Title: Structure Formation in a nuCDM Universe

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Abstract: Cosmic background neutrinos are nearly as abundant as cosmic microwave background photons, but their mass, which determines the strength of their gravitational clustering, is unknown. Neutrino oscillation data gives a strict lower limit on neutrino mass, while cosmological datasets provide the most stringent upper limit. Even if the neutrino masses are the minimum required by oscillation data, their gravitational effects on structure formation will nevertheless be detectable in â€” and in fact required to explain â€” data within the next decade. I will discuss the physical effects of the cosmic neutrino background on structure formation and present a new signature that may be used to measure neutrino mass with large galaxy surveys.

Structure Formation in νCDM

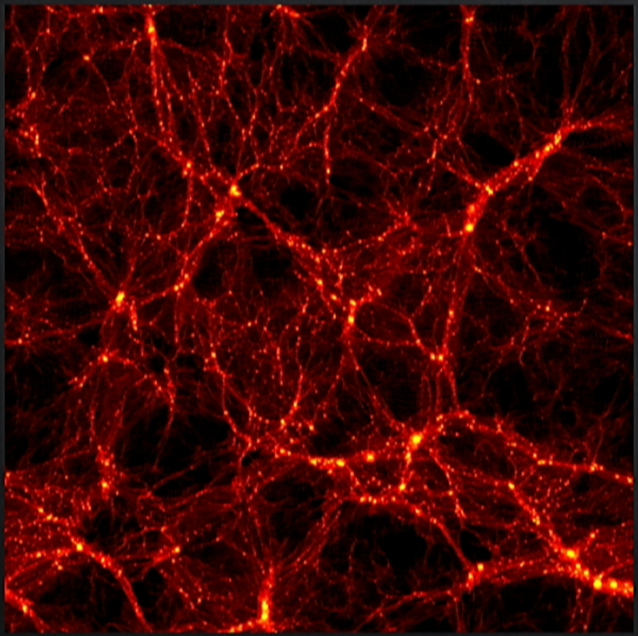
Marilena LoVerde
C. N. Yang Institute for Theoretical Physics, Stony Brook University

Outline

- Neutrino CDM Universe!
- Neutrino effects in large-scale structure: The linear regime
- *NEW* neutrino effects in large-scale structure
- Conclusion

Large-scale Structure

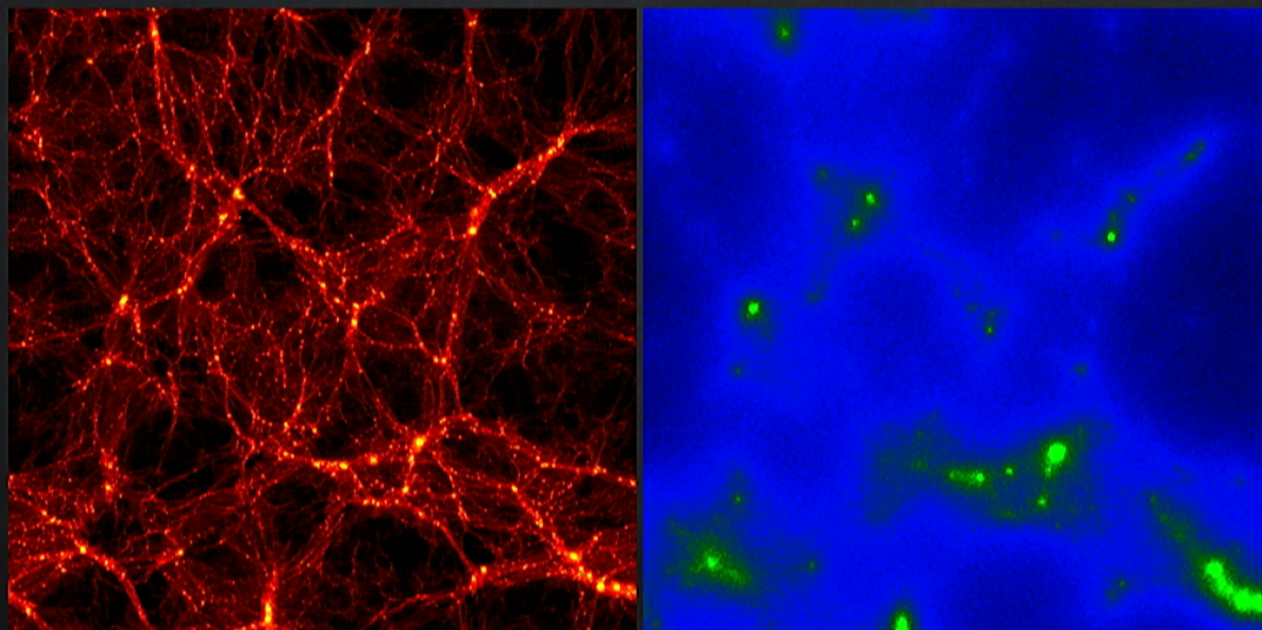
cold dark matter



(Villaescusa-Navarro, Bird, Pena-Garay, Viel 2013)

Large-scale Structure

cold dark matter | neutrino dark matter



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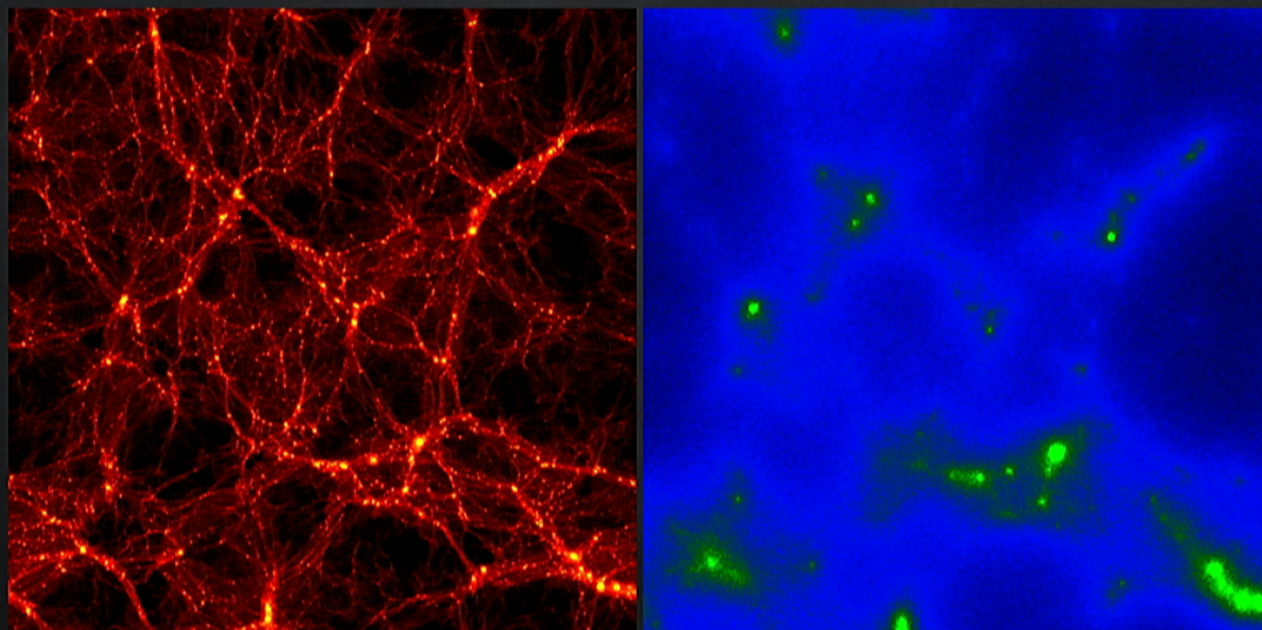
Large-scale Structure

cold dark matter | neutrino dark matter



$$\frac{\rho_\nu}{\rho_{cdm} + \rho_{baryon} + \rho_\nu} \gtrsim 0.005 \qquad n_\nu \sim 10^{10} n_{baryon}$$

(Villaescusa-Navarro, Bird, Pena-Garay, Viel 2013)

Neutrinos: what do we know?

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

Neutrinos: what do we know?

flavor eigenstates mass eigenstates

flavor eigenstates ≠ mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

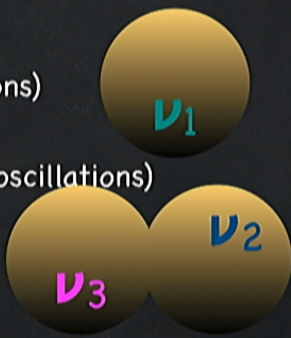
Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962

Neutrinos: what do we know?

Oscillation data gives mass splittings

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

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



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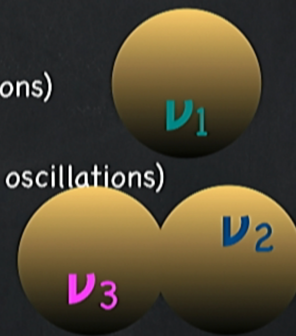

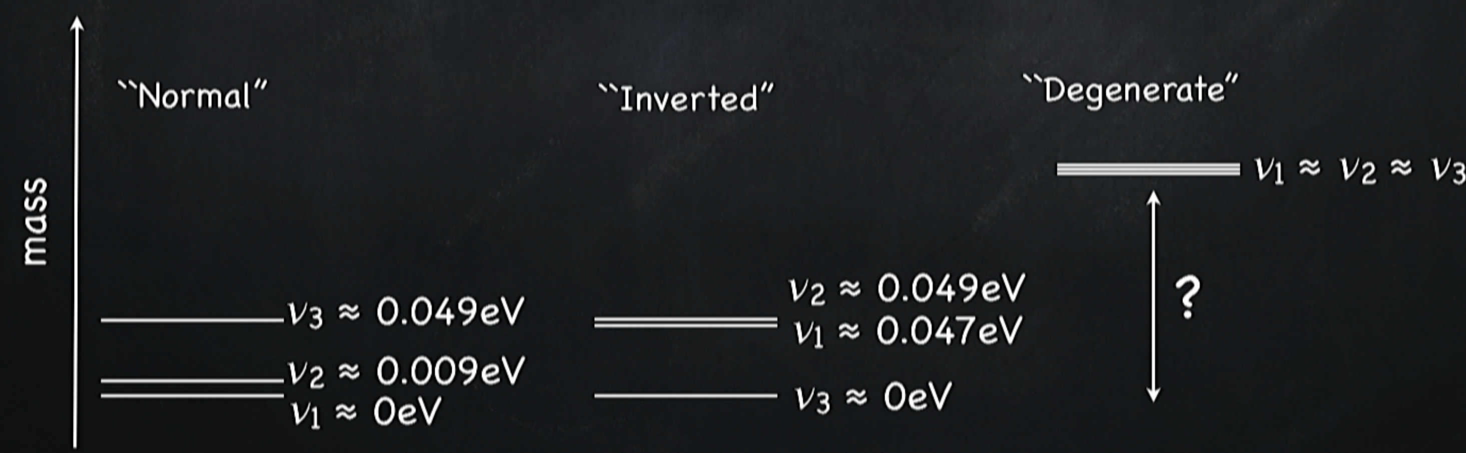

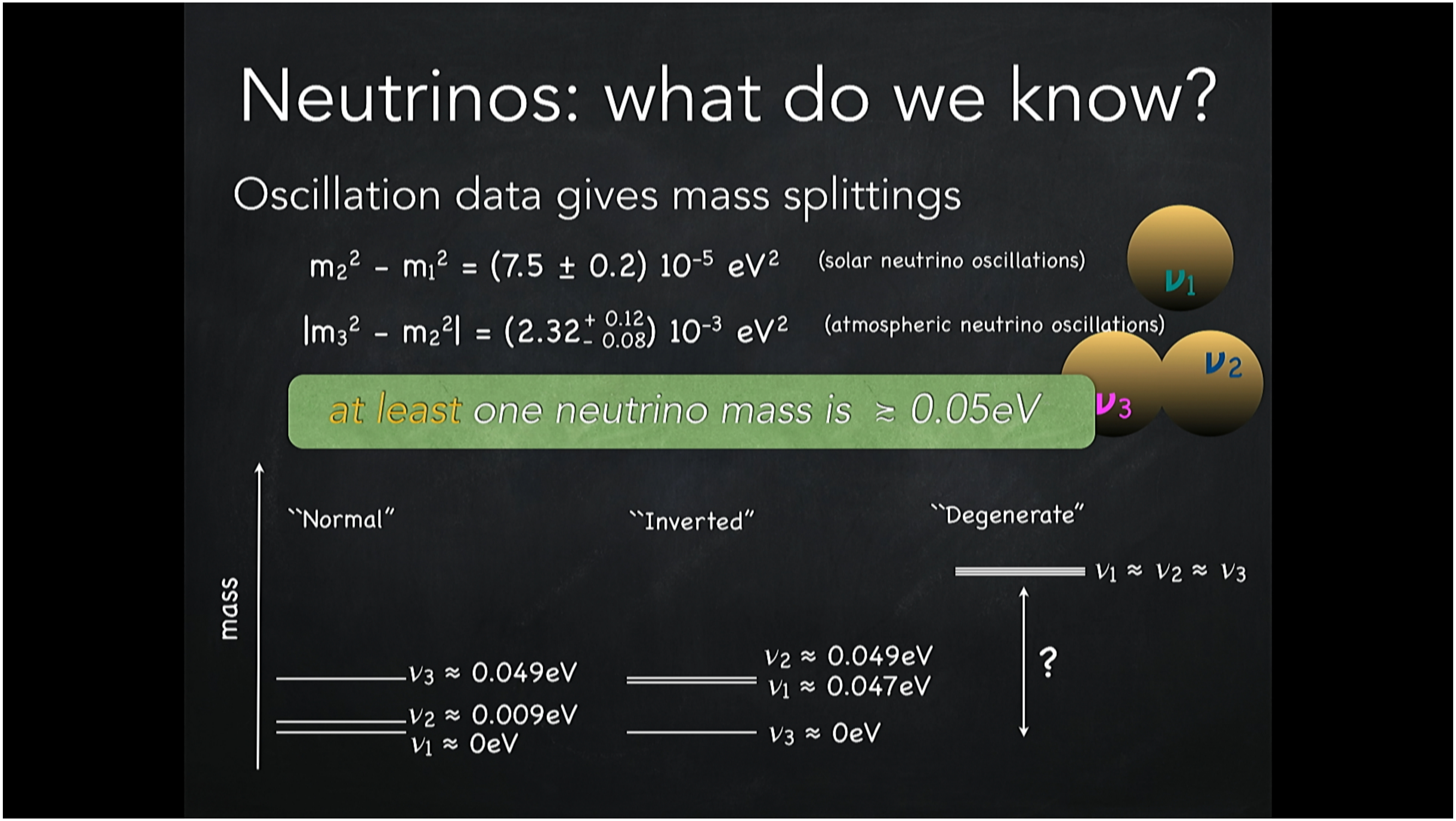
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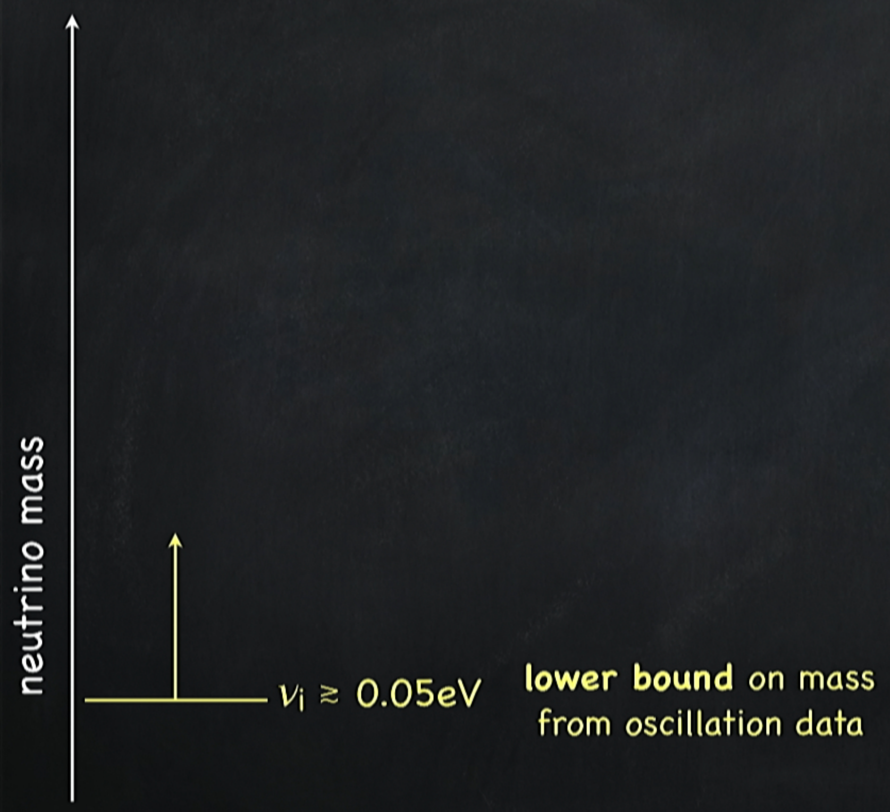
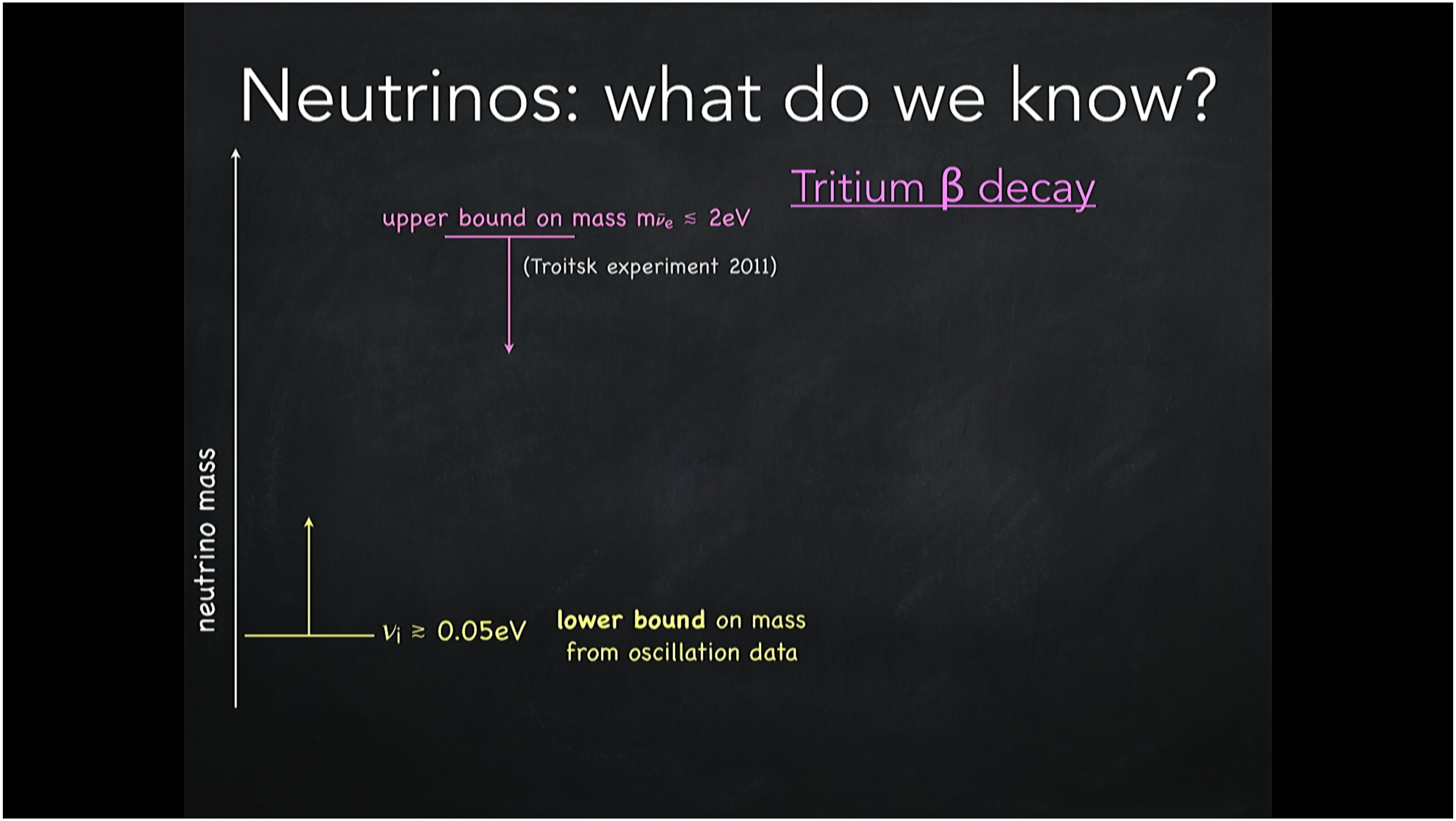
Oscillation data gives mass splittings
m2² - m1² = (7.5 ± 0.2) 10⁻⁵ eV²
(solar neutrino oscillations)
|m3² - m2²| = (2.32 +0.12 -0.08) 10⁻³ eV²
(atmospheric neutrino oscillations)
ν1
ν2
ν3
at least one neutrino mass is ≳ 0.05eV
mass
"Normal"
ν3 ≈ 0.049eV
ν2 ≈ 0.009eV
ν1 ≈ 0eV
"Inverted"
ν2 ≈ 0.049eV
ν1 ≈ 0.047eV
ν3 ≈ 0eV
"Degenerate"
ν1 ≈ ν2 ≈ ν3
?

Neutrinos: what do we know?




Neutrinos: what do we know?
Tritium β decay
upper bound on mass $m_{\bar{\nu}_e} \lesssim 2eV$
(Troitsk experiment 2011)
neutrino mass
$\nu_i \gtrsim 0.05eV$
lower bound on mass
from oscillation data

Neutrinos: what do we know?

