Neutrino properties from Cosmology

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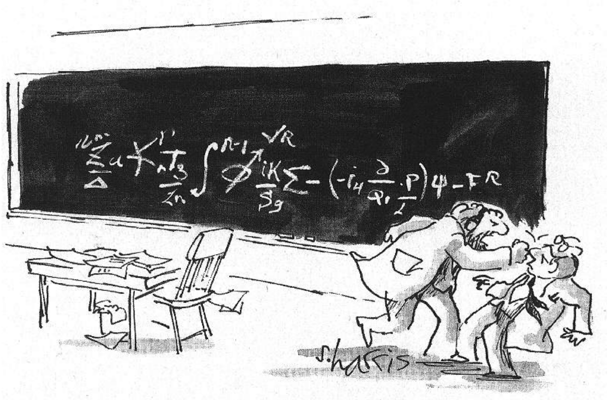
Neutrino16, July 16

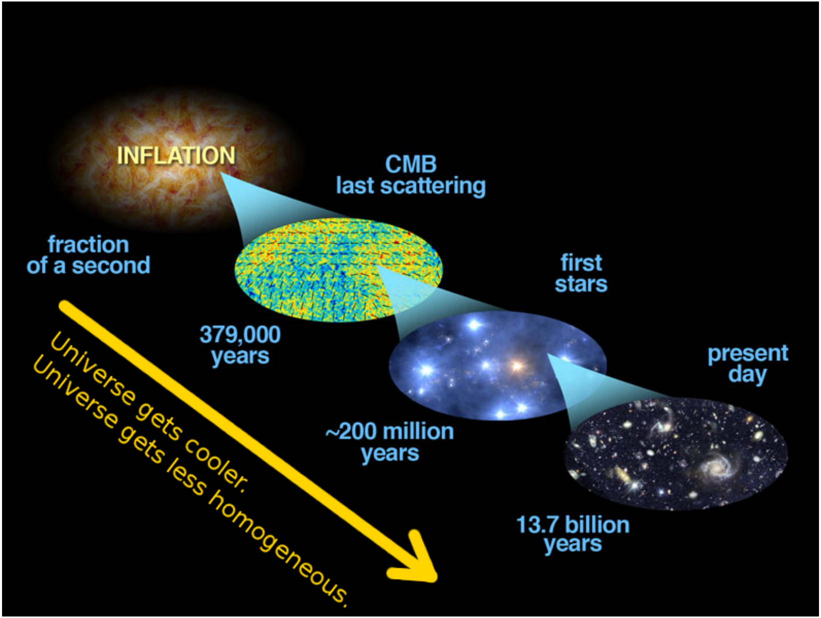
plan for the talk

- Pedagogical introduction to the role neutrinos play in Cosmology aimed at a non-cosmo community
- Neutrinos detected at $\sim$10 sigma, neutrino mass expected in the next decade
- Model dependence is not a big issue, but systematics are

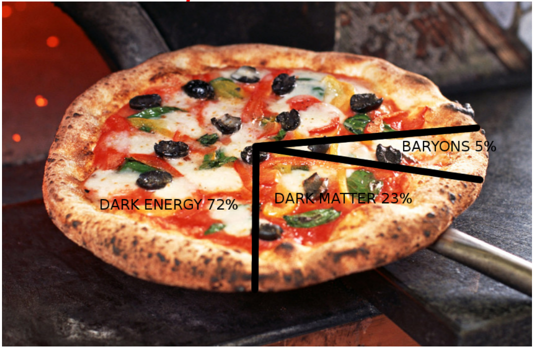


"YOU WANT PROOF? I'LL GIVE YOU PROOF!"

universe's timeline



cosmic pizza ***TODAY***



Smallest component of Universe:

- *Baryons:* Stuff we see that makes up the world around us: electrons, protons, neutrons, ...
- Stuff we know & love

However, we also have:

- *Dark Matter:*
  - Cold, pressureless, non-interacting stuff
  - Collapses under its own gravity
  - Without it, Universe wouldn't have time to form galaxies, stars, planets and us
- Dark Energy:
  - Drives accelerated expansion of the Universe - biggest surprise of the last decade

the dark sector

- *Macroscopic* behaviour well understood:
  - we have many independent detections/confirmations of both dark components
  - GR stress-energy tensor can be written exactly
- *Microscopic* understanding lacking:
  - How the dark sector fits with the standard model of particle physics?
  - Does gravity obey general relativity on all scales and at all energies?
- The same is true for neutrinos: in general, cosmology can answer questions about macroscopic properties of a neutrino gas, but can only indirectly probe microscropic ones

neutrinos in cosmology

- Universe homogeneous and in thermal equilibrium when neutrino background is formed
- Assuming **massless**, neutrinos are like photons, except:
  - **decouple before** e^--e^+ annihilation:
    - Temperature ratio can be calculated assuming conservation of entropy:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.95\mathrm{K}$$

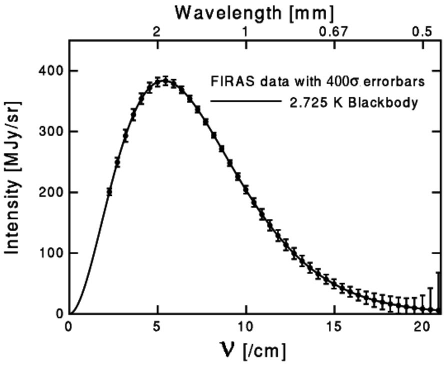
      (note $T_\gamma = T_{\mathrm{CMB}} = 2.72548 \pm 0.00057$. $n \sim 56/\mathrm{cm}^3$, but very cold)
  - **fermions** rather than bosons:
    - Contribute $7/8$ of photon energy density at the same temperature:
  - **3 generations** of ν, $\bar{\nu}$
  - Hence:

$$\rho_\nu c^2 = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

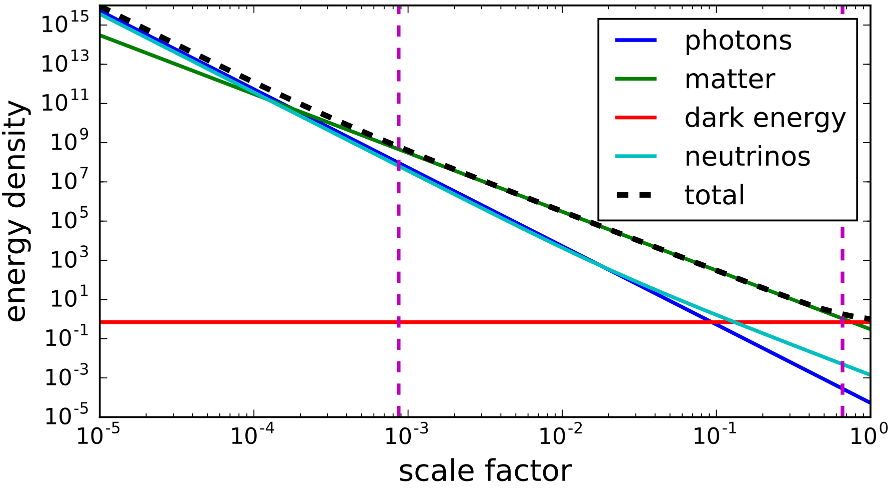
neutrinos in cosmology

$$\rho_\nu c^2 = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

- Neutrinos are born ultra-relativistic and behave like radiation in the early universe, but uncoupled
- **In terms of energy density, neutrinos as important as radiation in the early universe**
- Radiation energy density cools as a^{-4}: neutrinos eventually start behaving like dark matter
  - We know the temperature of CMB exquisitely well, hence assuming standard early universe can make very firm predictions



