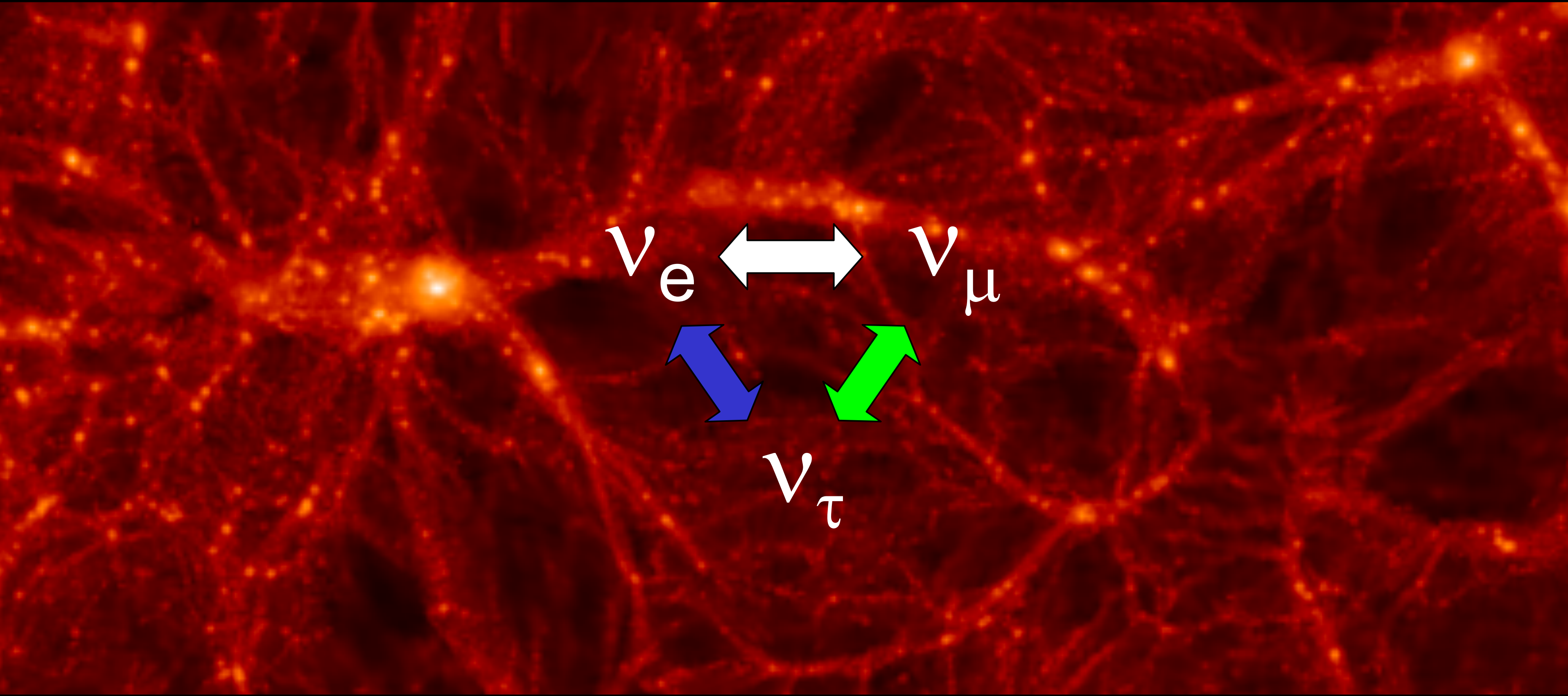
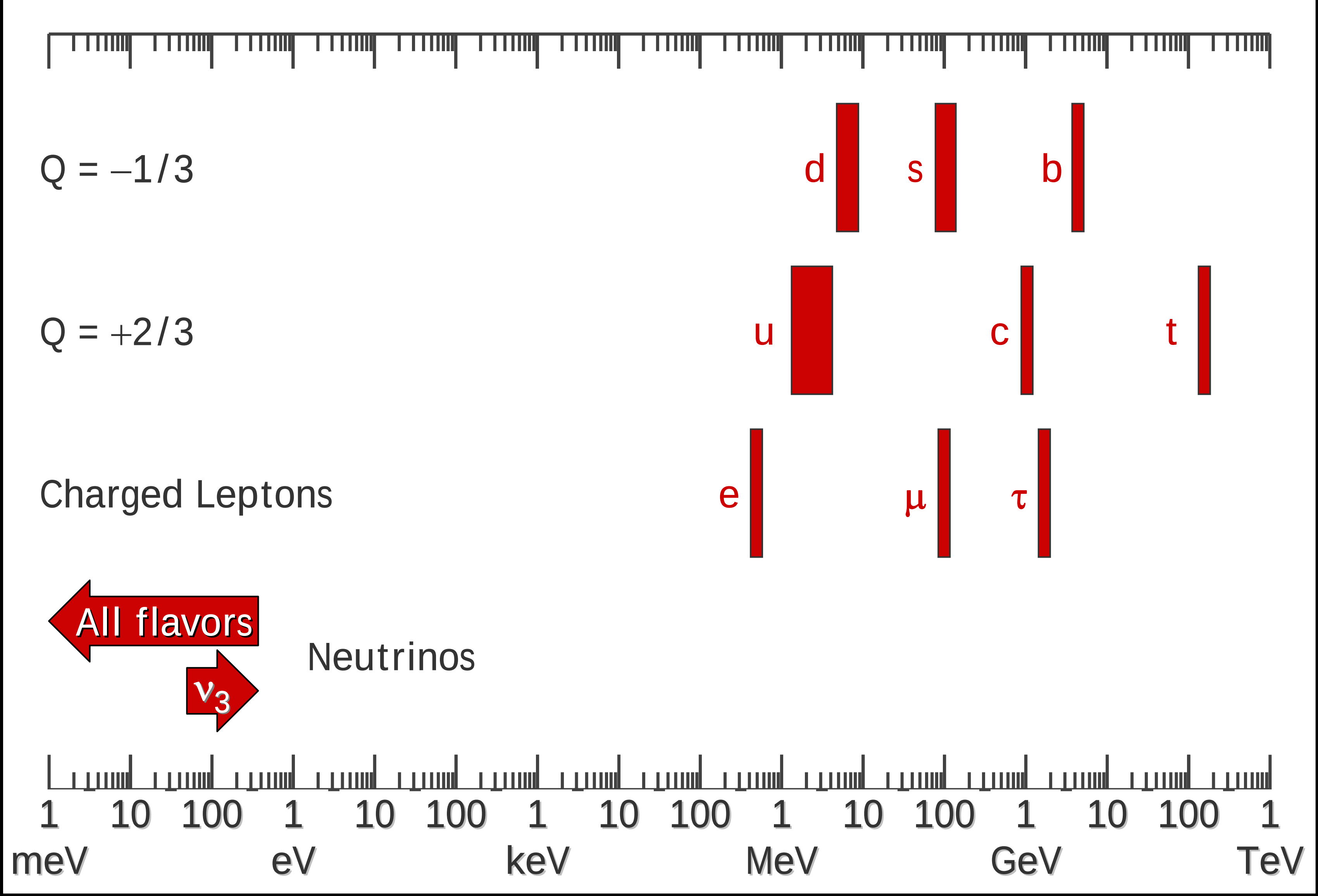
NEUTRINO PHYSICS FROM COSMOLOGY
EVIDENCE FOR NEW PHYSICS?



STEEN HANNESTAD
DESY 23-24 NOVEMBER 2010

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)

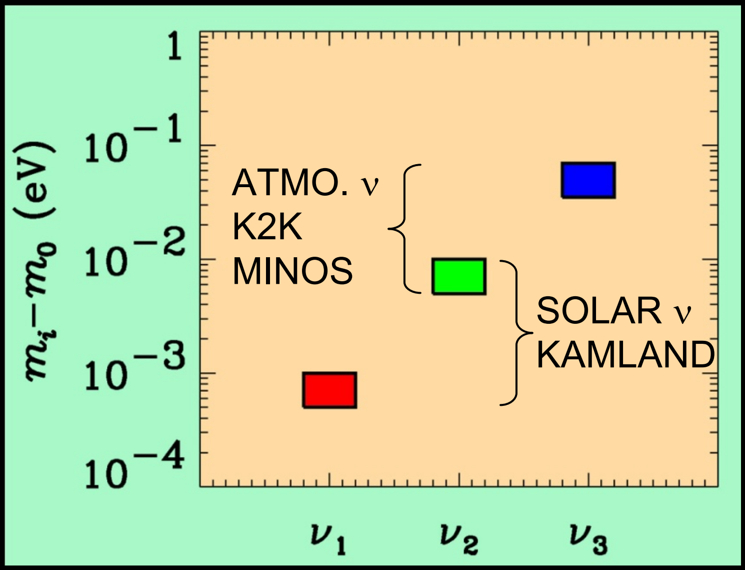
$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

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

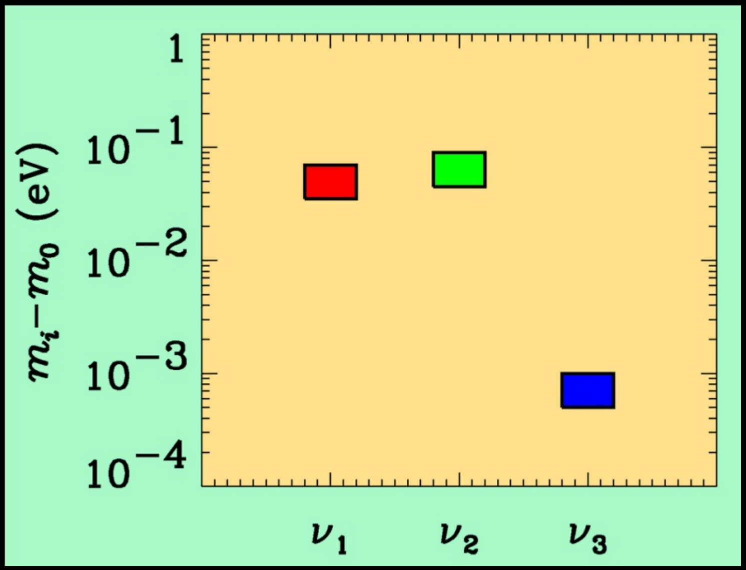
$$s_{12} = \sin\theta_{12}$$

FORTUNATELY WE ONLY HAVE TO CARE ABOUT THE MASS STATES

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



Normal hierarchy



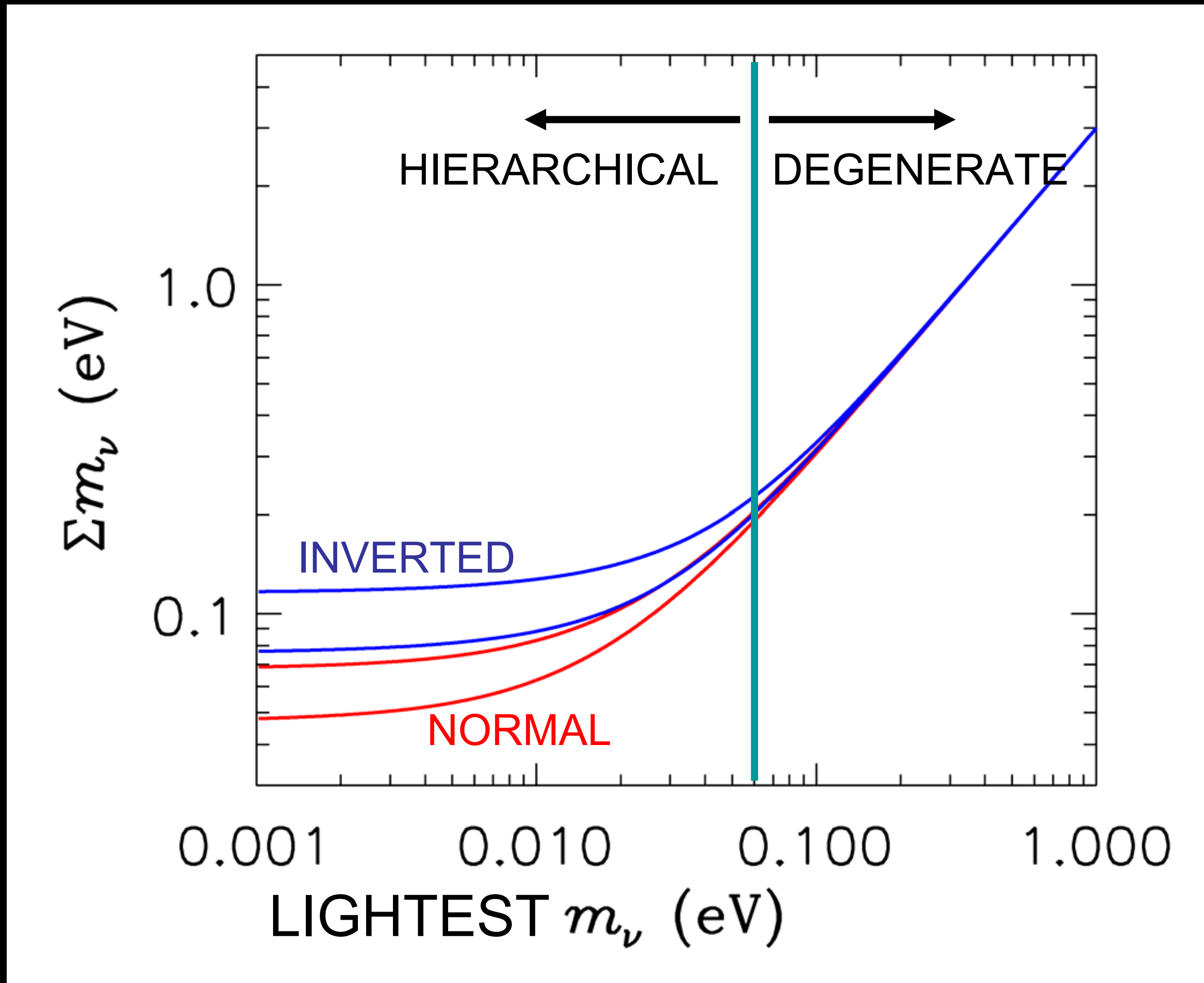
Inverted hierarchy

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
Σm_ν (eV)
LIGHTEST m_ν (eV)

