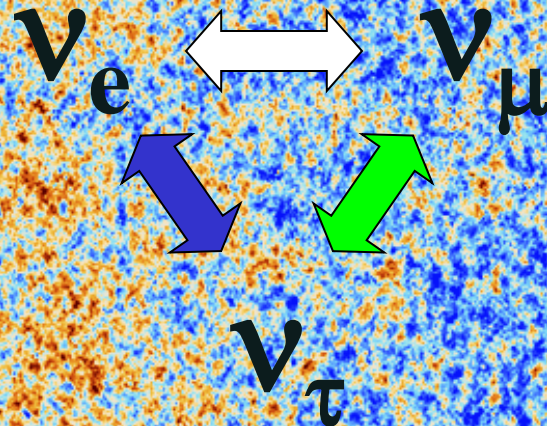
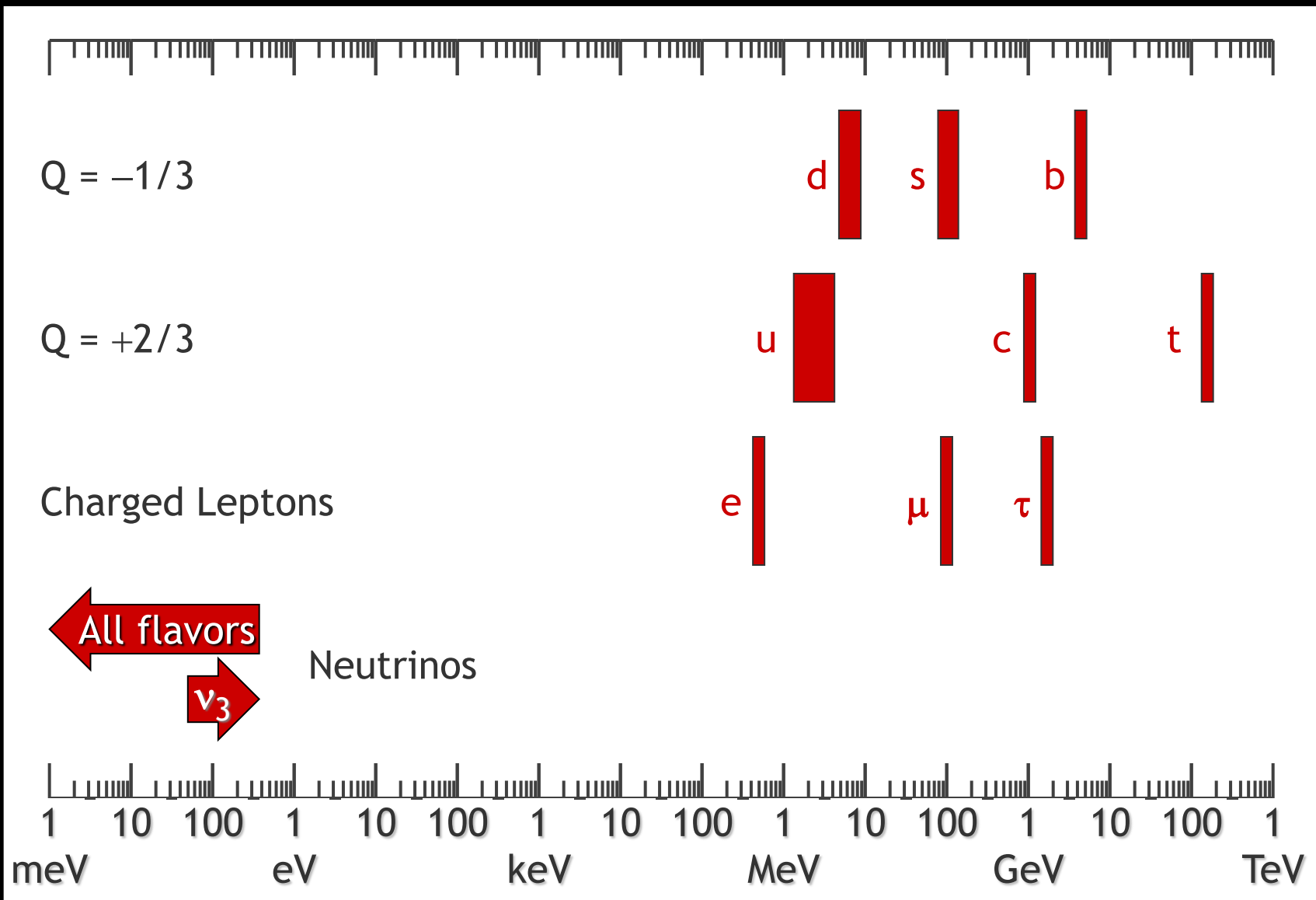


NEUTRINO COSMOLOGY AFTER PLANCK



STEEN HANNESTAD, AARHUS UNIVERSITY
PRAGUE, 23 MAY 2013

Fermion Mass Spectrum



NEUTRINO MIXING (SEE TALK BY S. PASCOLI)

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)

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

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)

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & 0 \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$s_{12}c_{13}$ **"SOLAR ANGLE"**

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

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)

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

"ATMOSPHERIC ANGLE"

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

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)

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

"REACTOR ANGLE"

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

FLAVOUR STATES

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

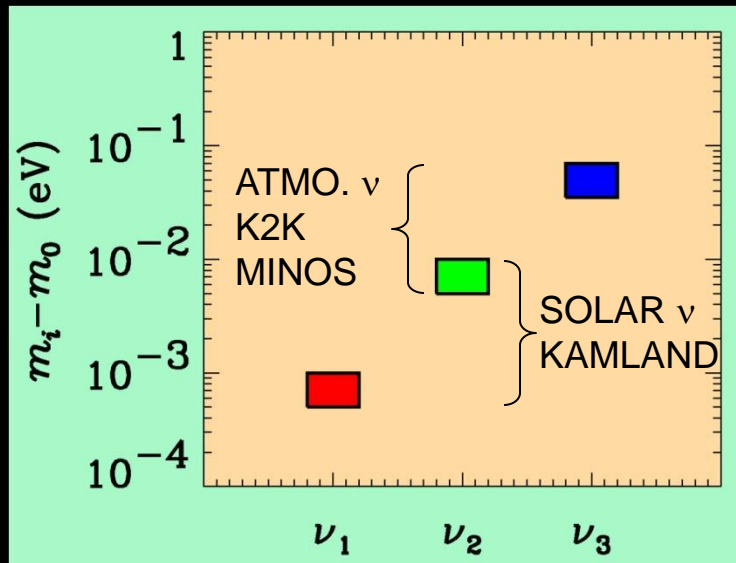
PROPAGATION STATES

MIXING MATRIX (UNITARY)

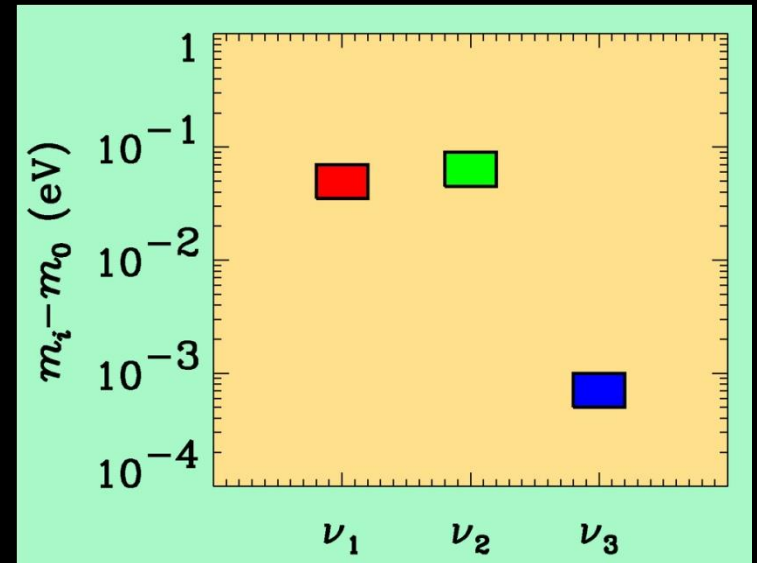
$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{12}s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}e^{i\delta} & s_{23} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}s_{23} + s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

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

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



Normal hierarchy



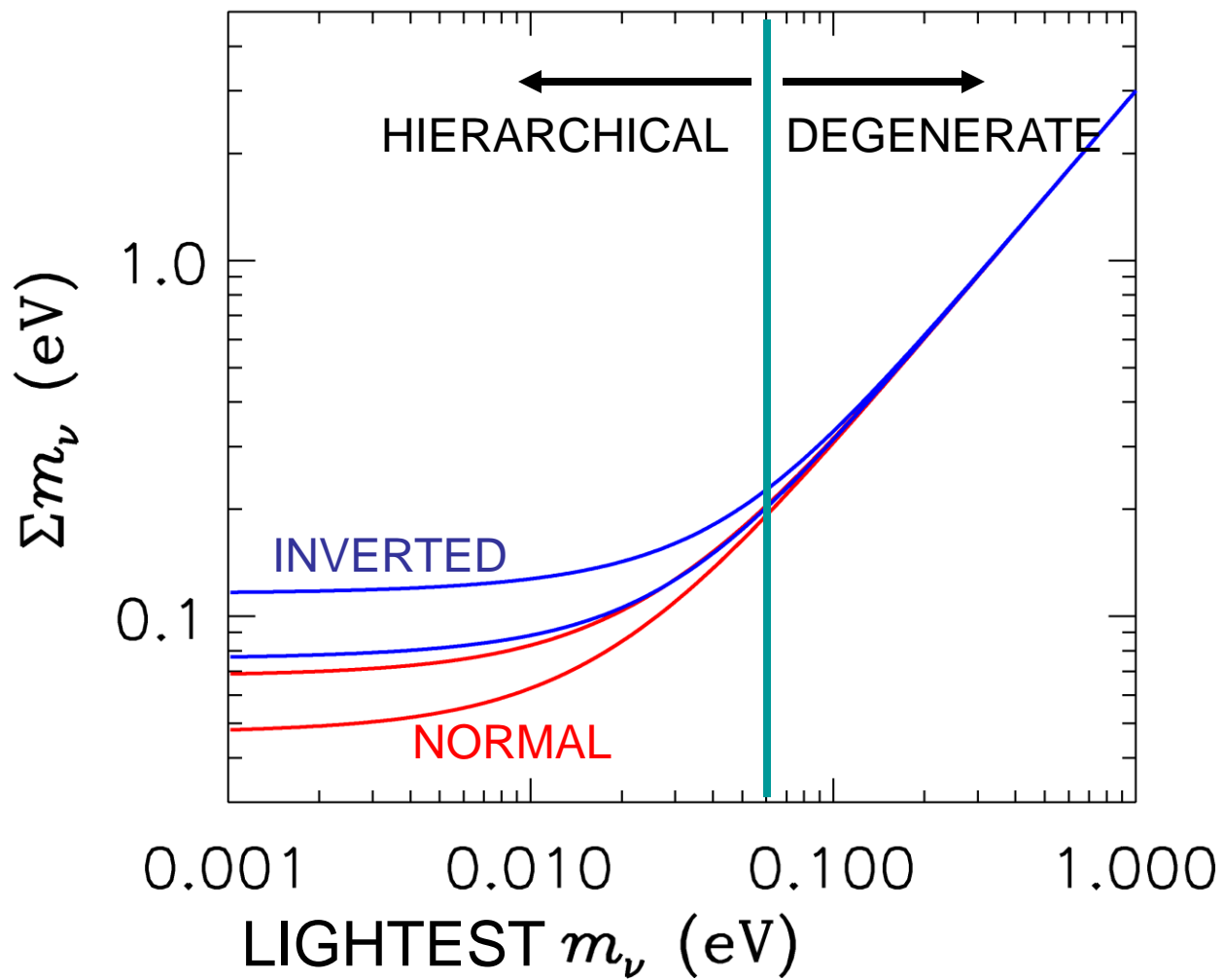
Inverted hierarchy

However, if neutrino masses are degenerate

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

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



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

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

Mainz experiment, final analysis (Kraus et al.)

