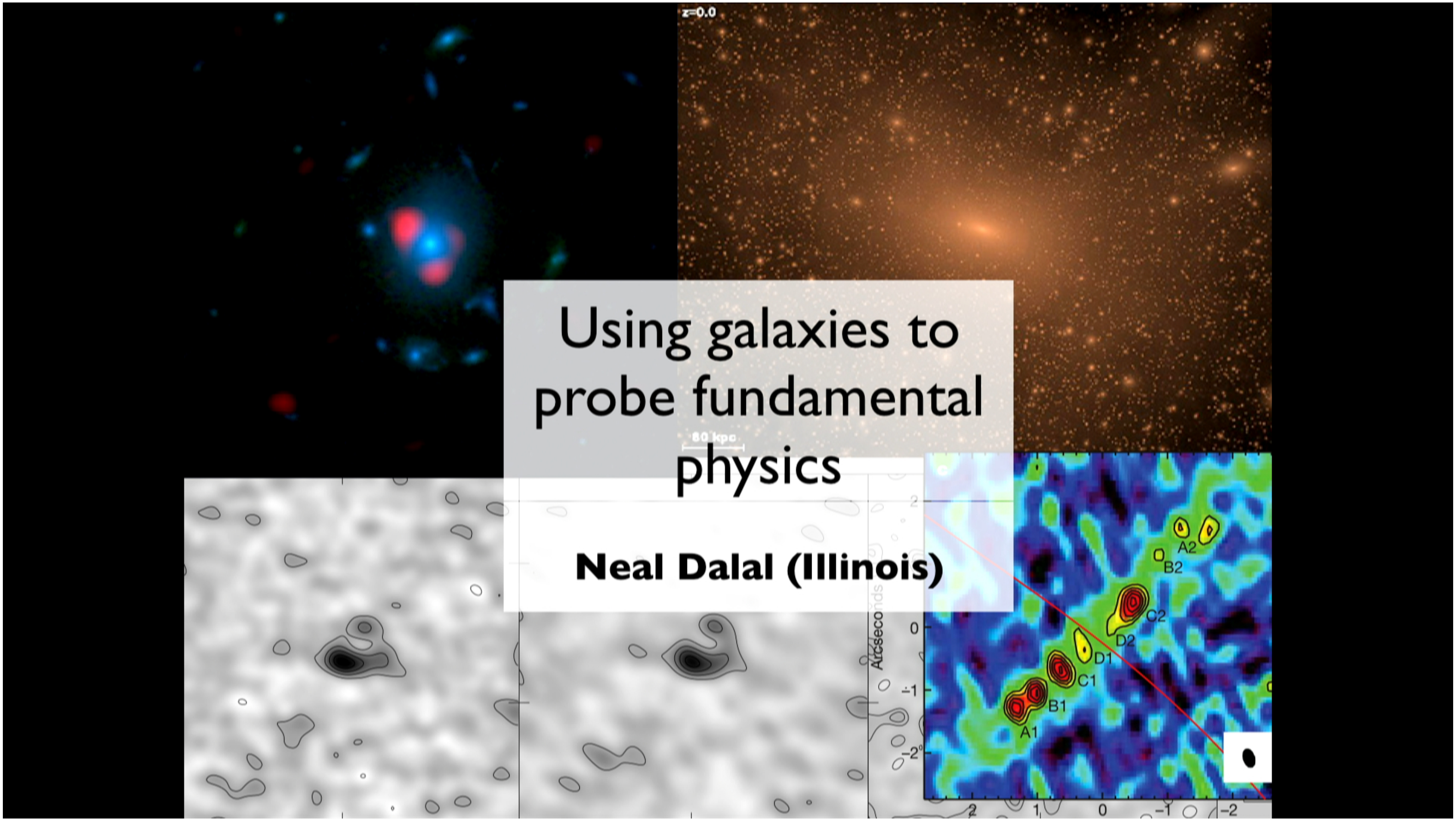
Title: Probing fundamental physics with galaxies

Date: Nov 30, 2016 02:00 PM

URL: http://pirsa.org/16110038

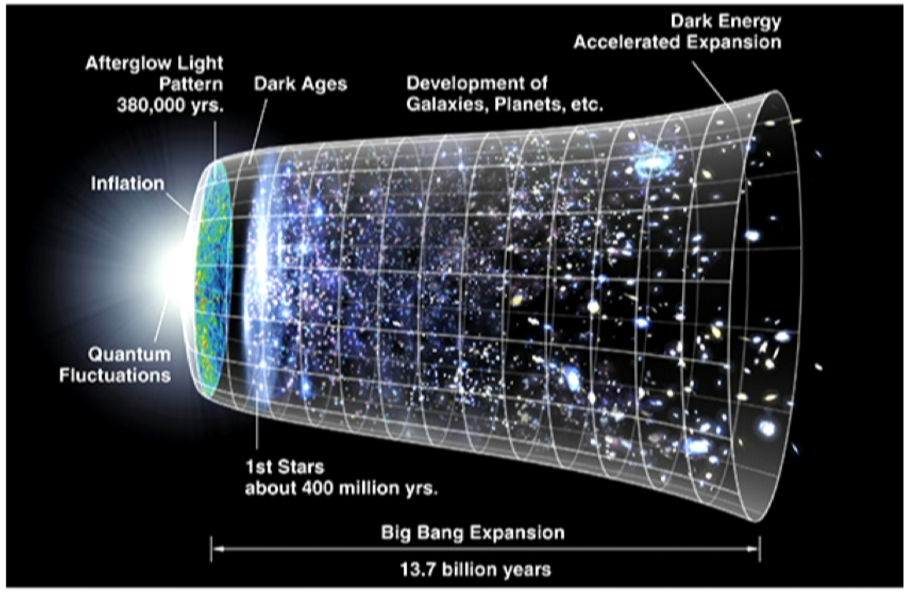
Abstract: <p>In recent years, precise cosmological measurements have provided strong evidence for new physics beyond the Standard Model, occurring both in the very early universe and also today. In the near future, large-scale galaxy surveys will open another window on many different areas of physics, including tests of gravity, probes of dark energy, and cosmic inflation. However, interpreting galaxy surveys presents new challenges, because galaxies are sensitive to astrophysics that are unimportant for the cosmic microwave background. I will discuss how galaxies may be used to study cosmology, and will argue that the messy astrophysics in galaxies actually offers entirely new probes of fundamental physics. I will illustrate this with 3 examples, related to inflation, neutrino masses, and the properties of dark matter.</p>


Using galaxies to probe fundamental physics
Neal Dalal (Illinois)
z=0.0
A1
B1
C1
D1
A2
B2
C2
D2

People

- Illinois
  - **S. Adhikari**
  - **A. Banerjee**
  - G. Holder
  - J. Shelton
- Penn
  - E. Baxter
  - C. Chang
  - J. Clampitt
  - B. Jain
- Stanford
  - R. Blandford
  - **Y. Hezaveh**
  - **W. Morningstar**
  - R. Wechsler
- CITA
  - N. Murray
- Chicago
  - C. Chang
  - A. Kravtsov

The Standard Model (of Cosmology): ΛCDM



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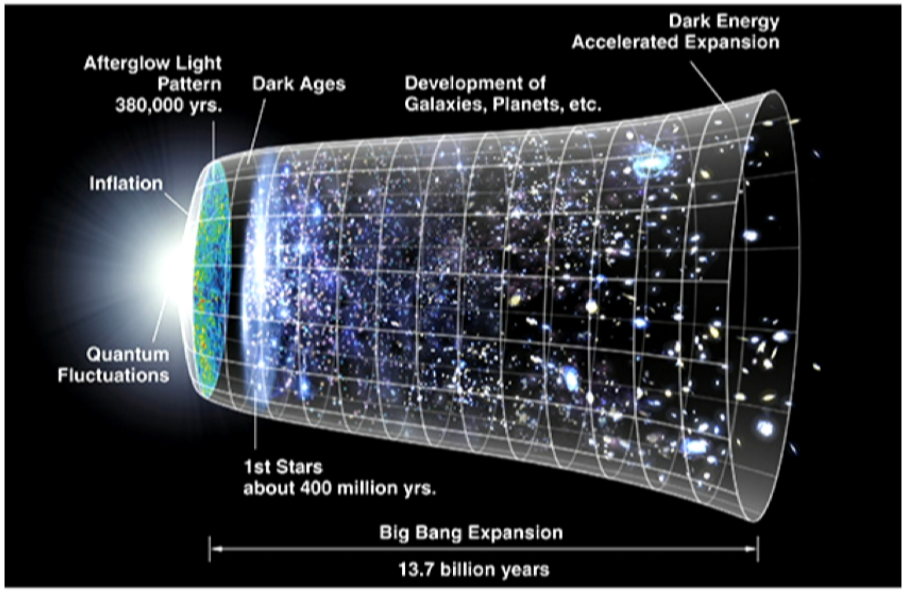
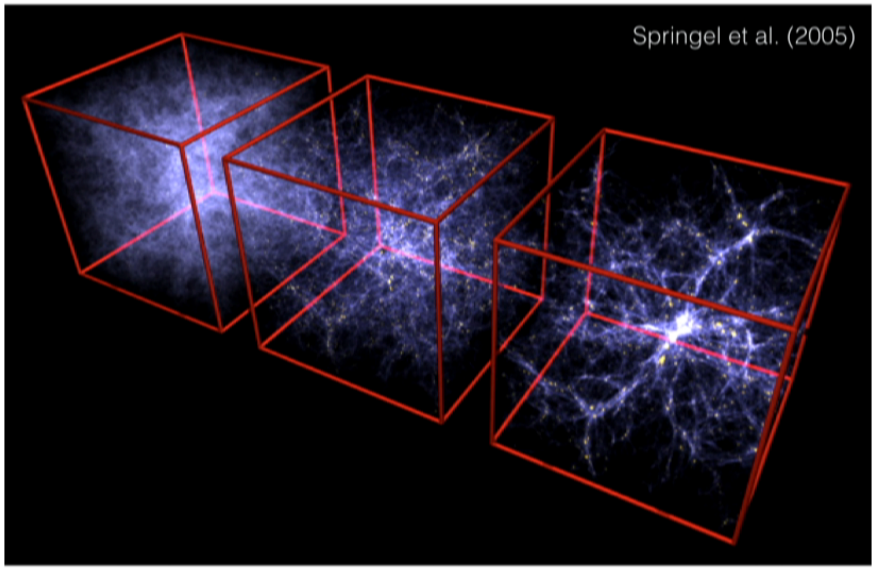


