Neutrinos in Large-scale structure

Marilena LoVerde
University of Chicago
(Fall 2015 —> Yang Institute for Theoretical Physics, Stony Brook University)

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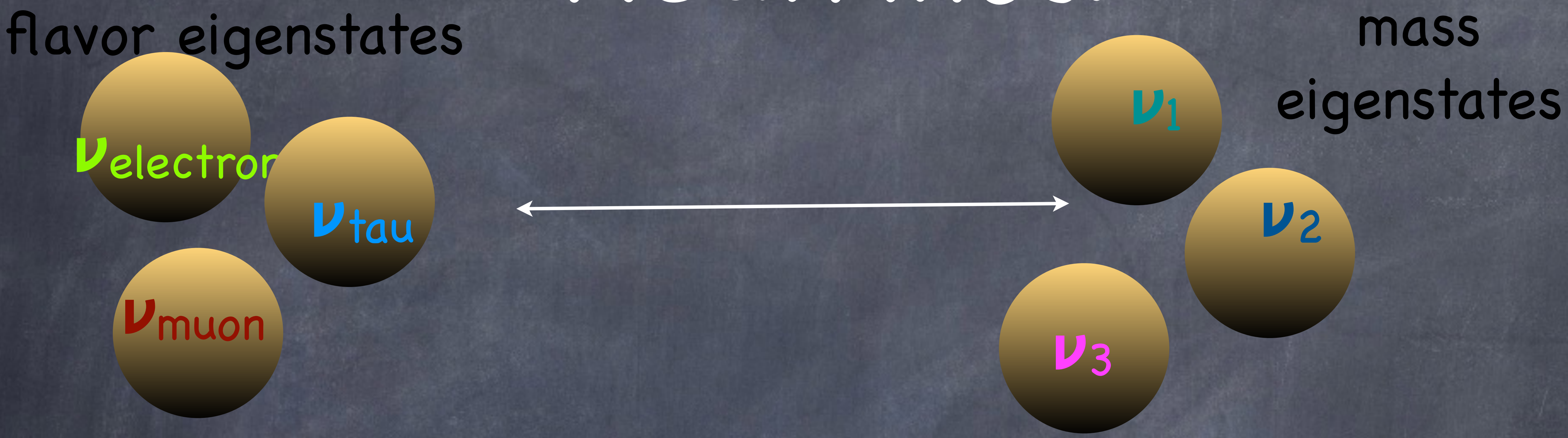
ML and Zaldarriaga 1310.6459
ML 1405.4855
ML 1404:4858
ML in prep.

Outline

- Neutrinos in Cosmology
- Scale-dependent structure growth from massive neutrinos
- Scale-dependent halo bias from massive neutrinos
- Observational Consequences

Neutrinos

Neutrinos!

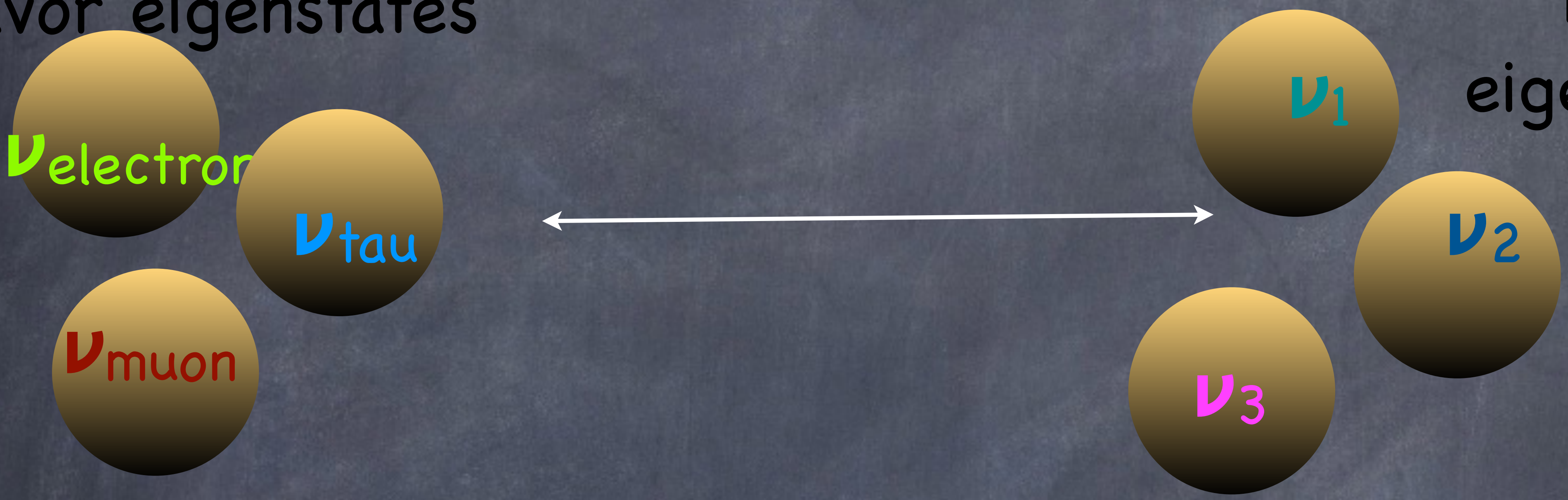


Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962

Neutrinos!

flavor eigenstates

mass eigenstates



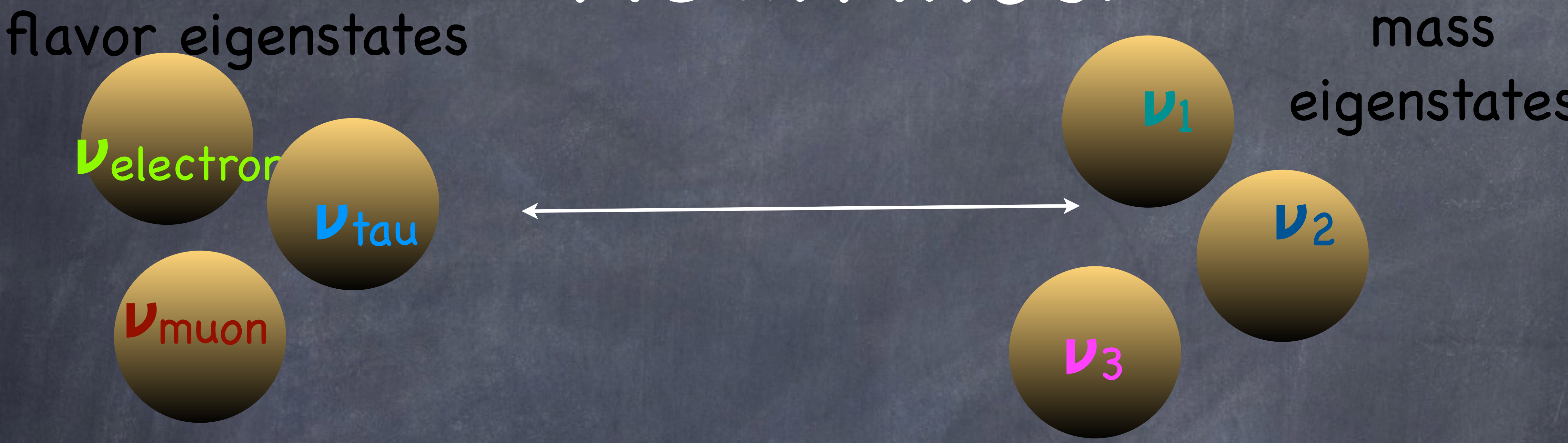
oscillation data gives mass splittings

$$m_2^2 - m_1^2 = (7.5 \pm 0.2)\ 10^{-5}\ eV^2$$ (solar neutrino oscillations)

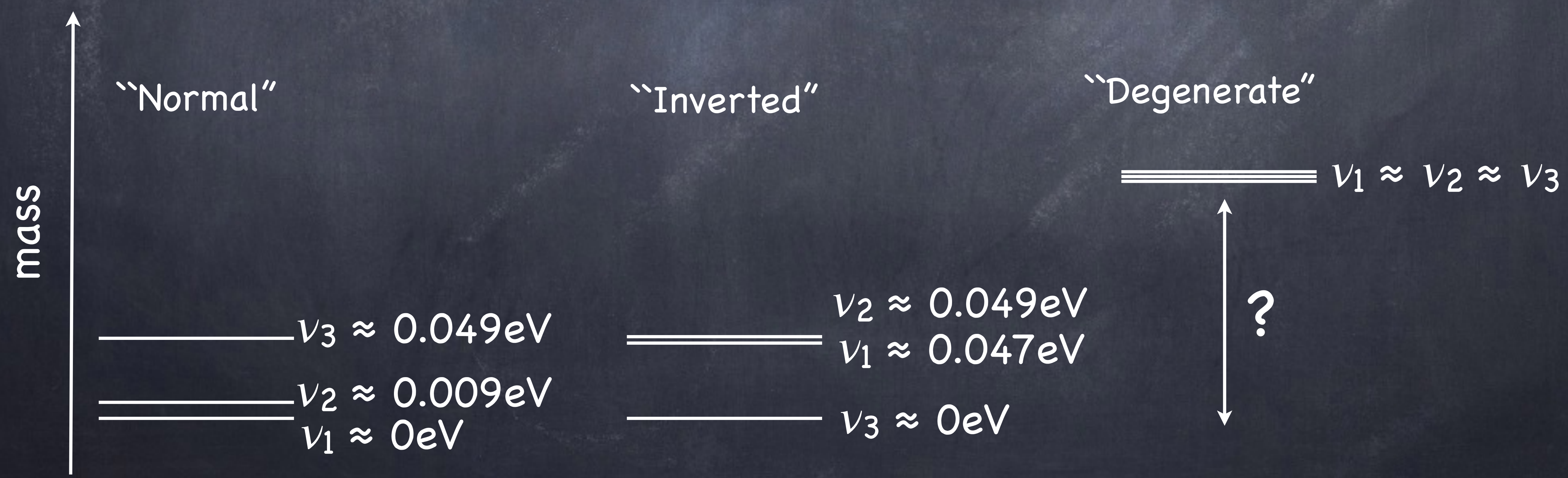
$$|m_3^2 - m_2^2| = (2.32^{+0.12}_{-0.08})\ 10^{-3}\ eV^2$$ (atmospheric neutrino oscillations)

Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962

Neutrinos!



but the absolute masses are unknown!



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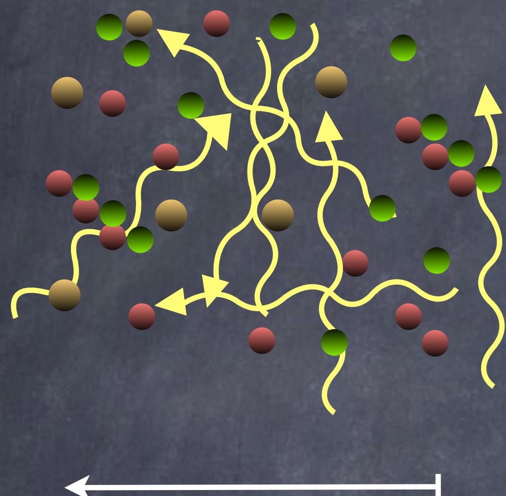
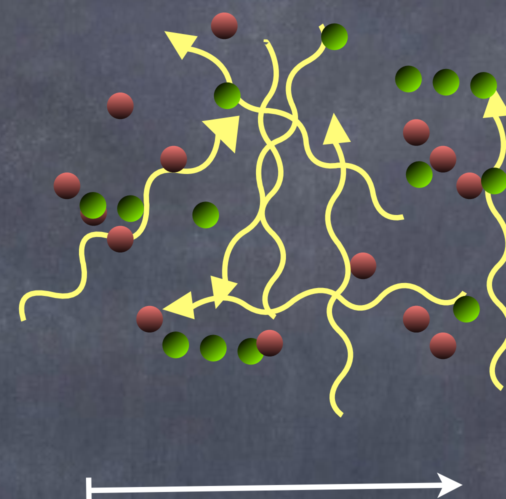
Neutrinos in Cosmology

Neutrinos in cosmology



neutrinos in equilibrium with photons e +, e-

$T_\gamma = T_\nu \propto 1/a$



neutrinos decoupled

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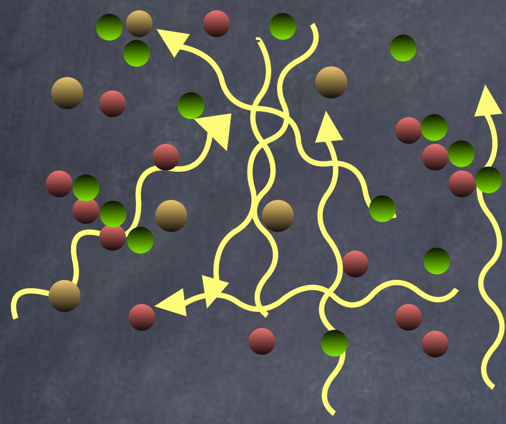
Neutrinos in cosmology



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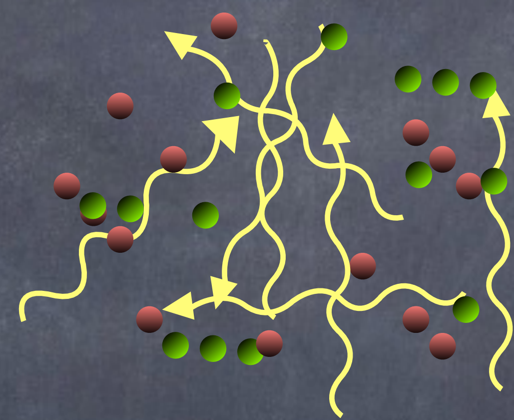

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$T_\nu \propto 1/a$

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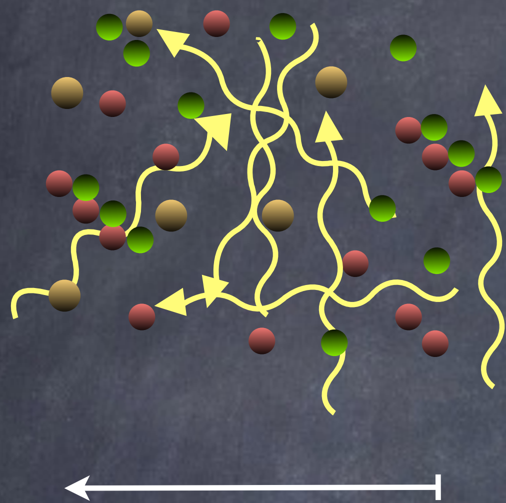
relativistic, in thermal equilibrium at early times

$$n_{1\nu} \sim T_\nu^3$$

$$T_\gamma \approx \left(\frac{11}{4}\right)^{1/3} T_\nu$$

Neutrinos in cosmology



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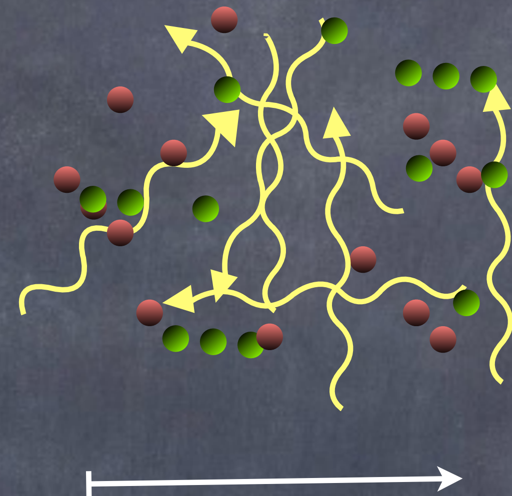

