Institute for Computational Cosmology

Neutrinos in Cosmology

Elise Jennings

Durham University

S. Pascoli & C. M. Baugh

Higgs Maxwell Workshop

10 February 2010

MARIE CURIE ACTIONS

Durham University

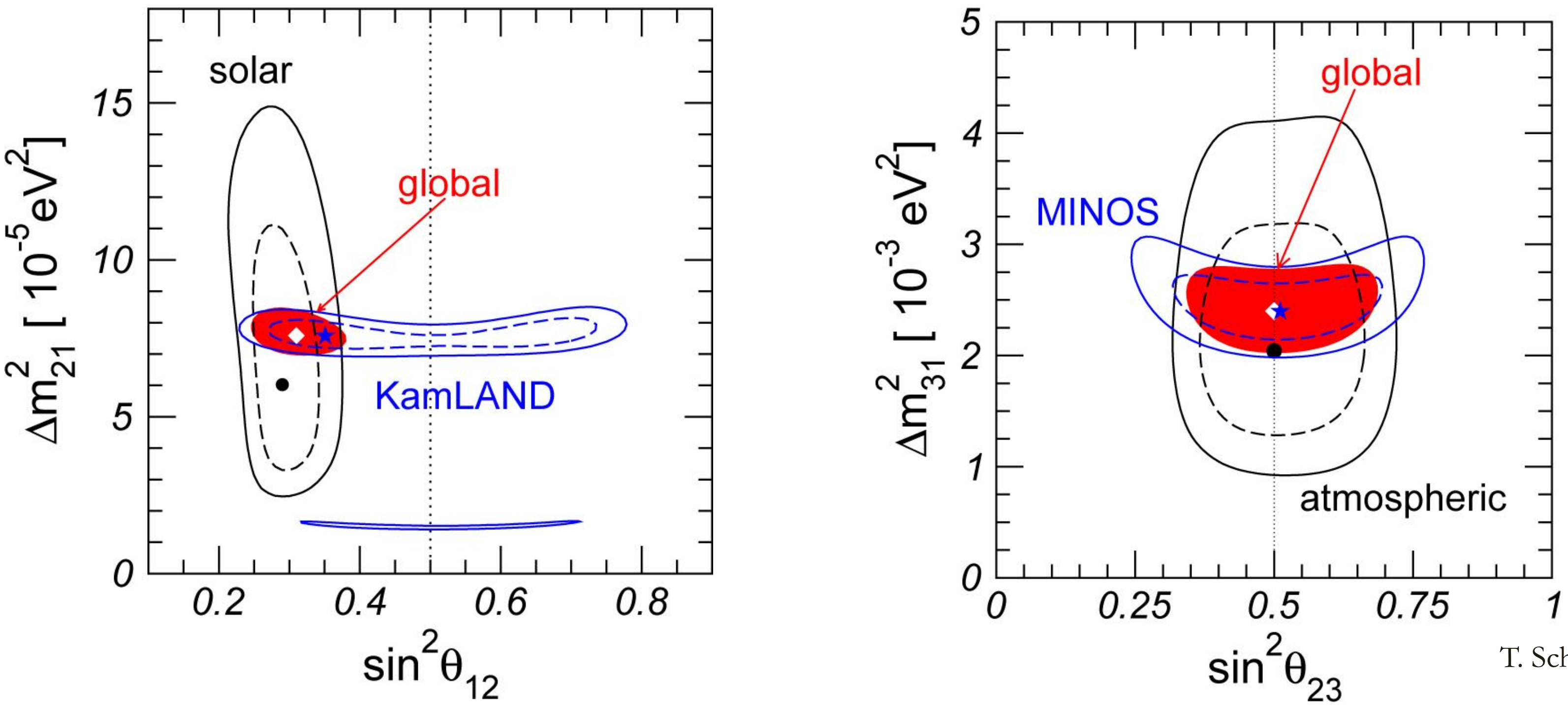
Introduction

- Present knowledge of neutrino masses
- Determining nature of neutrino mass and mass scale
- Neutrino masses in cosmology and N-body simulations
- Conclusions

Present status of neutrino masses

Neutrino oscillations $\Rightarrow$ neutrinos are massive & they mix

ν oscillations are sensitive to Δm^2



T. Schwetz et al. 2008

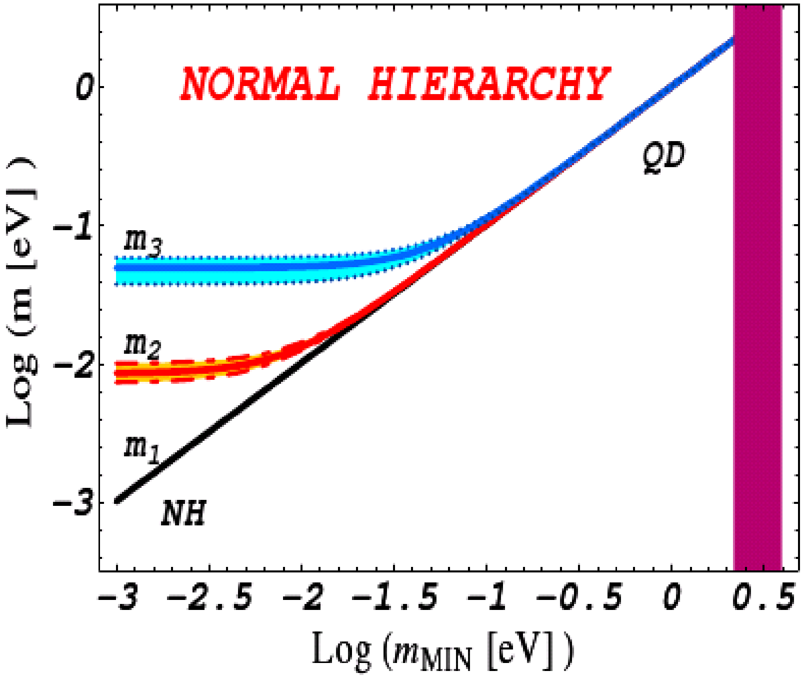
Solar neutrinos and KamLAND $\Delta m^2_{\odot} = 7.65 \times 10^{-5}\ \mathrm{eV}^2$

