Neutrino physics imprinted in the Cosmic Microwave Background

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Massive Neutrinos and Cosmology: Overview

Masses, number, BSM ν scattering, large asymmetry …

Early phase

BBN

Primary CMB

structure formation

Lensed CMB

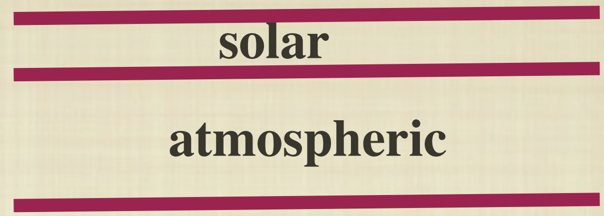
Cosmic shear

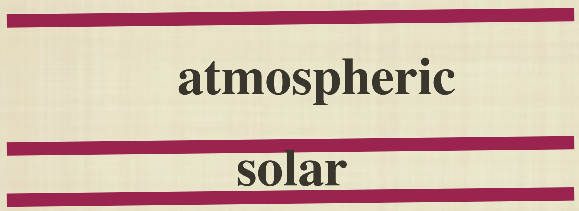
Galaxies
Ly-α forest
21 cm

Future of Laboratory Constraints

- Tritium endpoint
  - Aim: $m_{\nu_e} < 0.2$ eV at 95% CL (KATRIN)
- $0\nu\beta\beta$:
  - Test if neutrinos are Majorana particles
  - Next gen ~ 100 meV and lower in double beta decay mass

Mass schemes from measurement of neutrino oscillation



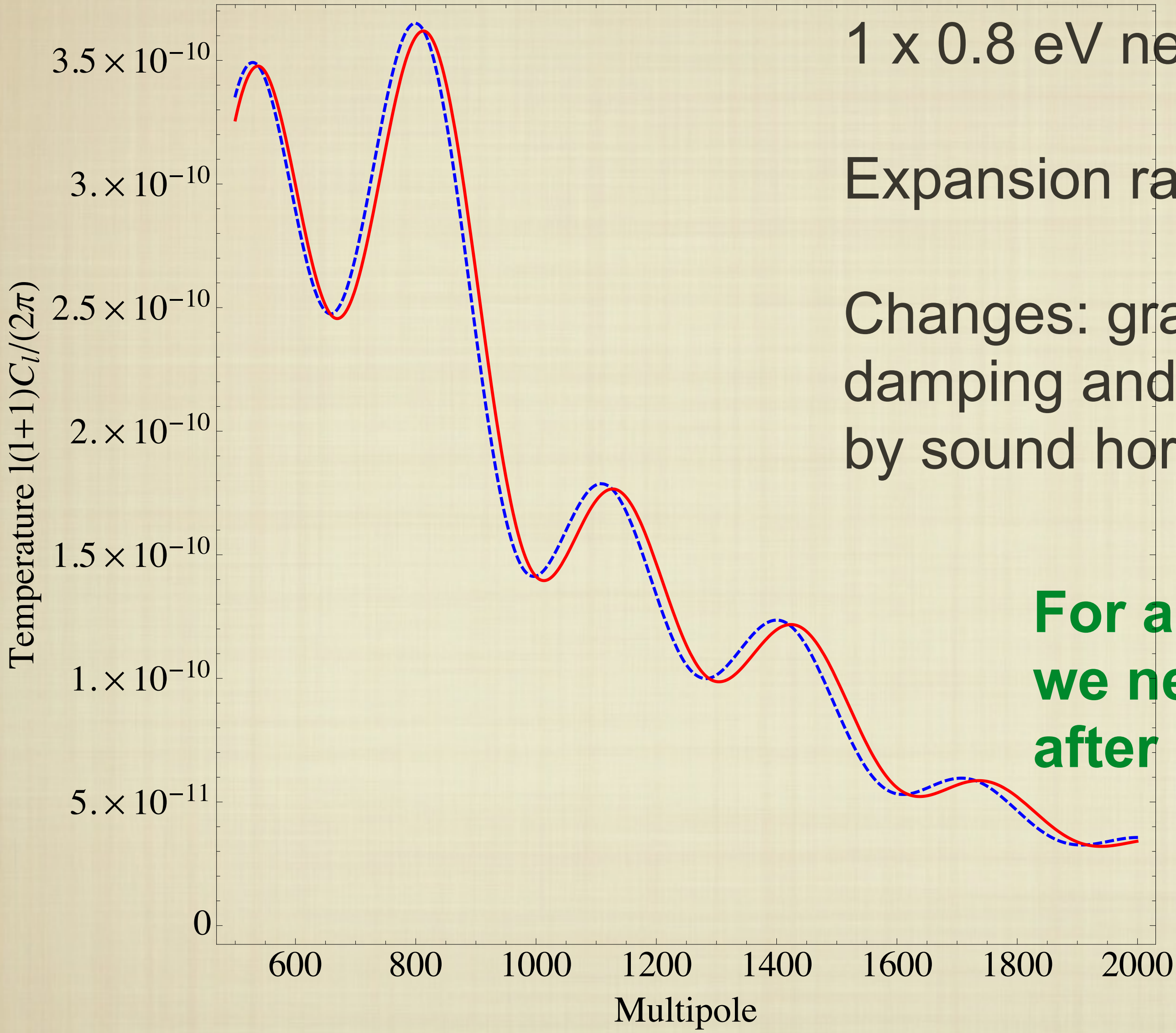


Sum of neutrino masses greater than about 60 meV

Sum of neutrino masses greater than about 100 meV

Both double beta decay experiments and cosmology should be able to probe this regime.

Massive Neutrino and Primary CMB



1 x 0.8 eV neutrino (dashed)

Expansion rate increases

Changes: gravitational potential, damping and angle subtended by sound horizon

For a precision probe, we need the physics after last scattering.

