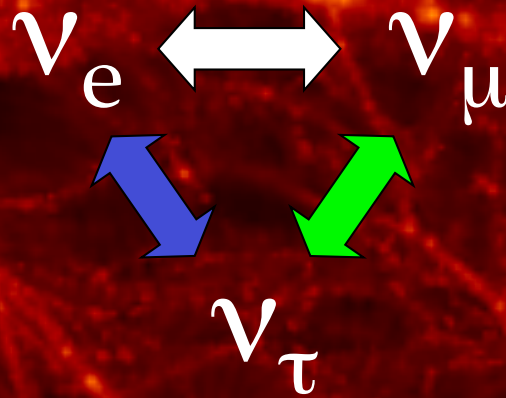
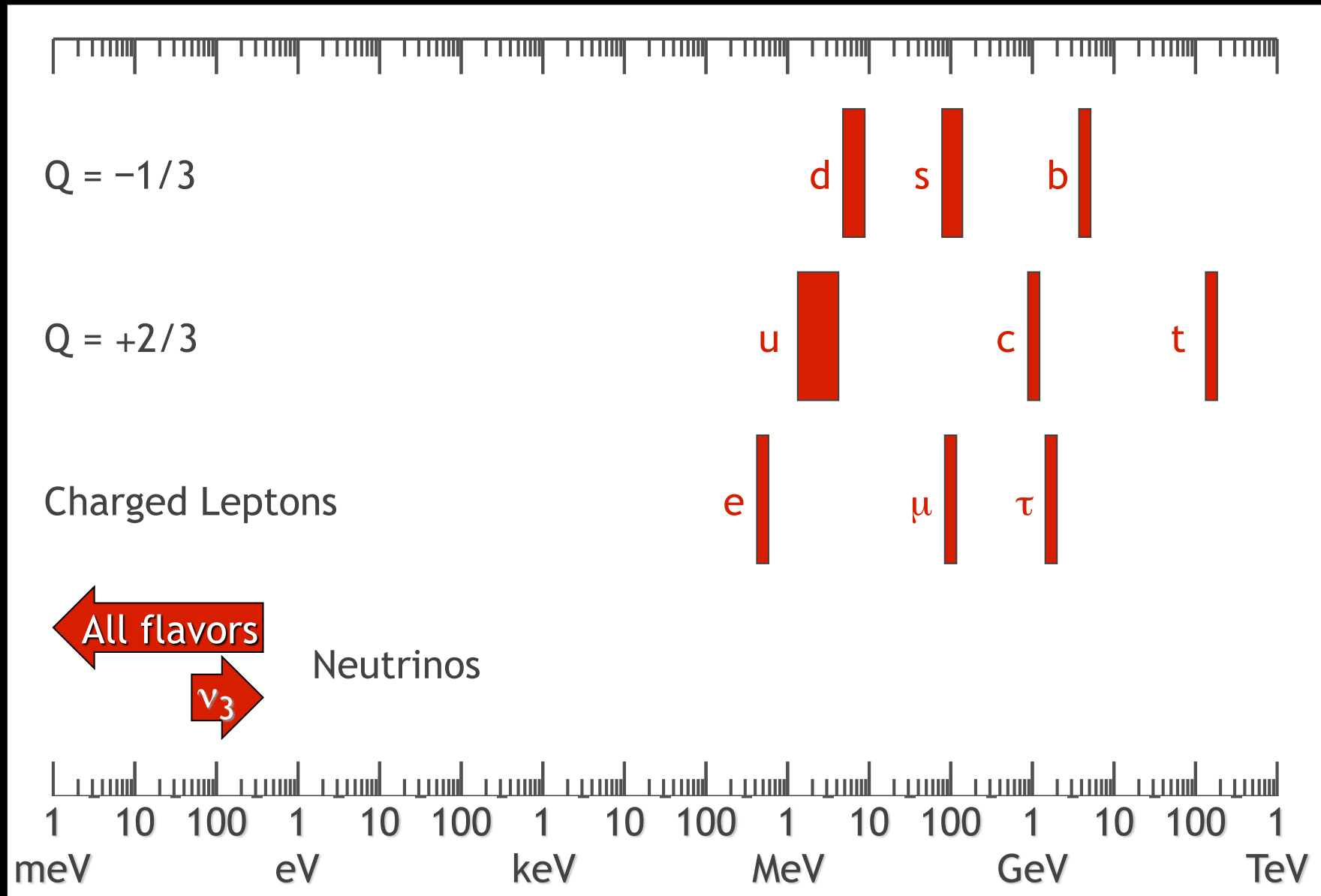


NEUTRINO PHYSICS FROM PRECISION COSMOLOGY



STEEN HANNESTAD, AARHUS UNIVERSITY
FUERTUVENTURA, 6 JUNE 2014

Fermion Mass Spectrum



NEUTRINO MIXING

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

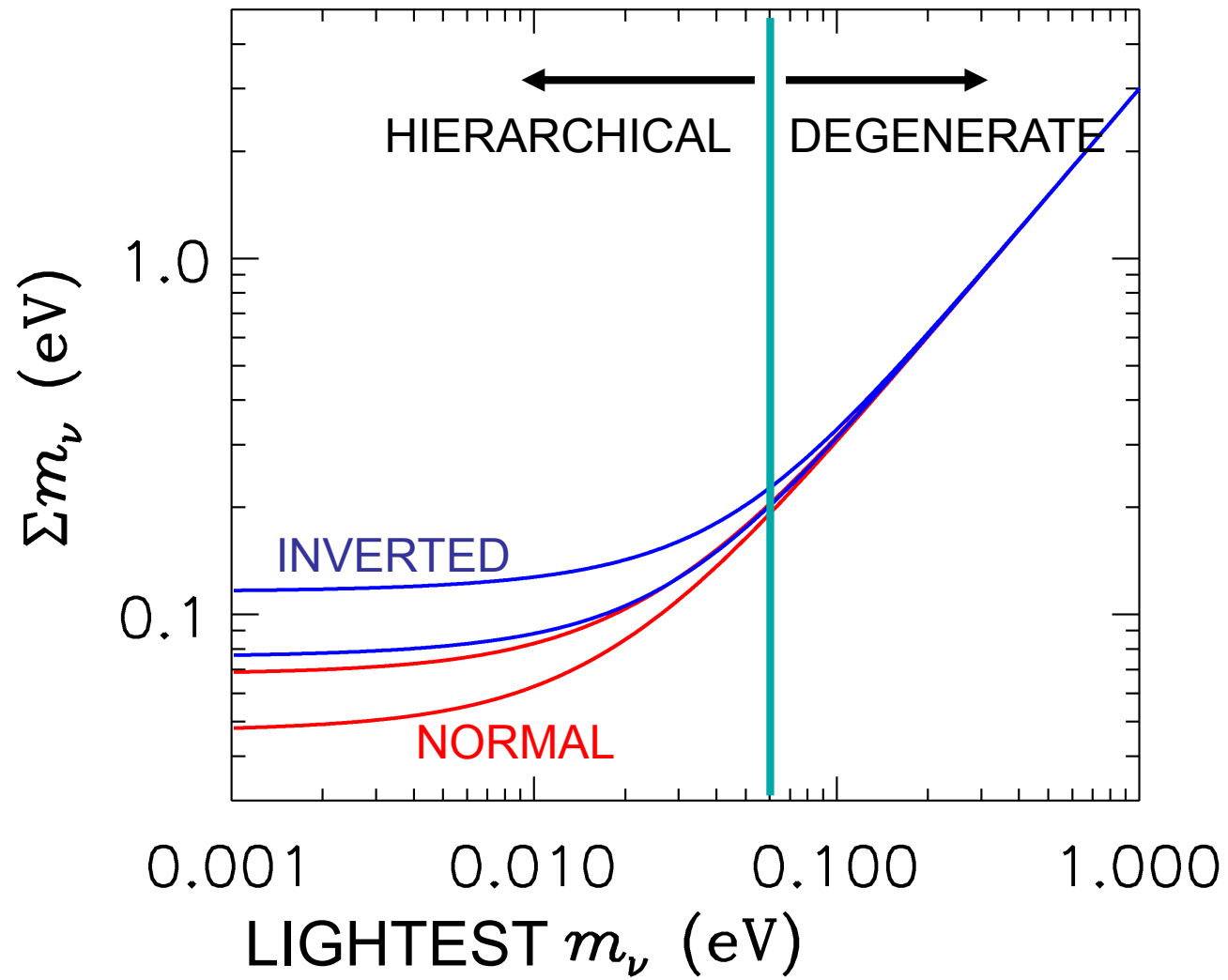
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1(m_1) \\ \nu_2(m_2) \\ \nu_3(m_3) \end{pmatrix}$$

PROPAGATION STATES

MIXING MATRIX (UNITARY)

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

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

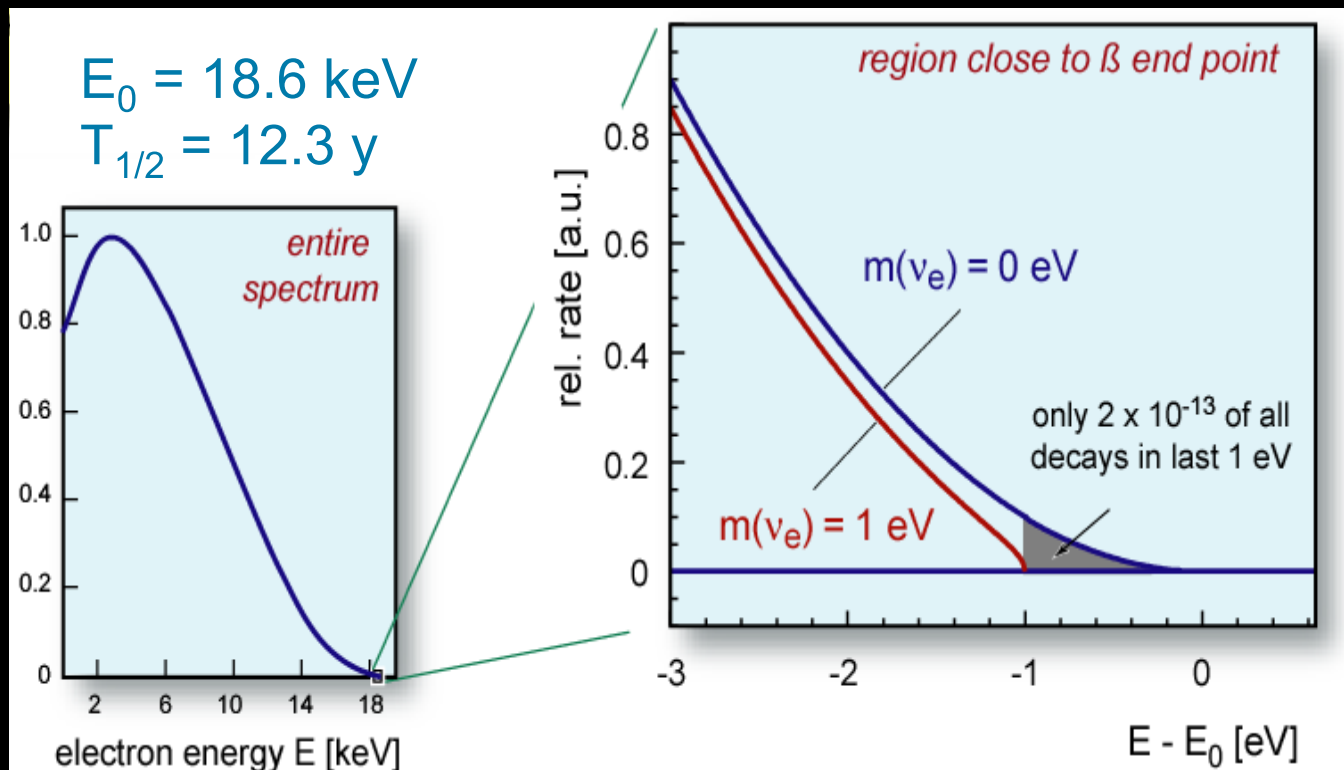


β -decay and neutrino mass

model independent neutrino mass from β -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 \downarrow observable is m_ν^2



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

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

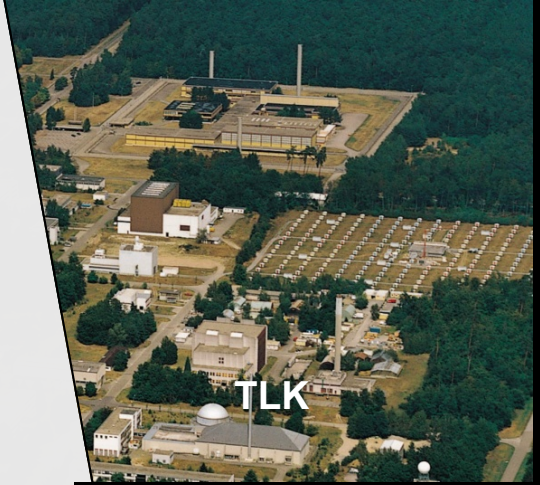
Mainz experiment, final analysis (Kraus et al.)

