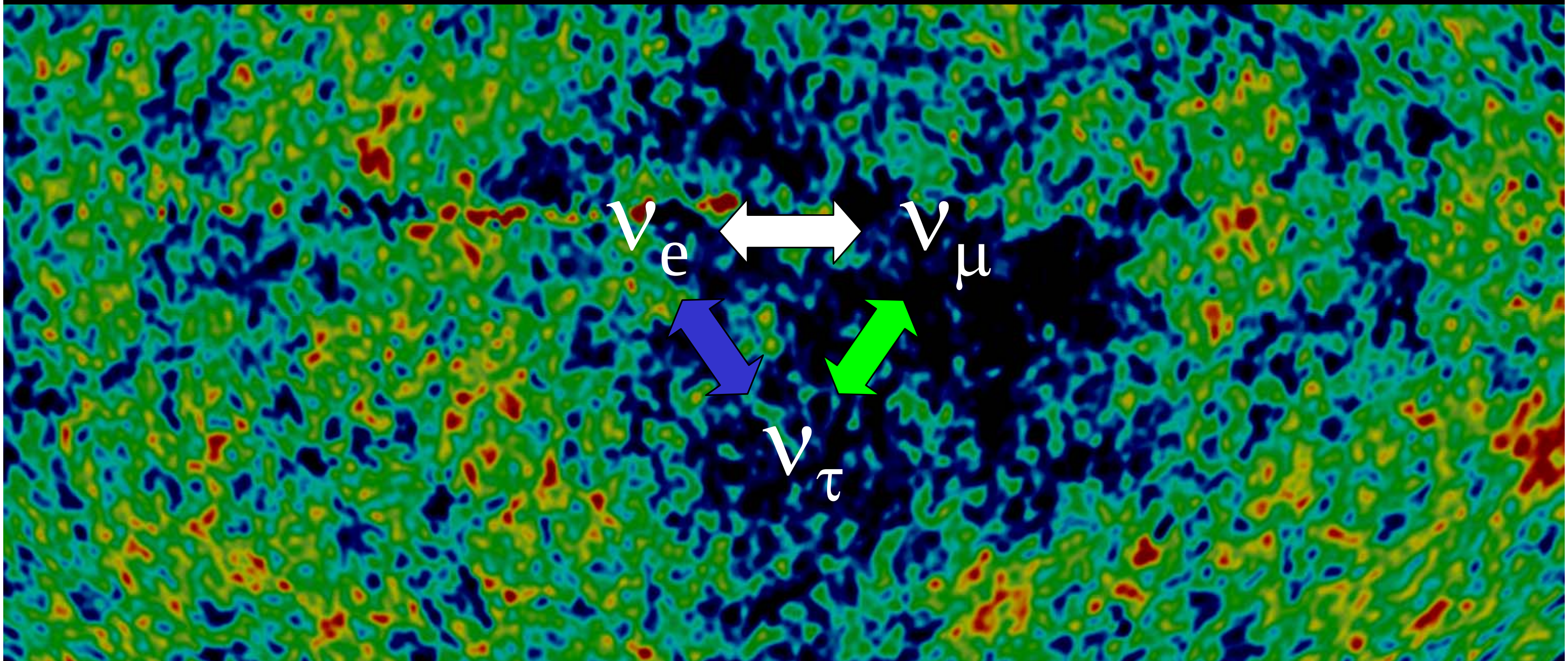
NEUTRINOS AND COSMIC STRUCTURE FORMATION



STEEN HANNESTAD

Neutrino Frontiers 2008

Minneapolis, 24 October 2008

NEUTRINOS AND COSMOLOGY

↓

O MY GOD! CONTINUAL SNORES…

FLAVOUR STATES

PROPAGATION STATES

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1(m_1) \\ \nu_2(m_2) \\ \nu_3(m_3) \end{pmatrix}$$

MIXING MATRIX (UNITARY)

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \cdots & \cdots & \cdots \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e & -c_{12}s_{23} - s_{12}c_{23}s_{13}e & c_{23}c_{13} \end{bmatrix}$$

$\cos\theta_{12}$

$\sin\theta_{12}$

LATE-TIME COSMOLOGY IS (ALMOST) INSENSITIVE TO THE MIXING STRUCTURE

θ_{12} is the "solar" mixing angle

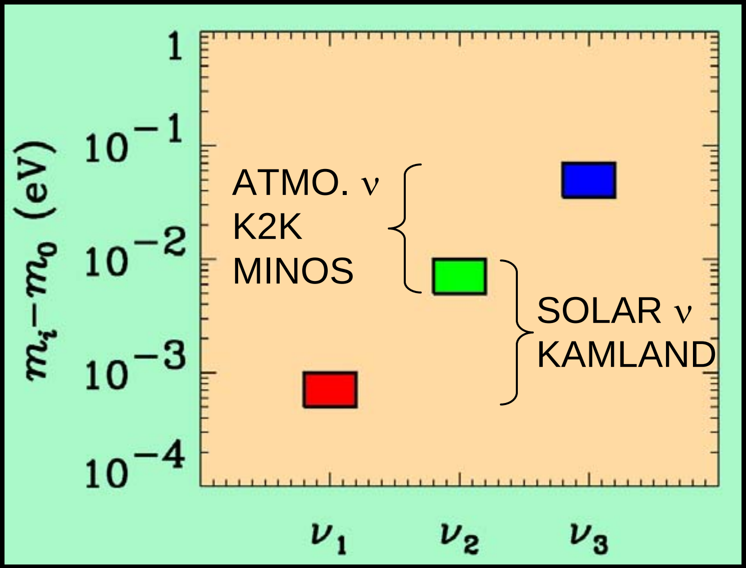
θ_{23} is the "atmospheric" mixing angle

θ_{13}

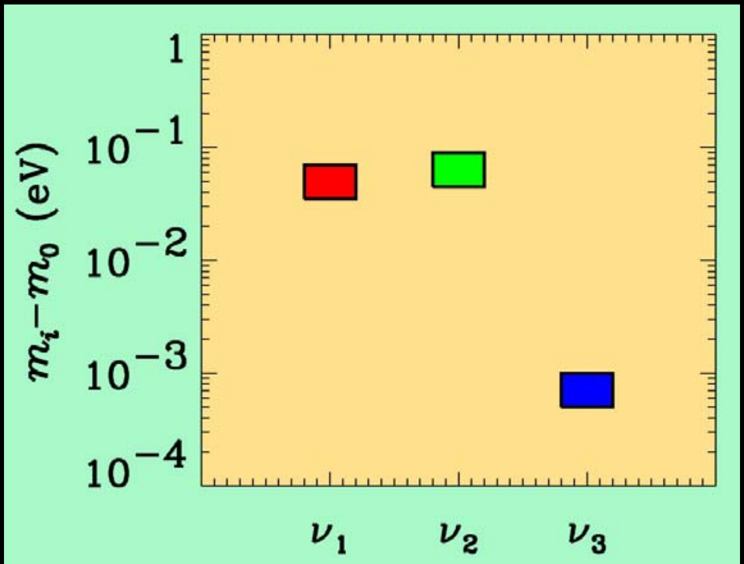
δ Dirac CP violating phase

Possibly 2 additional Majorana phases

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses



Normal hierarchy



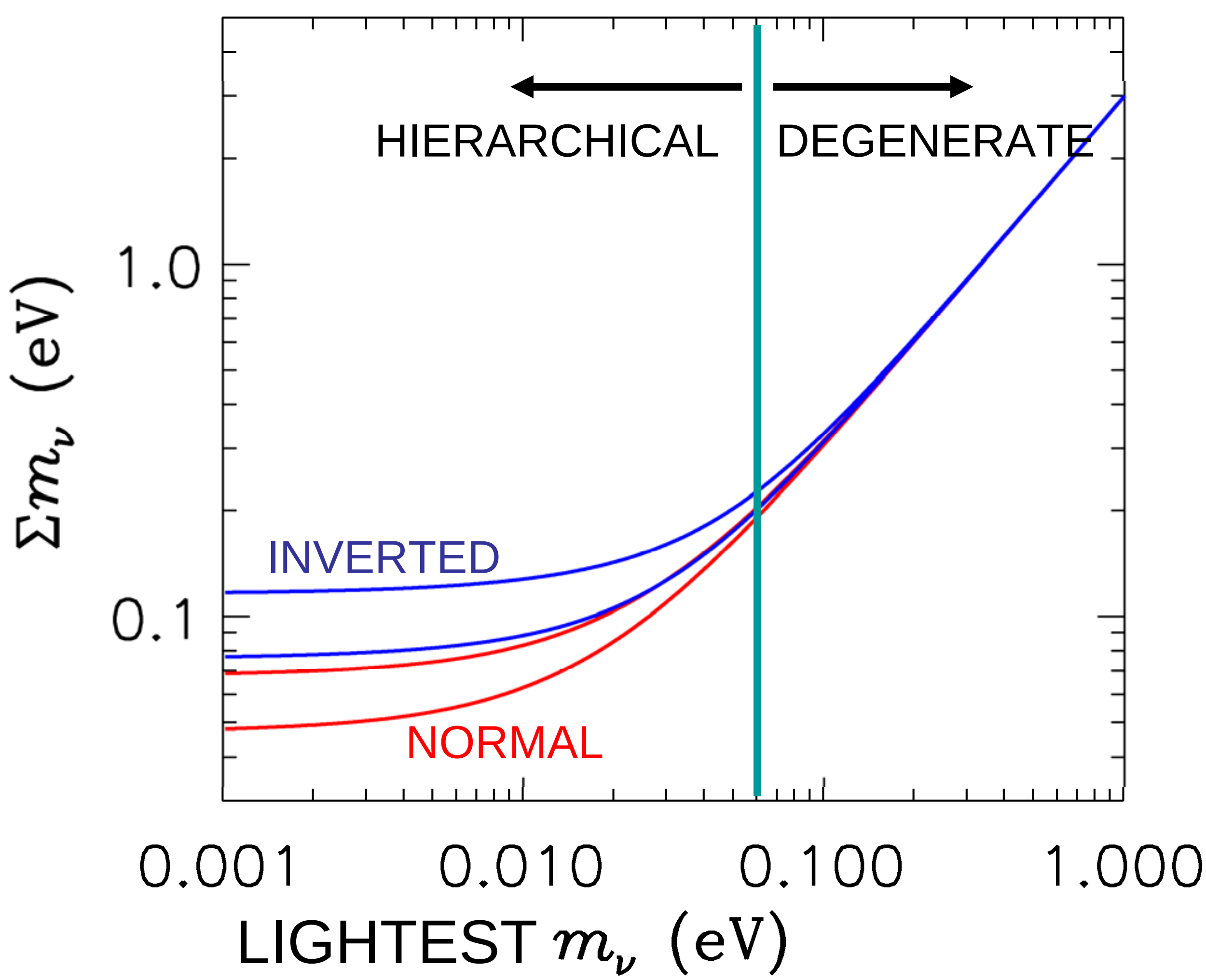
Inverted hierarchy

However, if neutrino masses are degenerate

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

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



Lesgourgues and Pastor 2006

Tritium decay endpoint measurements have provided limits on the electron neutrino mass