inflation

dark matter

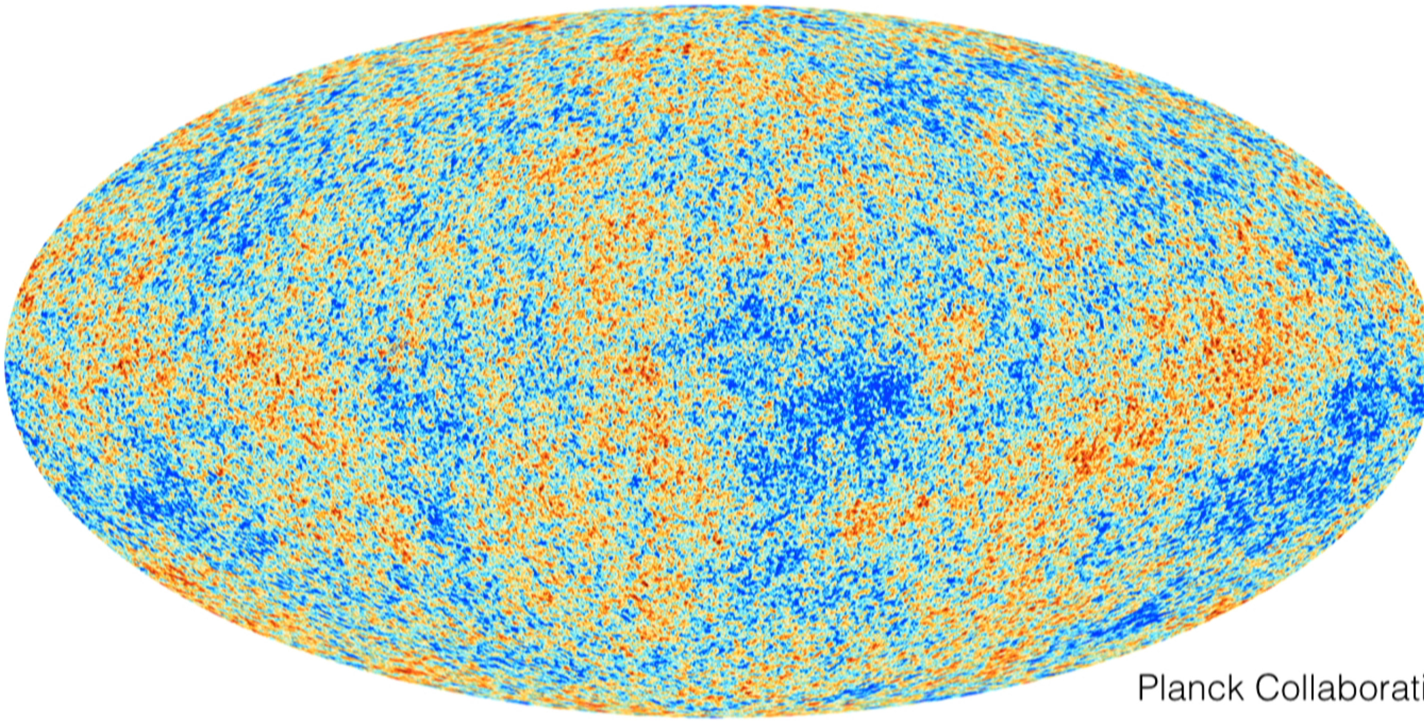
dark energy

large-scale structure



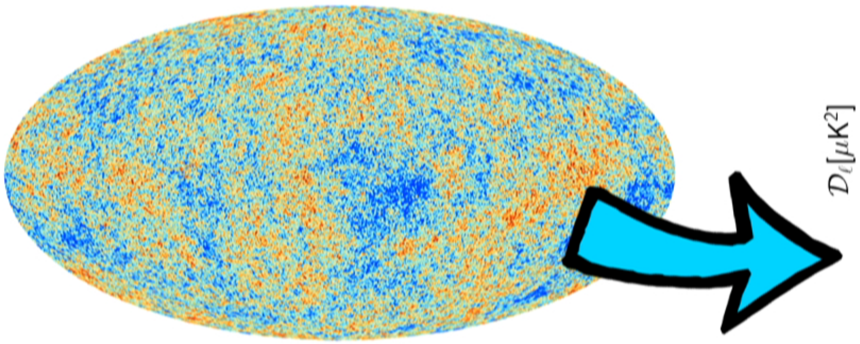
Formation and evolution of cosmic structures $\delta_m(x,t)$
is sensitive to physics across a range of time.

