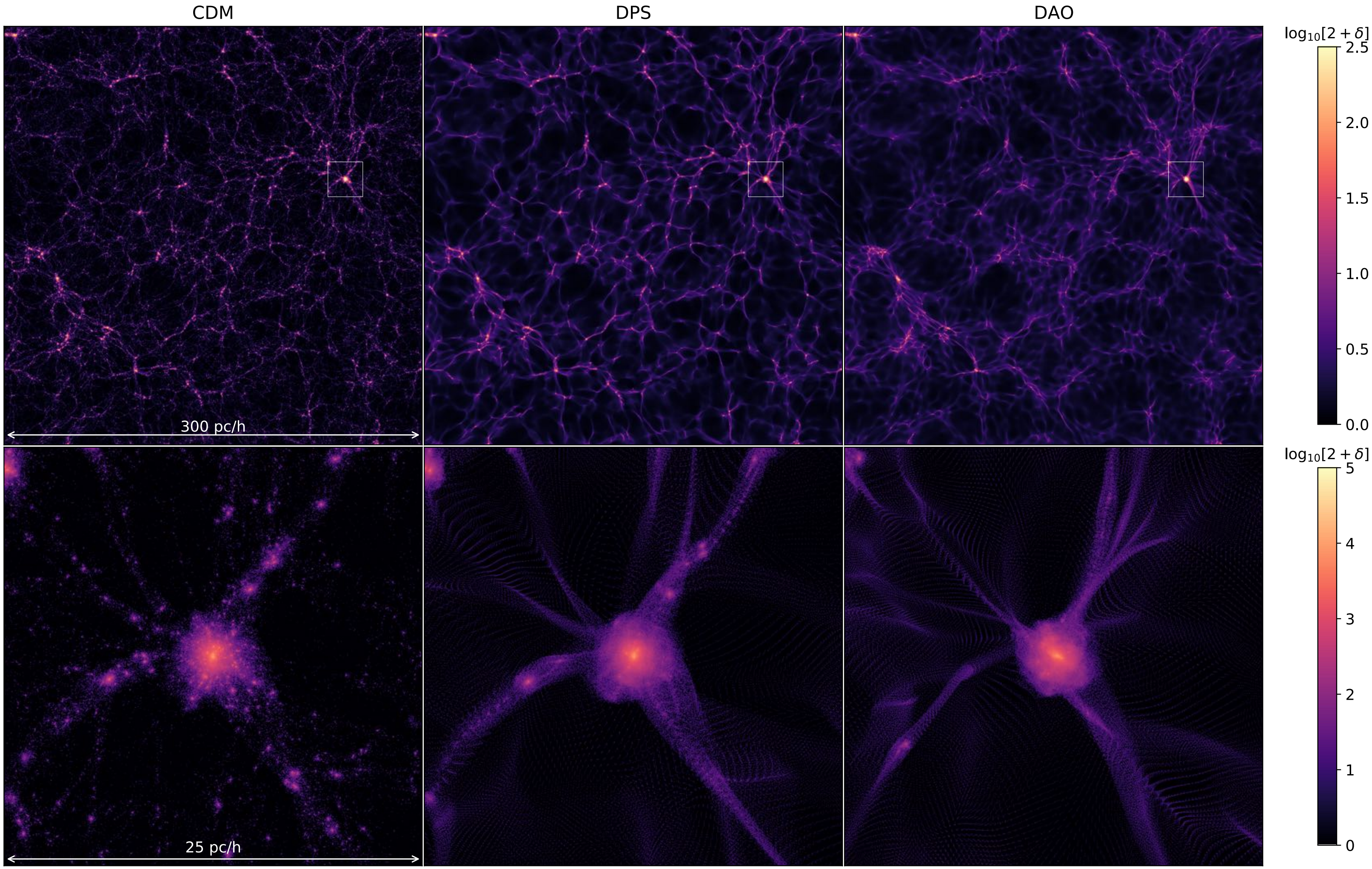


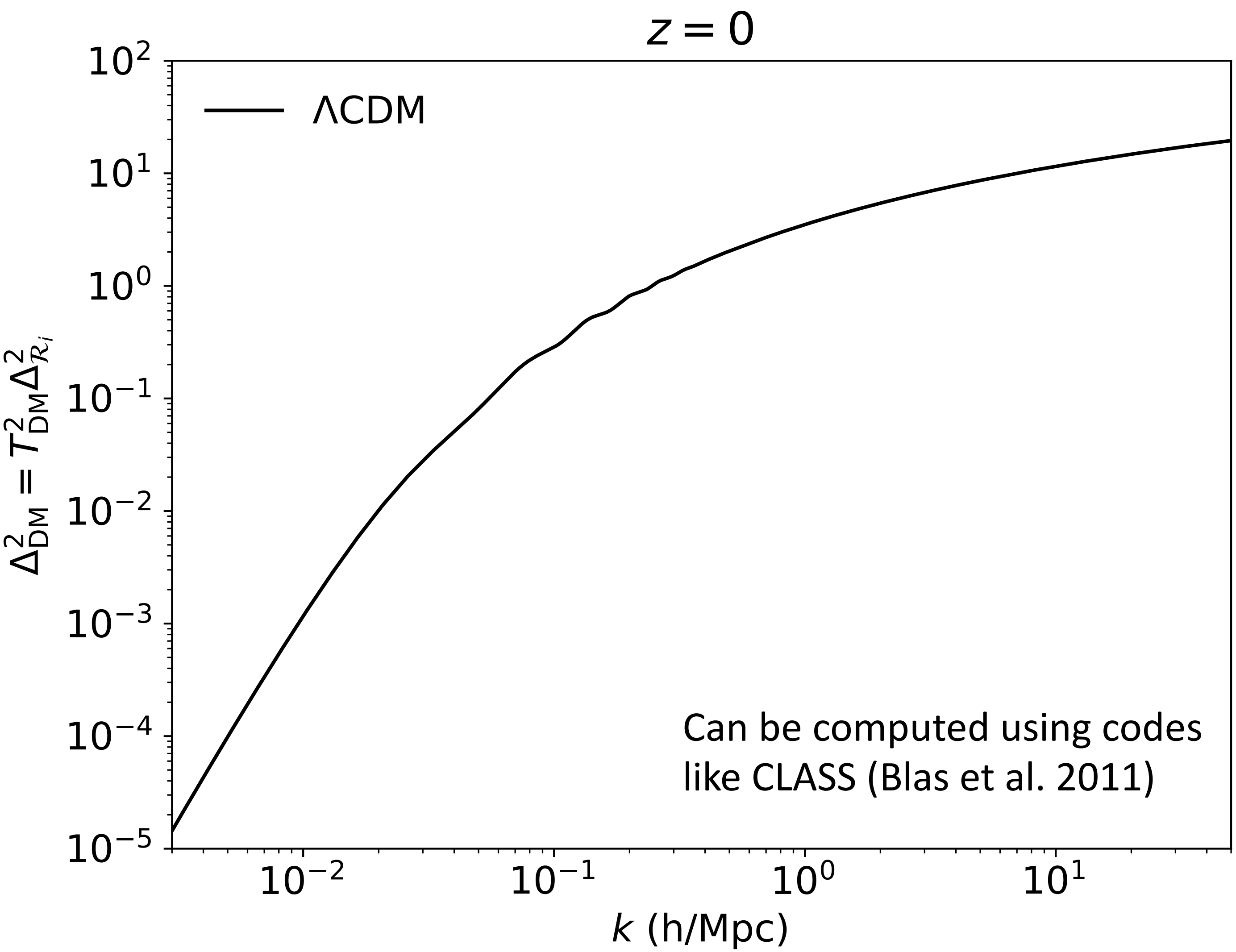
Halos throughout the Cosmic Dark Ages

Derek Inman   Kavli IPMU Postdoc Colloquium   October 6, 2022

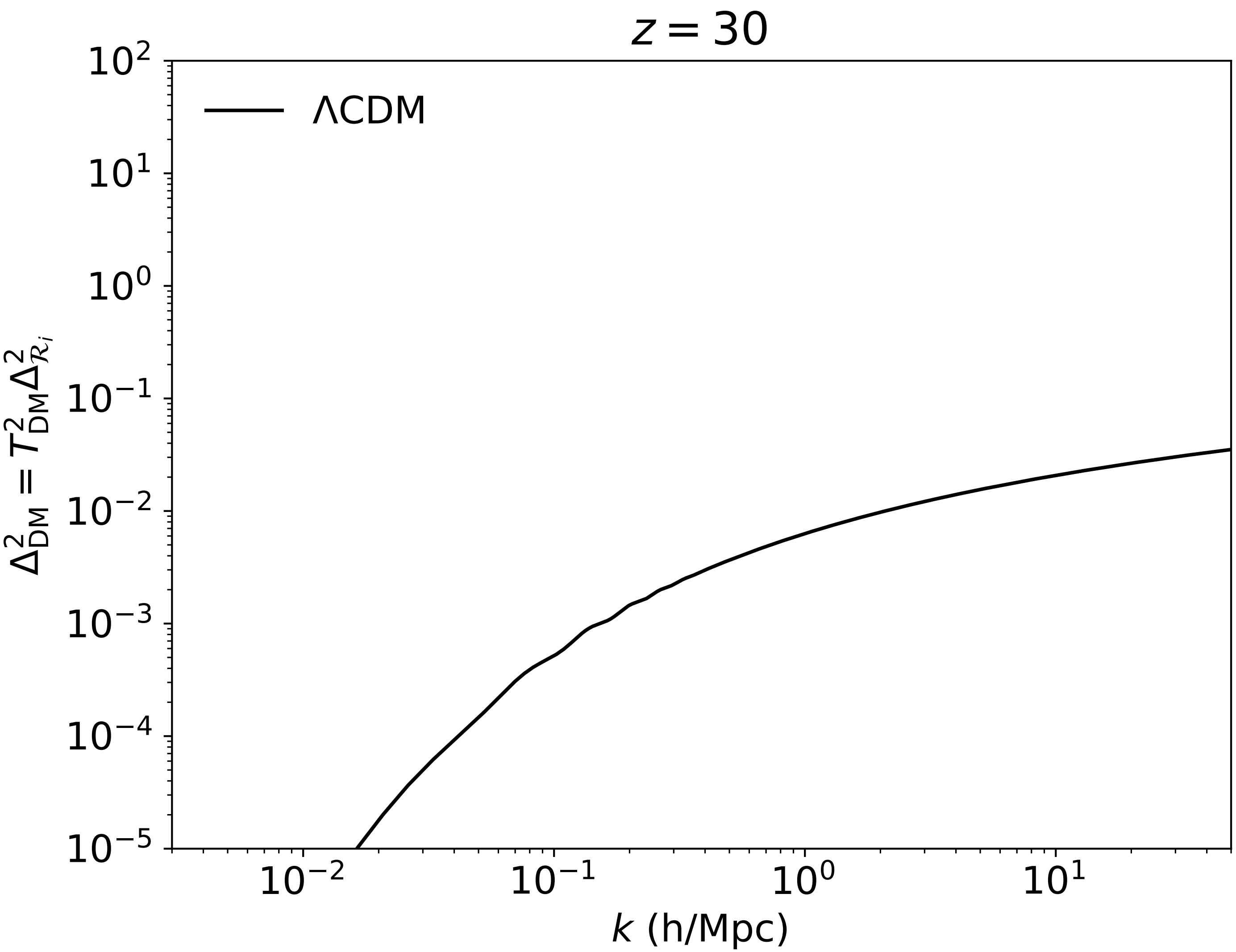
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Inman & Kohri (2022) arXiv:2207.14735

