Recent Results

CMB+LSS

Shahab Joudaki
Collaborators: M. Kaplinghat & K. Abazajian
Center for Cosmology
University of California, Irvine

Agenda

- Signatures of neutrinos
- Neutrino constraints in extended spaces
- Massive Sterile neutrinos
- Neutrino forecast

How many neutrinos?

Open questions: Effective number of neutrinos and their masses

Present Data

- WMAP7+BAO+HST: N_{EFF} = 4.34 +/- 0.87
  (WMAP alone > 2.7 (95% CL))
  Komatsu et al (2011)

- WMAP7+BAO+HST+ACT: N_{EFF} = 4.56 +/- 0.75
  (WMAP+ACT: 5.3 +/- 1.3)
  Dunkley et al (2011)

- WMAP7+BAO+HST+SPT: N_{EFF} = 3.86 +/- 0.42
  (WMAP+SPT: 3.85 +/- 0.62)
  Keisler et al (2011)

How robust are these estimates?

Signatures of N_{eff} (z_{eq}, $\Omega_b h^2$, θ_s, θ_d)

- Matter-radiation equality:

$$1 + z_{\mathrm{eq}} = \frac{\Omega_m}{\Omega_r} = \frac{\Omega_m h^2}{\Omega_\gamma h^2} \frac{1}{1 + 0.2271 N_{\mathrm{eff}}}$$

Keeping z_{eq} and $\Omega_b h^2$ fixed as N_{eff} increases achieved by boosting DM density

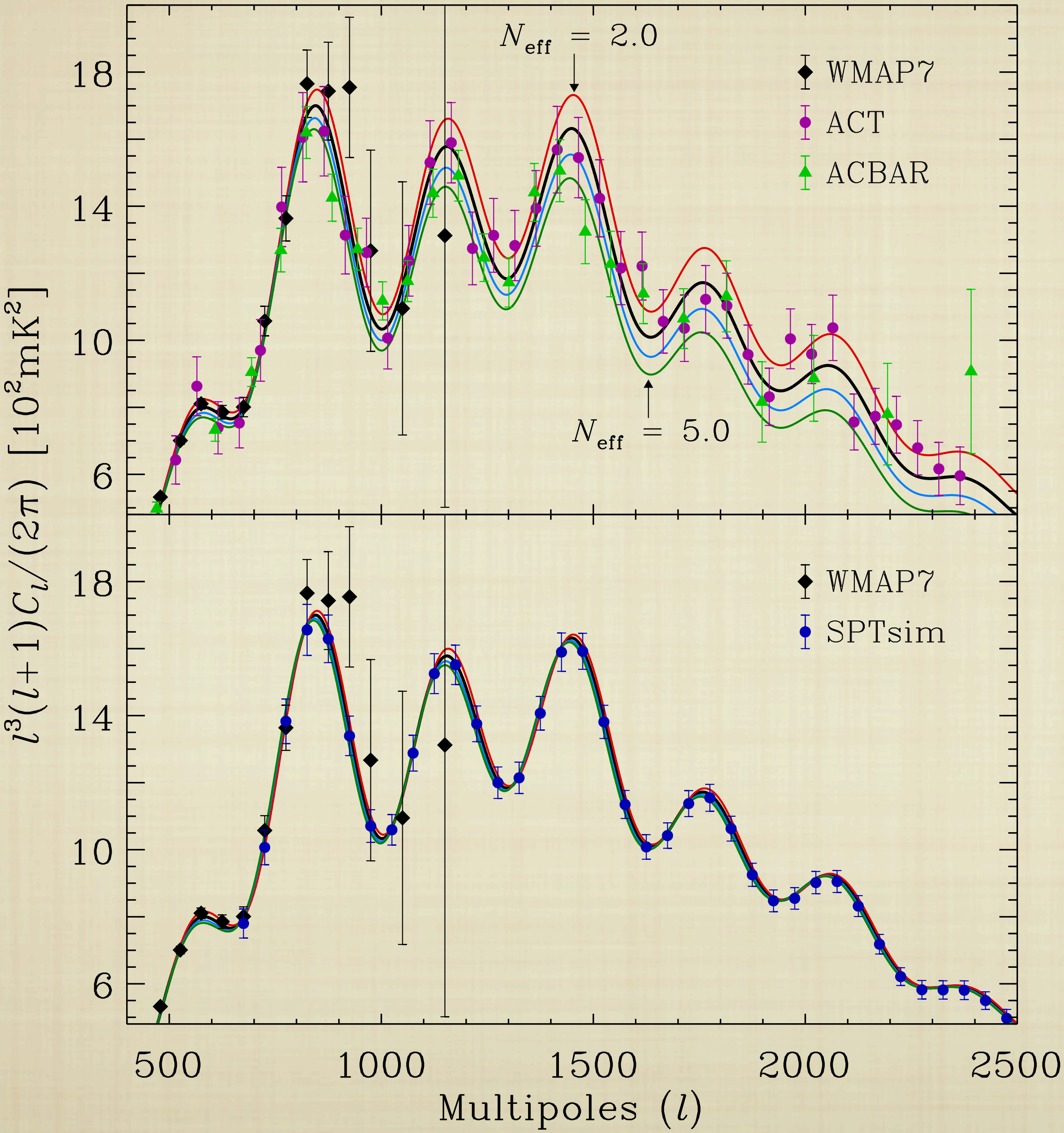
- An increase in N_{eff} gives an increased expansion rate. Keeping θ_s fixed:

$$\theta_d \propto (1 + f_\nu)^{0.25} / \sqrt{1 - Y_p}\, \theta_s$$

Hou et al (2011)

Thus, suppression of CMB damping tail picked out as $N_{\mathrm{eff}} > 3$ when Y_P is known. Constraints relax when Y_P is free.

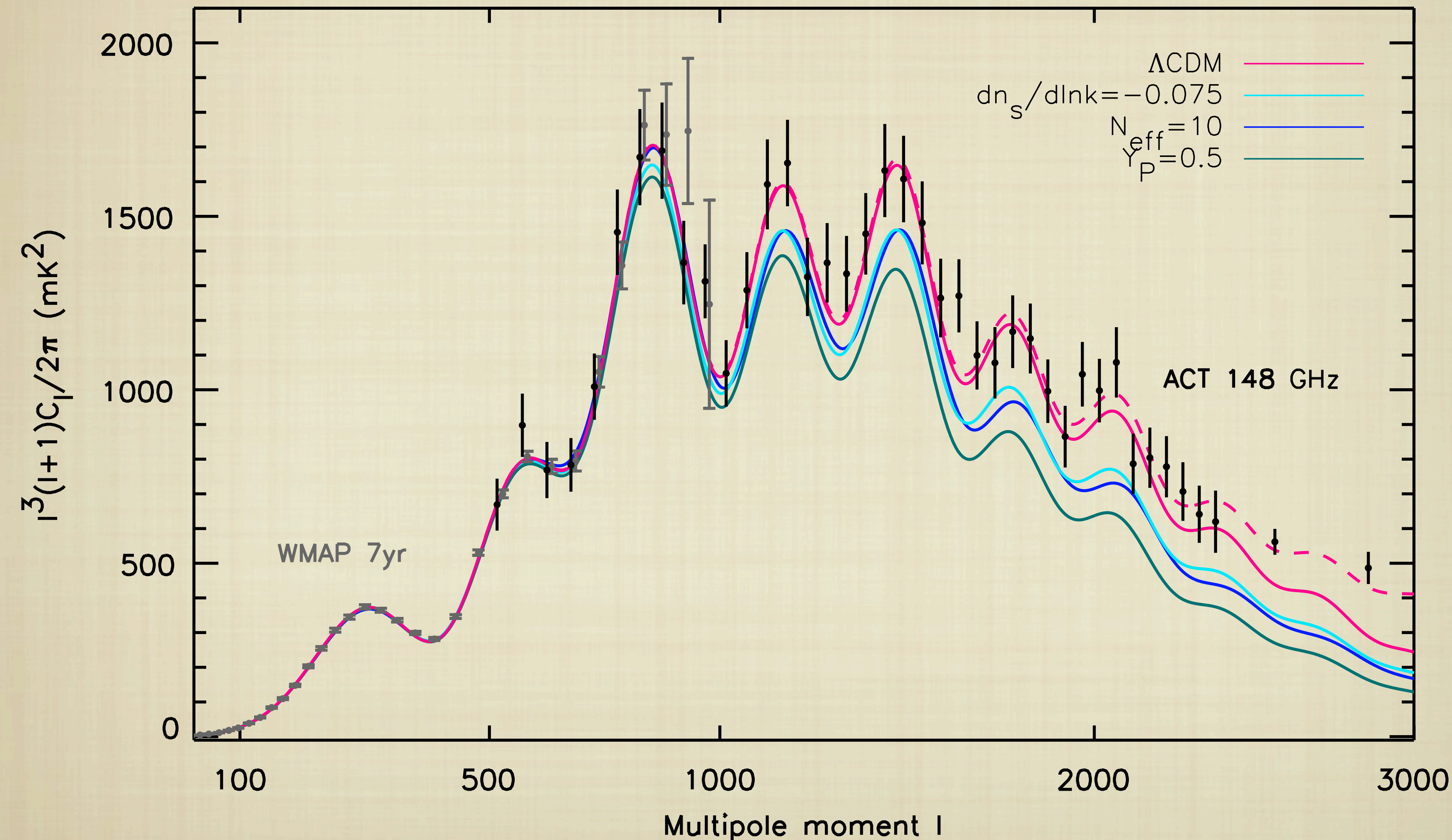
N_{eff} and Y_P



Hou et al (2011)

...And running.

$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_0)\left(\frac{k}{k_0}\right)^{n_s(k_0)-1+\frac{1}{2}\ln(k/k_0)dn_s/d\ln k}$$



Dunkley et al (2011)

Distances

Constraint on N_{eff} can be improved via low-redshift distances and H_0, as these are useful in constraining DM density, and by extension N_{eff}.

However, distances suffer from ignorance of dark energy. Accurate SN distances critical.

