Neutrino Mass and Cosmology

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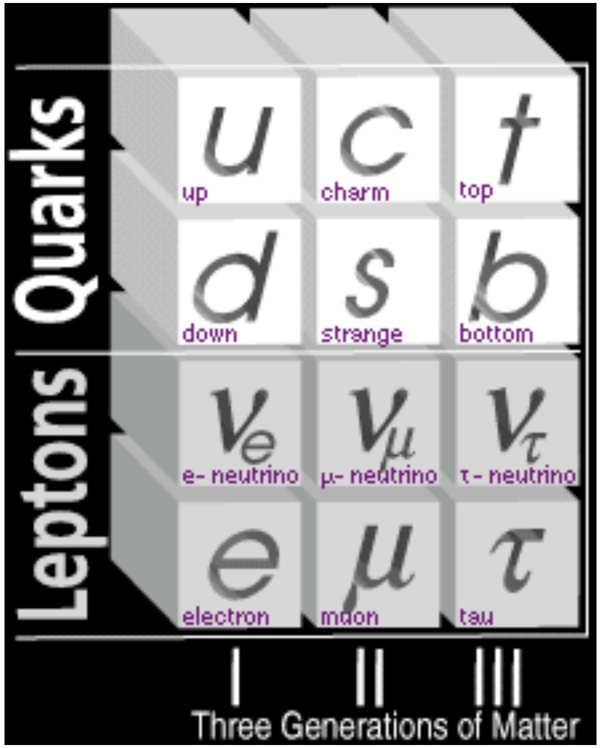
Neutrinos

- 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



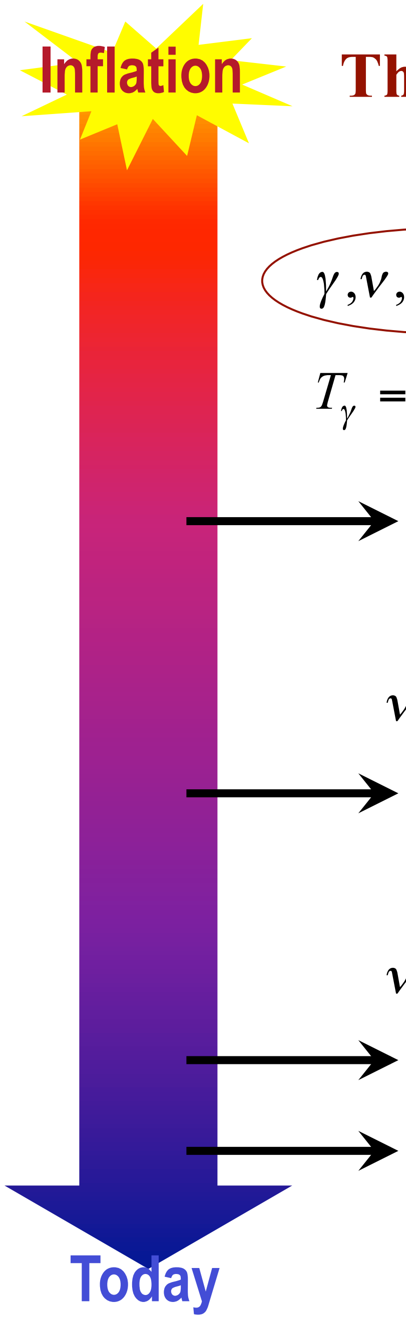
The Nobel Prize of Physics, 2002

Prof. Koshiba

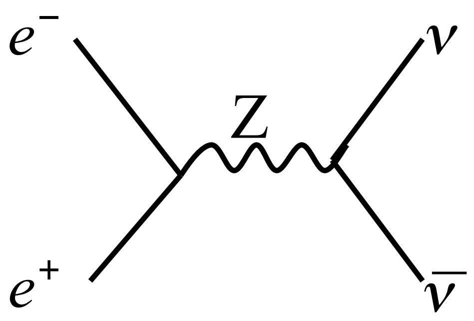
Prof. Davis

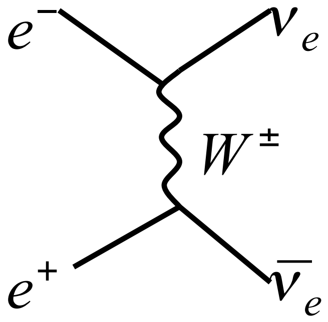
No doubt neutrinos are very interesting particles to explore!

Cosmic Thermal History



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





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

$T_\gamma = T_e = T_\nu$

T~ a few MeV: neutrinos decouple

Neutrinos didn't annihilate to photons

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

T~0.5MeV: electrons and positrons annihilate

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

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

T~1eV: matter-radiation equality

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

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

n_ν,0~100 cm^-3

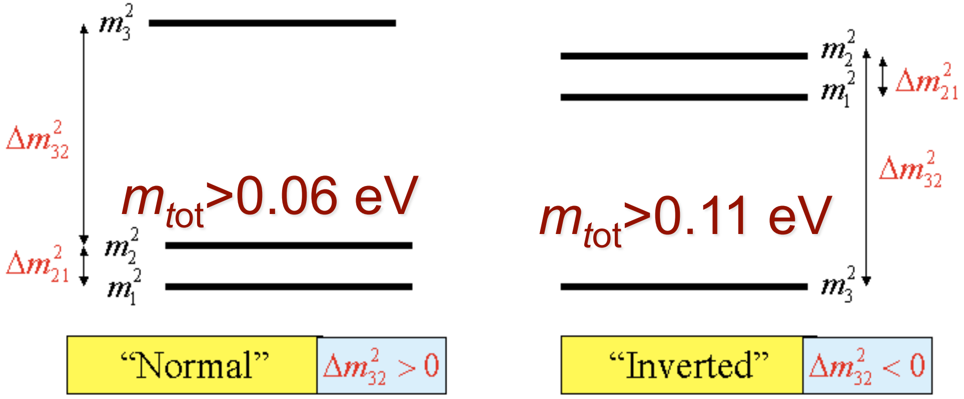
Neutrinos mass!

- 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

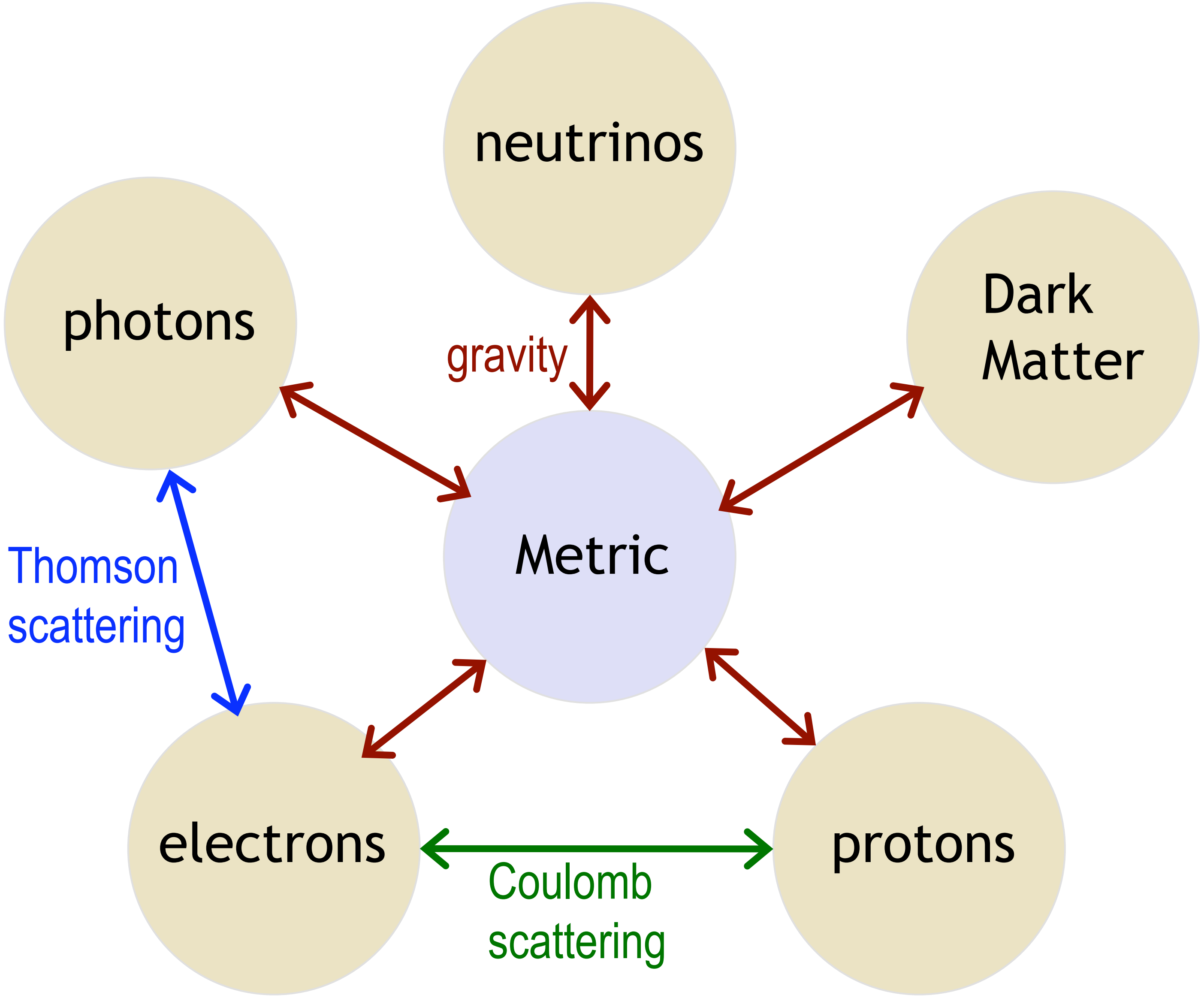
$$\boxed{\begin{aligned} &\Omega_{\mathrm{m0}} = \Omega_{\mathrm{cdm0}} + \Omega_{\mathrm{baryon0}} + \Omega_{\nu 0} \\ &f_\nu \equiv \frac{\Omega_{\nu 0}}{\Omega_{\mathrm{m0}}} = \frac{m_{\nu,\mathrm{tot}}}{94.1\mathrm{eV}\Omega_m h^2} > 0.005 \end{aligned}}$$



m_{tot}>0.06 eV

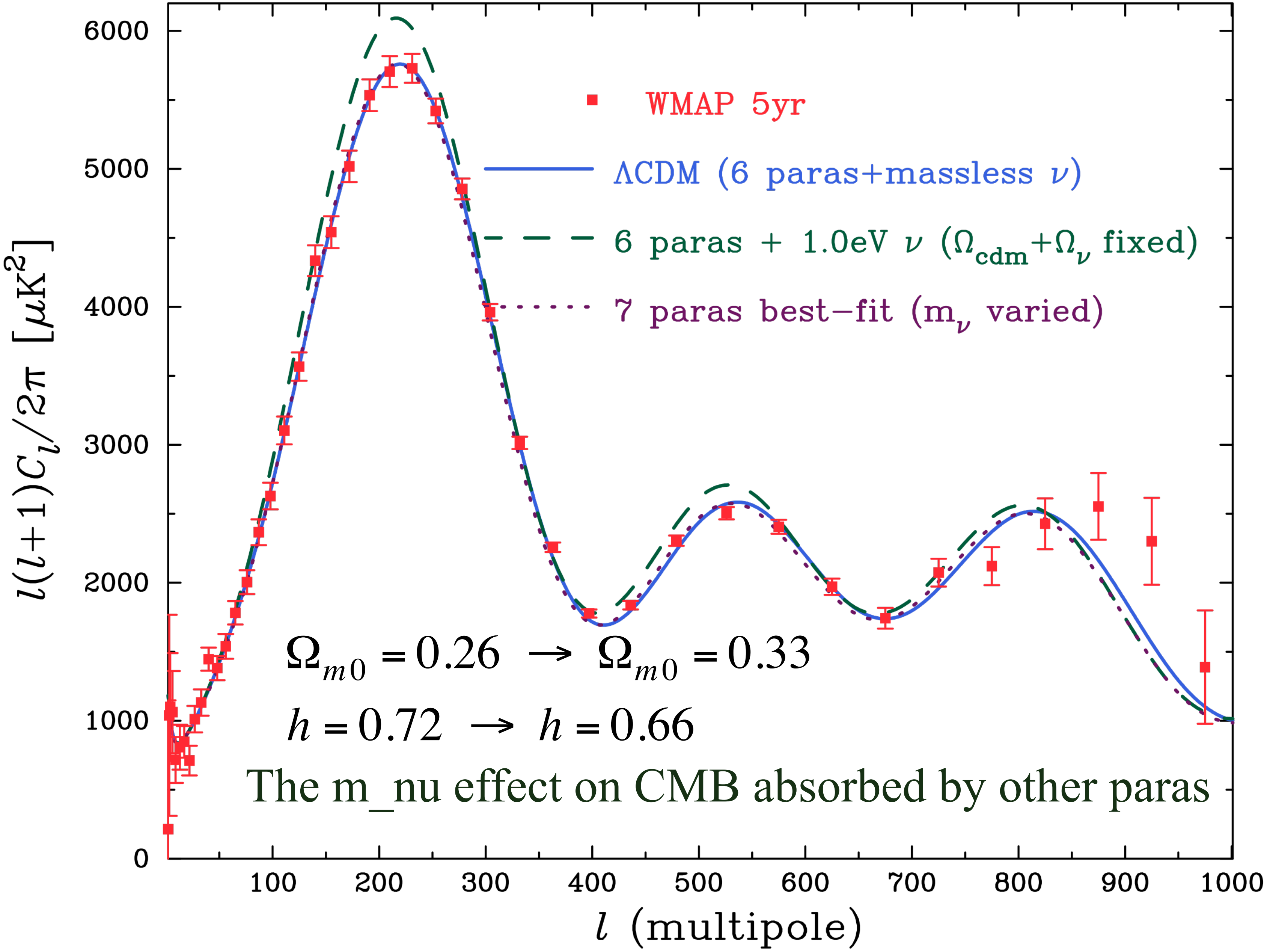
m_{tot}>0.11 eV

Coupled Einstein-Boltzmann Equations



In particular the cosmological linearized perturbation theory is remarkably successful: gives very robust, secure model predictions in structure formation

