The path to a neutrino mass sum measurement from cosmology

Thejs Brinckmann

Based primarily on

Bolliet, **TB**, Chluba, Lesgourgues 1906.10359

TB, Hooper, Archidiacono, Lesgourgues, Sprenger 1808.05955

Sprenger, Archidiacono, **TB**, Clesse, Lesgourgues 1801.08331

BNL Forum – Sep 3, 2019

Stony Brook University

Overview

1. Current status
2. Forecast setup
3. Theoretical modelling uncertainty
4. Results

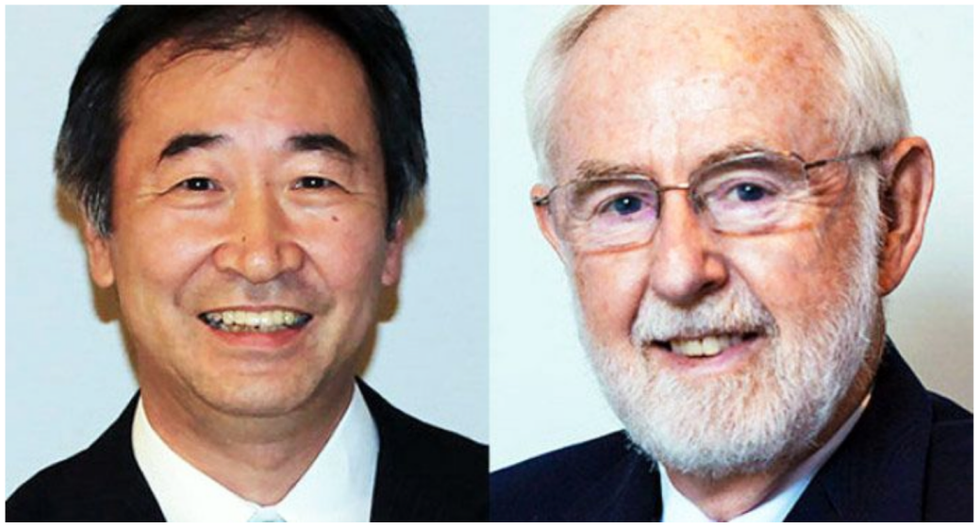
Status of neutrino physics

- Absolute mass and sum of masses not known

- Mass splittings known:
  $|\Delta m^2_{atm}| \approx 2.45 \times 10^{-3}$ eV^2
  $|\Delta m^2_{sol}| \approx 7.50 \times 10^{-5}$ eV^2
  (e.g. Esteban et al. 1611.01514)

SK atmospheric + SNO solar = Nobel Prize 2015!

"...for the discovery of neutrino oscillations, which shows that neutrinos have mass"

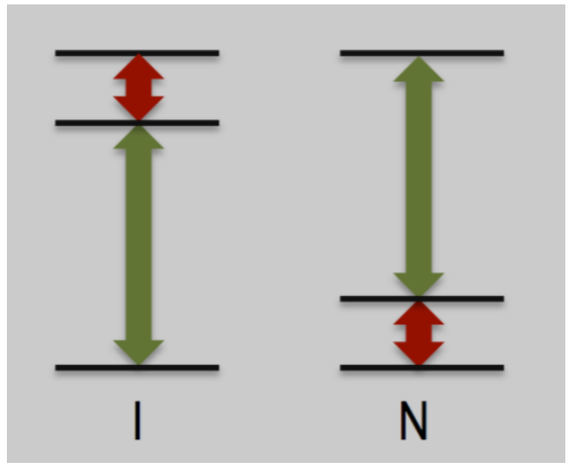


Takaaki Kajita **Art McDonald**

Δm_{atm} sign not known, only magnitude

Two possibilities

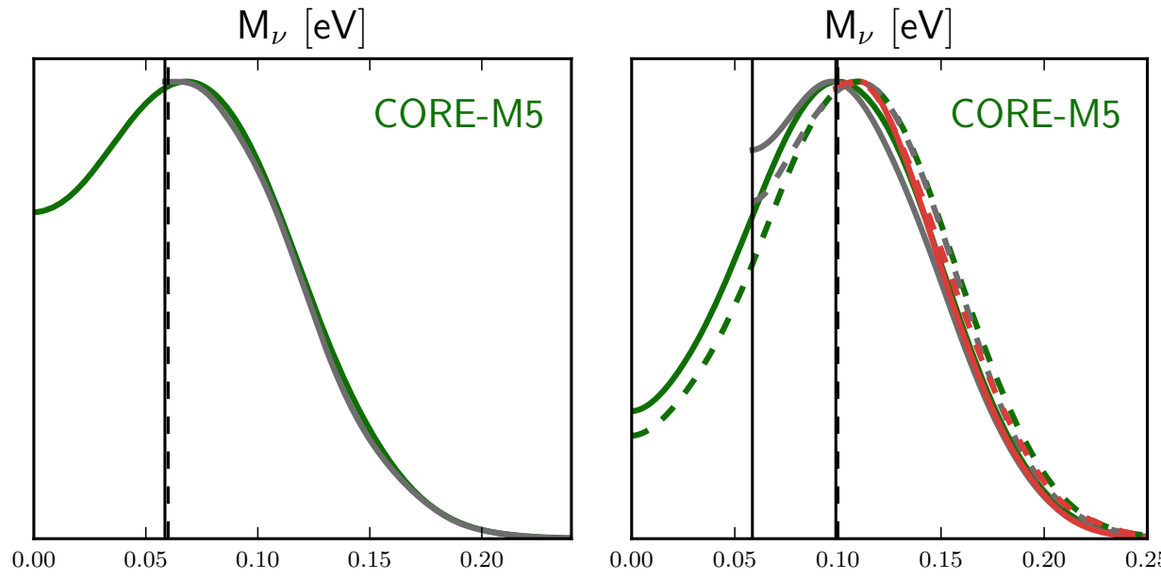
- Normal ordering minimum $\sum m_\nu \gtrsim 58.5$ meV
- Inverted ordering minimum $\sum m_\nu \gtrsim 99$ meV



Status of neutrino physics

- If neutrinos are Majorana: Future particle experiments may be sensitive to hierarchy

- Cosmological experiments *only* sensitive to neutrino mass sum



Di Valentino, **TB**, Gerbino, Poulin et al. 1612.00021

- Current bounds e.g. Planck18 TT,TE,EE + lowE + lensing + BAO

  $\sum m_\nu < 0.12$ eV (95% CL, ΛCDM + $\sum m_\nu$)

