Imprints of Standard Model processes on the matter fluctuation spectrum

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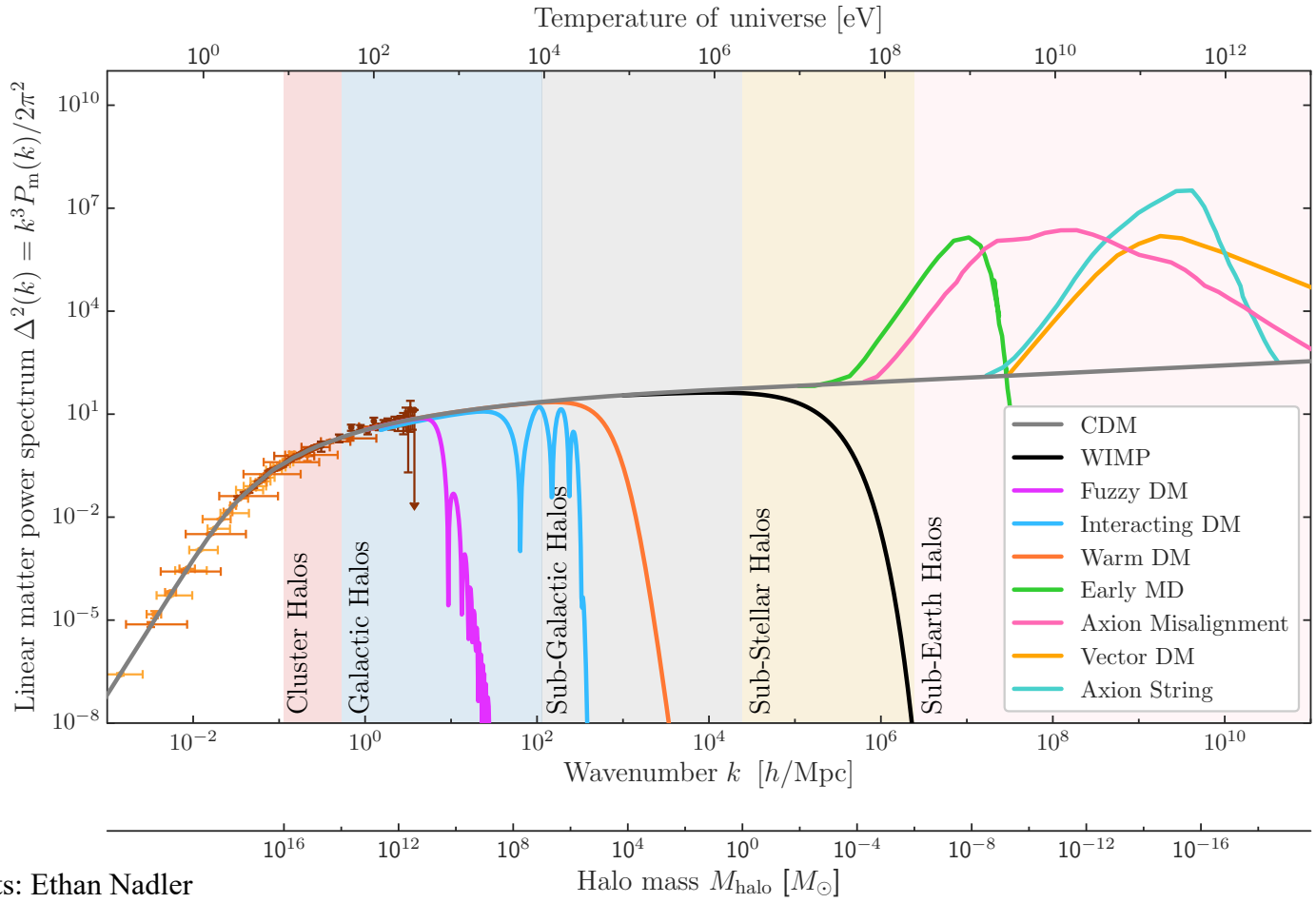
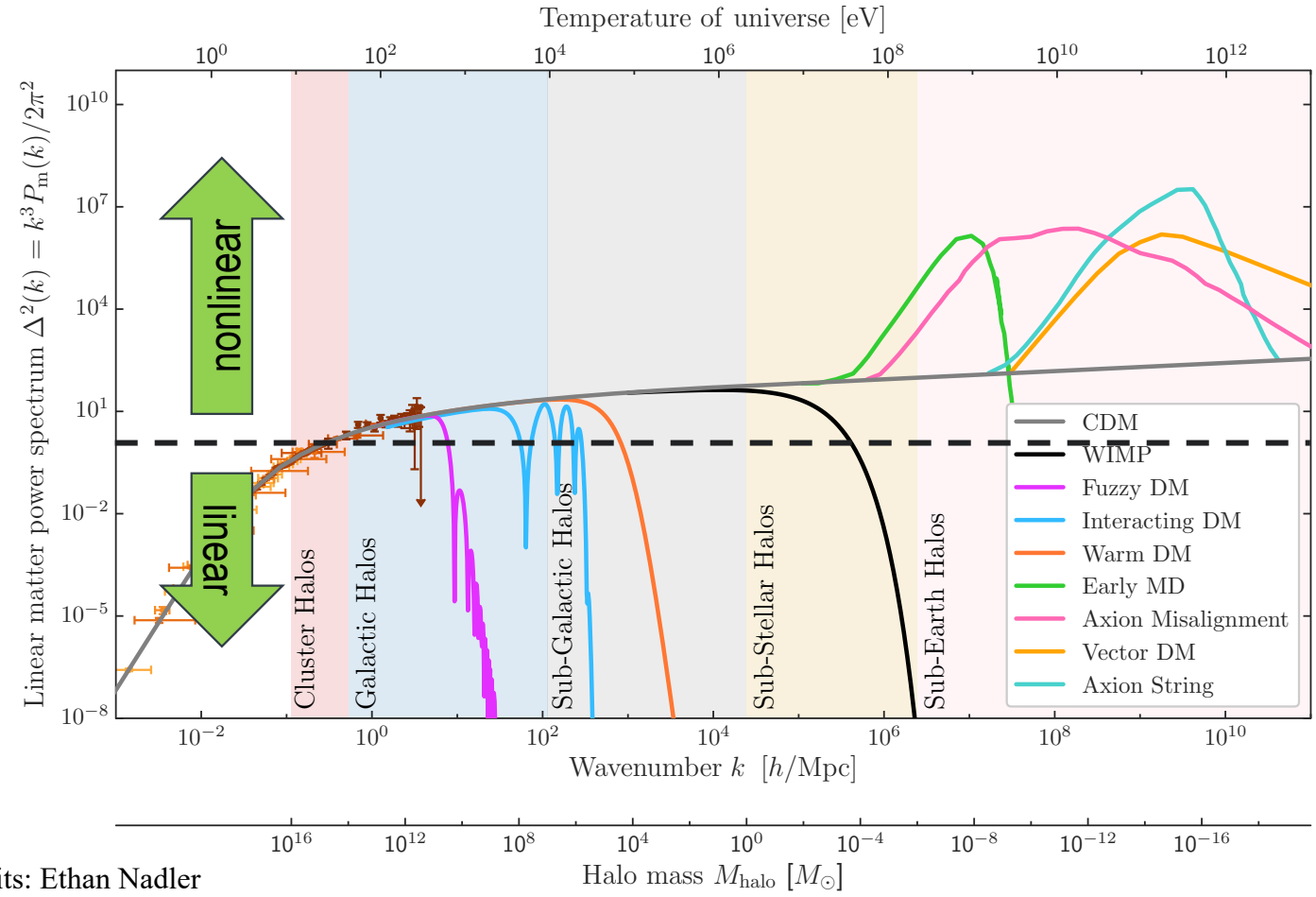
The spectrum of matter fluctuations



Credits: Ethan Nadler

The spectrum of matter fluctuations

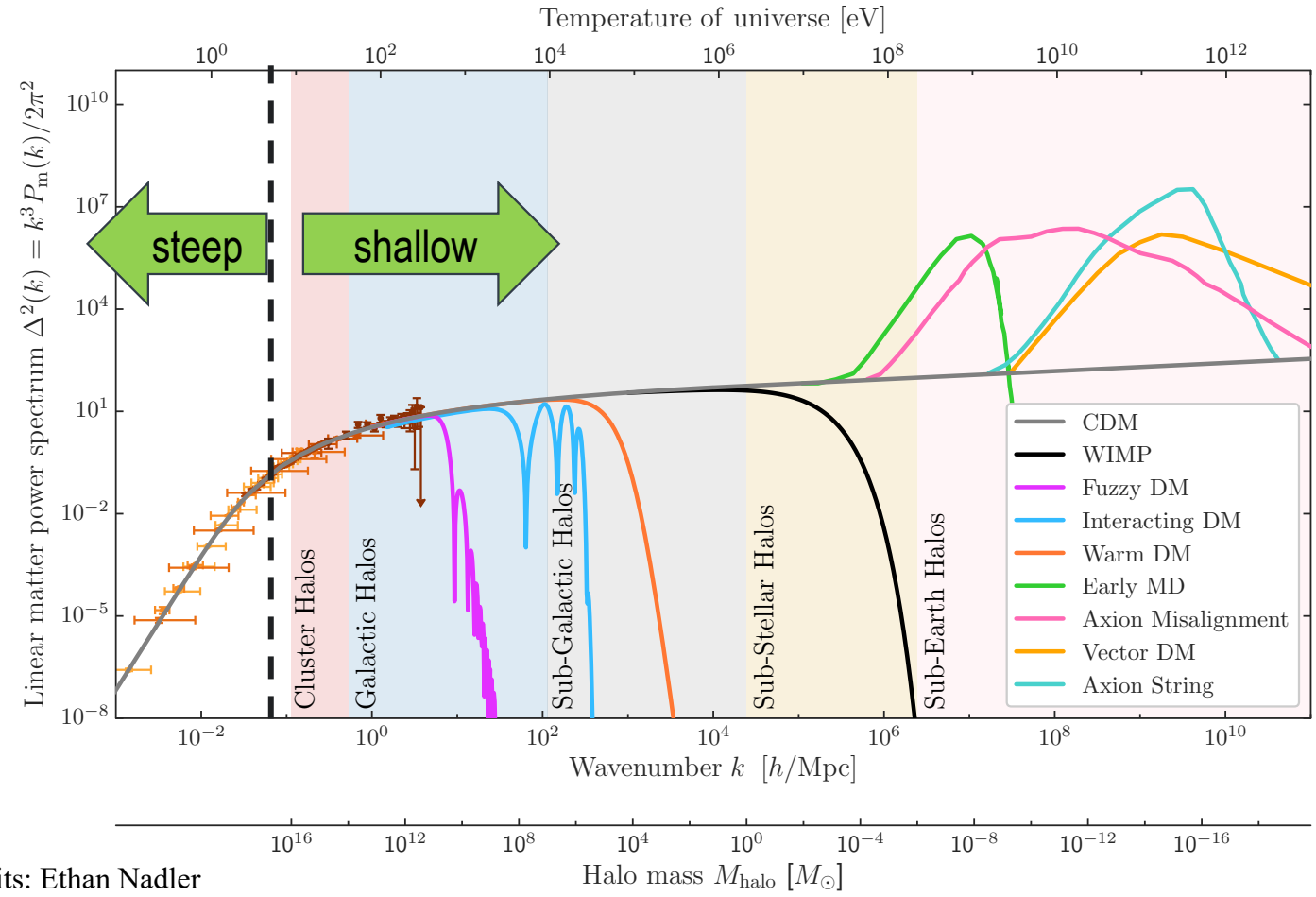
- Two regimes of structure formation: linear vs nonlinear



