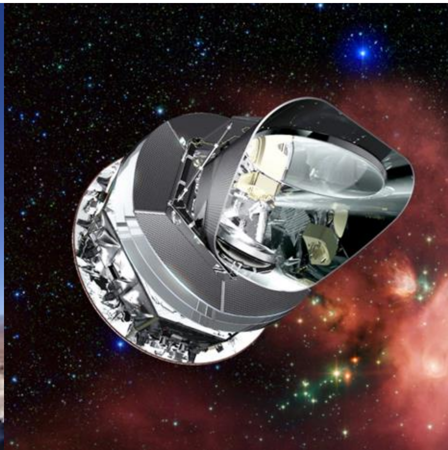
Neutrinos properties from cosmology: status and outlook including sterile neutrinos

Tijmen de Haan - LBNL

Figures from:
NASA/WMAP Science team
SNOWMASS document (Azabajian+ 2013)
SPT PS (Story+2014)
SPT clusters (de Haan+2017)
Planck 2018 Publications
CMB-S4 Science Book



Conclusions

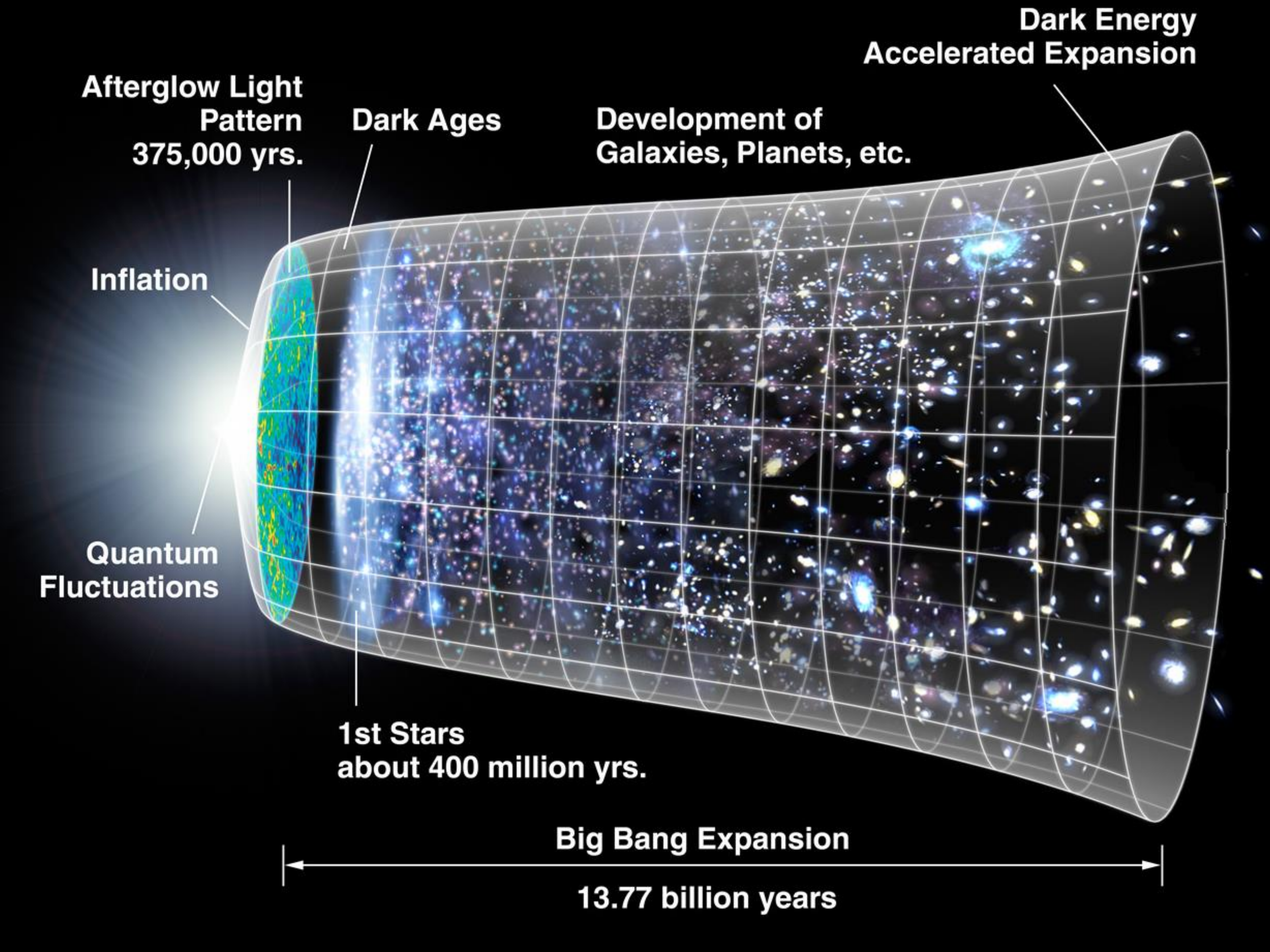
- The sum of the masses of the neutrinos is $0.06\ \mathrm{eV} < \Sigma m_\nu < 1\ \mathrm{eV}$
  - The minimum allowed neutrino mass with a normal hierarchy ($\Sigma m_\nu = 0.06\ \mathrm{eV}$) is the best fit model.
    - The minimum allowed neutrino mass with an inverted hierarchy ($\Sigma m_\nu = 0.11\ \mathrm{eV}$) is also allowed.
    - Σm_ν will be measured at $\sim 4\ \sigma$ in the next 5-10 years, even in the worst case scenario where $\Sigma m_\nu = 0.06\ \mathrm{eV}$
- There is strong evidence against a thermalized light sterile neutrino at $\sim 6\ \sigma$

