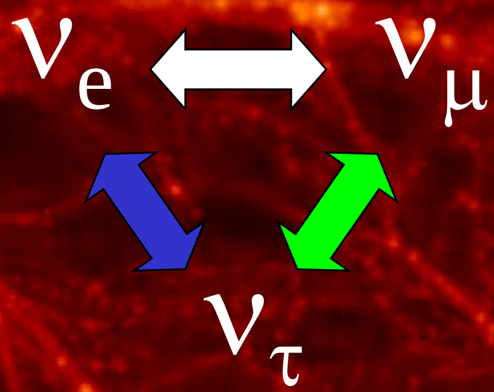
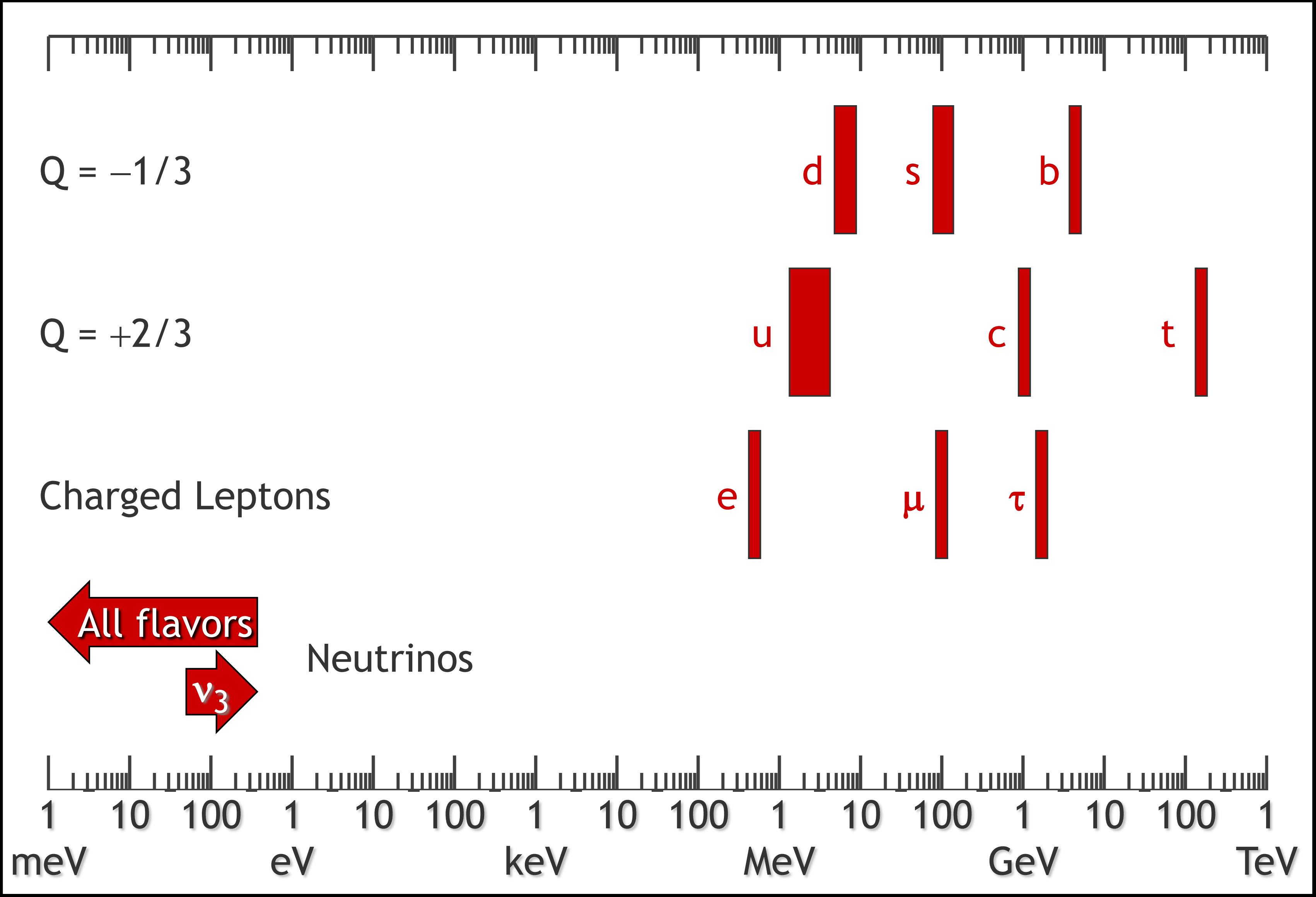
# NEUTRINO PHYSICS FROM PRECISION COSMOLOGY




STEEN HANNESTAD

JIGSAW’10 – 23 FEBRUARY 2010

# Fermion Mass Spectrum



FLAVOUR STATES

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

PROPAGATION STATES

MIXING MATRIX (UNITARY)

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

$$c_{12} = \cos\theta_{12}$$

$$s_{12} = \sin\theta_{12}$$

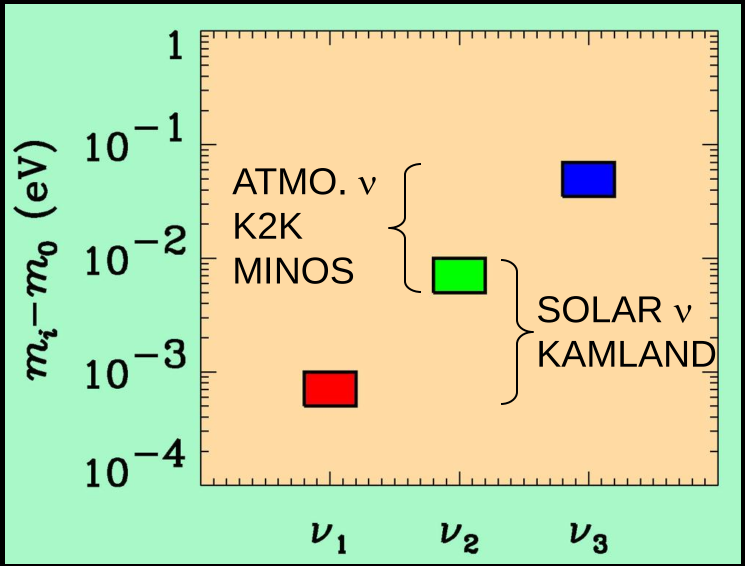
$\theta_{12}$ is the “solar” mixing angle

$\theta_{23}$ is the “atmospheric” mixing angle

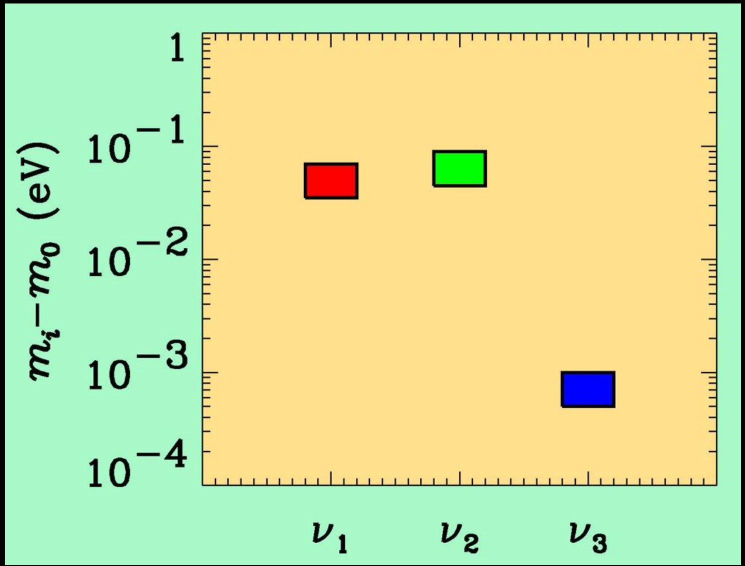
$\theta_{13}$ is the “reactor” mixing angle

$\delta$ is the Dirac CP violating phase

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




Normal hierarchy



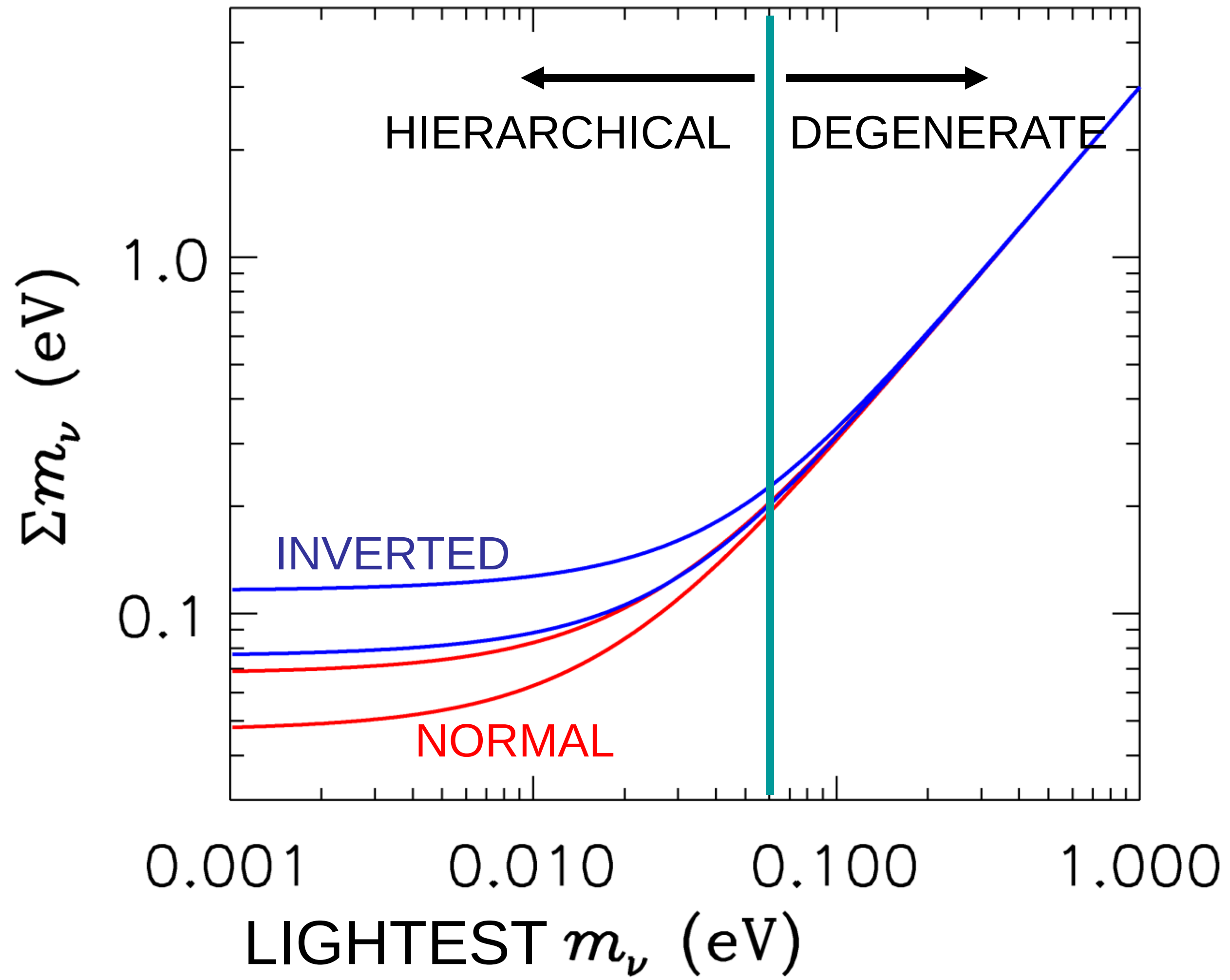

Inverted hierarchy

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 $m_0$


HIERARCHICAL
DEGENERATE
INVERTED
NORMAL
1.0
0.1
0.001
0.010
0.100
1.000
$\Sigma m_\nu$ (eV)
LIGHTEST $m_\nu$ (eV)

