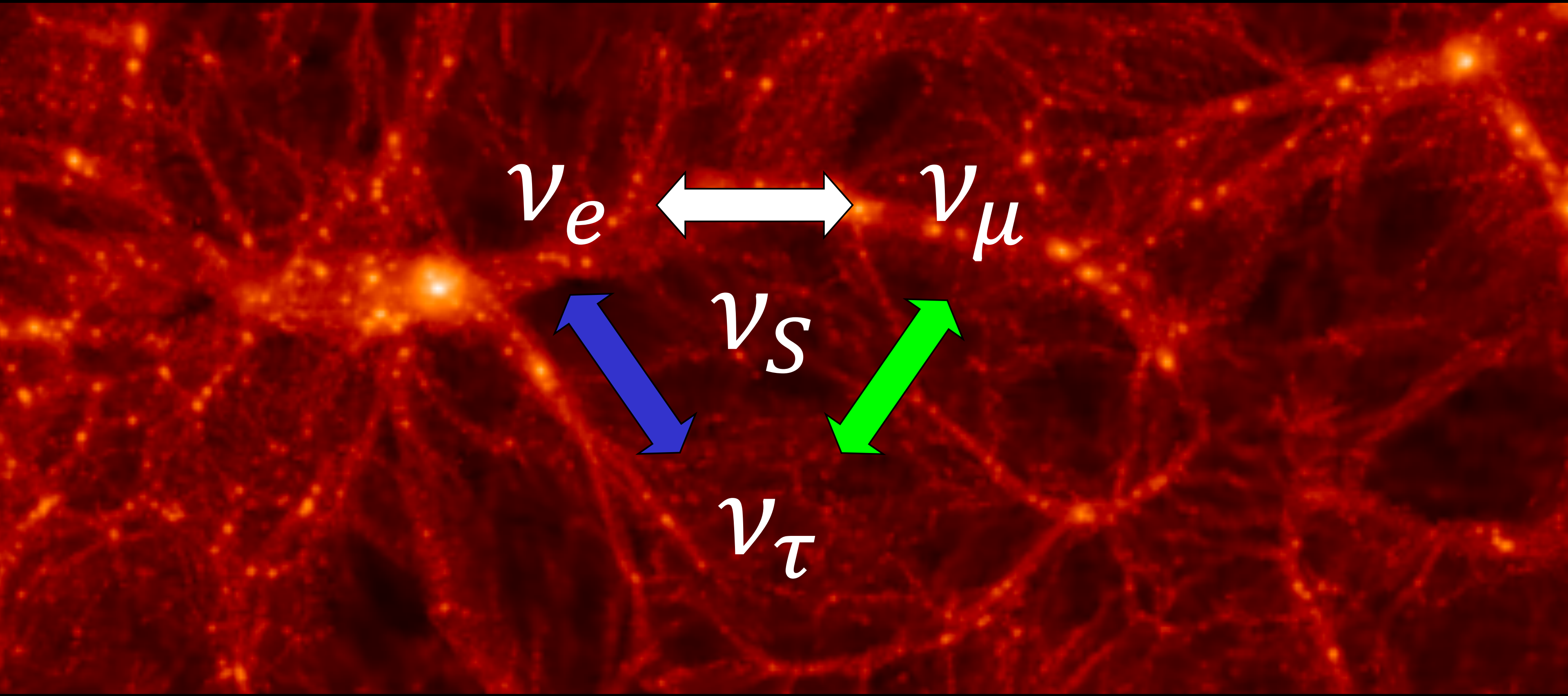
NEUTRINOS IN THE ERA OF PRECISION COSMOLOGY



STEEN HANNESTAD, AARHUS UNIVERSITY
HAMBURG, 6 JANUARY 2016

What do we know about neutrinos?

- They are light (but not massless) fermions - $m_\nu \leq \mathrm{eV}$
- The carry no electric or strong charge
- They do carry weak charge
- 3 known charged current eigenstates: ν_e, ν_μ, ν_τ
- Must correspond to three eigenstates of energy and momentum: ν_1, ν_2, ν_3
- Charged current eigenstates and energy/momentum eigenstates are NOT identical
- Provided that $m(\nu_1), m(\nu_2), m(\nu_3)$ are not identical this leads to neutrino oscillations

NEUTRINO MIXING IN THE STANDARD PICTURE

FLAVOUR STATES → PROPAGATION STATES

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$U=$ (Atmospheric, Long Baseline) $\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & \text{(Reactor)} & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}$ (Solar, Reactor) (Only relevant for 0ν2β decay)

Atmospheric
Long Baseline

Reactor

Solar
Reactor

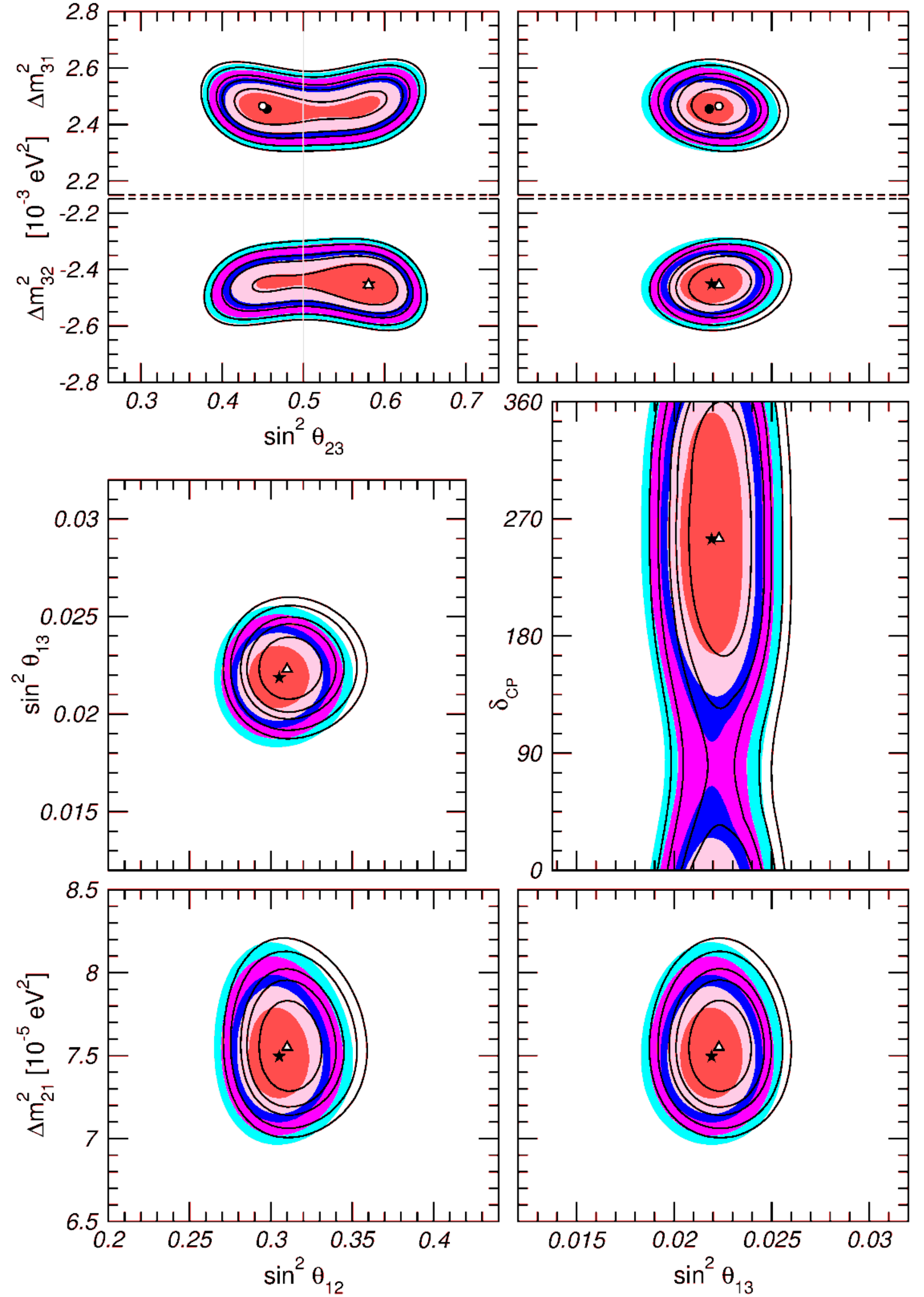
Only relevant
for 0ν2β decay

$c_{23} = \cos\theta_{23}$ etc., $\theta_{12}, \theta_{13}, \theta_{23}$ are the Euler angles of 3D rotation

δ is the Dirac CP phase

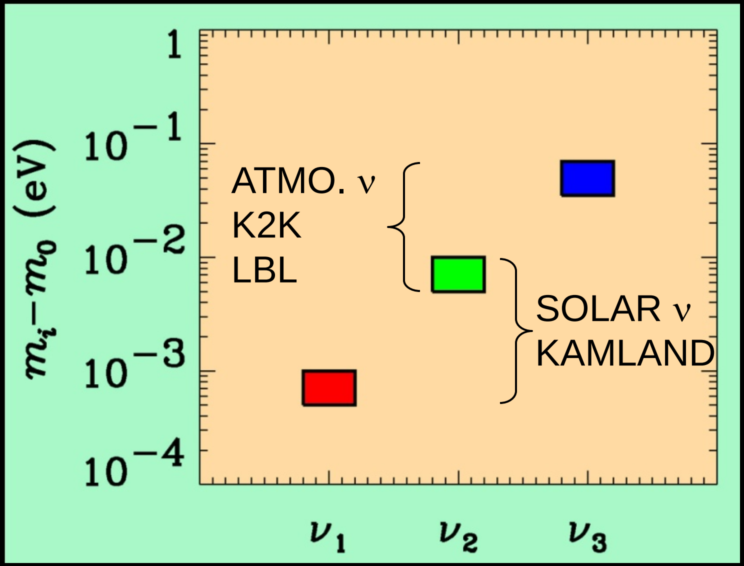
α_1, α_2 are Majorana phases (relevant only if neutrinos are Majorana particles)

Status of 3-neutrino oscillations

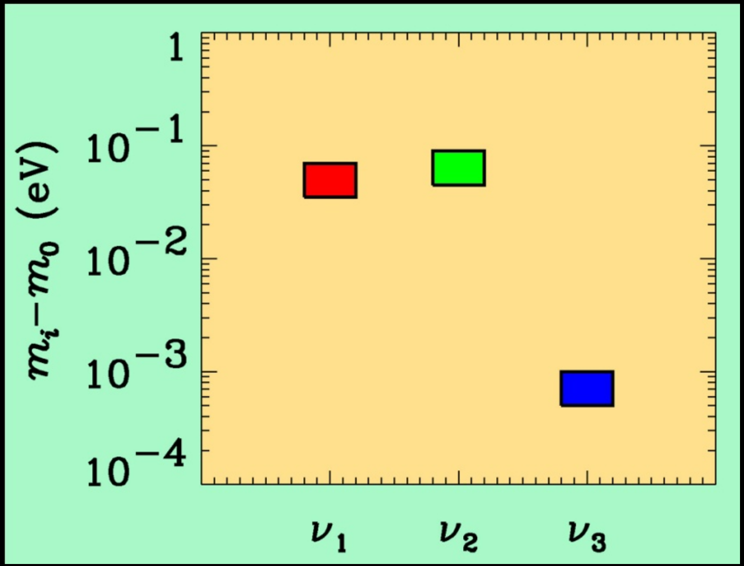


Gonzalez-Garcia, Maltoni, Schwetz
1409.5439

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



Normal hierarchy



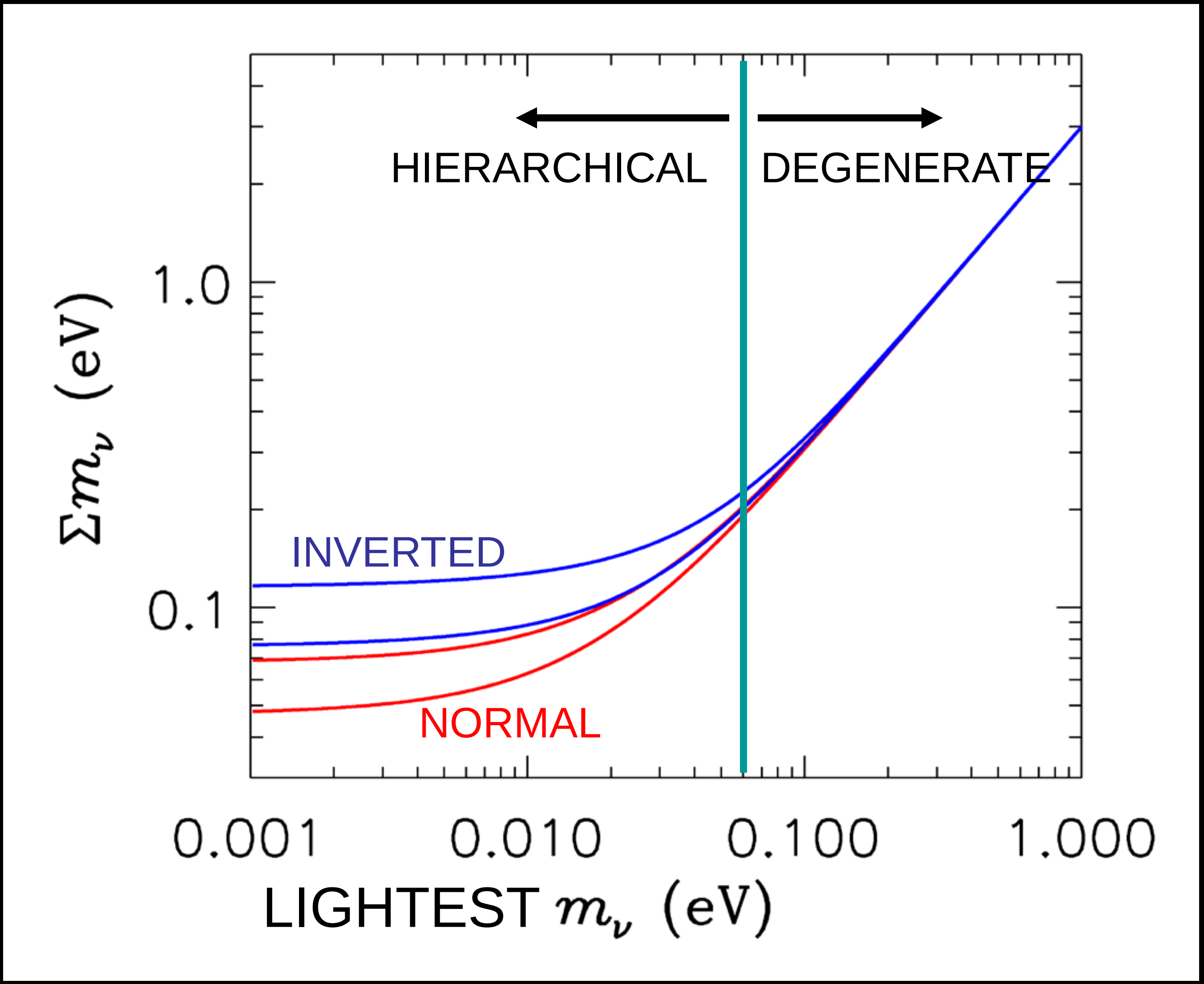
Inverted hierarchy

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
INVERTED
NORMAL
1.0
0.1
Σm_ν (eV)
0.001
0.010
0.100
1.000
LIGHTEST m_ν (eV)