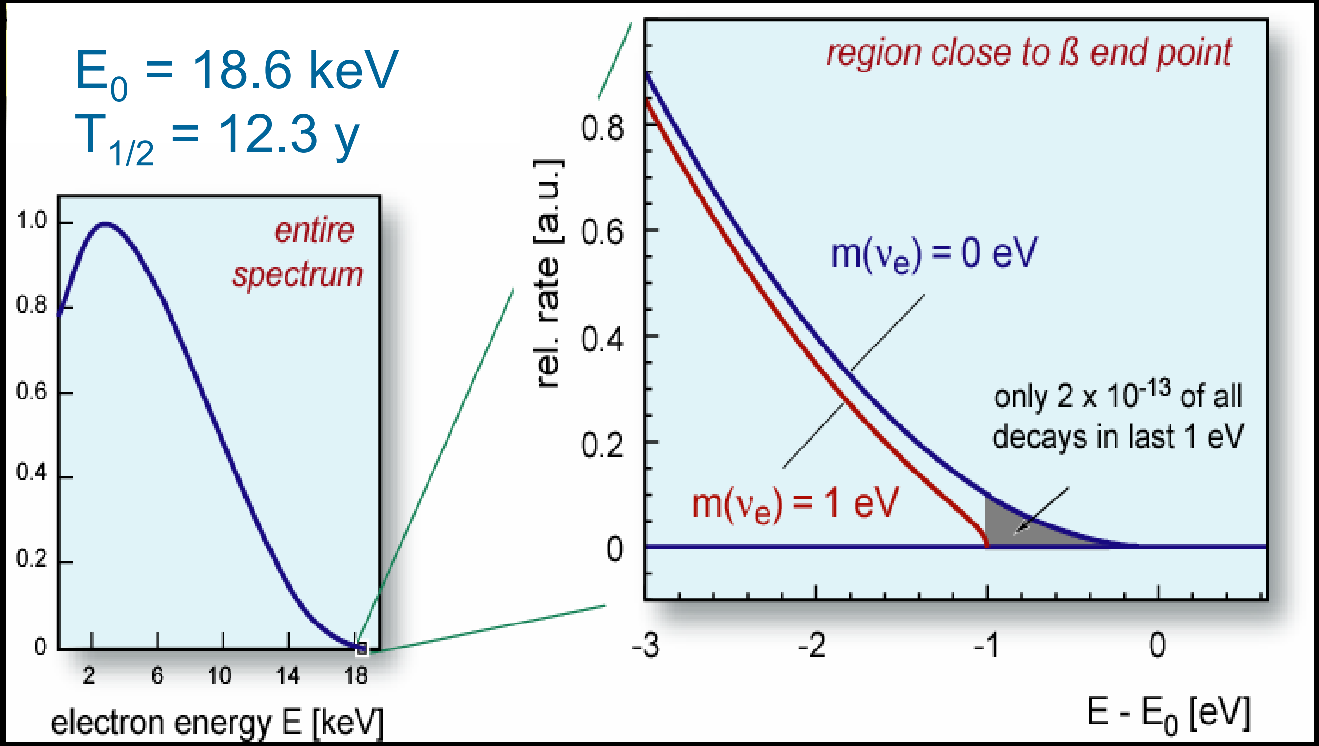
ß-decay and neutrino mass

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 provided limits on the electron neutrino mass

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

Mainz experiment, final analysis (Kraus et al.)

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

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

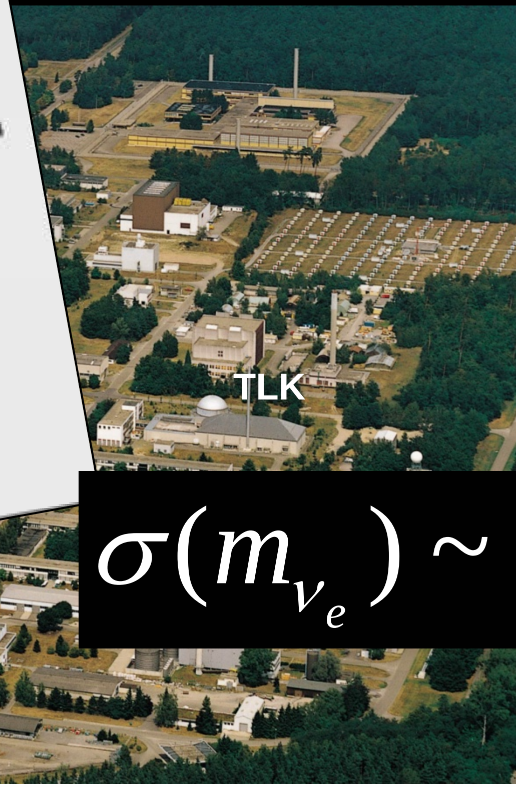
KATRIN experiment


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft
Wissenschaftliche Berichte
FZKA 7090
NPI ASCR Řež EXP-01/2005
MS-KP-0501

KATRIN Design Report 2004

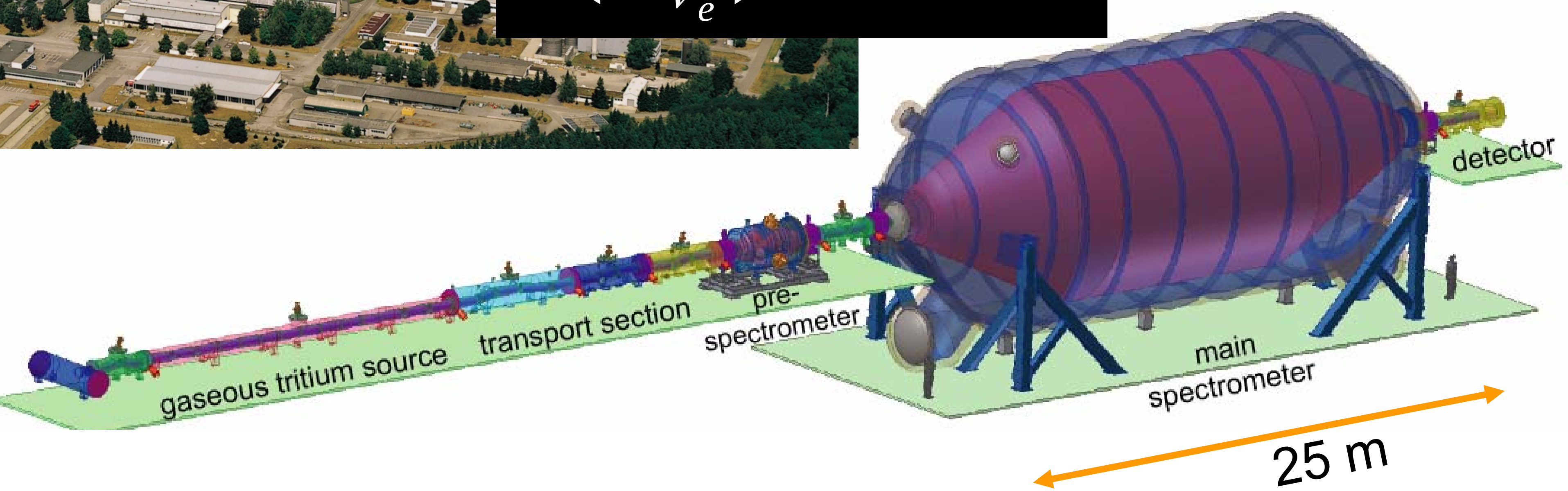
KATRIN Collaboration

Februar 2005



Karlsruhe **Tri**tium **N**eutrino Experiment
at Forschungszentrum Karlsruhe
Data taking starting early 2012

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



NEUTRINO MASS AND ENERGY DENSITY FROM COSMOLOGY

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

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

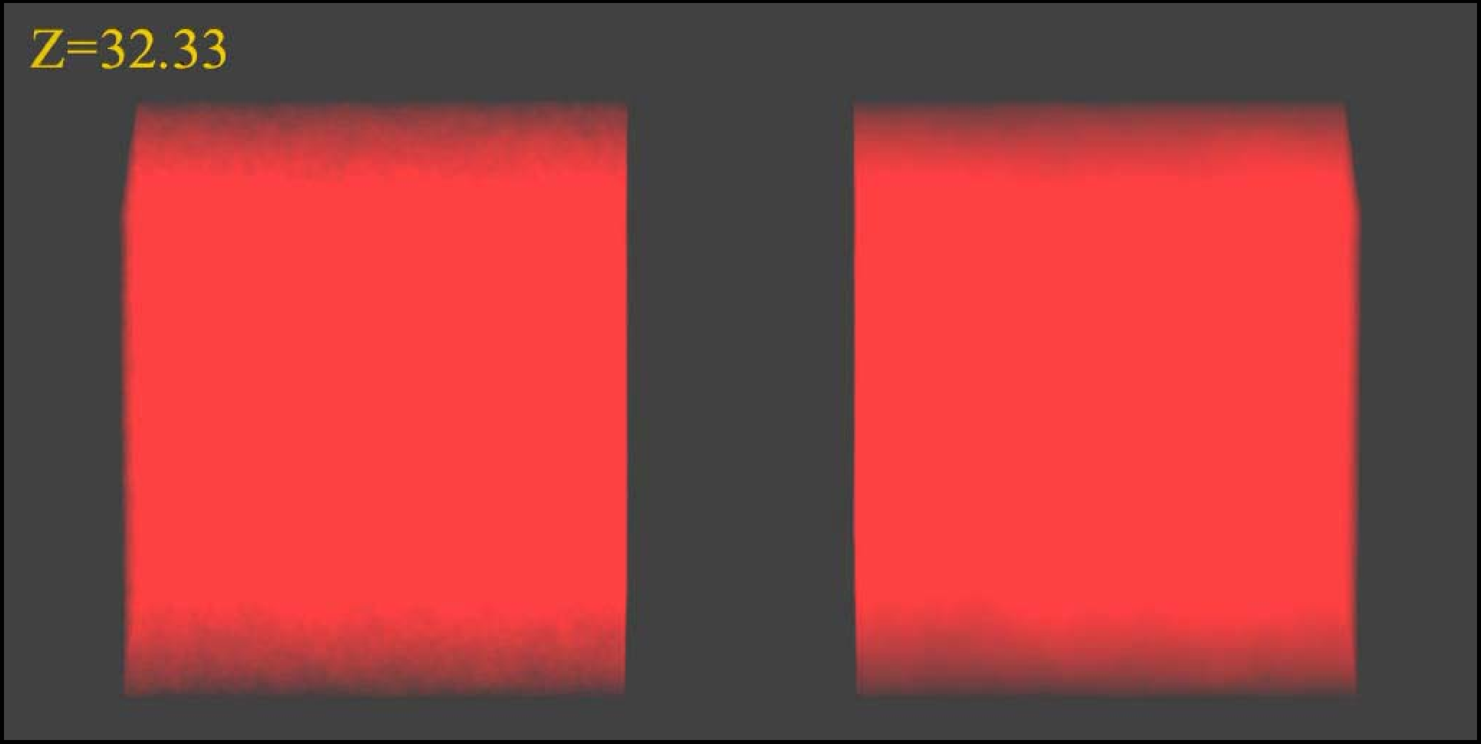
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

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

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

The number and energy density for a given species, X, is given by the Boltzmann equation

$$\frac{\partial f_X}{\partial t} + pH\frac{\partial f_X}{\partial p} = C_e[f_X] + C_i[f_X]$$

$C_e[f]$: *Elastic collisions*, conserves particle number but energy exchange possible (e.g. $X + i \rightarrow X + i$)
[scattering equilibrium]

$C_i[f]$: *Inelastic collisions*, changes particle number (e.g. $X + \bar{X} \rightarrow i + \bar{i}$)
[chemical equilibrium]

Usually, $C_e[f] >> C_i[f]$ so that one can assume that elastic scattering equilibrium always holds.

If this is true, then the form of f is always Fermi-Dirac or Bose-Einstein, but with a possible chemical potential.

Particle decoupling

The inelastic reaction rate per particle for species *X* is

$$\Gamma_{\text{int}} = \int C_i\left[f_X\right]\frac{d^3 p_X}{(2\pi)^3} = n_X\langle\sigma v\rangle$$

In general, a species decouples from chemical equlibrium when

$$\Gamma_{\text{int}} \approx H$$

$$H \approx \frac{T^2}{m_{Pl}}$$

The prime example is the decoupling of light neutrinos ($m < T_D$)

$$\Gamma_{weak} = n\langle \sigma v \rangle \approx T^3 G_F^2 T^2 \Rightarrow T_D \approx 1\,\text{MeV}$$

After neutrino decoupling electron-positron annihilation takes place (at T~m_e/3)

Entropy is conserved because of equilibrium in the e^+- e^-- γ plasma and therefore

$$s_i = s_f \Rightarrow (2+4\frac{7}{8})T_i^3 = 2T_f^3 \Rightarrow \frac{T_f}{T_i} = \left(\frac{11}{4}\right)^{1/3}$$

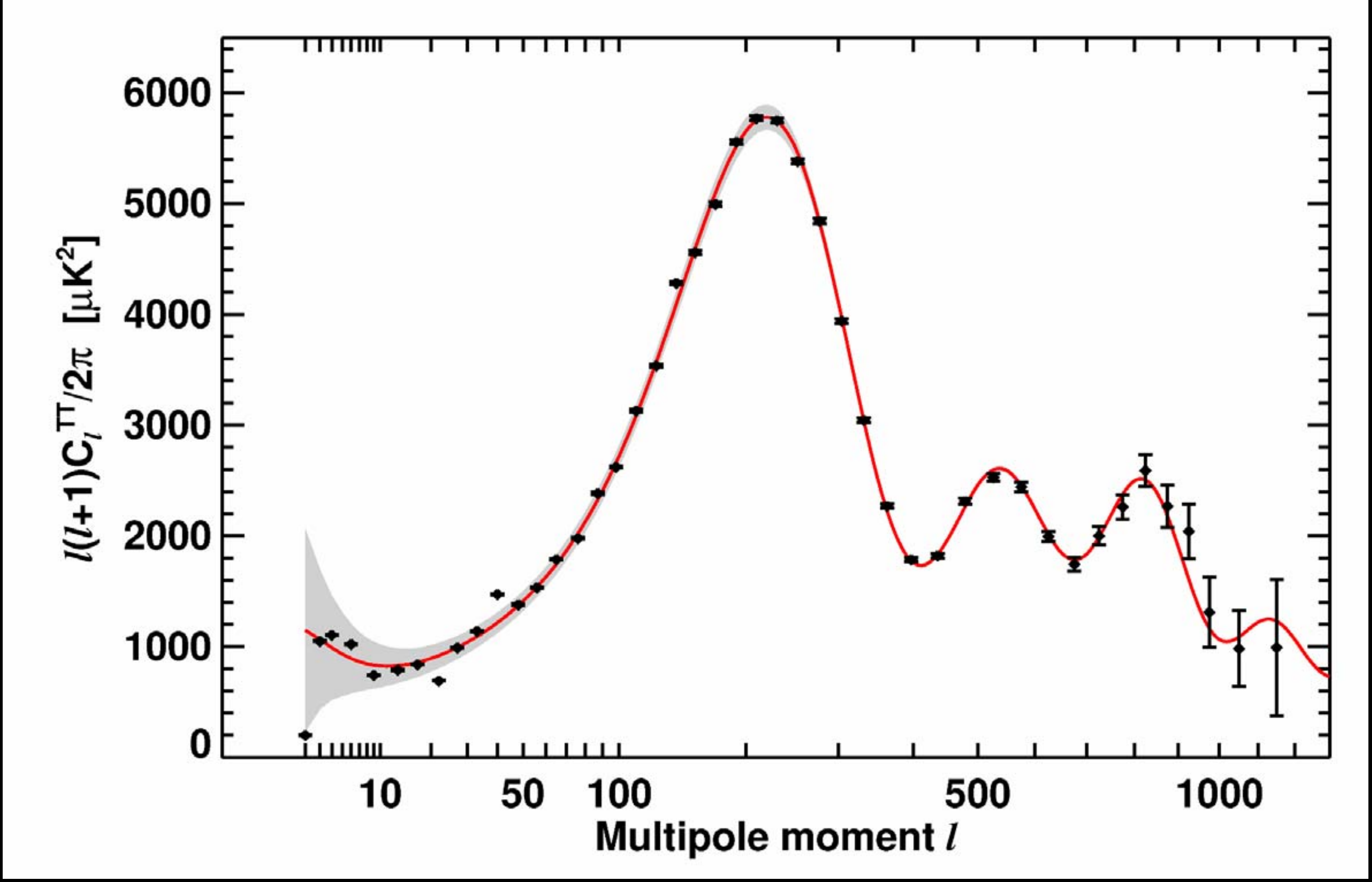
The neutrino temperature is unchanged by this because they are decoupled and therefore

$$T_\nu = (4/11)^{1/3} T_\gamma \approx 0.71 T_\gamma \quad \text{(after annihilation)}$$

