The Effects of a Hidden Sector on The Matter Power Spectrum

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with

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[in prep.]

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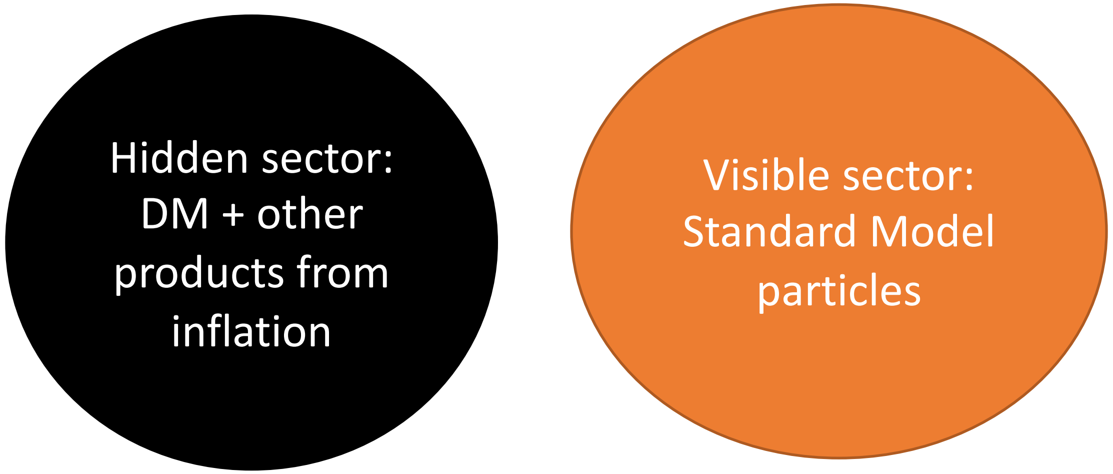
Motivations

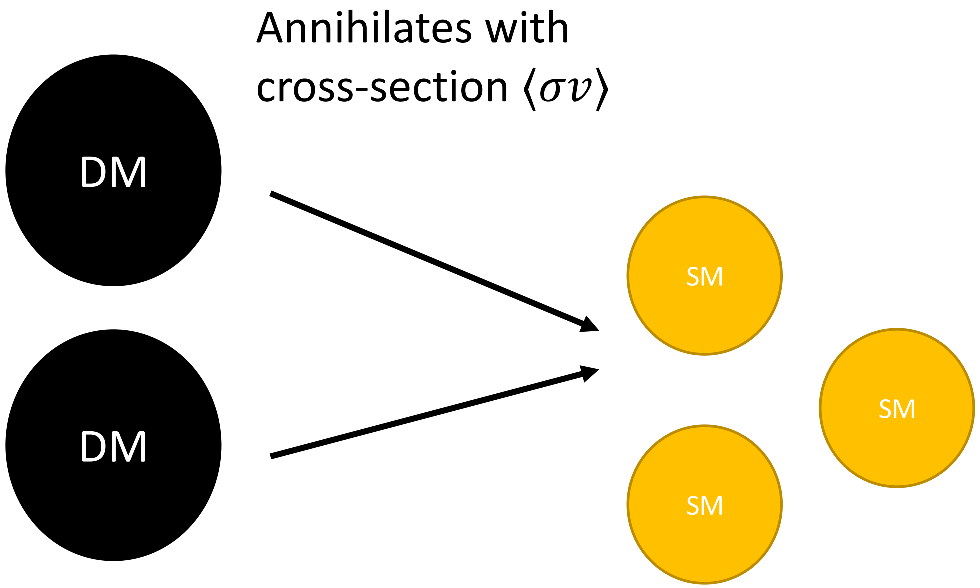
- No conclusive signatures of DM in collider and direct detection experiments.

- DM might be part of a **hidden sector**, minimally coupled to the Standard Model.

[Pospelov+ 2007 (0711.4866), Arkani-Hamed+ 2009 (0810.0713), Hooper+ 2012 (1206.2929), Berlin+ 2014 (1405.5204)]



Signatures of Annihilation

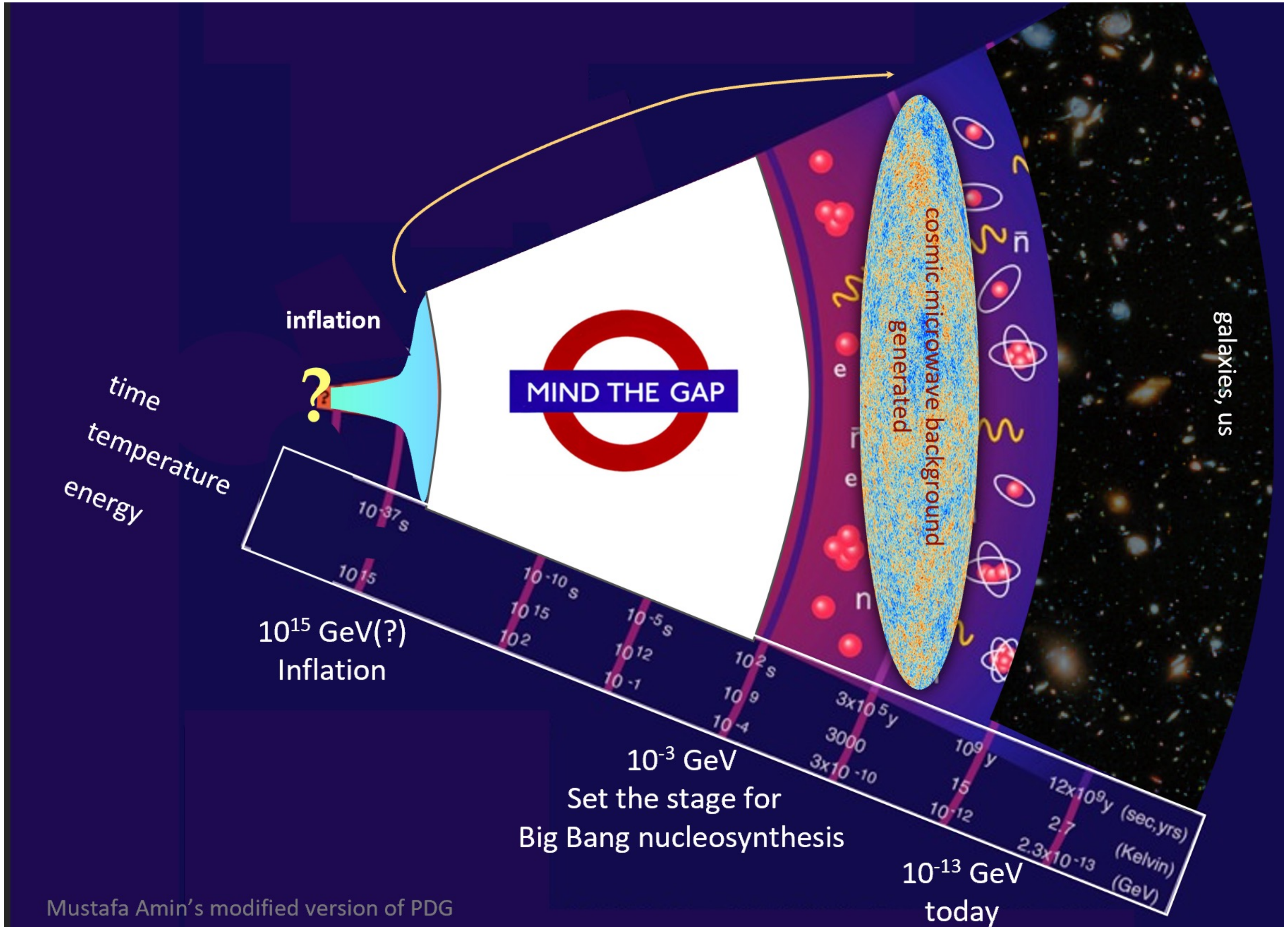


Annihilation power $\propto \rho^2$

Annihilation Boost: The "extra" annihilation signal due to "clumpiness" in the distribution of DM.

