Neutrino Physics and Mass from Cosmology

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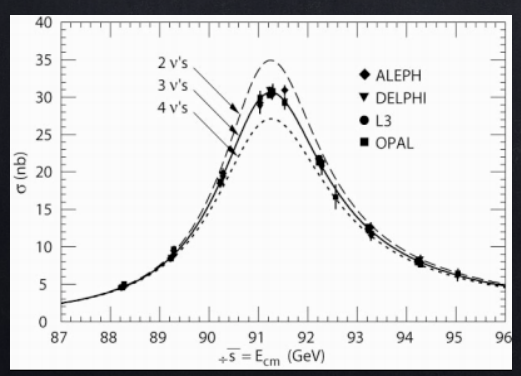
Outline

- Neutrinos!
- Cosmic background neutrinos
- Neutrino effects in large-scale structure: The linear regime
- *More* neutrino effects in large-scale structure (the nonlinear regime)
- Conclusion

Neutrinos

Neutrinos: what do we know?

three flavors



(LEP constraints from width of Z)

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

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

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

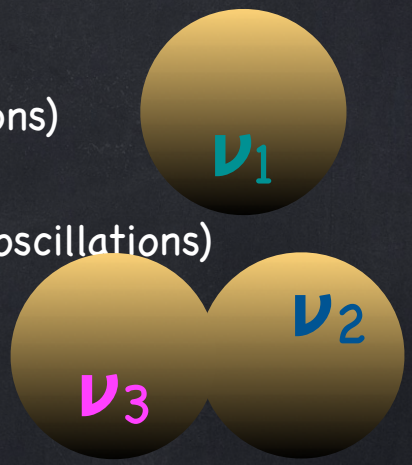
Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962

Neutrinos: what do we know?

Oscillation data gives mass splittings

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

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



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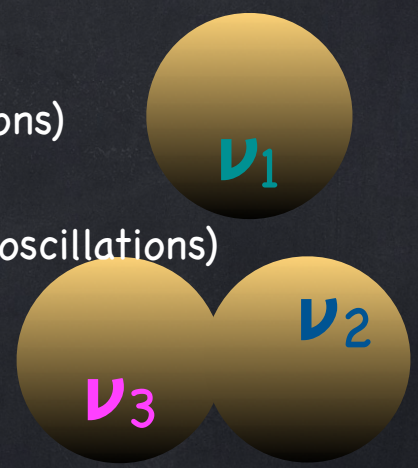

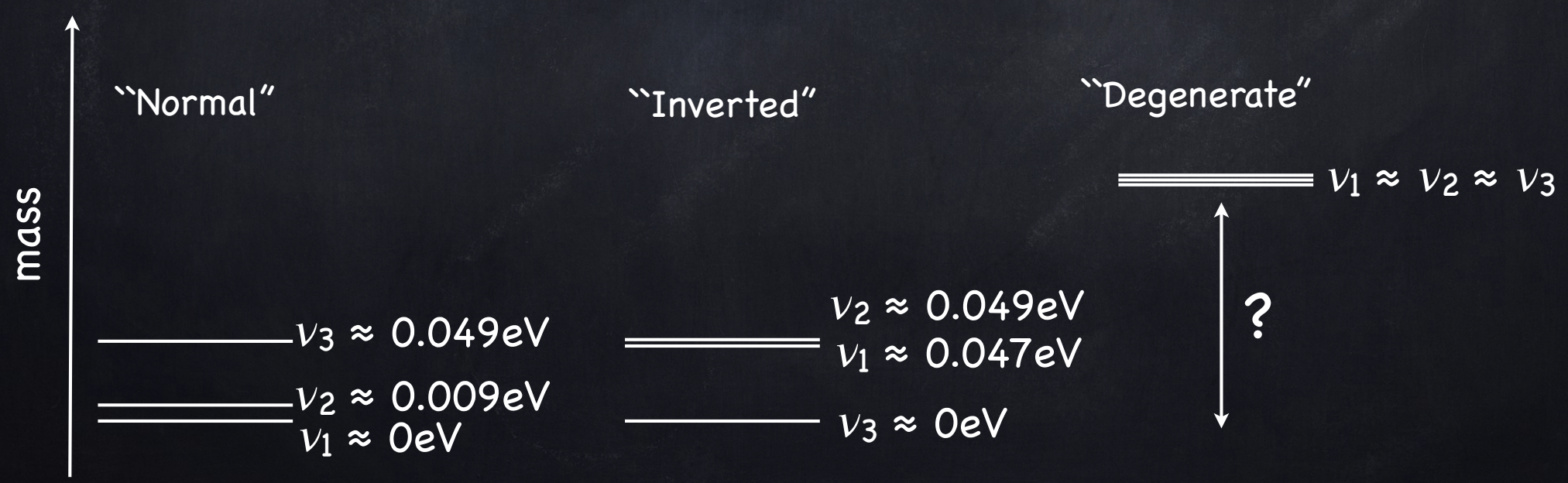

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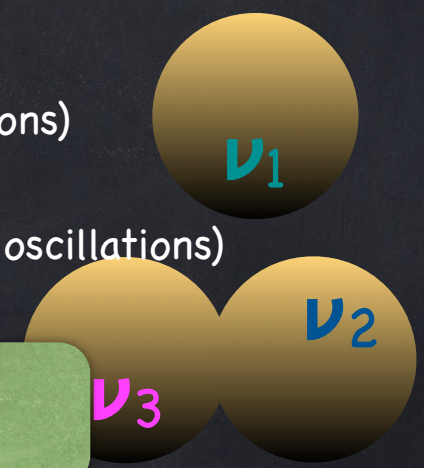
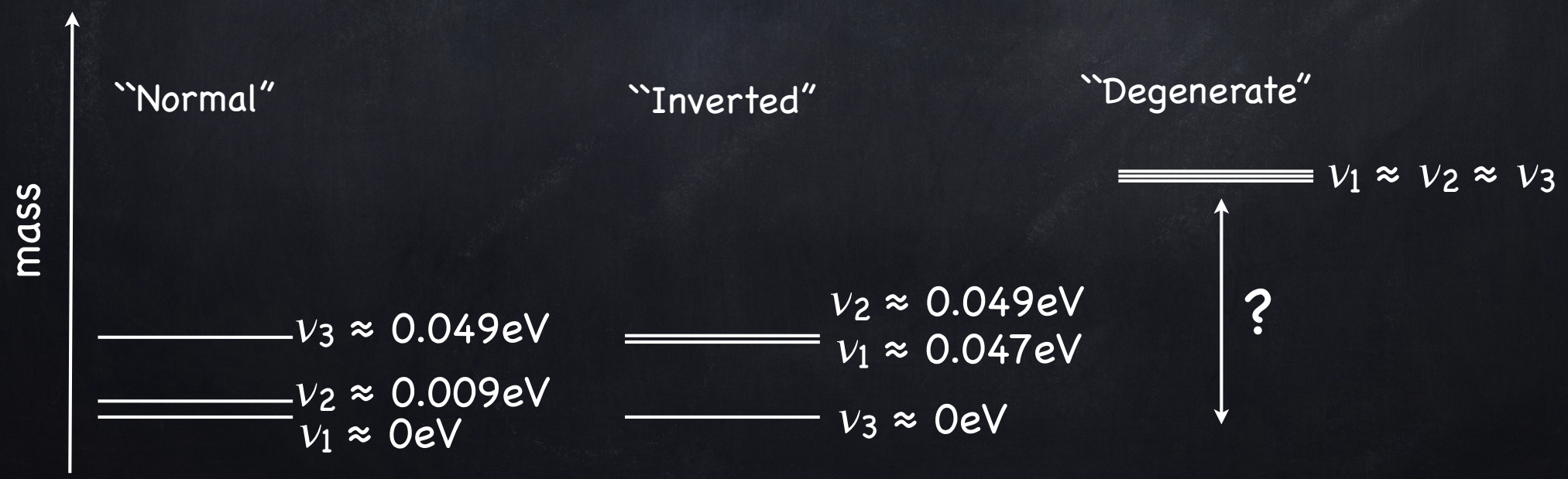


at least one neutrino mass is $\gtrsim 0.05$eV



Neutrinos: what do we know?

lower bound on mass
from oscillation data

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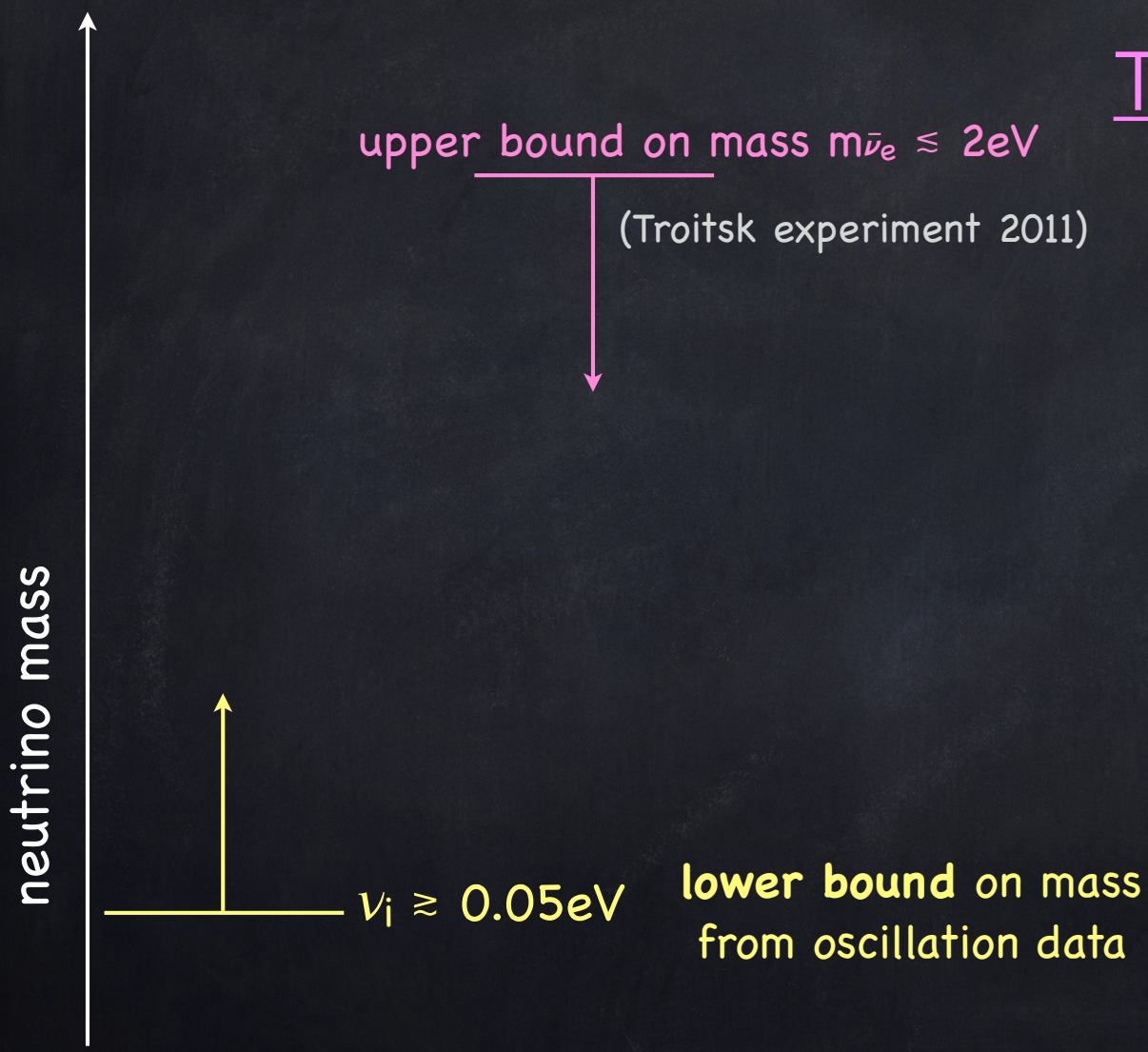

Neutrinos: what do we know?

neutrino mass

Tritium β decay

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

(Troitsk experiment 2011)

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

(KATRIN/Project 8/PTOLEMY 20xx?)

$\nu_i \gtrsim 0.05\text{eV}$ **lower bound** on mass from oscillation data

Neutrinos: what do we know?

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Cosmology

upper bound on sum of masses $\sum m_\nu \lesssim 0.49\text{eV}$

(CMB alone, Planck 2015)

$\sum m_\nu \lesssim 0.17\text{eV}$

(CMB + BAO, Planck 2015)

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lower bound on mass from oscillation data

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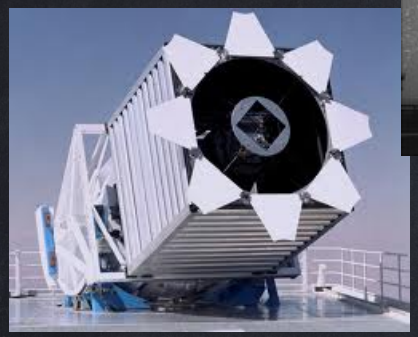
lower bound on mass from oscillation data

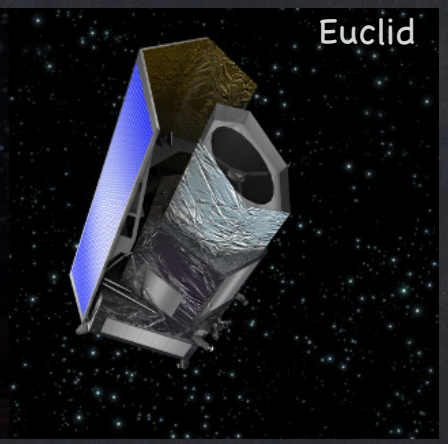
future detection via astrophysics!

Future detection via astrophysical datasets

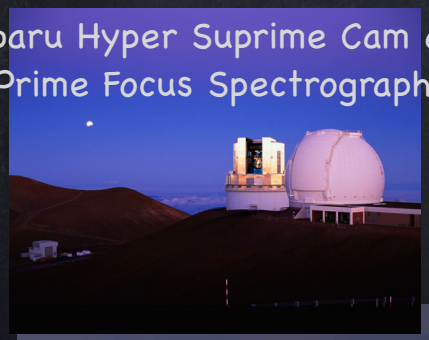
Large-scale structure surveys

Sloan Digital Sky Survey





Subaru Hyper Suprime Cam and
Prime Focus Spectrograph



SPHEREX

Hobby-Eberly Telescope
Dark Energy EXperiment

21 CM experiments

Future detection via astrophysical datasets

Large-scale structure surveys

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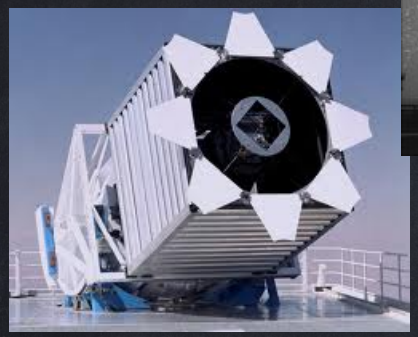

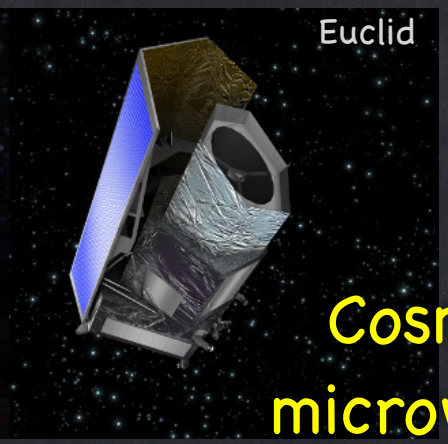

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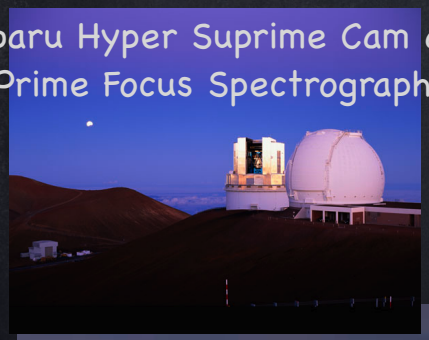

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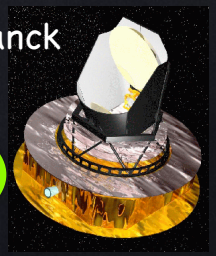
Cosmic microwave background experiments

Planck



CMB ``Stage IV''

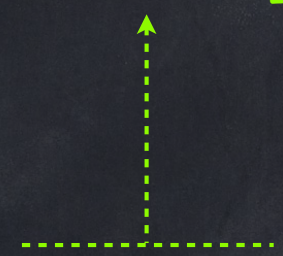
$$\sigma_{\Sigma m_\nu} \sim 0.02\text{eV}$$

e.g. Snowmass 2013 1309.5383

Neutrinos: what do we know?

lower bound on mass from oscillation data

Funny Stuff



LSND, MiniBooNE, reactor anomalies suggest a splitting $\Delta m^2 \sim 1\text{eV}^2$

$\Rightarrow$ additional neutrino mass states and a sterile ν?

Neutrinos: what do we know?

Funny Stuff

Light Sterile Neutrinos: A White Paper

In summary, there are a number of experimental results that appear anomalous in the context of the standard 3 neutrino framework, and can be explained by a sterile neutrino with mass around 1 eV. At the same time, there are a number of results which are in conflict with this interpretation. The data collected to date present an incomplete, perhaps even contradictory picture, where 2-3 σ agreement *in favor of* and *in contradiction to* the existence of sterile neutrinos is present. The need

The three active neutrinos should be there, but let's remain open to the possibility that additional, more massive neutrinos exist

see e.g. Abazajian et al 2012; Conrad, Louis, Shaevitz 2013

Neutrino unknowns

Big Questions

- Where do neutrino masses come from?
- What is the absolute mass scale?
- Are there additional sterile neutrinos?
- Can neutrinos generate matter-antimatter asymmetry of the universe?

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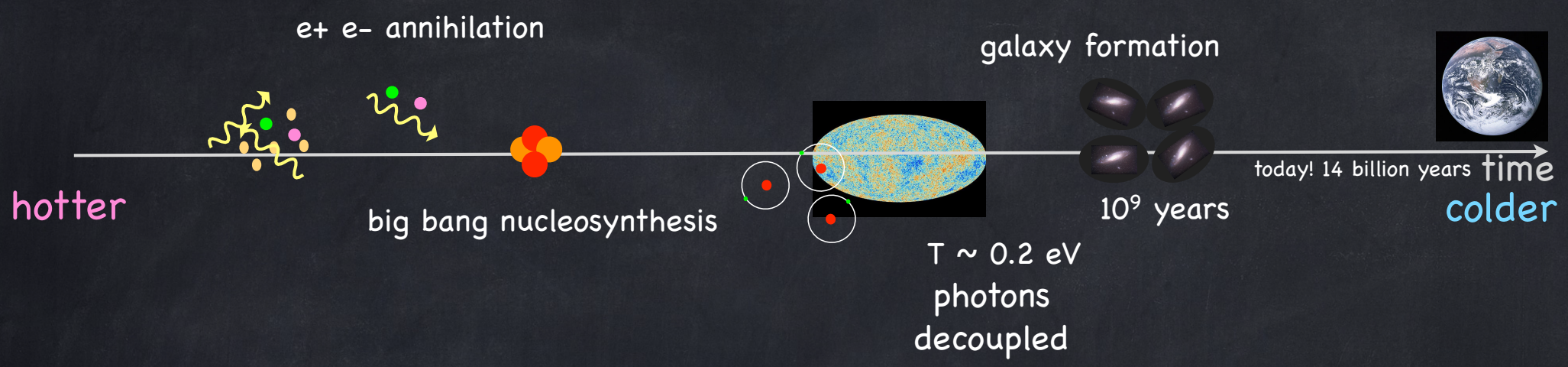
Astrophysics has previously informed neutrino physics!
(solar neutrino problem $\Longrightarrow$ neutrino oscillations)

Neutrinos in Cosmology

Neutrinos in Thermal History of the Universe



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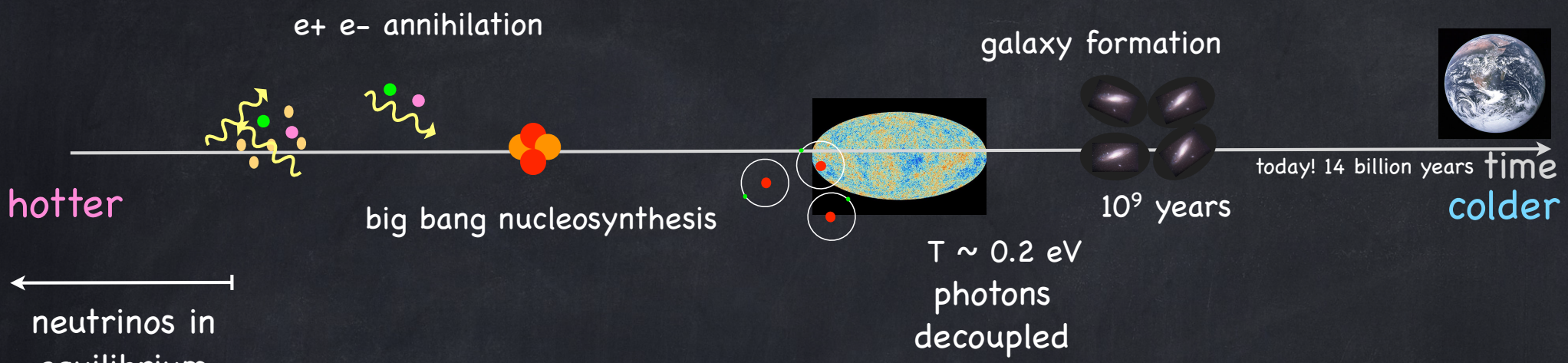

neutrinos in equilibrium with photons e+, e-

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

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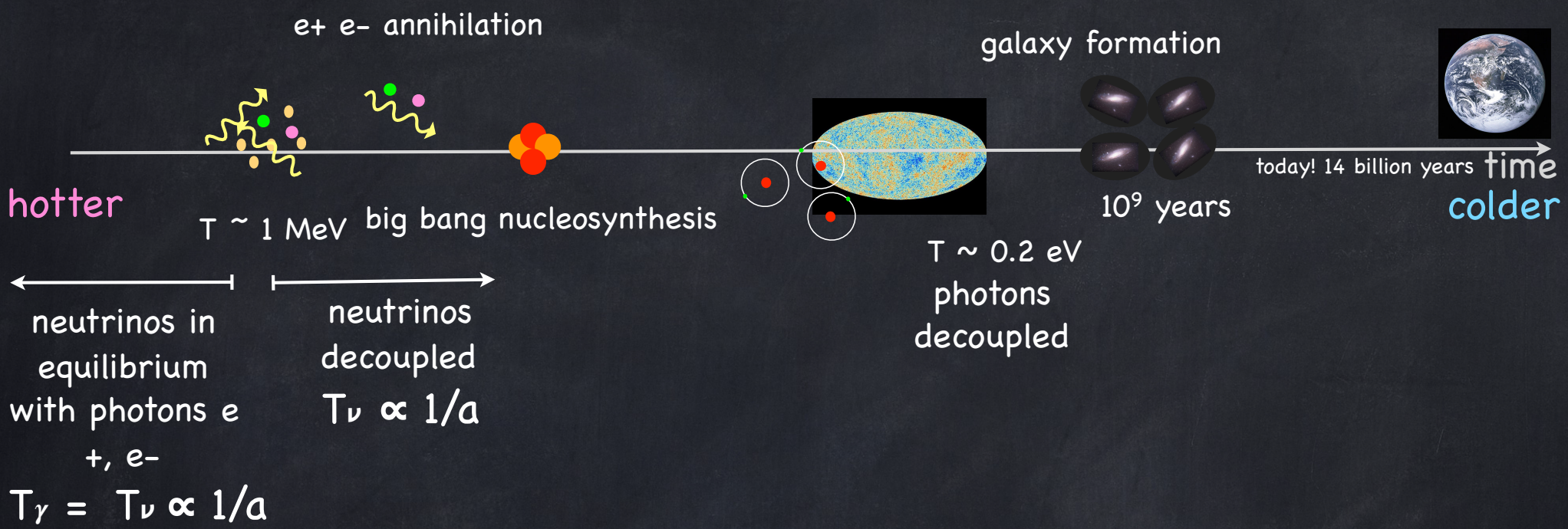

