Neutrinos, Quintessence, and Structure Formation in the Universe

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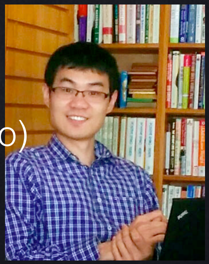
ML 1405.4855, 1602.08108

Hu, Chiang, Li, ML 1605.01412

Chiang, Li, Hu, ML 1609.01701 + in progress

Wayne Hu (KICP, Chicago)



Yin Li (Berkeley & IPMU, U Tokyo)

Chi-Ting Chiang (YITP, Stony Brook)

Outline

- Overview of Large-scale Structure
- Large-scale Structure Beyond Cold Dark Matter
- Nonlinear Gravitational Evolution of Structure
- The Fake Separate Universe Approach
- First Simulations Results: A proof of principle with quintessence
- Conclusion

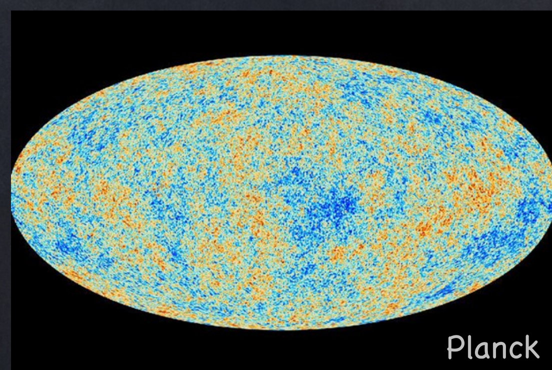
Overview of Structure in the Universe

Structure in the Universe

quantum fluctuations

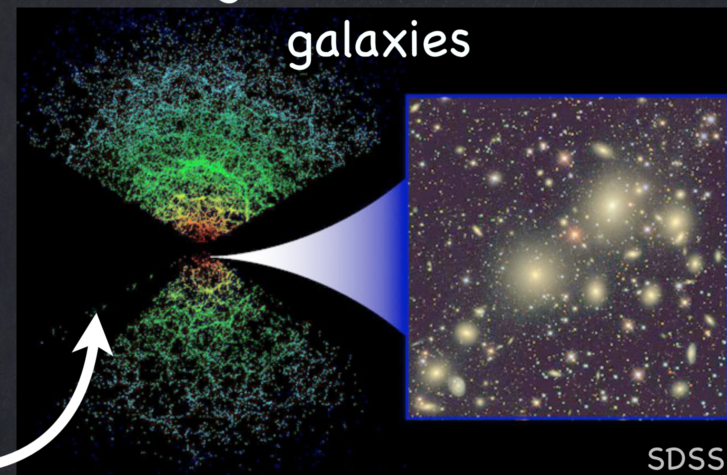
inflation

small matter & energy fluctuations



(Kravtsov)

stars, galaxies, clusters of galaxies

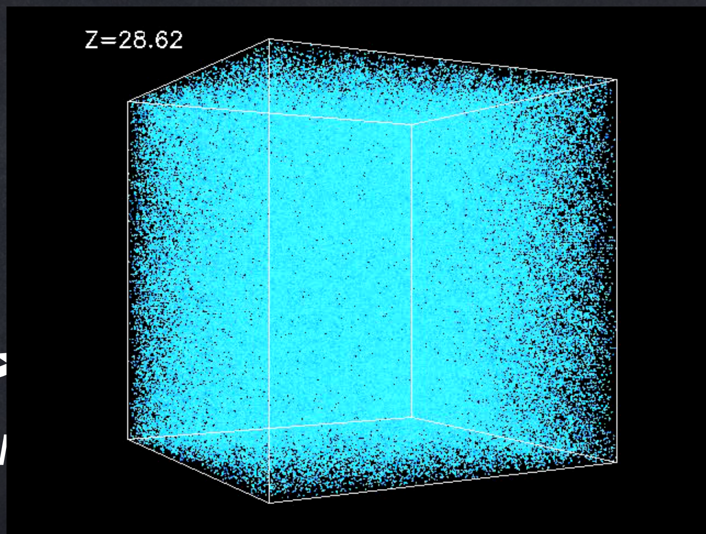


gravitational collapse

Structure in the Universe

quantum fluctuations

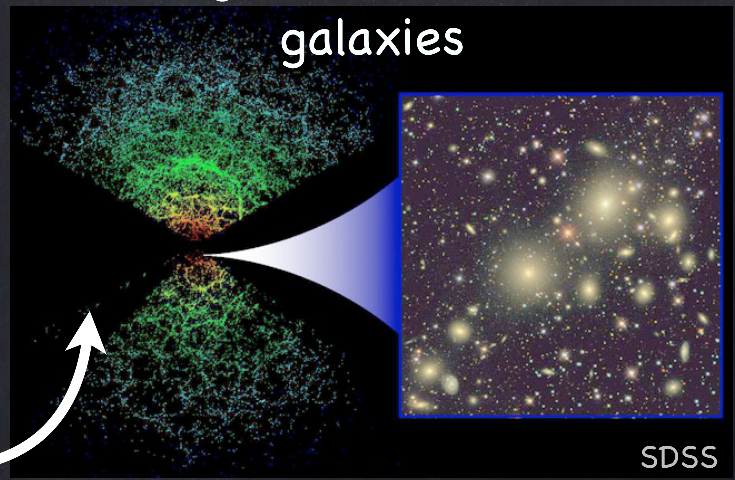
inflation



(Kravtsov)

gravitational collapse

stars, galaxies, clusters of galaxies



Structure in the Universe

The Thermal History of the Universe

The Universe is expanding,

10^{-12} 10^{-9} 10^{-3} 10^{-1} 1

"size" of universe
compared to today

Structure in the Universe

The Thermal History of the Universe

The Universe is expanding,

10^{-12} 10^{-9} 10^{-3} 10^{-1} 1

"size" of universe compared to today

and cooling,

hotter 10^{13} K 10^{9} K 10,000 K colder 3 K

temperature

Structure in the Universe

The Thermal History of the Universe

The Universe is expanding,

10^{-12} 10^{-9} 10^{-3} 10^{-1} 1

"size" of universe compared to today

and cooling.

hotter 10^{13} K 10^{9} K 10,000 K colder 3 K

temperature

and the matter in the Universe changes states as the universe cools

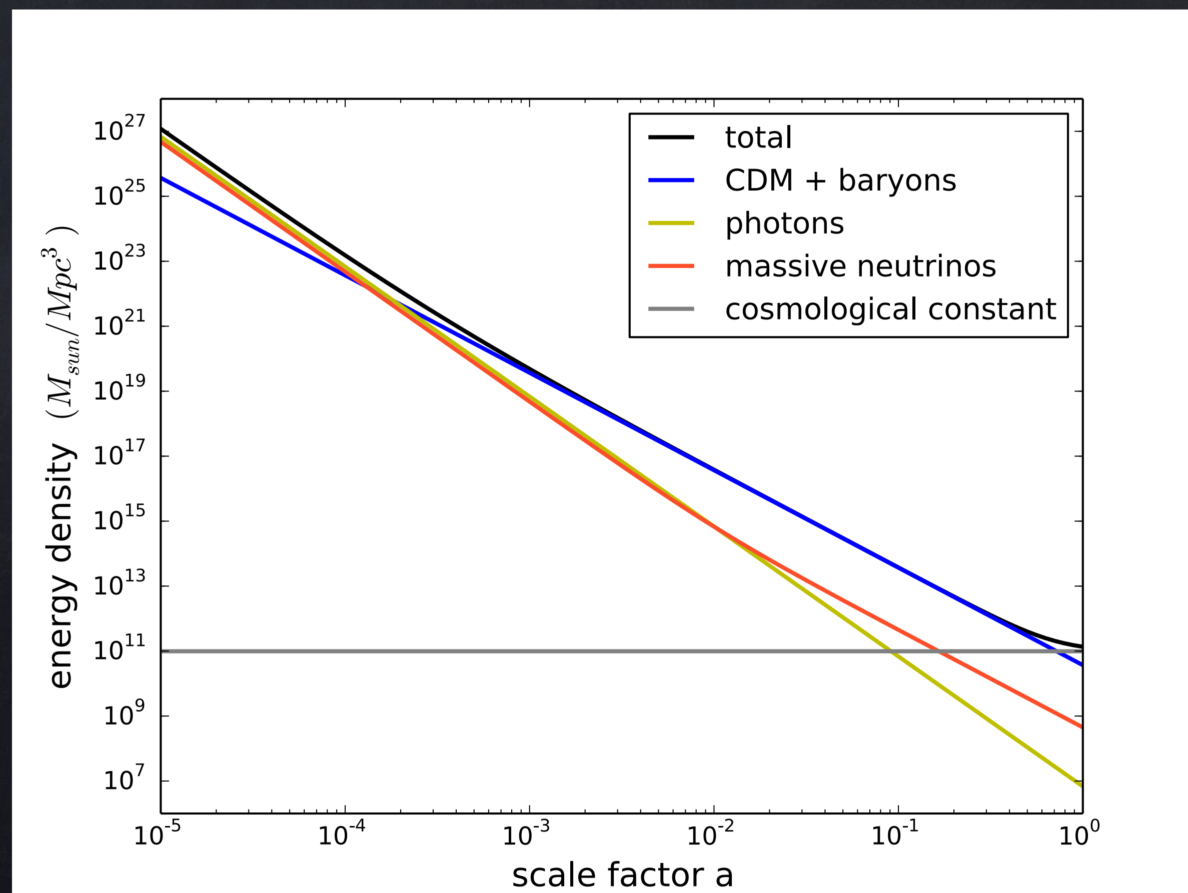
Structure in the Universe

The Expansion History of the Universe

10^{-12} 10^{-9} 10^{-3} 10^{-1} 1

a = "size" of universe compared to today

The energy density of different types of matter dilutes differently as the Universe expands



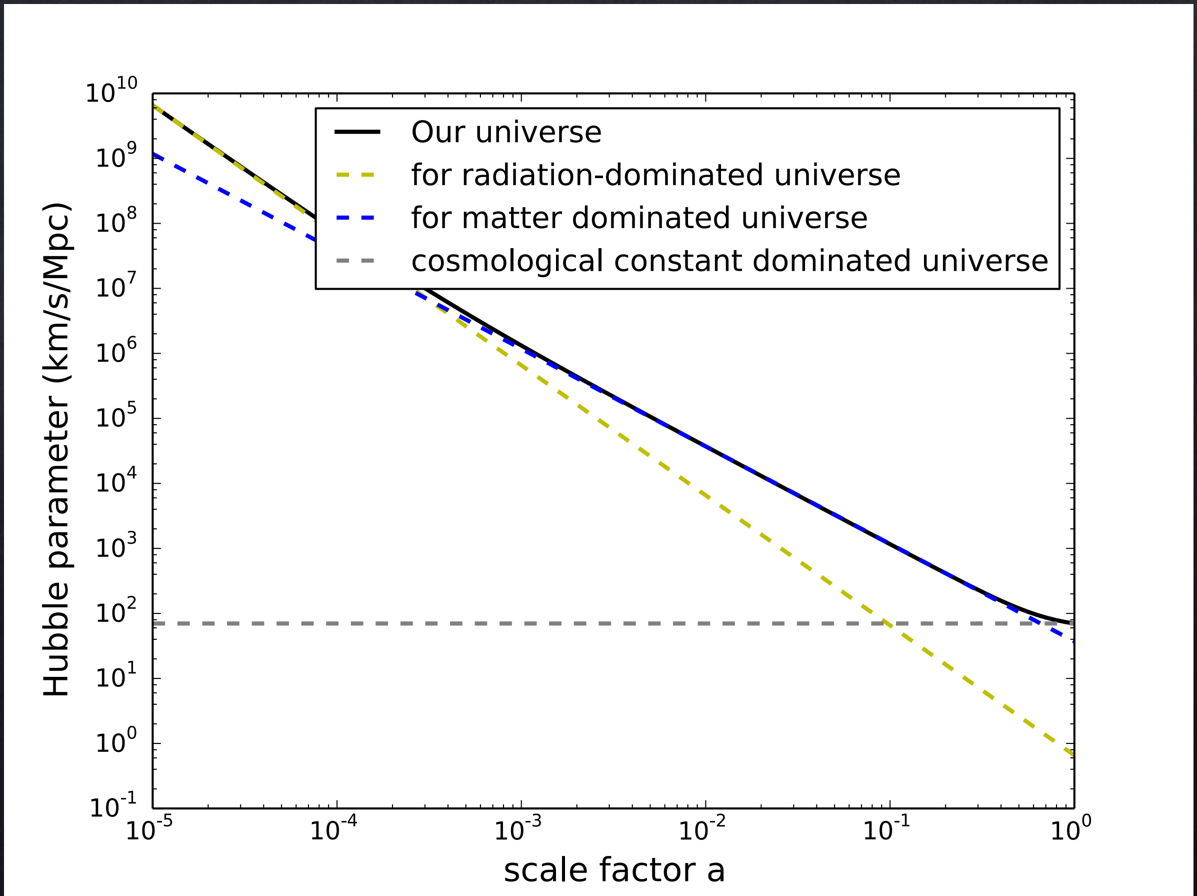
Structure in the Universe

The Expansion History of the Universe

10^{-12} 10^{-9} 10^{-3} 10^{-1} 1

a = "size" of universe compared to today

And the different types of matter gravitate differently, so the expansion rate changes throughout the history of the universe



Structure in the Universe

The History of Structure in the Universe

gravitational evolution of perturbations in
cold dark matter density $\delta\rho/\rho$

time

Structure in the Universe

The History of Structure in the Universe

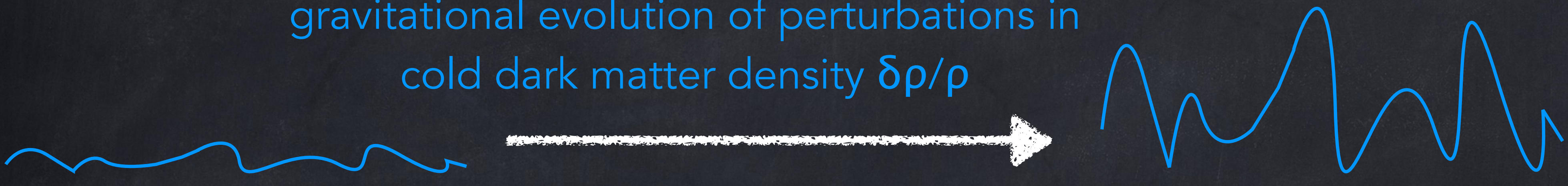
gravitational evolution of perturbations in
cold dark matter density $\delta\rho/\rho$

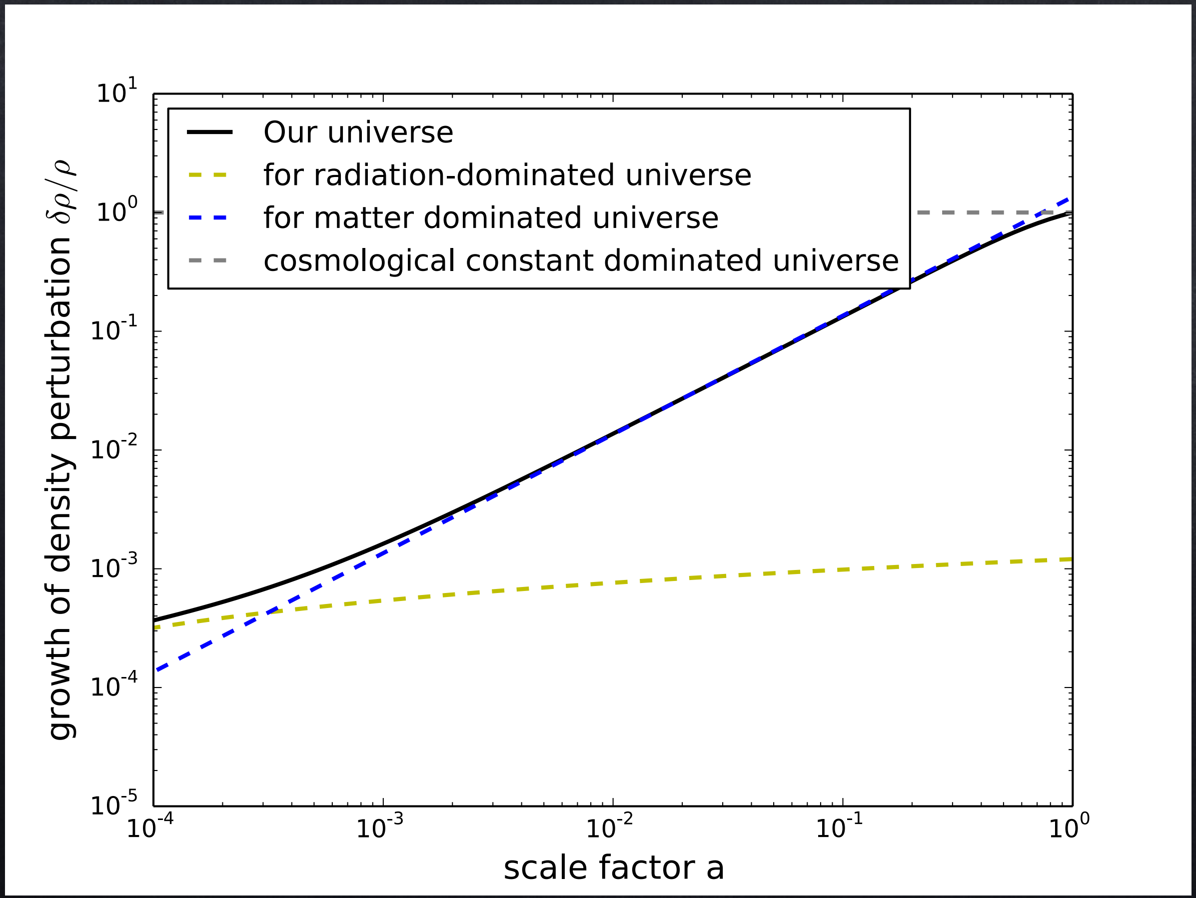
Self-gravity of perturbations competes with expansion of the Universe

Structure in the Universe

The History of Structure in the Universe

gravitational evolution of perturbations in
cold dark matter density **δρ/ρ**

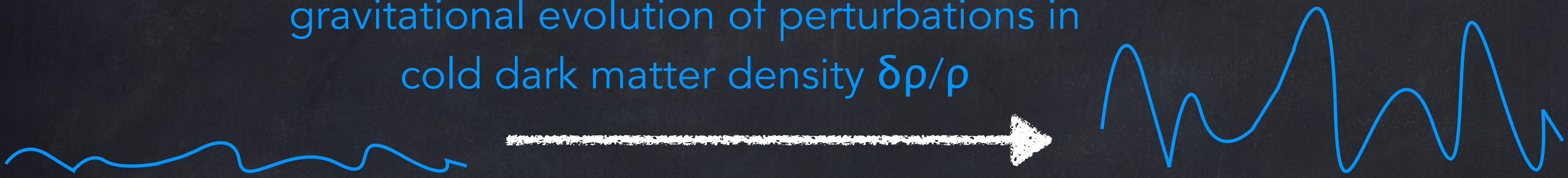


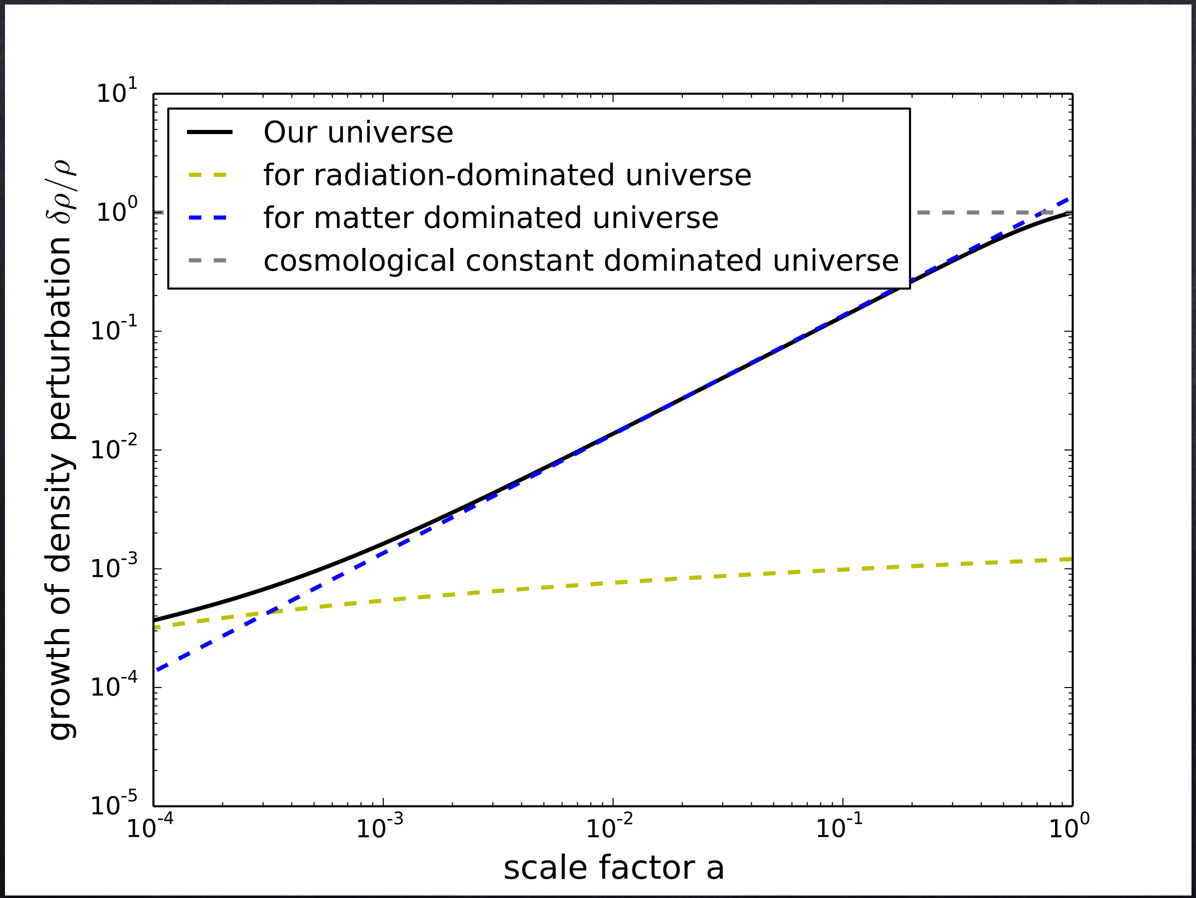


Structure in the Universe

The History of Structure in the Universe

gravitational evolution of perturbations in cold dark matter density $\delta\rho/\rho$

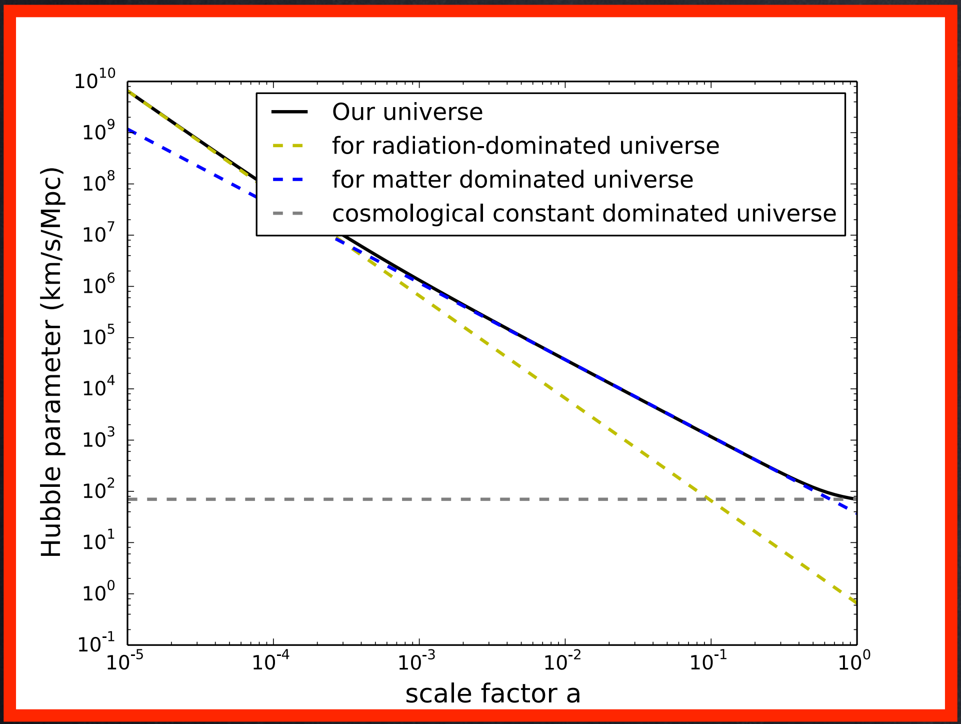




evolution of $\delta\rho/\rho$ depends on expansion rate of the Universe

Structure in the Universe

The History of Structure in the Universe



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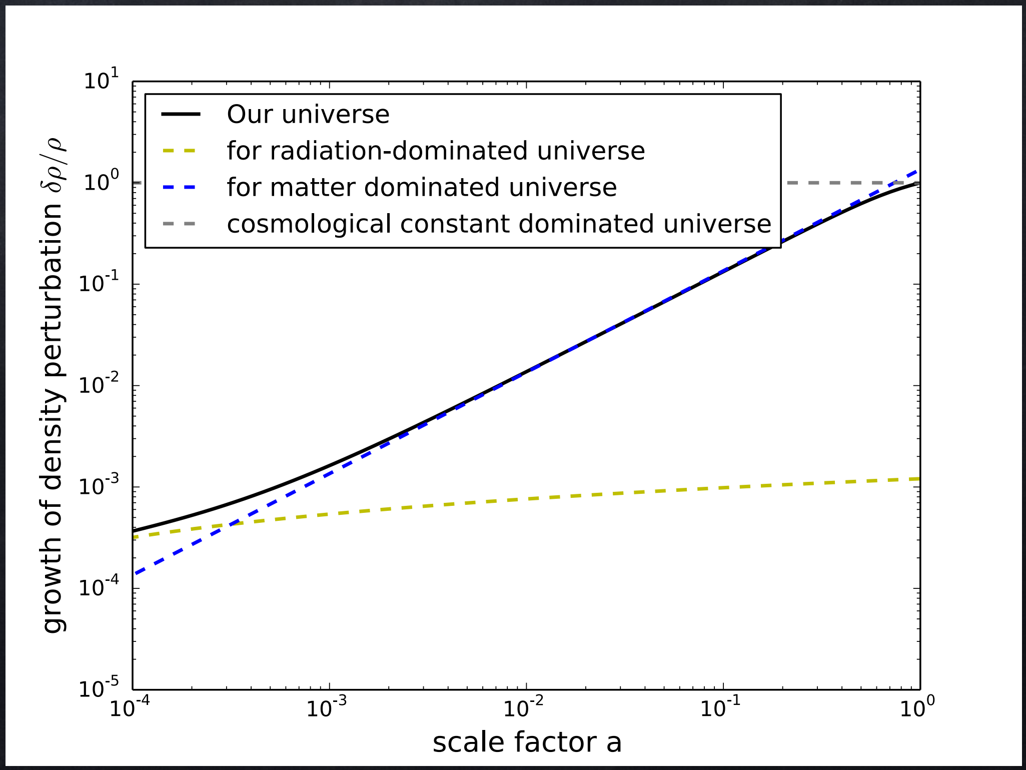
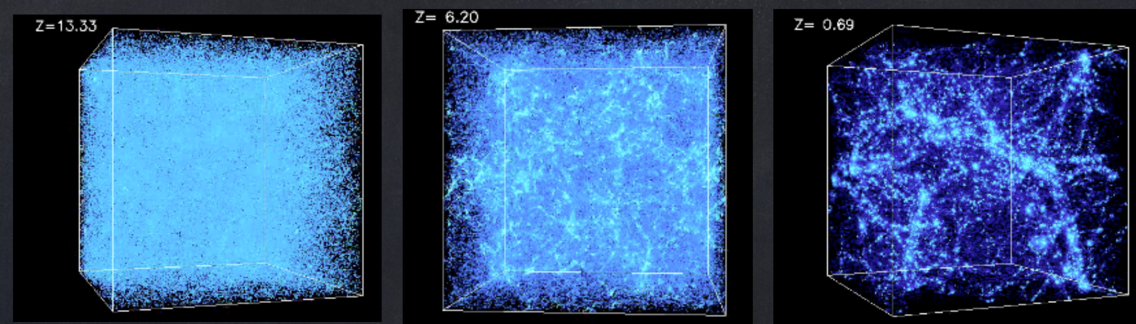
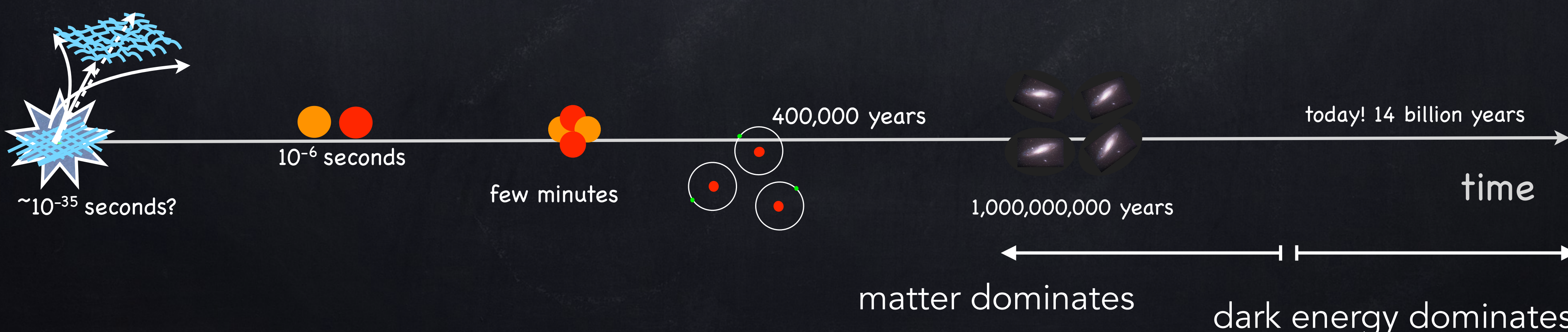