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

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

This sensitivity will be improved by at least an order of magnitude by KATRIN – See talk by F. Glück

NEUTRINO MASS AND ENERGY DENSITY FROM COSMOLOGY

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

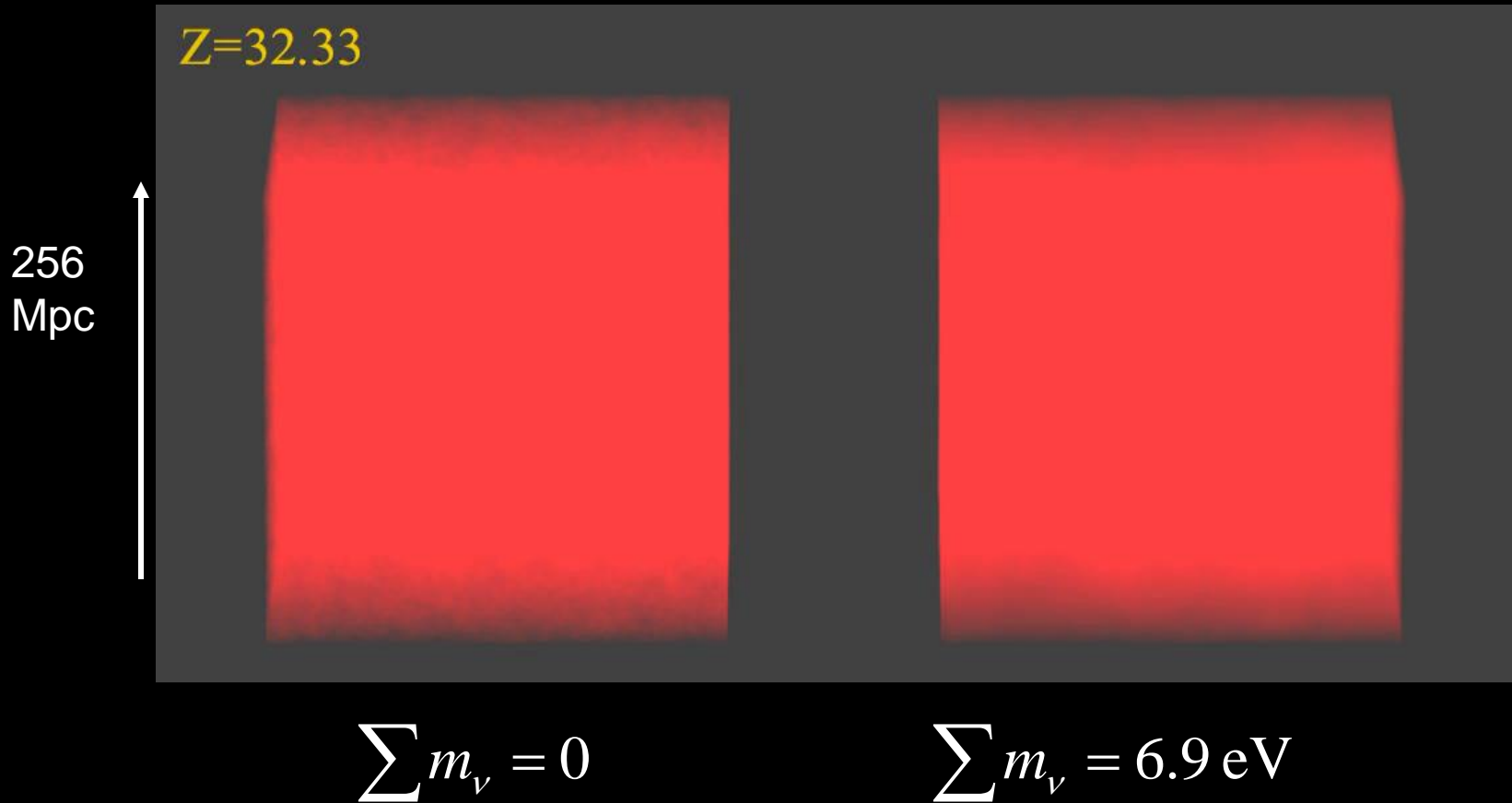
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93 \text{ eV}} \quad \text{FROM} \quad T_\nu = T_\gamma \left(\frac{4}{11} \right)^{1/3} \approx 2 \text{ K}$$

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

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

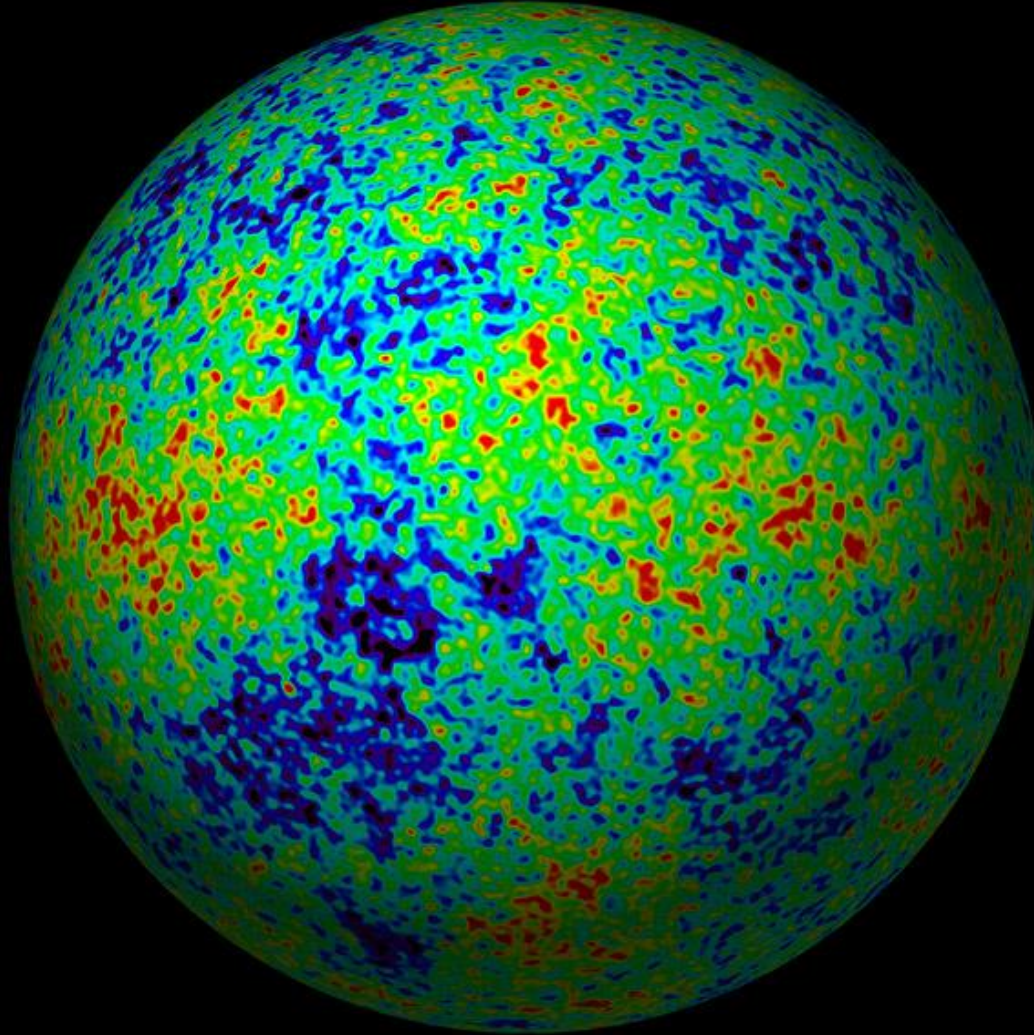
SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO
SUPPRESSION OF POWER ON SMALL SCALES

