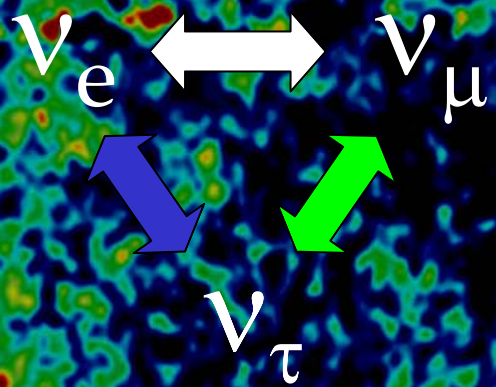
NEUTRINO COSMOLOGY



STEEN HANNESTAD
UNIVERSITY OF AARHUS
PARIS, 27 OCTOBER 2006

OUTLINE

A BRIEF REVIEW OF PRESENT COSMOLOGICAL DATA

BOUNDS ON THE NEUTRINO MASS

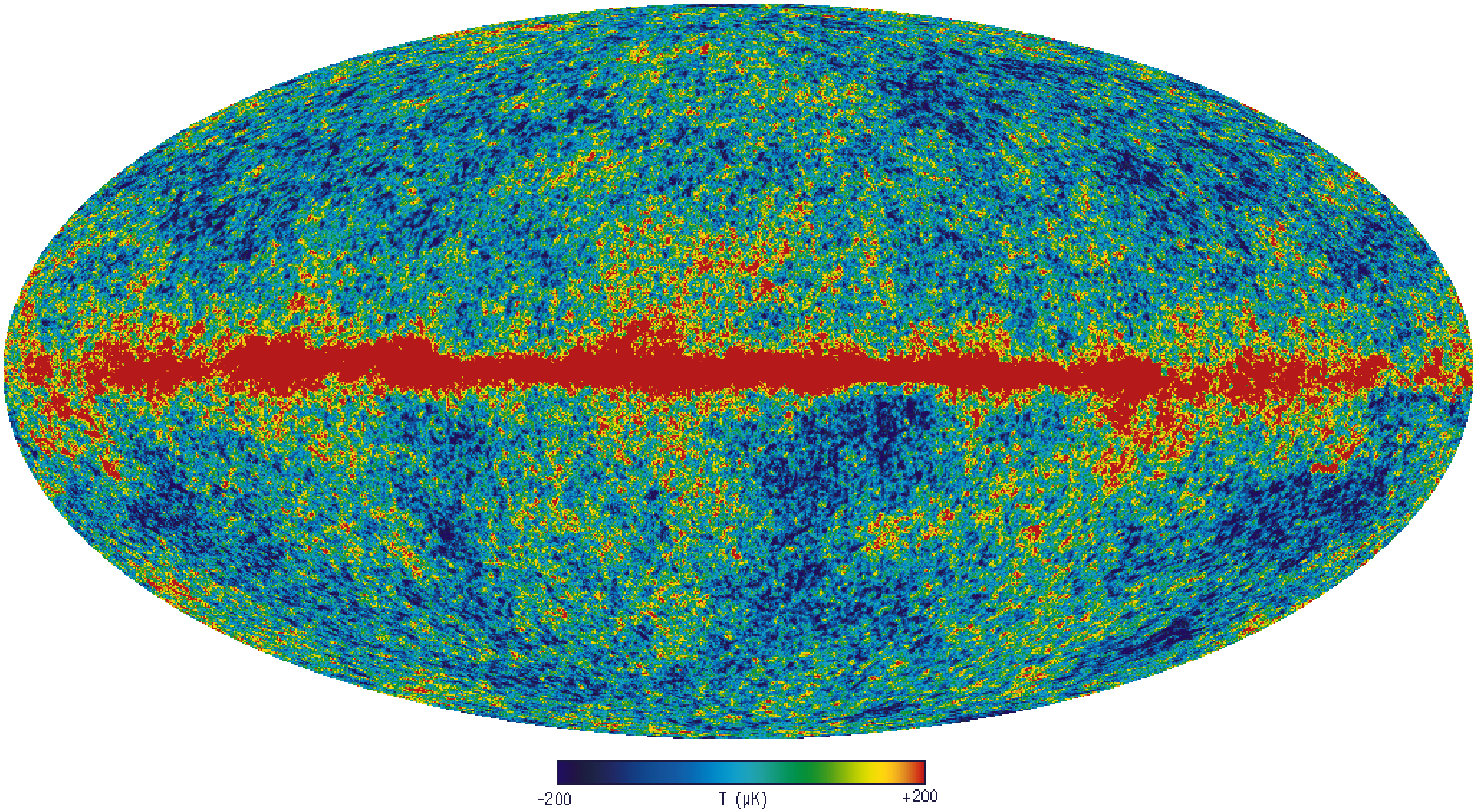
STERILE NEUTRINOS

WHAT IS TO COME IN THE FUTURE?

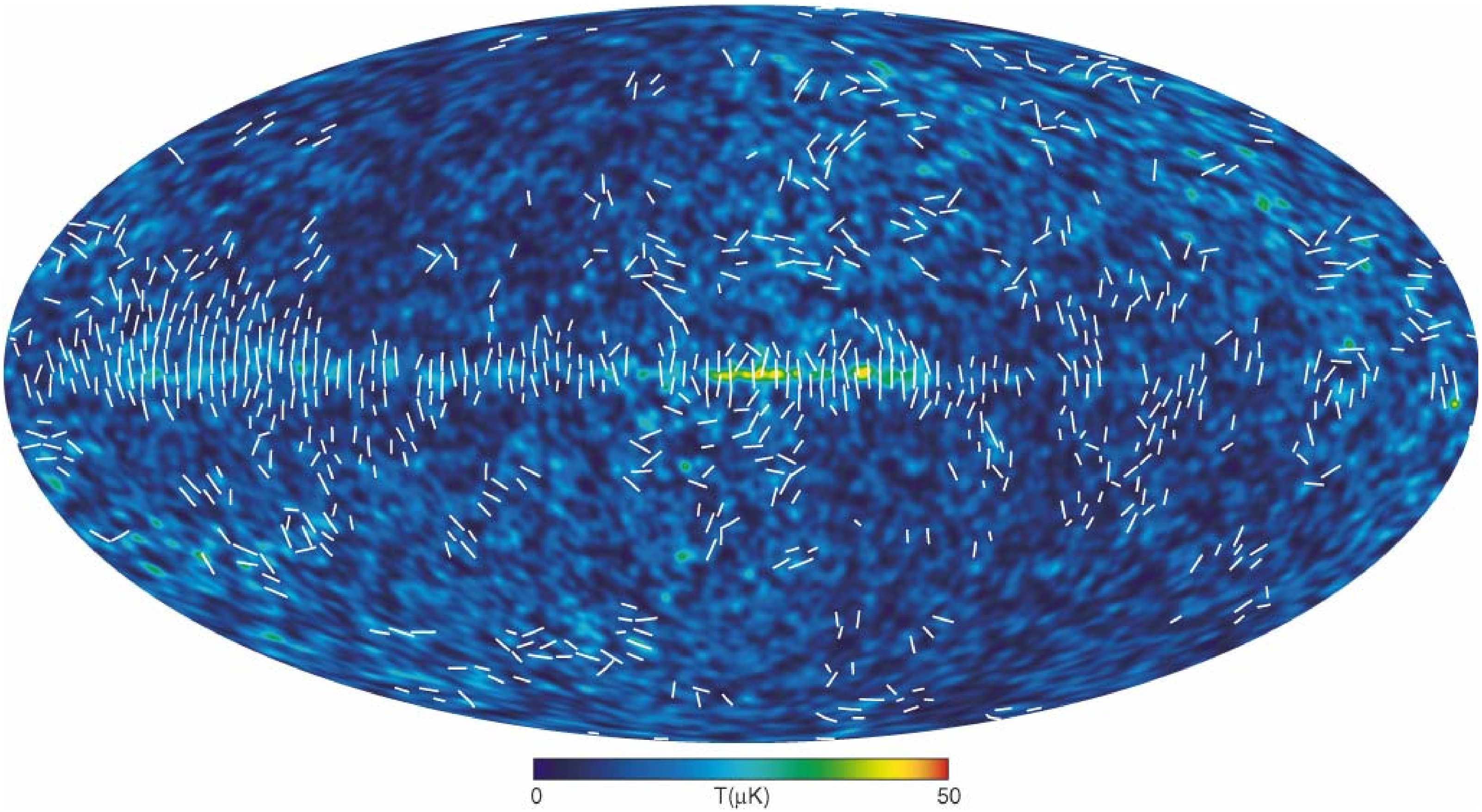
IF THERE IS TIME:
BOUNDS ON NEW NEUTRINO INTERACTIONS

THE COSMIC MICROWAVE BACKGROUND

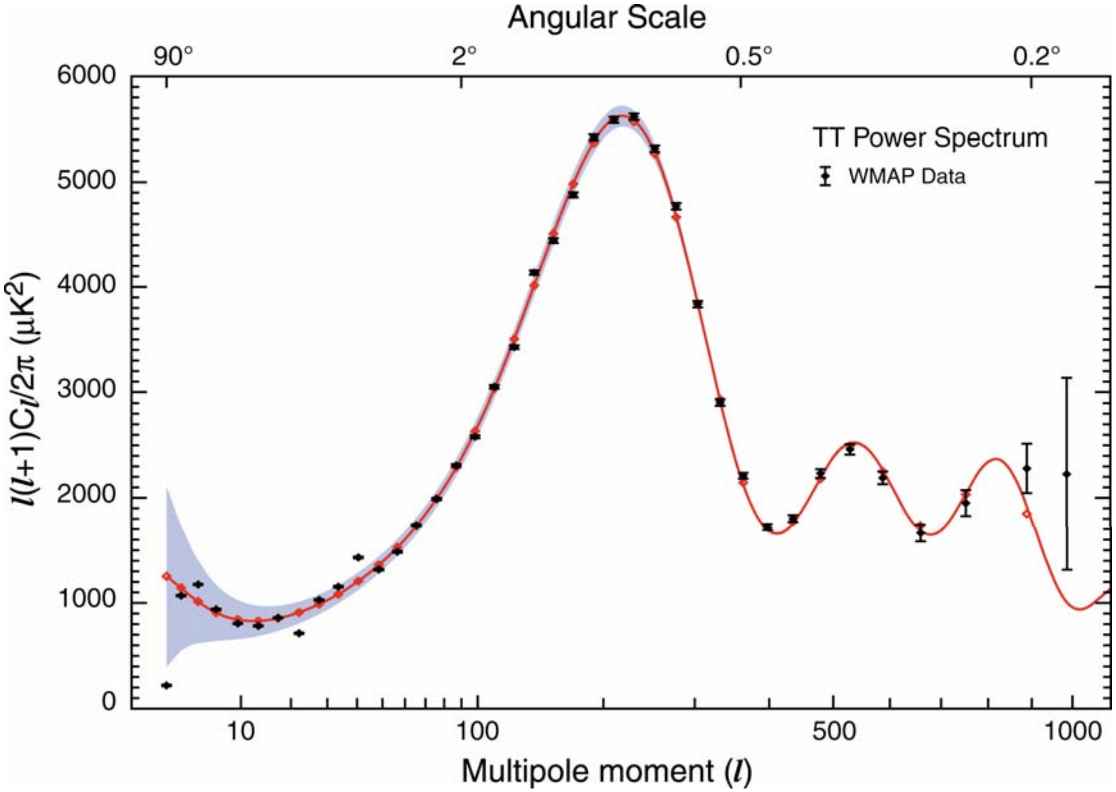
WMAP TEMPERATURE MAP IN THE 94 GHZ CHANNEL



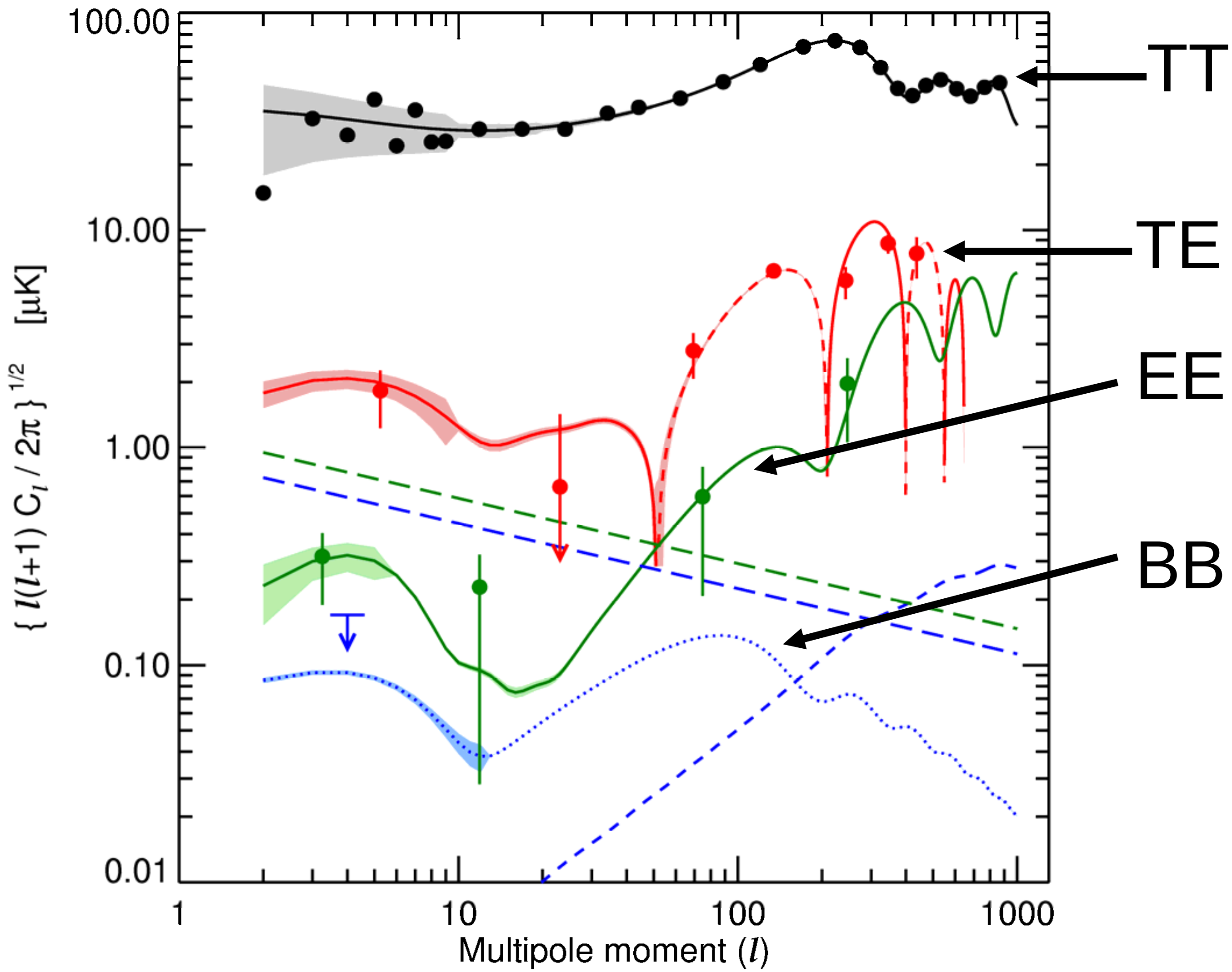
WMAP POLARIZATION MAP IN THE 94 GHZ CHANNEL



