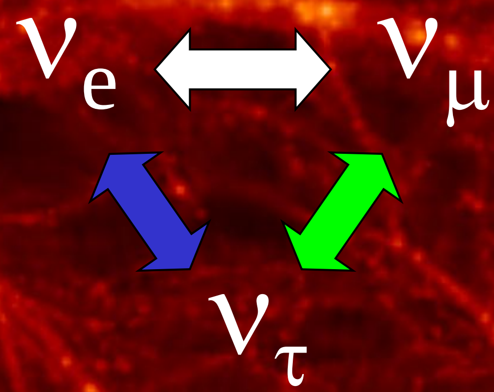
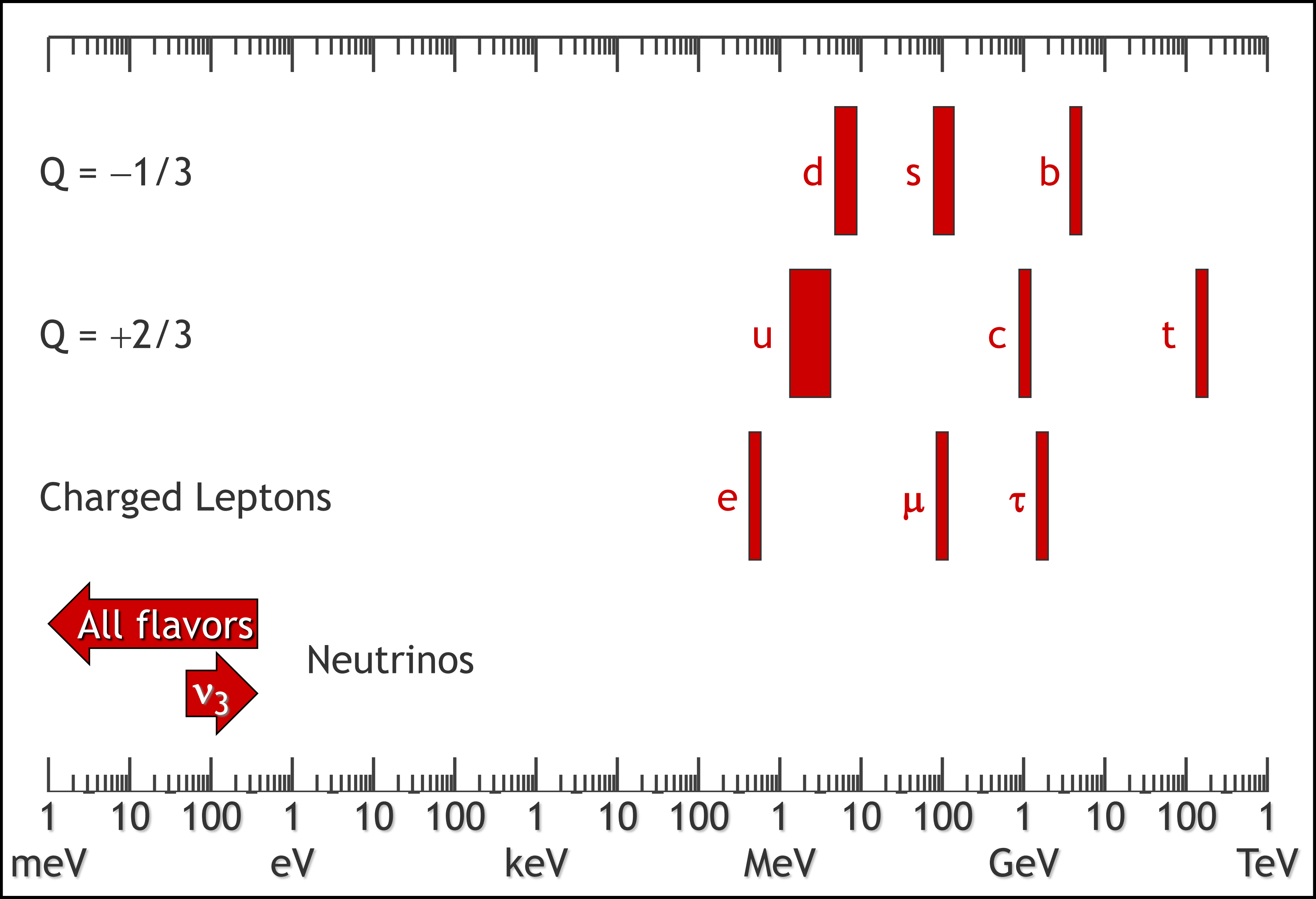
NEUTRINO PHYSICS AND COSMOLOGY



STEEN HANNESTAD, AARHUS UNIVERSITY
HAP CONFERENCE, 19 FEBRUARY 2013

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)

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

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

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

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)

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{1}\ldots & \ldots^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

"SOLAR ANGLE"

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

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

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)

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

"ATMOSPHERIC ANGLE"

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

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

FLAVOUR STATES

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)

"REACTOR ANGLE"

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

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

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

FLAVOUR STATES

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

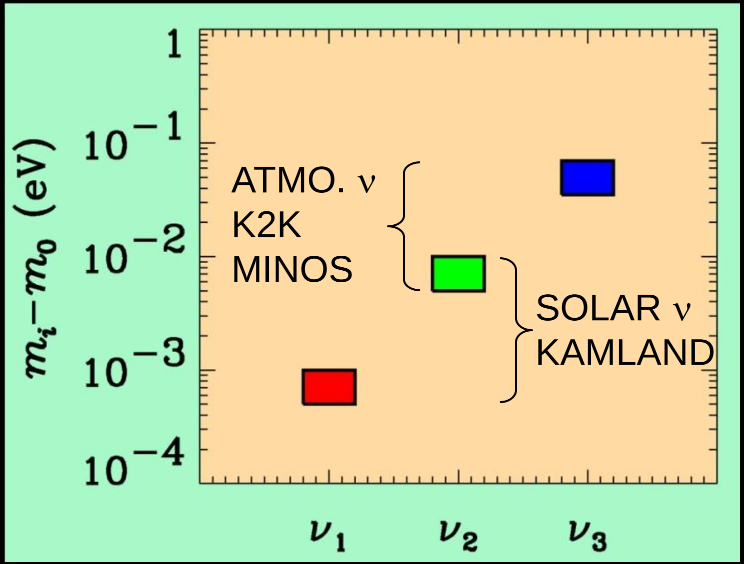
PROPAGATION STATES

MIXING MATRIX (UNITARY)

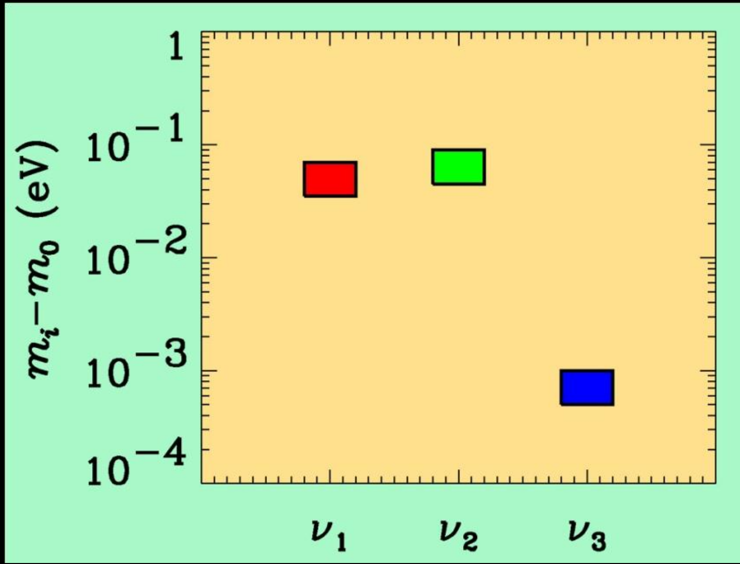
LATE-TIME COSMOLOGY IS (ALMOST) INSENSITIVE TO THE MIXING STRUCTURE

$U =$ [… $s_{13}e^{-i\delta}$ … ; $s_{12}s_{23} - c_{12}c_{23}s_{13}e$ … $-c_{12}s_{23} - s_{12}c_{23}s_{13}e$ … $c_{23}c_{13}$]

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



Normal hierarchy



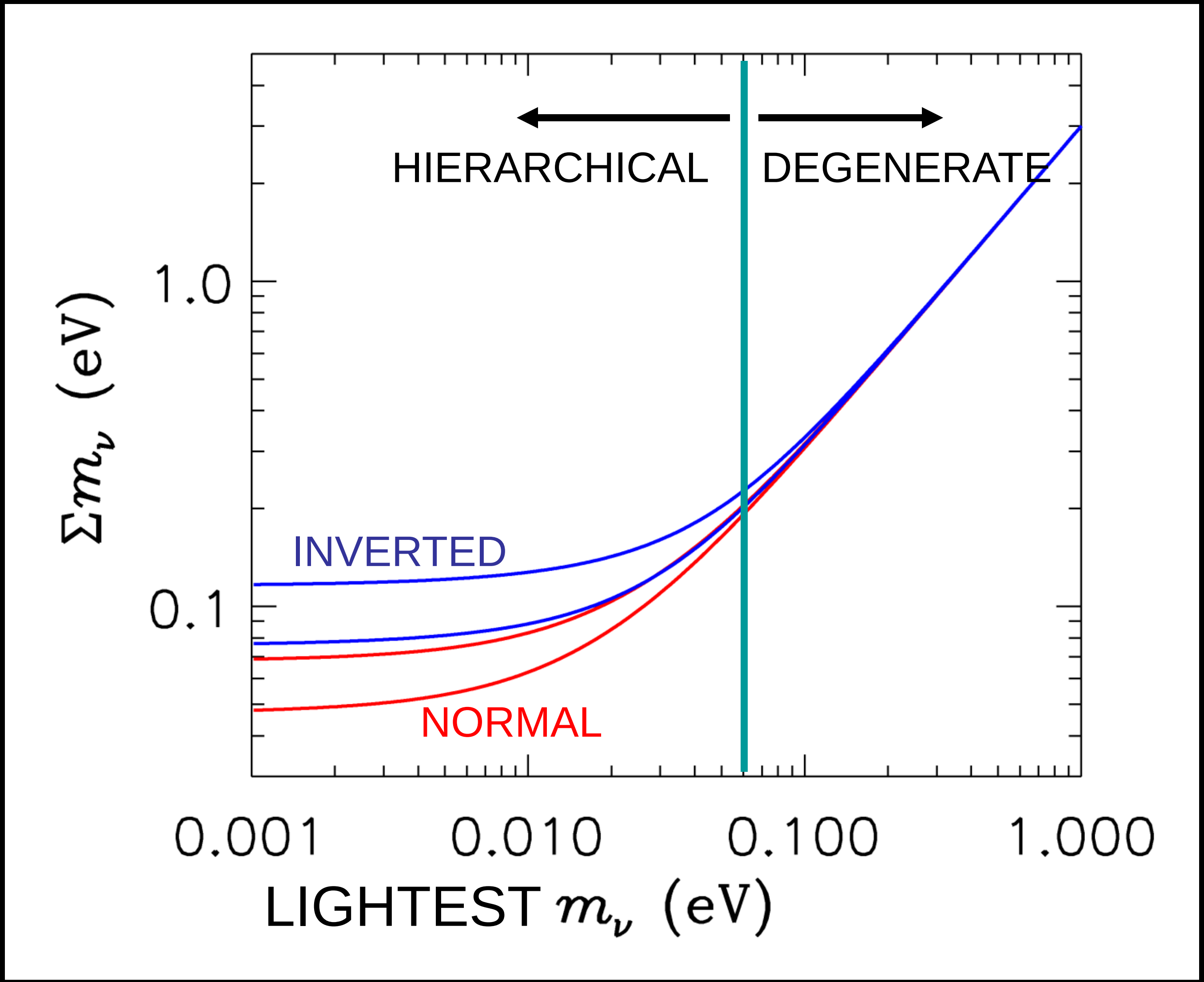
Inverted hierarchy

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)

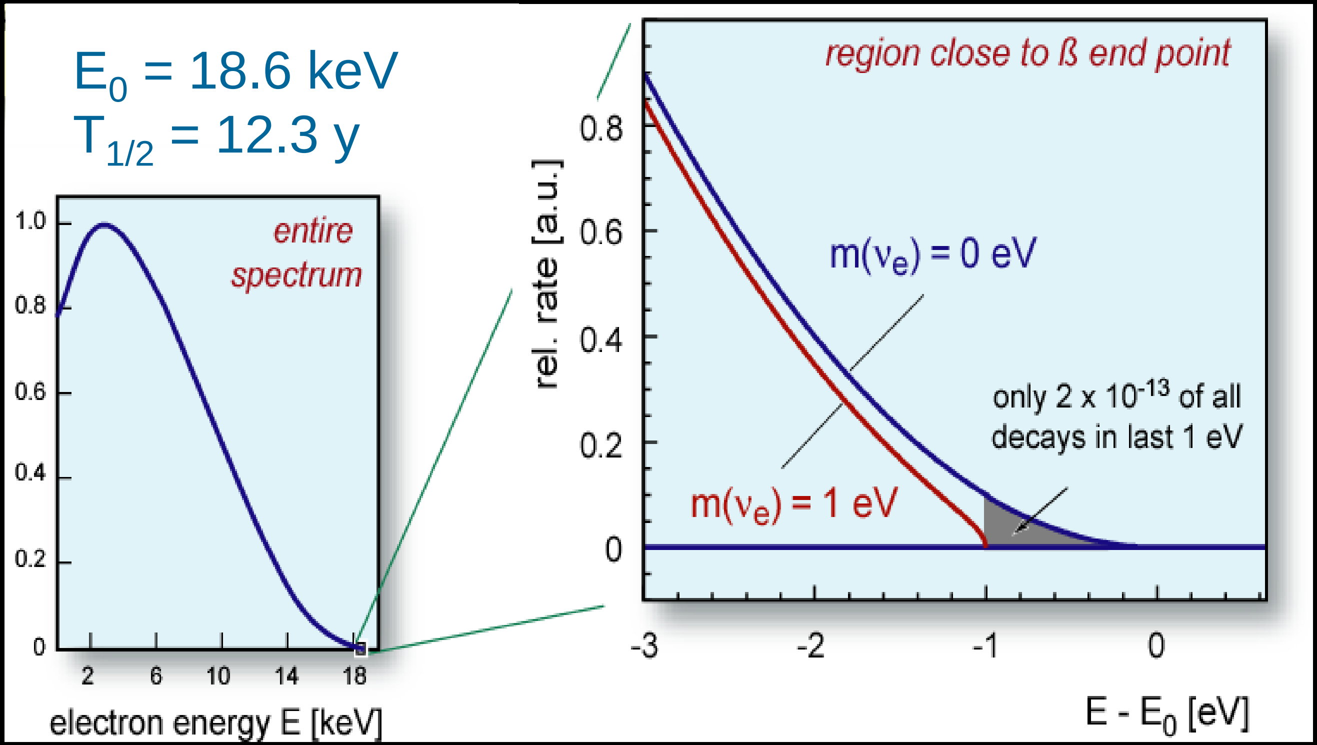
ß-decay and neutrino mass

model independent neutrino mass from ß-decay kinematics

only assumption: relativistic energy-momentum relation

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

experimental observable is m_ν^2



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

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

Mainz experiment, final analysis (Kraus et al.)

