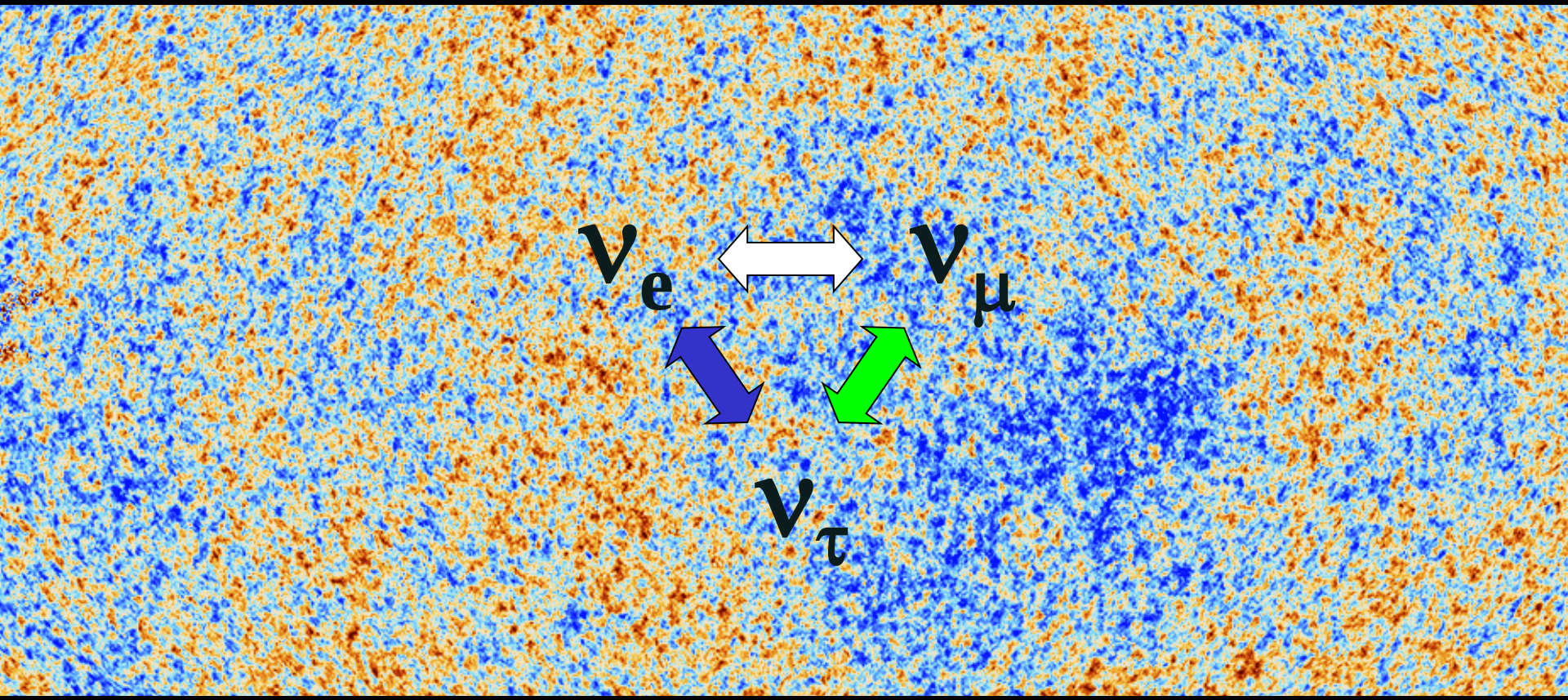
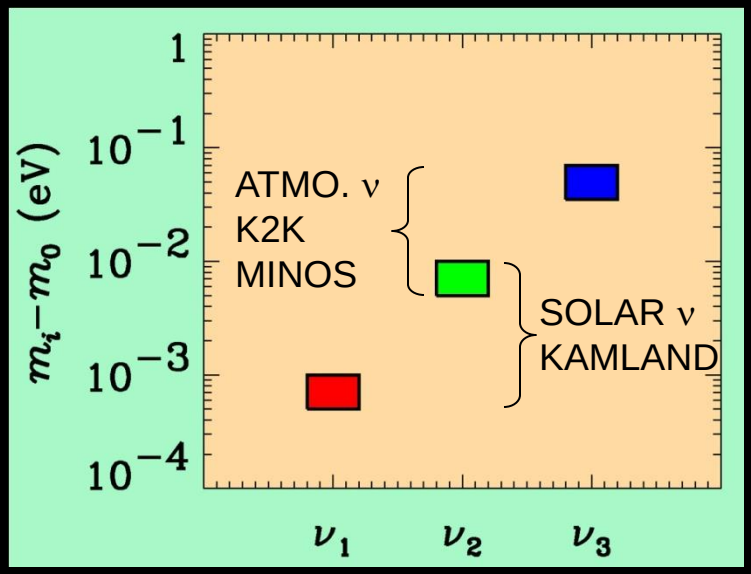
NEUTRINO IN COSMOLOGY



