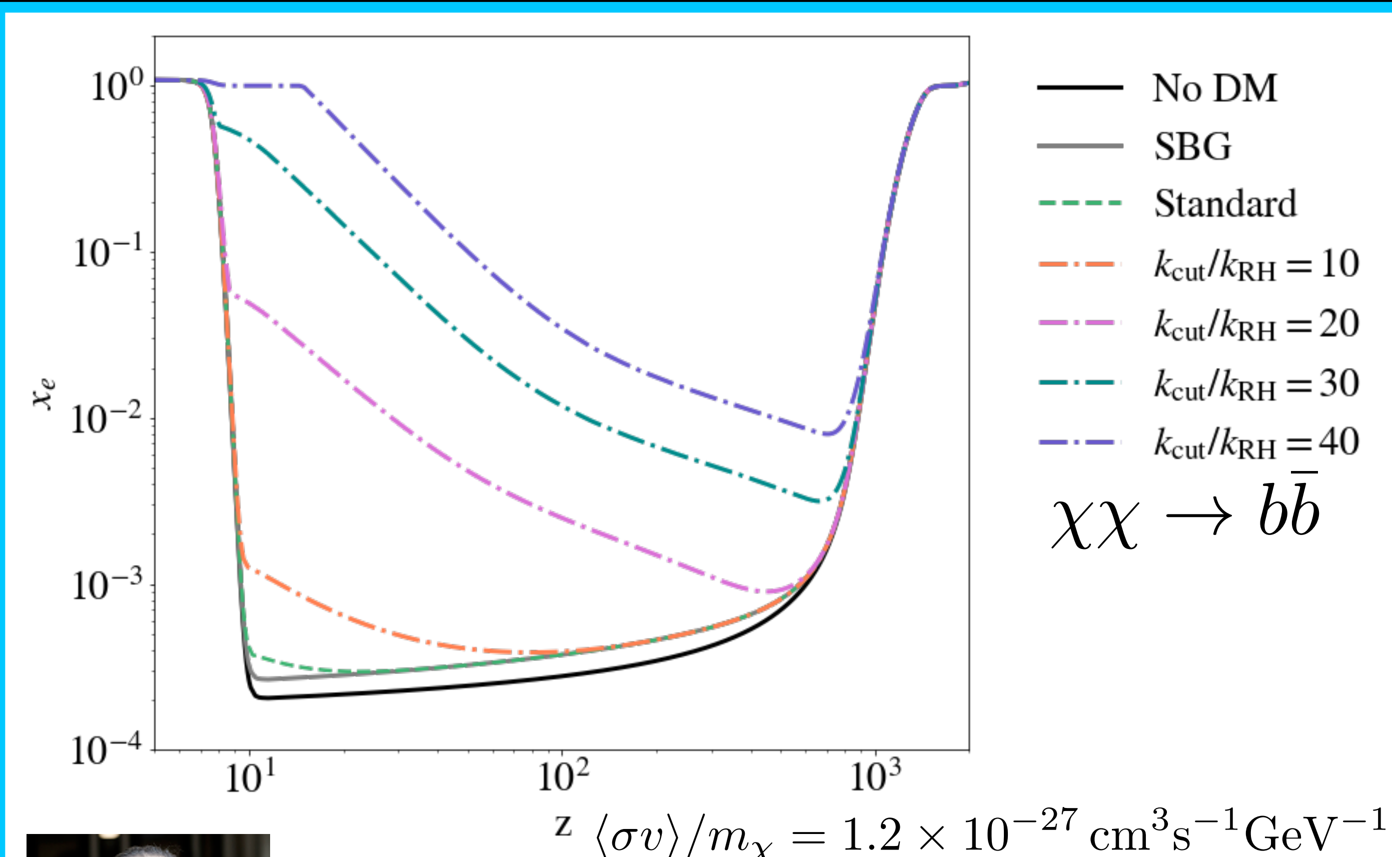

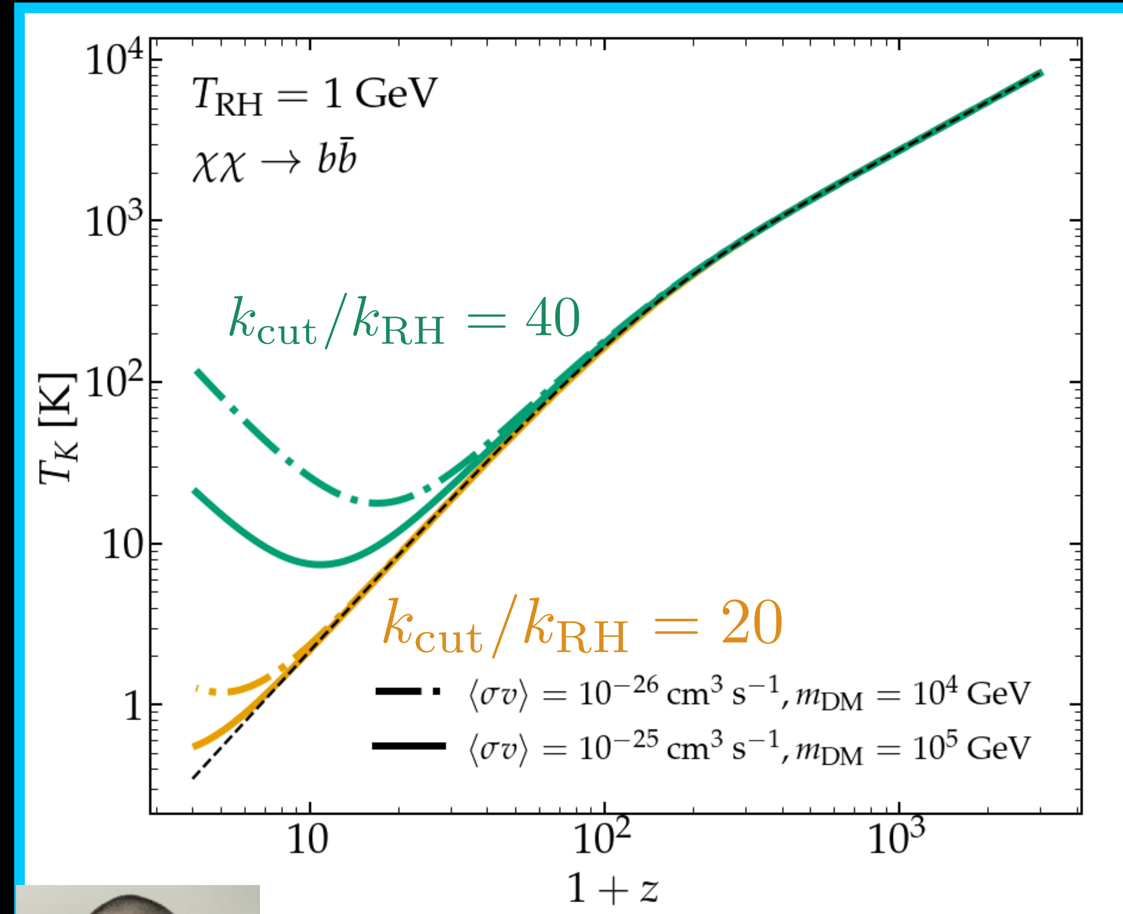

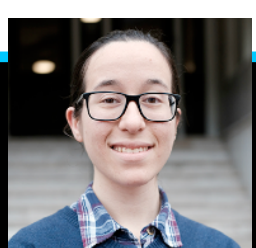

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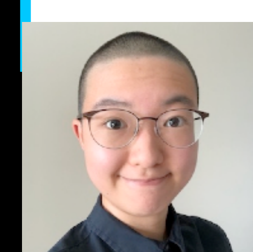

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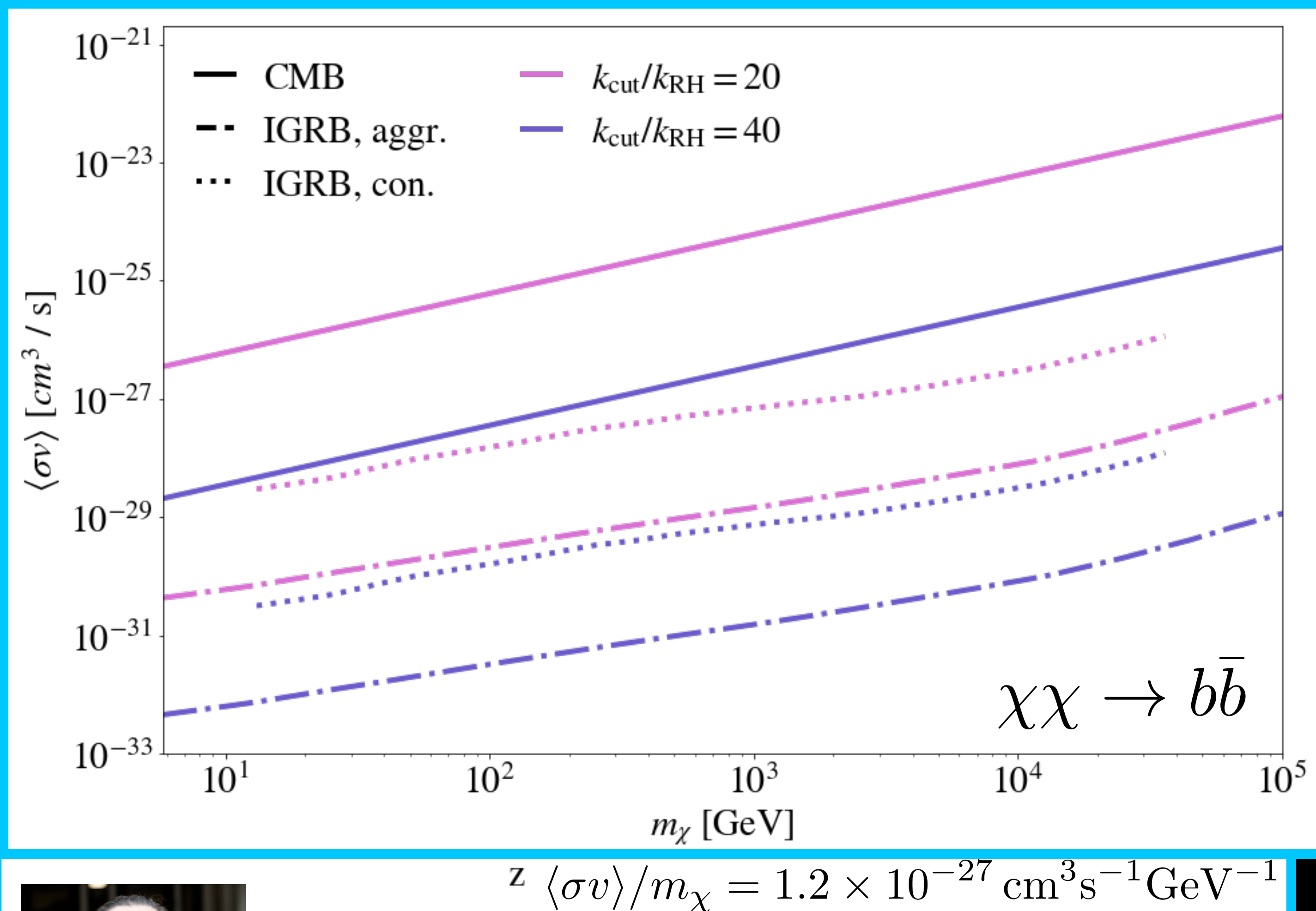

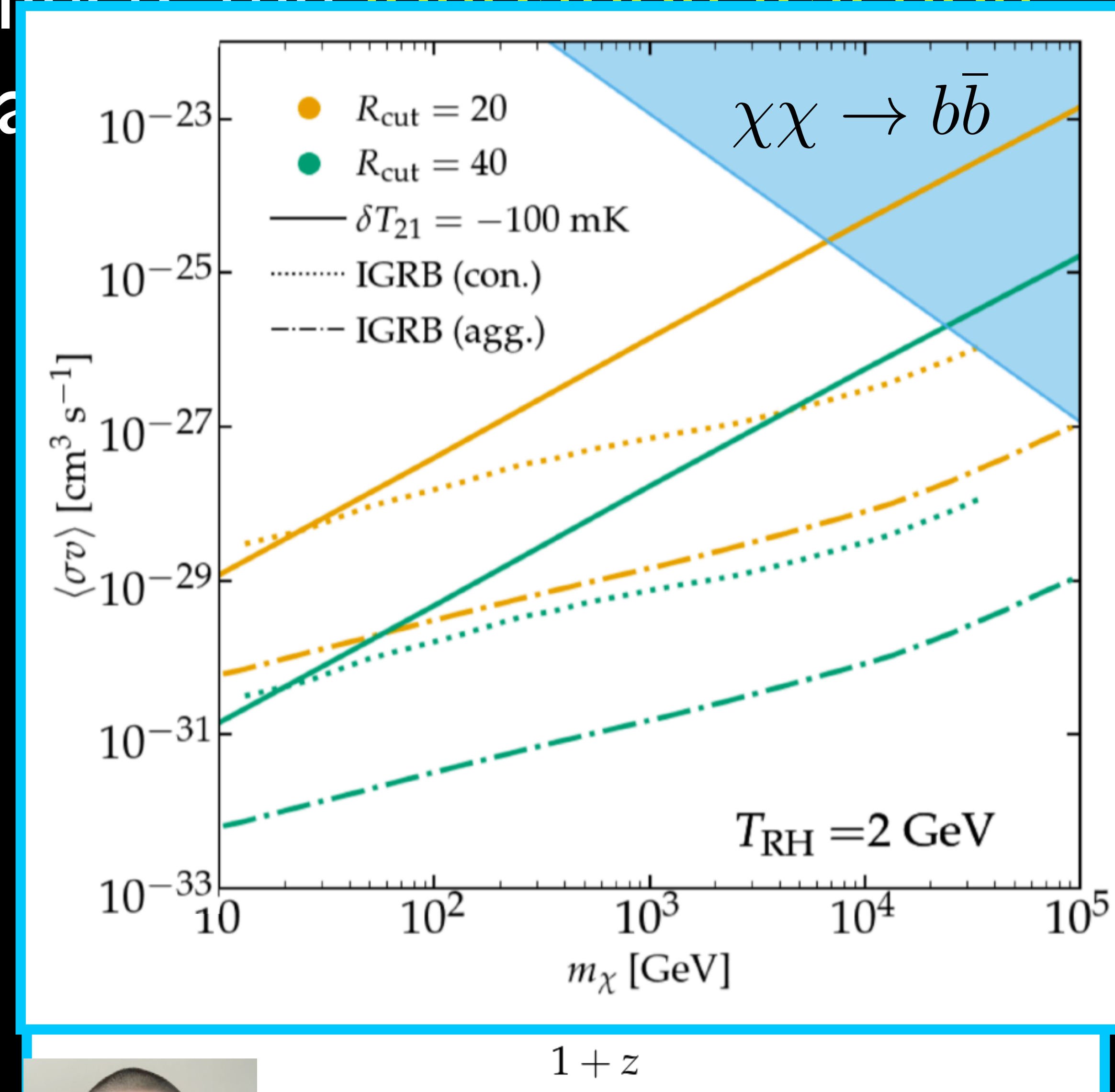

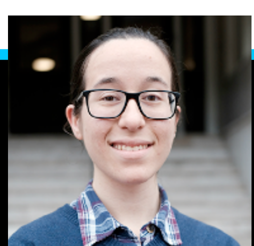

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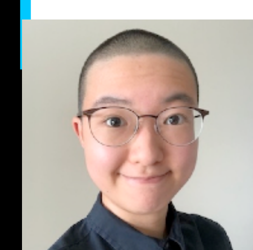

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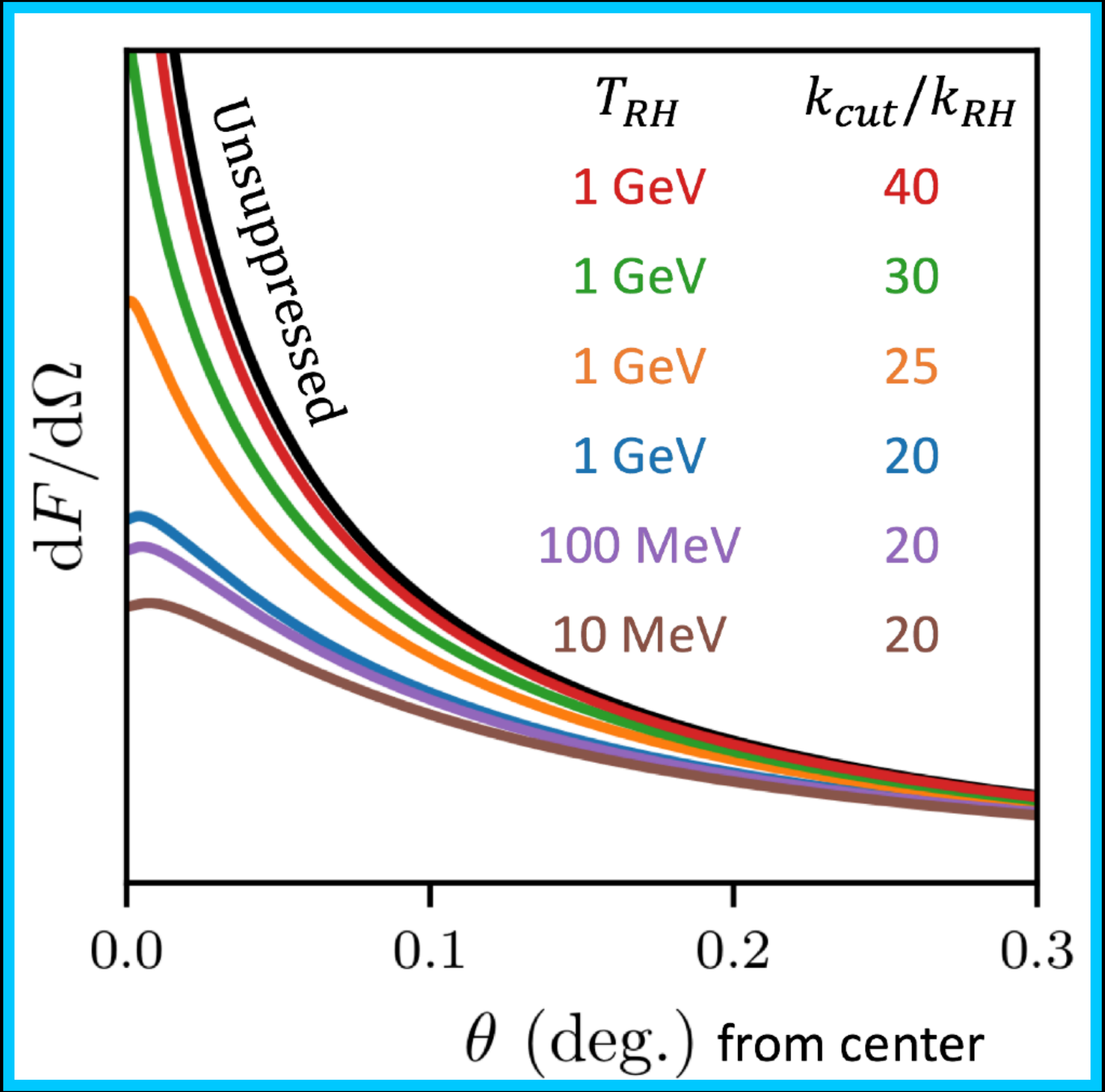
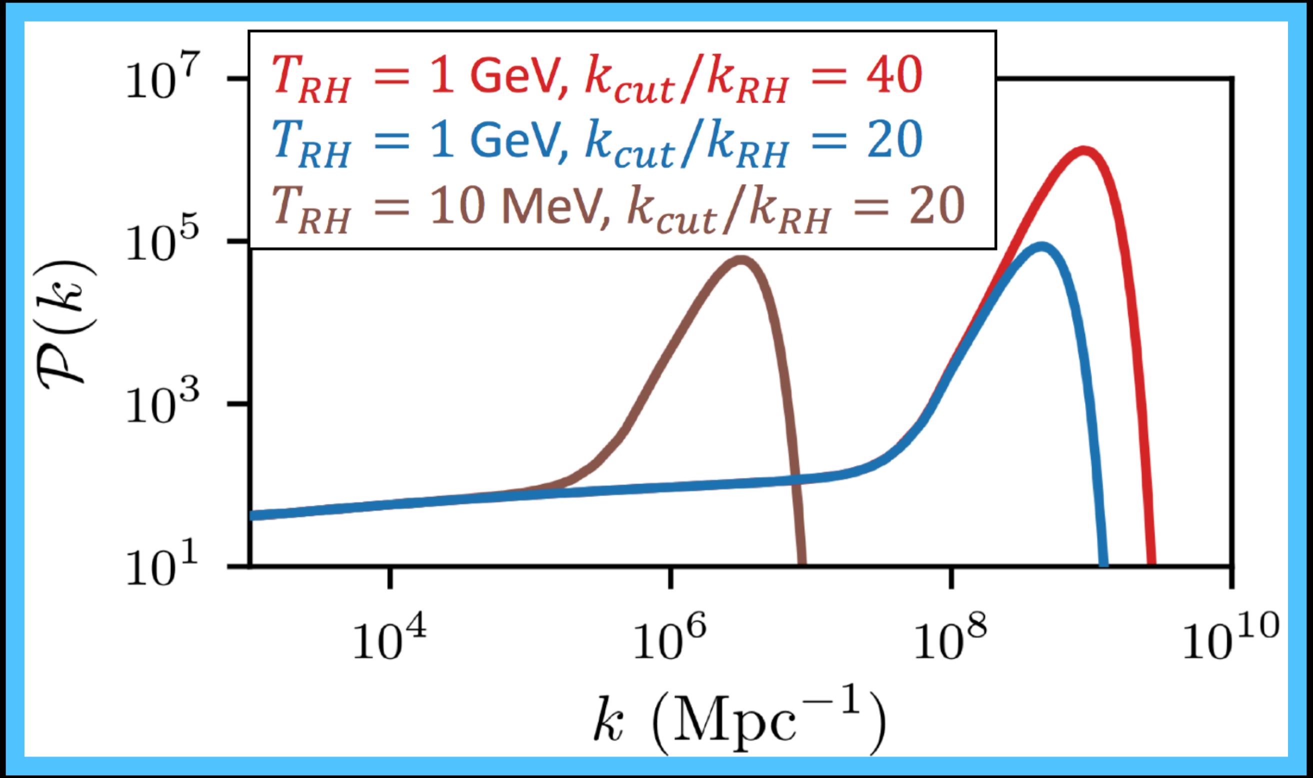
Microhalos within Dwarf Galaxies

Case study: Draco

Sten Delos, Tim Linden, ALE 2019

Microhalos in the central region are disrupted by stars and tides, reducing the annihilation signature.





Since $k_{\rm cut}/k_{\rm RH}$ determines the microhalos' densities, it sets how much they are disrupted.

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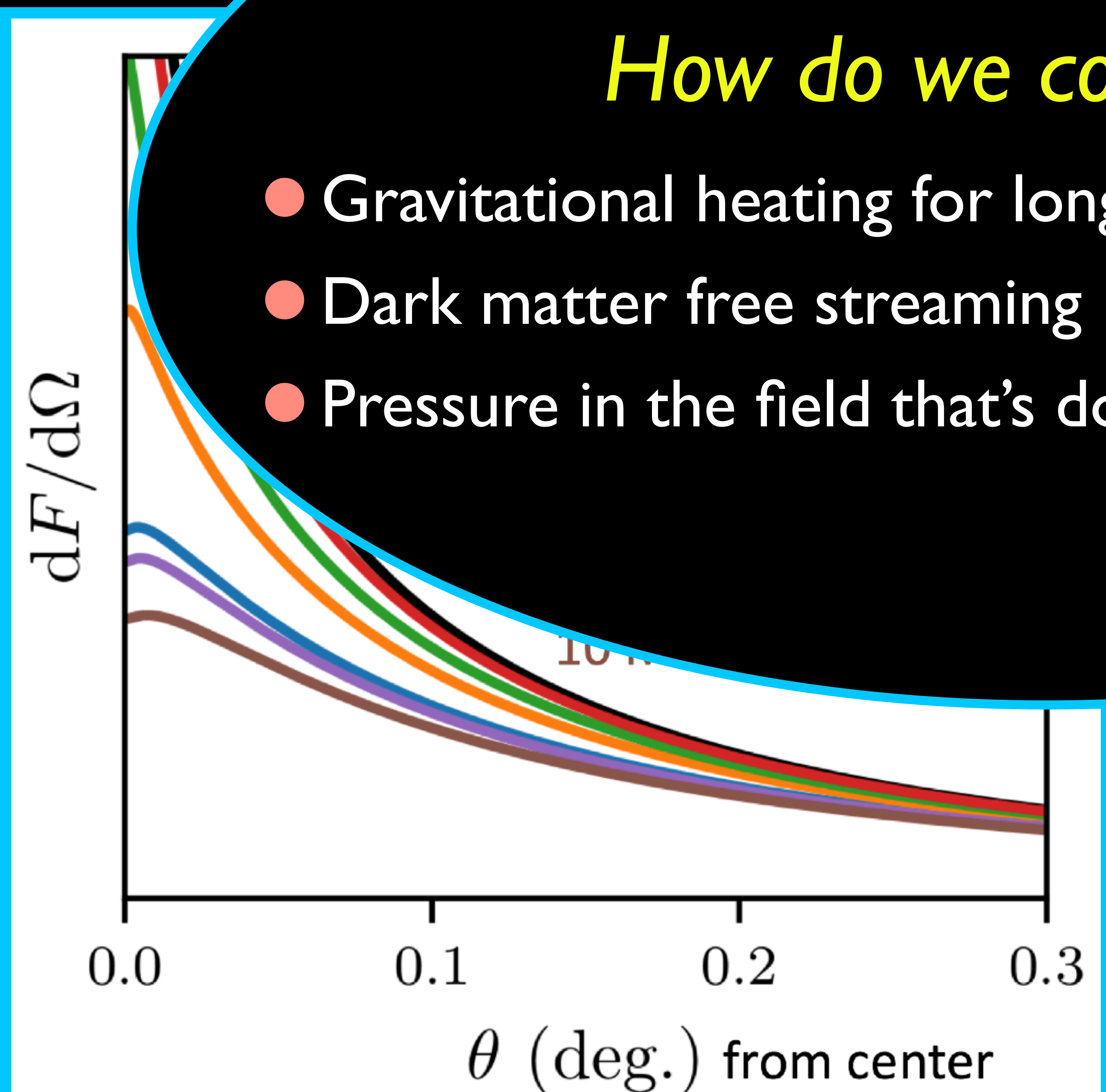
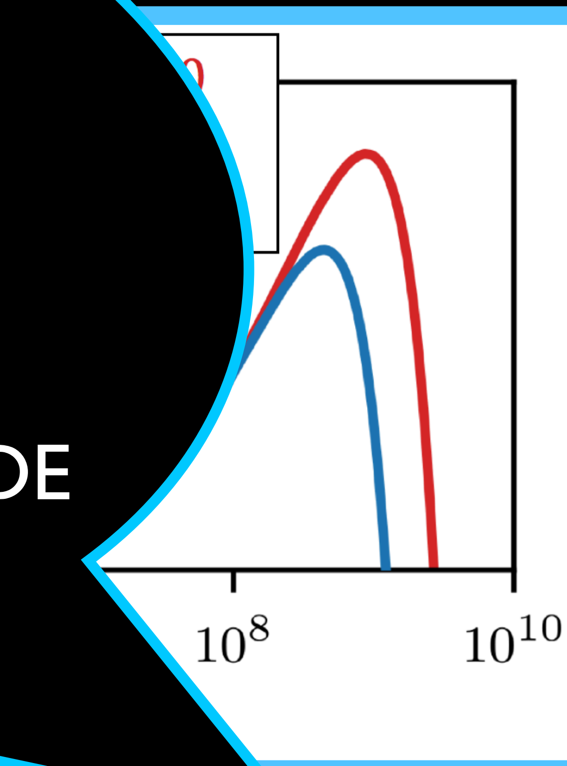
Microhalos in th… stars and tides, red…





One remaining question:
How do we compute $k_{\rm cut}$?