WMAP-3 TEMPERATURE POWER SPECTRUM

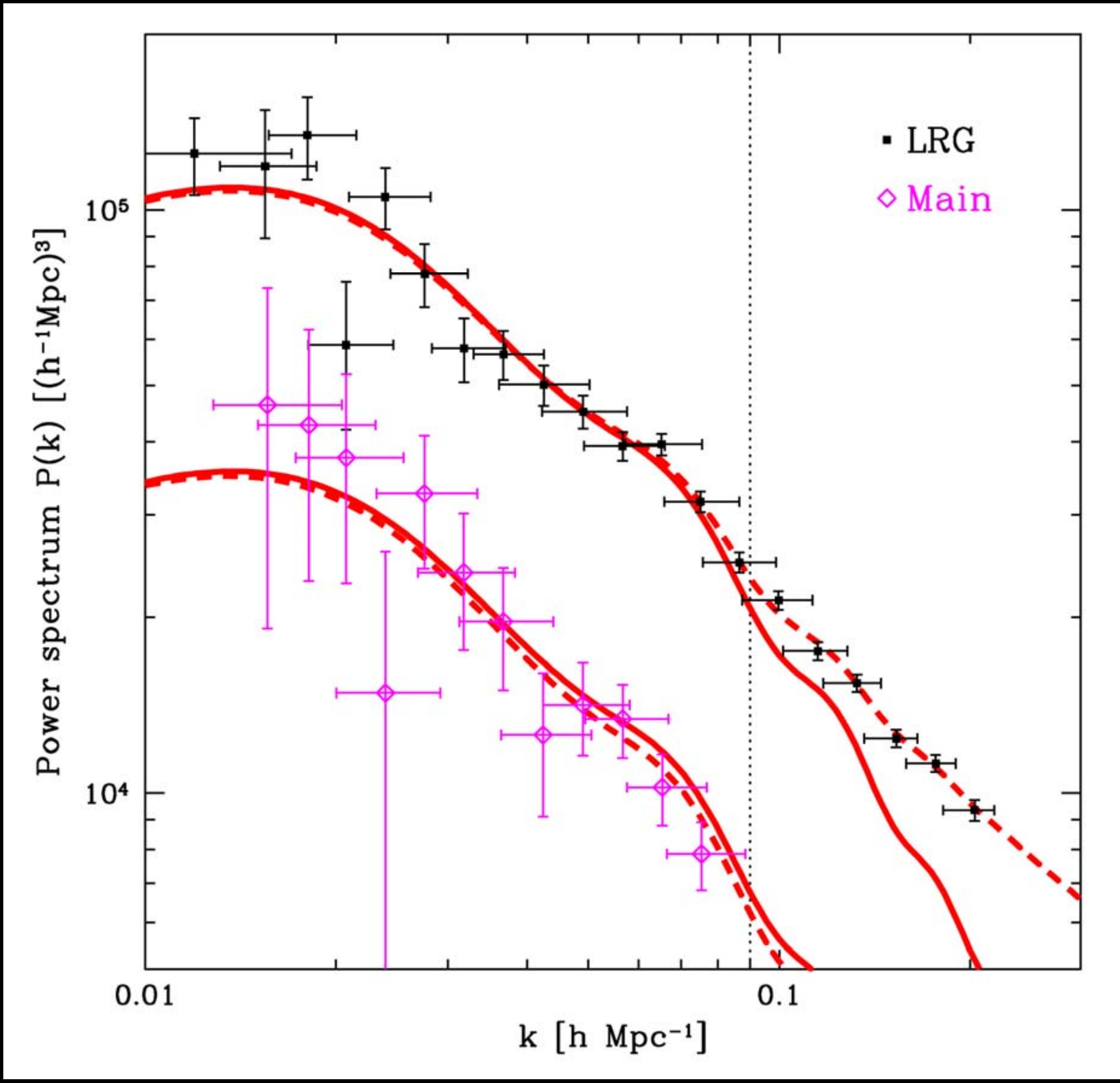


WMAP POLARIZATION MEASUREMENTS



LARGE SCALE STRUCTURE

SDSS SPECTRUM
TEGMARK ET AL. 2006



Astro-ph/0608632

OTHER AVAILABLE STRUCTURE FORMATION DATA:

THE LYMAN ALPHA FOREST (THE FLUX POWER SPECTRUM ON SMALL SCALES AT HIGH REDSHIFT)

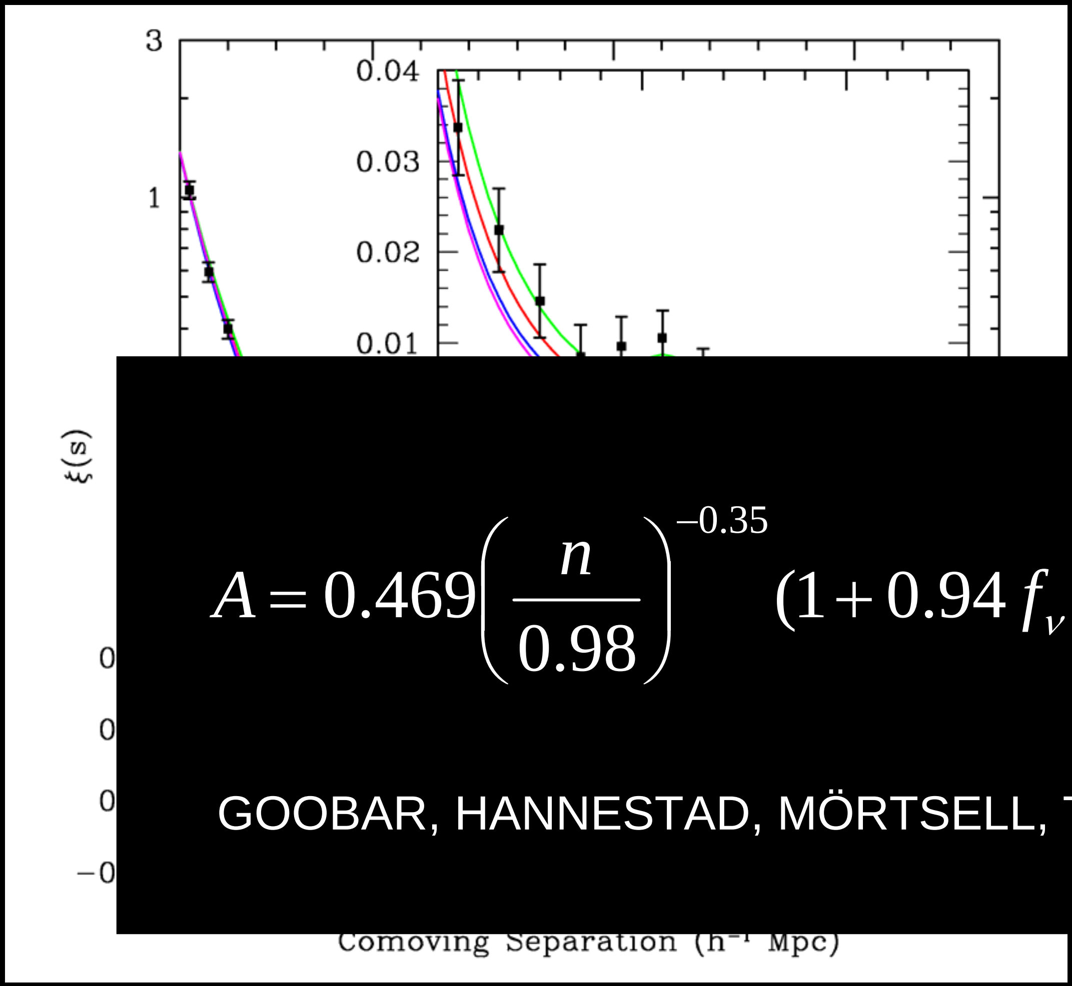
McDonald et al. astro-ph/0407377 (SDSS)

Viel et al.