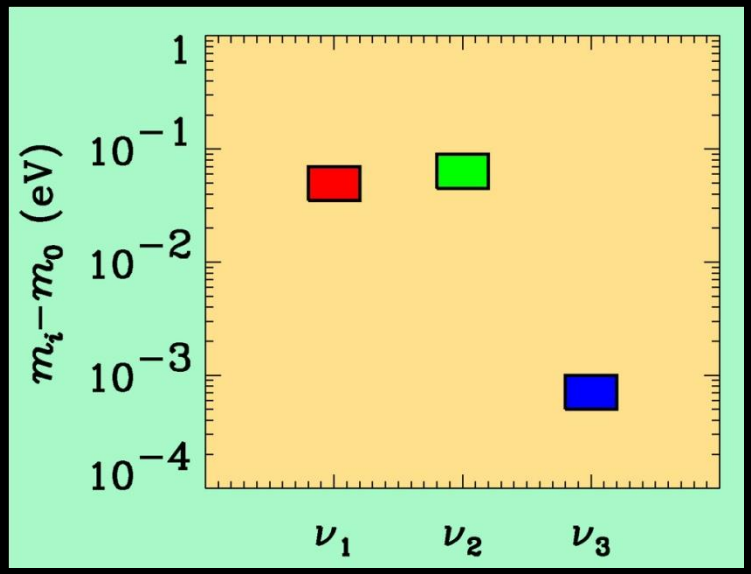
STEEN HANNESTAD, AARHUS UNIVERSITY

STOCKHOLM, 20 JULY 2013

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



Normal hierarchy



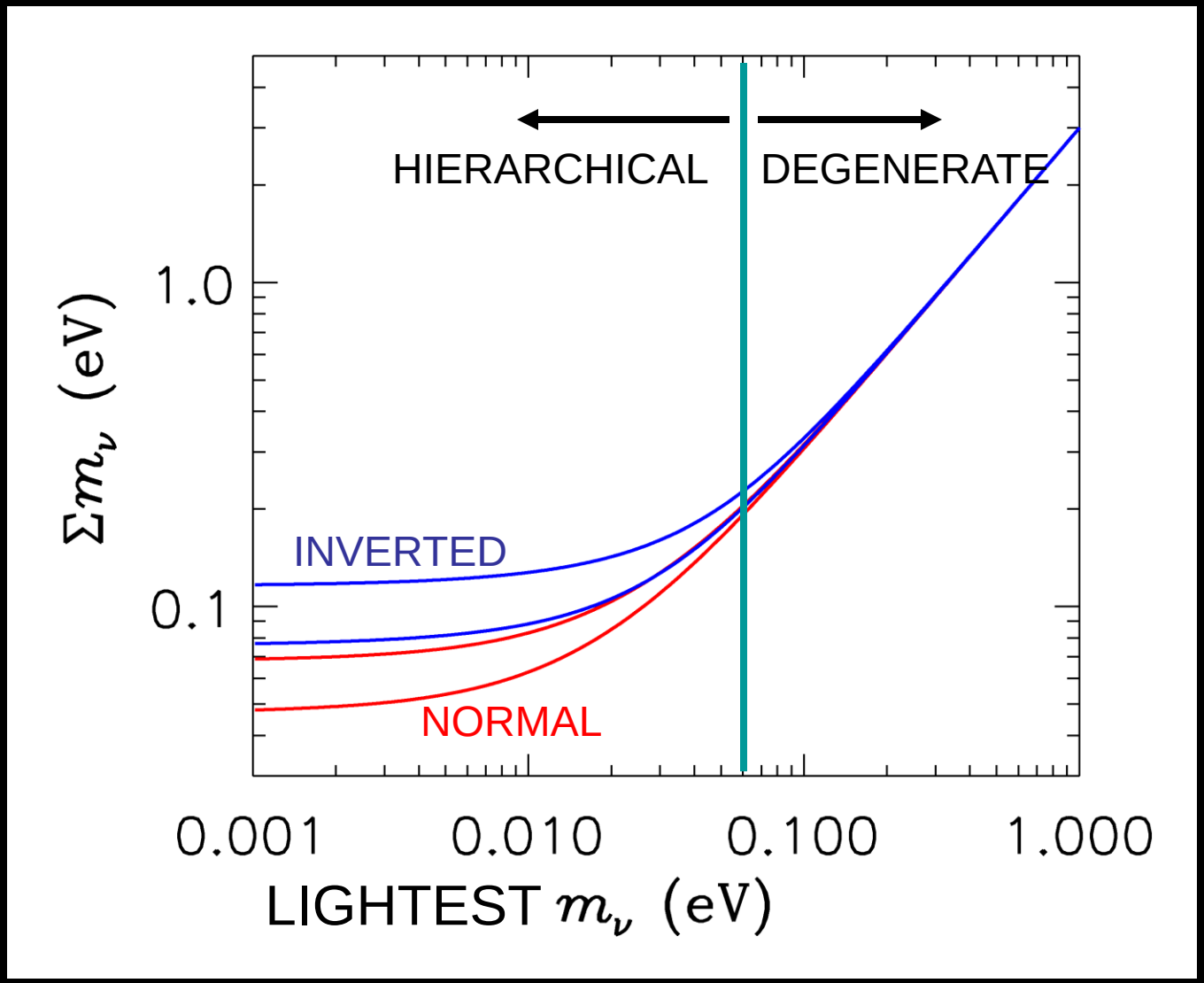
Inverted hierarchy

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
Σm_ν (eV)
0.001
0.010
0.100
1.000
LIGHTEST m_ν (eV)

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

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

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

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

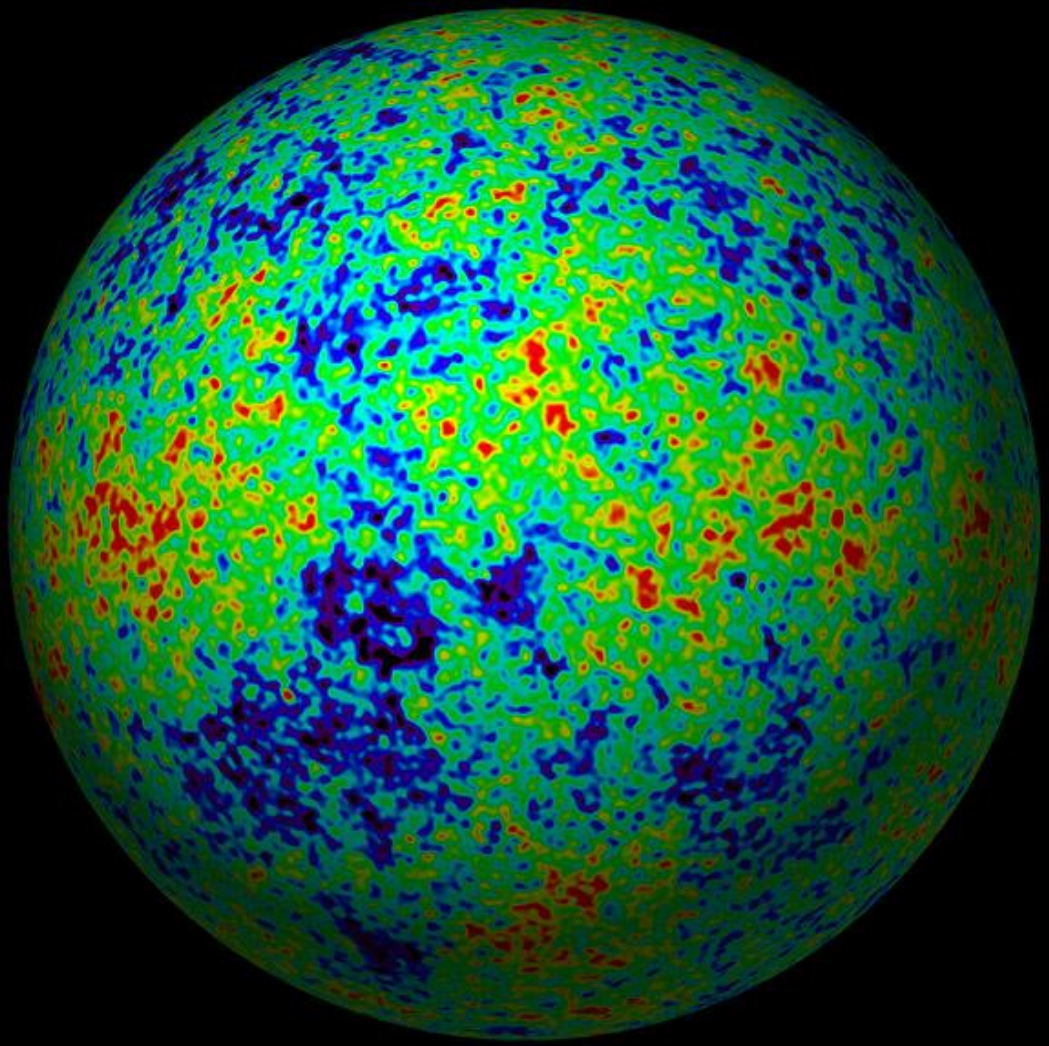
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