THE TOTAL ENERGY DENSITY IN NEUTRINOS AND OTHER WEAKLY INTERACTING, LIGHT PARTICLES IS A MEASURABLE QUANTITY JUST LIKE THE NEUTRINO MASS

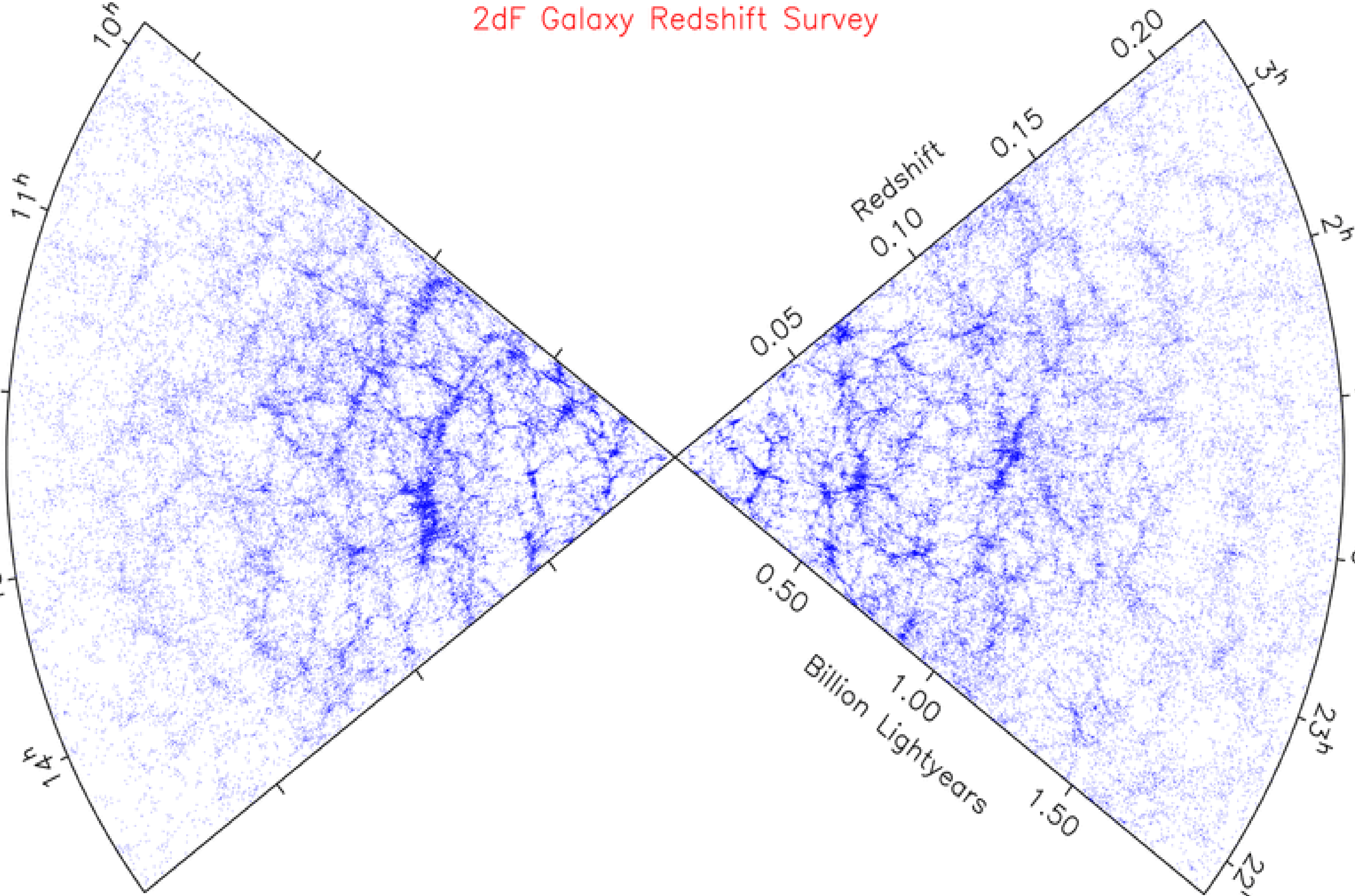
AVAILABLE COSMOLOGICAL DATA

WMAP-7 TEMPERATURE POWER SPECTRUM

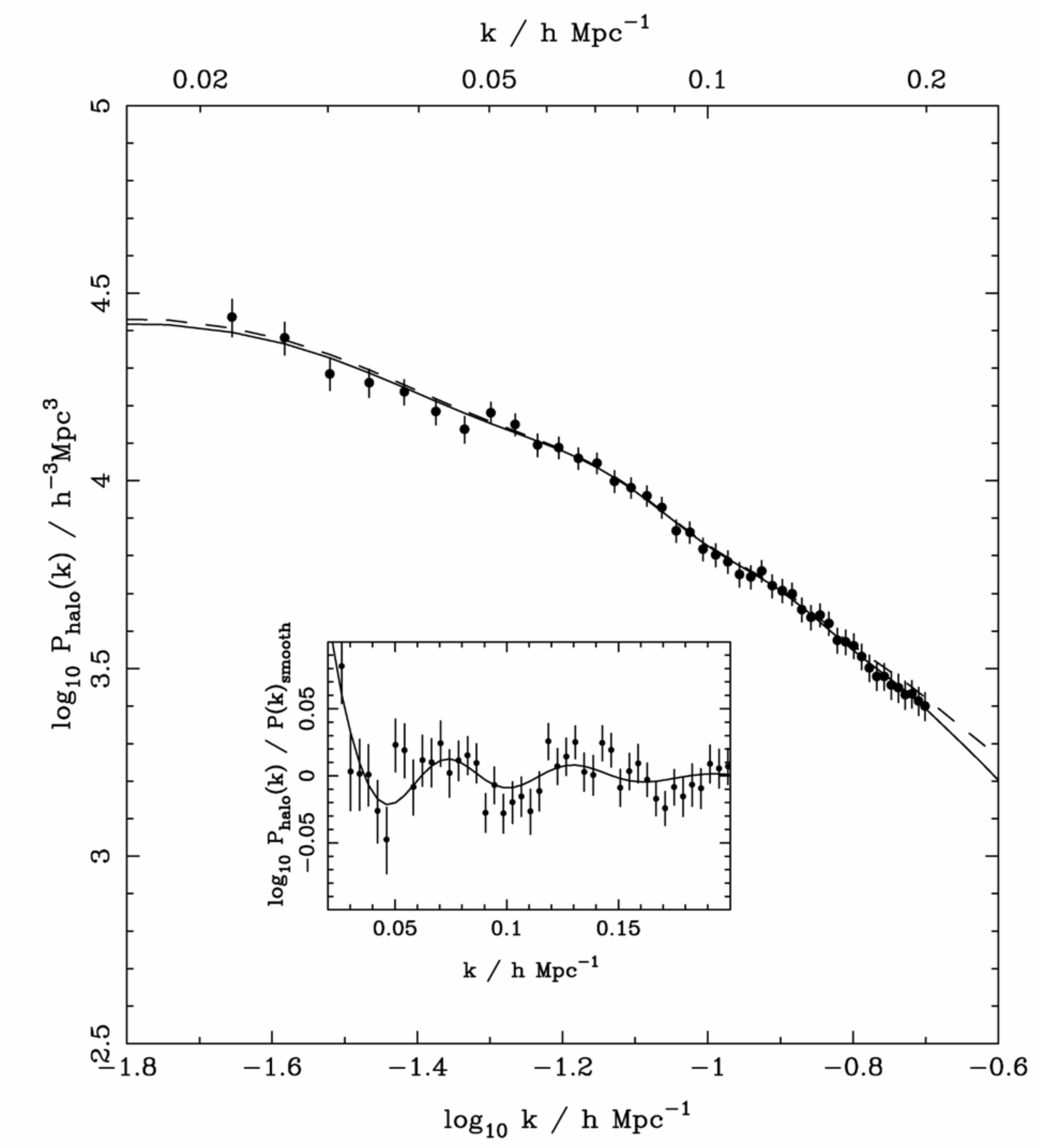


LARSON ET AL, ARXIV 1001.4635

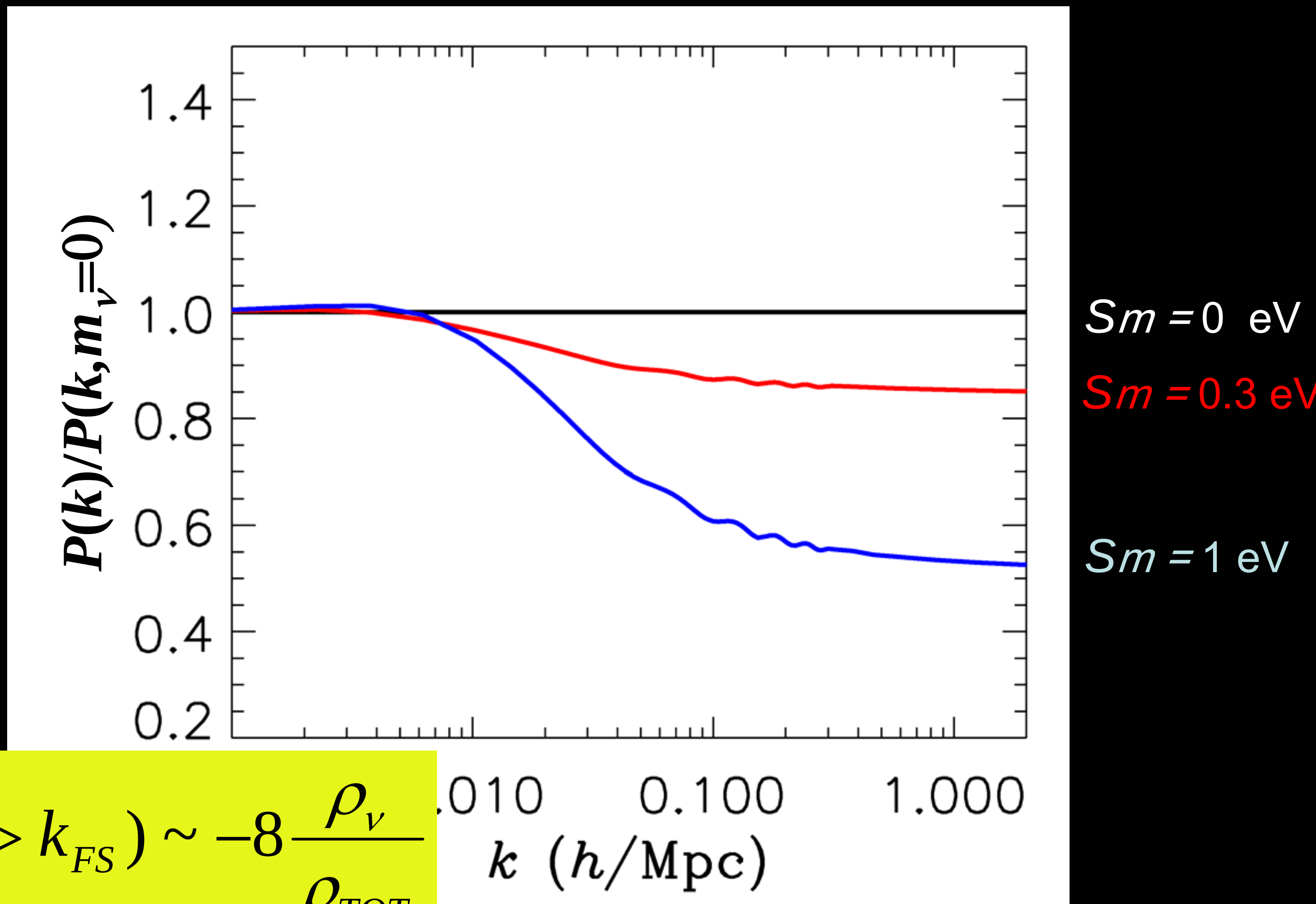
LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS



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?

DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

THERE ARE MANY ANALYSES IN THE LITERATURE

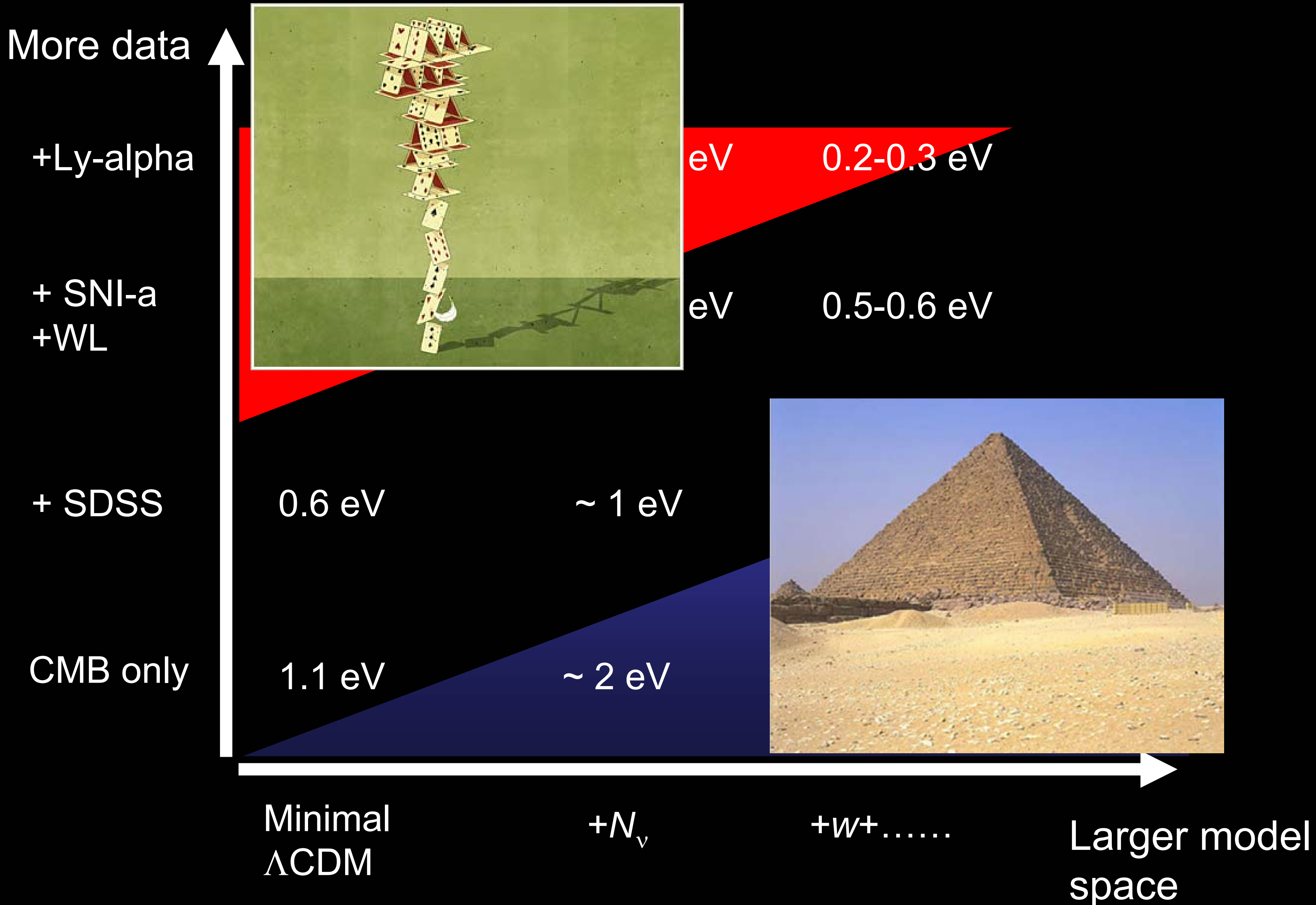
$$\sum m_\nu \leq 0.44\,\mathrm{eV}\ @\ 95\,\mathrm{C.L.}$$

