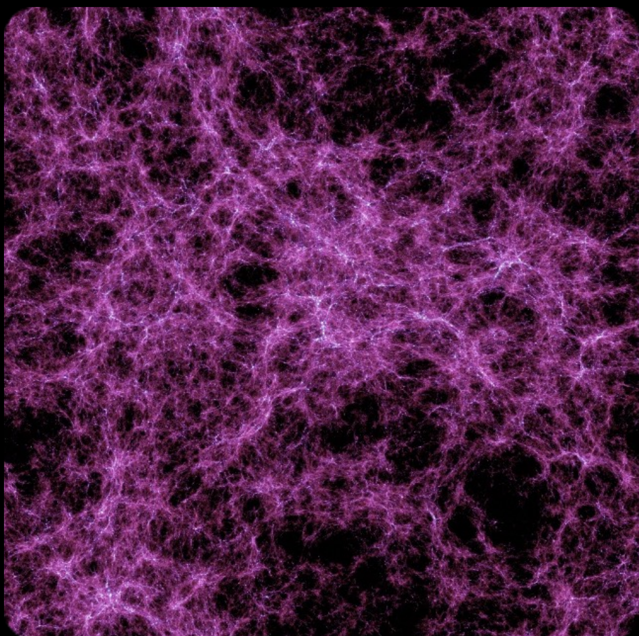
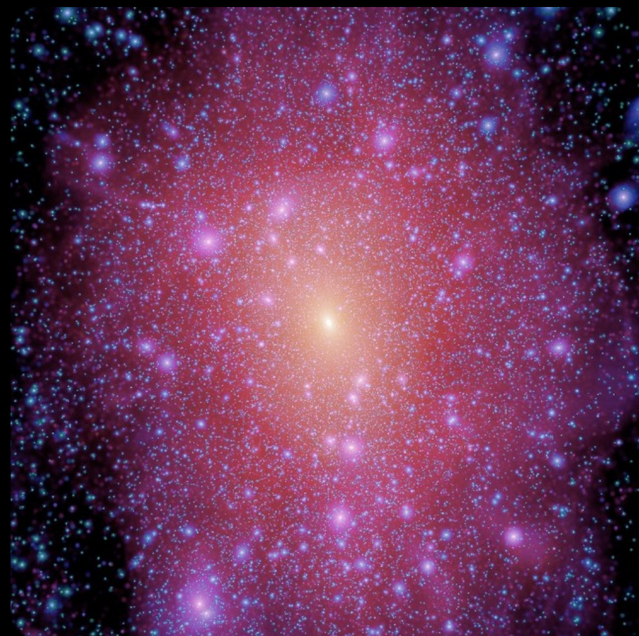
Simulations Beyond CDM