THE BARYON ACOUSTIC PEAK (SDSS) – THE CMB OSCILLATION PATTERN SEEN IN BARYONS

WEAK GRAVITATIONAL LENSING

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 ANALYSIS

$$A = 0.469\left(\frac{n}{0.98}\right)^{-0.35}(1+0.94 f_\nu) \pm 0.017$$

GOOBAR, HANNESTAD, MÖRTSELL, TU 2006

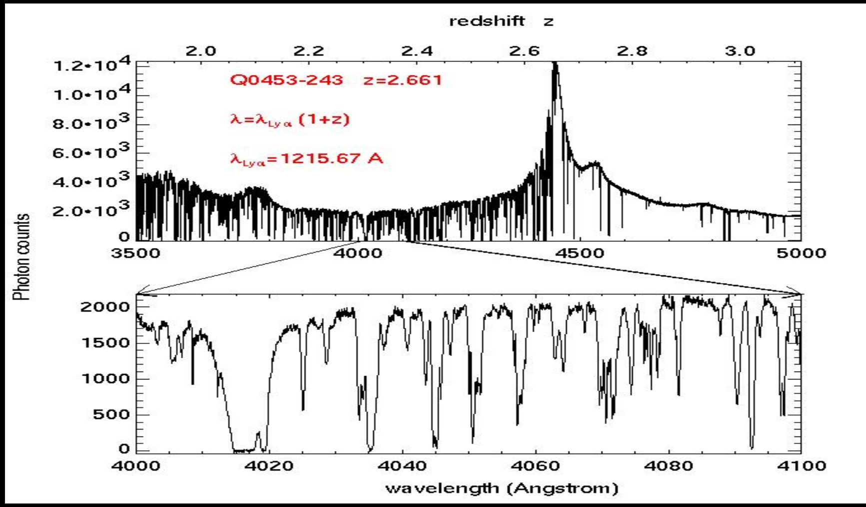
THE LYMAN-ALPHA FOREST AS A TOOL FOR MEASURING THE MATTER POWER SPECTRUM

Ly-α forest analysis

- Raw data: quasar spectra

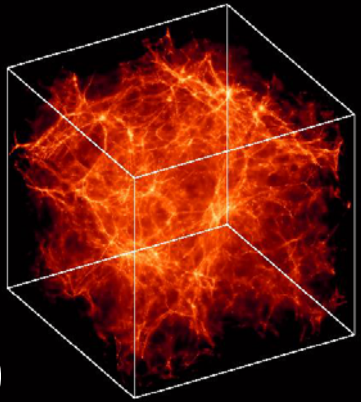
  remove data not tracing

  (quasi-linear) Lyα absorption



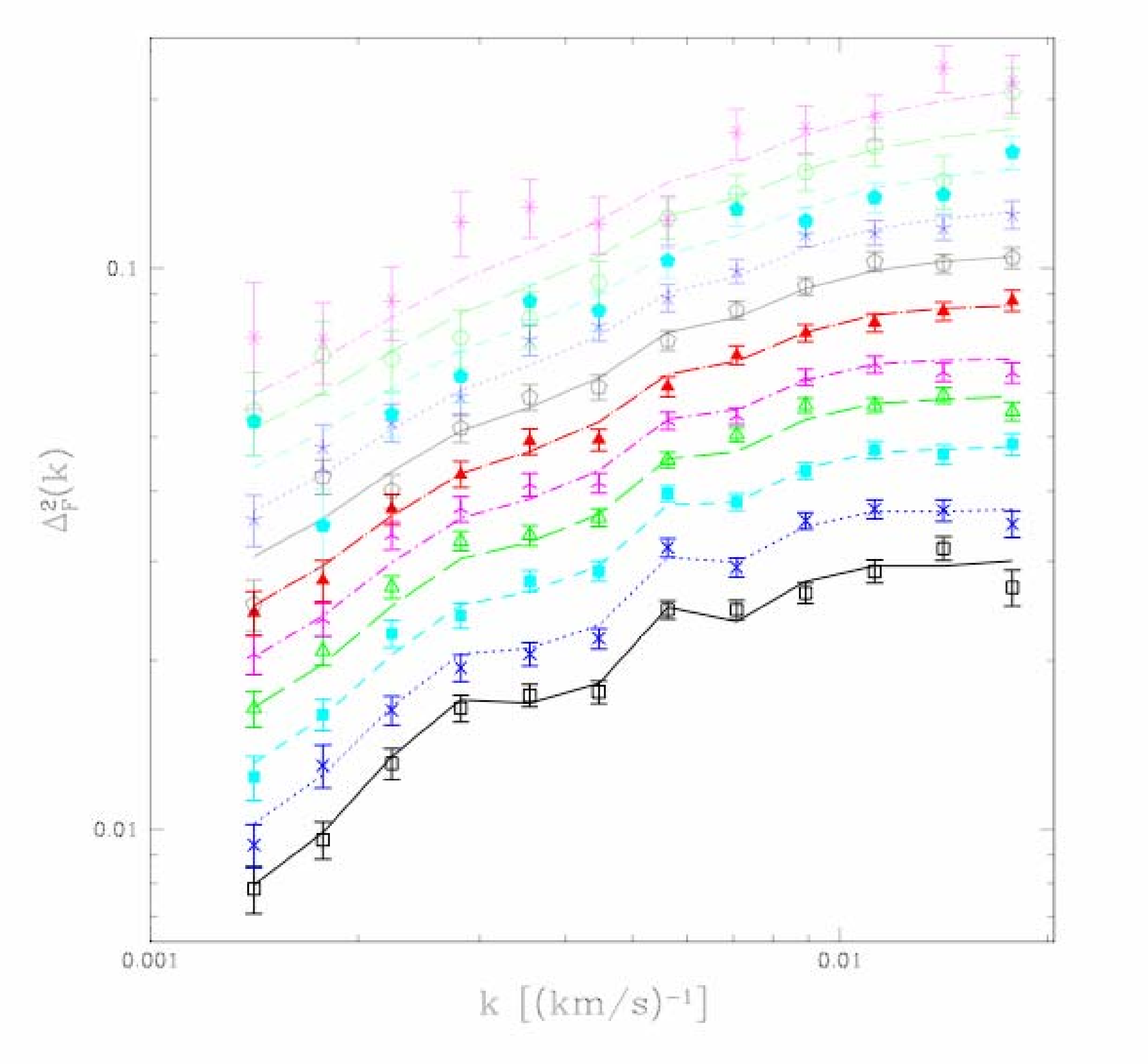
- Flux power spectrum $P_F(k)$

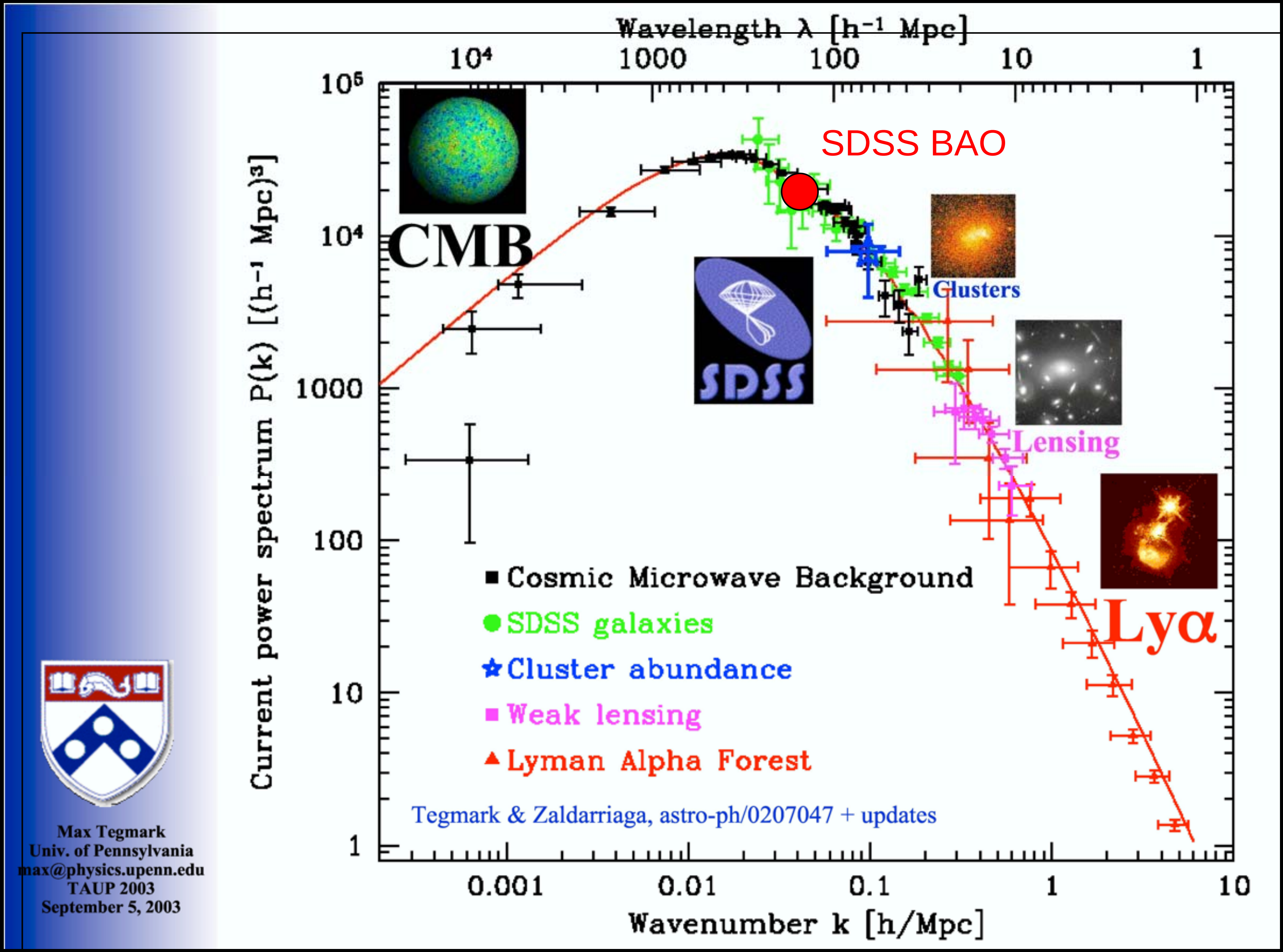
  hydrodynamical simulations
  + assumptions on thermodynamics
  of IGM



- Linear power spectrum P(k)

Example of power spectrum analysis (McDonald etal 2004)

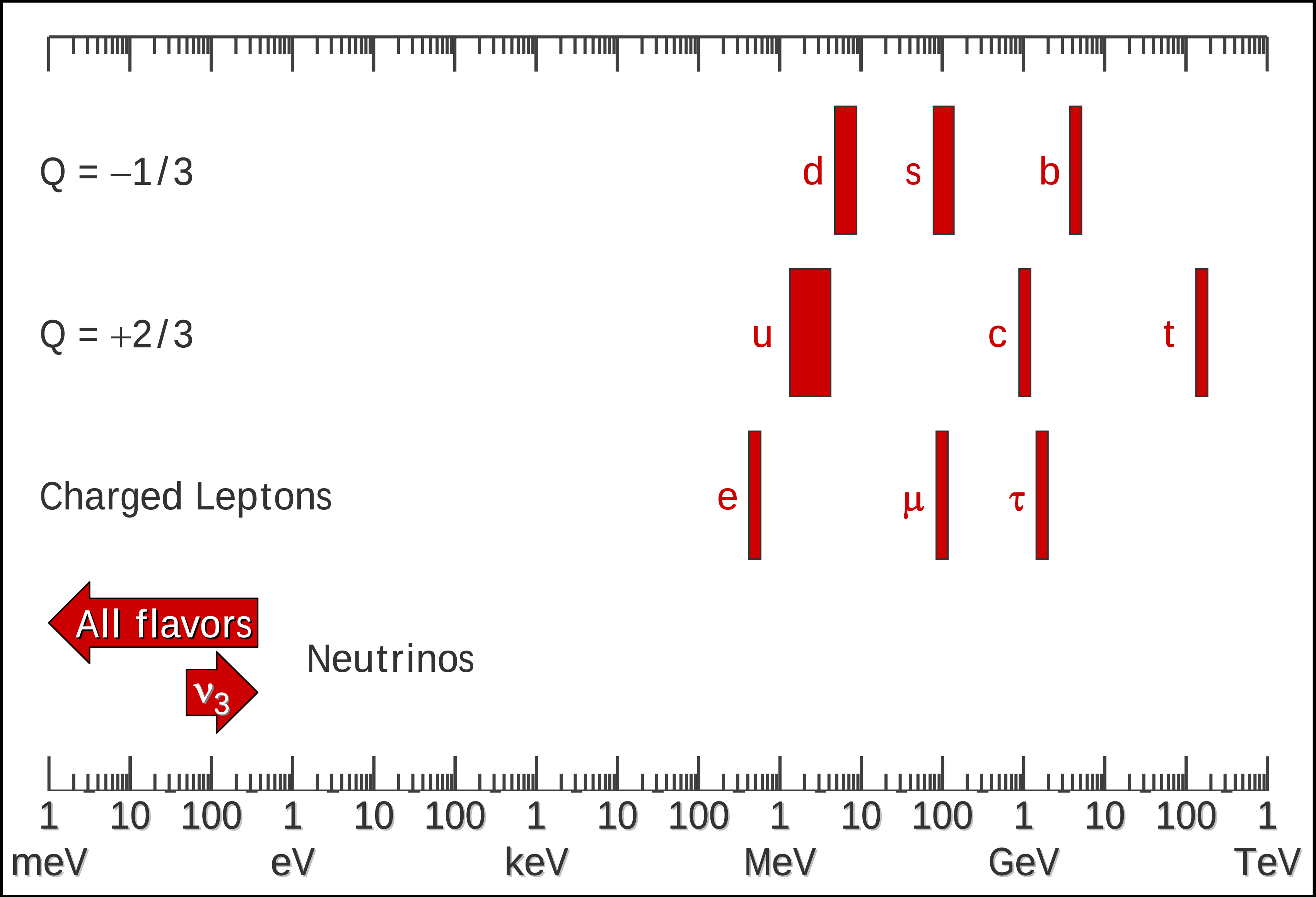




FROM MAX TEGMARK

NEUTRINO PHYSICS

Fermion Mass Spectrum



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)

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

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

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

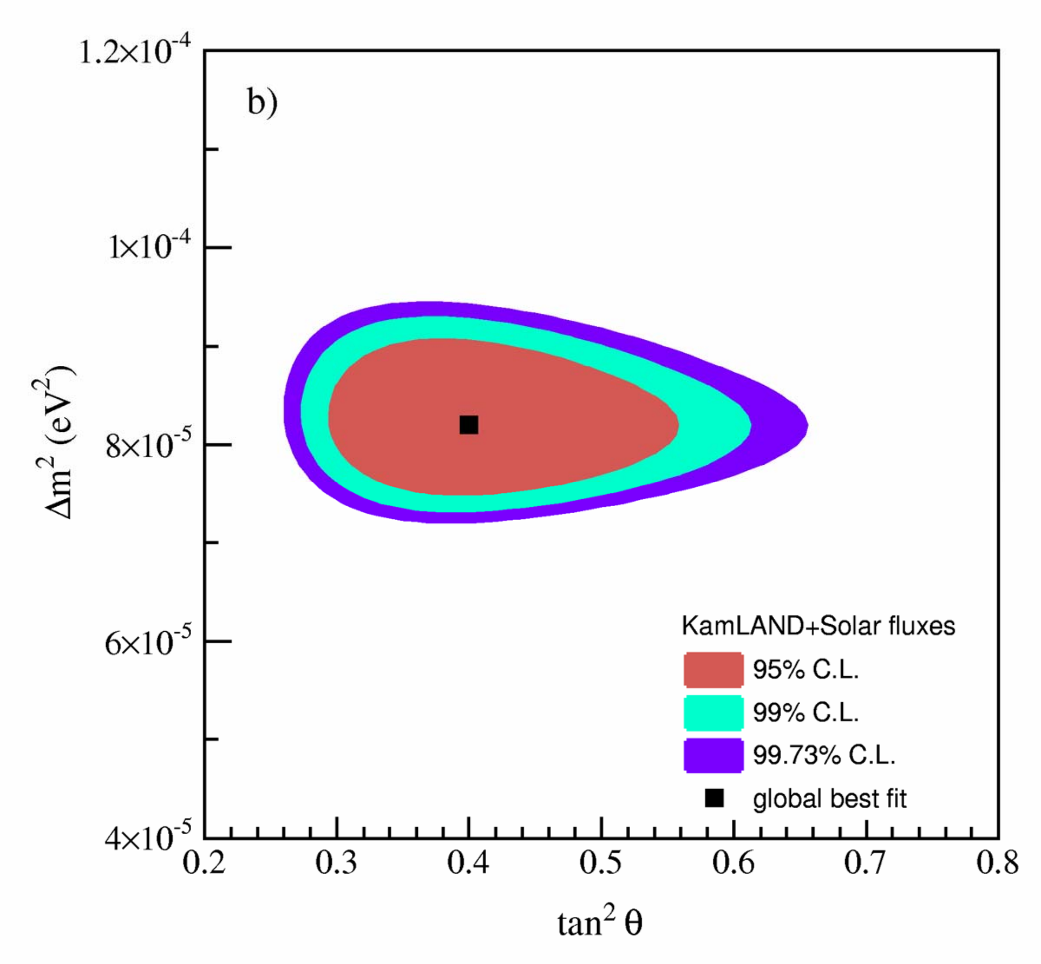
θ_{12} is the ``solar'' mixing angle

θ_{23} is the ``atmospheric'' mixing angle

θ_{13} is the "reactor" mixing angle

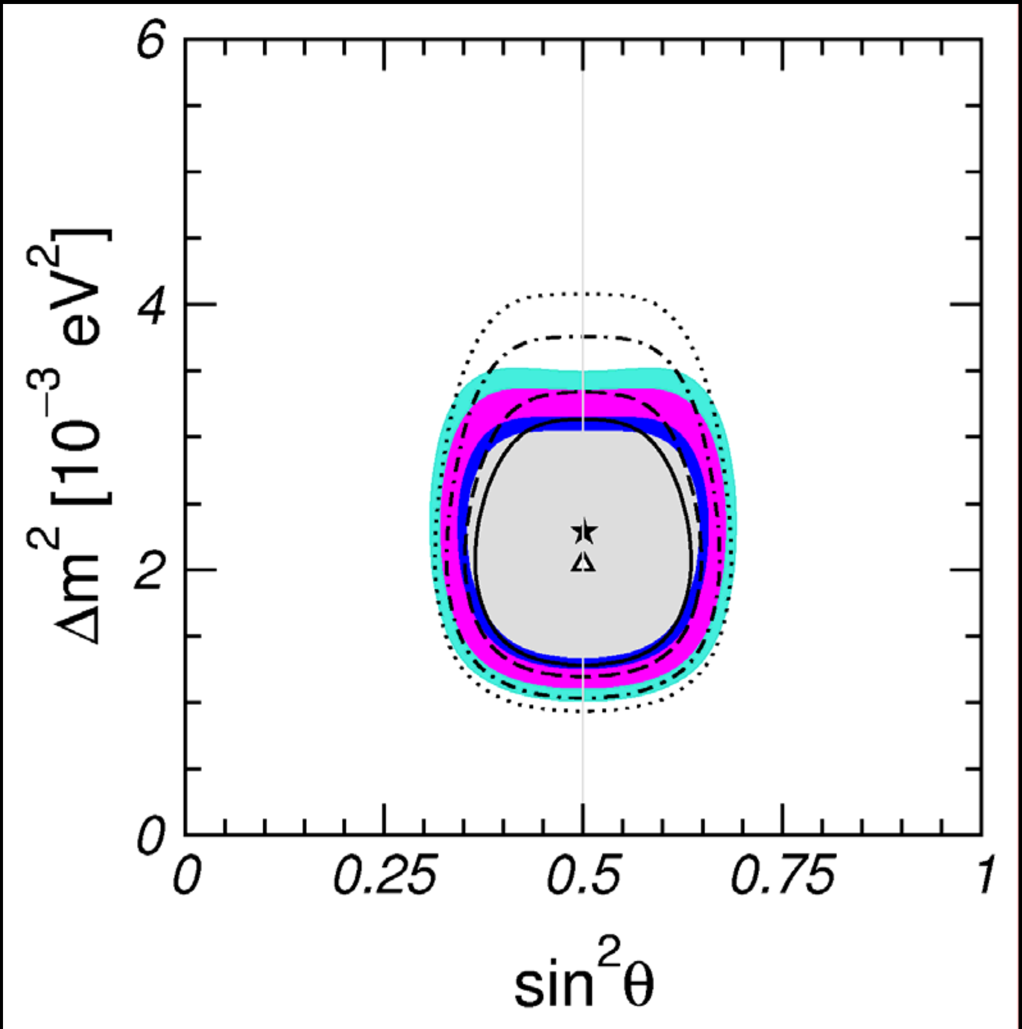
δ is the Dirac CP violating phase

STATUS OF 1-2 MIXING (SOLAR + KAMLAND)



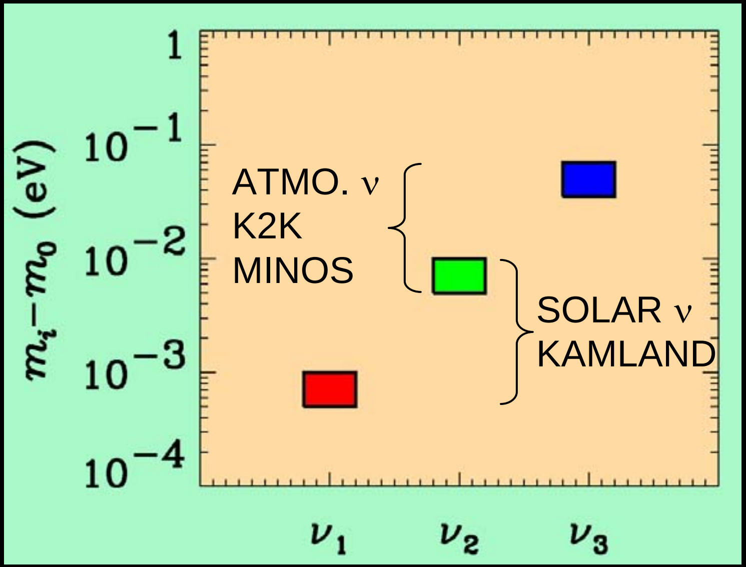
Araki et al. hep-ex/0406035

STATUS OF 2-3 MIXING (ATMOSPHERIC + K2K + MINOS)

