Title: Structure formation with hot particles

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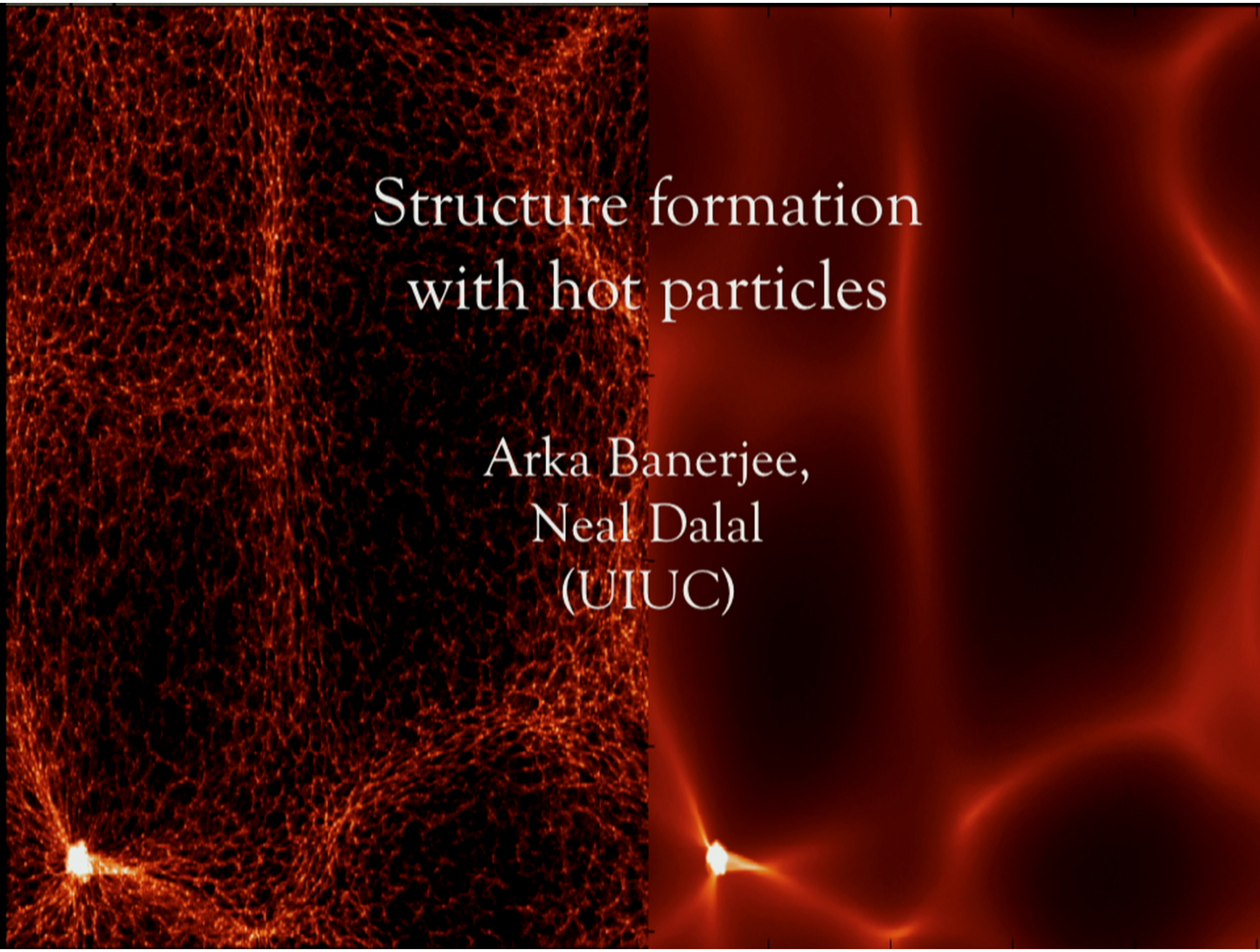
Abstract: I will describe a novel method for simulating nonlinear structure formation in cosmologies that have hot or warm collisionless species. After introducing the method, I will show results of our simulations for universes with massive neutrinos, and warm dark matter simulations.


Structure formation
with hot particles
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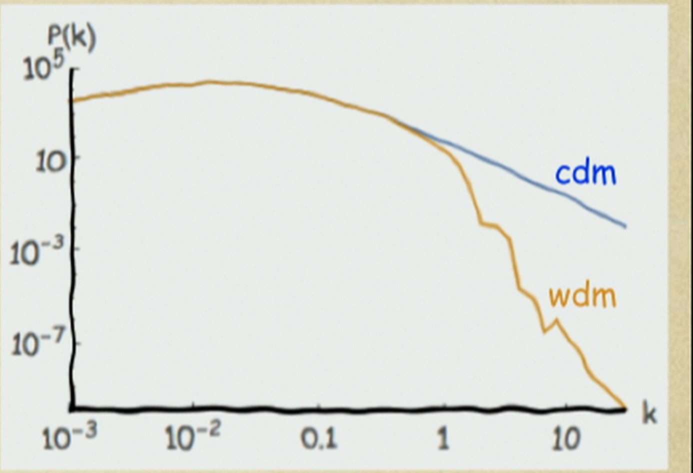
Cosmologies with fast particles

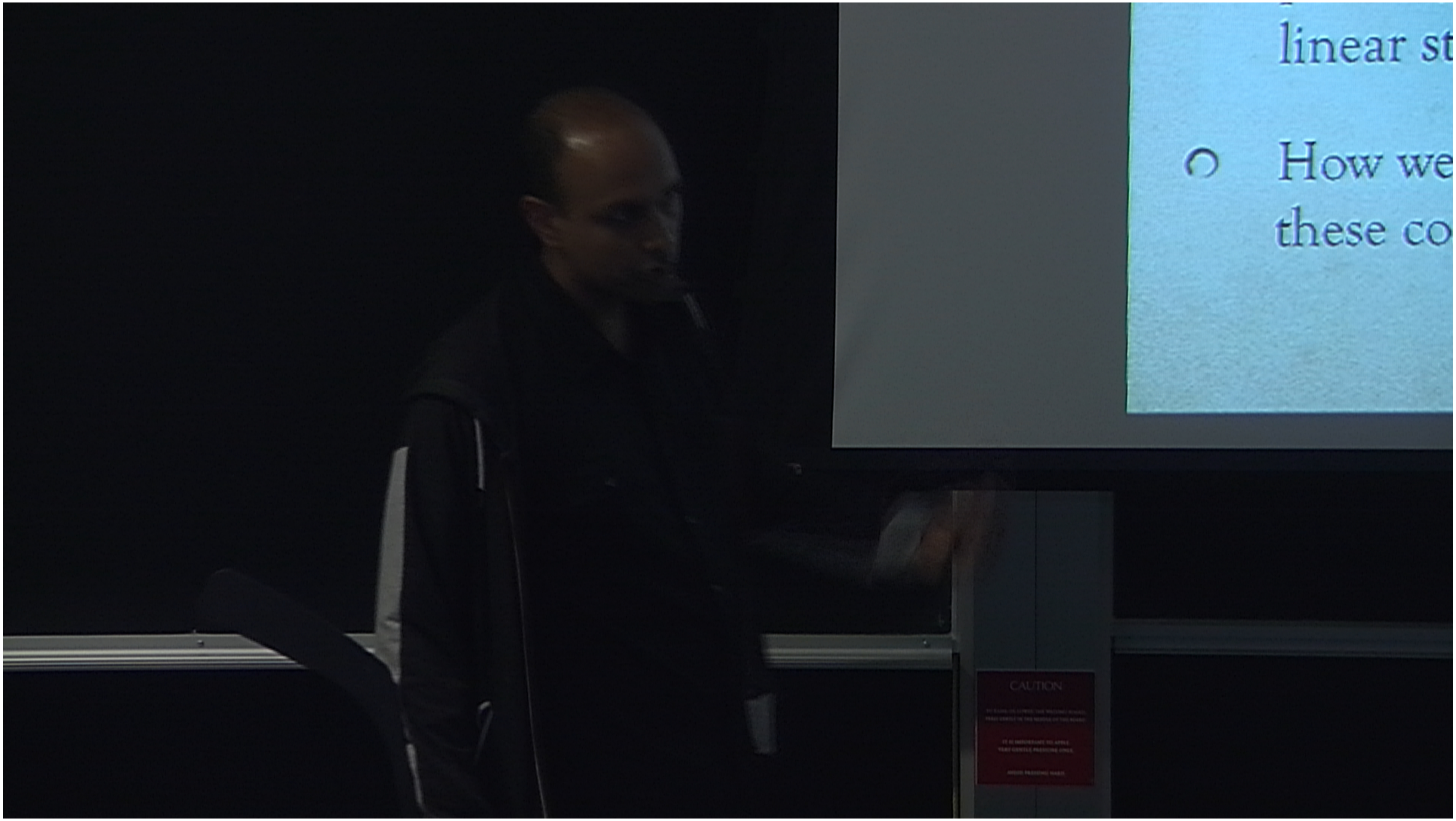
- Normally, in calculations of structure formation, we can neglect the thermal motions of matter.
- But not always! Sometimes particles move quickly, e.g. **massive neutrinos**, or **Warm Dark Matter**
- Thermal motions damp structure on small scales, due to the streaming of particles.