Standard ΛCDM



Standard ΛCDM – first halos



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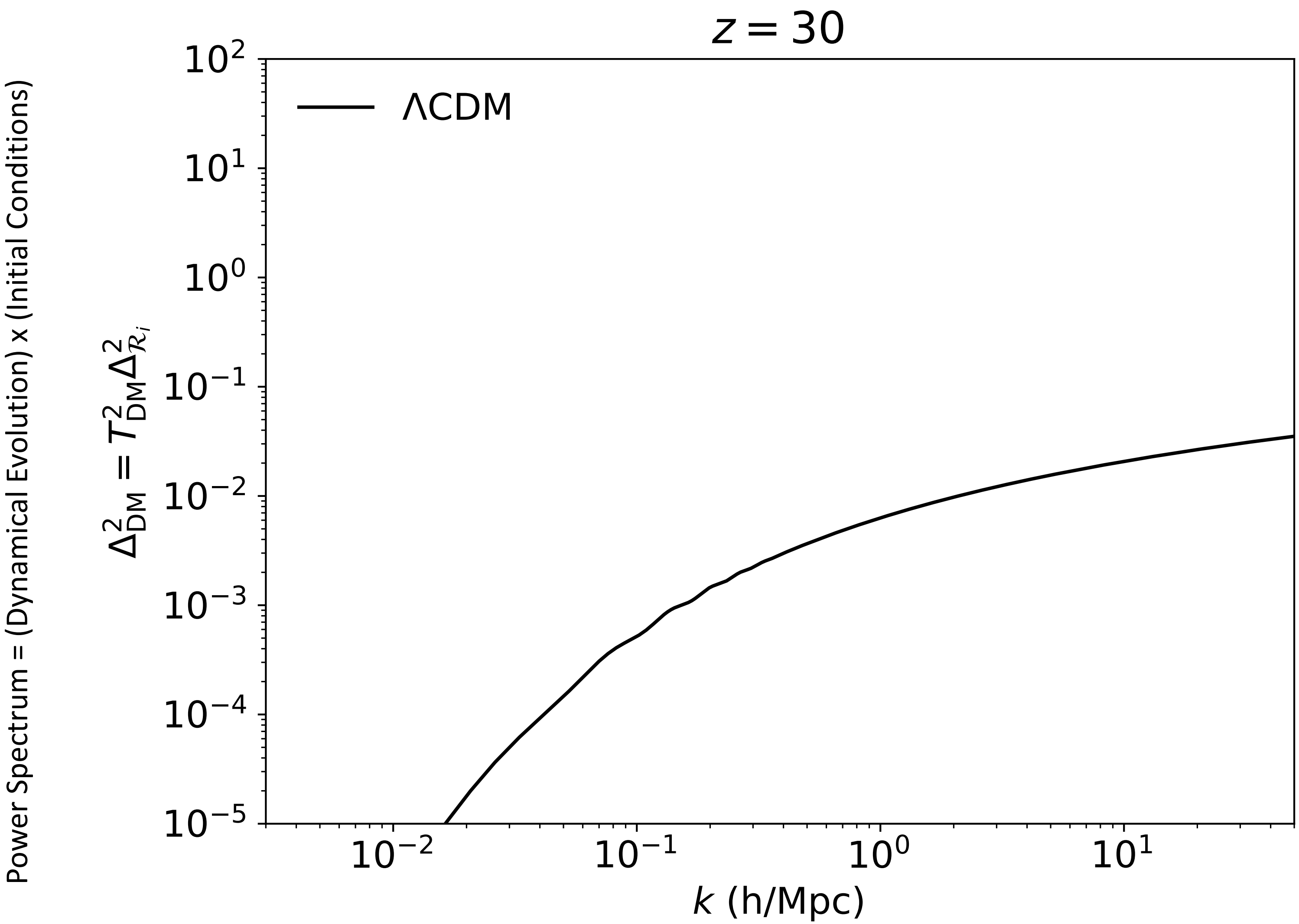
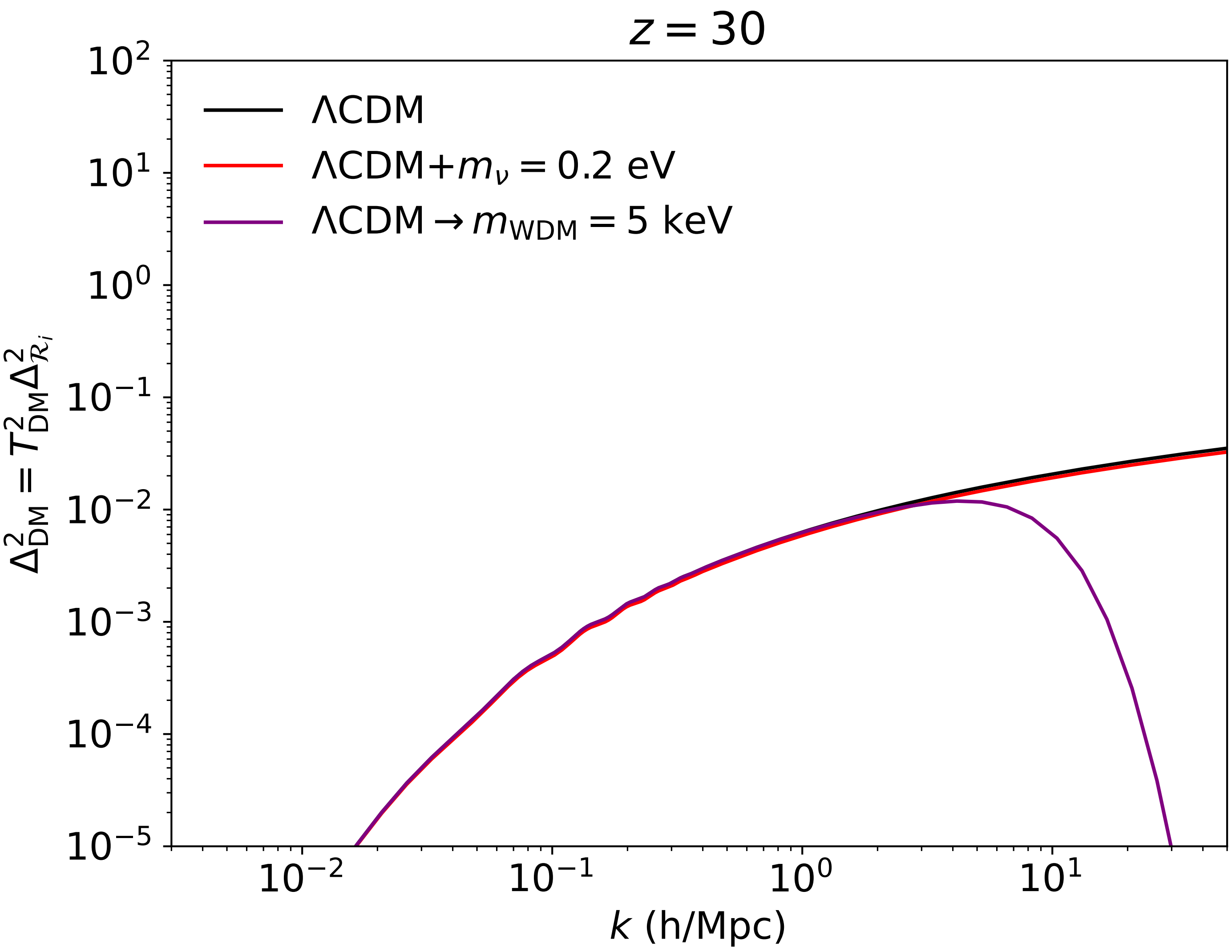
