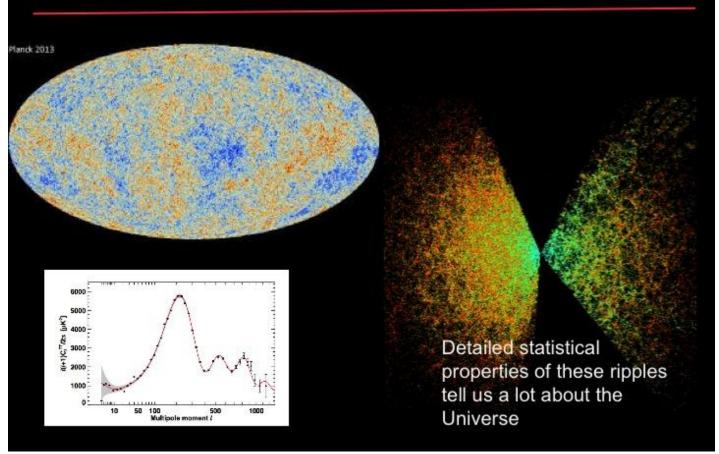


Avalanche of data over the last ~10 yr



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: Any statement is model dependent

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): Any statement depends on the data-set chosen

Results will depend on the data you (are willing to) consider.

CMB has so far been considered AAA (might need more fine tuning, experiment dependent)

....And the Blessing

We can observe all there is to see

What is a neutrino? (for cosmology)

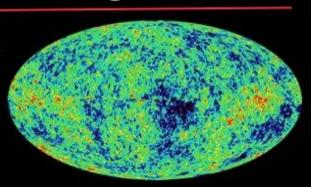


- Behaves like radiation at T~ eV (recombination/decoupling)
- Eventually (possibly) becomes non-relativistic, behaves like matter
- Small interactions (not perfect fluid)
- Has a high velocity dispersion (is "HOT")



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 (mv << Tv) → large velocity dispersions (1eV ~ 100 Km/s)

Recall:

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

60Billion nu/s/cm² from the sun ~100nu/cm³ 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

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

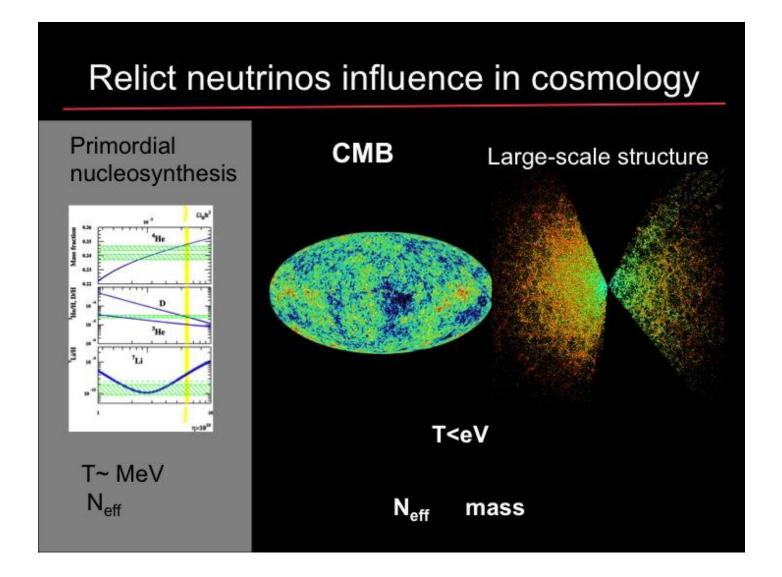
With a density of:

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

That, for a massive neutrino translates in:

$$\Omega_{v} = \frac{n_{v_{k}, \bar{v}_{k}} m_{v}}{\rho_{c}} \approx \frac{1}{h^{2}} \frac{m_{v}}{93.2 eV} \Rightarrow \Omega_{v} h^{2} = \frac{\sum_{v} m_{v}}{93.2 eV}$$

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



What do we know and what would we like to know? How many neutrinos? Have we really seen the cosmic neutrino background? (i.e. Are we really sure it's neutrinos?) Their total mass The individual masses (hierarchy)

Neutrinos beyond the Standard Model?

Until 2013 or so cosmological analyses consistently used to give best fit values >3.04.

