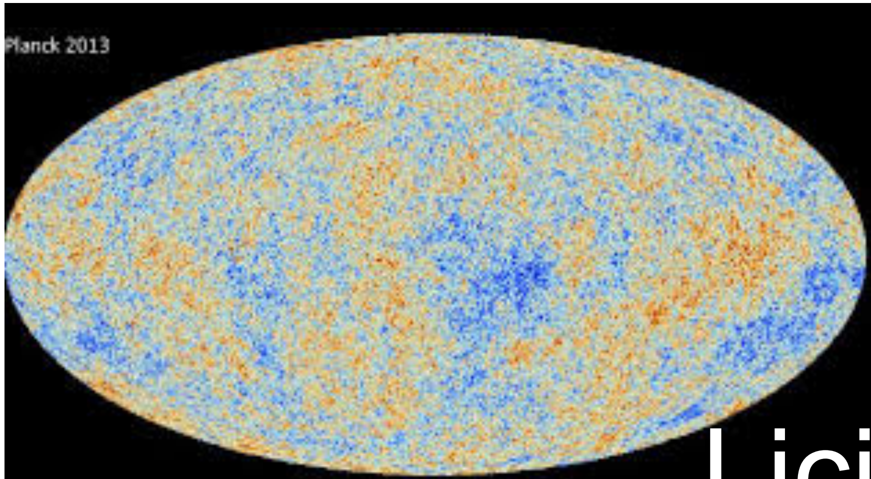

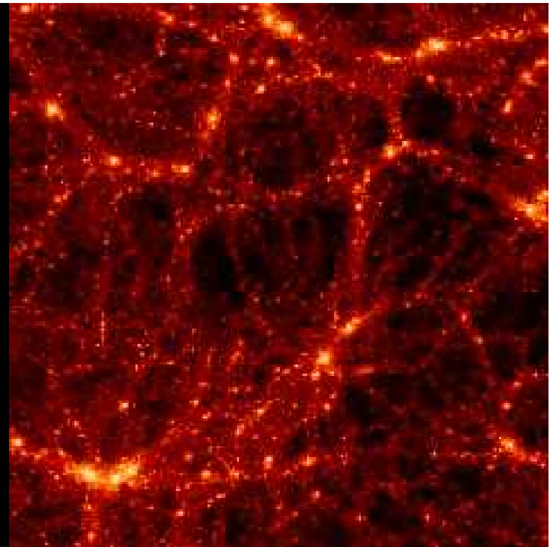

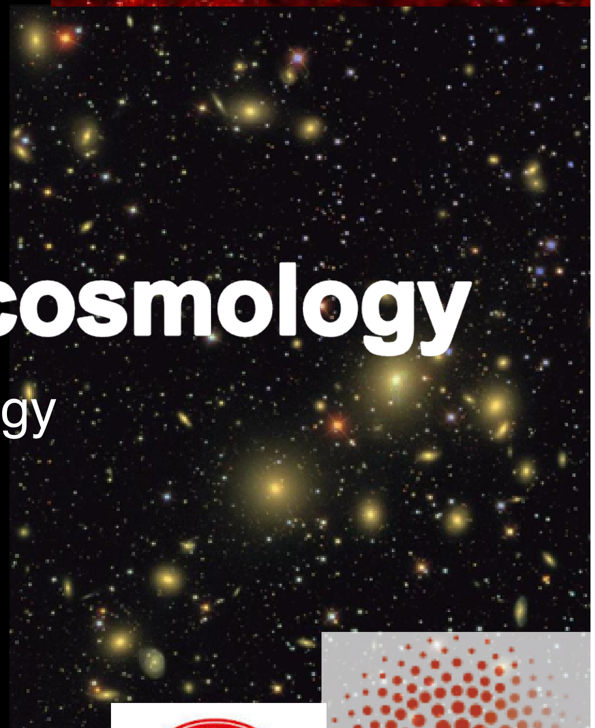

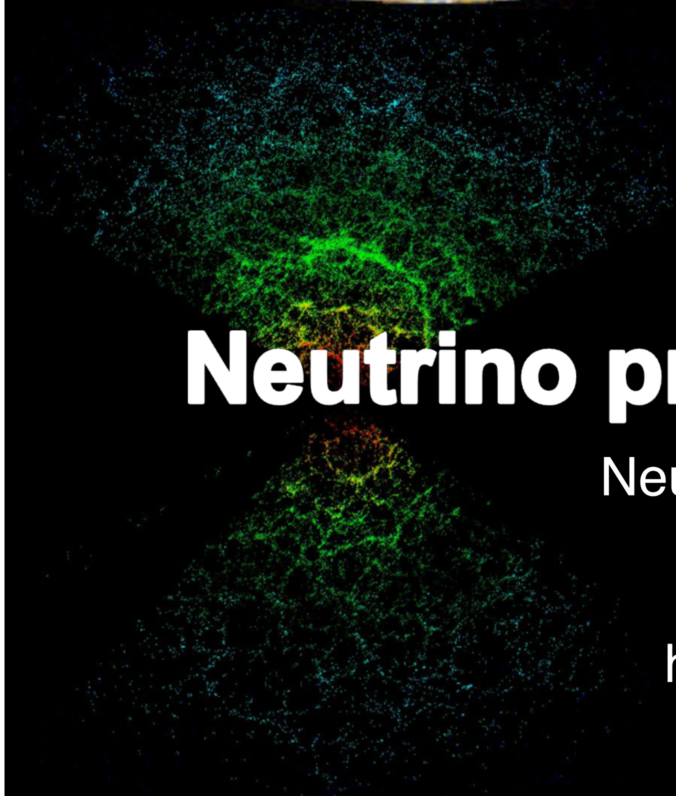

Licia Verde

ICREA & ICC-UB-IEEC
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OiU, Oslo, Norway

Neutrino properties and cosmology

Neutrino masses from cosmology

http://icc.ub.edu/~liciaverde

icrea Institució Catalana de Recerca i Estudis Avançats
ICCUB Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA
IEEC
UNIVERSITAS OSLOENSIS MDCCCXI
erc

Recent developments: data

CMB (Planck and ACT/SPT)

Sloan Digital Sky Survey BOSS, WIGGLEZ

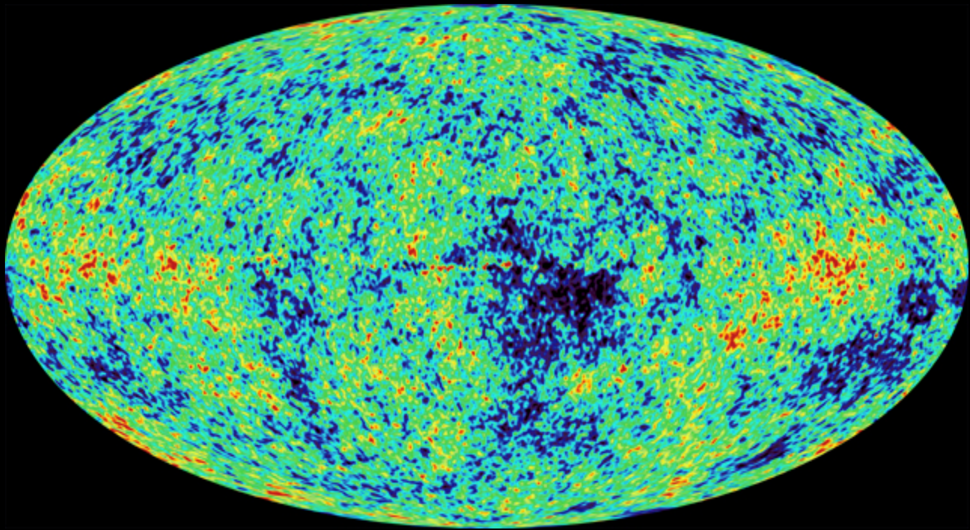
Baryon Acoustic Oscillations & clustering

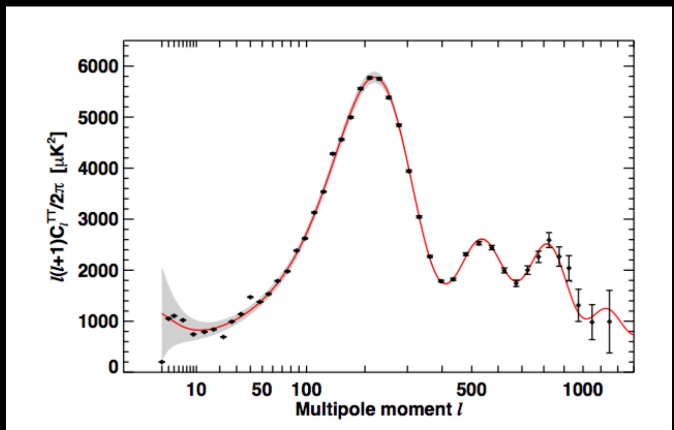
NEWS: FUTURE DATA

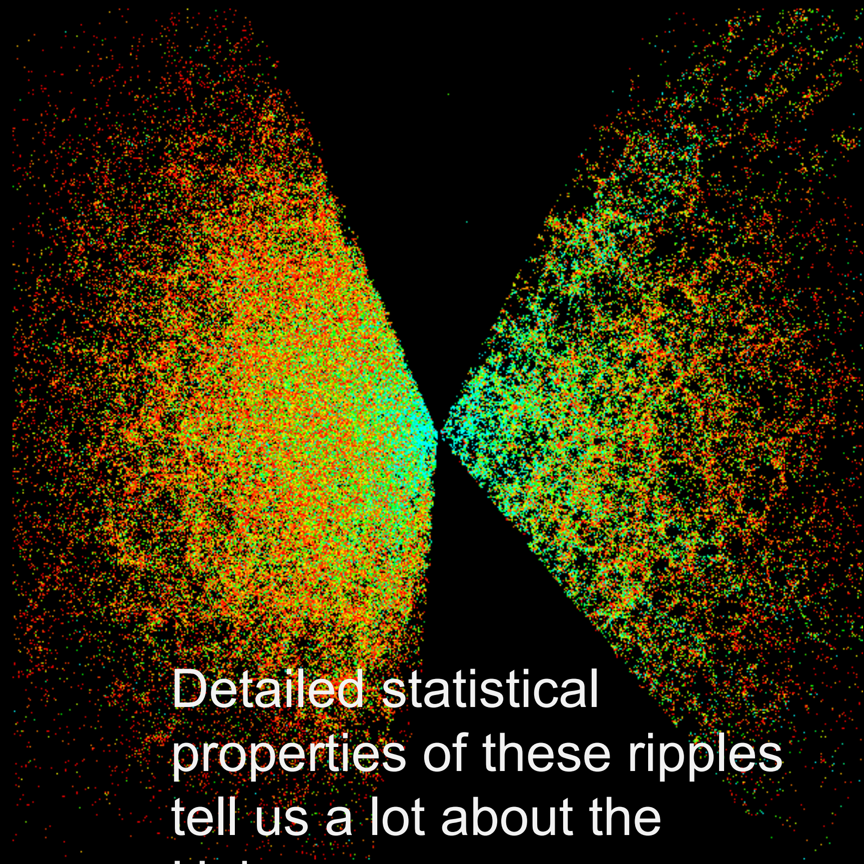
recent developments: theory

Better modeling of non-linearities via N-body simulations (and perturbation theory)

Avalanche of data over the last ~10 yr

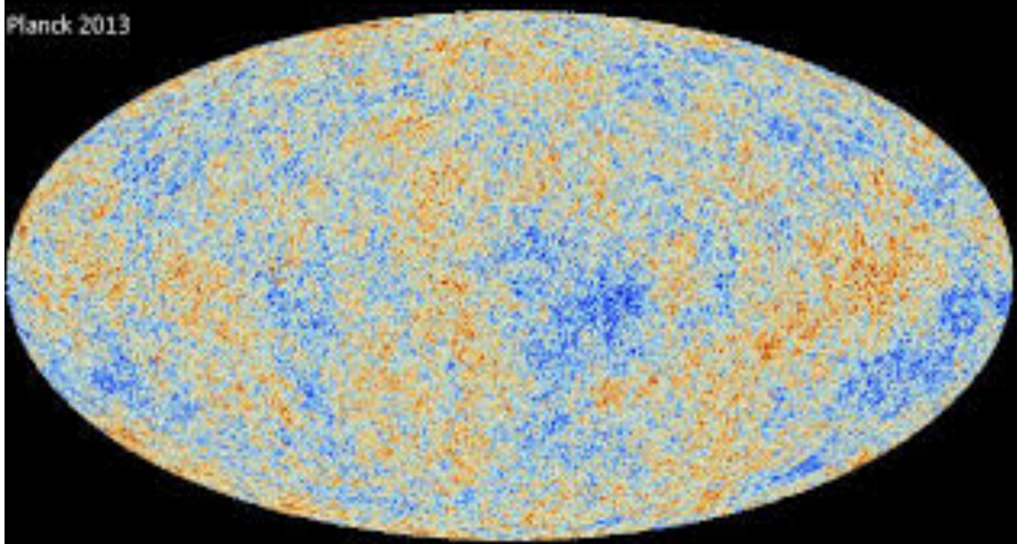


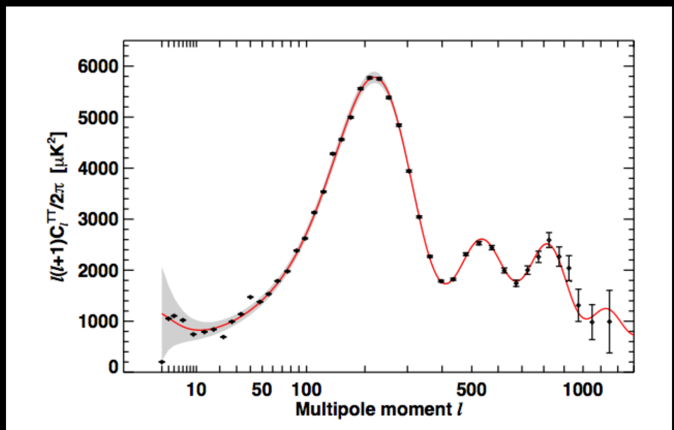


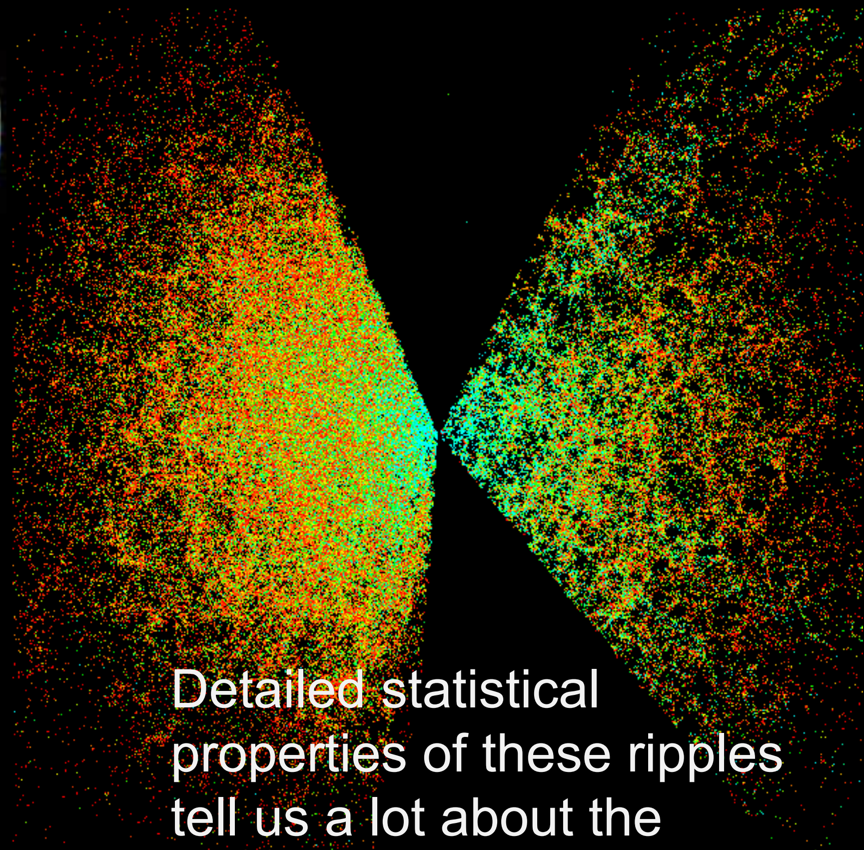


Detailed statistical properties of these ripples tell us a lot about the Universe

