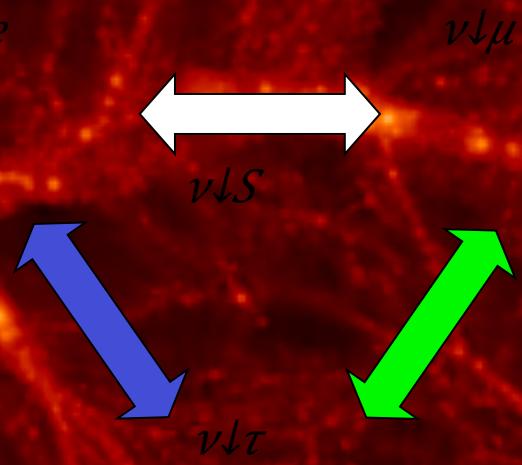
NEUTRINOS AND OTHER LIGHT RELICS IN THE ERA OF PRECISION COSMOLOGY



STEEN HANNESTAD, AARHUS UNIVERSITY
MPI-K, 25 MAY 2016

What do we know about neutrinos?

- They are light (but not massless) fermions -
- The carry no electric or strong charge
- They do carry weak charge
- 3 known charged current eigenstates:
- Must correspond to three eigenstates of energy and momentum:
- Charged current eigenstates and energy/momentum eigenstates are NOT identical
- Provided that are not identical this leads to neutrino oscillations

NEUTRINO MIXING IN THE STANDARD PICTURE

FLAVOUR STATES

PROPAGATION STATES

U

Atmospheric Long Baseline

Reactor

Solar Reactor

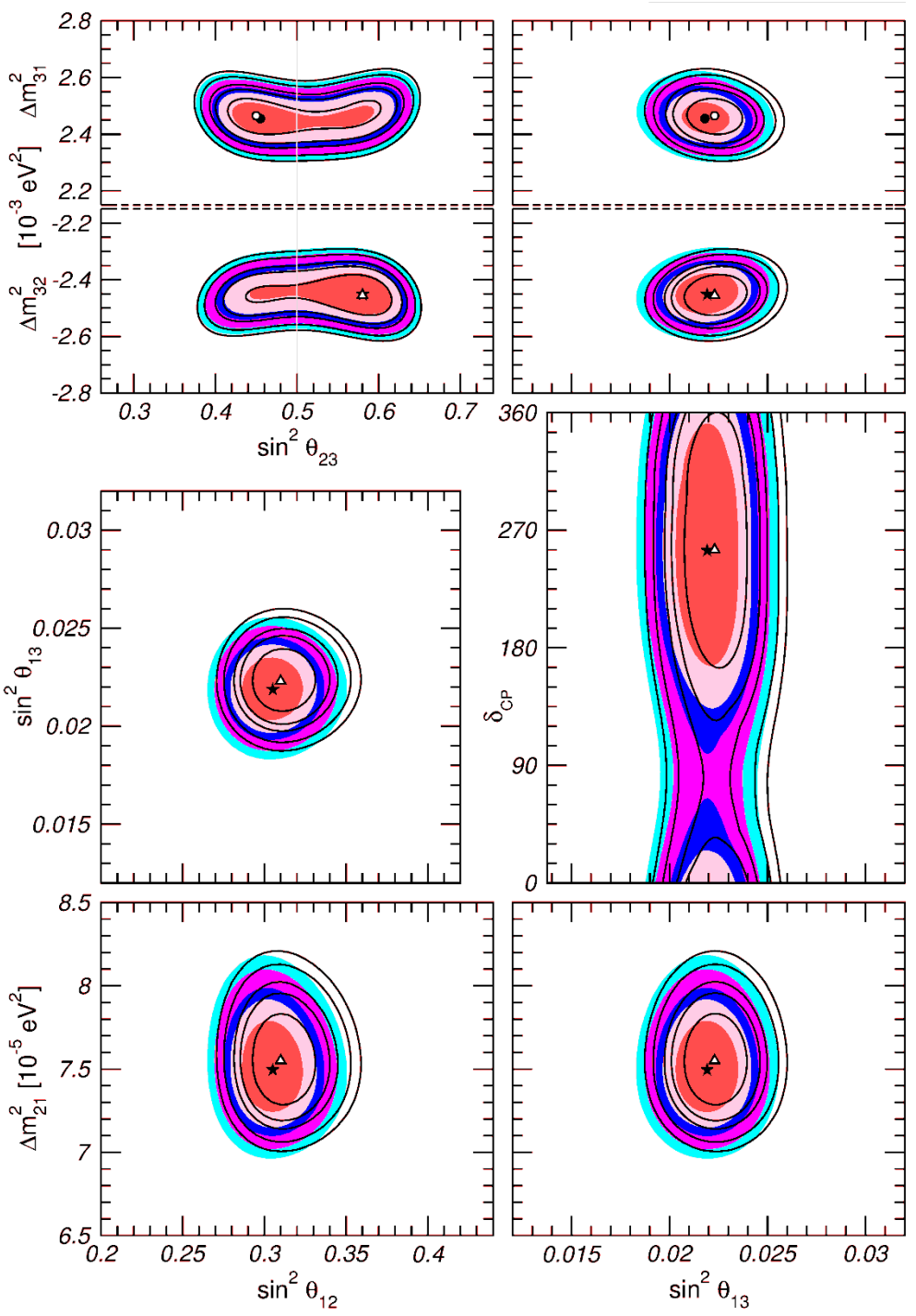
Only relevant for $0\nu2\beta$ decay

etc., are the Euler angles of 3D rotation

is the Dirac CP phase

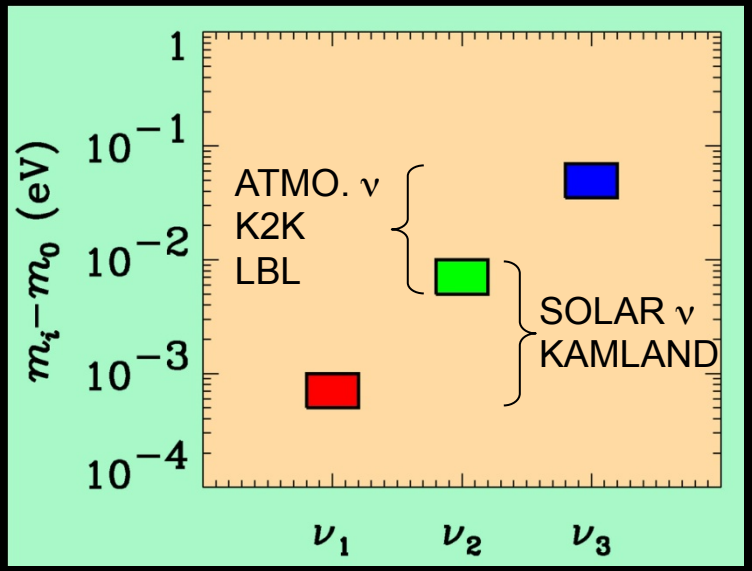
are Majorana phases (relevant only if neutrinos are Majorana particles)