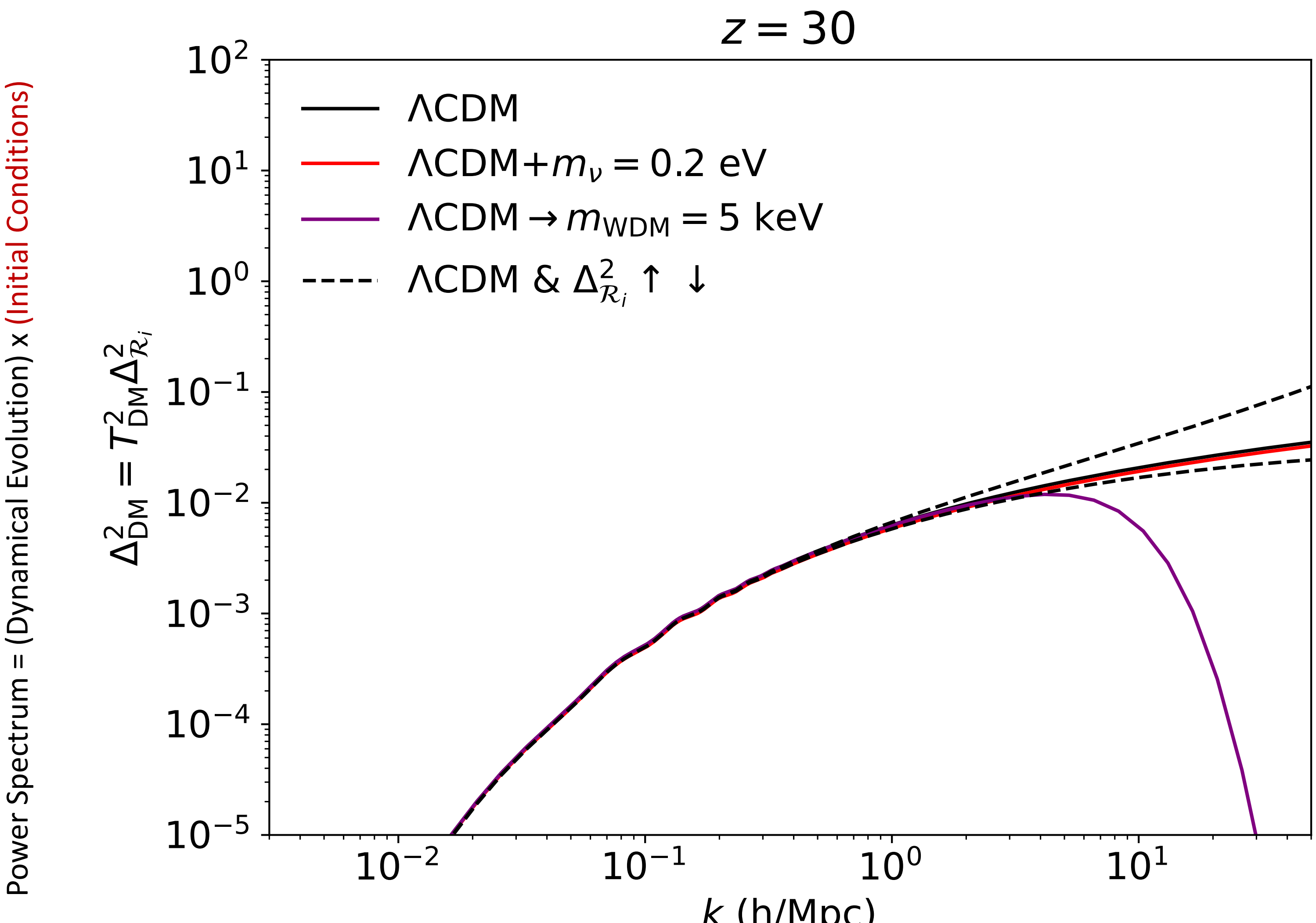


Beyond ΛCDM



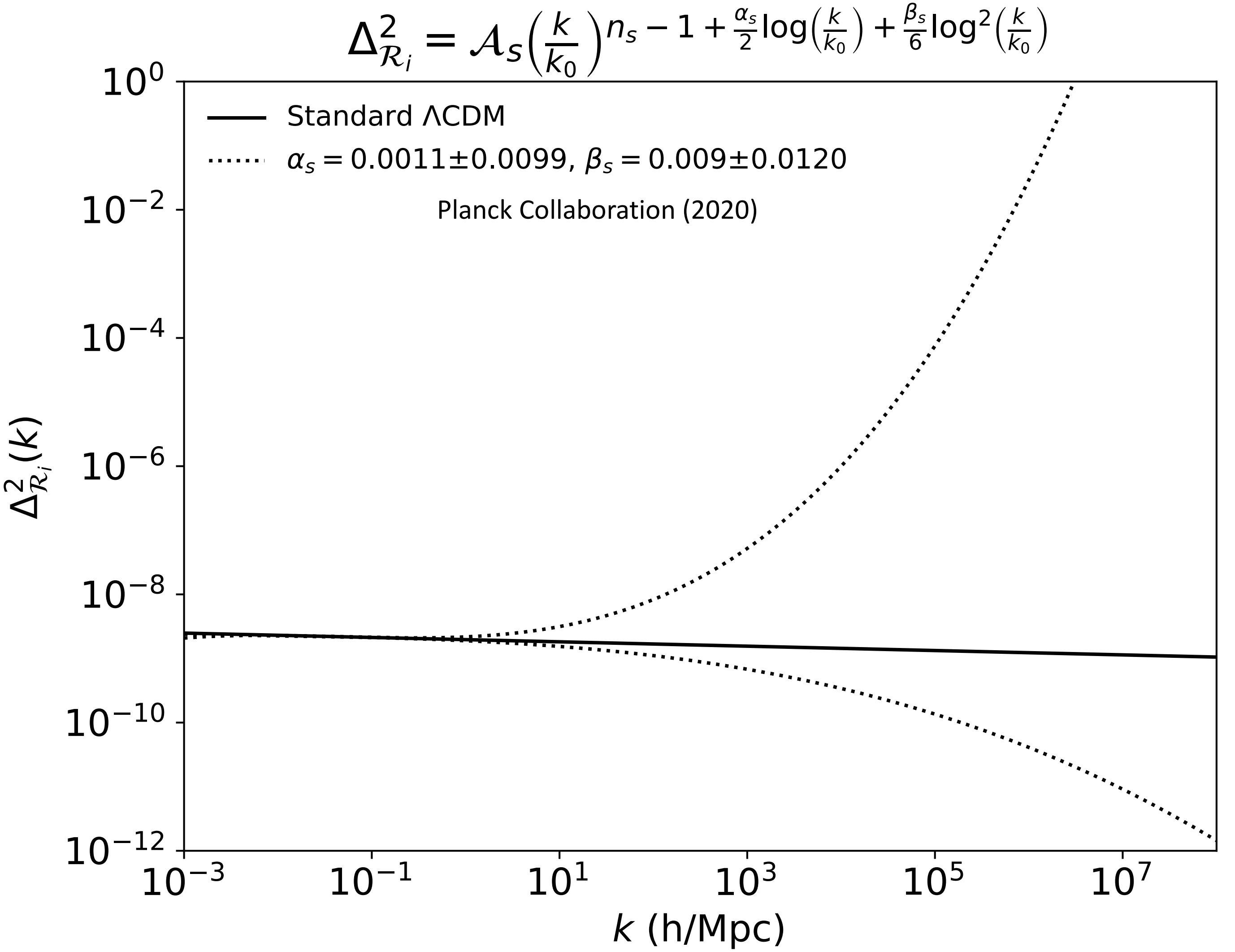
Power Spectrum = (Dynamical Evolution) x (Initial Conditions)

