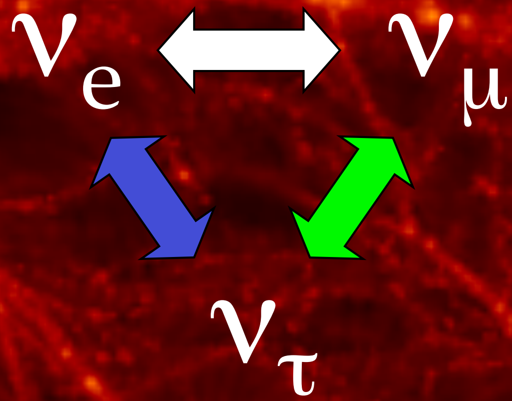
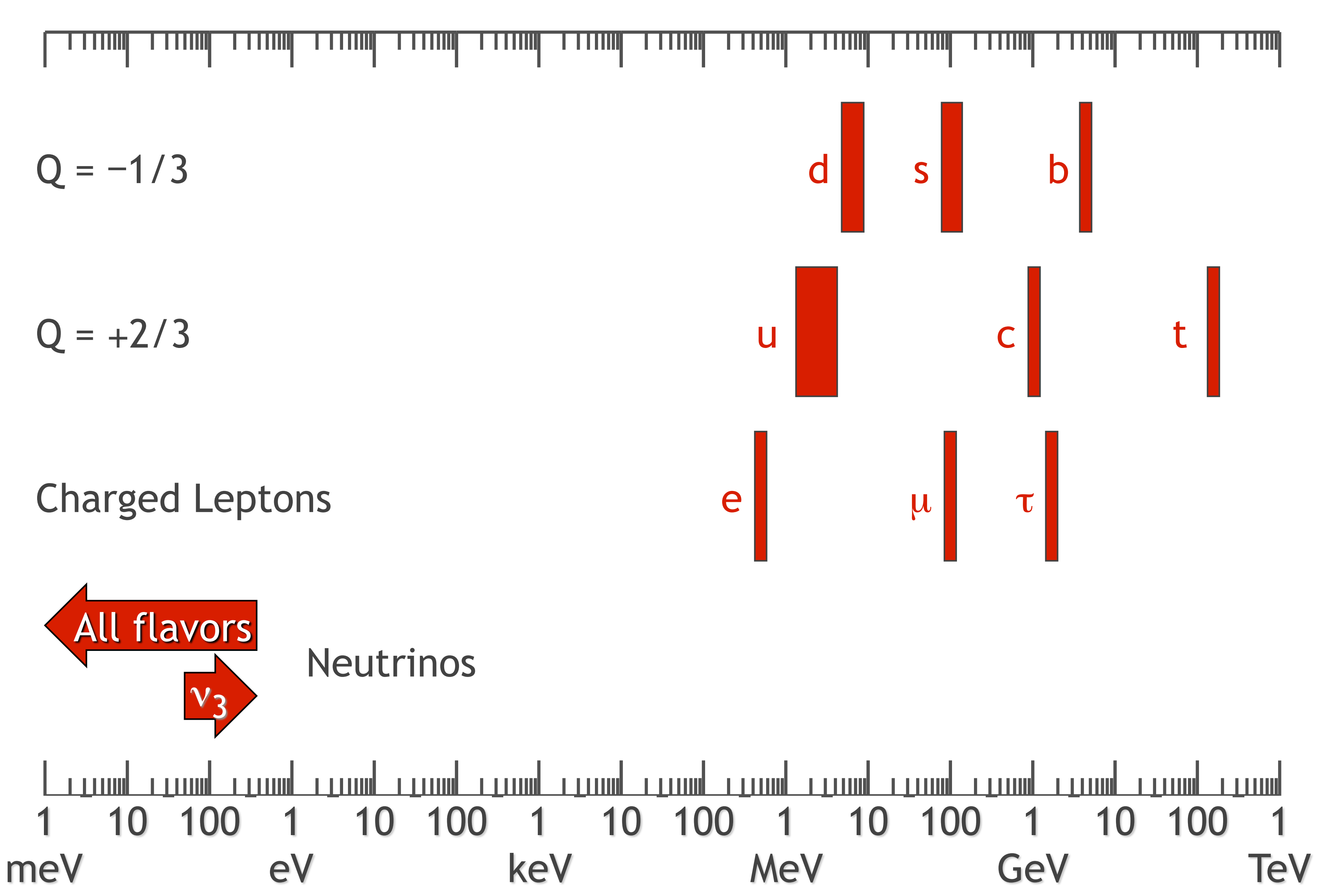
NEUTRINO PHYSICS FROM PRECISION COSMOLOGY



STEEN HANNESTAD, AARHUS UNIVERSITY

PARIS, 10 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)

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

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

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

FLAVOUR STATES

PROPAGATION STATES

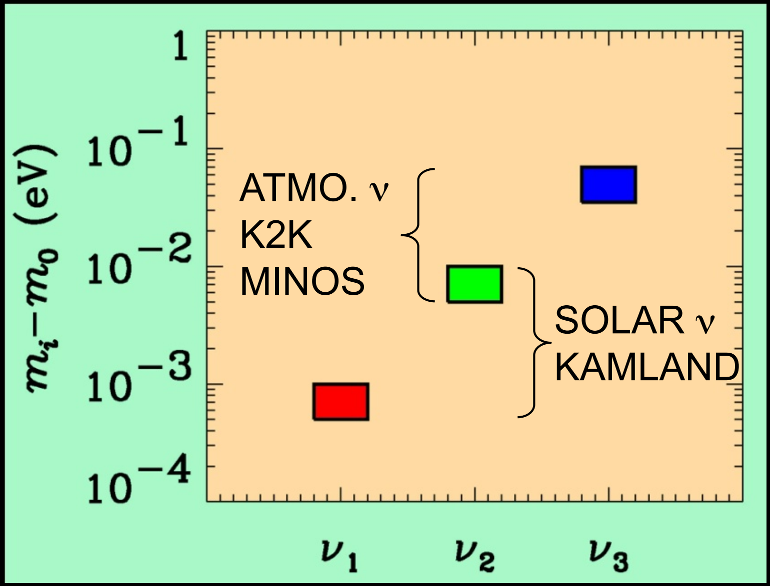
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1(m_1) \\ \nu_2(m_2) \\ \nu_3(m_3) \end{pmatrix}$$

MIXING MATRIX (UNITARY)

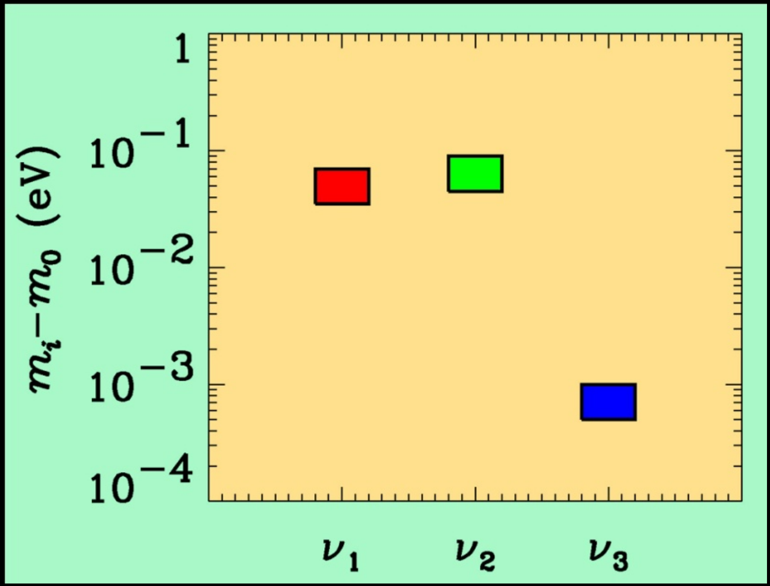
$U = $ [$c_{12}c_{13}$ … $s_{12}c_{13}$ … $s_{13}e^{-i\delta}$ … $s_{12}s_{23} - c_{12}c_{23}s_{13}e$ … $-c_{12}s_{23} - s_{12}c_{23}s_{13}e$ … $c_{23}c_{13}$] … $\cos\theta_{12}$ … $\sin\theta_{12}$

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

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



Normal hierarchy



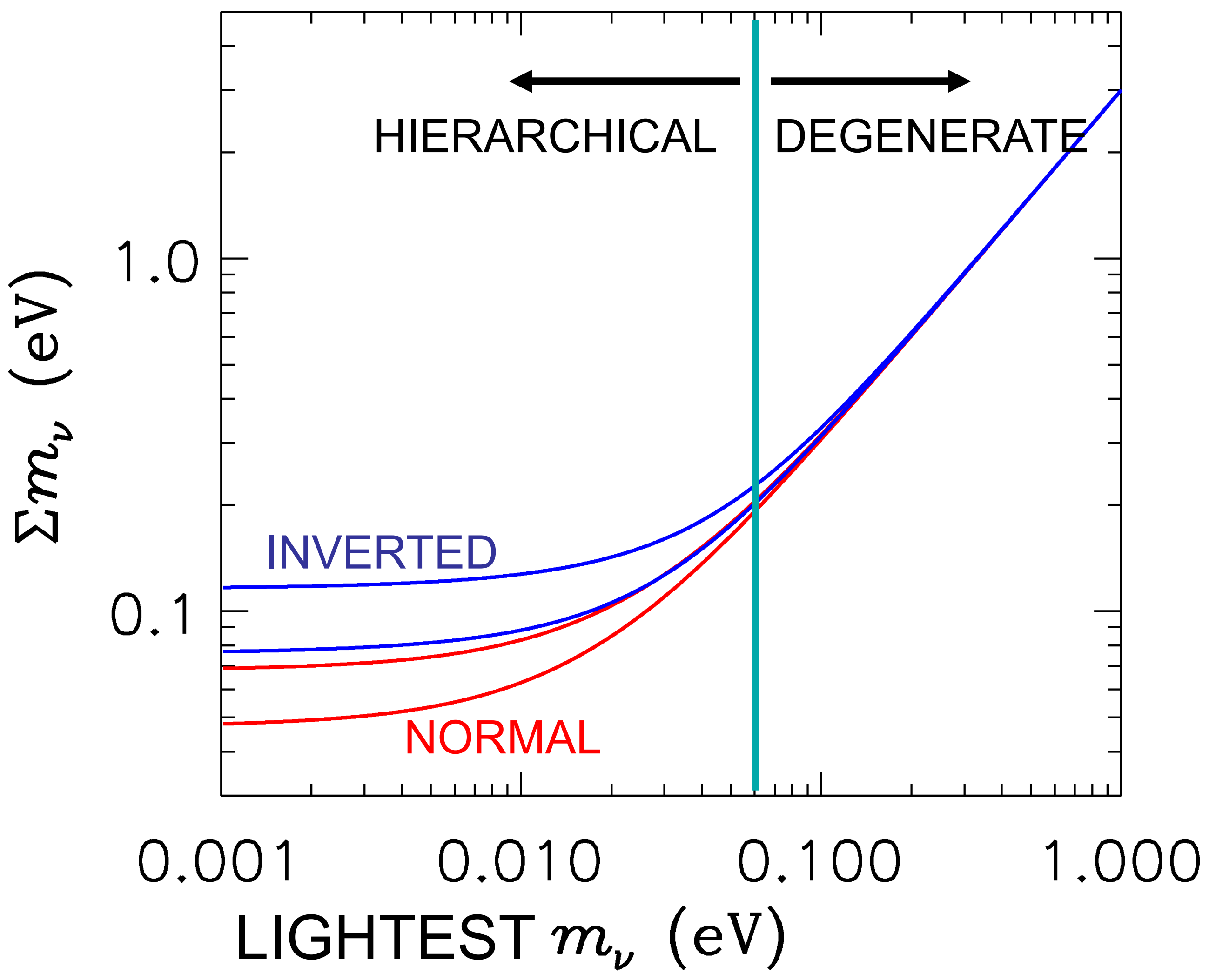
Inverted hierarchy

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)

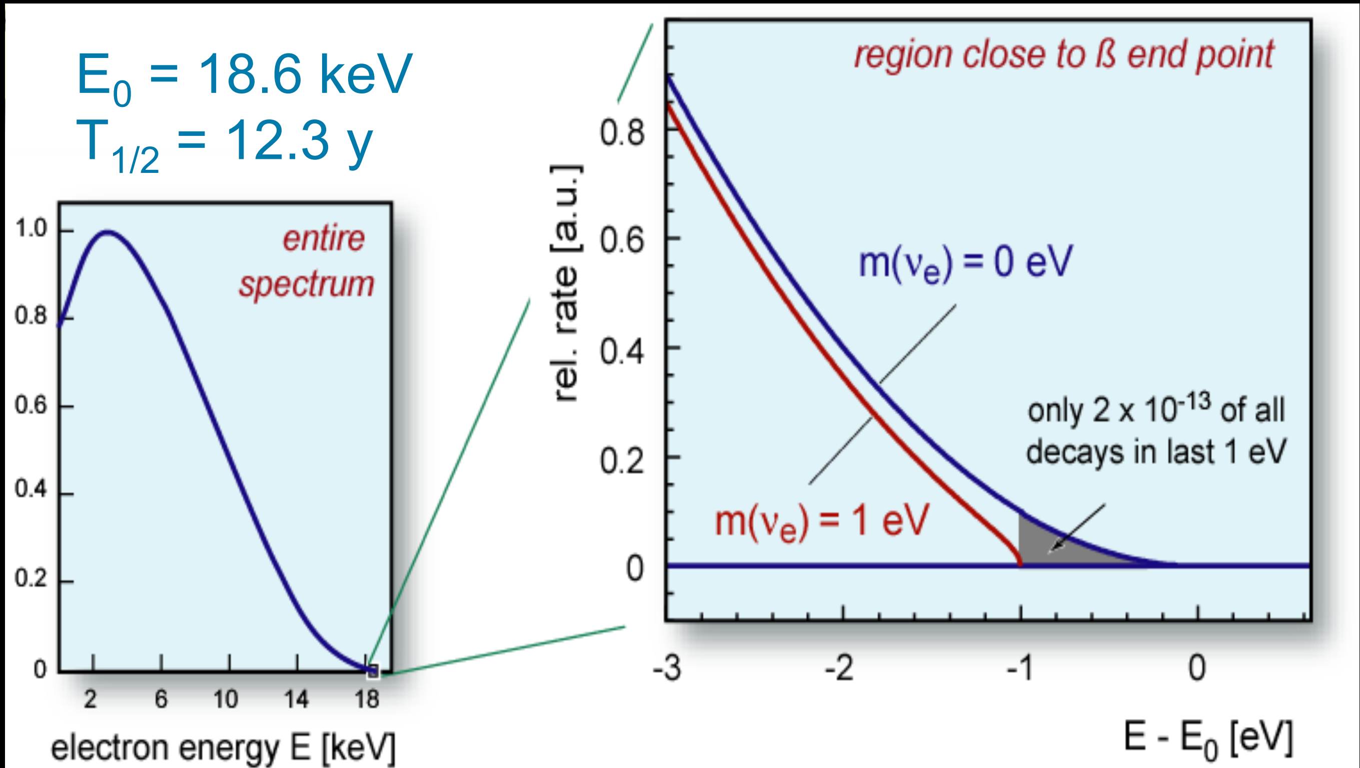
ß-decay and neutrino mass

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

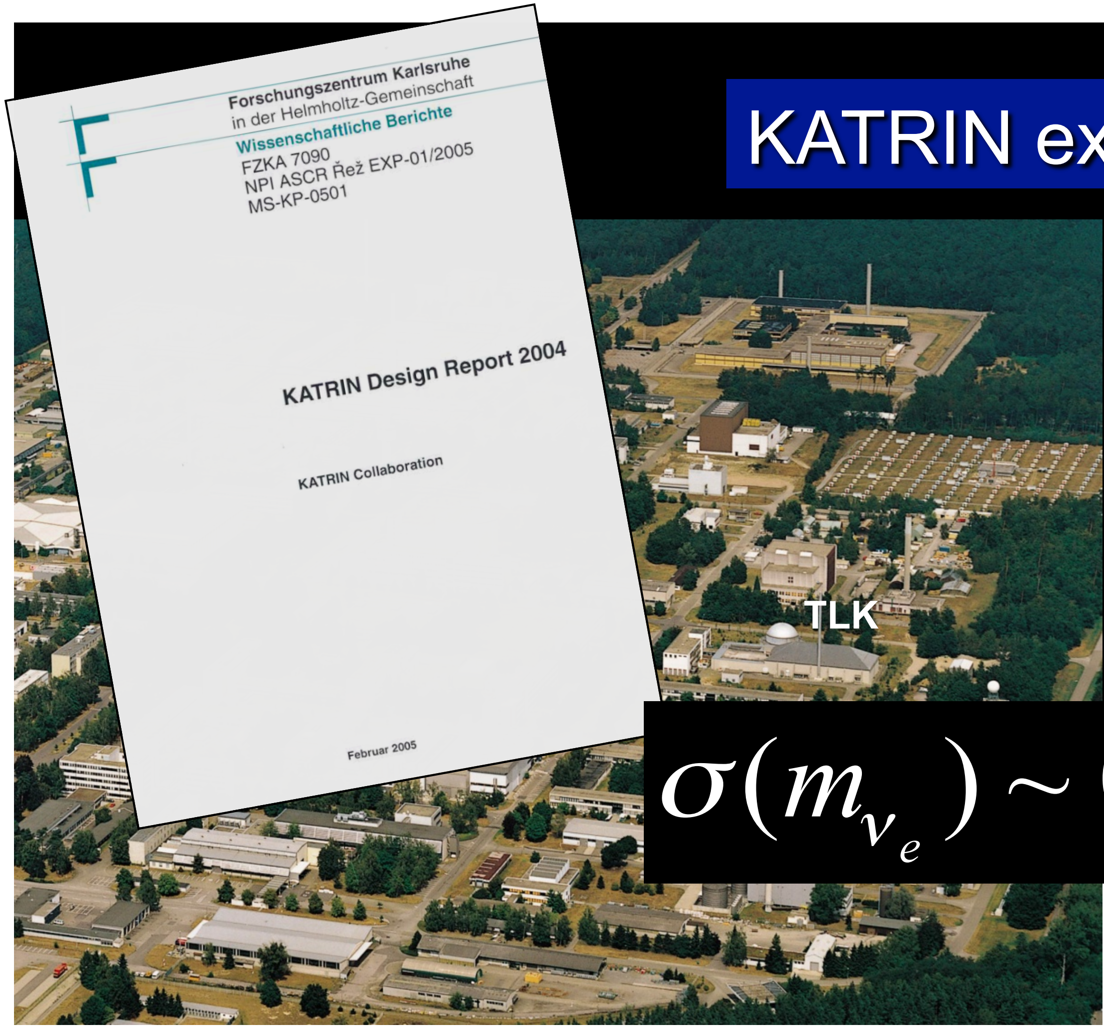
$$m_{\nu_e} = \left(\sum |U_{ei}|^2 m_i^2\right)^{1/2} \leq 2.3\,\mathrm{eV}\ \ (95\%)$$

Mainz experiment, final analysis (Kraus et al.)