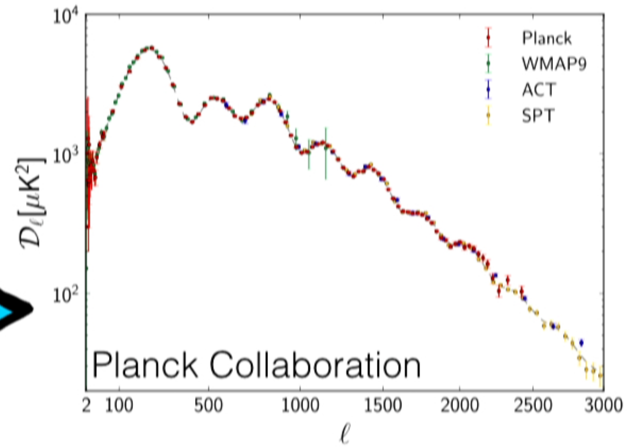
Cosmic microwave background



Planck Collaboration

Cosmic microwave background

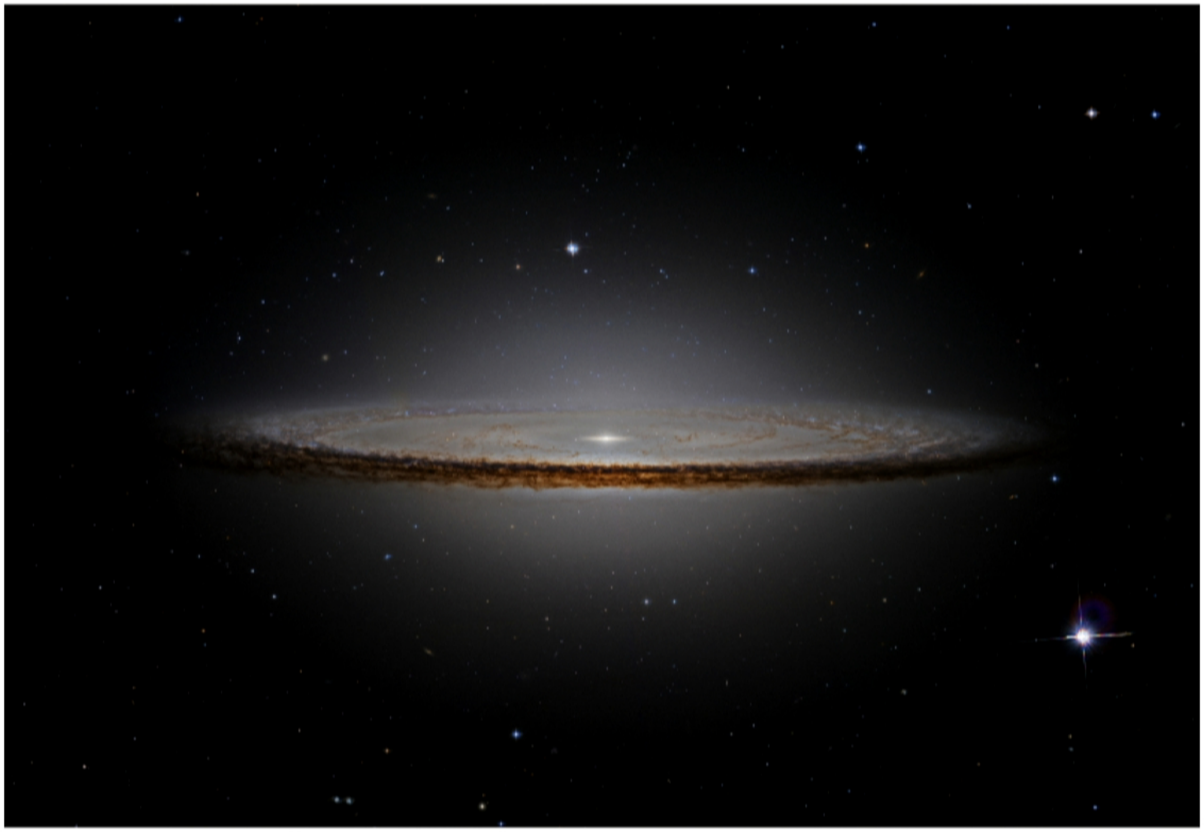


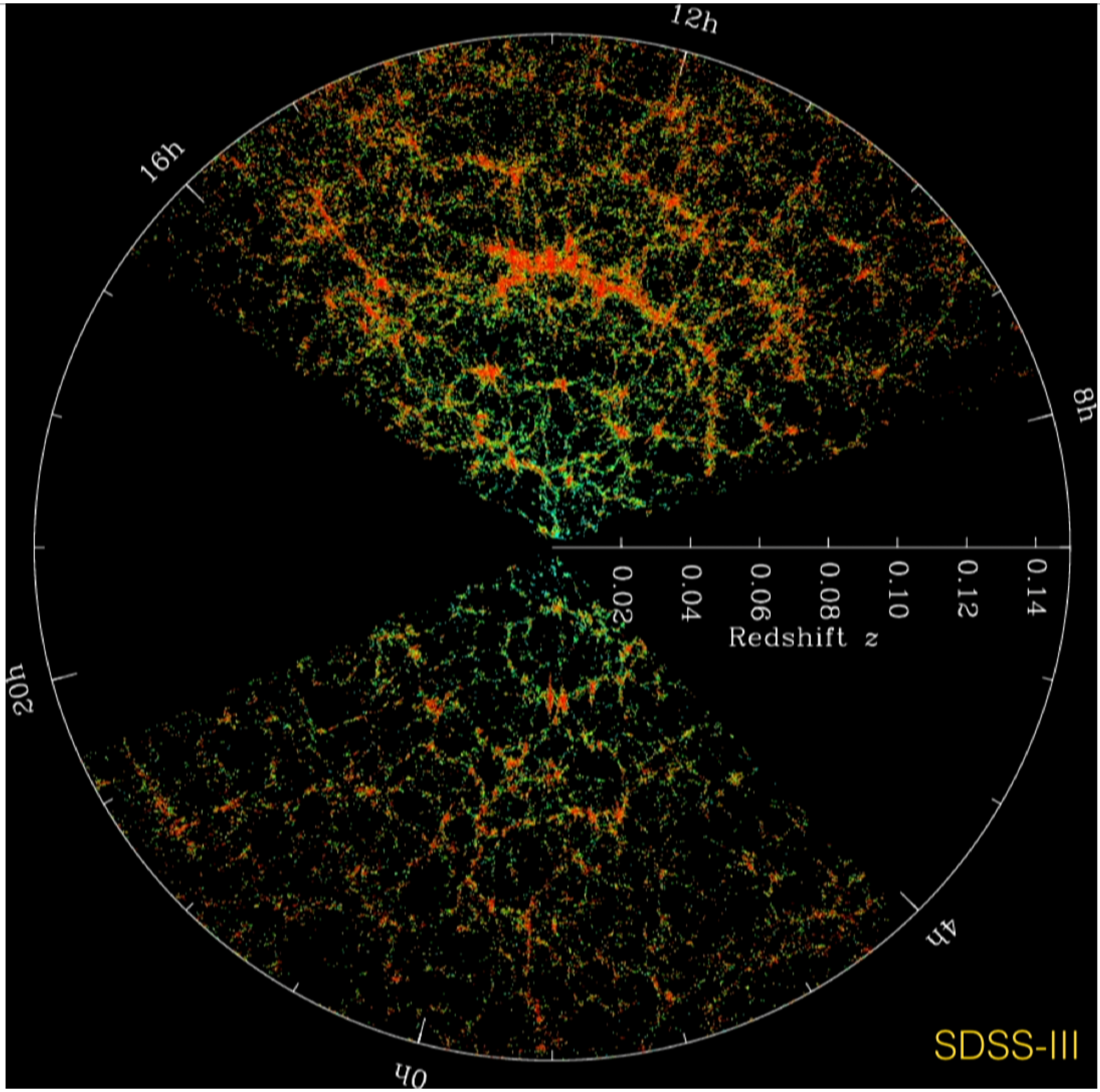


- We use N-point statistics of anisotropies to infer density & potential perturbations δ_m, constrain physical parameters (age of the universe, matter density, etc.)

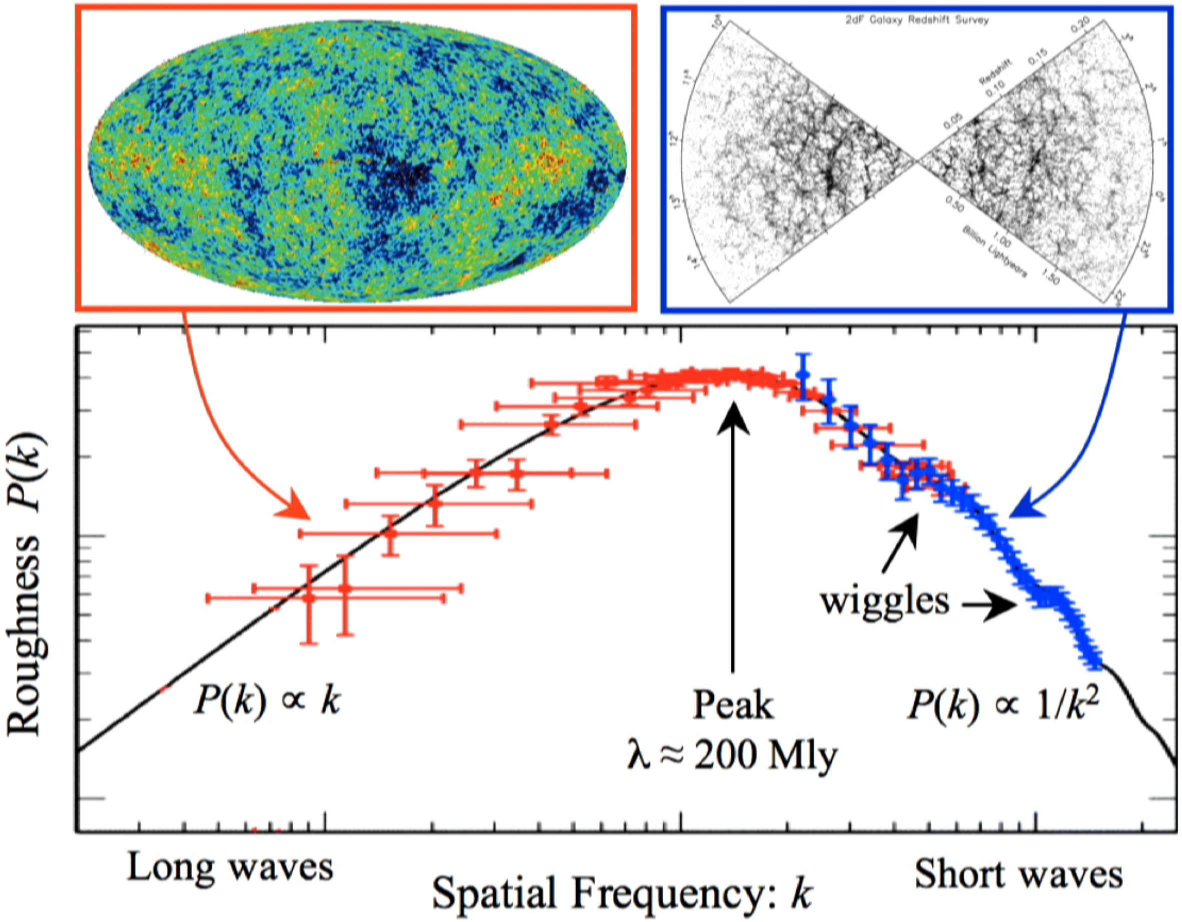
- But the CMB only gives a 2-D snapshot

Galaxies




12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
SDSS-III

translate observed structure into
measurements of the matter field $\delta_m(x,t)$



Mark Wittle

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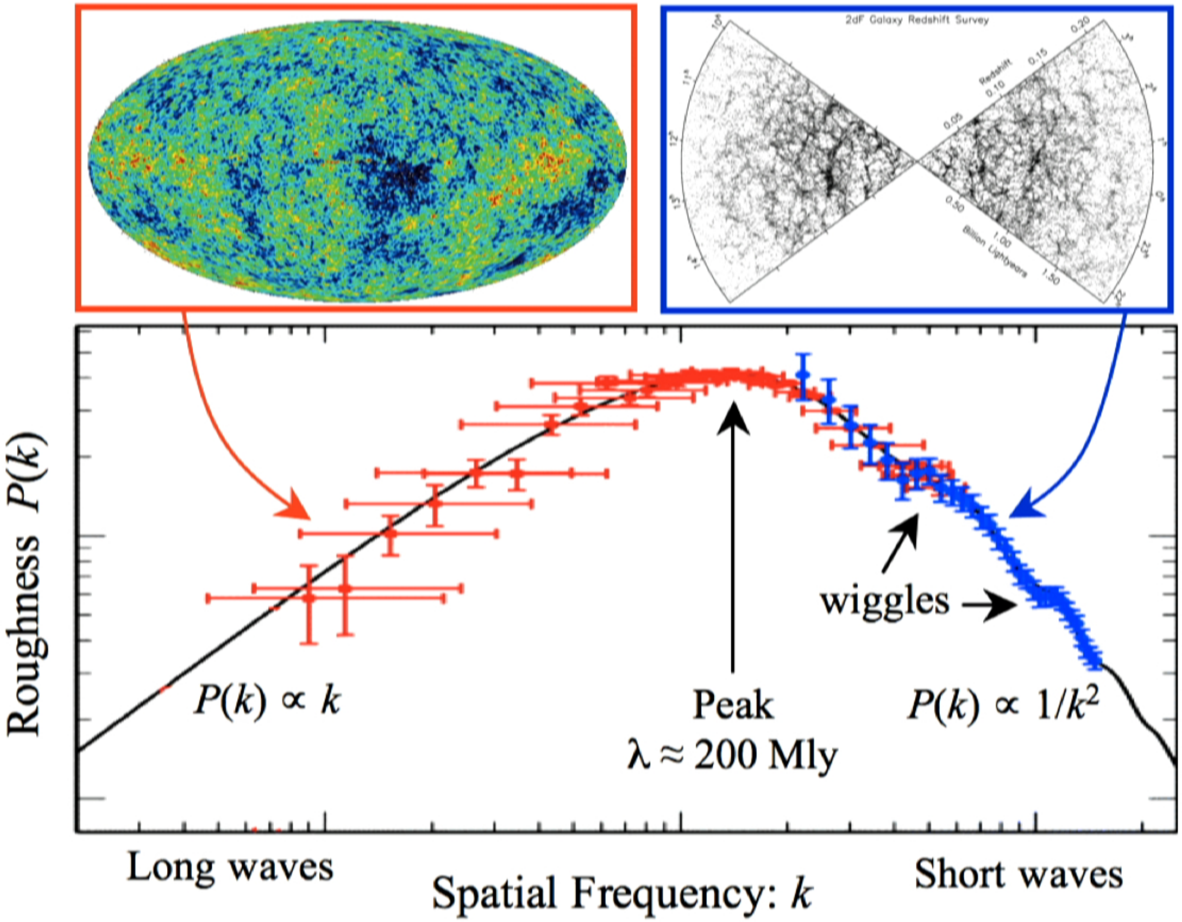
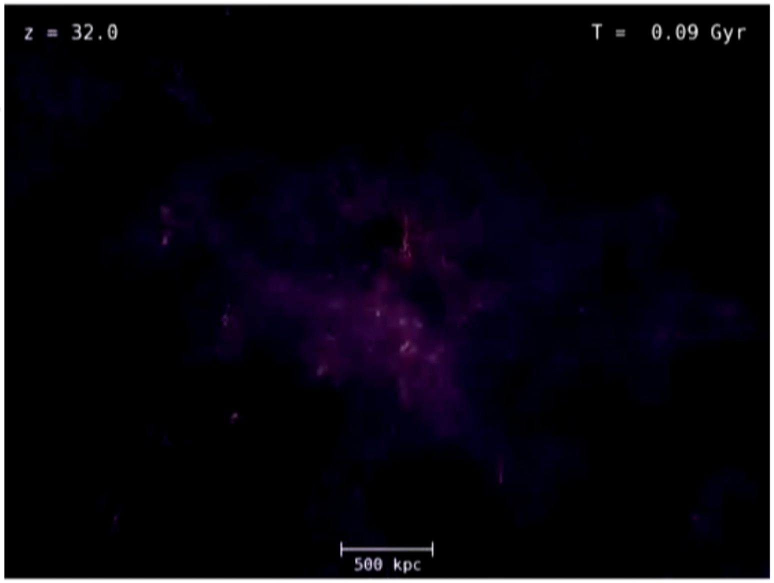