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

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

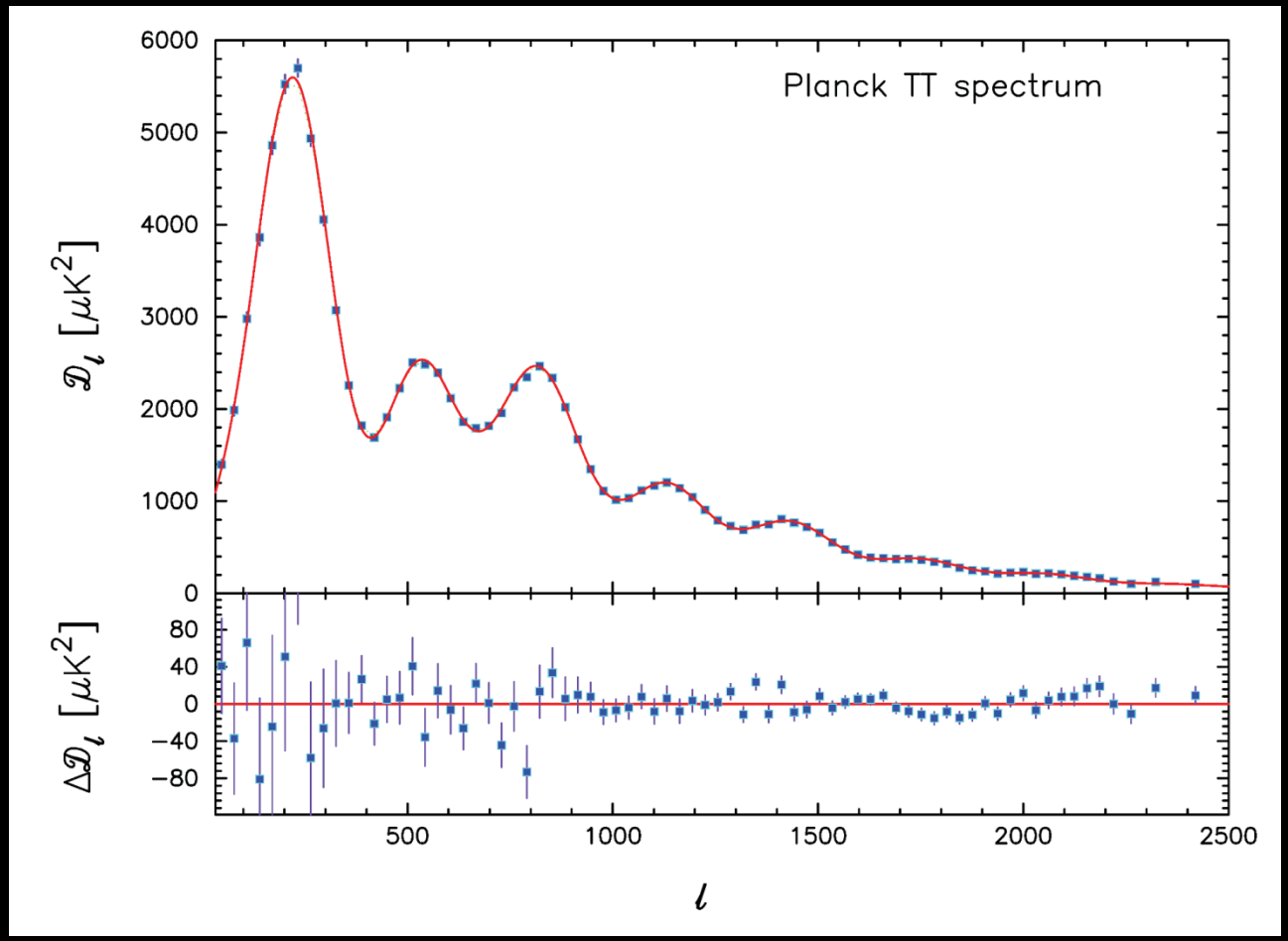
AVAILABLE COSMOLOGICAL DATA

THE COSMIC MICROWAVE BACKGROUND



CMB TEMPERATURE MAP

PLANCK TEMPERATURE POWER SPECTRUM