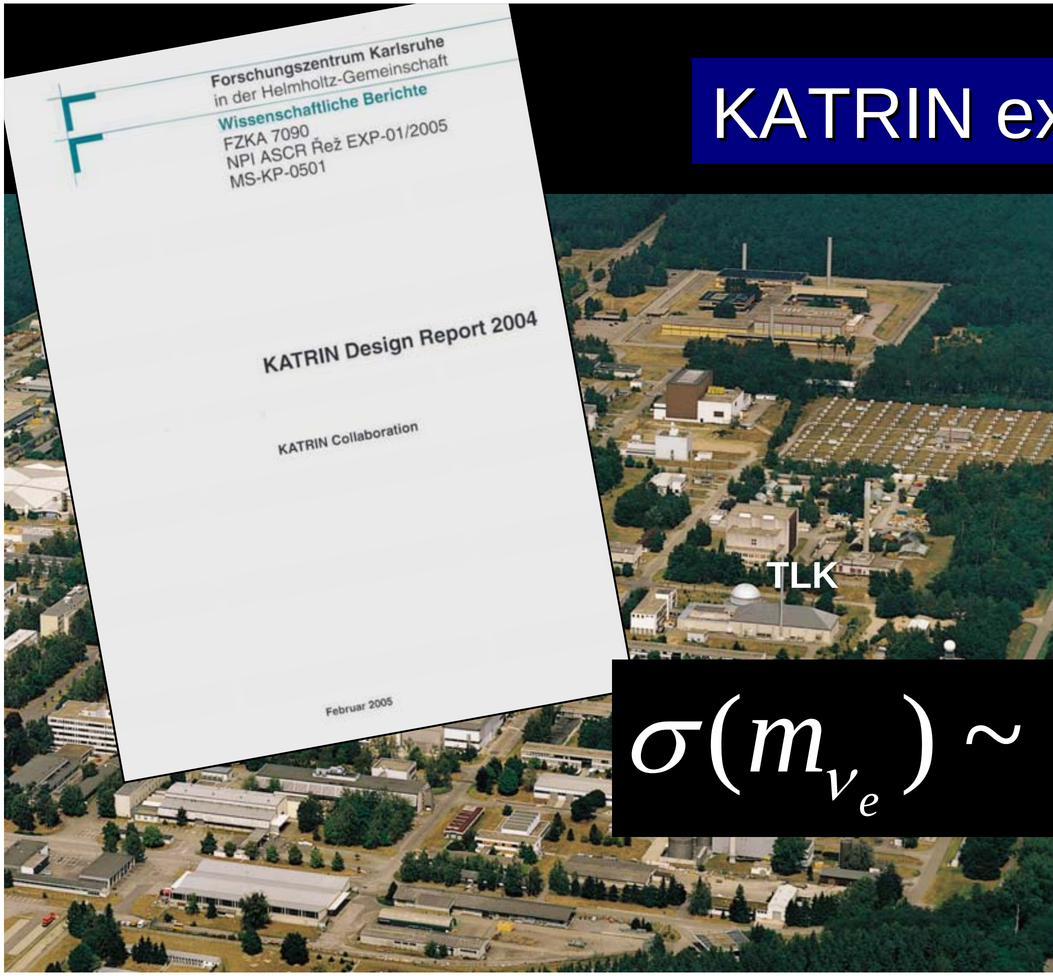
$$m_{\nu_e} = \left(\sum |U_{ei}|^2 m_i^2 \right)^{1/2} \leq 2.3\,\mathrm{eV} \;\; (95\%)$$

Mainz experiment, final analysis (Kraus et al.)

This translates into a limit on the sum of the three mass eigenstates

$$\sum m_i \leq 7\,\mathrm{eV}$$

KATRIN experiment

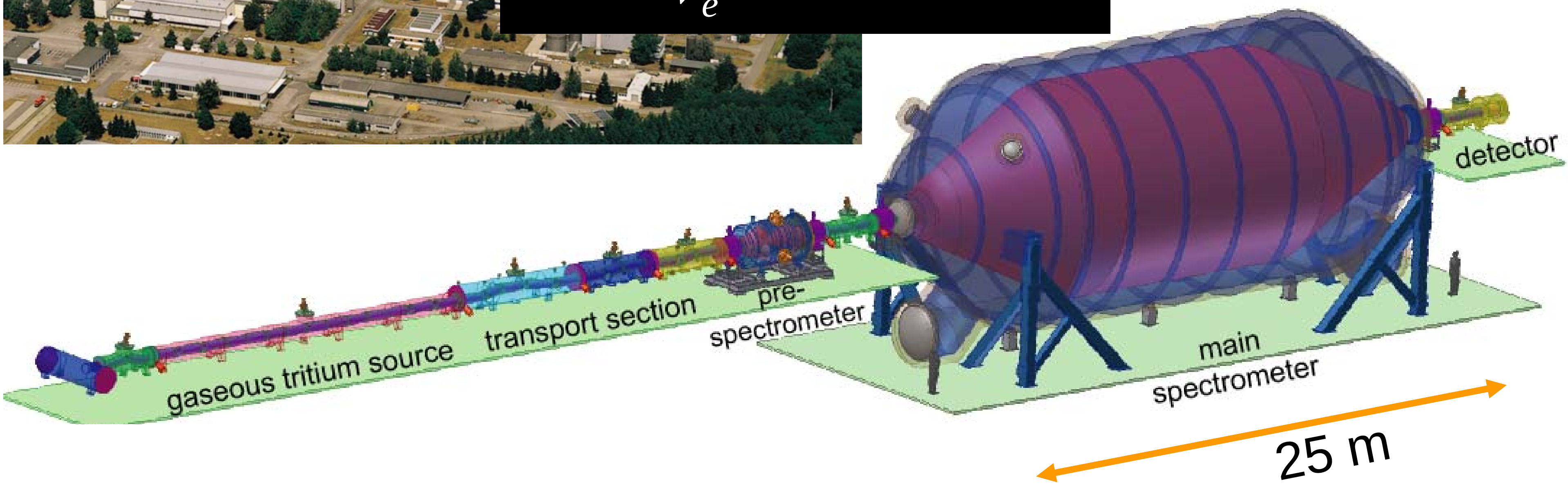


Karlsruhe **Tri**tium **N**eutrino Experiment

at Forschungszentrum Karlsruhe

Data taking starting early 2011

$$\sigma(m_{\nu_e}) \sim 0.2\,\mathrm{eV}$$



A DANISH VERSION OF KATRIN???

THE CARLSBERG NEUTRINO MASS EXPERIMENT

THE ABSOLUTE VALUES OF NEUTRINO MASSES FROM COSMOLOGY

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

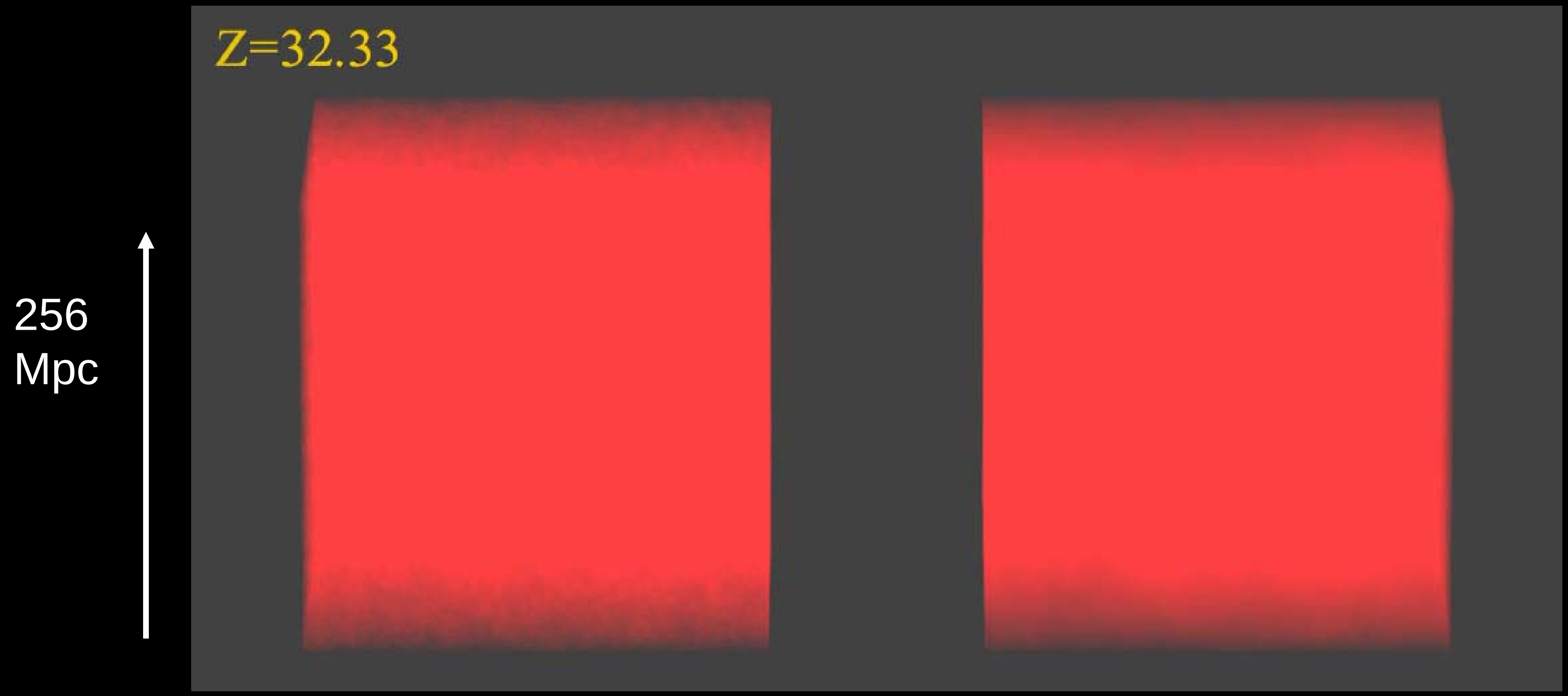
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93\,\text{eV}}$$ FROM $$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \approx 2\,\text{K}$$

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

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

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

N-BODY SIMULATIONS OF ΛCDM WITH AND WITHOUT NEUTRINO MASS (768 Mpc^3) – GADGET 2



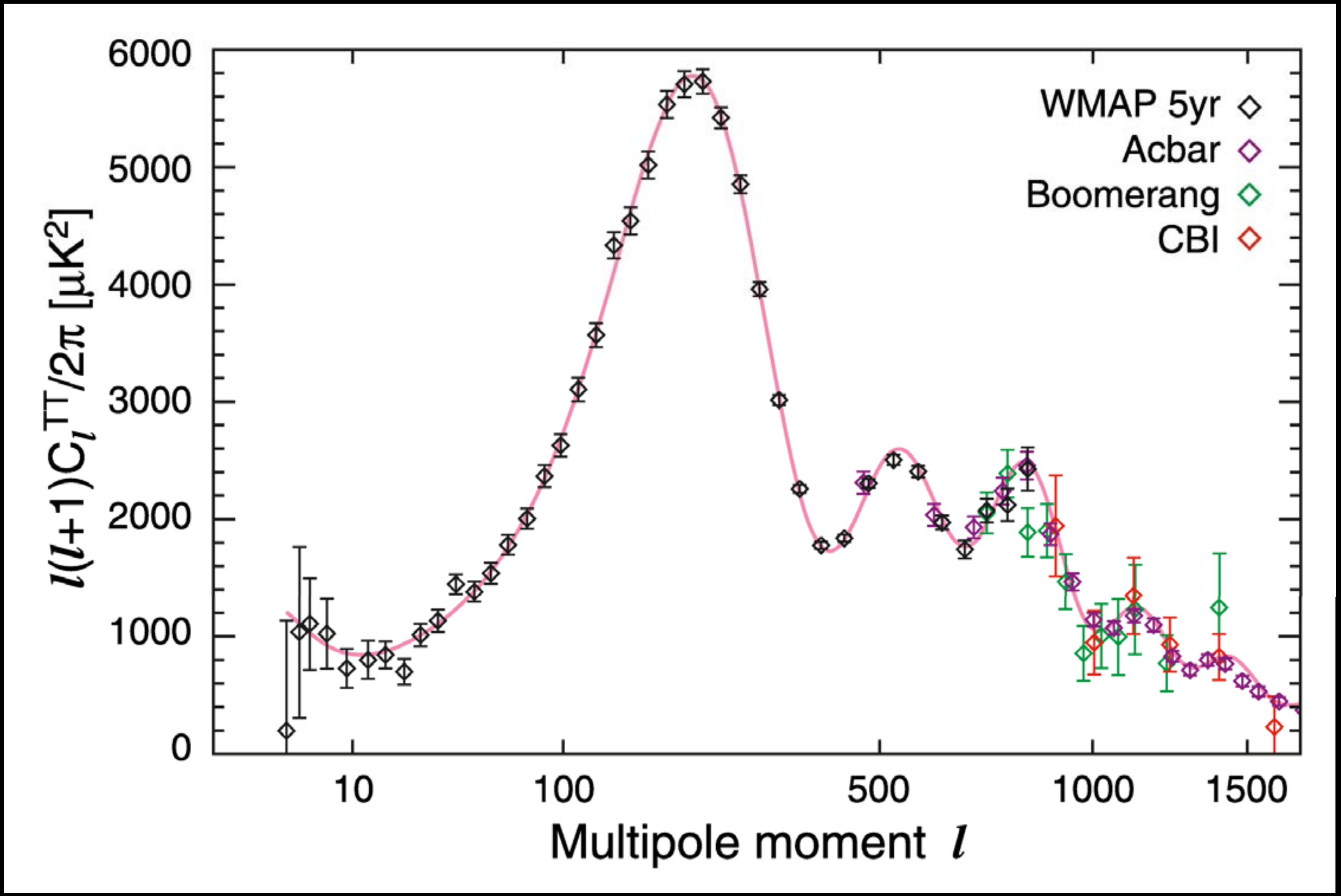
$$\sum m_\nu = 0 \qquad\qquad \sum m_\nu = 6.9\,\mathrm{eV}$$