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

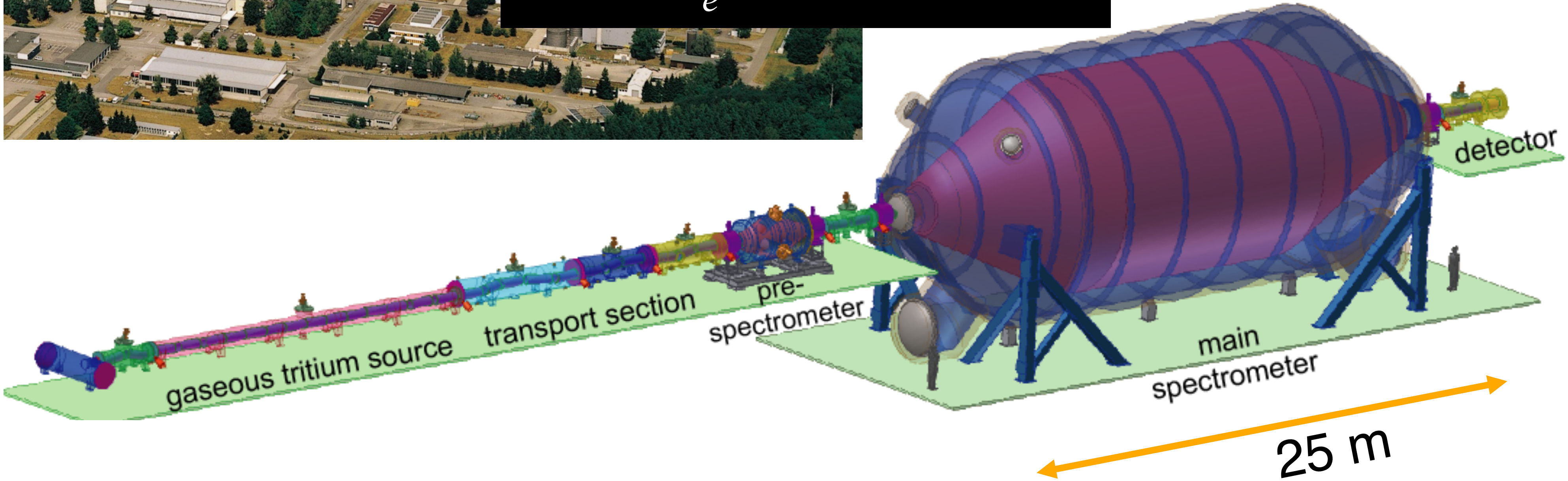
$$\sum m_i \leq 7\ \mathrm{eV}$$

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

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

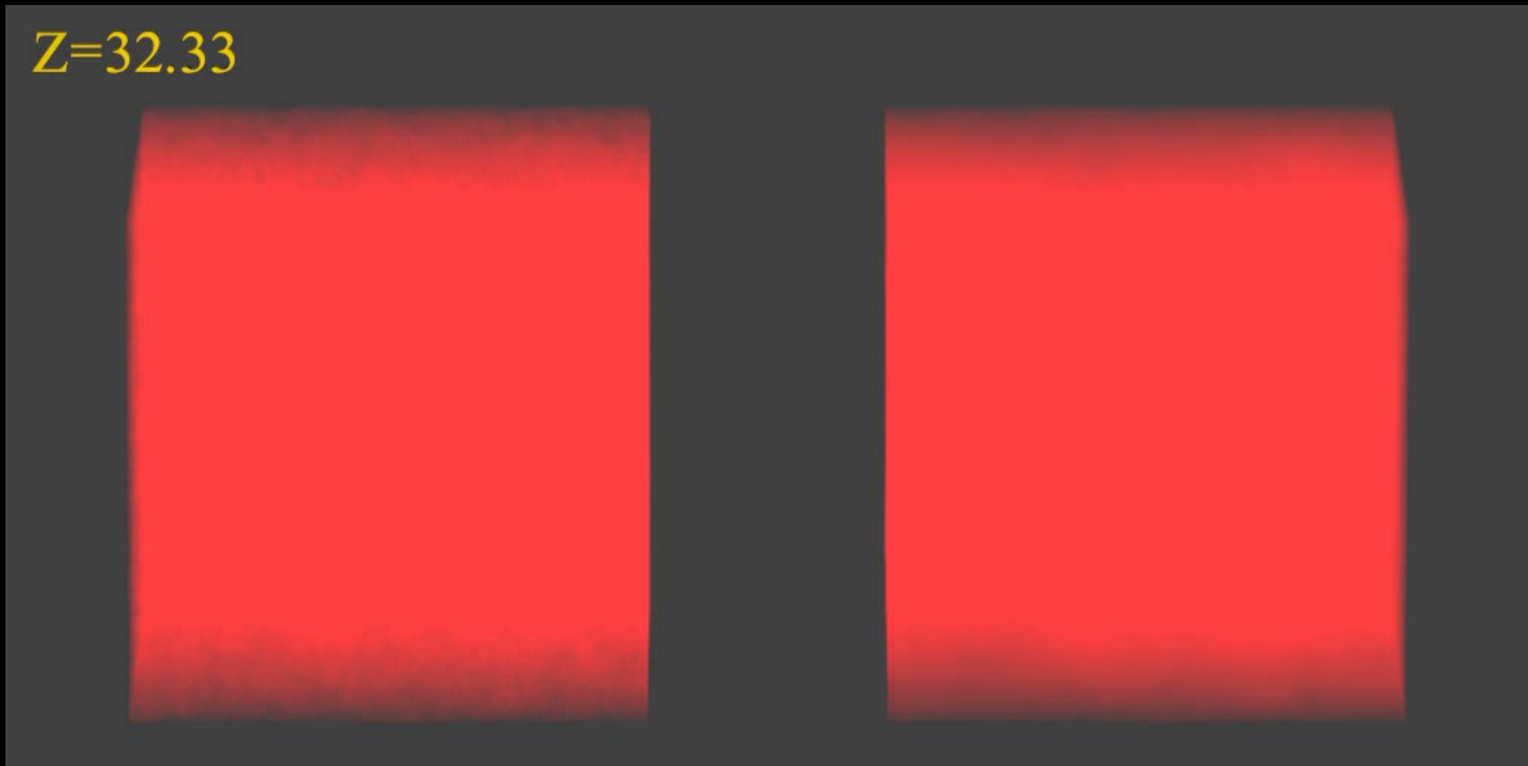
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