Tritium β decay

upper bound on mass $m_{\bar{\nu}_e} \lesssim 2eV$

(Troitsk experiment 2011)

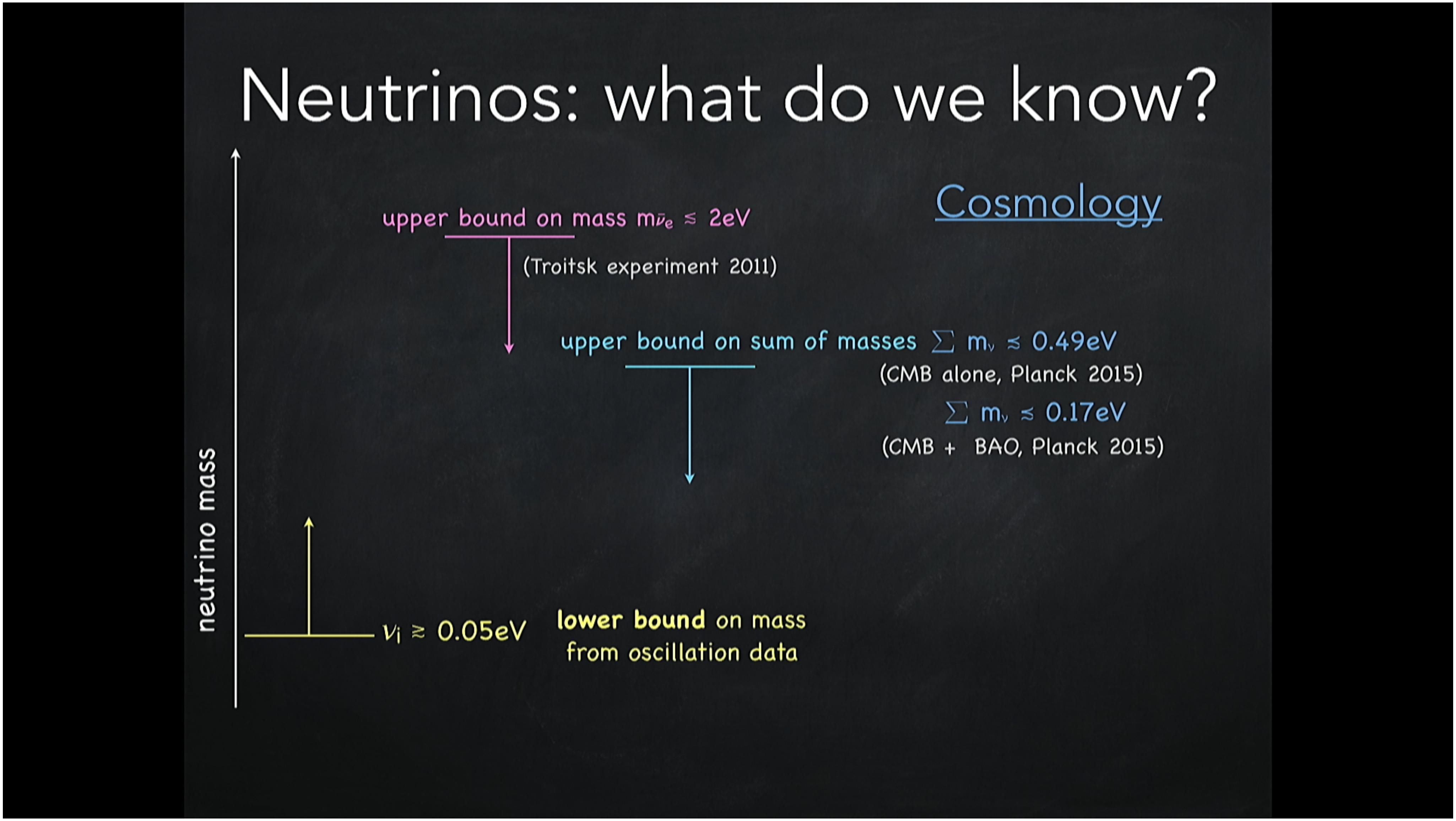
future upper bound on mass $m_{\bar{\nu}_e} \lesssim 0.2eV$

(KATRIN/Project 8/PTOLEMY 20xx?)

neutrino mass

$\nu_i \gtrsim 0.05eV$

lower bound on mass
from oscillation data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Cosmology
upper bound on mass $m_{\bar{\nu}_e} \lesssim 2eV$
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upper bound on sum of masses $\sum m_\nu \lesssim 0.49eV$
(CMB alone, Planck 2015)
$\sum m_\nu \lesssim 0.17eV$
(CMB + BAO, Planck 2015)
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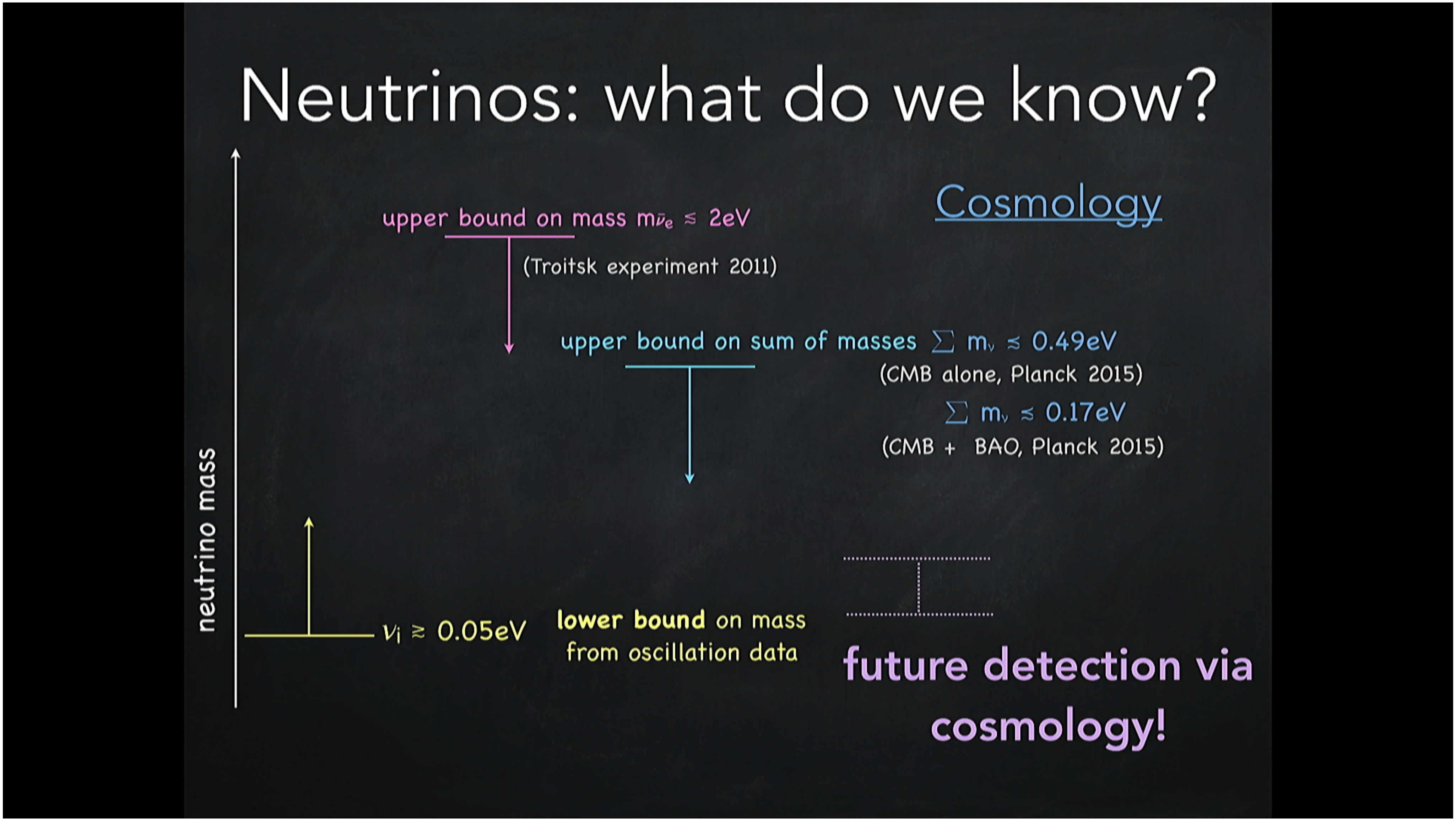

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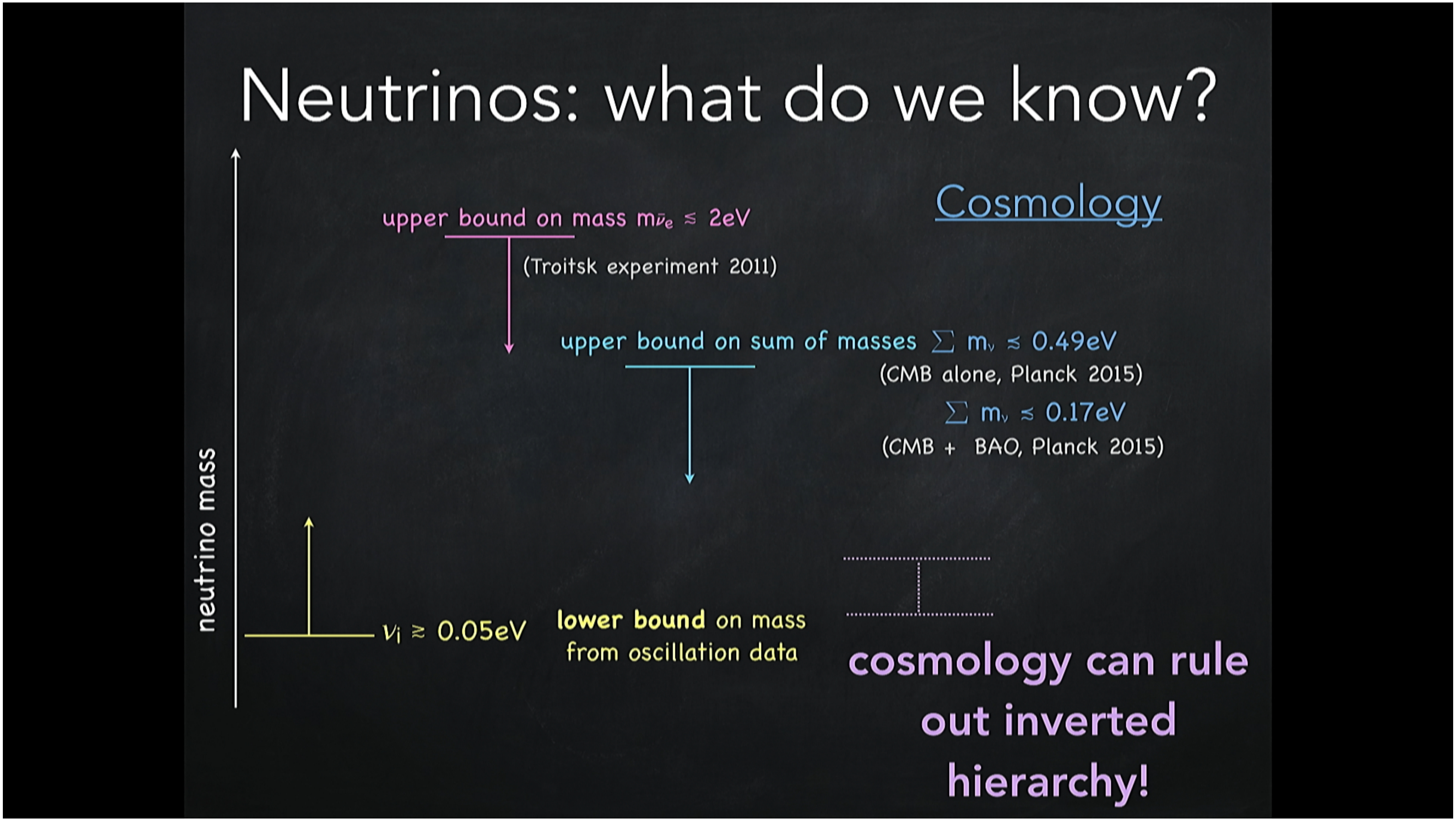
lower bound on mass
from oscillation data
future detection via
cosmology!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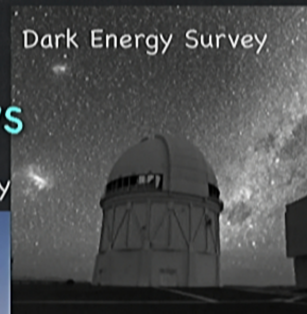
neutrino mass
$\nu_i \gtrsim 0.05eV$
lower bound on mass
from oscillation data
cosmology can rule
out inverted
hierarchy!

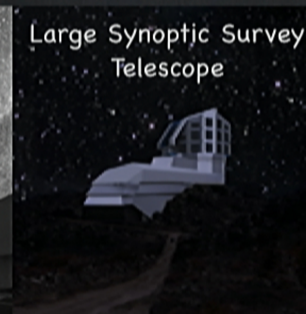
Future detection via astrophysical datasets

Large-scale structure surveys

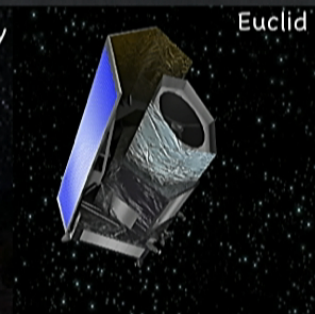
Dark Energy Survey



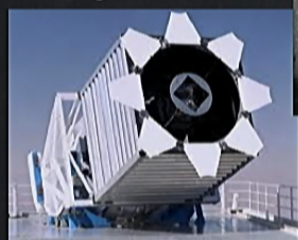
Large Synoptic Survey Telescope



Euclid

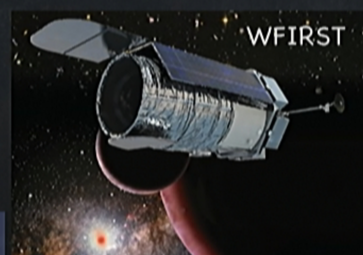


Sloan Digital Sky Survey



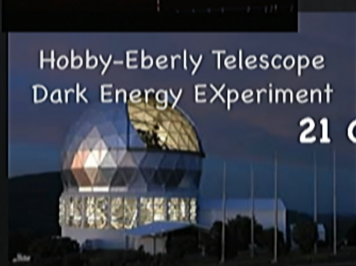
Subaru Hyper Suprime Cam and Prime Focus Spectrograph

WFIRST

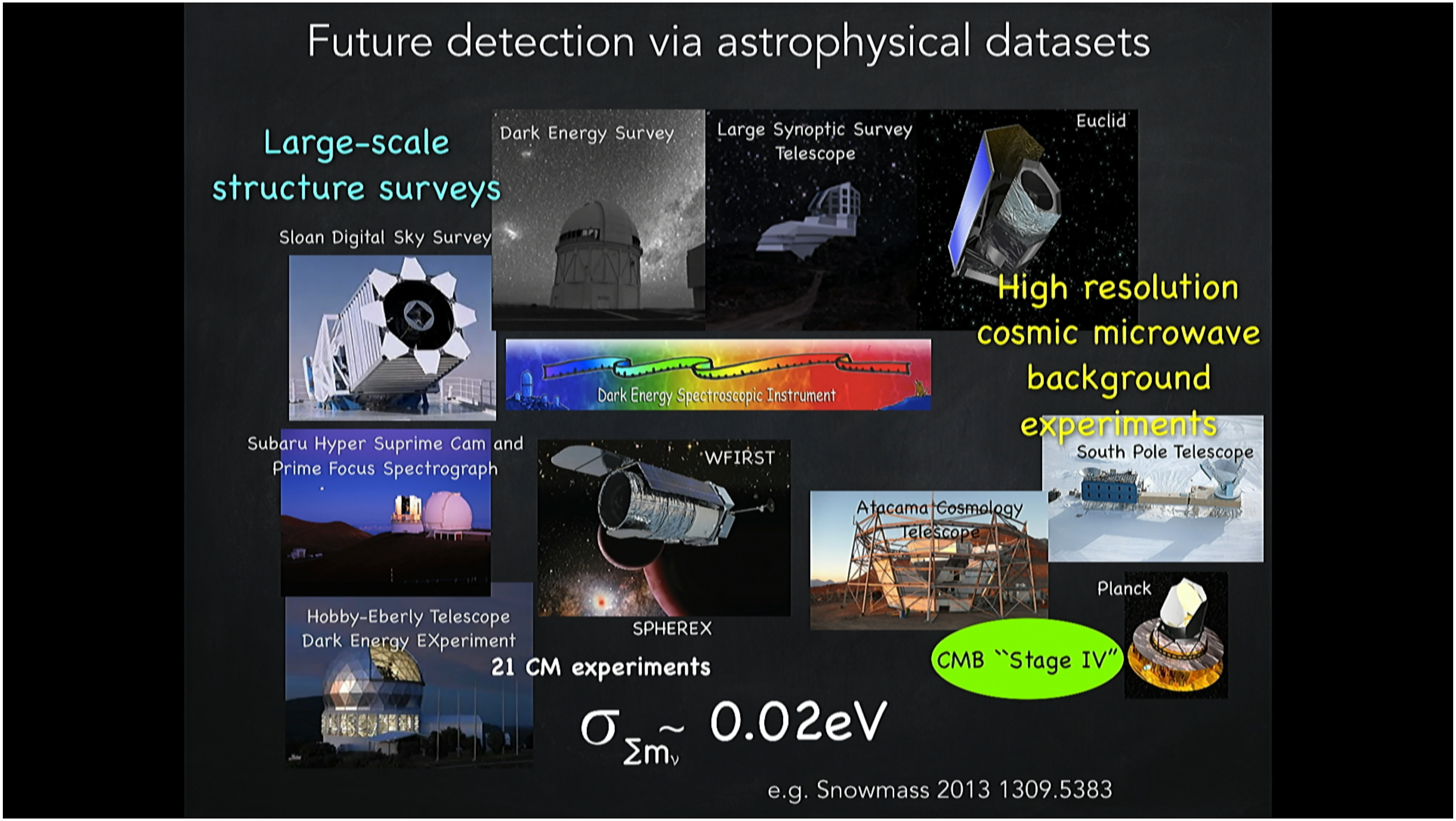


SPHEREX

Hobby-Eberly Telescope Dark Energy EXperiment

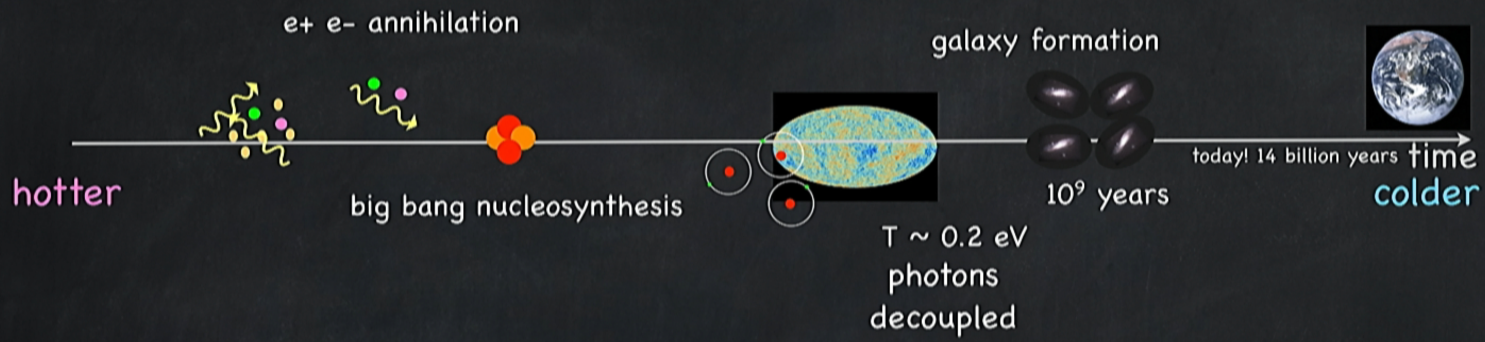


21 CM experiments


Future detection via astrophysical datasets
Large-scale structure surveys
Dark Energy Survey
Large Synoptic Survey Telescope
Euclid
Sloan Digital Sky Survey
High resolution cosmic microwave background experiments
Dark Energy Spectroscopic Instrument
Subaru Hyper Suprime Cam and Prime Focus Spectrograph
WFIRST
South Pole Telescope
Atacama Cosmology Telescope
Planck
Hobby-Eberly Telescope Dark Energy EXperiment
SPHEREX
21 CM experiments
CMB ``Stage IV"
$\sigma_{\Sigma m_\nu} \sim 0.02\,\text{eV}$
e.g. Snowmass 2013 1309.5383

Neutrinos in Cosmology

Neutrinos in Thermal History of the Universe



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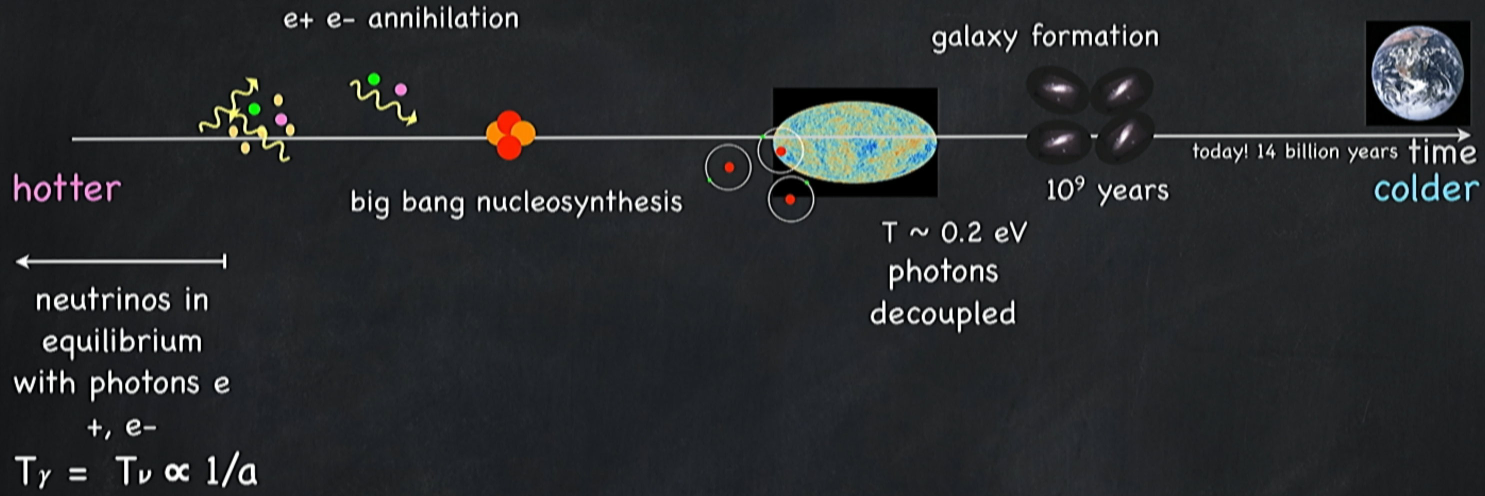

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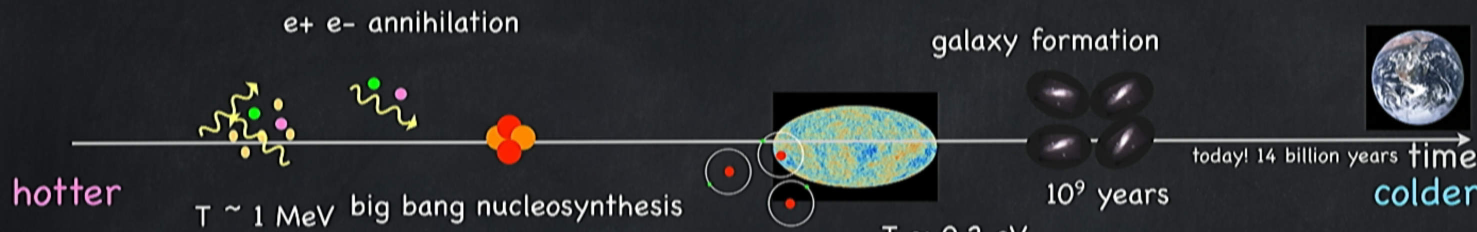


T ~ 0.2 eV
photons
decoupled

neutrinos in equilibrium with photons e+, e-

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

neutrinos decoupled

$T_\nu \propto 1/a$

decouple while relativistic

$$n_{1\nu} = 2 \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{p/T_\nu} + 1} \sim T_\nu^3$$

$$\rho_{1\nu} = 2 \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2 + m^2}}{e^{p/T_\nu} + 1} \sim T_\nu^4$$

Neutrinos in Thermal History of the Universe

Total energy density in radiation:

$$\rho_{radiation} = \frac{\pi^2}{30}\left(2T_\gamma^4 + \frac{7}{8}(N_{eff} \times 2)\, T_\nu^4\right)$$

cosmic microwave background

cosmic neutrino background

Neutrinos in Thermal History of the Universe

Total energy density in radiation:

$$\rho_{radiation} = \frac{\pi^2}{30}\left(2T_\gamma^4 + \frac{7}{8}(N_{eff} \times 2)\, T_\nu^4\right)$$

cosmic microwave background → $2T_\gamma^4$

cosmic neutrino background → T_ν^4 term

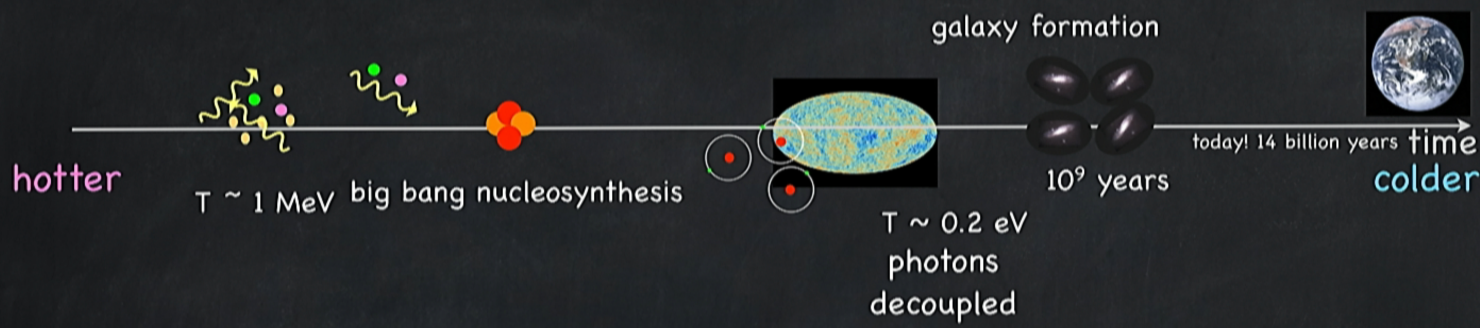
measurements of the radiation density in the early universe can be used to test the number of neutrino-like degrees of freedom

N_{eff} =	3.13 ± 0.32	*Planck* TT+lowP ;
N_{eff} =	3.15 ± 0.23	*Planck* TT+lowP+BAO ;
N_{eff} =	2.99 ± 0.20	*Planck* TT, TE, EE+lowP ;
N_{eff} =	3.04 ± 0.18	*Planck* TT, TE, EE+lowP+BAO .

