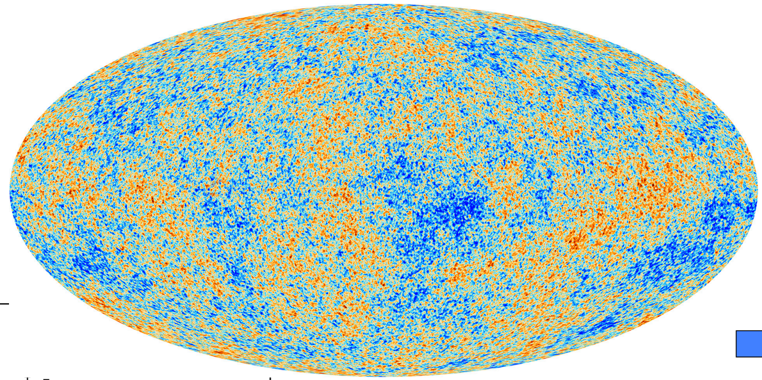
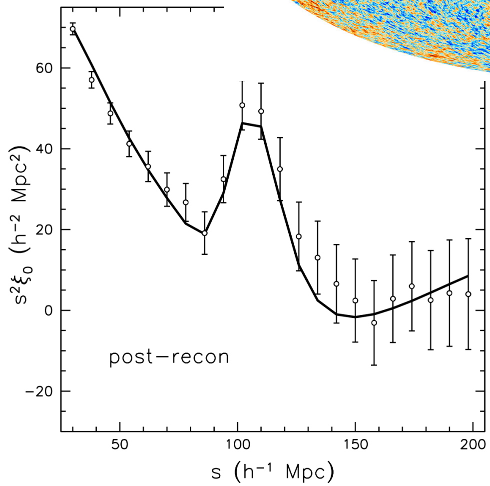
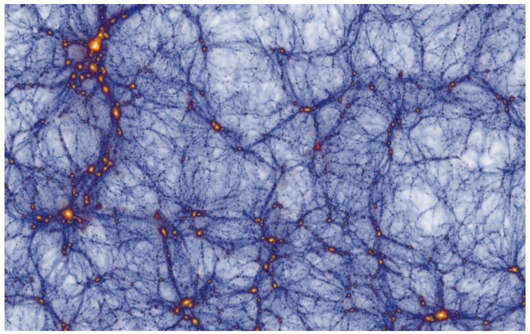
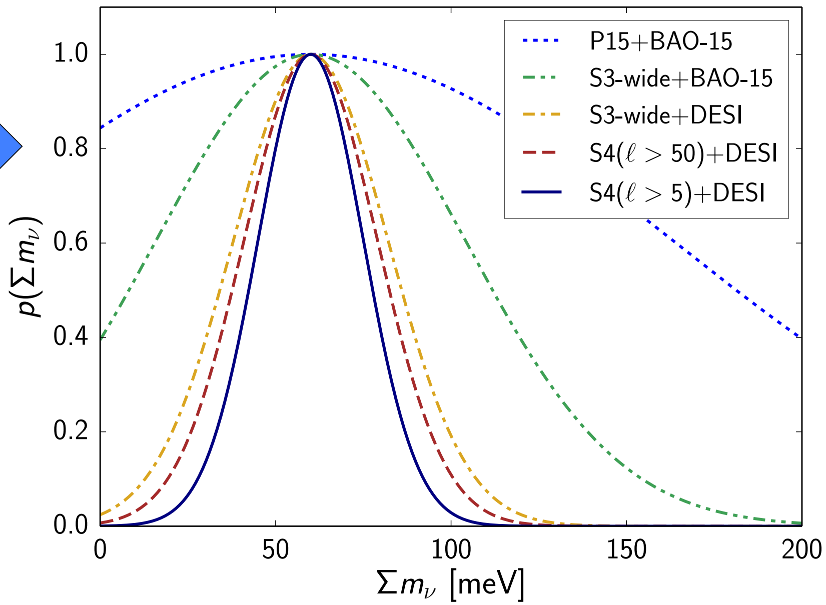
COSMOLOGICAL NEUTRINO MASS DETECTION IN THE NEXT FIVE YEARS









Rupert Allison, University of Oxford

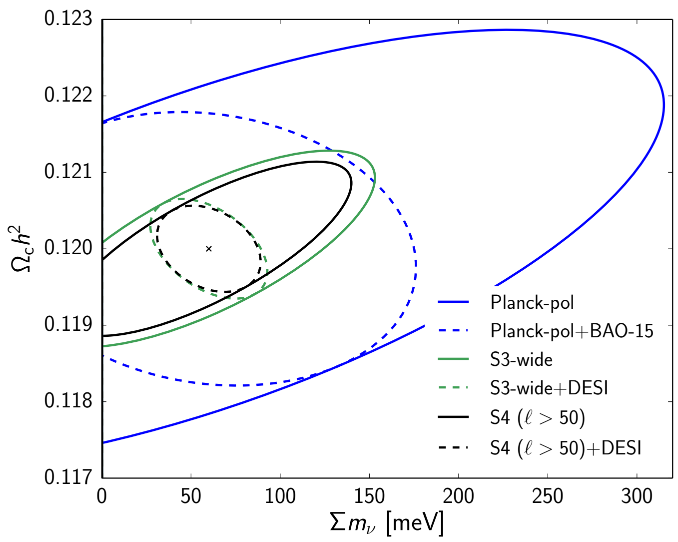
Institut d'Astrophysique, 16th November 2015

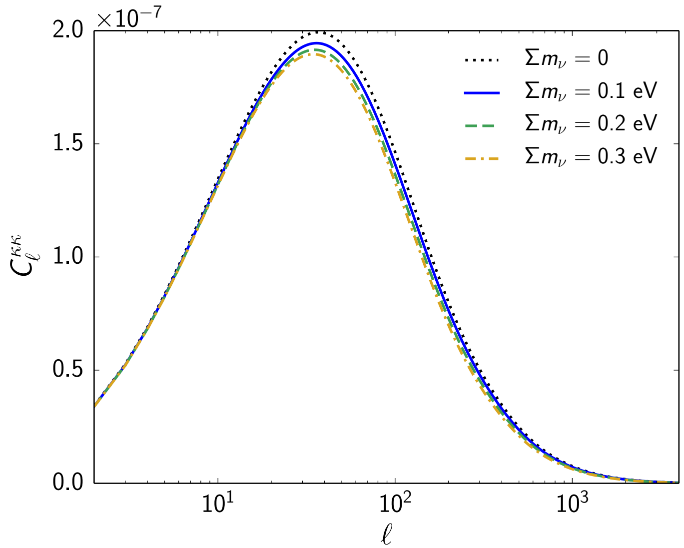
Collaborators: Paul Caucal, Erminia Calabrese, Jo Dunkley, Thibaut Louis

OUTLINE OF THE TALK

- Motivation and current status
- Cosmological effects of neutrinos
- Neutrino mass measurement in the next 5 years
- Experimental details and degeneracies
- Conclusions

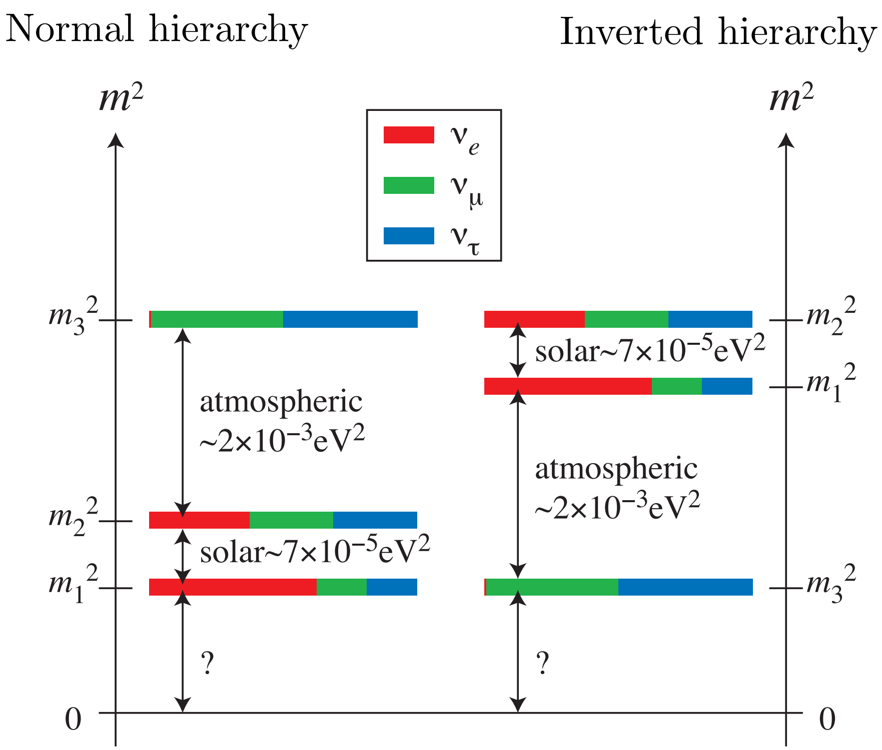
Allison et al. (2015), arXiv:1509.07471





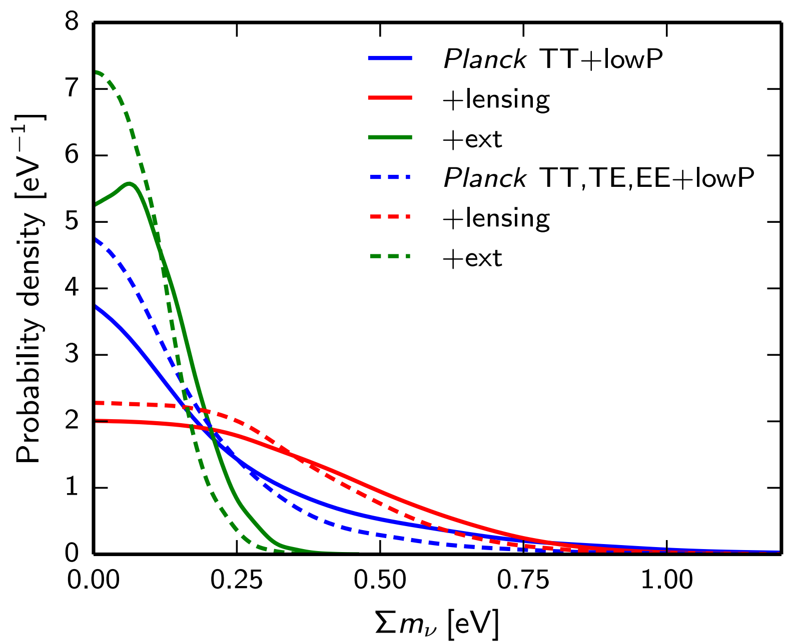
MOTIVATION

Mass hierarchy



King & Luhn (2013)