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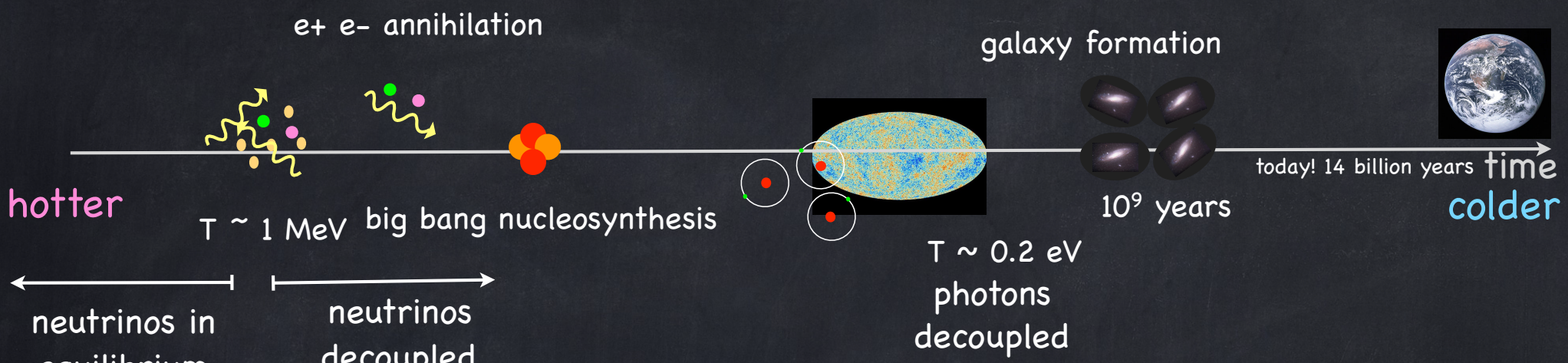

neutrinos in equilibrium with photons e+, e-

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neutrinos decoupled

$T_\nu \propto 1/a$

decouple while relativistic

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

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

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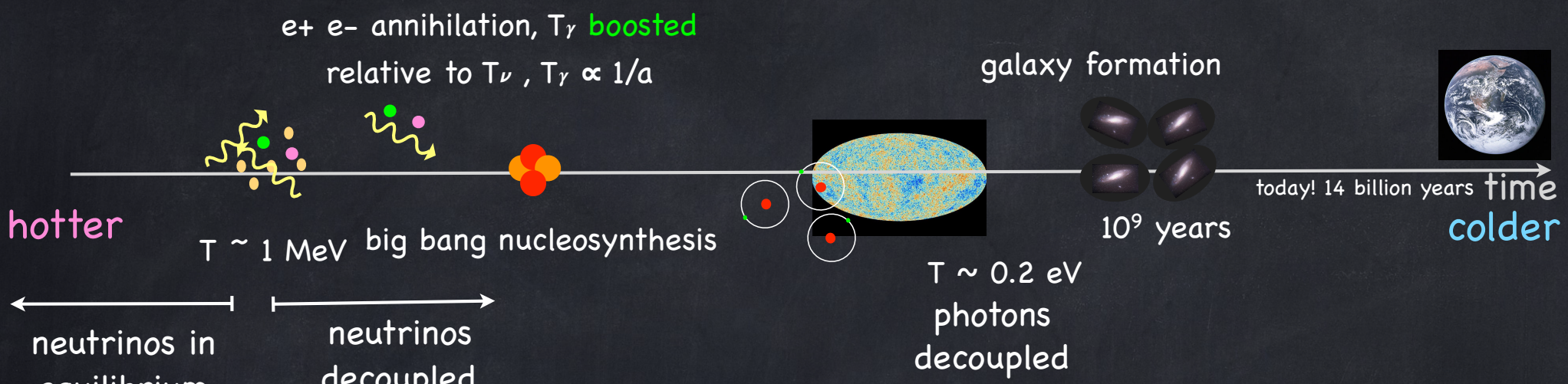

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$$\xrightarrow{T_\gamma \approx \left(\frac{11}{4}\right)^{1/3} T_\nu}$$

$n_\nu \approx 336/\mathrm{cm}^3$

$T_\nu \approx 0.17$ meV

$(\approx 2\mathrm{K})$

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

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cosmic microwave background

cosmic neutrino background

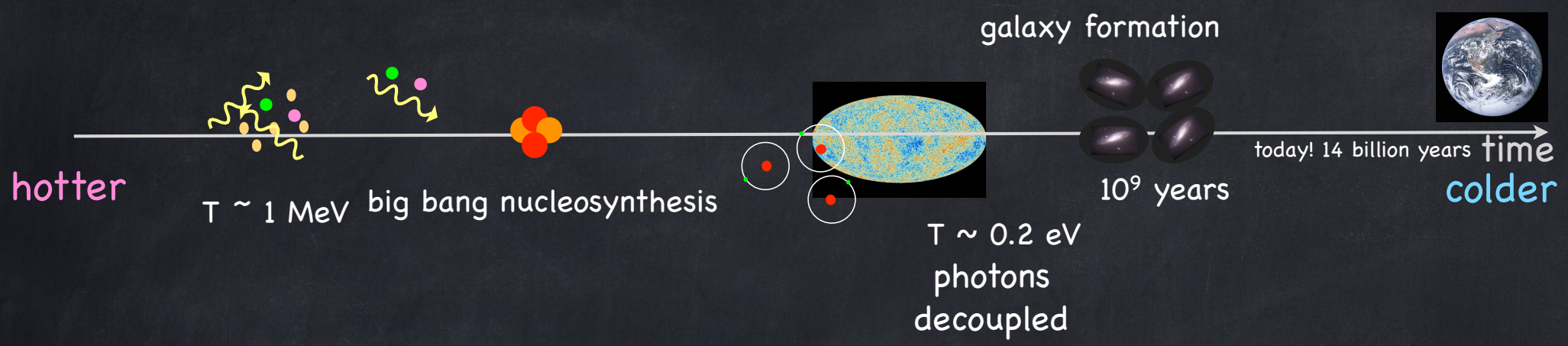
measurements of the radiation density in the early universe can be used to test the number of neutrino-like degrees of freedom

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

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

Planck 2015

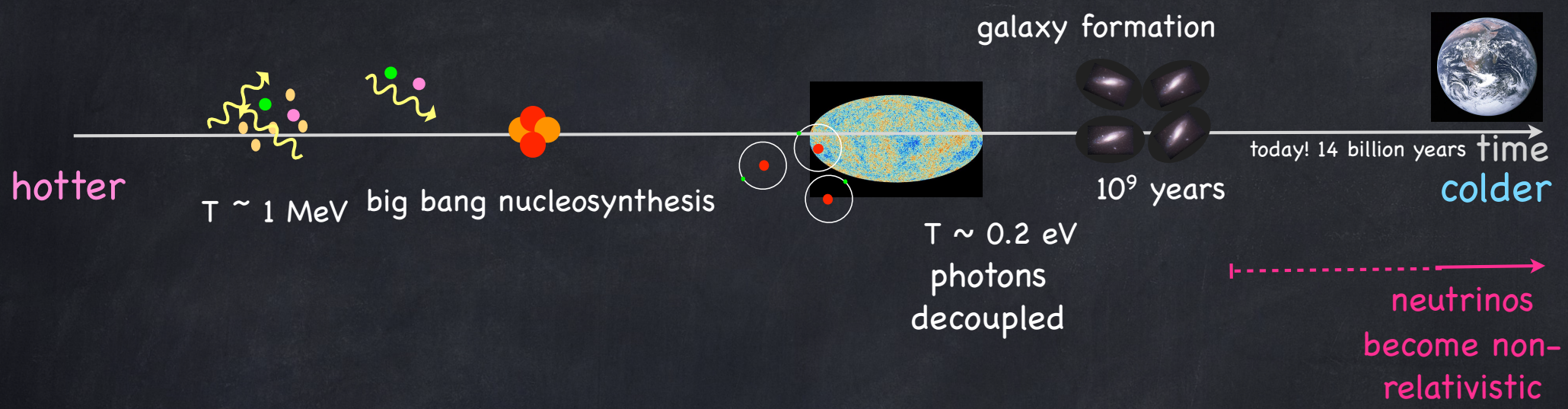
Neutrinos in Thermal History of the Universe



Neutrino momenta decrease with the expansion of the universe

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

Neutrinos in Thermal History of the Universe



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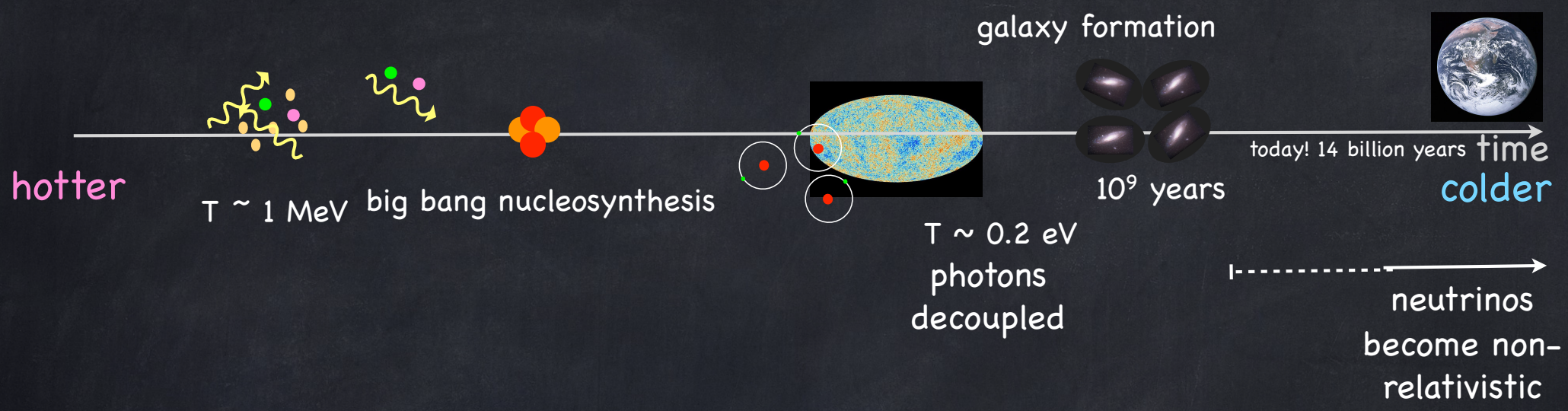

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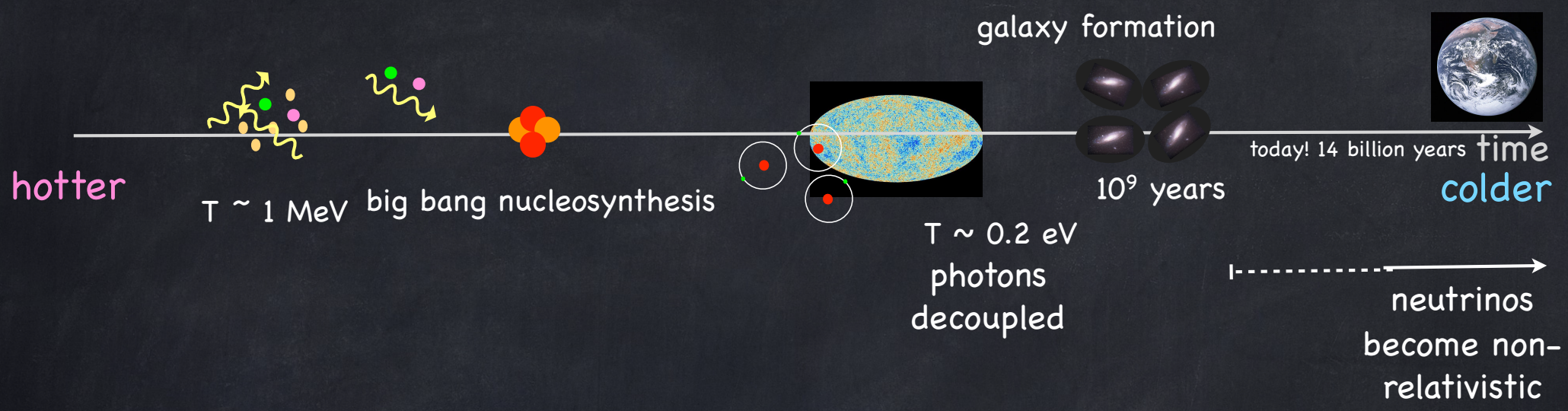

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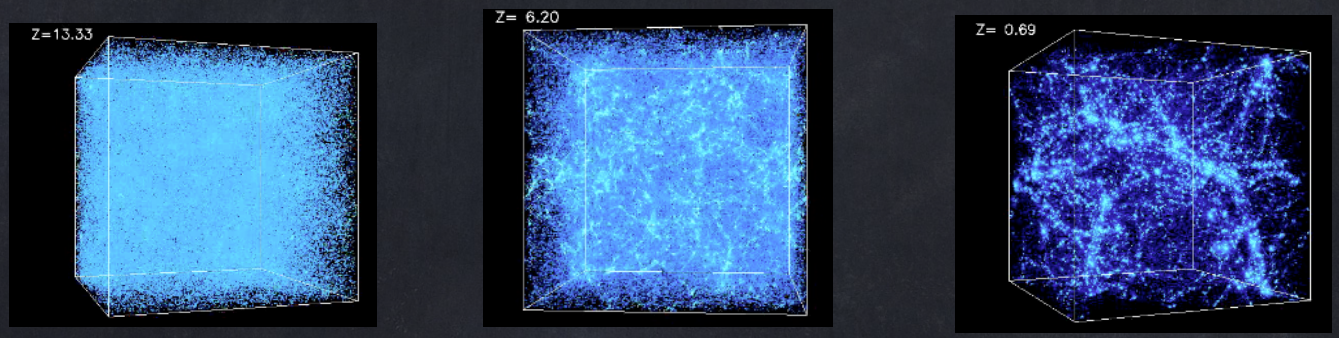
a measurement of ρ_ν yields Σm_ν

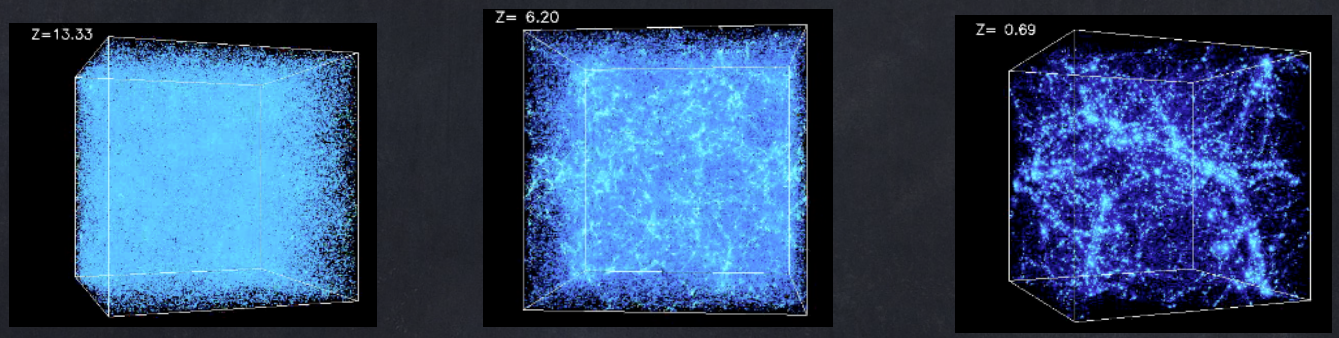
Neutrinos in Large-scale Structure



(Kravtsov)

time

Neutrinos in Large-scale Structure



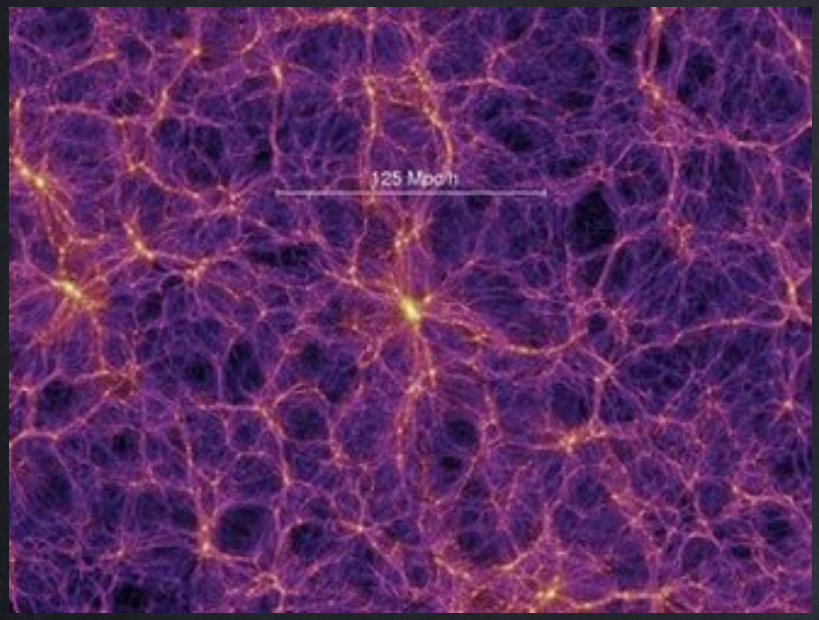
(Kravtsov)

time

massive neutrinos alter this process

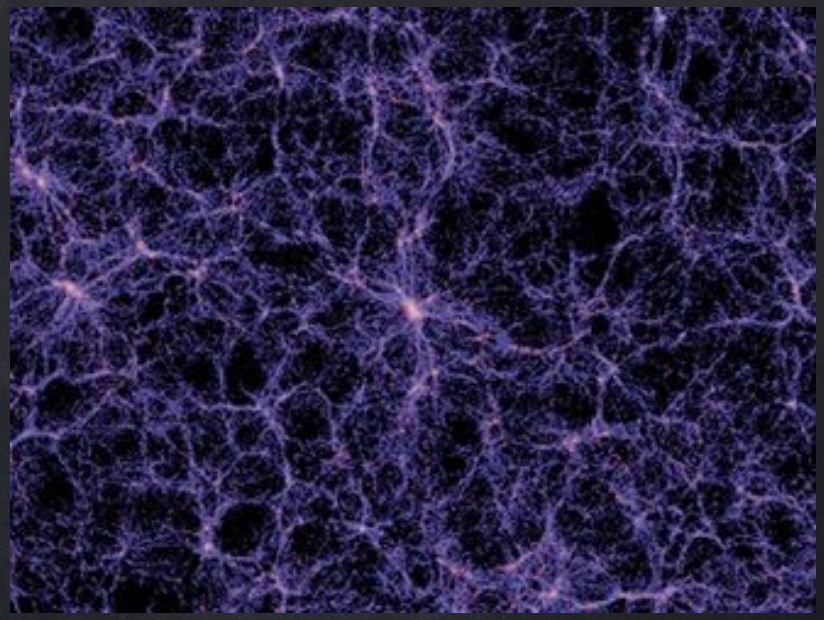
Large-scale Structure

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



(Springel)

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



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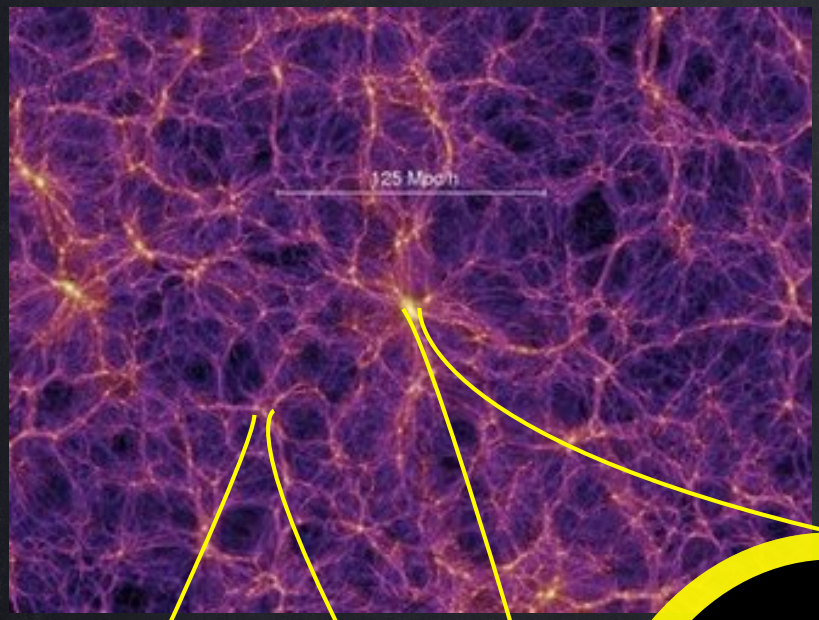

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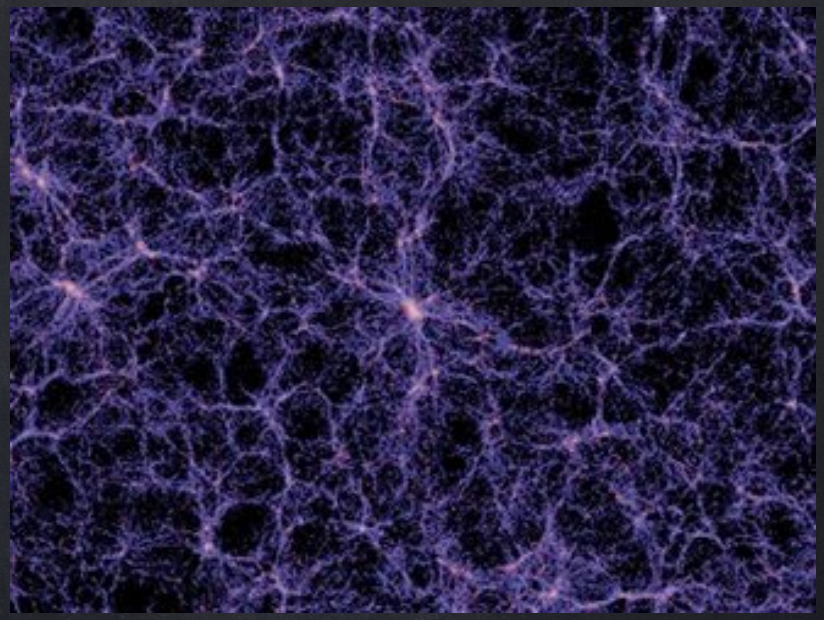

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dark matter "halos"

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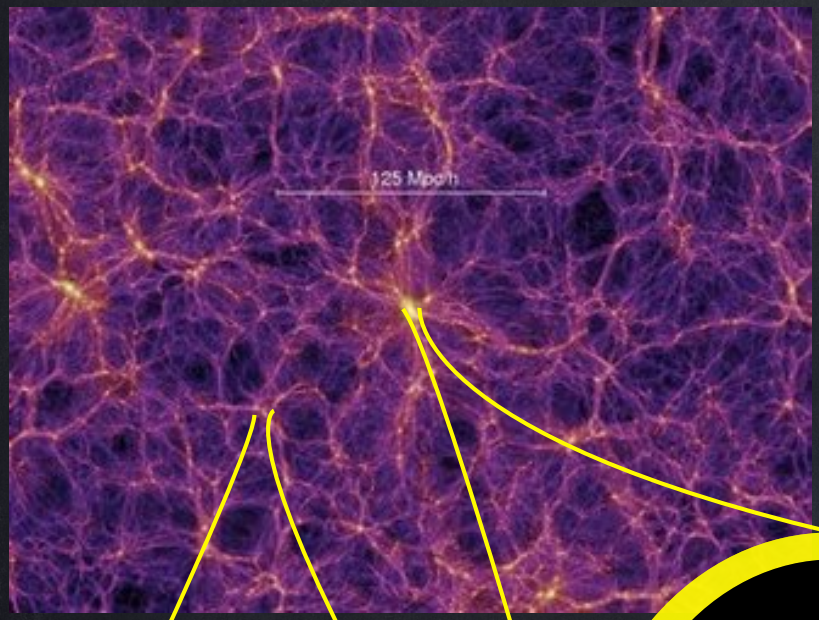

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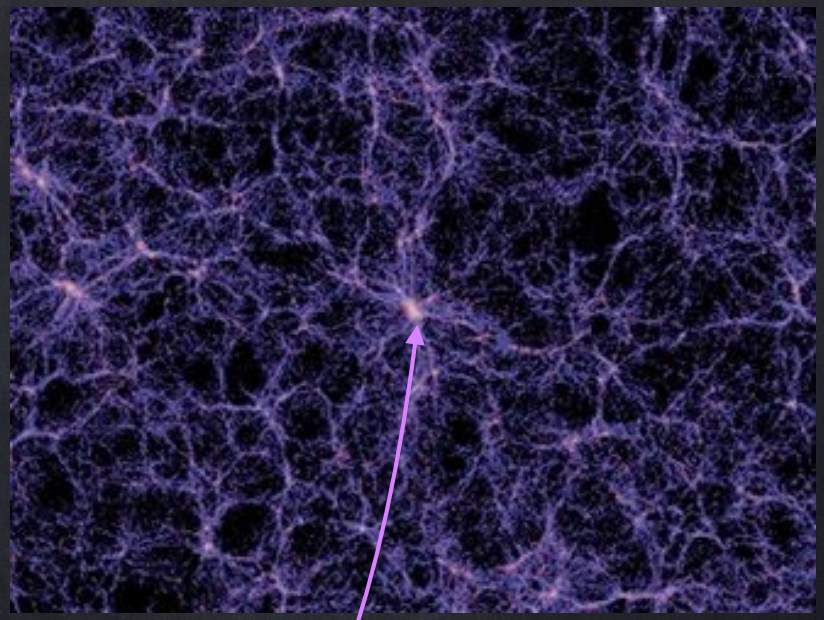