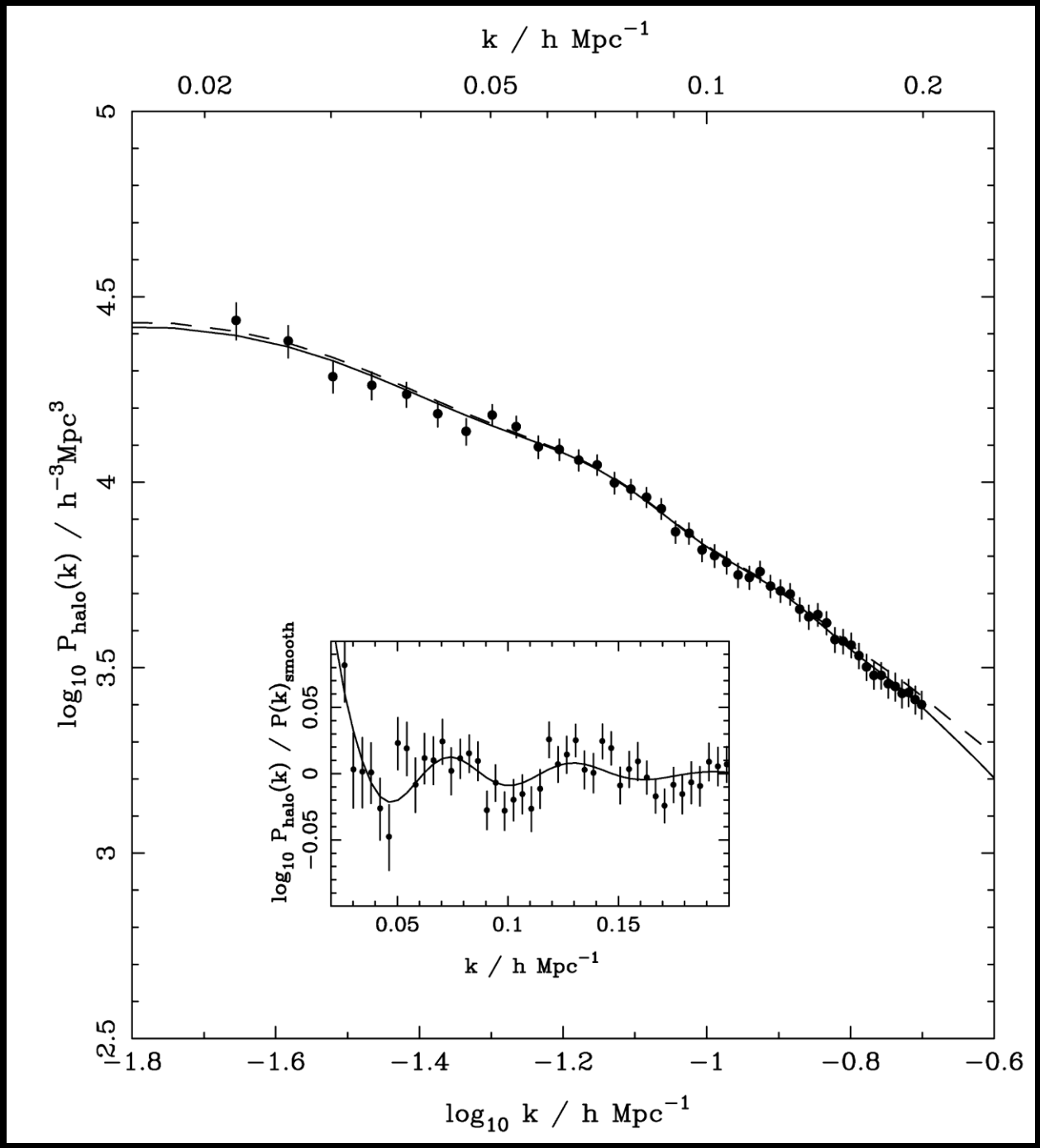


ADE ET AL, ARXIV 1303.5076

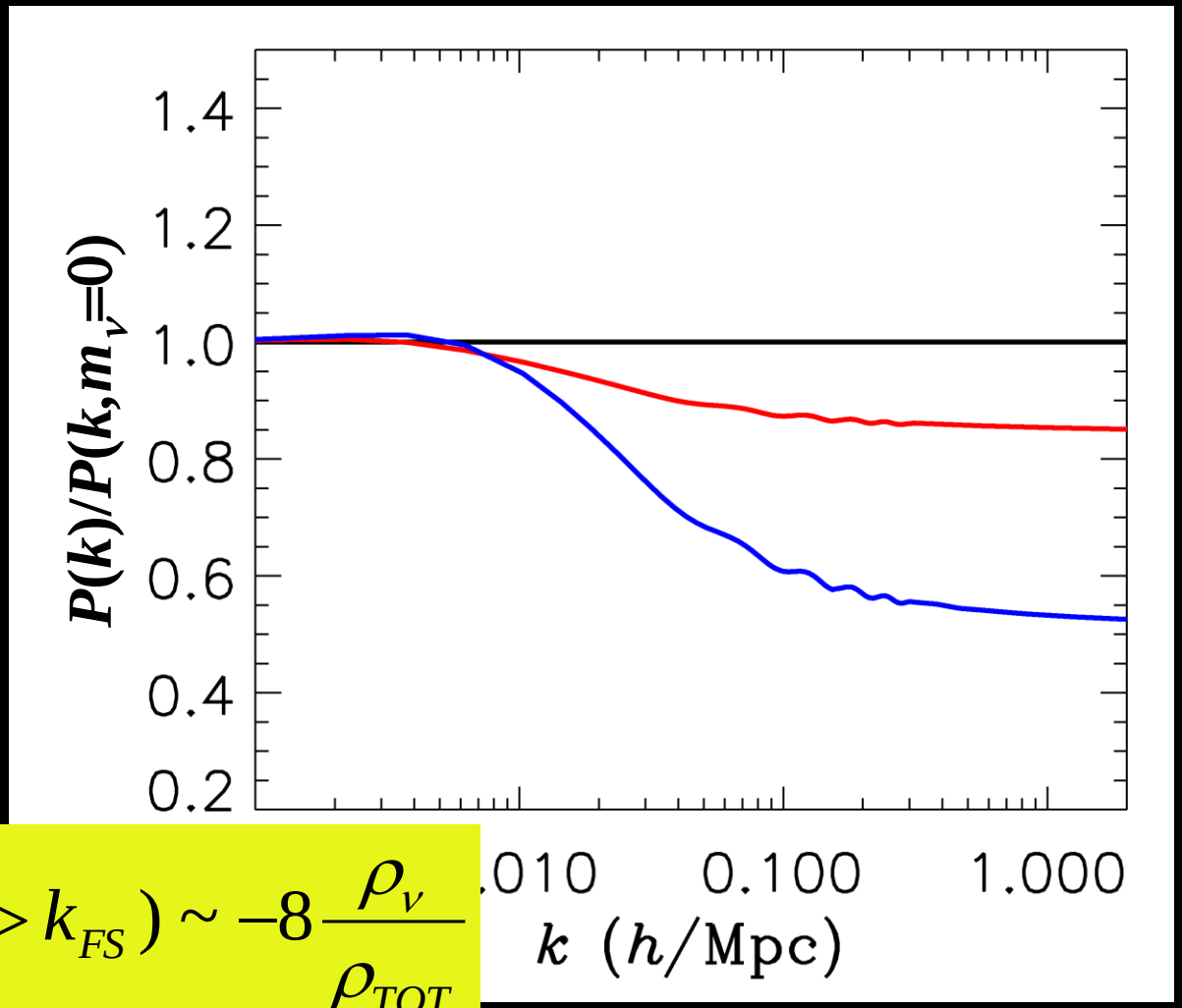
ADDITIONAL DATA ON SMALLER SCALES FROM
ATACAMA COSMOLOGY TELESCOPE (Sievers et al. 2013)
SOUTH POLE TELESCOPE (Hou et al. 2012)