Avalanche of data over the last ~10 yr







Detailed statistical properties of these ripples tell us a lot about the Universe

Extremely successful standard cosmological model
Look for deviations from the standard model

Test physics on which it is based and beyond it

- Dark energy
- Nature of initial conditions: Adiabaticity, Gaussianity
- Neutrino properties
- Inflation properties
- Beyond the standard model physics…

ASIDE: We only have one observable universe

The curse of cosmology

We can only make observations (and only of the observable Universe) not experiments: we fit models (i.e. constrain numerical values of parameters) to the observations: <u>Any statement is model dependent</u>

Gastrophysics and non-linearities get in the way :
Different observations are more or less "trustable", it is however somewhat a question of personal taste (think about Standard & Poor's credit rating for countries): <u>Any statement depends on the data-set chosen</u>

Results will depend on the data you (are willing to) consider.
I try to use > A rating ;)

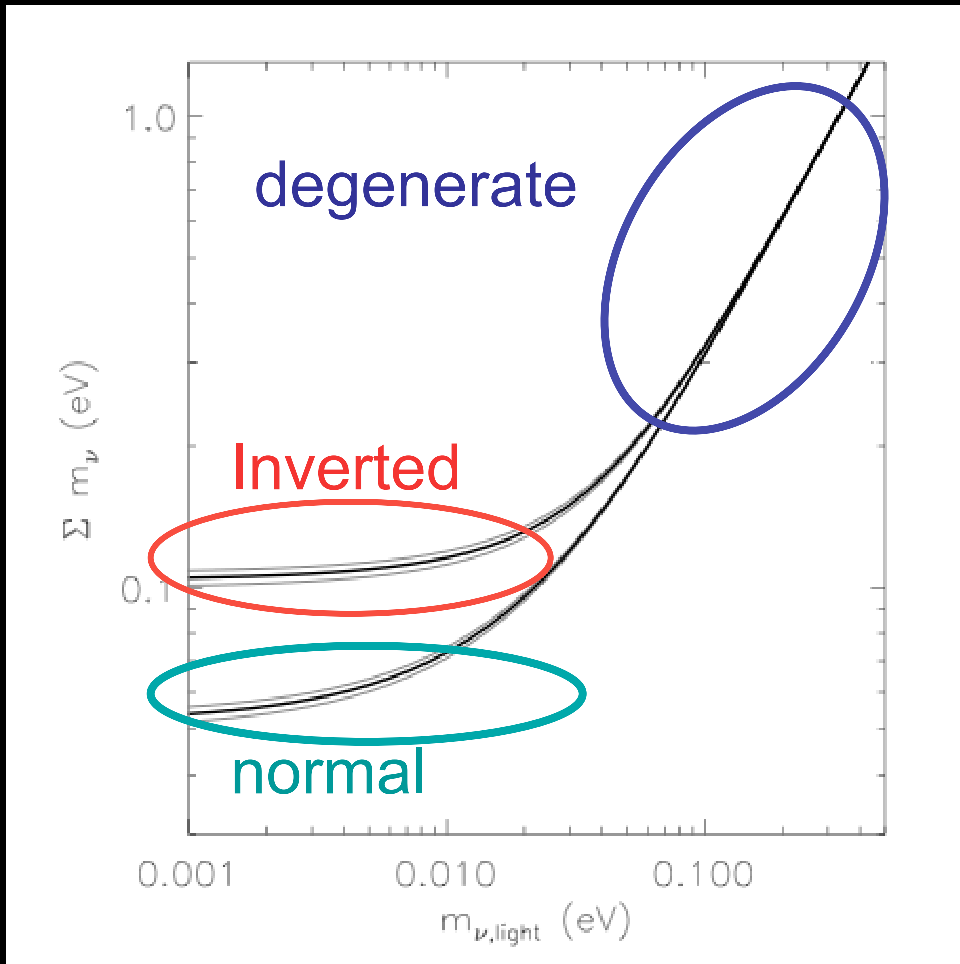
….And the Blessing

We can observe all there is to see

What is a neutrino? (for cosmology)

- Behaves like radiation at T~ eV (recombination/decoupling)
- Eventually (possibly) becomes non-relativistic, behaves like matter
- Small interactions (not perfect fluid)
- Has a high velocity dispersion (is “HOT”)

Cosmology is key in determining the absolute mass scale



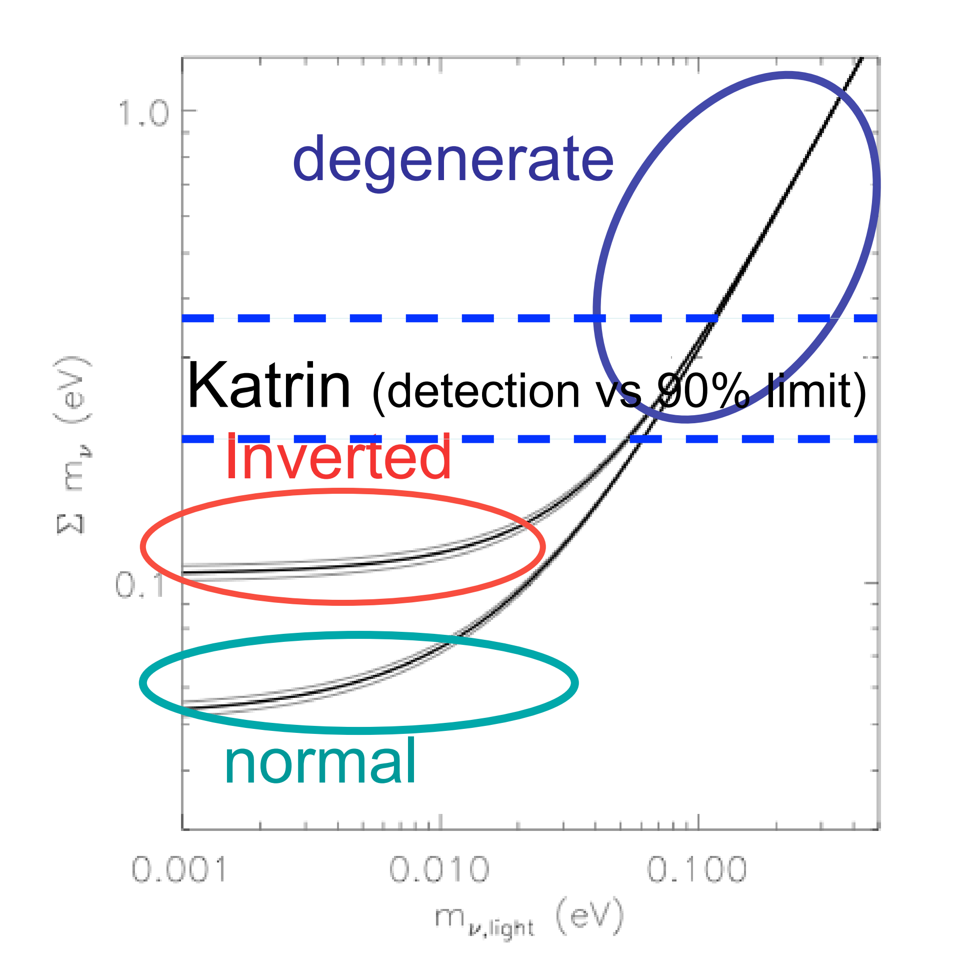
The problem is systematic errors

This means that neutrinos contribute at least to ~0.5% of the total matter density

The KATRIN Experiment

Ambitious terrestrial experiment

Cosmology is key in determining the absolute mass scale

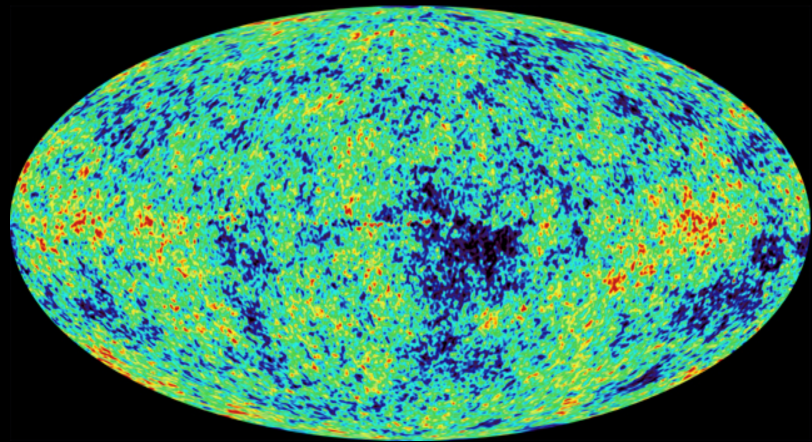


The problem is systematic errors

This means that neutrinos contribute at least to ~0.5% of the total matter density

Cosmic Neutrino Background

A relict of the big bang, similar to the CMB except that the CvB decouples from matter after 2s (~ MeV) not 380,000 years



At decoupling they are still relativistic ($m\nu << T\nu$) ➔ large velocity dispersions (1eV ~ 100 Km/s)

Recall:
T~1eV Matter-radiation equality,
T=0.26eV Recombination

60Billion nu/s/cm^2 from the sun
~100nu/cm^3 from CvB

For aficionados

- Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature 1MeV
- We then have today a Cosmological Neutrino Background at a temperature

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

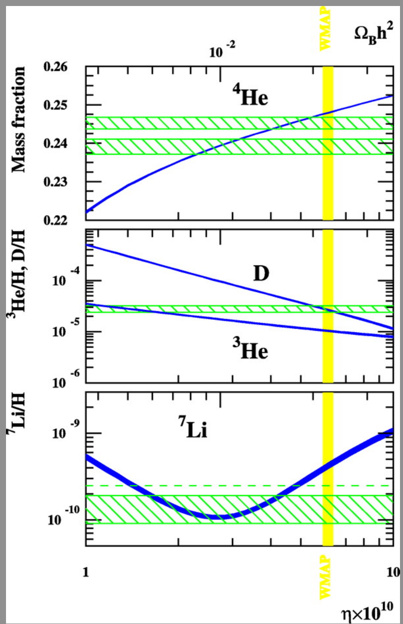
That, for a massive neutrino translates in:

$$\Omega_\nu = \frac{n_{\nu_k,\bar{\nu}_k} m_\nu}{\rho_c} \approx \frac{1}{h^2}\frac{m_\nu}{93.2eV} \Rightarrow \Omega_\nu h^2 = \frac{\sum_\nu m_\nu}{93.2eV}$$

Neutrinos affect the growth of cosmic clustering so they can leave key imprints on the cosmological observables