"dark radiation"

But analyses were NOT independent

(WMAP always in common, H0 many times in common)

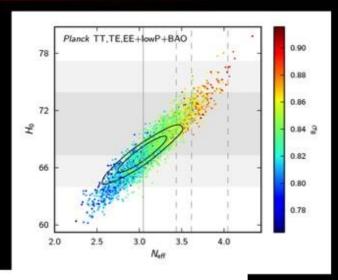


W3+ACT+SPT+BAO+H0¹⁶
W7+SPT-BAO+H0¹⁶
W7+SPT-BAO+H0¹⁶
W7+SPT-BAO+H0¹⁶
W7+SPT-BAO+H0¹⁶
W7+SPT-BAO+H0¹⁶
W7+ACBAR+ACT+SPT+SDSS+MS+0¹⁶
W7+ACBAR+ACT+SPT+SDSS+MS+0¹⁶
W7+ACBAR+ACT+SPT+SDSS+MS+0¹⁶
W7+ACBAR+ACT+SPT+SDSS+MS+0¹⁶
W7+ACBAR+ACT+SPT+SDSS+MS+0¹⁶
W7+ACBAR+ACT+SPT+SDSS+MS+0¹⁶
W7+BO-W1-BAO+H0¹⁶
W7+BO-W1-BAO+H0¹⁶
W7+BO-W1-BAO+H0¹⁶
W7+BO-W1-BAO+H0¹⁶
W7+SPT-BAO+H0¹⁶
W7+SPT-BAO+H

See also the white paper Abazajian et al. arXiv:1204.5379

Riemer-Sørensen et al. [2013]

Results from Planck 2015



 $N_{\text{eff}} = 3.13 \pm 0.32$ Planck TT+lowP;

 $N_{\text{eff}} = 3.15 \pm 0.23$ Planck TT+lowP+BAO;

 $N_{\text{eff}} = 2.99 \pm 0.20$ Planck TT, TE, EE+lowP;

 $N_{\text{eff}} = 3.04 \pm 0.18$ Planck TT, TE, EE+lowP+BAO.

N_{eff}=0 excluded at 17sigma

Also, the possibility of a 4th neutrino is fading away (dashed lines)

How robust is the detection of the cosmic neutrino background?

Predicted in 1953 with correct temperature (Tv = (4/11)4/3 Ty) by Alpher, Follin & Herman:

PHYSICAL REVIEW

VOLUME 92, NUMBER 6

DECEMBER 15, 1953

Physical Conditions in the Initial Stages of the Expanding Universe*.

RALPH A. ALPHER, JAMES W. FOLLIN, JR., AND ROBERT C. HERMAN Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland (Received September 10, 1953)

$$\omega_R = \omega_\gamma (1 + N_{\text{eff}} \times 7/8 (4/11)^{4/3})$$
 with $N_{\text{eff}} = 3.046$

62 years later we ask...

...are we sure it exists?

B. Audren, E. Bellini, A. Cuesta, S. Gontcho A Gontcho, J. Lesgourgues, V. Niro, M. Pellejero-Ibanez, I. Pérez-Ràfols, V. Poulin, T. Tram, D. Tramonte, L. Verde arXiv:1412.5948 (JCAP 2015)

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

Could be anything behaving like radiation...

other light decoupled relics (axions, gravitinos, etc.)

background of gravitational waves

scalar field oscillating in quartic potential

standard neutrinos

neutrinos with exotic interactions (self-inter., or with dark sector)

other light relics with interactions (self-inter., or with dark sector)

effects from modified gravity, extra dimensions...

Fig adapted from J. Lesgourgues

Can we probe the *nature* of the perturbations?

Neutrinos density/pressure perturbations, energy flux and anisotropic pressure/shear act as sources in Einstein equations: gravitational interactions with photons, baryons.

Affects the amount of gravitational boost of CMB acoustic oscillations just after Hubble crossing.

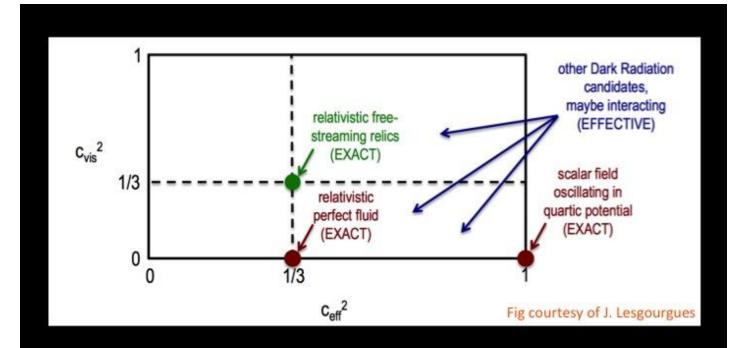
Controls amplitude and phase of CMB acoustic oscillations.

Can we see these free-streaming effects?

Approach

Define two phenomenological parameters changing the perturbation equations:

- 1) Effective sound speed : $\delta p = c_{eff}^2 \delta p$
- 2) Effective viscosity speed cvis controlling the amount of anisotropic pressure / shear



For a model LCDM+c_{eff}+c_{vis}

from Planck (2013) data we have learned that there is no compelling evidence for deviations from standard values

BUT... how robust is this statement?

Our approach: brute force, really...