The expected number of neutrino species is seen in the CMB!

Planck 2015

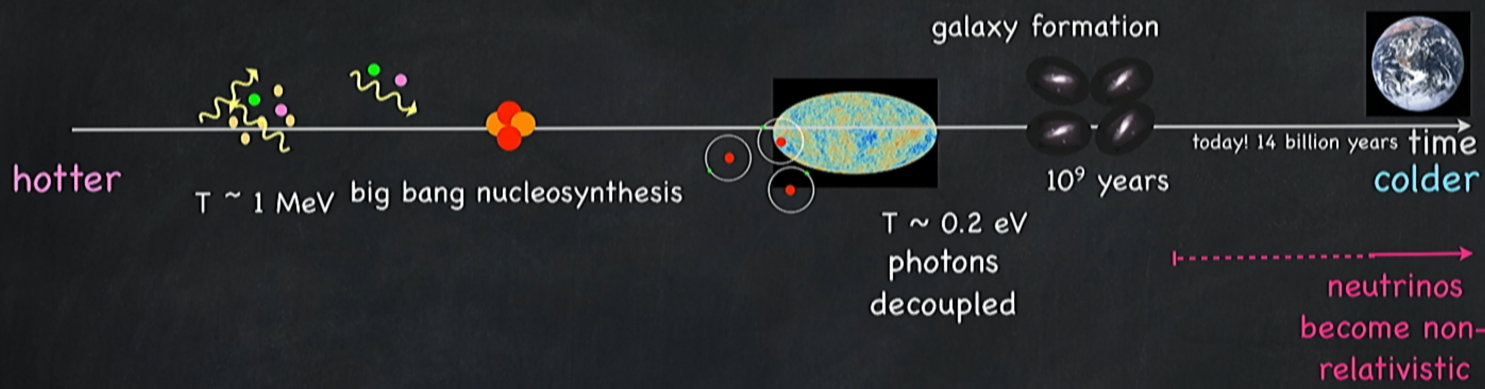
Neutrinos in Thermal History of the Universe



Neutrino momenta decrease with the expansion of the universe

$$p_\nu \propto 1/a$$

Neutrinos in Thermal History of the Universe



Neutrino momenta decrease with the expansion of the universe

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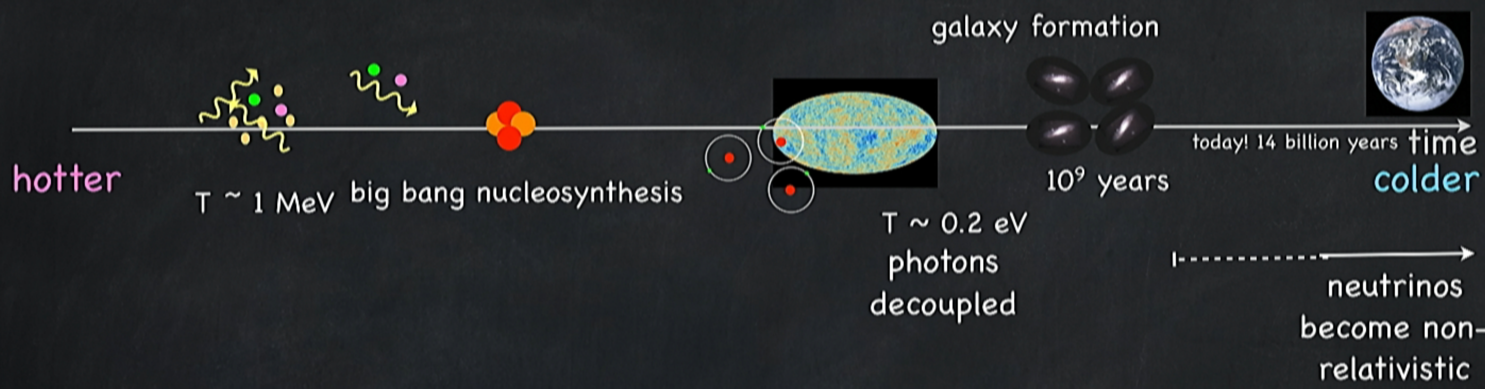
When $p_\nu \ll m_\nu$, neutrinos are non-relativistic
and energy density is dominated by mass

Neutrinos in Thermal History of the Universe



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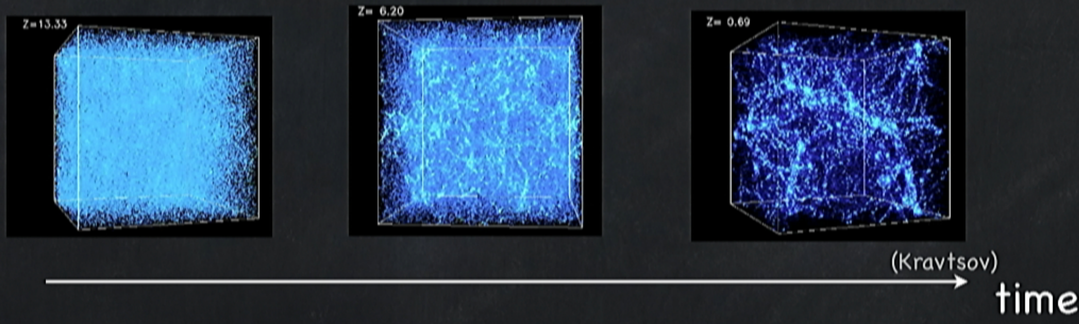
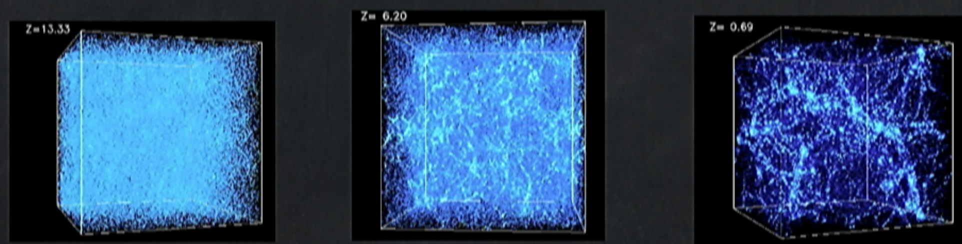
neutrino energy density, $\rho_\nu \propto \Sigma$ (number density) m_ν

Neutrinos in Large-scale Structure



Neutrinos in Large-scale Structure



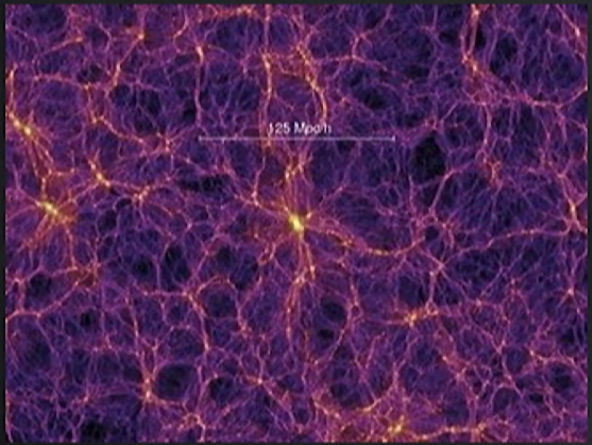
(Kravtsov)

time

massive neutrinos alter this process

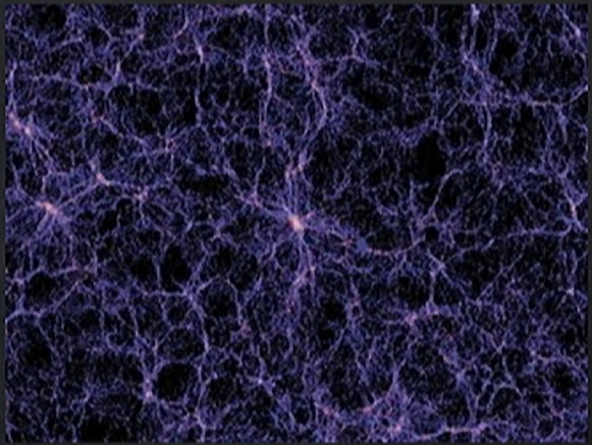
Large-scale Structure

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



(Springel)

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



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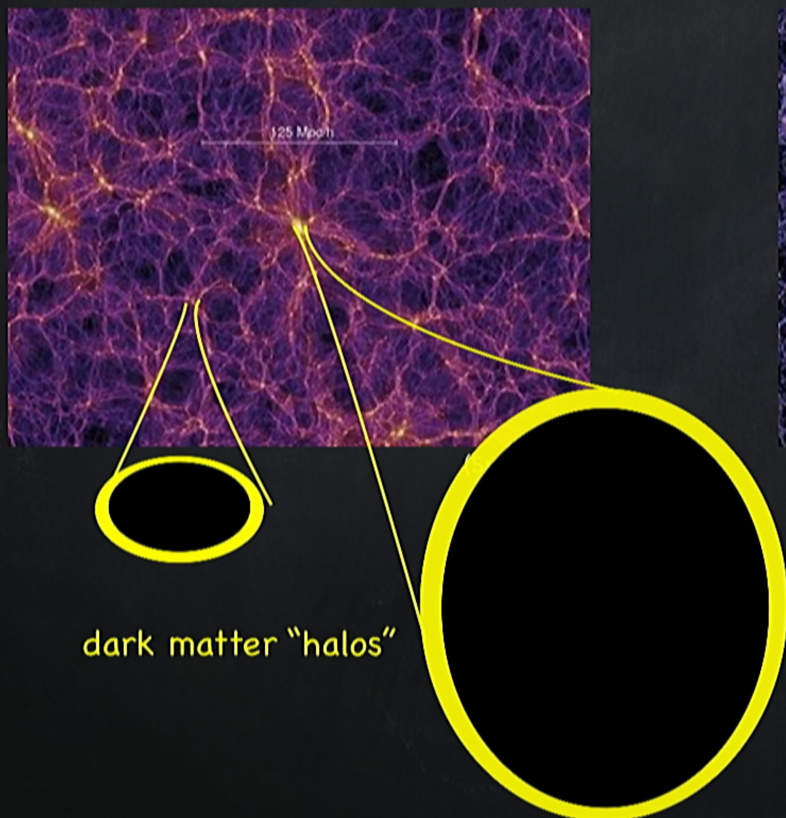

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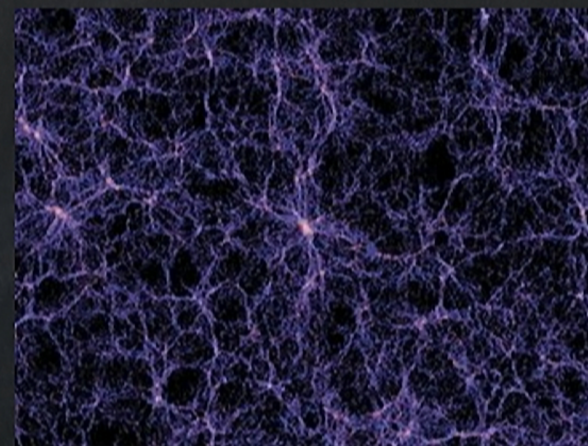
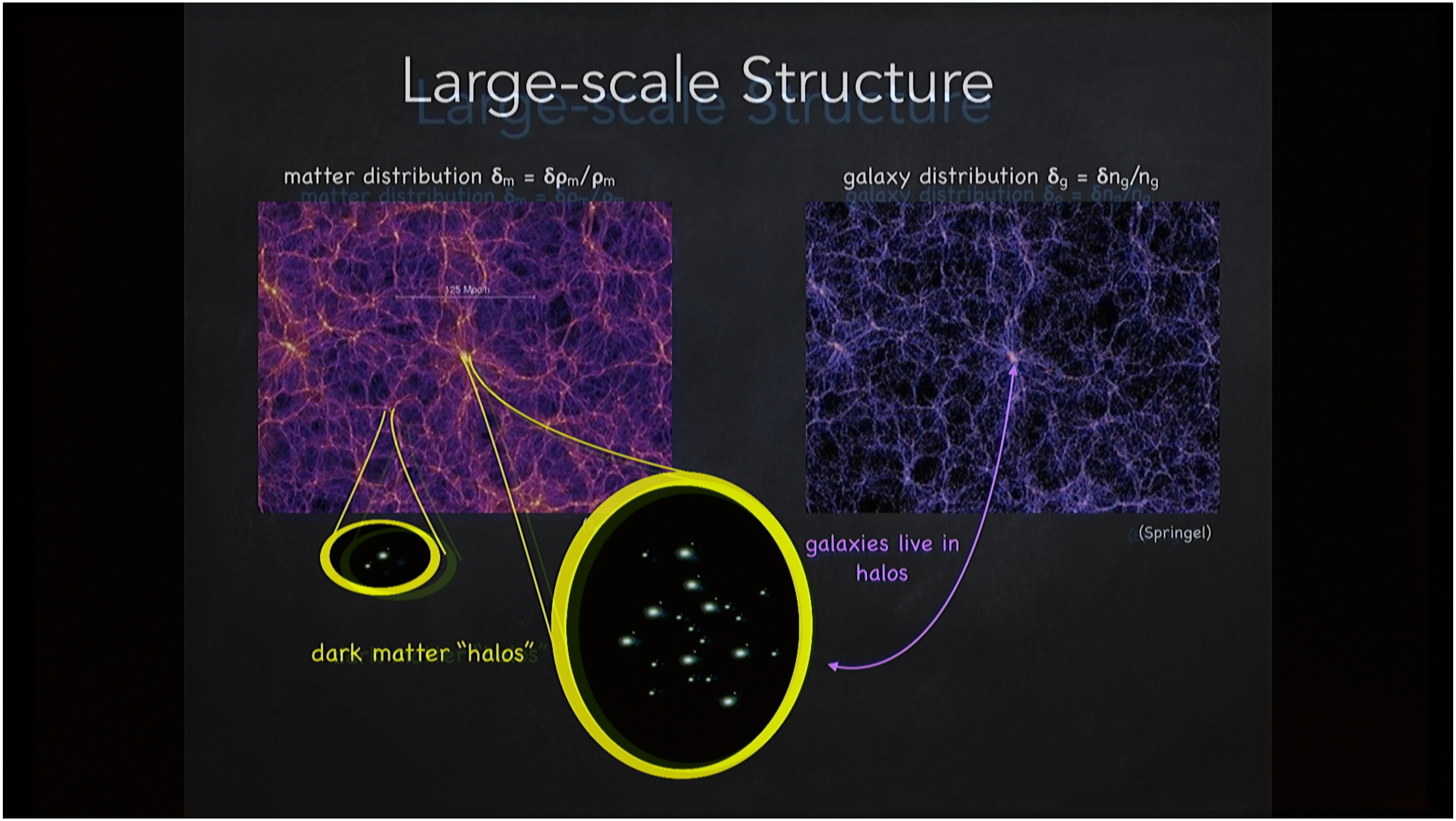
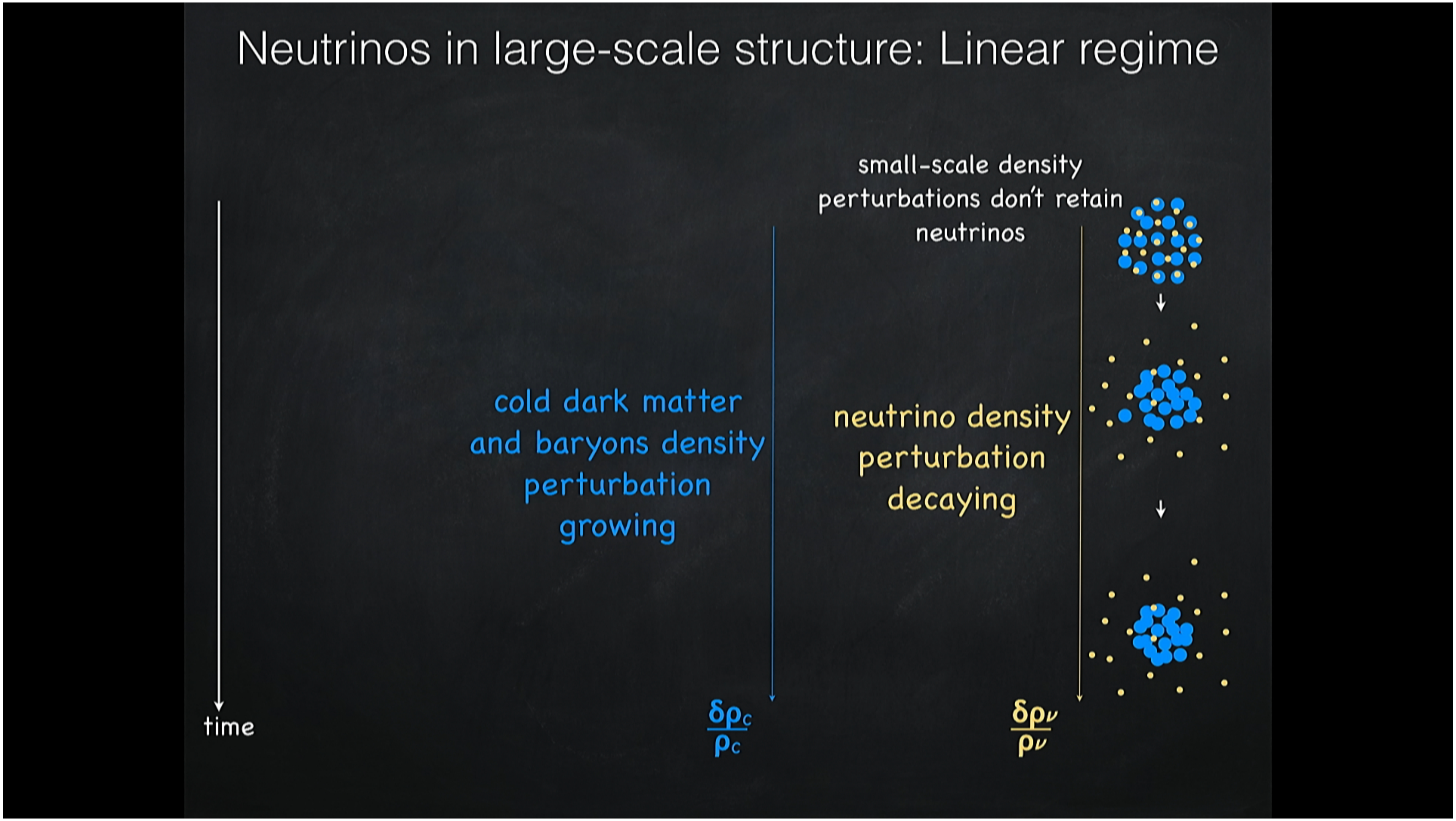


(Springel)

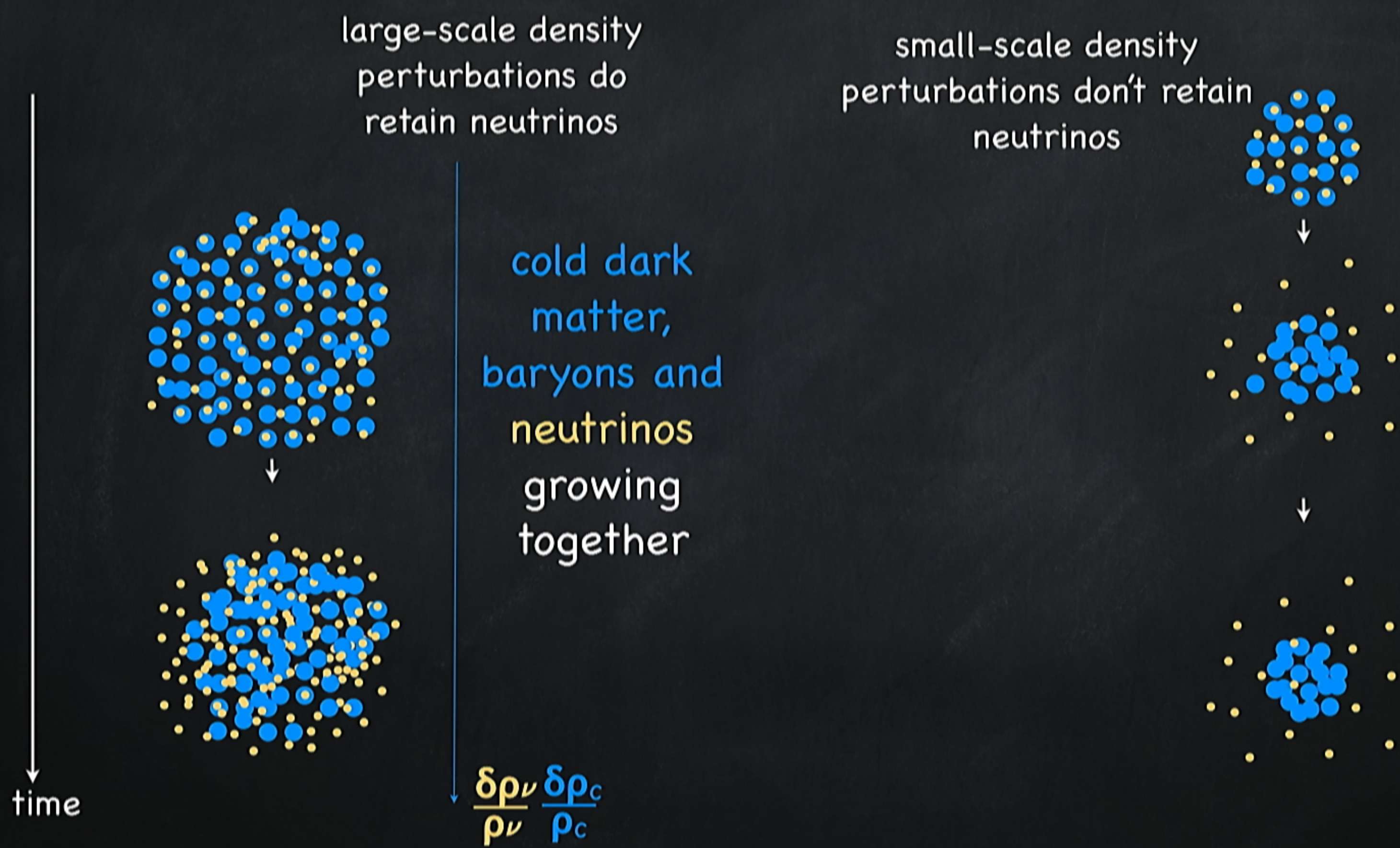


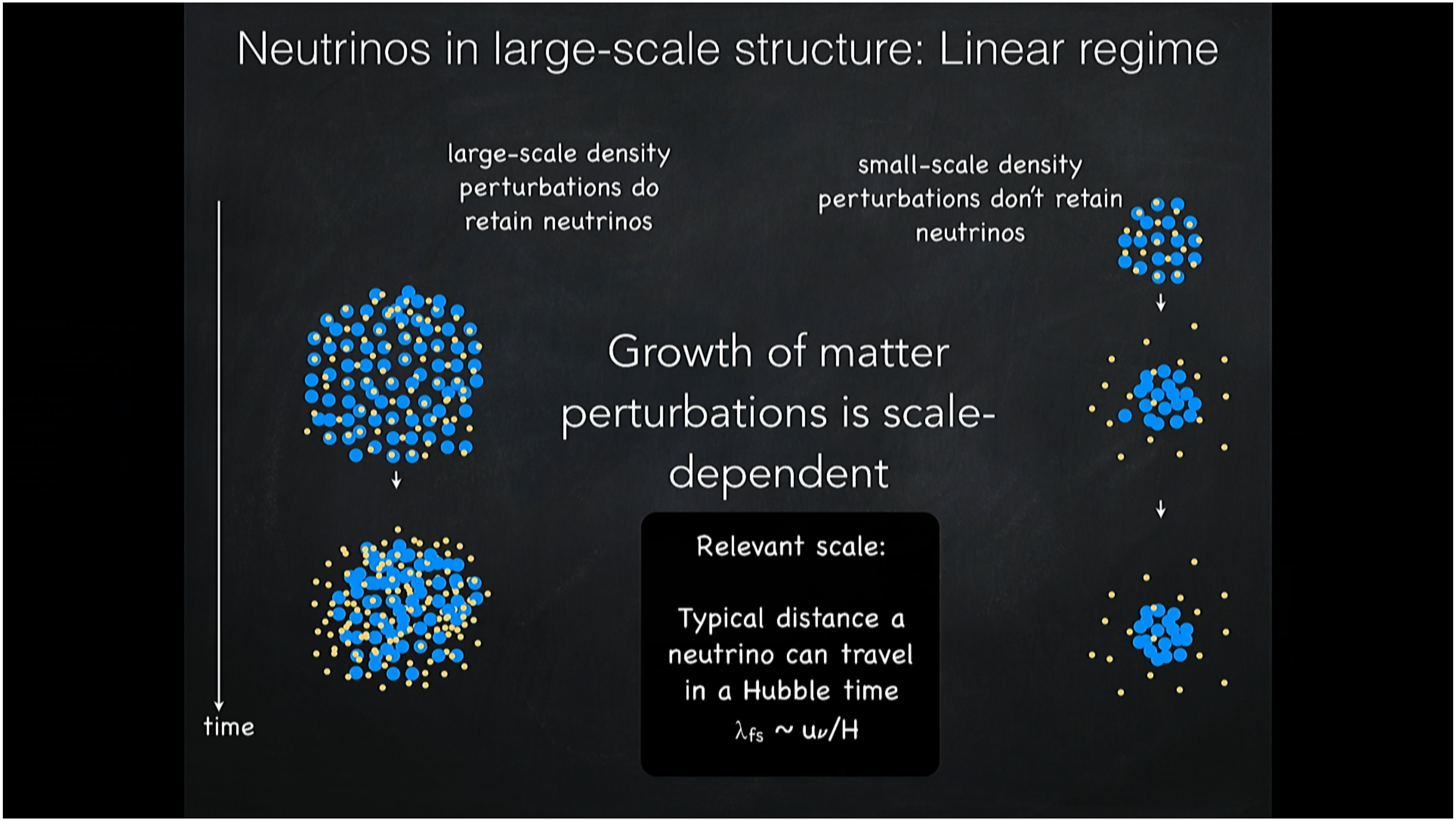
Large-scale Structure
matter distribution $\delta_m = \delta\rho_m/\rho_m$
galaxy distribution $\delta_g = \delta n_g/n_g$
125 Mpc/h
(Springel)
galaxies live in halos
dark matter "halos"