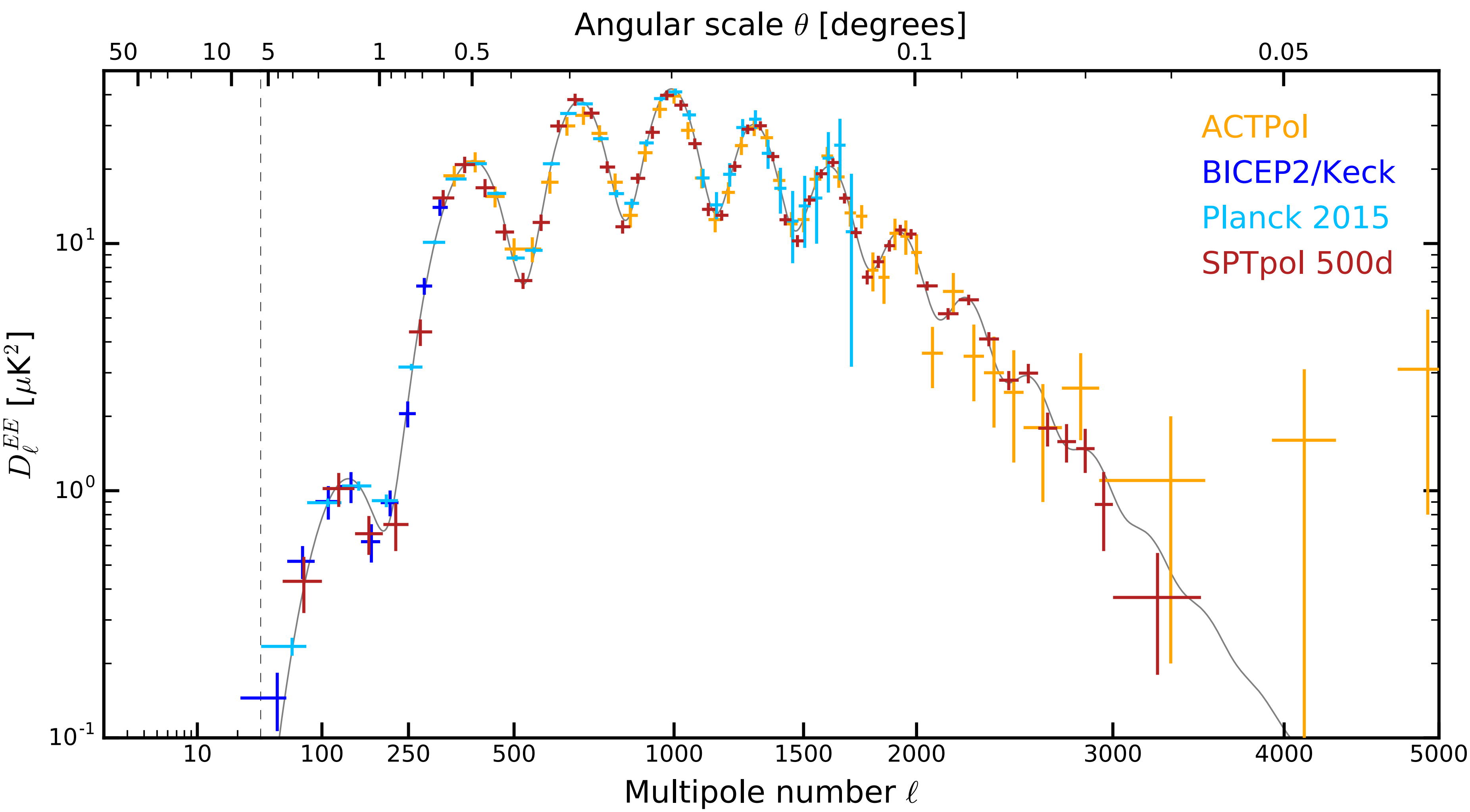
Mike Boylan-Kolchin

The University of Texas at Austin

KITP

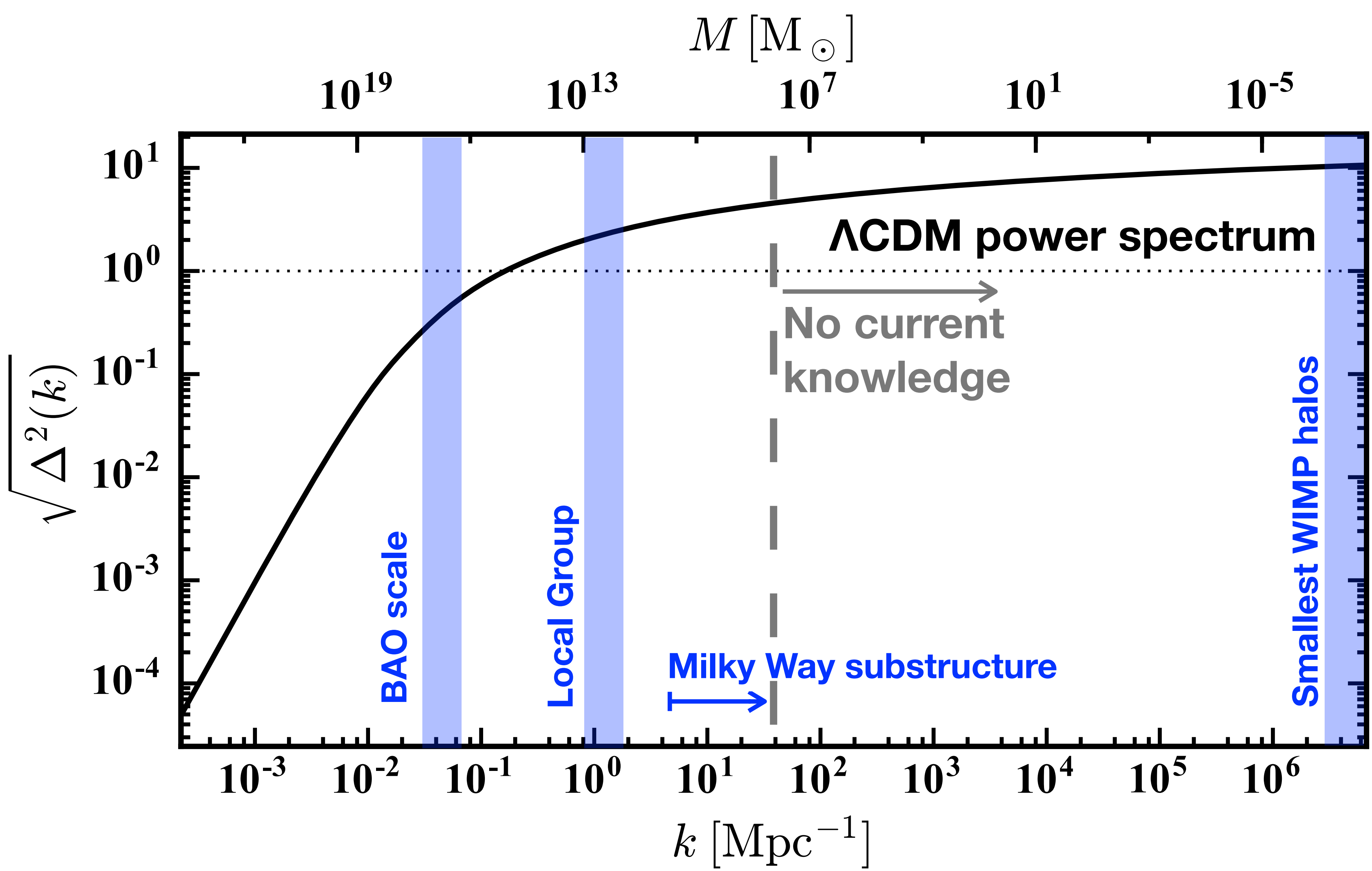
21 June 2018

Large Scales: Concordance ΛCDM



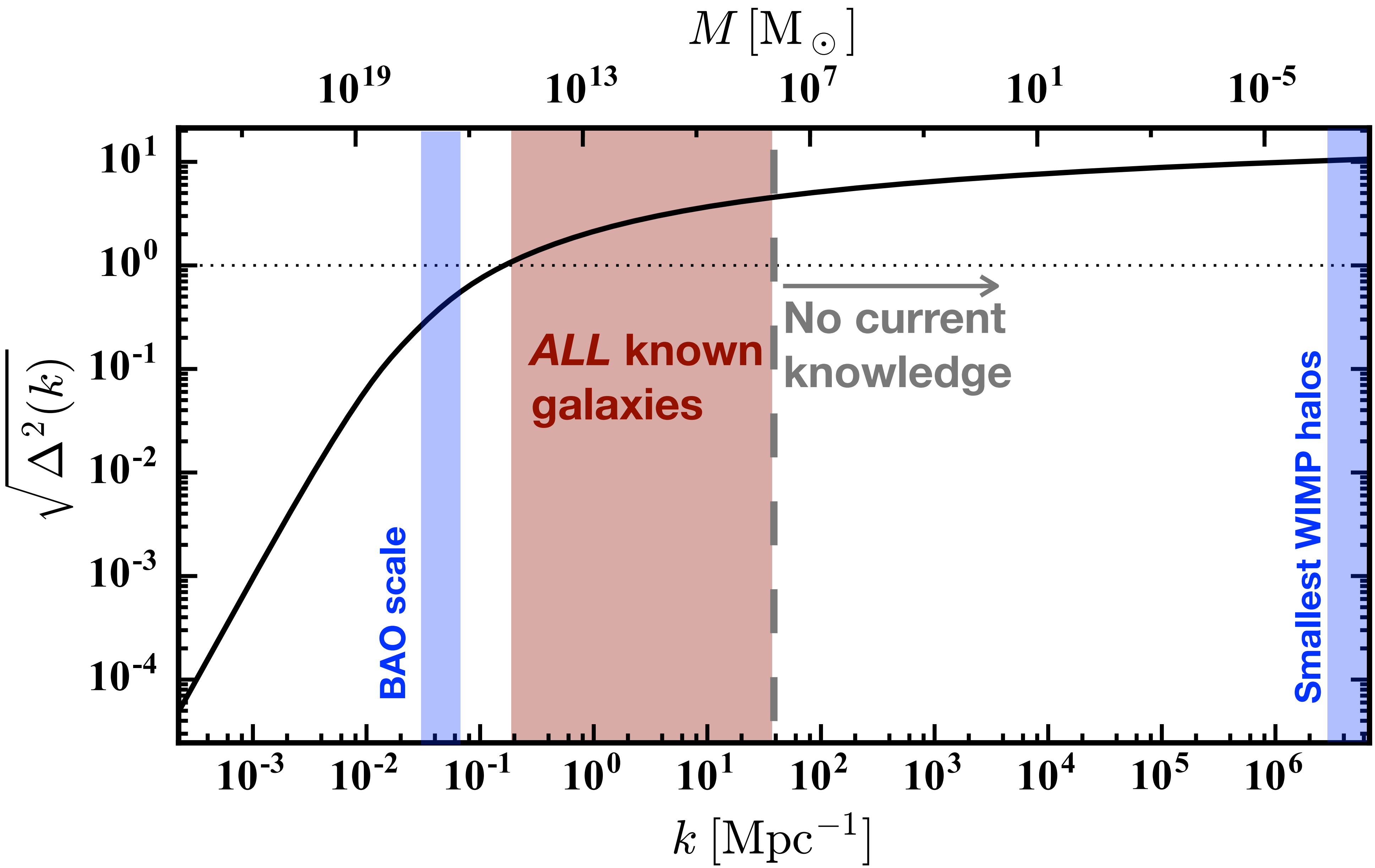
Henning et al. (2018)