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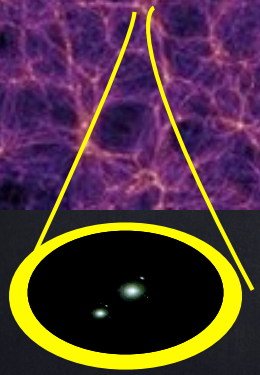

dark matter "halos"

galaxies live in 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

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

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

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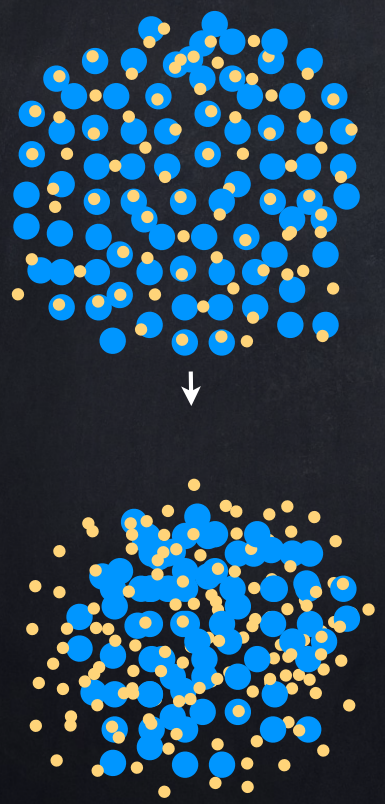
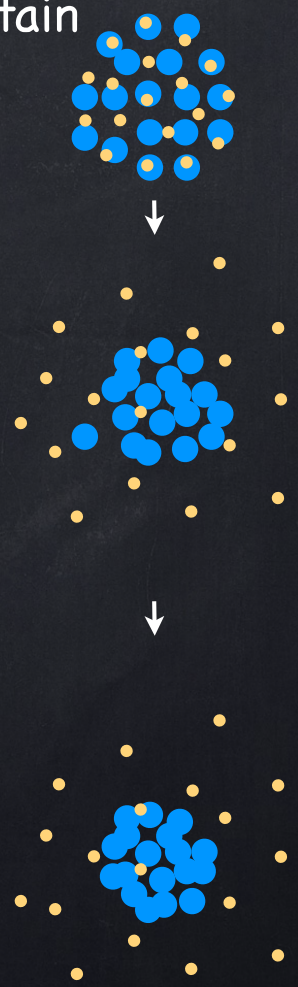
small-scale density perturbations don't retain neutrinos



cold dark matter, baryons and neutrinos growing together



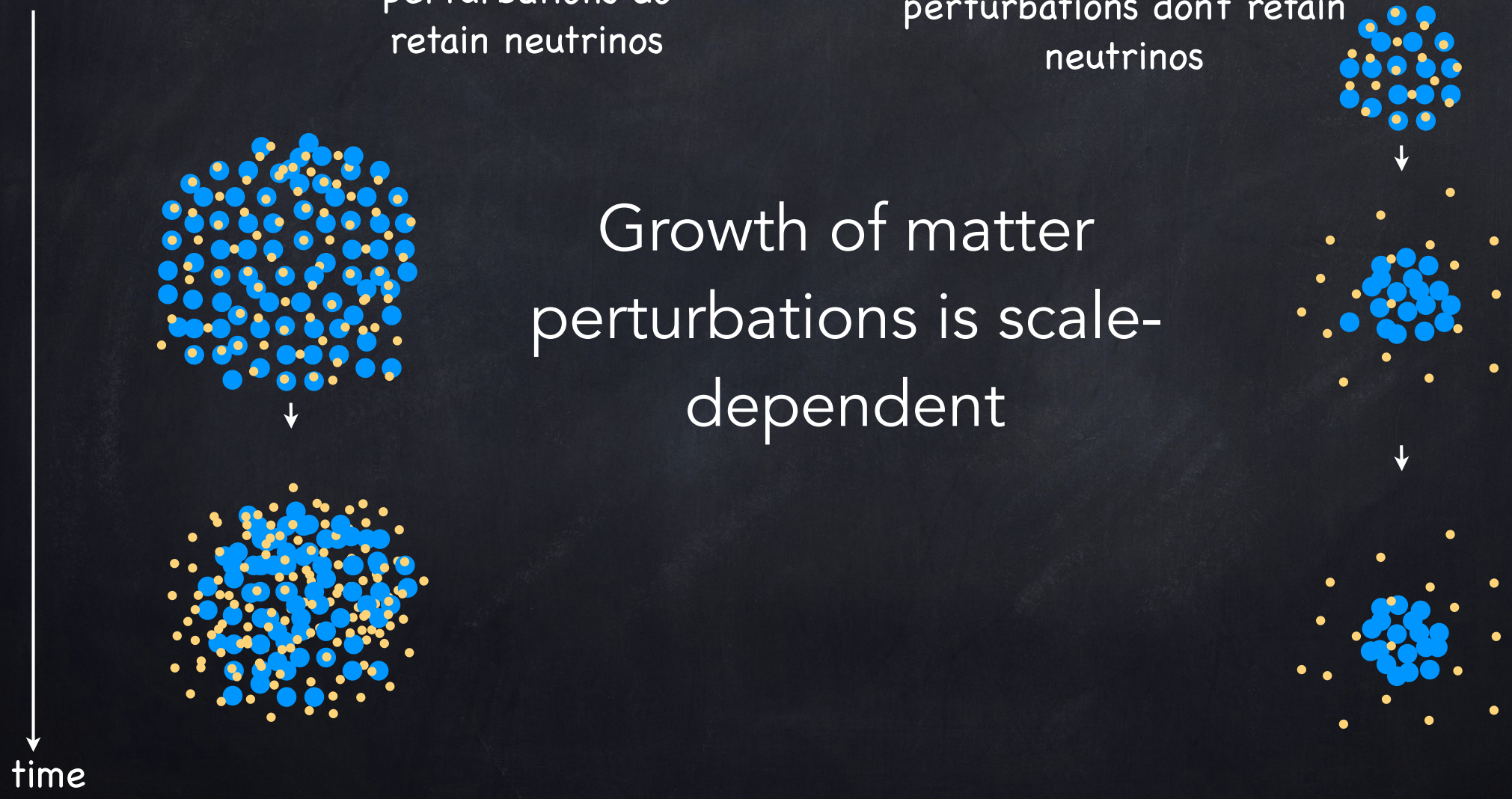
time

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

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

Neutrinos in large-scale structure: Linear regime

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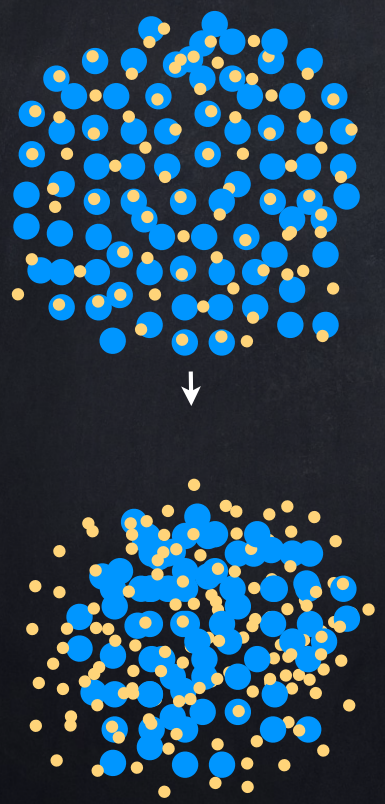
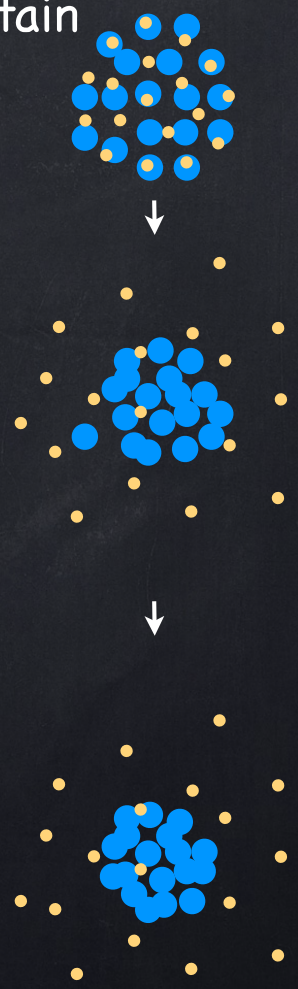
small-scale density perturbations don't retain neutrinos





time

Growth of matter perturbations is scale-dependent

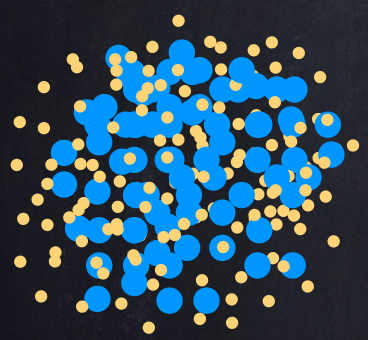
Relevant scale:

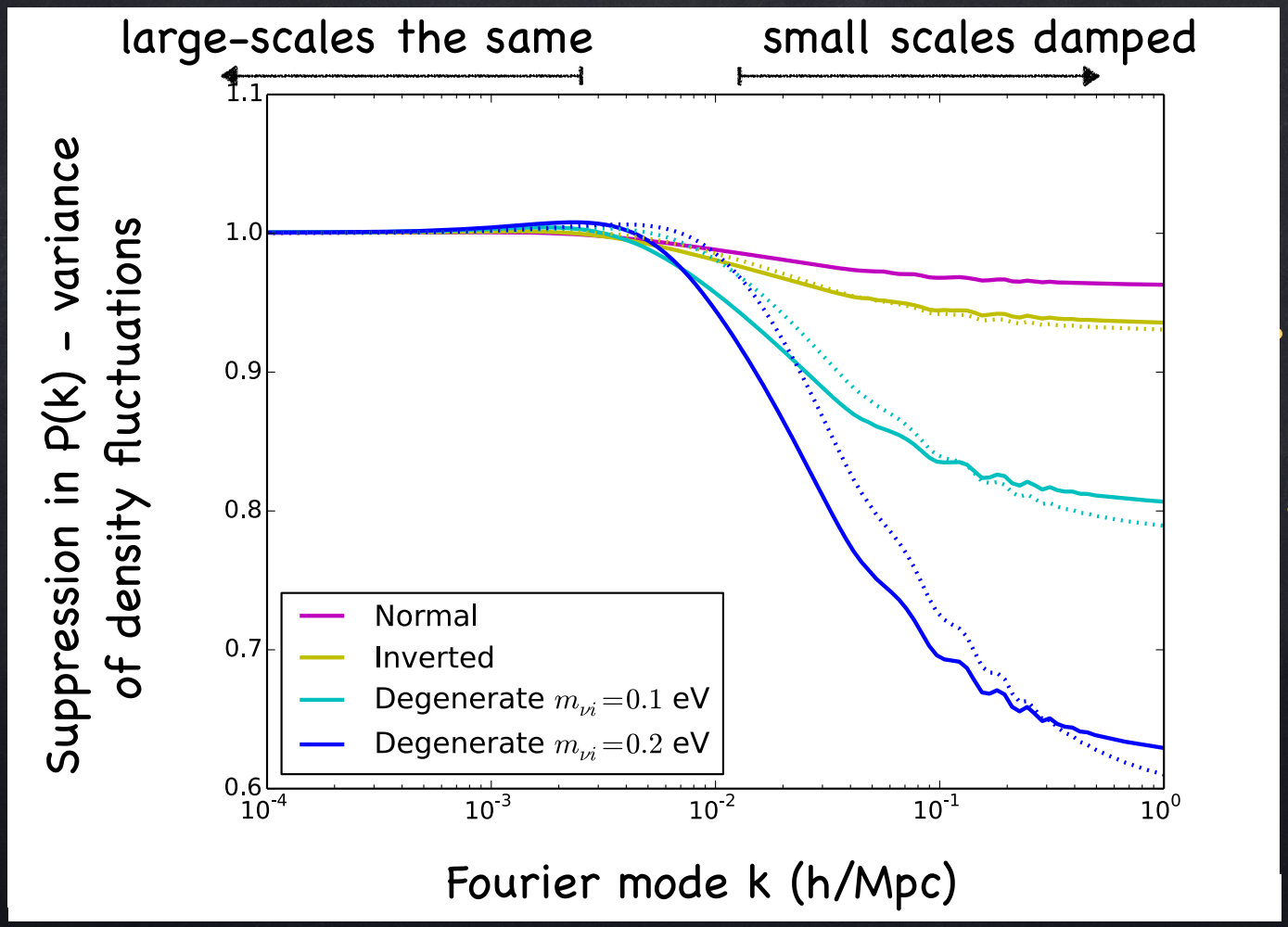
Typical distance a neutrino can travel in a Hubble time

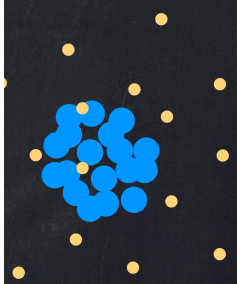
$\lambda_{fs} \sim u_\nu/H$

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

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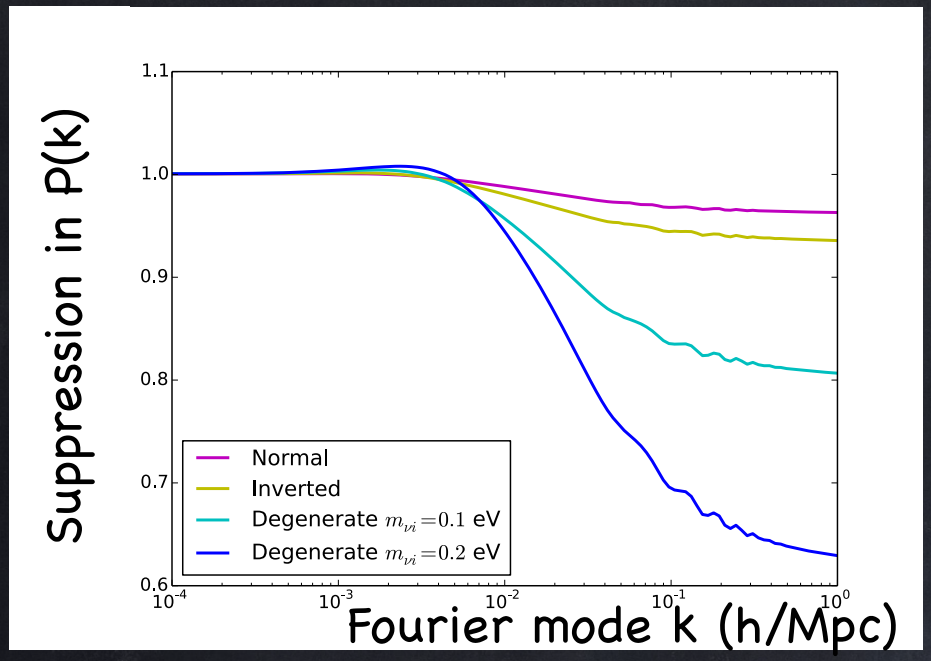
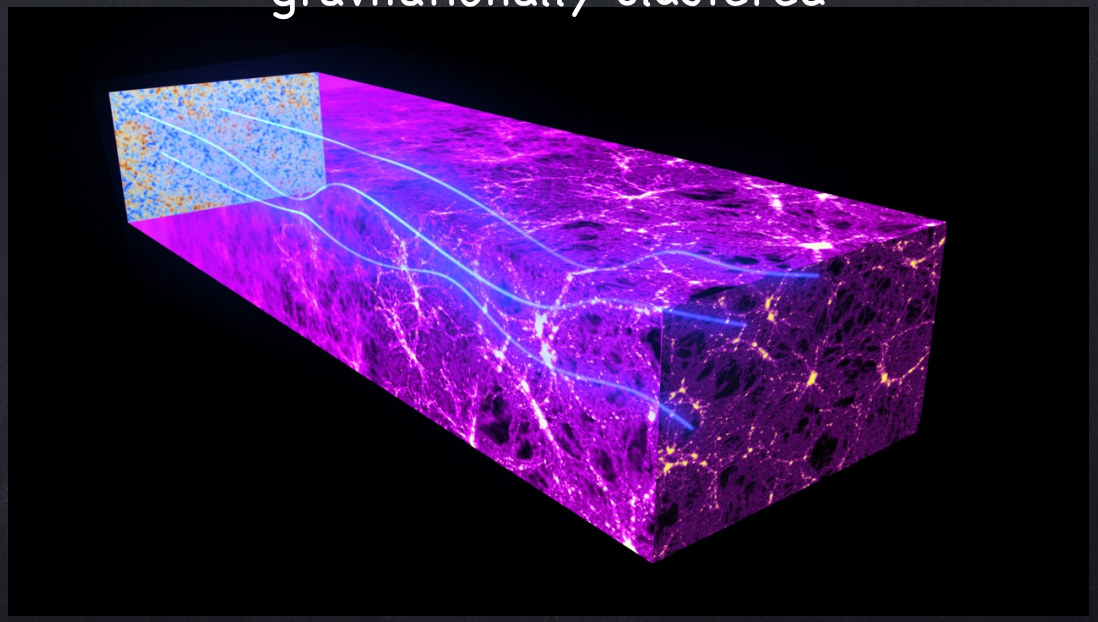


—> less gravitational lensing than a universe where all matter is gravitationally clustered



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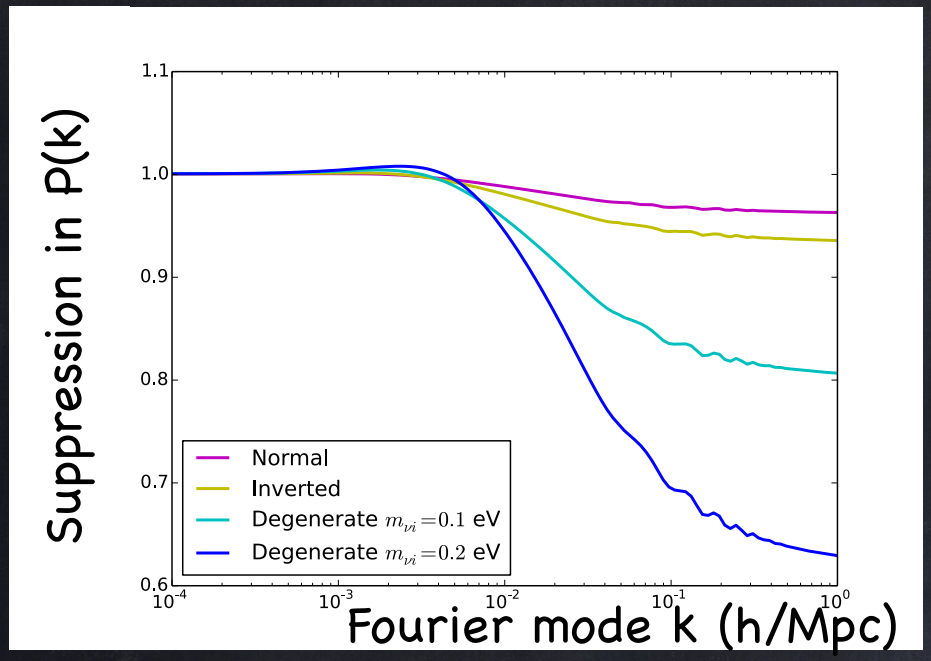
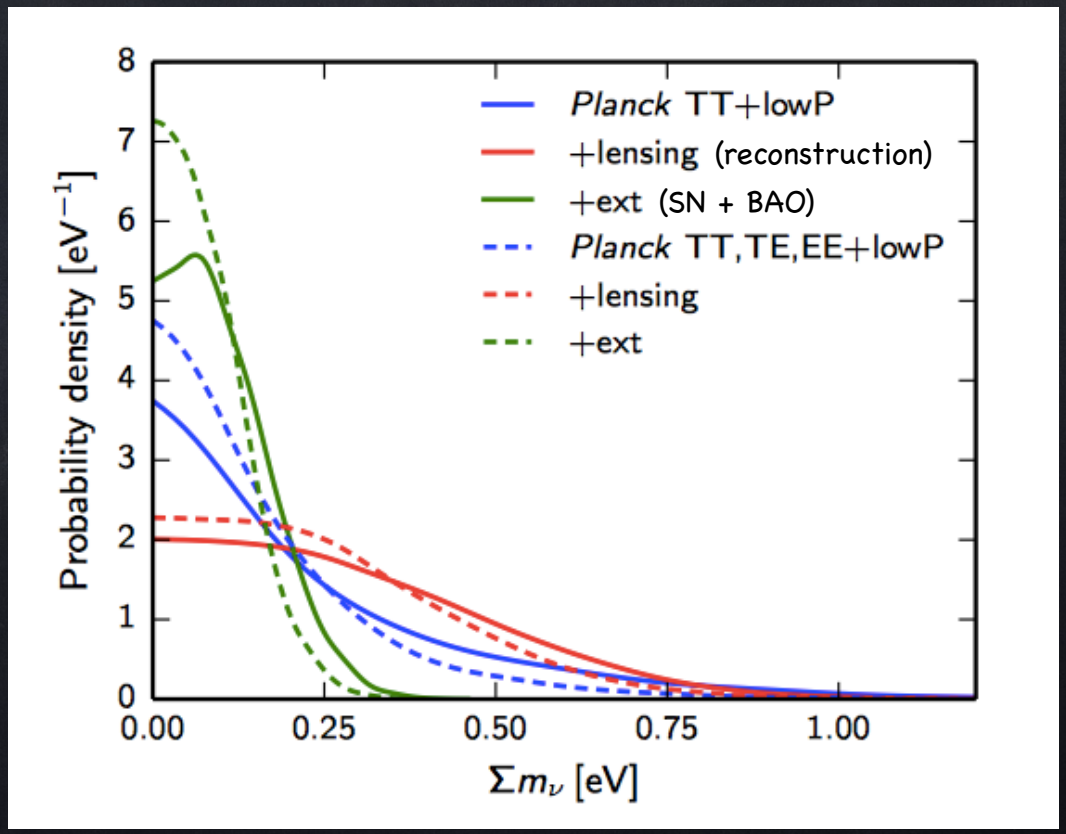


Current constraints from CMB



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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)

Neutrinos in large-scale structure: Linear regime

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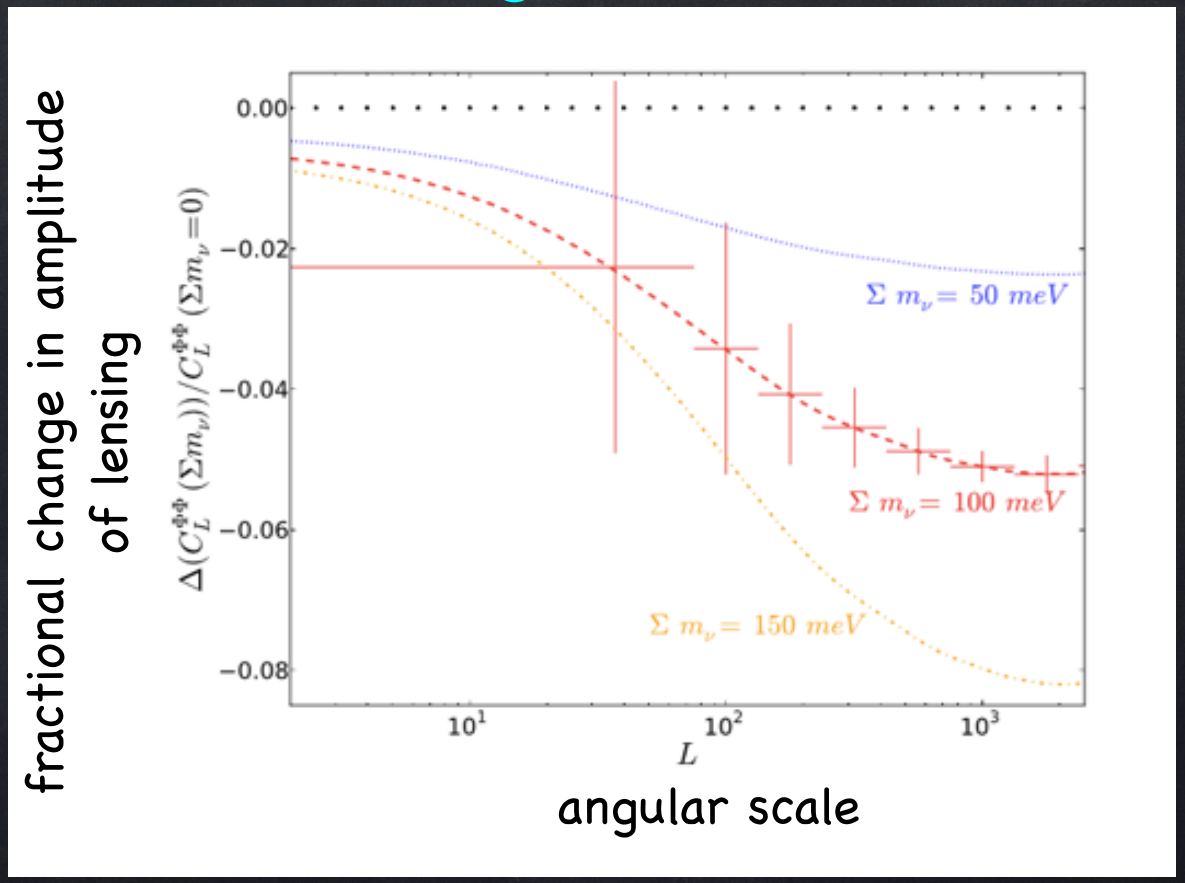