N-BODY SIMULATIONS OF Λ CDM WITH AND WITHOUT NEUTRINO MASS (768 Mpc³) – GADGET 2



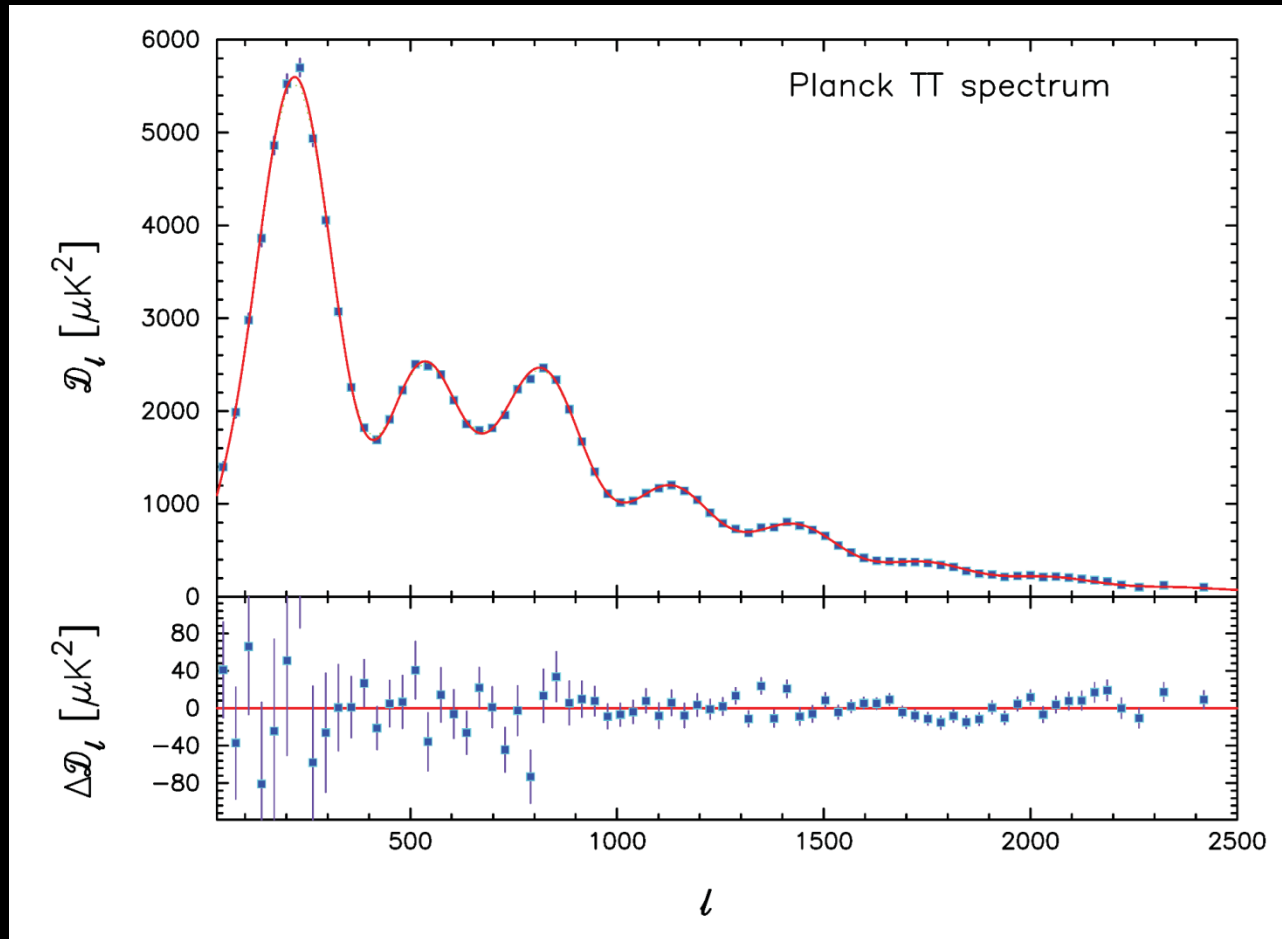
AVAILABLE COSMOLOGICAL DATA

THE COSMIC MICROWAVE BACKGROUND



CMB TEMPERATURE MAP

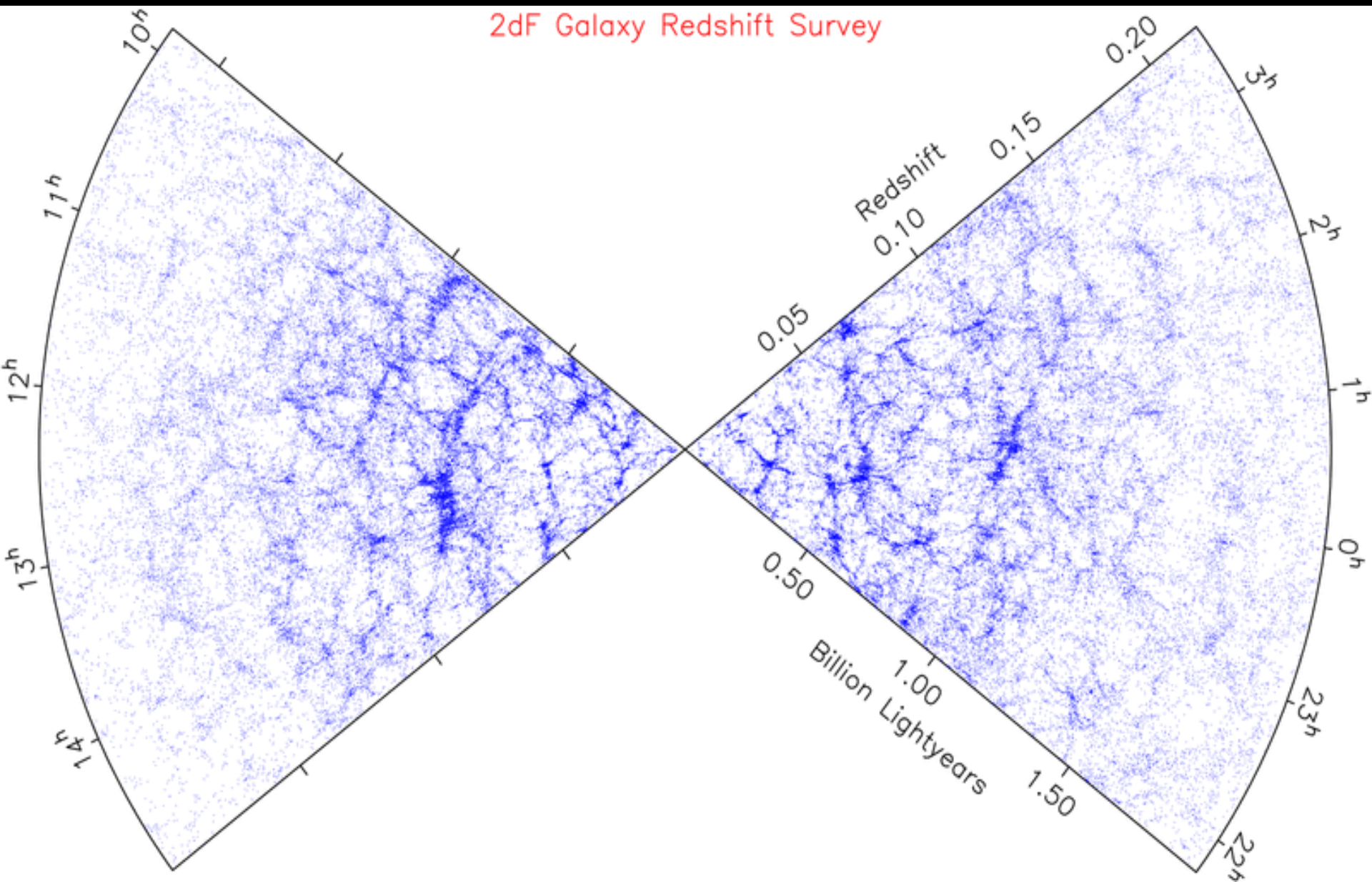
PLANCK TEMPERATURE POWER SPECTRUM



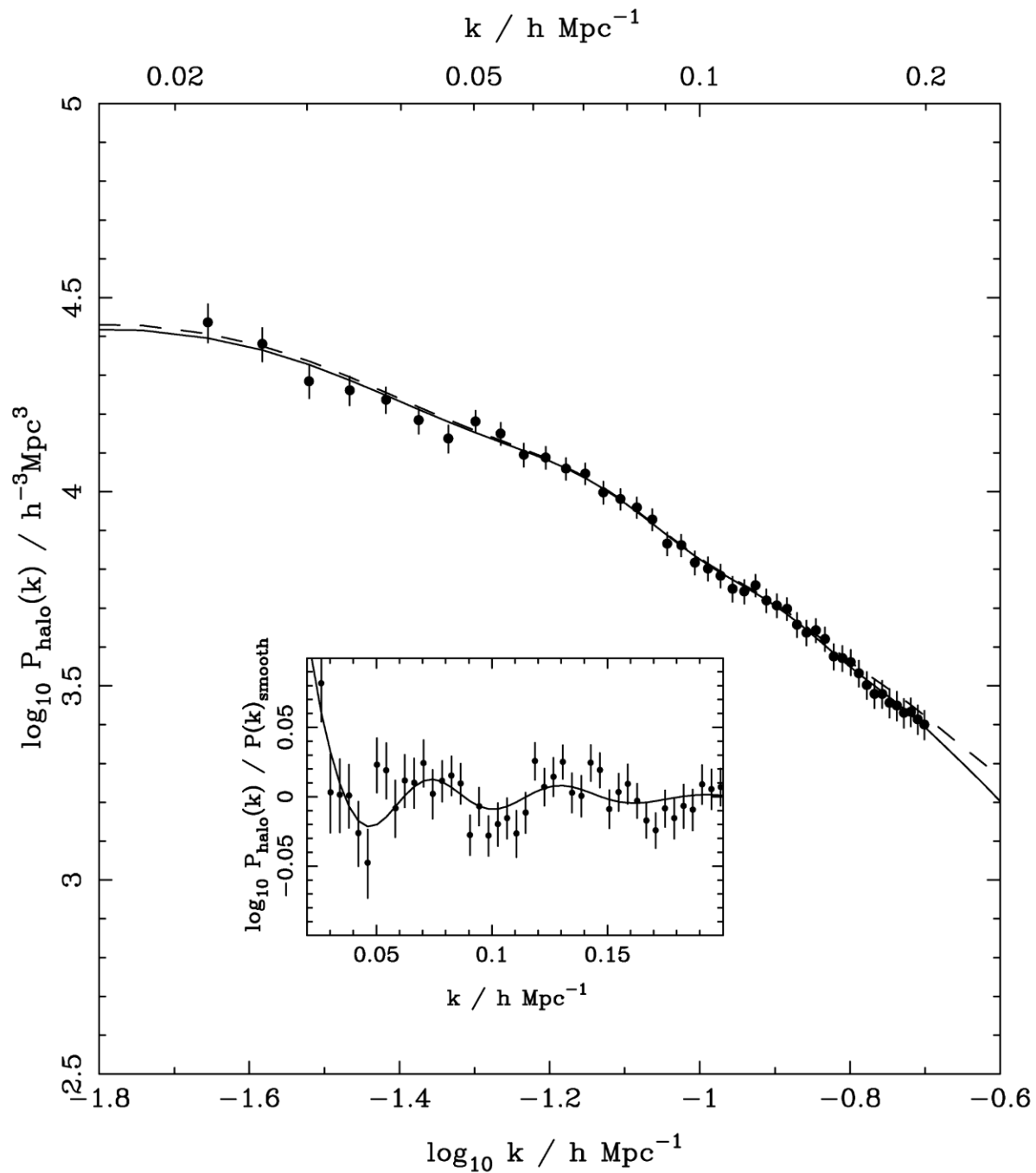
ADE ET AL, ARXIV 1303.5076

ADDITIONAL DATA ON SMALLER SCALES FROM
ATACAMA COSMOLOGY TELESCOPE (Sievers et al. 2013)
SOUTH POLE TELESCOPE (Hou et al. 2012)

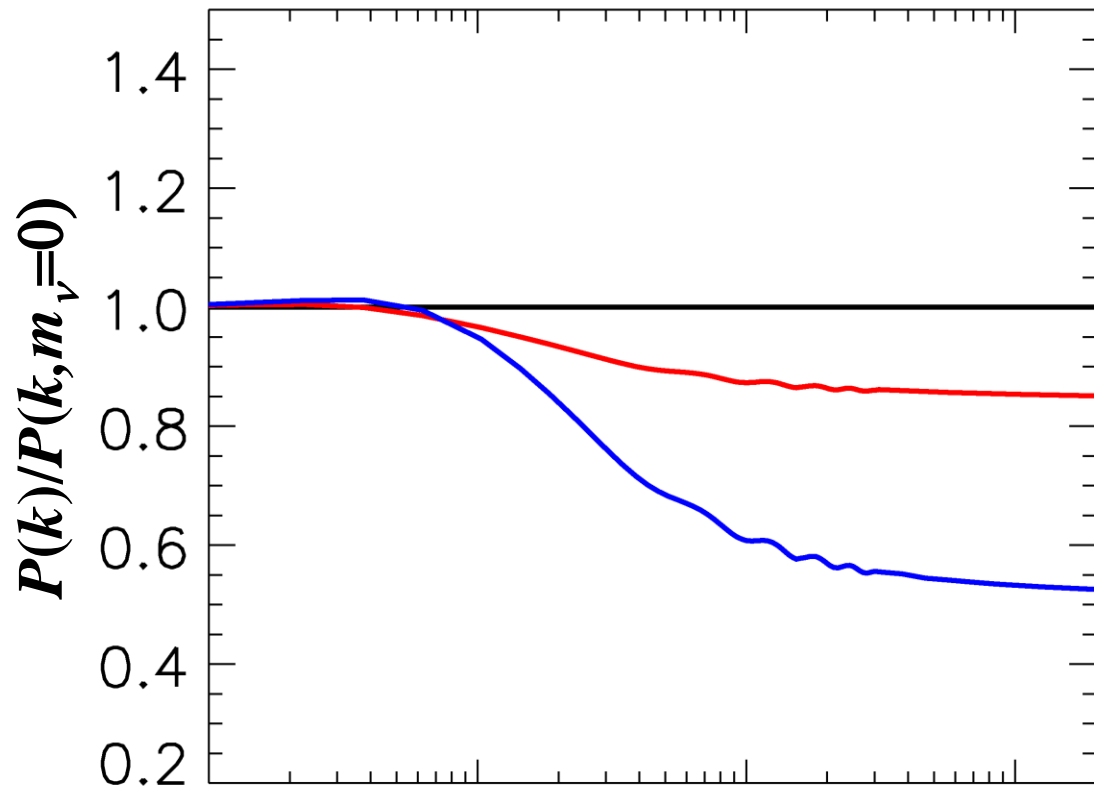
LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS



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



$\Sigma m = 0 \text{ eV}$

$\Sigma m = 0.3 \text{ eV}$

$\Sigma m = 1 \text{ eV}$

$$\frac{\Delta P}{P_{m=0}} (k \gg k_{FS}) \sim -8 \frac{\rho_\nu}{\rho_{TOT}} \frac{1}{k} \quad k \text{ (h/Mpc)}$$

NOW, WHAT ABOUT NEUTRINO
PHYSICS?

WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

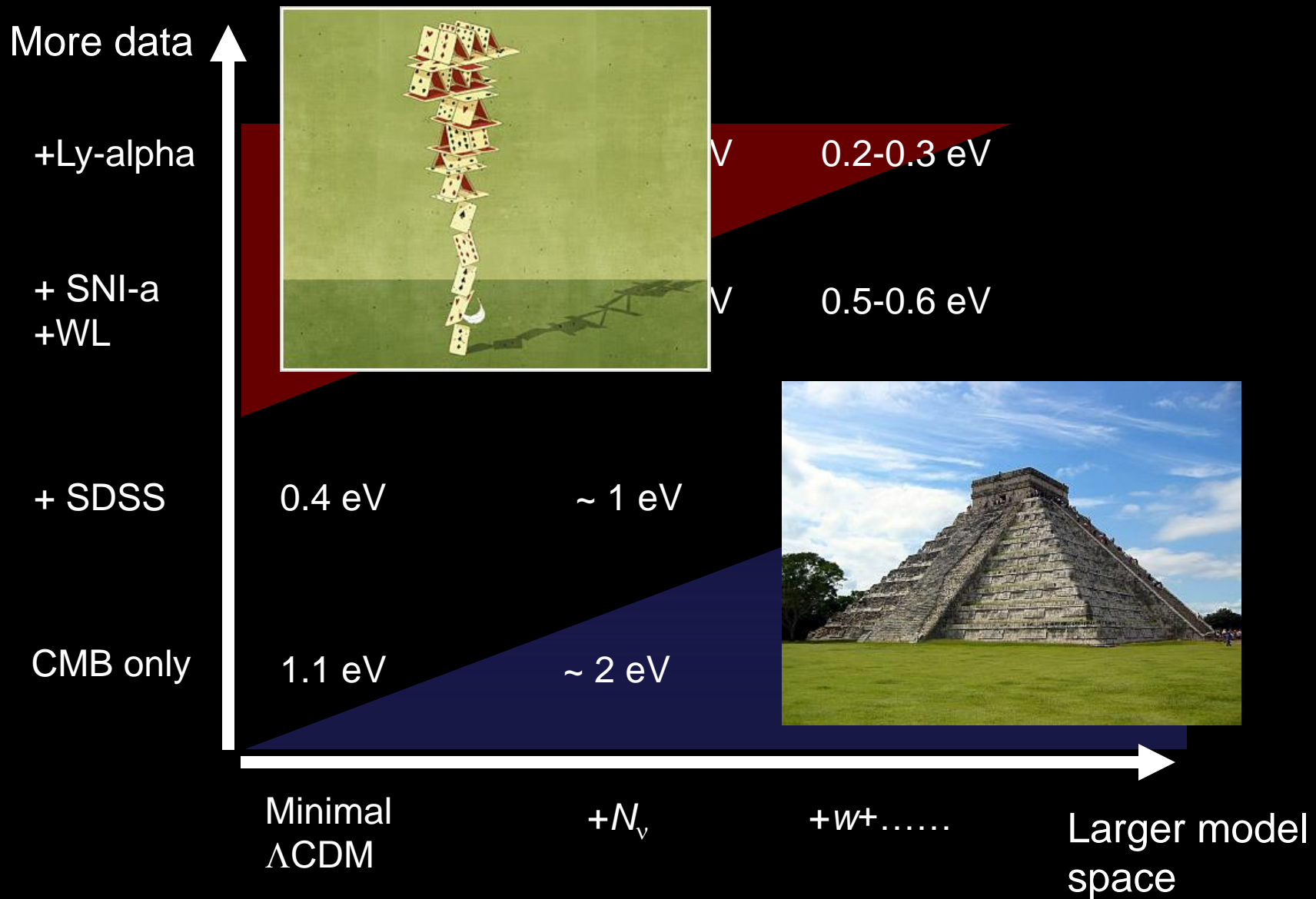
THERE ARE MANY ANALYSES IN THE LITERATURE

$$\sum m_\nu \leq 1.08 \text{ eV @ 95 C.L. Planck only}$$

$$\sum m_\nu \leq 0.32 \text{ eV @ 95 C.L. Planck + BAO}$$

arXiv:1303.5076 (Planck)

THE NEUTRINO MASS FROM COSMOLOGY PLOT



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

WHAT IS N_ν ?