Beyond ΛCDM

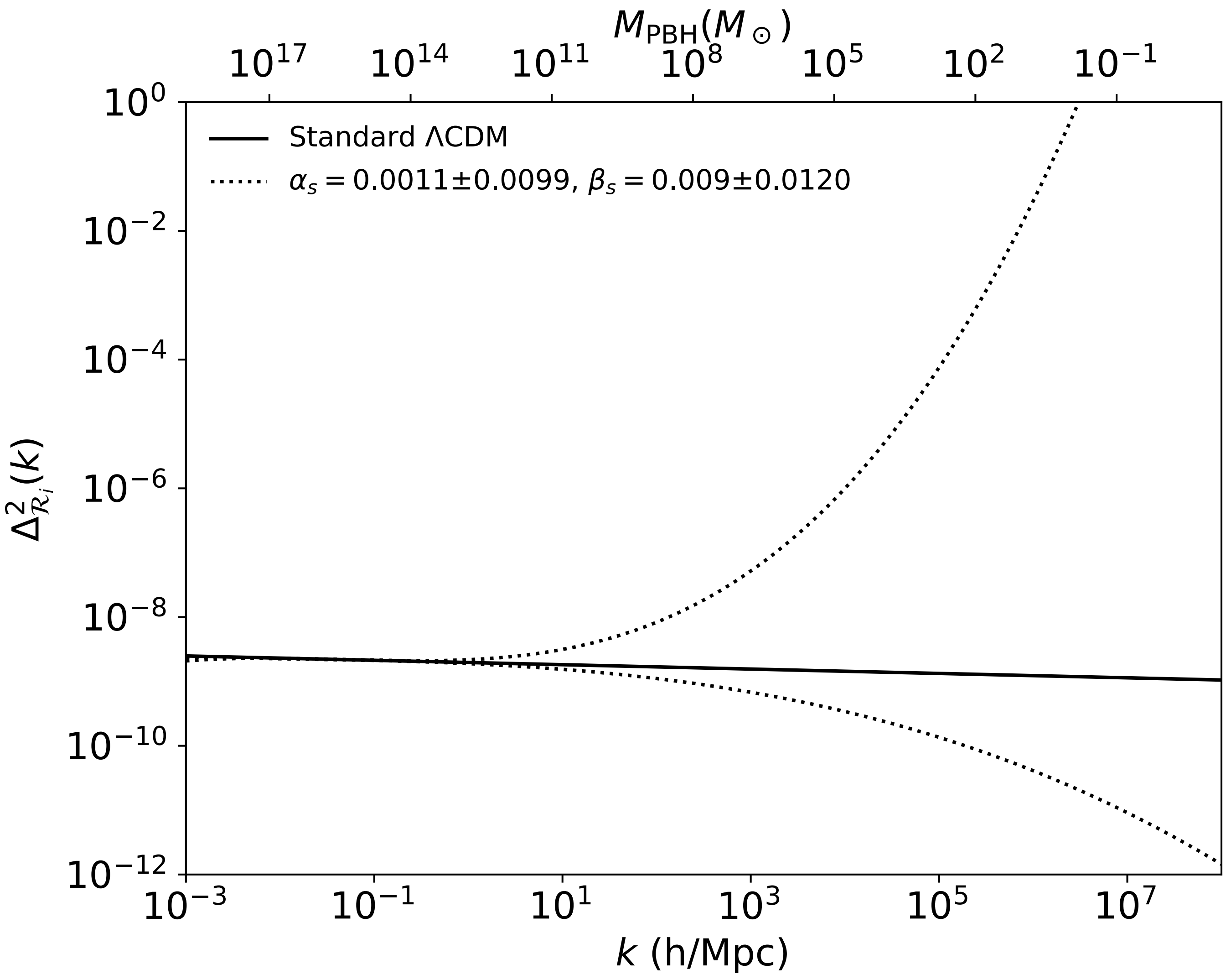


$z = 30$
ΛCDM
ΛCDM+$m_\nu = 0.2$ eV
ΛCDM → $m_{\rm WDM} = 5$ keV
ΛCDM & $\Delta^2_{\mathcal{R}_i}$ ↑ ↓
$\Delta^2_{\rm DM} = T^2_{\rm DM}\Delta^2_{\mathcal{R}_i}$
k (h/Mpc)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-2}
10^{-1}
10^{0}
10^{1}
Power Spectrum = (Dynamical Evolution) x (Initial Conditions)