Current constraints

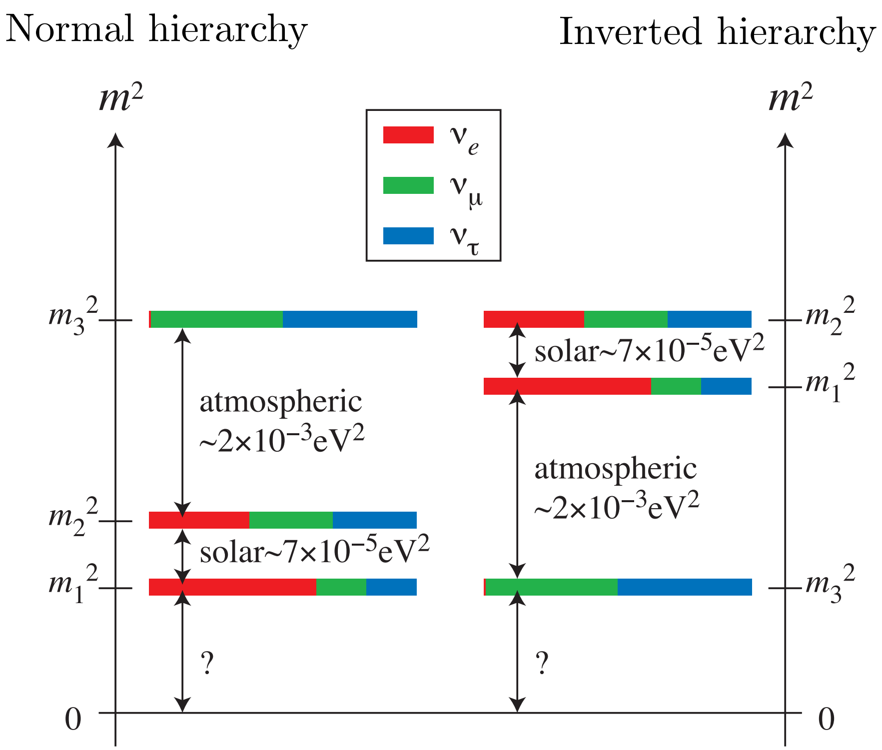


Planck Collaboration XIII (2013)

$$\Sigma m_\nu < 680 \text{ meV (CMB alone)}$$
$$\Sigma m_\nu < 230 \text{ meV (CMB+BAO)}$$

Motivation

Mass hierarchy



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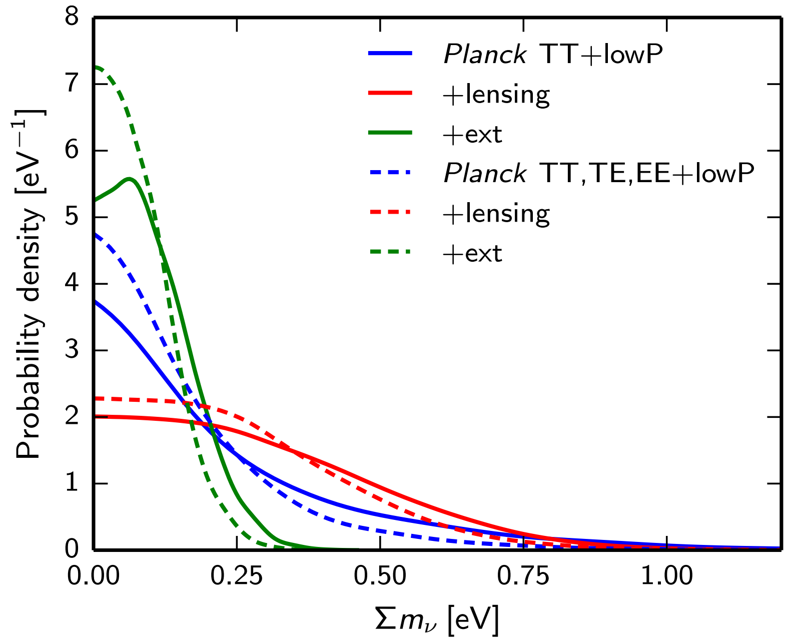
Current constraints



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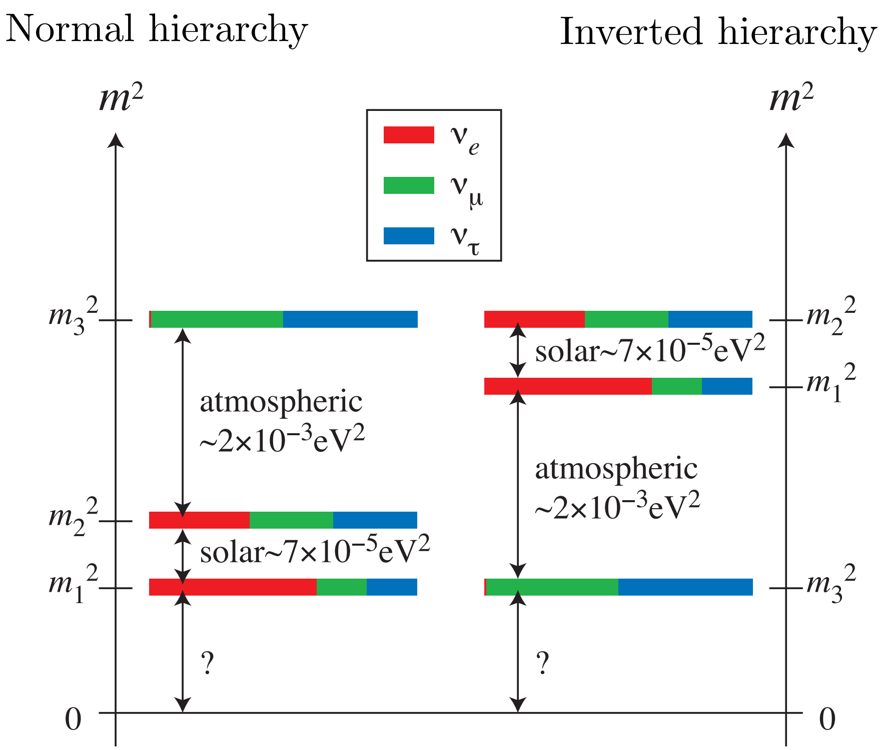

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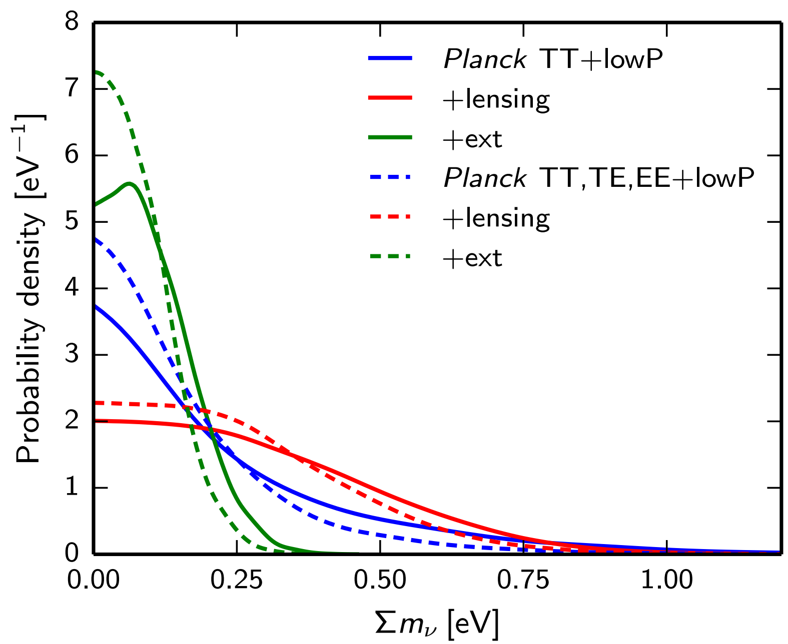