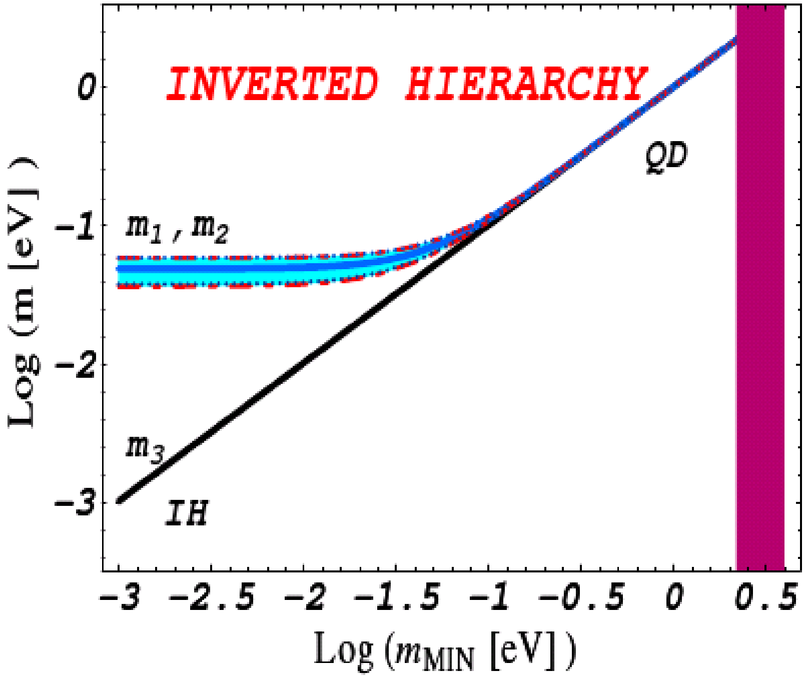
Atmospheric and accelerator neutrinos $\Delta m^2_{atm} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$

Neutrino masses

$\Delta m^2_\odot \ll \Delta m^2_A$ implies at least **3 neutrinos**

[Mohapatra et al., 2003]





We can identify 3 types of spectra:

and 2 interpolating ones.

$$NH: m_1 << m_2 << m_3$$

$$IH: m_3 << m_1 \approx m_2$$

$$QD: m_1 \approx m_2 \approx m_3$$

Measuring neutrino masses requires $\mathbf{m_{MIN}}$ and $\mathbf{sign(\Delta m^2_{31})}$

Measuring neutrino masses

- LBL neutrino experiments:

The **type of hierarchy** can be determined by searching for matter-enhanced neutrino oscillations for long baselines (superbeams, betabeams, neutrino factory)

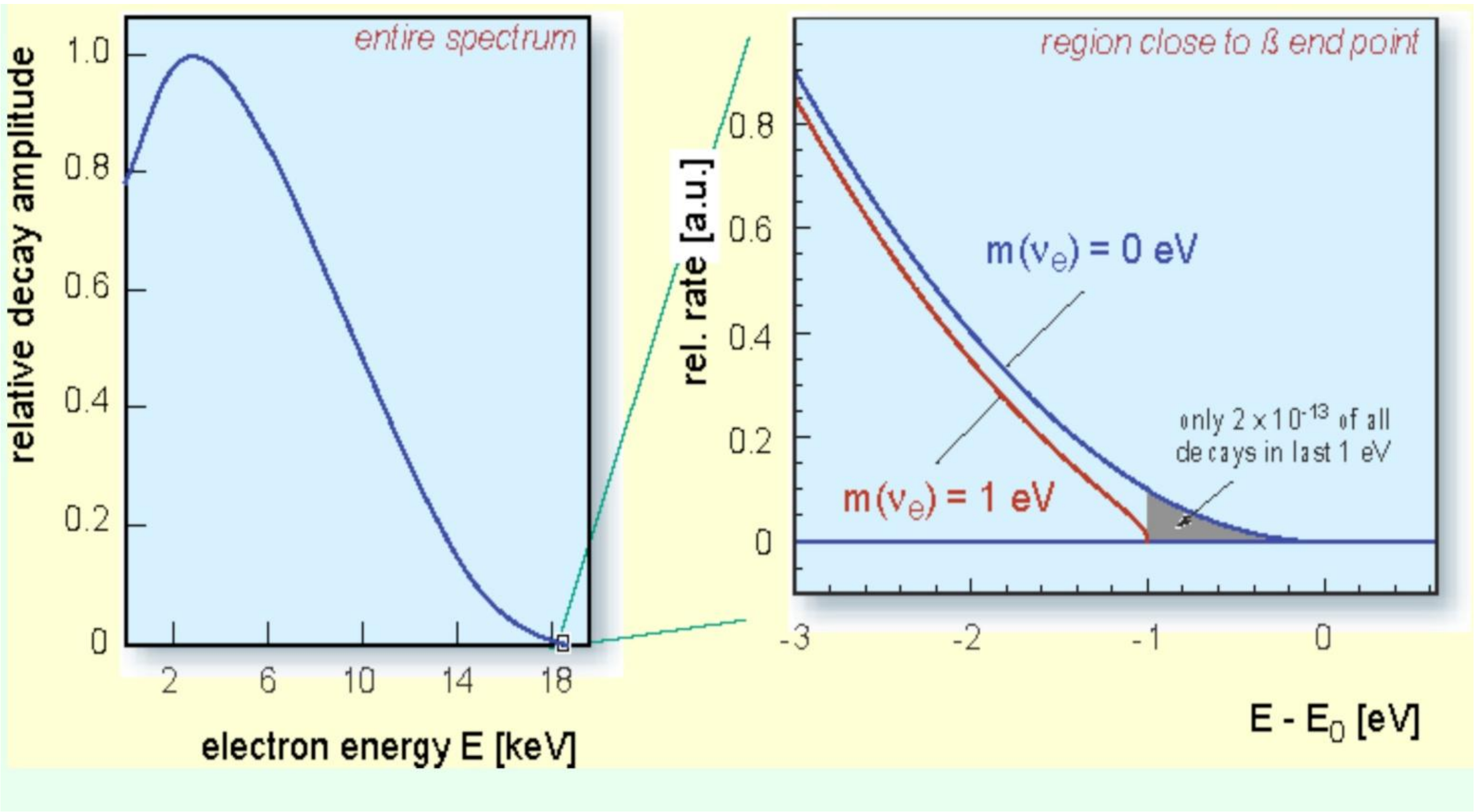
- Direct mass searches in tritium beta decay experiments

- Neutrino-less double beta decay

- Cosmological observations

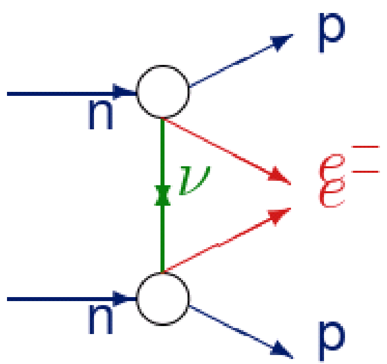
Direct mass searches

Neutrinos with mass distort the endpoint electron spectra in beta-decay



- Current upper bound: **m< 2.2 eV** (95% CL) [Troiztk and Mainz]
- KATRIN can reach a sensitivity of **0.2 eV**

