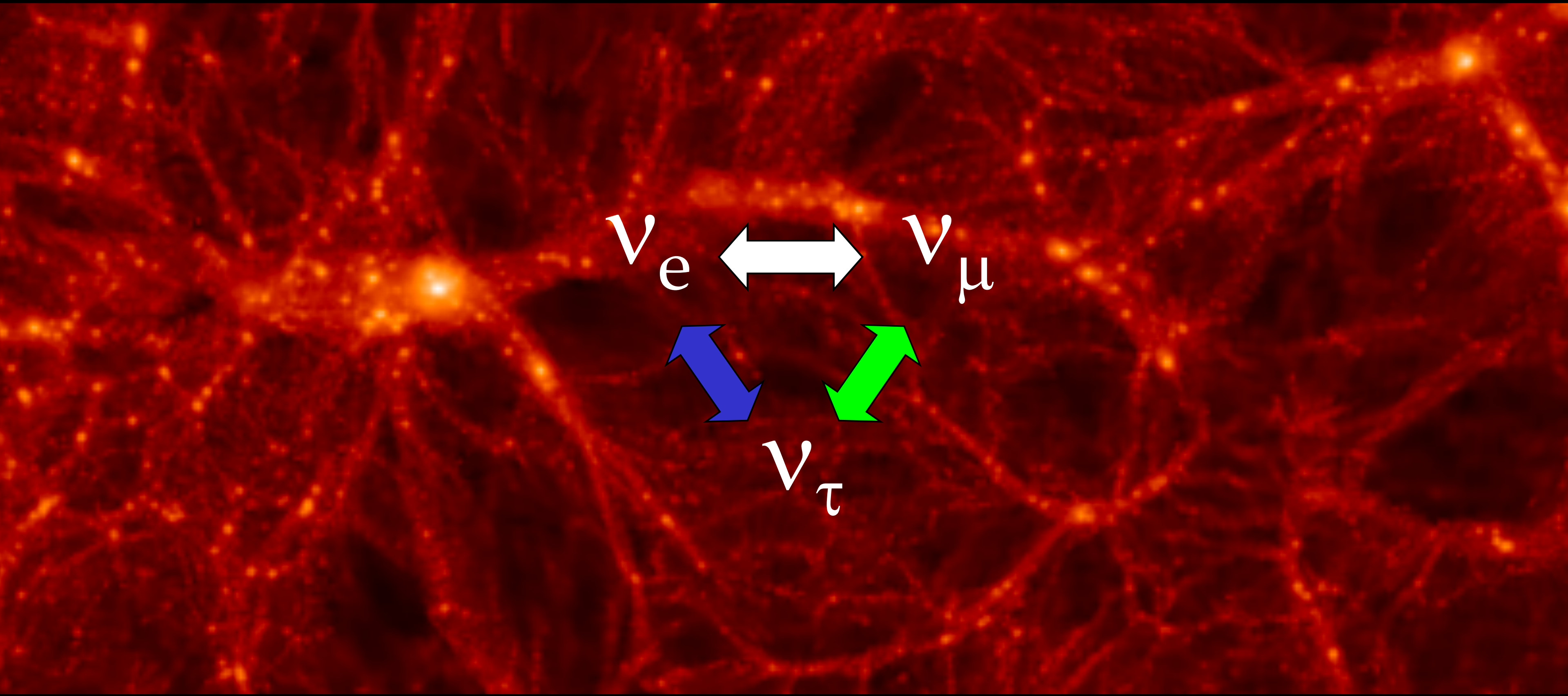
THE CONNECTION OF NEUTRINO PHYSICS WITH COSMOLOGY AND ASTROPHYSICS

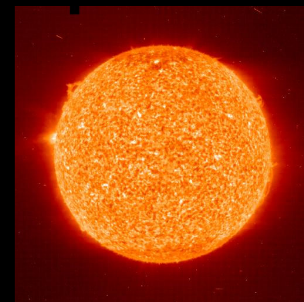


STEEN HANNESTAD

CERN, 1 OCTOBER 2009

Where do Neutrinos Appear in Nature?

✓ Nuclear Reactors

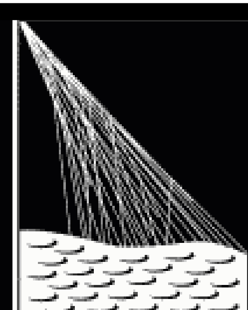


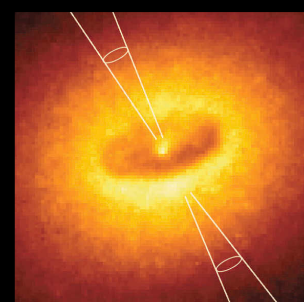
Sun ✓

✓ Particle Accelerators

Supernovae
(Stellar Collapse)
SN 1987A ✓

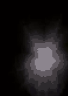
✓ Earth Atmosphere
(Cosmic Rays)





Astrophysical
Accelerators
Soon ?

✓ (2005) Earth Crust
(Natural
Radioactivity)



Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

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)

