# The impact of finite-mass neutrinos on large-scale structure

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# Collaborators

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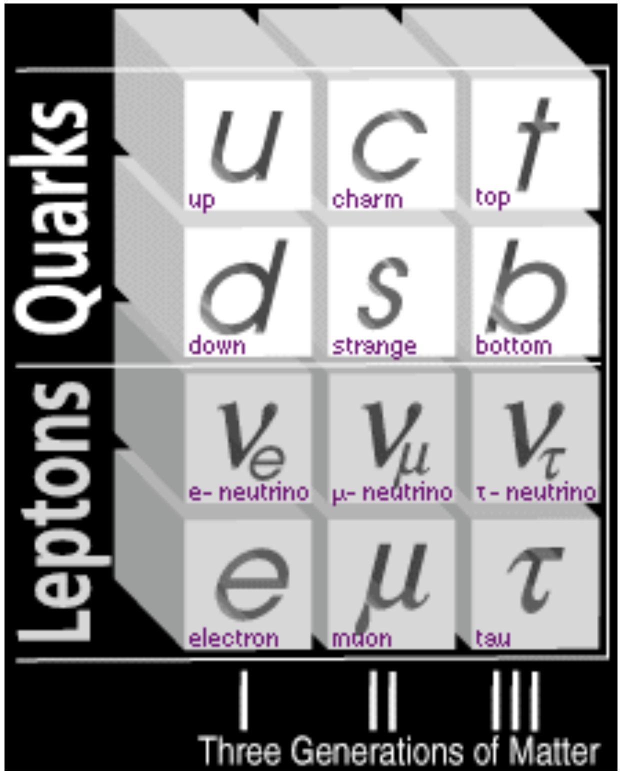
Shun Saito, MT, Atsushi Taruya, Phys. Rev. Lett., 2008

MT, Komatsu, Futamase, PRD, 2006

Ichiki, MT, Takahashi, to be submitted soon

# Neutrinos

- Known as one of fundamental elementary particles, involved in SM
- Only has weak interactions (no charge and very light), so very difficult to directly see
- Yet not know much about neutrinos, mass unknown yet




**The Nobel Prize of Physics, 2002**

Prof. Koshiba

Prof. Davis

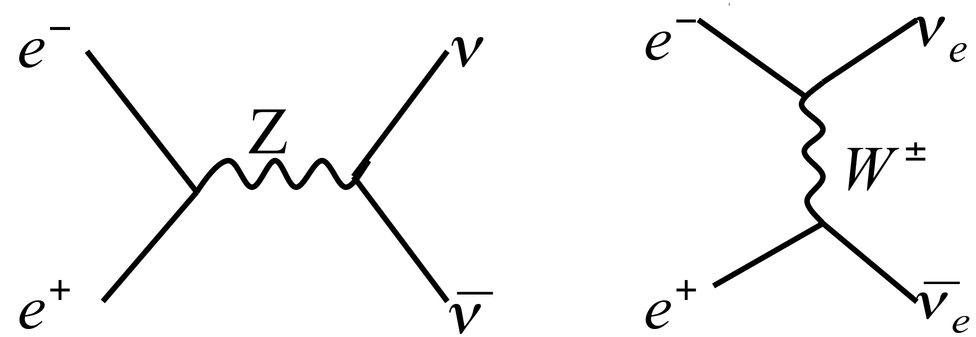
**No doubt neutrinos are very interesting particles to explore!**

# Cosmic Thermal History


**Thermal equilibrium** $f(\varepsilon) = \left[\exp(\varepsilon / T) \pm 1\right]^{-1}$

$\gamma, \nu, \bar{\nu}, e^-, e^+$

$T_\gamma = T_e = T_\nu$




T~ a few MeV: neutrinos decouple

**Neutrinos didn't annihilate to photons**

$\nu, \bar{\nu}$ $\gamma, e^-, e^+$ $T_\gamma = T_e = T_\nu$

T~0.5MeV: electrons and positrons annihilate

$e^- + e^+ \to 2\gamma$

$\nu, \bar{\nu}$ $\gamma$, a few $p, e^-$ $T_\gamma > T_\nu$

T~1eV: matter-radiation equality

T~0.24eV(~3000K): recombination, CMB

$\gamma, \quad e^- + p \to H$

n_ν,0~100 cm^-3

# Neutrinos have finite masses!

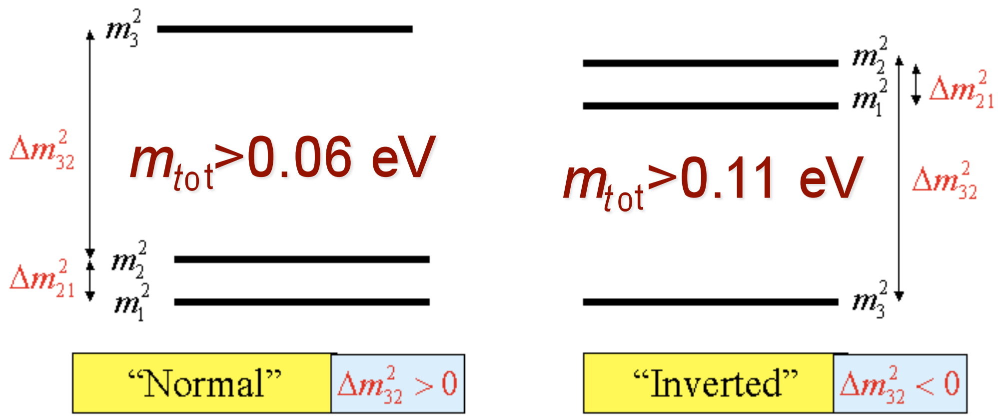
- The experiments (Kamiokande, SK, SNO, KamLAND) imply the total mass, m_tot>0.06 eV; but the mass scale yet unknown
- Neutrinos became non-relativistic at redshift when $T_{\nu,\mathrm{dec}} \sim m_\nu$

$$\boxed{1+z_{\mathrm{nr}} \approx 189\left(m_\nu/0.1\mathrm{eV}\right)}$$

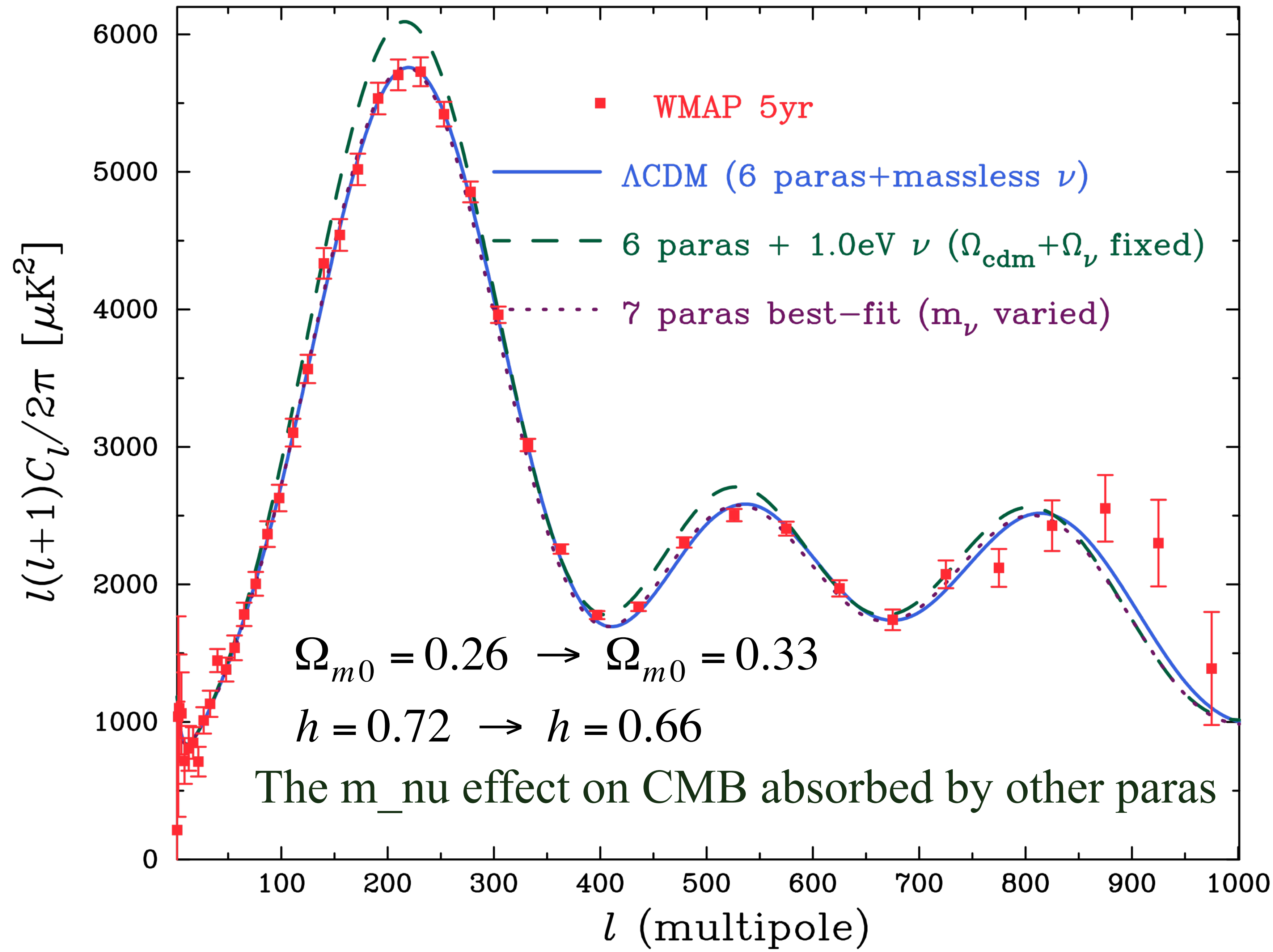
  – If *m_nu>0.6eV*, the neutrino became non-relativistic before recombination, therefore larger effect on CMB, vice versa

- The cosmological probes measure the total matter density: CDM + baryon + massive neutrinos