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

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

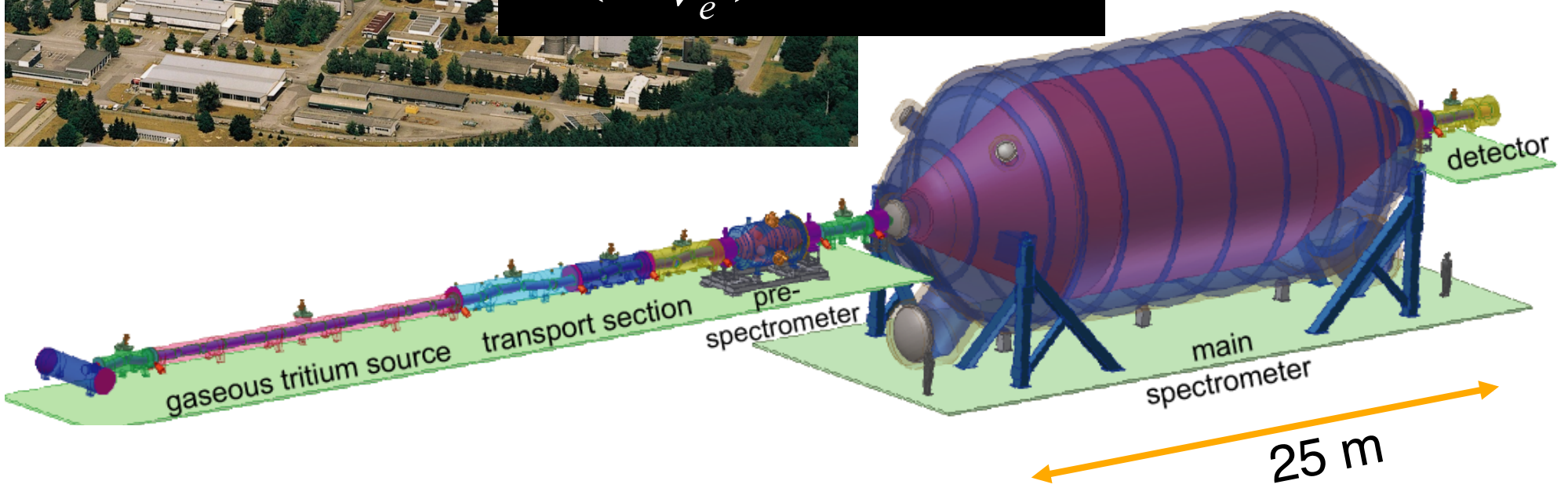


KATRIN experiment



Karlsruhe Tritium Neutrino Experiment

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





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
($n \sim 100 \text{ cm}^{-3}$)

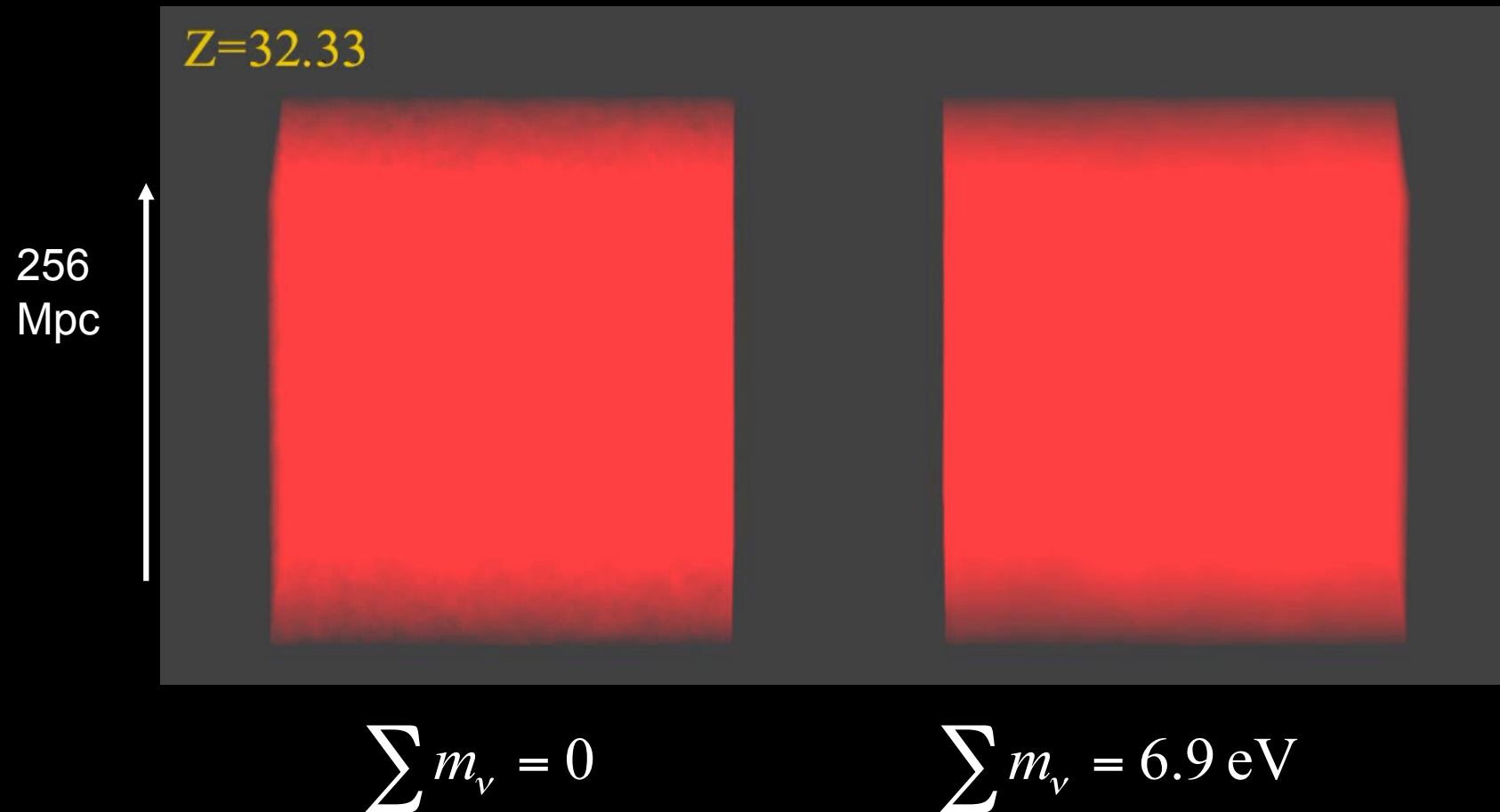
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93 \text{ eV}} \quad \text{FROM} \quad T_\nu = T_\gamma \left(\frac{4}{11} \right)^{1/3} \approx 2 \text{ K}$$

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

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

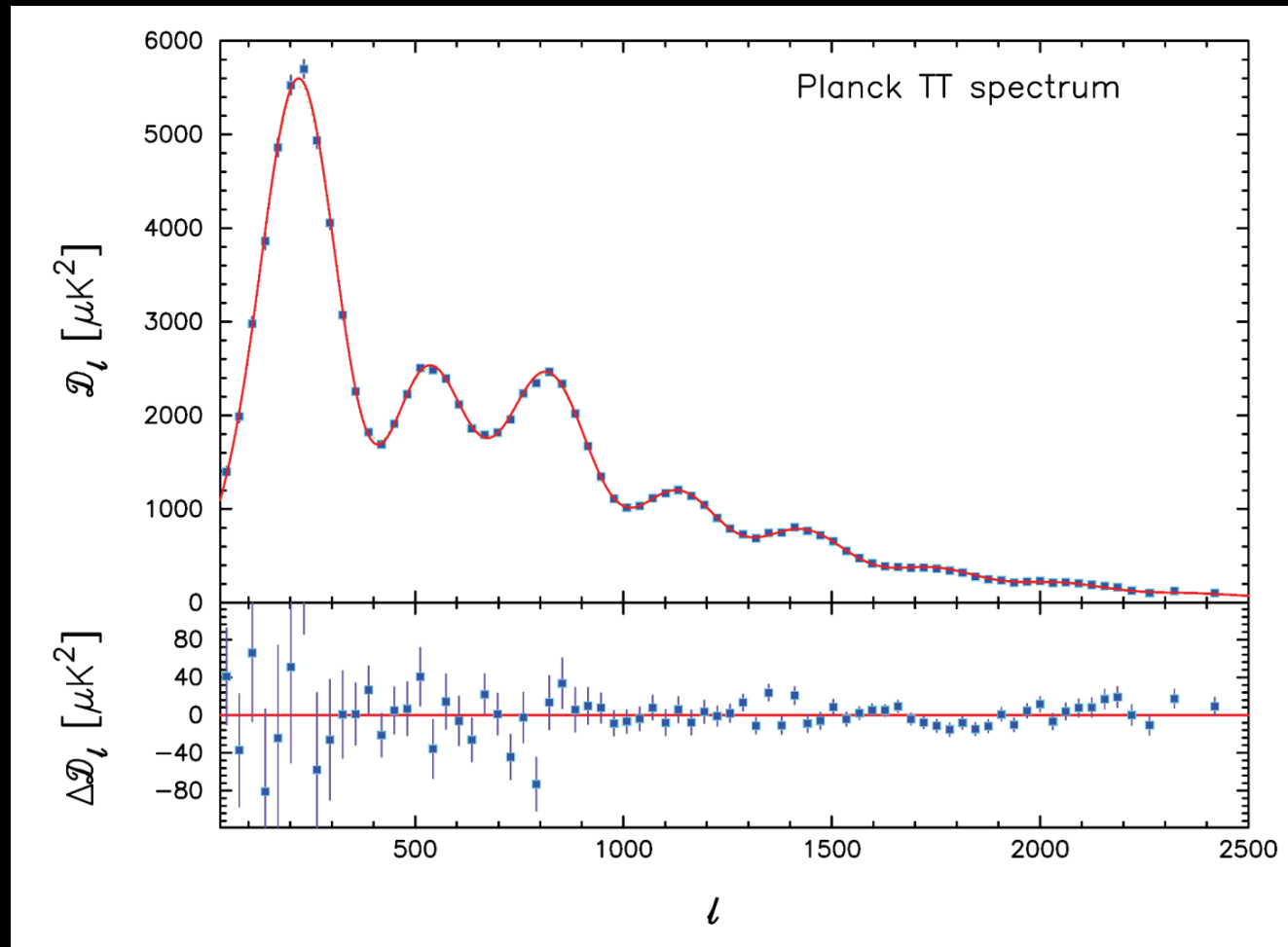
SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO
SUPPRESSION OF POWER ON SMALL SCALES