Neutrinos in large-scale structure: Linear regime


Neutrinos in large-scale structure: Linear regime
small-scale density
perturbations don't retain
neutrinos
cold dark matter
and baryons density
perturbation
growing
neutrino density
perturbation
decaying
time
$\frac{\delta\rho_c}{\rho_c}$
$\frac{\delta\rho_\nu}{\rho_\nu}$

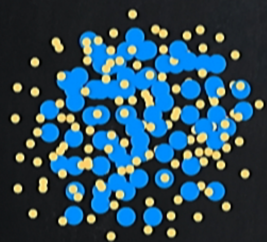
Neutrinos in large-scale structure: Linear regime

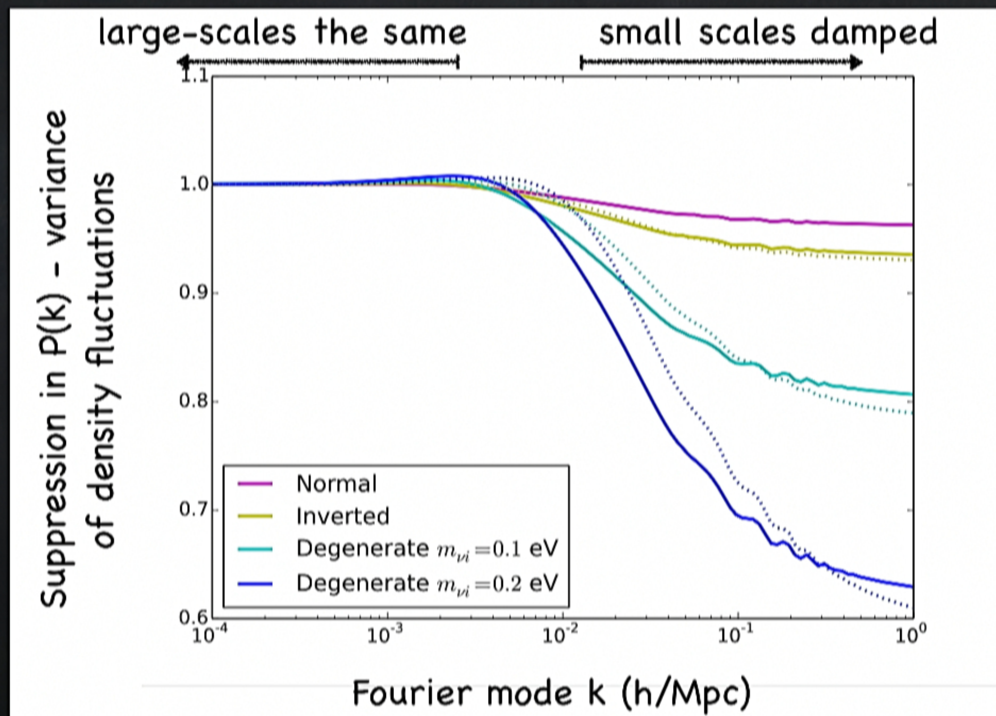


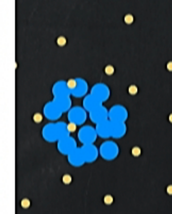

Neutrinos in large-scale structure: Linear regime
large-scale density perturbations do retain neutrinos
small-scale density perturbations don't retain neutrinos
Growth of matter perturbations is scale-dependent
Relevant scale:
Typical distance a neutrino can travel in a Hubble time
$\lambda_{fs} \sim u_\nu / H$
time

Neutrinos in large-scale structure: Linear regime

massive neutrinos reduce the typical amplitude of density perturbations







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

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

Neutrinos in large-scale structure: Linear regime

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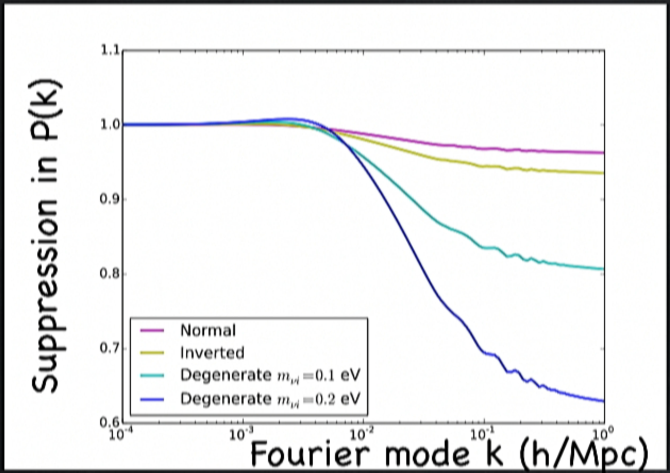
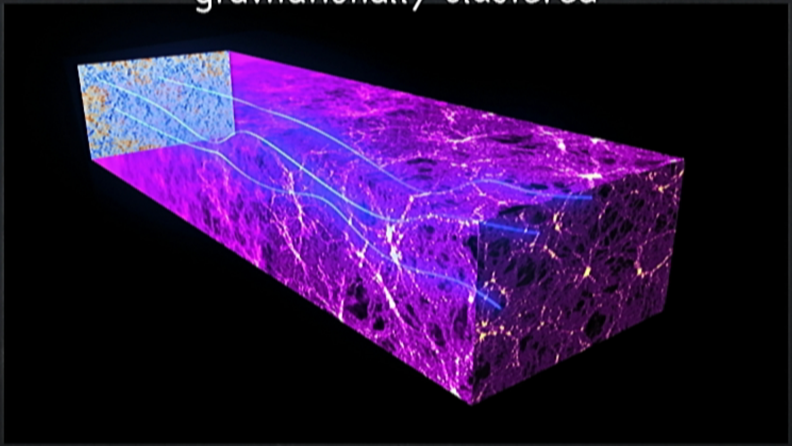


—> less gravitational lensing than a universe where all matter is gravitationally clustered



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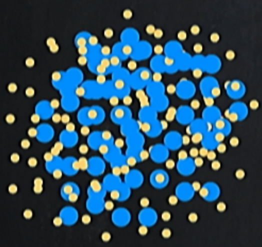

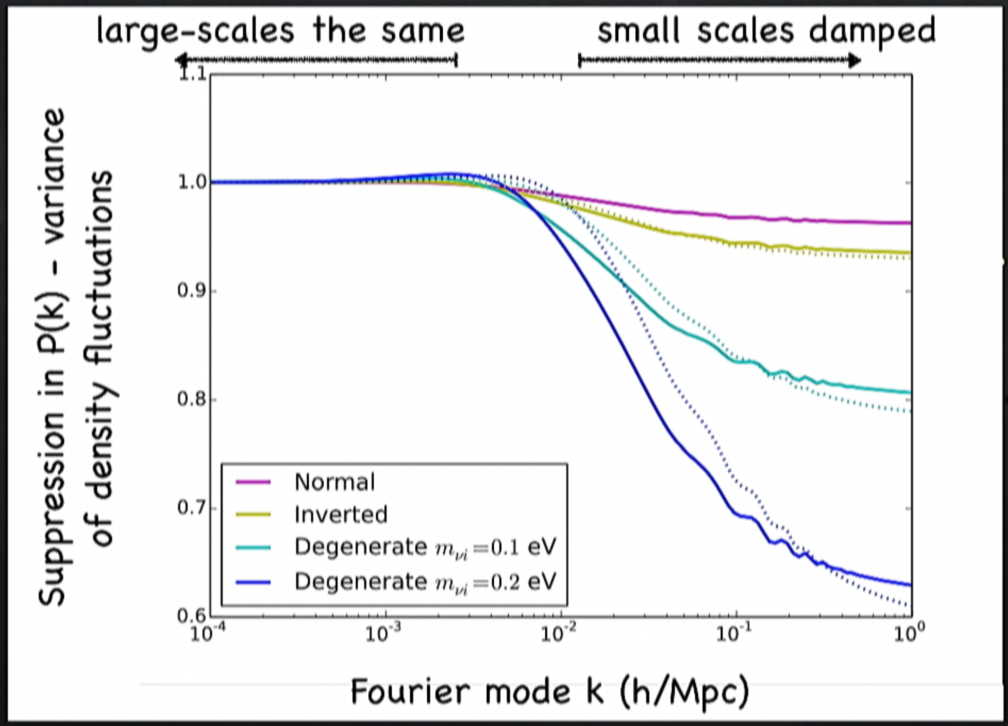

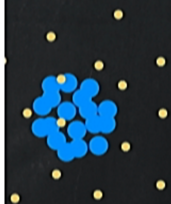

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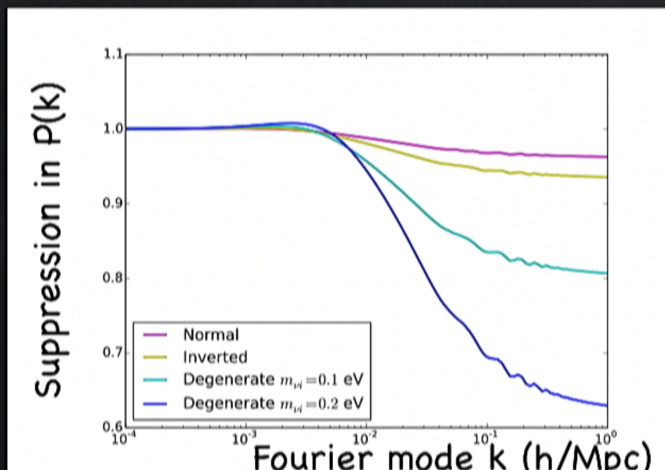
$P(k) = \langle \delta_m(k) \delta_m(k) \rangle$ where $\delta_m(k) = \frac{\delta\rho_{matter}}{\rho_{matter}}$

Neutrinos in large-scale structure: Linear regime

massive neutrinos reduce the typical amplitude of density perturbations



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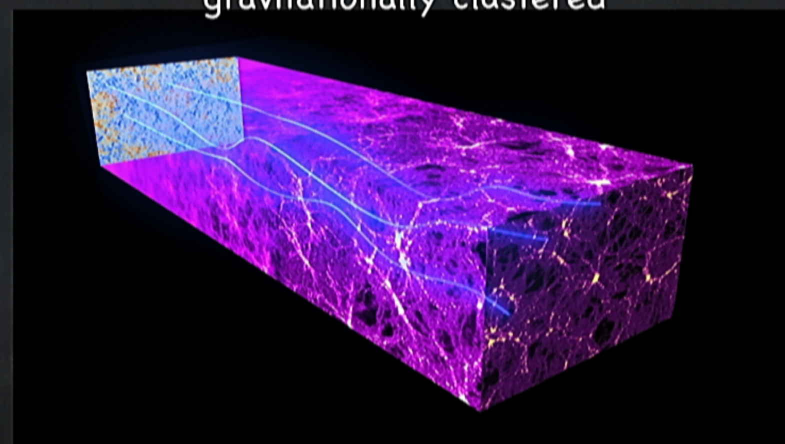

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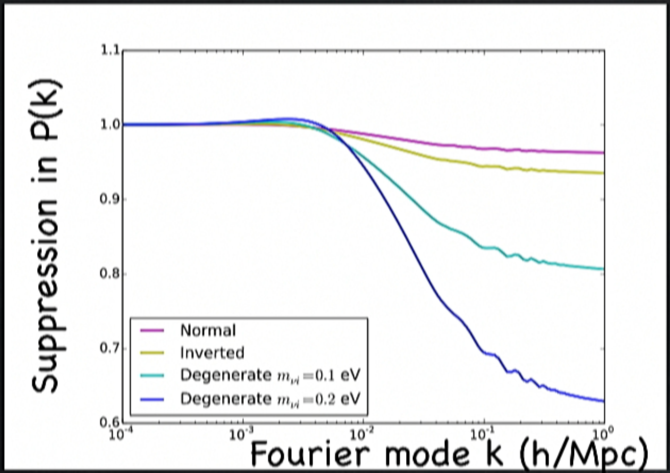
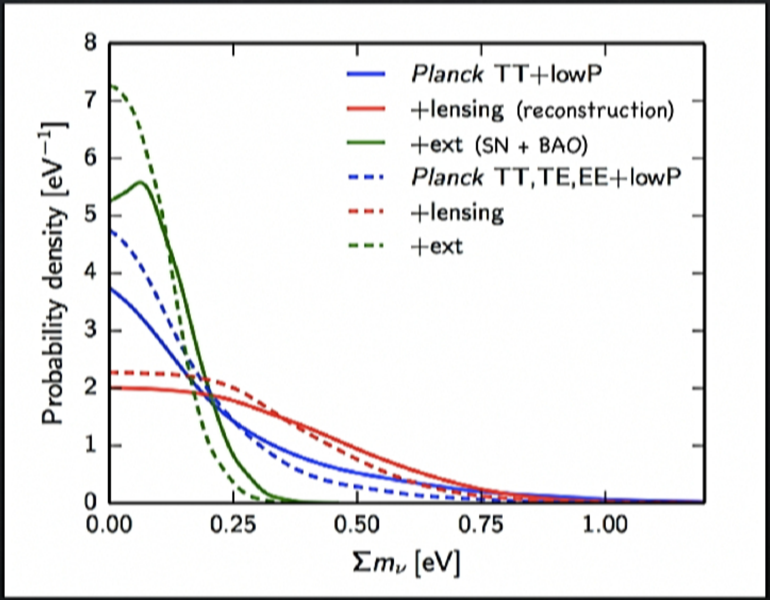
Neutrinos in large-scale structure: Linear regime

massive neutrinos reduce the typical amplitude of density perturbations



Current constraints from CMB



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

Planck 2015

Neutrinos in large-scale structure: Linear regime

Future:

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

3 σ detection of Normal Hierarchy (0.06eV)

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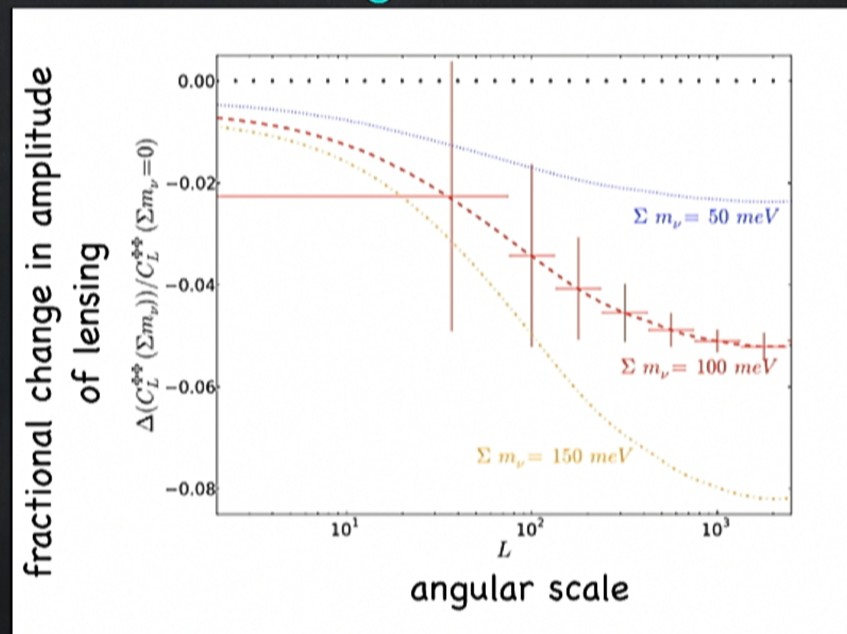
"Stage IV CMB"



Abazajian et al 2013

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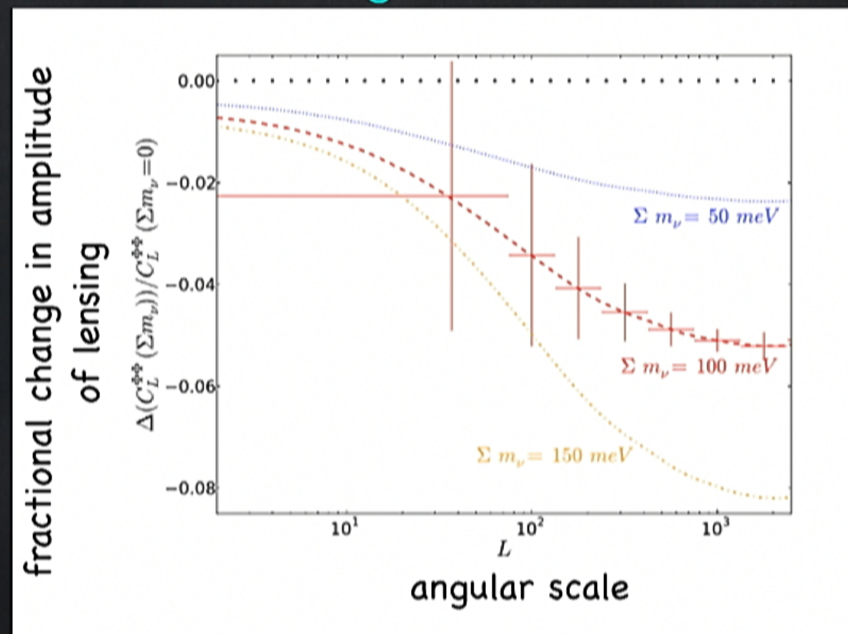

Abazajian et al 2013

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

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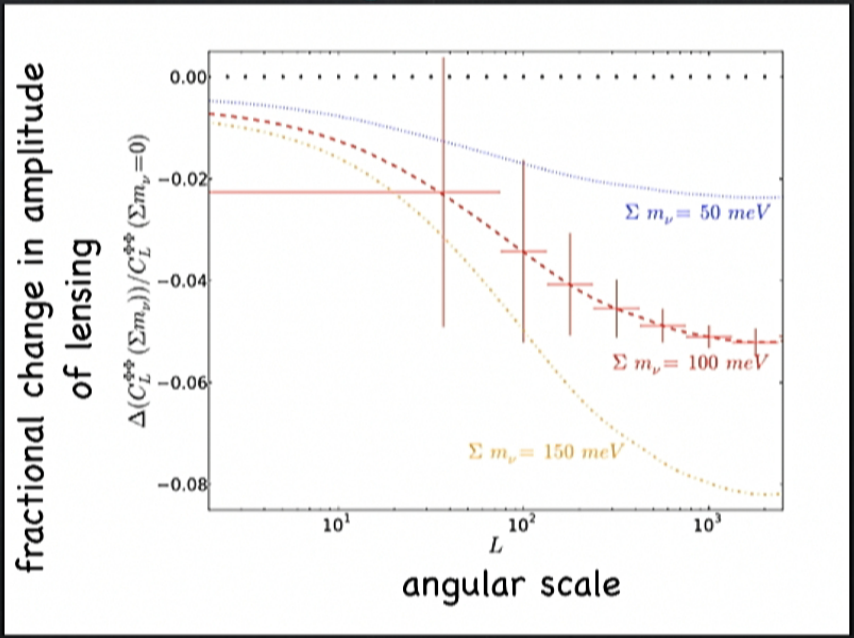

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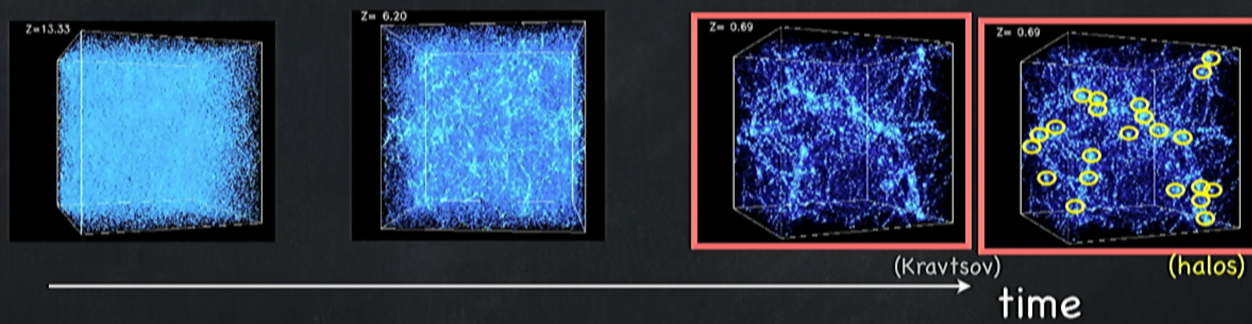
Neutrinos in Large-scale Structure



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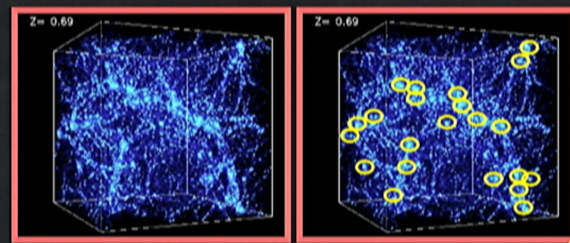


(halos)

- Suppressed matter power spectrum (test via gravitational lensing, galaxy power spectra, cluster abundance) ✓

new!