The scales of ΛCDM



Bullock & Boylan-Kolchin 2017

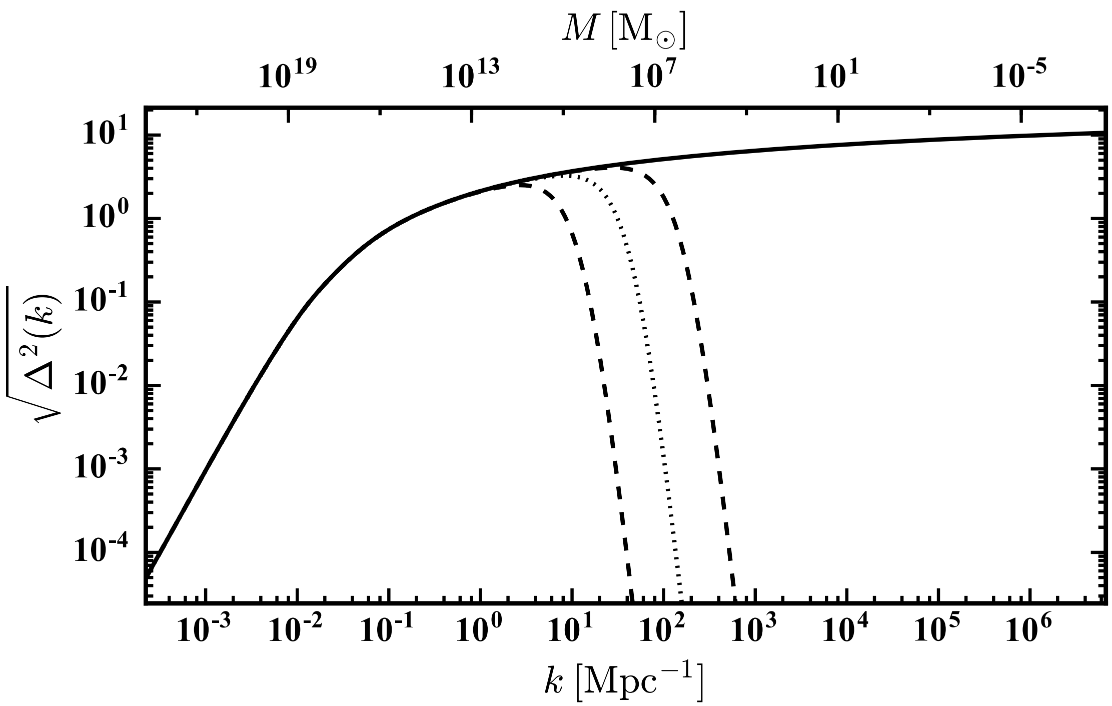
The scales of ΛCDM

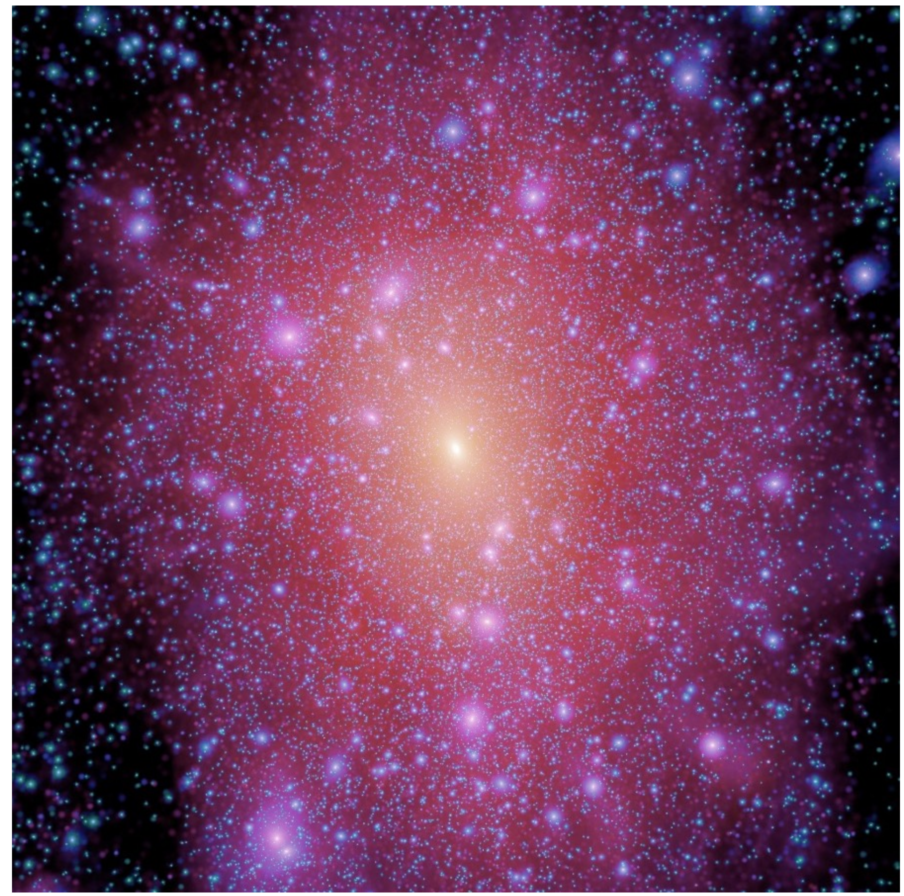


Bullock & Boylan-Kolchin 2017

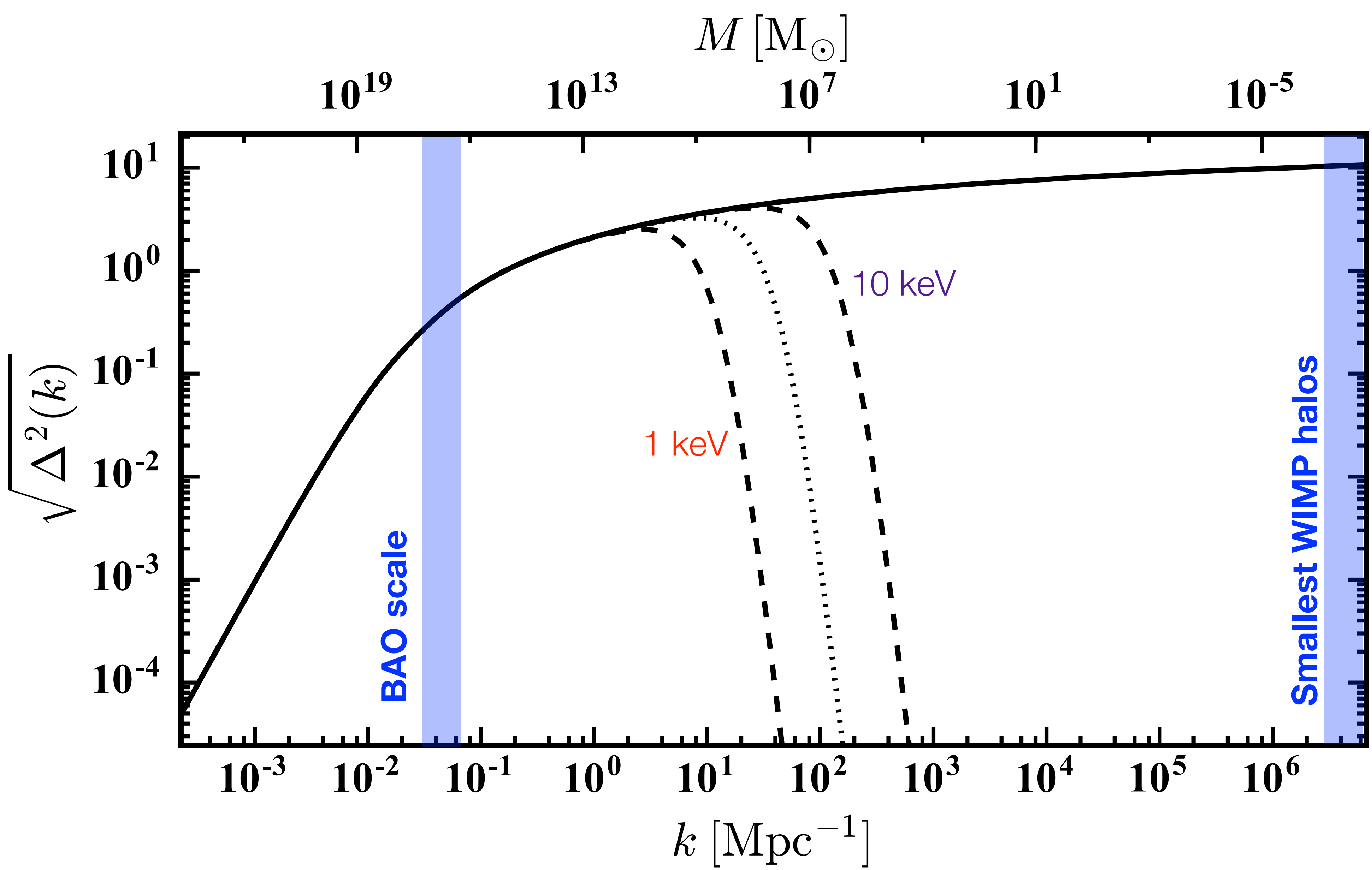
Alternative Dark Matter Models

Modify *linear* physics or *non-linear* physics or ***both***





Beyond CDM: power spectrum modifications



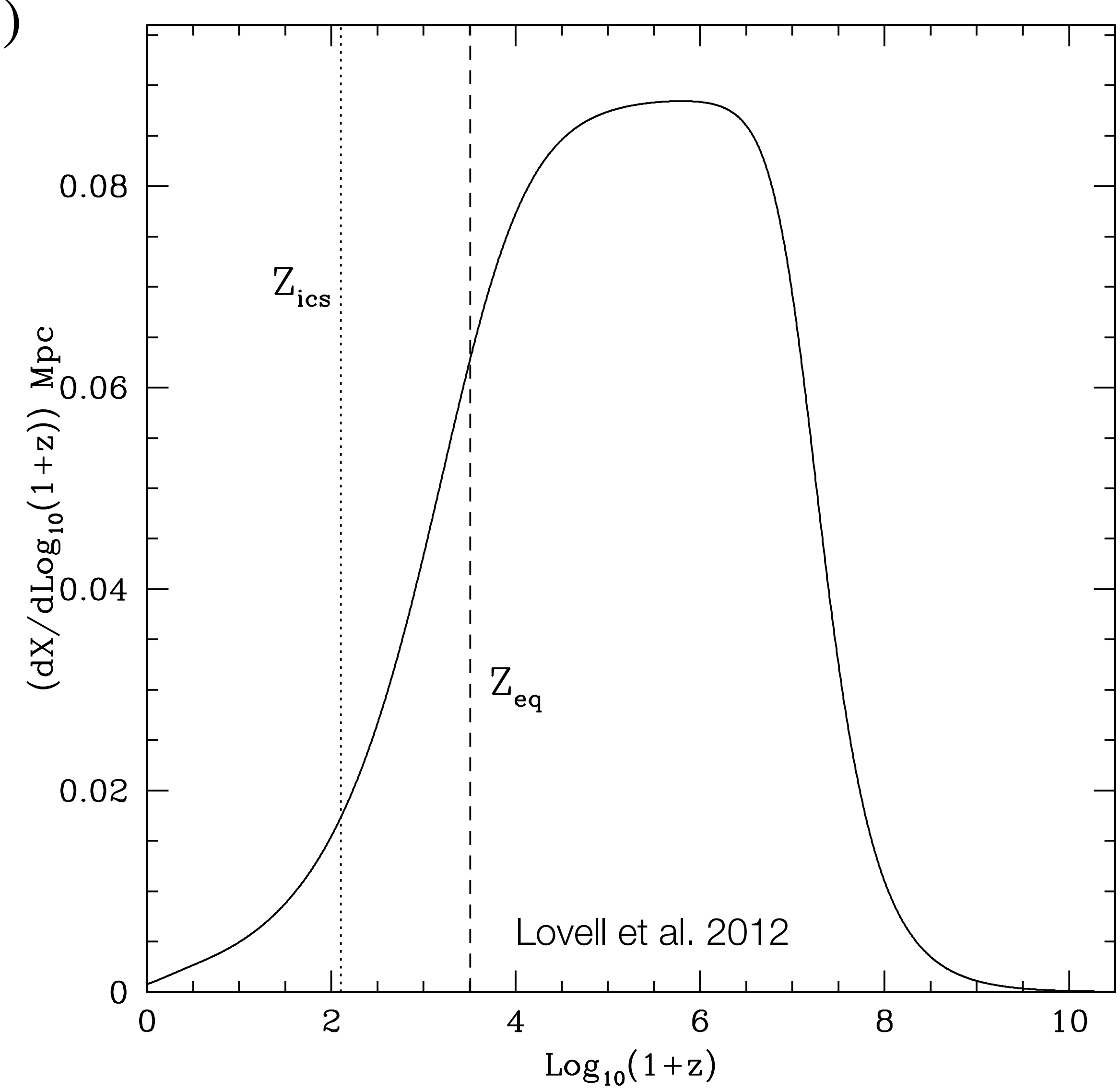