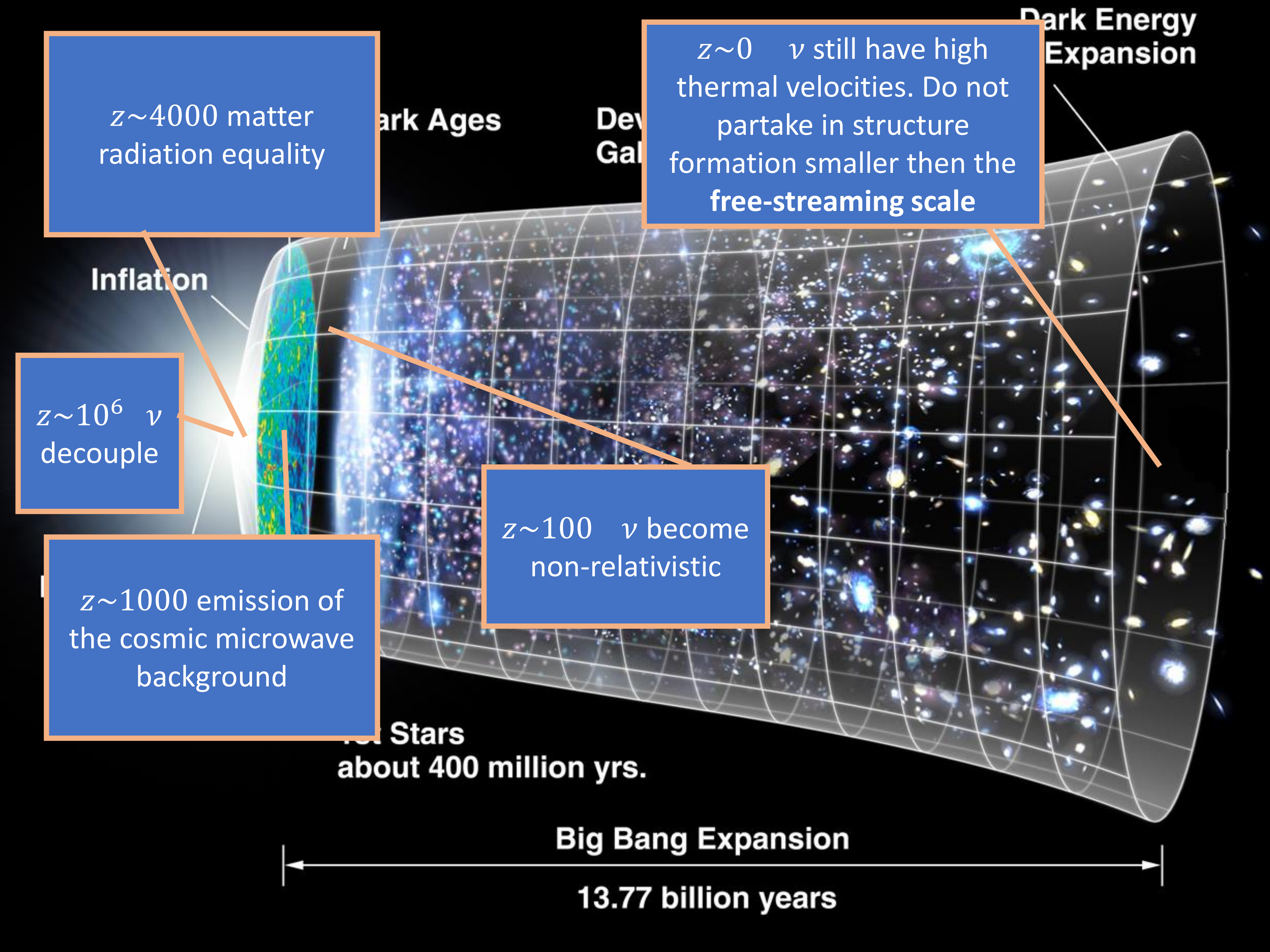
Outline

- ΛCDM model
- Cosmological probes
  - The cosmic microwave background is the most powerful probe.
  - ΛCDM is an amazingly robust phenomenological model.
  - There are many other cosmological probes (distance ladder, baryon acoustic oscillations, etc.).
    - By and large, ΛCDM continues to fit.
    - A relevant discrepancy is disagreement on the Hubble constant.
- Additional relativistic degrees of freedom (e.g. a sterile neutrino)
- Neutrino mass constraints
- Outlook