THE MATTER POWER SPECTRUM

E.G. 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

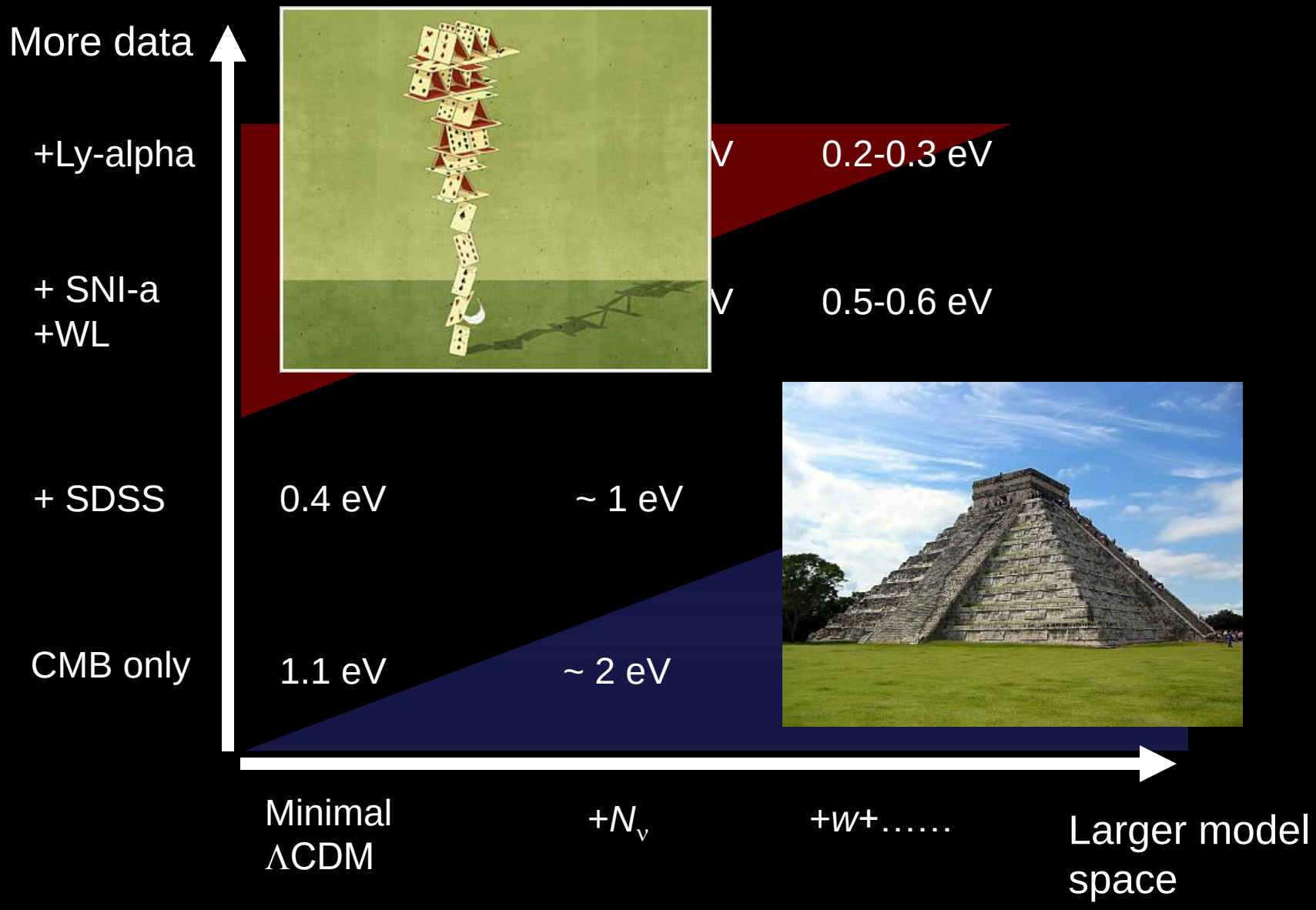
THERE ARE <u>MANY</u> ANALYSES IN THE LITERATURE

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

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

arXiv:1303.5076 (Planck)

THE NEUTRINO MASS FROM COSMOLOGY PLOT



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

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

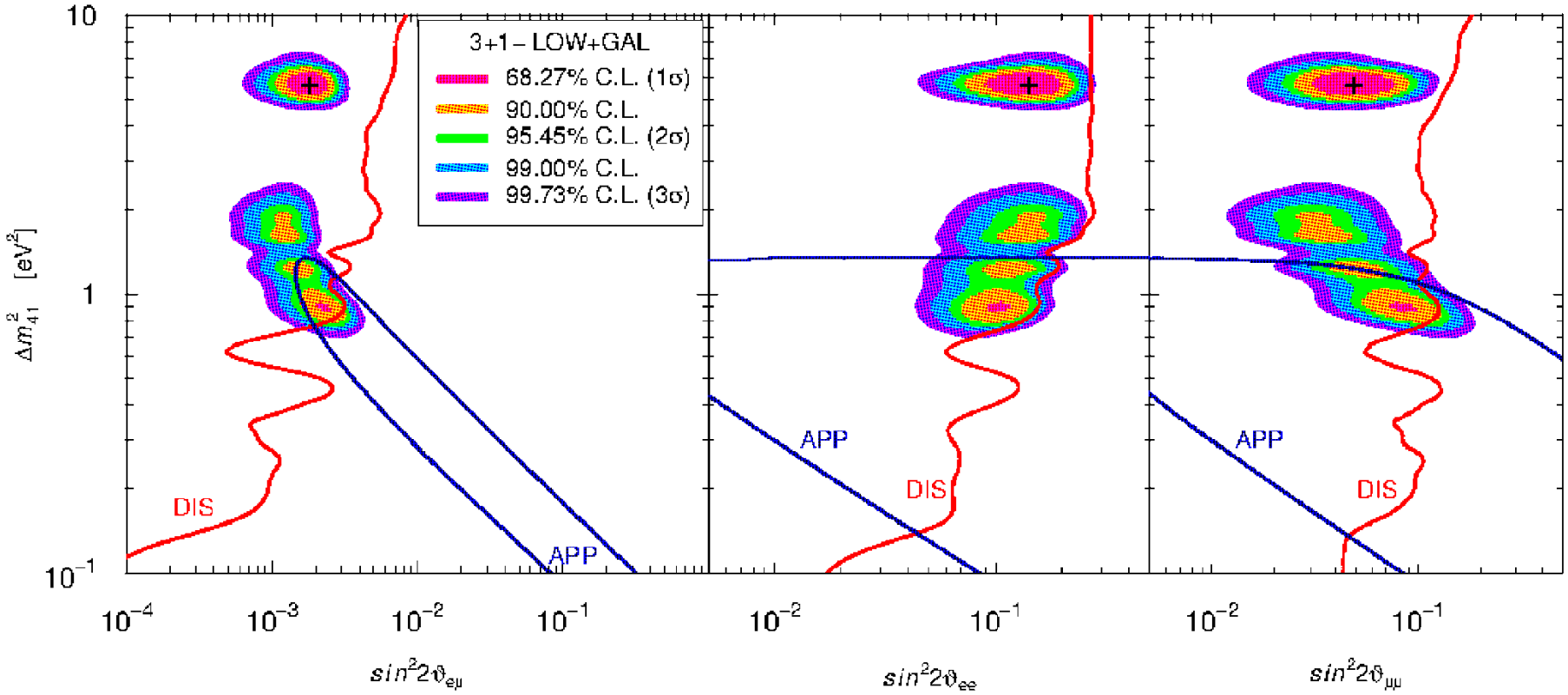
$N_{eff} = 3.52^{+0.48}_{-0.45}$ @ 95% Planck+BAO+H_0