Effect of finite-mass neutrinos on CMB

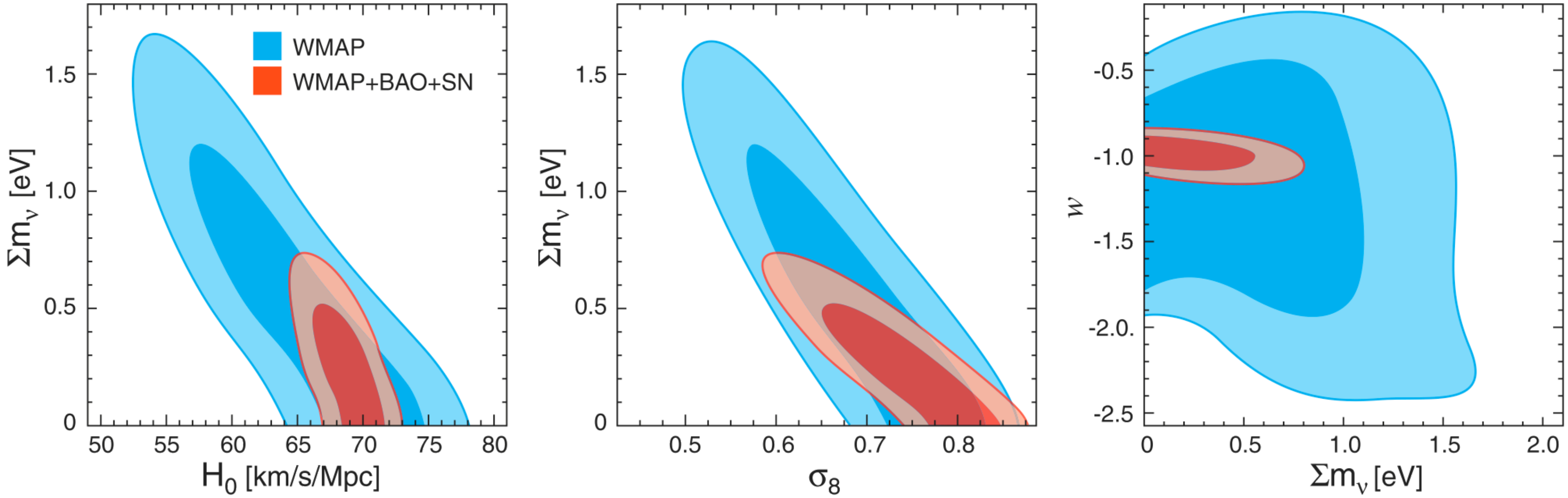


$$\Omega_{m0} = 0.26 \rightarrow \Omega_{m0} = 0.33$$

$$h = 0.72 \rightarrow h = 0.66$$

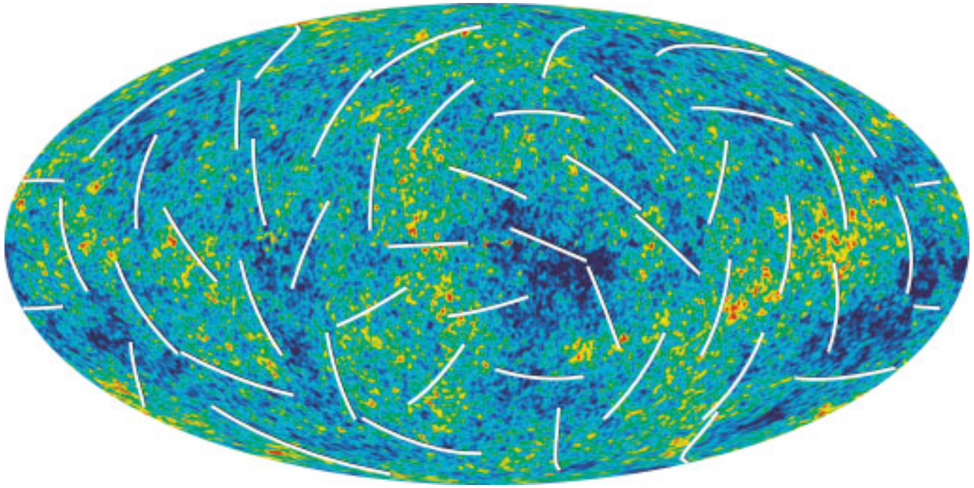
The m_nu effect on CMB absorbed by other paras

WMAP5yr (Komatsu+08)



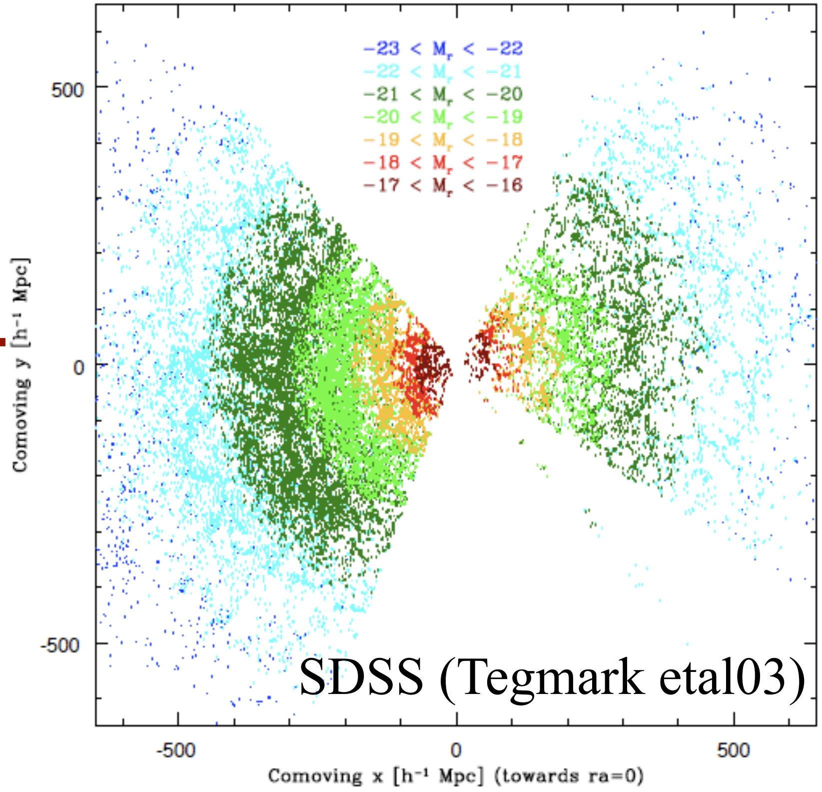
- The m_nu effect on CMB degenerate with *h* and Ω_m that are sensitive to the distance (Ichikawa+ 05)
- WMAP5: CMB alone m_nu,tot<1.3eV; **WMAP5 + SN + BAO (*no galaxy P(k)*) m_nu,tot<0.6eV (CMB + geometrical probes)**
- Seems best-available constraint from this method; if m_nu<0.6eV, as neutrinos become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

CMB + Large-Scale Structure (LSS)



WMAP (z~10^3)

+



SDSS (Tegmark etal03)

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)

ΛCDM: SF scenario

- The density fluctuation field of total matter (mainly CDM) in the linear regime

$$\boxed{\delta_m(\boldsymbol{x},z) \equiv \frac{\rho_m(\boldsymbol{x},z) - \bar{\rho}_m(z)}{\bar{\rho}_m(z)} = D(z)\delta_m(\boldsymbol{x},z \approx 1000)}$$

- The 2nd-order diff. eqn. to govern the redshift evolution of density pert.: (FRW eqns + linearized Einstein eqns.) $\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$

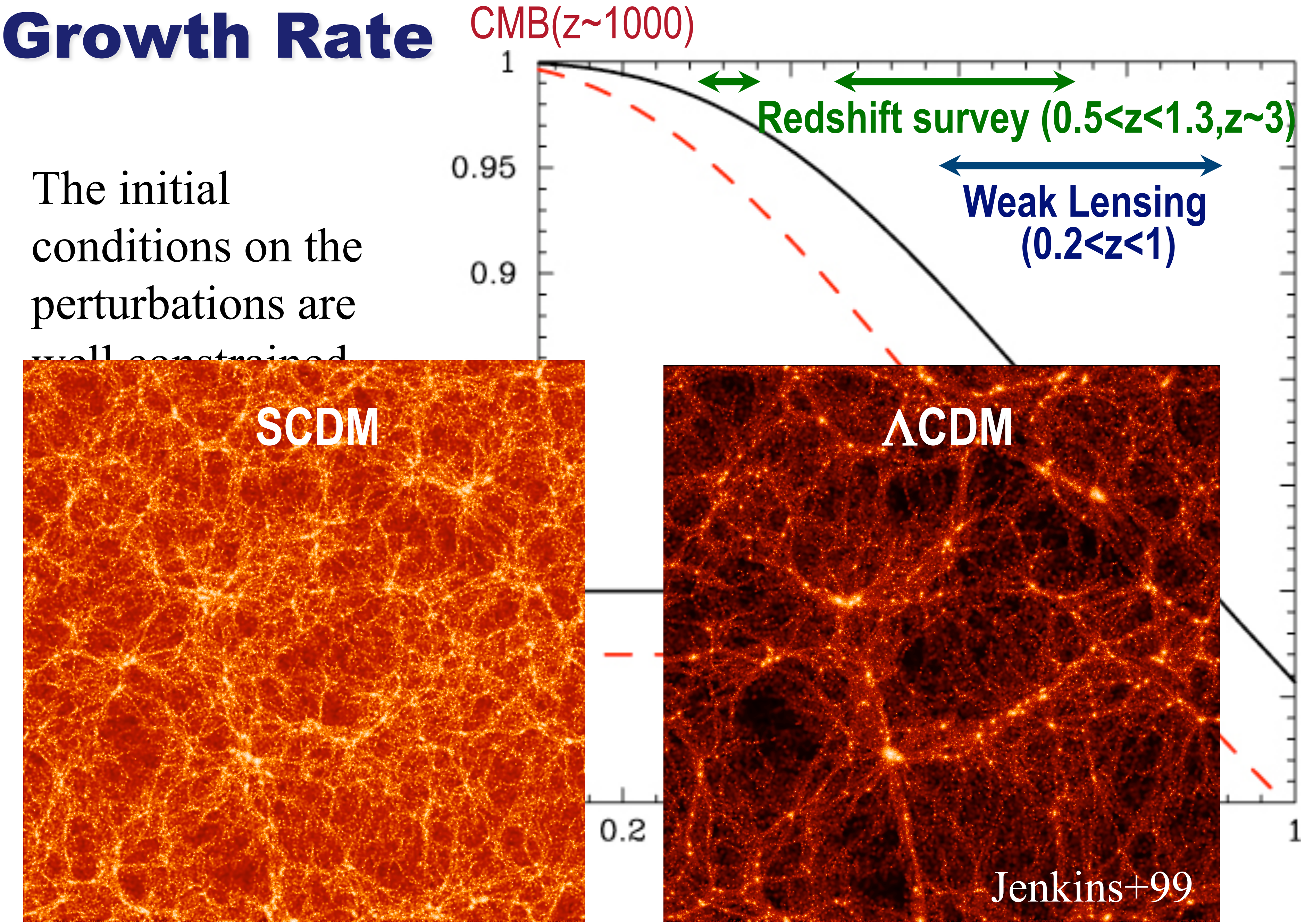
$$\boxed{\ddot{D} + \underbrace{2H\dot{D}}_{\textbf{Friction due to cosmic exp.}} - \underbrace{4\pi G\bar{\rho}_m D}_{\textbf{Gravitational instability}} = 0}$$

where $H^2(z) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\underbrace{\Omega_{\mathrm{m0}}(1+z)^3}_{\textbf{Matter}} + \underbrace{\Omega_{\mathrm{de0}}(1+z)^{3(1+w)}}_{\textbf{Dark energy}}\right]$ $(\Omega_{\mathrm{m0}} + \Omega_{\mathrm{de0}} = 1)$

- *Cosmic acceleration ➔ the density growth is suppressed*

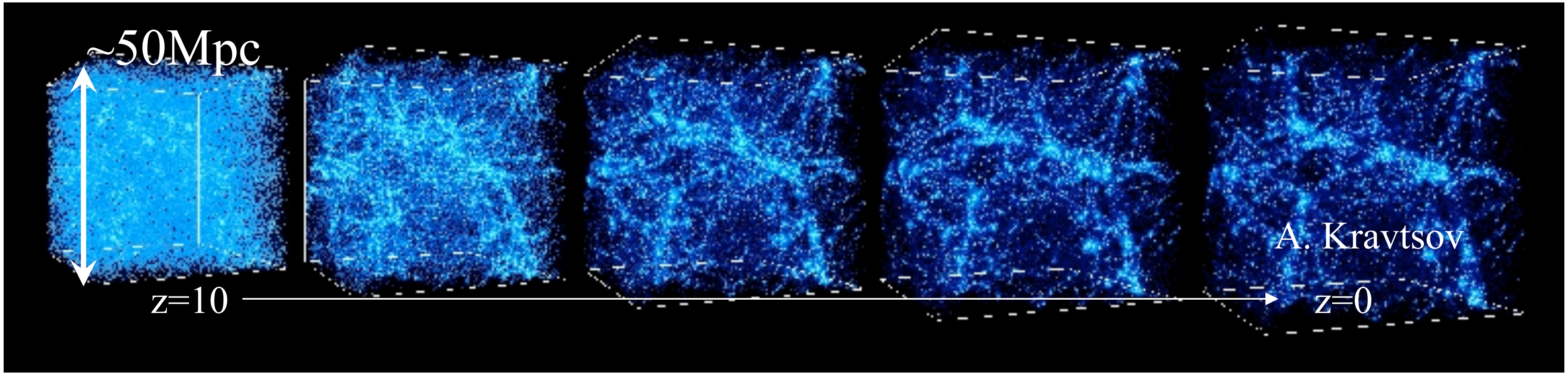
Growth Rate

- The initial conditions on the perturbations are well constrained



Modeling nonlinear LSS formation - N-body simulations -

- The initial conditions of SF is now well constrained by CMB
- In a CDM model, gravity due to dark matter distribution plays a major role
- N-body simulation is the most powerful tool to study nonlinear clustering processes in structure formation
  - N-body particle = DM super particle; e.g. each N-body particle = 10^11 M_sun = 10^50 DM particles
  - Cold particle = no thermal velocity
- Simulations have been used in various cosmological studies
- A model with CDM plus neutrinos is still computationally challenging