T Haugboelle, University of Aarhus

AVAILABLE COSMOLOGICAL DATA

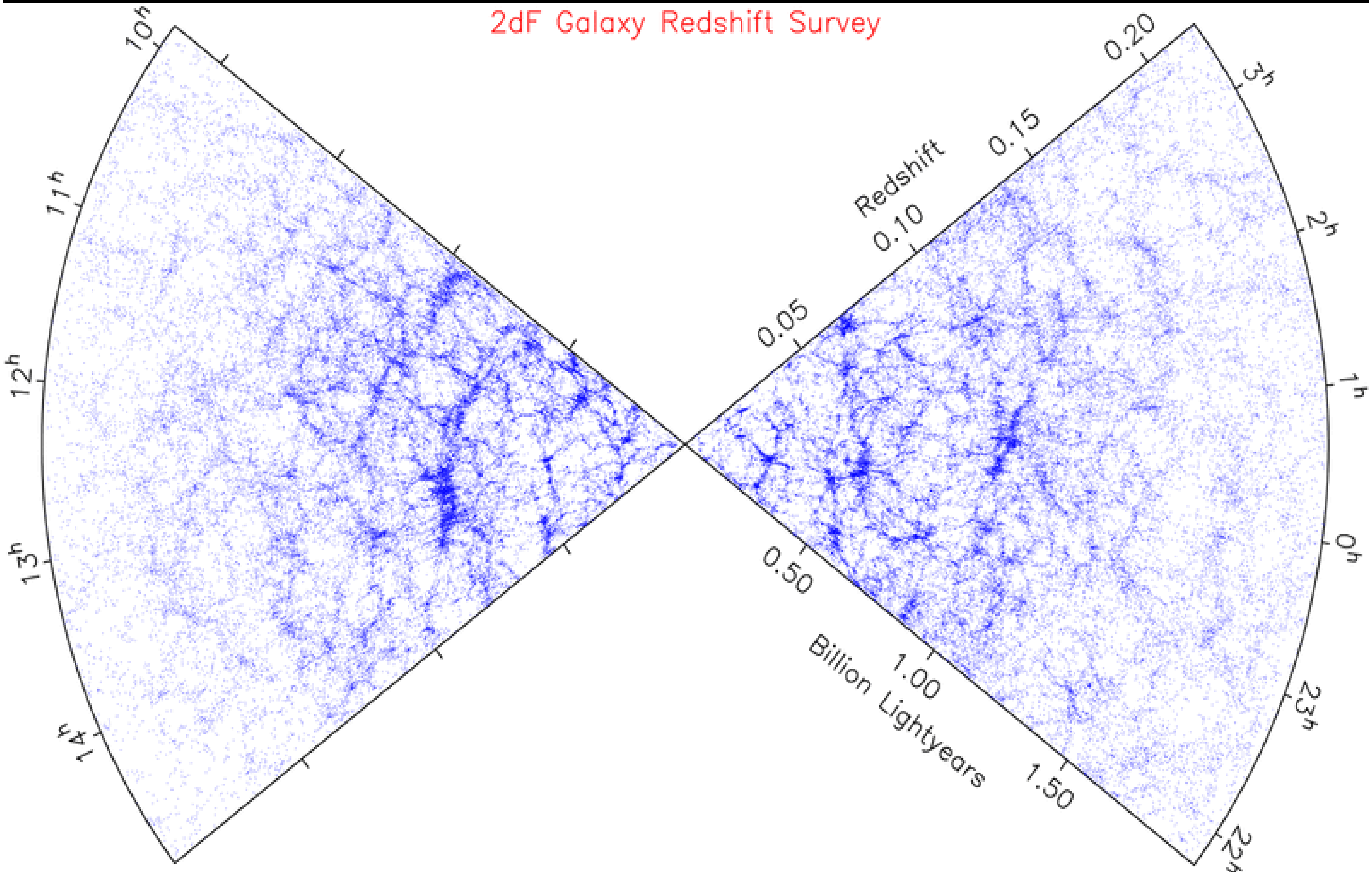
THE COSMIC MICROWAVE BACKGROUND

WMAP-5 TEMPERATURE POWER SPECTRUM

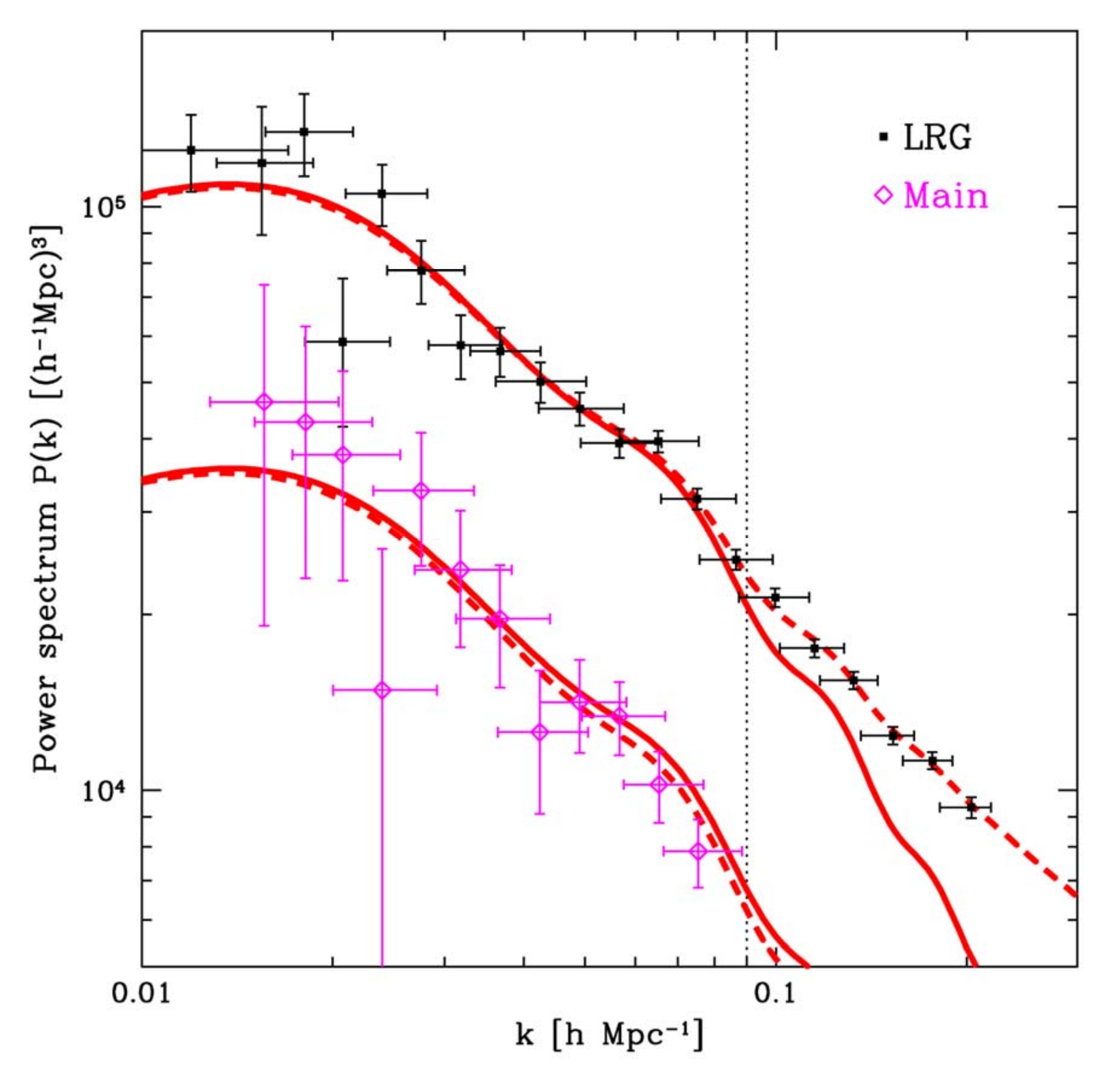


M NOLTA ET AL., arXiv:0803.0593

LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS

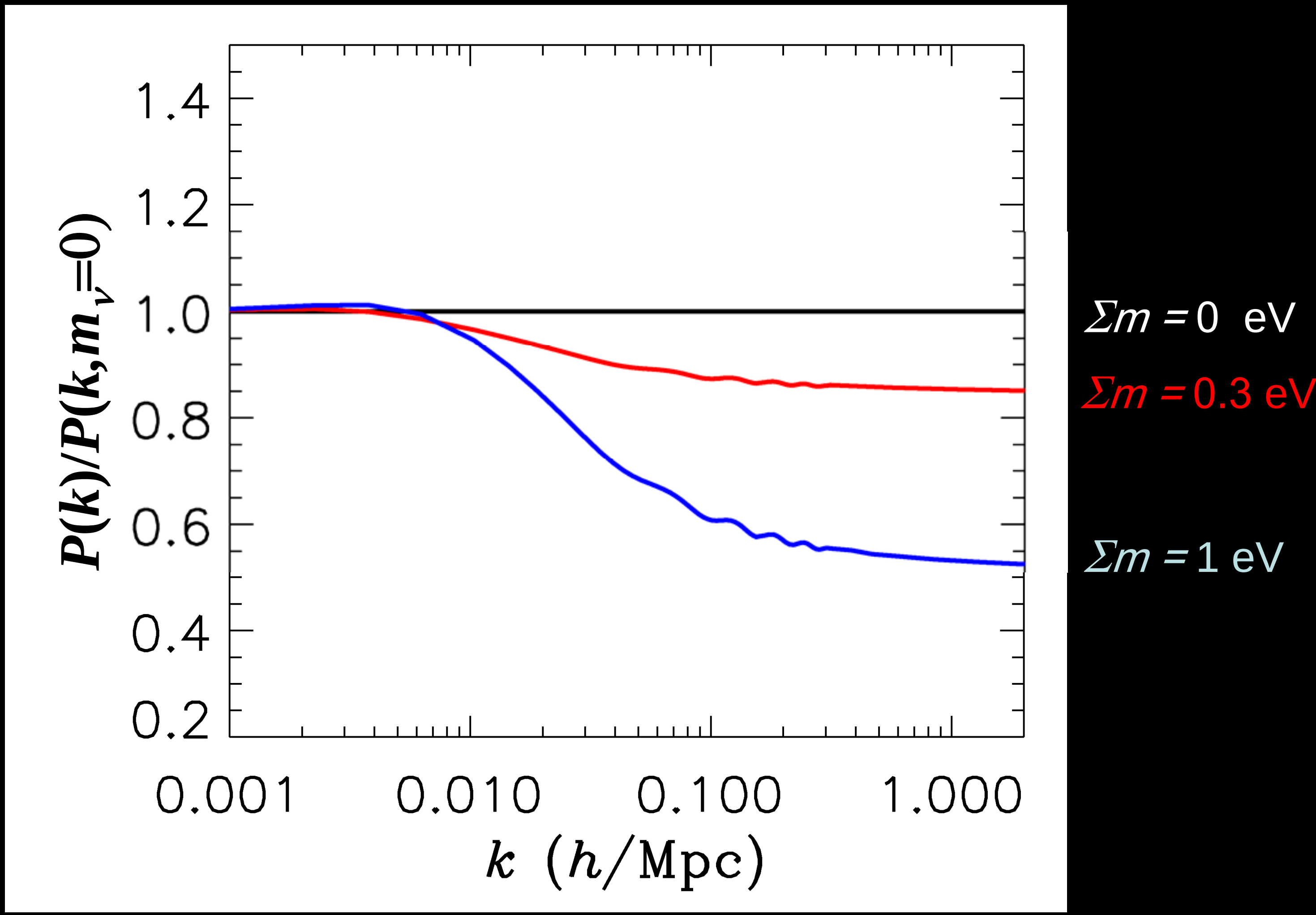


SDSS SPECTRUM
TEGMARK ET AL. 2006



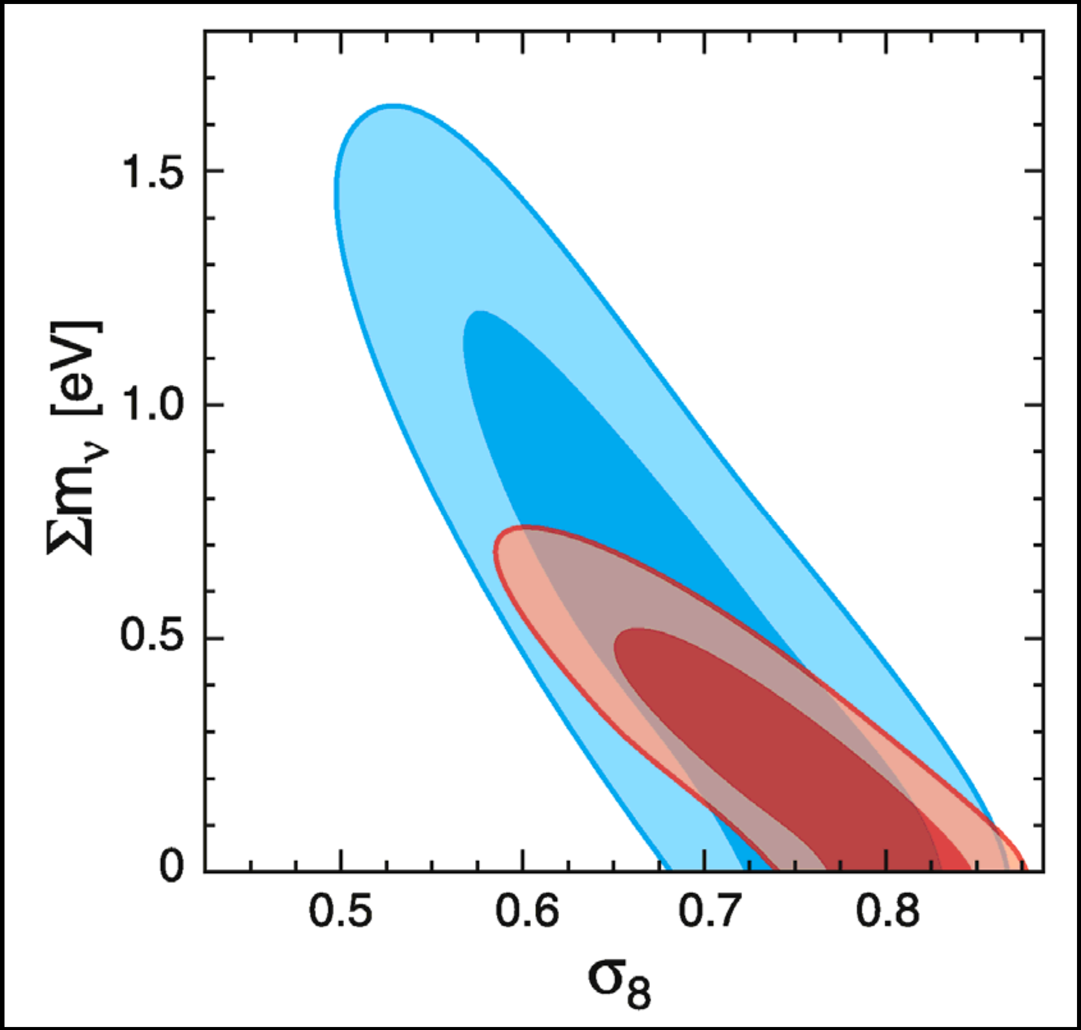
astro-ph/0608632

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



NOW, WHAT ABOUT NEUTRINO PHYSICS?

WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

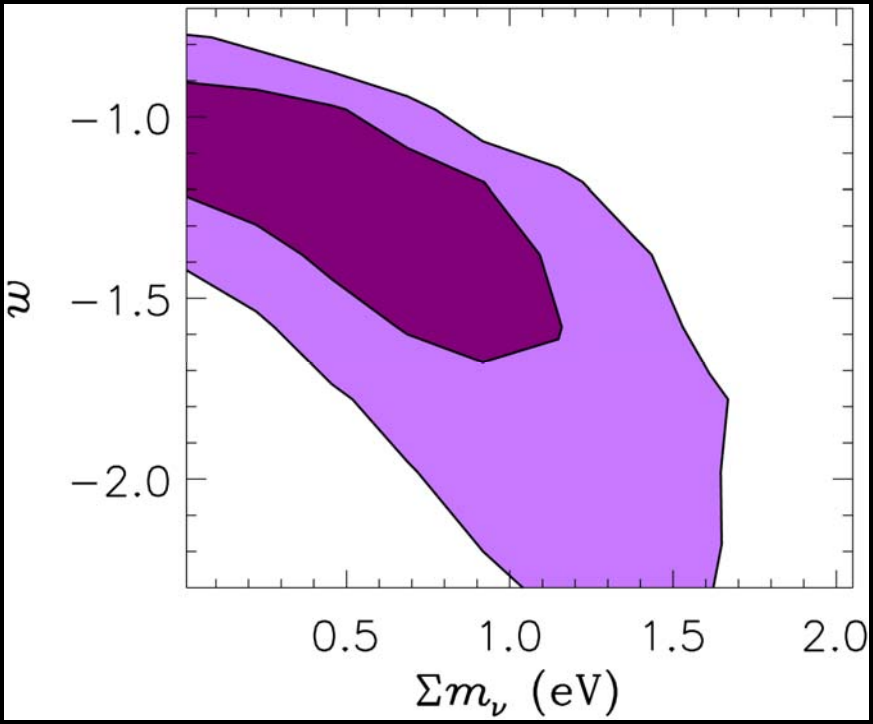


WMAP-5 ONLY ~ 1.3 eV
WMAP + OTHER 0.67 eV

Komatsu et al., arXiv:0803.0547

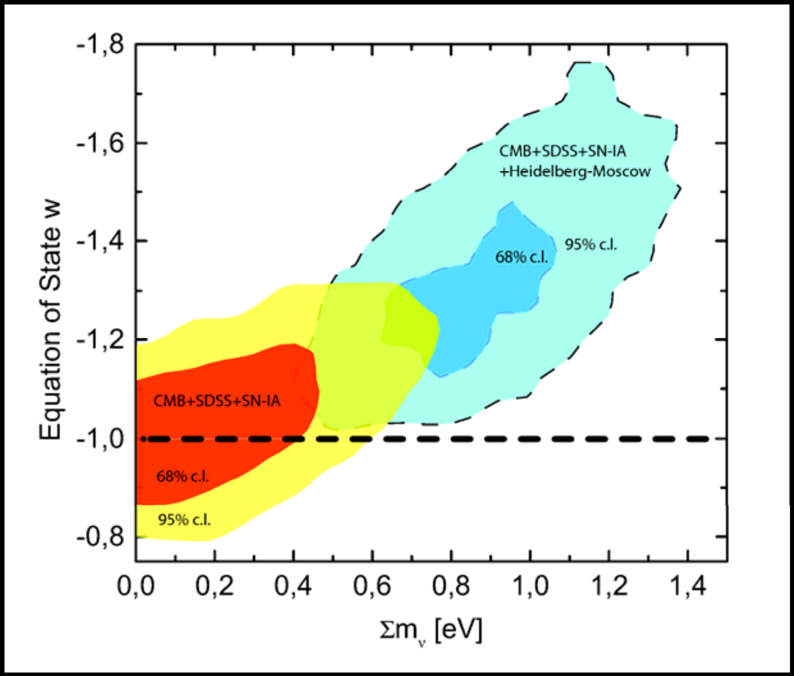
HOW CAN THE BOUND BE AVOIDED?

THERE IS A VERY STRONG DEGENERACY BETWEEN NEUTRINO MASS AND THE DARK ENERGY EQUATION OF STATE WHEN CMB, LSS AND SNI-A DATA IS USED.