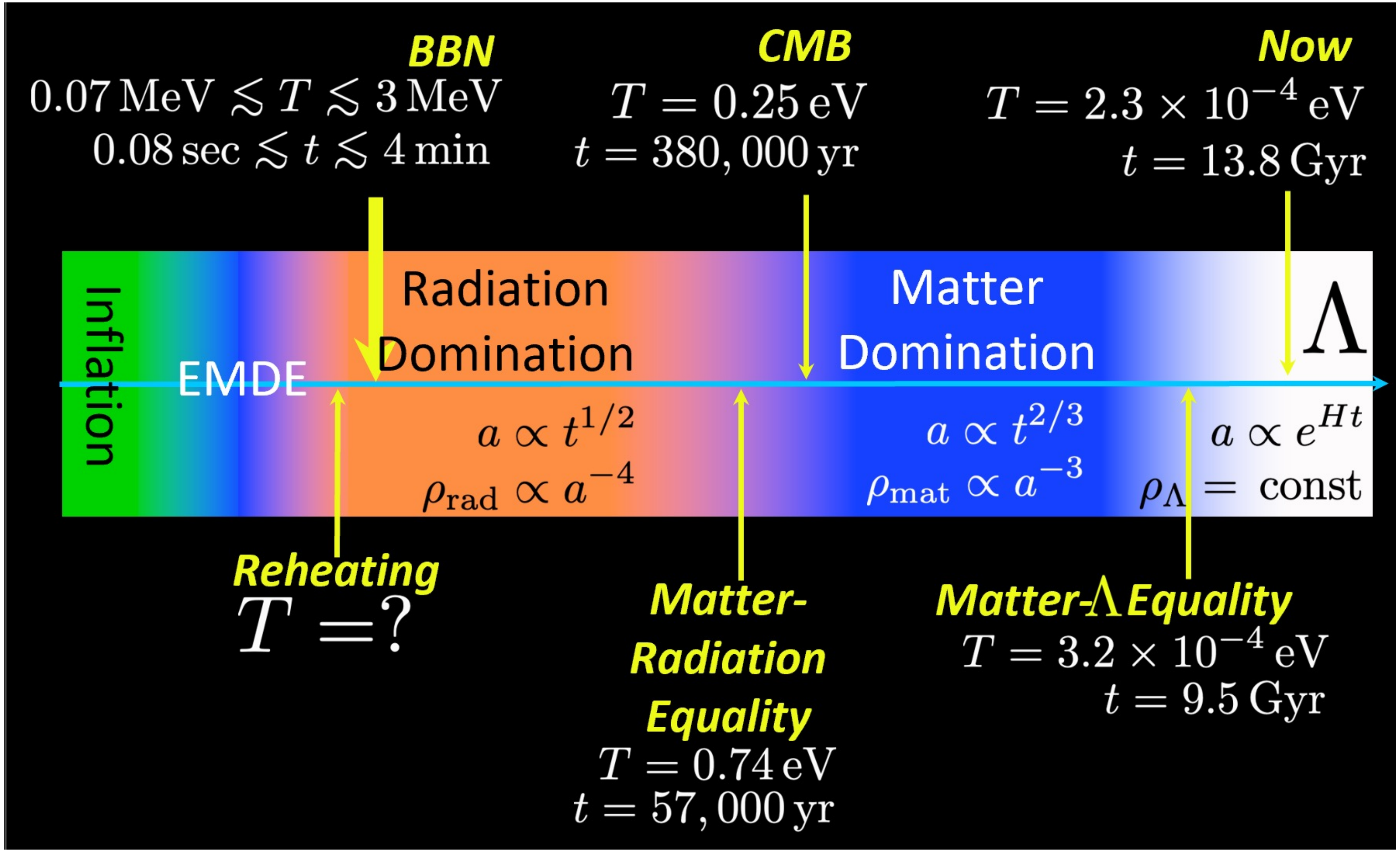
$$1 + B \propto \frac{\langle \rho^2 \rangle}{\bar{\rho}^2}$$

A Gap In The History of the Universe



Mustafa Amin’s modified version of PDG

Alternative Thermal Histories and EMDEs



Credit: Adrienne Erickcek

A possible period of matter domination between inflation and BBN, caused by particles in the hidden sector.

Zhang 2015 (1502.06983)

Berlin+ 2016 (1602.08490)

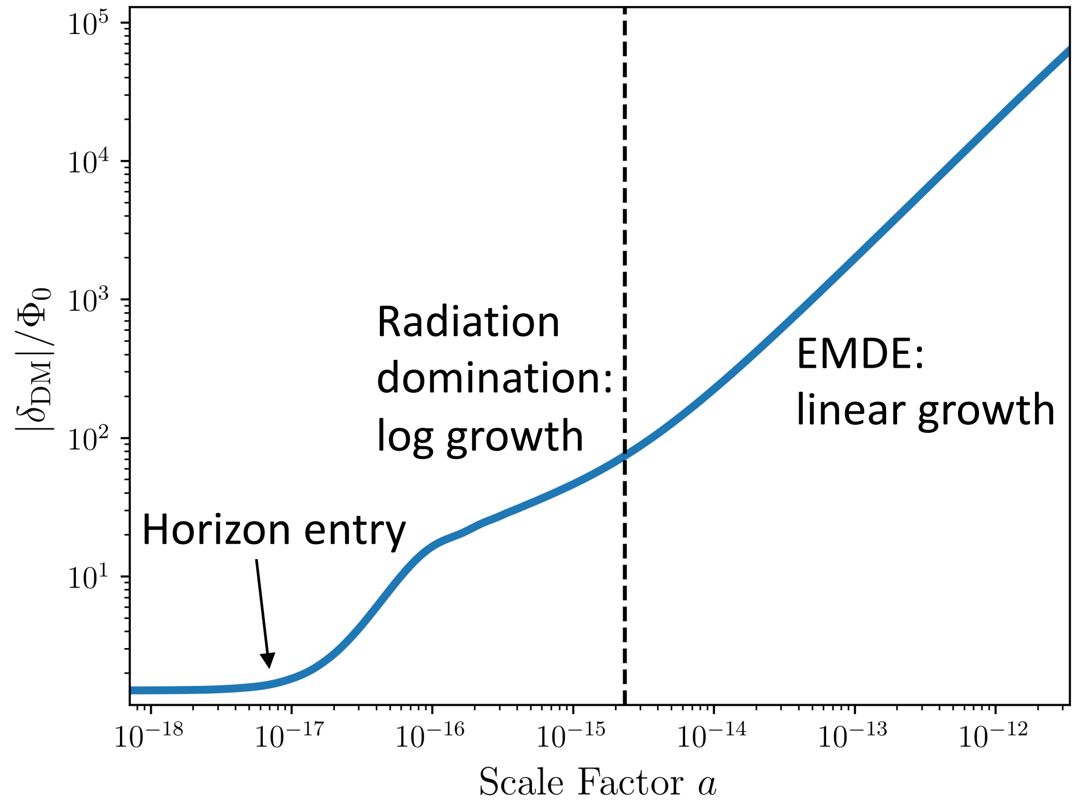
Dror+ 2016 (1607.03110)

See 2006.16182 for a general review

Effects of an EMDE

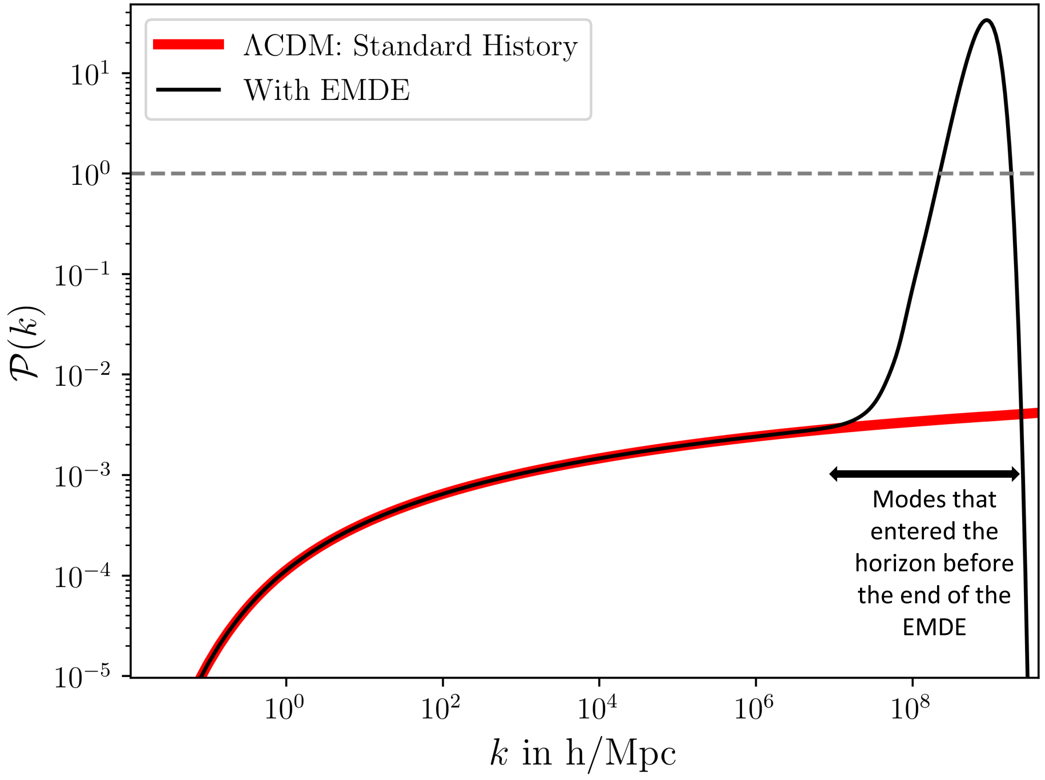
DM perturbations grow linearly with scale factor in the EMDE.