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



AVAILABLE COSMOLOGICAL DATA

PLANCK TEMPERATURE POWER SPECTRUM

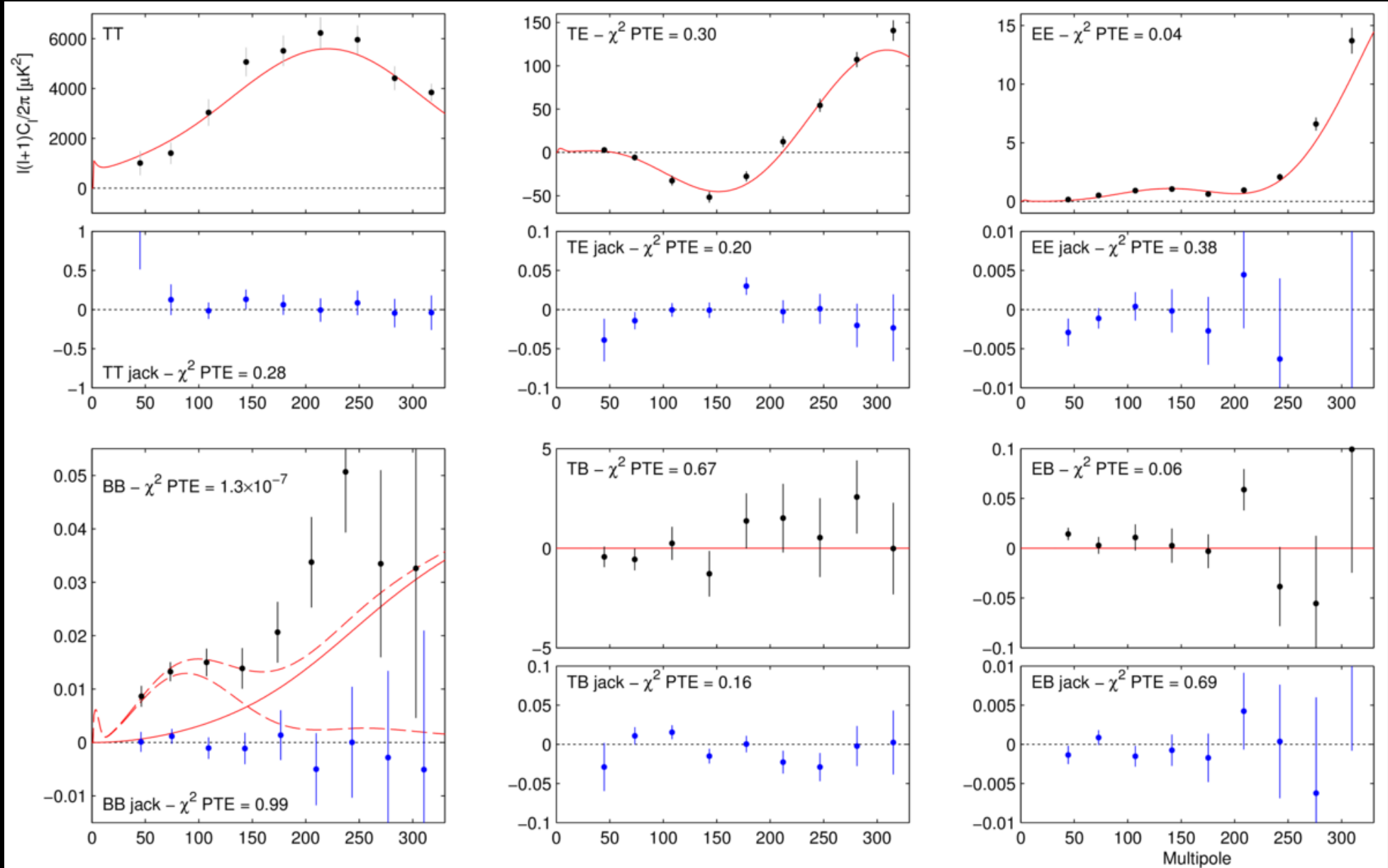


ADE ET AL, ARXIV 1303.5076

ADDITIONAL DATA FROM
ATACAMA COSMOLOGY TELESCOPE , SOUTH POLE TELESCOPE,

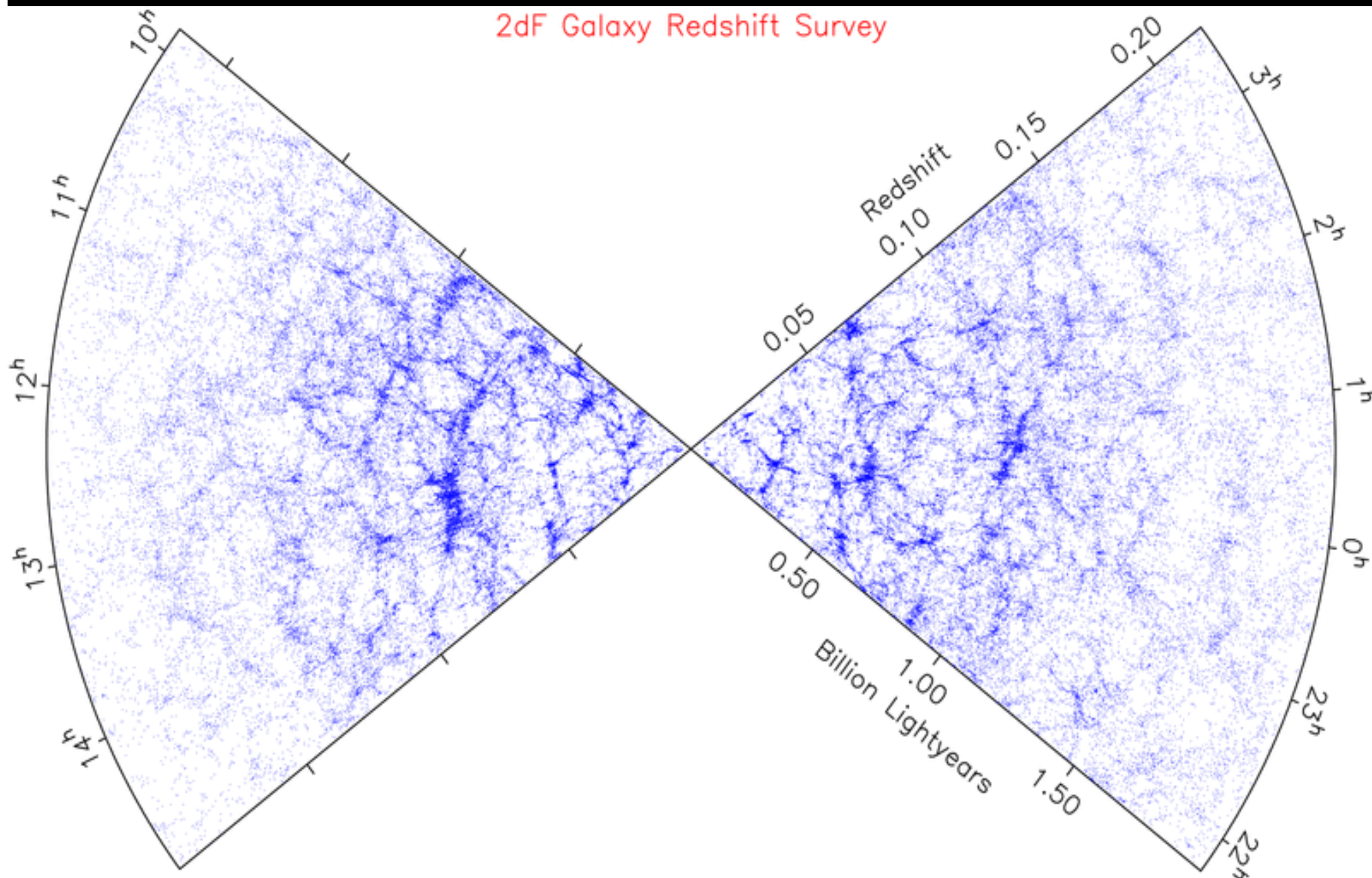
.....

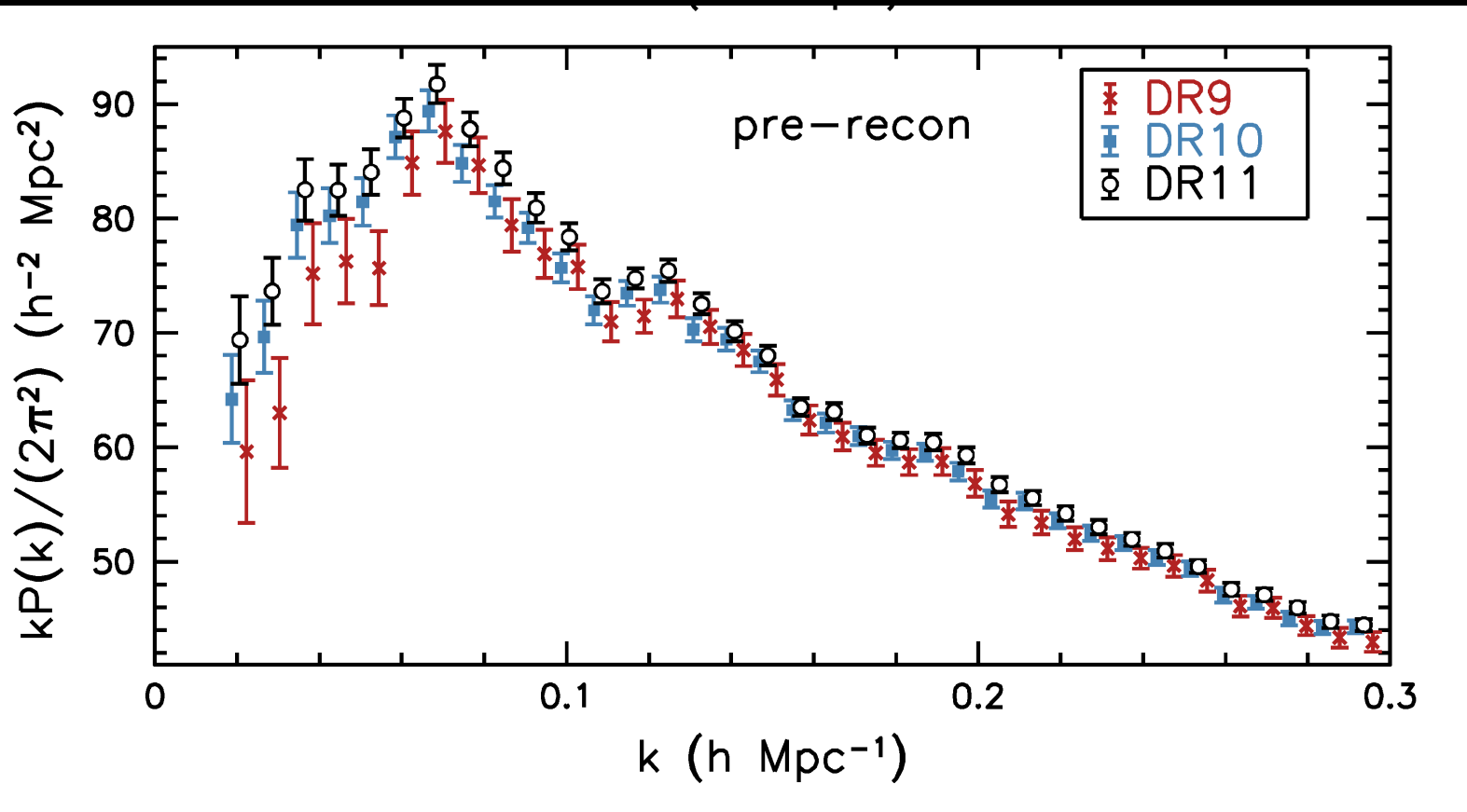
...AND OF COURSE THE B-MODE DETECTION FROM BICEP2



LARGE SCALE STRUCTURE SURVEYS

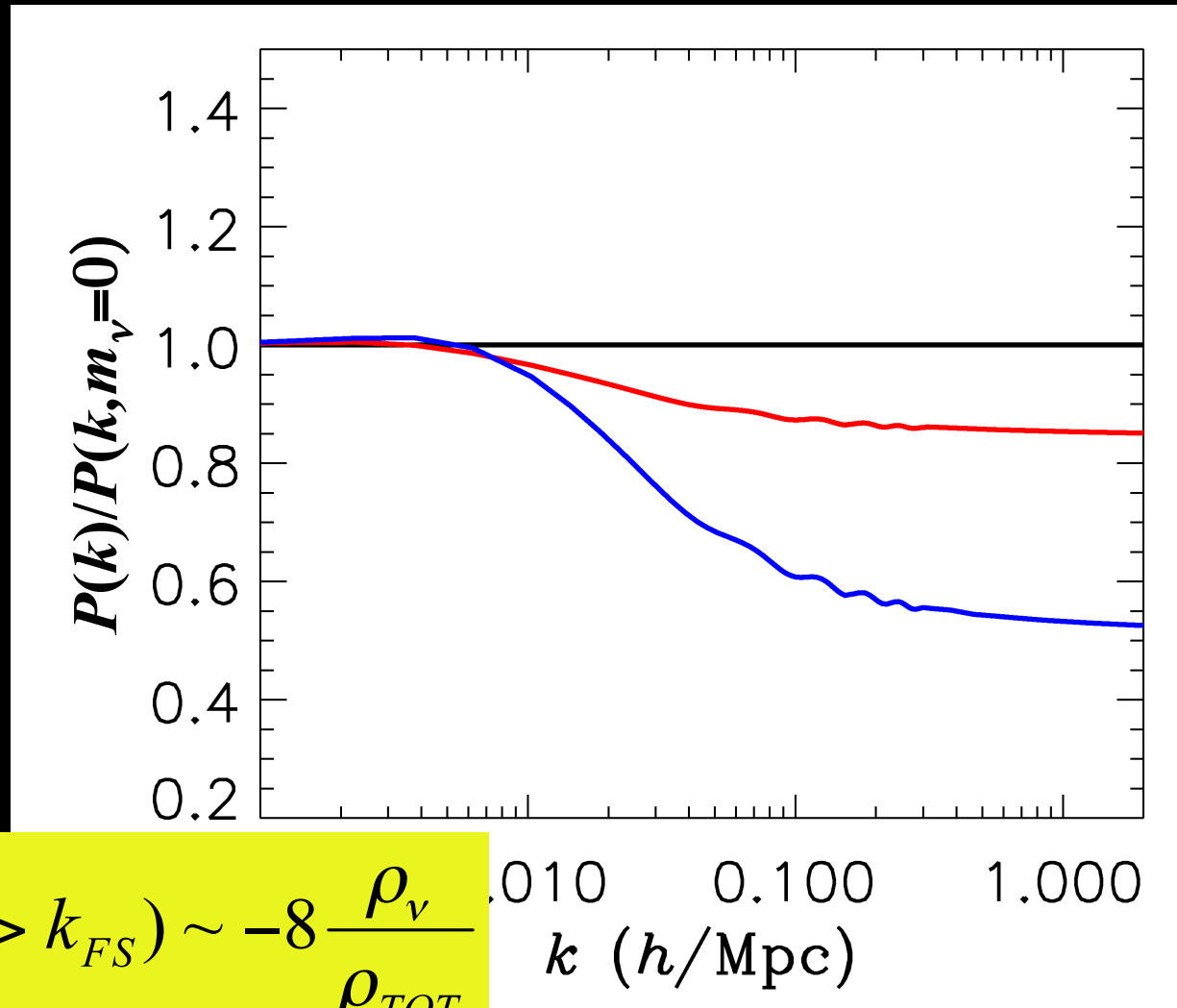
2dF Galaxy Redshift Survey





Anderson et al. 1312.4877 (SDSS) – Talk by A. Cuesta

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



$m_\nu = 0$ eV

$m_\nu = 0.3$ eV

$m_\nu = 1$ eV

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

NOW, WHAT ABOUT NEUTRINO
PHYSICS?

WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

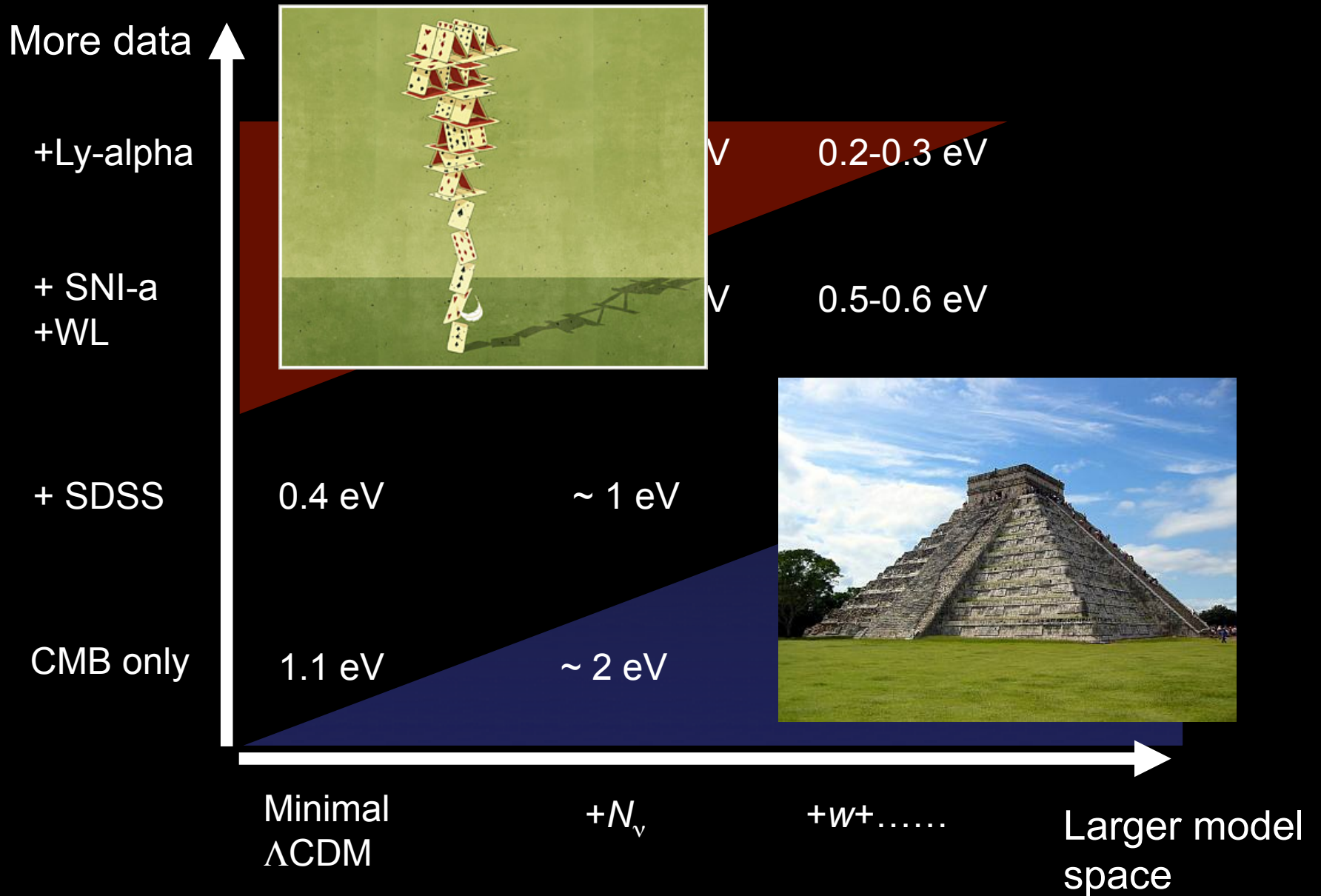
THERE ARE MANY ANALYSES IN THE LITERATURE