  Planck Collaboration 1807.06209

- Trivial to convert mass sum bounds to upper bound on lightest mass state

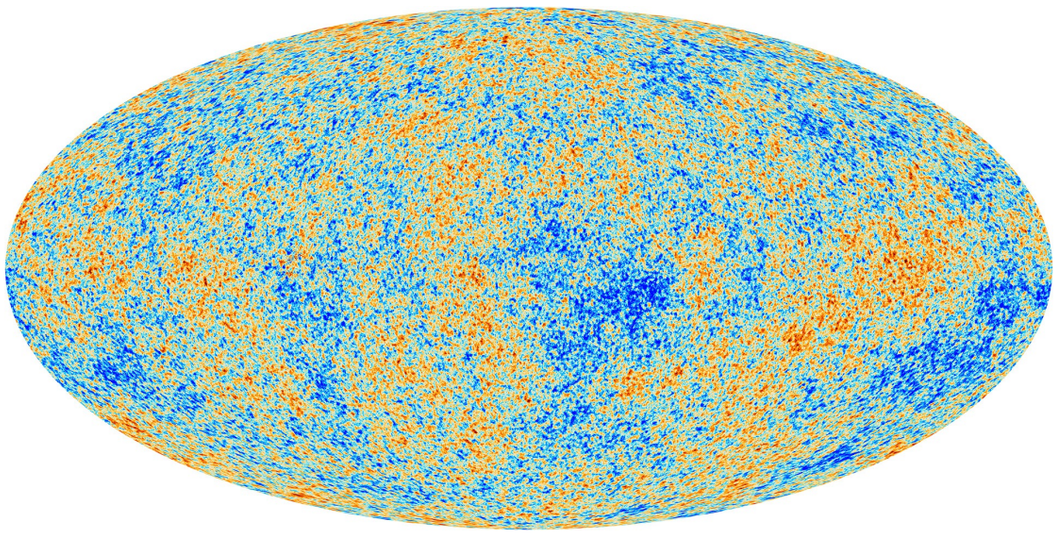
- Constraints degrade with extended models, e.g. Planck15 TT + BAO + SZ cluster counts + optical depth prior

  $\sum m_\nu < 0.149$ eV (95% CL, ΛCDM + $\sum m_\nu$)

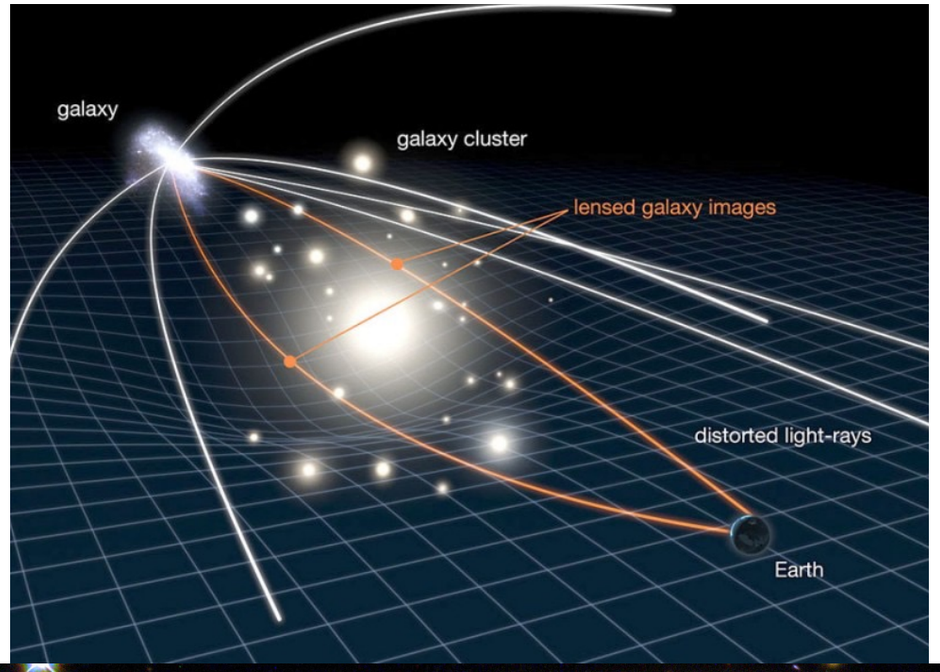
  $\sum m_\nu < 0.32$ eV (95% CL, CDM + $\sum m_\nu + w_0$)