Primordial Power Spectrum

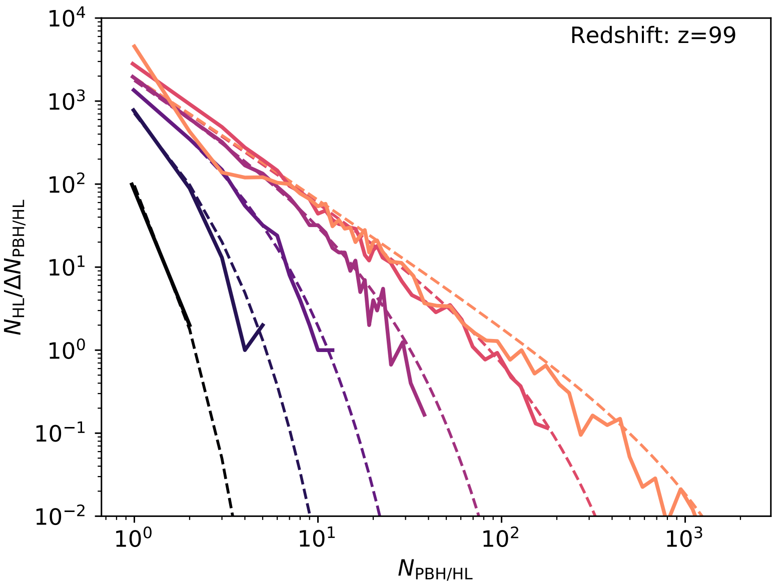


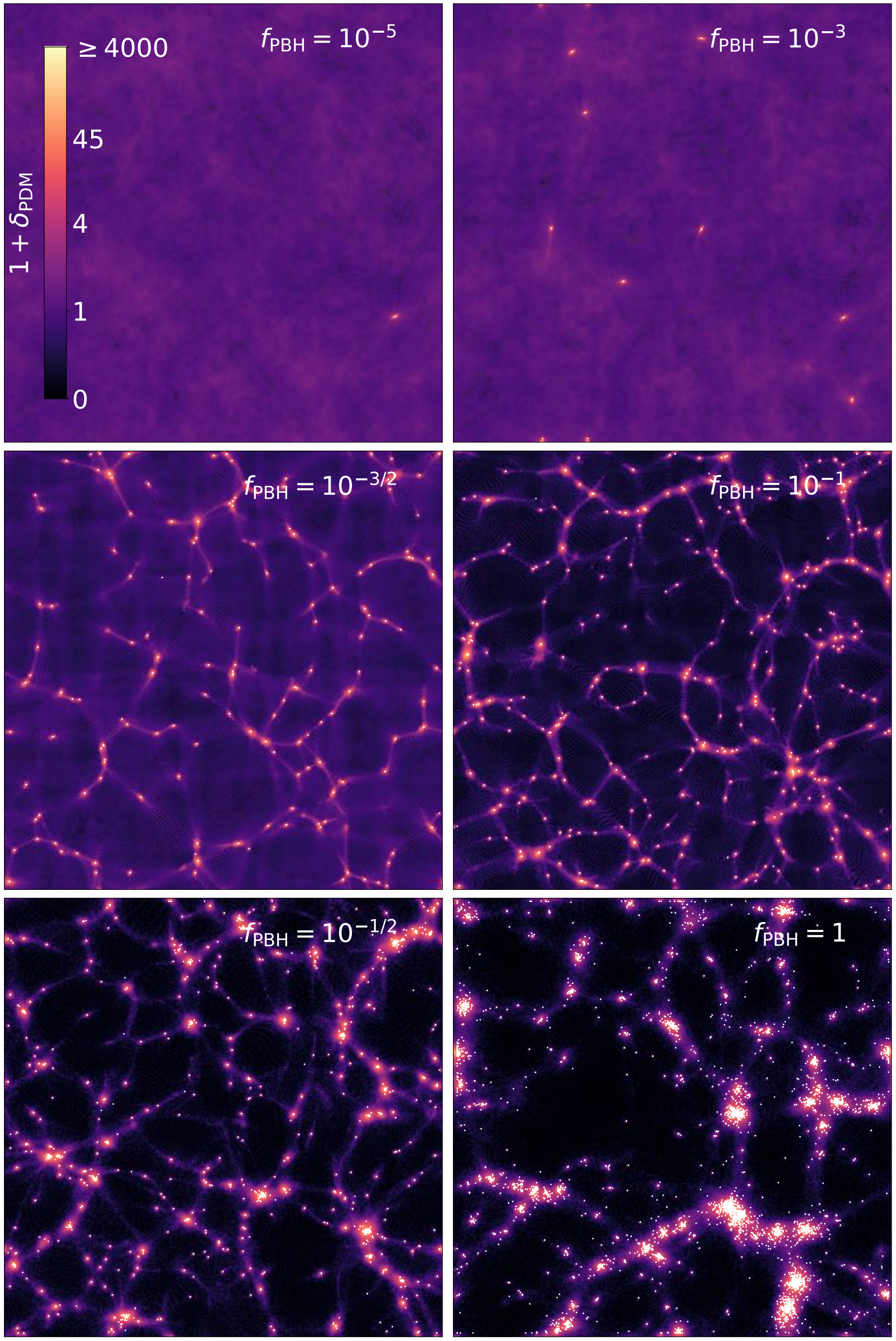
Primordial Black Holes



Primordial Black Holes

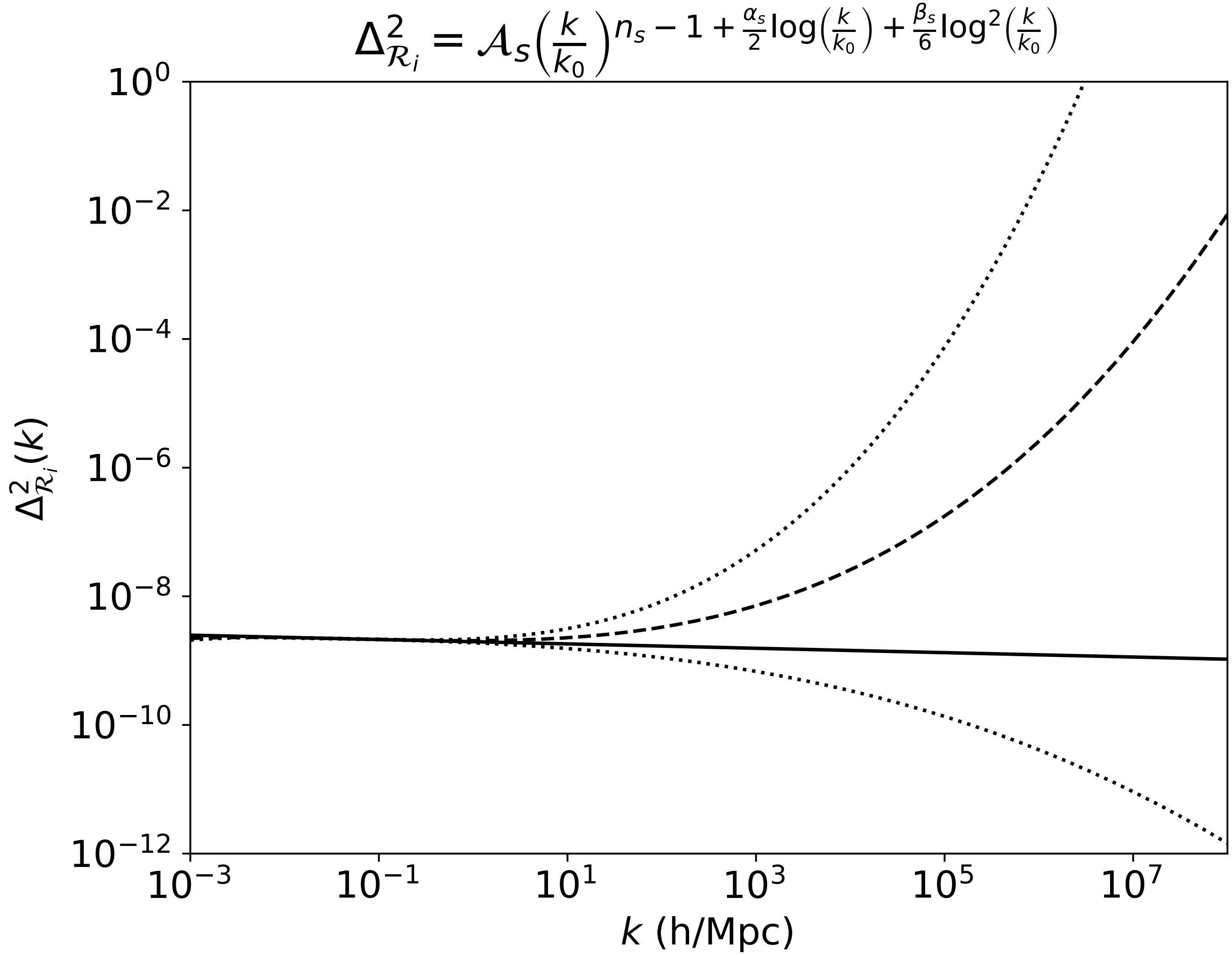
- PBHs are initially Poisson distributed
- After matter-radiation equality PBHs begin to cluster → Halos!





Inman & Ali-Haïmoud (2019)

Enhanced power spectrum without PBHs



Weakly Interacting Massive Particles

- WIMPs (e.g. Bringmann 2009)
  - Mass $m_\chi > \text{ GeV}$, freeze out when $\mathrm{T} < m_\chi$ → abundances set at GeV scales
    - Today: assume that WIMPs make up all of the dark matter
  - Elastic scattering with electrons/neutrinos → perturbations set at MeV scales
    - Power spectrum is truncated at 10^6 h/Mpc by diffusive/friction processes
  - WIMPs then free-stream until gravitational collapse → halos set at eV scales
    - Minimum halo mass around the Earth mass

WIMP Dynamics

- Boltzmann-Fokker-Planck Equation:

$$\dot{f} + \frac{\vec{v}}{a} \cdot \vec{\nabla}_x f + \left[\vec{v}\dot{\phi} - a\vec{\nabla}_x \psi\right] \cdot \vec{\nabla}_v f = a\gamma(1+\psi)\vec{\nabla}_v \cdot \left[(\vec{v} - a\vec{V}_R)f + \frac{a^2 T_R}{m_\chi}\vec{\nabla}_v f\right]$$

Bertschinger (2006), Binder et al. (2016)

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Free-streaming: $\frac{\vec{v}}{a} \cdot \vec{\nabla}_x f$

Gravitational Collapse: $a\vec{\nabla}_x \psi$

Momentum Exchange: $(\vec{v} - a\vec{V}_R)f$

Diffusion: $\frac{a^2 T_R}{m_\chi}\vec{\nabla}_v f$

Bertschinger (2006), Binder et al. (2016)

WIMP Dynamics

- Boltzmann-Fokker-Planck Equation:

Momentum Exchange

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Free-streaming

Gravitational Collapse

Bertschinger (2006), Binder et al. (2016)

- Background & Linear solutions:

$$f_0 = \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left[-\frac{1}{2}\frac{v^2}{\sigma^2}\right]$$

$$\delta_\chi(\eta) = \delta_\chi(\eta \to 0) G_\eta(\eta \to 0) + \int_0^\eta d\eta' S_\eta(\eta') G_\eta(\eta')$$

WIMP Dynamics

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Free-streaming

Gravitational Collapse

Bertschinger (2006), Binder et al. (2016)

- Approximate solution scheme:

1. Solve decoupling assuming linear and deep in radiation era
2. Propagate towards matter era assuming linear and collisionless
3. Use N-body simulations to obtain nonlinear results