Consider a minimal collection of state-of-the art data (CMB Planck, BAO) and explore whether $c_{\rm eff}$ and $c_{\rm vis}$ are degenerate with neutrino mass, effective number of species, dark energy ...etc.

We conclude: not to worry about degeneracies with cosmologys

With Mv, Neff or both : very little if at all

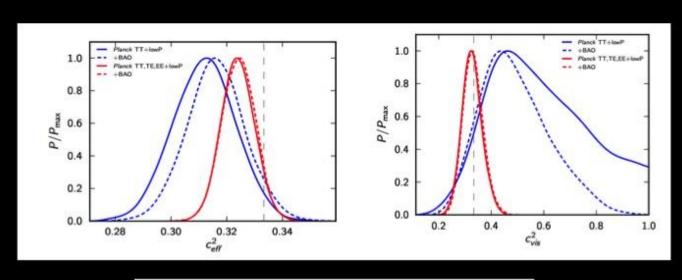
With running of spectra index: some anti-correlation, but small

With w: no

Upshot: you can take the Planck 2015 results (done in Λ CDM); they hold also for more general cosmologies

PS small scale polarization is key

Back to Planck 2015 results



$$c_{\text{eff}}^2 = 0.3242 \pm 0.0059$$

 $c_{\text{vis}}^2 = 0.331 \pm 0.037$ | Planck TT,TE,EE+lowP+BAO. (69d)

Everything else here is LCDM
But -I have just shown- this will hold for LCDM++

Can we observe these free-streaming effects?

YES!

other light decoupled relics (axions, gravitinos, etc.)

backeround of gravitational waves scalar field oscillating in quartic potential

standard neutrinos

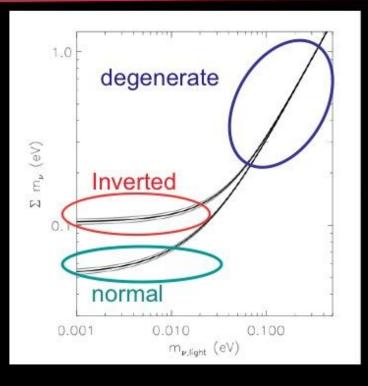
neutrinos with exotic interactions (self-inter., or with dark sector)

other light relics with intera (self-inter., or with dark see

effects from modified gravity, extra dimensions...

Disfavored!

Cosmology is key in determining the absolute mass scale



The problem is systematic errors

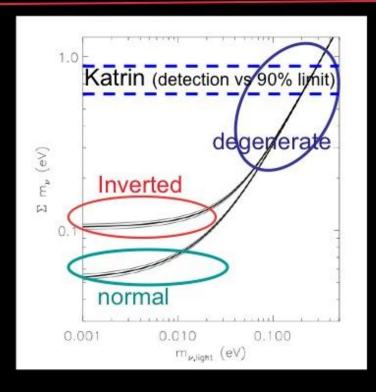
This means that neutrinos contribute at least to ~0.5% of the total matter density

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

Neutrino mass: Physical effects

Total mass >~1 eV become non relativistic before recombination

CMB

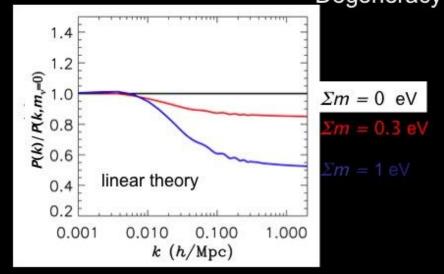
Total mass <~1 eV become non relativistic after recombination: alters matter-radn equality but effect can be "cancelled" CMB