  Bolliet, **TB**, Chluba, and Lesgourgues in 1906.10359

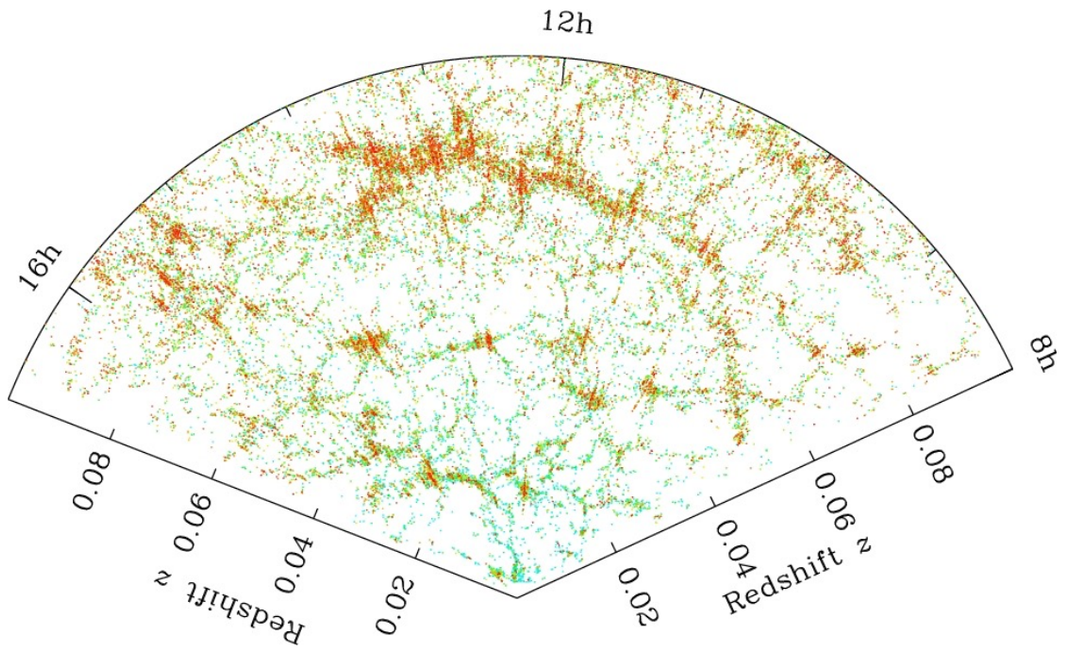
Observables



Credit: Planck collaboration



Credit: NASA/ESA



Credit: Sloan Digital Sky Survey

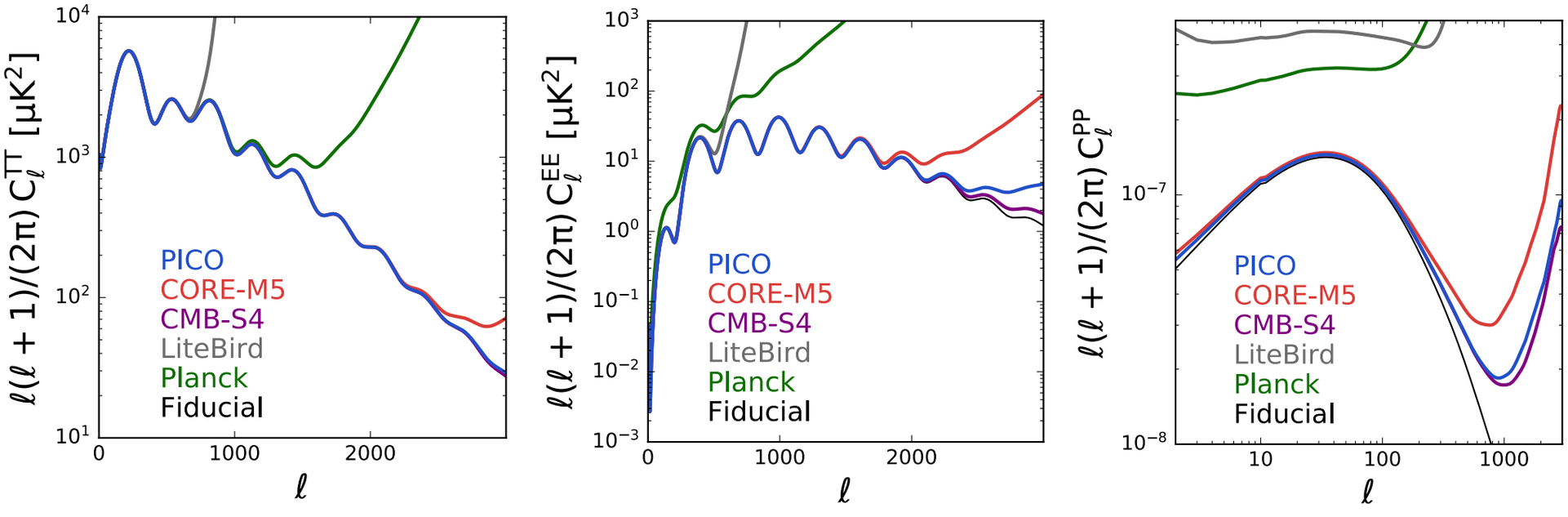
Simulated mock surveys (CMB)

Temperature (TT), polarisation (EE), cross-correlation (TE), lensing (PP)

- Planck $\ell_{max} = 3000$ for 57% sky coverage ~Planck 2018
- LiteBIRD $\ell_{max} = 1350$ for 70% sky Suzuki et al. 1801.06987
- CMB-S4 $\ell_{min} = 30$, $\ell_{max} = 3000$ for 40% sky Abazajian et al. 1610.02743
- CORE-M5 $\ell_{max} = 3000$ for 70% sky Di Valentino, **TB**, Gerbino, Poulin et al. 1612.00021
- PICO $\ell_{max} = 3000$ for 70% sky Sutin et al. 1808.01368, Young et al. 1808.01369

Noise spectra computed with FuturCMB (Perrotto & Lesgourgues)

Theoretical C_ℓ + noise spectra



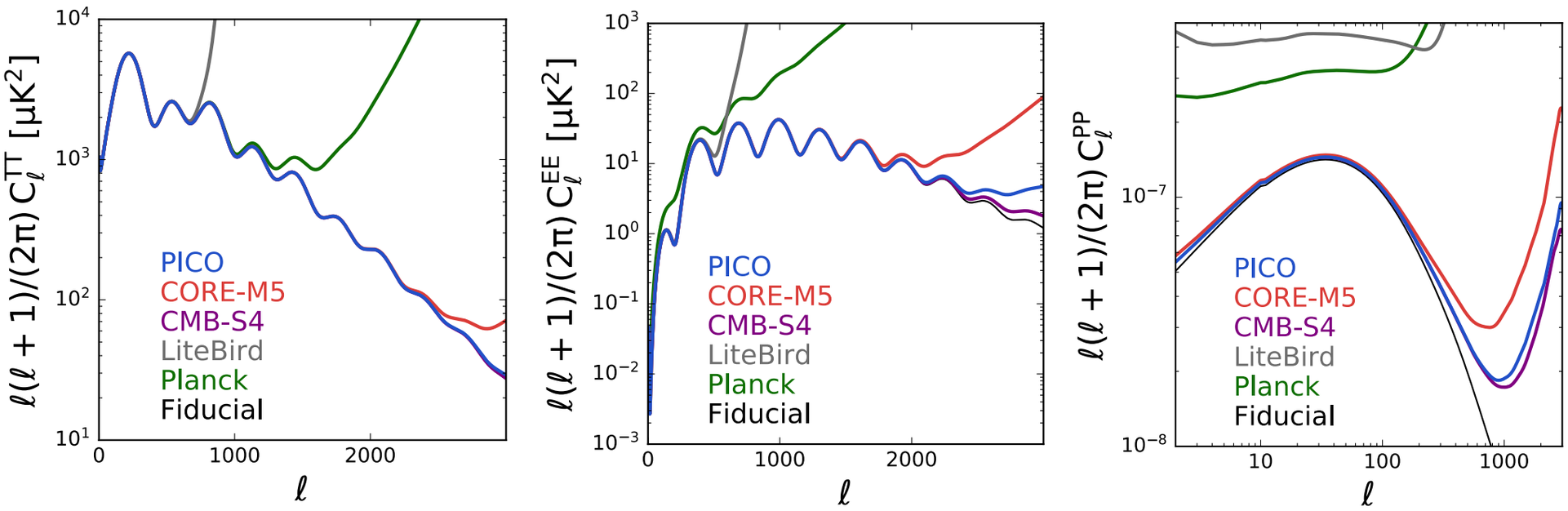
Simulated mock surveys (CMB)

CMB-S4 combined with other surveys

- CMB-S4 $\ell_{min} = 51$, $\ell_{max} = 3000$ for 40% sky
- LiteBIRD $\ell_{max} = 50$ for 70% sky and $\ell_{min} = 51$, $\ell_{max} = 1350$ for 30% sky
- CORE-M5 $\ell_{max} = 50$ for 70% sky and $\ell_{min} = 51$, $\ell_{max} = 3000$ for 30% sky

Noise spectra computed with FuturCMB (Perrotto & Lesgourgues)

Theoretical C_ℓ + noise spectra



Simulated mock surveys (LSS)

Mock large-scale structure surveys		Planned start	Duration	
1. DESI	baryon acoustic oscillations	2020	5 years	Vargas-Margaña et al. 1901.01581
2. Euclid	cosmic shear, galaxy clustering	2022	5 years?	Amendola et al. 1606.00180
3. SKA1-MID	21cm intensity mapping	Mid 2020s	30+years? (incl. SKA2)	Bacon et al. 1811.02743
4.	independent $\tau_{\rm reio}$ measurement			

Redshift range		
0.1 - 1.9	DESI	baryon acoustic oscillations
0.7 - 2.0	Euclid	cosmic shear, galaxy clustering
0.05 - 0.45	SKA1-MID band 2	intensity mapping

Tools

- MontePython v3.0
  Audren et al. 1210.7183,
  Brinckmann & Lesgourgues 1804.07261

