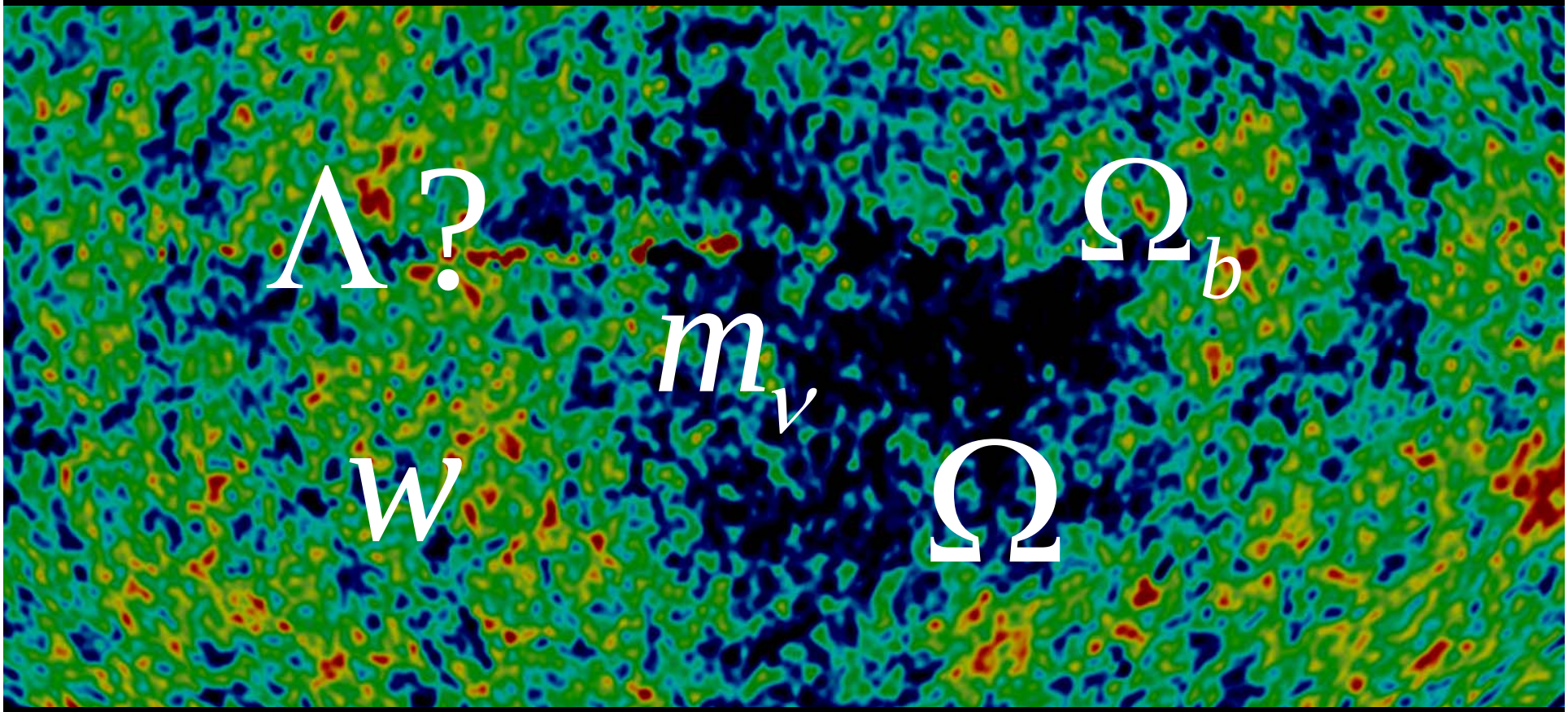
DARK MATTER AND DARK ENERGY



STEEN HANNESTAD
UNIVERSITY OF AARHUS
NDM06, 7 SEPTEMBER 2006

OUTLINE

A BRIEF REVIEW OF PRESENT COSMOLOGICAL DATA

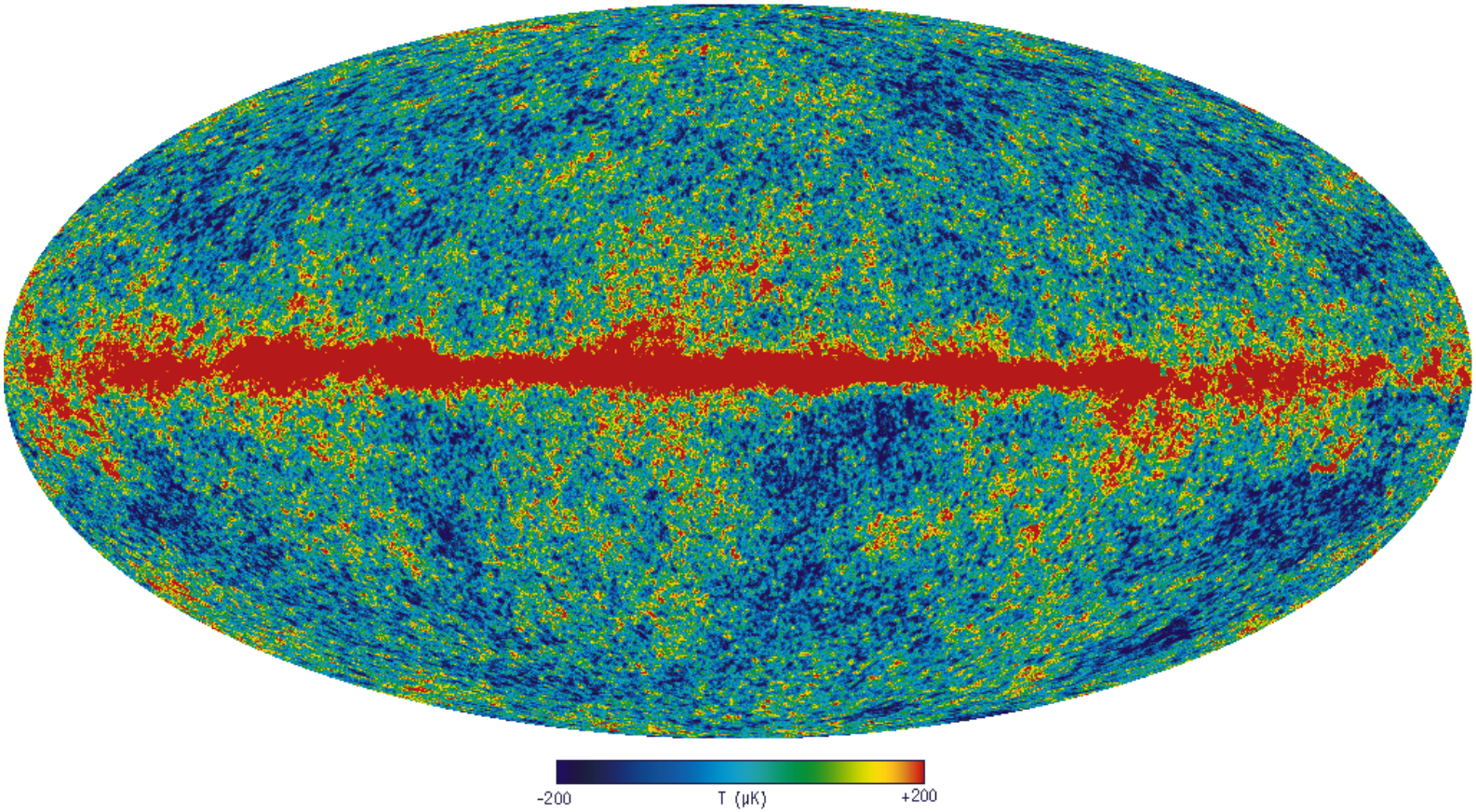
BOUNDS ON DARK MATTER AND DARK ENERGY PARAMETERS

NEUTRINOS AS DARK MATTER

FUTURE OBSERVATIONAL PROBES

THE COSMIC MICROWAVE BACKGROUND

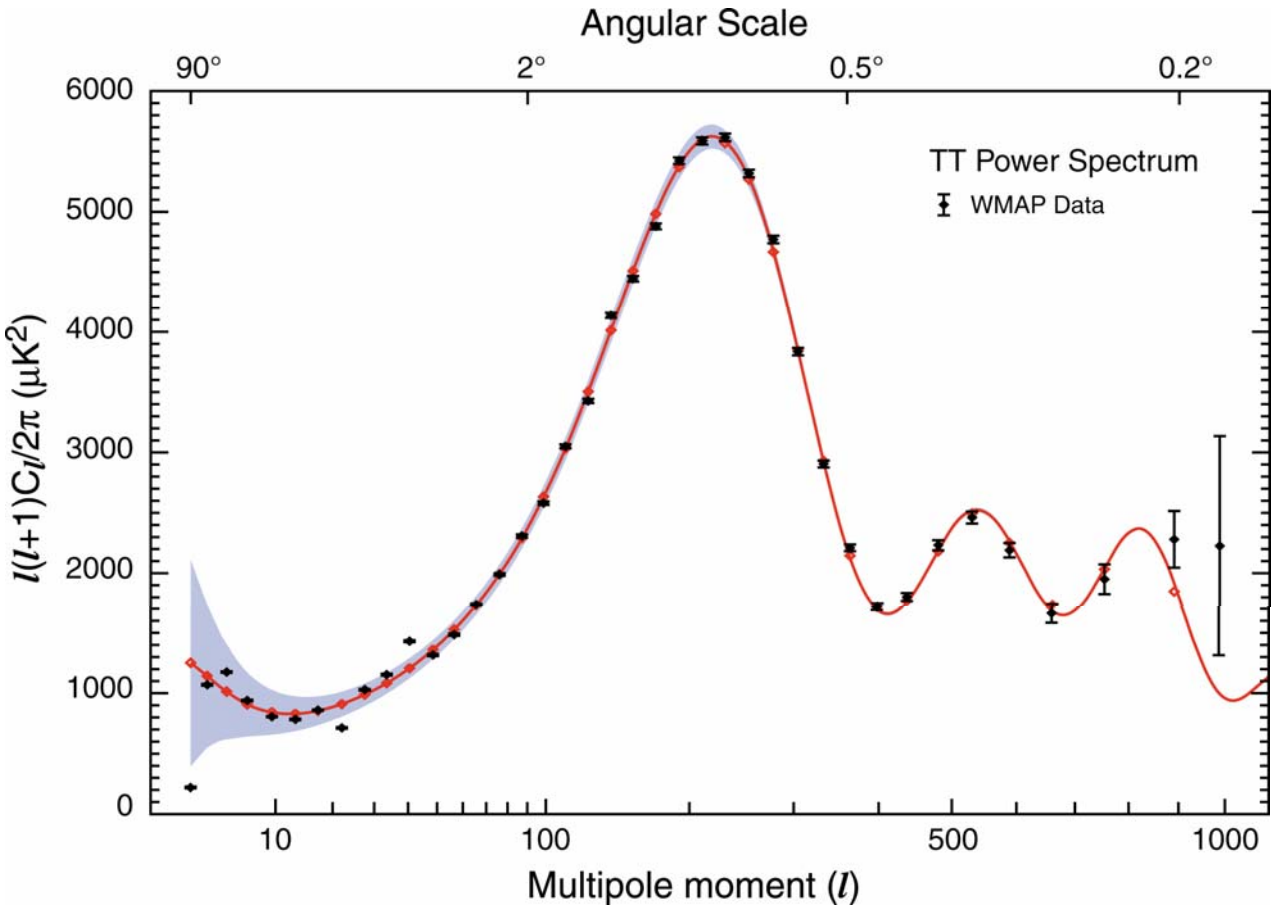
WMAP 3-YEAR DATA PUBLISHED RESULTS MARCH 2006