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:

ADDITIONAL DATA TO BREAK THE Ω_m, *w*, *h* DEGENERACY

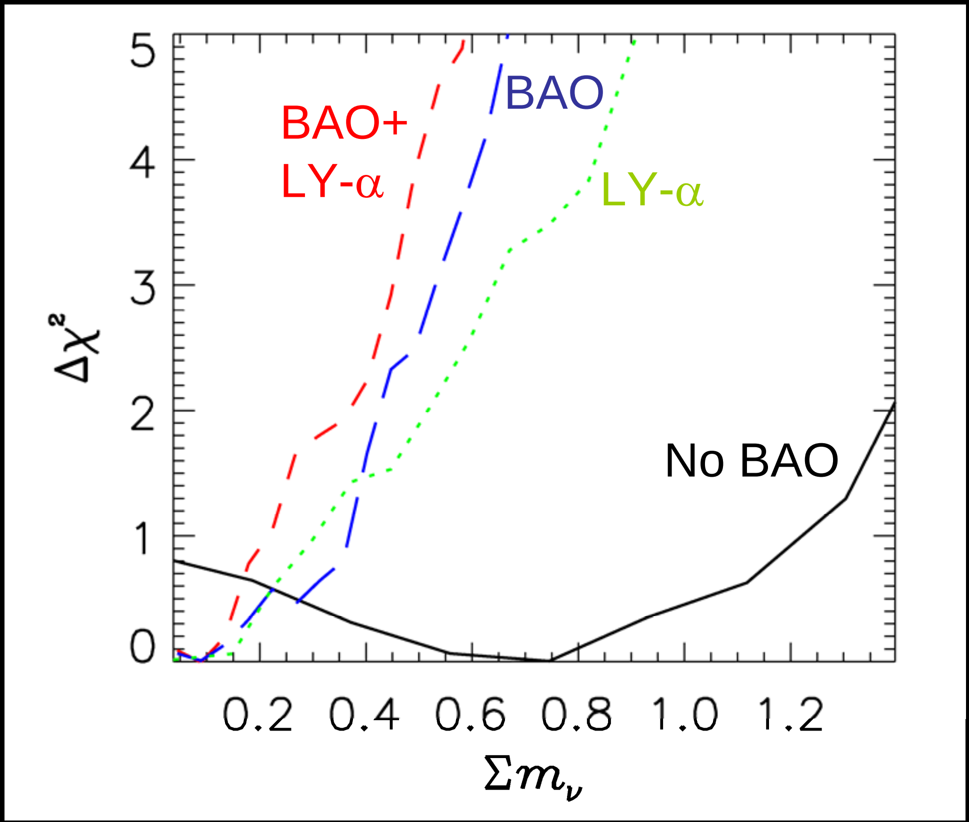
- THE BARYON ACOUSTIC PEAK
- H(z) MEASUREMENTS

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

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

12 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, HST
SNLS SNI-A, SDSS BARYONS

IN MORE RESTRICTED MODELS THE BOUND IS STRONGER
(BUT BEWARE OF THE PARAMETER DEGENERACIES)

ADDITIONAL RELATIVISTIC ENERGY DENSITY

$$N_{\rm eff} = N_{\nu,\rm SM} + \frac{\rho_{\rm extra}}{\rho_{\nu,0}}$$

COULD BY CAUSED BY A NUMBER OF DIFFERENT EFFECTS

ADDITIONAL PARTICLE SPECIES

DECAY OF HEAVY SPECIES

NEUTRINO CHEMICAL POTENTIAL

.....

USING WMAP3+SDSS-LRG+SNI-A

$$N_\nu = 3.9^{+2.0}_{-1.6} \text{ (95\% C.L.)}$$

HAMANN, STH, RAFFELT, WONG arXiv:0705.0979 (JCAP)

$N_\nu = 0$ IS EXCLUDED AT ABOUT 5 SIGMA!