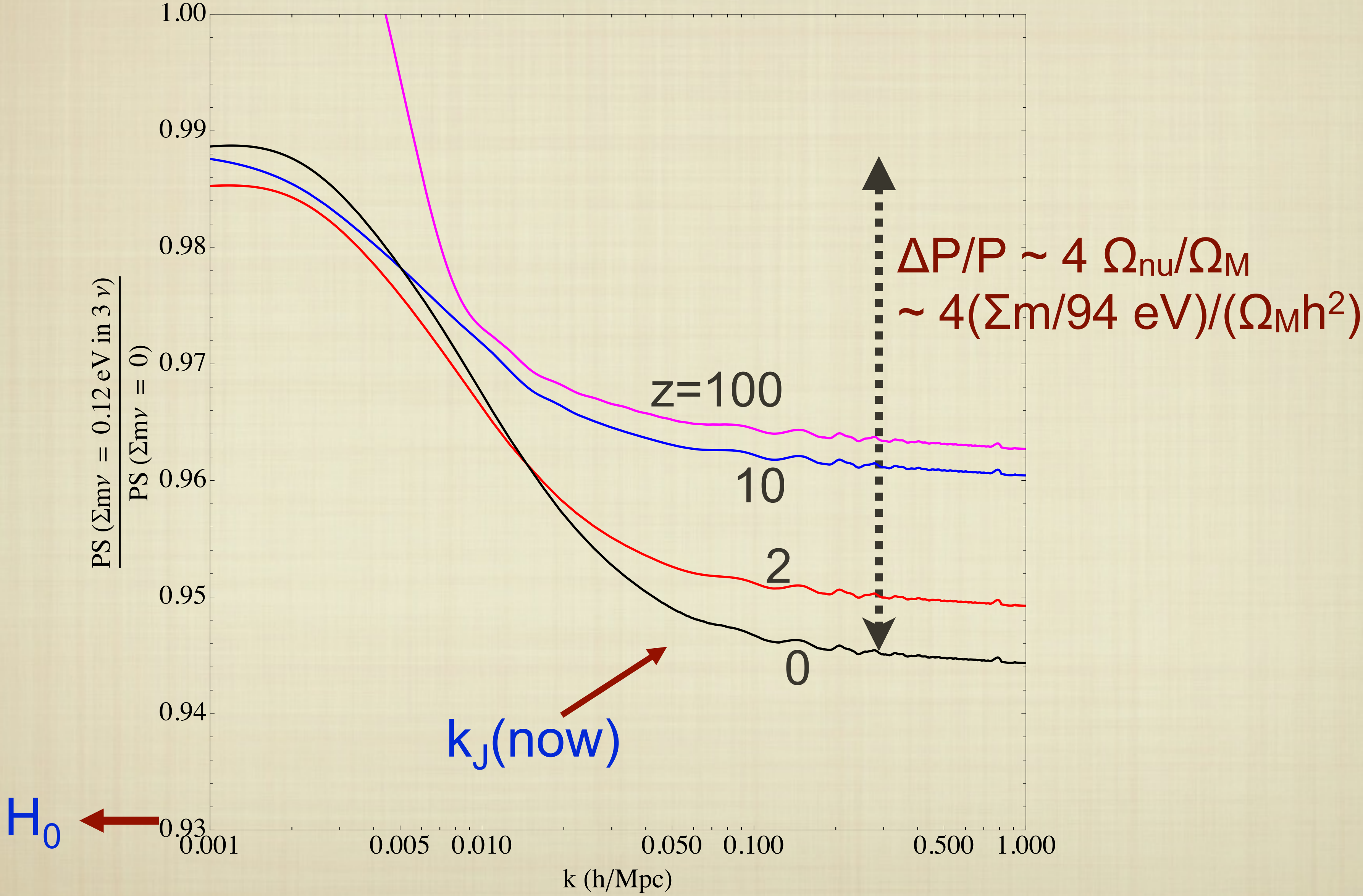
Jeans Instability for Neutrinos

Neutrino perturbations on length scales larger than the Jeans length become unstable and collapse into dark matter potential wells.

$$k_J(z)^{-1} = \frac{v_\nu(1+z)}{\sqrt{4\pi G\rho_m}}$$

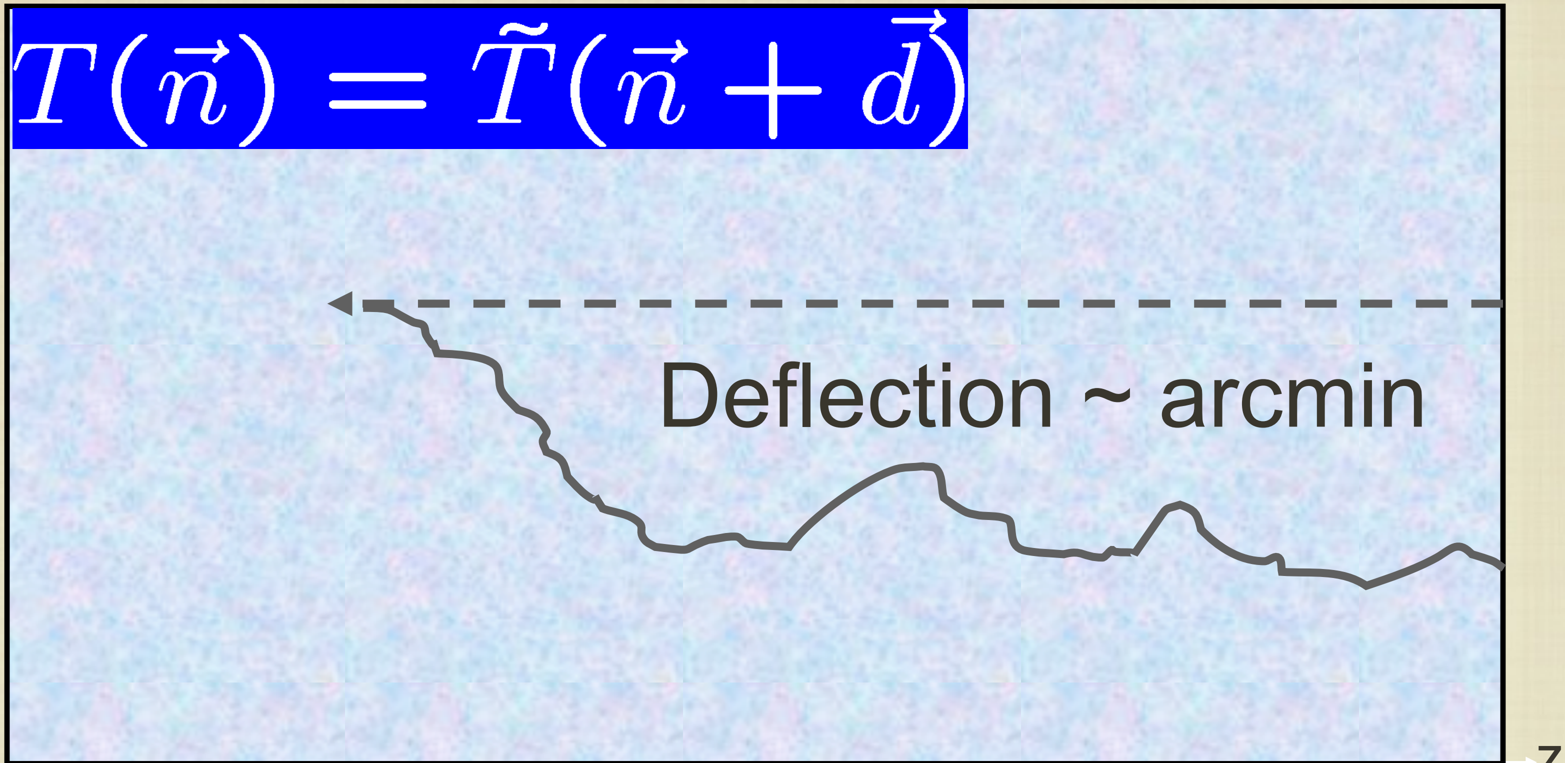
Bond and Szalay, ApJ 274, 443 (1983)
Hu and Eisenstein, ApJ 498, 497 (1998)
Hu, Eisenstein and Tegmark, PRL 80, 5255 (1998)