THE TEMPERATURE MAP IN THE 94 GHZ CHANNEL

ADDITIONAL MEASUREMENT OF POLARIZATION (EE AND TE)

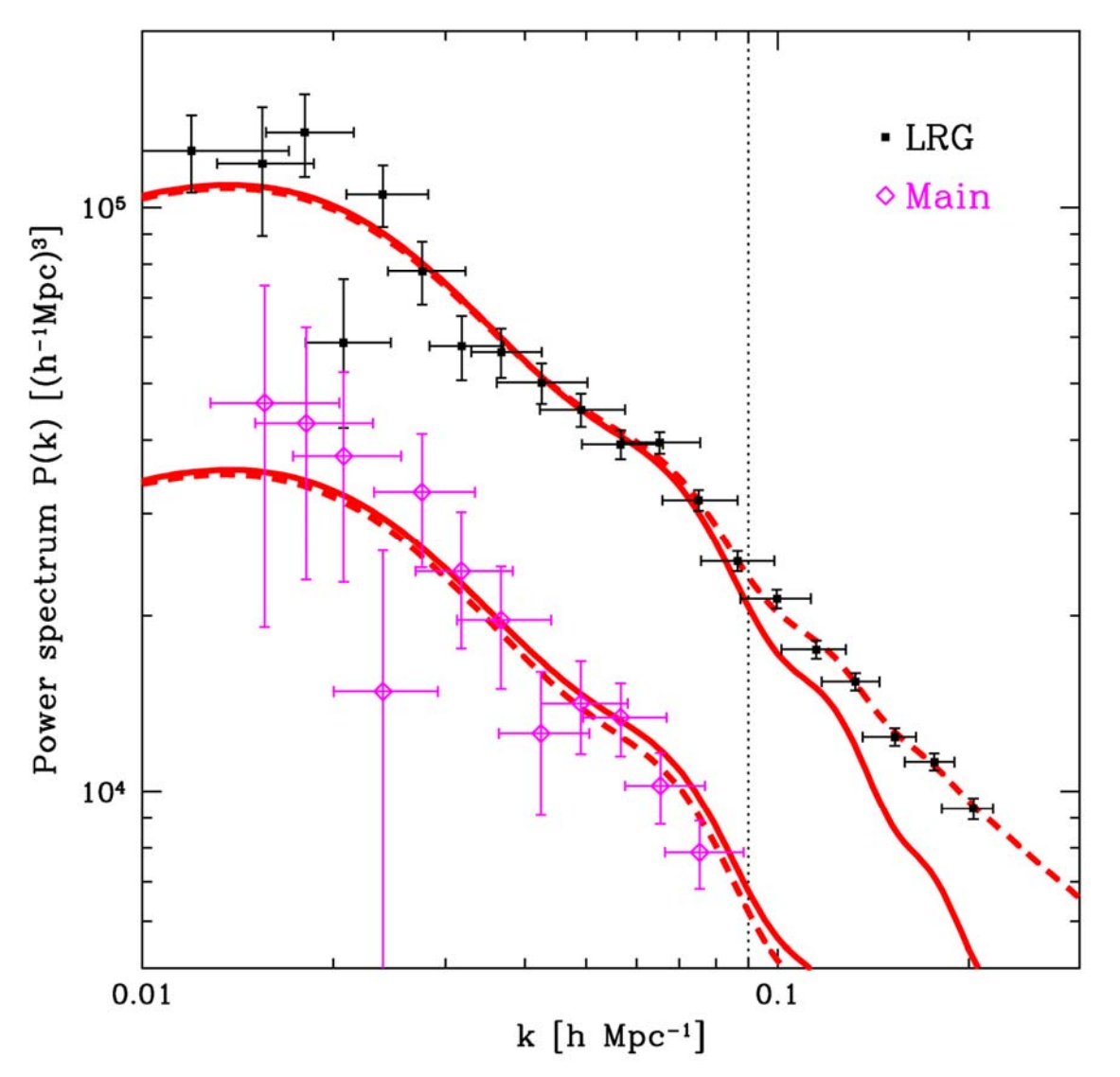
WMAP-3 TEMPERATURE POWER SPECTRUM



MEASUREMENTS ARE COSMIC VARIANCE LIMITED TO l ~ 400 WITH 3-YEAR DATA

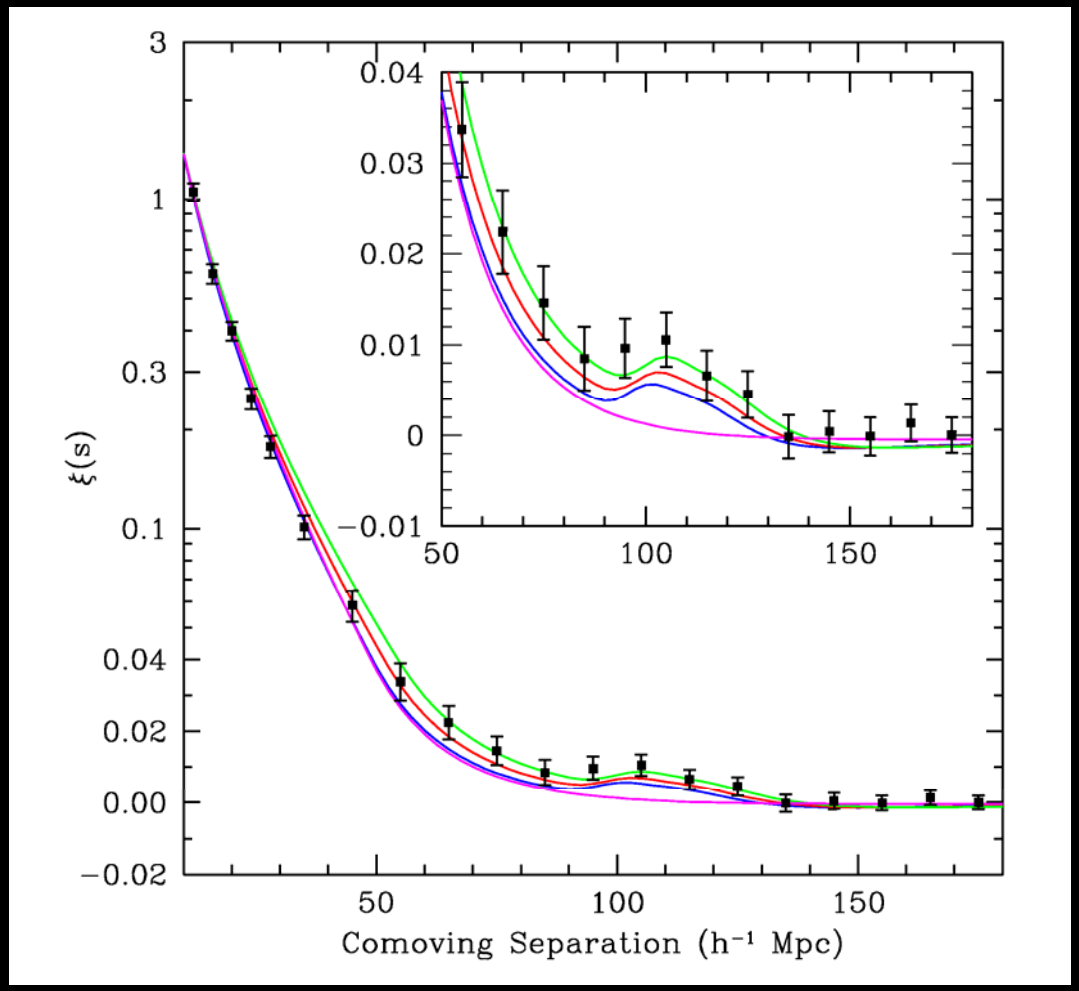
LARGE SCALE STRUCTURE

SDSS SPECTRUM
TEGMARK ET AL. 2006



Astro-ph/0608632

THE SDSS MEASUREMENT OF BARYON OSCILLATIONS IN THE POWER SPECTRUM PROVIDES A FANTASTICALLY PRECISE MEASURE OF THE ANGULAR DISTANCE SCALE AND TURNS OUT TO BE EXTREMELY USEFUL FOR PROBING NEUTRINO PHYSICS

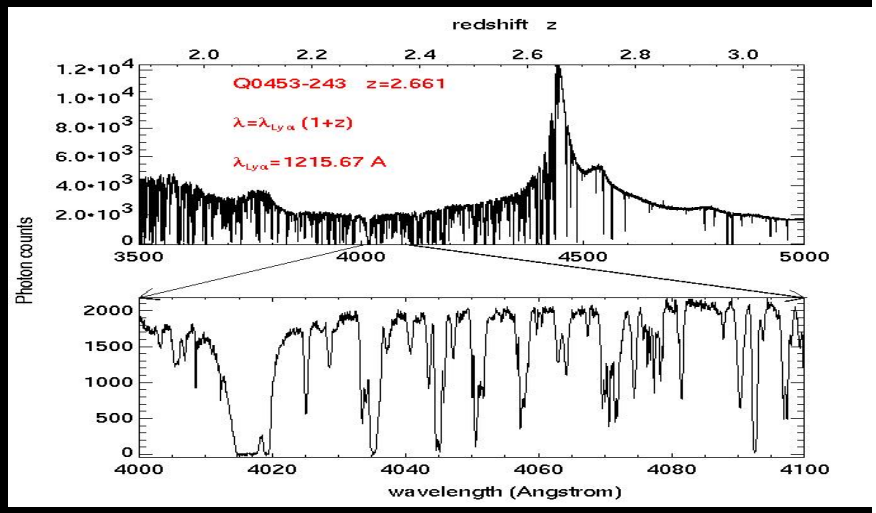


EISENSTEIN ET AL. 2005 (SDSS)