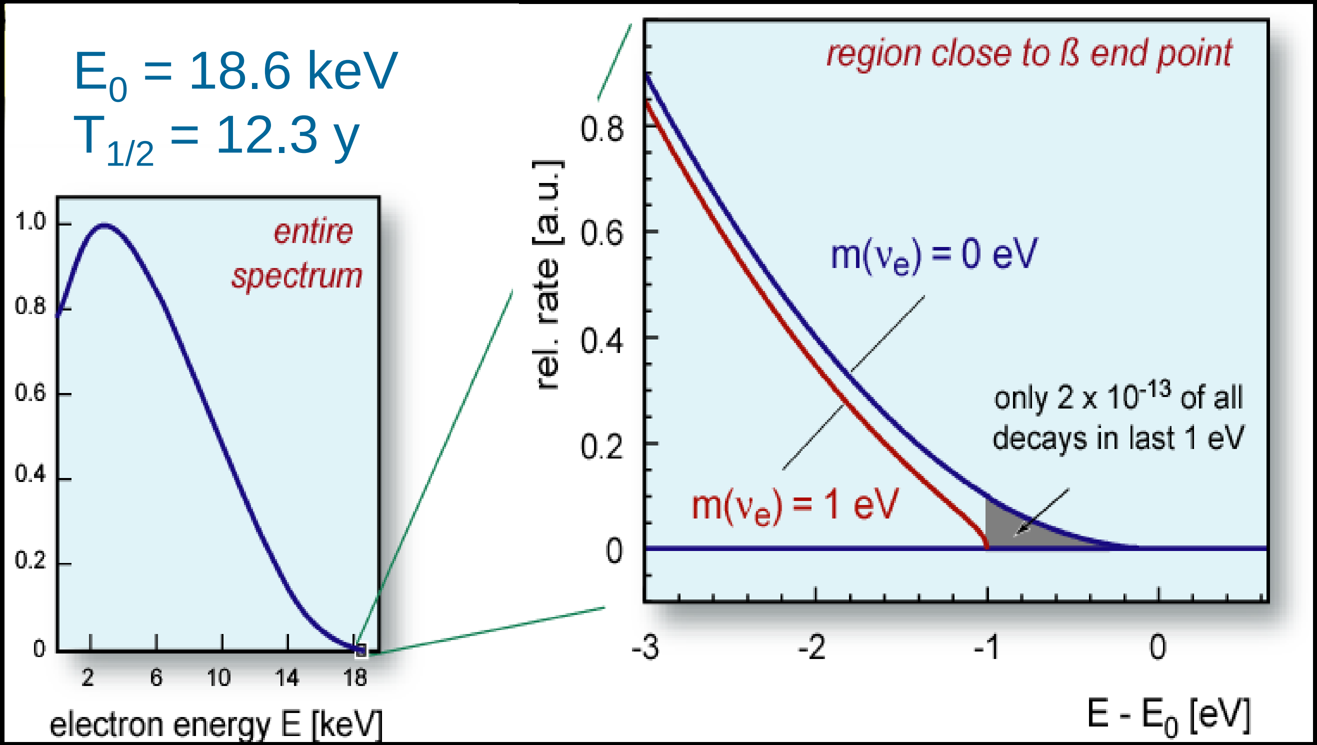
# ß-decay and neutrino mass

model independent neutrino mass from ß-decay kinematics

only assumption: relativistic energy-momentum relation

$$\frac{d\Gamma_i}{dE} = C\, p\, (E + m_e)\, (E_0 - E) \sqrt{(E_0 - E)^2 - m_i^2}\, F(E)\, \theta(E_0 - E - m_i)$$

*experimental observable is $m_\nu^2$*



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

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

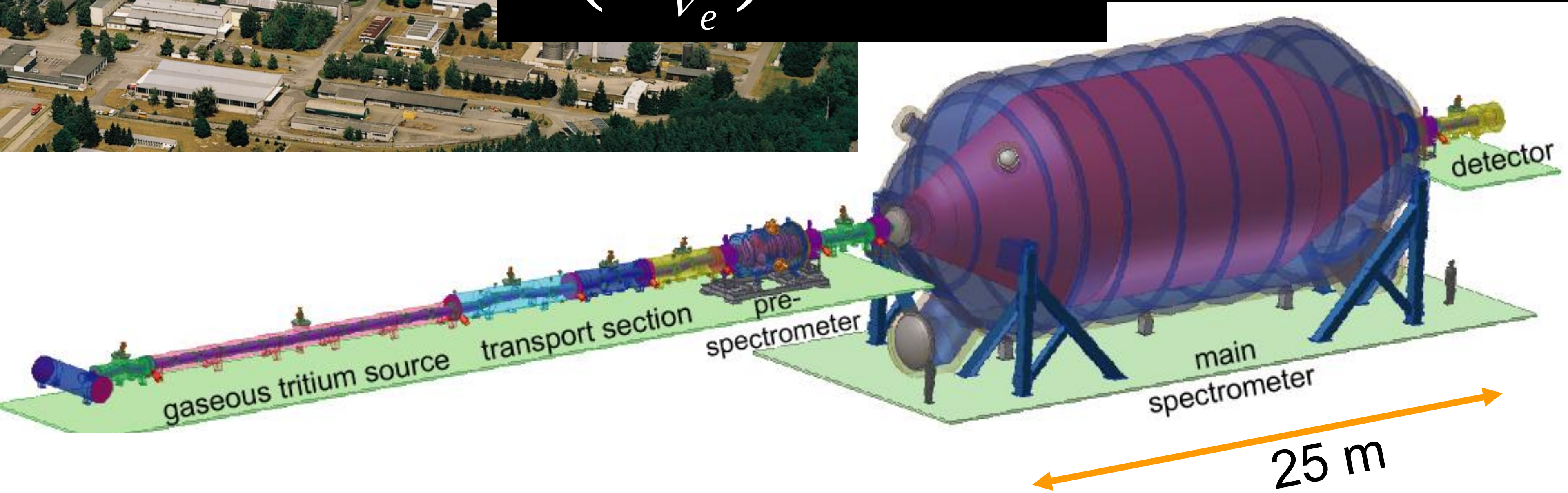
# KATRIN experiment


**Ka**rlsruhe **Tri**tium **N**eutrino Experiment

at Forschungszentrum Karlsruhe

Data taking starting early 2012

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



# THE ABSOLUTE VALUES OF NEUTRINO MASSES FROM COSMOLOGY

NEUTRINOS AFFECT STRUCTURE FORMATION BECAUSE THEY ARE A SOURCE OF DARK MATTER ($n$ ~ 100 cm$^{-3}$)

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

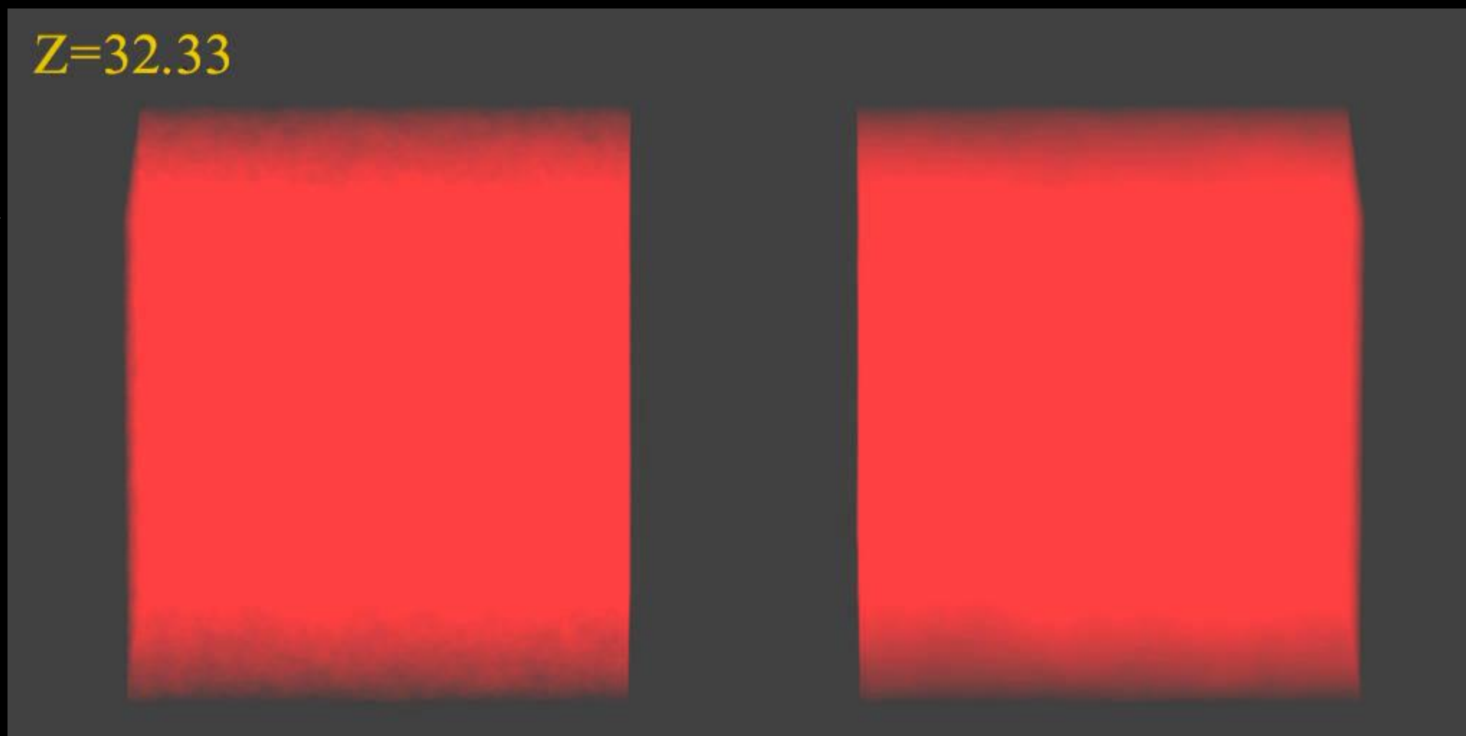
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