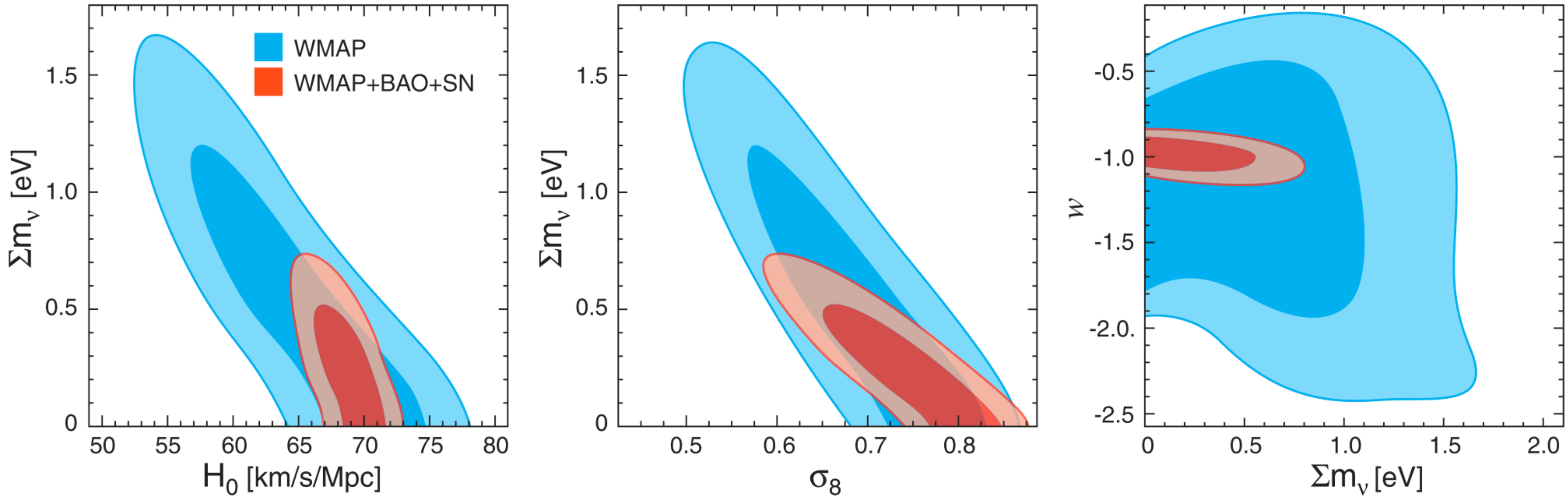
$$\boxed{\begin{aligned}\Omega_{\mathrm{m0}} &= \Omega_{\mathrm{cdm0}} + \Omega_{\mathrm{baryon0}} + \Omega_{\nu 0} \\ f_\nu &\equiv \frac{\Omega_{\nu 0}}{\Omega_{\mathrm{m0}}} = \frac{m_{\nu,\mathrm{tot}}}{94.1\mathrm{eV}\Omega_m h^2} > 0.005\end{aligned}}$$



# Effect of finite-mass neutrinos on CMB

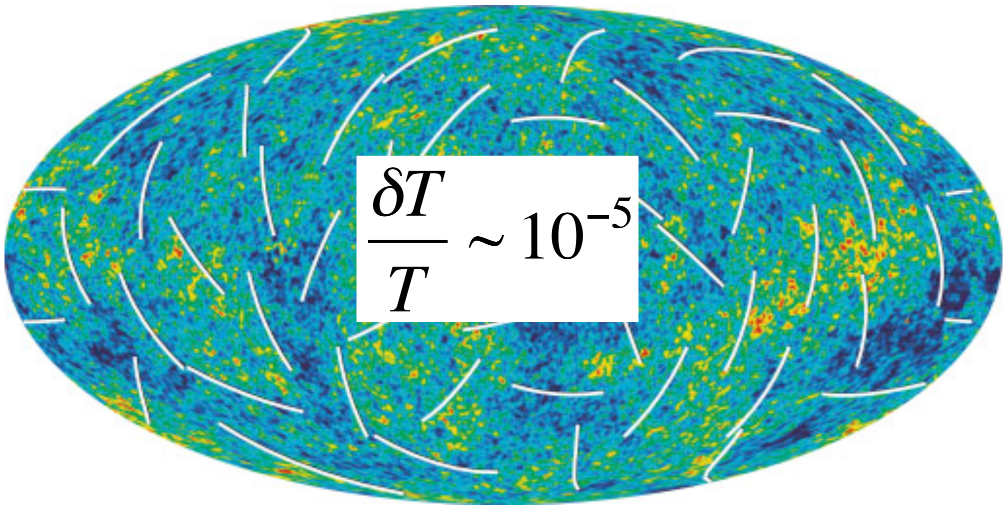


# WMAP5yr (Komatsu+08)



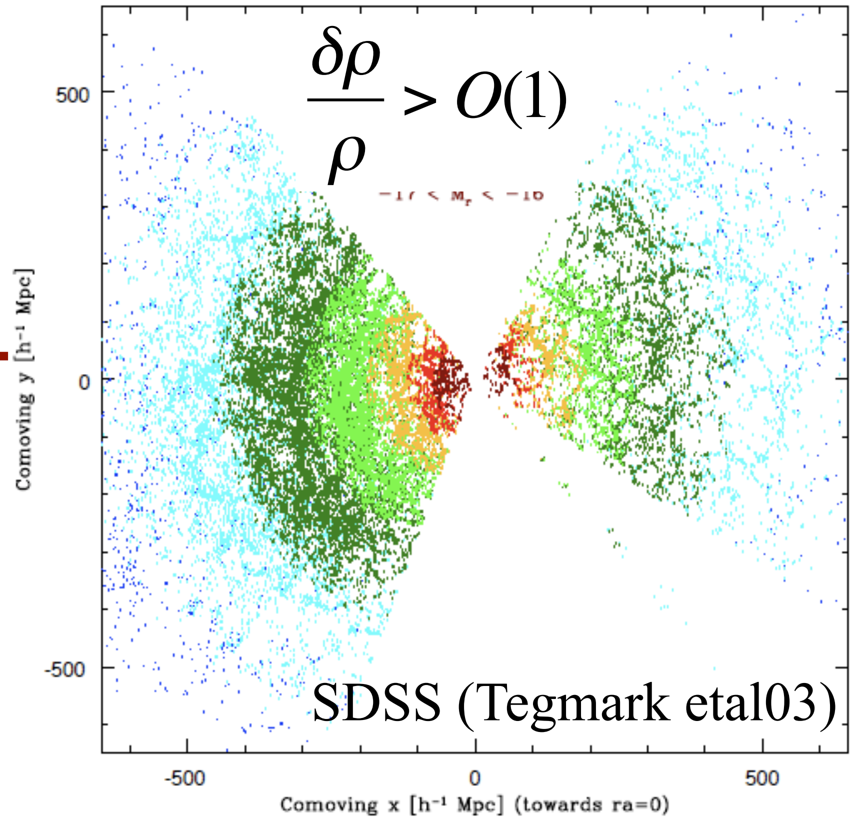

- The m_nu effect on CMB degenerate with *h* and Ω_m that are sensitive to the distance out to $z_*$~1100(Ichikawa+ 05)
- WMAP5: CMB alone m_nu,tot<1.3eV; **WMAP5 + SN + BAO (*no galaxy P(k)*) m_nu,tot<0.6eV (CMB + geometrical probes)**
- Seems best-available constraint from this method; if m_nu<0.6eV, as neutrinos become non-rel. btw z~1100 and today

# CMB + Large-Scale Structure (LSS)




WMAP (z~10^3)

+




LSS (0<z<3)

- Given the precise CMB constraints, combining CMB and LSS allows to probe the evolution of structure formation over z=[0,10^3], thereby tightening the neutrino mass constraints (Hu, Eisenstein & Tegmark 98)

# Free-streaming scale of neutrino

- Neutrinos are very light compared to CDM/baryon
- The phase-space distribution of neutrinos, even after decoupling, obeys the relativistic FD dist. (specified by m_ν)
- The thermal velocity at redshift *z* relevant for LSS is larger than the gravity induced peculiar velocity

$$\boxed{\sigma_\nu(z) = \sqrt{\left\langle \frac{p^2}{2m_\nu} \right\rangle} \approx 1800\mathrm{km/s}\left(\frac{m_\nu}{0.1\mathrm{eV}}\right)^{-1}(1+z)}$$

  – Even a massive cluster can't much trap neutrinos

- *The free-streaming scale*, the distance neutrino can travel with the thermal vel. during cosmic expansion

$$\boxed{\lambda_{\mathrm{fs}}(z) \approx \sigma_\nu H^{-1} a^{-1} \Rightarrow k_{\mathrm{fs}}(z) \approx \frac{0.037}{(1+z)^{1/2}}\left(\frac{m_\nu}{0.1\mathrm{eV}}\right)\left(\frac{\Omega_m}{0.3}\right)^{1/2} h\ \mathrm{Mpc}^{-1}}$$

**λ_fs is a 100Mpc scale, similar to BAO scales**

# Suppression in growth of LSS

- A mixed DM model: Structure formation is induced by the density fluctuations of total matter

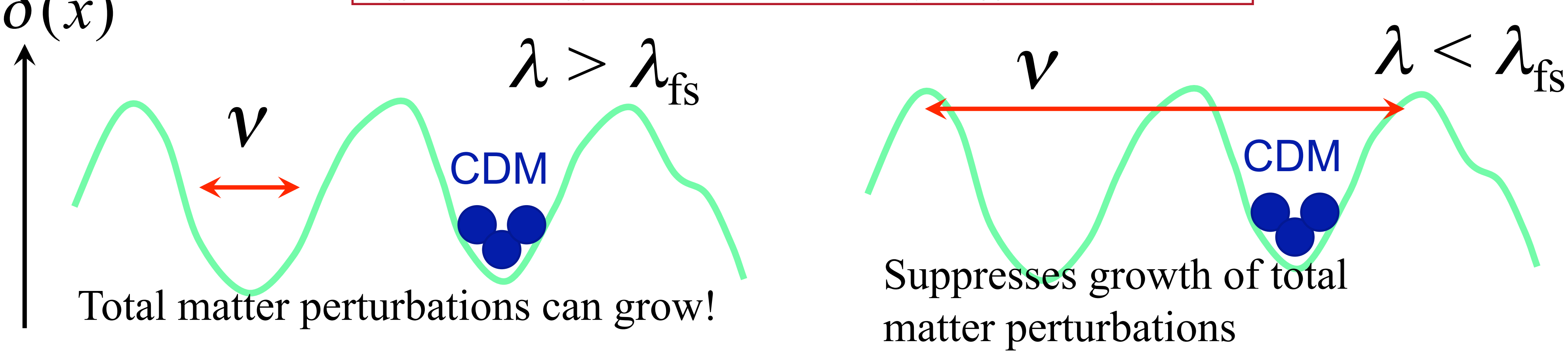
$$\boxed{\delta_m = \frac{\bar{\rho}_c\delta_c + \bar{\rho}_b\delta_b + \bar{\rho}_\nu\delta_\nu}{\bar{\rho}_c + \bar{\rho}_b + \bar{\rho}_\nu} \equiv f_c\delta_c + f_b\delta_b + f_\nu\delta_\nu}$$