NEUTRINO MASSES ARE THE LARGEST SYSTEMATIC ERROR NOT ACCOUNTED FOR IN THE INITIAL ANALYSIS

Ly-α forest analysis

- Raw data: quasar spectra

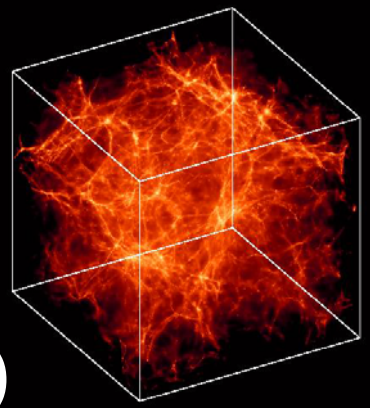


remove data not tracing

(quasi-linear) Lyα absorption

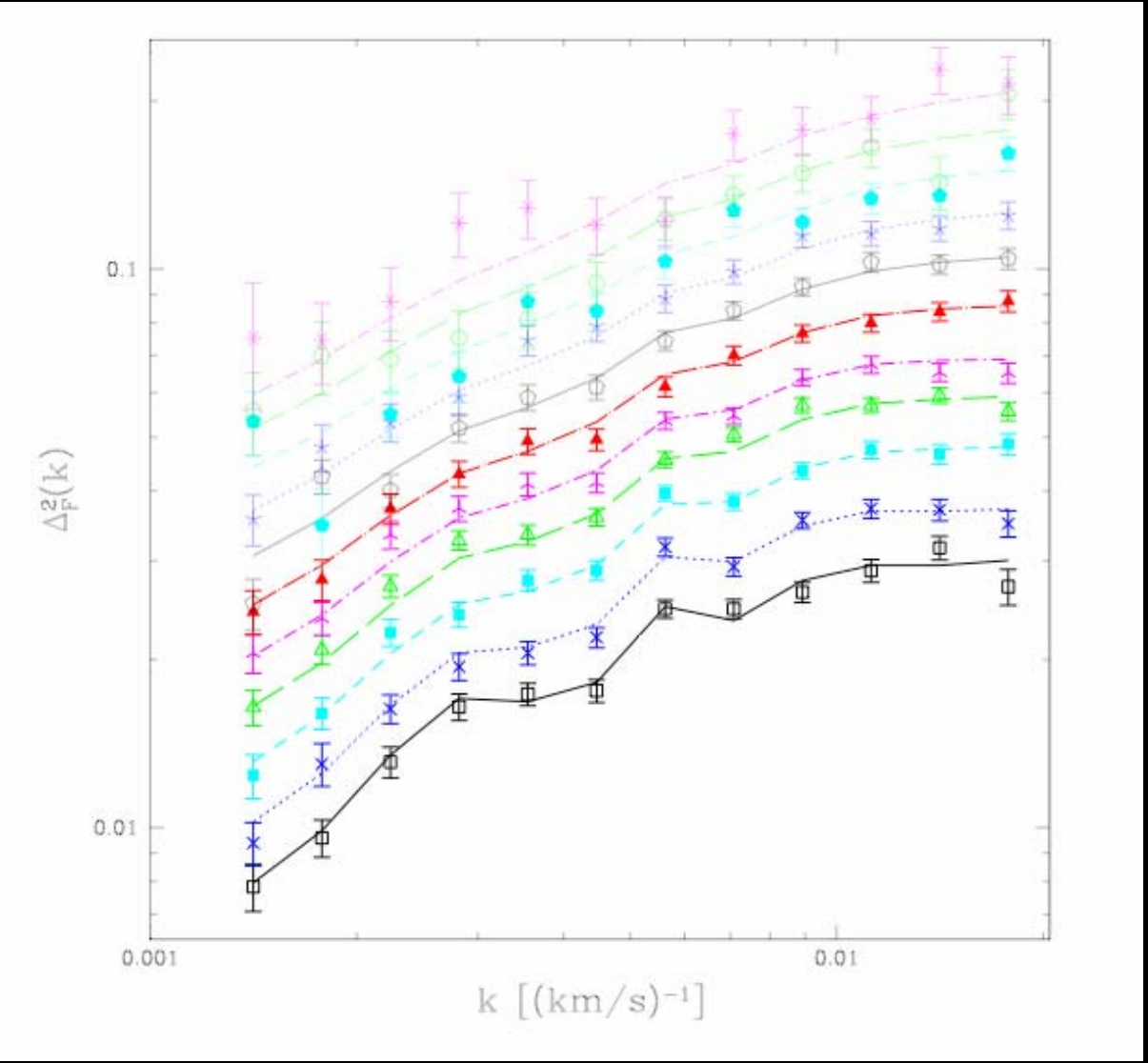
- Flux power spectrum $P_F(k)$

hydrodynamical simulations
+ assumptions on thermodynamics
of IGM



- Linear power spectrum P(k)

Example of power spectrum analysis (McDonald etal 2004)



NOW, WHAT ABOUT THE COSMOLOGICAL PARAMETERS?

THE ENERGY DENSITY BUDGET

Ω_B BARYONS

Ω_{CDM} COLD DARK MATTER

Ω_ν NEUTRINOS

Ω_{DE} DARK ENERGY

$$\Omega_{TOT} = \Omega_B + \Omega_{CDM} + \Omega_\nu + \Omega_{DE}$$

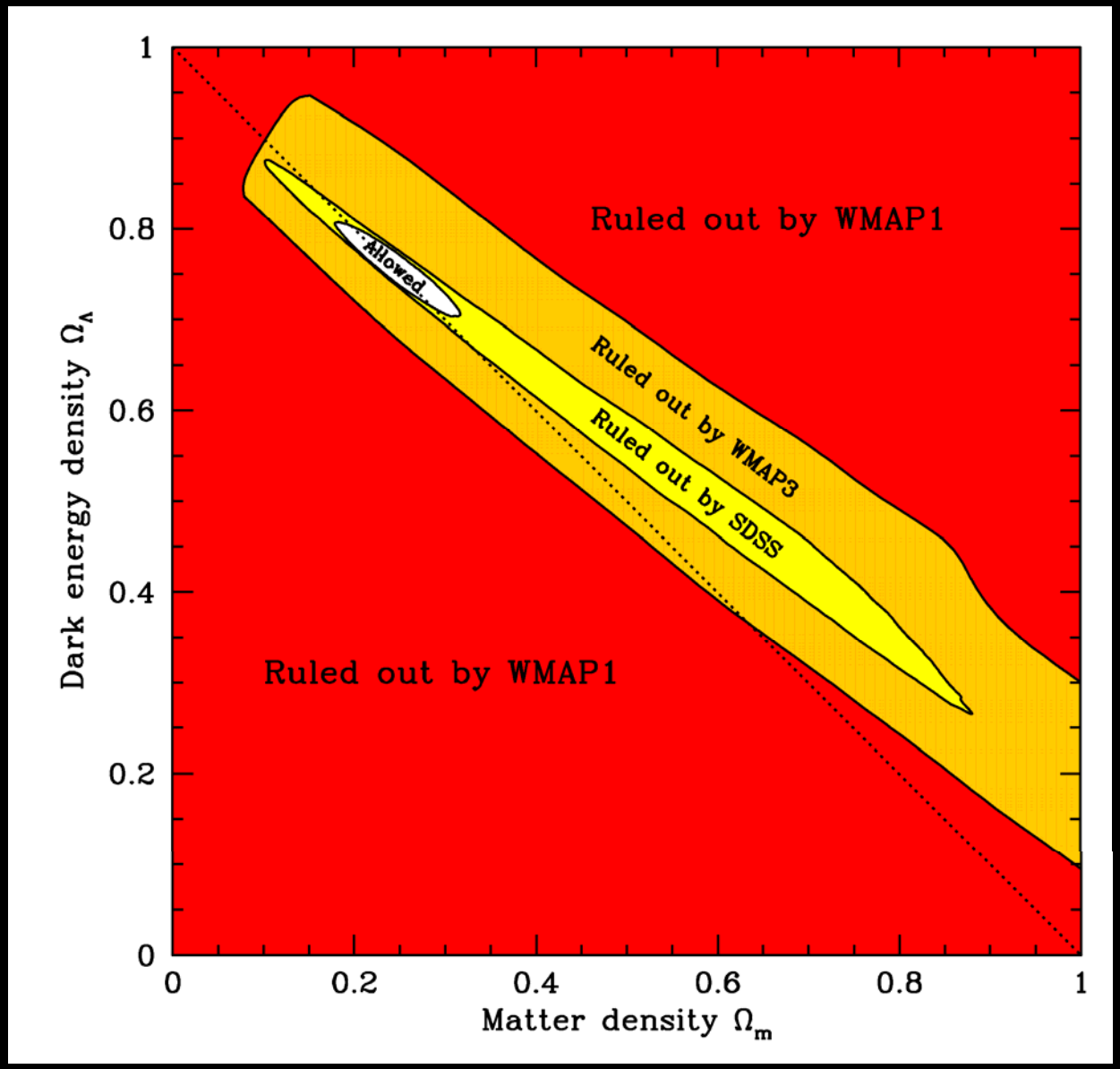
UNKNOWNS FROM THE DARK ENERGY SECTOR

$w = P / \rho$ EQUATION OF STATE

$c_{\text{sound}}^2 \equiv \dfrac{\delta P}{\delta \rho}$ SPEED OF SOUND

NOTE: THERE ARE MANY MORE RELEVANT PARAMETERS NOT DIRECTLY RELATED TO DARK MATTER OR DARK ENERGY

STATUS AFTER WMAP AND SDSS



TEGMARK ET AL. 2006

THE BOUND ON THE PHYSICAL DARK MATTER ENERGY DENSITY ($\Omega_{CDM}h^2$) IS MUCH STRONGER (THIS IS THE PARAMETER COMBINATION WHICH IS IMPORTANT TO DARK MATTER SEARCHES)