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

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

This sensitivity will be improved by at least an order of magnitude by KATRIN.

NEUTRINO MASS AND ENERGY DENSITY FROM COSMOLOGY

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

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93\,\mathrm{eV}}$$

FROM

$$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \approx 2\,\mathrm{K}$$

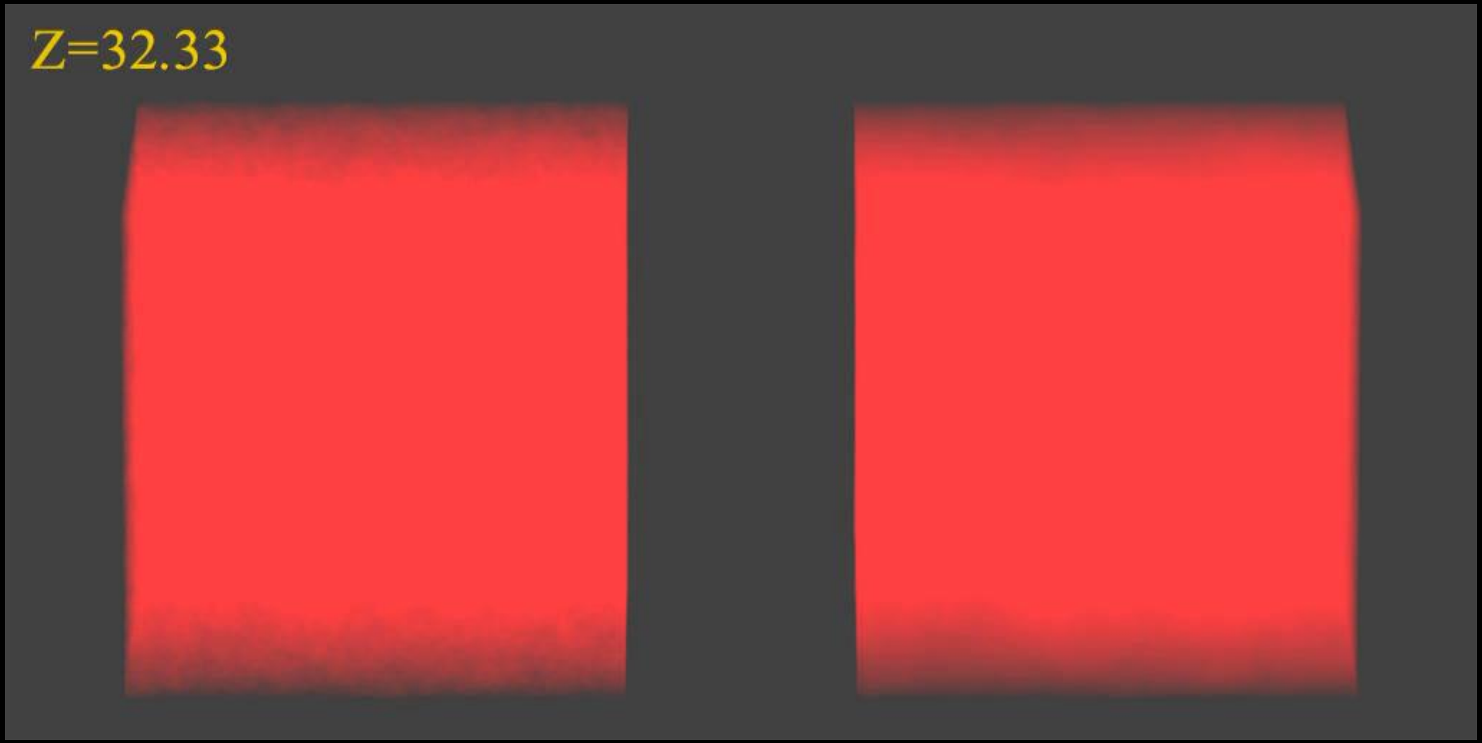
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