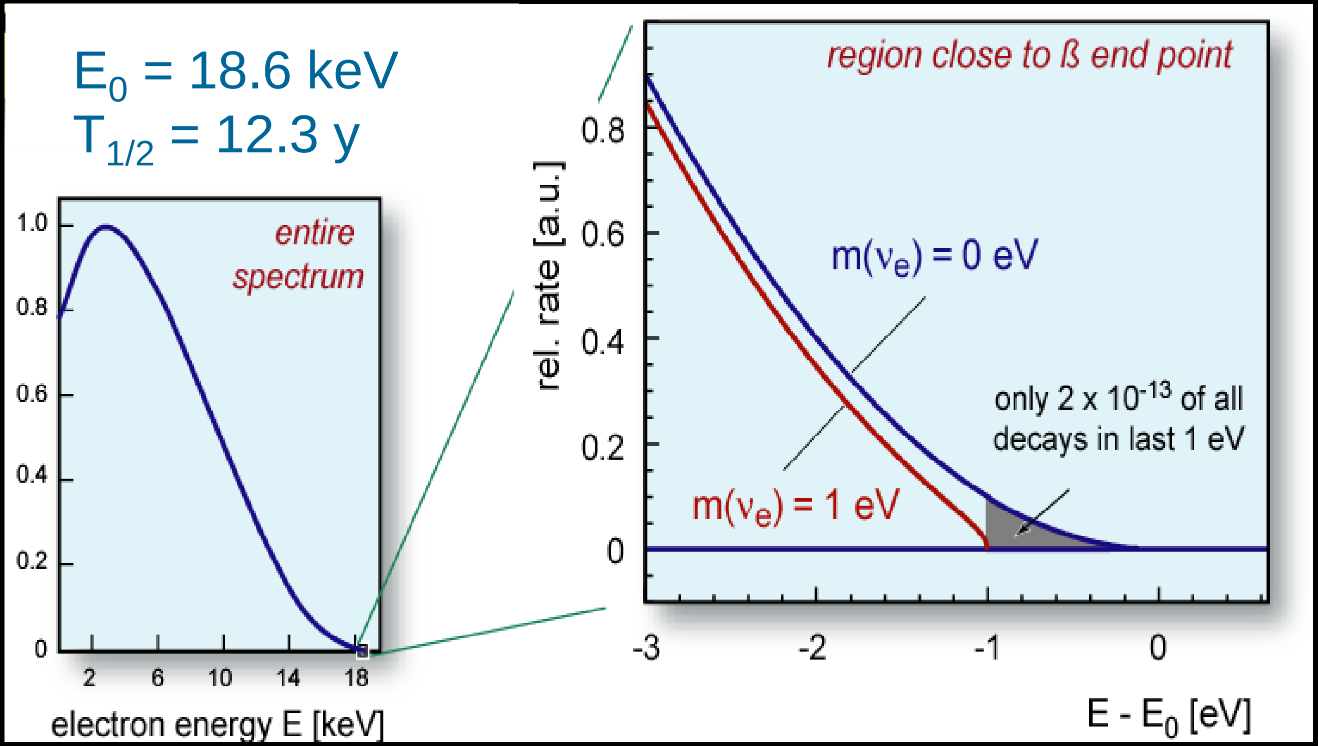
ß-decay and neutrino mass

Model independent neutrino mass from ß-decay kinematics

Only assumption: relativistic energy-momentum relation

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

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.)

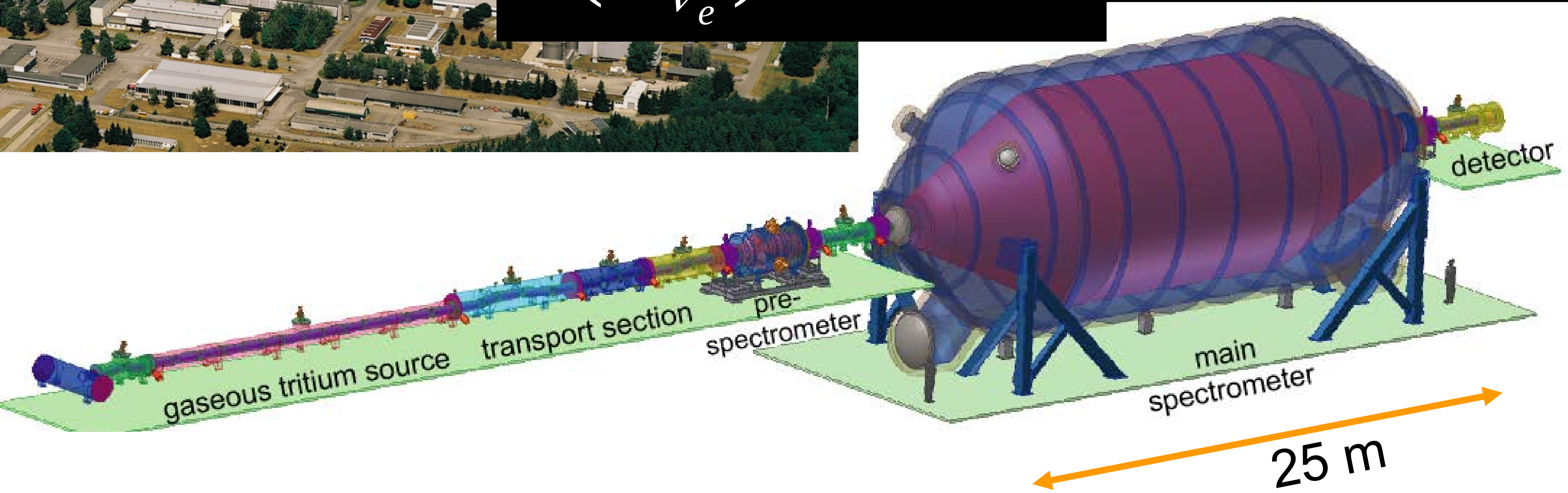
This translates into a limit on the sum of the three mass eigenstates

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

KATRIN experiment

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

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



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 ~ 100 cm^{-3})

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

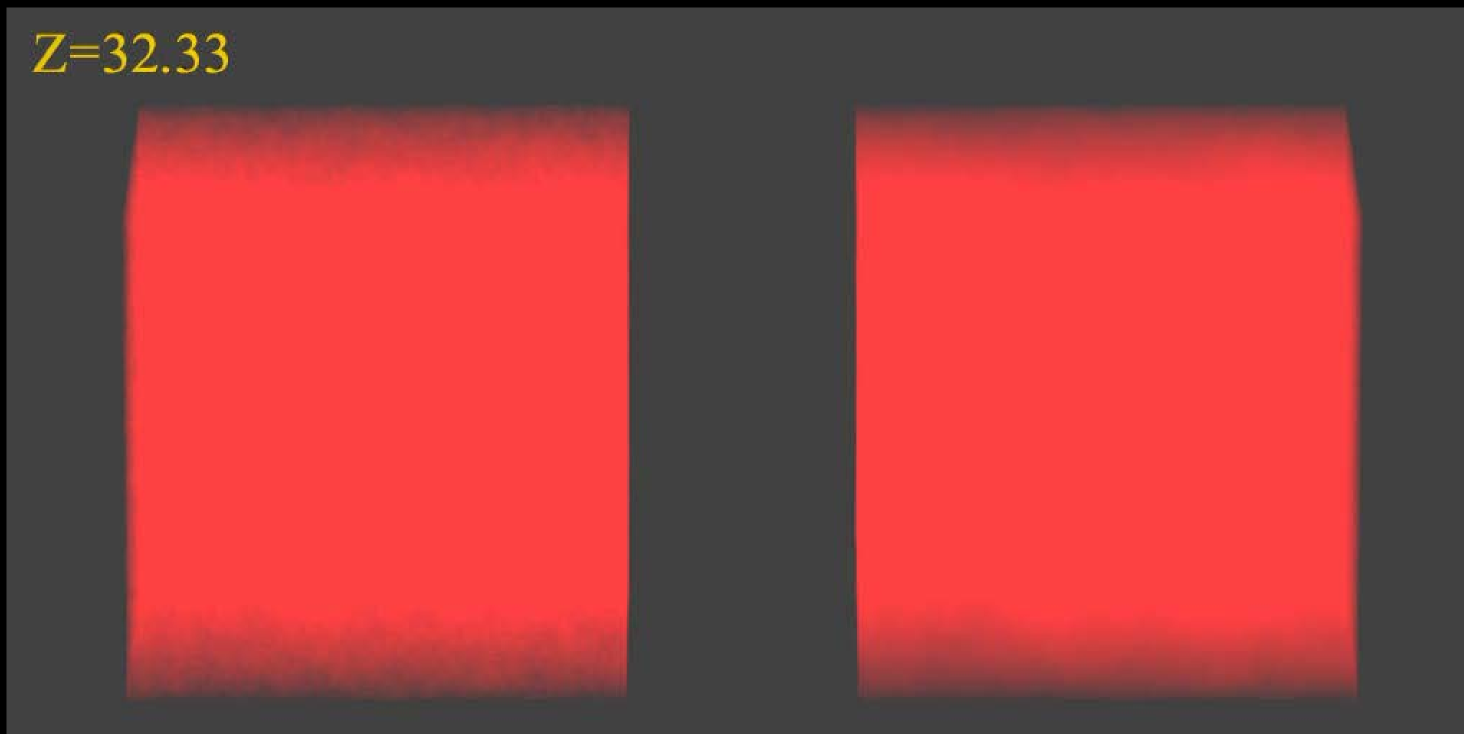
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