USING THE MINIMAL COSMOLOGICAL MODEL

STH, MIRIZZI, RAFFELT, WONG (arxiv:1004:0695)
HAMANN, STH, LESGOURGUES, RAMPF & WONG (arxiv:1003.3999)

JUST ONE EXAMPLE

THE NEUTRINO MASS FROM COSMOLOGY PLOT



Model	Observables	Σm_ν (eV) 95% Bound
$o\omega$CDM $+ \Delta N_{\rm rel} + m_\nu$	CMB+HO+SN+BAO	≤ 1.5
$o\omega$CDM $+ \Delta N_{\rm rel} + m_\nu$	CMB+HO+SN+LSSPS	≤ 0.76
ΛCDM $+ m_\nu$	CMB+H0+SN+BAO	≤ 0.61
ΛCDM $+ m_\nu$	CMB+H0+SN+LSSPS	≤ 0.36
ΛCDM $+ m_\nu$	CMB (+SN)	≤ 1.2
ΛCDM $+ m_\nu$	CMB+BAO	≤ 0.75
ΛCDM $+ m_\nu$	CMB+LSSPS	≤ 0.55
ΛCDM $+ m_\nu$	CMB+H0	≤ 0.45

Gonzalez-Garcia et al., arxiv:1006.3795

WHAT IS N_ν?

A MEASURE OF THE ENERGY DENSITY IN NON-INTERACTING RADIATION IN THE EARLY UNIVERSE

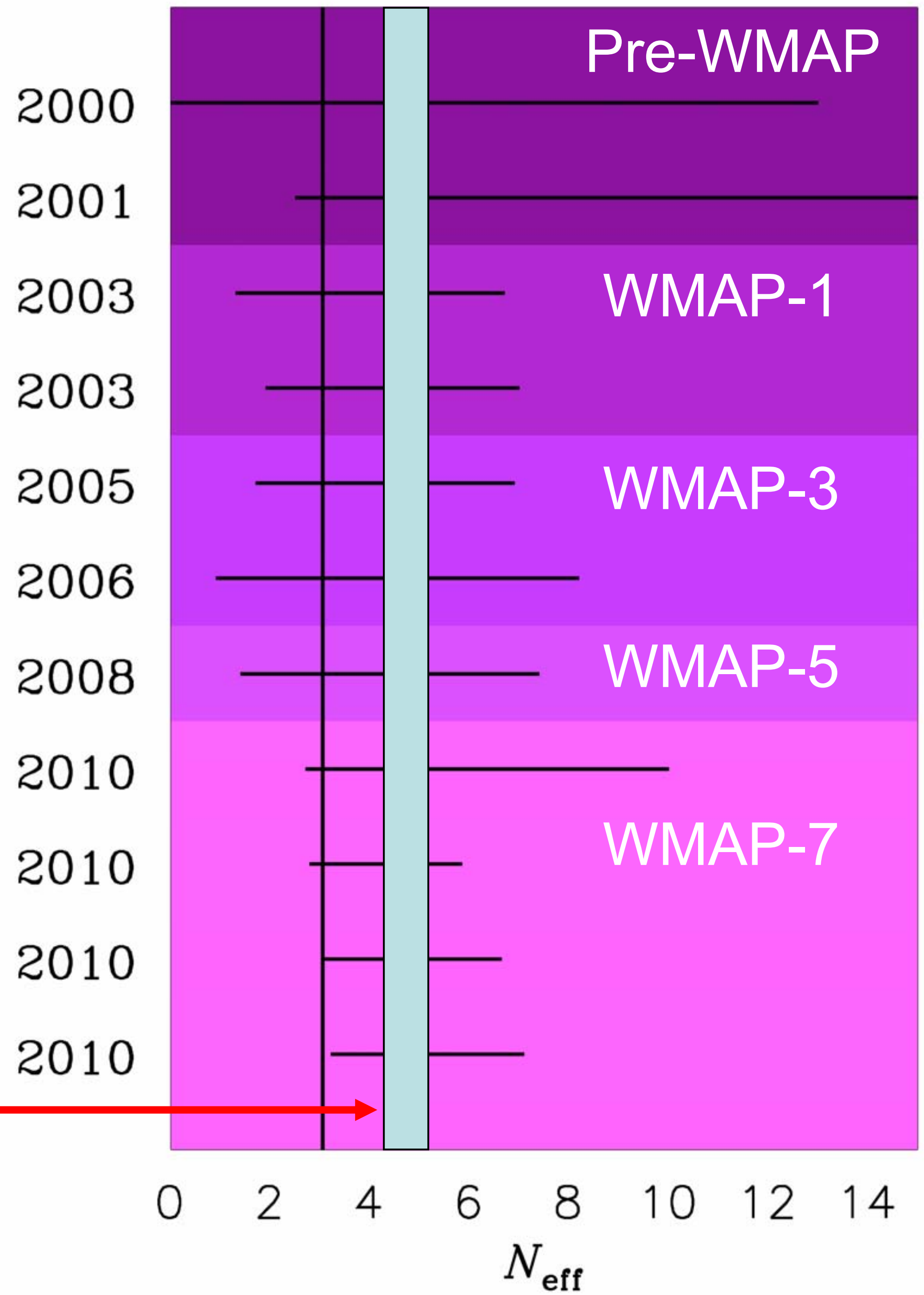
THE STANDARD MODEL PREDICTION IS

$$N_\nu \equiv \frac{\rho}{\rho_{\nu,0}} = 3.046 \quad , \quad \rho_{\nu,0} \equiv \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

Mangano et al., hep-ph/0506164

BUT ADDITIONAL LIGHT PARTICLES (STERILE NEUTRINOS, AXIONS, MAJORONS,.....) COULD MAKE IT HIGHER

TIME EVOLUTION OF THE 95% BOUND ON N_ν



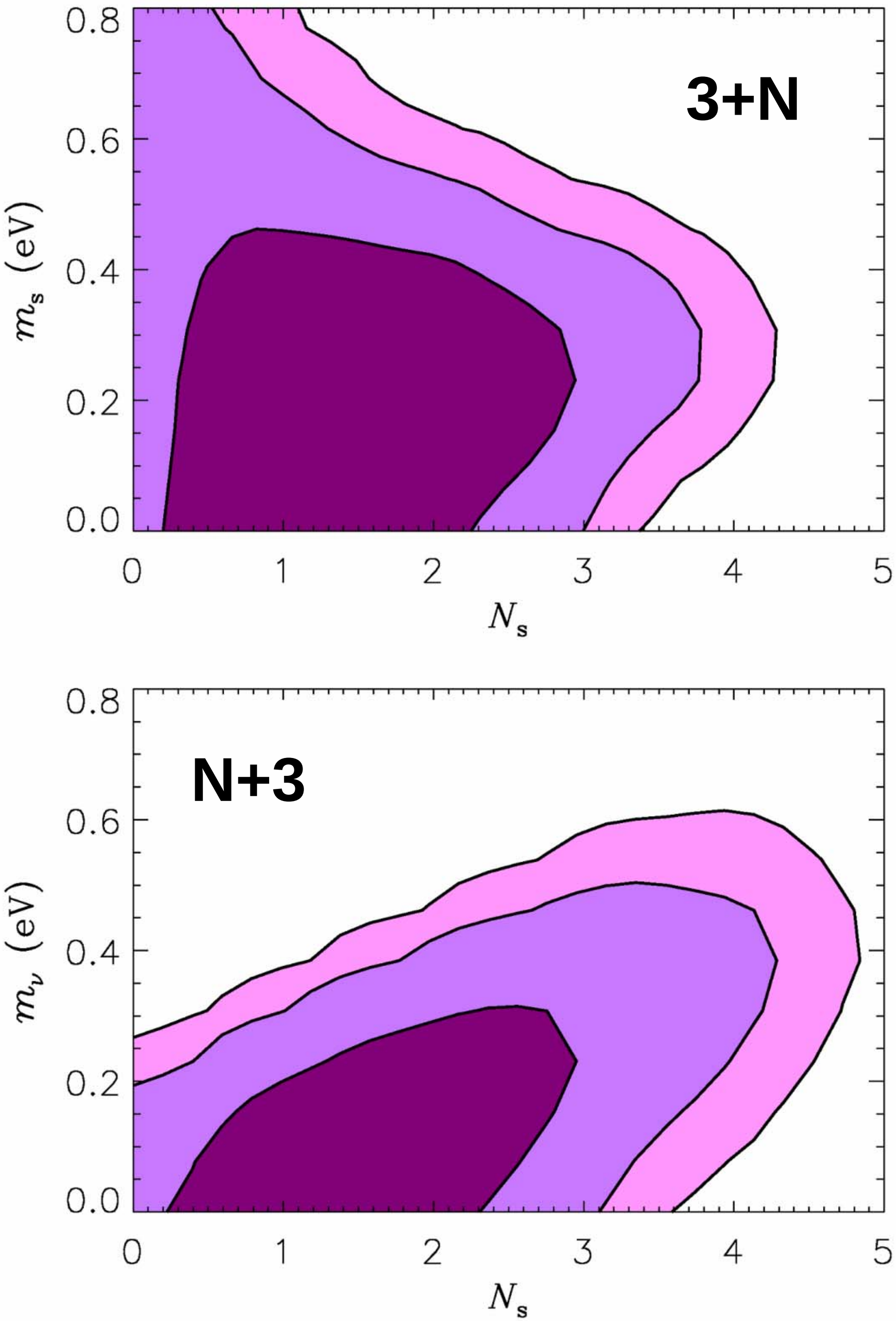
ESTIMATED PLANCK SENSITIVITY

A STERILE NEUTRINO IS PERHAPS THE MOST OBVIOUS CANDIDATE FOR AN EXPLANATION OF THE EXTRA ENERGY DENSITY

ASSUMING A NUMBER OF ADDITIONAL STERILE STATES OF APPROXIMATELY EQUAL MASS, TWO QUALITATIVELY DIFFERENT HIERARCHIES EMERGE

Hamann, STH, Raffelt, Tamborra, Wong, arxiv:1006.5276

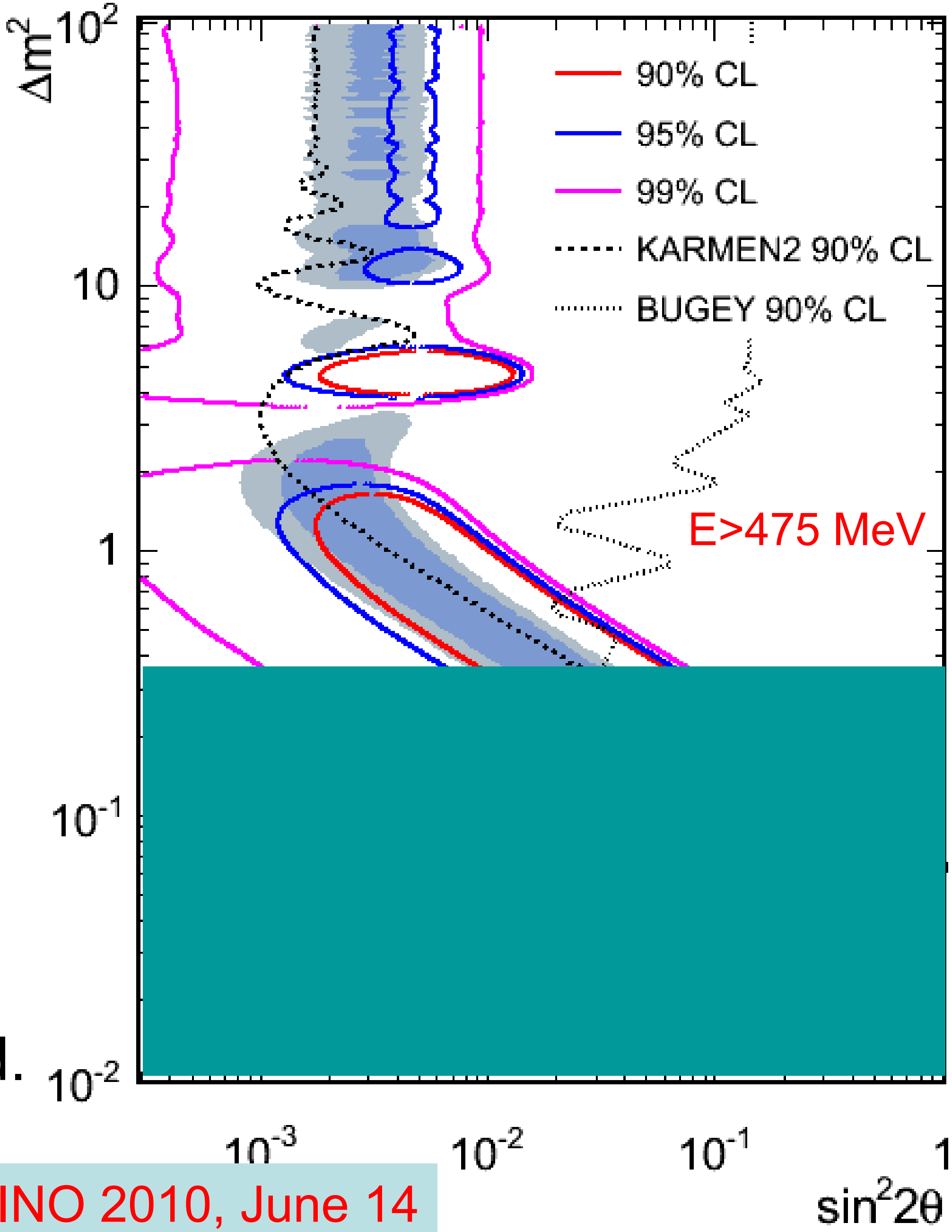
COSMOLOGY AT PRESENT NOT ONLY MARGINALLY PREFERS EXTRA ENERGY DENSITY, BUT ALSO ALLOWS FOR QUITE HIGH NEUTRINO MASSES!