1. Decoupling in the radiation era

- Background is Gaussian with dispersion:

$$\frac{\sigma^2}{\sigma_d^2} = \exp\left[\frac{1}{y^{n_\gamma}}\right]\Gamma\left[\frac{n_\gamma - 1}{n_\gamma}, \frac{1}{y^{n_\gamma}}\right]$$

$$\sigma_d^2 = \frac{a_d^2 T_d}{m_\chi}$$

$$y = \frac{a}{a_d} = \frac{T_d}{T}$$

$$\gamma \propto \left(\frac{T}{T_d}\right)^{2+n_\gamma}$$

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- Perturbations have a simple approximation (Bertschinger 2006)
  1. Solve equations assuming no diffusion:

$$\frac{d\delta_{\chi 0}}{dy} + \eta_d \theta_{\chi 0} = 3\frac{d\phi}{dy}$$

$$\frac{d\eta_d\theta_{\chi 0}}{dy} + \frac{1}{y}\eta_d\theta_{\chi 0} = (k\eta_d)^2\phi + \frac{n_\gamma}{2}\frac{\eta_d\theta_R - \eta_d\theta_{\chi 0}}{y^{1+n_\gamma}}$$

$$\therefore \delta_{\chi 0} = \delta_\chi(\eta \to 0) + \int_0^y dx \left[3\frac{d\phi}{dx} - u_y(x)\left(\frac{n_\gamma}{2}\frac{\eta_d\theta_R}{x^{n_\gamma}} + x(k\eta_d)^2\phi\right)\right]$$

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- Perturbations have a simple approximation (Bertschinger 2006)
  1. Solve equations assuming no diffusion:
  2. Multiply by a diffusion damping term:

$$\delta_\chi = \delta_{\chi 0} G_\eta(\eta \to 0)$$

$$G_\eta(\eta \to 0) = \exp\left[-\frac{T_d}{m_\chi}(k\eta_d)^2 \int_{\eta'}^{\eta} a\gamma_0 \frac{a^2}{a_d^2}\frac{T_0}{T_d} u_\eta^2(\eta'')d\eta''\right]$$

$$u_\eta(\eta') = \int_{\eta'}^{\eta} \frac{d\eta''}{\eta_d}\frac{a_d}{a} \exp\left[-\int_{\eta'}^{\eta''} a\gamma_0 d\eta'''\right]$$

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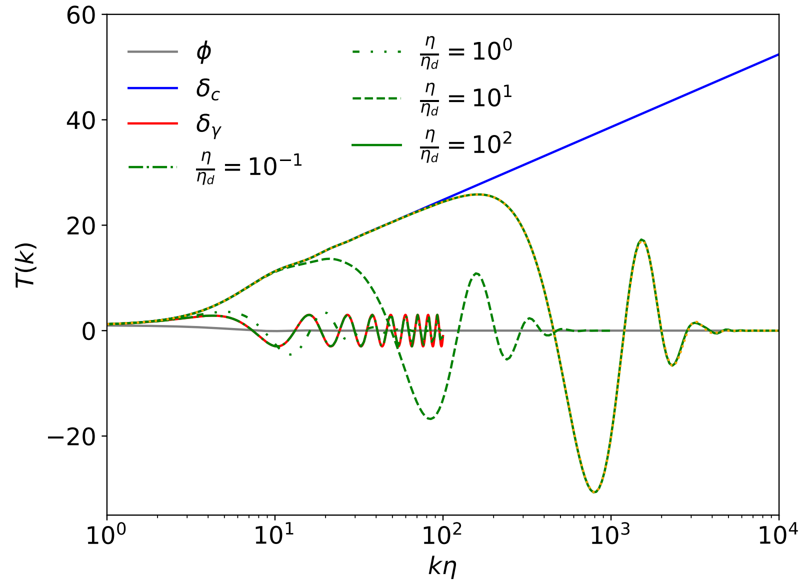

Inman & Kohri (2022)

2. Collisionless evolution

- After decoupling:
  - Collisionless evolution
  - WIMPs are also gravitationally decoupled (Voruz et al 2014) → Self-gravity

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$$\delta_\chi(\tau) \simeq \delta_\chi^r(\tau) + \frac{3}{2} f_c H_r^2 \int_{\gg \tau_d}^{\tau} d\tau' (\tau - \tau') \frac{a}{a_{\rm eq}} \delta_\chi(\tau') \exp\left[-\frac{1}{2} \left(k\sigma(\tau - \tau')\right)^2 \right]$$

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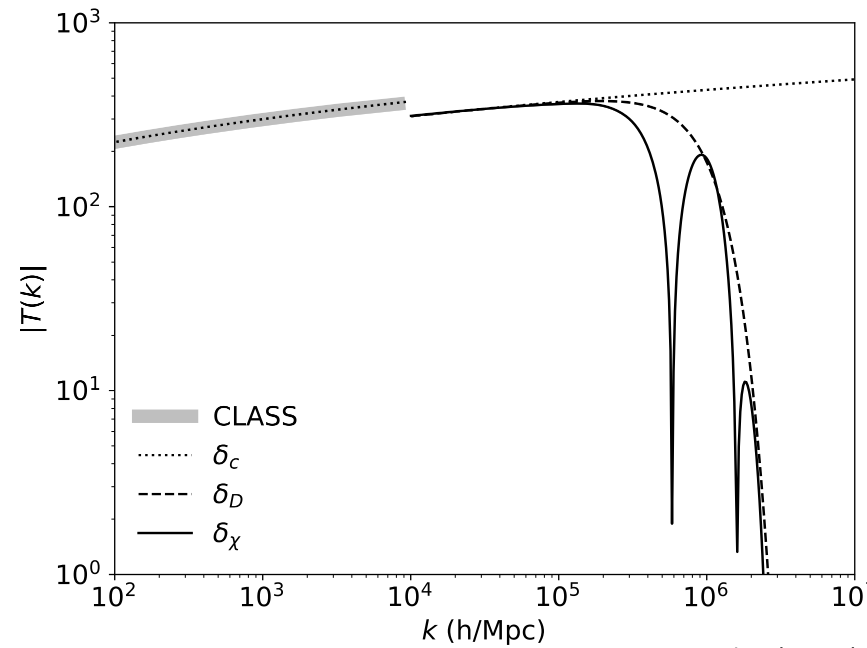

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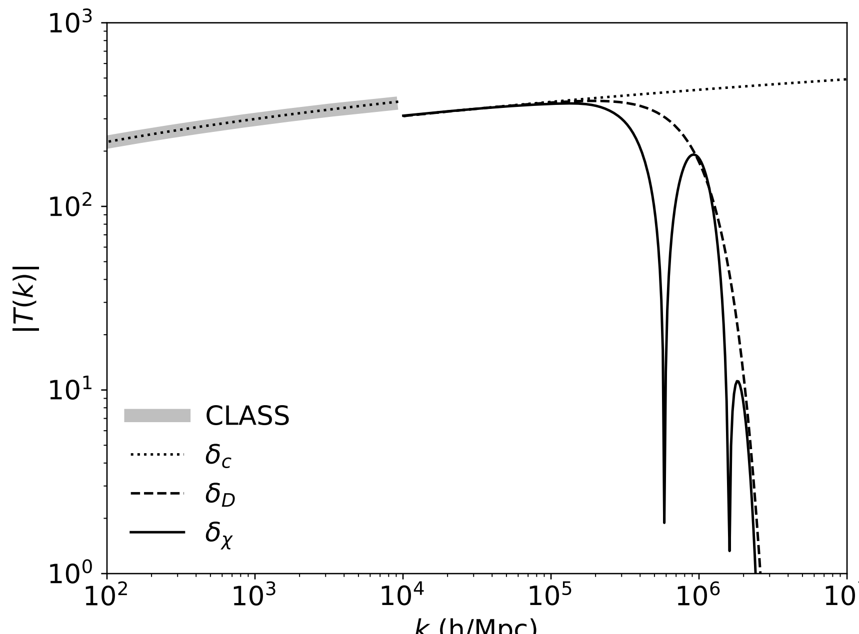
- Not included in our calculation
  - Neutrino free-streaming
  - Electron/positron annihilation