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

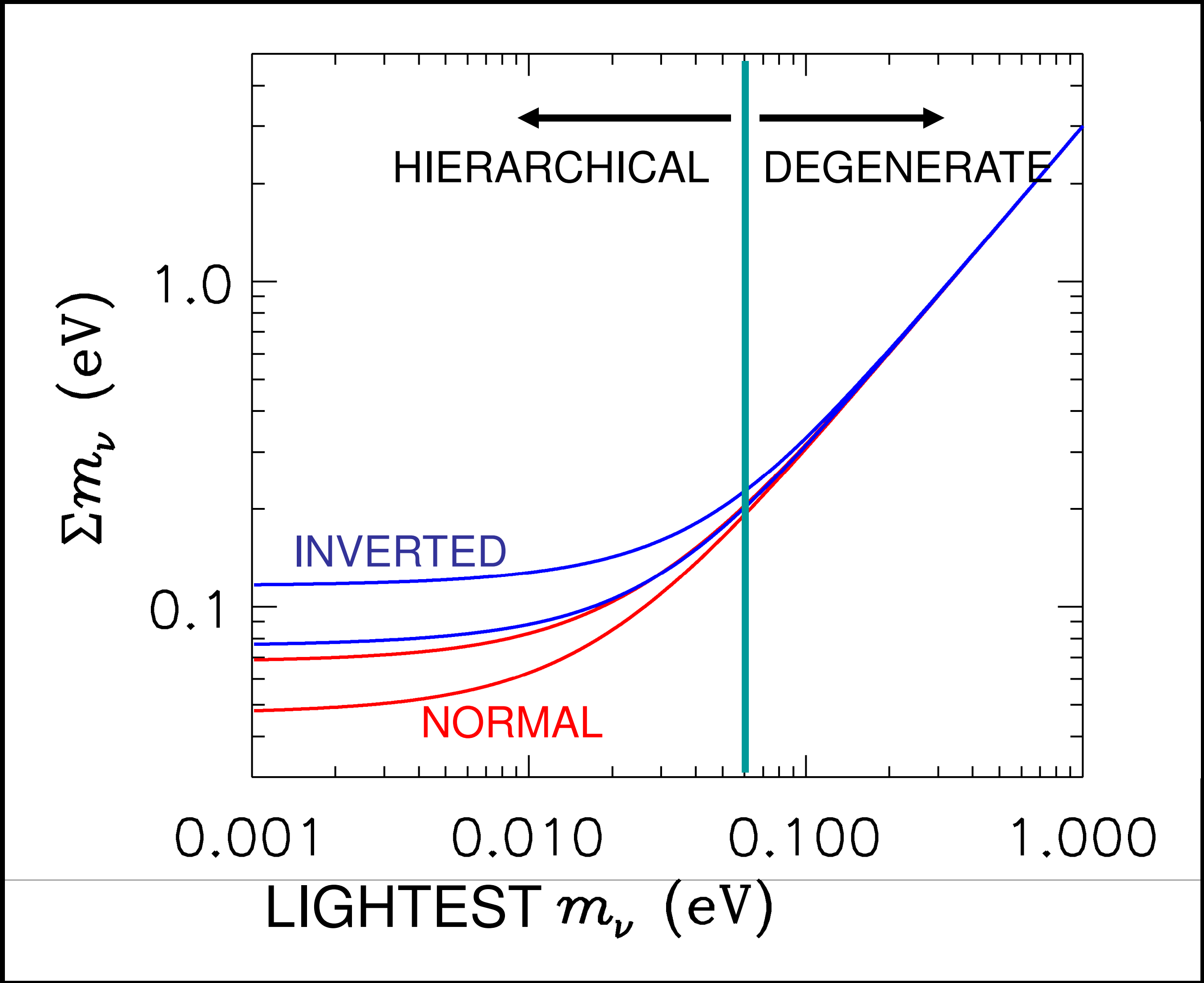
$\cos\theta_{12}$

$\sin\theta_{12}$

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

A COSMOLOGISTS' VIEW OF NEUTRINO MASSES



Lesgourgues and Pastor 2006

THE ABSOLUTE VALUES OF NEUTRINO MASSES FROM COSMOLOGY

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

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

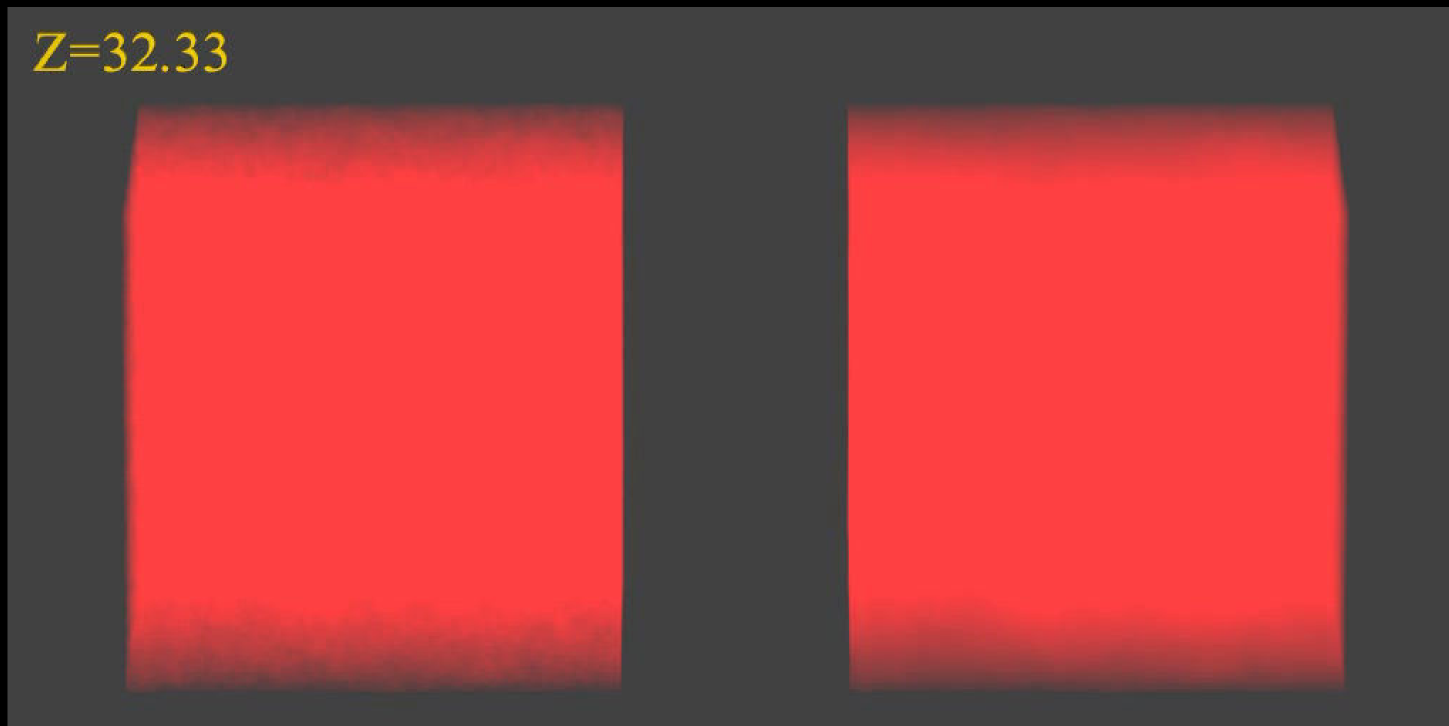
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