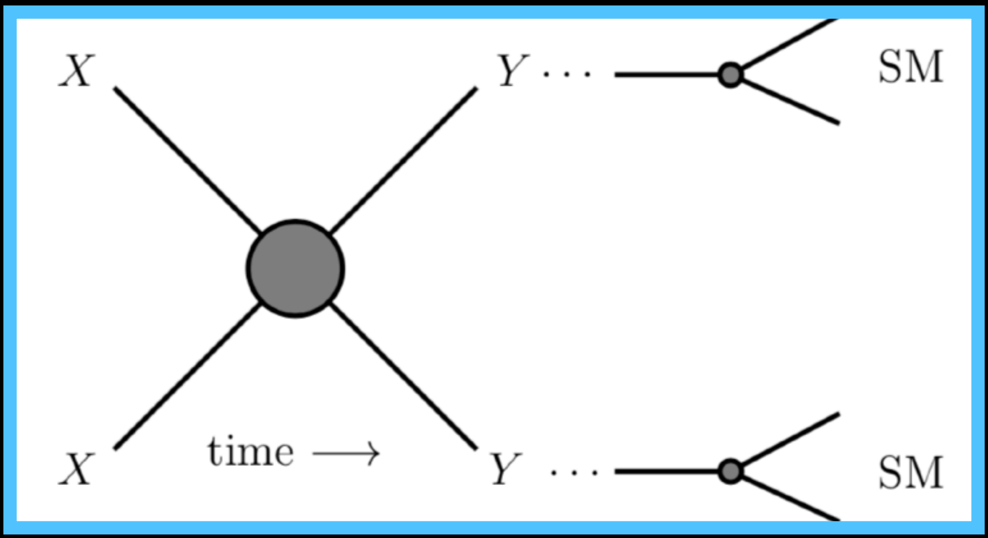
- Gravitational heating for long EMDEs
- Dark matter free streaming
- Pressure in the field that's dominant during the EMDE

Since $k_{\rm cut}/k_{\rm RH}$ determines the microhalos' densities, it sets how much they are disrupted.

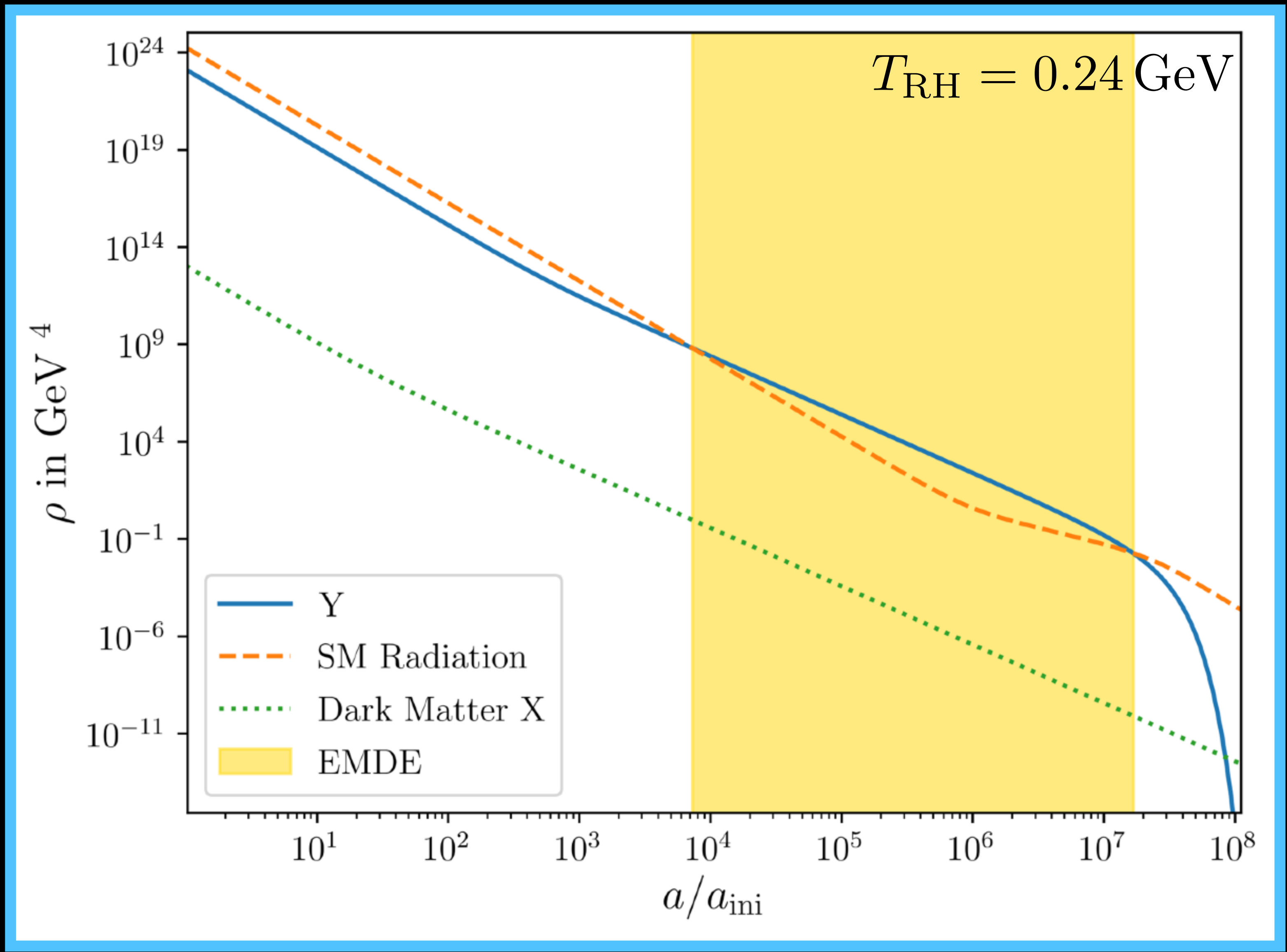
The Hot Hidden Sector

If dark matter is part of a hidden sector, it may never interact with the Standard Model, and it could be very, very cold.

- Dark matter free-streaming is often NOT the cause of the small-scale cut-off.
- Instead, the properties of the dominant hidden particle set the cut-off.



- The Y particles are initially relativistic, but then they cool and come to dominate the Universe.
- The HS and the SM have different temperatures.

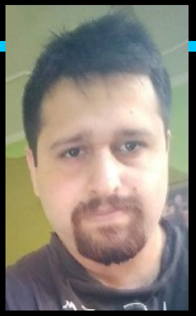


Y Perturbation Evolution

During the EMDE, dark matter particles fall into gravitational wells sourced by Y particles:

$$\delta_X \to \delta_Y$$

Himanish Ganjoo,
ALE, W. Lin, K. Mack
2023

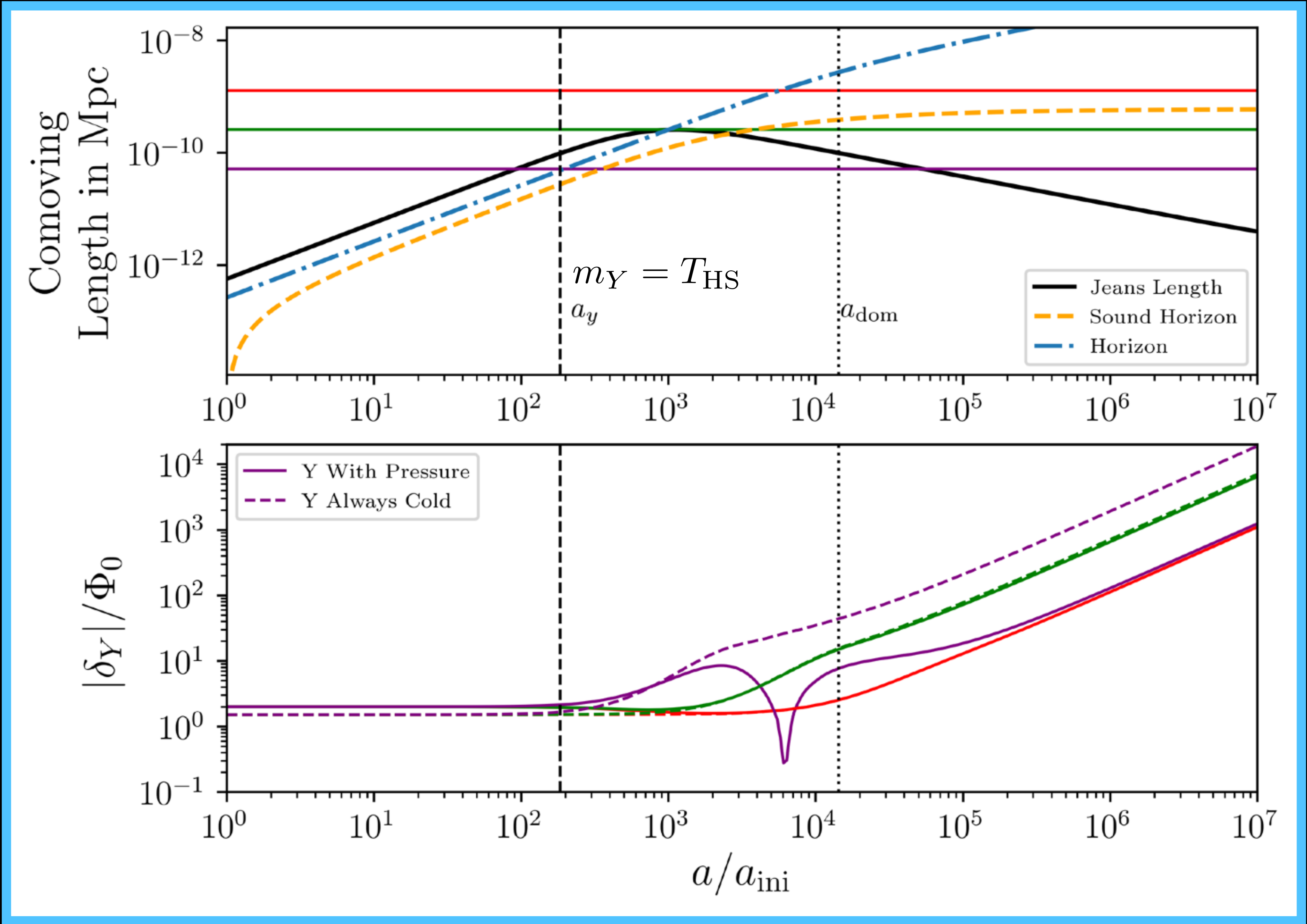


The Y particles have pressure support for $\lambda < \lambda_J$

$$\lambda_J = \sqrt{\frac{2}{3}}\frac{c_{sY}}{aH}\frac{\rho_R + \rho_Y}{\rho_Y}$$

$$\lambda_J \propto a \quad \mathrm{RD}; m_Y < T_D$$

$$\lambda_J \propto a^{-1/2} \quad \mathrm{YD}; m_Y > T_D$$



The Small Scale Cut-off

During the EMDE, dark matter particles fall into gravitational wells sourced by Y particles:

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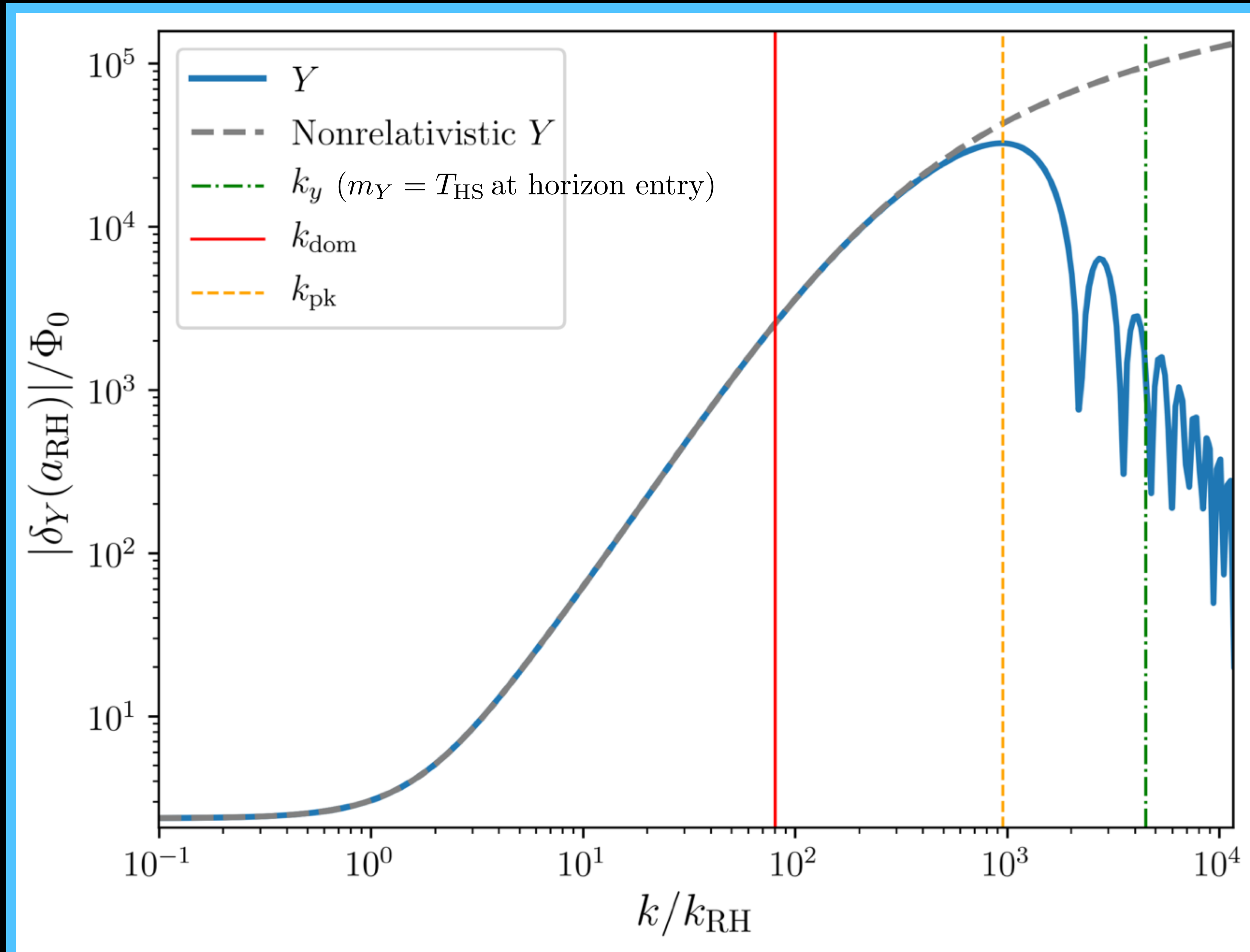
Himanish Ganjoo,
ALE, W. Lin, K. Mack
2023

- Modes that enter the horizon while the Y particles are semi-relativistic are suppressed.
- The peak occurs at a fixed value of λ/λ_J at horizon entry:

$$\frac{k_{\rm pk}}{k_{\rm dom}} \simeq 0.3 \left(\frac{m_Y}{T_{\rm dom}}\right)^{8/9}$$

- Changing the cut-off suppresses both the boost and gravitational heating.



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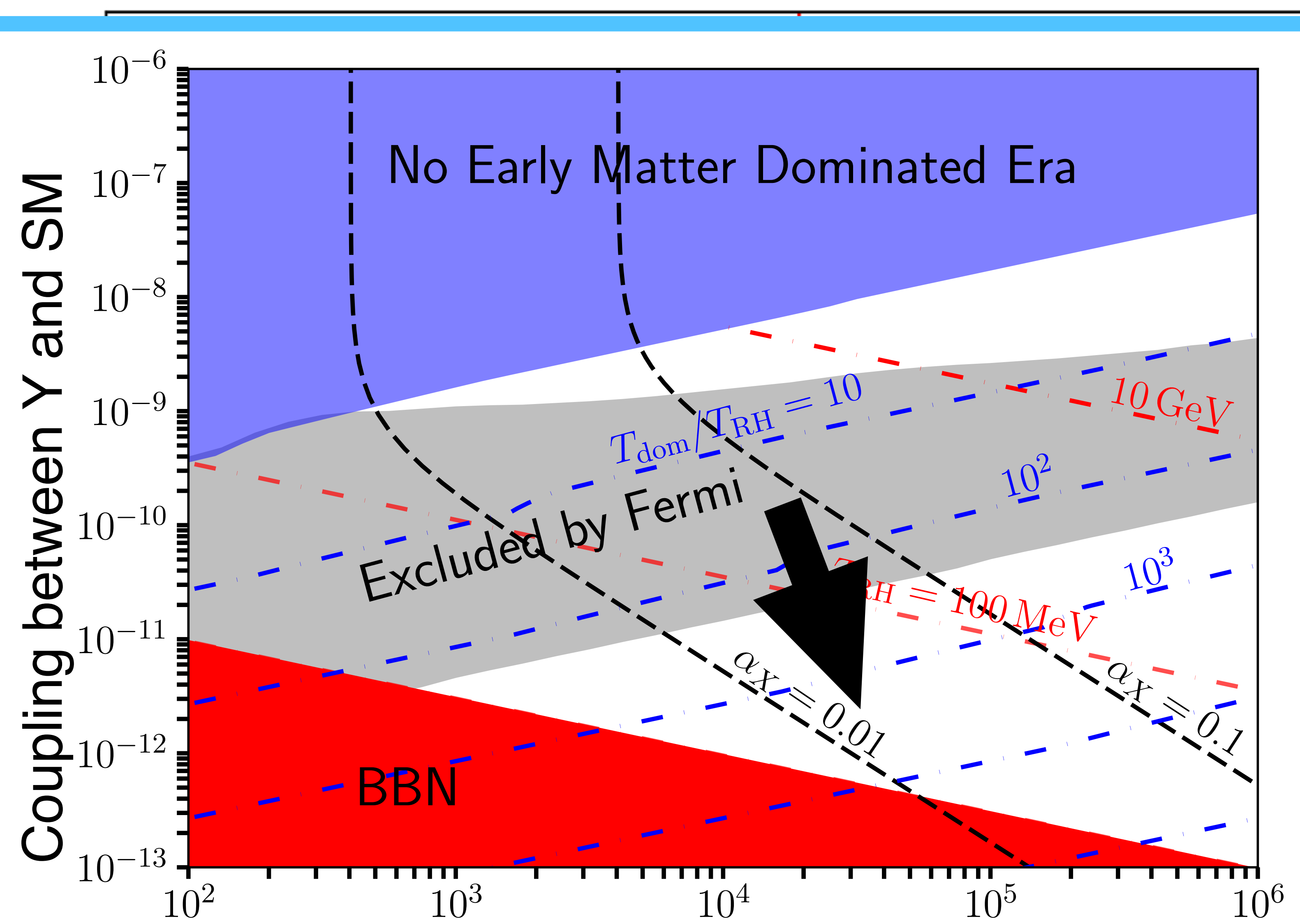


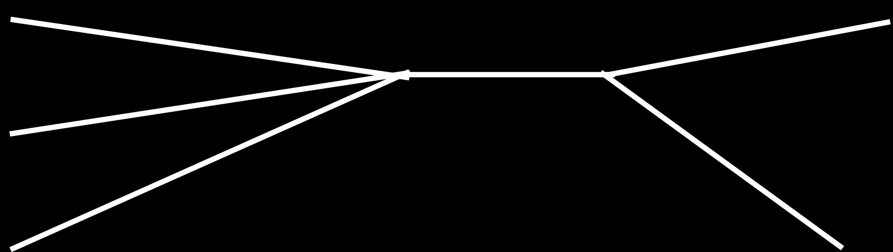
Blanco, Delos, ALE, Hooper 2019

Cannibalism within the Hidden Sector

Now suppose that the Y particle is a scalar with

$$\mathcal{L}_{\rm can} = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi - \frac{1}{2}m^2\varphi^2 - \frac{g}{3!}\varphi^3 - \frac{\lambda}{4!}\varphi^4.$$

This allows 3-to-2 cannibal interactions:



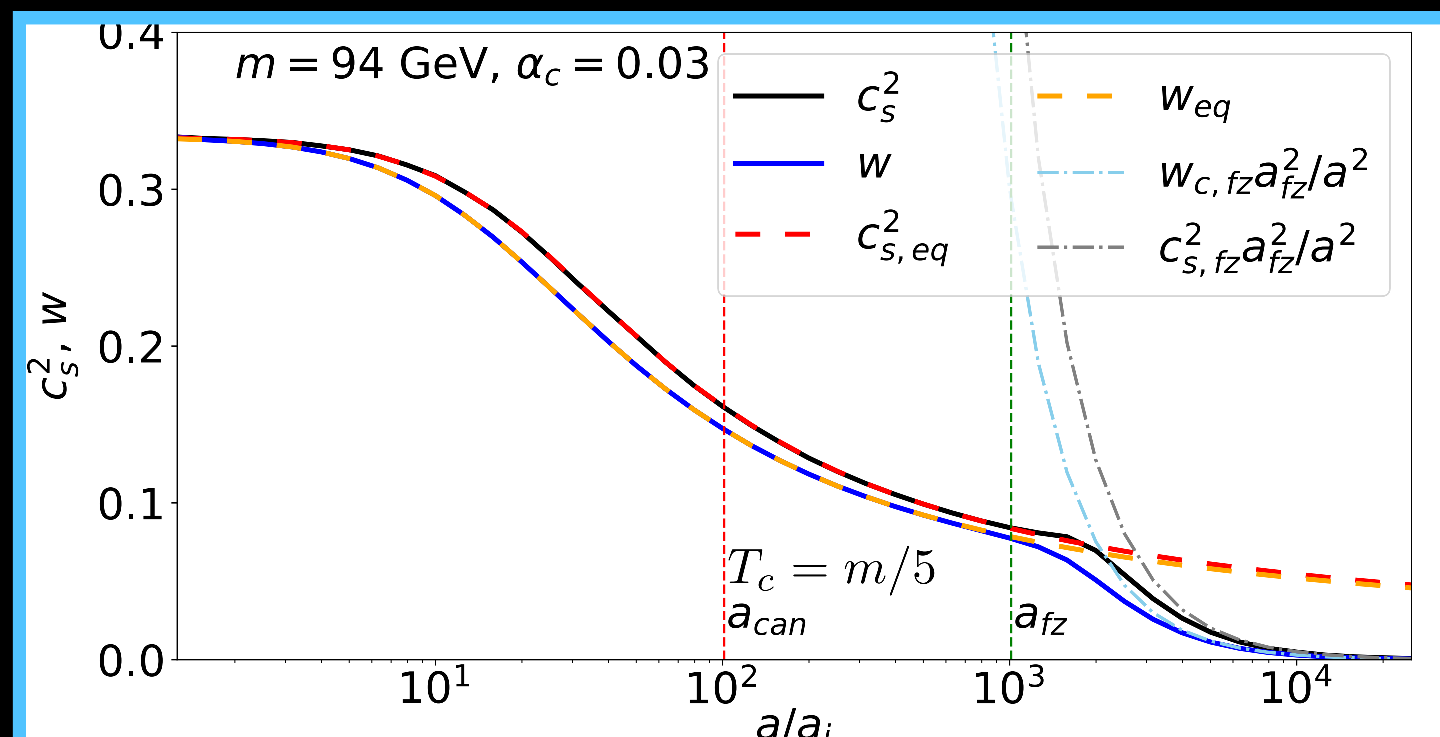
$$\langle\sigma v^2\rangle_{\rm can} = \frac{25\sqrt{5}(g/m)^2[(g/m)^2-3\lambda]^2}{147456\pi m^5} \equiv \frac{25\sqrt{5}\pi^2\alpha_c^3}{5184 m^5}$$

Pappadopulo, Ruderman, Trevisan 2016
Farina, Pappadopulo, Ruderman, Trevisan 2016
ALE, Ralegankar, Shelton 2022