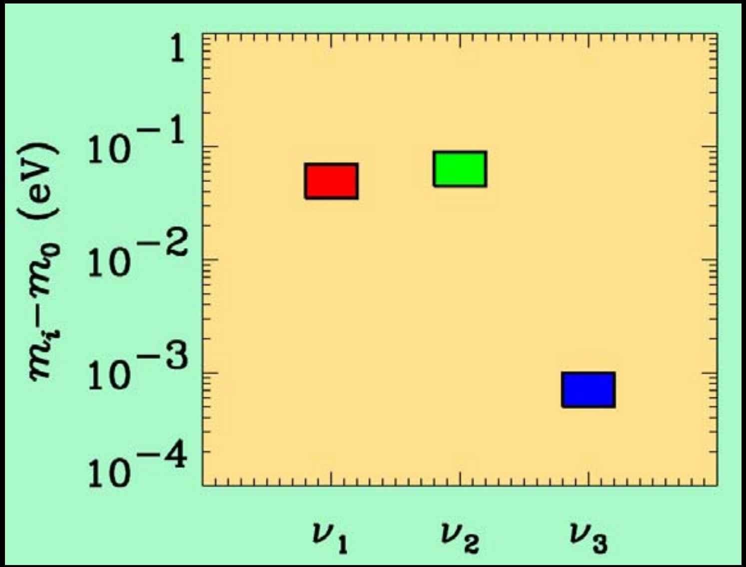


Maltoni et al. hep-ph/0405172

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



Normal hierarchy



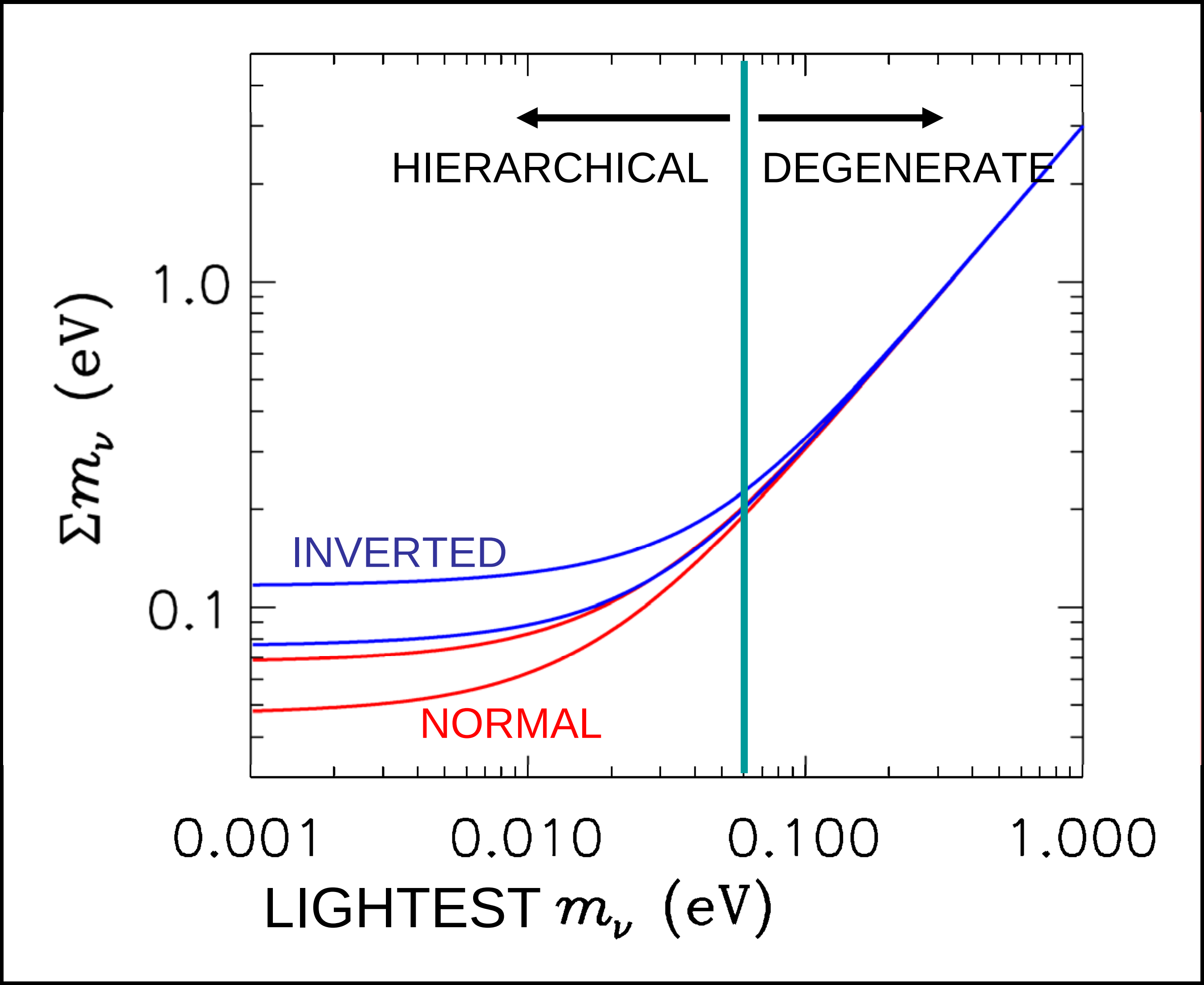
Inverted hierarchy

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
1.0
0.1
INVERTED
NORMAL
0.001
0.010
0.100
1.000
LIGHTEST m_ν (eV)
Σm_ν (eV)

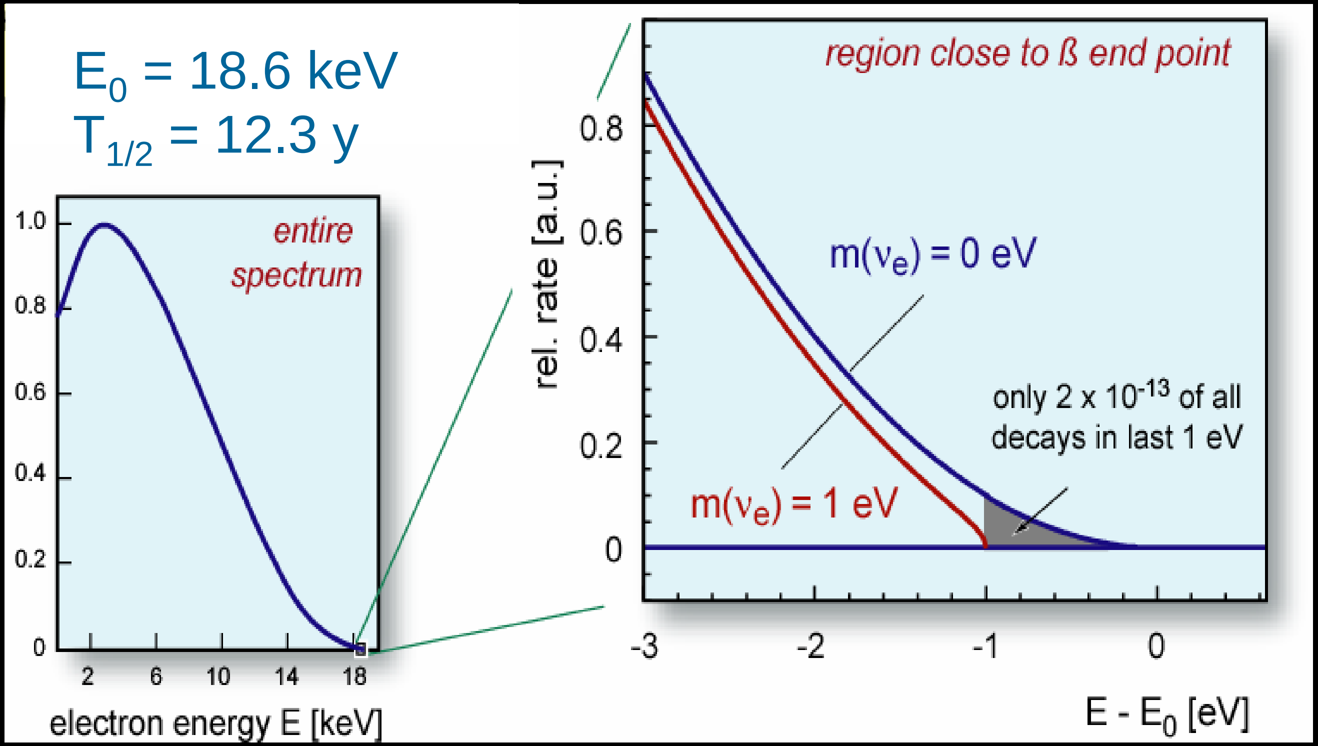
ß-decay and neutrino mass

model independent neutrino mass from ß-decay kinematics

only assumption: relativistic energy-momentum relation

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

experimental observable is m_ν^2



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

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

Mainz experiment, final analysis (Kraus et al.)

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

$$\sum m_i \leq 7\ \text{eV}$$

THE ABSOLUTE VALUES OF NEUTRINO MASSES FROM COSMOLOGY

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

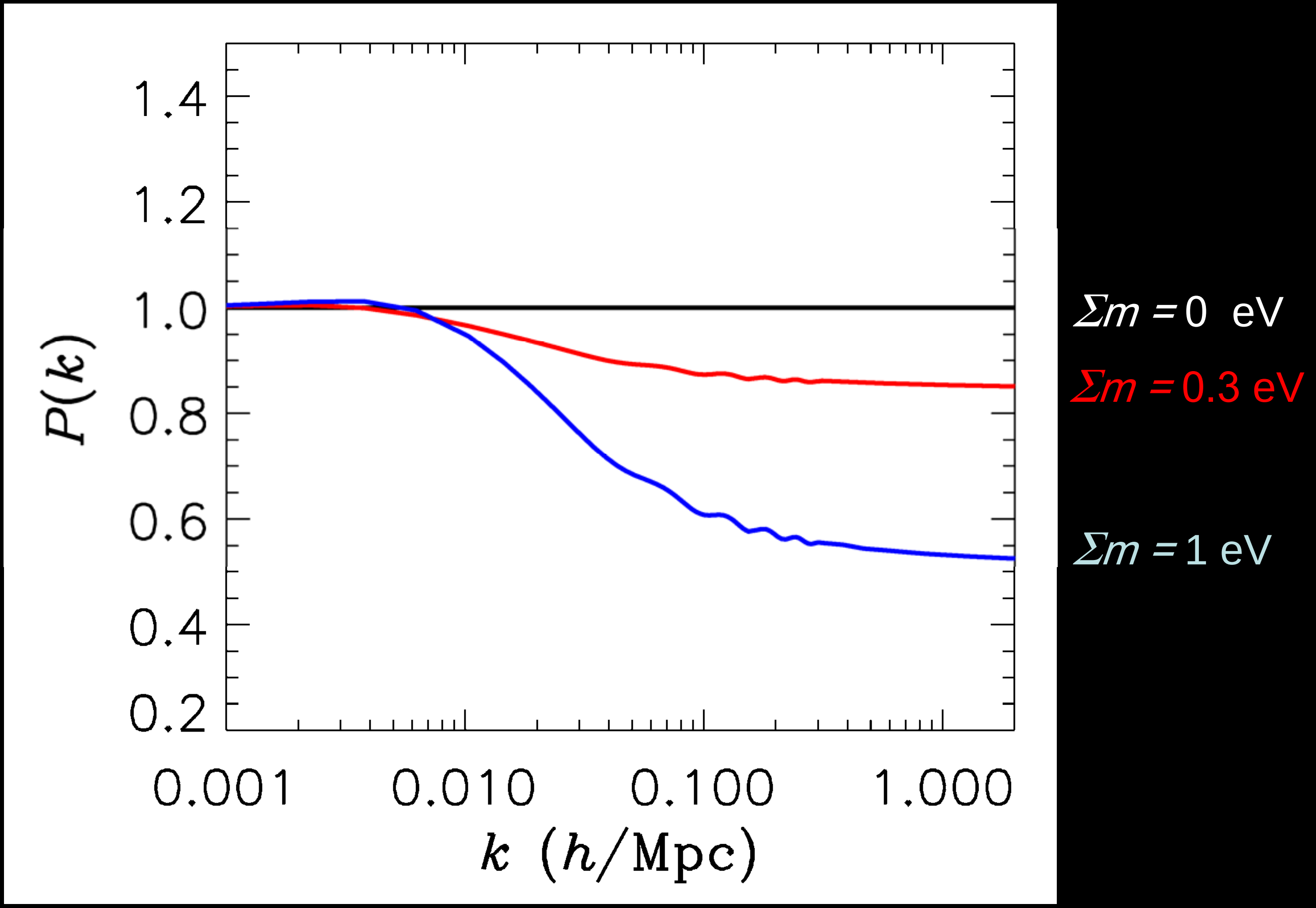
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93\,\mathrm{eV}} \qquad \text{FROM} \qquad T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \approx 2\,\mathrm{K}$$

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

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

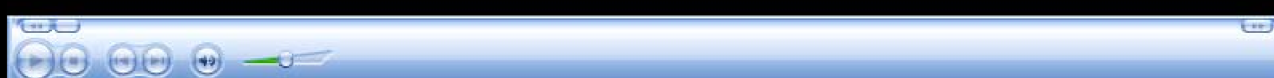
SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO SUPPRESSION OF POWER ON SMALL SCALES