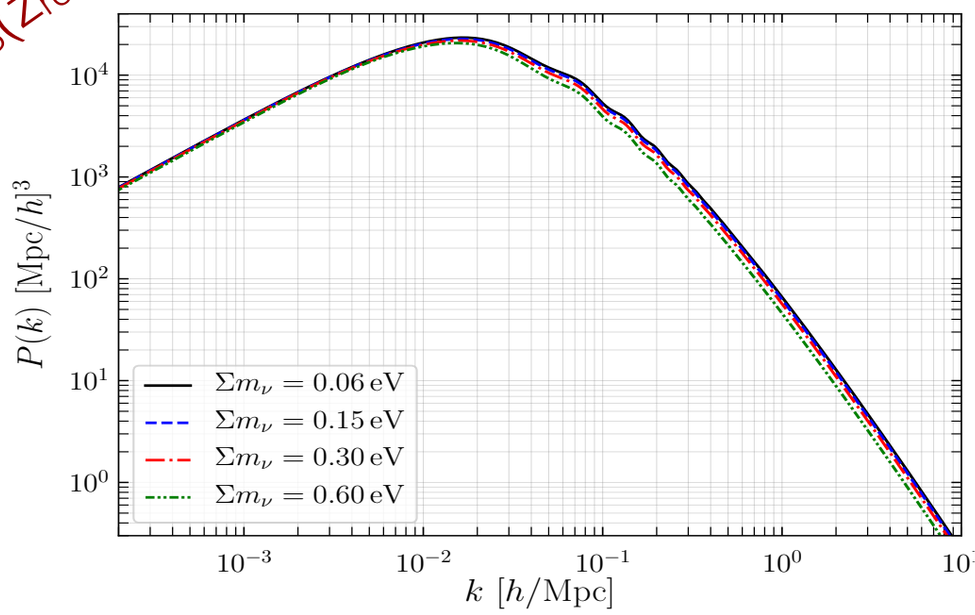
  New version 3.2 with many new likelihoods
  https://github.com/brinckmann/montepython_public
  Problems? See issues page!
  Python 3 compatibility + new likelihoods with upcoming v3.3

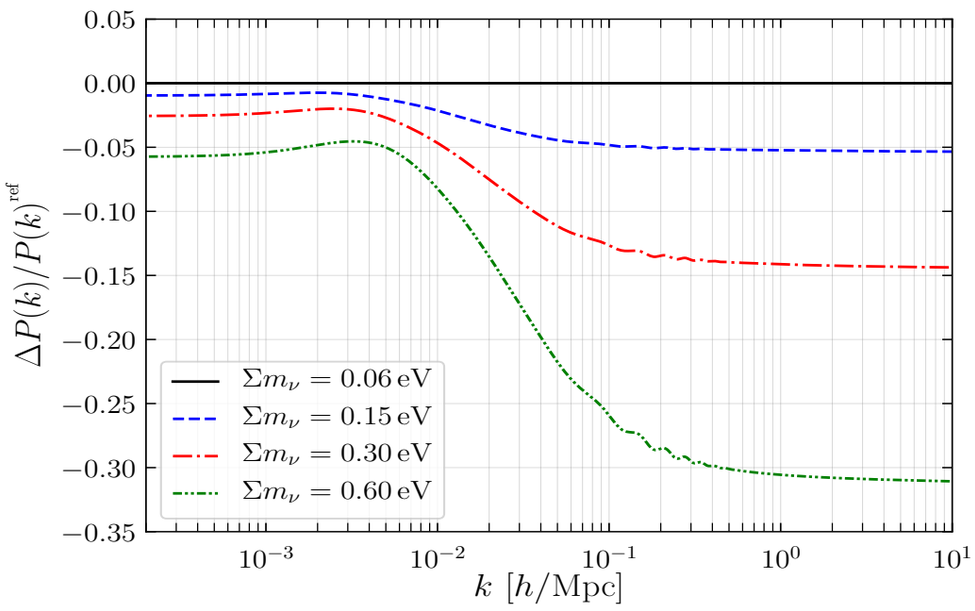
- CLASS
  Blas, Lesgourgues, Tram 1104.2933

  https://github.com/lesgourg/class_public

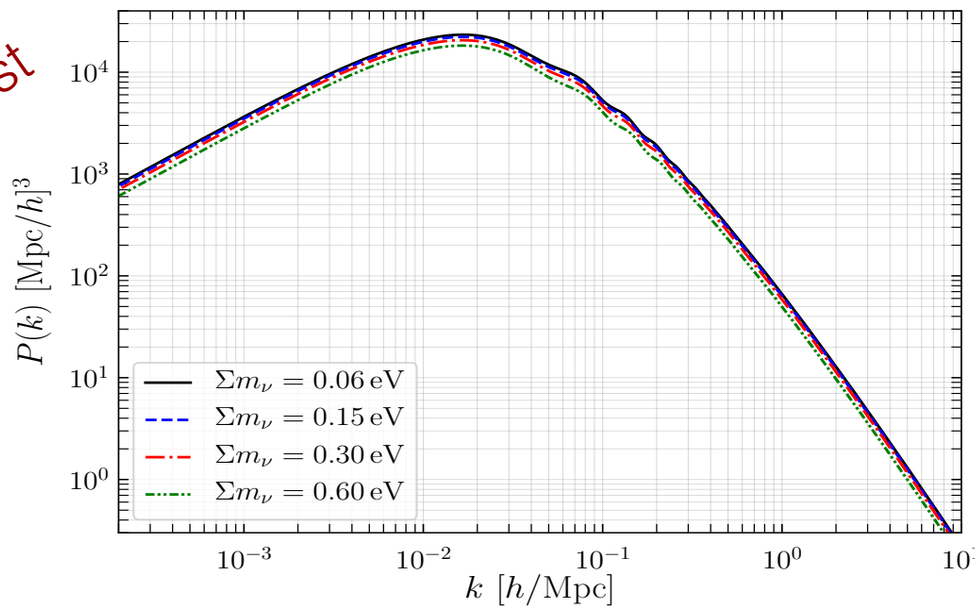
Effect of neutrinos: matter power spectrum

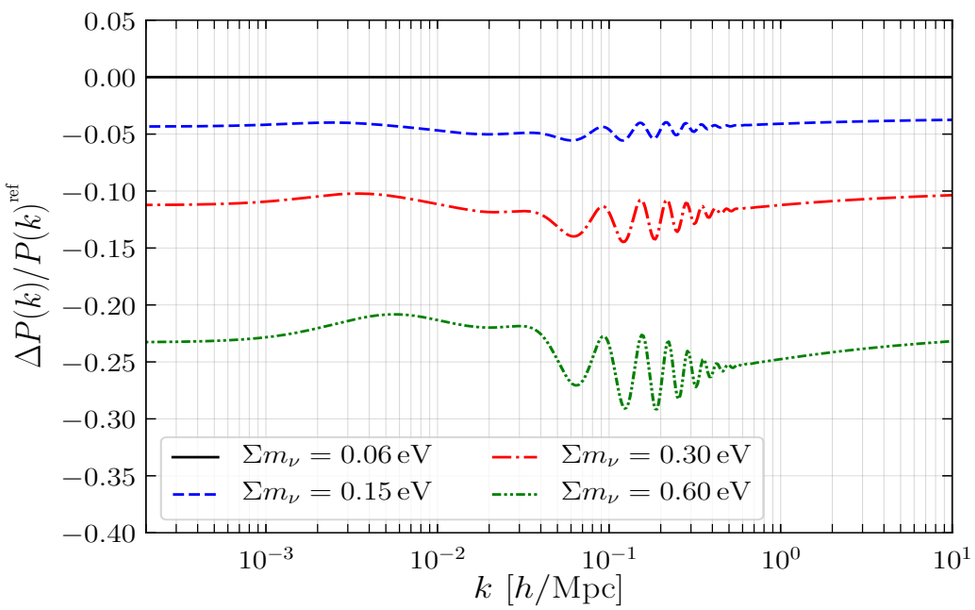
Fix $\Omega_m h^2$ by adjusting h, changing $d_A(z_{rec})$, $r_s(z_{rec})$ and so θ_s