Cannibalism self-heats the cannibal field while $m_\varphi < T_{\rm HS}$:

$$T_c \propto \frac{1}{\ln(a/a_{\rm can})}$$

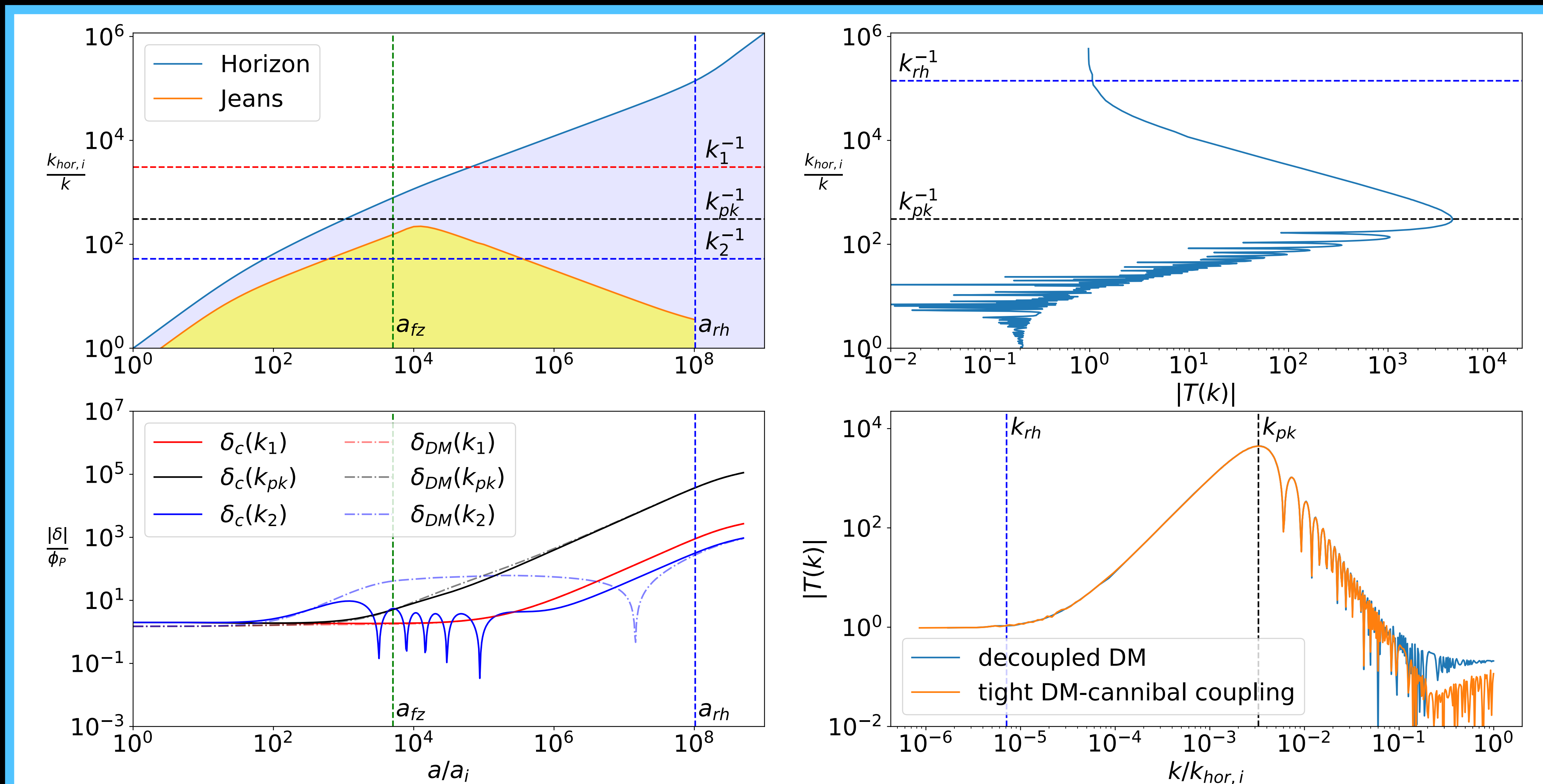
$$\rho_c \propto \frac{1}{a^3\ln(a/a_{\rm can})}$$



Cannibal Perturbations

*ALE, **Pranjal Ralegankar**, Jessie Shelton 2021*

If the cannibals dominate the Universe at cannibal freeze-out:

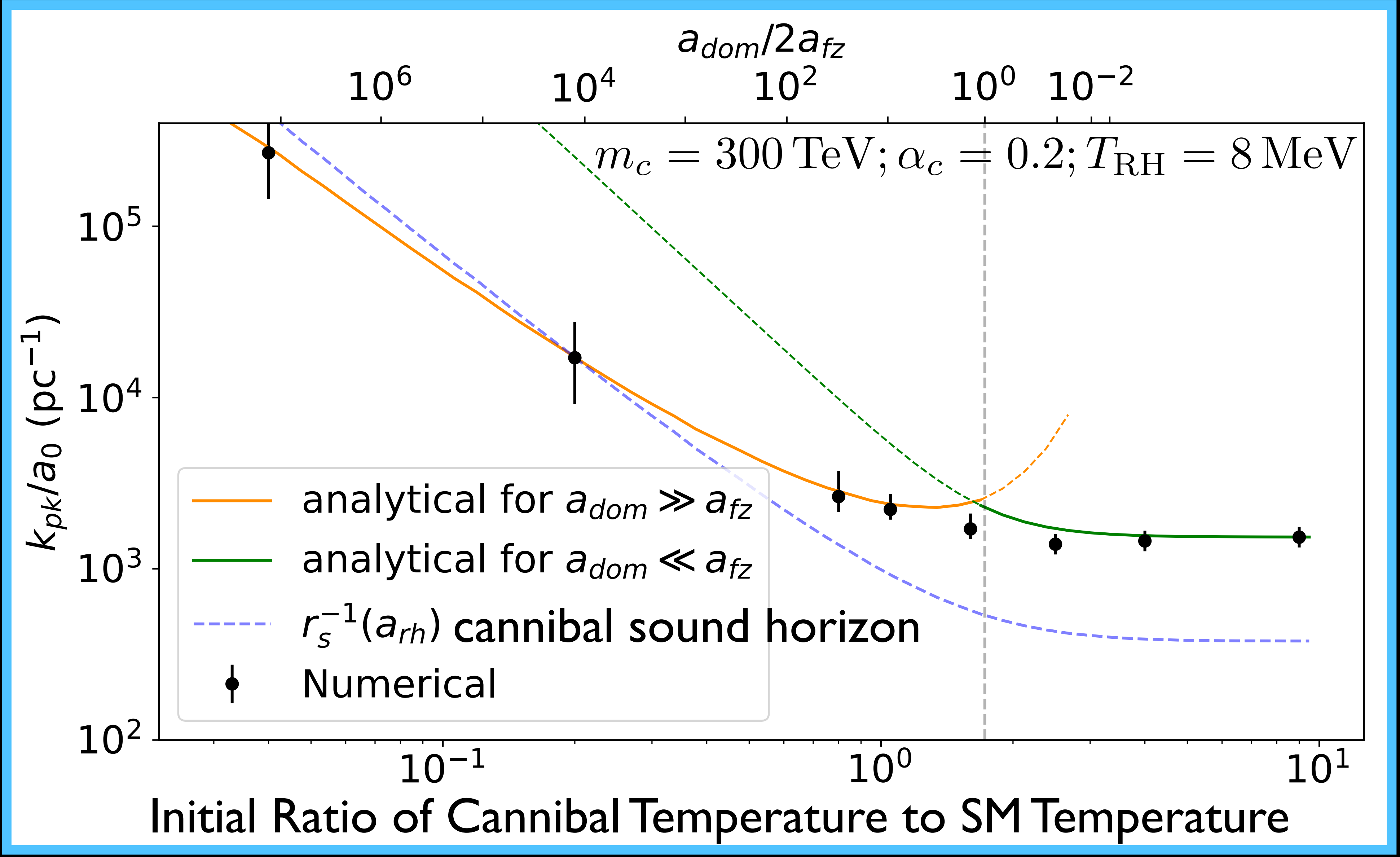


- Again, dark matter falls into gravitational wells sourced by cannibals.
- Maximum Jeans length set by cannibal freeze-out.
- Peak scale $k_{\rm pk} \simeq k_J(2a_{\rm fz})/1.4 \sim 40{\rm pc}^{-1}\left(\frac{\alpha_c}{0.02}\right)^{-1/3}\left(\frac{T_{\rm rh}}{10{\rm MeV}}\right)^{1/3}\left(\frac{m_c}{\rm TeV}\right)^{7/9}$

Cannibalism's Lingering Impact

ALE, **Pranjal Raleganakar**, Jessie Shelton 2022

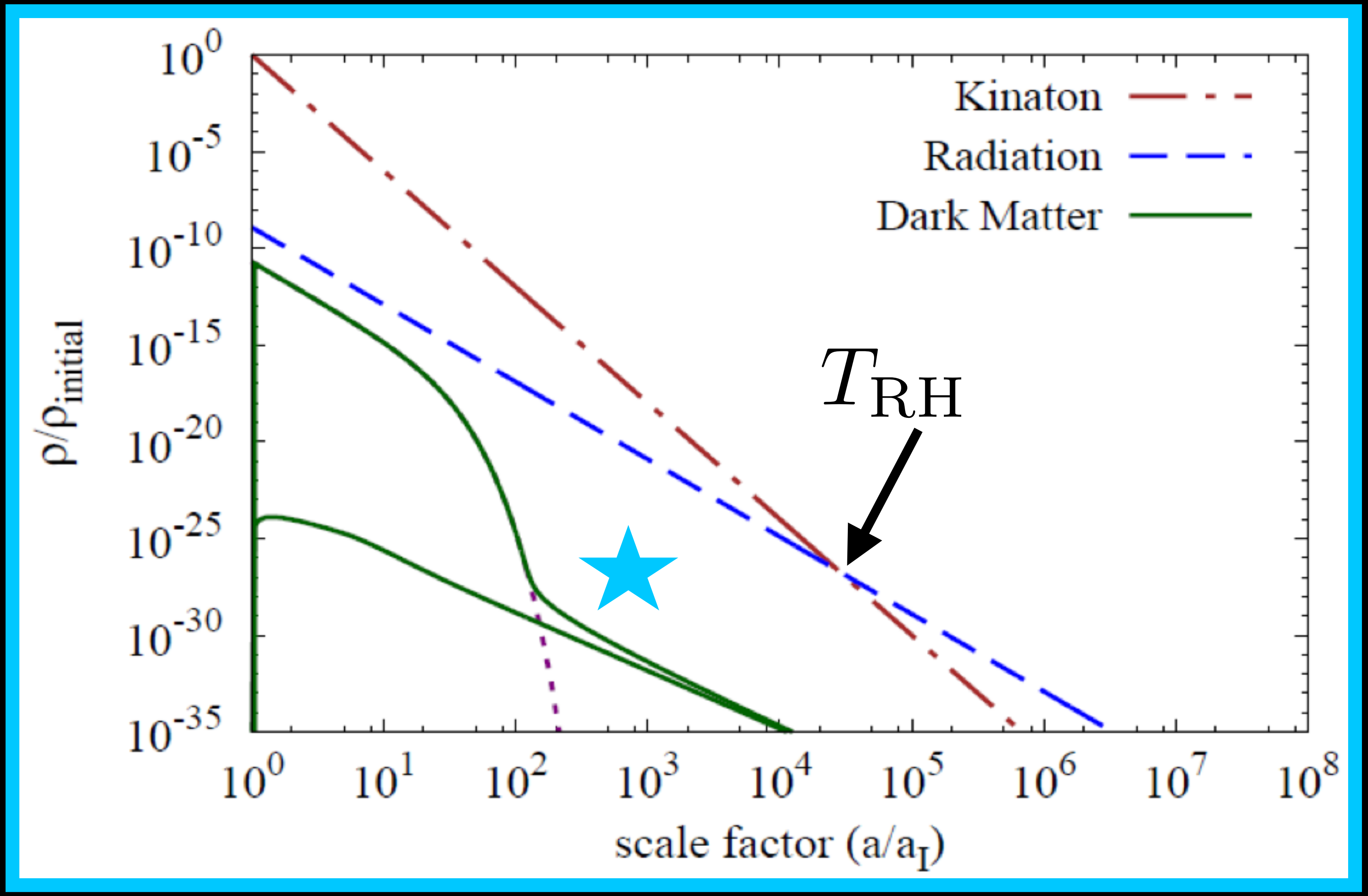
If cannibal interactions freeze-out before the cannibal field becomes dominant, cannibalism still sets the minimum halo mass!



- The cannibal sound horizon roughly sets the scale of the peak in the power spectrum.
- We can connect the mass and density of smallest microhalos to cannibal properties.

Constraints on Dark Matter Production During Kination

DM Production During Kination



Kayla Redmond, ALE 2017

★ Relentless annihilation:

$$\rho_\chi \propto \frac{1}{a^3 \ln(a/a_f)}$$

See also D'Eramo et al. 2017

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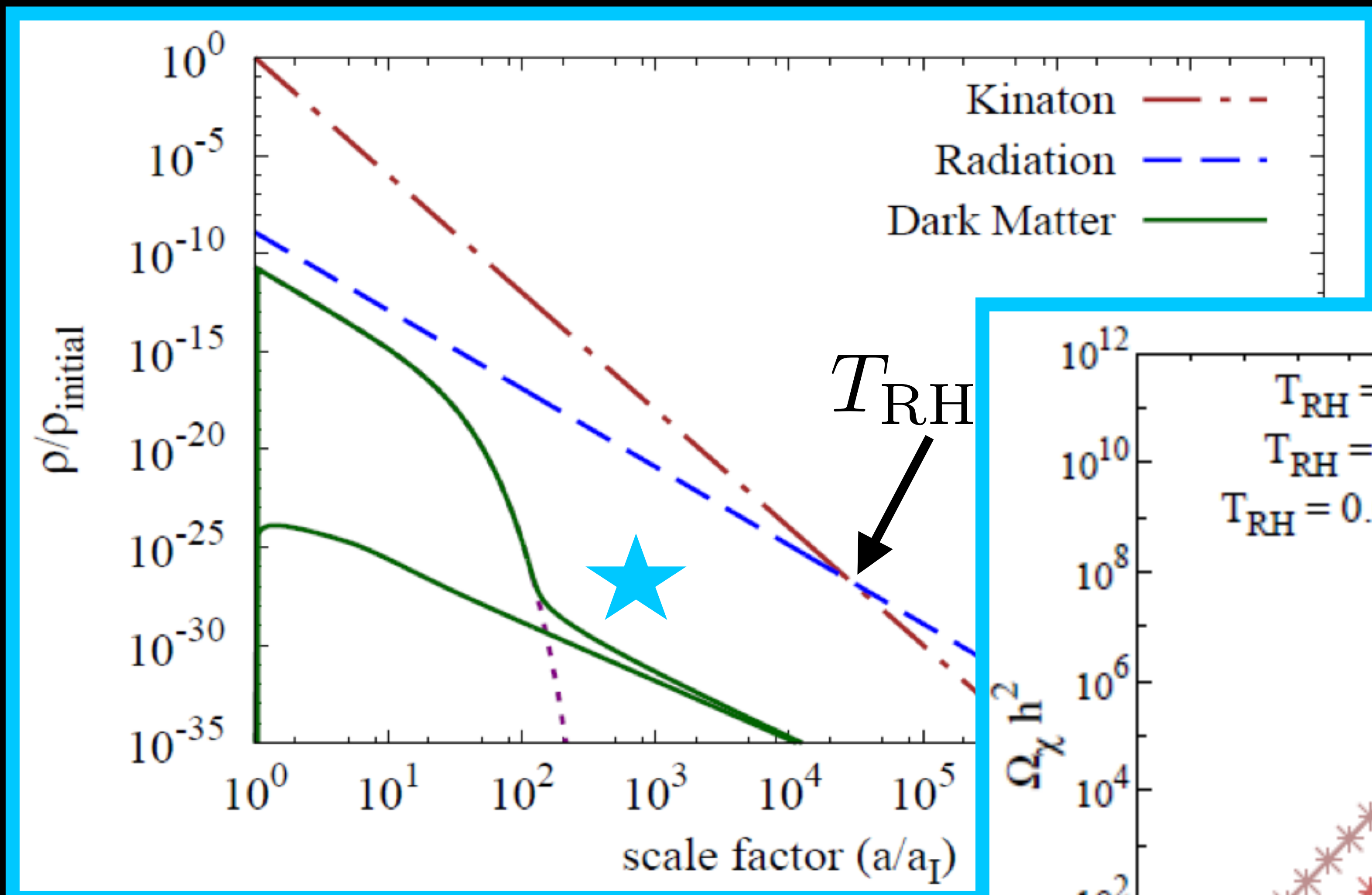
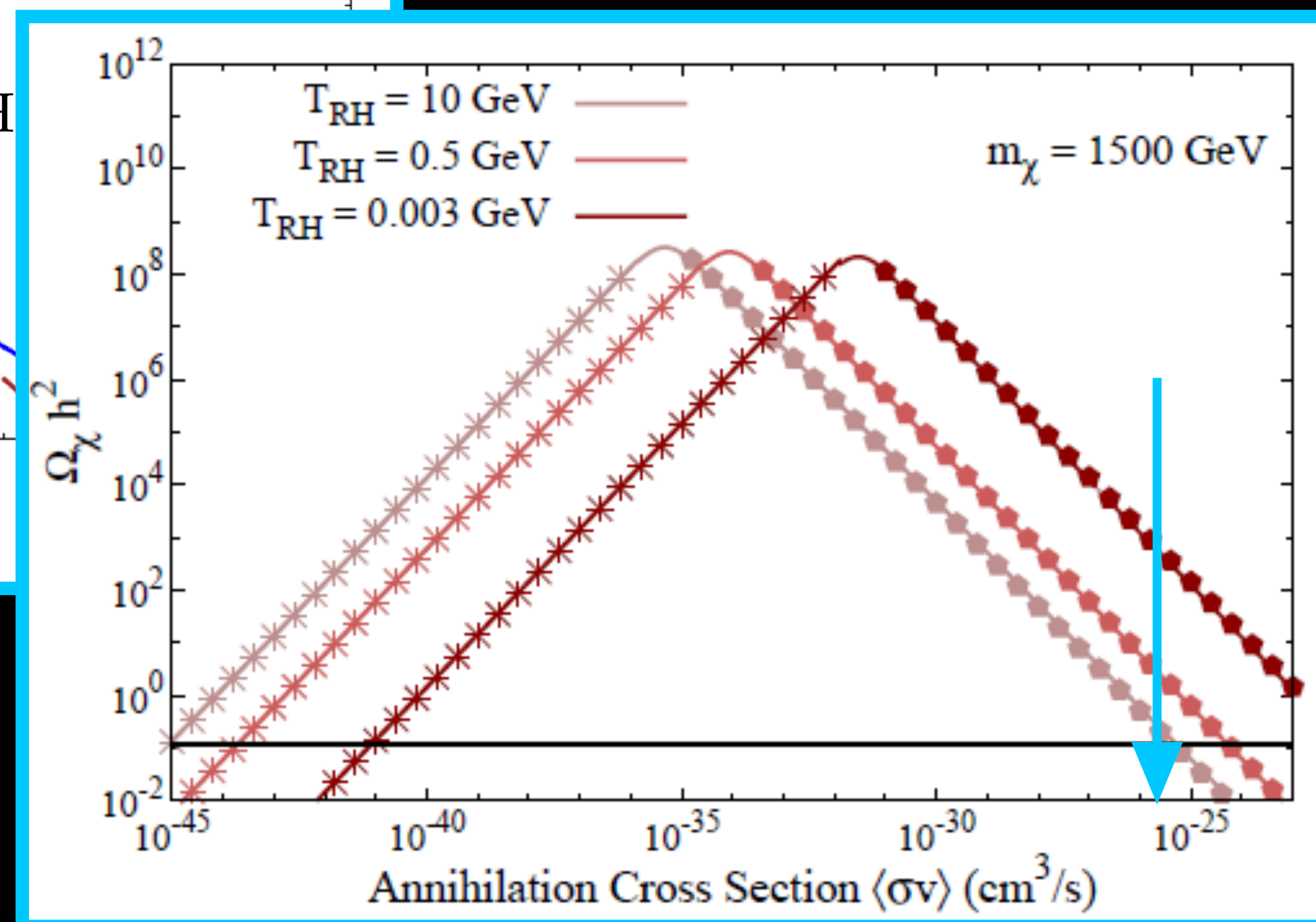
Kayla Redmond, ALE 2017





★ Relentless annihilation:

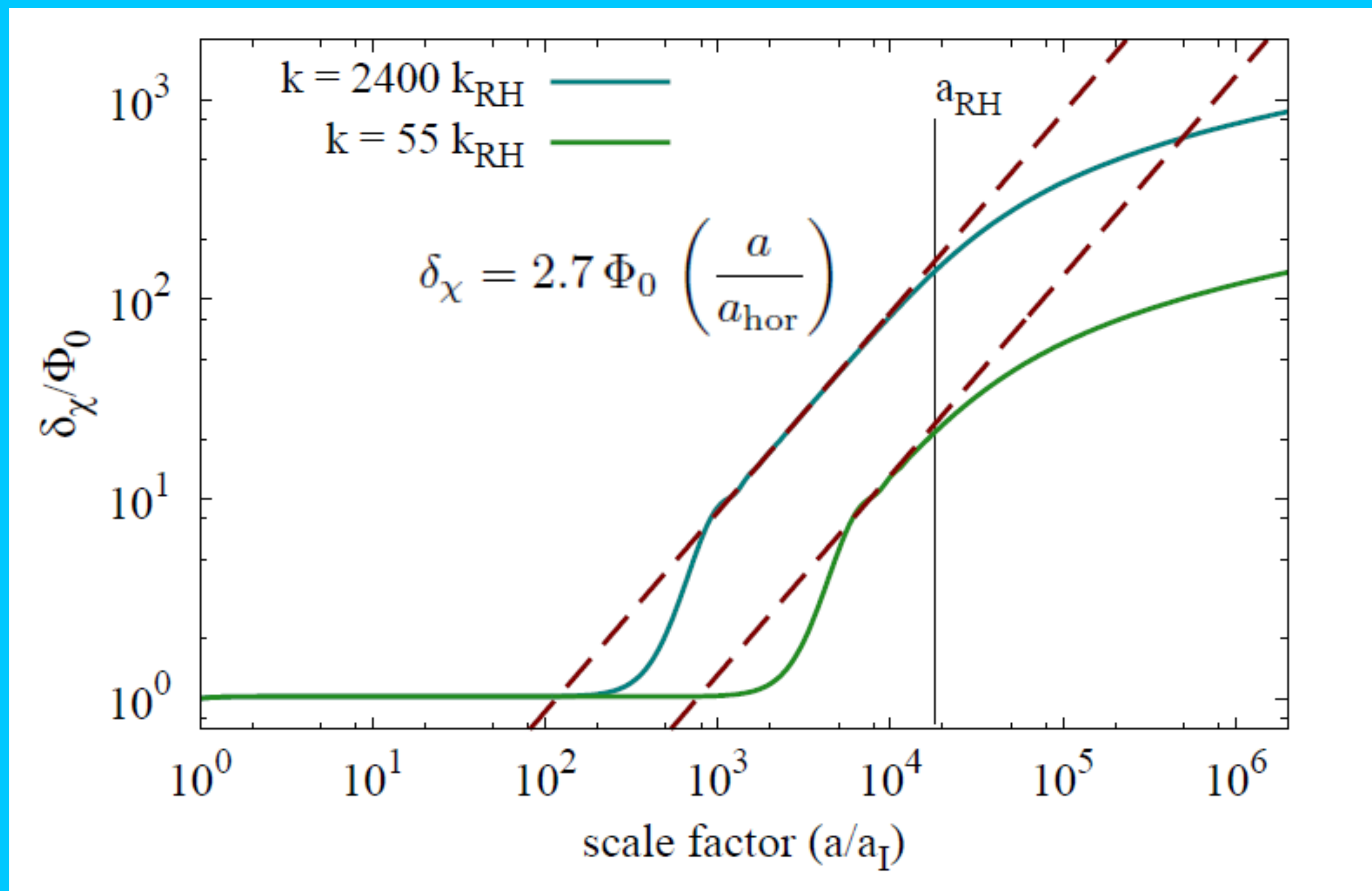
$$\rho_\chi \propto \frac{1}{a^3 \ln(a/a_f)}$$

See also D'Eramo et al. 2017

- faster expansion rate *H(T)* during kination implies earlier freeze-out
- larger annihilation cross section needed to match observed abundance

Perturbation Growth during Kination

Kayla Redmond, Anthony Trezza, ALE 2018



Dark matter density fluctuations grow linearly during kination, just like during matter domination!