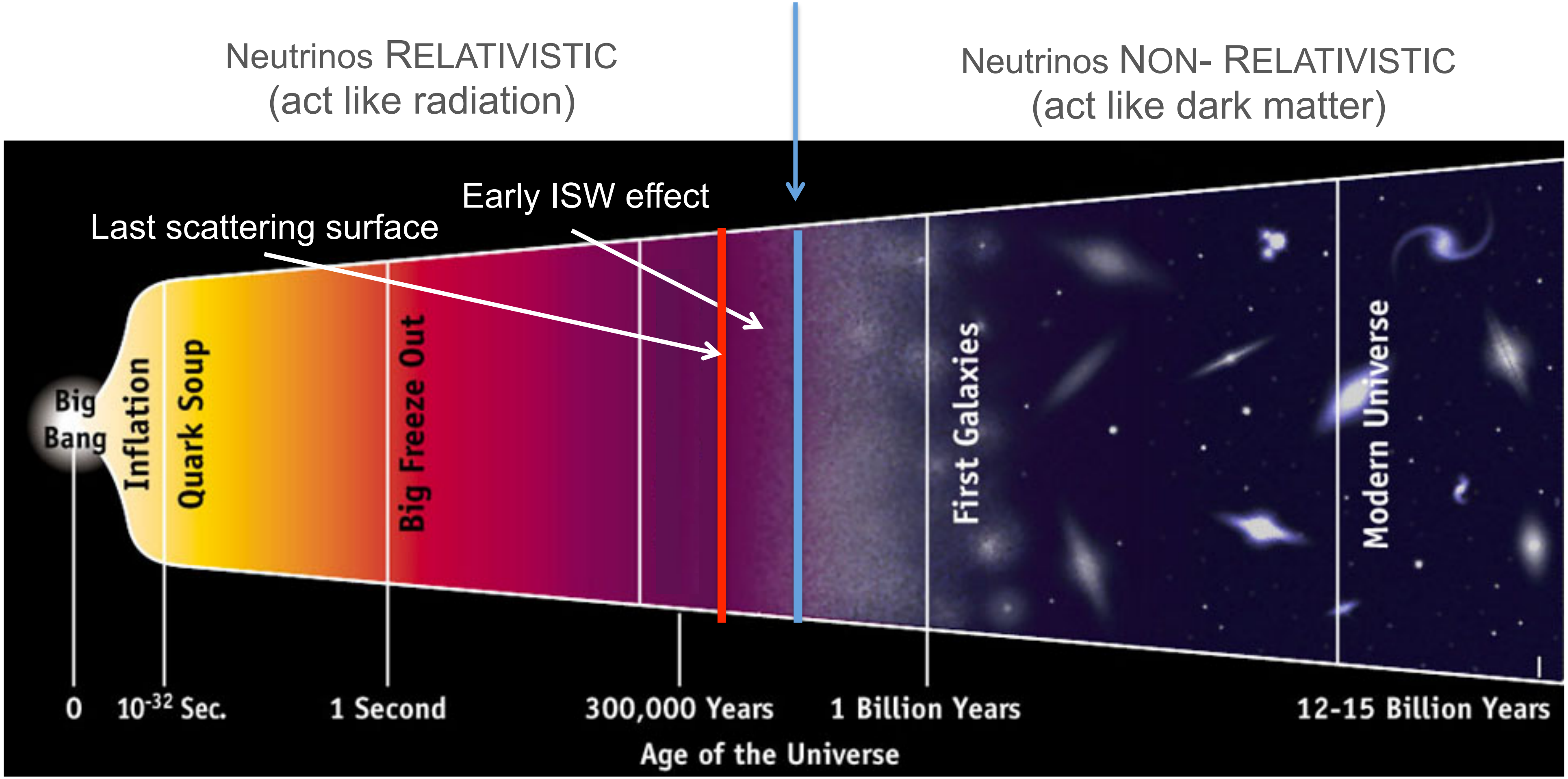
Planck Collaboration XIII (2013)

$$60 \text{ meV} < \Sigma m_\nu < 230 \text{ meV}$$

(ν oscillations + CMB + BAO)

COSMOLOGICAL EFFECTS OF NEUTRINOS

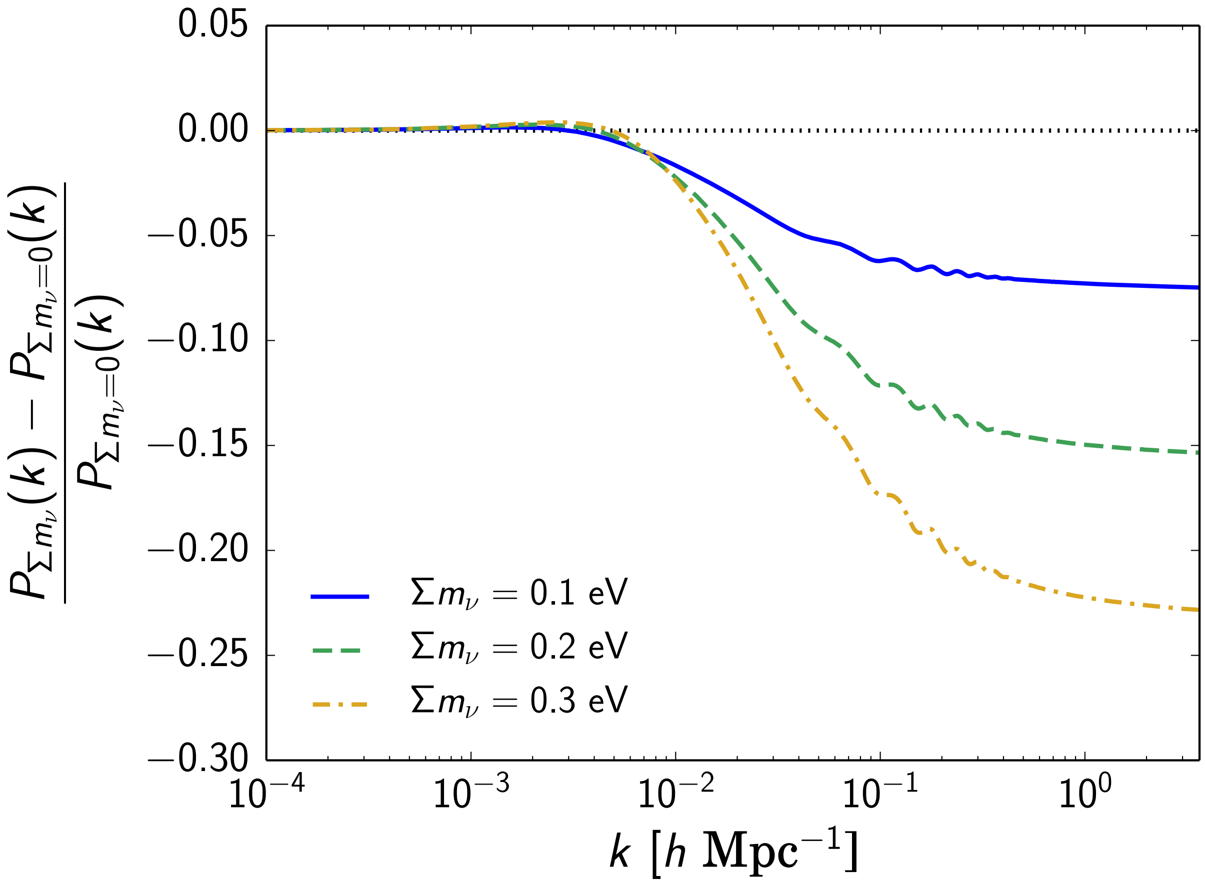
$$\text{Neutrino of mass } m_\nu = 100 \text{ meV transitions at } z \sim 200$$



Cosmological Effects of Neutrinos

Neutrino free-streaming

$$\frac{P_{\Sigma m_\nu}(k) - P_{\Sigma m_\nu=0}(k)}{P_{\Sigma m_\nu=0}(k)} \approx -0.07 \left(\frac{\Sigma m_\nu}{0.1\text{eV}}\right) \left(\frac{\Omega_m h^2}{0.136}\right)^{-1}$$



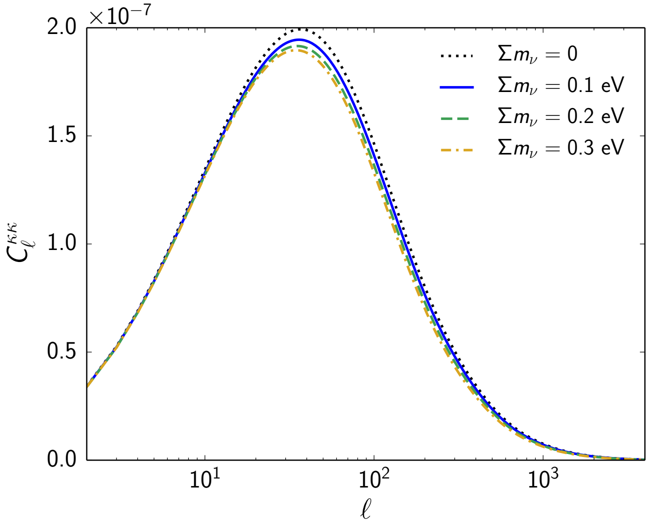
- At early times neutrinos relativistic and decoupled from photon-baryon fluid
- Don't cluster – diffuse (*free stream)* out of over-densities
- Suppresses structure growth on scales below horizon size when neutrinos become non-relativistic *c.f.* CDM-only universe

$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{93\text{eV}}$$

COSMOLOGICAL EFFECTS OF NEUTRINOS

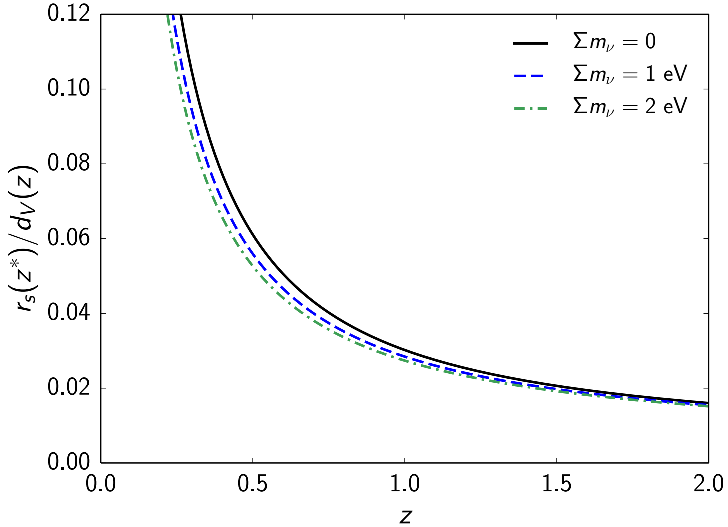
Observables

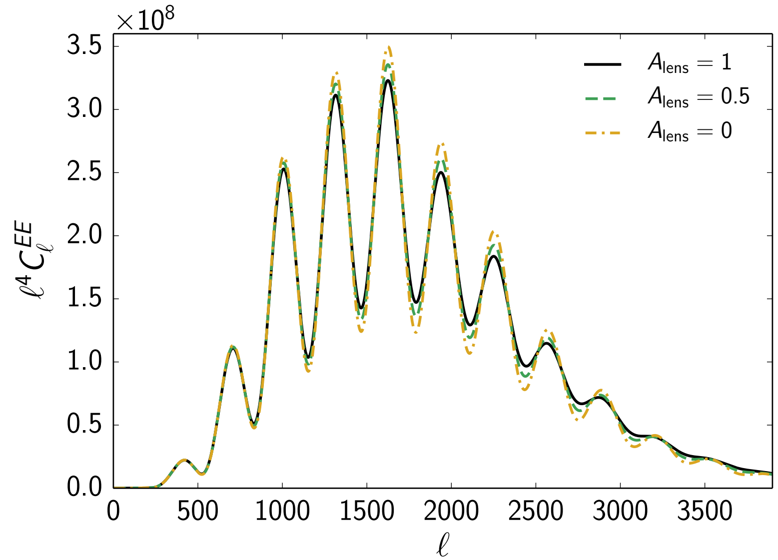
- CMB primary
- CMB lensing
- BAO distance ratio
- SNe
- Cluster counts
- Galaxy clustering
- Galaxy weak lensing
- …



$$C_\ell^{\kappa\kappa} = \int_0^{\chi_H} d\chi \frac{W^2(\chi)}{f_k^2(\chi)} P\left(\frac{\ell}{f_k(\chi)}, \chi\right)$$

$$W(\chi) = \frac{3\Omega_m H_0^2}{2c^2} \frac{f_k(\chi) f_k(\chi^* - \chi)}{a(\chi) f_k(\chi^*)}$$