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

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

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

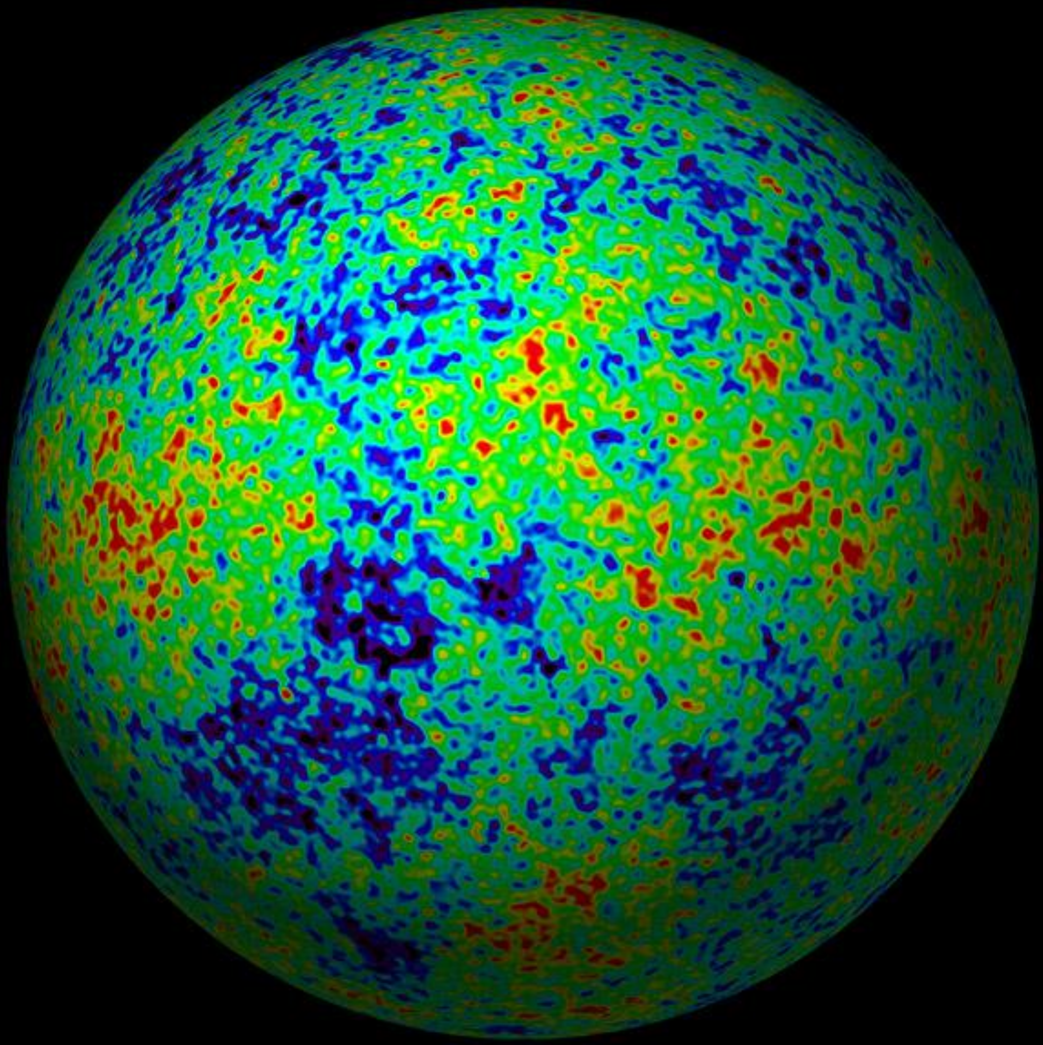
256
Mpc



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

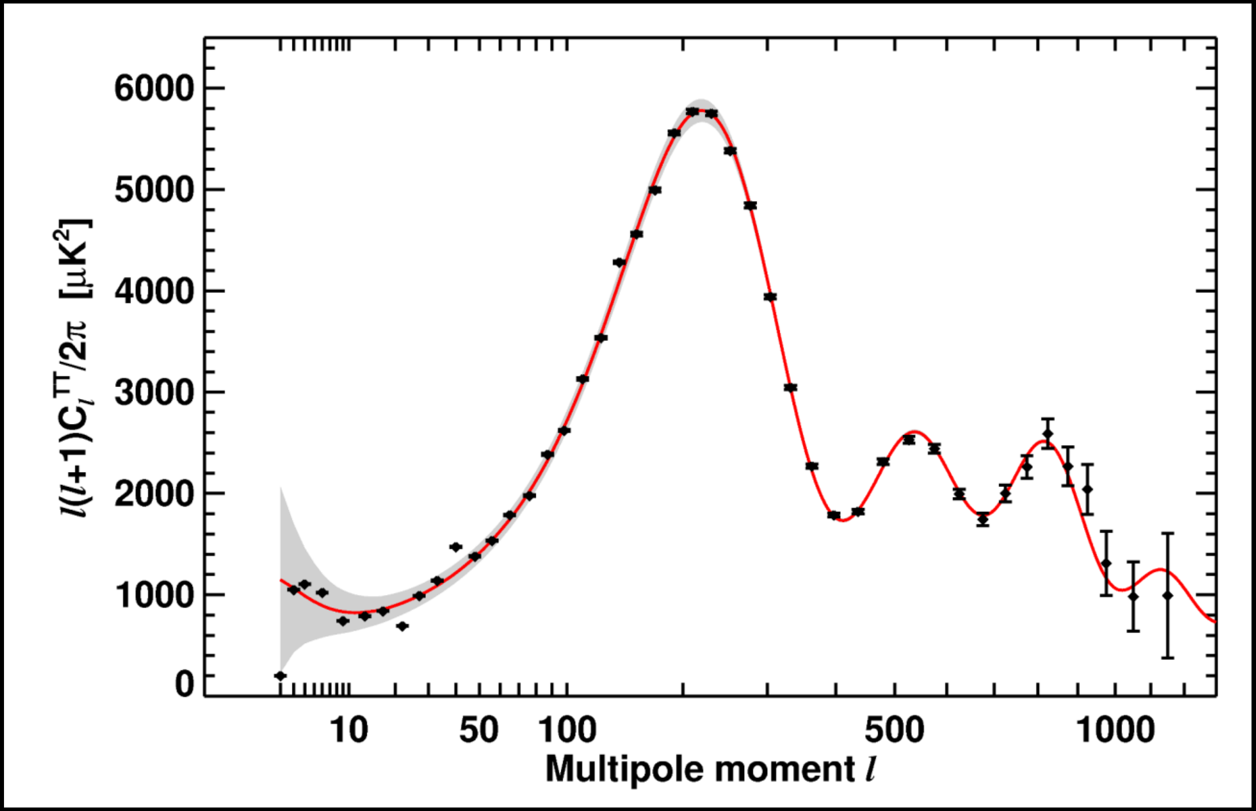
AVAILABLE COSMOLOGICAL DATA

THE COSMIC MICROWAVE BACKGROUND



WMAP TEMPERATURE MAP

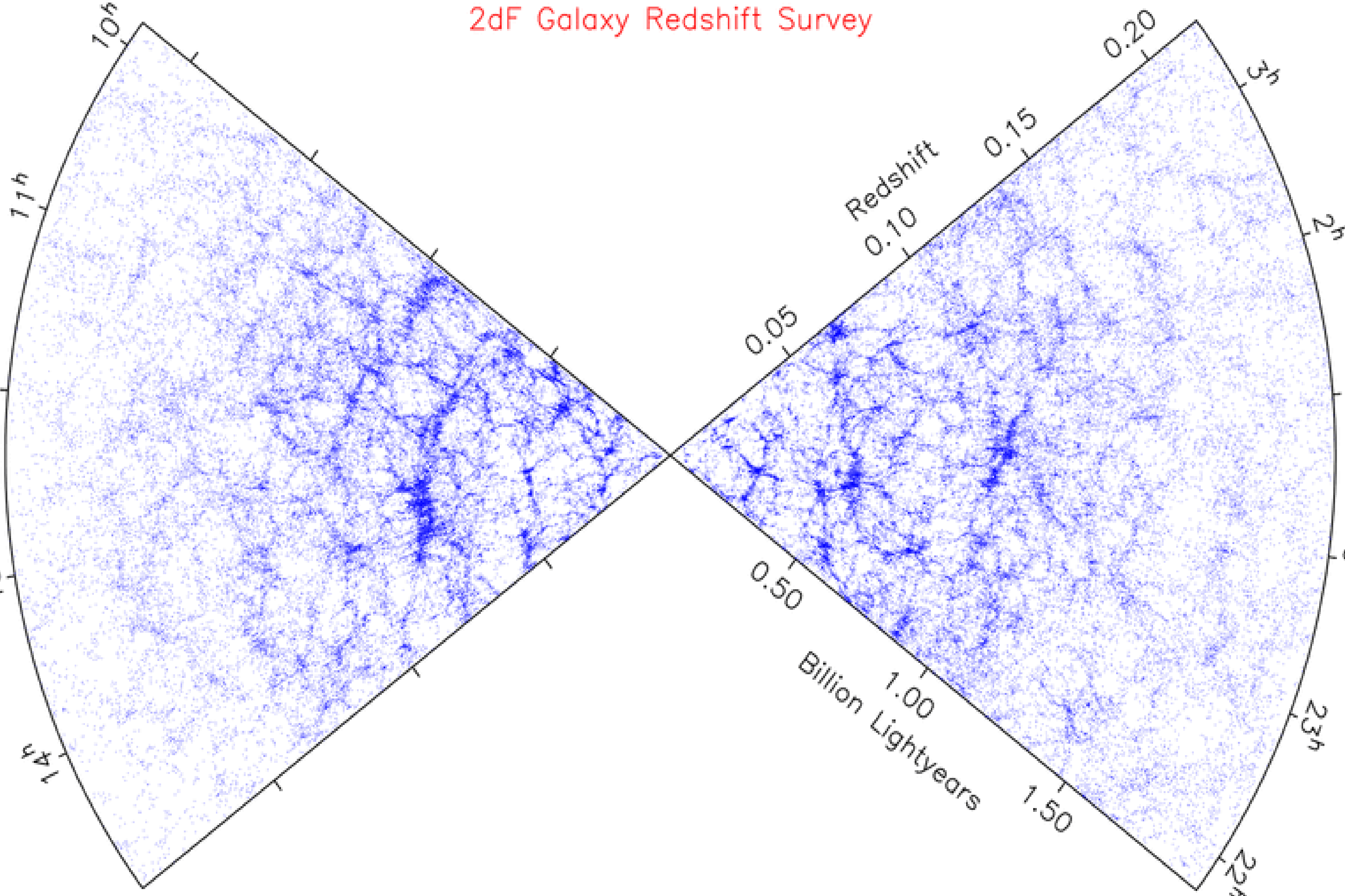
WMAP-9 TEMPERATURE POWER SPECTRUM



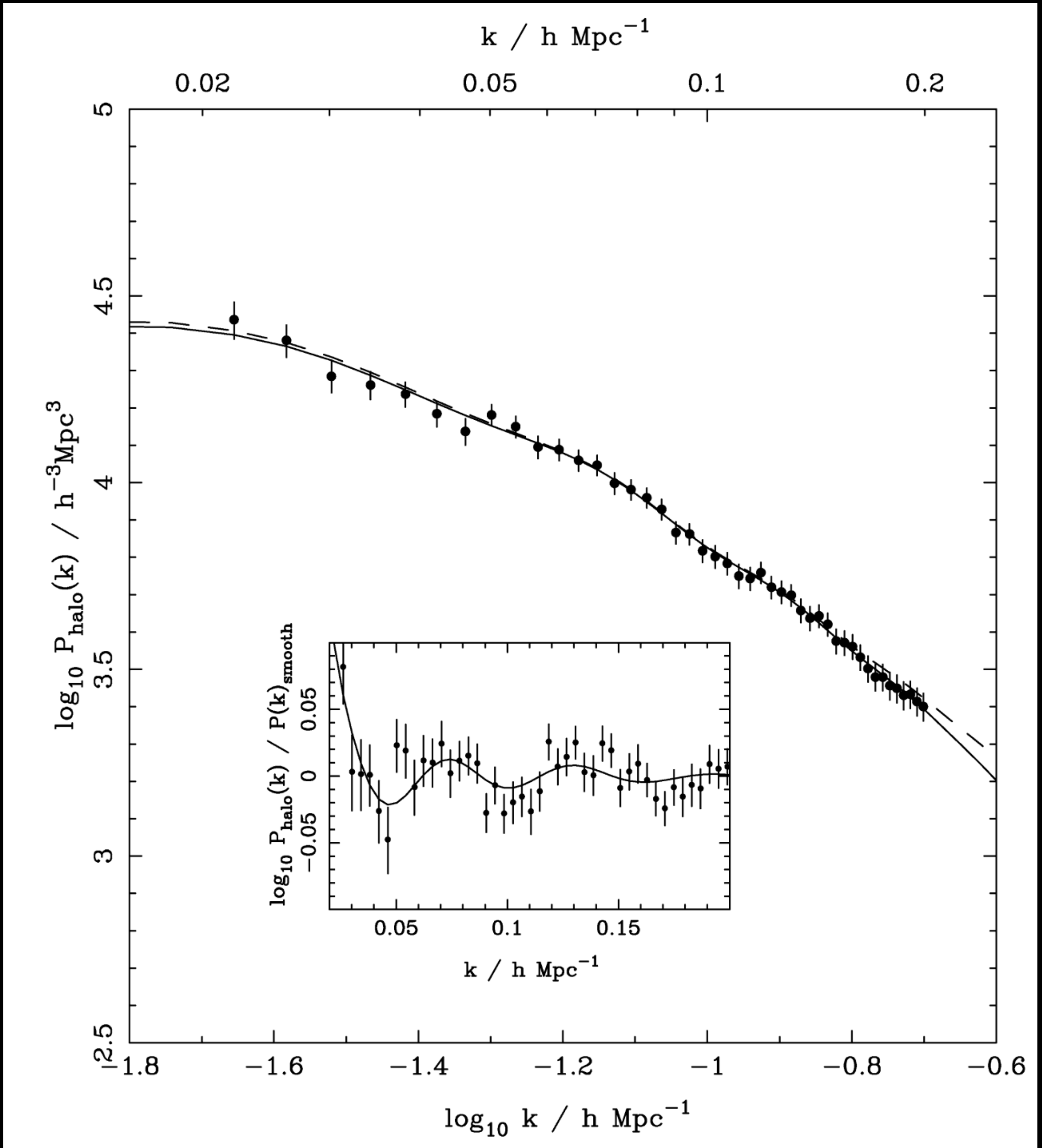
HINSHAW ET AL, ARXIV 1212.5226

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

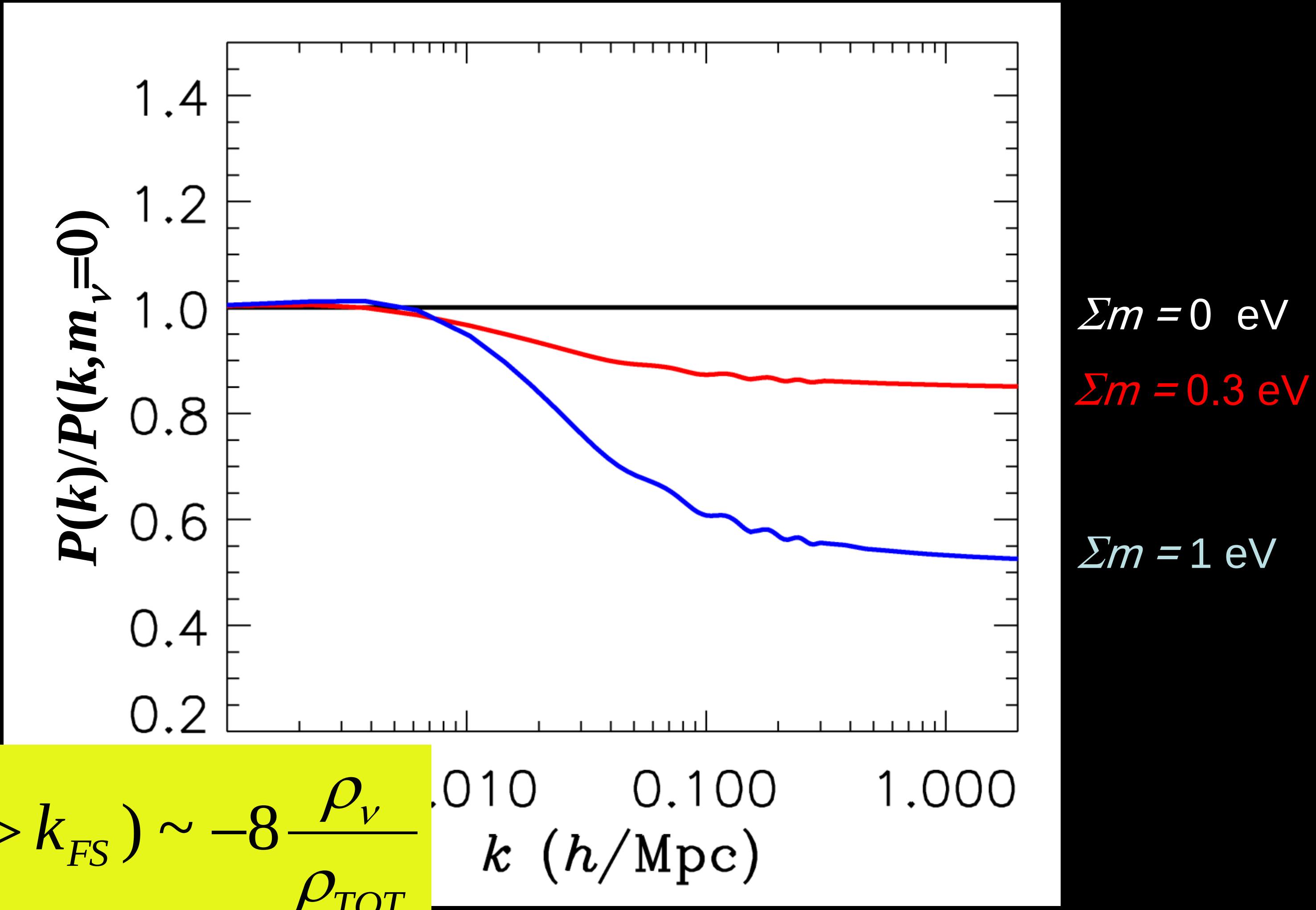
LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS



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



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

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

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

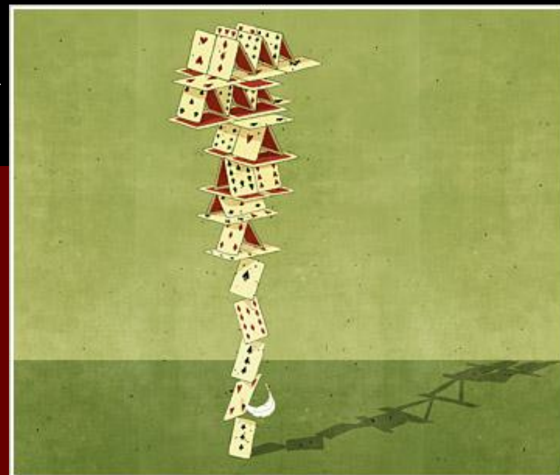
USING THE MINIMAL COSMOLOGICAL MODEL

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

JUST ONE EXAMPLE

THE NEUTRINO MASS FROM COSMOLOGY PLOT

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
ΛCDM

$+N_{\nu}$

$+w+$……

Larger model
space

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

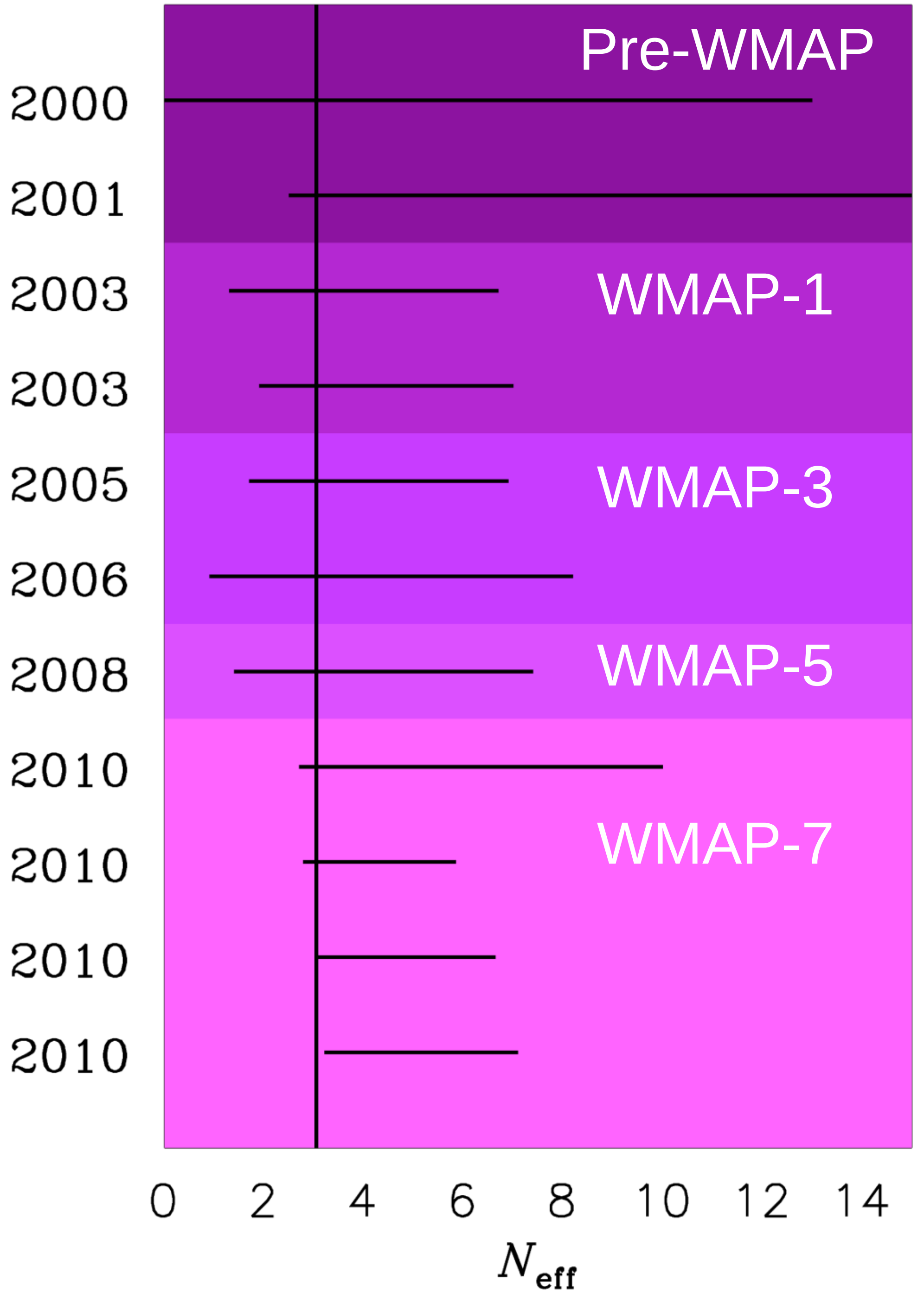
THE STANDARD MODEL PREDICTION IS

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

Mangano et al., hep-ph/0506164

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

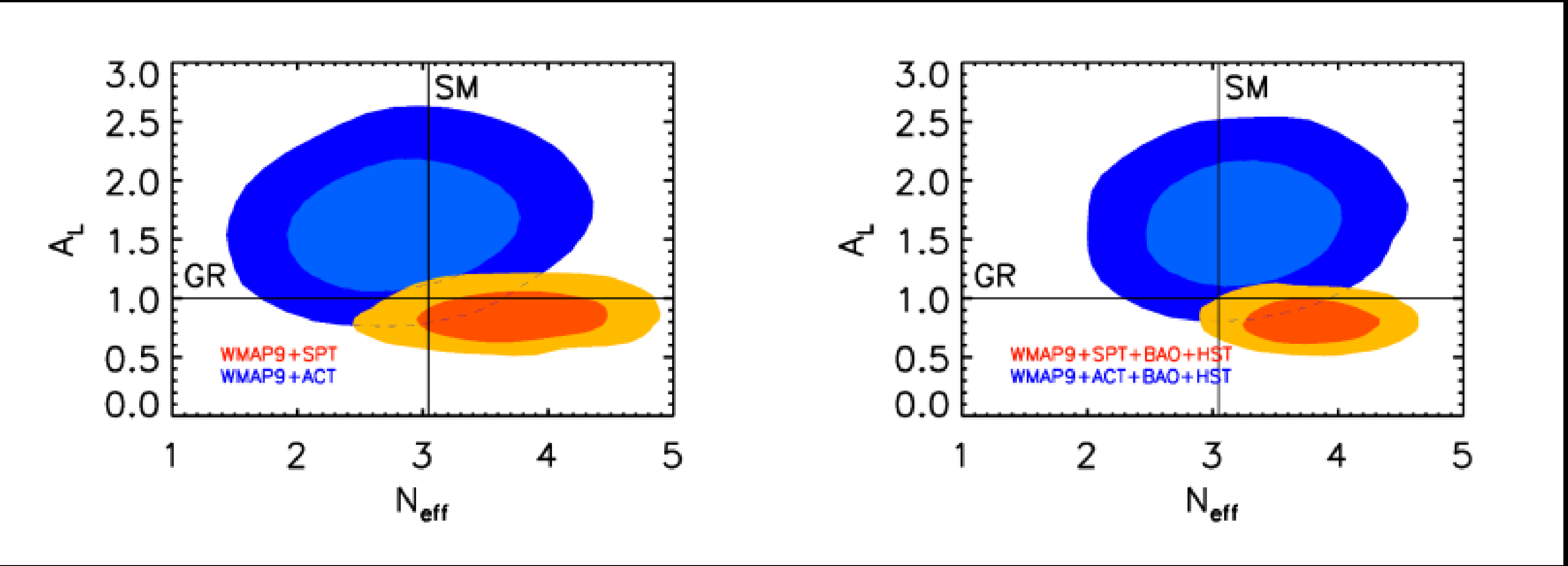
TIME EVOLUTION OF THE 95% BOUND ON N_ν



LATEST RESULTS NEUTRINO MASS AND NUMBER:

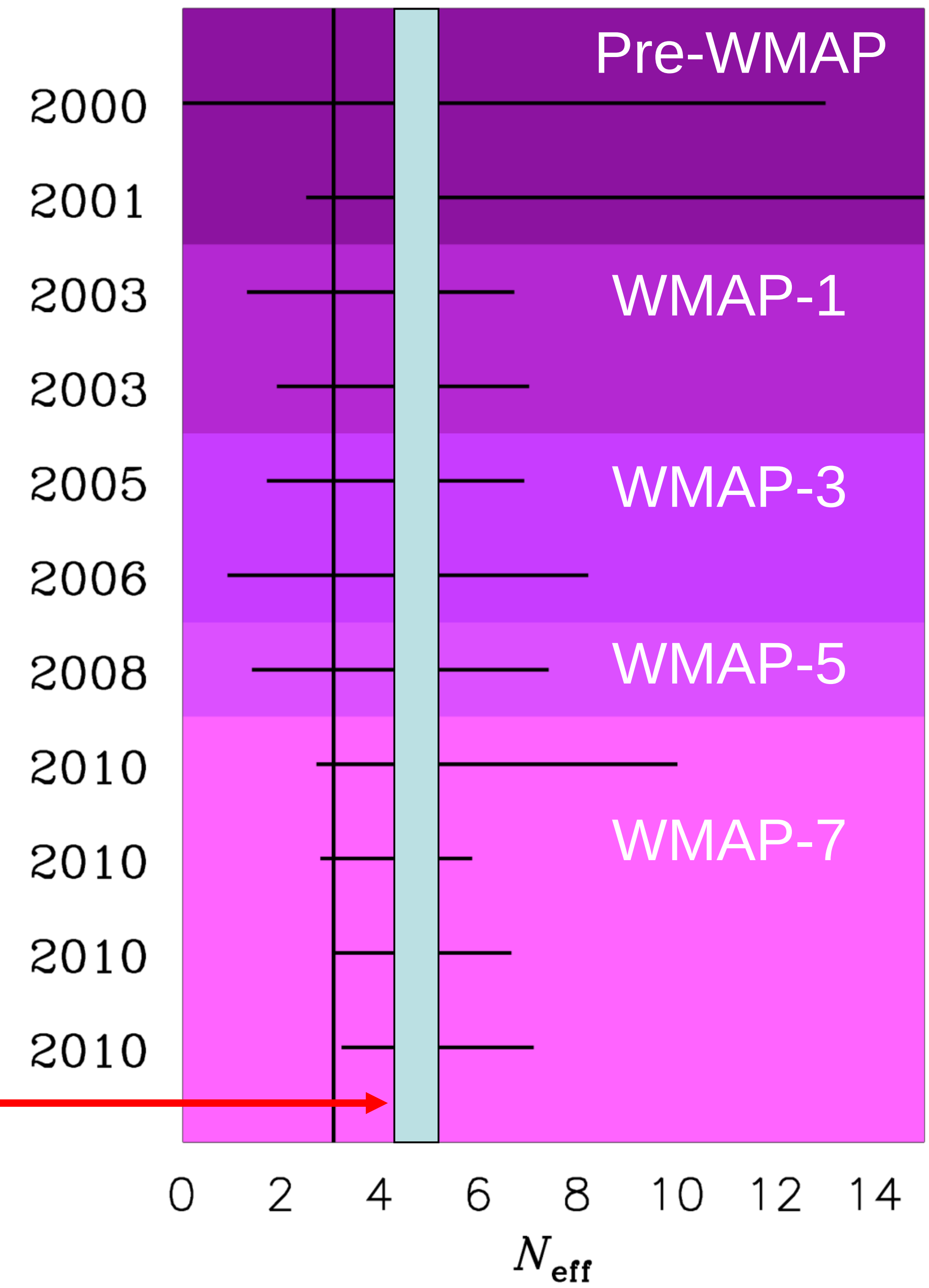
Data	$N_{\rm eff}$	$\sum m_\nu$	Ref
WMAP-9	> 1.7	< 1.3 eV	arXiv:1212.5226 (WMAP-9)
WMAP-9 + ACT (2011) + SPT (2011) +BAO+H_0	3.84 ± 0.40	< 0.44 eV	arXiv:1212.5226 (WMAP-9)
WMAP-9 + SPT (2012) + BAO + H_0	3.76 ± 0.34	—	arXiv:1301.7343
WMAP-9 + ACT (2013) + BAO + H_0	3.23 ± 0.47	—	arXiv:1301.7343

THE DIFFERENCE BETWEEN ACT AND SPT CAN BE TRACED TO A DIFFERENCE IN THE CORRECTION FOR WEAK LENSING

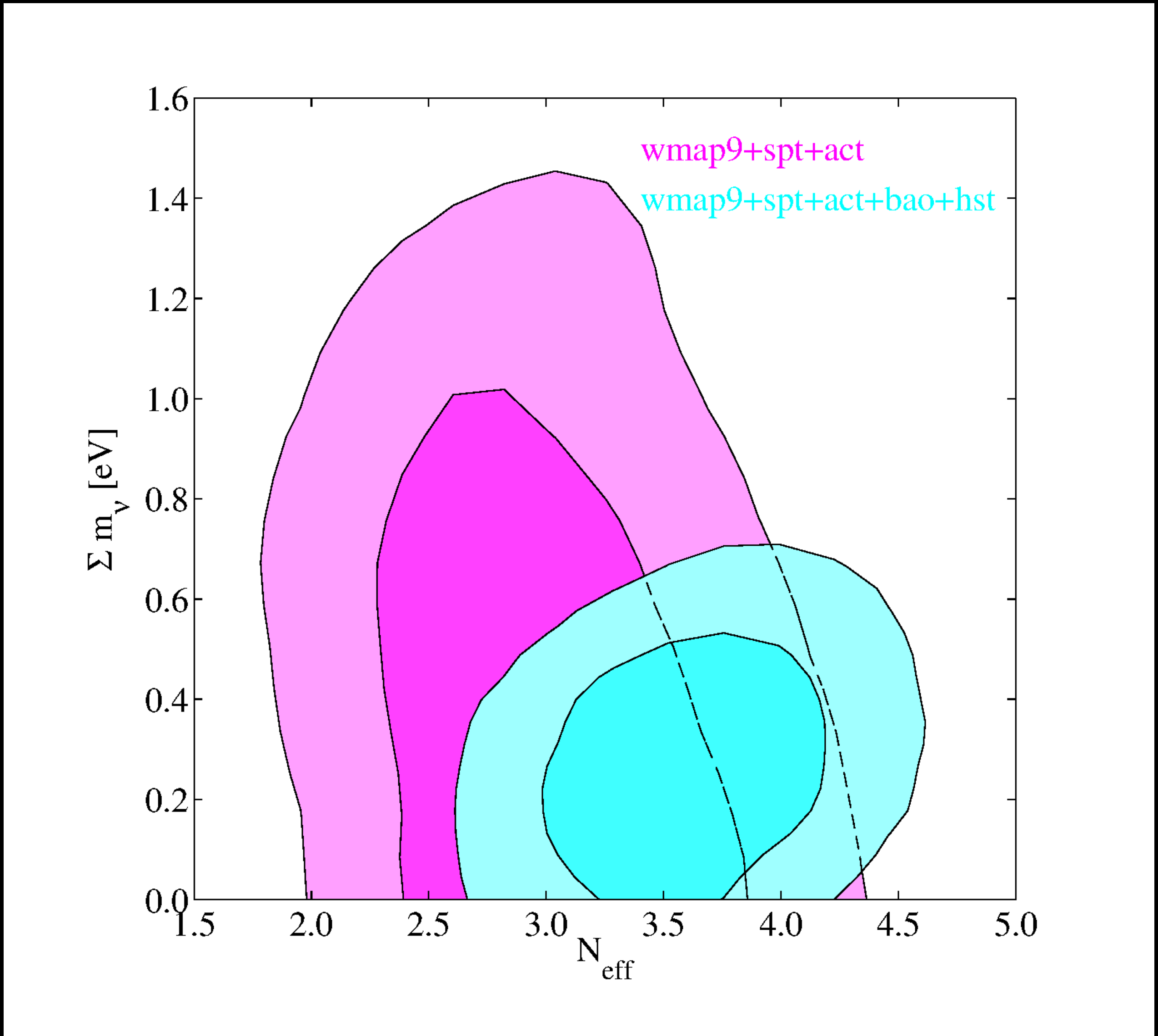


VALENTINO ET AL. 1301.7343

TIME EVOLUTION OF THE 95% BOUND ON N_ν



ESTIMATED PLANCK SENSITIVITY



ARCHIDIACONO, FORNENGO, GIUNTI, STH, MELCHIORRI
IN PREPARATION

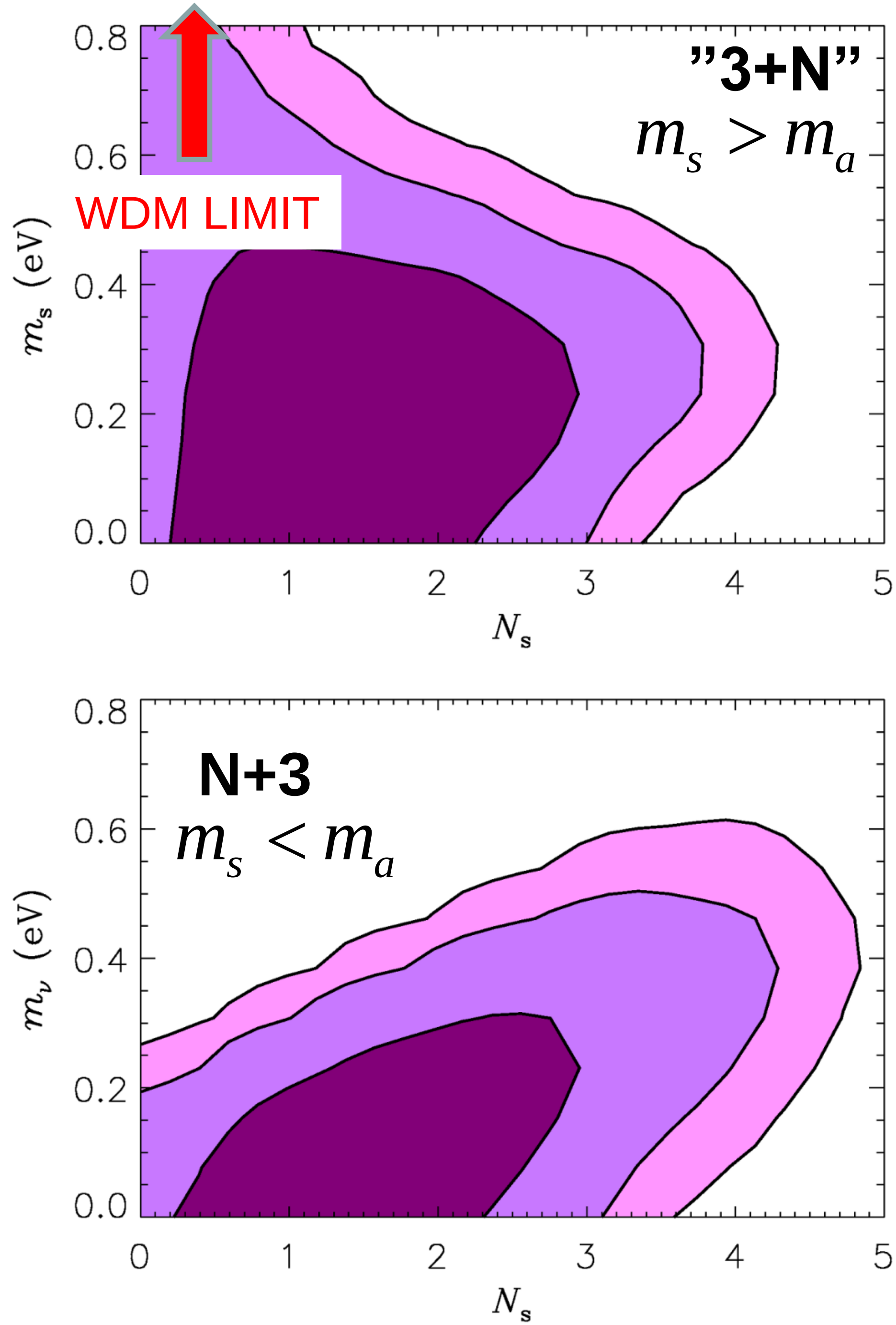
A STERILE NEUTRINO IS PERHAPS THE MOST OBVIOUS CANDIDATE FOR AN EXPLANATION OF THE EXTRA ENERGY DENSITY