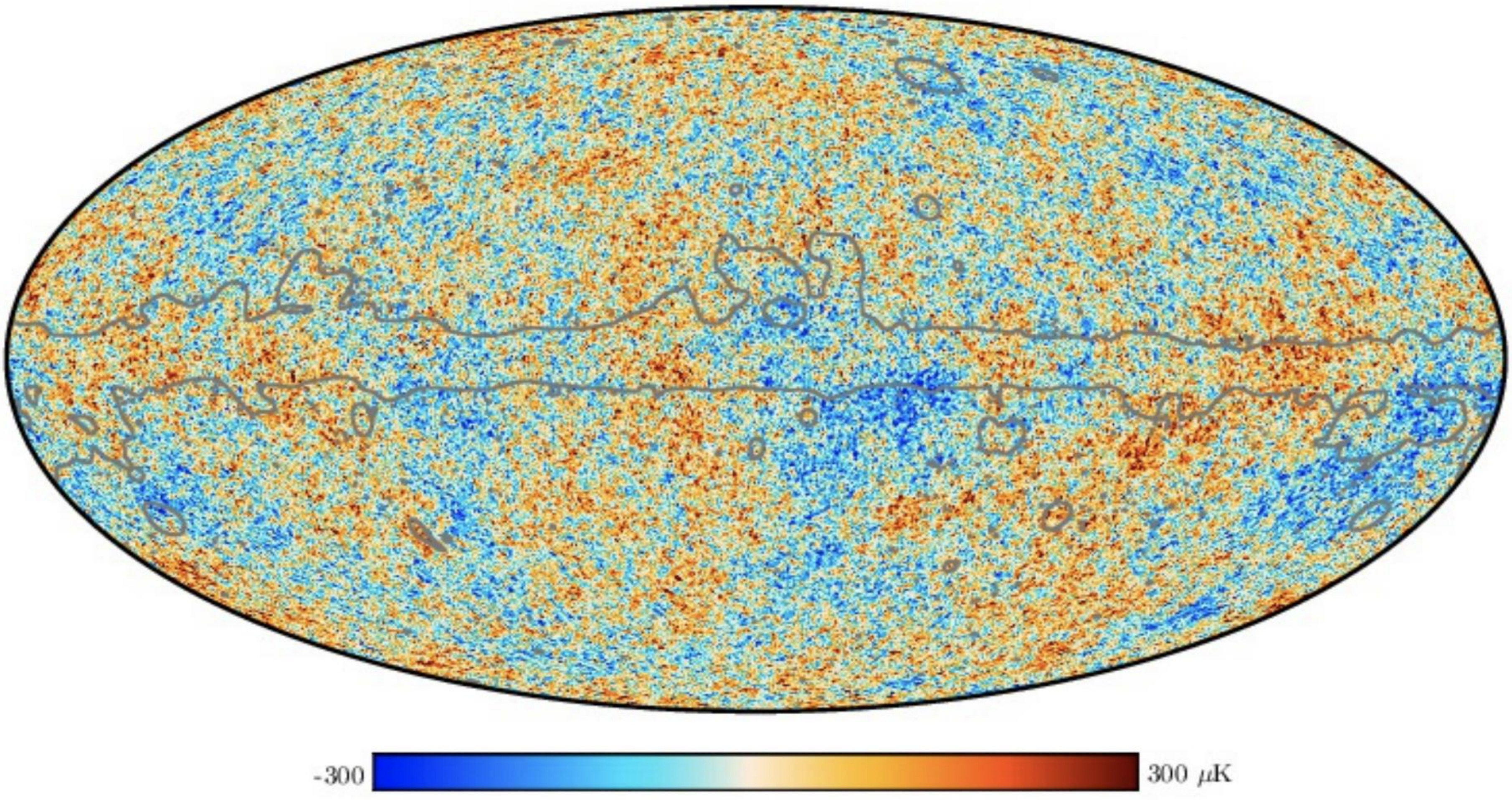
Main Assumptions in ΛCDM

- At early times, the observable universe was
  - hot and dense,
  - cooling off,
  - spatially flat,
  - filled nearly uniformly,
  - with a gaussian random field of small, adiabatic density fluctuations.
- The universe consists of
  - Standard model particles
  - Dark matter
  - Dark energy
- Note: we can add other constituents to ΛCDM with some parameterization, and place constraints on their properties, given the cosmological data.
  - These models are extensions of ΛCDM.