- The neutrinos slow down LSS on small scales
  - On large scales $\lambda>\lambda_{fs}$, the neutrinos can grow together with CDM

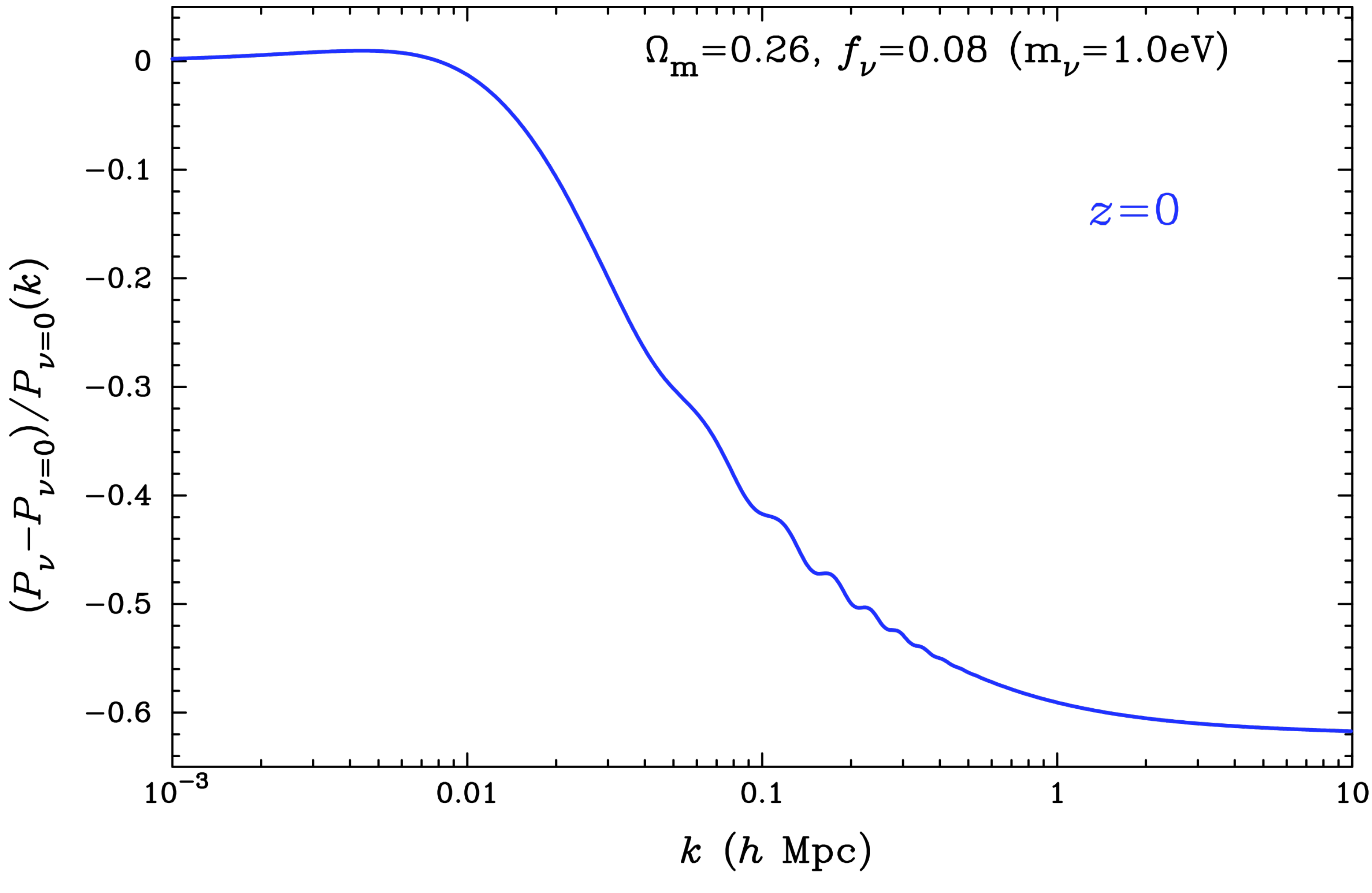
$$\boxed{\delta_c = \delta_b = \delta_\nu}$$

  - On small scales $\lambda<\lambda_{fs}$, the neutrinos are smooth, $\delta_\nu=0$, therefore weaker gravitational force compared to a pure CDM case

$$\boxed{\ddot{\delta}_{cb} + 2H\dot{\delta}_{cb} - 4\pi G\bar{\rho}_{\mathrm{m}}(1 - f_\nu)\delta_{cb} = 0,\ \delta_\nu \approx 0}$$

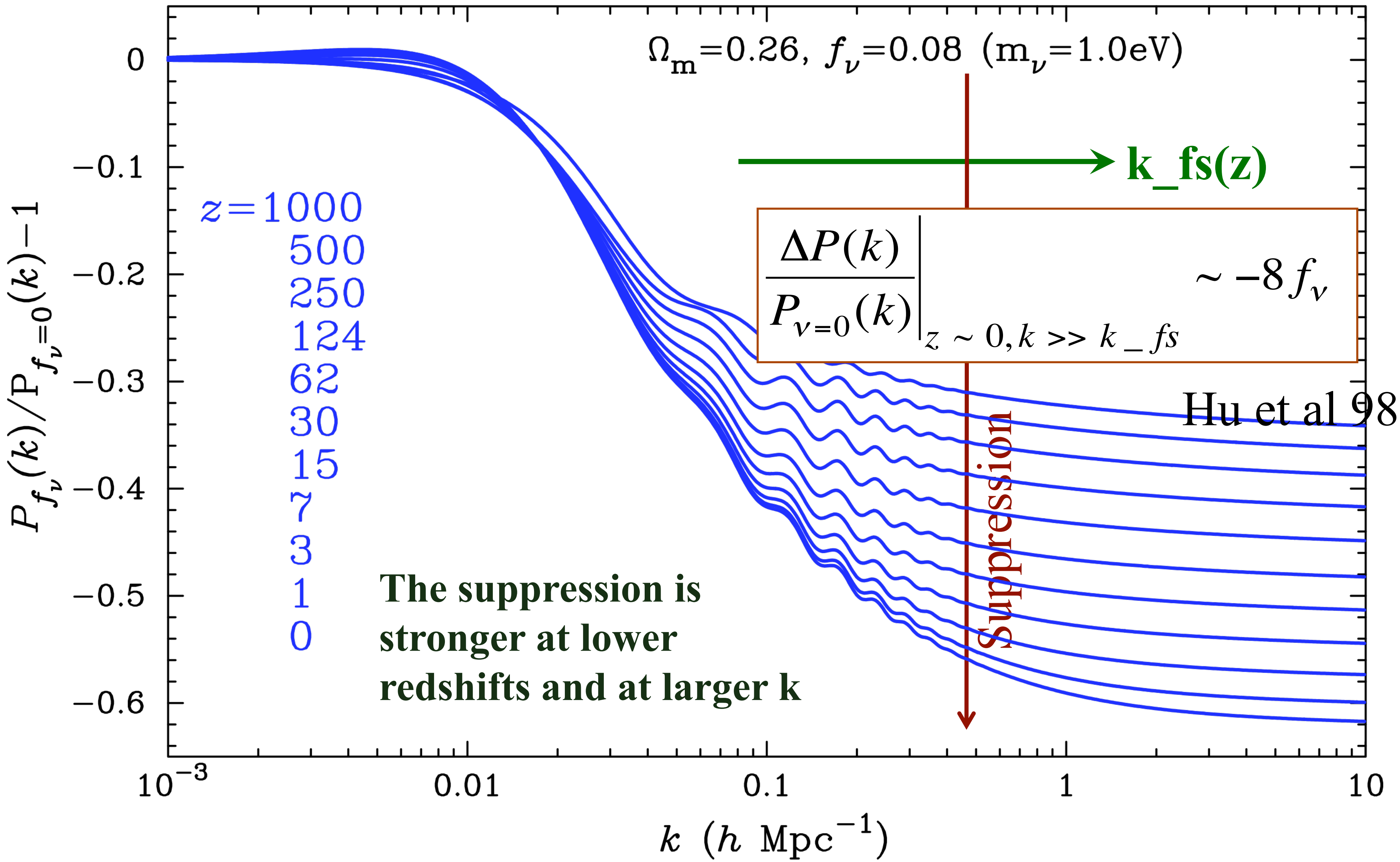


# Suppression of linear P(k)



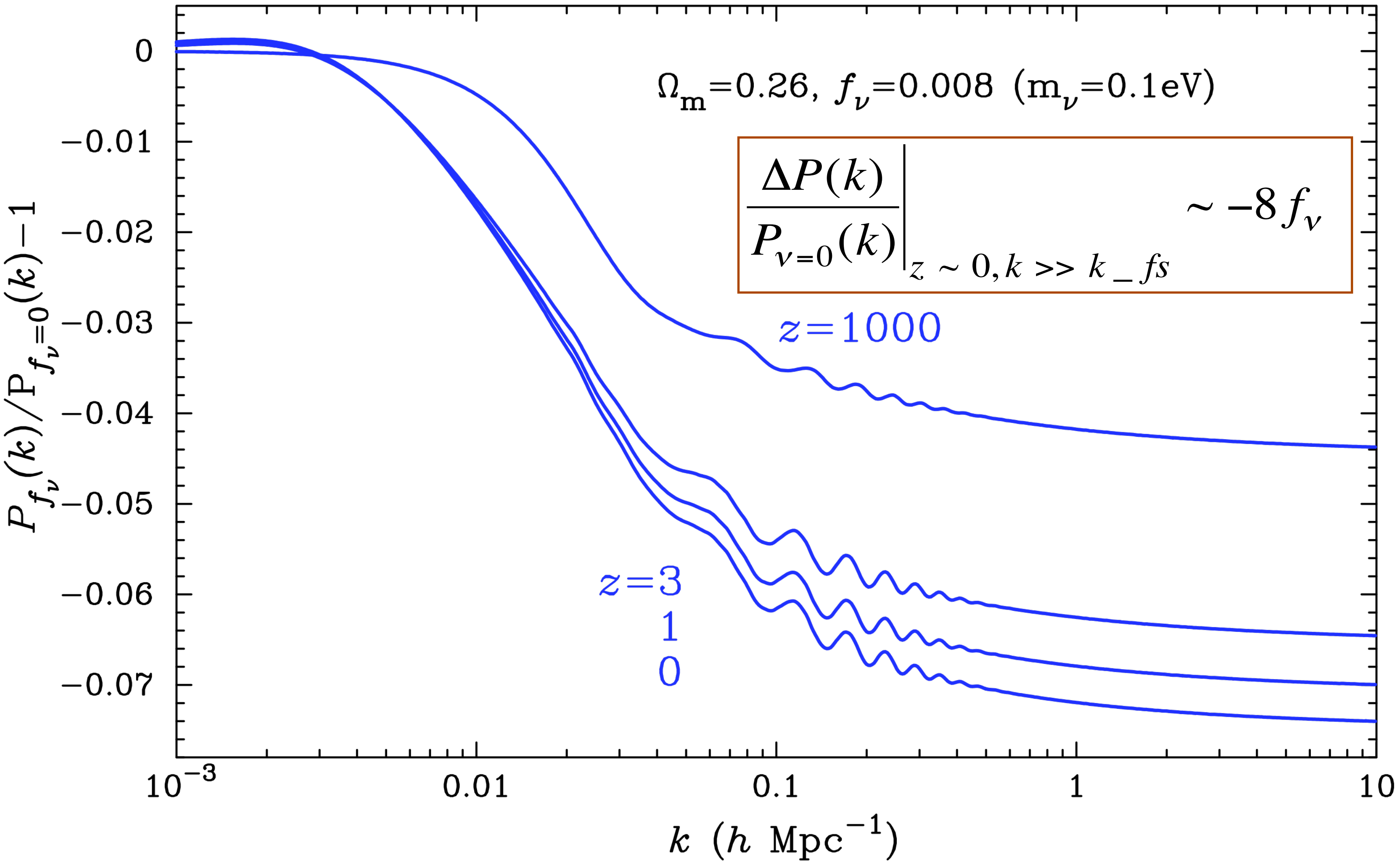
# Suppression of linear P(k) (contd.)