ν+ΛCDM model

- 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

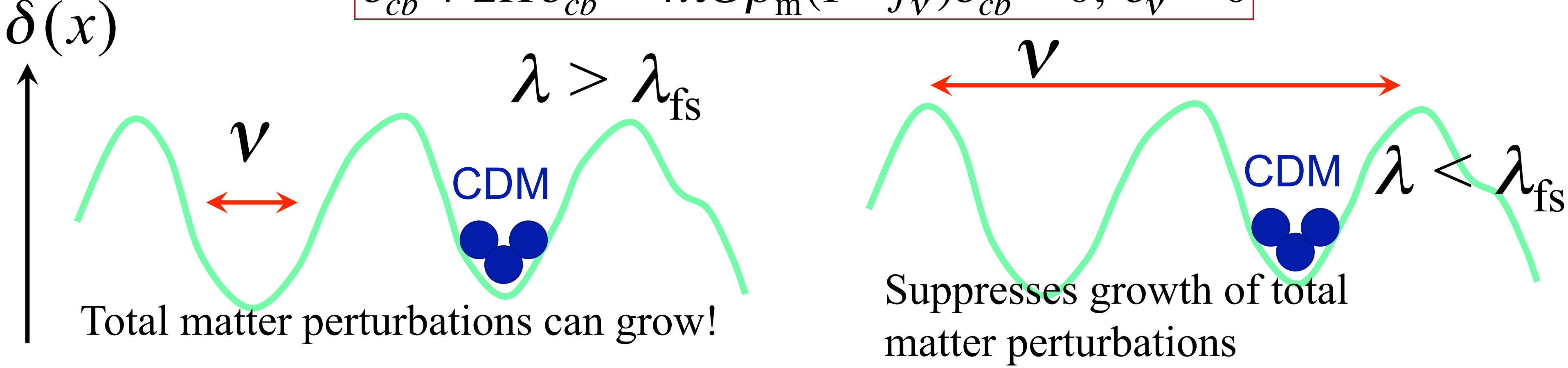
$$\boxed{\delta_m = \frac{\bar{\rho}_c\delta_c + \bar{\rho}_b\delta_b + \bar{\rho}_\nu\delta_\nu}{\bar{\rho}_c + \bar{\rho}_b + \bar{\rho}_\nu} \equiv f_c\delta_c + f_b\delta_b + f_\nu\delta_\nu}$$

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

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

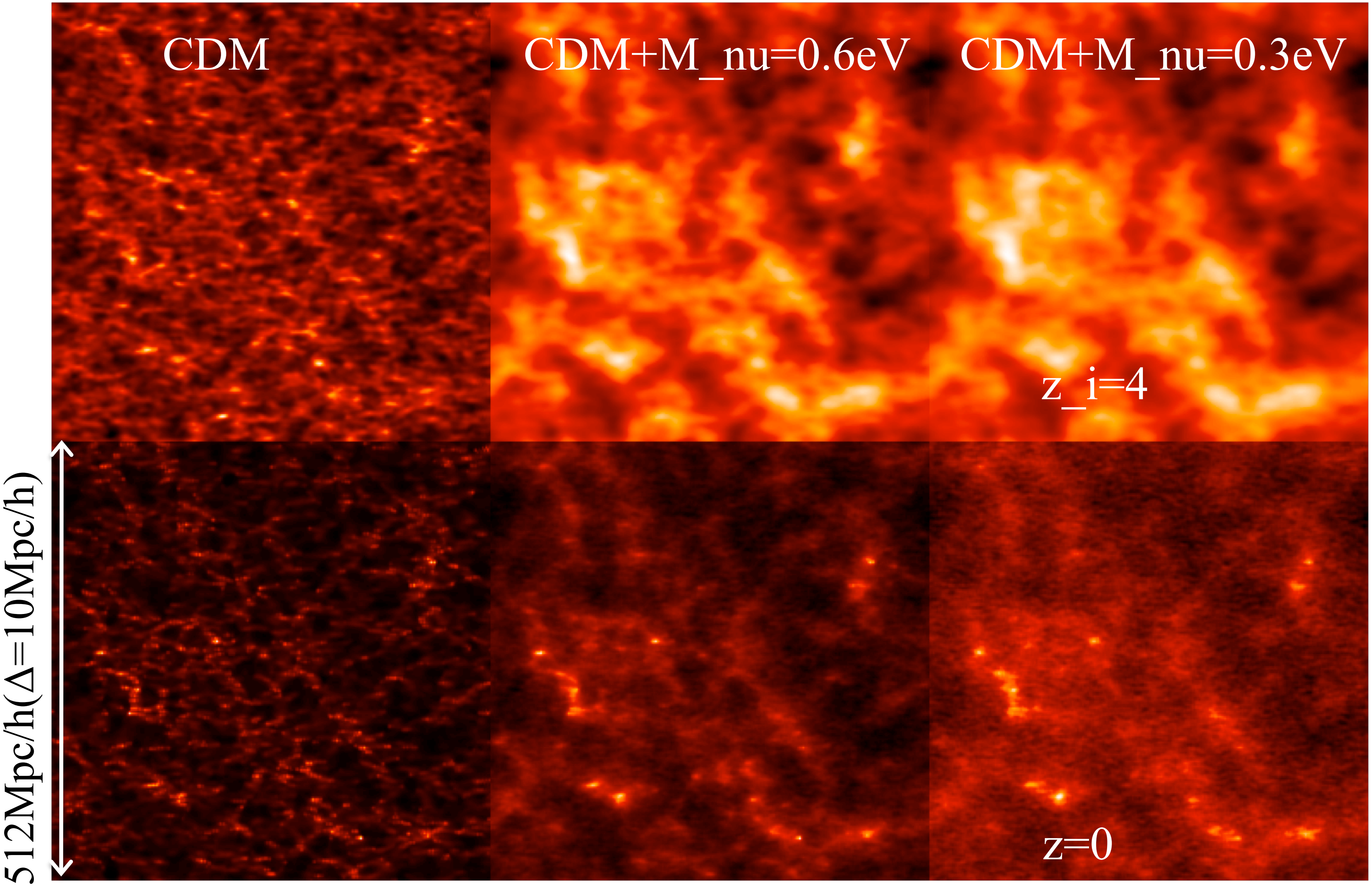
  - On small scales $\lambda<\lambda_{fs}$, the neutrinos are smooth, $\delta_\nu=0$, therefore weaker gravitational force compared to a pure CDM case

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



Total matter perturbations can grow!

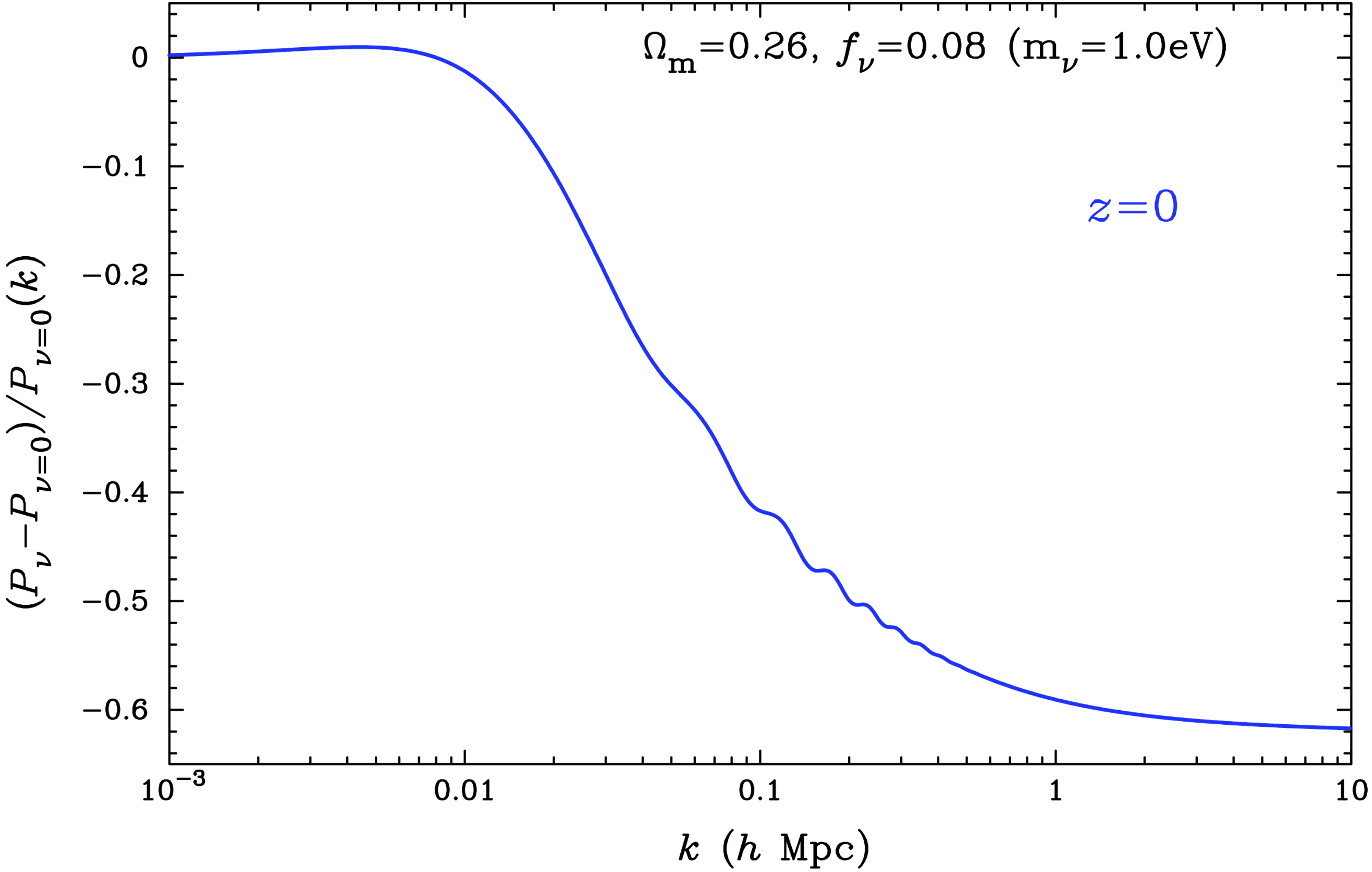
Suppresses growth of total matter perturbations



Brandbyge, Hannestad, Haugbolle, Thomsen 08

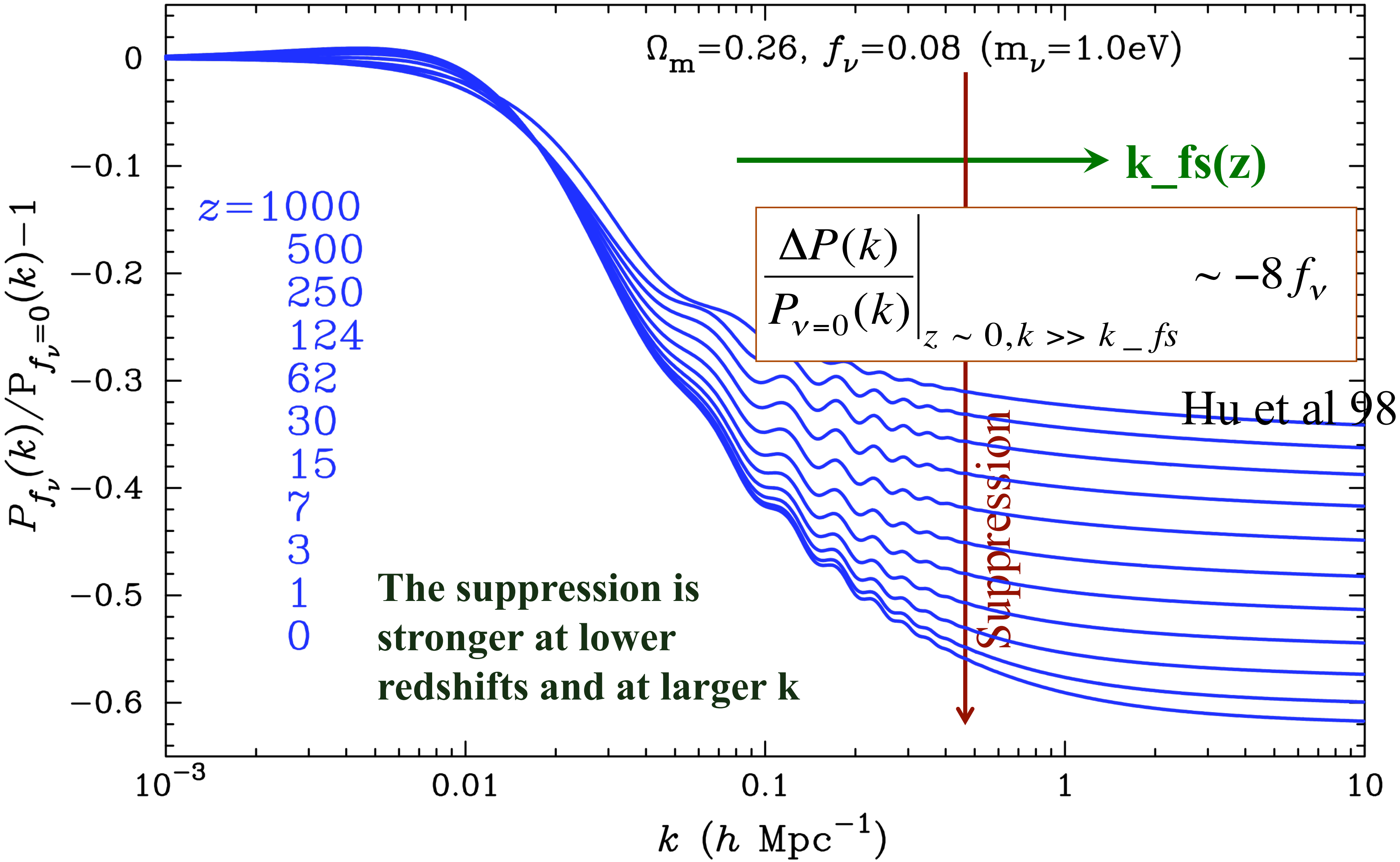
Suppression of linear P(k)

Note: linear theory



Suppression of linear P(k) (contd.)