Abazajian et al 2013

Neutrinos in large-scale structure: Linear regime

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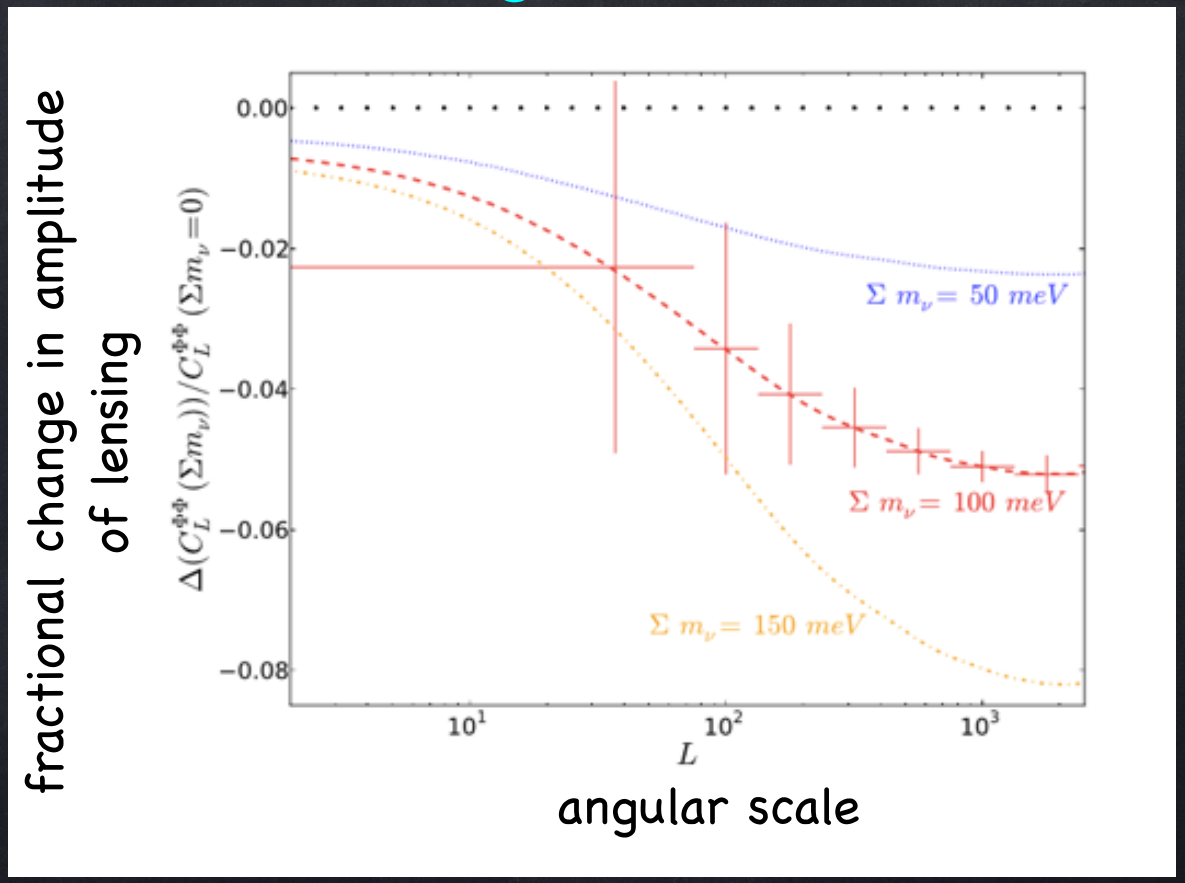
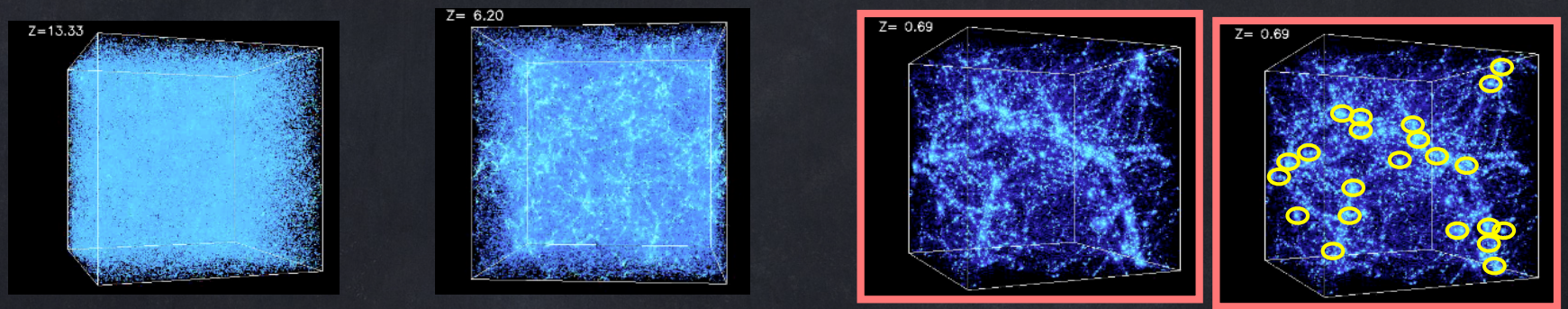


Abazajian et al 2013

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

Neutrinos in Large-scale Structure

easier ← → harder → much harder

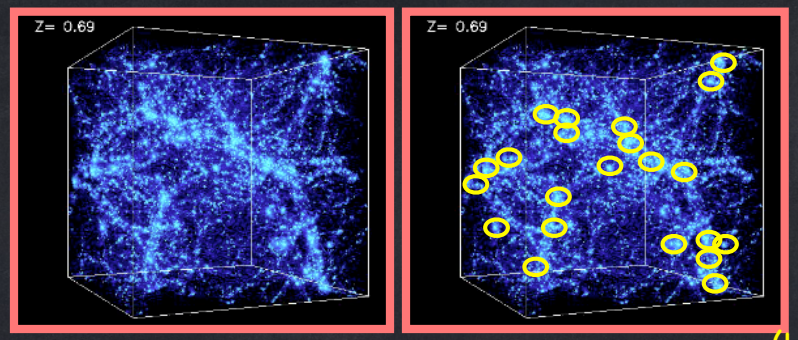


(Kravtsov) (halos)

time →

$\frac{\delta\rho_c}{\rho_c} \ll 1$ $\frac{\delta\rho_c}{\rho_c} \gtrsim 1$ $\frac{\delta\rho_c}{\rho_c} \gg 1$

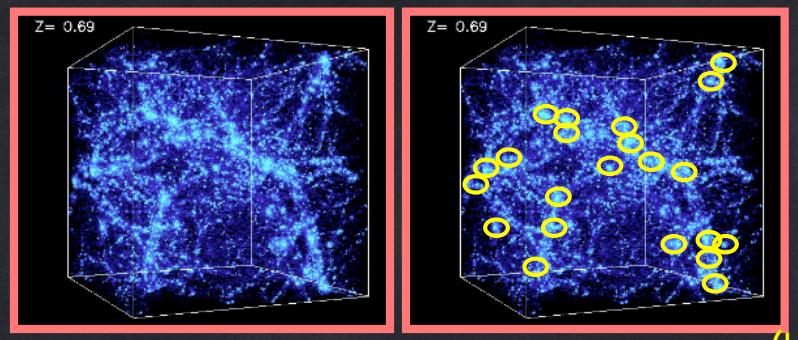
Neutrinos in Large-scale Structure



(halos)

- Suppressed matter power spectrum (test via gravitational lensing, galaxy power spectra) ✓
- Fewer massive halos hosting galaxy clusters
- Neutrino feature in the halo bias
- Accreted neutrino halos around CDM

Neutrinos in Large-scale Structure



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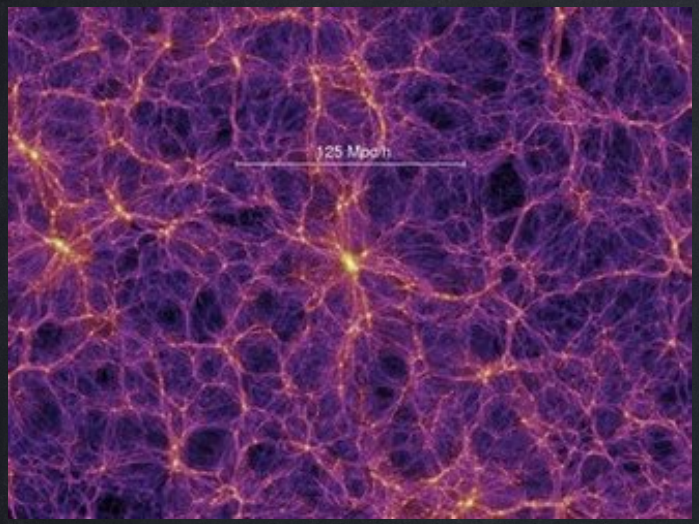
Scale-dependent halo bias from massive neutrinos

Halo bias

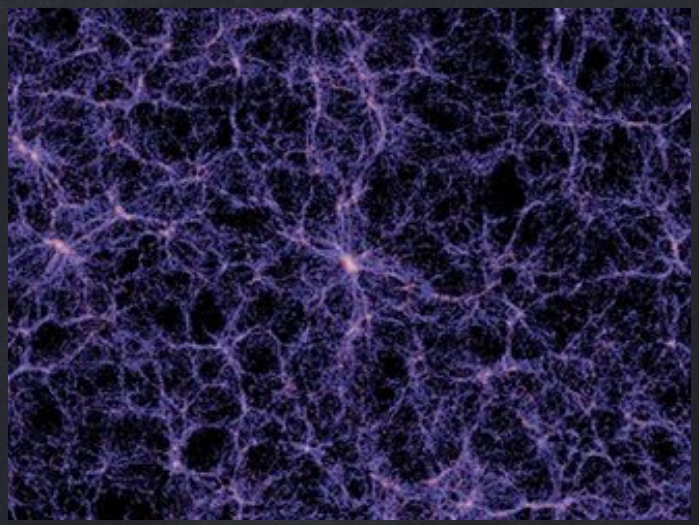
Halo bias

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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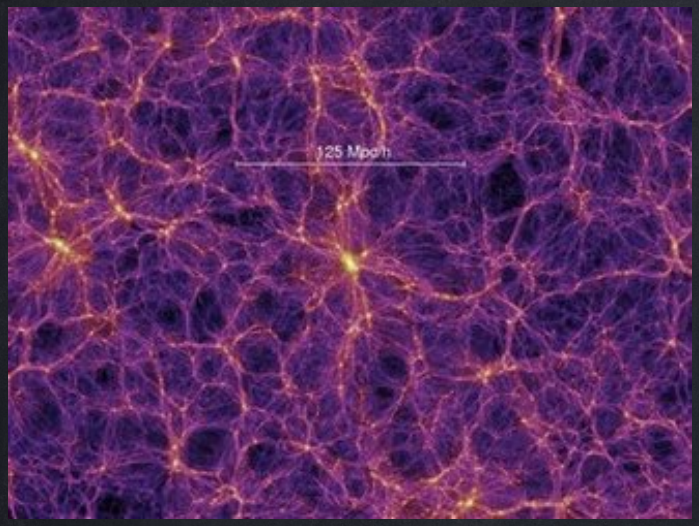

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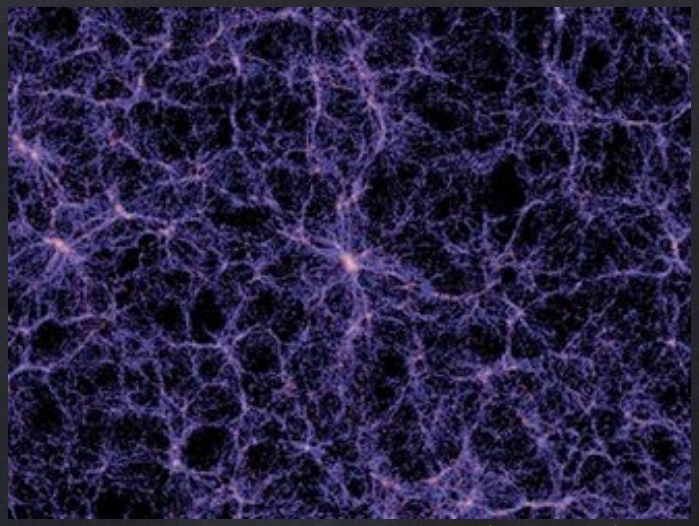

(Springel)

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>

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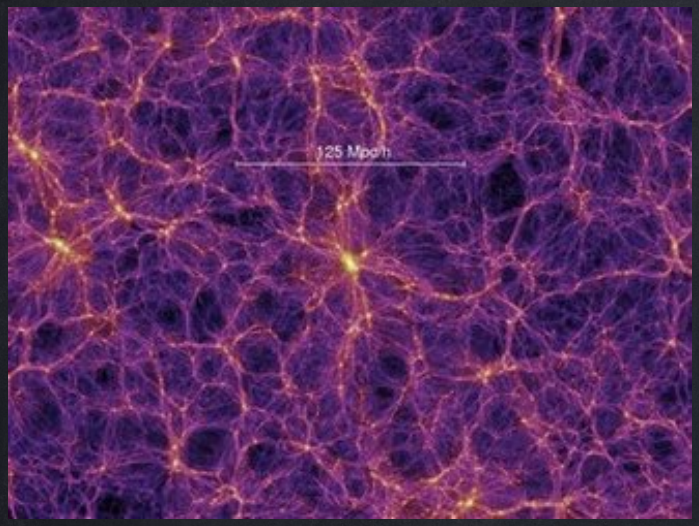

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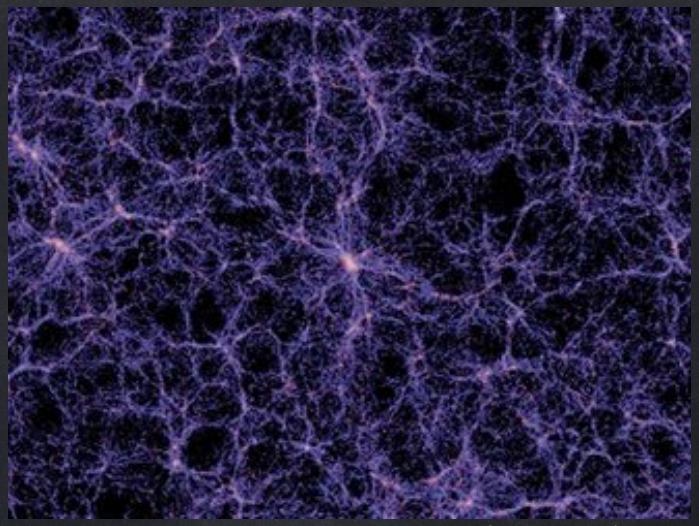

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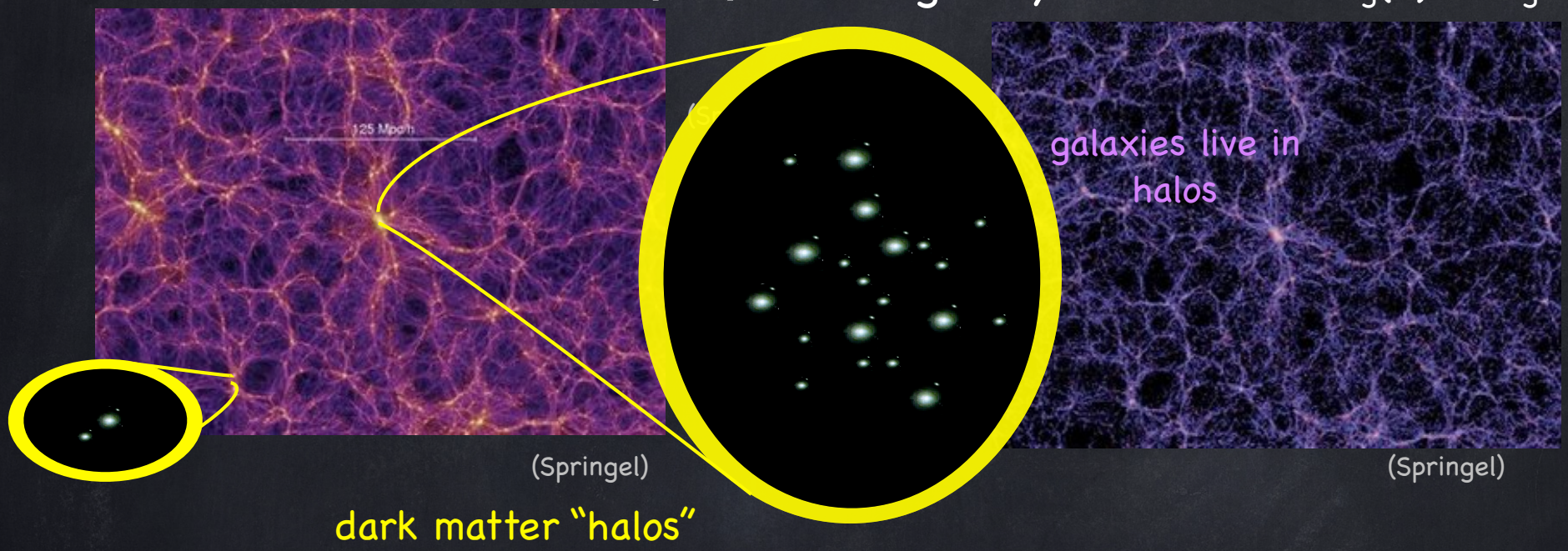
The value of b depends on the type of object you are looking at (e.g. the mass or luminosity of the galaxies you've measured) and rare objects have a larger value of b.

Halo bias

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

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



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

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

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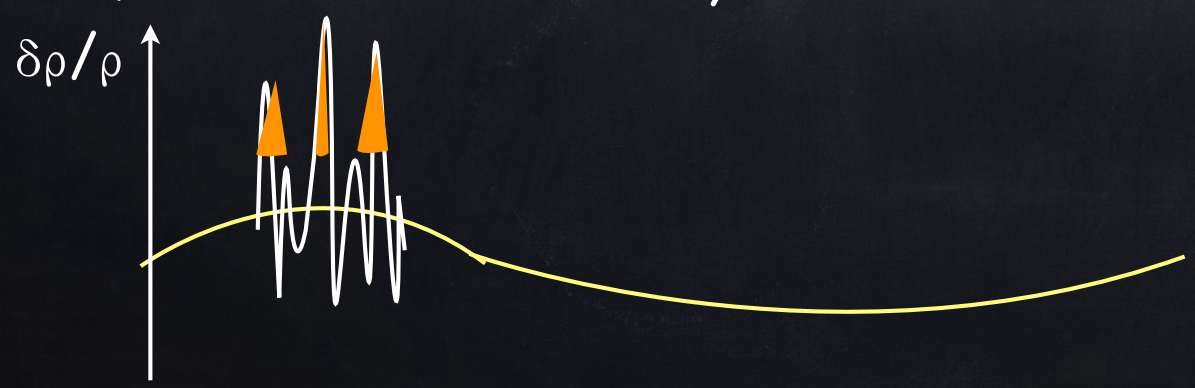
initially over-dense regions occupy less volume at late times, so the number density there is increased



Halo bias - simplest model

(I)

(II)

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

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

Gunn & Gott 1972 Press & Schechter 1974

Halo bias - simplest model

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(II)

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$\equiv$ b **halo bias**

Gunn & Gott 1972 Press & Schechter 1974

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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

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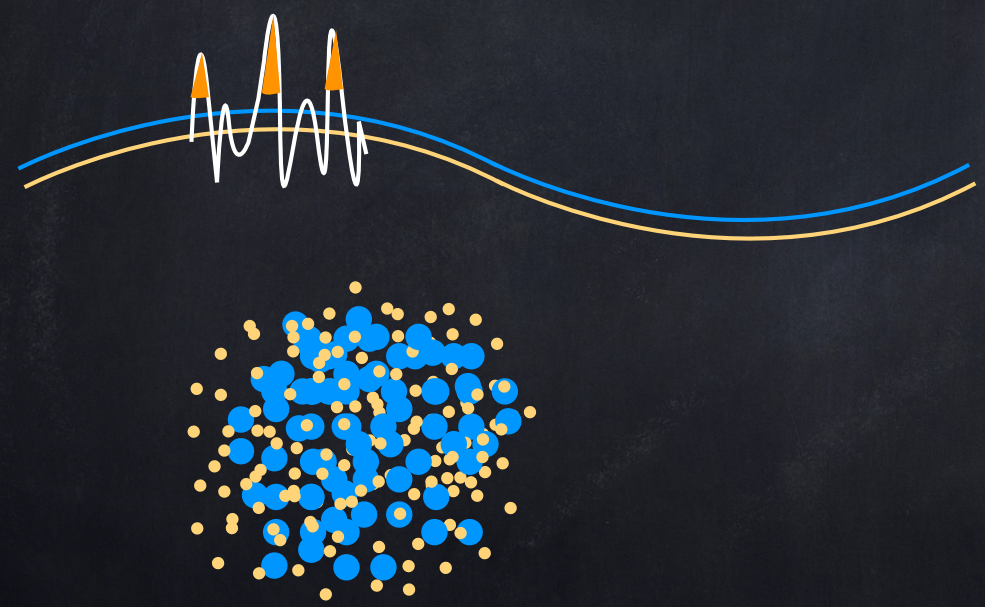
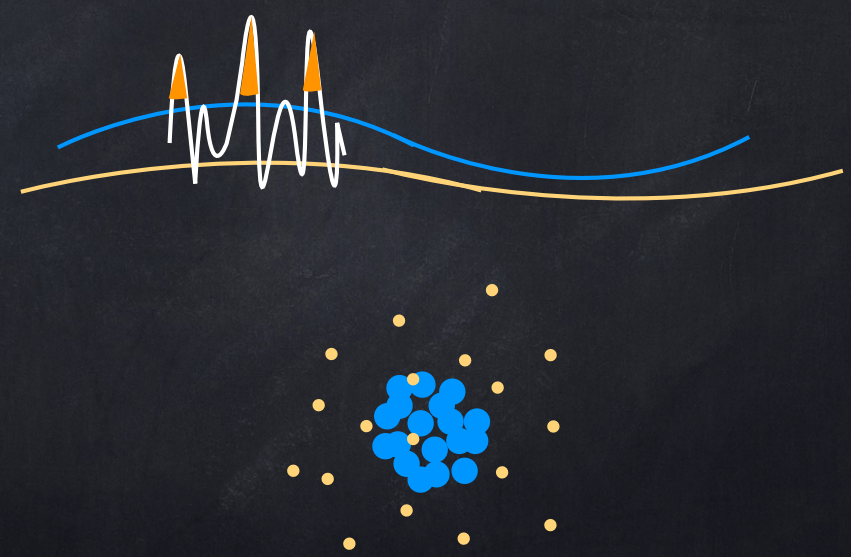


(same as a universe with only CDM)



(grows more slowly)