THIS RESULT IS CONSISTENT WITH WMAP-5

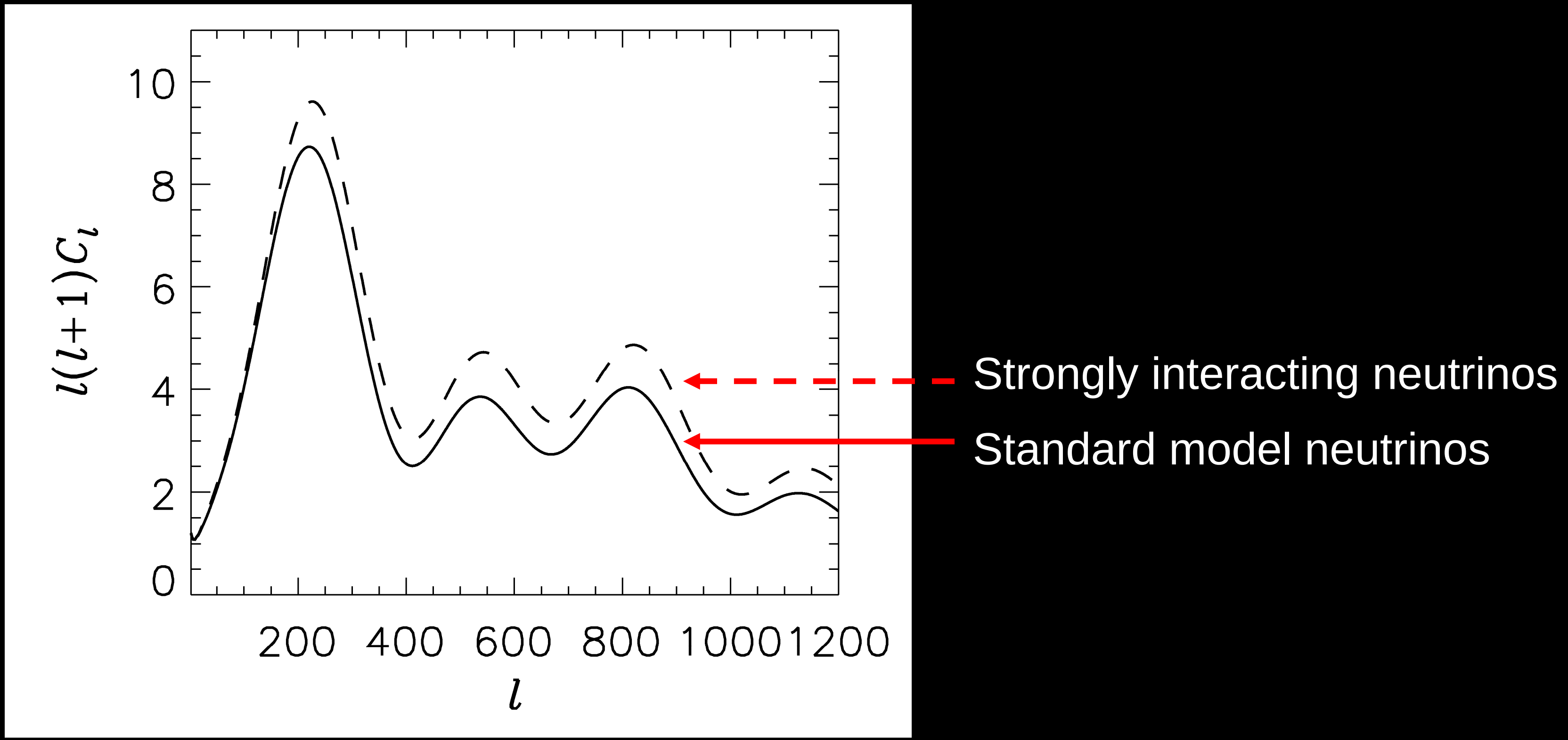
$$N_\nu = 4.4^{+1.4}_{-1.4} \text{ (68\% C.L.)}$$ (WMAP-5 ONLY)

ALSO DE BERNARDIS ET AL 2008,
HAMANN, LESGOURGUES & MANGANO 2008
SELJAK, SLOSAR & MCDONALD 2007

DO WE KNOW THAT "NEUTRINOS" ARE FREE-STREAMING?

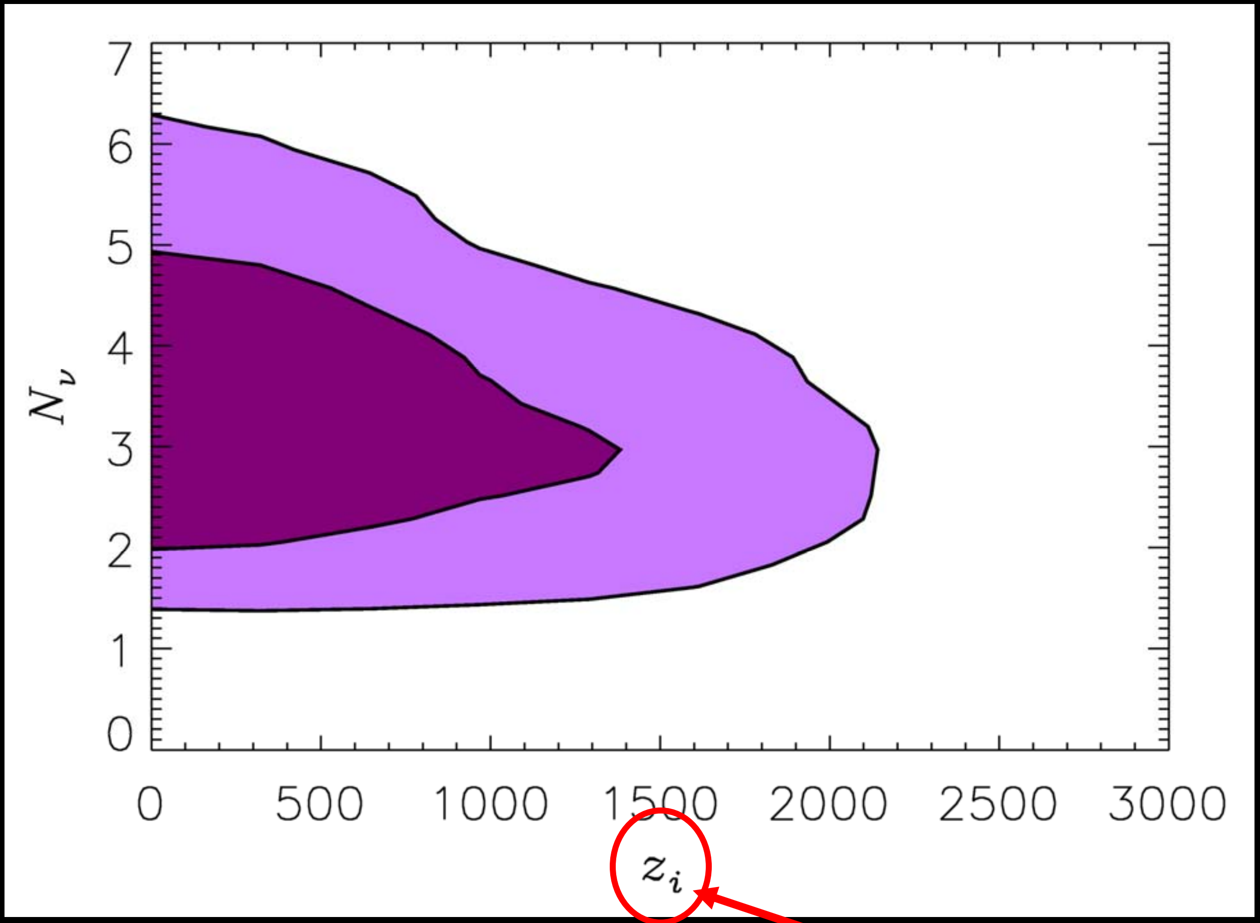
FRE-STREAMING NEUTRINOS PRODUCE A DISTINCT SIGNATURE ON CMB AND LSS (BECAUSE OF ANISOTROPIC STRESS)

Bashinsky & Seljak 04, STH 04, Trotta & Melchiorri 05, Bell, Pierpaoli & Sigurdson 06, De Bernardis et al 08



Sth, astro-ph/0411475 (JCAP)

FROM CMB + LSS DATA THE ANISOTROPIC STRESS IS DETECTED AT FAIRLY HIGH SIGNIFICANCE (MORE THAN 4 SIGMA)



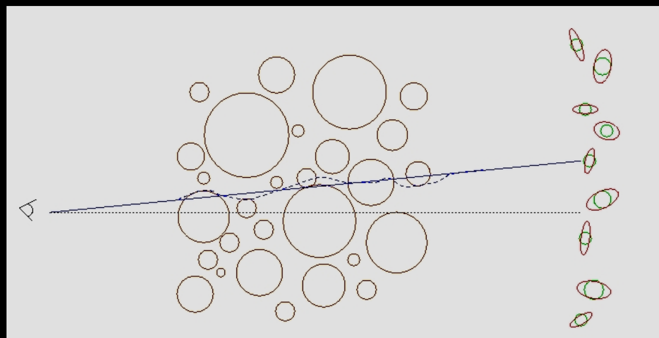
Basbøll, Bjælde, STH, Raffelt 2008

Earliest possible redshift where neutrinos can be strongly interacting

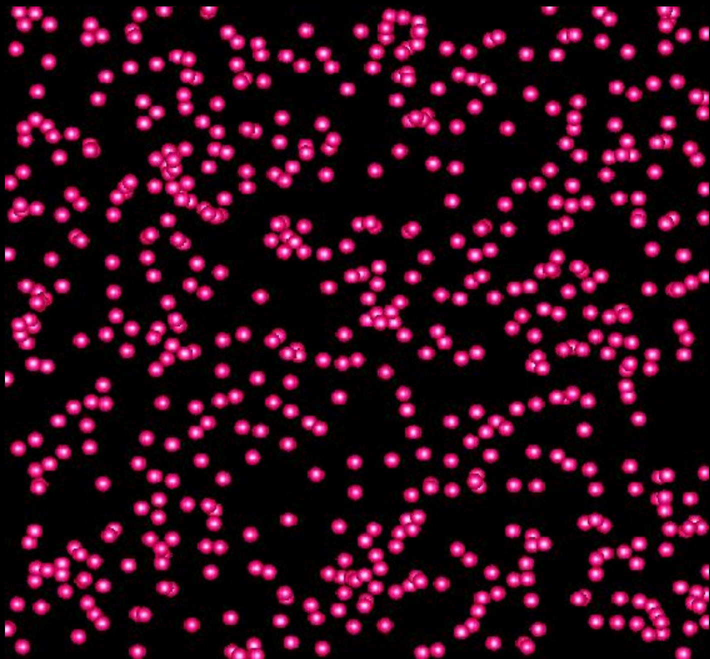
WHAT IS IN STORE FOR THE FUTURE?

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

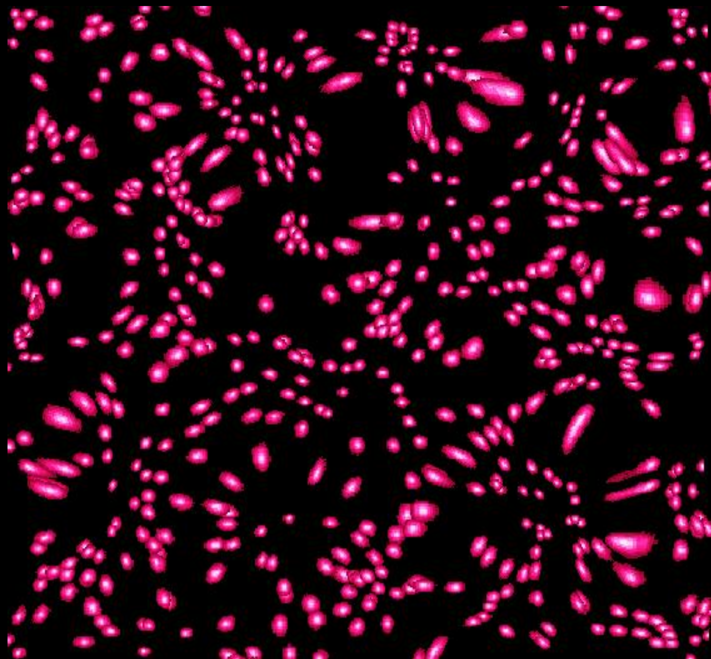
WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE



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

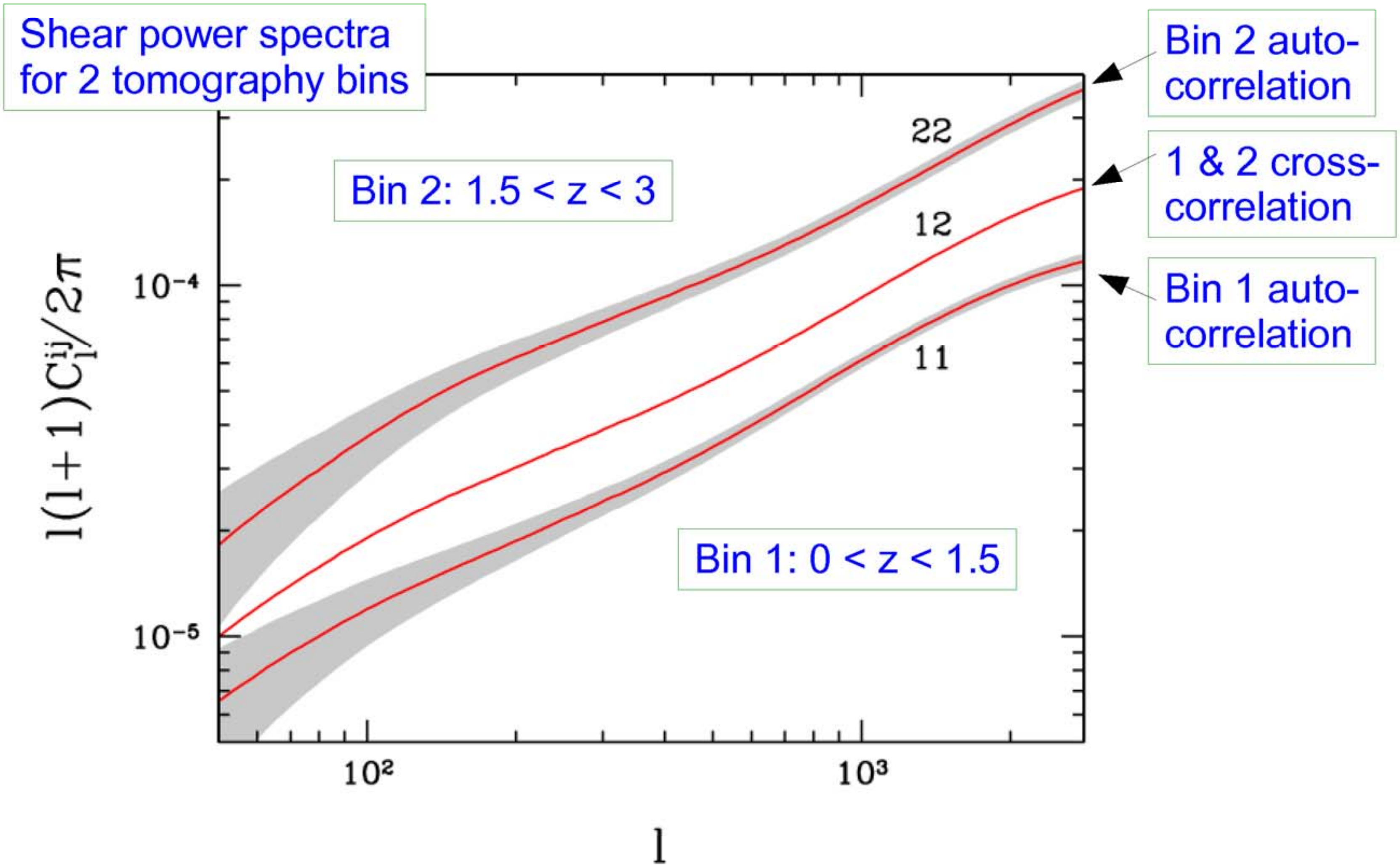
$$C_\ell = \frac{9}{16} H_0^4 \Omega_m^2 \int_0^{\chi_H} \left[\frac{g(\chi)}{a\chi} \right]^2 P(\ell / r, \chi) d\chi$$