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

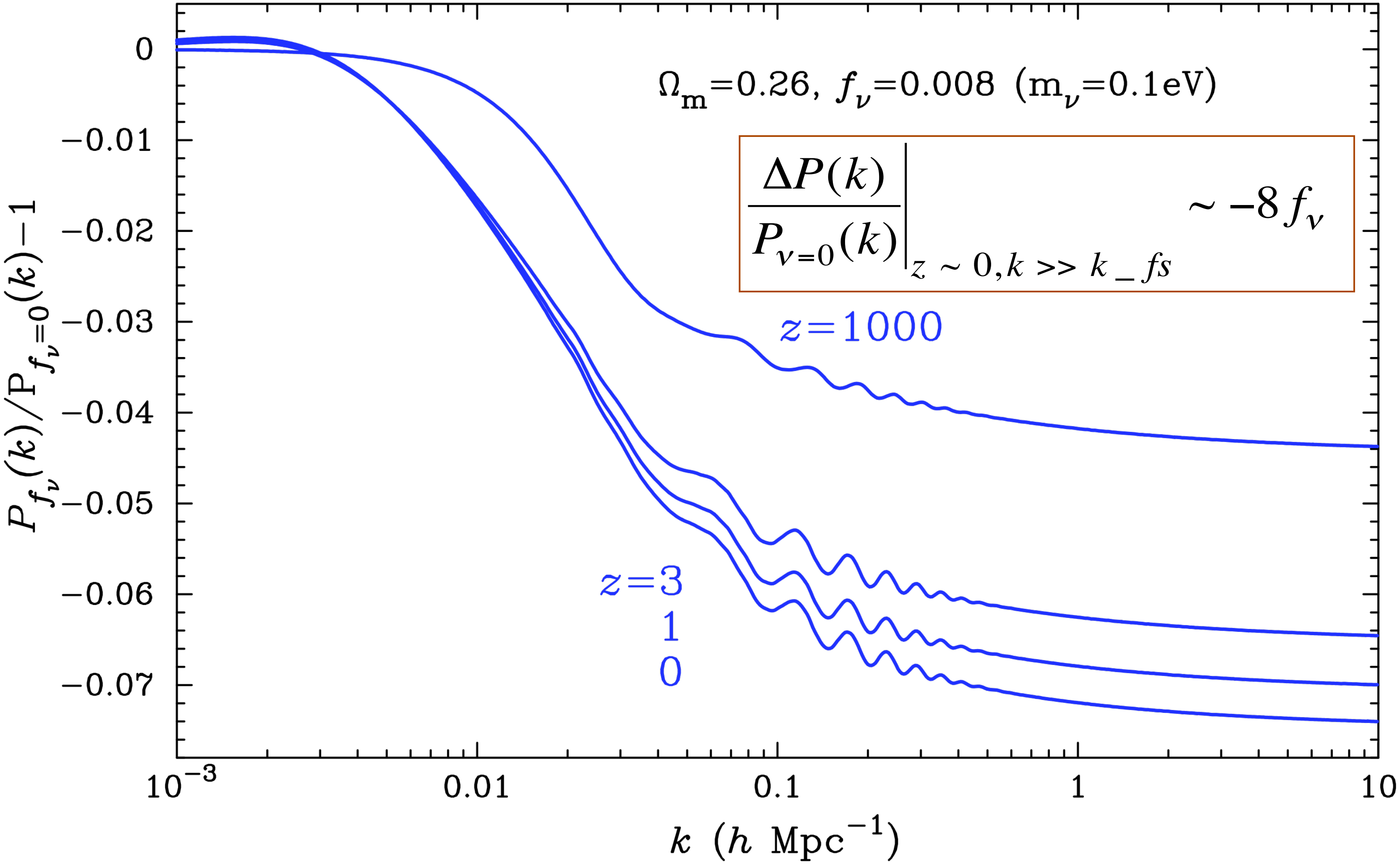


$$\left.\frac{\Delta P(k)}{P_{\nu=0}(k)}\right|_{z\,\sim\,0,k\,>>\,k\_fs} \sim -8f_\nu$$

The suppression is stronger at lower redshifts and at larger k

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%



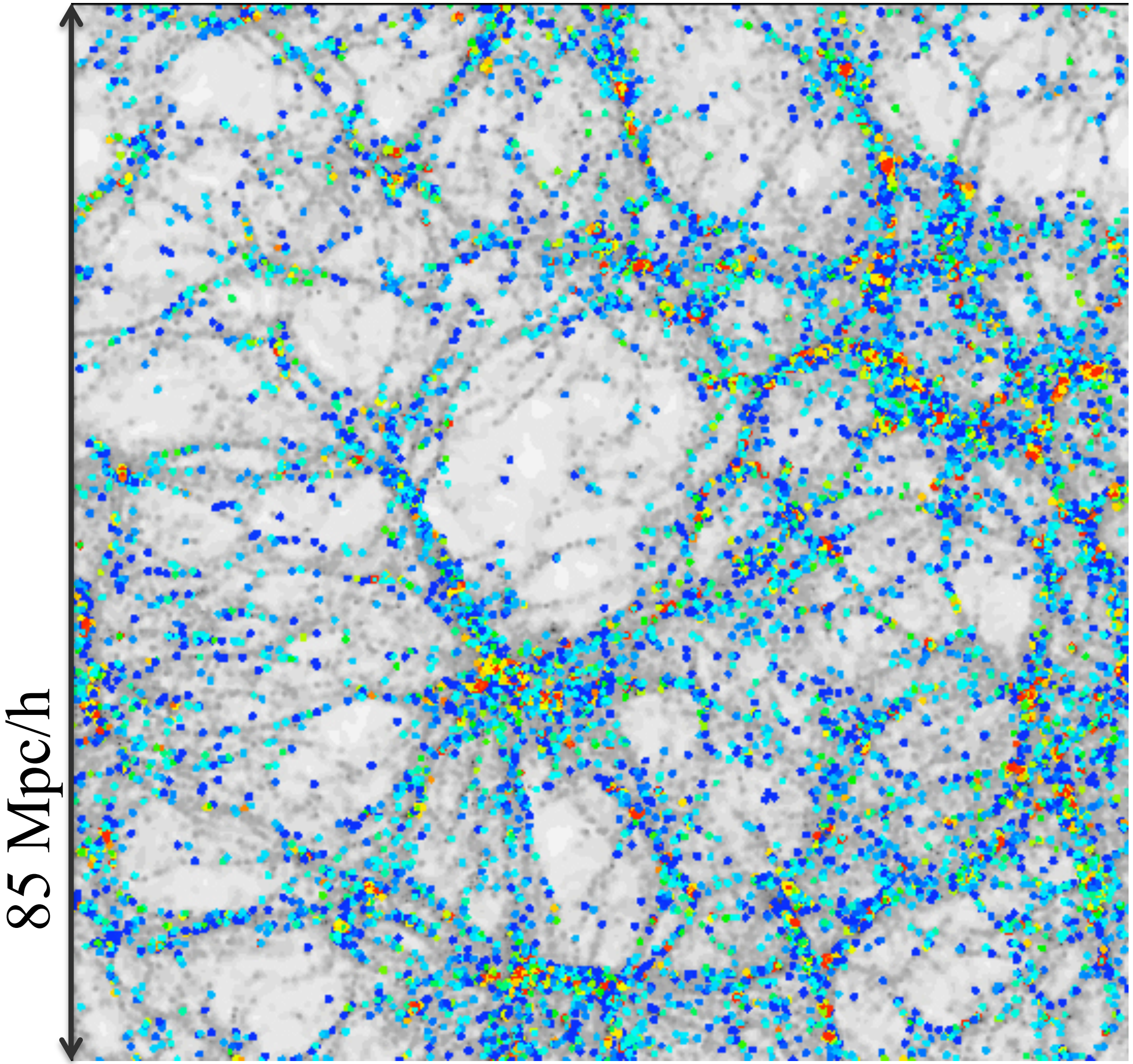
Dark Energy

Dark Matter

Neutrinos

We observe visible to explores invisibles

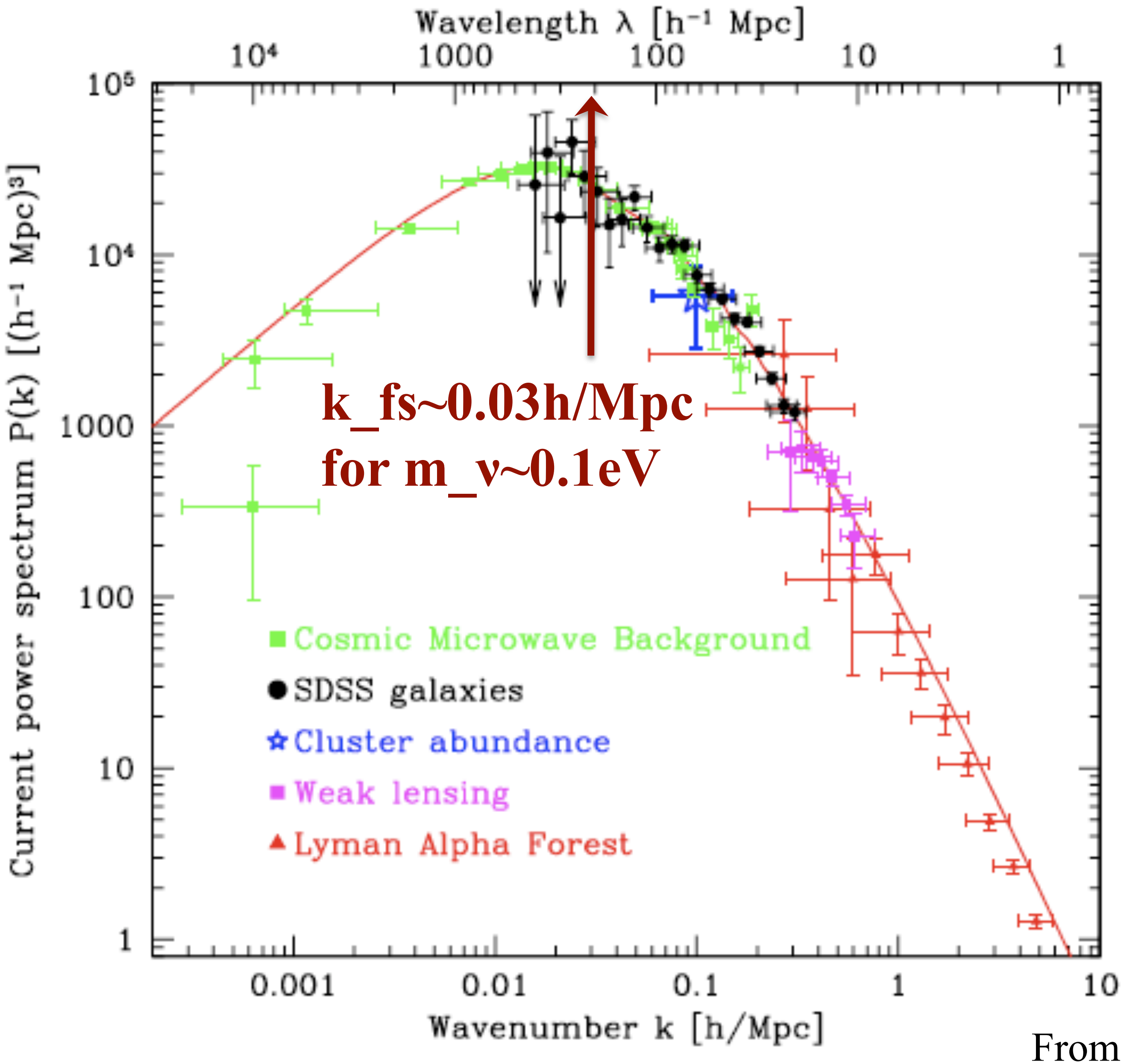
Caution: “light” is biased tracers of mass



From the Virgo Consortium

Different types of galaxies (and clusters) trace the total matter (mostly DM) distribution in different ways