Mark Wittle

Galaxies as tracers

- in principle we can use galaxies to measure 3D structure
- in practice, this is hard! galaxies involve **nonlinear** physics, can be messy:
- Use numerical simulations to compute evolution of structure formation.



Aquarius simulation,
Springel et al. (2008)

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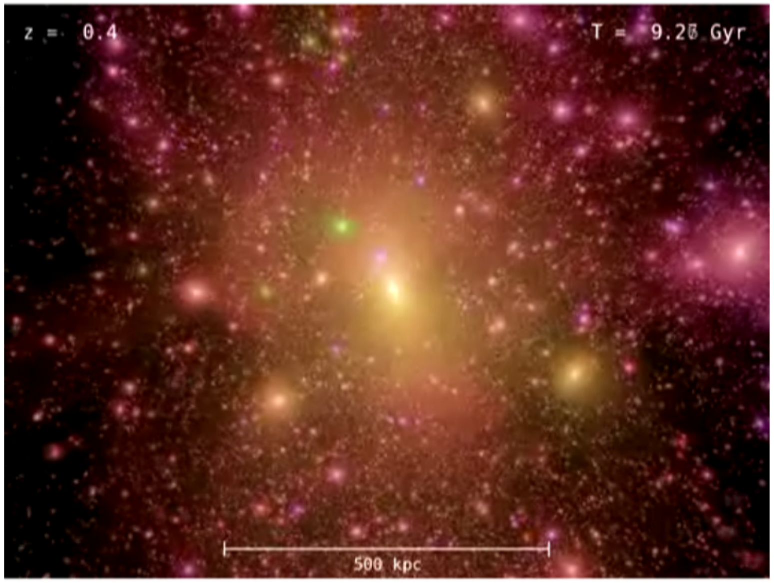


Aquarius simulation, Springel et al. (2008)

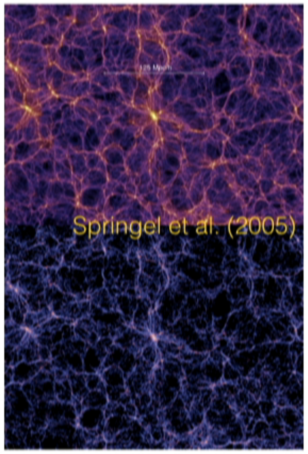
Galaxies as tracers

- We want to know matter density

$$\delta_m = \delta\rho \,/\, \langle\rho\rangle$$

- We measure galaxy density

$$\delta_g = \delta n \,/\, \langle n \rangle$$



Galaxies as tracers

- We want to know matter density

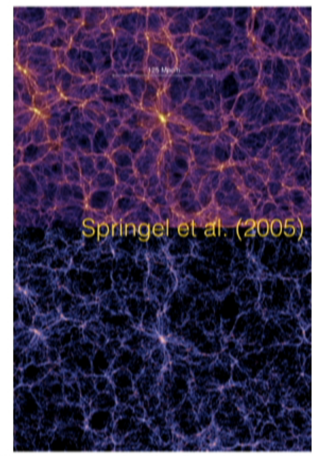
$$\delta_{\rm m} = \delta\rho \,/\, \langle\rho\rangle$$

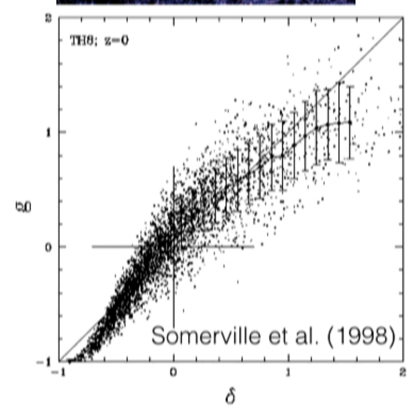
- We measure galaxy density

$$\delta_{\rm g} = \delta n \,/\, \langle n\rangle$$

- The two are *related* but not the same

$$\delta_{\rm g} = F(\delta_{\rm m}, \ldots)$$





Galaxies as tracers

- On large scales, $|\delta_m| \ll 1$. If we Taylor expand mean relation $\delta_g = F(\delta_m)$ to lowest order, we see

$$\delta_g = b\ \delta_m + \ldots$$

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- If galaxy formation can be considered to be **local** on scales below some r, then $b(k) \to \mathrm{const}$, independent of wavenumber k, for $kr \ll 1$.

Galaxies as tracers

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  - e.g. amplitude of $P_{\mathrm{m}}(k) = b^{-2} P_{\mathrm{g}}(k)$ is uncertain

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  - e.g. BAO uses $k \sim 0.1$
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3 examples

- inflation (primordial non-gaussianity)
- neutrino masses
- dark matter substructure

Inflation

Cosmologists trying to describe the size of the Big Bang

- epoch of great interest!
- thought to be epoch when universe grew exponentially in size, soon after the Big Bang
- quantum fluctuations during this time seeded all the structure we see today (galaxies, stars, people)
- but we don't understand the physics responsible, or even if inflation actually occurred

Inflation

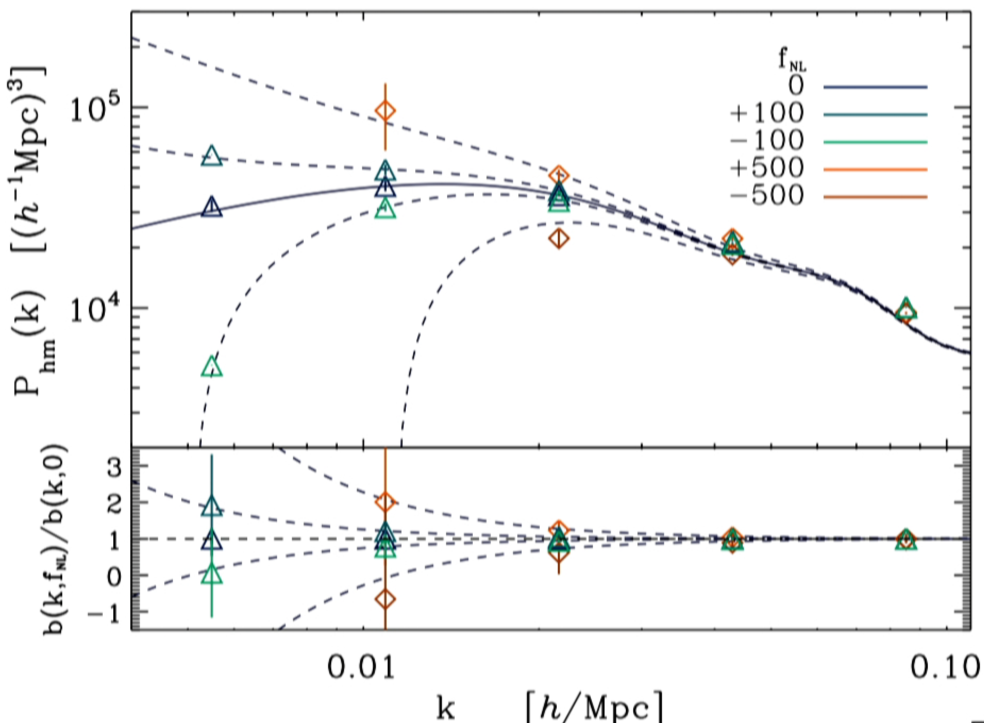
- useful probe: non-gaussianity of perturbations (N-point functions beyond power spectrum), sensitive to interactions, multiple fields, non-slow roll, etc.
    - Arkani-Hamed & Maldacena (2015): “cosmological collider physics”
- example: multi-field inflation produces specific coupling of long-wavelength & short-wavelength modes, called ‘local’ non-gaussianity
- ANY nonzero detection of local NG would rule out single-field inflation!