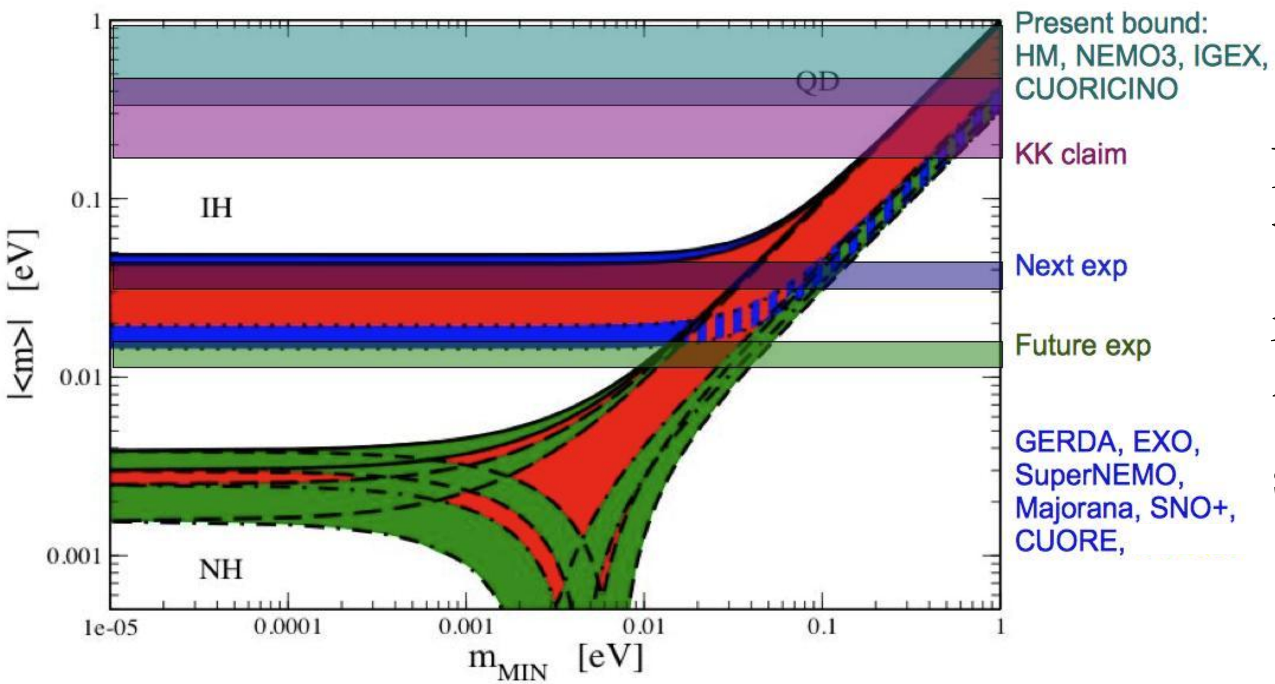
$(\beta\beta)_{0\nu}$-decay : $(A,Z) \rightarrow (A,Z+2)+2e^-$



Dirac or **Majorana**

lepton number conserved

lepton number broken



SP, S. Petcov

Neutrinoless double beta decay can give information on the type of neutrino mass spectrum.

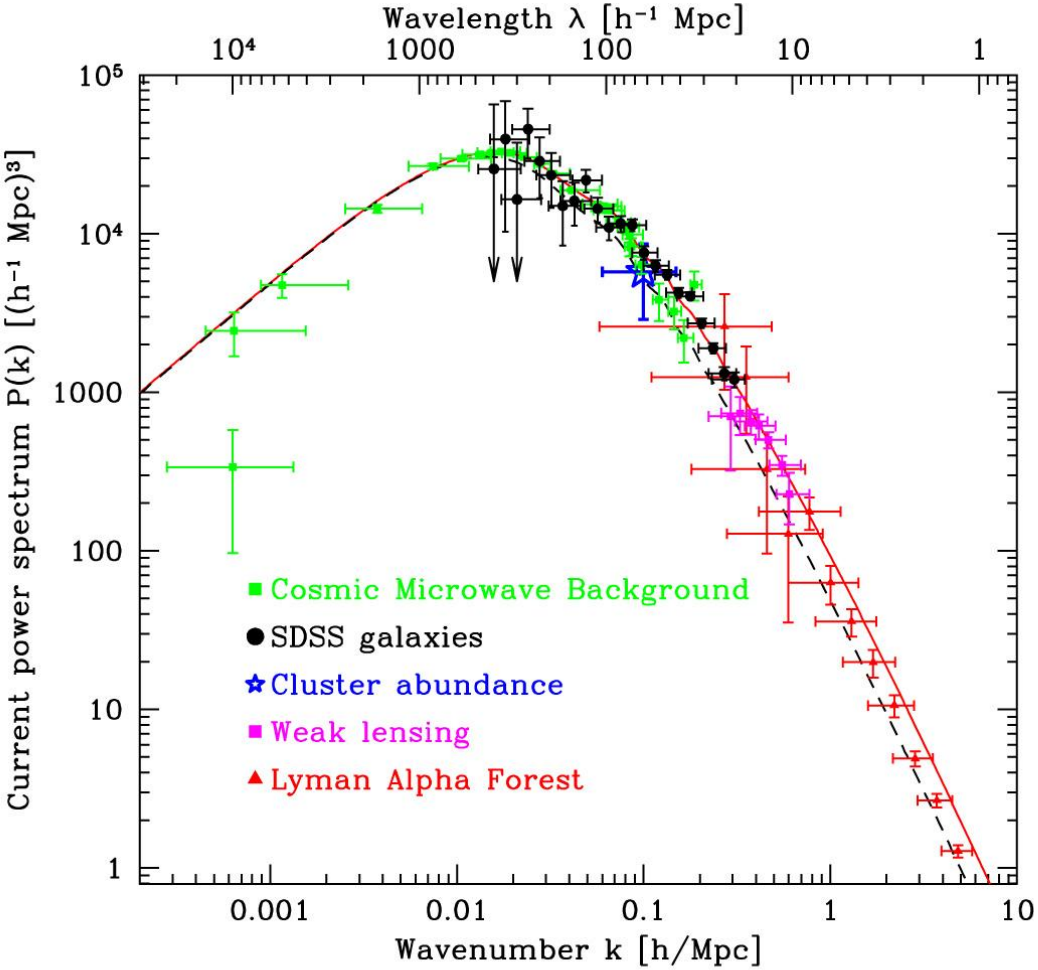
Neutrino mass in cosmology

•Large scales structure (LSS)

Growth of structure suppressed below free-streaming scale

$$P(k,z) = <\delta_m{}^2> = P_0(k)T(k,z)$$

$$\lambda_{FS} \approx 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{eV}{m_\nu}\right)h^{-1}Mpc$$