Structure in the Universe

History of Structure in the Universe: Summary

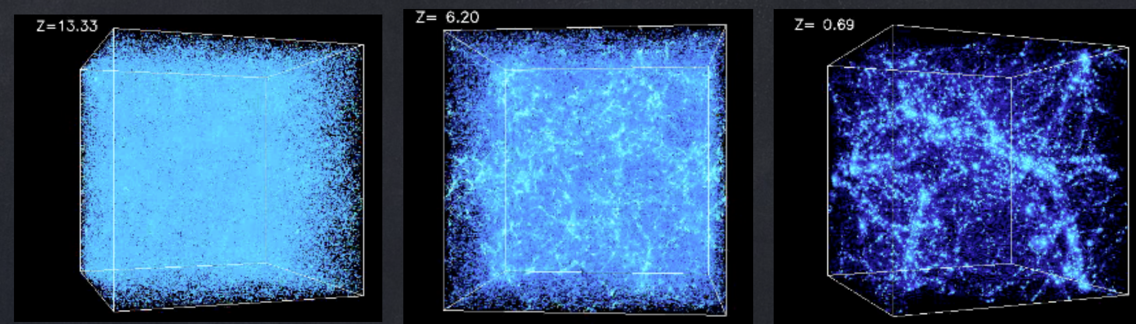


(Kravtsov)



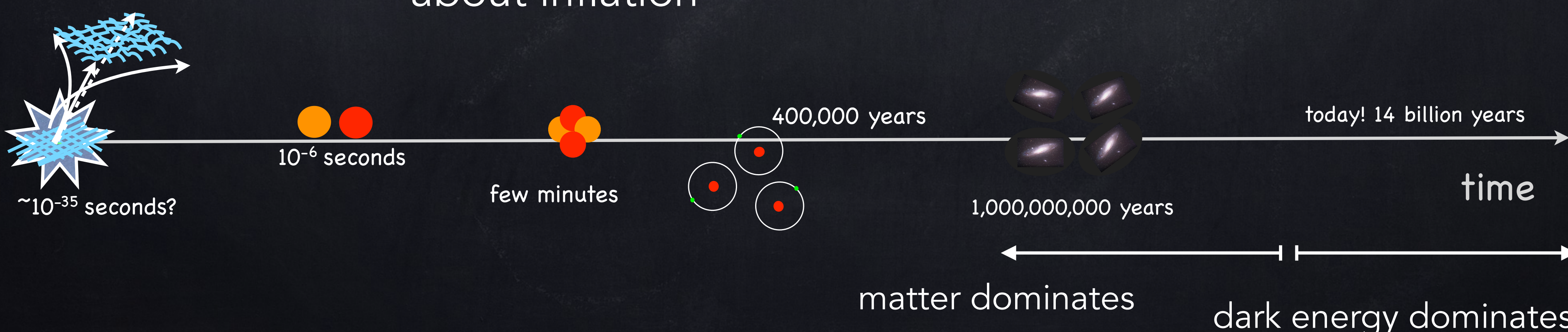
Structure in the Universe

History of Structure in the Universe: Summary



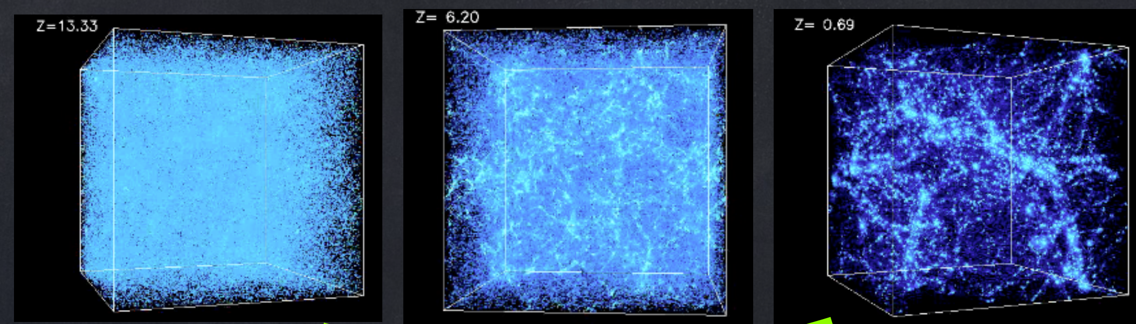
(Kravtsov)

initial density perturbations tell us about inflation



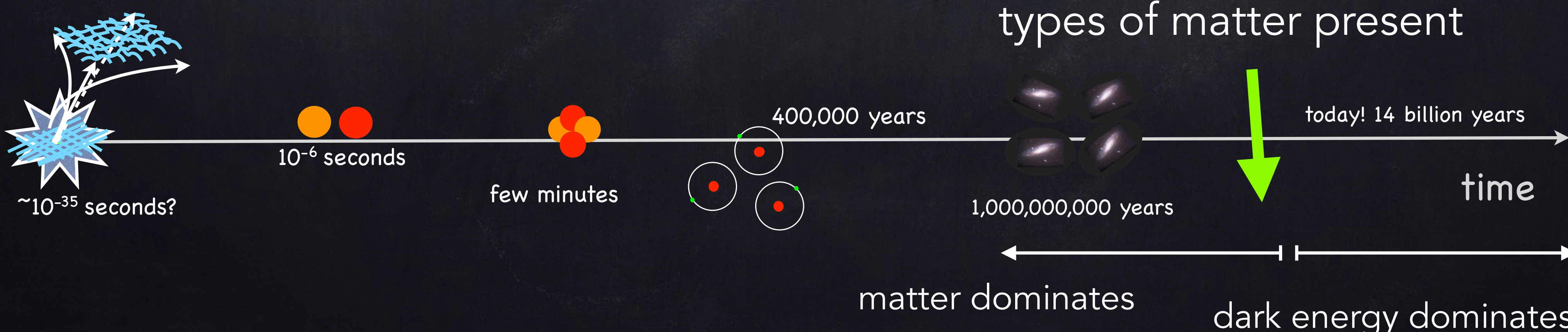
Structure in the Universe

History of Structure in the Universe: Summary



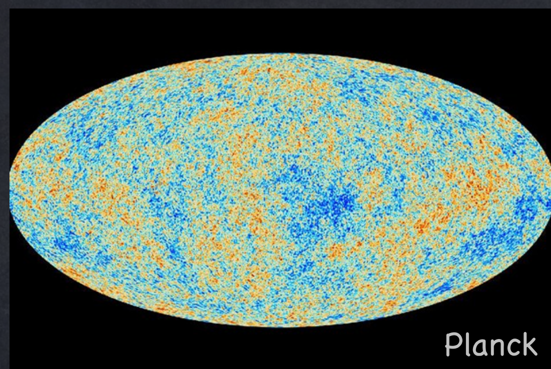
(Kravtsov)

evolution of density perturbations tells us about dark energy & types of matter present

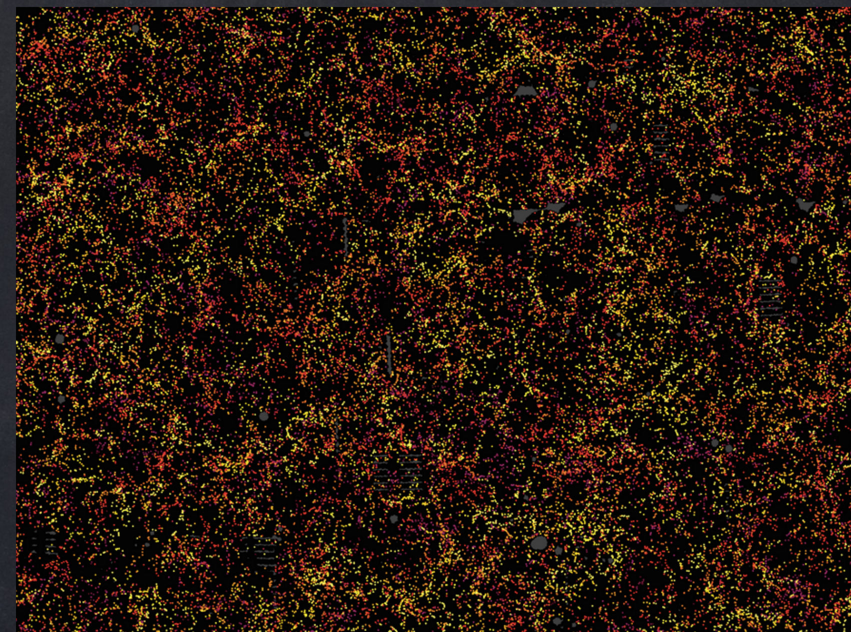


Structure in the Universe

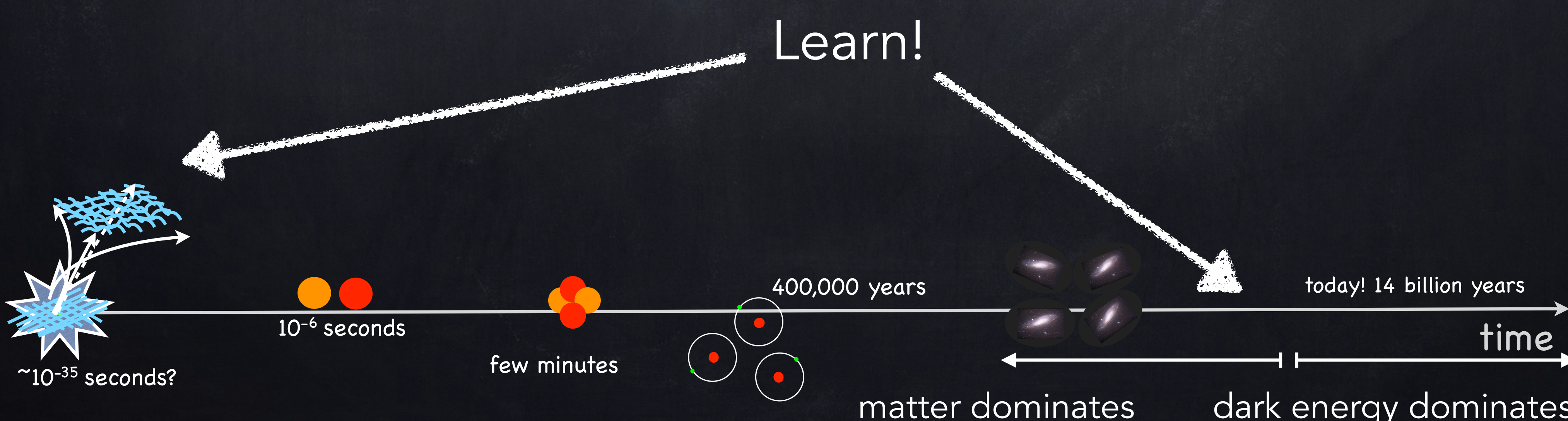
Cosmic Microwave Background Anisotropy



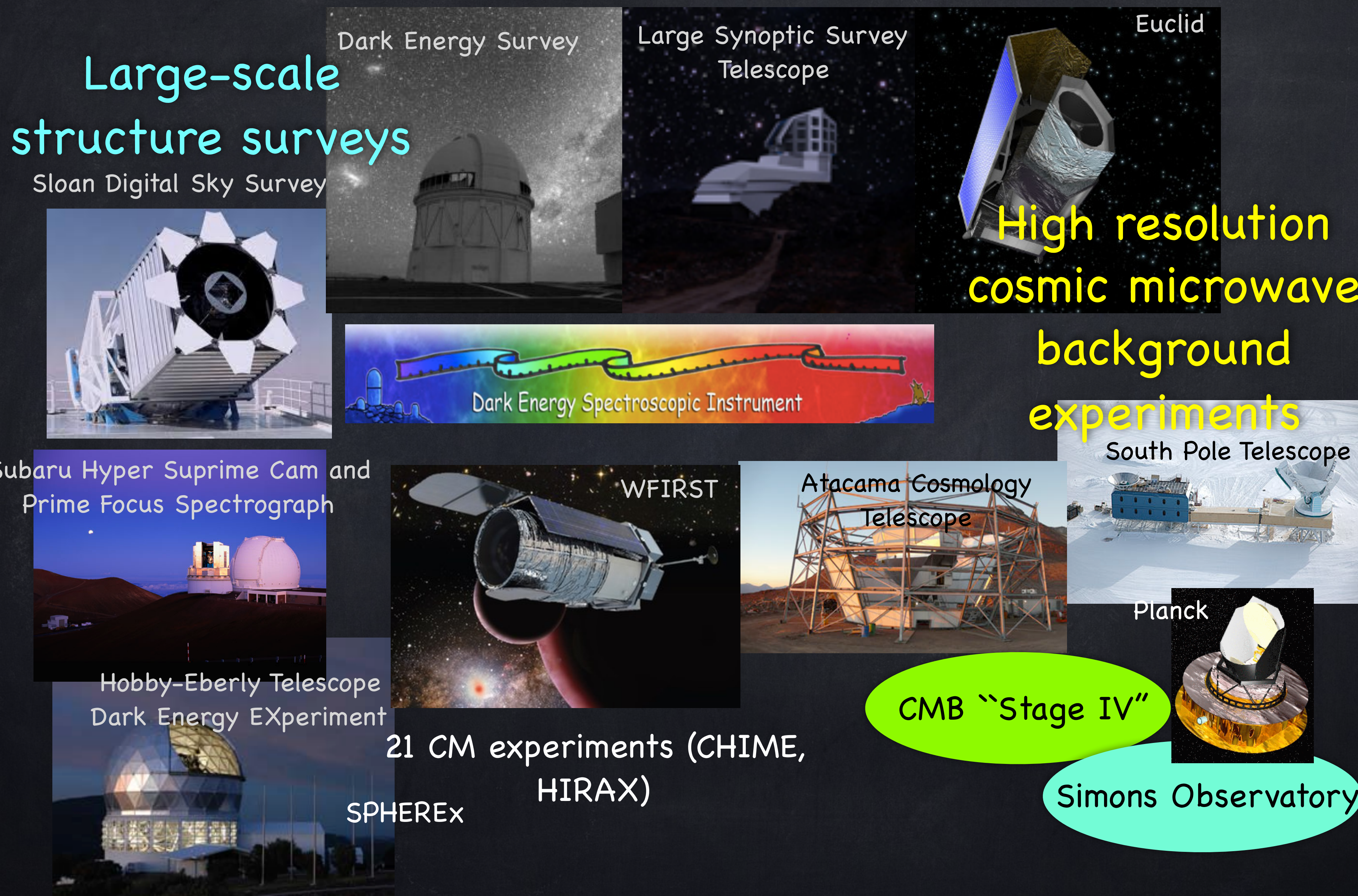
Galaxy Distribution Mapped by SDSS



Eisenstein and SDSS Collaboration



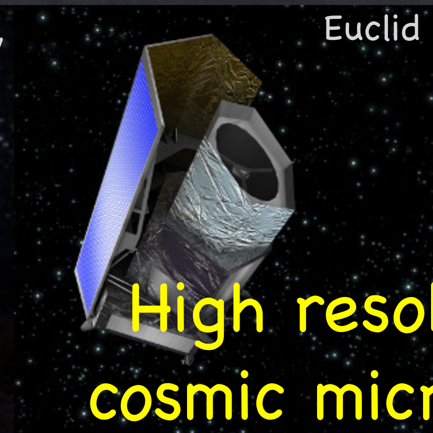
Many opportunities to learn about structure!



Many opportunities to learn about structure!

Large-scale structure surveys

Sloan Digital Sky Survey

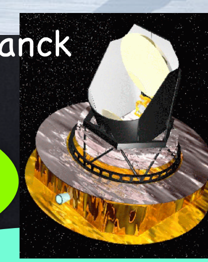


SPHEREx

21 CM experiments (CHIME, HIRAX)

High resolution cosmic microwave background experiments

Planck



CMB ``Stage IV"

Simons Observatory

And much to learn! (inflation, dark energy, neutrino properties)

Recap: The evolution of structure depends on the expansion history of the Universe

Large-scale Structure Beyond Cold Dark Matter

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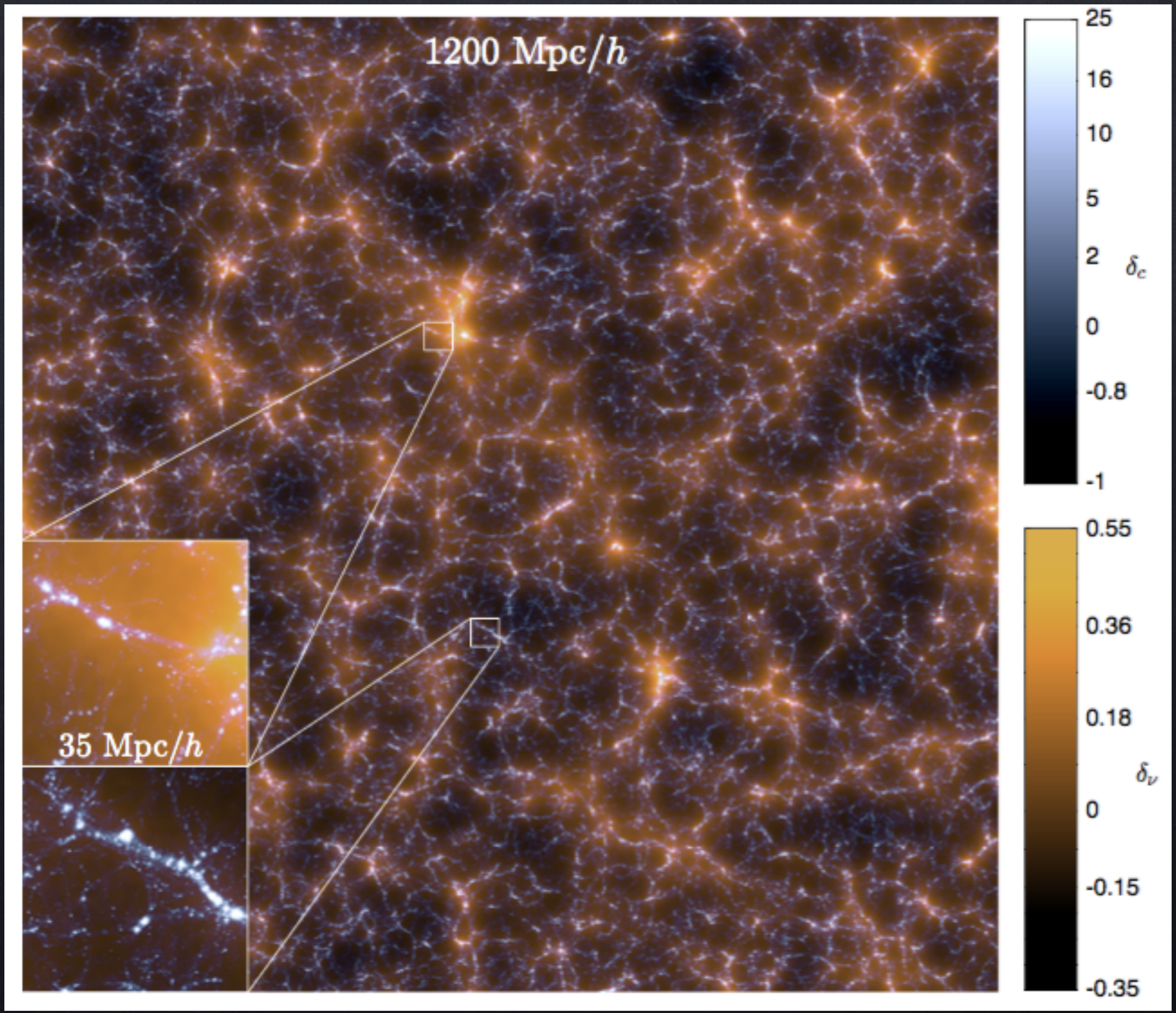
(I) Massive Neutrinos

Large-scale Structure Beyond Cold Dark Matter

(I) Massive Neutrinos



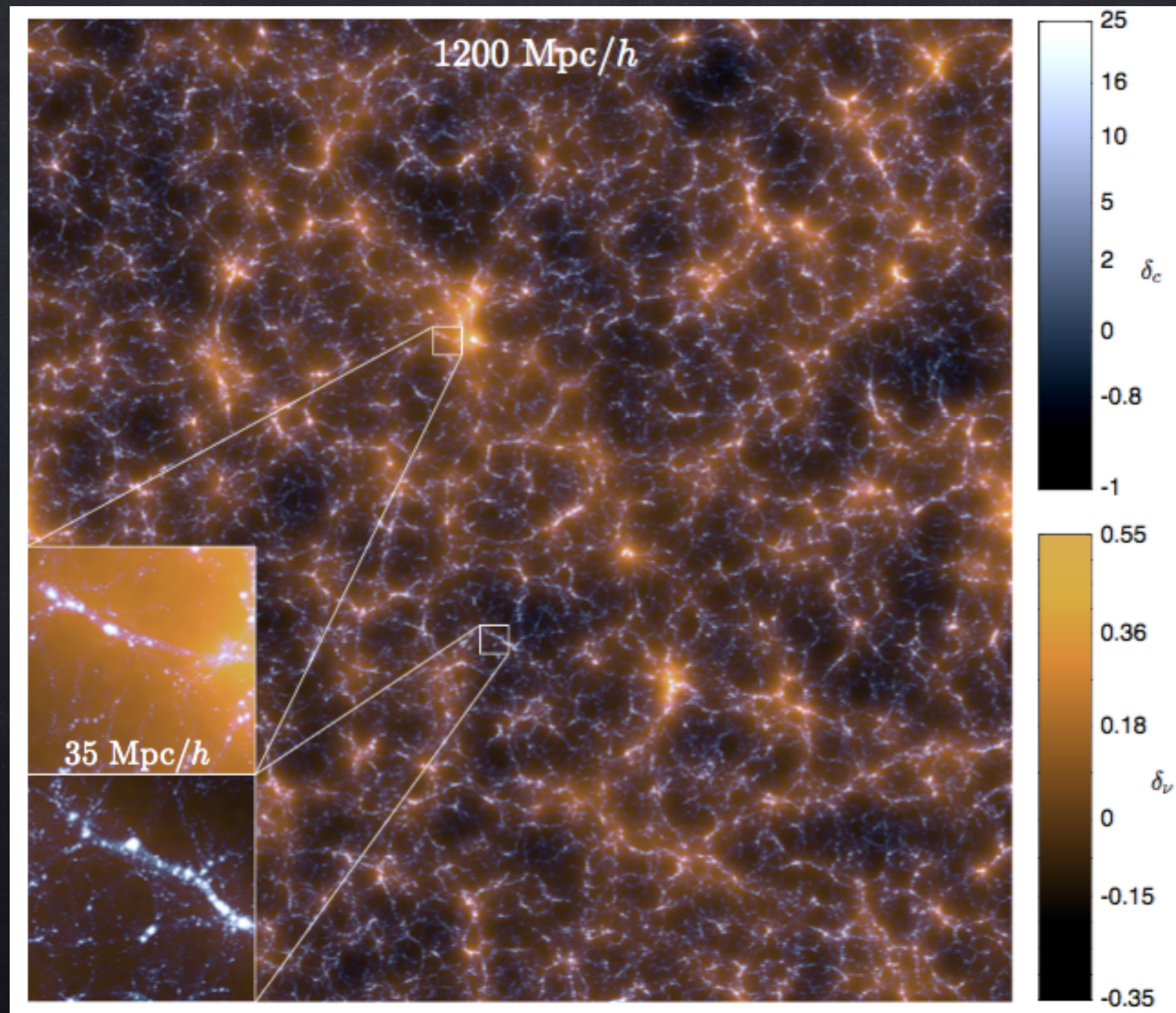
(TianNu simulation, Yu et al 2016)

Large-scale Structure Beyond Cold Dark Matter

(I) Massive Neutrinos

$$\frac{\rho_\nu}{\rho_{cdm} + \rho_{baryon} + \rho_\nu} \gtrsim 0.005$$

$$n_\nu \sim 10^{10} n_{baryon}$$



(TianNu simulation, Yu et al 2016)

Large-scale Structure Beyond Cold Dark Matter

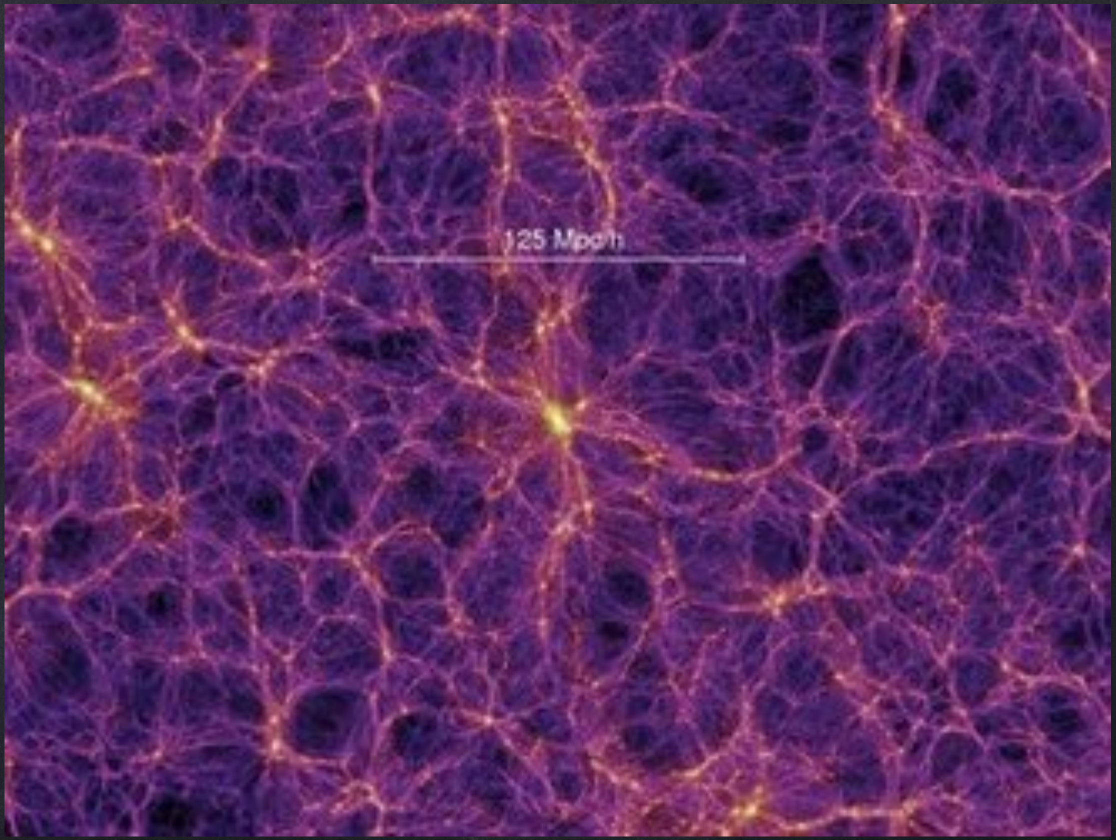
(II) Quintessence

Large-scale Structure Beyond Cold Dark Matter

(I) Quintessence

(scalar field dark energy)

$\rho_{\text{dark energy}} \sim \rho_{\text{matter}}$



(Springel)

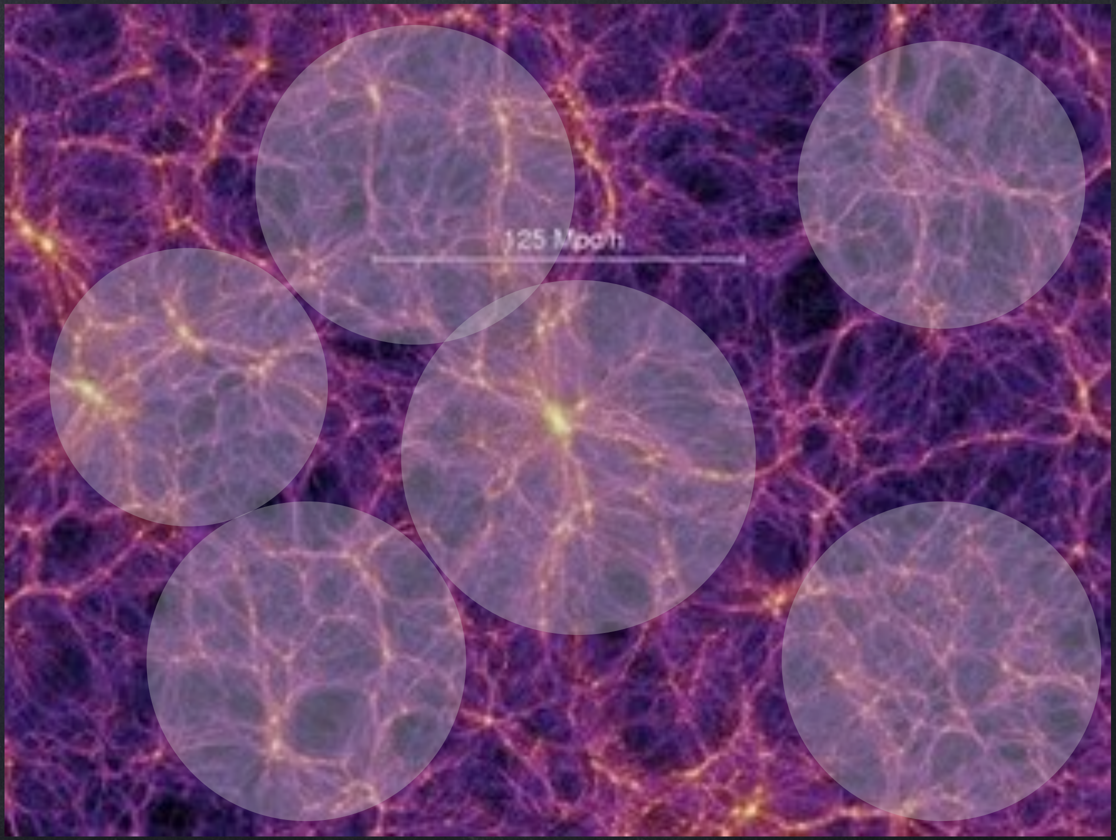
Large-scale Structure Beyond Cold Dark Matter

(I) Quintessence

(scalar field dark energy)

$\rho_{\text{dark energy}} \sim \rho_{\text{matter}}$

could dark energy cluster too?