But the growth isn't gravitational…

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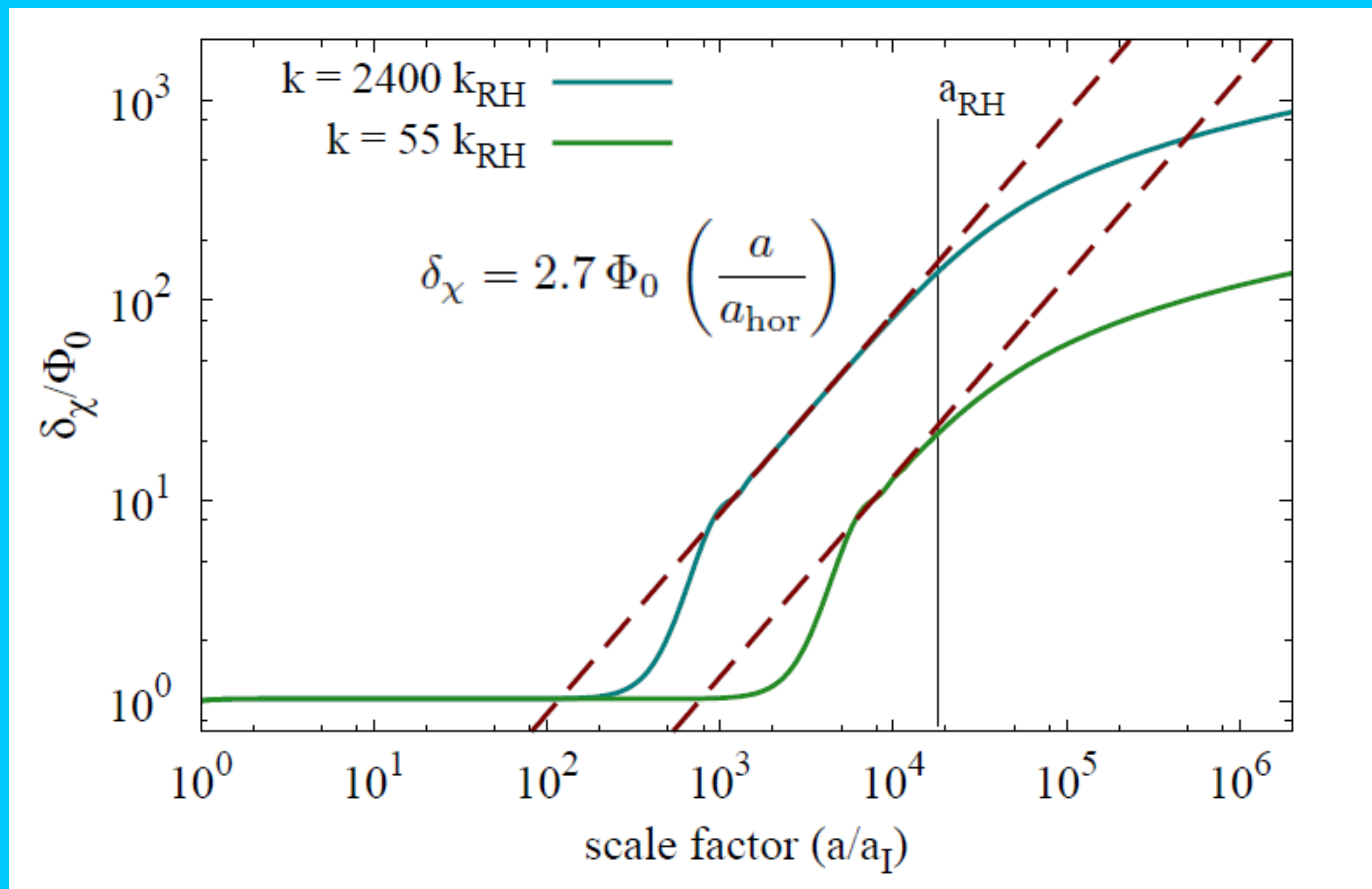

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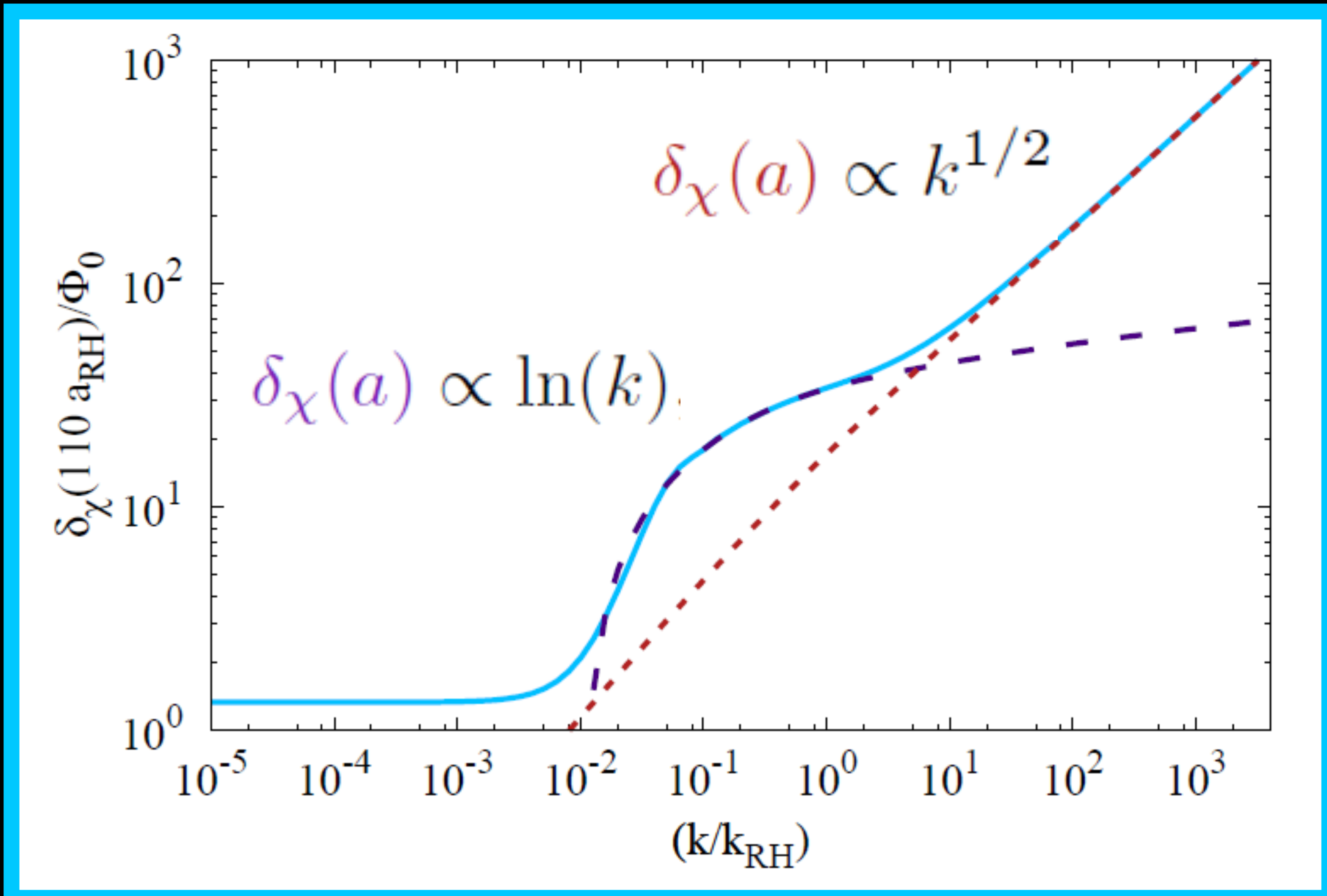
Comoving drift: $s = \int v \frac{dt}{a} \propto \int \frac{da}{a^3 H} \propto \begin{cases} a & \text{Kination} \\ \ln a & \text{Radiation Domination} \end{cases}$

Impact on the Matter Power Spectrum



M. Sten Delos, Kayla Redmond, ALE 2023

Kination enhances small-scale density perturbations,

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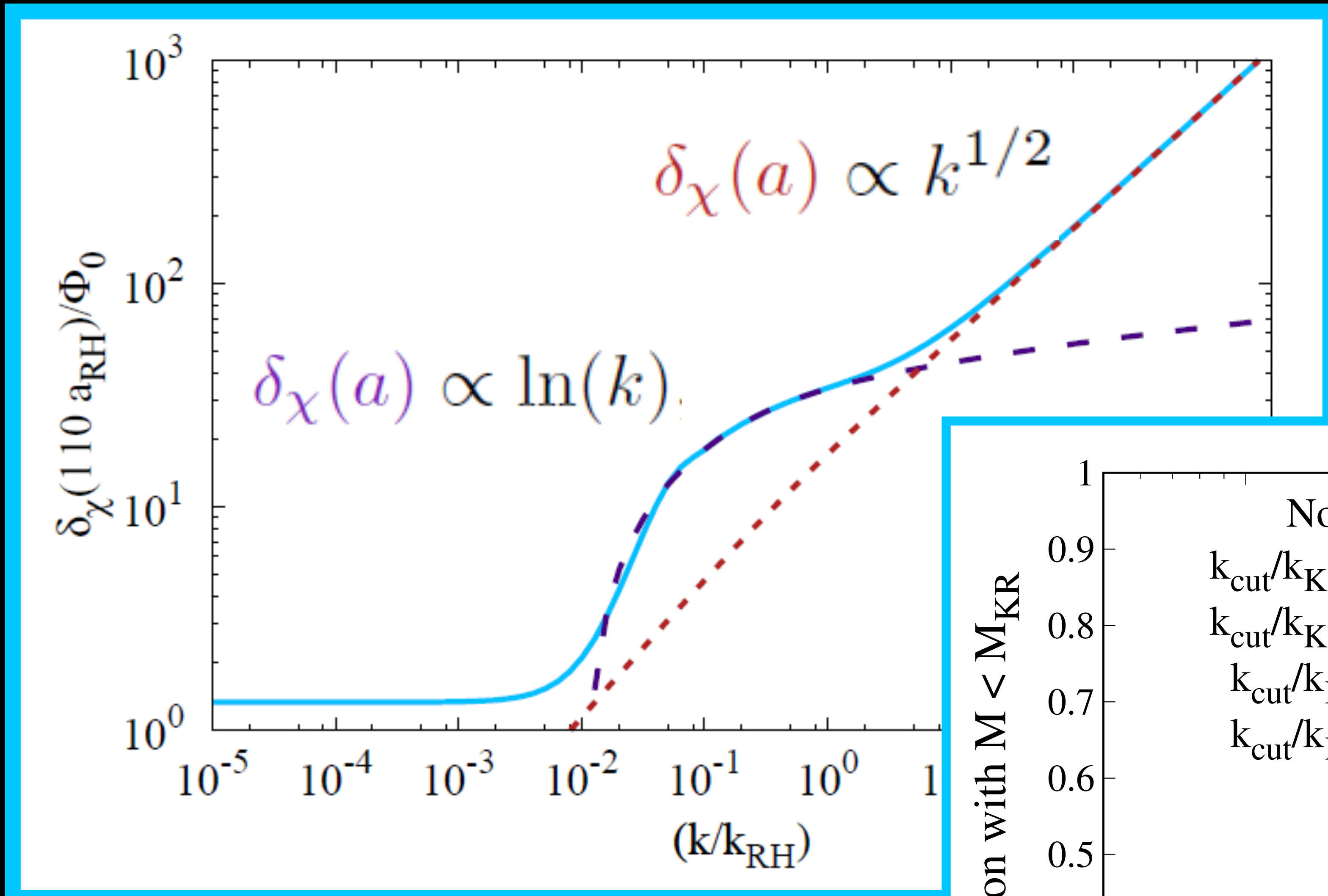

M. Sten Delos, Kayla Redmond, ALE 2023

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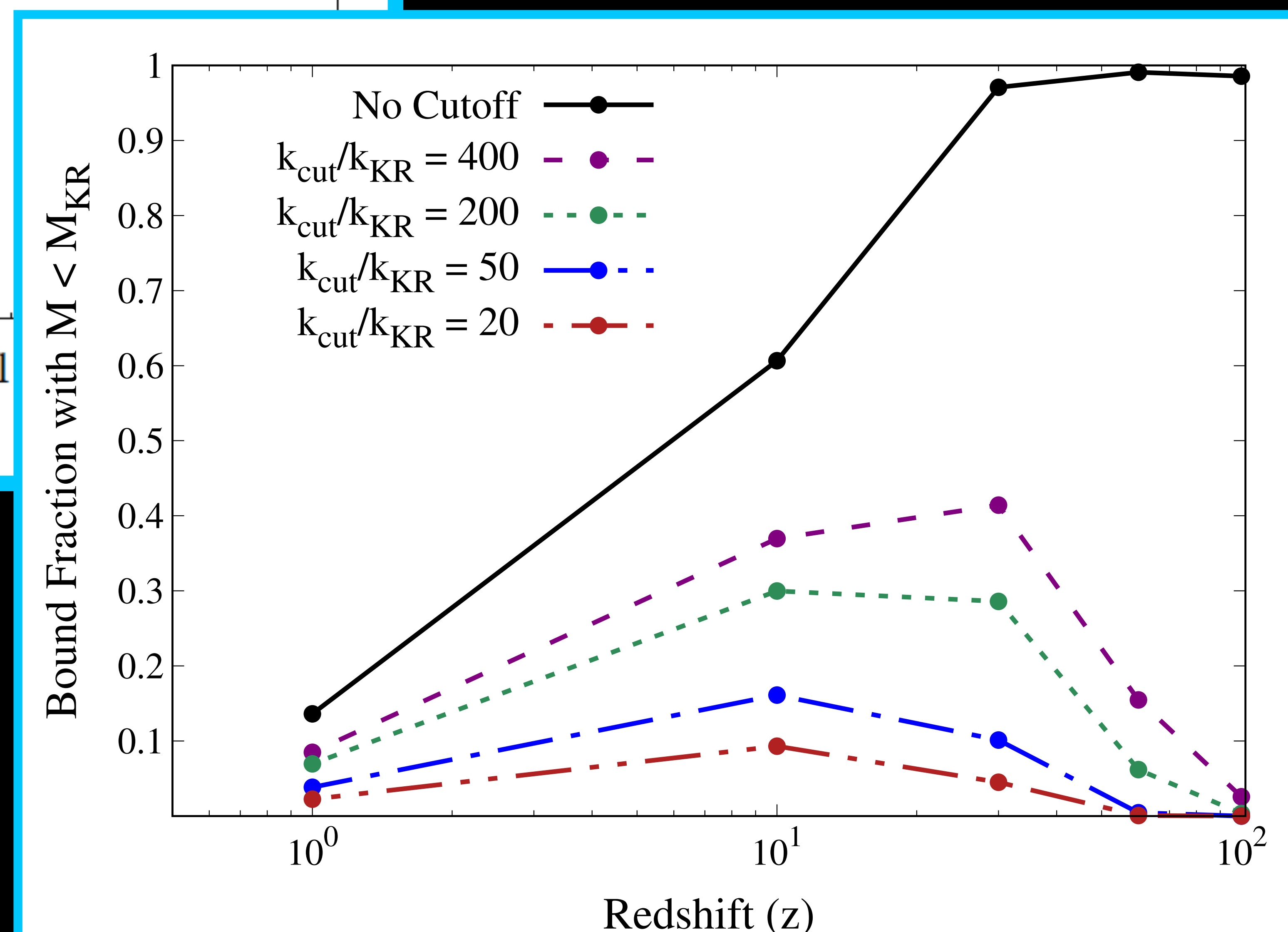
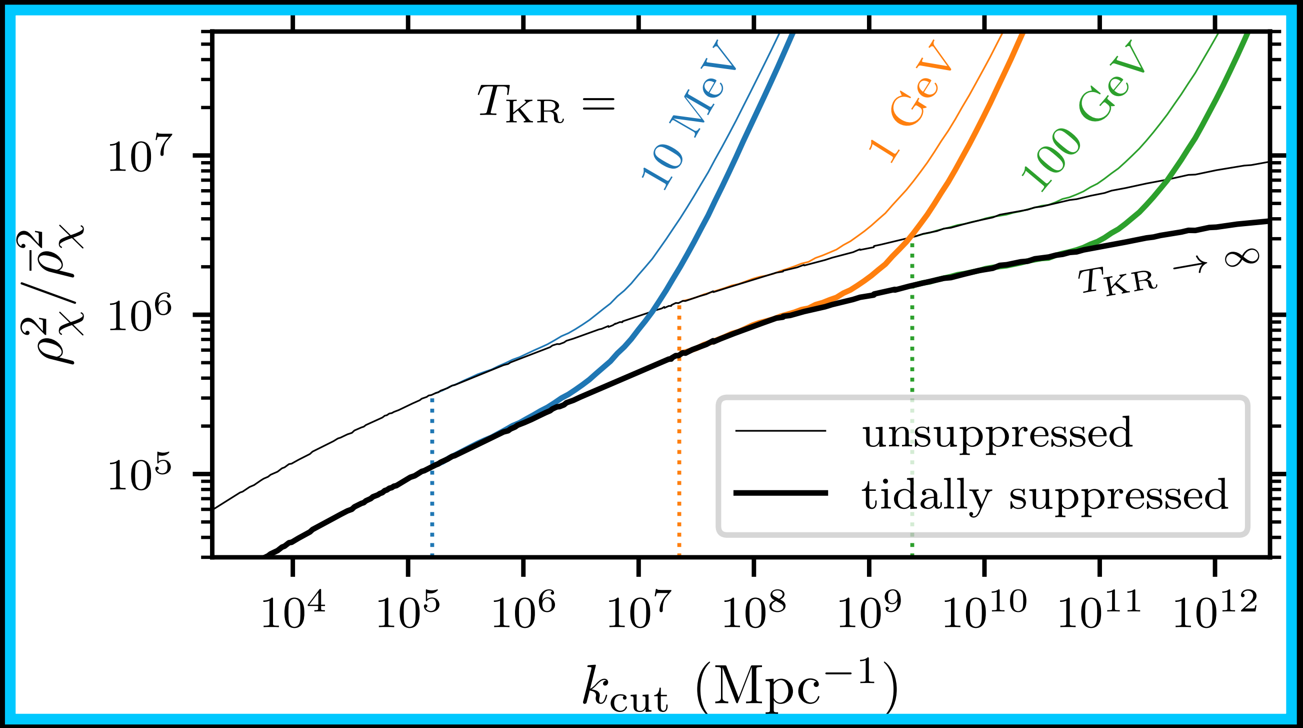


which leads to increased small-scale inhomogeneity and more microhalos.

Constraining Kination



M. Sten Delos, Kayla Redmond, ALE 2023

- P2H method gives boost due to kination.
- Significant boosts require $k_{\rm cut} \gtrsim 20 k_{\rm KR}$
- If DM decouples from SM, these scenarios have the largest annihilation cross sections.

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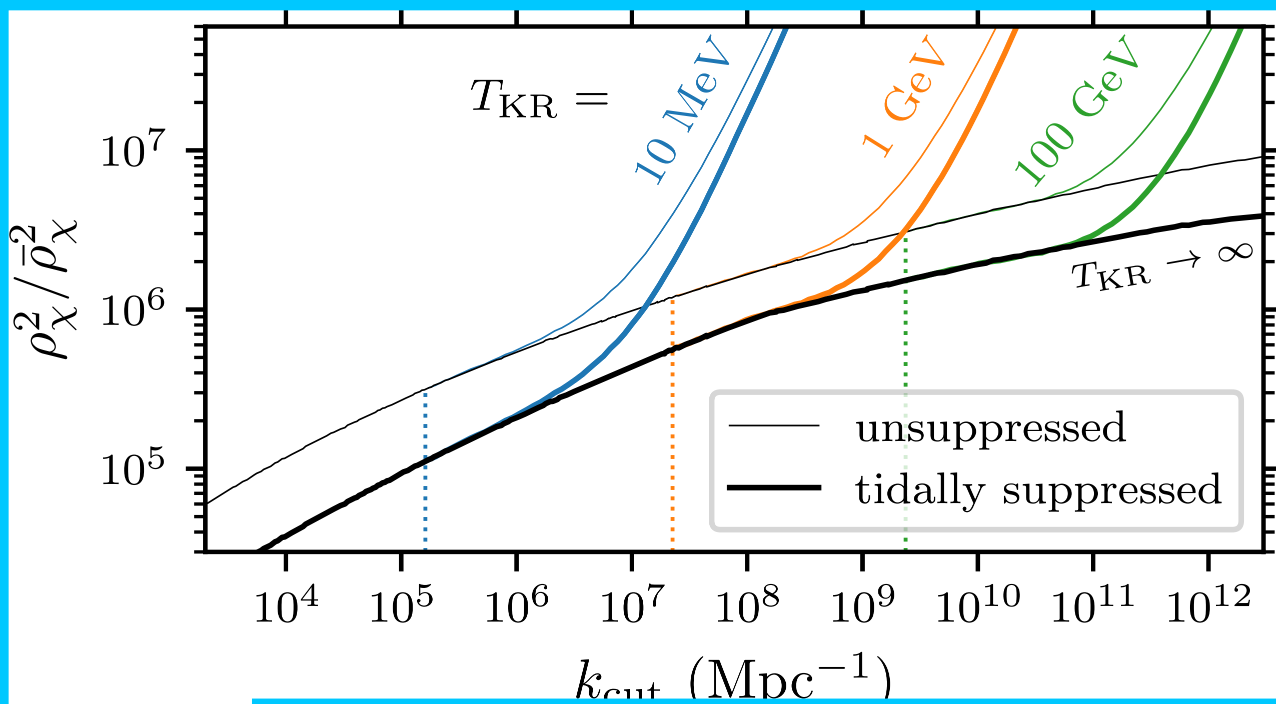

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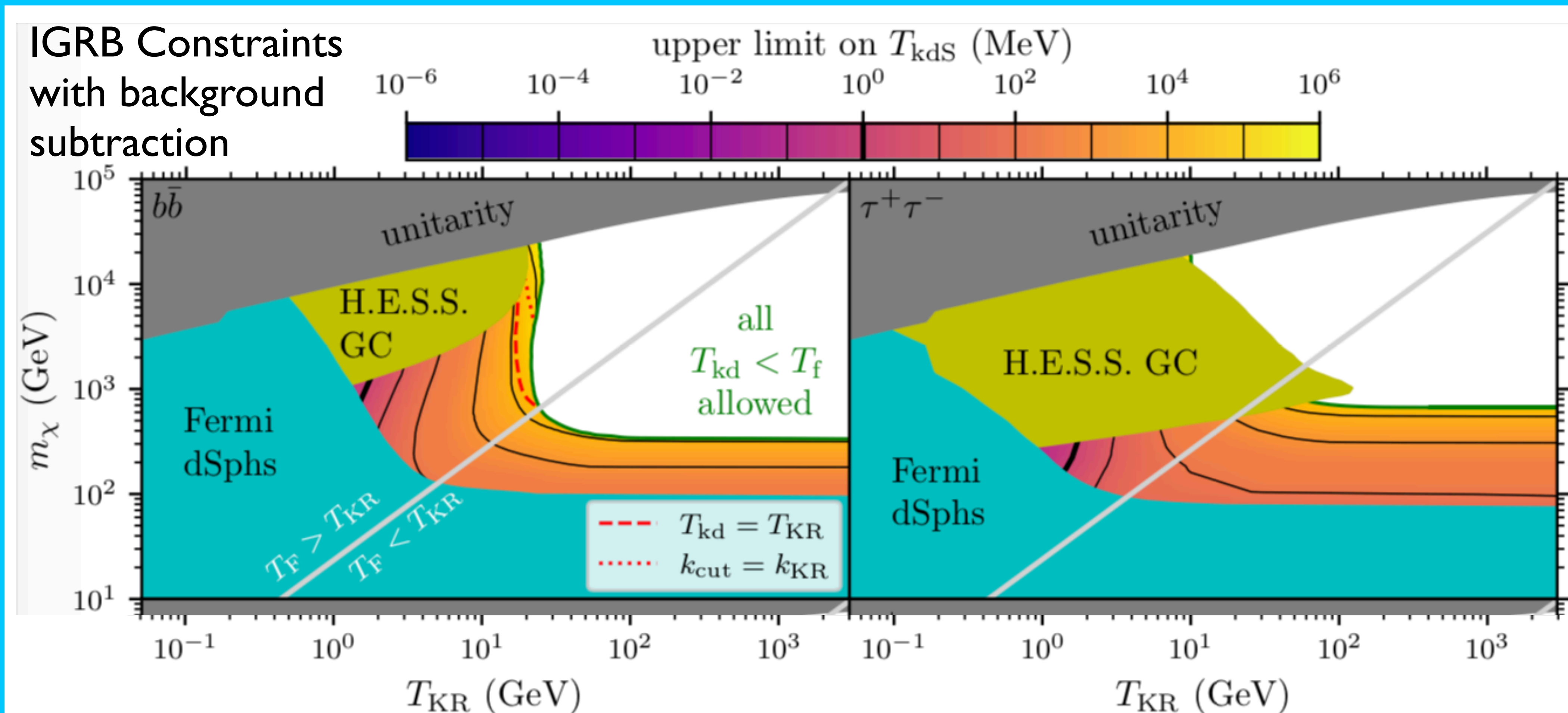
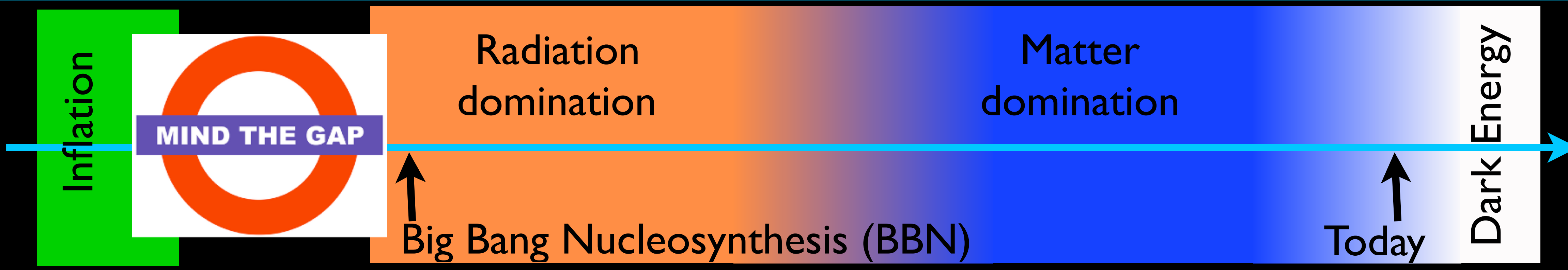


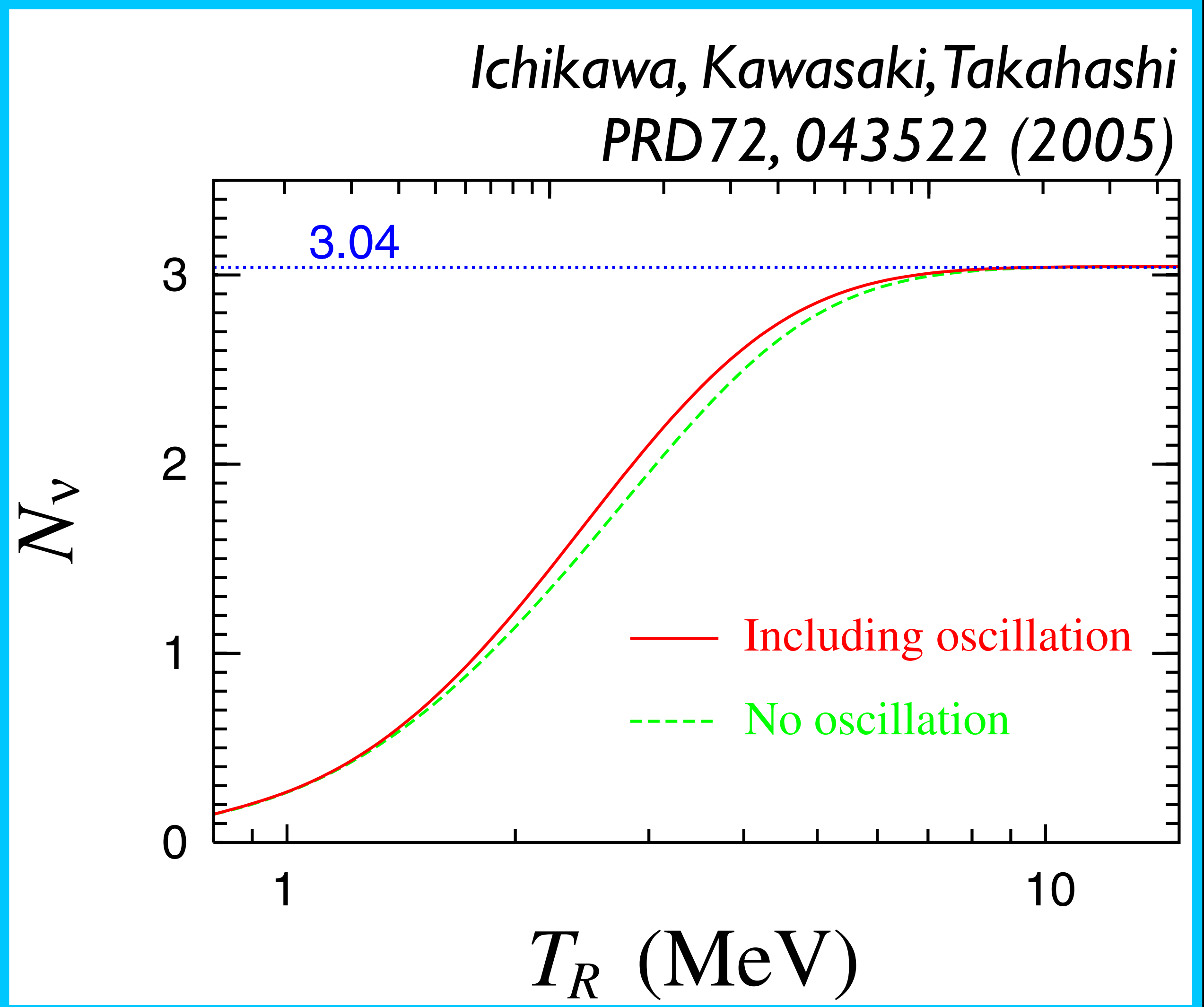
Unlocking the Clues in Microhalos

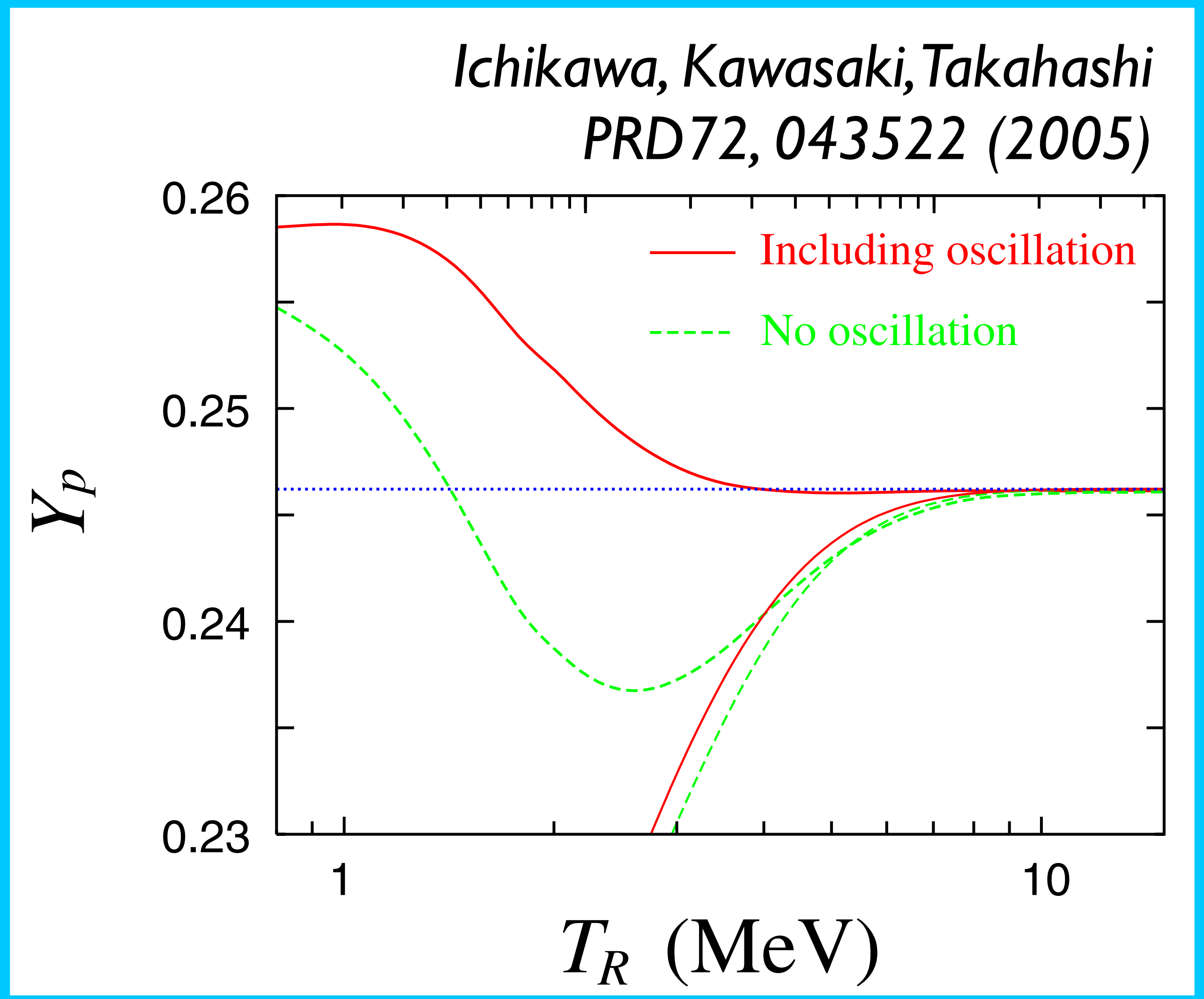


- There is a gap in the cosmological record between inflation and neutrino decoupling: $10^{15}\ \mathrm{GeV} \gtrsim T \gtrsim 10^{-3}\ \mathrm{GeV}$
- Dark matter is likely produced in this gap!
- An early matter-dominated era (EMDE) and a period of kination both enhance the abundance of dark matter microhalos.
- We can use CMB, 21cm, and gamma-ray observations to probe the evolution of the early Universe and narrow the field of thermal relics.
- Signal depends strongly on cut-off scale, which is another window into the dark sector.