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



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

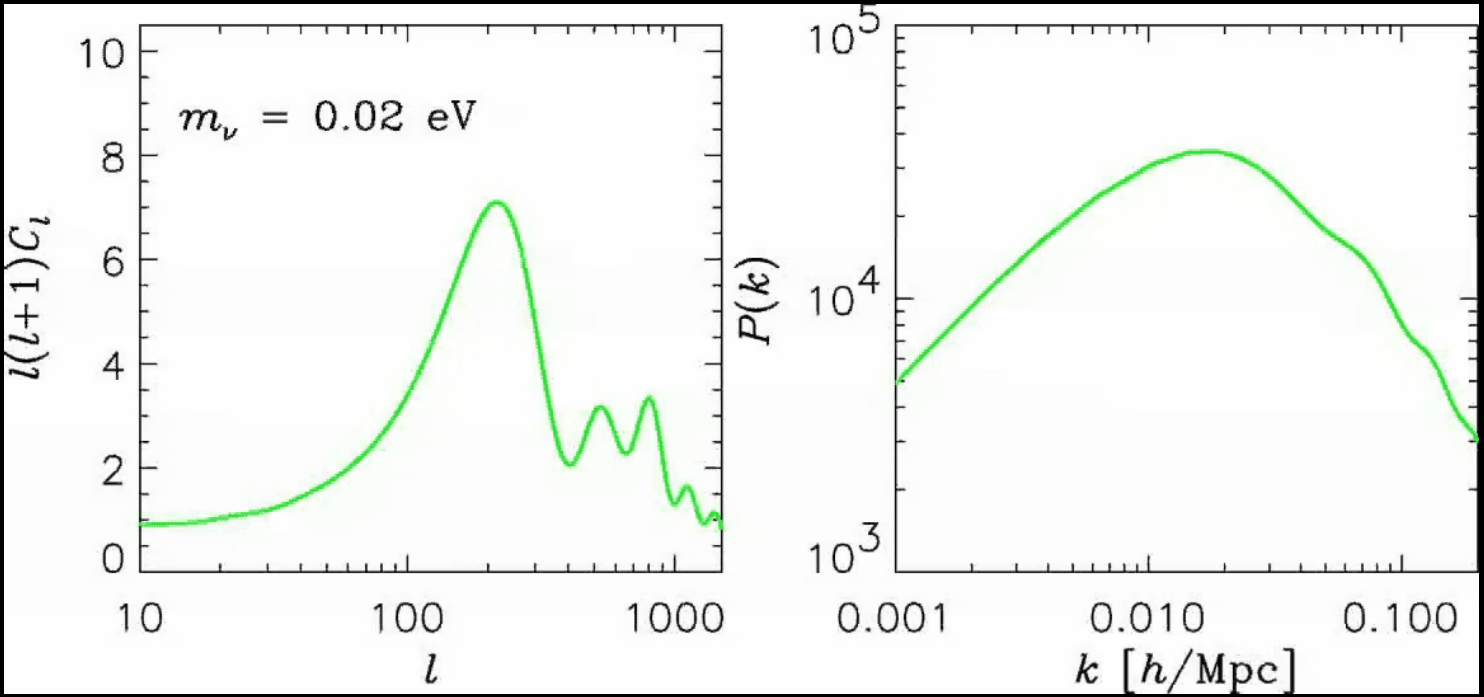
256 Mpc



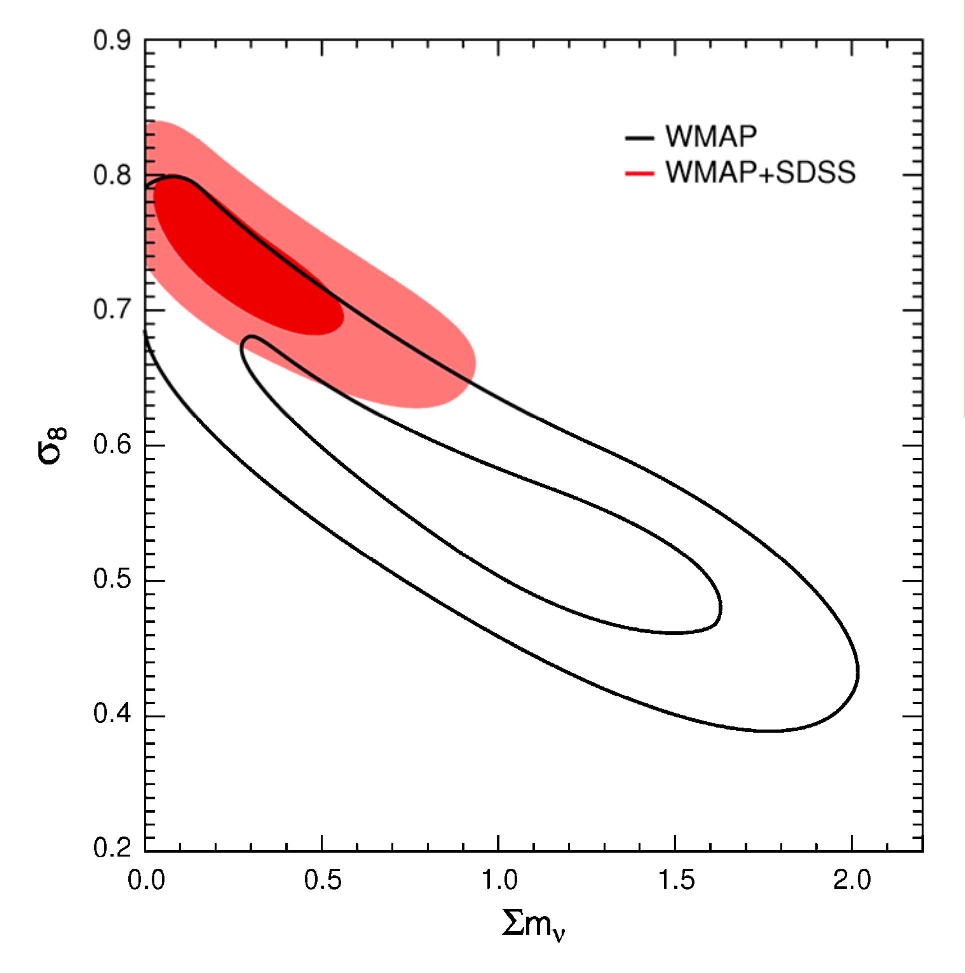
$$\sum m_\nu = 0 \qquad \sum m_\nu = 6.9\,\mathrm{eV}$$

T Haugboelle, University of Aarhus

WHILE NEUTRINO MASSES HAVE A PRONOUNCED INFLUENCE ON THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING SCALE THERE IS ONLY A VERY LIMITED EFFECT ON THE CMB



WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?



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

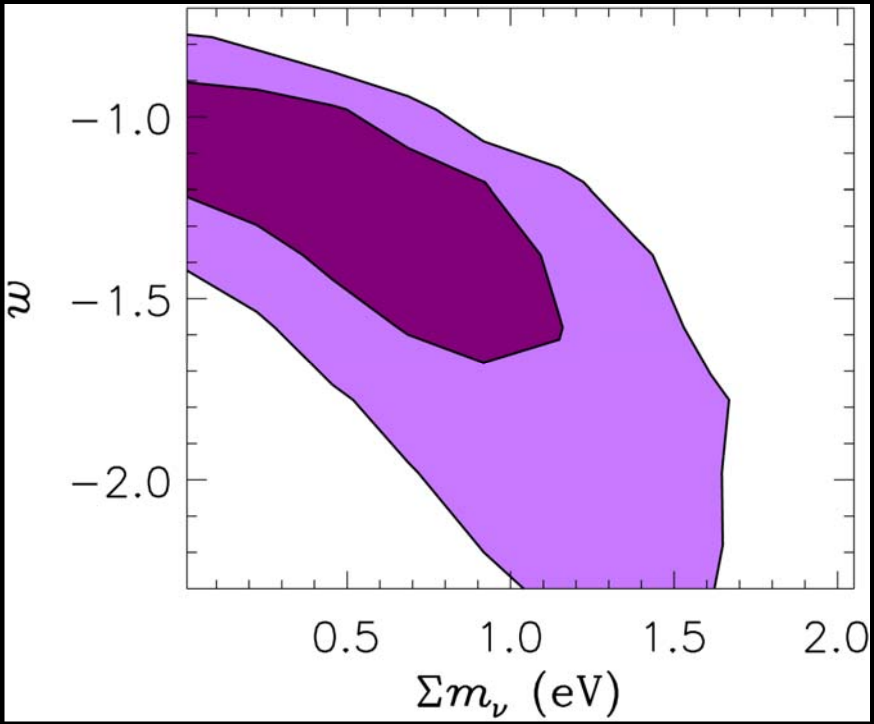
WMAP-3 ONLY ~ 2.0 eV
WMAP + LSS 0.68 eV

COMPARE WITH WMAP-I:

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

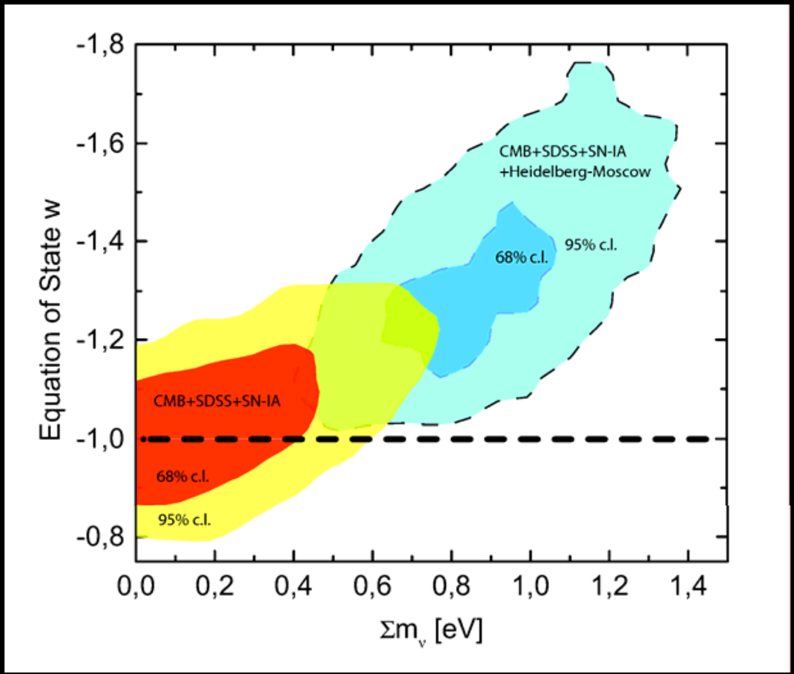
HOW CAN THE BOUND BE AVOIDED?

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 Ω_m – *w* DEGENERACY

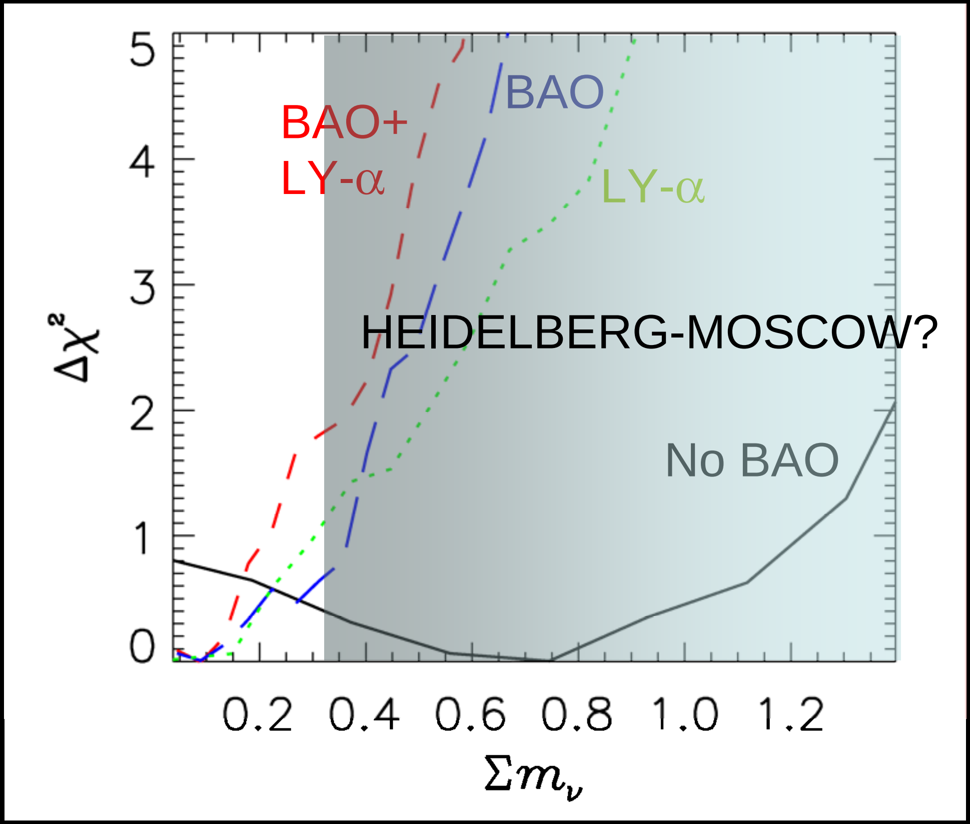
THE BARYON ACOUSTIC PEAK

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

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

12 FREE PARAMETERS

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

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

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.

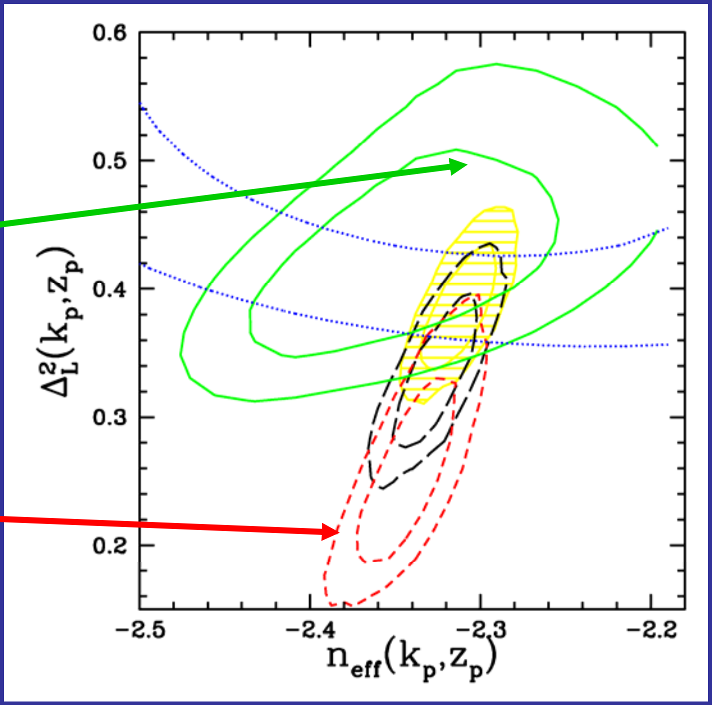
NOTE, HOWEVER, THAT THIS DATA IS (EVEN MORE) INCOMPATIBLE WITH THE WMAP NORMALIZATION.