$$k_{\rm fs}(z) \approx 0.35(1+z)^{-1/2}\left(\frac{m_\nu}{1\rm eV}\right)\left(\frac{\Omega_m}{0.26}\right)^{1/2} h{\rm Mpc}^{-1}$$

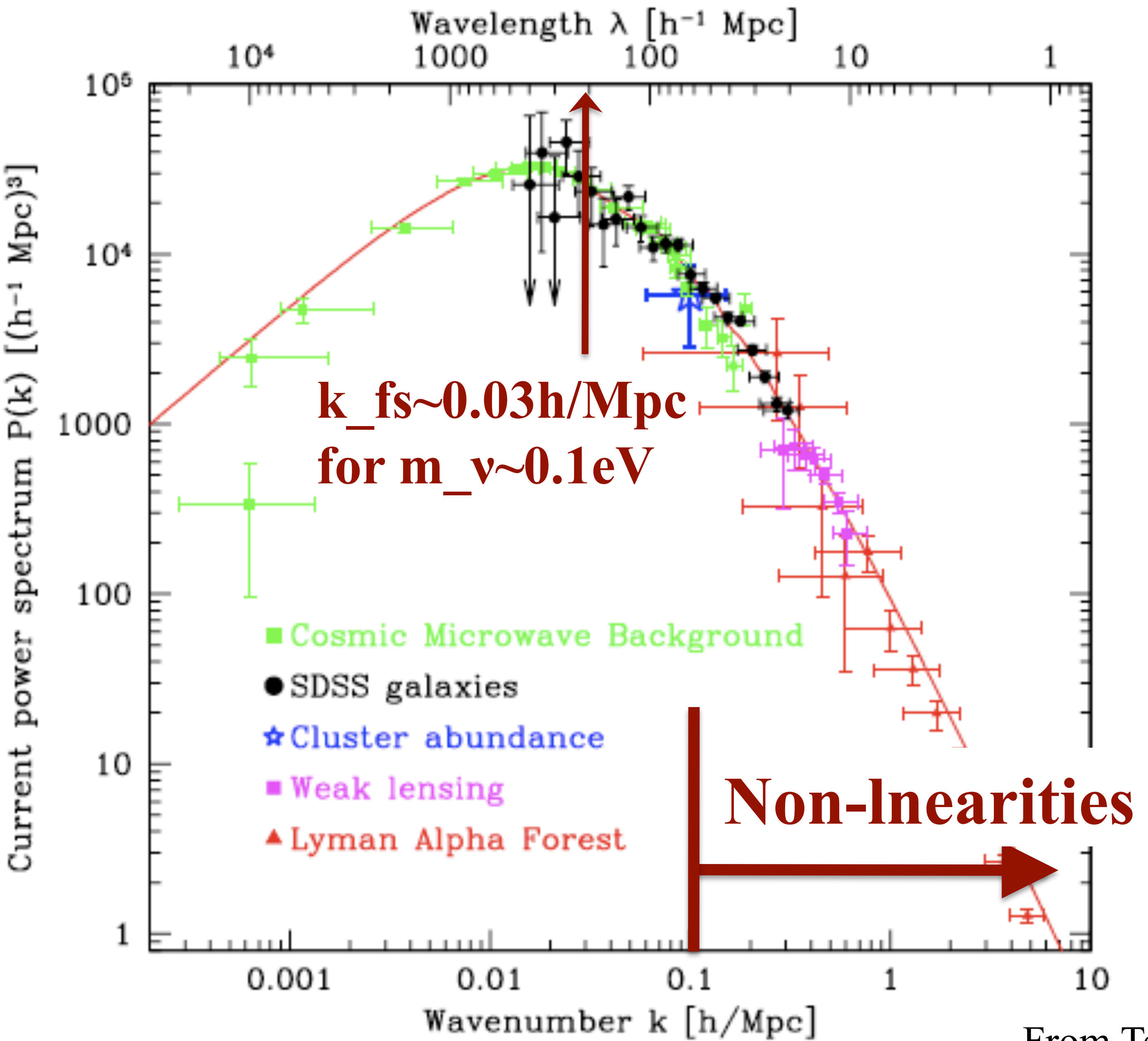


# Suppression of linear P(k) (contd.)

- A more realistic f_nu~0.01 (m_nu~0.1eV): the neutrinos became non-relativistic after z~10^3
- The power spectrum amplitude is suppressed by ~8%



# Probes of P(k)




From Tegmark+04

# Modeling NL P(k) for a MDM model (*Saito*, MT, Taruya PRL 08)

- The first attempt to analytically model P(k) in the weakly NL regime, based on cosmological perturbation theory (PT)
- Have to work with multi-component fluid system
  - NL clustering on small scales is mainly driven by CDM + baryon
  - Neutrinos with light masses remain to stay in the linear regime (can't be much trapped by halos)

$$\delta_{\mathrm{cdm+baryon}} \equiv \delta_{\mathrm{cb}} = \delta_{\mathrm{cb}}^{(1)} + \delta_{\mathrm{cb}}^{(2)} + \delta_{\mathrm{cb}}^{(3)} + \cdots$$ ← Apply PT

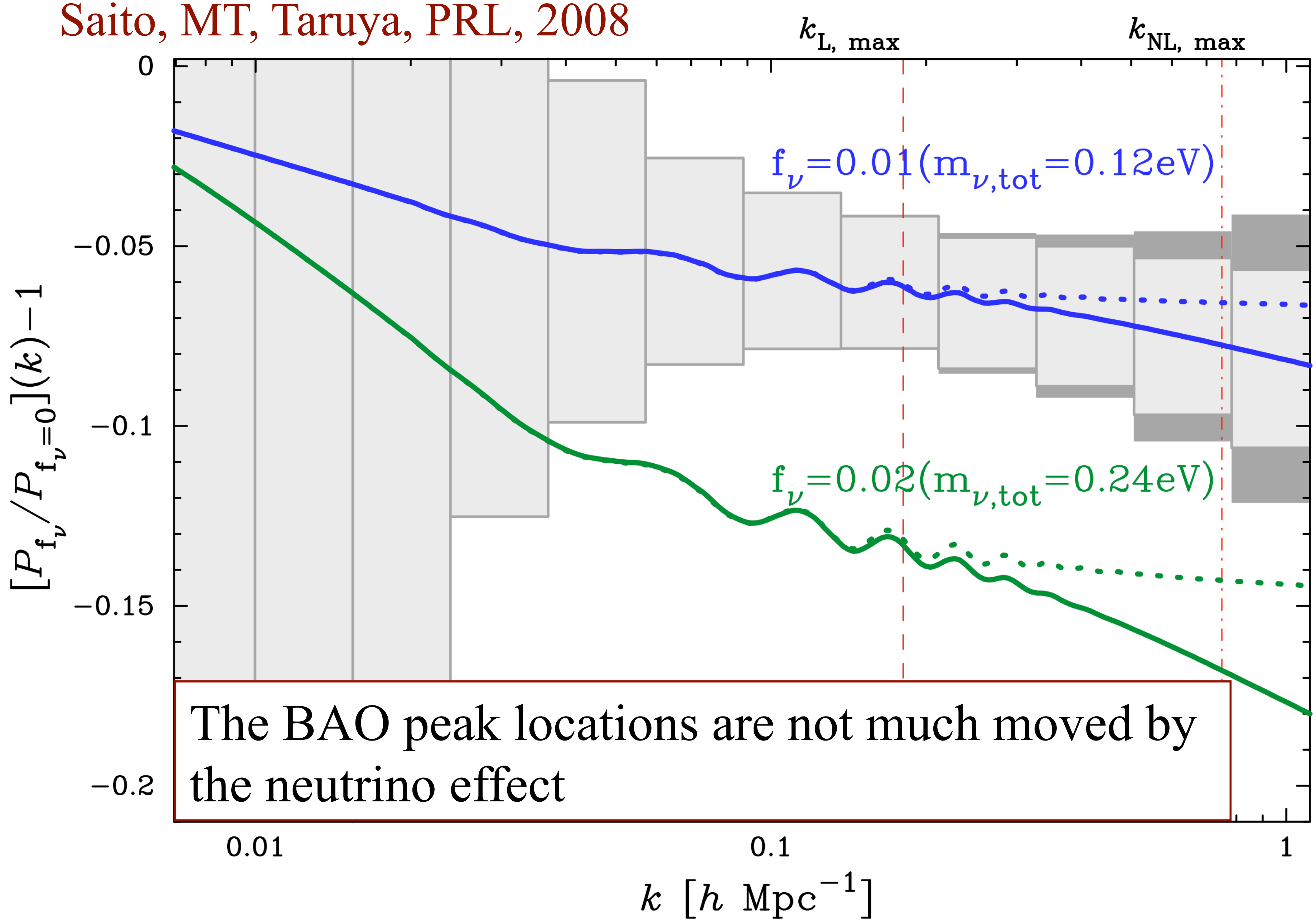
$$\delta_\nu \approx \delta_\nu^{(1)}$$ ← Linear theory (Solve Boltzmann eqns)