COSMOLOGICAL EFFECTS OF NEUTRINOS

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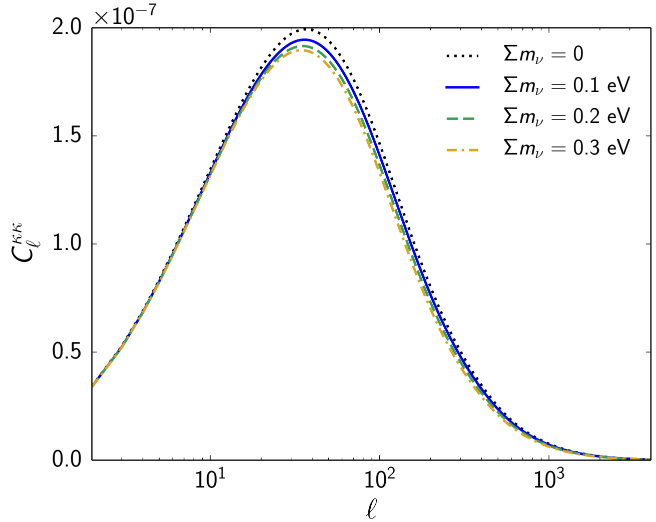
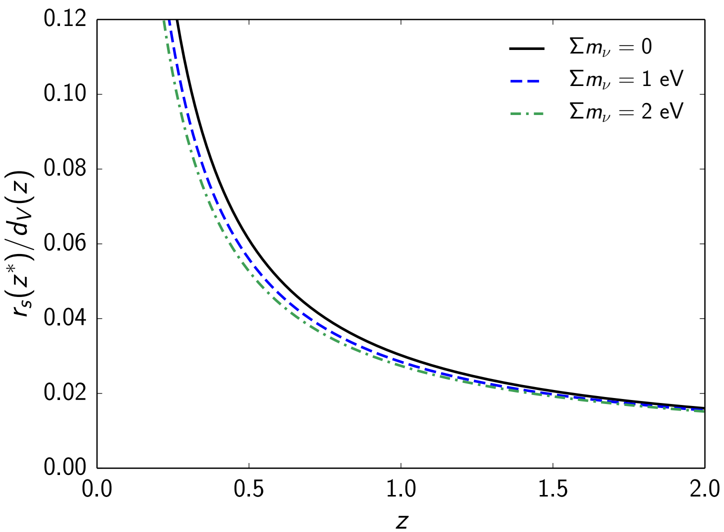
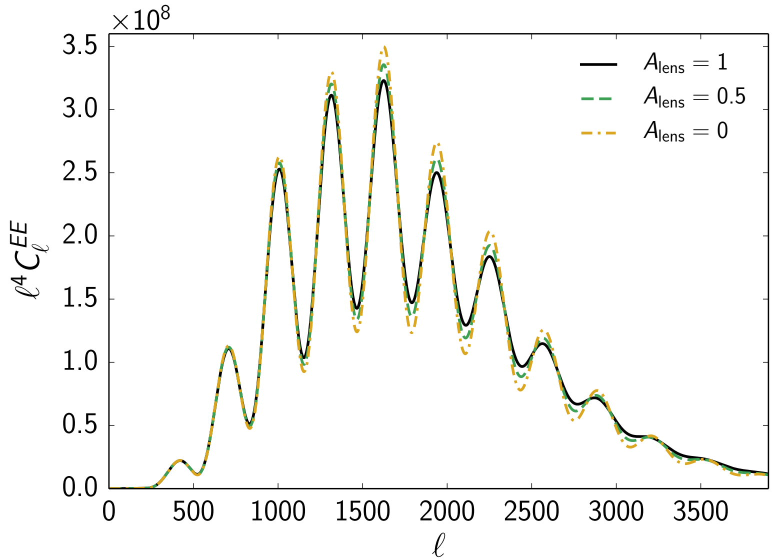


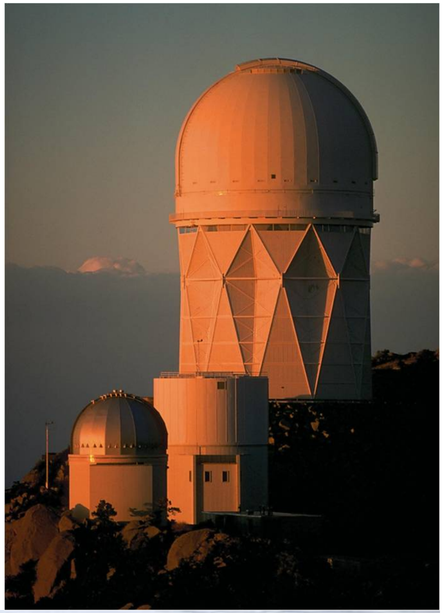
$$C_\ell^{\kappa\kappa} = \int_0^{\chi_H} d\chi \frac{W^2(\chi)}{f_k^2(\chi)} P\left(\frac{\ell}{f_k(\chi)}, \chi\right)$$

$$W(\chi) = \frac{3\Omega_m H_0^2}{2c^2} \frac{f_k(\chi) f_k(\chi^* - \chi)}{a(\chi) f_k(\chi^*)}$$





MASS CONSTRAINTS IN NEXT 5-10 YEARS

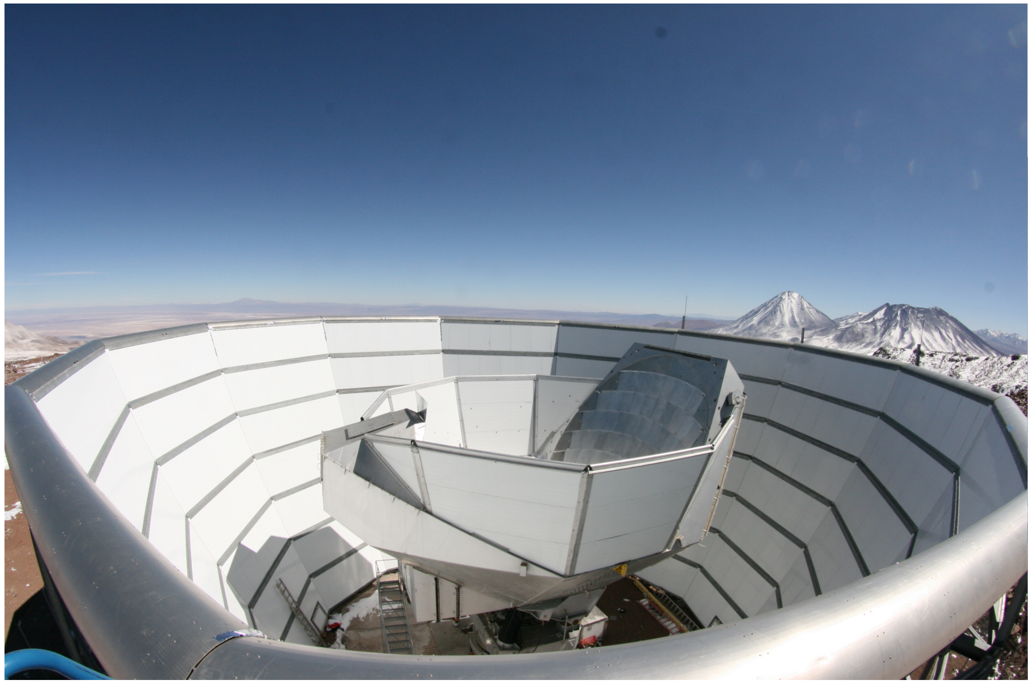


Experiments

CMB
Planck 2015
Full Planck *(large-scale HFI pol.)*
CMB S3 *e.g. AdvACT, SPT-3G*
CMB S4