Primordial non-gaussianity

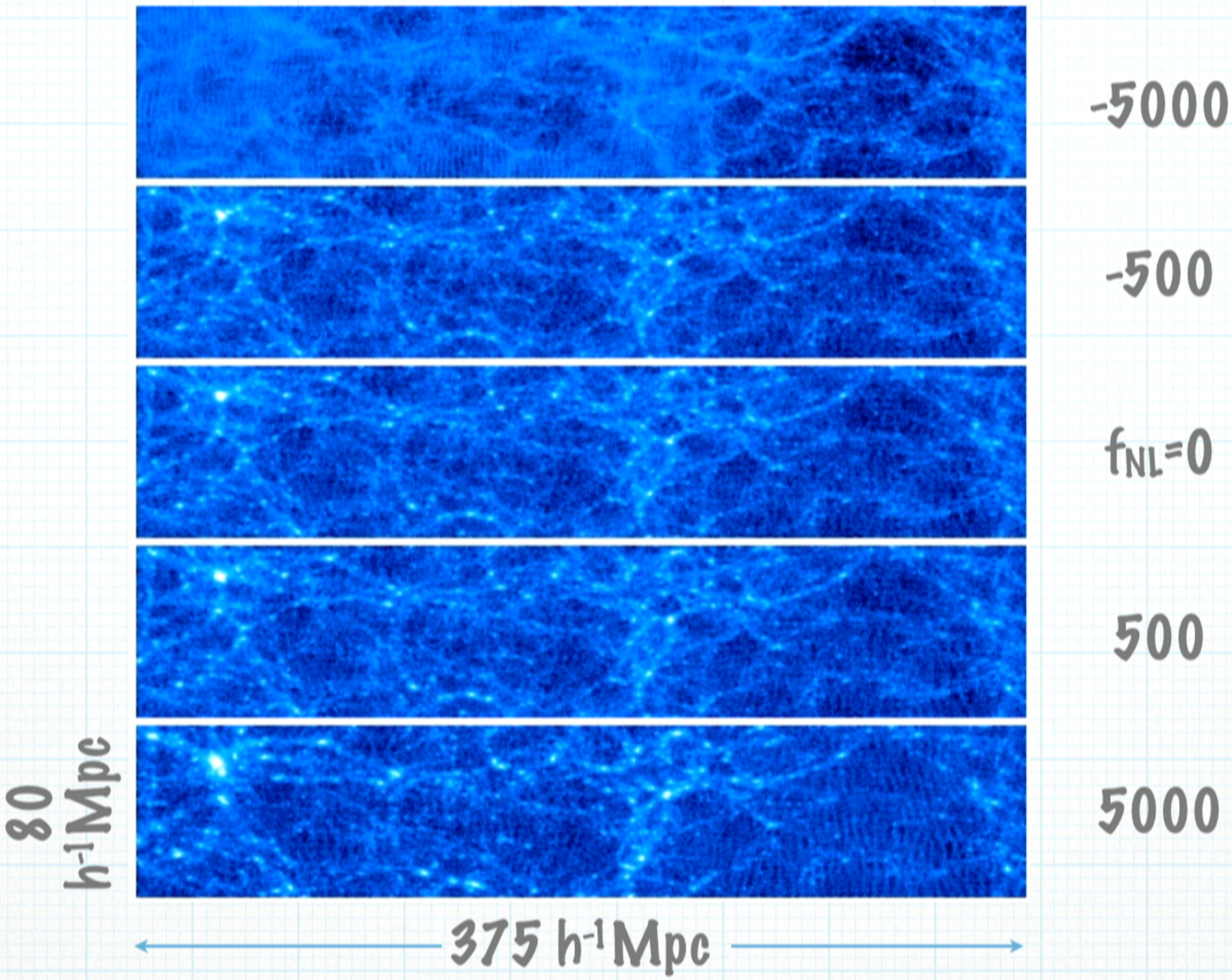
- Currently best constraints come from CMB (Planck) $|f_{NL}| \lesssim 5$
- Galaxy surveys starting to make measurements of 3-point function
- But are there new signatures *specific* to galaxies?

Scale-dependent bias

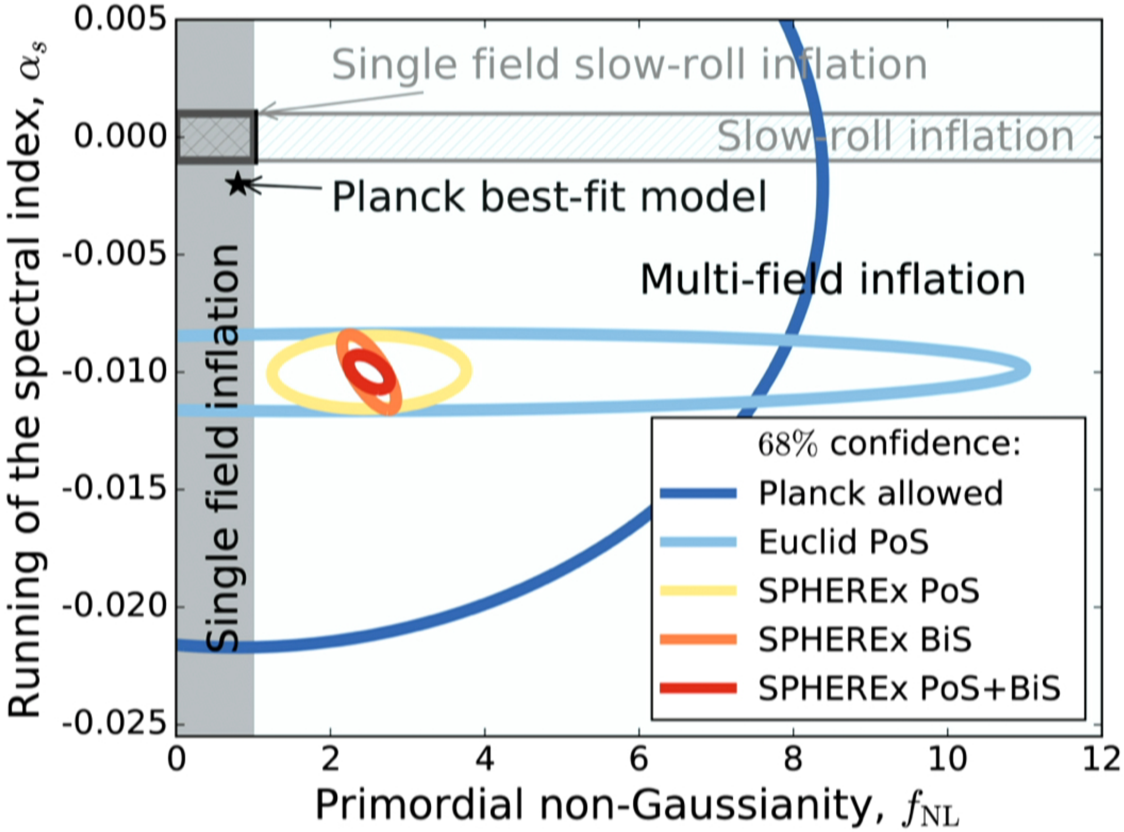
$$\Delta b(k) \propto f_{NL}/k^2$$



Dalal et al. (2008)


-5000
-500
fNL=0
500
5000
80 h-1Mpc
375 h-1Mpc

Forecasted constraints from galaxies



Galaxy bias

- Primordial NG is just one example of how galaxies can reveal fundamental physics in surprising ways
- Key feature of NG producing scale-dependent $b(k)$ was *non-locality*, coupling widely-separated regions
- What else can break locality of galaxy formation?
  - species which stream long distances, e.g. *neutrinos*

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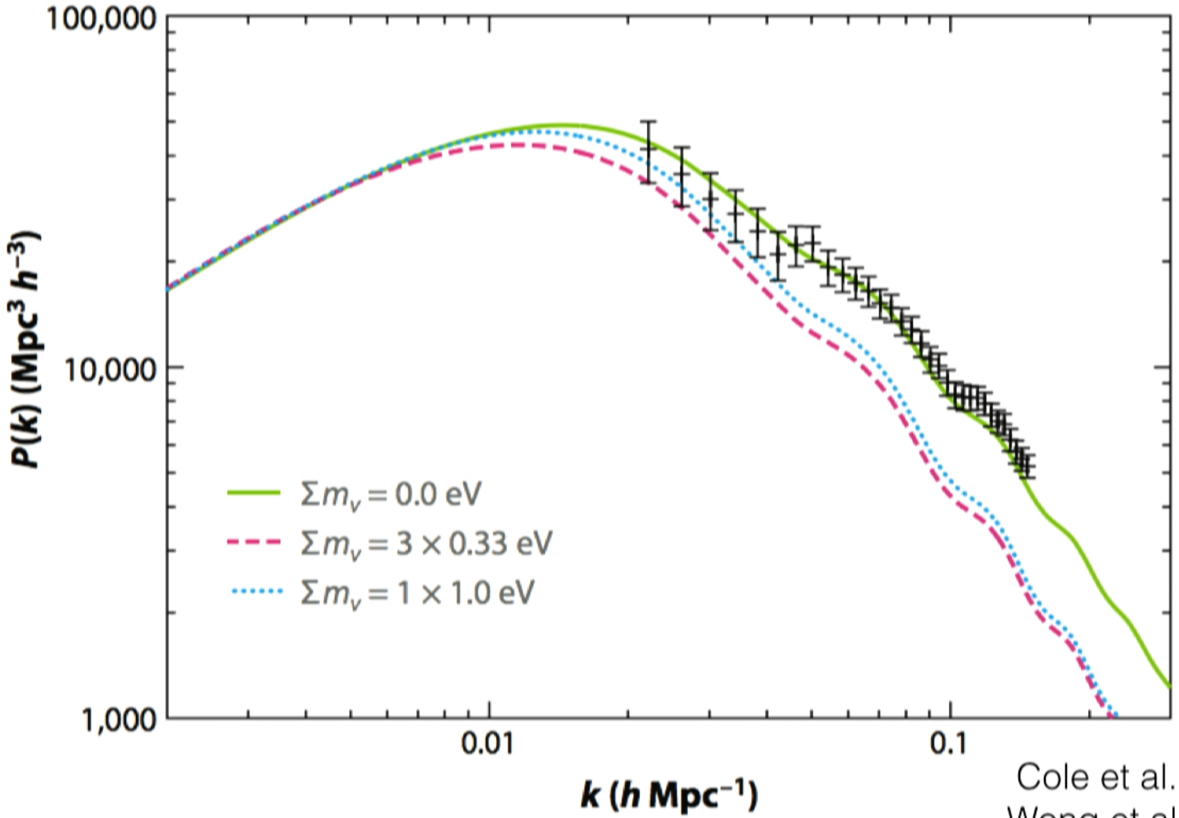
Neutrinos & LSS

- Neutrinos are neutral, light particles ($m < 1$ eV) with weak interactions.
- Origin of this mass scale is unclear, but theoretical models (e.g. seesaw mechanism) involve ~ GUT scale physics,

$$m_H^2/m_{GUT} \sim 10^{-2} \text{ eV}$$

- Neutrino absolute masses unknown, but mass differences measured by oscillation experiments $\Delta m^2 \sim (8\text{-}50 \text{ meV})^2$
- Cosmology can measure absolute mass scale using large-scale structure, in the very near future!