Linear power spectrum from CLASS

Are those cosmologies relevant?

- There *may* be tension between ΛCDM predictions and actual observations of small scale structure:
  - missing satellites, TBTF, cusp/core, etc.
  - So, modifying $P(k)$ on small scales might be interesting!
- The shape of $P(k)$ is set by primordial physics (inflation) *and* by late-time physics (DM transfer functions). Can we distinguish those effects?
- Also: neutrinos definitely exist, and they definitely have mass!
- Cosmology provides a very promising route to measure neutrino masses, <u>if</u> we can predict the effect of ν's on large-scale structure.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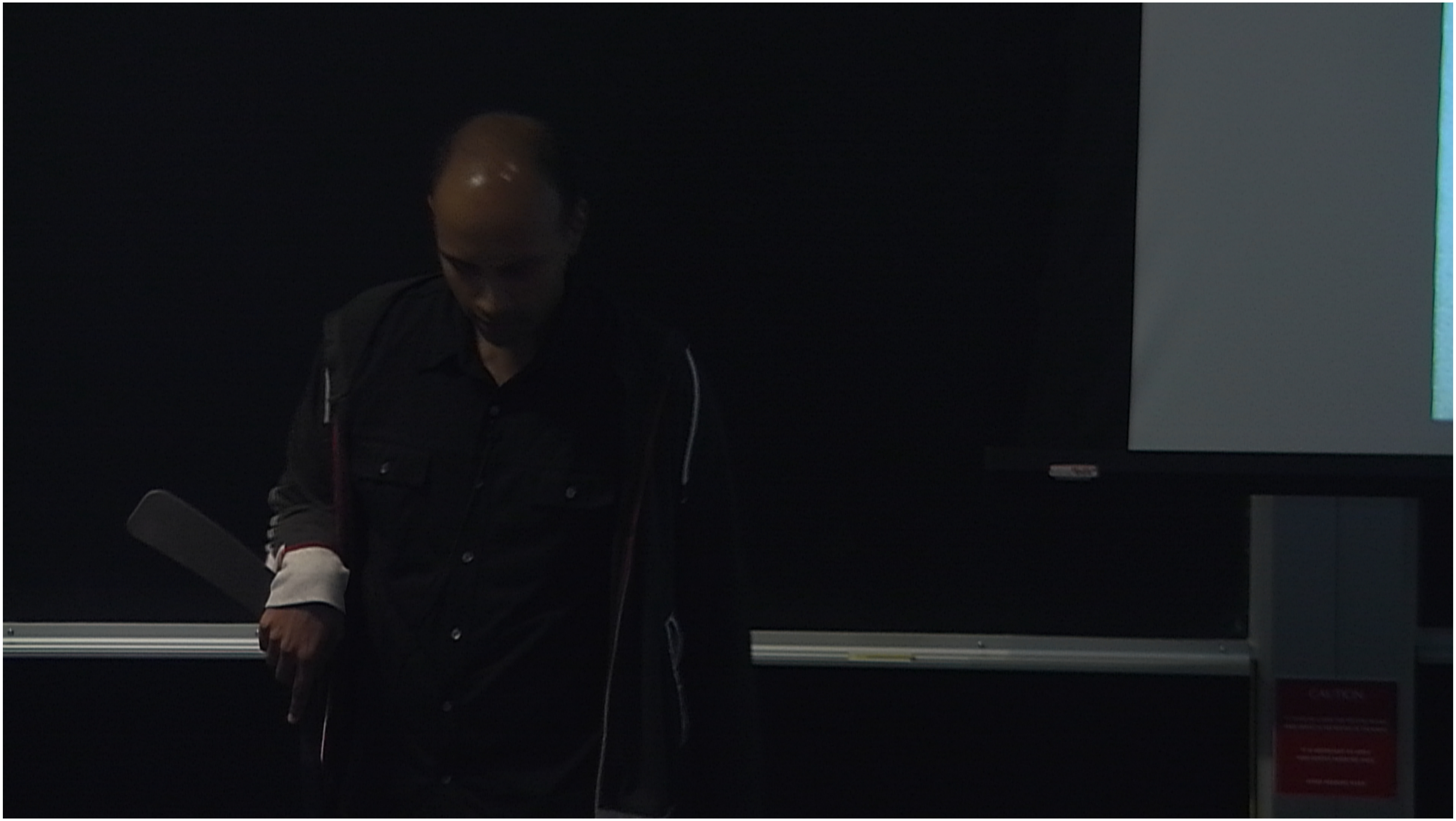
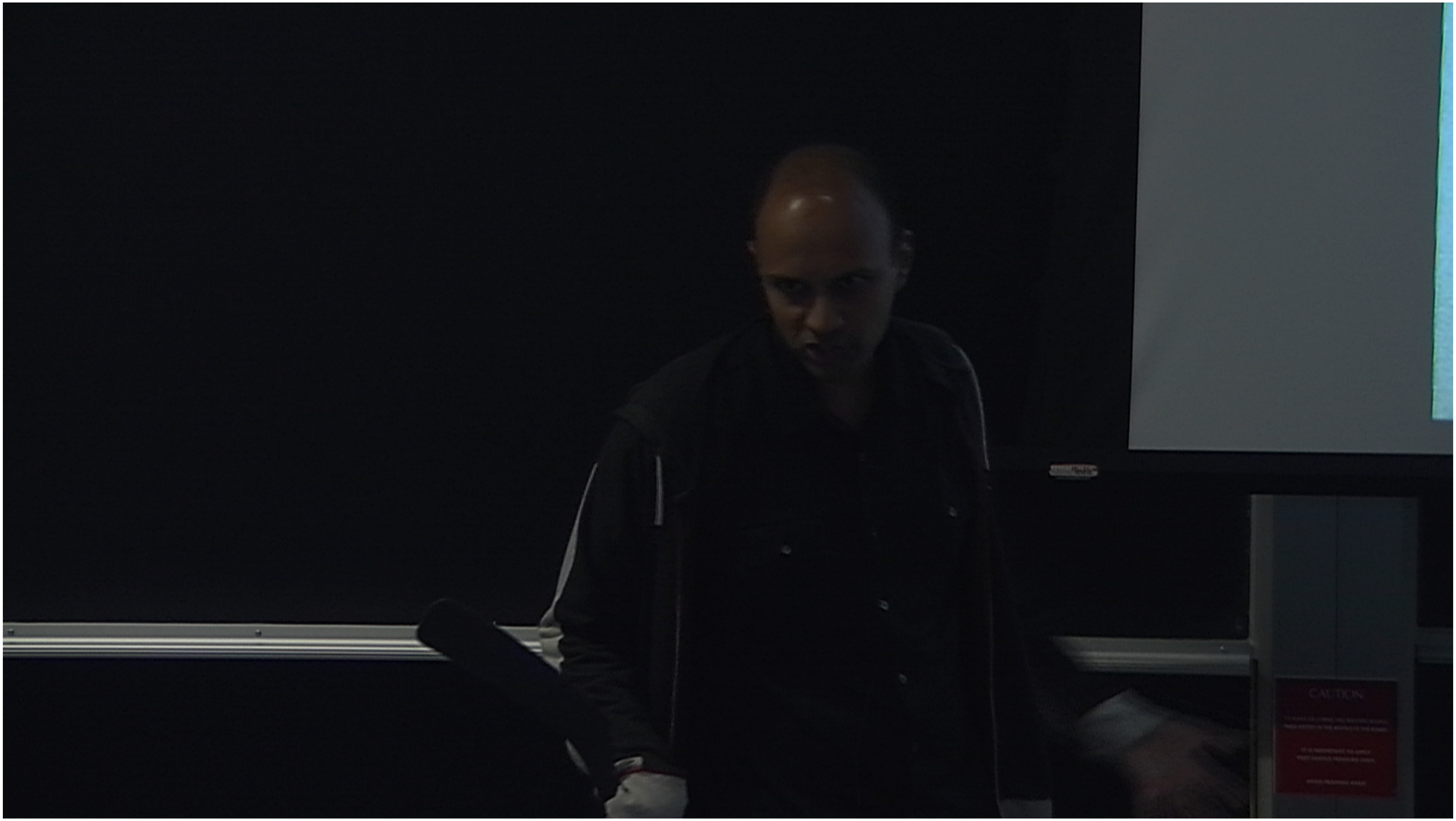
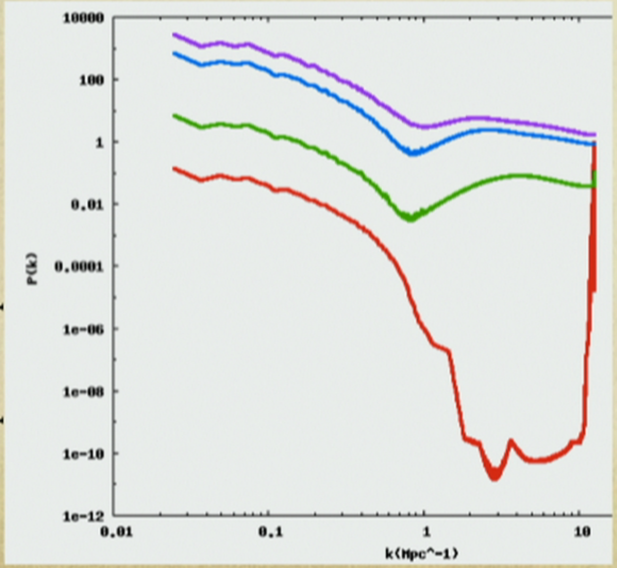