THE SITUATION IS (UNFORTUNATELY) NOT YET RESOLVED….

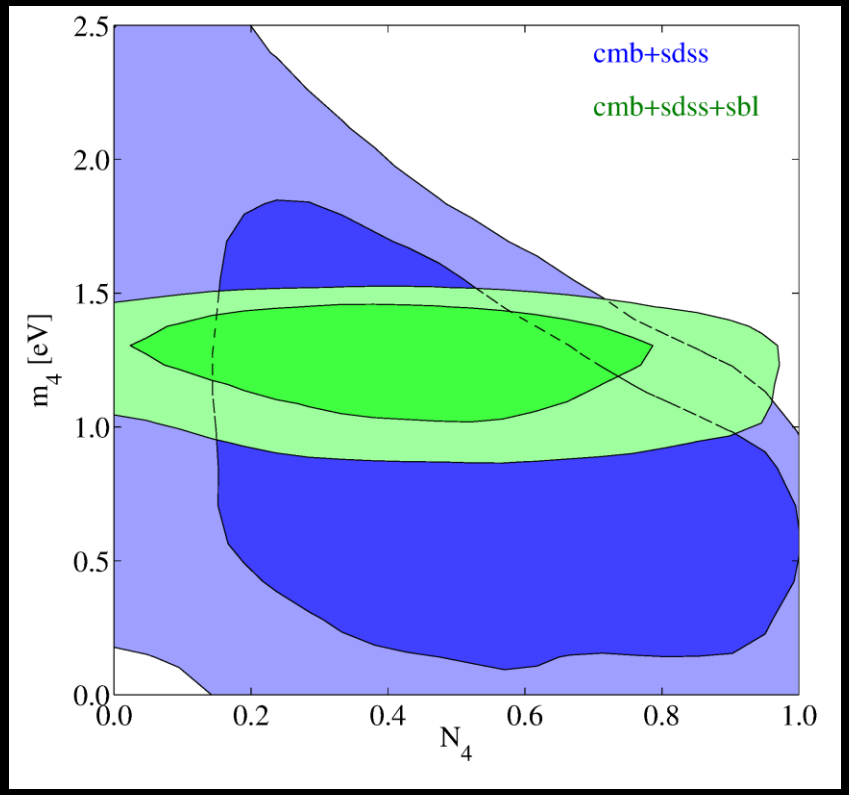
A STERILE NEUTRINO IS PERHAPS THE MOST OBVIOUS CANDIDATE FOR AN EXPLANATION OF THE POSSIBLE EXTRA ENERGY DENSITY (HAMANN ET AL. 2010 AND MANY OTHERS)

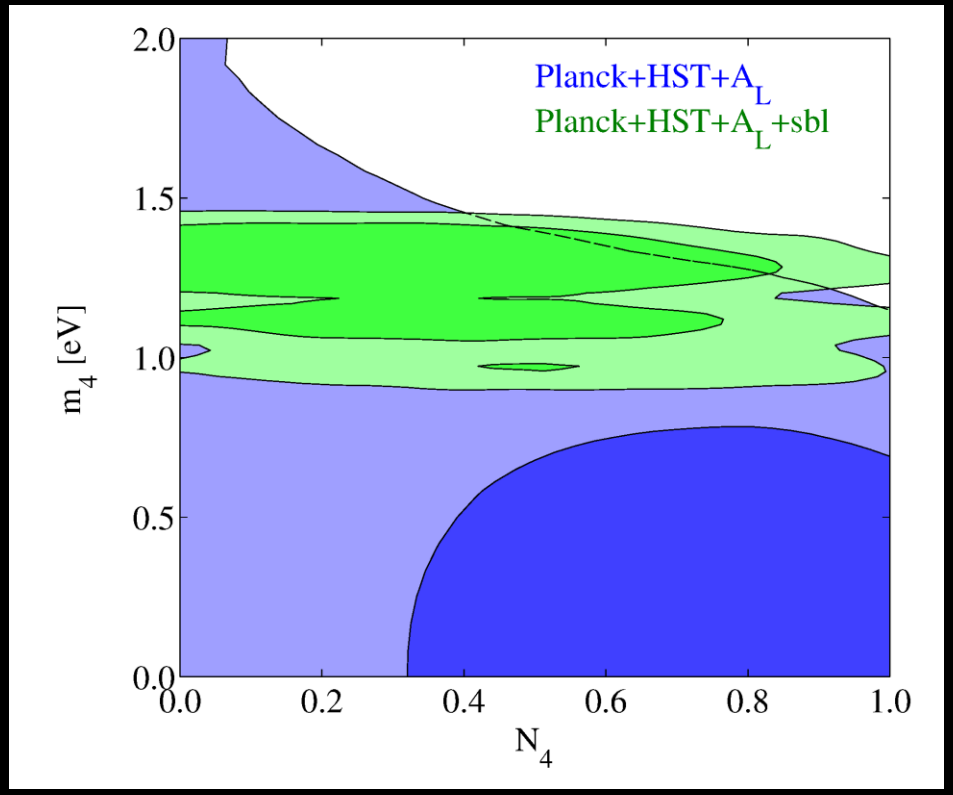
ASSUMING A NUMBER OF ADDITIONAL STERILE STATES OF APPROXIMATELY EQUAL MASS, TWO QUALITATIVELY DIFFERENT HIERARCHIES EMERGE