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

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

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

256
Mpc



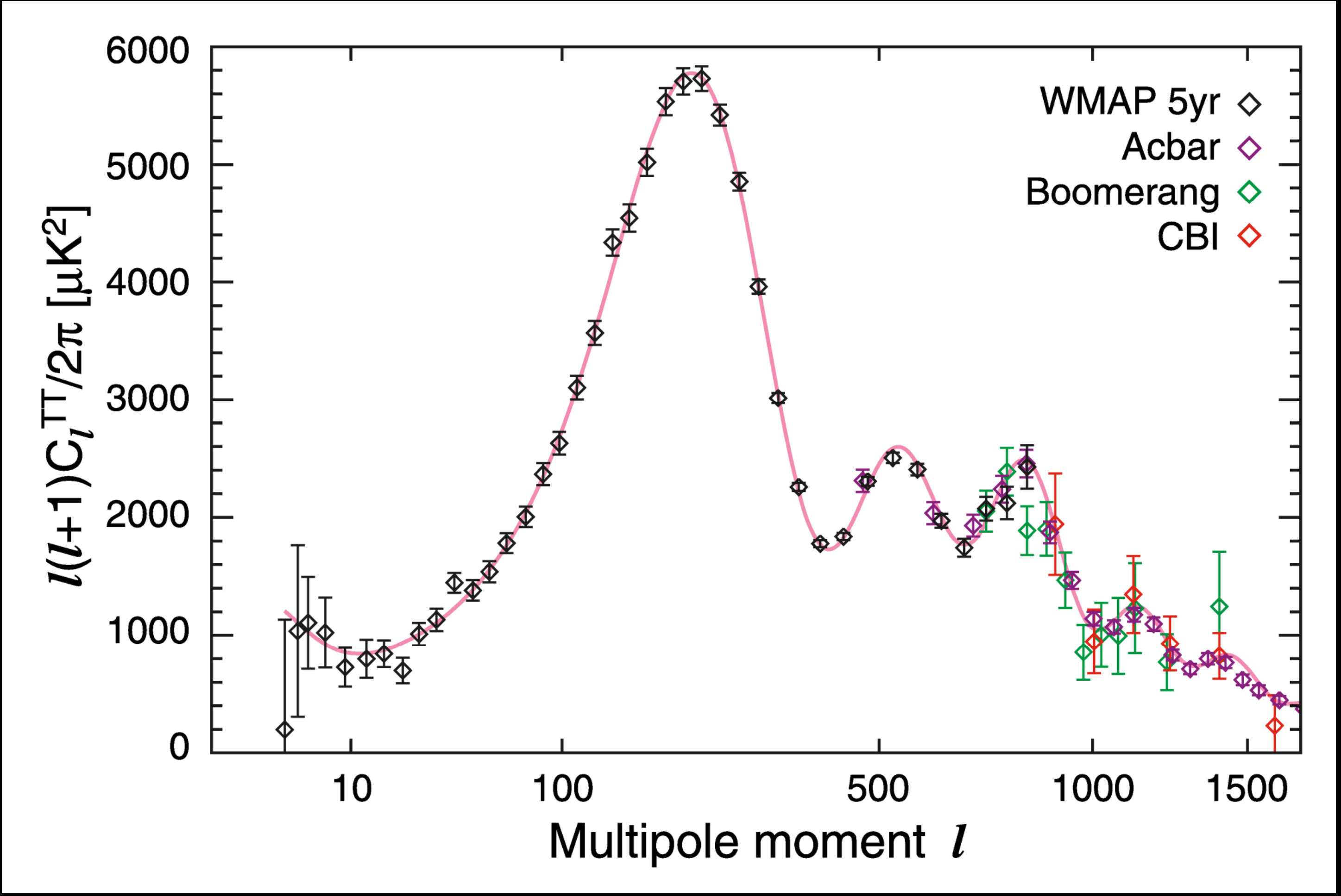
$$\sum m_\nu = 0$$

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

T Haugboelle, University of Aarhus

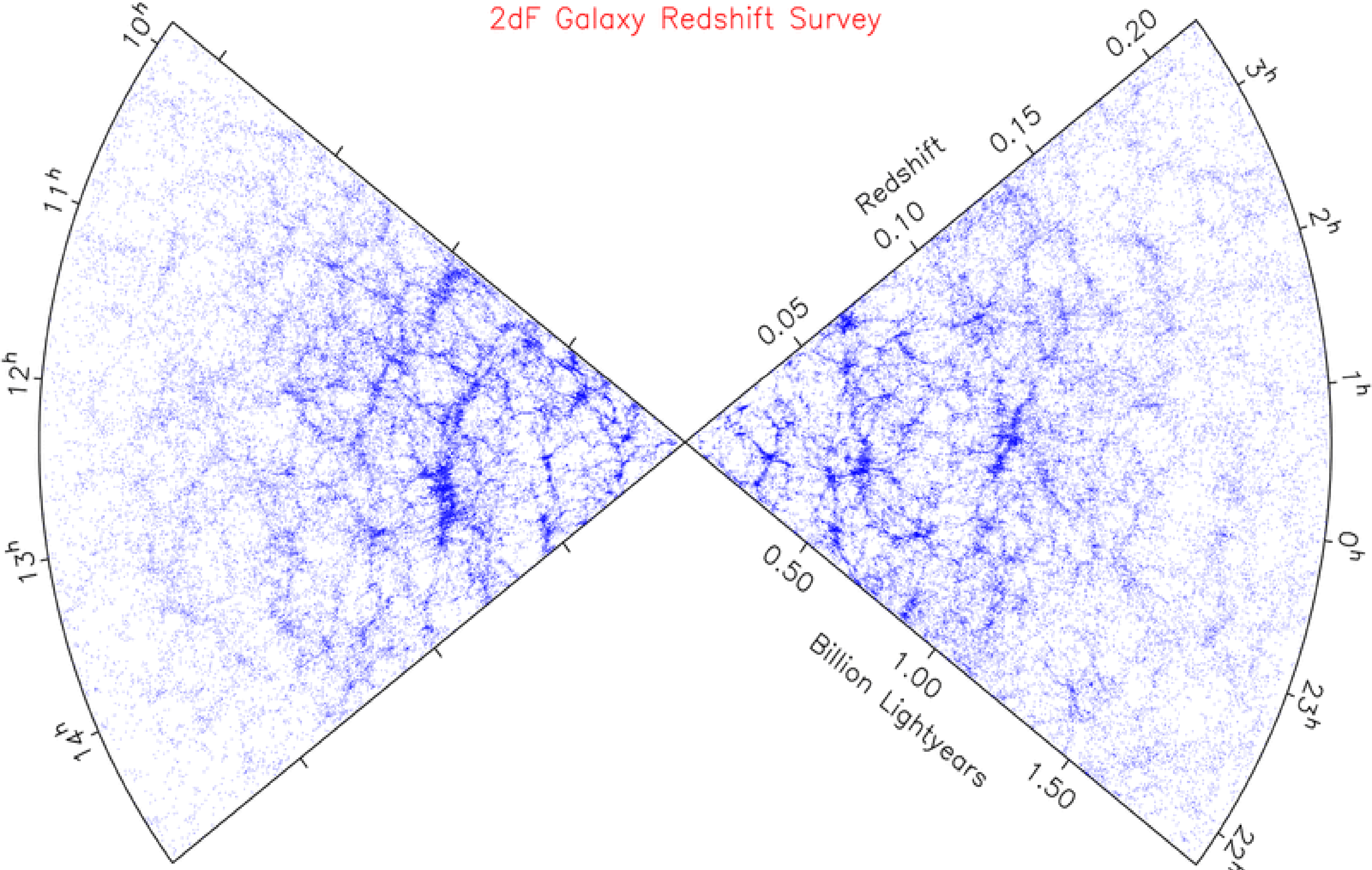
AVAILABLE COSMOLOGICAL DATA

WMAP-5 TEMPERATURE POWER SPECTRUM

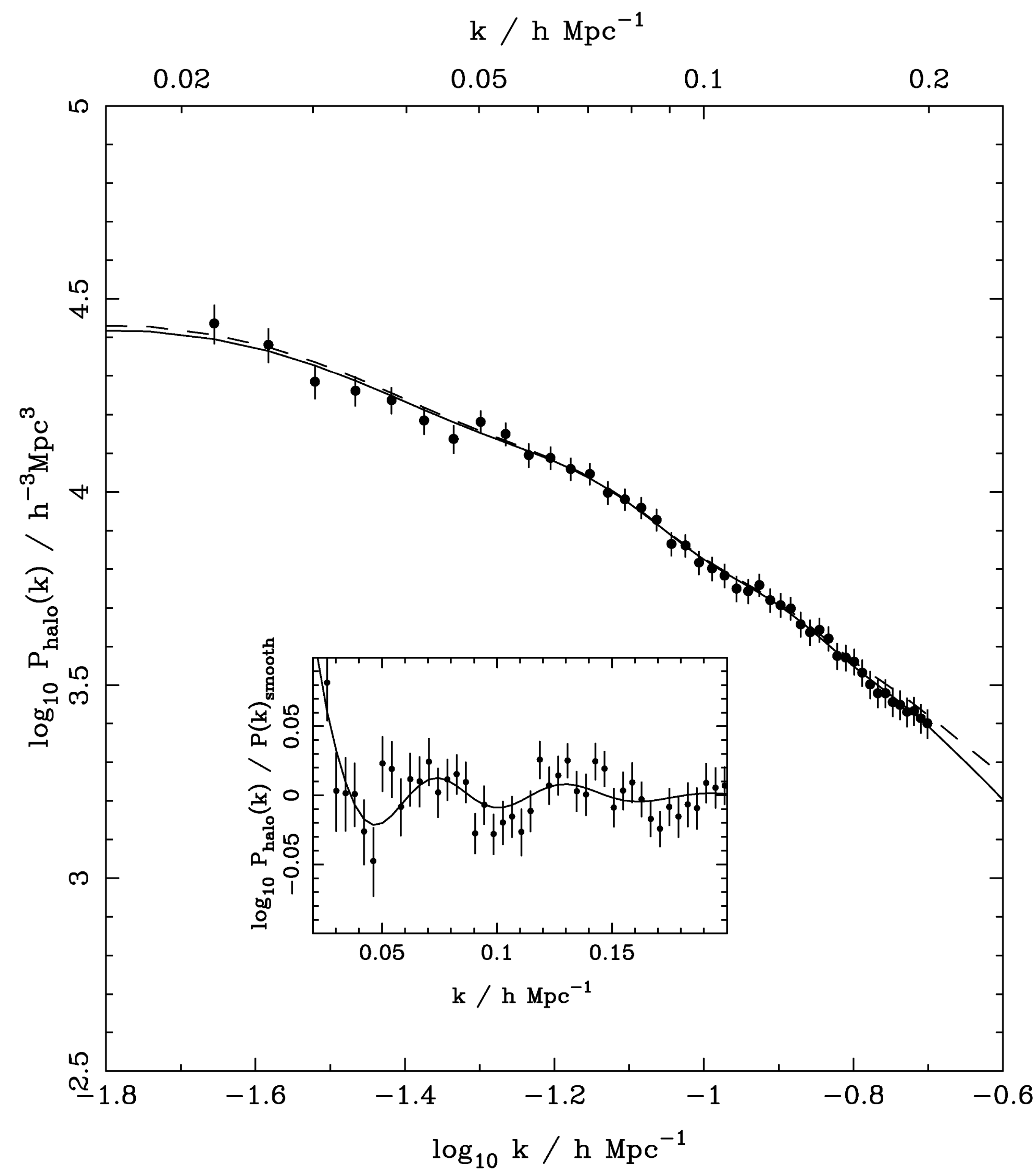