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

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

# N-BODY SIMULATIONS OF $\Lambda$CDM WITH AND WITHOUT NEUTRINO MASS (768 $Mpc^3$) – GADGET 2

256 Mpc

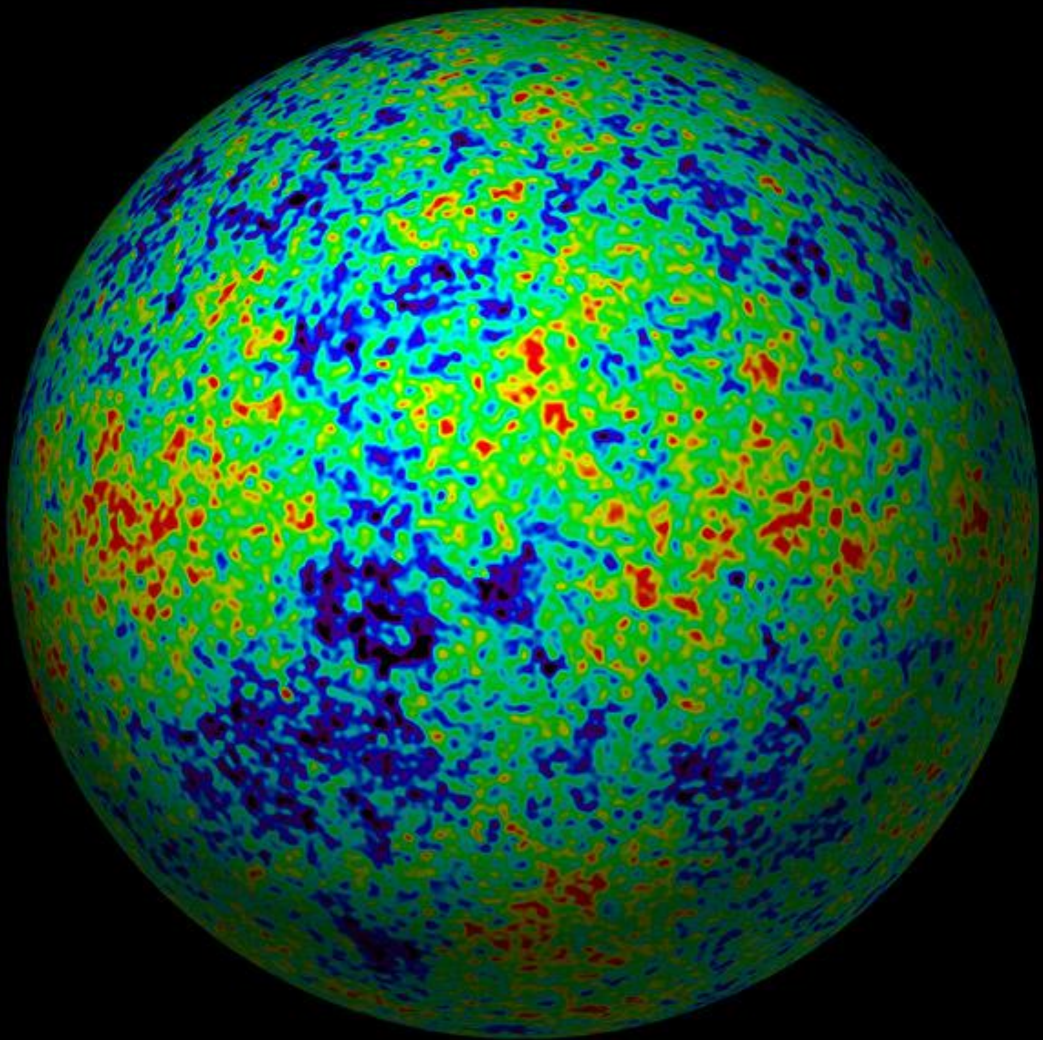



$$\sum m_\nu = 0 \qquad \sum m_\nu = 6.9\,\mathrm{eV}$$

T Haugboelle, University of Aarhus

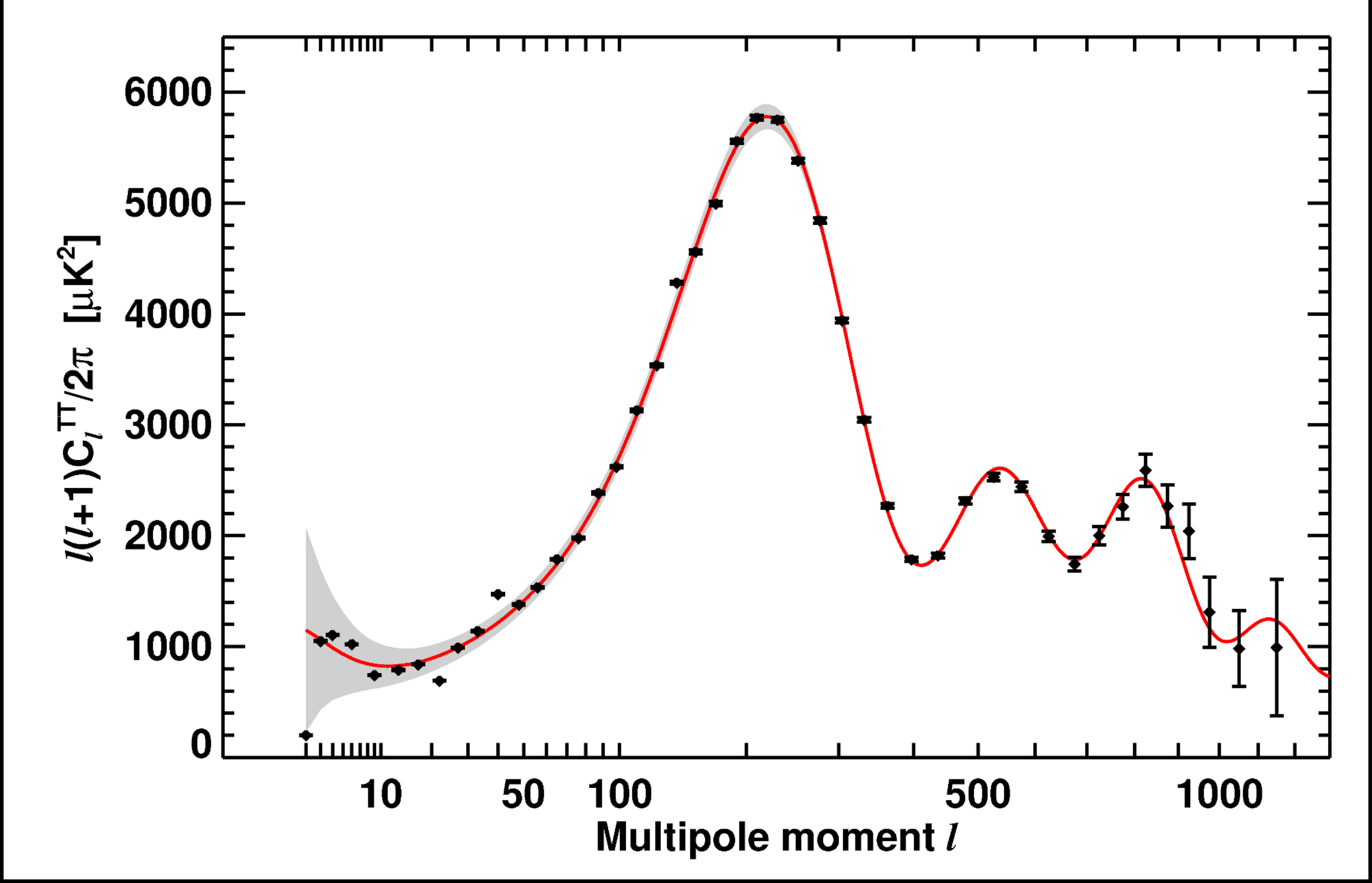
# AVAILABLE COSMOLOGICAL DATA

# THE COSMIC MICROWAVE BACKGROUND



WMAP TEMPERATURE MAP
DATA RELEASE 6 MARCH 2008!!!

# WMAP-7 TEMPERATURE POWER SPECTRUM

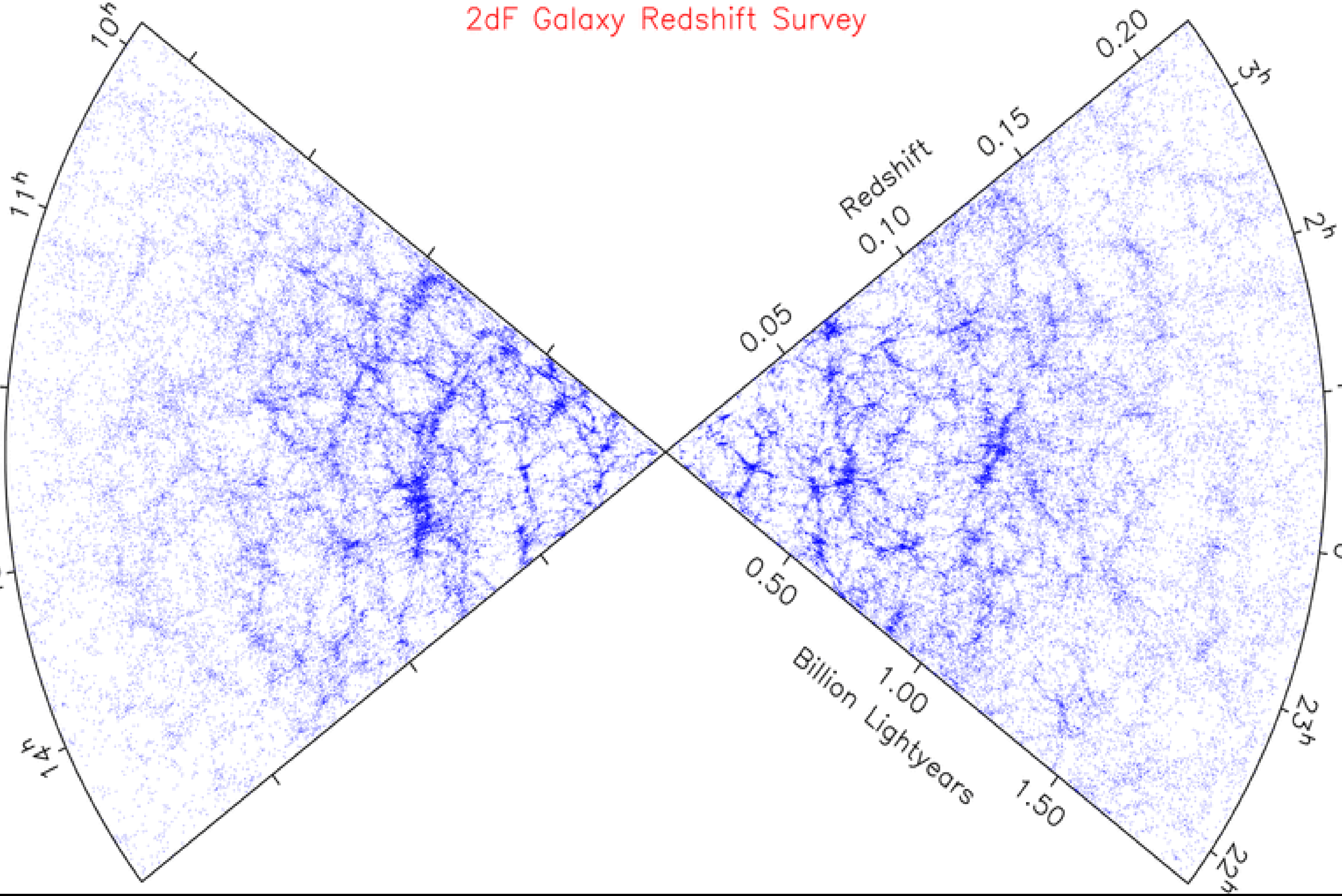



LARSON ET AL, ARXIV 1001.4635

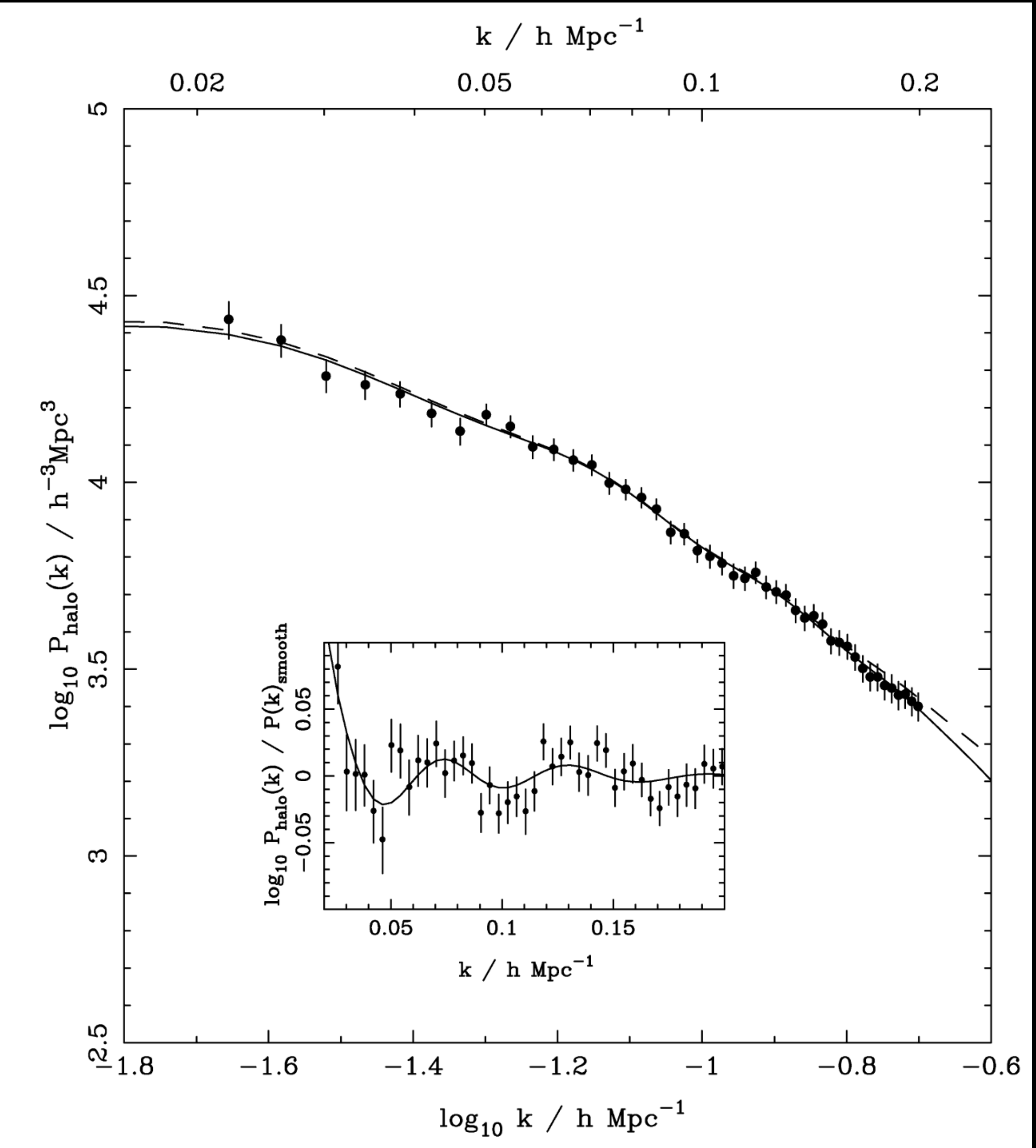
# LARGE SCALE STRUCTURE

SDSS SURVEY (1,000,000 galaxies)