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

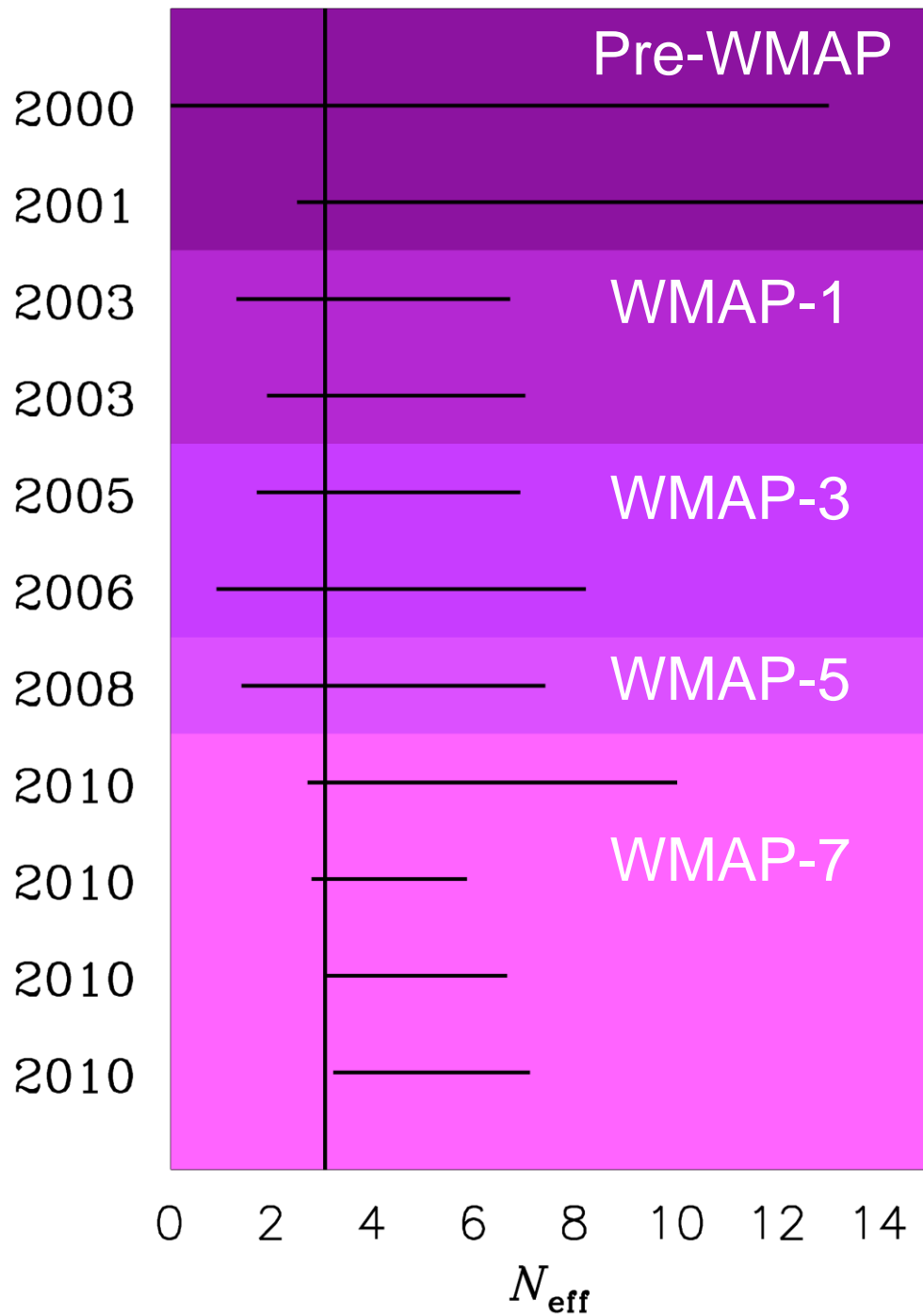
THE STANDARD MODEL PREDICTION IS

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

Mangano et al., hep-ph/0506164

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

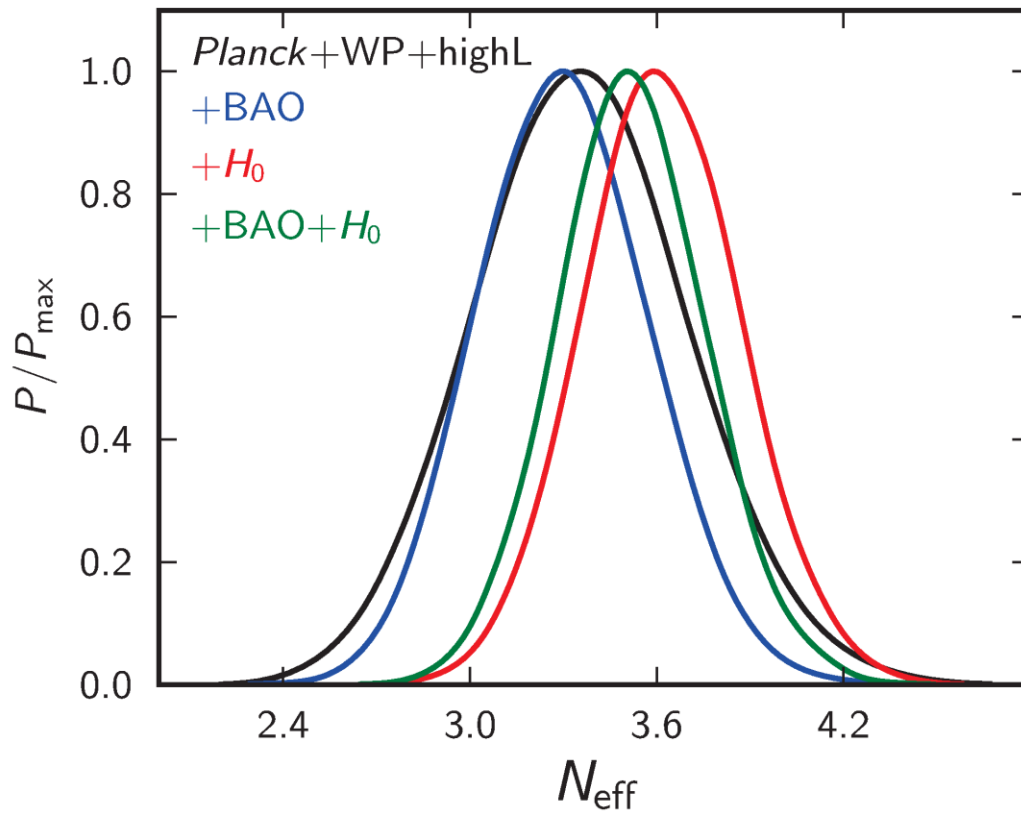
TIME EVOLUTION OF
THE 95% BOUND ON
 N_{ν}



$$N_{eff} = 3.36_{-0.64}^{+0.68} @ 95\% \quad \text{Planck only}$$

$$N_{eff} = 3.52_{-0.45}^{+0.48} @ 95\% \quad \text{Planck+BAO+}H_0$$

THE SITUATION (UNFORTUNATELY) NOT YET RESOLVED....



ADE ET AL. 2013

THE CULPRIT IS THE HUBBLE PARAMETER MEASUREMENT

$$H_0 = 67.3 \pm 1.2 \quad \text{Planck, assuming } \Lambda\text{CDM}$$

$$H_0 = 74 \pm 2 \quad \text{HST data}$$

CAN BE MADE CONSISTENT PROVIDED THERE IS "DARK RADIATION"

A STERILE NEUTRINO IS PERHAPS THE MOST OBVIOUS CANDIDATE FOR AN EXPLANATION OF THE POSSIBLE 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 (PRL)

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

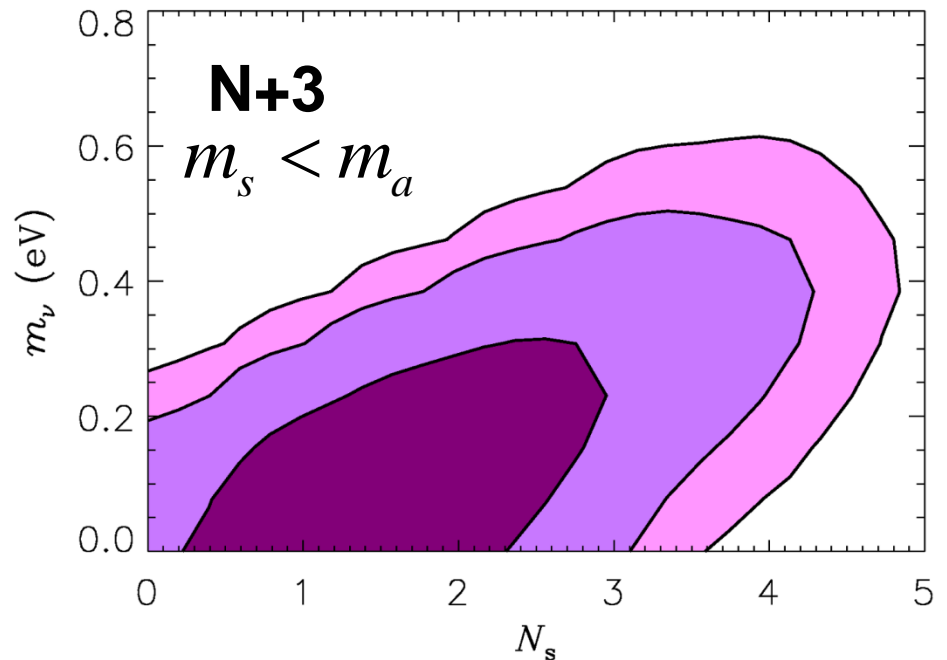
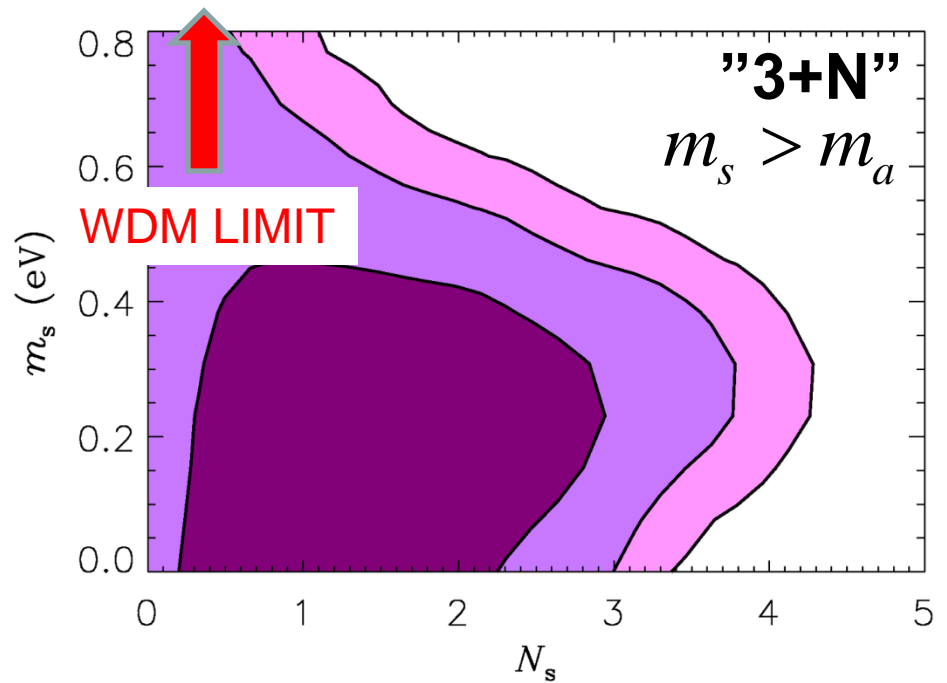
Hamann et al 2011

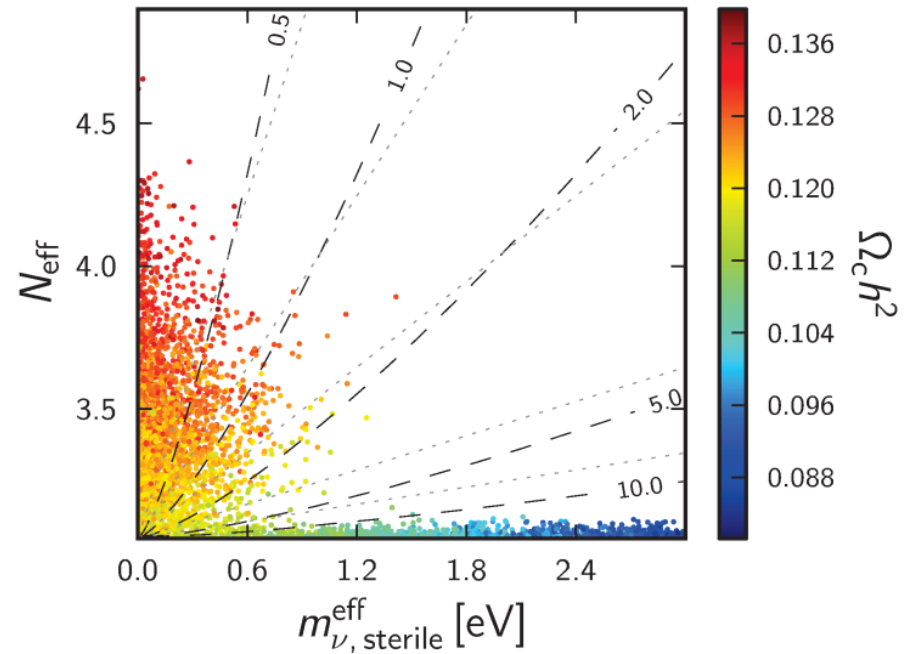
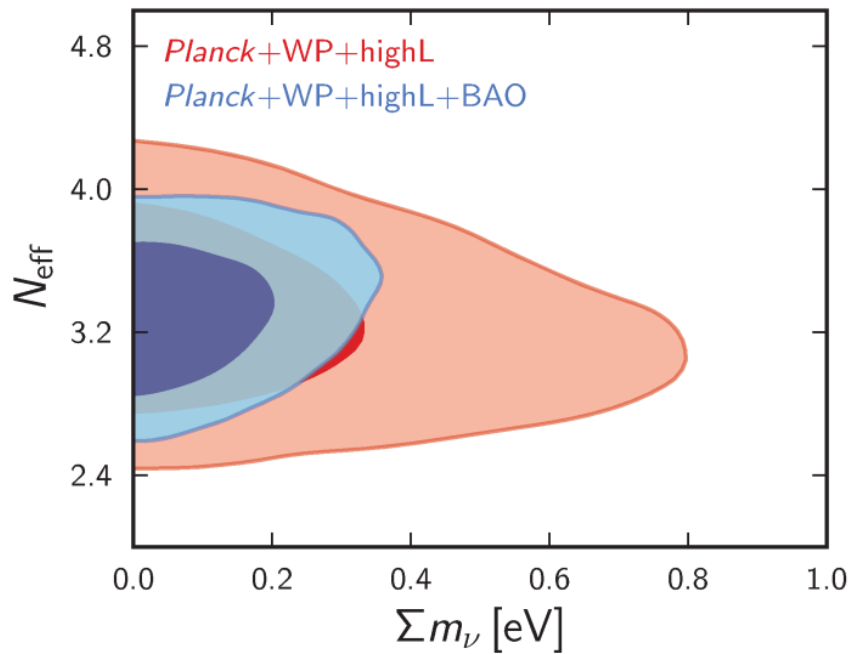
Joudaki et al 2012