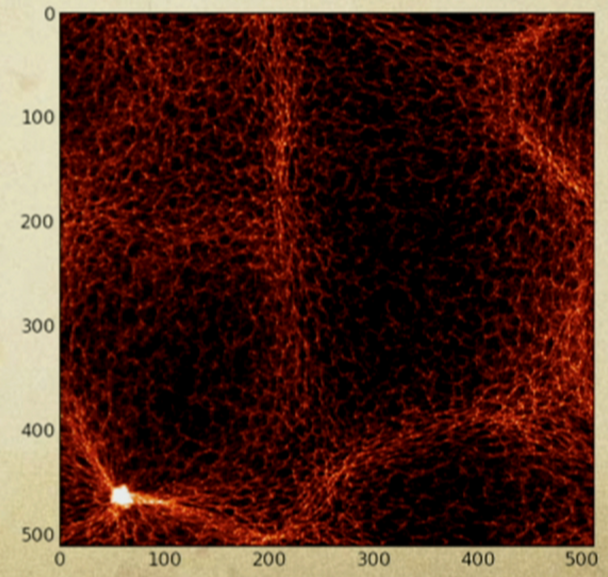
N-body sims with hot starts

- If we initialize particles with random thermal velocities (called a hot start), the results are plagued by shot noise and fake halos below the streaming length.

power spectrum

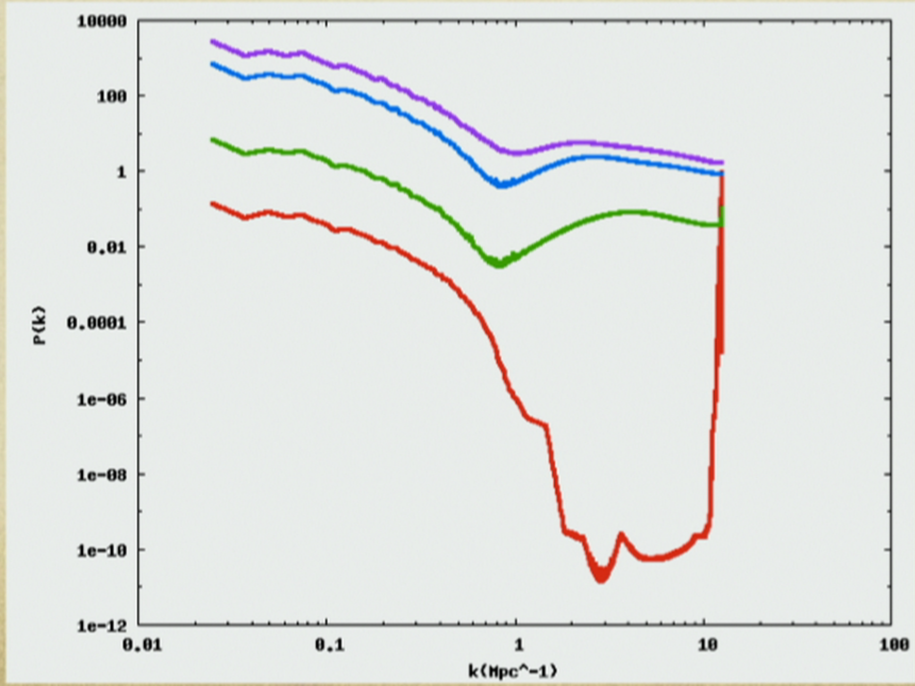


wavenumber



More particles?