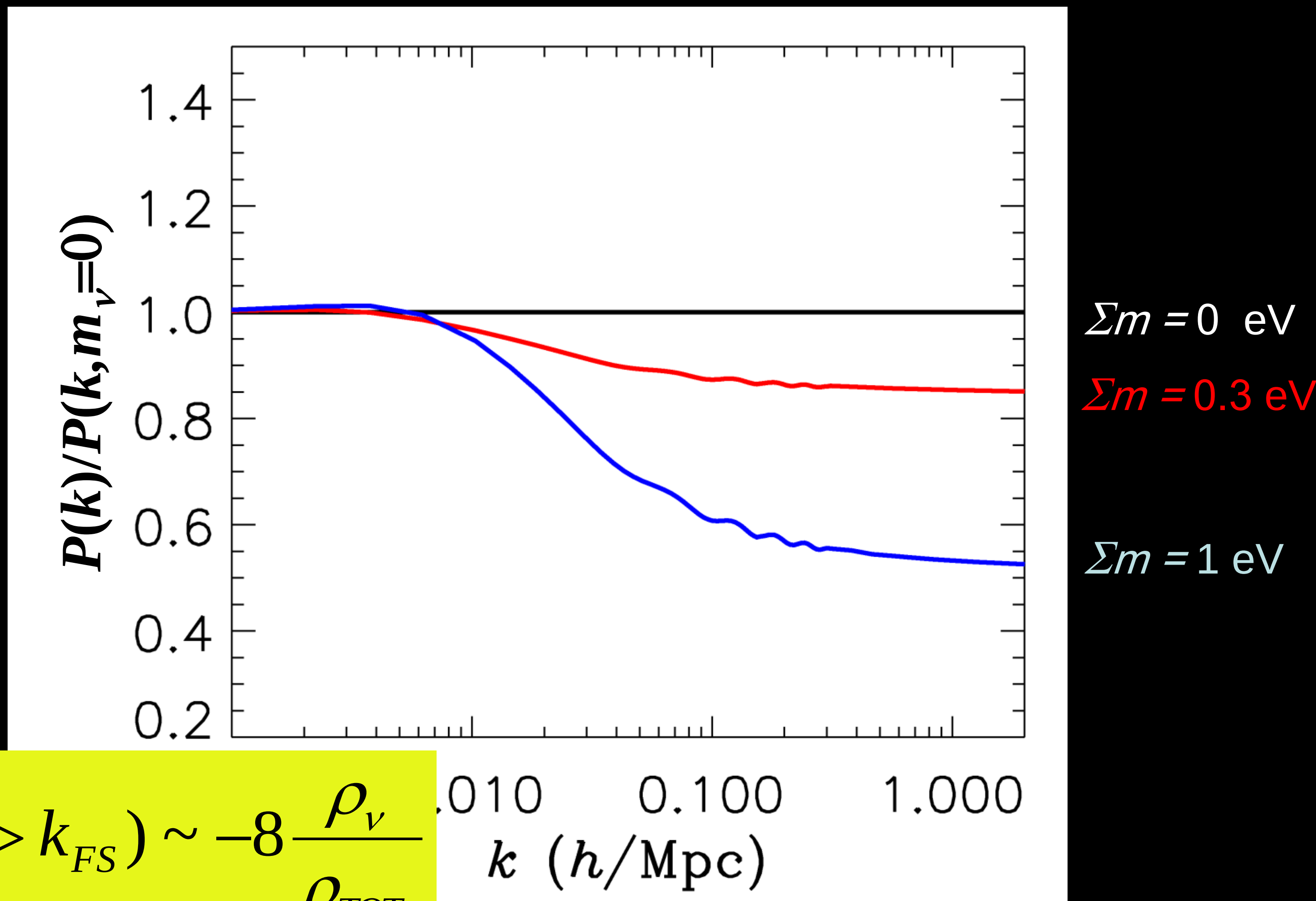
# LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS



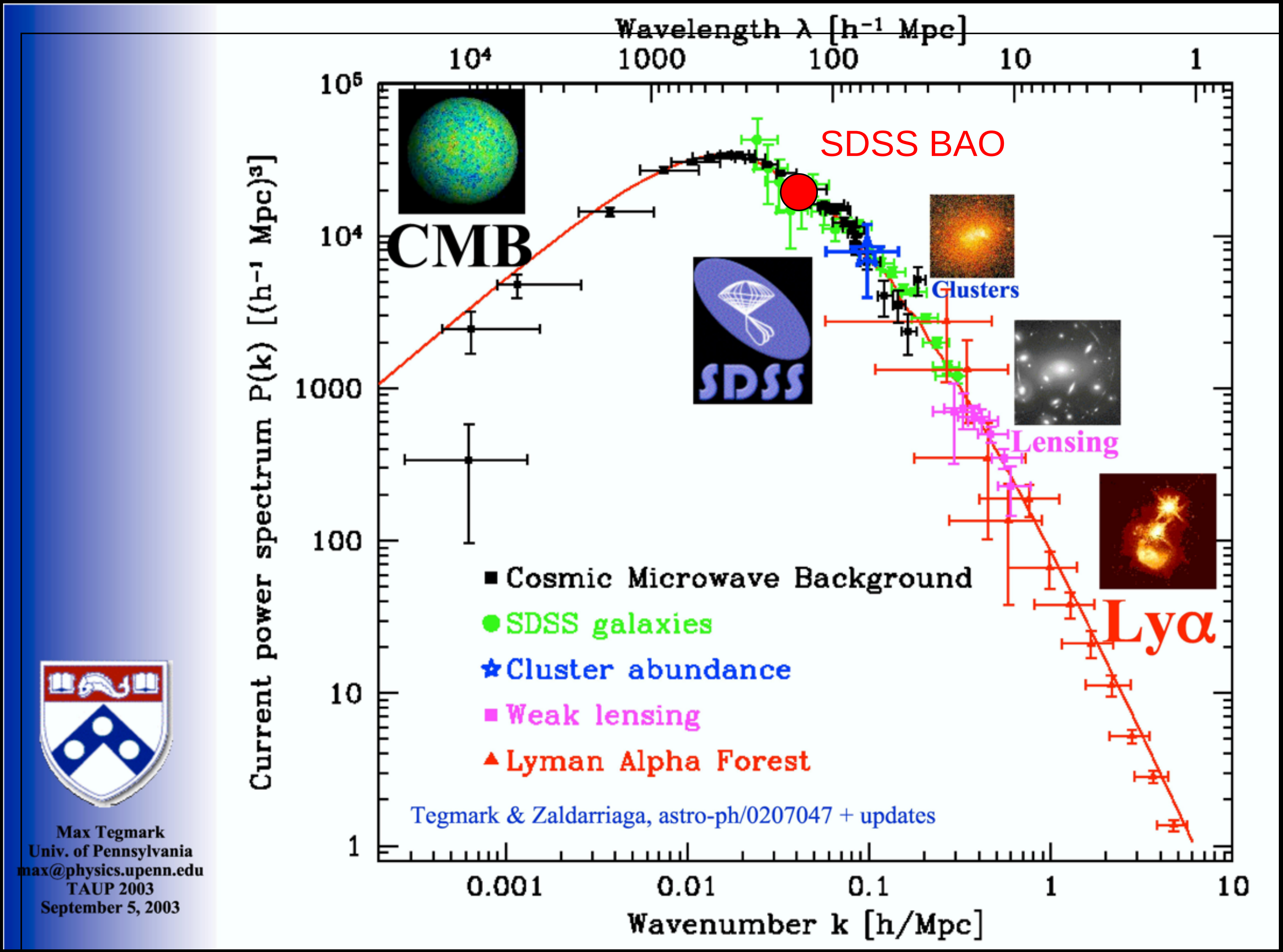
SDSS DR-7
LRG SPECTRUM
(Reid et al '09)



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



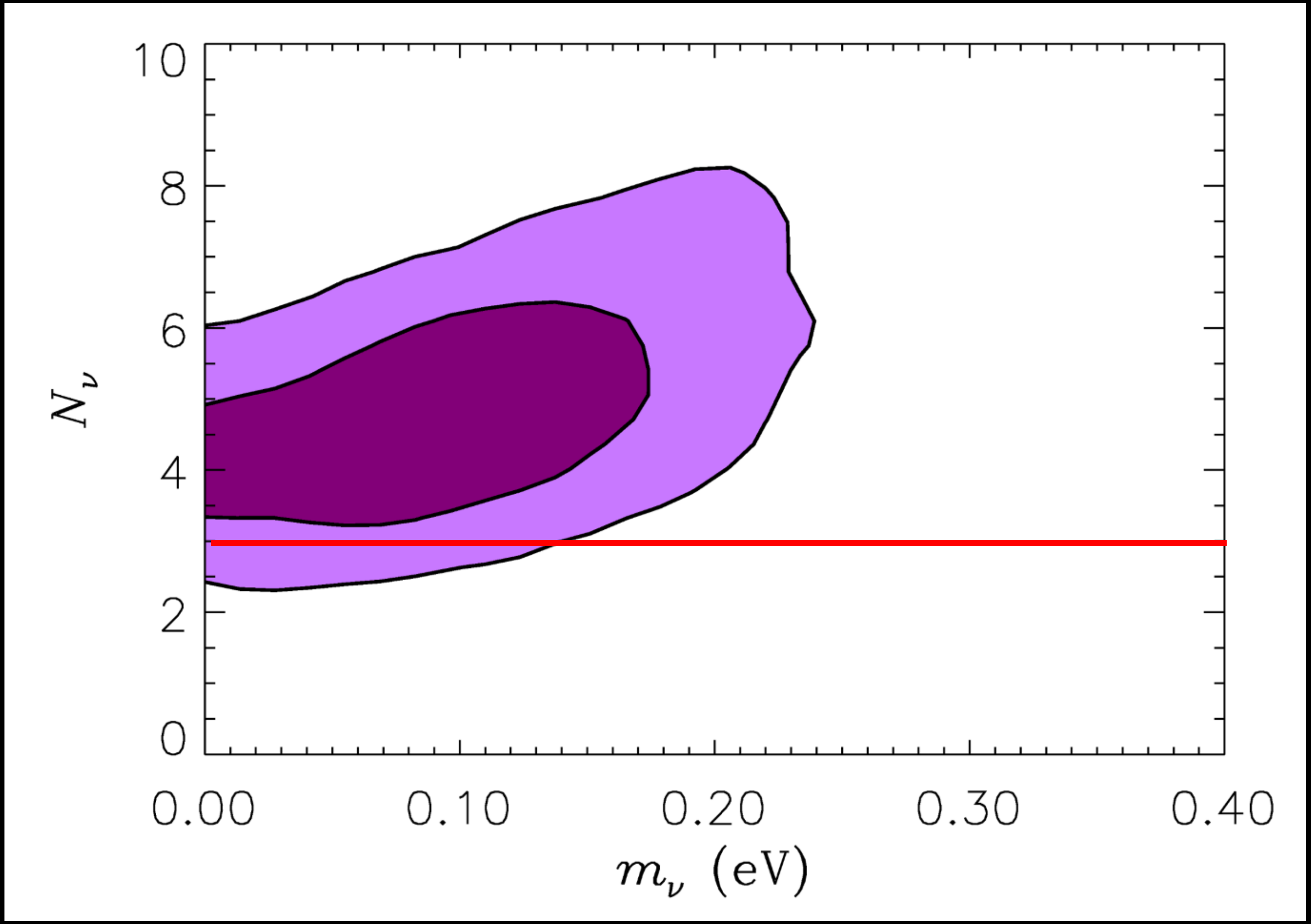

$$\frac{\Delta P}{P_{m=0}}(k >> k_{FS}) \sim -8\frac{\rho_\nu}{\rho_{TOT}}$$




FROM MAX TEGMARK

NOW, WHAT ABOUT NEUTRINO PHYSICS?

# WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

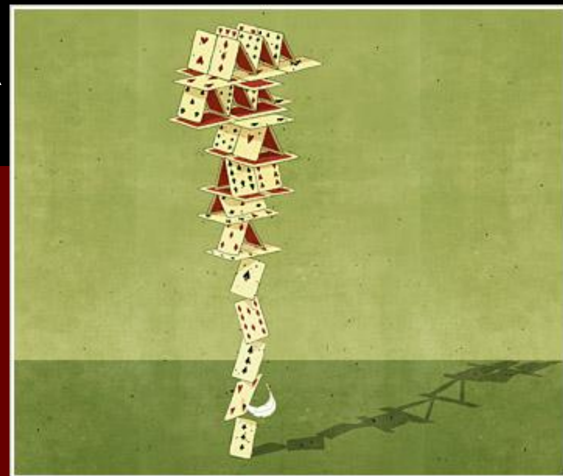



HAMANN, STH, LESGOURGUES & WONG (TO APPEAR)

$$\sum m_\nu \leq 0.19\,\mathrm{eV}\ @\ 95\,\mathrm{C.L.}$$

USING THE MINIMAL COSMOLOGICAL MODEL

# THE NEUTRINO MASS FROM COSMOLOGY PLOT



More data

+Ly-alpha eV 0.2-0.3 eV

+ SNI-a
+WL eV 0.5-0.6 eV

+ SDSS 0.6 eV ~ 1 eV

CMB only 1.1 eV ~ 2 eV

Minimal
$\Lambda$CDM

+$N_{\nu}$

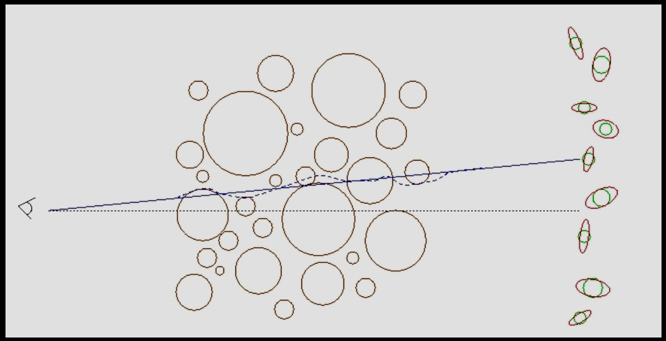
+$w$+……

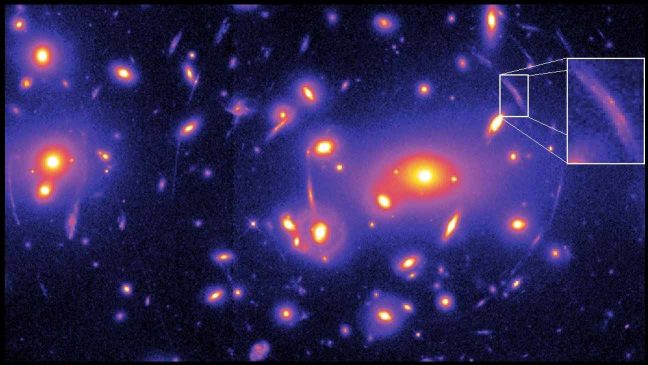
Larger model
space

# WHAT IS IN STORE FOR THE FUTURE?

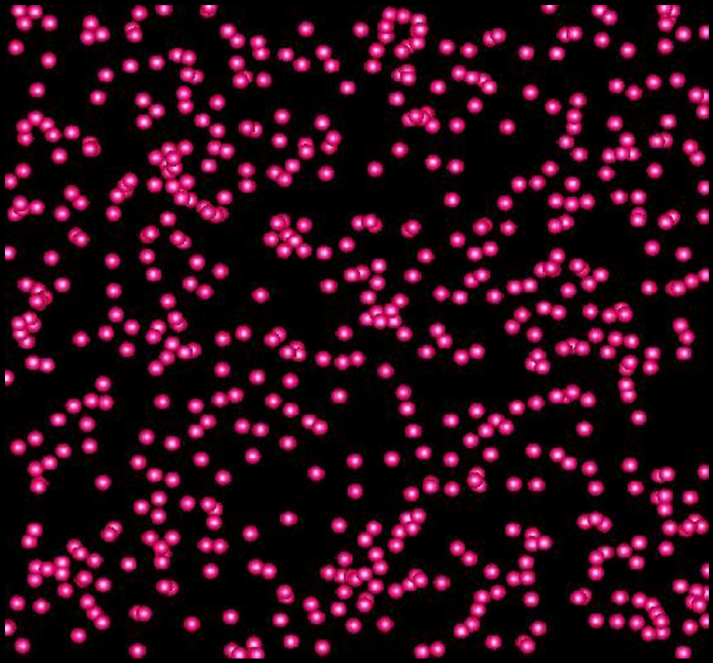
- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS (PLANCK)
- LARGE SCALE STRUCTURE SURVEYS AT HIGH REDSHIFT
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES

# WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE

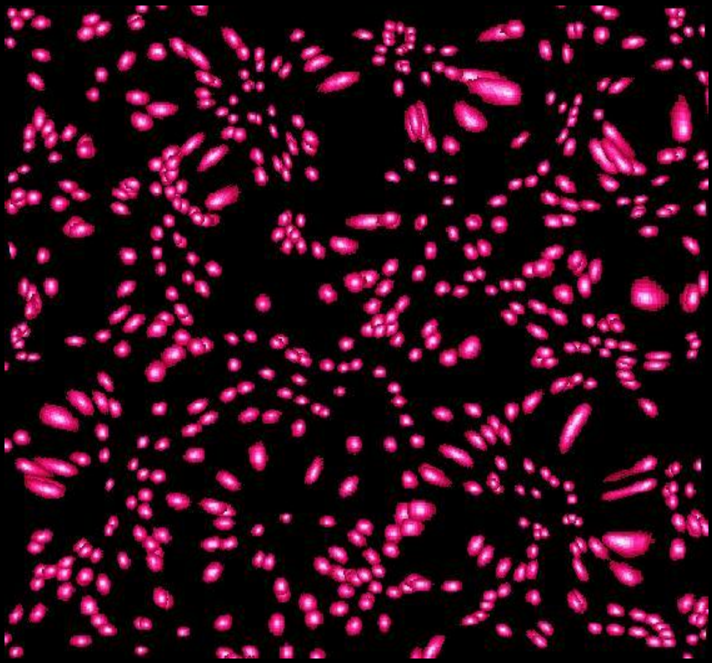




**Distortion of background images by foreground matter**



**Unlensed**



**Lensed**

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

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

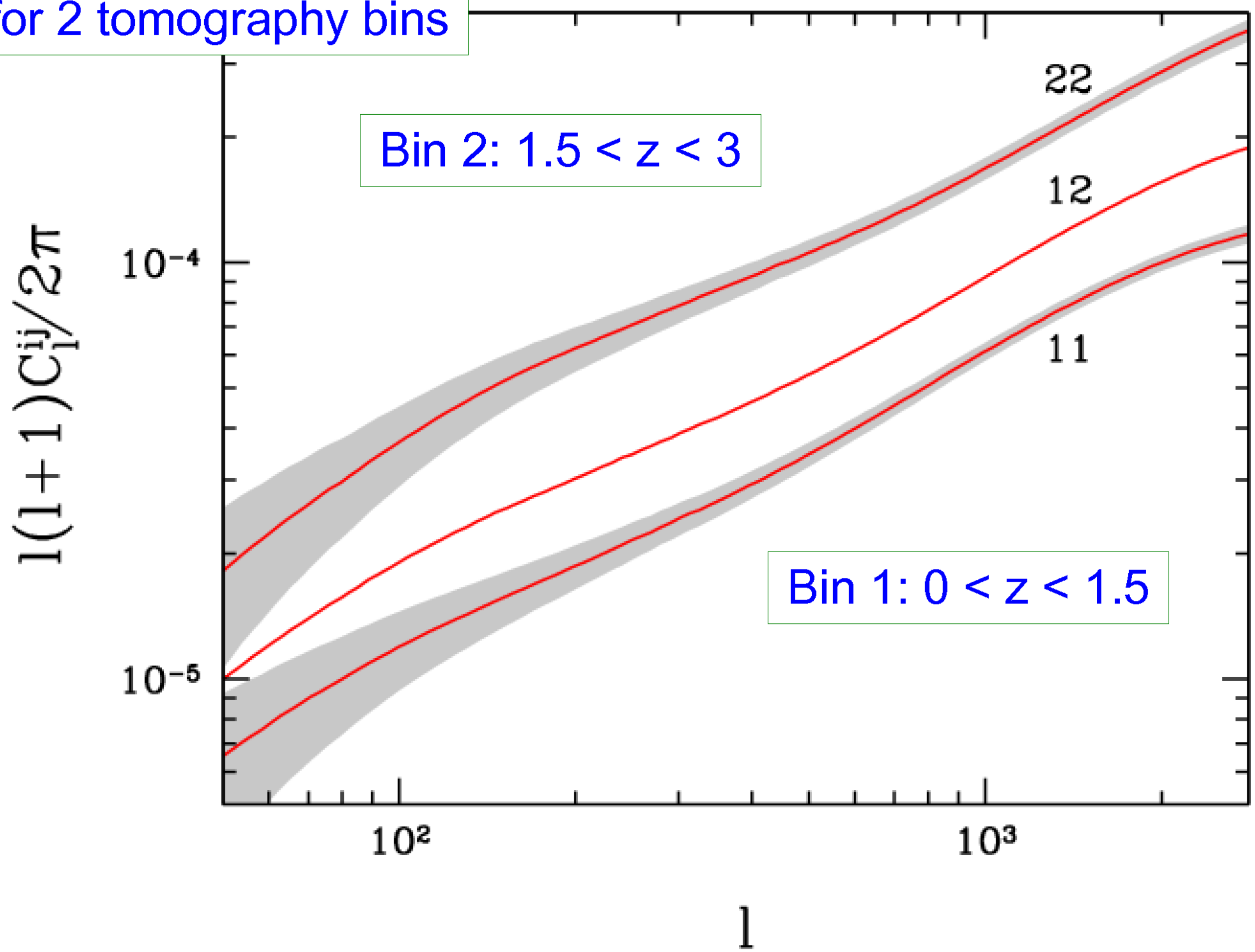
$P(\ell / r, \chi)$ MATTER POWER SPECTRUM (NON-LINEAR)