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

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

arXiv:1303.5076 (Planck)

THE NEUTRINO MASS FROM COSMOLOGY PLOT



GOING BEYOND THE MASS

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

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

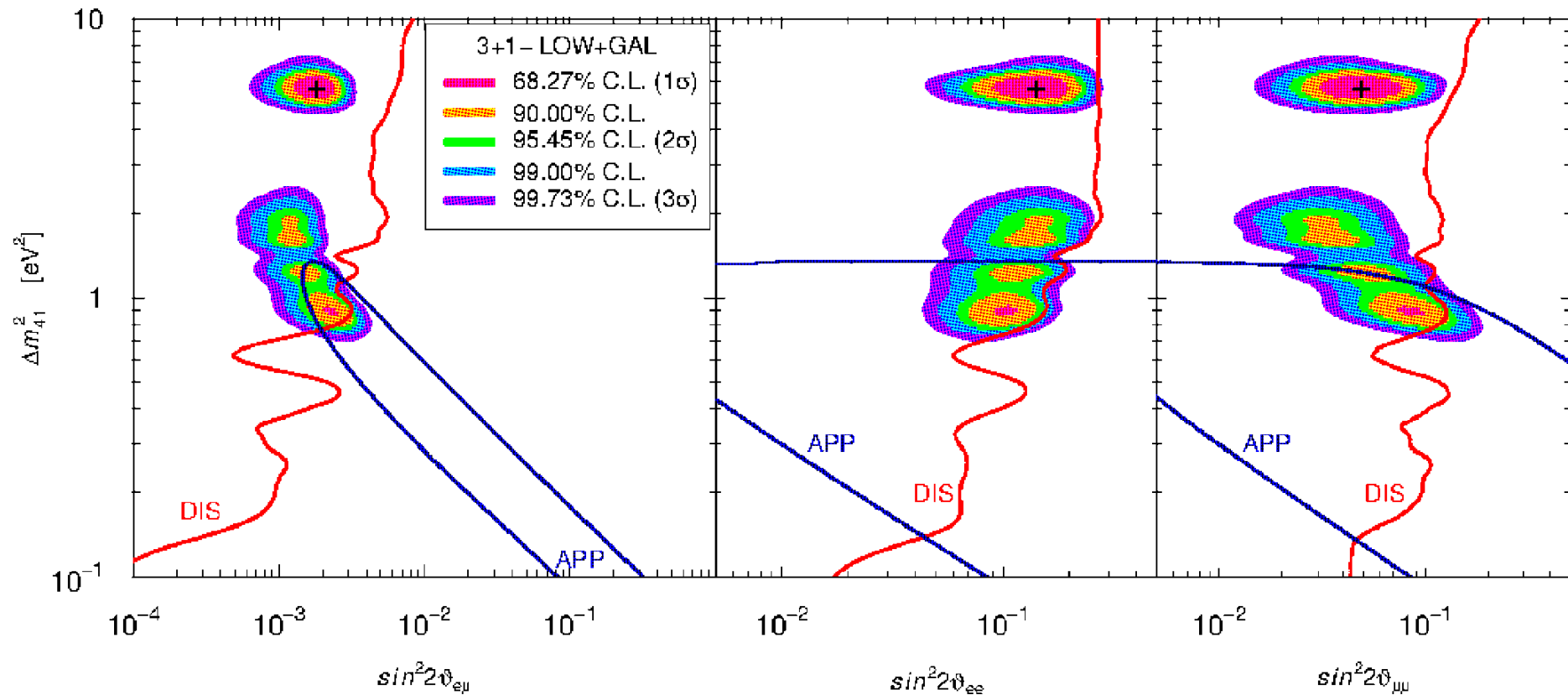
$$N_{eff} = \frac{\rho_{\nu,rel}}{\rho_{\nu 0}} \quad \rho_{\nu 0} = \frac{7}{8} \left(\frac{T_{\nu}}{T_{\gamma}} \right)^4 \rho_{\gamma}$$

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

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

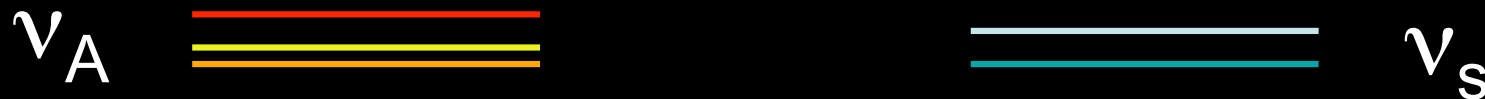
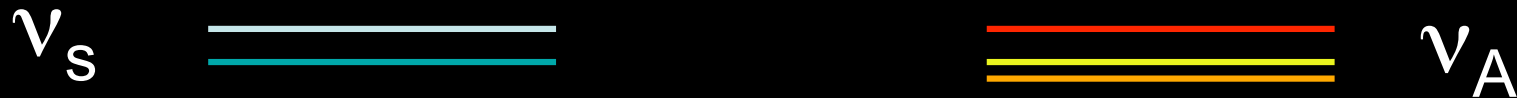
$$N_{eff} = 3.52_{-0.45}^{+0.48} @ 95\% \quad \text{Planck+BAO+}H_0$$

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

ASSUMING A NUMBER OF ADDITIONAL STERILE STATES OF APPROXIMATELY EQUAL MASS, TWO QUALITATIVELY DIFFERENT HIERARCHIES EMERGE. IN ANALOGY WITH THE STANDARD MODEL NEUTRINO HIERARCHY WE CAN CALL THEM NORMAL AND INVERTED HIERARCHY



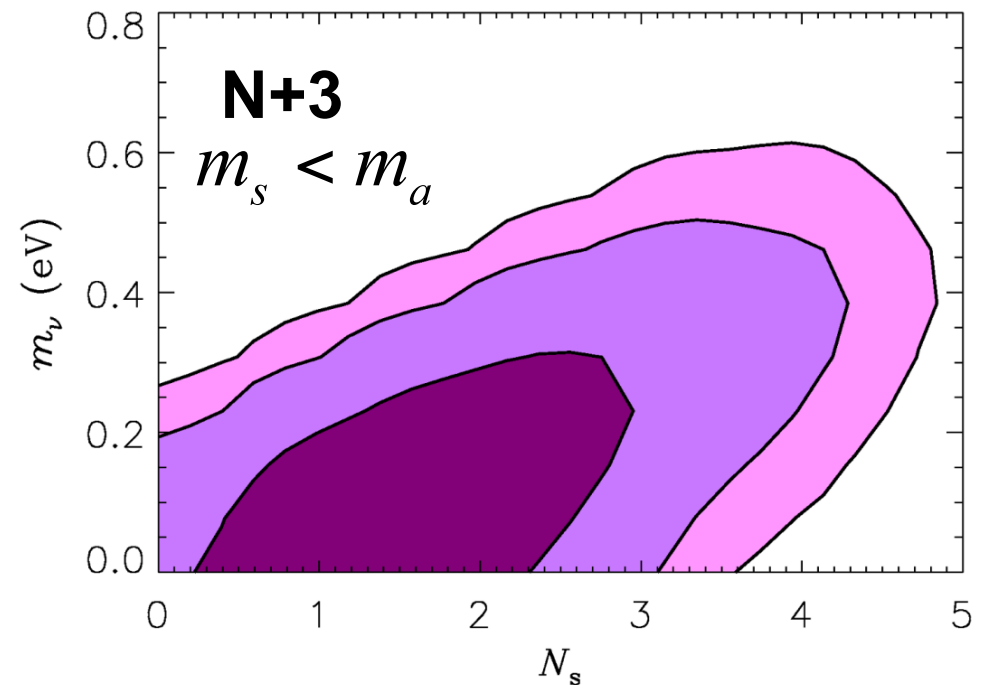
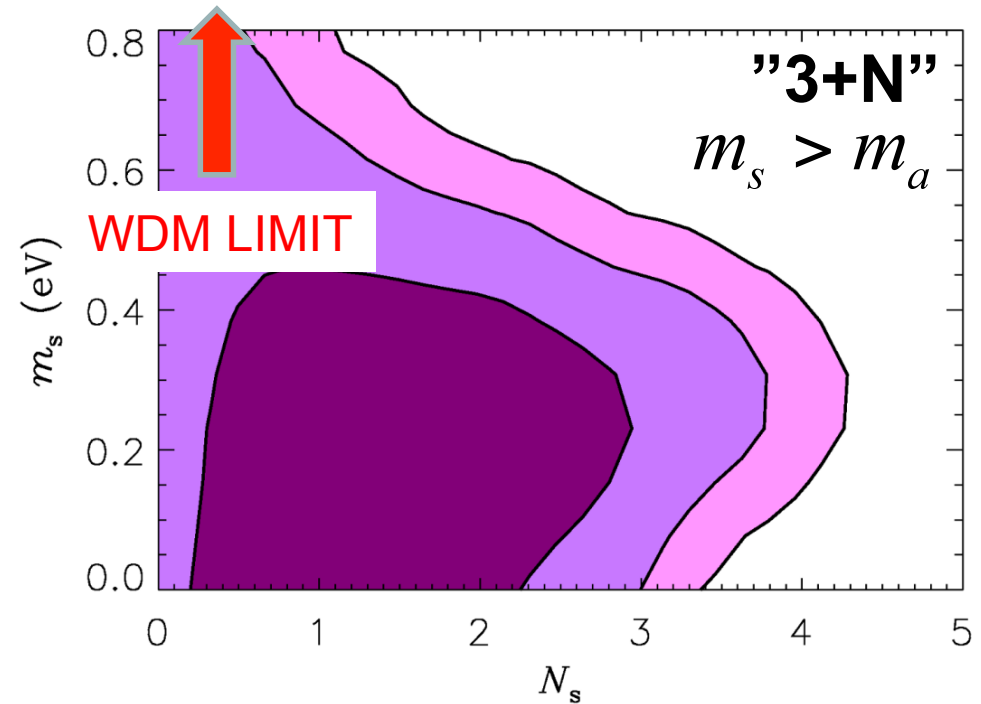
3+N (NORMAL)

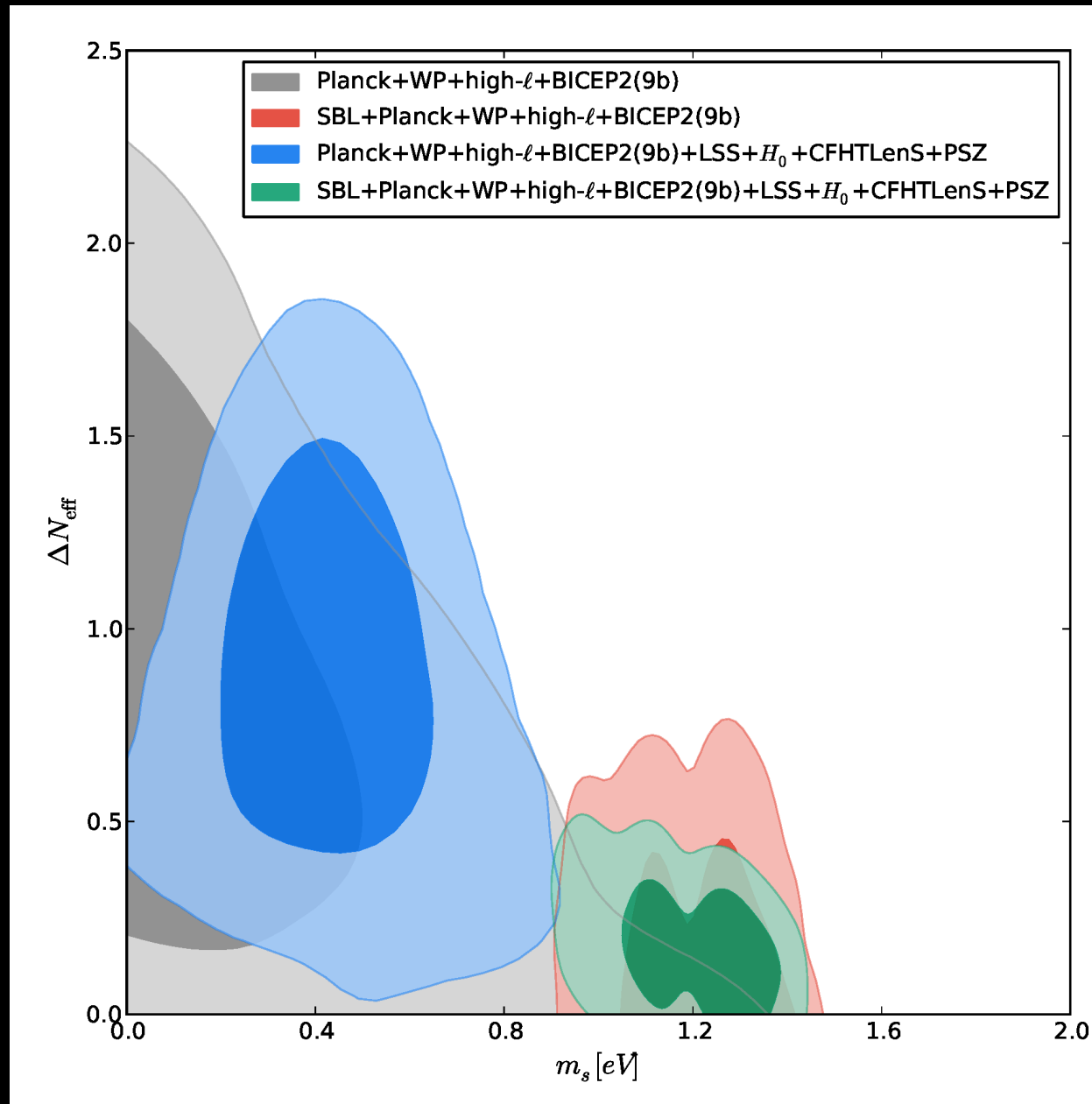
N+3 (INVERTED)