Credits: Ethan Nadler

The spectrum of matter fluctuations

- Two regimes of structure formation: steep vs shallow



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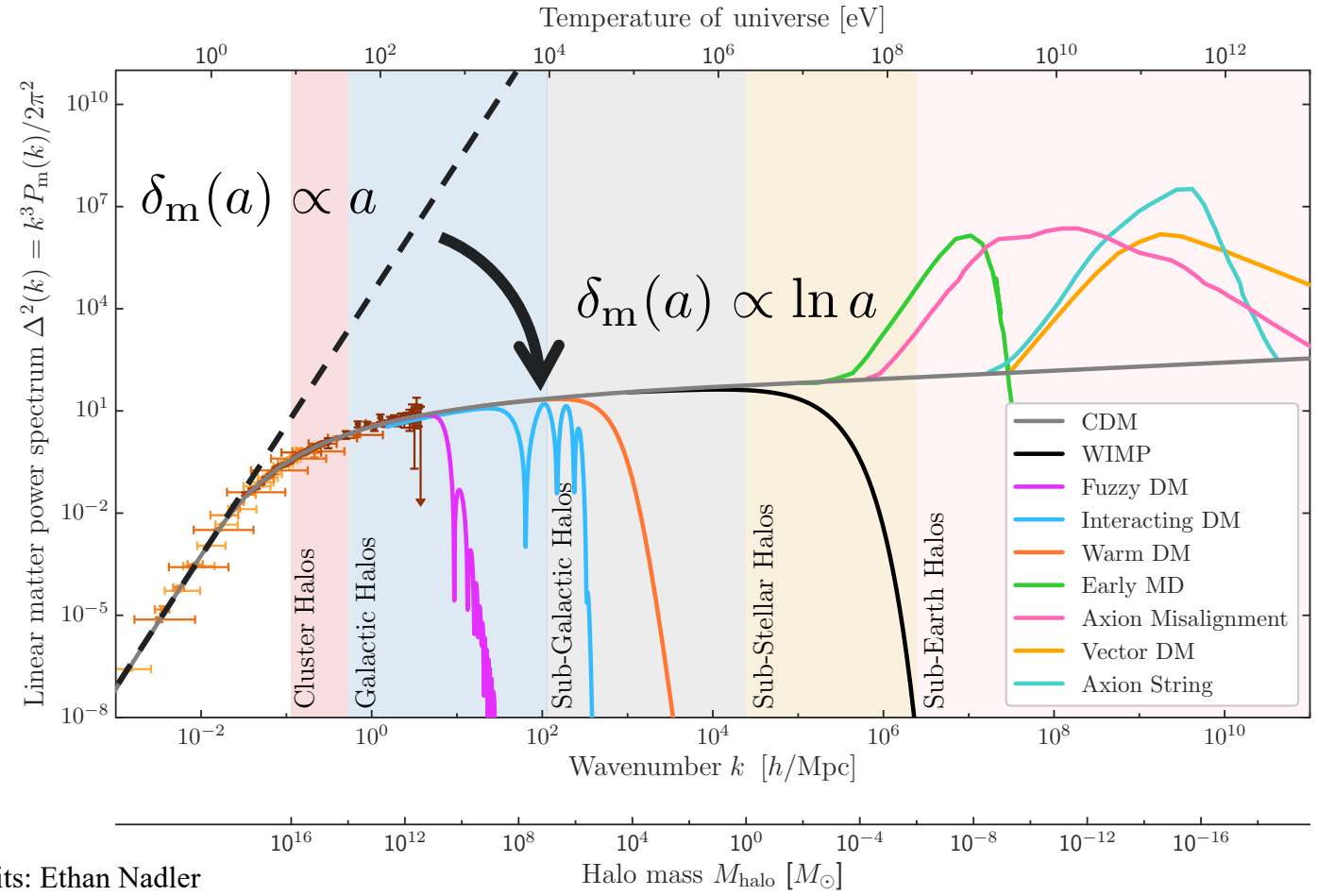
The spectrum of matter fluctuations

- Fluctuation amplitude reflects state of Universe when a scale becomes causal.



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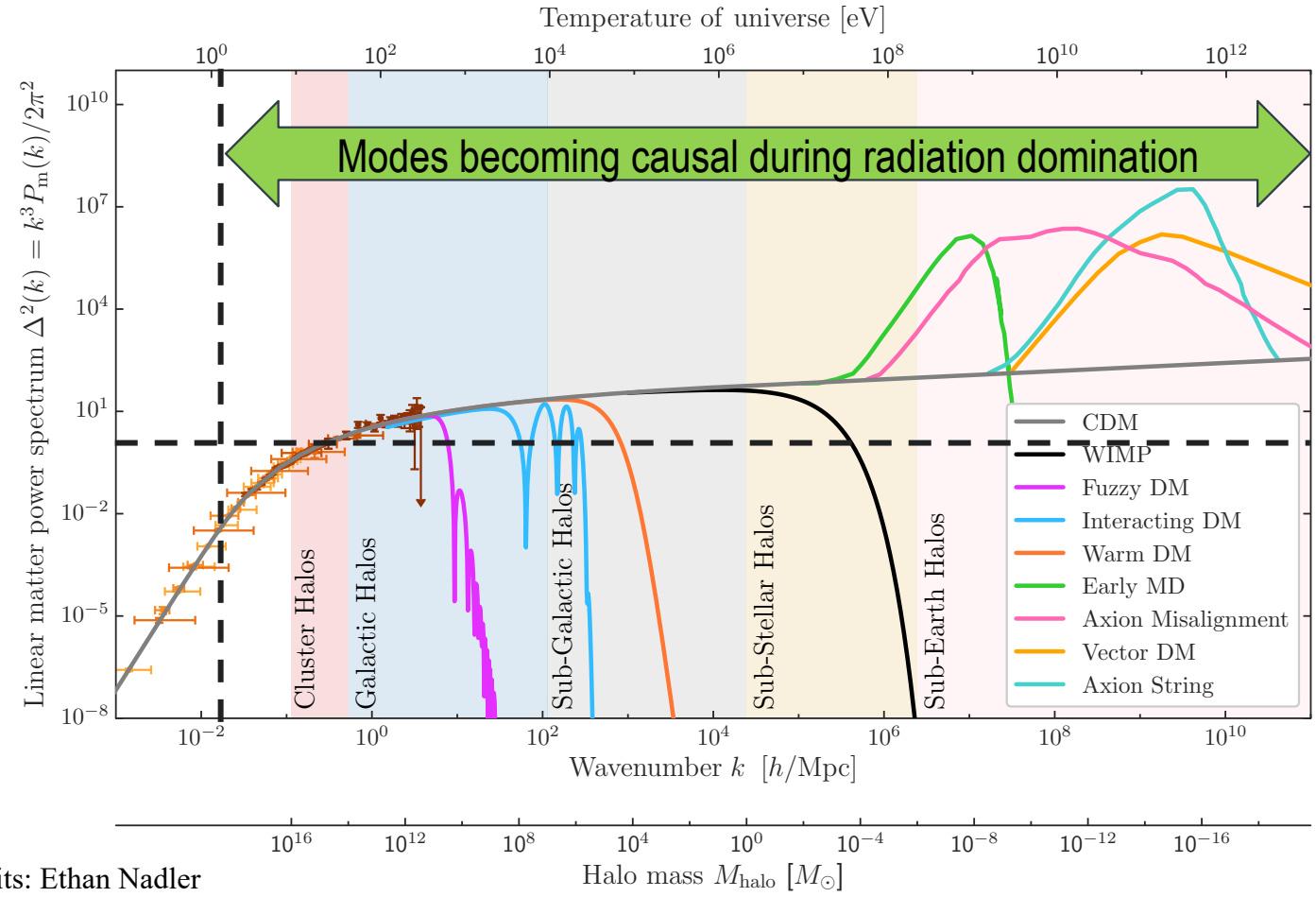
All astrophysical objects populating the cosmos come from initial fluctuations that started growing during radiation domination