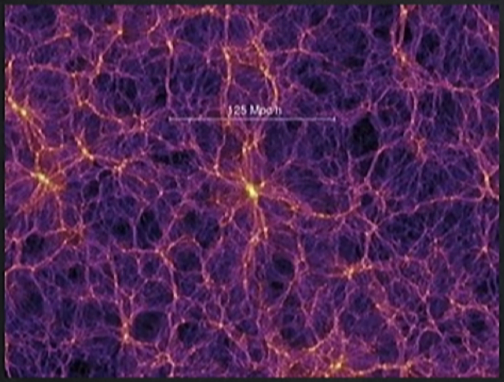
- Neutrino feature in the halo bias
- Neutrino Halos are not like CDM halos

Scale-dependent halo bias from massive neutrinos

Halo bias

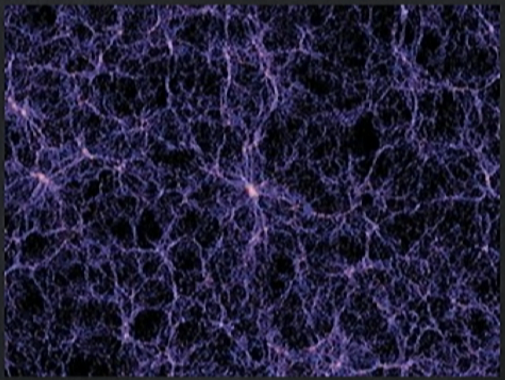
Halo bias

matter distribution $\delta_m(x) = \delta\rho_m/\rho_m$



(Springel)

galaxy distribution $\delta_g(x) = \delta n_g/n_g$



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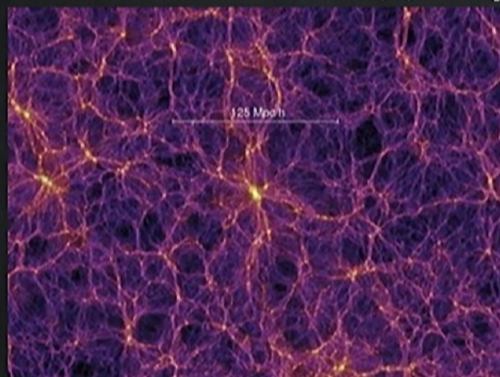

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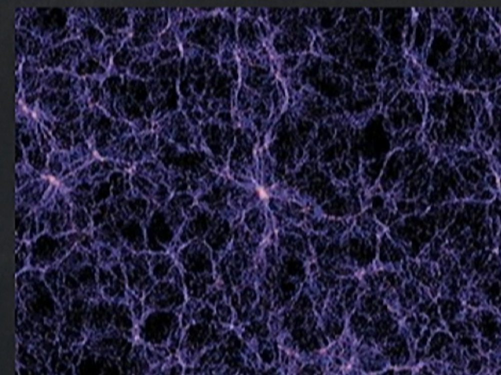
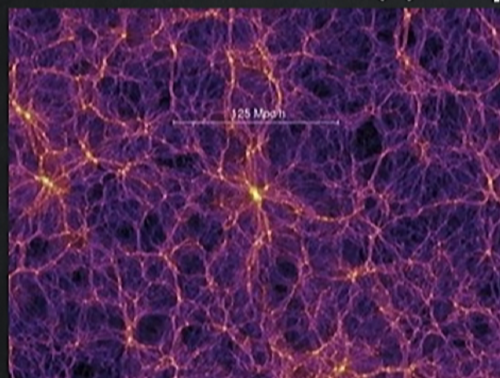


(Springel)

For large separations, $\langle\delta_g(x_1)\delta_g(x_2)\rangle \approx b^2\langle\delta_m(x_1)\delta_m(x_2)\rangle$, where b is what astronomers call <u>the bias</u>

Halo bias

matter distribution $\delta_m(x) = \delta\rho_m/\rho_m$



(Springel)

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(Springel)

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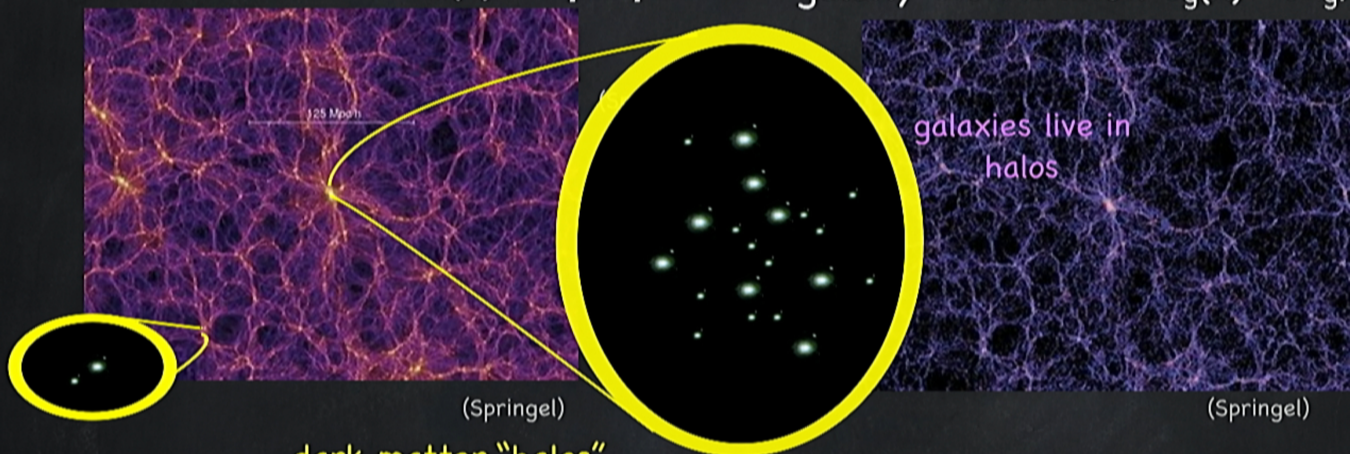
The value of b depends on the type of object you are looking at (e.g. the mass or luminosity of the galaxies you've measured) and rare objects have a larger value of b.

Halo bias

matter distribution $\delta_m(x) = \delta\rho_m/\rho_m$ galaxy distribution $\delta_g(x) = \delta n_g/n_g$



(Springel) (Springel)

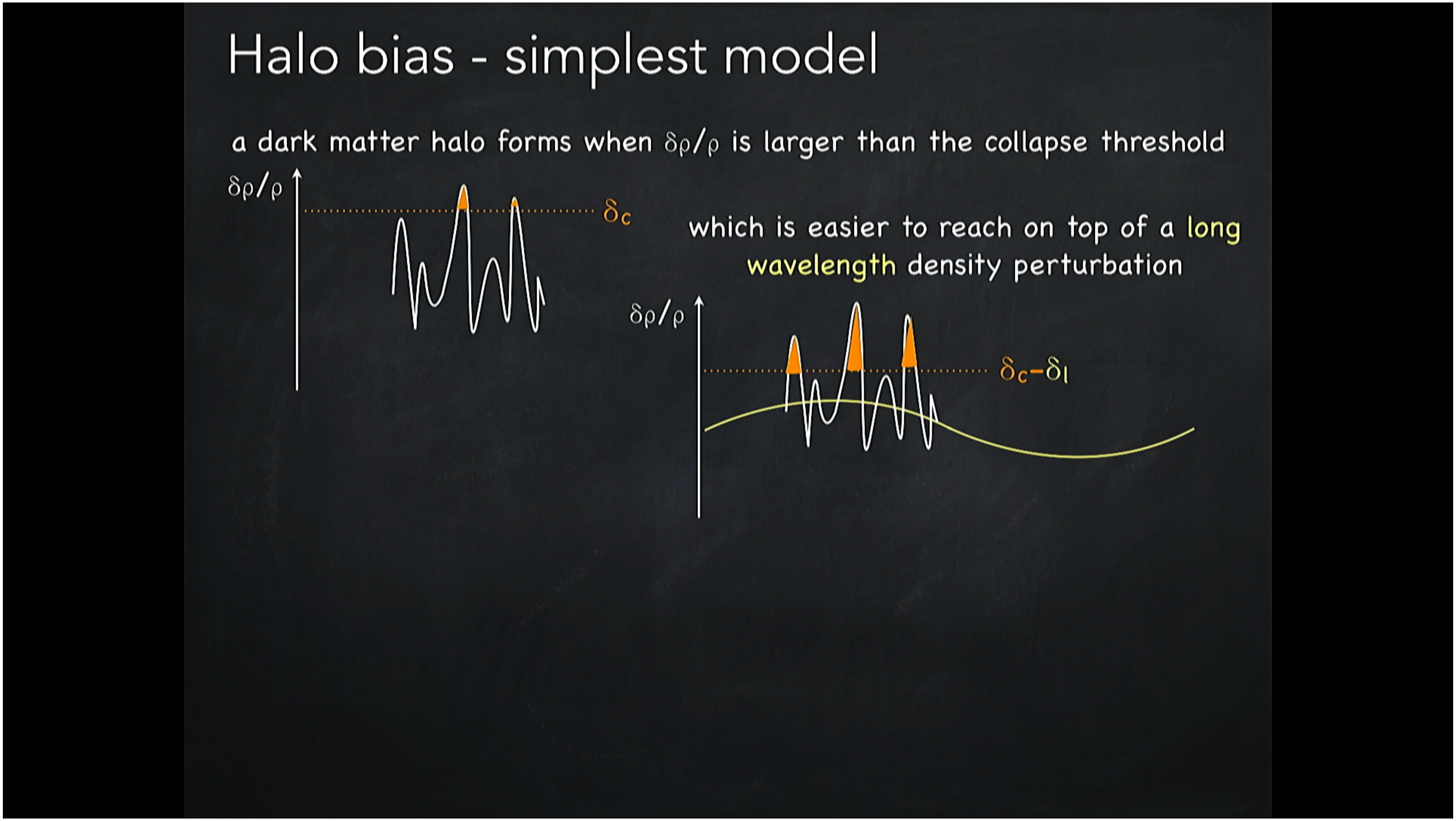
dark matter "halos"

Galaxies live in halos, so I'm going to use halo bias and galaxy bias interchangeably but reality is more complicated.

Halo bias - simplest model

Halo bias - simplest model

a dark matter halo forms when $\delta\rho/\rho$ is larger than the collapse threshold


Halo bias - simplest model
a dark matter halo forms when δρ/ρ is larger than the collapse threshold
δρ/ρ
δc
which is easier to reach on top of a long wavelength density perturbation
δρ/ρ
δc−δl

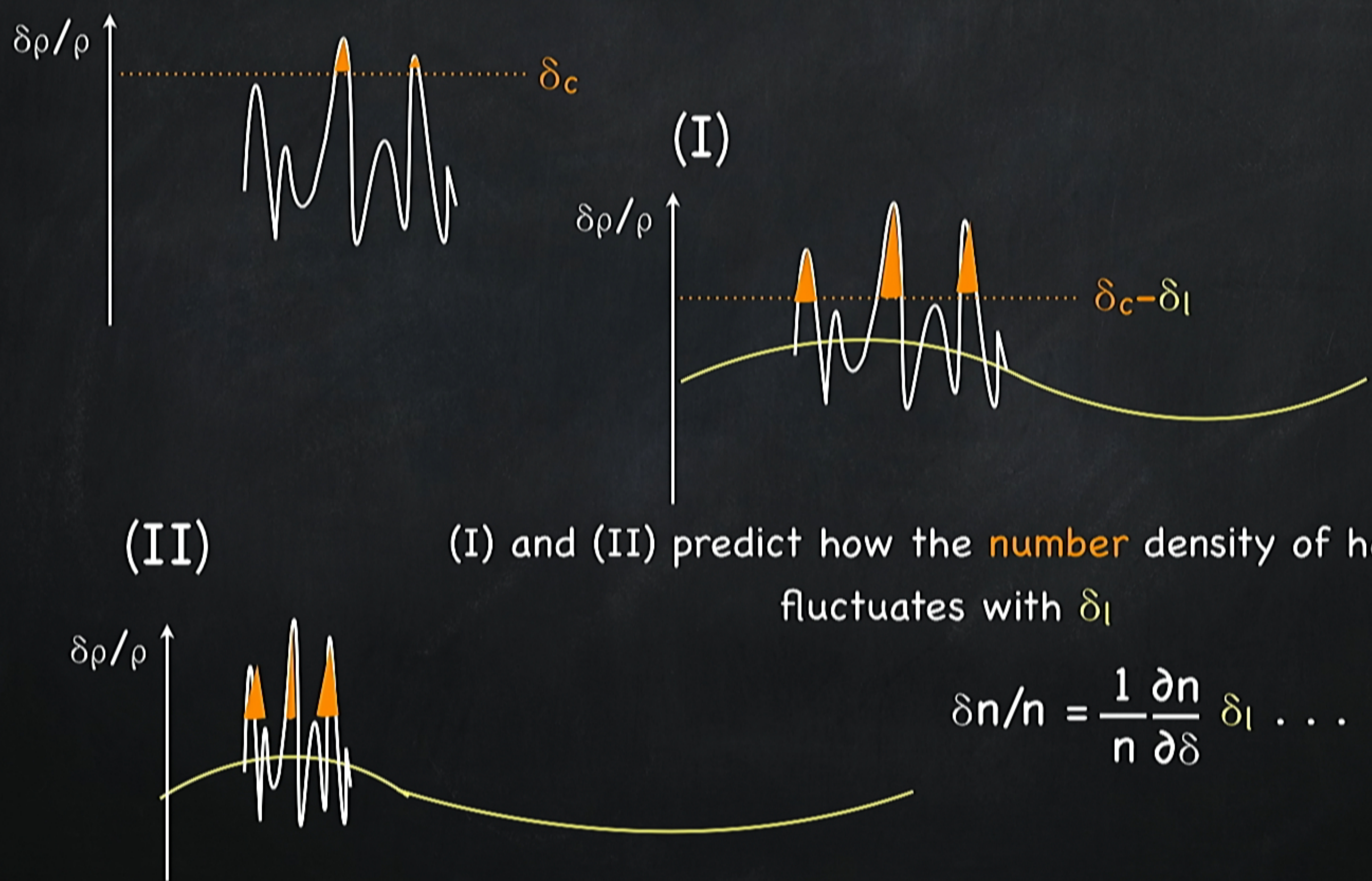
Halo bias - simplest model

a dark matter halo forms when $\delta\rho/\rho$ is larger than the collapse threshold

which is easier to reach on top of a long wavelength density perturbation

initially over-dense regions occupy less volume at late times, so the number density there is increased

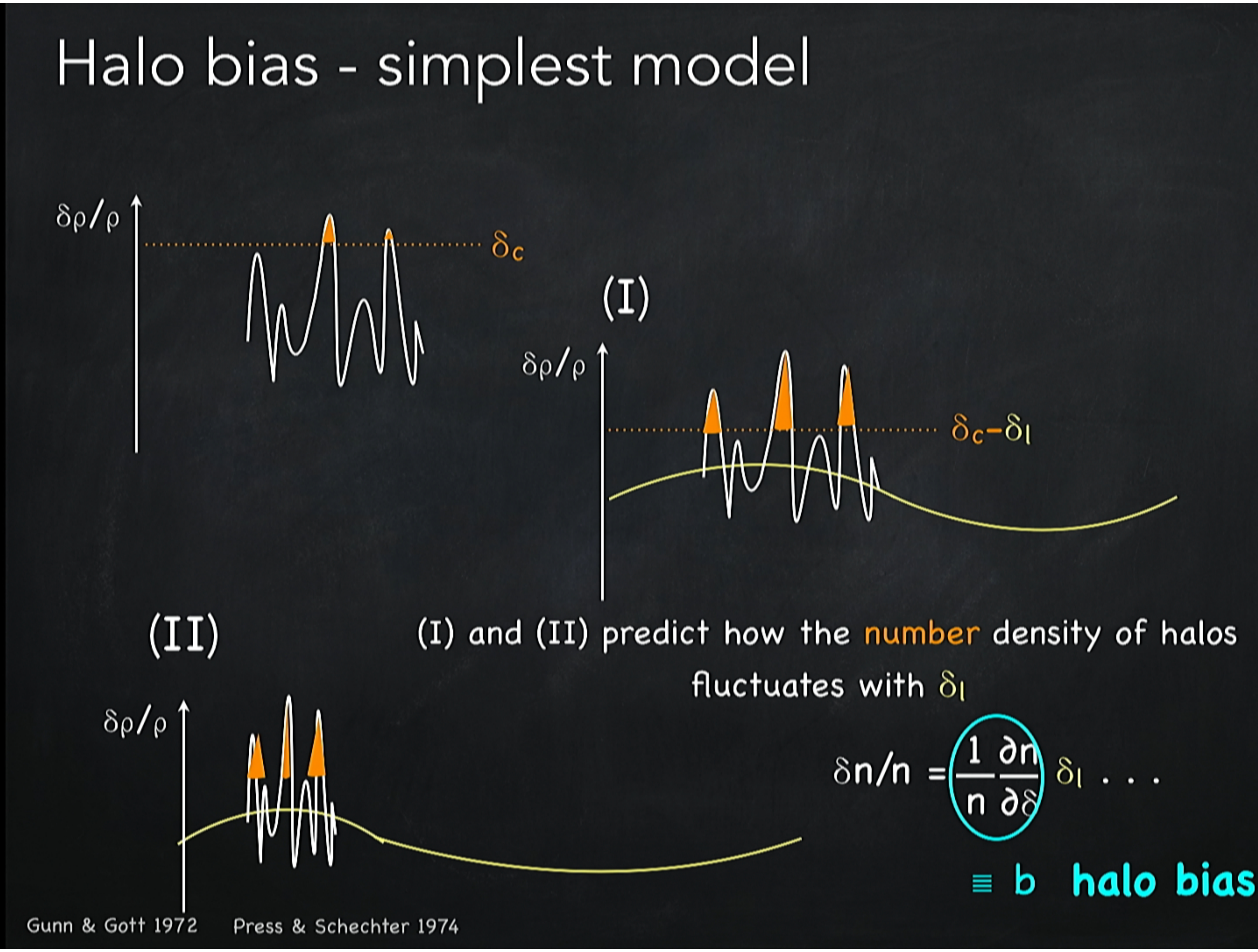
Halo bias - simplest model



(I) and (II) predict how the number density of halos fluctuates with δ_l

$$\delta n/n = \frac{1}{n}\frac{\partial n}{\partial \delta}\,\delta_l \ldots$$

Gunn & Gott 1972   Press & Schechter 1974



Halo bias - simplest model
δρ/ρ
δc
(I)
δρ/ρ
δc−δl
(II)
(I) and (II) predict how the number density of halos fluctuates with δl
δρ/ρ
δn/n = (1/n ∂n/∂δ) δl . . .
≡ b halo bias
Gunn & Gott 1972
Press & Schechter 1974

Halo bias - simplest model

Add neutrinos:

- For low neutrino masses, can ignore neutrino contribution to halo mass (M_ν in halo $\ll M_{halo}$)

ML and Zaldarriaga 2013

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- BUT, neutrino effects on evolution of δ_l can't be ignored — halos are forming in different background

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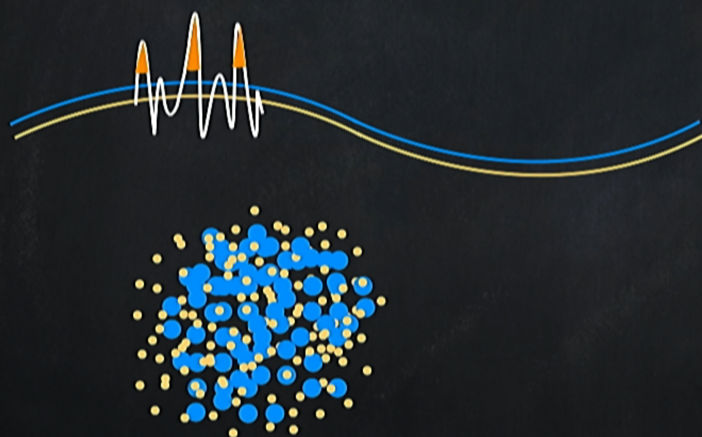
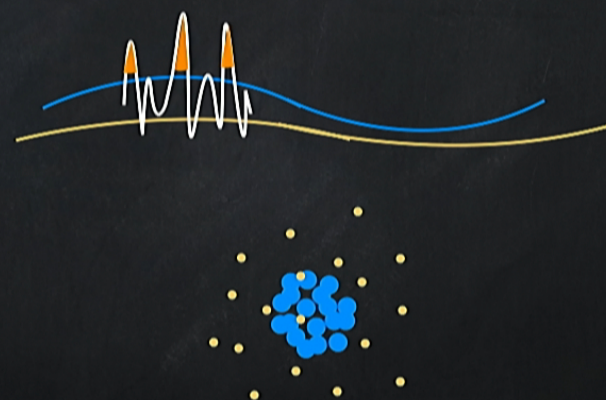


(same as a universe with only CDM)



(grows more slowly)

Halo bias - simplest model

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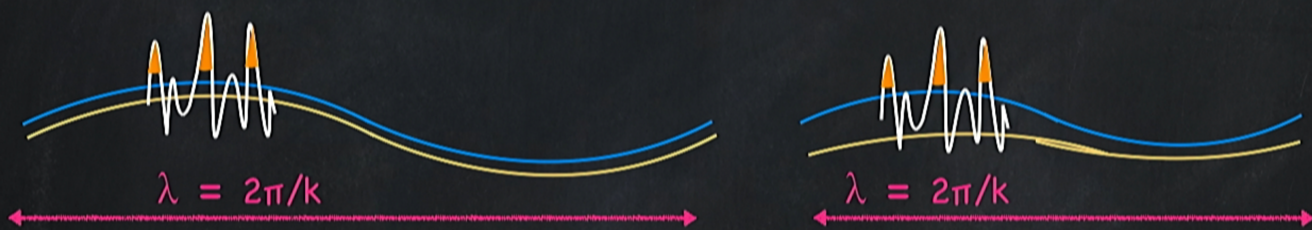
- For low neutrino masses, can ignore neutrino contribution to halo mass (M_ν in halo $\ll M_{halo}$) ML and Zaldarriaga 2013

- BUT, neutrino effects on evolution of δ_l can't be ignored — halos are forming in different background



The k-dependent evolution of δ_l causes the threshold for collapse to depend on k also

ML 2014b

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

Halo bias - simplest model

Add neutrinos:

The k-dependent evolution of δ_l causes the threshold for collapse to depend on k also   ML 2014b

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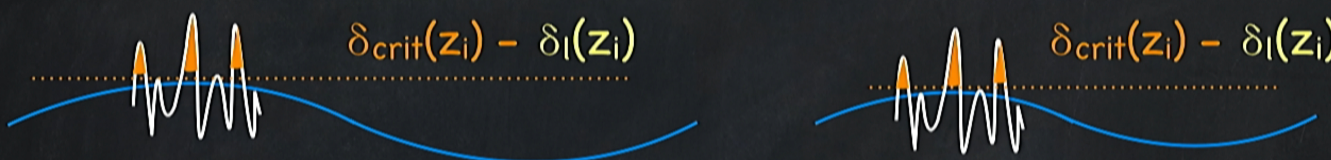
Sketch:



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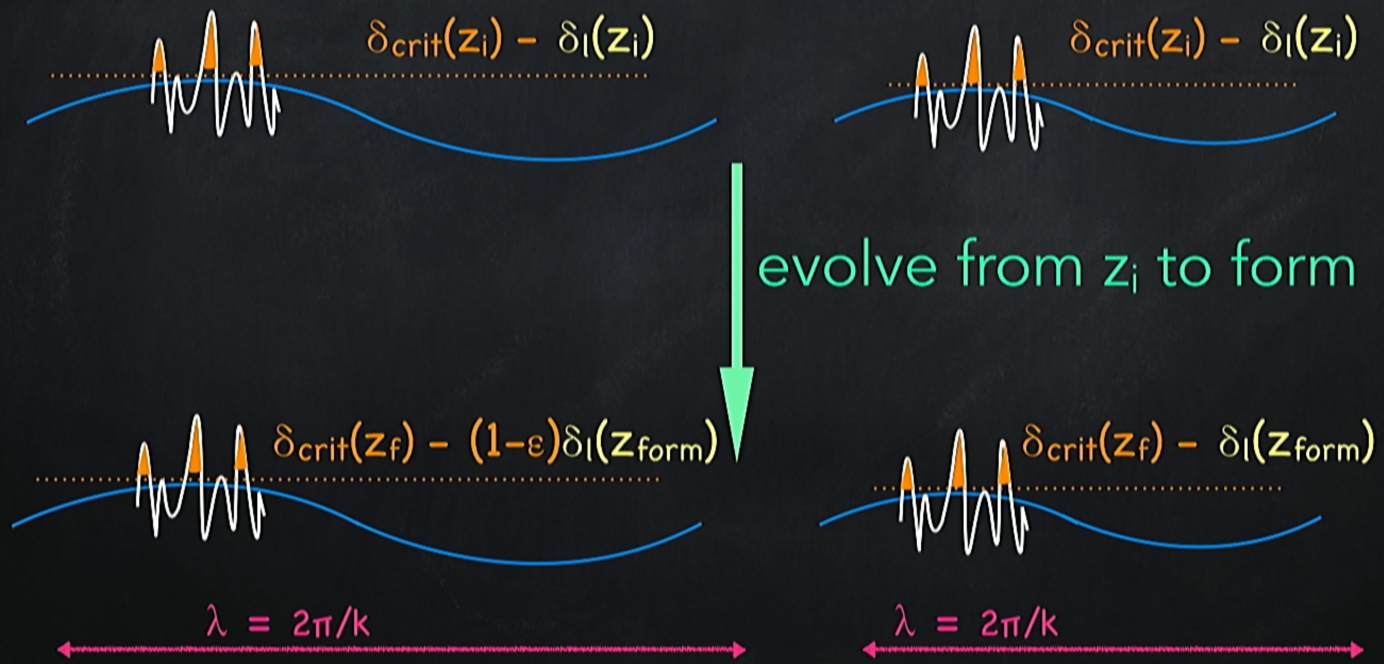