Don't Mess with BBN

Reheat Temperature = Temperature at Radiation Domination





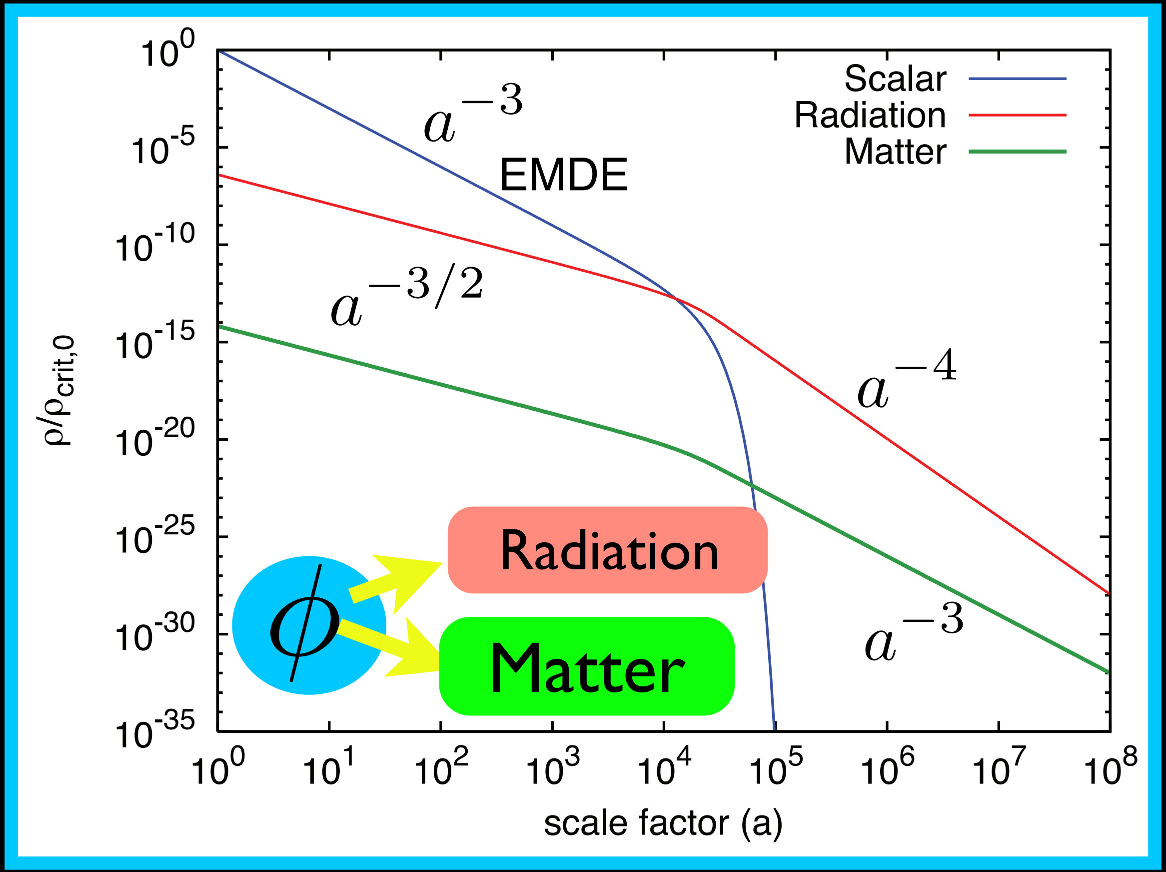
Lowering the reheat temperature results in fewer neutrinos.

- 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

Alternate Thermal Histories



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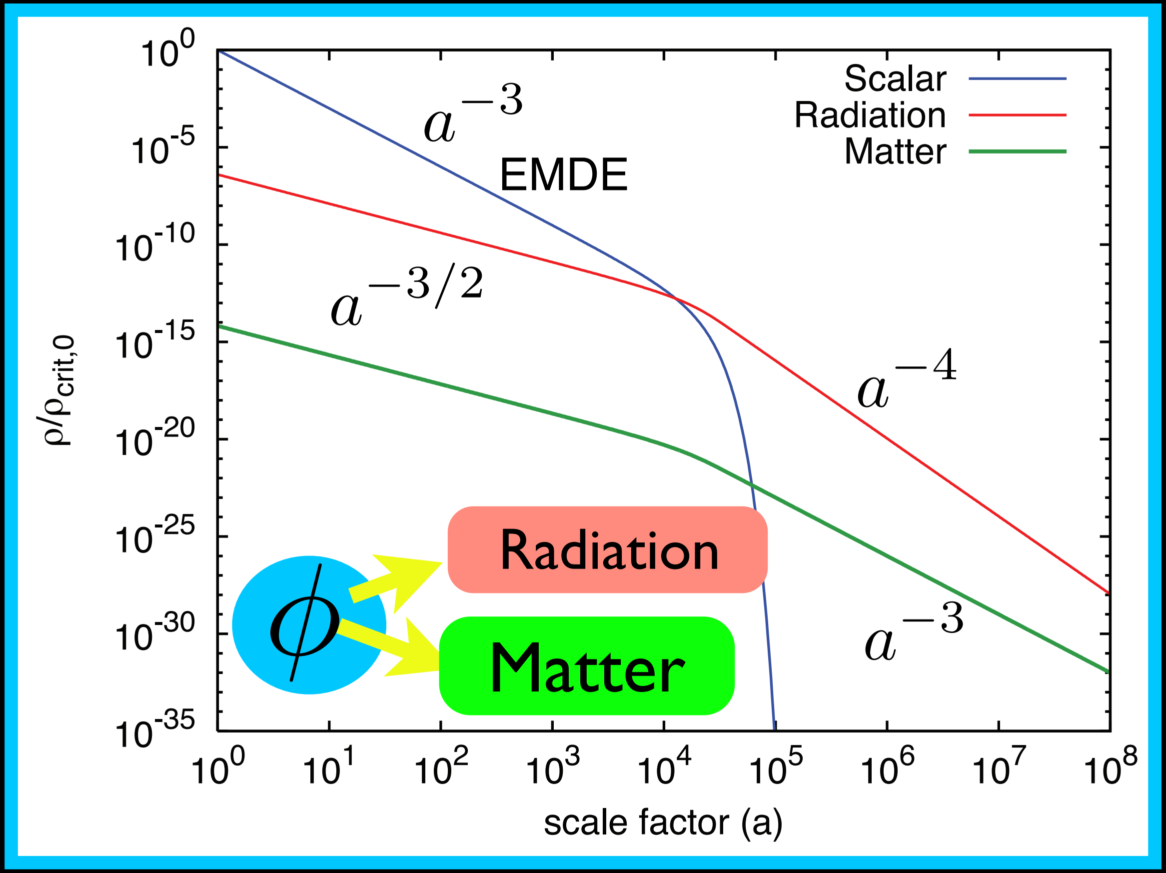

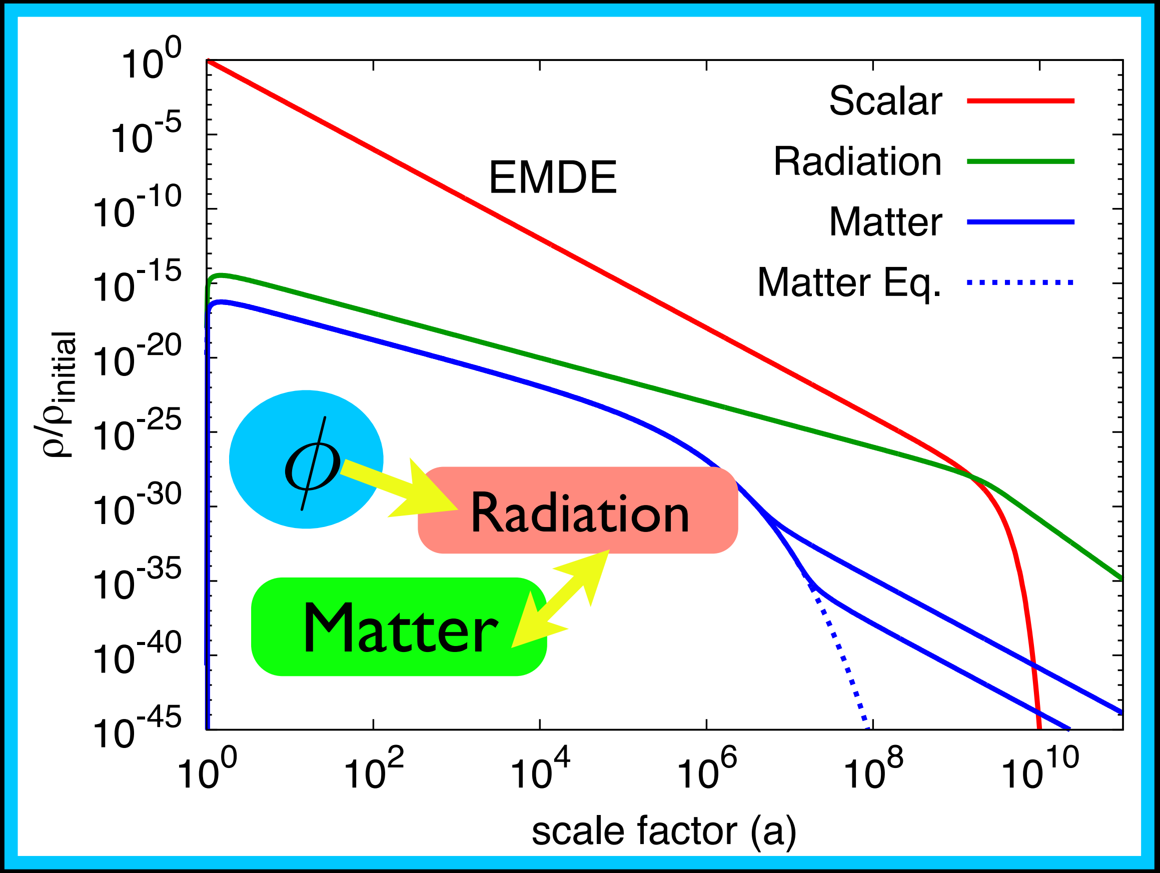

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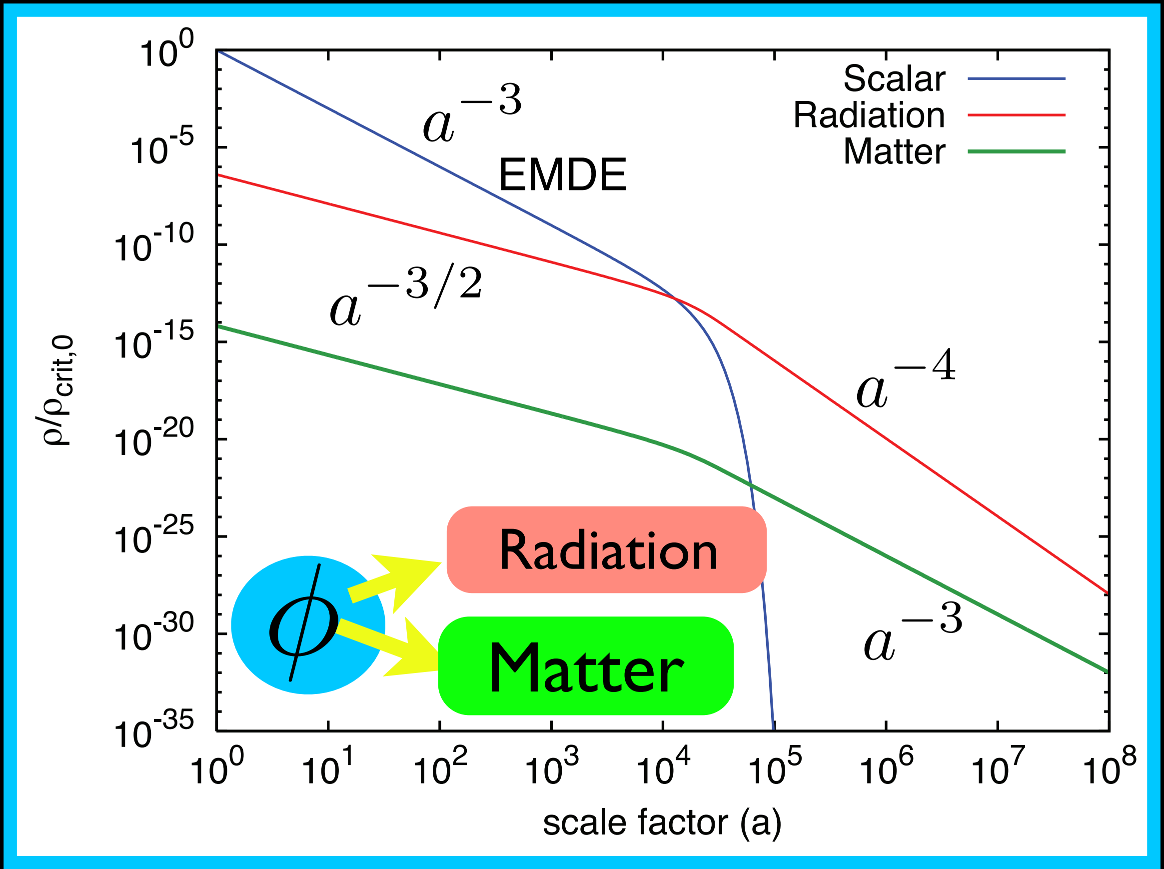
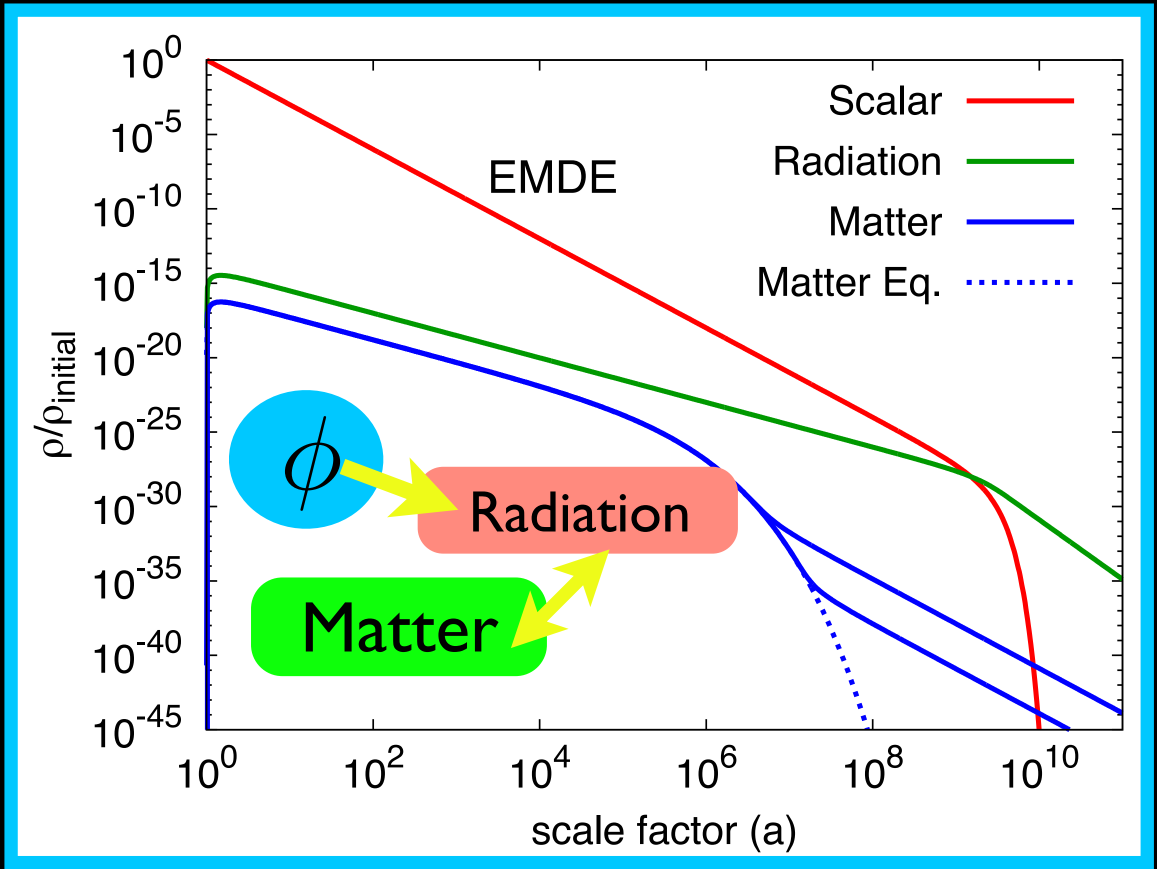
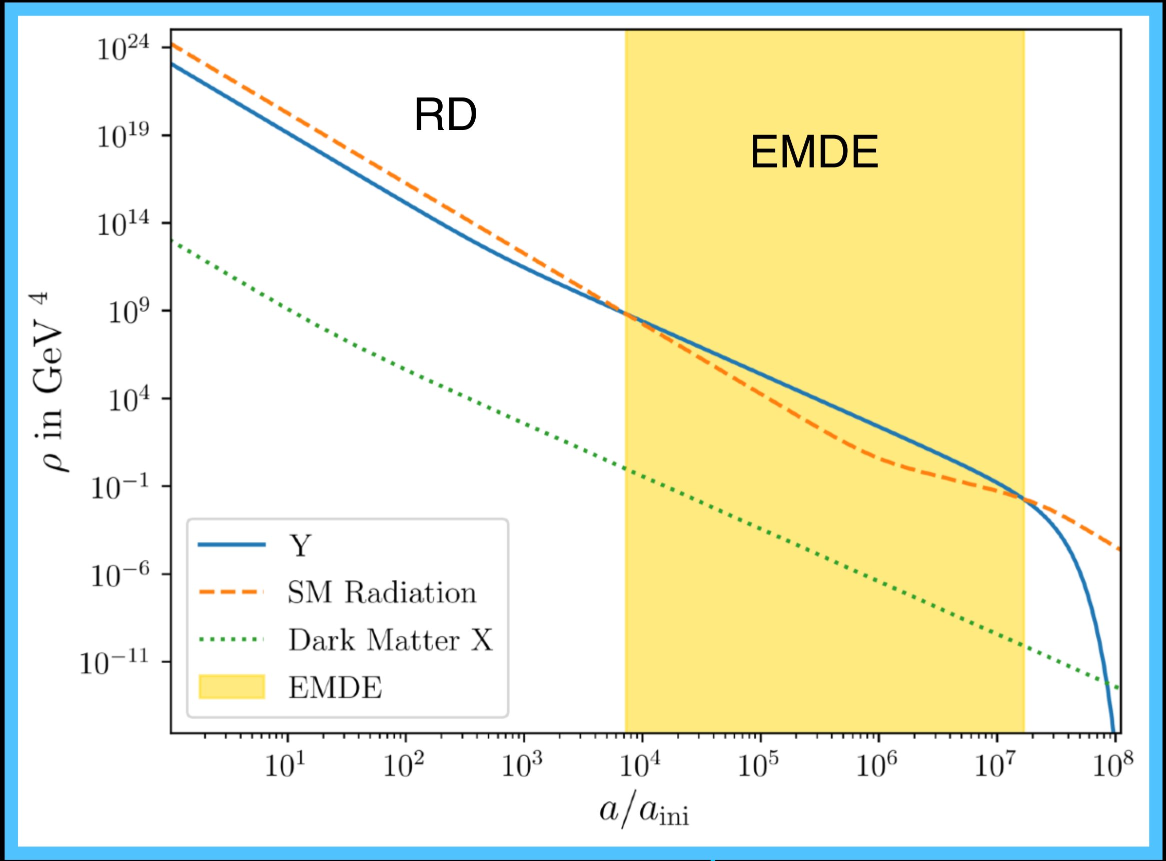