Motohashi et al. 2012

Archidiacono et al 2012, 2013

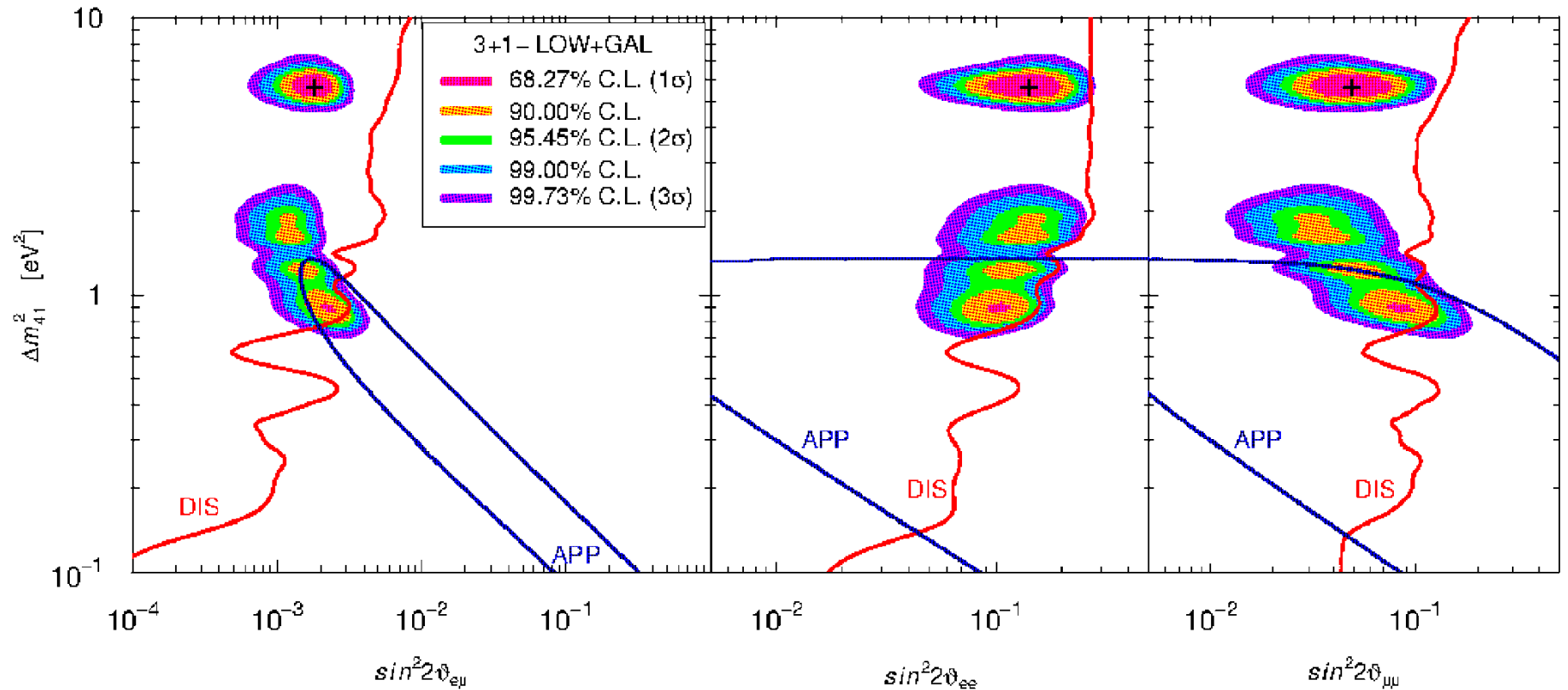
and many others



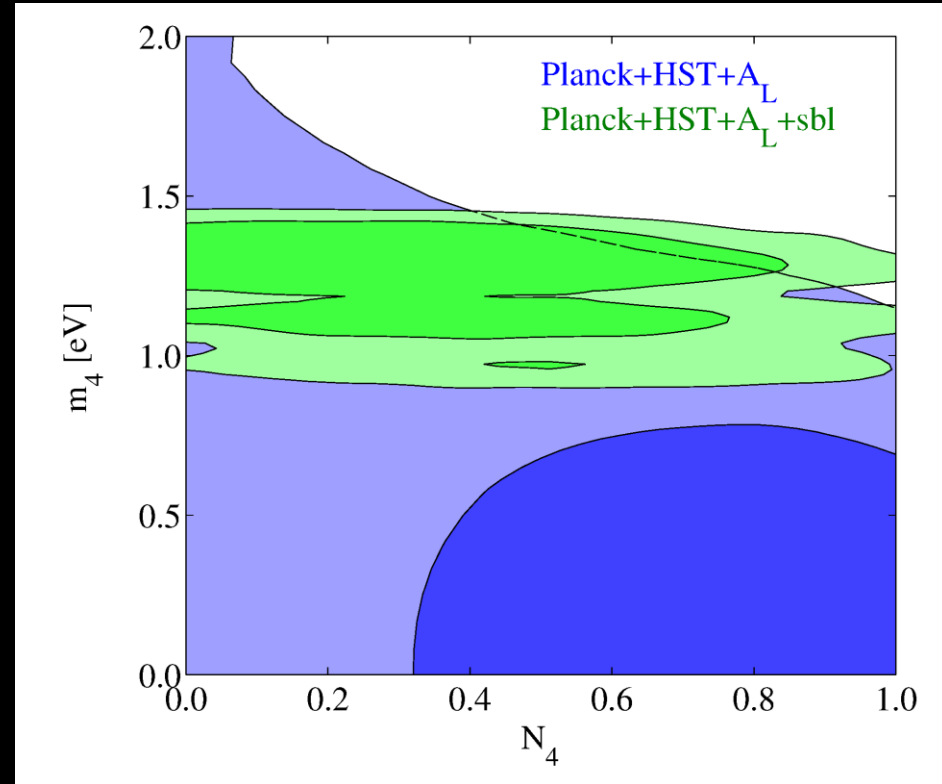
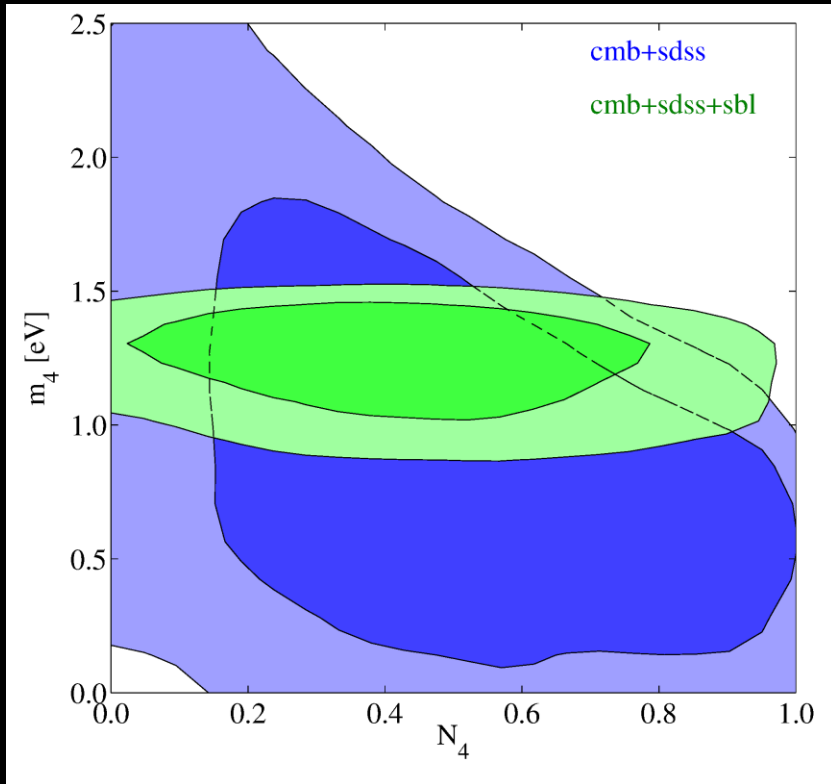


ADE ET AL. 2013 (WITHOUT HUBBLE DATA!)

THERE ARE A NUMBER OF HINTS FROM EXPERIMENTS THAT A FOURTH, eV-MASS STERILE STATE MIGHT BE NEEDED: LSND, MiniBoone, reactor anomaly, Gallium



Giunti & Laveder 2011 (and many other analyses)



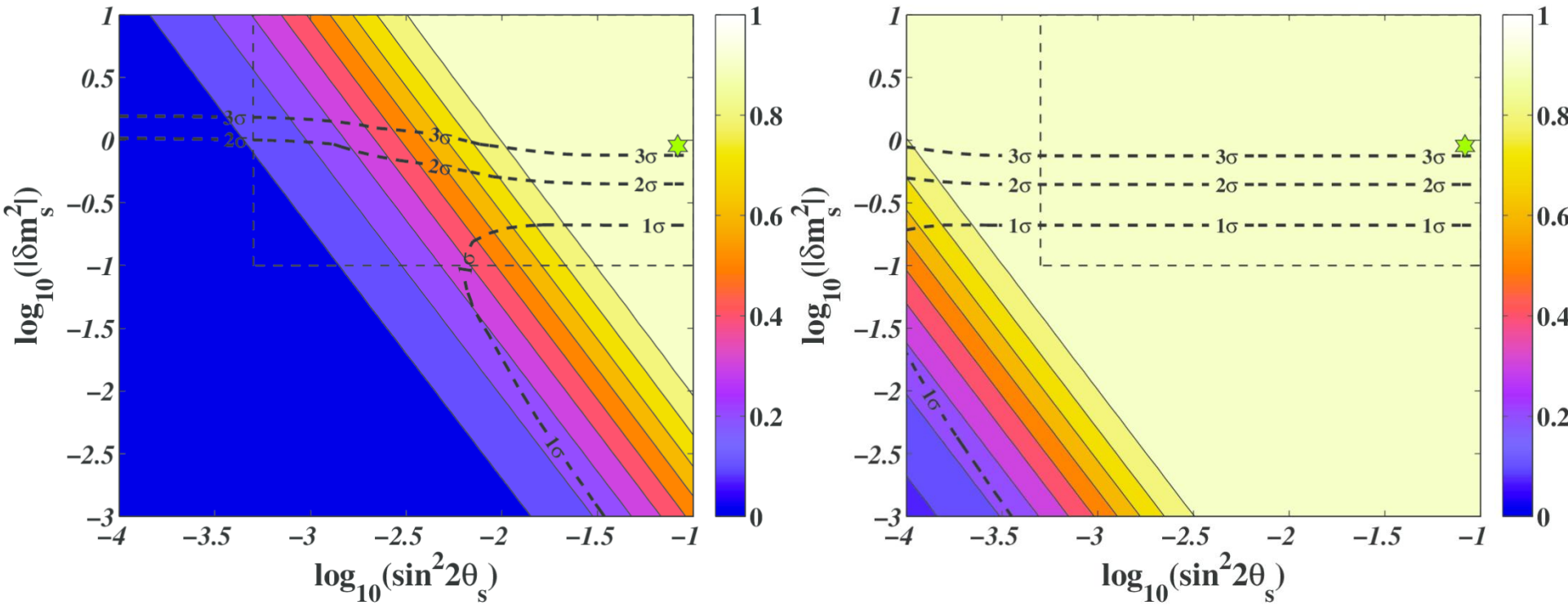
Archidiacono, Fornengo, Giunti, STH, Melchiorri, arXiv:1302.6720 (to appear in PRD)

HOW DO THESE TWO HINTS FIT TOGETHER? CAN THEY BE EXPLAINED BY THE SAME PHYSICS?

SHORT ANSWER: IT IS DIFFICULT WITHOUT MODIFYING COSMOLOGY BUT DEPENDS ON THE SPECIFIC ANALYSIS
(Hamann et al. 2011, Joudaki 2012)

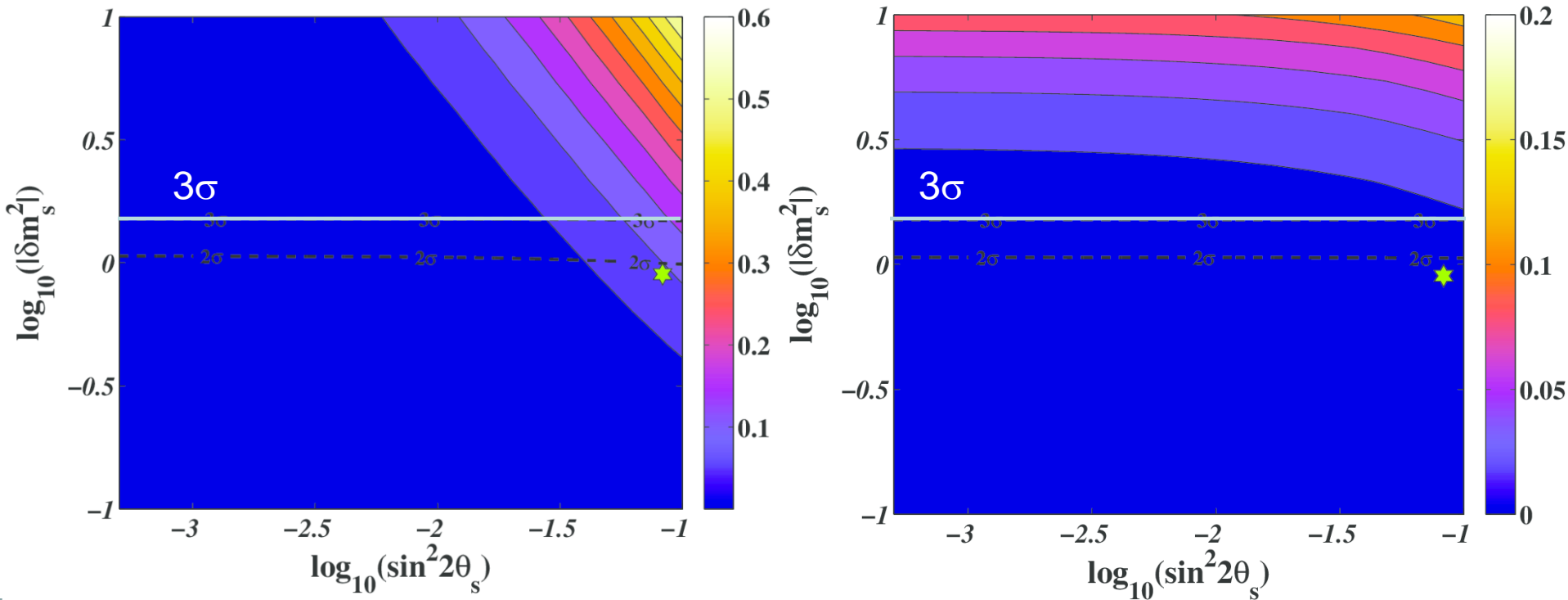
A LARGE PRIMORDIAL LEPTON ASYMMETRY CAN RECONCILE THE DATA (STH, Tamborra, Tram 2012)