BAO
BAO-15: *BOSS Low-Z, CMASS, 6dFGS, SDSS MGS.*
DESI

For each experiment must define noise properties, f_{sky}, l_{min}, l_{max}, …



See bonus slide for detailed specifications

Mass Constraints In Next 5-10 Years

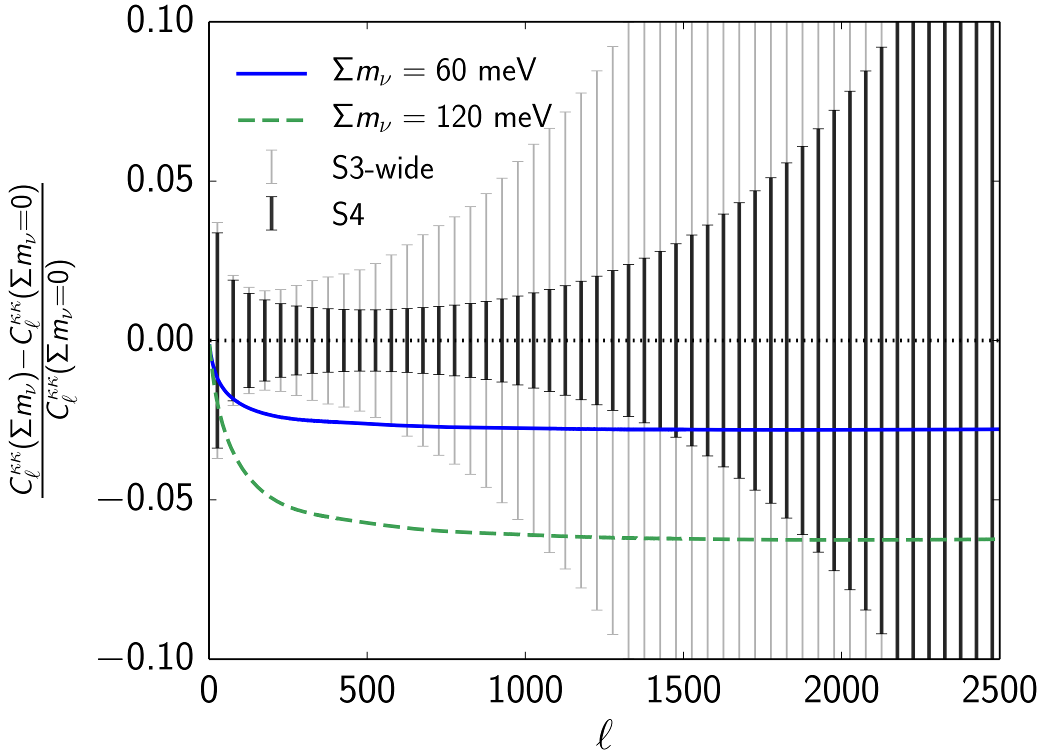
Fisher matrix forecasting

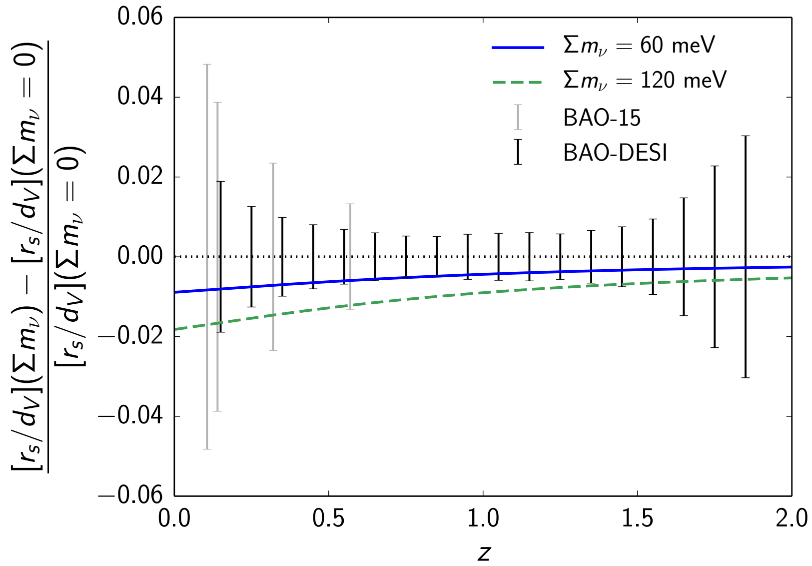
Visualising the constraining power of CMB lensing and BAO

$$F_{ij}(\boldsymbol{\theta}) = \left\langle -\frac{\partial^2 \ln p(\boldsymbol{\theta}|d)}{\partial\theta_i \partial\theta_j} \right\rangle$$

$$\mathbb{C}_{ij} = (F^{-1})_{ij}$$

$$F_{ij} = \sum_{\ell} \frac{\partial C_\ell^T}{\partial\theta_i} \mathrm{Cov}_\ell^{-1} \frac{\partial C_\ell}{\partial\theta_j}$$

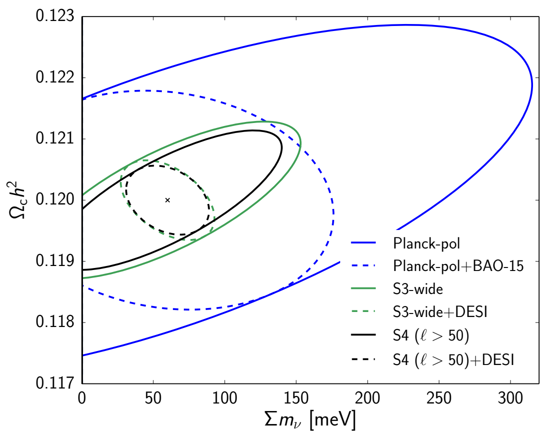




arXiv:
1509.07471

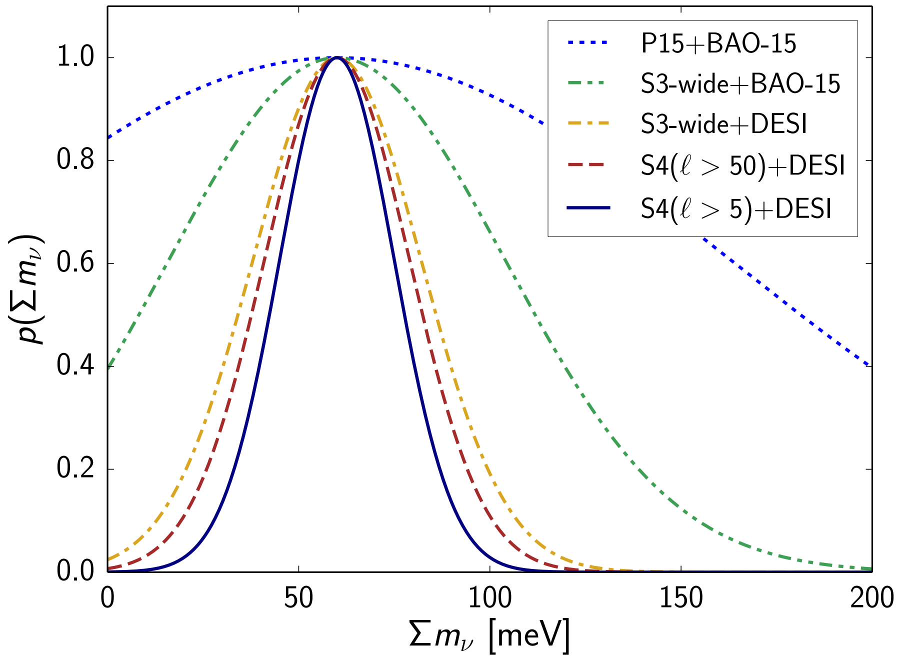
MASS CONSTRAINTS IN NEXT 5-10 YEARS

- Constraints marginalised over LCDM parameters
- BAO helps to break degeneracies in the CMB
- Lensing information in primary spectra (T + E) and 4-point function is important



Forecast constraints

$$\frac{\sigma(\Sigma m_\nu)}{\mathrm{meV}} = \begin{cases} 103 & (\mathrm{P15} + \mathrm{BAO\text{-}15}) \\ 44 & (\mathrm{S3\text{-}wide} + \mathrm{BAO\text{-}15}) \\ 22 & (\mathrm{S3\text{-}wide} + \mathrm{DESI}) \\ 19 & (\mathrm{S4}\ (\ell > 50) + \mathrm{DESI}) \\ 15 & (\mathrm{S4}\ (\ell > 5) + \mathrm{DESI}) \end{cases}$$



Current constraints

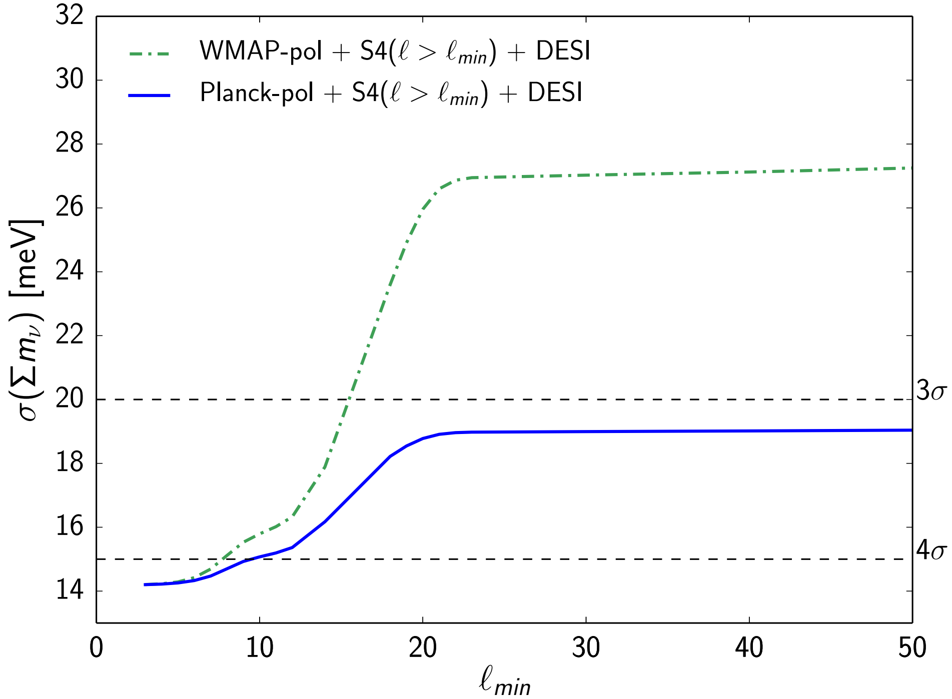
$$60\ \mathrm{meV} < \Sigma m_\nu < 230\ \mathrm{meV}$$
$$(\nu\ \mathrm{oscillations} + \mathrm{CMB} + \mathrm{BAO})$$

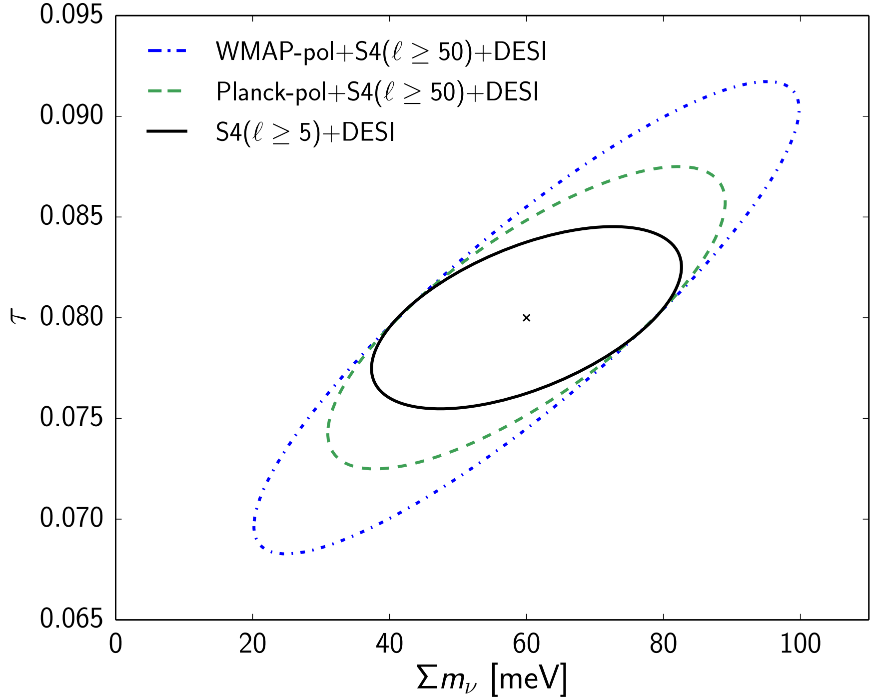
arXiv:

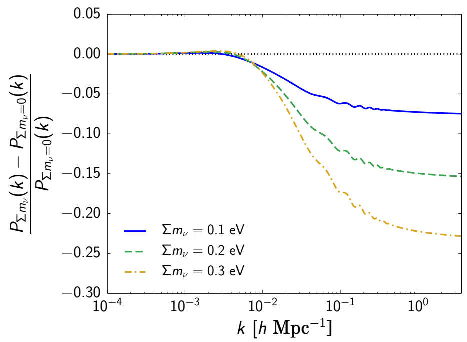
Importance Of Large-Scale Polarisation

$$\text{Primary CMB normalisation} \sim A_s e^{-2\tau}$$

$$C_\ell^{\kappa\kappa} = \int_0^{\chi_H} d\chi \frac{W^2(\chi)}{f_k^2(\chi)} P\left(\frac{\ell}{f_k(\chi)}, \chi\right)$$







Reionisation bump at $\ell \sim 10 : C_\ell^{EE} \sim \tau^2$

arXiv:

Importance Of Large-Scale Polarisation

Primary CMB normalisation $\sim A_s e^{-2\tau}$

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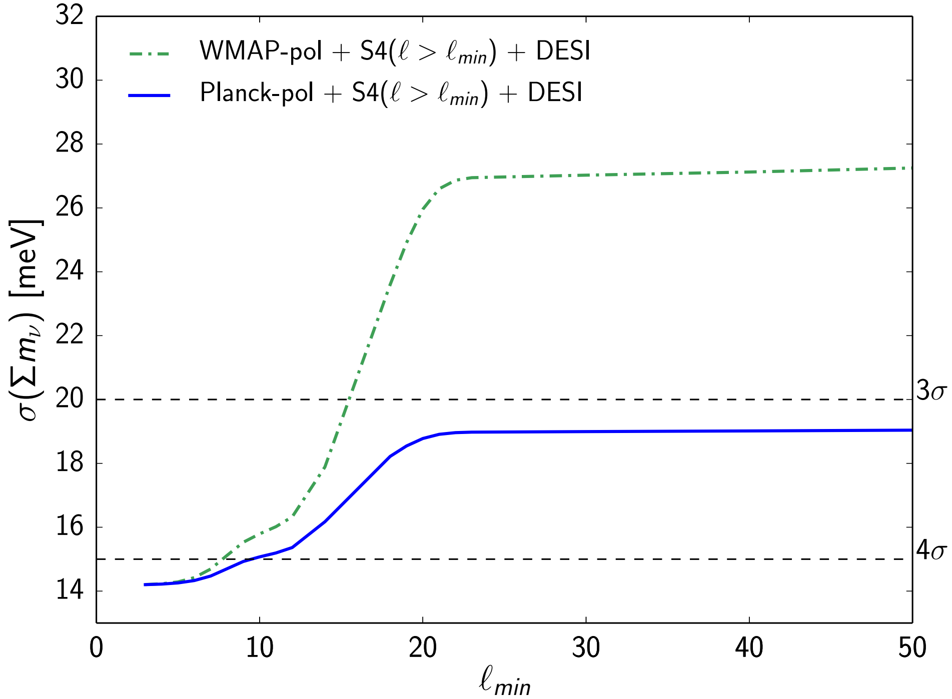
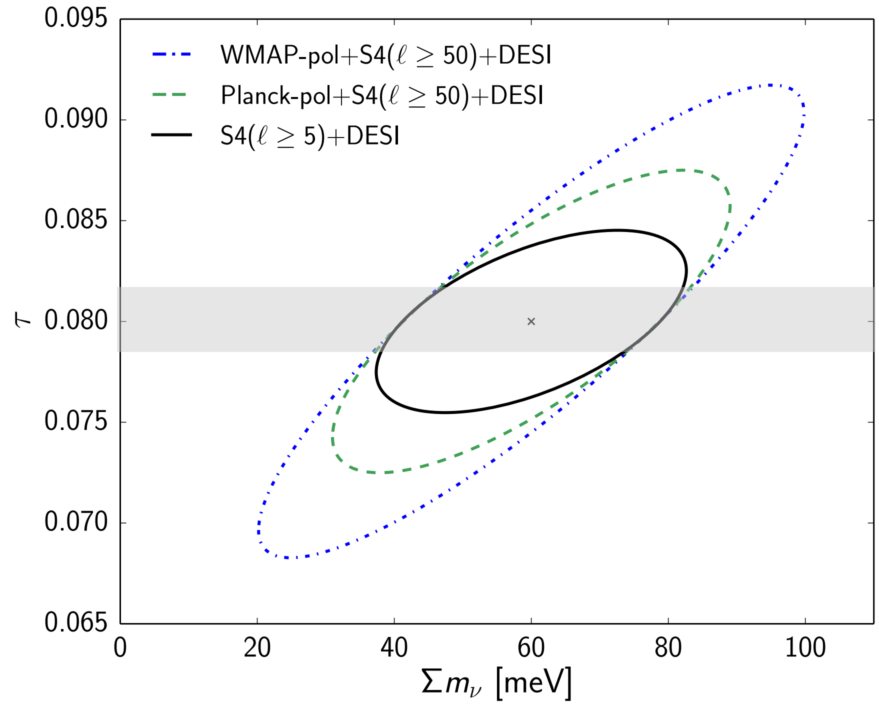
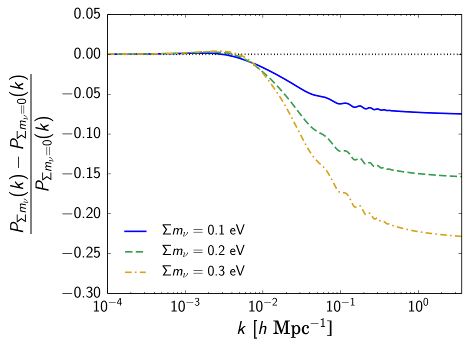


Reionisation bump at $\ell \sim 10$: $C_\ell^{EE} \sim \tau^2$





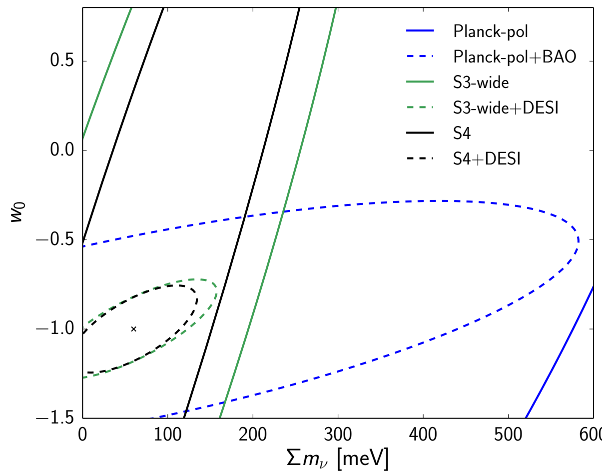
+21cm cosmology: Liu et al. (2015) arXiv: 1509.08463