- The shot noise appears particles move random distances. The fractional error in particle density scales as $N^{-1/2}$. So the error in the power spectrum then is $\propto n^{-1}$.



Alternate approach

- One way of estimating quantities using more particles is to smooth on a certain scale (below λ_{Jeans}).
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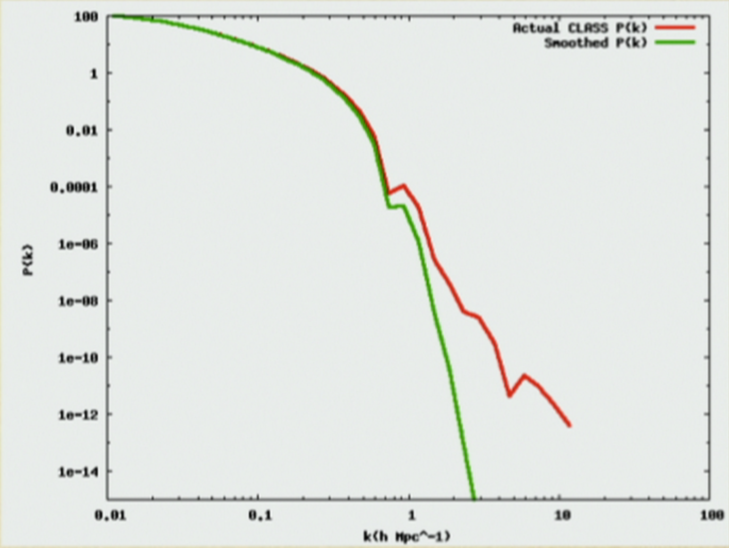
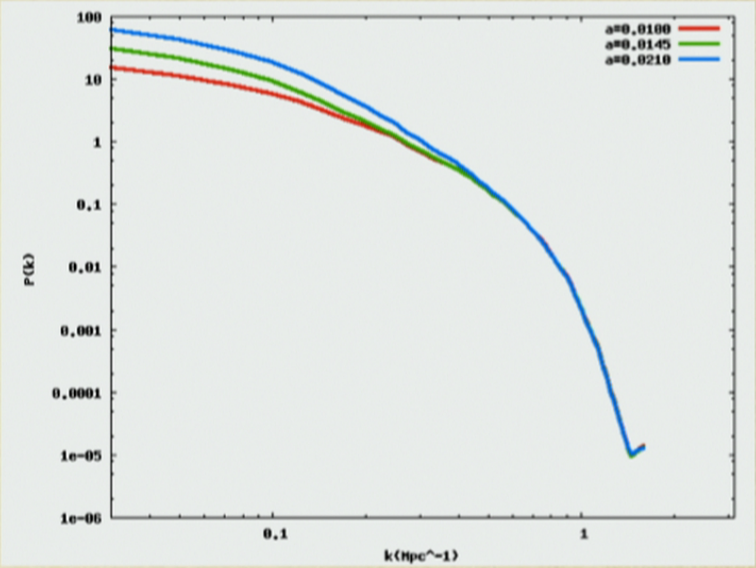
- Which quantities can we smooth?
- First guess is to smooth density. But smoothing the density field means that on small scales the power is completely washed out.



Smoothed velocity field

- The next simplest approach would be to estimate a velocity field from the particles and use the continuity equation to evolve the overdensities on a grid.
- But averaging the velocity field has the same problem.



$$\dot{\delta} + \vec{\nabla} \cdot \vec{v} = 0 \quad \Rightarrow \quad \dot{\delta}_k = i\vec{k} \cdot \vec{v}_k$$

Smoothed velocity dispersion

- Take this process a step forward, and use both the Euler and the continuity equations. To do this we need the stress tensor

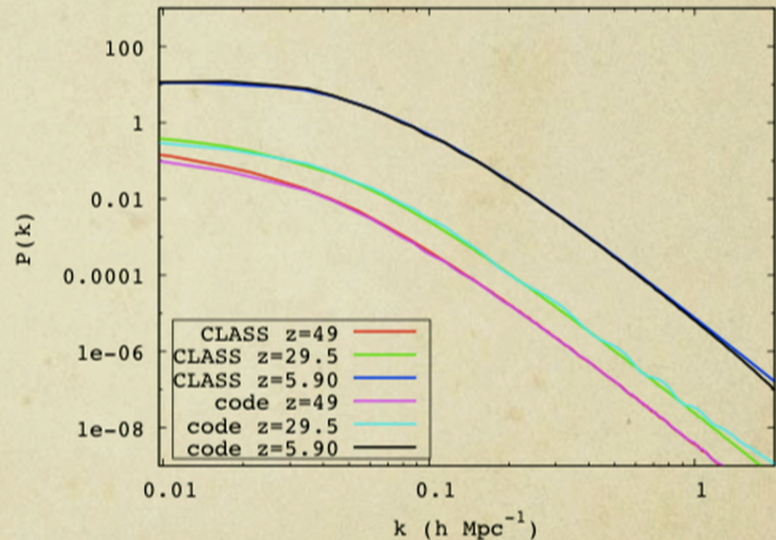
$$\rho\langle(v_i - \langle v_i\rangle)\,(v_j - \langle v_j\rangle)\rangle.$$

- In linear theory,

$$(\delta\rho)\,\bar{w} \gg \bar{\rho}\,(\delta w)$$

- Physically, we do not expect the velocity dispersion to change much at scales below the local Jeans scale.

- Comparison with linearized Boltzmann code (CLASS)



Choosing a smoothing length

- We want our estimates to be accurate compared to other quantities relevant to structure formation. Also, we shouldn't smooth above the local Jeans scale, to avoid erasing real structure.
- Velocities sourced by gravity are of order $v^2 \sim \Phi_{\mathrm{rms}}$. The scatter in particle velocities is $\sigma_v{}^2 \sim w$, so with N particles, the error in dispersion tensor is $\sim w/N^{1/2}$.

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- To keep error on T^{ij} below ε we need $N > (w/\Phi_{\rm rms}\varepsilon)^2$ particles per smoothing length.
- Since $N \sim n\, L_s{}^3$, the smoothing length is $L_s = \eta\, (w^2/\Phi_{\rm rms}{}^2\, n)^{1/3}$ for some η.