Effect of non-zero neutrino mass on the density perturbations



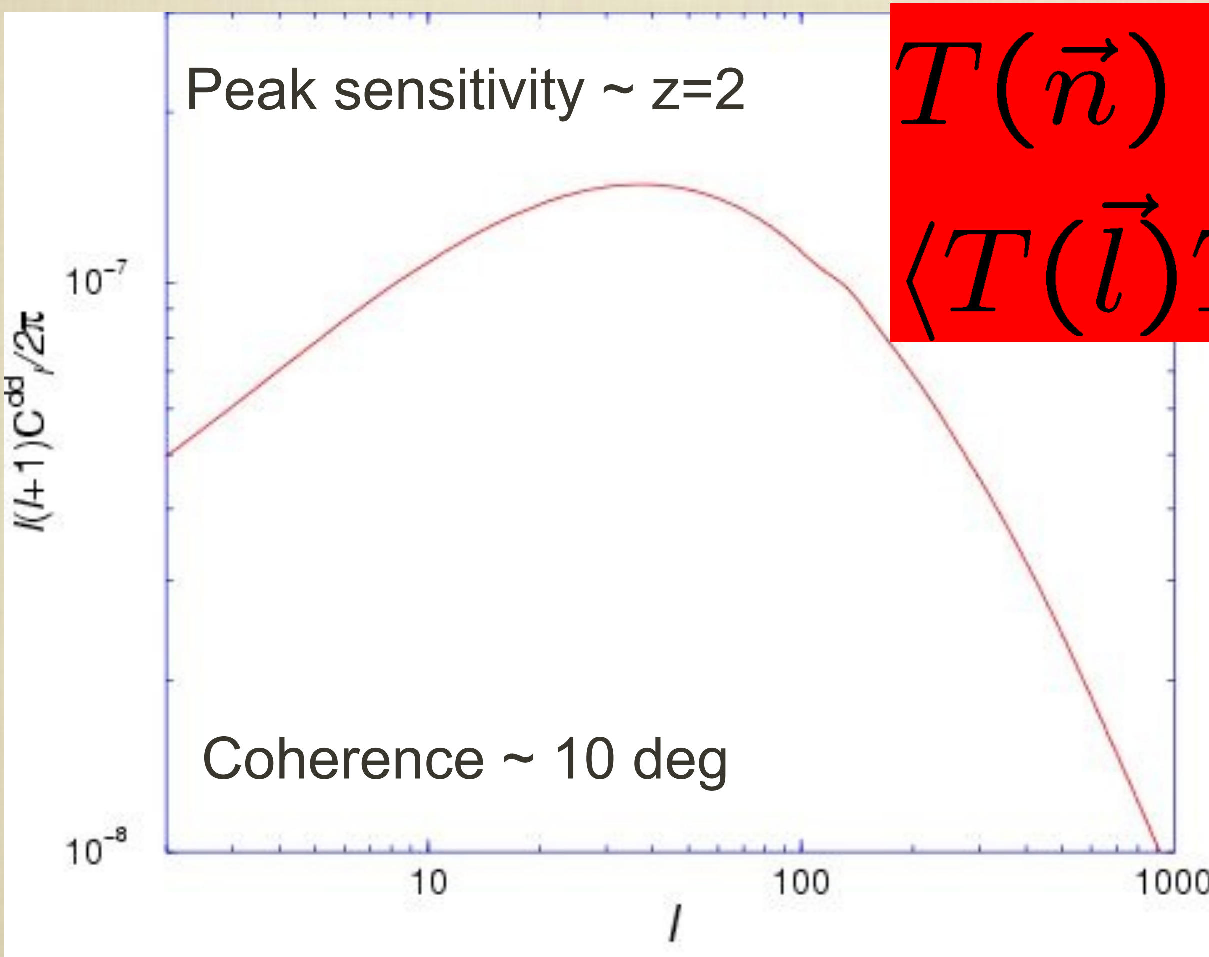
Effect of Lensing on the CMB

$$T(\vec{n}) = \tilde{T}(\vec{n} + \vec{d})$$



$$\vec{d} = \nabla \int_0^1 da\, \mathcal{P}(a)\, \delta_m(a)$$

Coherence of (CMB) Lensing Deflection

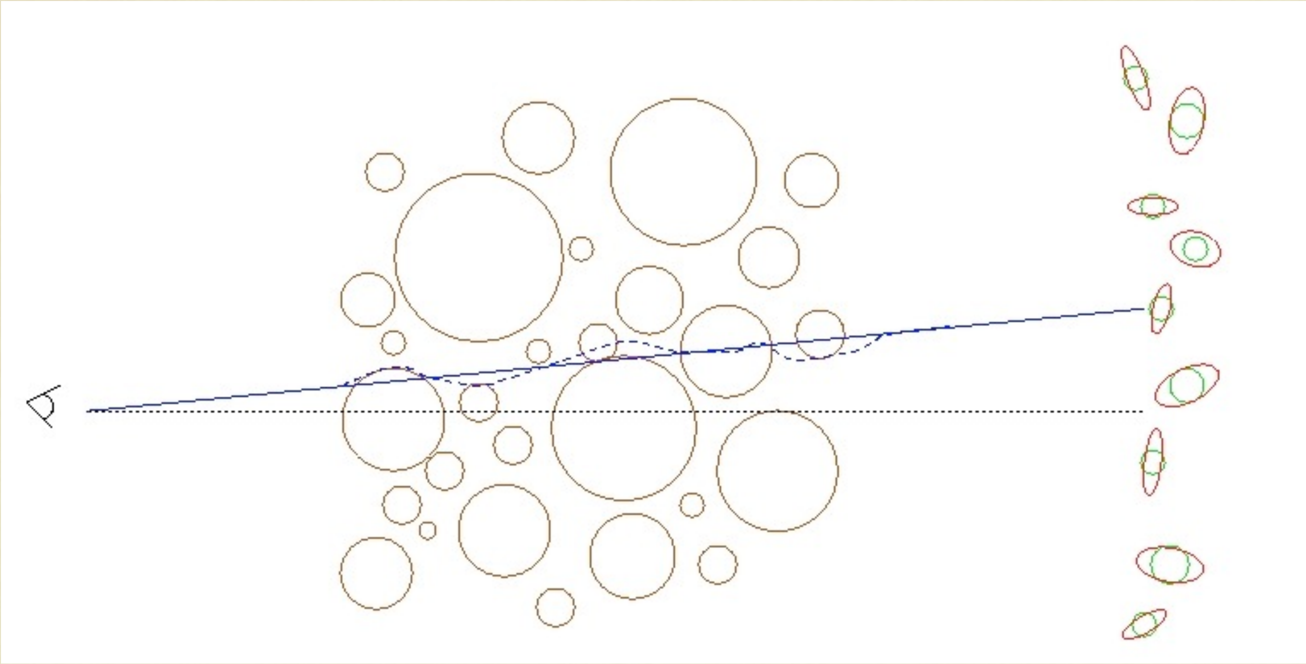


$$T(\vec{n}) = \tilde{T}(\vec{n} + \vec{d})$$

$$\langle T(\vec{l})T(\vec{l}\,')\rangle \propto \vec{d}$$

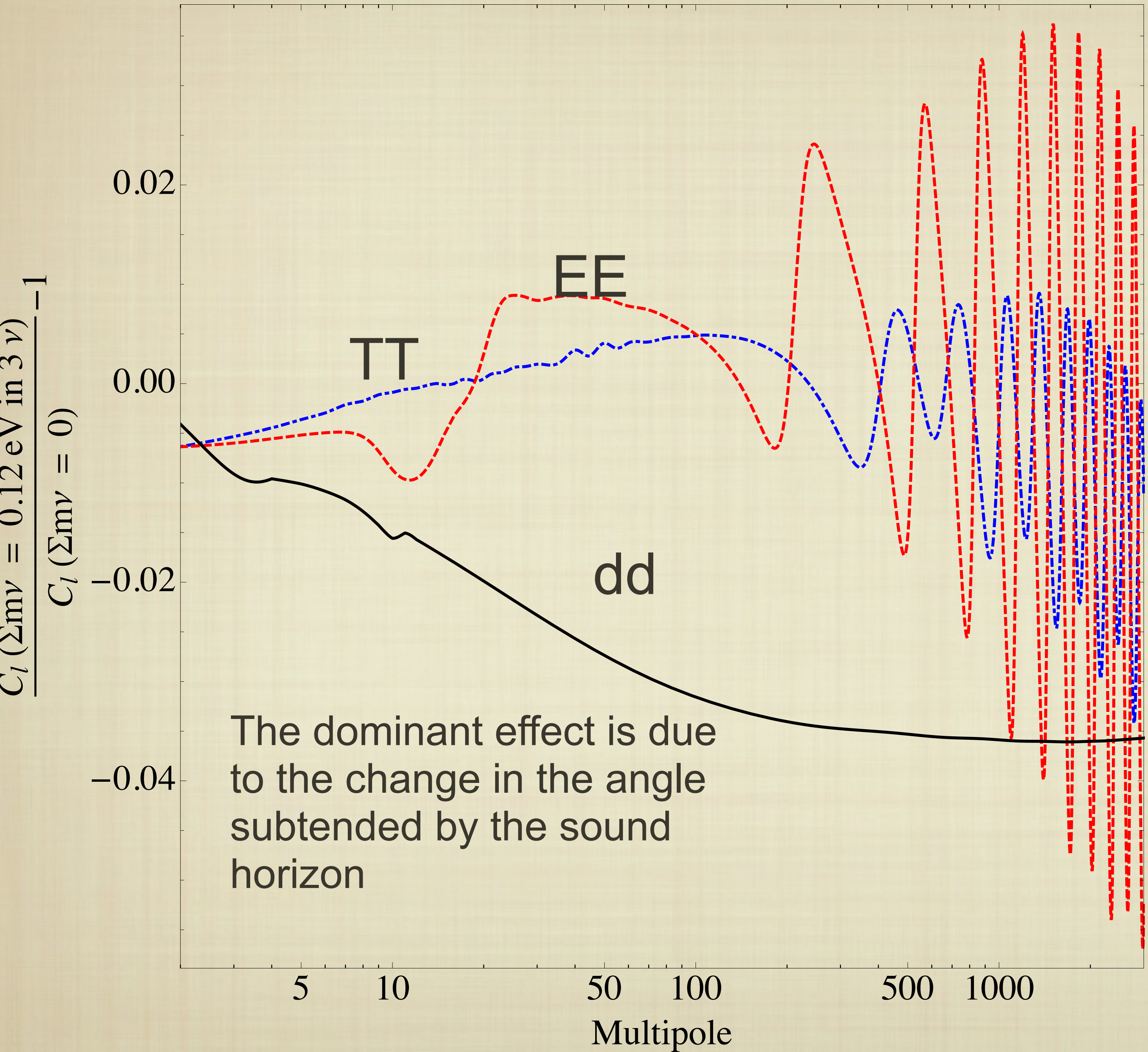
Estimate **d** from CMB maps
Hu and Okamoto, 2002