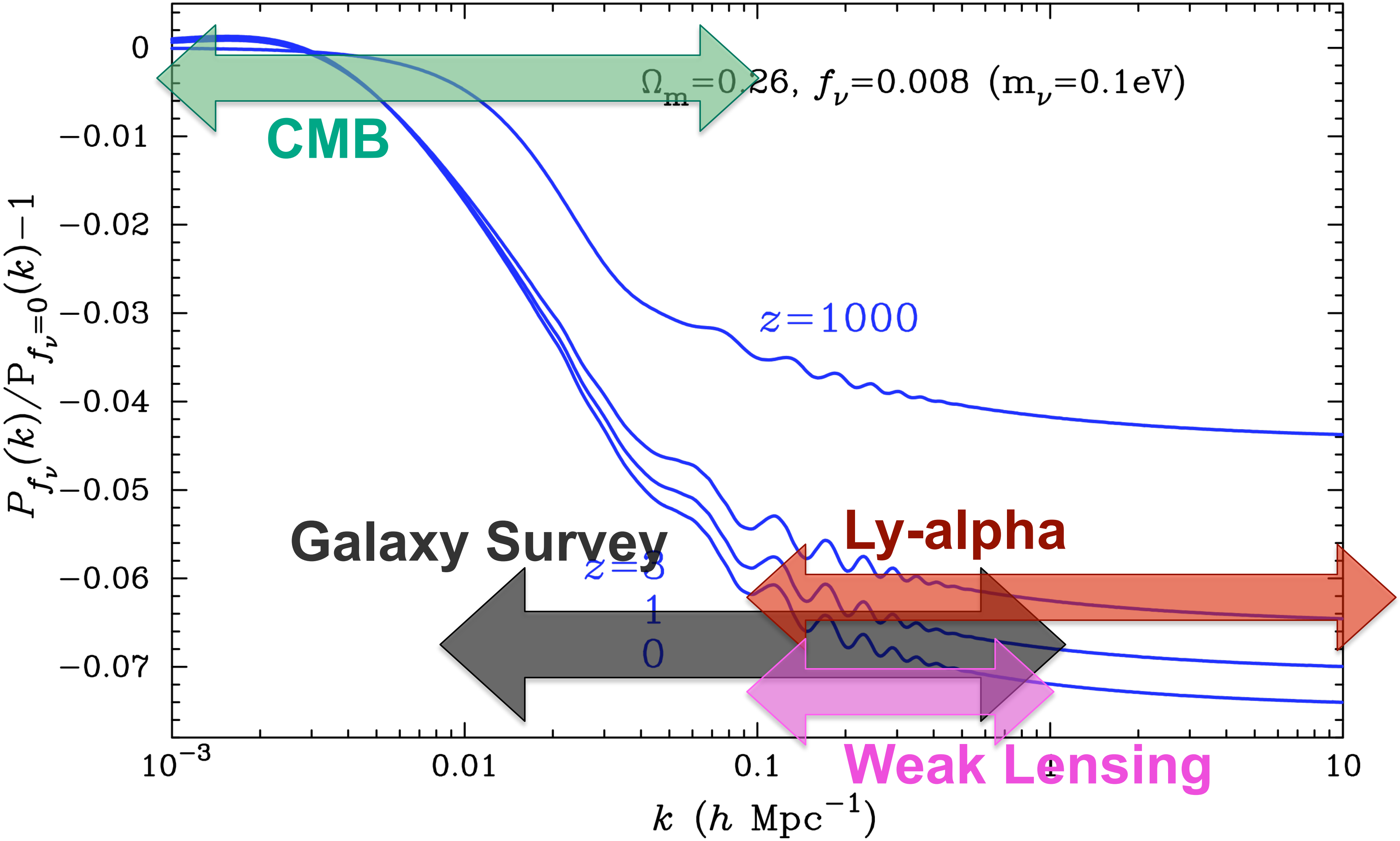
Large-scale structure probes



k_fs~0.03h/Mpc
for m_ν~0.1eV

From Tegmark+04

Sensitivity window of each probe



Cosmological constraints on M_ν

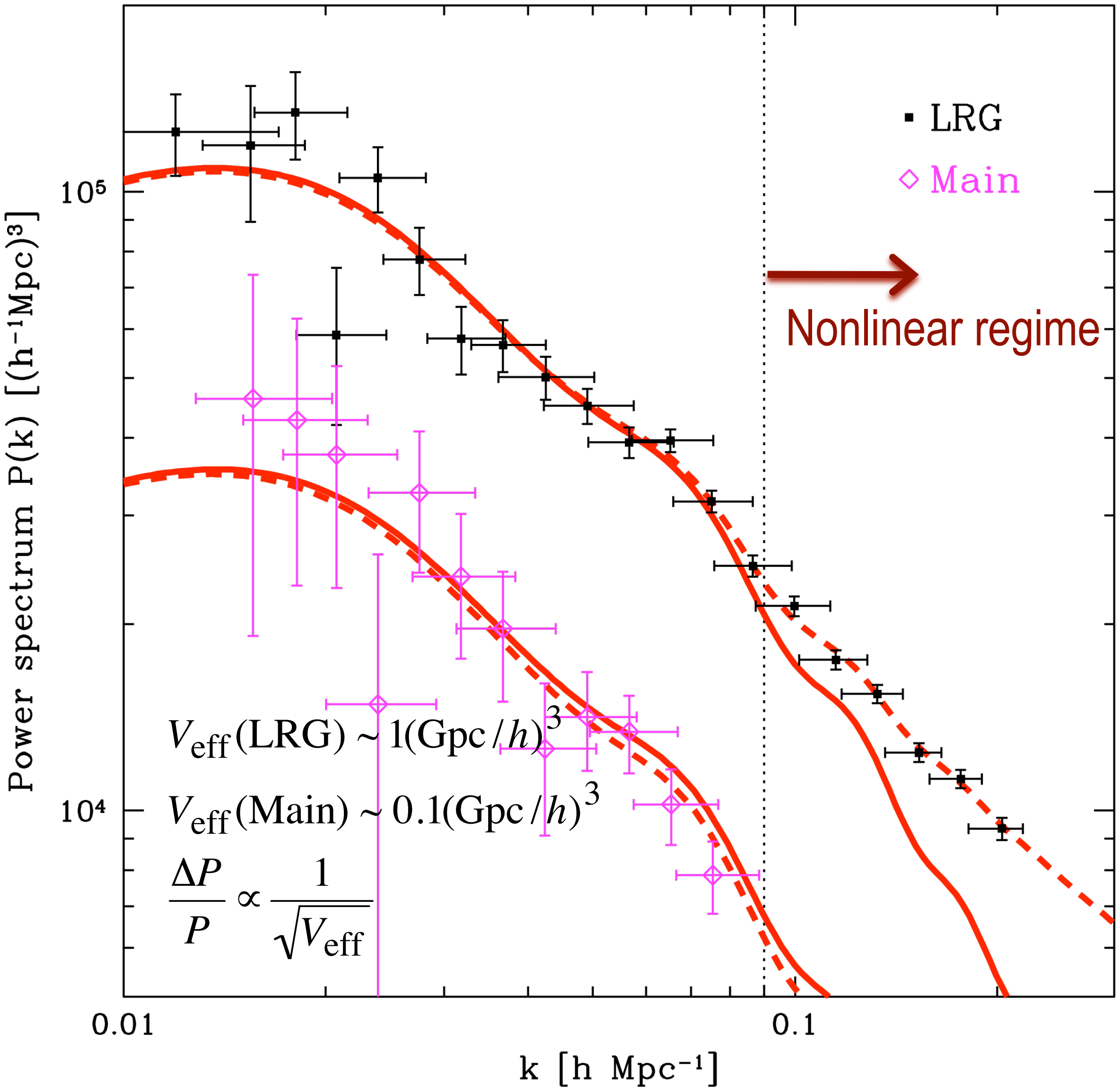
- **CMB alone**
  - Pros: precise modeling available, linear scale
  - Cons: smaller effect if M_nu<0.6eV
- **Galaxy survey**
  - Pros: relatively easier to model in the weakly NL regime, a unique way to probe the scale-dependent suppression
  - Cons: galaxy bias uncertainty degenerate with M_nu
- **Weak lensing (CMB lensing, cosmic shear)**
  - Pros: directly probe mass clustering
  - Cons: degenerate with z_s, sensitive to NL clustering
- **Ly-alpha forest**
  - Pros: probe smallest, linear scales, higher statistical precision
  - Cons: not straightforward to model

Cosmological constraints on M_ν (contd.)

Note: Lab. $m_{e,\nu}$<a few eV

- **CMB alone**
  - Ichikawa+(05) $m_{\nu,tot}<2eV$ (95%CL) for a flat model; WMAP5(Komatsu +08), 1.5eV (note: 0.6eV if BAO+SN added, CMB lensing)
- **Galaxy clustering**
  - 2dF: Elgaroy+(02) $m_{\nu,tot}<2eV$ (k_max=0.1h/Mpc) with the prior on Ω_m
  - SDSS: Tegmark et al (06) $m_{\nu,tot}<0.9eV$ (k_max=0.2h/Mpc) when combined with WMAP
- **Weak lensing**
  - Ichiki, MT, Takahashi (09) CFHTWL ~34 deg^2+WMAP5, $m_{\nu,tot}<1eV$
- **Ly-alpha forest** (+ galaxy survey)
  - SDSS: Seljak, Slosar & McDonald (06); $m_{\nu,tot}<0.17eV$

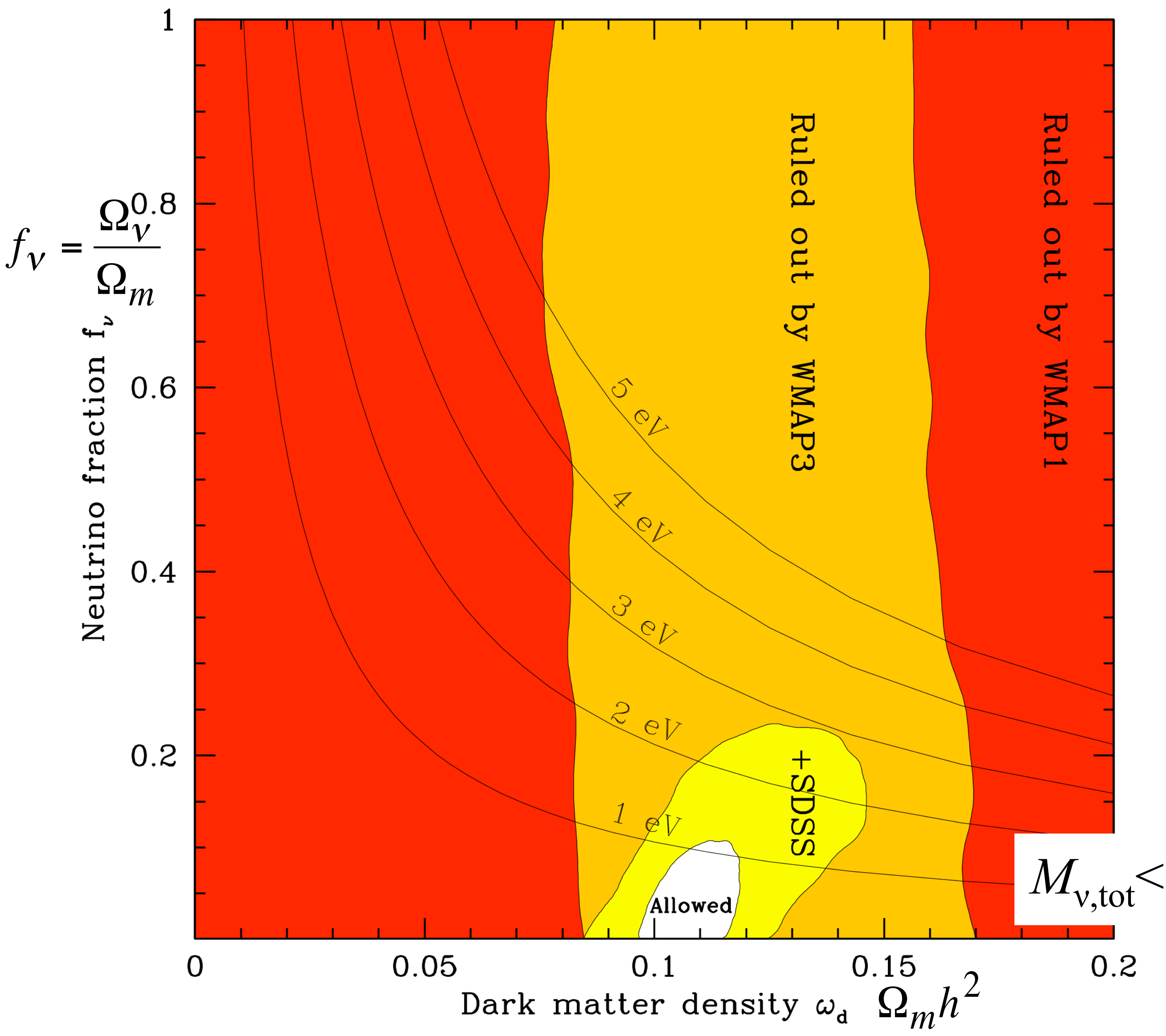
SDSS: Tegmark et al. 06



$$P_g(k) = b^2 P_m^L(k) \frac{1 + Q_{\rm nl} k^2}{1 + 1.4k}$$

- The linear theory ceases to be accurate even on these large length scales (~50Mpc: δ~O(0.1))
- The empirical model is employed: nuisance parameters Q and b introduced

SDSS: Tegmark et al. 06 (contd.)



$M_{\nu,\mathrm{tot}}$<0.94eV(95%C.L.)

Perturbation theory for structure formation

- The linear theory assuming δ_m<<1 is not sufficient
- The density perturbation is still small O(δ_m)~0.1on relevant length scales
- The perturbation theory offers a yet another method for structure formation in the weakly nonlinear regime (Makino, Suto, Sasaki 92; Jain & Bertschinger 94)

$$\delta_m = \delta_m^{(1)} + \delta_m^{(2)} + \delta_m^{(3)} + \cdots$$

⇓

Mass conservation eq.
Euler eq.
Poisson eq.

$$\boxed{P_m(k) = \left\langle \left(\delta_m^{(1)} + \delta_m^{(2)} + \delta_m^{(3)} + \cdots \right)^2 \right\rangle = P_m^{(11)} + P_m^{(22)} + P_m^{(13)} + \cdots}$$

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)

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

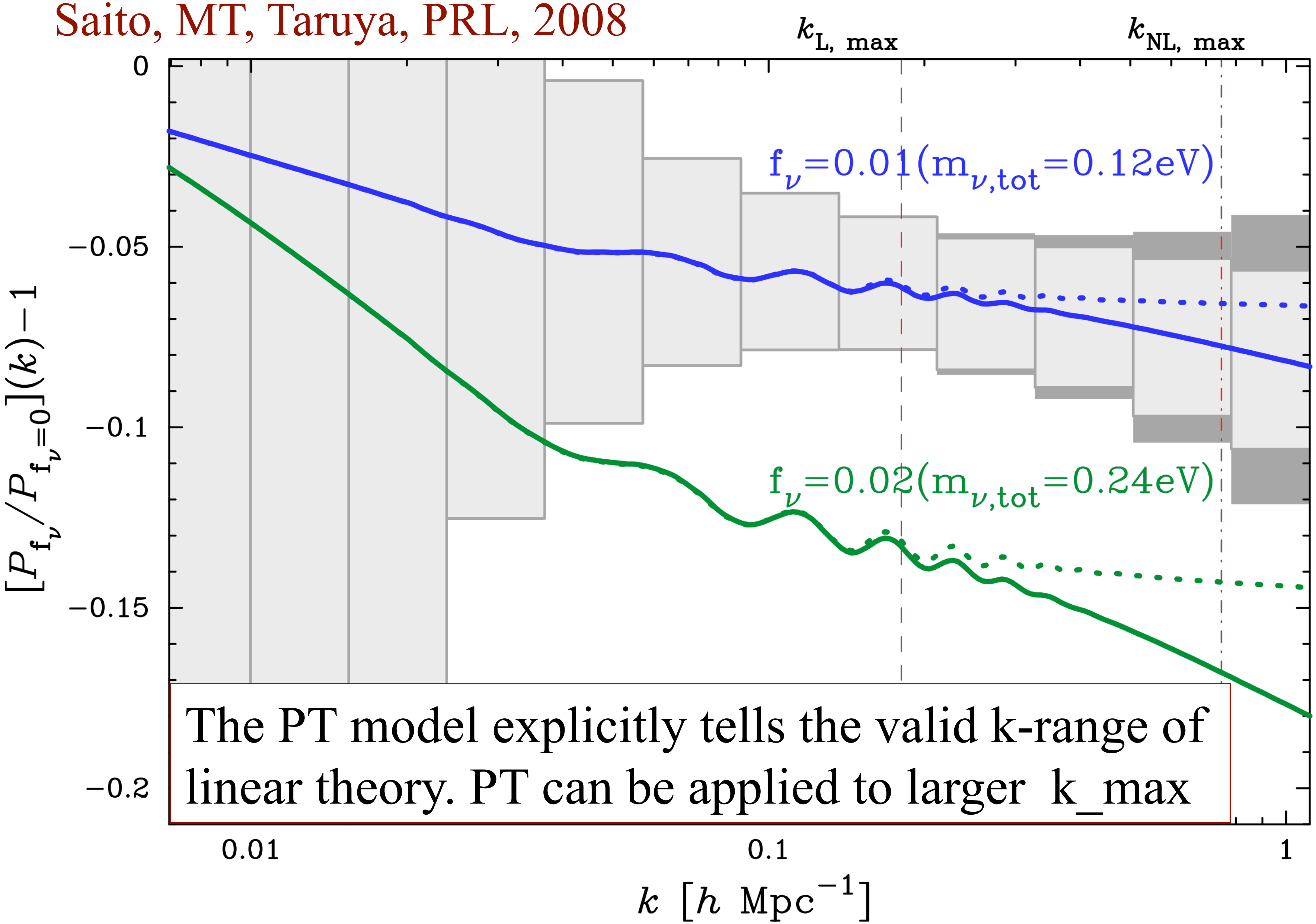
$$\delta_\nu \approx \delta_\nu^{(1)}$$ ← Linear theory (Solve Boltzmann eqns)