Bullock & Boylan-Kolchin 2017

Origin of cut-off: free-streaming

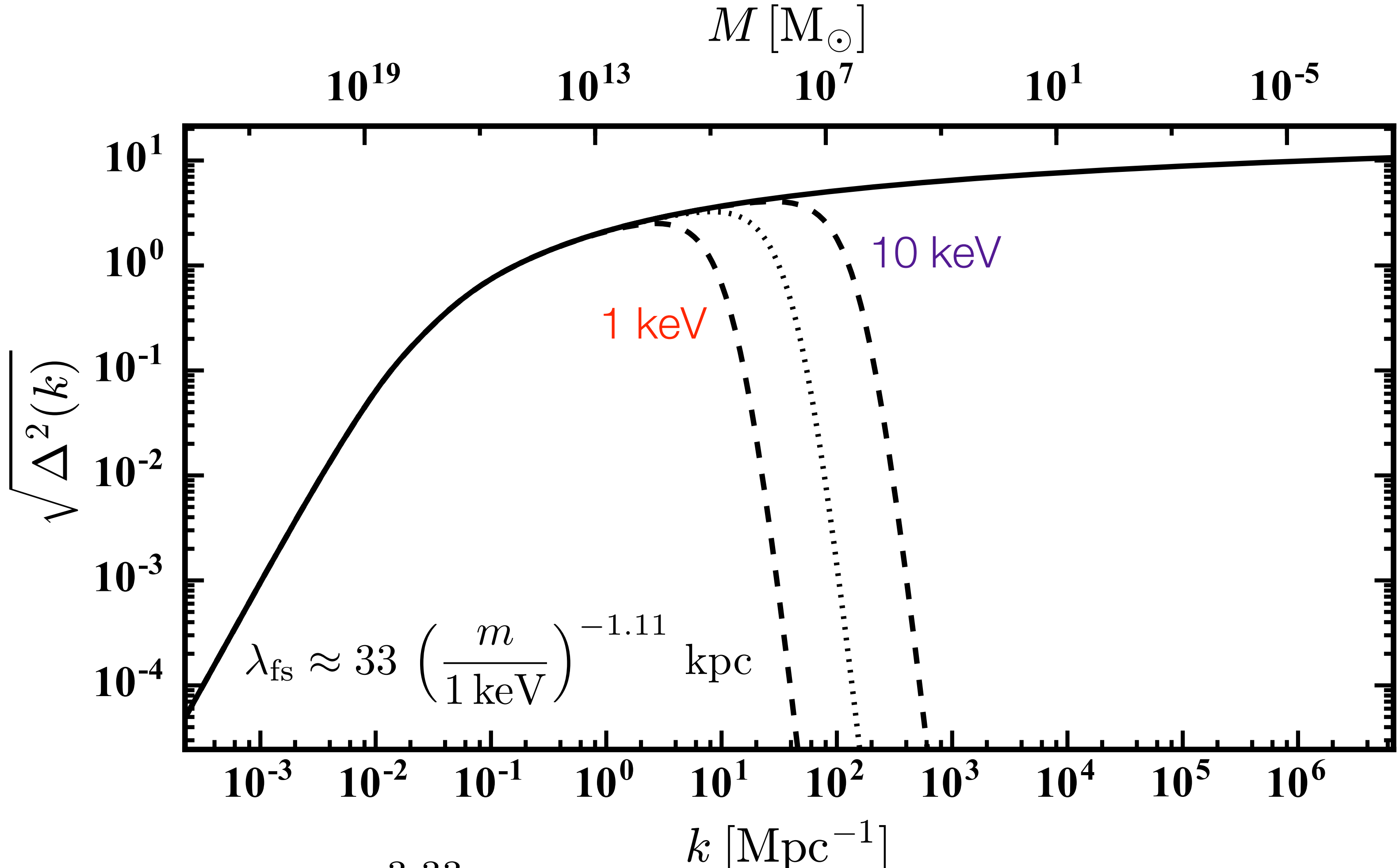
$T_{\rm CMB}(z=0) \sim 2.5 \times 10^{-4}\,{\rm eV}$

$m \sim T$ at $z \sim 10^7$ (for $m \sim 2\,{\rm keV}$)

$v(z=0) \sim 25\,{\rm m\,s^{-1}}$ (for $m \sim 2\,{\rm keV}$)



Origin of cut-off: free-streaming



$$M_{\rm fs} \approx 2 \times 10^7 \left(\frac{m}{1\,{\rm keV}}\right)^{-3.33} M_\odot$$