[Erickcek and Sigurdson 2011 (1106.0536)]



This linear growth introduces a rise in the matter power spectrum.

As a result, structure can form much earlier than in a LCDM Universe, contributing to the DM annihilation boost.

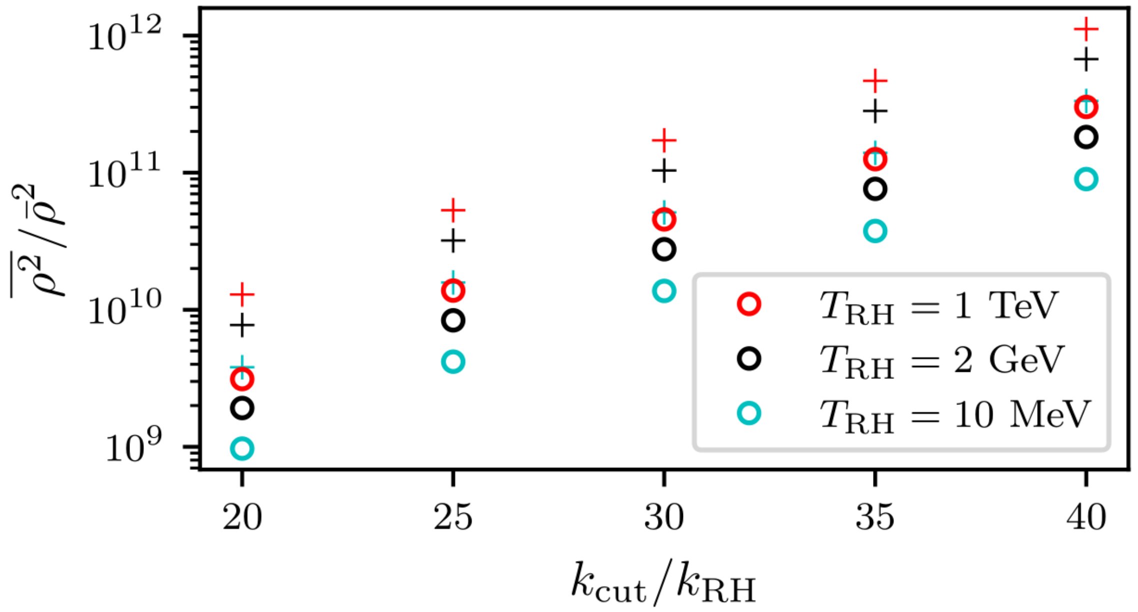


Impact of a Small-Scale Cut-Off

- The DM annihilation boost is sensitive to any small-scale cut-off in the matter power spectrum.

- The cut-off scale sets the sizes and formation times of the microhalos that form due to an EMDE.

- Changing the cut-off scale by a factor of 2 changes the boost by a factor of roughly a 100! (Delos+ 2020: 1910.08553)



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Scenario: Long-Lived Particle in the Hidden Sector

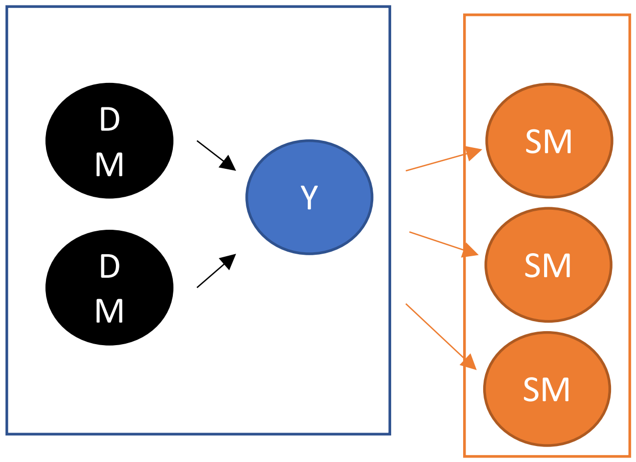
Y Particles
Dark matter
(hidden sector)

Standard Model
Radiation
(visible sector)

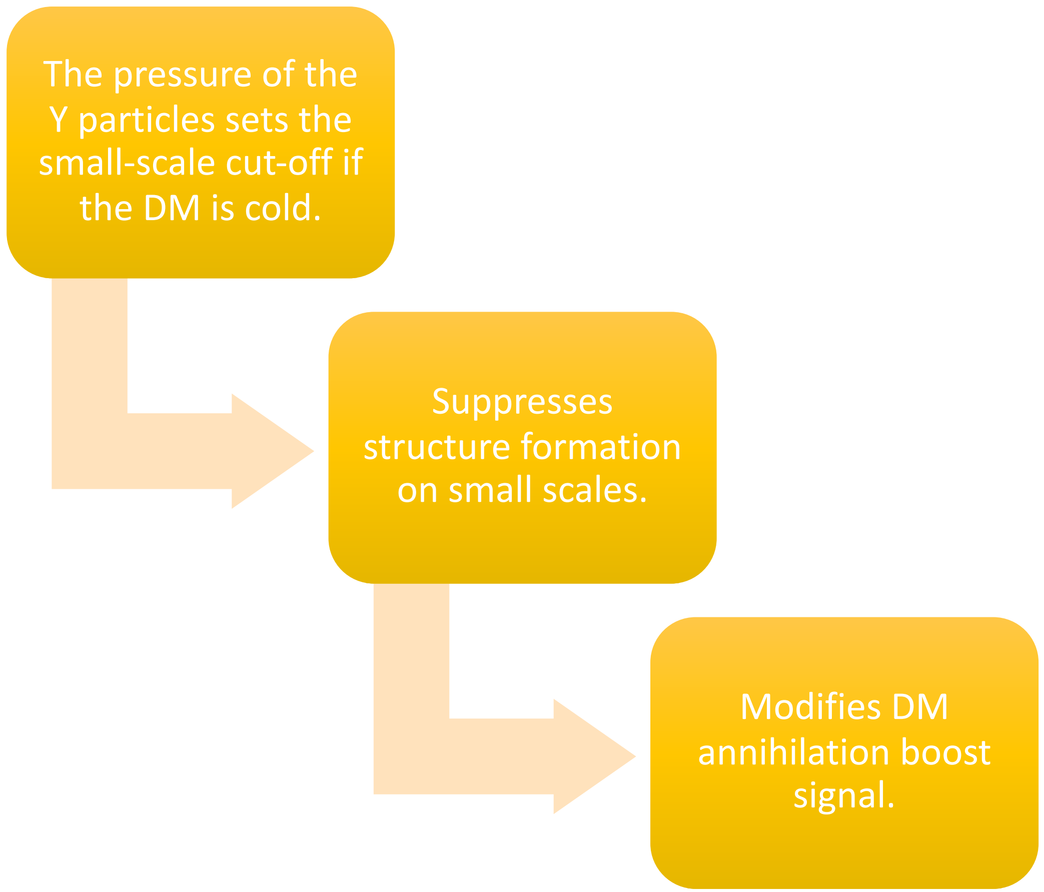
Y particles: Feebly coupled to SM -- decay into SM particles, via:

Higgs portal [Burgess+ 2011 (hep-ph/0011335)]
Vector portal [Krolikowski 2008 (0803.2977)]
Lepton portal [Bai+Berger 2014 (1402.6696)]

DM annihilation channel:



The Y particles are relativistic in the early universe



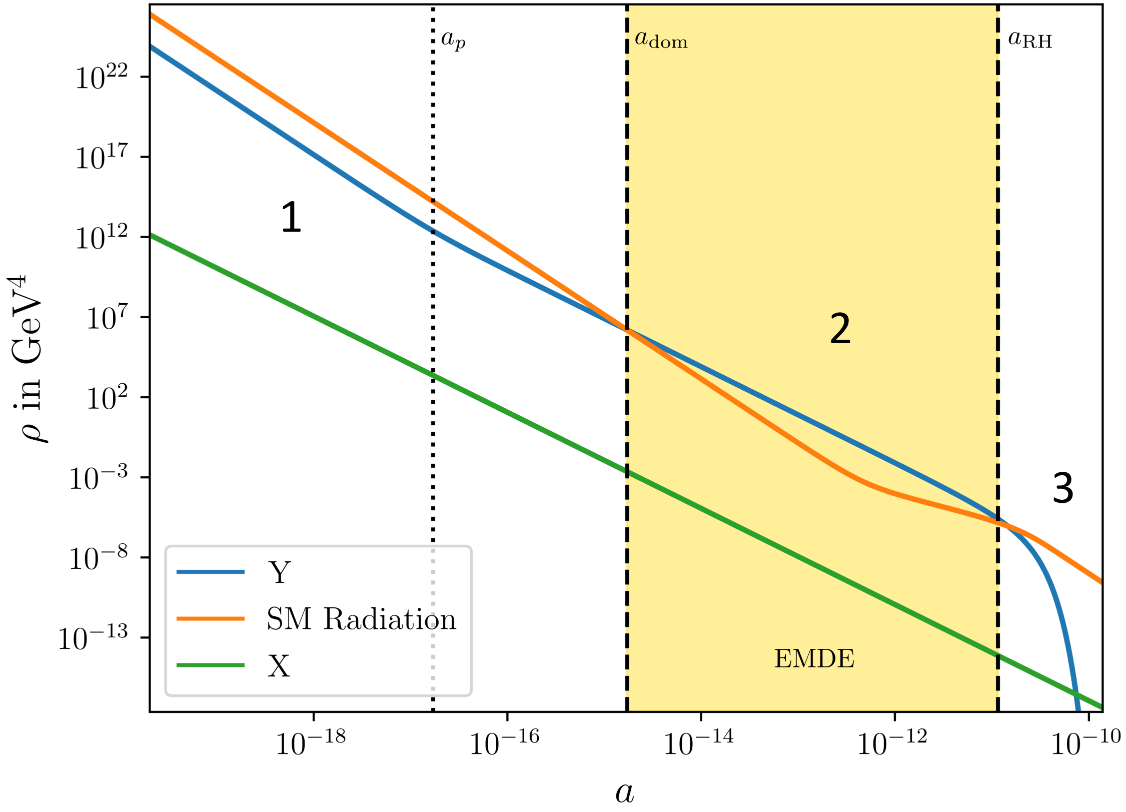
Homogeneous Background Evolution

Universe has three components: Y particles, DM, and the bath of relativistic SM particles.

1. Y particles in hidden sector: initially relativistic and transitions to nonrelativistic behavior.

2. The energy density of the Y particles dominates the Universe after the particles become nonrelativistic. This is the EMDE.

3. Y particles are minimally coupled to the Standard Model and decay into the SM bath with decay rate Γ. Y particle decay increases rapidly at **reheating** and radiation domination is restored.



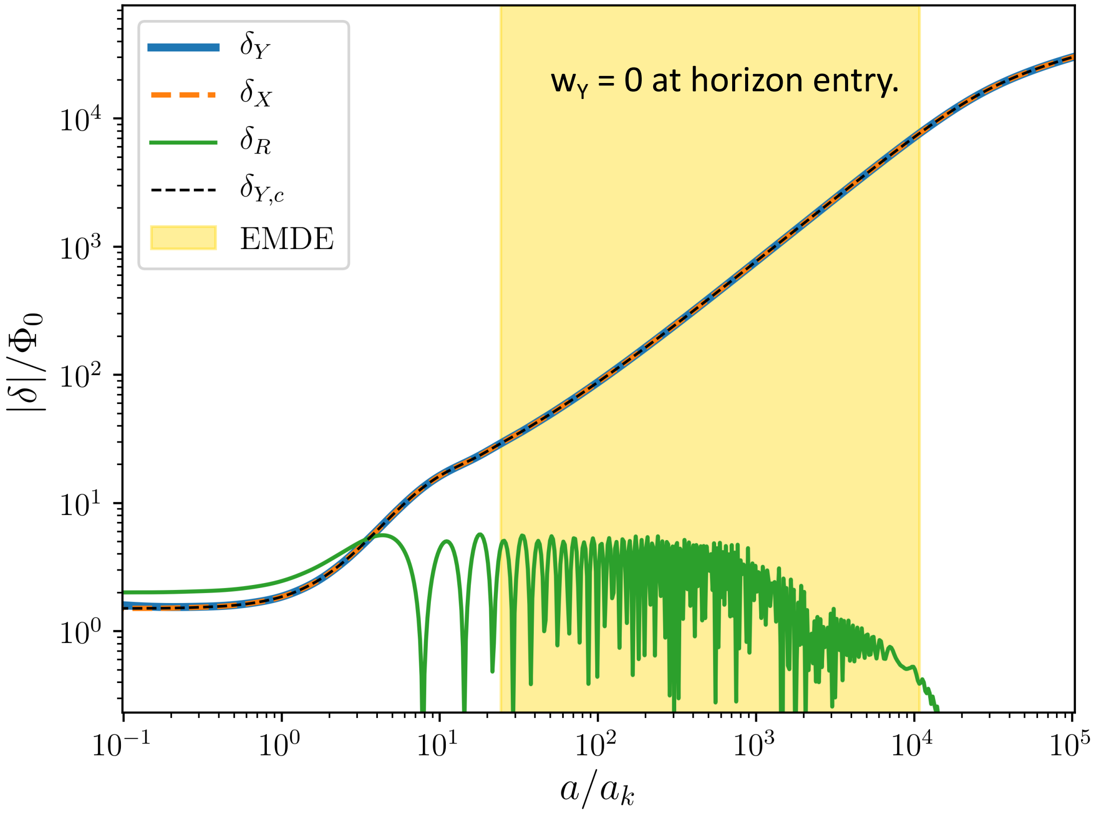
$$\frac{d\rho_Y}{dt} + 3H(1+w_Y)\rho_Y = -\Gamma m n_Y$$

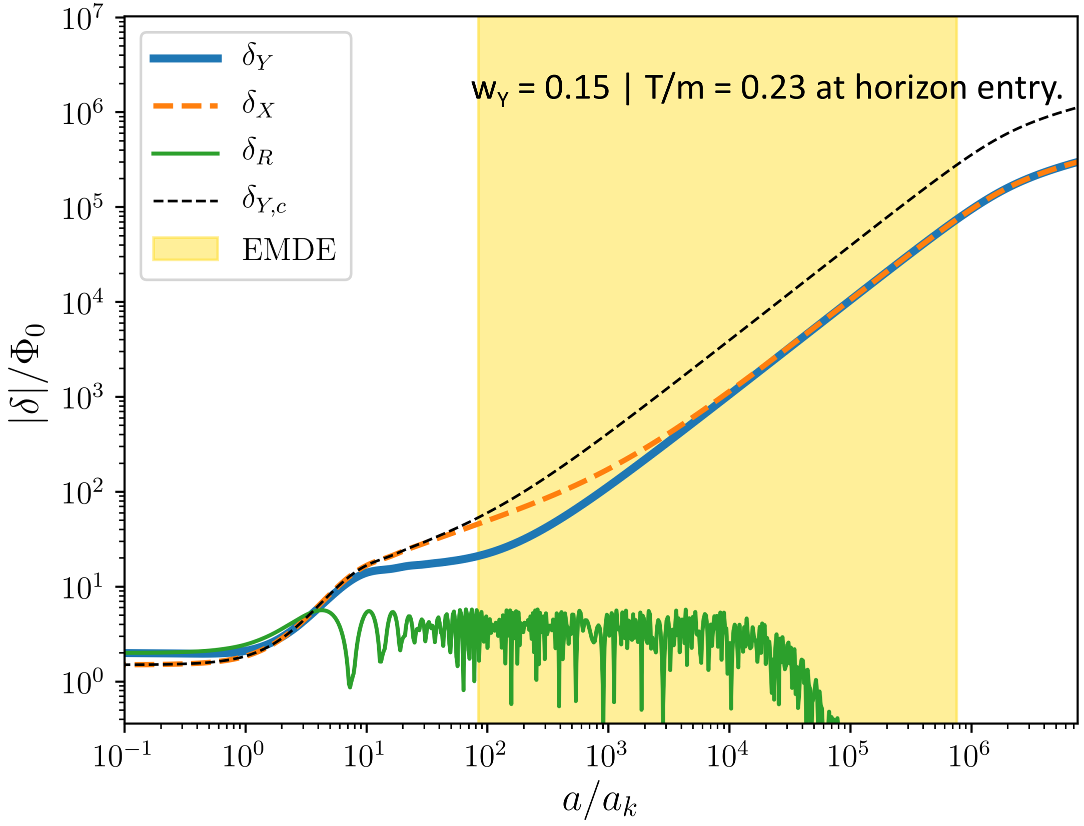
$$\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma m n_Y$$

$$\frac{d\rho_X}{dt} + 3H\rho_X = 0$$

Perturbation Evolution

We employ a Boltzmann solver to evolve the density and velocity perturbations in DM, Y, and radiation.