M NOLTA ET AL., arXiv:0803.0593

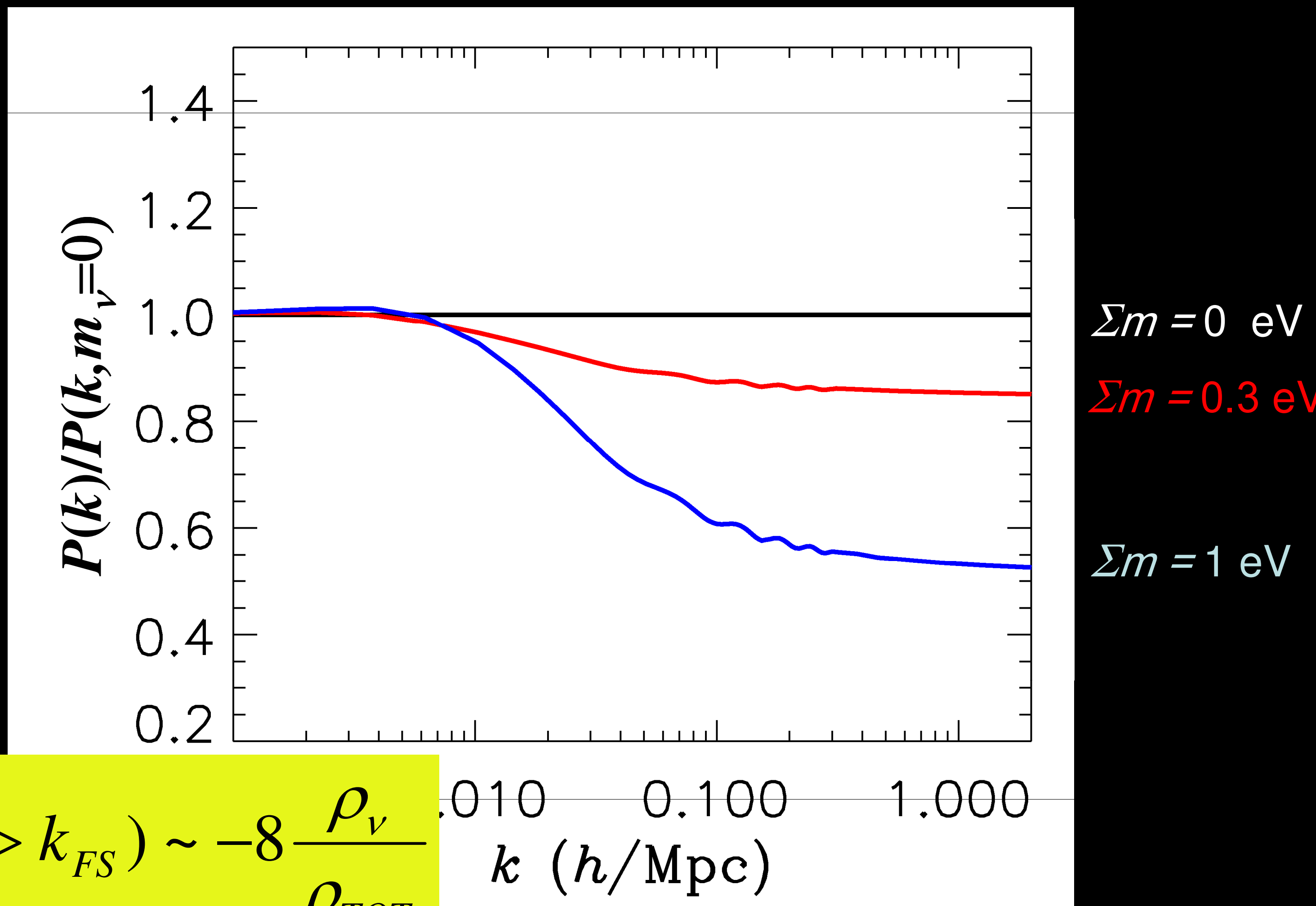
LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS



SDSS DR-7
LRG SPECTRUM
(Reid et al '09)



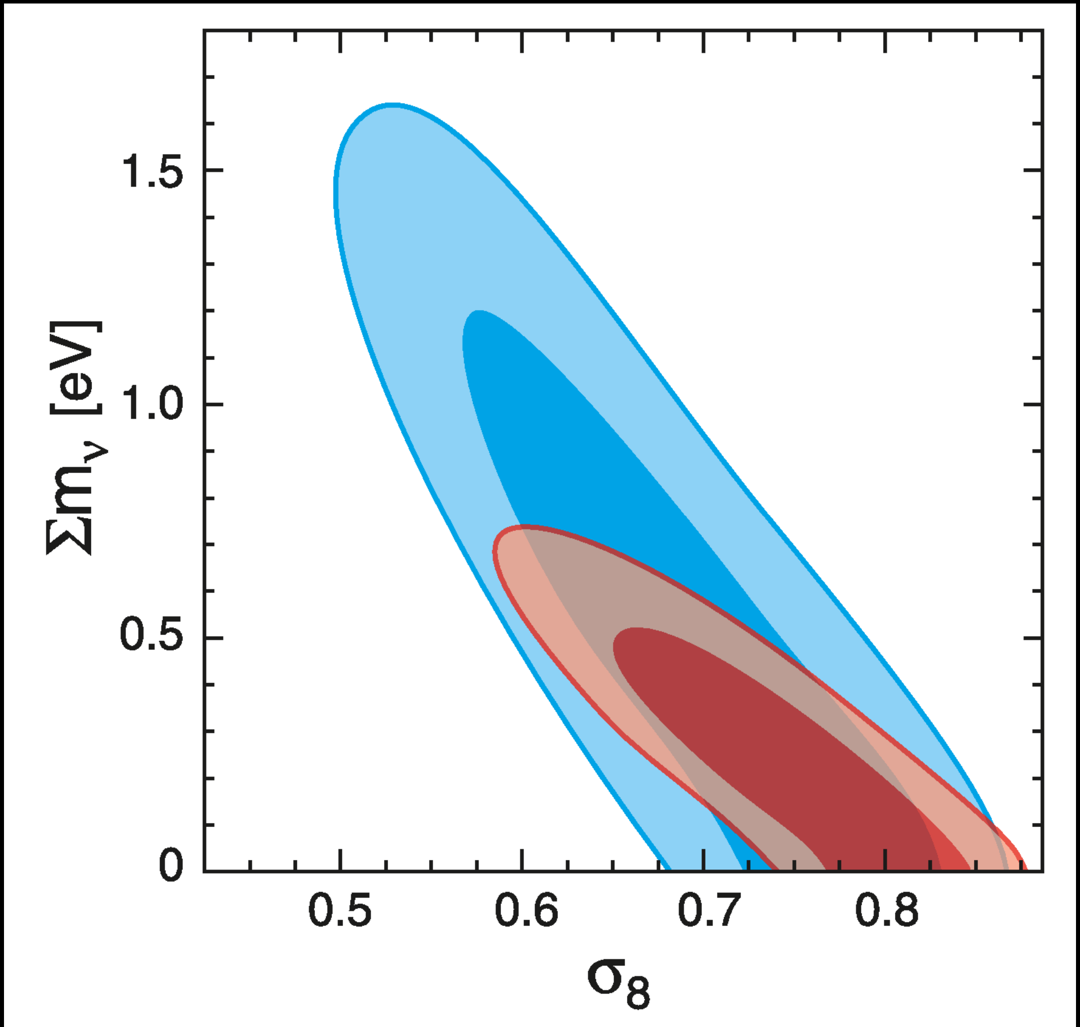
FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



$$\frac{\Delta P}{P_{m=0}}(k >> k_{FS}) \sim -8\frac{\rho_\nu}{\rho_{TOT}}$$

NOW, WHAT ABOUT NEUTRINO PHYSICS?

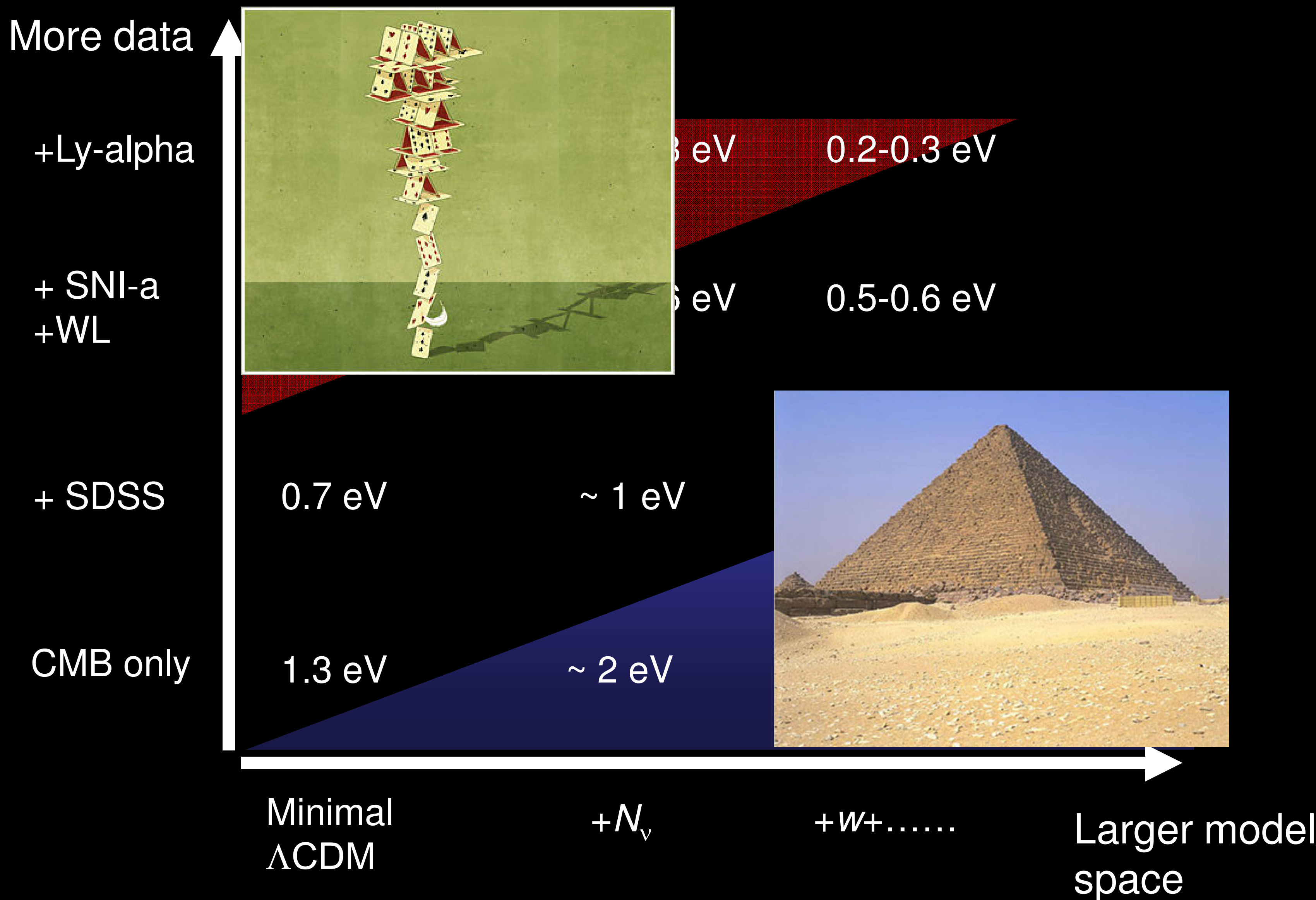
WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?