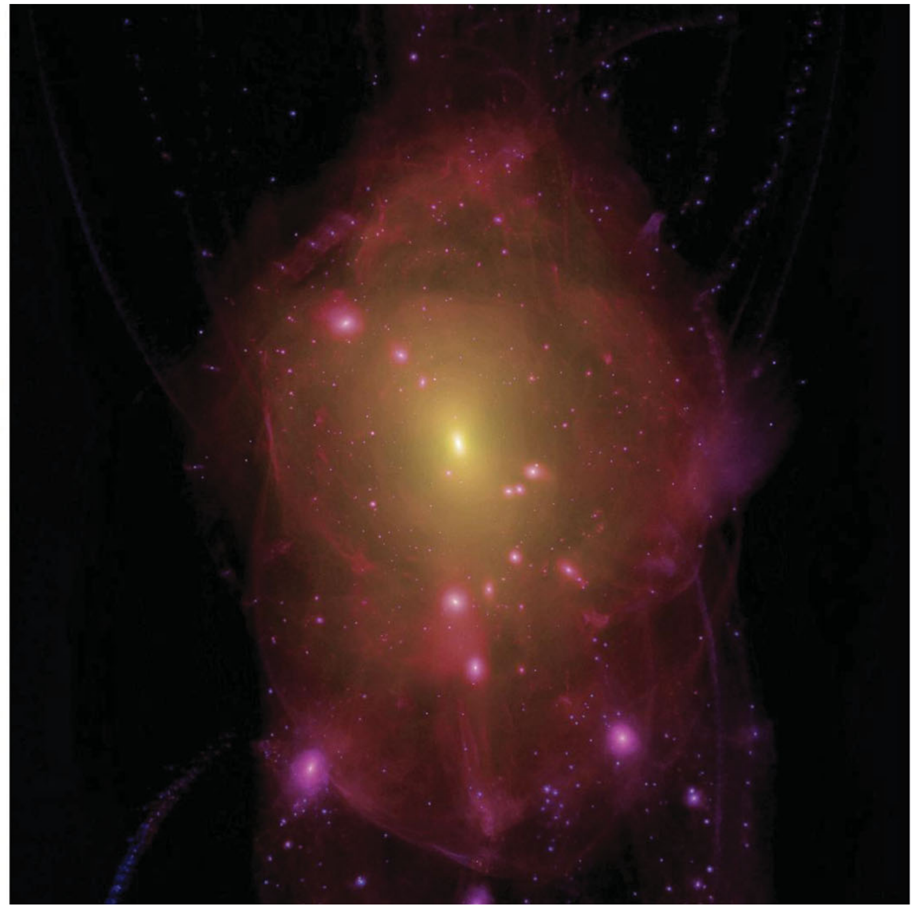
$$M_{\rm hm} \approx 5.5 \times 10^{10} \left(\frac{m}{1\,{\rm keV}}\right)^{-3.33} M_\odot$$

Bullock & Boylan-Kolchin 2017

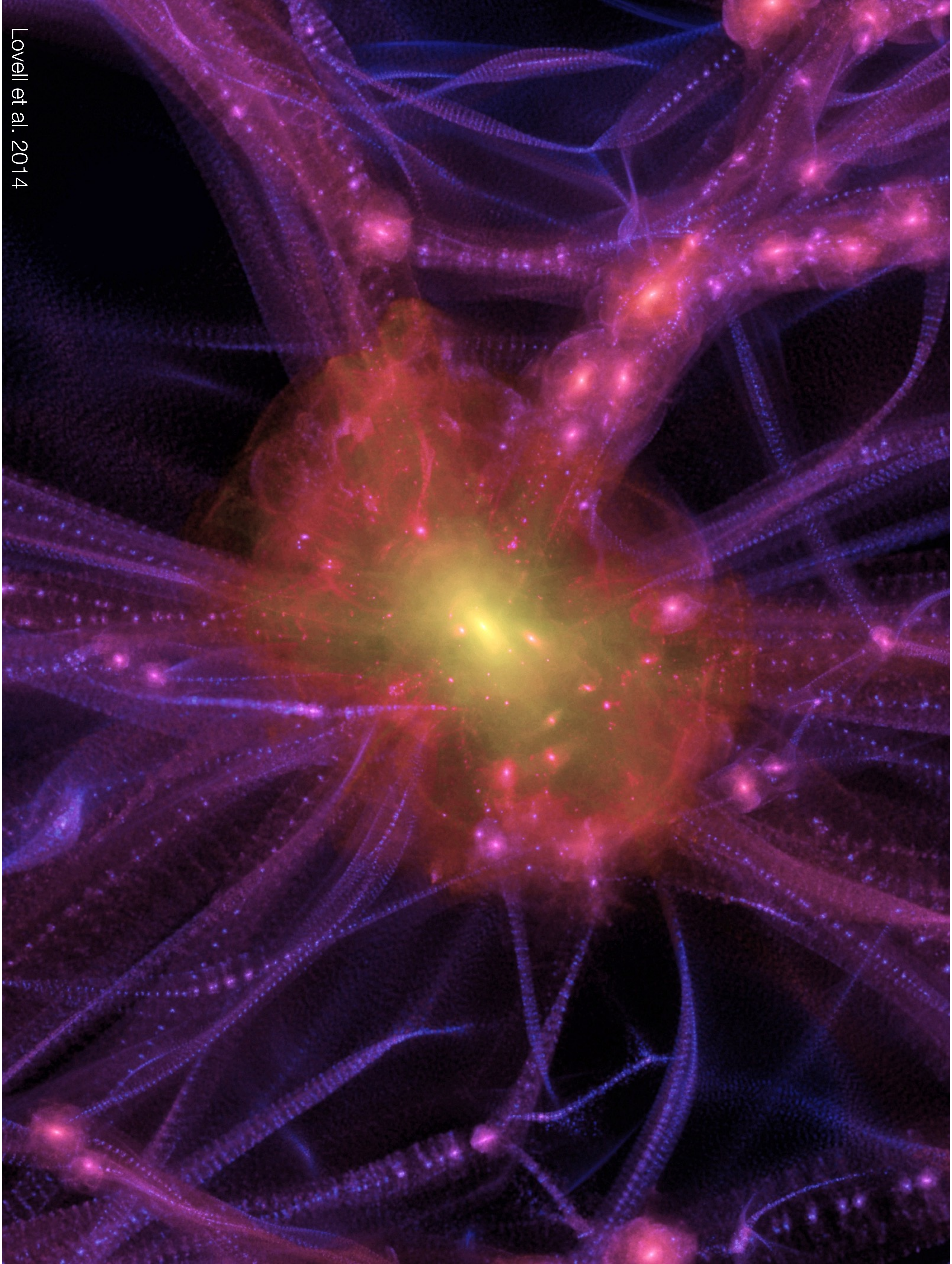
Simulating Warm Dark Matter

CDM

WDM (~2 keV)