CMB constrains $\Omega_c h^2$, $\Omega_b h^2$, θ_s well → fix these, adjust Ω_m and h





Galaxy clustering

We correct for observational effects

$$P_g(k,\mu,z) = f_{\rm AP}(z) \times f_{\rm res}(k,\mu,z) \times f_{\rm RSD}(\hat{k},\hat{\mu},z) \times b^2(z) \times P_{cb}(\hat{k},z)$$

Alcock-Paczinsky effect

effect due to limited resolution

redshift-space distortions

galaxy bias

Massive neutrinos: P_{cb} not P_m

and account for uncertainty in the modelling with nuisance parameters $\sigma_{\rm NL}$ $\beta_0^{\rm Euclid}$ $\beta_1^{\rm Euclid}$

$$f_{\rm RSD}(\hat{k},\hat{\mu},z) = \left(1+\beta(\hat{k},z)\,\hat{\mu}^2\right)^2 e^{-\hat{k}^2\hat{\mu}^2\sigma_{\rm NL}^2}$$

$$\beta(\hat{k},z) = -\frac{1+z}{2b(z)} \cdot \frac{d\ln P_{cb}(\hat{k},z)}{dz}$$

Massive neutrinos: P_{cb} not P_m

e.g. Vagnozzi, **TB**, Archidiacono, Freese, Gerbino Lesgourgues, and Sprenger 1801.08331

We assume a simple linear bias

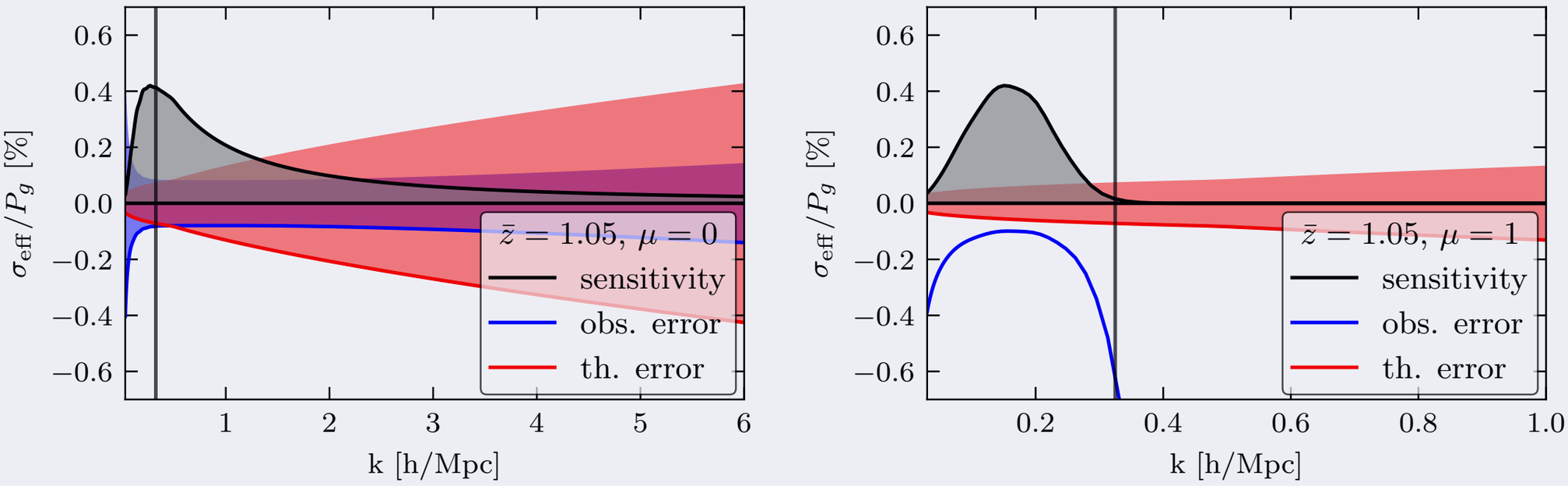
$$b(z) = \sqrt{1+z}$$

including nuisance parameters

$$b(z) = \beta_0^{\rm Euclid}(1+z)^{0.5\beta_1^{\rm Euclid}}$$

Clustering theoretical uncertainty

Euclid galaxy clustering



Common non-linear approach:
Non-linear cut-off e.g. $k_{max} = 0.2$ h/Mpc

Our non-linear method:
Theoretical uncertainty due to non-linear modelling

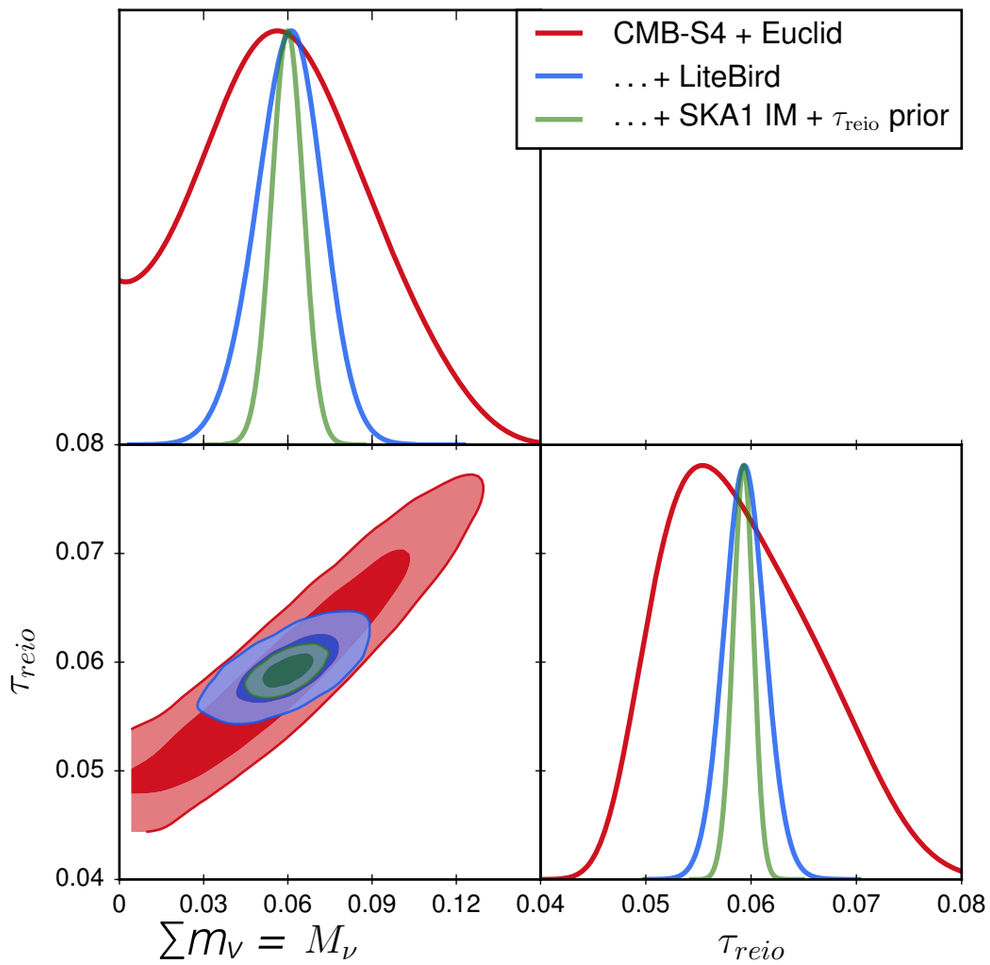
"Conservative"
Non-linear cut-off $k_{max}(z=0) = 0.2$ h/Mpc
+ theoretical uncertainty