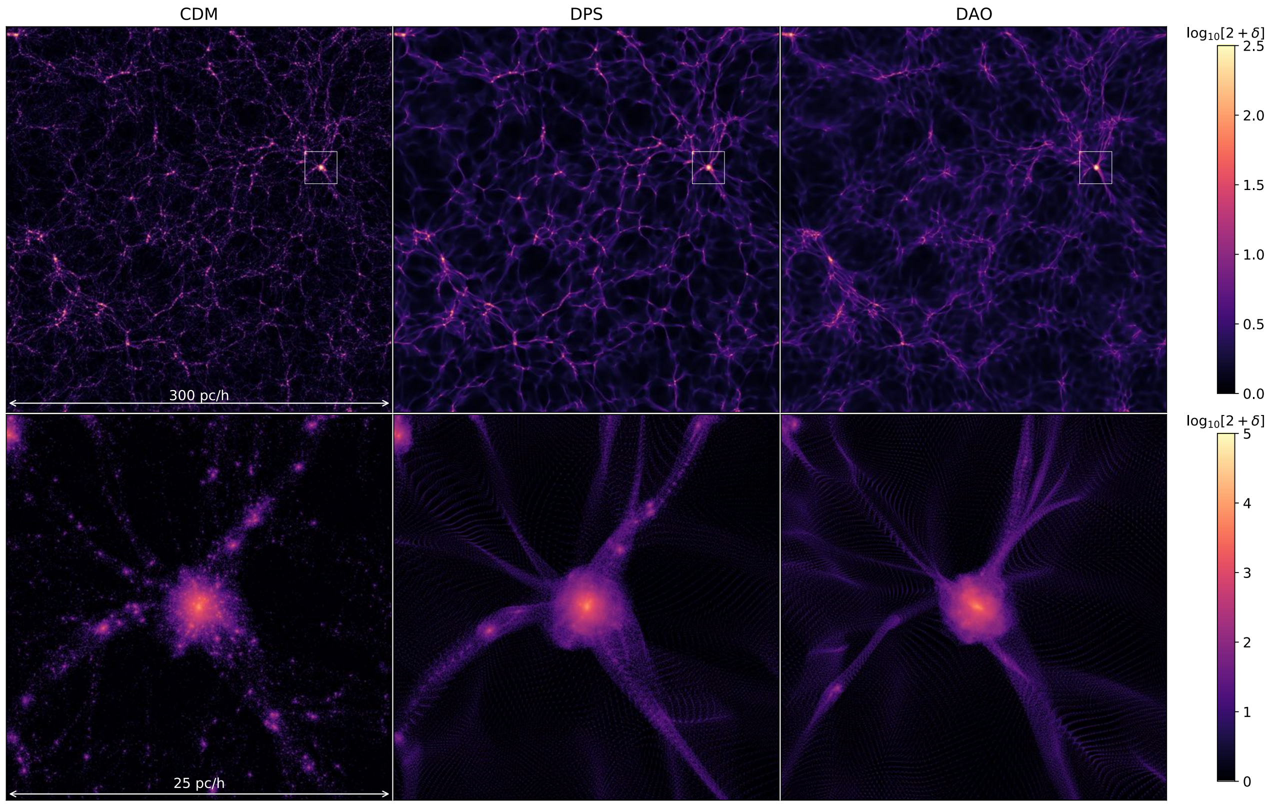
- Use Hu & Sugiyama (1996) approximation on larger scales



Inman & Kohri (2022)

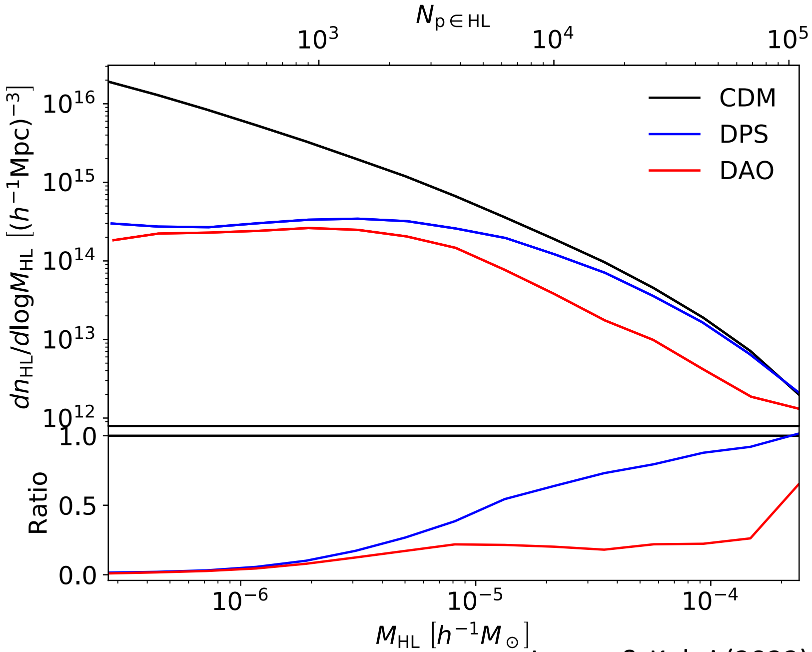
3. N-body calculation

- Cosmological simulations starting in the radiation era ($z=10^5$) with $2x768^3$ particles in a $(300pc/h)^3$ volume using transfer functions computed from BFP equation and evolved to z=300.



Inman & Kohri (2022)

Halos at z>100!



Inman & Kohri (2022)

Halo mass function:

- Truncated at a scale characteristic of WIMP decoupling
- Evidence for spurious halos due to artificial fragmentation (Wang & White 2007)

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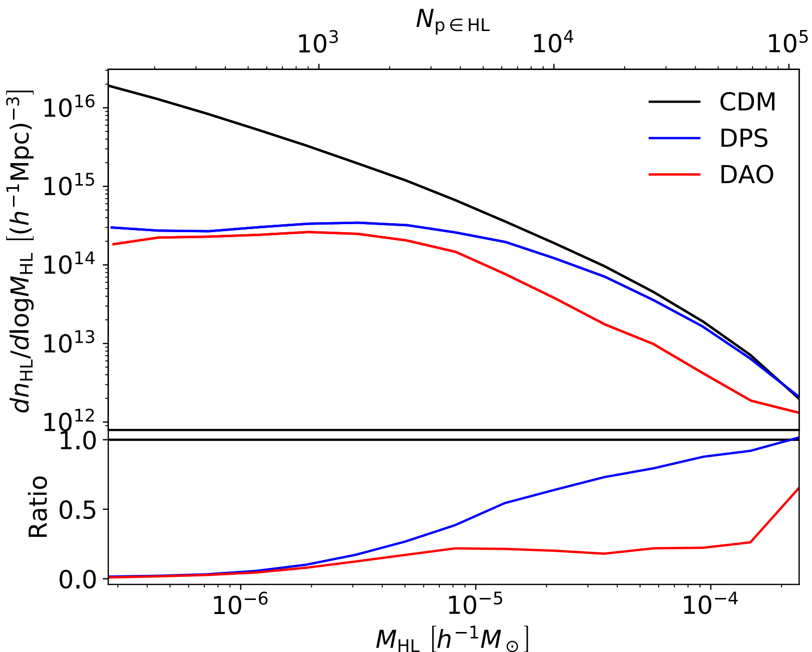

Inman & Kohri (2022)

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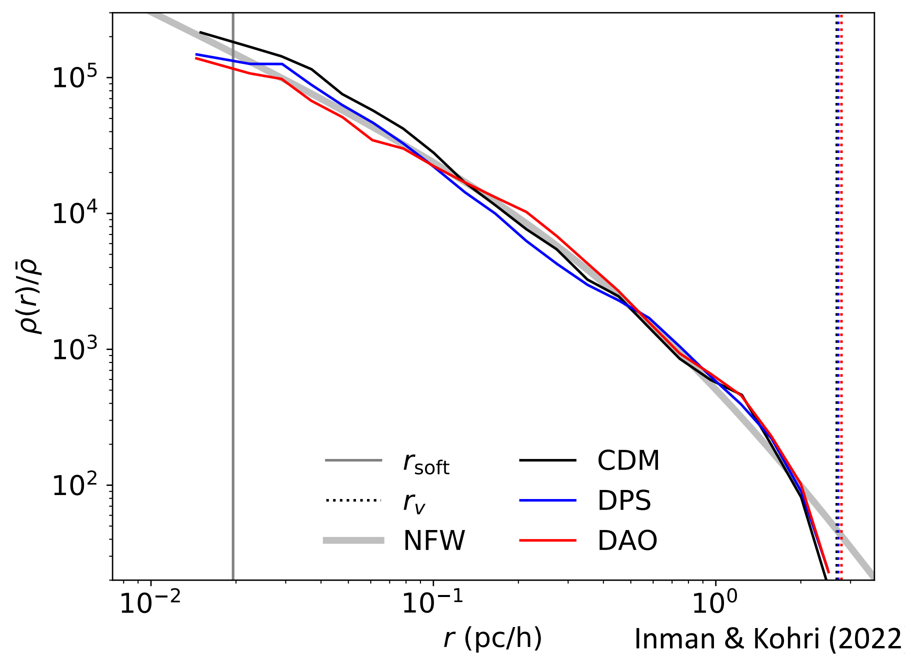
Halo density profile