STERILE NEUTRINO THERMALISATION WITH ZERO LEPTON ASYMMETRY



STH, Tamborra, Tram 2012

STERILE NEUTRINO THERMALISATION WITH LARGE LEPTON ASYMMETRY

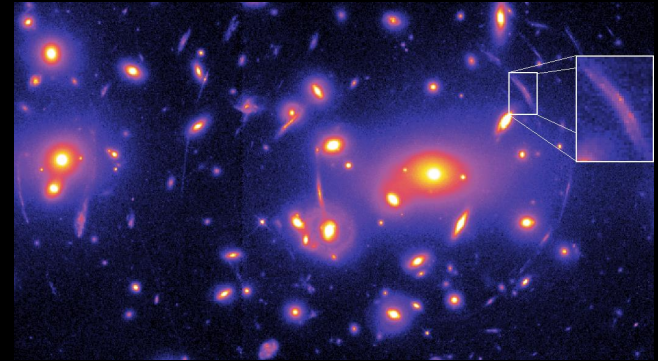
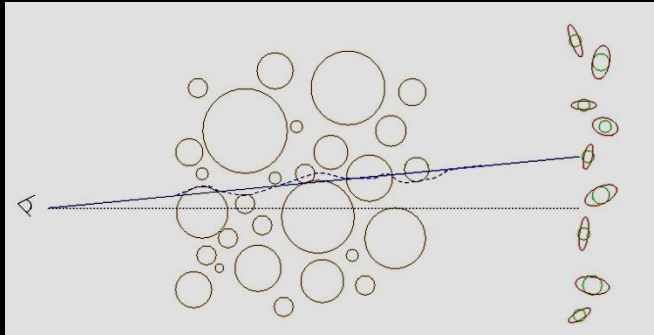


STH, Tamborra, Tram 2012

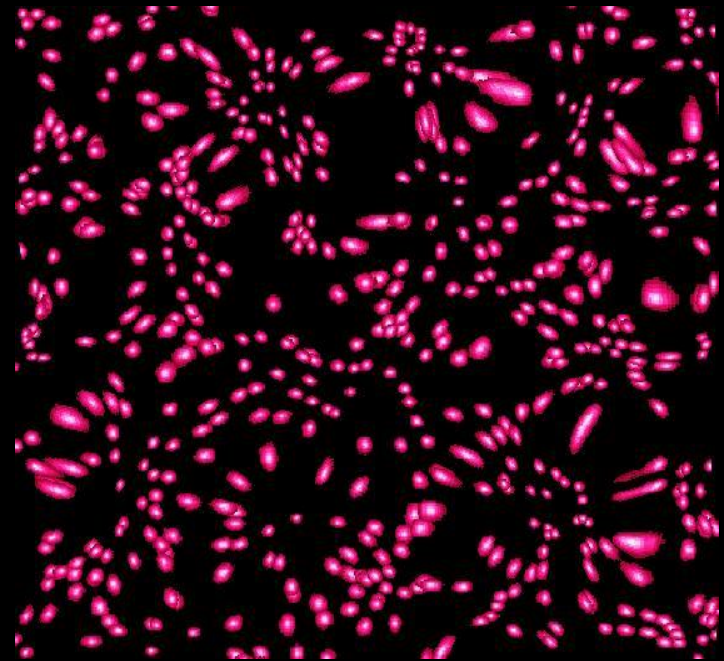
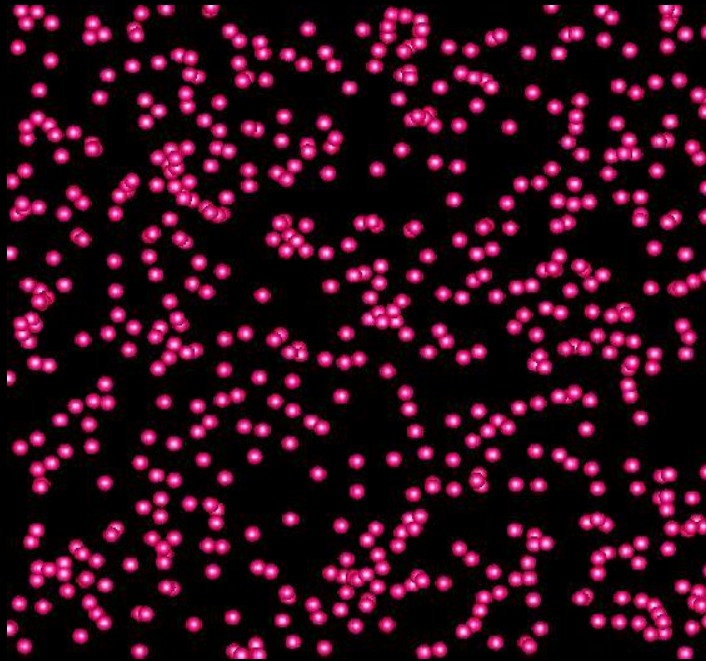
WHAT IS IN STORE FOR THE FUTURE?

- BETTER CMB POLARIZATION MEASUREMENTS (PLANCK)
- LARGE SCALE STRUCTURE SURVEYS AT HIGHER REDSHIFT AND IN LARGER VOLUMES
- 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

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

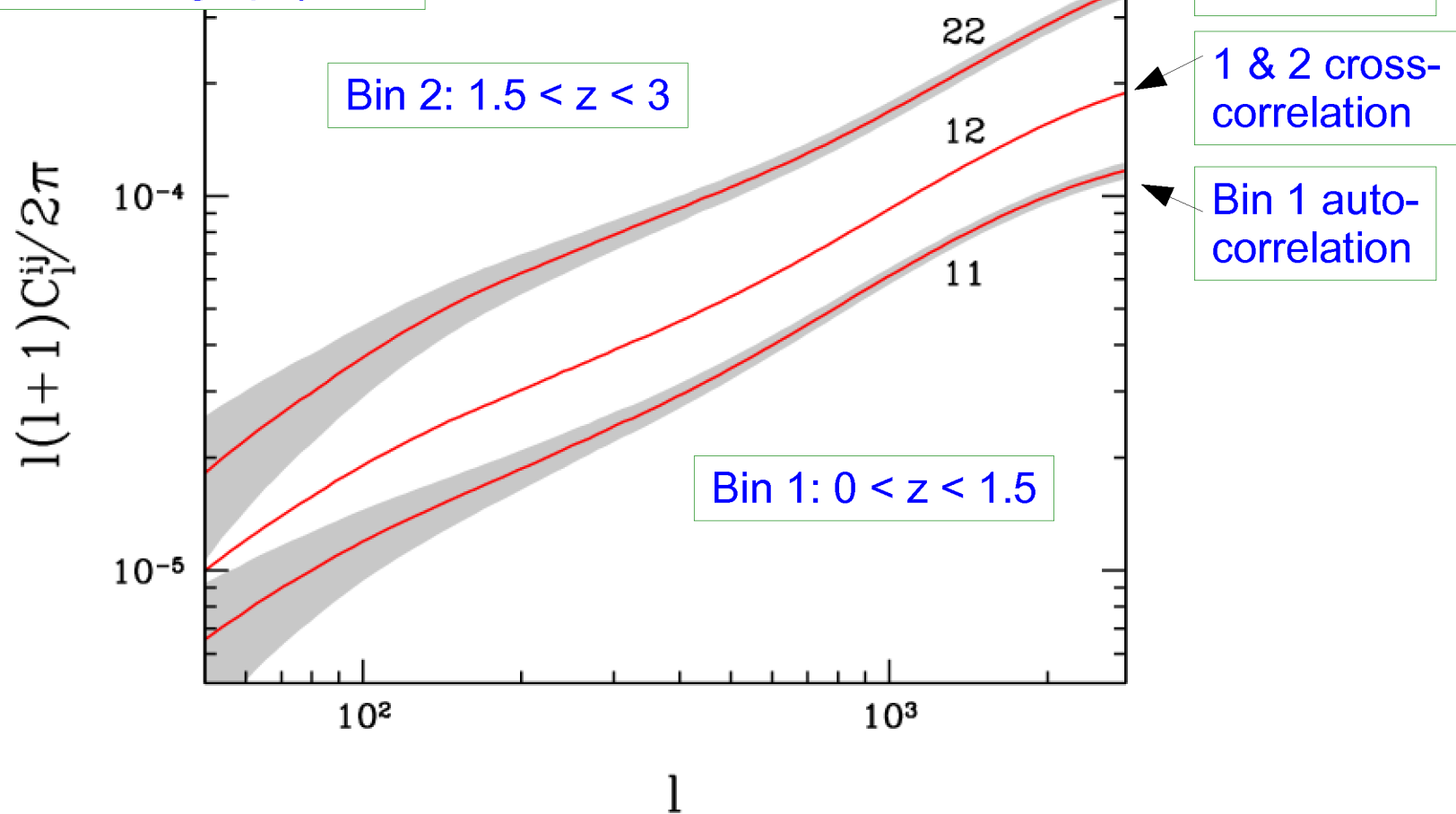
$P(\ell/r, \chi)$ MATTER POWER SPECTRUM (NON-LINEAR)

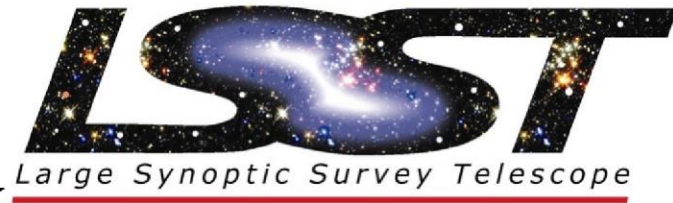
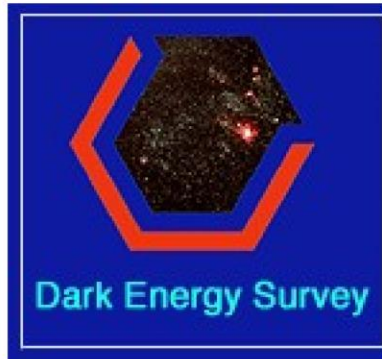
$$g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi'$$