Relict neutrinos influence in cosmology

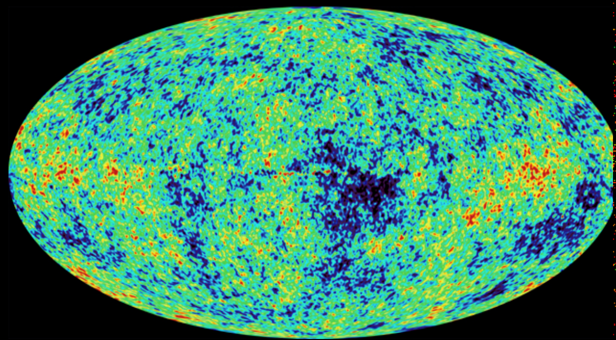
Primordial nucleosynthesis



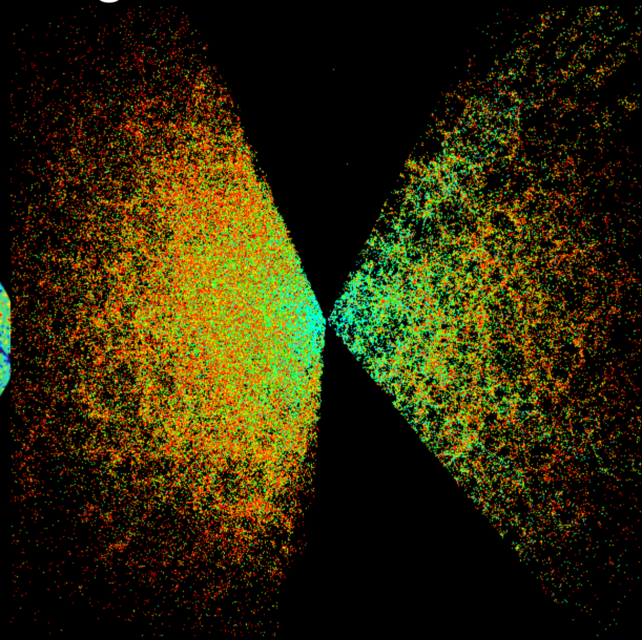
T~ MeV

N_{eff}

CMB



Large-scale structure



T<eV

N_{eff} mass

Neutrino mass: Physical effects

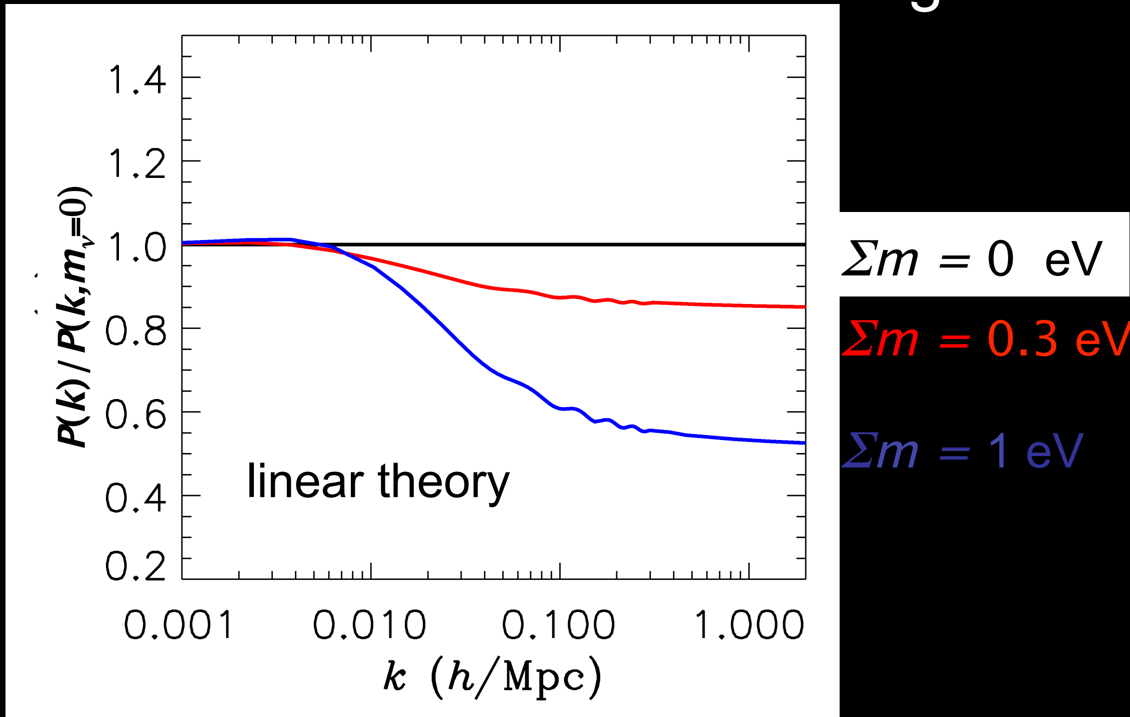
Total mass >~1 eV become non relativistic before recombination CMB

Total mass <~1 eV become non relativistic after recombination: alters matter-radn equality but effect can be "cancelled" by other parameters

CMB Degeneracy

After recombination

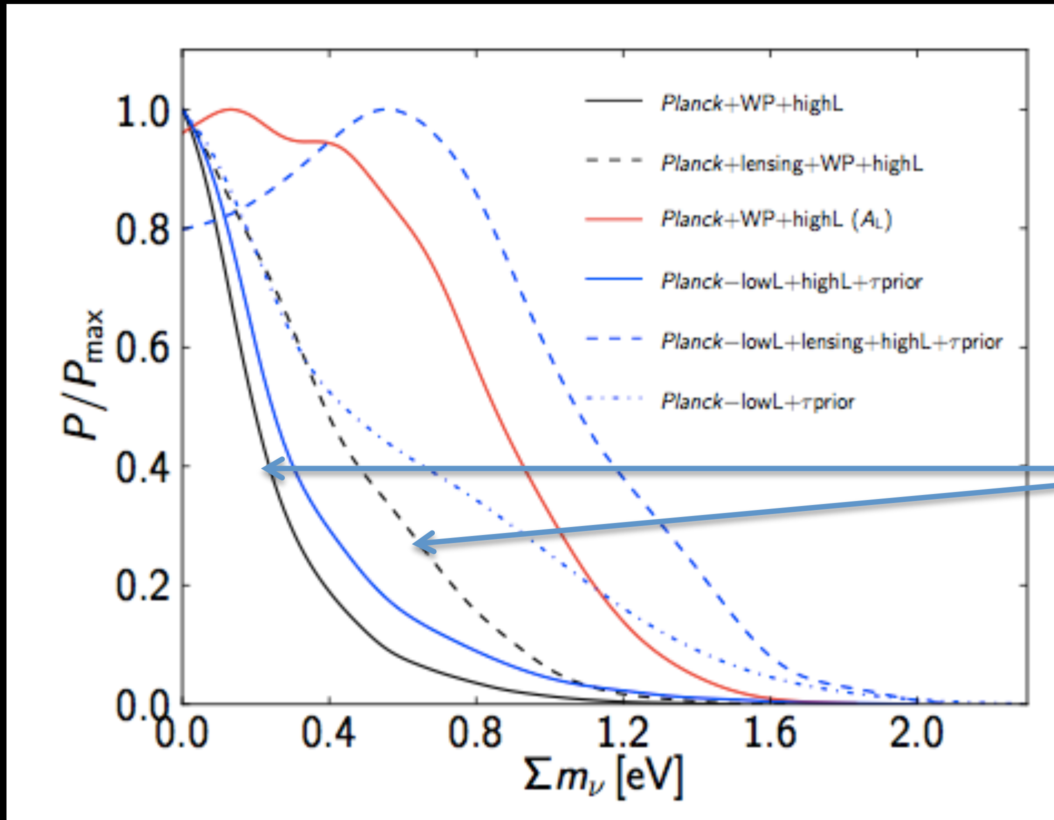
FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



Different masses become non-relativistic a slightly different times
Cosmology can yield information about neutrino mass hierarchy

The CMB (Planck) has spoken:

Planck collaboration, 2013, paper XVI



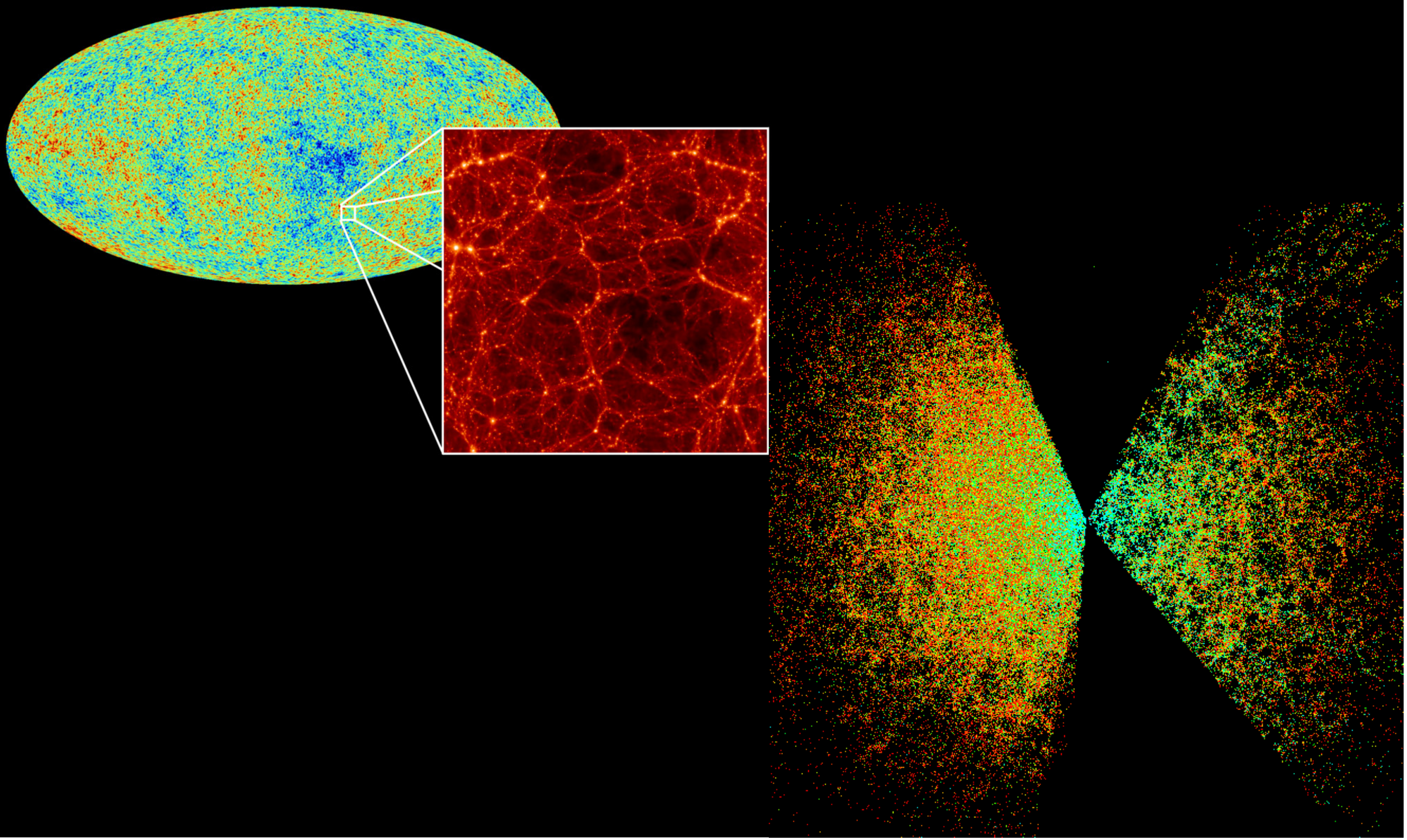
Concentrate on These 2 lines

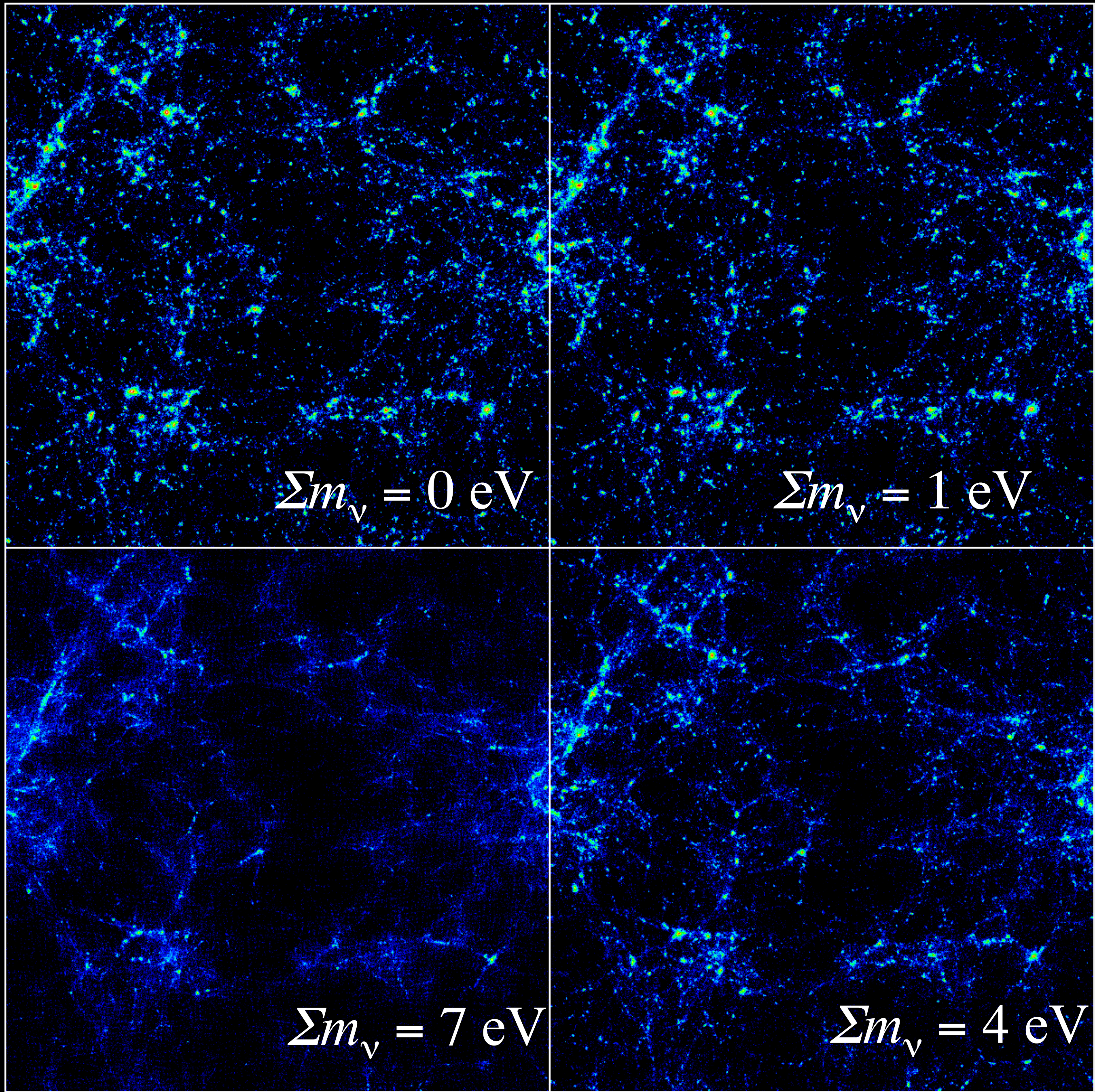
$\sum m_\nu < 0.66\,\mathrm{eV}$ (95%; *Planck*+WP+highL).

$\sum m_\nu < 0.23\,\mathrm{eV}$ (95%; *Planck*+WP+highL+BAO).