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

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

Neutrino effect on nonlinear P(k)

Saito, MT, Taruya, PRL, 2008

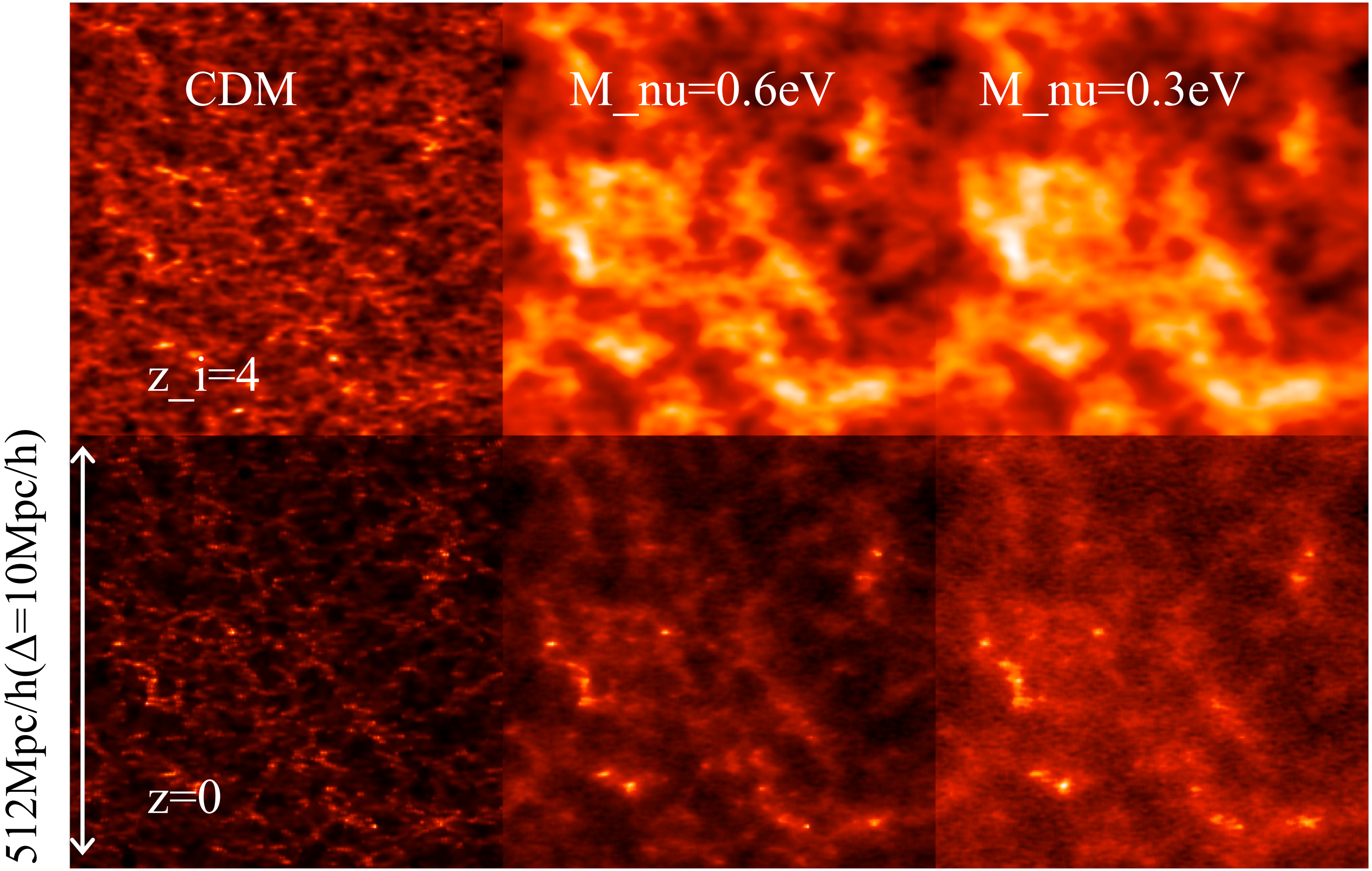


The PT model explicitly tells the valid k-range of linear theory. PT can be applied to larger k_max

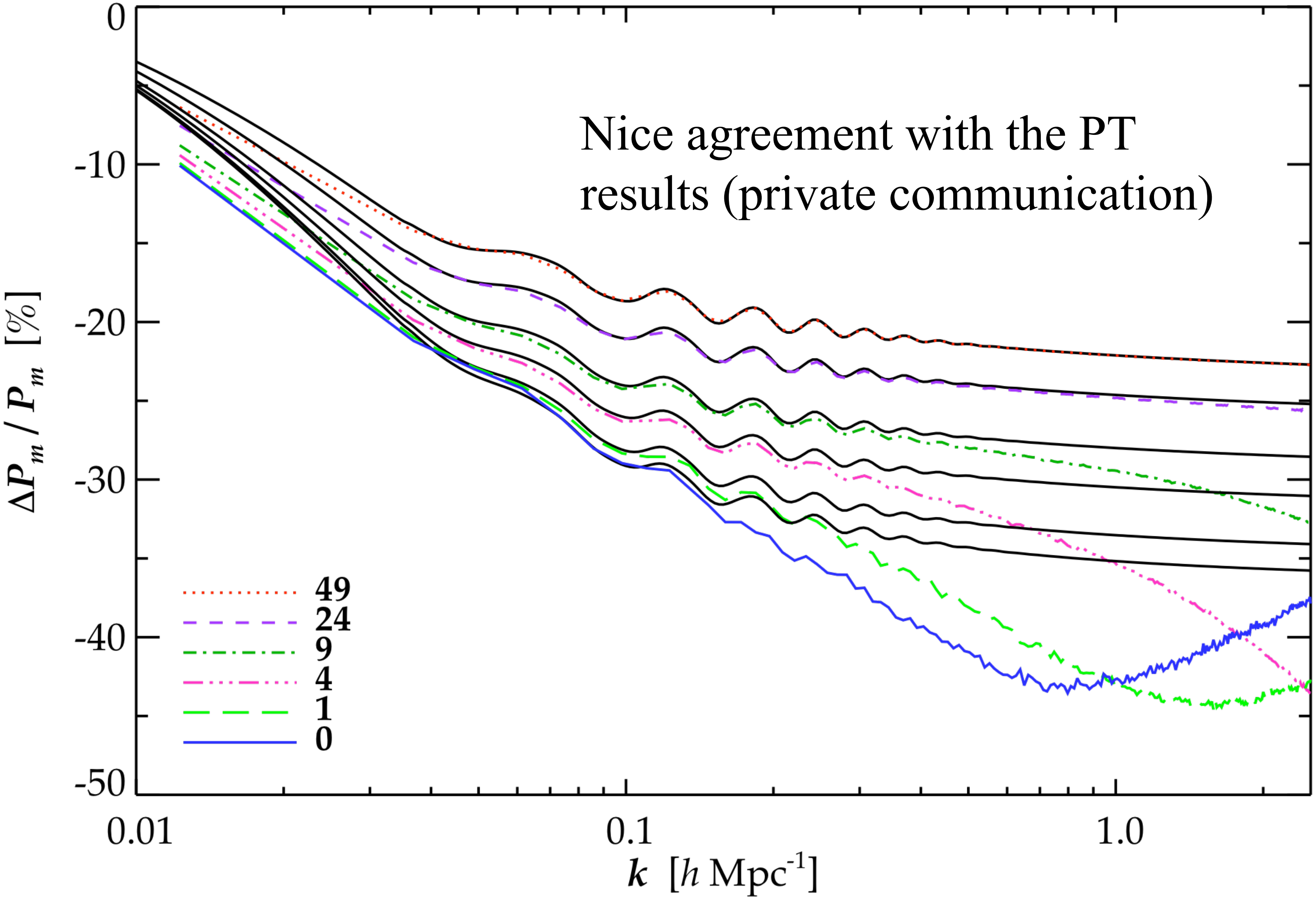
A MDM Simulation

(Brandbyge, Hannestad08)

256^3 CDM particles + 512^3 neutrino particles



Brandbyge, Hannestad08



Nice agreement with the PT results (private communication)

Galaxy bias

Saito, MT, Taruya 09, PRD in press

- In weakly nonlinear regime, straightforward to include a galaxy biasing effect in a perturbation theory manner, if galaxy bias is a local type

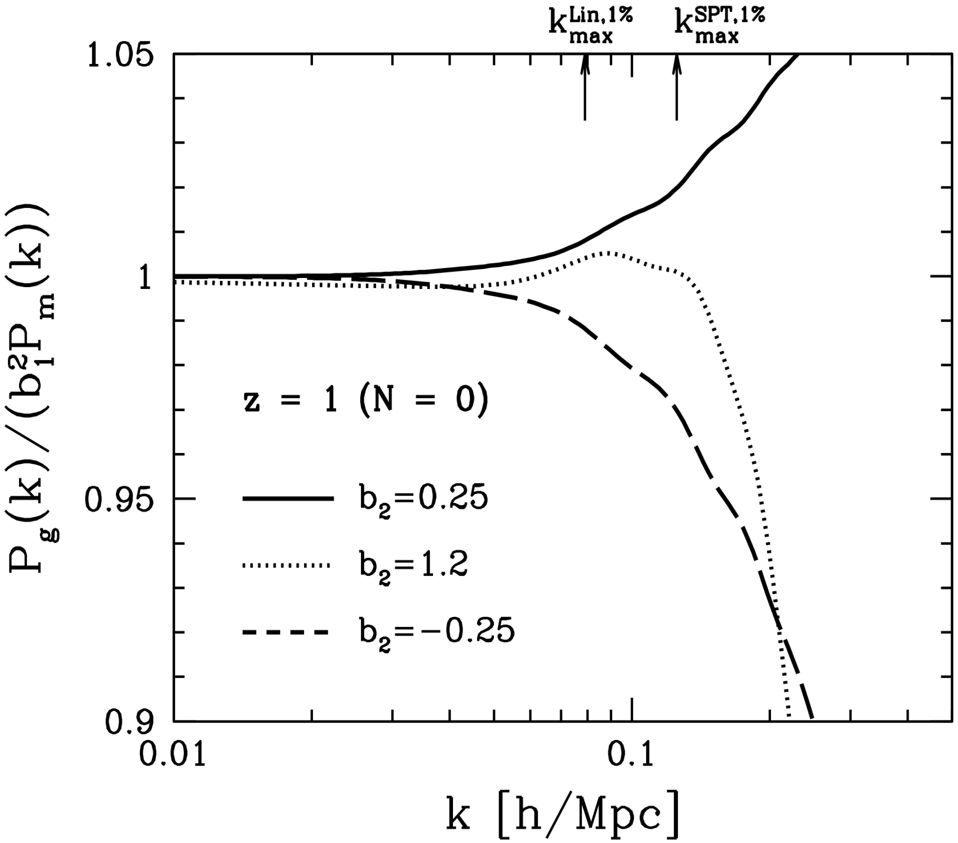
$$
\begin{aligned}
\delta_g(\boldsymbol{x}) &= f[\delta_m(\boldsymbol{x})] \\
&= b_1\delta_m(\boldsymbol{x}) + \frac{1}{2}b_2[\delta_m(\boldsymbol{x})]^2 + \frac{1}{3!}b_3[\delta_m(\boldsymbol{x})]^3 + \cdots \\
&= b_1\left[\delta_m^{(1)} + \delta_m^{(2)} + \delta_m^{(3)} + \cdots\right] + \frac{1}{2}b_2\left[\delta_m^{(1)} + \delta_m^{(2)} + \delta_m^{(3)} + \cdots\right]^2 + \cdots
\end{aligned}
$$

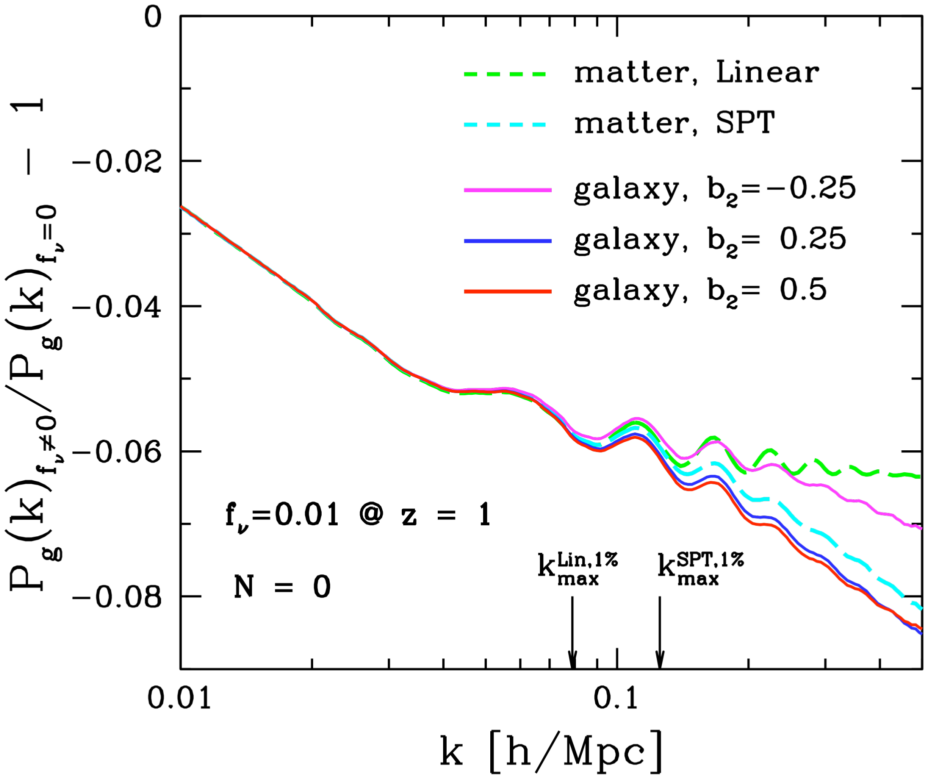
$$
P_g(k) = b_1^2\left[P_m(k) + b_2\underbrace{P_{b2,m}(k)}_{>0} + b_2^2\underbrace{P_{b22}}_{<0}\right] + N
$$