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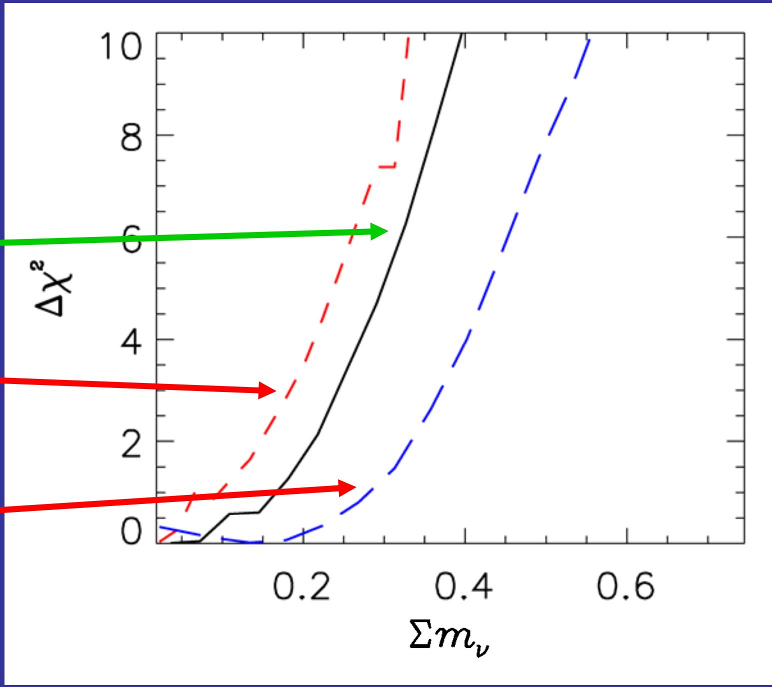
GOOBAR, HANNESTAD, MORTSELL, TU (ASTRO-PH/0602155)

OLD SDSS LYMAN-ALPHA

NEW SDSS LYMAN-ALPHA

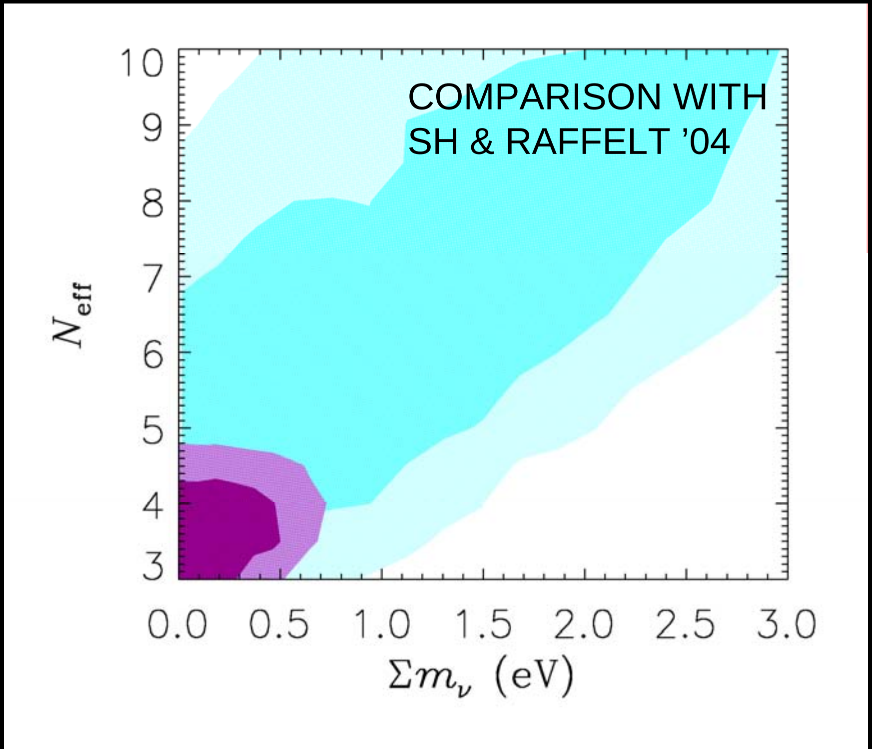
VIEL ET AL. LYMAN-ALPHA

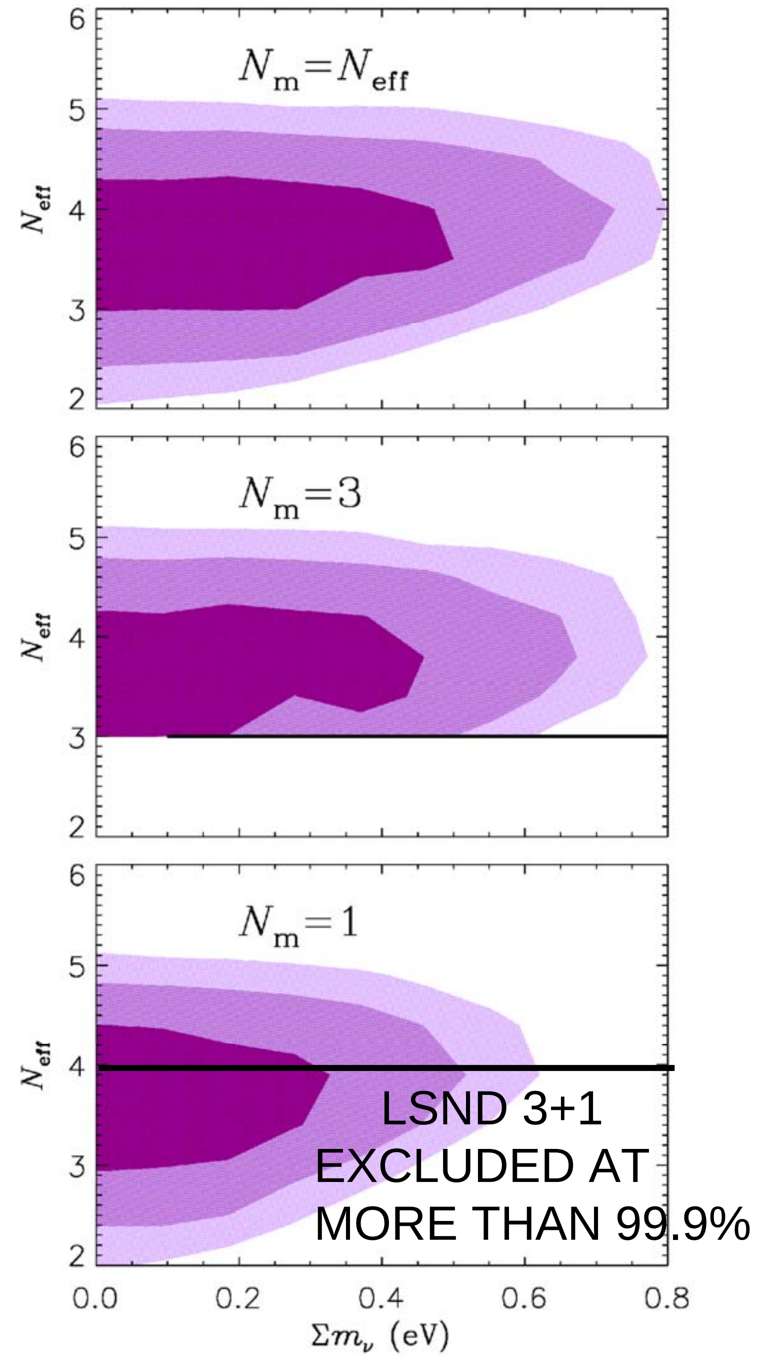


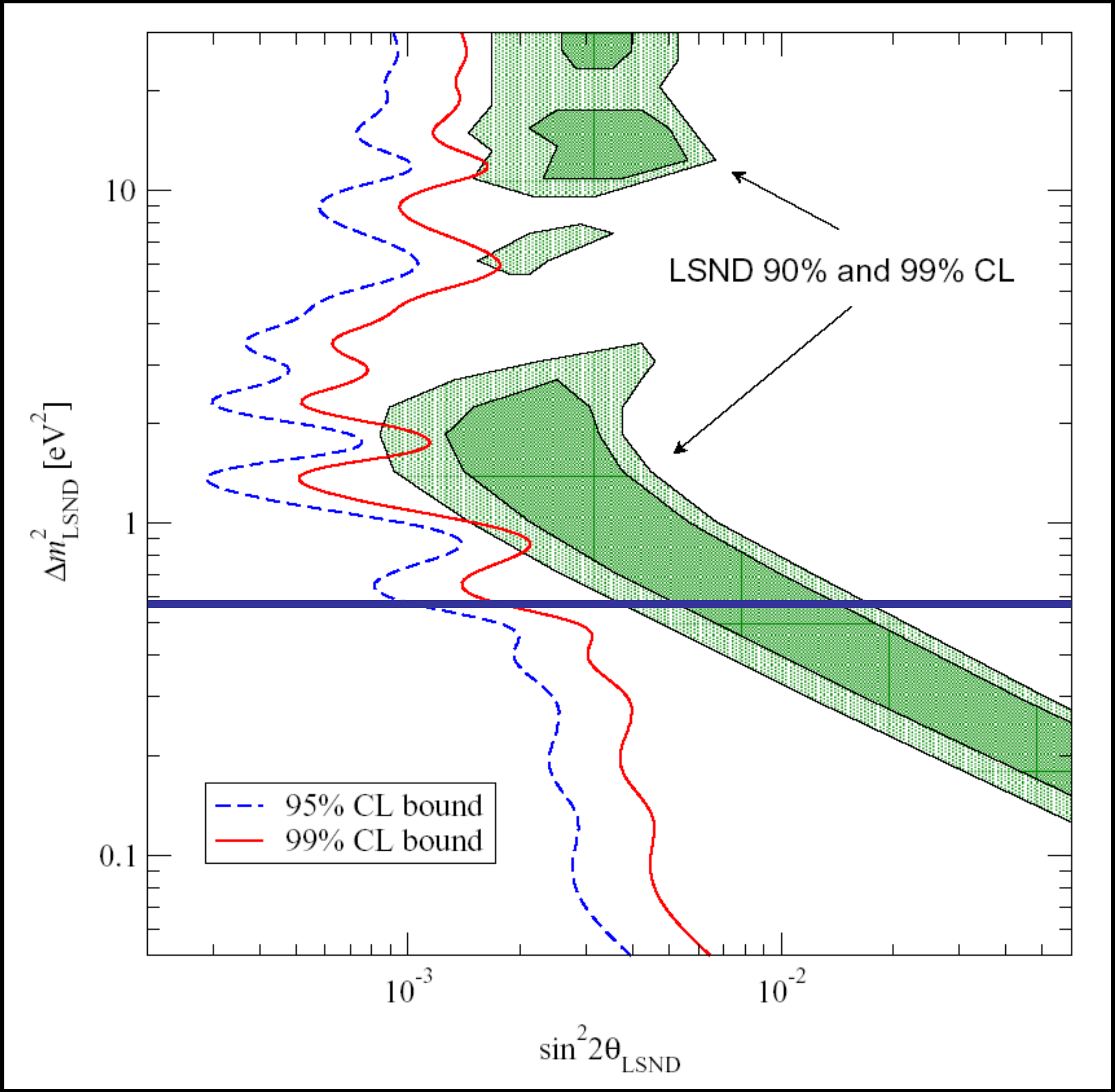
ADDITIONAL LIGHT DEGREES OF FREEDOM (STERILE NEUTRINOS, eV AXIONS, ETC)

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

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



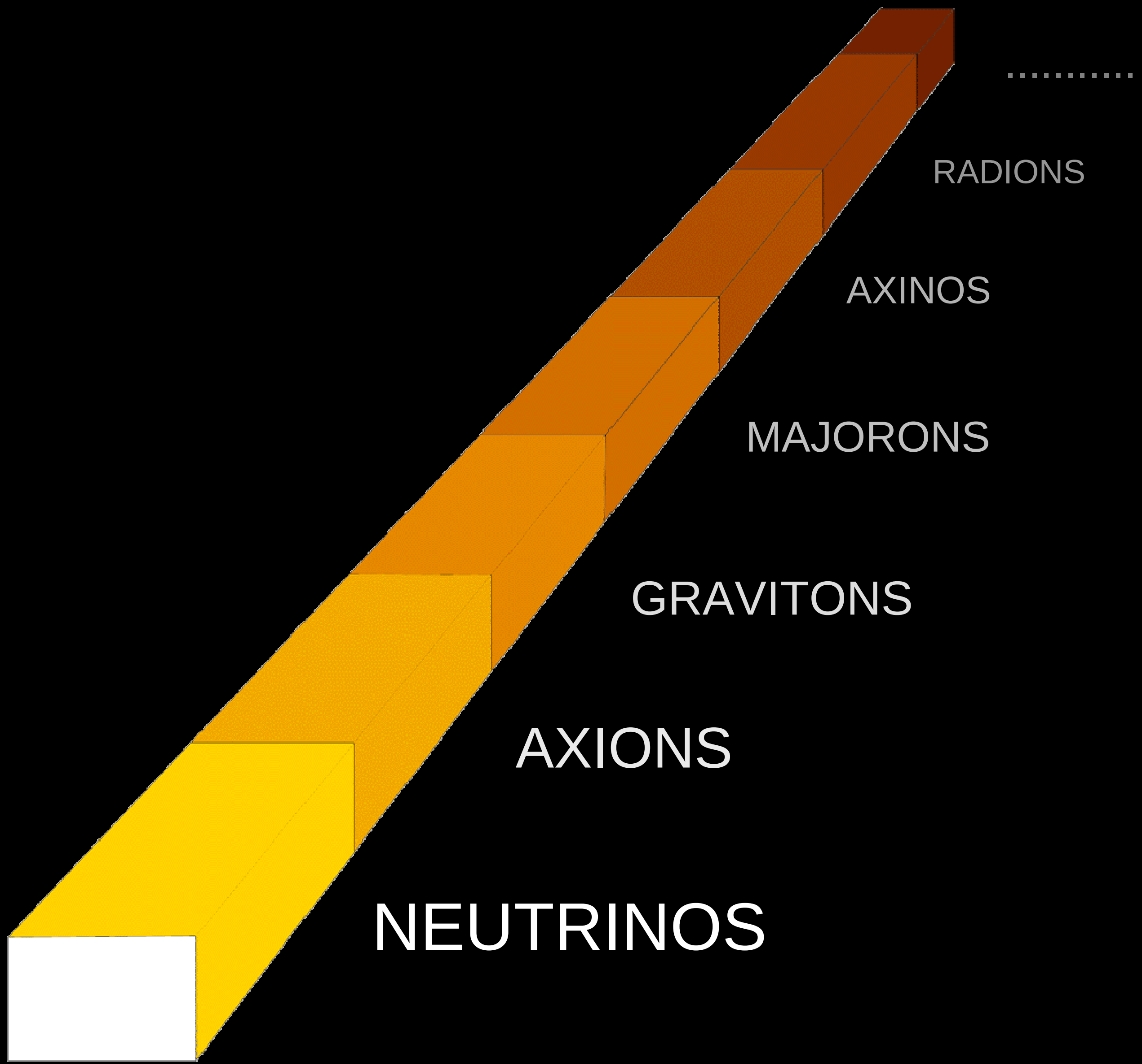




WMAP-3 + LSS + BAO
99% C.L.

VALLE ET AL.

WHAT ABOUT OTHER LIGHT, THERMALLY PRODUCED PARTICLES?



FOR ANY THERMALLY PRODUCED PARTICLE IT IS STRAIGHTFORWARD TO CALCULATE THE DECOUPLING EPOCH ETC.
FOR RELATIVISTICALLY DECOUPLED SPECIES THE ONLY IMPORTANT PARAMETERS ARE

m_X AND $g_{*,X}$

WHERE g_* IS THE EFECTIVE NUMBER OF DEGREES OF FREEDOM WHEN X DECOUPLES.