Effect of Lensing on galaxy shapes: Cosmic Shear



Distortion matrix : $\nabla_i d_j$

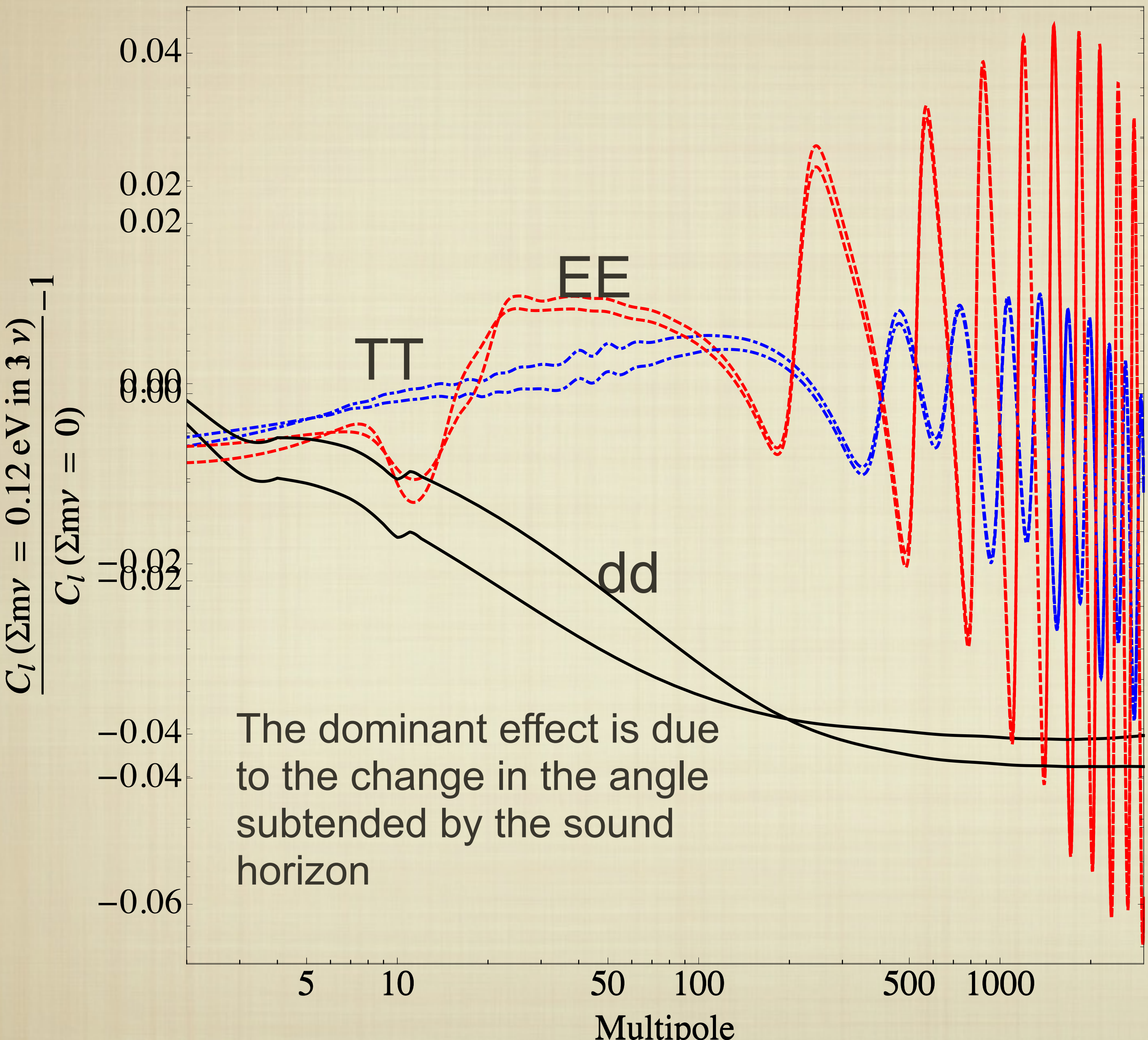
Effect of massive neutrino on CMB lensing



Unlensed TT, EE not the way for precision Σm_ν.

Best CMB constraints from lensing deflection measure (dd)

Effect of massive neutrino on CMB lensing

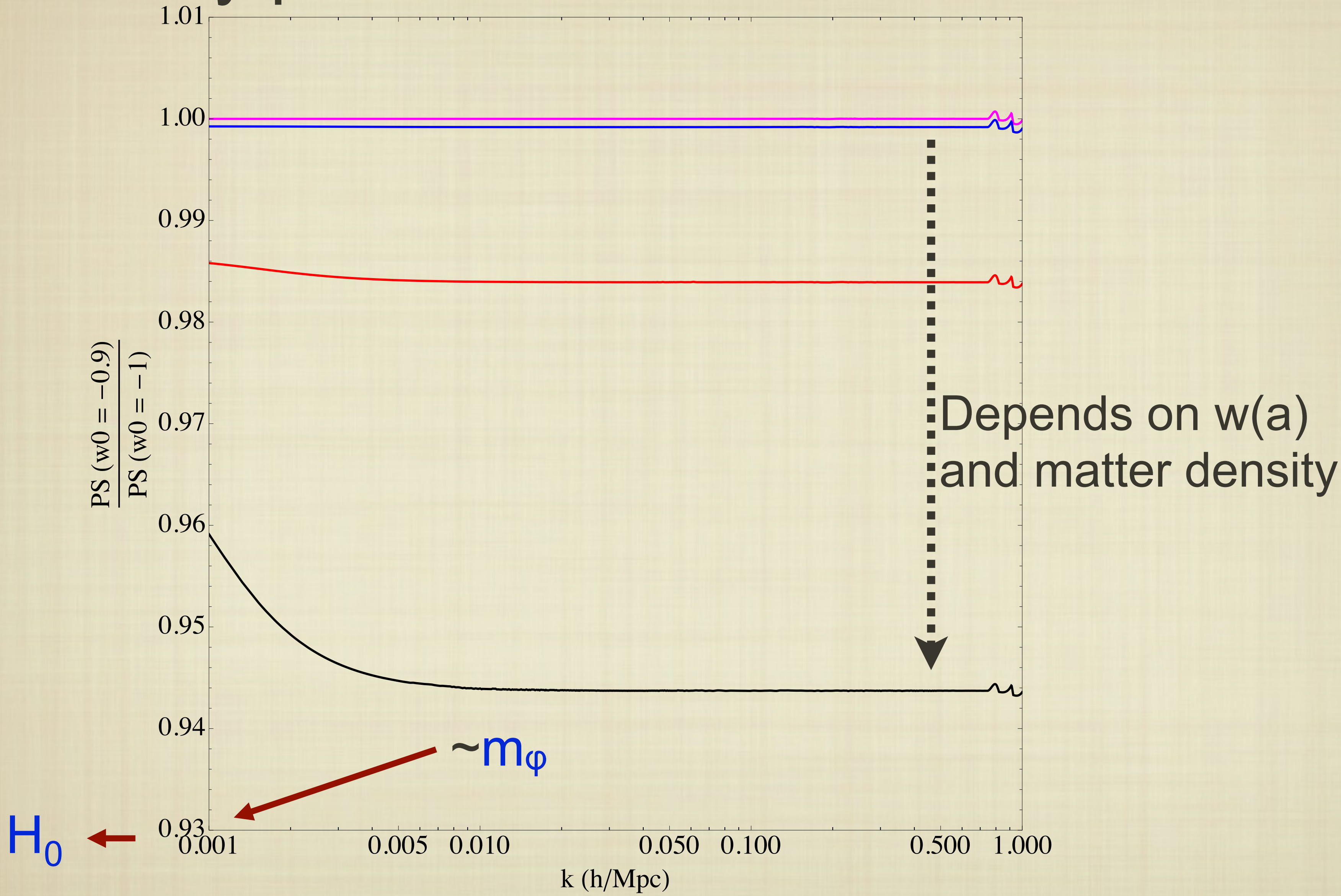


Unlensed TT, EE not the way for precision Σm_ν.