evolution of energy densities



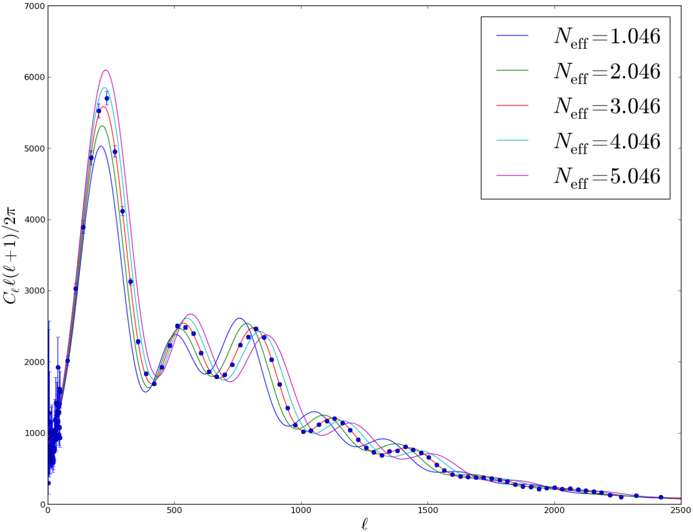
N_{eff}

- Neutrinos dynamically as important as radiation, but they interact only gravitationally, while radiation is coupled to baryons
- Neutrinos change the matter-radiation equality scale and affect the damping of fluctuations on small scales
- Can parametrize the effective number of neutrinos

$$\rho_\nu c^2 = N_{\mathrm{eff}} \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

and fit.

N_{eff} *and Planck*



N_{eff}, *continued*

- The standard model $N_{\mathrm{eff}} = 3.046$ instead of 3, due to
  - neutrino interactions when e^--e^+ annihilation begins
  - the energy dependence of neutrino interactions
  - finite temperature QED corrections
- Since spectral distortions redshift irrespective of energy, their effect is completely encoded into corrections to N_{eff}
- Measurements of N_{eff} to this precision would bring a striking confirmation of our understanding of early universe
- A non-standard N_{eff} means more ultra-relativistic stuff in the early universe - not necessarily neutrinos or fermions, etc.
- Latest Planck measurement $N_{\mathrm{eff}} = 3.15 + / - 0.23$, **over 10 sigma detection of neutrino background**

finite neutrino mass

- For typical neutrino masses, we can assume neutrinos to be ultra-relativistic when they decouple and non-relativistic today
- In that case, their energy density today is given by

$$\begin{aligned} \text{physical density} &= \text{number density of neutrinos} \times \text{mass} \\ \Omega_\nu h^2 &= \frac{\sum m_\nu}{94eV} \end{aligned}$$

- Ω_ν is the fraction of energy density in neutrinos
- h is the reduced Hubble's constant $h = H_0/(100\mathrm{km/s/Mpc})$
- Given Friedman equation $H^2 \propto \rho$, multiplying a fractional density by h^2 gives something akin physical density
- A mass of 16eV per species would close the Universe, dramatically changing all observations
- Compare this with Tritium-β decay, where limits around $\sim$ 10eV were obtained in 1990s using sophisticated experiments, correcting previous claims of mass detections

can neutrinos be dark matter?

NO!

They free-stream out of over-dense regions, qualitatively changing the structure formation picture from bottom-up to top-down.