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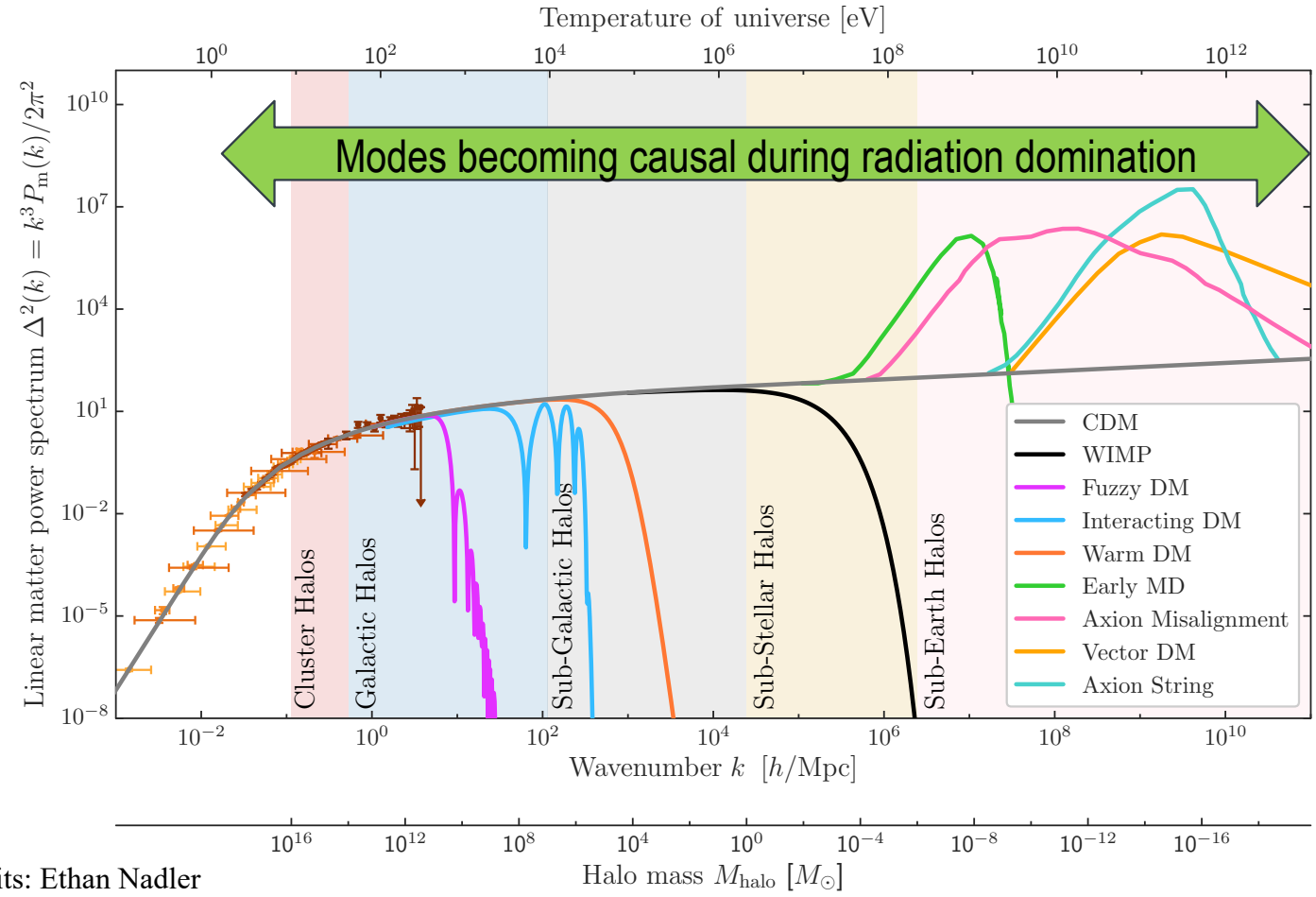
Must pay close attention to evolution of matter fluctuations in radiation domination



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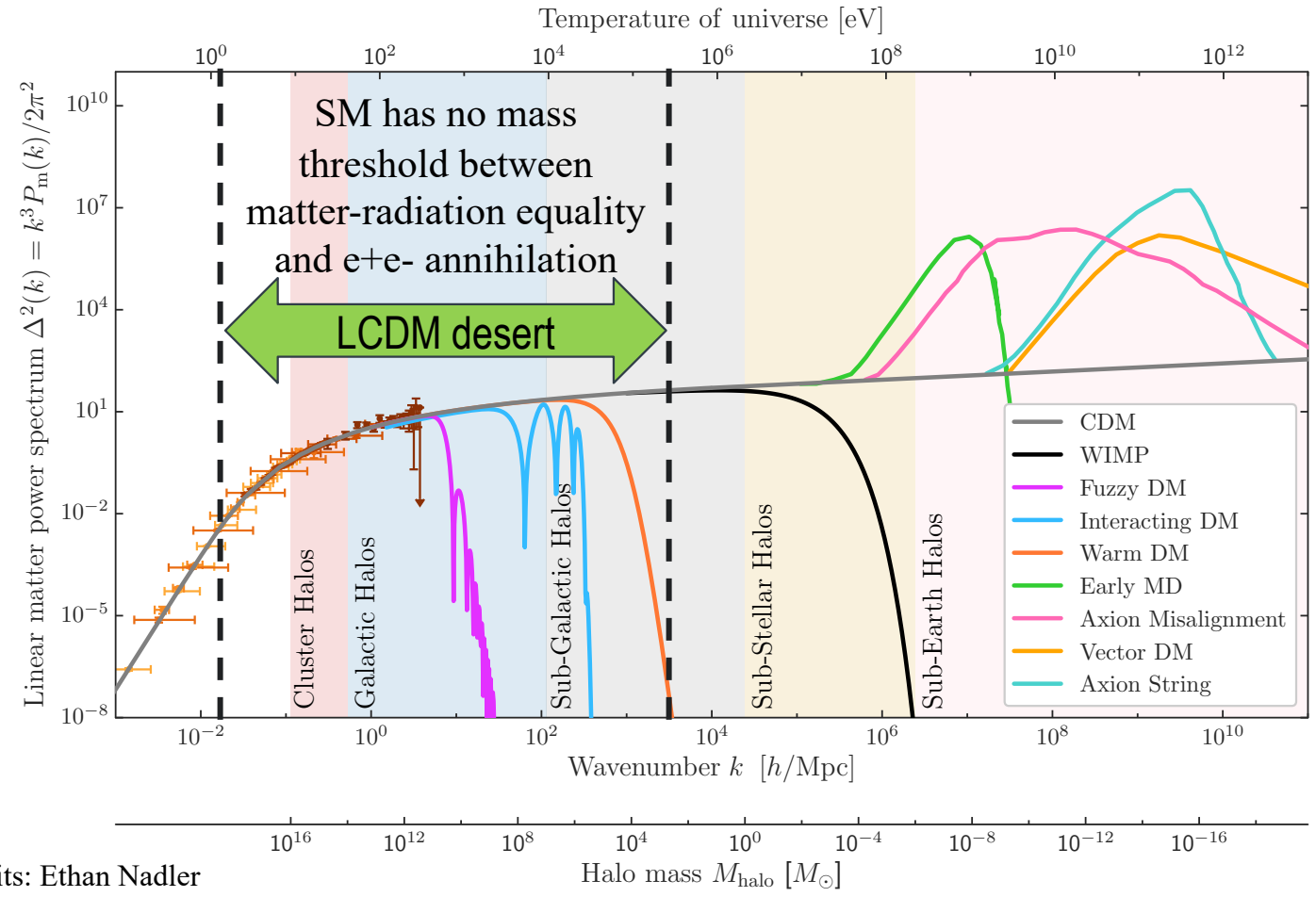
Why is the matter fluctuation spectrum so featureless at k > 0.1 h/Mpc?



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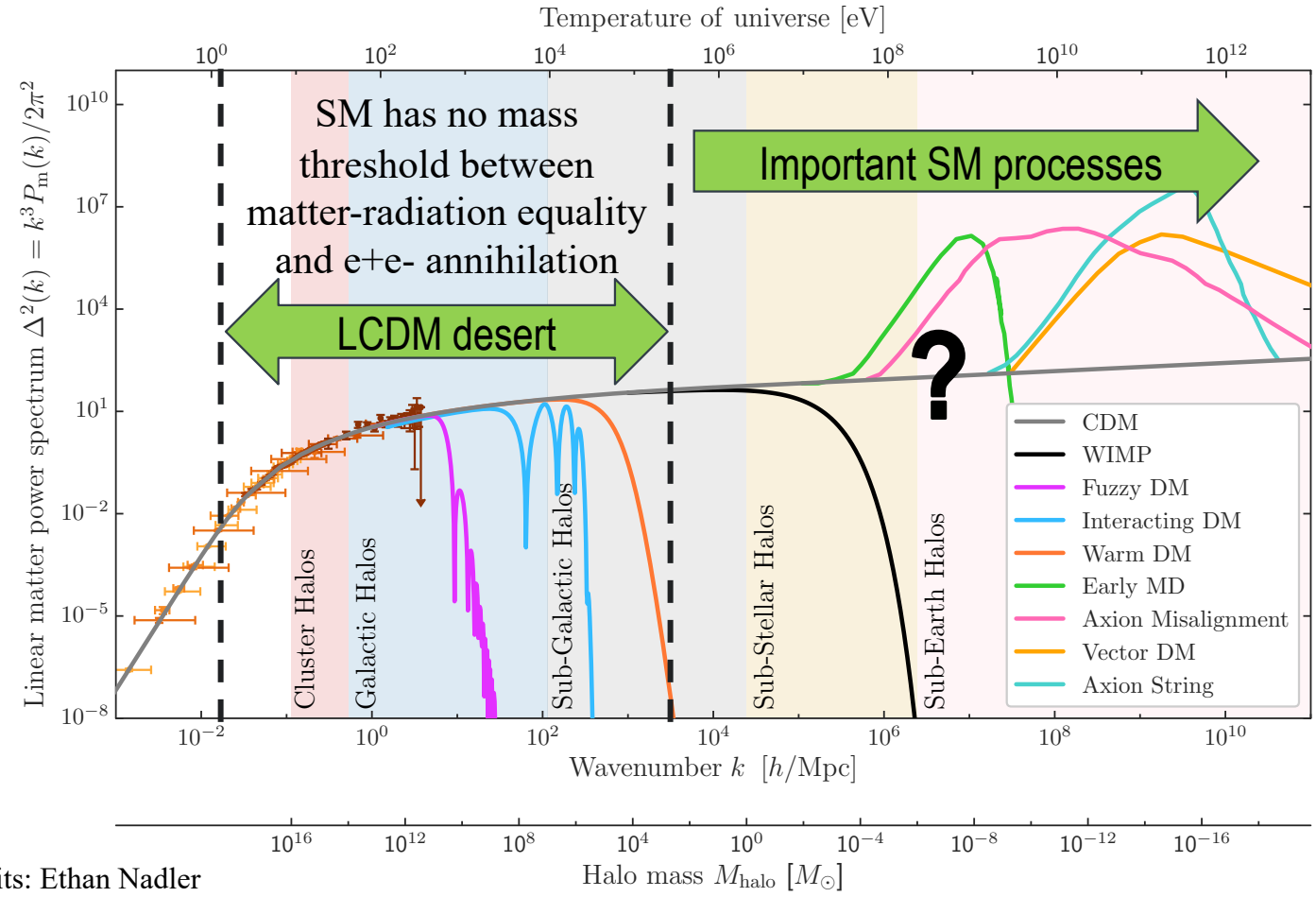
However, above $T_{SM} \sim m_e$ the SM goes through important mass/energy thresholds