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

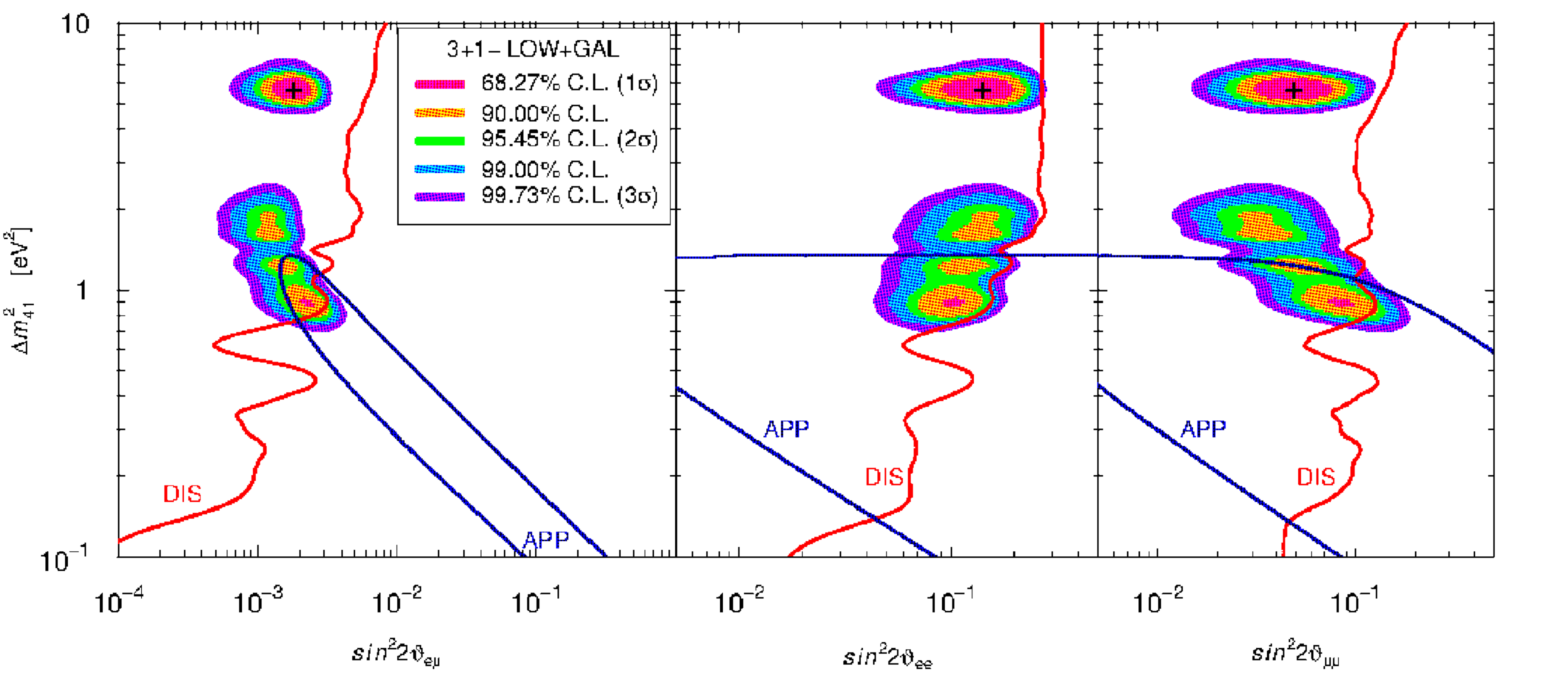
Hamann, STH, Raffelt, Tamborra, Wong, arxiv:1006.5276 (PRL)

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
and many others



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



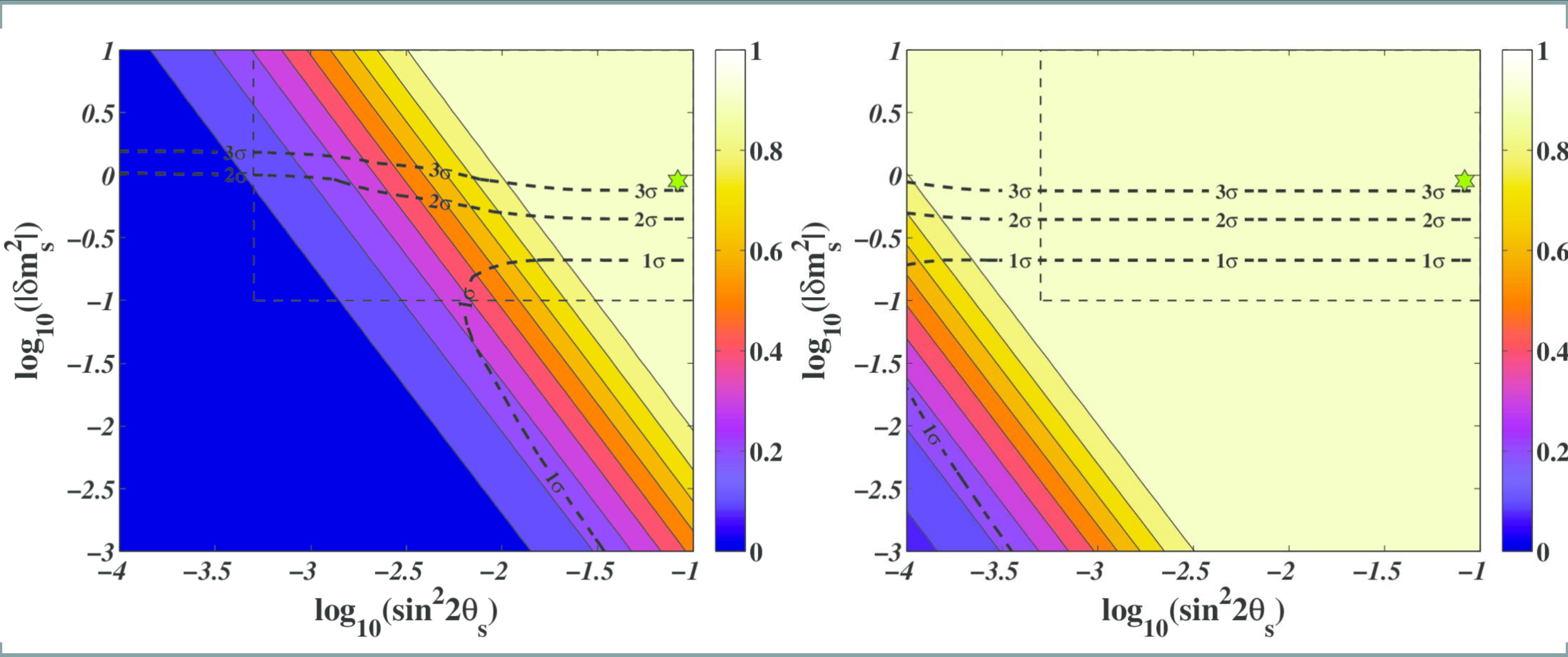
Giunti & Laveder 2011 (and many other analyses)

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)

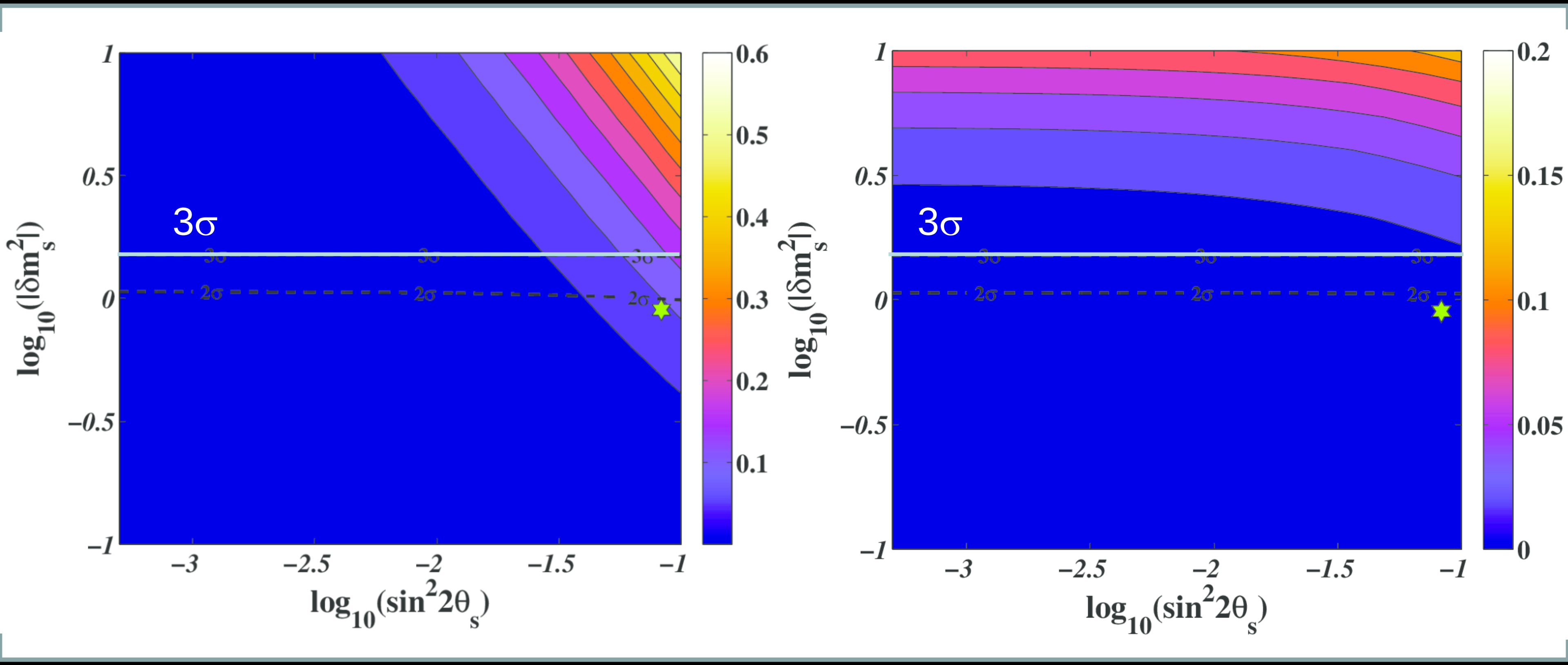
A LARGE PRIMORDIAL LEPTON ASYMMETRY CAN RECONCILE THE DATA (STH, Tamborra, Tram 2012)

STERILE NEUTRINO THERMALISATION WITH ZERO LEPTON ASYMMETRY



STH, Tamborra, Tram 2012

STERILE NEUTRINO THERMALISATION WITH LARGE LEPTON ASYMMETRY

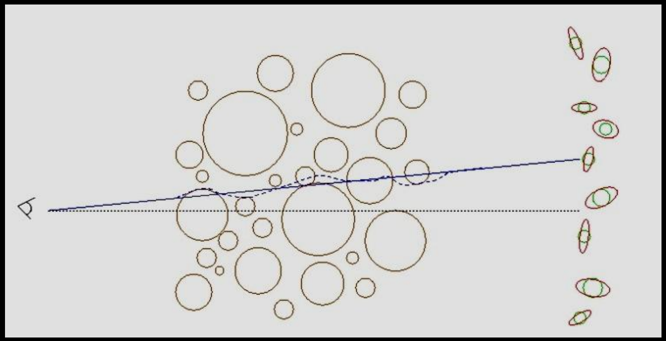


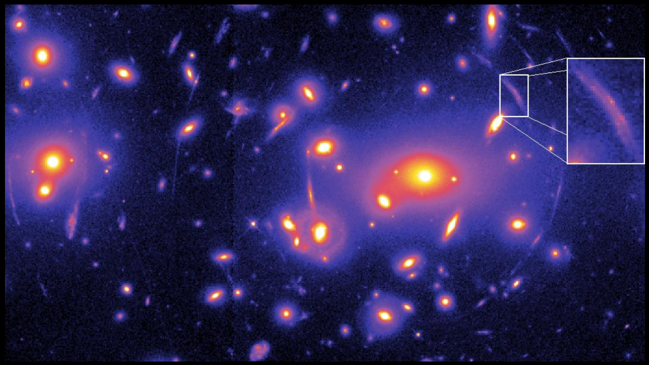
STH, Tamborra, Tram 2012

WHAT IS IN STORE FOR THE FUTURE?