$\sum m_\nu < 0.85\,\mathrm{eV}$ (95%; *Planck*+lensing+WP+highL),

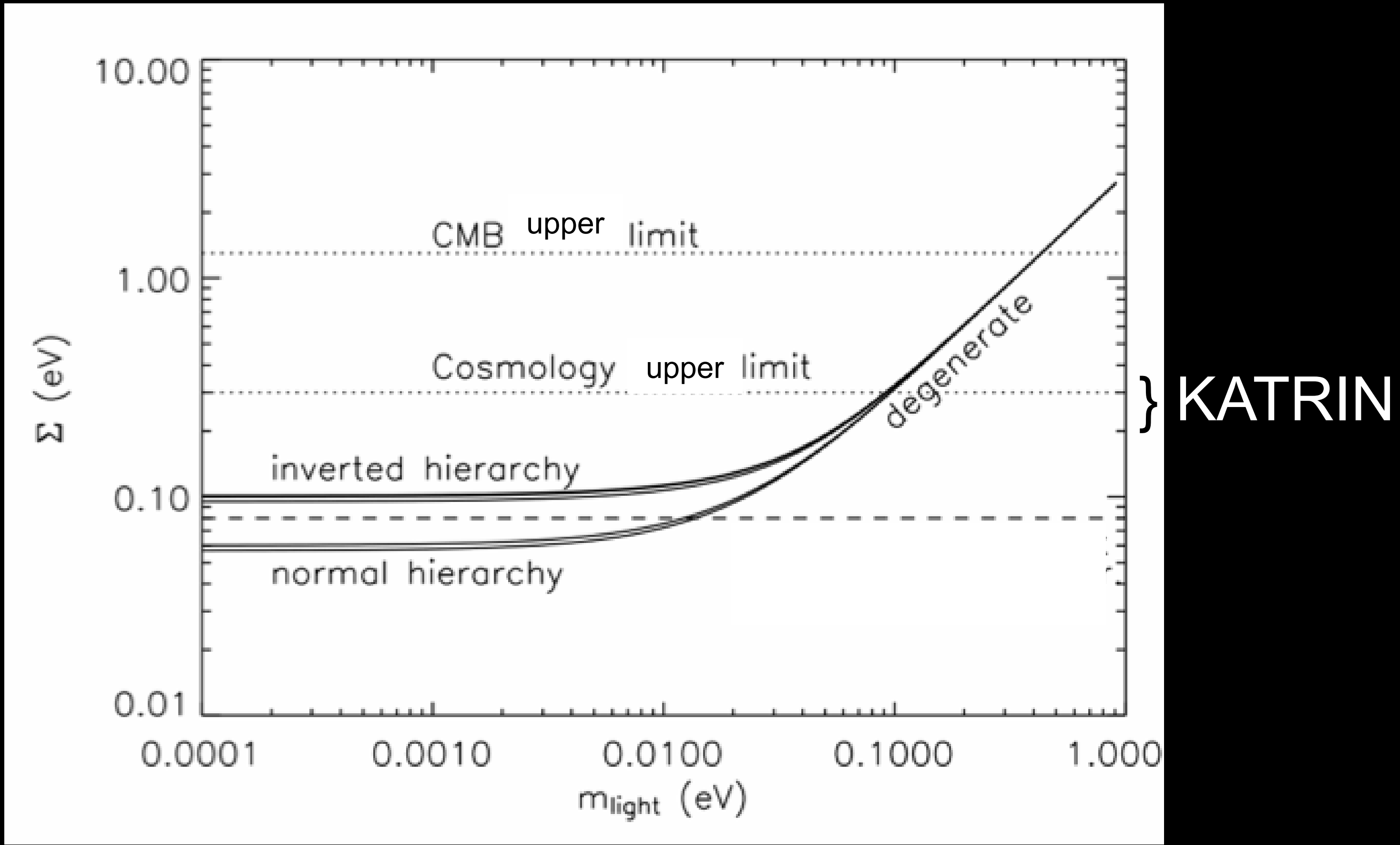
Explore low(er)-redshift Universe





Ma ’96

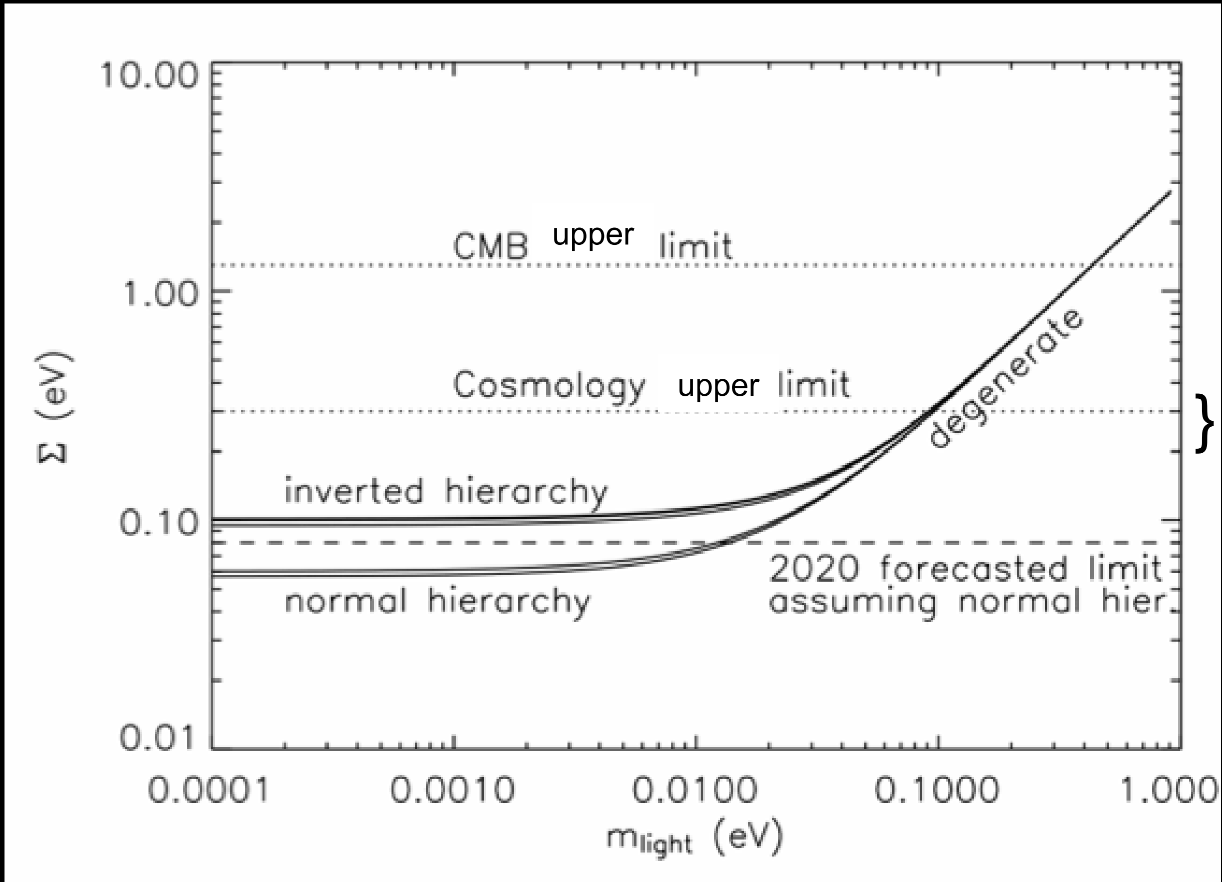
The Cosmology limits



Σ<0.3 (95%CL) in a minimal LCDM scenario

Until recently (pre-Planck) was the consensus

The Cosmology limits

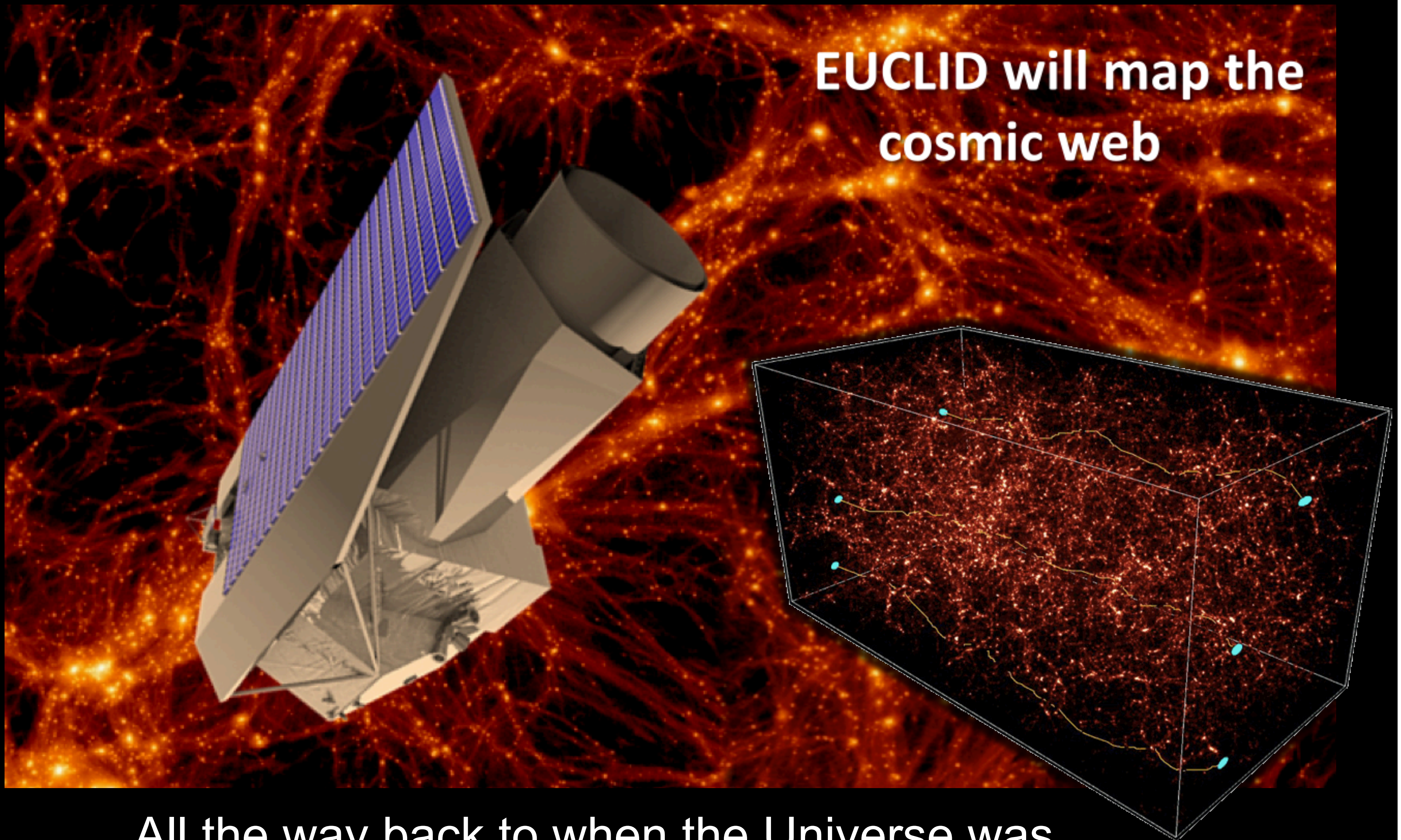


} KATRIN

Σ<0.3 (95%CL) in a minimal LCDM scenario

Until recently (pre-Planck) was the consensus

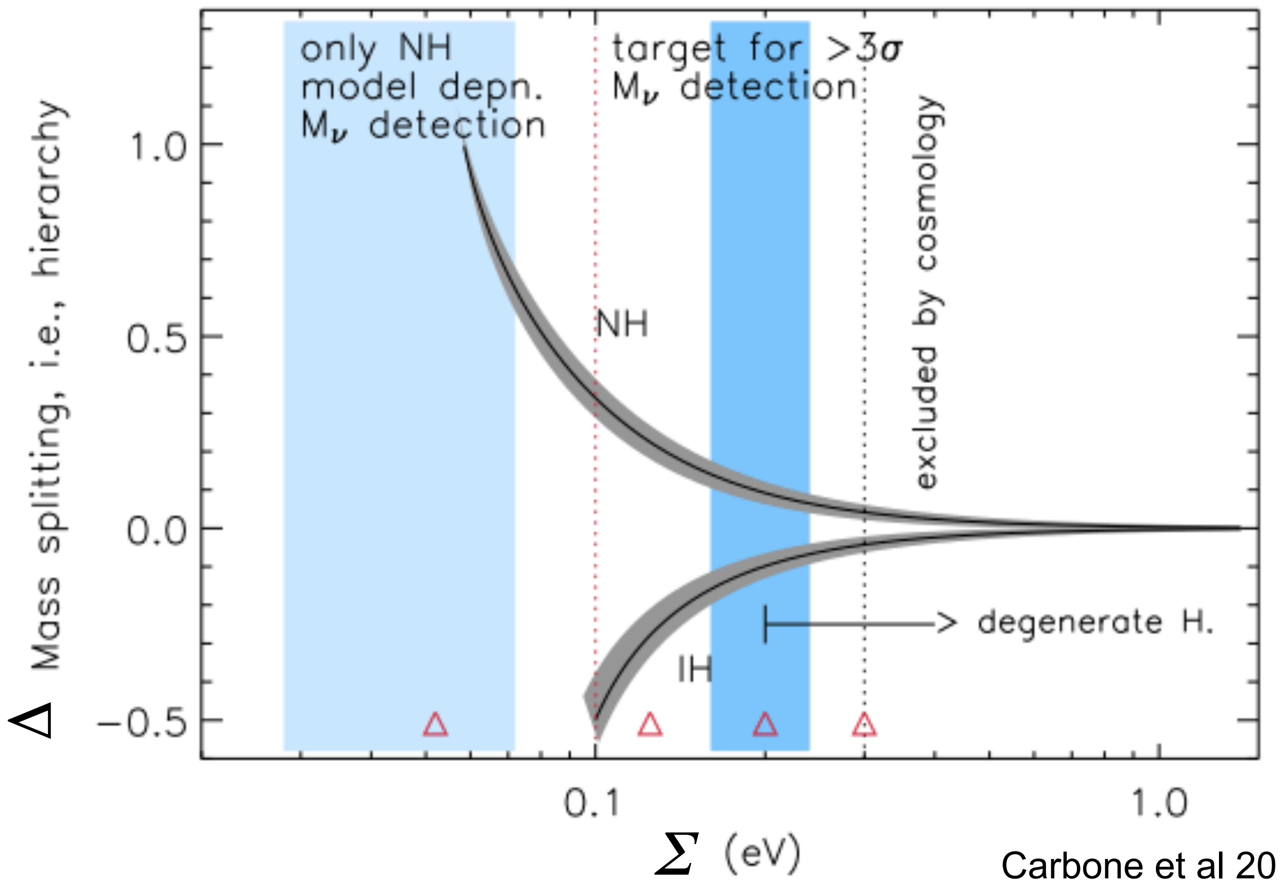
In the future



All the way back to when the Universe was
1/3 of current size and less than ¼ of current age

The Role of Euclid: forecasts

$$\mathrm{NH}: \quad \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma$$
$$\mathrm{IH}: \quad \Sigma = m + 2M \quad \Delta = (m - M)/\Sigma$$



Carbone et al 2011

Detailed errors depend on what assumptions about underlying cosmology one is willing to make

Different groups working independently agree

Beware of systematics!!!!!