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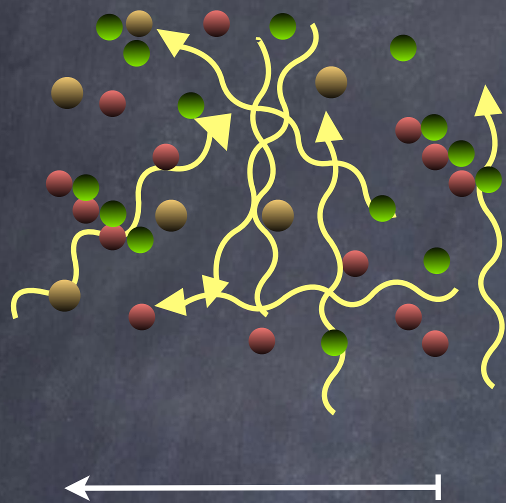
energy density dominated by mass at late times

$$\rho_\nu \sim \sum_i m_{\nu_i} n_{1\nu}$$

Neutrinos in cosmology



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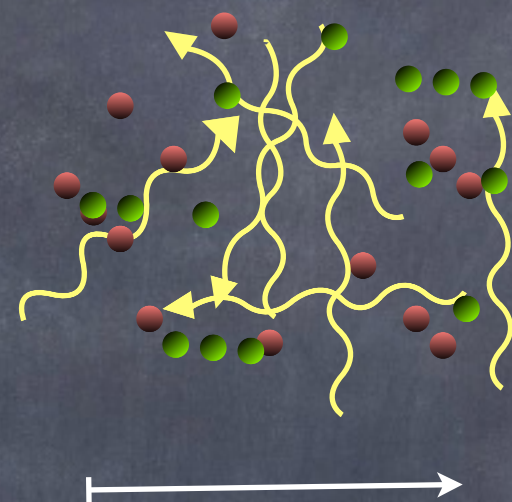

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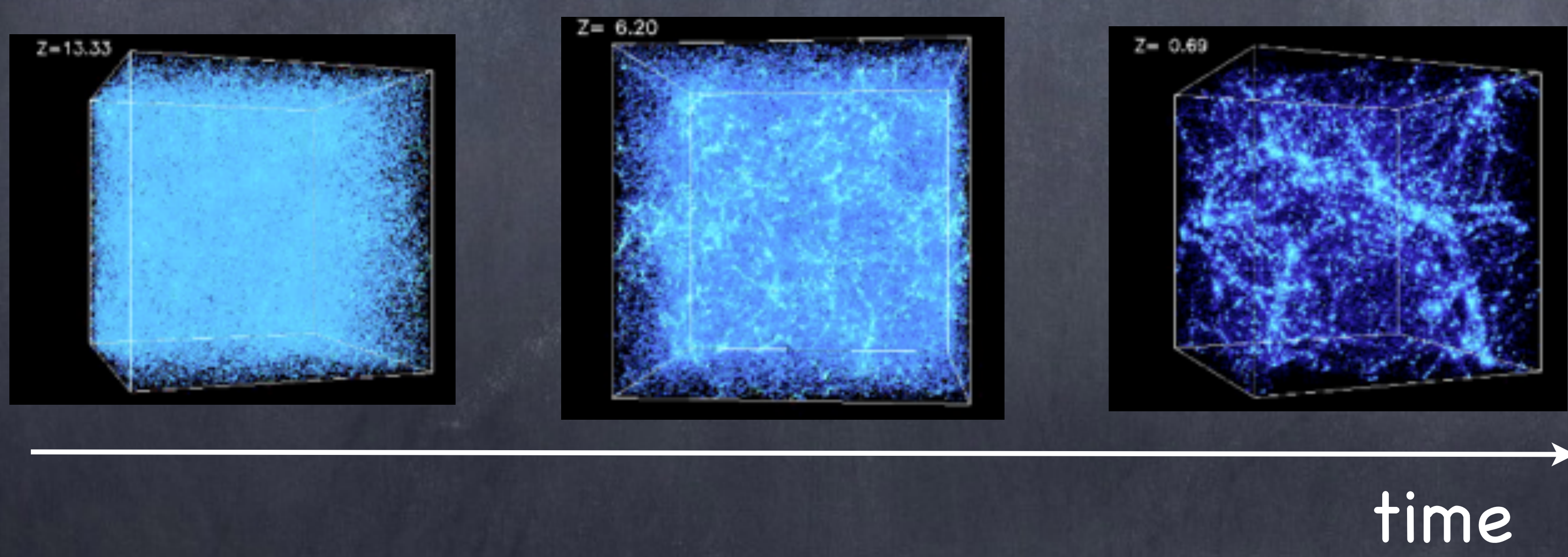
energy density dominated by mass at late times

$$\rho_\nu \sim \sum_i m_{\nu_i} n_{1\nu}$$

$n_{1\nu}$ is known, so a measurement of ρ_ν gives $\Sigma\, m_\nu$

Neutrinos in Large-scale structure



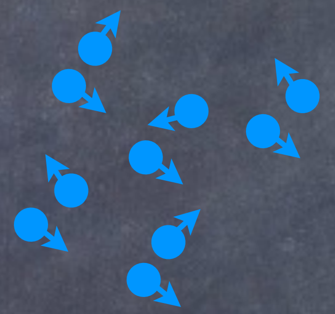
(Kravtsov)

Massive neutrinos and linear structure growth

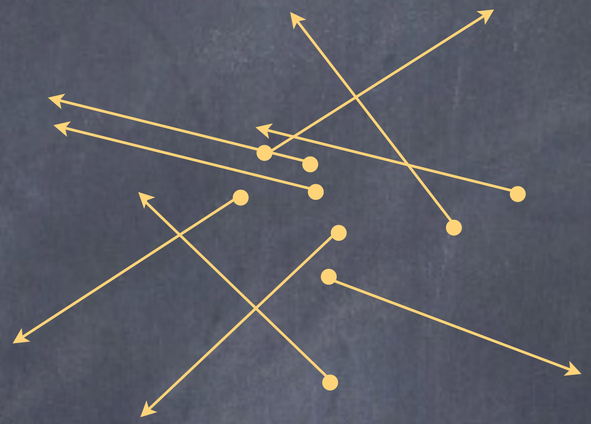
The gravitational evolution of large-scale structure is different for fast and slow moving particles

Massive neutrinos and linear structure growth

The gravitational evolution of large-scale structure is different for fast and slow moving particles



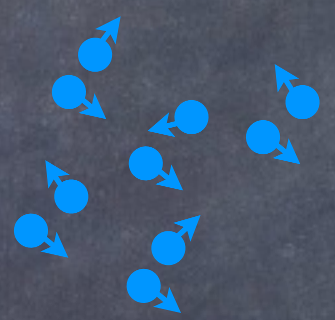
(clump easily)



(don't clump easily)

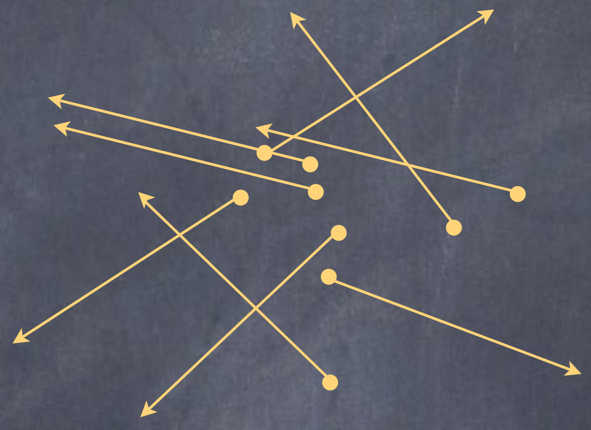
Massive neutrinos and linear structure growth

The gravitational evolution of large-scale structure is different for fast and slow moving particles



(clump easily)

baryons and cold dark matter



(don't clump easily)

neutrinos (or other exotic light dark matter)

Massive neutrinos and linear structure growth

small-scale density perturbations don't retain neutrinos

time

cold dark matter and baryons density perturbation growing

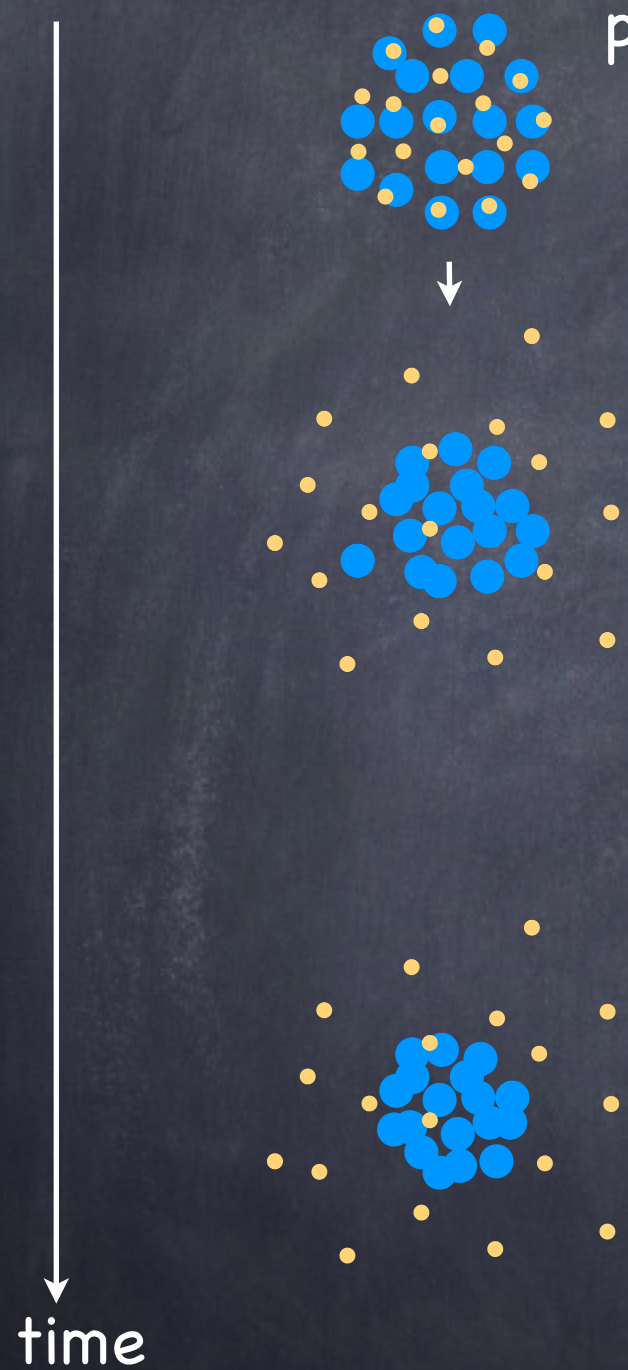
$\frac{\delta\rho_c}{\rho_c}$

neutrino density perturbation decaying

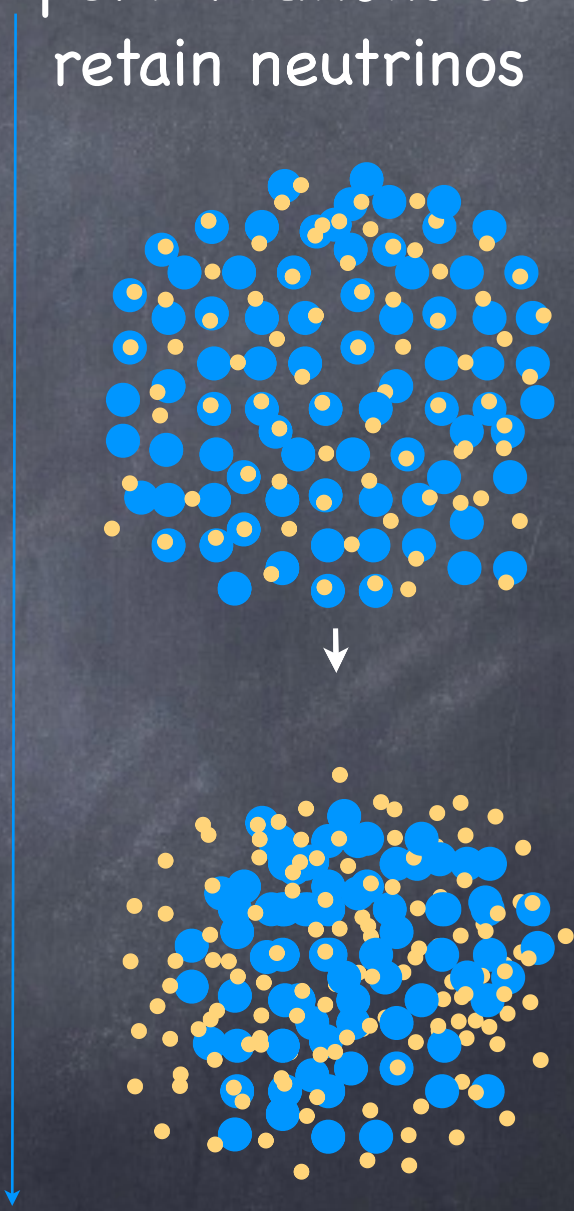
$\frac{\delta\rho_\nu}{\rho_\nu}$

Massive neutrinos and linear structure growth

small-scale density perturbations don't retain neutrinos



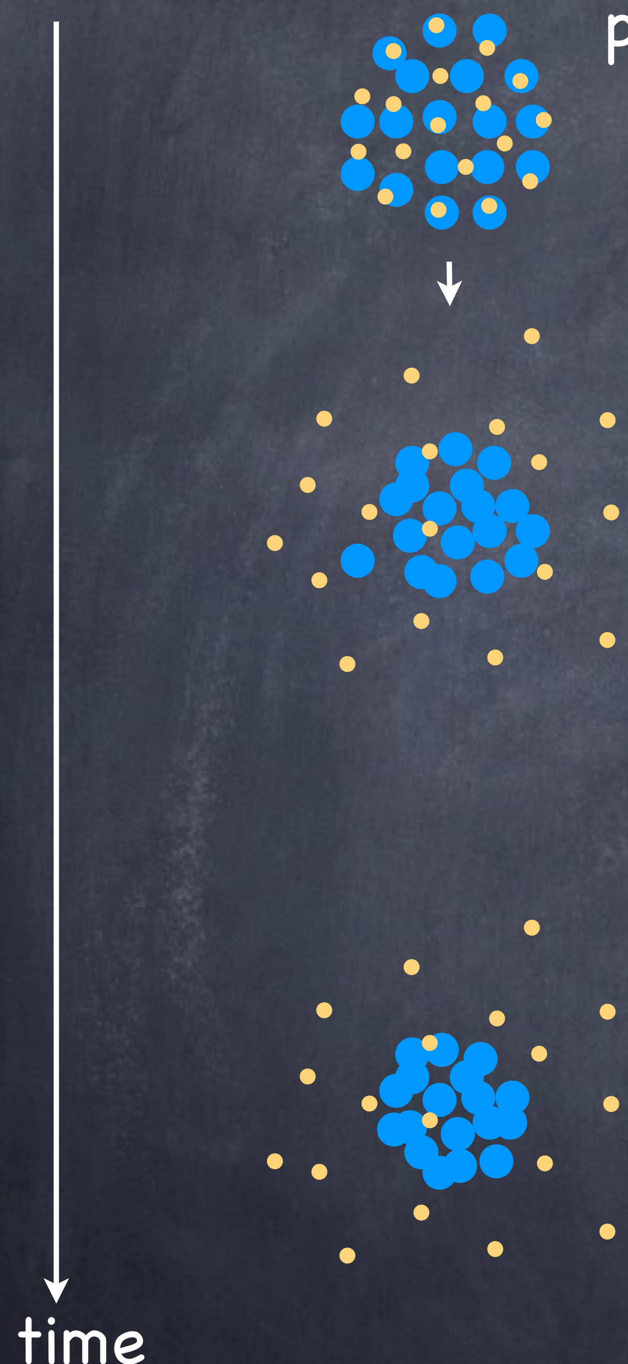
large-scale density perturbations do retain neutrinos



cold dark matter, baryons and neutrinos growing together

$$\frac{\delta\rho_\nu}{\rho_\nu} \; \frac{\delta\rho_c}{\rho_c}$$

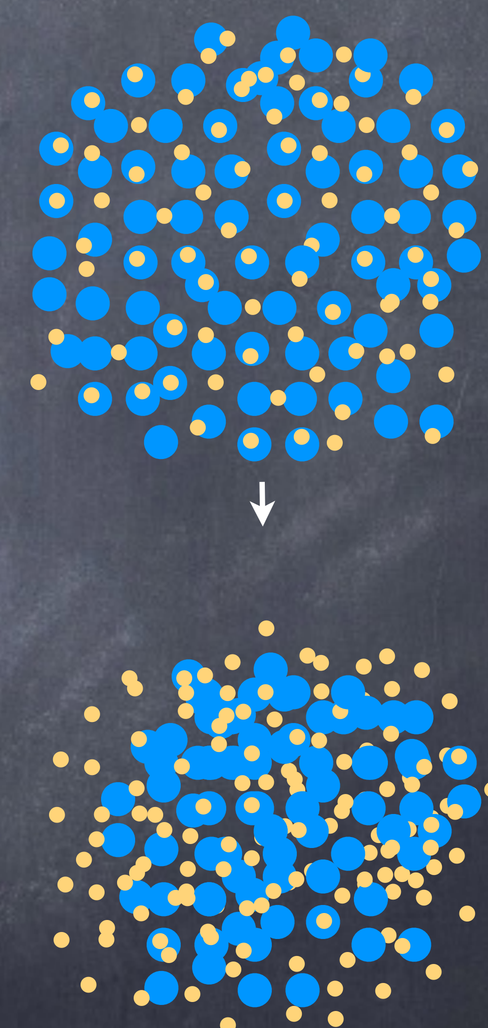
Massive neutrinos and linear structure growth