WMAP ONLY $$\Omega_{CDM}h^2 = 0.1044^{+0.0072}_{-0.0095}$$

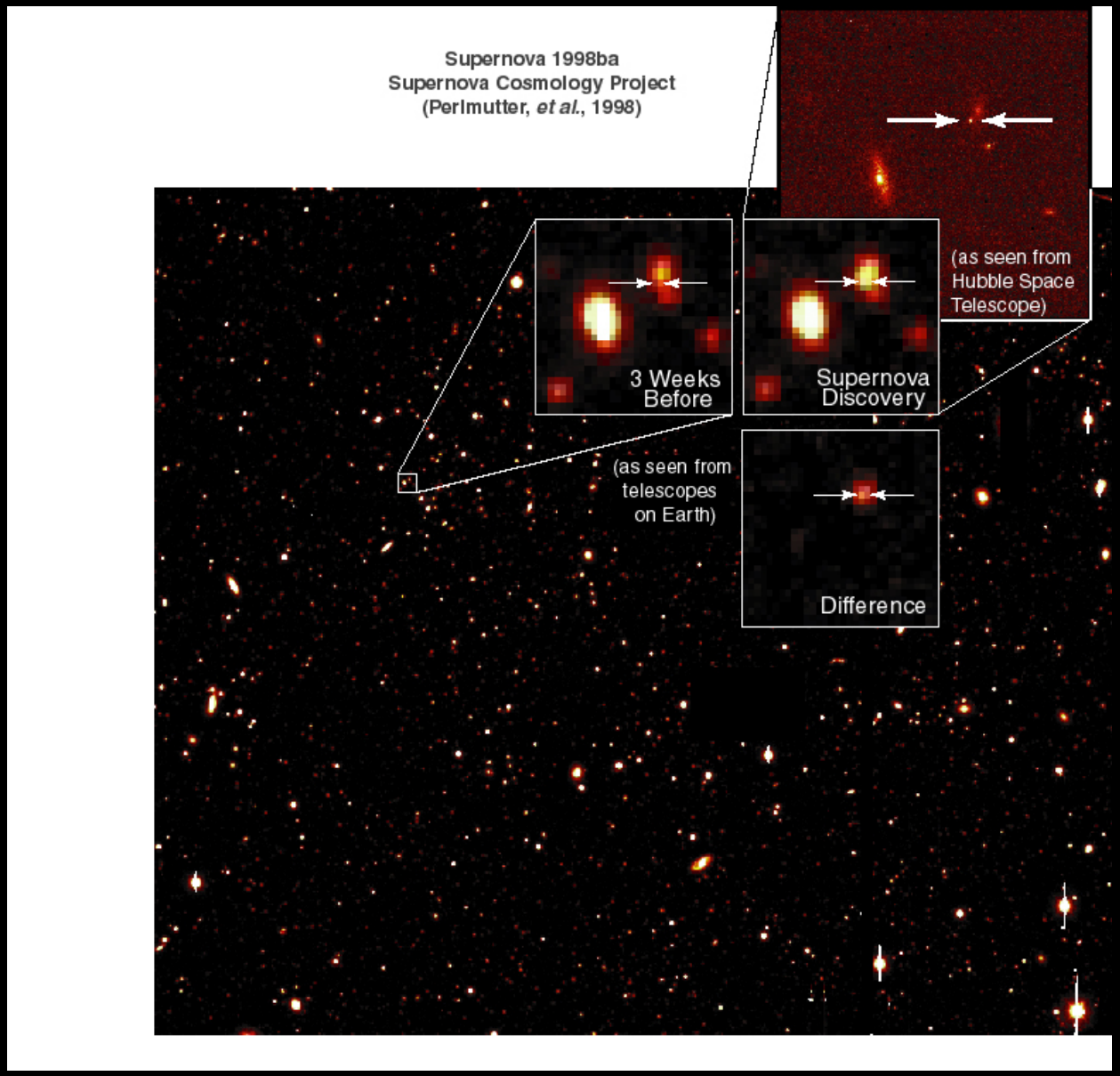
WMAP + SDSS $$\Omega_{CDM}h^2 = 0.1157^{+0.056}_{-0.075}$$

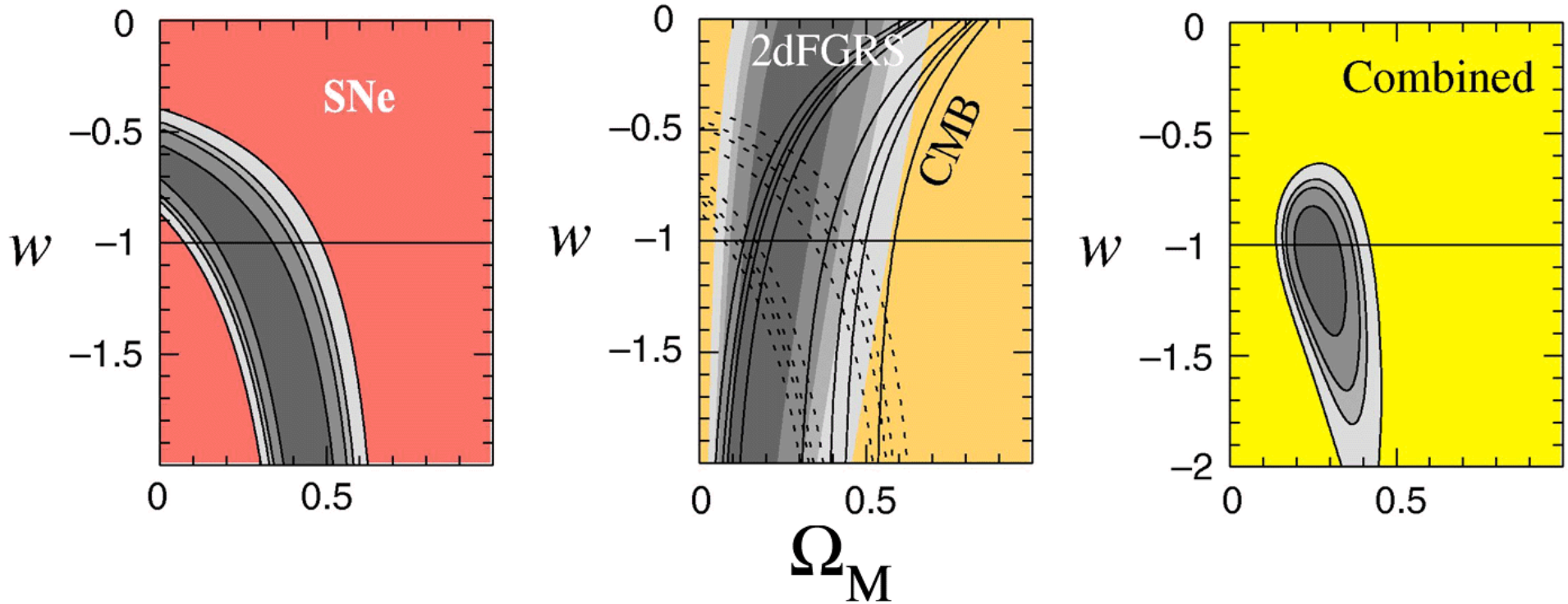
WMAP + SDSS + SNI-A $$\Omega_{CDM}h^2 = 0.1072^{+0.056}_{-0.072}$$

SPERGEL ET AL. 2006

MUCH MORE ABOUT SEACHES FOR SPECIFIC CANDIDATES IN THE NEXT TALKS

THE DARK ENERGY EQUATION OF STATE





Knop et al. 2003

THE MOST RECENT RESULTS ARE:

$$w = -0.941^{+0.087}_{-0.101}$$

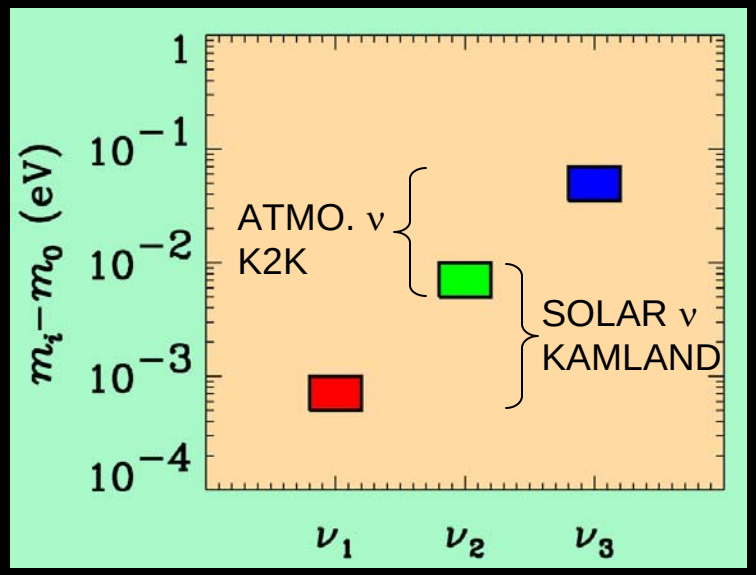
WMAP-3 + SDSS BRG
(TEGMARK ET AL 2006)

$$w = -1.040^{+0.065}_{-0.066}$$

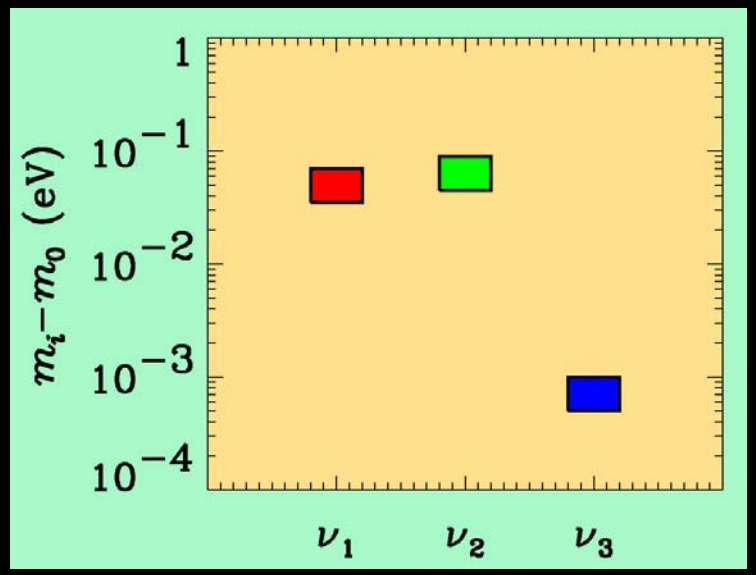
WMAP-3 + SDSS + SNI-a + Lyman-alpha
(SELJAK ET AL. 2006)

TALKS BY STROLGER AND REGNAULT FOR MORE DETAILS

NEUTRINO MASSES



Normal hierarchy



Inverted hierarchy

Oscillation experiments provide two mass differences. However, if neutrino masses are degenerate so that

$$m_0 >> \delta m_{\text{atmospheric}}$$

no information can be gained from such experiments. Experiments which rely on either the kinematics of neutrino mass or the spin-flip in neutrinoless double beta decay are the most efficient for measuring m_0