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

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

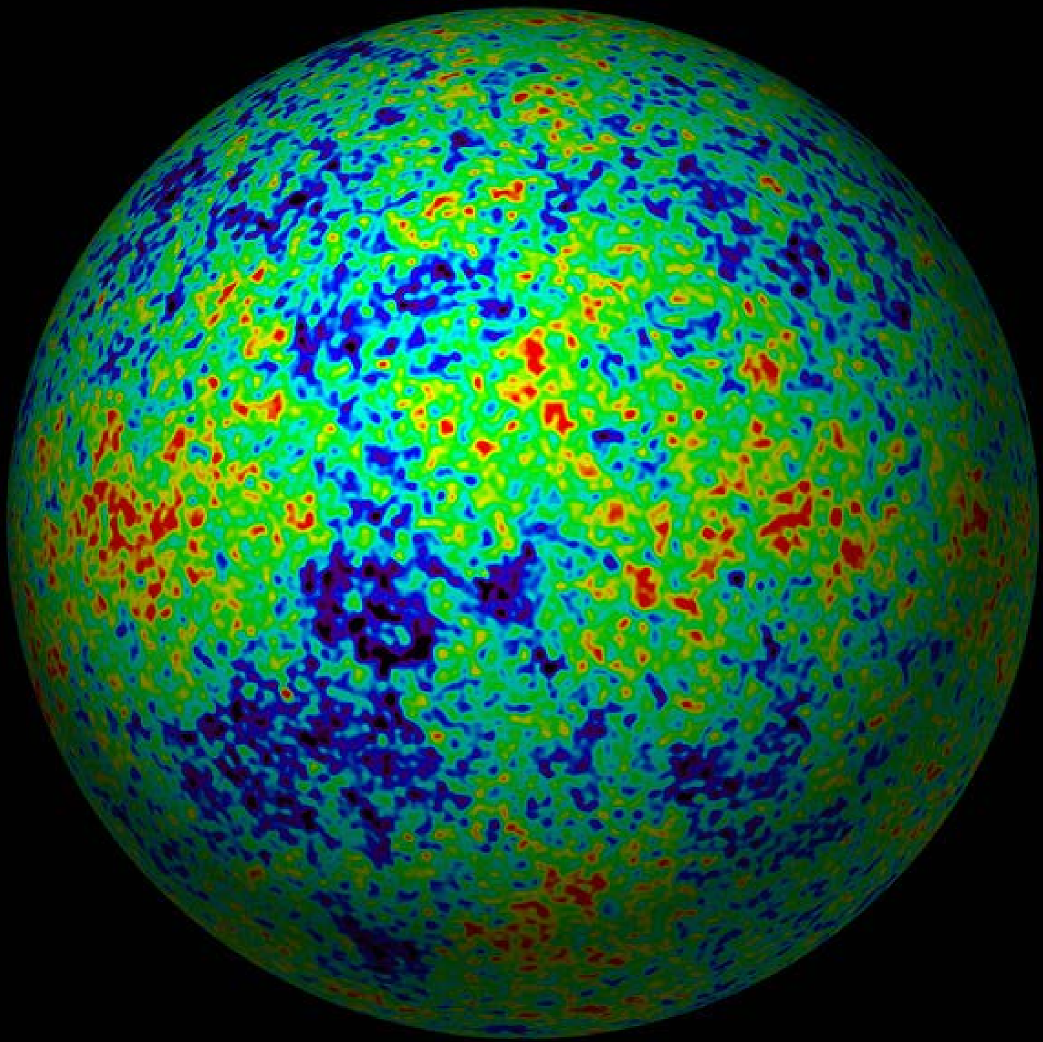


$$\sum m_\nu = 0 \qquad \sum m_\nu = 6.9\,\mathrm{eV}$$

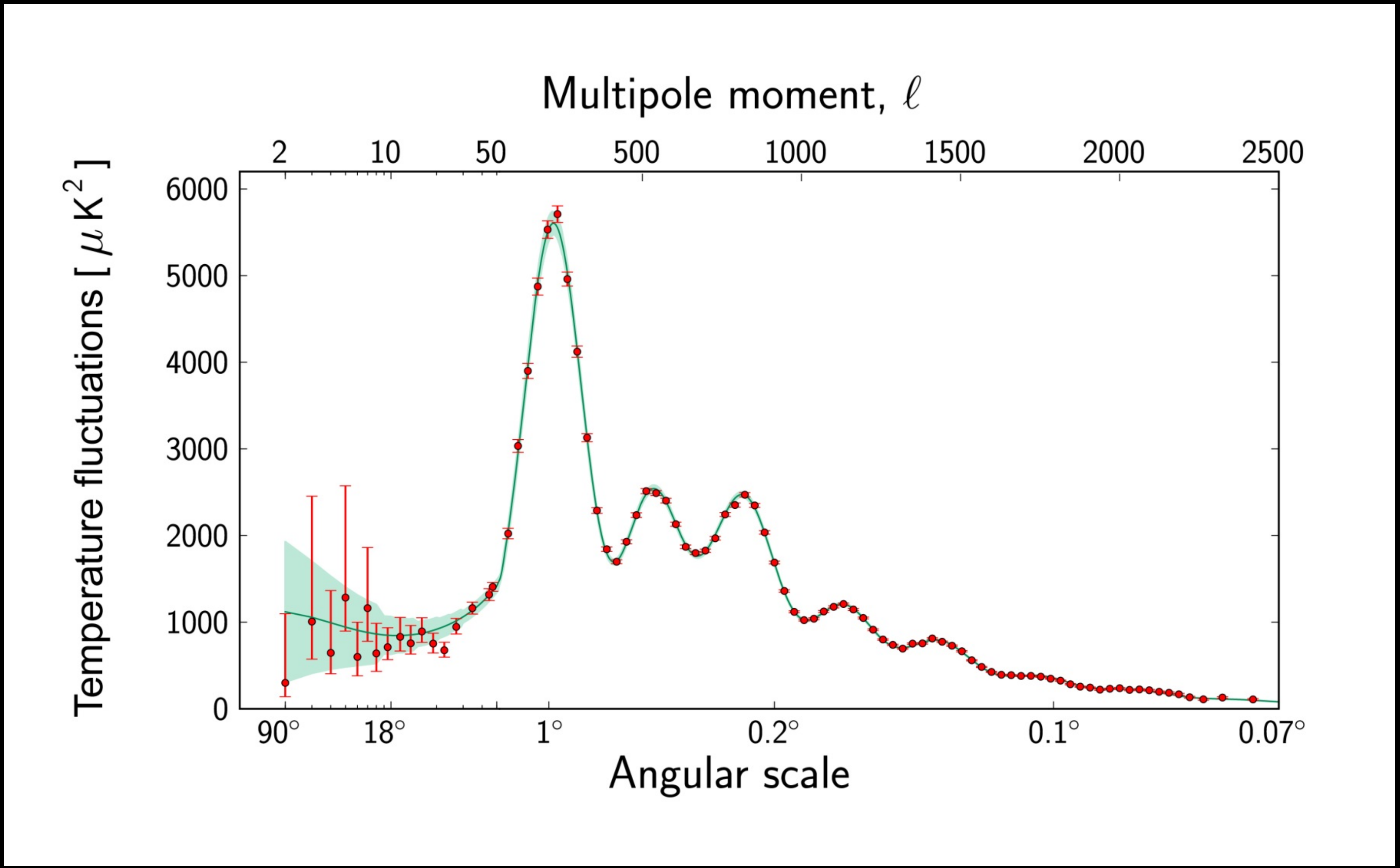
T Haugboelle, Aarhus University

AVAILABLE COSMOLOGICAL DATA

THE COSMIC MICROWAVE BACKGROUND

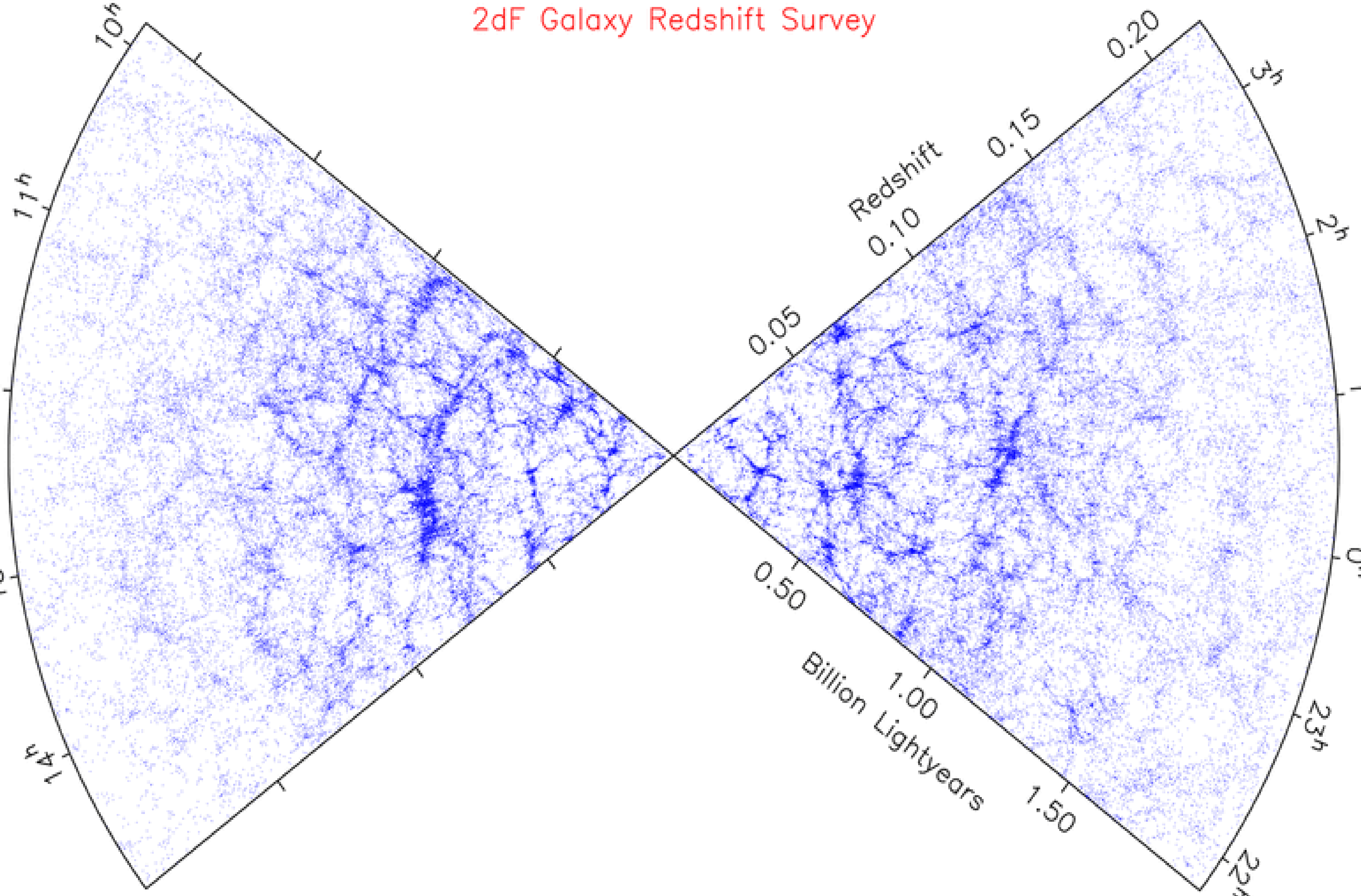


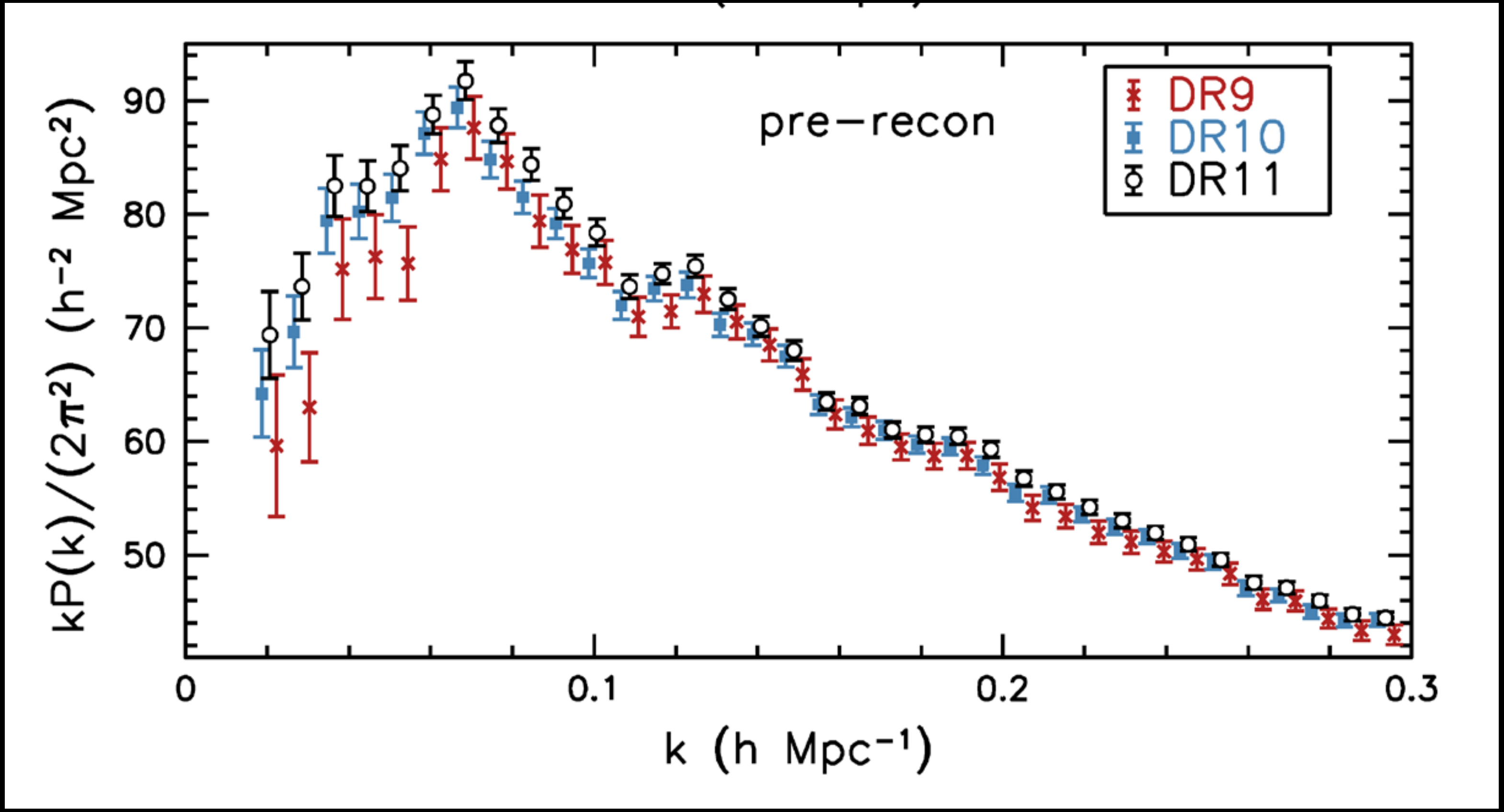
CMB TEMPERATURE AND POLARISATION



Ade et al. 2015 (Planck)

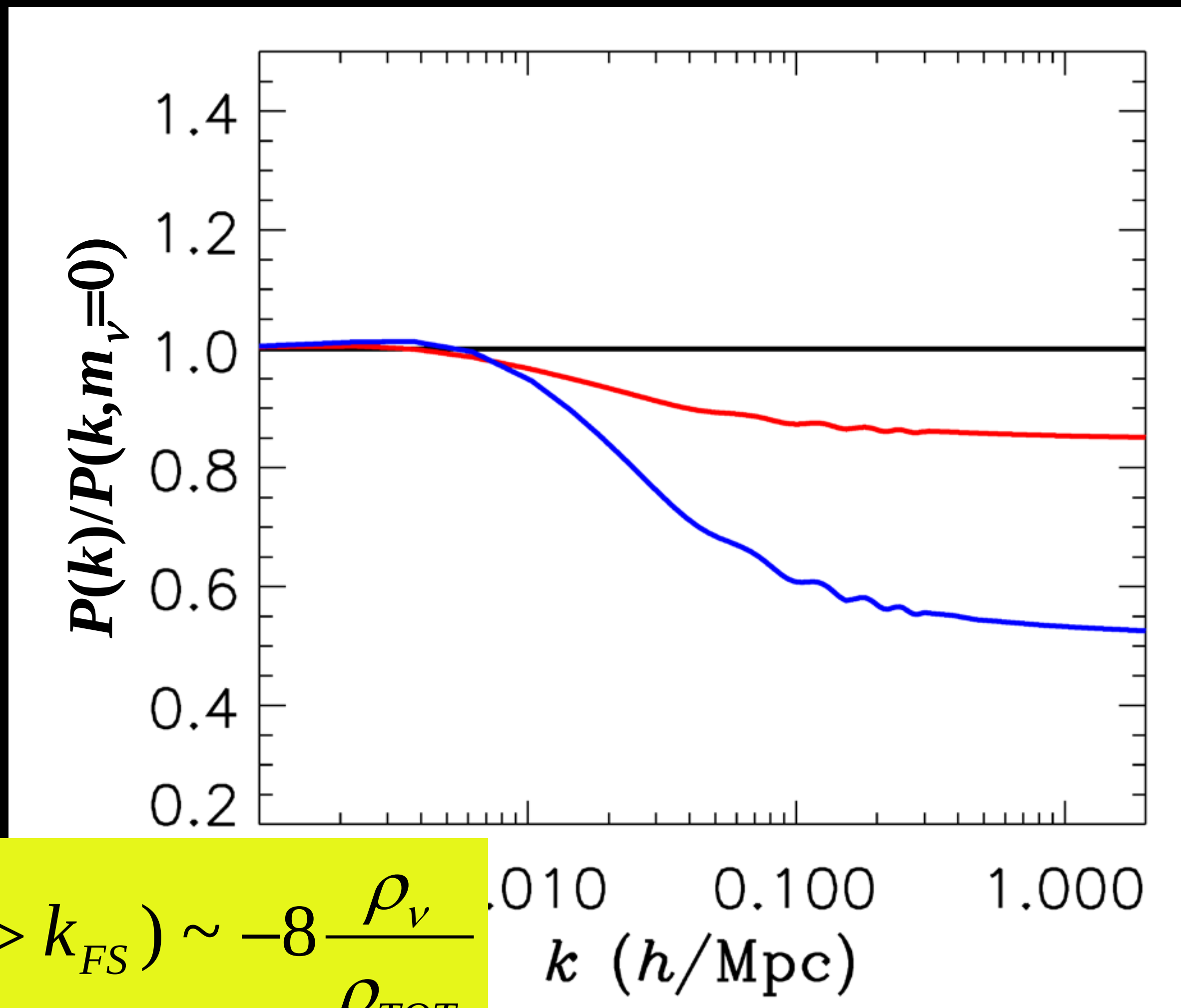
LARGE SCALE STRUCTURE SURVEYS





Anderson et al. 1312.4877 (SDSS)