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

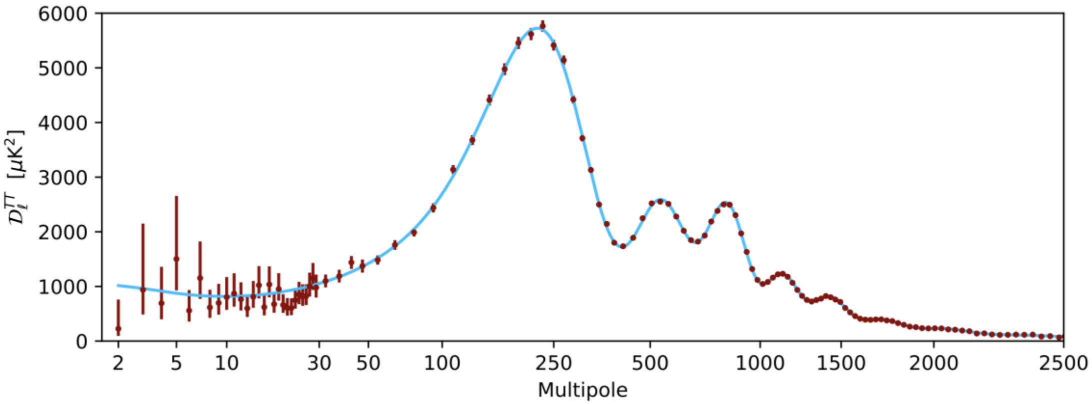

$z \sim 4000$ matter radiation equality
$z \sim 0$ ν still have high thermal velocities. Do not partake in structure formation smaller then the **free-streaming scale**
$z \sim 10^6$ ν decouple
$z \sim 100$ ν become non-relativistic
$z \sim 1000$ emission of the cosmic microwave background
Dark Energy Expansion
ark Ages
Inflation
Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Cosmic Microwave Background



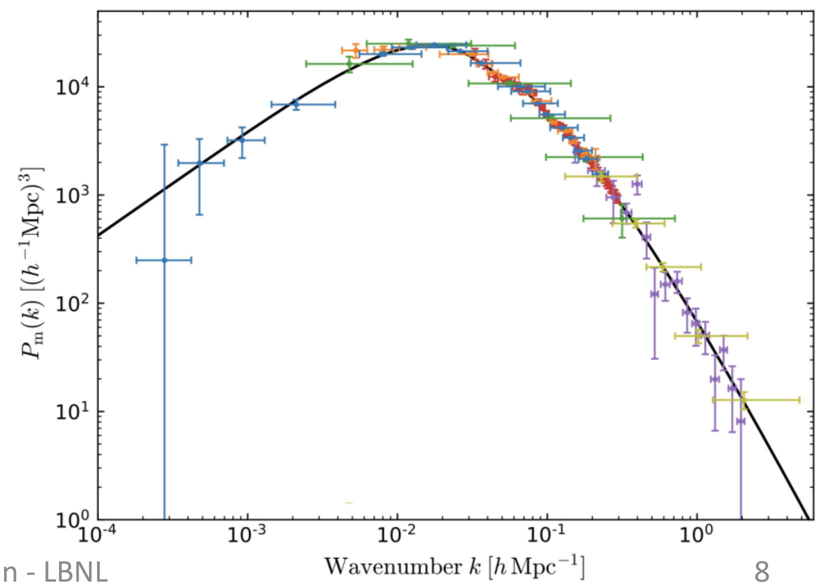
CMB power spectrum

- Gaussian random field: the information is in the power spectrum.
- 2-D spherical harmonic transform at z=1100:

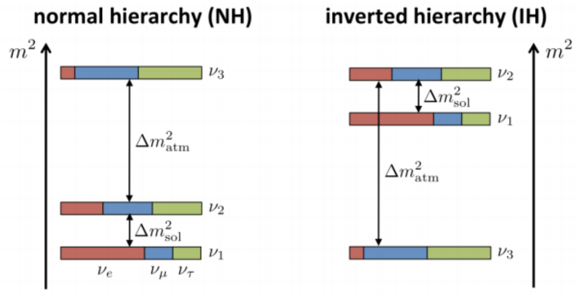


- ΛCDM has 6 free parameters and fits well.
- No evidence for a 7th parameter.
- Polarization spectra independently agree on the ΛCDM parameters.