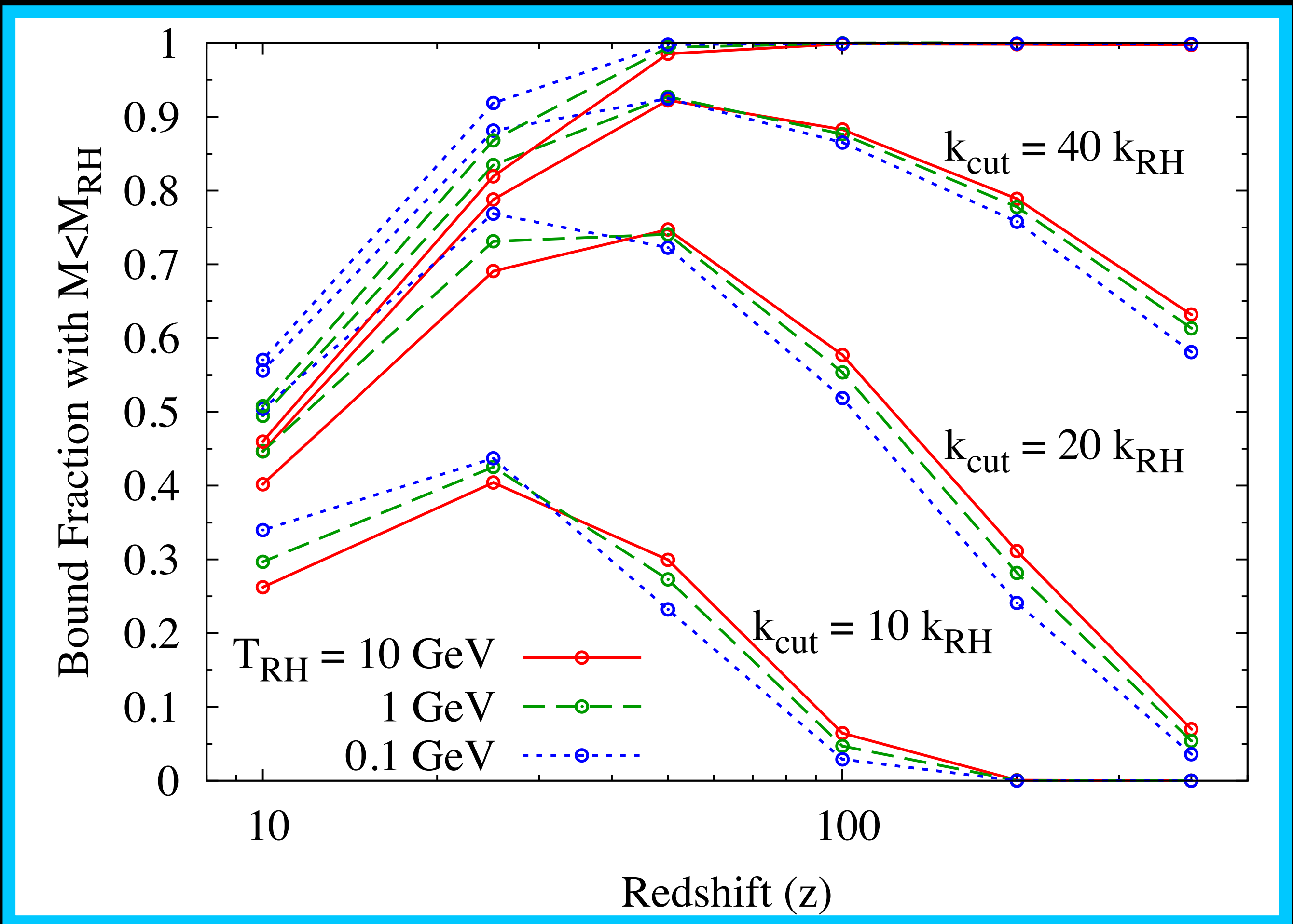


Estimating the Boost Factor

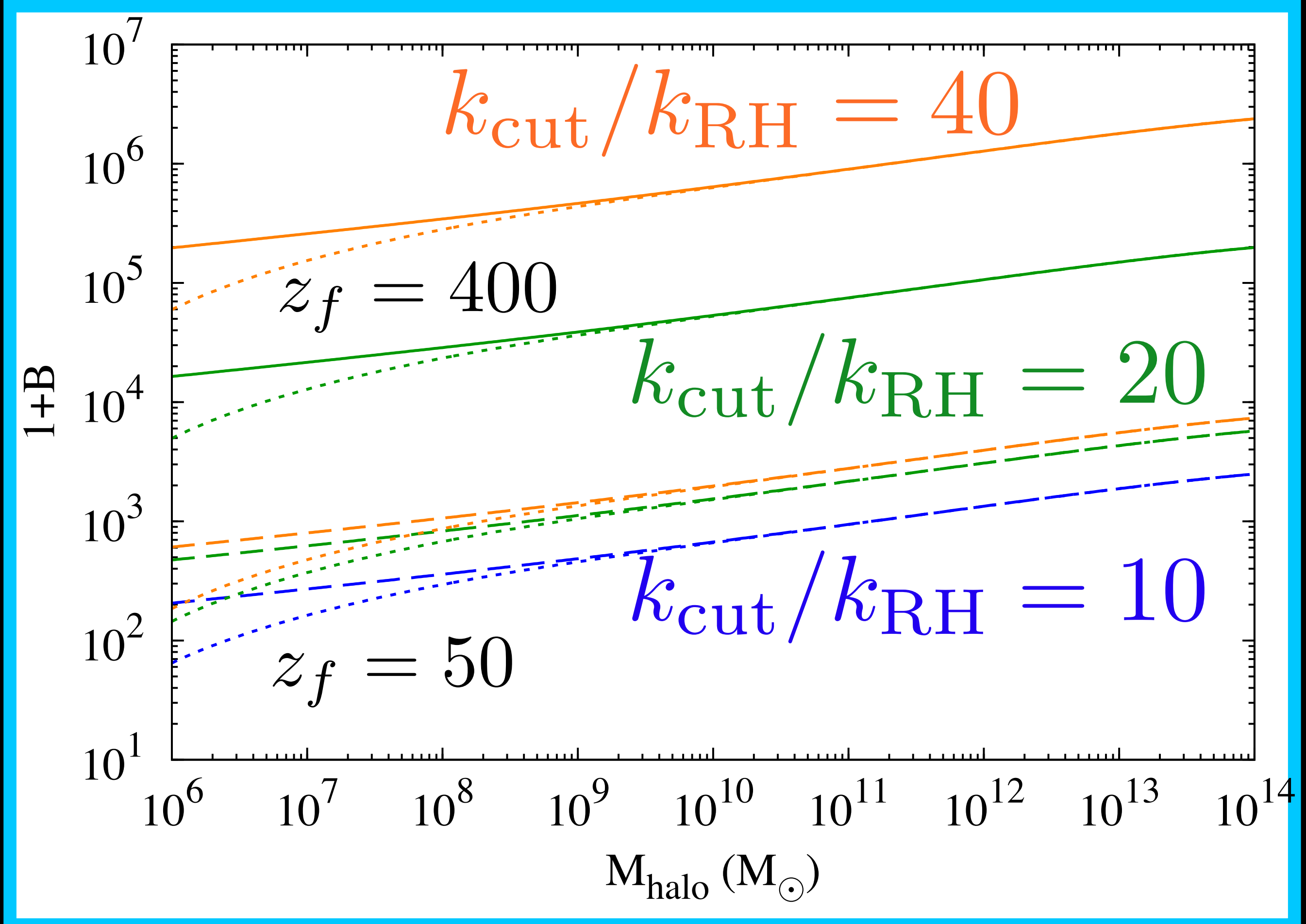
Dark matter annihilation rate: $\Gamma = \frac{\langle \sigma v \rangle}{2m_\chi^2} \int \rho^2(r) d^3r \equiv \frac{\langle \sigma v \rangle}{2m_\chi^2} J$

Boost Factor assuming that microhalos forming at z_f survive:

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



ALE 2015



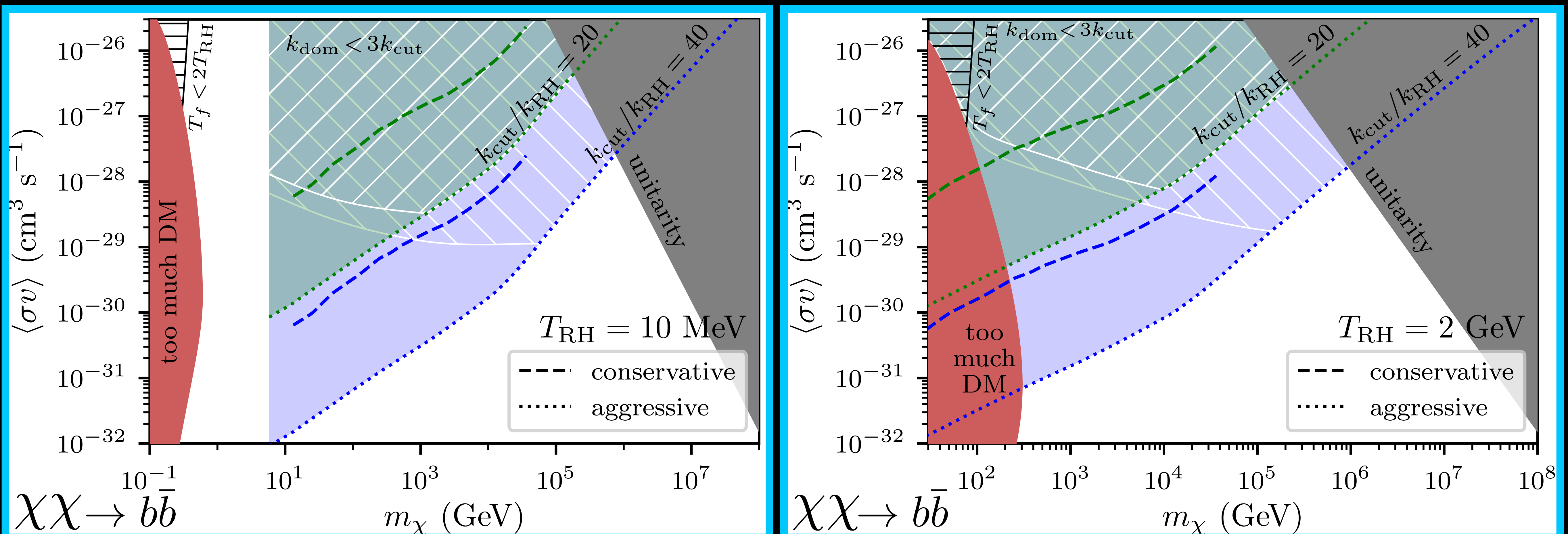
Boost from Microhalos

Observational Constraints

Sten Delos, Tim Linden, ALE 2019

The isotropic gamma-ray background significantly restricts the field of viable thermal relics.

- Constraints use microhalo population predicted by Delos, Bruff, ALE 2019
- Constraints depend on $k_{\rm cut}/k_{\rm RH}$: larger means more dense microhalos
- Constraints are tentative for short EMDEs ($k_{\rm dom} < 3k_{\rm cut}$)



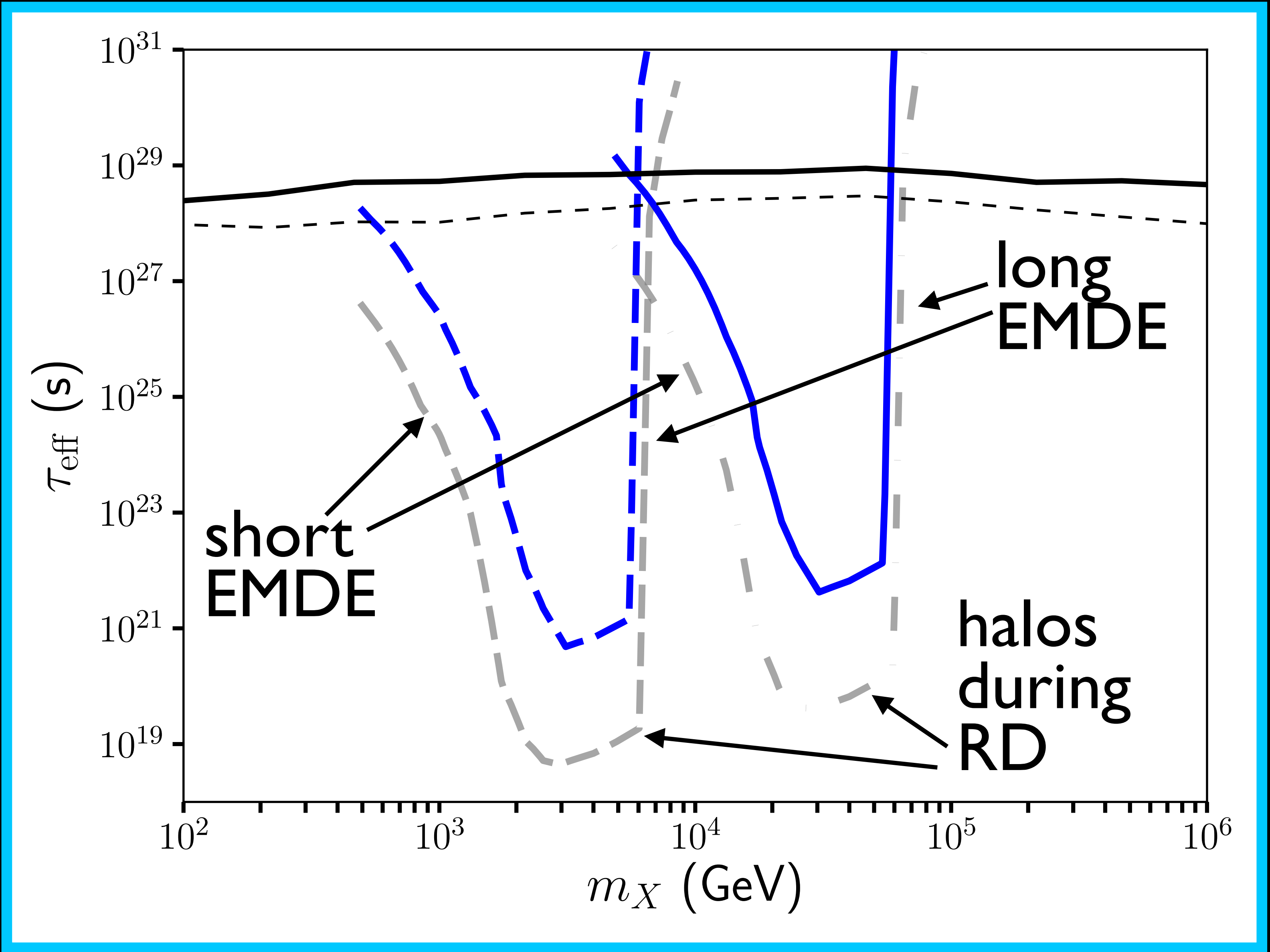
DM Annihilation within Microhalos

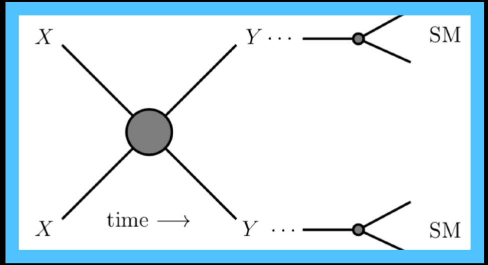
Dark matter annihilation within early-forming microhalos dominates all other emission, mimicking the signal of decaying dark matter.

- Annihilation rate per DM mass is set by the density within the first halos and is constant in time and space.
- Can translate into an effective decay rate:

$$\tau_{\rm eff} = \frac{1}{2m_\chi(\Gamma/M_\chi)}$$

- For hidden sector dark matter, the isotropic gamma-ray background provides powerful constraints.





Blanco, Delos, ALE, Hooper 2019

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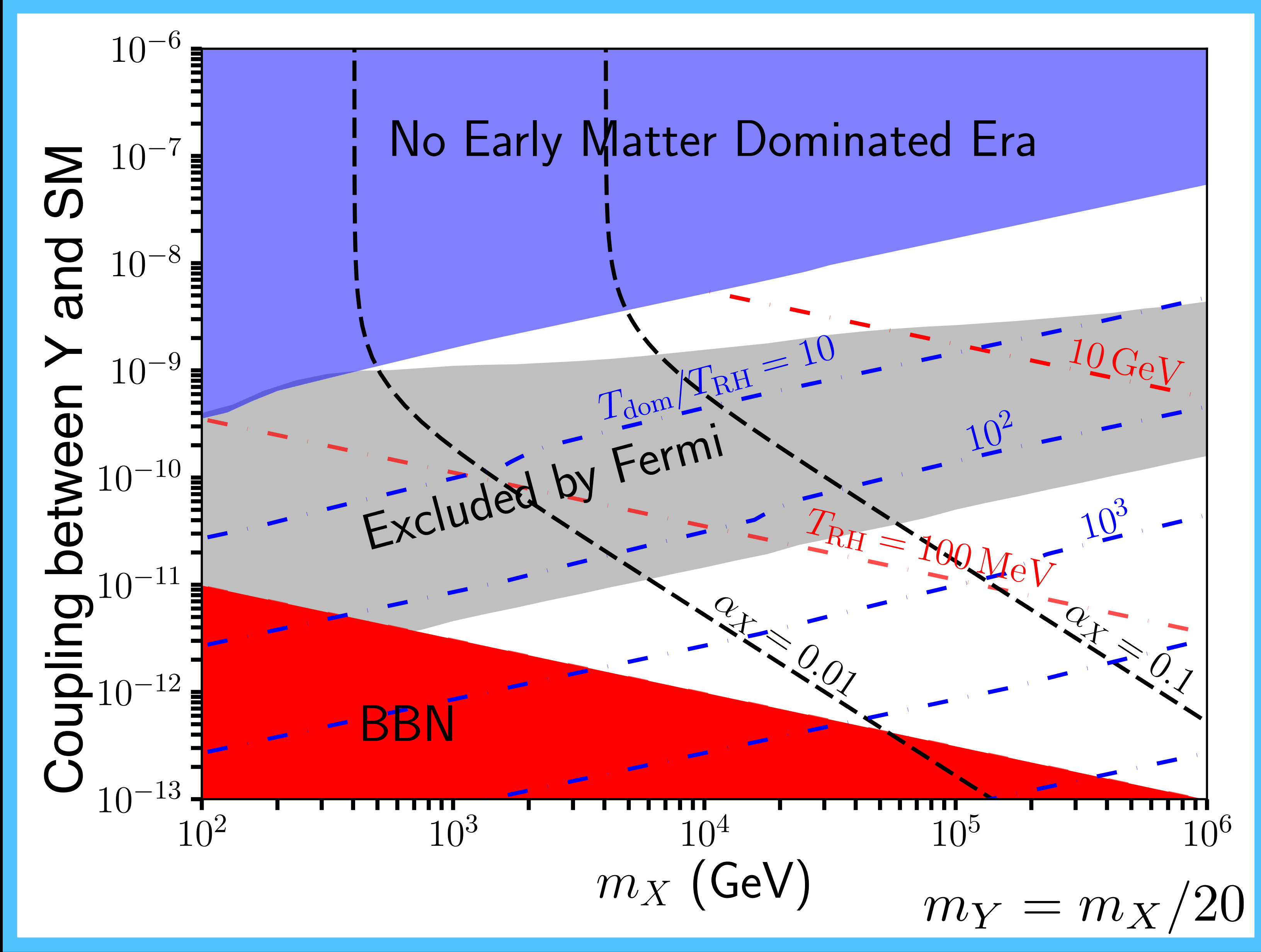

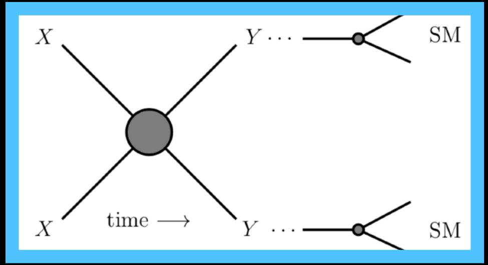

Blanco, Delos, ALE, Hooper 2019

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ALE, ***Pranjal Raleganka****r,*
Jessie Shelton 2022

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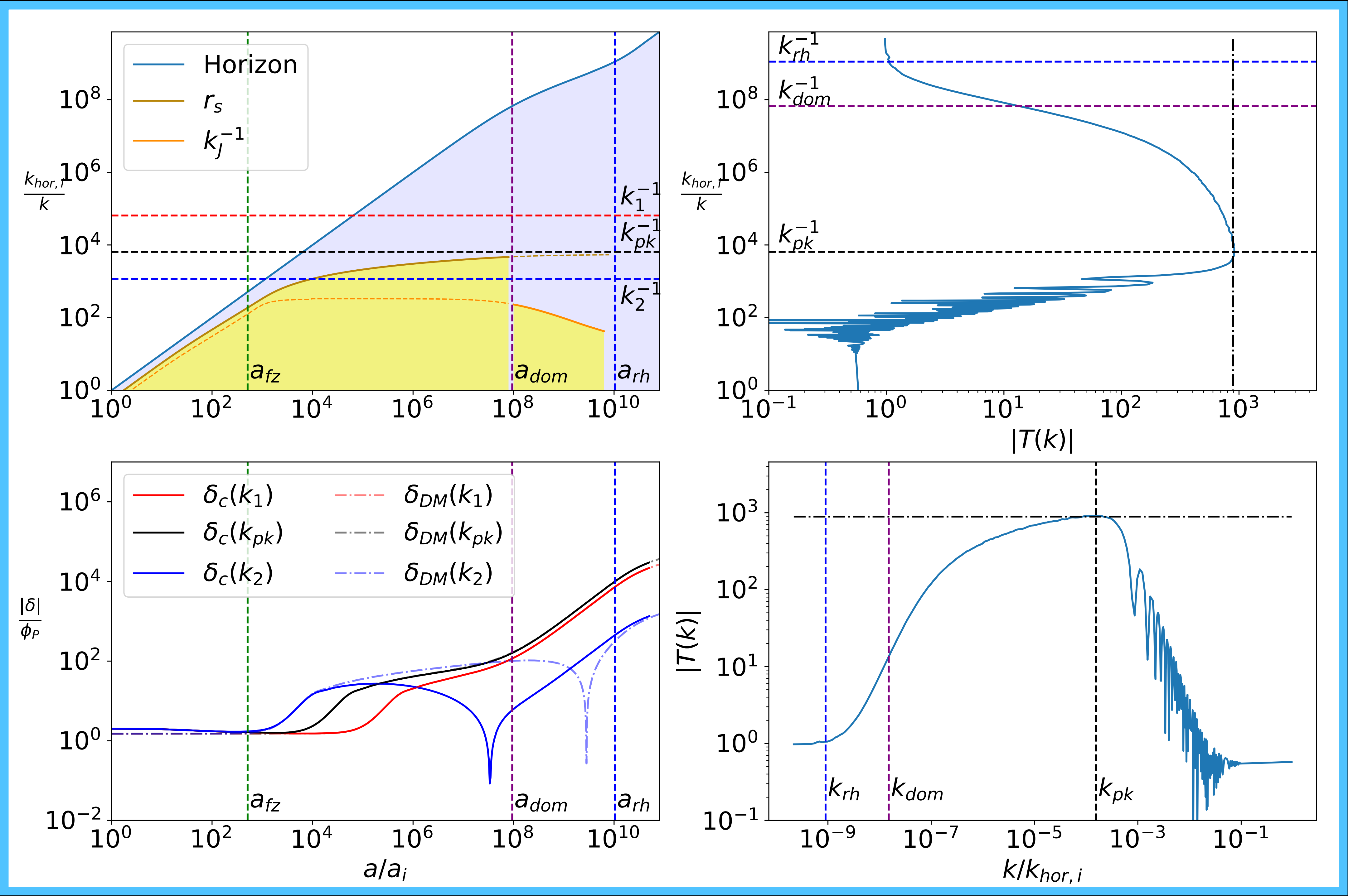
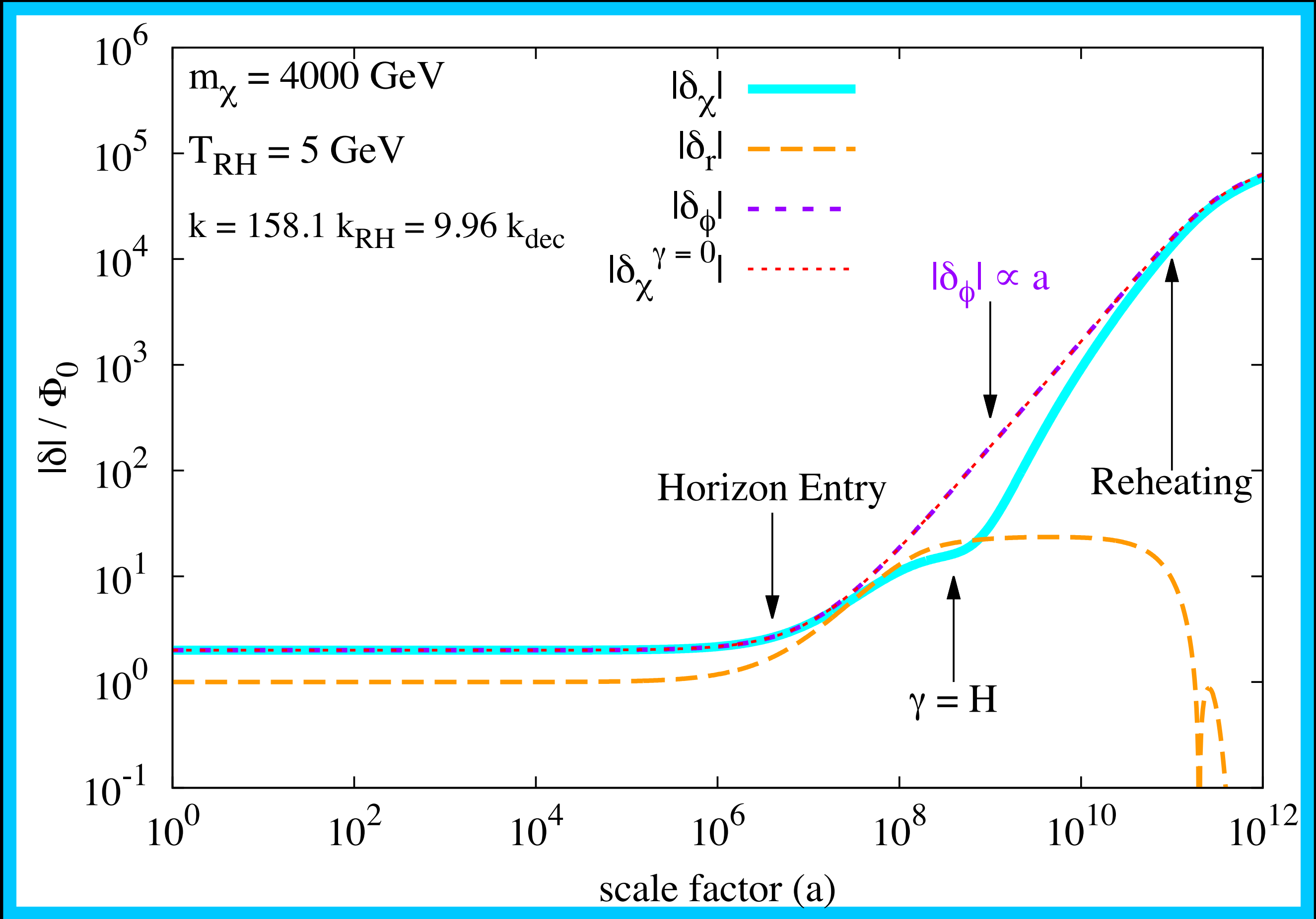


Kinetic Decoupling during an EMDE

__Isaac Waldstein__, ALE, Charlie Mace, 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...

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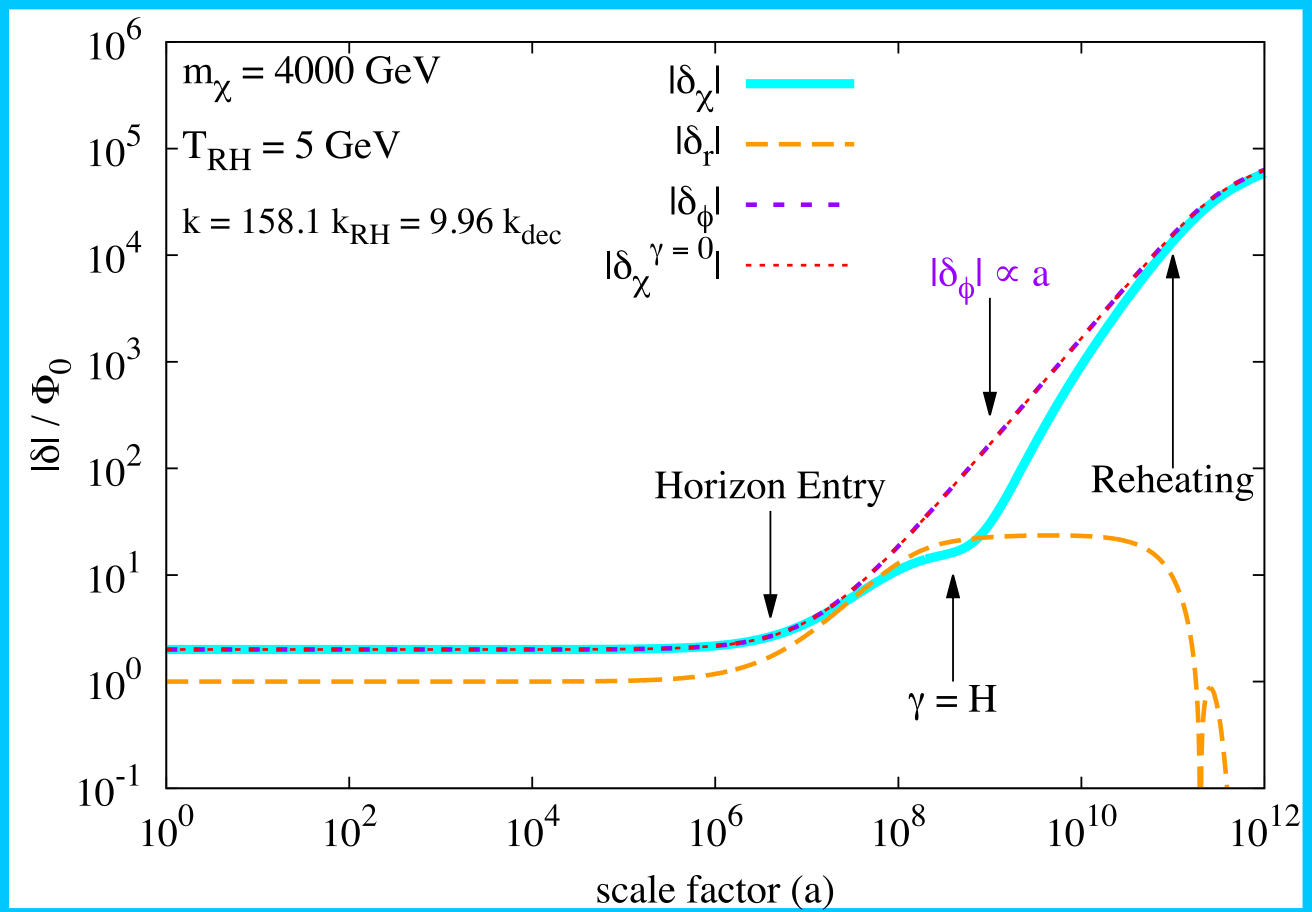