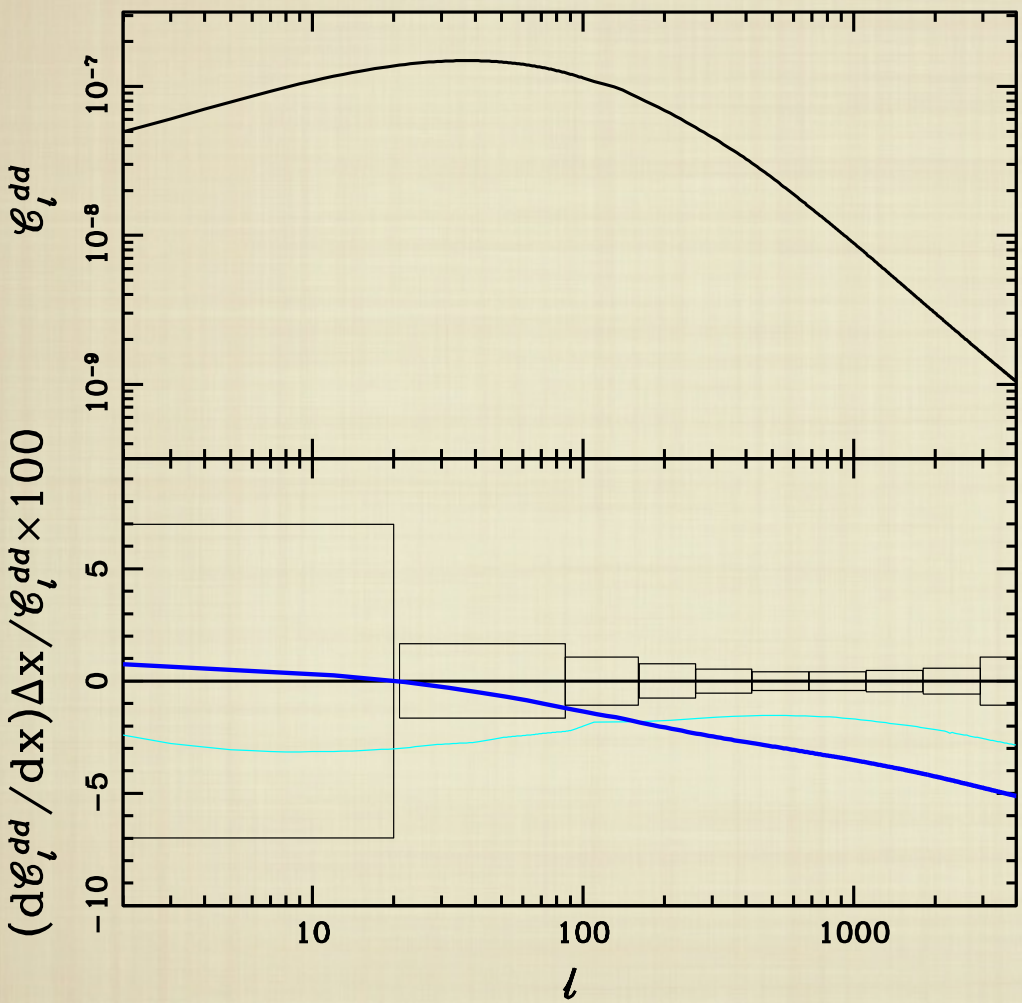
Best CMB constraints from lensing deflection measure (dd)

The dominant effect is due to the change in the angle subtended by the sound horizon

Effect of dynamical dark energy on the density perturbations



Neutrino mass and dark energy: can we infer them separately?



Kaplinghat, Knox and Song, PRL (2003)

The answer is yes! **

** if DE is only important at late times

Both ν mass and DE are unknown late-time effects.

Prospects: CMB Lensing

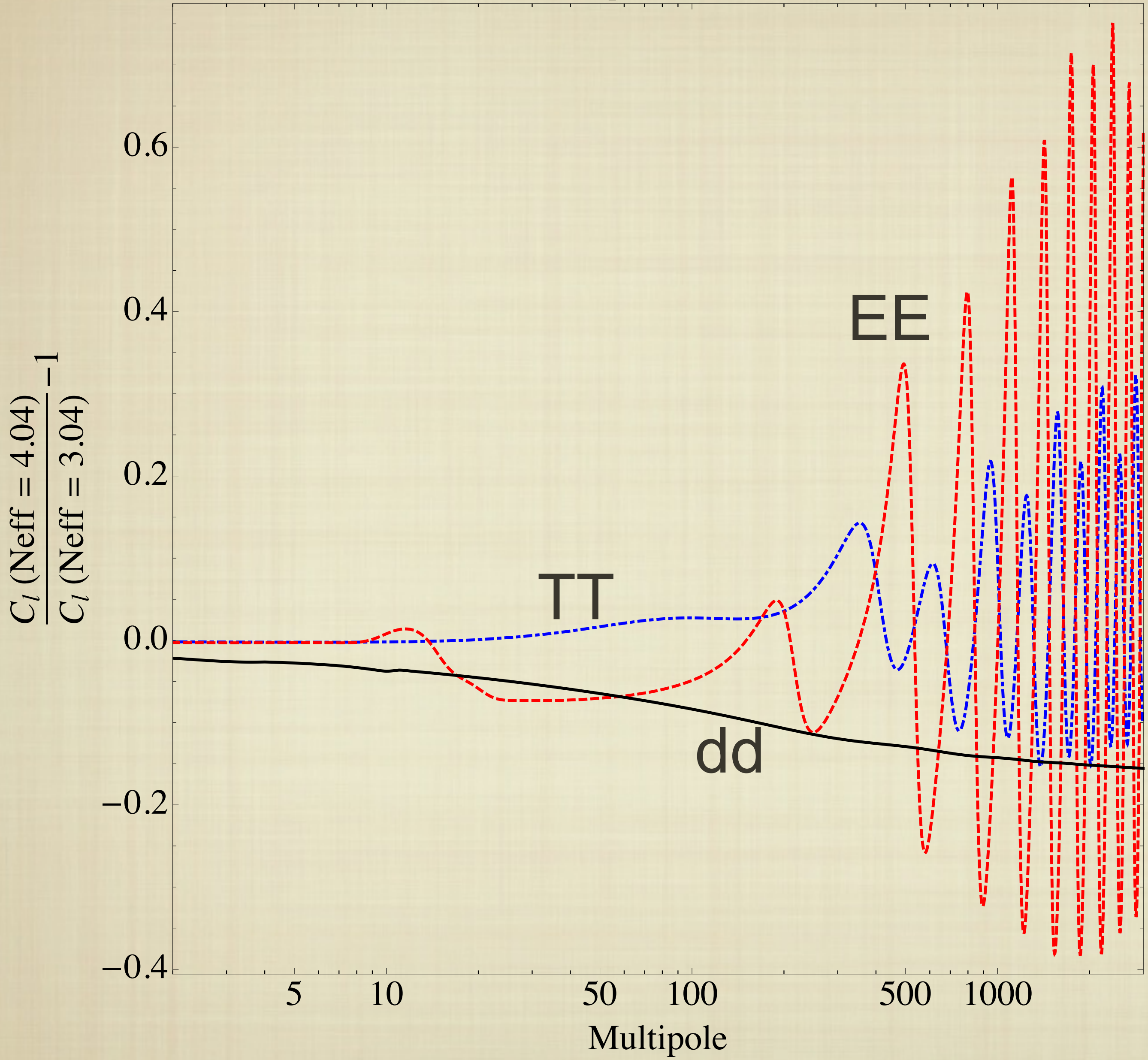
CMB lensing (by itself) can measure the effect of finite neutrino mass allowing for DE EOS and running at the level of ~ 40 meV (1σ).