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

WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY

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

Shear power spectra for 2 tomography bins

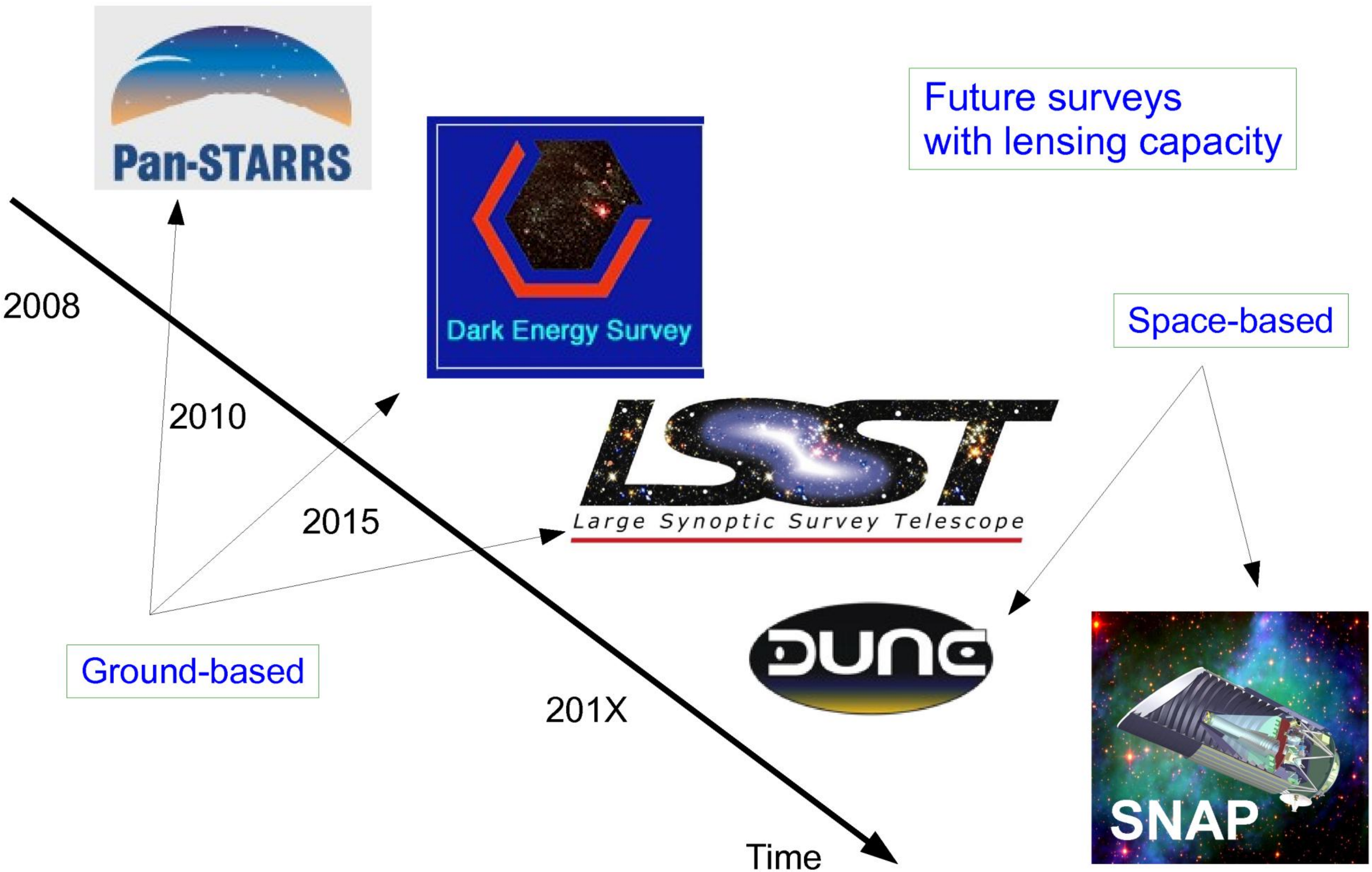



Bin 2 auto-correlation

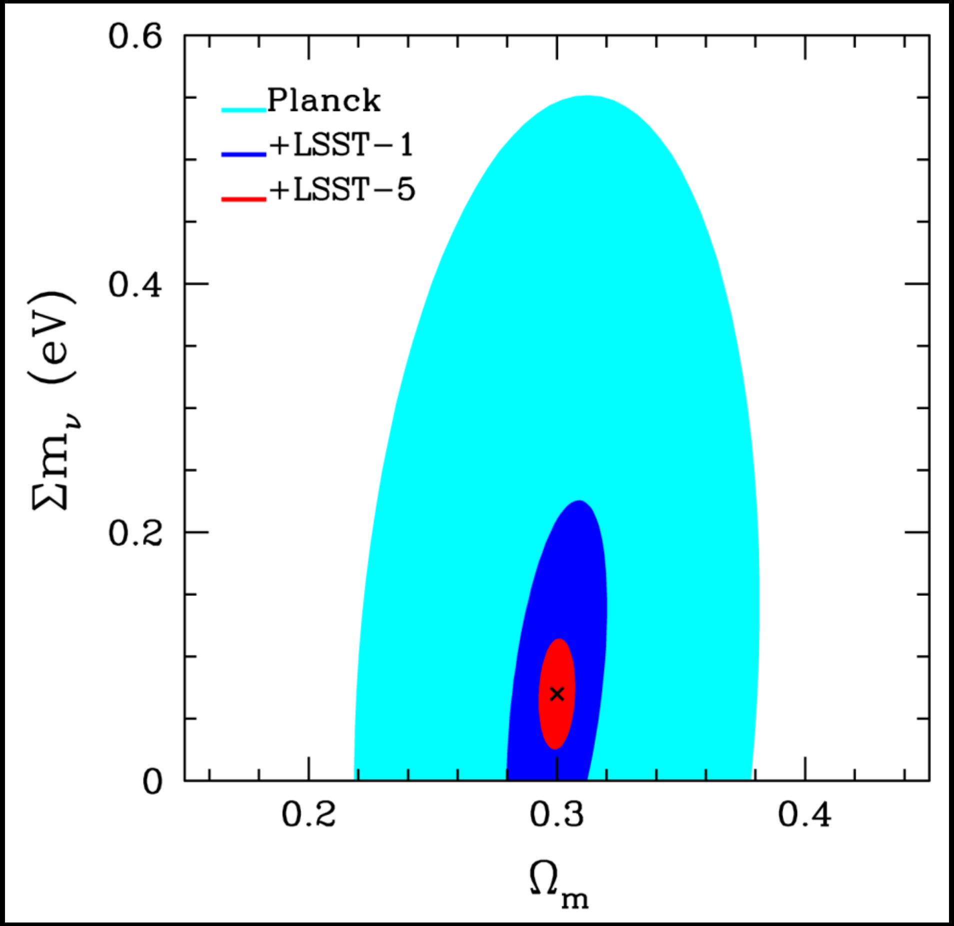
1 & 2 cross-correlation

Bin 1 auto-correlation

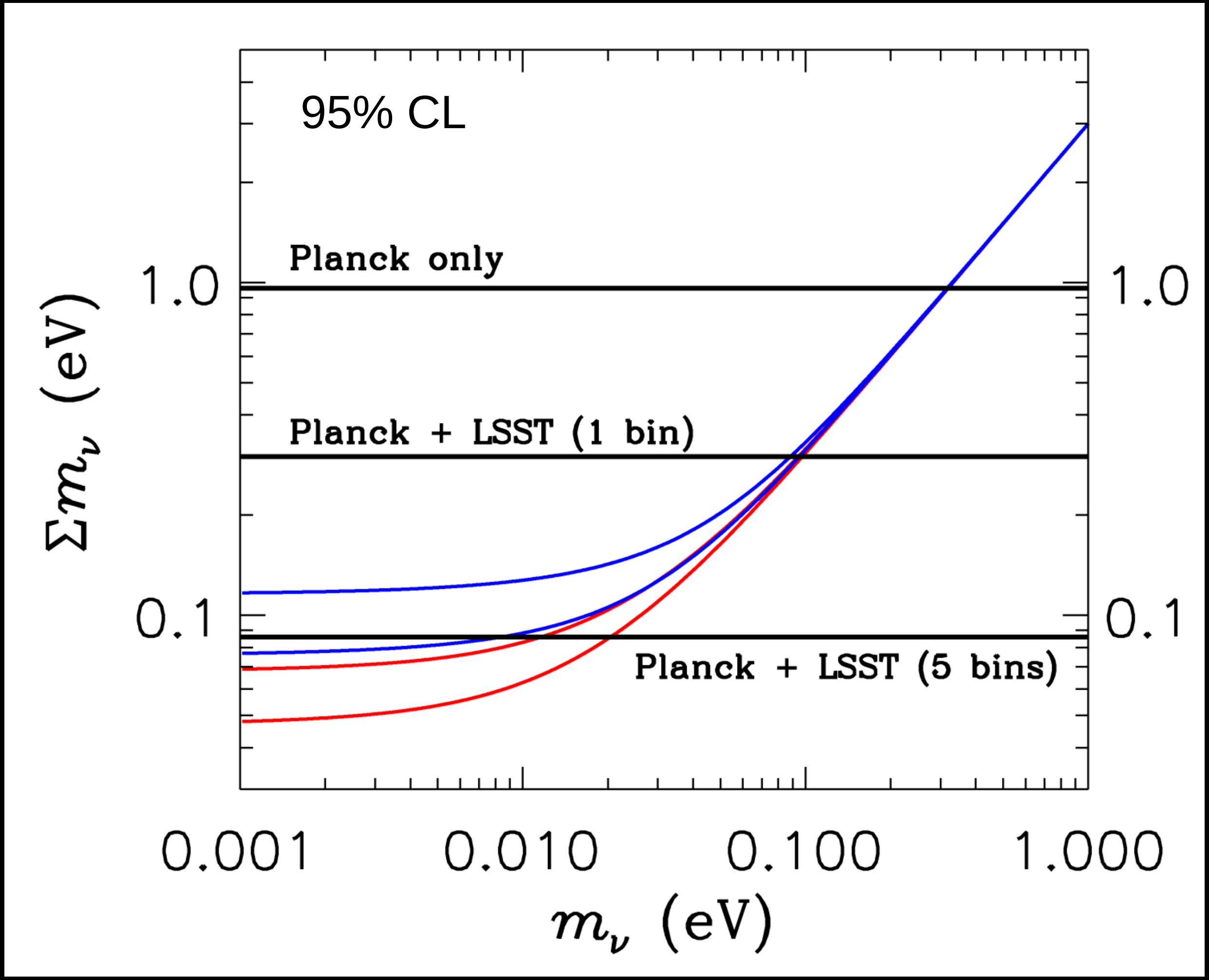
STH, TU, WONG 2006


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

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

# WHY IS WEAK LENSING TOMOGRAPHY SO GOOD?

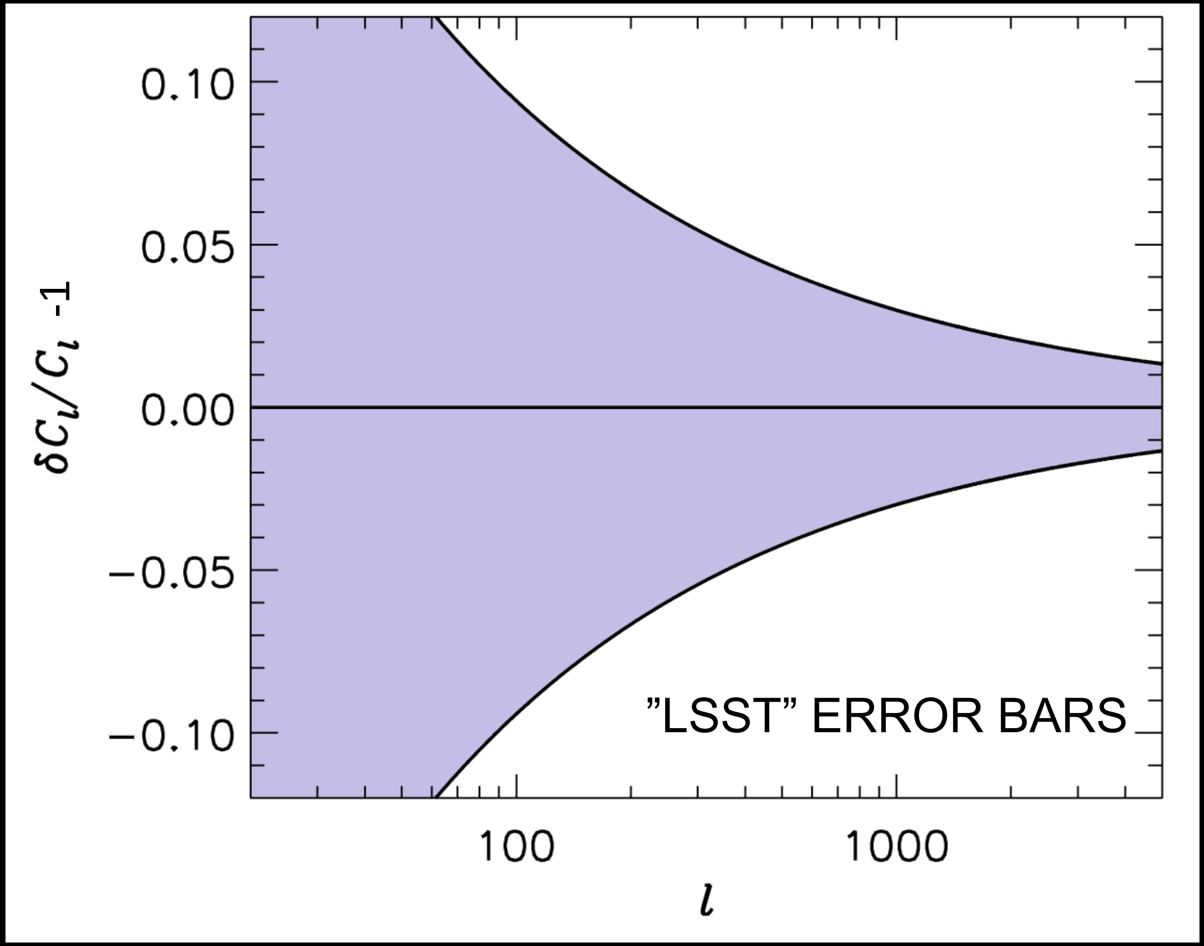
IF MEASURED AT ONLY ONE REDSHIFT THE NEUTRINO SIGNAL IS DEGENERATE WITH OTHER PARAMETERS

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

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

THIS SOUNDS GREAT, BUT UNFORTUNATELY THE THEORETICIANS CANNOT JUST LEAN BACK AND WAIT FOR FANTASTIC NEW DATA TO ARRIVE.....

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

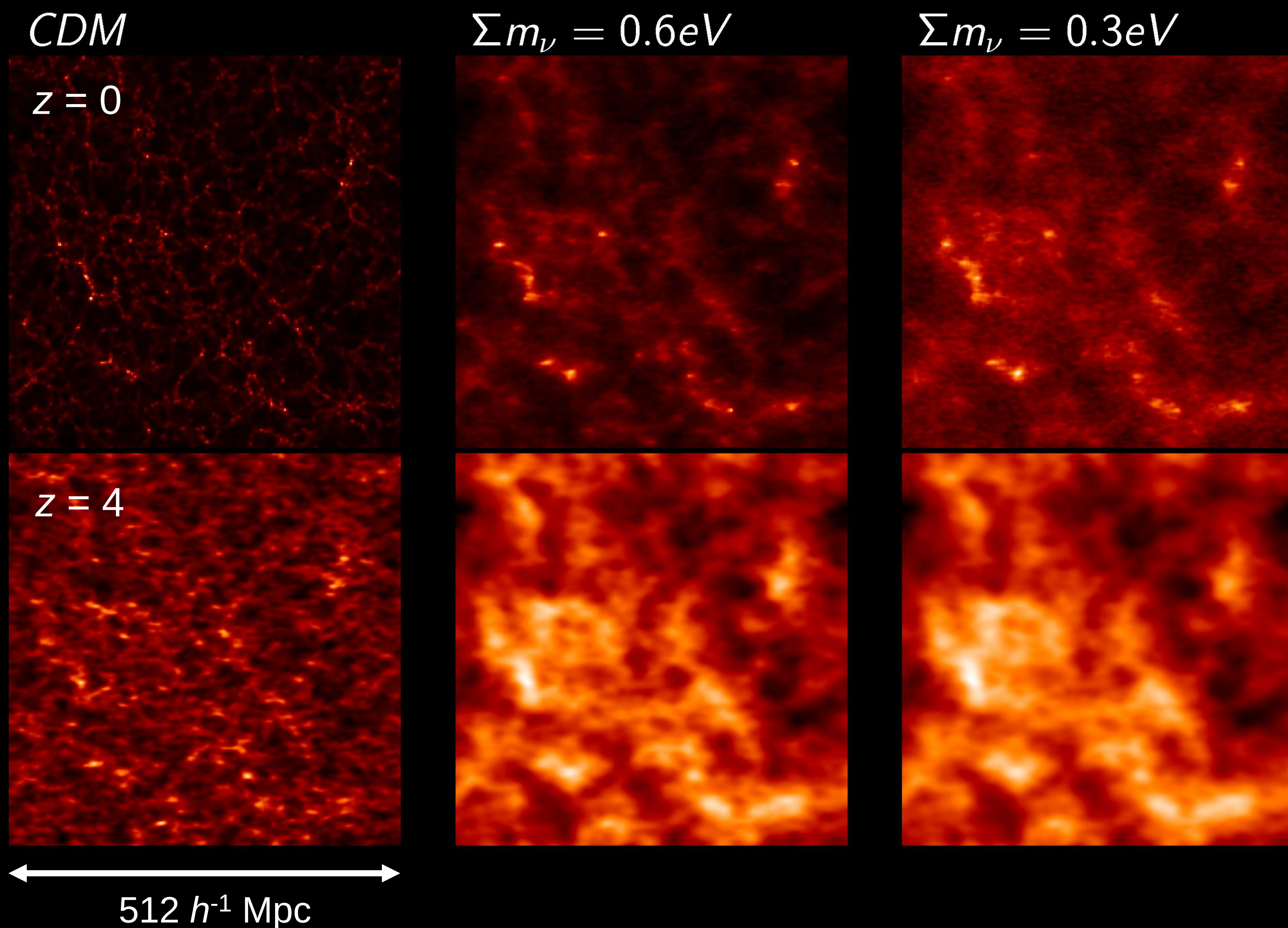



WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM TO AT LEAST THE SAME PRECISION!