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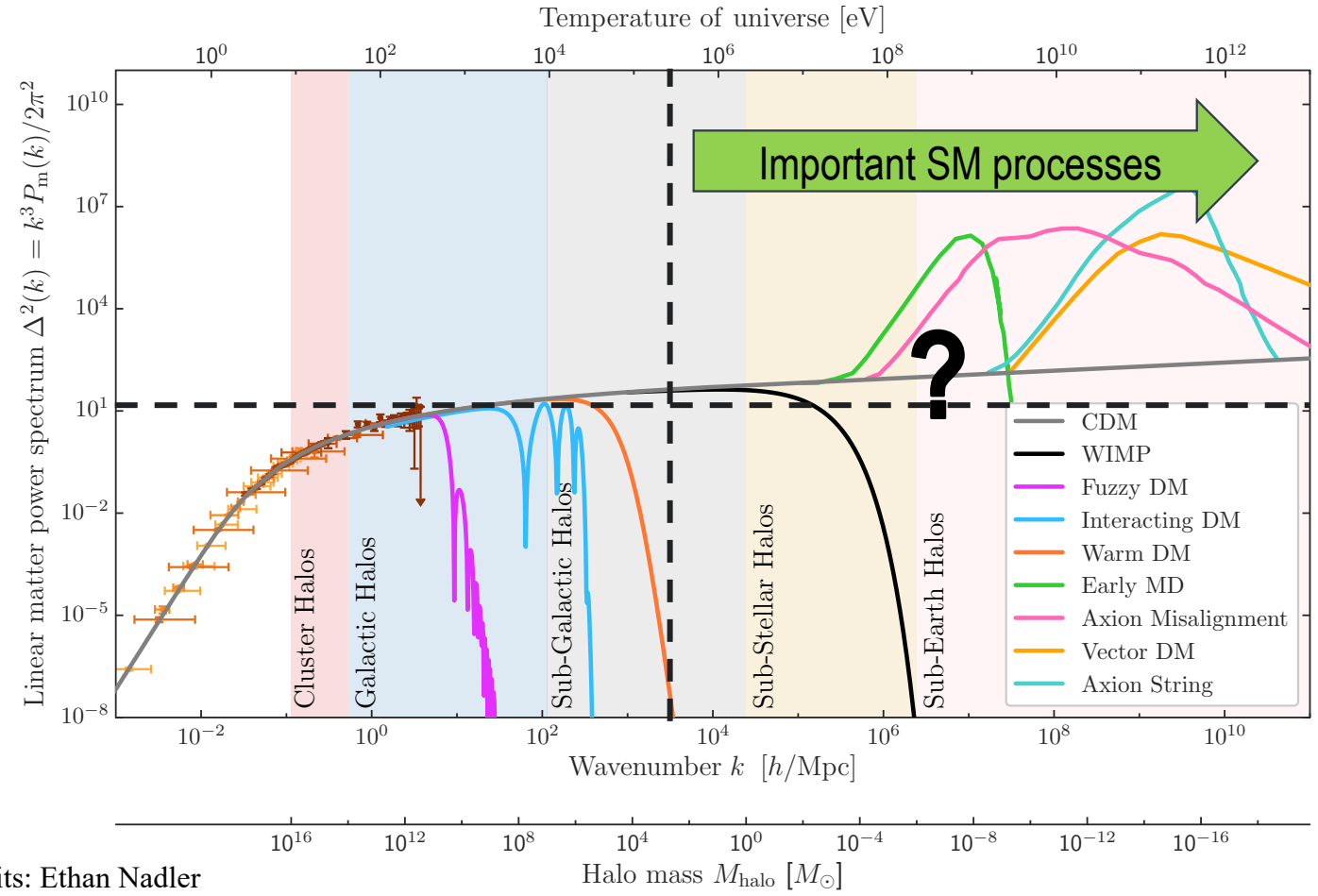
Why do we care? In the naïve featureless case, nearly all sub-galactic modes go nonlinear at the same time



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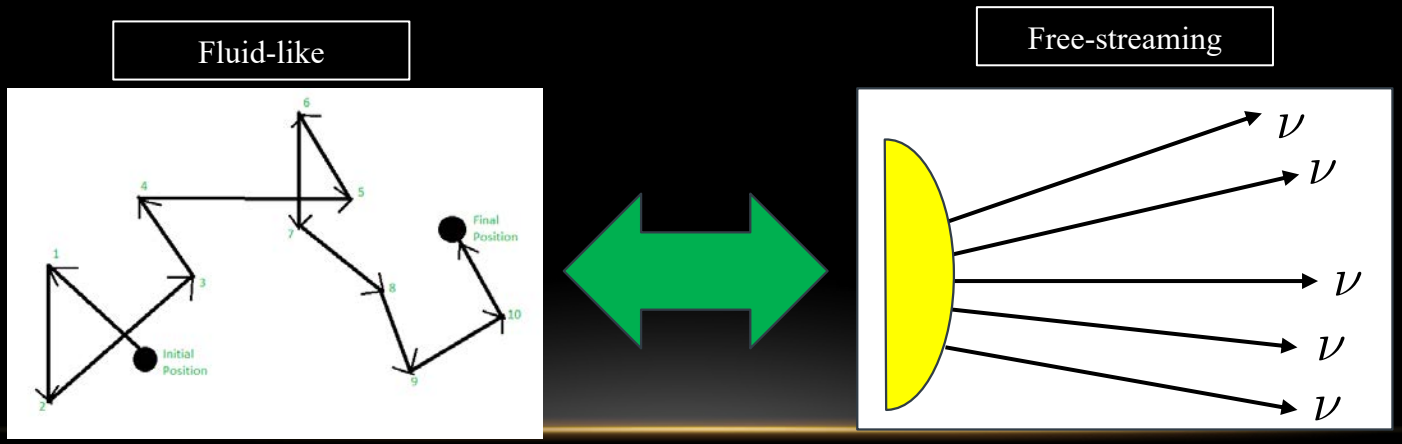
Two classes of SM effects for the high-k matter fluctuation spectrum

- Mass/energy thresholds (e.g. e+e- annihilation, **μ+μ-** annihilation, QCD, etc.) => rescales clock.

- Radiation behavior (e.g. fluid like vs free-streaming).

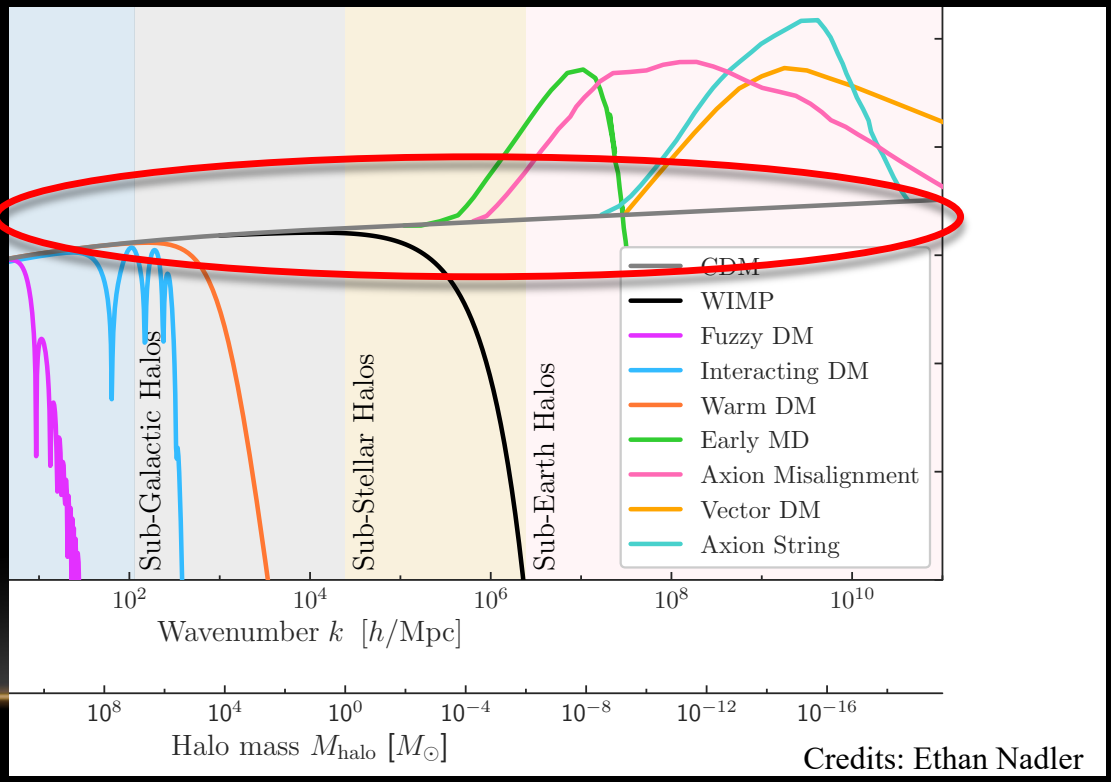


Mass/Energy Thresholds

- The very shallow, featureless high-k matter spectrum is the result of a scaling solution during radiation domination:

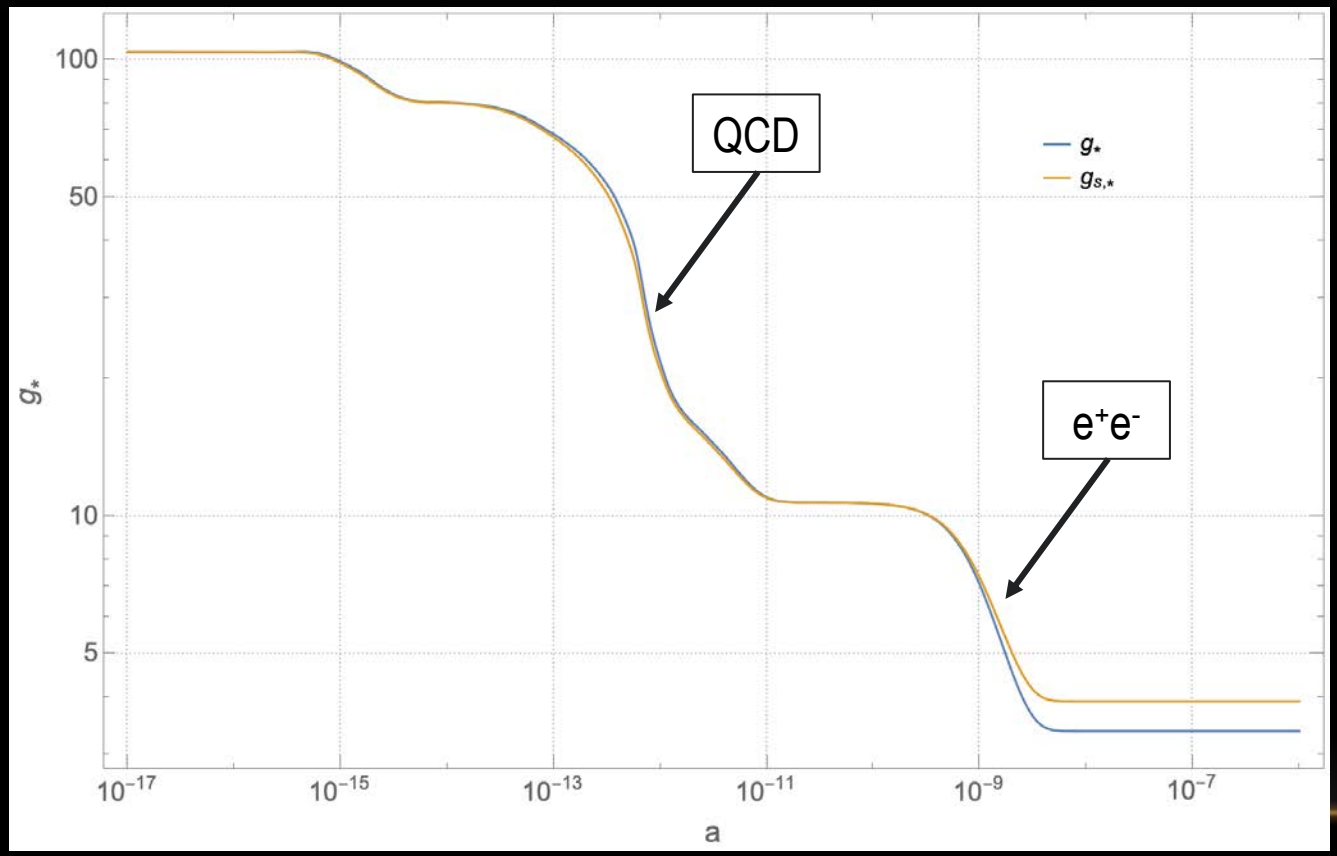
$$a^2 H = \text{constant}$$

This scaling is however broken when crossing mass thresholds.



Mass/energy thresholds in the SM

- This is usually described via the effective number of relativistic degrees of freedom:

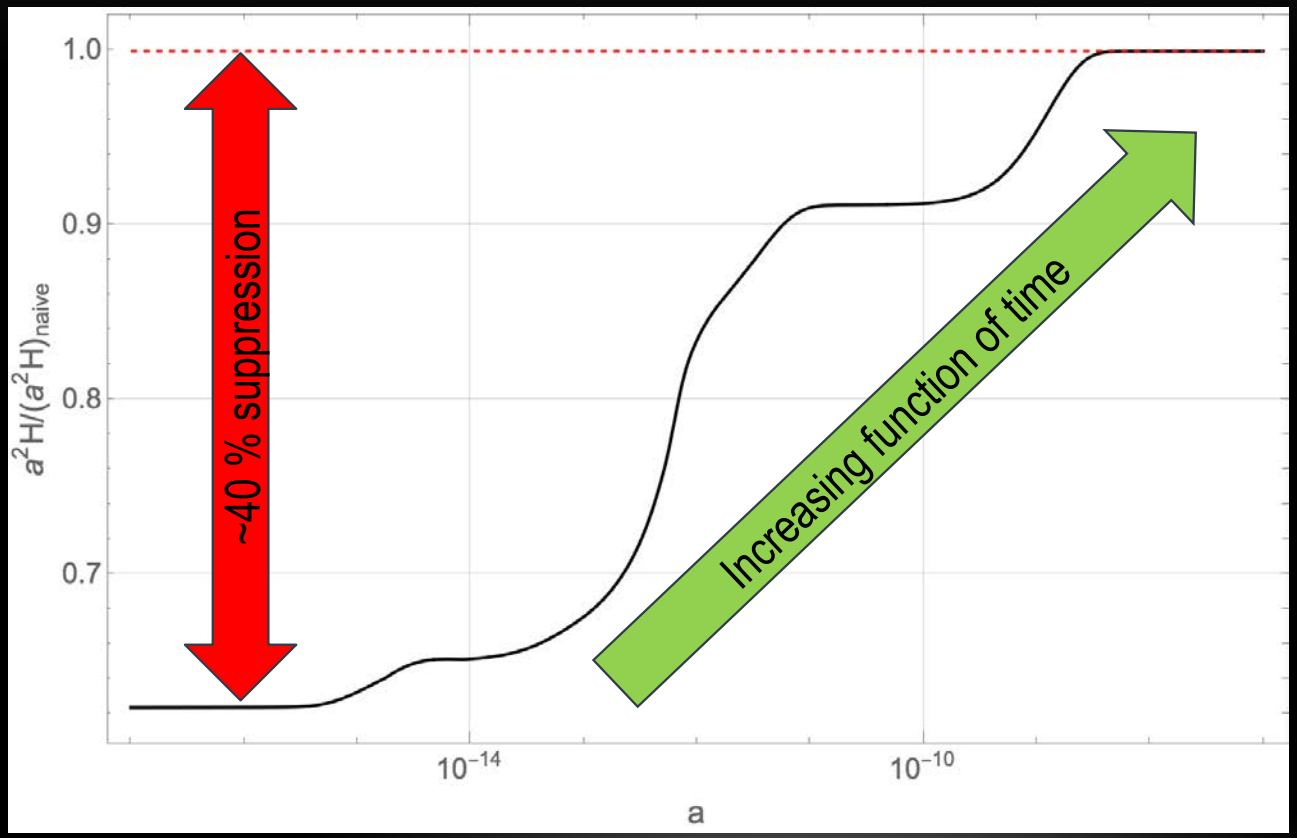


$$H \propto \frac{\sqrt{g_*(T)}T^2}{M_{\rm pl}}$$

$$g_{*s}(T)T^3a^3 = C$$

Mass/energy thresholds in the SM

- Breaking from the a^2H scaling behavior => modes enter the horizon earlier than predicted by naïve scaling



$$k = \frac{a^2 H}{a}$$

Earlier start of log growth for matter fluctuations!

Growth of dark matter fluctuations in radiation domination

- Breaking from the a^2H scaling behavior => modified growth for dark matter fluctuations*

$$d_{\rm c}'' + \left[\frac{1}{a} + \frac{d\ln\left(a^2H\right)}{da}\right] d_{\rm c}' = \frac{1}{2}\frac{k^2\Phi_+}{(a^2H)^2}$$

Extra damping contribution

Boost of the source term

$$\Phi_+ = \phi + \psi$$

$$d_{\rm c} = \frac{n_{\rm c} - \bar{n}_{\rm c}}{\bar{n}_{\rm c}} = \delta_{\rm c} - 3\phi$$