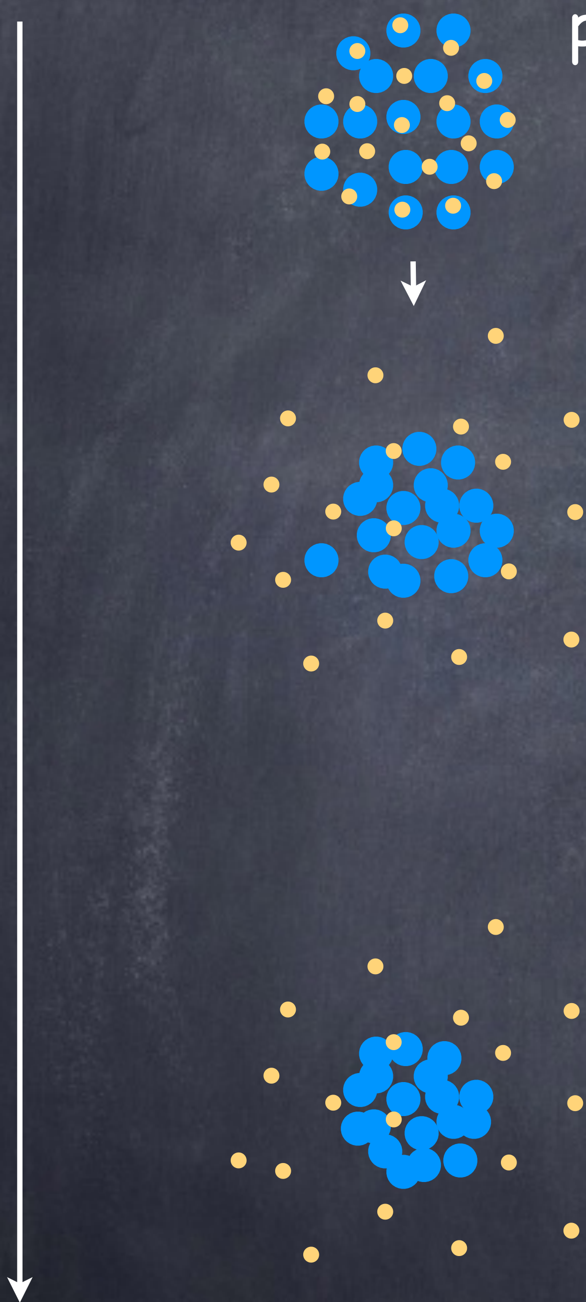
small-scale density perturbations don't retain neutrinos

large-scale density perturbations do retain neutrinos

Growth of matter perturbations is scale-dependent



Massive neutrinos and linear structure growth



time

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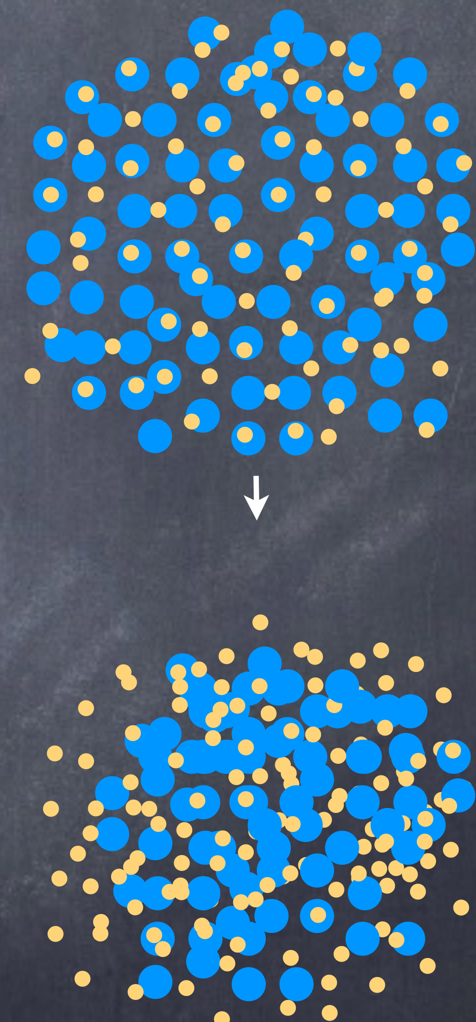


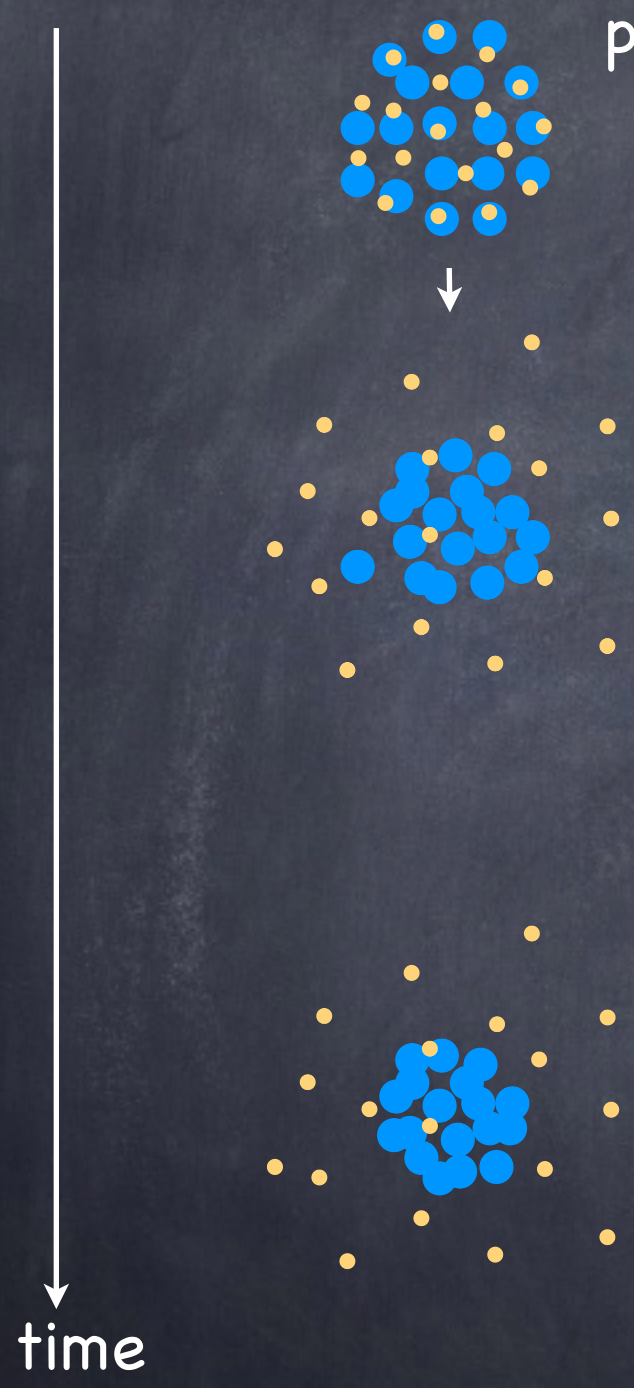
Growth of matter perturbations is scale-dependent

Relevant scale:

Typical distance a neutrino can travel in a Hubble time

$\lambda_{fs} \sim u_\nu/H$

Massive neutrinos and linear structure growth



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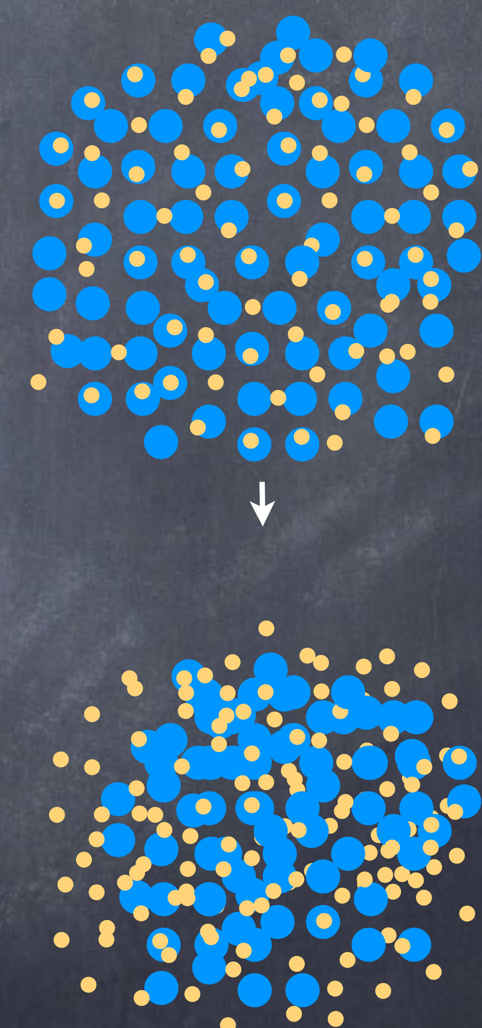


Growth of matter perturbations is scale-dependent

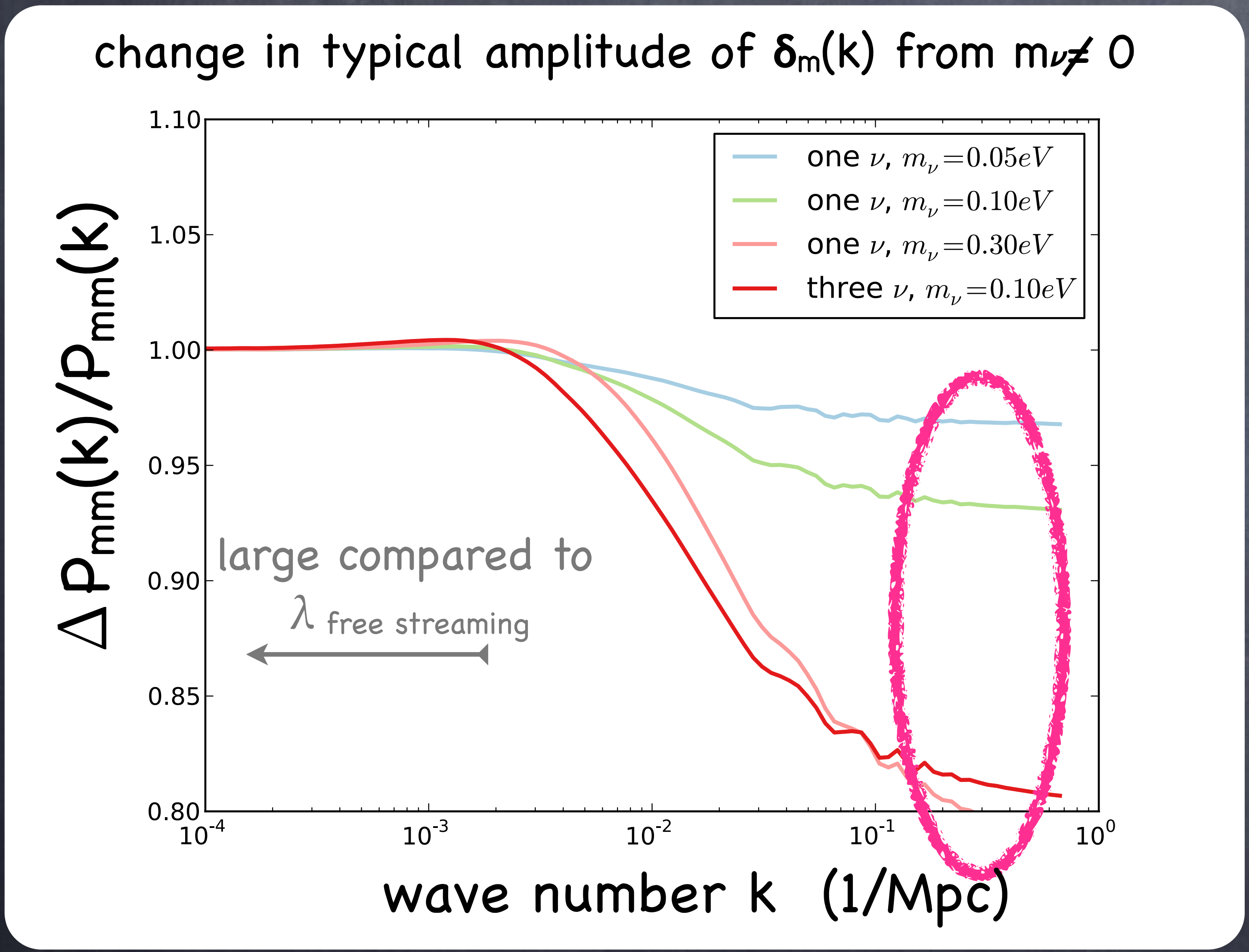
Relevant scale:

Typical distance a neutrino can travel in a Hubble time

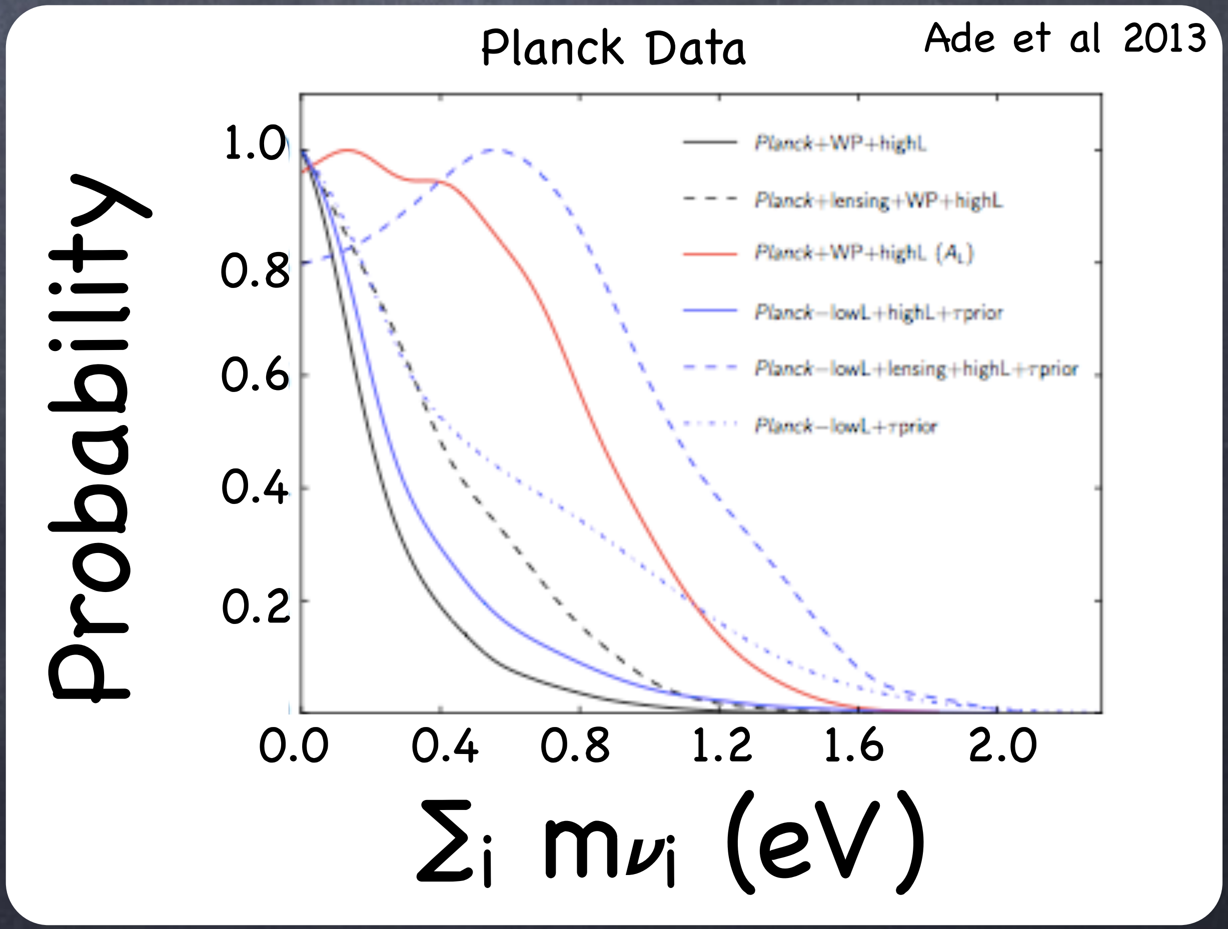
$\lambda_{fs} \sim u_\nu / H$

"free-streaming scale"

Scale-dependent growth



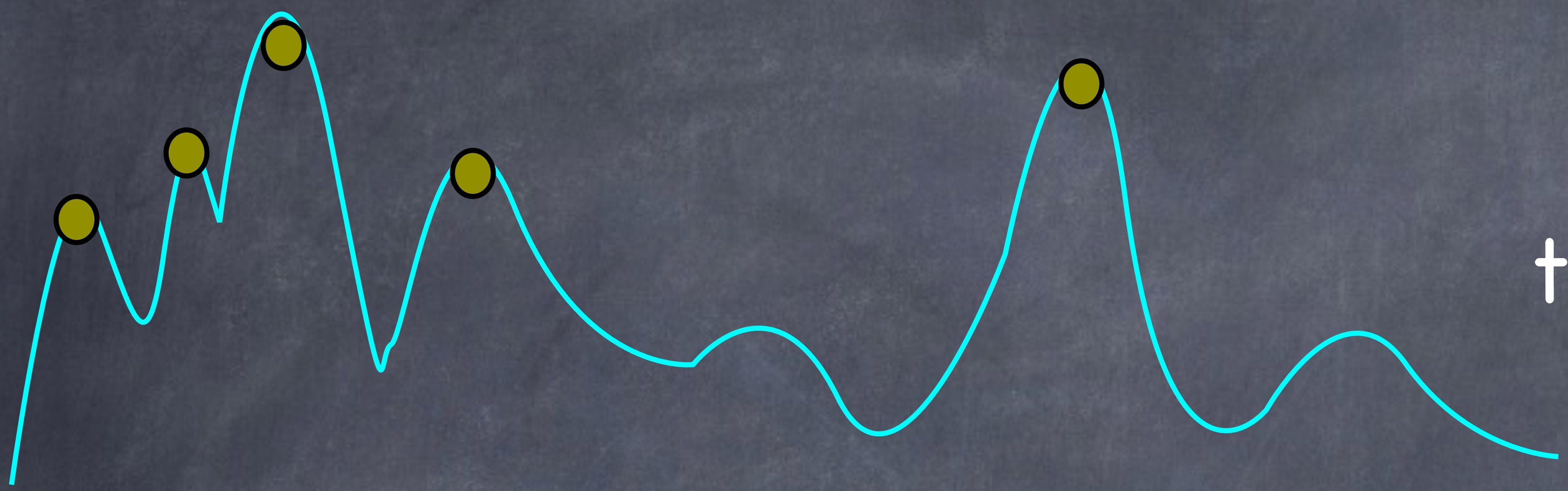
cosmological constraints!



Bond, Efstathiou, Silk 1980
Hu, Eisenstein, Tegmark 1998

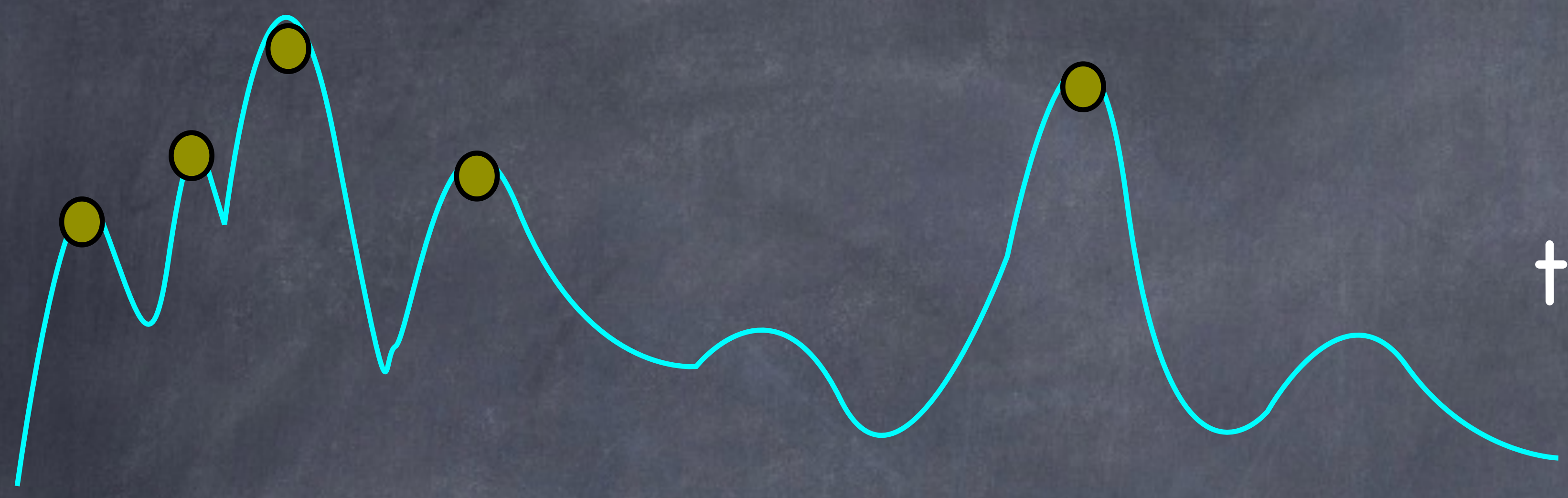
The scale-dependent growth of density perturbations causes halo bias to be scale dependent

Scale-dependent bias:



halos are biased tracers of the matter density field

Scale-dependent bias:



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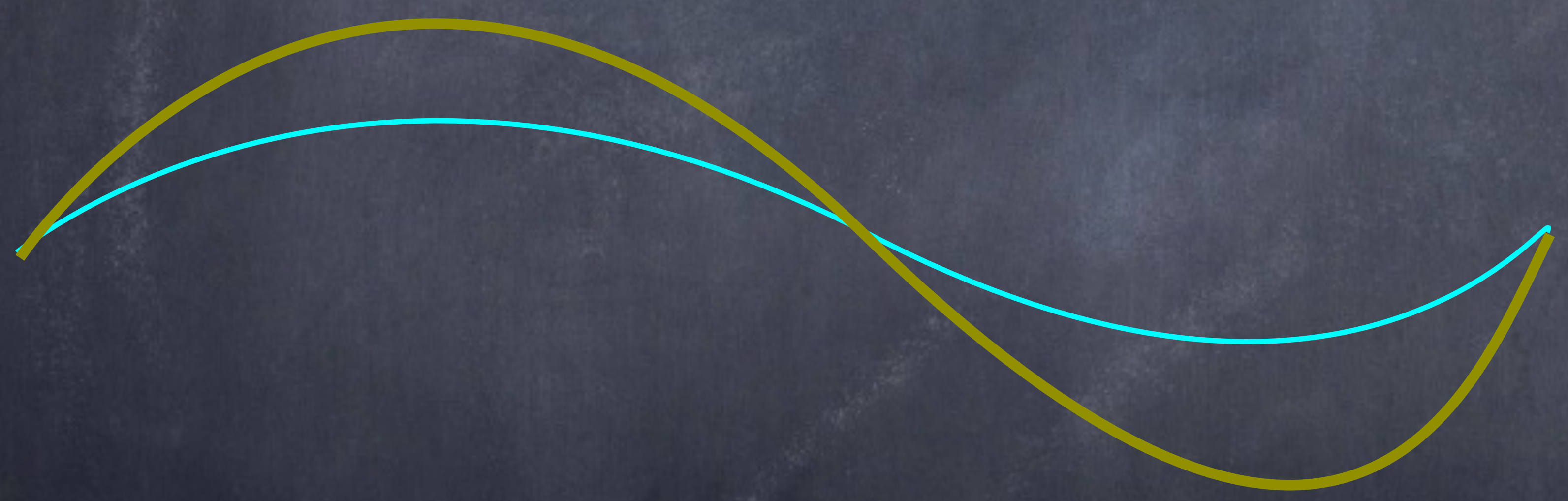

the number density of halos is modulated by long-wavelength fluctuations in the matter density field

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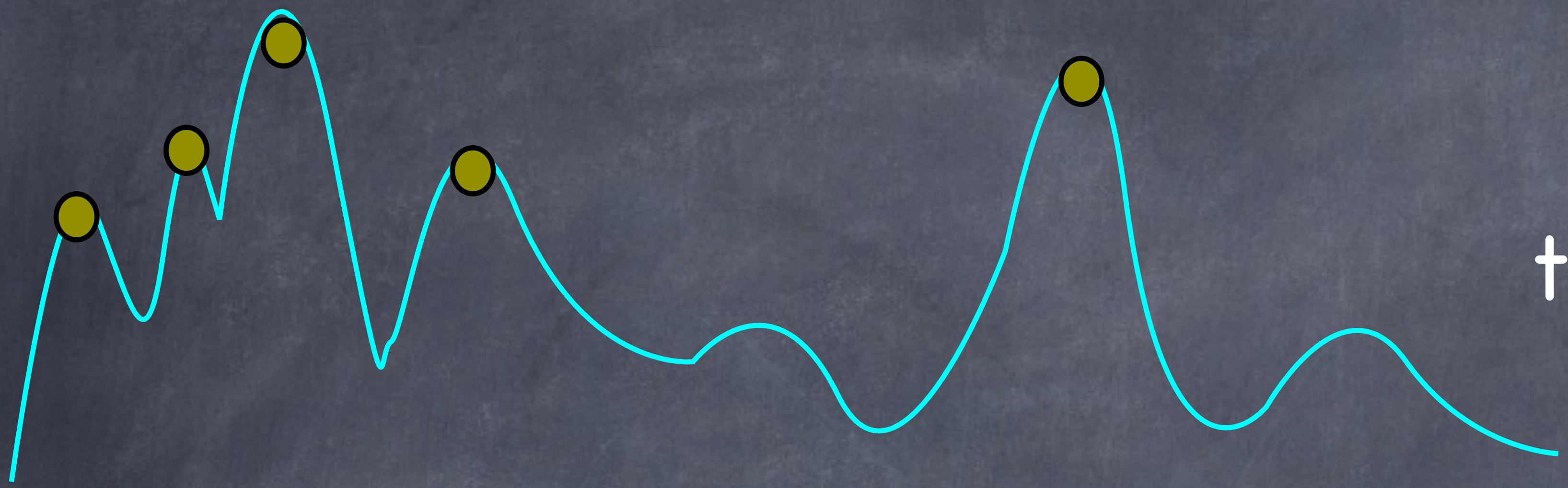
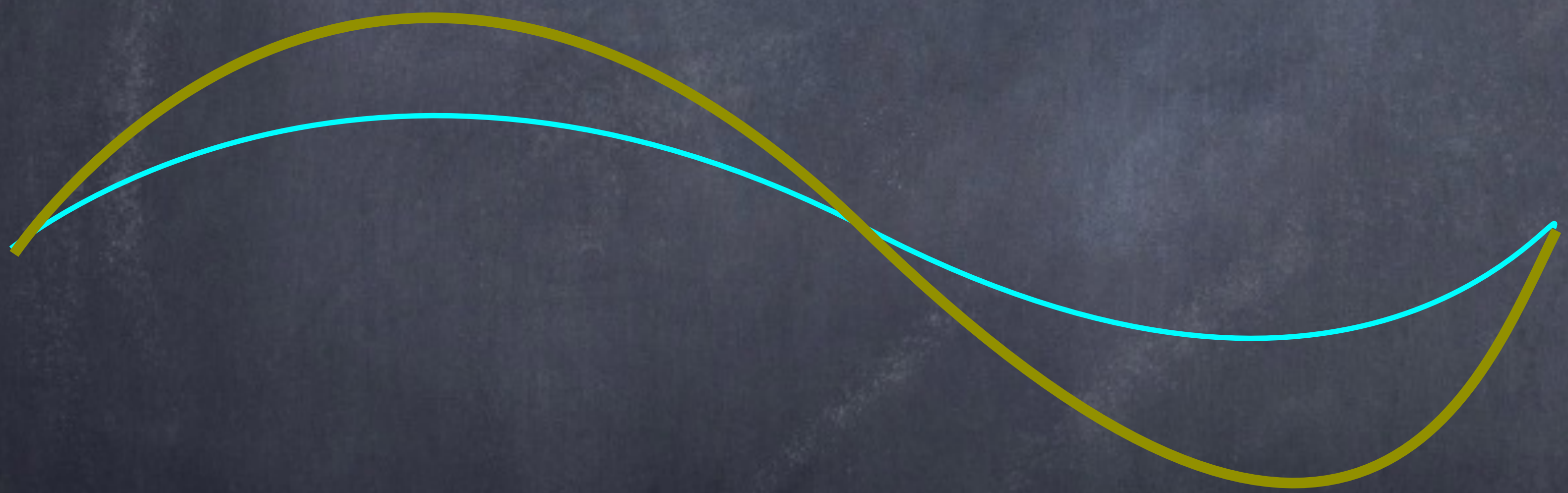


halos are biased tracers of the matter density field



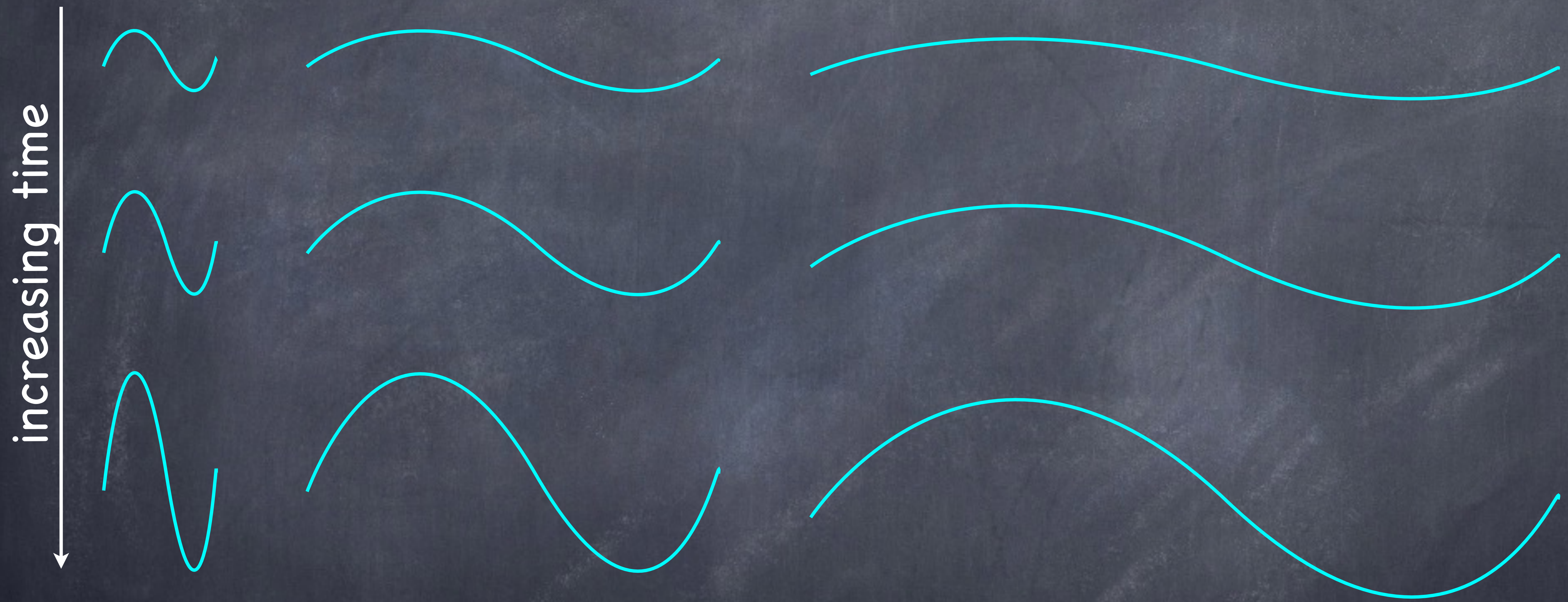
the number density of halos is modulated by long-wavelength fluctuations in the matter density field

$$\frac{\delta n}{n} \equiv b \left.\frac{\delta\rho}{\rho}\right|_{\text{long-wavelength}}$$

b is the halo bias

Scale-dependent bias:

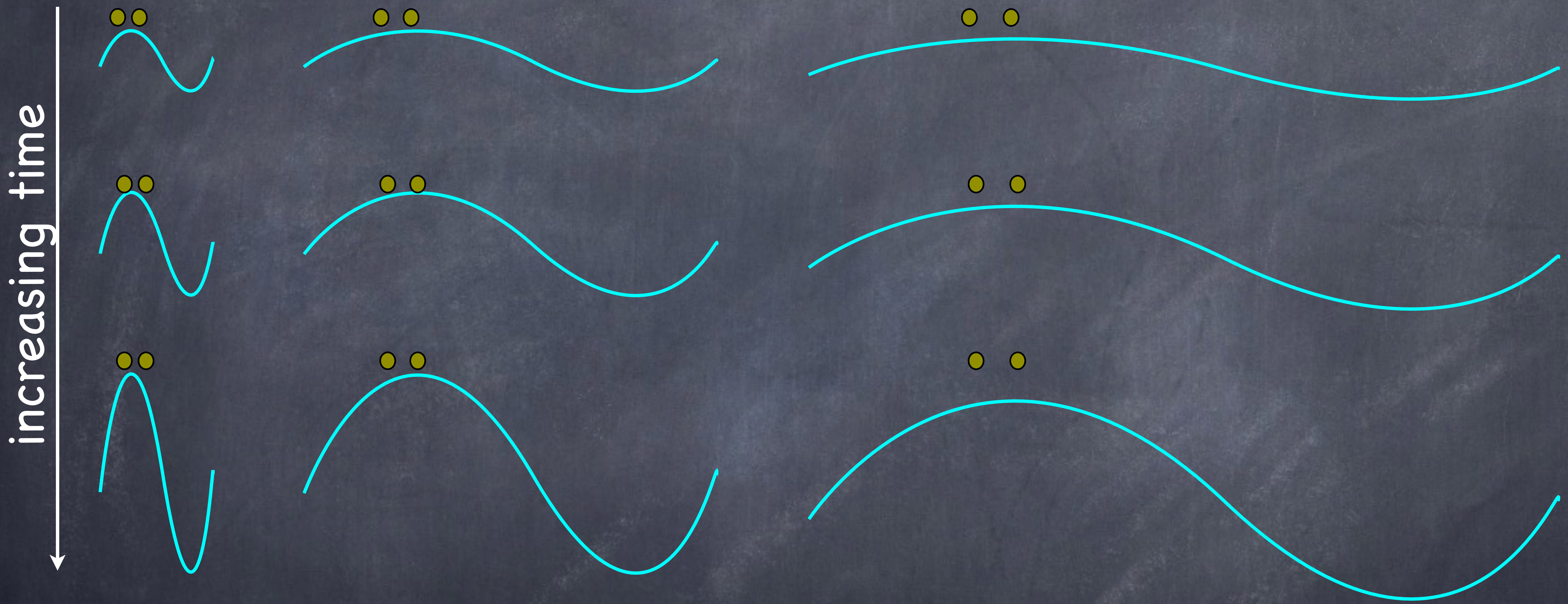
In a universe with CDM only, the linear evolution of matter fluctuations is independent of their wavelength



$$\frac{\delta\rho}{\rho}(k, z_{final}) \propto D(z_{final})\, \frac{\delta\rho}{\rho}(k, z_{initial})$$

Scale-dependent bias:

In a universe with CDM only, the linear evolution of matter fluctuations is independent of their wavelength



$$\frac{\delta\rho}{\rho}(k, z_{\rm final}) \propto D(z_{\rm final})\,\frac{\delta\rho}{\rho}(k, z_{\rm initial})$$

halos can't tell the wavelength of the background matter density perturbation

Scale-dependent bias:

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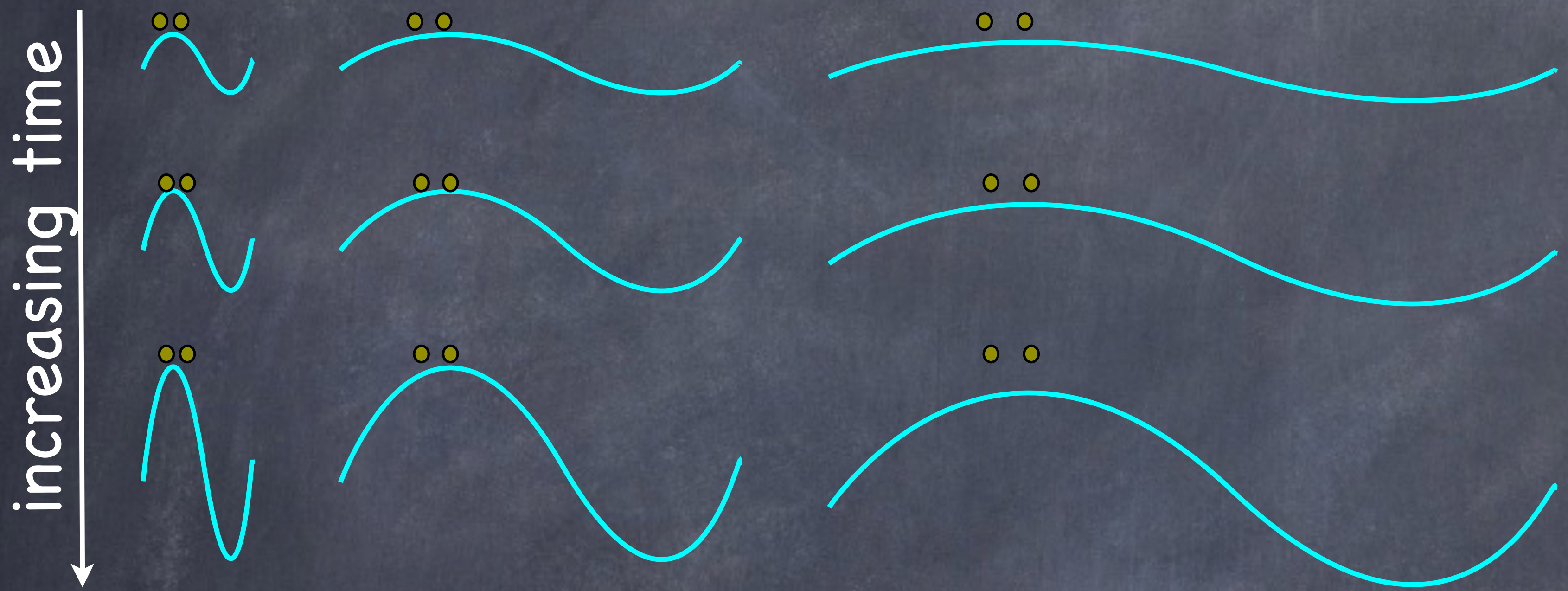


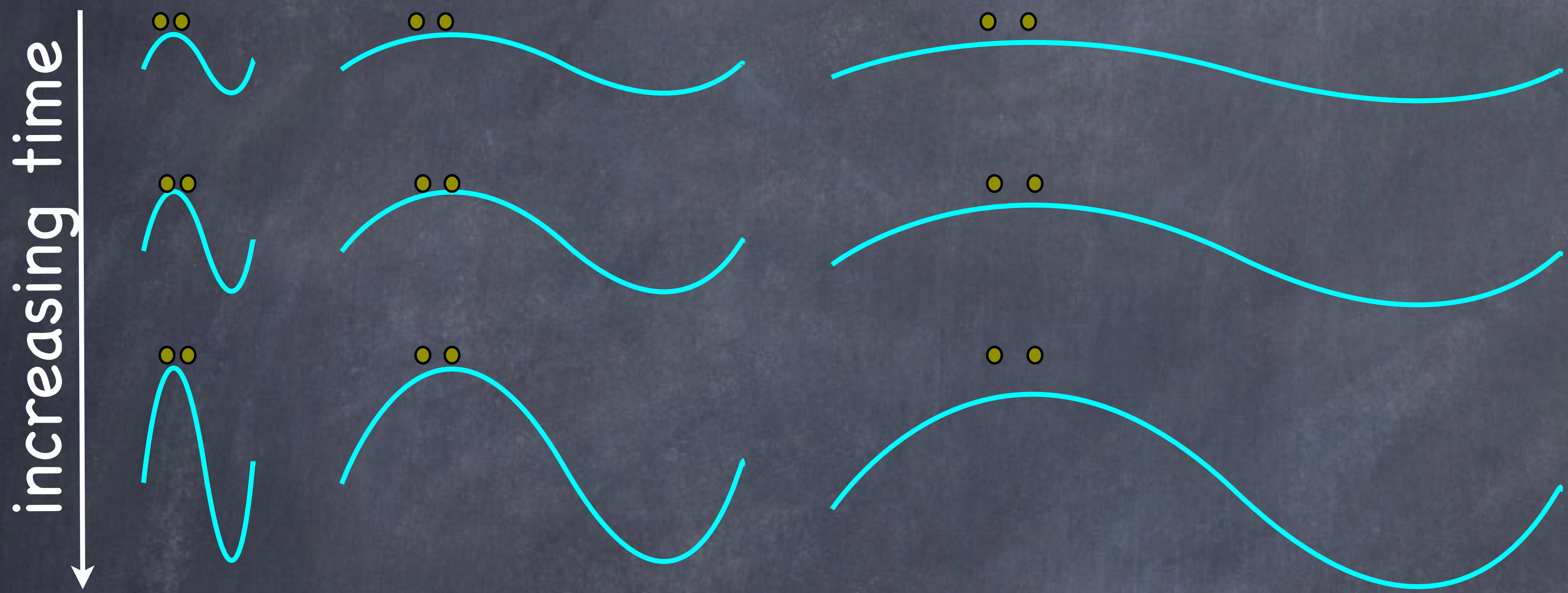
halos can't tell the wavelength of the background matter density perturbation

↓

the effect of $\frac{\delta\rho}{\rho}$ on the halo field (the linear bias) is independent of k

Scale-dependent bias:

In a universe with CDM only, the linear evolution of matter fluctuations is independent of their wavelength



halos can't tell the wavelength of the background matter density perturbation

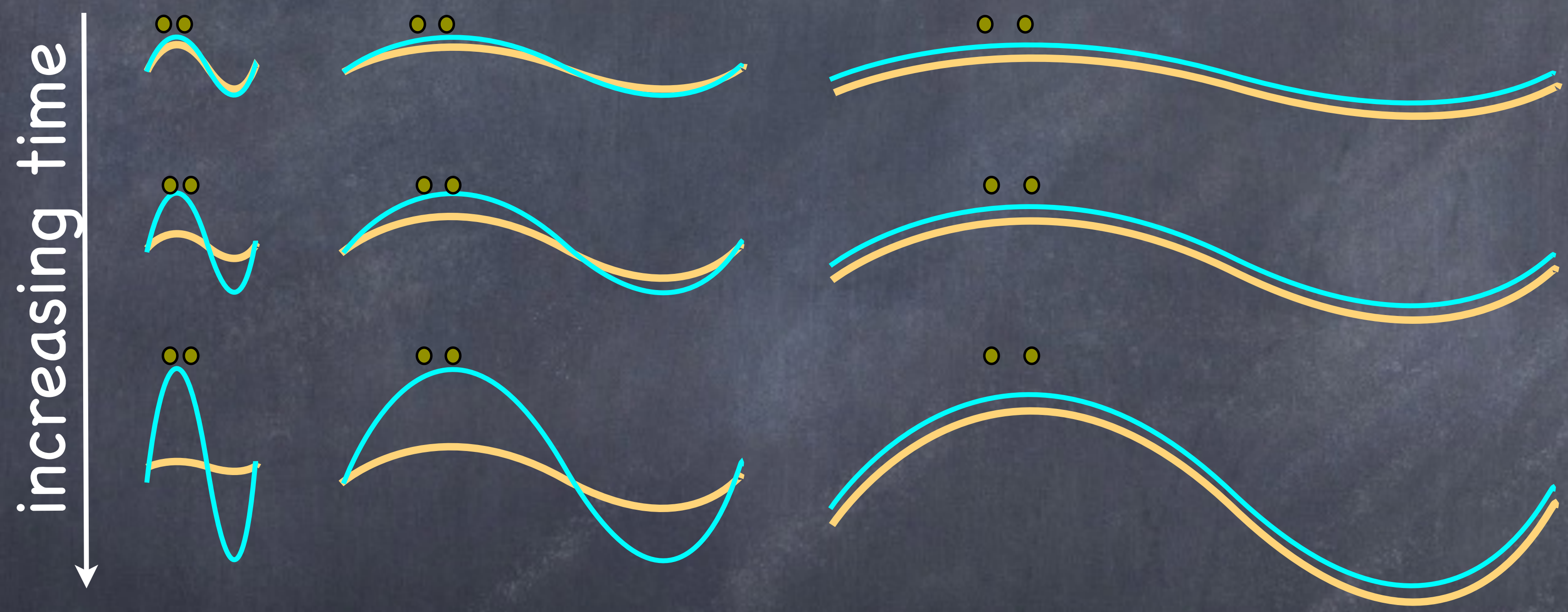
↓

the effect of $\frac{\delta\rho}{\rho}$ on the halo field (the linear bias) is independent of k

massive neutrinos break this

halo bias can depend on k

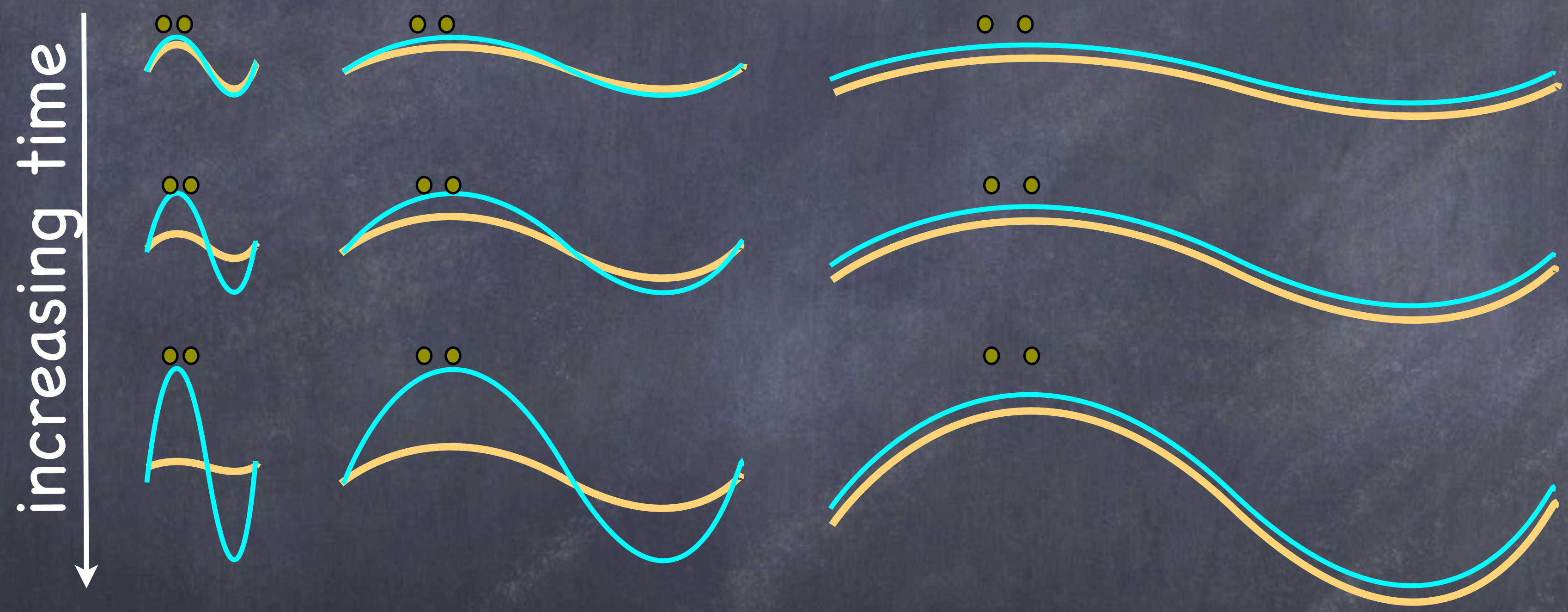
Scale-dependent bias:



neutrinos
cold dark matter

Scale-dependent bias:

WANT: estimate of k-dependence of the halo bias caused by massive neutrinos



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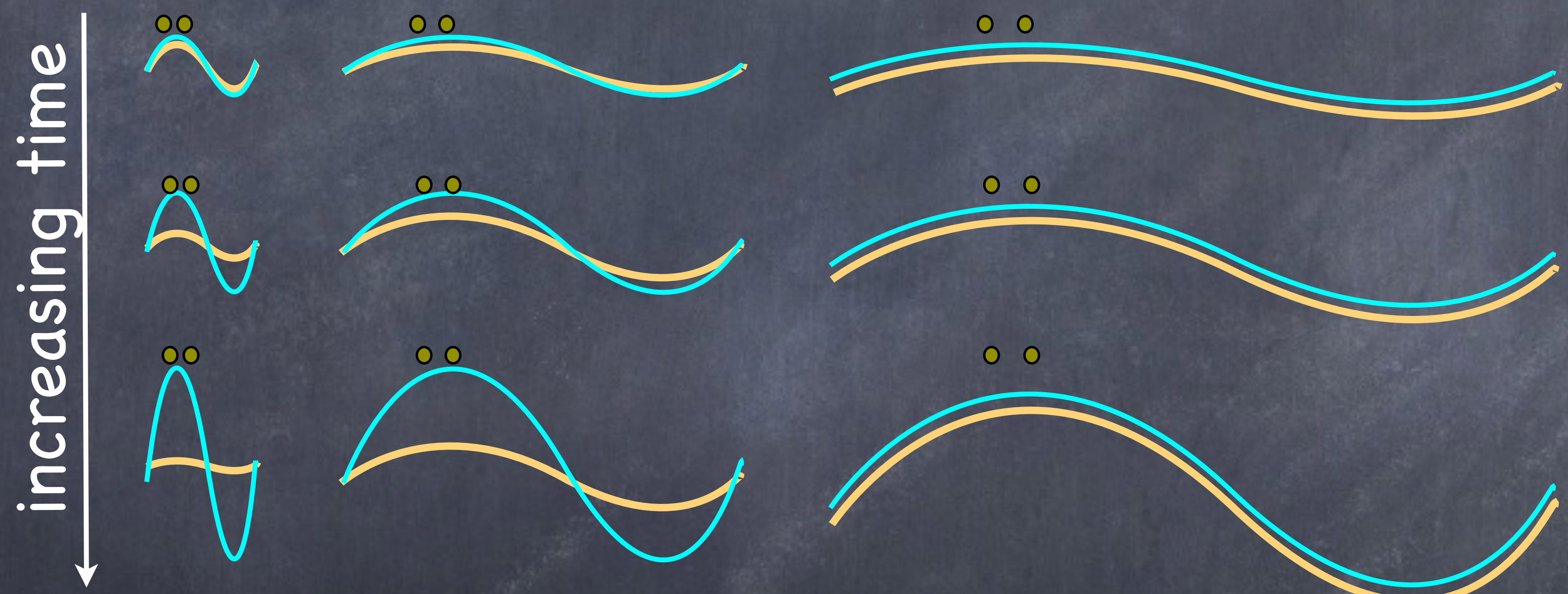


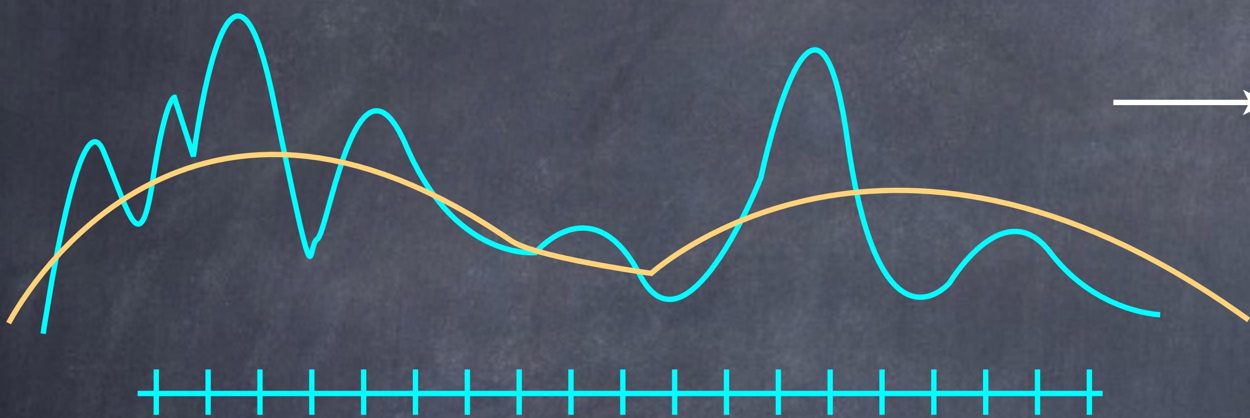
neutrinos
cold dark matter

(see also Hui & Parfrey 2008; Parfrey, Hui, Sheth 2011;)

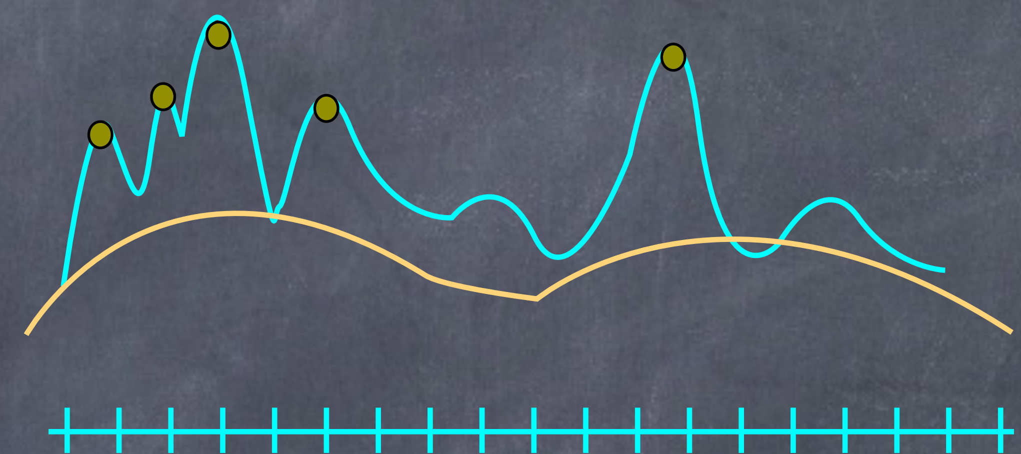
Prescription for calculating the halo bias in a universe with massive neutrinos

Prescription for calculating the halo bias

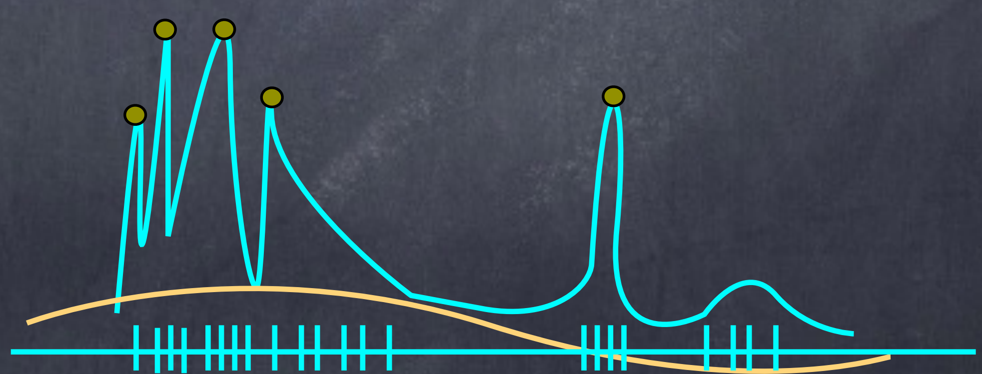
initial density field



initial proto-halo distribution



late time halo distribution



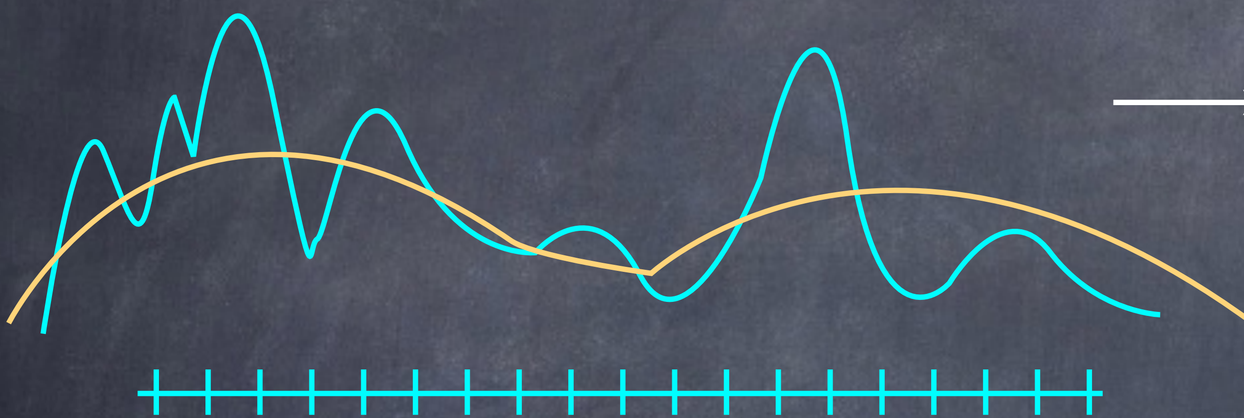
$$\frac{\delta n}{n} \equiv b \left.\frac{\delta \rho}{\rho}\right|_{\text{long-wavelength}}$$

(ML 2014)

Gunn & Gott 1972
Press & Schechter 1974

Prescription for calculating the halo bias

initial density field



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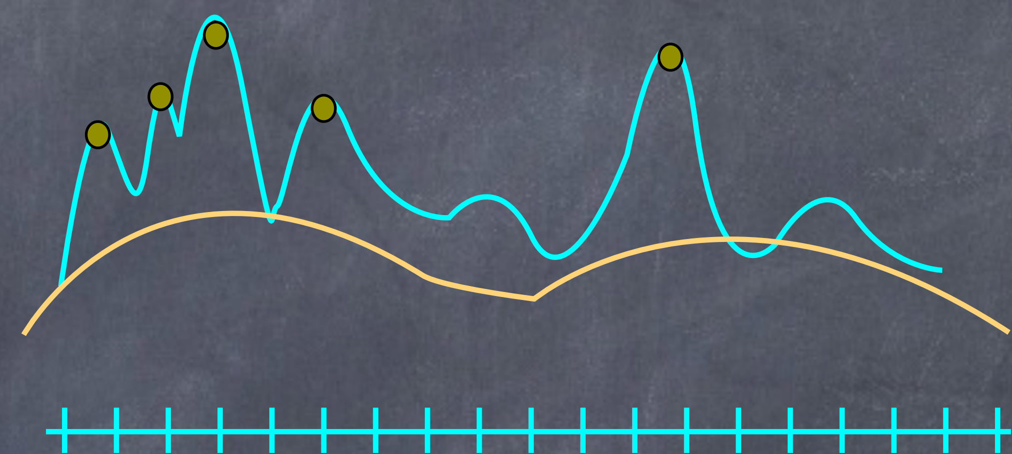

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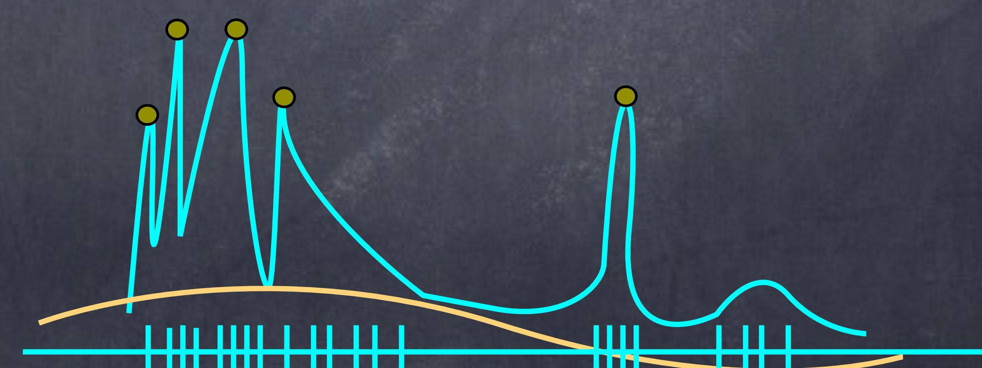


$$\frac{\delta n}{n} \equiv b \left.\frac{\delta\rho}{\rho}\right|_{\text{long-wavelength}}$$

want this!