BUT! See Boyarski's talk!

effect of the finite neutrino mass

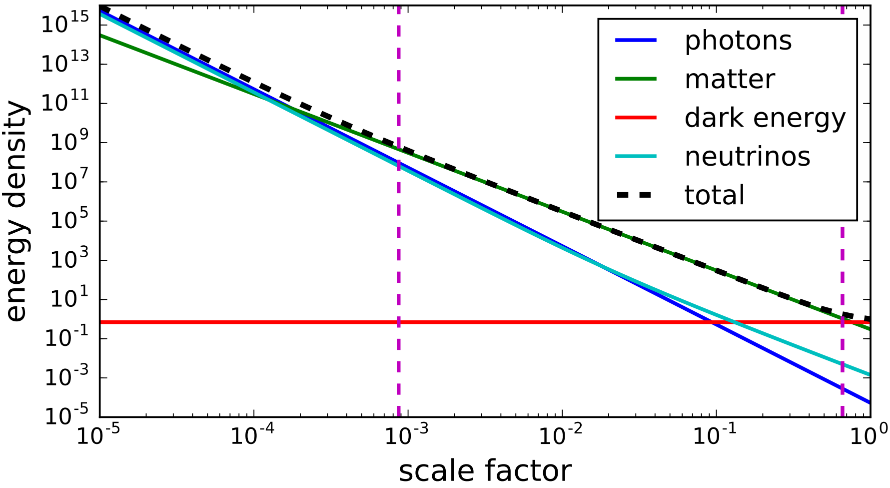
- Neutrinos transition from relativistic to non-relativistic at redshift

$$z \sim 2000 \frac{m_\nu}{1\mathrm{eV}}$$

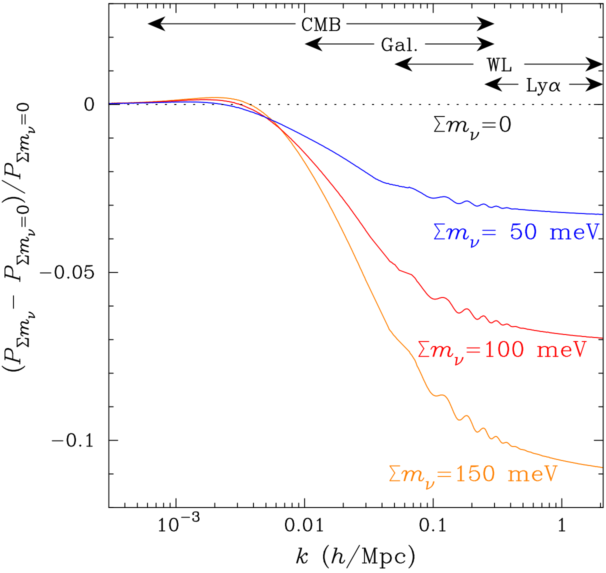
- Before transition: radiation-like, $\rho \propto a^{-4}$, free stream out of over-dense regions
- After transition: dark-matter like, $\rho \propto a^{-3}$, collapse in over-dense regions
- Two effects:
  - **Change in the expansion history** of the Universe: today Ω_M includes neutrinos at CMB epoch it does not
  - **A characteristic suppression** on scales smaller than the free streaming wave-number k_f. Averaged over cosmic history, the power is suppressed on scales less than (Lesgourgues & Pastor 06)

$$k_{\mathrm{nr}} \simeq 0.018 \sqrt{\Omega_m \frac{m_\nu}{1eV}}\, h/\mathrm{Mpc} \tag{1}$$

evolution of energy densities



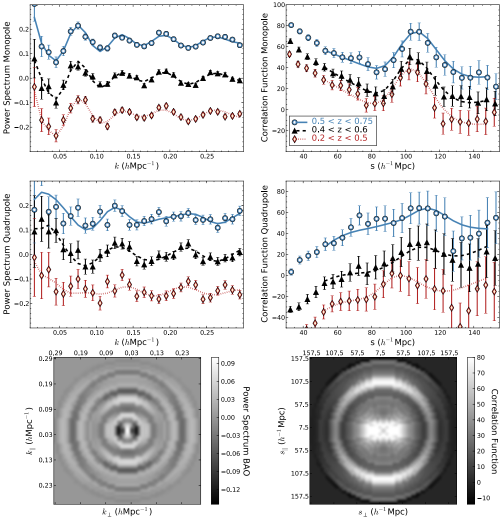
effect of the finite neutrino mass



- Relatively large effects: O(5%)
- Different probes sensitive on different scales
- Measure the unique suppression using one probe
- Combine two probes at two different scales
- **Note characteristic scale and shape of neutrino mass suppression.**