Status of 3-neutrino oscillations

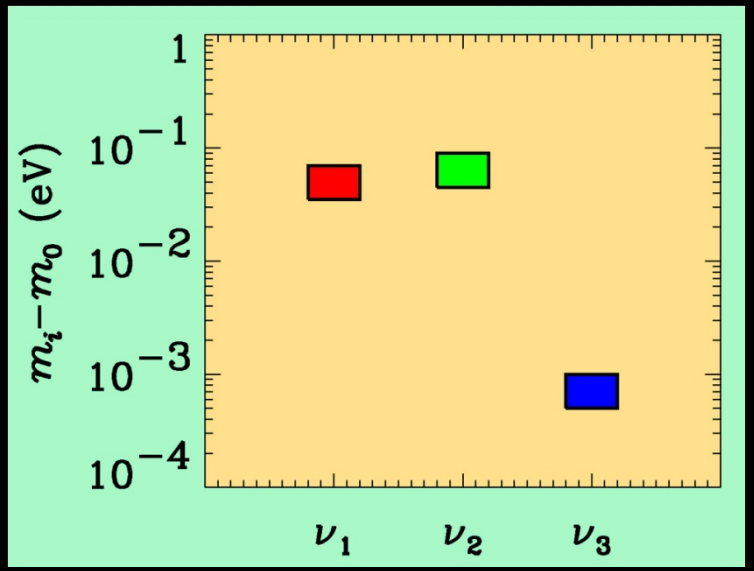


Gonzalez-Garcia, Maltoni, Schwetz
1409.5439

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



Normal hierarchy



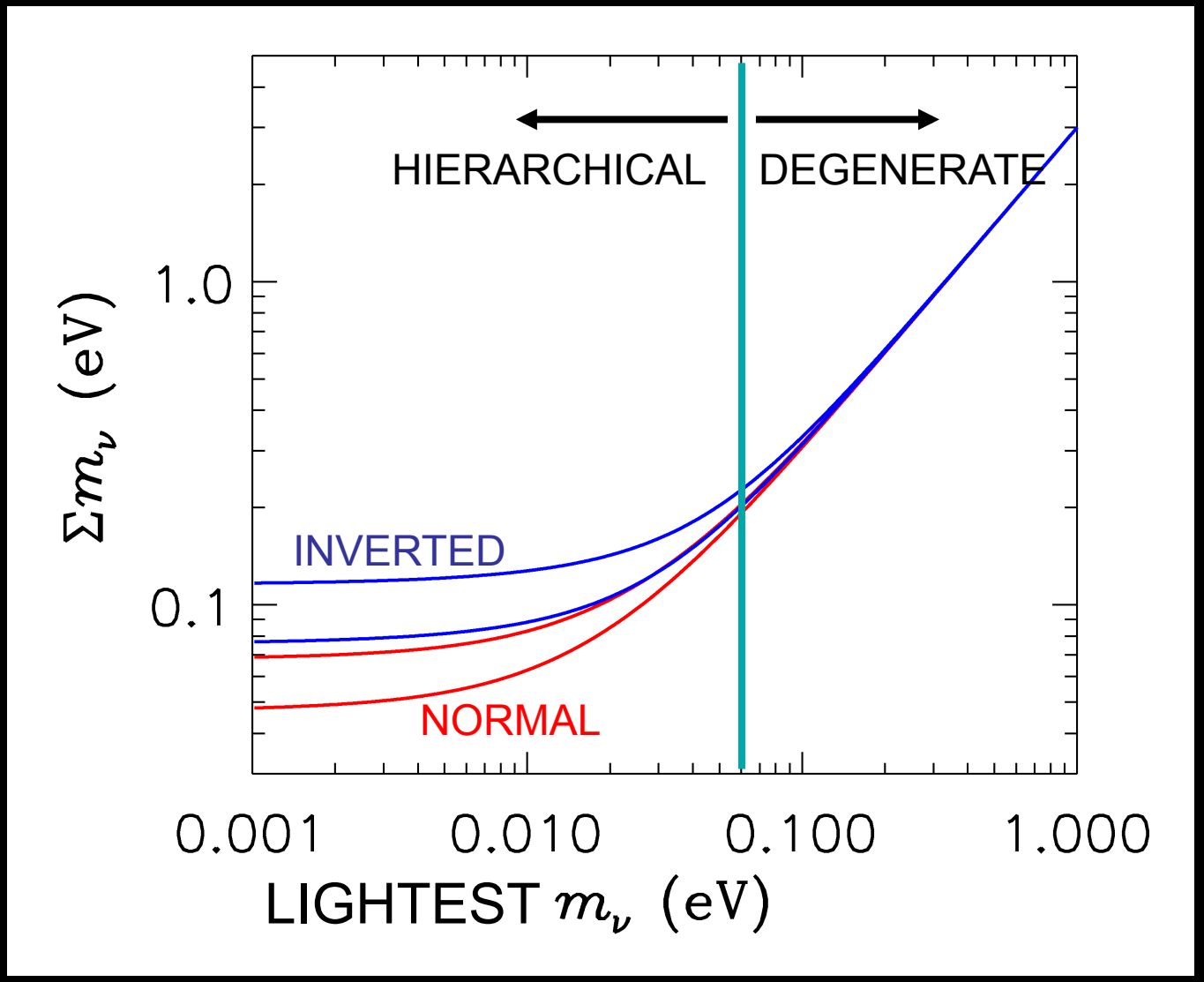
Inverted hierarchy

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

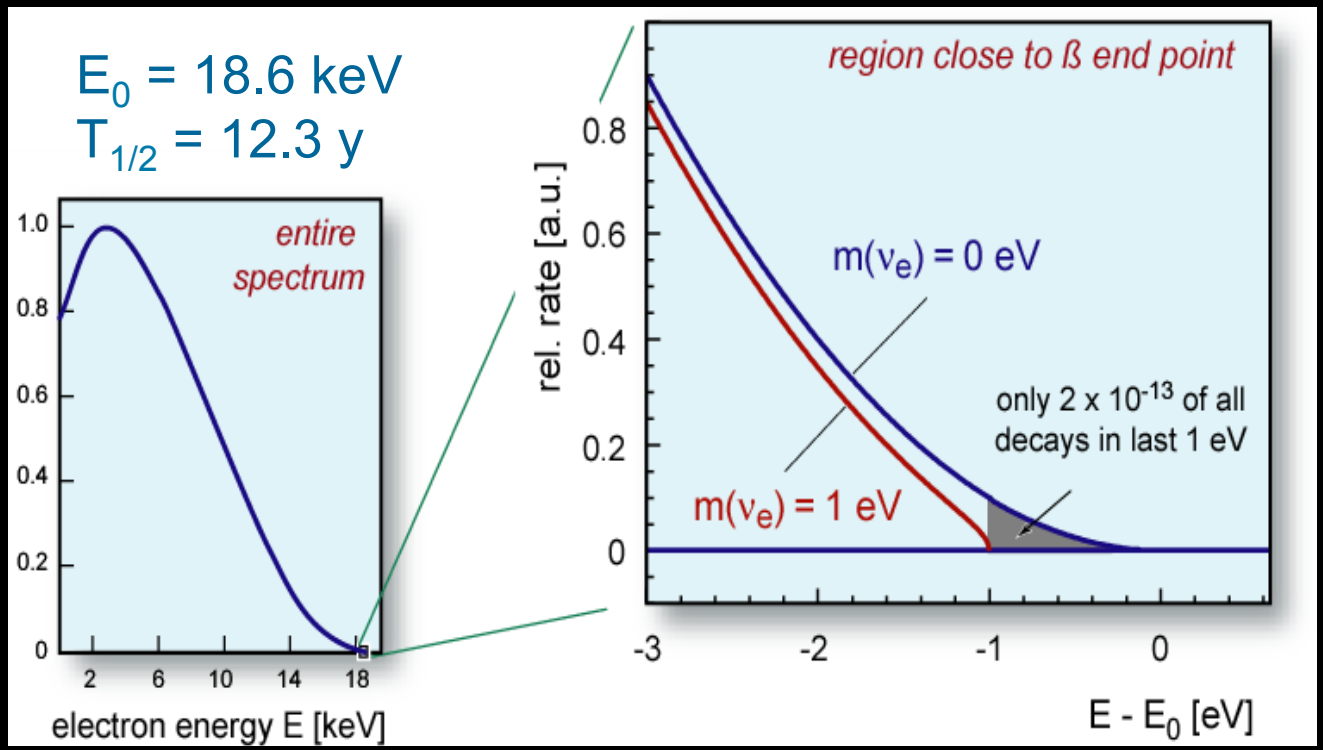
ß-decay and neutrino mass

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

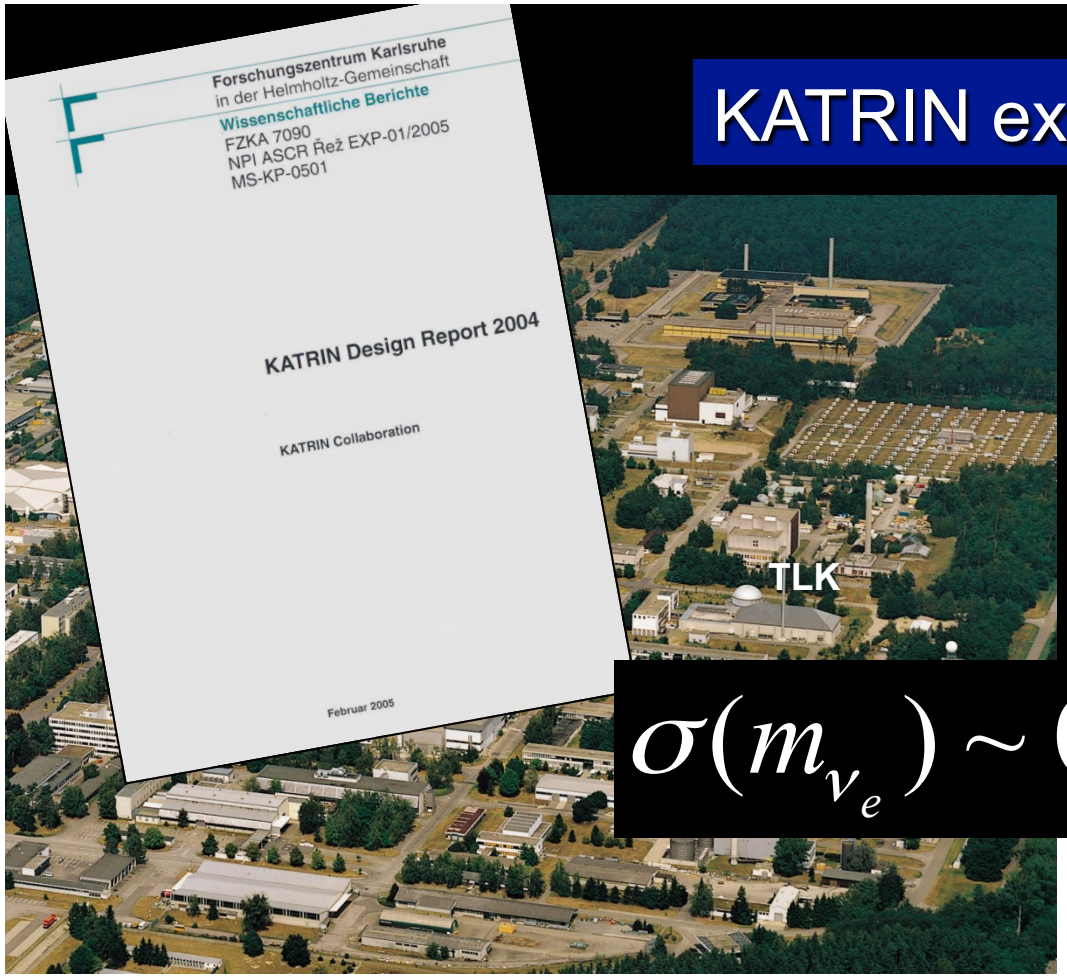
$$m_{\nu_e} = \left(\sum |U_{ei}|^2 m_i^2 \right)^{1/2} \leq 2.3\,\text{eV} \;\; (95\%)$$

Mainz experiment, final analysis (Kraus et al.)

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

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

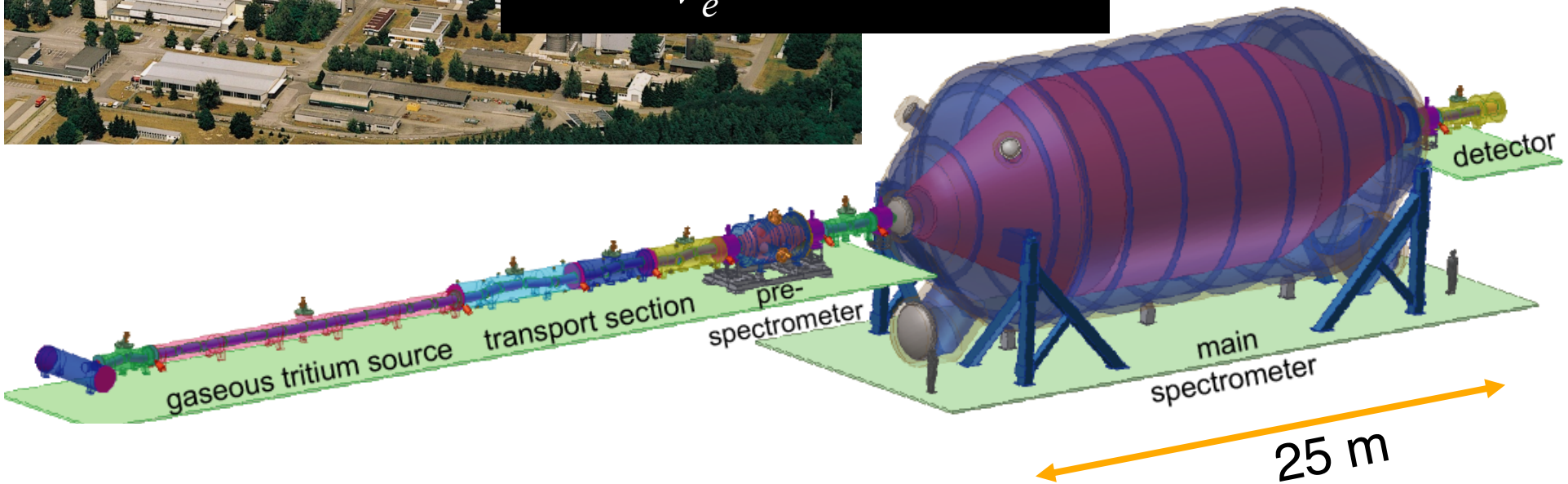
KATRIN experiment



Karlsruhe **Tri**tium **N**eutrino Experiment

Data taking by end of 2016

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



A DANISH VERSION OF KATRIN???

THE CARLSBERG NEUTRINO MASS EXPERIMENT

NEUTRINO MASS AND ENERGY DENSITY FROM COSMOLOGY

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

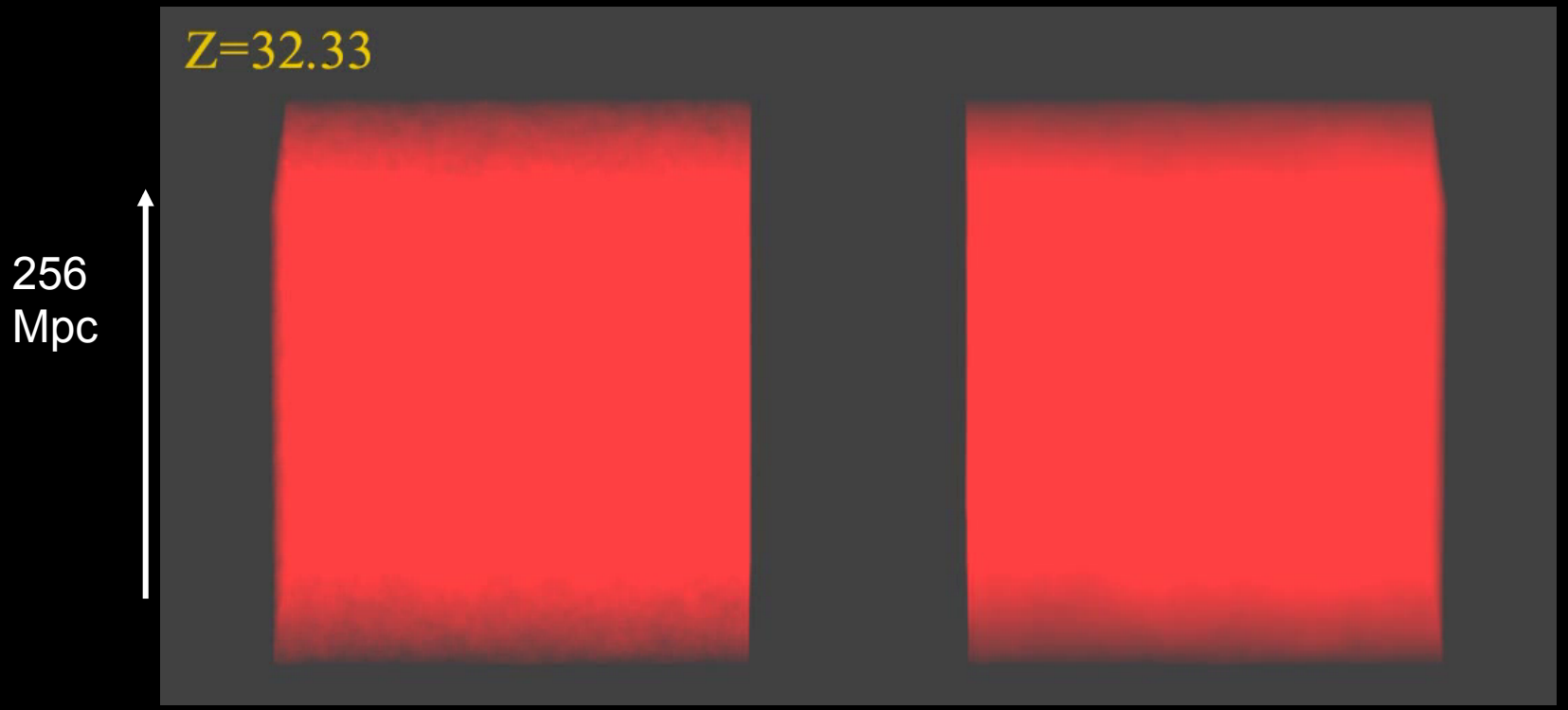
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93\,\mathrm{eV}} \qquad \text{FROM} \qquad T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \approx 2\,\mathrm{K}$$

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

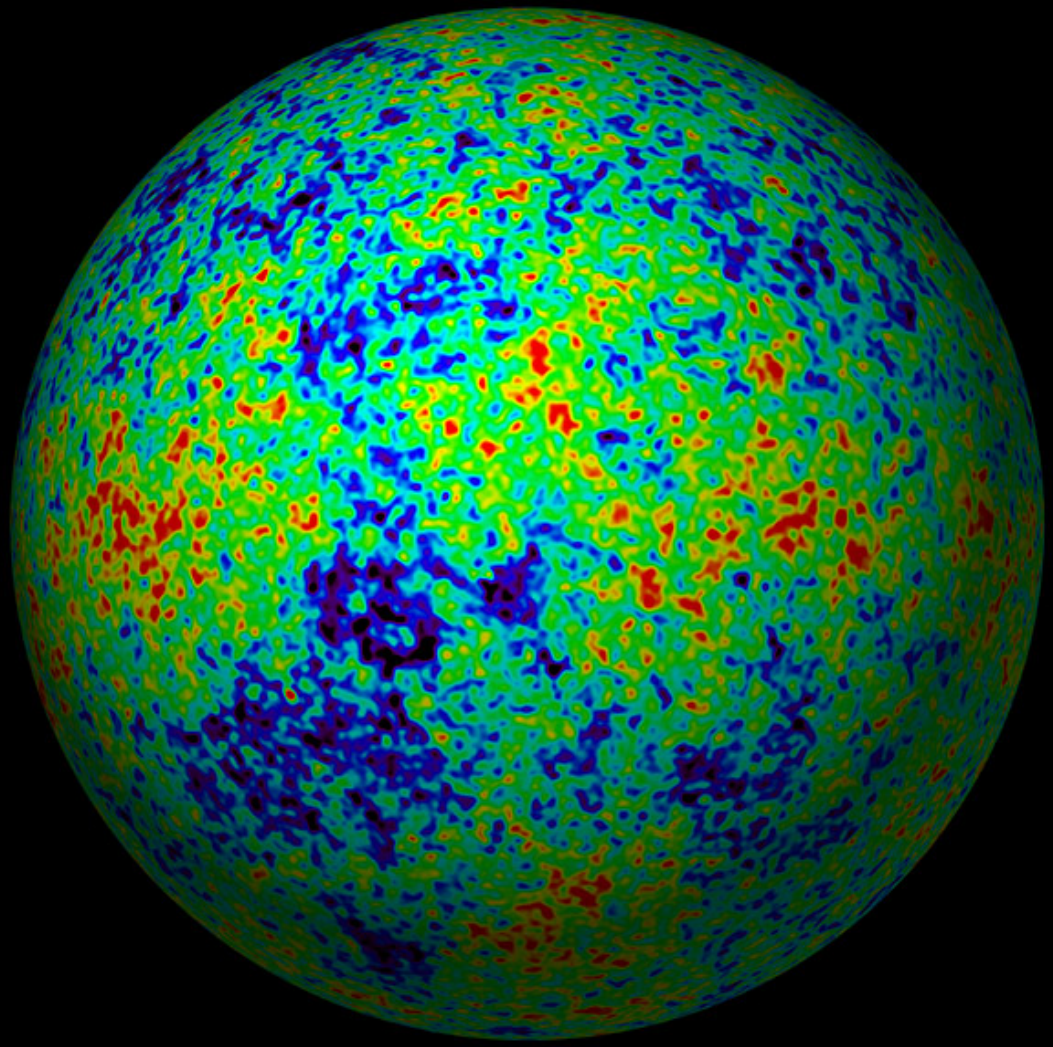
N-BODY SIMULATIONS OF ΛCDM WITH AND WITHOUT NEUTRINO MASS (768 Mpc^3) – GADGET 2