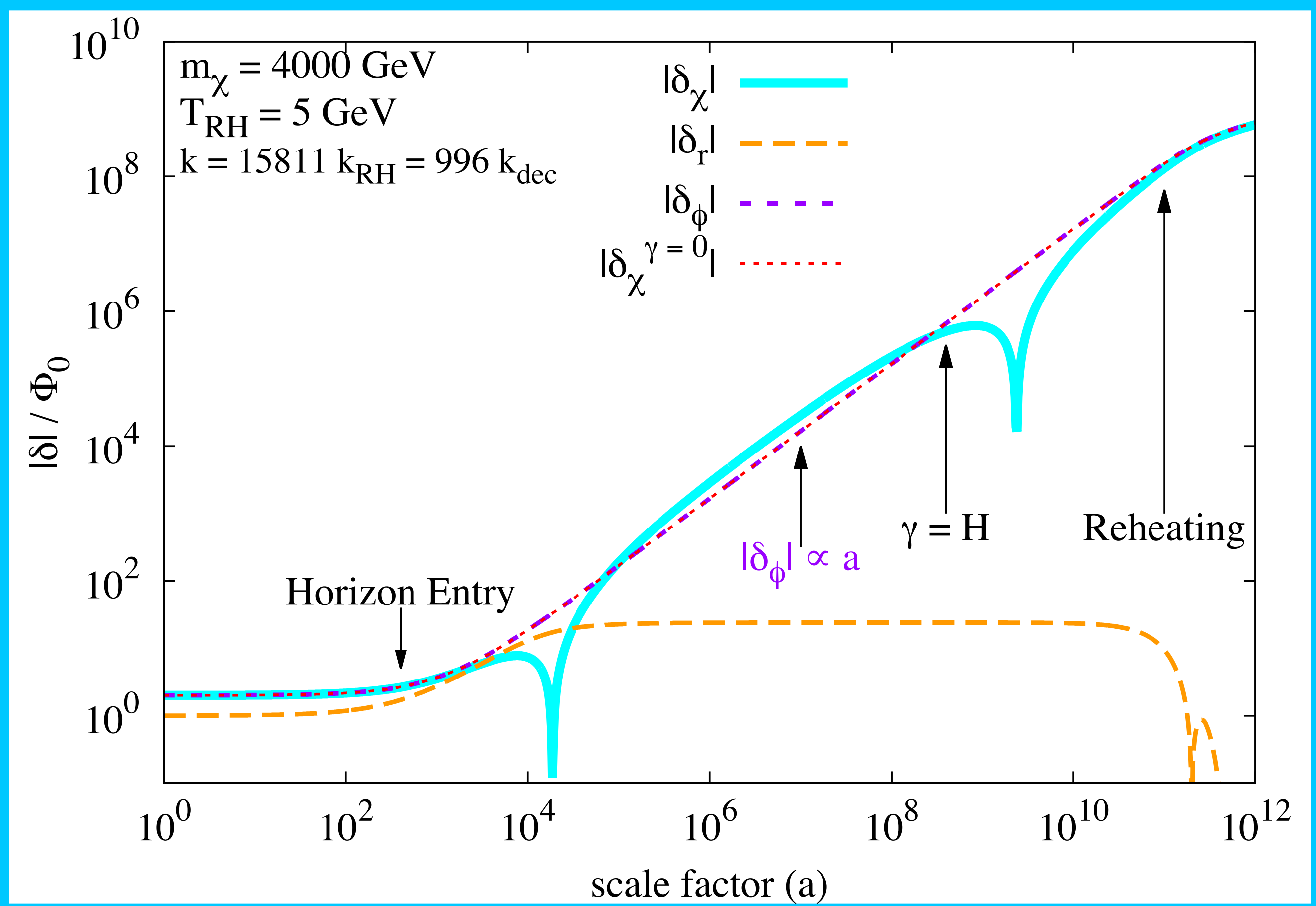

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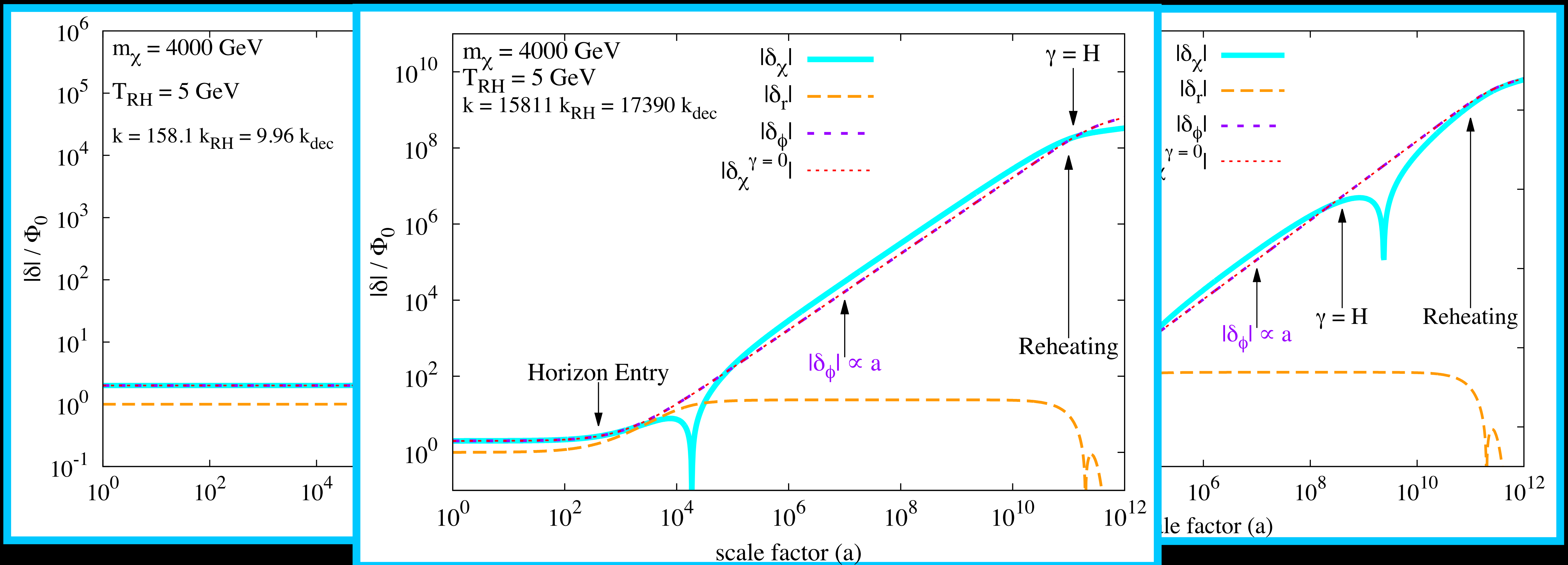

Interactions do not significantly suppress the perturbations,
even if the dark matter remains coupled to the relativistic particles well into the EMDE... and even through reheating!

see also Choi, Gong, Shin 2015

The DM temperature

Isaac Waldstein, ALE, Cosmin Ilie 2017

The evolution of the DM temperature is governed by

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

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

momentum transfer rate: $\gamma \propto T^6$

expansion rate: H

- 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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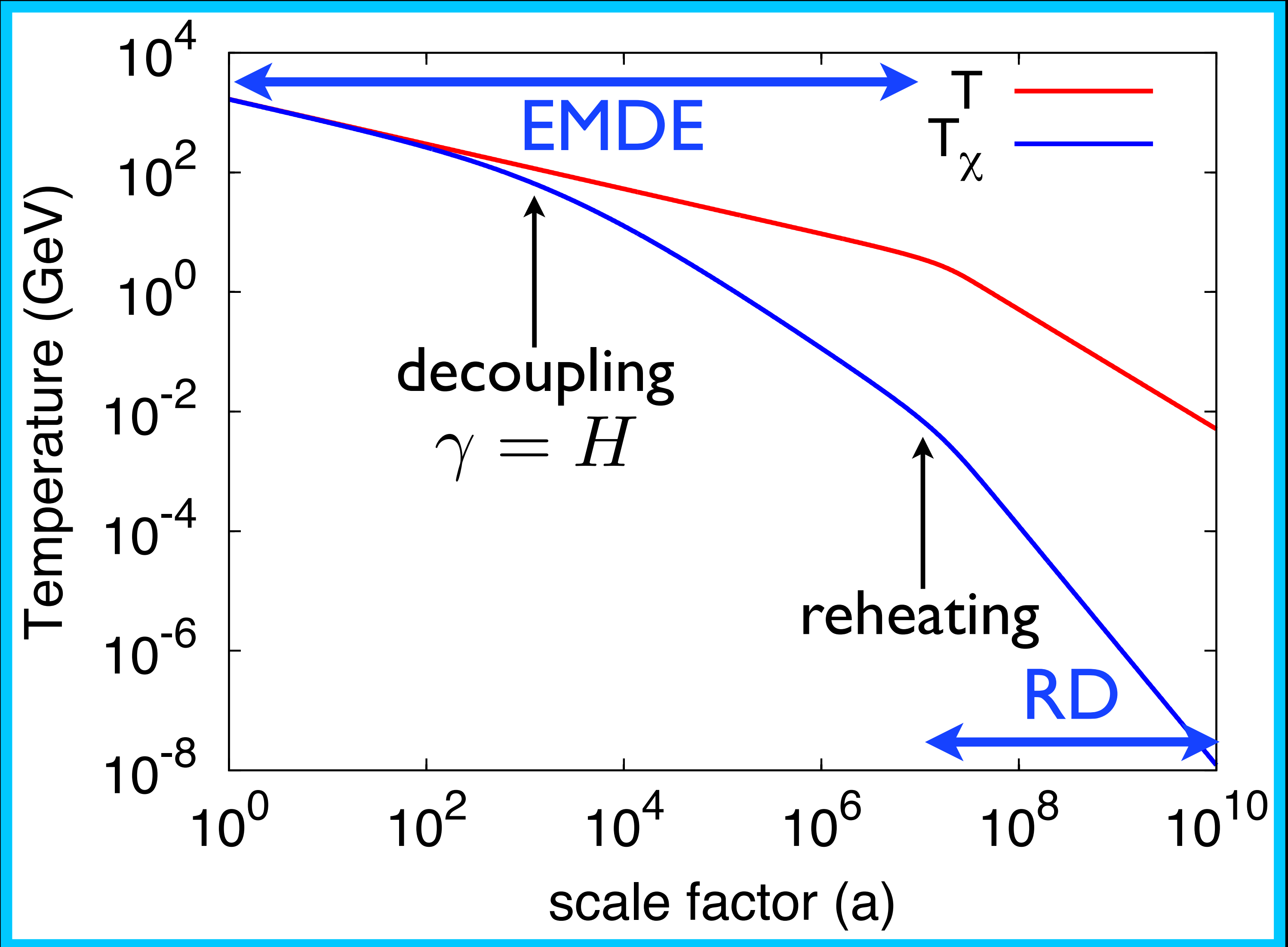

- fully coupled:
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- fully decoupled:
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- But during an EMDE
  $$\frac{\gamma}{H}T \propto \frac{T^6}{T^4}T \propto T^3 \propto a^{-9/8}$$
- quasi-decoupled: $T_\chi \propto a^{-9/8}$

Isaac Waldstein,
ALE, Cosmin Ilie
2017

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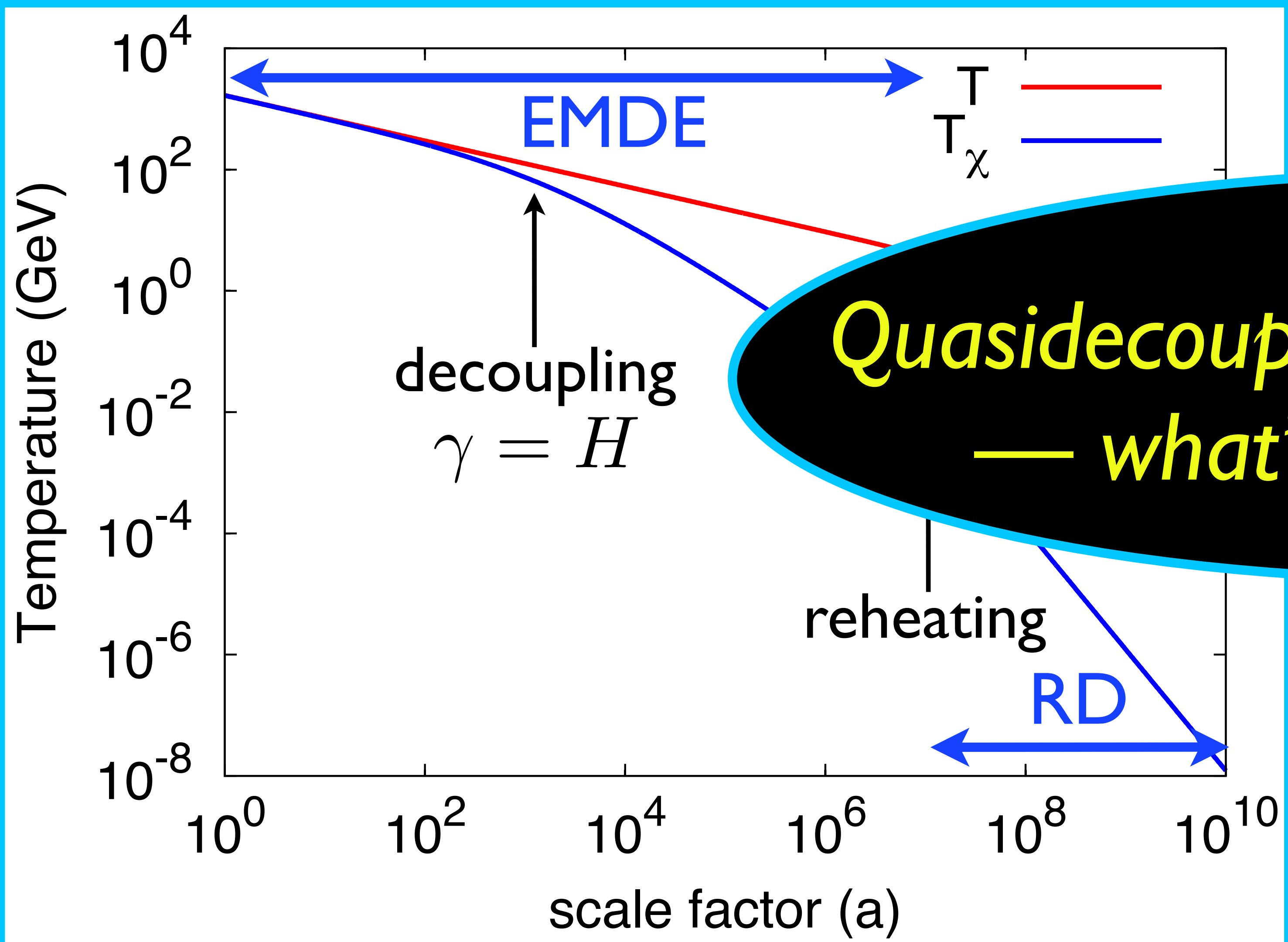


- fully coupled: $H \gg T_\chi \simeq T$

Quasidecoupling can't last forever — what's really going on?

- But during an EMDE

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

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

Quasi-Decoupling Reconsidered

***Isaac Waldstein**, ALE, Charlie Mace, Cosmin Ilie, coming soon*

The temperature evolution eqn. $a\frac{dT_\chi}{da} + 2T_\chi = -2\frac{\gamma}{H}(T_\chi - T)$ assumes that each collision imparts a small change to the DM particles' momentum.

$$\frac{\Delta p}{p} \ll 1 \Longleftrightarrow \frac{T_L}{\sqrt{m_\chi T_\chi}} \ll 1$$

This is true for cold DM prior to kinetic decoupling, but it is violated after that as the DM cools faster than the radiation.

Quasi-Decoupling Reconsidered

***Isaac Waldstein**, ALE, Charlie Mace, Cosmin Ilie, coming soon*

The temperature evolution eqn. $a\frac{dT_\chi}{da} + 2T_\chi = -2\frac{\gamma}{H}(T_\chi - T)$ assumes that each collision imparts a small change to the DM particles' momentum.

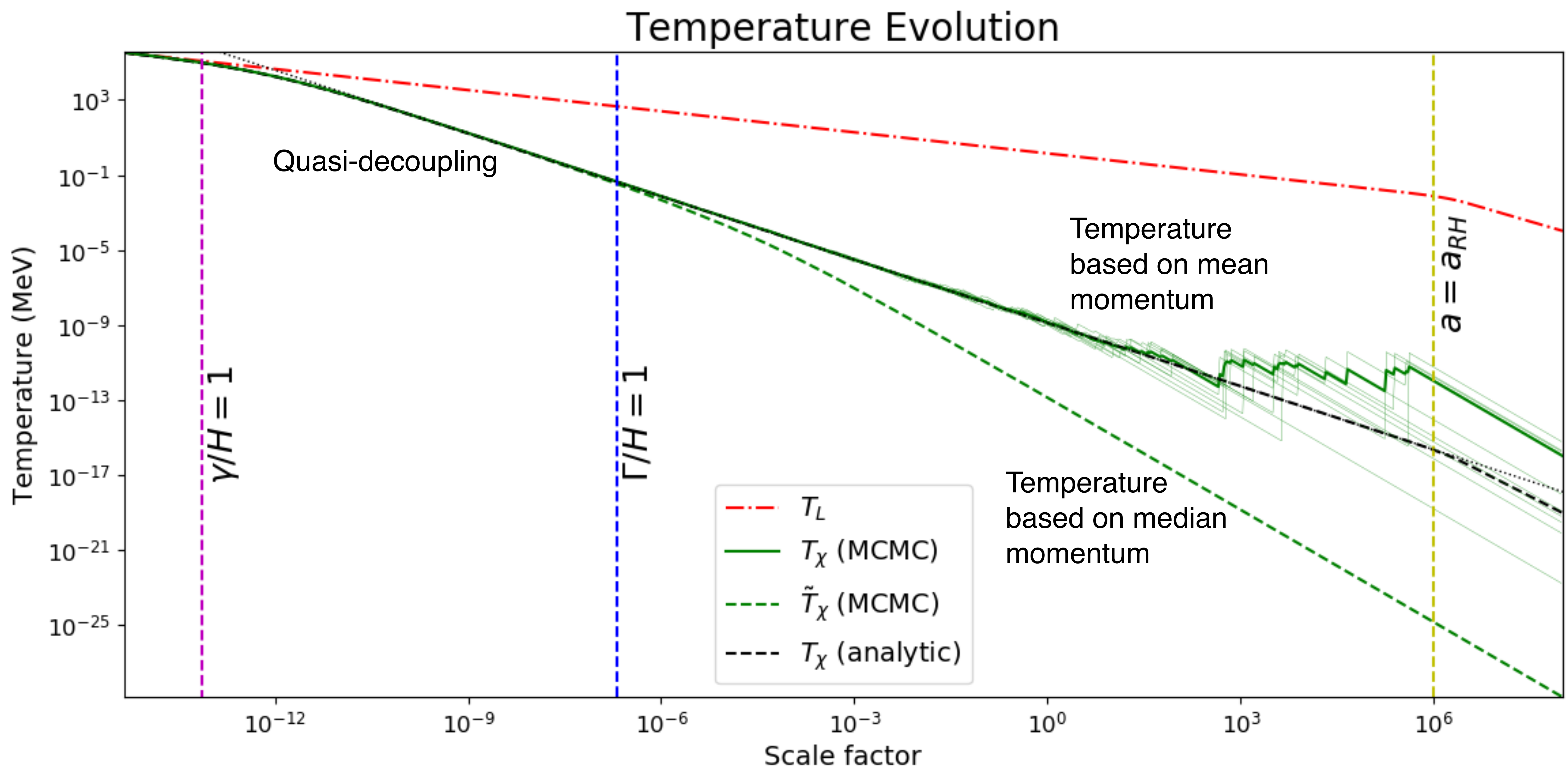
$$\frac{\Delta p}{p} \ll 1 \Longleftrightarrow \frac{T_L}{\sqrt{m_\chi T_\chi}} \ll 1$$

This is true for cold DM prior to kinetic decoupling, but it is violated after that as the DM cools faster than the radiation.

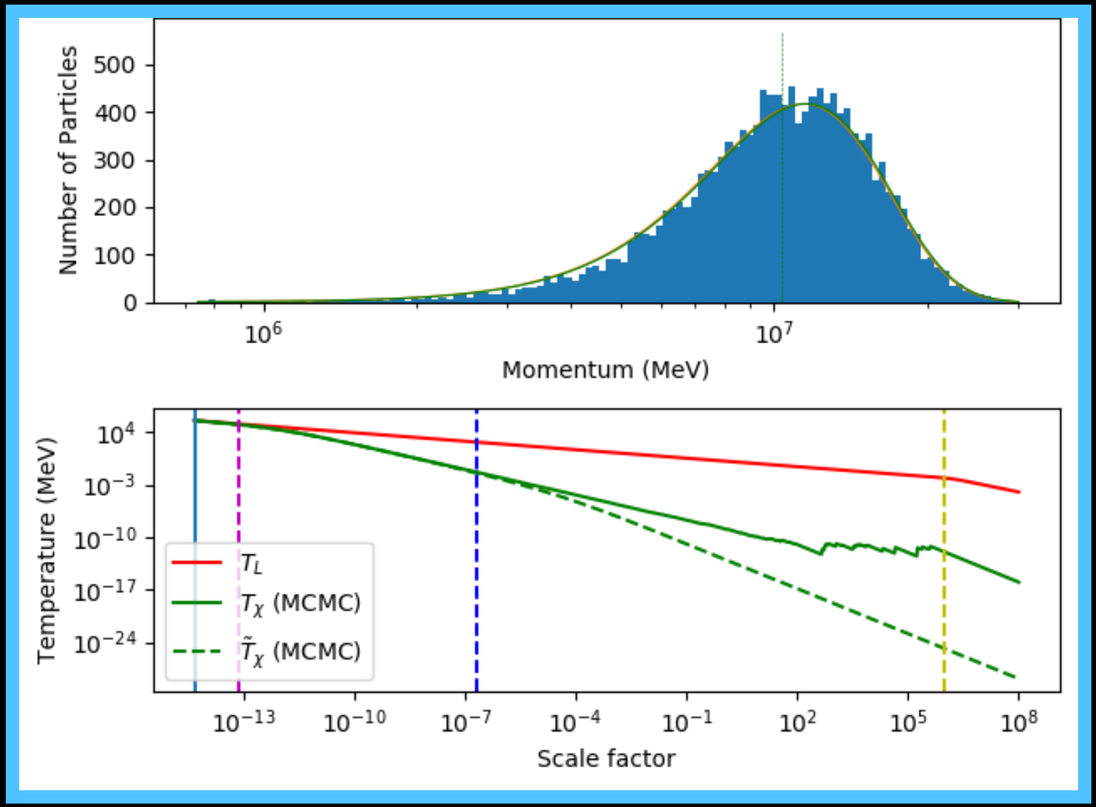
- Radiation domination: violation after it's no longer relevant.
- EMDE: violation shortly before collision rate equals Hubble rate.
- EMDE: dark matter particles experience collisions with hot leptons that greatly increase their momenta.
- Let's simulate this!