- NL total matter P(k) for a MDM model up to the 1-loop correct.

$$\boxed{P_m(k) = \left\langle \left( \frac{\delta\rho_m}{\bar{\rho}_m} \right)^2 \right\rangle = \left\langle \left\{ f_{cb} \left( \delta_{cb}^{(1)} + \delta_{cb}^{(2)} + \delta_{cb}^{(3)} \right) + f_\nu \delta_\nu^{(1)} \right\}^2 \right\rangle}$$

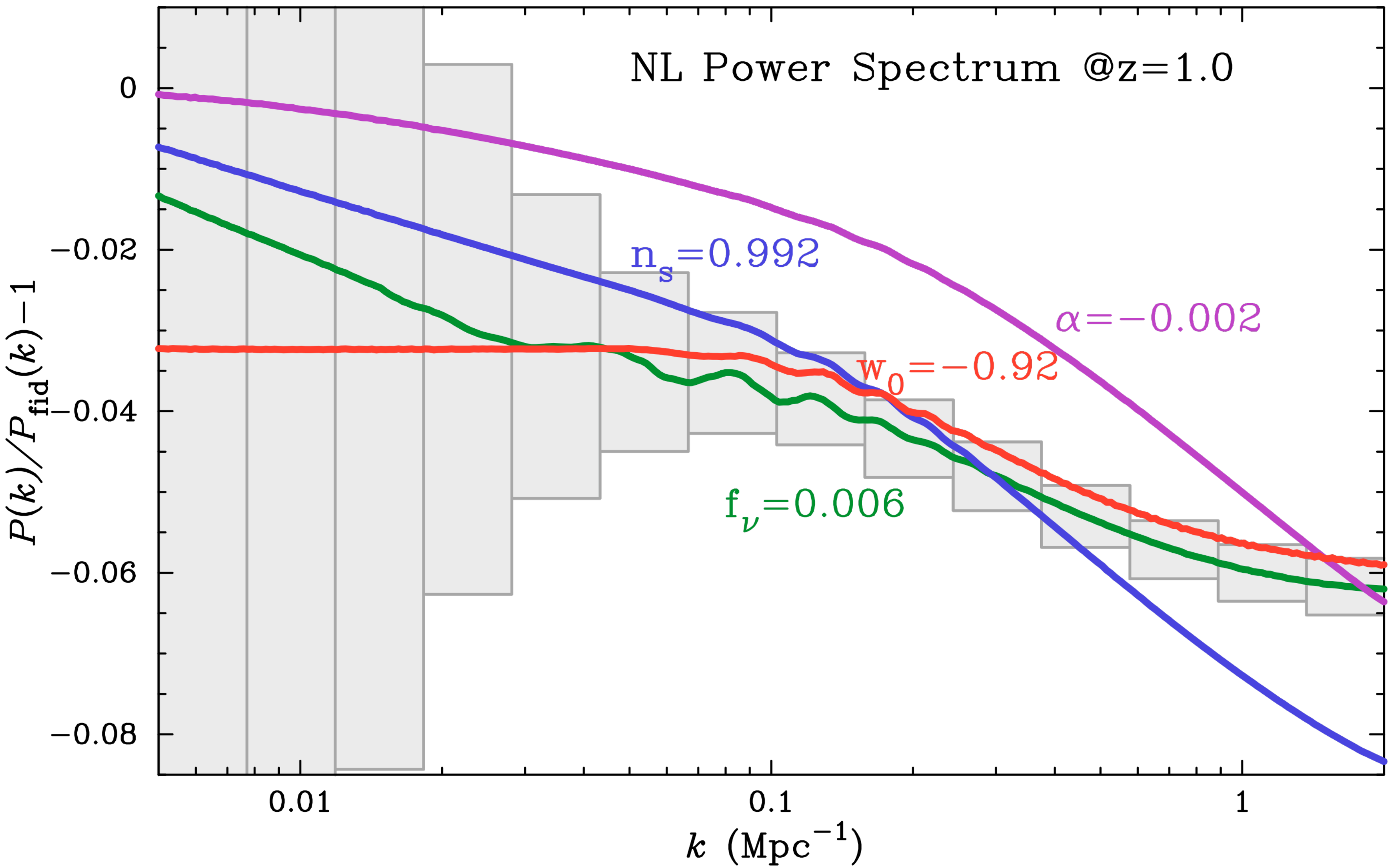
# Effect of m_nu on nonlinear P(k)

Saito, MT, Taruya, PRL, 2008




The BAO peak locations are not much moved by the neutrino effect

# Parameter degeneracy in P(k)

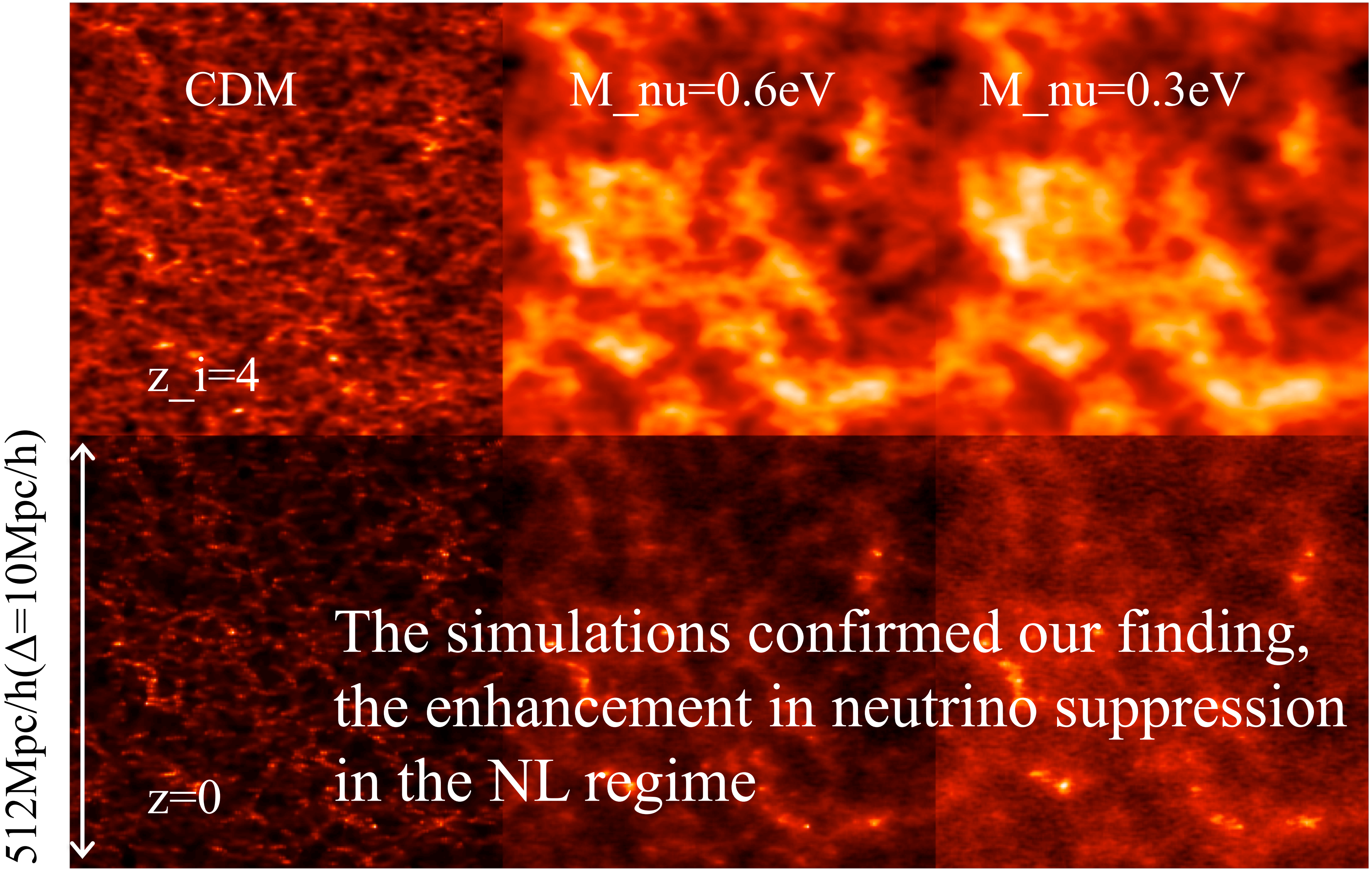



- Different paras affect P(k) in fairly different ways
- Combining galaxy survey with CMB is an efficient way to break degeneracies btw f_nu, n_s and alpha (MT, Komatsu & Futamase 2005)

# A MDM Simulation

(Brandbyge, Hannestad+08)