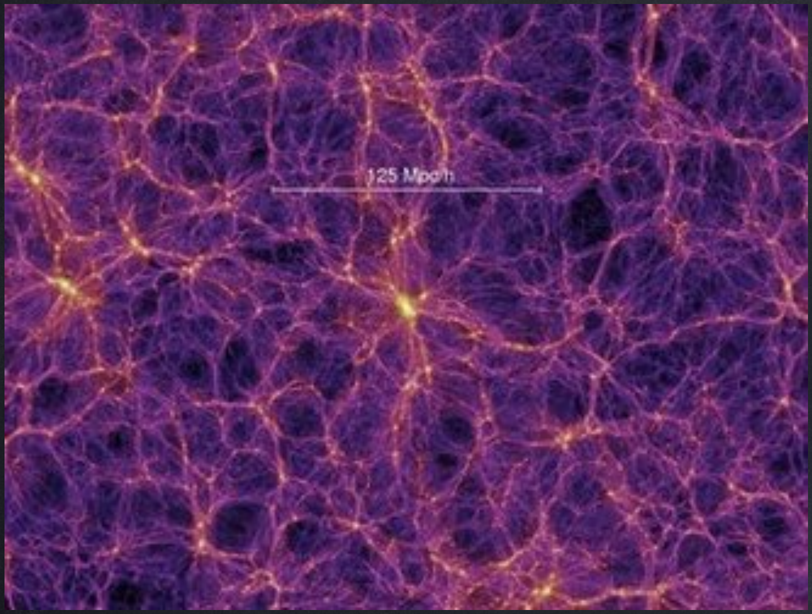


(Springel)

The Formation of (nonlinear) Structure

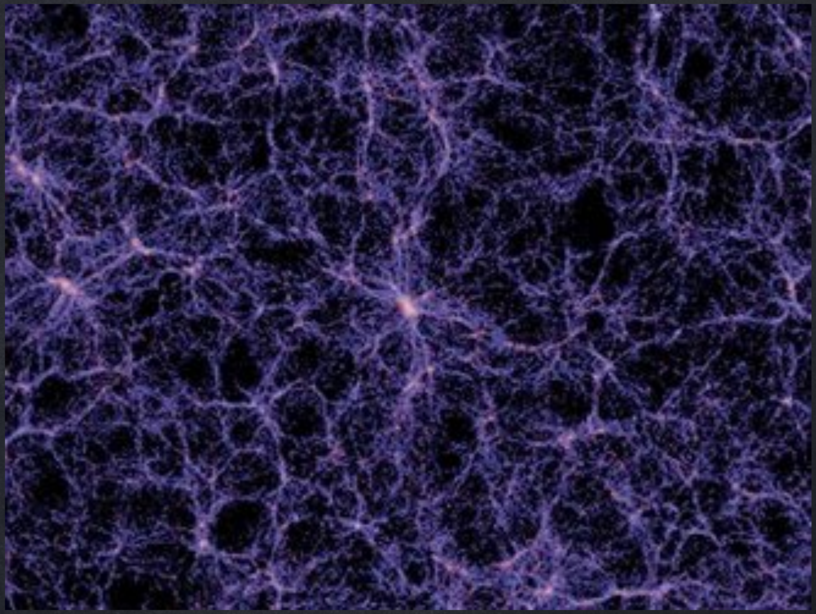
Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



(Springel)

galaxy distribution $\delta_g = \delta n_g/n_g$



(Springel)

Large-scale Structure

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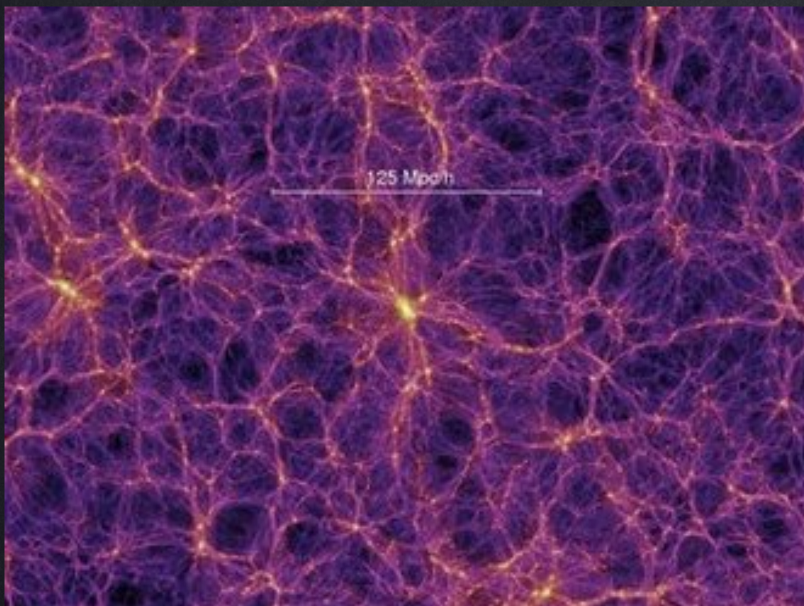

(Springel)

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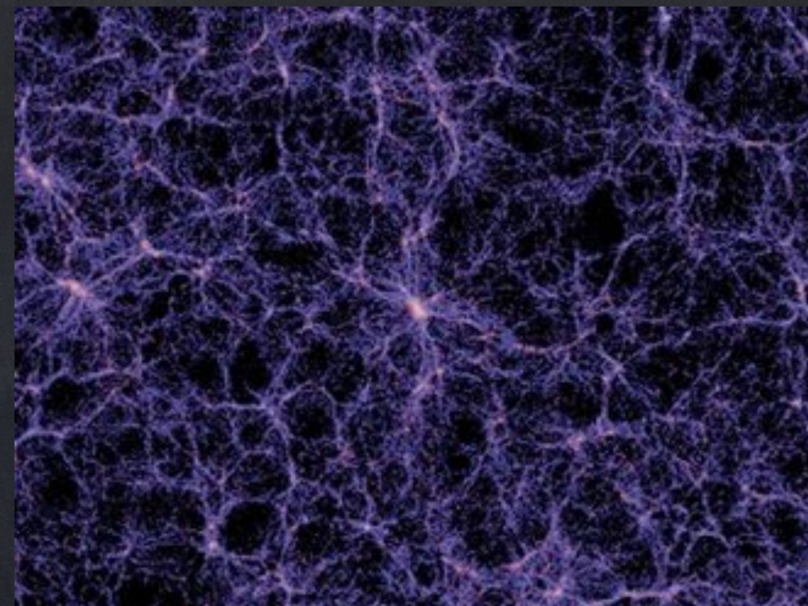
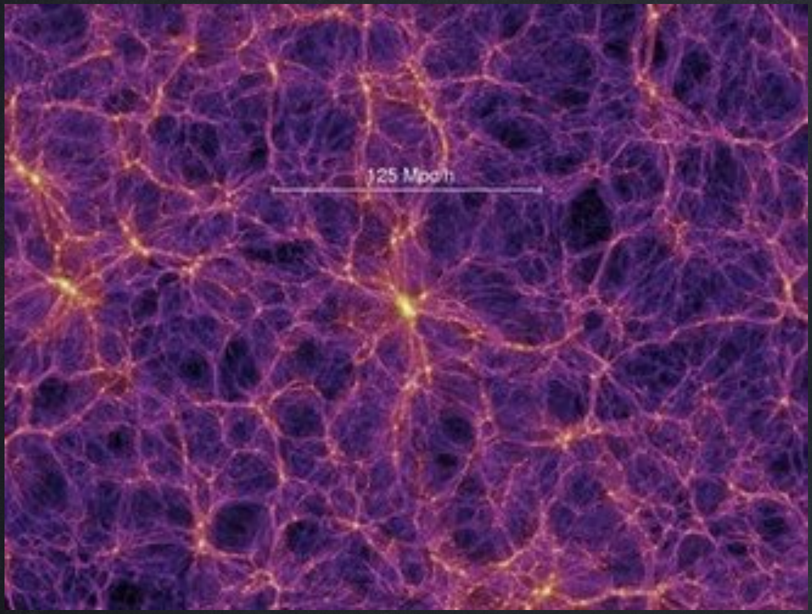


(Springel)

matter = cold dark matter (CDM), baryons (behaves like CDM, mostly), massive neutrinos, . . . ?!

Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



(Springel)

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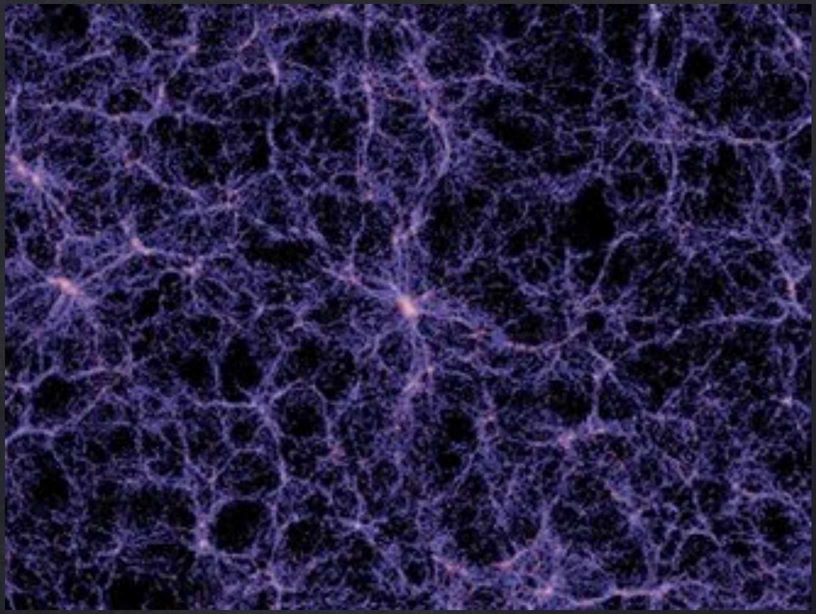
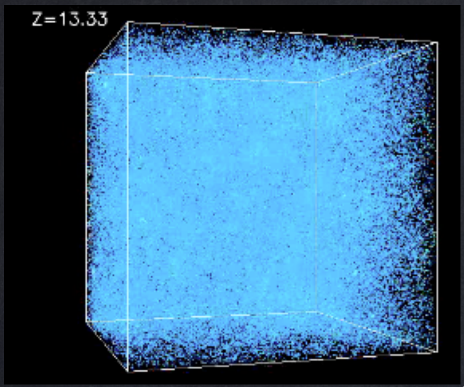
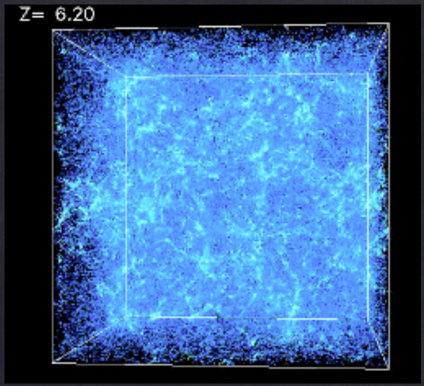


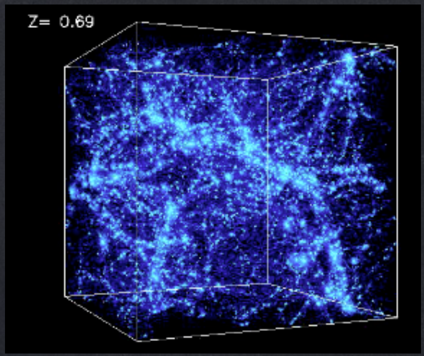
(Springel)

Accurate models of the large-scale matter distribution, and the large-scale galaxy distribution are <u>crucial</u> for extracting cosmological information from cosmological datasets

Large-scale Structure

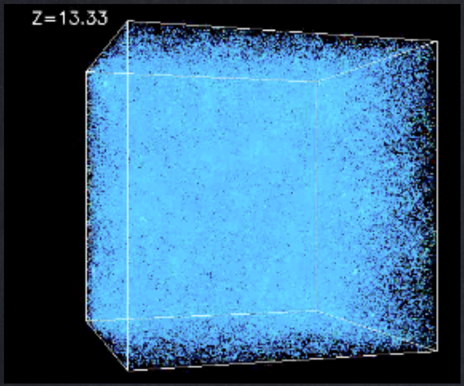


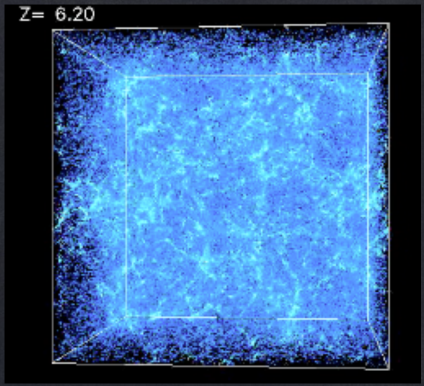


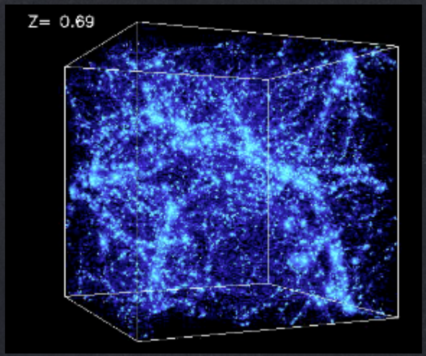


when matter density fluctuations are small, can linearize the equations and gravitational evolution is easy

Large-scale Structure



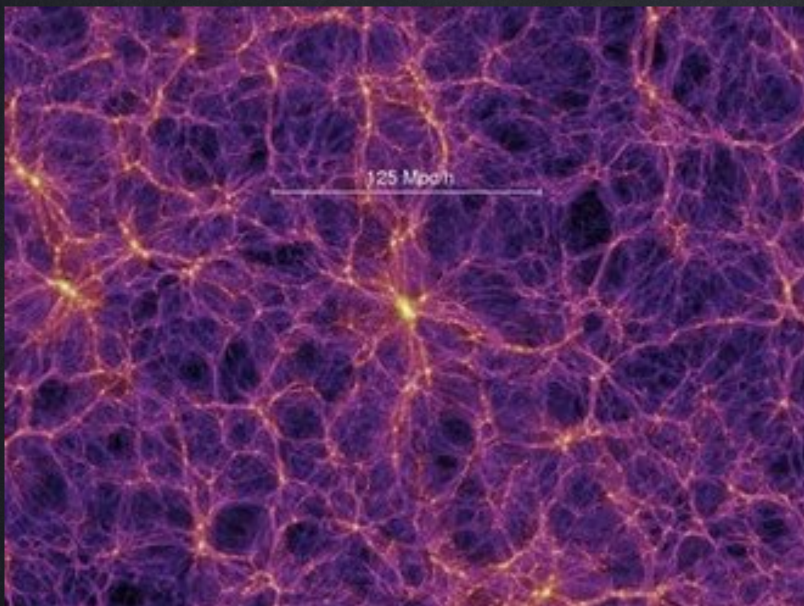




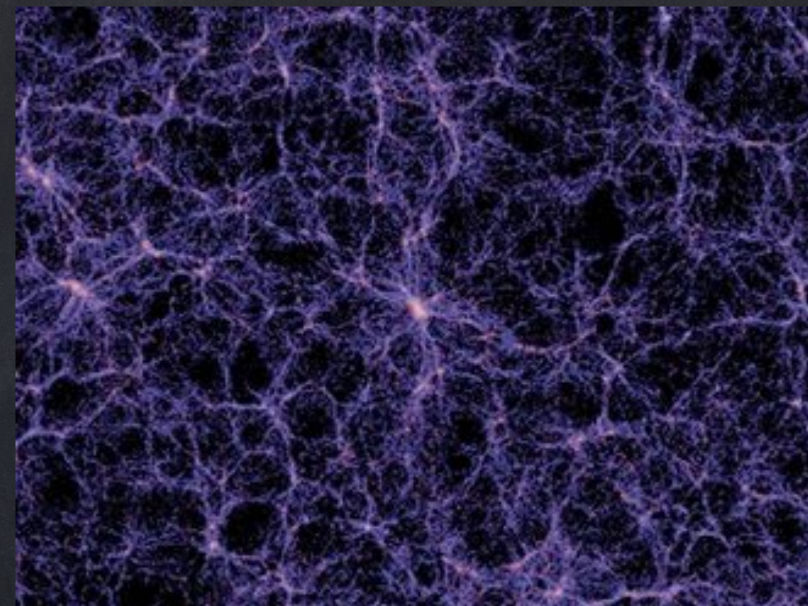
when matter density fluctuations become large ($\delta\rho/\rho \sim 1$) gravity couples modes, evolution is hard! Need simulations or tricks

Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



galaxy distribution $\delta_g = \delta n_g/n_g$

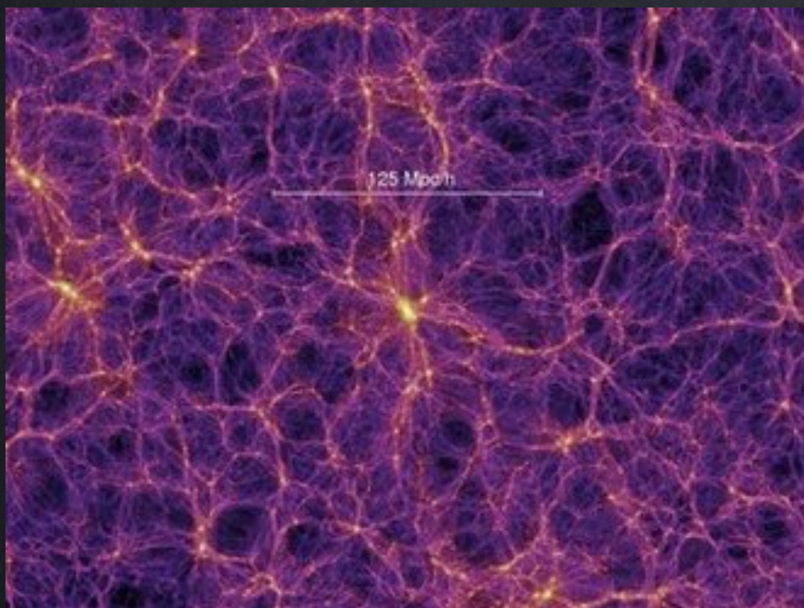


(Springel)

A particularly hard thing to understand is relationship between *galaxy* distribution and the *matter* distribution

Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



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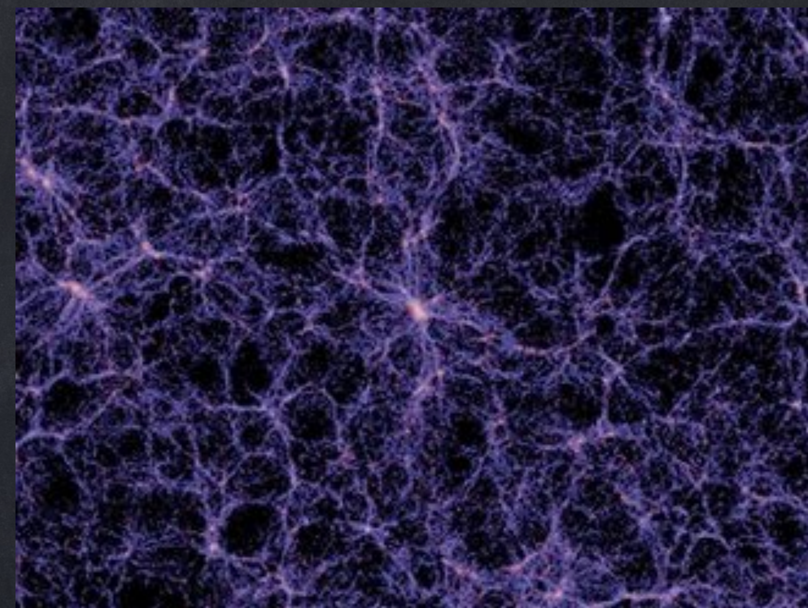


(Springel)

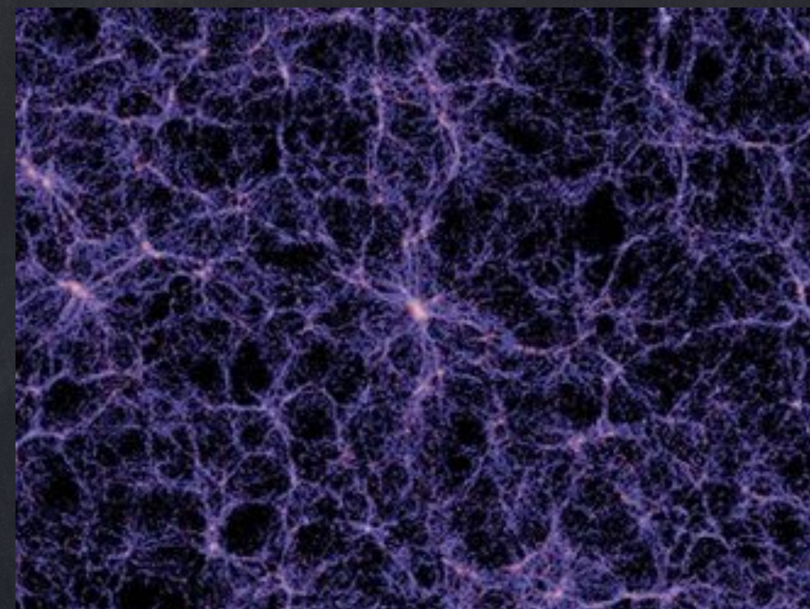
Understanding the relationship between the galaxies and the matter is even harder when there is more than one type of matter around!

(e.g. our universe! which, at least has neutrino dark matter and possibly dynamical dark energy or quintessence)

Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$

galaxy distribution $\delta_g = \delta n_g/n_g$



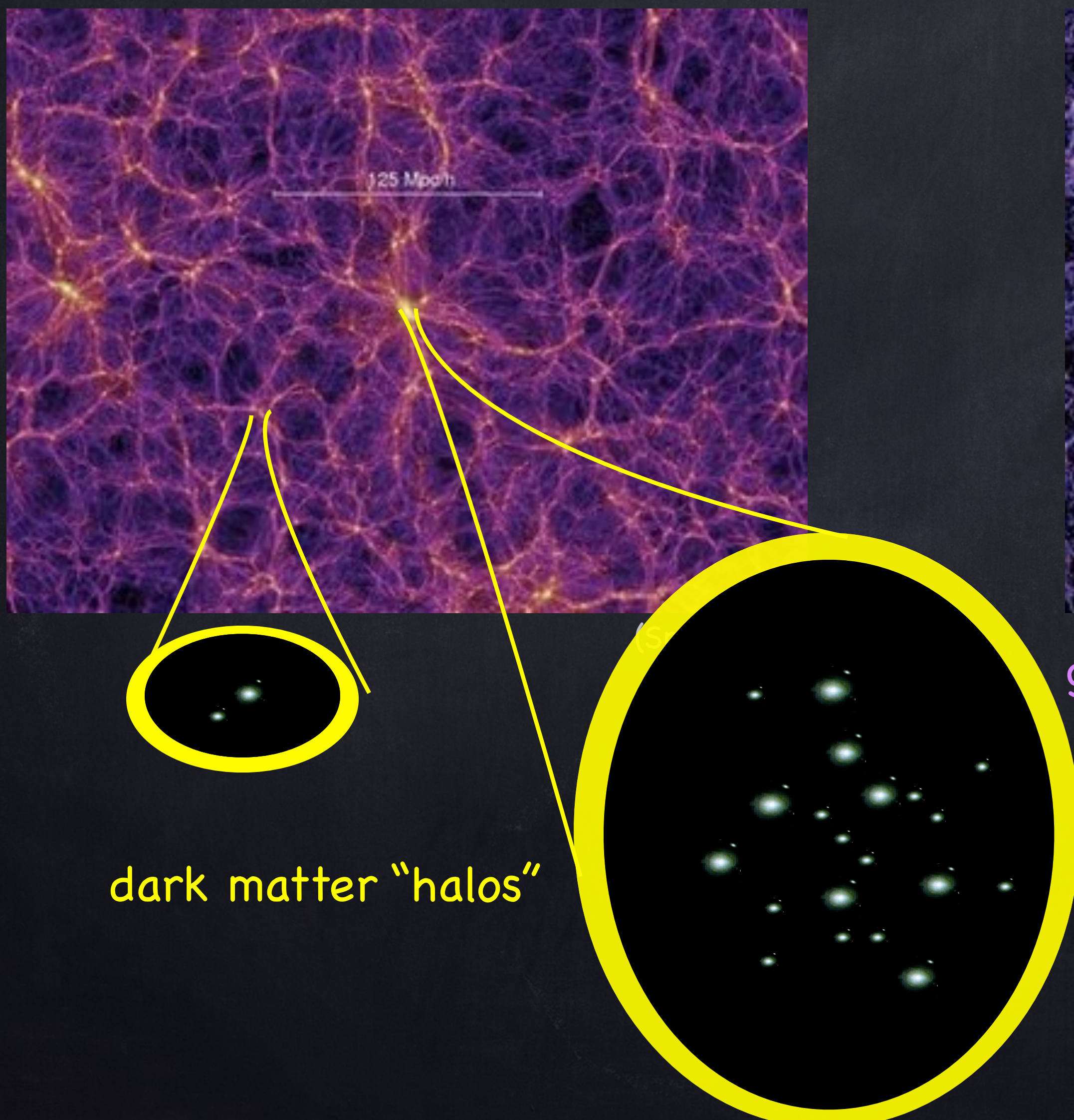
(Springel)

An intermediate step

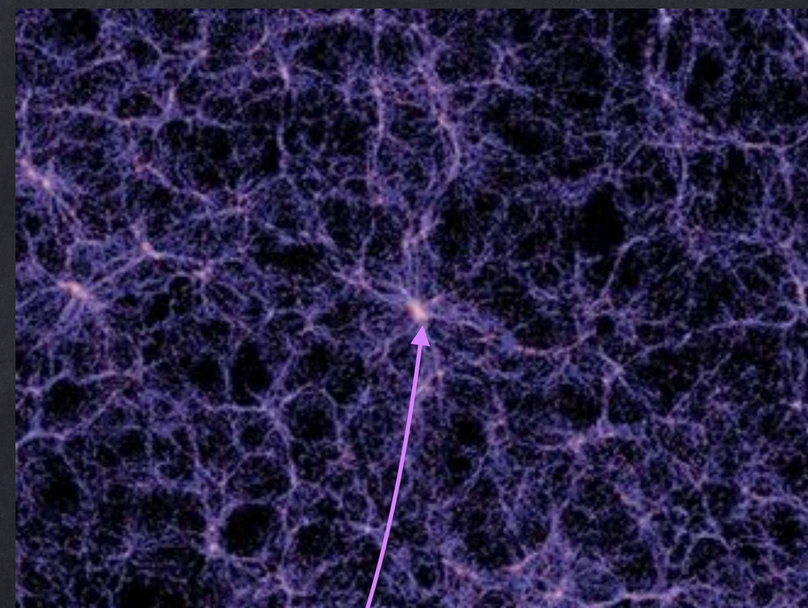
Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$

galaxy distribution $\delta_g = \delta n_g/n_g$



dark matter "halos"



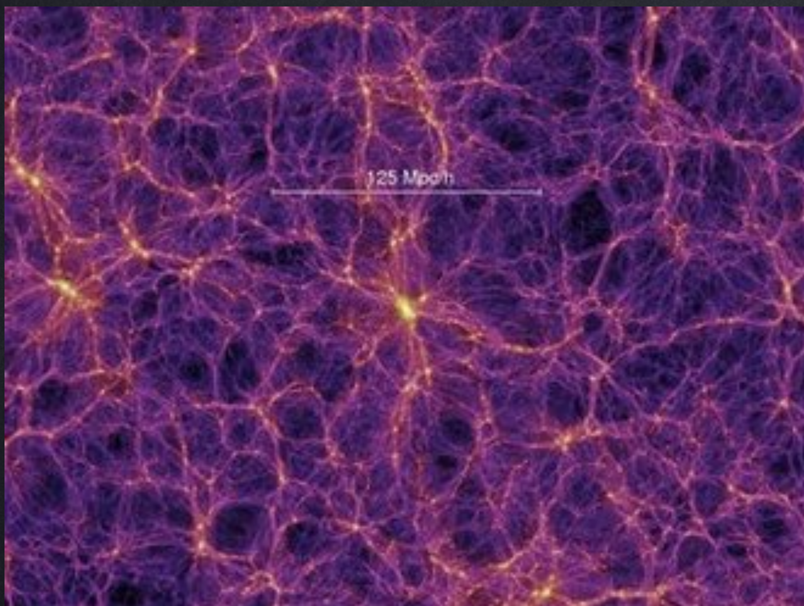
(Springel)

galaxies live in halos

An intermediate step

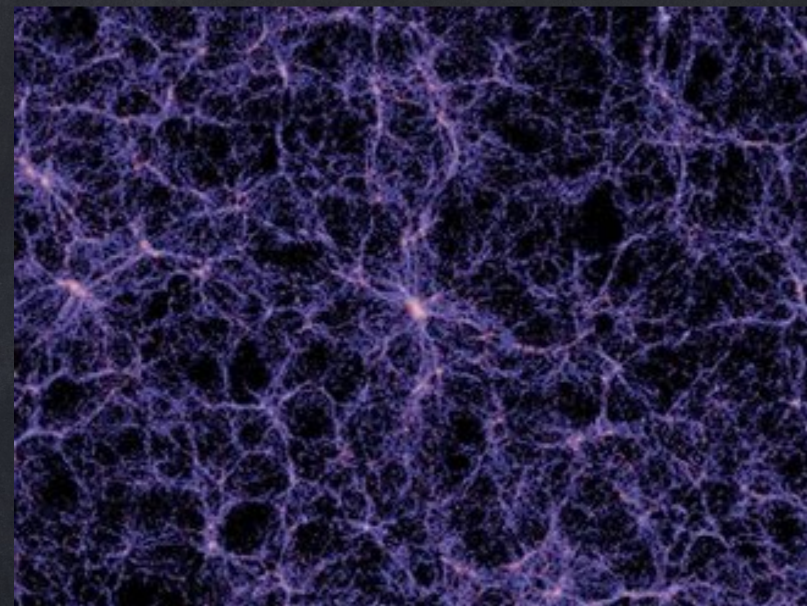
Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