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

Komatsu et al., arXiv:0803.0547

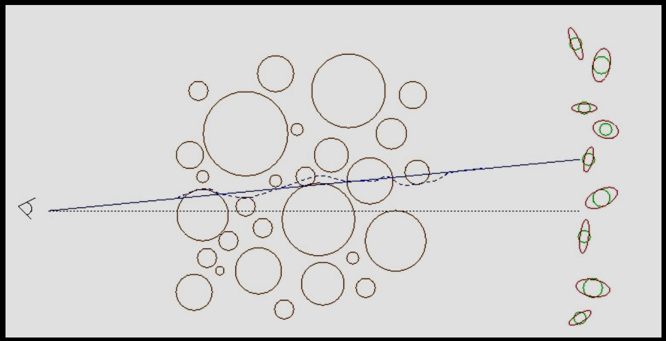
THE NEUTRINO MASS FROM COSMOLOGY PLOT

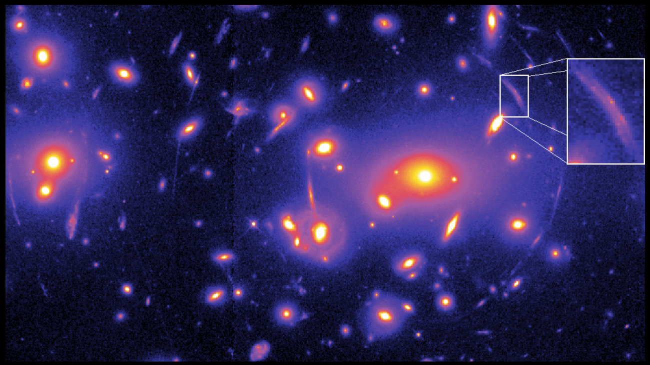


WHAT IS IN STORE FOR THE FUTURE?

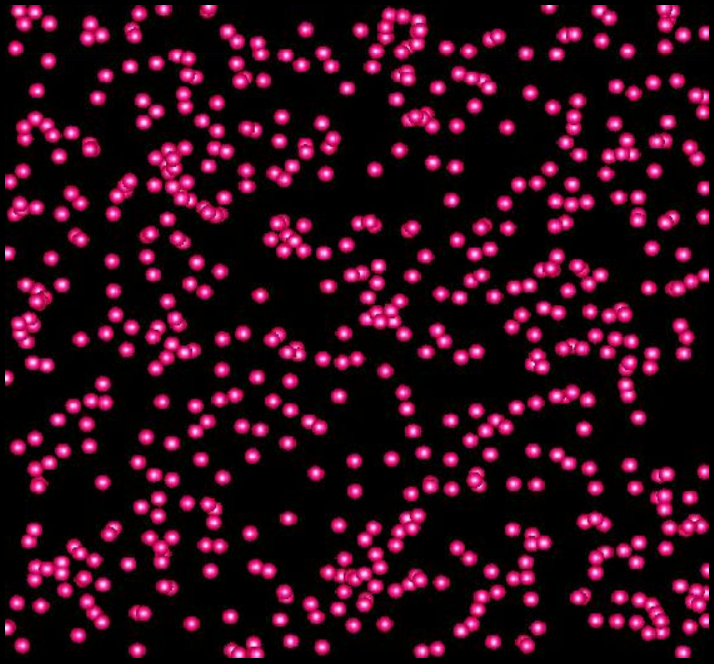
- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS (PLANCK)
- LARGE SCALE STRUCTURE SURVEYS AT HIGH REDSHIFT
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES

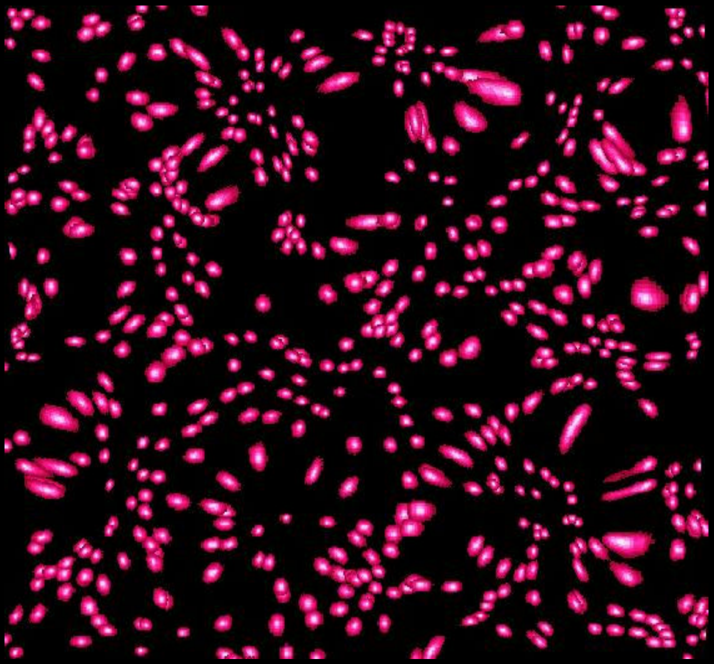
WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE