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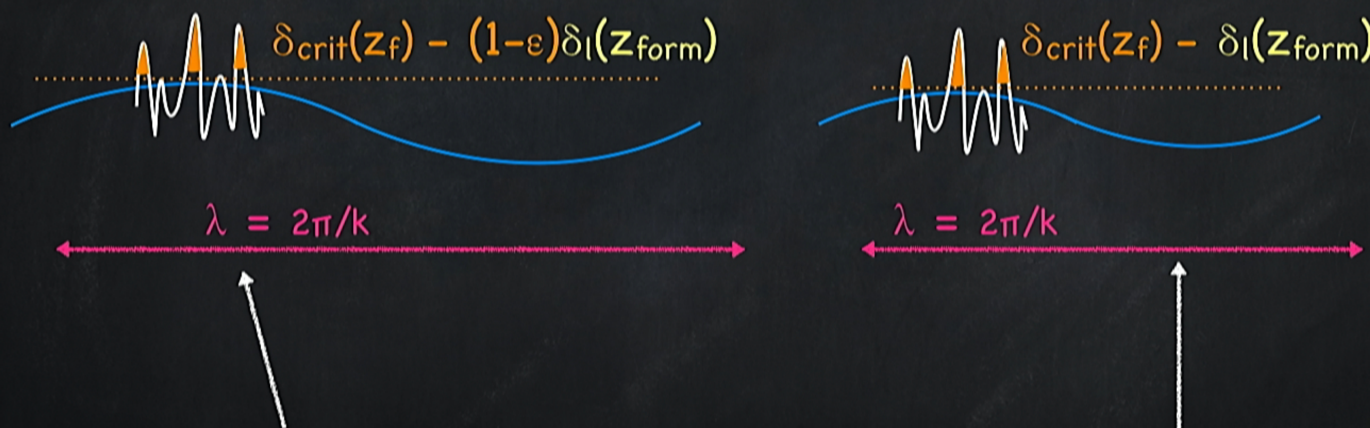


these halos a bit less biased than these

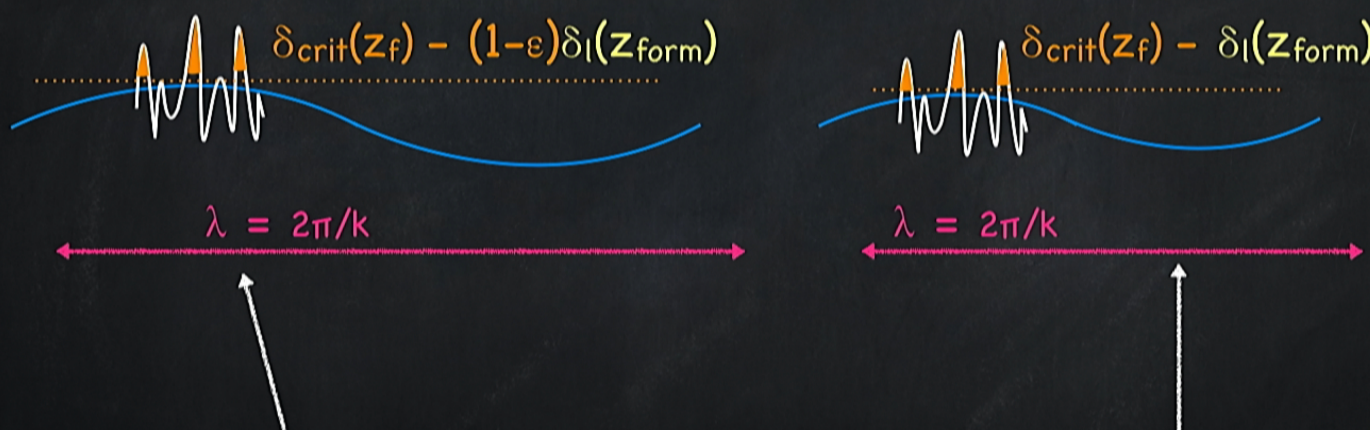
(see also Hui & Parfrey 2008; Parfrey, Hui, Sheth 2011)

Halo bias - simplest model

Add neutrinos:

The k-dependent evolution of δ_l causes the threshold for collapse to depend on k also   ML 2014b

Sketch:



these halos a bit less biased than these

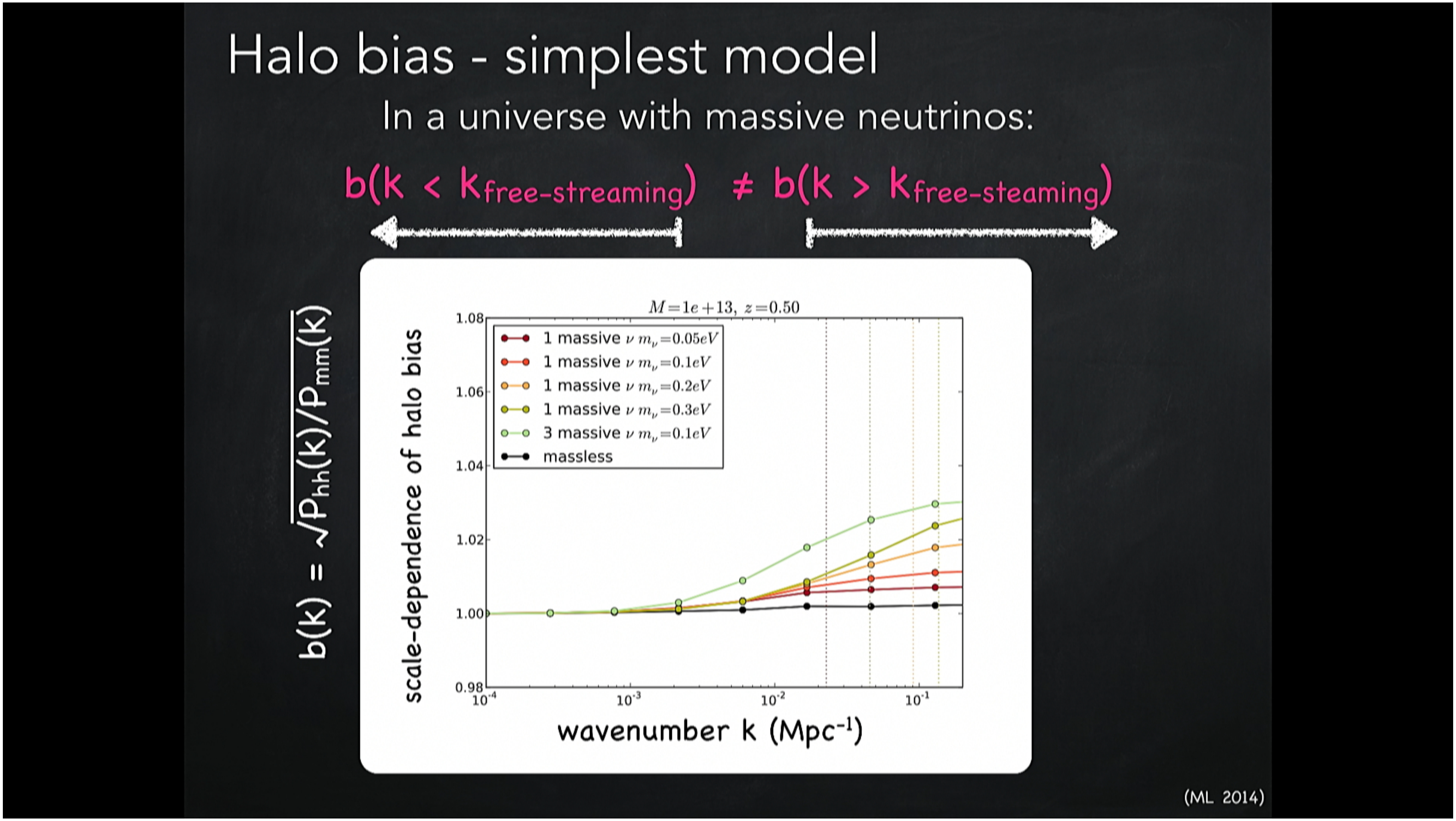
** Neutrinos have scale-dependent growth at all times, so the truth is more complicated than the sketch here **

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

Halo bias - simplest model

In a universe with massive neutrinos:

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



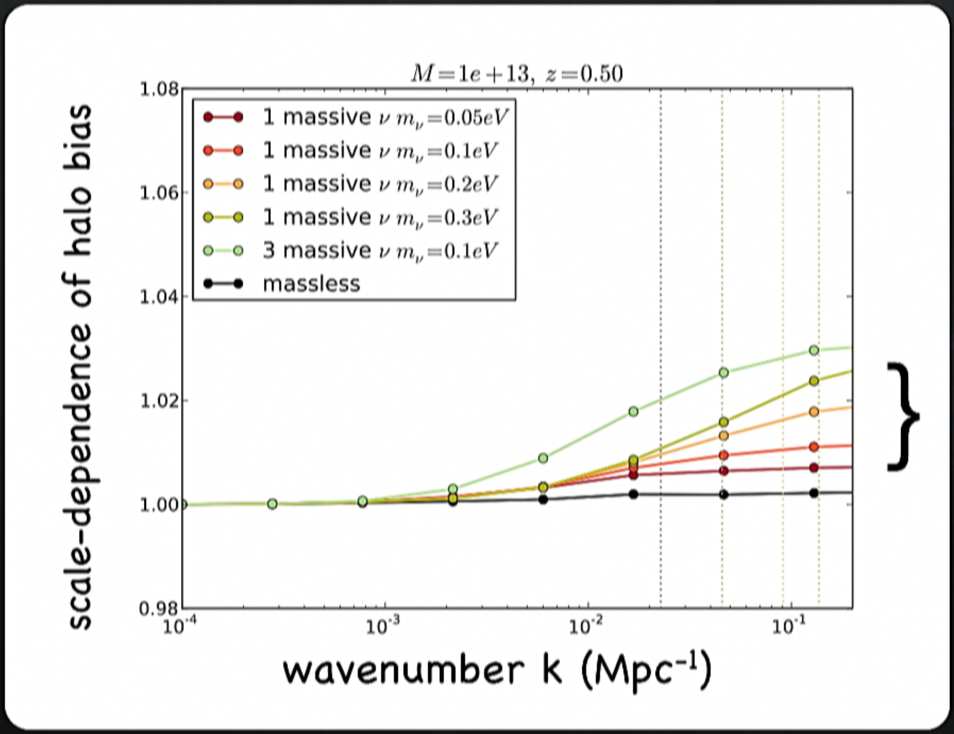
Halo bias - simplest model
In a universe with massive neutrinos:
b(k < k_free-streaming) ≠ b(k > k_free-steaming)
b(k) = √(P_hh(k)/P_mm(k))
M=1e+13, z=0.50
1 massive ν m_ν=0.05eV
1 massive ν m_ν=0.1eV
1 massive ν m_ν=0.2eV
1 massive ν m_ν=0.3eV
3 massive ν m_ν=0.1eV
massless
scale-dependence of halo bias
wavenumber k (Mpc⁻¹)
1.08
1.06
1.04
1.02
1.00
0.98
10⁻⁴
10⁻³
10⁻²
10⁻¹
(ML 2014)

Halo bias - simplest model

In a universe with massive neutrinos:

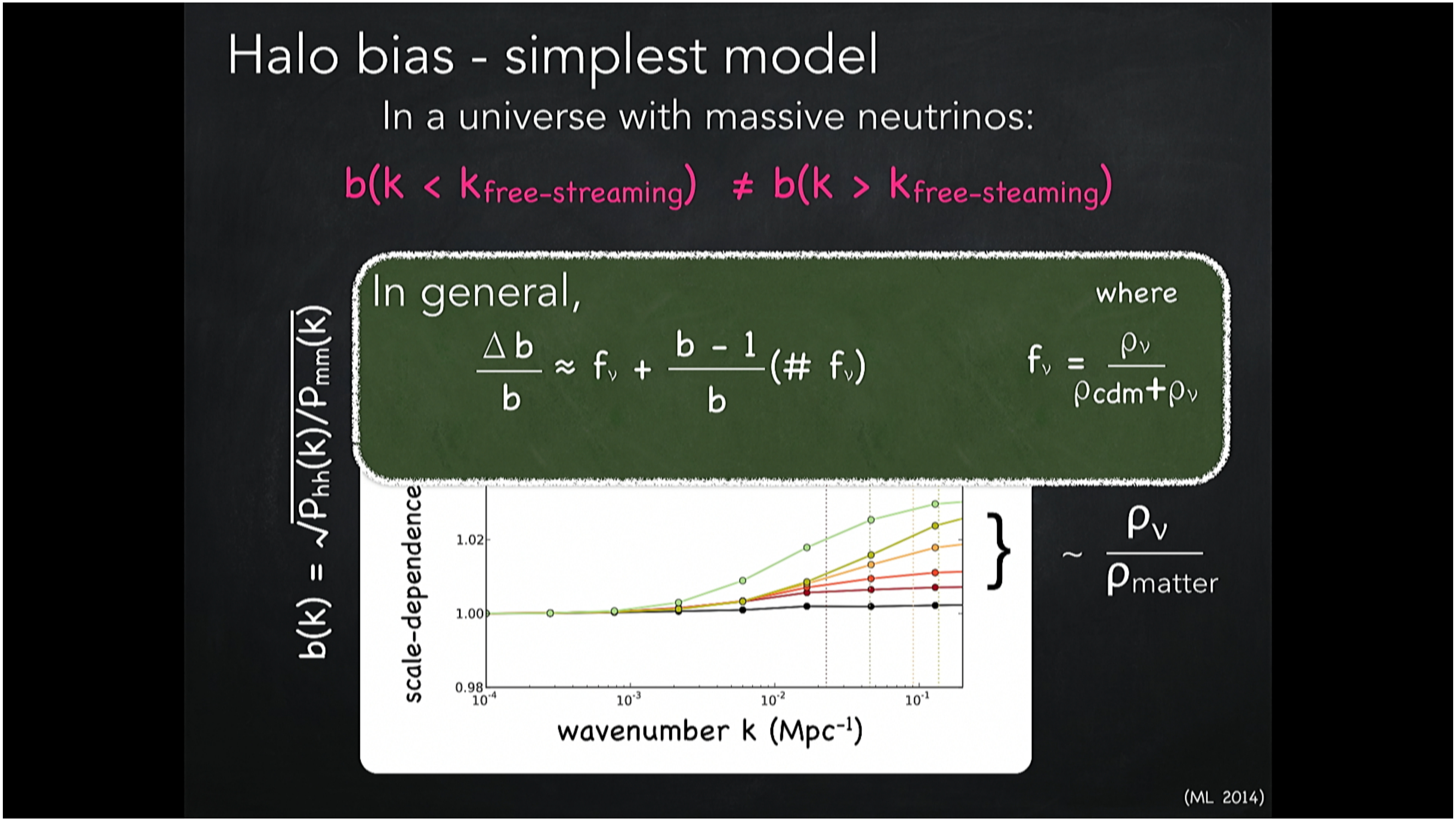
$b(k < k_{free\text{-}streaming}) \neq b(k > k_{free\text{-}steaming})$

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



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

(ML 2014)


Halo bias - simplest model
In a universe with massive neutrinos:
b(k < k_free-streaming) ≠ b(k > k_free-steaming)
In general,
where
Δb/b ≈ f_ν + (b - 1)/b (# f_ν)
f_ν = ρ_ν / (ρ_cdm + ρ_ν)
b(k) = √(P_hh(k)/P_mm(k))
scale-dependence
1.02
1.00
0.98
10^-4
10^-3
10^-2
10^-1
wavenumber k (Mpc^-1)
~ ρ_ν / ρ_matter
(ML 2014)

Observational consequences

Scale-dependent change in the halo bias:

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

The fraction of energy in neutrinos may be tiny ($f_\nu \gtrsim 0.5\%$)

(ML 2014)

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The fraction of energy in neutrinos may be tiny ($f_\nu \gtrsim 0.5\%$)

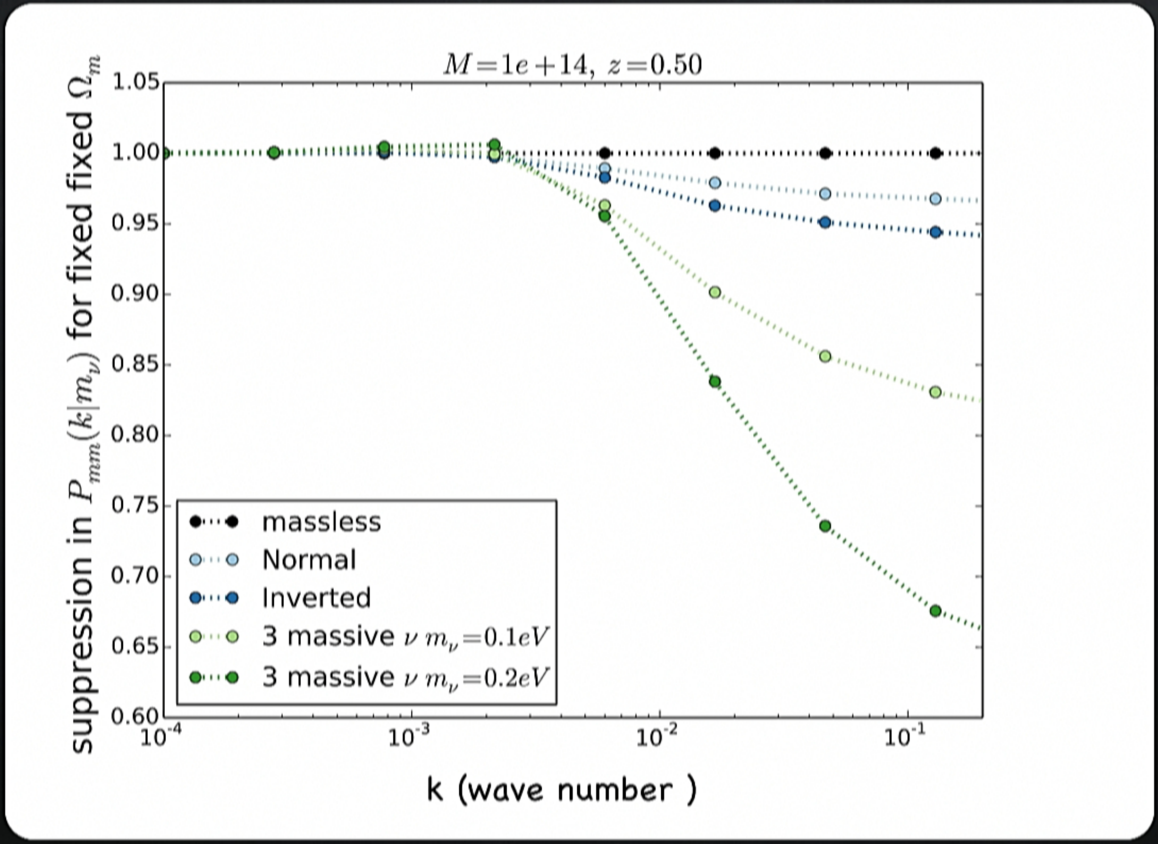
Why care about such a small change to the halo bias?

- Because the feature in the halo bias can be used to measure neutrino mass

(ML 2014)

A systematic for measurements of m_ν from galaxy clustering

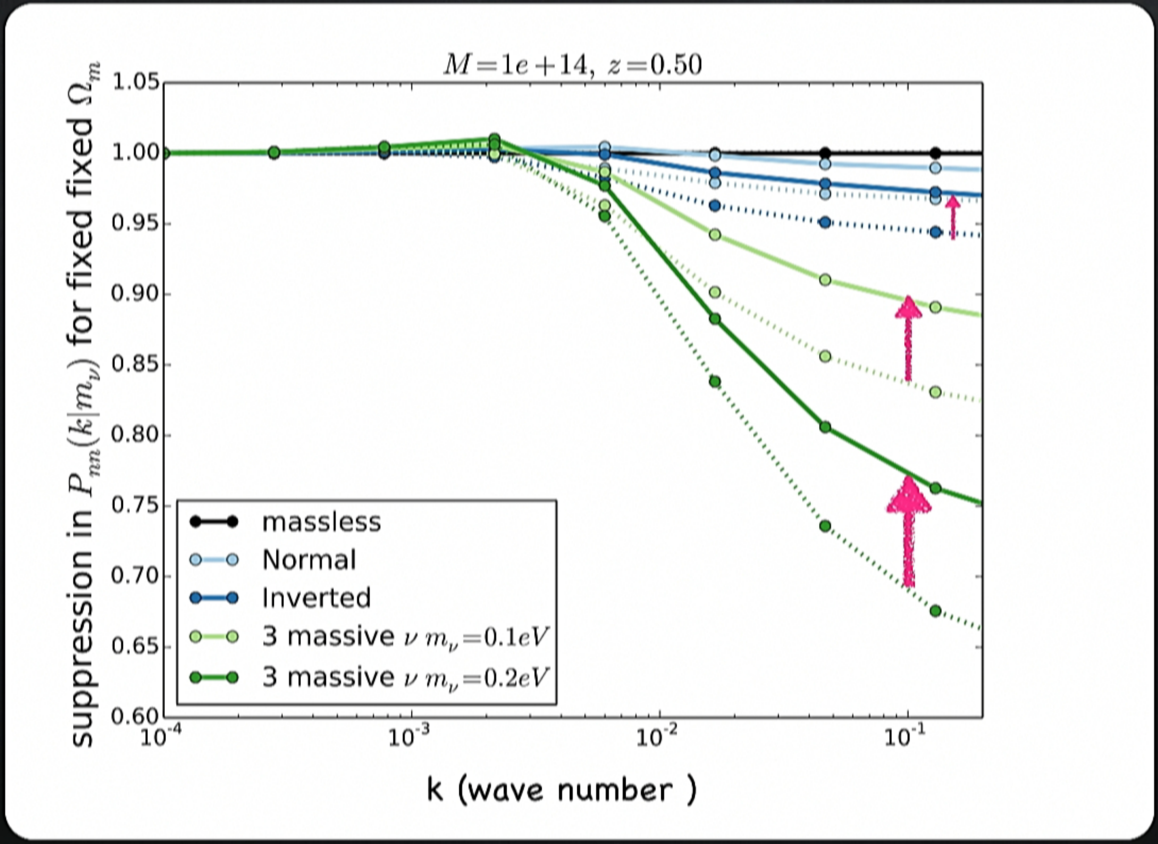
Without scale-dependent bias neutrinos produce identical changes to $P_{galaxy\text{-}galaxy}(k)$ and $P_{matter\text{-}matter}(k)$, ($P_{galaxy\text{-}galaxy}(k) = b^2 P_{matter\text{-}matter}(k)$)



(ML 2014)

A systematic for measurements of m_ν from galaxy clustering

With scale-dependent bias neutrinos don't suppress $P_{galaxy\text{-}galaxy}(k)$ as much as $P_{matter\text{-}matter}(k)$, ($P_{galaxy\text{-}galaxy}(k) = b(k)^2 P_{matter\text{-}matter}(k)$)



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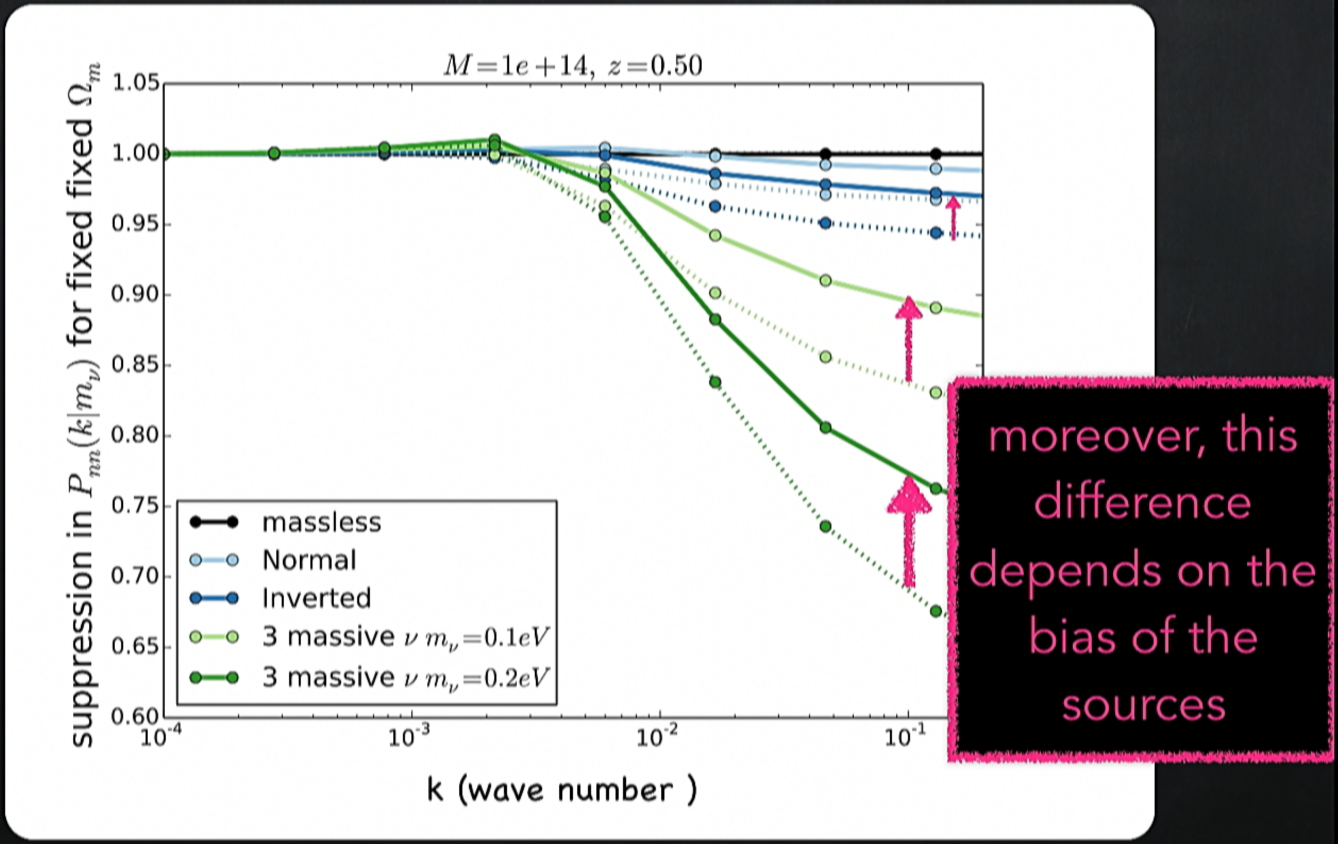