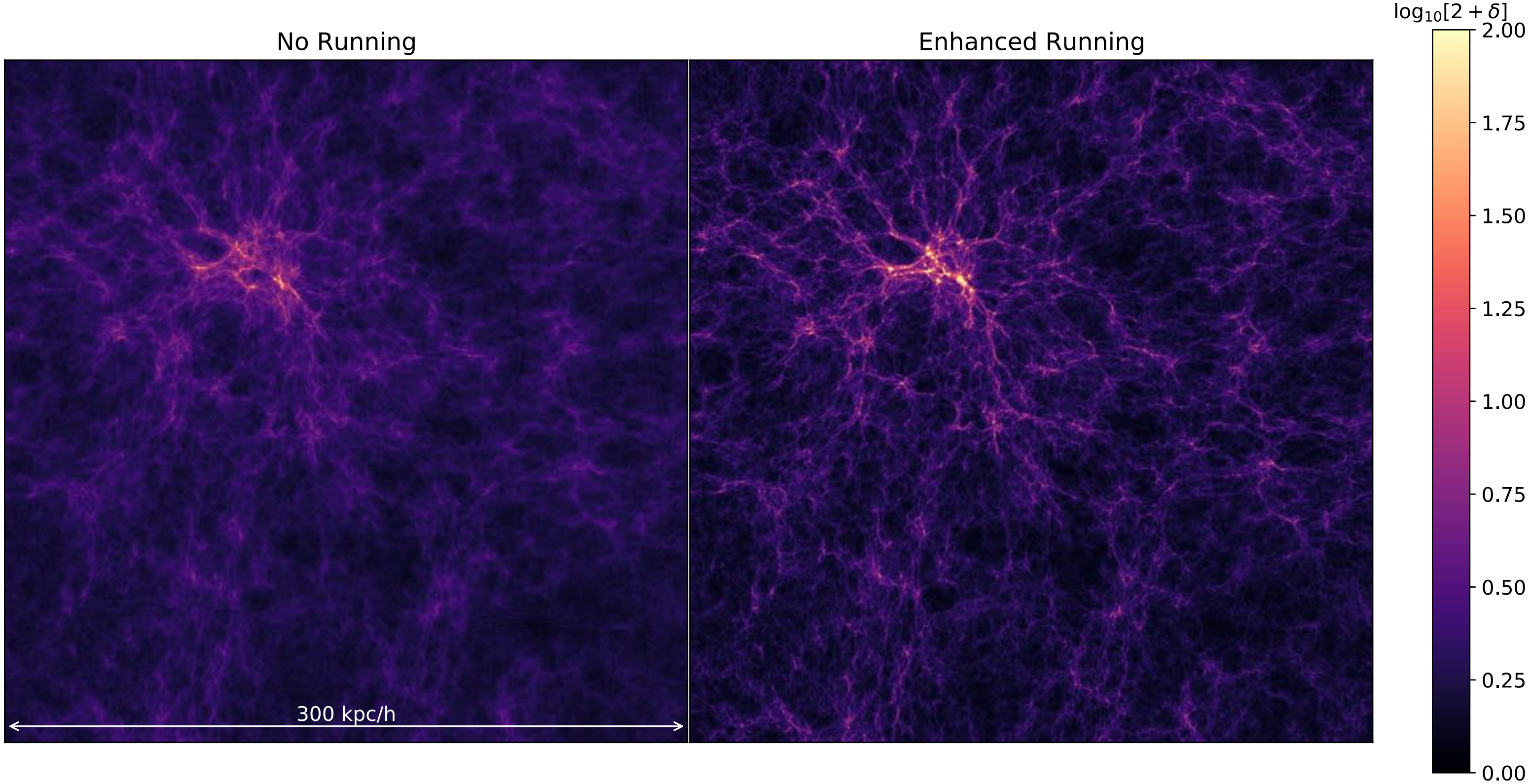
- Most massive halo has NFW profile
  - Halos near minimum mass may not (e.g. Delos & White 2022)



Inman & Kohri (2022)

Halos at z<100!

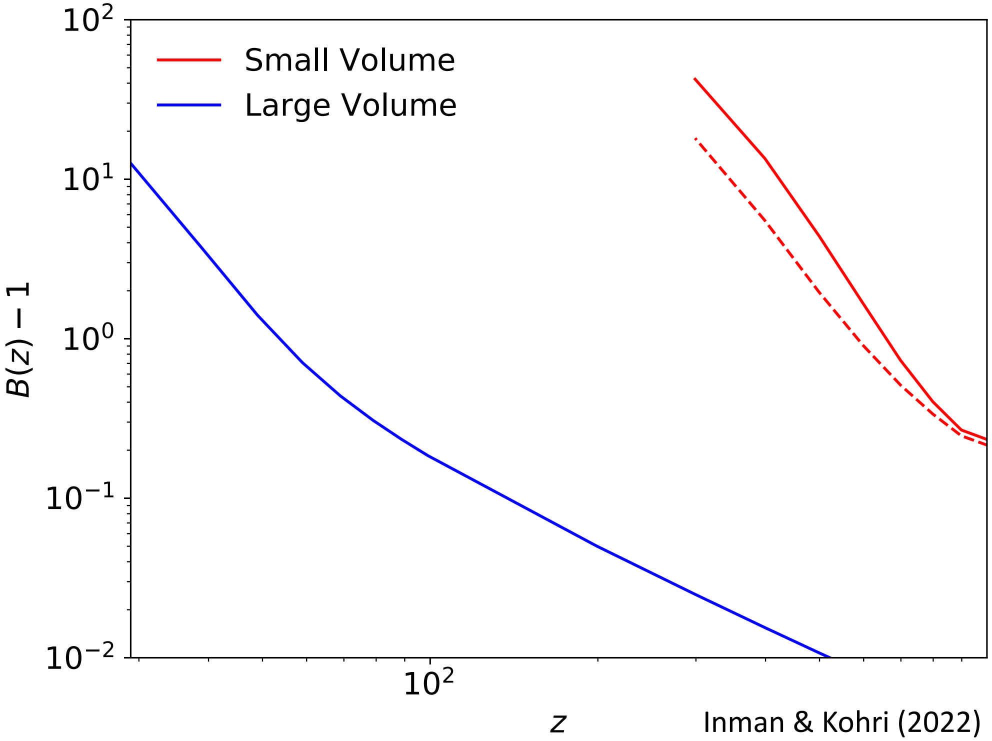
- Can't evolve small volumes to very low redshifts
- BUT can evolve larger volumes: $(300\ \text{kpc/h})^3$ at z=30



Inman & Kohri (2022)

Potential consequences

- WIMP Annihilation:
  - (density)^2 process
  - Boost factor is large after matter-radiation equality



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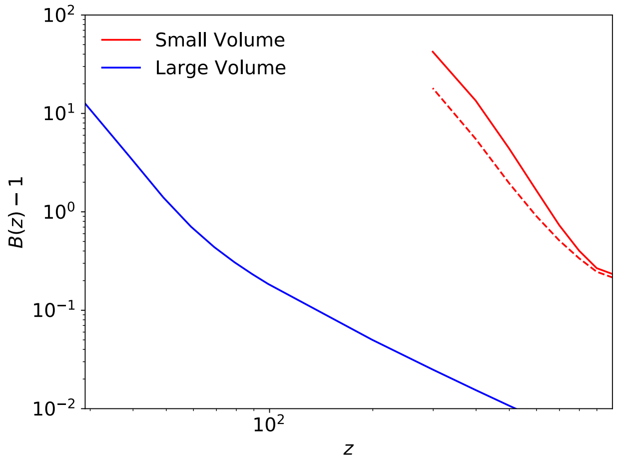

Inman & Kohri (2022)

- First galaxies and stars
  - Halos that host the first stars form earlier (see also Hirano et al. 2015)

	$M > 10^4 M_o h^{-1}$	$M > 10^5 M_o h^{-1}$	$M_{\max}\ (10^5 M_o h^{-1})$
Enhanced	436	8	3.2
Standard	8	0	0.4

Conclusion

- Halos can form throughout the cosmic dark ages!
  - Minimum halo mass set by particle microphysics
  - If enhancement is over a broad range of scales, can affect both lightest halos and halos that start cosmic dawn
- Next steps:
  - Numerical improvements:
    - Transfer functions → neutrinos free-streaming, electron/positron annihilation
    - N-body simulations → implement thermal velocities, deal with artificial fragmentation
  - Phenomenology & Analysis
    - Different primordial power spectra affect and associated phenomenology
    - When do baryons start being affected?
    - Constraining this scenario with CMB and first stars

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