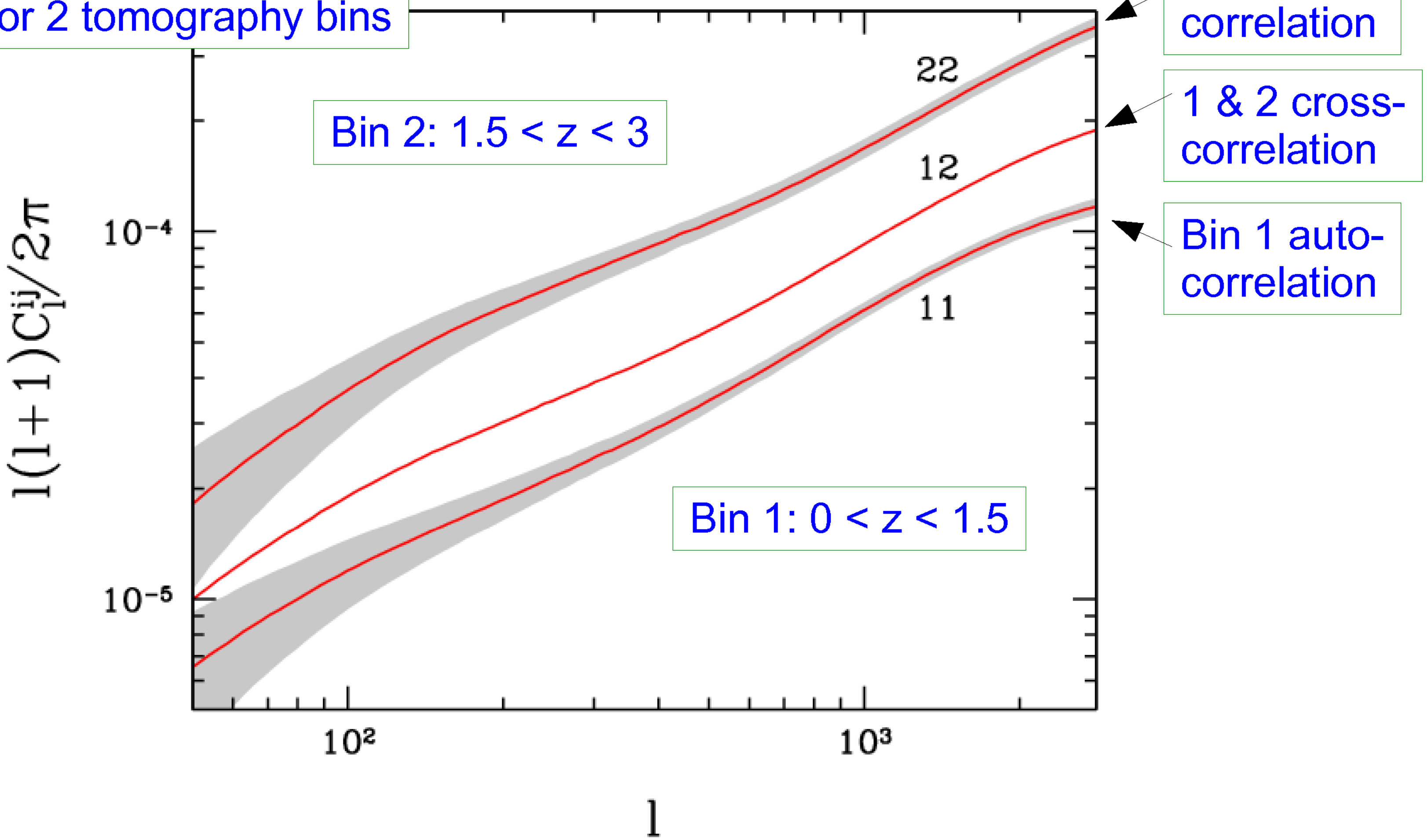
Distortion of background images by foreground matter