Halo bias - simplest model

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ML and Zaldarriaga 2013

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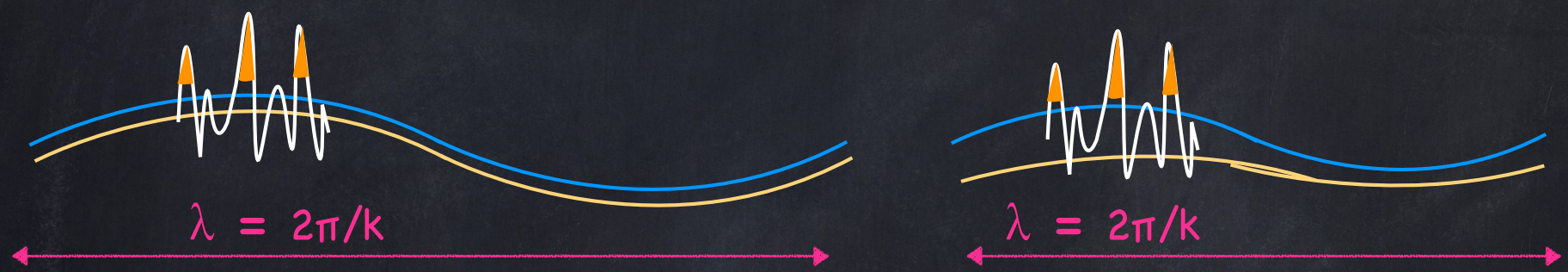

The k-dependent evolution of δ_l causes the threshold for collapse to depend on k also

ML 2014b, ML in prep

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

Halo bias - simplest model

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ML and Zaldarriaga 2013

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ML 2014, ML in prep

In a universe with massive neutrinos:

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

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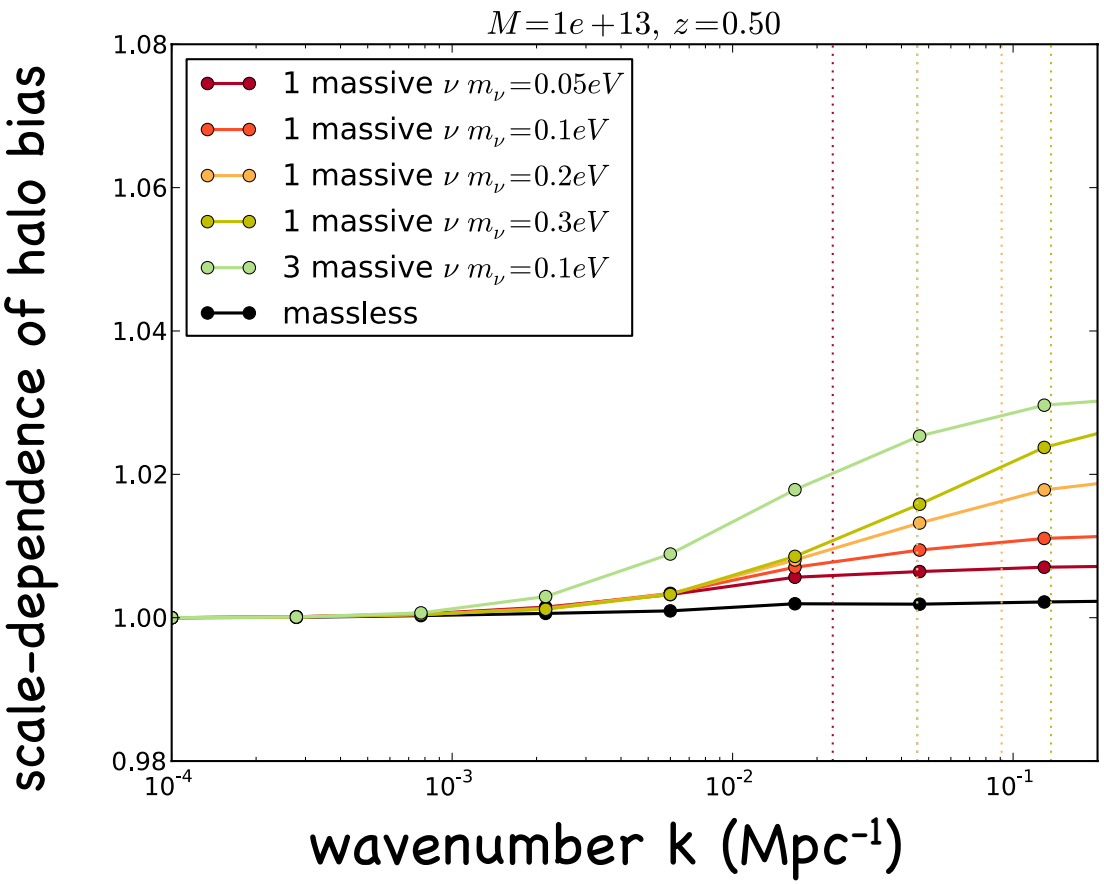
$b(k) = \sqrt{P_{hh}(k)/P_{mm}(k)}$



(ML 2014)

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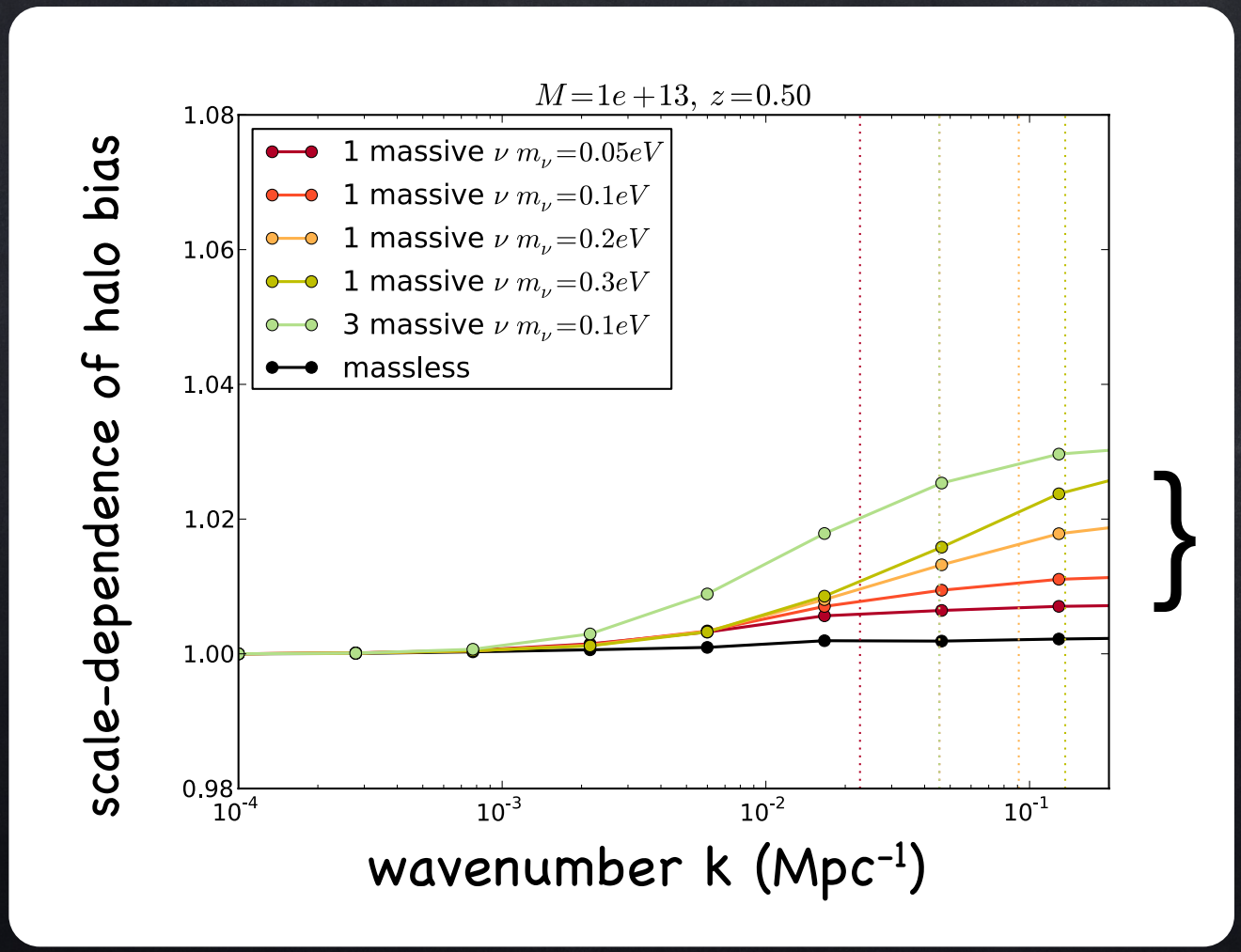


$\sim \dfrac{\rho_\nu}{\rho_{matter}}$

(ML 2014)

In a universe with massive neutrinos:

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

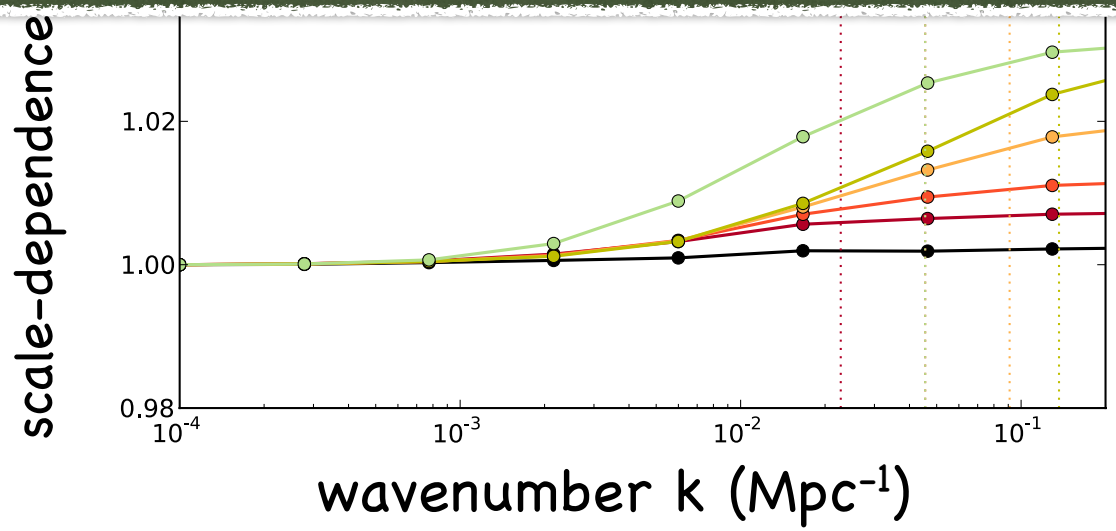
In general, we find

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

where

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

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



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

(ML 2014)

Observational consequences

Scale-dependent change in the halo bias:

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(ML 2014)

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(ML 2014)

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

(ML 2014)

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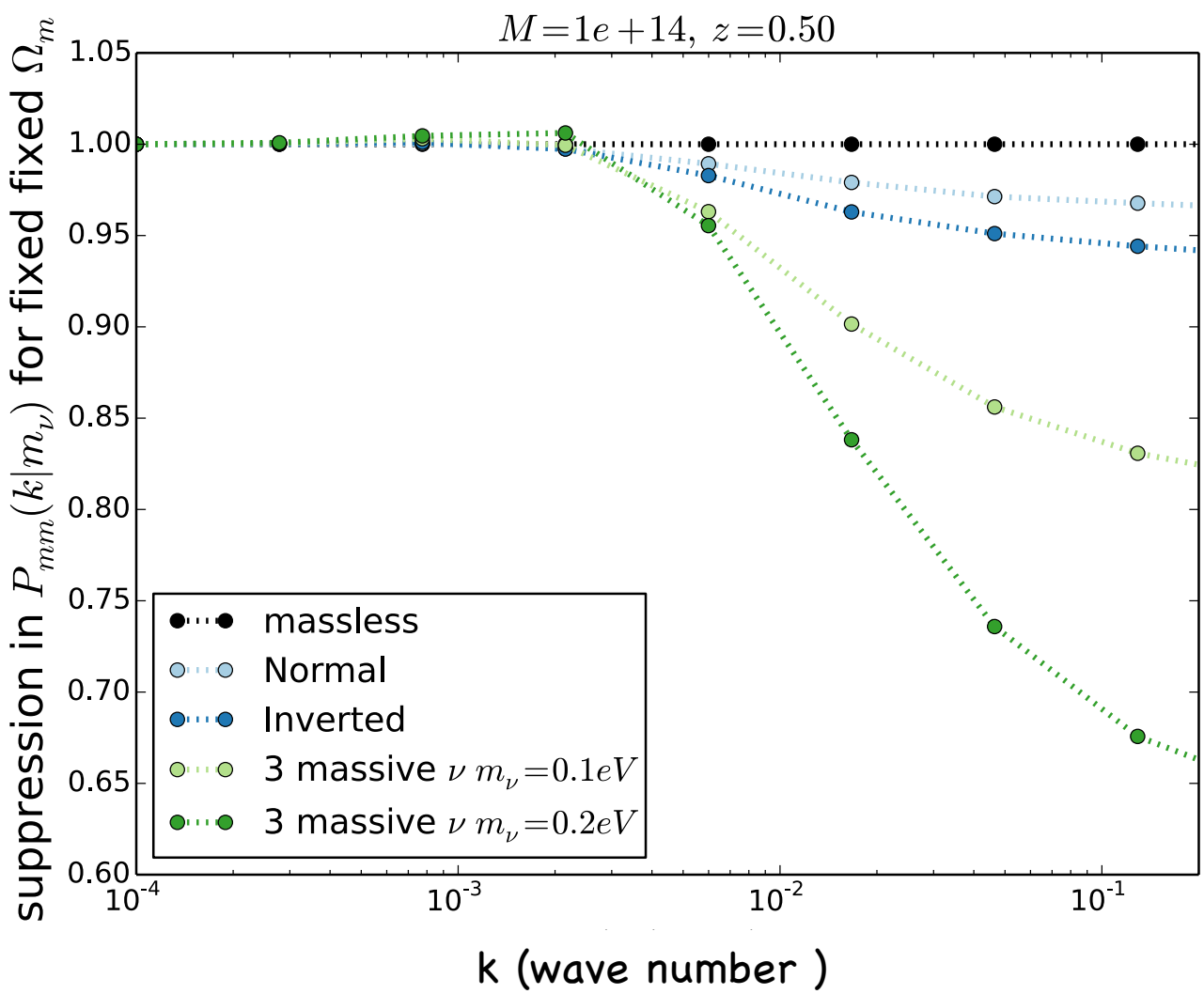
Why care about such a small change to the halo bias?

- 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)

A systematic for measurements of m_ν from galaxy clustering

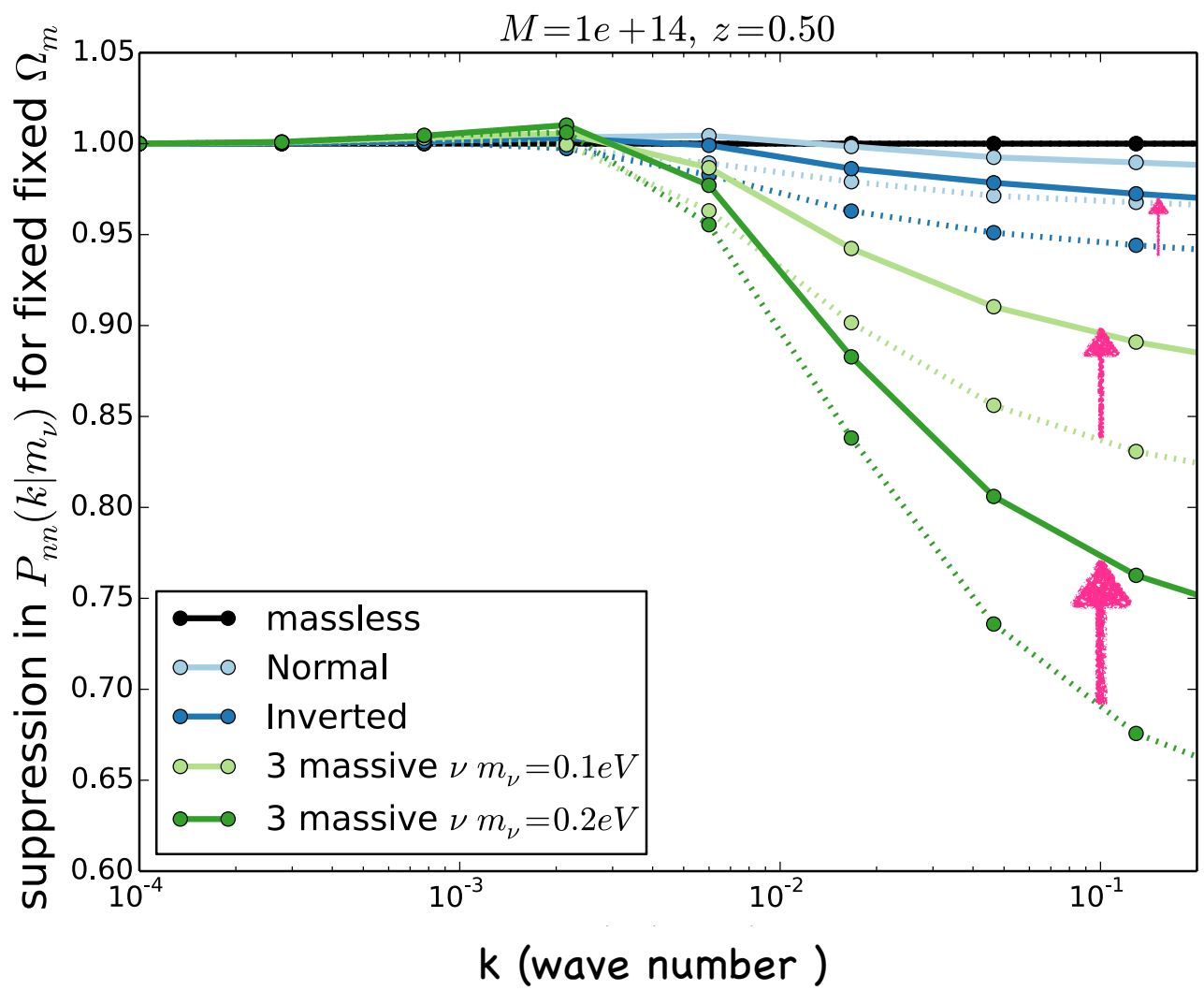
Without scale-dependent bias neutrinos produce identical changes to $P_{galaxy\text{-}galaxy}(k)$ and $P_{matter\text{-}matter}(k)$, ($P_{galaxy\text{-}galaxy}(k) = b^2 P_{matter\text{-}matter}(k)$)



(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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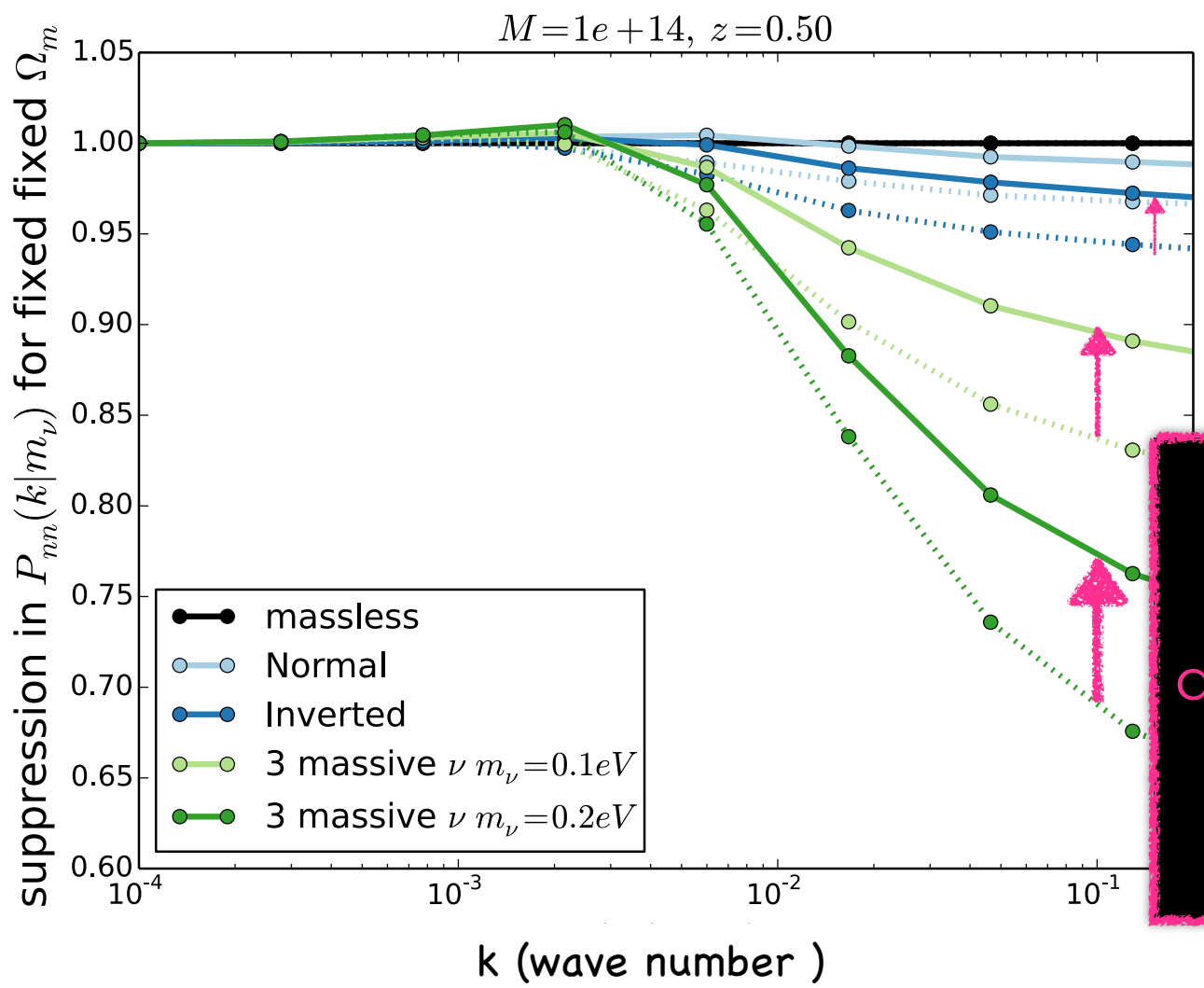


moreover, this difference depends on the bias of the sources

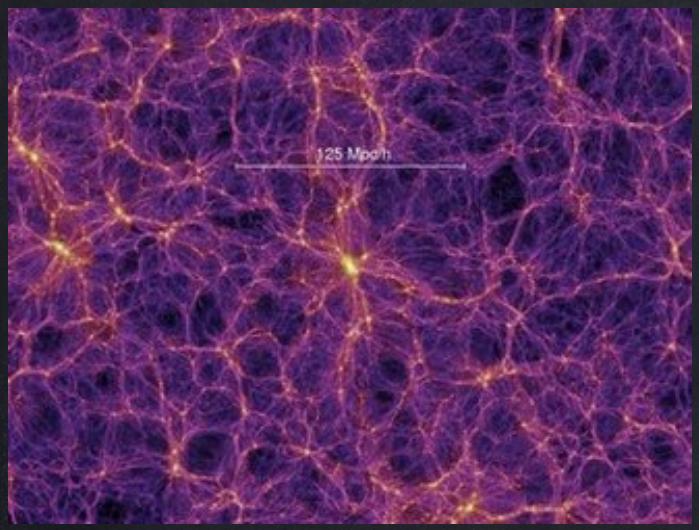
(ML 2014)

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

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

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)

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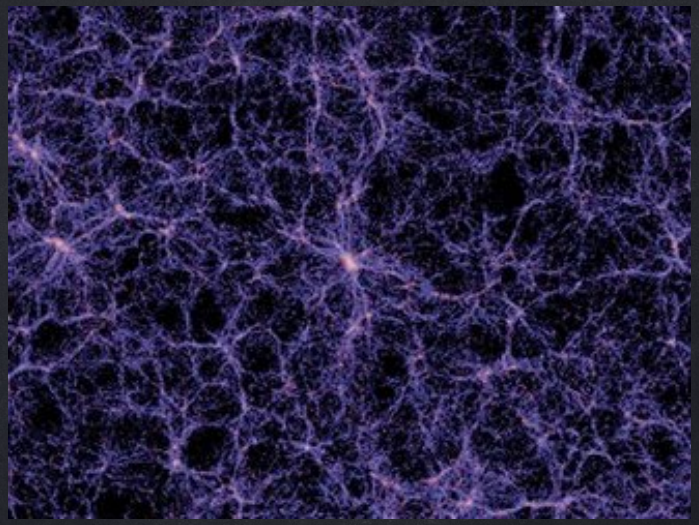