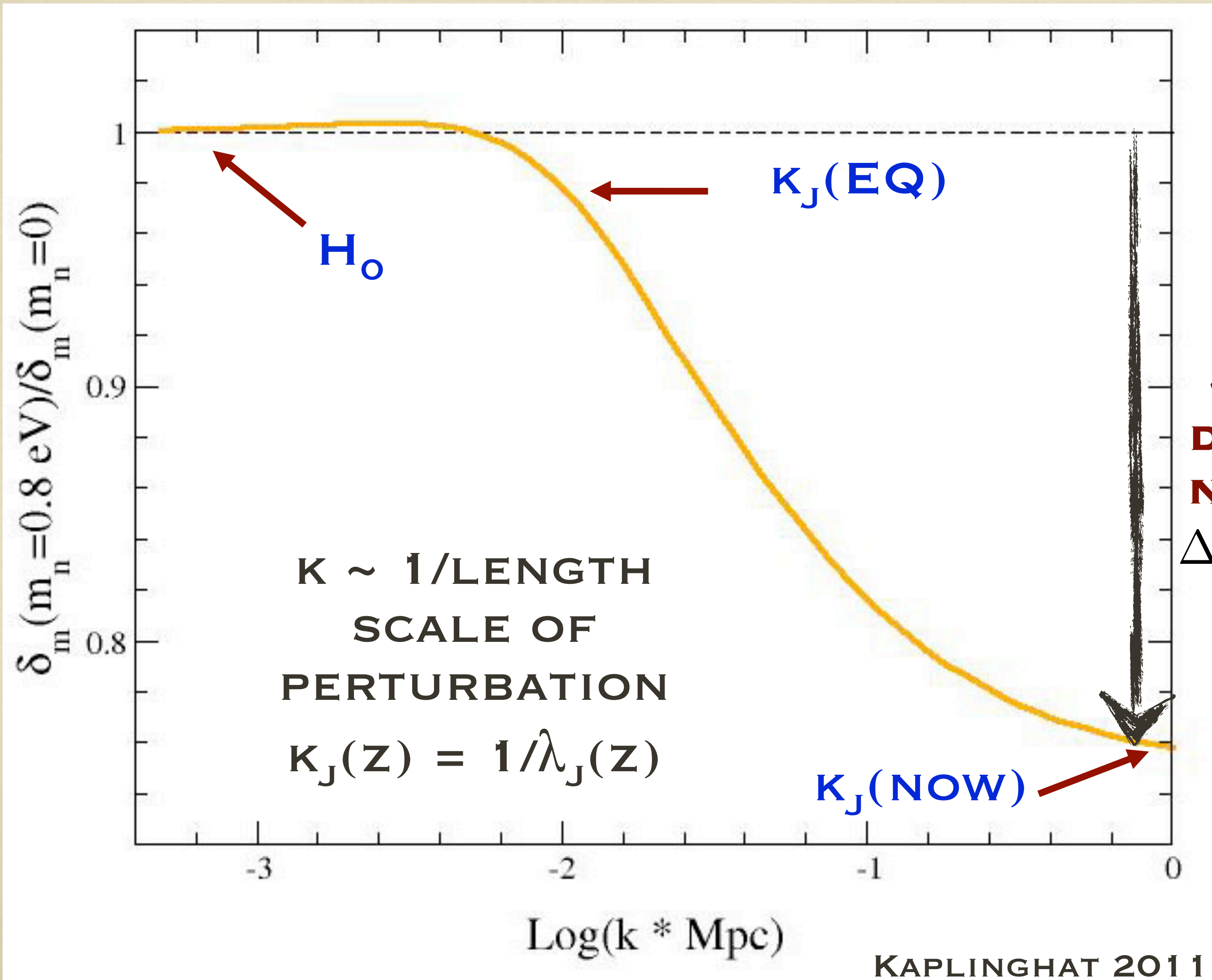
Dark energy moreover correlated with neutrino mass. In CMB TT, neutrino masses shift first peak position to lower ℓ by changing fraction of matter-radiation at decoupling.

Will be correlated with the curvature. Use BAO and H_0 to reduce correlations.

Overdensities w/ Massive Neutrinos

Horizon scale

Galaxy scale



~ energy density in neutrinos

$$\Delta P_m(k)/P_m(k)$$
$$\propto -8\ \Omega_\nu/\Omega_m$$

Agenda

- Signatures of neutrinos
- Neutrino constraints in extended spaces
- Massive Sterile neutrinos
- Neutrino forecast

Constraints in expanded spaces

Given the preference for N_{eff} >3, we relax the strong inflation prior. Large curvature in stringy models and large negative running in multi-field models.

Parameter	Symbol	Prior
Baryon density	$\Omega_b h^2$	$0.005 \to 0.1$
Dark matter density	$\Omega_{\rm dm} h^2$	$0.01 \to 0.99$
Angular size of sound horizon	θ_s	$0.5 \to 10$
Optical depth to reionization	τ	$0.01 \to 0.8$
Scalar spectral index	n_s	$0.5 \to 1.5$
Amplitude of scalar spectrum	$\ln(10^{10} A_s)$	$2.7 \to 4$
Effective number of neutrinos	$N_{\rm eff}$	$1.047 \to 10$
Sum of neutrino masses	$\sum m_\nu$ [eV]	$0 \to 5$
Constant dark energy EOS	w	$-3 \to 0$
Running of the spectral index	$\frac{dn_s}{d\ln k}$	$-0.2 \to 0.2$
Curvature of the universe	Ω_k	$-0.4 \to 0.4$
Primordial helium abundance	Y_p	$0 \to 1$
Present dark energy EOS	w_0	$-3 \to 0$
Derivative of dark energy EOS	w_a	$-10 \to 10$
Early dark energy density	Ω_e	$0 \to 0.2$

Joudaki 2012

ΛCDM with massive neutrinos

SPT+WMAP+H_0+BAO

		ΛCDM	ΛCDM $+ N_{\rm eff}$	ΛCDM $+ \sum m_\nu$
Primary	n_s	0.9648 ± 0.0092	0.981 ± 0.013	0.9661 ± 0.0096
Extended	$N_{\rm eff}$	—	3.87 ± 0.42	—
	$\sum m_\nu$ [eV]	—	—	< 0.45
	Y_p	—	—	—
Derived	σ_8	0.811 ± 0.018	0.862 ± 0.033	0.758 ± 0.042

		ΛCDM $+N_{\rm eff}+\sum m_\nu$	ΛCDM $+N_{\rm eff}+Y_p$	ΛCDM $+N_{\rm eff}+\sum m_\nu+Y_p$
Primary	n_s	0.987 ± 0.013	0.983 ± 0.013	0.987 ± 0.013
Extended	$N_{\rm eff}$	4.00 ± 0.43	3.70 ± 0.54	3.99 ± 0.59
	$\sum m_\nu$ [eV]	< 0.67	—	< 0.73
	Y_p	—	0.277 ± 0.037	0.261 ± 0.039
Derived	σ_8	0.798 ± 0.053	0.860 ± 0.034	0.796 ± 0.055

$\sum M_\nu$ bound competitive with CMASS 0.36 eV

σ_8 decreases as $\sum M_\nu$ increases

$N_{\rm eff}$ 2.2σ when mass included

Spectral index unity at 1-2 σ

From metal-poor extragalactic HII regions: Y_P = 0.2534 +/- 0.0083 (Aver et al 2011)

Joudaki 2012

wCDM with massive neutrinos

SPT+WMAP+H_0+BAO

		wCDM	ΛCDM $+N_{\rm eff}+\sum m_\nu$	wCDM $+N_{\rm eff}+\sum m_\nu$
Primary	n_s	0.958 ± 0.011	0.987 ± 0.013	0.968 ± 0.022
Extended	w	-1.10 ± 0.11	—	-1.31 ± 0.30
	$N_{\rm eff}$	—	4.00 ± 0.43	3.59 ± 0.57
	$\sum m_\nu$ [eV]	—	< 0.67	< 1.2
	Y_p	—	—	—
Derived	σ_8	0.848 ± 0.049	0.798 ± 0.053	0.775 ± 0.063

With w: $N_{\rm eff}$ consistent with 3 to 1σ (down from 2.2σ)

$\sum m_\nu < 1.2$ eV - factor of 2 worse

constraint on w degrades by factor of 3 b/c neutrinos

Joudaki 2012

RELAXING THE STRONG INFLATION PRIOR

SPT+WMAP+H_0+BAO

		ΛCDM $+N_{\rm eff}+\sum m_\nu$ $+\frac{dn_s}{d\ln k}+\Omega_k$	wCDM $+N_{\rm eff}+\sum m_\nu$ $+\frac{dn_s}{d\ln k}+\Omega_k$	wCDM $+N_{\rm eff}+\sum m_\nu+Y_p$ $+\frac{dn_s}{d\ln k}+\Omega_k$
Primary	n_s	0.978 ± 0.015	0.955 ± 0.025	0.949 ± 0.027
Extended	w	—	-1.46 ± 0.39	-1.35 ± 0.41
	$N_{\rm eff}$	3.74 ± 0.58	3.10 ± 0.74	3.38 ± 0.86
	$\sum m_\nu$ [eV]	< 1.2	< 1.2	< 1.4
	$\frac{dn_s}{d\ln k}$	-0.011 ± 0.019	-0.018 ± 0.019	-0.033 ± 0.031
	$100\Omega_k$	0.75 ± 0.93	0.13 ± 0.99	0.76 ± 1.5
	Y_p	—	—	0.196 ± 0.084
Derived	σ_8	0.768 ± 0.070	0.803 ± 0.085	0.779 ± 0.091

$N_{\rm eff}$ 1.2σ instead of 2.2σ (mainly b/c running)

$\sum m_\nu < 1.2$ eV - factor of 2 worse (mainly b/c curvature)

(mass bound at 1.2 eV even when w+curvature)

σ_8 decreases (from 0.80) as $\sum m_\nu$ increases.

Further agreement with $N_{\rm eff}$=3 when w and Y_p included.

Large error bars. curv, w, run within 1σ of null values.