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

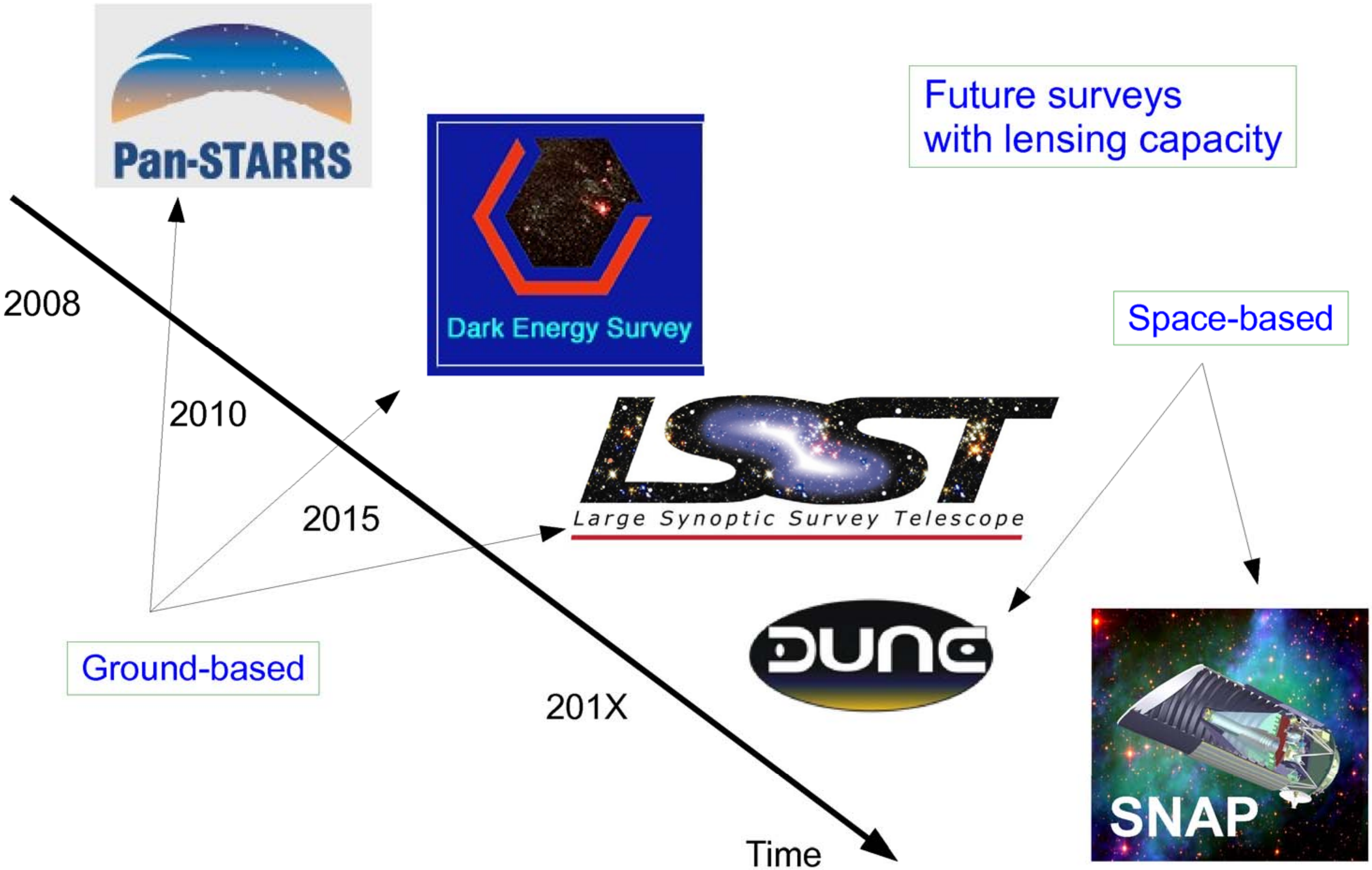
$$g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi'$$

WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY

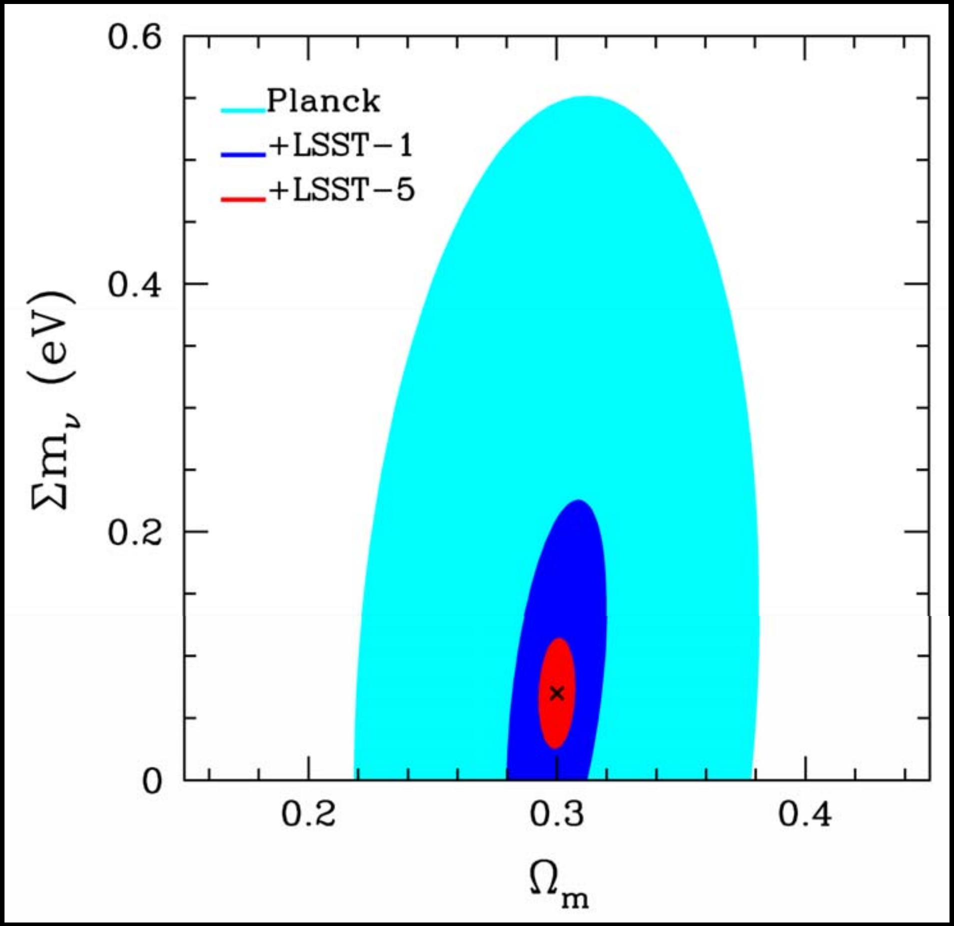
(SEE FOR INSTANCE JAIN & SELJAK '96, ABAZAJIAN & DODELSON '03, SIMPSON & BRIDLE '04)



STH, TU, WONG 2006


Future surveys
with lensing capacity
Pan-STARRS
Dark Energy Survey
Large Synoptic Survey Telescope
SNAP
2008
2010
2015
201X
Time
Ground-based
Space-based

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)

WHY IS WEAK LENSING TOMOGRAPHY SO GOOD?

IF MEASURED AT ONLY ONE REDSHIFT THE NEUTRINO SIGNAL IS DEGENERATE WITH OTHER PARAMETERS

- CHANGING DARK ENERGY EQUATION OF STATE
- INITIAL CONDITIONS WITH BROKEN SCALE INVARIANCE

HOWEVER, BY MEASURING AT DIFFERENT REDSHIFTS THIS DEGENERACY CAN BE BROKEN

ADVANTAGES OF PROBING STRUCTURE AT HIGH REDSHIFT

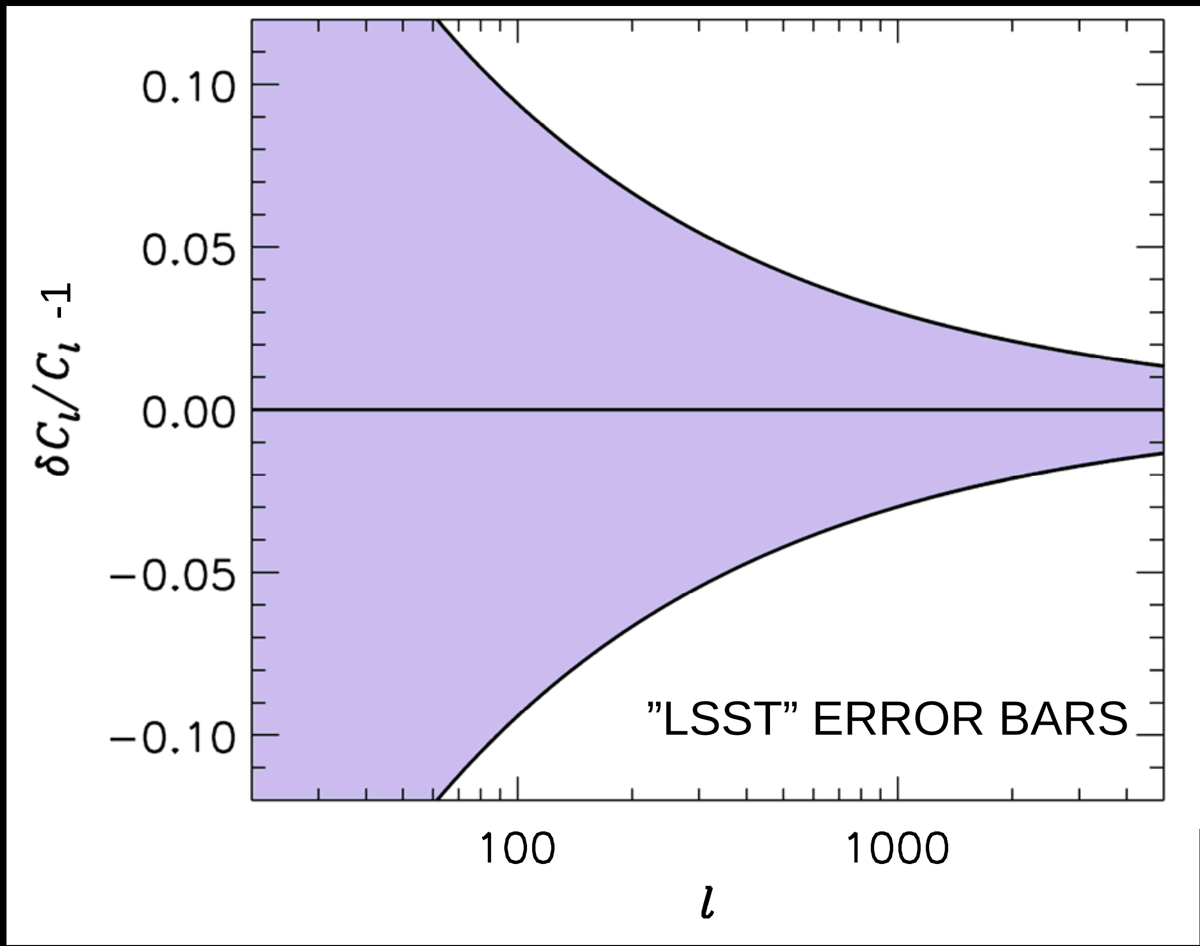
- STRUCTURES ARE MORE LINEAR
- VOLUME IS LARGER (THE HORIZON VOLUME IS ~ 1000 TIMES LARGER THAN THE SDSS-LRG VOLUME)

HOW TO DO IT?