(ML 2014)

Gunn & Gott 1972
Press & Schechter 1974

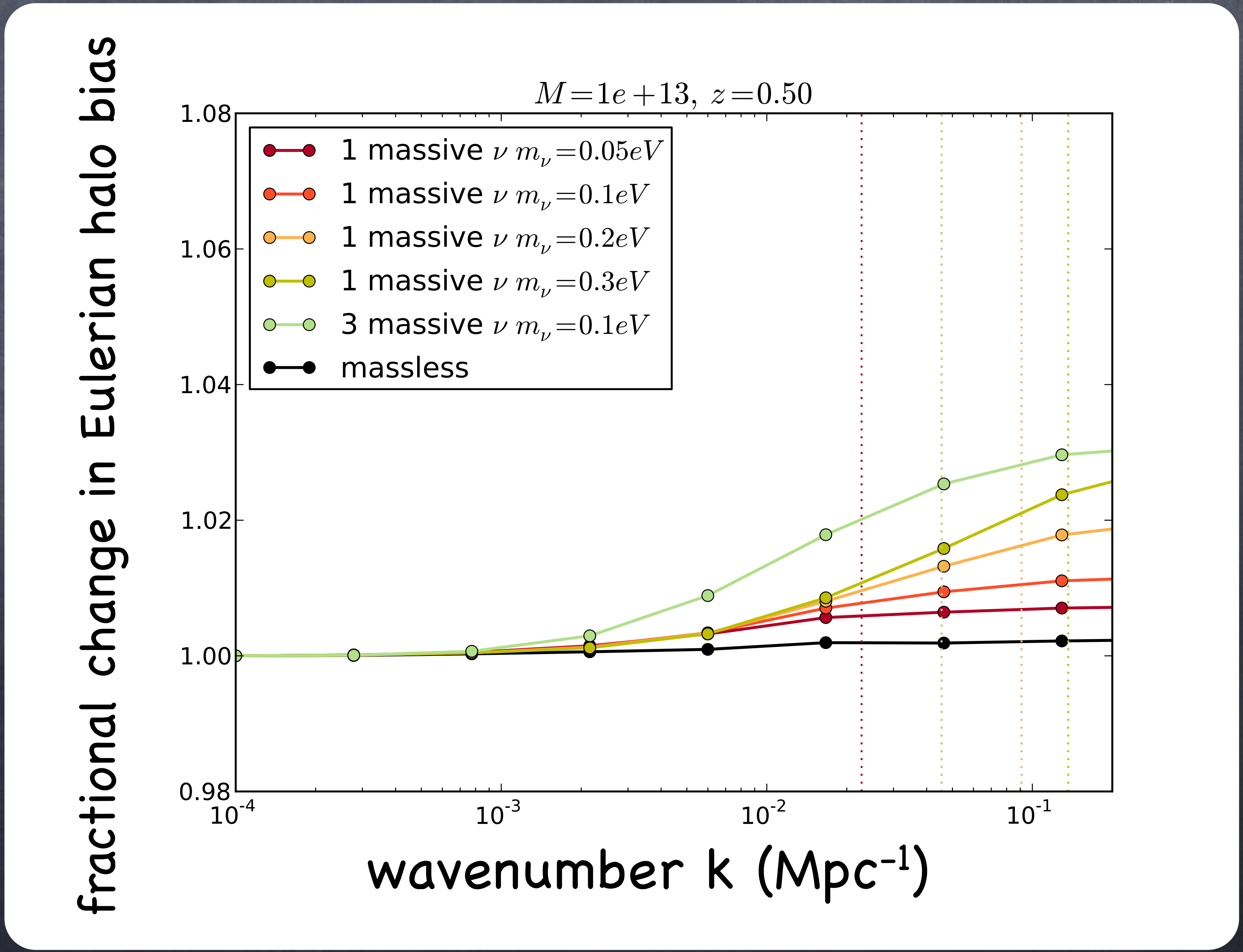
Numerical estimates for scale-dependent halo bias

Numerical results for halo bias

scale-dependent change
to final bias

$$\delta n(k)/n = b(k)\ \delta_{matter}(k)$$

$$b(k) = \sqrt{P_{hh}(k)/P_{mm}(k)}$$



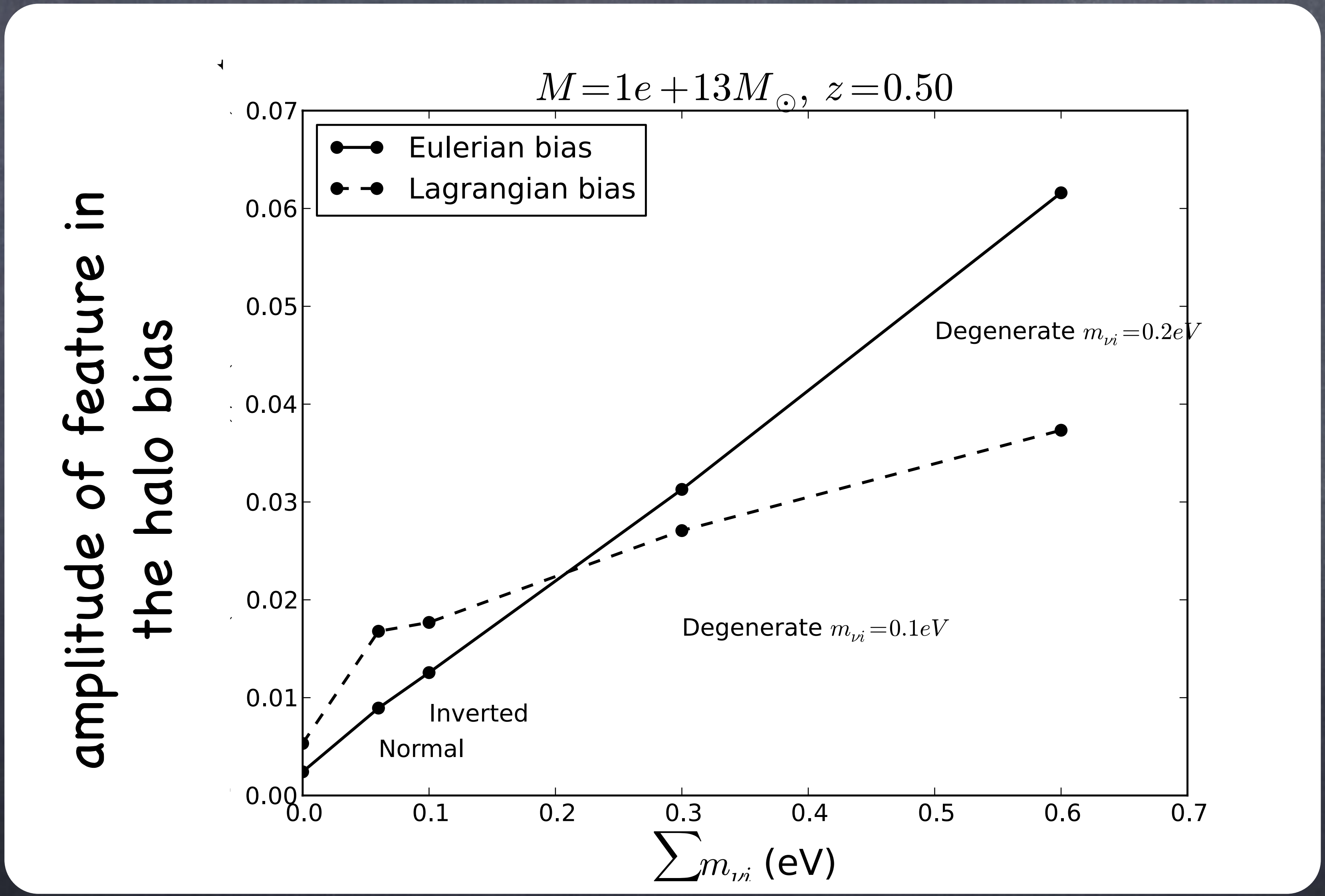
(Use Bhattacharya et al 2011 for $n(M|\ \delta_{crit})$)

(ML 2014)

Numerical results for halo bias

scale-dependent change to final bias

$\delta n(k)/n = b(k)\ \delta_{matter}(k)$



(Use Bhattacharya et al 2011 for $n(M|\ \delta_{crit})$)

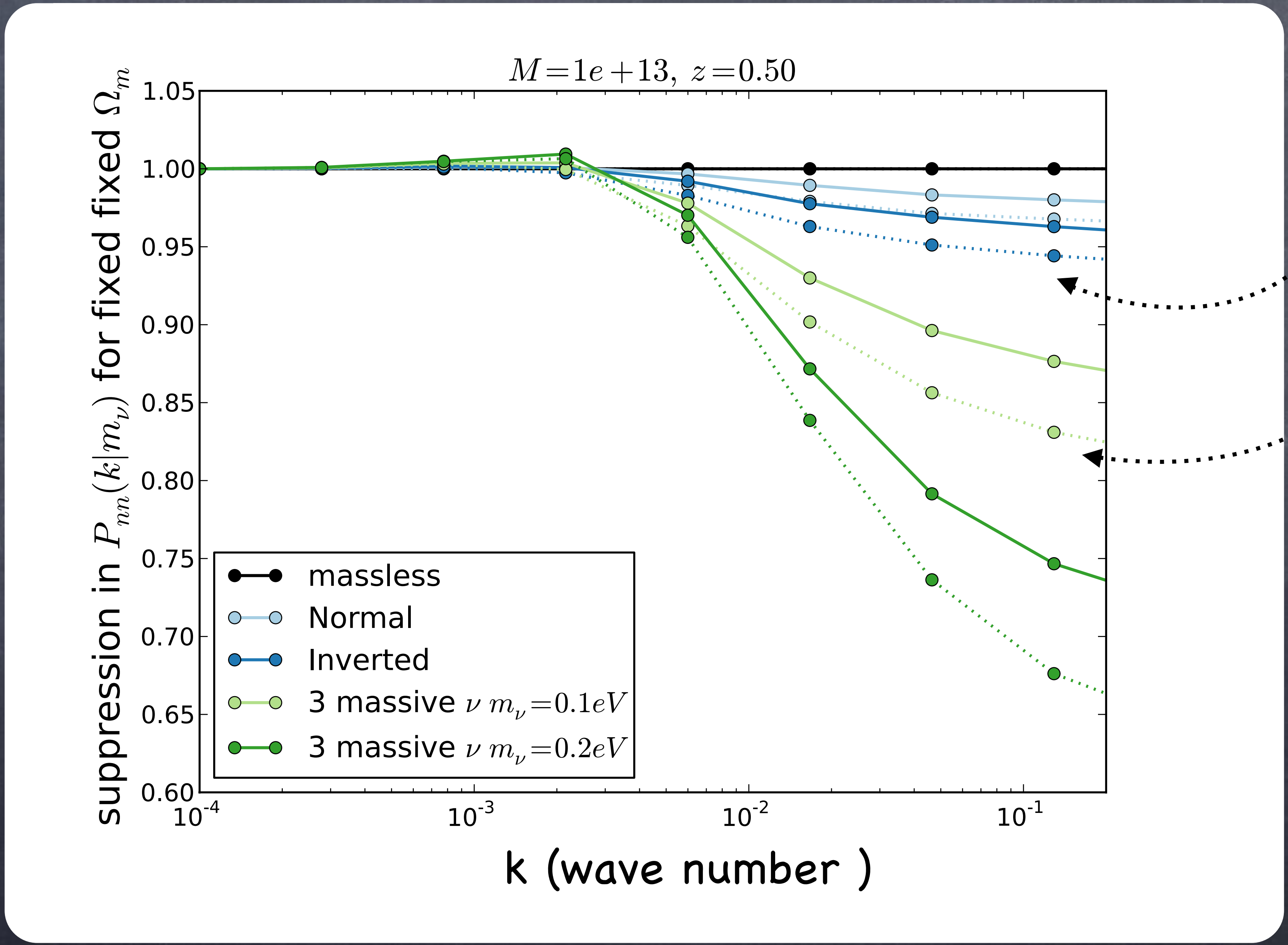
(ML 2014)

Observational consequences of scale-dependent bias?

Observational consequences of scale dependent bias?