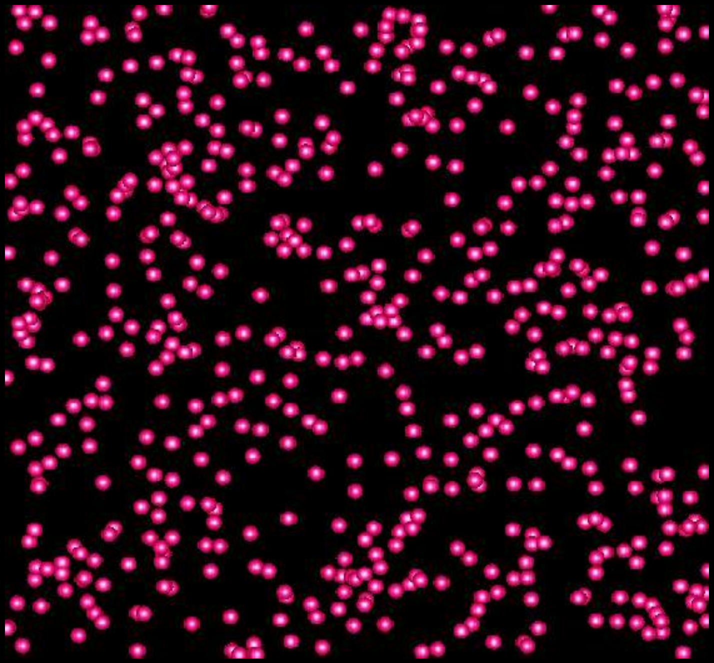
- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS (PLANCK) – TALK BY DODELSON
- LARGE SCALE STRUCTURE SURVEYS AT HIGHER REDSHIFT AND IN LARGER VOLUMES
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES

WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE

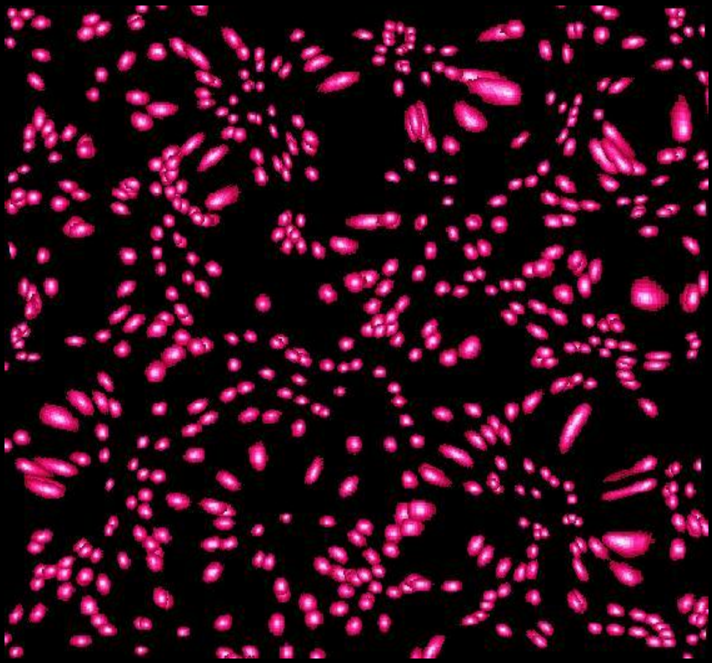




Distortion of background images by foreground matter



Unlensed



Lensed

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

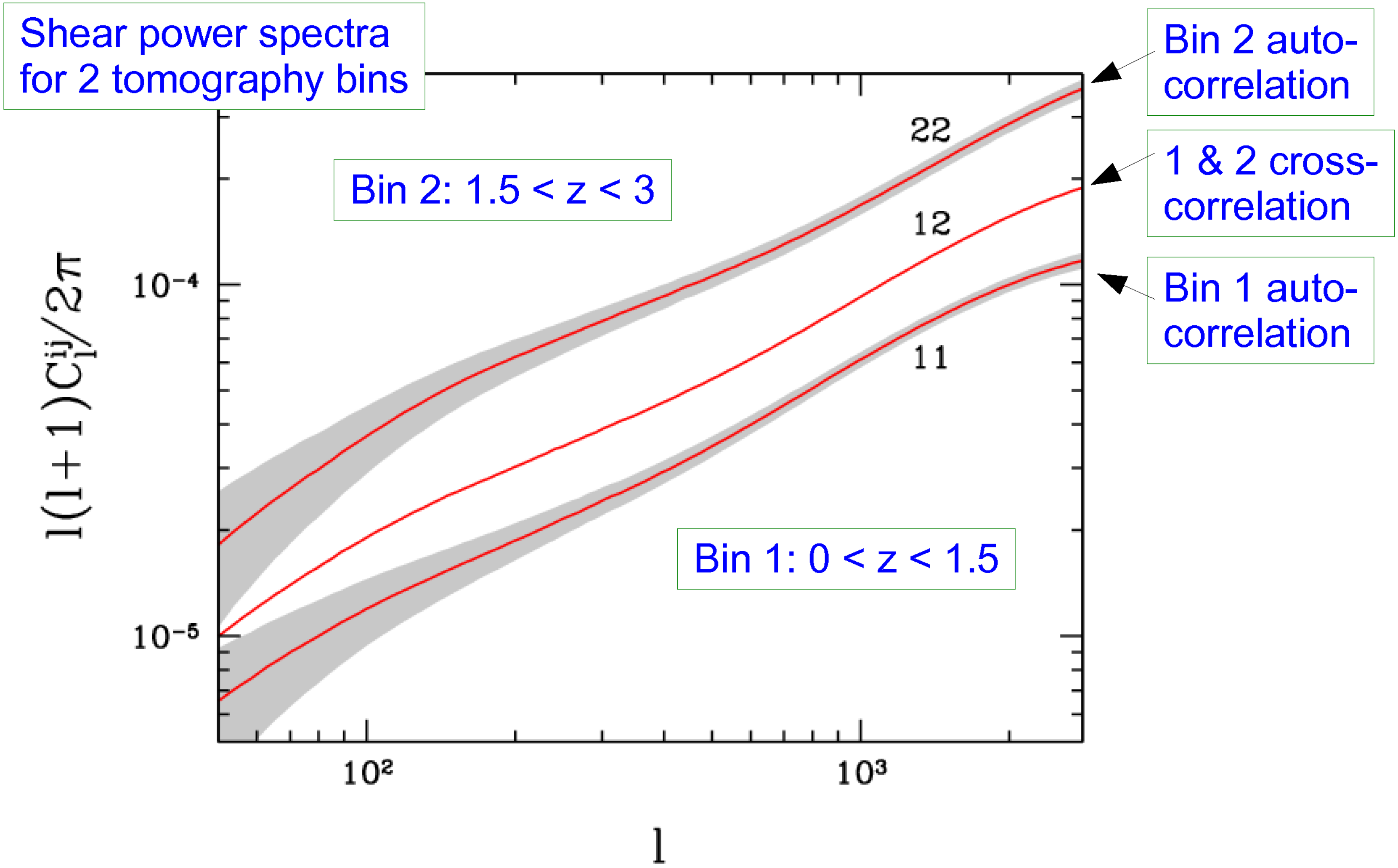
$$C_\ell = \frac{9}{16} H_0^4 \Omega_m^2 \int_0^{\chi_H} \left[\frac{g(\chi)}{a\chi} \right]^2 P(\ell / r, \chi) d\chi$$

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

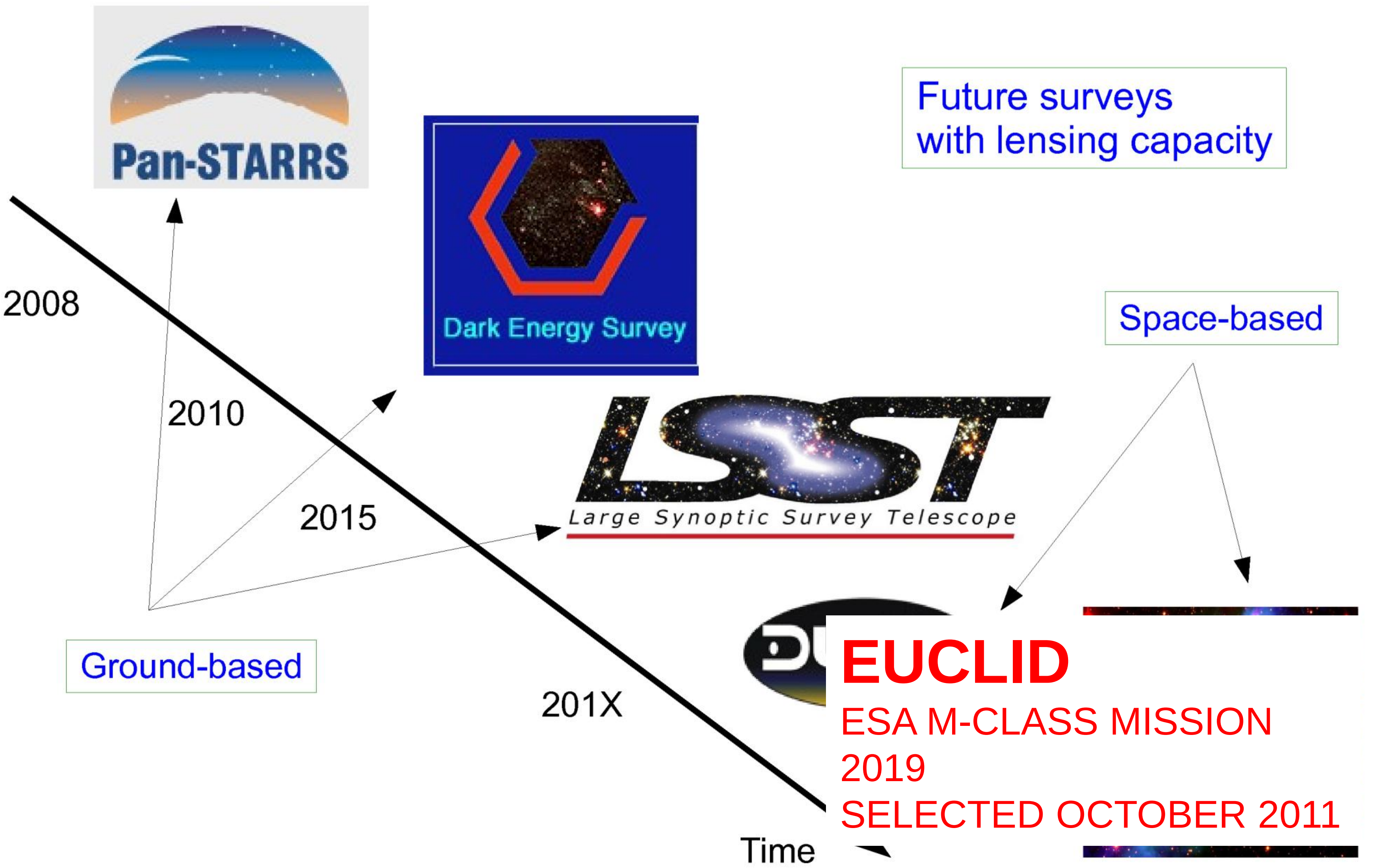
$$g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi'$$

WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY

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



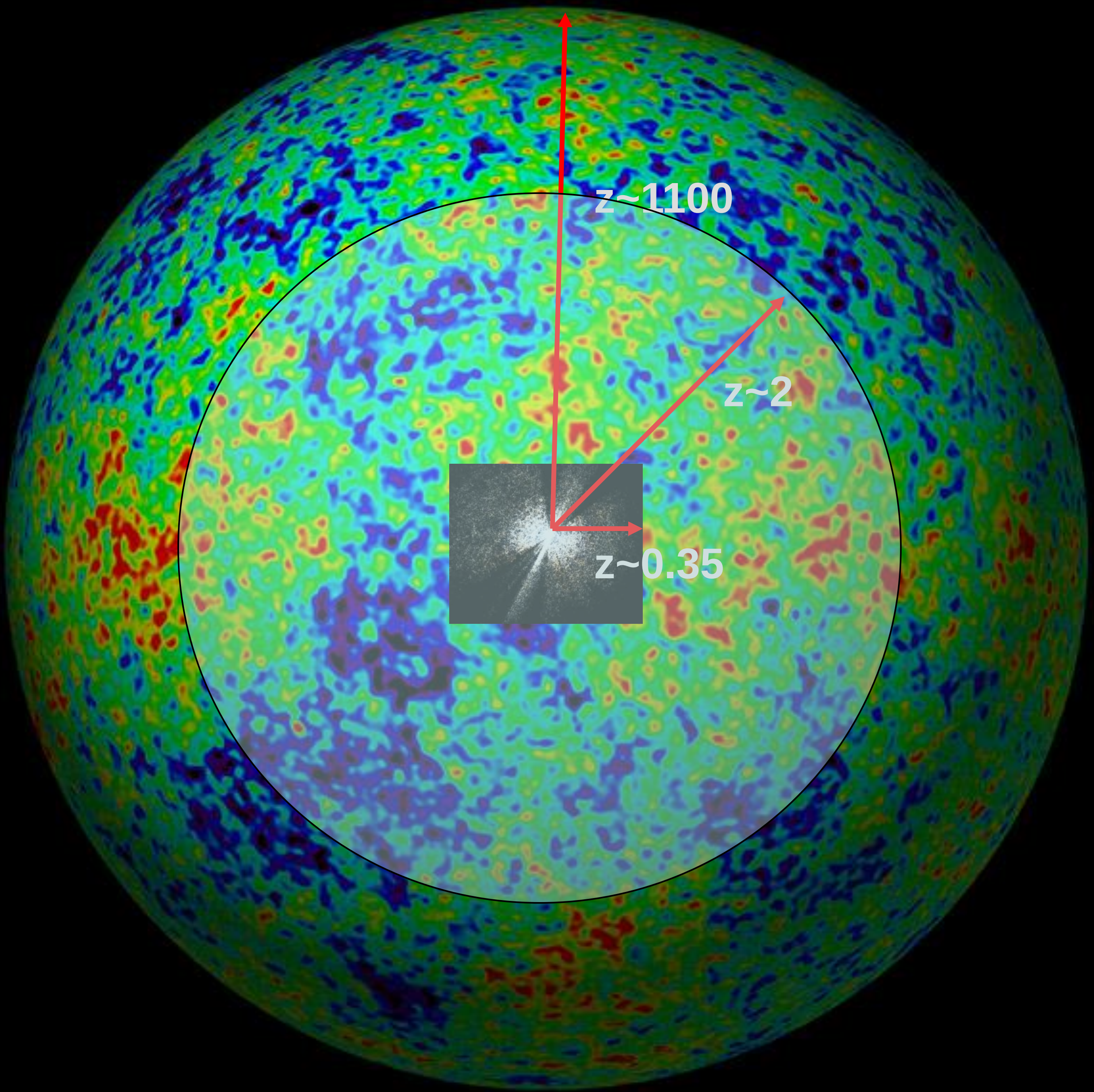
STH, TU, WONG 2006


Pan-STARRS
Future surveys
with lensing capacity
Dark Energy Survey
2008
2010
2015
201X
Space-based
Large Synoptic Survey Telescope
Ground-based
Time
EUCLID
ESA M-CLASS MISSION
2019
SELECTED OCTOBER 2011