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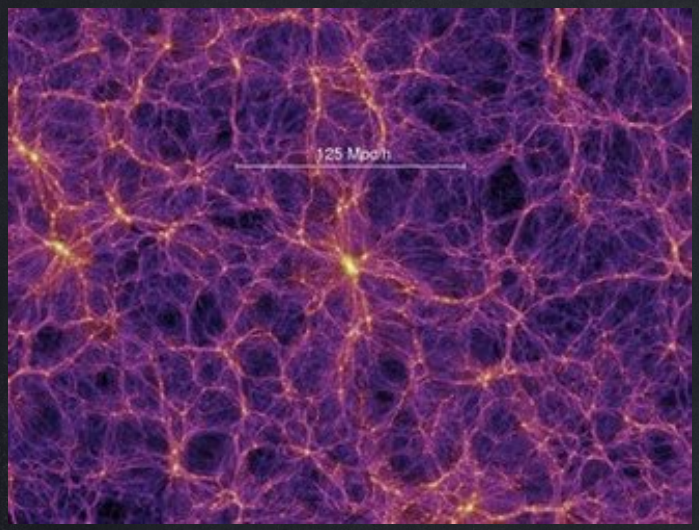

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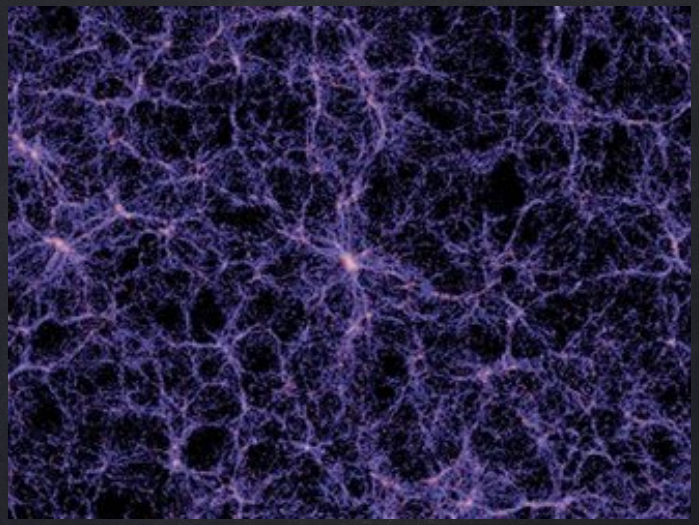

(Springel)

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

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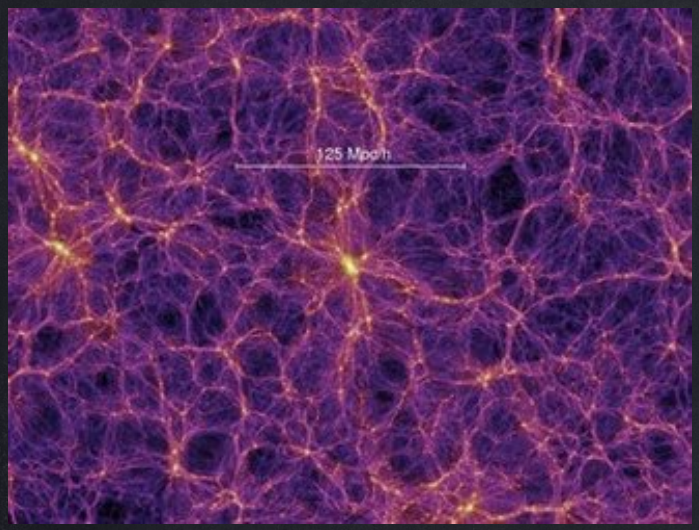
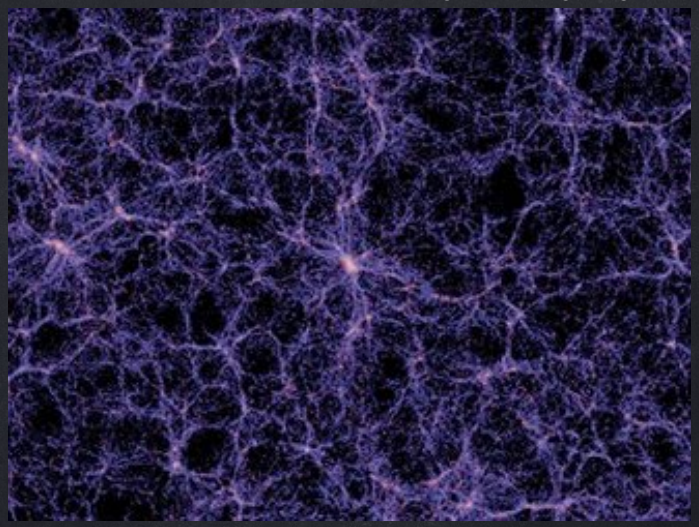


(Springel)

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



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

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

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

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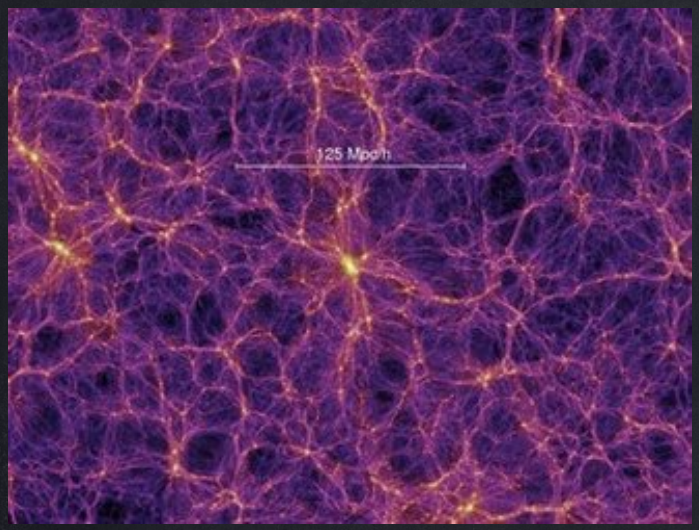

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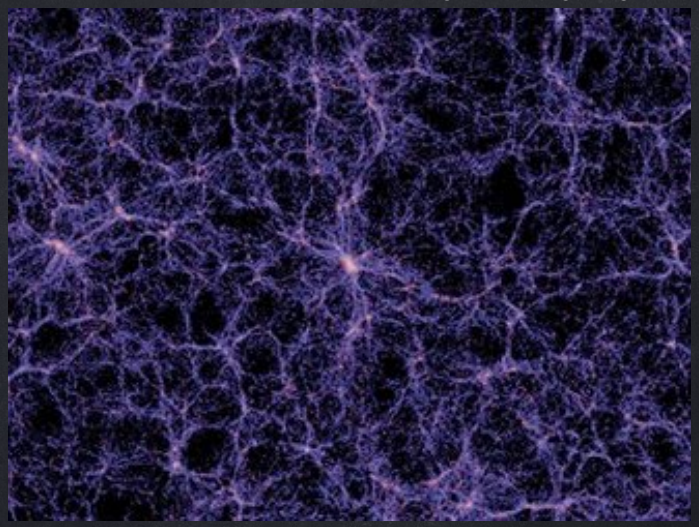

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Compare:

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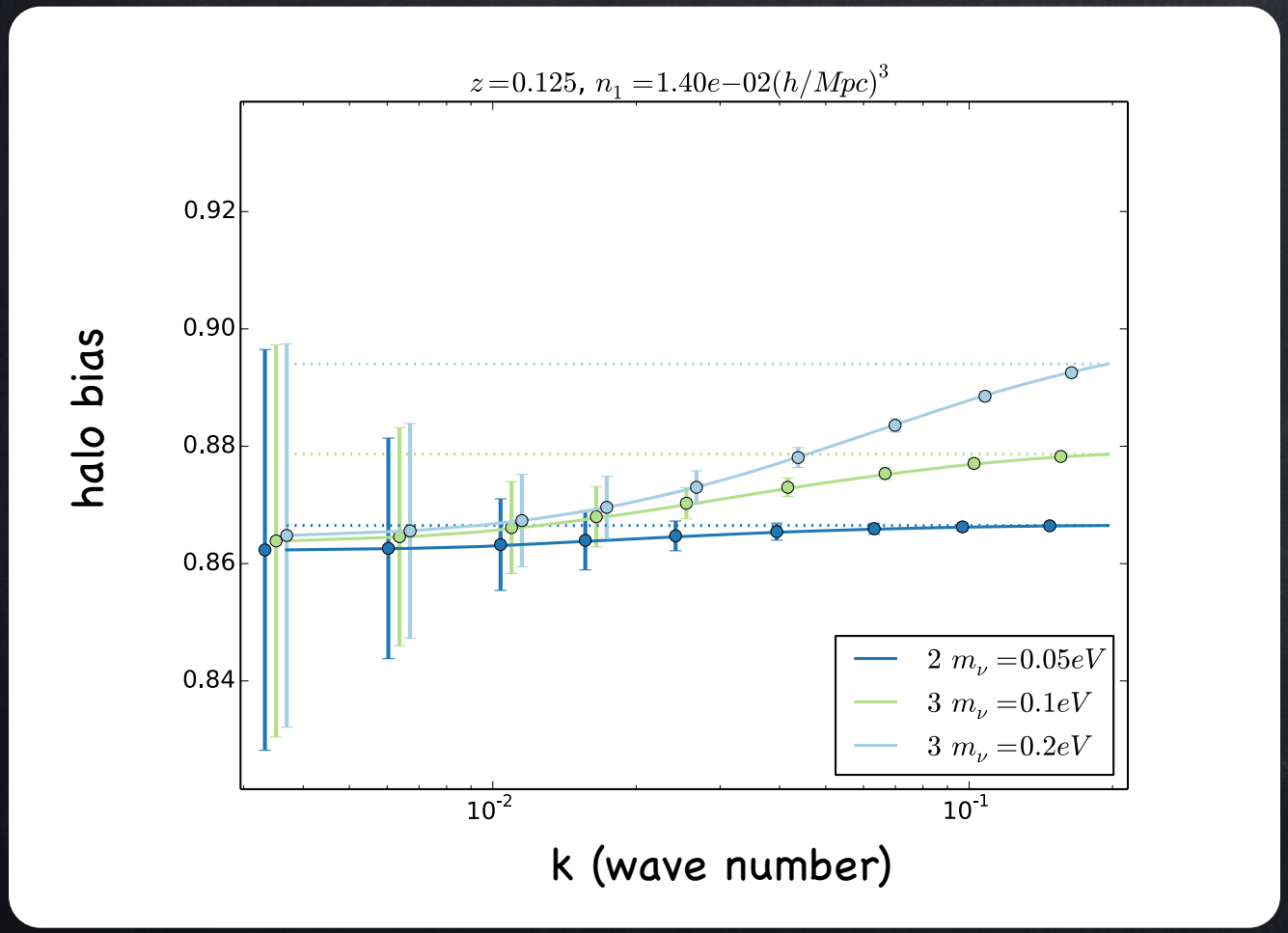

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(ideal huge number density of sources, super-ideal lack of systematics)

(ML 2016)

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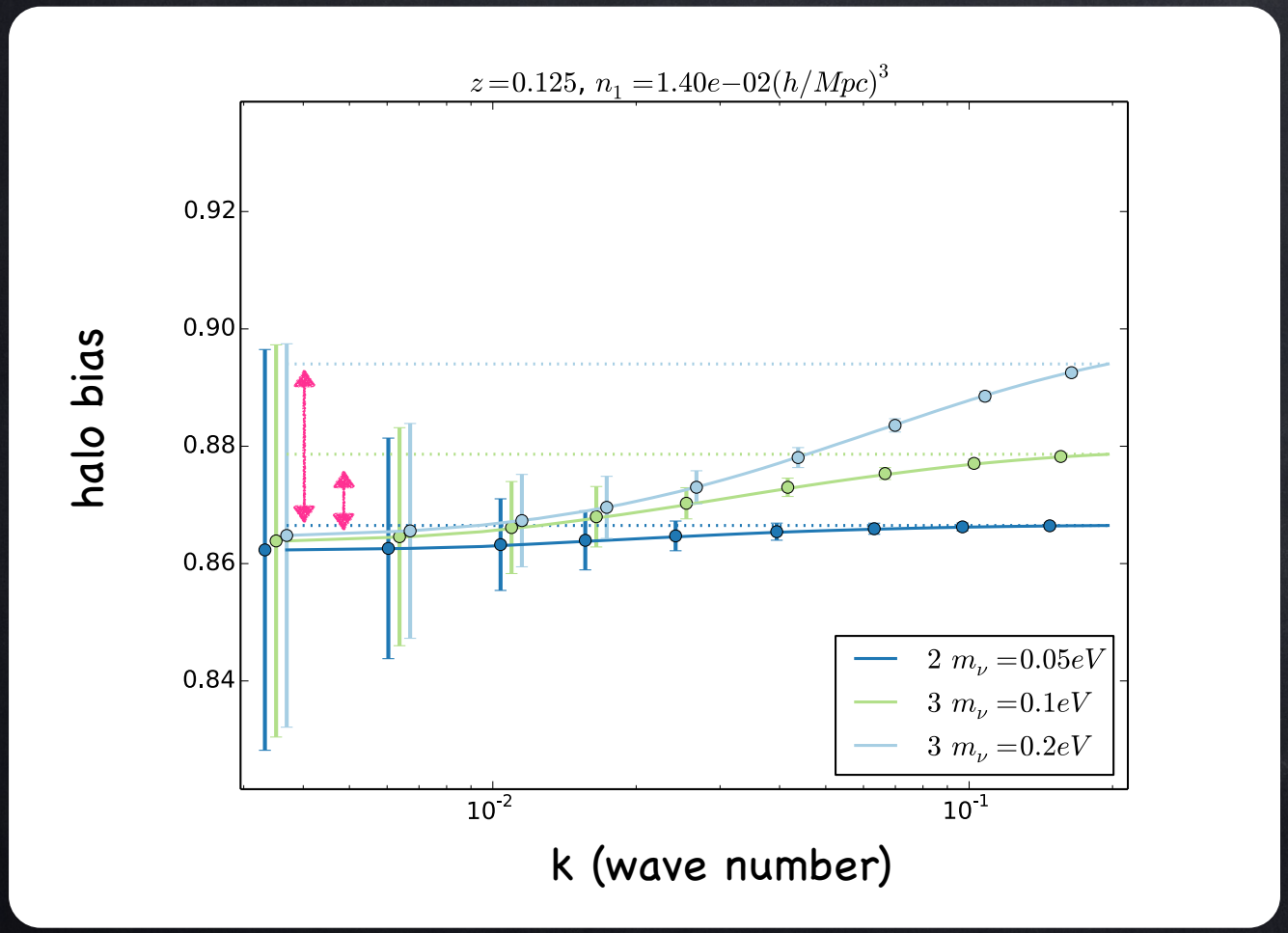

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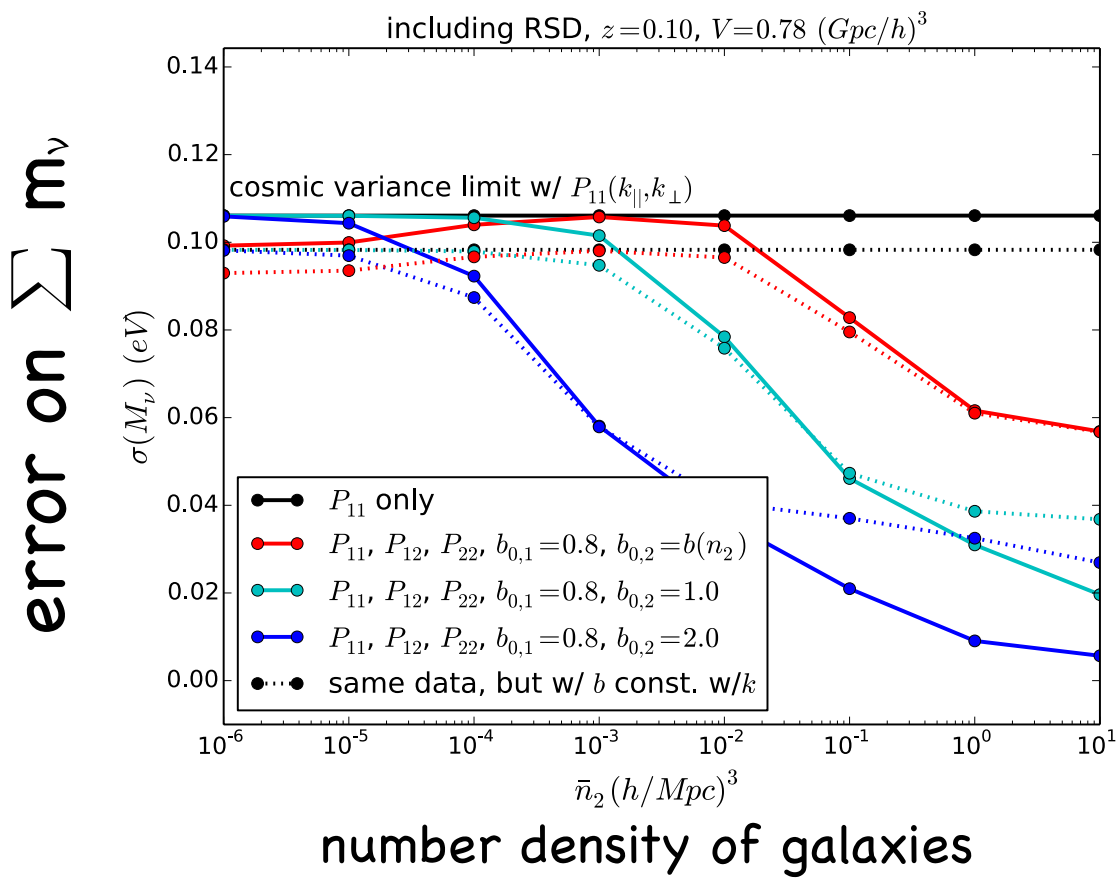

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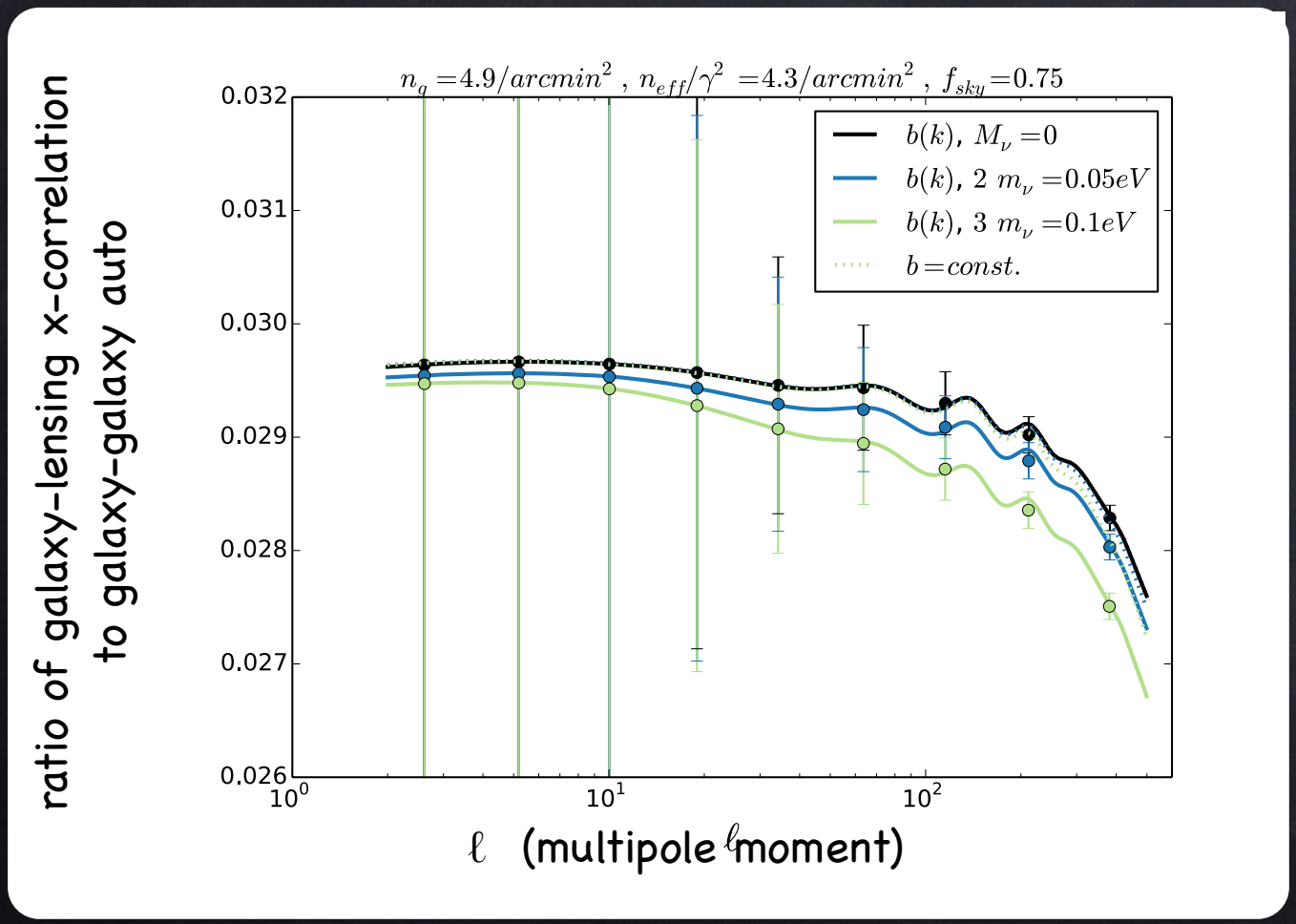

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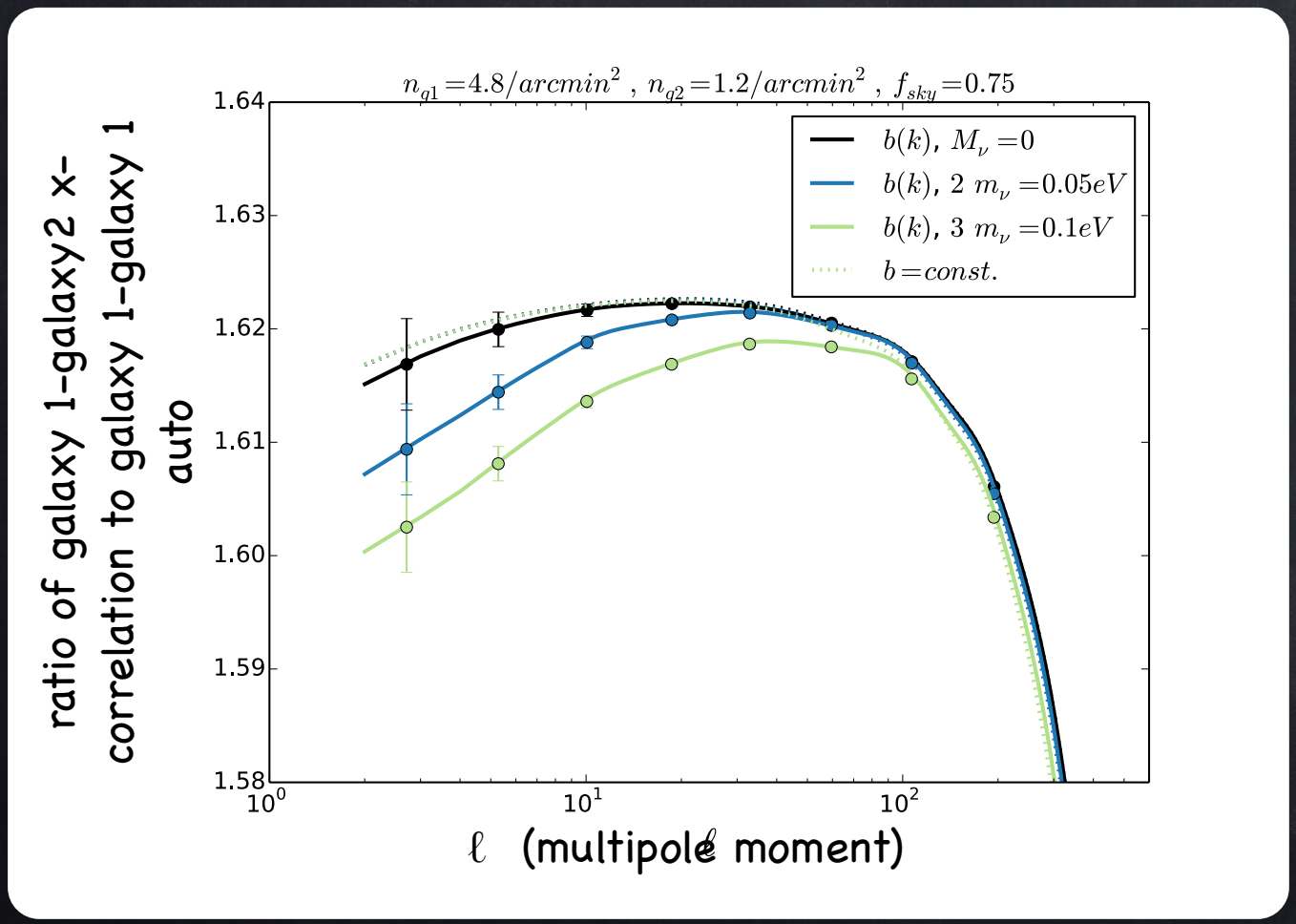