THE ABSOLUTE VALUES OF NEUTRINO MASSES FROM COSMOLOGY

NEUTRINOS AFFECT STRUCTURE FORMATION BECAUSE THEY ARE A SOURCE OF DARK MATTER

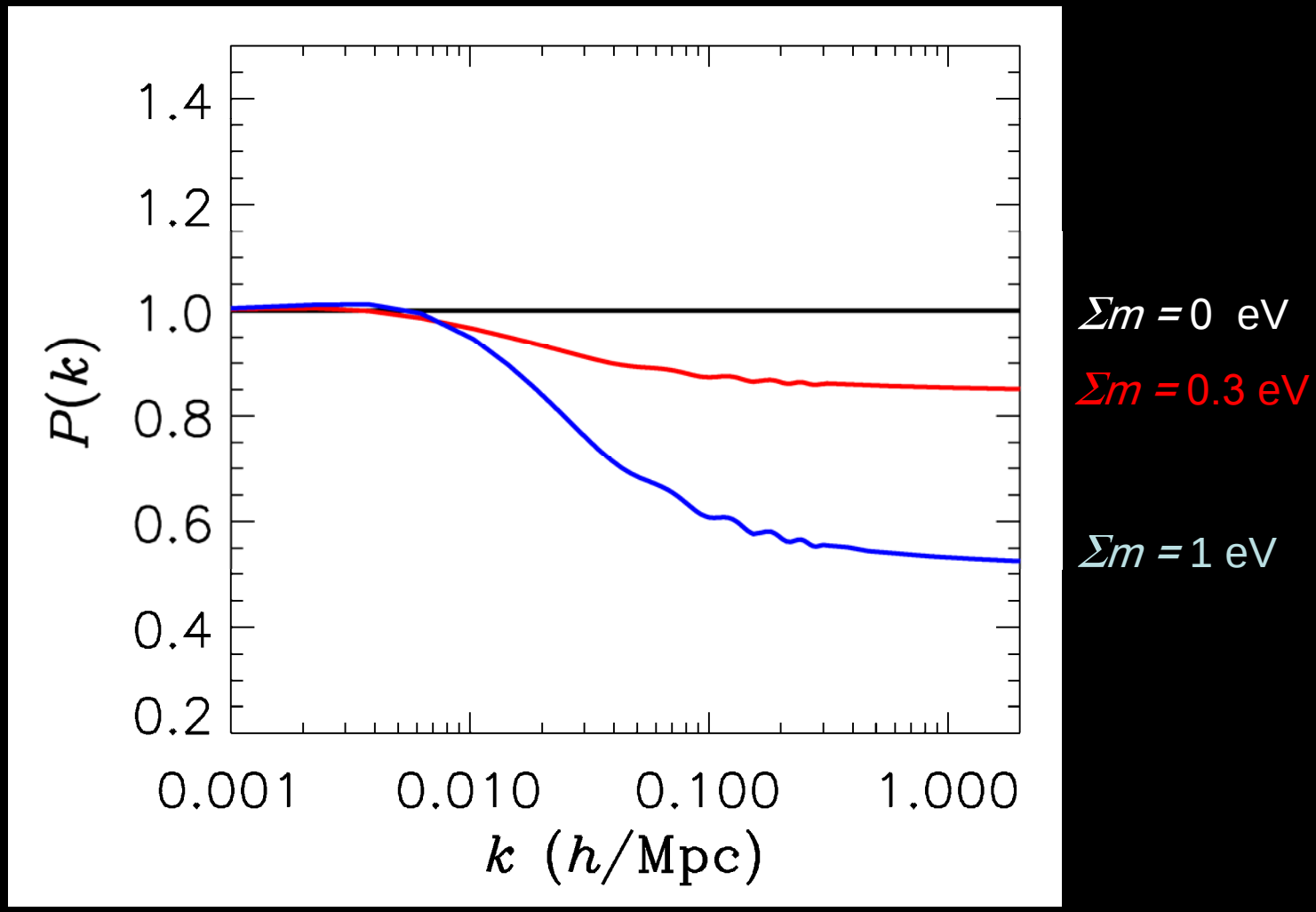
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93\,\mathrm{eV}}$$ FROM $$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \approx 2\,\mathrm{K}$$

HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

$$d_{\mathrm{FS}} \sim 1\,\mathrm{Gpc}\, m_{\mathrm{eV}}^{-1}$$

SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO SUPPRESSION OF POWER ON SMALL SCALES

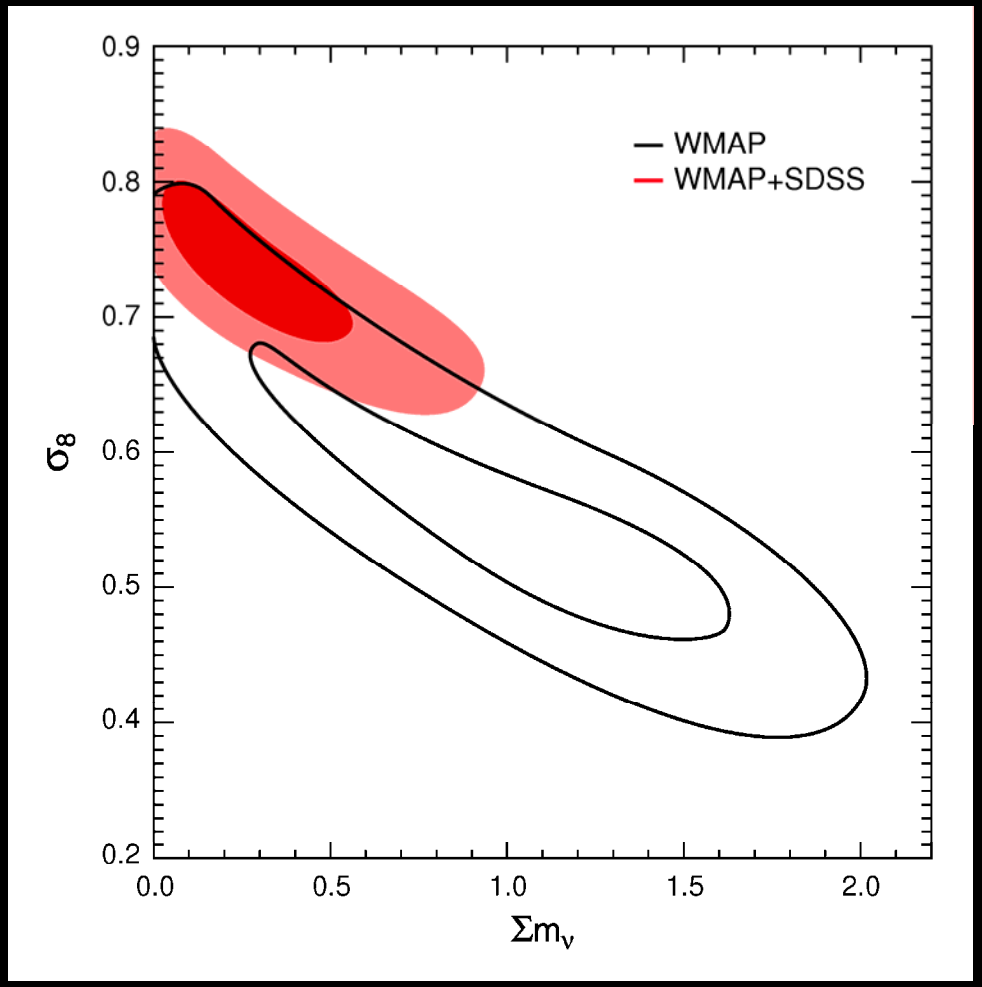
FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



Σm_ν = 2.3 eV Σm_ν = 0 eV

256 Mpc^3 simulations with GADGET-2 by Troels Haugbølle

WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?



COMBINED ANALYSIS OF WMAP AND LSS DATA (Spergel et al. 2006)

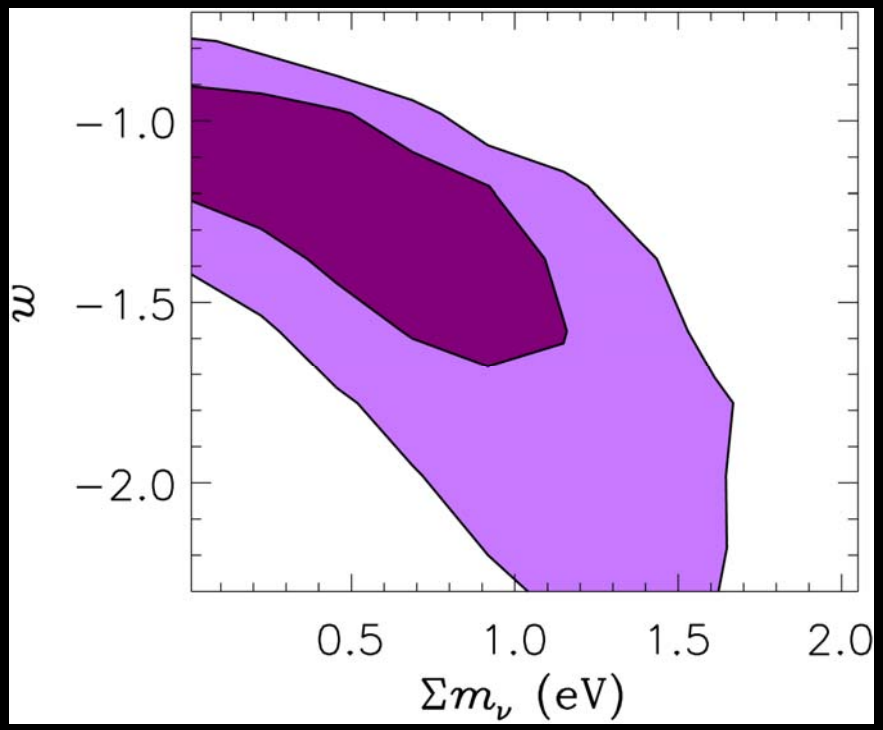
WMAP-3 ONLY ~ 2.0 eV
WMAP + LSS 0.68 eV

COMPARE WITH WMAP-I:

WMAP-1 ONLY ~ 2.1 eV
WMAP + LSS ~ 0.7 eV
(without information on bias)

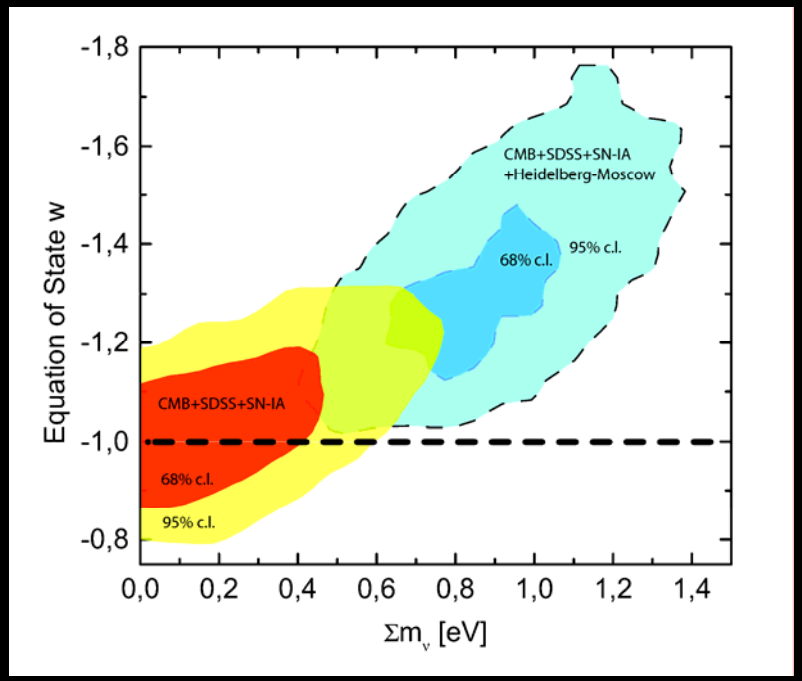
HOW CAN THE BOUND BE AVOIDED?

THERE IS A VERY STRONG DEGENERACY BETWEEN NEUTRINO MASS AND THE DARK ENERGY EQUATION OF STATE
THIS SIGNIFICANTLY RELAXES THE COSMOLOGICAL BOUND ON NEUTRINO MASS



STH, ASTRO-PH/0505551 (PRL)

IF A LARGE NEUTRINO MASS IS MEASURED EXPERIMENTALLY THIS SEEMS TO POINT TO *w* < -1



DE LA MACORRA ET AL. ASTRO-PH/0608351

HOW CAN THE BOUND BE STRENGTHENED?