*: prime symbol means scale factor derivative

Growth of dark matter fluctuations in radiation domination

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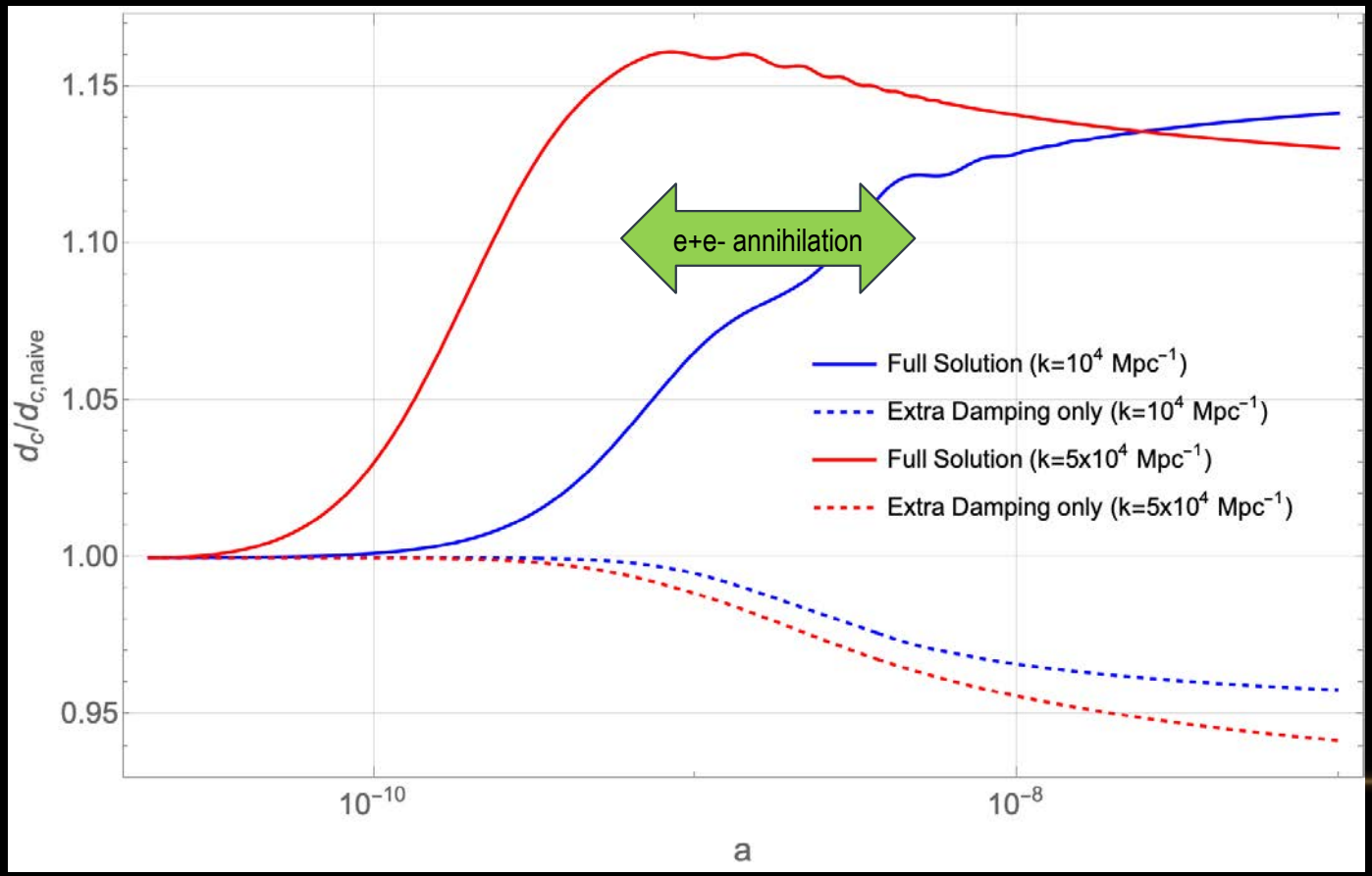

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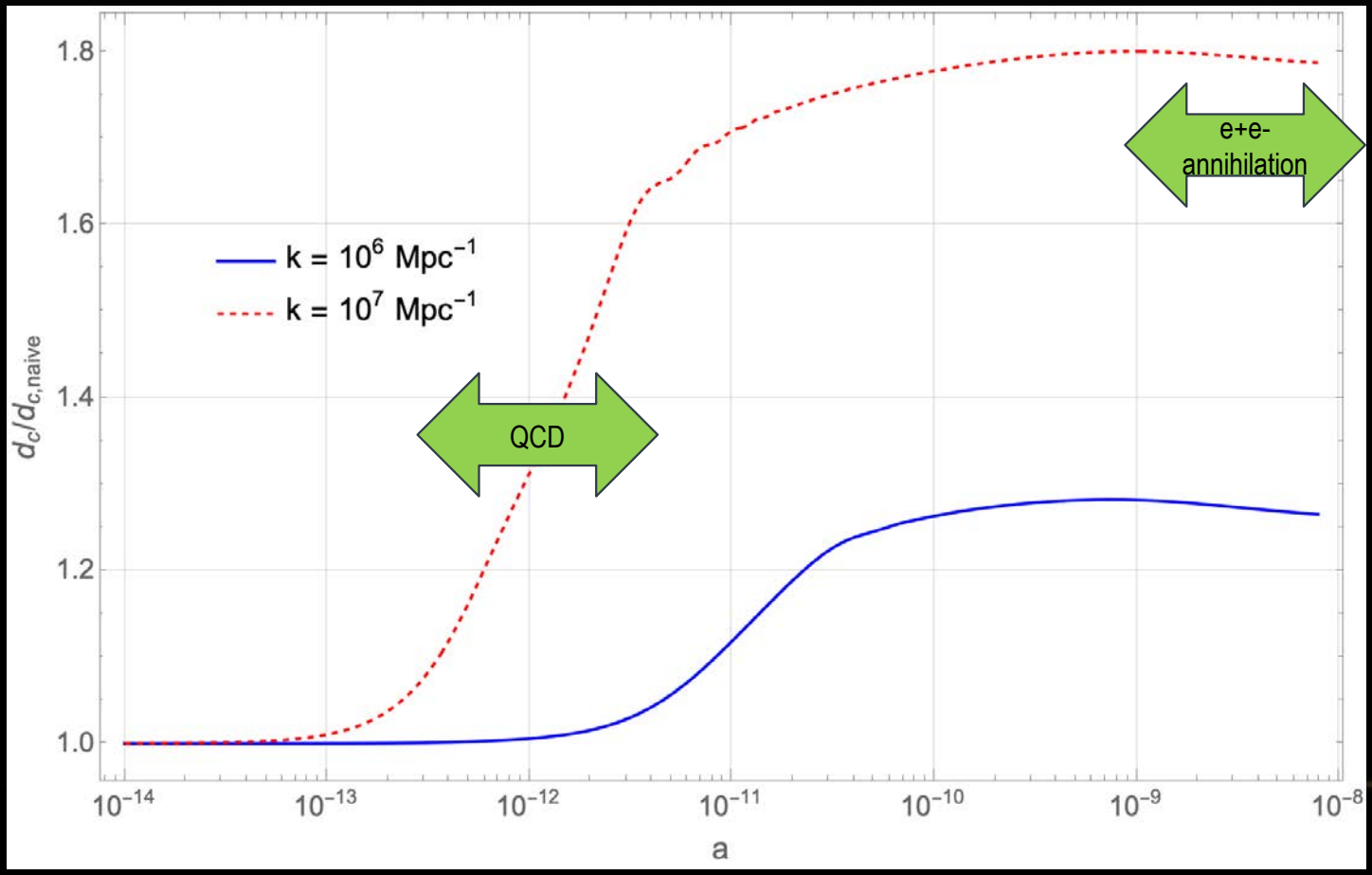
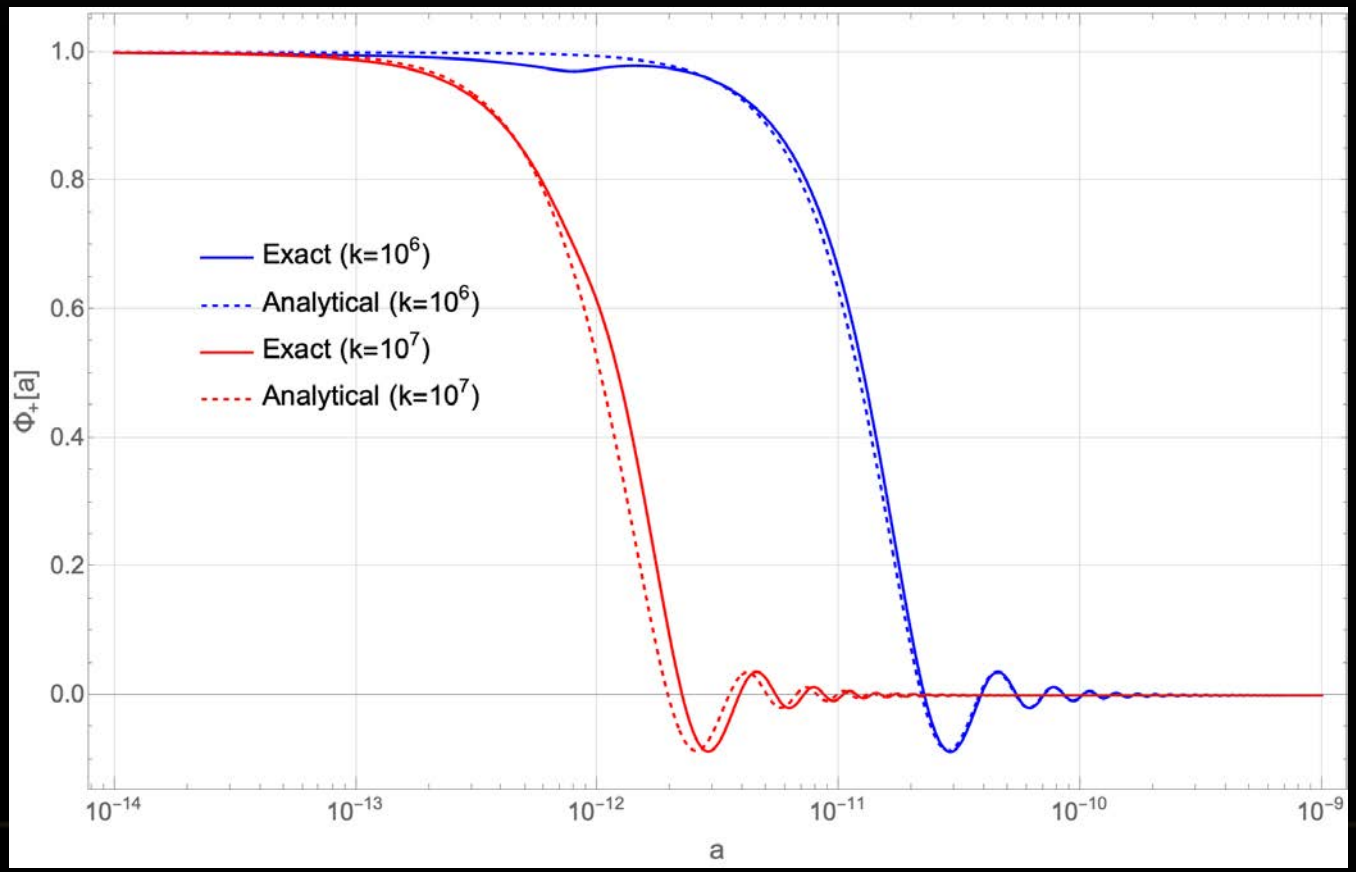