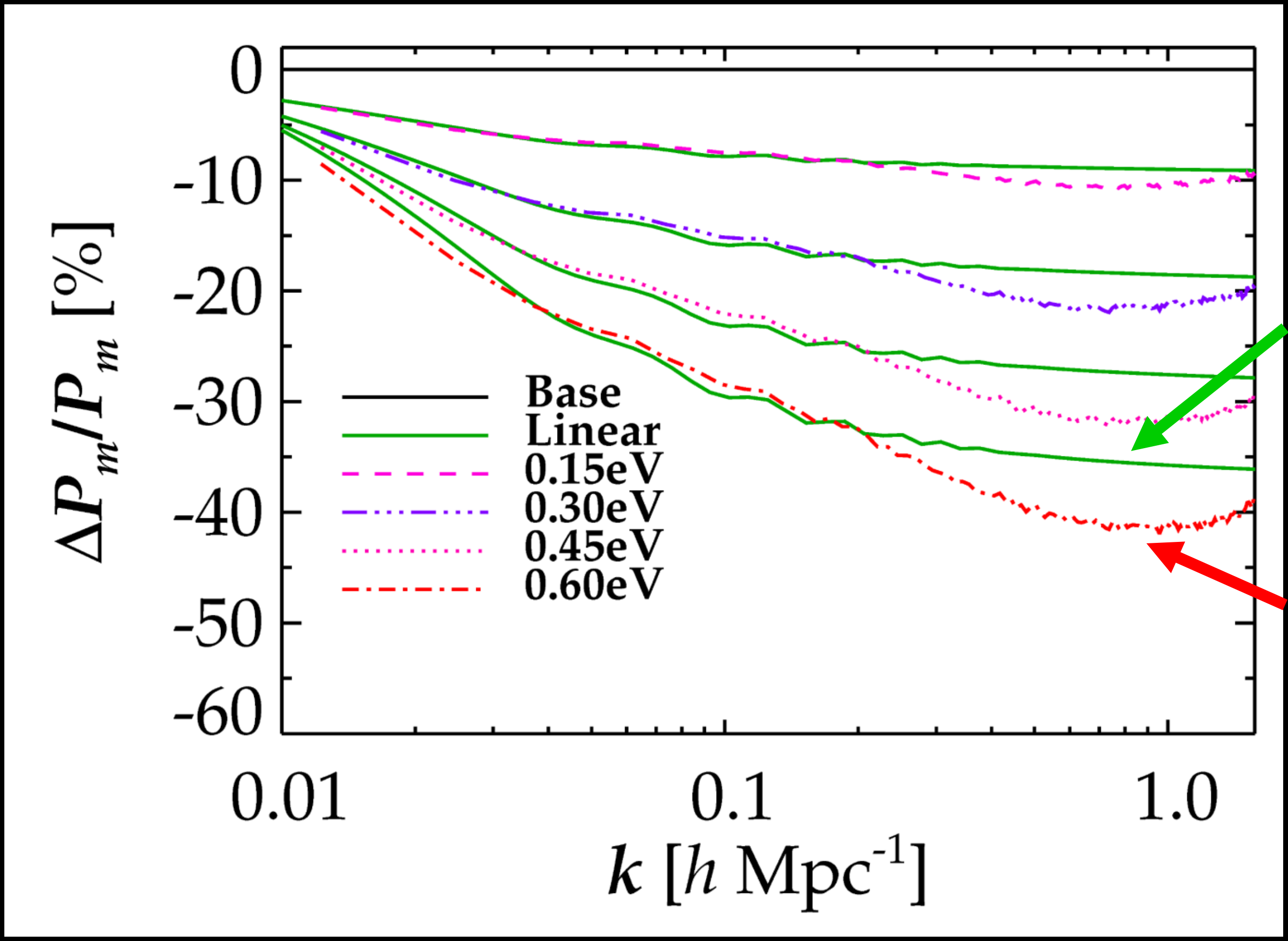
IN ORDER TO CALCULATE THE POWER SPECTRUM TO 1% ON THESE SCALES, A LARGE NUMBER OF EFFECTS MUST BE TAKEN INTO ACCOUNT

- BARYONIC PHYSICS – STAR FORMATION, SN FEEDBACK,.....
- NEUTRINOS, EVEN WITH NORMAL HIERARCHY
- NON-LINEAR GRAVITY
- ..........................

# 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

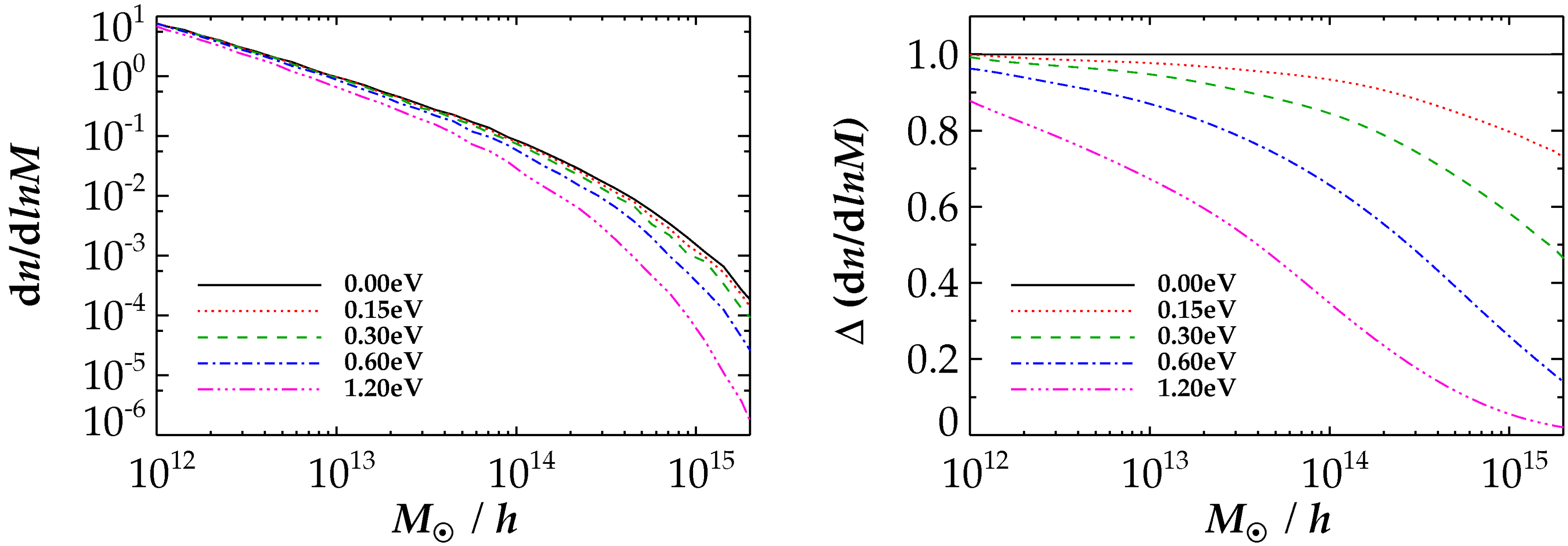
$$\frac{\Delta P}{P} \sim -9.6\,\frac{\Omega_\nu}{\Omega_m}$$

Brandbyge, STH, Haugbølle, Thomsen, arXiv:0802.3700 (ApJ)
Brandbyge & STH ’09, ’10

ANOTHER IMPORTANT ASPECT OF STRUCTURE FORMATION WITH NEUTRINOS:

THE NUMBER OF BOUND OBJECTS (HALOS) AS WELL AS THEIR PROPERTIES ARE CHANGED WHEN NEUTRINOS ARE INCLUDED

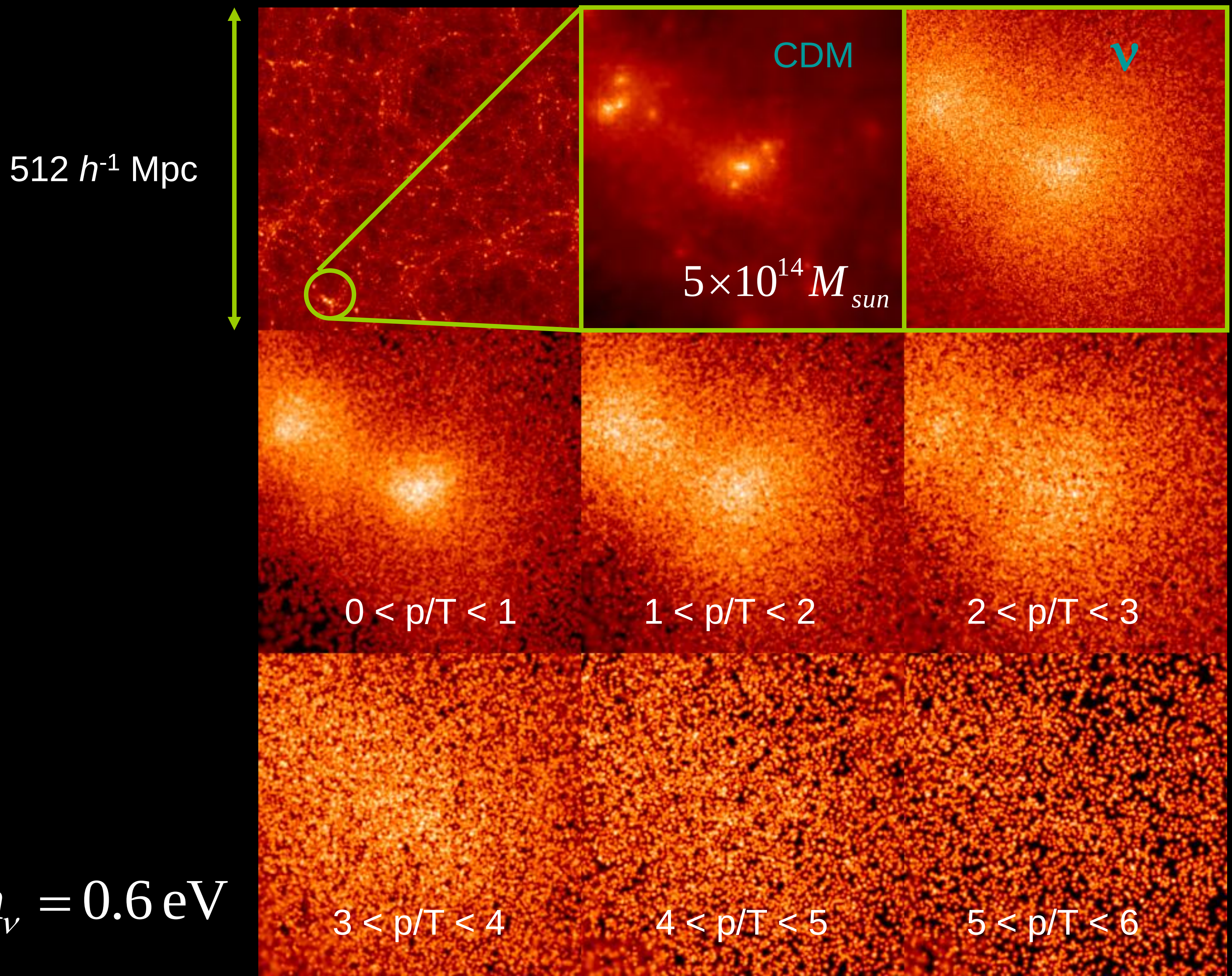
# THE CLUSTER MASS FUNCTION WITH NEUTRINOS




Brandbyge, STH, Haugboelle, Wong (to appear)

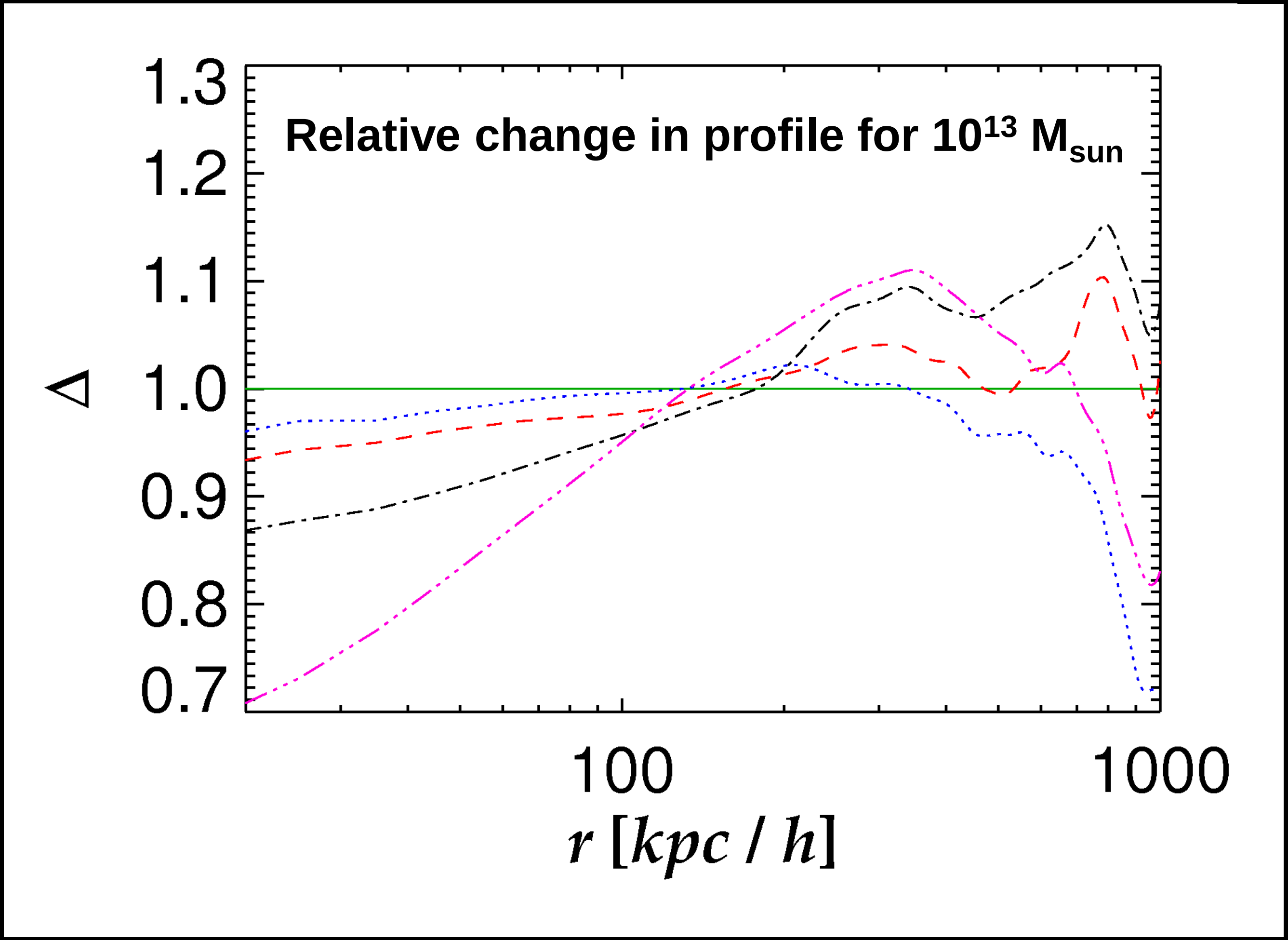
CLUSTER SURVEYS MAY ALSO REACH A SENSITIVITY OF ~ 0.05 eV IN THE NEXT DECADE (Wang et al. 06)