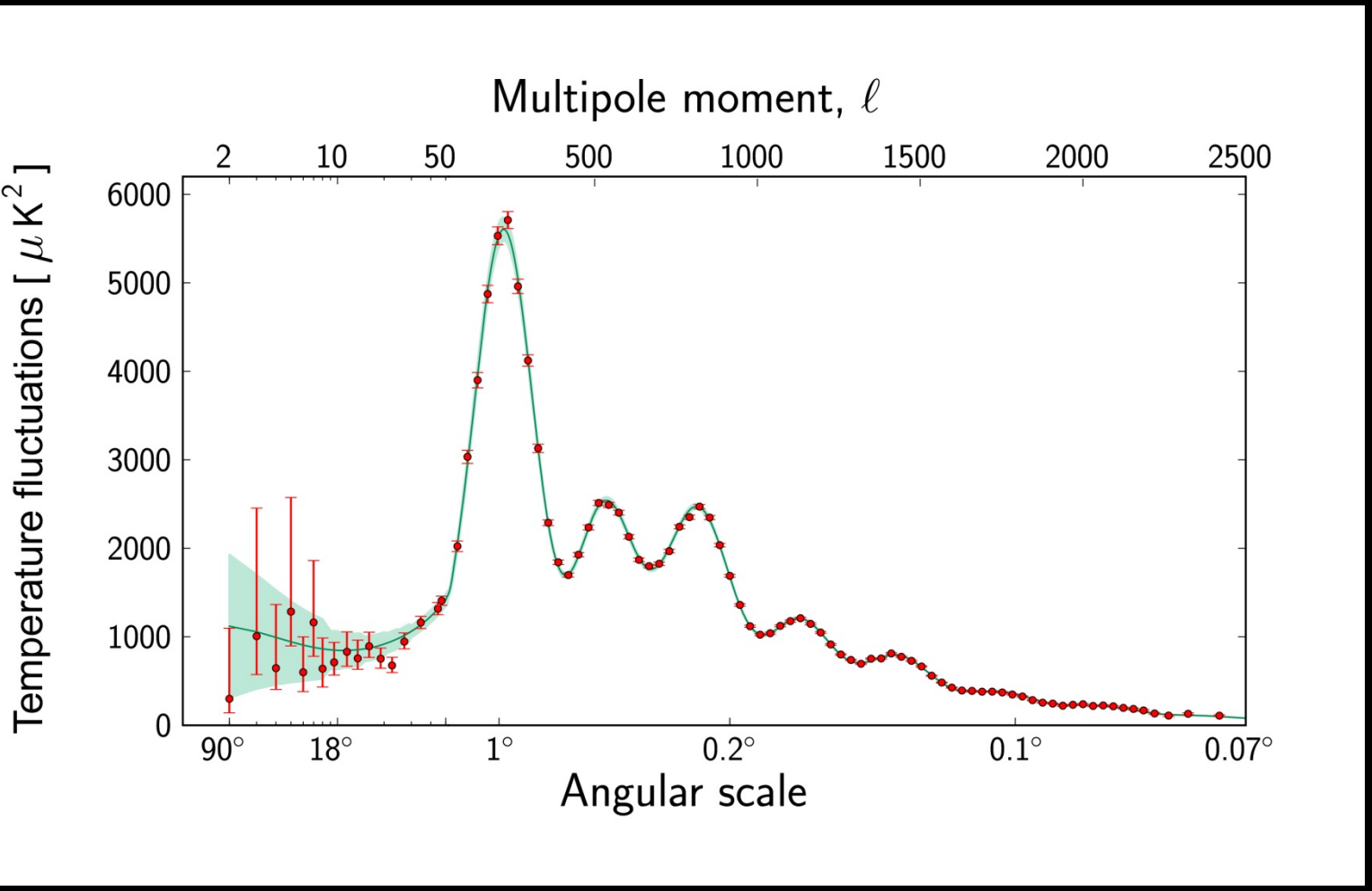
T Haugboelle, Aarhus University

AVAILABLE COSMOLOGICAL DATA

THE COSMIC MICROWAVE BACKGROUND

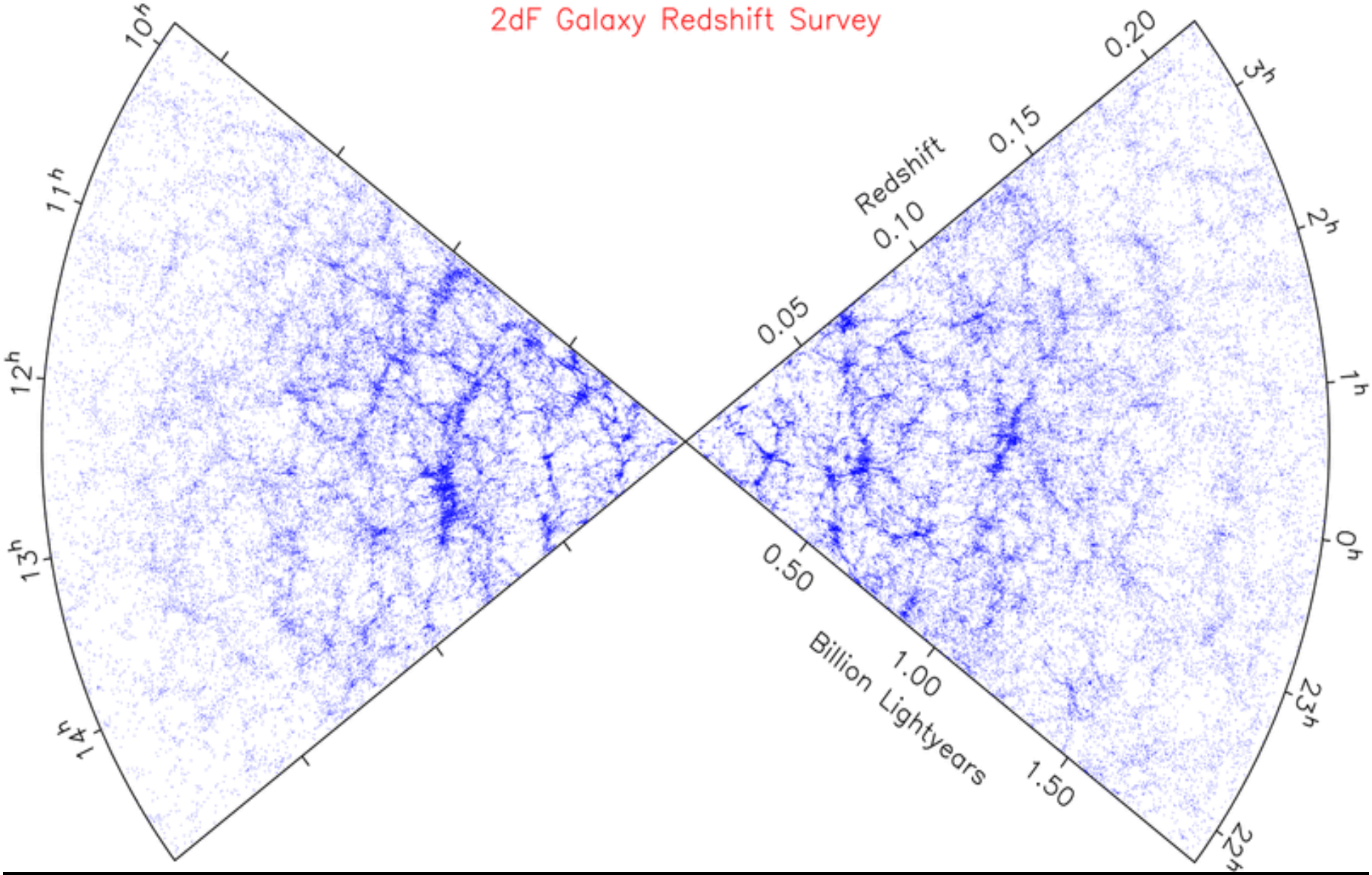


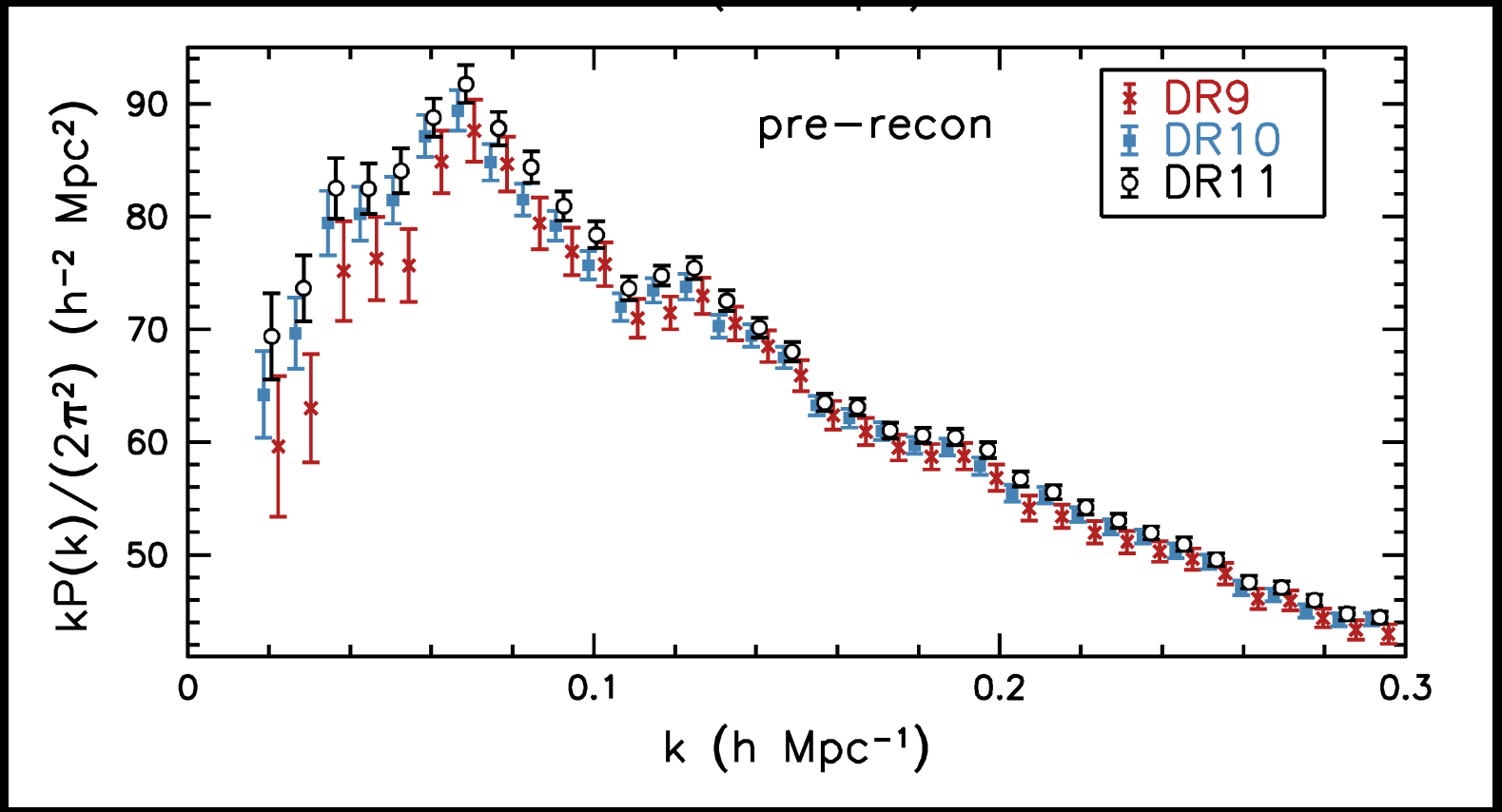
CMB TEMPERATURE AND POLARISATION



Ade et al. 2015 (Planck)

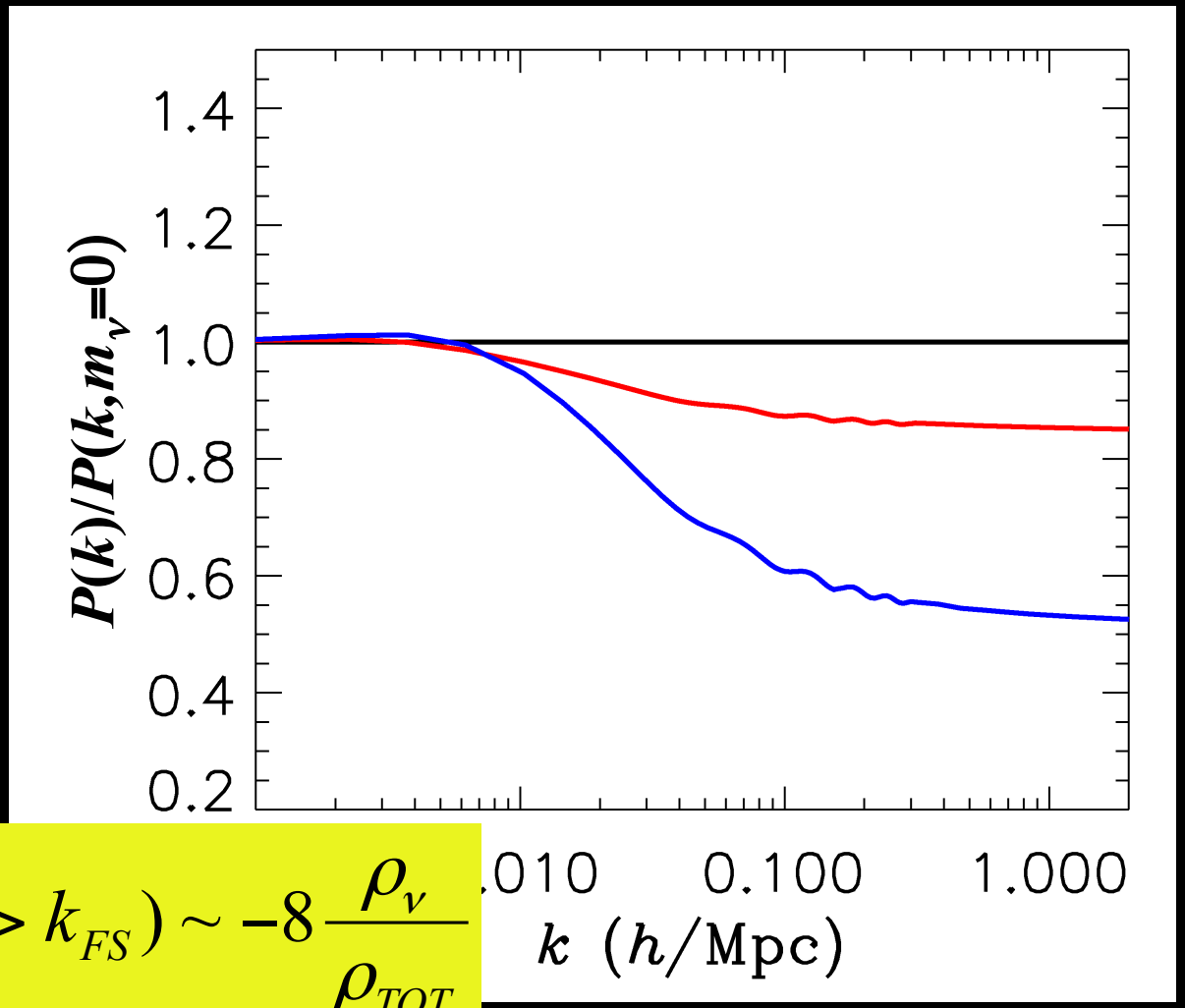
LARGE SCALE STRUCTURE SURVEYS





Anderson et al. 1312.4877 (SDSS)

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



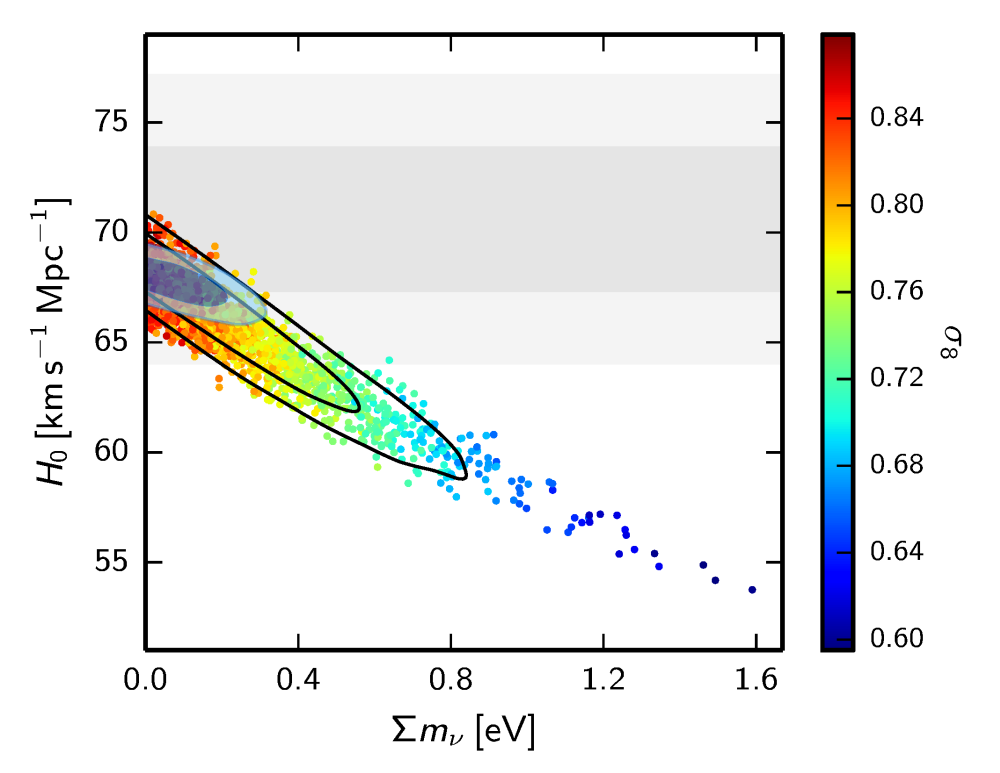
$$\frac{\Delta P}{P_{m=0}}(k >> k_{FS}) \sim -8\frac{\rho_\nu}{\rho_{TOT}}$$

NOW, WHAT ABOUT NEUTRINO PHYSICS?

WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

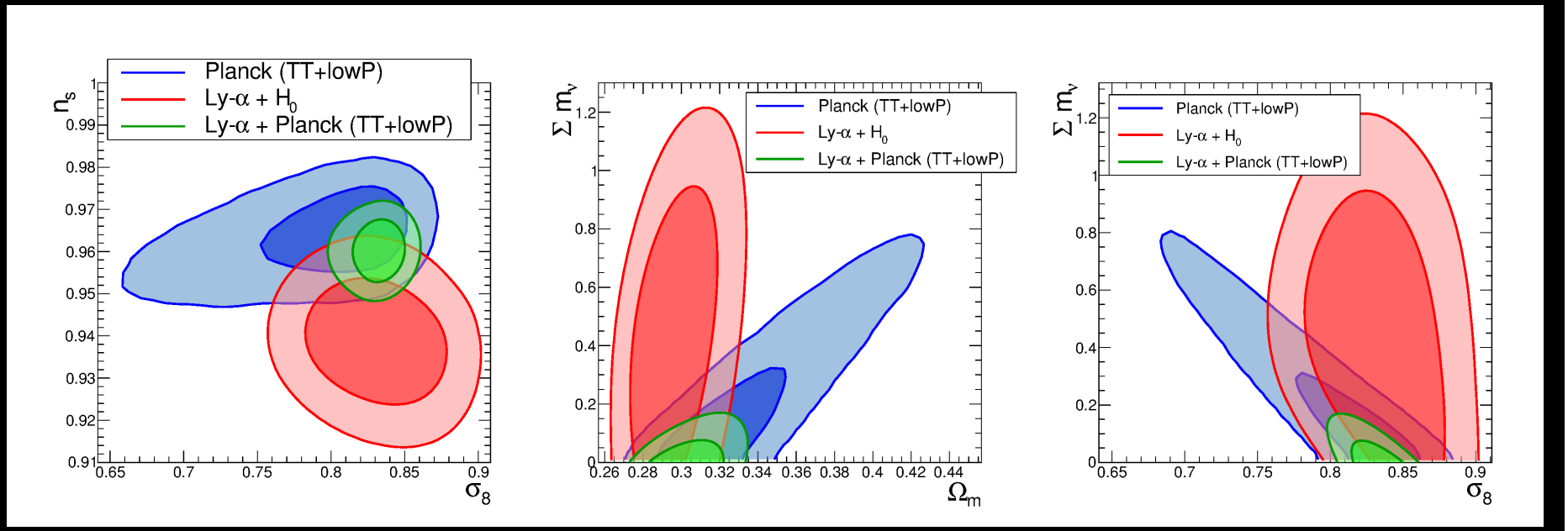
DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

THERE ARE MANY ANALYSES IN THE LITERATURE



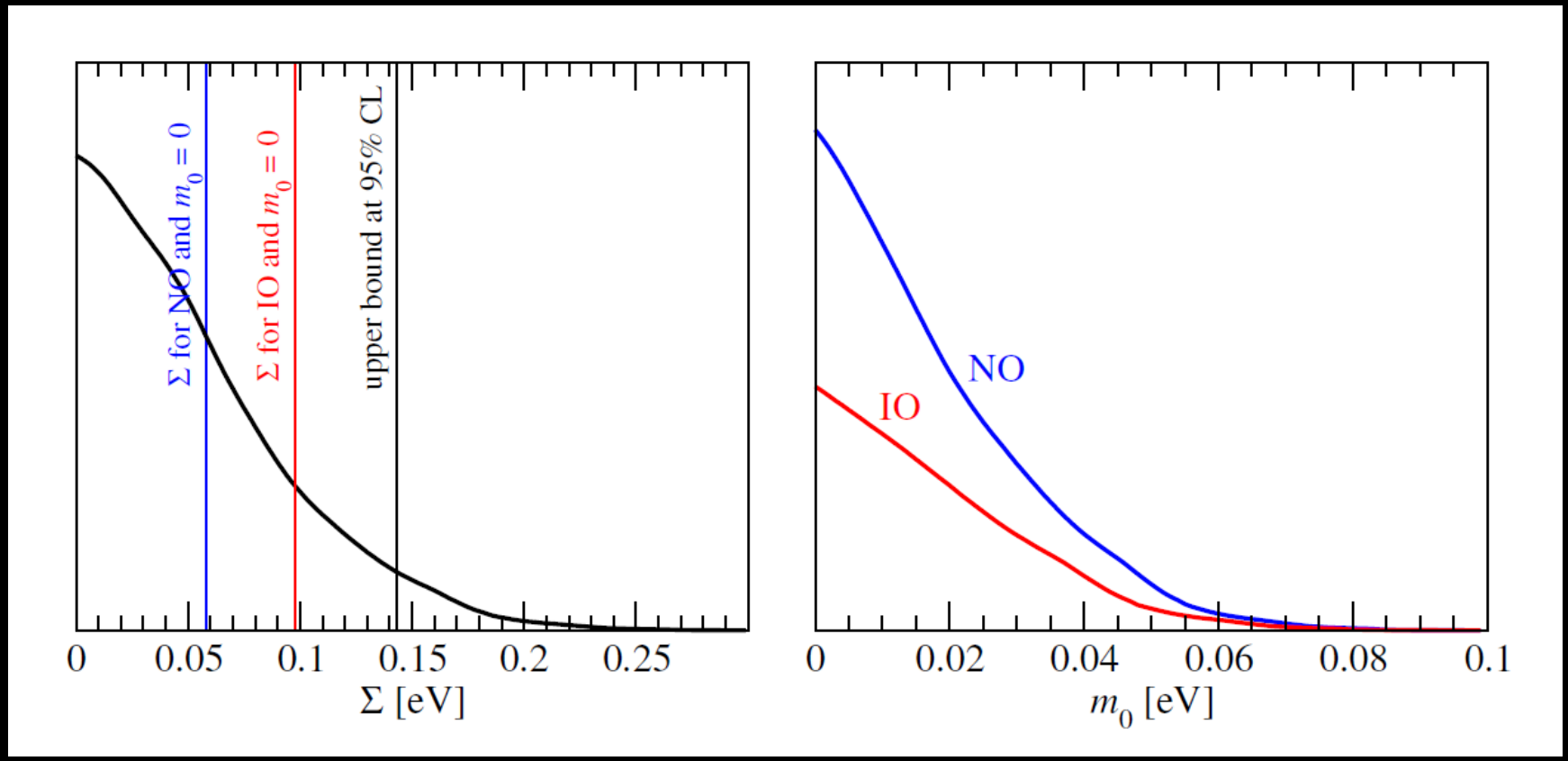
ADE ET AL.
ARXIV:1502.01589

THE STRONGEST BOUND IS CURRENTLY eV BUT THIS IS DERIVED FROM THE COMBINATION OF CMB AND LYMAN- DATA



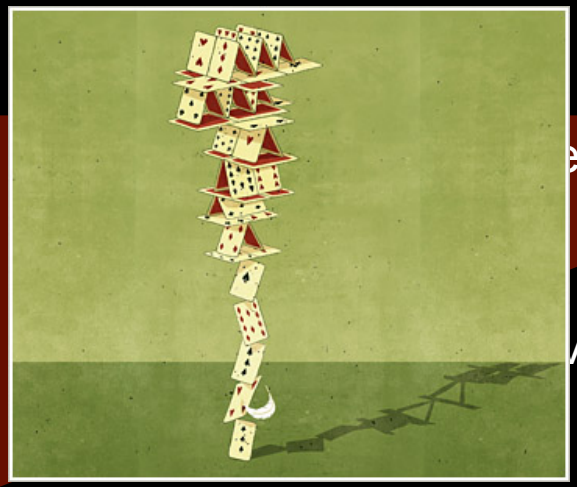
Palanque-Delabrouille et al. 1506.05976

Is the inverted hierarchy already disfavoured?
Not really – a significantly better sensitivity is still required for such a statement even with the most optimistic data combinations



STH & Schwetz, in preparation

THE NEUTRINO MASS FROM COSMOLOGY PLOT



More data

+Ly-alpha

+ SNI-a
+WL

+ SDSS

CMB only

eV 0.2-0.3 eV

V 0.5-0.6 eV

~0.15 eV ~ 0.5 eV

0.7 eV ~ 1 eV

Minimal
ΛCDM

+N_ν

+w+……

Larger model
space

HOW CAN THE BOUND BE AVOIDED?

Without modifying either cosmology or neutrino physics
The current bound is robustly below eV

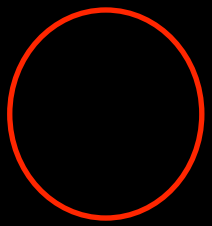
Modifying cosmology?

- Changing dark energy behaviour
- Coupling neutrinos and dark energy

Modifying neutrino physics?

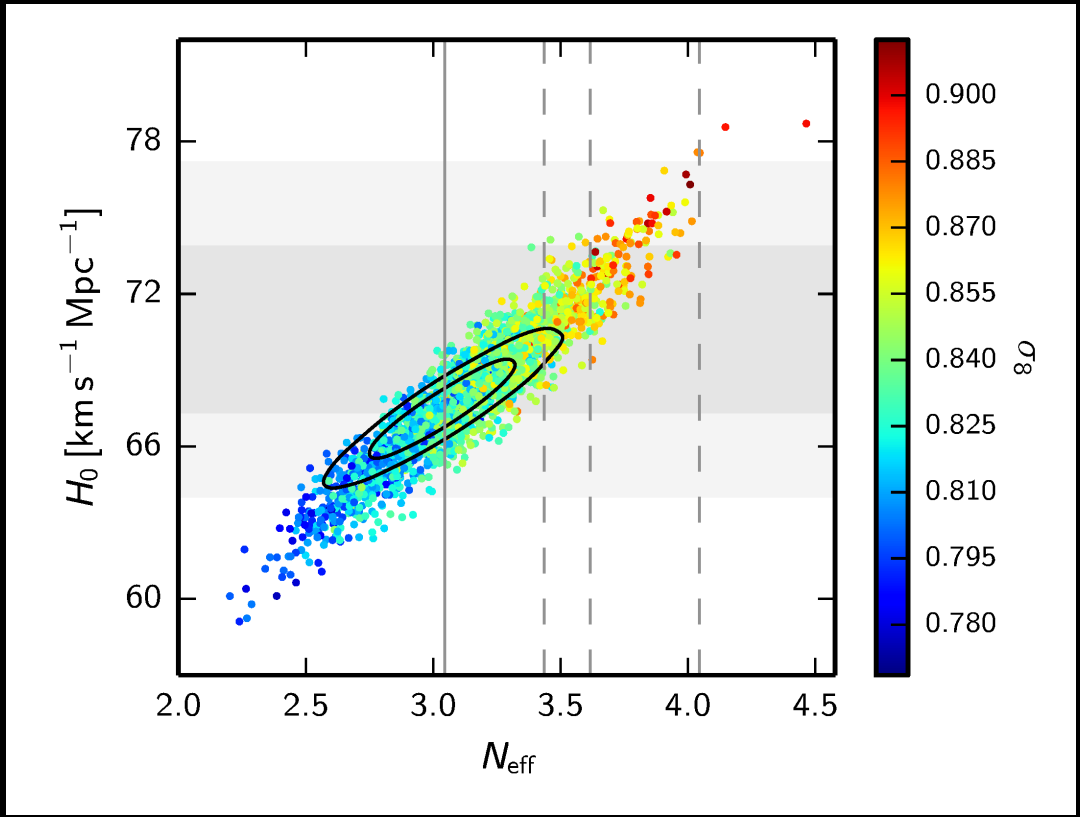
- Make neutrinos strongly interacting

GOING BEYOND THE MASS



Normally , but could be different. Normally the relativistic
energy density in neutrinos is quantified through the relation

is a measure of any type of ”dark radiation”



THE CONCLUSION SEEMS TO BE THAT THERE IS NO EVIDENCE FOR ANY PHYSICS BEYOND THE STANDARD MODEL

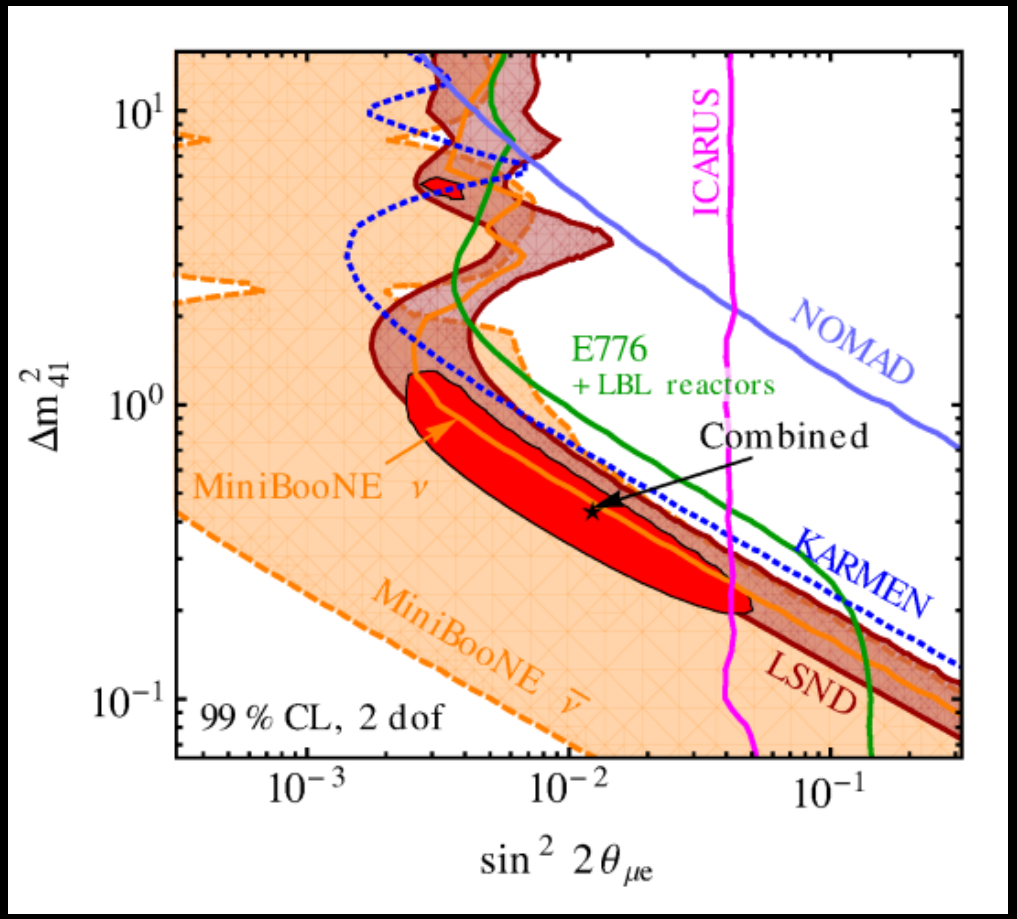
BUT BE AWARE THAT IN EXTENDED MODELS THIS CAN BE VERY DIFFERENT!