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

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

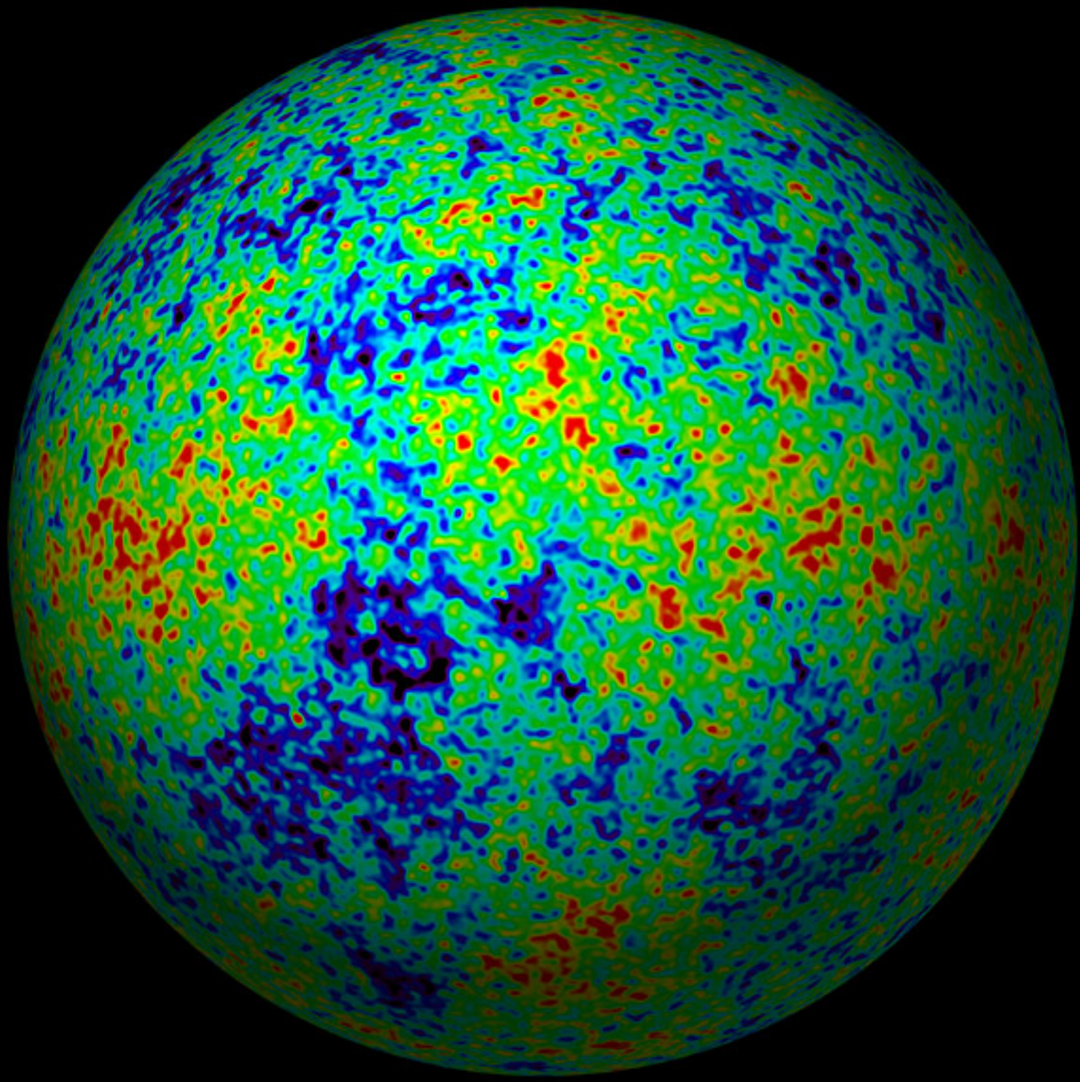


$\sum m_\nu = 0$ $\qquad$ $\sum m_\nu = 6.9\,\text{eV}$

T Haugboelle, Aarhus University

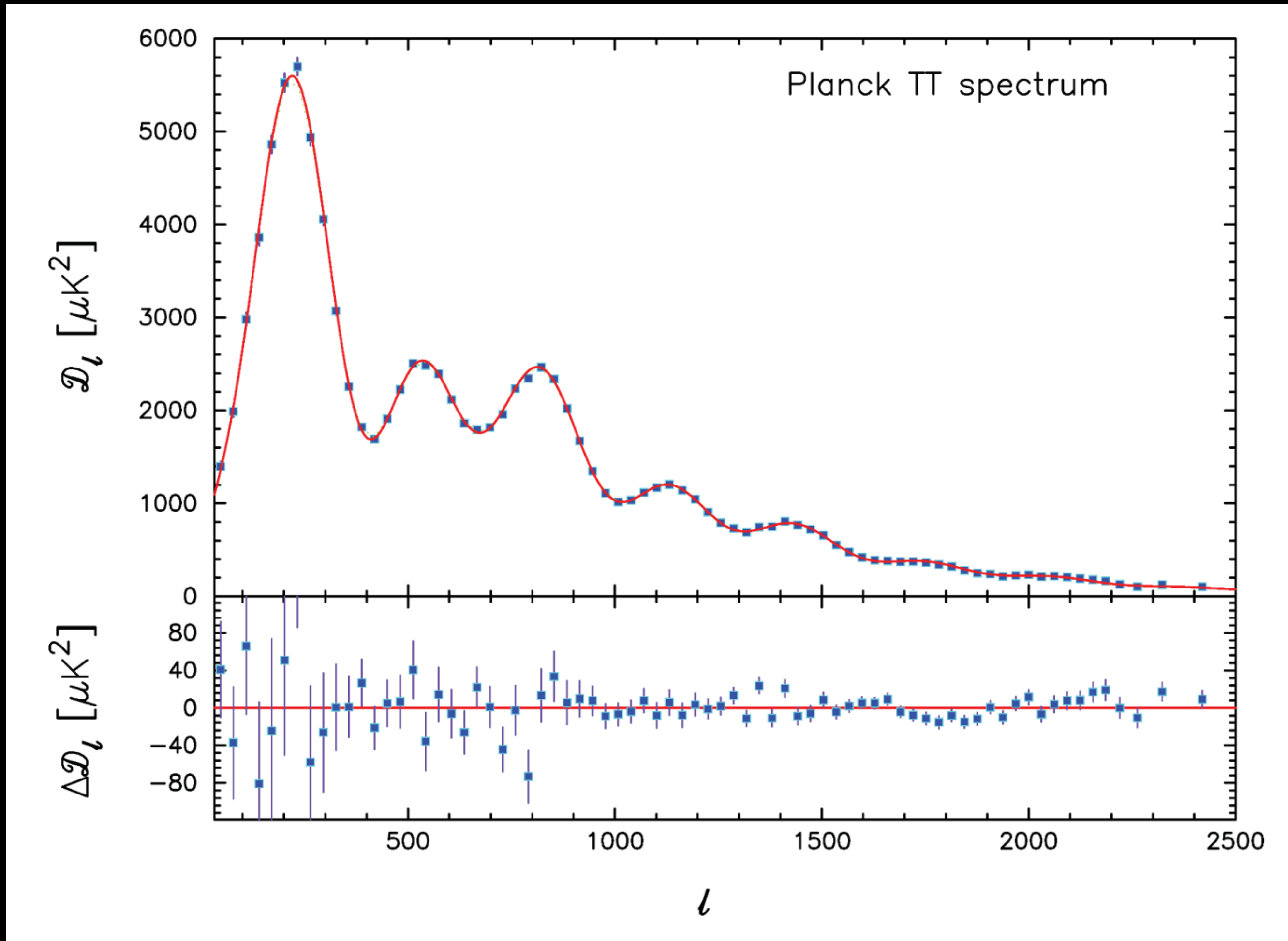
AVAILABLE COSMOLOGICAL DATA

THE COSMIC MICROWAVE BACKGROUND



CMB TEMPERATURE MAP

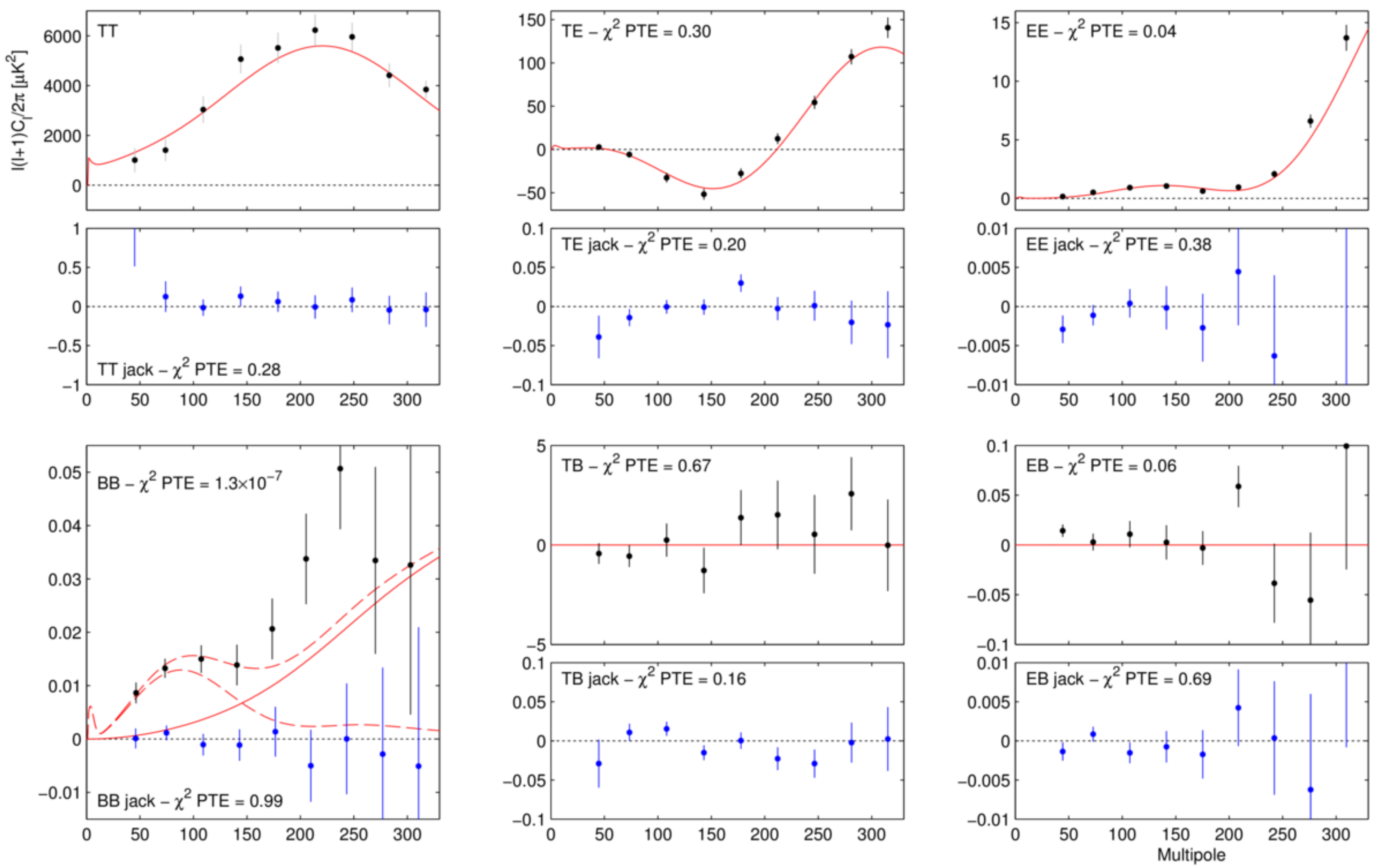
PLANCK TEMPERATURE POWER SPECTRUM



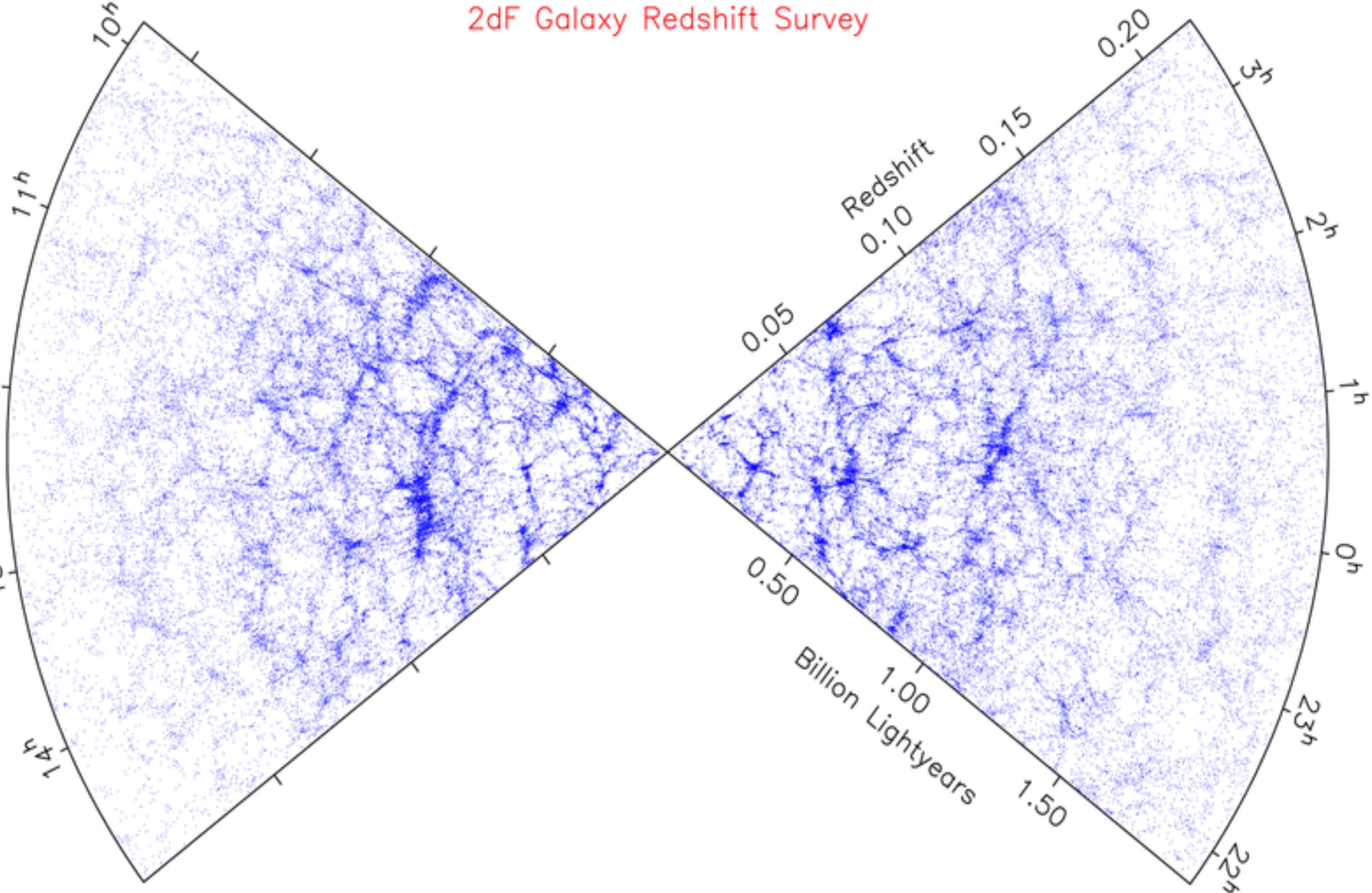
ADE ET AL, ARXIV 1303.5076

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

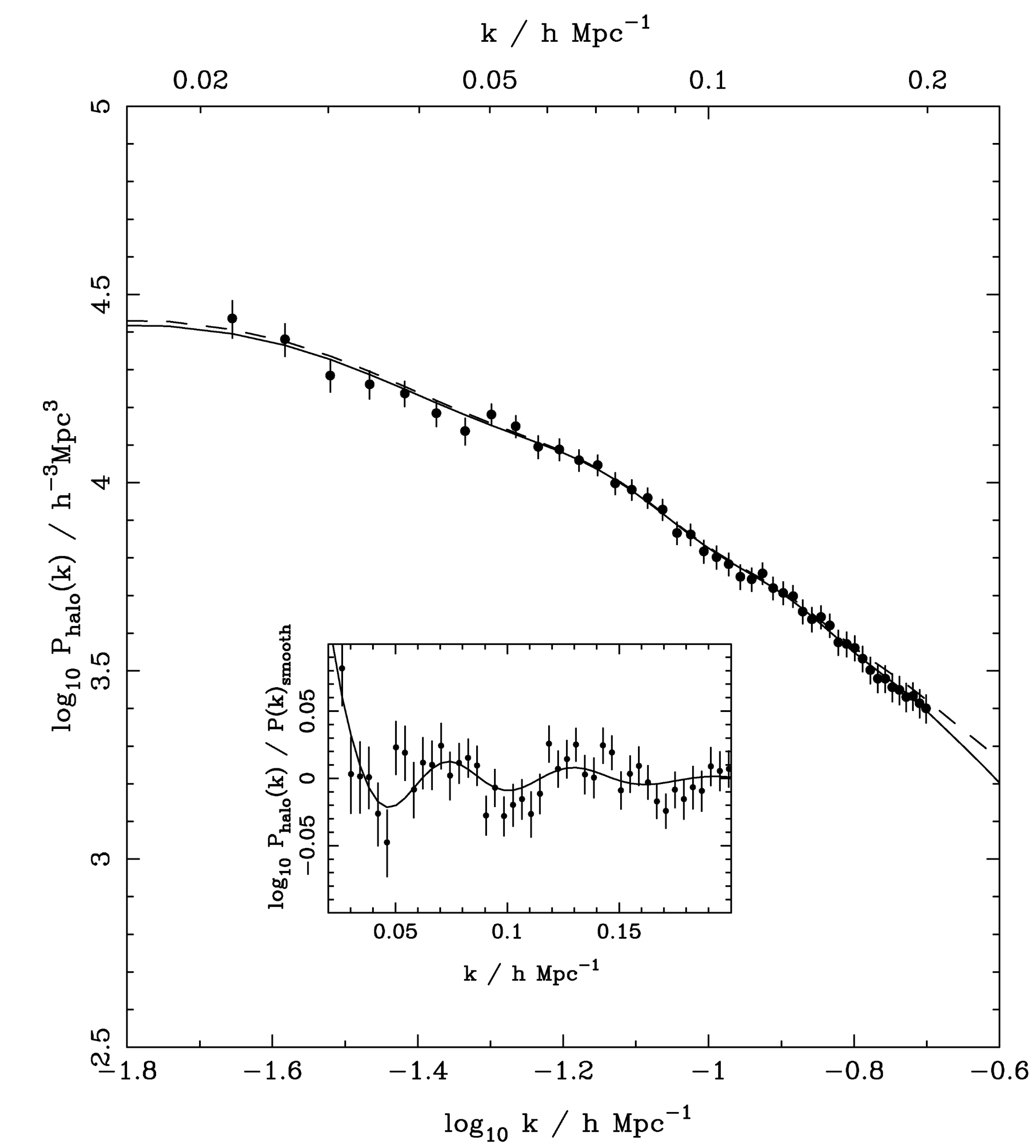
…AND OF COURSE THE B-MODE DETECTION FROM BICEP2

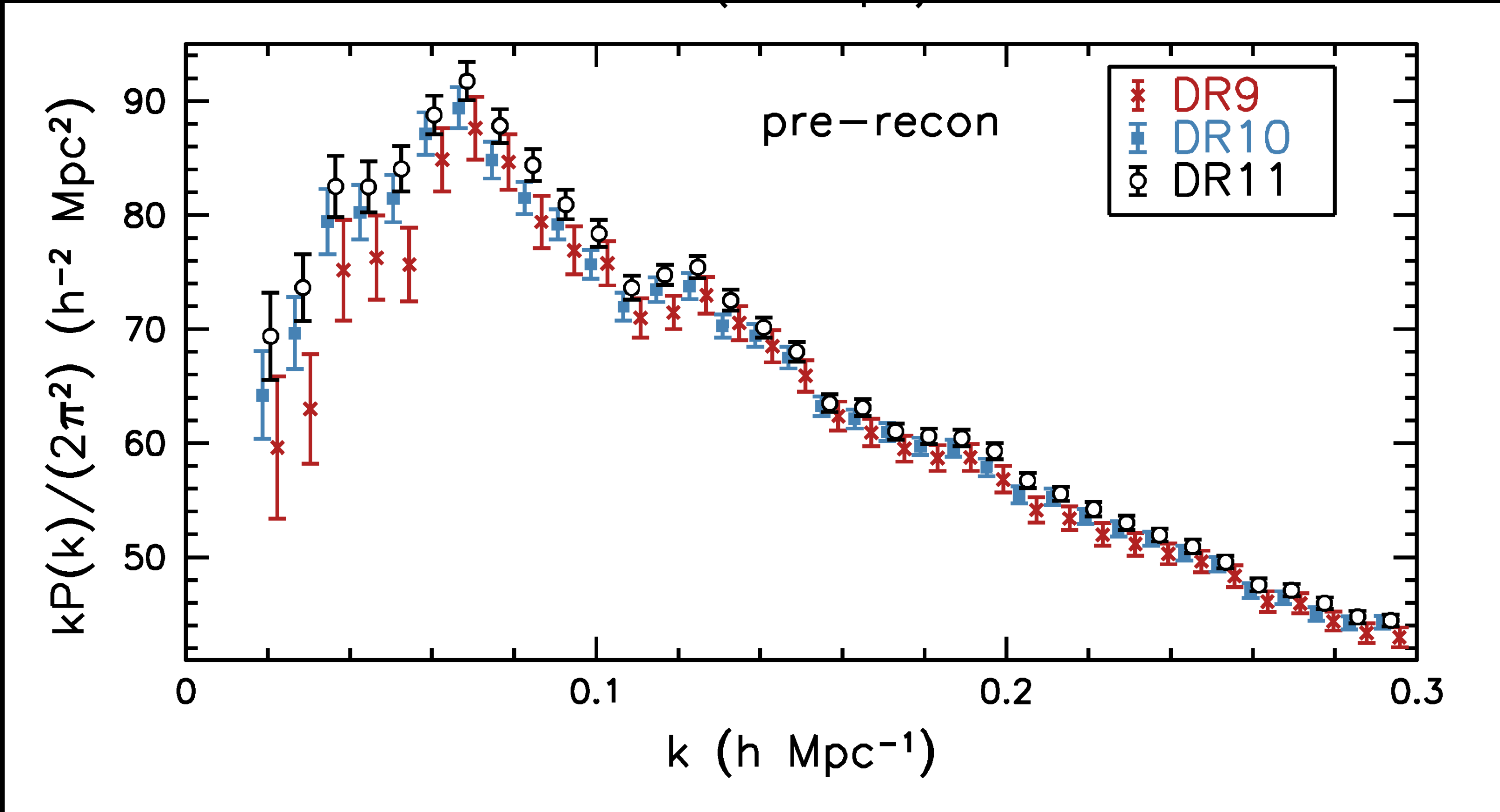


LARGE SCALE STRUCTURE SURVEYS



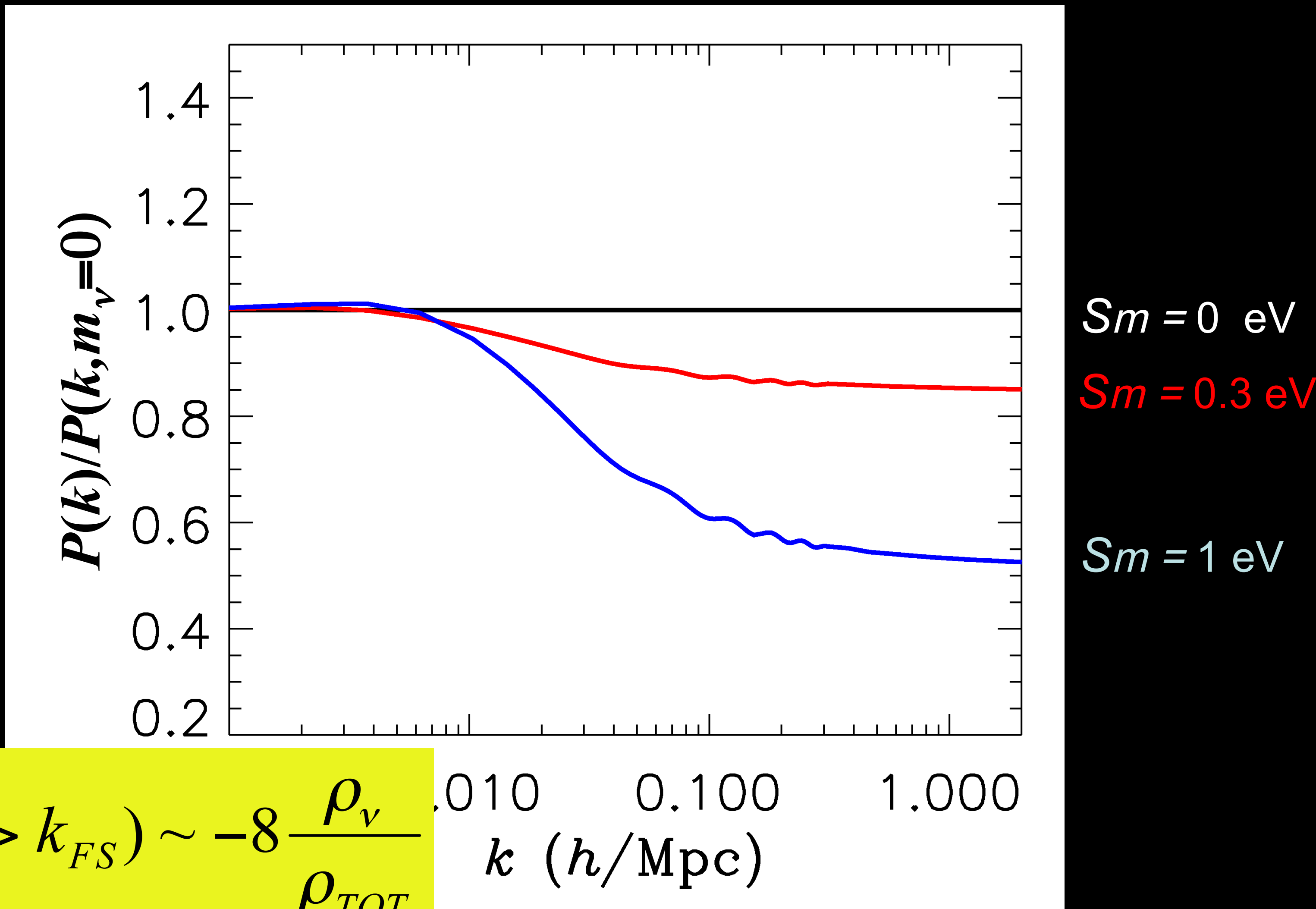
SDSS DR-7
LRG SPECTRUM
(Reid et al '09)





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?