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

$$N_s = \frac{\rho_s}{\rho_{\nu,0}} = N_{eff} - 3$$

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

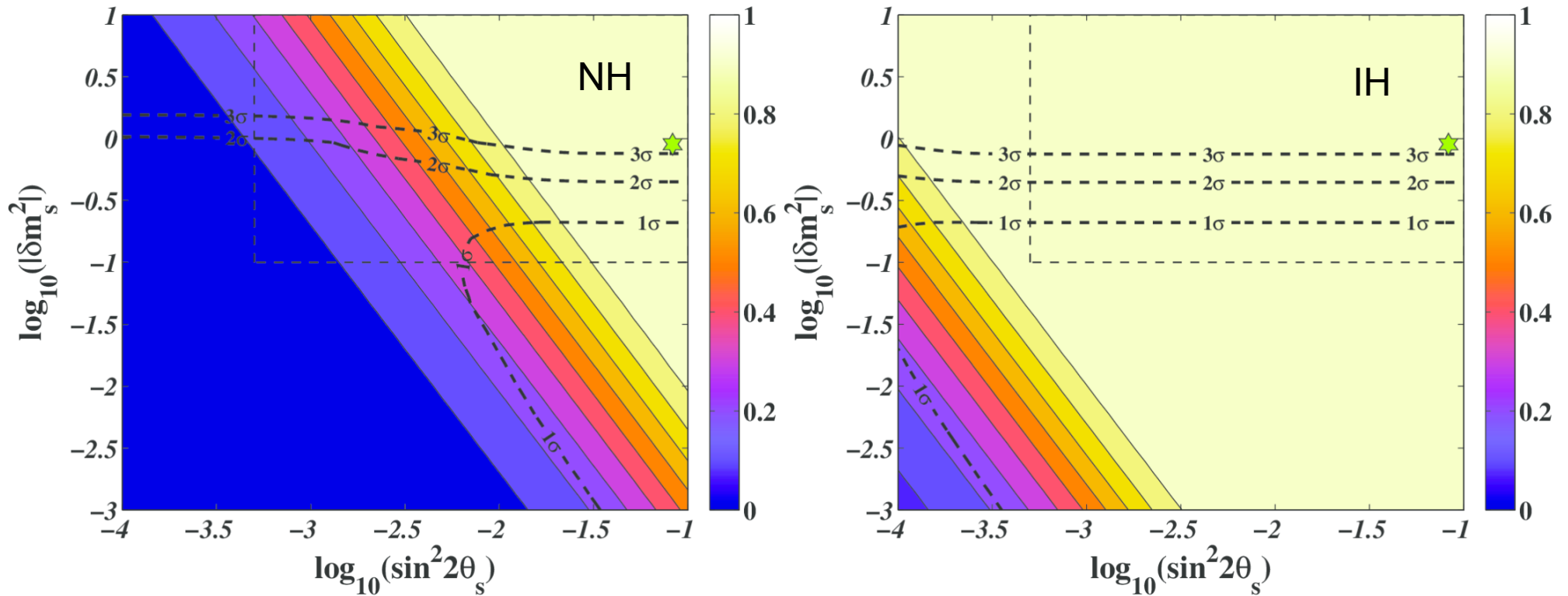




Archidiacono, Fornengo, Gariazzo, Giunti, STH, Laveder, arXiv:1404.1794

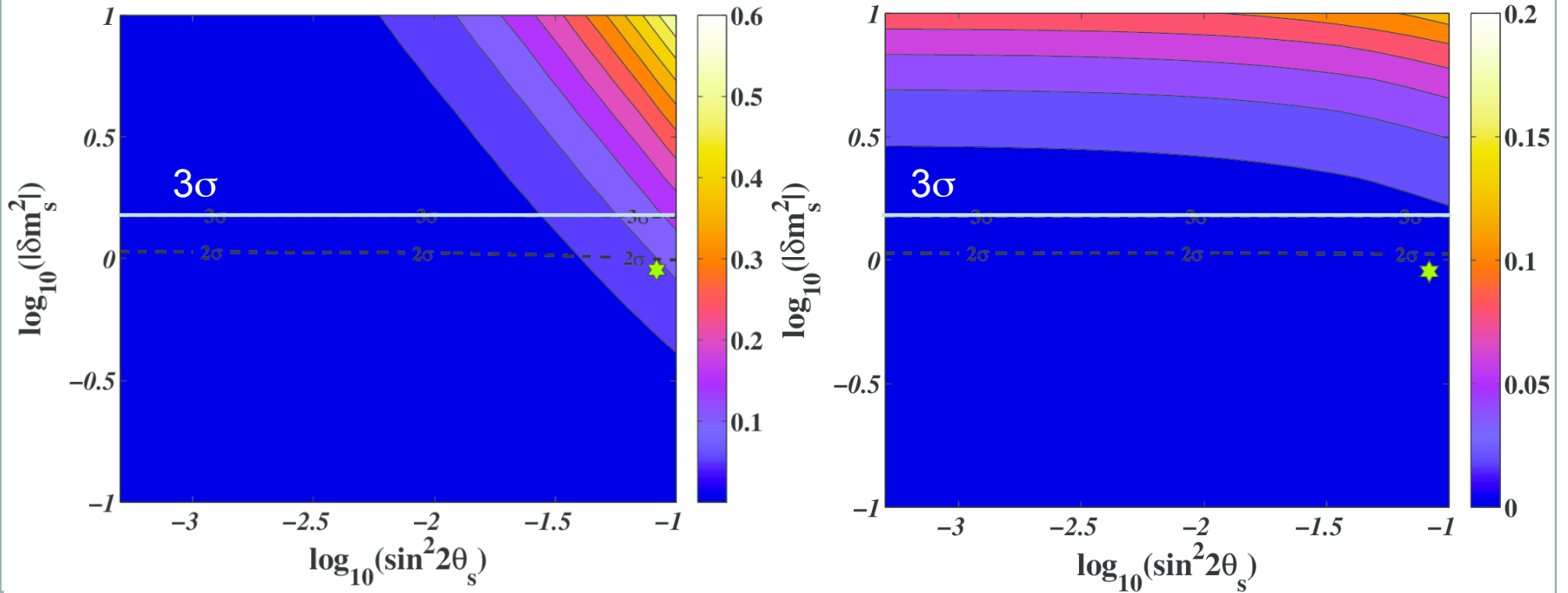
Bottom line: Sterile neutrinos in the mass range preferred by SBL data can be accommodated by cosmology, but **ONLY** if they are not fully thermalised

STERILE NEUTRINO THERMALISATION WITH ZERO LEPTON ASYMMETRY



STH, Tamborra, Tram 2012 (arXiv:1204.5861)

STERILE NEUTRINO THERMALISATION WITH LARGE LEPTON ASYMMETRY



STH, Tamborra, Tram 2012 (arXiv:1204.5861)
(see also Saviano et al. arXiv:1302.1200)

The presence of a significant asymmetry can block the production of steriles and make them compatible with cosmology.

However, from a model building perspective the generation of the asymmetry is difficult because it must be done at low energy

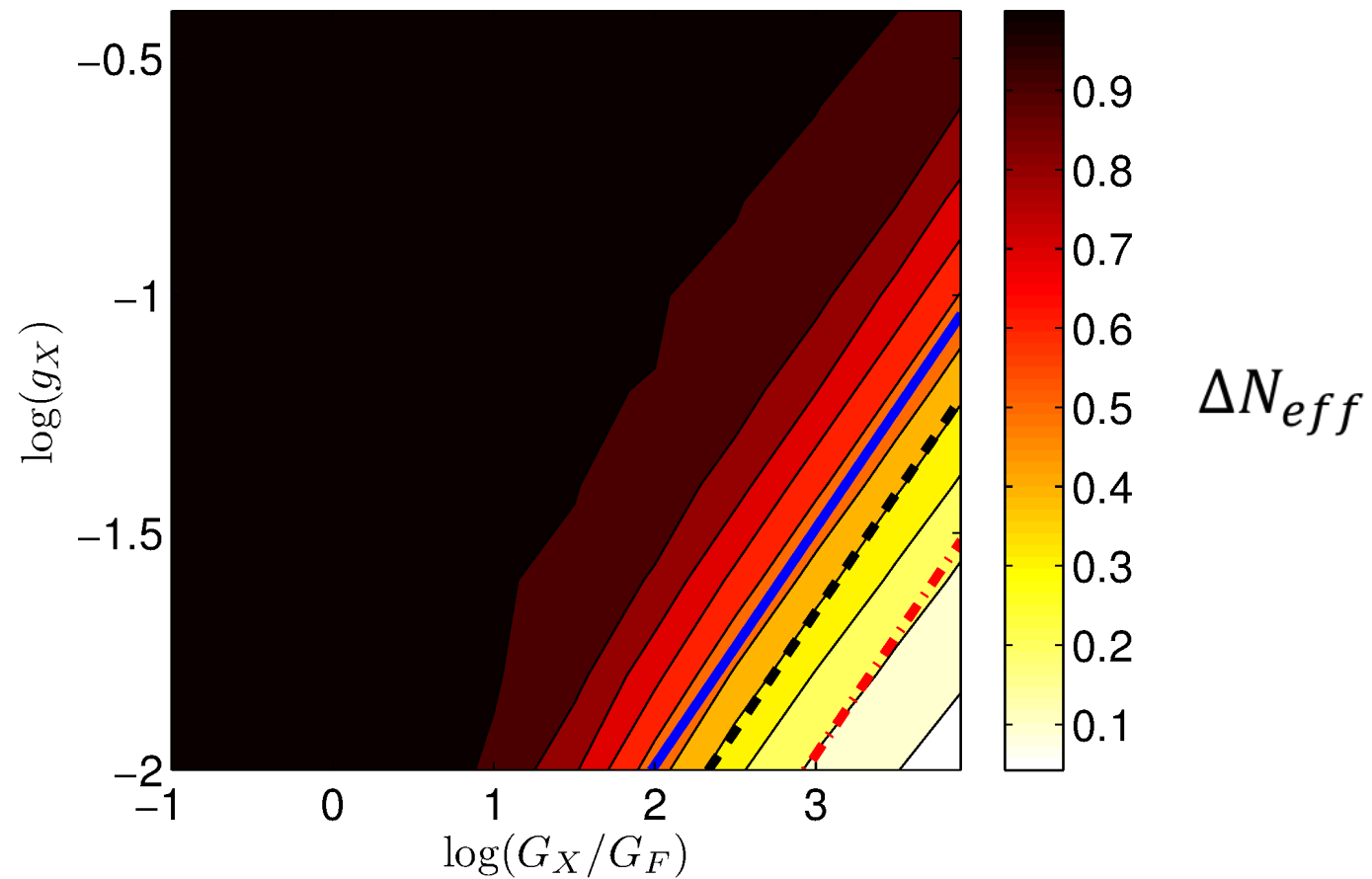
Could there be another way of modifying the matter potential?

YES! Non-standard interactions for either active or sterile neutrinos

Interactions must be relatively strong and for active neutrinos they might be excluded.

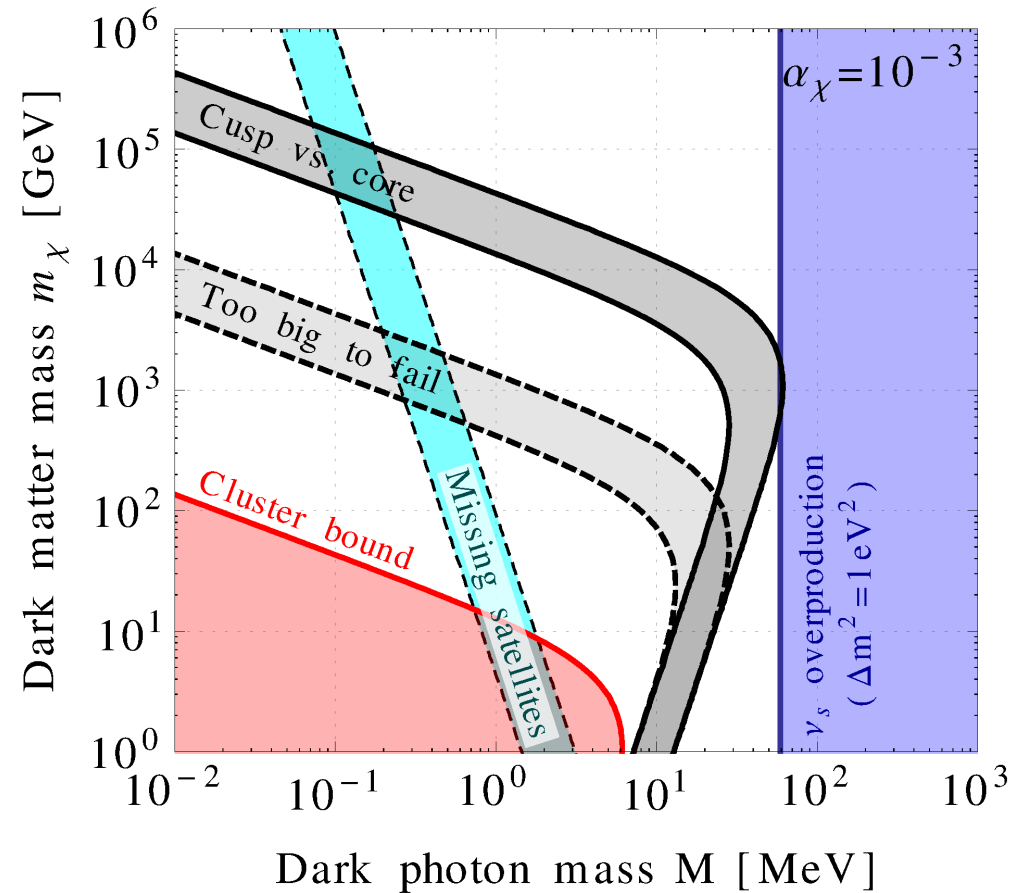
Sterile neutrino self-interactions are possible, and perhaps even natural.