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



$\Sigma m = 0$ eV

$\Sigma m = 0.3$ eV

$\Sigma m = 1$ eV

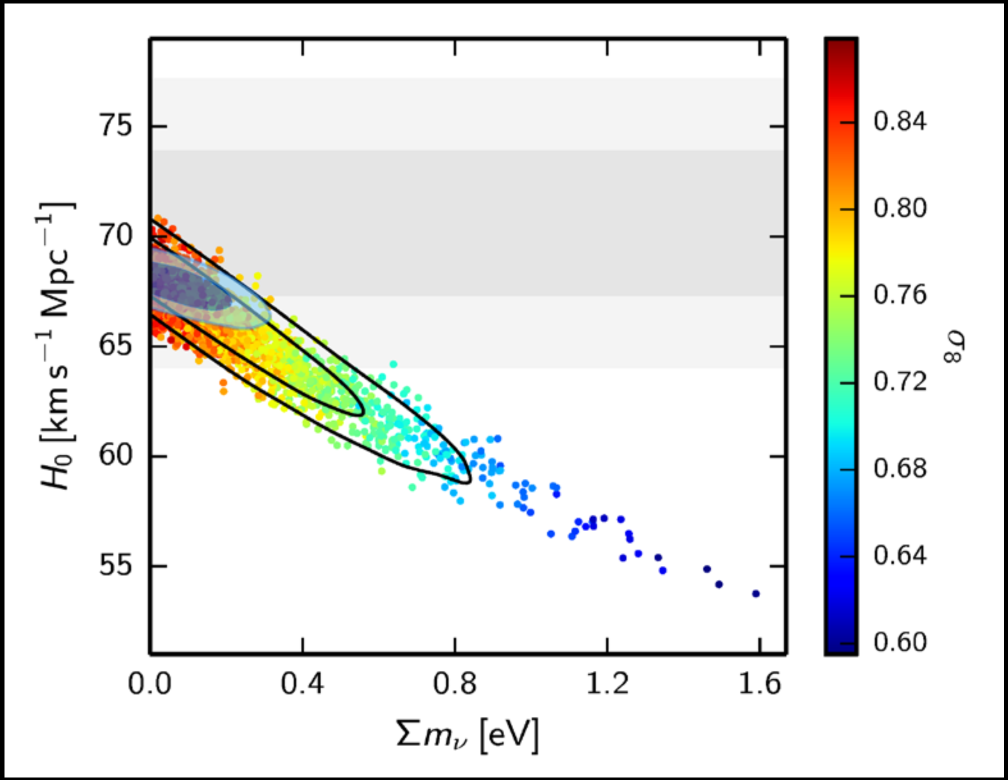
$$\frac{\Delta P}{P_{m=0}}(k >> k_{FS}) \sim -8\frac{\rho_\nu}{\rho_{TOT}}$$

NOW, WHAT ABOUT NEUTRINO PHYSICS?

WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

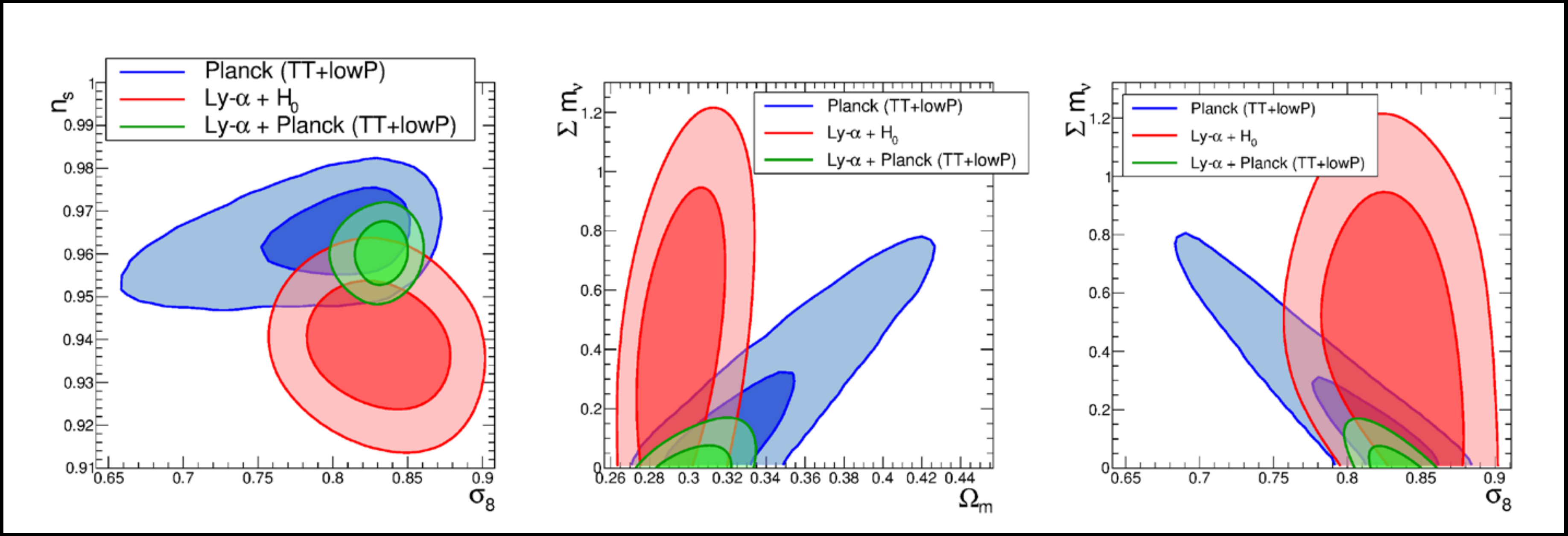
DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

THERE ARE MANY ANALYSES IN THE LITERATURE



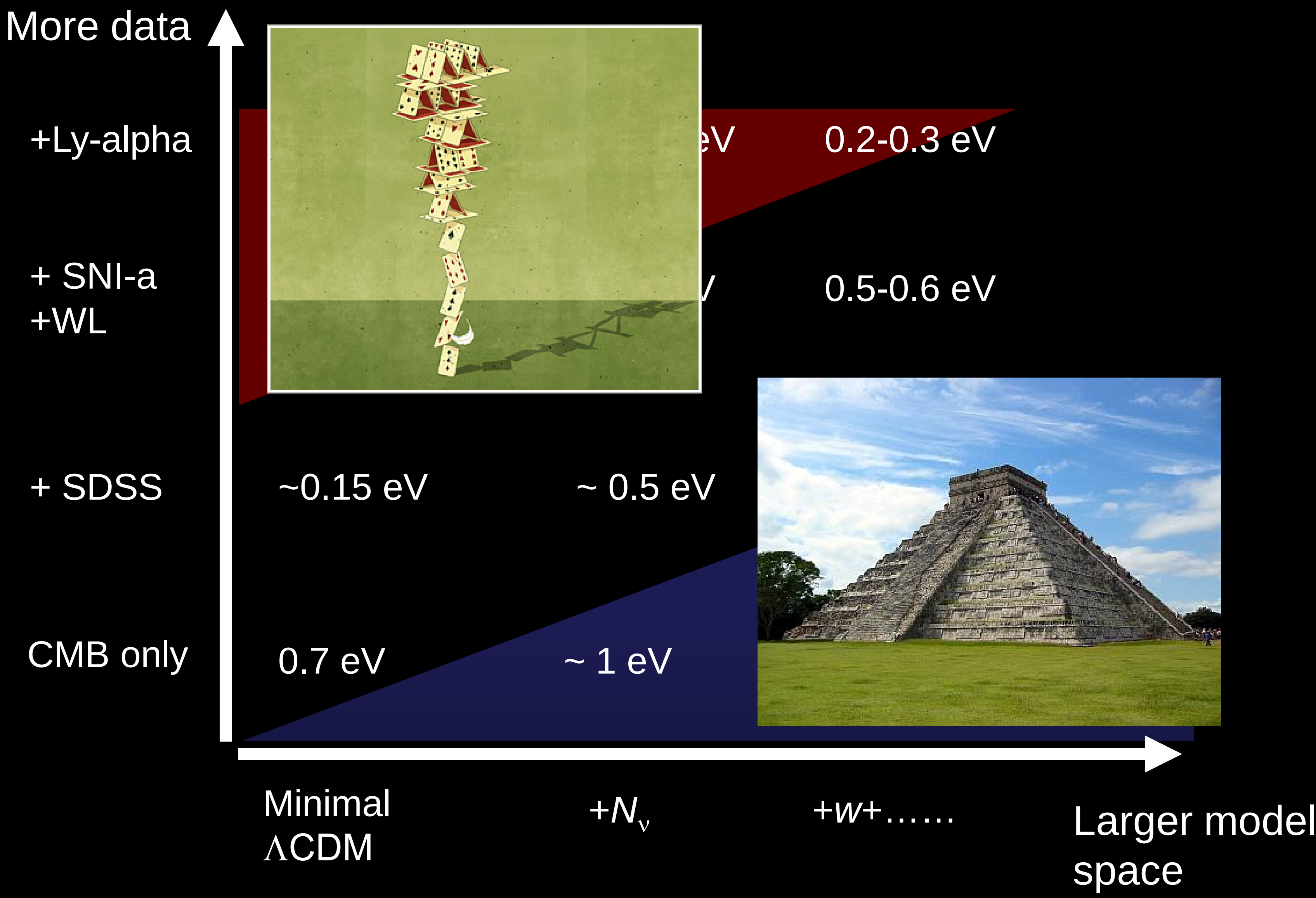
ADE ET AL.
ARXIV:1502.01589

THE STRONGEST BOUND IS CURRENTLY $\sum m_\nu < 0.12$ eV BUT THIS IS DERIVED FROM THE COMBINATION OF CMB AND LYMAN-α DATA AND PERHAPS NOT VERY ROBUST



Palanque-Delabrouille et al. 1506.05976

THE NEUTRINO MASS FROM COSMOLOGY PLOT



HOW CAN THE BOUND BE AVOIDED?

CHANGE THE PRIMORDIAL SPECTRUM?

NOT MUCH

TOPOLOGICAL DEFECTS?

NOT MUCH

MAKE THE NEUTRINOS STRONGLY INTERACTING

PERHAPS (MORE TO COME)

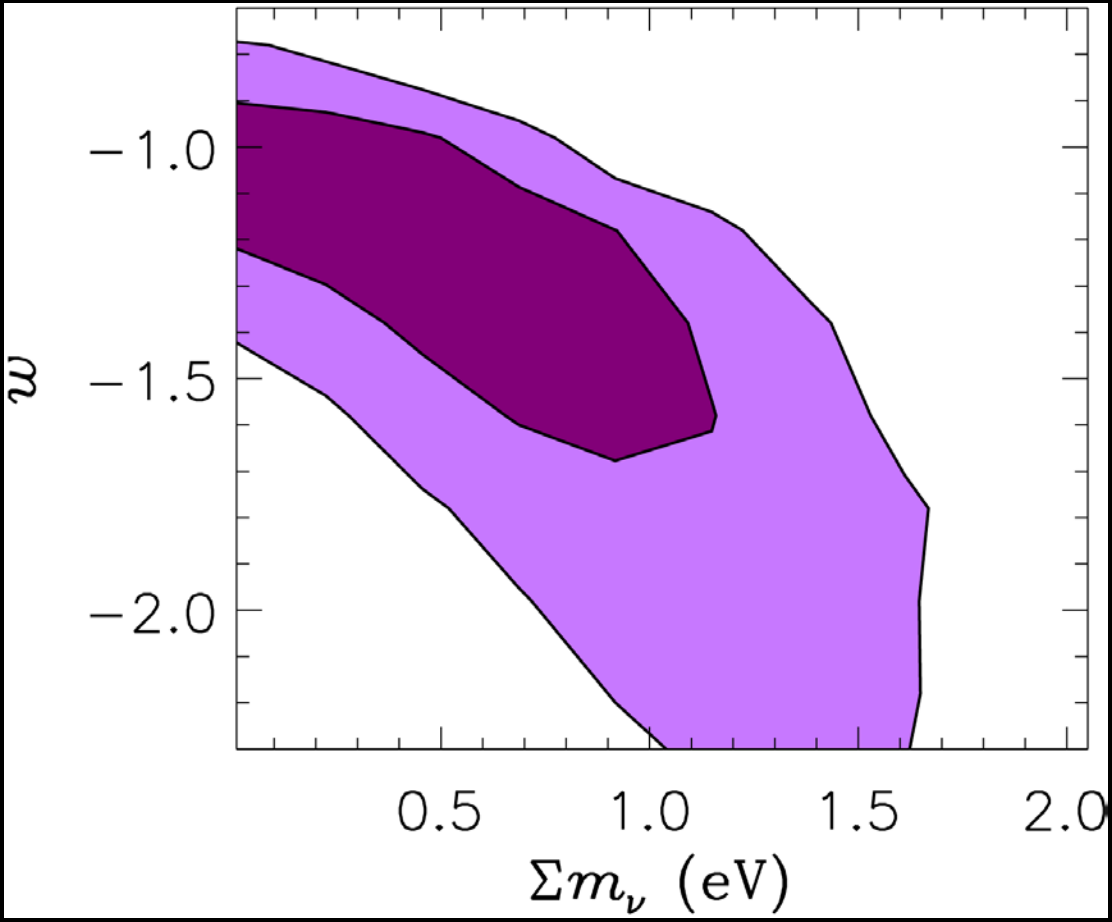
MODIFIED GRAVITY / DARK ENERGY

YES

……

EXAMPLE:

THERE IS A VERY STRONG DEGENERACY BETWEEN NEUTRINO MASS AND THE DARK ENERGY EQUATION OF STATE
THIS SIGNIFICANTLY RELAXES THE COSMOLOGICAL BOUND ON NEUTRINO MASS