Joudaki 2012

Including Union2 SNe

SPT+WMAP+H_0+BAO+SNe		wCDM	wCDM $+N_{\rm eff}+\sum m_\nu$	wCDM $+N_{\rm eff}+\sum m_\nu$ $+\frac{dn_s}{d\ln k}+\Omega_k$	wCDM $+N_{\rm eff}+\sum m_\nu+Y_p$ $+\frac{dn_s}{d\ln k}+\Omega_k$
Primary	n_s	0.960 ± 0.010	0.981 ± 0.015	0.970 ± 0.019	0.953 ± 0.026
Extended	w	-1.049 ± 0.072	-1.09 ± 0.11	-1.10 ± 0.11	-1.13 ± 0.12
	$N_{\rm eff}$	—	3.88 ± 0.44	3.58 ± 0.60	3.78 ± 0.61
	$\sum m_\nu$ [eV]	—	< 0.92	< 1.2	< 1.7
	$\frac{dn_s}{d\ln k}$	—	—	-0.013 ± 0.019	-0.035 ± 0.030
	$100\Omega_k$	—	—	0.64 ± 0.95	1.2 ± 1.1
	Y_p	—	—	—	0.176 ± 0.079
Derived	σ_8	0.830 ± 0.038	0.790 ± 0.060	0.774 ± 0.072	0.751 ± 0.081

SNe constrain w: 35% reduction for single parameter extension, and factor 4 in full extension.
This helps break correlation with $N_{\rm eff}$ - back to 2σ.
But relaxing strong inflation prior - again 1σ.

Joudaki 2012

Alternative dark energy parameterizations

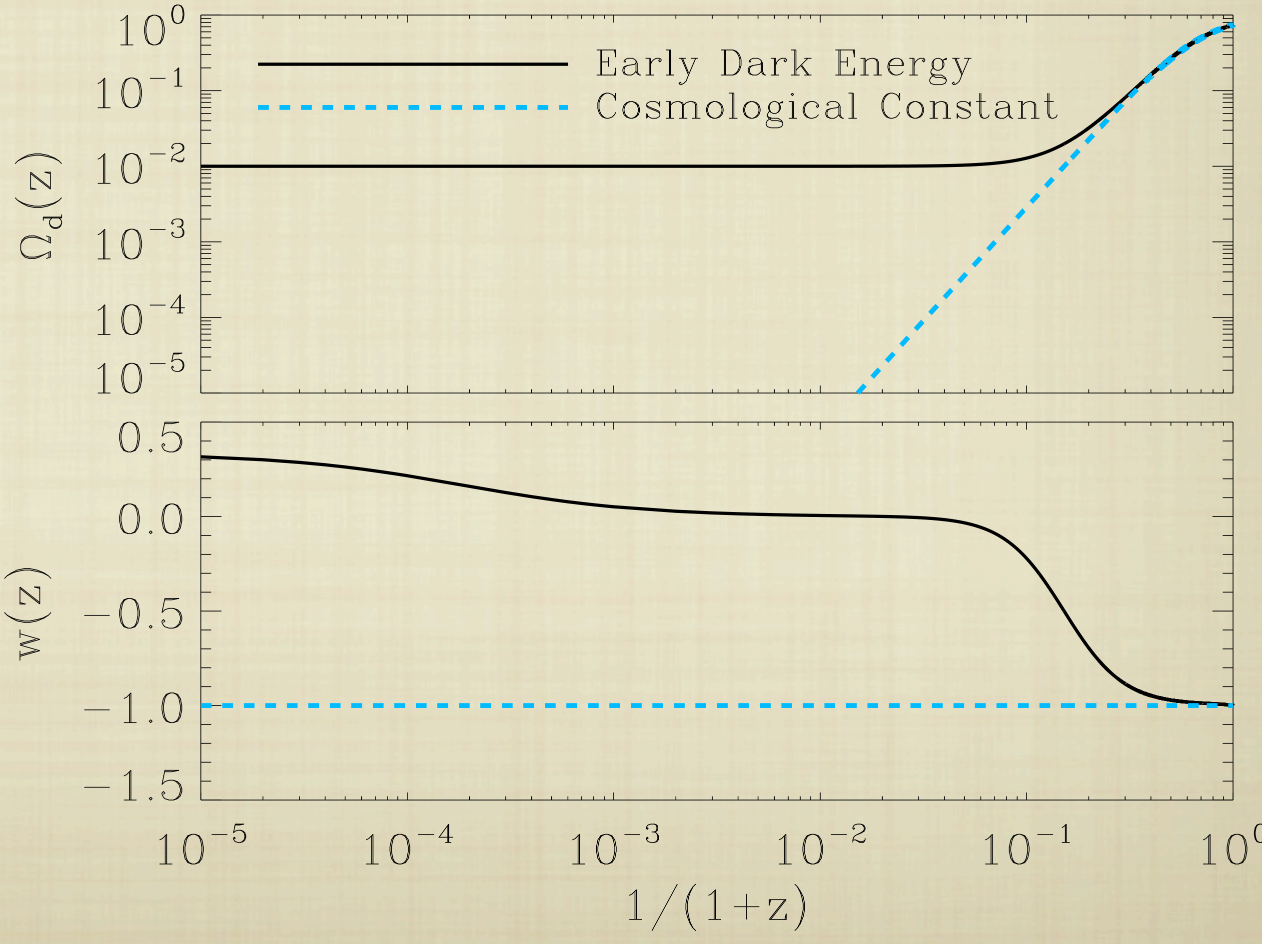
$$w(a) = w_0 + (1-a)w_a$$

Inflation prior enforced: $\sum m_\nu < 1.2$ eV (from 0.9 eV)
Inflation prior relaxed: $\sum m_\nu < 1.4$ eV (from 1.2 eV)

$$N_{\rm eff} = 3.24 \pm 0.63$$
$$\sum m_\nu < 1.6 \text{ eV}$$

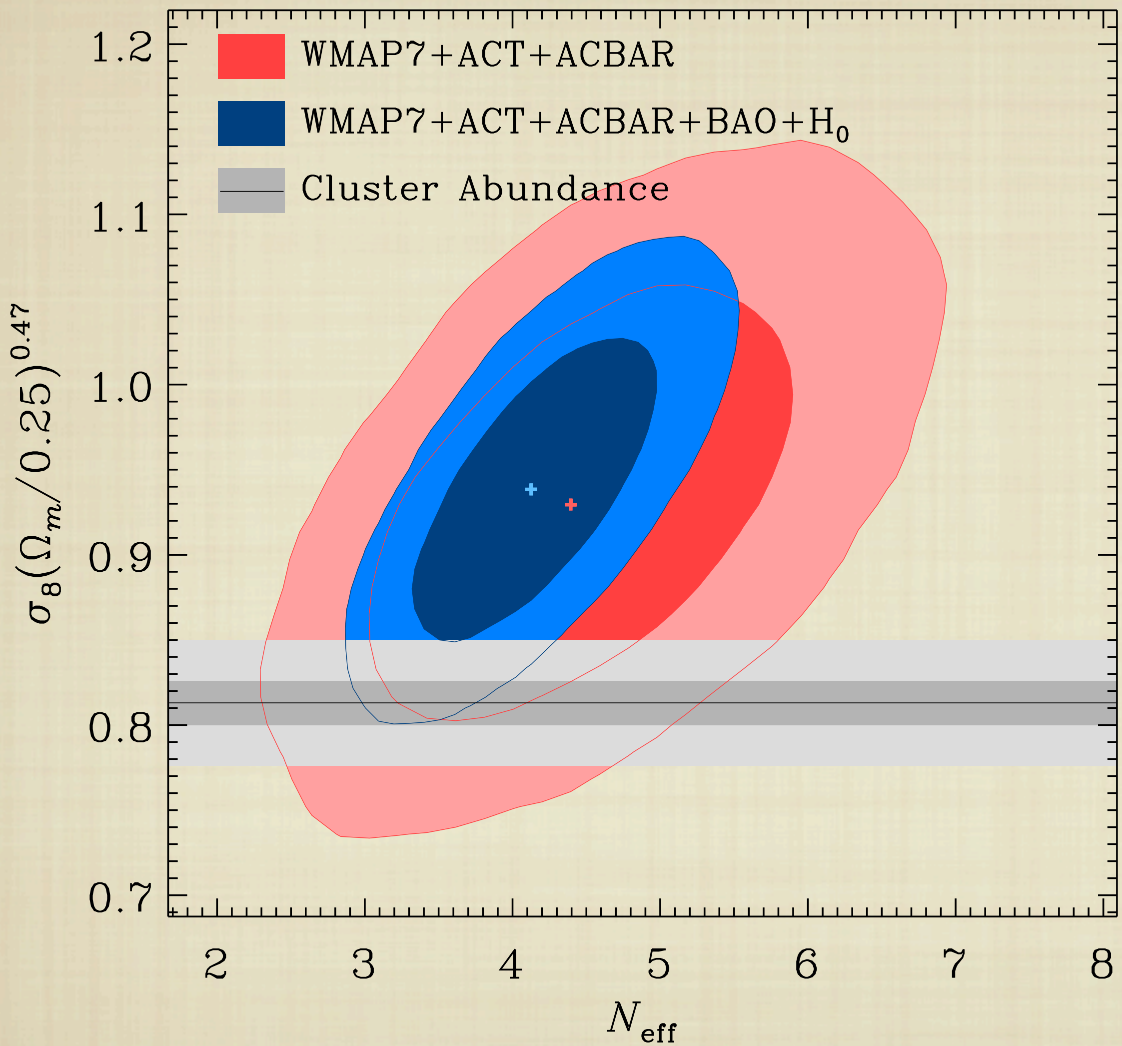
(compared to:
$N_{\rm eff}$ = 3.58 +/- 0.60)
$\sum m_\nu < 1.2$ eV)

w_0 ~ -1.1 +/- 0.2
w_a ~ -0.4 +/- 1
EDE < 0.05



Joudaki 2012

Is there a tension with clusters?