# INDIVIDUAL HALO PROPERTIES




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

Brandbyge, STH, Haugboelle, Wong (to appear)



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 C$\nu$B (dating back to Weinberg ’62)

E.g.

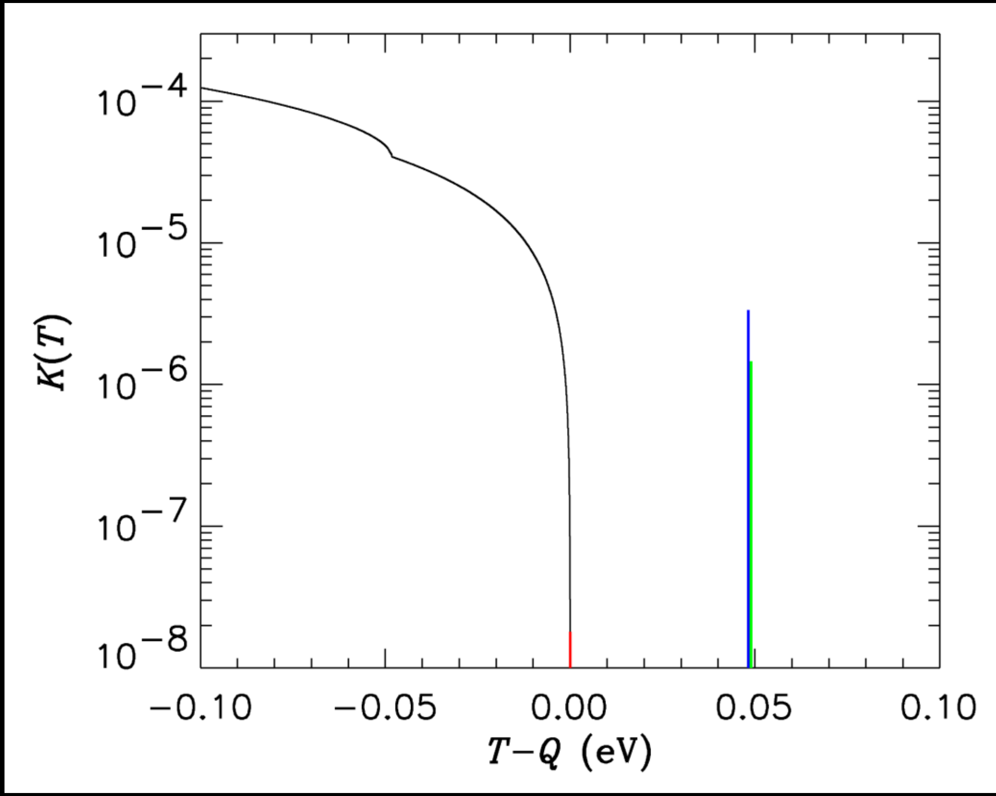
$$\nu_e + {}^3H \rightarrow {}^3He + e$$

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 $\Theta_{13}$ 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 $|U_{ei}|^2 n_i$

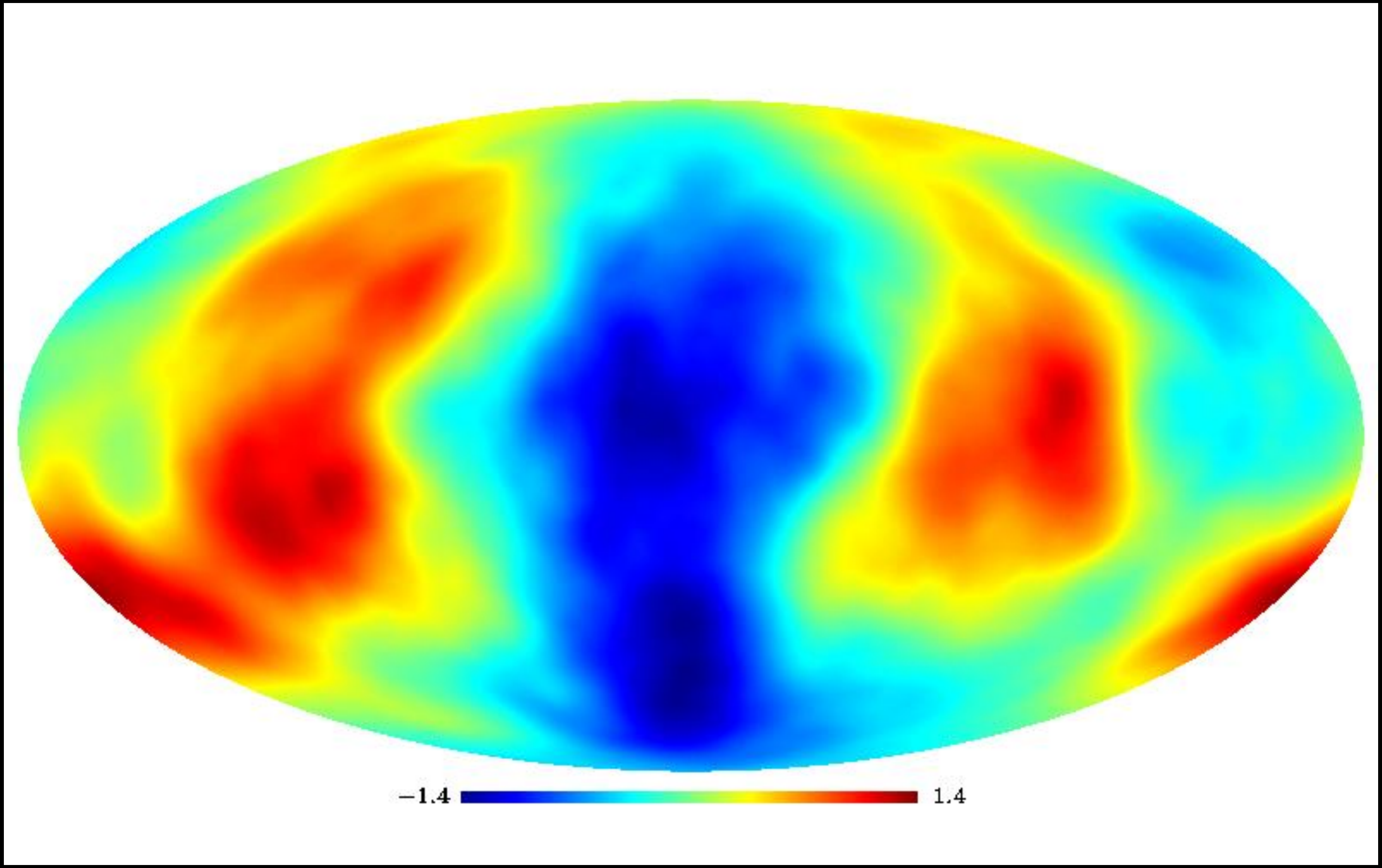
AND FINALLY: IN THE FAR DISTANT FUTURE WE MIGHT BE OBSERVING THE C$\nu$B ANISOTROPY

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

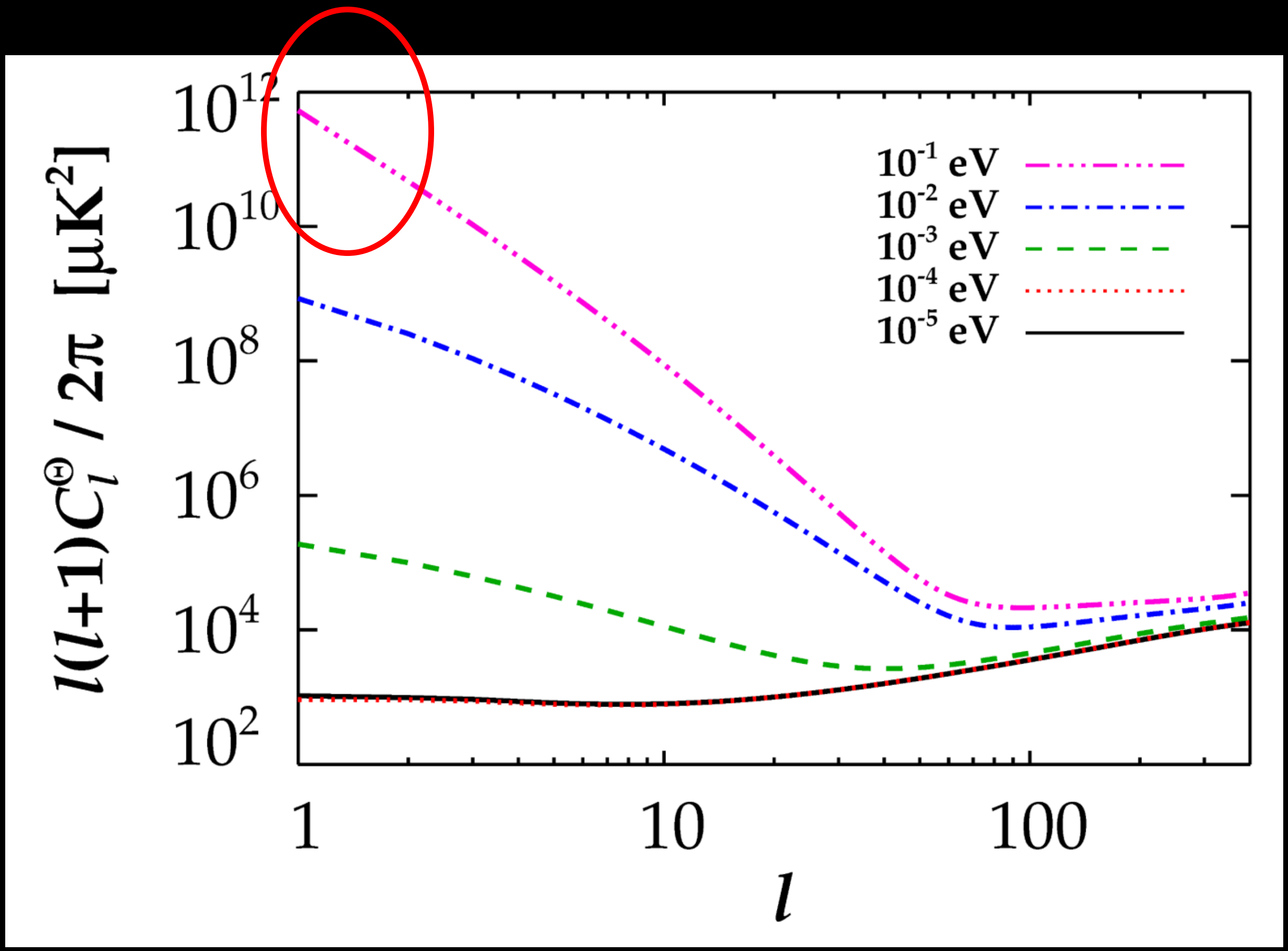
STH & Brandbyge, arXiv:0910.4578 (JCAP)
(see also Michney, Caldwell astro-ph/0608303)

# REALISATIONS OF THE CνB FOR DIFFERENT MASSES




$m = 10^{-2}$ eV

ANISOTROPY ~ $O(1)$




STH & Brandbyge, arXiv:0910.4578 (JCAP to appear)

# CONCLUSIONS

- NEUTRINO PHYSICS IS PERHAPS THE PRIME EXAMPLE OF HOW TO USE COSMOLOGY TO DO 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