Fluid equations

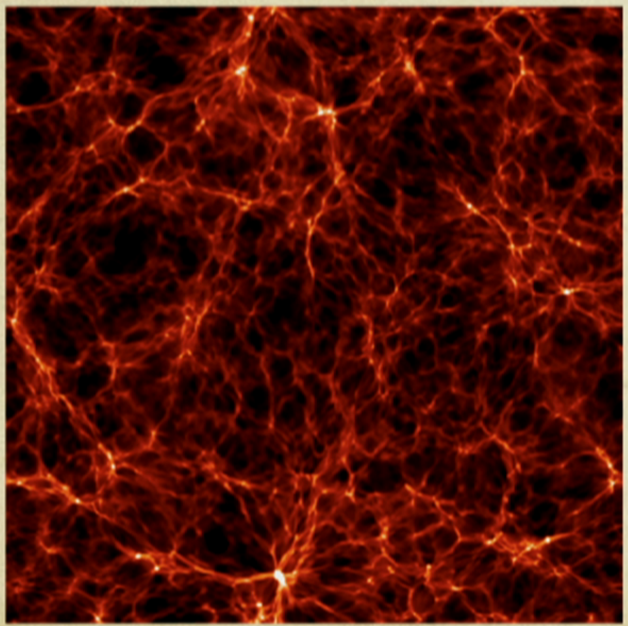
- Our full set of fluid equations (in Newtonian gauge) are :
  - continuity:

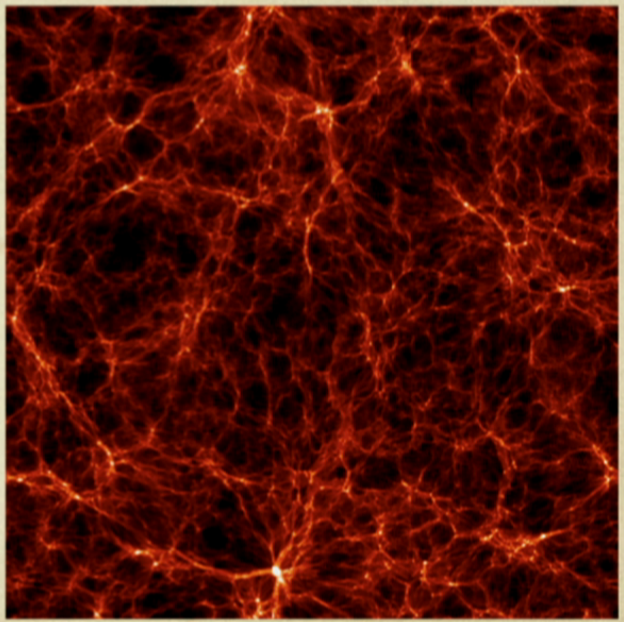
$$\dot{\delta} + \frac{1}{a}\partial_i[(1+2\psi)\Pi^i] + 3\dot{\phi}(1+\delta)\big(1+w(x)\big) + 3\frac{\dot{a}}{a}(1+\delta)\big(w(x)-\bar{w}\big) = 0$$

  - Euler: $$\dot{\Pi}^i + \left(4\dot{\phi} + (1-3\bar{w})\frac{\dot{a}}{a}\right)\Pi^i + \frac{(1+\psi)}{a}\partial_j T^{ij} + \frac{(1+\delta)}{a}\partial_i\psi + \frac{1}{a}\partial_j(\psi T^{ij}) = 0$$

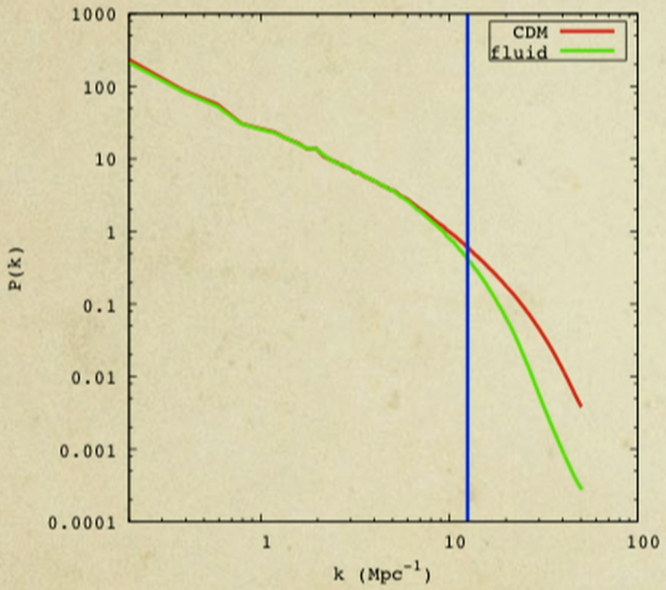
  - Poisson: $$\nabla^2\psi = 4\pi G a^2\left[\bar{\rho}\delta - 3\frac{\dot{a}}{a}\bar{\rho}(1+\bar{w})\theta\right]$$