STH 05

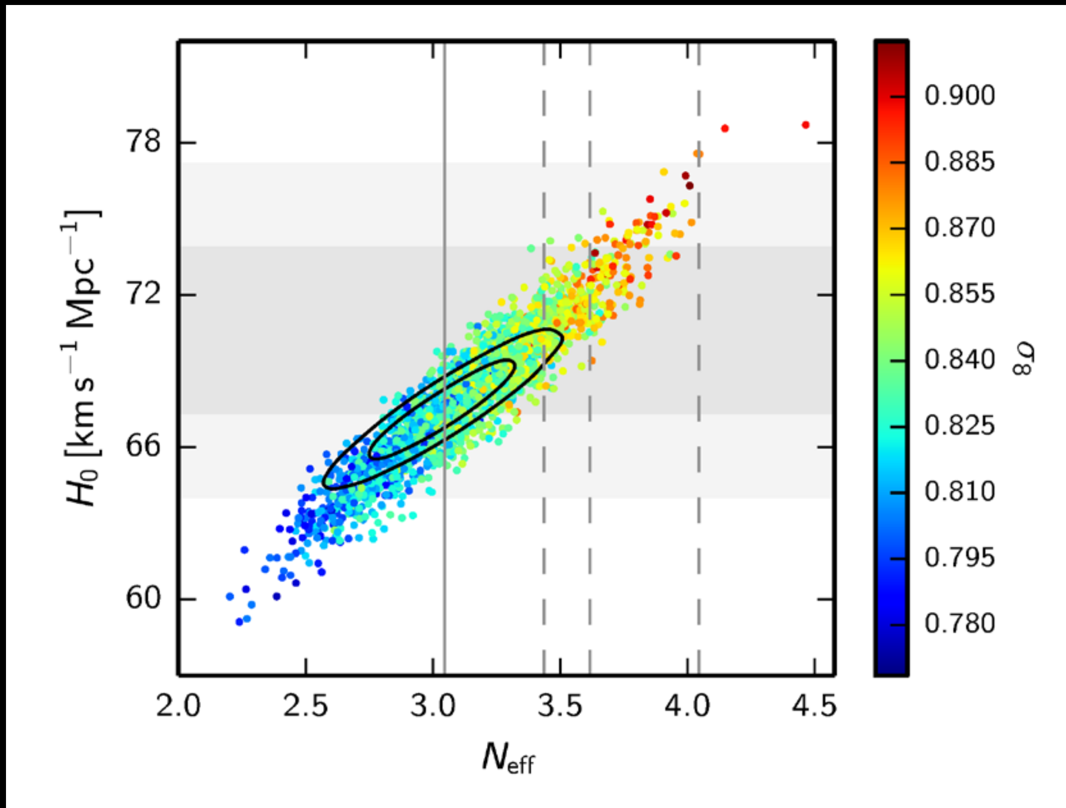
GOING BEYOND THE MASS

$$\Omega = \frac{\rho}{\rho_c} = \sum m_{\nu,i} n_{\nu,i} \qquad n_\nu = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma$$

Normally $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$, but could be different. Normally the relativistic energy density in neutrinos is quantified through the relation

$$N_{eff} = \frac{\rho_{\nu,rel}}{\rho_{\nu 0}} \qquad \rho_{\nu 0} = \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 \rho_\gamma$$

N_{eff} is a measure of any type of ”dark radiation”



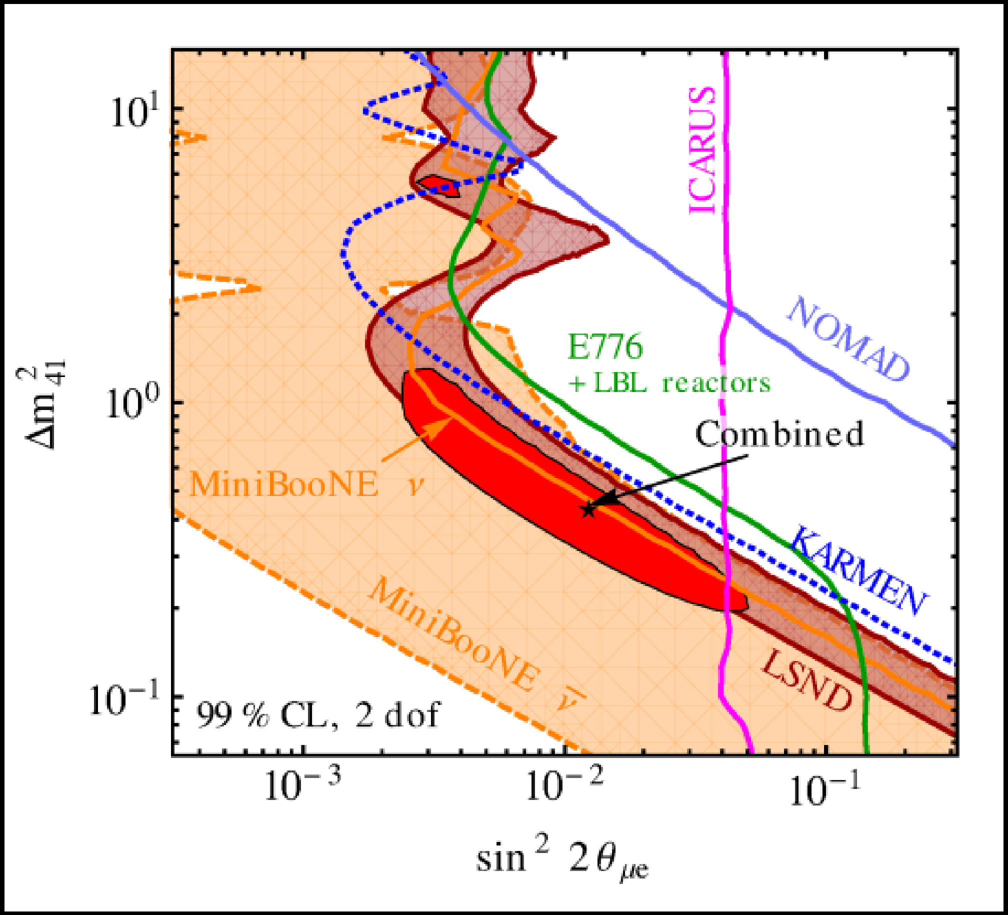
THE CONCLUSION SEEMS TO BE THAT THERE IS NO EVIDENCE FOR ANY PHYSICS BEYOND THE STANDARD MODEL

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.

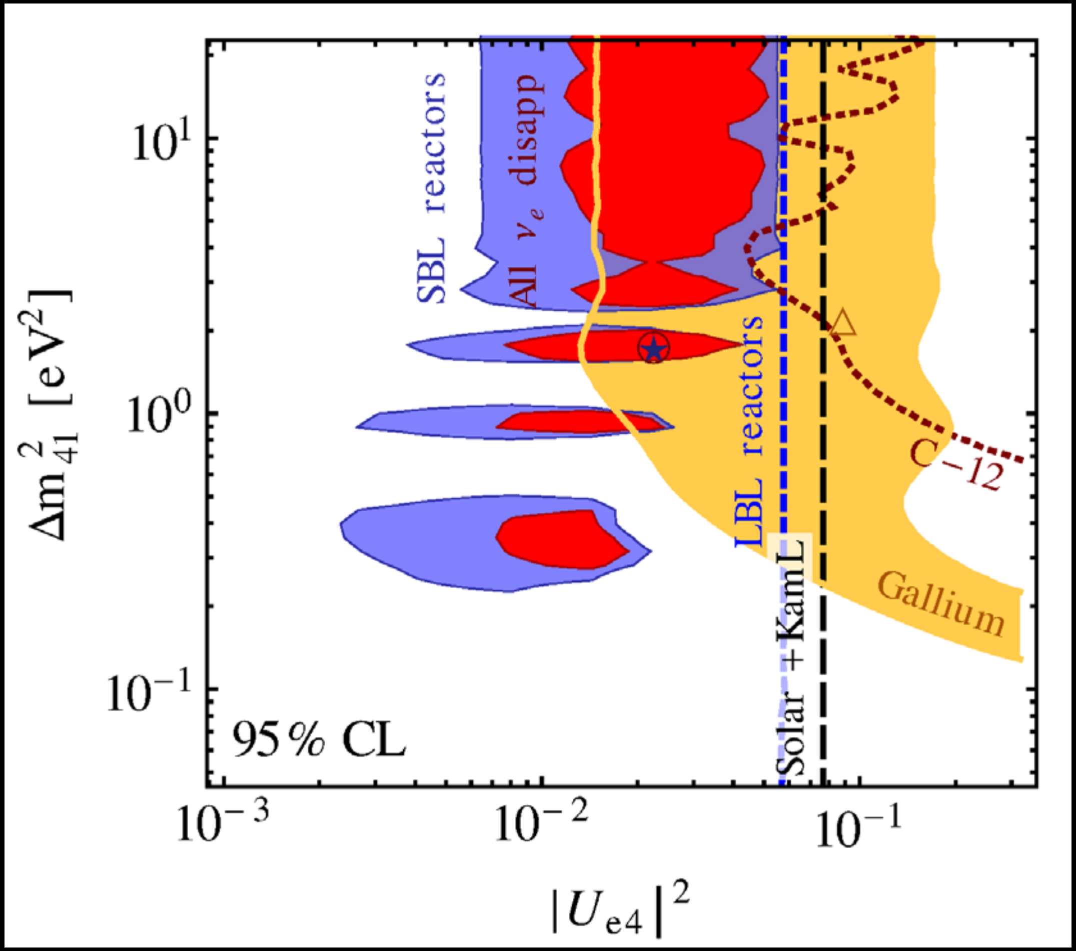
A variety of different terrestrial experiments show hints of the presence of a 4th neutrino mass state (possibly even a 5th), most likely with a mass around 1 eV

ν_e APPEARANCE



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

ν_e DISAPPEARANCE

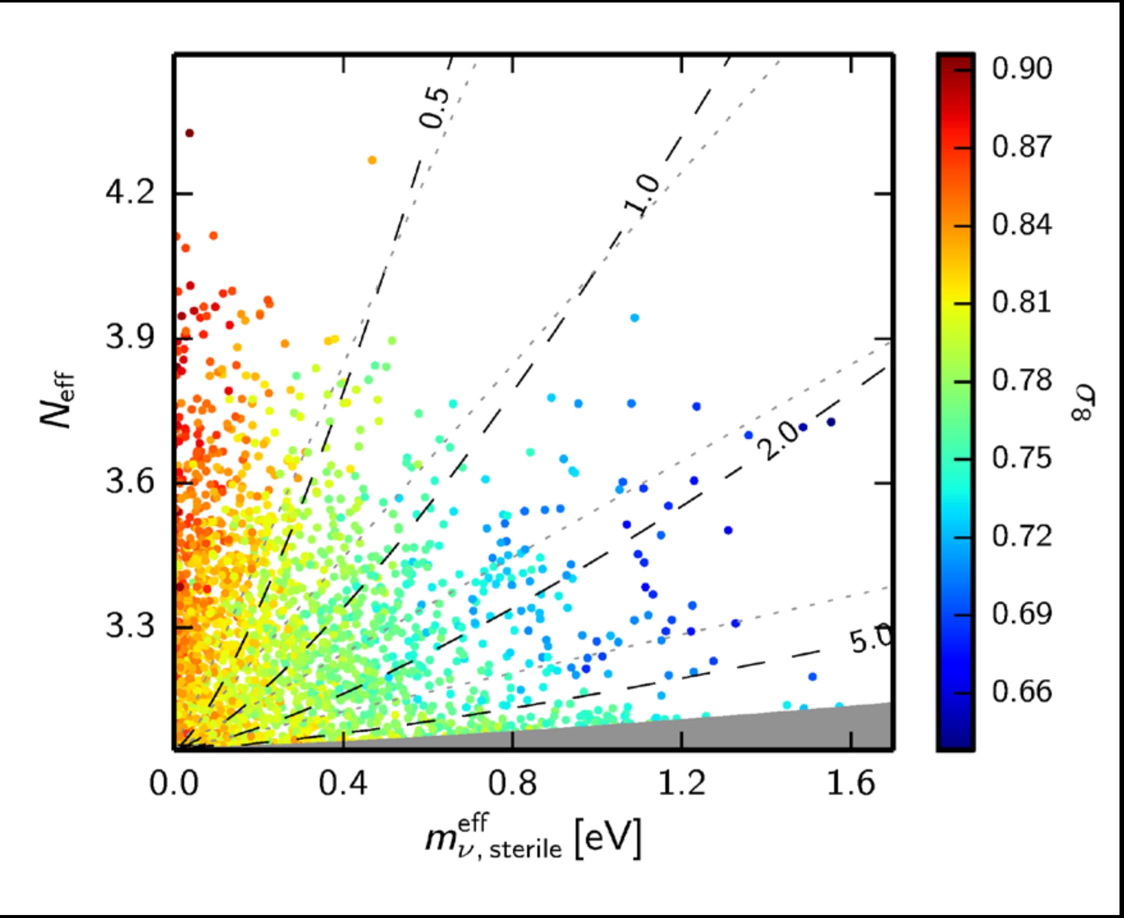


Kopp, Machado, Maltoni & Schwetz, 1303.3011

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

$$N_{eff} = \frac{\rho_s + \rho_a}{\rho_{\nu,0}}$$



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)

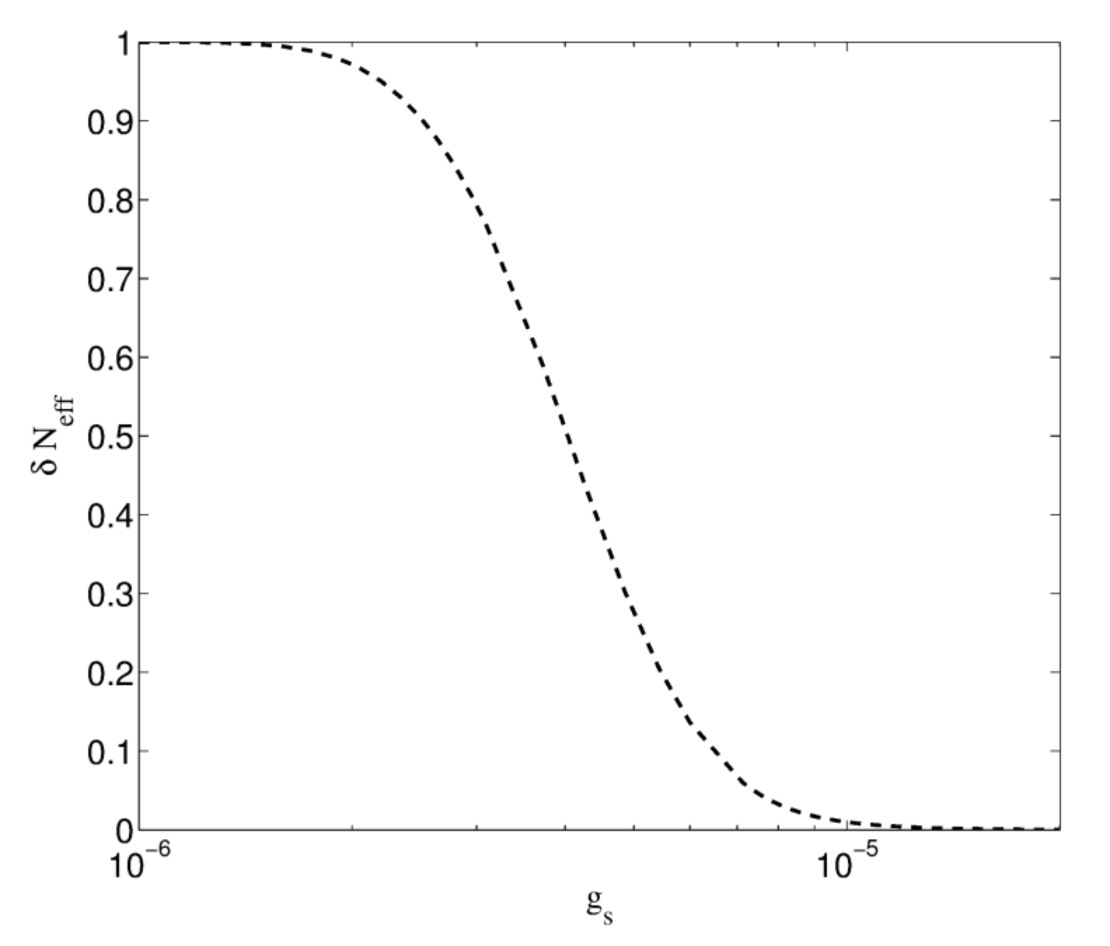
The neutrino matter potential is important and a very large potential could in principle prevent thermalisation

How can this be achieved?