(Springel)

galaxy distribution $\delta_g = \delta n_g/n_g$



(Springel)

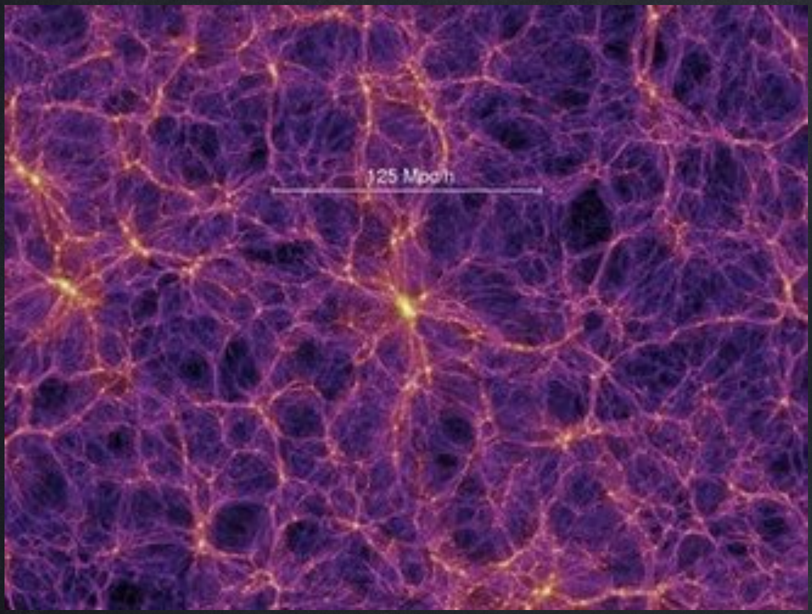
on large scales, halos and galaxy abundances vary with matter density, but the fractional over/under-densities are not identical

$$n_g(x) = \overline{n}_g(1 + \delta_g(x)),\ \rho_m(x) = \overline{\rho}_m(1 + \delta_m(x))$$

$$\delta_g \approx \frac{d\ln n_g}{d\delta_m}\,\delta_m \approx b\,\delta_m$$

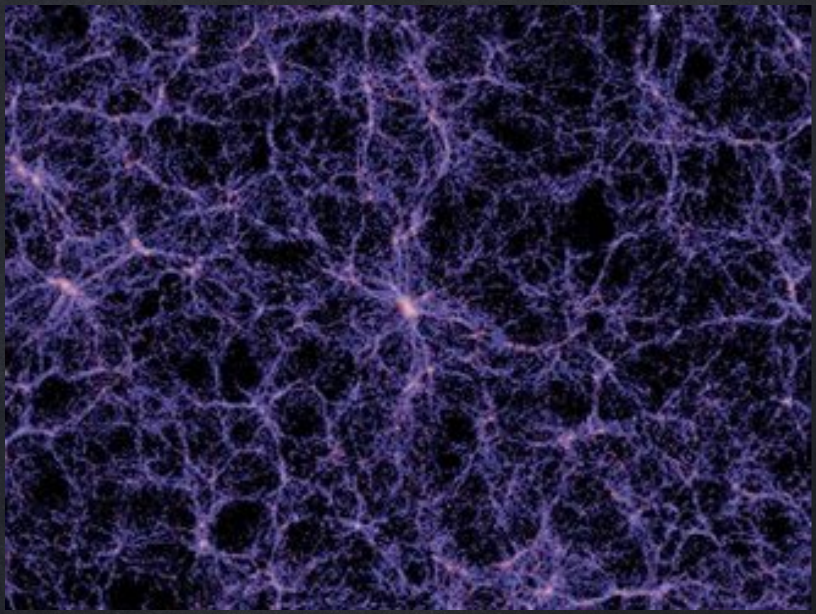
Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



(Springel)

galaxy distribution $\delta_g = \delta n_g/n_g$



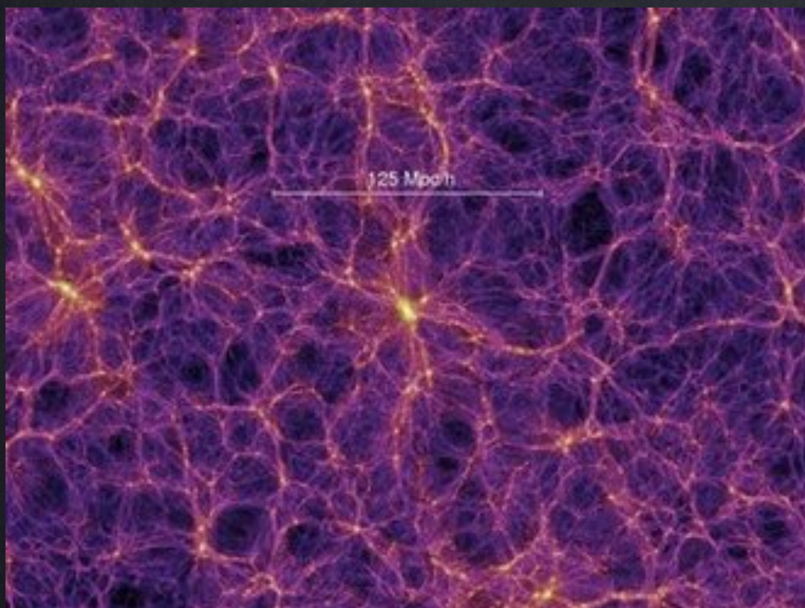
(Springel)

halos and galaxies are *biased* tracers of the matter distribution

$$\delta_g \approx \frac{d\ln n_g}{d\delta_m}\,\delta_m \approx b\,\delta_m$$

Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



(Springel)

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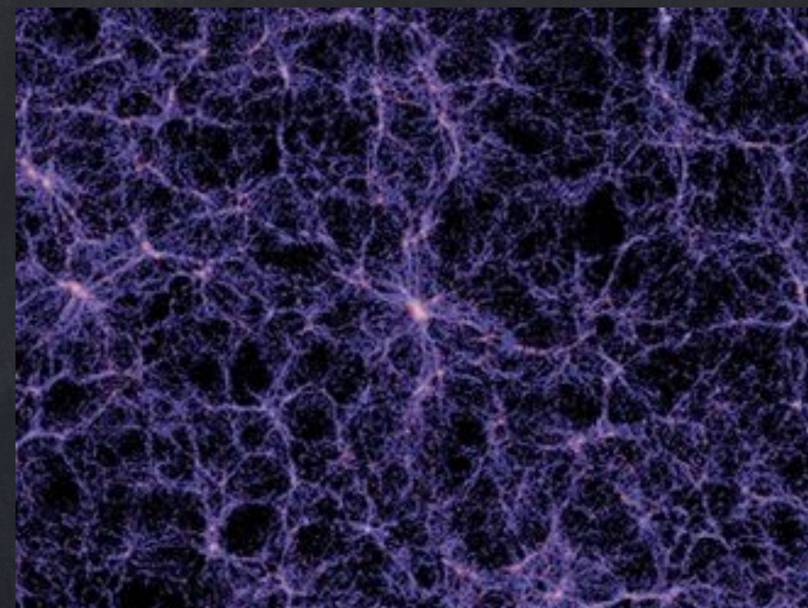


(Springel)

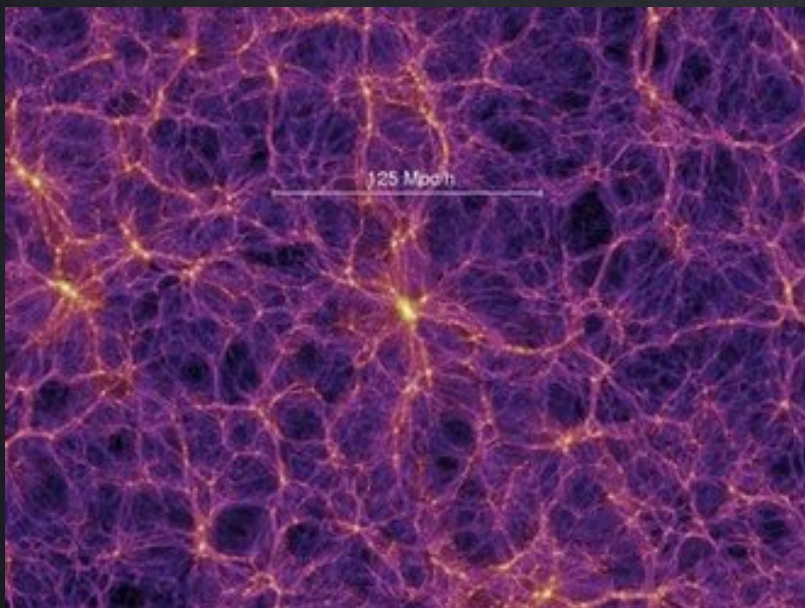
the bias

$$\delta_g \approx \frac{d\ln n_g}{d\delta_m}\,\delta_m \approx b\,\delta_m$$

halos and galaxies are *biased* tracers of the matter distribution

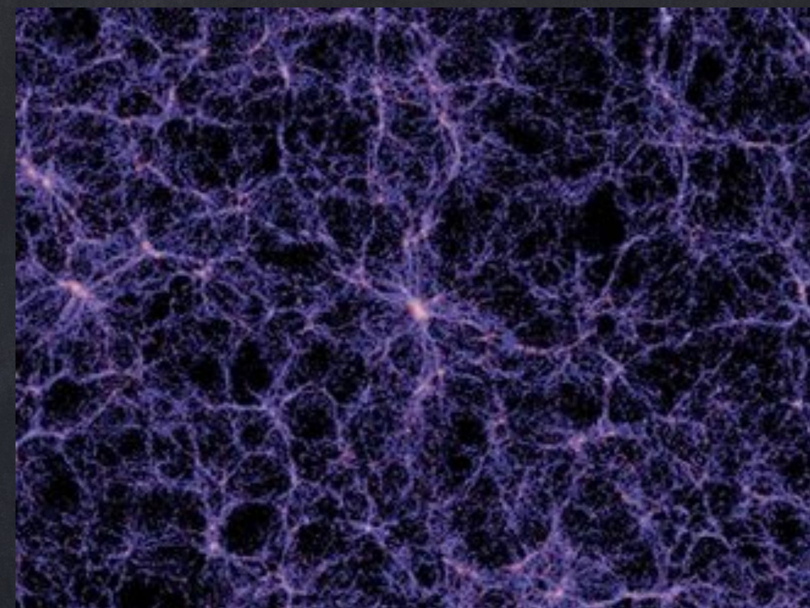
Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



(Springel)

galaxy distribution $\delta_g = \delta n_g/n_g$



(Springel)

the bias

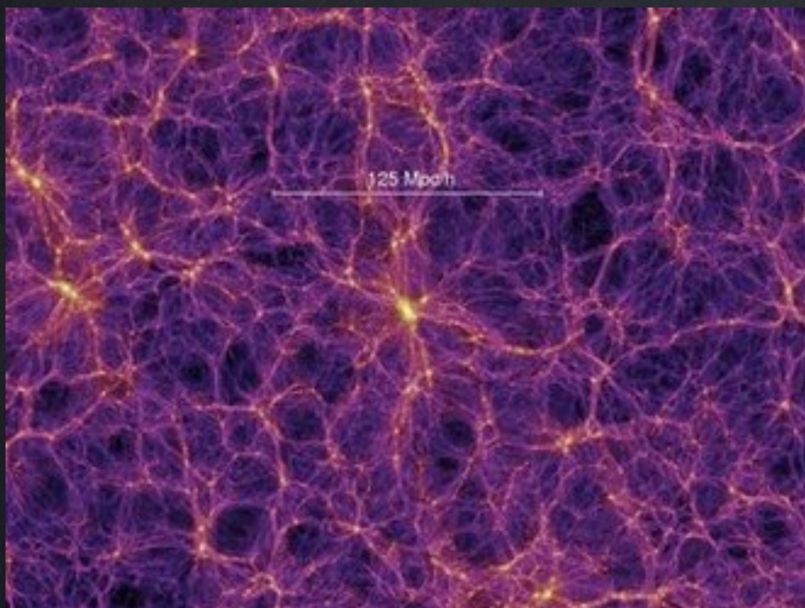
A parameter that depends on mass, luminosity or other properties of the tracer

$$\delta_g \approx \frac{d\ln n_g}{d\delta_m}\,\delta_m \approx b\,\delta_m$$

halos and galaxies are *biased* tracers of the matter distribution

Large-scale Structure

matter distribution $\delta_m = \delta\rho_m/\rho_m$



(Springel)

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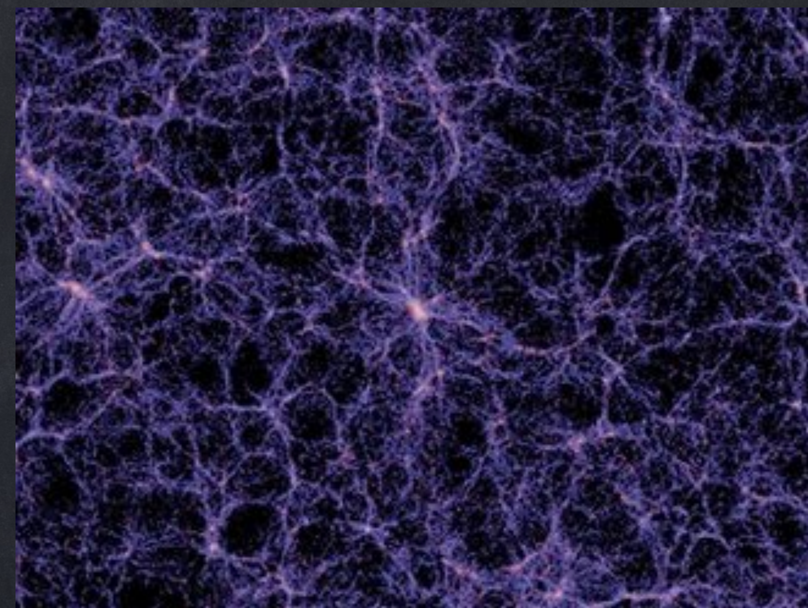

(Springel)

*From now on use halo bias and galaxy and galaxy bias interchangeably, even though the truth is more complicated!

the bias

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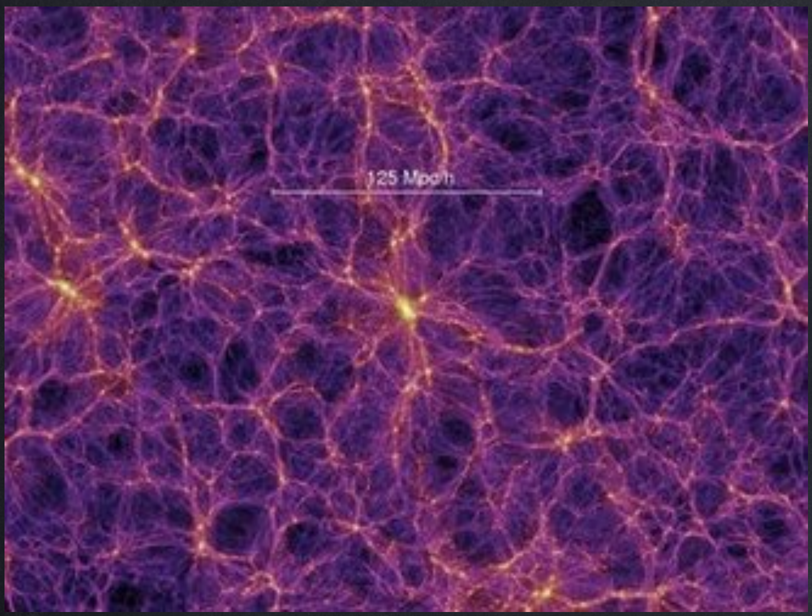

(Springel)

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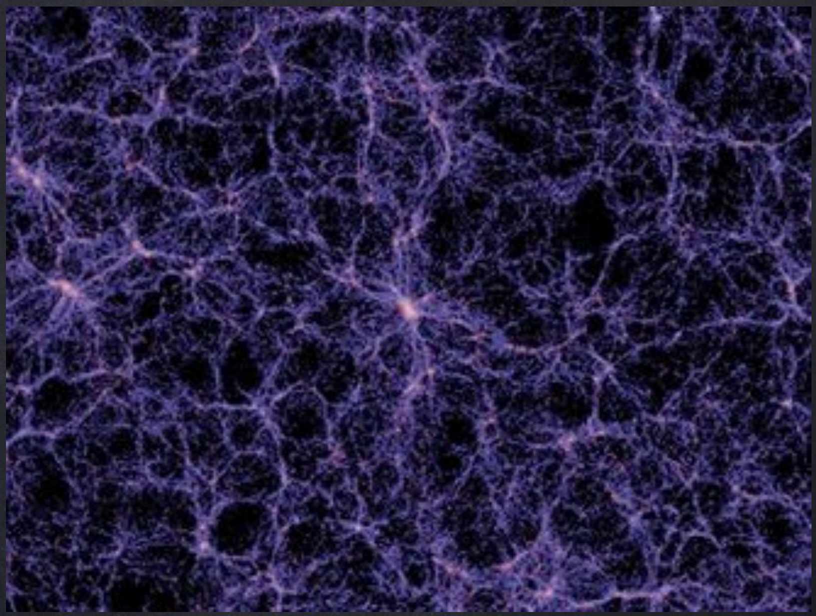

(Springel)

It's generally much easier to predict δ_m but much easier to observe δ_g so understanding bias is important

the bias

$$\delta_g \approx \frac{d\ln n_g}{d\delta_m}\,\delta_m \approx b\,\delta_m$$

halos and galaxies are *biased* tracers of the matter distribution

Separate Universe Approach

(To nonlinear evolution and bias)

Separate Universe Approach

The bias is a measure of the response of the number of halos to a long wavelength density fluctuation

$$\delta_h \approx \frac{d\ln n_h}{d\delta_m}\,\delta_m \approx b\,\delta_m$$

$$n_h(x) = \bar{n}_h$$

$$\delta_m = 0$$

$$n_h(x) = \bar{n}_h(1 + \delta_h(x))$$

$$\delta_m > 0$$

Separate Universe Approach

The bias is a measure of the response of the number of halos to a long wavelength density fluctuation

$$\delta_h \approx \frac{d\ln n_h}{d\delta_m}\,\delta_m \approx b\,\delta_m$$

Usually measure by correlating halo fluctuation $\delta_h(x)$ with matter fluctuation $\delta_m(x)$

$$n_h(x) = \bar{n}_h(1 + \delta_h(x))$$

$$\delta_m > 0$$

$$b \approx \langle\delta_h(x_1)\delta_m(x_2)\rangle / \langle\delta_m(x_1)\delta_m(x_2)\rangle$$

Separate Universe Approach

The bias is a measure of the response of the number of halos to a long wavelength density fluctuation

$$\delta_h \approx \frac{d\ln n_h}{d\delta_m}\,\delta_m \approx b\,\delta_m$$

But from this perspective, can also

$$n_h(x) = \overline{n}_h(1 + \delta_h(x))$$

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Separate Universe Approach

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$$\delta_m < 0$$

$$b = \frac{1}{n_h}\,\frac{n_h(\delta_m > 0) - n_h(\delta_m < 0)}{2\,\delta_m}$$

Separate Universe Approach

Similarly, the ``squeezed” *bispectrum* is a measure of the response of the small-scale power spectrum to a long-wavelength mode

Separate Universe Approach

Similarly, the ``squeezed” *bispectrum* is a measure of the response of the small-scale power spectrum to a long-wavelength mode

$$P(k, x) \approx P(k)_{average} + \frac{\partial P(k)}{\partial \delta_m} \delta_m(x)$$

$$B(k\ , -k\ -k_L, k_L) \approx \frac{\partial P(k)}{\partial \delta_m} P(k_L)$$

$P(k) = P(k)_{average}(1 + \delta P)$

$P(k) = P(k)_{average}$

$\delta_m = 0$

$\delta_m > 0$

Separate Universe Approach

The Separate Universe Approach formalizes this

average density region $\Longleftrightarrow$ Our universe

Ω_m, Ω_Λ, Ω_K, h, . . .

$\delta_m = 0$

Sirko 2005;
Gnedin & Kravtsov 2011
Baldauf, Seljak, Senatore, Zaldarriaga 2011, 2015
Li, Hu, Takada 2014, 2016
Chiang, Wagner, Schmidt, Komatsu 2014a, (+perm) 2014b

Separate Universe Approach

The Separate Universe Approach formalizes this

average density region $\Longleftrightarrow$ Our universe

$\delta_m = 0$

$\Omega_m, \Omega_\Lambda, \Omega_K, h, \ldots$

Large overdense region $\Longleftrightarrow$ Separate, Closed Universe

$\delta_m > 0$

$\Omega_{mW}, \Omega_{\Lambda W}, \Omega_{KW}, h_{W}, \ldots$

(i.e. universe w/different cosmological parameters)

Sirko 2005;
Gnedin & Kravtsov 2011
Baldauf, Seljak, Senatore, Zaldarriaga 2011, 2015
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Separate Universe Approach

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Large overdense region

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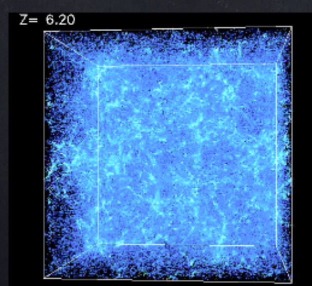
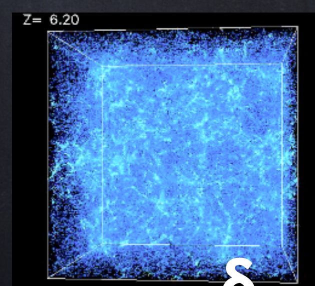
Separate, Closed Universe

$\Omega_{mW}, \Omega_{\Lambda W}, \Omega_{\kappa W}, h_{W}, \ldots$

$\Omega_m, \Omega_\Lambda, \Omega_\kappa, h, \ldots$



$\Omega_{mW}, \Omega_{\Lambda W}, \Omega_{\kappa W}, h_{W}, \ldots$



$\delta_m > 0$

To study coupling between δ_m and small scale modes, or halo abundance, just run calculations with the new cosmological parameters!

Sirko 2005;
Gnedin & Kravtsov 2011
Baldauf, Seljak, Senatore, Zaldarriaga 2011, 2015
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Large overdense region

$\delta_m > 0$

$\Longleftrightarrow$

Separate, Closed Universe

Ω_{mW}, $\Omega_{\Lambda W}$, Ω_{KW}, h_{W}, . . .

So far, restricted to CDM and ΛCDM so that there is <u>only one type</u> of energy fluctuation $\boldsymbol{\delta}_m$

Sirko 2005;
Gnedin & Kravtsov 2011
Baldauf, Seljak, Senatore, Zaldarriaga 2011, 2015
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Separate Universe Approach

What if?

Large overdense region

$\delta_{cdm} > 0$

$\delta_{neutrino} > 0$ $\Longleftrightarrow$??

$\delta_{cdm} > 0$

$\delta_{quintessence} > 0$

Separate Universe Approach

What if?

Large overdense region

$\delta_{cdm} > 0$

$\delta_{neutrino} > 0$

$\delta_{cdm} > 0$

$\delta_{quintessence} > 0$

$\Longleftrightarrow$

??

does this look like a separate, curved universe with

Ω_{mW}, $\Omega_{neutrinoW}$, $\Omega_{\kappa W}$, h_{W}, . . .

or

Ω_{mW}, Ω_{QW}, $\Omega_{\kappa W}$, h_{W}, . . .

??

Separate Universe Approach

What if?

Large overdense region

$\delta_{cdm} > 0$

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??

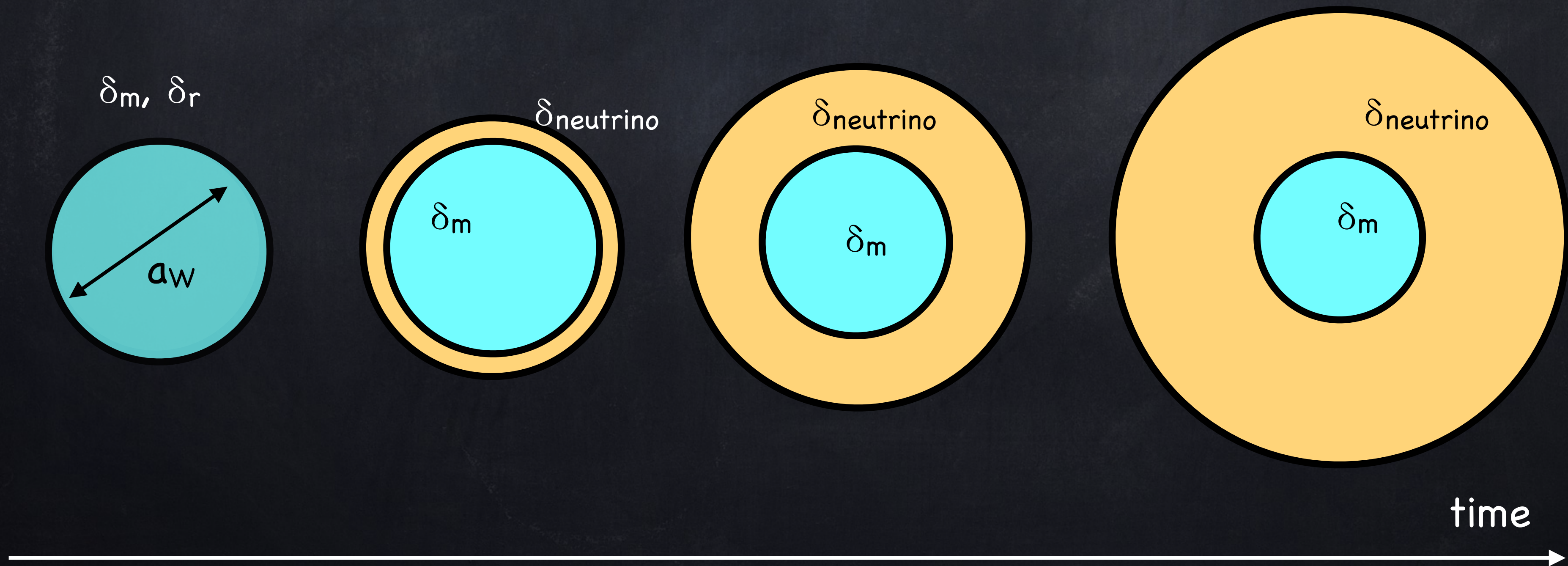
In particular, another fluid may have non-gravitational interactions or other behavior that prevents the energies from evolving like they would in a separate universe

Separate Universe Approach

In particular, another fluid may have non-gravitational interactions or other behavior that prevents it from evolving like a separate universe

Example I

quick thought experiment: initially coherent matter and neutrino perturbations



Separate Universe Approach

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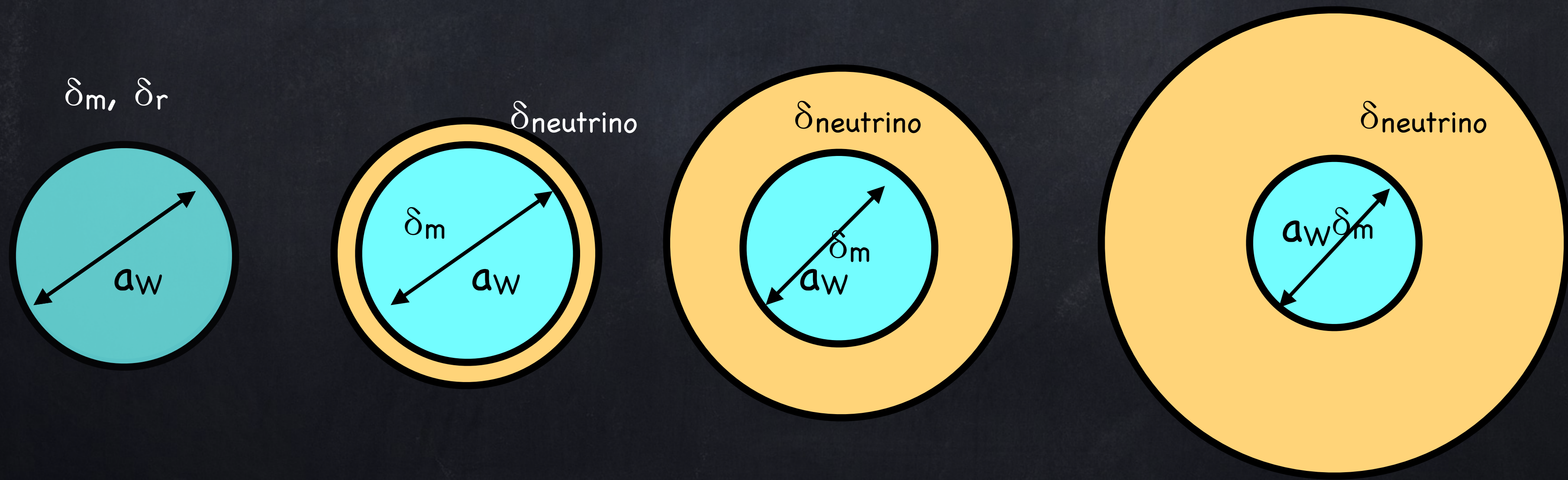