WEIGHT FUNCTION
DESCRIBING LENSING
PROBABILITY

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

Shear power spectra
for 2 tomography bins





Future surveys
with lensing capacity

Space-based

Ground-based

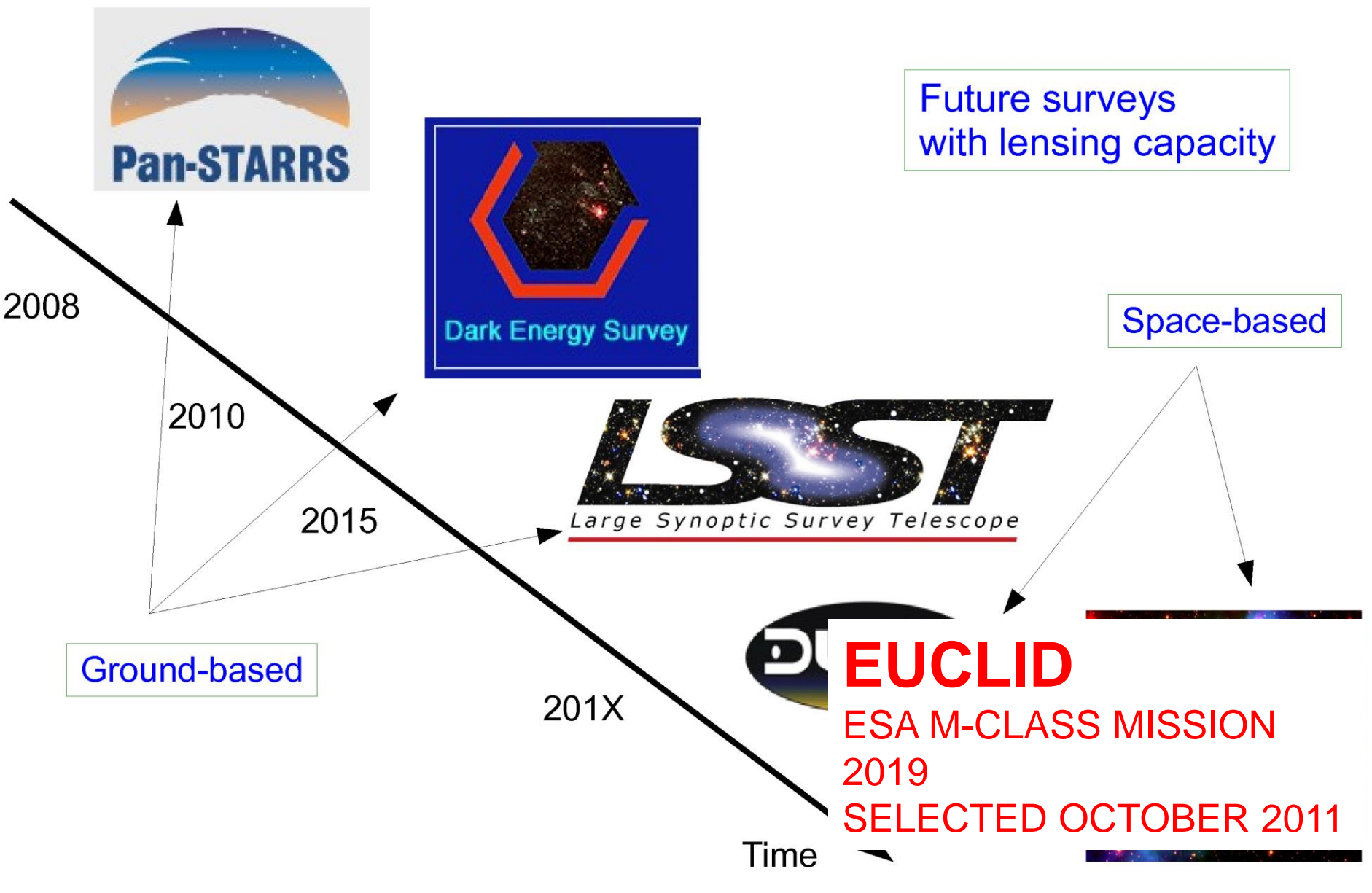
2008

2010

2015

201X

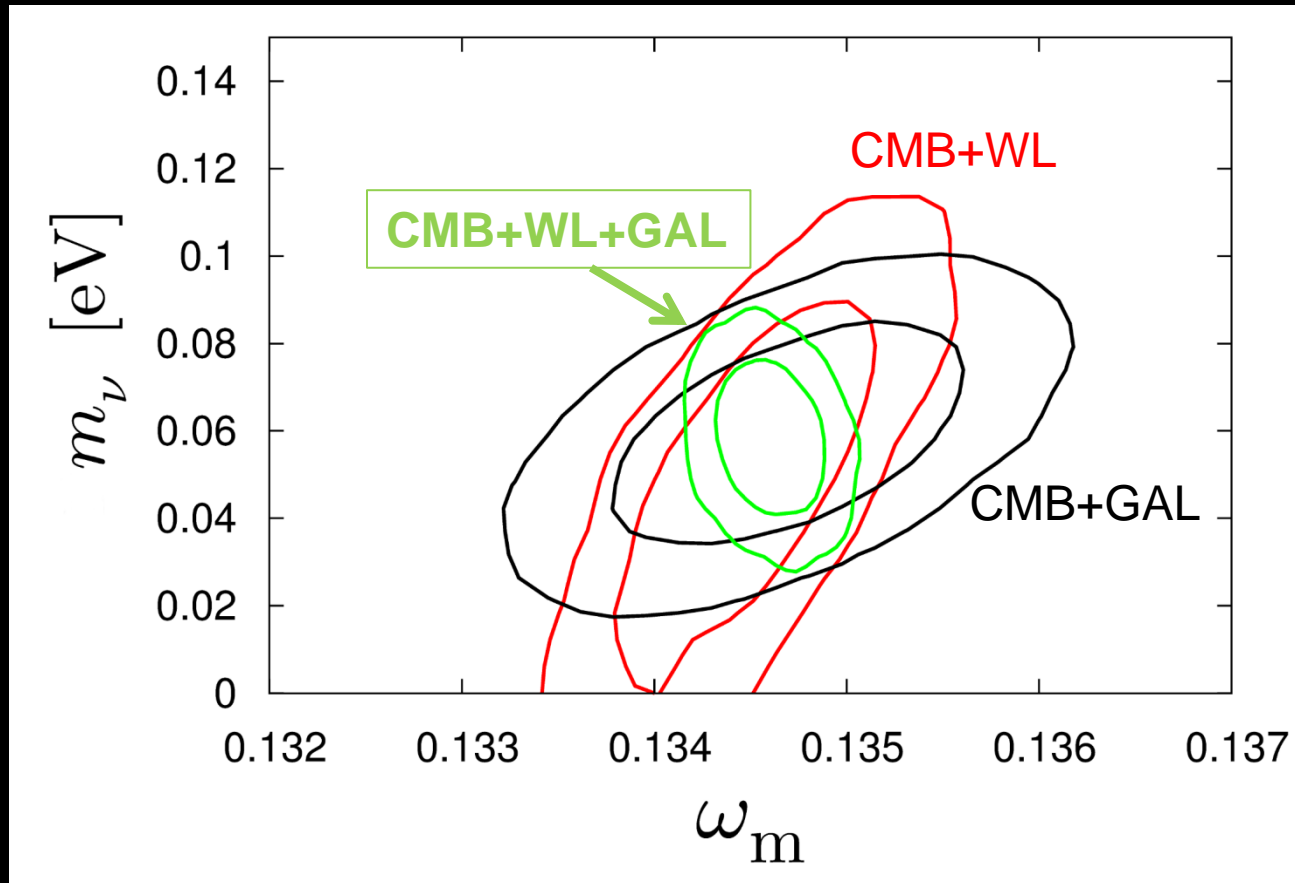
Time



EUCLID WILL FEATURE:

- A WEAK LENSING MEASUREMENT OUT TO $z \sim 2$, COVERING APPROXIMATELY 20,000 deg^2 (THIS WILL BE MAINLY PHOTOMETRIC)
- A GALAXY SURVEY OF ABOUT $\text{few} \times 10^7$ GALAXIES (75 x SDSS)
- A WEAK LENSING BASED CLUSTER SURVEY

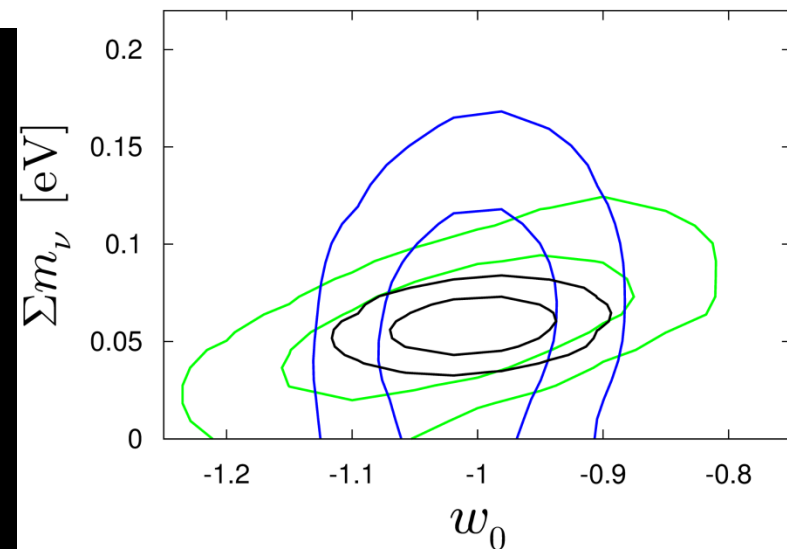
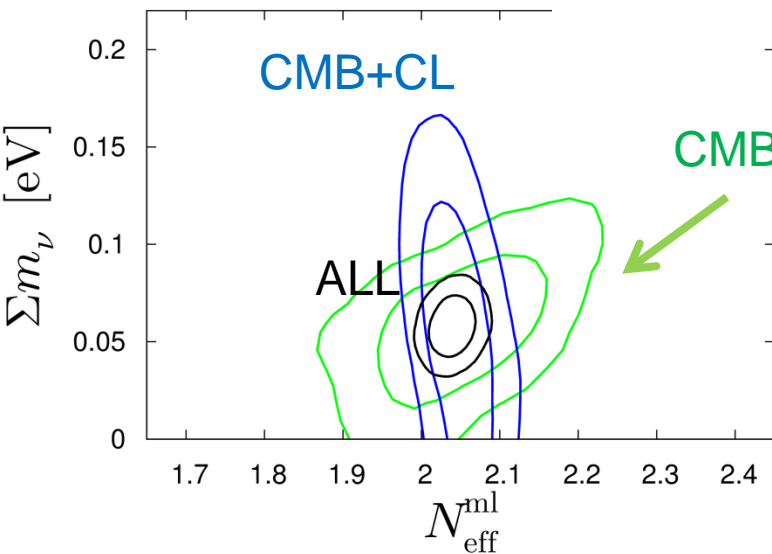
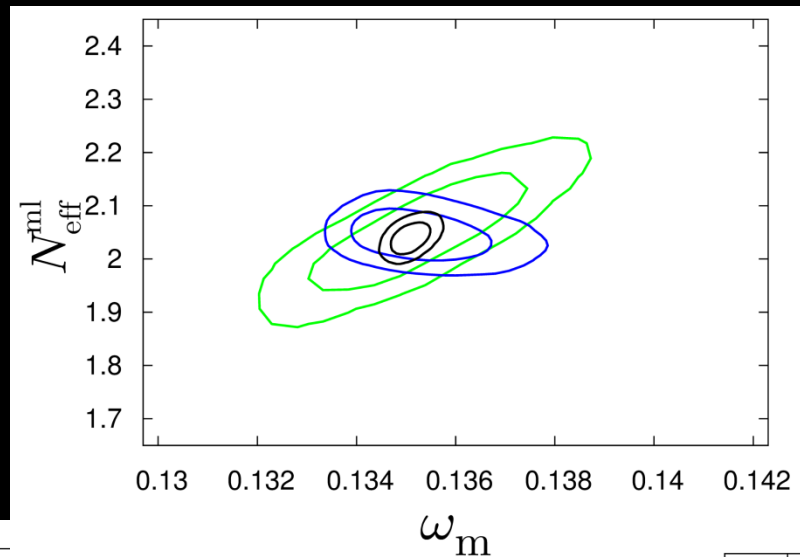
HAMANN, STH, WONG 2012: COMBINING THE EUCLID WL AND GALAXY SURVEYS WILL ALLOW FOR AT A 2.5-5 σ DETECTION OF THE NORMAL HIERARCHY (DEPENDING ON ASSUMPTIONS ABOUT BIAS)



arXiv:1209.1043

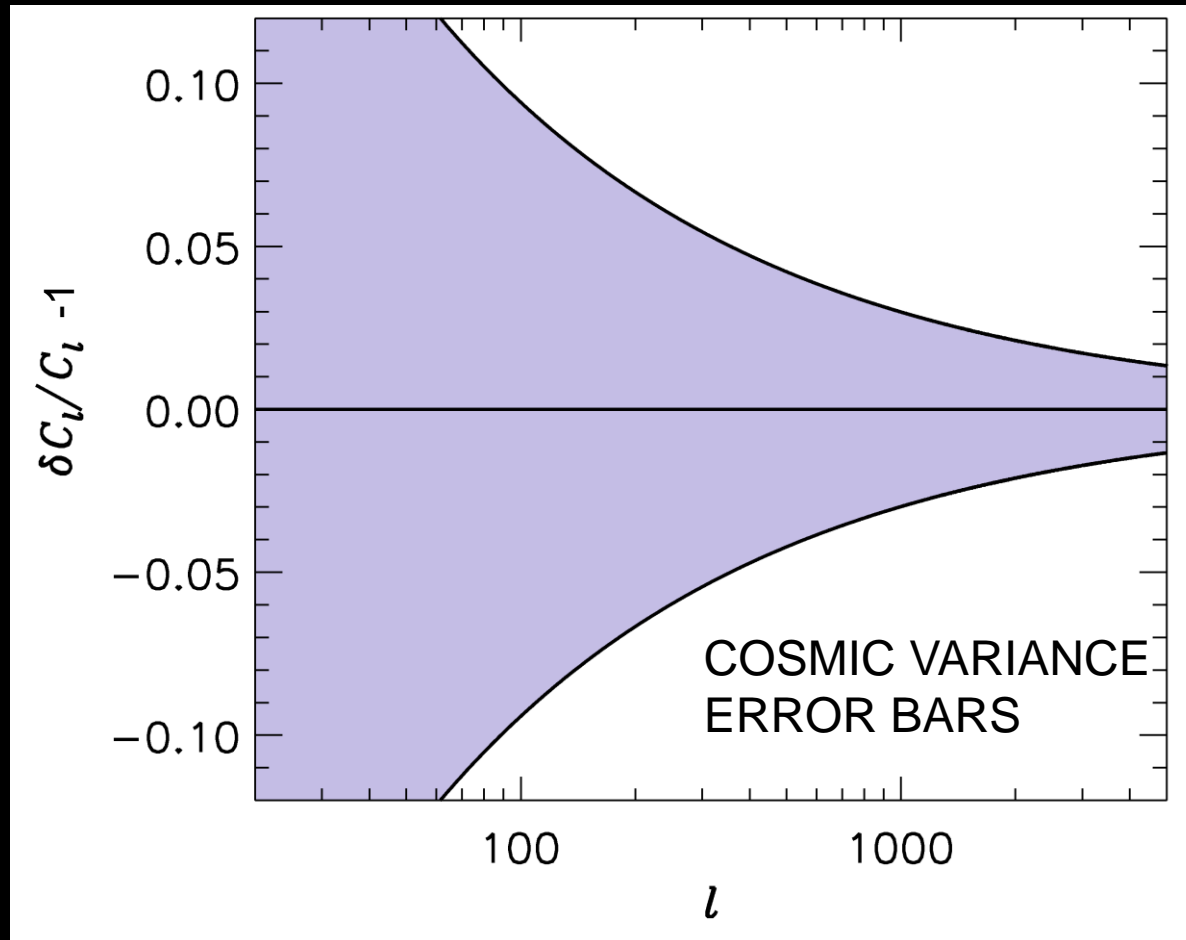
Basse, Bjælde, Hamann, STH, Wong 2013: Adding information on the cluster mass function will allow for a 5σ detection of non-zero neutrino mass, even in very complex cosmological models with time-varying dark energy

arXiv:1304.2321



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

FUTURE SURVEYS LIKE EUCLID 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

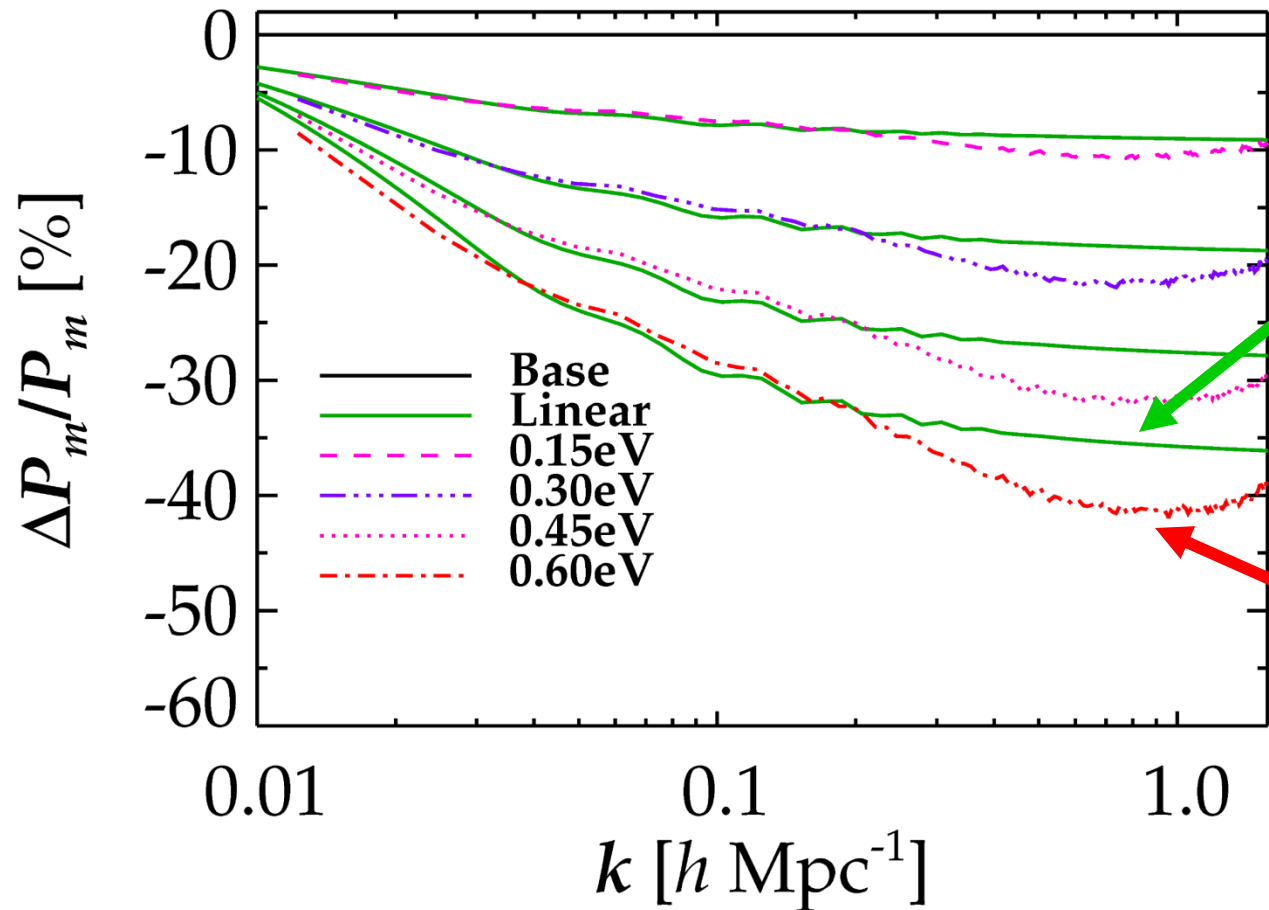
- BARYONIC PHYSICS - STAR FORMATION, SN FEEDBACK,.....