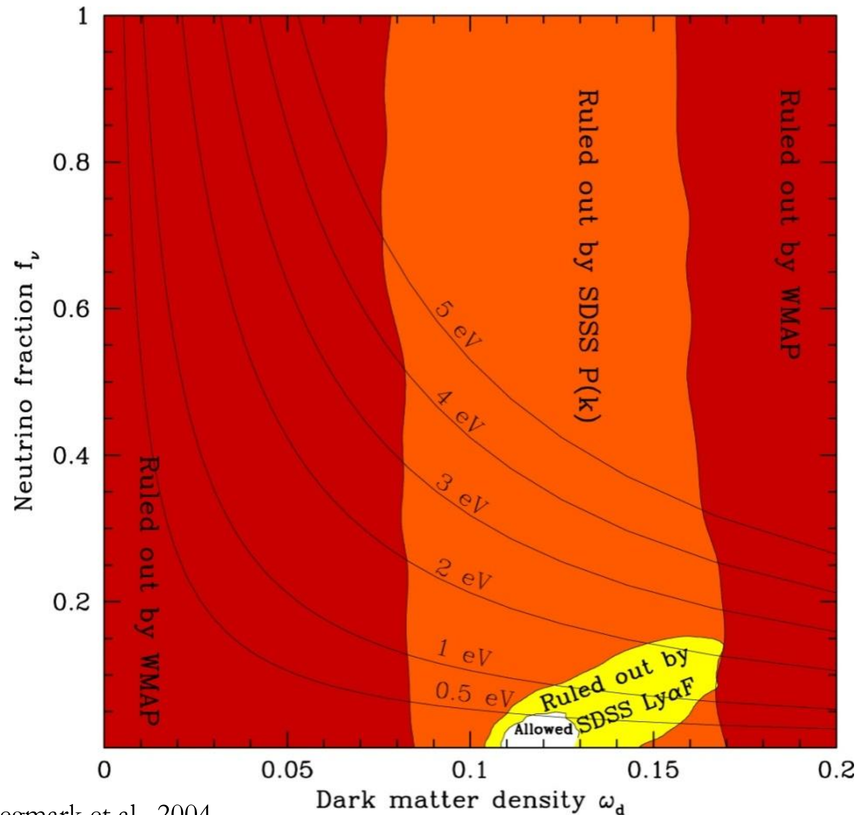


[Tegmark et al., 2004]

•CMB measurements

Shift in the time of matter radiation equality

Current constraints



[Tegmark et al., 2004,
Seljak et al. 2004]

WMAP + SDSS galaxy clustering data

$\Sigma m < 1.7$ eV (95%CL)

+ SDSS galaxy bias

$\Sigma m < 0.6\text{-}0.7$ eV

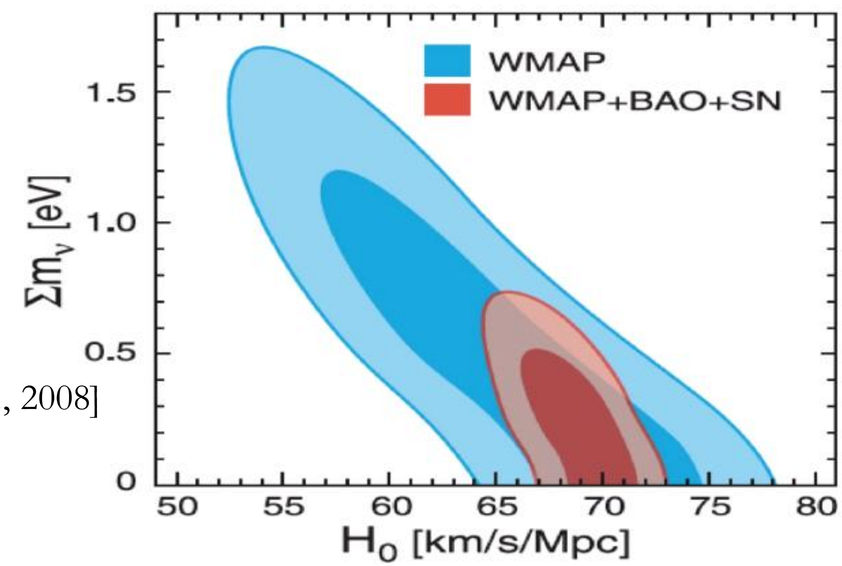
[Tegmark et al., 2004]

+ Lyman alpha forest

$\Sigma m < 0.42$ eV

WMAP + 2dF galaxy clustering data

$\Sigma m < 1.2$ eV [Sanchez et al., 2006]



WMAP 5 yr only

$\Sigma m < 1.3$ eV (95%CL)

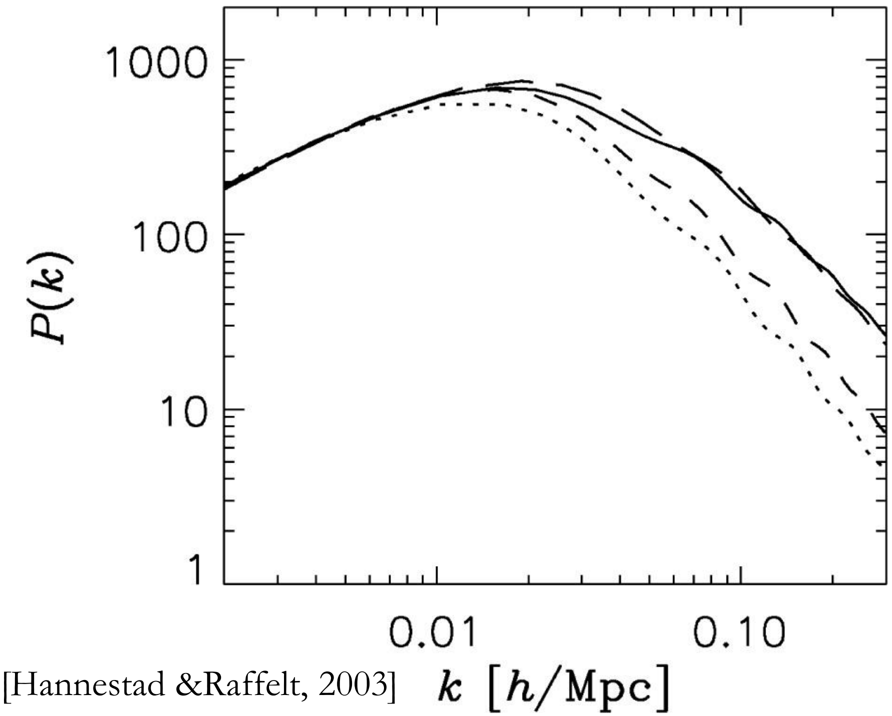
WMAP+BAO+SN

$\Sigma m < 0.67$ eV

[E. Komatsu et al., 2008]

[Dunckley et al., 2008]

Linear theory P(k) with massive neutrinos



[Hannestad &Raffelt, 2003]

- Ω_m=0.25, Ω_ν = 0, N_ν =3
- Ω_m=0.25, **Ω_ν = 0.05**, N_ν =3
- Ω_m=0.25, Ω_ν = 0.05, **N_ν =8**
- **Ω_m=0.35**, Ω_ν = 0.05, **N_ν =8**