Which Modes Are Affected?

Damped harmonic oscillator

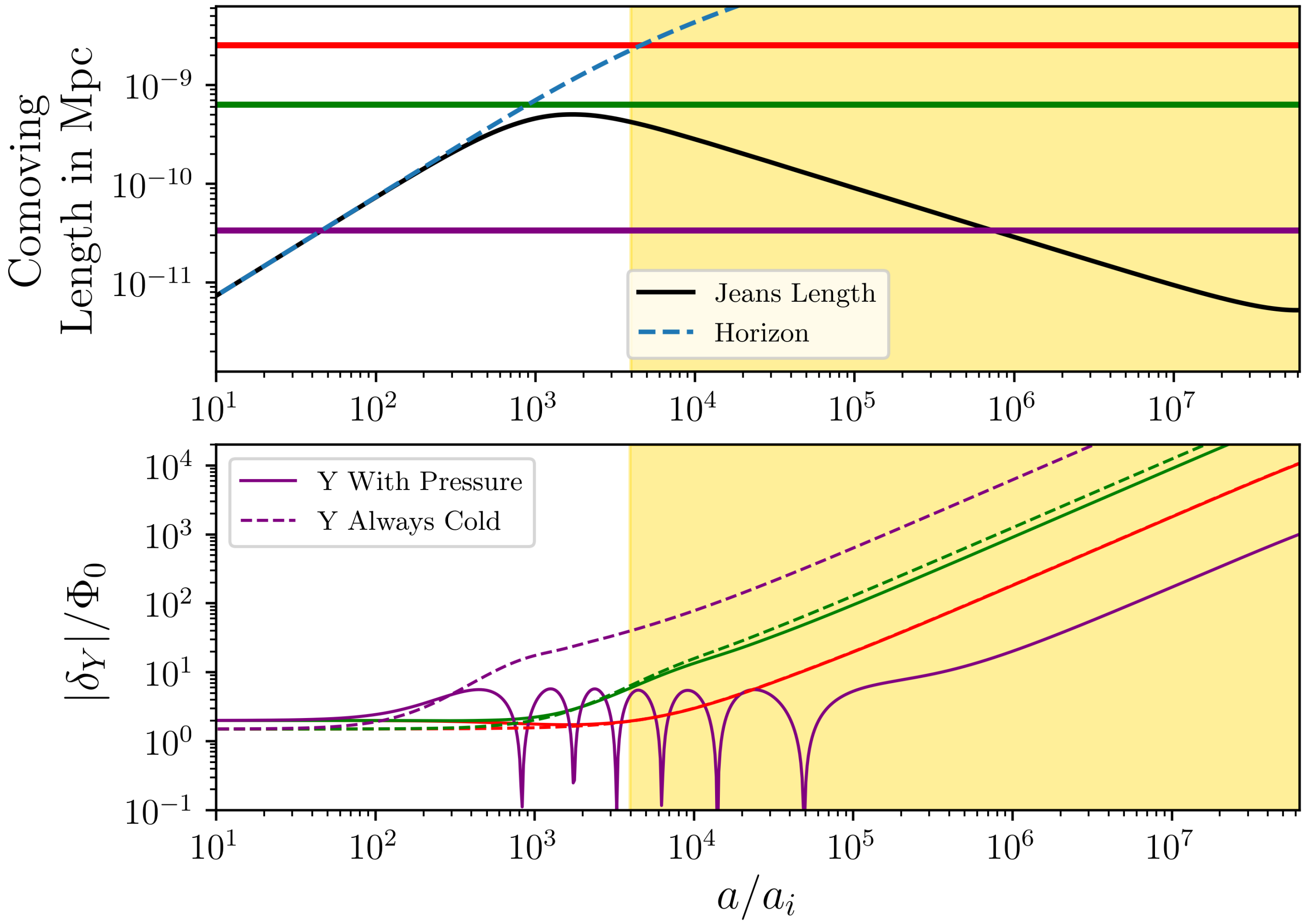
$$\frac{d^2\delta_Y}{da^2} + \frac{1}{a}\frac{d\delta_Y}{da} + \frac{c_{sY}^2}{(a^2H)^2}\left[k^2 - k_J^2\right]\delta_Y = 0$$

Effective frequency

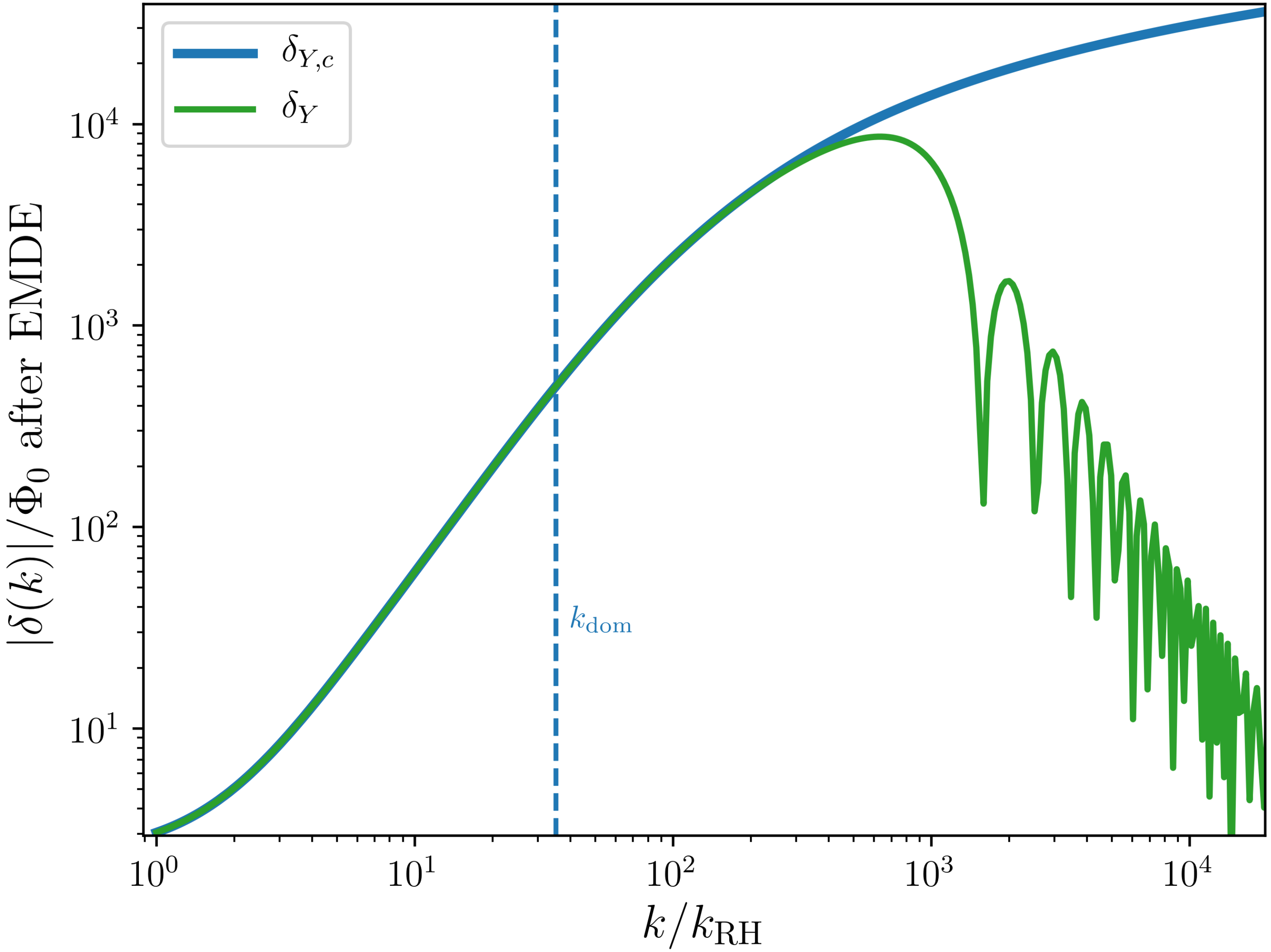
Effective Jeans wavenumber:

$$k_J^2(a) \equiv \frac{3}{2}\frac{1}{c_{sY}^2}\frac{\rho_Y}{\rho_R + \rho_Y}a^2H^2$$

Sound speed - pressure



Perturbation Amplitude in k-space



Transfer Functions

$\delta_{Y,c}$ is calculated easily. Calculating δ_Y is expensive.

The transfer function models the relationship between the two:

$$T(k) = \frac{\delta_Y(k)}{\delta_{Y,c}(k)}$$

Encodes the effect of the pressure of the Y particles on the power spectrum.