It would be of great value to have an internal consistency check
(more later)

What about non-linearities?

Approaches: Analytic i.e. Perturbation theory e.g., Saito et al.

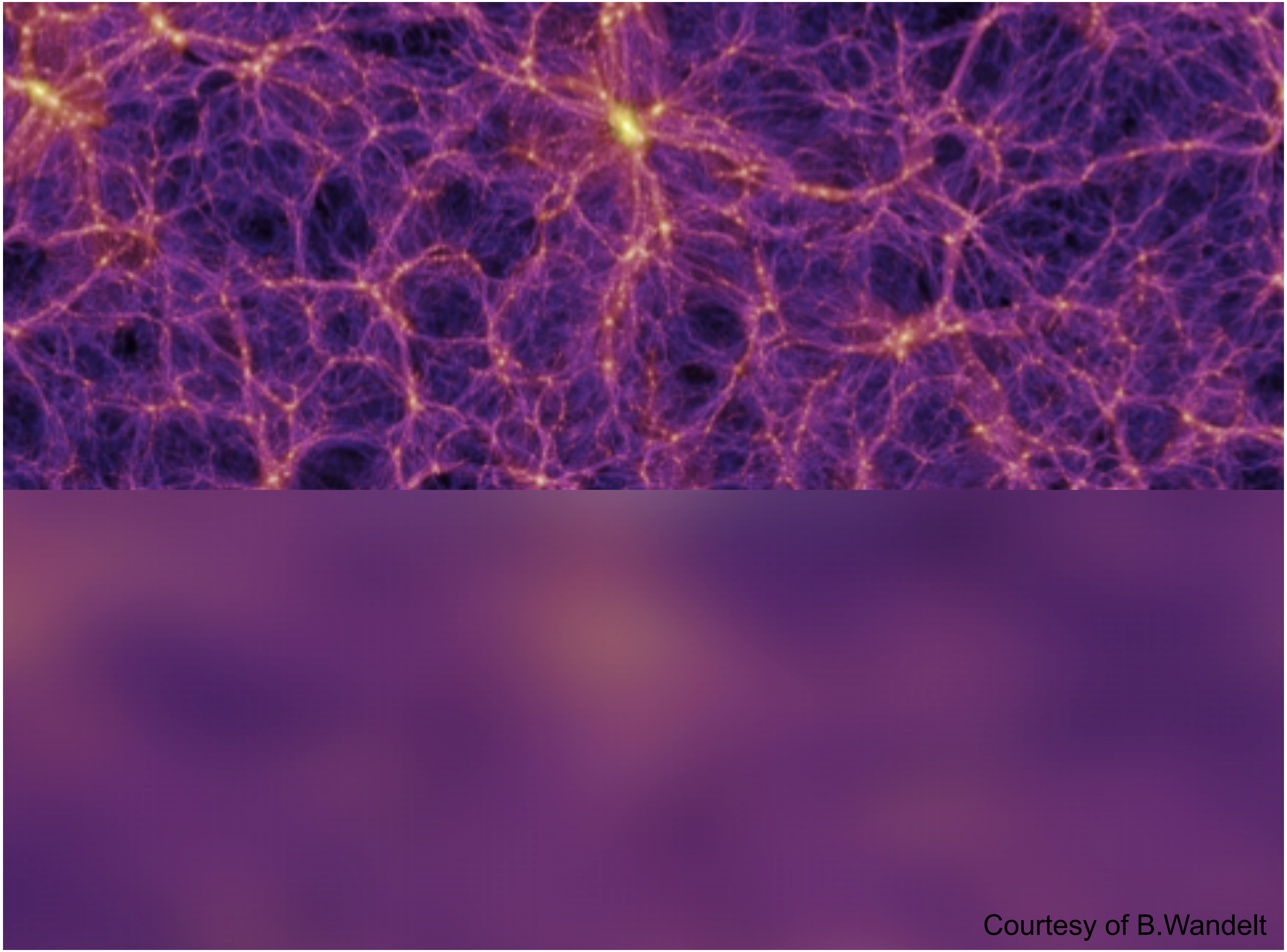
N-body Simulations Bandbyge, Hannestad et al.
Viel, Springel et al.

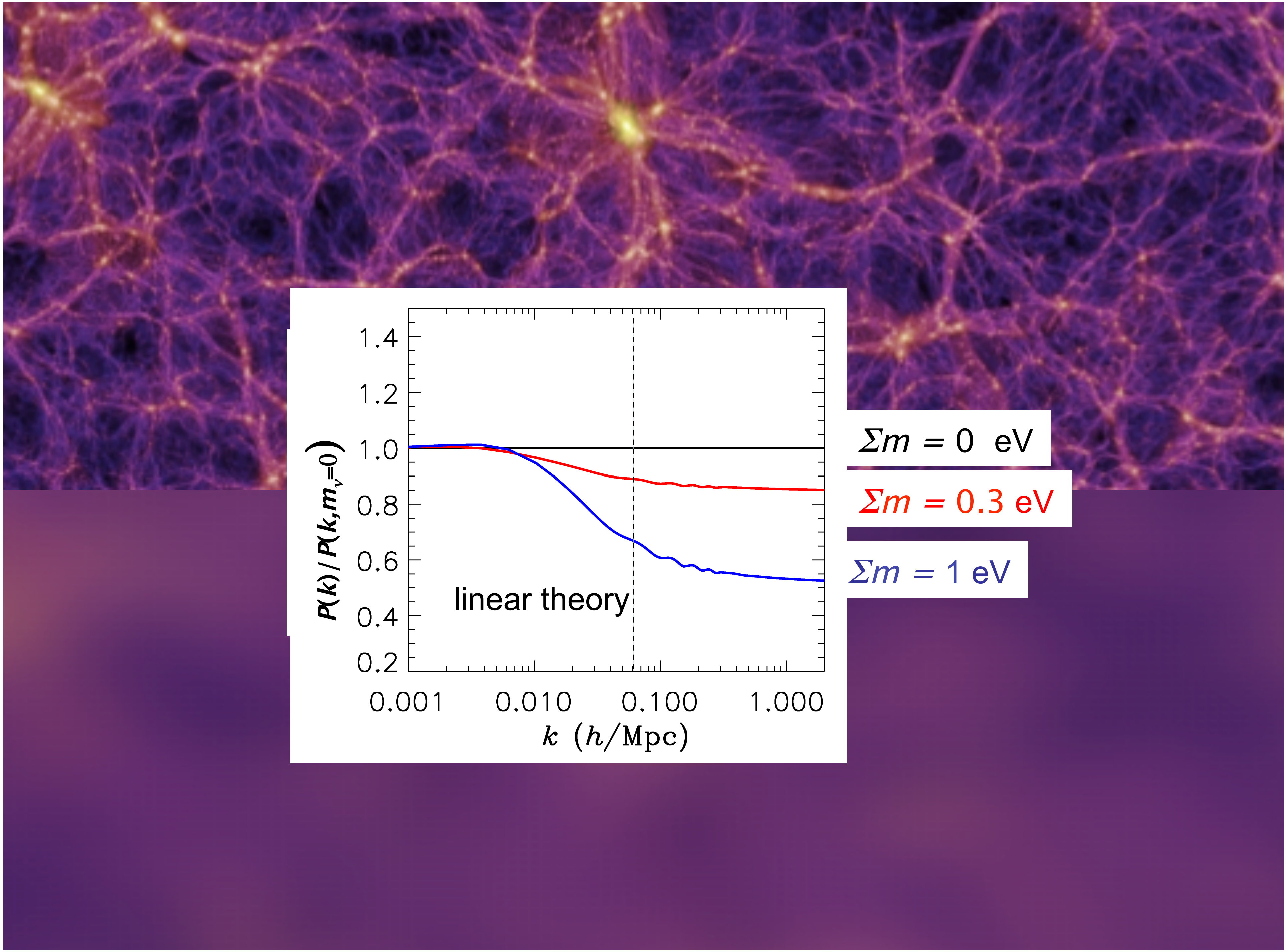
Intermediate: Agarval &Feldman

Options:

Simulate just neutrino masses	Use particles Use grids Use hybrid

Simulate also hierarchy

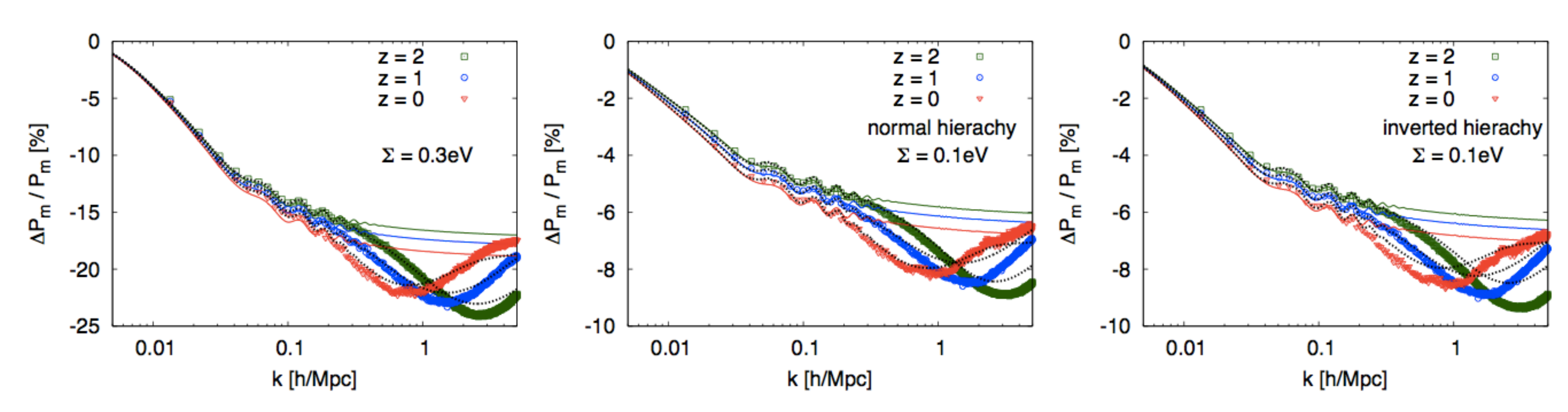

Courtesy of B.Wandelt



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.001
0.010
0.100
1.000
k (h/Mpc)
$P(k)/P(k,m_\nu=0)$
linear theory
Σm = 0 eV
Σm = 0.3 eV
Σm = 1 eV

Neutrinos effect on the matter P(k)

Σ (total mass)



Note that non-linearities enhance the signal

This is for MATTER in real space

Current constraints:Σ<0.3eV

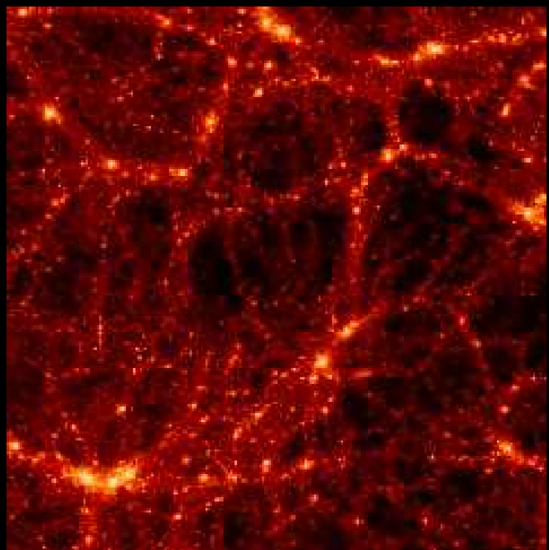
The future is bright!

Wagner, LV, Jimenez, 2012

What about real world effects?

- Baryonic physics (lensing and galaxy surveys)
- Bias (galaxy surveys)
- redshift space (galaxy surveys)

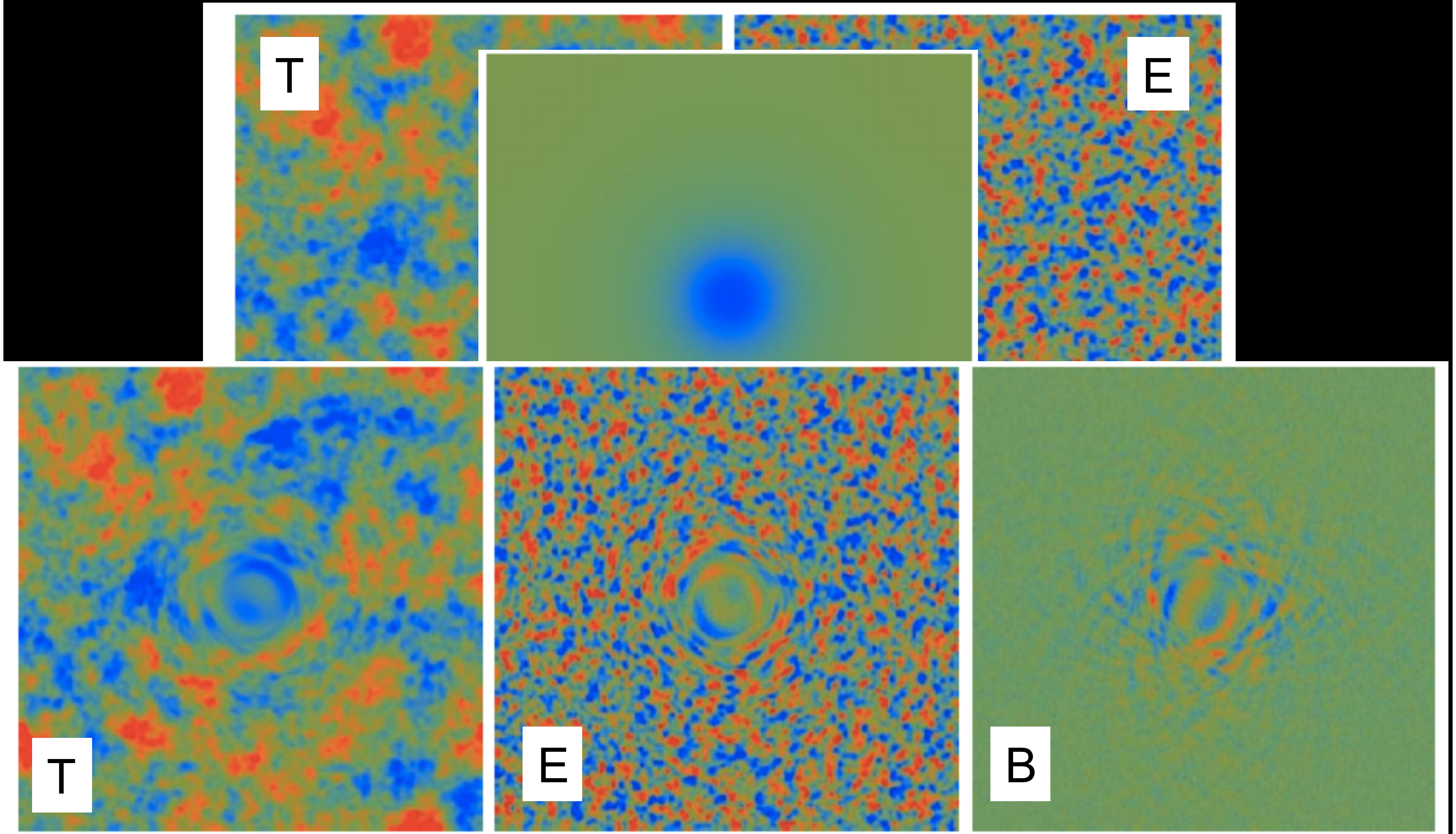
Active research area!