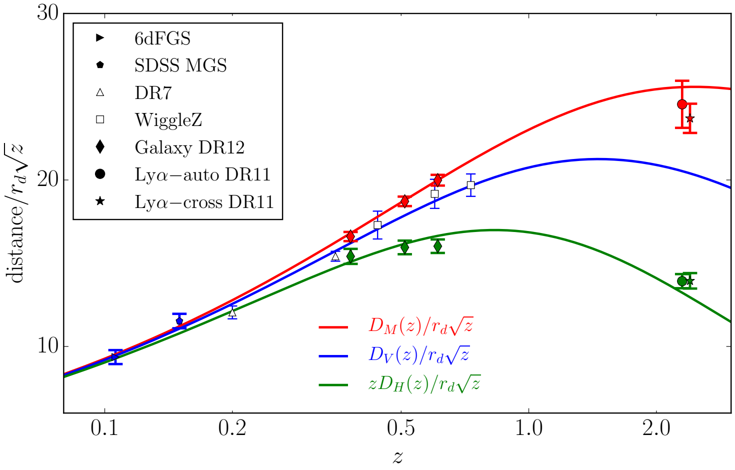
neutrino mass from expansion history

- Currently most robust method of measuring expansion history is the Baryon Acoustic Oscillations method
- Relies on a sharp feature imprinted into the correlation function



BOSS Data Release 12 galaxy

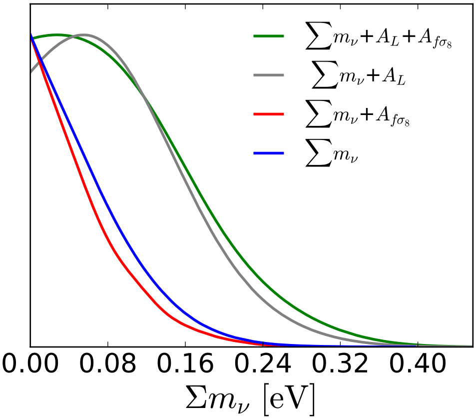
world BAO data, post DR12



- Line is not a fit, but the Planck prediction assuming ΛCDM

BOSS DR12 preliminary constraints

- BAO + Planck data constrain neutrino mass both from background and fluctuations
- Background information comes from treating both low-z galaxies and high-z galaxies as a BAO experiment: gives $\sum m_\nu < 0.25$eV
- Suppression comes from Planck amplitude compared to low-z amplitude measured by Planck gravitational lensing: gives $\sum m_\nu < 0.16$eV



  - See talks by **Matteo Viel** and **and Ofer Lahav**: different data, combinations and forecasts

aside: can we trust galaxy clustering?

Two very robust assumption about the galaxy formation process:

- The only field that matters on large scales are the fluctuations in the matter fluctuations $\rho_m = \bar{\rho}_m(1 + \delta_m)$
- The galaxy formation process is local on some scale R:

$$\delta_g(\mathbf{x}) = F[\delta_m], \tag{2}$$

  where F is an arbitrary functional that, however vanishes for distances larger than R from $\mathbf{x}$.

Under these assumptions, in the $k \to 0$ limit, galaxies in redshift-space must trace dark-matter following

$$\delta_g(\mathbf{k}) = (b_\delta + b_\eta f \mu^2)\delta_m(\mathbf{k}) + \epsilon, \tag{3}$$

where bs are bias parameters and ϵ is a white noise stochastic variable.