"Realistic"
Non-linear cut-off $k_{max}(z=0) = 10$ h/Mpc
+ theoretical uncertainty

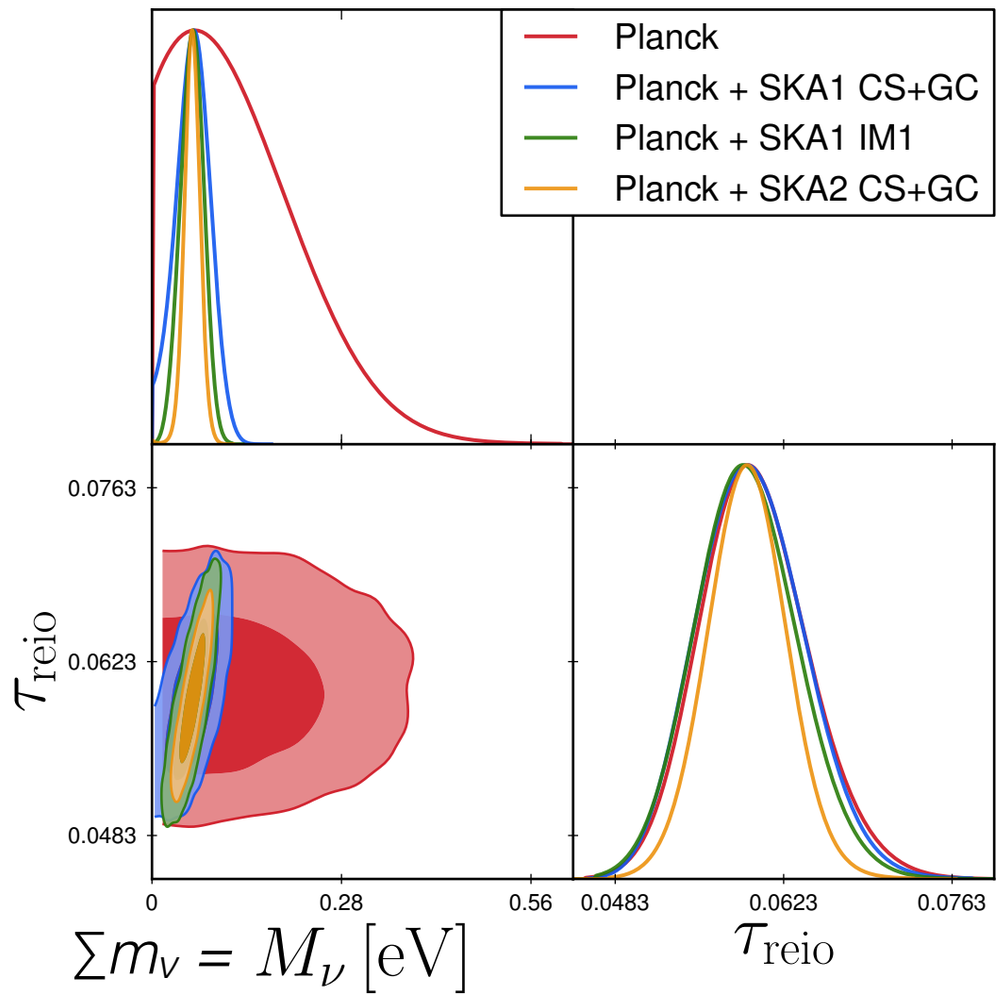
$$k_{\rm NL}(z) = k_{\rm NL}(0) \cdot (1+z)^{2/(2+n_s)}$$

Optical depth to reionization?

TB, Hooper, Archidiacono, Lesgourgues, and Sprenger 1808.05955



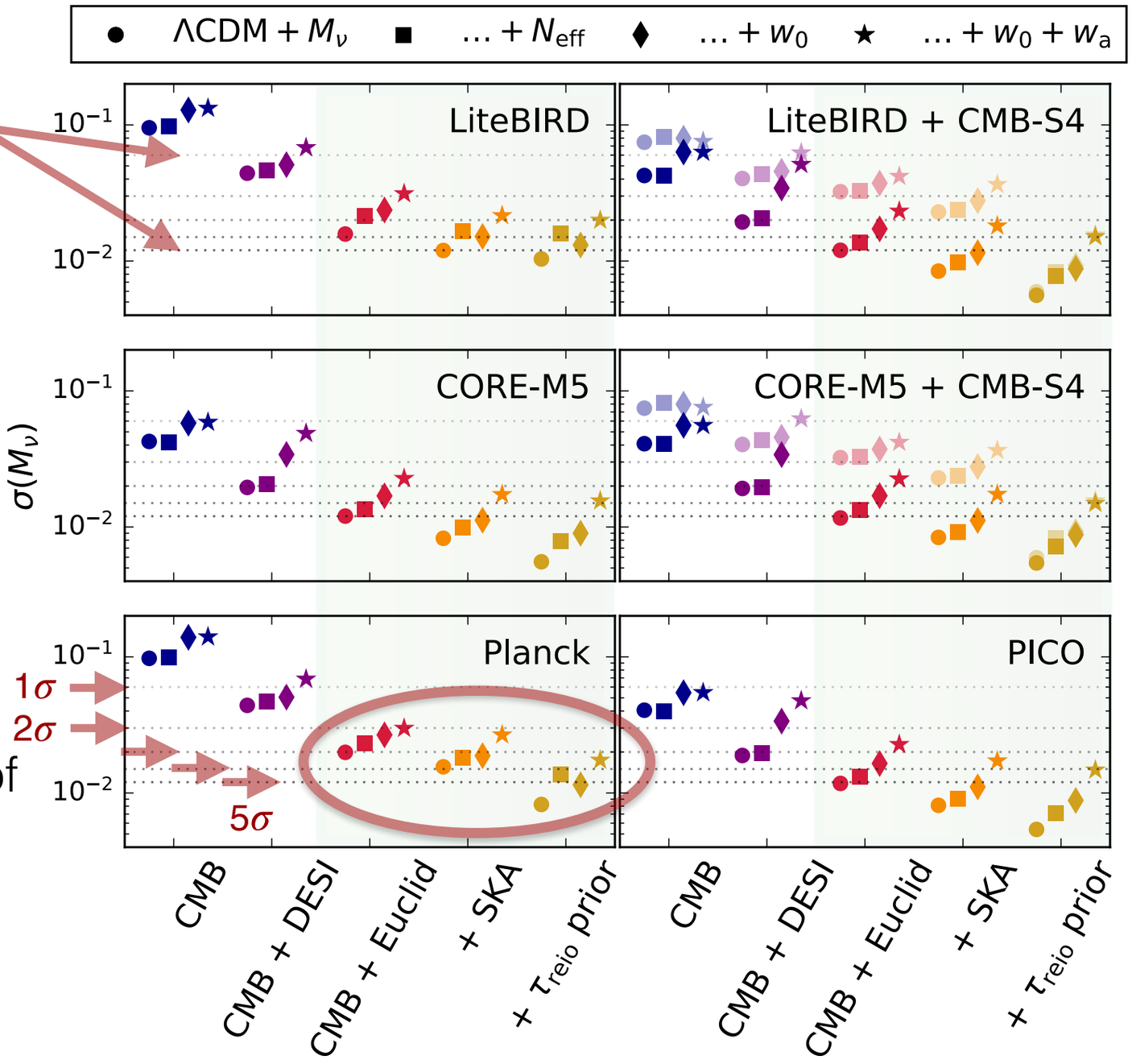
Sprenger, Archidiacono, **TB**, Clesse, and Lesgourgues 1801.08331