- LYMAN-ALPHA?
- BAO? (WFMOS)
- GALAXIES? (LSST)
- 21-CM? (SKA)

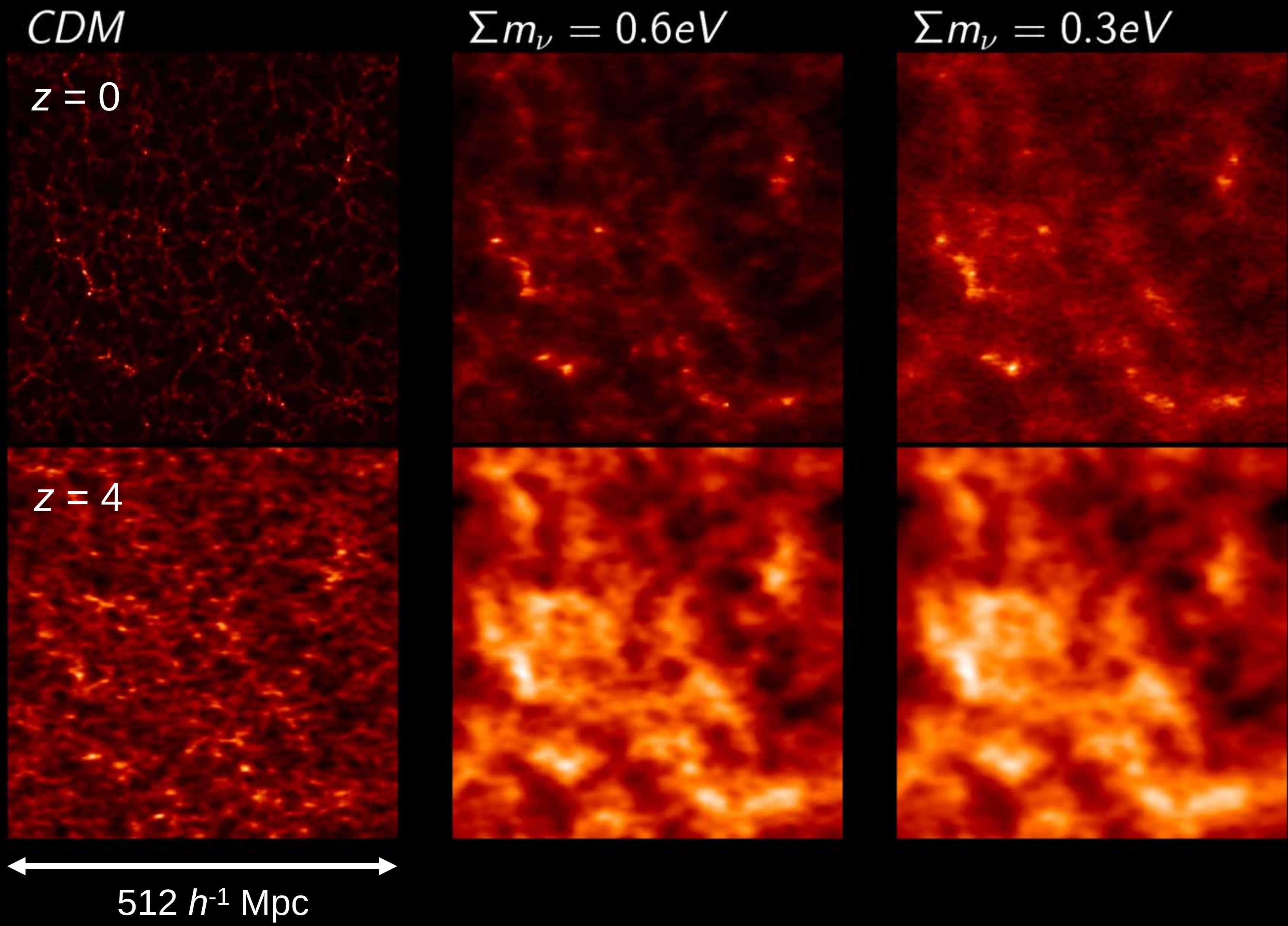
THIS SOUNDS GREAT, BUT UNFORTUNATELY THEORY MUST BE AT THE SAME LEVEL OF PRECISION BY THE TIME DATA-TAKING STARTS

FUTURE SURVEYS LIKE LSST WILL PROBE THE POWER SPECTRUM TO ~ 1-2 PERCENT PRECISION

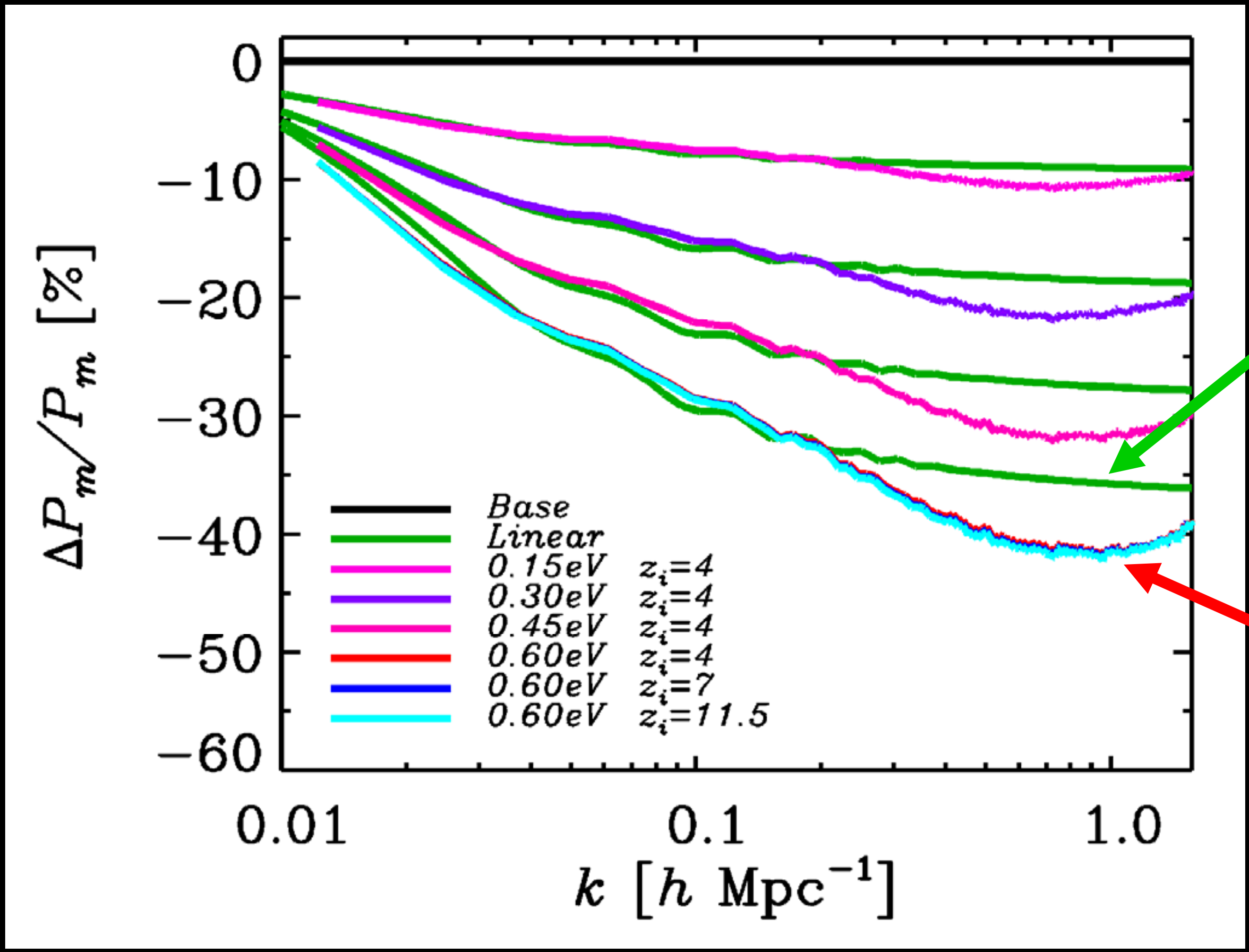


WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM TO AT LEAST THE SAME PRECISION!

EVOLUTION OF NEUTRINO DENSITY FIELD



NON-LINEAR EVOLUTION PROVIDES AN ADDITIONAL AND VERY CHARACTERISTIC SUPPRESSION OF FLUCTUATION POWER DUE TO NEUTRINOS (COULD BE USED AS A SMOKING GUN SIGNATURE)



LINEAR THEORY

$$\frac{\Delta P}{P} \sim -8\frac{\Omega_\nu}{\Omega_m}$$

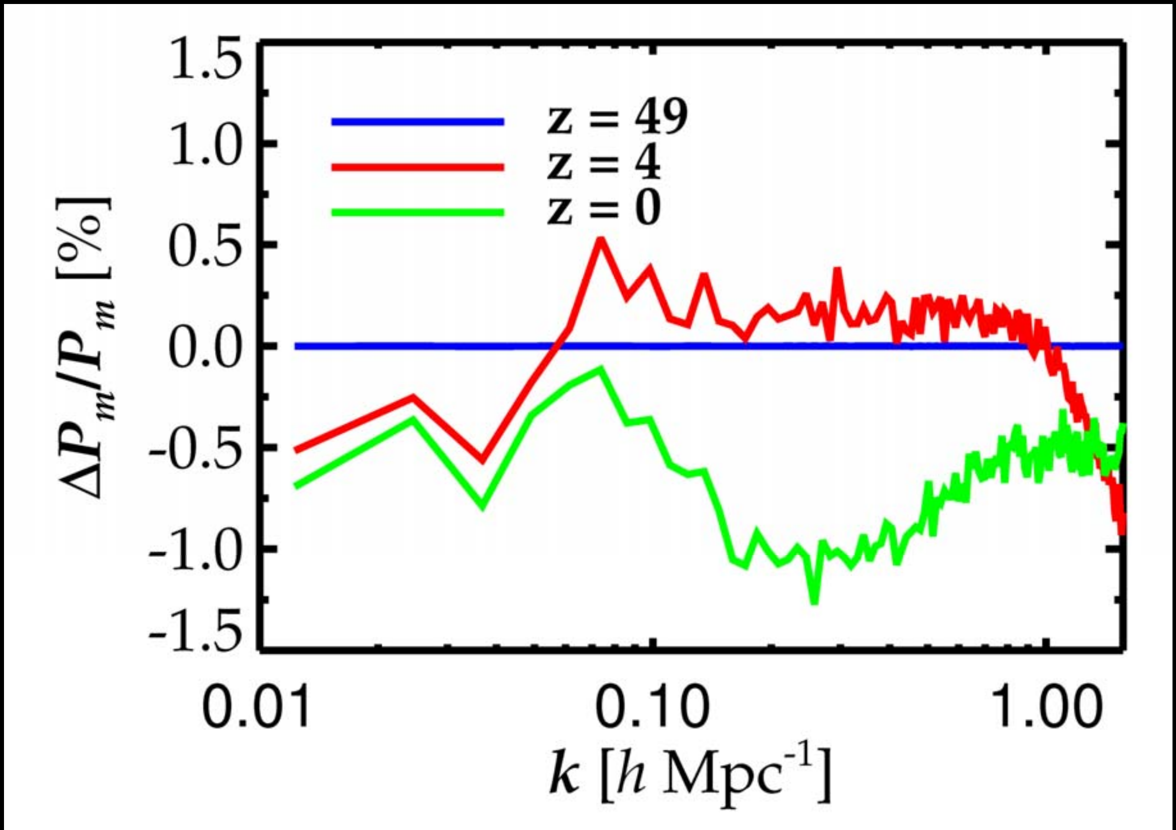
FULL NON-LINEAR

$$\frac{\Delta P}{P} \sim -9.6\frac{\Omega_\nu}{\Omega_m}$$

Brandbyge, STH, Haugbølle, Thomsen, arXiv:0802.3700 (ApJ)