It is possible that the sterile states couple to a new, hidden Fermi-like Interaction characterised by a coupling strength $G_X = g_X^2/m_X^2$



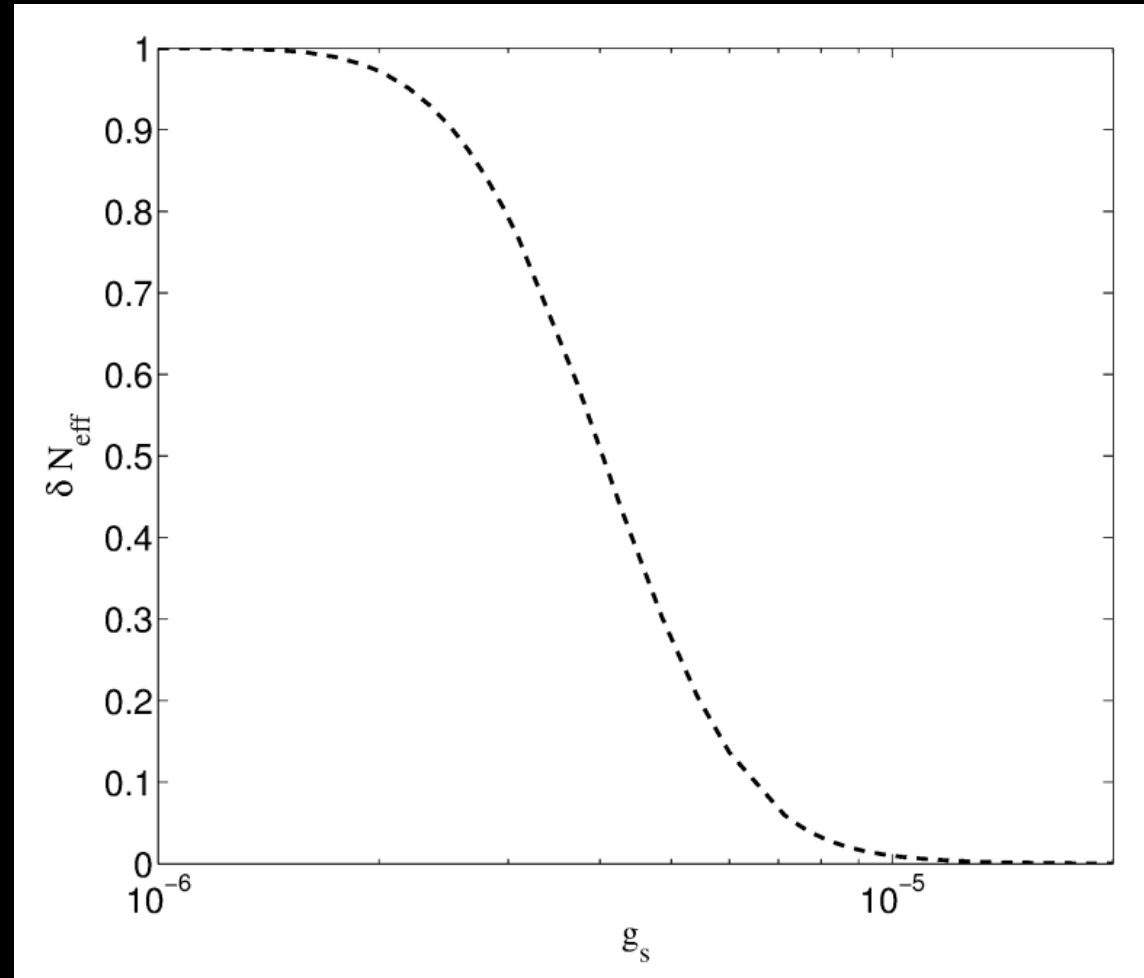
Hannestad, Hansen, Tram, 2013 (arXiv:1310.5926, PRL)

If dark matter couples to the new vector boson it causes self-interactions which have implications for structure formation

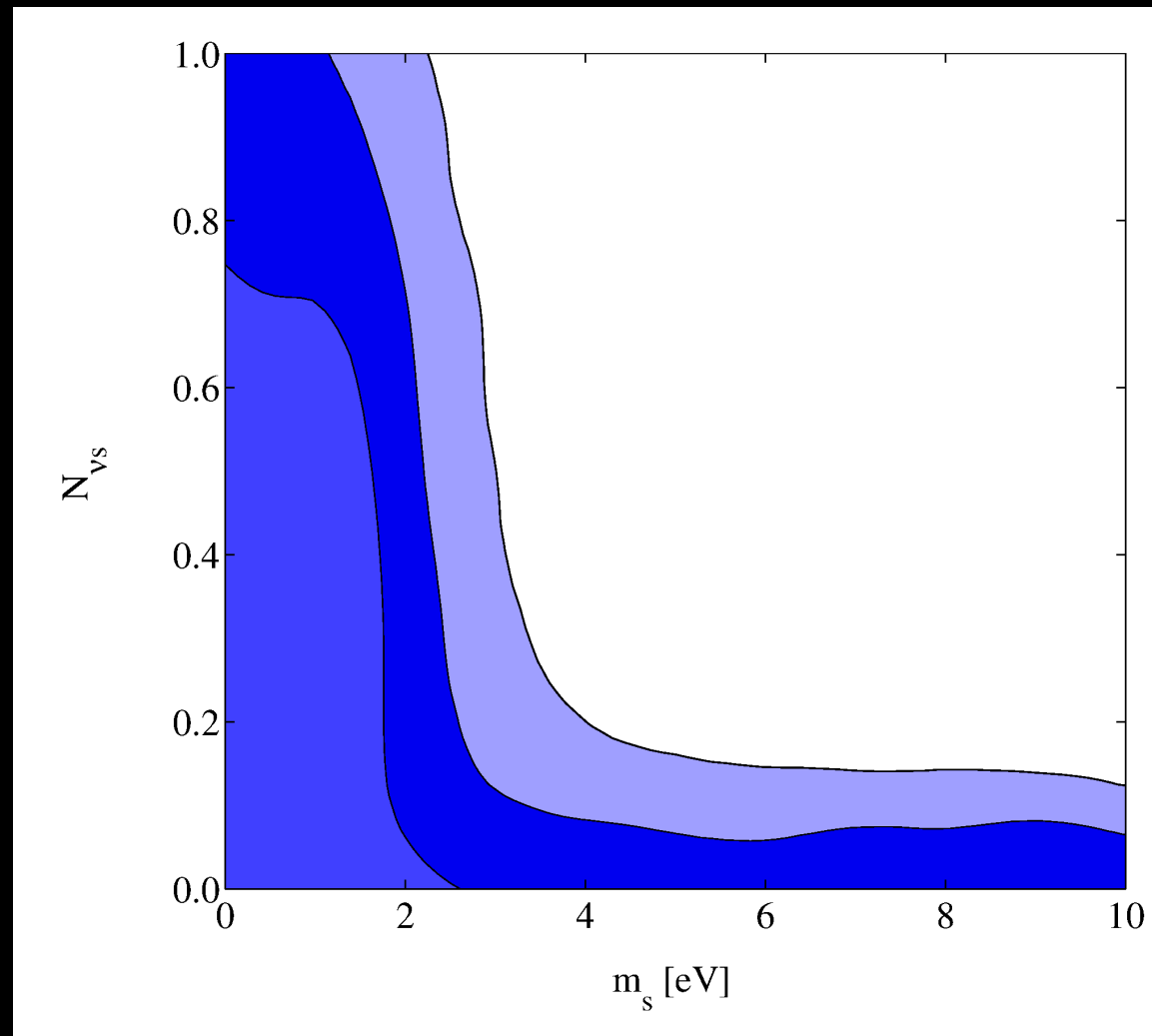


However, sterile neutrinos and dark matter might also couple to a light or massless pseudoscalar. In that case a background potential appears even in a CP-symmetric medium and suppressing oscillations requires only a very weak coupling.

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

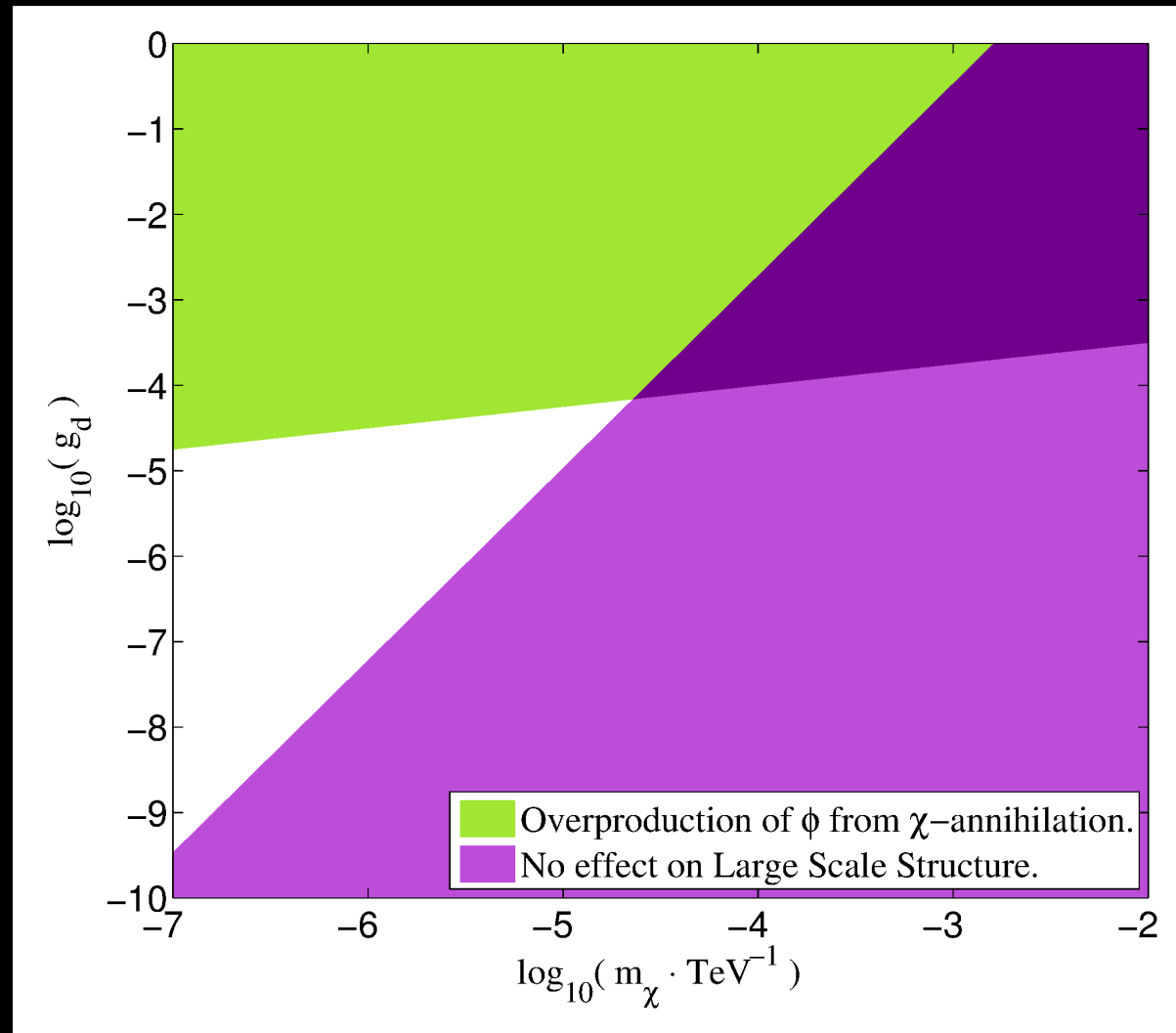


Neutrinos coupled to a massless mediator become strongly interacting at late times. This is excluded for the active neutrinos, but not for partially thermalised steriles!