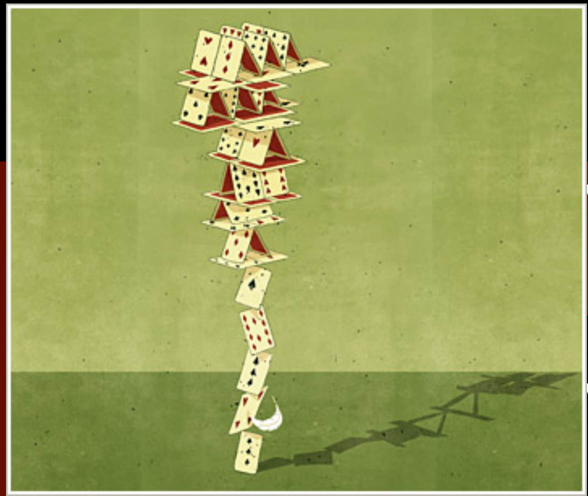
DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

THERE ARE MANY ANALYSES IN THE LITERATURE

$$\sum m_\nu \leq 1.08\,\mathrm{eV}\ @\ 95\ \mathrm{C.L.} \quad \mathrm{Planck\ only}$$
$$\sum m_\nu \leq 0.32\,\mathrm{eV}\ @\ 95\ \mathrm{C.L.} \quad \mathrm{Planck + BAO}$$

arXiv:1303.5076 (Planck)

THE NEUTRINO MASS FROM COSMOLOGY PLOT



More data

+Ly-alpha 0.2-0.3 eV

+ SNI-a
+WL 0.5-0.6 eV

+ SDSS 0.4 eV ~ 1 eV

CMB only 1.1 eV ~ 2 eV

Minimal ΛCDM | $+N_\nu$ | $+w+$…… | Larger model space

GOING BEYOND THE MASS

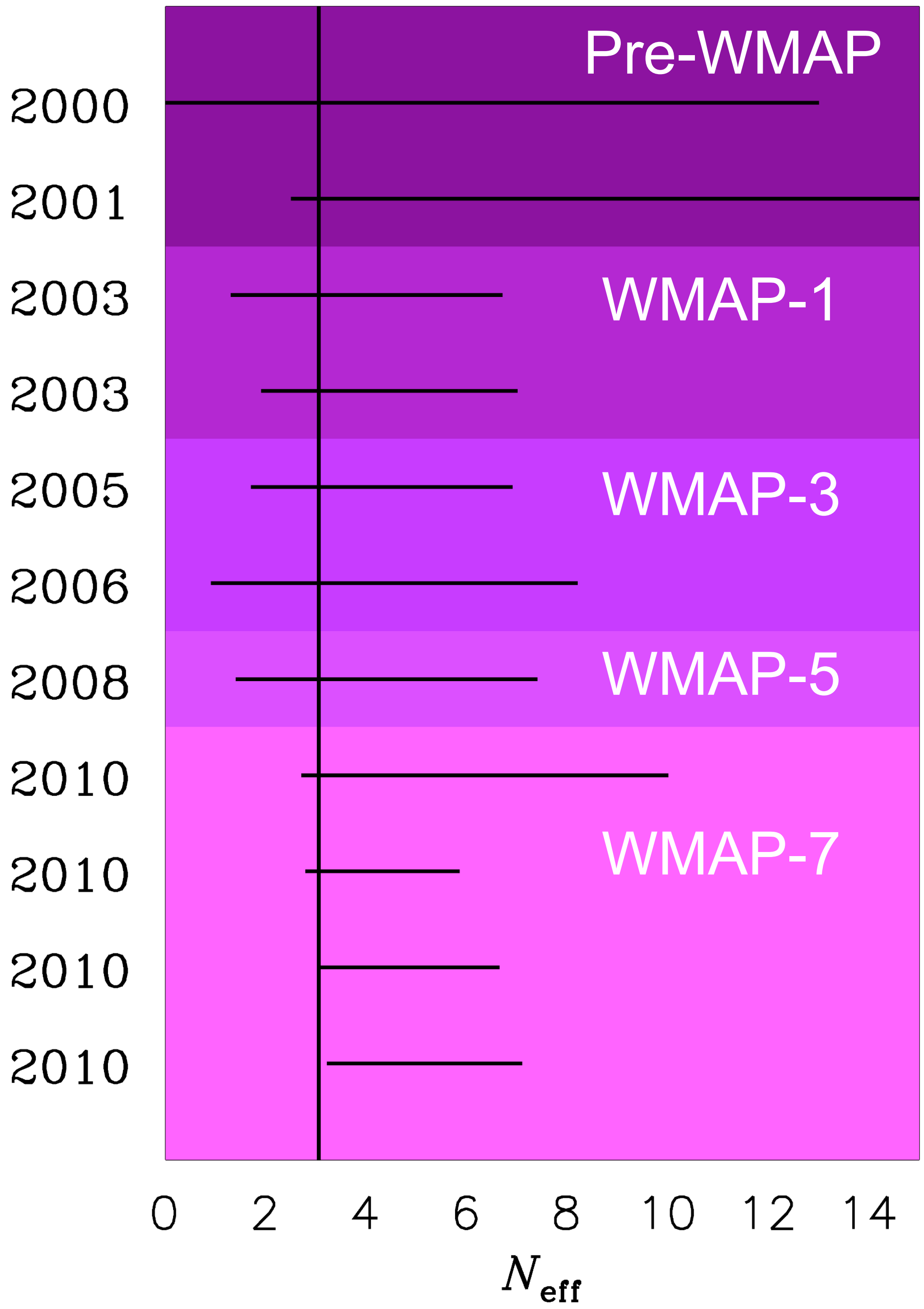
$$\Omega = \frac{\rho}{\rho_c} = \sum m_{\nu,i} n_{\nu,i} \qquad n_\nu = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma$$

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”

PRE-PLANCK
EVOLUTION OF THE
95% BOUND ON N_ν



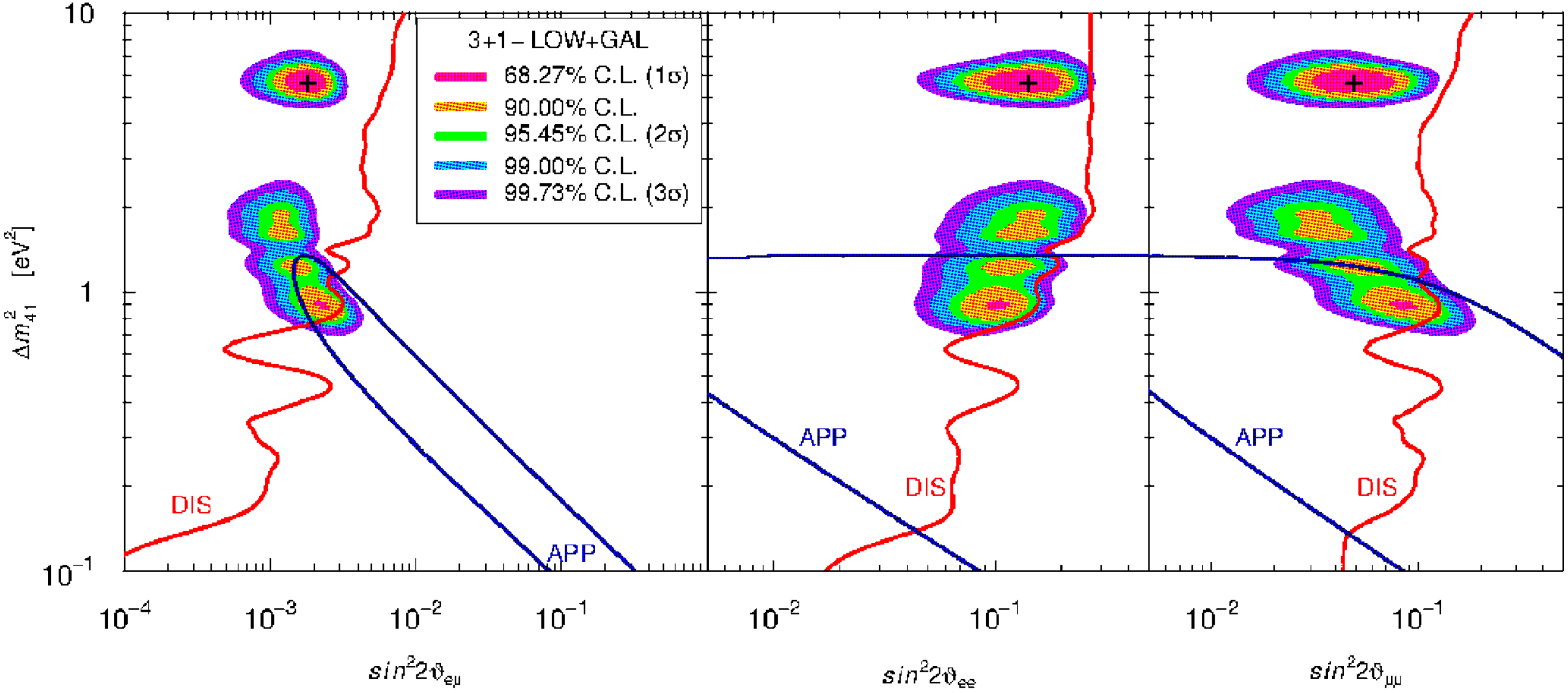
$N_{eff} = 3.36^{+0.68}_{-0.64}$ @ 95% Planck only

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

THE SITUATION IS (UNFORTUNATELY) NOT YET RESOLVED….

IF THERE IS EXTRA, DARK RADIATION, WHAT IS IT?

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



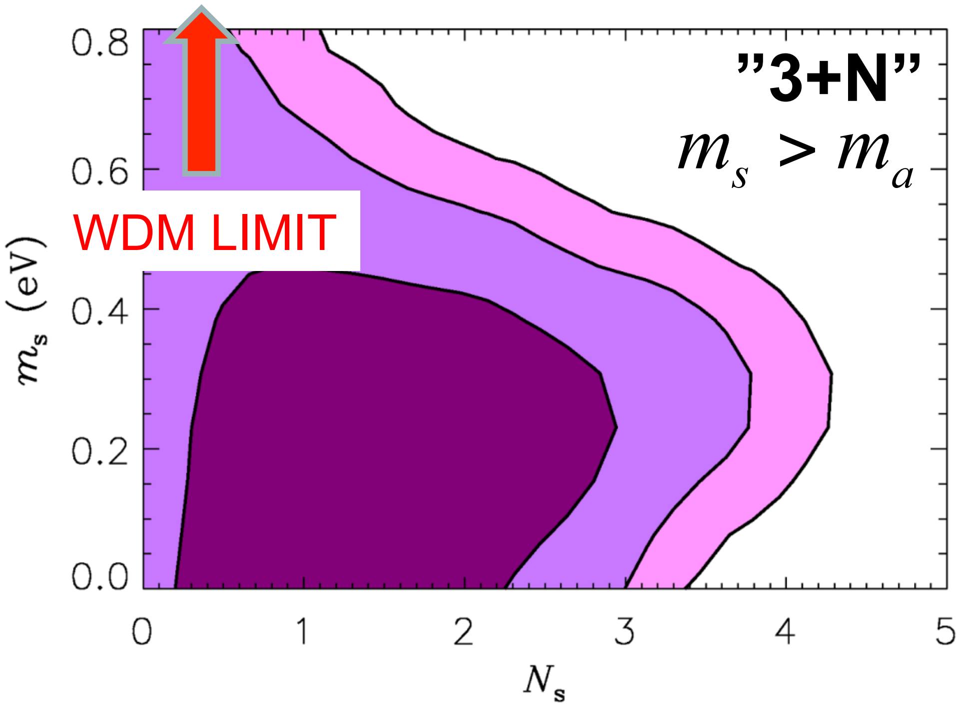
Giunti & Laveder 2011

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

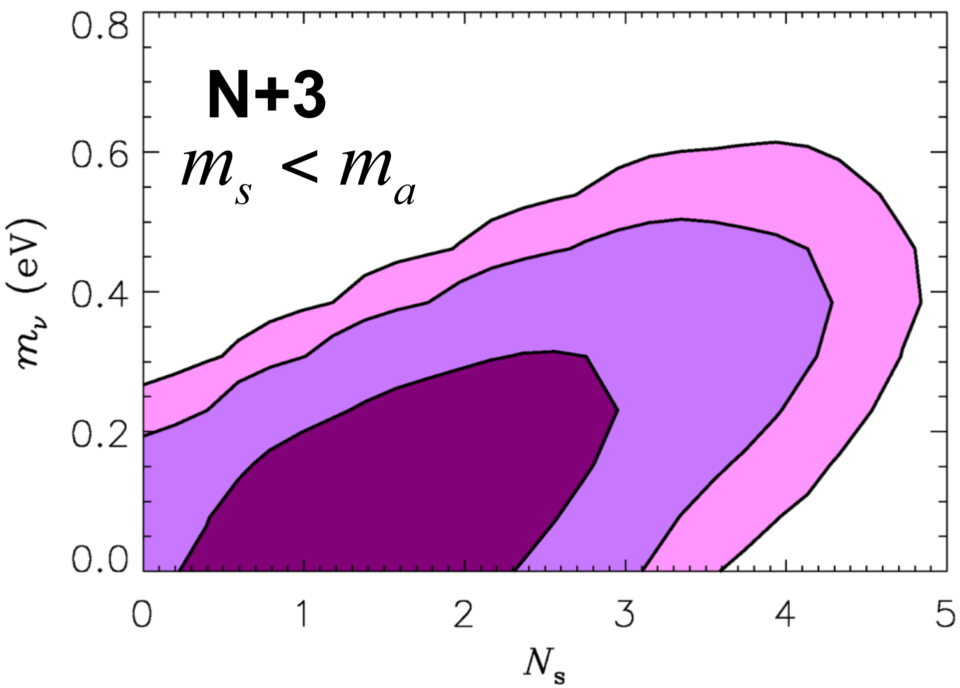
3+N (NORMAL) **N+3 (INVERTED)**

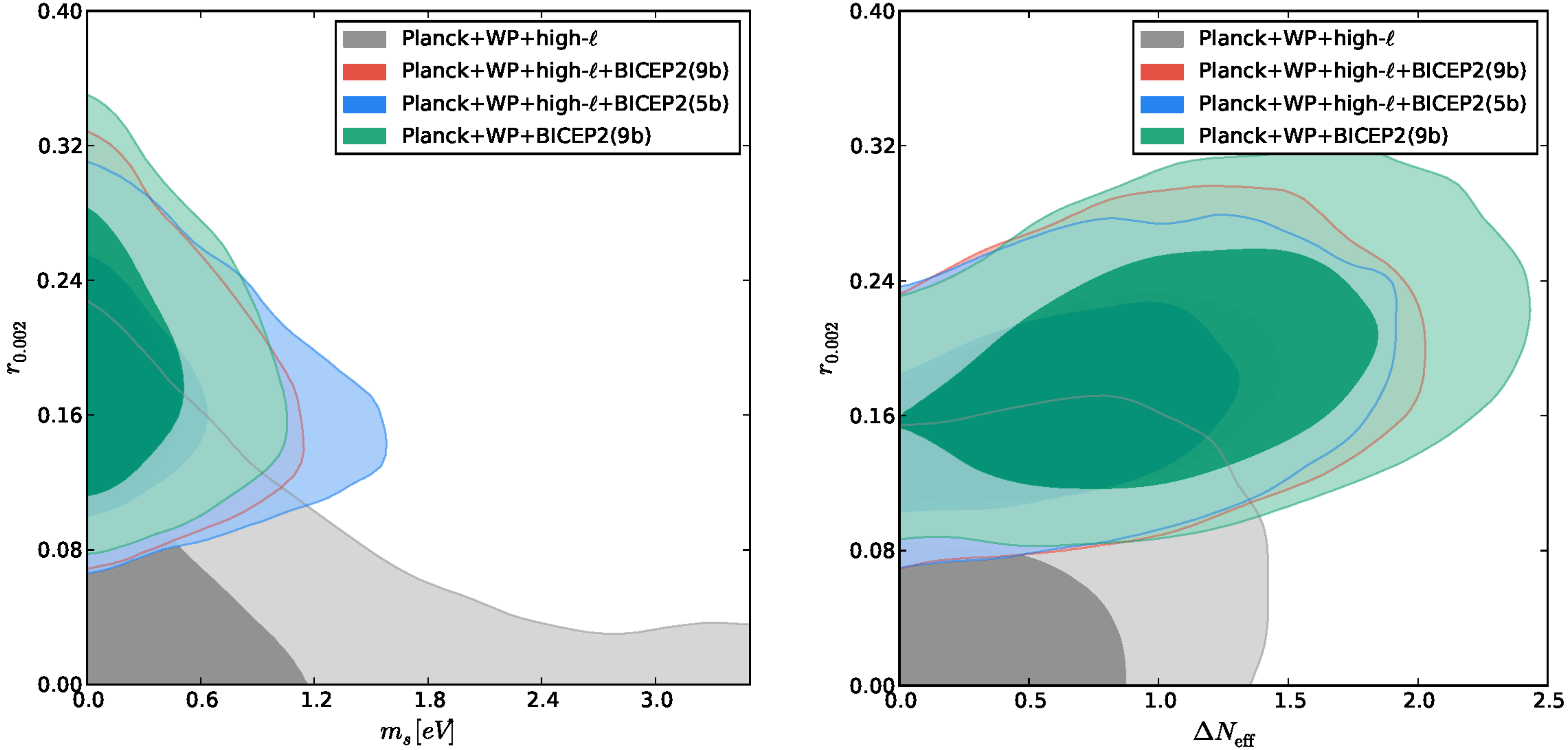
Hamann, STH, Raffelt, Tamborra, Wong, arxiv:1006.5276 (PRL)