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)

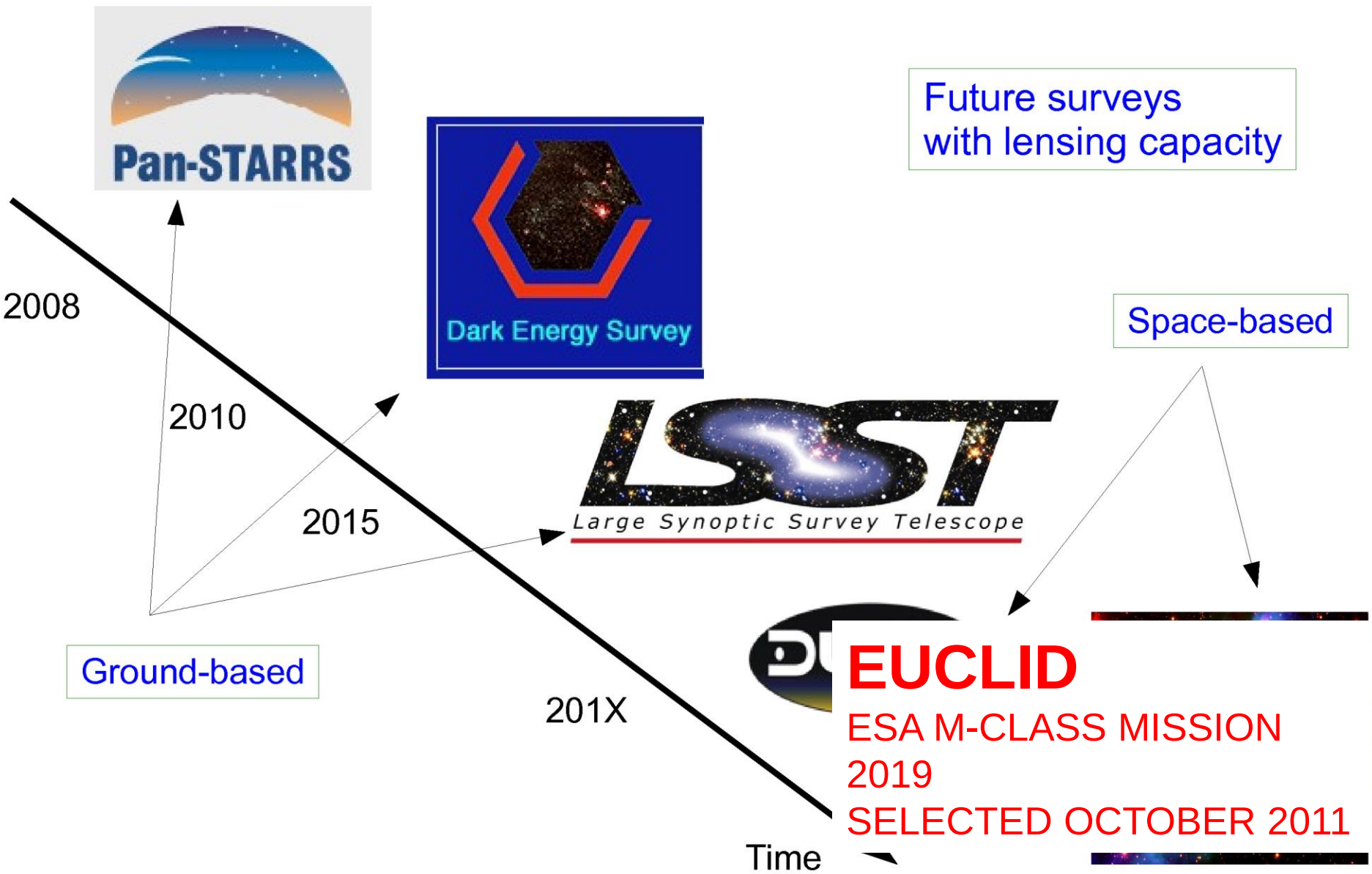
HOW DO THESE TWO HINTS FIT TOGETHER? CAN THEY BE EXPLAINED BY THE SAME PHYSICS?

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

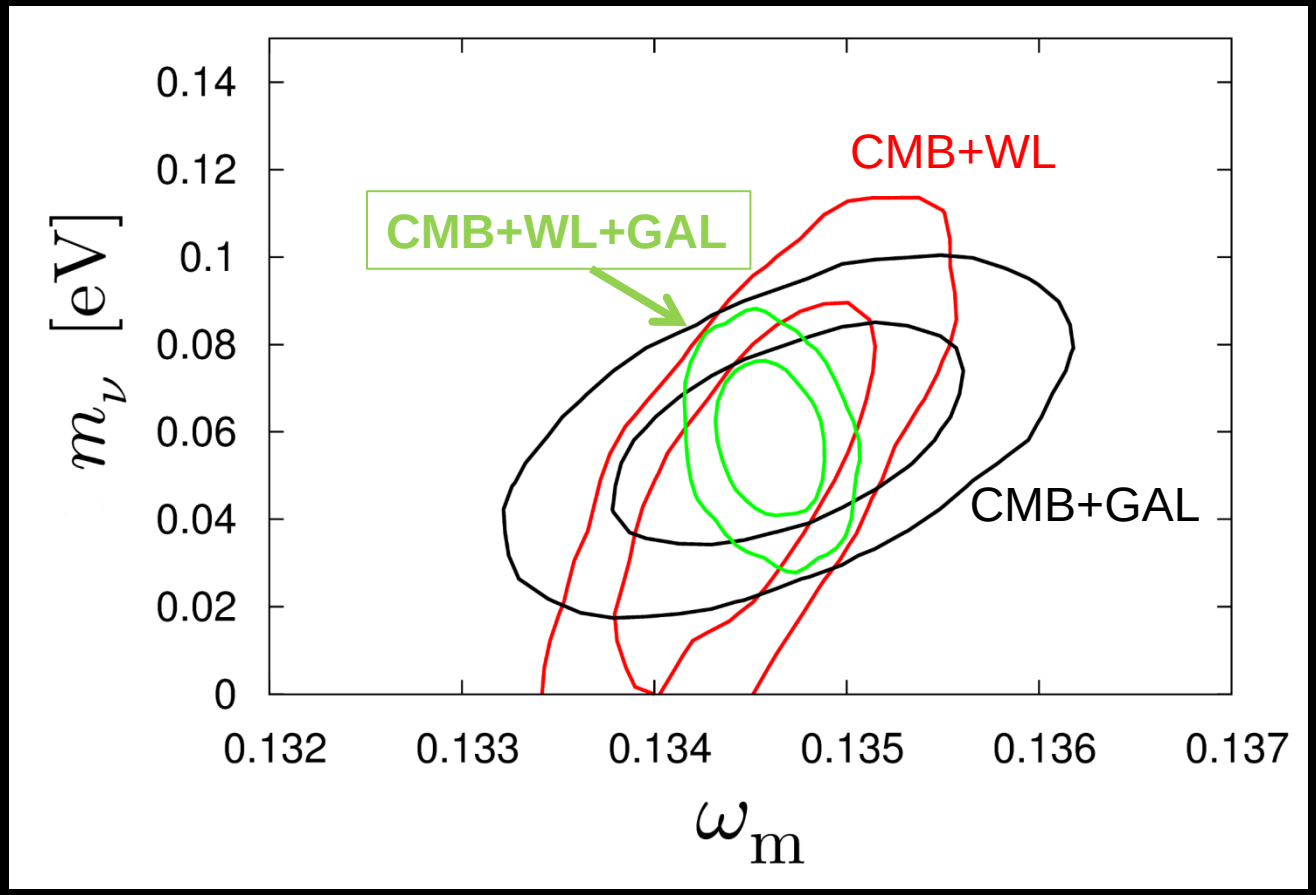
A LARGE PRIMORDIAL LEPTON ASYMMETRY CAN RECONCILE THE DATA (STH, Tamborra, Tram 2012)