Neutrino fraction

$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{94eV}$$

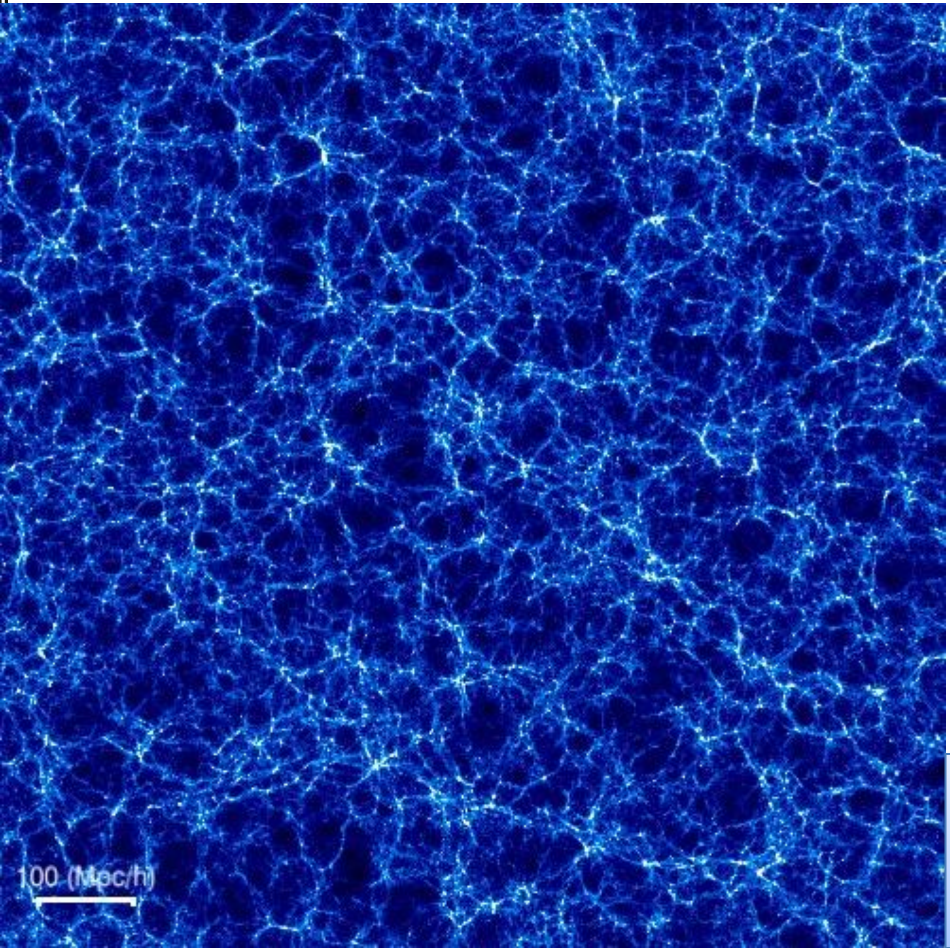
Suppression of power spectrum $\quad \dfrac{\Delta P(k)}{P(k)} = -8\dfrac{\Omega_\nu}{\Omega_m} = -8 f_\nu$

Need to take into account non-linear effects on growth of structure!

N-body simulations of large scale structure

Essential for accessing the effects of nonlinear fluctuation growth, peculiar motions, nonlinear and scale dependent bias, halo structure and substructure.

[Jennings et al., 2009]



Initial conditions: uniform particle distribution which is perturbed by a random realisation of a **linear theory P(k)** with cosmological parameters **Ω_m, Ω_b, Ω_Λ, Ω_ν, f_ν ...**

e.g. CAMB, CMBFAST

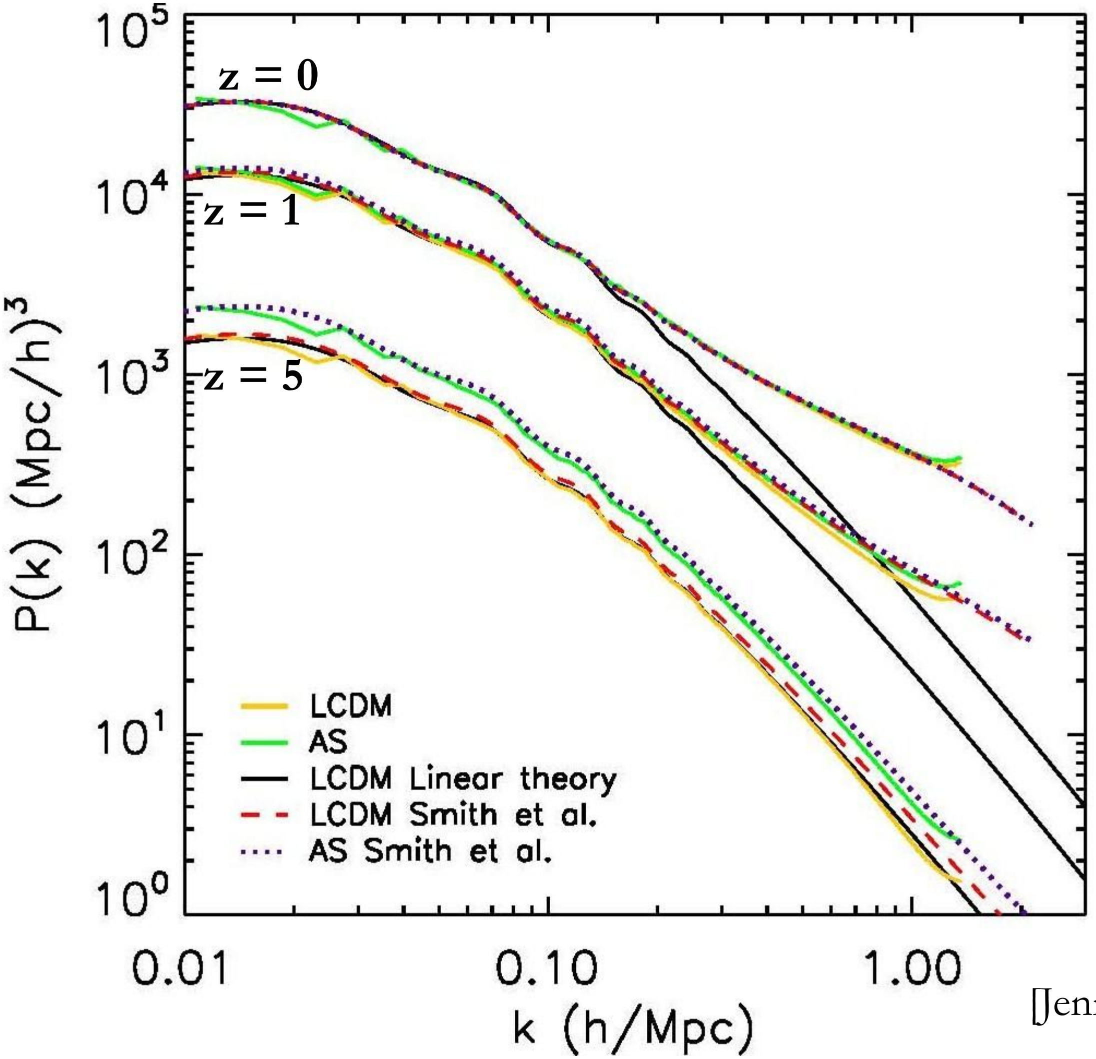
[Lewis & Bridle 2002, Seljak &Zaldarriaga 1996]