Kaplinghat, Knox and Song, PRL 2003

Free parameters:	8 parameters of minimal ΛMDM				same + $\{\alpha, w, N_{\rm eff}\}$			
Lensing extraction:	no	no	yes	yes	no	no	yes	yes
Foreground cleaning:	perfect	none	perfect	none	perfect	none	perfect	none
QUaD+BICEP	1.3	1.6	0.31	0.36	1.5	1.9	0.36	0.40
BRAIN+ClOVER	1.5	1.8	0.34	0.43	1.7	2.0	0.42	0.51
Planck	0.45	0.49	0.13	0.14	0.51	0.56	0.15	0.15
SAMPAN	0.34	0.40	0.10	0.17	0.37	0.44	0.12	0.18
Planck+SAMPAN	0.32	0.36	0.08	0.10	0.34	0.40	0.10	0.12
Inflation Probe	0.14	0.16	0.032	0.036	0.25	0.26	0.035	0.039

Lesgourgues, Perroto, Pastor, Piat PRD 2006

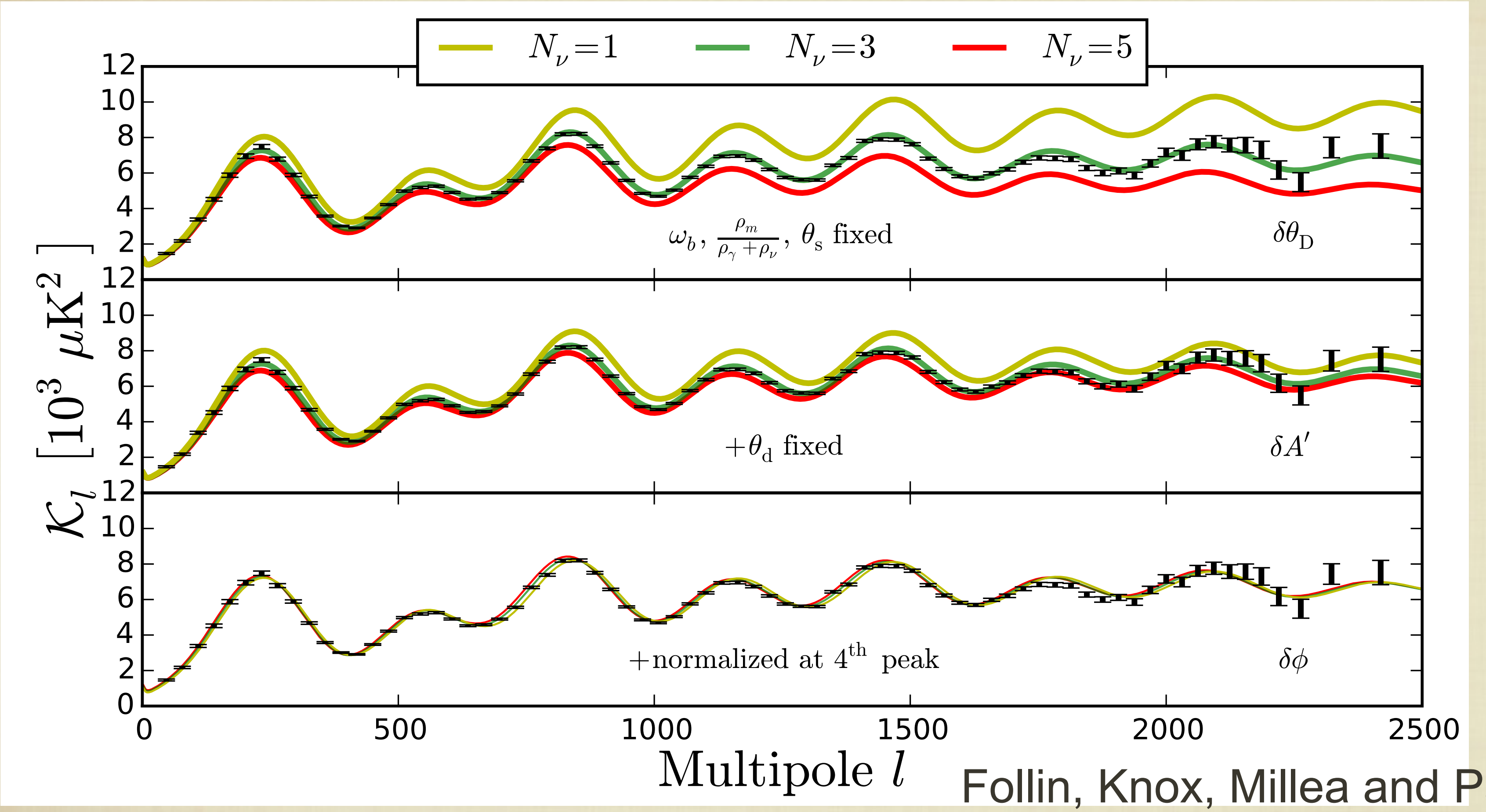
Extra radiation parameterized as N_{eff}



Not a late time effect, but since CMB lensing is an integrated effect, this is important.

Phase shift: a way to measure N_{eff} precisely

Information in phase shift: Bashinsky and Seljak 2004
(separate from damping!)



Follin, Knox, Millea and Pan 2015

Future: $\sigma(N_\nu)$ ~ 0.3 (Planck polarization), 0.1 (CMB-S4)

Baumann, Green, Meyers and Wallisch 2015 (very nice description of the physics)

Key caveat

Cosmological probes are sensitive to the energy density of neutrinos.

While the Jeans length does depend on the mass, it does not seem that we will be able to exploit this scale dependence to measure the mass hierarchy *directly.*

Current limits: assuming base ΛCDM model

$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP};$$
$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO};$$
$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$
$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

95% C.L. assuming ΛCDM (Planck 2015 results XIII)

WMAP+HST+CMASS (conservative): $\sum m_\nu < 0.36$ eV

(95% C.L. De Putter et al 2012)

Current limits: effect of dark energy EOS

DE with constant EOS+CDM+flatness (wCDM)

WMAP7+H_0+BAO (SDSS): $\sum m_\nu<1.3$ eV

WMAP7+SNe (constitution)+BAO (SDSS): $\sum m_\nu<0.9$ eV

WMAP7+LRGs (SDSS)+H_0: $\sum m_\nu<0.8$ eV

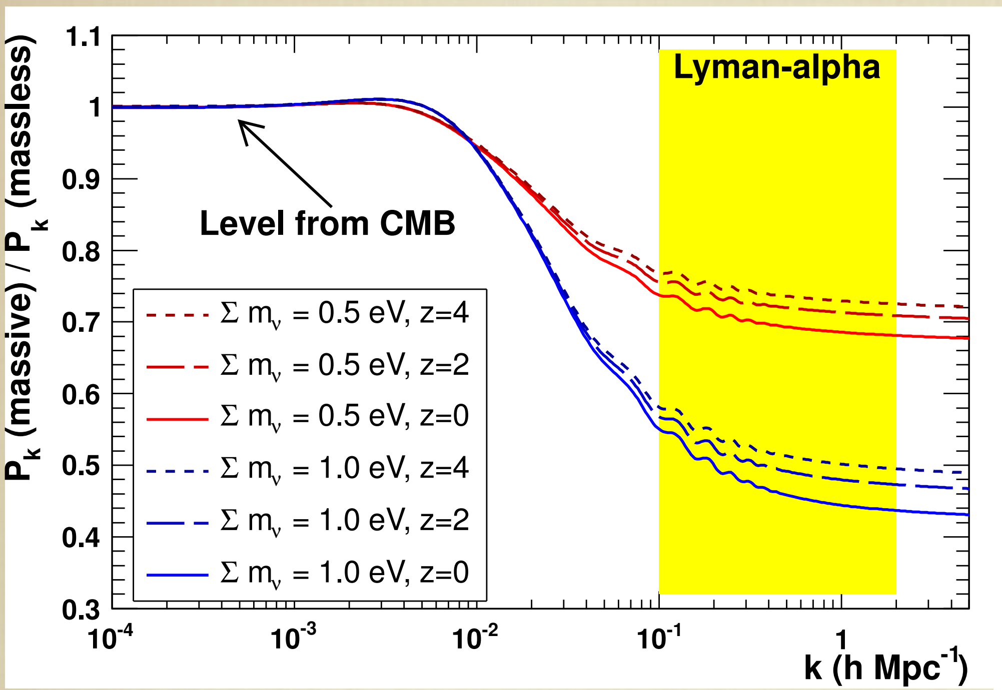
Previous+SNe (constitution): $\sum m_\nu<0.5$ eV