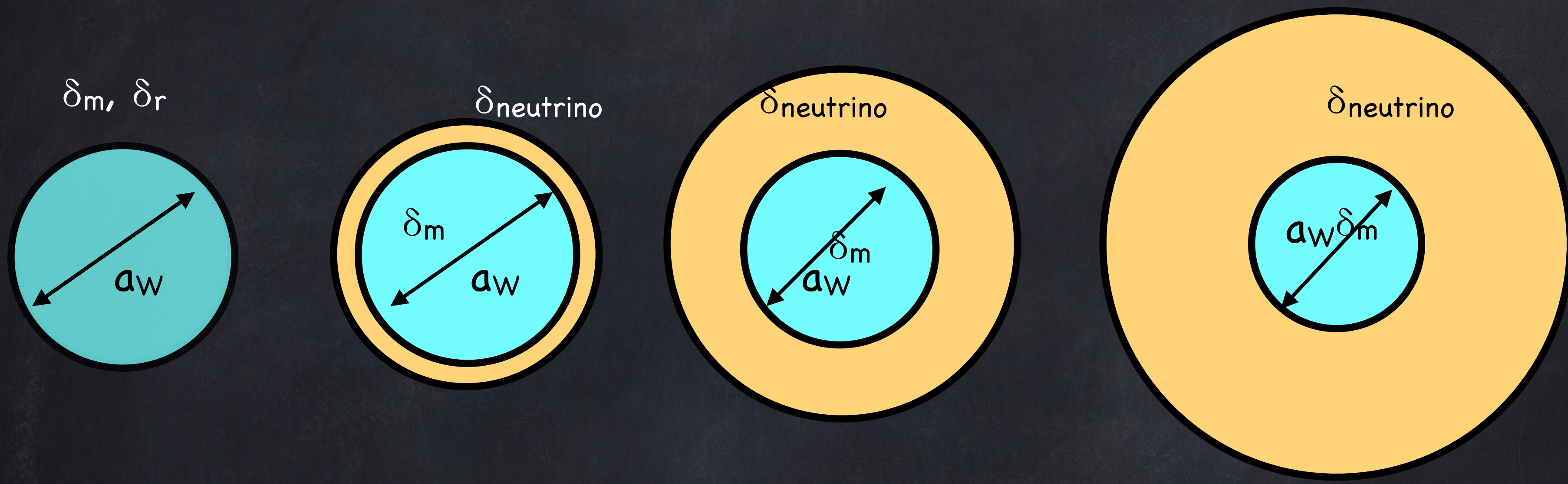
$\rho_m(a_W) \sim a_W^{-3}$ but $\rho_{neutrino}(a_W)$ dilutes faster

time

Separate Universe Approach

Example I

quick thought experiment: initially coherent matter and neutrino perturbations



$\rho_m (a_W) \sim a_W^{-3}$ but $\rho_{neutrino}(a_W)$ dilutes faster time

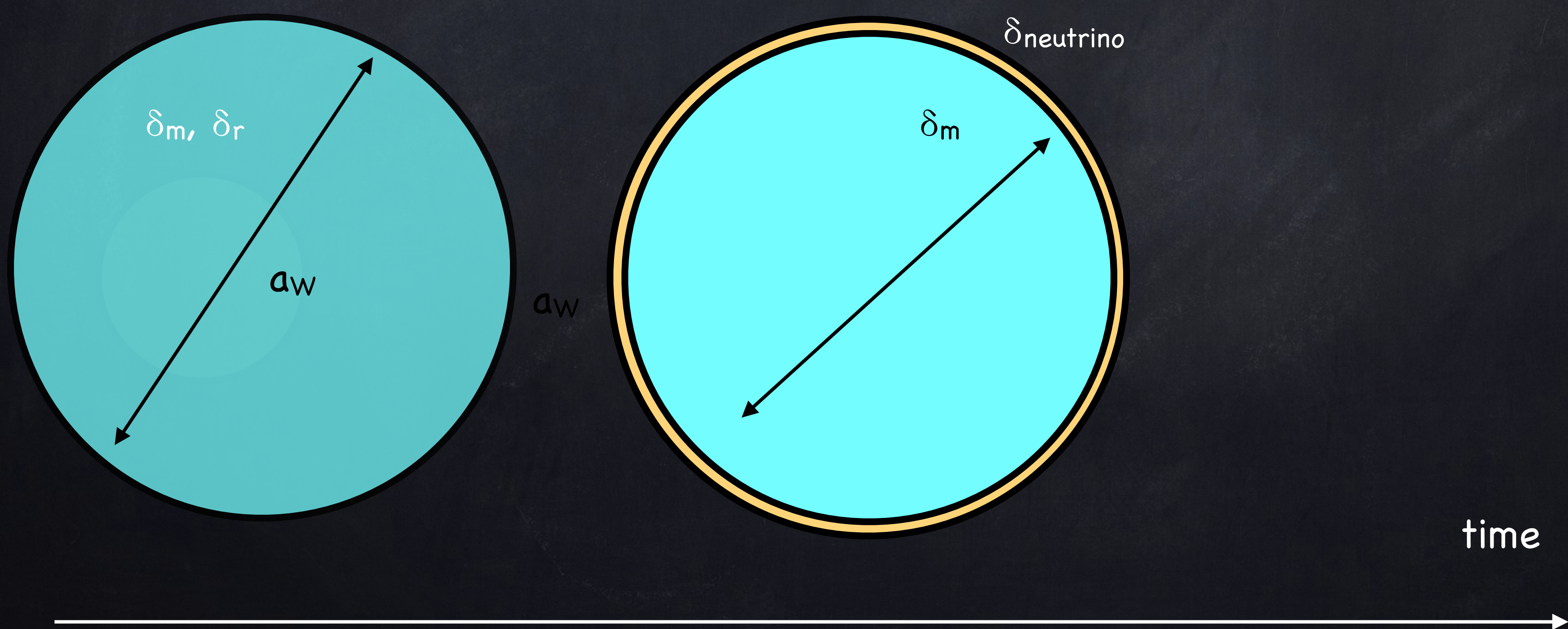
a_W does not look like scale factor for another universe with matter, neutrinos

Separate Universe Approach

Example I

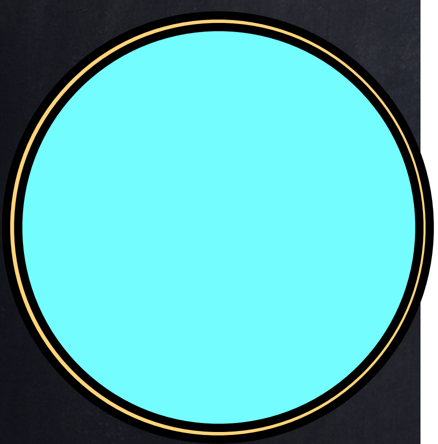
quick thought experiment: initially coherent matter and neutrino perturbations

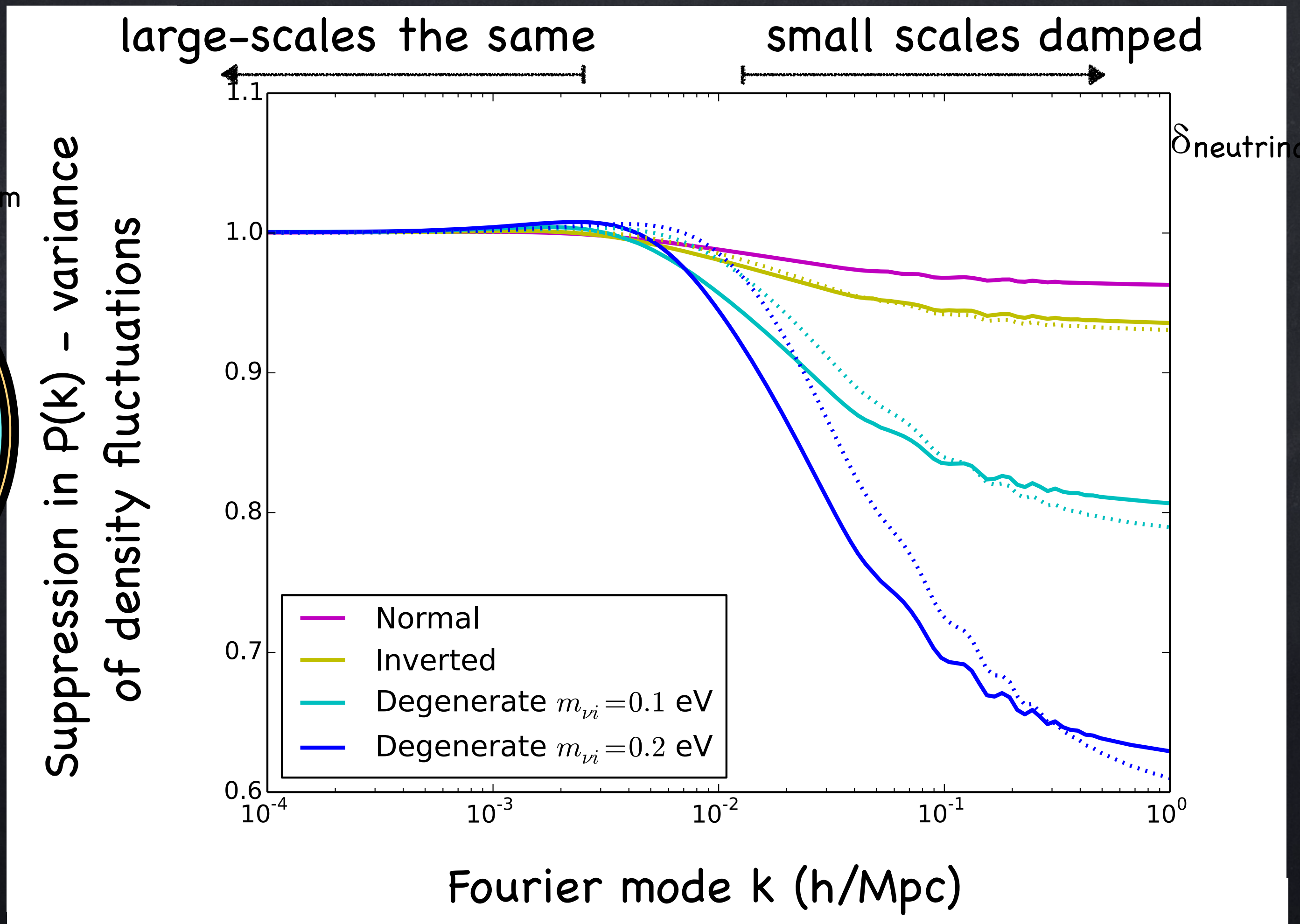
On the other hand, a very large scale perturbation

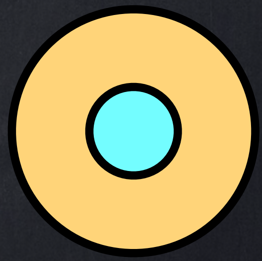


Neutrinos Aside:

This scale-dependent growth is the effect that gives main cosmological constraints on neutrino mass





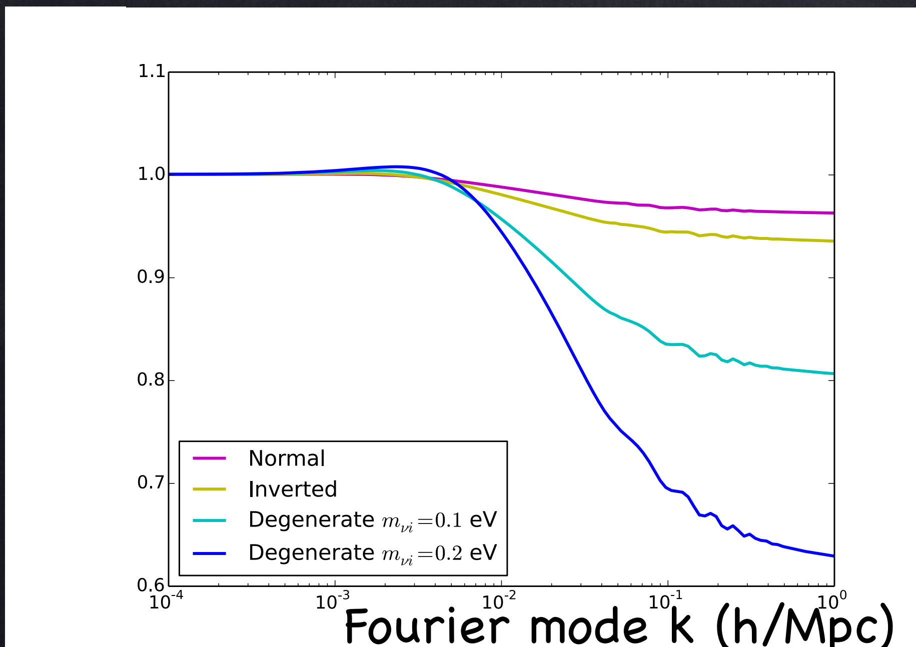


$$P(k) = \langle \delta_m(k)\delta_m(k) \rangle \quad \text{where} \quad \delta_m(k) = \frac{\delta\rho_{matter}}{\rho_{matter}}$$

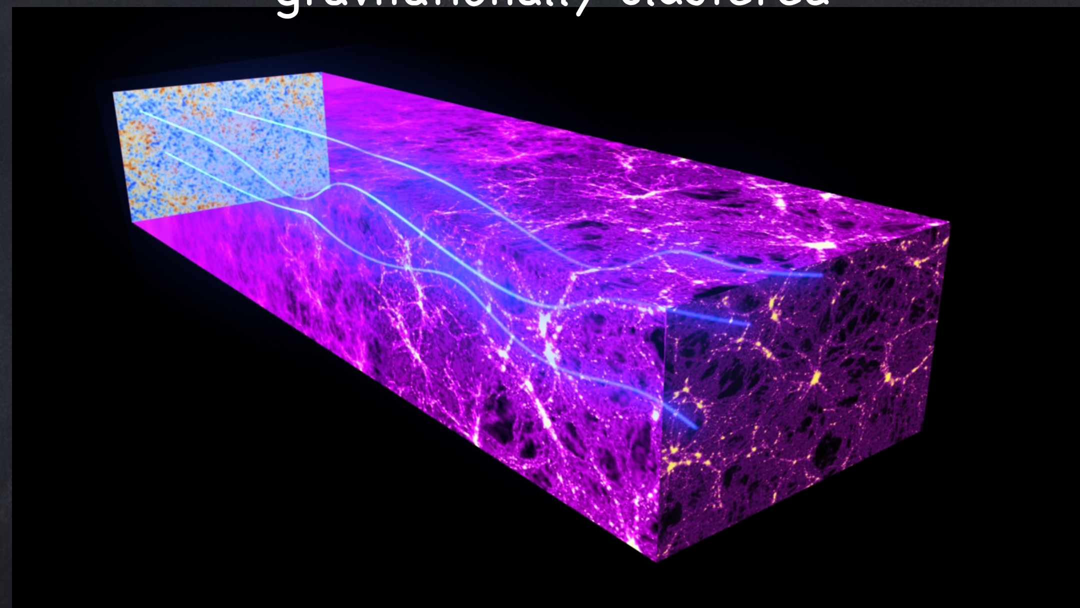
Bond, Efstathiou, Silk 1980
Hu, Eisenstein, Tegmark 1998

Neutrinos Aside:

massive neutrinos reduce the typical amplitude of density perturbations



—> less gravitational lensing than a universe where all matter is gravitationally clustered



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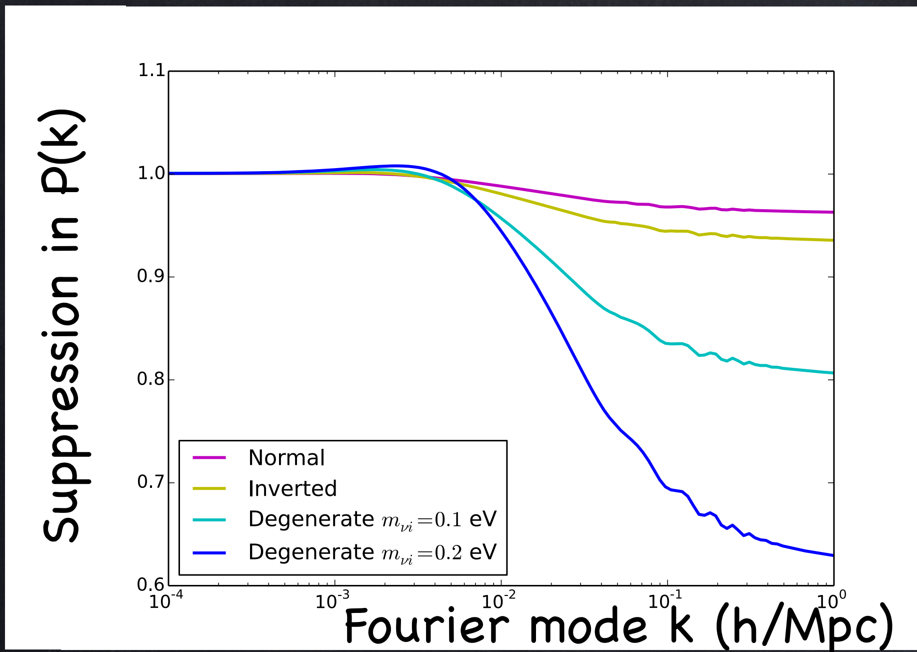
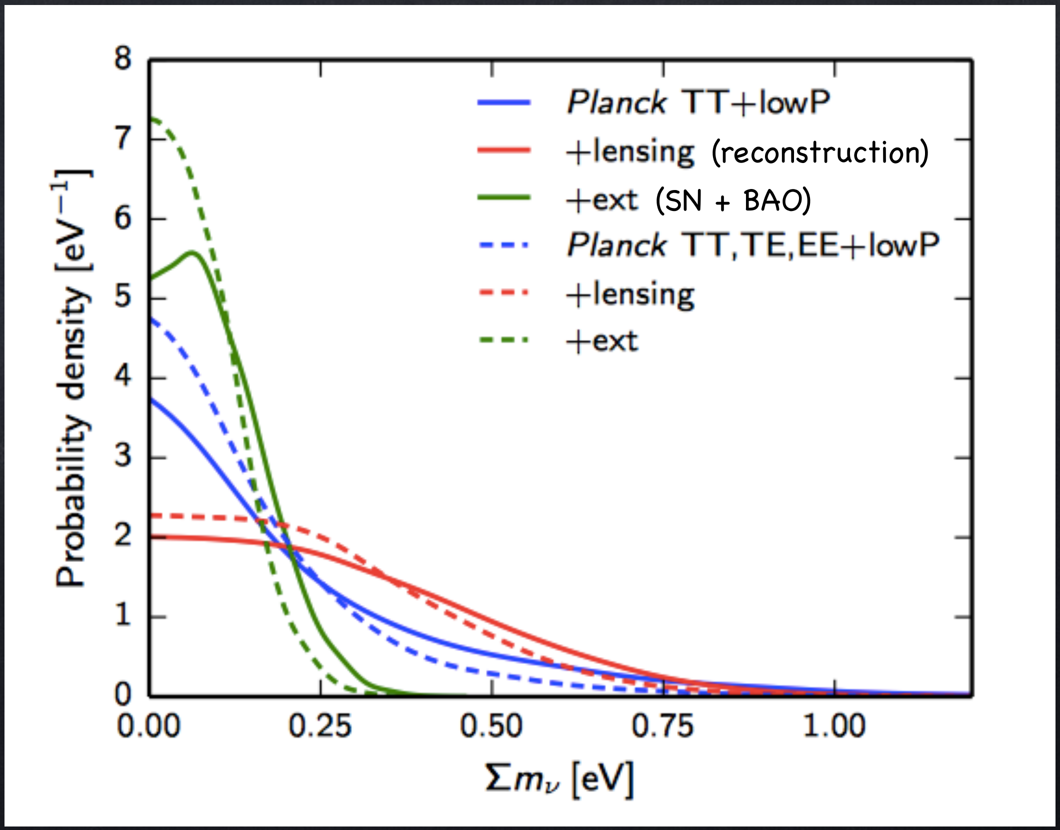


Current constraints from CMB



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

Planck 2015

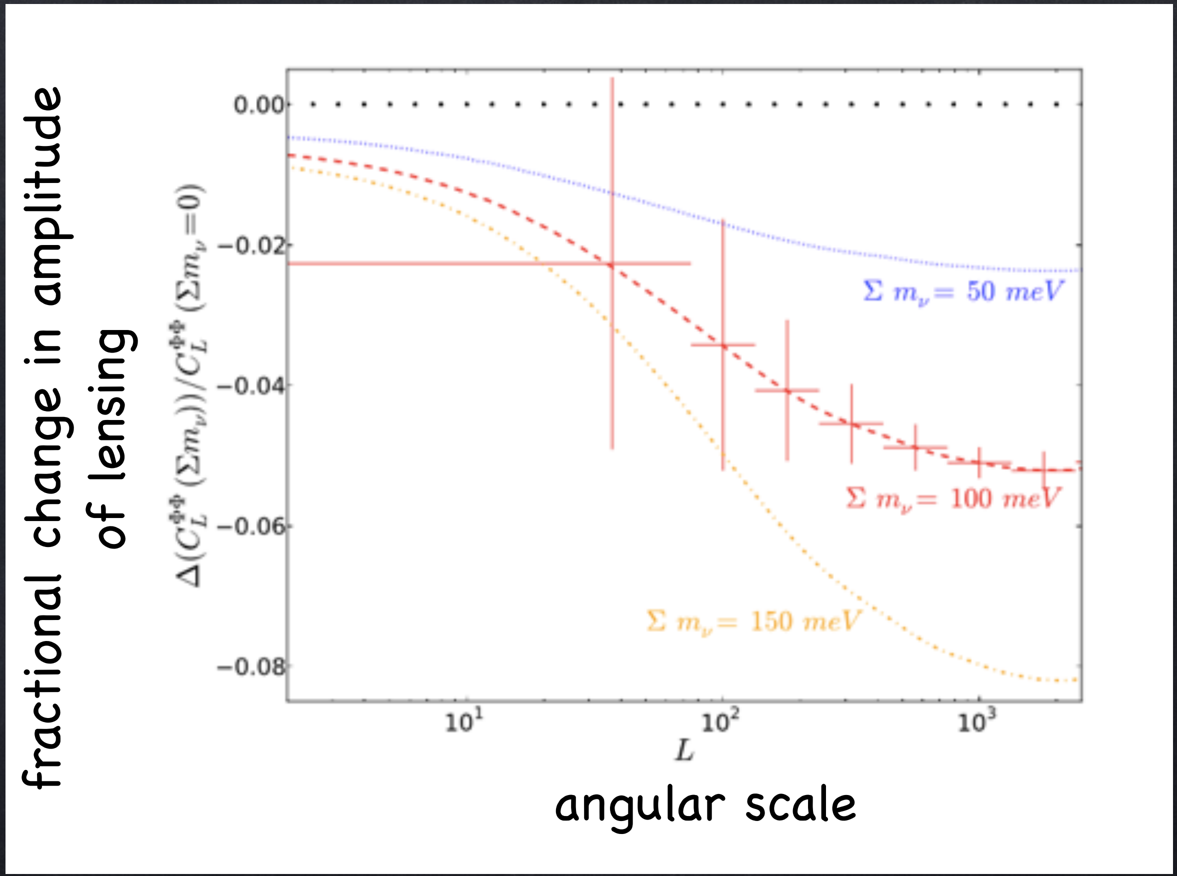
Neutrinos Aside:

Future:

$\sigma_{M\nu} \approx 0.02$ eV ??

3 σ detection of Normal Hierarchy (0.06eV)

"Stage IV CMB"



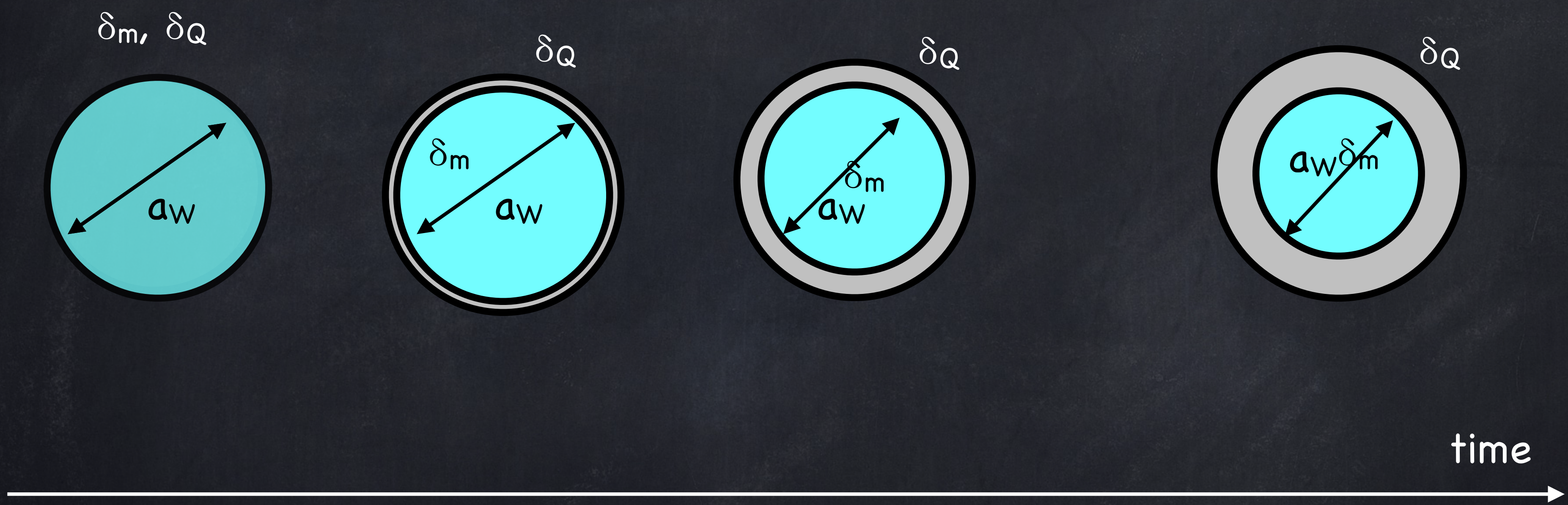
Abazajian et al 2013

CMB S4, LSST (Large Synoptic Survey Telescope), DESI (Dark Energy Spectroscopic Instrument), WFIRST, Euclid (ESA mission), SPHEREx . . .

Separate Universe Approach

Example II

quick thought experiment: initially coherent matter and quintessence perturbations **below** quintessence Jeans scale



Separate Universe Approach

Example II

quick thought experiment: initially coherent matter and quintessence perturbations **below** quintessence Jeans scale

$\rho_m\,(a_W) \sim a_W^{-3}$ $\rho_Q\,(a_W)$ pressure supported, dilutes faster relative to ρ_m time

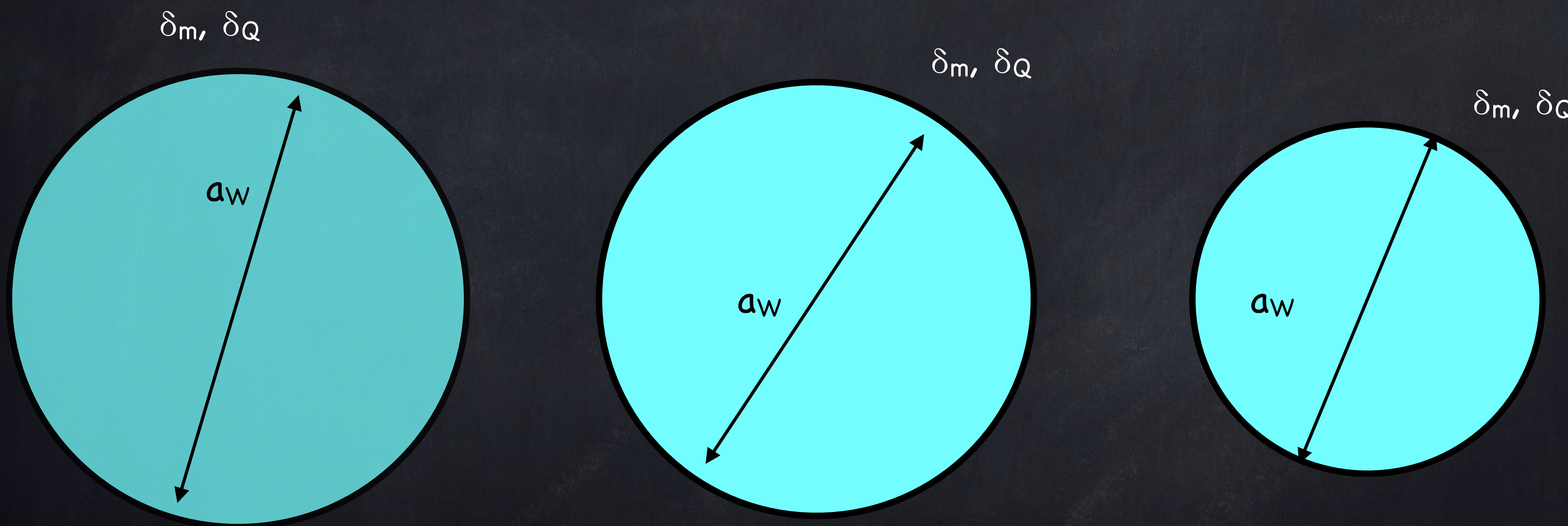
a_W does <u>not</u> look like scale factor for another universe with matter, quintessence behaving the same way

Hu, Chiang, Li, ML 1605.01412

Separate Universe Approach

Example II

quick thought experiment: initially coherent matter and quintessence perturbations **above** quintessence Jeans scale



Hu, Chiang, Li, ML 1605.01412

Separate Universe

It turns out that even in the funny, sub-Jeans cases one can still construct a "fake separate universe"

Large overdense region

$\delta_{cdm} > 0$

$\delta_{neutrino} > 0$

$\delta_{cdm} > 0$

$\delta_{quintessence} > 0$

Separate Universe with additional weird energy densities

Ω_{mW}, $\Omega_{neutrinoW}$, $\Omega_{\kappa W}$, $\boldsymbol{\Omega_{SW}}$, h_W, . . .