Cosmology shows no evidence for non-standard physics in the neutrino sector. However, cosmology might have to accomodate it after all.

A variety of different terrestrial experiments show hints of the presence of a 4th neutrino mass state (possibly even a 5th), most likely with a mass around 1-10 eV

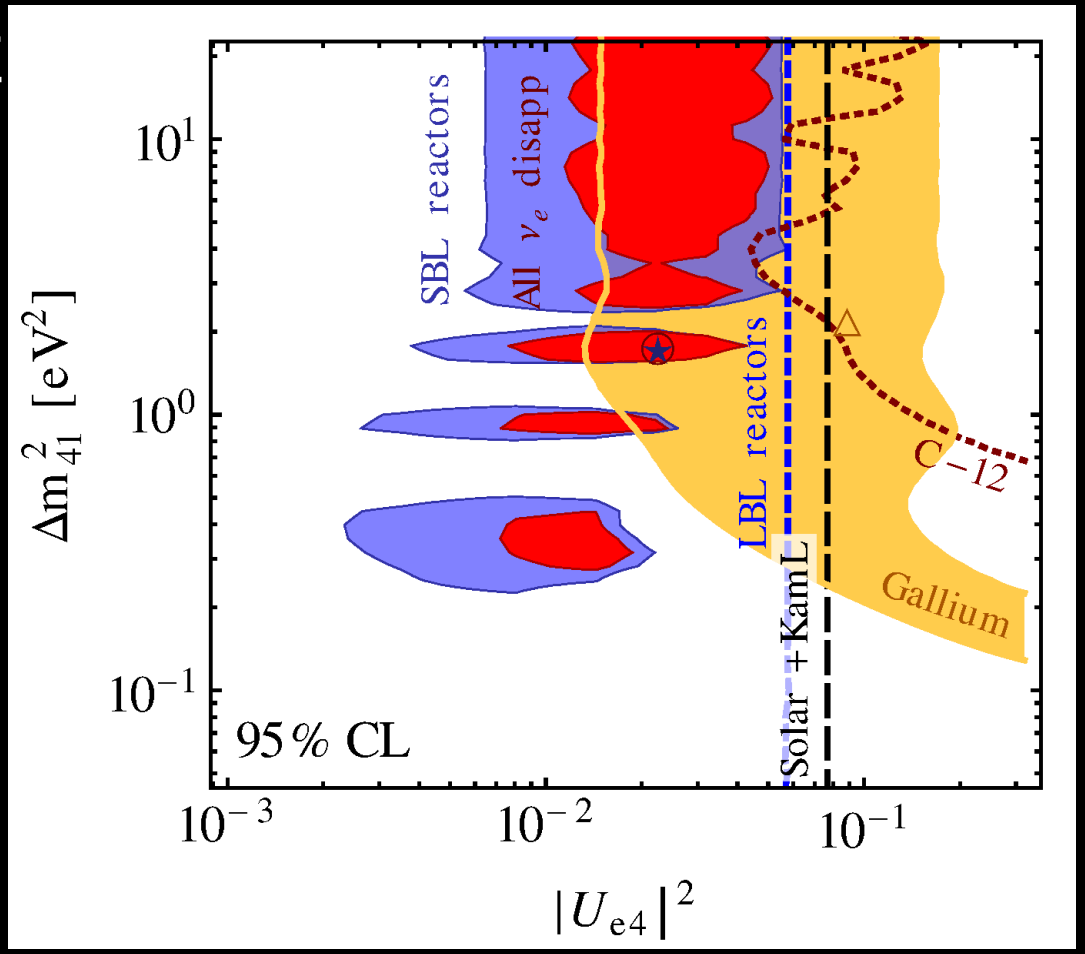
However, the evidence is conflicting

APPEARANCE



Kopp, Machado, Maltoni & Schwetz, 1303.3011
(see also e.g. Gariazzo, Giunti & Laveder, 1309.3192)

DISAPPEARANCE



Kopp, Machado, Maltoni & Schwetz, 1303.3011

Note also recent analyses from

ICECUBE (1605.01990)

Constraining lower right corner of oscillation parameter space

MINOS (1605.04544)

Excluding parts of parameter space around 1.5 and 8 eV

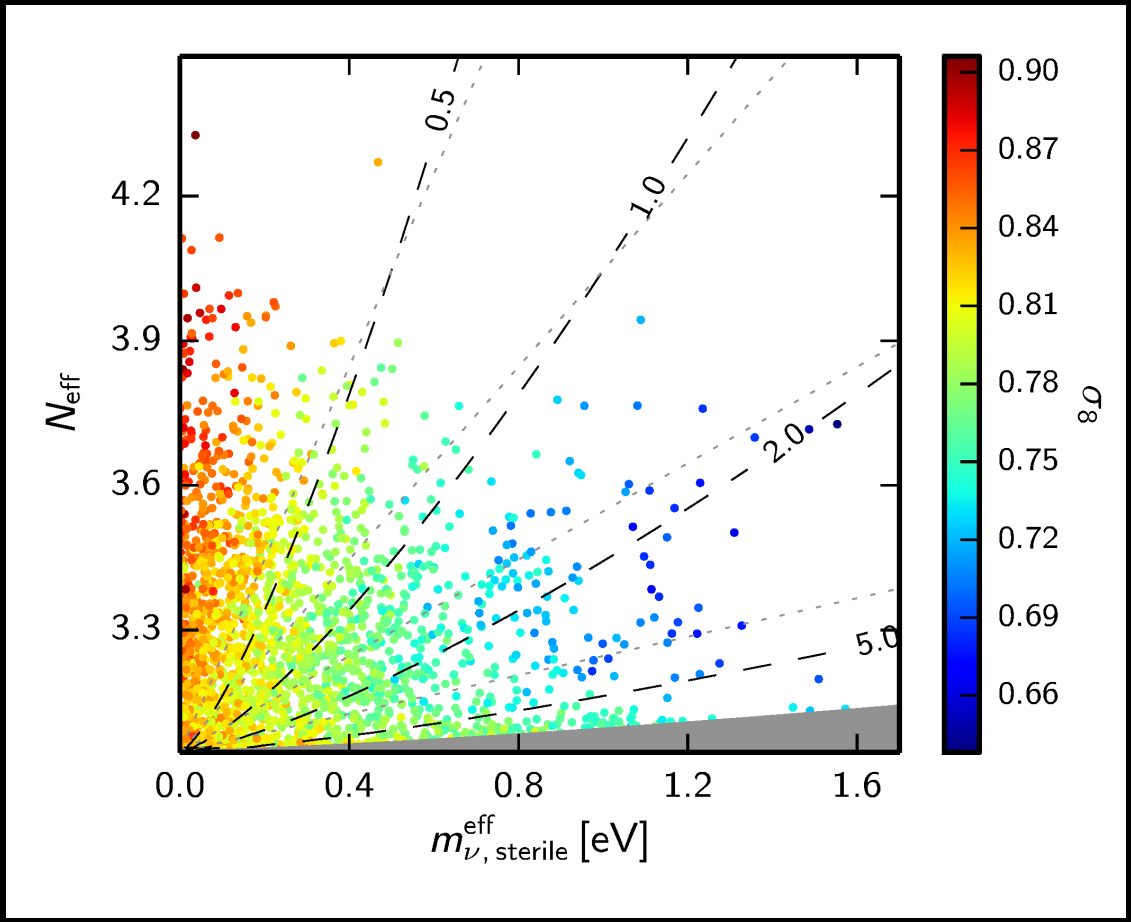
NEUTRINO-4 reactor experiment (1605.05909)

Seemingly finding indications of deficit

Current situation is unclear at best…..

An additional neutrino with such a mass and mixing should be fully thermalised in the early Universe and act completely like a standard model neutrino of equal mass.

This, however, is excluded by data roughly at 5.5σ



ADE ET AL. 2015 (Planck)

Bottom line: Sterile neutrinos in the mass range preferred by SBL data can be accomodated by cosmology, but ONLY if they are not fully thermalised

Sterile neutrinos are thermalised via a combination of oscillation and scattering
(Barbieri & Dolgov 91; Enqvist, Kainulainen & Maalampi 91, Raffelt & Sigl 93, McKellar & Thomson 94)

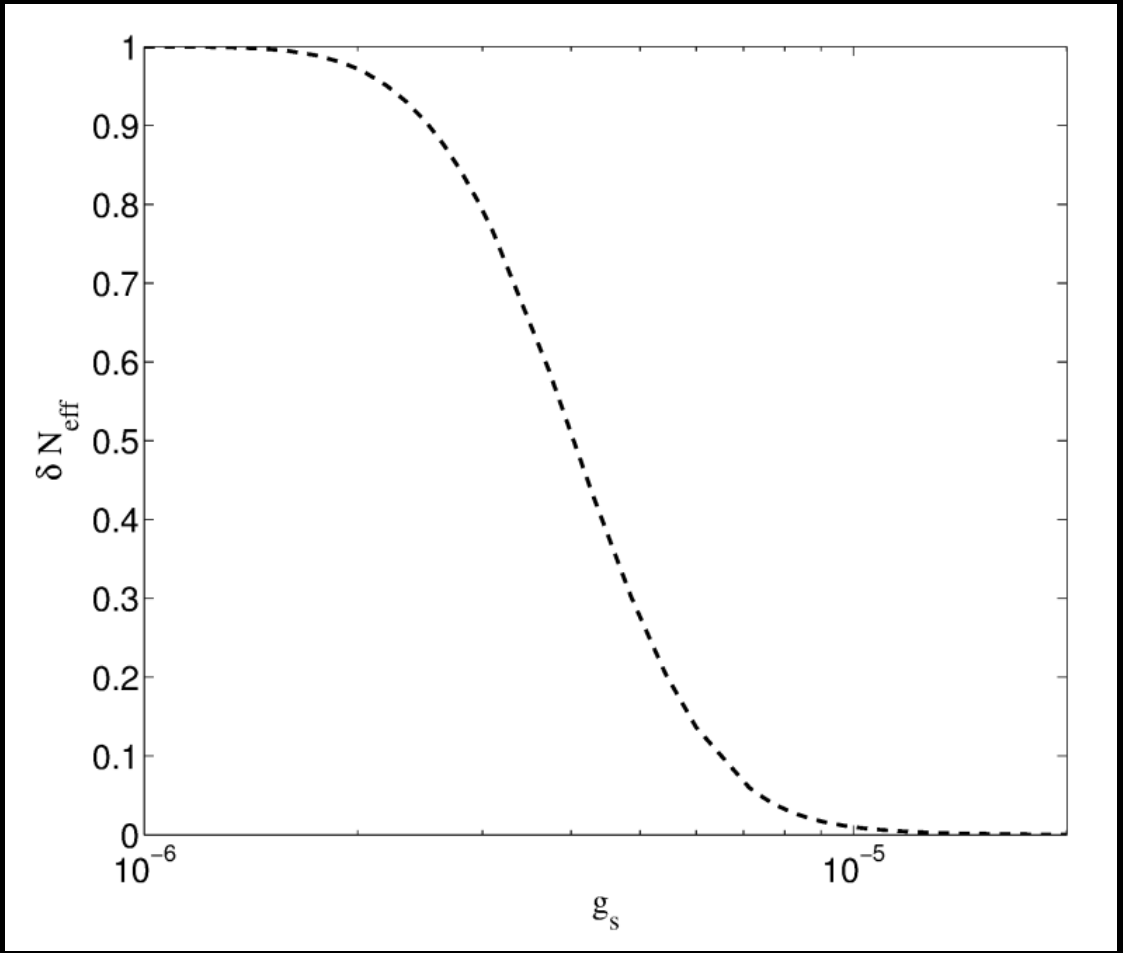
The neutrino matter potential is important and a very large potential could in principle prevent thermalisation

How can this be achieved?

A large neutrino lepton asymmetry
(see e.g. STH, Tamborra, Tram 1204.5861, Saviano et al. arXiv:1302.1200)

New, non-standard interactions in the sterile sector
(e.g. STH, Hansen, Tram, 1310.5926, Dasgupta & Kopp 1310.6337, Bringmann, Hasenkamp & Kersten 1312.4947, Archidiacono, STH, Hansen, Tram 1404.5915 Chu, Dasgupta & Kopp 1505.02795)

Sterile neutrinos can couple to a light or massless pseudoscalar.
In that case a background potential appears even in a CP-symmetric medium and suppressing oscillations requires only a very weak coupling.