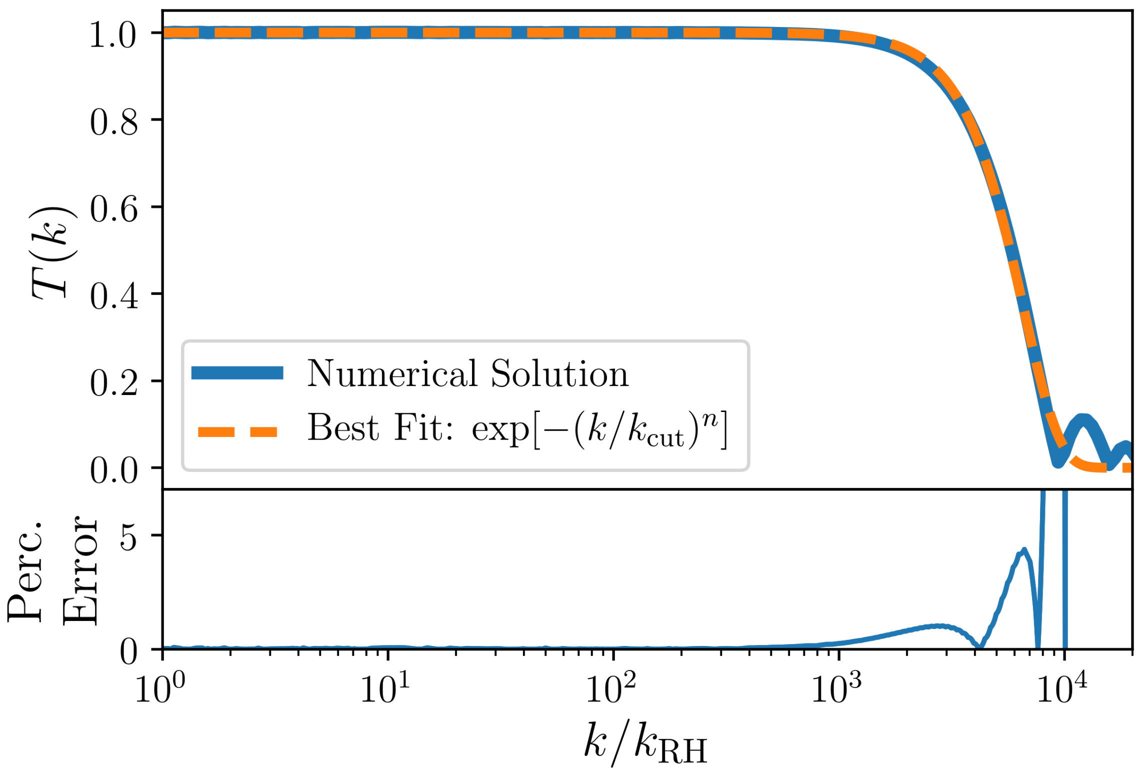
Transfer Functions

Fit to the functional form $\exp\left[-\left(\frac{k}{k_{\rm cut}}\right)^n\right]$

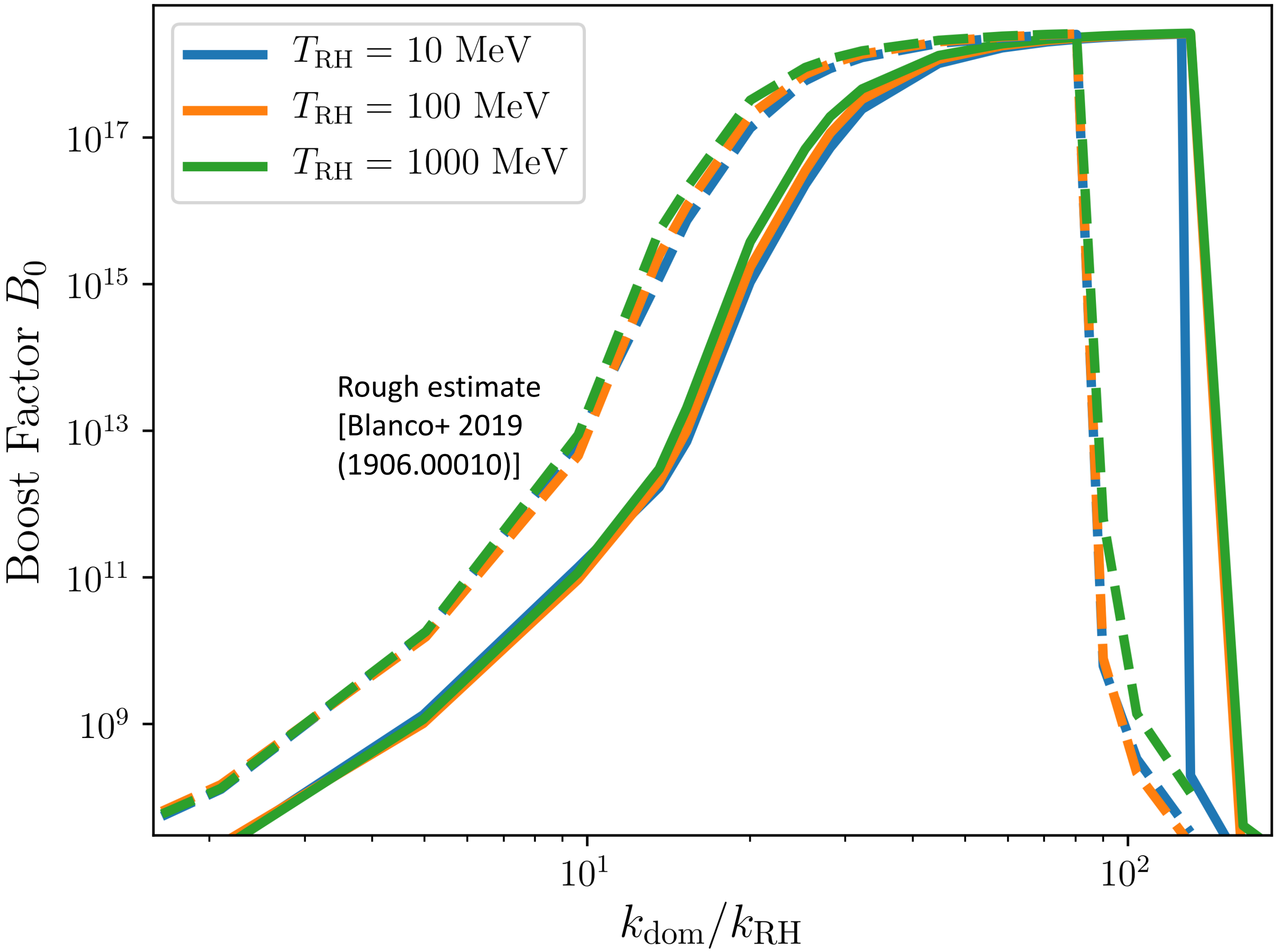
We provide the cut-off scale and *n* in terms of model parameters:

- η: the initial ratio of Y to SM energy densities
- m: the mass of the Y particles
- The statistics of the Y particles

We find that our expressions show excellent agreement with numerical results!



Calculating the Boost $1 + B_0 \propto \frac{\langle \rho^2 \rangle}{\bar{\rho}^2}$