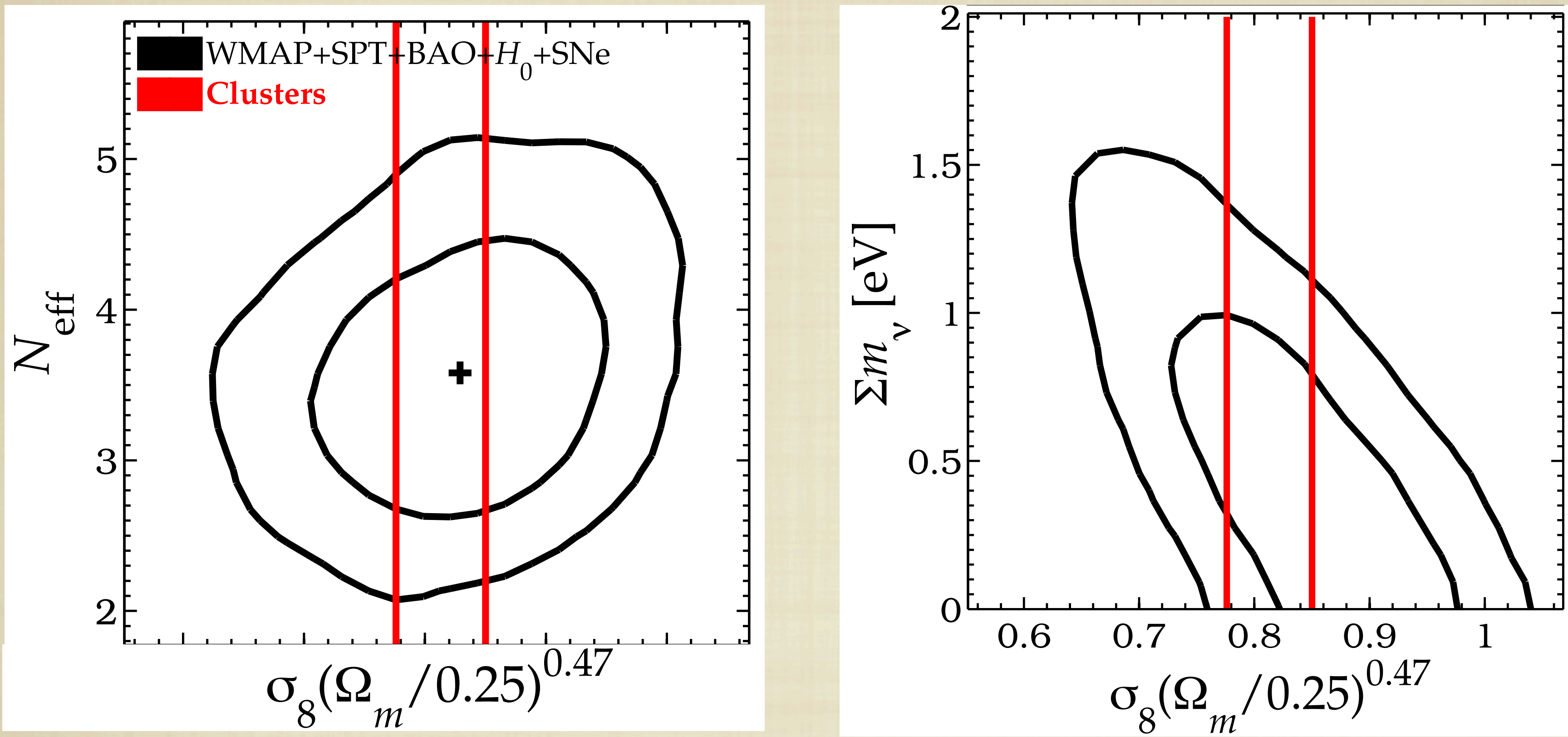
Hou et al (2011)

SPT+*WMAP7*+H_0+BAO+Clusters ⟶ $N_{\rm eff} = 3.42 \pm 0.32$

Keisler et al (2011)

...Not in extended spaces

$\text{vanilla}+N_{\text{eff}}+\sum m_\nu+w+\Omega_k+dn_s/d\ln k$



$\text{WMAP7}+\text{SPT}+H_0+\text{BAO}+\text{SNe}$

Joudaki 2012

Summary

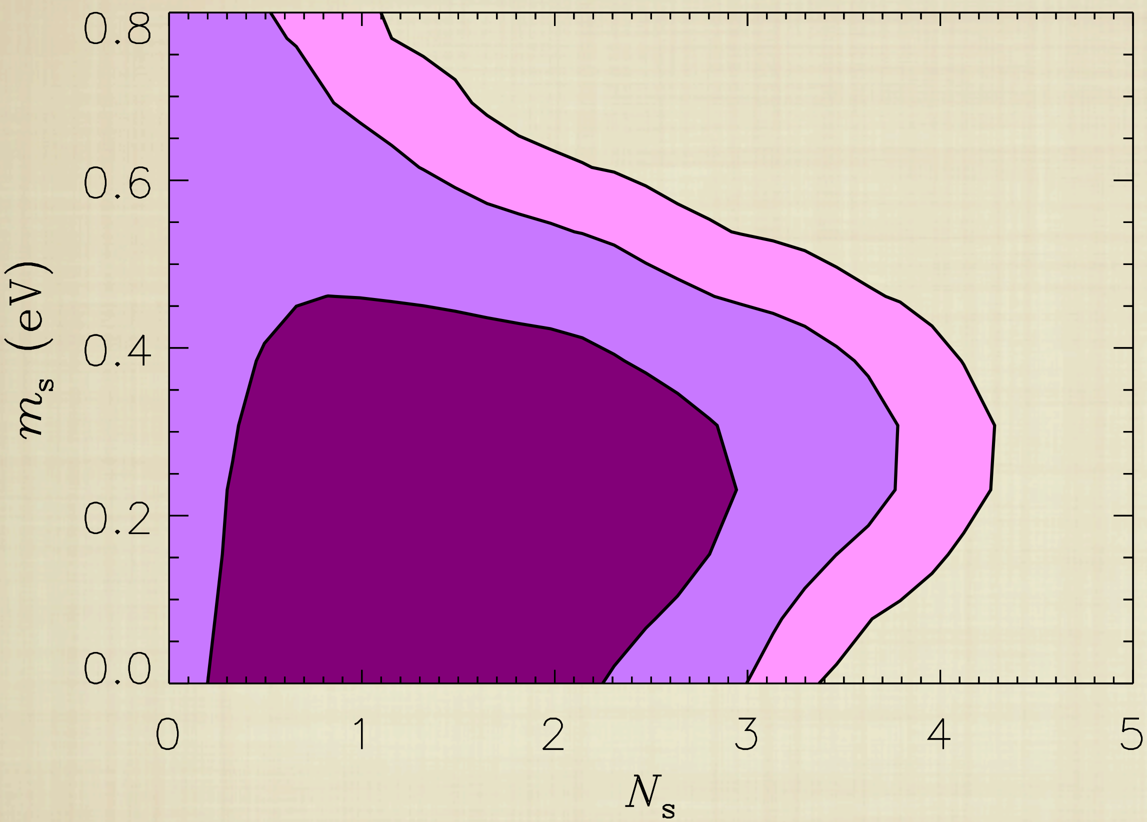
- Given WMAP7+SPT+BAO+HST+SNe, explored dependence of constraints on N_{eff} and $\sum m_\nu$ on underlying cosmology.
- In combined analysis with the mass, $N_{eff} > 3$ at 2.2σ. This becomes consistent with $N_{eff} = 3$ at 1σ in extended spaces.
- The neutrino mass bound degrades from 0.45 eV (95% CL) to 1.0 eV when curvature included, and down to 1.2 eV when DE, N_{eff}, running also included. Further adding helium abundance and EDE degrades bound to 2.0 eV.
- In extensions of cosmological model, σ_8 consistent with cluster abundances at 1σ, Y_P consistent with HII regions at 1σ, and spectral index consistent with unity at 1-2 σ.

Agenda

- Signatures of neutrinos
- Neutrino constraints in extended spaces
- Massive Sterile neutrinos
- Neutrino forecast

Massive Sterile Neutrinos in the Universe?

Let extra contributions to N_{eff} be massive instead of massless.



WMAP7+ACBAR +QUAD+BICEP +P(k)+HST

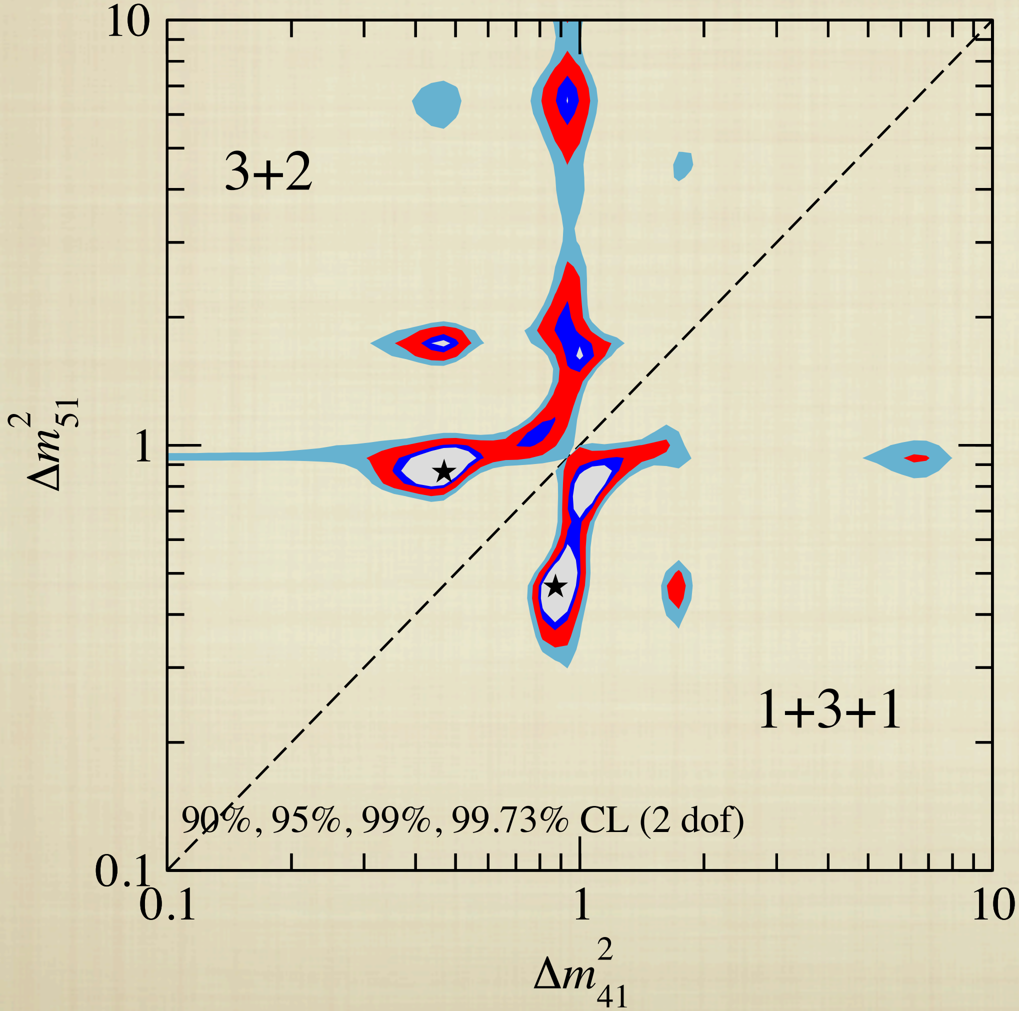
Cosmology does not exclude sterile neutrinos if they are not too massive.