Ω_{mW}, Ω_{QW}, $\Omega_{\kappa W}$, $\boldsymbol{\Omega_{SW}}$, h_W, . . .

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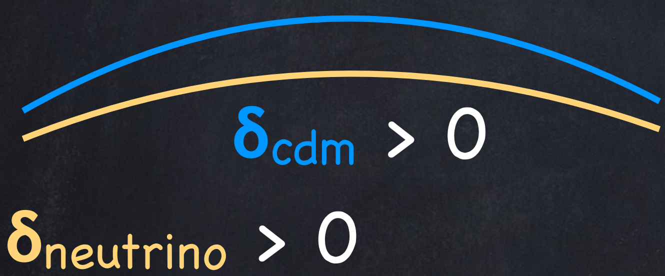

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But the separate universe construction is still well-defined if we know evolution of δ_{cdm} , $\delta_{neutrino}$, $\delta_{Quintessence}$

Hu, Chiang, Li, ML 1605.01412

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But the separate universe construction is still well-defined if we know evolution of

$\delta_{cdm}(t)$, $\delta_{neutrino}(t)$, $\delta_{Quintessence}(t)$

define local expansion history

$a_W(t)$, $H_W(t)$

Hu, Chiang, Li, ML 1605.01412

Separate Universe Logic Applied to Spherical Collapse Model for Halos

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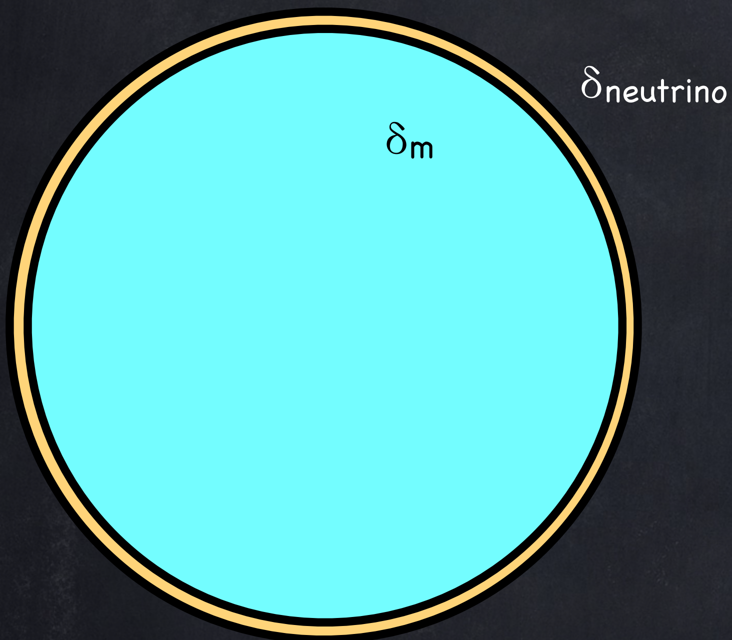

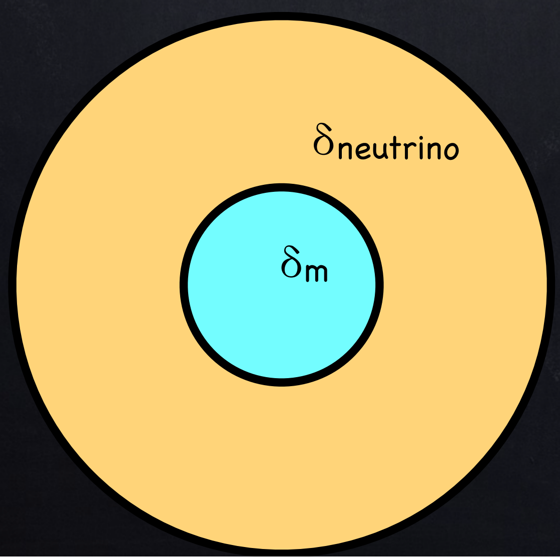

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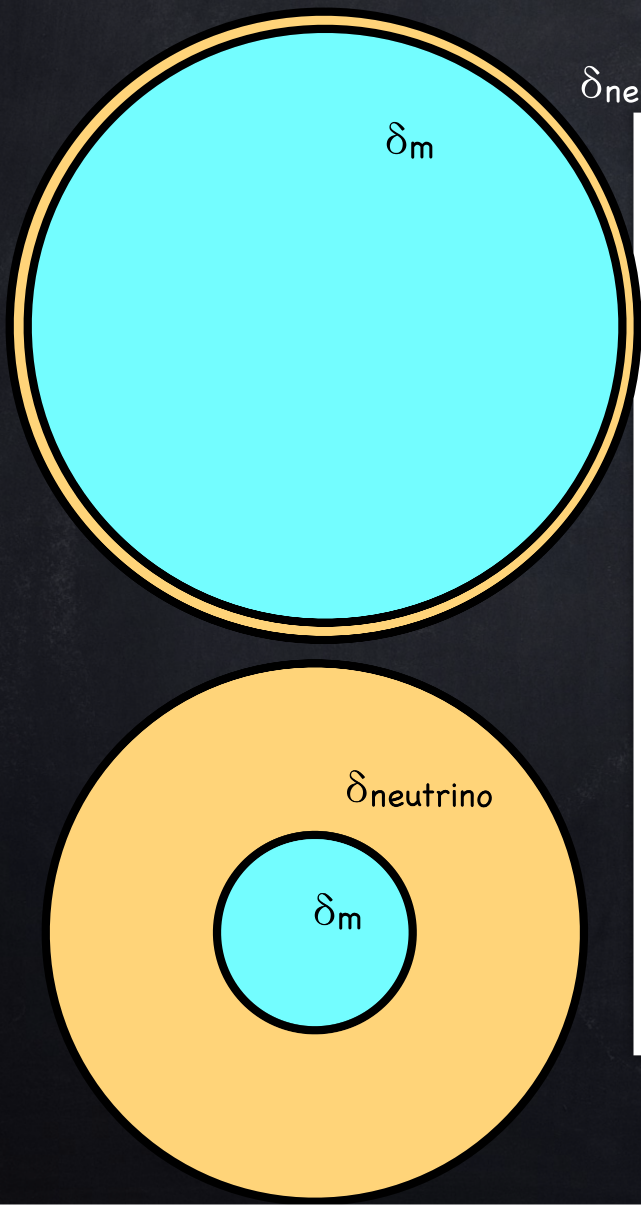

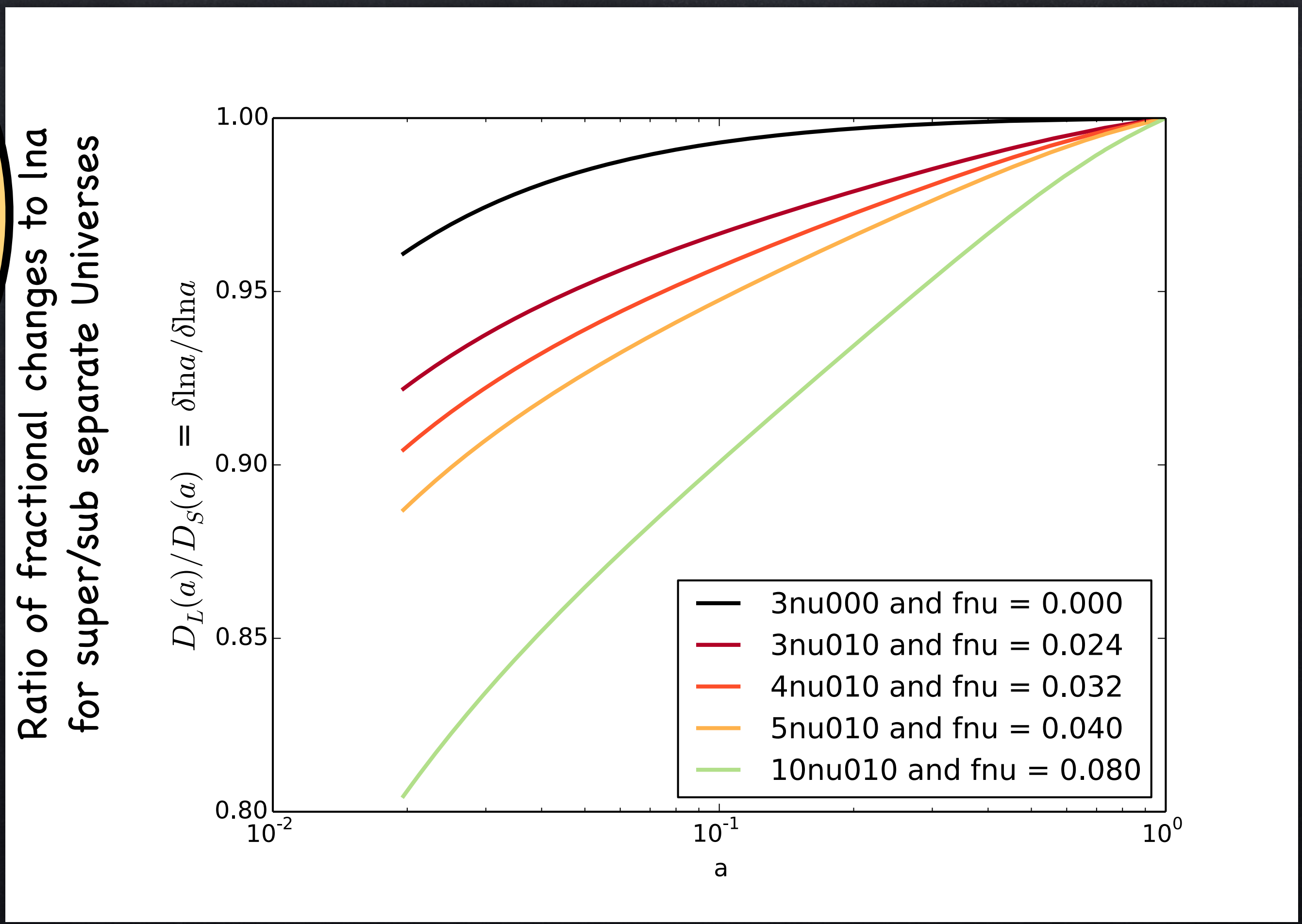

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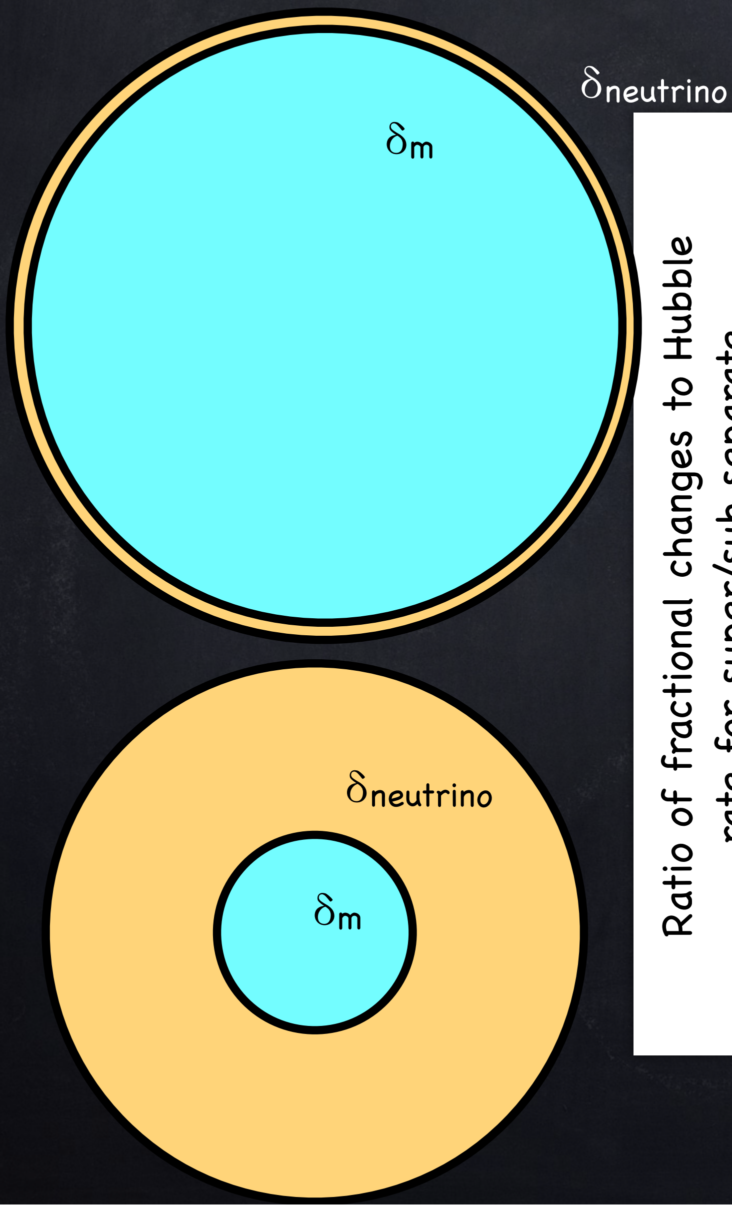

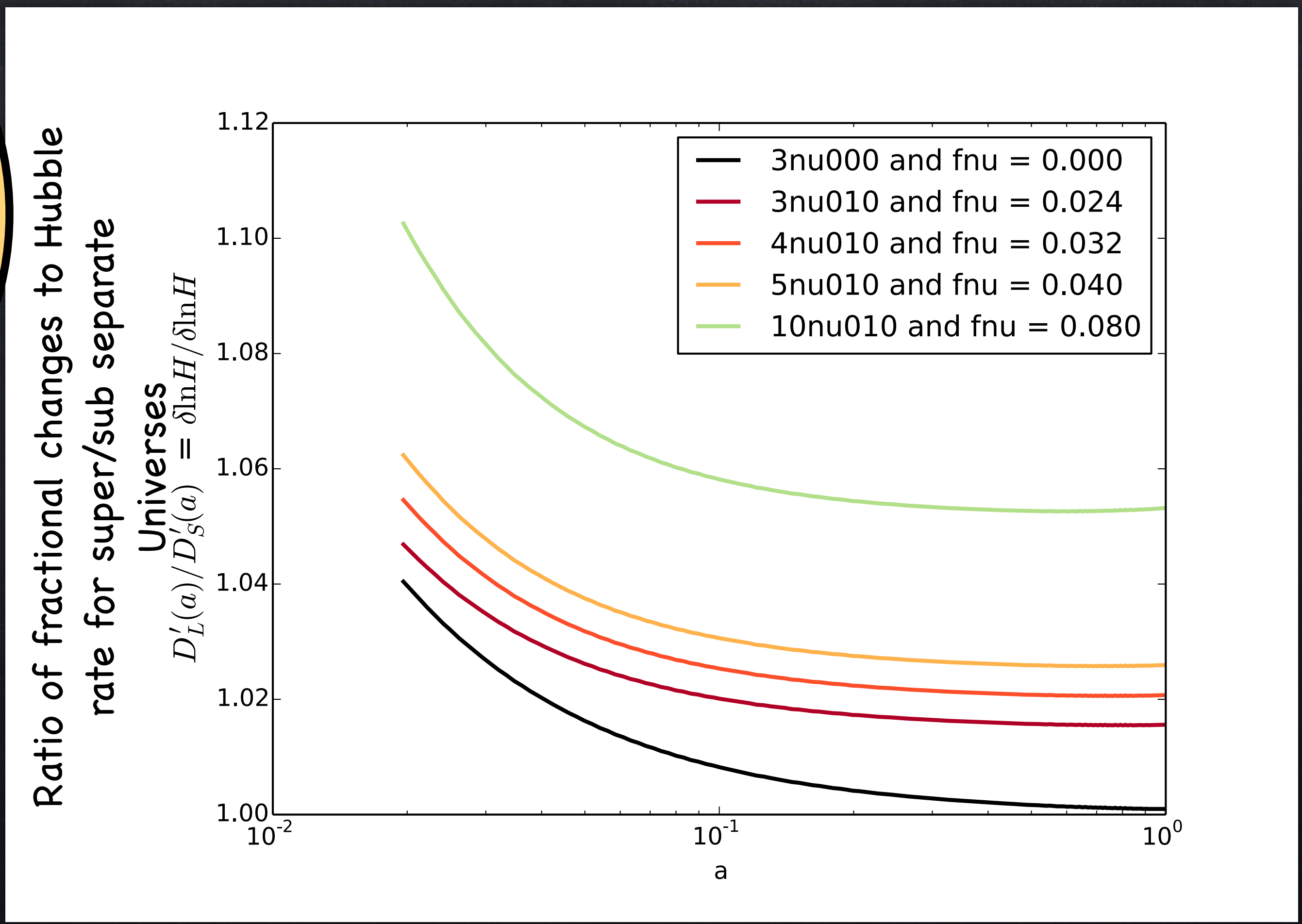

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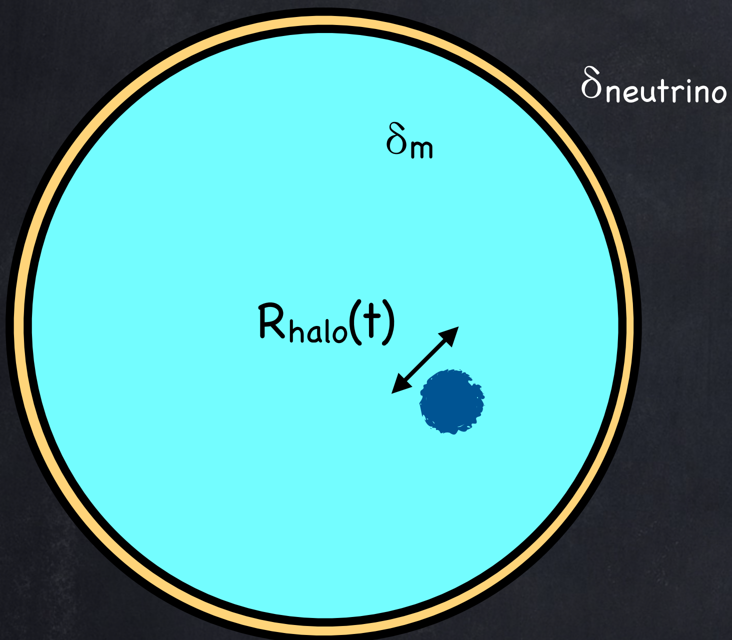
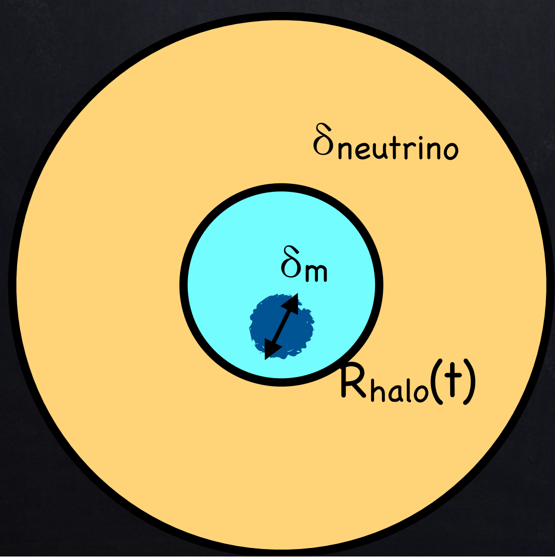


Solve the nonlinear evolution of spherical over density (spherical cow halo) in two regions



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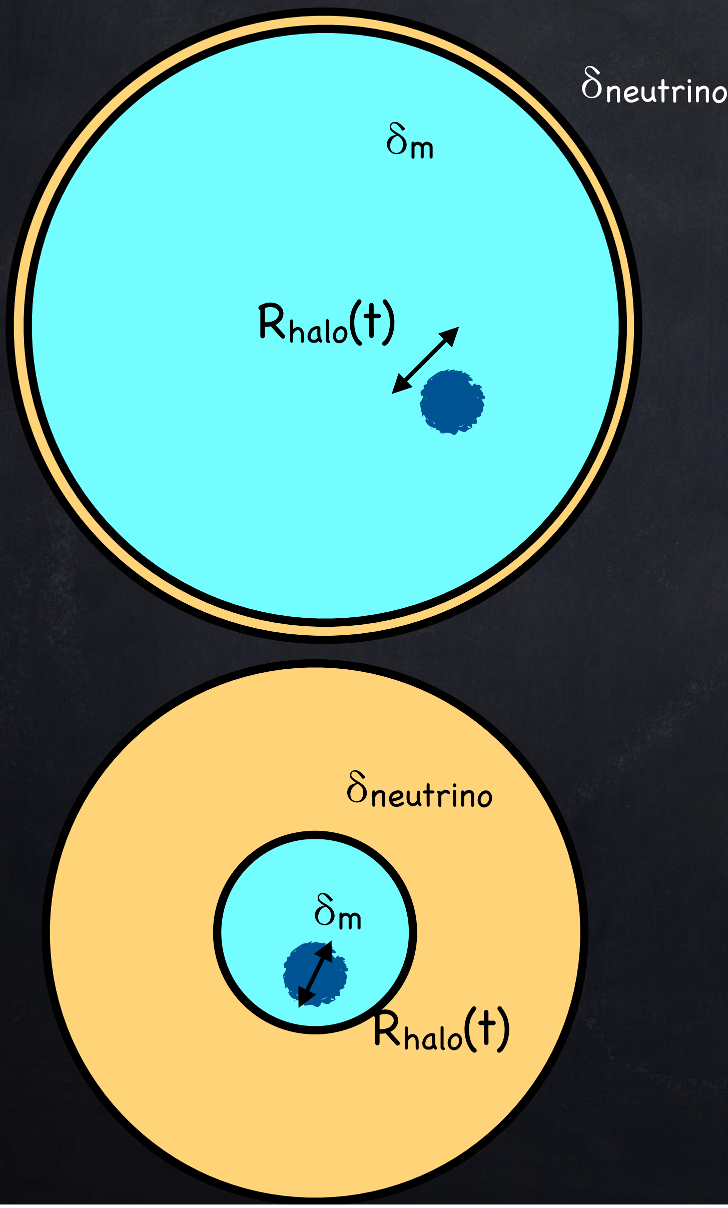

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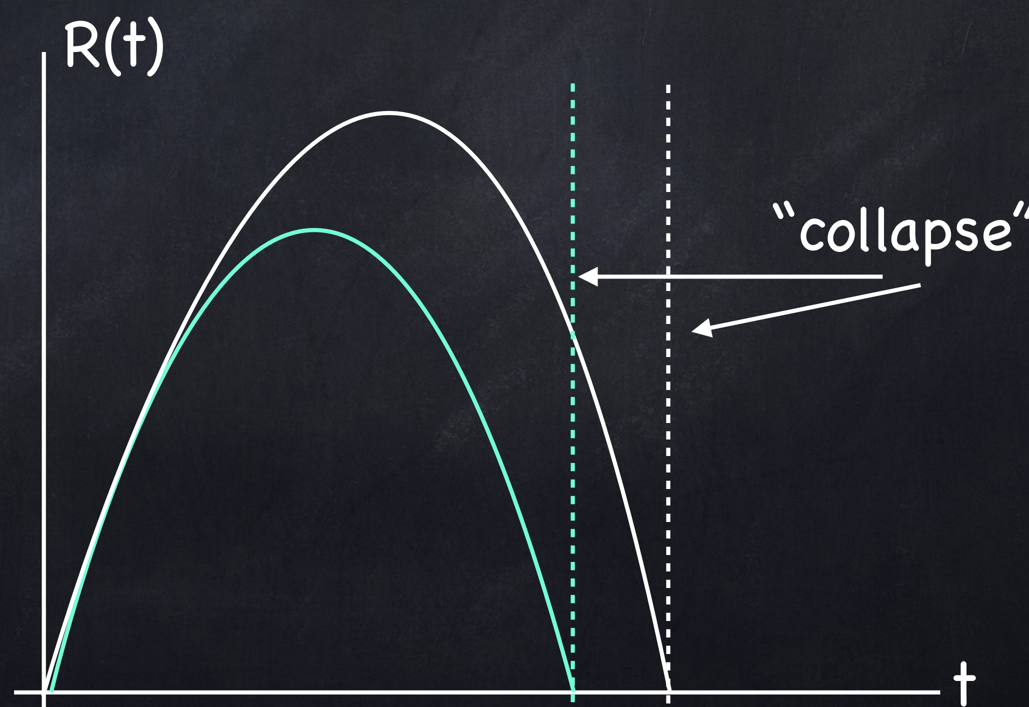

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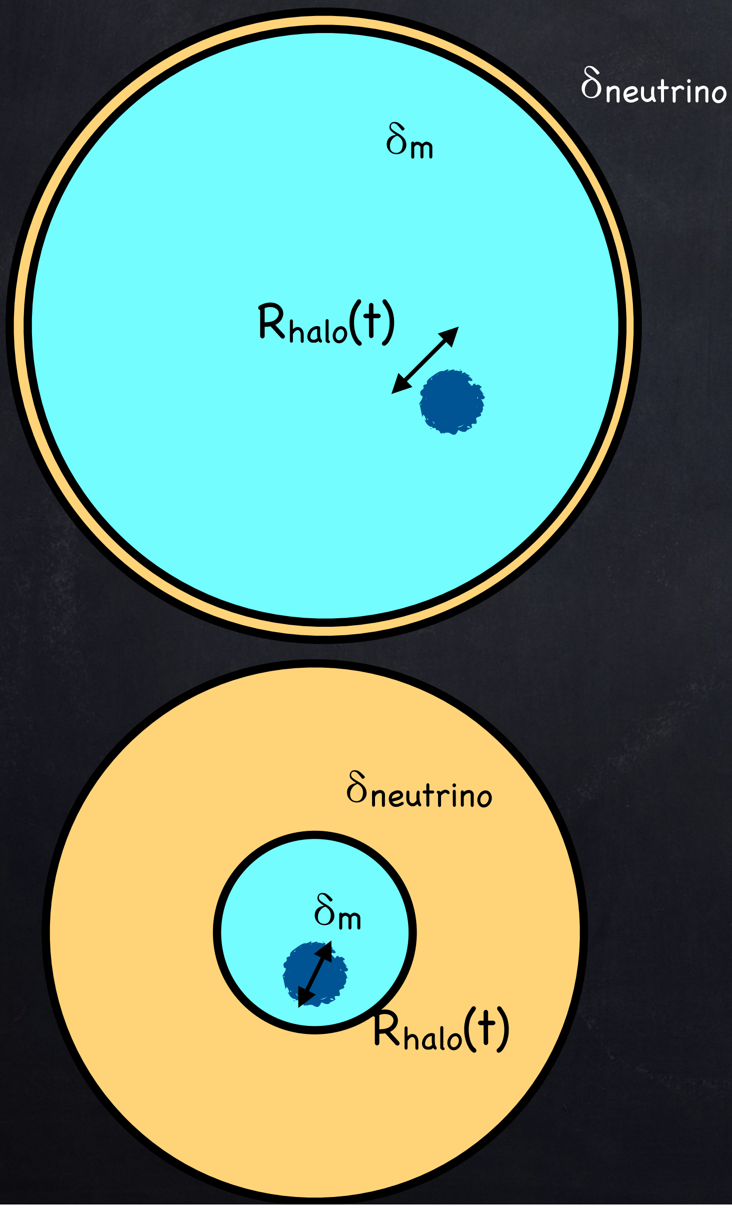