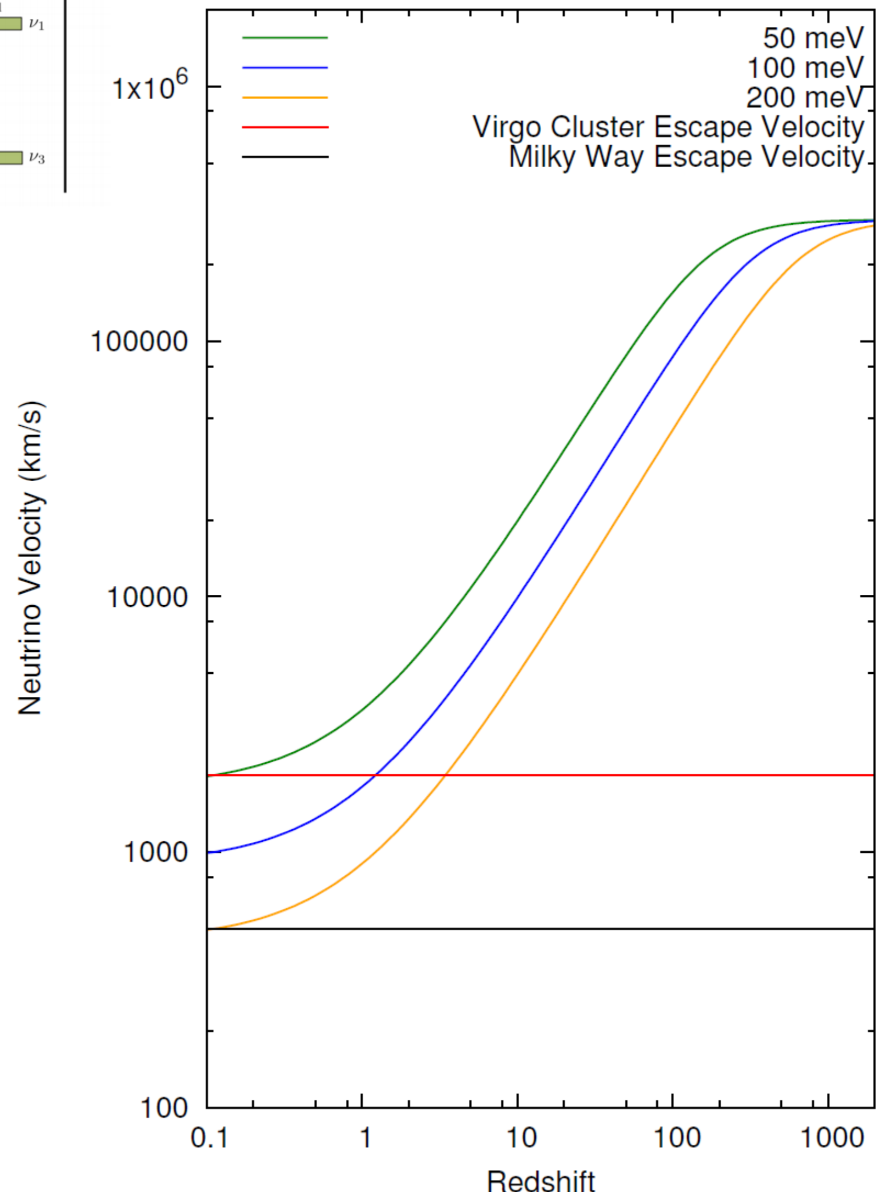
- Can straight-forwardly calculate the growth of structure given ΛCDM (or its extensions)
- At z=0, now as a 3-D matter power spectrum:



How does cosmology constrain neutrino mass?



- The contents of the universe affect:
  - Expansion rate
  - Growth of structure
- The cosmic neutrino background makes up 0.1% of the energy density of the universe today, but O(1) in the past.
- The now non-relativistic neutrinos that make up the CvB still have high thermal velocities and will not partake in the formation of structures of a characteristic size.
  - "free streaming scale"
- Primarily sensitive to the species-summed/total mass



N. Whitehorn, UC Berkeley

Effect of neutrino mass on matter power spectrum

- At $z = 0$, 5-10% effect on matter power spectrum
- Primary CMB measures the normalization at $z \sim 1000$
- Many other probes measure the normalization at low z
- Also: measure free-streaming scale in $P(k, z)$ directly