CDM comparison vs. N-body

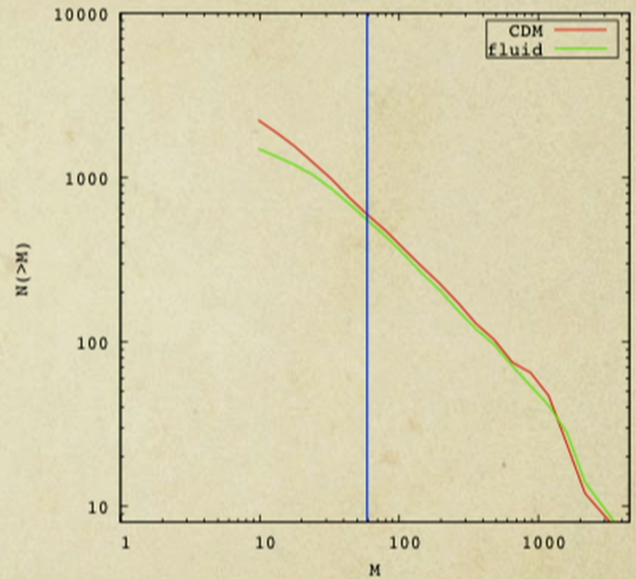




CDM comparison

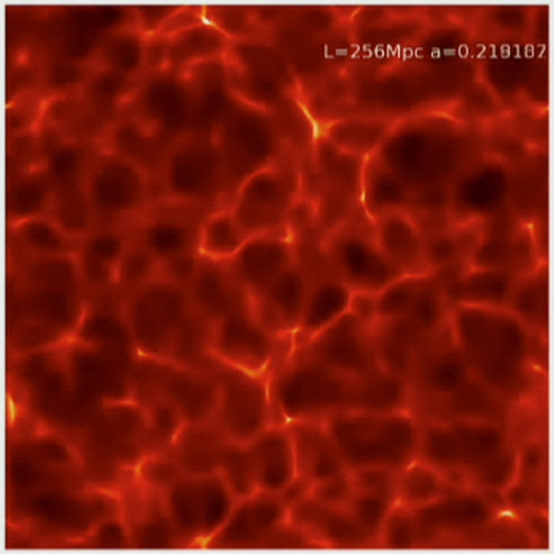


power spectrum

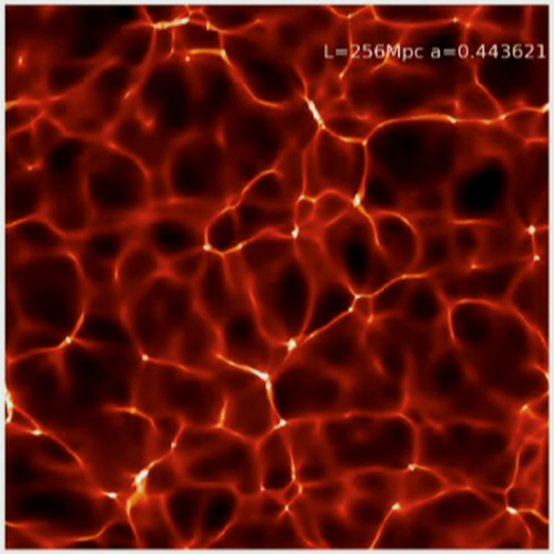


SO mass function

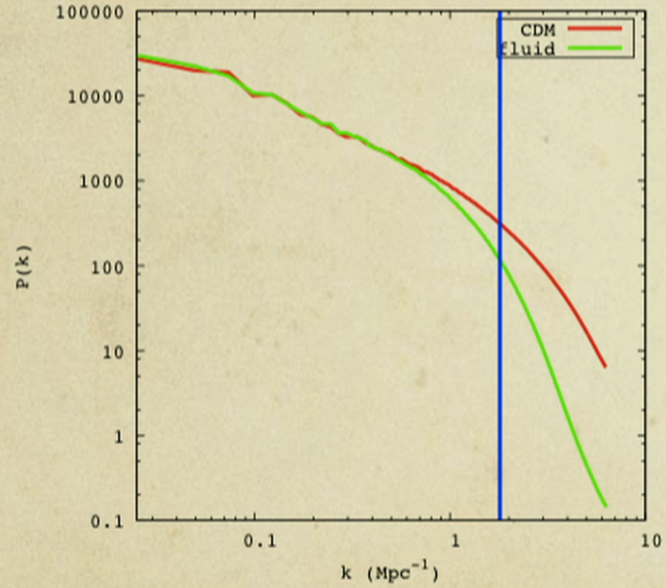
WDM simulation

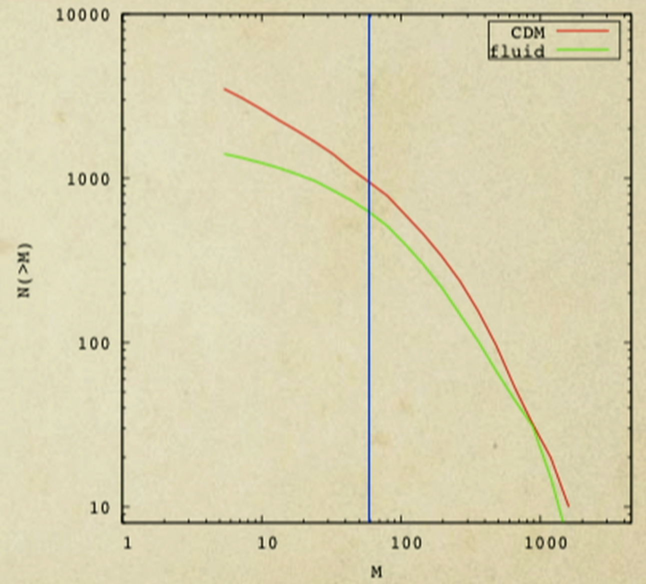


WDM simulation



CDM vs. WDM





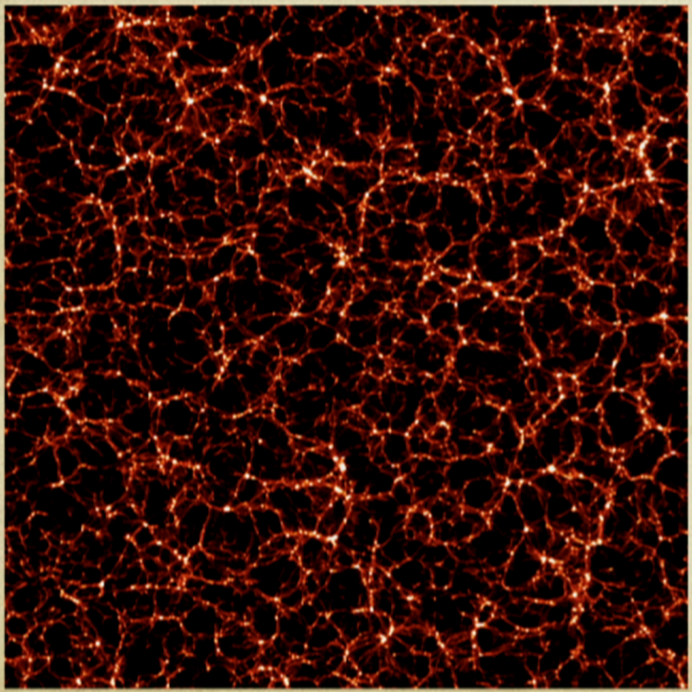
We plan to study this more in the future!

Neutrinos

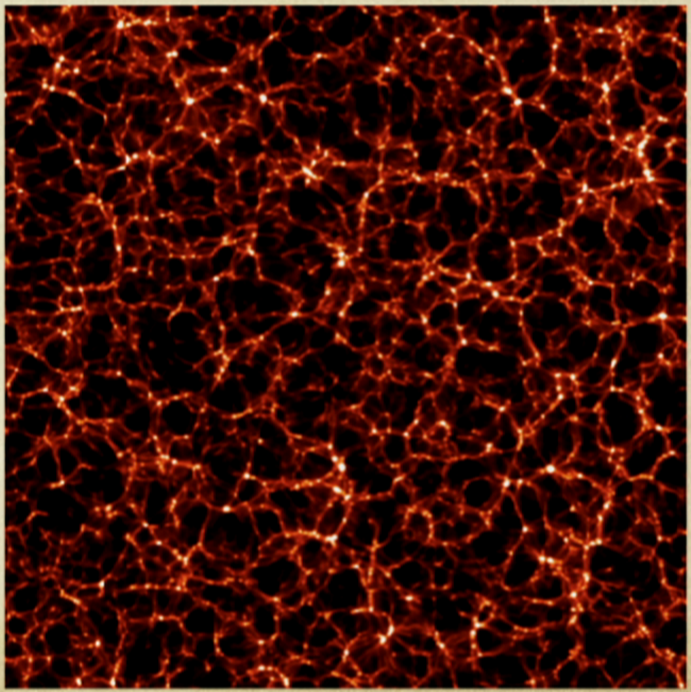
- Neutrinos do have mass and are hot at high z. Cosmology offers a promising route for measuring their masses.
- Most information comes from small scales ⇒ simulations needed!
- Neutrinos are subdominant to matter, so the effect of their clustering on the matter power spectrum is small. However, their thermal velocities are larger.
- If we are interested in the neutrino power spectrum itself, there will once again be large fractional errors if N-body methods are used.