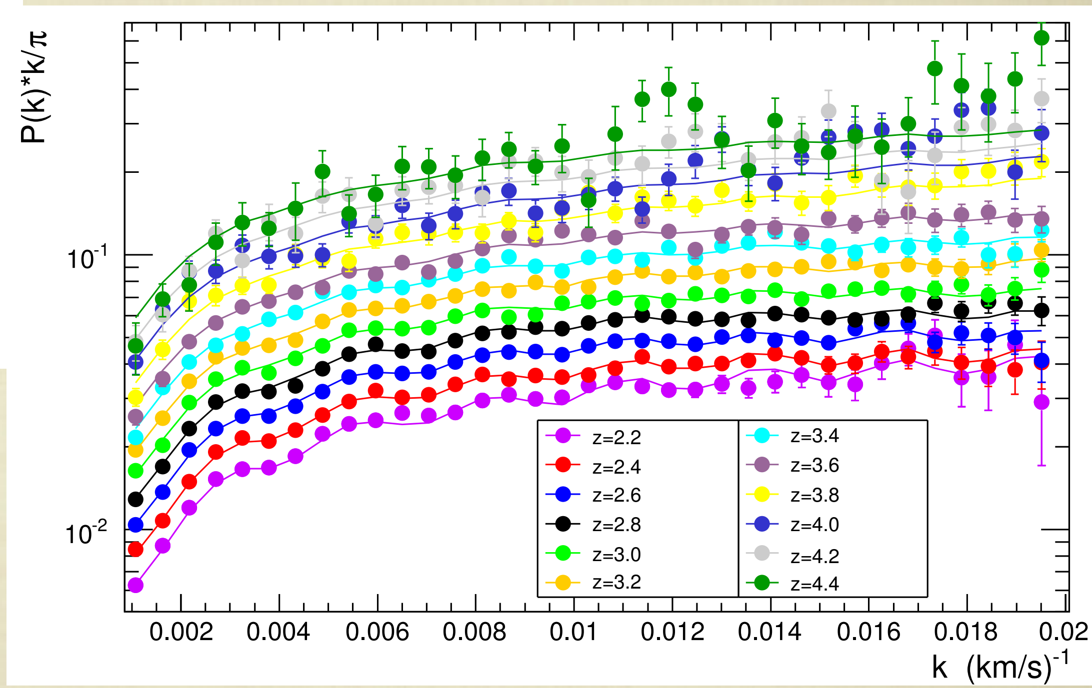
(95% C.L. WMAP collaboration)

Planck (including lensing)+WMAPpol+SDSS DR9: $\sum m_\nu<0.48$ eV

(95% C.L. Guisarma et al 2013)

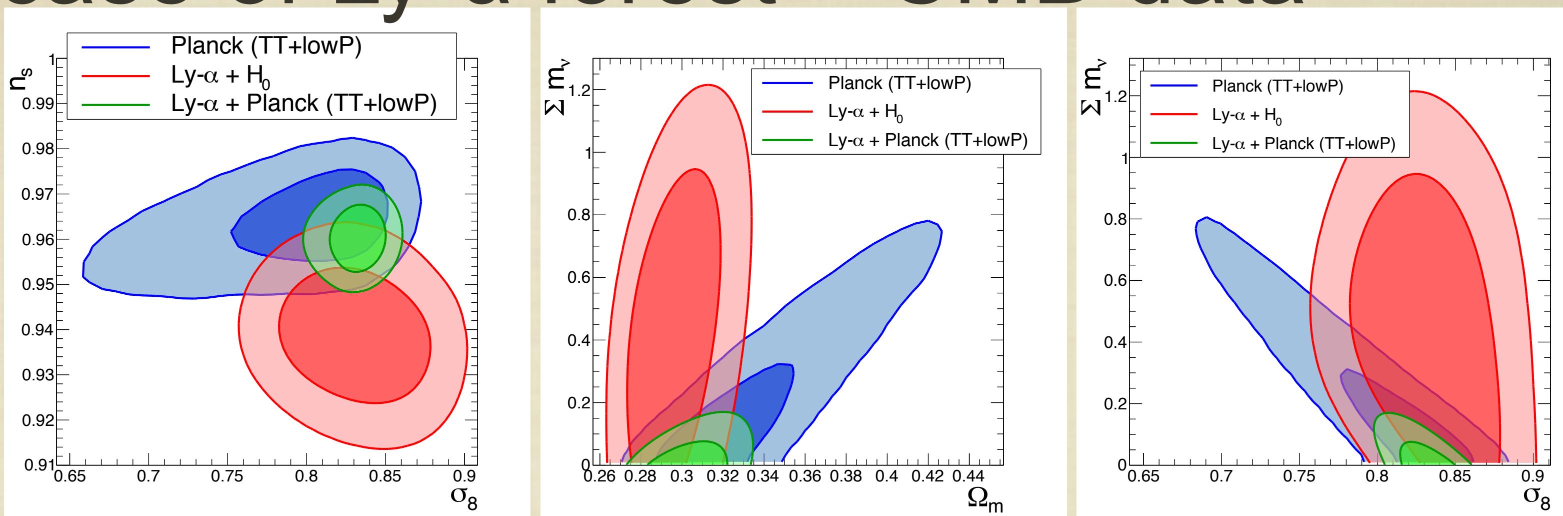
Current limits: complementarity of data sets — the case of Ly-α forest + CMB data





Palanque-Delabrouille et al 2015
(BOSS + Planck 2015)

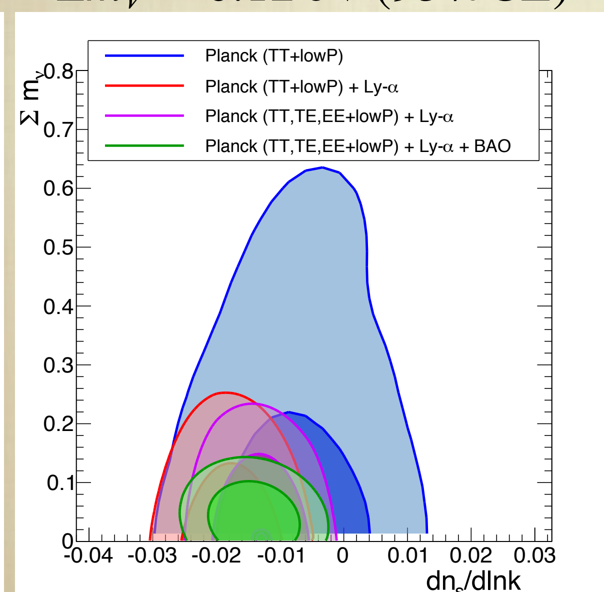
Current limits: complementarity of data sets — the case of Ly-α forest + CMB data



$\Sigma m_\nu < 0.19\,\mathrm{eV}\ (95\%\mathrm{CL})$ Planck (TT, TE, EE + lowP) + Lyα

$\Sigma m_\nu < 0.12\,\mathrm{eV}\ (95\%\mathrm{CL})$ Planck (TT, TE, EE + lowP) + BAO + Lyα

Palanque-Delabrouille et al 2015



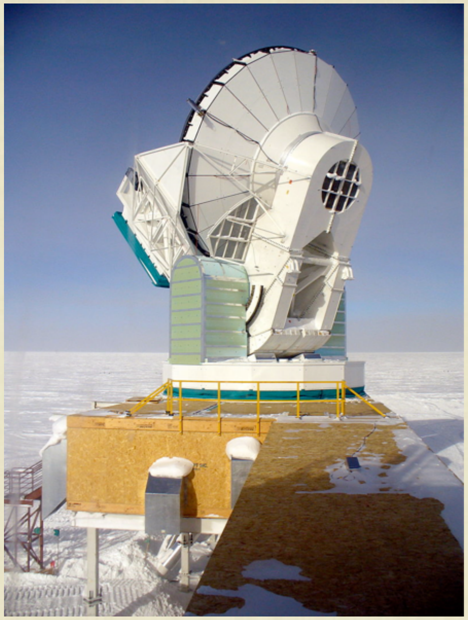
~ 3σ preference for negative running

~ 2σ with older Ly-α data (Minor and Kaplinghat 2014).