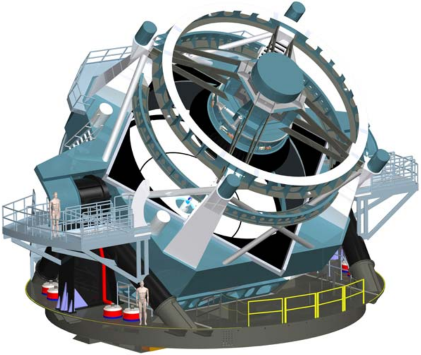
At non-zero k, a controlled perturbative bias expansion is possible

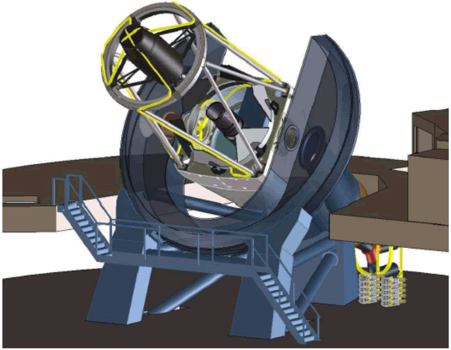
near Future

Lots of stuff:

- LSST (DOE/NSF)
- DESI (DOE)
- CMB S4 (DOE/NSF)
- Euclid (ESA)
- WFIRST (NASA)
- PFS/HSC/DES (intermediate)
- SKA

near future: DOE land





LSST:

- Photometric experiment: takes pictures of the sky
- 5 bands can give an estimate of a redshift
- Passed CD3 in August 2015

DESI:

- Spectroscopic experiment: takes spectra
- Spectra give redshifts - real 3D experiment
- Passed CD3 in May 2016

fisher forecasts

We did a paper with extensive Fisher forecast for DESI:

- `arXiv:1308.4164`
- The title is "DESI and other dark energy experiments in the era of neutrino mass measurements", but could as well have been "Reams and Reams of Tables"
- It is important to do forecast with a single code, to have directly comparable results
- See paper for gory details on method
- Our forecasts for some of the existing quantities are withing 10%-20% accurate
- We assumed we will be able to use all information available in power spectrum modes up to $k = 0.1h/\mathrm{Mpc}$ (cons.) or $k = 0.2h/\mathrm{Mpc}$ (opt.) – in practice will fit to higher k to constrain biases
- Important to marginalize over $\sum m_\nu$, since we *know* neutrinos have mass – it is not a fancy extension of the model, like N_{eff}.

results on neutrino mass

- Natural goal: $\sum m_\nu = 0.06$eV.
- To get 3σ, need error better than 0.02eV.
- Maybe universe is nice to use, in which case a 0.04eV sensitivity could give you a 3-σ detection at 0.12eV.

	ω_m	ω_b	θ_s	Σm_ν	$\log_{10}(A)$	n_s
value	0.141	0.0221	0.597	0.0600	-8.66	0.961
P	0.0037	0.00015	0.00035	0.35	0.0039	0.0038
$P + BgB + BIB$	0.00074	0.00015	0.00014	0.10	0.0038	0.0038
$P + BgA0.1 + BIB$	0.00070	0.00013	0.00014	0.068	0.0037	0.0031
$P + BgA0.2 + BIB$	0.00071	0.00012	0.00015	0.046	0.0037	0.0028
$P + DES$	0.0013	0.00013	0.00017	0.041	0.0036	0.0032
$P + BBgA0.1 + BBIB$	0.00044	0.00011	0.00014	0.024	0.0036	0.0024
$P + BBgA0.2 + BBIB$	0.00042	0.00010	0.00014	0.017	0.0035	0.0022
$P + LSST$	0.00080	0.00011	0.00015	0.020	0.0030	0.0029
$P + BBgA0.1 + BBIB + LSST$	0.00042	0.00010	0.00013	0.015	0.0028	0.0021
$P + BBgA0.2 + BBIB + LSST$	0.00041	0.00010	0.00013	0.014	0.0026	0.0020
$P + BB24gA0.2 + BB24IA + I1D + euA0.2 + LSST$	0.00032	$9.5e-05$	0.00013	0.011	0.0024	0.0014