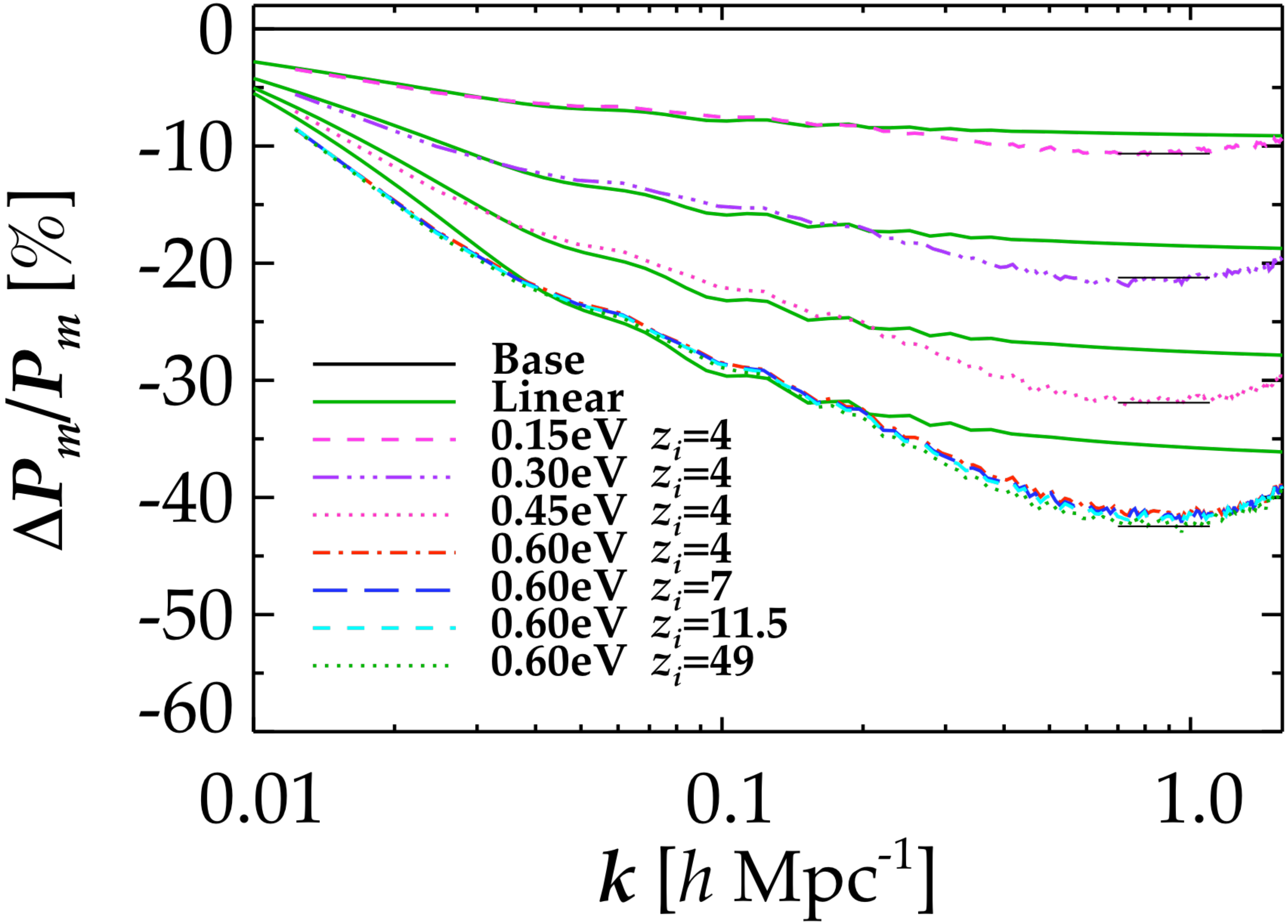
256^3 CDM particles + 512^3 neutrino particles




The simulations confirmed our finding, the enhancement in neutrino suppression in the NL regime

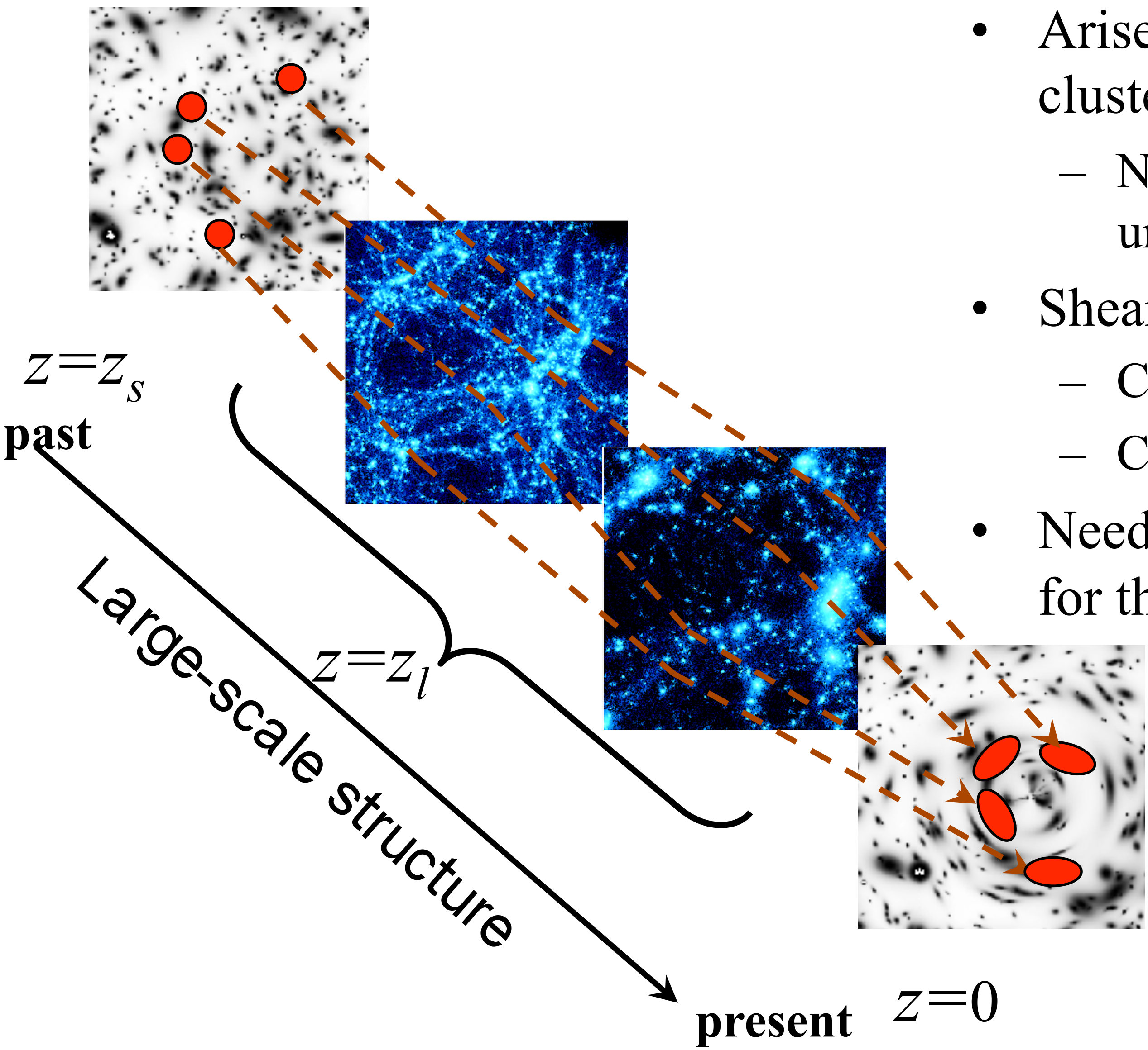
# Hybrid Simulations (contd.):

Brandbyge, Hannestad+08



# Constraining Neutrino Masses with WL

Ichiki, MT, Takahashi soon




- Arises from total matter clustering
  - Not affected by galaxy bias uncertainty
- Shear amplitudes:
  - Cluster scale: γ~O(0.1)
  - Cosmic shear: γ~O(0.01)
- Need numerous (~$10^8$) galaxies for the precise measurements

observables

$$\gamma = \frac{a-b}{a+b}$$

$$\gamma_1 = \gamma \cos 2\varphi$$

$$\gamma_2 = \gamma \sin 2\varphi$$

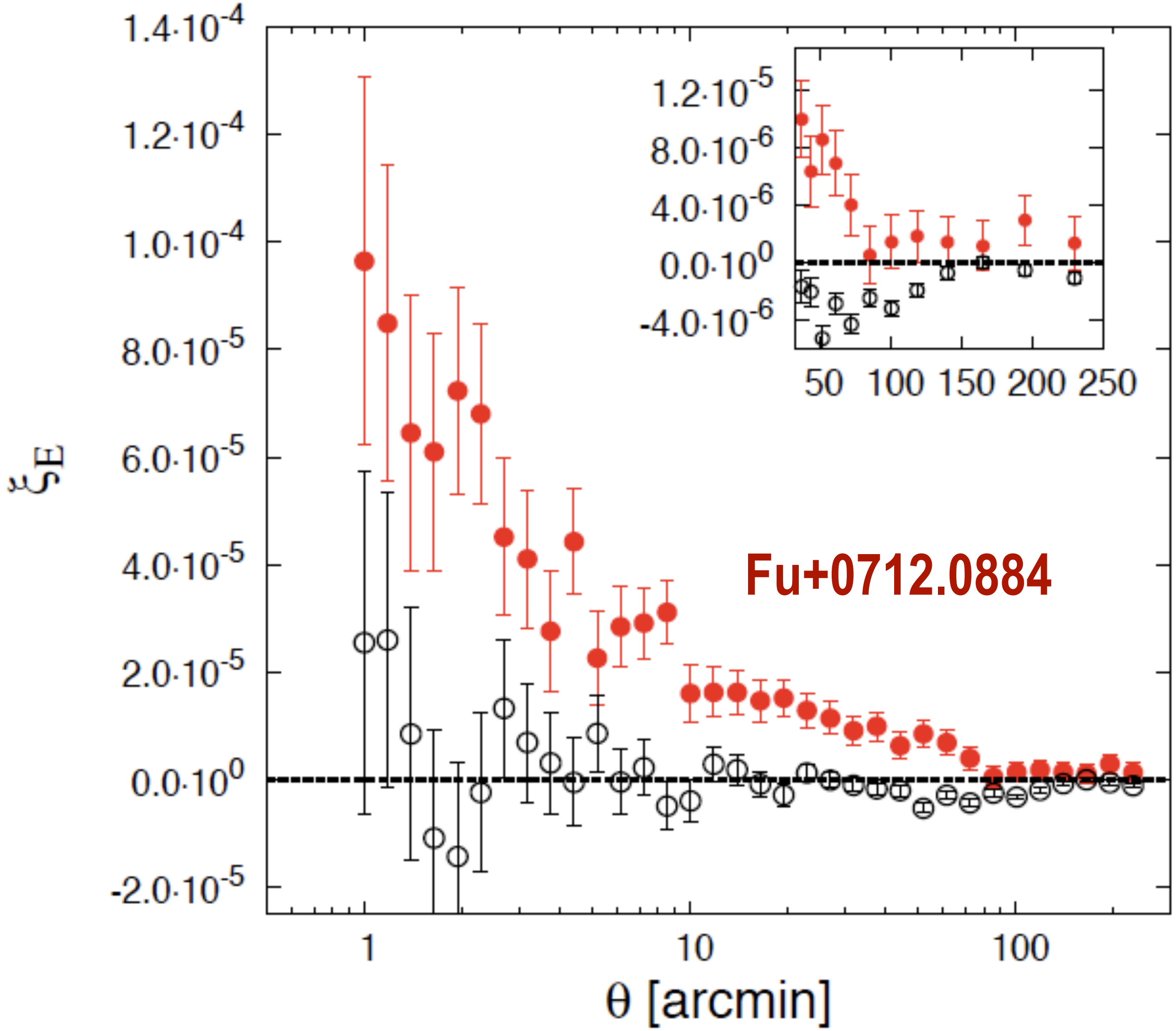
# Cosmic shear sensitivity to cosmology

$$\gamma(\boldsymbol{\theta}) \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d_{LS}(z_L, z_S) d_L(z_L)}{d_S(z_S)} \delta(z_L, \boldsymbol{\theta})$$

for a source galaxy at $z_s$

- Lensing efficiency function: $W_{\mathrm{gl}}$
  - Overall amplitude is proportional to $\Omega_{\mathrm{m}}$, i.e. $\Omega_{\mathrm{de}}$ if combined with CMB or a flat universe is *a prior* assumed
  - Sensitive to Hubble expansion through $d_{\mathrm{A}}$, i.e. DE
  - Depends on source redshift – uncertainty in weak lensing measurements if redshift info is not available
- Mass clustering part: δ
  - Sensitive to primordial power spectrum (amplitude and shape)
  - **Neutrinos suppress the growth of mass clustering**
  - Redshift history of the growth rate is sensitive to DE