$\tau_{\rm reio}$ is important, but not crucial!

Results

dotted lines indicate 1–5 σ detection for a minimal normal hierarchy mass sum $\sum m_\nu \approx 60$ meV



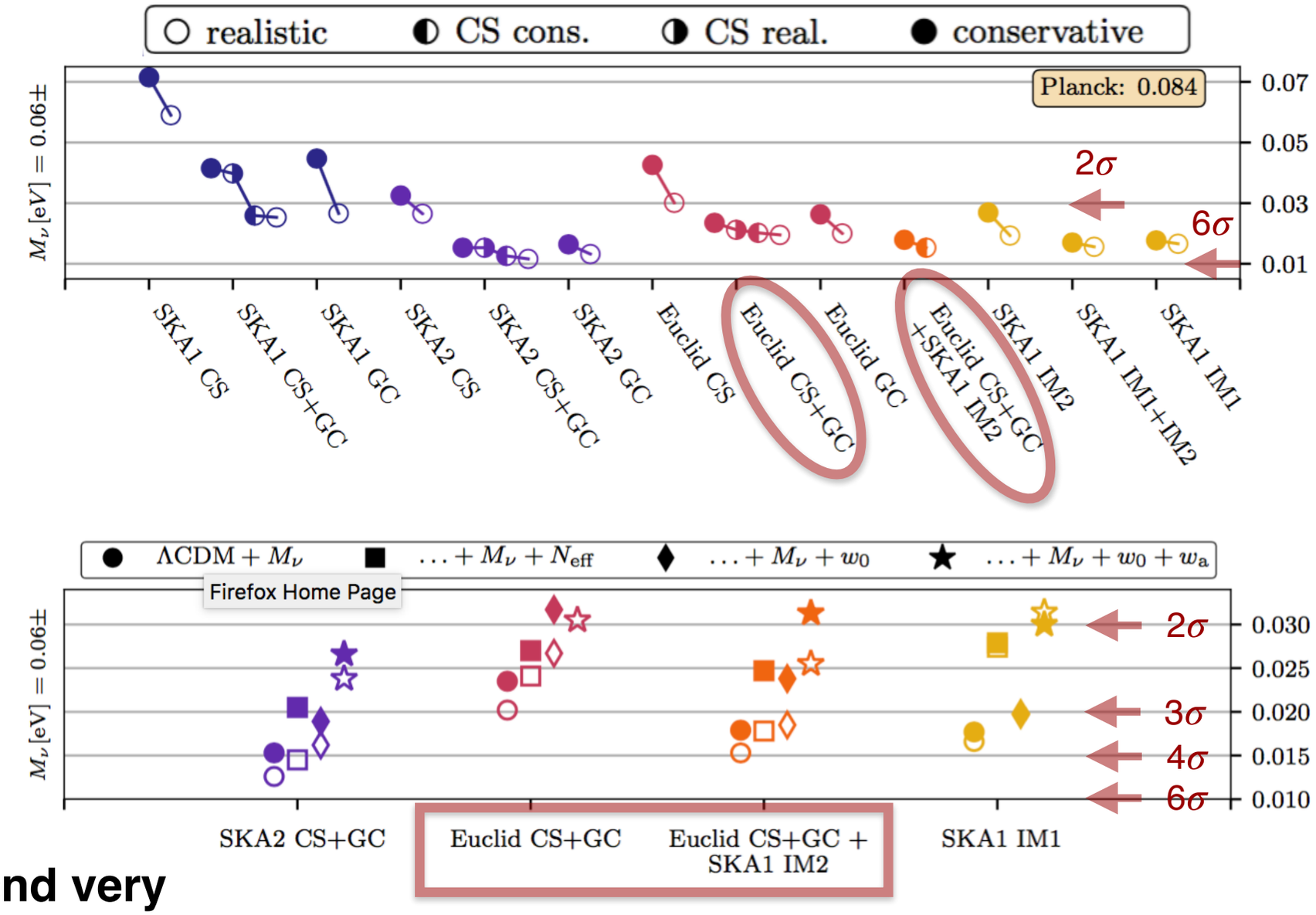
1. Once we add Euclid any of the CMB experiments are expected to do very well, **even Planck**!
2. The low redshift SKA1 probe complements Euclid by extending the redshift range
3. An independent measurement of the optical depth to reionization all but guarantees 5 σ

Results

Always including Planck

Galaxy clustering

- *conservative* theoretical uncertainty + $k_{max} = 0.2$ h/Mpc
- *realistic* theoretical uncertainty + $k_{max} = 10$ h/Mpc



Cosmic shear

- *conservative* $k_{max} = 0.5$ h/Mpc
- *realistic* $k_{max} = 2.0$ h/Mpc

Conclusion does not depend very strongly on non-linear treatment!