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

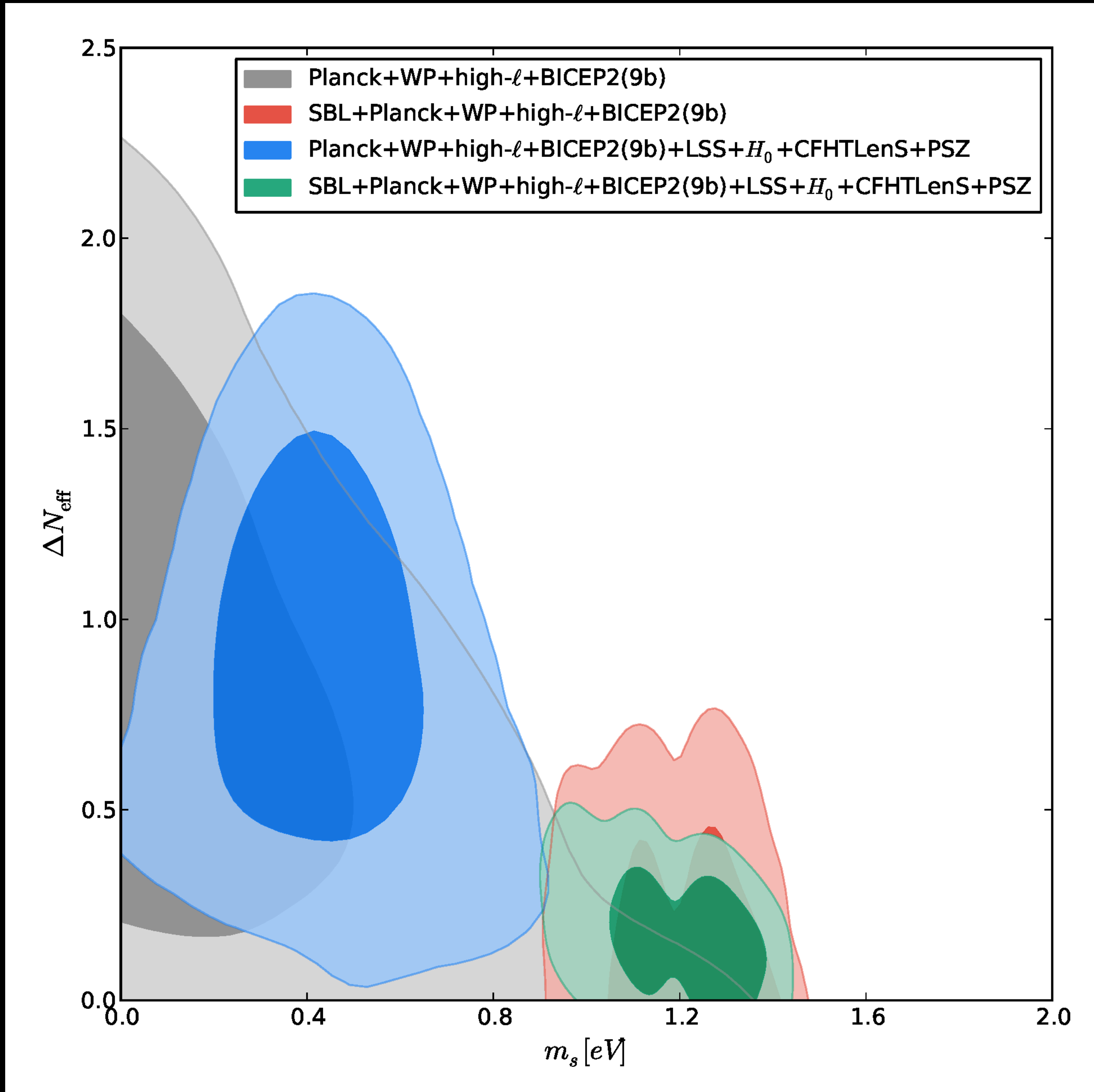


See also
Dodelson et al. 2006
Melchiorri et al. 2009
Acero & Lesgourgues 2009
Hamann et al 2011
Joudaki et al 2012
Motohashi et al. 2012
Archidiacono et al 2012, 2013
and many others





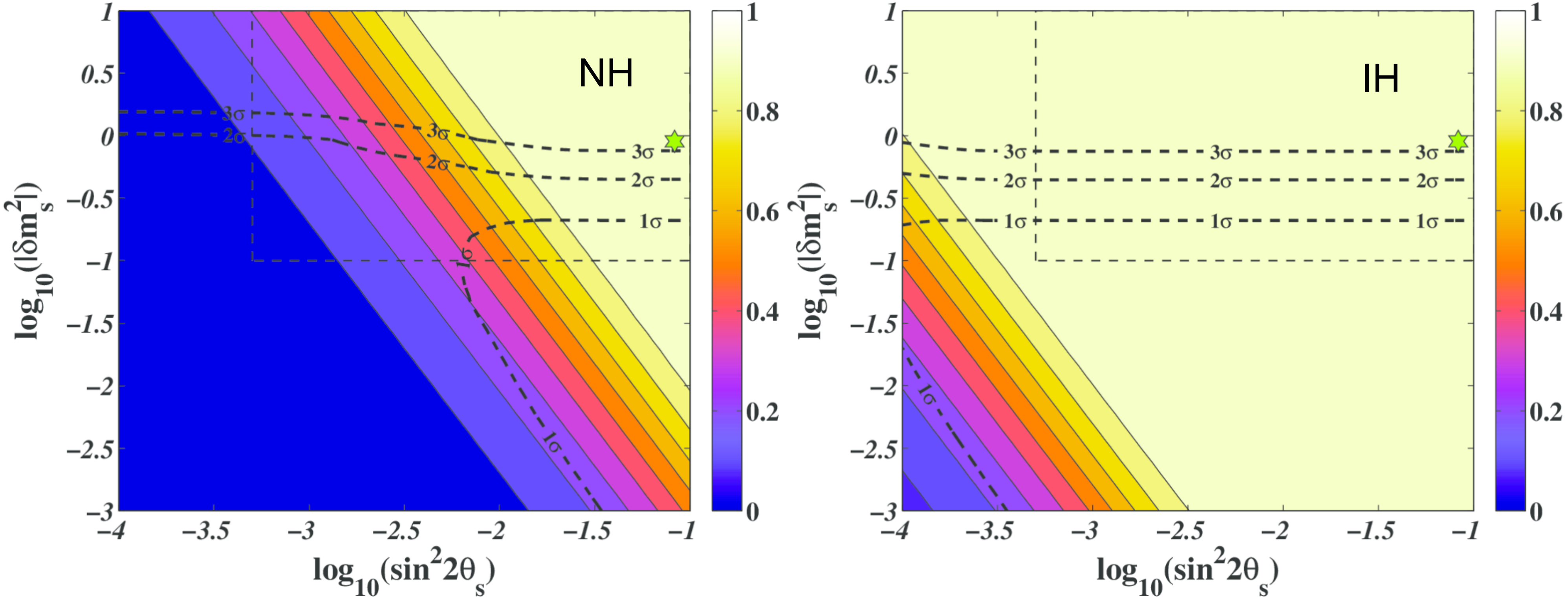
Archidiacono, Fornengo, Gariazzo, Giunti, STH, Laveder, arXiv:1404.1794 (JCAP)



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

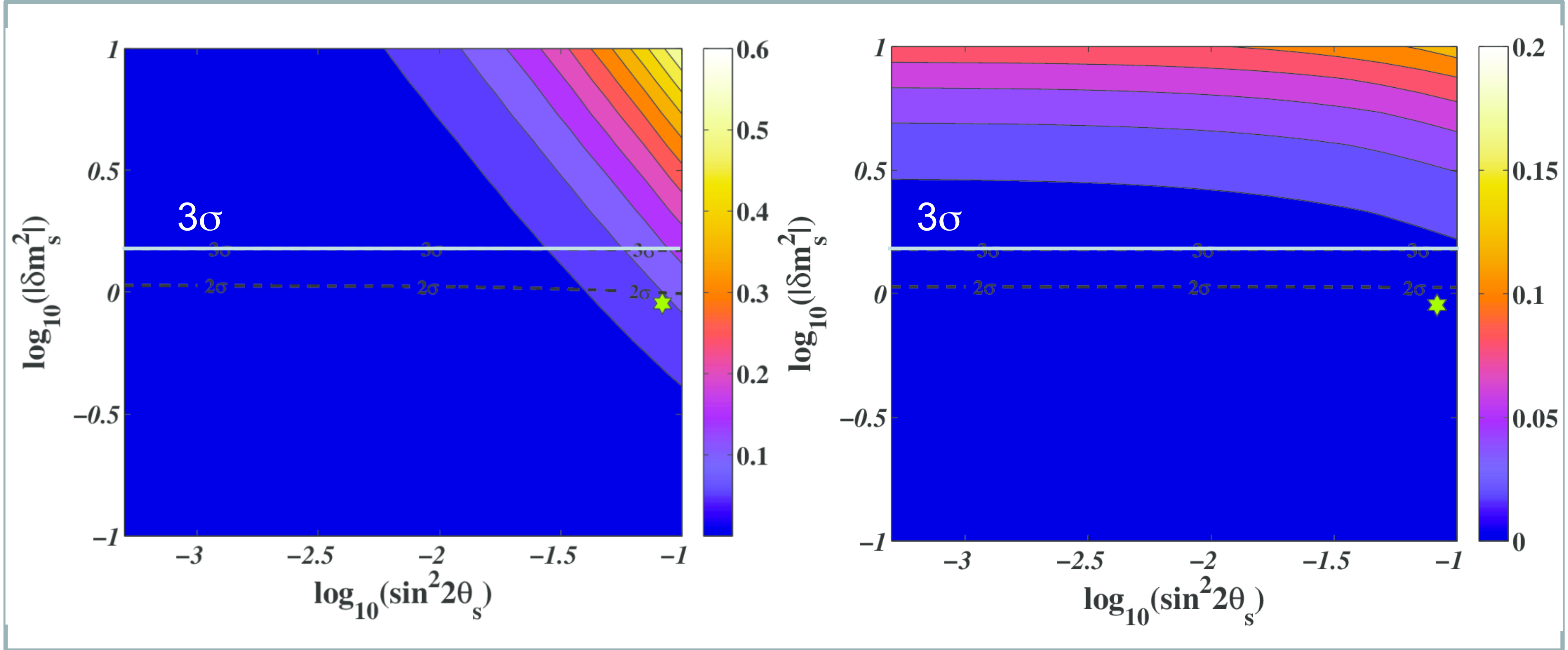
Bottom line: Sterile neutrinos in the mass range preferred by SBL data can be accomodated by cosmology, but ONLY if they are not fully thermalised

STERILE 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

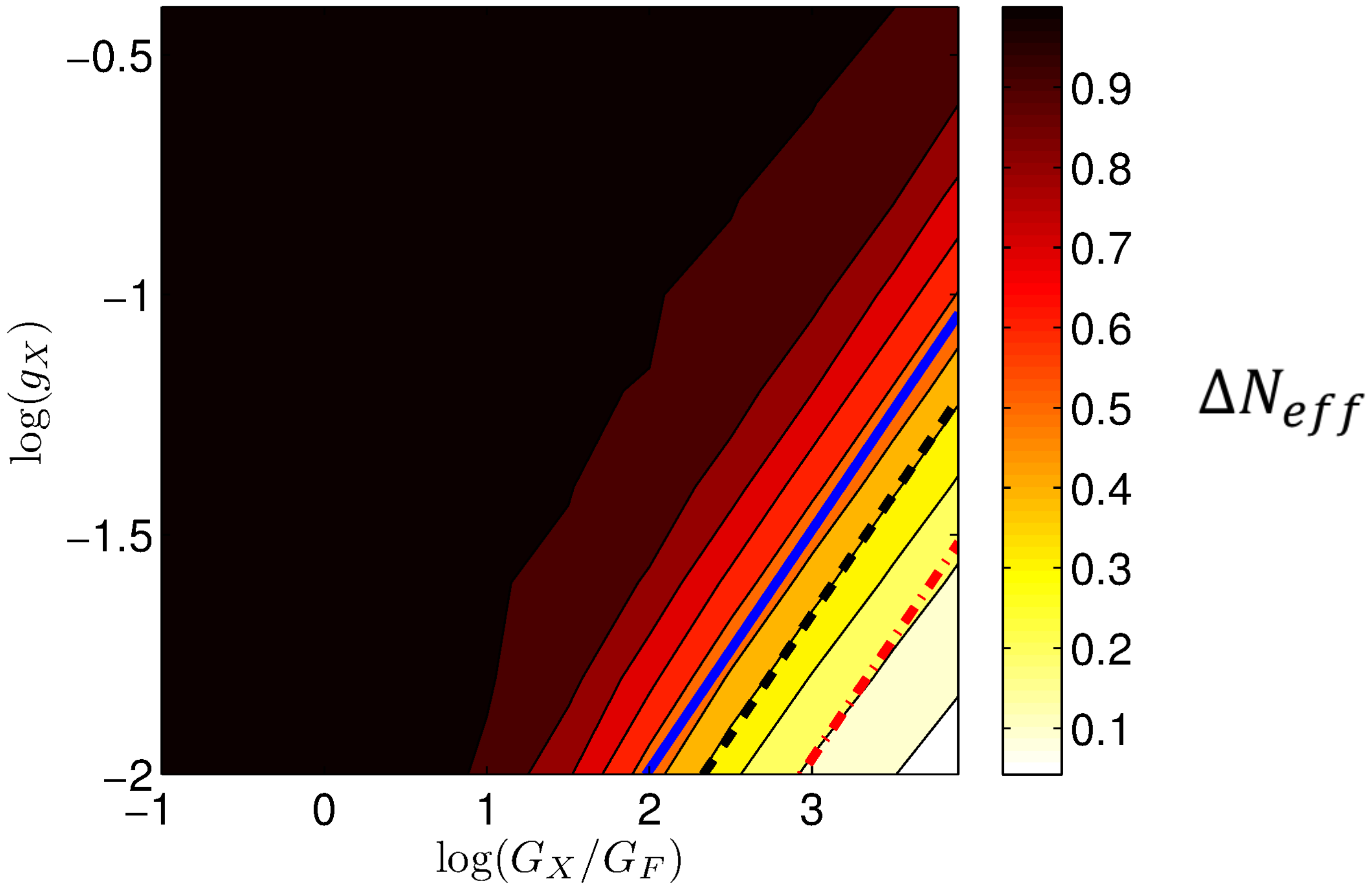
Could there be another way of modifying the matter potential?