Simulating Decoupling

***Charlie Mace**, ALE, coming soon*



Post-Decoupling Velocities



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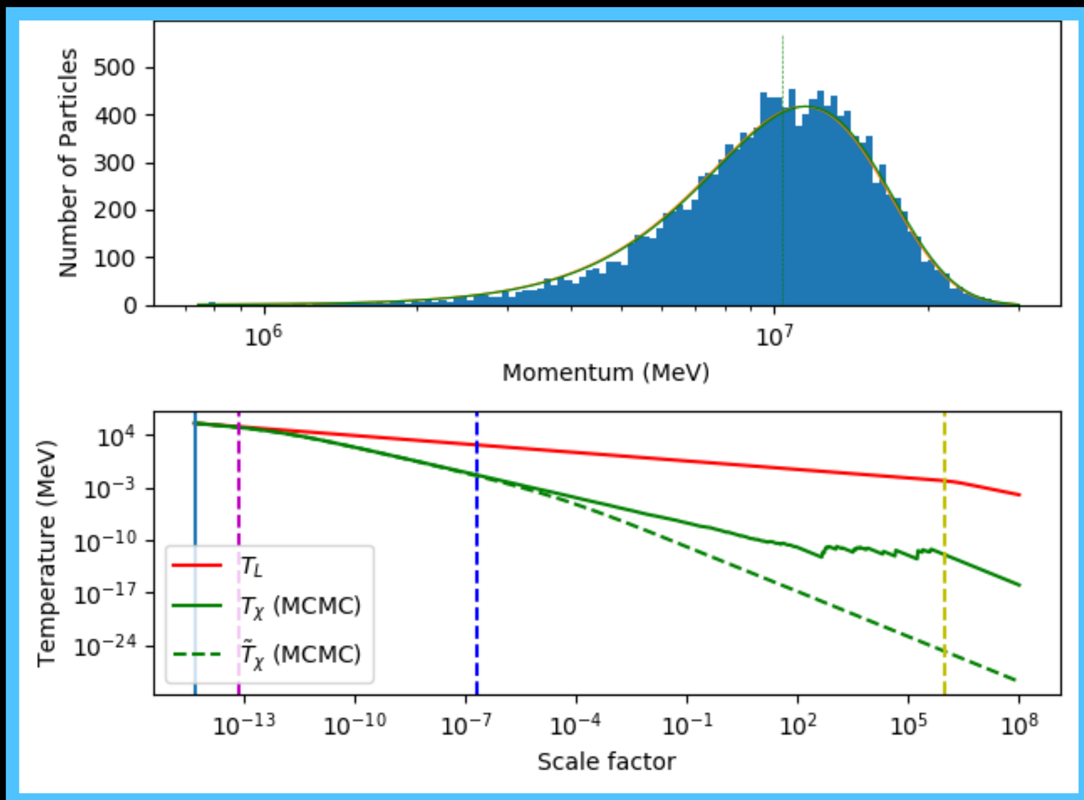
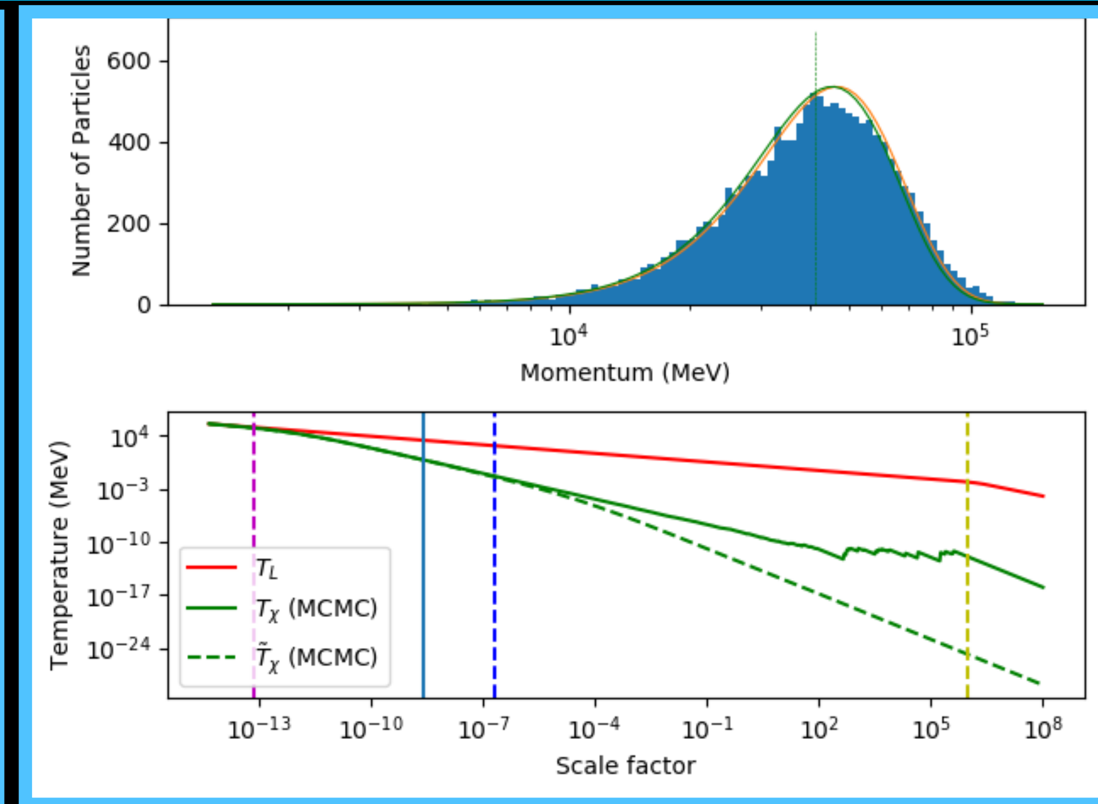
Post-Decoupling Velocities





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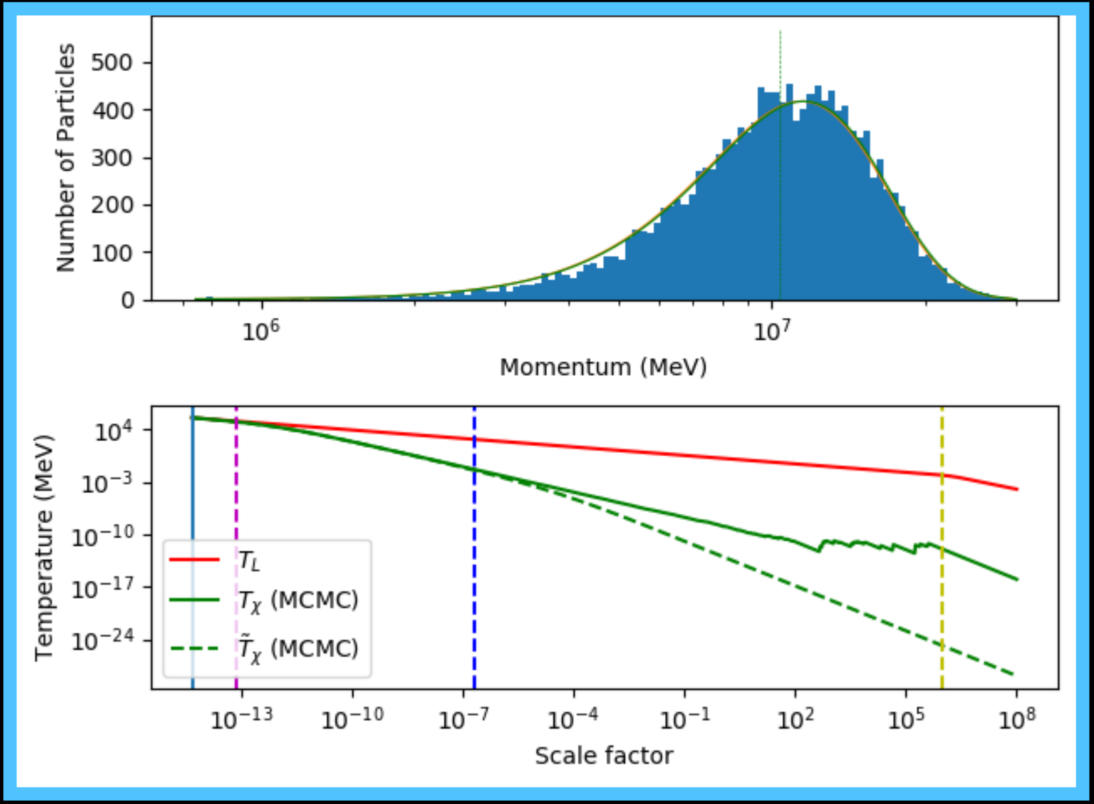
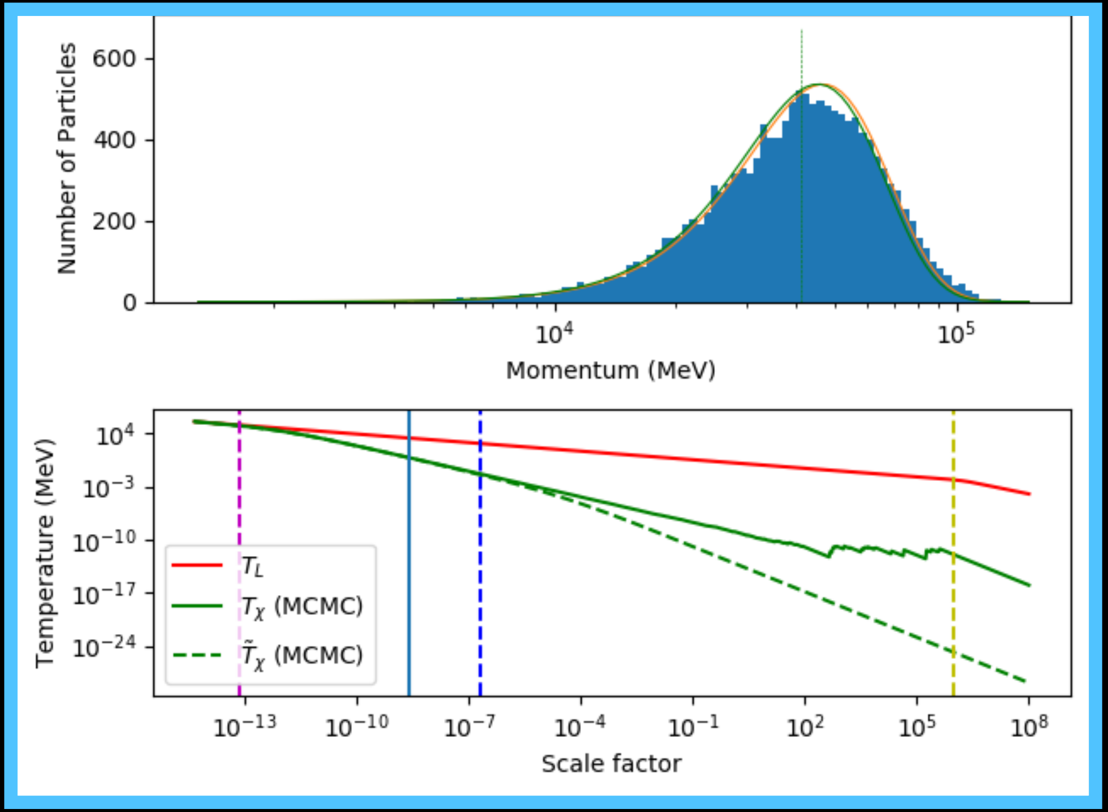
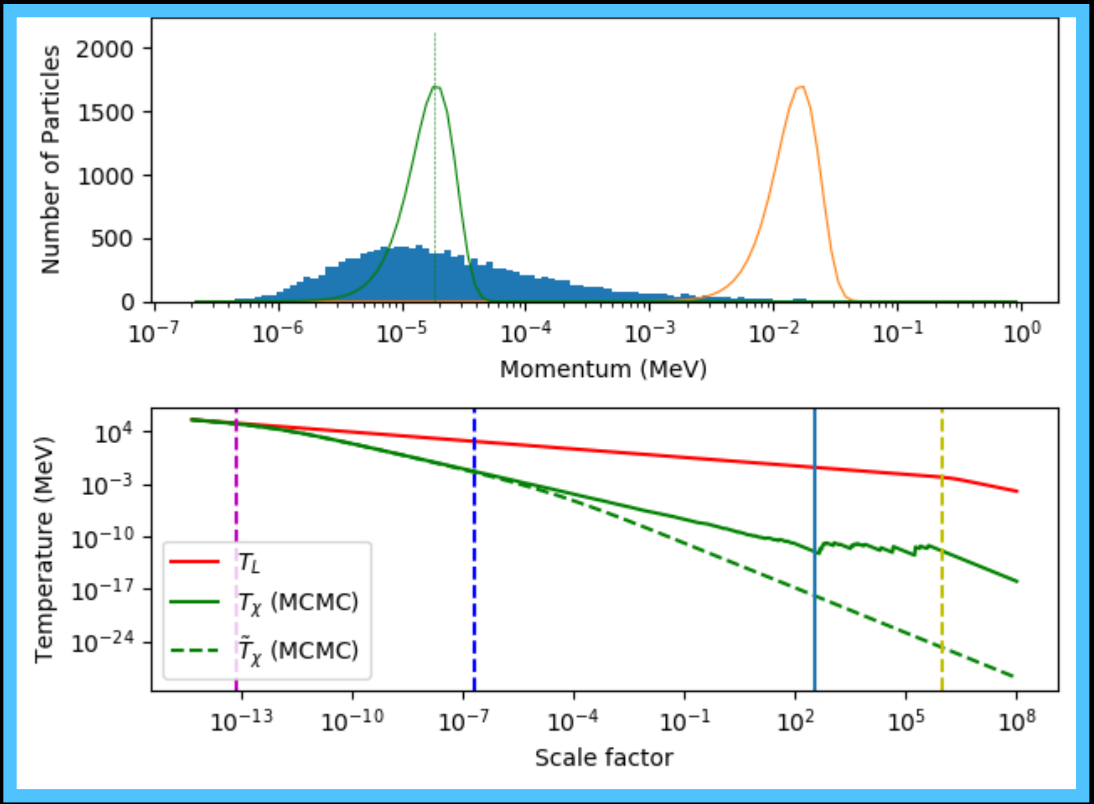
Post-Decoupling Velocities







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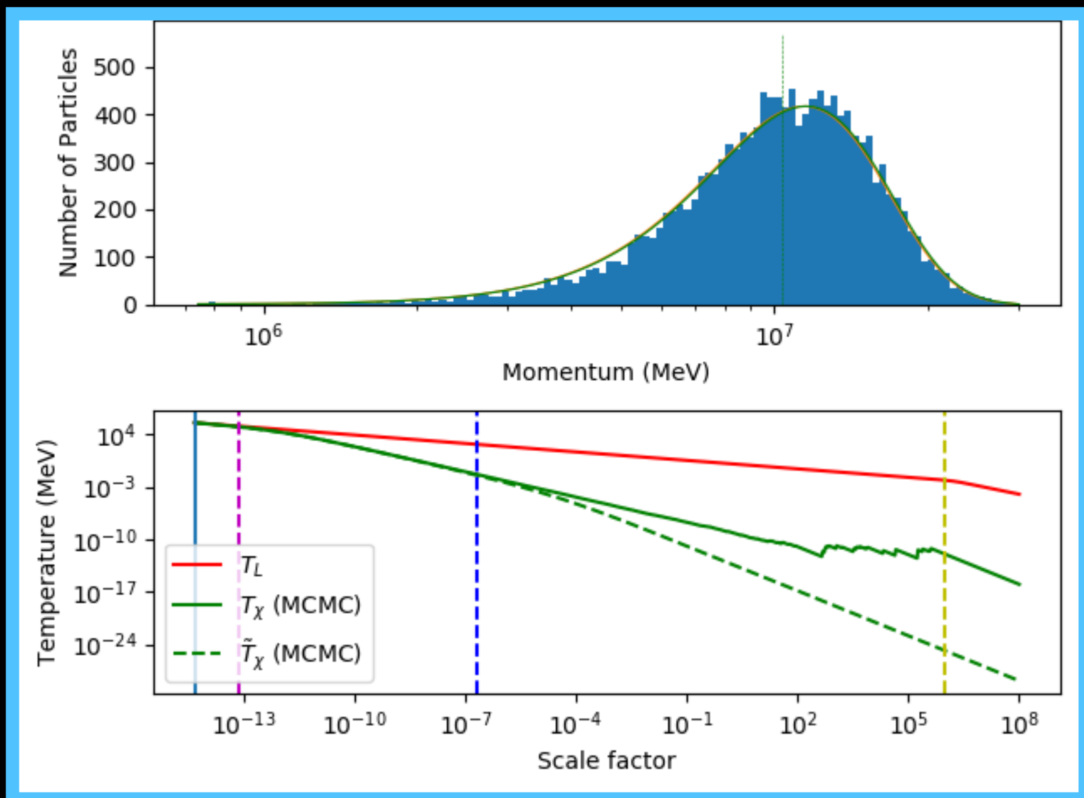
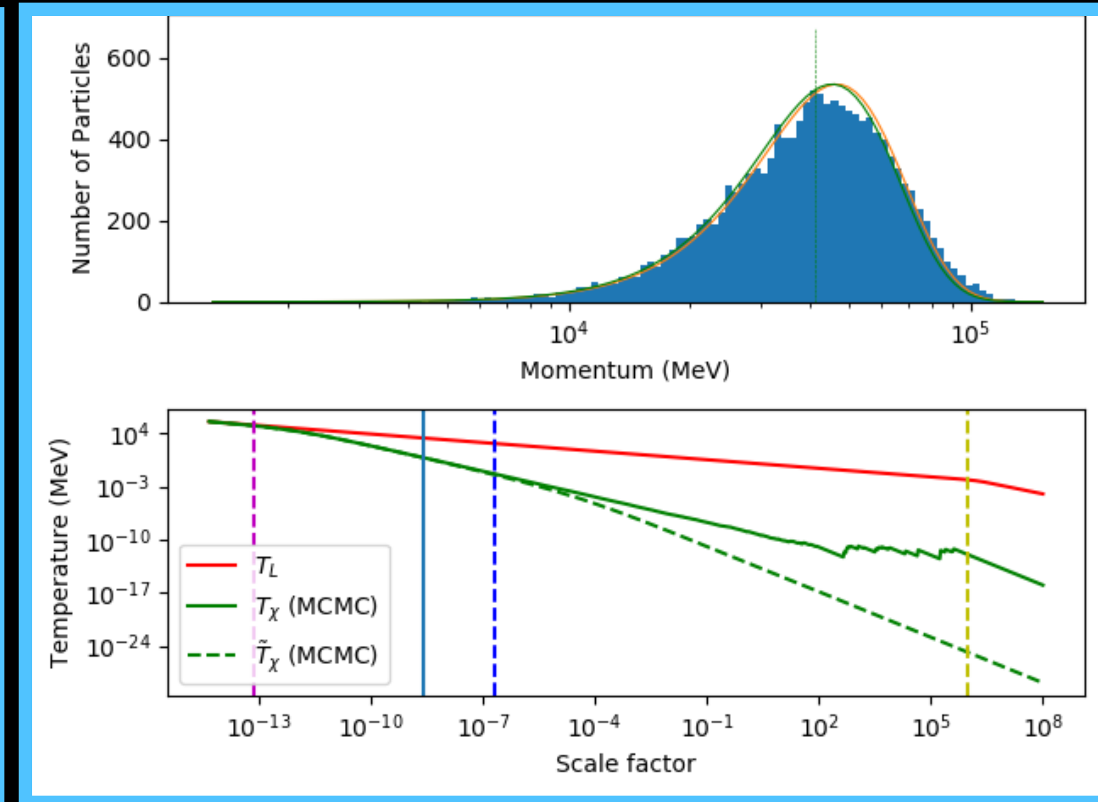
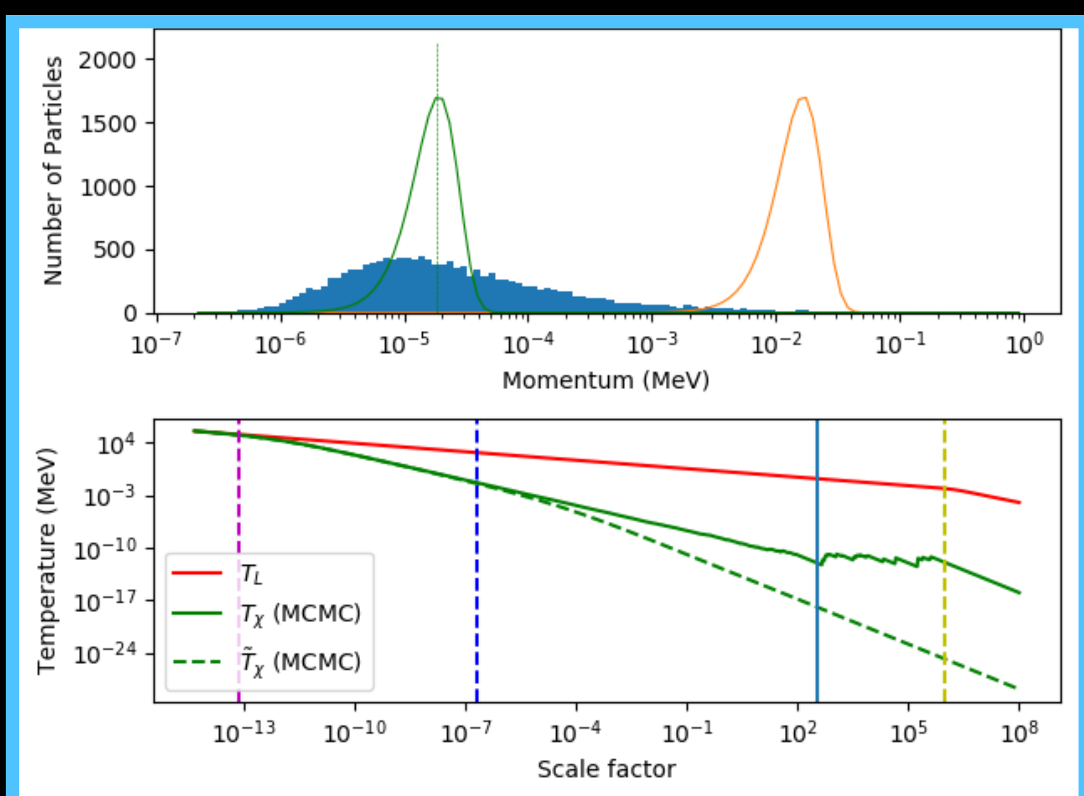
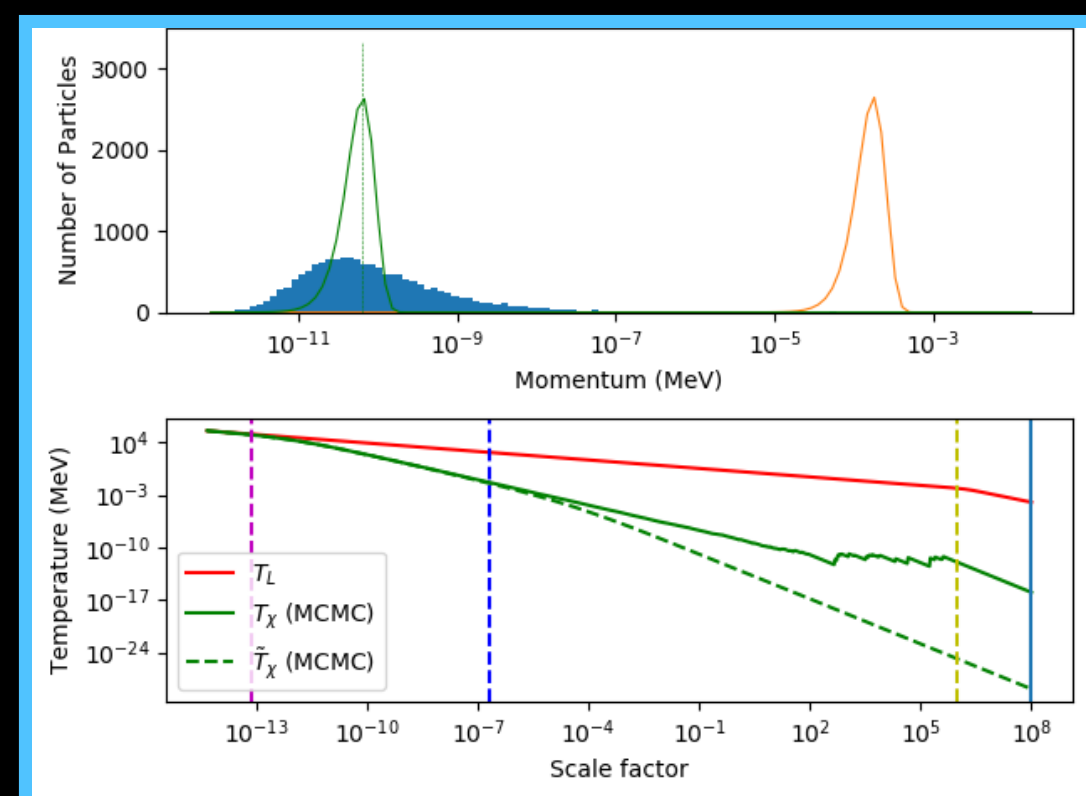
Post-Decoupling Velocities









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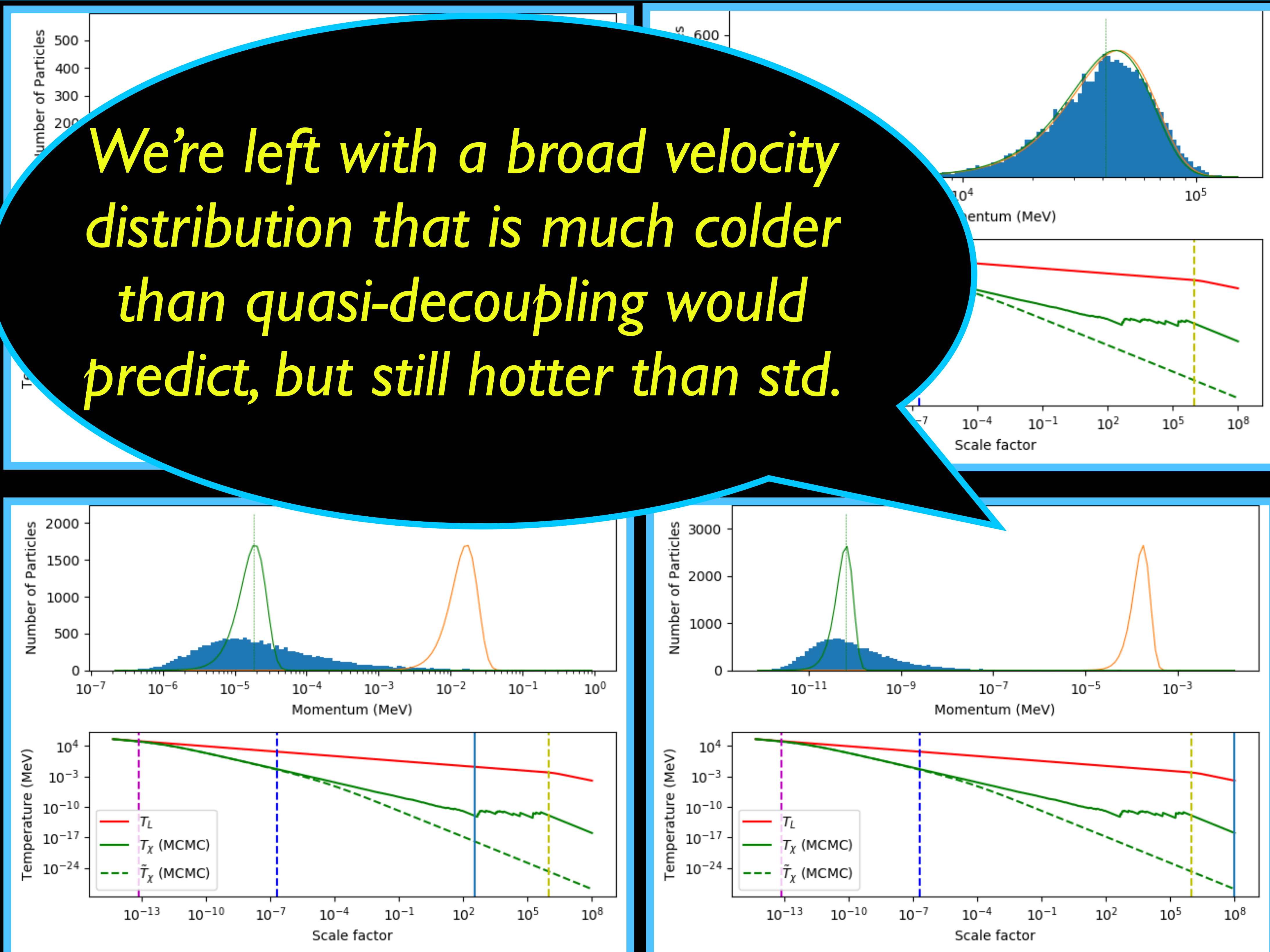
Post-Decoupling Velocities



We're left with a broad velocity distribution that is much colder than quasi-decoupling would predict, but still hotter than std.

Charlie Mace, *ALE, coming soon*