Hamann et al 2010

Extended with w and N_{eff} - Potentially larger masses allowed.

Hamann et al 2011

Are there sterile neutrinos at the eV scale?



Δm^2_{41} = 0.47 eV²

Δm^2_{51} = 0.87 eV²

Kopp, Maltoni, Schwetz (2011)

Use Kopp et al 2011 as prior

3+1:

Δm^2_{41} = 1.78 eV²

Minimal ΛCDM:

$\Delta\chi^2$ = 24.7

curved wCDM:

$\Delta\chi^2$ = 12.0

3+2:

Δm^2_{41} = 0.47 eV²

Δm^2_{51} = 0.87 eV²

Minimal ΛCDM:

$\Delta\chi^2$ = 22.6

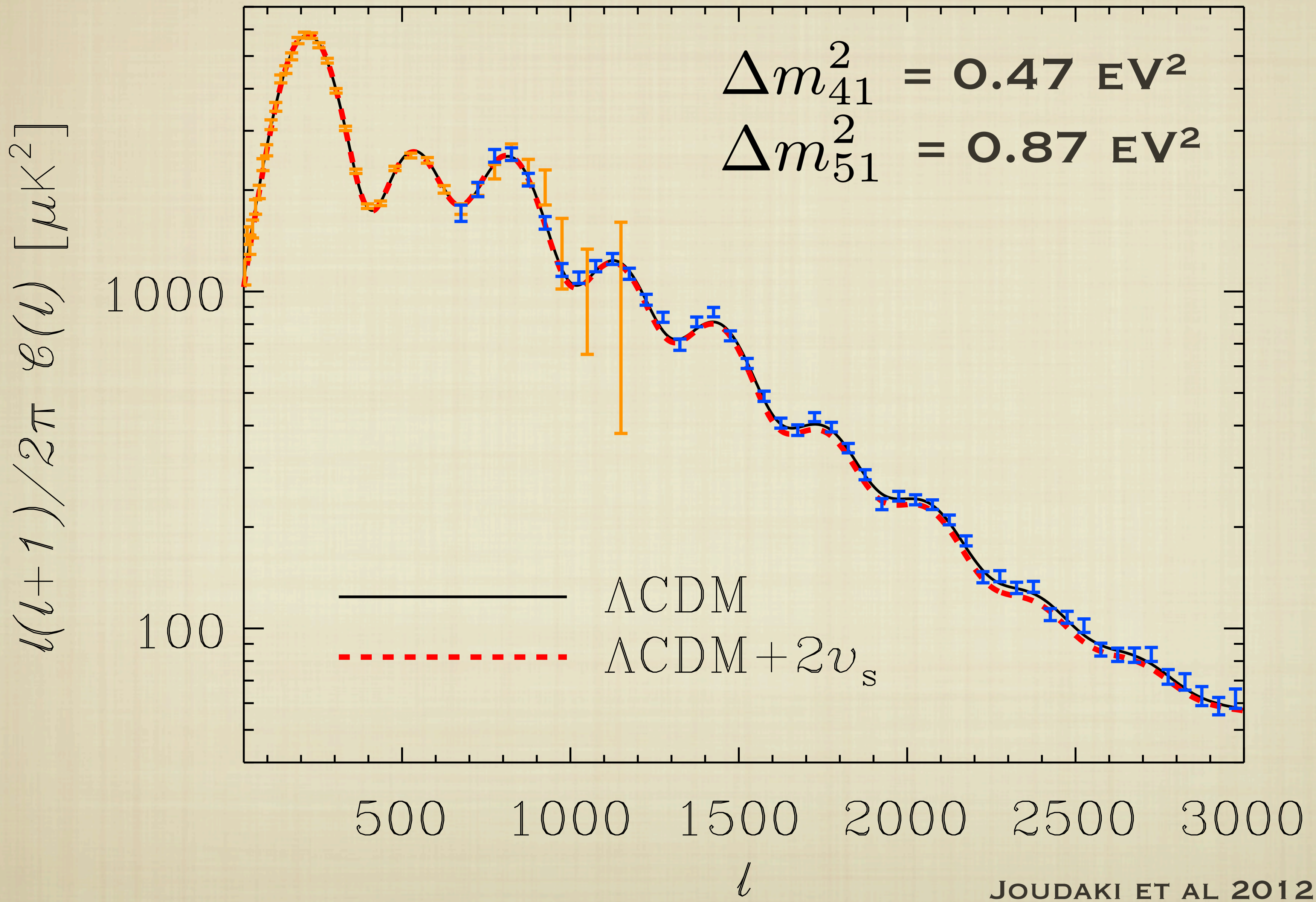
curved wCDM:

$\Delta\chi^2$ = 9.3

WMAP7+P(k)+HST
+SNe (Union2)

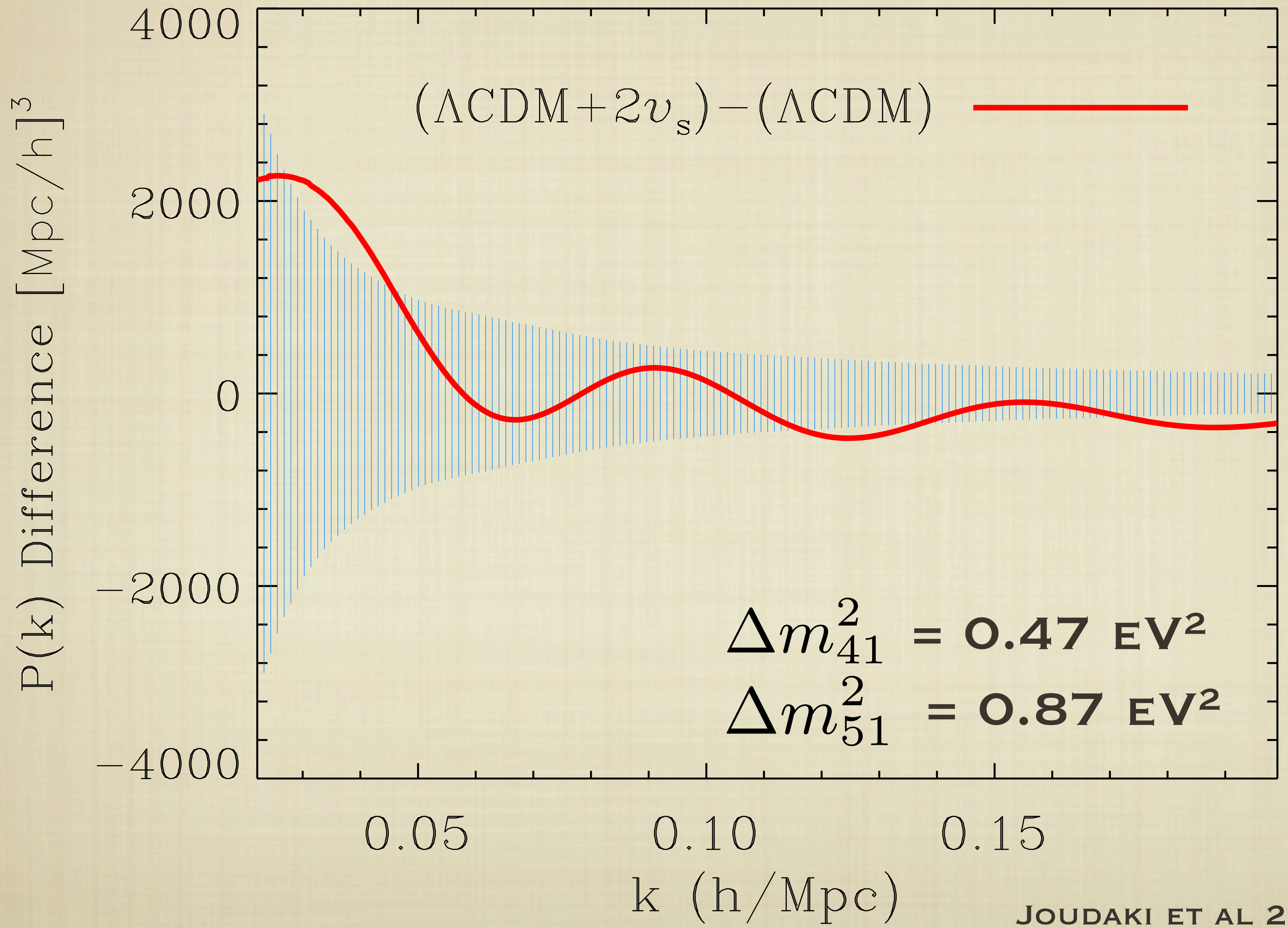
Kristiansen & Elgaroy (2011)

Use Kopp et al 2011 as prior: CMB



Joudaki et al 2012
(in prep)

Use Kopp et al 2011 as prior: P(k)



Joudaki et al 2012
(in prep)

Is 3+2 consistent with cosmology?

WMAP7+SPT+P(k)+HST+SNE (Union2 or SDSS)

		ΛCDM	ΛCDM $+2\nu_s$	ΛCDM $+\text{SNe}_{\text{Union2}}$	ΛCDM $+2\nu_s+\text{SNe}_{\text{Union2}}$	ΛCDM $+\text{SNe}_{\text{SDSS}}$	ΛCDM $+2\nu_s+\text{SNe}_{\text{SDSS}}$
χ^2_{eff}	CMB	7512.4	7517.2	7511.7	7517.9	7513.2	7516.7
	$P(k)$	23.9	28.9	24.5	30.2	23.2	28.7
	H_0	1.5	2.9	1.2	1.5	4.6	3.5
	SNe	—	—	530.8	536.0	245.9	237.9
	FG	0.1	0.6	0.4	0.7	0.1	0.7
	Total	7537.9	7549.5	8068.5	8086.2	7787.0	7787.4
DIC	Total	7554.1	7566.1	8085.2	8103.0	7803.4	7804.1
$\Delta\chi^2_{\text{eff}}$	Total	—	11.6	—	17.7	—	0.4
ΔDIC	Total	—	12.0	—	17.8	—	0.7

$$\text{DIC} = \chi^2_{\text{eff}}(\hat{\theta}) + 2C_b$$

$$C_b = \overline{\chi^2_{\text{eff}}(\theta)} - \chi^2_{\text{eff}}(\hat{\theta})$$

→ If $\Delta C_b = 0$, then $\Delta\text{DIC} = \Delta\chi^2_{\text{eff}}$.