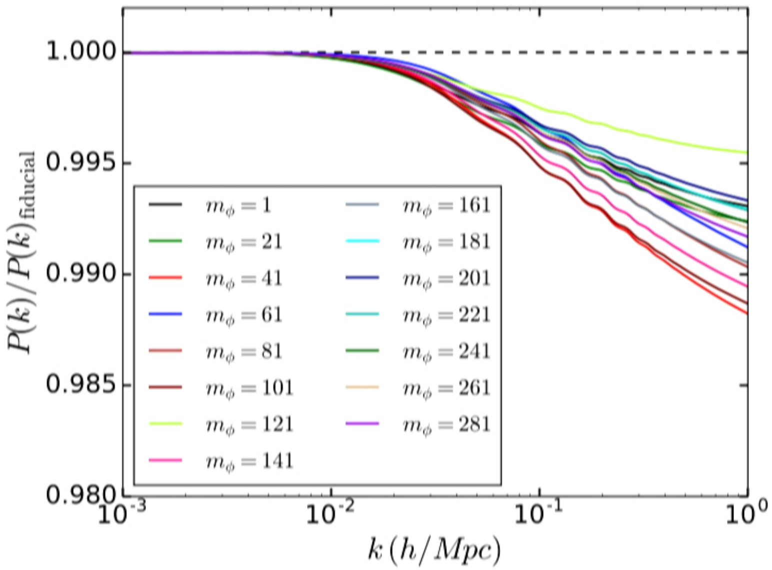
Neutrinos & LSS



Cole et al. (2005)
Wong et al. (2011)

Neutrinos & LSS

- Similarly, LSS is sensitive to neutrino-*like* species, e.g. dark radiation.
- A recent example: NNaturalness model to solve the hierarchy problem (Arkani-Hamed et al. 2016), generically predicts many light neutrino-like particles.
- To linear order, these suppress growth of LSS. But to use galaxies we need nonlinear calculations.



Banerjee et al. (in prep)

Neutrinos & LSS

- Neutrinos stream large distances and gravitate ⇒ can violate locality of galaxy formation ⇒ might produce signatures in galaxy bias (e.g., LoVerde 2014)

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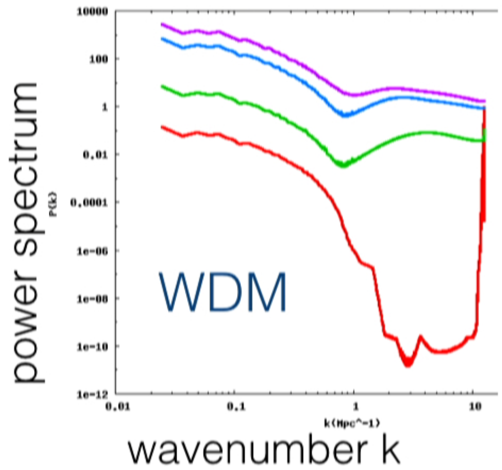
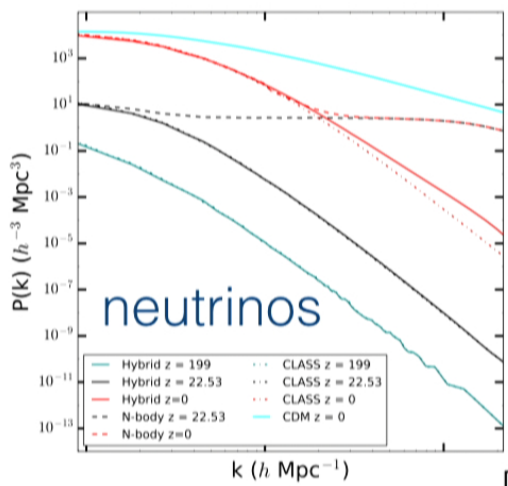
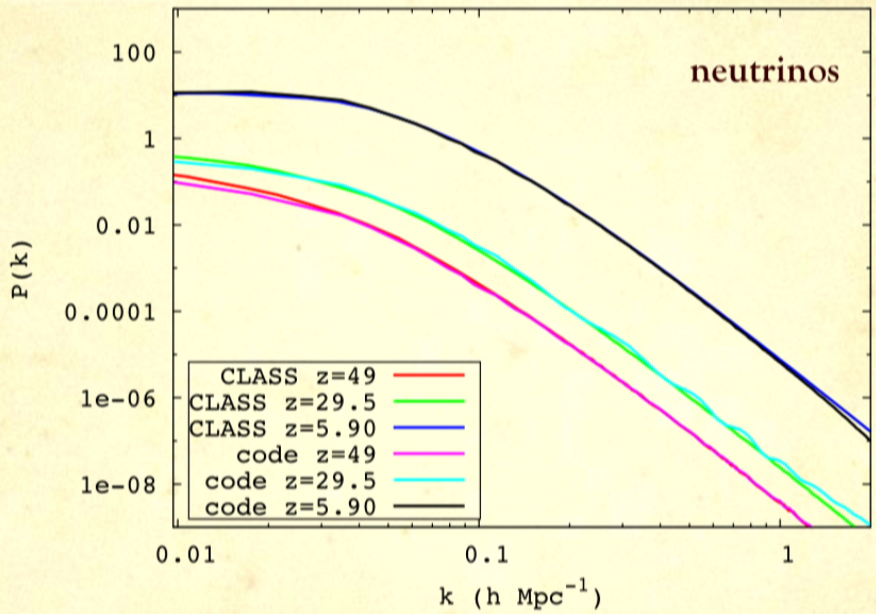
- Simulating this effect using is hard because neutrinos produce *huge* errors in N-body simulations!





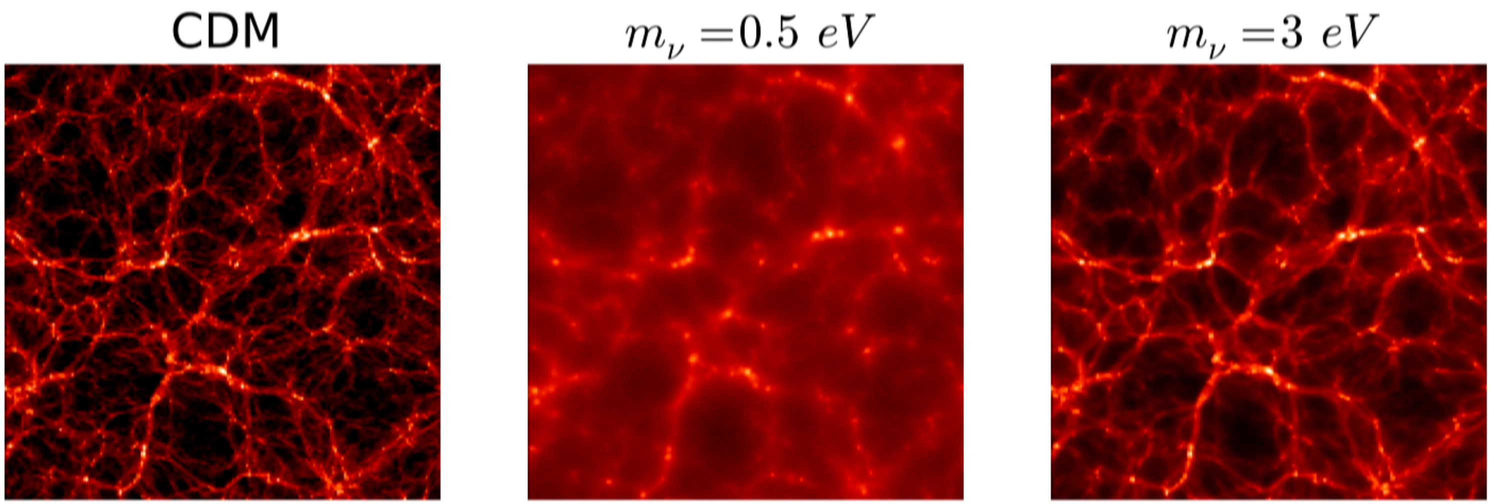
Banerjee & Dalal (2016)

Tests in linear regime



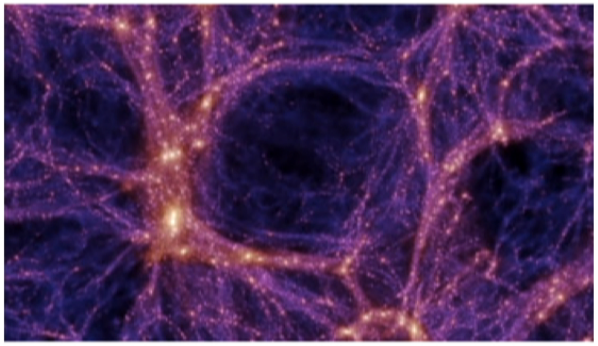
- This method agrees with linear theory in the linear regime, unlike N-body.