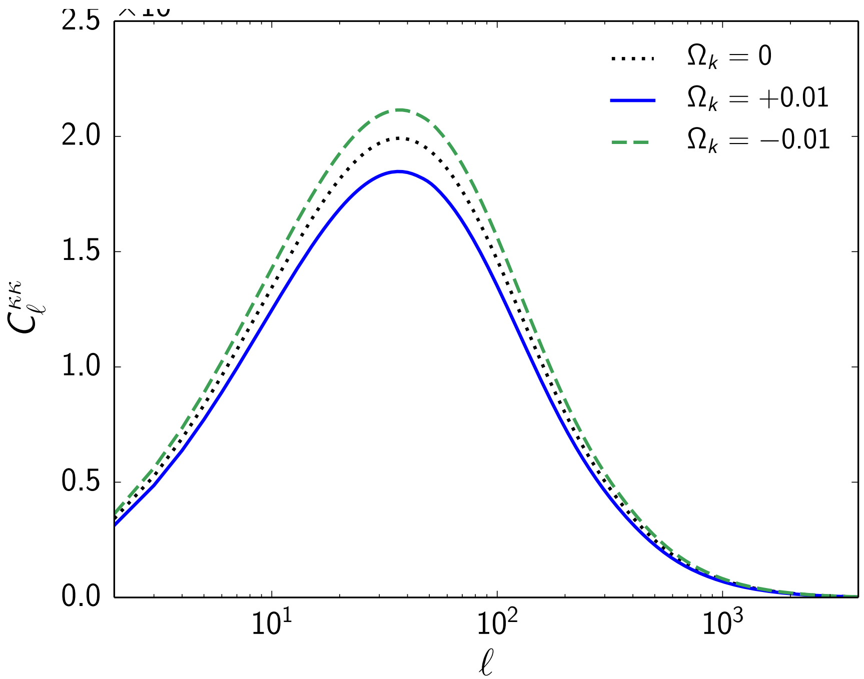
arXiv: 1509.07471

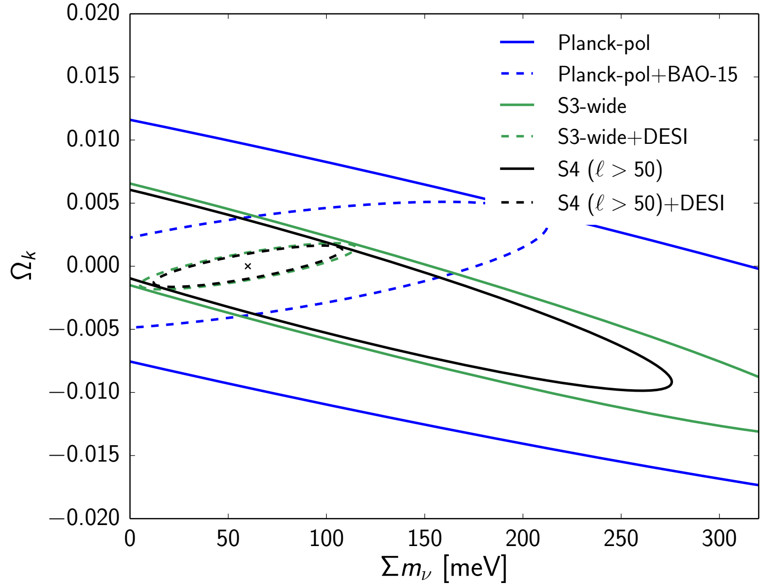
Degeneracies With ΛCDM Extensions

S4 ($l > 50$) + Planck Pol. + DESI constraints

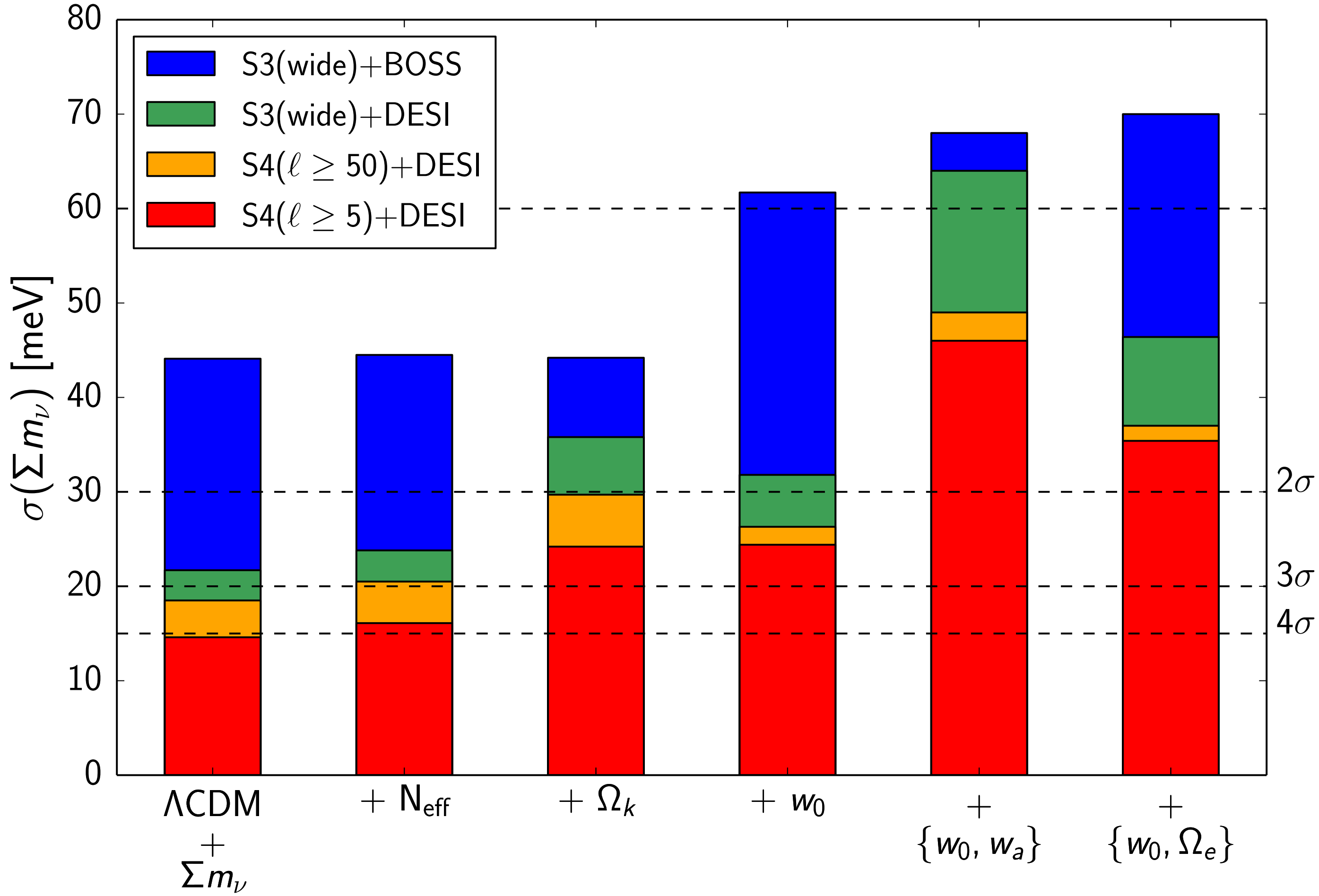
$$\frac{\sigma(\Sigma m_\nu)}{\text{meV}} = \begin{cases} 19 & (\Lambda\text{CDM}+\Sigma m_\nu) \\ 30 & (\Lambda\text{CDM}+\Sigma m_\nu+\Omega_k) \\ 27 & (\Lambda\text{CDM}+\Sigma m_\nu+w_0) \\ 46 & (\Lambda\text{CDM}+\Sigma m_\nu+w_0+w_a) \\ 37 & (\Lambda\text{CDM}+\Sigma m_\nu+\Omega_e+w_0) \\ 64 & (\Lambda\text{CDM}+\Sigma m_\nu+w_0+w_a+\Omega_k) \end{cases}$$







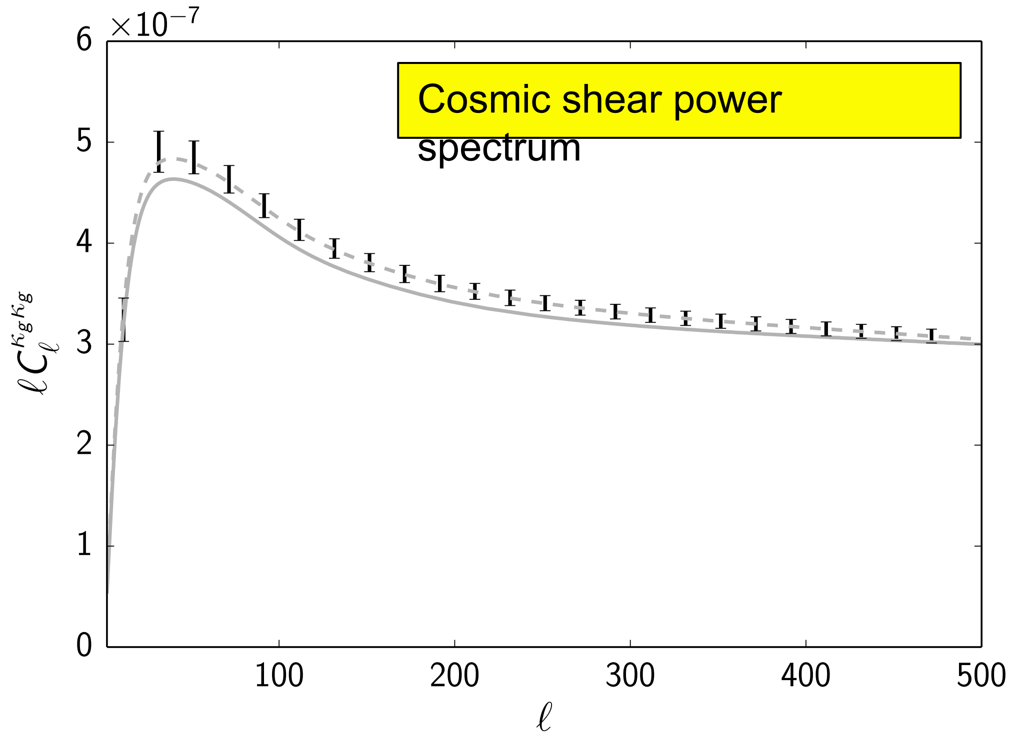
Degeneracies With ΛCDM Extensions



arXiv:1509.07471

Degeneracies With ΛCDM Extensions

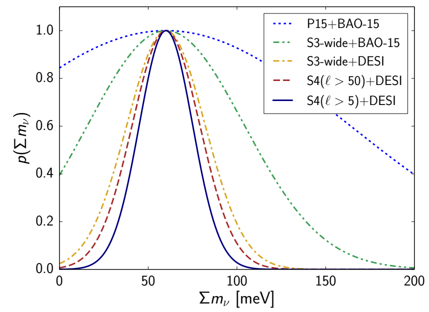
- Use other LSS probes e.g., galaxy shear
- Q: How to discriminate / account for multiple extension models ?
- Q: Do the data require more complex models than LCDM to be explained? Or is simple LCDM enough?
- Ans.: *Bayesian model averaging*
- Massive neutrinos more natural extension to LCDM than DE or curvature.

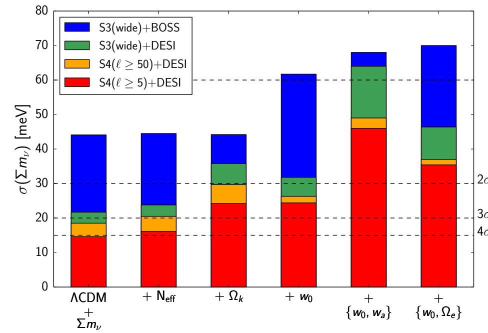


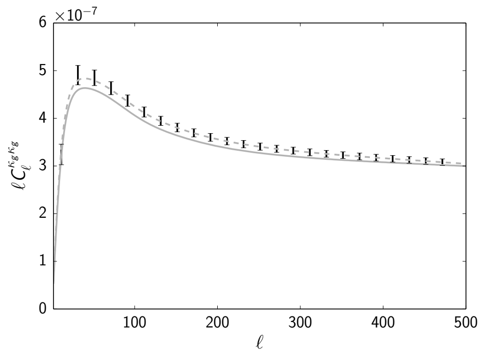
Black uncertainties represent a hypothetical future weak-lensing survey (f_{sky} = 0.5, n_{gal} = 10 arcmin^{-2}, LSST 'gold sample' redshift distribution).