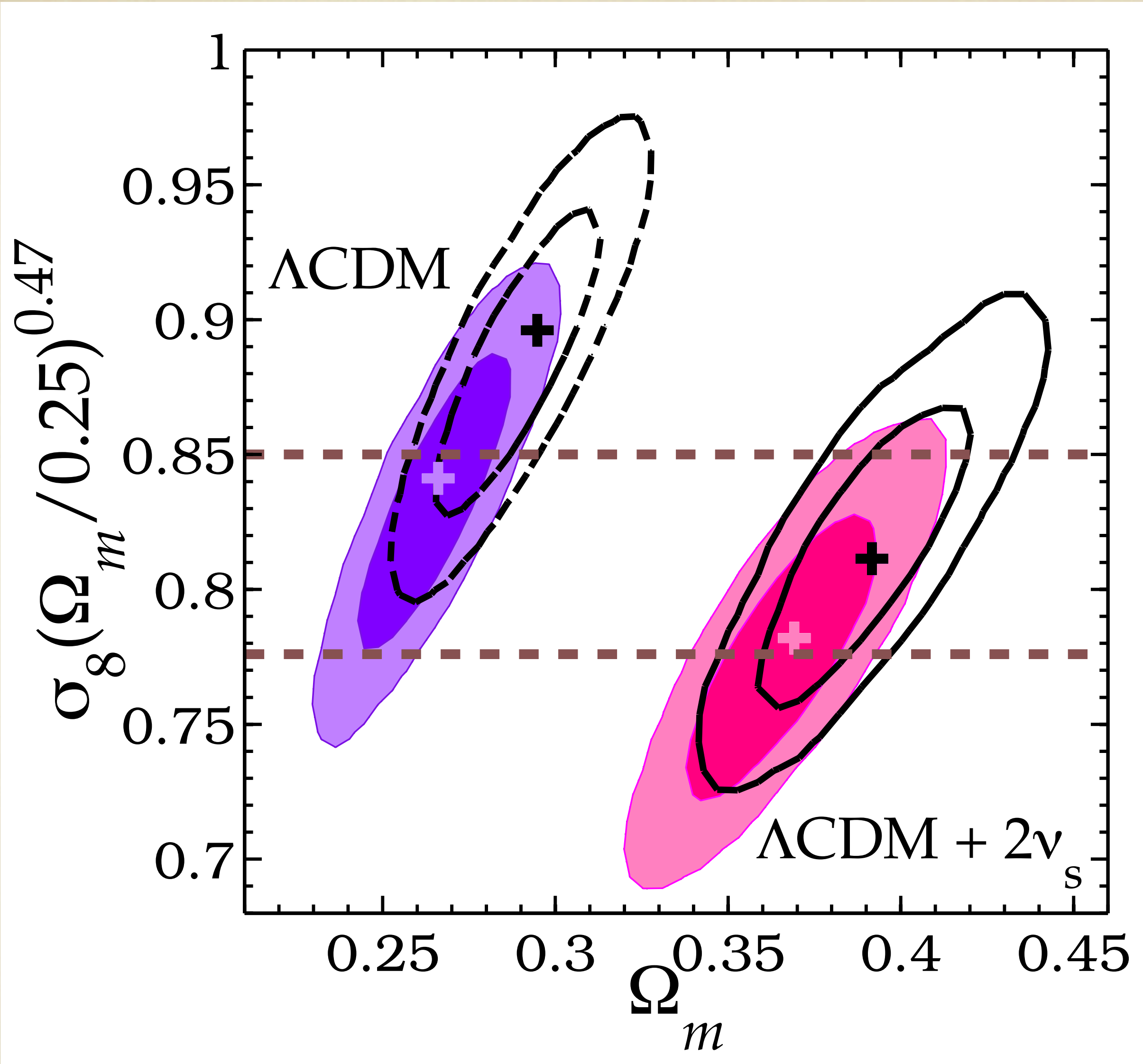
CMB: SPT for small scales

P(k): cutoff at 0.1 h/Mpc (+5 in $\Delta\chi^2$ if out to 0.2 h/Mpc)

Joudaki et al 2012 (in prep)

Increased matter density

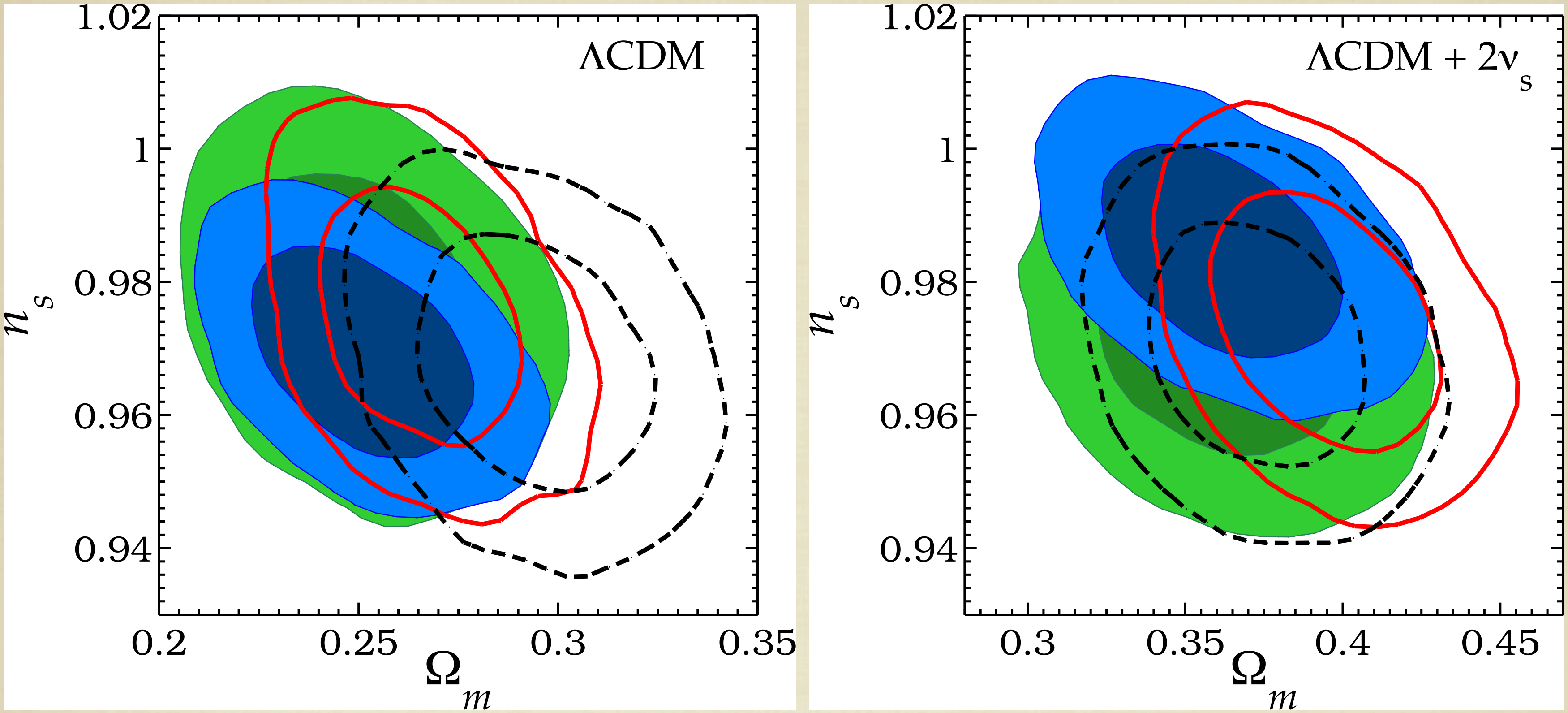
WMAP7+SPT+P(k)+HST+SNe



Filled: Union2
Unfilled: SDSS

Joudaki et al 2012
(in prep)

Consistency of data sets



Green: WMAP Blue: WMAP+SPT Red: WMAP+P(k)

Black: WMAP+SNe (SDSS)

Joudaki et al 2012
(in prep)

Extended parameter spaces

Different results depending on choice of SN light curve fitter. Excluding SNe, to what extent can $\Delta\chi^2 = 11.6$ decrease via parameter extension?

Separately:

w and curvature ~ 2

N_{eff}, Y_P, running ~ 1

2σ extra massless

Jointly: 8.6 --> $\Delta\chi^2 = 3.0$, but ΔDIC = 11.5

Union2: $\Delta\chi^2 = 6.4$ (from 17.7), ΔDIC = 11.5 (from 17.8)

SDSS-SALT2: $\Delta\chi^2 = 7.4$ (from 20.1), ΔDIC = 13.8 (from 19.4)

expanded to expanded (no SNe): $\Delta\chi^2 = 7.2$, ΔDIC = 8.0

Exclude HST. replace P(k) with BAO.