Here

$$
\begin{aligned}
P_{\mathrm{b}2,\delta}(k) &\equiv 2\int\frac{d^3\boldsymbol{q}}{(2\pi)^3}\,P_{\mathrm{m}}^{\mathrm{L}}(q)P_{\mathrm{m}}^{\mathrm{L}}(|\boldsymbol{k}-\boldsymbol{q}|)\mathcal{F}_\delta^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q}), \\
P_{\mathrm{b}22}(k) &\equiv \frac{1}{2}\int\frac{d^3\boldsymbol{q}}{(2\pi)^3}\,P_{\mathrm{m}}^{\mathrm{L}}(q)[P_{\mathrm{m}}^{\mathrm{L}}(|\boldsymbol{k}-\boldsymbol{q}|) - P_{\mathrm{m}}^{\mathrm{L}}(q)].
\end{aligned}
$$

Galaxy P(k) for a MDM model



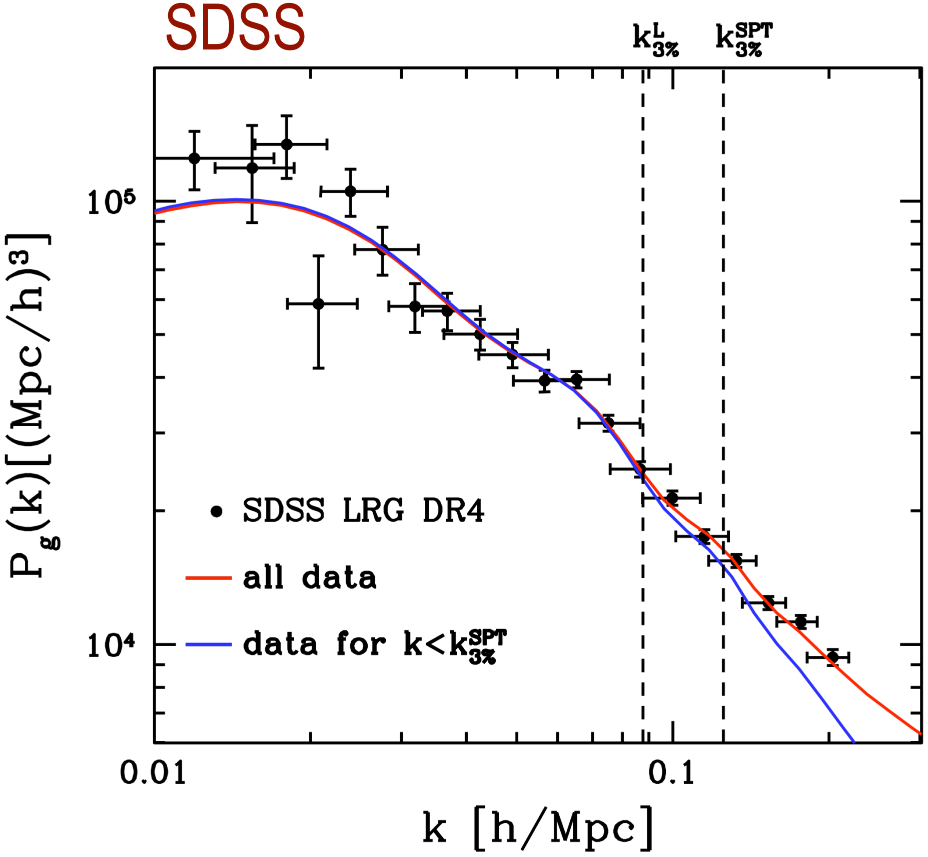


- Nonlinear bias parameter b_2 introduces a scale-dependent modification on P(k)
- Even so, the galaxy P(k) amplitude is suppressed by neutrino effect

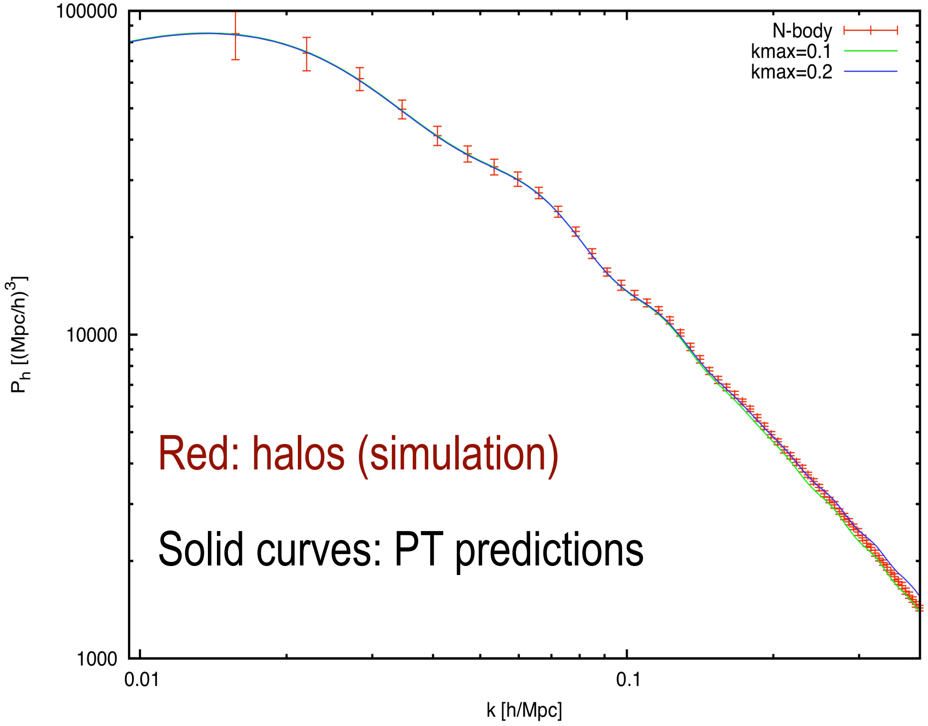
Galaxy P(k) for a MDM model (contd.)

Saito et al. in prep.

SDSS



Simulations



Red: halos (simulation)

Solid curves: PT predictions

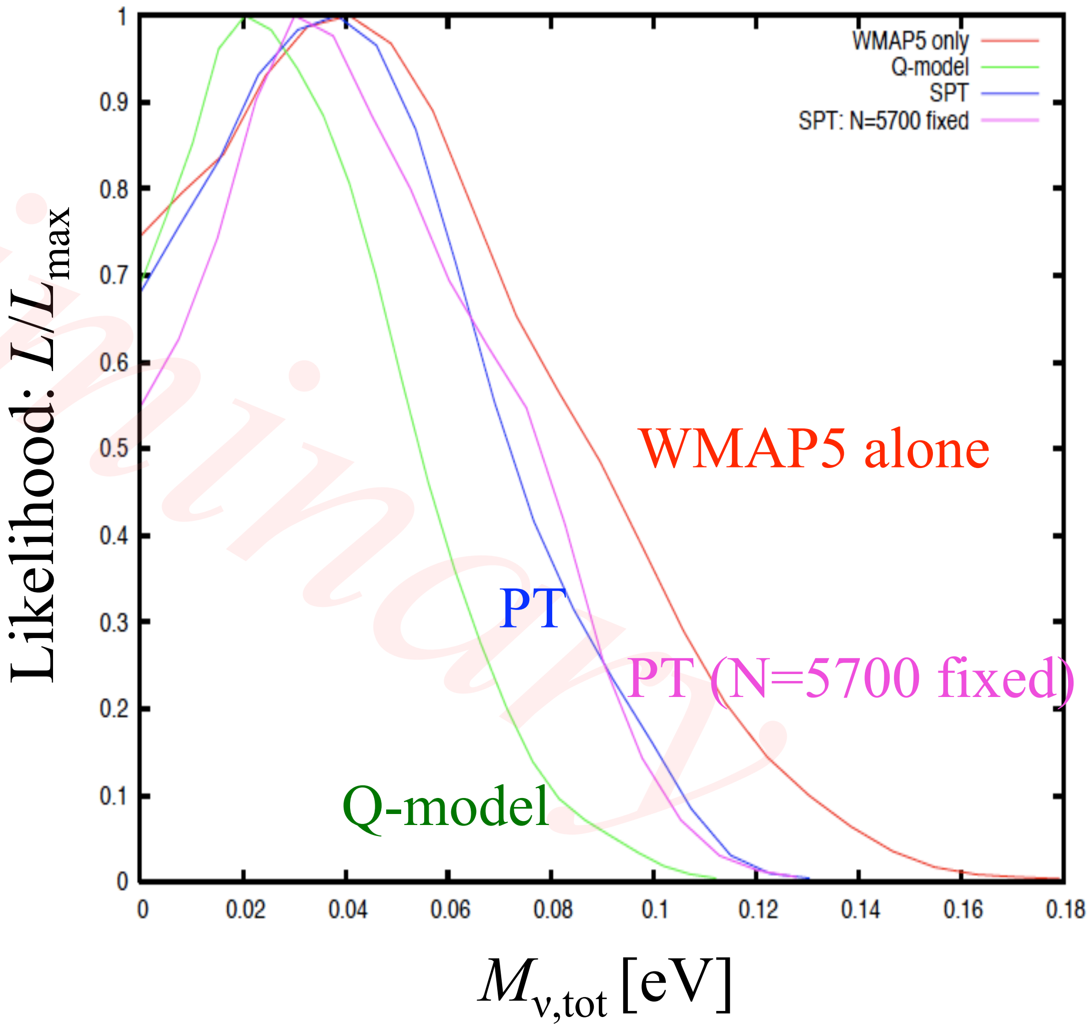
- There seems a space of bias parameters to reproduce the SDSS power spectrum and the simulated halo power spectrum
- More physically reliable model, compared to Q_nl model

$$P_g(k) = b^2 P_m^L(k) \frac{1+Q_{\rm nl}k^2}{1+1.4k}$$

Applying to SDSS DR4

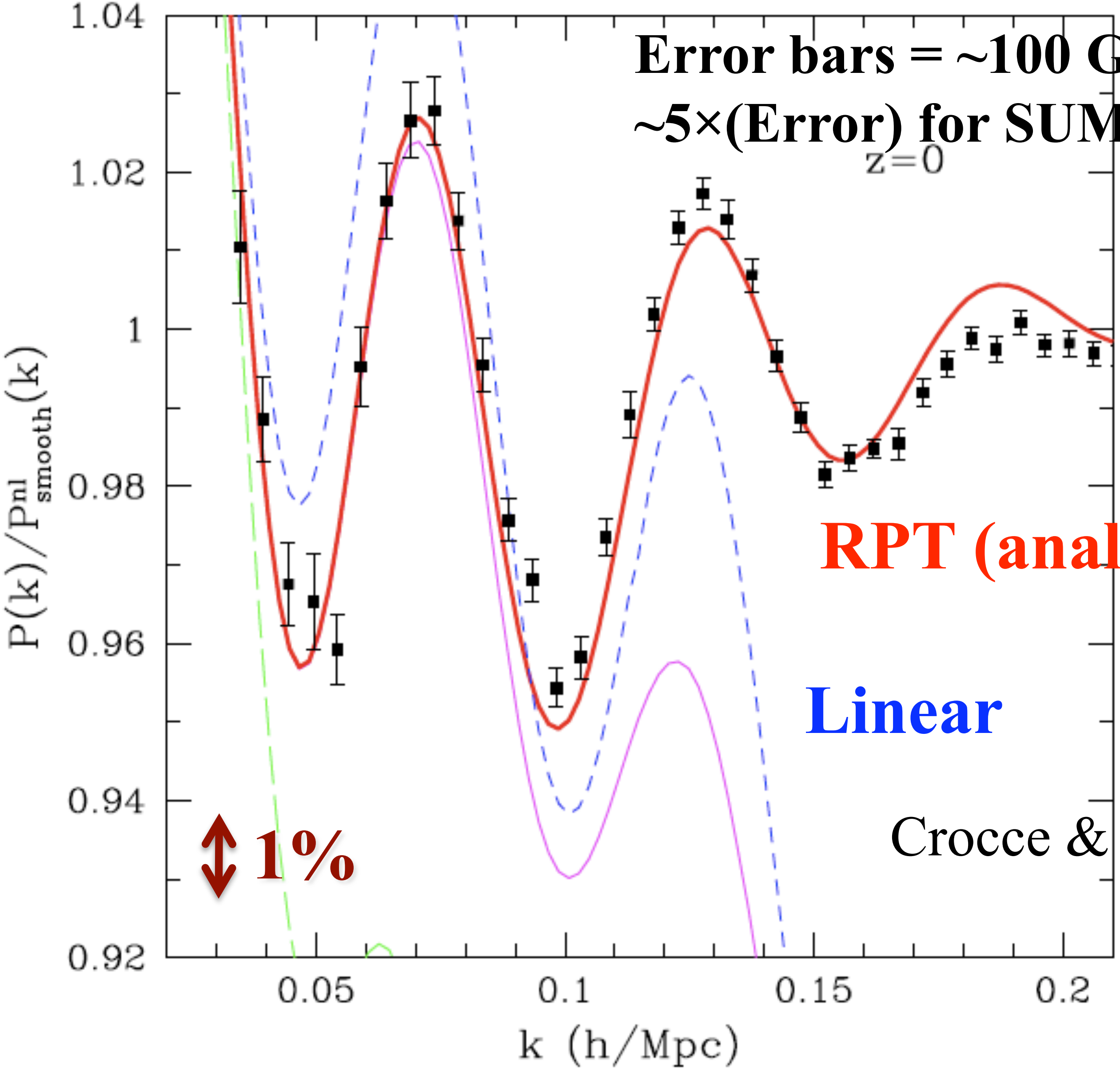
Saito et al. in prep.