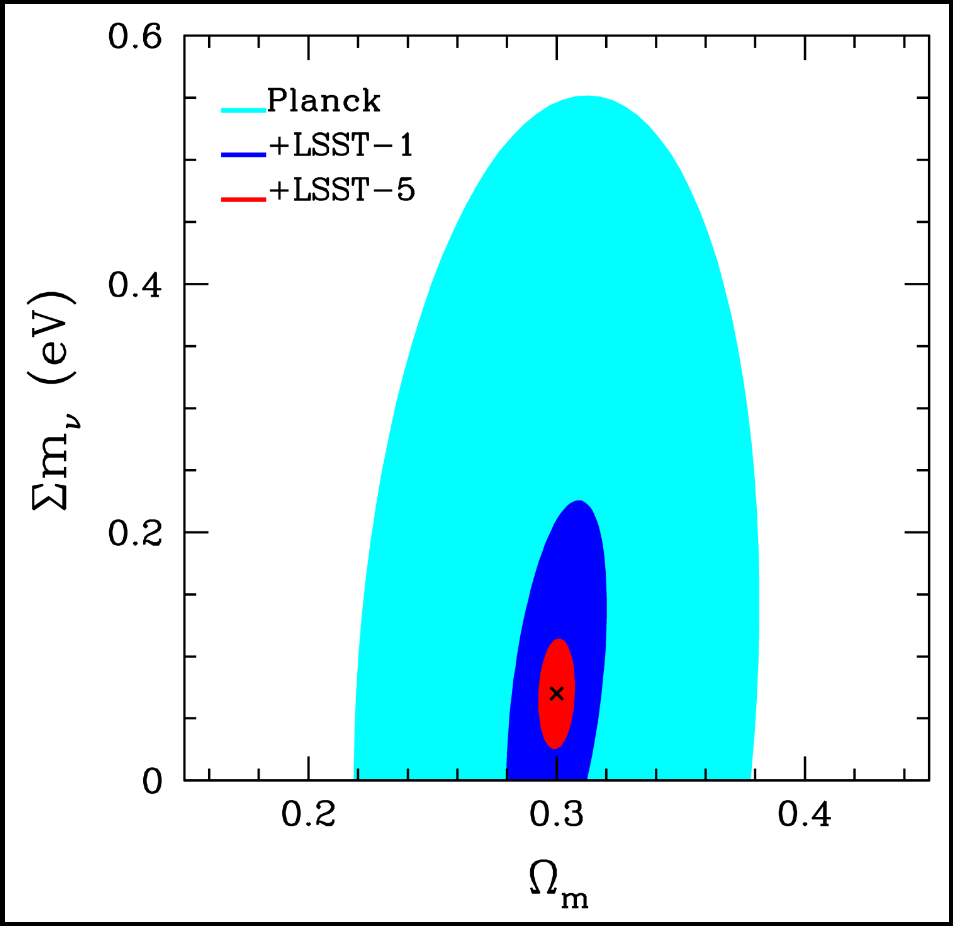
Unlensed **Lensed**

Shear power spectra for 2 tomography bins

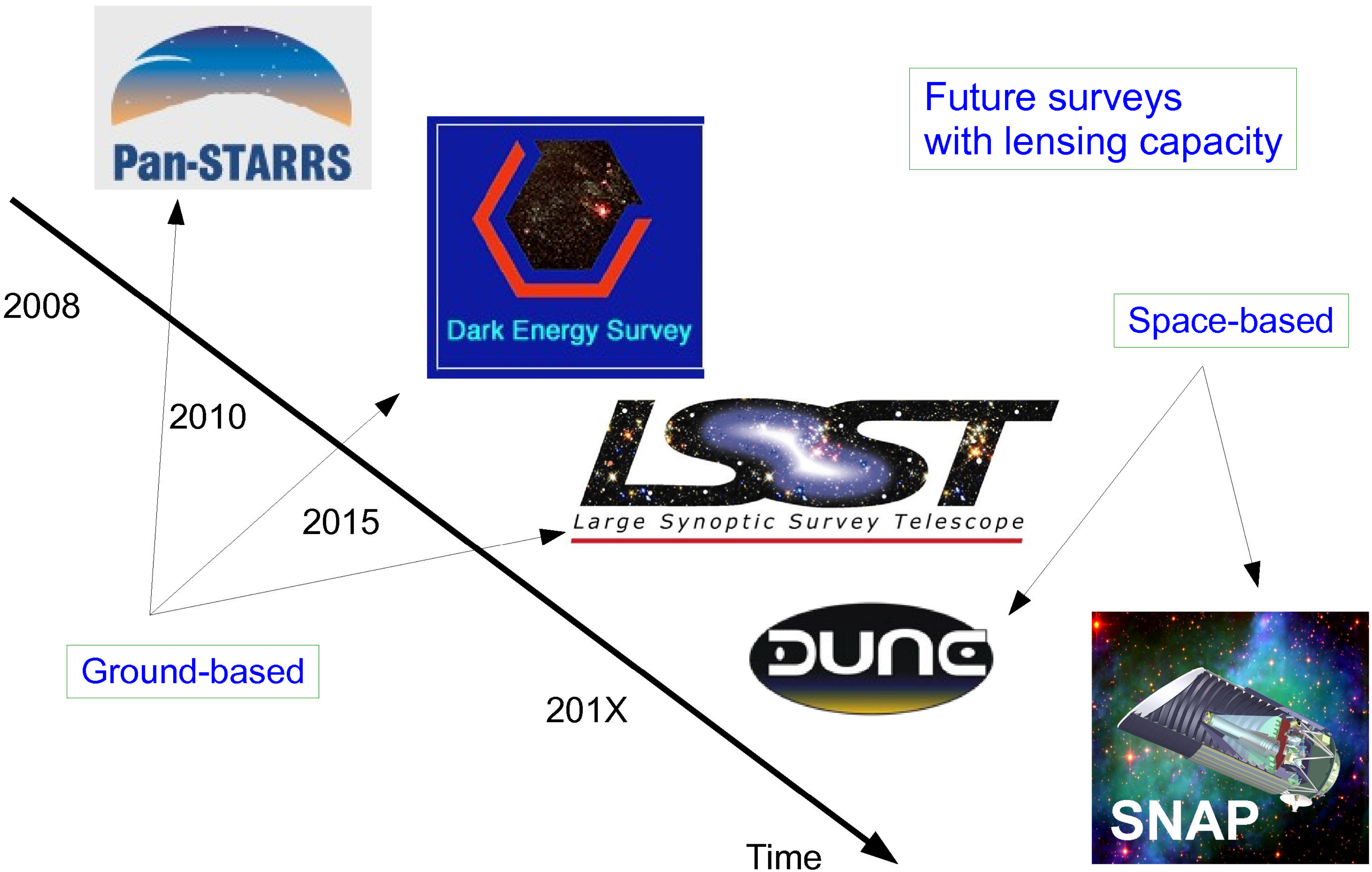


STH, TU, WONG 2006

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



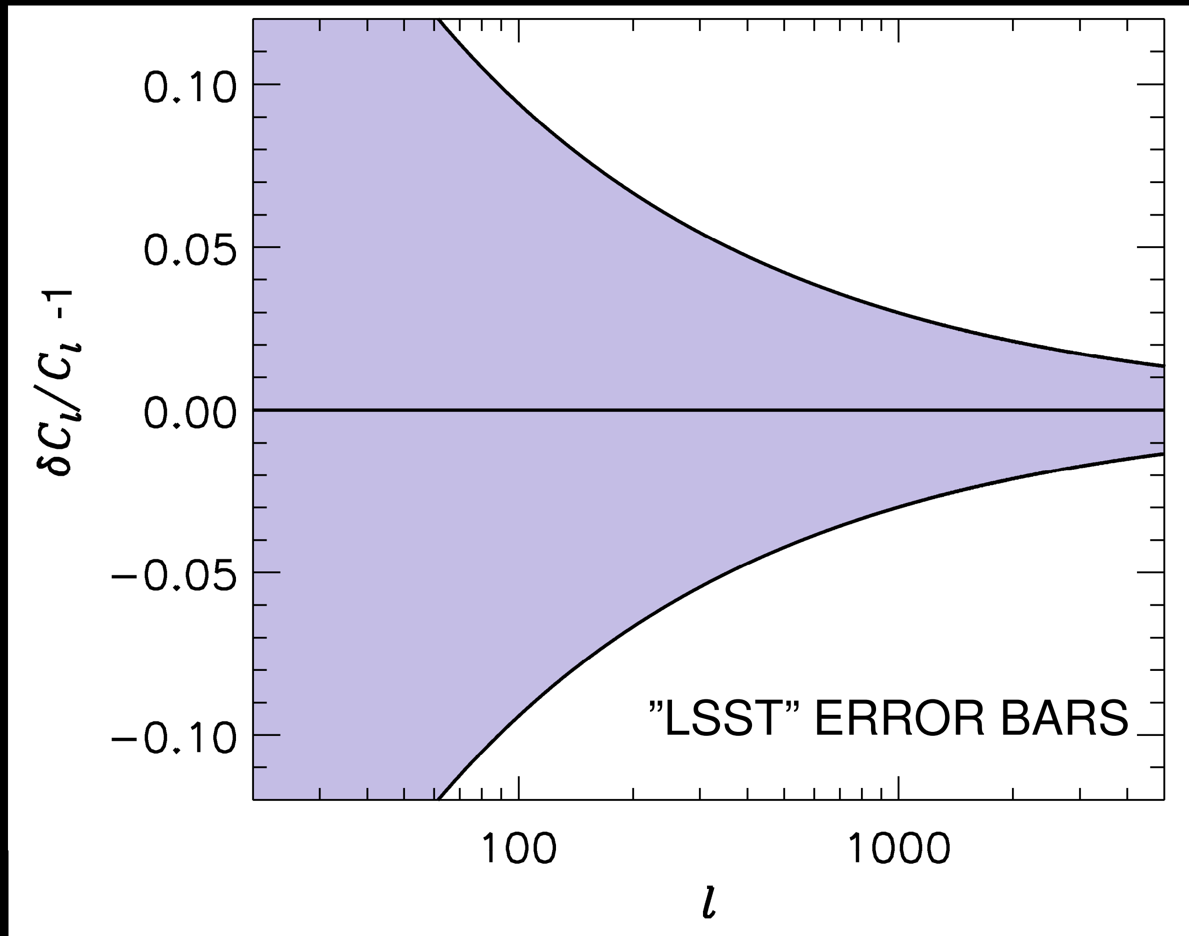
STH, TU & WONG 2006 (ASTRO-PH/0603019, JCAP)



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

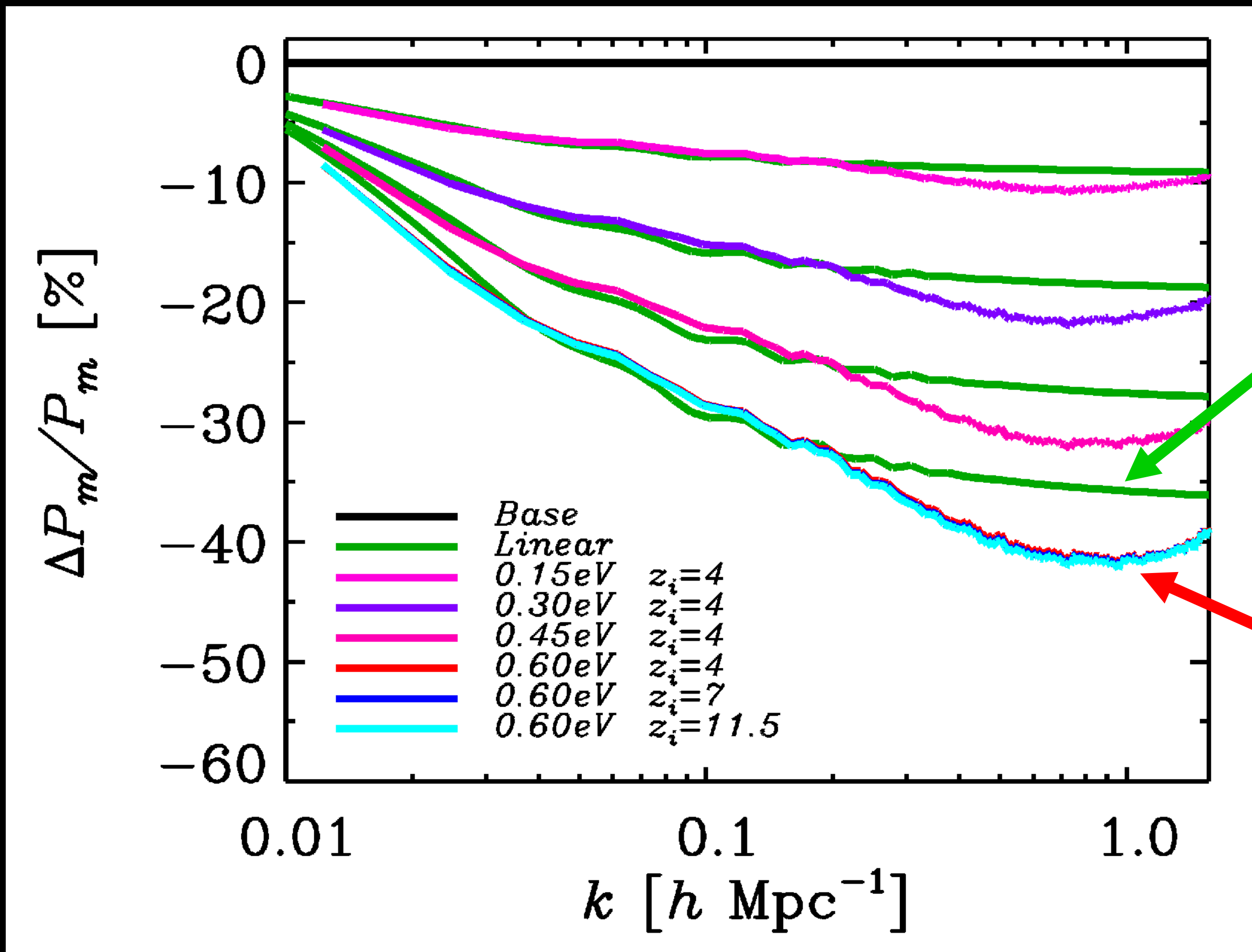
THIS SOUNDS GREAT, BUT UNFORTUNATELY THEORY MUST BE AT THE SAME LEVEL OF PRECISION BY THE TIME DATA-TAKING STARTS

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!