CMB back to the rescue

Lensing

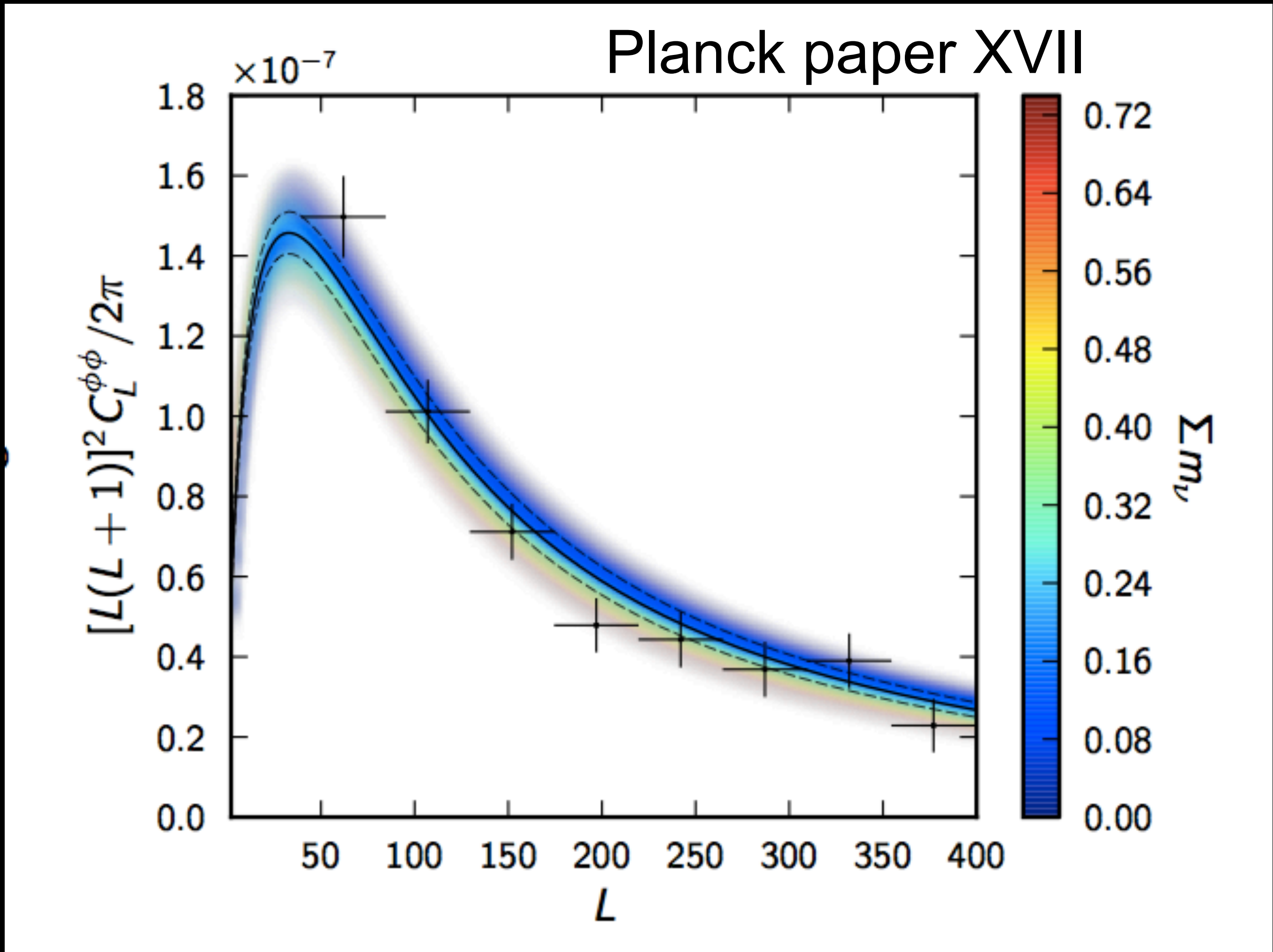
From Hu Okamoto 2001



CMB back to the rescue

Lensing

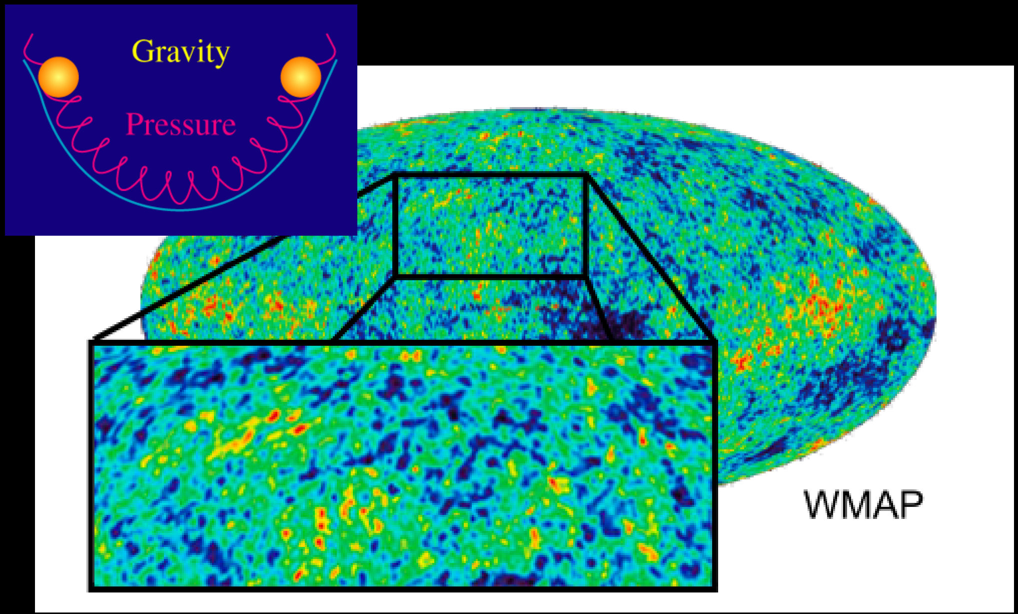
A new measurement!

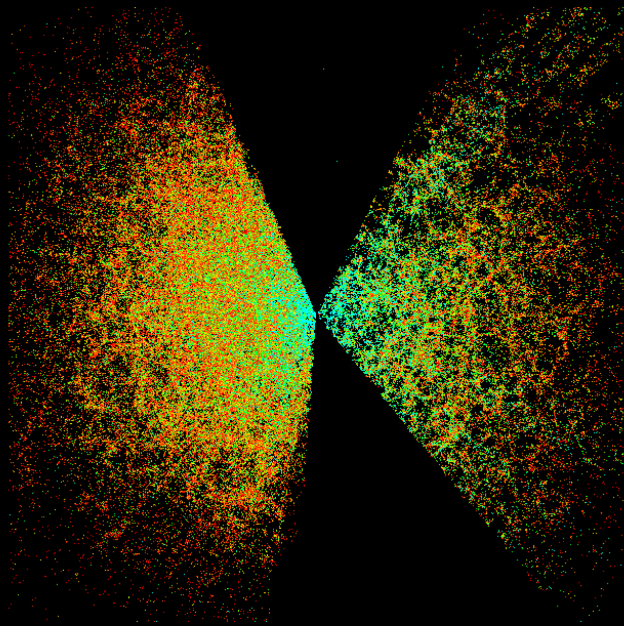


In the meantime..

BAOs????

Baryon acoustic oscillations





Observe photons

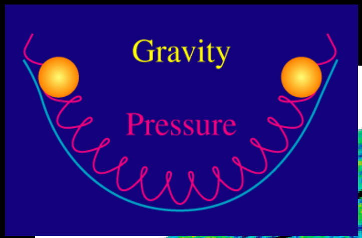
Photons coupled to baryons

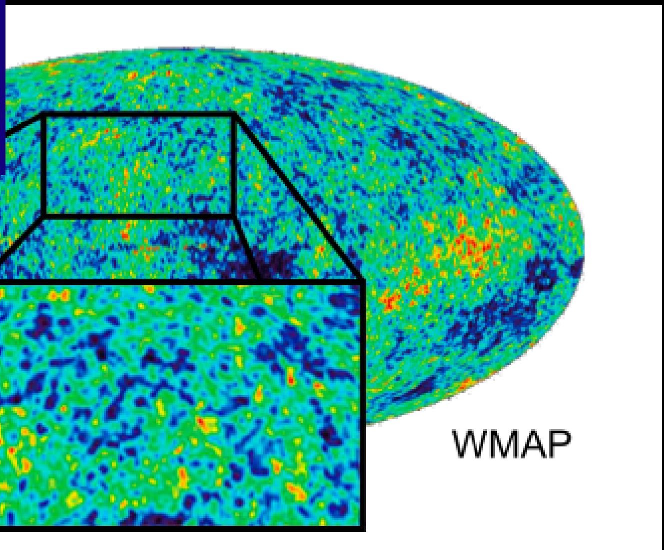
“See” dark matter

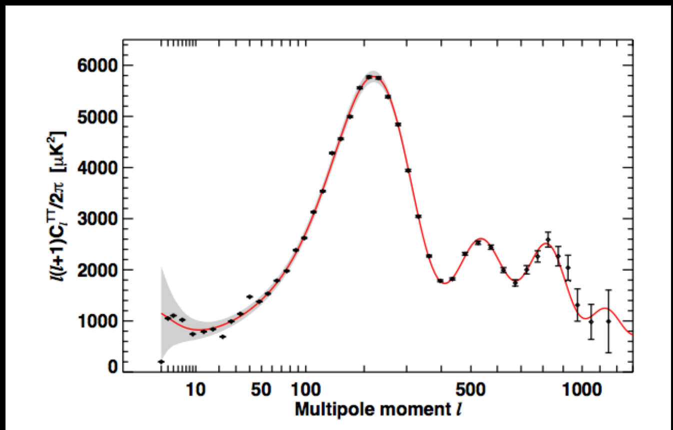
AS baryons are ~1/6 of the dark matter these baryonic oscillations leave some imprint in the dark matter distribution (gravity is the coupling)

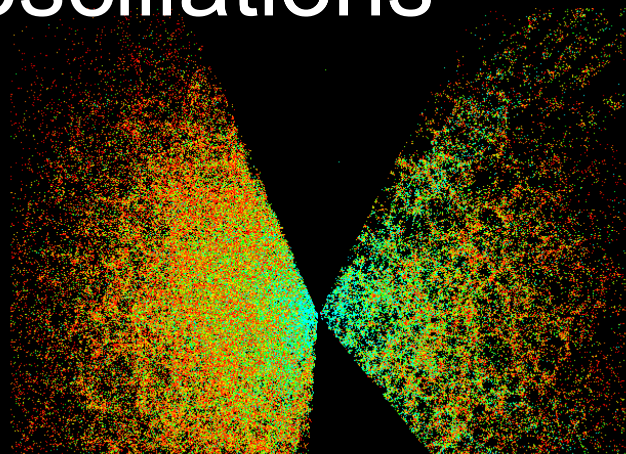
BAOs????