- WMAP5+SDSS (PT model)
  - $M_{\nu,\mathrm{tot}}$ <1.01eV(95%C.L.)
- WMAP5+SDSS (Q-model)
  - $M_{\nu,\mathrm{tot}}$ <0.84eV(95%C.L.)
- Can be further improved by adding SN constraints
- Quantify a bias in parameter estimation for Q-model



Improving PT model

Include higher-order loop corrections



Real-space Power Spectrum

Error bars = ~100 Gpc^3 (all-sky)
~5×(Error) for SUMIRE(5Gpc^3)

RPT (analytic model)

Linear

↕ 1%

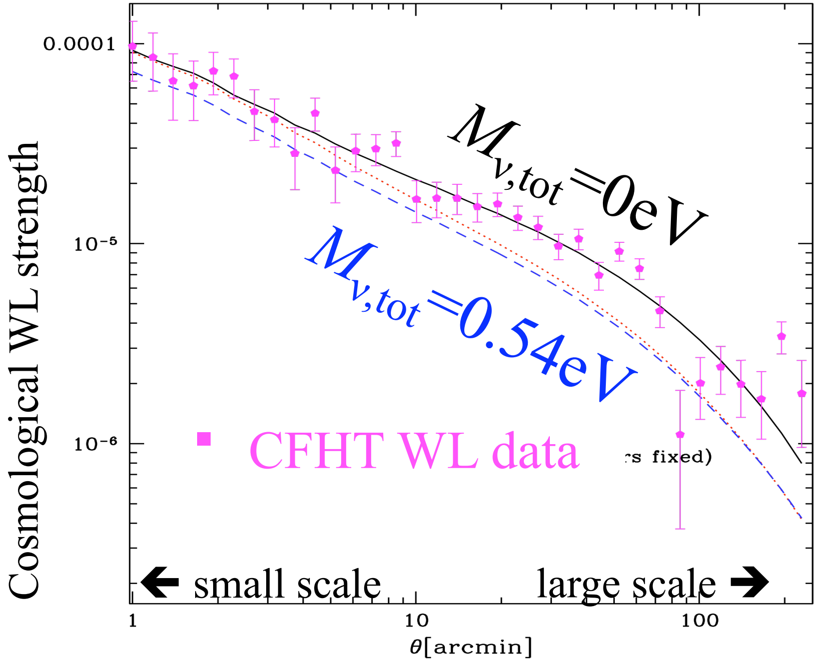
Crocce & Scoccimarro 08

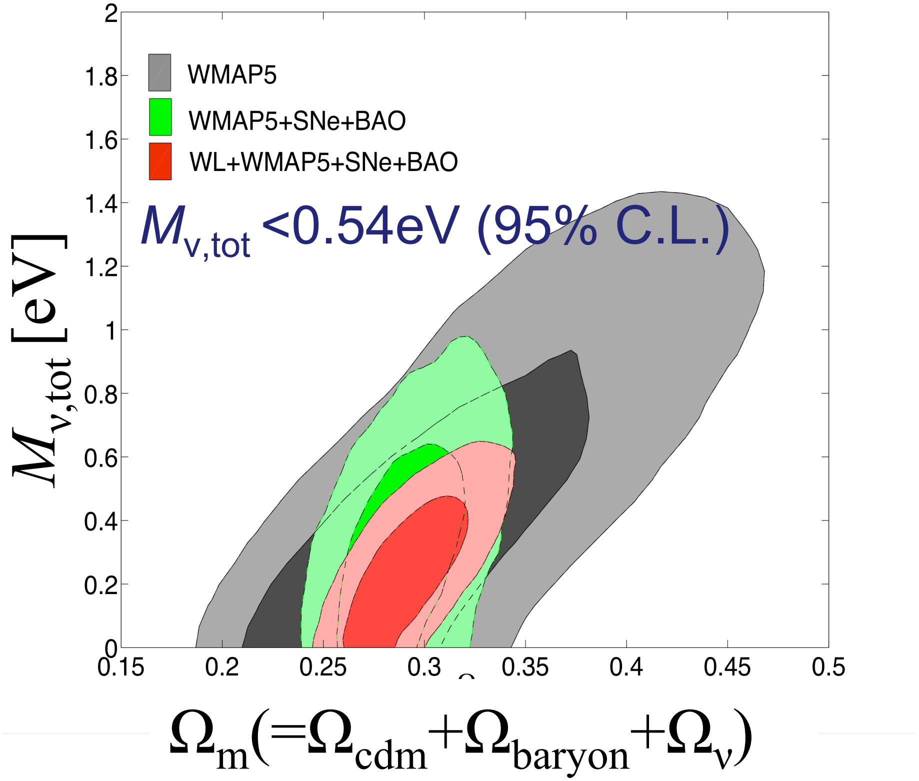
Also Suto & Sasaki 91
Jeong & Komatsu 06
Taruya & Hiramatsu 08
Matsubara 08

Constraining neutrino mass with cosmological WL

Ichiki, MT, Takahashi 09

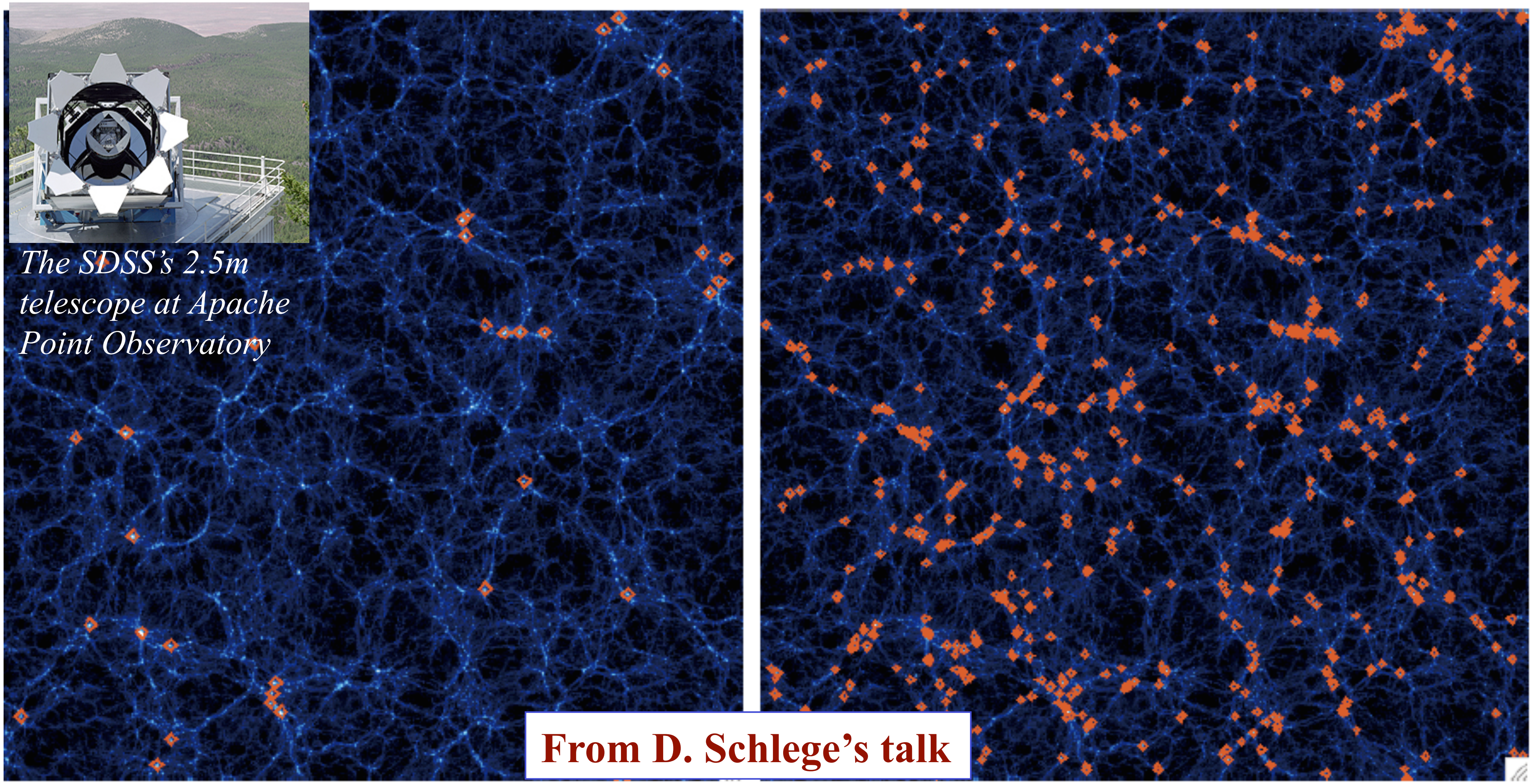
- Apply the NL model of P(k) to CFHT weak lensing data (~60deg^2)
- WL directory probe total matter (free of galaxy bias)
- Even though the data is from a small sky coverage (60deg^2), the constraint on M_nu is powerful: M_nu,tot <0.54 (WMAP5+SN +BAO)





BOSS: sampling the cosmic density field w/ galaxies

IPMU/U Tokyo is a full participating institute of SDSS-III



SDSS-I and SDSS-II

BOSS

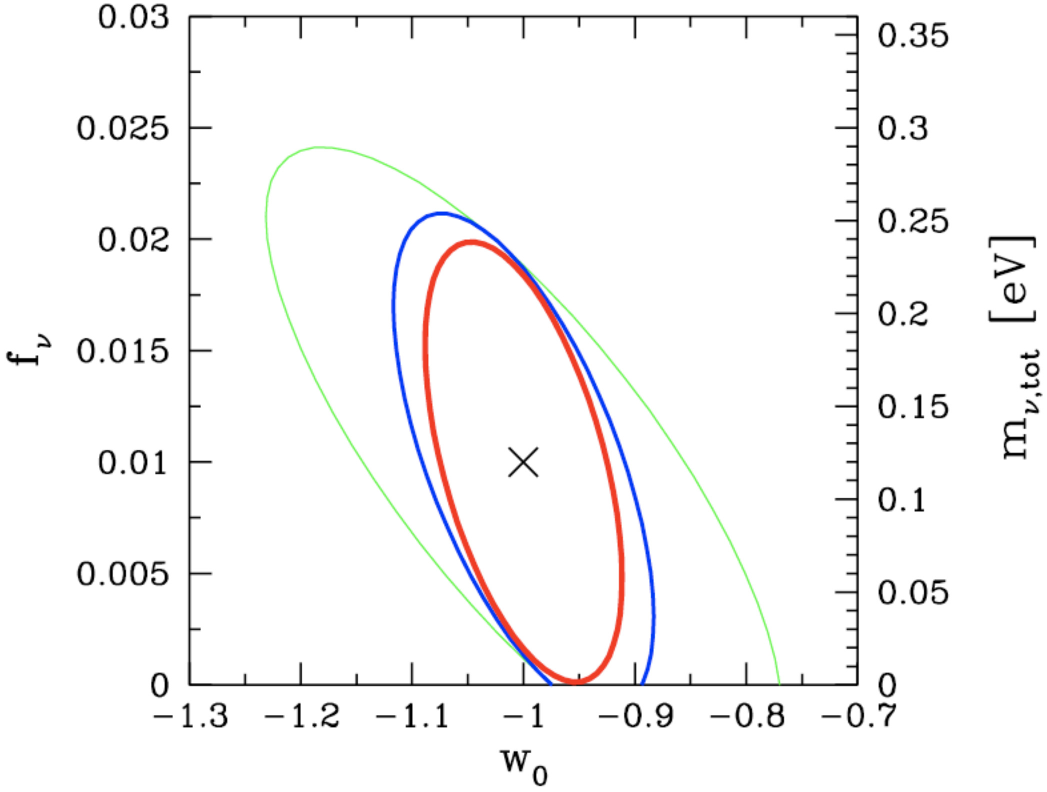
M.White

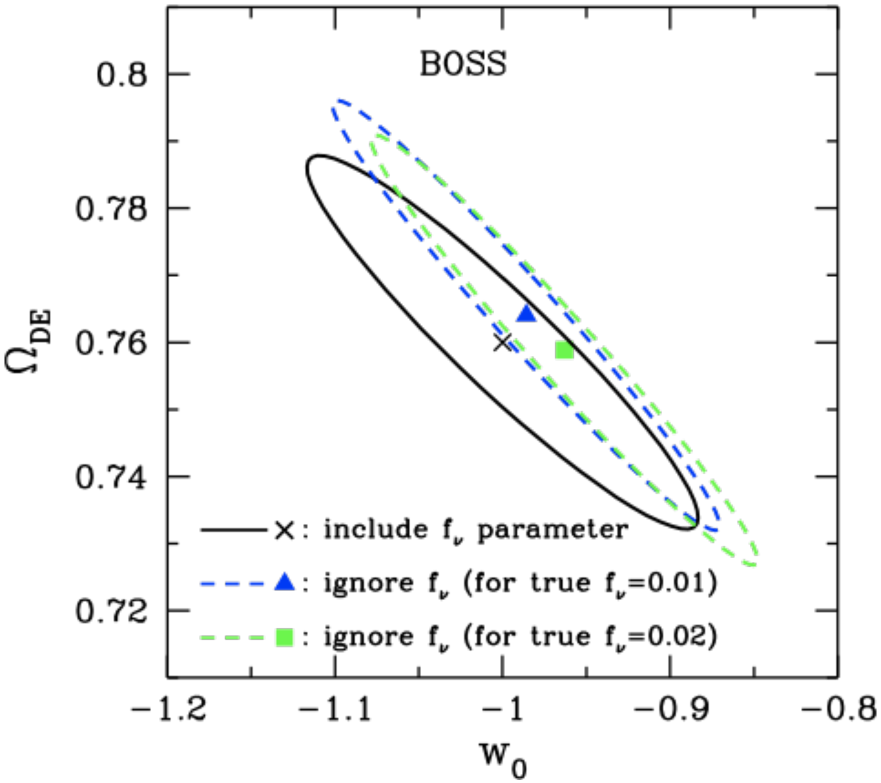
The SDSS's 2.5m telescope at Apache Point Observatory

From D. Schlege's talk

Horizon simluation: A slice 500 h^{-1}Mpc across and 10 h^{-} Mpc thick at z=0.5

Forecasts





- Planck+BOSS: $M_{\nu,\mathrm{tot}}<0.176\mathrm{eV}$(95%C.L.)
- Ignoring neutrino mass in the parameter estimation may cause a bias in DE equation of state: not negligible
- Japanese team is now trying to start the neutrino working group for BOSS

SUbaru Measurement of Images and REdshifts (SUMIRE)

From Hitoshi’s slides

ダークエネルギーを暴く

- この分野では日本は出遅れている
  - この提案で世界トップへ
- ダークエネルギーの増え方の速さを測る
- すばる望遠鏡は約１億個の遠方銀河を観測
- まずは銀河の形を精密に測れる超広視野カメラでダークマターの地図⇒世界レベル
- 次は銀河への距離を精密に測れる超広視野分光器でダークエネルギーの性質解明⇒世界トップ！
- 宇宙初期のブラックホールの成長も観測
- 電機、光学、検出器の分野で国内に新たな先端技術の中核を

すばる (国立天文台)

超広視野カメラ

超広視野分光器

WL+galaxy P(k)+Planck: M_nu ~0.1eV(95%C.L.) achievable

Summary

- Cosmological probes are, albeit indirect, a powerful method for constraining neutrino masses (total mass of three flavors)
- CMB + large-scale structure is particularly powerful
  - Galaxy clustering, Weak lensing, Ly-alpha
- Need to model structure formation up to the nonlinear regime for a mixed dark matter model
  - Perturbation theory method
  - A hybrid simulation
- Future cosmological surveys look very promising
  - The accuracy of 0.1eV (95%C.L.) achievable with SUMIRE
  - A byproduct science for dark energy experiments
  - A lot of room to improve the neutrino mass constraints (bispectrum, redshift distortion, combining WL and galaxy P(k))
  - CMB lensing: potentially achieve 0.1eV (95%) with CMBPol