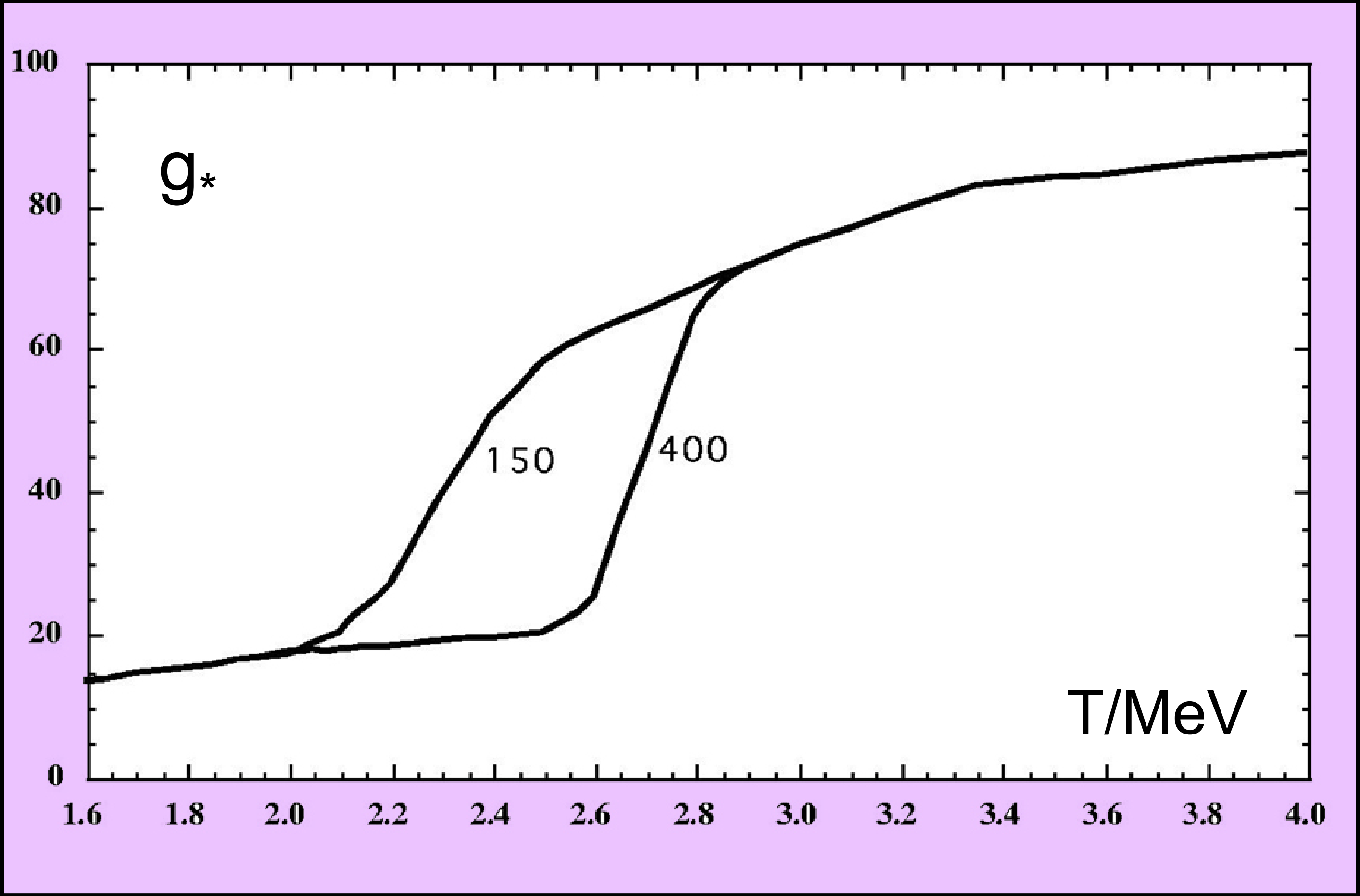
See also
Dodelson et al. 2006
Melchiorri et al. 2009
Acero & Lesgourgues 2009

Updated Antineutrino mode MB results for E>475 MeV
(official oscillation region)

- Results for **5.66E20 POT**
- Maximum likelihood fit.
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
- Best Fit Point
  $(\Delta m^2, \sin^2 2\theta) =$
  $(0.064\ eV^2, 0.96)$
  $\chi^2/NDF = 16.4/12.6$
  $P(\chi^2) = 20.5\%$
- Results to be published.

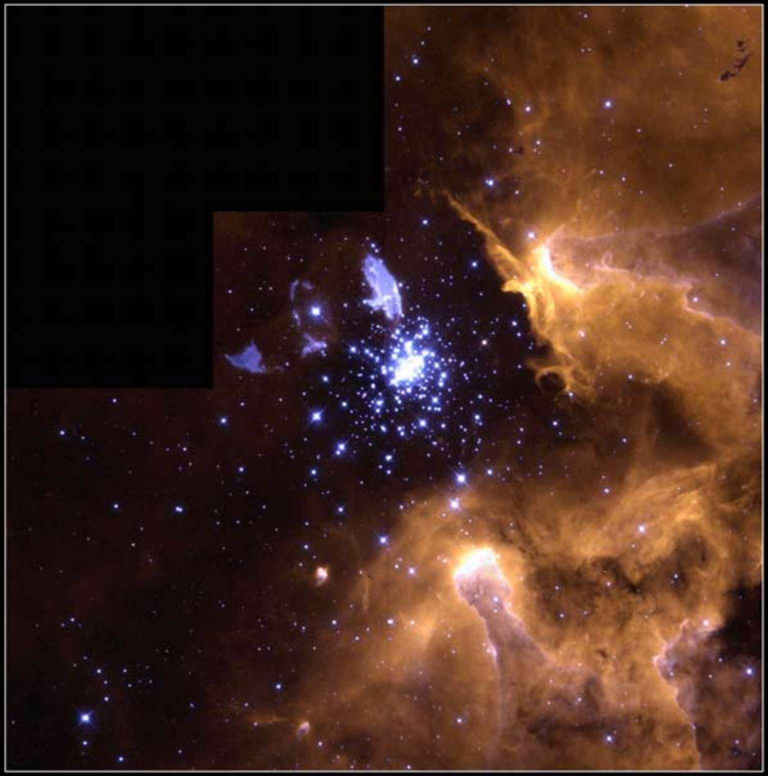


A general problem with extra energy density is that it must be produced after The QCD phase transition



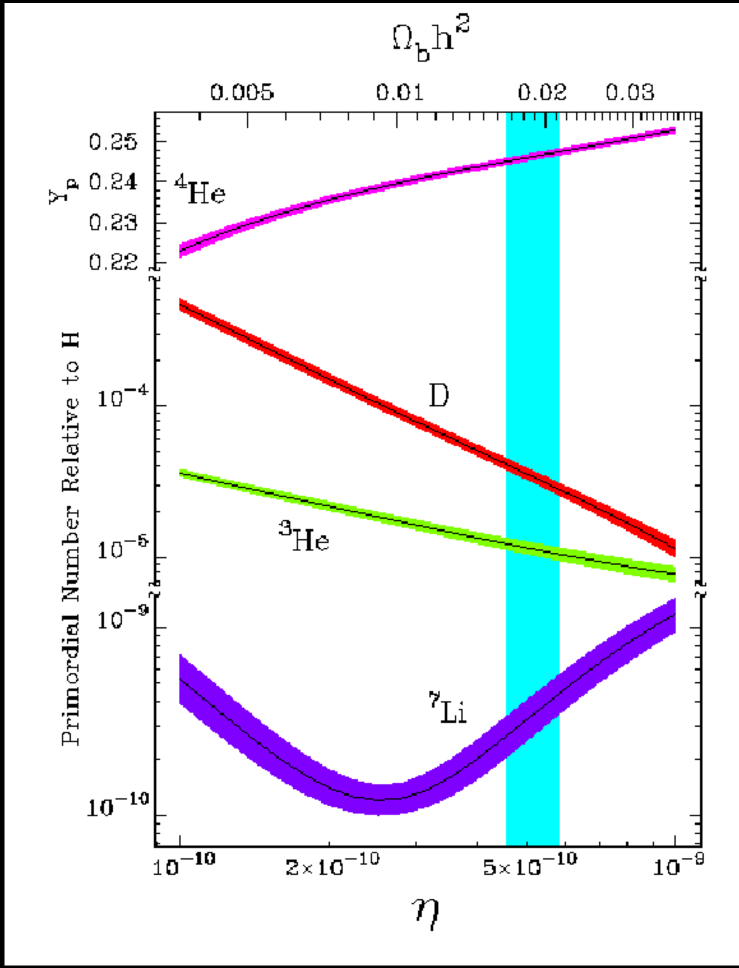
See e.g. Hamann, STH, Raffelt, Tamborra & Wong 2010
Nakayama, Takahashi & Yanagida 2010

BIG BANG NUCLEOSYNTHESIS

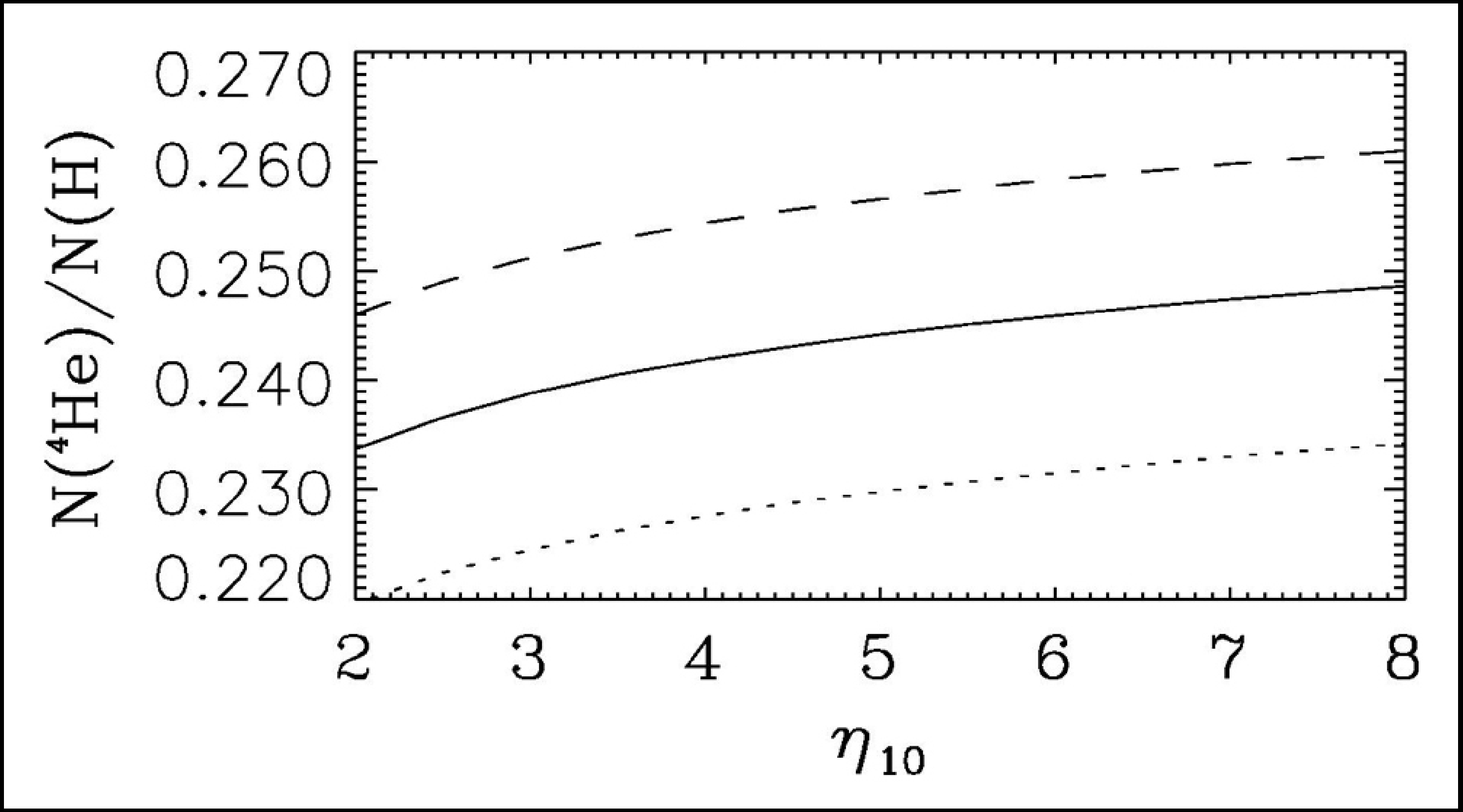


NGC 3603
Hubble Space Telescope • WFPC2

PRC99-20 • STScI OPO
Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington),
You-Hua Chu (University of Illinois, Urbana-Champaign) and NASA



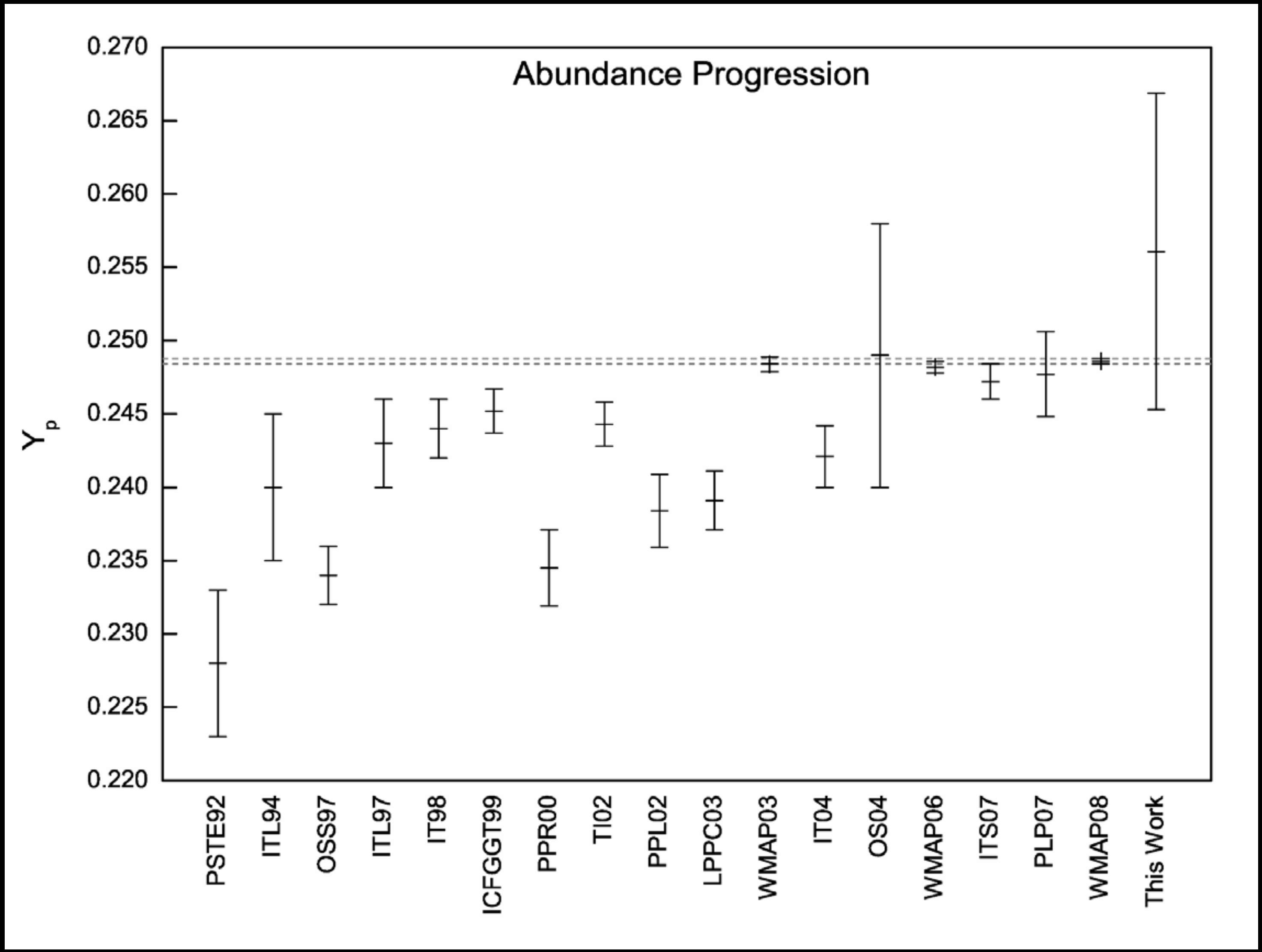
The helium production is very sensitive to N_ν