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

<u>New, non-standard interactions in the sterile sector</u>
(e.g. STH, Hansen, Tram, 1310.5926, Dasgupta & Kopp 1310.6337, Bringmann, Hasenkamp & Kersten 1312.4947, Archidiacono, STH, Hansen, Tram 1404.5915 Saviano et al. 1409.1680, 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)

This model provides a solution to the mass problem

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)

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 ΛCDM 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 2016)

TIMELINE WITH A MASSLESS MEDIATOR

$T \gg 1$ TeV: Neutrinos and phi equilibrated (not necessary)

Entropy production $T_\nu \gg T_s, T_\phi$

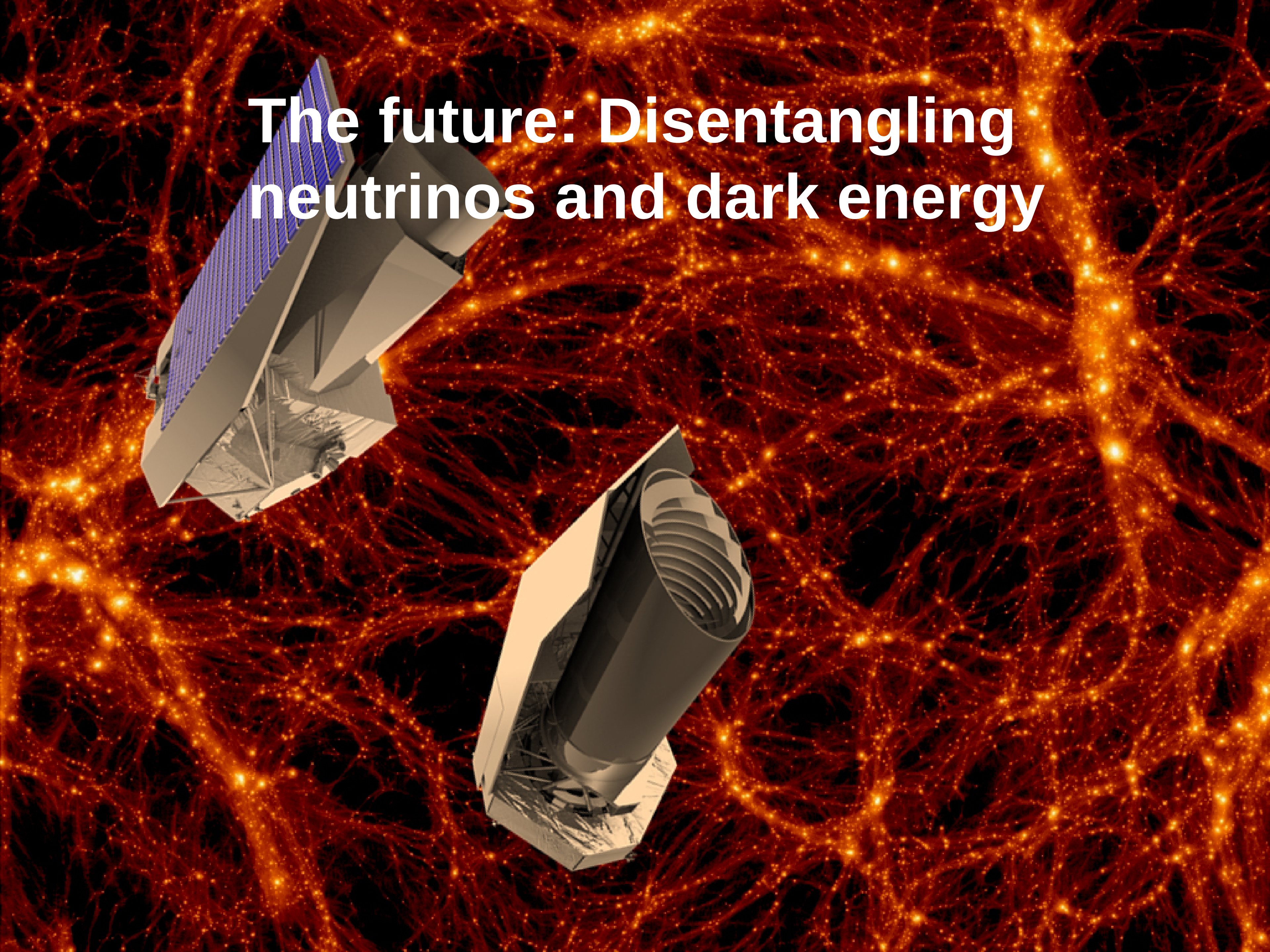
$T \sim 1 - 10$ MeV: Sterile production from via oscillations plus scatterings

$T < 1$ MeV: Equilibration of steriles with actives via oscillations (Mirizzi et al. 1410.1385)

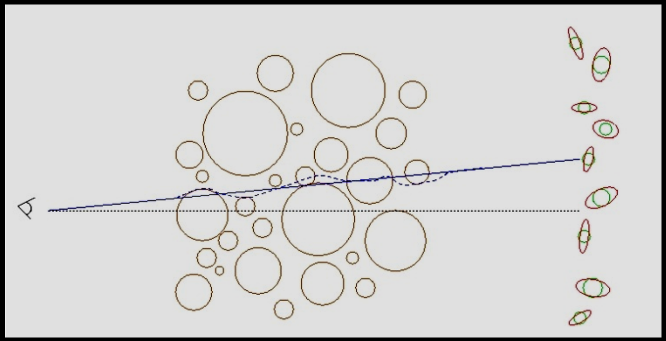
$T > 1\ \mathrm{eV}$: ν_s and ϕ come into chemical equilbrium and behave as a single fluid

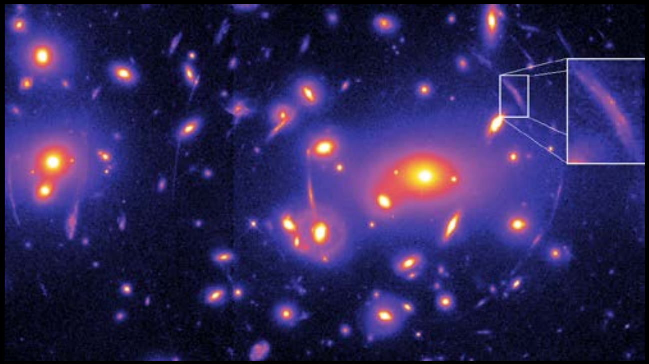
$T \sim 1\ \mathrm{eV}$: ν_s annihilates into ϕ

The future: Disentangling neutrinos and dark energy

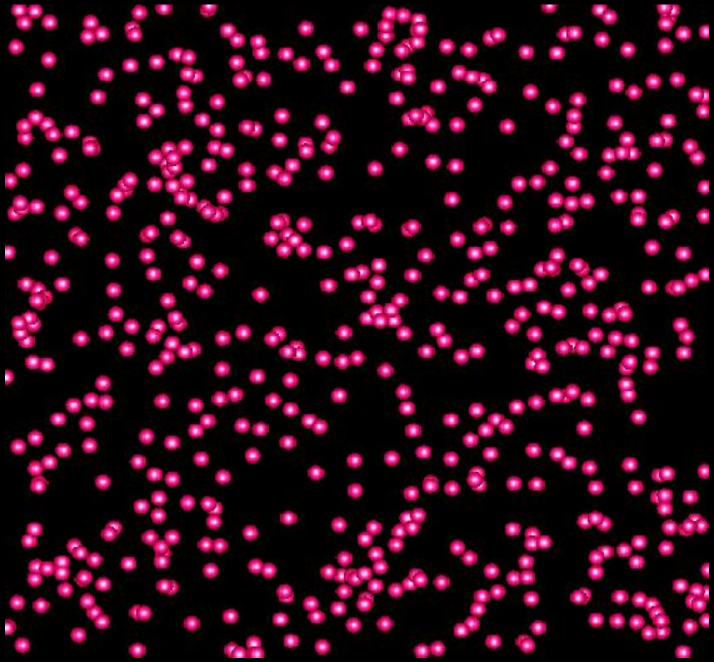


WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE

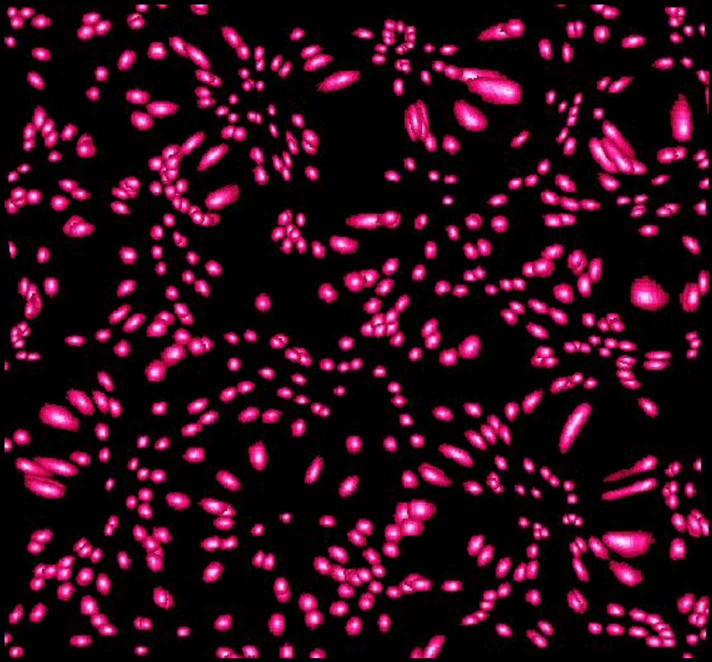




Distortion of background images by foreground matter



Unlensed



Lensed

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

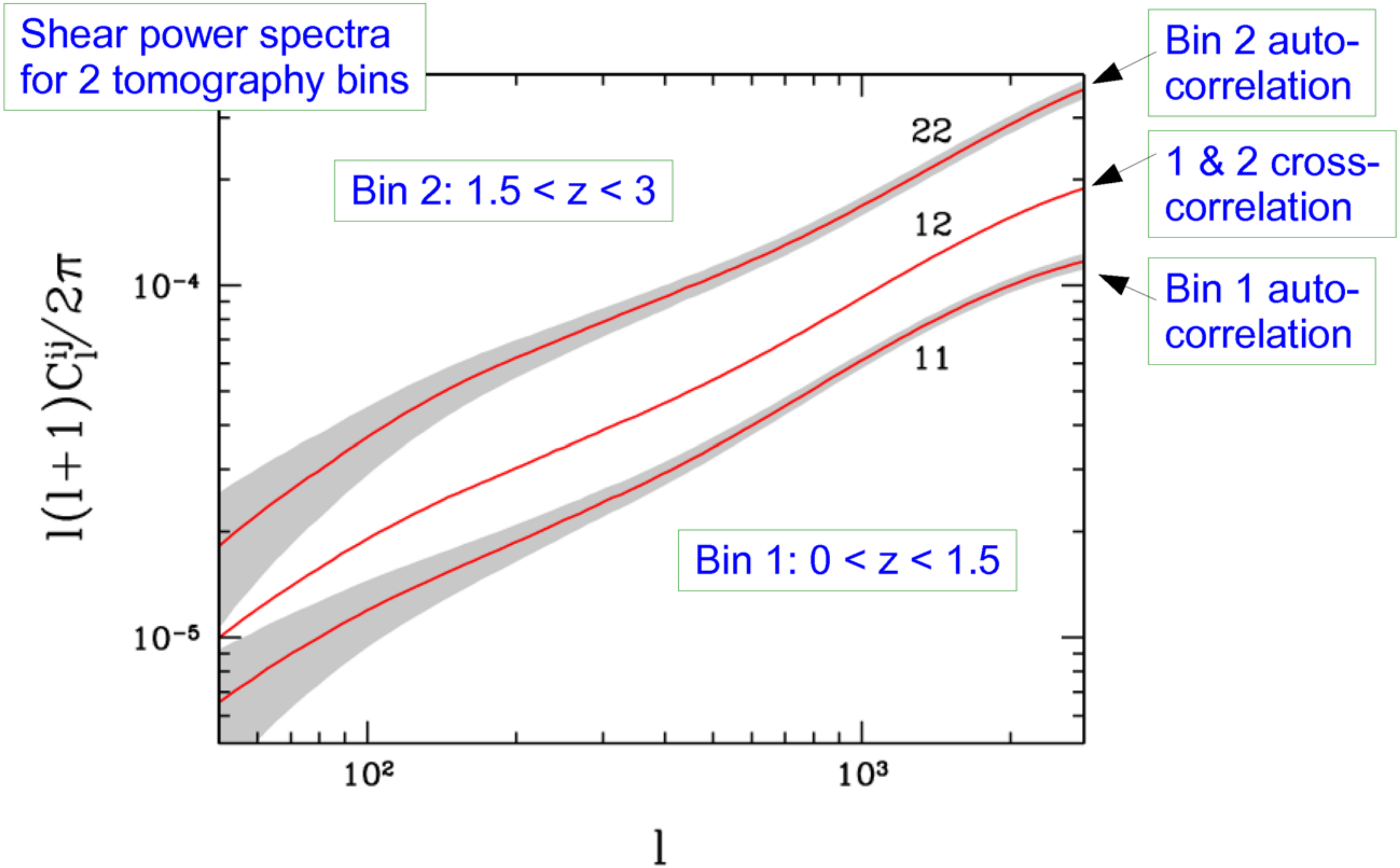
$$C_\ell = \frac{9}{16} H_0^4 \Omega_m^2 \int_0^{\chi_H} \left[\frac{g(\chi)}{a\chi} \right]^2 P(\ell / r, \chi) d\chi$$