by other parameters

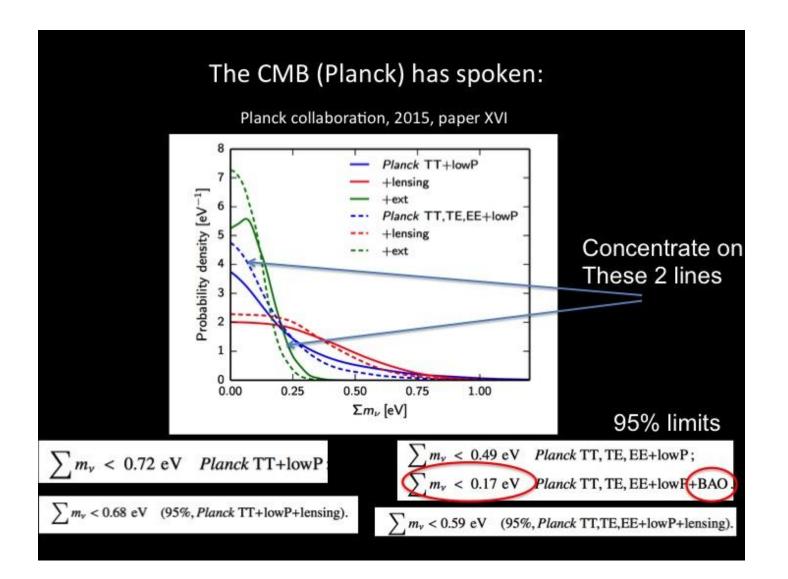
Degeneracy

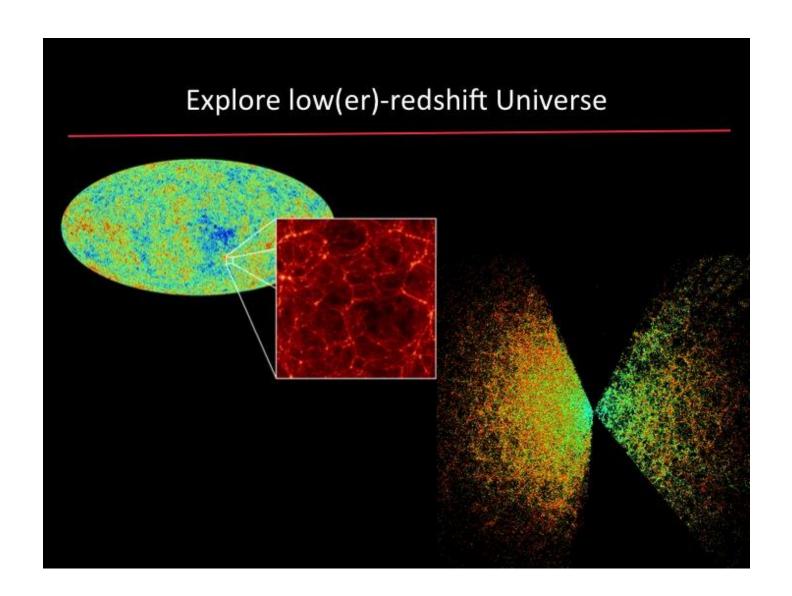
After recombination

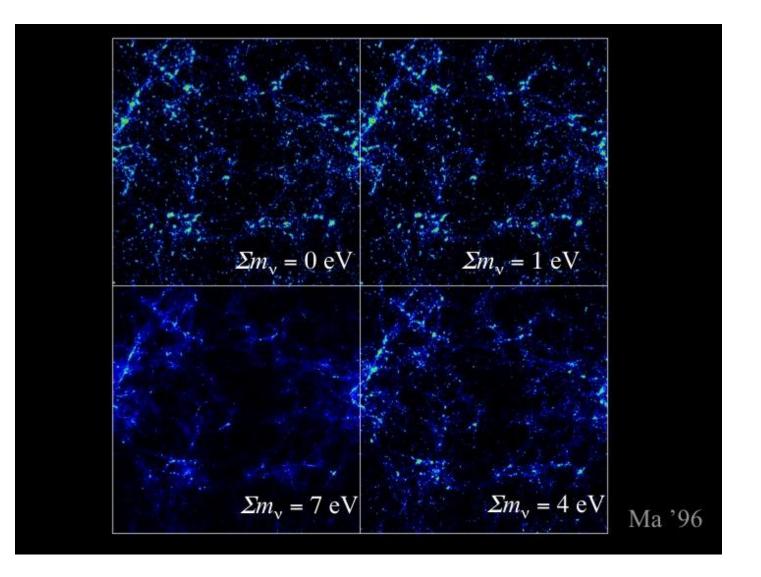
FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



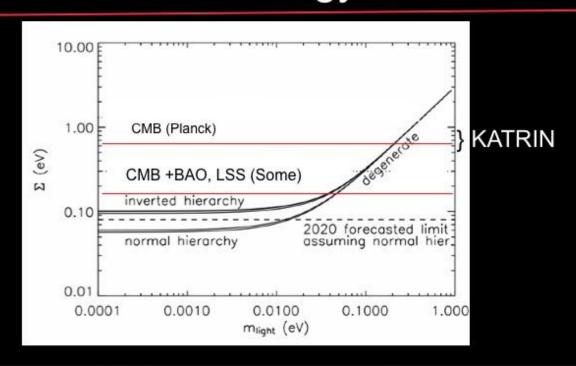
Different masses become non-relativistic a slightly different times Cosmology can yield information about neutrino mass hierarchy







The Cosmology limits



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

Until recently (pre-Planck) was the consensus

Claims of non-zero neutrino mass detection since March 2013

νΛCDM: 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

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 matter¹

arxiv:1308.3255

Jan Hamann^a Jasper Hasenkamp^{b,c}

^aTheory Division, Physics Department CERN, CH-1211 Geneva 23, Switzerland

^bCenter for Cosmology and Particle Physics, Physics Department New York University, New York, NY 10003, USA