Kopp Prior: $\sum m_\nu^{\mathrm{active}} < 0.19\ \mathrm{eV}$ (from 0.34 eV)

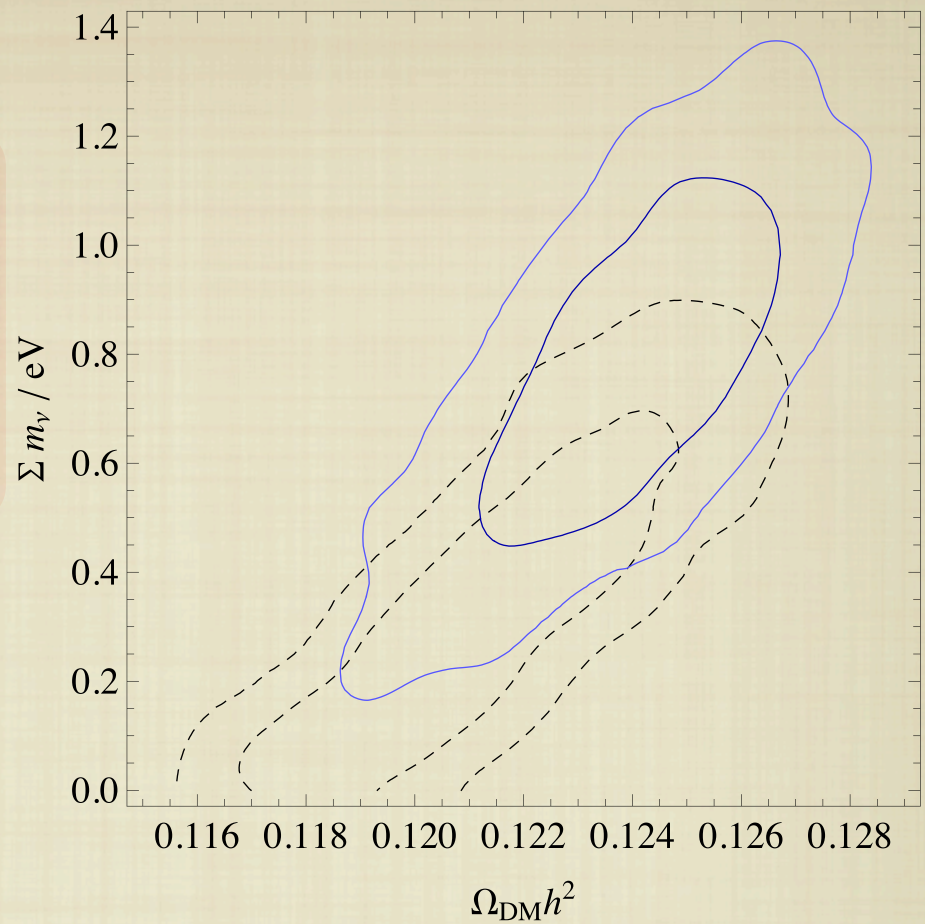
Joudaki et al 2012 (in prep)

F(R) GRAVITY HELPS

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}f(R) + S_m$$

$$\frac{G_{\rm eff}(t,k)}{G} = \frac{1 + 4\frac{k^2}{a^2}\frac{f''}{f'}}{1 + 3\frac{k^2}{a^2}\frac{f''}{f'}}$$

SMALL-SCALE BOOST OFFSETS MASSIVE STERILE NEUTRINOS



WMAP7+P(K)

1EV STERILE NEUTRINO:

$\Delta\chi^2$ = -21.4 (COMPARED TO ΛCDM + STERILE)

DATA: EXCLUDES SMALL-SCALE CMB, BUT K<0.02 H/MPC.
ANALYSIS: SHOULD COMPARE W/ NULL MODEL (E.G. -8.6).

MOTOHASHI, STAROBINSKY, YOKOYAMA (2012)

Summary

- Given WMAP7+SPT+P(k)+HST, 3+2 neutrinos disfavored at $\Delta\chi^2 = 12$. To reconcile with lab, need new physics?
- No single additional parameter can entirely bring $\Delta\chi^2$ or ΔDIC down to zero. Not even all parameters added jointly. Even more exotic physics required?
- However, shifts in $\Delta\chi^2$ of order 20 "easily" already occur in cosmological analyses. For example, based on choice of SN light curve fitter. If SN results converge toward MLCS fitter, then 3+2 perfectly allowed.
- If 3+2 is true, would have large ramifications for other cosmological quantities, such as much larger matter density (from 25% to 35% of critical density).

Agenda

- Signatures of neutrinos
- Neutrino constraints in extended spaces
- Massive Sterile neutrinos
- Neutrino forecast

Forecasting

w_0	Ω_{d0}	Ω_e	$\sum m_\nu(\mathrm{eV})$	n_s	$\frac{dn_s}{d\ln k}$
$10^{10}\Delta_R^2$	$\Omega_c h^2$	$10^3\Omega_b h^2$	$N_{\rm eff}$	τ	Ω_k

Aim: break degeneracies by wide combination of high-z and low-z probes. Functions of P(k) and distances.

First time such a comprehensive future dataset including both auto and cross correlations analyzed. Tough, but kind of cosmological data we will have.

2000
x 13
x 13

$$\mathbf{C}_\ell = \begin{pmatrix} C_\ell^{\{\kappa\}\{\kappa\}} & C_\ell^{\{\kappa\}\kappa_c} & C_\ell^{\{\kappa\}T} & 0 & C_\ell^{\{\kappa\}\{g\}} \\ C_\ell^{\kappa_c\{\kappa\}} & C_\ell^{\kappa_c\kappa_c} & C_\ell^{\kappa_c T} & 0 & C_\ell^{\kappa_c\{g\}} \\ C_\ell^{T\{\kappa\}} & C_\ell^{T\kappa_c} & C_\ell^{TT} & C_\ell^{TE} & C_\ell^{T\{g\}} \\ 0 & 0 & C_\ell^{ET} & C_\ell^{EE} & 0 \\ C_\ell^{\{g\}\{\kappa\}} & C_\ell^{\{g\}\kappa_c} & C_\ell^{\{g\}T} & 0 & C_\ell^{\{g\}\{g\}} \end{pmatrix}$$

Joudaki and Kaplinghat (2011)

Planck+LSST

How many neutrinos?

Present Data

- WMAP7+SPT+BAO+HST: N_{EFF} = 3.8 +/- 0.4

Keisler et al (2011)

However, we **know** neutrinos have mass. Moreover, including constant w, running, curvature:

- WMAP7+SPT+BAO+HST+SNe: N_{EFF} = 3.6 +/- 0.6

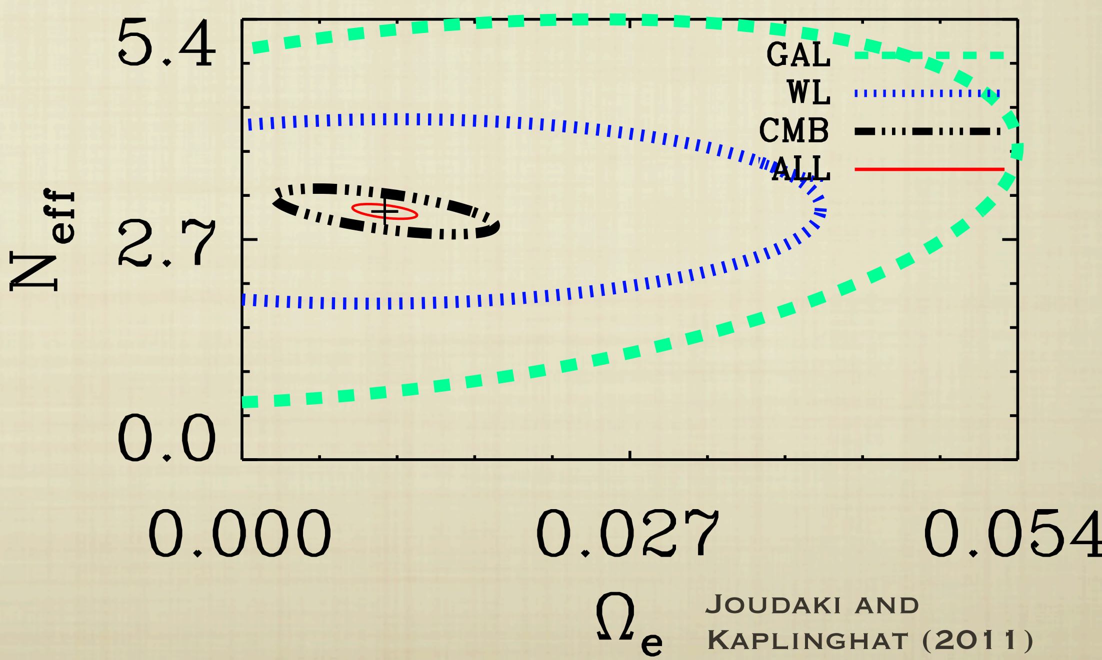
Joudaki 2012

Future Data

CMB:
N_{EFF} = +/- 0.28

ALL:
N_{EFF} = +/- 0.09

Includes neutrino mass, EDE, curvature, etc



Joudaki and Kaplinghat (2011)

Joint analysis: Massive Neutrinos

- Dominant constraint from CMB lensing: 0.2 eV from Planck

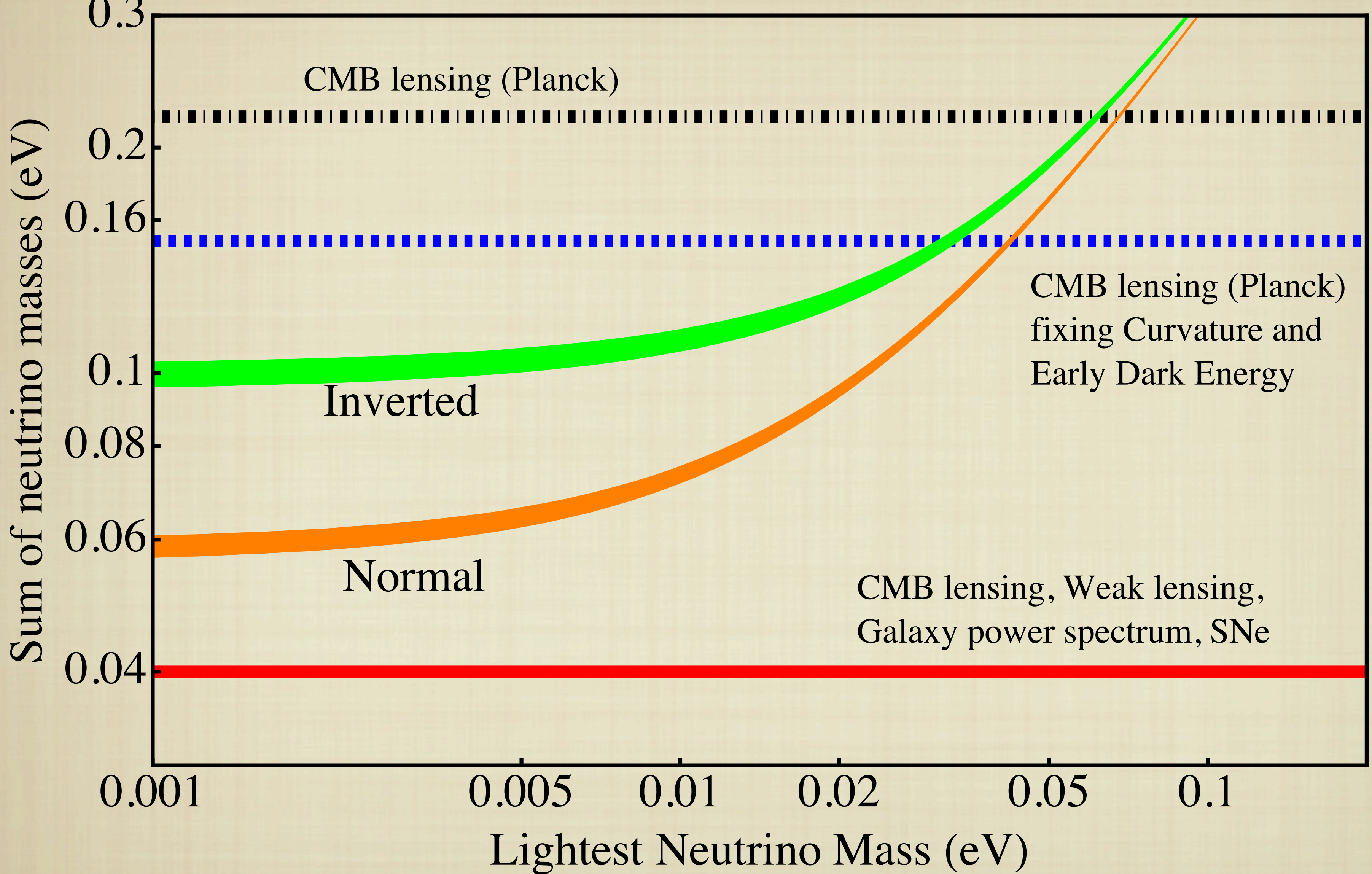
- Constraint improves by factor 5 in joint analysis with Planck. The joint constraints improve by factor <2 when EDE is not allowed to vary.