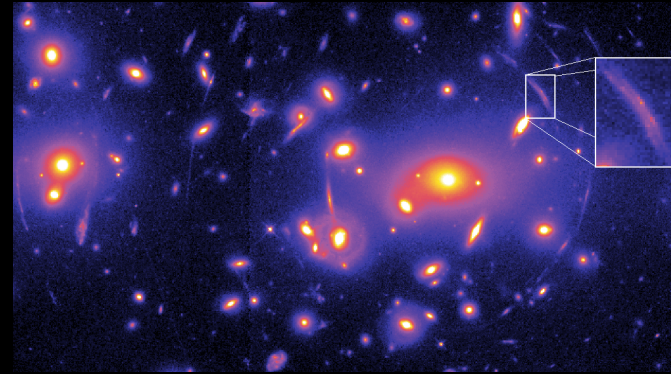
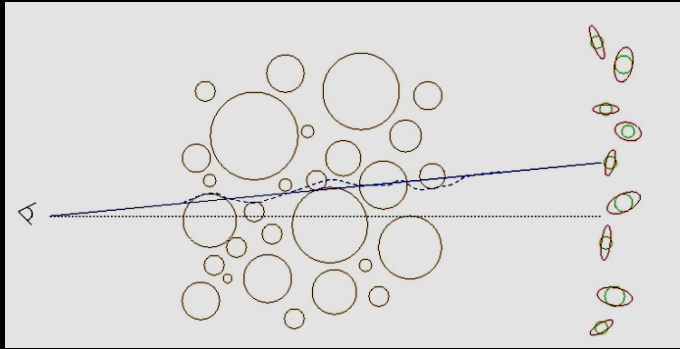
Archidiacono,
STH, Hansen, Tram
(arXiv:1404.5915)

A coupling with the same strength to dark matter can make dark matter sufficiently self-interacting to impact galactic dynamics.

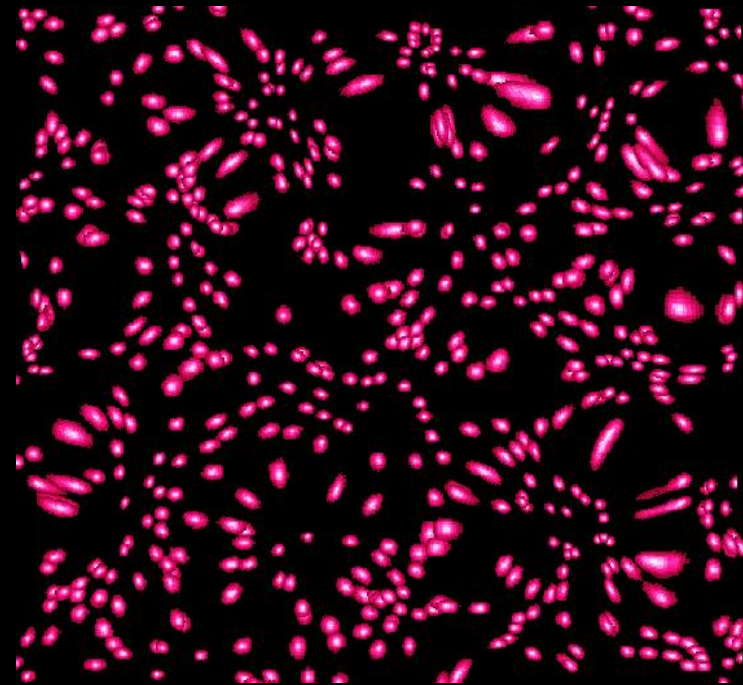
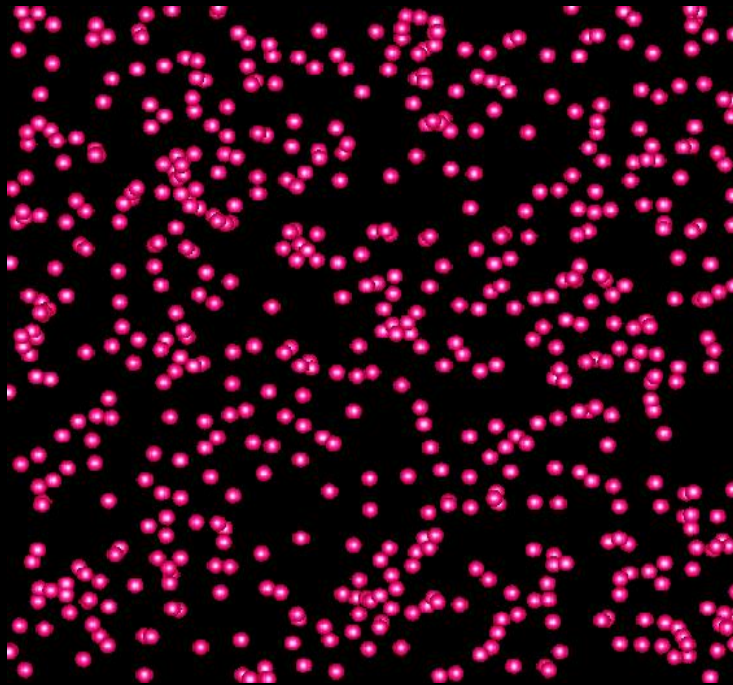


Archidiacono,
STH, Hansen, Tram
(arXiv:1404.5915)

WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE



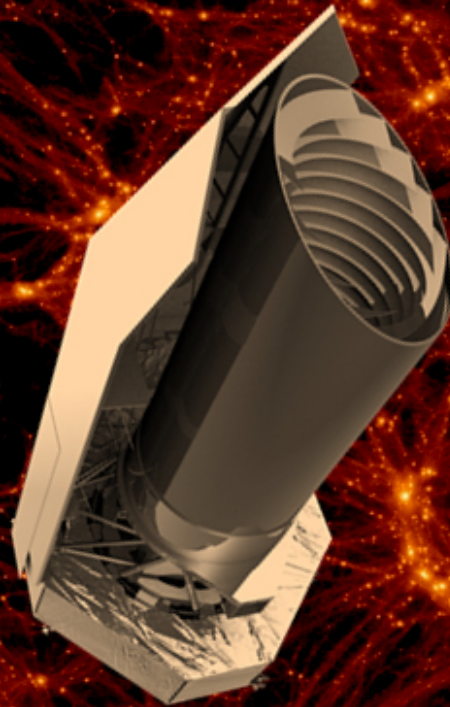
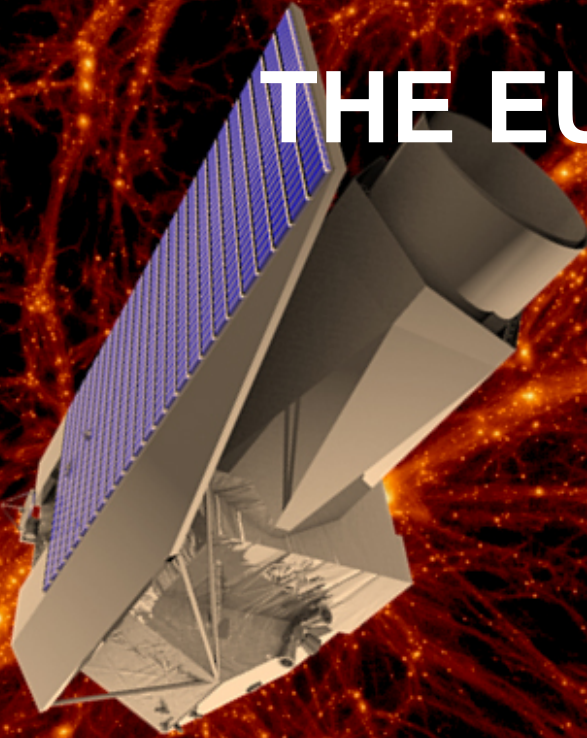
Distortion of background images by foreground matter



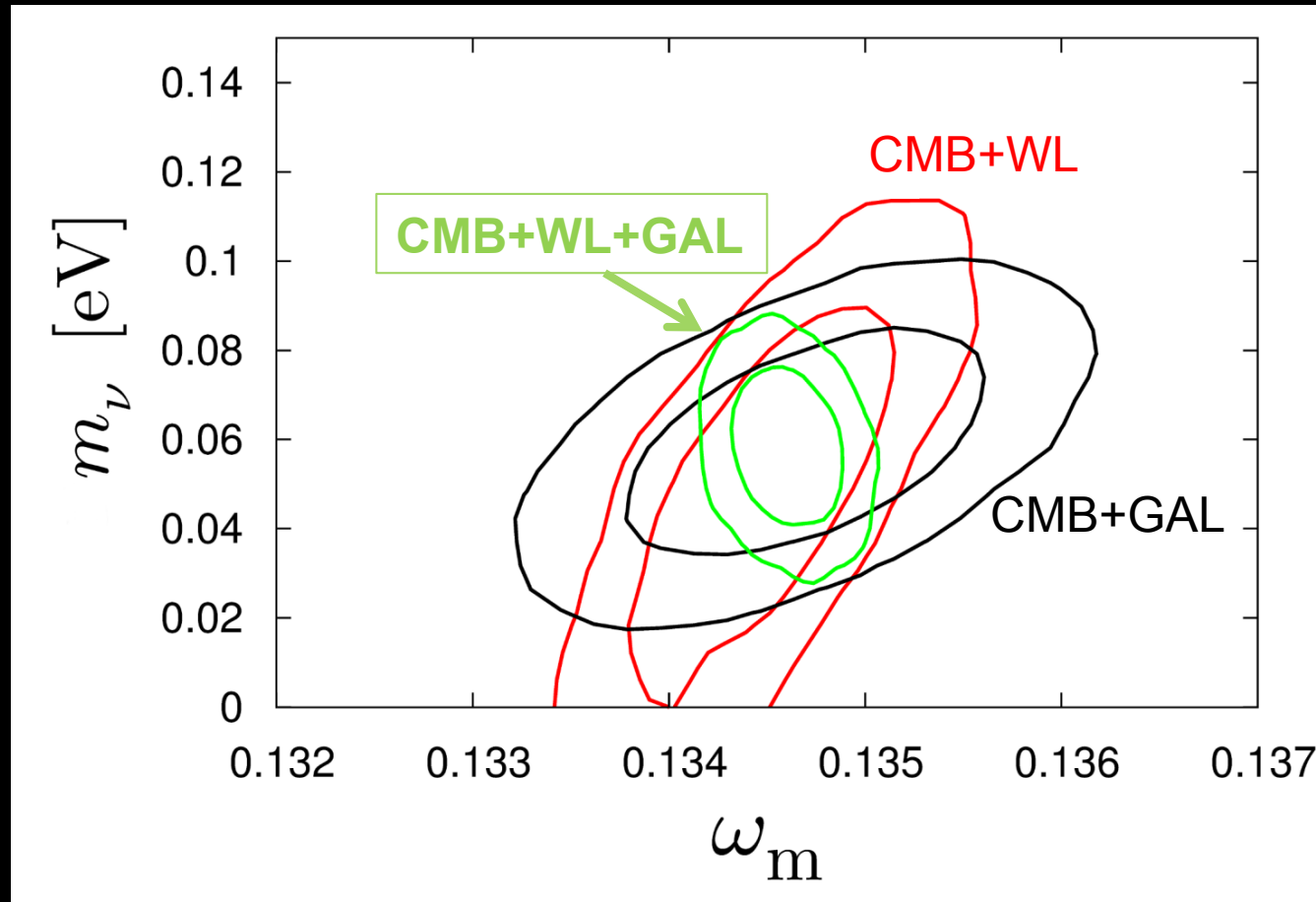
Unlensed

Lensed

THE EUCLID MISSION



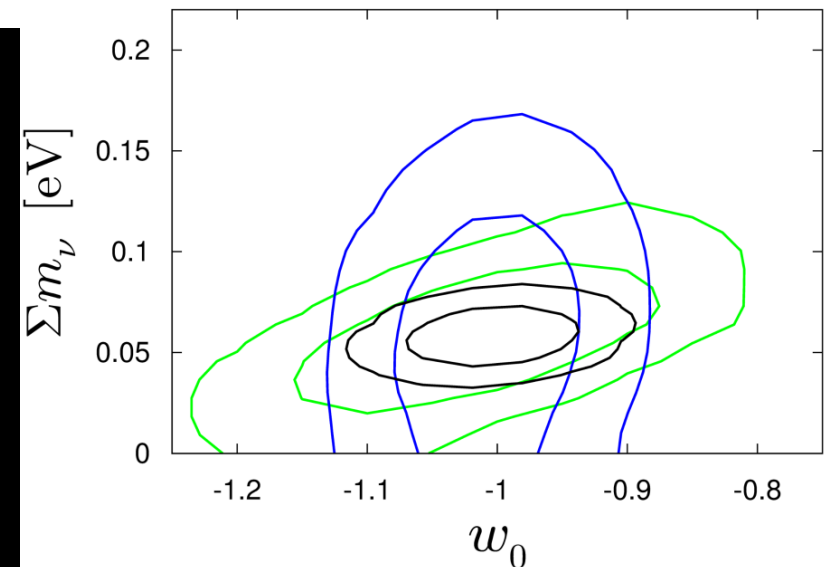
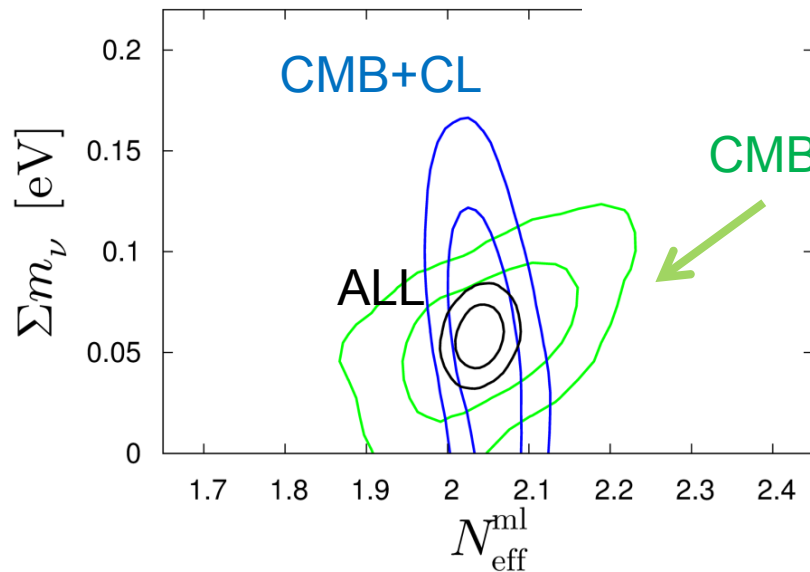
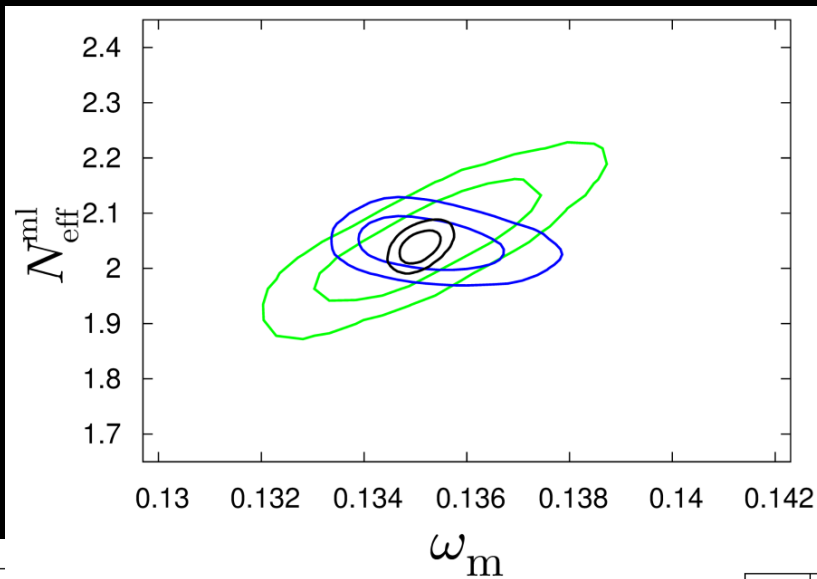
HAMANN, STH, WONG 2012: COMBINING THE EUCLID WL AND GALAXY SURVEYS WILL ALLOW FOR AT A 2.5-5 σ DETECTION OF THE NORMAL HIERARCHY (DEPENDING ON ASSUMPTIONS ABOUT BIAS)



arXiv:1209.1043 (JCAP)