THE EUCLID MISSION

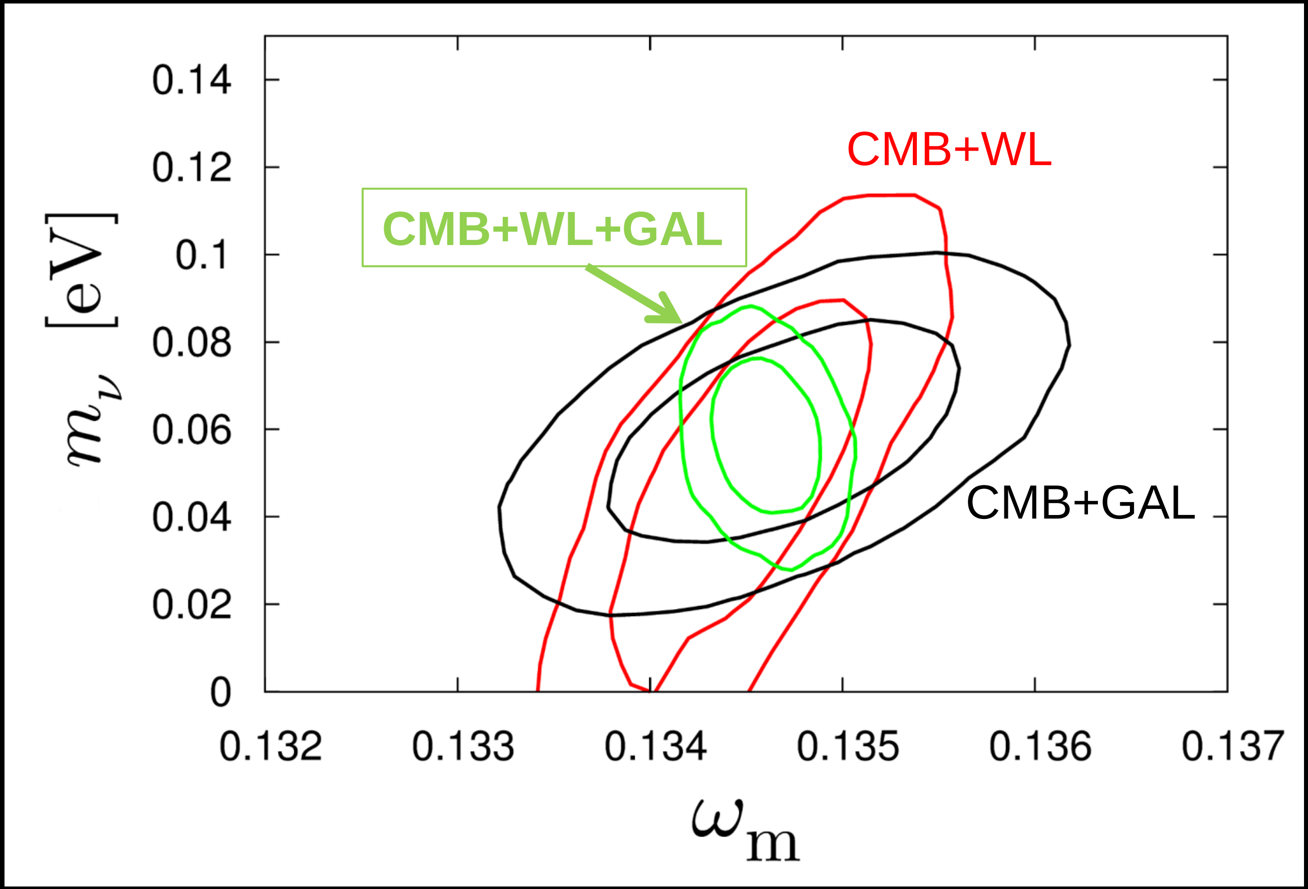
EUCLID WILL FEATURE:

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



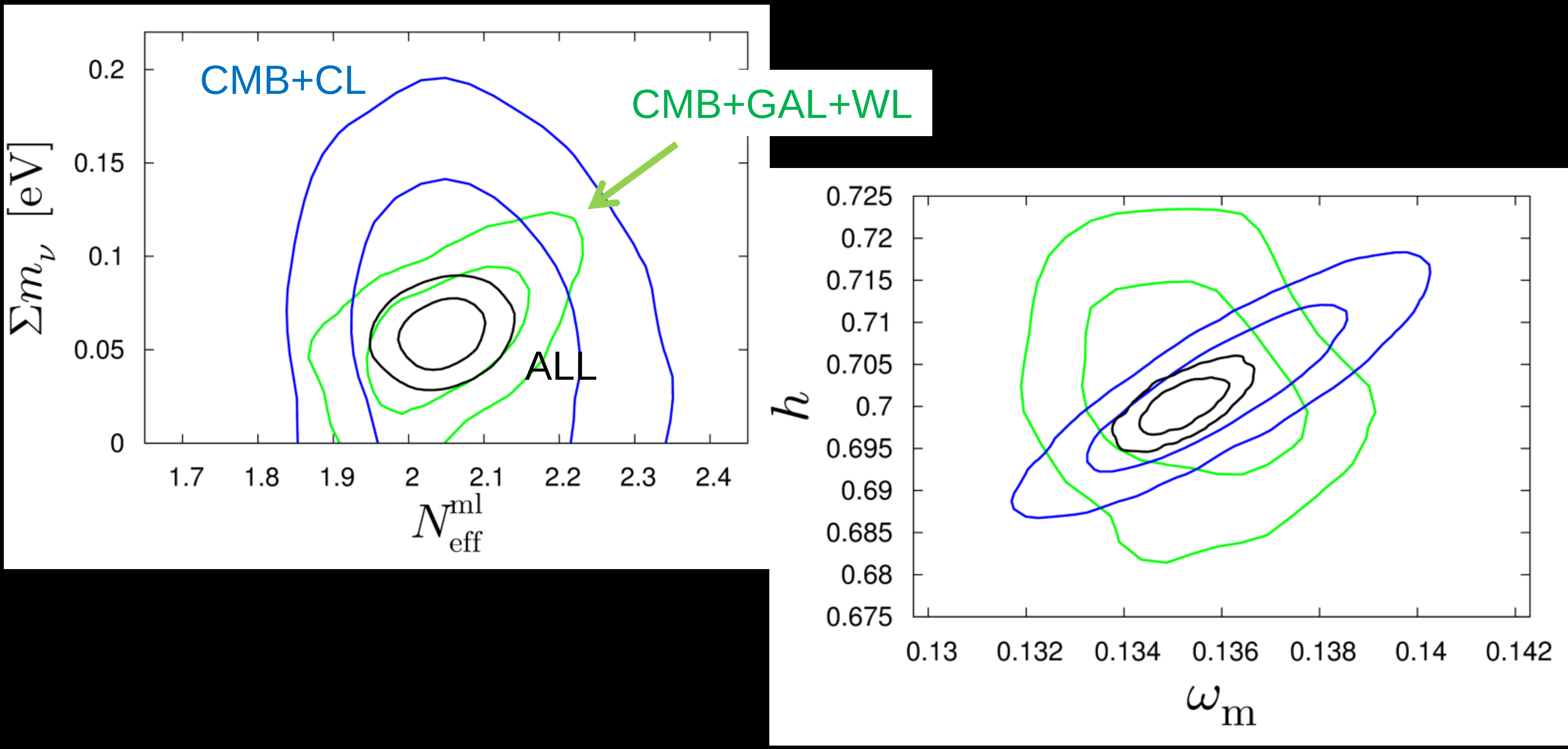
z~1100
z~2
z~0.35

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



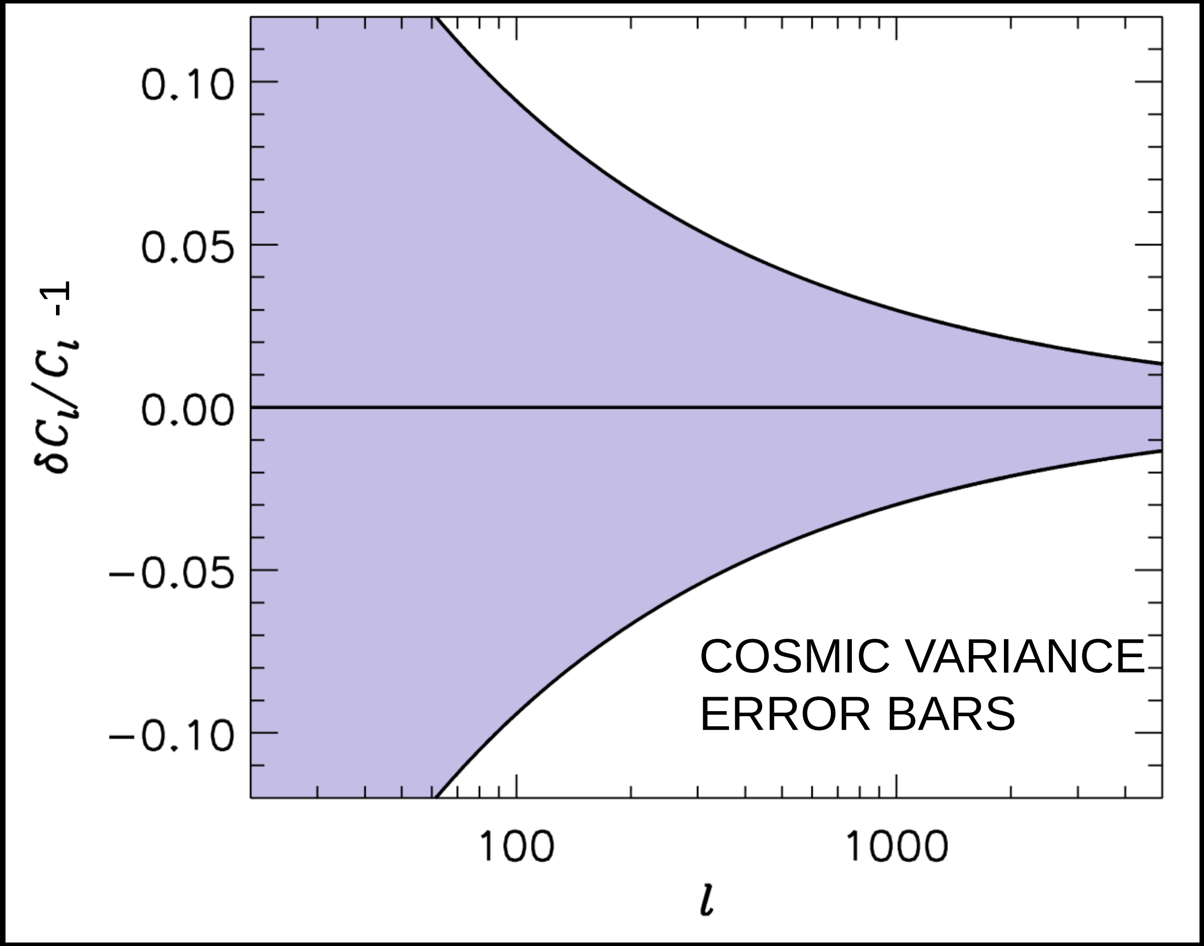
arXiv:1209.1043

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



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

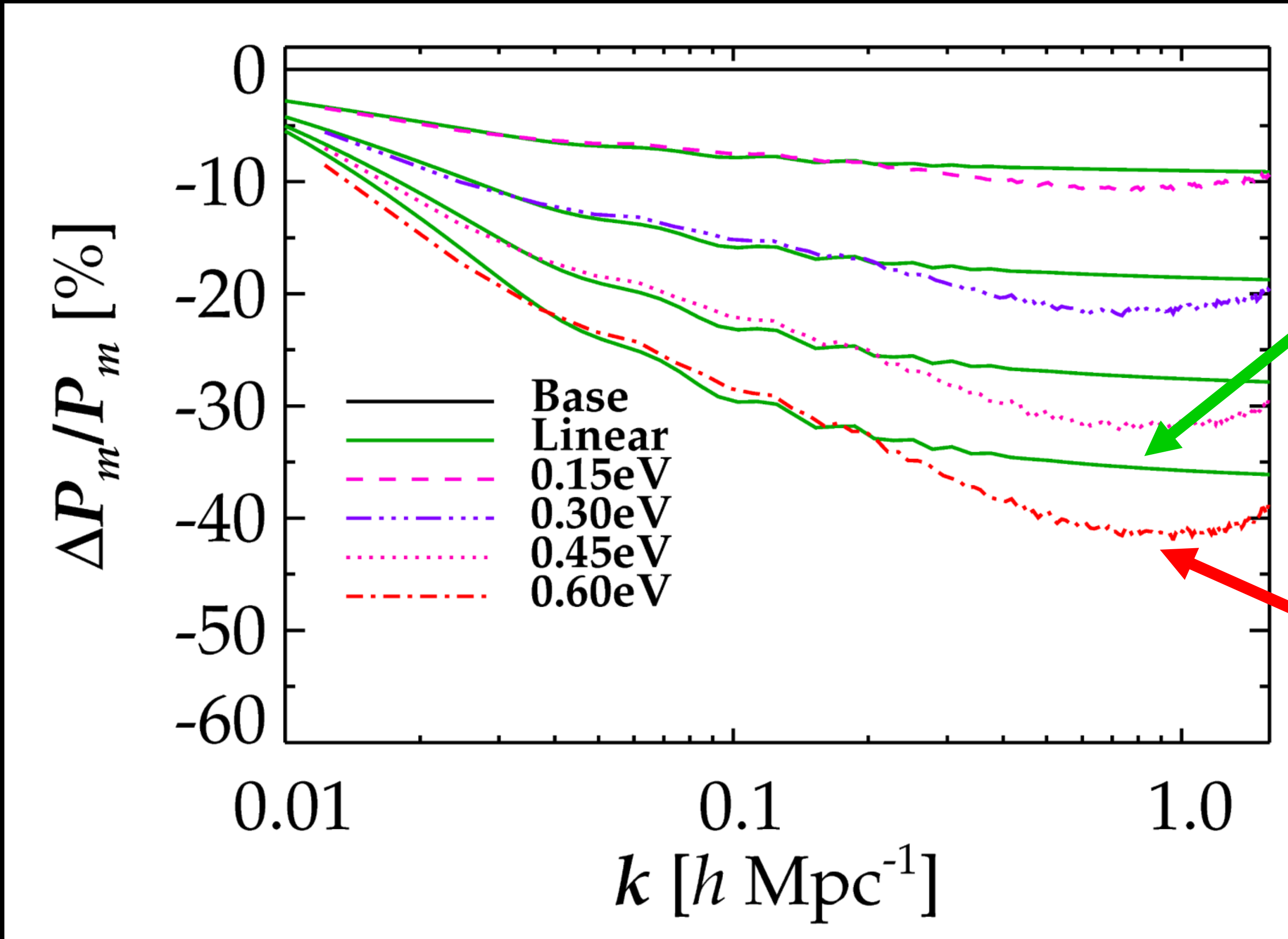


WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM TO AT LEAST THE SAME PRECISION!

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

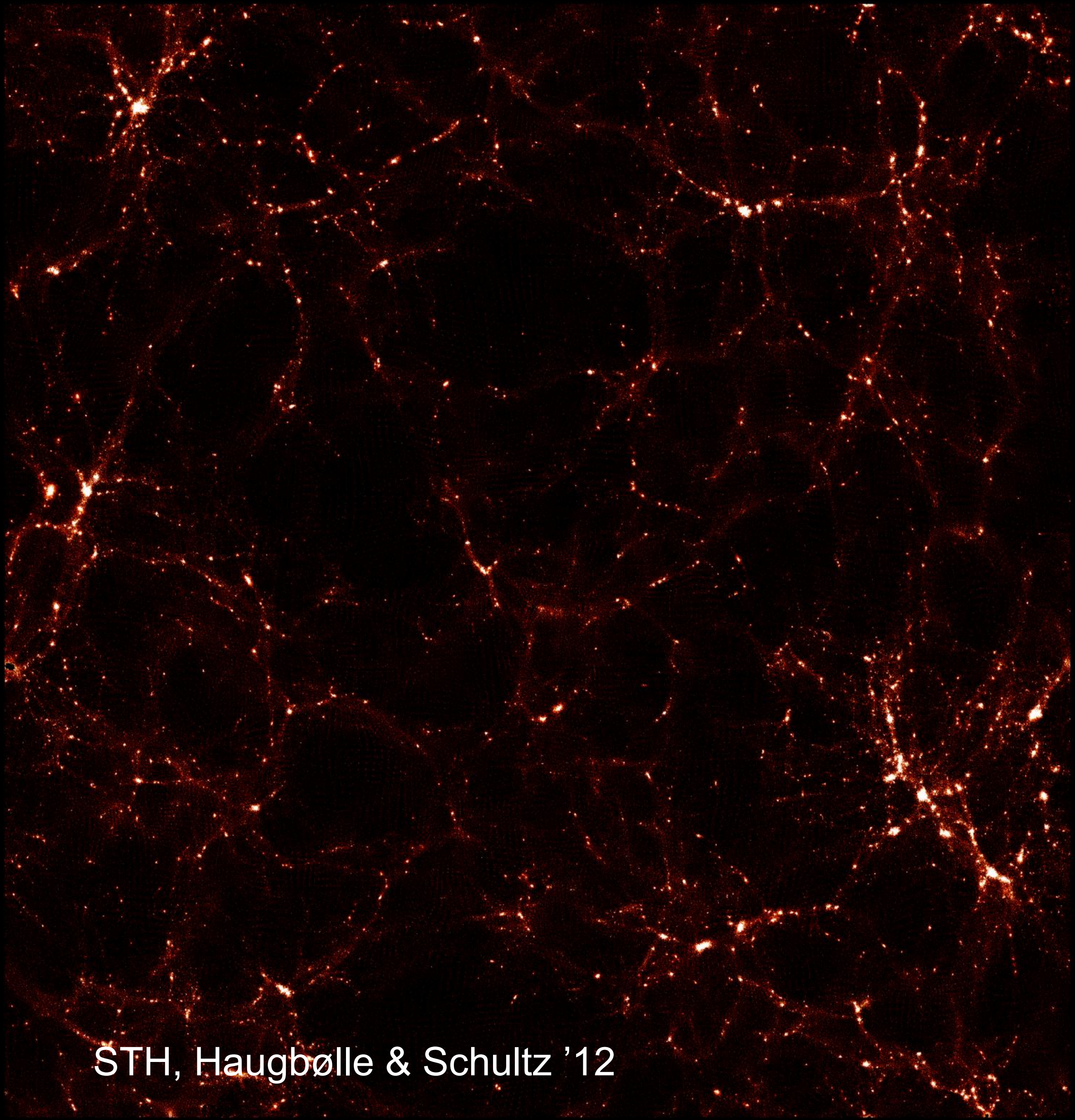
$$\frac{\Delta P}{P} \sim -8\,\frac{\Omega_\nu}{\Omega_m}$$

FULL NON-LINEAR

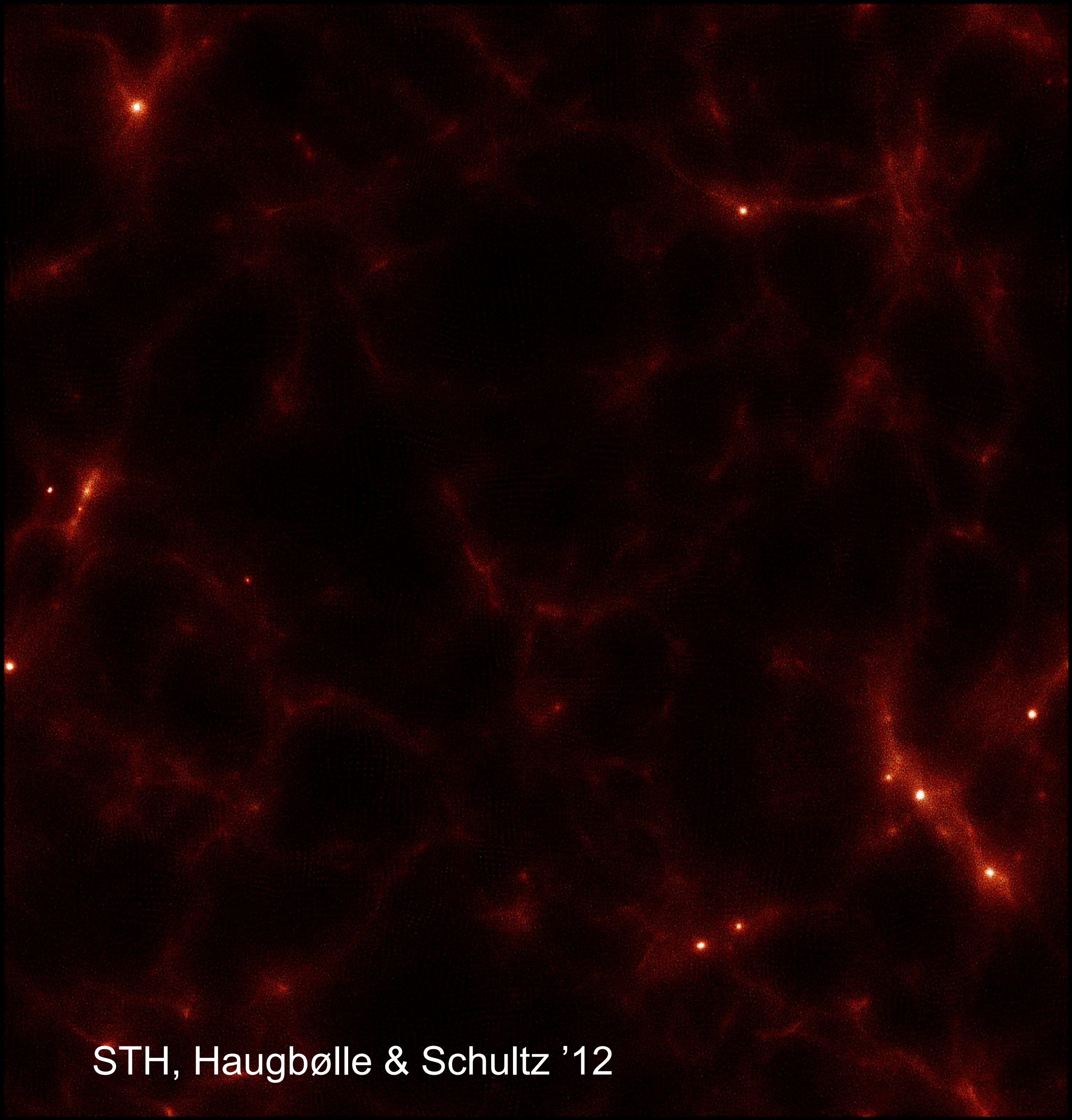
$$\frac{\Delta P}{P} \sim -9.6\,\frac{\Omega_\nu}{\Omega_m}$$

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

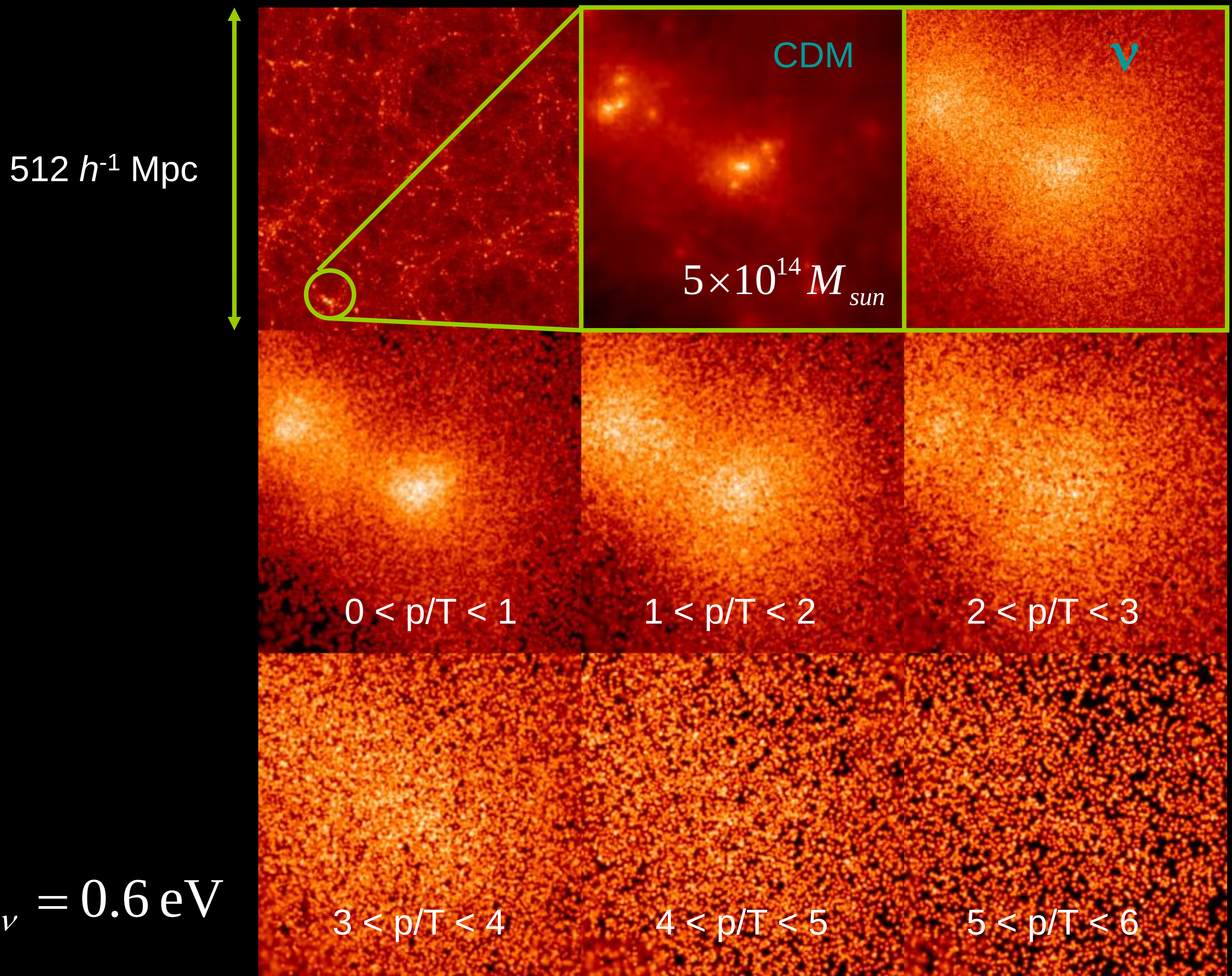
CDM



Neutrinos



INDIVIDUAL HALO PROPERTIES



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

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 PLANCK AND EUCLID WILL PROVIDE A POSITIVE DETECTION OF A NON-ZERO NEUTRINO MASS