CONTRIBUTION TO DENSITY

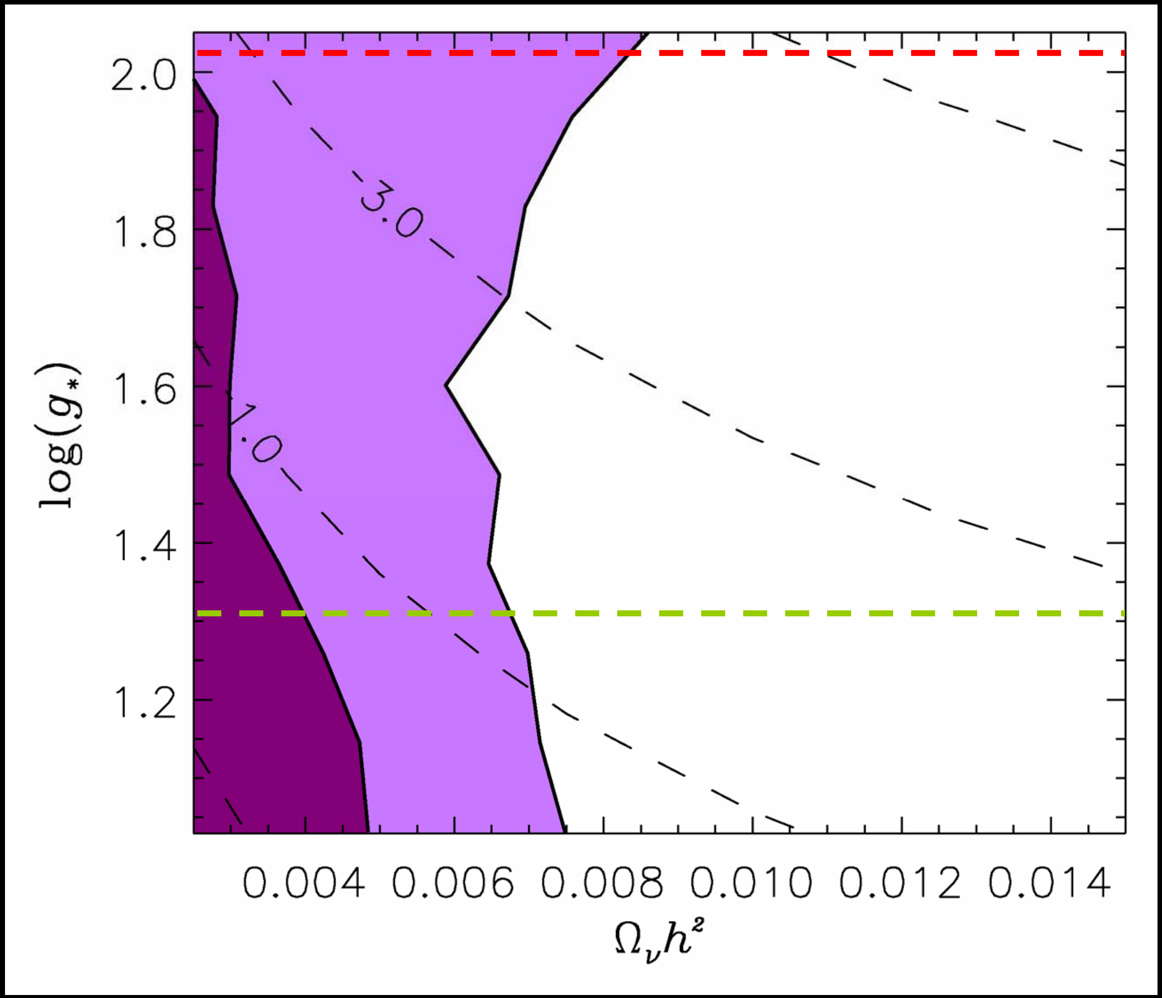
$$\Omega_X h^2 = \frac{m_X g_X}{183\,\mathrm{eV}} \frac{10.75}{g_{*X}} \times \begin{cases} 1 & \text{for fermions} \\ 4/3 & \text{for bosons} \end{cases}$$

FREE-STREAMING LENGTH

$$\lambda_{\mathrm{FS}} \sim \frac{20\,\mathrm{Mpc}}{\Omega_X h^2} \left(\frac{T_X}{T_\nu} \right)^4 \left[1 + \log\left(3.9 \frac{\Omega_X}{\Omega_m} \frac{T_\nu^2}{T_X^2} \right) \right]$$

Density bound for a Majorana fermion

Based on WMAP, SDSS, SNI-a and Lyman-α data,
No assumptions about bias!



EW transition (~ 100 GeV)
g_* = 106.75

MASS BOUND FOR SPECIES DECOUPLING AROUND EW TRANSITION

$$m \leq 5\,\text{eV}$$

Below QCD transition (~ 100 MeV) $g_* < 20$

DECOUPLING AFTER QCD PHASE TRANSITION LEADS TO

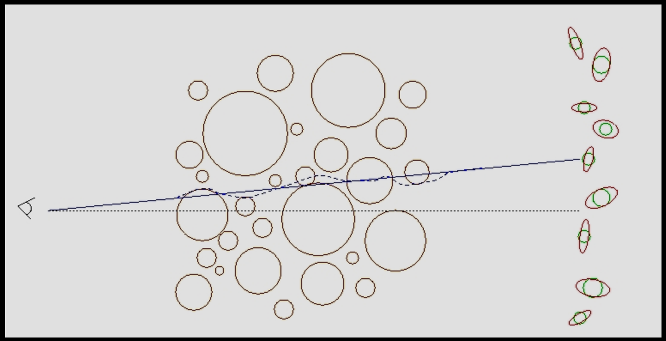
$$m \leq 1\,\text{eV}$$

STH, hep-ph/0409108 (See also STH & G Raffelt, JCAP 0404, 008)
Similar bound can be obtained for pseudoscalars (such a axions) – STH, Mirizzi & Raffelt 2005

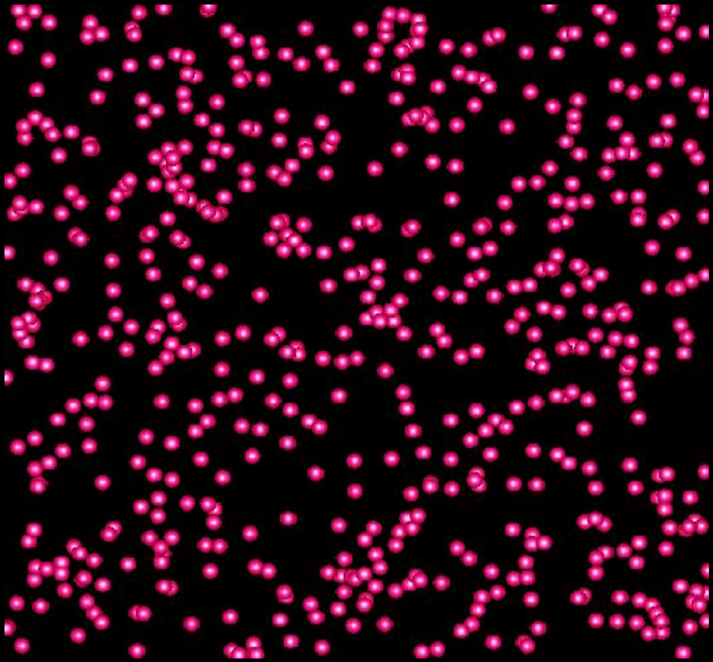
WHAT IS IN STORE FOR THE FUTURE?

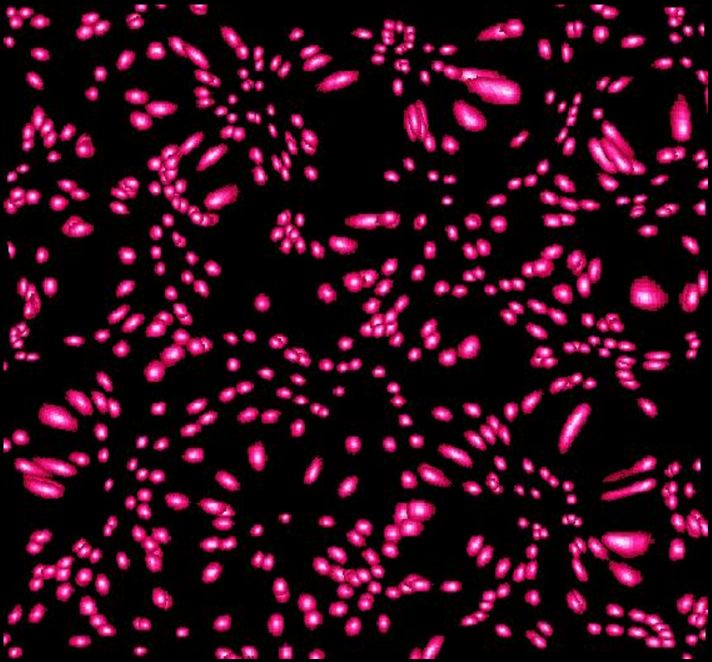
- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS (PLANCK)
- LARGE SCALE STRUCTURE SURVEYS AT HIGH REDSHIFT
- NEW SUPERNOVA SURVEYS
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES

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

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

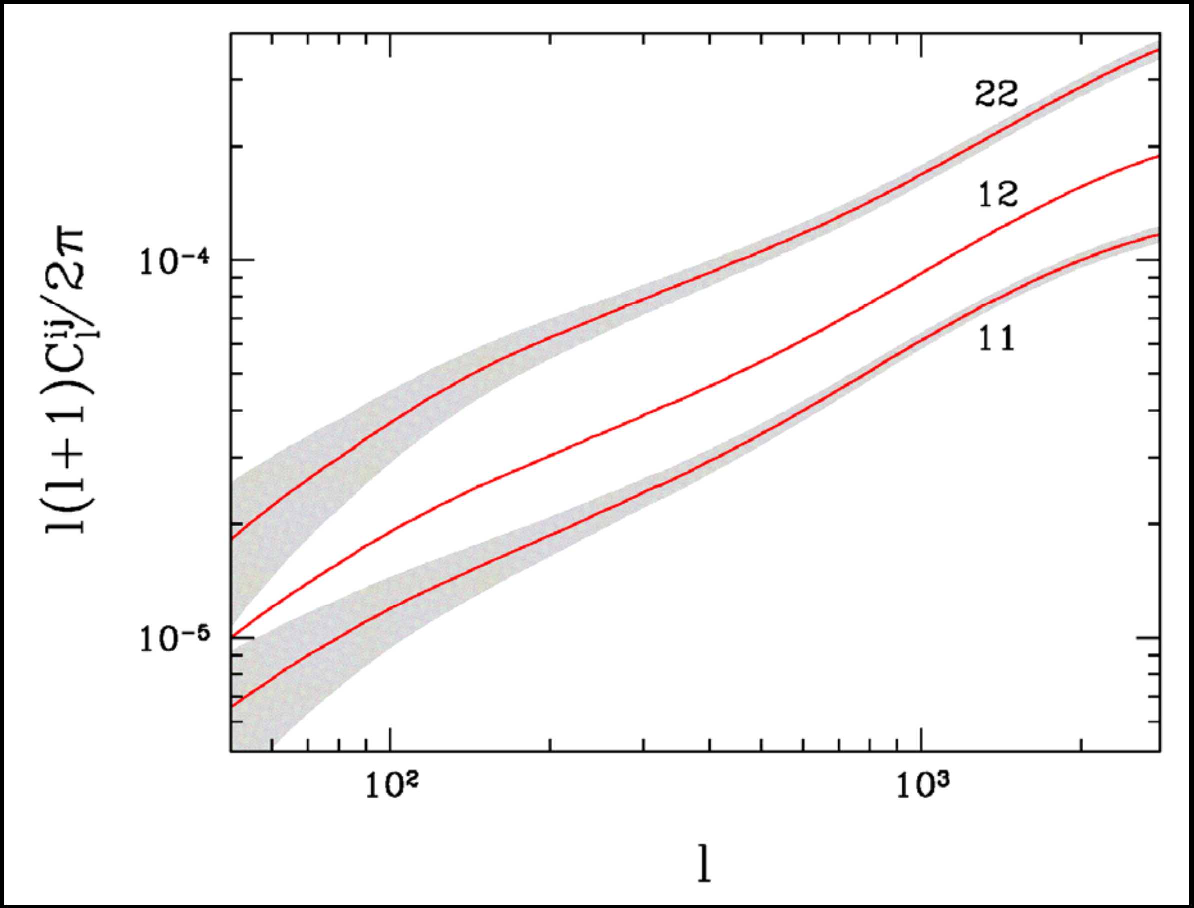
$P(\ell / r, \chi)$ MATTER POWER SPECTRUM (NON-LINEAR)