- We should clearly see something by mid 2020s, using three independent(ish) techniques:
  - Planck + redshift-space distortions (DESI)
  - Planck + weak gravitational lensing (LSST)
  - Planck + CMB S4 + BAO

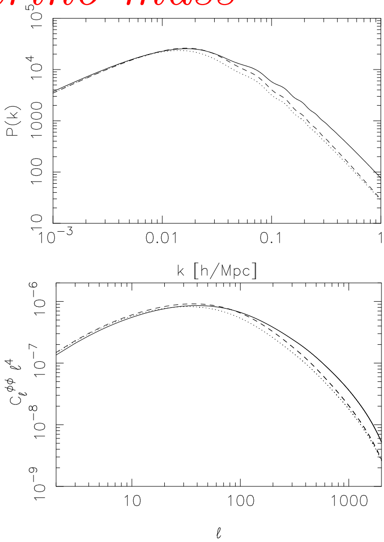
neutrino masses

Two more important observations:

- Marginalizing over neutrino masses really kills our ability to measure dark energy! For example FoM for DESI drops from 340 to 120 (Planck + Gal ps + Lyα BAO)
- Neutrino mass signal does not come from supression of the power spectrum, but instead from measuring the amplitude of the power spectrum through RSD.

Could we measure neutrino mass difference?

- Three different neutrino masses produce three different free-streaming lengths
- In principle, signal is there
- In practice, measurement extremely challenging:
  - masses are large $\rightarrow$ masses degenerate
  - masses are small $\rightarrow$ signal is small



Putting all neutrino mass in one neutrino or dividing it equally for $\sum m = 2\text{eV}$ case.

what could go wrong?

- In general, model dependence is not an issue:
  - We never do searches for new particles in the most general SUSY model – we do them inside standard model: same here
  - Experiments like KATRIN also depend on a lot of nuclear physics
  - Very non-minimal scenarios can hit you: neutrinos with non-trivial interactions and self-interactions can evade constraints, see .e.g. Beacom, Bell and Dodelson 2004, Dvali and Funcke 2016, etc.
- One very interesting degeneracy is with w, which is a crucial parameter in dark energy studies
- Degeneracy is not perfect, but one could imagine a situation in which you have either measured neutrino mass or discovered non-minimal dark energy!

what could go wrong?

- Systematics are big issues: these measurements are difficult to make
- They all rely on Planck, but this is arguably the most robust part
- Otherwise, systematics mostly independent between the three methods:
  - For CMB S4, foregrounds will be the dominant issue
  - For weak lensing: the estimator calibration and photo-z calibration
  - For redshift-space distortions: theory modeling and fingers of god
- Optical depth to the last scattering could be the limiting factor in the next decade

sterile neutrinos

- The standard scenario that could explain away some tensions with the data with a 4th state at $\sim$ 1eV is very strongly disfavoured by cosmology – they would be thermalised and are excluded at many sigma
- Again, baroque solutions can save the day but hard
- There is a separate "sterile neutrino as dark matter" direction; in these models:
  - dial down coupling to avoid thermalization
  - make them earlier to make them colder
- See talk by Boyarski

conclusions

By now, I'm likely to be over-time, so you need to read this by yourselves:

- Cosmology is an "adiabatic expansion" experiment on neutrino gas
- Standard physics linear and very well understood
- We can see existence of relativistic neutrino gas in CMB at $>$ 10sigma
- Current limits on neutrino masses in the range $\sum m_\nu <\sim 0.15 - 0.20$eV at 2 sigma
- Detection of mass guaranteed at $\sim$ 3 sigma using at least three different methods by mid 2020s
- Non-standard scenarios can be constrained if they produce thermalised species; similarly: standard results can be evaded by sufficiently fine-tuned non-standard interactions
- There is an entire world of astrophysics, but that is a different talk