Snapshot taken at $z = 0$
269×10^6 particles
$L_{box} = 1500$ Mpc/h

Solve **Poisson equation** iteratively to compute gravitational forces-update positions and velocities.

e.g. Gadget-2 (Springel 2005)

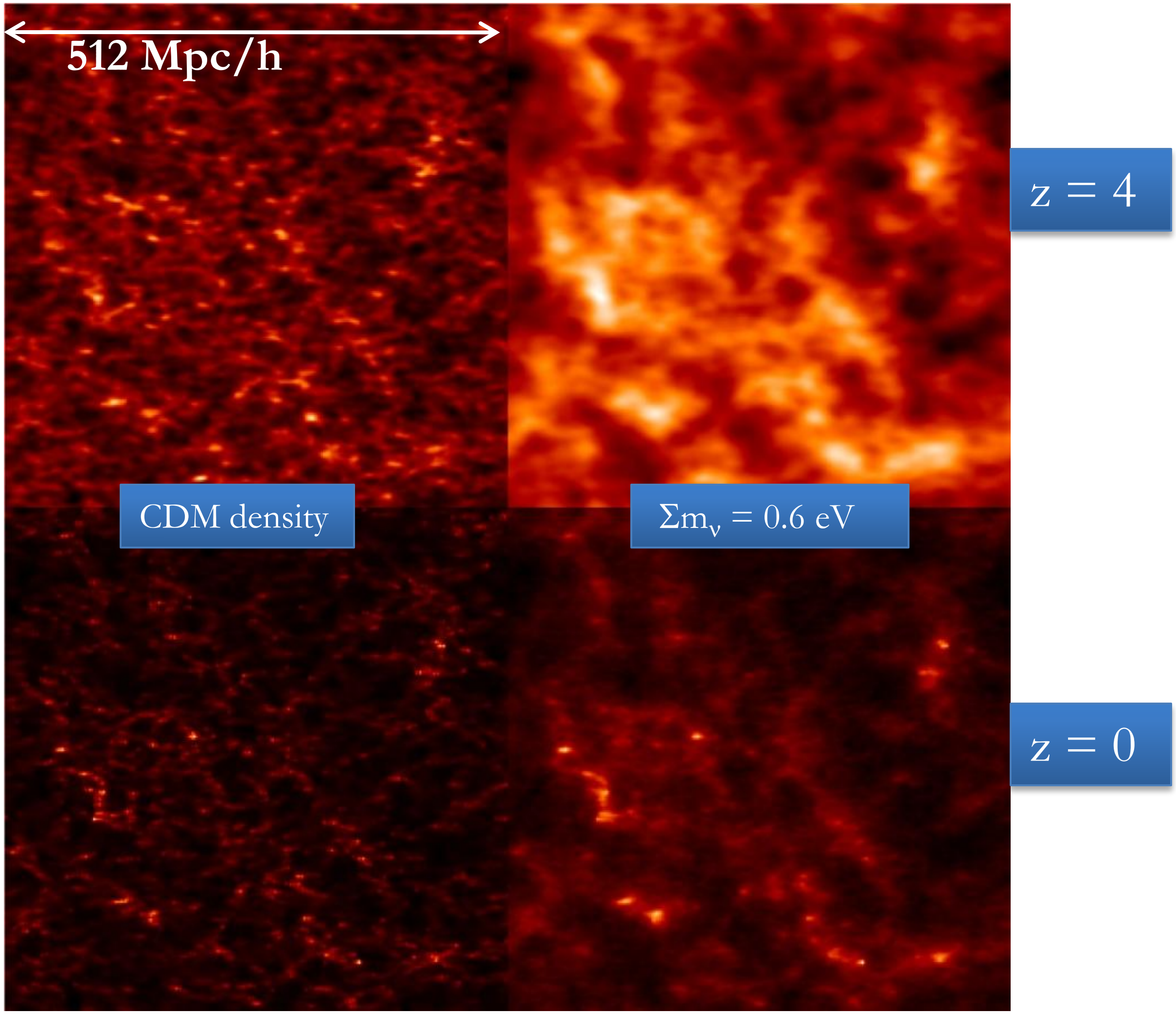
For example: N-body simulations of **Quintessence Dark Energy**



Different growth history in AS quintessence model compared to LCDM $\Rightarrow$ more non-linear structure formation

[Jennings et al.,2009.]