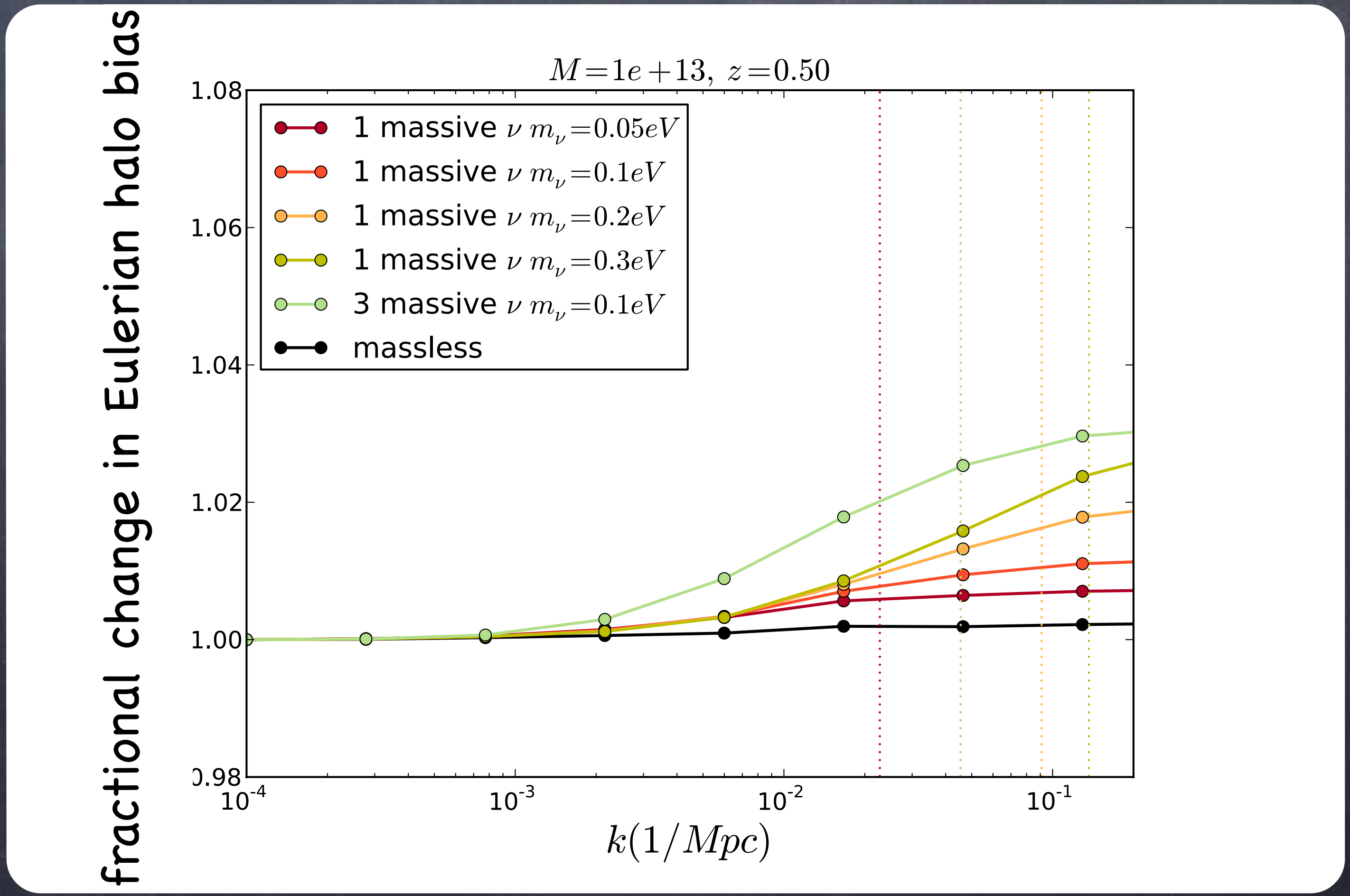
(incorrectly) assuming constant bias

suppression in galaxy power spectrum less than in matter power spectrum

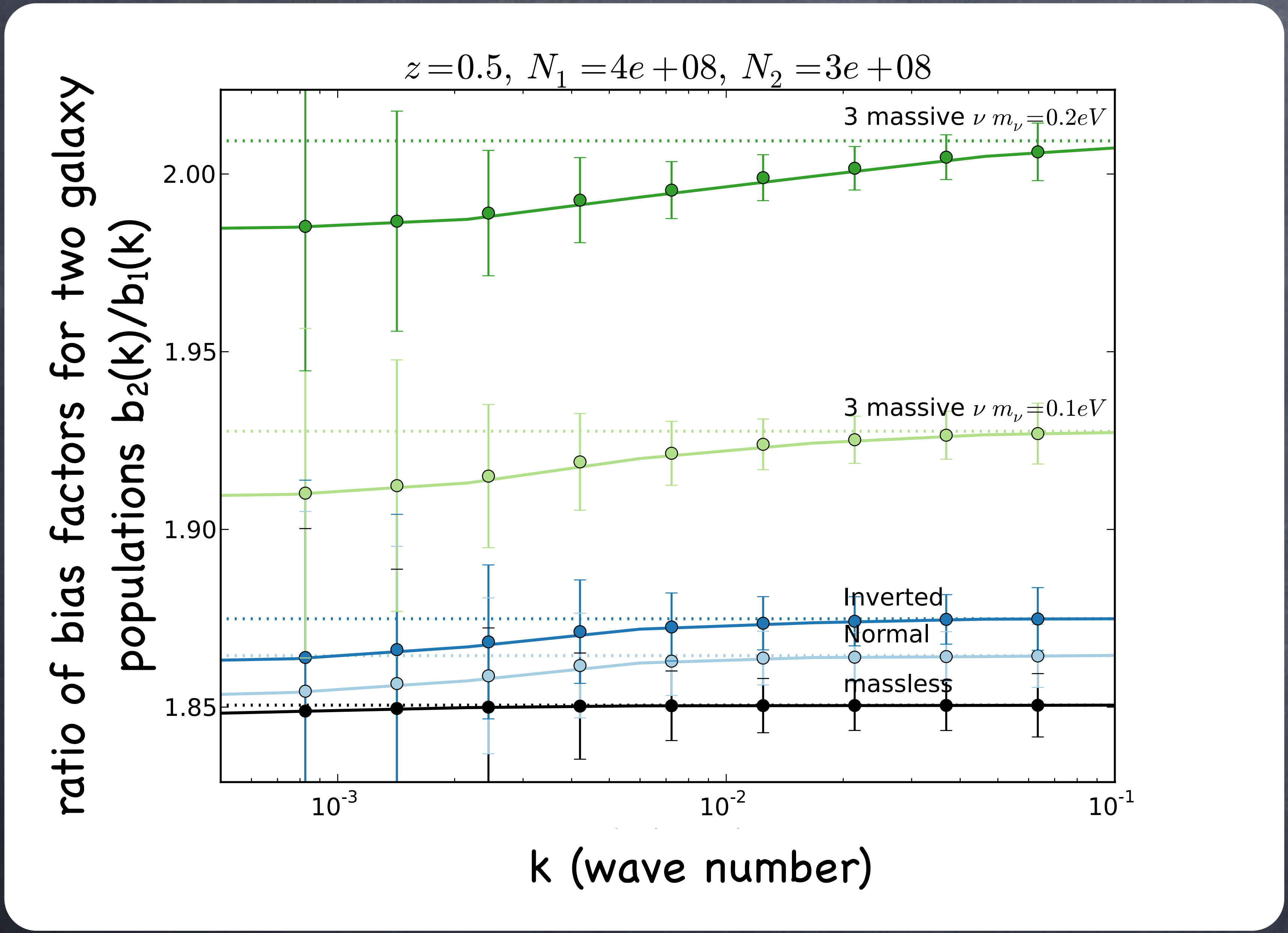


(ML 2014)

But the scale-dependent halo bias is itself an observable!



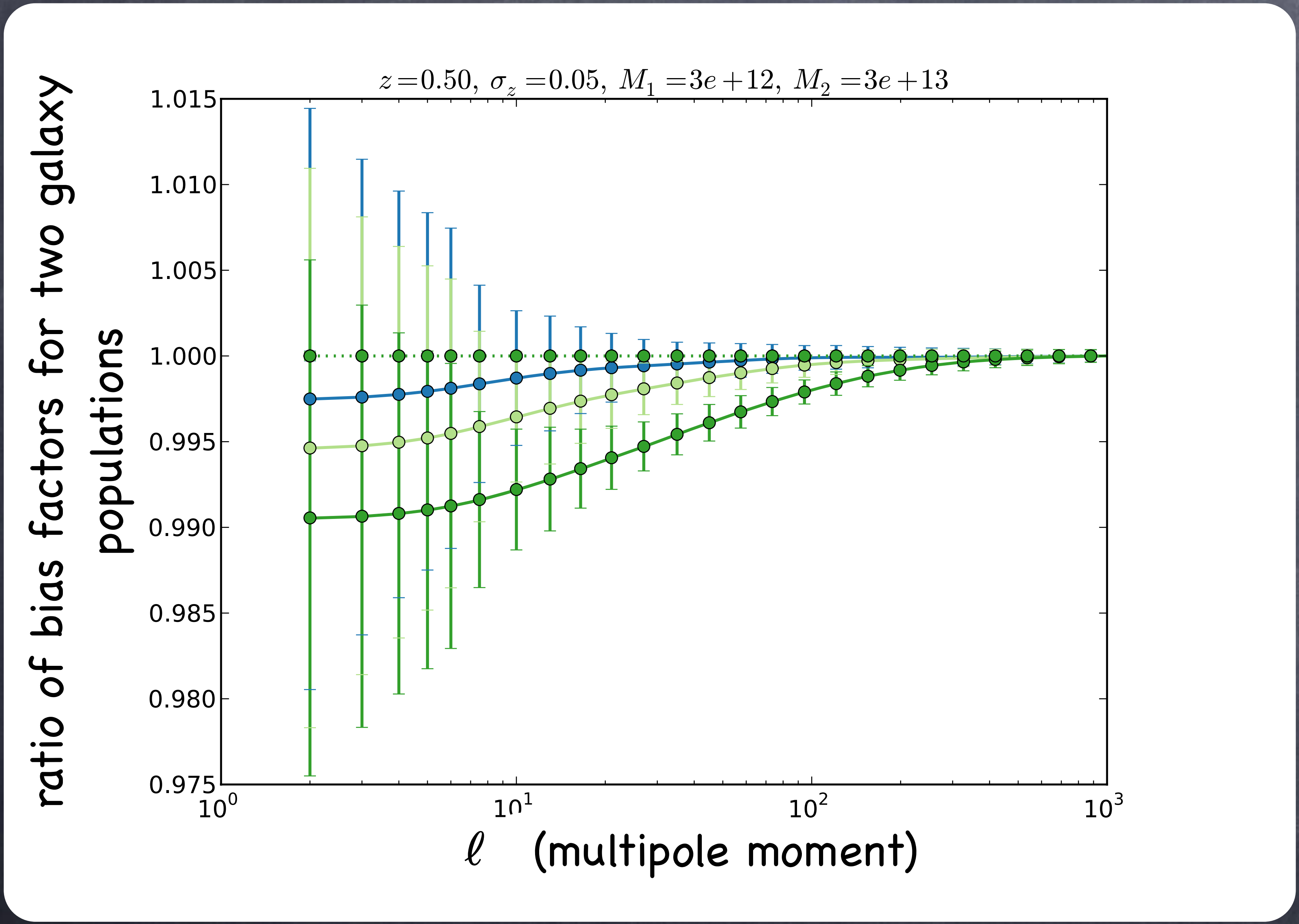
The scale-dependent halo bias is an observable!



$$\sigma_{b1/b2} \sim \frac{1}{\sqrt{n_1 P_{g2g2}}}$$

(ML in prep.)

The scale-dependent halo bias is an observable!



$$\sigma_{b1/b2} \sim \frac{1}{\sqrt{N_\ell n_1 C_{g2g2}}}$$

(ML in prep.)

Accuracy of these predictions?

N-body simulations are the community standard for cold dark matter structure.

Simulations with massive neutrinos?

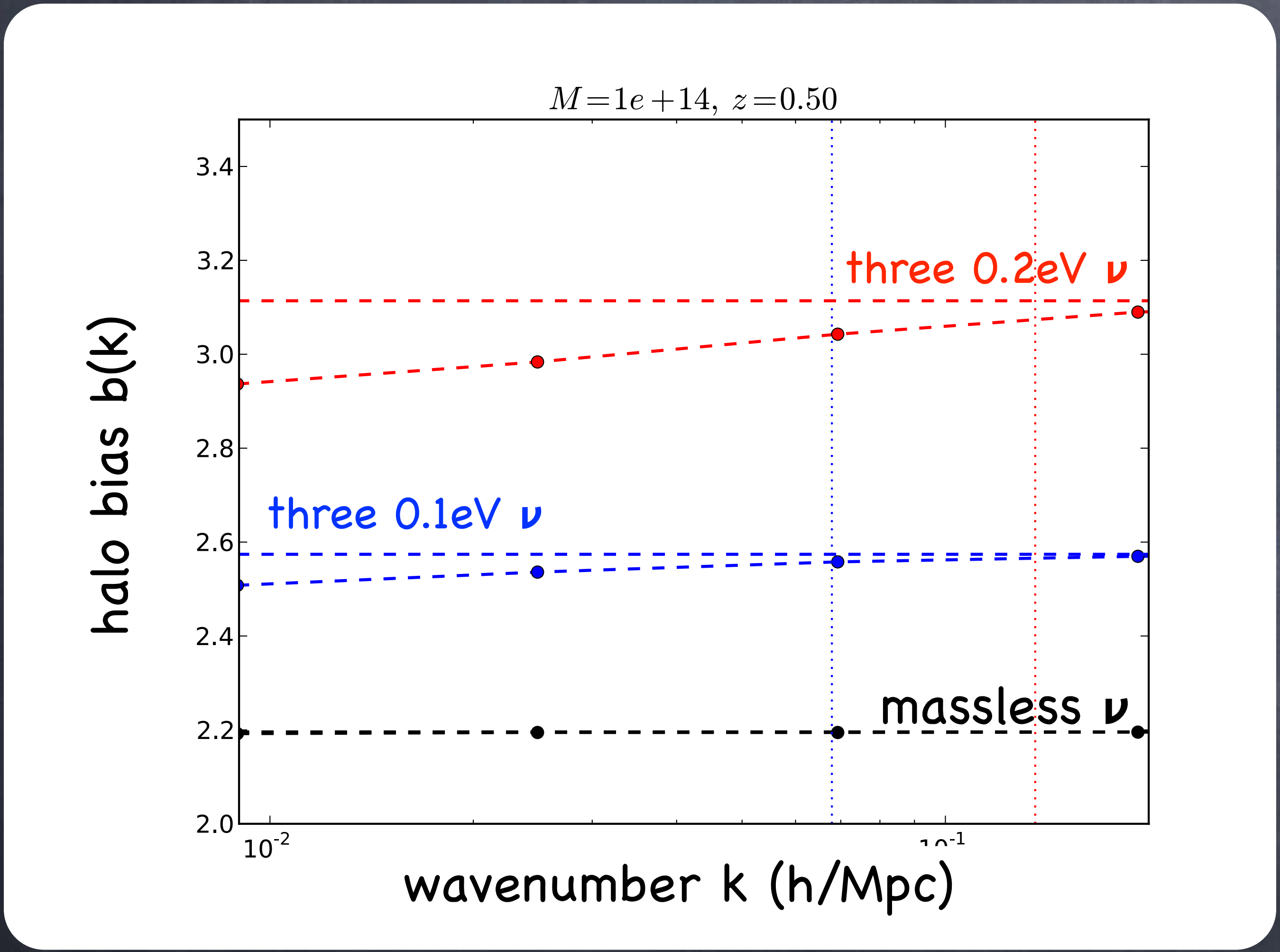
(i) Tricky. very few exist, very new
(ii) Want a model that provides insight into the physical processes responsible for new effects
(iii) Don't want to rerun for every possible neutrino mass hierarchy scenario
(iv) It will be great to make comparisons in the future!

Viel, Haehnelt, Springel 2010; Marulli, Carbone, Viel, Moscardini, Cimatti 2011; Agarwal & Feldman 2011; Brandbyge, Hannestad, Haugboelle, Wong 2012; Upadhye, Biswas, Pope, Heitmann, Habib 2013: Villaescusa-Navarro, Bird, Pena-Garay, Viel 2013;

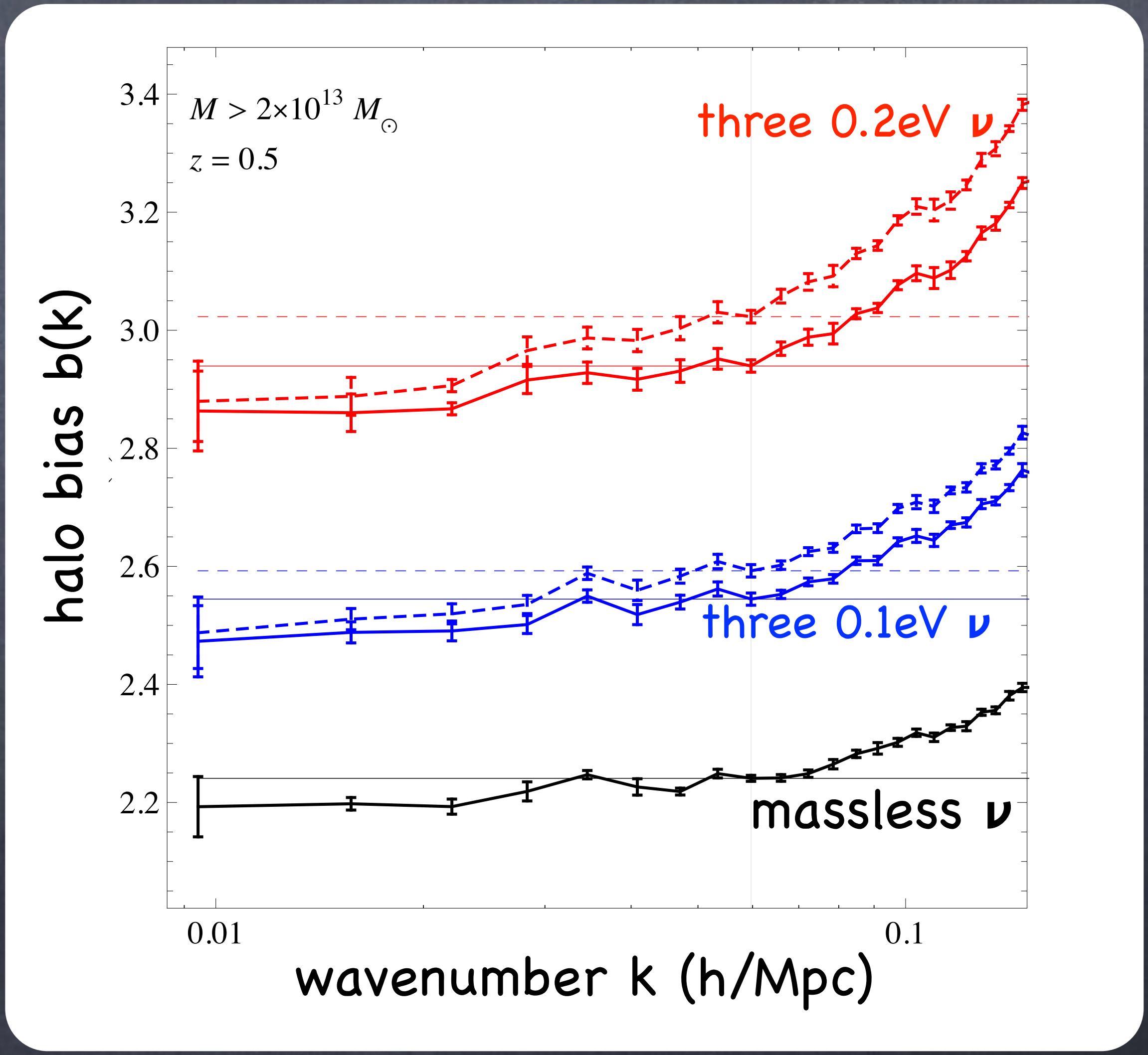
Scale-dependent bias from massive neutrinos

comparison with sims looks reasonable!

my calculations



simulations from Castorina et al 2013



(ML 2014)

Conclusions

- Cosmology provides interesting information about neutrino physics!
- Scale-dependent halo bias is a new signal of massive neutrinos in large-scale structure
- Scale-dependent halo bias is a new systematic for massive neutrinos in large-scale structure