°II. Institute for Theoretical Physics

University of Hamburg, 22761 Hamburg, Germany

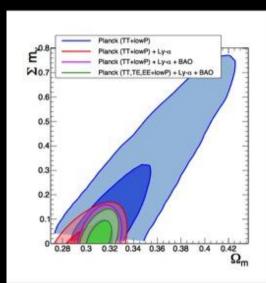
From Abazajian et al 2011

Probe	Current $\sum m_{\nu}$ (eV)	Forecast $\sum m_{\nu}$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measure- ments	WMAP, Planck	None
Lensing of CMB	∞	0.2 - 0.05	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLAR- BEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HET- DEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photo- metric redshifts	CFHT-LS [23], COS- MOS [50]	DES [84], Hy- per SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	0.1 - 0.006	Foregrounds, Astro- physical modeling		MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chan- dra [83]	DES, eRosita [87], LSST
Core-Collapse Super- novae	∞	$\theta_{13} > 0.001^*$	Emergent ν spectra	SuperK [98], ICECube[90]	Noble Liquids, Gad- zooks [7]

Ly α from BOSS survey

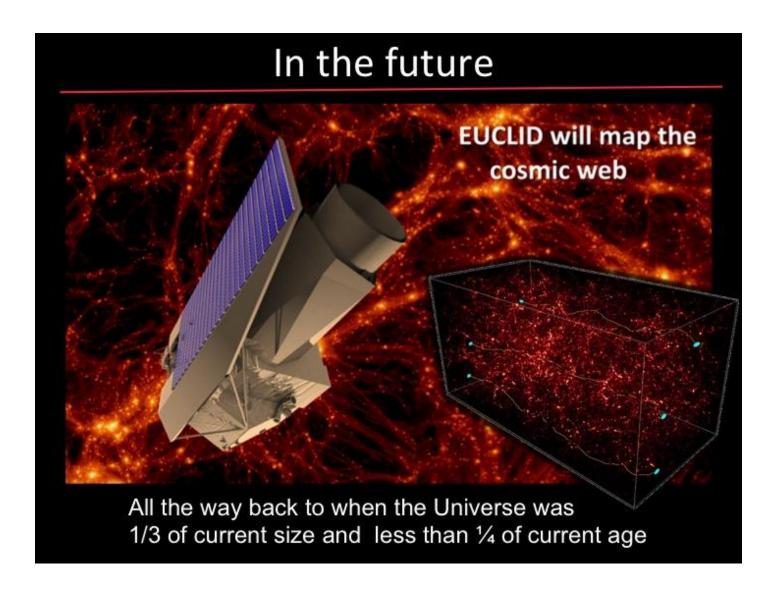
 $\sum m_{\nu} < 0.12 \text{ eV } (95\% \text{ C.L.})$

Planck +BOSS (BAO incl.)

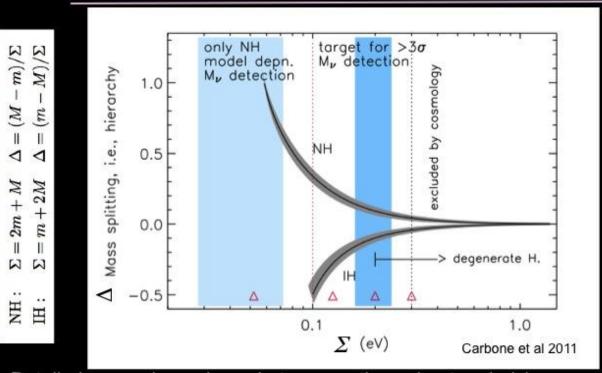


Palanque-Delabrouille et al. 2015

But also various claims of detection for 0.3-0.4eV mass.... (not with solely AAA ratings data sets)



The Role of Euclid: forecasts



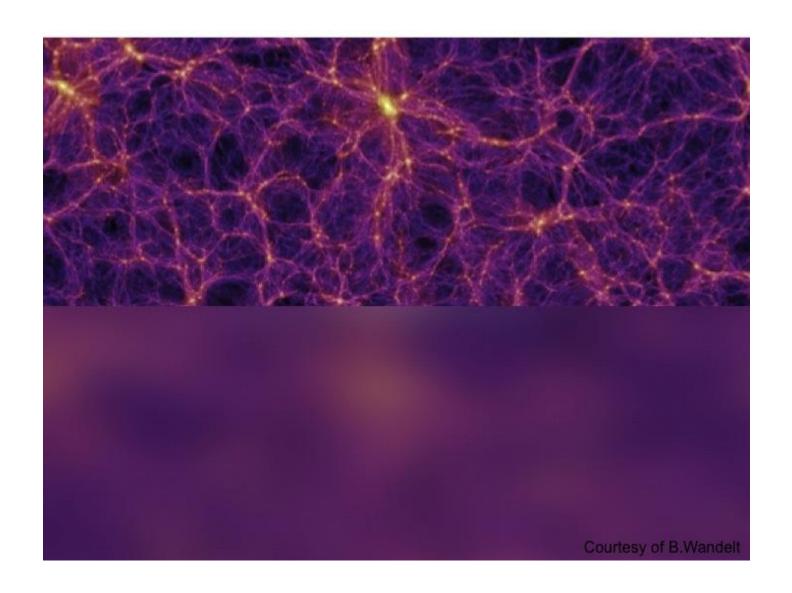
Detailed errors depend on what assumptions about underlying cosmology one is willing to make