N-body simulations with massive neutrinos

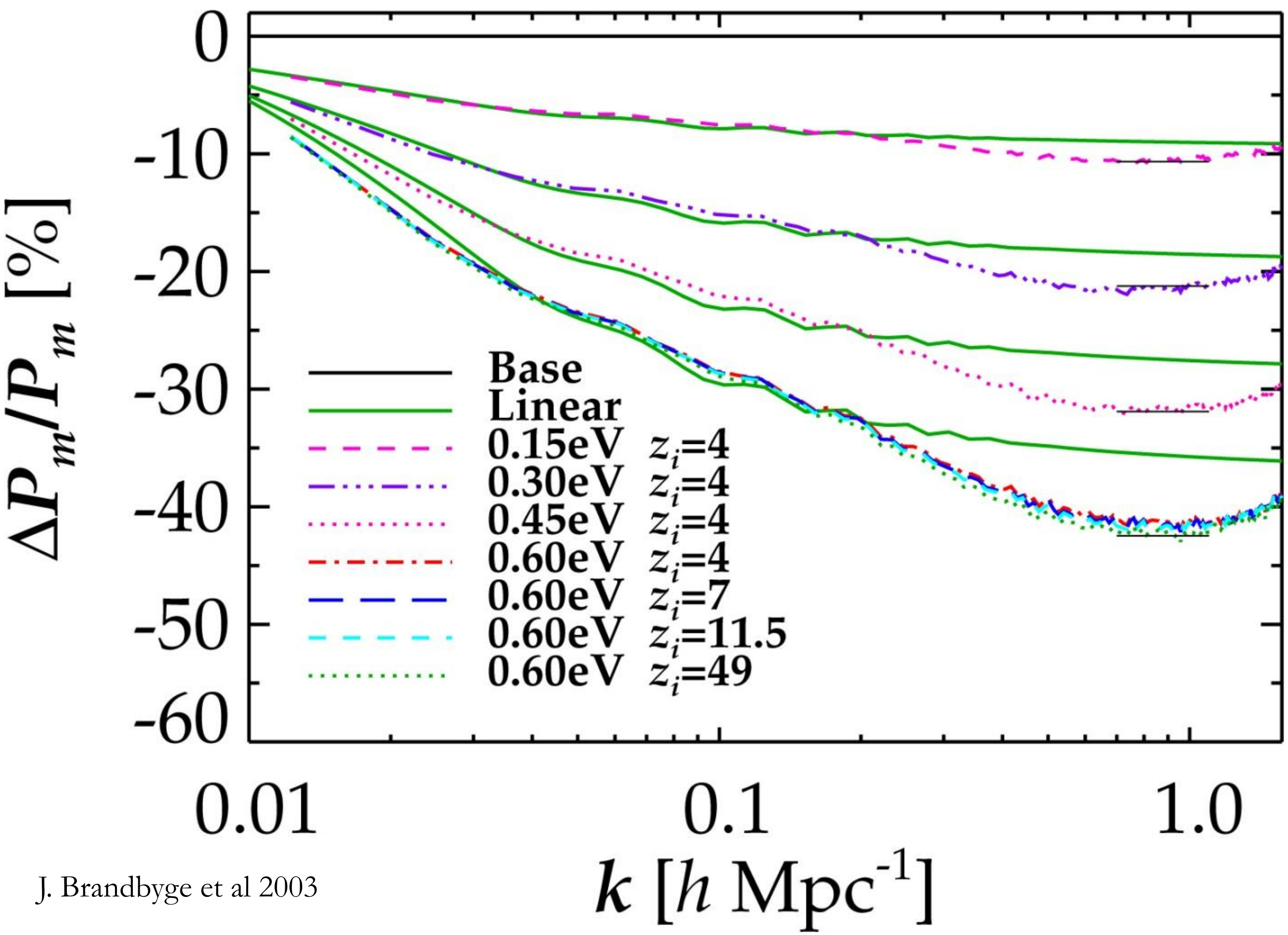


[J. Brandbyge et al 2003]

$$P(k,z) = P_0(k)T(k,z)$$

Particle representation for both CDM and neutrinos

Neutrino velocity = the **thermal velocity** drawn from a Fermi-Dirac distribution + **gravitational flow velocity**



J. Brandbyge et al 2003

Linear theory

$$\frac{\Delta P(k)}{P(k)} = -8\frac{\Omega_\nu}{\Omega_m} = -8 f_\nu$$

Add non-linear corrections

$$\frac{\Delta P(k)}{P(k)} = -9.8\frac{\Omega_\nu}{\Omega_m}$$

Simulations with massive neutrinos

•Neutrino **thermal velocity** $\Rightarrow$ start simulation at low redshifts close to NL regime

•Thermal velocities drawn from distribution $\Rightarrow$ increase **neutrino particle number**, need $>256^3$ particles for convergence at $k < 0.15$ h/Mpc

• **Low mass neutrinos** $\Sigma m_\nu \sim 0.3$eV small scale power is dominated by white noise term $\Rightarrow$ instead use neutrino density field on a grid

[E.J., C.M.B., S.P. & T.T. 2010 in prep.]

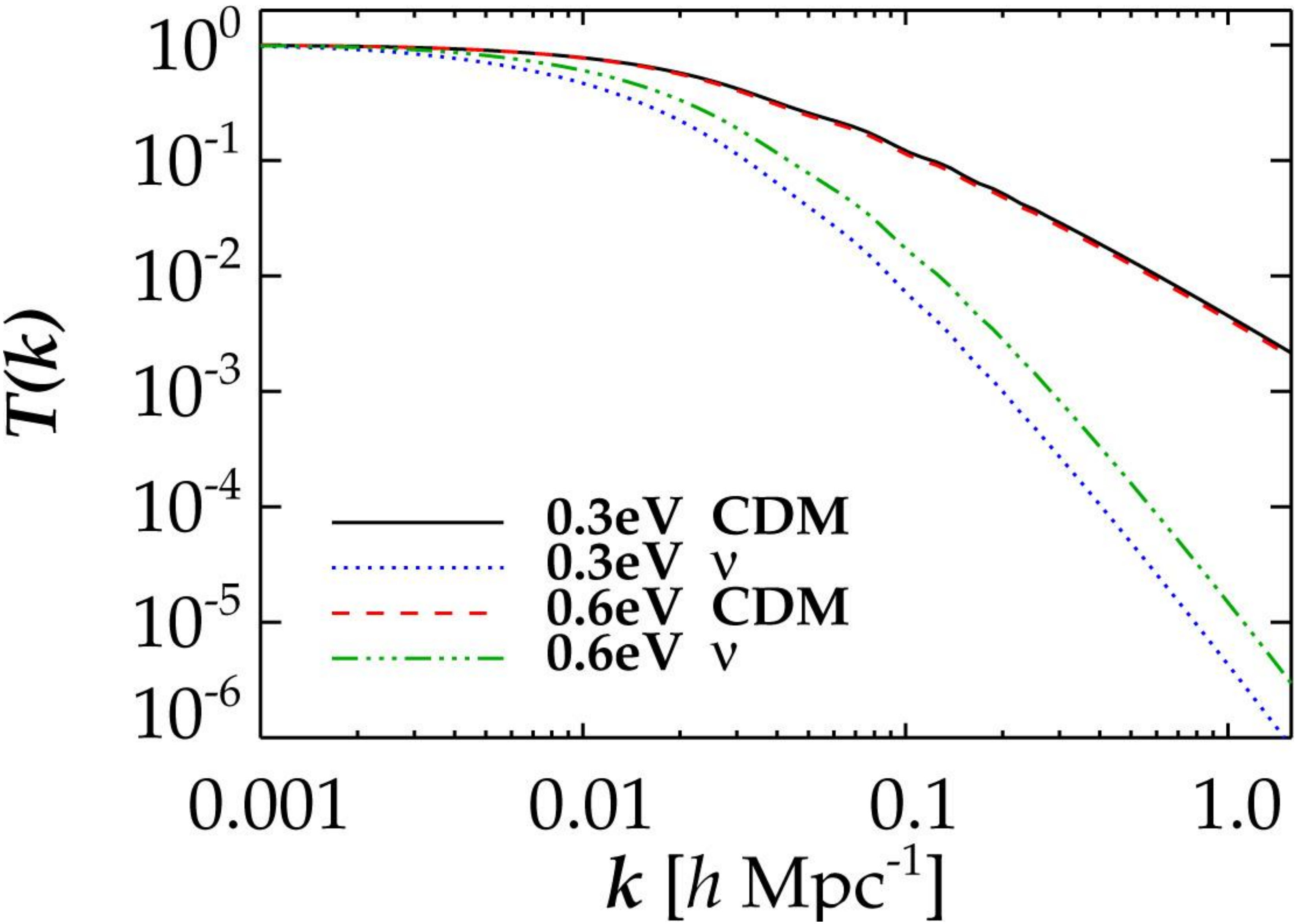
Summary

•Finding the **absolute values of neutrino masses** is one of the fundamental questions in neutrino physics

•**Cosmological observations** provide information on **mass scale**

•**Large scale structure** to probe neutrino physics

N-body simulations are essential for determining growth on non-linear scales



T(k)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0.001
0.01
0.1
1.0
k [h Mpc^-1]
0.3eV CDM
0.3eV ν
0.6eV CDM
0.6eV ν