Conclusions

- CMB + BAO will ‘detect’ the neutrino mass at 3σ within 5 years (even in minimal mass scenario)
- Large-scale CMB polarisation important
- Strong degeneracies with LCDM extensions: must be handled properly for convincing detection
- Other LSS probes will help!







Bonus Slides

Experimental Details

Experiment	$f_{\rm sky}$	ν/GHz	$l_{\rm min}$	$l_{\rm max}$	FWHM/arcmin	$\Delta T/\mu$K-arcmin	$\Delta P/\mu$K-arcmin
Planck-2015	0.44	30,44,70,100,143,217,353	2	2500	33,23,14,10,7,5,5,5	145,149,137,65,43,66,200	-,-,450,-,-,-,-
Planck-pol	”						-,-,450,103,81,134,406
WMAP-pol	0.74	33,41,64,94	2	1000	41,28,21,13	-,-,298,296	425,420,424,-

Experiment	$f_{\rm sky}$	Beam (arcmin)	ΔT (μK-arcmin)	ΔP (μK-arcmin)
S3-wide	0.4	1.4	8.0	11.3
S3-deep	0.06	1	4.0	5.7
S4	0.4	3	1	1.4
CV-low	0.4	60	1	1.4

Lensing Information

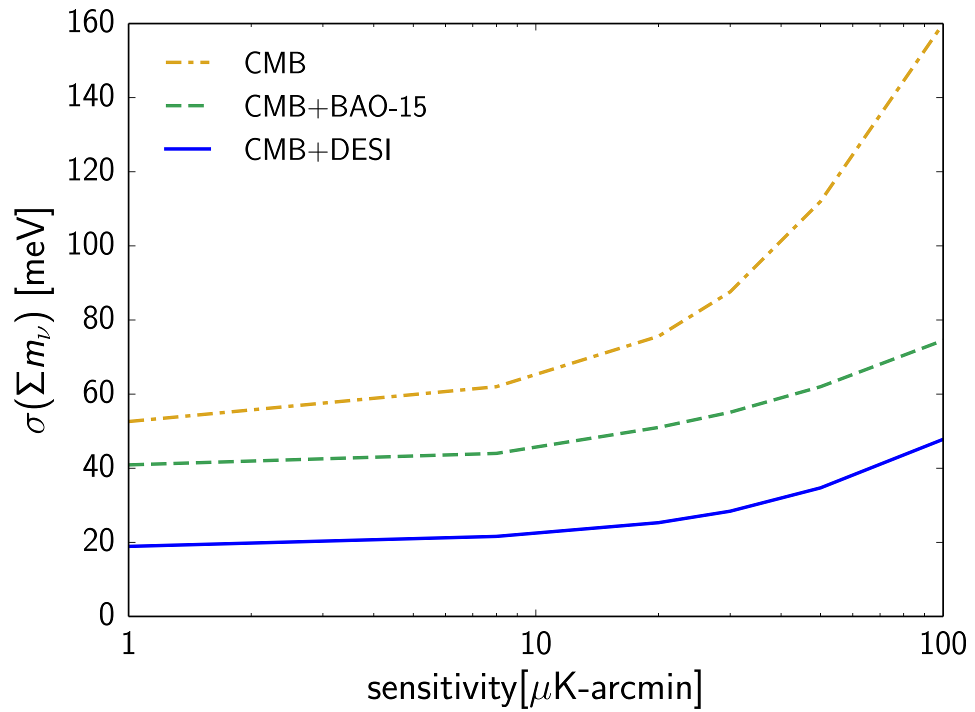
B-mode highly correlated with lensing potential since generated from lensing of the E-mode polarisation

Modeling correlation is difficult analytically since the lensed temperature and polarisation are non-Gaussian fields if the lensing potential is not fixed.

Benoit-Lévy et al.: for S4-like experiment, 20% inflation of neutrino mass uncertainty due to non-Gaussianity on neutrino mass.

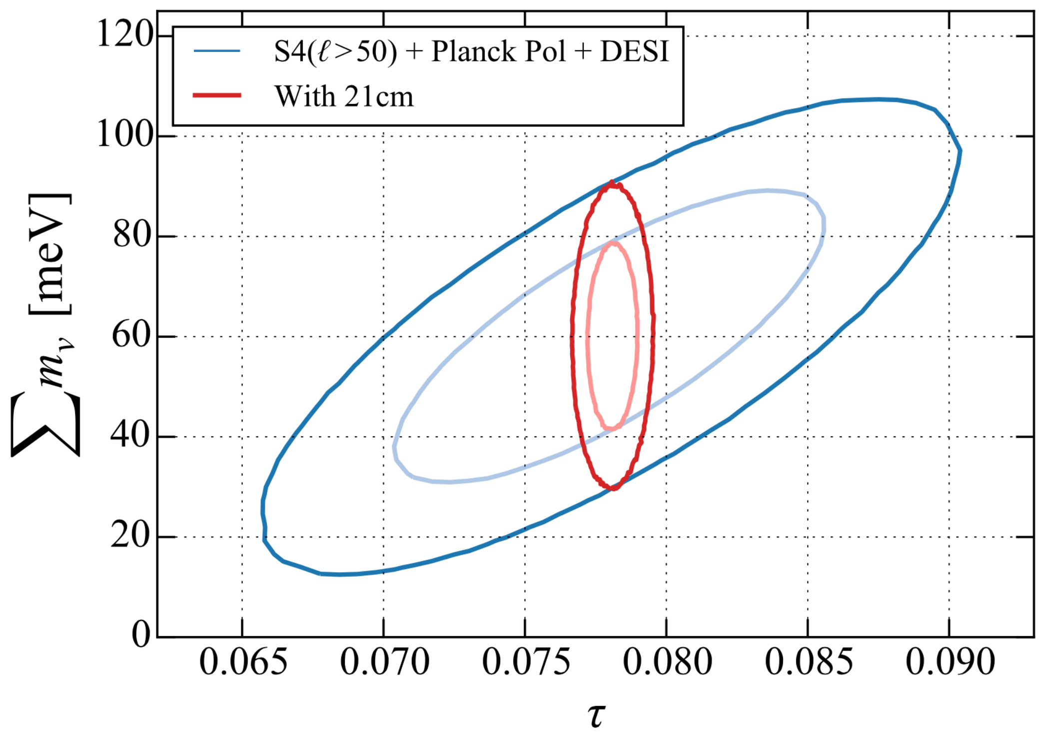
	Unlensed	Lensed TT, TE, EE (2-point only)	Unlensed+$\kappa\kappa$ (4-point only)
S3, $\sigma(\Sigma m_\nu)$:	435	75	61
S4, $\sigma(\Sigma m_\nu)$:	363	64	53

S3/S4 Comparison



$$\frac{\sigma(\Sigma m_\nu)}{\text{meV}} = \begin{cases} 22 & (\text{S3 } (\ell > 50) + \textit{Planck}\text{-pol} + \text{DESI}) \\ 19 & (\text{S4 } (\ell > 50) + \textit{Planck}\text{-pol} + \text{DESI}) \\ 17 & (\text{S3 } (\ell > 50) + \text{CV-low} + \text{DESI}) \end{cases}$$

21cm Tau Prior



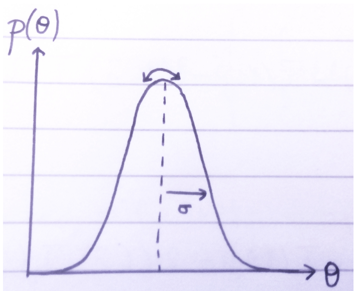
	Fiducial Value	S4$_{\ell>50}$+DESI +*Planck* Pol	$+P_{21}(k)$ +21 cm τ
$\sum m_\nu$ [meV] ...	60	± 19	± 12

Liu et al. (2015), arXiv:1509.08463

Fisher Matrix Forecasting

$$F_{ij}(\boldsymbol{\theta}) = \left\langle -\frac{\partial^2 \ln p(\boldsymbol{\theta}|d)}{\partial\theta_i \partial\theta_j} \right\rangle$$

Expectation value (over data realisations) of the curvature of the log posterior, evaluated at *fiducial parameters*



BAO

$$F_{ij}^{\mathrm{BAO}} = \sum_k \frac{1}{\sigma^2_{f,k}} \frac{\partial f_k}{\partial \theta_i} \frac{\partial f_k}{\partial \theta_j}$$

$$f_k \equiv f(z_k) = r_s / d_V(z_k)$$

CMB

$$\hat{C}_\ell^{XY} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{m=\ell} x^*_{\ell m} y_{\ell m}$$

$$-2\ln\mathcal{L}(\boldsymbol{\theta}) = -2\sum_\ell \ln p(\hat{C}_\ell|\boldsymbol{\theta})$$

$$= \sum_\ell \left[(\hat{C}_\ell - C_\ell(\boldsymbol{\theta}))^\top \mathbb{C}_\ell^{-1}(\boldsymbol{\theta}) (\hat{C}_\ell - C_\ell(\boldsymbol{\theta})) + \ln\det(2\pi\mathbb{C}_\ell(\boldsymbol{\theta})) \right]$$

$$\mathbb{C}(\hat{C}_l^{\alpha\beta}, \hat{C}_l^{\gamma\delta}) = \frac{1}{(2l+1) f_{\mathrm{sky}}} \left[(C_l^{\alpha\gamma} + N_l^{\alpha\gamma})(C_l^{\beta\delta} + N_l^{\beta\delta}) + (C_l^{\alpha\delta} + N_l^{\alpha\delta})(C_l^{\beta\gamma} + N_l^{\beta\gamma}) \right], \quad \text{(A.4)}$$

$$N_\ell^{\alpha\alpha} = (\Delta T)^2 \exp\left(\frac{\ell(\ell+1)\theta^2_{\mathrm{FWHM}}}{8\ln 2} \right)$$

$$F_{ij} = \sum_\ell \frac{\partial C_l^\top}{\partial \theta_i} \mathbb{C}_\ell^{-1} \frac{\partial C_l}{\partial \theta_j}$$