(ML 2014)

The feature in the halo bias can be used to measure neutrino mass

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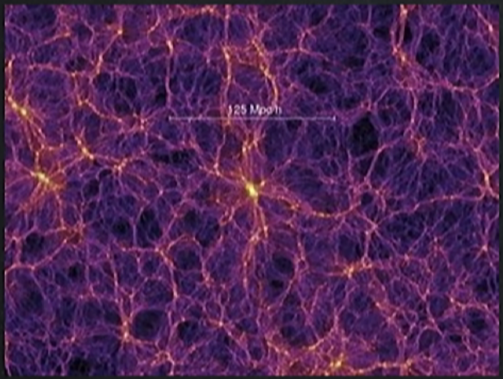
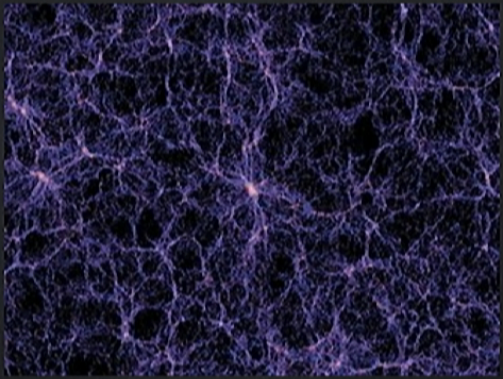
Suppose one has high number density of sources that trace the matter field $\delta\rho_m/\rho_m$ with a bias factor **b**, i.e. $\delta n_g/n_g = b\ \delta\rho_m/\rho_m$

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



(Springel)

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



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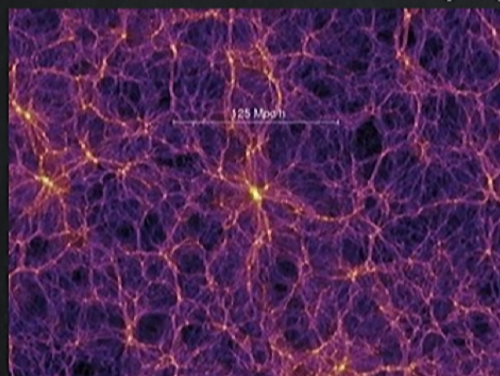

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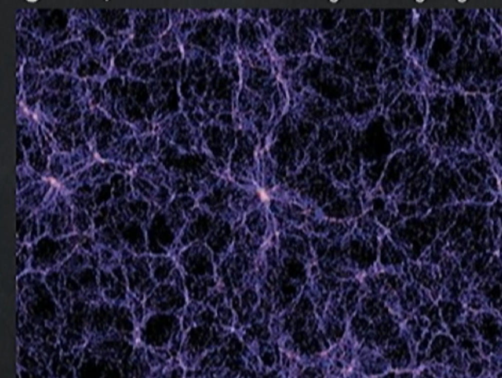

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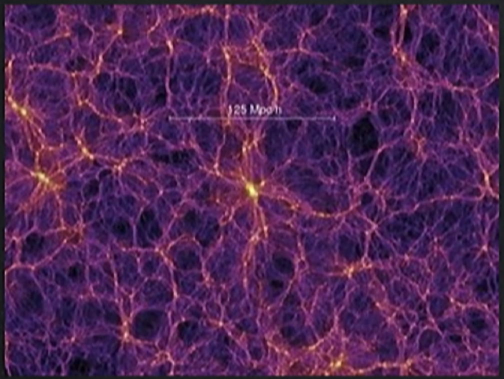

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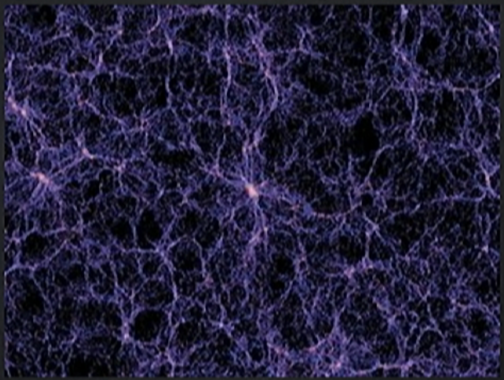

(Springel)

It turns out that the bias **b** can be measured without cosmic variance (Pen 2004, Seljak 2008)

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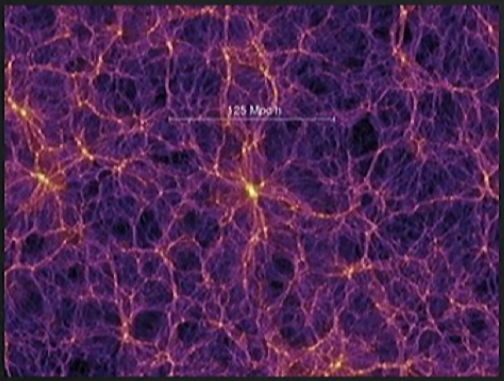

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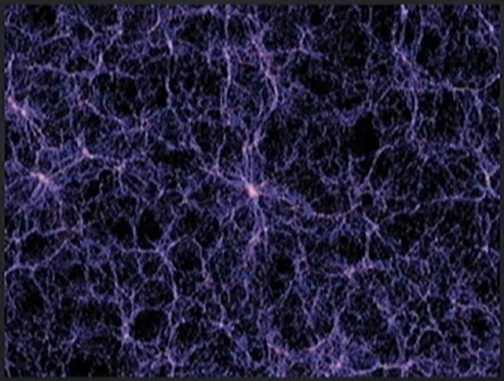

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$$\sigma_b \sim \frac{1}{\sqrt{n_{galaxies}\, P_{matter}}}$$

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Suppose one has high number density of sources that trace the matter field $\delta\rho_m/\rho_m$ with a bias factor **b**, i.e. $\delta n_g/n_g = b\,\delta\rho_m/\rho_m$

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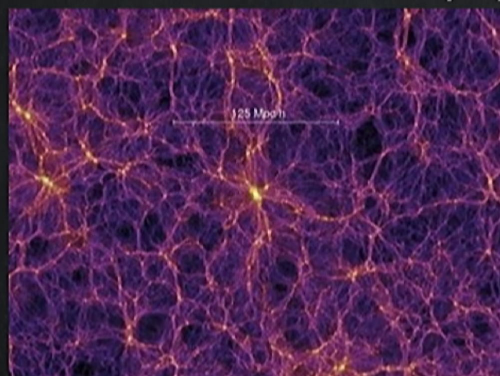

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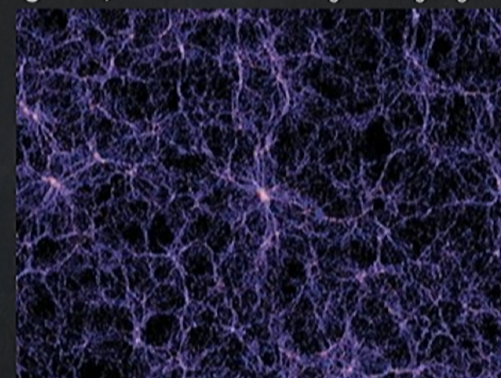

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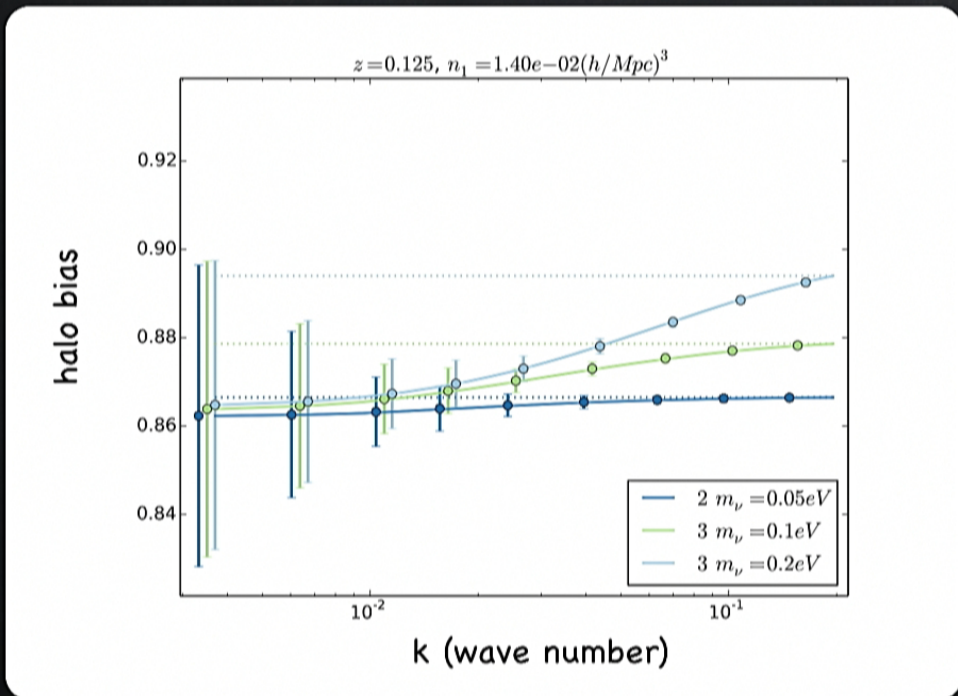
It turns out that the bias **b** can be measured without cosmic variance (Pen 2004, Seljak 2008)

$$\sigma_b \sim \frac{1}{\sqrt{n_{galaxies}\, P_{matter}}}$$

Compare:

$$\sigma_{Pk} \sim \frac{P(k)}{\sqrt{N_k}}$$

The feature in the halo bias can be used to measure neutrino mass

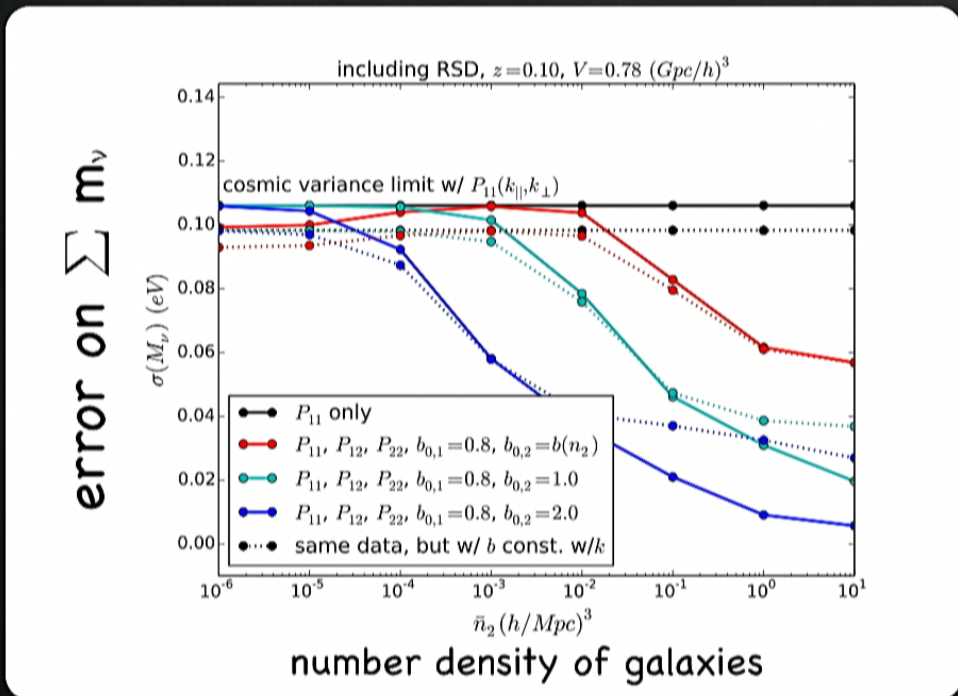


$$\sigma_b \sim \frac{1}{\sqrt{n_1 P_{mm}}}$$

(ideal huge number density of sources, super-ideal lack of systematics)

(ML 2016)

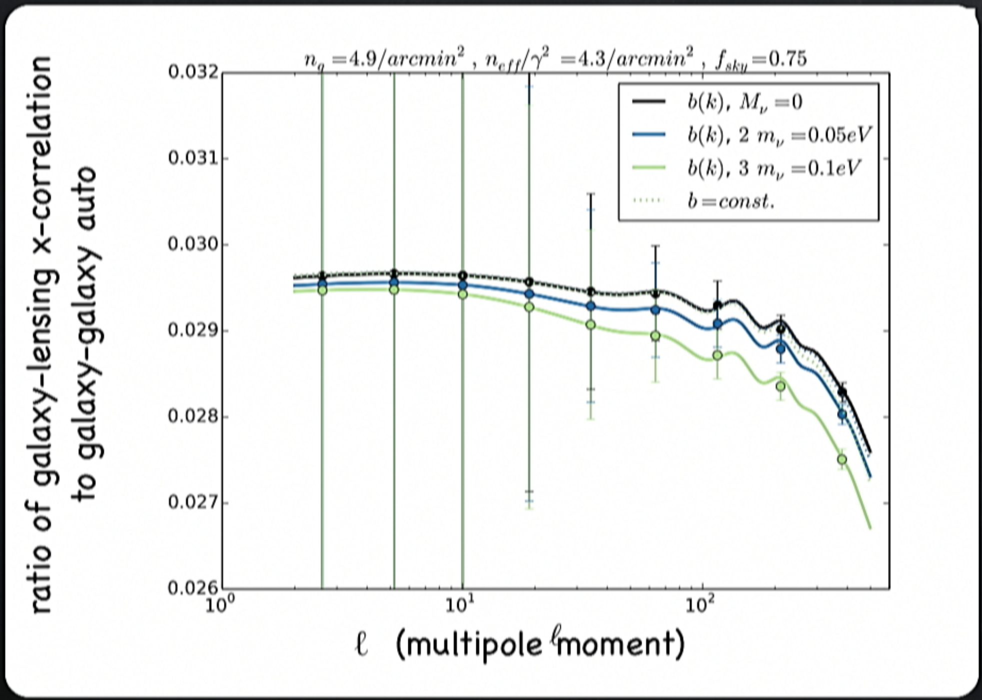
The feature in the halo bias can be used to measure neutrino mass



$$\sigma_b \sim \frac{1}{\sqrt{n_1 P_{mm}}}$$

(ML 2016)

The feature in the halo bias can be used to measure neutrino mass



(LSST-like number density of sources, super-ideal lack of systematics)

(ML 2016)

The key point

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To a local observer, these backgrounds are *inequivalent*

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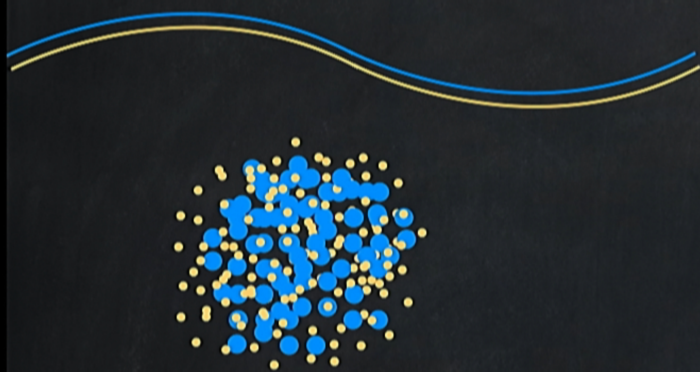

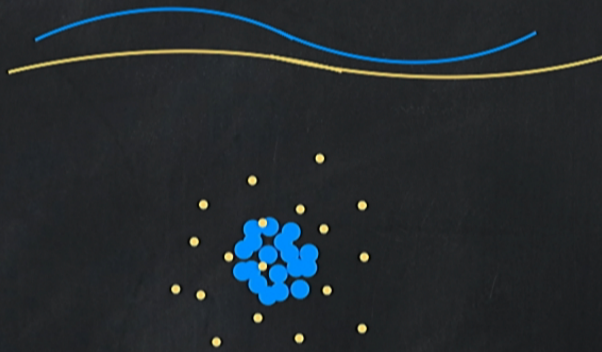

This can be mapped to an closed FRW with CDM and neutrinos evolving as $1/a_c^3$

Hu, Chiang, Li, LoVerde 2016

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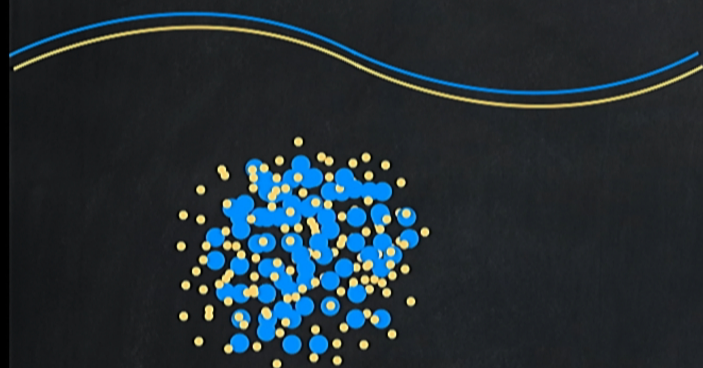

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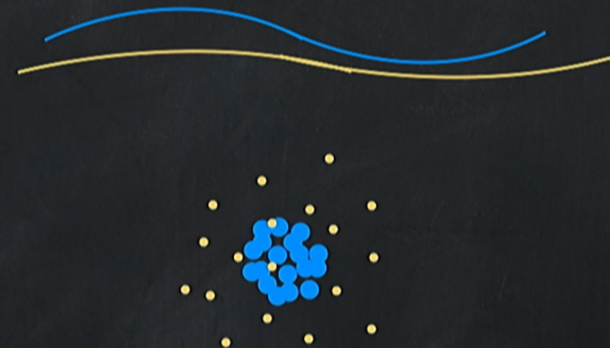

This can be mapped to closed FRW with CDM evolving as $1/a_c^3$, but the neutrinos appear to dilute faster, and curvature is not conserved

Hu, Chiang, Li, LoVerde 2016

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* If CDM is the only thing clustering on small scales, the nonlinear dynamics in both cases can still be described by the local comoving coordinate a_c defined by the dark matter

Hu, Chiang, Li, LoVerde 2016

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**This gives a *general* formalism for studying bias and mode-coupling with multiple fluids — e.g. massive neutrinos or clustered quintessence

Hu, Chiang, Li, LoVerde 2016

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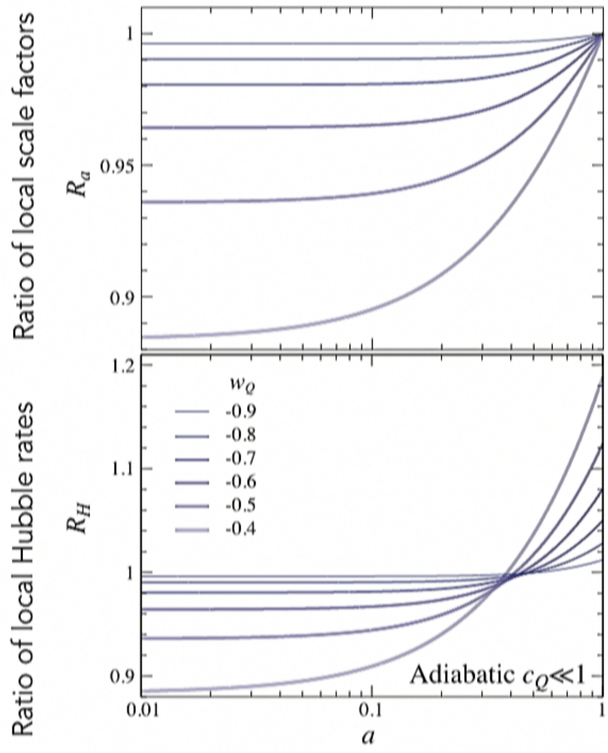
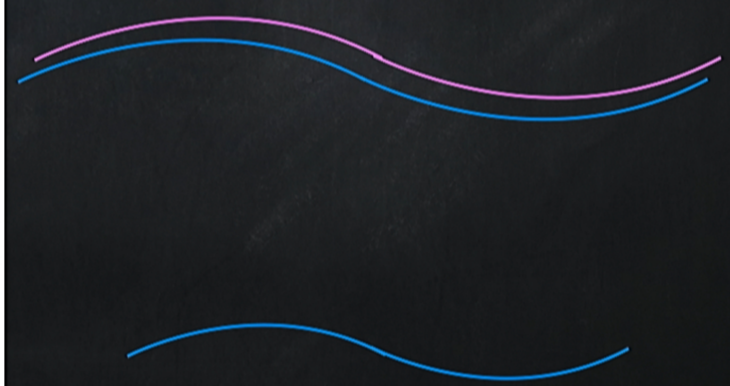
Example:



Compare local evolution for perturbations larger and smaller than quintessence Jeans scale



Hu, Chiang, Li, LoVerde 2016

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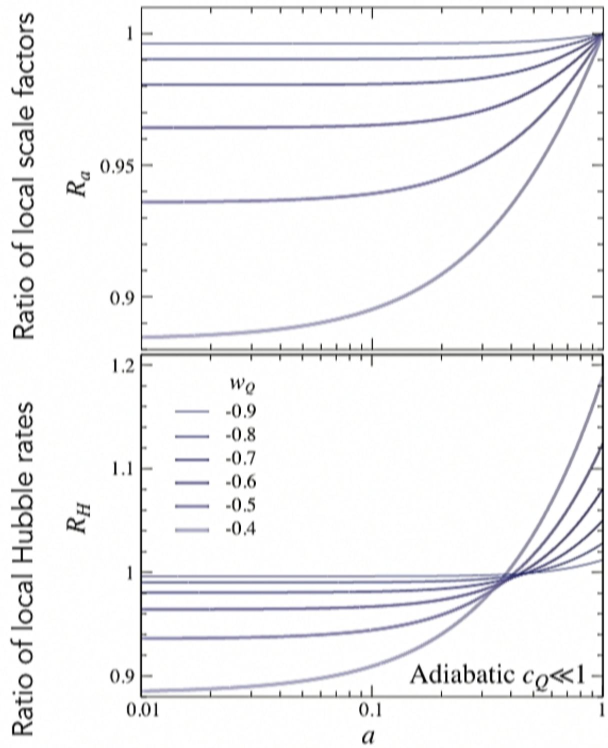

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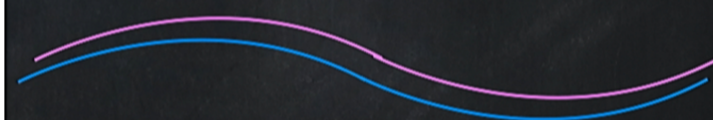

Stay Tuned!