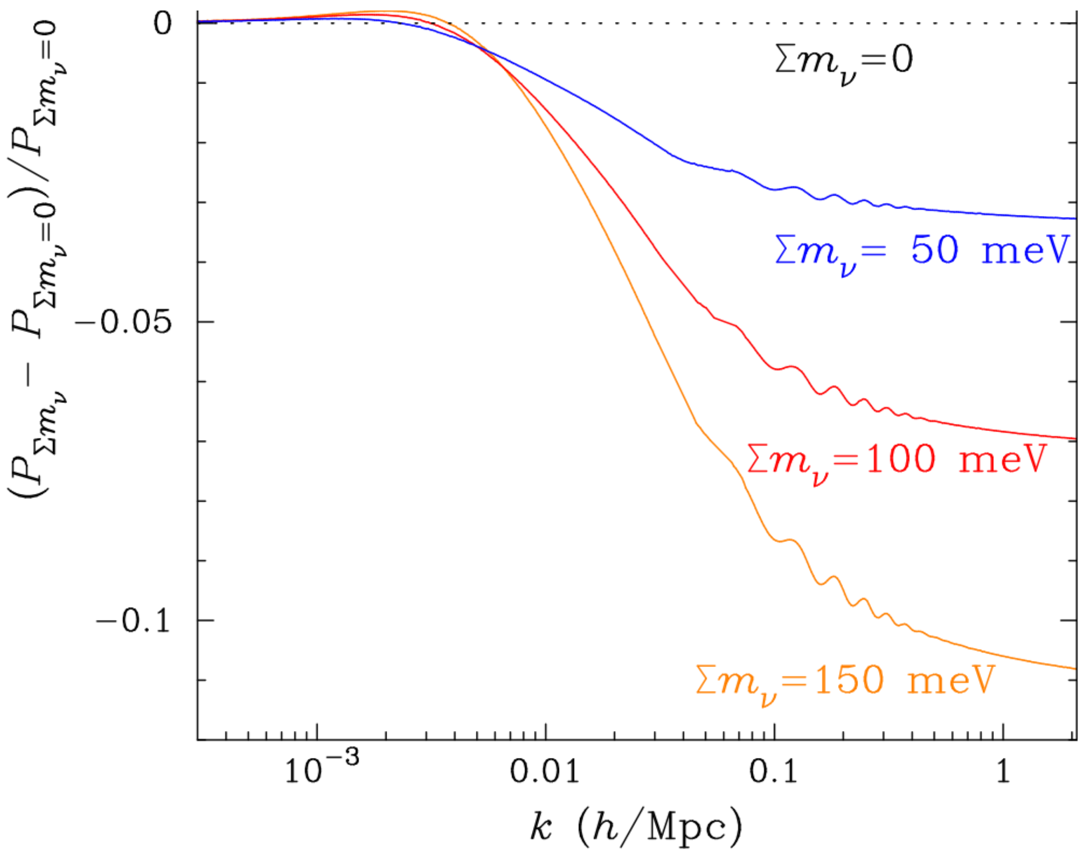


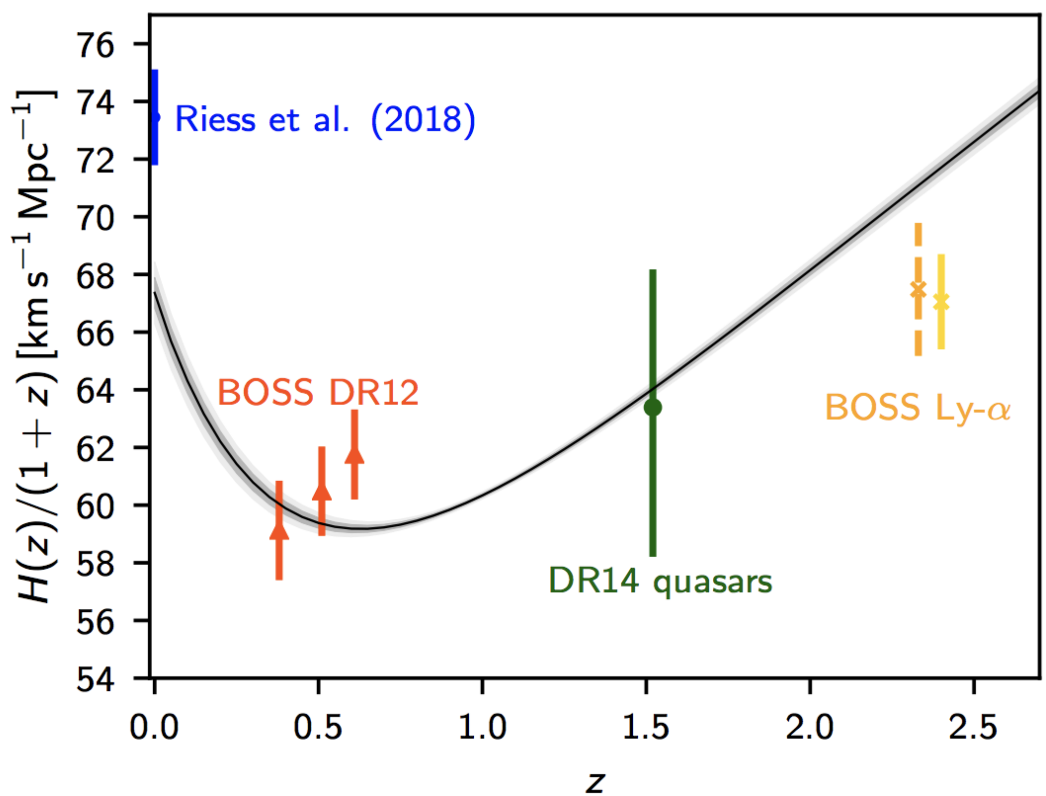
Figure 1. *Fractional change in the matter density power spectrum as a function of comoving wavenumber k for different values of $\sum m_\nu$. Neutrino mass suppresses the power spectrum due to free streaming below the matter-radiation equality scale. The shape of the suppression is highly characteristic and precision observations over a range of scales can measure the sum of neutrino masses (here assumed all to be in a single mass eigenstate). Also shown are the approximate ranges of experimental sensitivity in the power spectrum for representative probes: the cosmic microwave background (CMB), galaxy surveys (Gal.), weak lensing of galaxies (WL), and the Lyman-alpha forest (Lyα). The CMB lensing power spectrum involves (an integral over) this same power spectrum, and so is also sensitive to neutrino mass.*

Other Probes

- We have constraints on ΛCDM from measurements of baryon acoustic oscillations, the distance ladder, galaxy cluster counts, supernova distances, big bang nucleosynthesis element abundances, cosmic shear, stellar ages, galaxy clustering, cosmic microwave background lensing, redshift space distortions, strong lensing, Lyman-α forest, CMB polarization, Integrated Sachs-Wolfe effect, Alcock-Paczynski test, etc., etc.
- Given its empirical nature, ΛCDM has incredible:
  - Robustness
  - Predictive power
  - Small number of free parameters