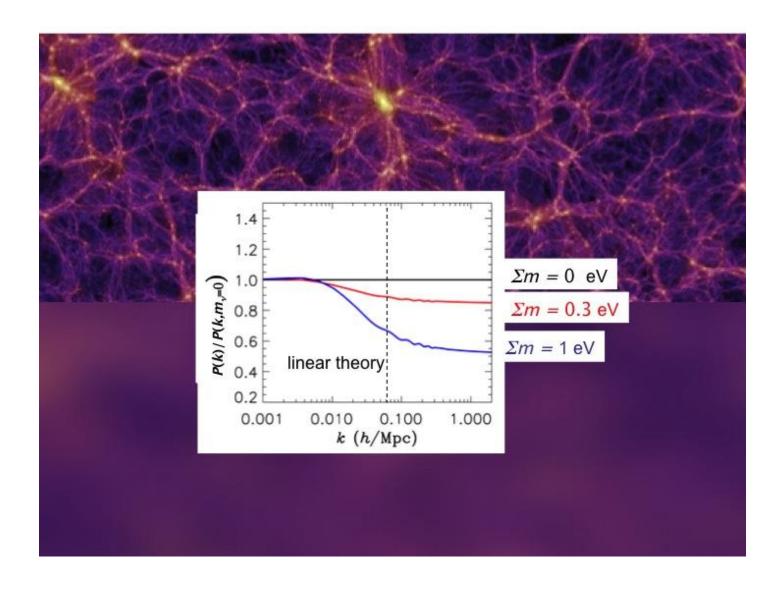
Different groups working independently agree



Beware of systematics!!!!!

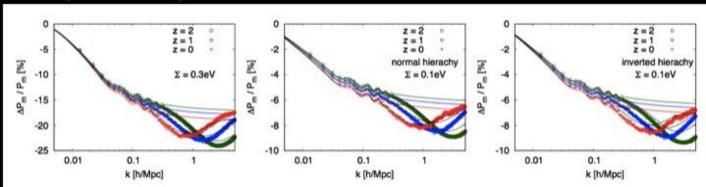
It would be of great value to have an internal consistency check (more later)





Neutrinos effect on the matter P(k)

Σ (total mass)



Note that non-linearities enhance the signal

This is for MATTER in real space

The future is bright!

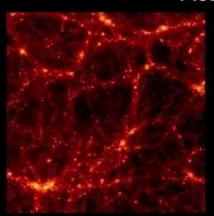
Wagner, LV, Jimenez, 2012

What about real world effects?

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

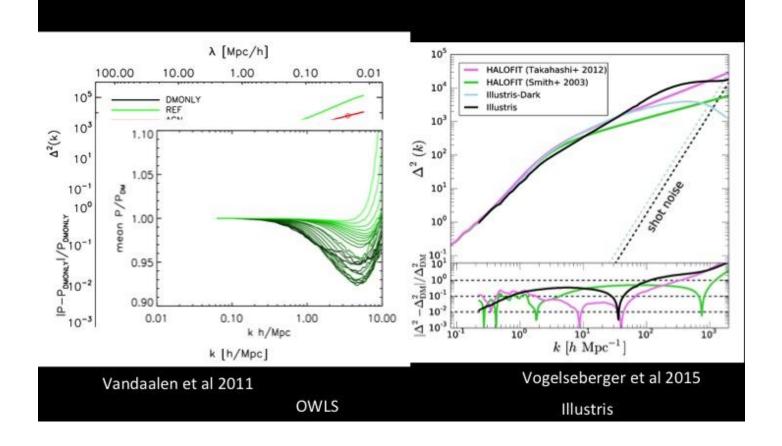


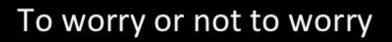
Active research area!