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)

RECENTLY THERE HAS BEEN RENEWED INTEREST IN THE POSSIBLE DETECTION OF THE COSMIC RELIC NEUTRINO BACKGROUND

THE MOST PROMISING POSSIBILITY IS TO USE NEUTRINO CAPTURE FROM THE CνB (dating back to Weinberg ’62)

E.g.

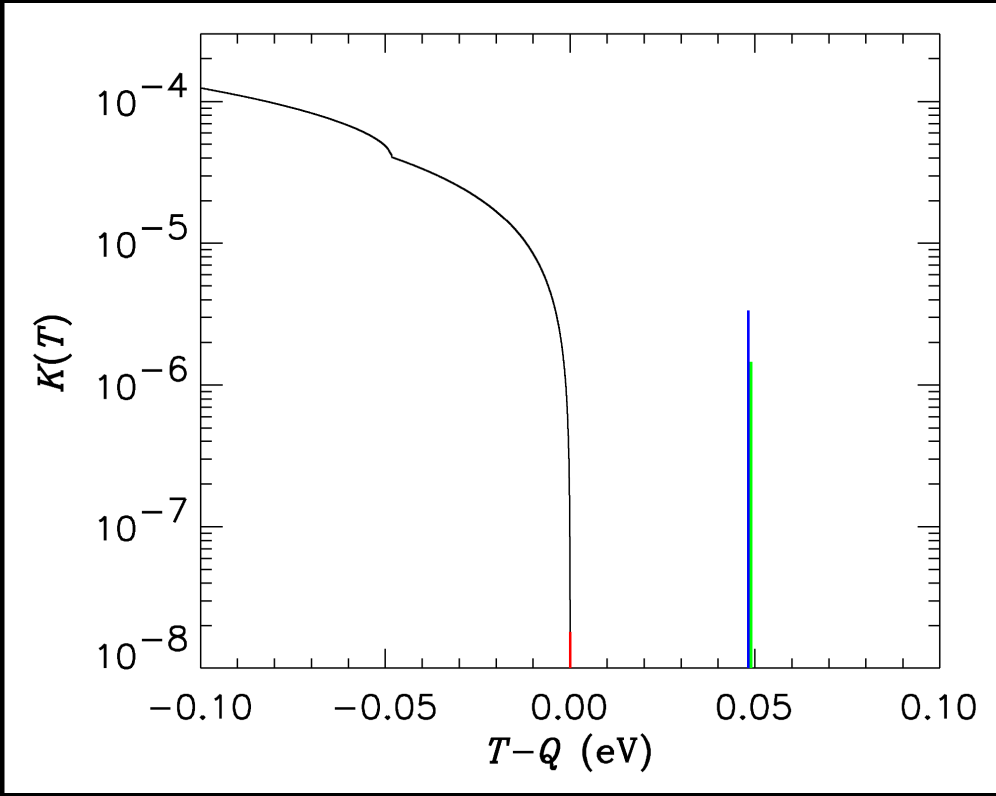
$$\nu_e + {}^3H \rightarrow {}^3He + e$$

ANY EXPERIMENT DESIGNED TO MEASURE THE BETA ENDPOINT (E.G. KATRIN) CAN BE USED TO PROBE THE COSMIC NEUTRINO BACKGROUND

PROBLEM: THE RATE IS TINY!!!

ANY EXPERIMENT OF THIS KIND WHICH MEASURED THE COSMIC NEUTRINO BACKGROUND WILL AUTOMATICALLY PROVIDE AN EXCELLENT MEASUREMENT OF THE NEUTRINO MASS

KURIE PLOT FOR TRITIUM – ASSUMES INVERTED HIERARCHY AND Θ_{13} CLOSE TO THE CURRENT UPPER BOUND



WITH INFINITELY GOOD ENERGY RESOLUTION THERE WILL BE 3 DISTINCT PEAKS FROM BACKGROUND ABSORPTION

AMPLITUDE OF EACH PROPORTIONAL TO $|U_{ei}|^2 n_i$

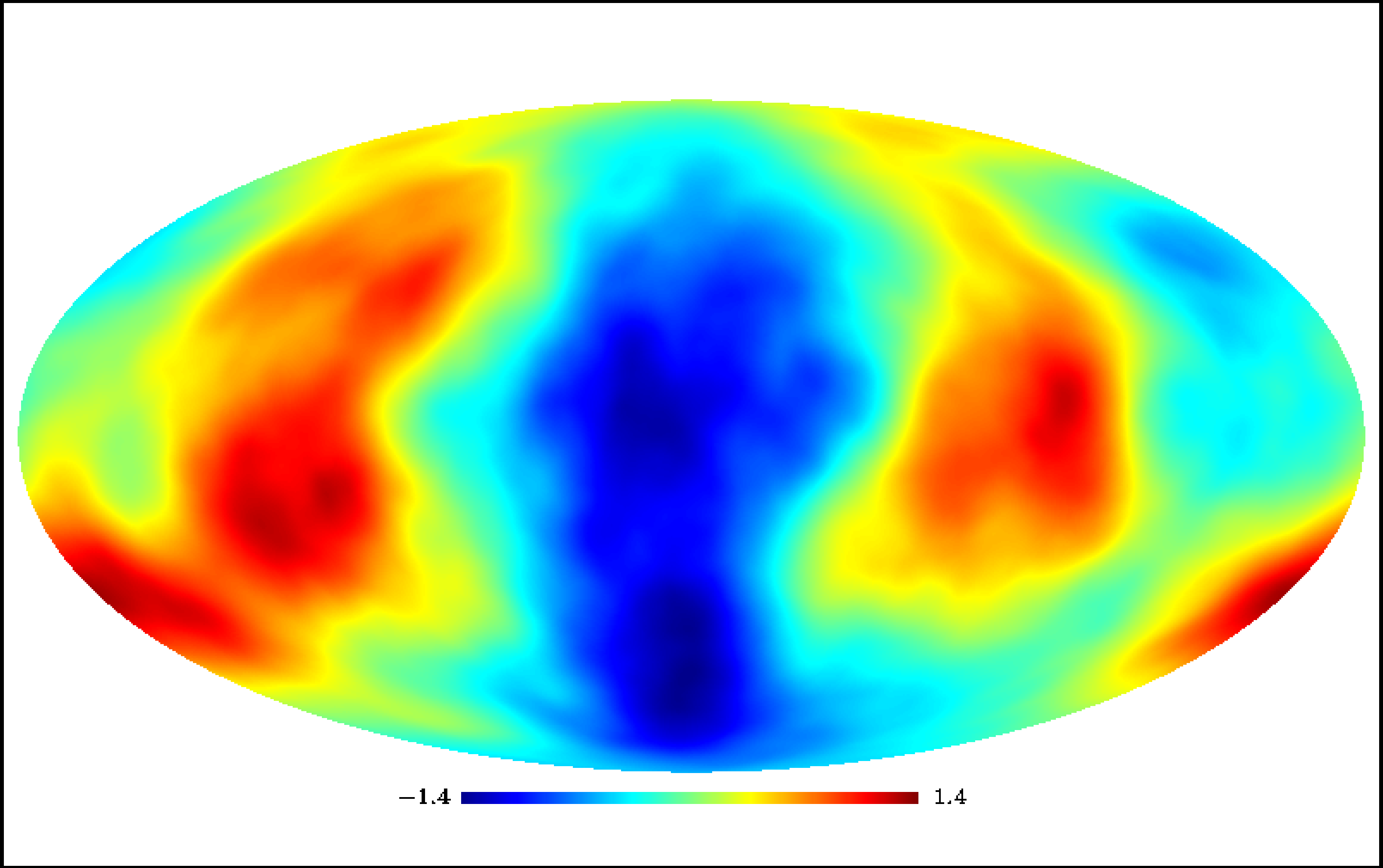
AND FINALLY: IN THE FAR DISTANT FUTURE WE MIGHT BE OBSERVING THE CνB ANISOTROPY

FOR SMALL MASSES IT CAN BE CALCULATED IN A WAY SIMILAR TO THE PHOTON ANISOTROPY, WITH SOME IMPORTANT DIFFERENCES:

- AS SOON AS NEUTRINOS GO NON-RELATIVISTIC ALL HIGH l MULTIPOLES ARE SUPPRESSED (ESSENTIALLY A GEOMETRIC EFFECT)
- GRAVITATIONAL LENSING IS MUCH MORE IMPORTANT THAN FOR MASSLESS PARTICLES

STH & Brandbyge, in preparation
(see also Michney, Caldwell astro-ph/0608303)

REALISATIONS OF THE CνB FOR DIFFERENT MASSES



$m = 10^{-2}$ eV

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