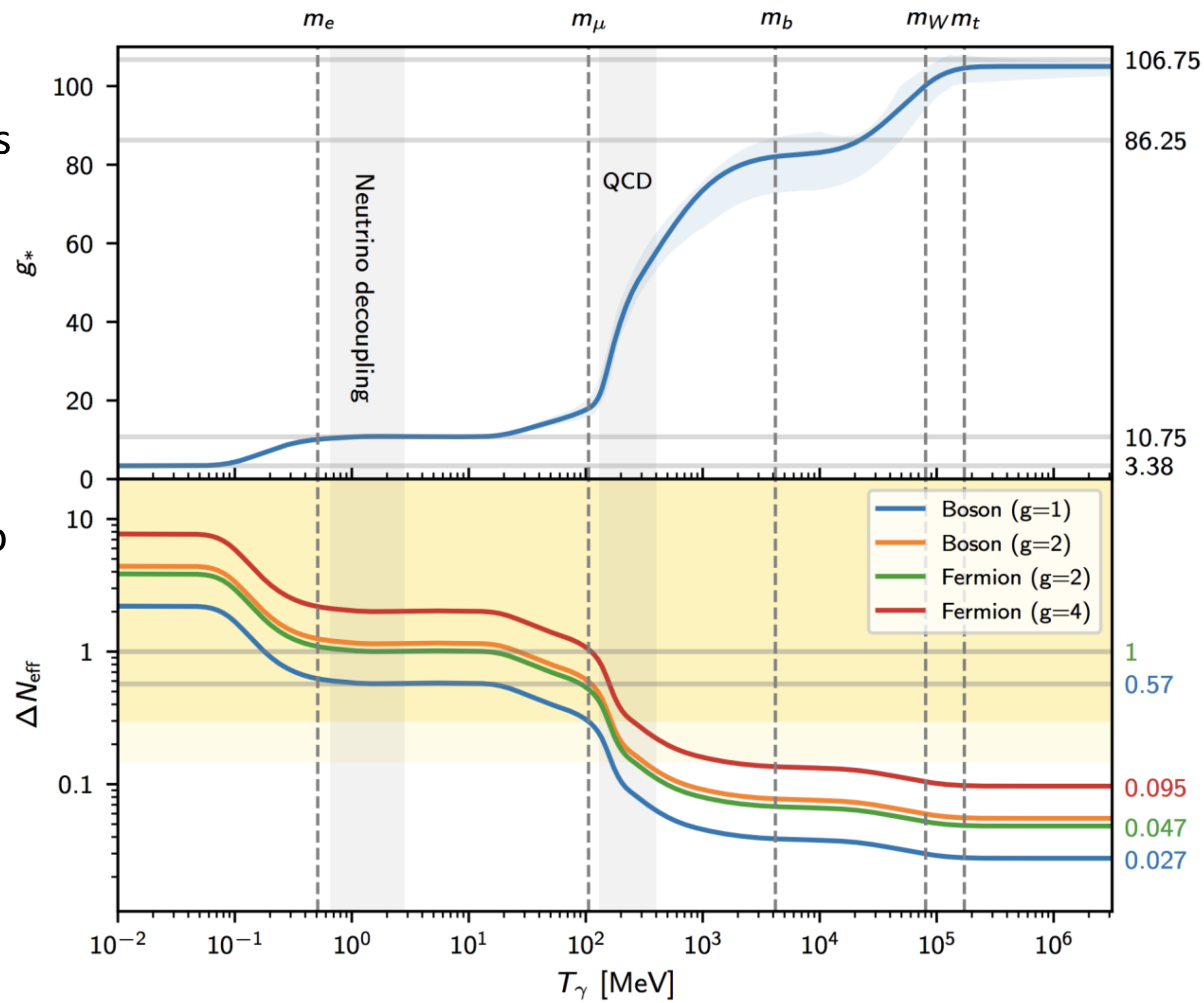
Other probes: Expansion rate

- Hubble constant measurements (expansion rate at $z = 0$) don't agree
  - Distance ladder result is $3.6\,\sigma$ discrepant
  - New physics? Unknown systematic error?