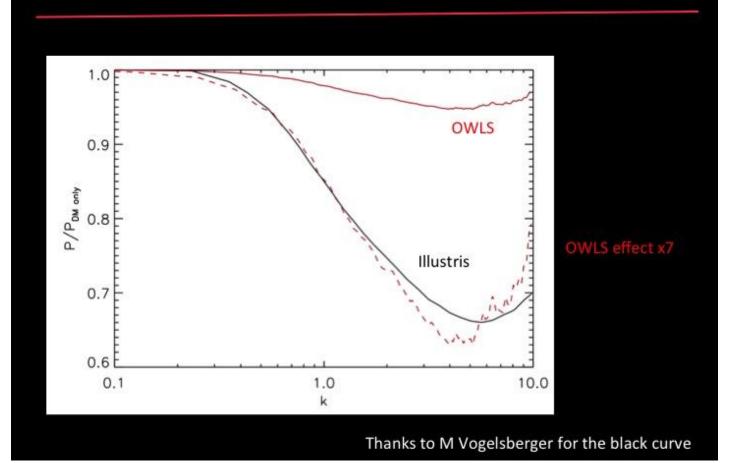




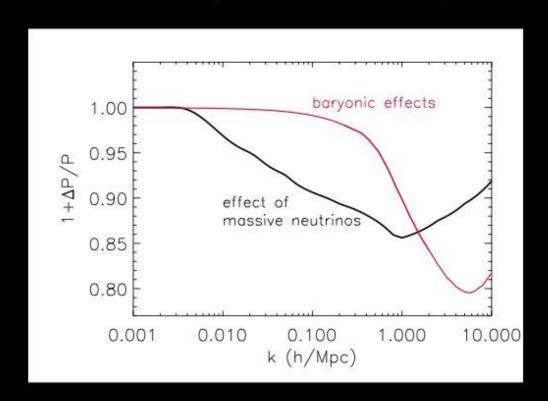
Baryonic effects?







To worry or not to worry



Designer statistics!

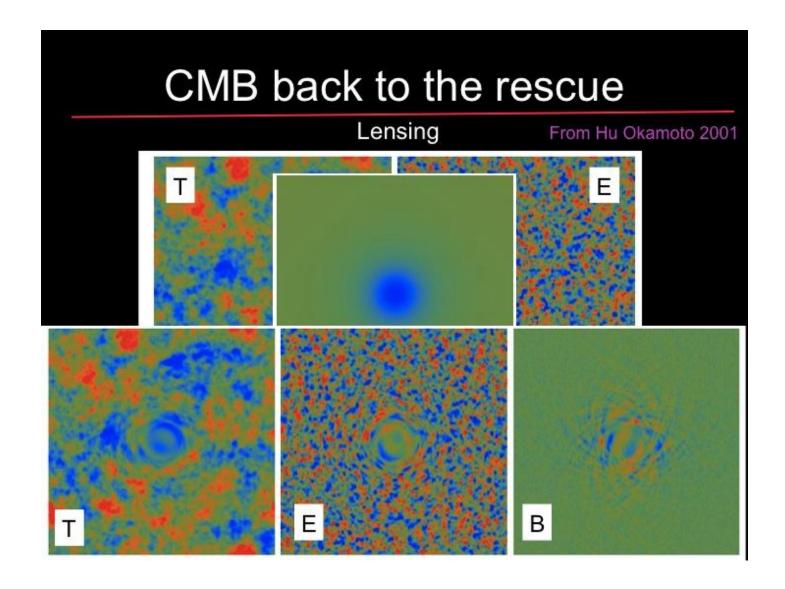
Precision versus accuracy

Nel mezzo del cammin di nostra vita....



E quindi uscimmo a riveder le stelle...

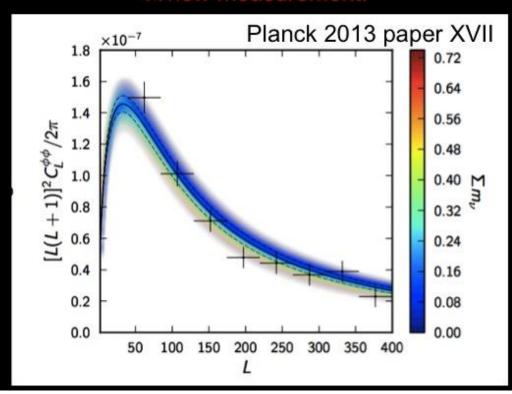




CMB back to the rescue I

Lensing

A new measurement!