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Neutrino Accretion

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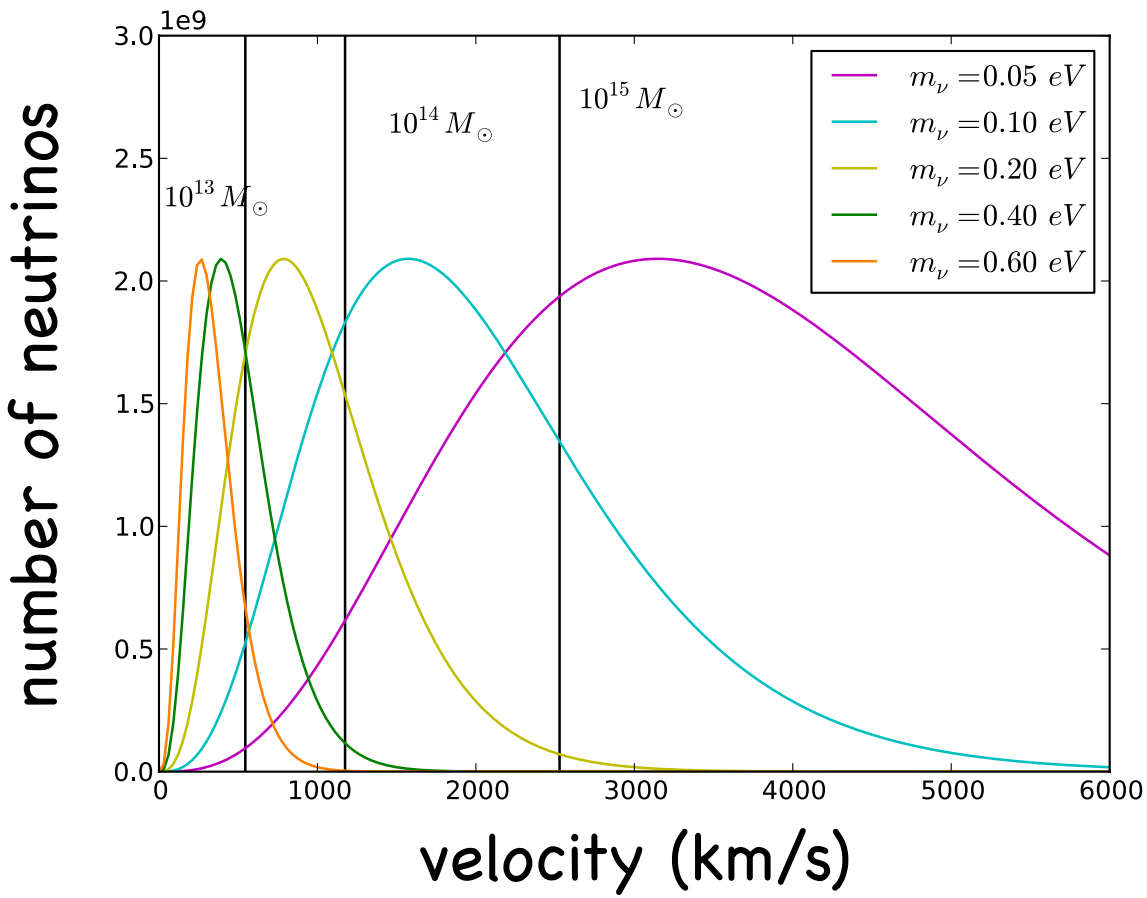
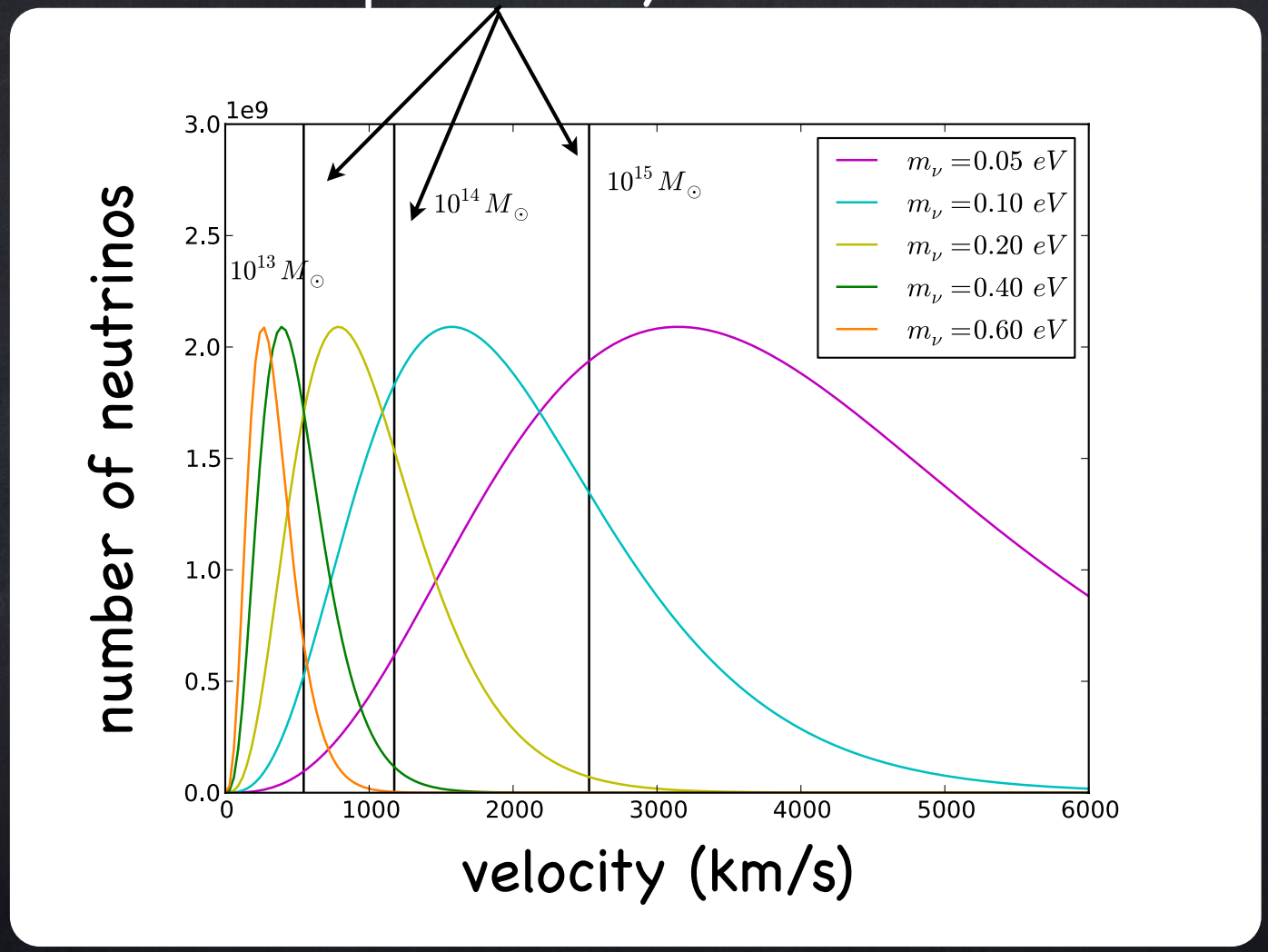


ML & Zaldarriaga 2013

Neutrino Accretion

escape velocity of dark matter halos

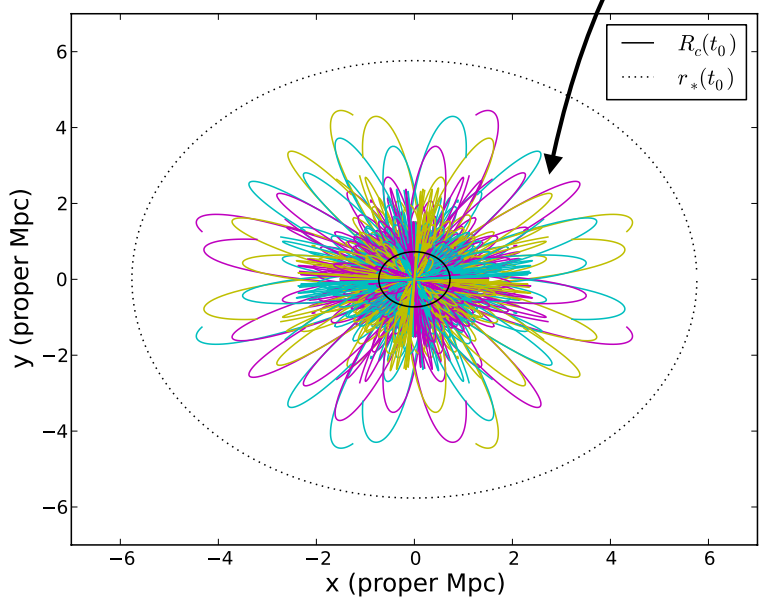


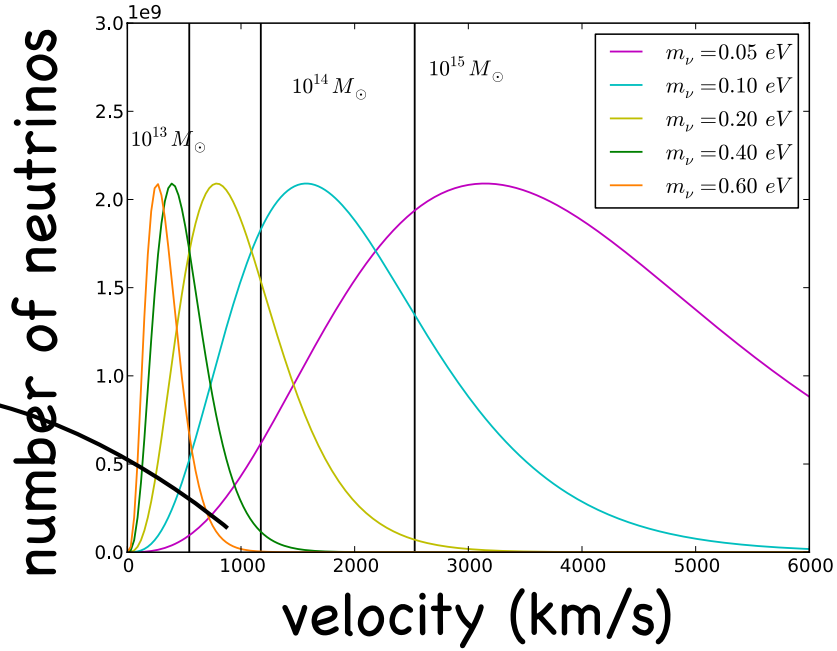
ML & Zaldarriaga 2013

Neutrino Accretion

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
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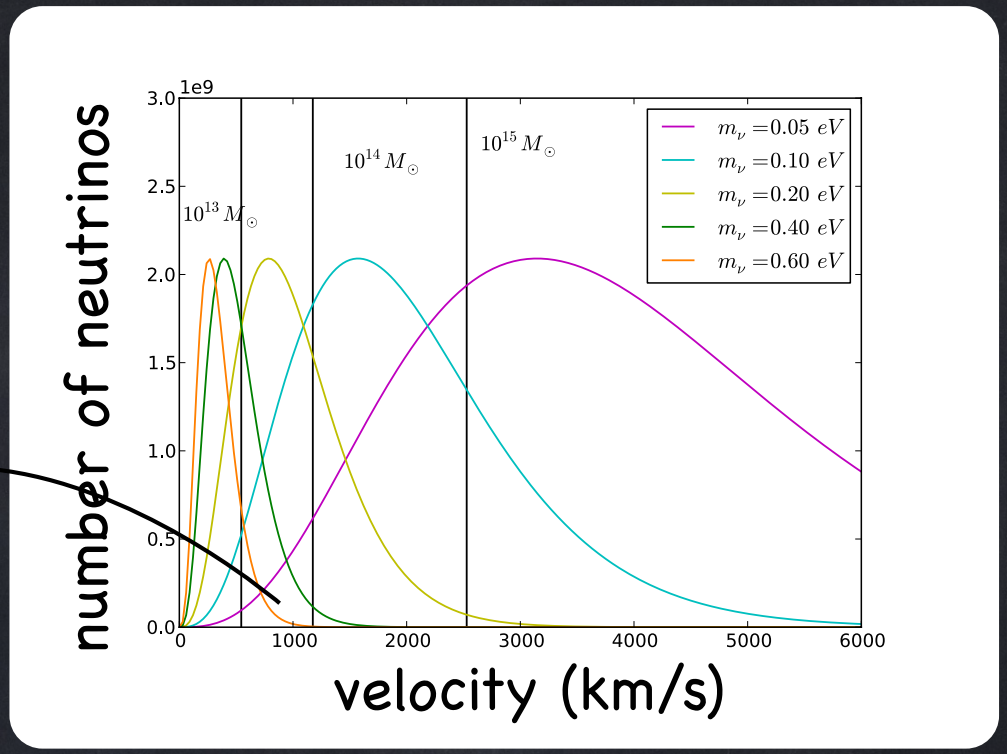

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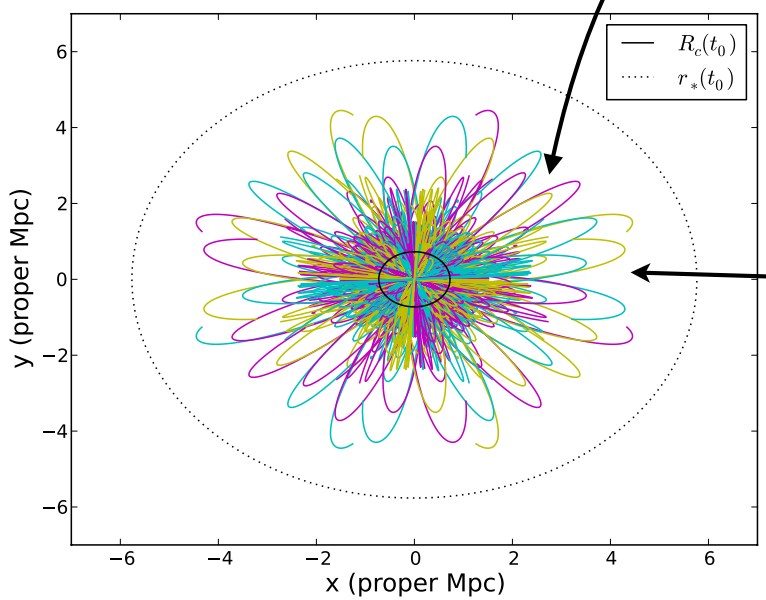

the accreted neutrino halo is puffy in comparison with the cold dark matter!

see also Ringwald & Wong 2004; Brandbyge, Hannestad, Haugboelle, Wong 2010
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ML & Zaldarriaga 2013

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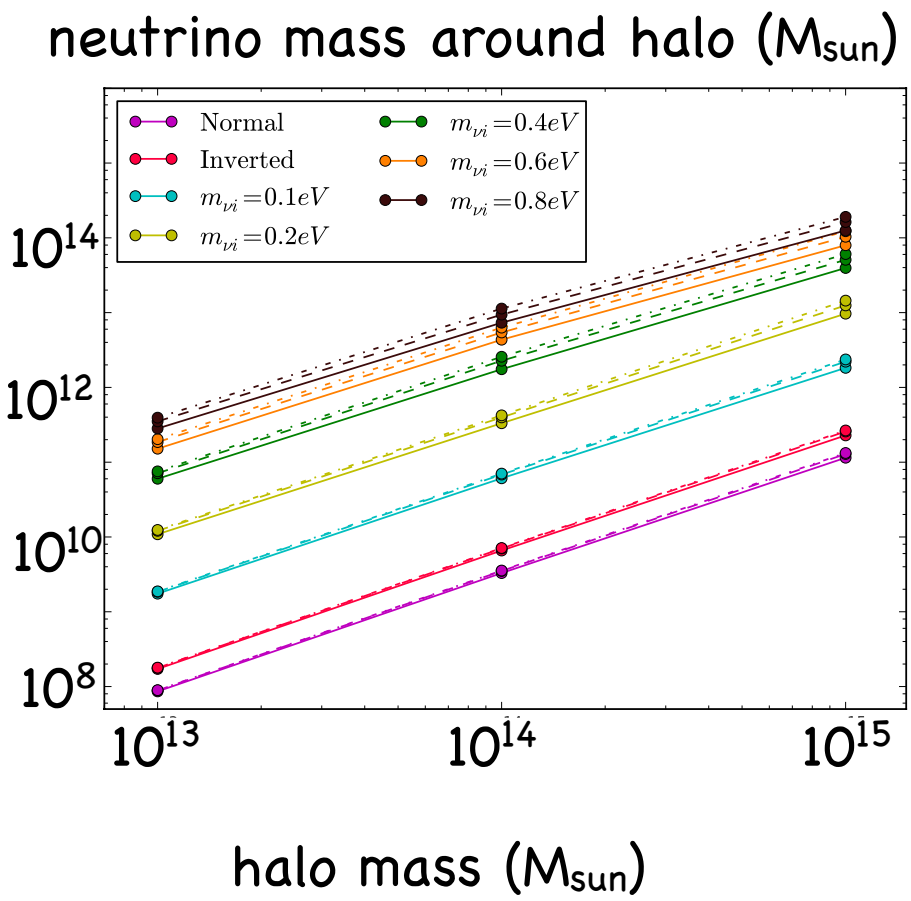
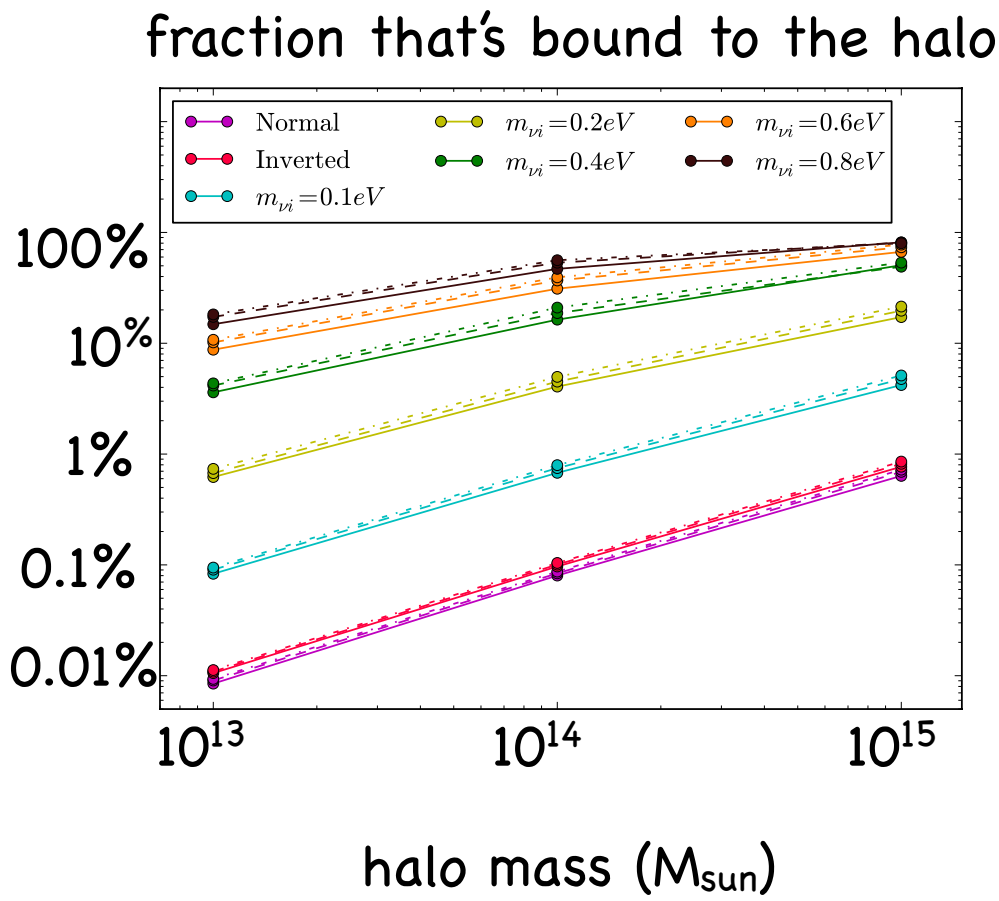


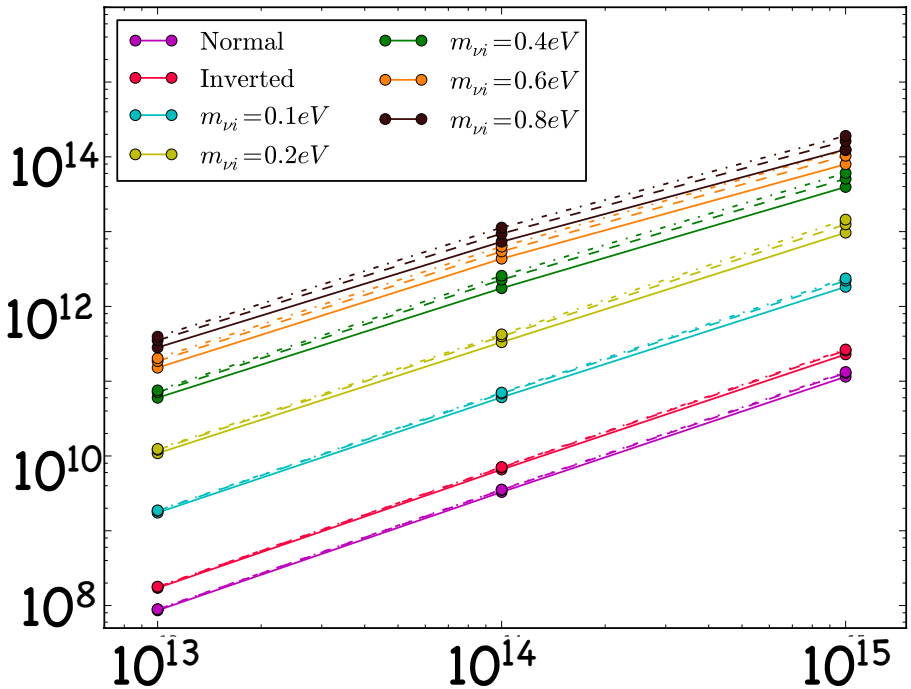


ML & Zaldarriaga 2013

Neutrino Accretion

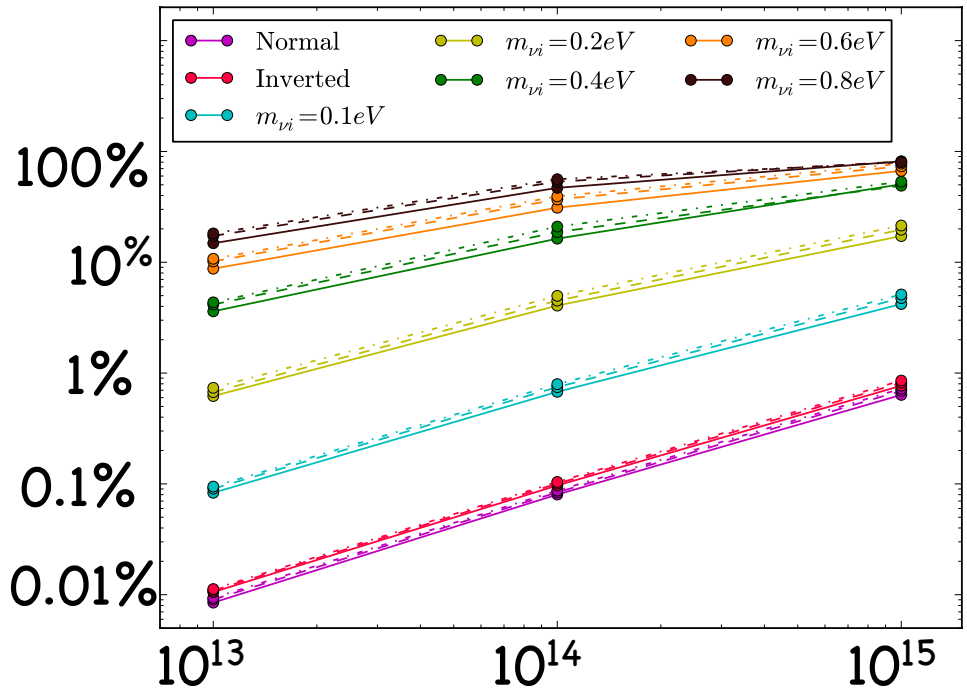
$$M_\nu \approx \sum_i 3 \times 10^9\, M_\odot \left(\frac{m_{\nu i}}{0.05\text{eV}}\right)^{2.6} \left(\frac{M_{halo}}{10^{14}\, M_\odot}\right)^{1.5}$$

neutrino mass around halo (M_{sun})



halo mass (M_{sun})

fraction that's bound to the halo



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ML & Zaldarriaga 2013

Neutrino Accretion - Relative Velocity Effects

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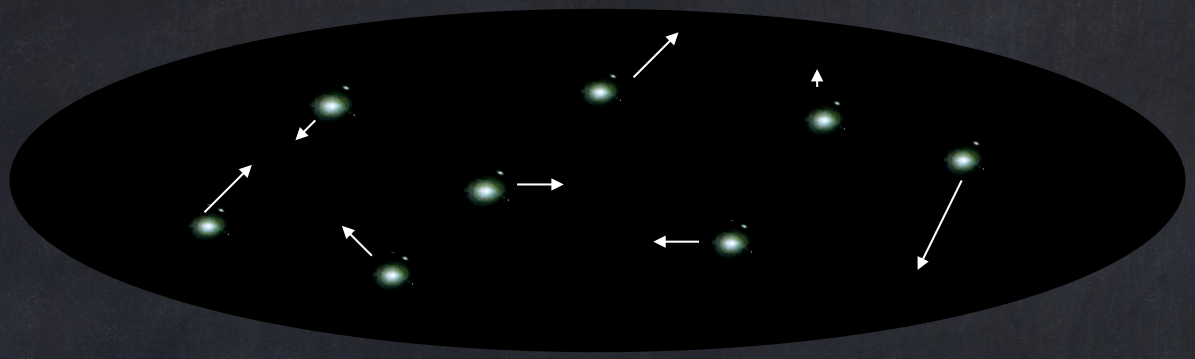
Cold dark matter halos are not at rest w.r.t. cosmic frame!