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


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

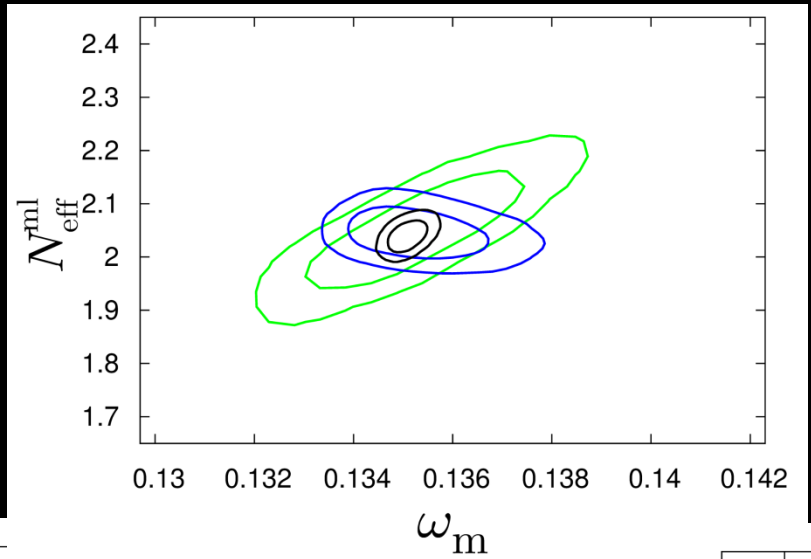
HAMANN, STH, WONG 2012: COMBINING THE EUCLID WL AND GALAXY SURVEYS WILL ALLOW FOR AT A 2.5-5σ DETECTION OF THE NORMAL HIERARCHY (DEPENDING ON ASSUMPTIONS ABOUT BIAS)

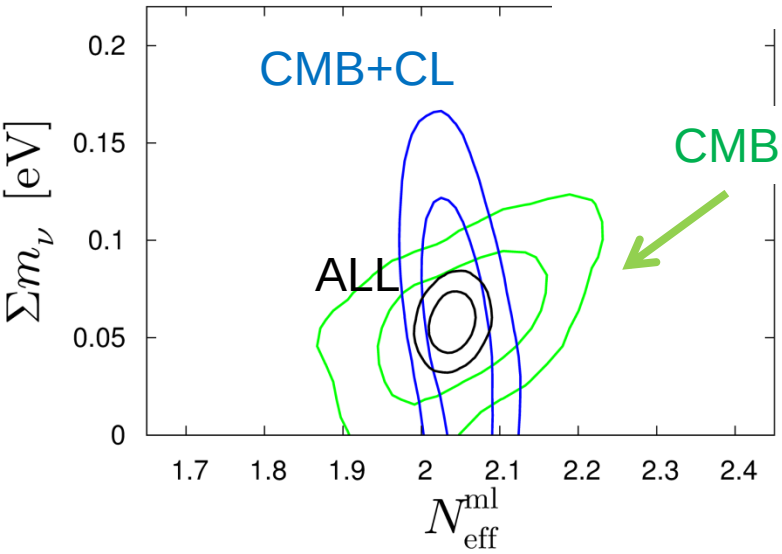


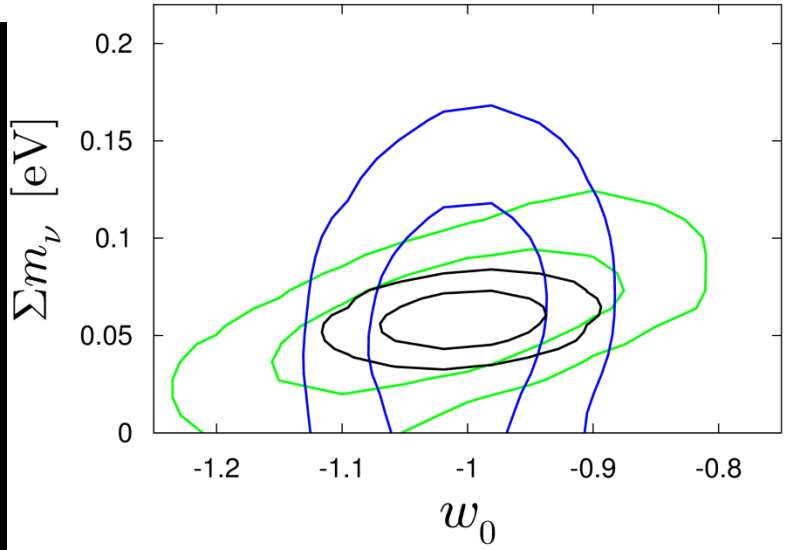
arXiv:1209.1043

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

arXiv:1304.2321







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