MAKING THE BOUND SIGNIFICANTLY STRONGER REQUIRES THE USE OF OTHER DATA:

EITHER ADDITIONAL DATA TO FIX THE $\Omega_m - w$ DEGENERACY

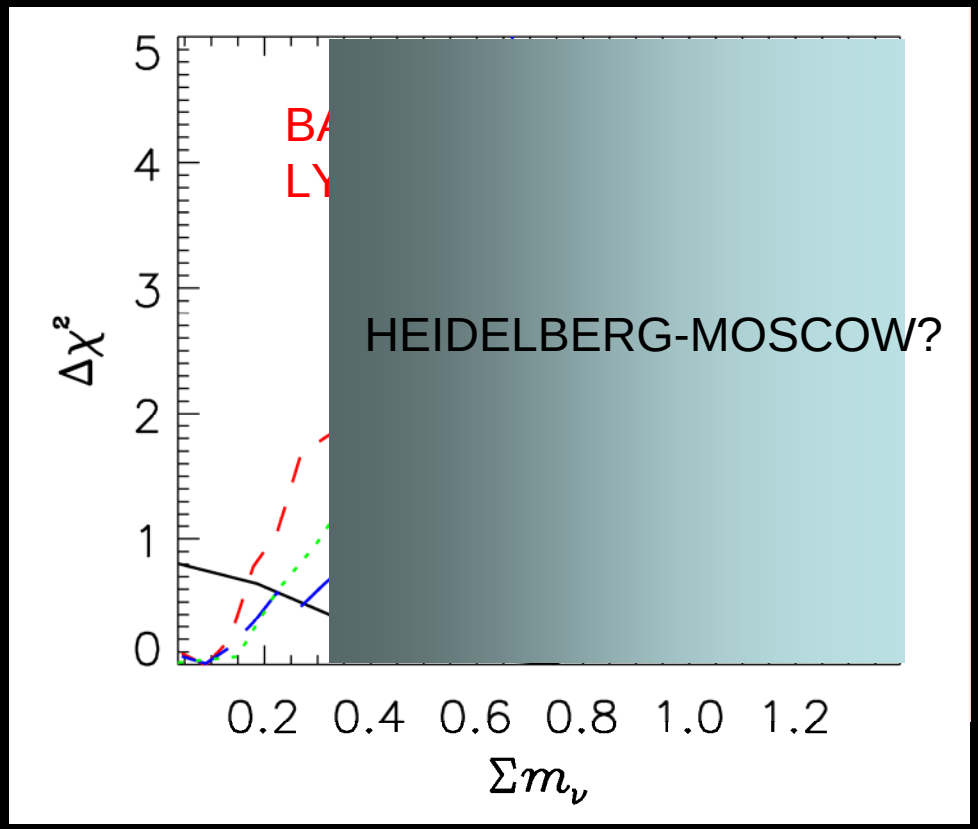
THE BARYON ACOUSTIC PEAK

OR

FIXING THE SMALL SCALE AMPLITUDE

LYMAN – ALPHA DATA

GOOBAR, HANNESTAD, MÖRTSELL, TU (astro-ph/0602155, JCAP)



USING THE BAO DATA THE BOUND IS STRENGTHENED, EVEN FOR VERY GENERAL MODELS

$$\sum m_\nu < 0.62\,\mathrm{eV}\ @\ 95\%$$

11 FREE PARAMETERS

$$\Omega_M, \Omega_B, H_0, n, \tau, A, b, m_\nu, N_\nu, Q, \alpha_s$$

WMAP-3, BOOMERANG, CBI
SDSS, 2dF
SNLS SNI-A, SDSS BARYONS

WITH THE INCLUSION OF LYMAN-ALPHA DATA THE BOUND STRENGTHENS TO

$$\sum m_\nu < 0.2 - 0.45\,\mathrm{eV}\ @\ 95\%$$

IN A SIMPLIFIED MODEL WITH 8 PARAMETERS

VERY SIMILAR RESULTS HAVE SUBSEQUENTLY BEEN OBTAINED BY CIRELLI & STRUMIA AND FOGLI ET AL.

SELJAK, SLOSAR & MCDONALD (ASTRO-PH/0604335) FIND

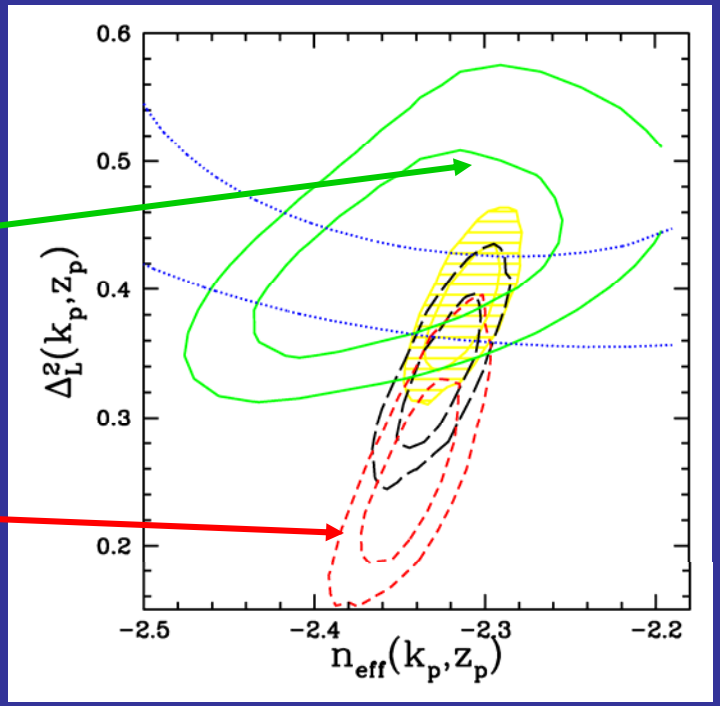
$$\sum m_\nu < 0.17\,\mathrm{eV} \;@\; 95\%$$

IN THE SIMPLEST 8-PARAMETER MODEL FRAMEWORK WITH NEW SDSS LYMAN-ALPHA ANALYSIS.
NOTE, HOWEVER, THAT THIS DATA IS (EVEN MORE) INCOMPATIBLE WITH THE WMAP NORMALIZATION.
VIEL ET AL. FIND DIFFERENT NORMALIZATION BASED ON DIFFERENT ANALYSIS OF THE SAME DATA.

SELJAK, SLOSAR & MCDONALD

SDSS LYMAN-ALPHA

WMAP-3 NORMALIZATION



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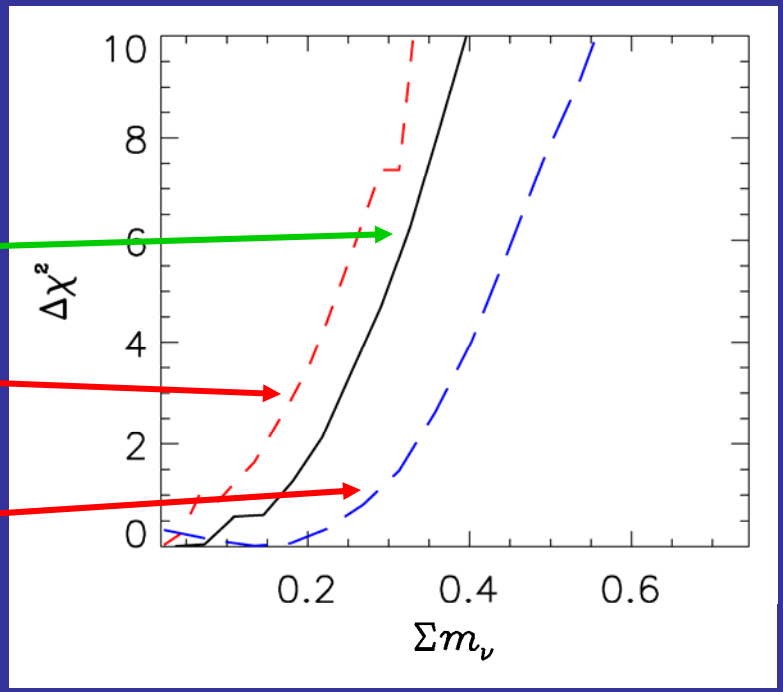
GOOBAR, HANNESTAD, MORTSELL, TU (ASTRO-PH/0602155)