LIGHT NEUTRINOS ARE ALMOST IMPOSSIBLE TO FOLLOW AT HIGH Z BECAUSE OF THERMAL NOISE

SOLUTION: FOLLOW NEUTRINOS USING LINEAR THEORY WITH A GRID-BASED METHOD, SIMULTANEOUSLY WITH THE CDM / BARYON N-BODY SOLVER



$$\sum m_\nu = 0.6\,\mathrm{eV}$$

DIFFERENCE BETWEEN GRID AND PARTICLE METHOD

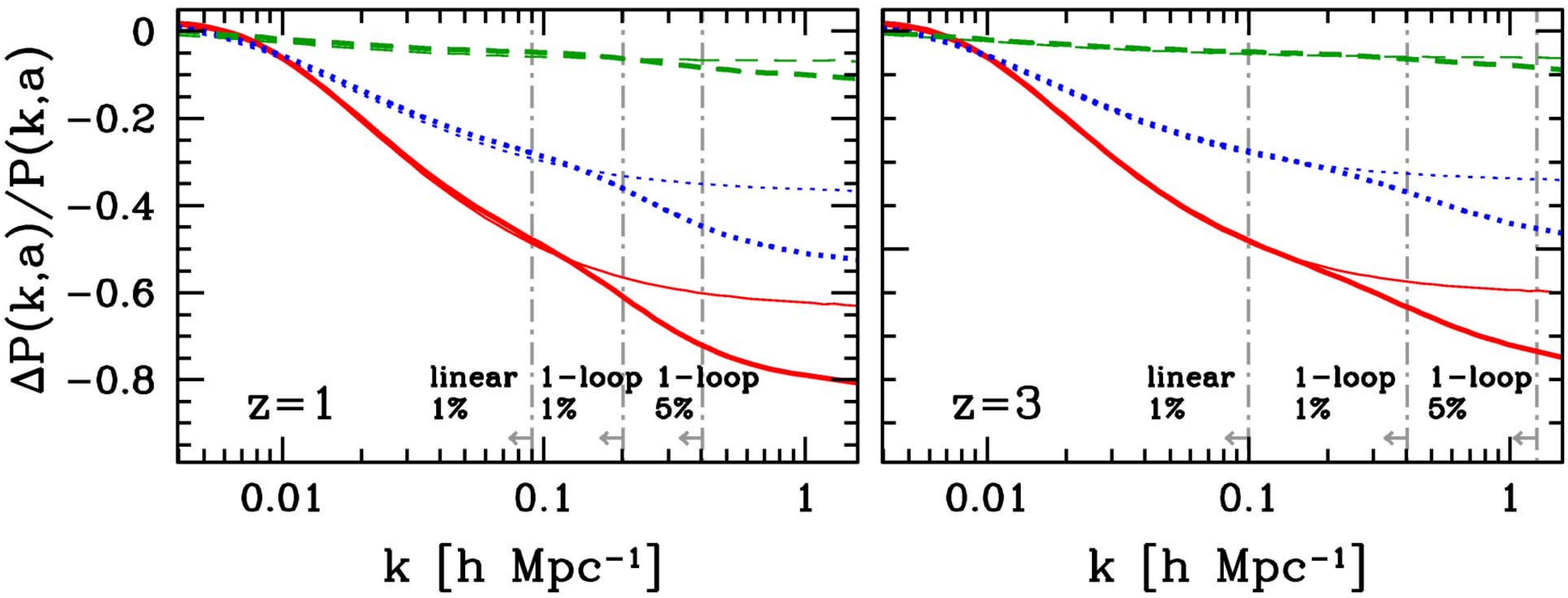
BRANDBYGE & STH 2008 (IN PREPARATION)

THIS METHOD WORKS FOR REALISTIC NEUTRINO MASSES (BELOW 0.5-0.6 eV) AT BETTER THAN 0.5% PRECISION

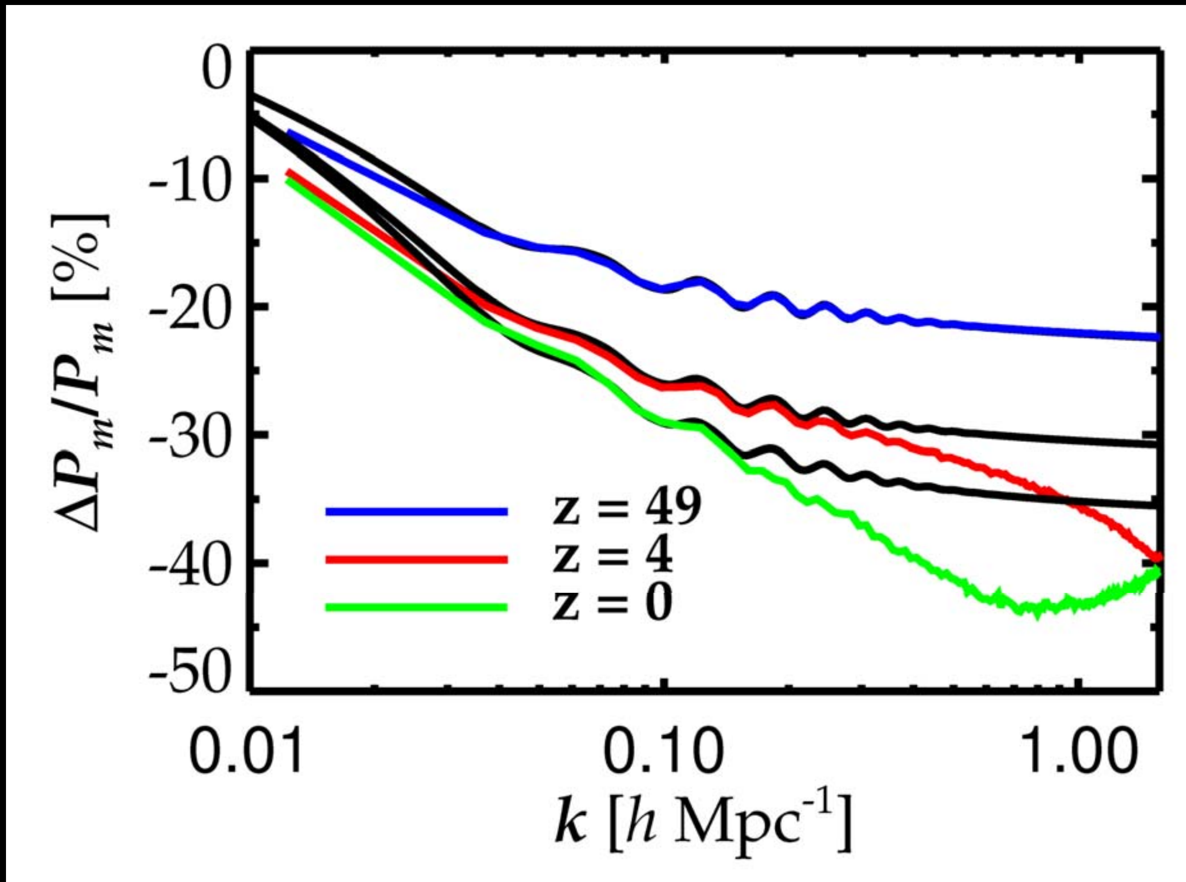
THE COMPUTATIONAL SPEED IS ESSENTIALLY THE SAME AS FOR A PURE CDM SIMULATION (FACTOR ~ 10 OR MORE FASTER THAN WITH NEUTRINOS AS PARTICLES)

FOR RELATIVELY SMALL NEUTRINO MASSES THE RESULTS CAN BE REPRODUCED USING HIGHER ORDER PERTURBATION THEORY FOR SCALES UP TO *k* ~ 0.1 *h* / Mpc (SAITO ET AL. 2008, WONG 2008)

THESE CALCULATIONS ALSO ASSUME THAT NEUTRINO STRUCTURES ARE LINEAR



WONG 2008

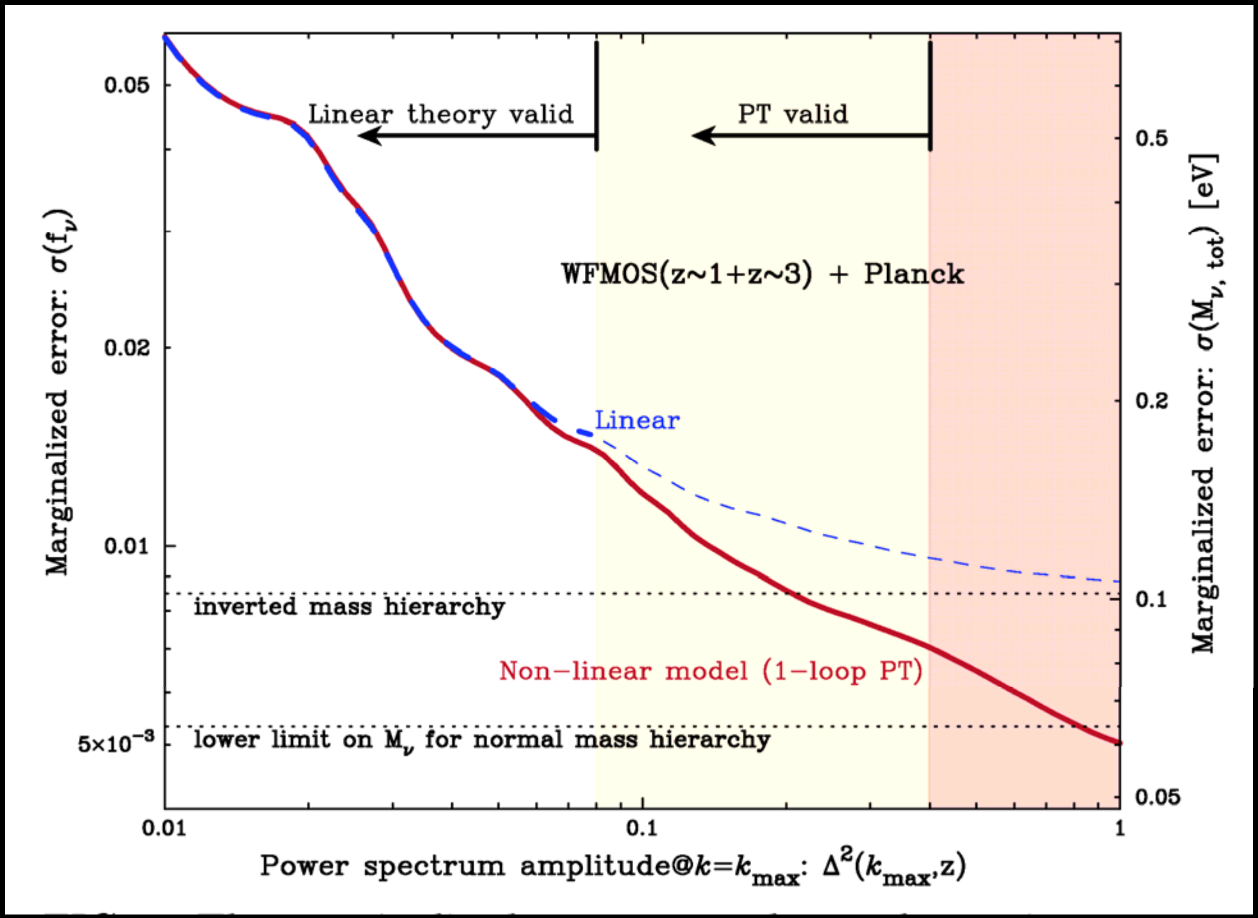


BRANDBYGE & HANNESTAD 2008 (IN PREPARATION)

$$\sum m_\nu = 0.6\,\mathrm{eV}$$

THE NON-LINEAR POWER SPECTRUM SUPPRESSION IS HIGHLY REDSHIFT DEPENDENT AND WILL BE IMPORTANT FOR FUTURE HIGH-Z STRUCTURE FORMATION SURVEYS

INCLUDING THE MODERATELY NON-LINEAR PART OF THE POWER SPECTRUM IS IMPORTANT FOR THE SENSITIVITY.



Saito et al. 2008

CONCLUSIONS

- NEUTRINO PHYSICS IS PERHAPS THE PRIME EXAMPLE OF HOW TO USE COSMOLOGY TO DO (ORDINARY) PARTICLE PHYSICS
- THE BOUND ON NEUTRINO MASSES IS SIGNIFICANTLY STRONGER THAN WHAT CAN BE OBTAINED FROM DIRECT EXPERIMENTS, ALBEIT MUCH MORE MODEL DEPENDENT
- FUTURE OBSERVATIONS WILL CONTINUE TO IMPROVE THE SENSITIVITY TO NEUTRINO PROPERTIES