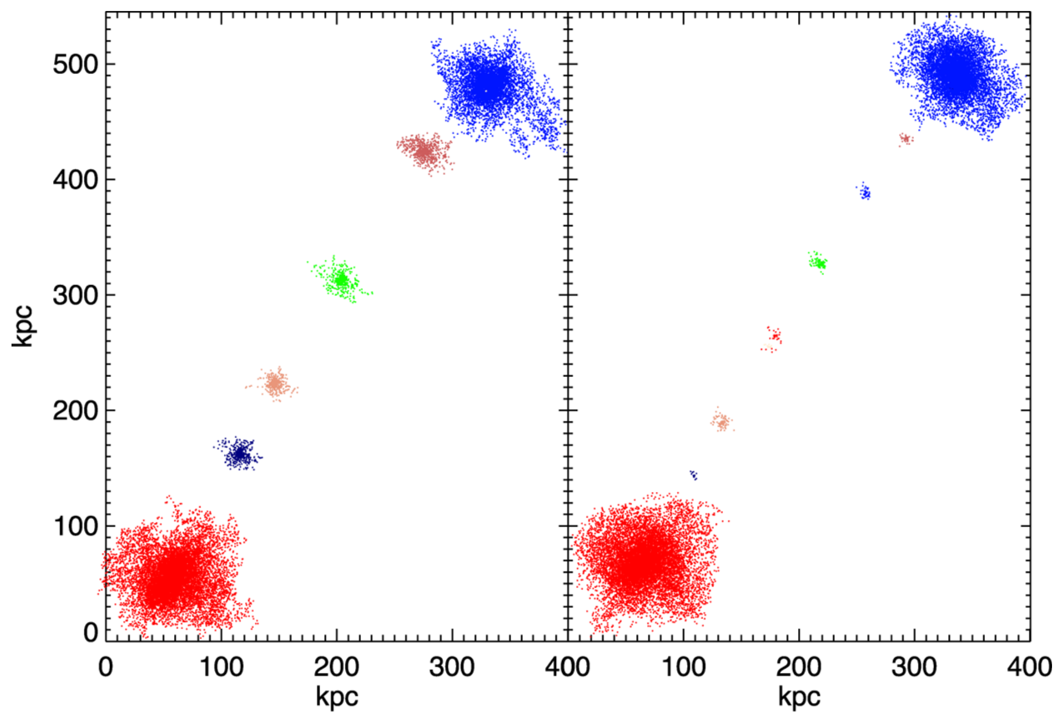


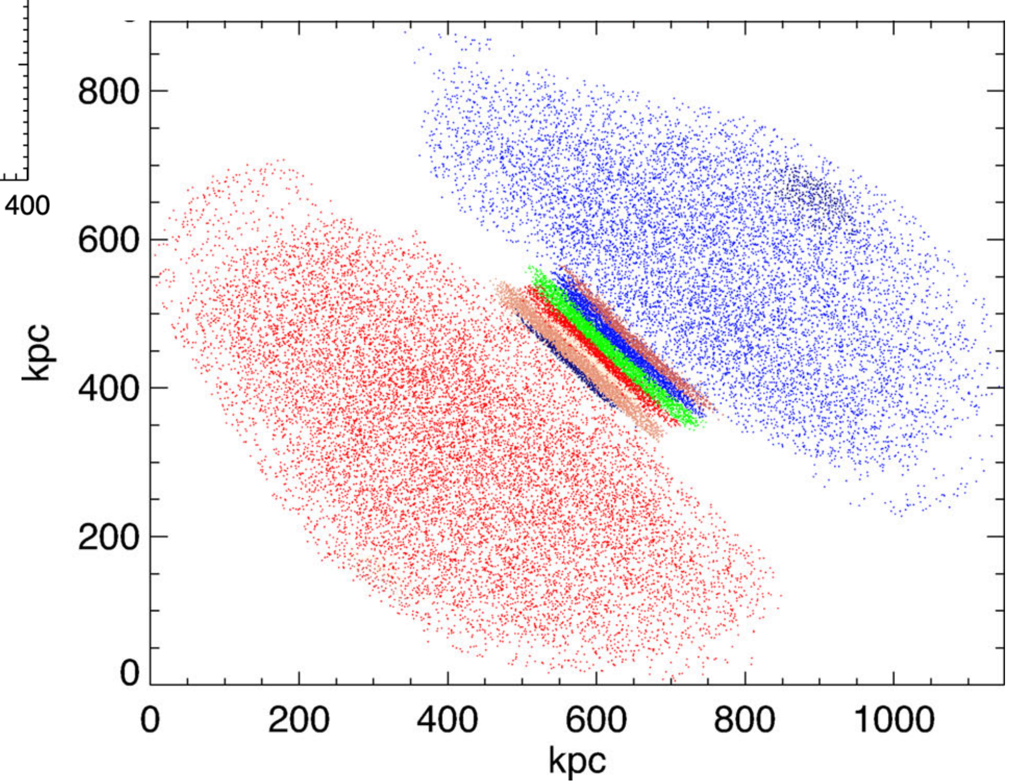
Lovell et al. 2012



Lovell et al. 2014

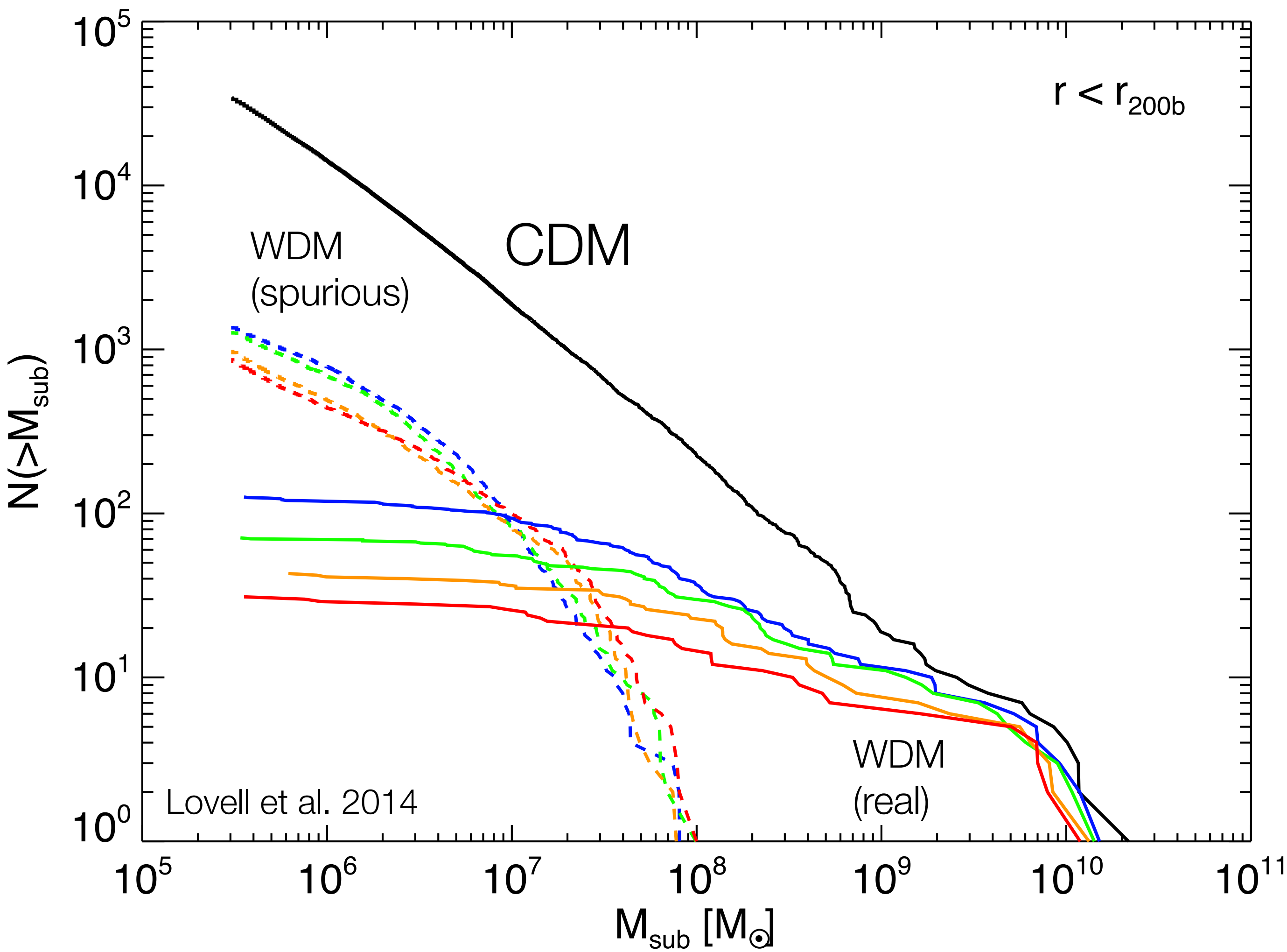
Identifying spurious halos





Lovell et al. 2014

Counts of spurious halos



Scale of spurious subhalos is related to the mean interparticle separation (scales with $m_p^{1/3}$)

Simulating ultra-light axions

- Basic idea: different regimes for dark matter

- if dark matter is made of particles with very low mass, get quantum behavior on astrophysical scales

$$\lambda = \frac{h}{mv} \approx 4\,\mathrm{kpc}\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1}\left(\frac{v}{30\,\mathrm{km\,s^{-1}}}\right)^{-1}$$

Hu et al. 2000, along with other earlier work. Discussion here follows Mocz et al. 2018 and Hui et al. 2017

Some math

$$i\hbar\left(\frac{\partial\psi}{\partial t}\right) = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi,$$