Neutrino simulations

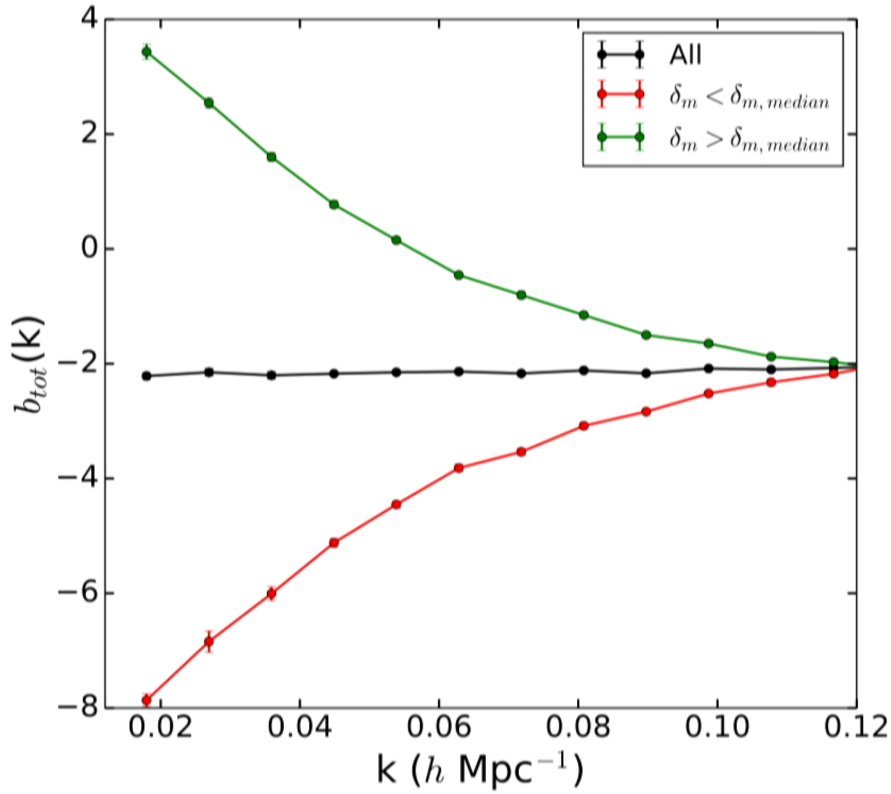


Neutrinos in LSS

- For galaxies, the bias effect for realistic neutrinos is small (e.g. Villaescusa-Navarro et al. 2014)
- Problem is that neutrinos don't cluster much in galaxies
- But there are other structures for which bias effect can be large!
- example: cosmic voids

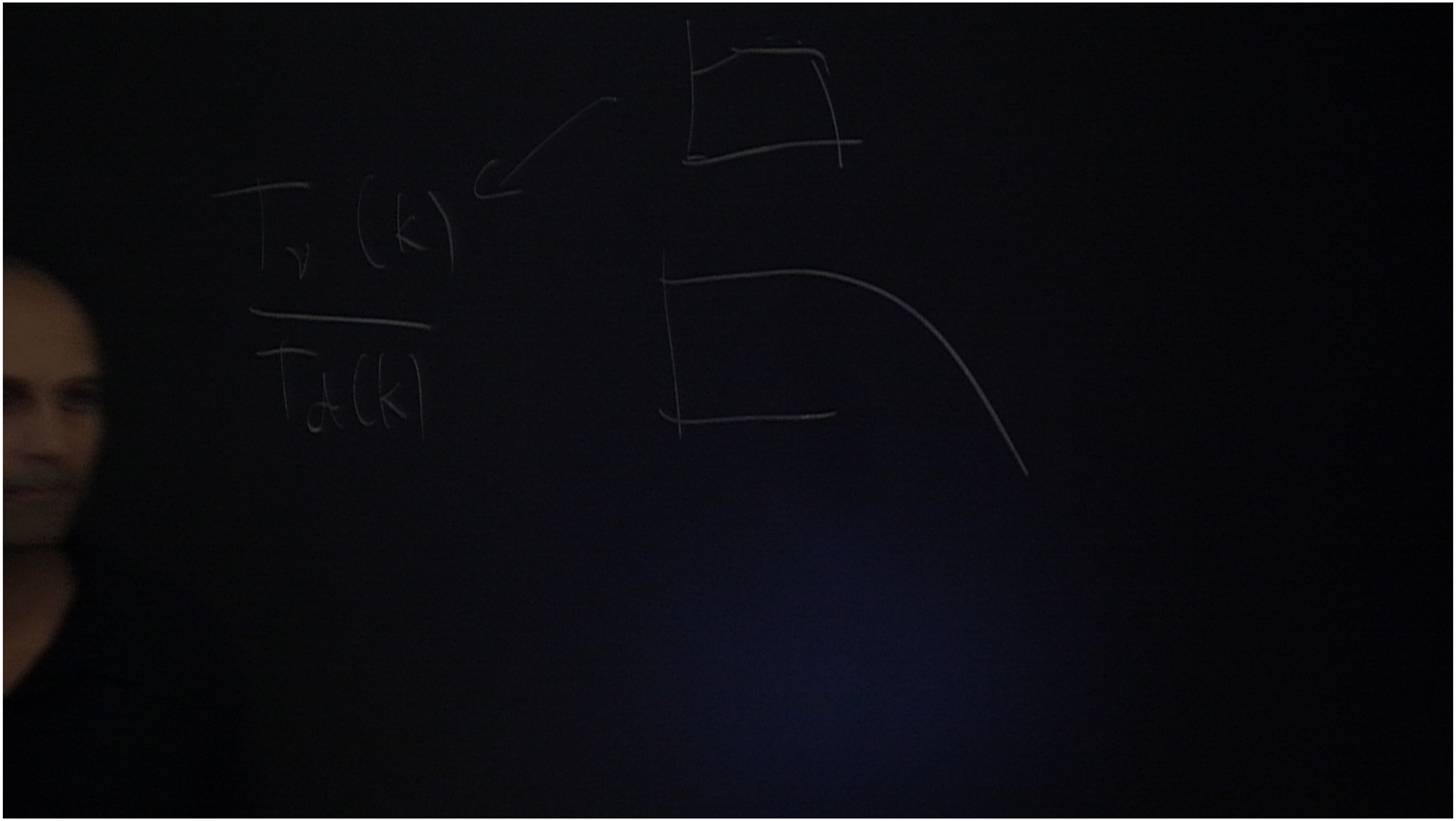


Bias of voids



Neutrinos & LSS

- Bias effect is completely independent of usual method for constraining neutrino mass (e.g. CMB lensing)
- Potentially observable already! We're working with DES collaboration to look for this.
- Another example of how messy astrophysics can be useful for probing fundamental physics


Tv(k)
Td(k)

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Dark matter substructure

"Via Lactea"
Diemand et al. 2006

substructure is sensitive to DM physics

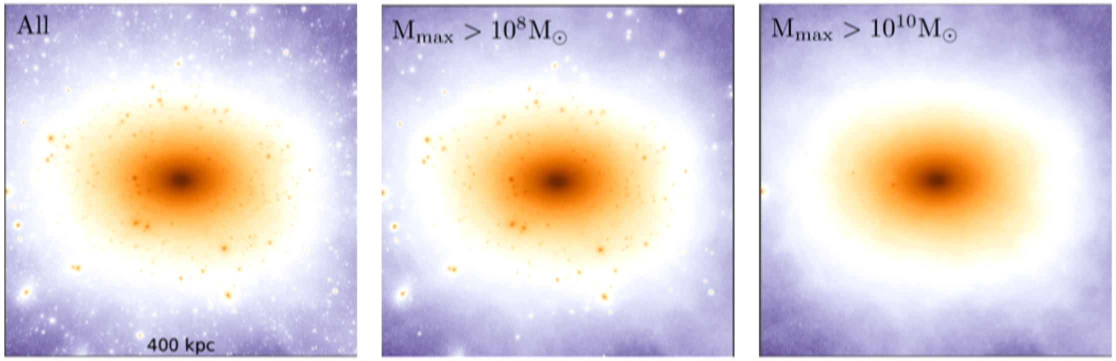
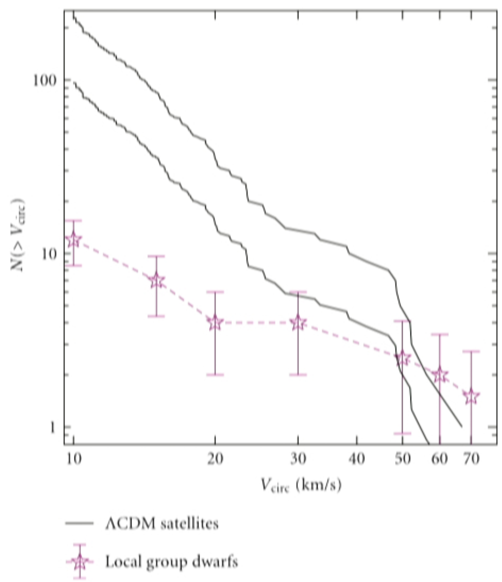
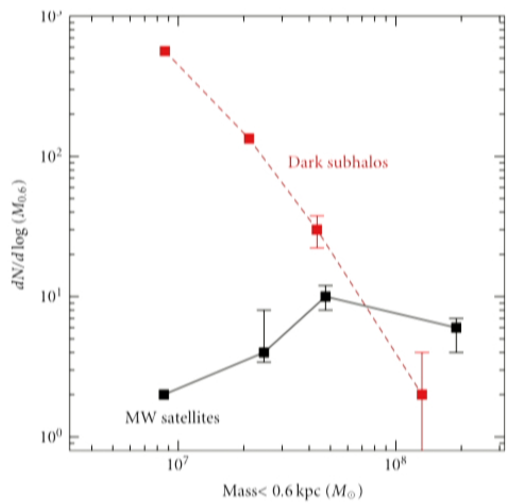


Figure 1: **Left:** Density projection in the Via Lactea-II simulation [18]. **Middle:** Similar, but excluding particles belonging to subhalos whose masses never exceeded $10^8 M_\odot$ any time throughout the simulation. **Right:** Like the middle panel, but excluding subhalos with $M_{max} < 10^{10} M_\odot$. This sequence should qualitatively illustrate the effect of truncating the power spectrum on substructure content in DM halos.

How to measure?