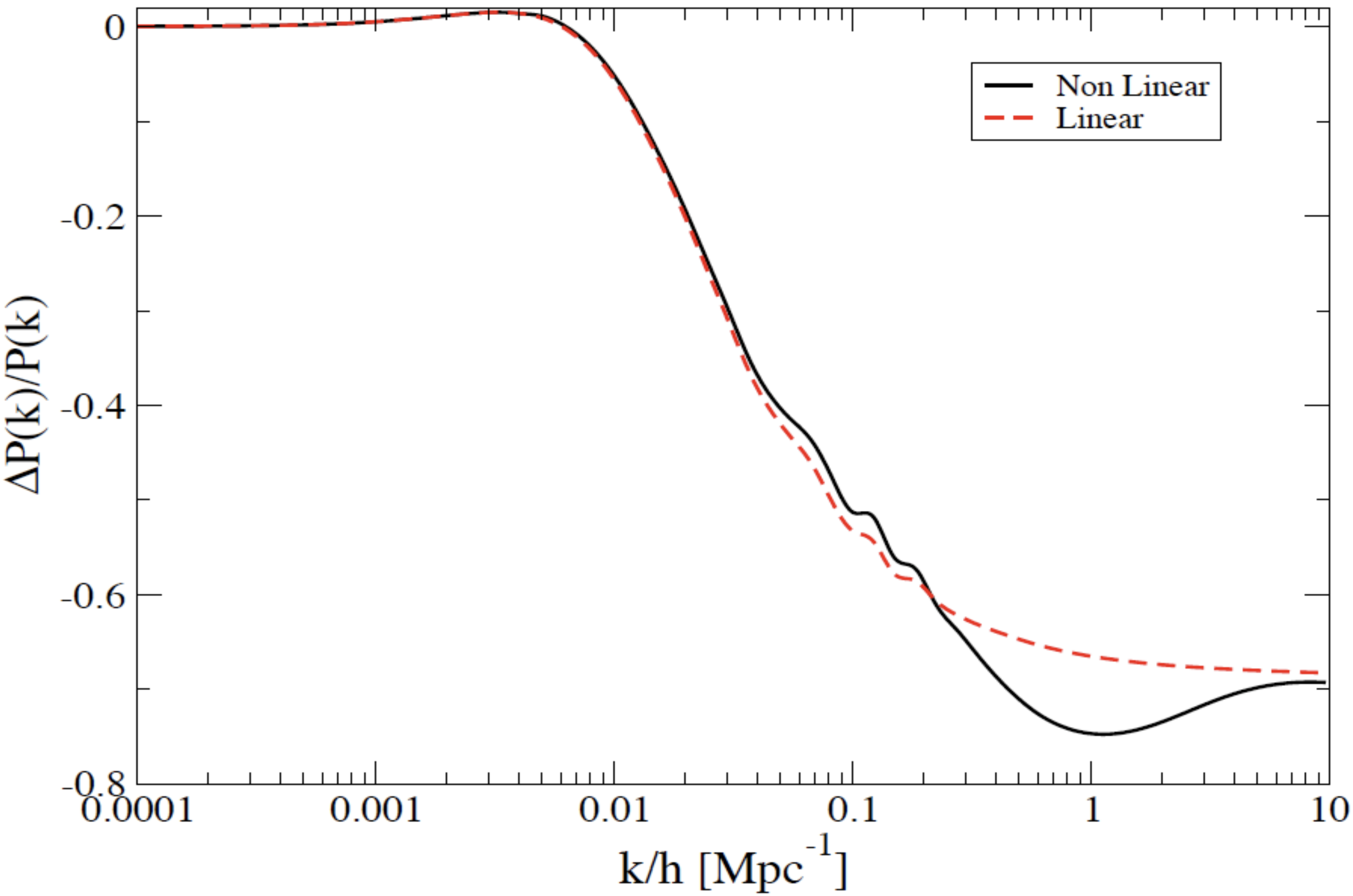
# CFHT WL Survey



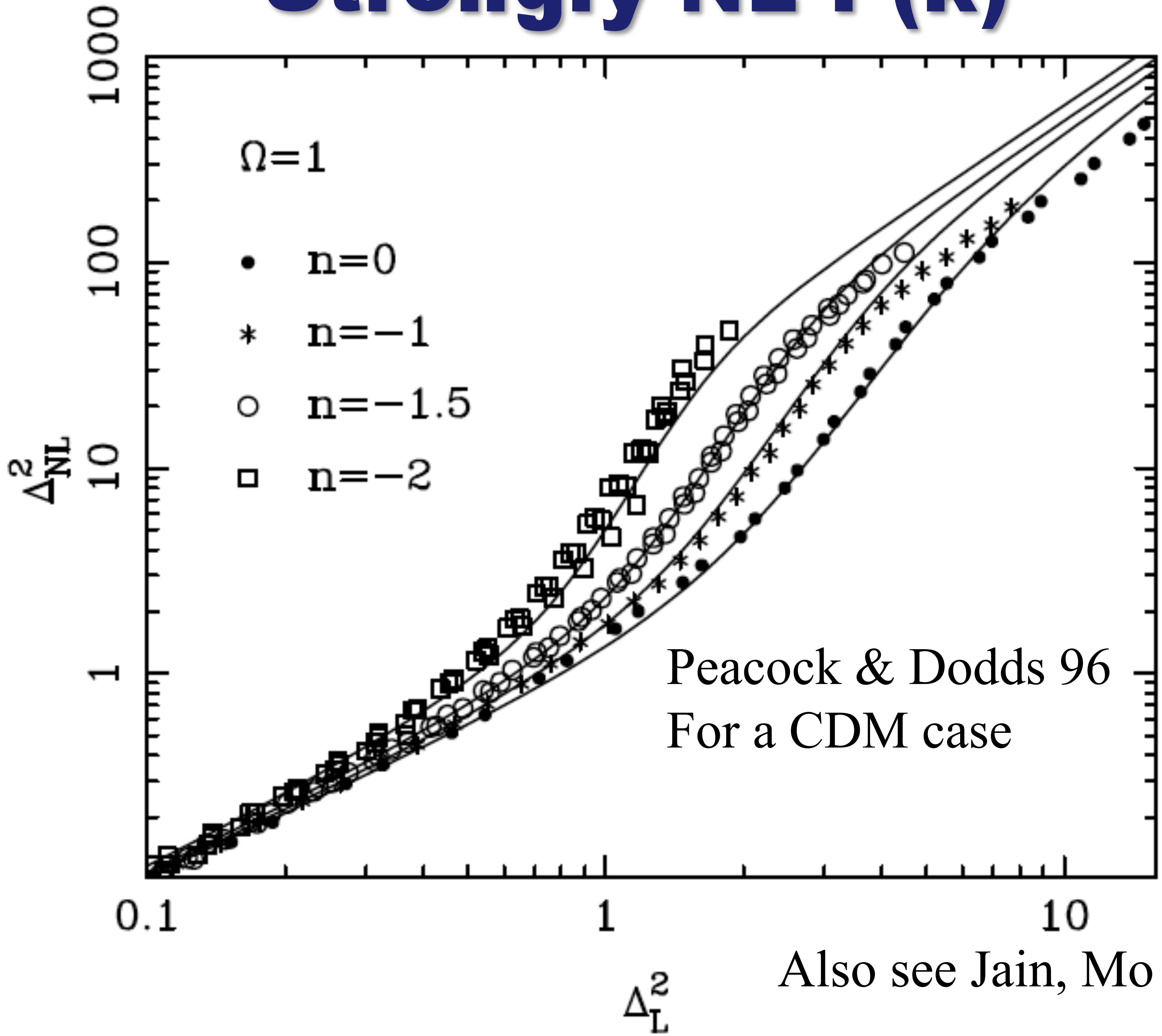

- ~60 sq deg^2 (effectively ~34deg^2)
- *i'*_AB~24.5, <z>~0.9
- n(z) fairly accurately known: calibrate n(z) with the CFHT deep survey and the VVSD
- **~20σ detection,** over a range of few arcminutes to a few degrees