Schrödinger-Poisson

$$\nabla^2 V = 4\pi G(\rho - \overline{\rho})$$

$$\psi = \sqrt{\rho}\mathrm{e}^{iS/\hbar}$$

$$\mathbf{u} \equiv \nabla S/m$$

Some more math

$$i\hbar\left(\frac{\partial\psi}{\partial t}\right) = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi,$$

$$\psi = \sqrt{\rho}\mathrm{e}^{iS/\hbar}$$

$$\mathbf{u} \equiv \nabla S/m$$

$$\nabla^2 V = 4\pi G(\rho - \overline{\rho})$$

$$V_{\mathrm{Q}} \equiv -\frac{\hbar^2}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}.$$

$$\nabla V_{\mathrm{Q}} = \frac{m}{\rho}\nabla\cdot\mathbb{P}_{\mathrm{Q}},$$

$$\mathbb{P}_{\mathrm{Q}} \equiv -\left(\frac{\hbar}{2m}\right)^2 \rho\nabla\otimes\nabla\ln\rho.$$

Correspondence

Schrödinger-Poisson

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla V - \frac{1}{\rho} \nabla \cdot \mathbb{P}_{\mathrm{Q}}$$

$$\mathbb{P}_{\mathrm{Q}} \equiv -\left(\frac{\hbar}{2m}\right)^2 \rho \nabla \otimes \nabla \ln \rho.$$

Jeans/Euler

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \langle \mathbf{v} \rangle) = 0$$

$$\frac{\partial \langle \mathbf{v} \rangle}{\partial t} + \langle \mathbf{v} \rangle \cdot \nabla \langle \mathbf{v} \rangle = -\nabla V - \frac{1}{\rho} \nabla \cdot \mathbb{P}_{\mathrm{J}}$$

$$\mathbb{P}_{\mathrm{J}} \equiv \rho \sigma_{ij}^2 = \rho \left(\langle v_i v_j \rangle - \langle v_i \rangle \langle v_j \rangle \right)$$

Another look

Madelung Equations

$$\dot{\rho} + 3H\rho + \frac{1}{R}\boldsymbol{\nabla}\cdot(\rho\mathbf{v}) = 0,$$

$$\dot{\mathbf{v}} + H\mathbf{v} + \frac{1}{R}(\mathbf{v}\cdot\boldsymbol{\nabla})\mathbf{v} = -\frac{1}{R}\boldsymbol{\nabla}\Phi + \frac{\hbar^2}{2R^3m^2}\boldsymbol{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

Phenomenology

$$\lambda \lesssim R_{\rm vir} = GM/V^2$$

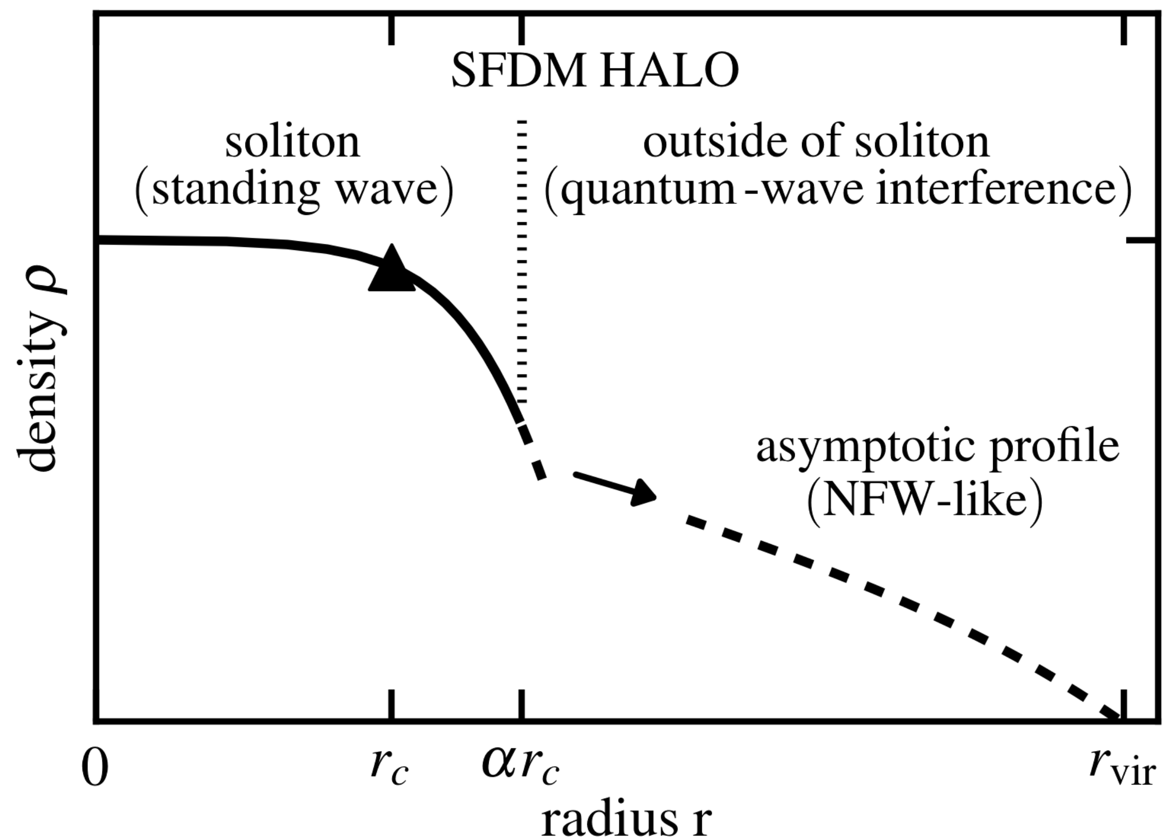
Stationary solution, spherical symmetry:

$$r_{1/2} \geq 3.925 \frac{\hbar^2}{GMm^2} = 0.335 \text{ kpc} \frac{10^9 \ M_\odot}{M} \left(\frac{10^{-22} \text{ eV}}{m} \right)^2$$

$$\begin{aligned} \rho_c &\leq 0.0044 \left(\frac{Gm^2}{\hbar^2} \right)^3 M^4 \\ &= 7.05 \ M_\odot \text{ pc}^{-3} \left(\frac{m}{10^{-22} \text{ eV}} \right)^6 \left(\frac{M}{10^9 \ M_\odot} \right)^4 . \end{aligned}$$

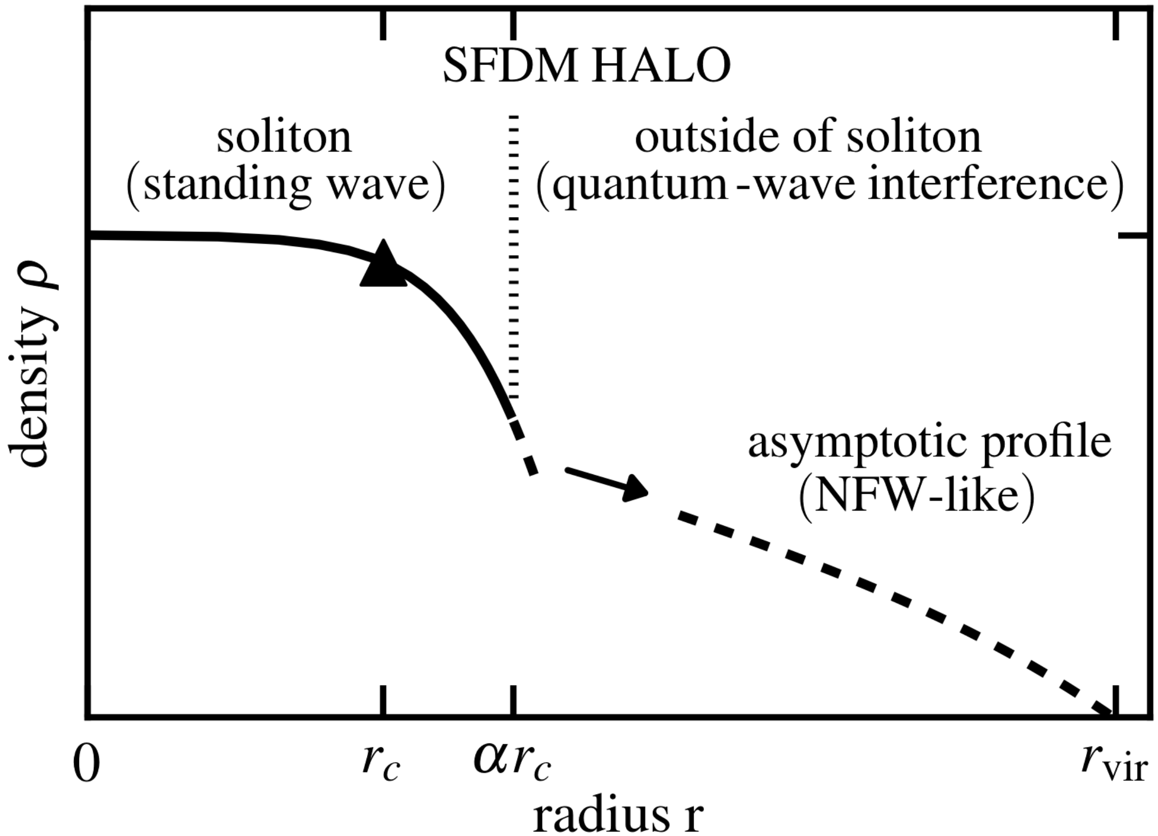
Central “soliton” (standing wave)