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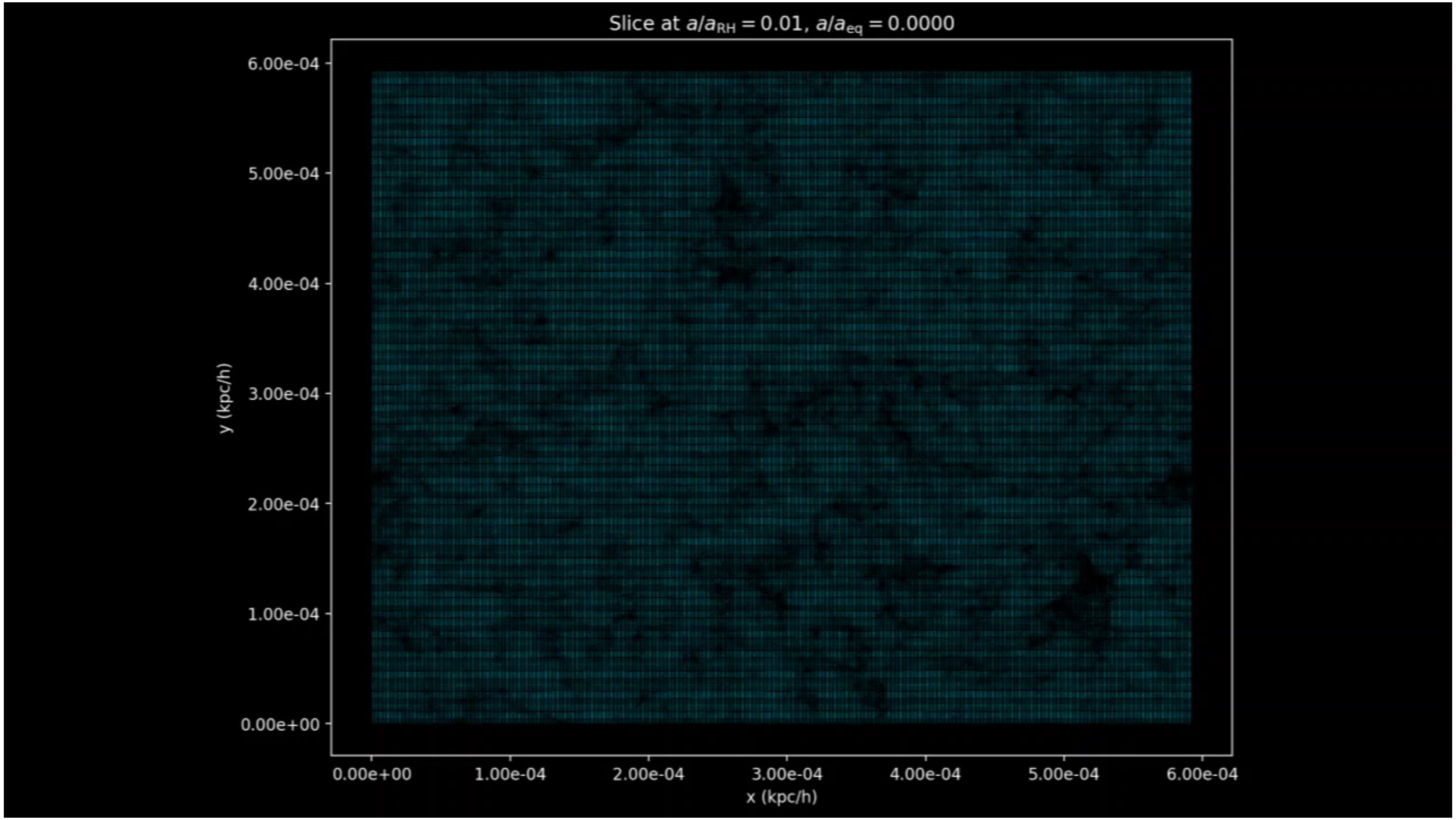
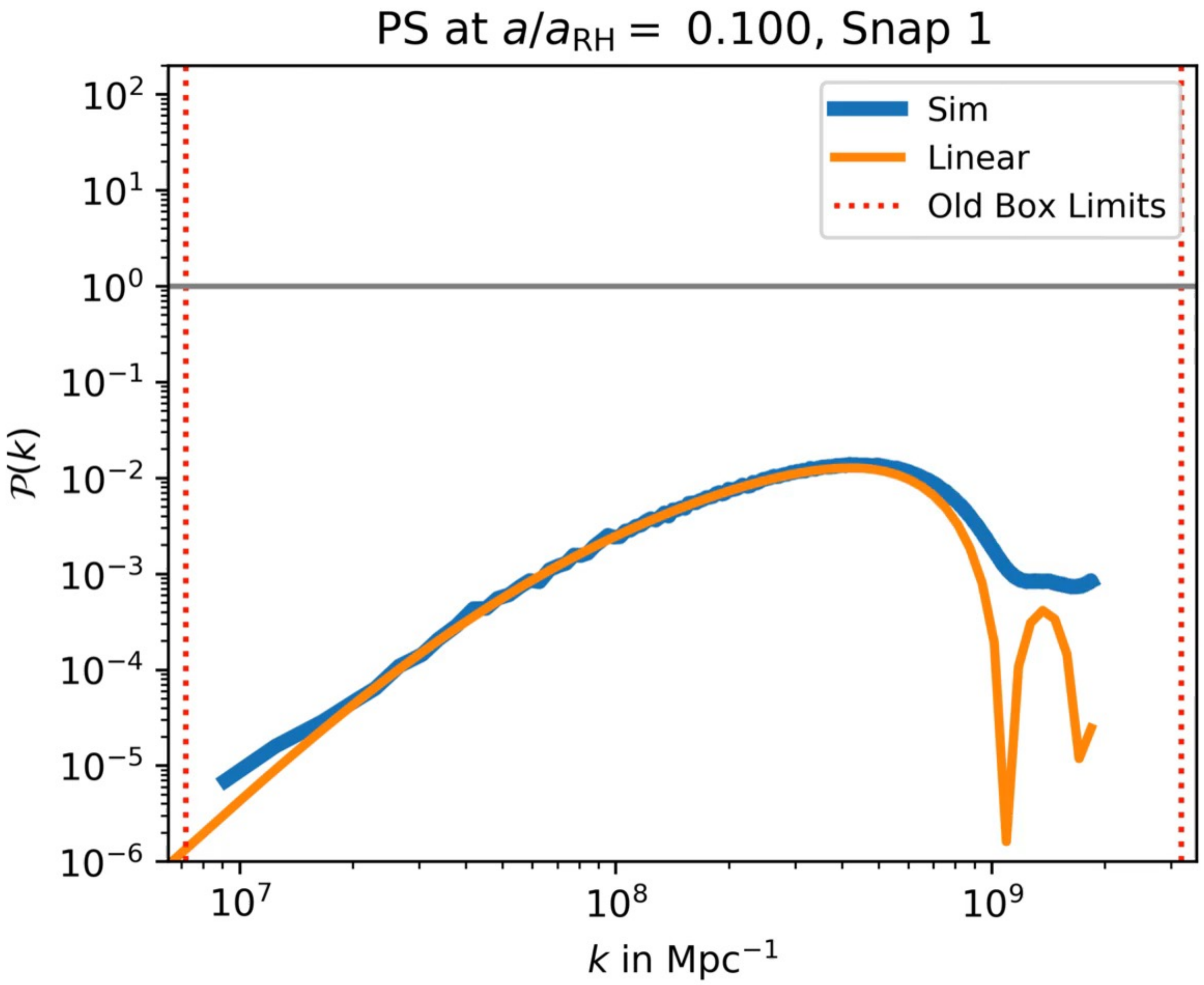
Gravitational Heating: Destroying Structure



Free-Streaming via Gravitational Heating



Summary

- We solved for the evolution in the density perturbations for this long-lived particle and DM, analyzing the suppression of perturbation growth due to the relativistic pressure of the Y particles.
- We provided transfer functions to reproduce the effect of the pressure of the dominant hidden sector particle on the matter power spectrum. We related the transfer function parameters to physical properties of the hidden sector.
- We have calculated the DM annihilation boost resulting from an EMDE using our transfer functions.
- Future work: simulating gravitational heating.