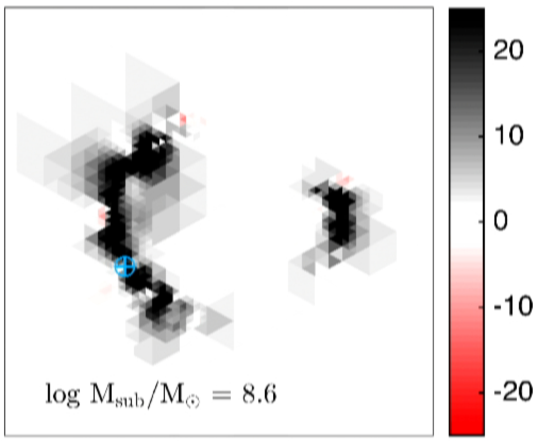
- count small galaxies / satellites
  - ➡ missing satellite problem (see Kravtsov 2012 for a review)

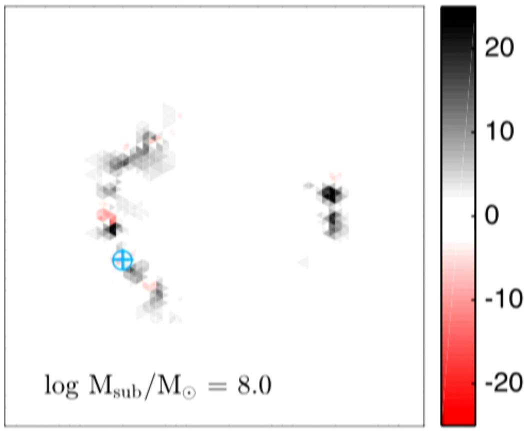




Other subhalos?

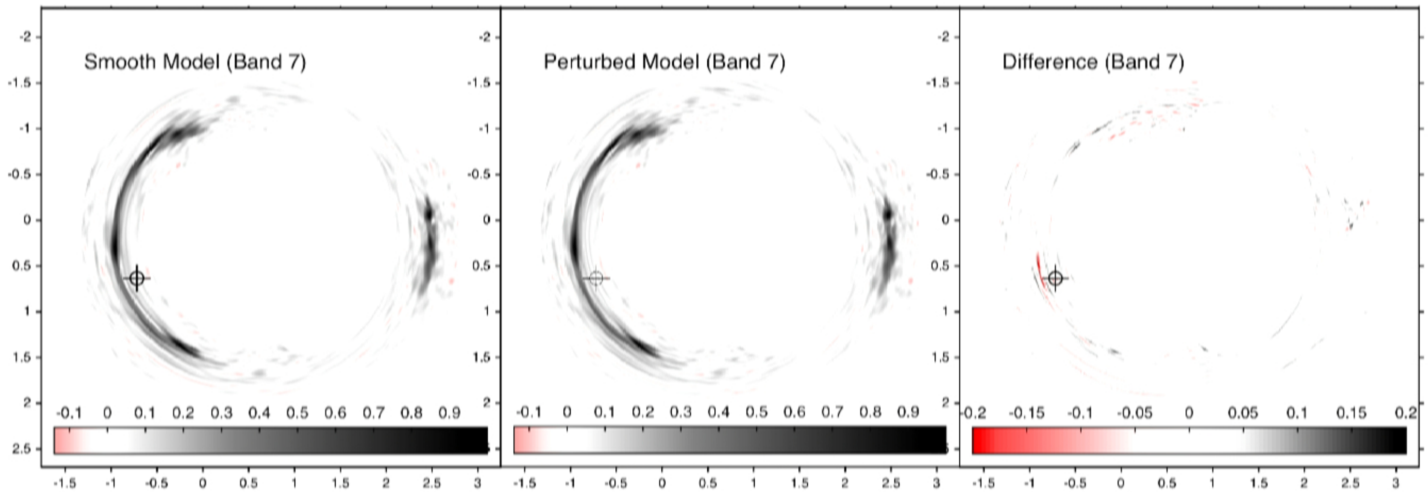
- this map shows how the fit improves ($\Delta\chi^2$) as we add a subhalo at various other locations...





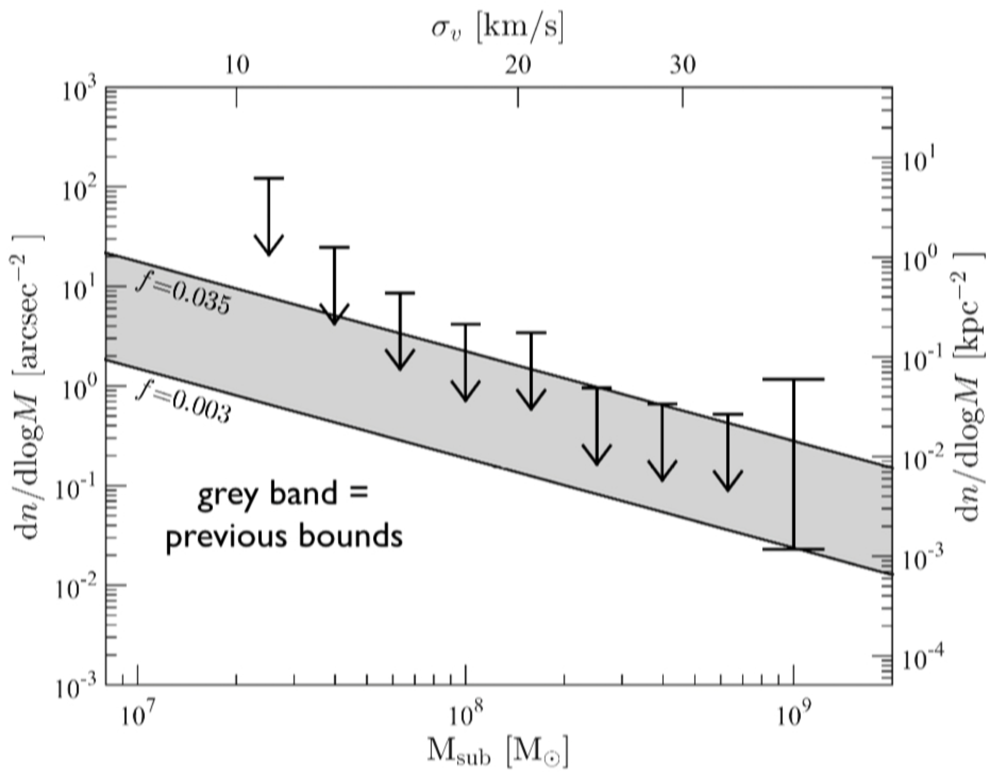
- seems to be ~ 4.5σ hint for an additional subhalo with $M=10^8\ M_{\odot}$

Subhalo detection

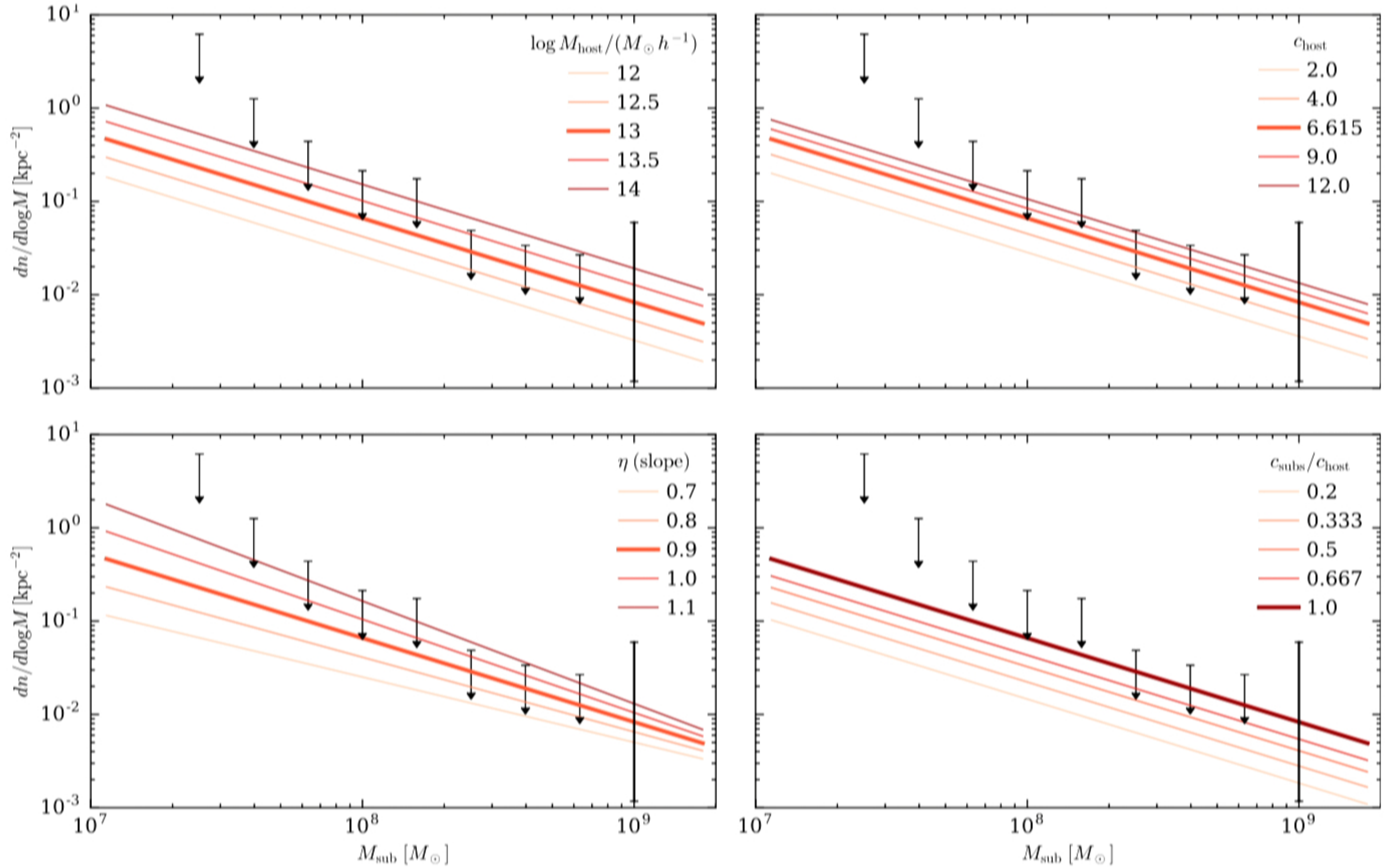


- a $M=10^9\ M_\odot$ subhalo is detected at ~ 7-sigma confidence in the first system we analyzed

bounds on the subhalo mass function



comparison with theory



Summary

- Galaxies are useful! Not only as tracers but for finding new probes of fundamental physics
  - galaxy measurements can rule out single-field inflation
  - galaxy voids provide a new *independent* probe of neutrino masses
  - galaxy lensing is the most sensitive way to find DM substructure across the universe