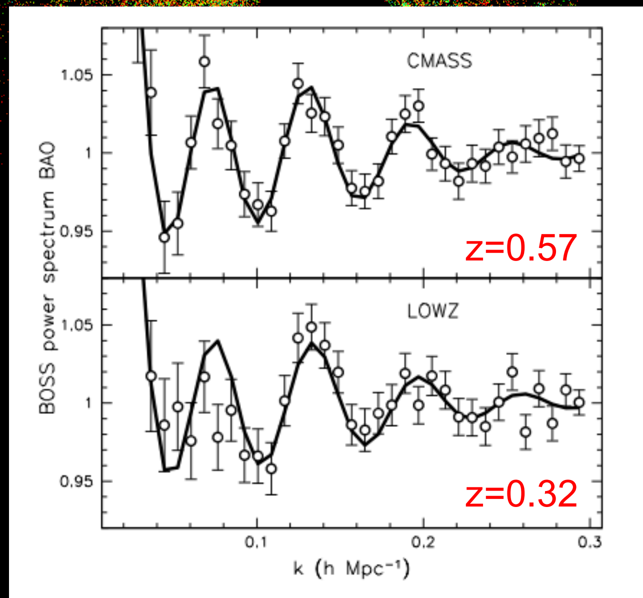
Baryon acoustic oscillations





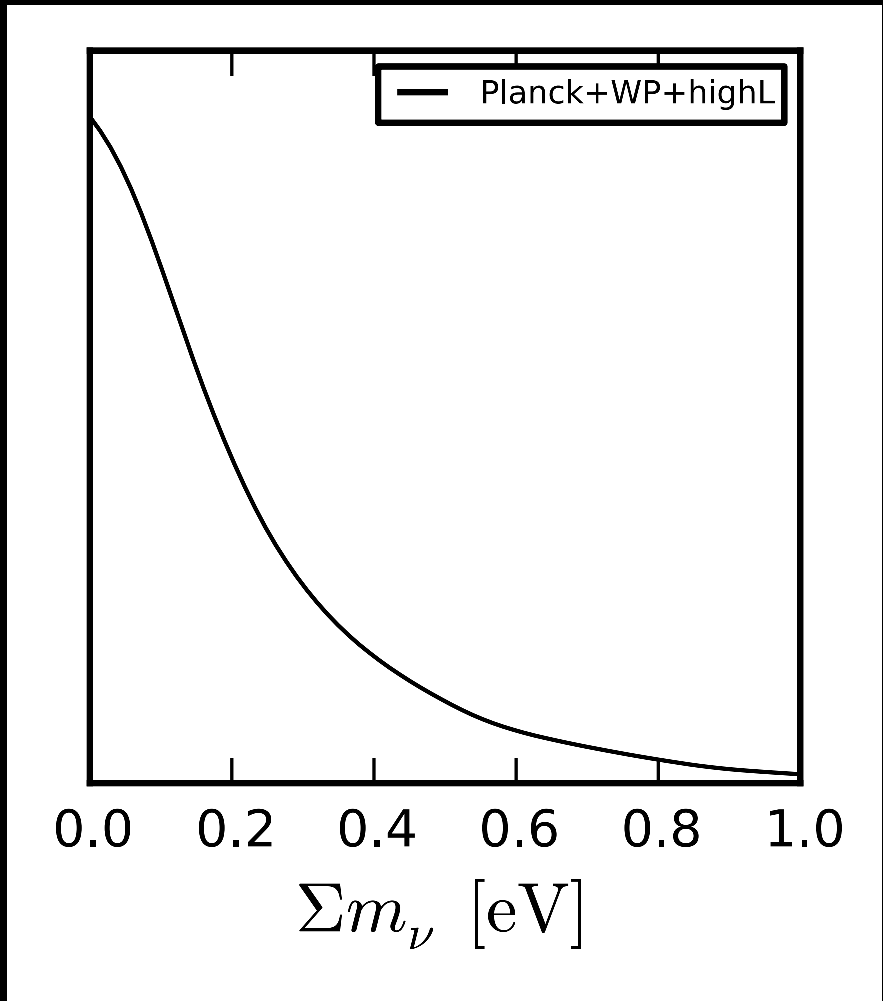






Anderson et al (SDSS3 BOSS collab) 2013

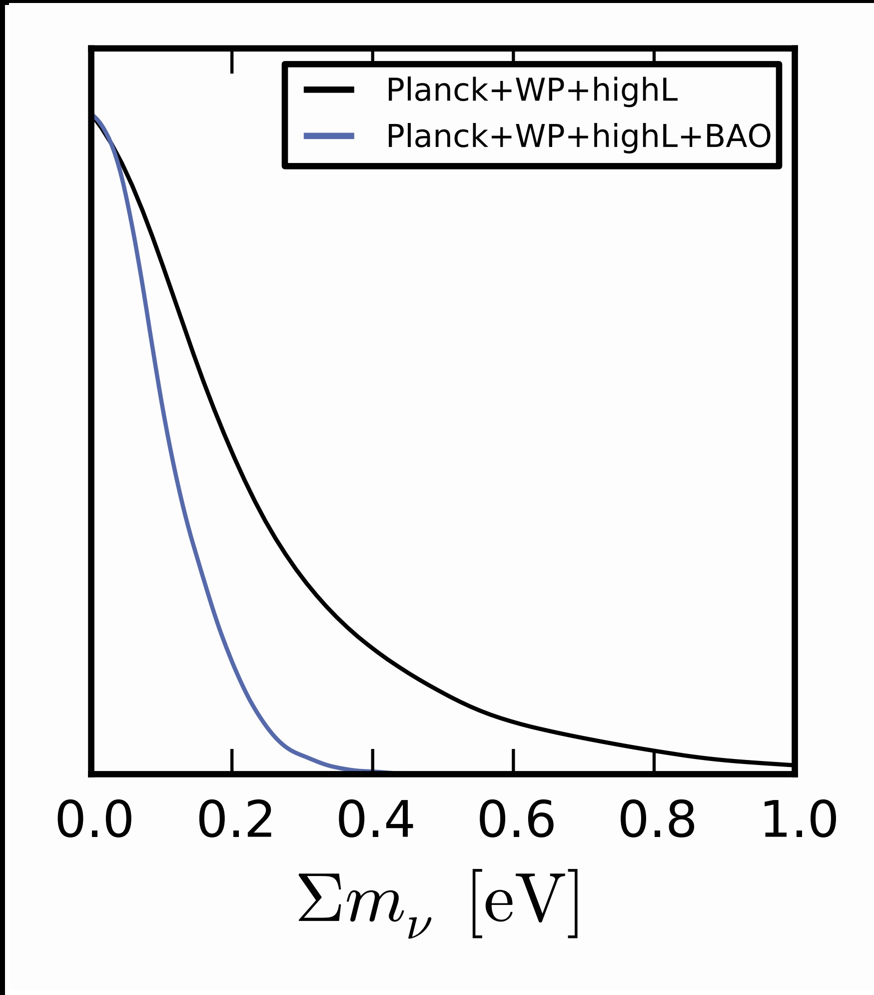
Breaking degeneracies



Σ<0.66 eV

Fig. courtesy of A. Cuesta

Breaking degeneracies



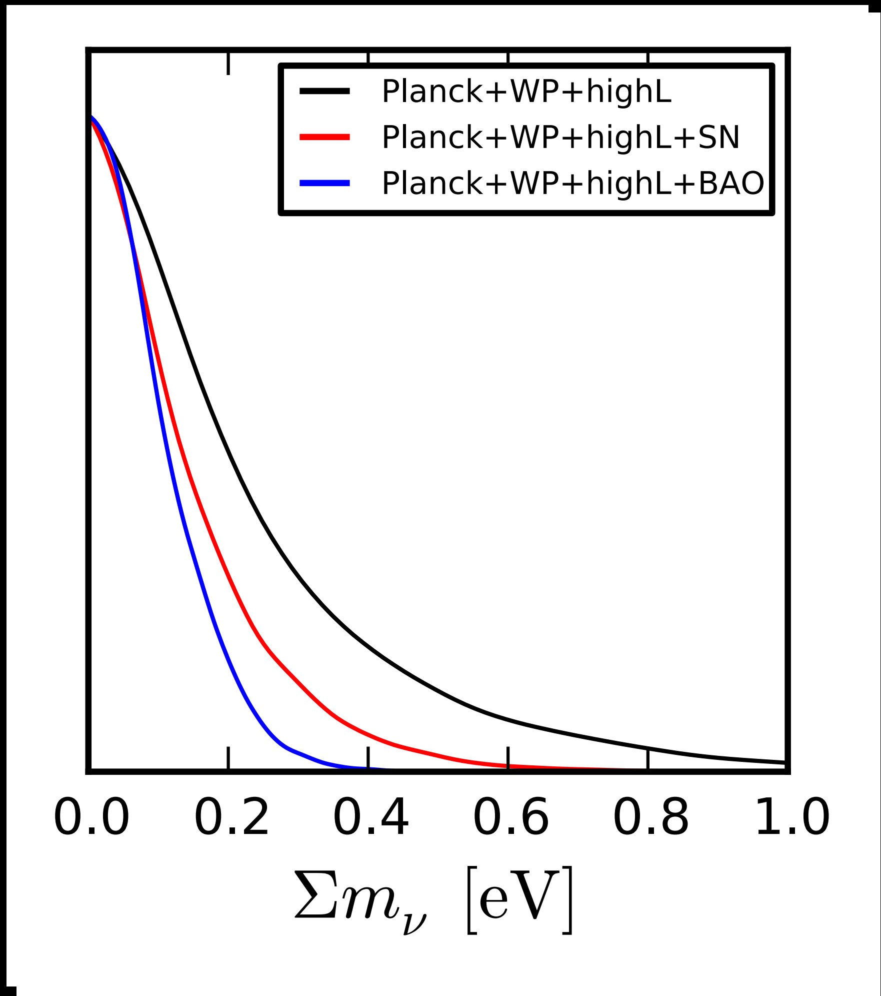
6dF+
LOWZ+CMASS+LyaF

Σ<0.66 eV

Σ<0.22 eV

Fig. courtesy of A. Cuesta

Breaking degeneracies



Σ<0.66 eV

Σ<0.22 eV

Σ<0.36 eV

Fig. courtesy of A. Cuesta

Claims of non-zero neutrino mass detection since March 2013

$\nu\Lambda$CDM: Neutrinos reconcile Planck with the Local Universe

arxiv:1307.7715

Mark Wyman,* Douglas H. Rudd, R. Ali Vanderveld, and Wayne Hu

Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, U.S.A

Evidence for massive neutrinos from CMB and lensing observations

arxiv:1308.5870

Richard A. Battye*

Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, U.K.

Adam Moss†

Centre for Astronomy & Particle Theory, University of Nottingham, University Park, Nottingham, NG7 2RD, U.K.

A new life for sterile neutrinos: resolving inconsistencies using hot dark matter[1]

arxiv:1308.3255

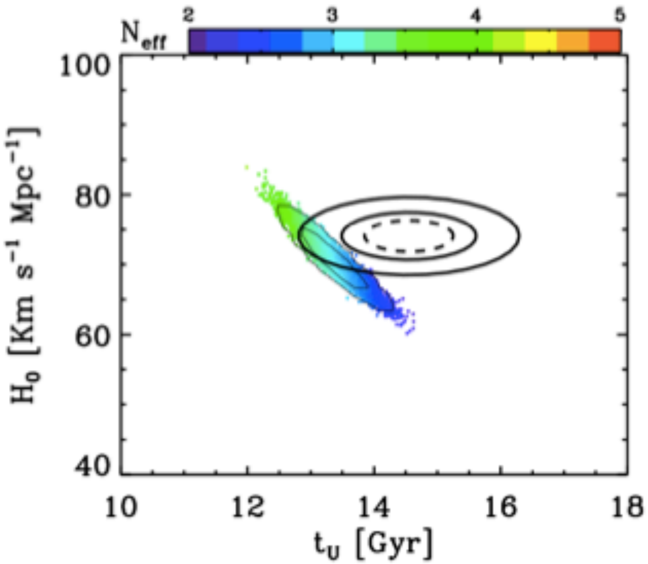
Jan Hamann[a] **Jasper Hasenkamp**[b,c]

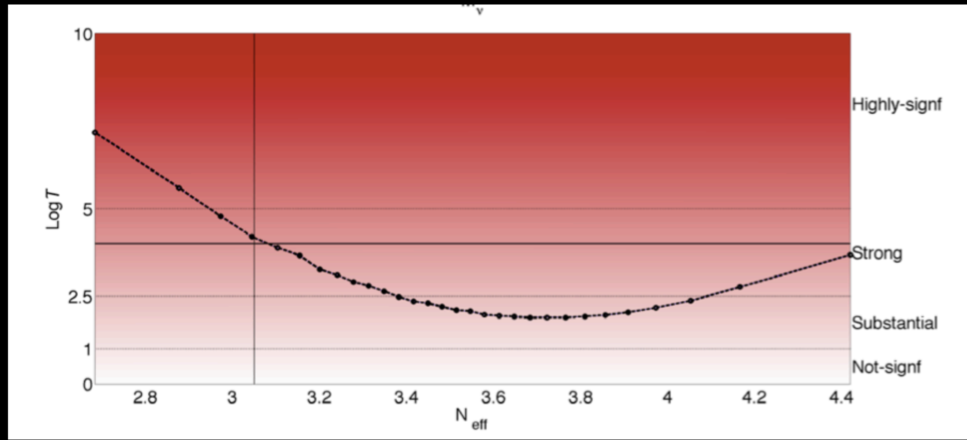
[a]Theory Division, Physics Department CERN, CH-1211 Geneva 23, Switzerland

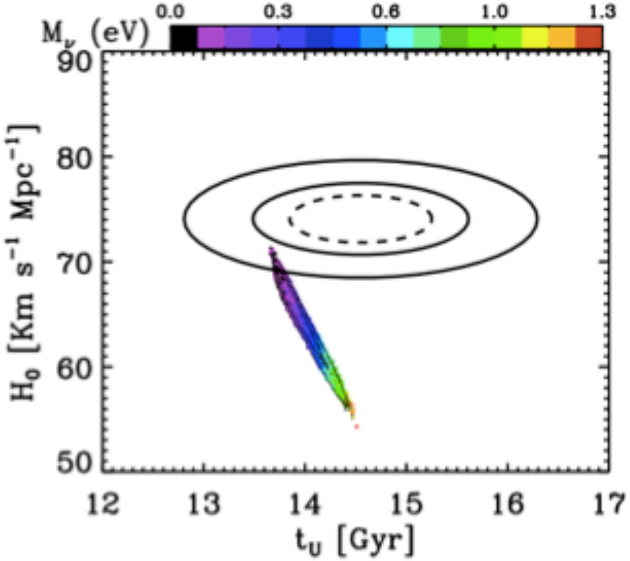
[b]Center for Cosmology and Particle Physics, Physics Department New York University, New York, NY 10003, USA

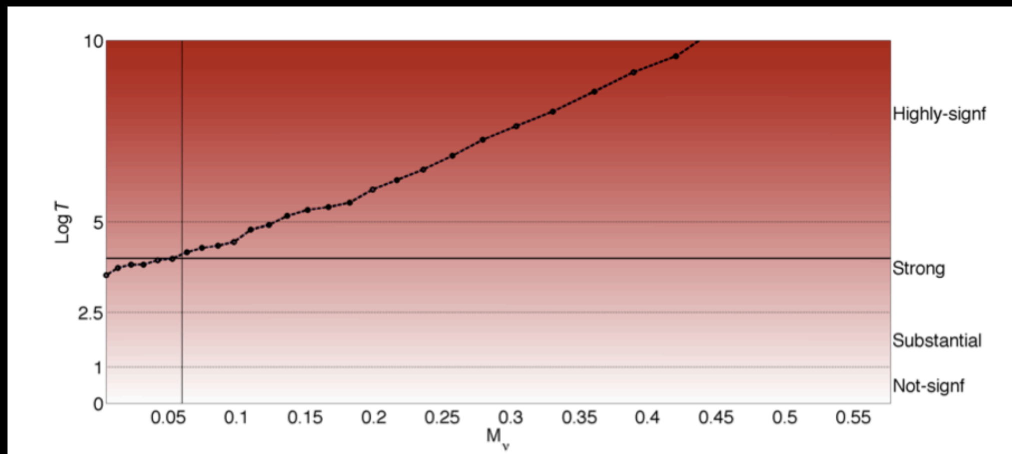
[c]II. Institute for Theoretical Physics University of Hamburg, 22761 Hamburg, Germany