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

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

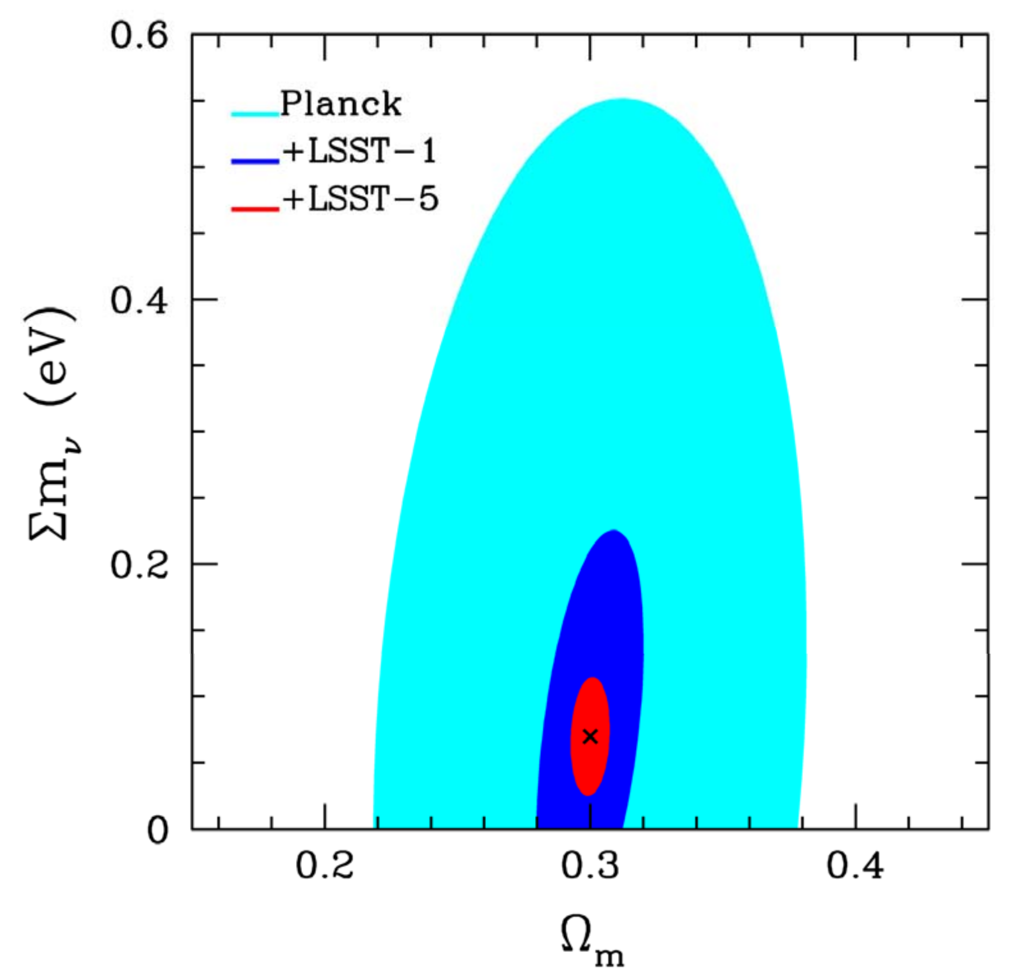


HIGH REDSHIFT

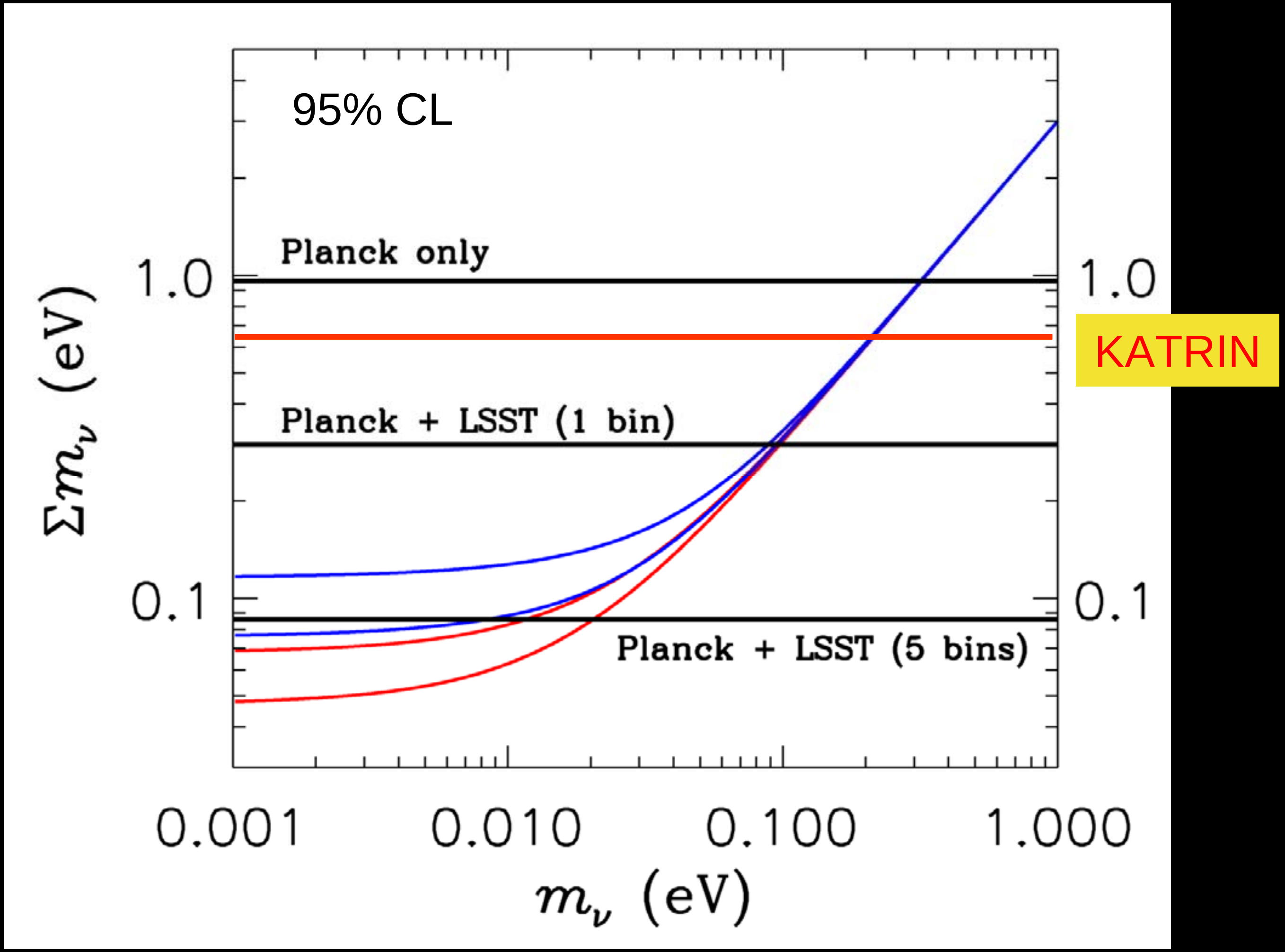
LOW REDSHIFT

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)



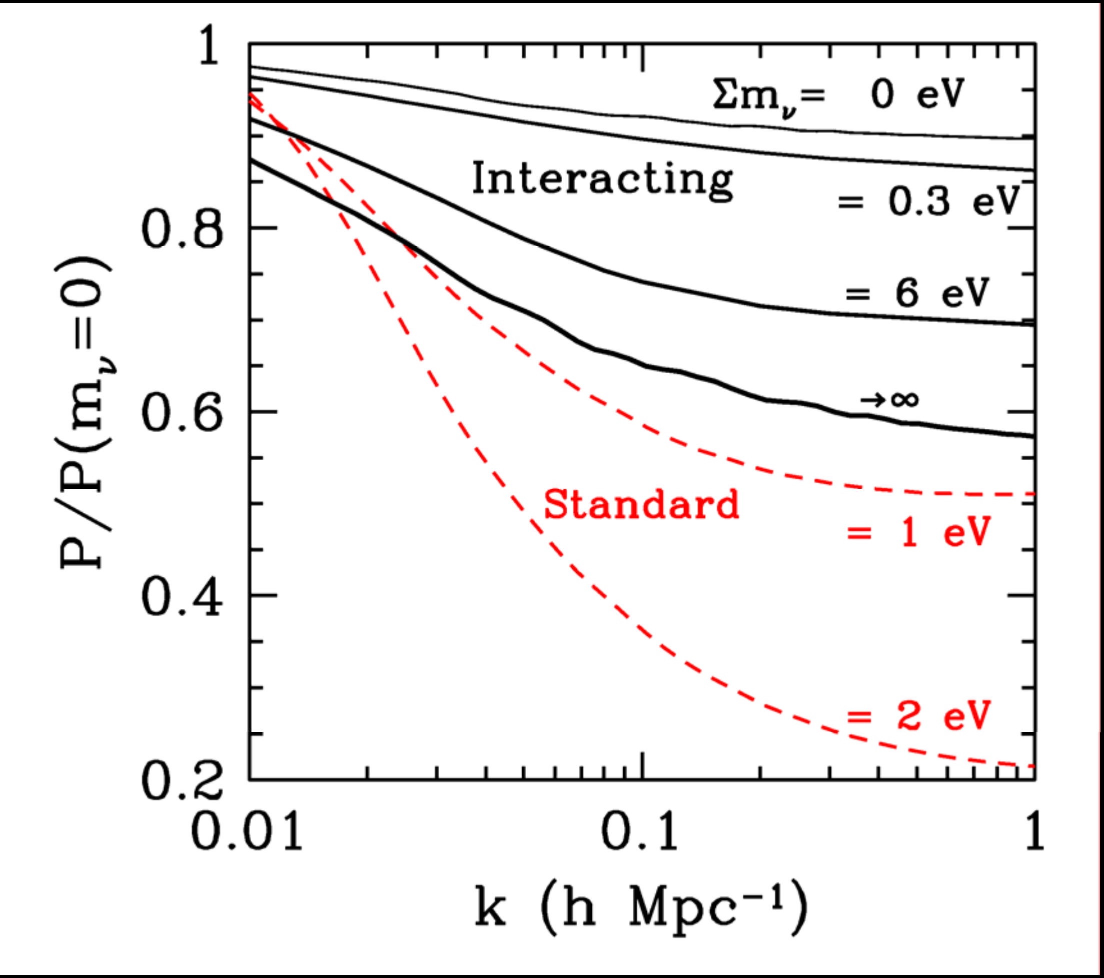
STH, TU & WONG 2006 (ASTRO-PH/0603019, JCAP)

COULD NEUTRINOS BE STRONGLY INTERACTING?

BEACOM, BELL & DODELSON (2004) SUGGESTED A WAY TO EVADE THE COSMOLOGICAL NEUTRINO MASS BOUND:

IF NEUTRINOS COUPLE STRONGLY ENOUGH WITH A MASSLESS SCALAR OR PSEUDO-SCALAR THEY CAN BE VERY MASSIVE, BUT HAVE NO EFFECT ON THE MATTER POWER SPECTRUM, EXCEPT FOR A SLIGHT SUPPRESSION DUE TO MORE RELATIVISTIC ENERGY DENSITY

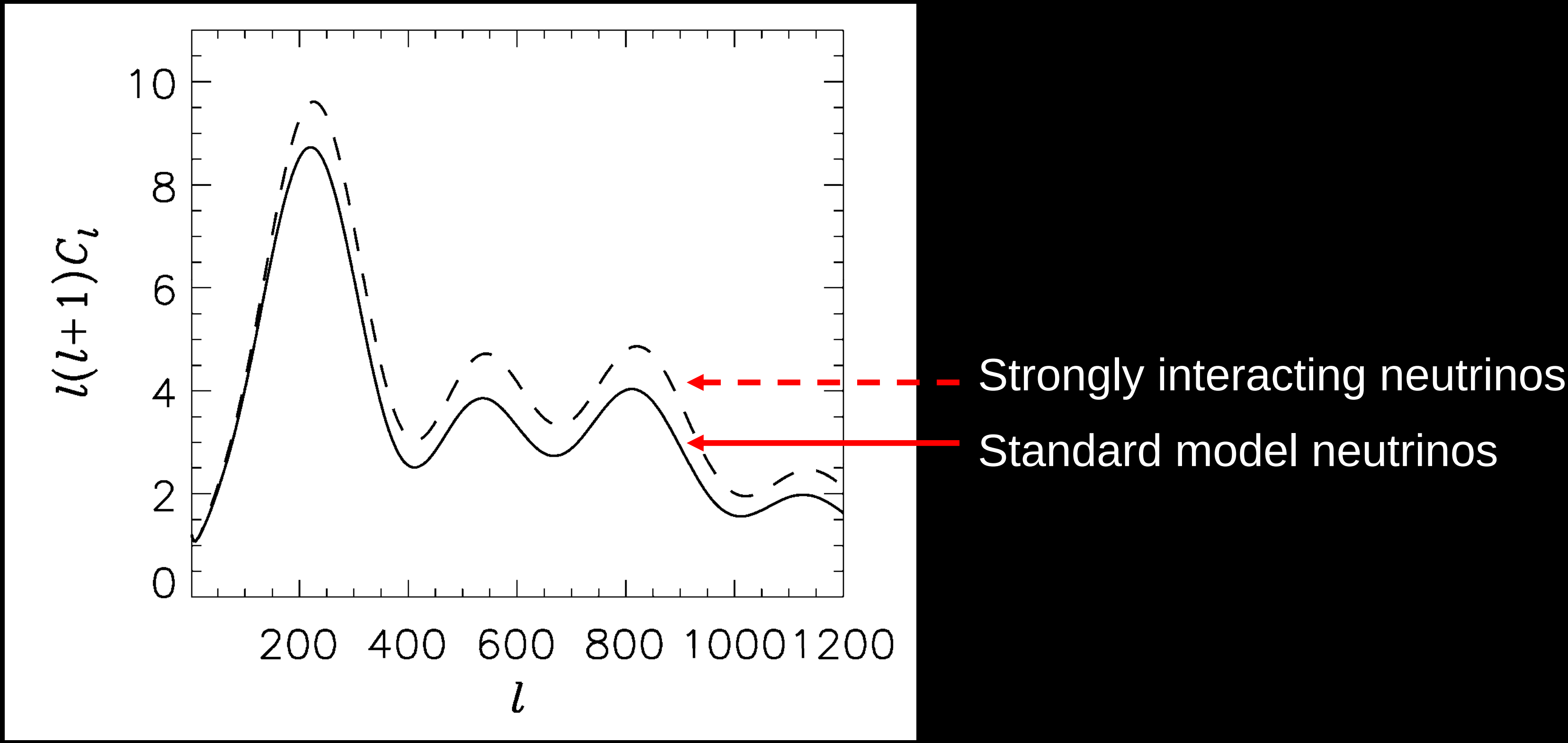
WHY? BECAUSE NEUTRINOS WOULD ANNIHILATE AND DISAPPEAR AS SOON AS THEY BECOME NON-RELATIVISTIC



BEACOM, BELL & DODELSON 2004

HOWEVER, NEUTRINOS WHICH ARE STRONGLY INTERACTING DURING RECOMBINATION ARE NOT AFFECTED BY SHEAR (EFFECTIVELY THEY BEHAVE LIKE A FLUID).
THIS HAS IMPLICATIONS FOR CMB BECAUSE THE NEUTRINO POTENTIAL FLUCTUATIONS SOURCING THE CMB FLUCTUATIONS DO NOT DECAY

THIS INCREASES THE CMB AMPLITUDE ON ALL SCALES SMALLER THAN THE HORIZON AT RECOMBINATION



Sth, astro-ph/0411475 (JCAP)

SUCH STRONGLY INTERACTING NEUTRINOS ARE HIGHLY DISFAVOURED BY DATA
(STH 04, BELL, PIERPAOLI & SIGURDSON 05
CIRELLI & STRUMIA 06)
ALTHOUGH THE EXACT VALUE OF THE DISCREPANCY IS NOT FULLY SETTLED (but at least by $\Delta\chi^2 > 20$ even with more d.o.f.)

THIS CAN BE USED TO PUT THE STRONGEST KNOWN CONSTRAINTS ON NEUTRINO COUPLINGS TO MASSLESS SCALARS OR PSEUDOSCALARS (STH & RAFFELT HEP-PH/0509278 (PRD))

WE FIND

Diagonal elements $g_{ii} < 1 \times 10^{-7}$

Off-diagonal elements $g_{ij} < 1 \times 10^{-11} (0.05\,\mathrm{eV}/m)^2$

FOR DERIVATIVE COUPLINGS THE BOUND WOULD BECOME EVEN STRONGER

THE BOUND ON g CAN BE TRANSLATED INTO A BOUND ON THE NEUTRINO LIFETIME

$$\tau > 2 \times 10^{10}\ \mathrm{s}\,(m / 0.05\,\mathrm{eV})^3$$

THIS BOUND FOR INSTANCE EXCLUDES THAT THERE SHOULD BE SIGNIFICANT NEUTRINO DECAY IN BEAMS FROM HIGH-ENERGY ASTROPHYSICAL SOURCES (STH & RAFFELT 2005)

CONCLUSIONS

- NEUTRINO PHYSICS IS PERHAPS THE PRIME EXAMPLE OF HOW TO USE COSMOLOGY TO DO PARTICLE PHYSICS
- THE BOUND ON NEUTRINO MASSES IS ALREADY AN ORDER OF MAGNITUDE STRONGER THAN THAT FROM DIRECT EXPERIMENTS, ALBEIT MORE MODEL DEPENDENT
- WITHIN THE NEXT 5-10 YEARS THE MASS BOUND WILL REACH THE LEVEL NEEDED TO DETECT HIERARCHICAL NEUTRINO MASSES
- THE FACT THAT CMB DOES NOT ALLOW STRONGLY INTERACTING NEUTRINOS SETS VERY INTERESTING CONSTRAINTS ON NEUTRINO PROPERTIES