Neutrinos have a **thermal velocity**

$$< v_{thermal} > \approx 81(1+z)\left(\frac{eV}{m_{\nu}}\right) km/s$$

Dwarf galaxy velocity v ~ 10 km/s
Galaxy velocity v ~ 100 km/s

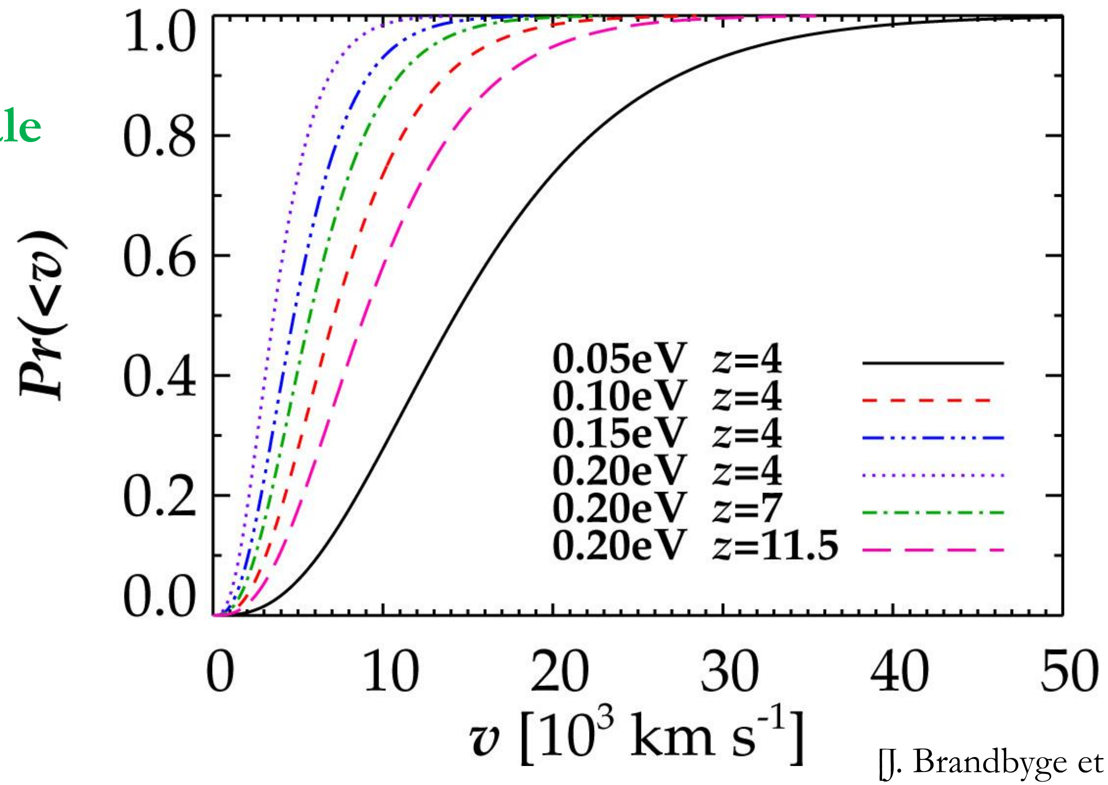
N-body simulations have shown that neutrinos cannot be galactic dark matter

[White et al 1983]

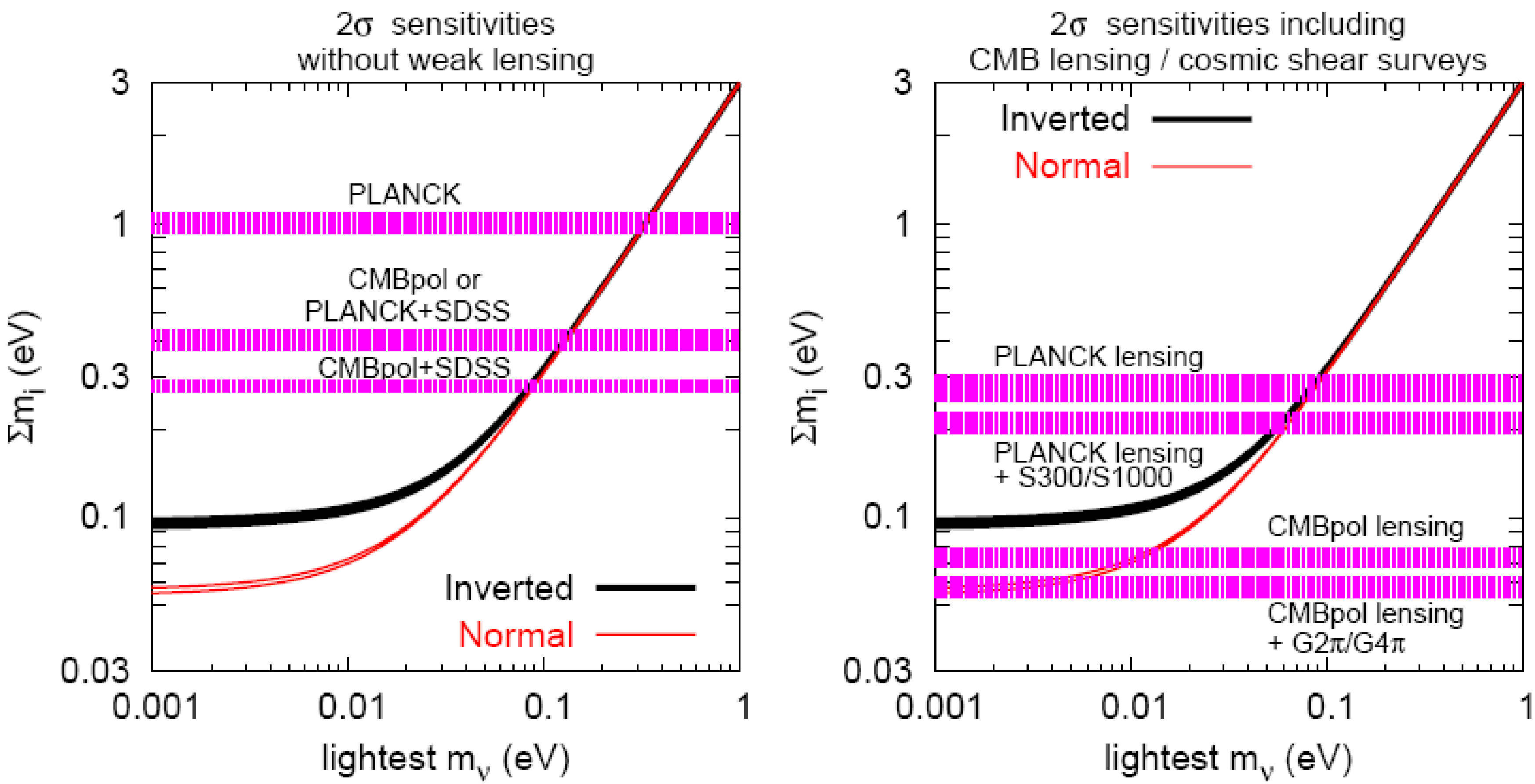
Free streaming length scale

$\lambda \gg \lambda_{FS}$ Neutrinos cluster

$\lambda \ll \lambda_{FS}$ Nonclustering



[J. Brandbyge et al 2003]



[Lesgourgues & Pastor, (2006)]