Planck and the local Universe: tension with H0





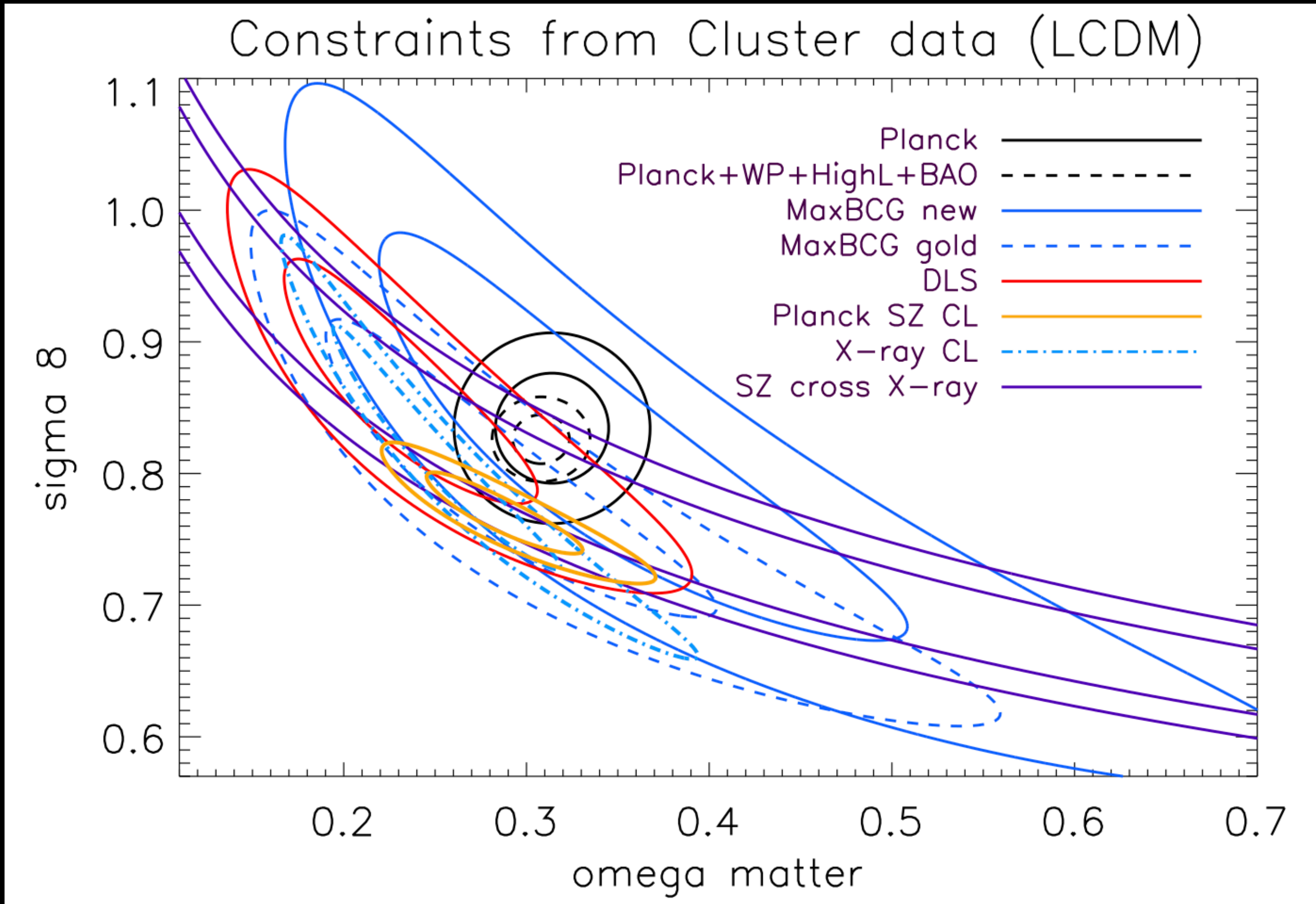




LV, Protopapas, Jimenez, DARK 2013

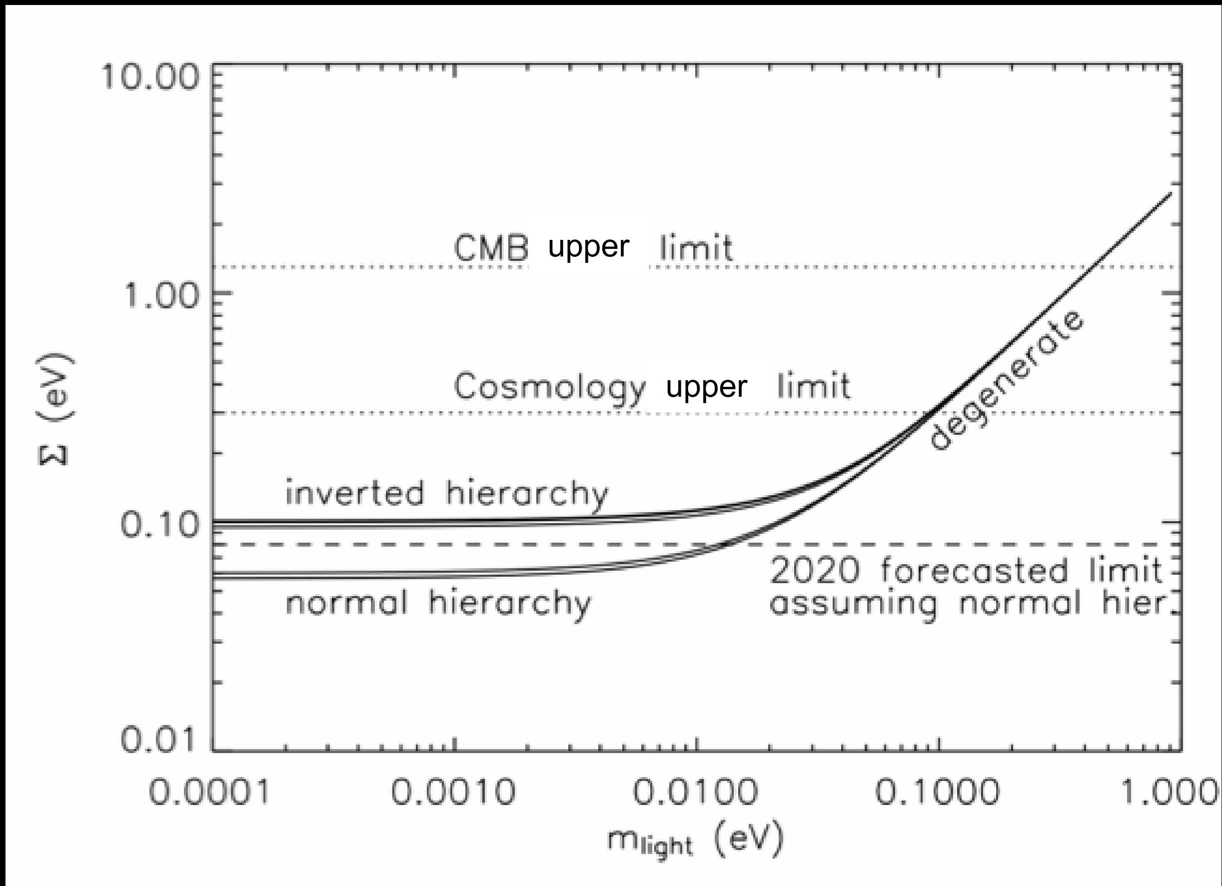
Are clusters of galaxies reliable standard candles????

Are current weak lensing σ_8 determinations accurate as well as precise?



Leistedt, Verde, Peiris in prep.

Outlook towards the future

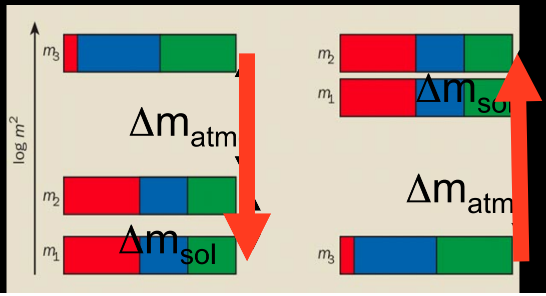


Can the hierarchy be determined?

Are neutrino Majorana or Dirac?

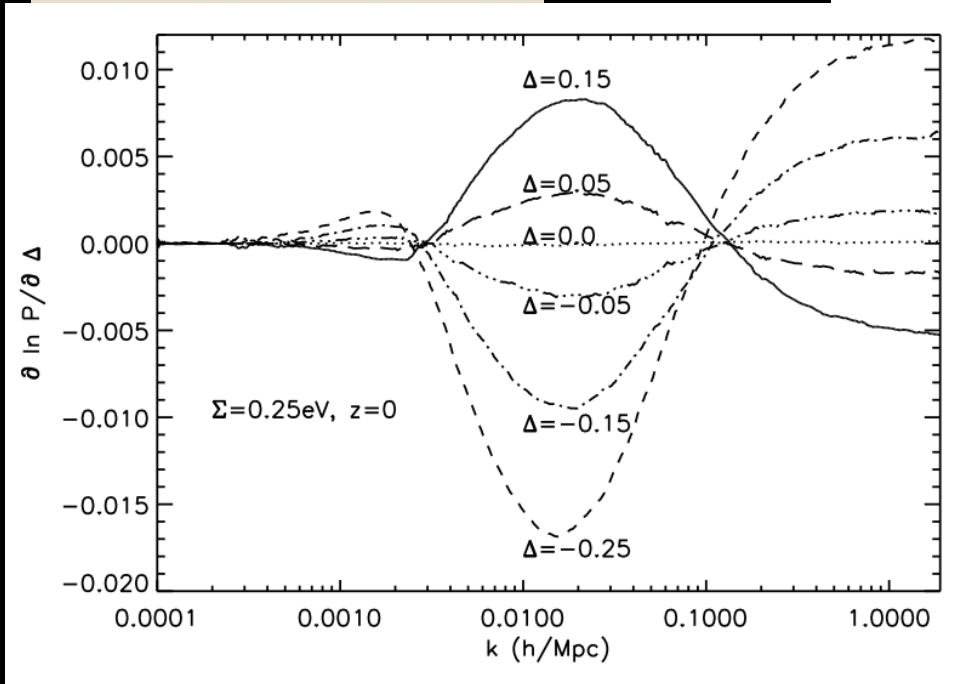
Jimenez, Kitching, Penya-Garay, Verde, 2010

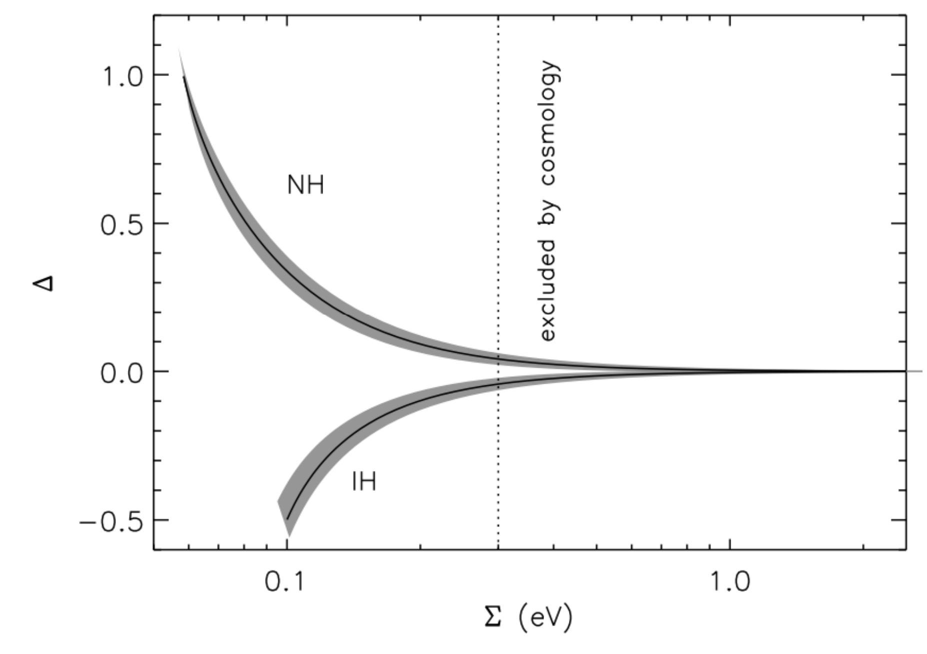
Hierarchy effect on the shape of the linear matter power spectrum



Neutrinos of different masses have different transition redshifts from relativistic to non-relativistic behavior, and their individual masses and their mass splitting change the details of the radiation-domination to matter- domination regime.

$$\text{NH}: \quad \Sigma = 2m + M \quad \Delta = (M-m)/\Sigma$$
$$\text{IH}: \quad \Sigma = m + 2M \quad \Delta = (m-M)/\Sigma$$





Jimenez, Kitching, Penya-Garay, Verde, JACP2010

Cosmology is (mostly) sensitive to $|\Delta|$

Still offers a powerful consistency check

What would it take to measure Δ?

Basically: the ultimate experiment

In combination with $\nu 0\beta\beta$ experiements can help answering:
Are neutrinos Dirac or Majorana?

Conclusions

- Precision cosmology means that we can start (or prepare for) constraining interesting physical quantities
- Neutrino properties: absolute mass scale, number of families, possibly hierarchy
- My "bet": $\Sigma m_\nu <\sim 0.25$ eV (95%) (once the dust has settled)
- Large future surveys means that sub % effects become detectable, which brings in a whole new set of challenges and opportunities (e.g., mass, hierarchy)
- The (indirect) detection of neutrino masses is within the reach of forthcoming experiments (even for the minimum mass allowed by oscillations)
- Systematic and real-world effects are the challenge, need for in-build consistency checks!

END