Archidiacono,
STH, Hansen, Tram
(arXiv:1404.5915)

If the mediator is massless the sterile couples strongly at low temperatures

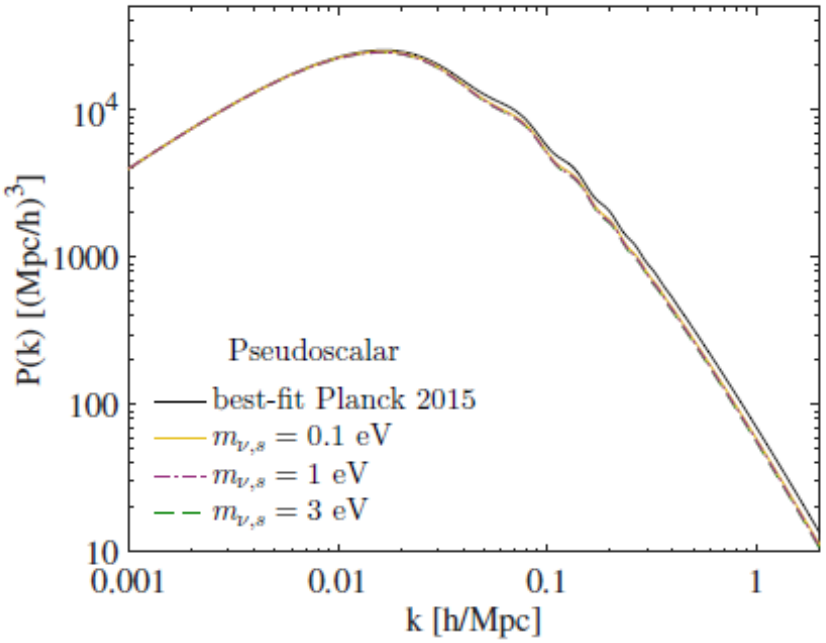
As soon as it goes non-relativistic it annihilates and leads to what is known as the ”neutrinoless universe”
(Beacom, Bell & Dodelson 2004, STH 2004)

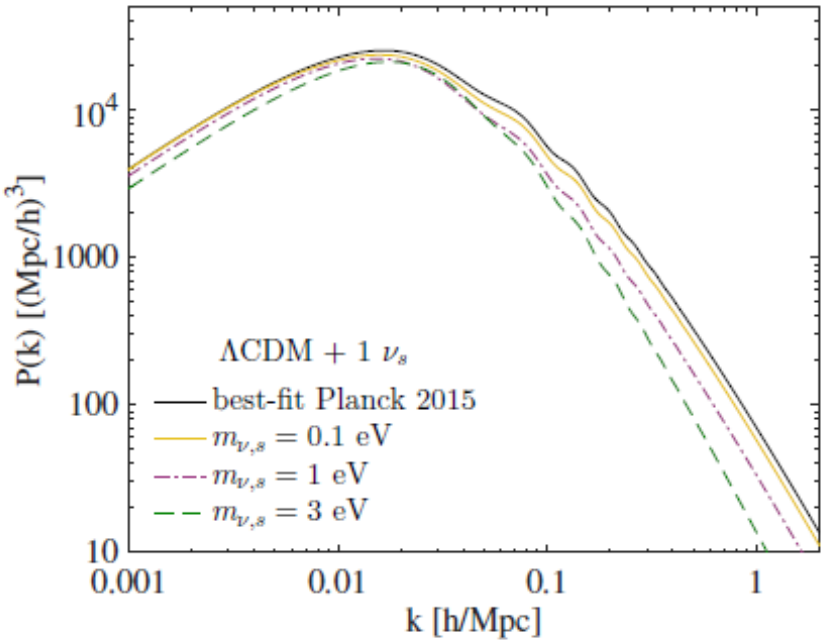
Very different low energy phenomenology: The combined sterile/ pseudoscalar fluid is strongly self-interacting and has no anisotropic stress (STH 2004)

The model with a strongly interacting, new mass state in the eV range actually provides a better fit to all cosmological data than CDM and favours a Hubble parameter compatible with local measurements (Archidiacono, STH, Hansen, Tram, arXiv:1404.5915)

This conclusion is unchanged with Planck2015 data (Archidiacono, STH, Hansen, Tram 15)

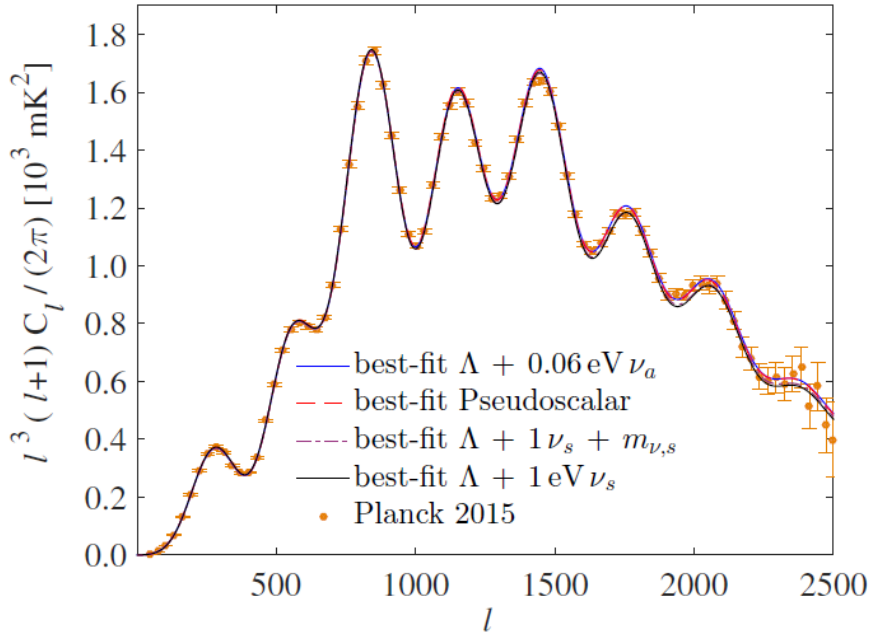
Evidence further increases with new Hubble measurement (Riess et al. 16) to from cosmology alone (Archidiacono, Gariazzo, Giunti, STH, Hansen, Laveder, Tram, in preparation)





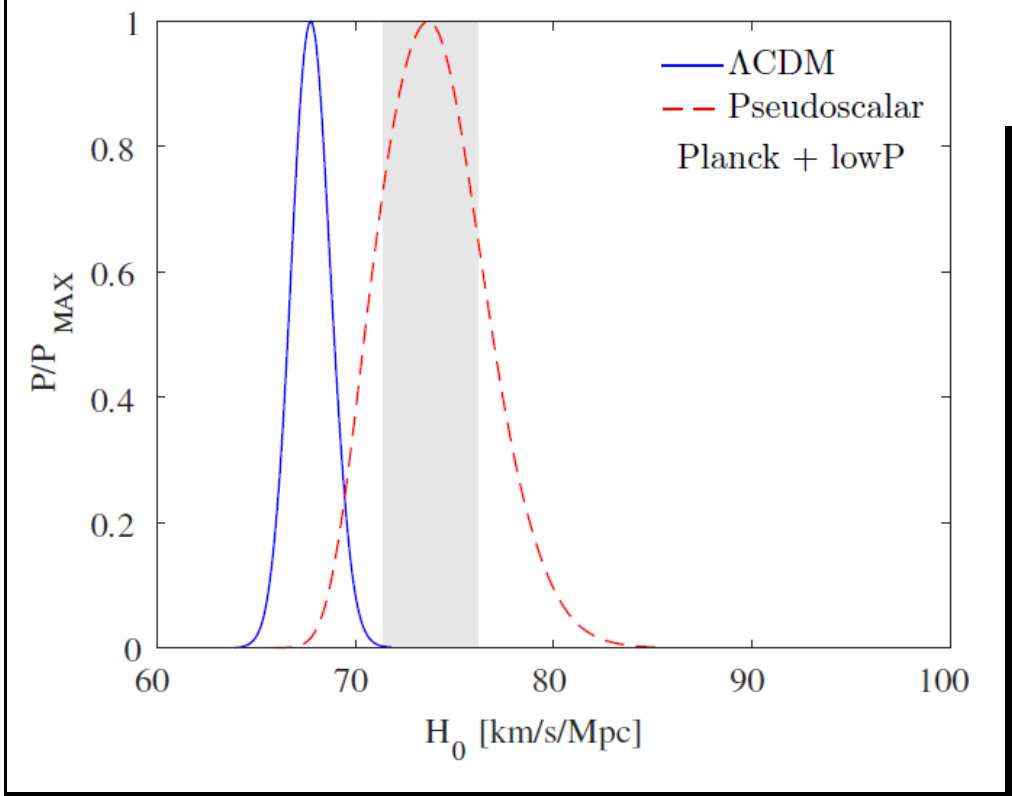
The usual suppression of matter power does not occur because the massive neutrinos disappear as soon as they go non-relativistic

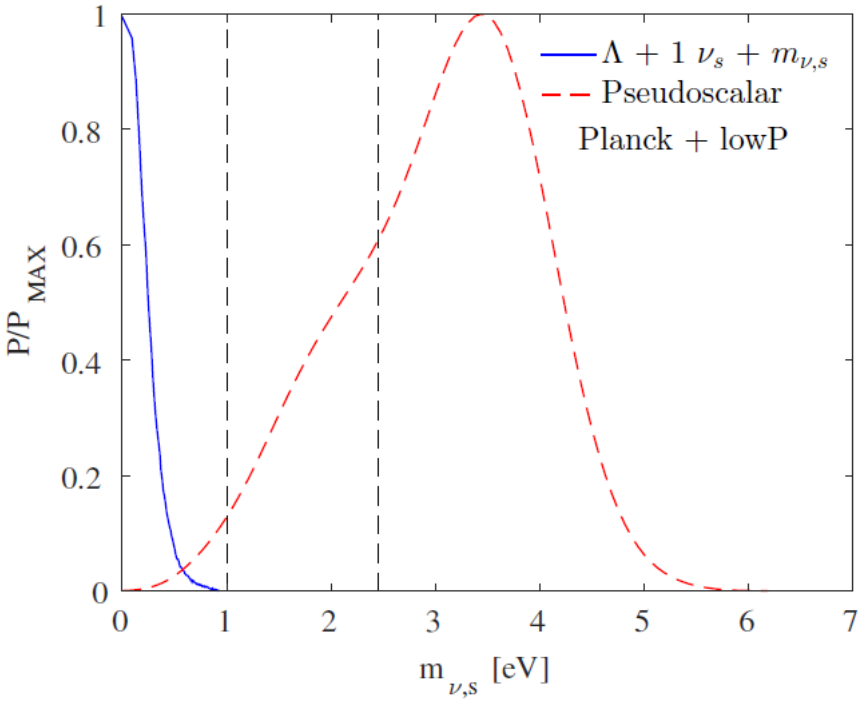
It does not create excess power in the CMB spectrum



Archidiacono, STH, Hansen, Tram, arXiv: 1508:02504

The model naturally predicts a high value of the Hubble parameter, in accordance with local Universe measurements





TIMELINE WITH A MASSLESS MEDIATOR

TeV: Neutrinos and phi equilibrated (not necessary)

Entropy production

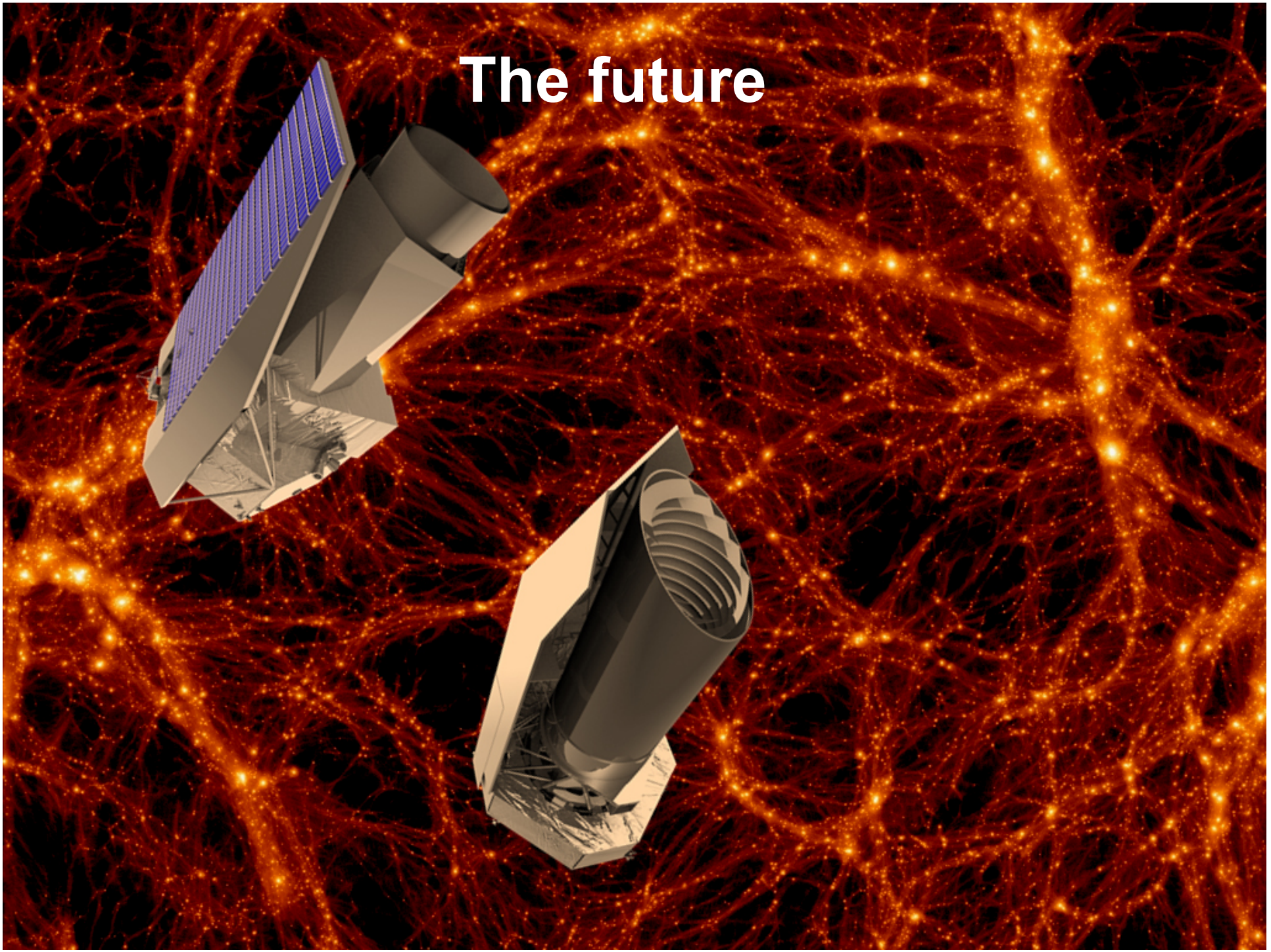
MeV: Sterile production from via oscillations plus scatterings