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

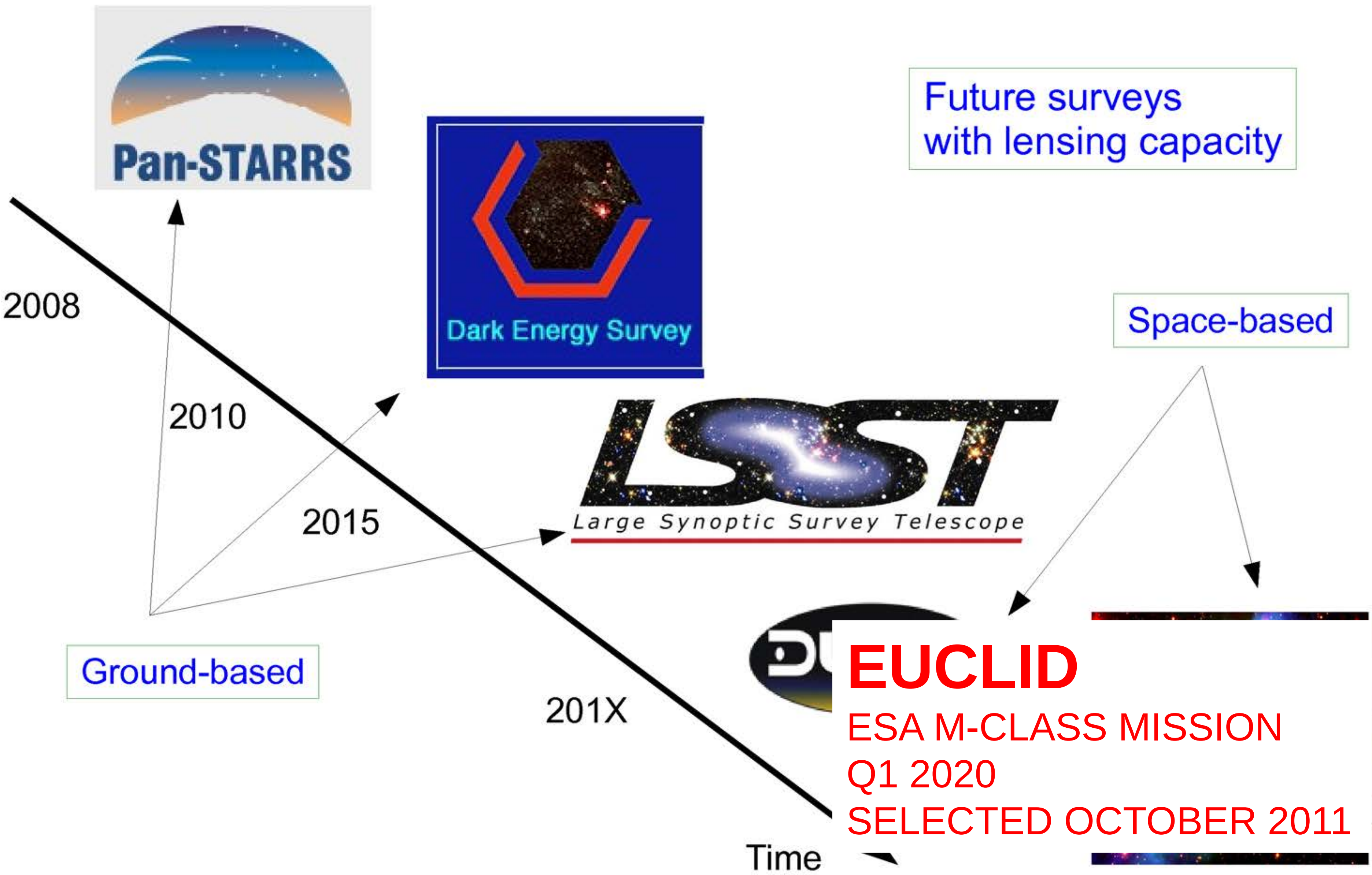
$$g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi'$$

WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY

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



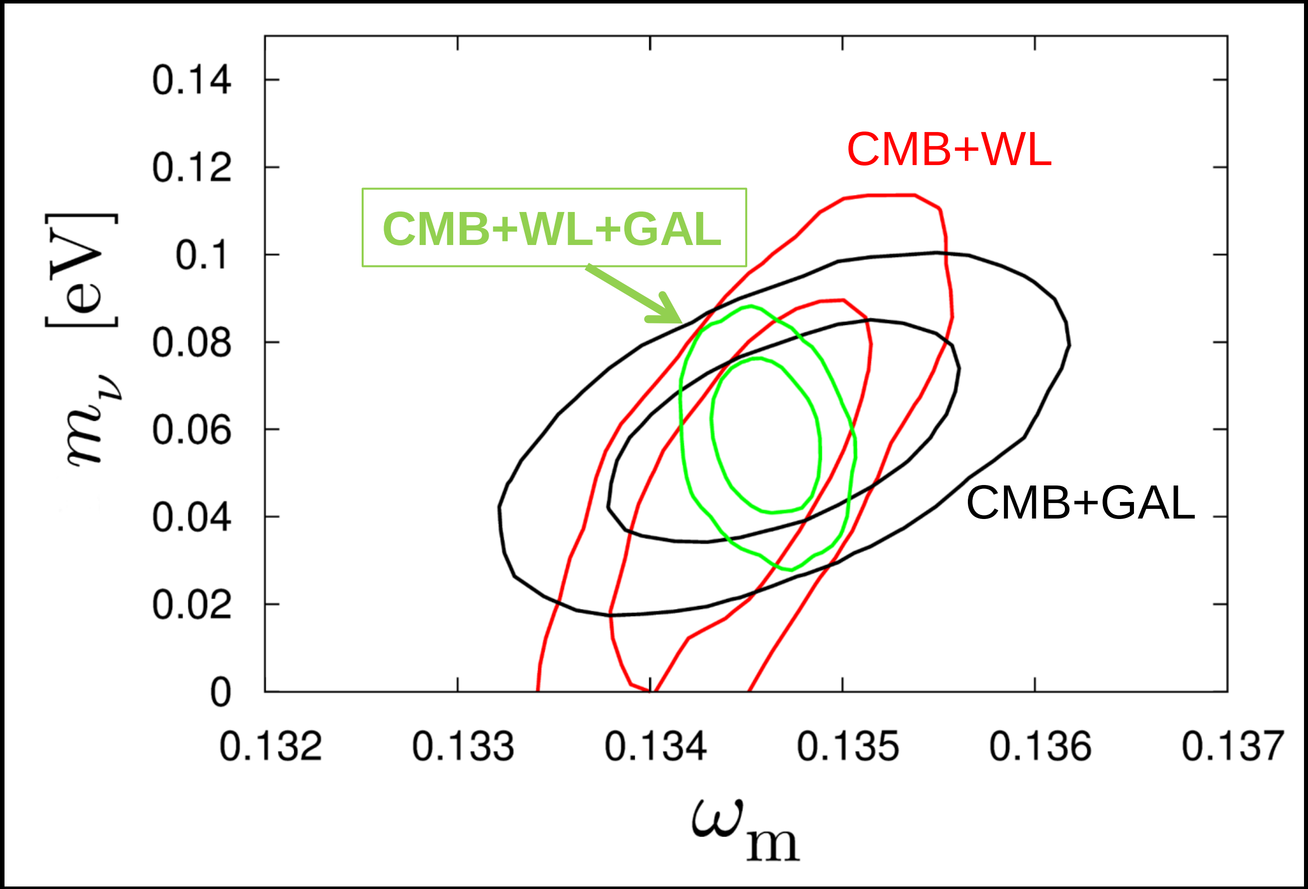
STH, TU, WONG 2006


Pan-STARRS
Future surveys
with lensing capacity
Dark Energy Survey
2008
2010
Space-based
LSST
Large Synoptic Survey Telescope
2015
Ground-based
201X
EUCLID
ESA M-CLASS MISSION
Q1 2020
SELECTED OCTOBER 2011
Time

EUCLID WILL FEATURE:

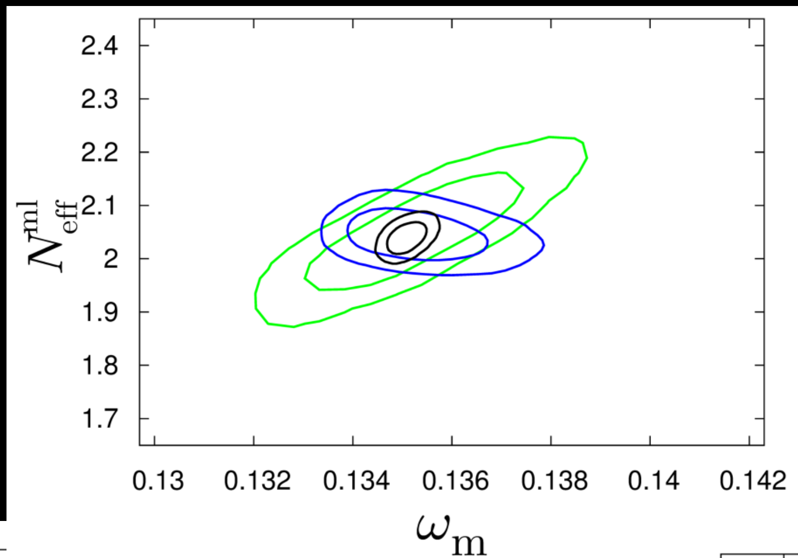
- A WEAK LENSING MEASUREMENT OUT TO z ~ 2, COVERING APPROXIMATELY 20,000 deg^2
(THIS WILL BE MAINLY PHOTOMETRIC)
- A GALAXY SURVEY OF ABOUT 10^7 GALAXIES (10 x SDSS)
- A WEAK LENSING BASED CLUSTER SURVEY

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

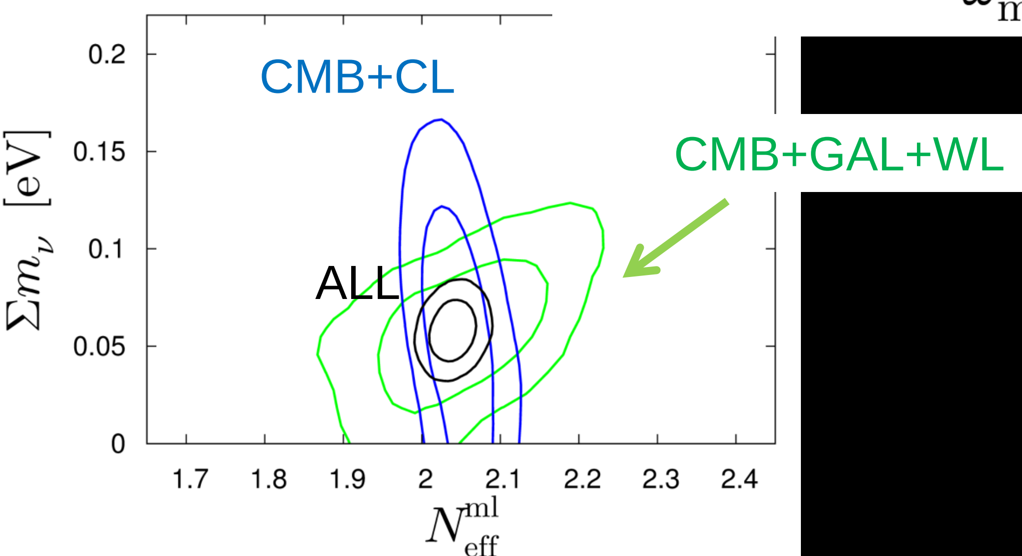


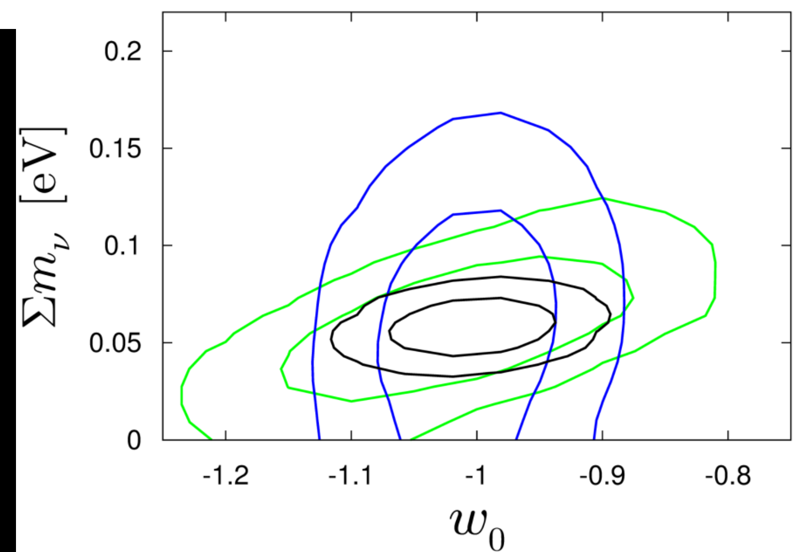
arXiv:1209.1043 (JCAP)