Observational Constraints

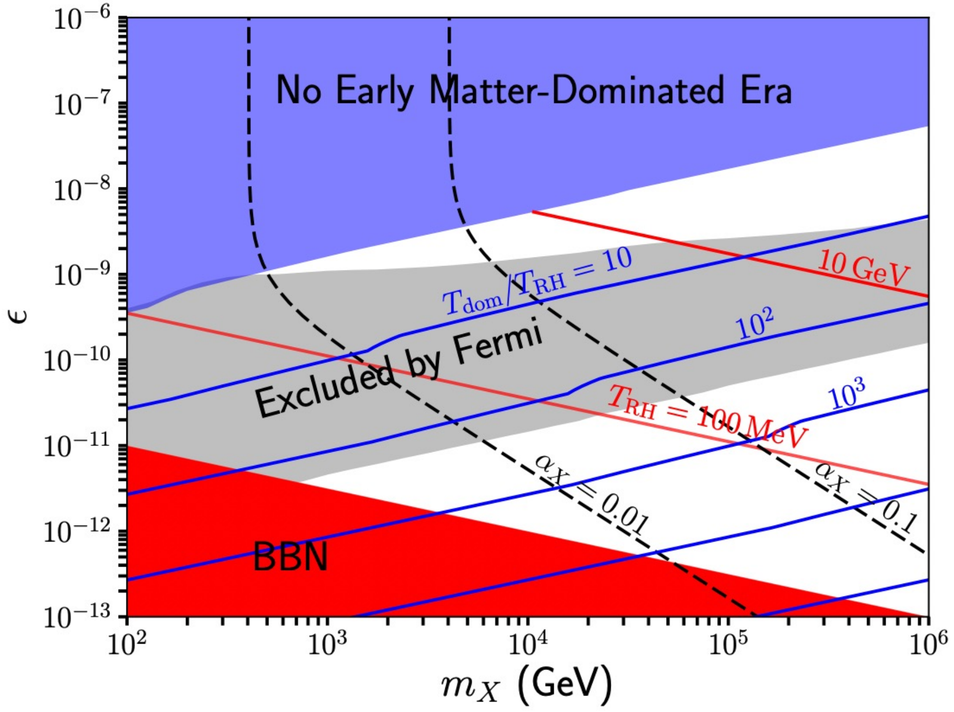


FIG. 5. Some of the features and constraints found across the parameter space of the vector portal dark matter model, for the case of $\xi_{\rm inf} = 1$ and $m_X/m_{Z'} = 20$. The dashed curves represent the regions of this plane which yield a relic abundance equal to the measured dark matter density, $\Omega_X h^2 \simeq 0.11$, for choices of $\alpha_X = 0.01$ and $\alpha_X = 0.1$. In the blue region, the hidden sector never dominates the energy density of the early universe, and the red region is excluded by the measured light element abundances and other cosmological considerations. Throughout the grey region, the EMDE leads to the formation and survival of a large population of microhalos, resulting in large boost factors (following our conservative procedure) that are currently ruled out by Fermi's measurement of the high-latitude gamma-ray background. In the lower right portions of this figure, gravitational heating leads to the suppression of this microhalo population, reducing the boost factors and resulting gamma-ray emission to acceptable levels. Note that in the lowest portions of the region labeled "No Early Matter-Dominated Era", the energy density of the Z' population is still sizable, leading to non-negligible contributions to the annihilation boost factor.

Blanco+ 2019 (1906.00010)

Constraints Using Fermi IGRB

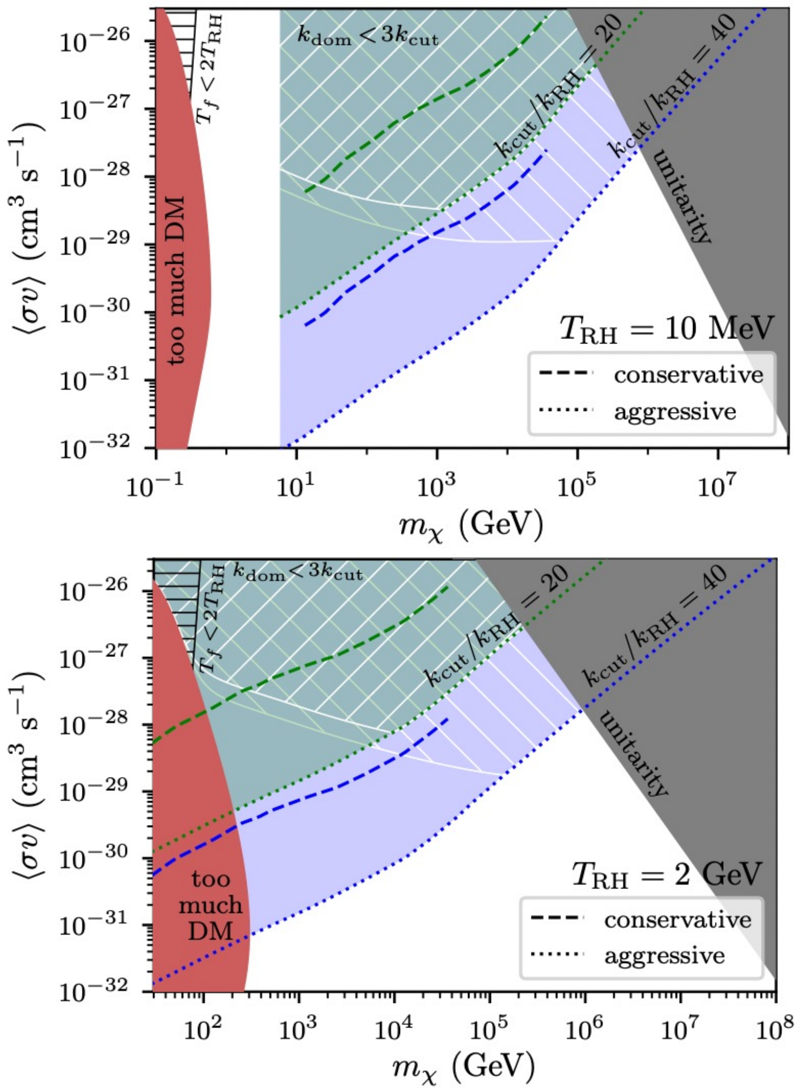


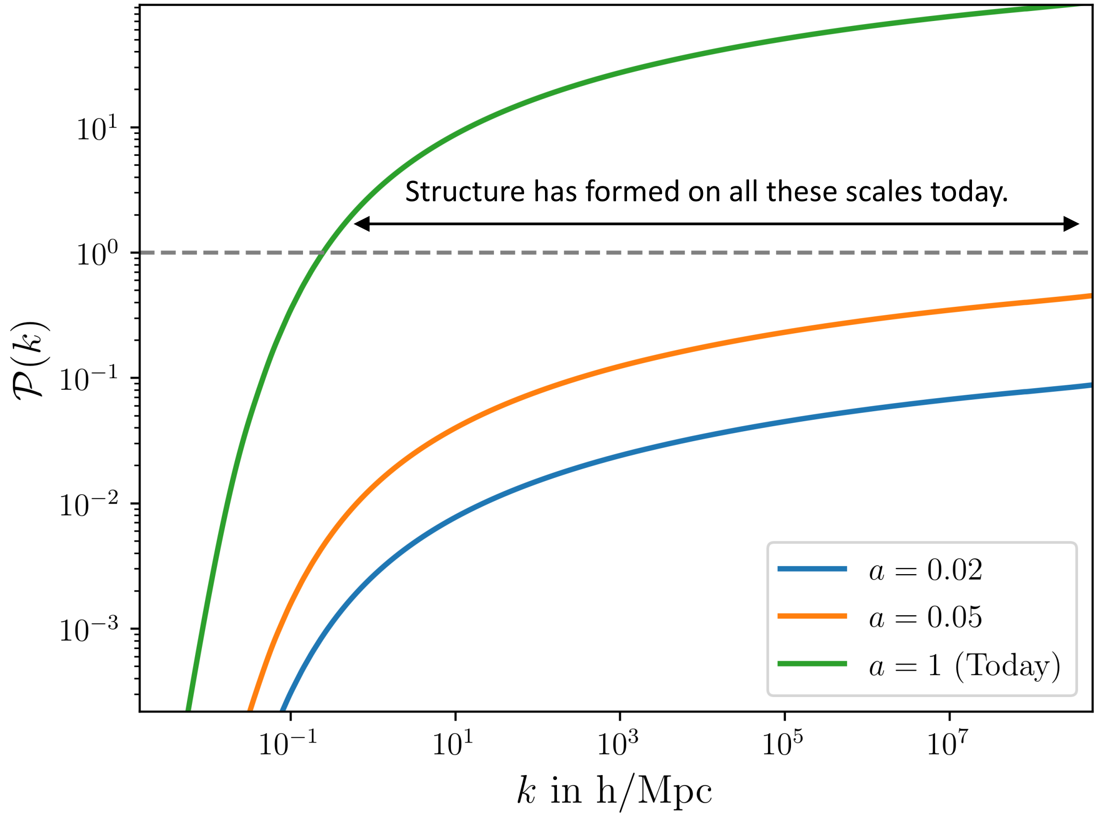
FIG. 9. Upper bounds on the cross section for dark matter annihilating to $b\bar{b}$ for two reheat temperatures $T_{\rm RH} = 10$ MeV (top) and $T_{\rm RH} = 2$ GeV (bottom). In each case, we consider both $k_{\rm cut}/k_{\rm RH} = 20$ (green) and $k_{\rm cut}/k_{\rm RH} = 40$ (blue) and plot both the conservative and aggressive bounds derived from Fermi-LAT's measurement of the IGRB; see the text. The shaded region on the left is disallowed because it would over-close the Universe, while the shaded region on the right marks where the dark matter's coupling constant exceeds unity. The black hatched region fails Eq. (2) while the white hatched regions (different for each $k_{\rm cut}/k_{\rm RH}$) fail Eq. (1). The density fluctuation power spectra we employed do not apply within these regions, so constraints therein are tentative; further work is needed to account for the altered power spectra.

Sten Delos+ 2020 (1910.08553)

Growth of Structure

Power spectrum: Measures the "clumpiness" of DM at a given time as a function of scale, in Fourier space.

Fourier transform of the two-point correlation function of the perturbation field.



Density perturbation:

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

$$\mathcal{P}(k, a) = \langle \delta^2(k, a) \rangle$$

When $\langle \delta \rangle \sim 1$ at any scale, the matter is dense enough to form a bound structure that remains bound by gravity and overcomes the expansion of the universe.