MeV: Equilibration of steriles with actives via oscillations

and come into chemical equilbrium and behave as a single fluid

annihilates into

The future

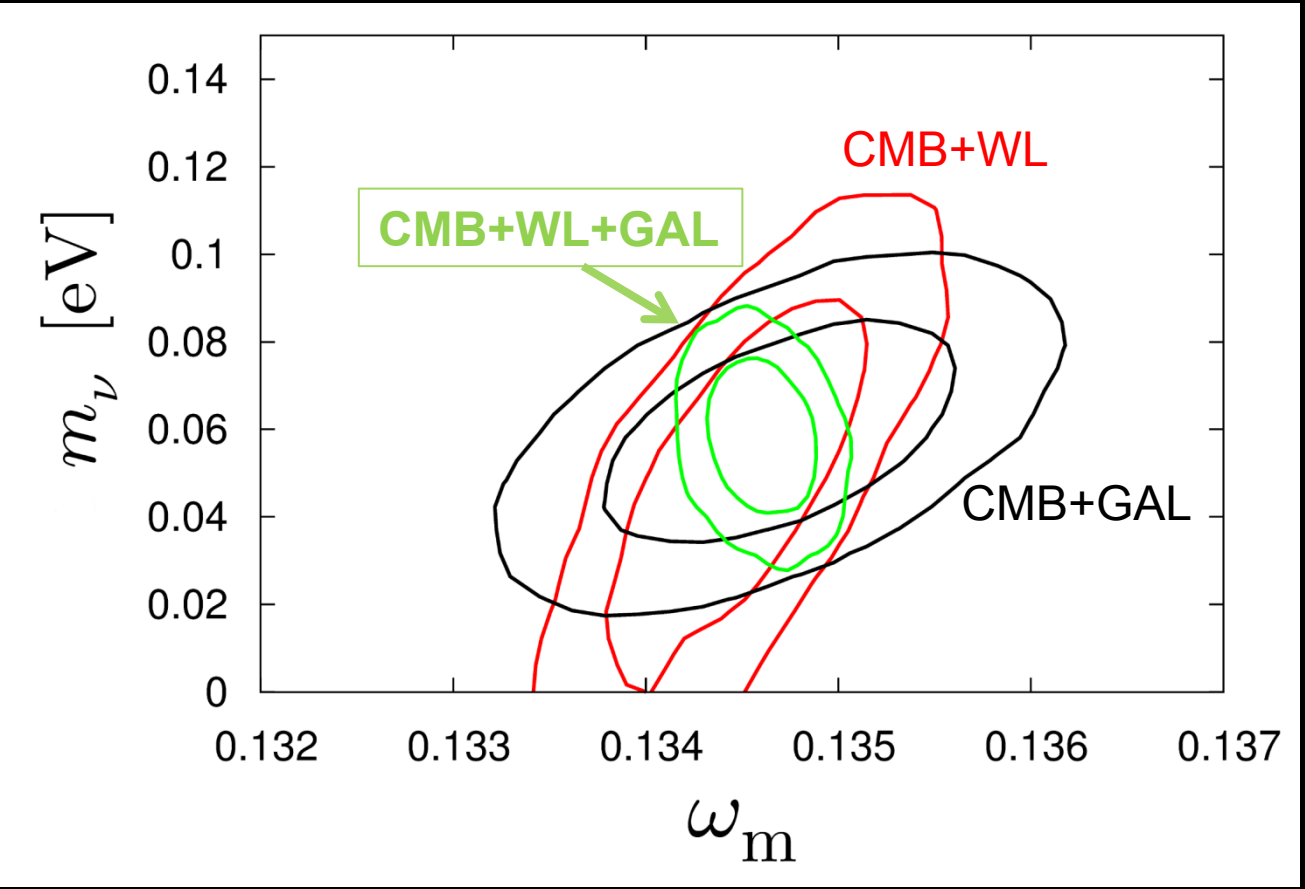


Dataset	$\sigma\left(\sum m_\nu\right)$ [meV]	$\sigma\left(N_{\rm eff}\right)$
Galaxy Clustering (current CMB):		
Planck + BOSS BAO	100	0.18
Planck + BOSS galaxy clustering	46/68	0.14/0.17
Planck + eBOSS BAO	97	0.18
Planck + eBOSS galaxy clustering	36/52	0.13/0.16
Planck + DESI BAO	91	0.18
Planck + DESI galaxy clustering	**17/24**	0.08/0.12
CMB Lensing (current galaxy clustering):		
Stage-IV CMB	45	**0.021**
Stage-IV CMB + BOSS BAO	**25**	0.021
CMB Lensing + Galaxy clustering:		
Stage-IV CMB + eBOSS BAO	23	0.021
Stage-IV CMB + DESI BAO	**16**	0.020
Stage-IV CMB no lensing + DESI galaxy clustering	15/20	0.022/0.024
Galaxy Weak Lensing:		
Planck + LSST [51]	23	0.07
Planck + Euclid [48]	25	NA†

†Ref. [48] did not include a forecast for $N_{\rm eff}$.

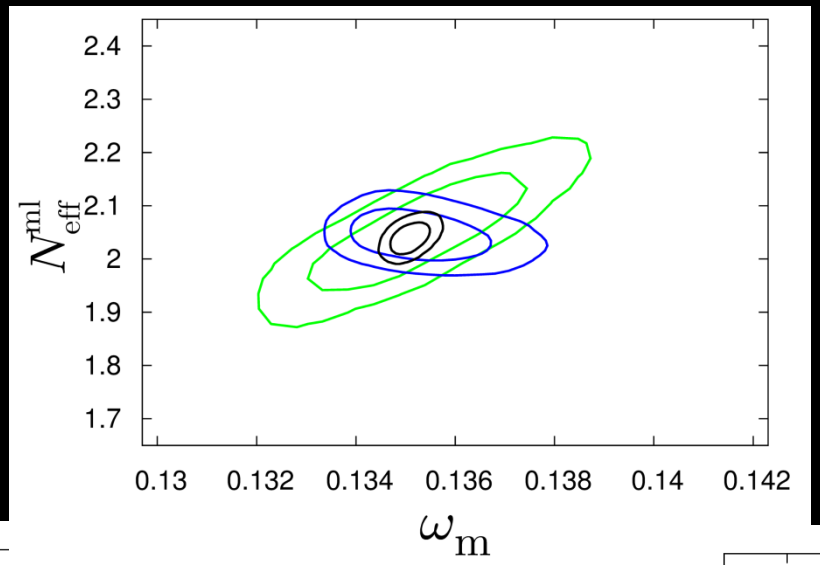
Abazajian et al., arXiv:1309.5383

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)

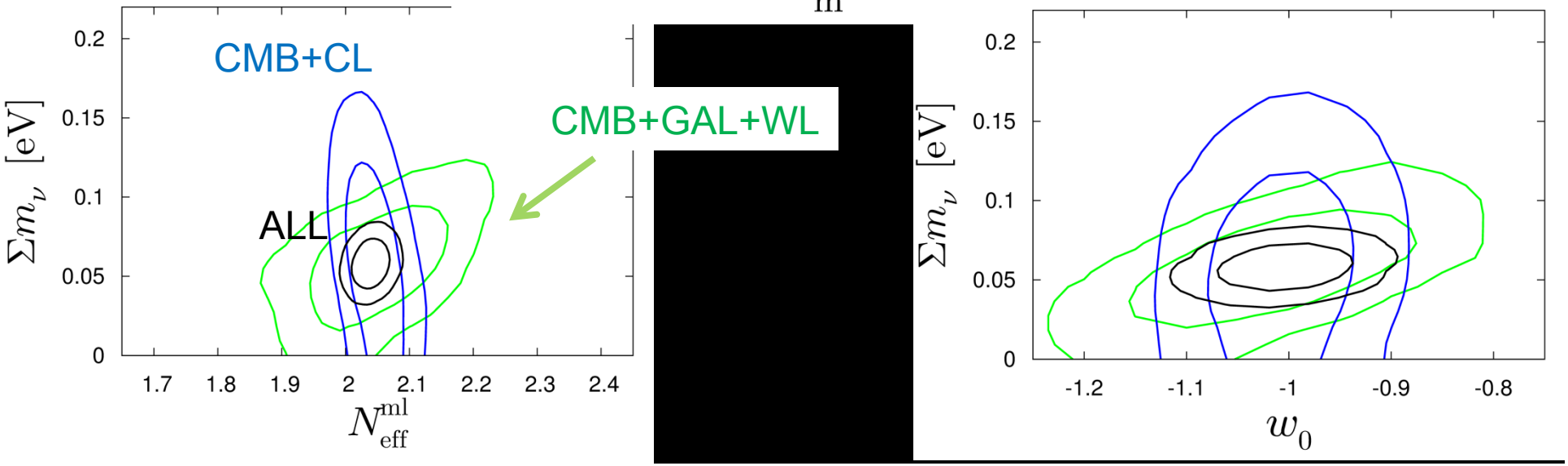


arXiv:1209.1043 (JCAP)

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

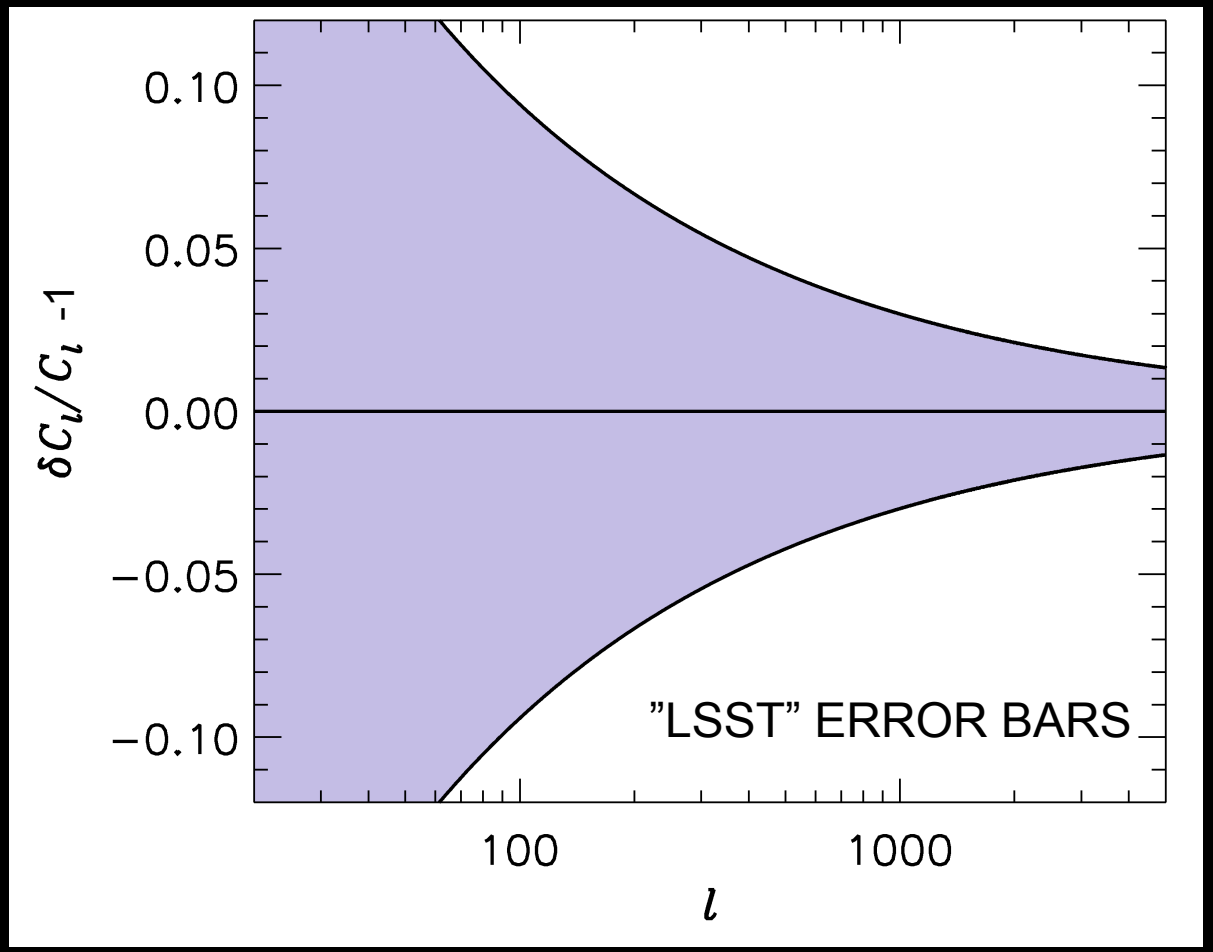


arXiv:1304.2321
(JCAP)



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

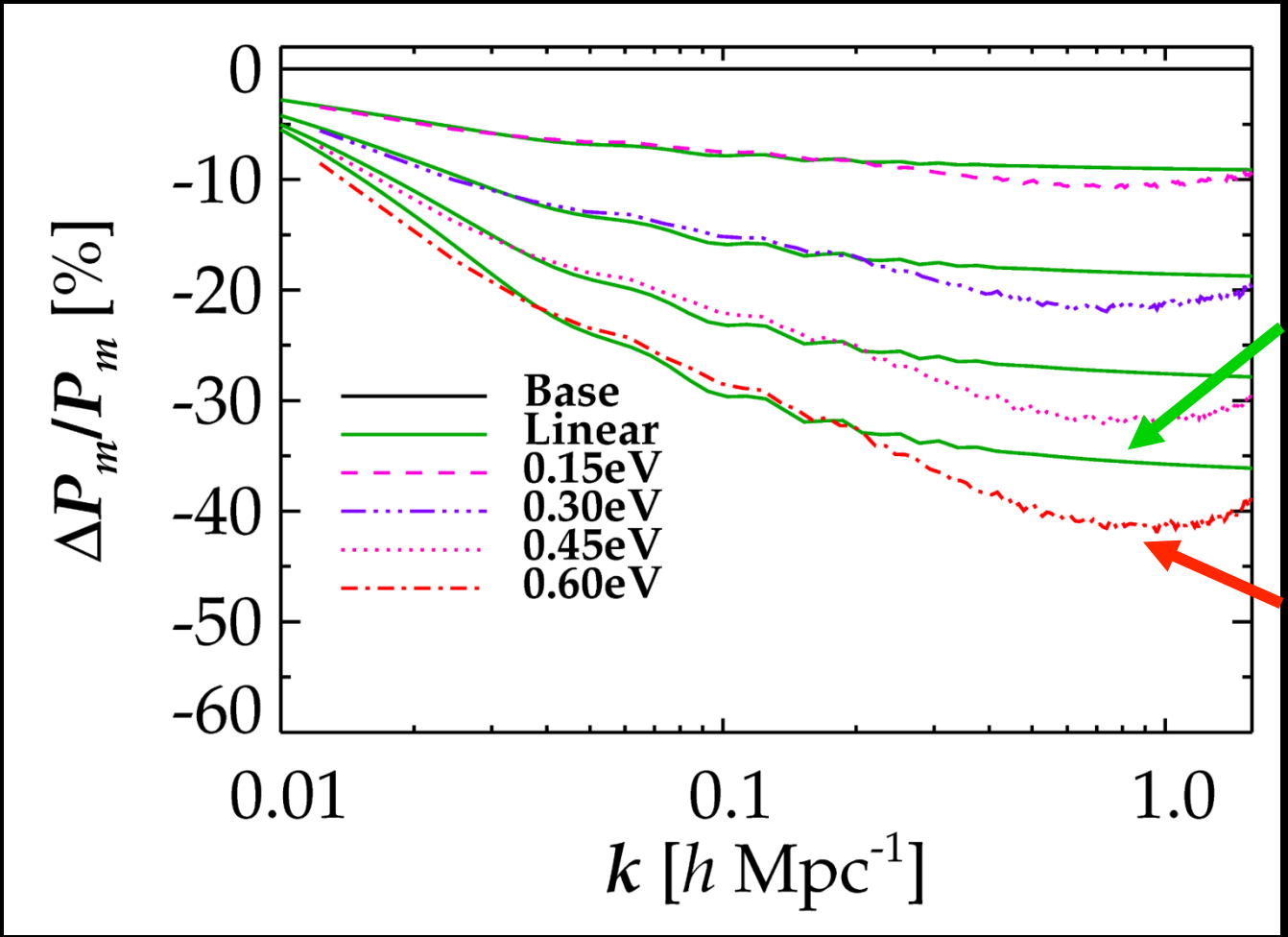


WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM TO AT LEAST THE SAME PRECISION!