Hu, Chiang, Li, LoVerde 2016

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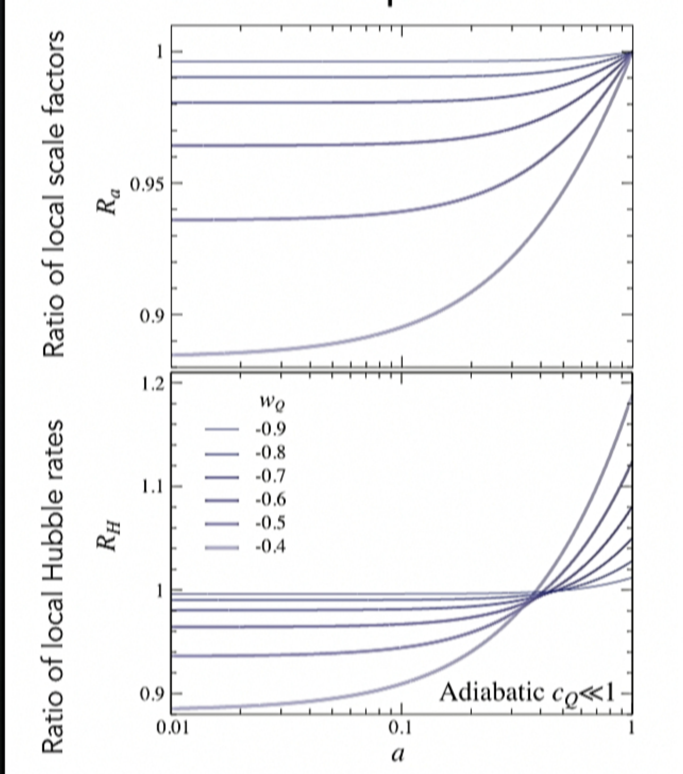

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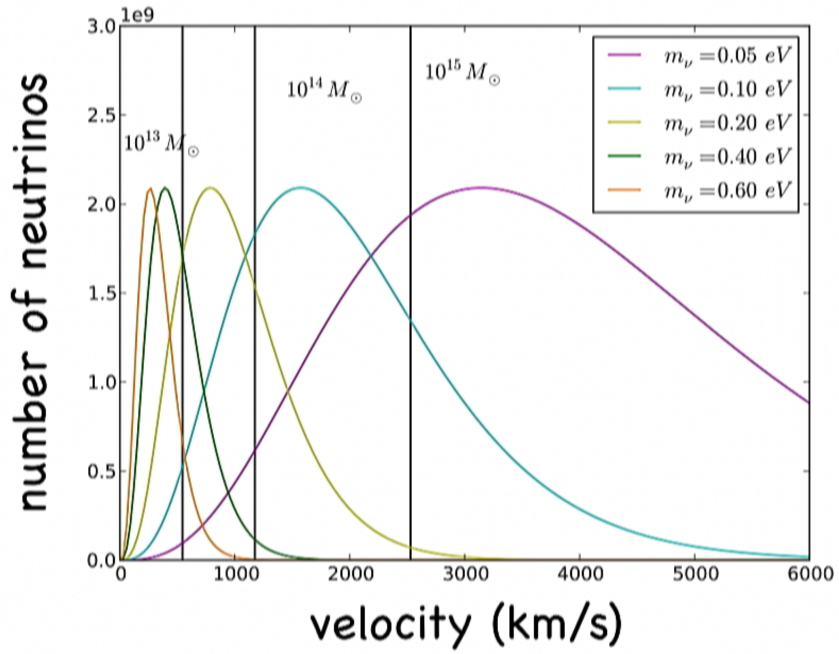
Hu, Chiang, Li, LoVerde 2016

Neutrino Halos

ML & Zaldarriaga 2013

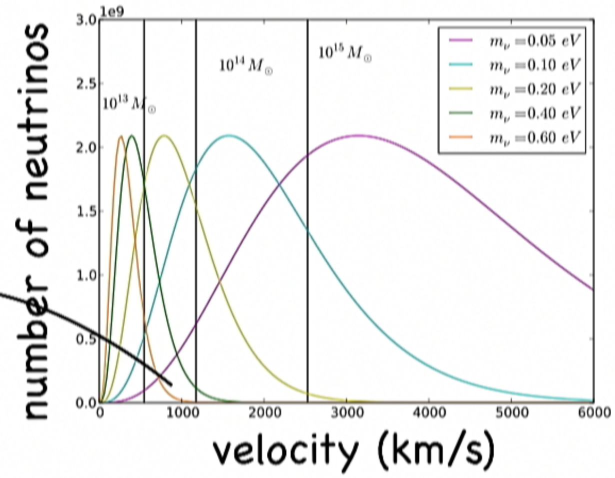
Neutrino Halos



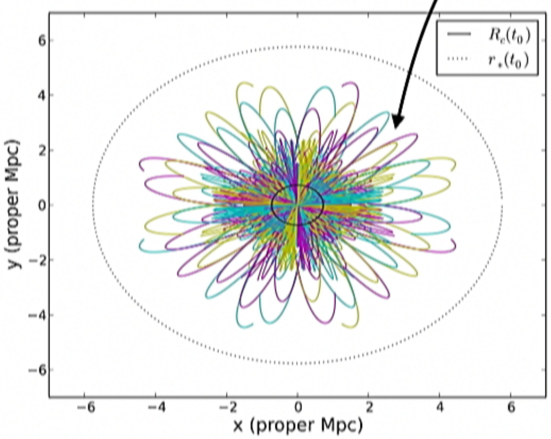
ML & Zaldarriaga 2013

Neutrino Halos

low velocity neutrinos end up bound in halos



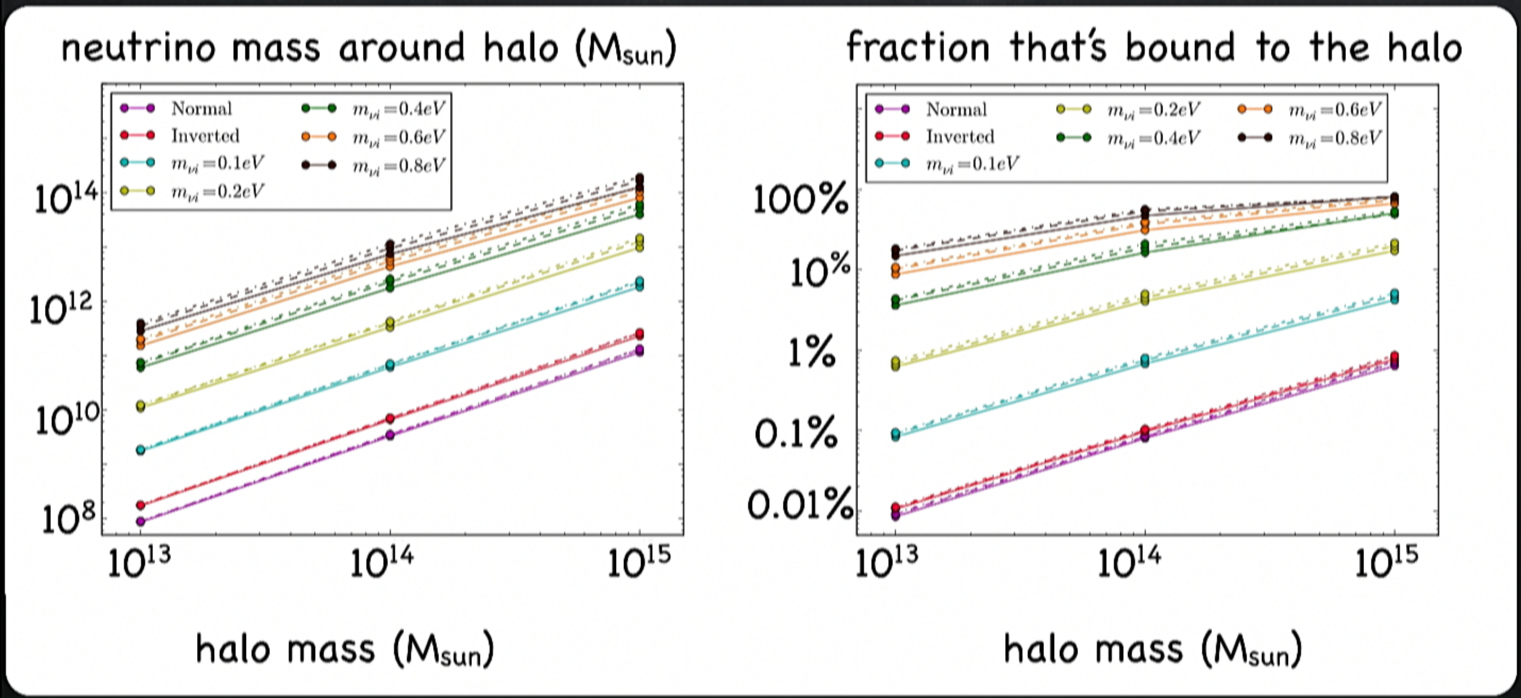
shown are m_ν = 0.05eV neutrinos around M = 10^{14} M_{sun} halo



see also Ringwald & Wong 2004; Brandbyge, Hannestad, Haugboelle, Wong 2010
Villaescusa-Navarro, Bird, Pena-Garay, Viel 2013

ML & Zaldarriaga 2013

Neutrino Halos



ML & Zaldarriaga 2013

Neutrino Halos - Relative Velocity Effects

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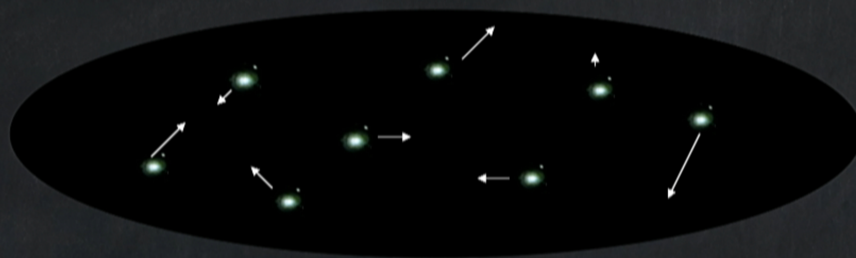
Cold dark matter halos are not at rest w.r.t. cosmic frame!



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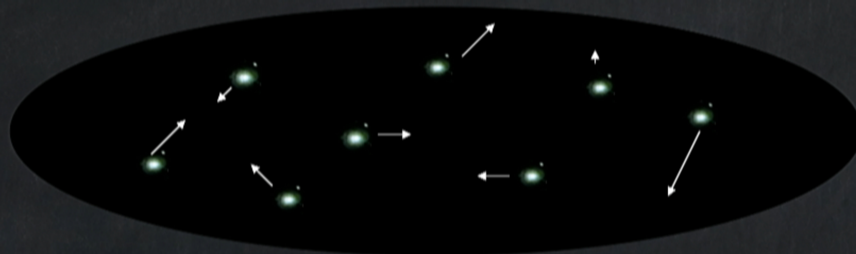

(The Milky Way is moving at ~ 550 km/s w.r.t the CMB)

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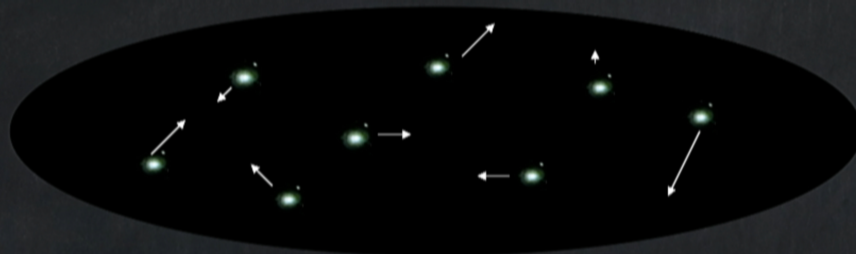
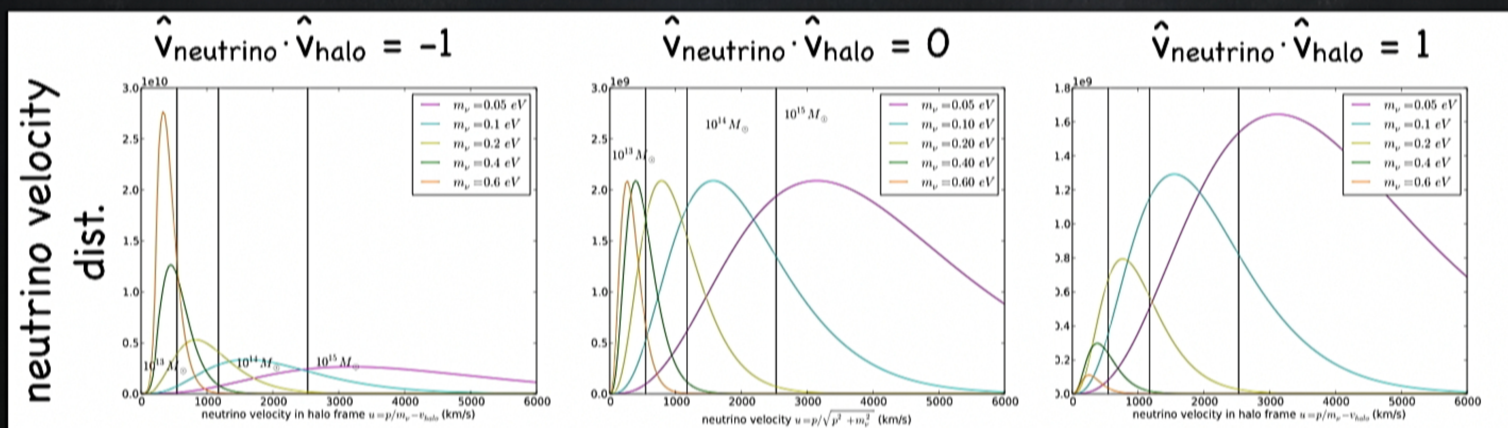


(The Milky Way is moving at ~ 550 km/s w.r.t the CMB)

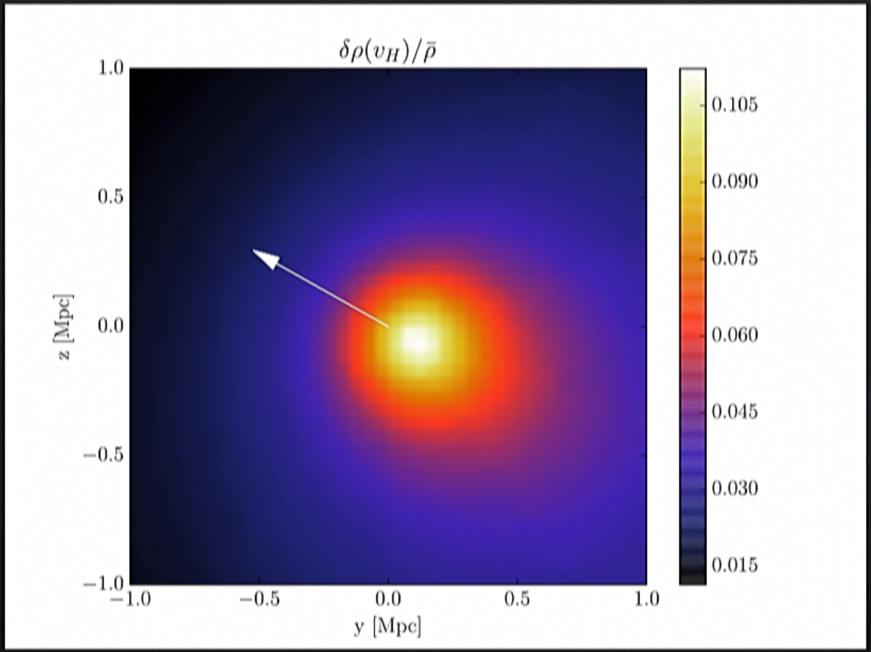
Halos moving through neutrino "wind"



ML & Zaldarriaga

Neutrino Halos - Relative Velocity Effects

Qualitative difference between how halos acquire CDM and neutrino mass



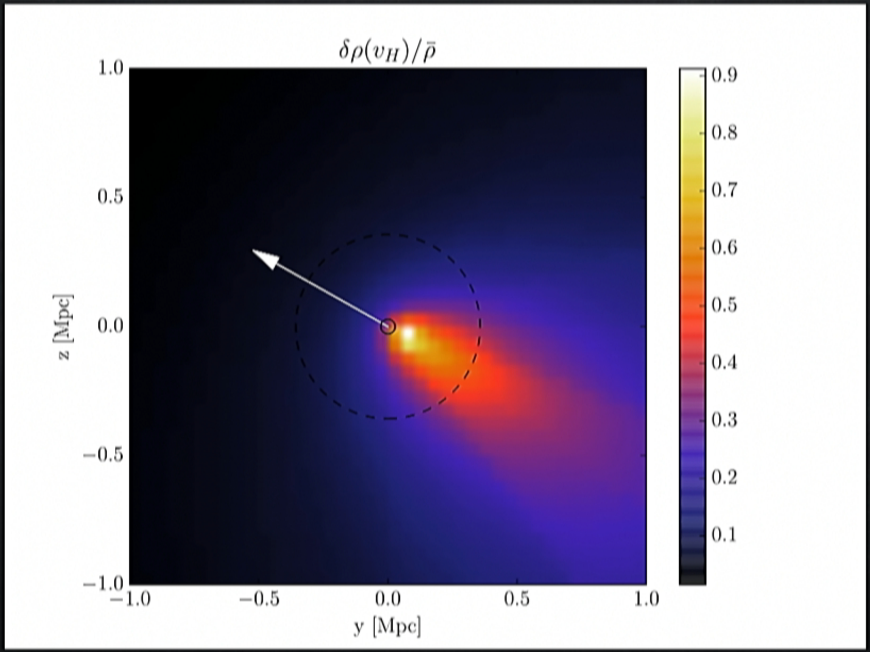
$M_{halo} = 10^{12}\ M_{sun}$; $v_{halo} = v_{milky\text{-}way}$; $m_\nu = 0.1$ eV

WORK IN PROGRESS

work in progress with TY Lin, Ben Safdi

Neutrino Halos - Relative Velocity Effects

Qualitative difference between how halos acquire CDM and neutrino mass

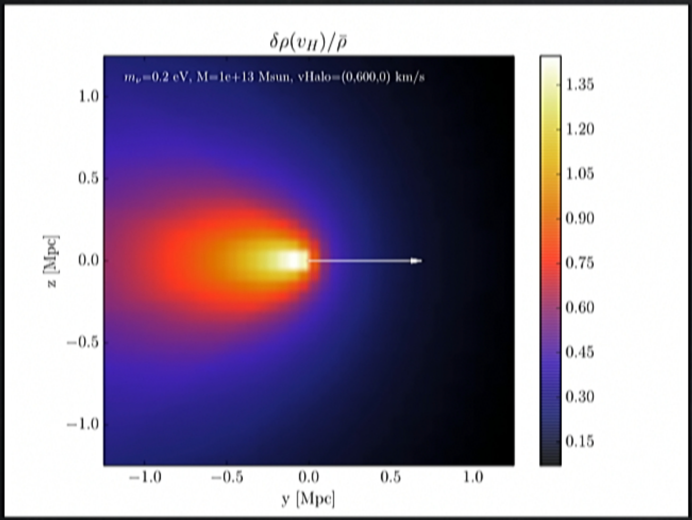


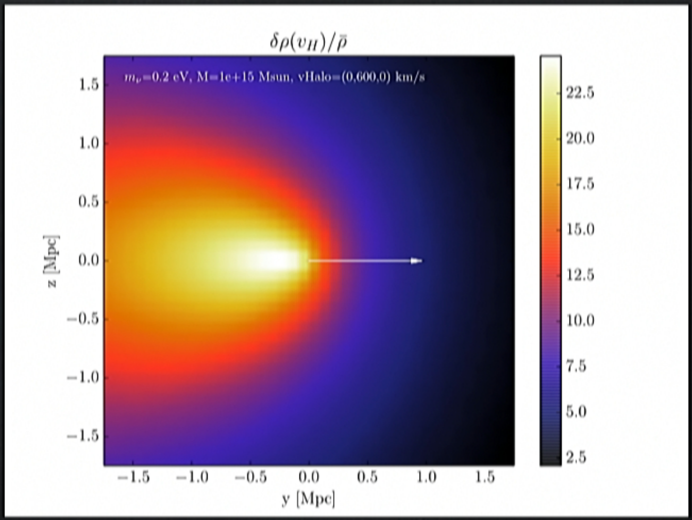
$M_{halo} = 10^{12}\ M_{sun}$; $v_{halo} = v_{milky\text{-}way}$; $m_\nu = 0.3$ eV

work in progress with TY Lin, Ben Safdi

Neutrino Halos - Relative Velocity Effects

Qualitative difference between how halos acquire CDM and neutrino mass





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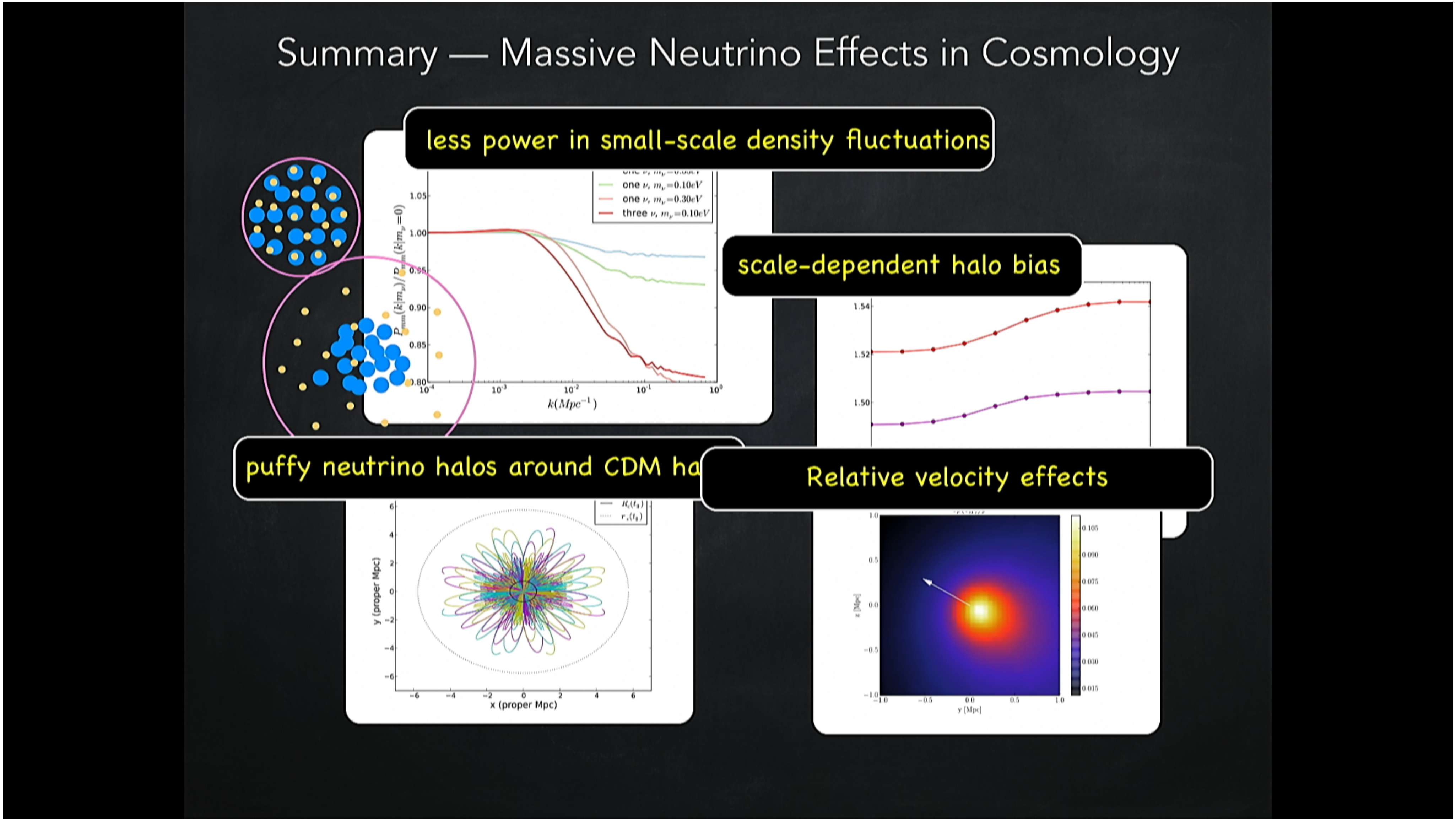
Summary — Massive Neutrino Effects in Cosmology
less power in small-scale density fluctuations
one ν, m_ν=0.10eV
one ν, m_ν=0.30eV
three ν, m_ν=0.10eV
$k(Mpc^{-1})$
scale-dependent halo bias
puffy neutrino halos around CDM ha
Relative velocity effects
y (proper Mpc)
x (proper Mpc)
y [Mpc]