Results for neutrinos

m_ν=1.6 eV



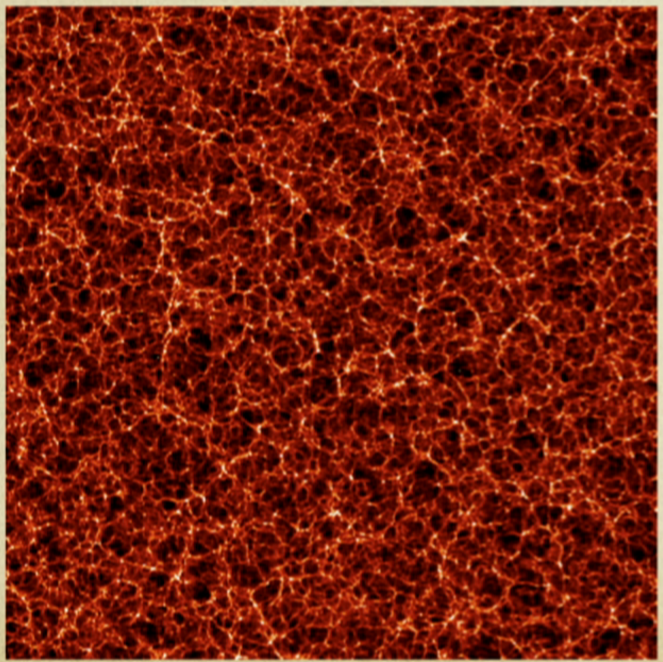
Dark matter at z=0



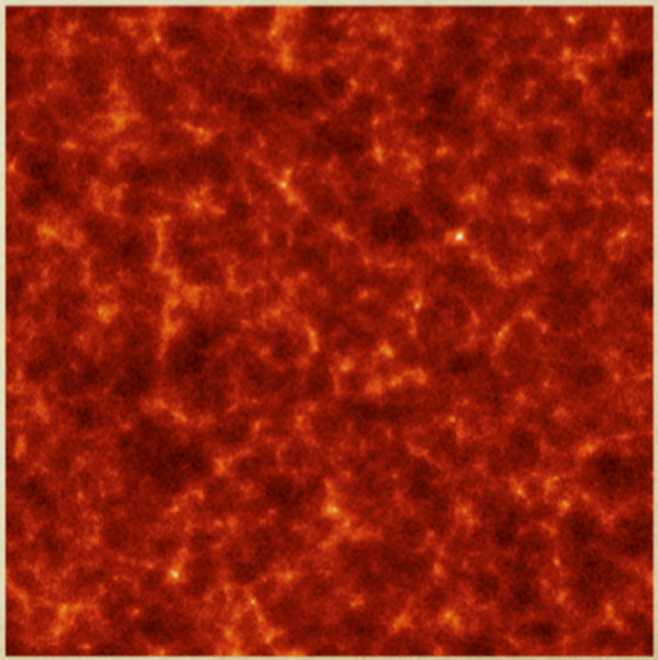
Neutrinos at z=0

Results for neutrinos

m_ν=0.1 eV



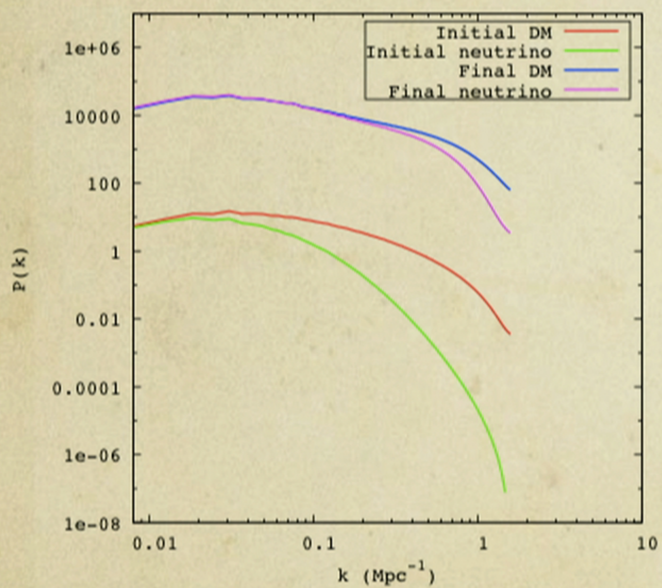
Dark matter at z=0



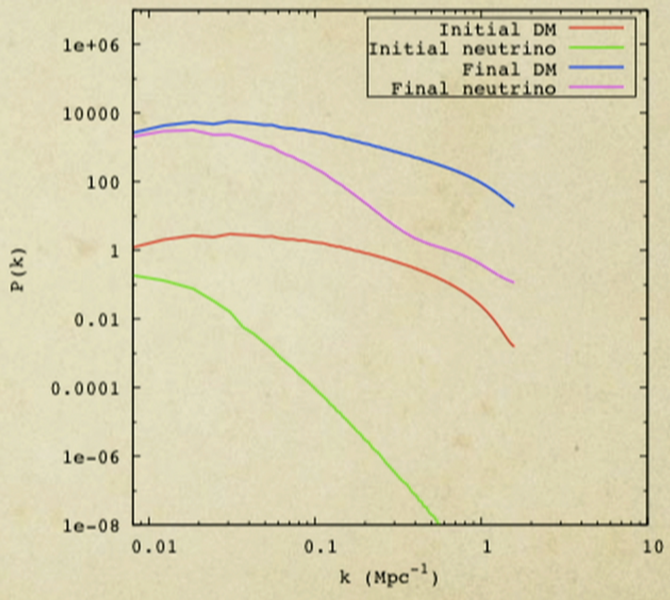
Neutrinos at z=0

Heavy vs. Light

m_ν=1.6 eV



m_ν=0.1 eV



Neutrinos in LSS

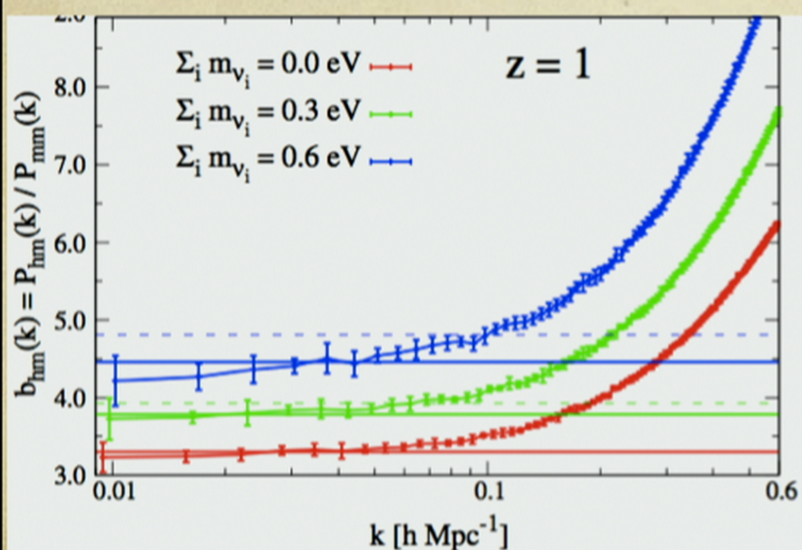
- It's well known that neutrinos affect the matter power spectrum. But they could also affect **biased tracers** of large-scale structure.