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

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

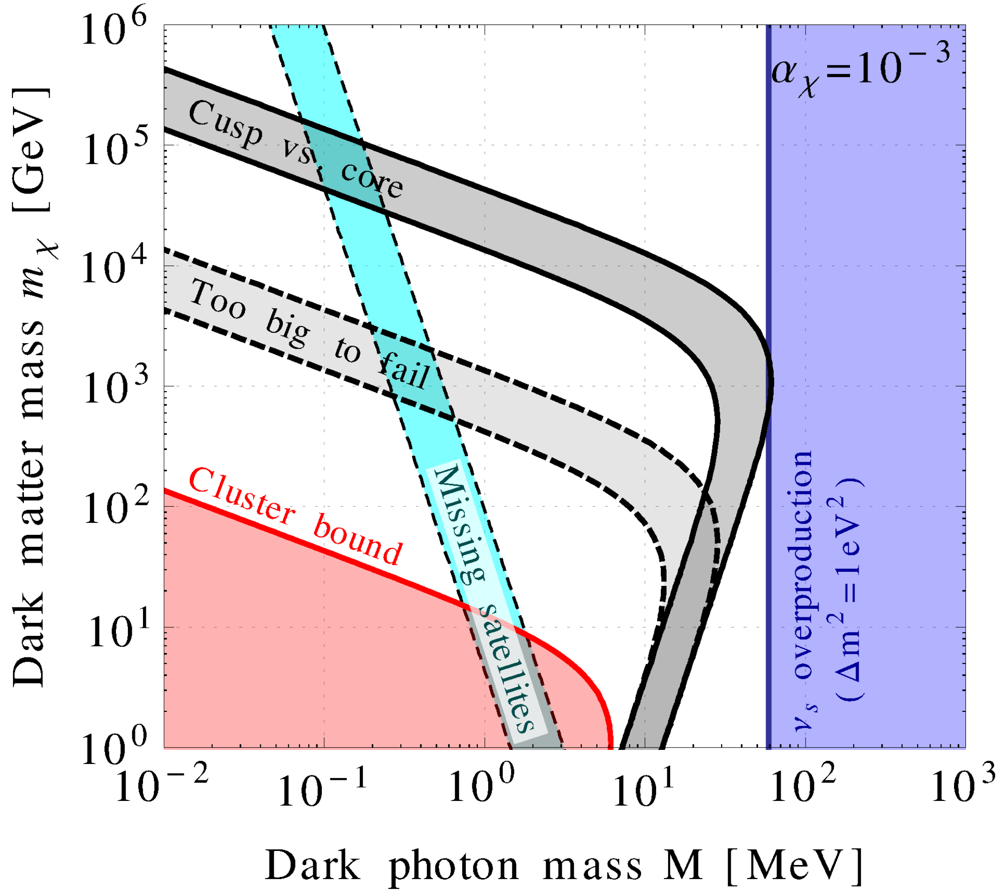
Sterile neutrino self-interactions are possible, and perhaps even natural.

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



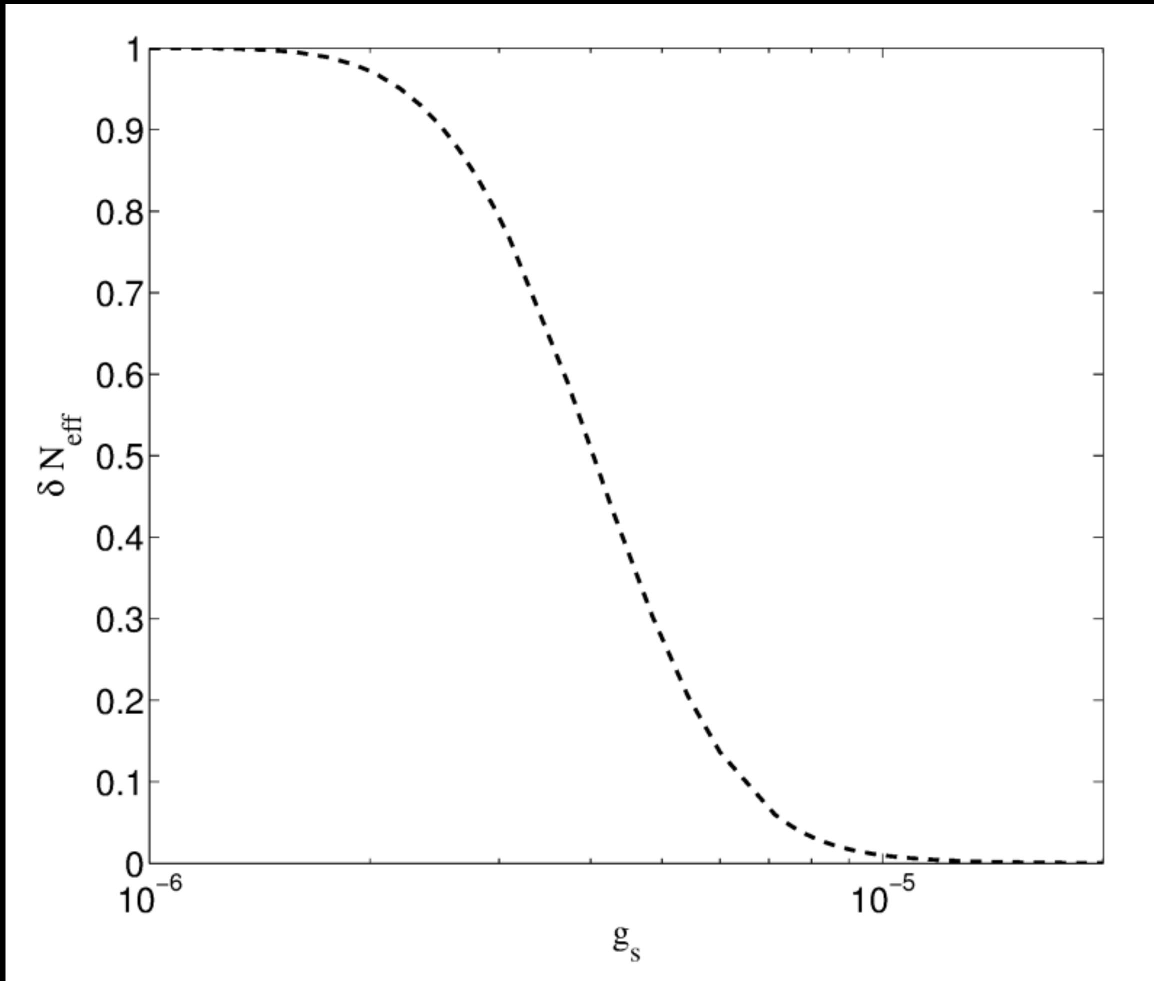
Hannestad, Hansen, Tram, 2013 (arXiv:1310.5926)

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



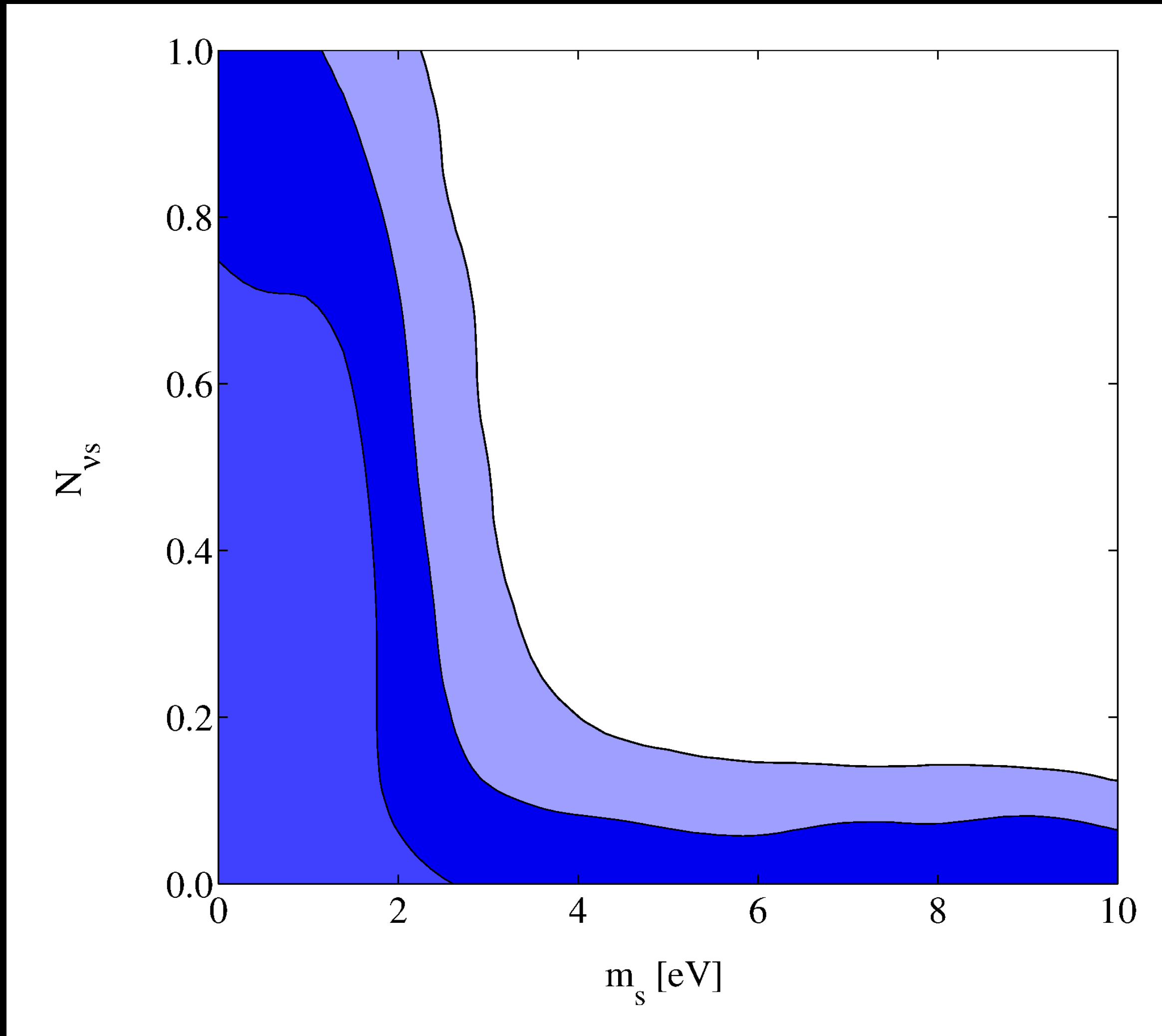
Dasgupta & Kopp 1310.6337

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.



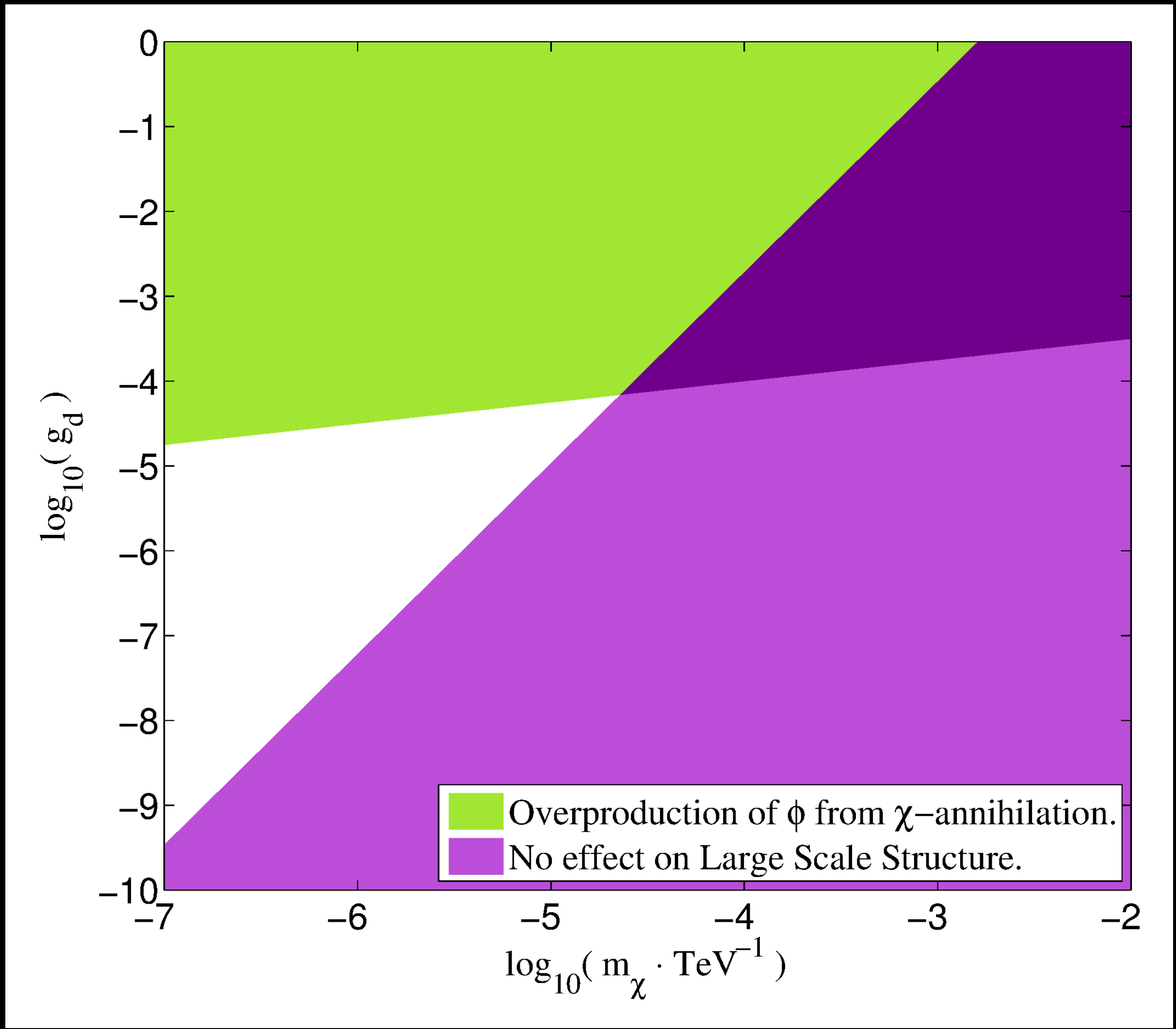
Archidiacono,
STH, Hansen, Tram
(arXiv:1404.5915)

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.

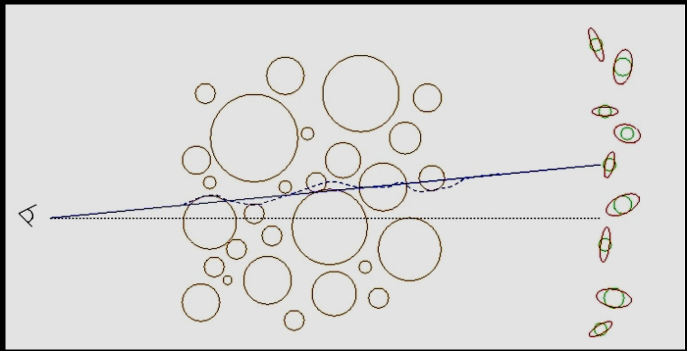


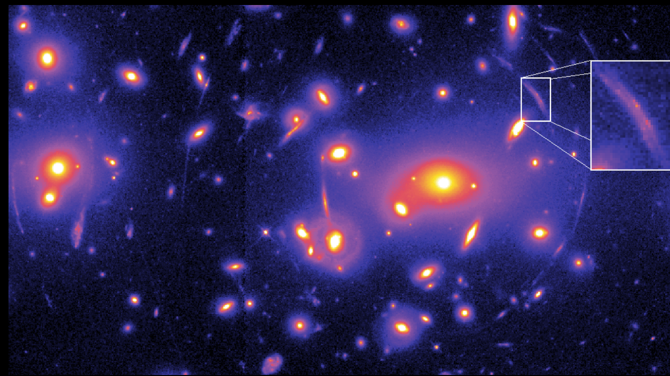
Archidiacono,
STH, Hansen, Tram
(arXiv:1404.5915)

WHAT IS IN STORE FOR THE FUTURE?