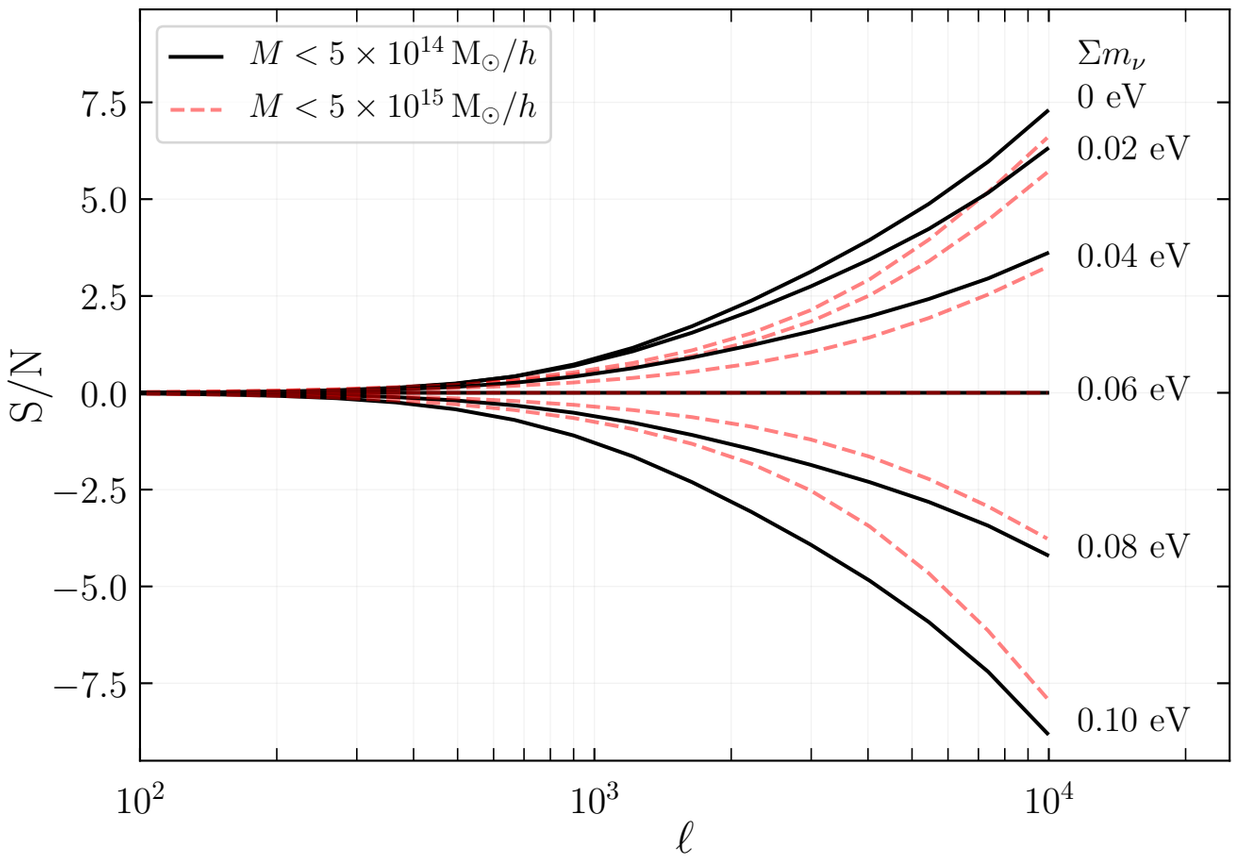
Conclusions

- Flat LCDM + M_ν: Planck + future LSS could detect a minimal normal hierarchy mass at around 4 σ
- Flat LCDM + M_ν: ***All future CMB surveys + future LSS exceed the 5 σ threshold!***
- Extended models with e.g. dynamical dark energy do not change this picture by a great amount

Next?

- With M. Knabenhans, J. Stadel, R. Teyssier: improved non-linear treatment with the Euclid Emulator Knabenhans, Stadel et al. 1809.04695
- More realistic galaxy bias and RSD modelling

Mock thermal SZ power spectrum

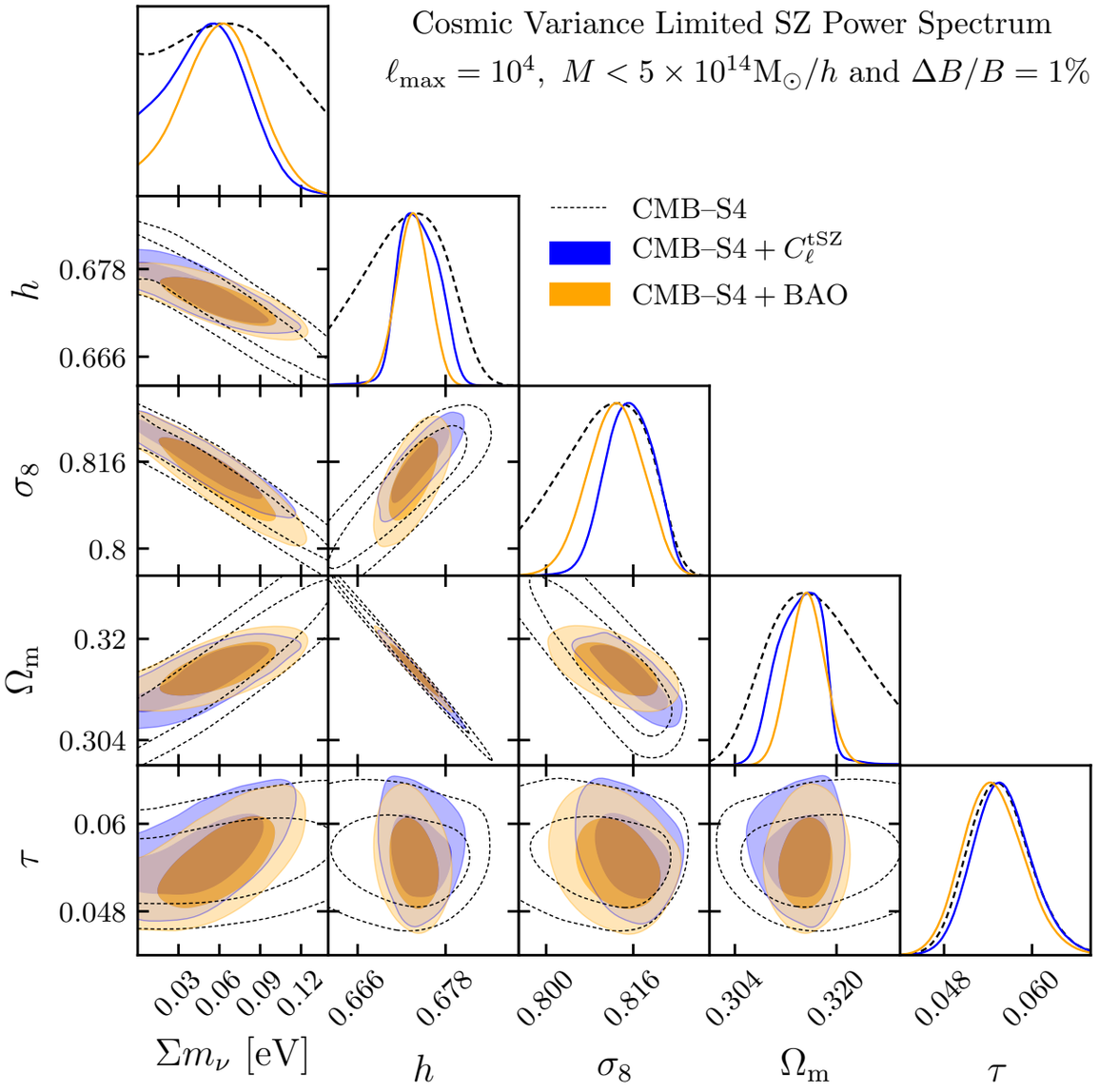


$\sigma(\Sigma m_\nu) = 31\,\mathrm{meV}$ ($\ell_{\mathrm{max}} = 10^4$, masking, 10% prior on B)

$\sigma(\Sigma m_\nu) = 29\,\mathrm{meV}$ ($\ell_{\mathrm{max}} = 10^4$, masking, 1% prior on B)

$\sigma(\Sigma m_\nu) = 26\,\mathrm{meV}$ ($\ell_{\mathrm{max}} = 10^4$, no masking, BAO)

$\sigma(\Sigma m_\nu) = 24\,\mathrm{meV}$ ($\ell_{\mathrm{max}} = 10^4$, masking, BAO)



https://github.com/bolliet/class_sz

SZ power spectrum likelihoods with upcoming MontePython v3.3