$N_\nu = 4$

$N_\nu = 3$

$N_\nu = 2$



Aver et al 2010

Current helium data also suggests extra radiation

$$N_{\nu} \sim 4 \pm 1 \text{ (95\% C.L.)}$$

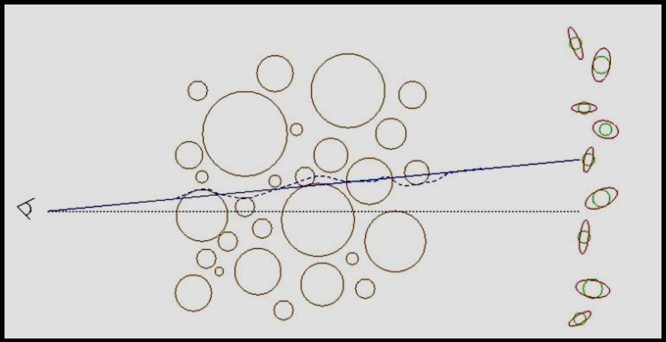
Aver et al 2010

Izotov & Thuan 2010

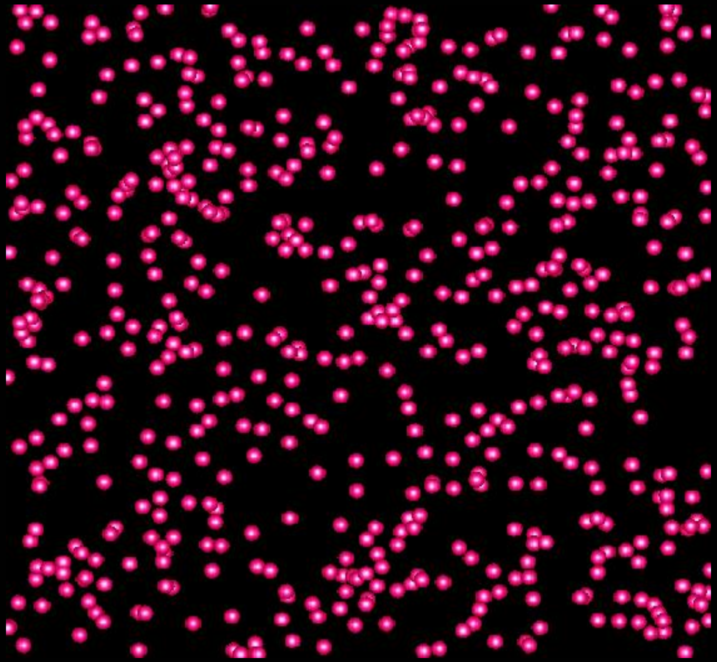
WHAT IS IN STORE FOR THE FUTURE?

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

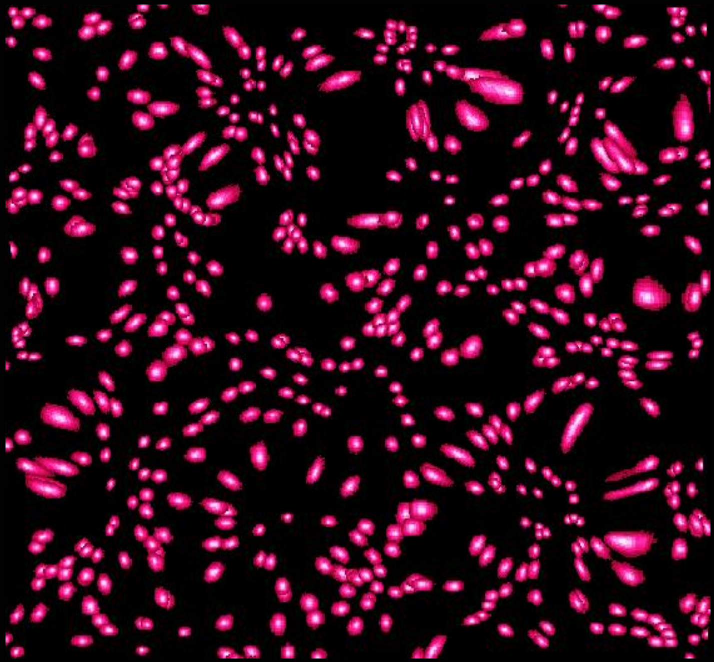
WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE



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

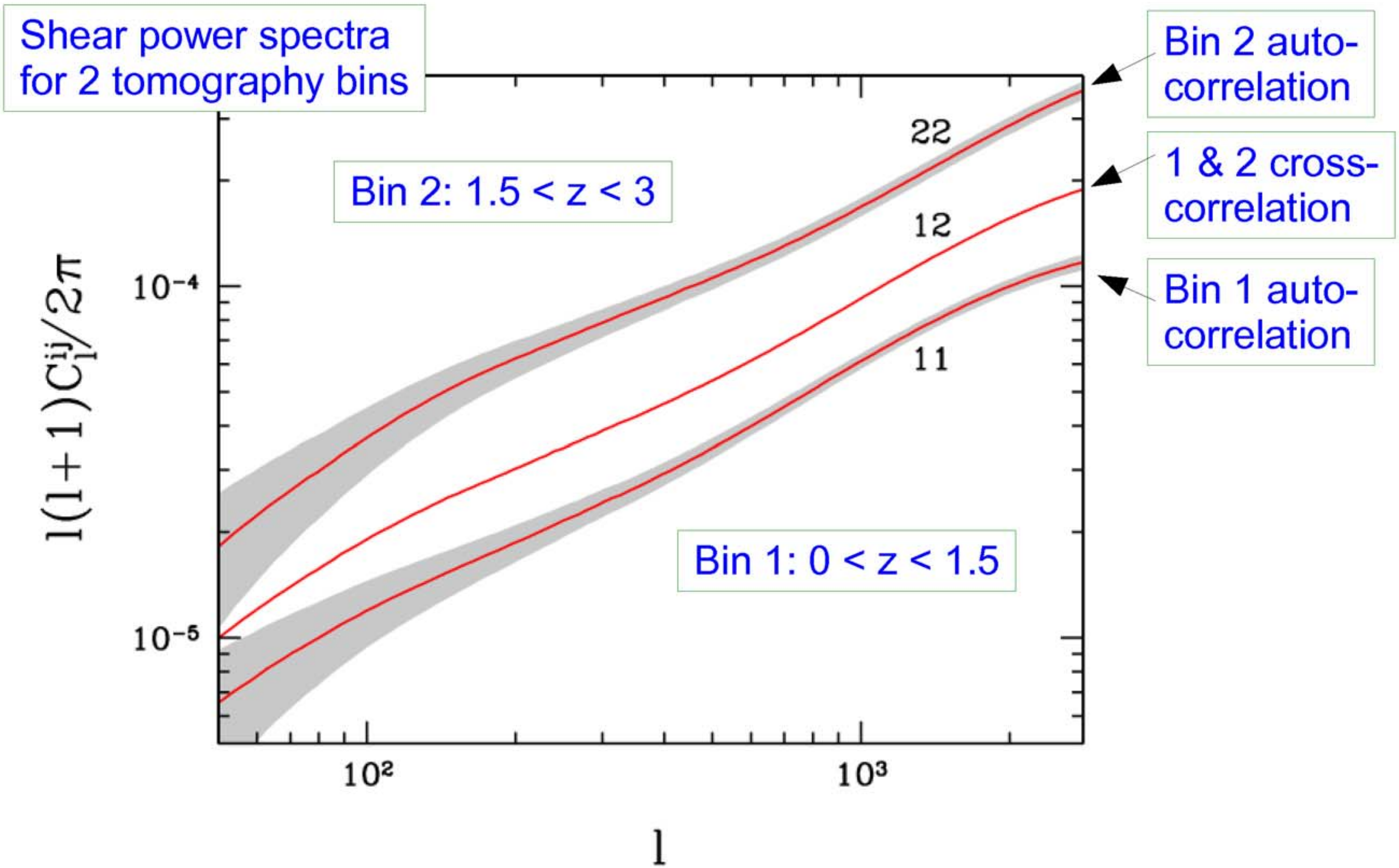
$$C_\ell = \frac{9}{16} H_0^4 \Omega_m^2 \int_0^{\chi_H} \left[\frac{g(\chi)}{a\chi} \right]^2 P(\ell / r, \chi) d\chi$$

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

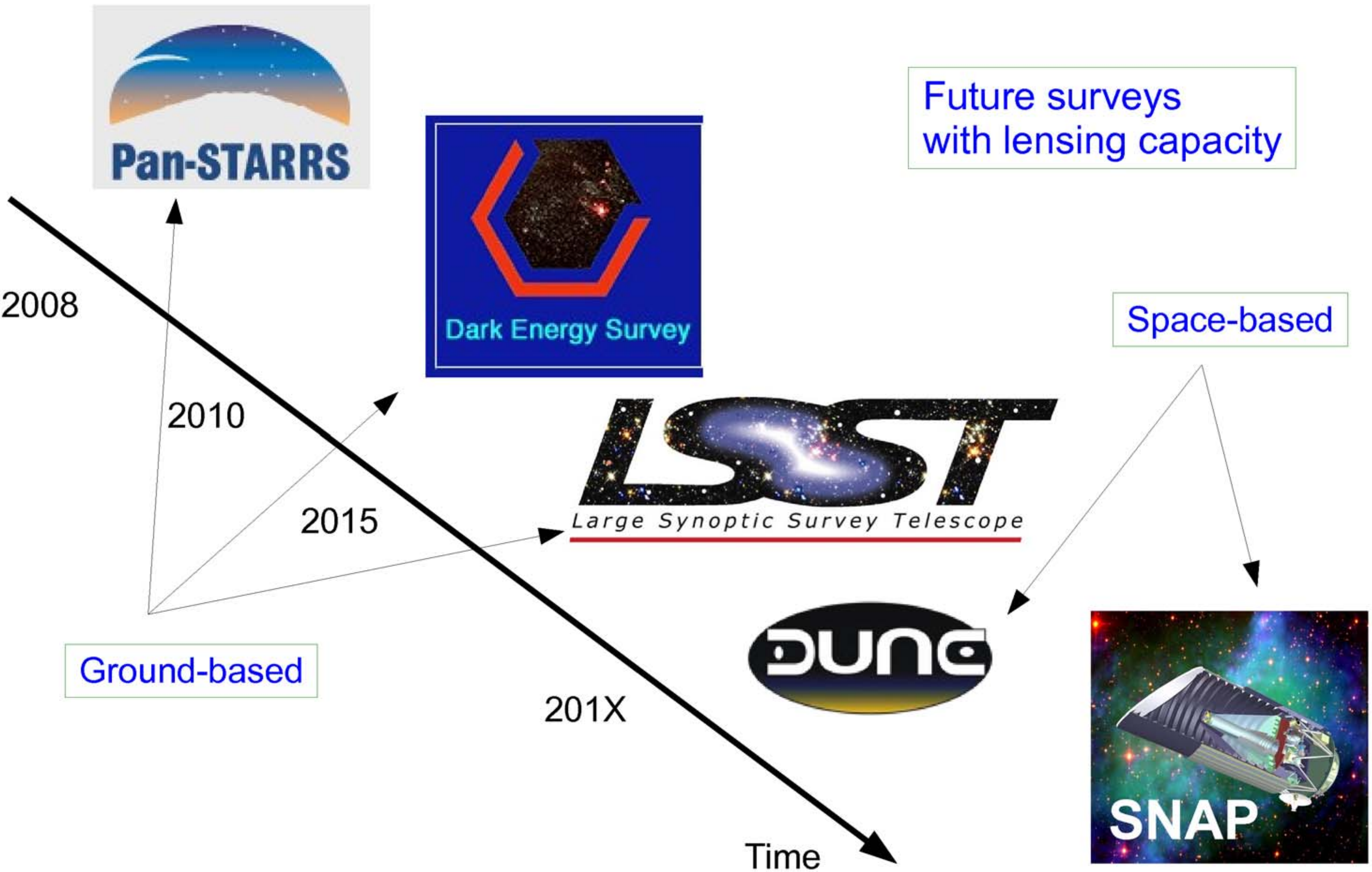
$$g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi'$$