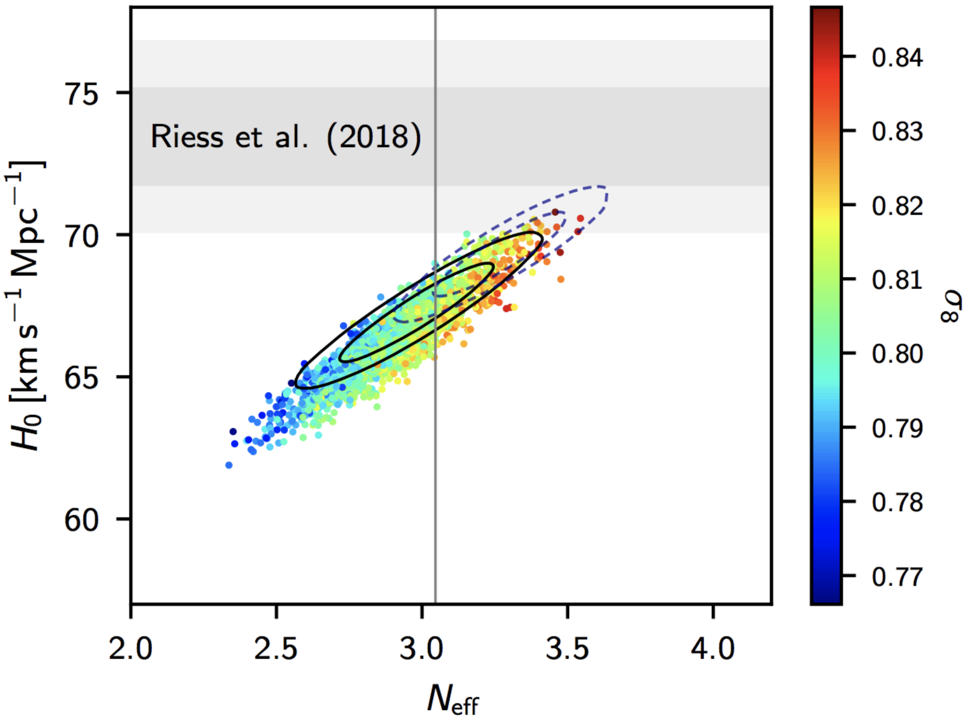
Effective number of relativistic degrees of freedom (N_{eff})

- Contribution to N_{eff} depends on the time of decoupling from the photons
- The active neutrinos give $N_{\mathrm{eff}} \approx 3$
- An additional particle that decouples between muon and positron decoupling also contributes $\Delta N_{\mathrm{eff}} \approx 1$
    - e.g. the type of sterile neutrino suggested by MiniBooNE/LSND



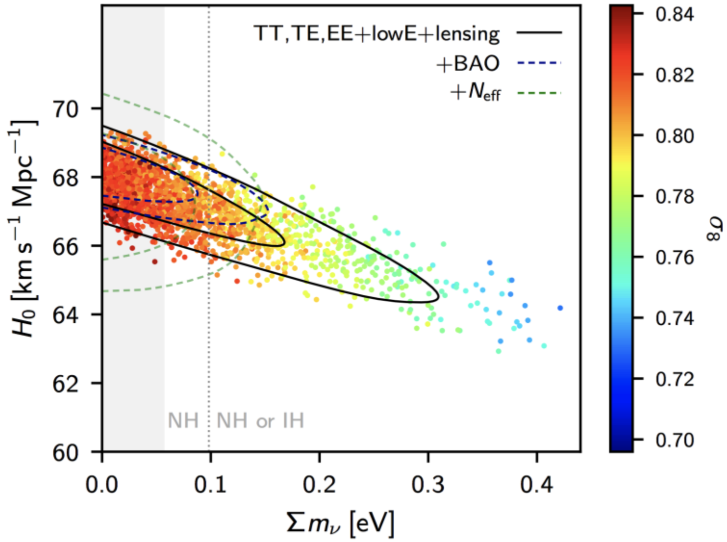
N_{eff} constraints

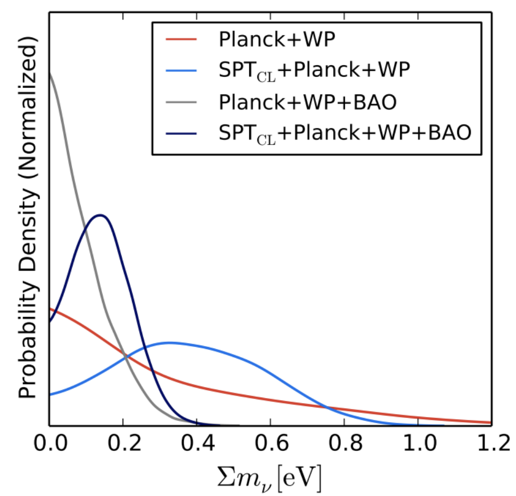
- Around 2014, $N_{\text{eff}} = 4$ was mildly preferred by some datasets over $N_{\text{eff}} = 3$
- As error bars have decreased, $N_{\text{eff}} \sim 4$ has become increasingly disfavored. From the 2018 Planck analysis $N_{\text{eff}} = 2.92 \pm 0.18$
- Including distance ladder measurements pulls this value up, but
  - does not increase N_{eff} by 1.
  - creates tension with geometric measurements (BAO).
- Bottom line: $N_{\text{eff}} = 4$ is now very unlikely



Neutrino mass constraints

- Assume $N_{\rm eff} = 3$ and float species-summed neutrino mass Σm_ν
- Planck 2018 analysis gives:
  $$\Sigma m_\nu < 0.27\ \mathrm{eV}\ \ (95\%)$$
- Adding BAO information:
  $$\Sigma m_\nu < 0.12\ \mathrm{eV}\ \ (95\%)$$
- Low-redshift large-scale structure measurements are powerful but prefer positive values





- South Pole/Atacama “ultimate” CMB experiment from the ground
- An official collaboration since March
- Will obtain $> 4\,\sigma$ neutrino mass measurement