Near Term CMB Lensing Experiments

Atacama Cosmology Telescope Polarization (ACTPol)

South Pole Telescope Polarization (SPTPol→SPT-3G)



Near: ACTPol and SPTPol: **$\sigma(\Sigma m_\nu)$ ~ 100 meV; $\sigma(N_{\mathrm{eff}})$ ~ 0.12**

Mid: SPT-3G forecast to **$\sigma(\Sigma m_\nu)$ ~ 74 meV; $\sigma(N_{\mathrm{eff}})$ ~ 0.076**

(Benson et al arXiv:1407.2973; CMB 2015 at U Minnesotta)

Key degeneracies for the future: spatial curvature of the universe

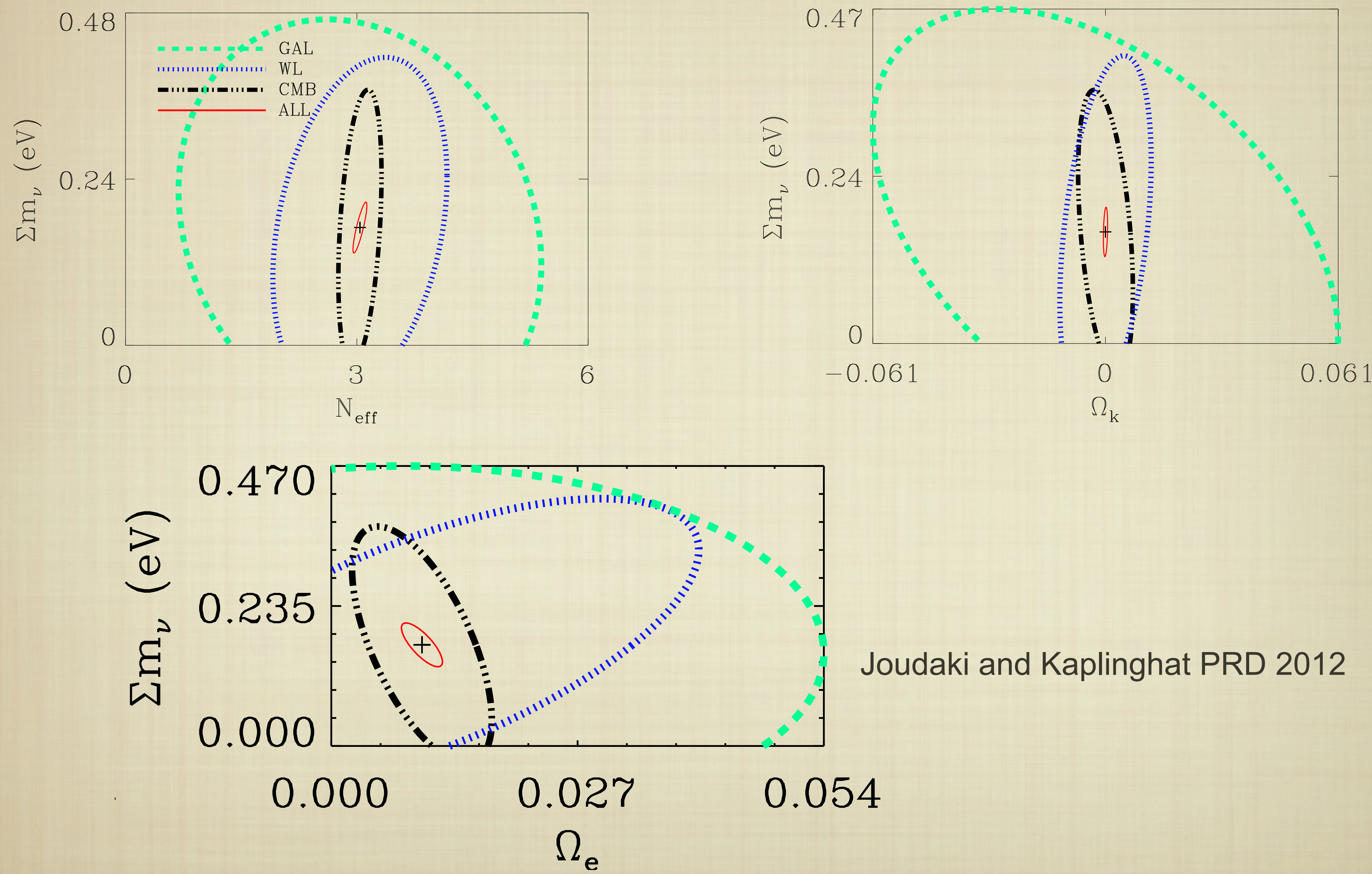
- Degeneracy between neutrino mass and curvature in lensing measurements. Smith, Hu and Kaplinghat, PRD 2004; PRD 2006.

- If neutrino mass measurement is known to 0.1 eV accuracy, then it helps in the determination of curvature (0.3%) and dark energy equation of state from next generation ground based CMB experiments, Planck and SNAP. Smith, Hu and Huterer, ApJL 2007

Key degeneracies for the future: unknown expansion history of the universe

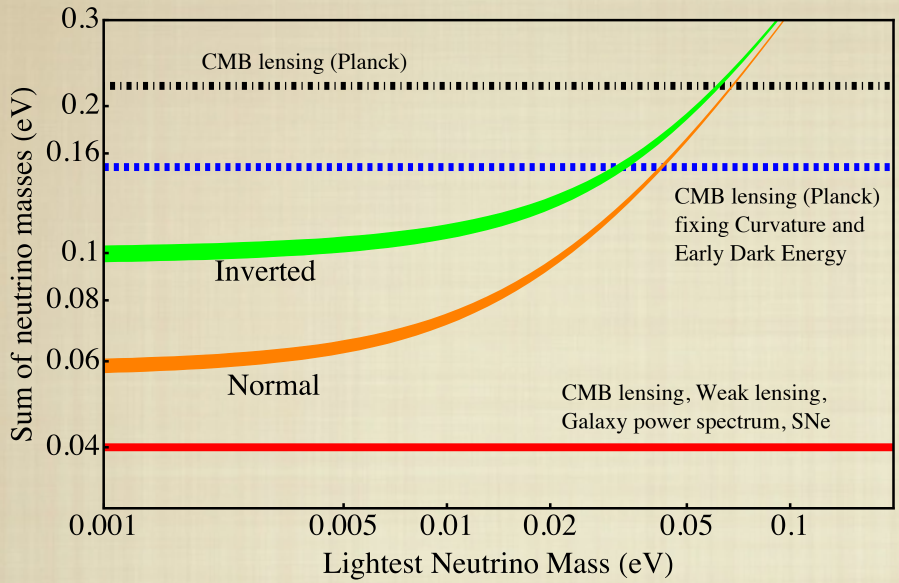
- Parameterizing our ignorance of H(z) in terms of early DE, we find this to be a significant source of degeneracy. (De Putter, Zahn, Linder PRD 2009, Joudaki and Kaplinghat, PRD 2012)
- This degeneracy can be tamed if other data sets are used. Specifically the cosmic shear and CMB lensing degeneracies are not aligned and the addition of these two data sets can extend the reach to the 40 meV level.

Complementarity of data sets: the future



Joudaki and Kaplinghat PRD 2012

Neutrino mass forecasts



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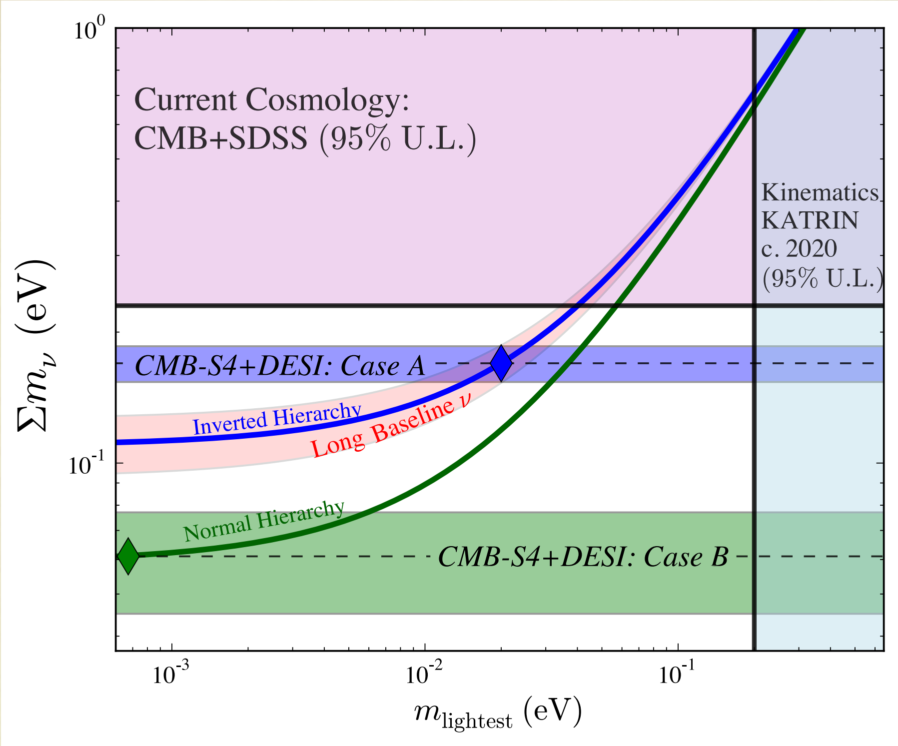

Abazajian et al 2013 (Snowmass)
Wu et al 2014