Growth of dark matter fluctuations in radiation domination

- Breaking from the a^2H scaling behavior => modified gravitational potential



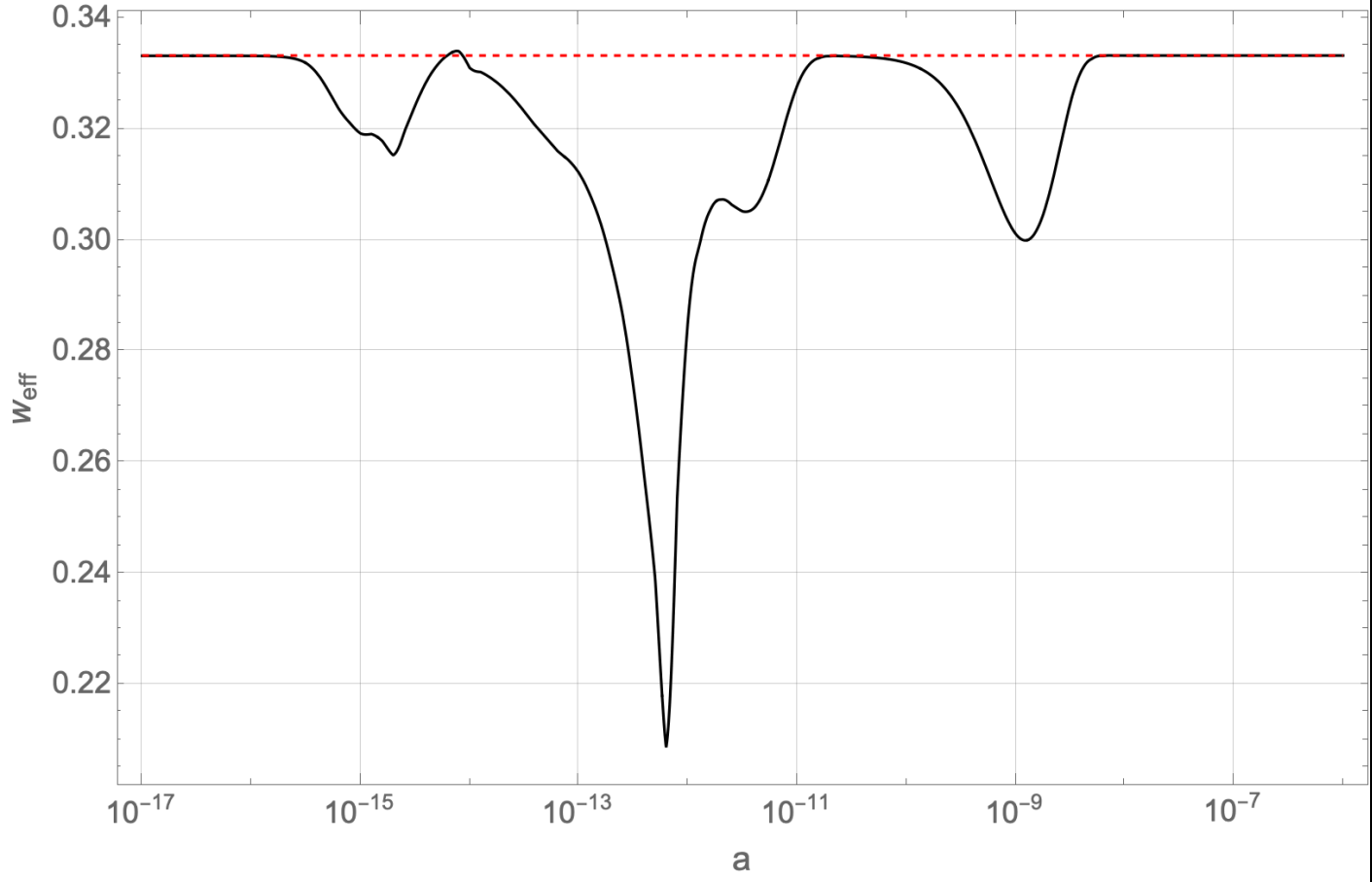
Impact of mass/energy thresholds on dark matter fluctuations

- Modes entering the horizon while a^2H is increasing experience a boost in growth, due to the effective equation of state falling below 1/3.

$$w_{\rm eff} = \frac{1}{3}\left[1 - 2\frac{d\ln\left(a^2 H\right)}{d\ln a}\right]$$

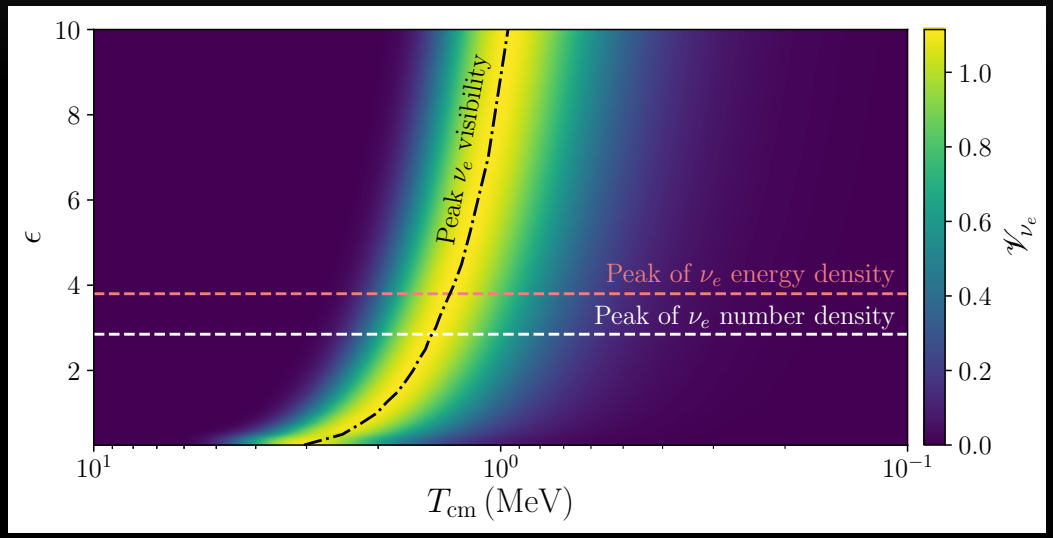
- For subhorizon modes, a^2H increasing leads to a reduced growth of dark matter fluctuations.

Effective equation of state



Impact of radiation behavior: Onset of neutrino free-streaming

- Neutrinos => first species to free-stream in the Universe



- Growth of neutrino anisotropic stress

Bond et al. (2024)

$$\Phi_- = -12\pi G a^2 (\bar{\rho}_\nu + \bar{p}_\nu)\sigma_\nu$$

$$\Phi_- = \phi - \psi$$

Impact of radiation behavior: Onset of neutrino free-streaming

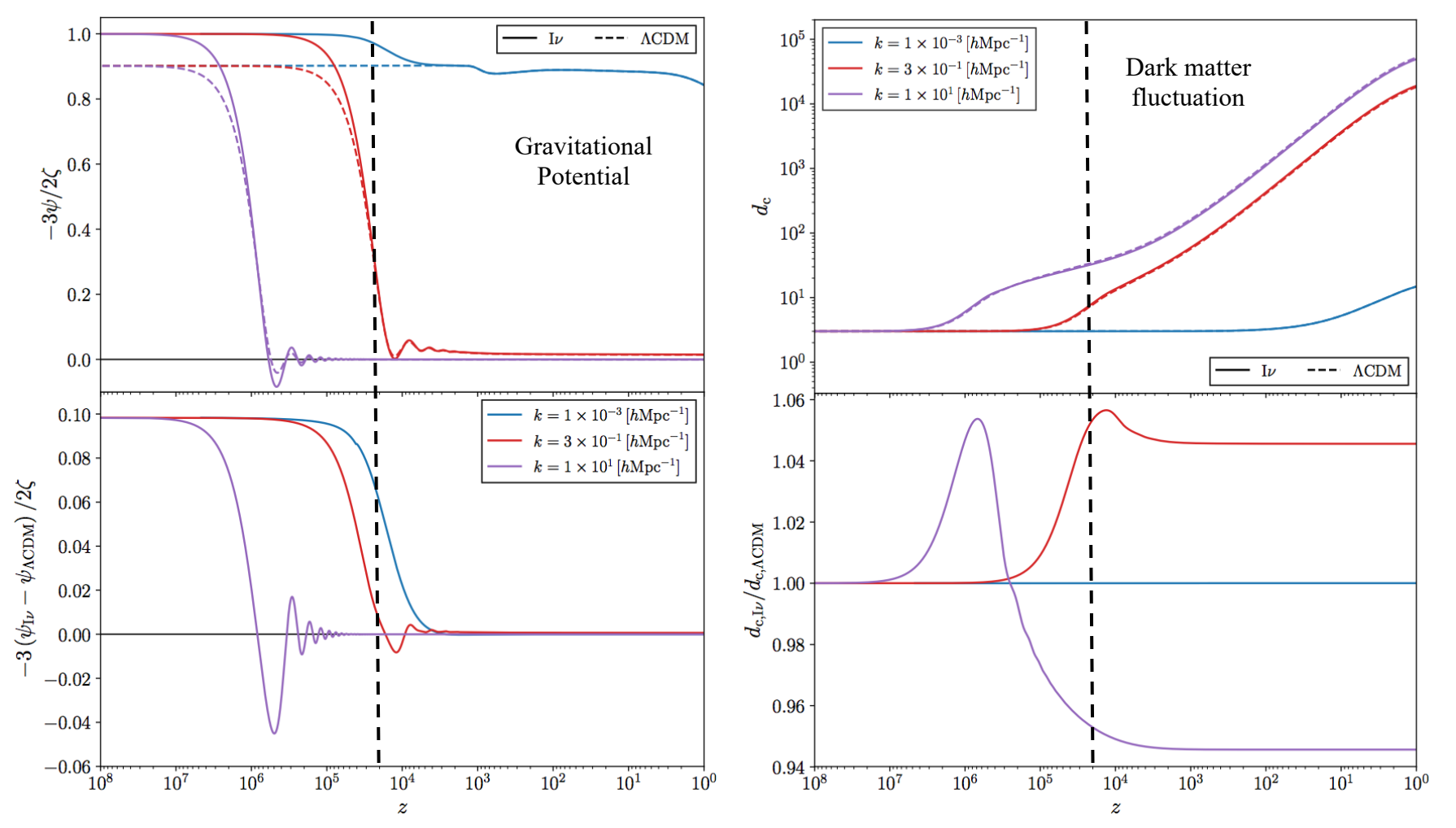
- Before neutrino decoupling:

$$d_{\rm c}'' + \left[\frac{1}{a} + \frac{d\ln\left(a^2 H\right)}{da}\right] d_{\rm c}' = \frac{1}{2}\frac{k^2 \Phi_+}{\left(a^2 H\right)^2}$$

- After neutrino decoupling (usually what we solve for in CMB and LSS analyses):

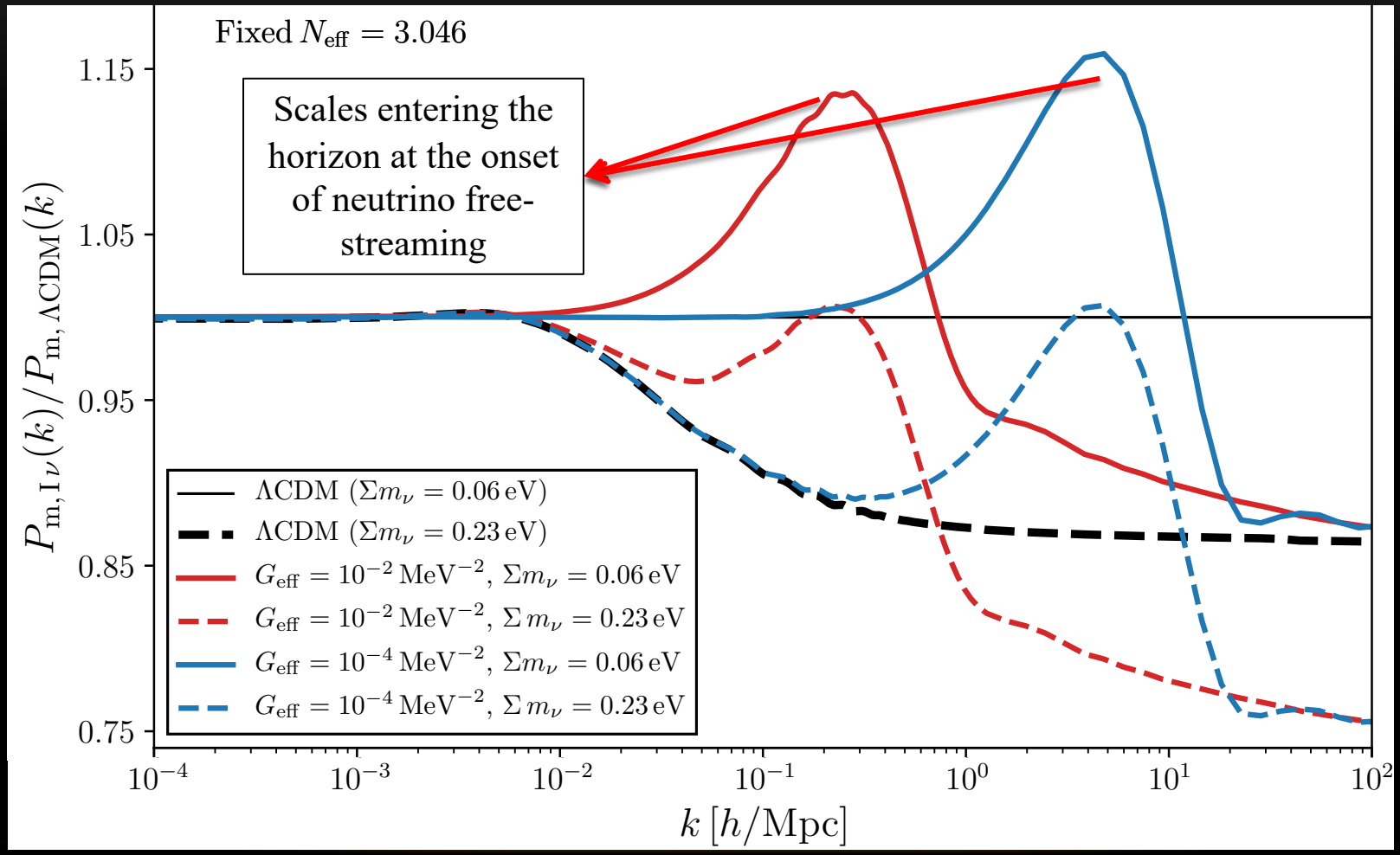
$$d_{\rm c}'' + \left[\frac{1}{a} + \frac{d\ln\left(a^2 H\right)}{da}\right] d_{\rm c}' = \frac{1}{2}\frac{k^2 \left(\Phi_+ - \Phi_-\right)}{\left(a^2 H\right)^2}$$

Impact of neutrino decoupling on matter clustering



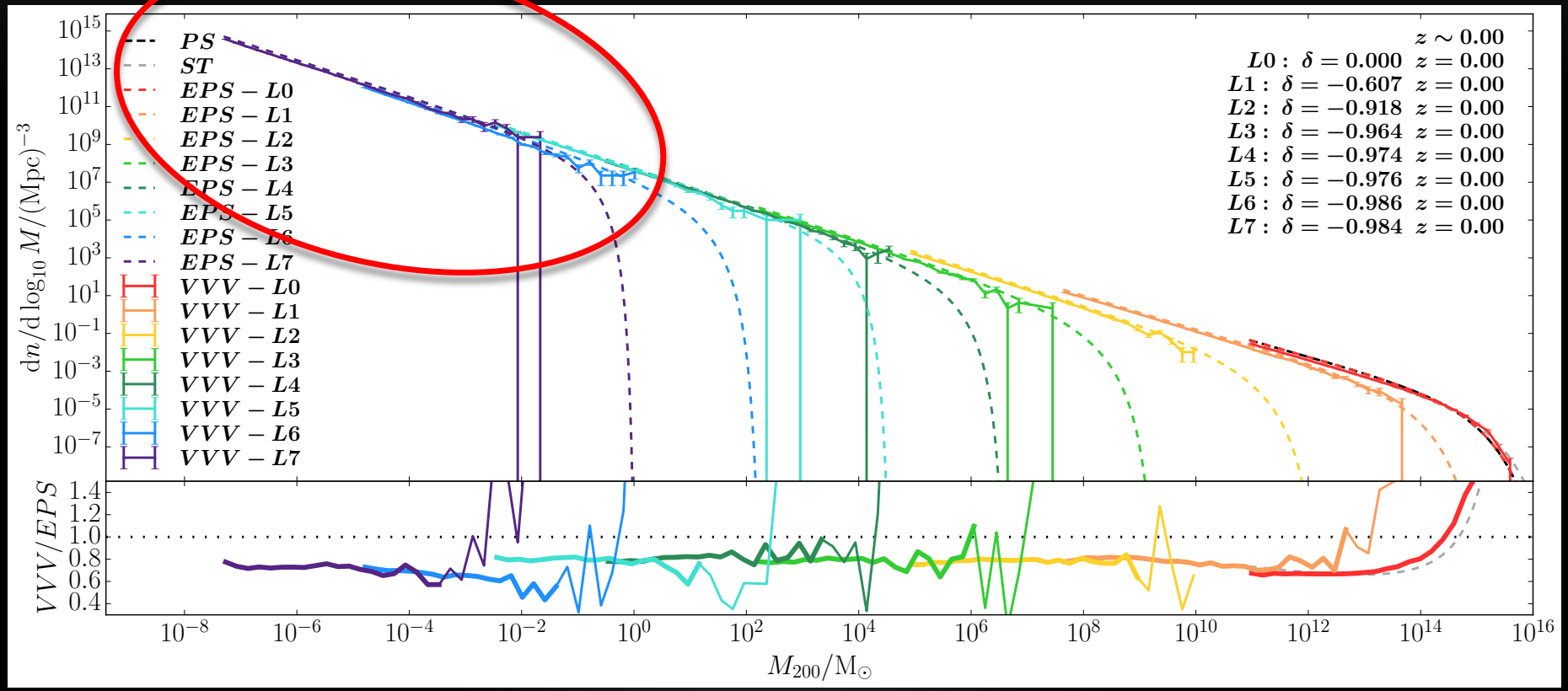
Kreisch, Cyr-Racine, Doré (2020)

Example of impact of neutrino decoupling



Kreisch, Cyr-Racine, Doré (2020)

Impact: Features in the mass function at small masses



Zheng et al. (2024)

Conclusions

- All dark matter halos comes from fluctuations that entered the horizon during radiation domination.
- Above the LCDM desert, SM processes will break the scaling solution, introducing features in the matter power spectrum.
- From background effects, we generally expect an enhancement of power for modes entering the horizon before e+e- annihilation.
- On the other hand, modes at $k > 10^4$ h/Mpc (i.e. becoming causal before neutrino streaming), do not get the ”free-streaming” boost.
- Stay tuned for net effect!