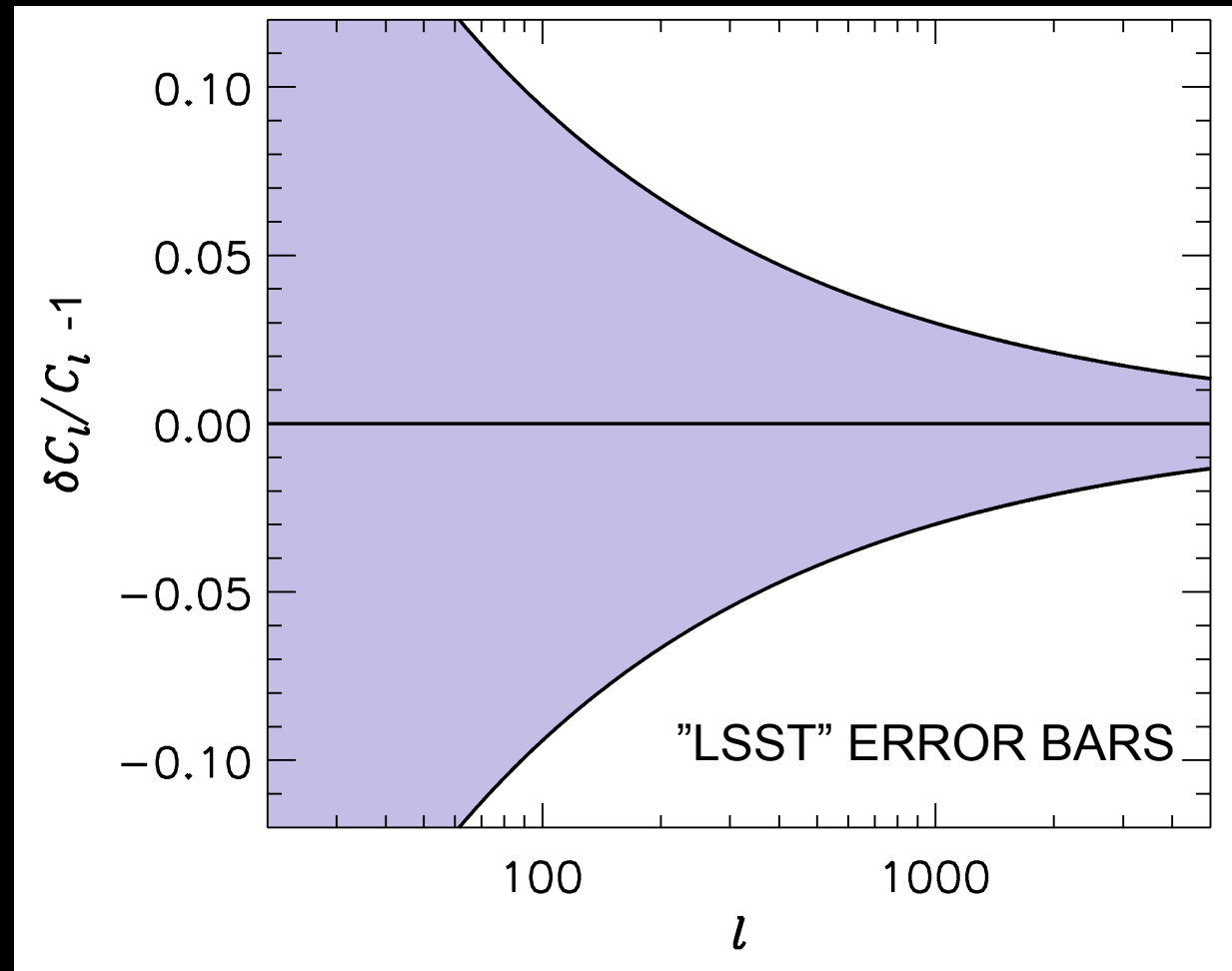
Basse, Bjælde, Hamann, STH, Wong 2013: Adding information on the cluster mass function will allow for a 5σ detection of non-zero neutrino mass, even in very complex cosmological models with time-varying dark energy

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 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

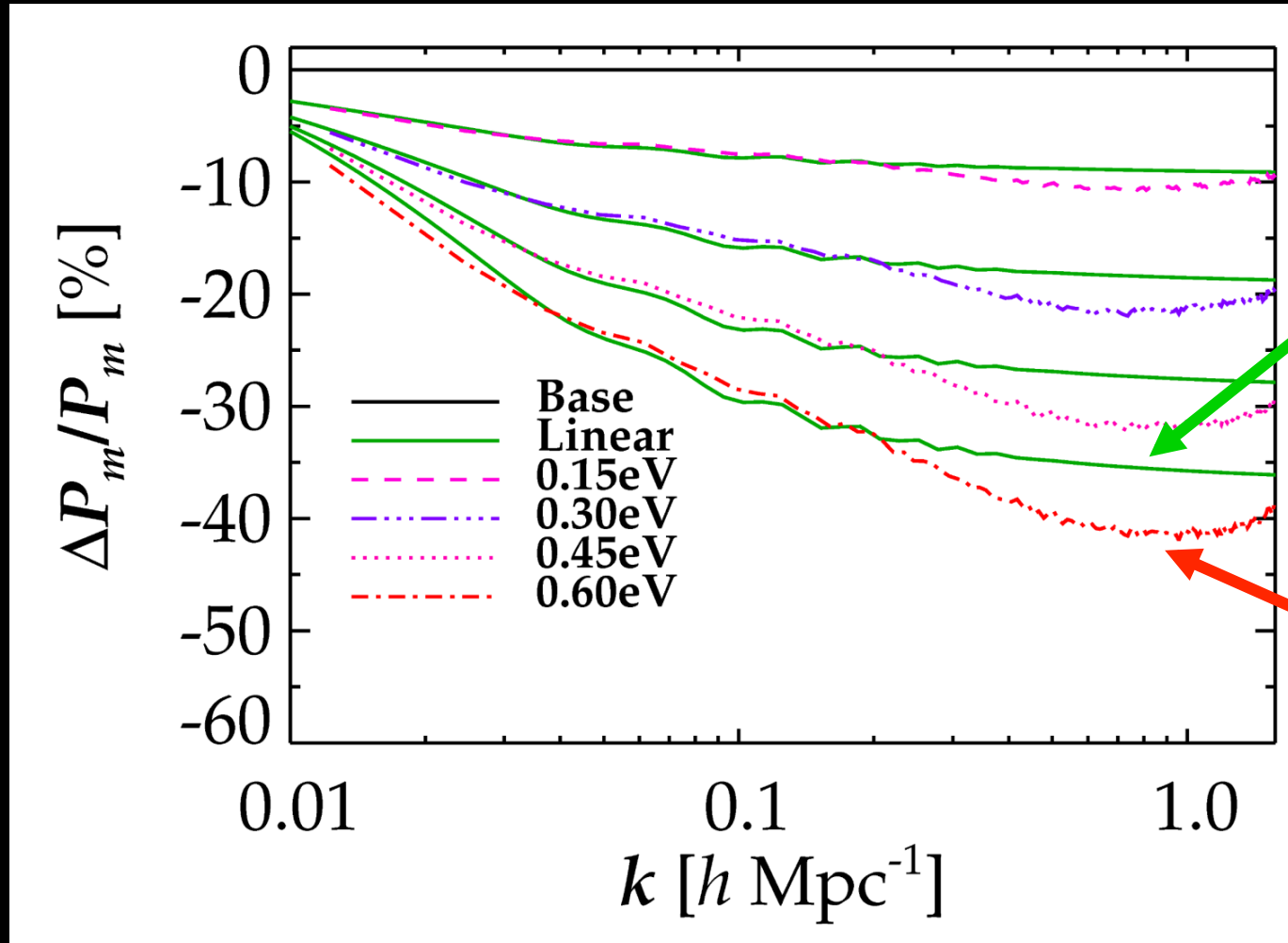
- BARYONIC PHYSICS - STAR FORMATION, SN FEEDBACK,.....

- 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

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

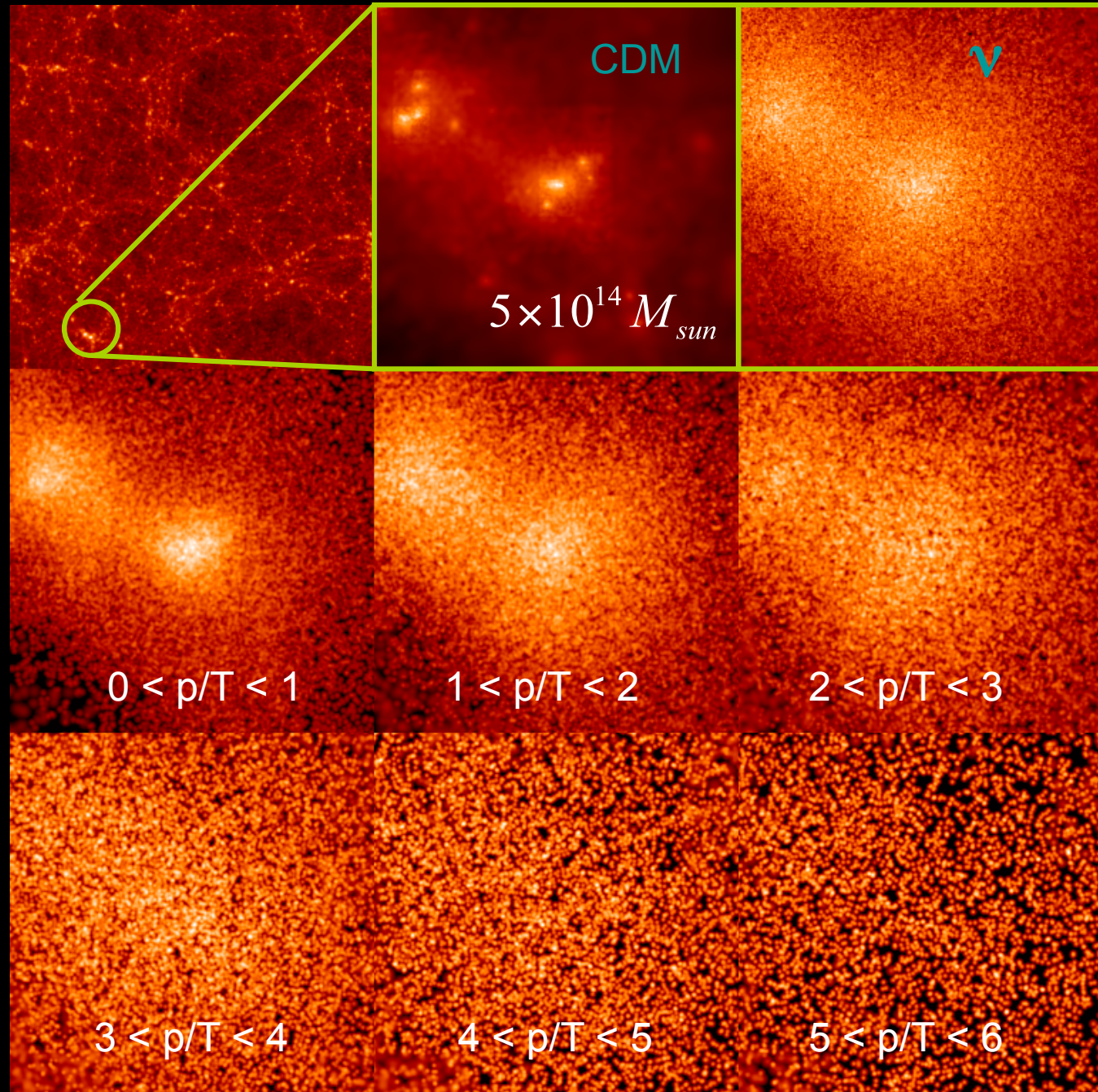
FULL NON-LINEAR

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

Brandbyge, STH, Haugbølle, Thomsen '08
 Brandbyge & STH '09, '10, Viel, Haehnelt, Springel '10
 STH, Haugbølle & Schultz '12, Wagner, Verde & Jimenez '12
 Villaescusa-Navarro et al. '13 (I-IV)

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