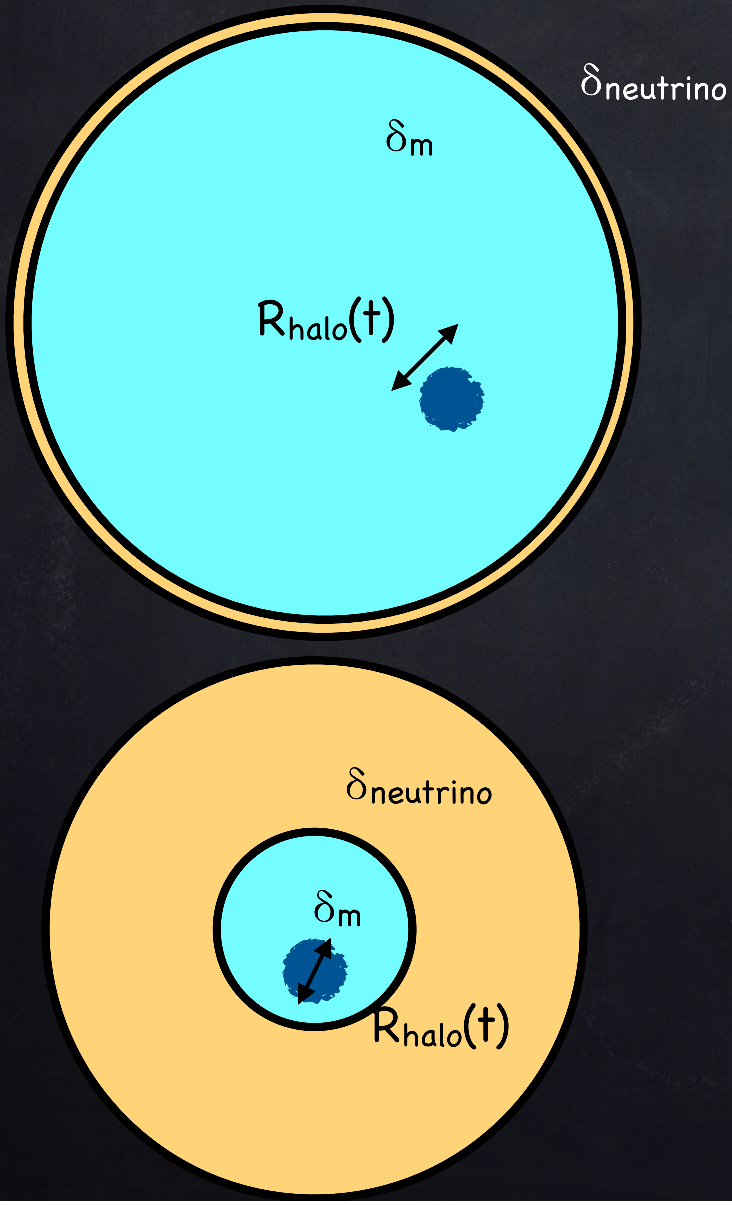
Solve the nonlinear evolution of spherical over density (spherical cow halo) in two regions

↓

Simplest prediction for number of halos that can collapse by time t

$n(M,t \mid \delta_m(t))$

Separate Universe Logic Applied to Spherical Collapse Model for Halos



Solve the nonlinear evolution of spherical over density (spherical cow halo) in two regions

↓

Simplest prediction for number of halos that can collapse by time t

$n(M,t \mid \delta_m(t))$

↓

Determine response bias in each region

$$b = \frac{1}{n_h} \frac{n_h(\delta_m > 0) - n_h(\delta_m < 0)}{2\,\delta_m}$$

Halo bias - simplest model

In a universe with massive neutrinos:

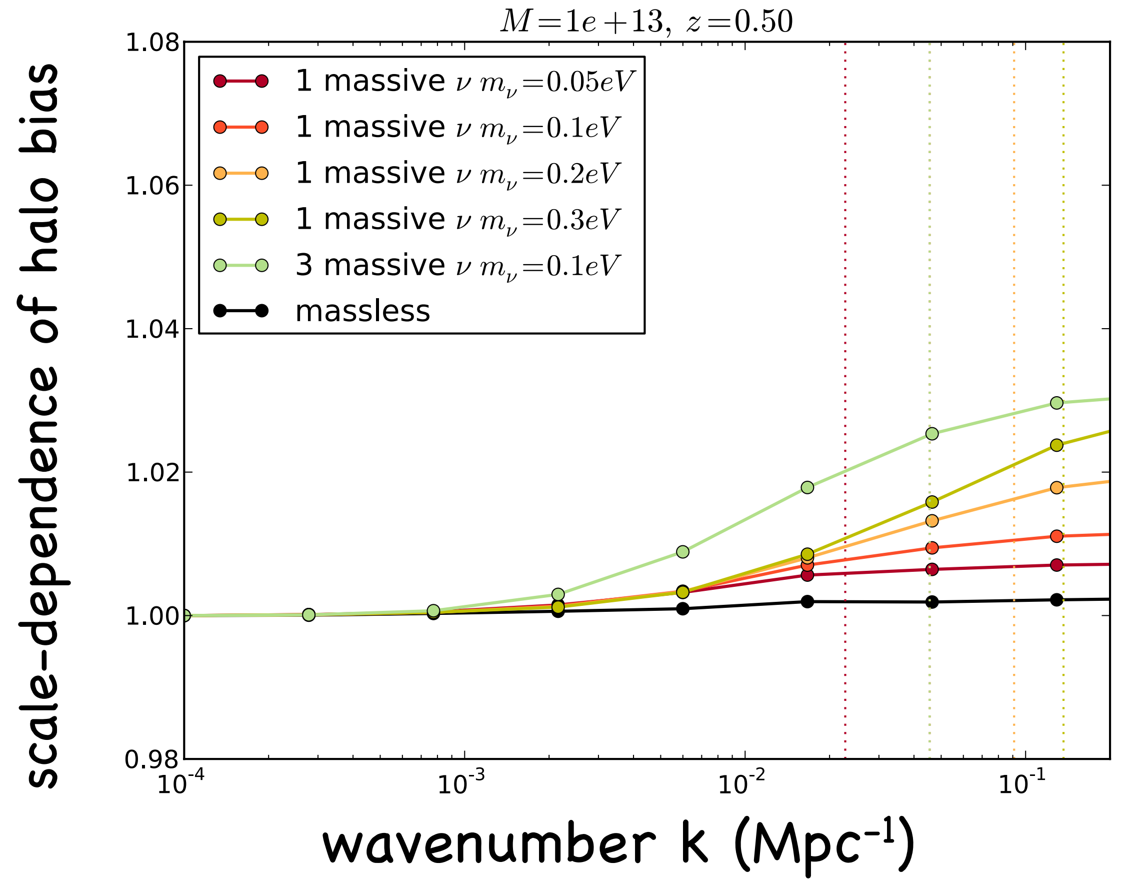
$$b(k < k_{\text{free-streaming}}) \neq b(k > k_{\text{free-steaming}})$$

Halo bias - simplest model

In a universe with massive neutrinos:

$b(k < k_{free\text{-}streaming}) \neq b(k > k_{free\text{-}steaming})$

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



(ML 2014)

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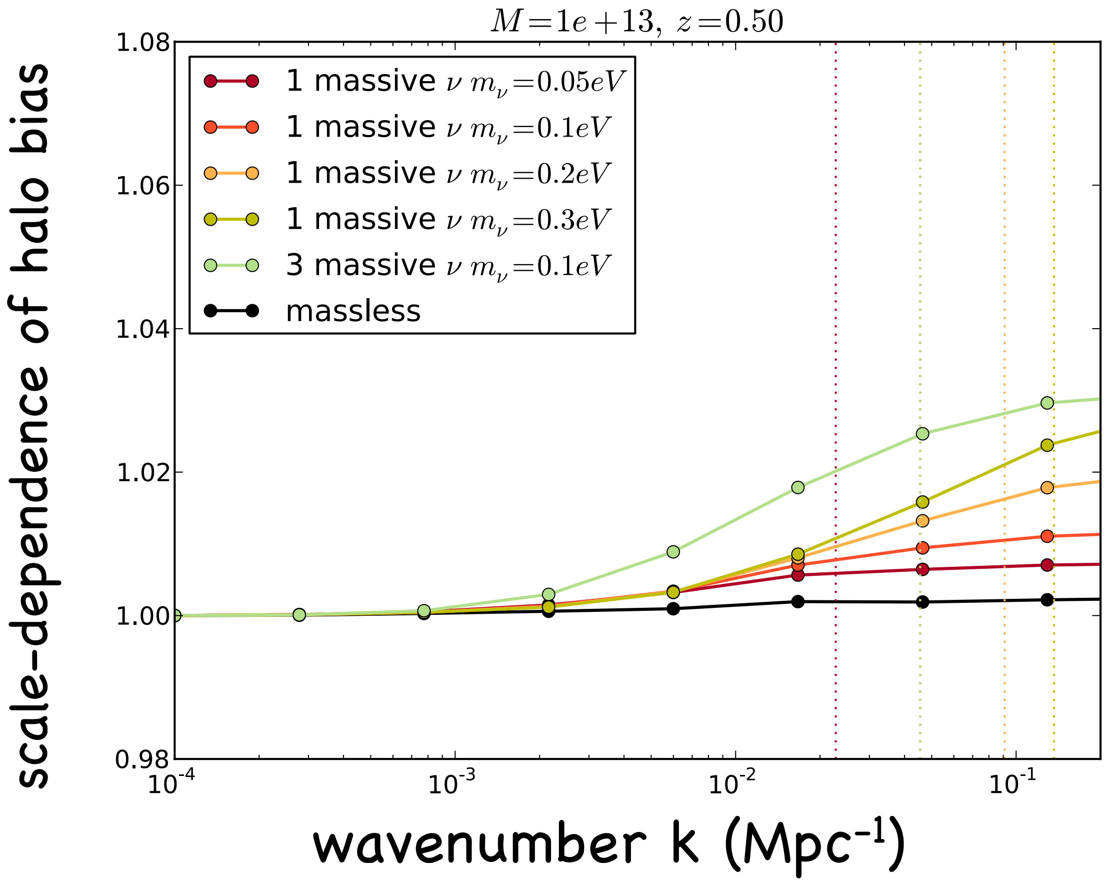


$\sim \frac{\rho_\nu}{\rho_{matter}}$

(ML 2014)

Halo bias - simplest model

In a universe with massive neutrinos:

$$b(k < k_{\text{free-streaming}}) \neq b(k > k_{\text{free-steaming}})$$

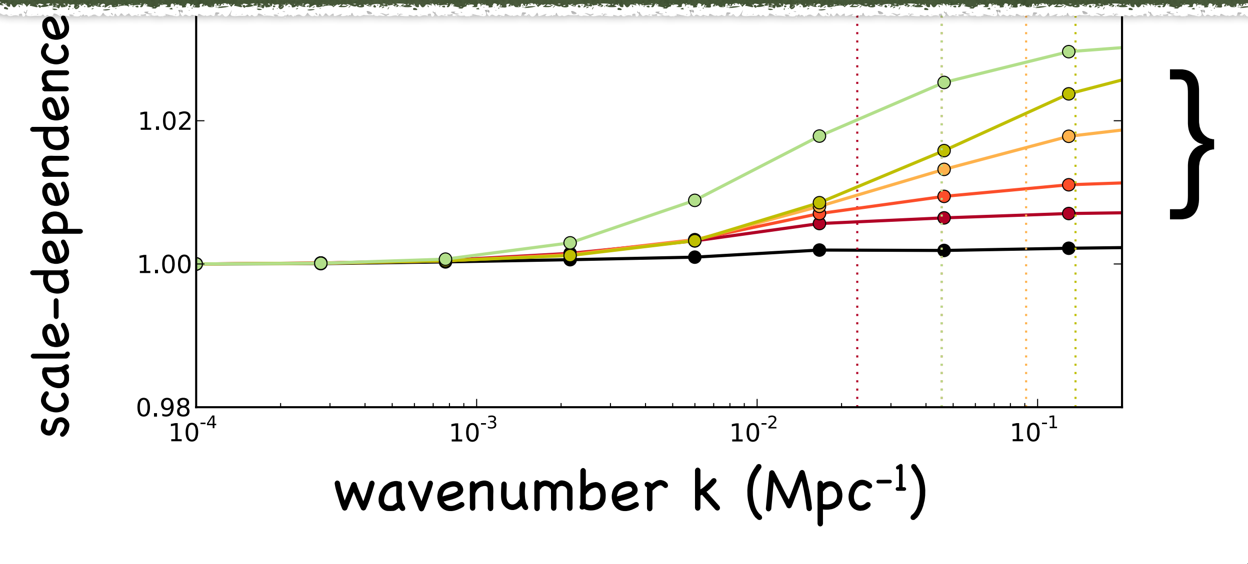
In general,

$$\frac{\Delta b}{b} \approx f_\nu + \frac{b-1}{b}(\# \; f_\nu)$$

where

$$f_\nu = \frac{\rho_\nu}{\rho_{cdm} + \rho_\nu}$$

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



$$\Bigg\} \sim \frac{\rho_\nu}{\rho_{\text{matter}}}$$

(ML 2014)

Observational consequences

Scale-dependent change in the halo bias:

$$\frac{\Delta b}{b} \approx f_\nu + \frac{b-1}{b}(\#\ f_\nu) \qquad \text{where} \qquad f_\nu = \frac{\rho_\nu}{\rho_{cdm}+\rho_\nu}$$

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(ML 2014)

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Why care about such a small change to the halo bias?

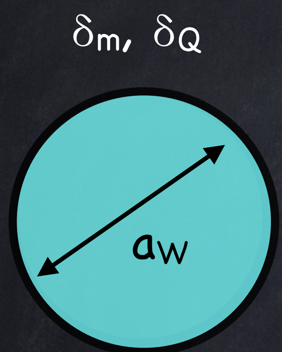
- Because the feature in the halo bias can be used to measure neutrino mass
- Because this may be a serious systematic for measurements of m_ν from galaxy clustering

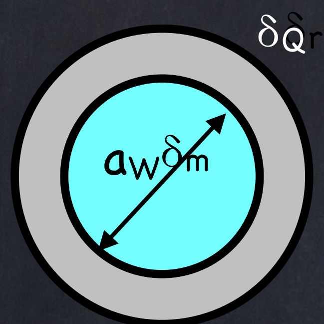
(ML 2014)

First Simulations Application: Quintessence

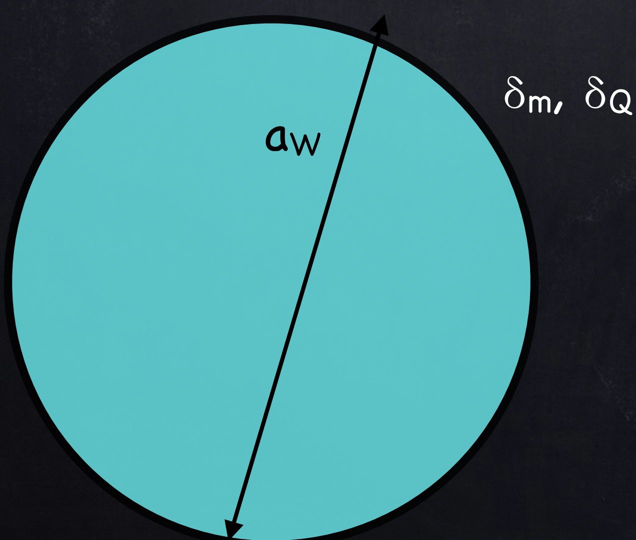
First Simulations Application: Quintessence

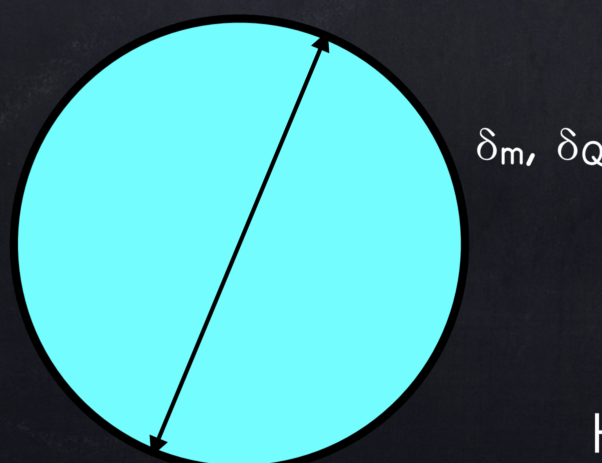
matter and quintessence perturbations **below** the quintessence Jeans scale





matter and quintessence perturbations **above** the quintessence Jeans scale





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First Simulations Application: Quintessence

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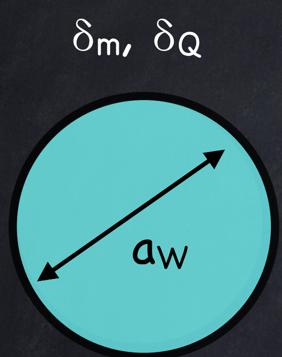
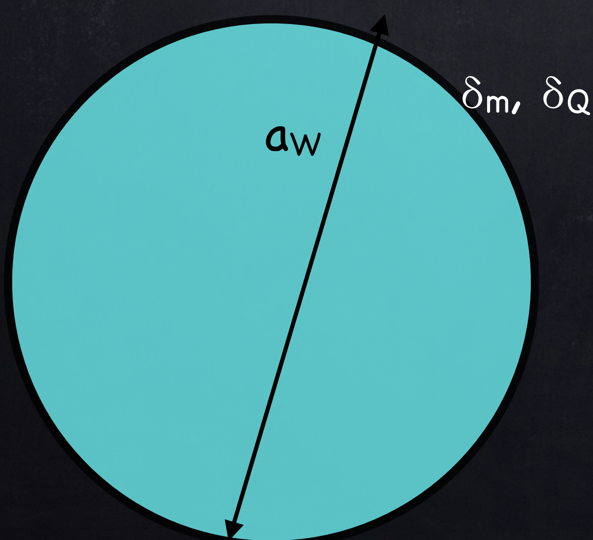
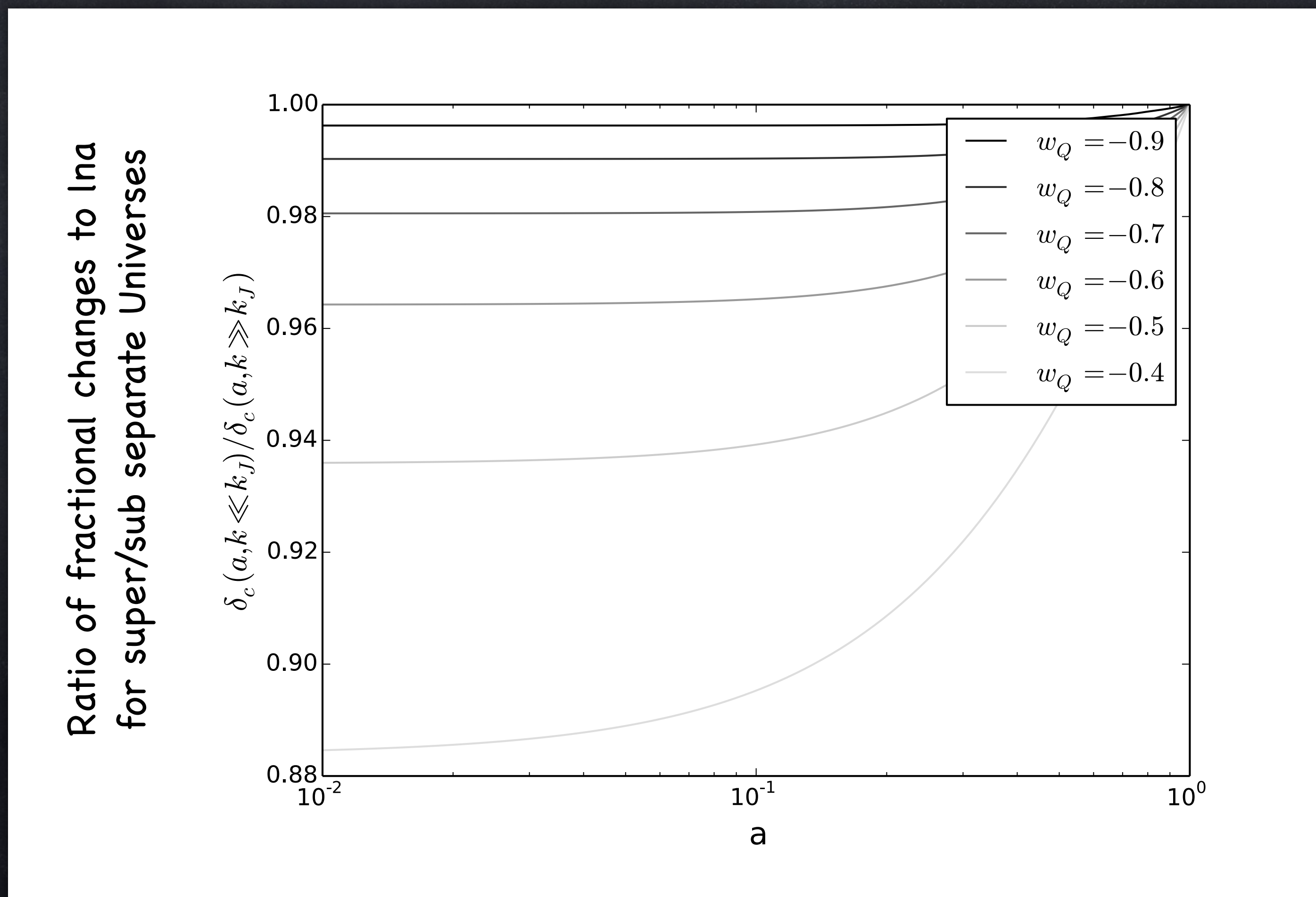


above the Jeans scale





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Application of the Fake Separate Universe Approach

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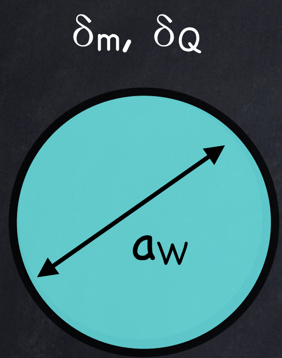

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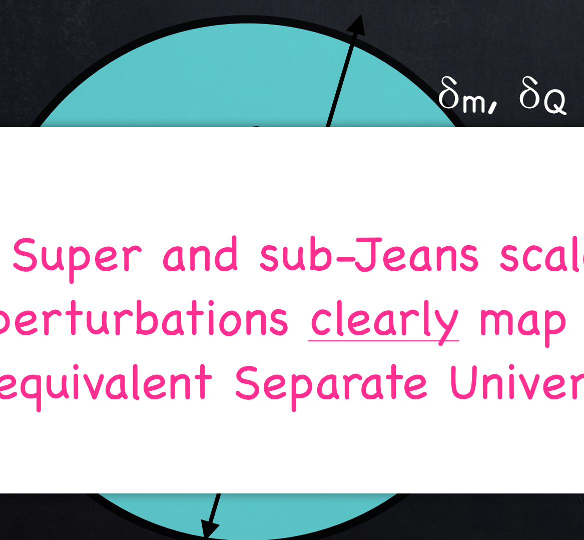

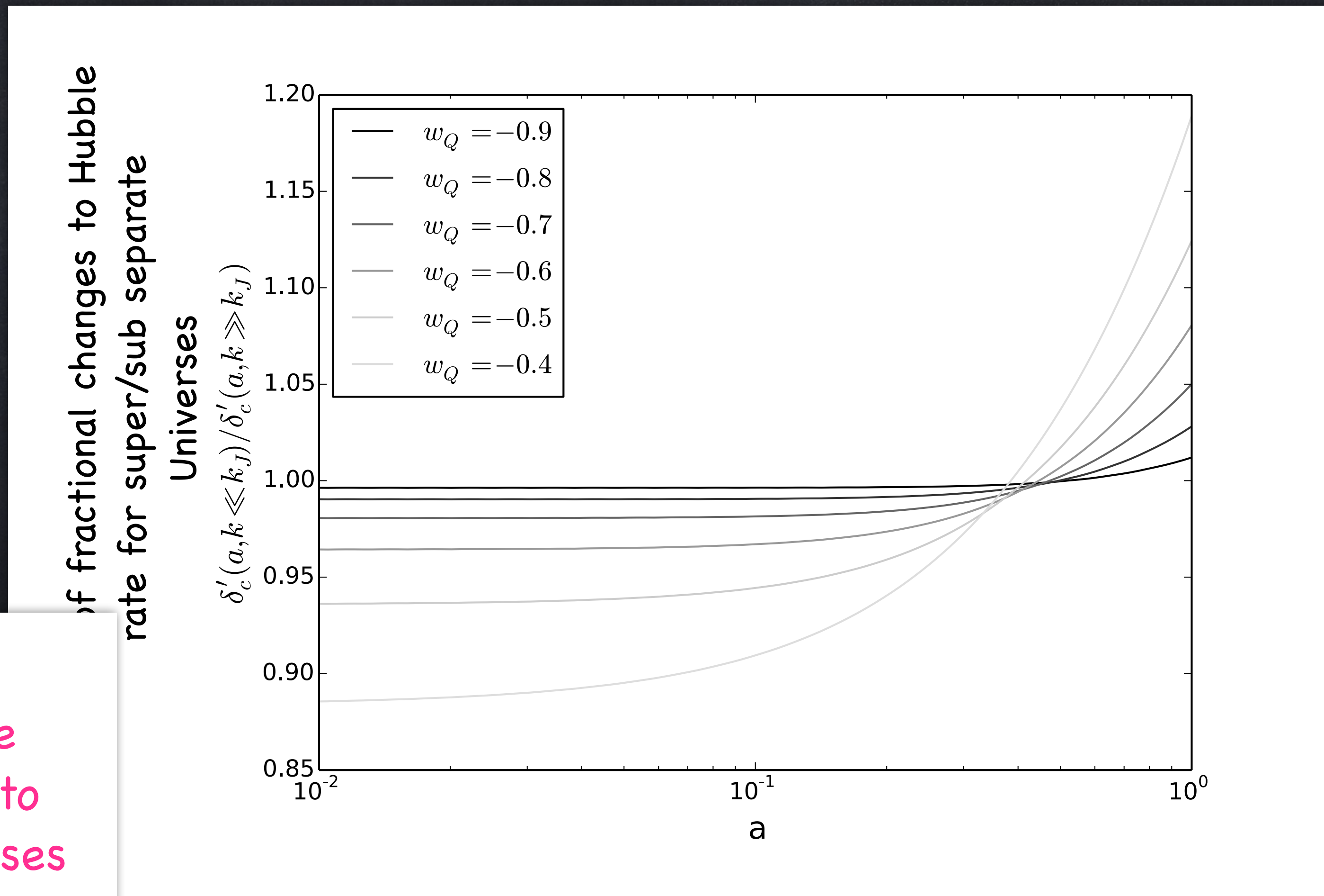

Super and sub-Jeans scale perturbations clearly map to inequivalent Separate Universes

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Application of the Fake Separate Universe Approach

Super and sub-Jeans scale perturbations clearly map to inequivalent Separate Universes

Small-scale observables in these universes should be different too

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Application of the Fake Separate Universe Approach

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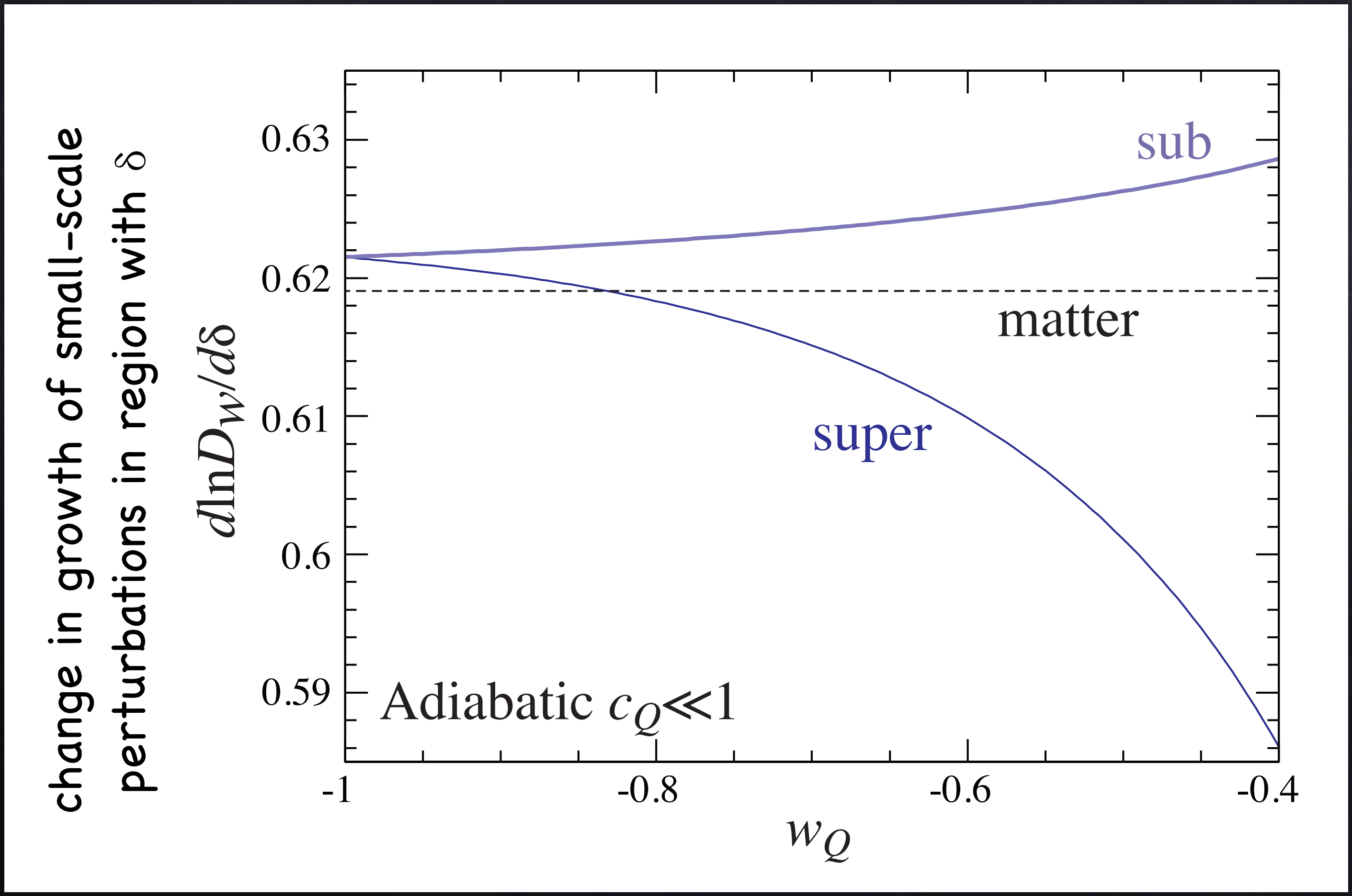

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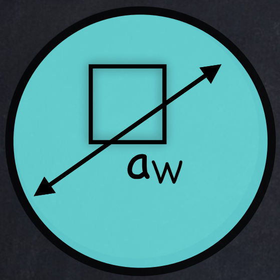
Application of the Fake Separate Universe Approach