OLD SDSS LYMAN-ALPHA

NEW SDSS LYMAN-ALPHA

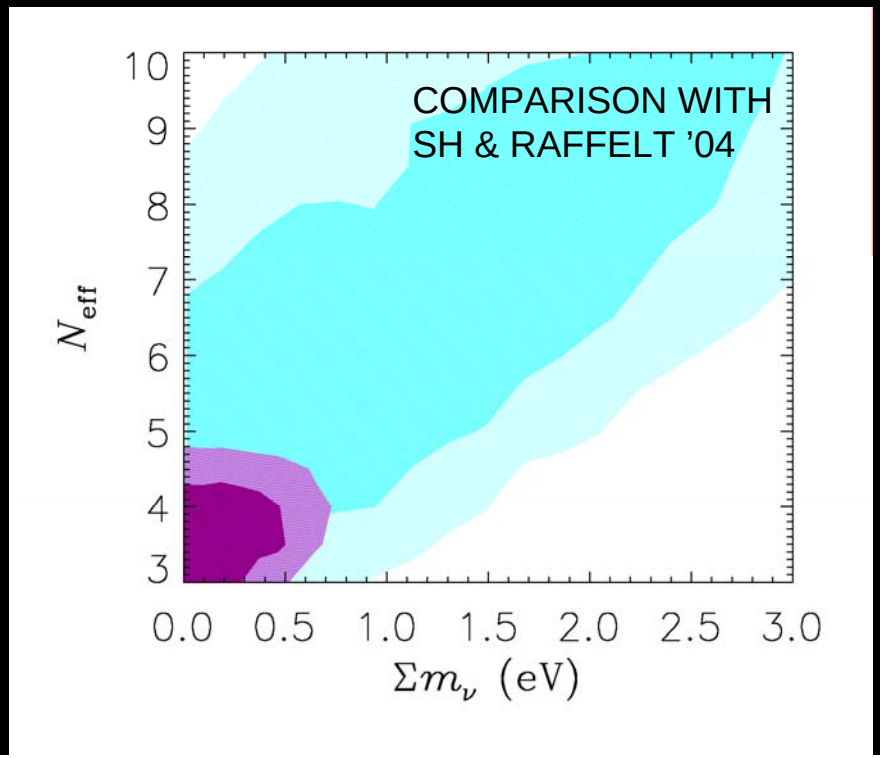
VIEL ET AL. LYMAN-ALPHA

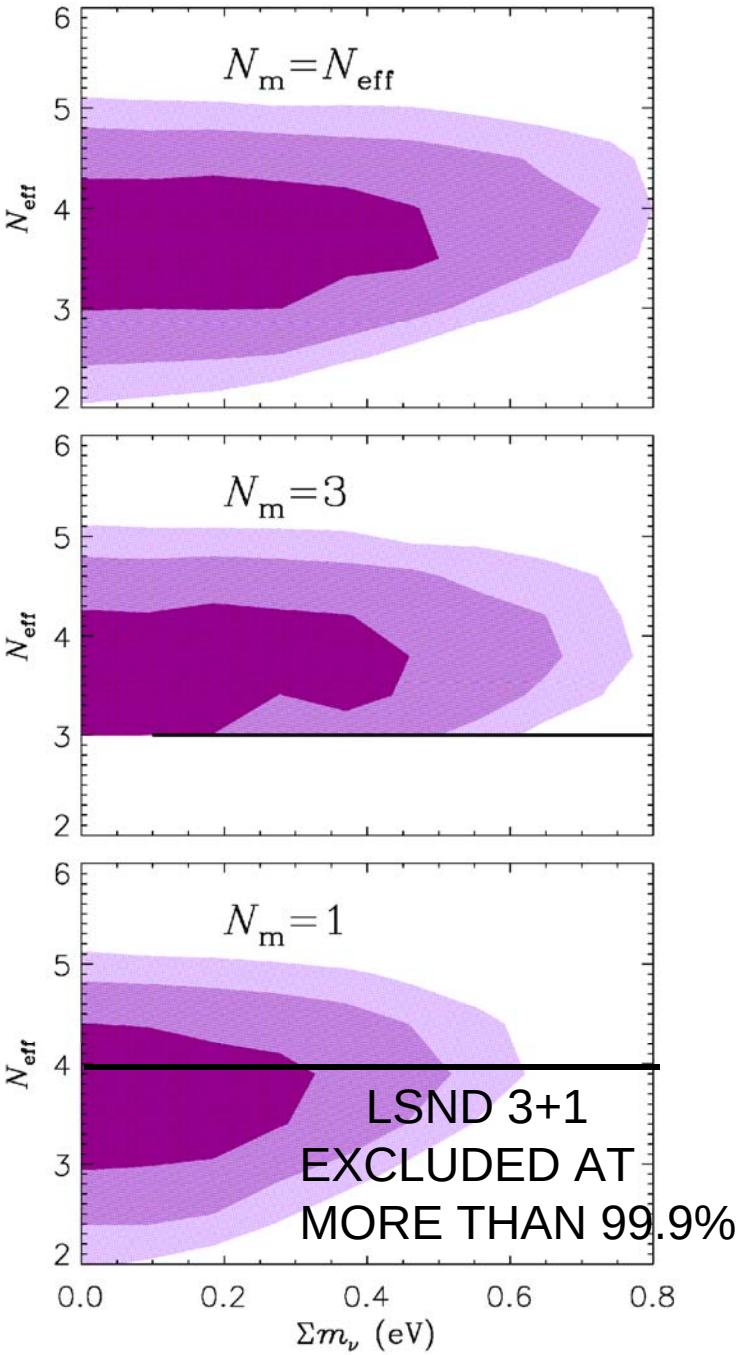


ADDITIONAL LIGHT DEGREES OF FREEDOM (STERILE NEUTRINOS, eV AXIONS, ETC)

STH & RAFFELT (ASTRO-PH/0607101) ANALYSIS <u>WITHOUT</u> LYMAN-ALPHA

LSND 3+1 UPPER LIMIT ON HEAVY EIGENSTATE OF ~ 0.6 eV AT 99% c.l. (0.9 eV AT 99.99%)

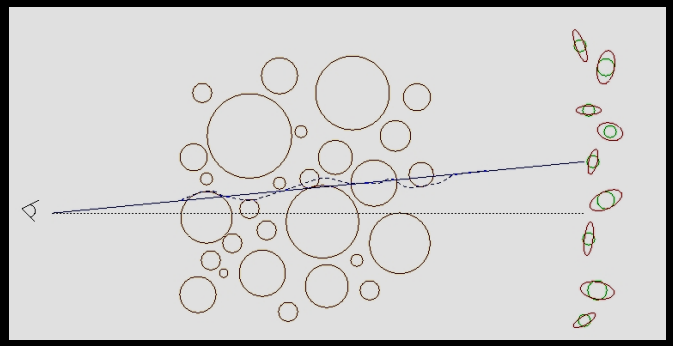


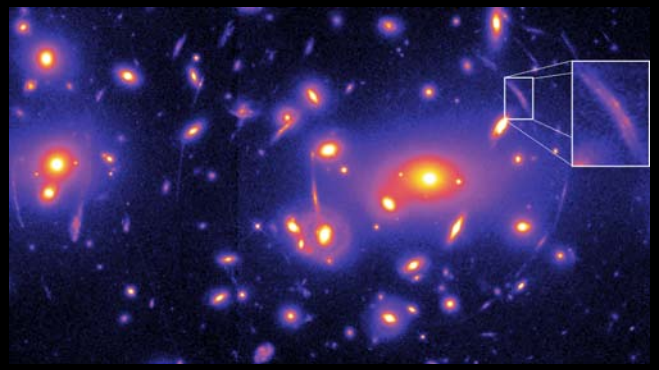


WHAT IS IN STORE FOR THE FUTURE?

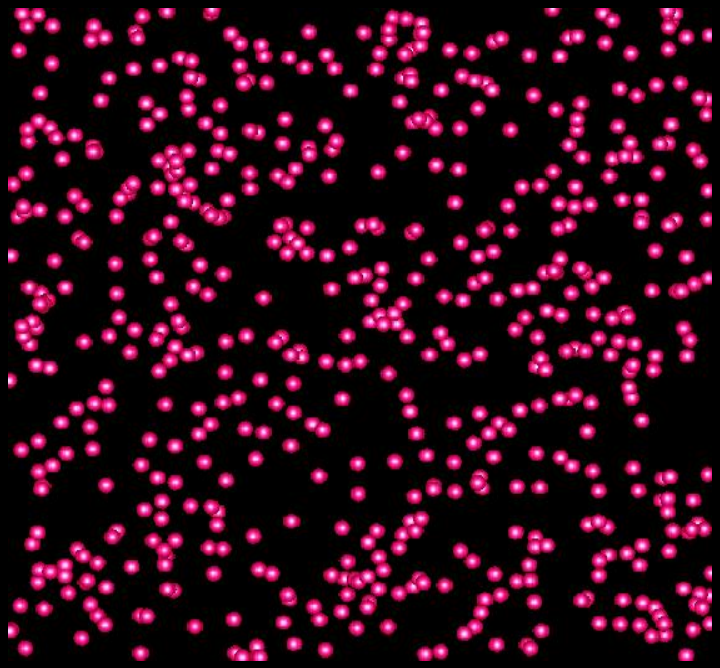
- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS (PLANCK)
- LARGE SCALE STRUCTURE SURVEYS AT HIGH REDSHIFT
- NEW SUPERNOVA SURVEYS
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES

WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE

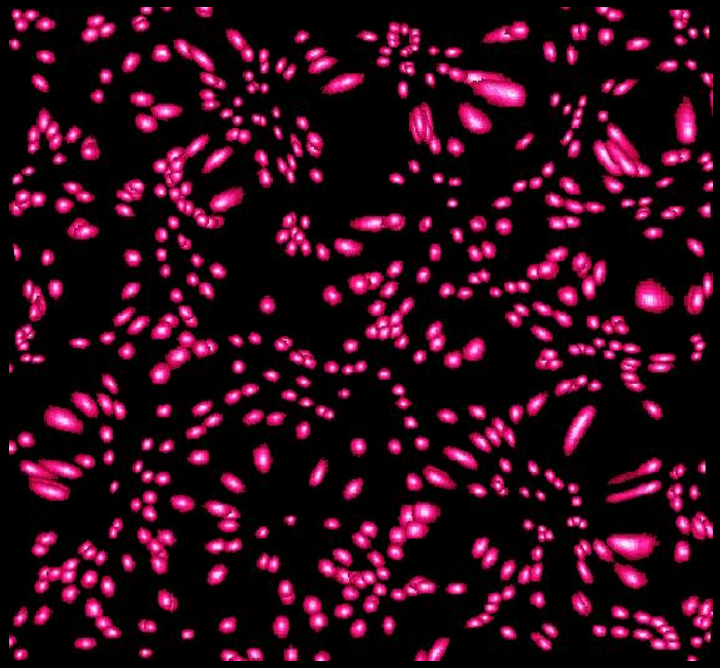




Distortion of background images by foreground matter



Unlensed



Lensed

FROM A WEAK LENSING SURVEY THE ANGULAR POWER SPECTRUM CAN BE CONSTRUCTED, JUST LIKE IN THE CASE OF CMB

$$C_\ell = \frac{9}{16} H_0^4 \Omega_m^2 \int_0^{\chi_H} \left[\frac{g(\chi)}{a\chi} \right]^2 P(\ell / r, \chi) d\chi$$

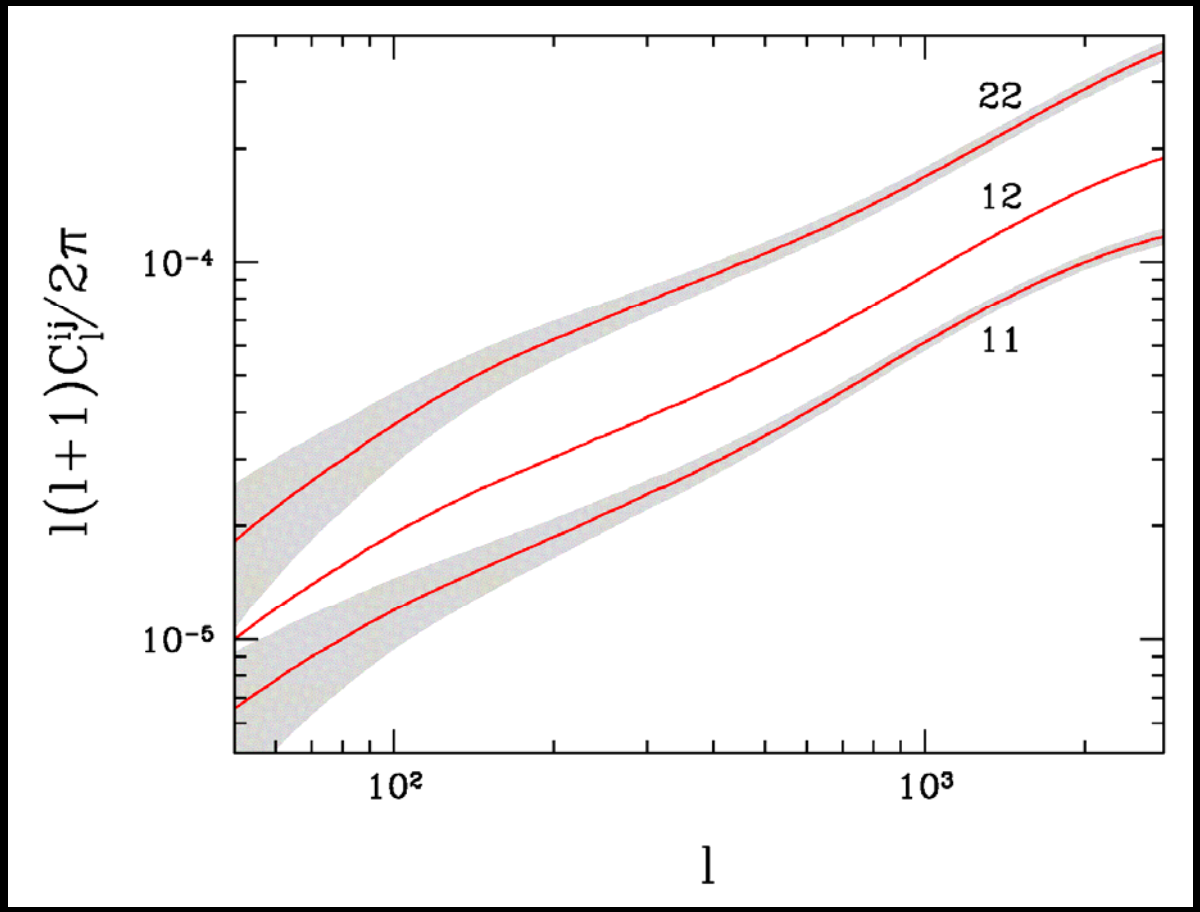
$P(\ell / r, \chi)$ MATTER POWER SPECTRUM (NON-LINEAR)