- These constraints unaffected by our ignorance of curvature, which can be constrained to 6×10^{-3} by CMB T +lensing alone, and improved by order of magnitude in the joint analysis.

- Throwing out nonlinear scales ($\ell>1000$) may not result in significant degradation. Including cross-corrs improves DE density and sum of neutrino masses by factor of 2.

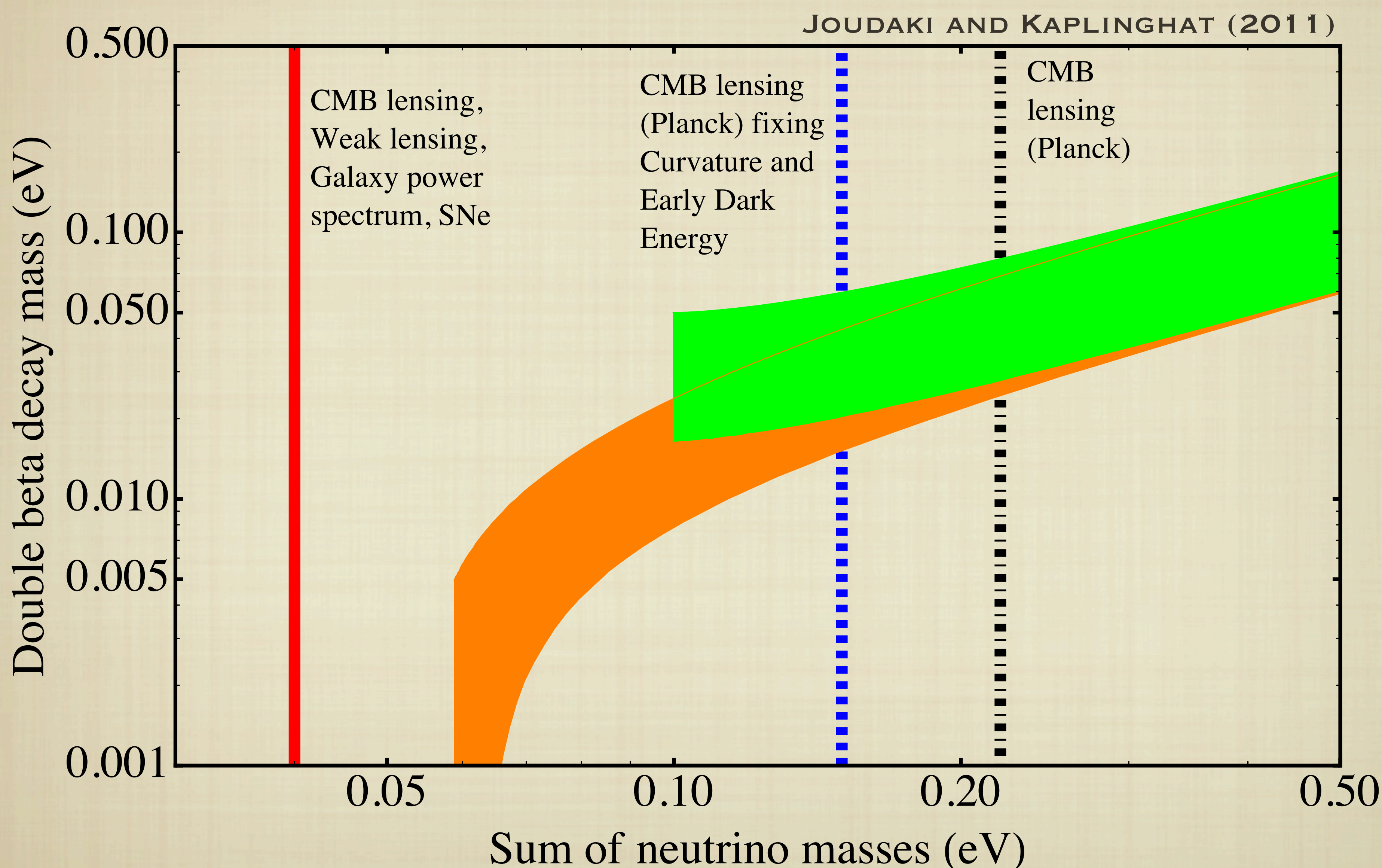
- Even modest 1% EDE, if not accounted for, may shift estimates of neutrino mass by 20% and number by 40%.

Neutrino mass forecasts

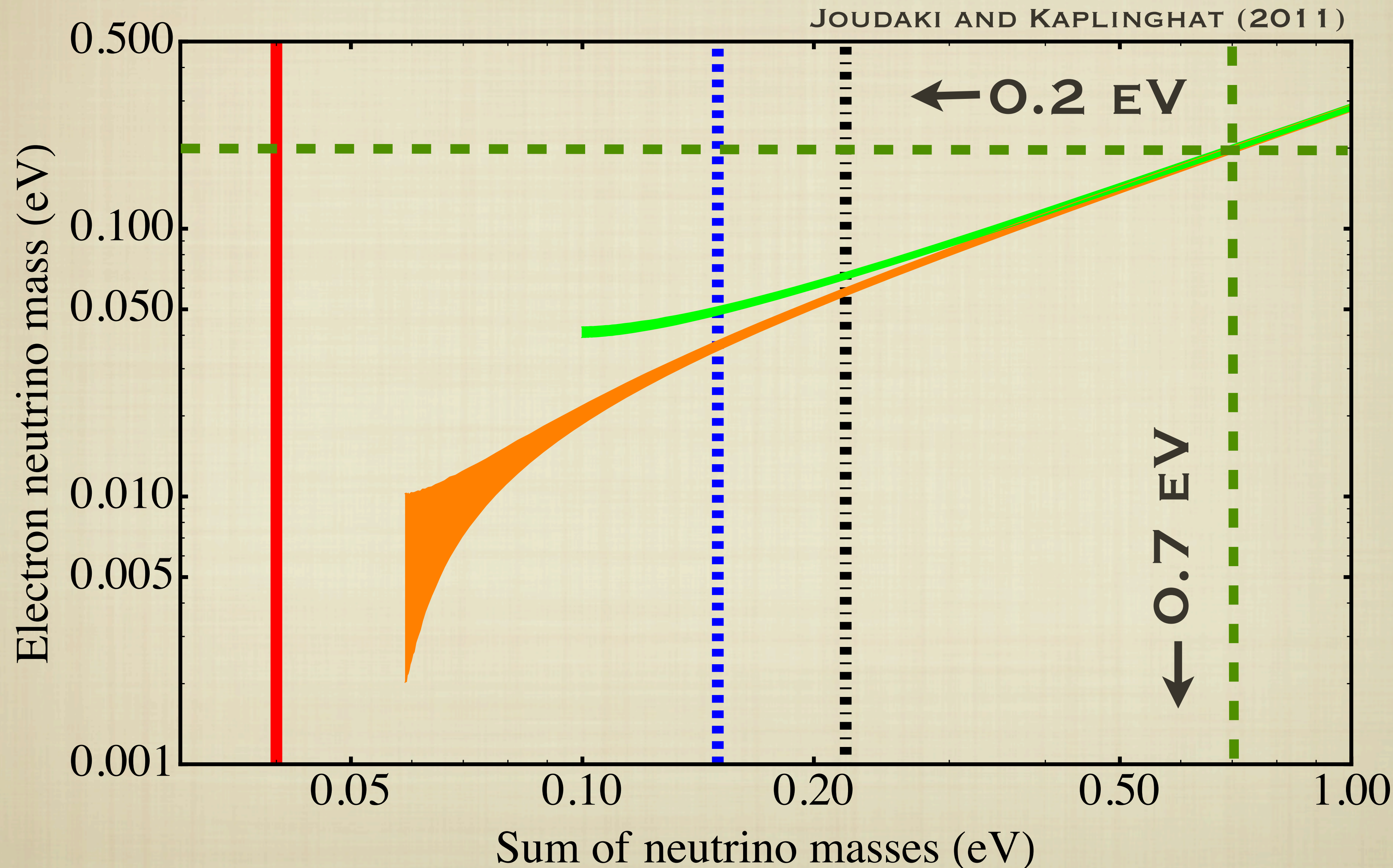


Joudaki and Kaplinghat (2011)

Complementarity with Double beta decay experiments



Complementarity with beta decay experiments



Summary

- comprehensive future datasets (Planck+LSST) including both auto and cross correlations analyzed for extensive parameter space.
- Effective number of neutrinos constrained to 0.3 level with Planck, and 0.1 level when combined with WL+galaxy survey. Includes extended parameters.
- not accounting for DE at high redshift may bias future estimates of $\sum m_\nu$ by 20% and N_{eff} by 40%.
- Cosmology can probe sum of neutrino masses down to an exquisite 0.04 eV even when allowing for non-flat geometry and unknown high redshift universe.
- Complementarity with laboratory experiments will be very interesting.

Thanks for listening.