Neutrinos in LSS

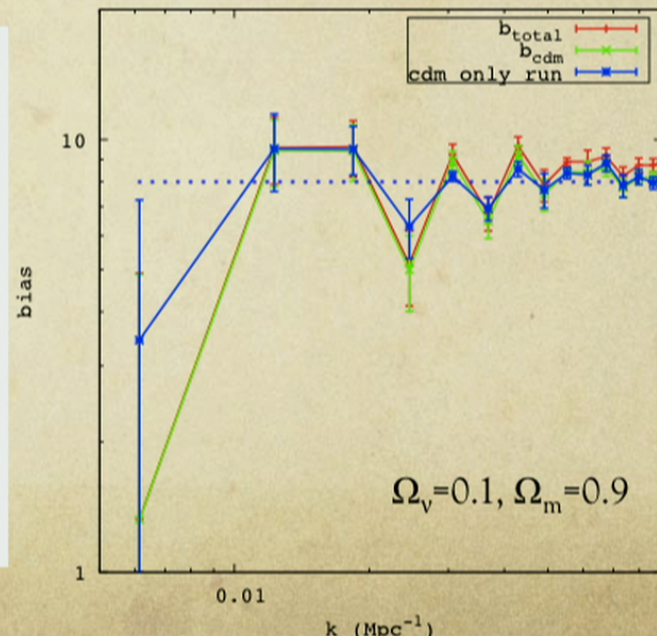
- The size of this effect will depend on how much mass neutrinos add to objects.
- Naively, we might expect it to be of order the cosmic neutrino mass fraction, $f_\nu = \Omega_\nu / \Omega_m$.
- But it's actually smaller! By Liouville's theorem, the phase space density is conserved. So the neutrino overdensity in halos is $\Delta_\nu \lesssim (v_{vir}/v_\nu)^3 \ll \Delta_{DM} \approx 200$
- To make neutrinos cluster in halos ($v_{vir} \lesssim 1000$ km/s), we have to make them so cold that they trace dark matter, killing the effect.

Halo bias with neutrinos

For halos, previous work (e.g. Villaescusa-Navarro et al. 2014, LoVerde 2014) found very small effects on halo bias from neutrinos. Our simulations appear consistent with that.



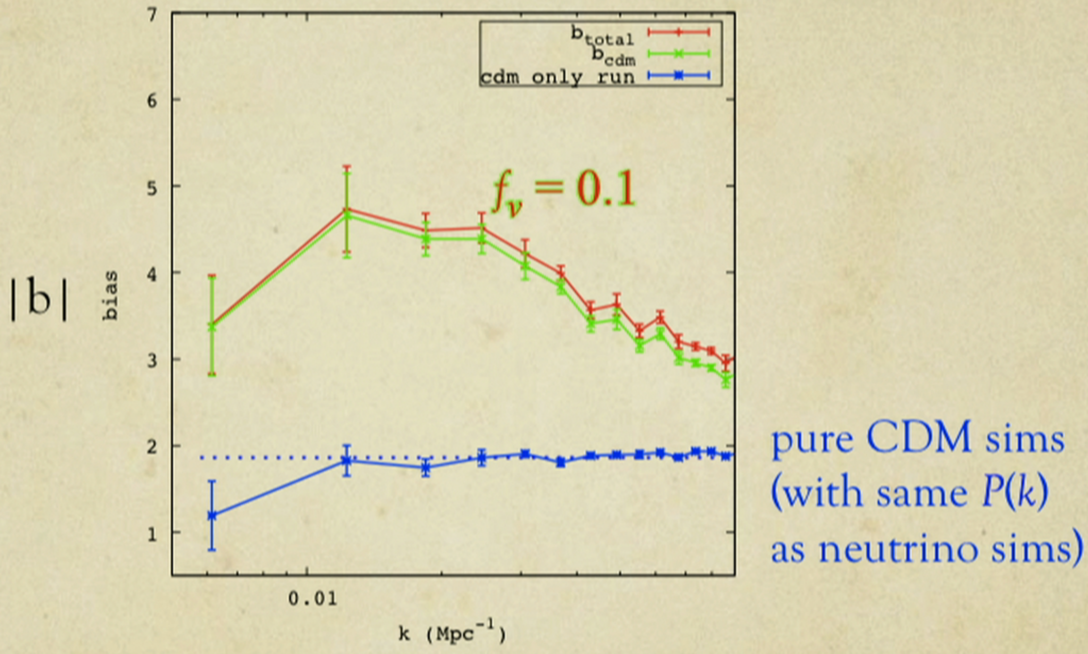
Villaescusa-Navarro et al. (2014)



Other signatures?

- Our problem was that in halos, hot neutrinos necessarily make up a tiny fraction of mass (since $\Delta_\nu \ll \Delta_{DM}$).
- Are there other nonlinear structures where that is not the case?
- In voids, the DM underdensity is bounded by $\Delta_{DM} > -1$. So in voids, $|\Delta_\nu|$ is not much less than $|\Delta_{DM}|$.
- Voids are now being found in large numbers! (e.g., Clampitt & Jain 2014, Sutter et al. 2014)

Void bias with neutrinos



For voids, we do see significant effects on bias from neutrinos, including pronounced scale dependence – for cosmologies with artificially high neutrino density.

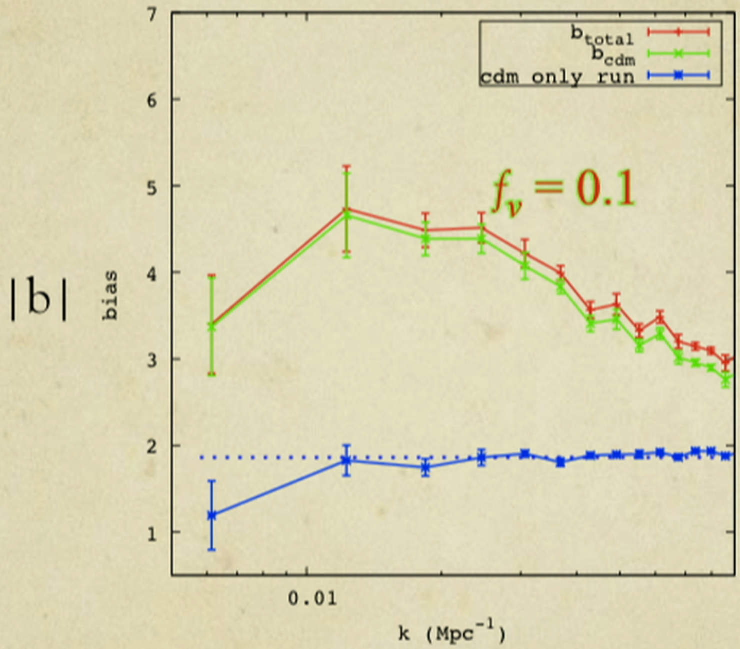
Is it measureable?

- The reason why we've focused on scale-dependent linear bias is that this signal cannot be mimicked by other effects in standard cosmologies.
- Additionally, the *form* of the scale-dependence is known, since it's determined by the neutrino power spectrum. This is not very sensitive to how voids are found or defined.
- So this feature should be able to be measured robustly: simply compare void-galaxy cross-spectrum to galaxy auto-spectrum. We just need a large enough sample of voids, which already are becoming available (e.g. Clampitt & Jain).
- For example: discovery of analogous effect from primordial NG improved the constraints on $f_{\rm NL}$ by an *order of magnitude*.

Summary and future work

- We have a viable method for simulating cosmologies with WDM and massive neutrinos which works for all redshifts.
- Based on preliminary simulations, it appears that massive neutrinos generate a characteristic signature in LSS. This could potentially improve neutrino constraints from LSS significantly.
- We're planning to do other things with this code as well, for example RSD with ν's, or halo substructure with WDM.
- Results so far were based on a serial, fixed grid code. We are working on implementing this scheme within AMR codes (Nyx, ART) to run on larger boxes.

Void bias with neutrinos



pure CDM sims (with same $P(k)$ as neutrino sims)

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