# Neutrino effect on NL P(k)

Ichiki, MT, Takahashi soon



# Strongly NL P(k)

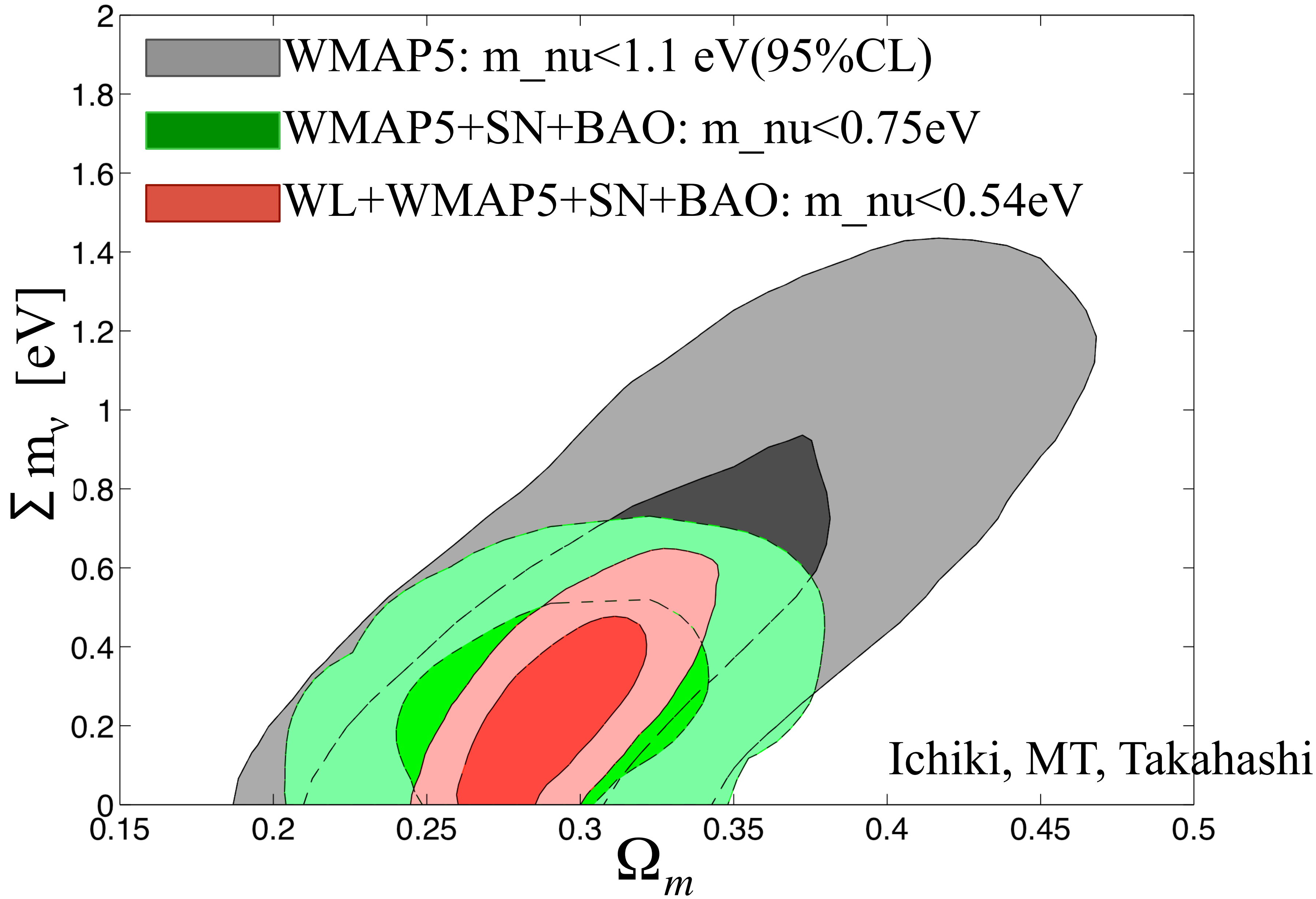


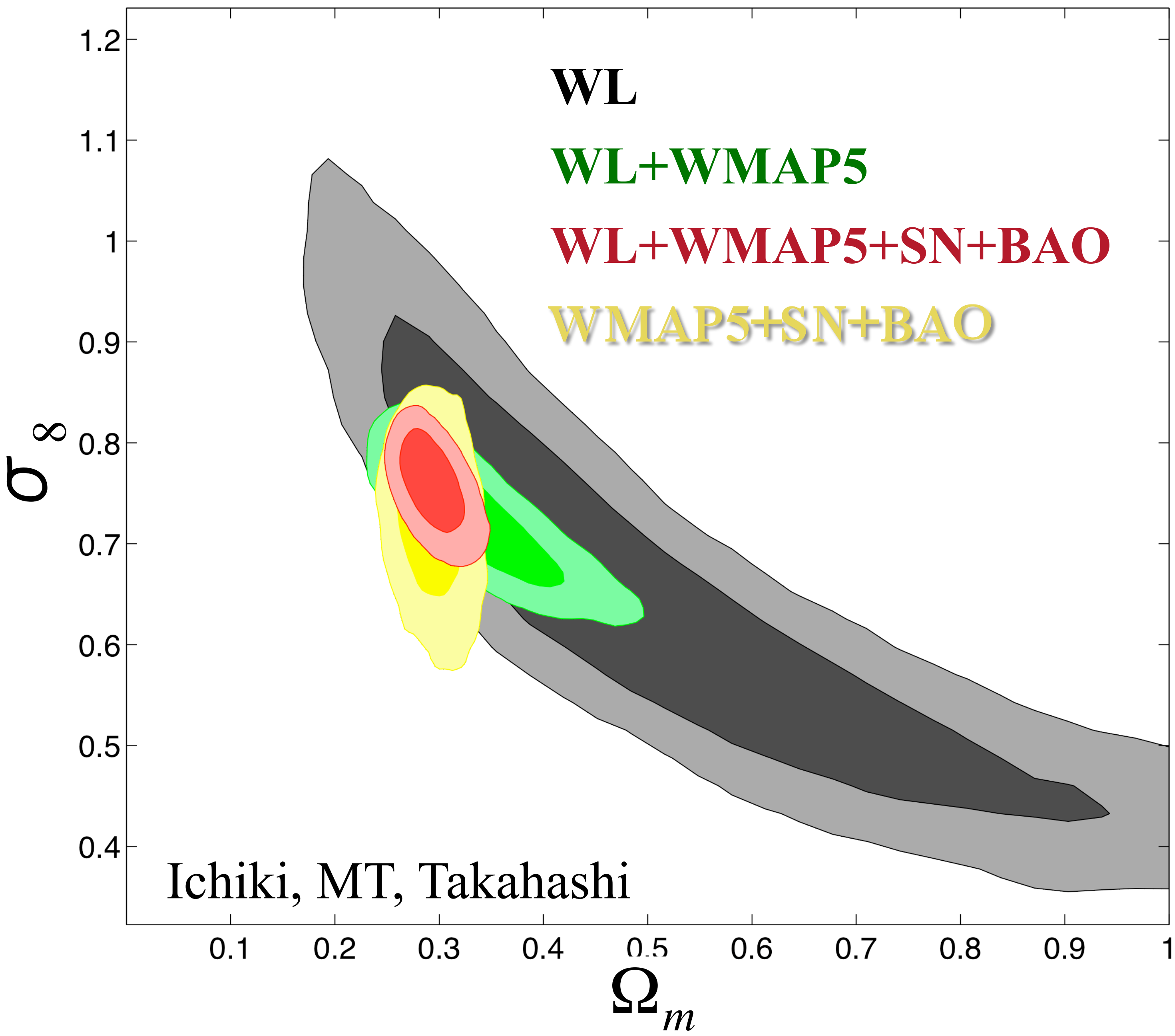

Peacock & Dodds 96
For a CDM case

Also see Jain, Mo & White 95

# WL+WMAP5+BAO+SN

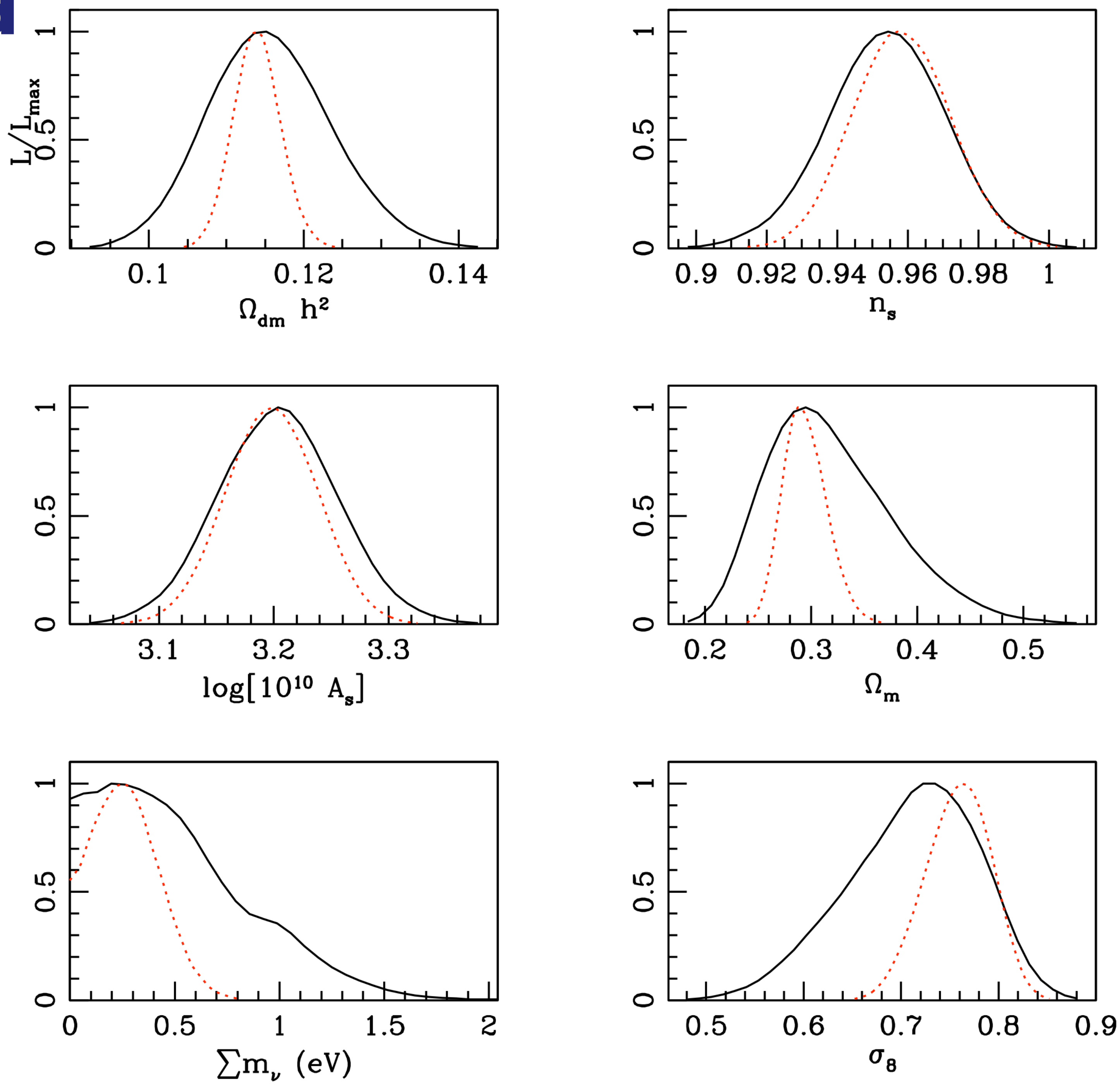
flat LambdaCDM + total neutrino mass






**Combining different probes can improve para constraints**

# 1D likelihood




**WMAP5**

**WMAP5+WL +BAO+SN**

# Summary

- The finite-mass neutrinos cause characteristic suppression in the growth of total matter clustering
- Combining CMB with probes of large-scale structures can be a powerful way of measuring the neutrino effect
- We developed the PT model to describe the nonlinear P(k) in the weakly nonlinear regime
- We compared the model prediction with the latest WL data, CFHT data, to constrain neutrino masses
  - **M_nu=0.54 eV(95%CL) for WL+WMAP5+SN+BAO**
  - **M_nu=1.1eV for WMAP5**