$$g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi'$$

WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY

(SEE FOR INSTANCE JAIN & SELJAK ’96, ABAZAJIAN & DODELSON ’03, SIMPSON & BRIDLE ’04)

WEAK LENSING HAS THE ADDED ADVANTAGE COMPARED WITH CMB THAT IT IS POSSIBLE TO DO TOMOGRAPHY BY MEASURING THE REDSHIFT OF SOURCE GALAXIES



HIGH REDSHIFT

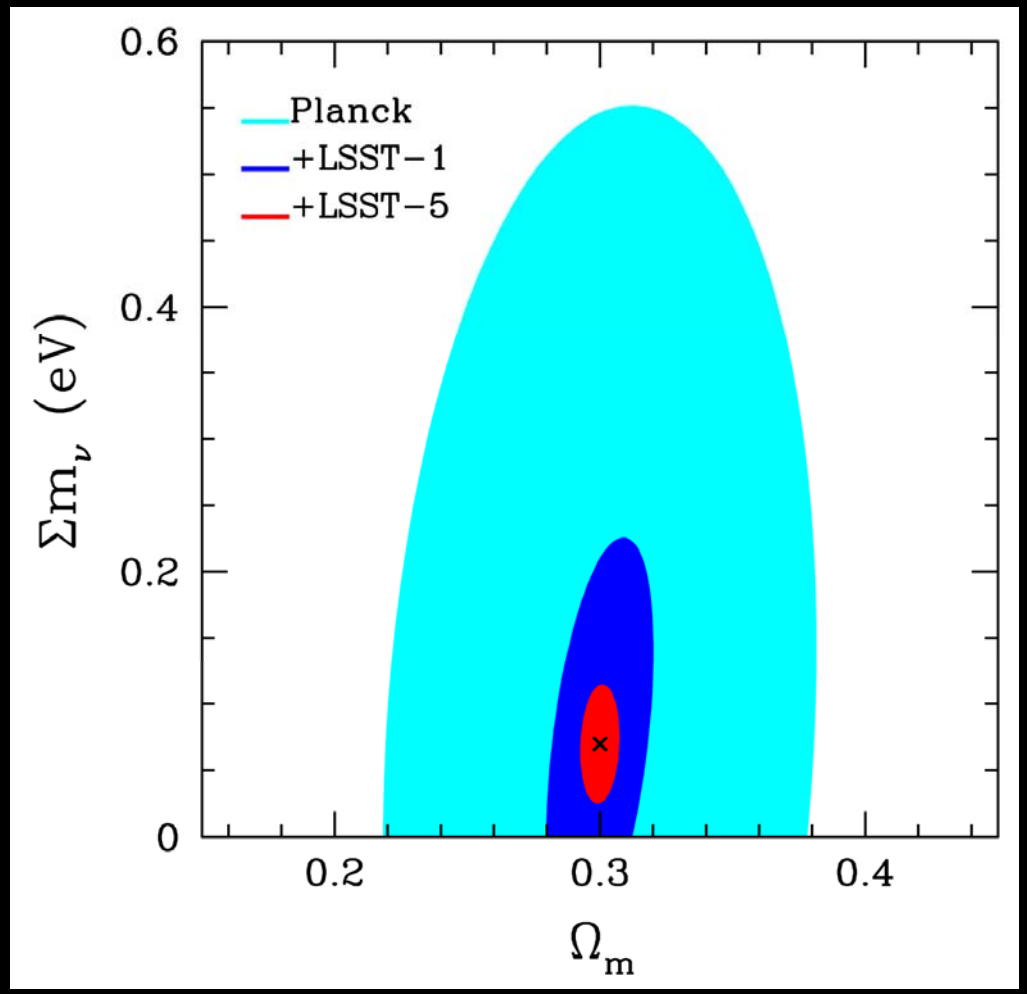
LOW REDSHIFT

SOME ERROR FORECASTS FOR FUTURE EXPERIMENTS:

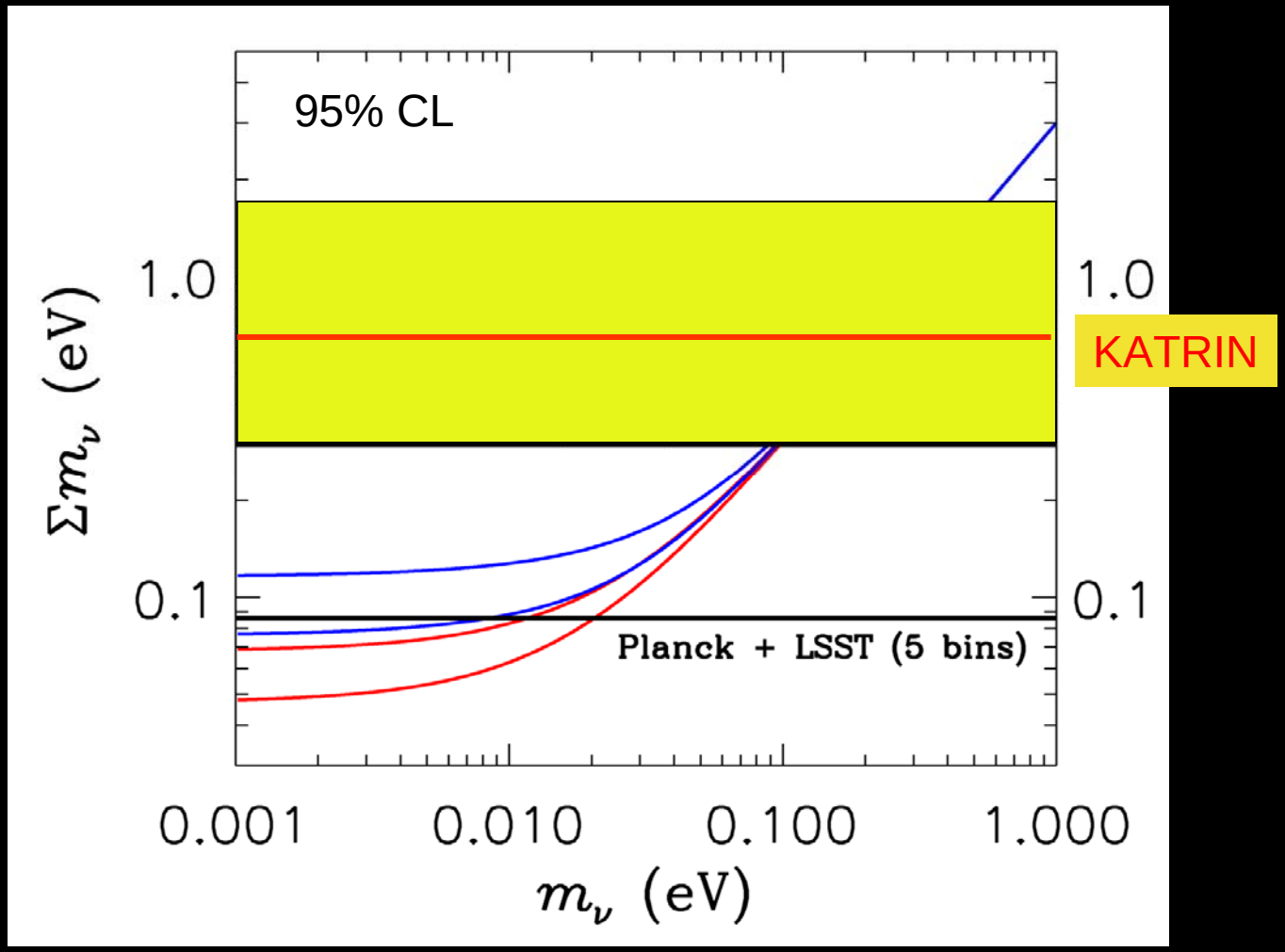
MATTER DENSITY

PLANCK	$\sigma(\Omega_M) = 0.10$	$\sigma(\Omega_M h^2) = 0.0025$
”IDEAL” CMB + LENSING	$\sigma(\Omega_M) = 0.01$	$\sigma(\Omega_M h^2) = 0.0004$
PRESENT (ALL DATA)	$\sigma(\Omega_M) = 0.02$	$\sigma(\Omega_M h^2) = 0.008$

THE SENSITIVITY TO NEUTRINO MASS WILL IMPROVE TO < 0.1 eV AT 95% C.L. USING WEAK LENSING
COULD POSSIBLY BE IMPROVED EVEN FURTHER USING FUTURE LARGE SCALE STRUCTURE SURVEYS



STH, TU & WONG 2006 (ASTRO-PH/0603019, JCAP)



STH, TU & WONG 2006 (ASTRO-PH/0603019, JCAP)

SEE ALSO TALK BY LAURENCE PEROTTO

CONCLUSIONS

- WE ARE NOW FIRMLY INTO THE ERA OF PRECISION COSMOLOGY
- COSMOLOGICAL CONSTRAINTS ARE NOW IMPORTANT FOR PARTICLE PHYSICS EXPERIMENTS
- SOME PARAMETERS (LIKE NEUTRINO MASSES) ARE MORE CONSTRAINED BY COSMOLOGY THAN BY EXPERIMENTS
- THE FUTURE IS LOOKING VERY BRIGHT, WITH PRECISION INCREASING BY AN ORDER OF MAGNITUDE IN THE NEXT DECADE!