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

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

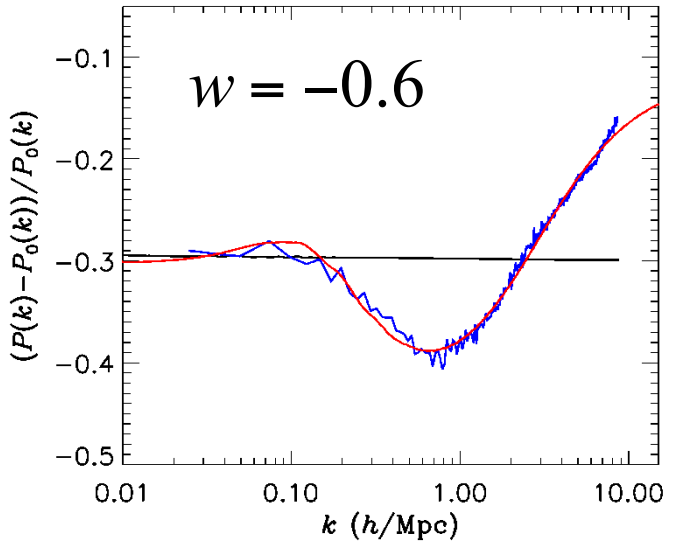
FULL NON-LINEAR

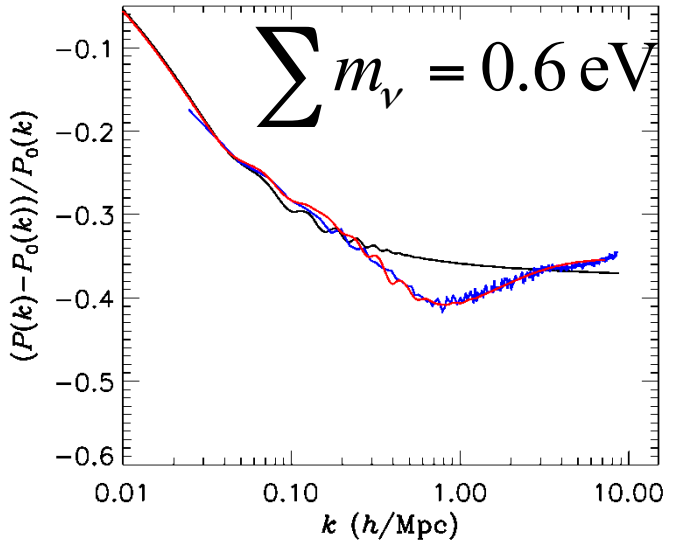
$$\frac{\Delta P}{P} \sim -9.6\frac{\Omega_\nu}{\Omega_m}$$

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

HOWEVER, IT TURNS OUT THAT THE ”DIP” IS A GENERIC FEATURE OF *ANY* MODEL WITH SUPPRESSED SMALL SCALE STRUCTURE

WHERE DOES THAT EFFECT COME FROM?

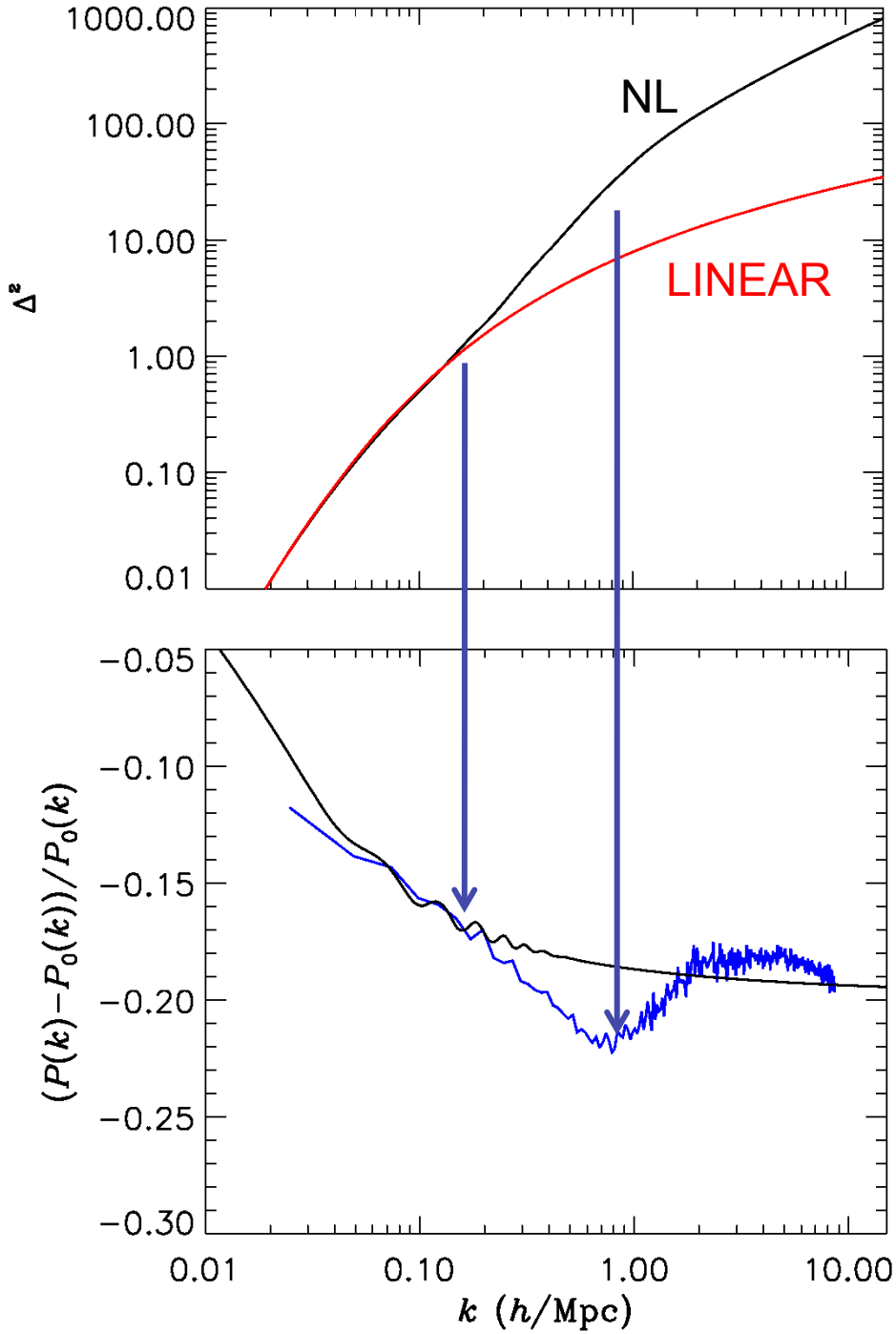




Linear theory

N-body

Analytic fit



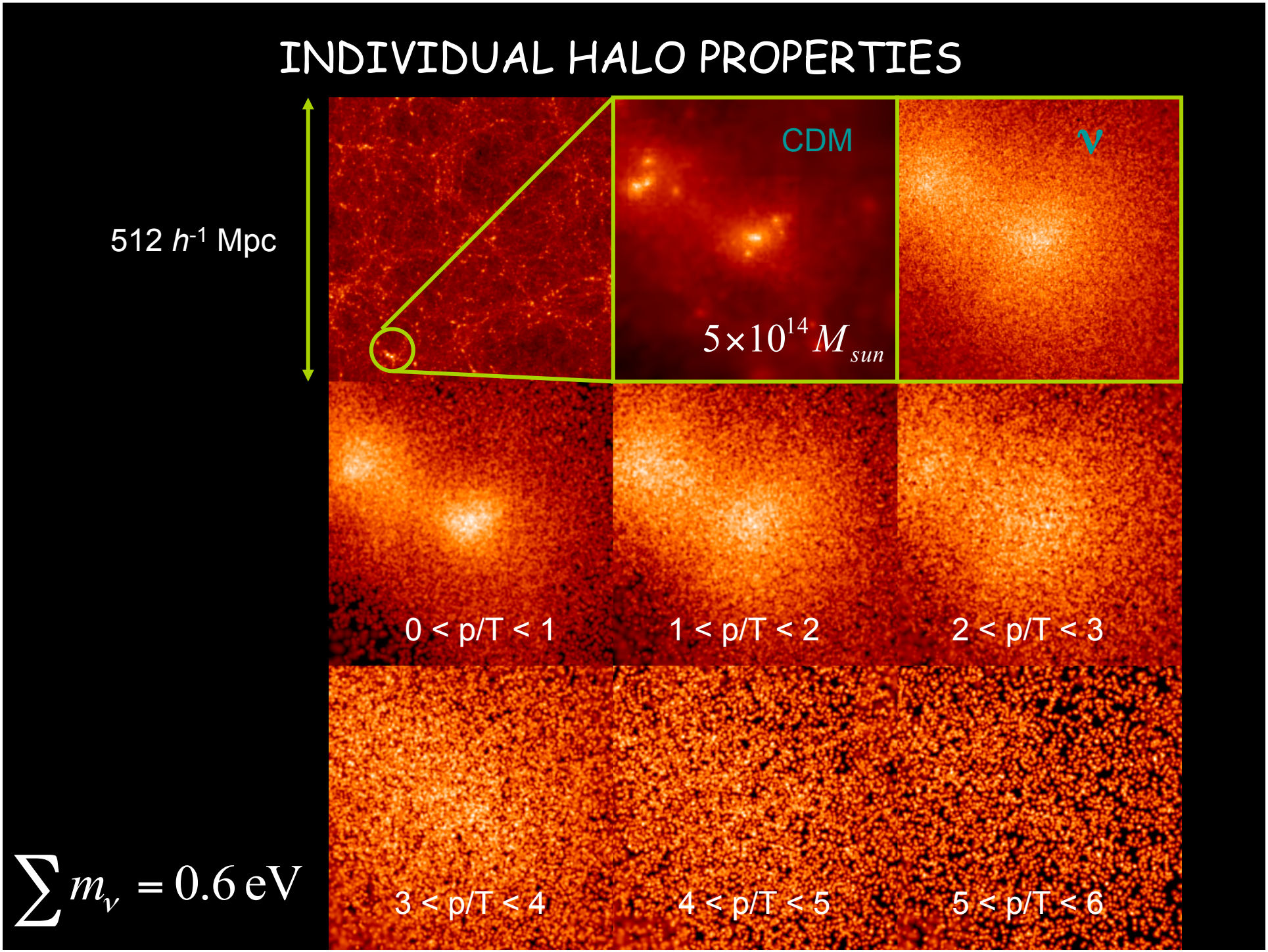
IT IS SIMPLY AN EFFECT OF THE RATE WITH WHICH THE AMPLITUDE OF FLUCTUATIONS GROW

THE EFFECT IS NOT SPECIFIC TO MODELS WITH NEUTRINOS. BUT UNDERSTANDING IT WILL HELP DEVELOP ACCURRATE SEMI-ANALYTIC MODELS OF STRUCTURE FORMATION

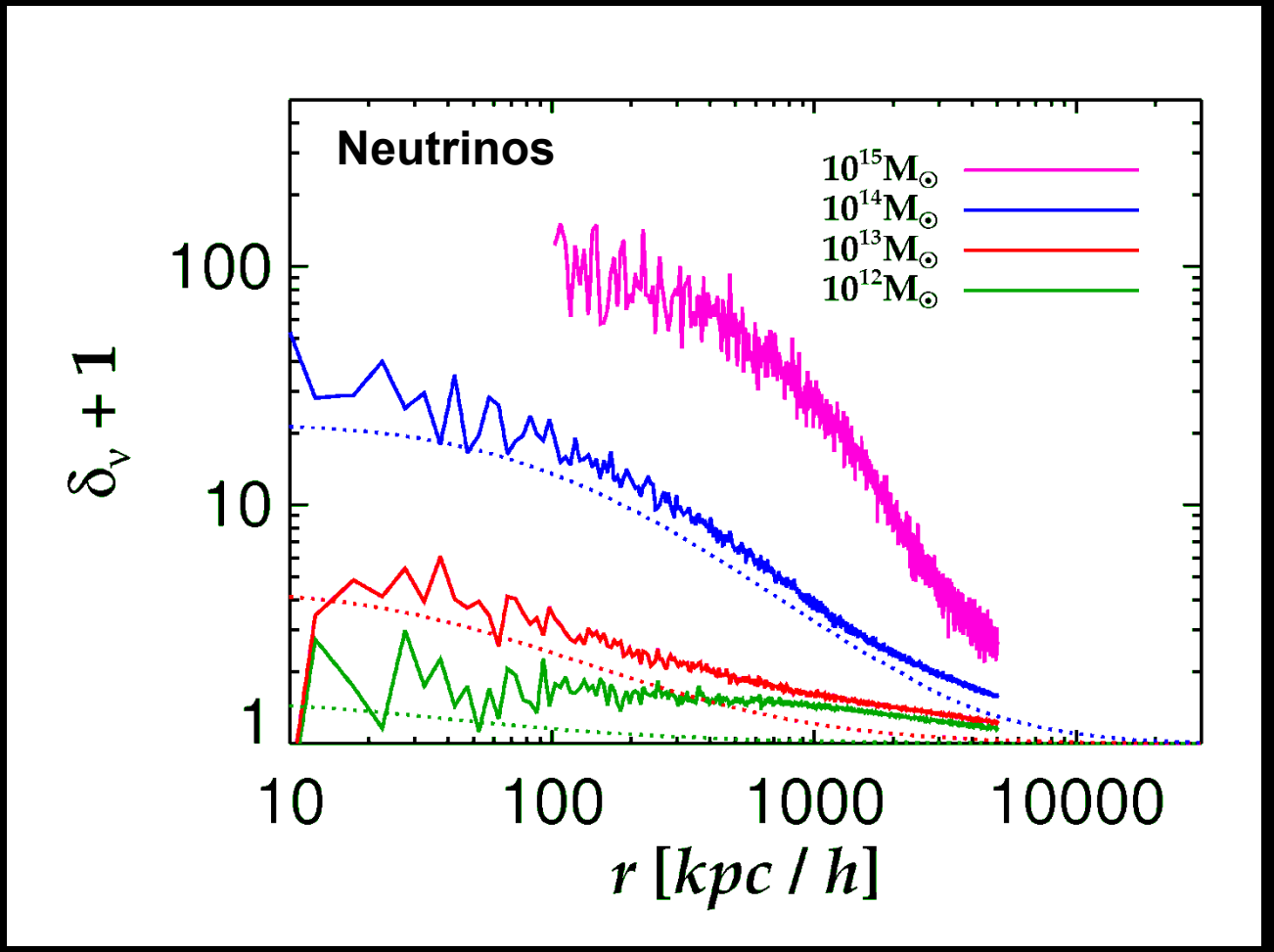
ANOTHER IMPORTANT ASPECT OF STRUCTURE FORMATION WITH NEUTRINOS:

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

INDIVIDUAL HALO PROPERTIES



Brandbyge, STH, Haugboelle, Wong, arxiv:1004.4105



See also Ringwald & Wong 2004

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 SHOWS NO EVIDENCE FOR NEW PHYSICS. HOWEVER, IF eV STERILE NEUTRINOS EXIST THERE MUST BE NEW PHYSICS IN ORDER TO RECONCILE THEM WITH COSMOLOGY
- NEW DATA FROM PLANCK AND EUCLID MAY PROVIDE A POSITIVE DETECTION OF A NON-ZERO NEUTRINO MASS