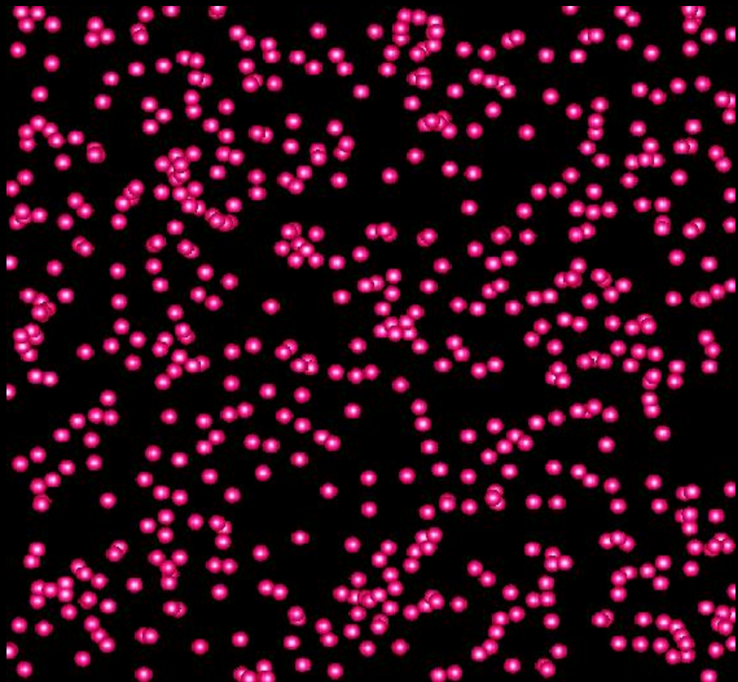
- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS
- LARGE SCALE STRUCTURE SURVEYS AT HIGHER REDSHIFT AND IN LARGER VOLUMES
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES

WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE

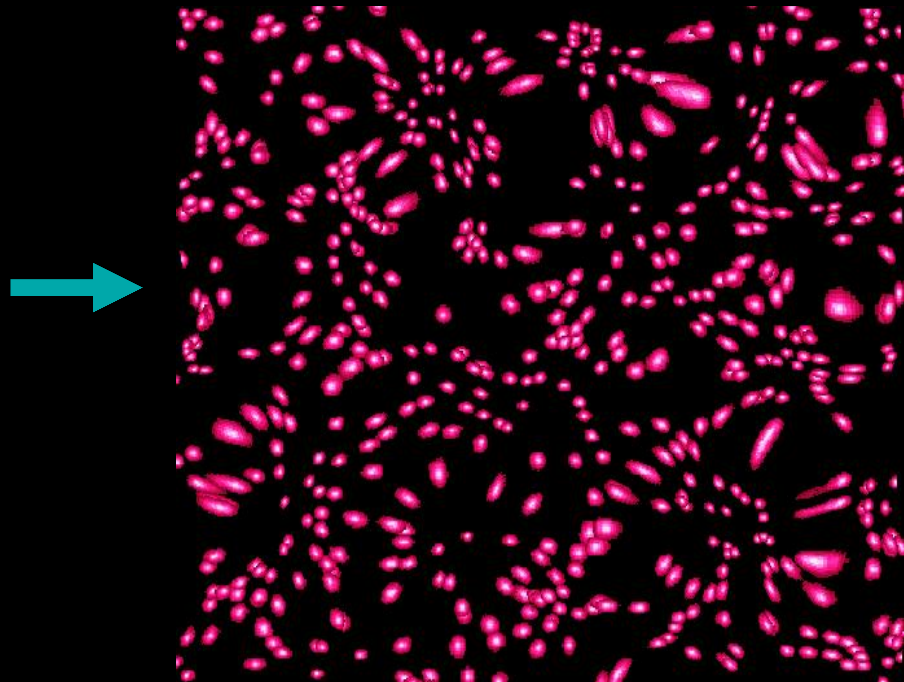




Distortion of background images by foreground matter



Unlensed



Lensed

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

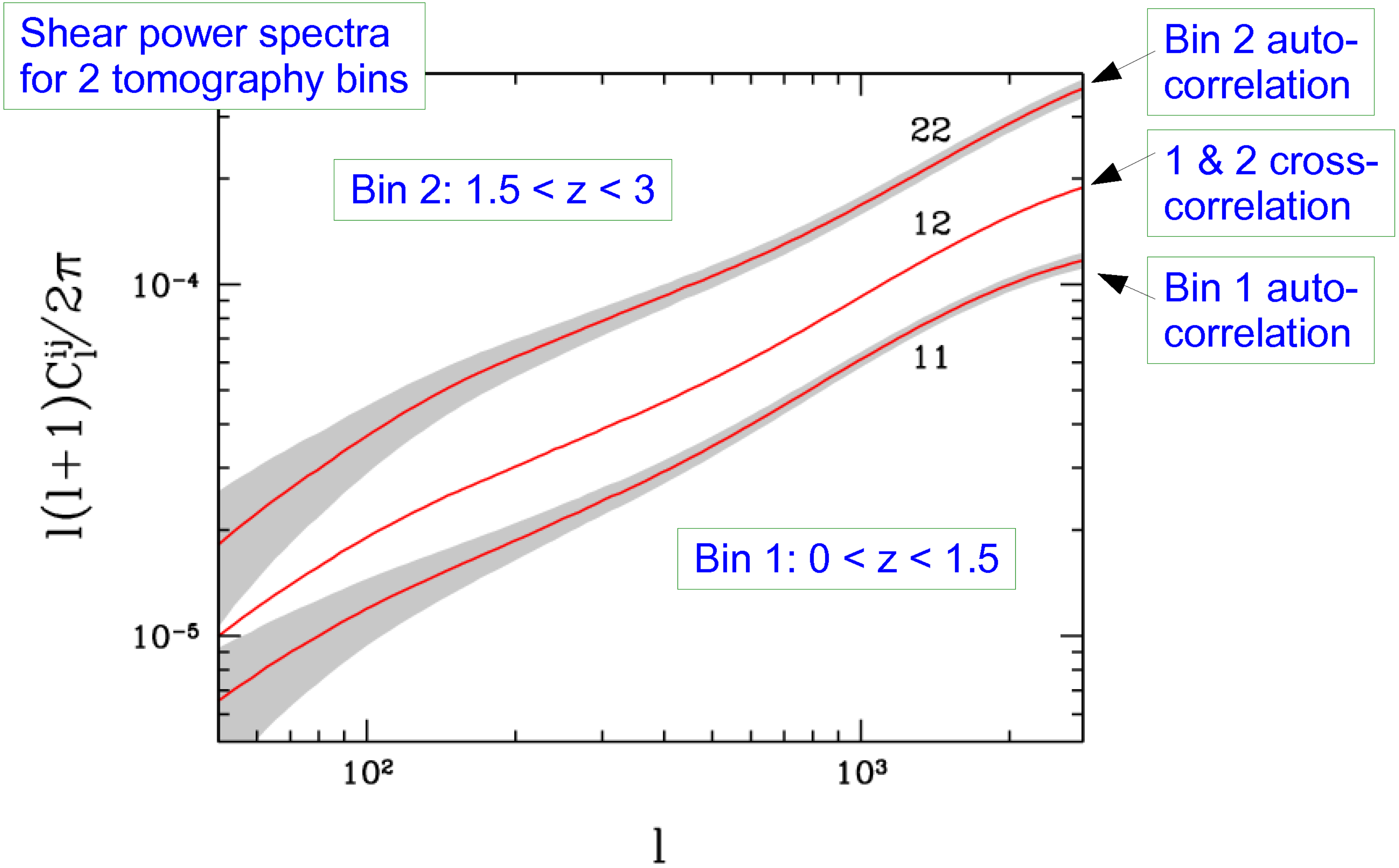
$$C_\ell = \frac{9}{16} H_0^4 \Omega_m^2 \int_0^{\chi_H} \left[\frac{g(\chi)}{a\chi} \right]^2 P(\ell / r, \chi) d\chi$$

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

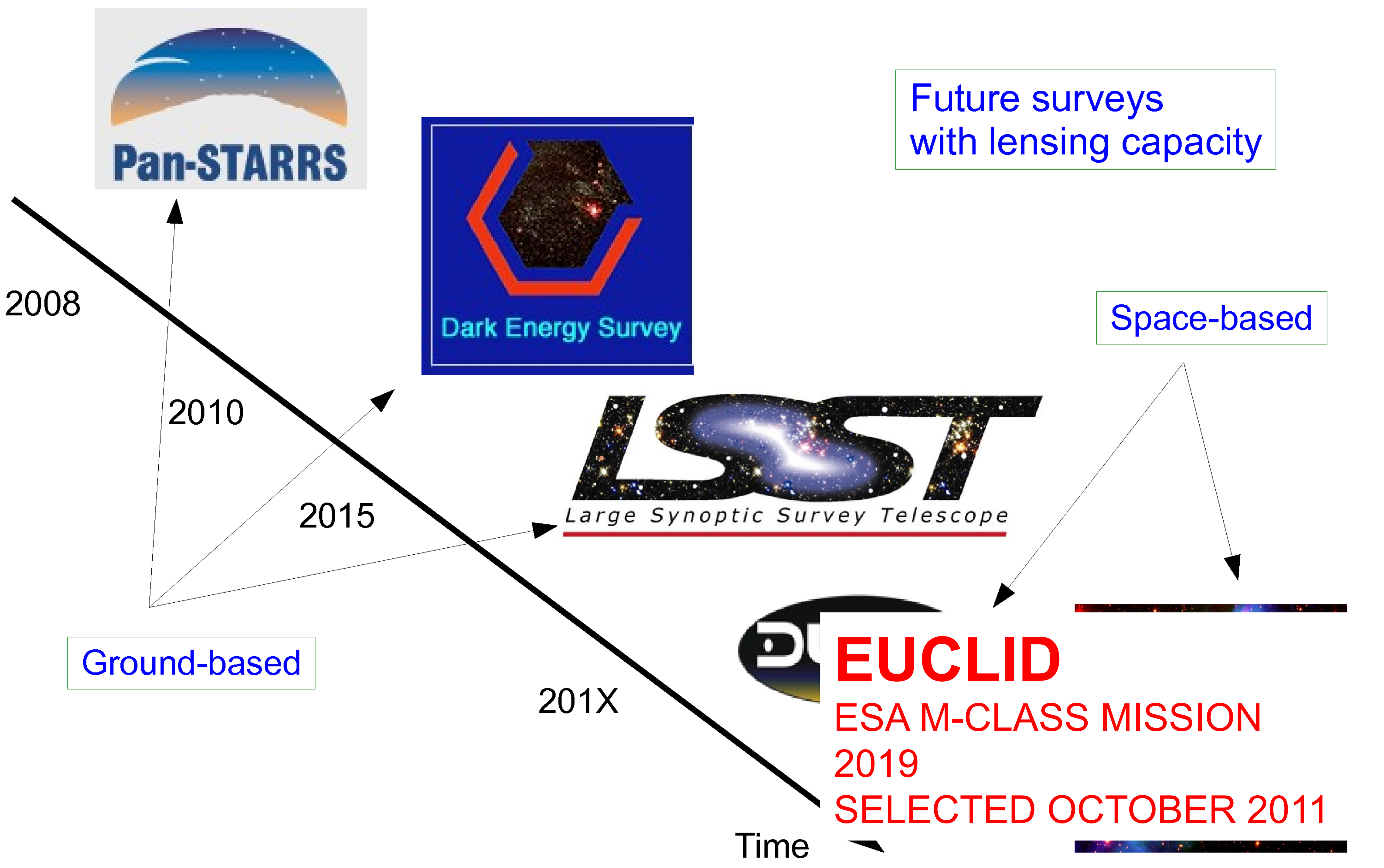
$$g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi'$$

WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY

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



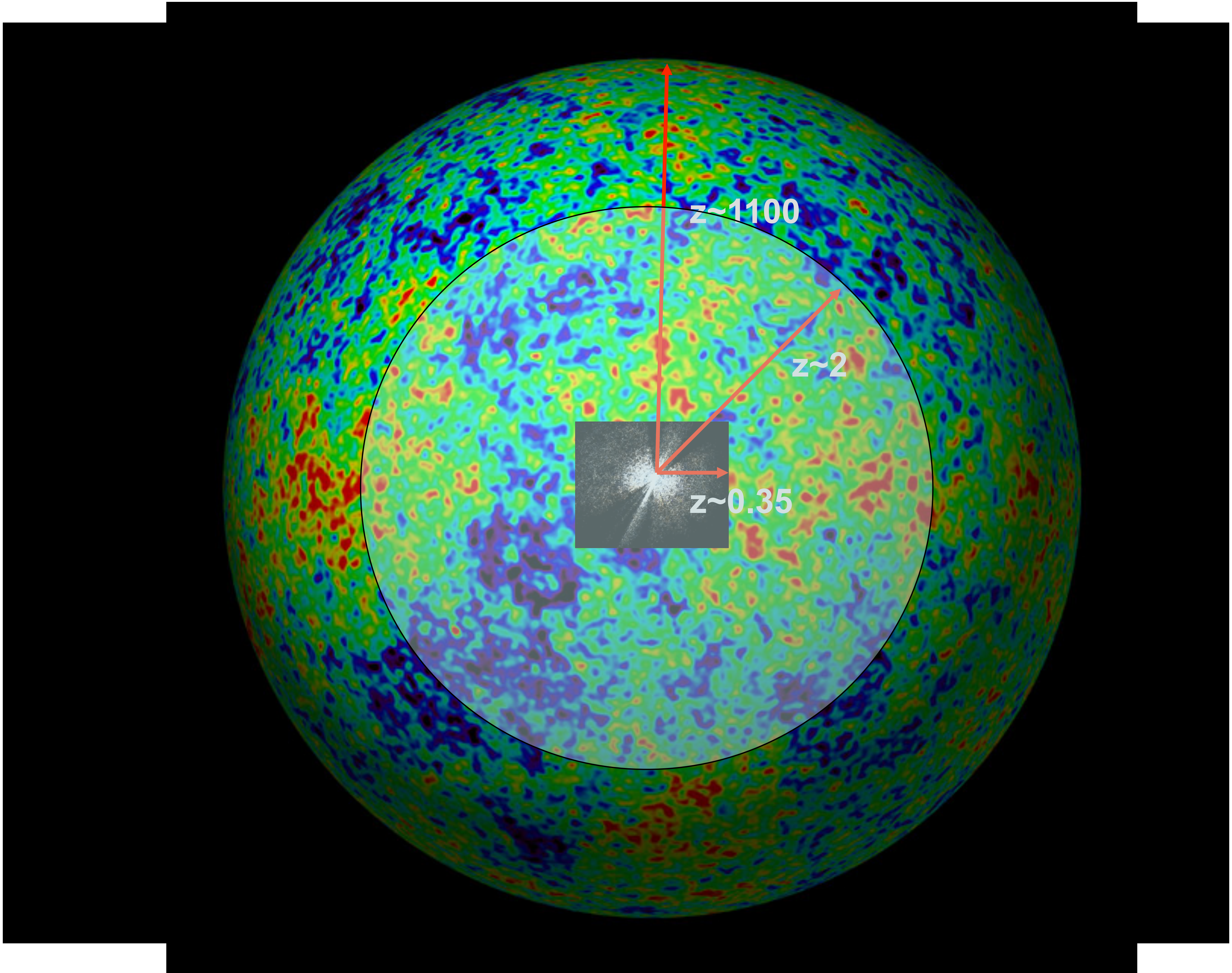
STH, TU, WONG 2006


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

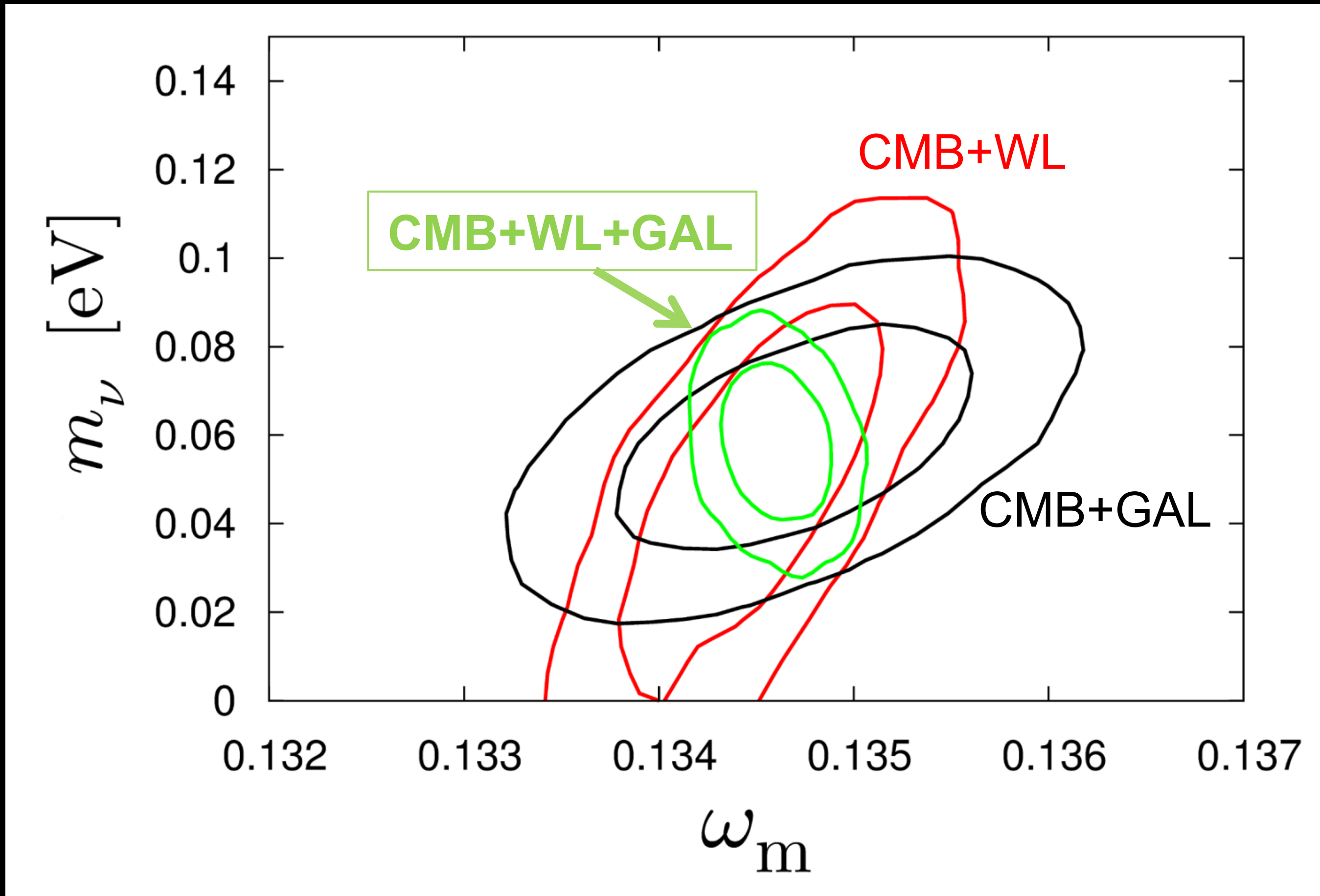
THE EUCLID MISSION

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

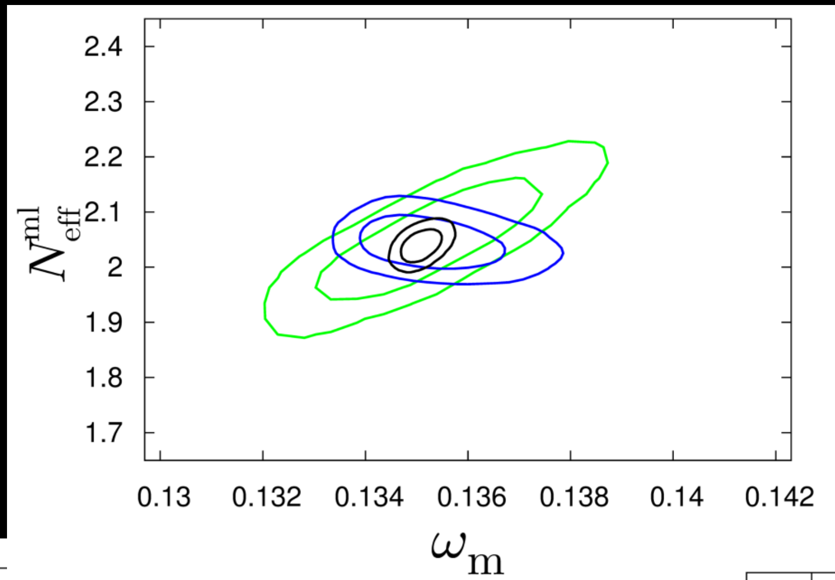

z~1100
z~2
z~0.35

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)