- NEUTRINOS, EVEN WITH NORMAL HIERARCHY

- NON-LINEAR GRAVITY

-

NON-LINEAR EVOLUTION PROVIDES AN ADDITIONAL SUPPRESSION OF FLUCTUATION POWER IN MODELS WITH MASSIVE NEUTRINOS



LINEAR THEORY

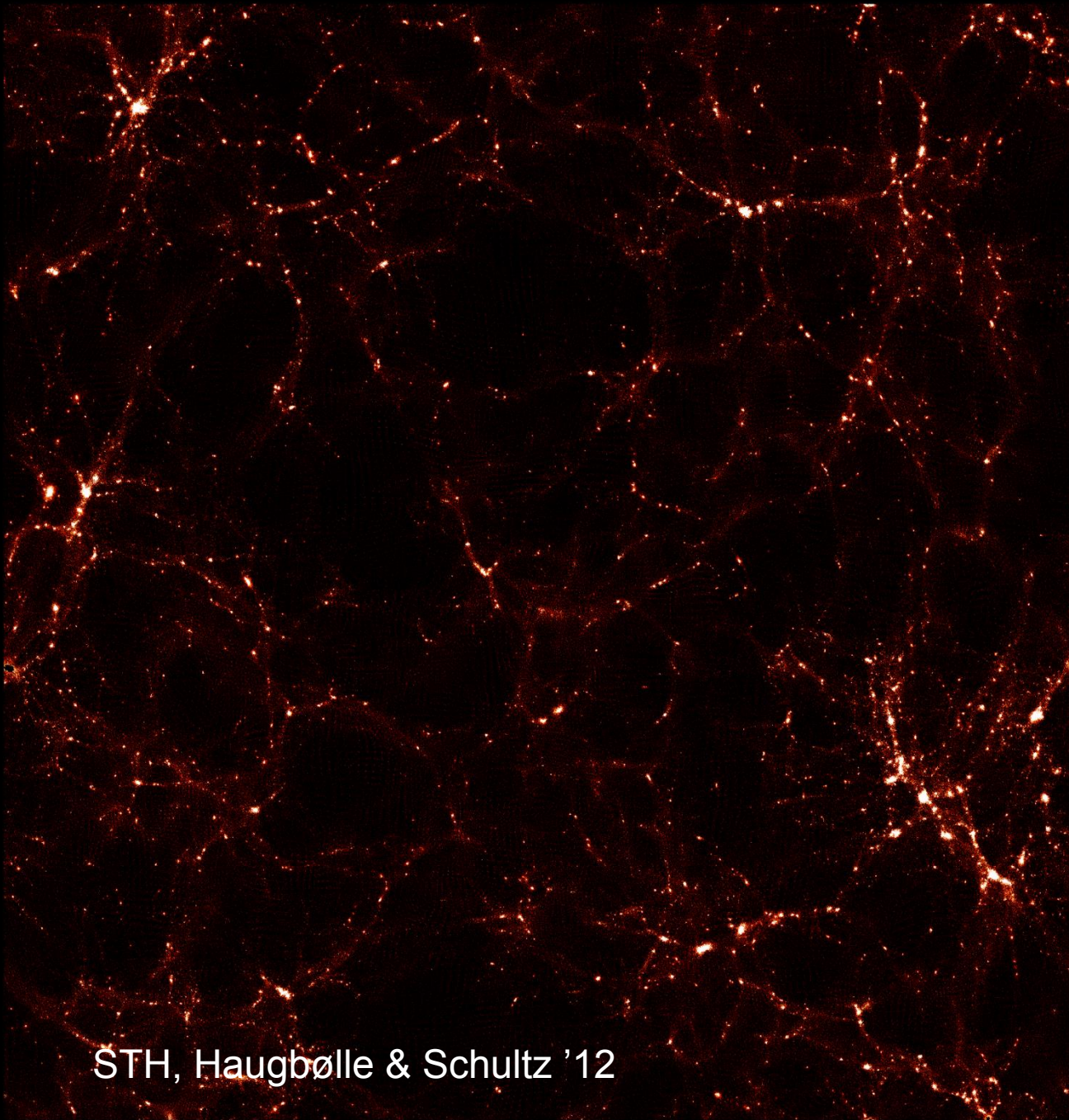
$$\frac{\Delta P}{P} \sim -8 \frac{\Omega_\nu}{\Omega_m}$$

FULL NON-LINEAR

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

Brandbyge, STH, Haugbølle, Thomsen '08
 Brandbyge & STH '09, '10, Viel, Haehnelt, Springel '10
 STH, Haugbølle & Schultz '12, Wagner, Verde & Jimenez '12
 Ali-Hamoud & Bird '12

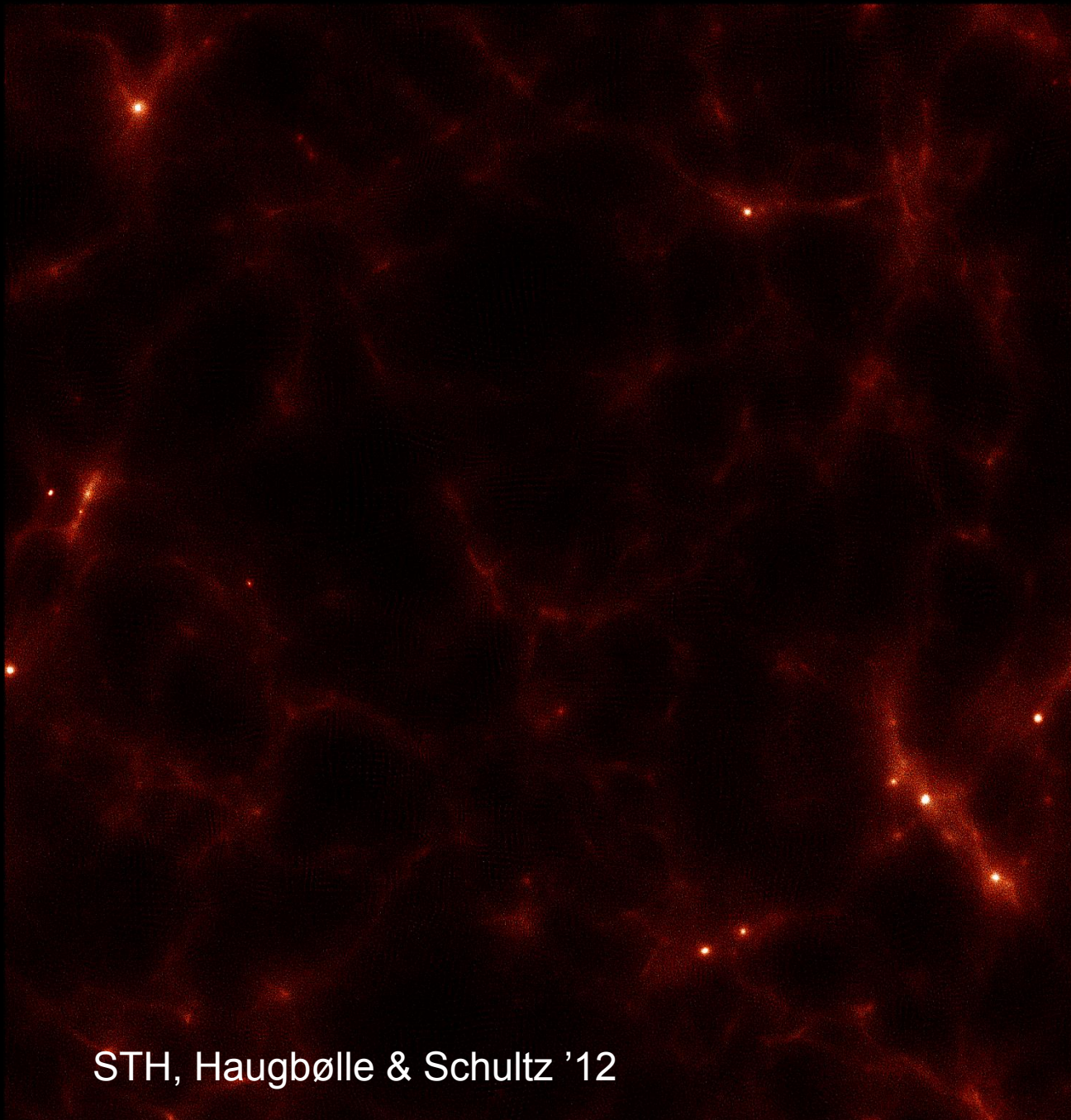
CDM



STH, Haugbølle & Schultz '12

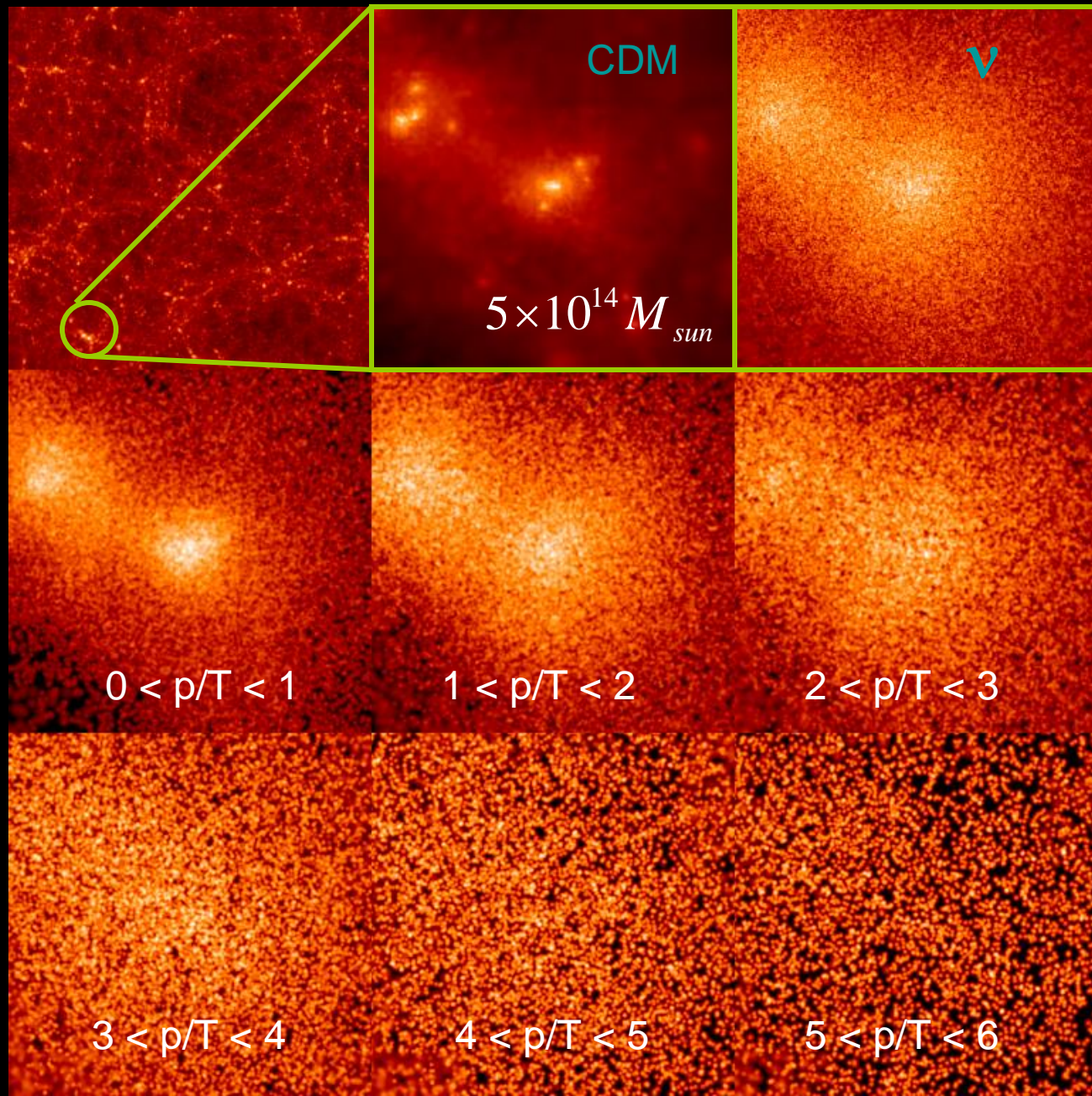
Neutrinos

STH, Haugbølle & Schultz '12



INDIVIDUAL HALO PROPERTIES

$512 h^{-1} \text{ Mpc}$



$$\sum m_\nu = 0.6 \text{ eV}$$

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
- NEW DATA FROM EUCLID WILL PROVIDE A POSITIVE DETECTION OF A NON-ZERO NEUTRINO MASS