CMB back to the rescue II

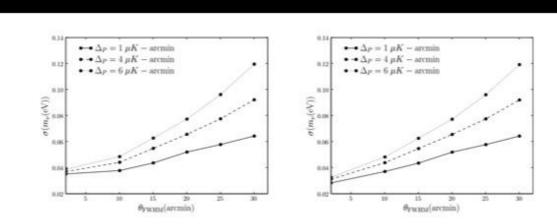
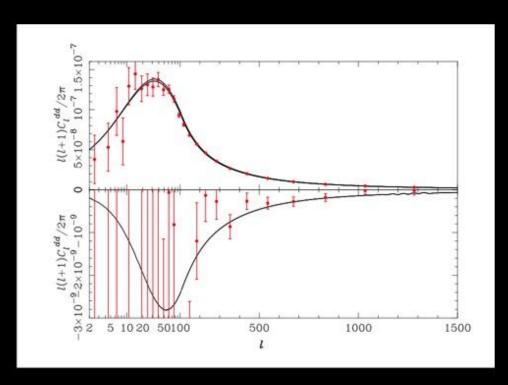


Figure 5: Uncertainty $\sigma(m_{\nu})$ on the neutrino mass as a function of beam size and noise level for $\ell_{\text{max}} = 2000$ (left panel) or $\ell_{\text{max}} = 4000$ (right panel) using CMB lens reconstruction, assuming fixed w, Ω_K .

From Smith et al, CMBPol white papers 2008(!)

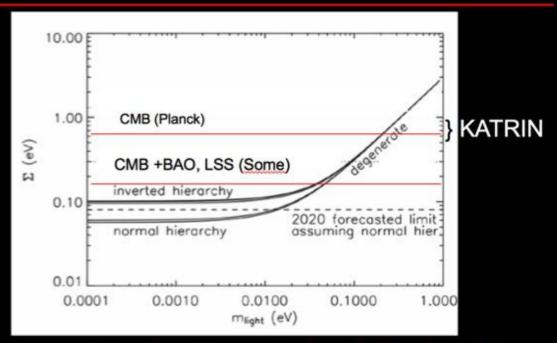
CMB back to the rescue II



 $\Sigma m_v = 0.1 \text{eV}$ vs 0 eV (3 σ)

From the CORE proposal, arXiv:1102.2181

Outlook towards the future

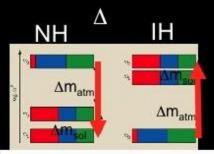


Can the hierarchy be determined?

Are neutrino Majorana or Dirac?

Jimenez, Kitching, Penya-Garay, Verde, 2010

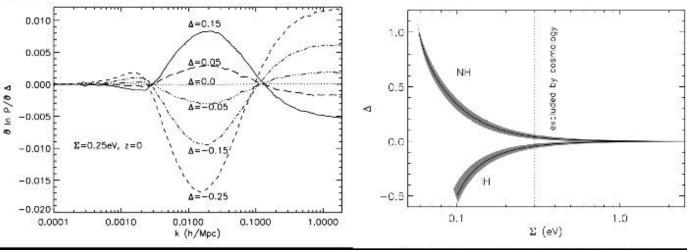
Hierarchy effect on the shape of the linear matter power spectrum



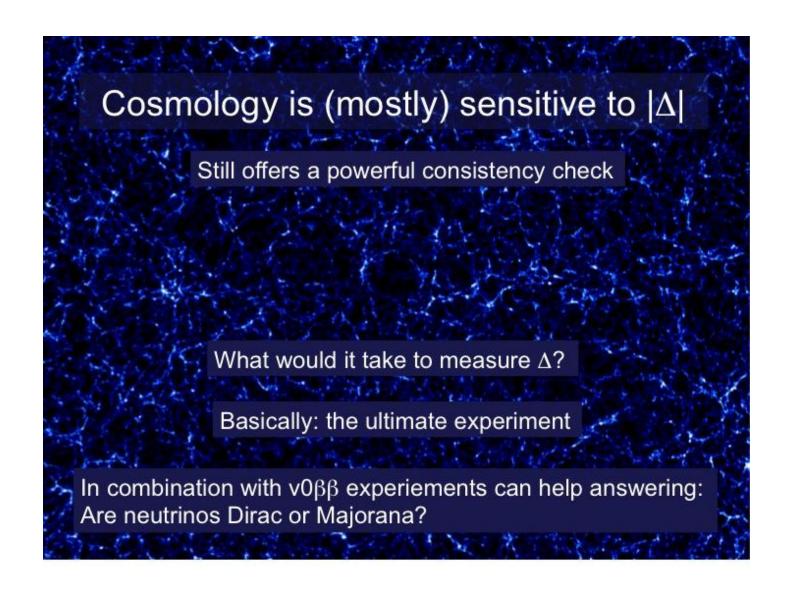
Neutrinos of different masses have different transition redshifts from relativistic to non-relativistic behavior, and their individual masses and their mass splitting change the details of the radiation-domination to matter- domination regime.

NH:
$$\Sigma = 2m + M$$
 $\Delta = (M - m)/\Sigma$

IH:
$$\Sigma = m + 2M$$
 $\Delta = (m - M)/\Sigma$



Jimenez, Kitching, Penya-Garay, Verde, JACP2010



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
- 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!
- Precision vs accuracy, aim for robust results rather than small errors (new territory)