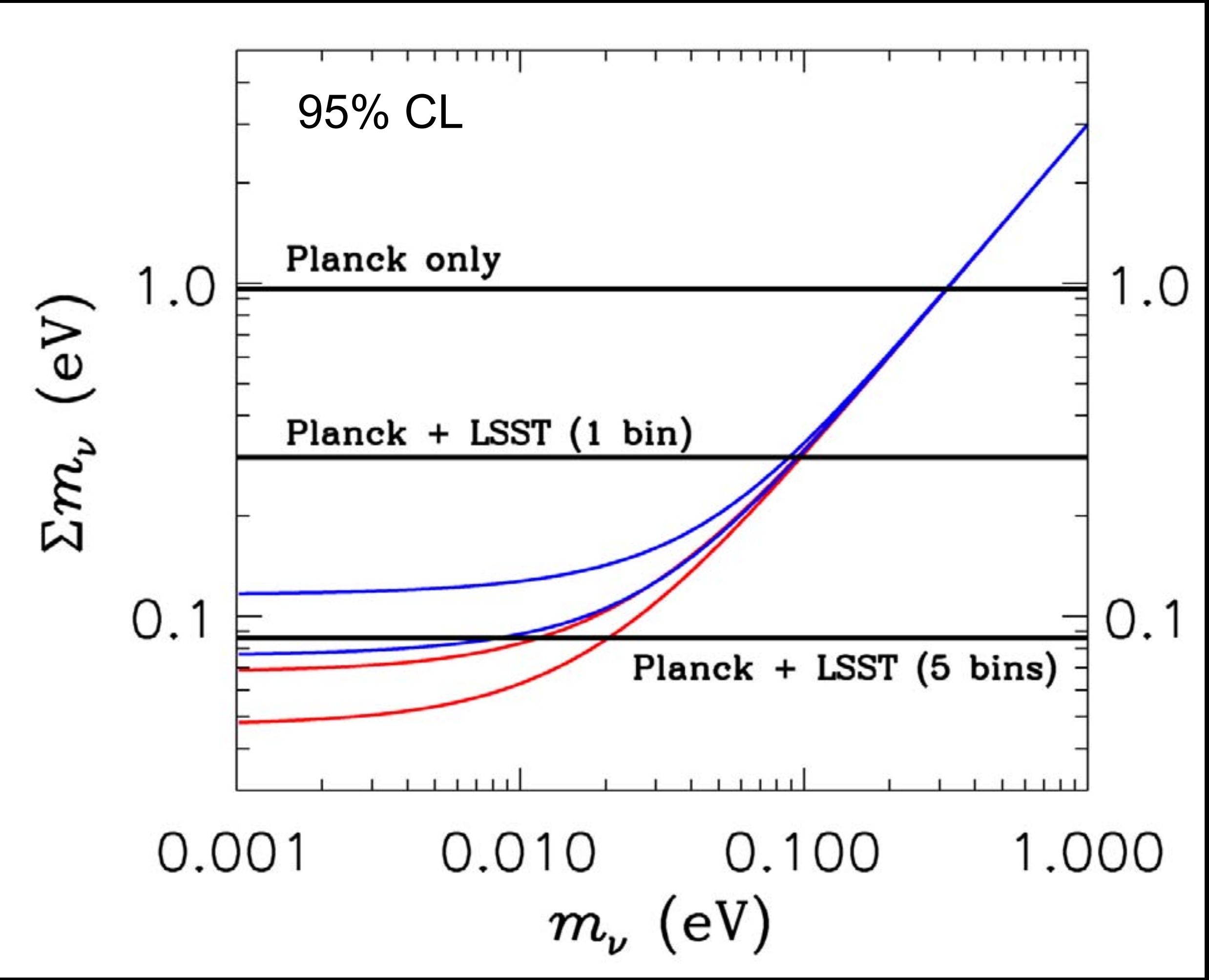
WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY

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



STH, TU, WONG 2006


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



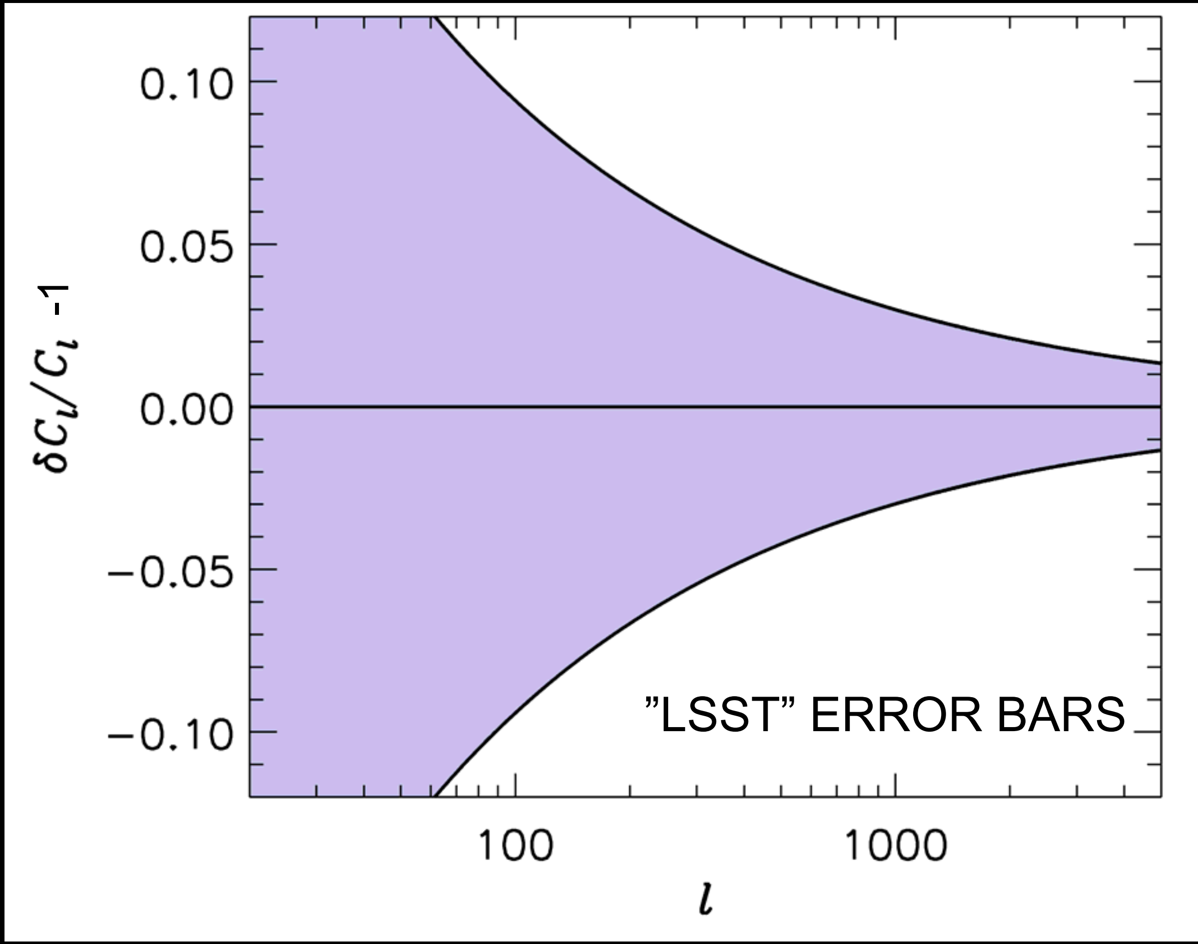
STH, TU & WONG 2006

	Planck	+Wide-1	+Wide-5	+Deep-1	+Deep-5
$\sigma(\sum m_\nu)$ (eV)	0.48	0.15	0.043	0.39	0.047
$\sigma(\Omega_{\rm de})$	0.08	0.020	0.0068	0.036	0.0099
$\sigma(\Omega_b h^2)$	0.00028	0.00016	0.00013	0.00024	0.00014
$\sigma(\Omega_c h^2)$	0.0026	0.0017	0.0015	0.0019	0.0015
$\sigma(w_0)$	0.83	0.093	0.034	0.35	0.045
$\sigma(w_a)$	4.0	0.39	0.081	1.7	0.063
$\sigma(\tau)$	0.0046	0.0043	0.0042	0.0045	0.0043
$\sigma(n_s)$	0.0089	0.0056	0.0028	0.0074	0.0047
$\sigma(\alpha_s)$	0.024	0.013	0.0061	0.020	0.012
$\sigma(\sigma_8)$	0.084	0.019	0.0076	0.030	0.0092
$\sigma(N_{\rm eff})$	0.19	0.11	0.067	0.14	0.093

STH, TU & WONG 2006

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

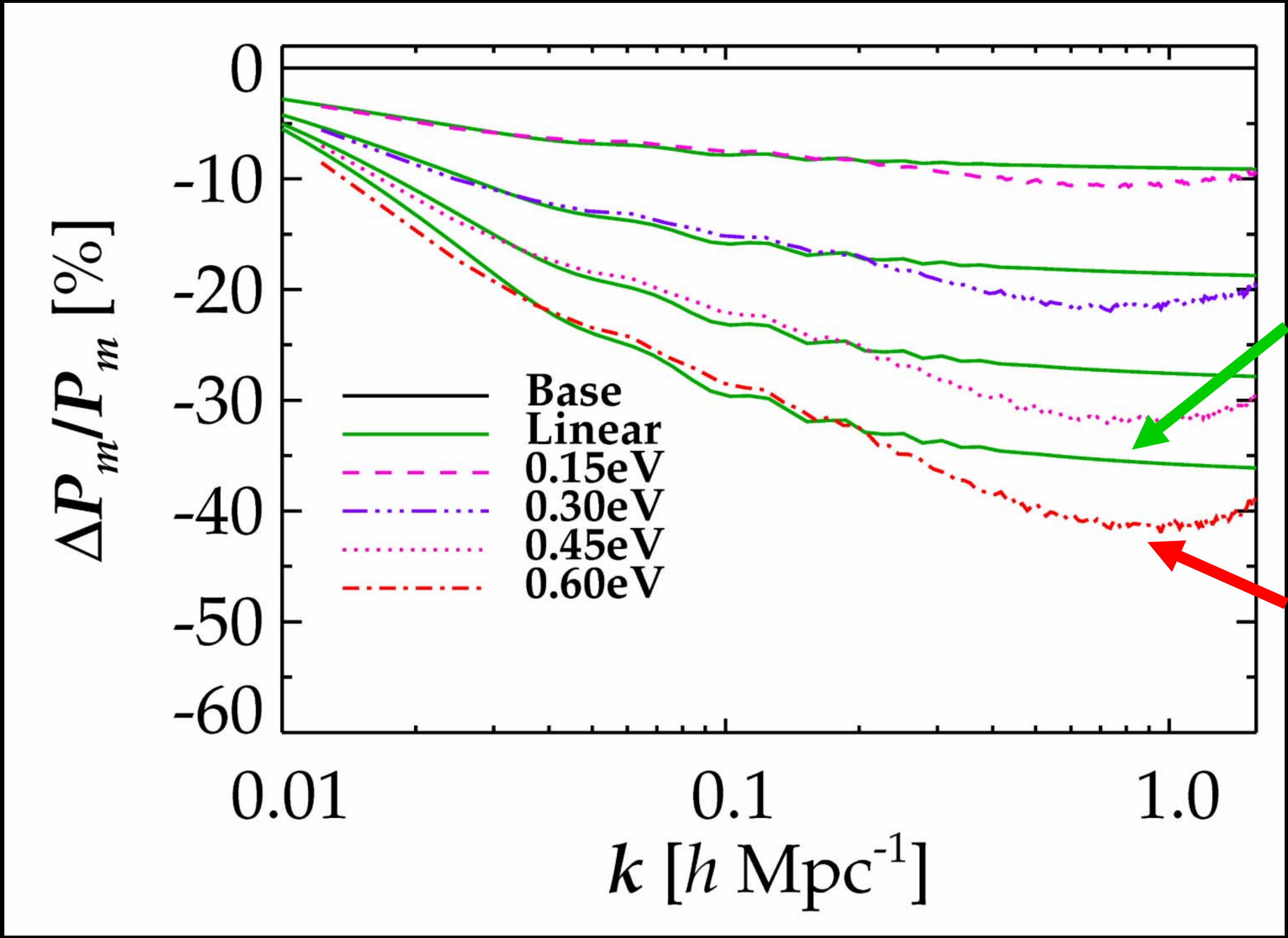


WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM TO AT LEAST THE SAME PRECISION!

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
- ....

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

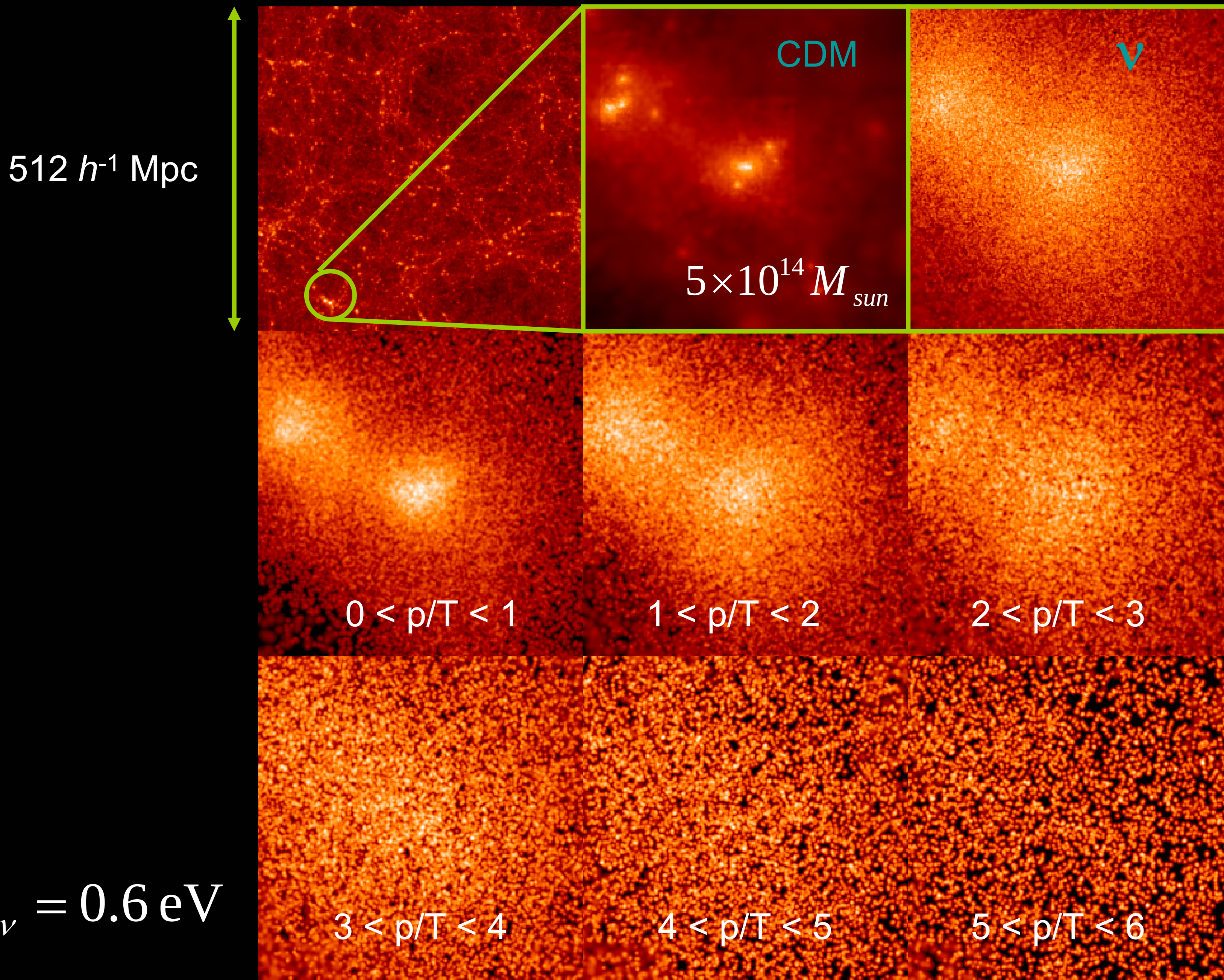
$$\frac{\Delta P}{P} \sim -9.6\frac{\Omega_\nu}{\Omega_m}$$

Brandbyge, STH, Haugbølle, Thomsen, arXiv:0802.3700 (JCAP)
Brandbyge & STH ’09, ’10 (JCAP), Viel, Haehnelt, Springel ’10

ANOTHER IMPORTANT ASPECT OF STRUCTURE FORMATION WITH NEUTRINOS:

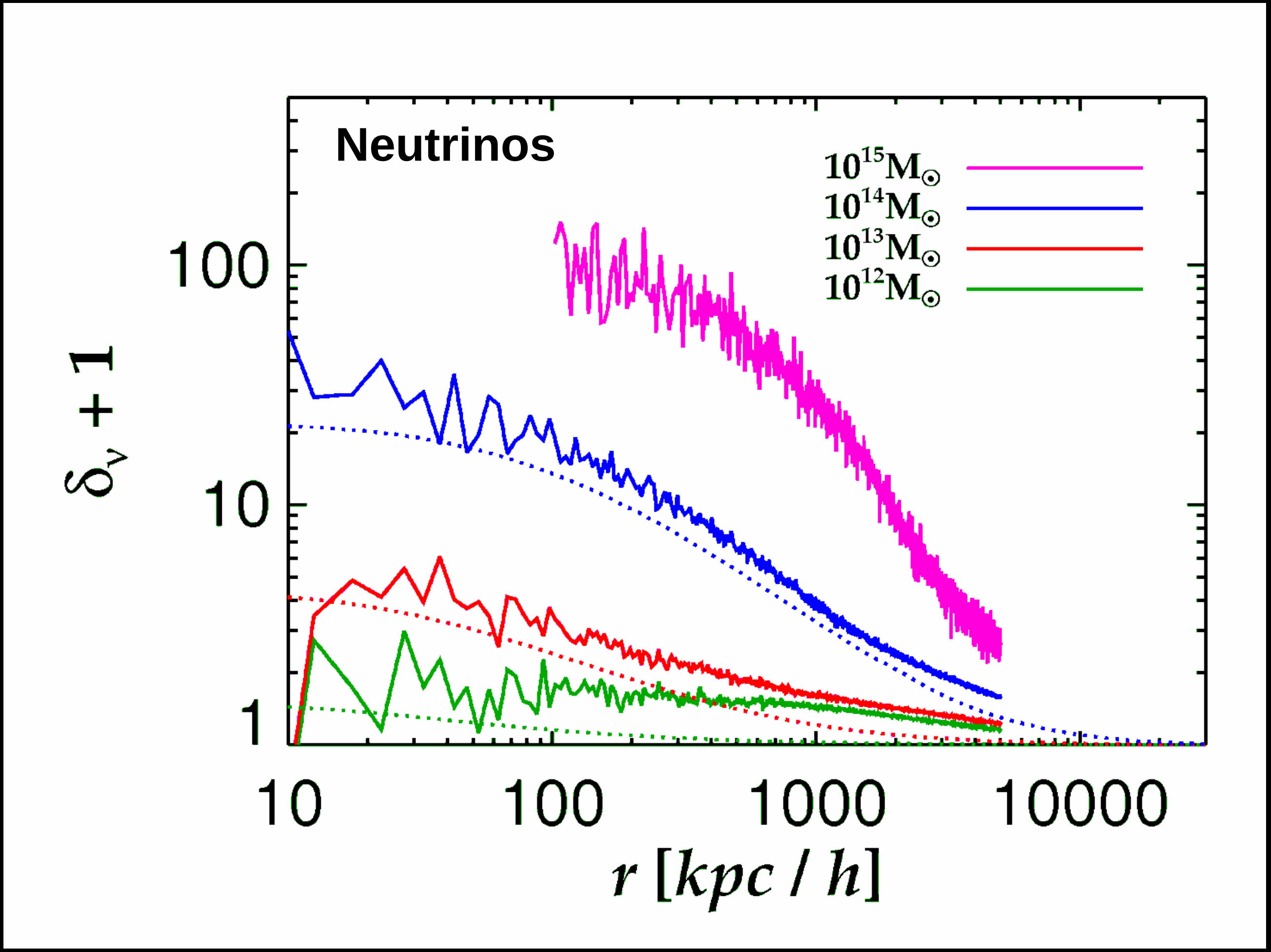
THE NUMBER OF BOUND OBJECTS (HALOS) AS WELL AS THEIR PROPERTIES ARE CHANGED WHEN NEUTRINOS ARE INCLUDED

INDIVIDUAL HALO PROPERTIES



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

Brandbyge, STH, Haugboelle, Wong, arxiv:1004.4105



See also Ringwald & Wong 2004

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.

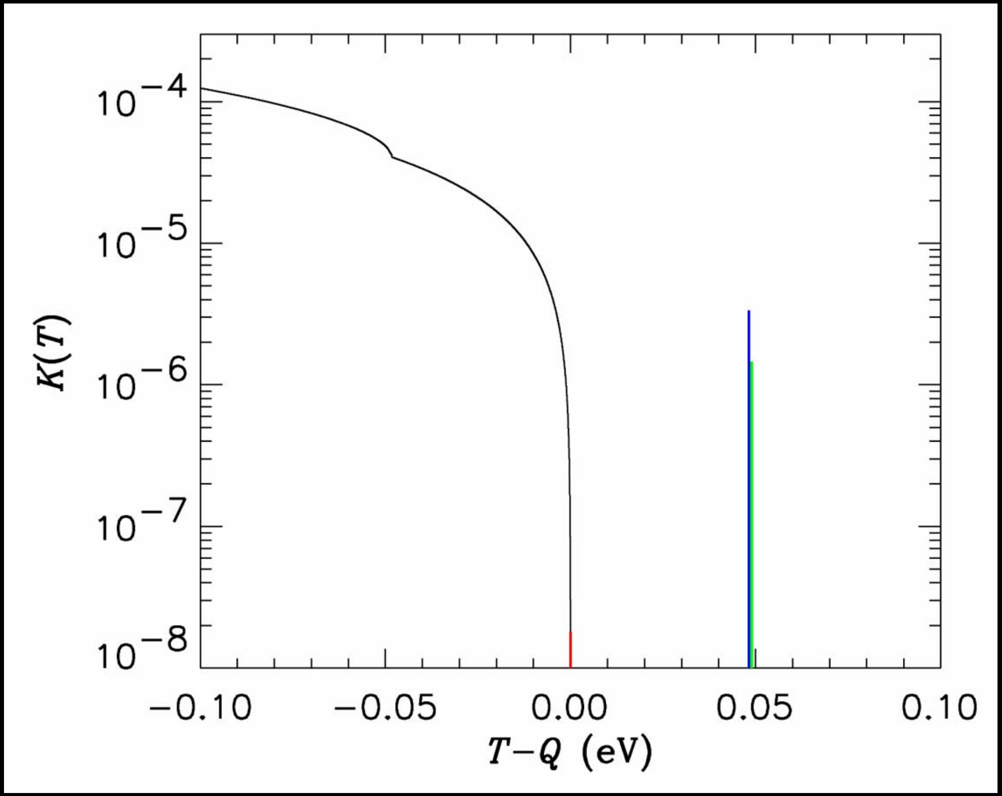
$$^{3}H \rightarrow {}^{3}He + e + \bar{\nu}_e \qquad\qquad \nu_e + {}^{3}H \rightarrow {}^{3}He + e$$

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 $|U_{ei}|^2 n_i$

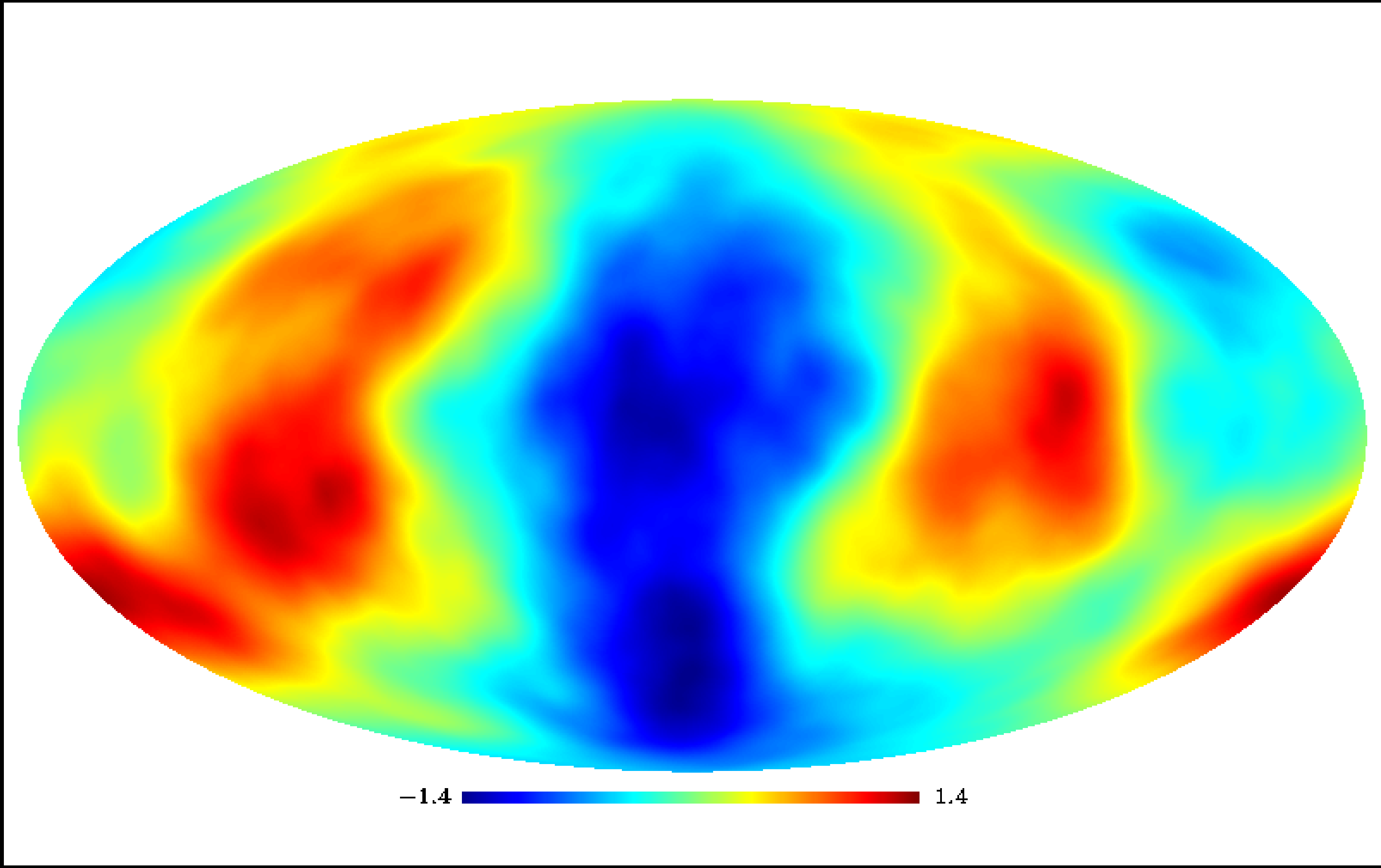
AND FINALLY: IN THE FAR DISTANT FUTURE WE MIGHT BE OBSERVING THE CνB ANISOTROPY

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

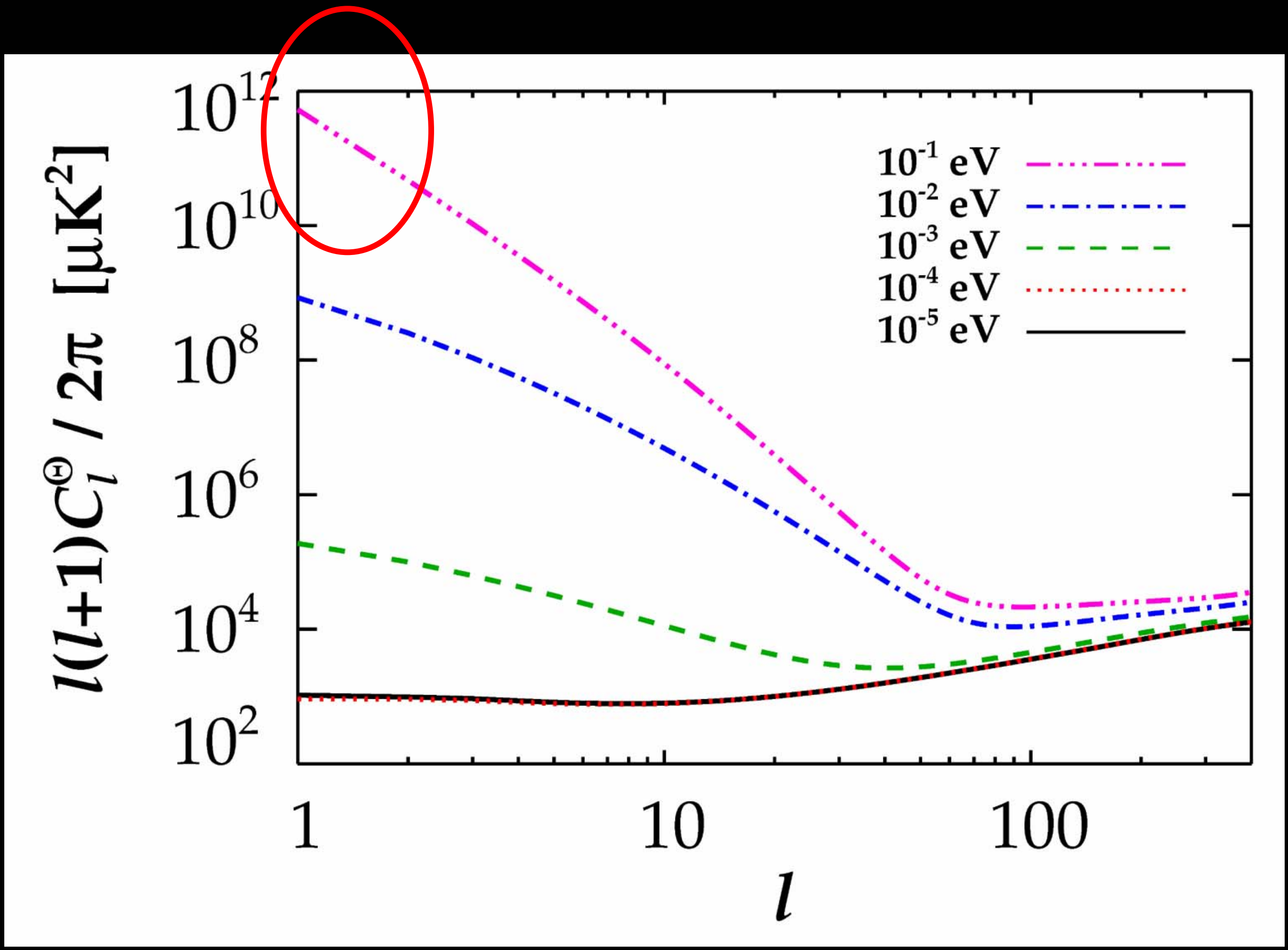
STH & Brandbyge, arXiv:0910.4578 (JCAP)
(see also Michney, Caldwell astro-ph/0608303)

REALISATIONS OF THE CνB FOR DIFFERENT MASSES



$m = 10^{-2}$ eV

ANISOTROPY ~ $O(1)$



STH & Brandbyge, arXiv:0910.4578 (JCAP)

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
- COSMOLOGICAL DATA MIGHT ACTUALLY BE POINTING TO PHYSICS BEYOND THE STANDARD MODEL IN THE FORM OF STERILE NEUTRINOS