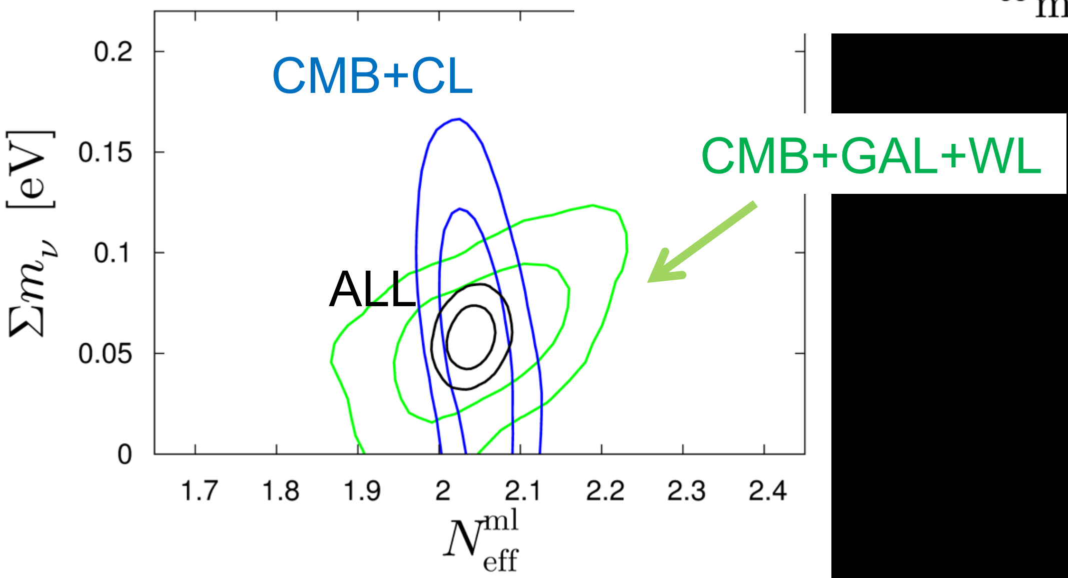


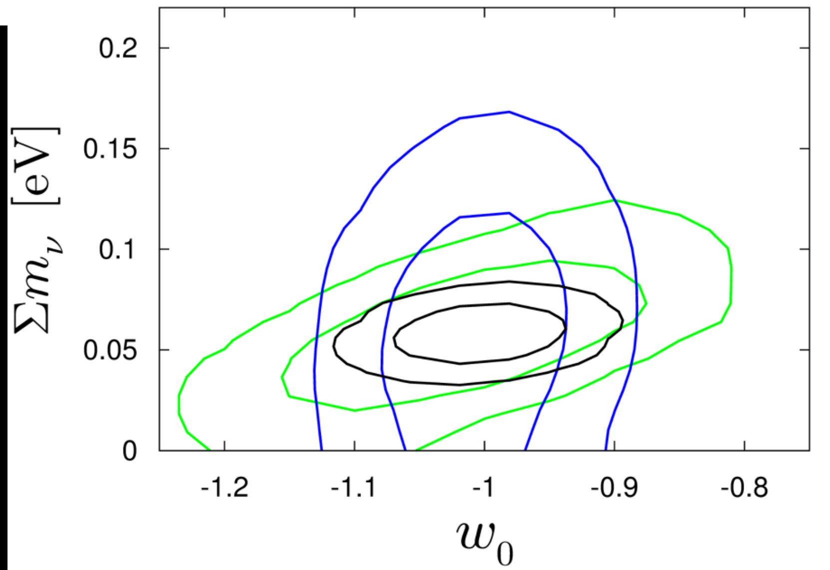
arXiv:1209.1043 (JCAP)

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



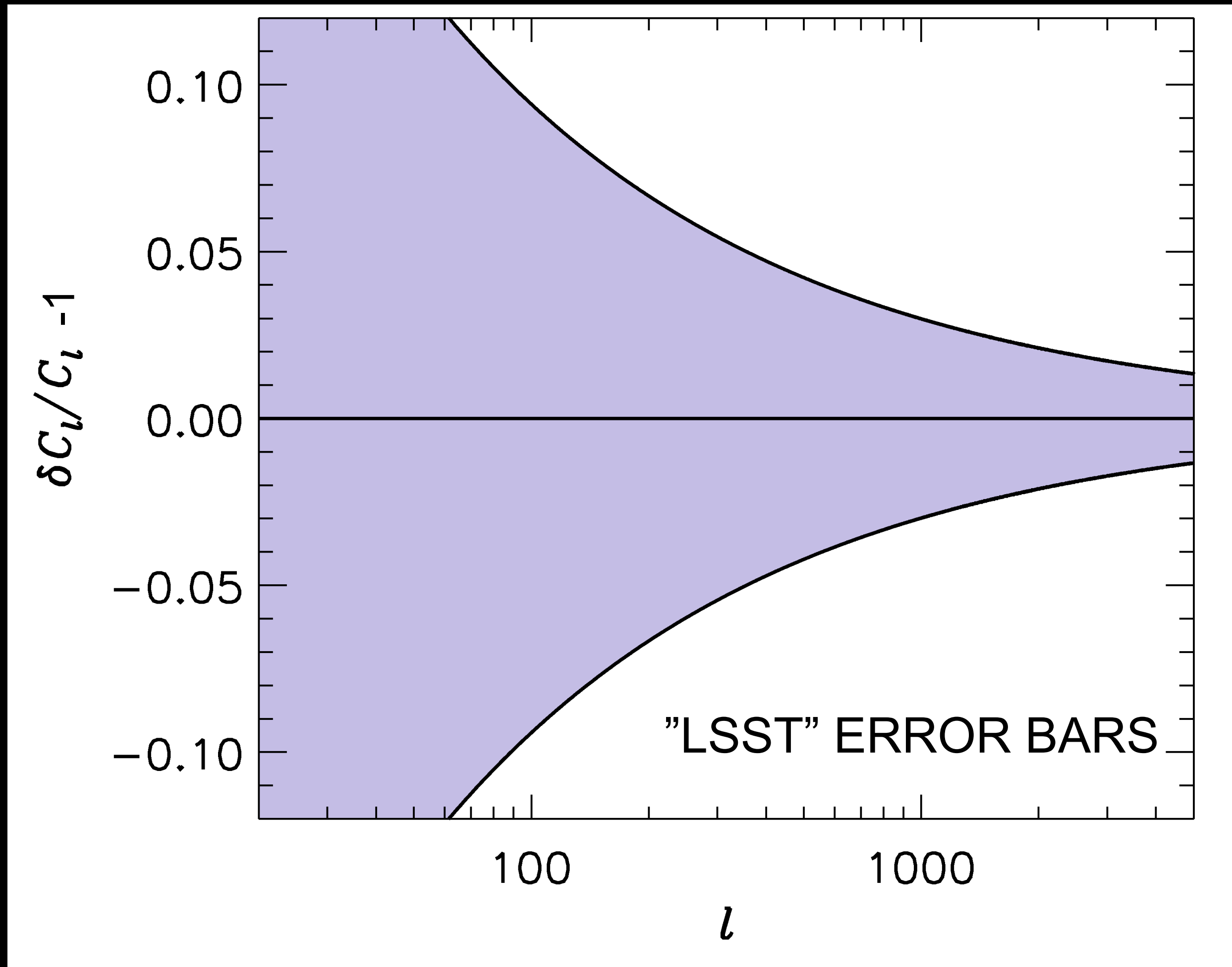
arXiv:1304.2321 (JCAP)





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

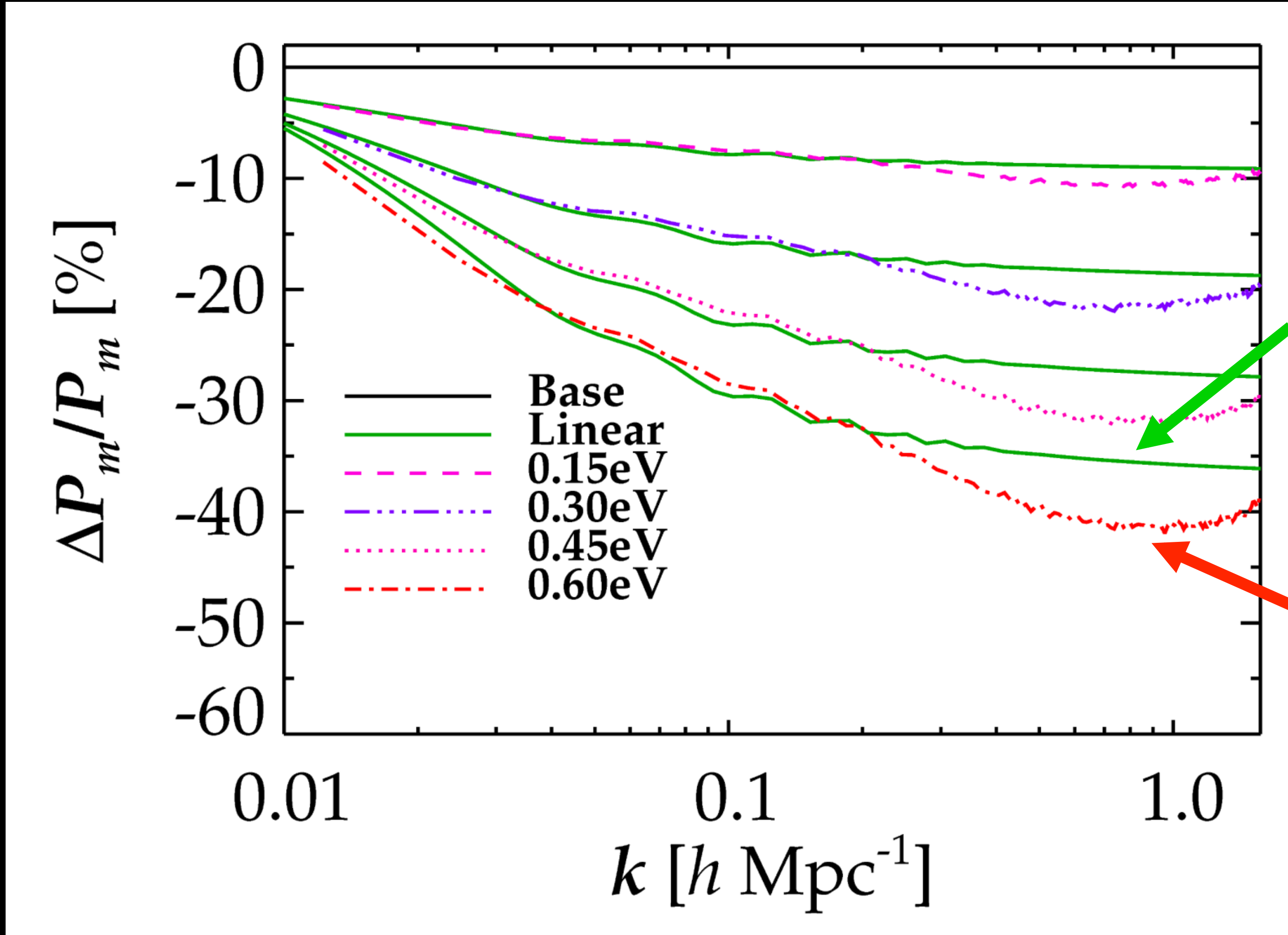


WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM
TO AT LEAST THE SAME PRECISION!

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

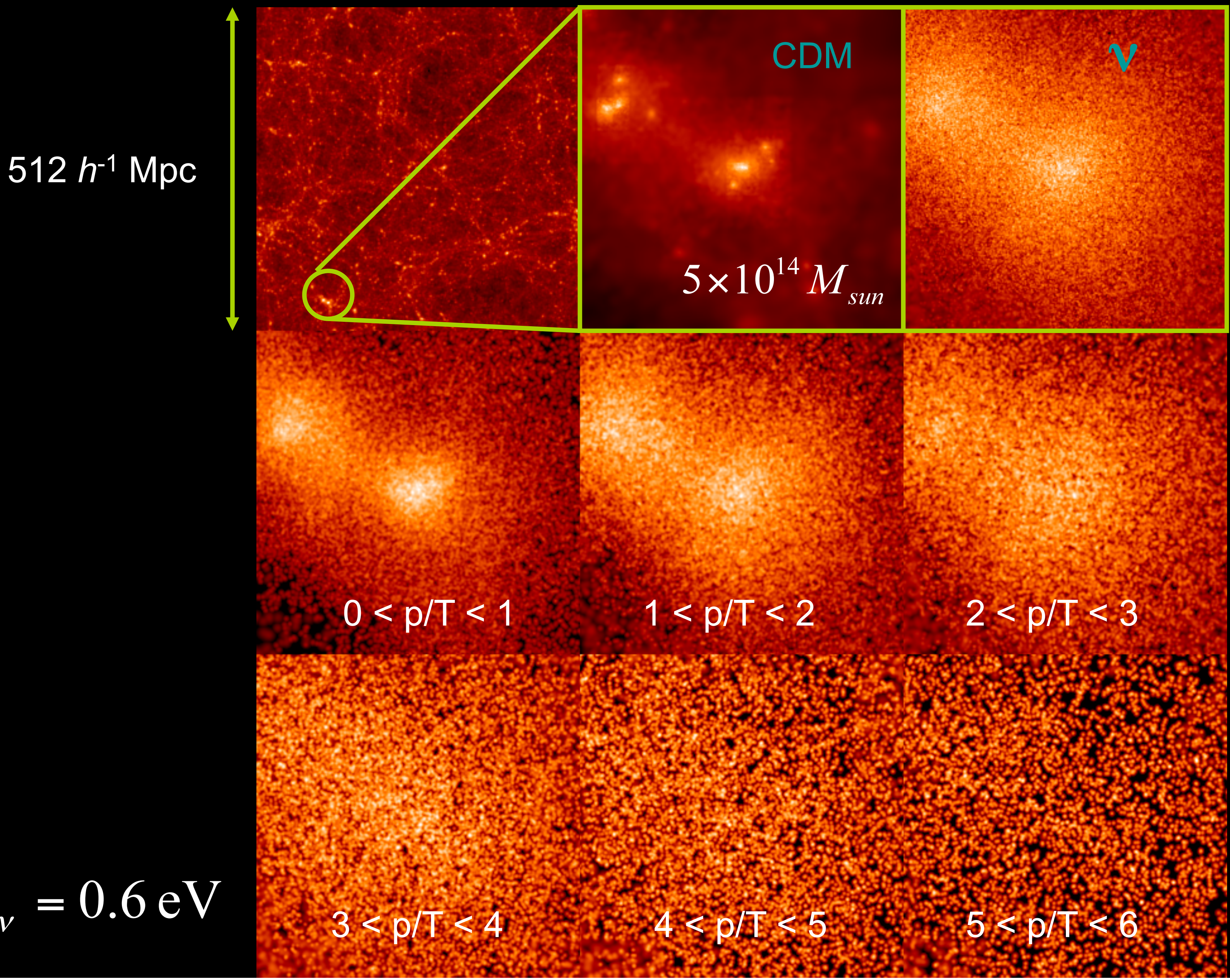
$$\frac{\Delta P}{P} \sim -8\frac{\Omega_\nu}{\Omega_m}$$

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



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

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 MAY PROVIDE A POSITIVE DETECTION OF A NON-ZERO NEUTRINO MASS