$\delta_m > 0, \delta_Q = 0$



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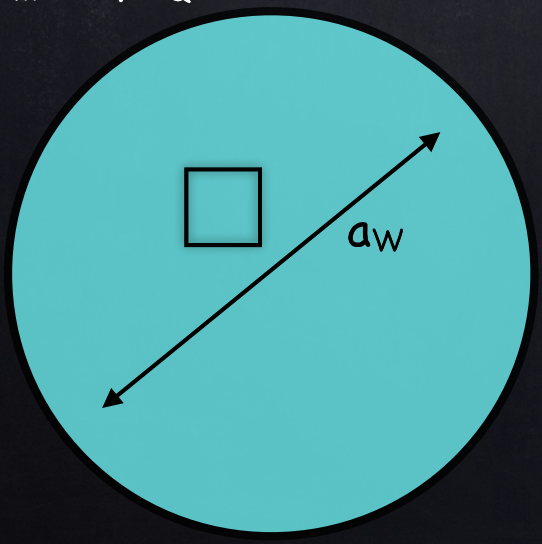
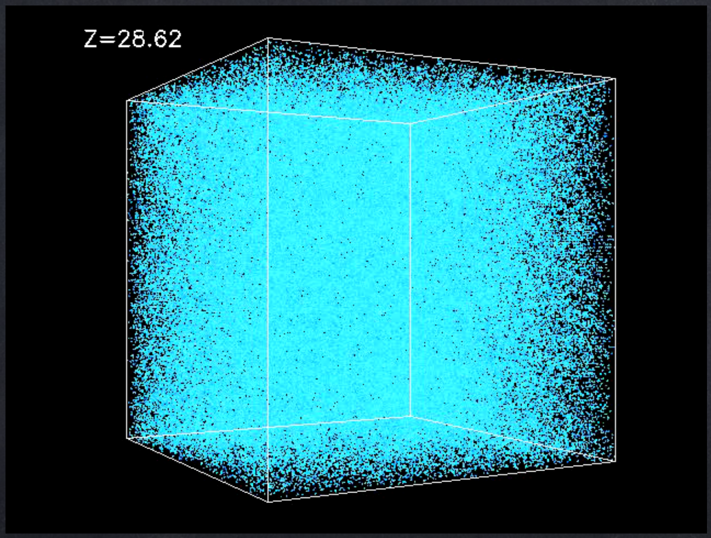


Run sims with each background evolution



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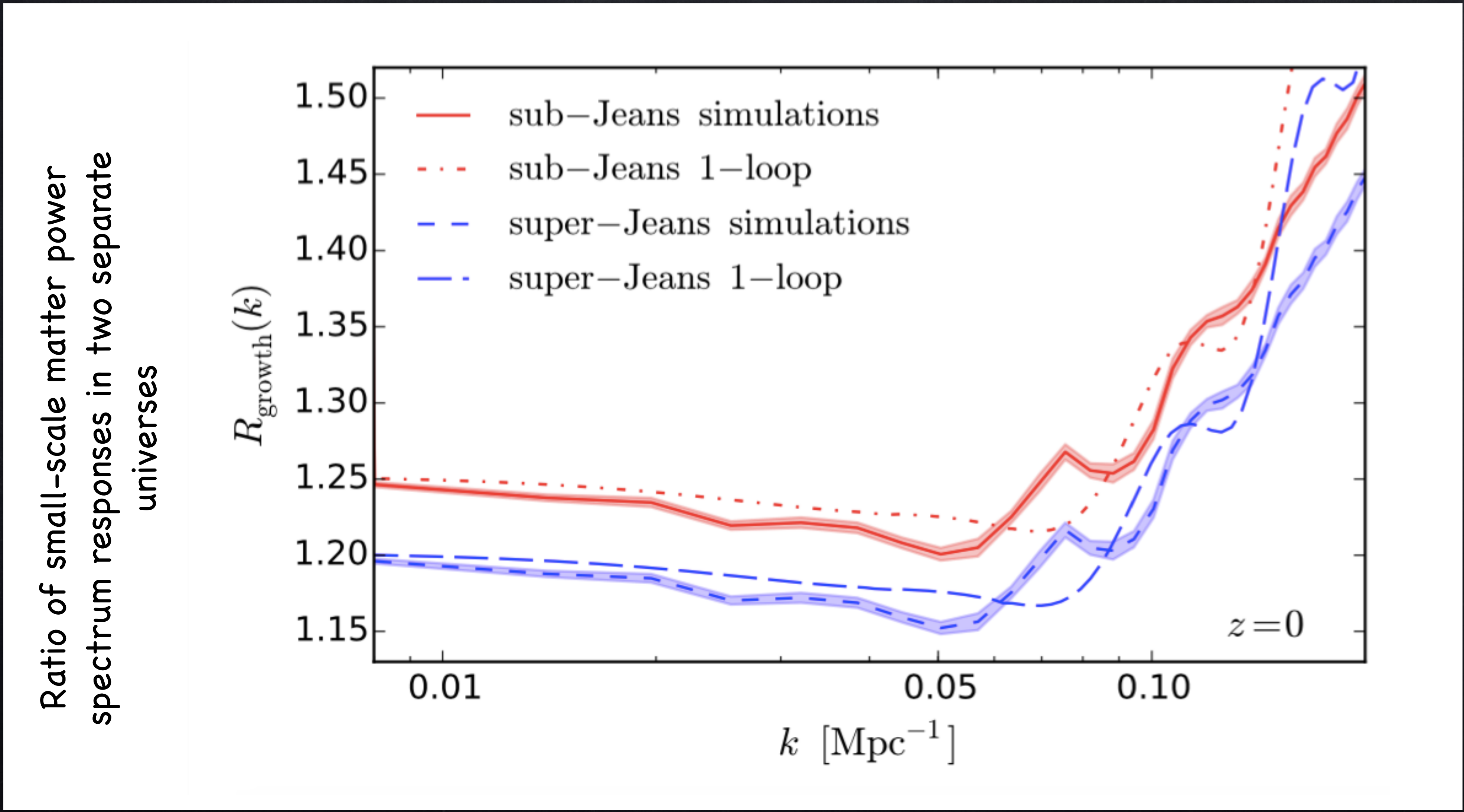
Application of the Fake Separate Universe

Amplitude of Power Spectrum is different at Final time



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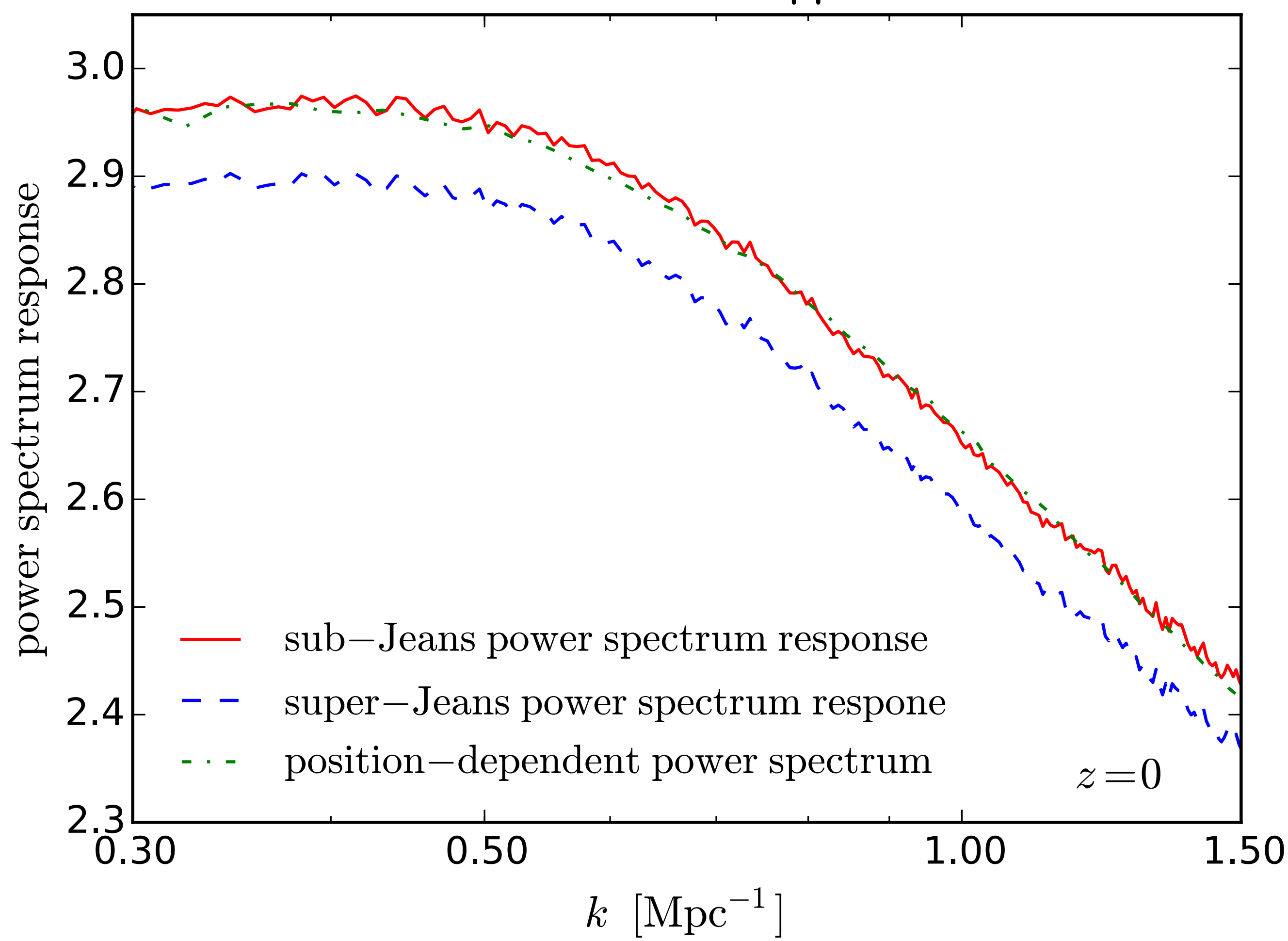
Application of the Fake Separate Universe

Amplitude of Power Spectrum is different at Final time

Separate Universe simulations agree with correlation between in power spectrum and environment in seen a larger box

Validation of the Approach



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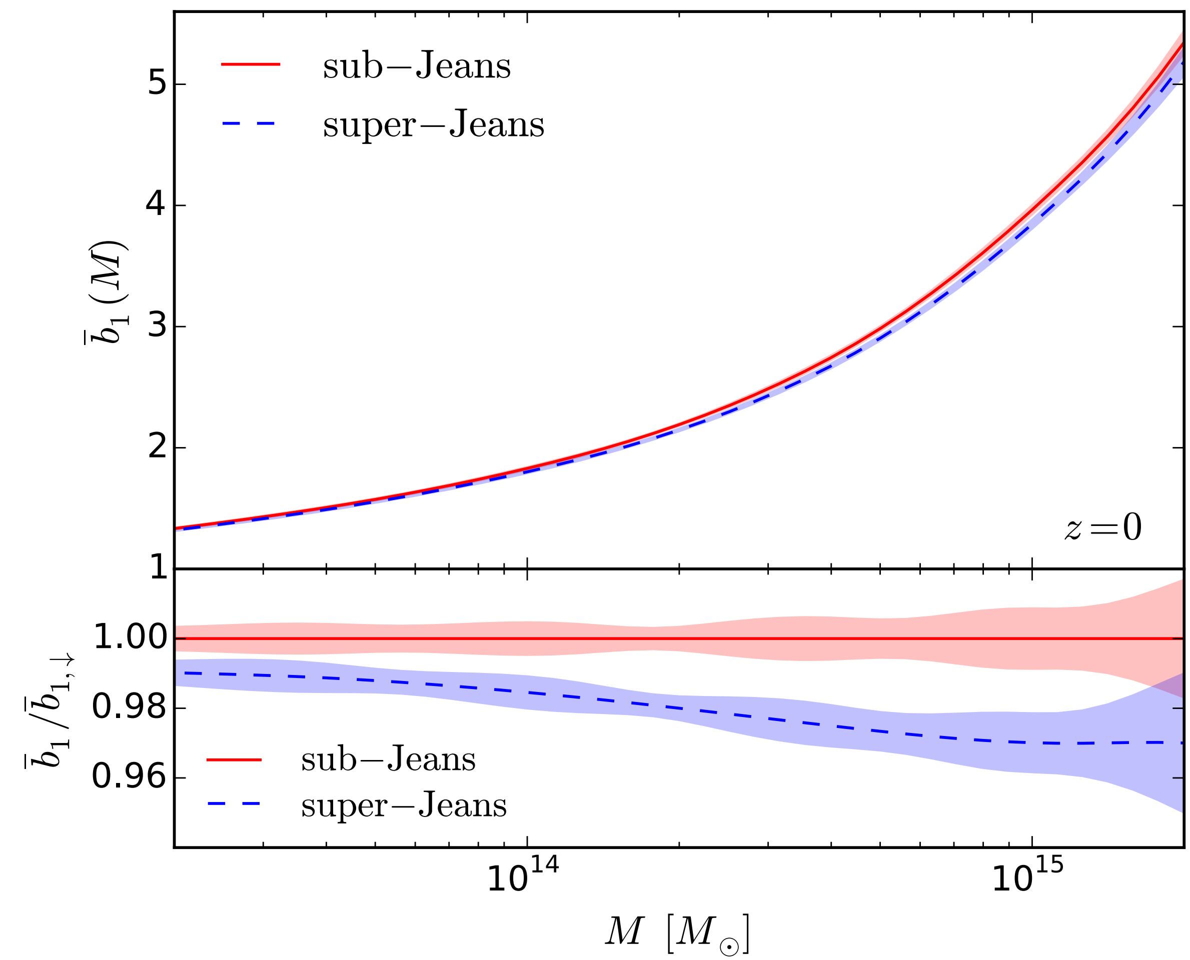
Application of the Fake Separate Universe

Abundance of Halos, and so halo bias b, is different at final time

Ratio of the change in the number density of halos in two separate universes



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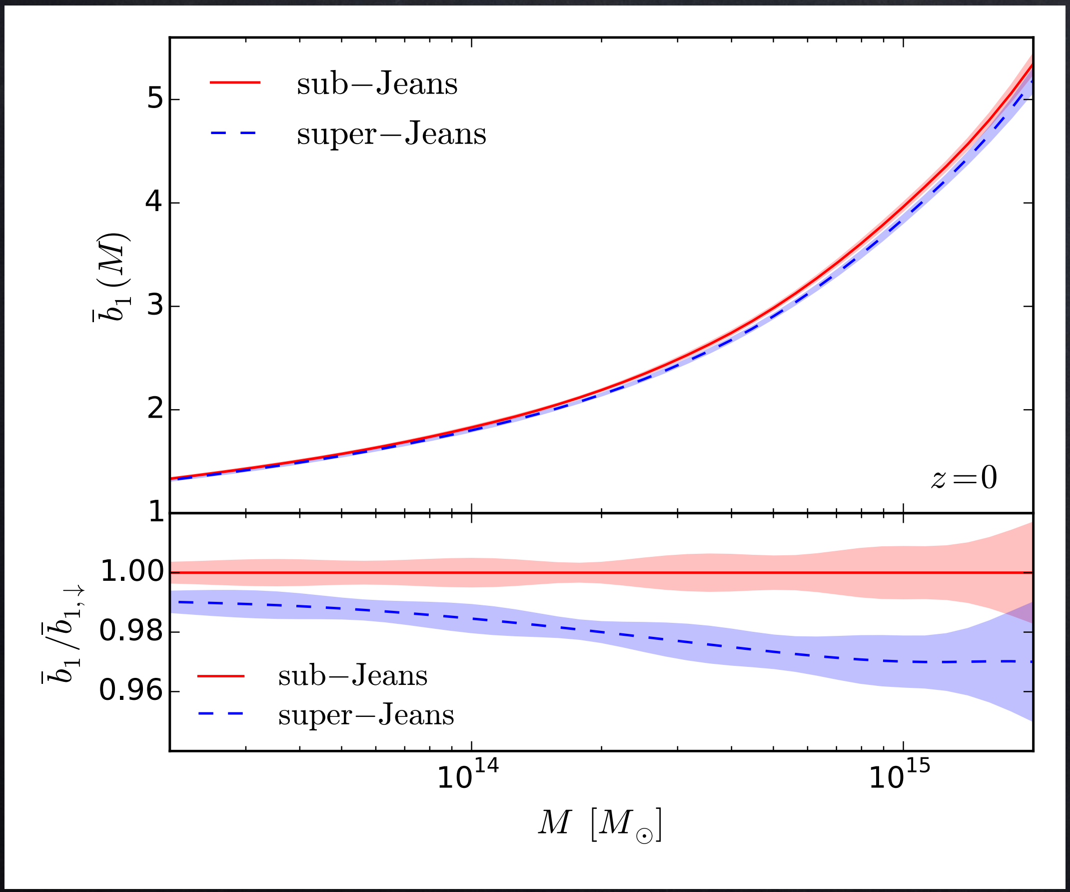
Application of the Fake Separate Universe

The difference between super and sub Jeans scale would correspond to a scale-dependent difference in non-linear quantities



e.g.

b ≈ $\langle\delta_h(x_1)\delta_m(x_2)\rangle / \langle\delta_m(x_1)\delta_m(x_2)\rangle$

for $|x_1 - x_2|$ < Jeans scale

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with b ≠ b

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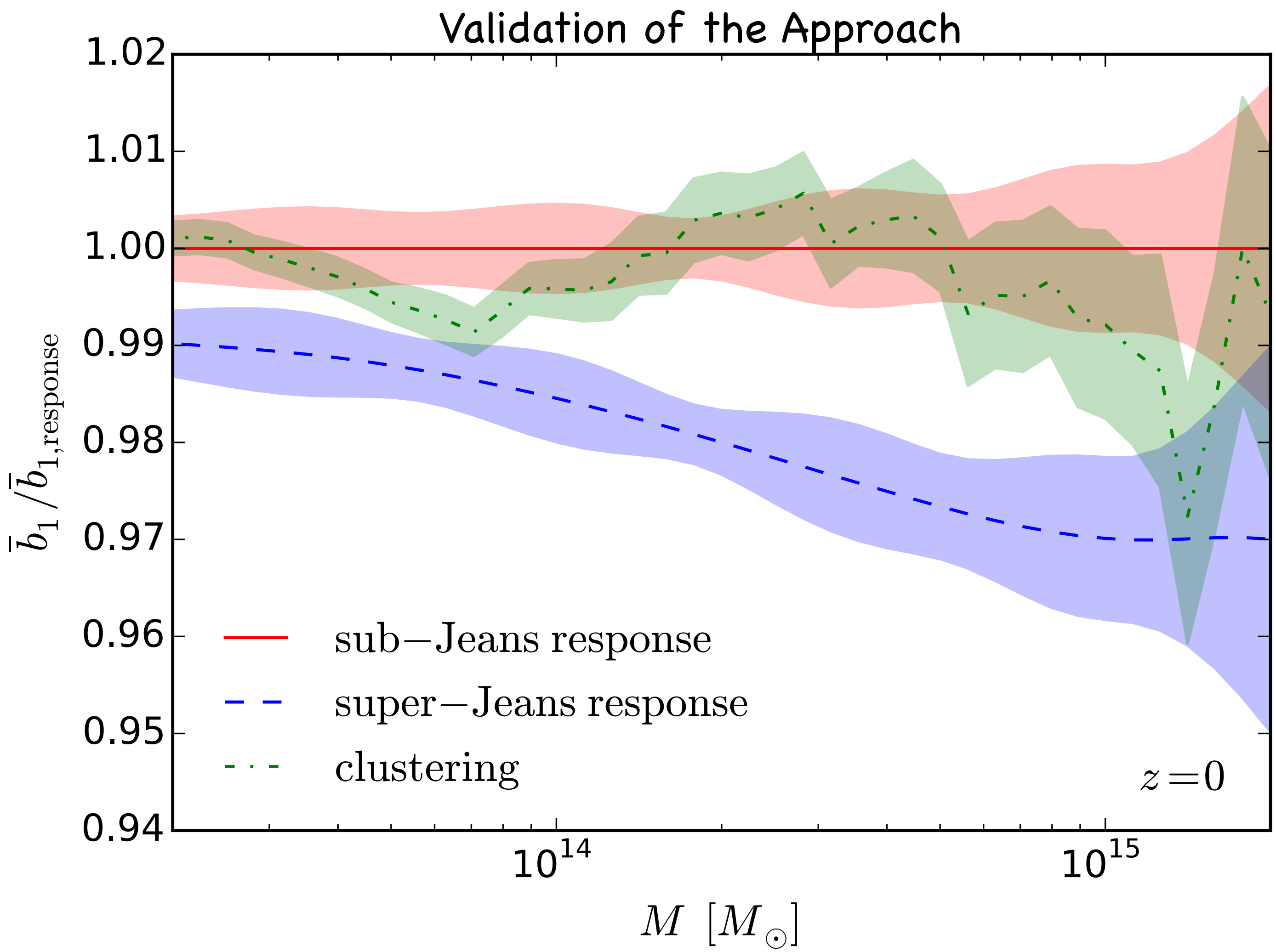
Application of the Fake Separate Universe

Separate Universe simulations agree with correlation between halo density and matter density



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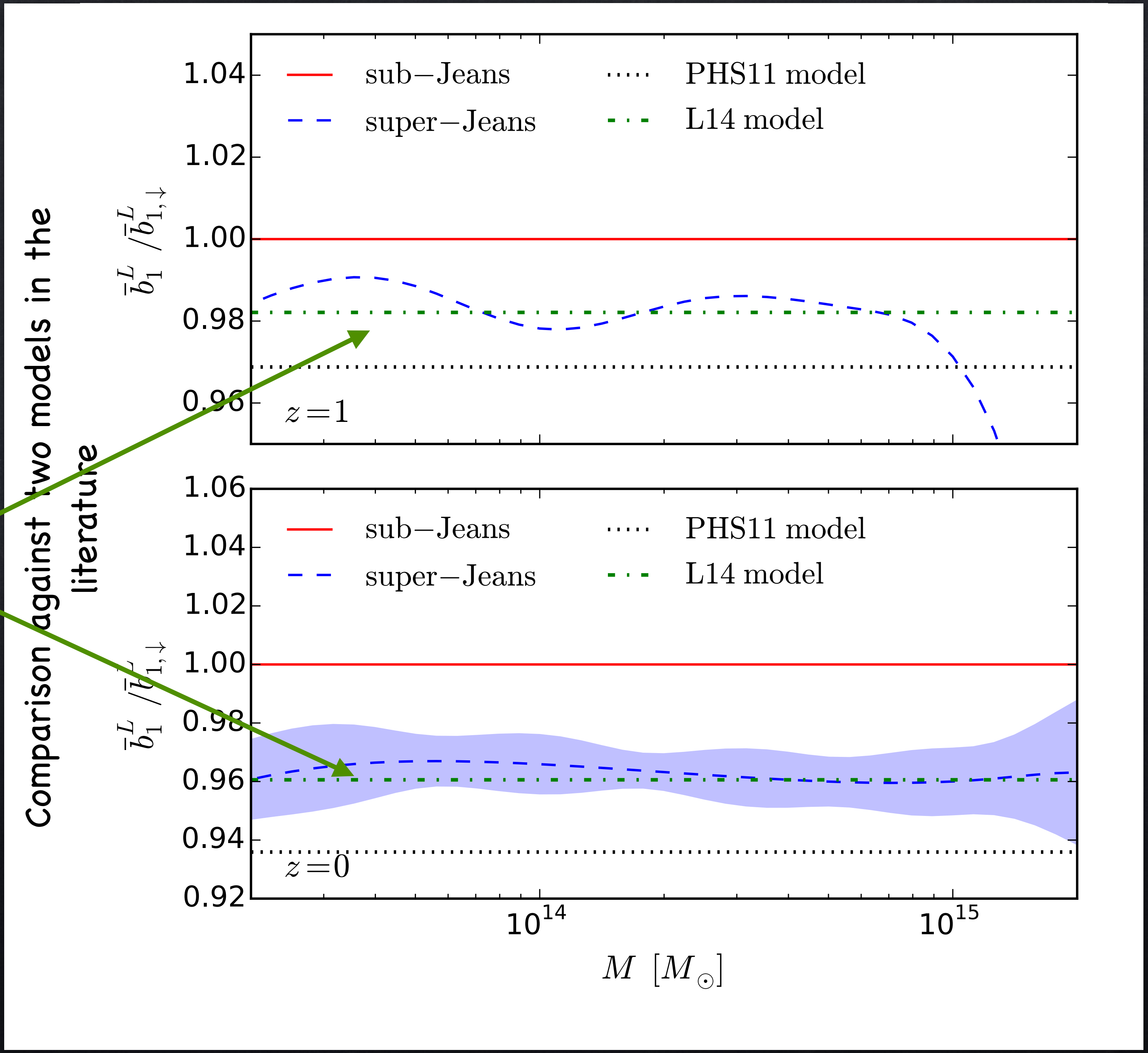
Application of the Fake Separate Universe

Our results are consistent with

$\Delta b_L / b_L$ = const

and with spherical cow model



Application of the Fake Separate Universe

Our results are consistent with

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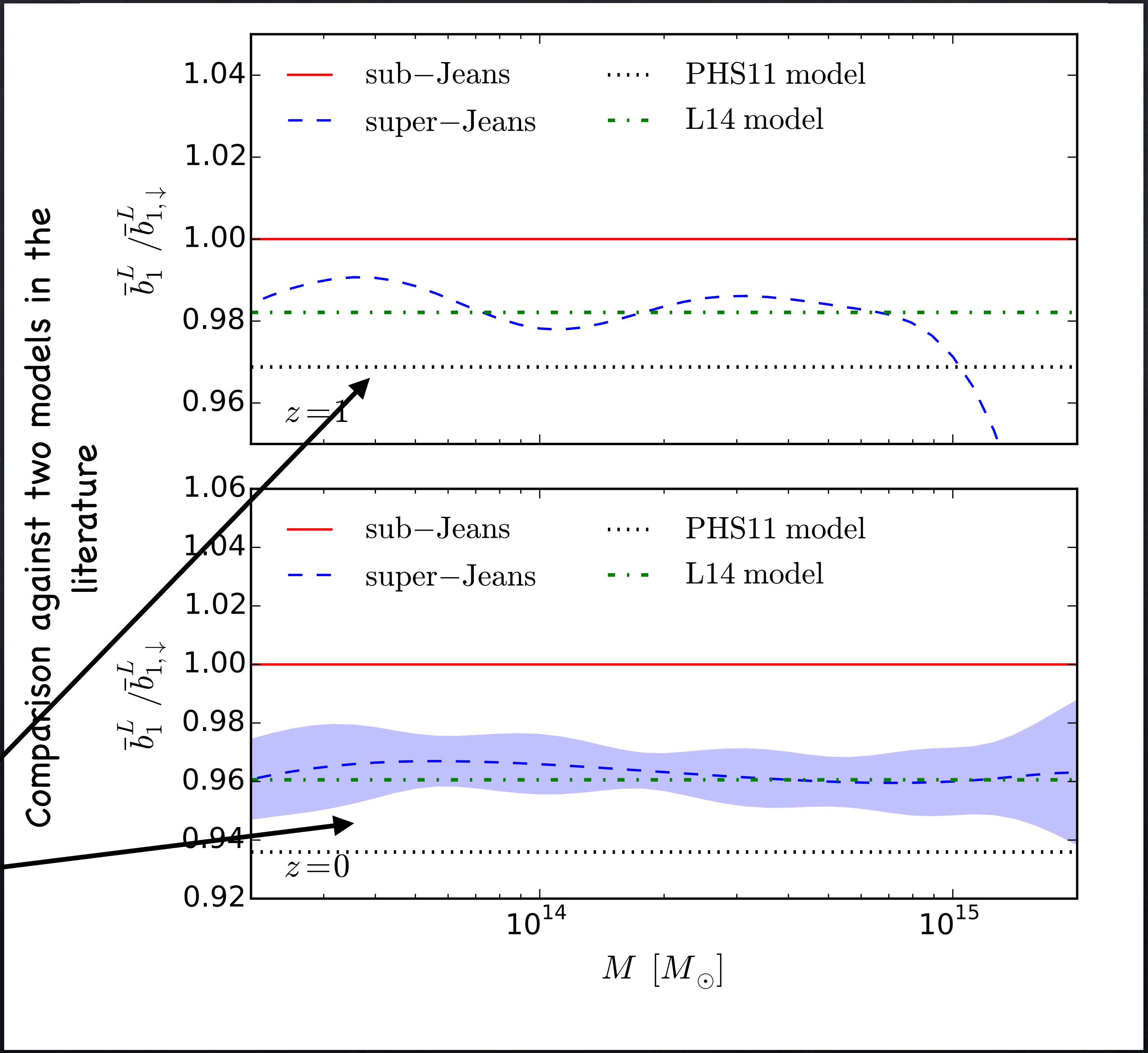
and are inconsistent with constant Lagrangian bias w.r.t initial $P_{mm}(k)$



Conclusions

- Nonlinear structure formation is complicated! But, can lead to new phenomena that may provide new insights into neutrinos, quintessence, and beyond!

Conclusions

- Nonlinear structure formation is complicated! But, can lead to new phenomena that may provide new insights into neutrinos, quintessence, and beyond!
- The separate universe can be extended to situations with non-gravitational forces and a Jeans scale
- This method provides a trick for being able to simulate (a limited set of important observables) in cosmologies with multiple fluids and non-gravitational forces
- The presence of a Jeans scale can lead to *new* observables (scale dependent bias, scale-dependent squeezed bispectrum)
- The distinction between super/sub-Jeans observables can be understood as a difference in the local expansion history in the two regimes - *a local model of halo bias can not capture this*