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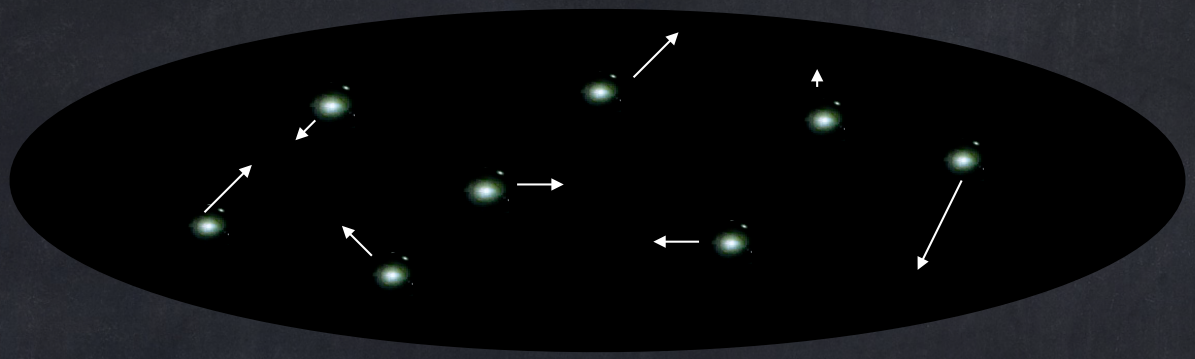

(The Milky Way is moving at ~ 550 km/s w.r.t the CMB)

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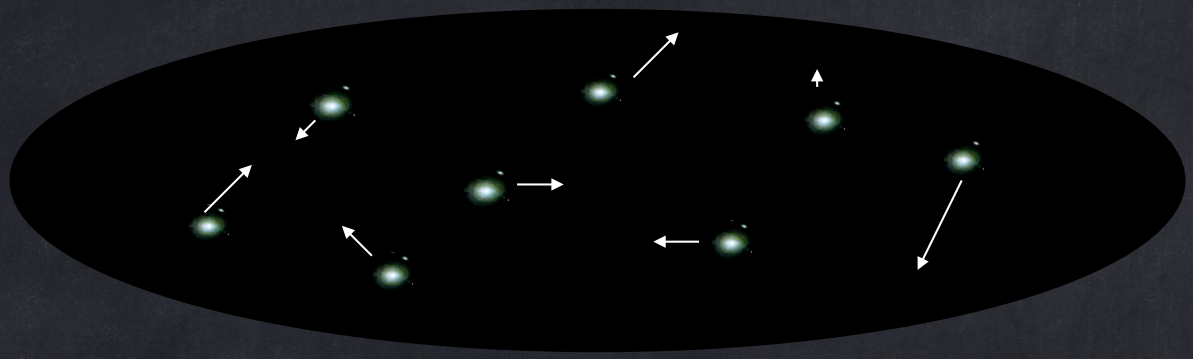
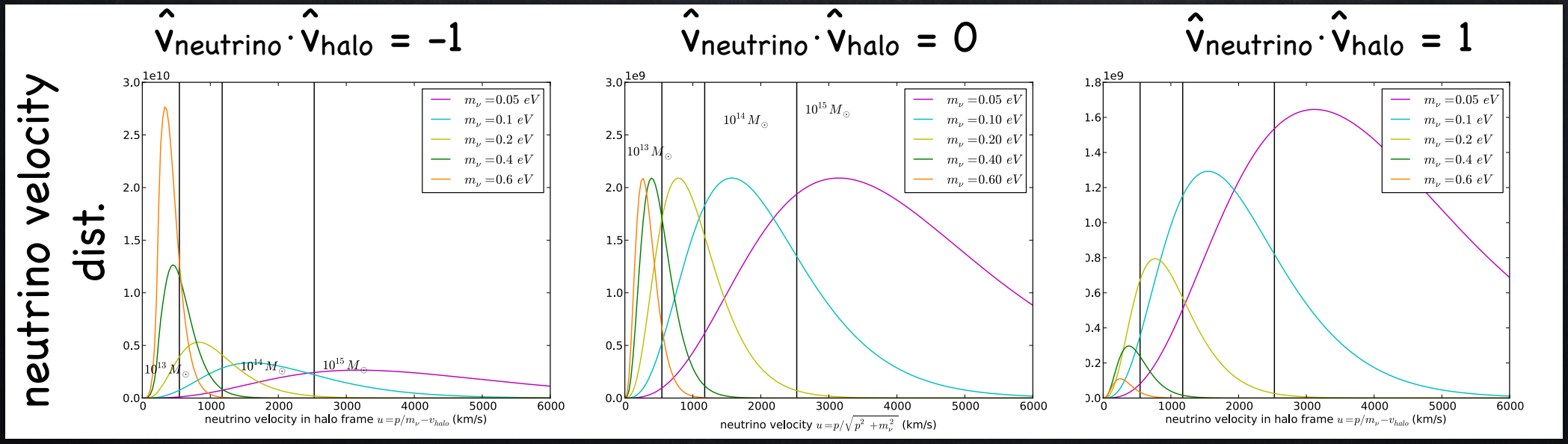


(The Milky Way is moving at ~ 550 km/s w.r.t the CMB)

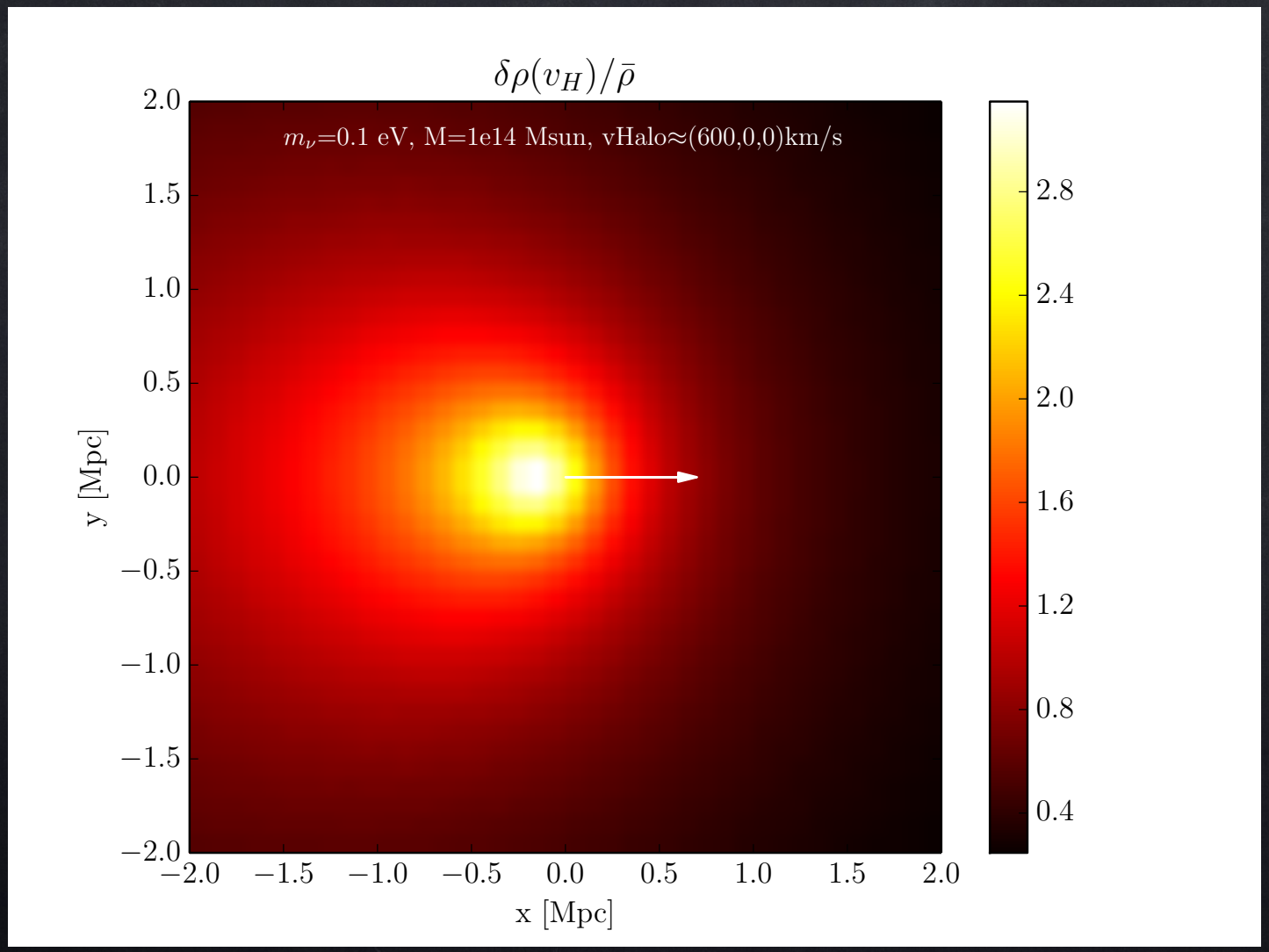
Halos moving through neutrino "wind"



ML & Zaldarriaga

Neutrino Accretion - Relative Velocity Effects

Qualitative difference between how halos acquire CDM and neutrino mass



work in progress with TY Lin, Ben Safdi

Neutrino Accretion - Relative Velocity Effects

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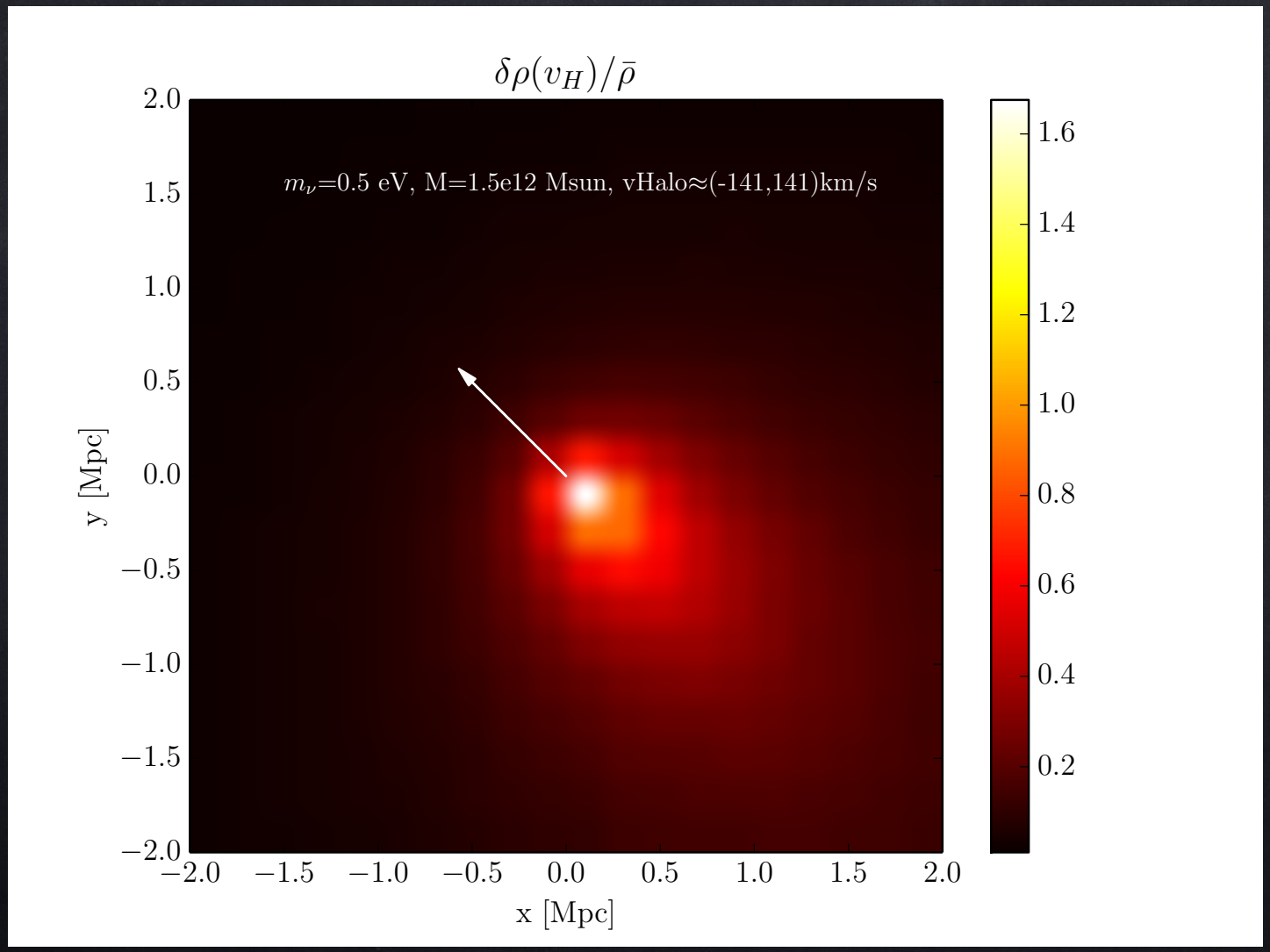

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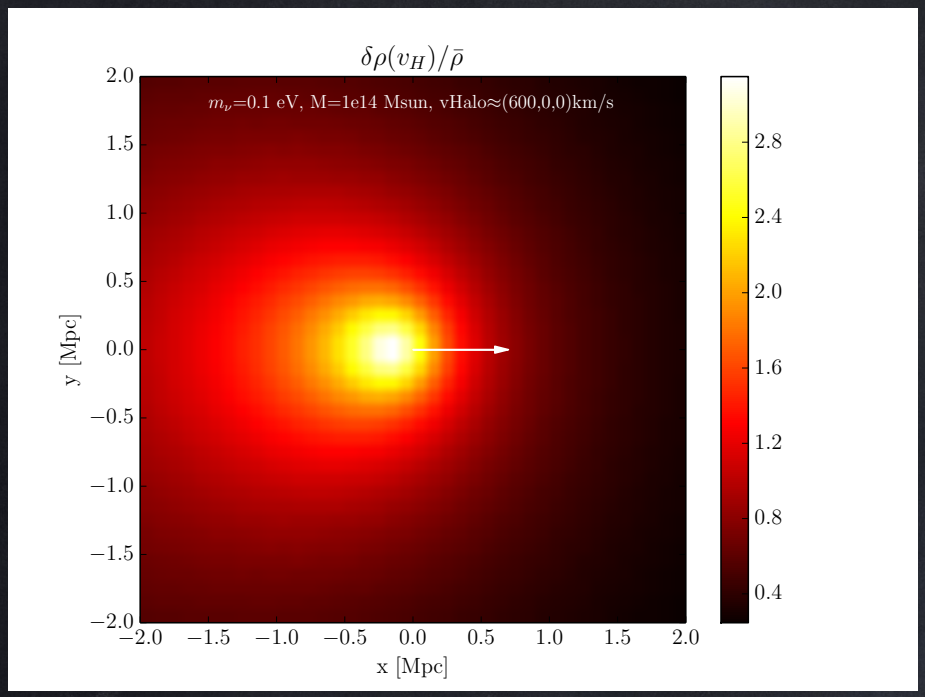
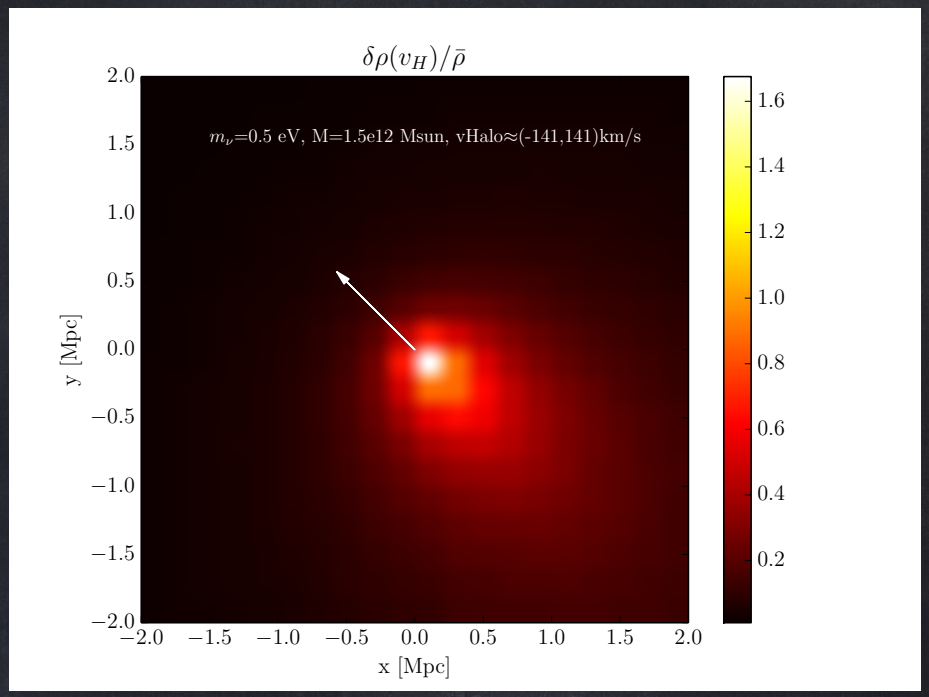




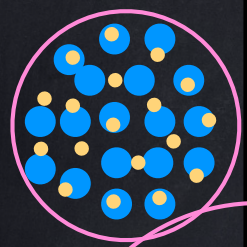
How does the relative velocity effect change the neutrino halos?

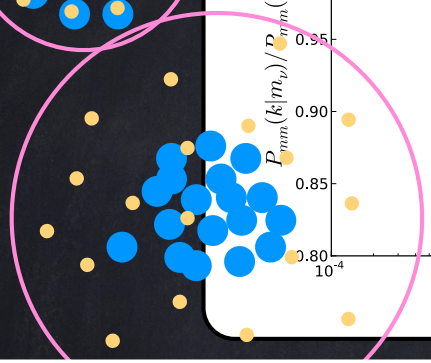
How does the relative velocity effect change the expected flux of cosmic background neutrinos for direct detection experiments?

How does the relative velocity effect change . . .?

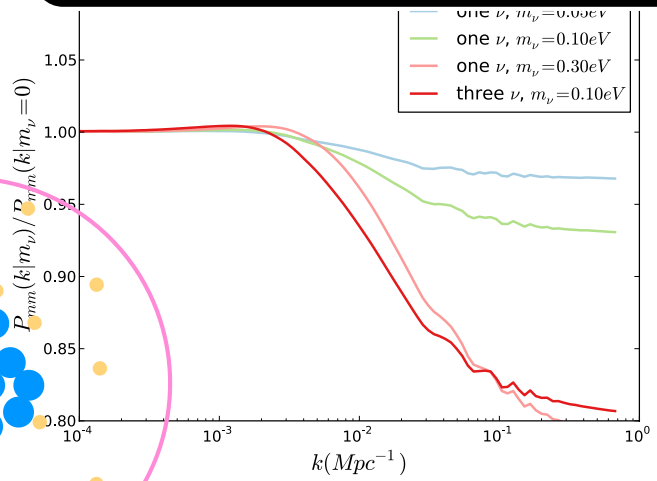
work in progress with TY Lin, Ben Safdi

Neutrinos Effects in Cosmology

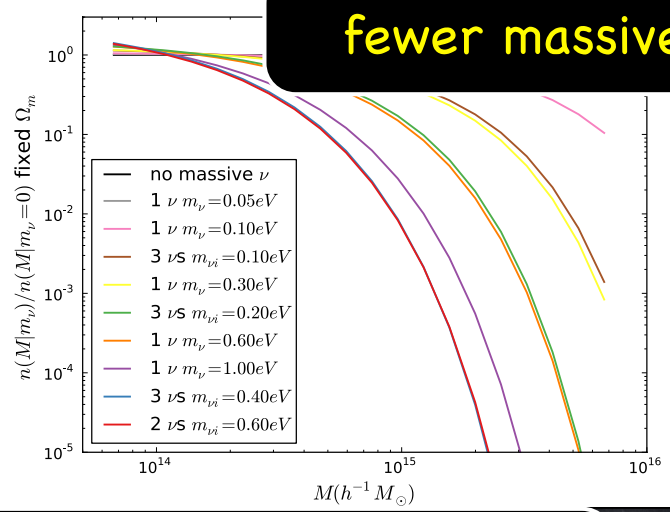




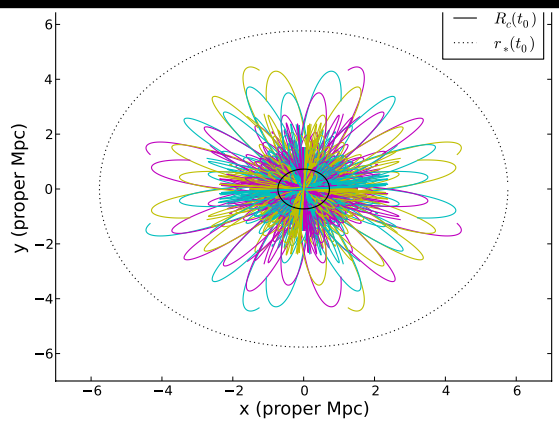
less power in small-scale density fluctuations



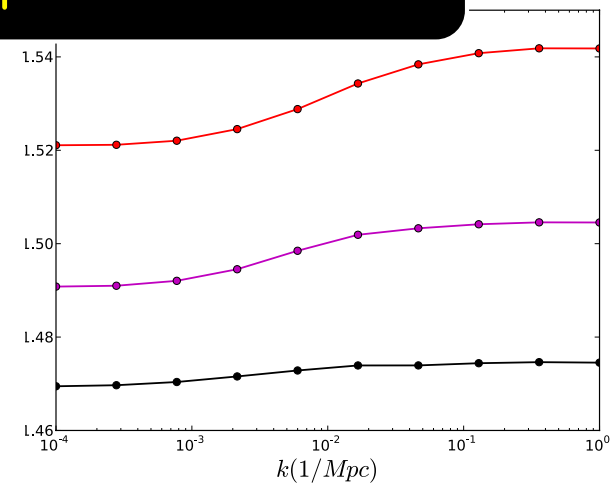
fewer massive halos



puffy neutrino halos around CDM halos



scale-dependent halo bias



Summary

- The cosmic neutrino background is key part of the standard cosmological model

- The energy density in the cosmic neutrino background has been detected at high significance in the early universe

- Neutrino mass qualitatively changes the growth the structure in the universe — so far there are only upper limits on these changes but future experiments <u>will</u> detect them providing a measure of the neutrino mass scale

- This opens a new era studying neutrinos and structure formation in the νCDM universe!