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



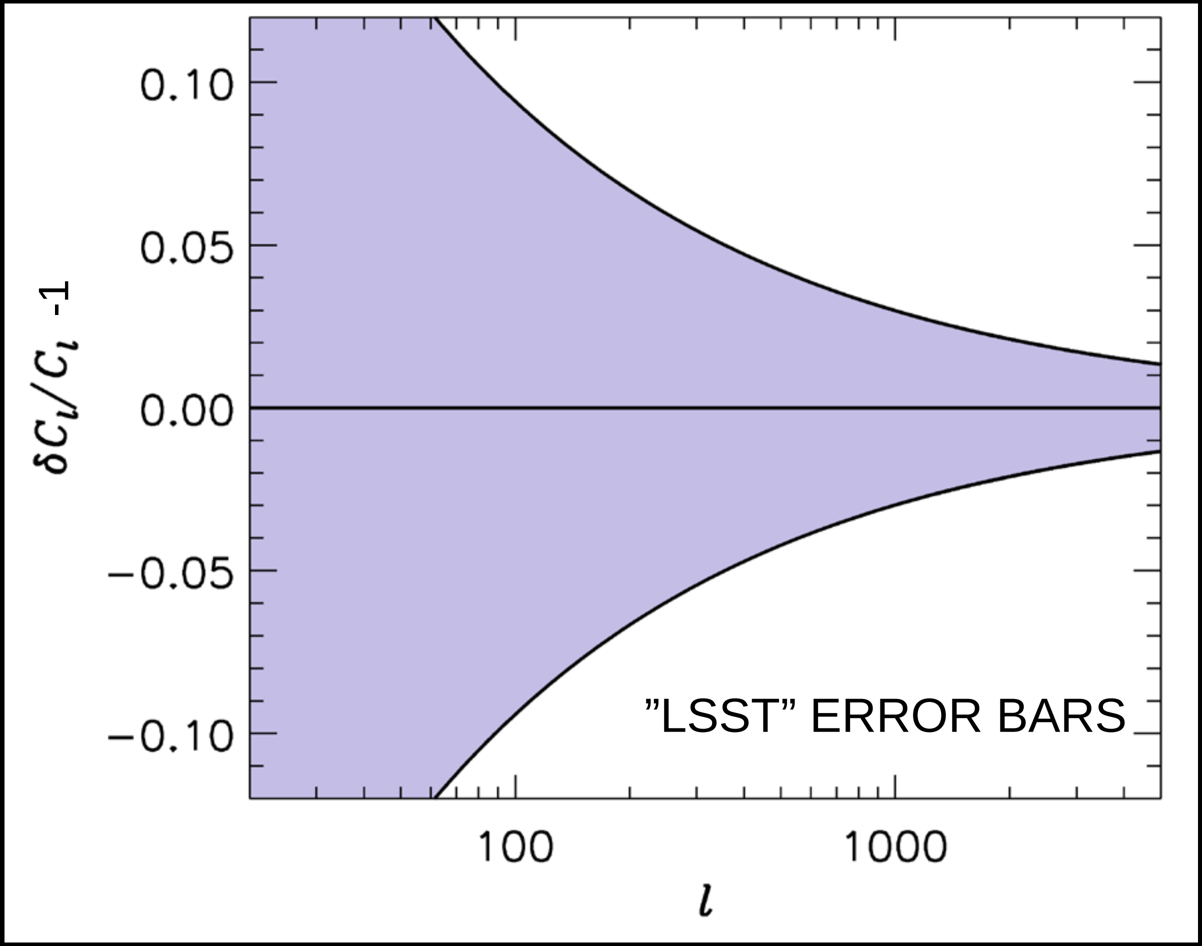
arXiv:1304.2321
(JCAP)





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

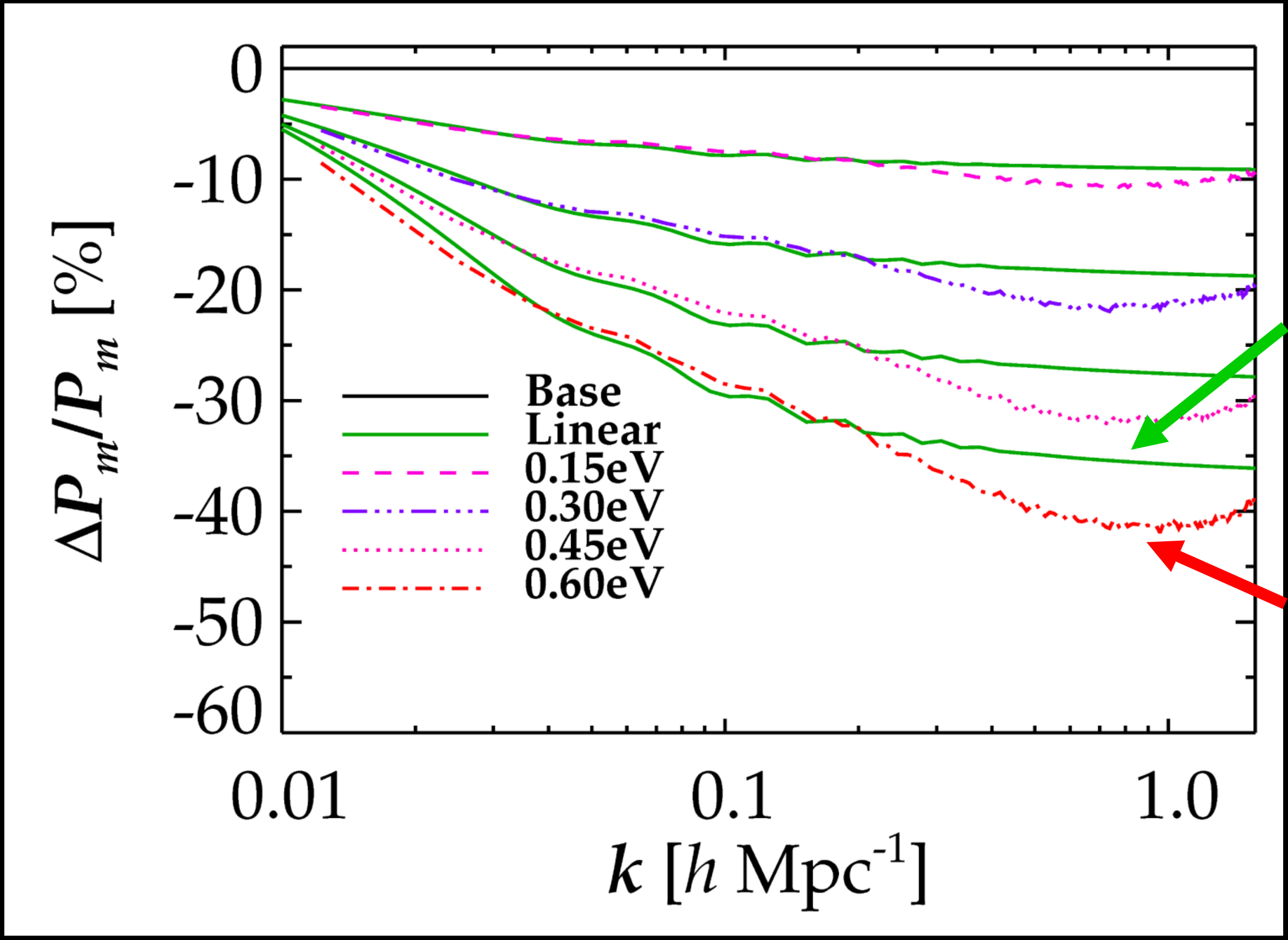


WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM TO AT LEAST THE SAME PRECISION!

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

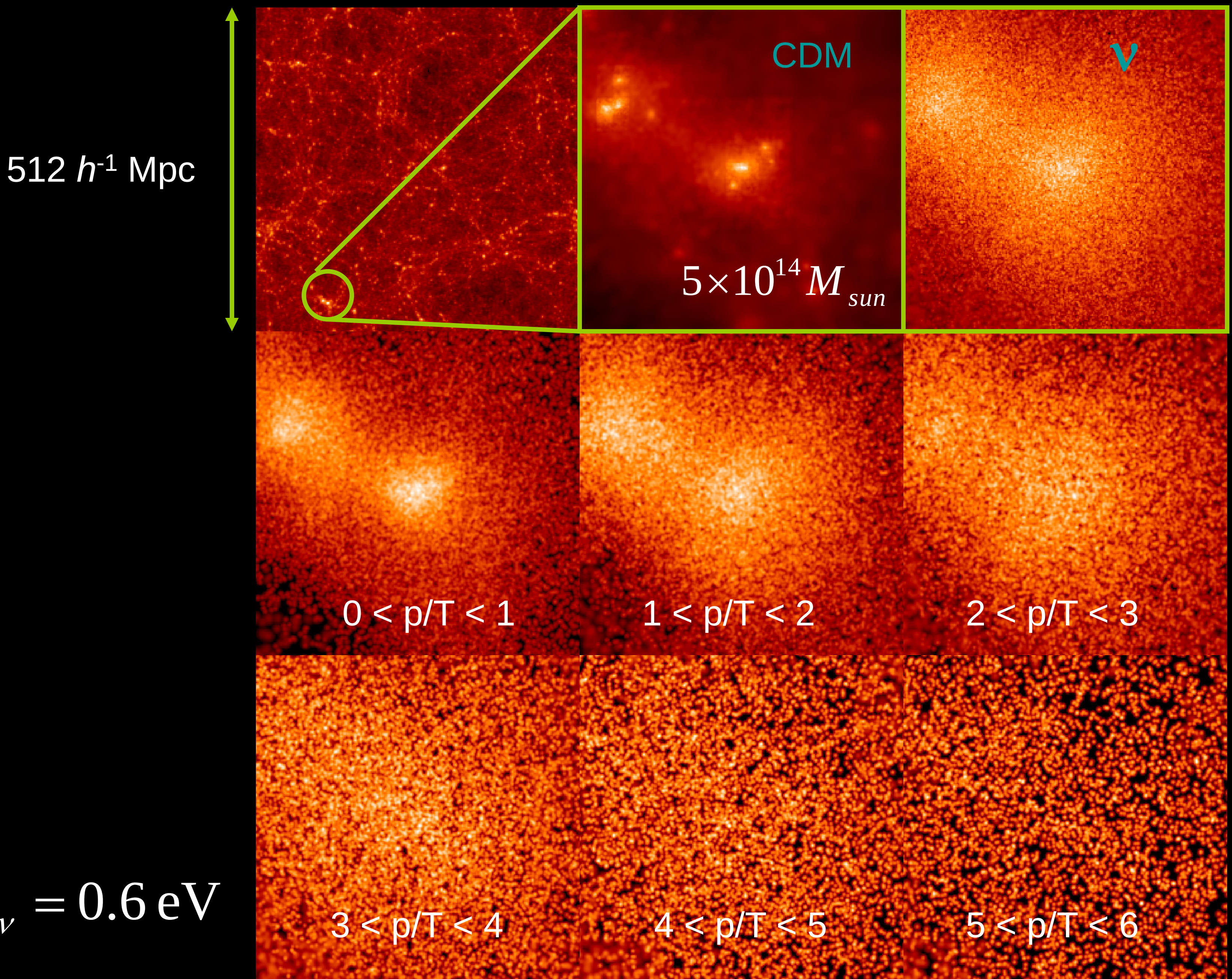
$$\frac{\Delta P}{P} \sim -9.6\frac{\Omega_\nu}{\Omega_m}$$

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

ANOTHER IMPORTANT ASPECT OF STRUCTURE FORMATION WITH NEUTRINOS:

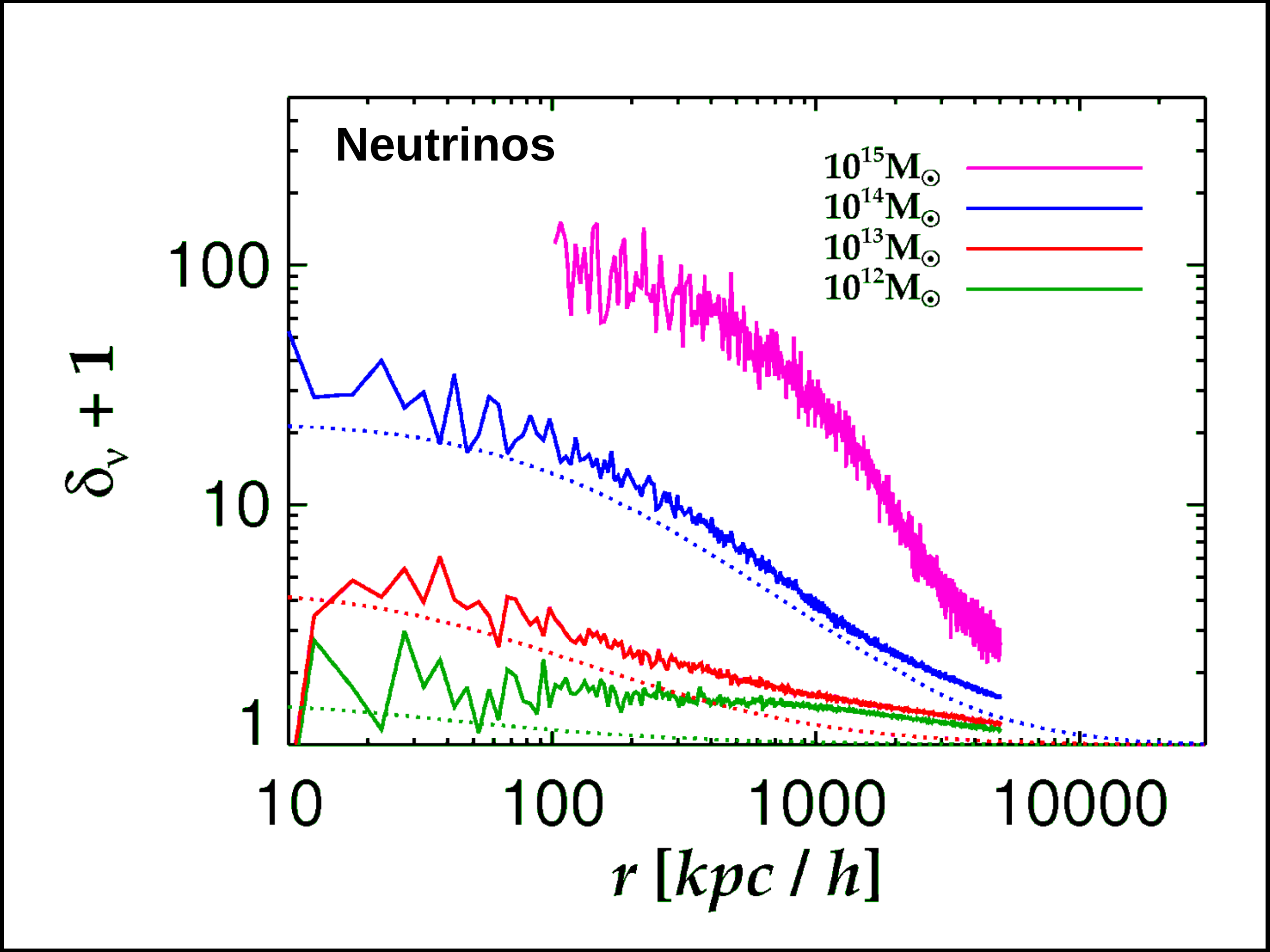
THE NUMBER OF BOUND OBJECTS (HALOS) AS WELL AS THEIR PROPERTIES ARE CHANGED WHEN NEUTRINOS ARE INCLUDED

INDIVIDUAL HALO PROPERTIES



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

Brandbyge, STH, Haugboelle, Wong, arxiv:1004.4105



See also Ringwald & Wong 2004

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