Schematic structure of halo



Robles, Bullock, MBK (in preparation)

Schematic structure of halo



Simple scaling:

$$r_{\rm core} \propto \lambda \propto (mv)^{-1}$$

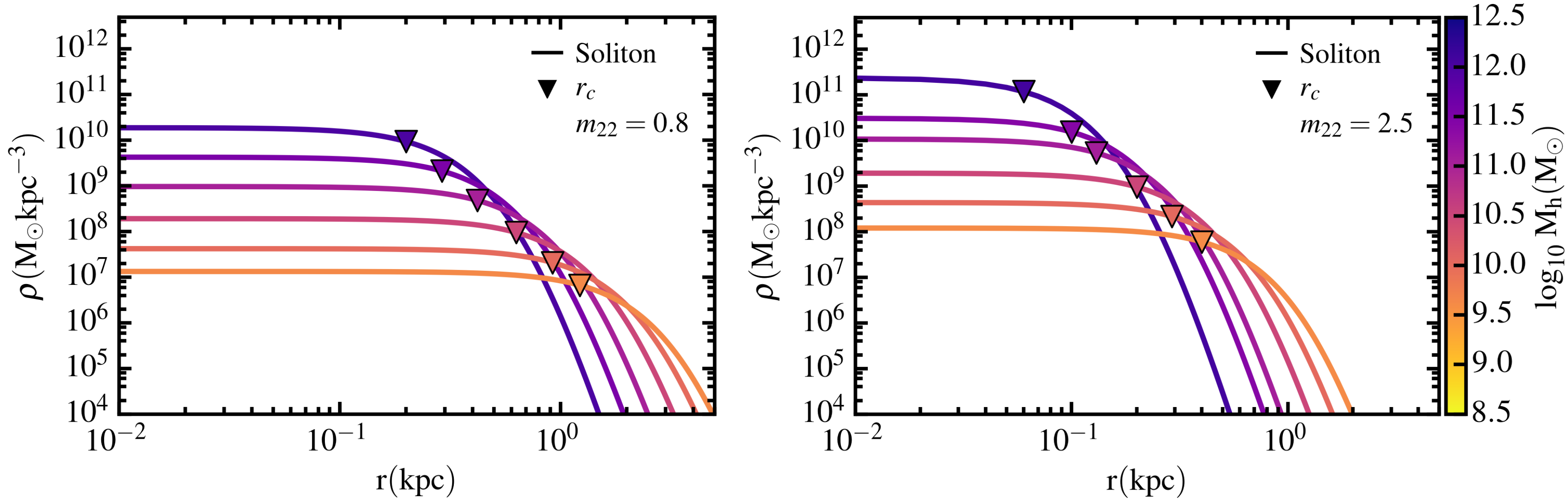
$$v \propto M_{\rm halo}^{1/3}$$

$$r_{\rm core} \propto 1/(m\, M_{\rm halo}^{1/3})$$

$$\frac{r_{\rm core}}{r_{\rm vir}} \propto 1/(m\, M_{\rm halo}^{2/3})$$

Robles, Bullock, MBK (in preparation)

Schematic structure of halo



lower-mass halo → lower density, larger solitonic core

Robles, Bullock, MBK (in preparation)

Numerical difficulties

$$\dot{\rho} + 3H\rho + \frac{1}{R}\boldsymbol{\nabla}\cdot(\rho\mathbf{v}) = 0,$$

$$\dot{\mathbf{v}} + H\mathbf{v} + \frac{1}{R}(\mathbf{v}\cdot\boldsymbol{\nabla})\mathbf{v} = -\frac{1}{R}\boldsymbol{\nabla}\Phi + \frac{\hbar^2}{2R^3m^2}\boxed{\boldsymbol{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)}$$

Numerically challenging to handle third derivatives of density

Quantum pressure term is neither isotropic nor (necessarily) positive-definite

Numerical frontiers

- Quantum pressure term can be handled in a similar way to Braginskii conduction or cosmic-ray diffusion (implementations of these exist in current codes)

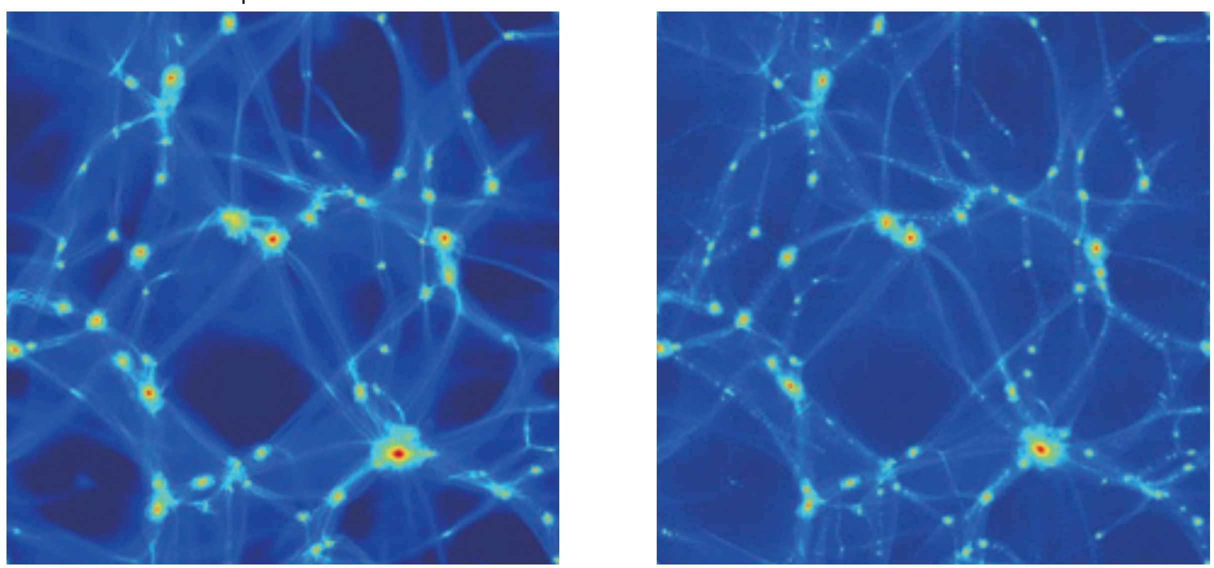
- Can we run fully cosmological simulations (with or without baryons) that resolve full non-linear structure of scalar field dark matter (including self-interference, quantum turbulence, caustics, …)?

- How does addition of baryons change soliton structure (particularly if baryons dominate central potential at some point? Can we use analytic models to understand these situations (similar to Kaplinghat et al. for SIDM)?

Cosmic structure as the quantum interference of a coherent dark wave

Hsi-Yu Schive[1], Tzihong Chiueh[1,2]* and Tom Broadhurst[3,4]

a ψDM **b** CDM



Mocz et al. 2017 (also Schwabe et al. 2016): idealized merger simulations