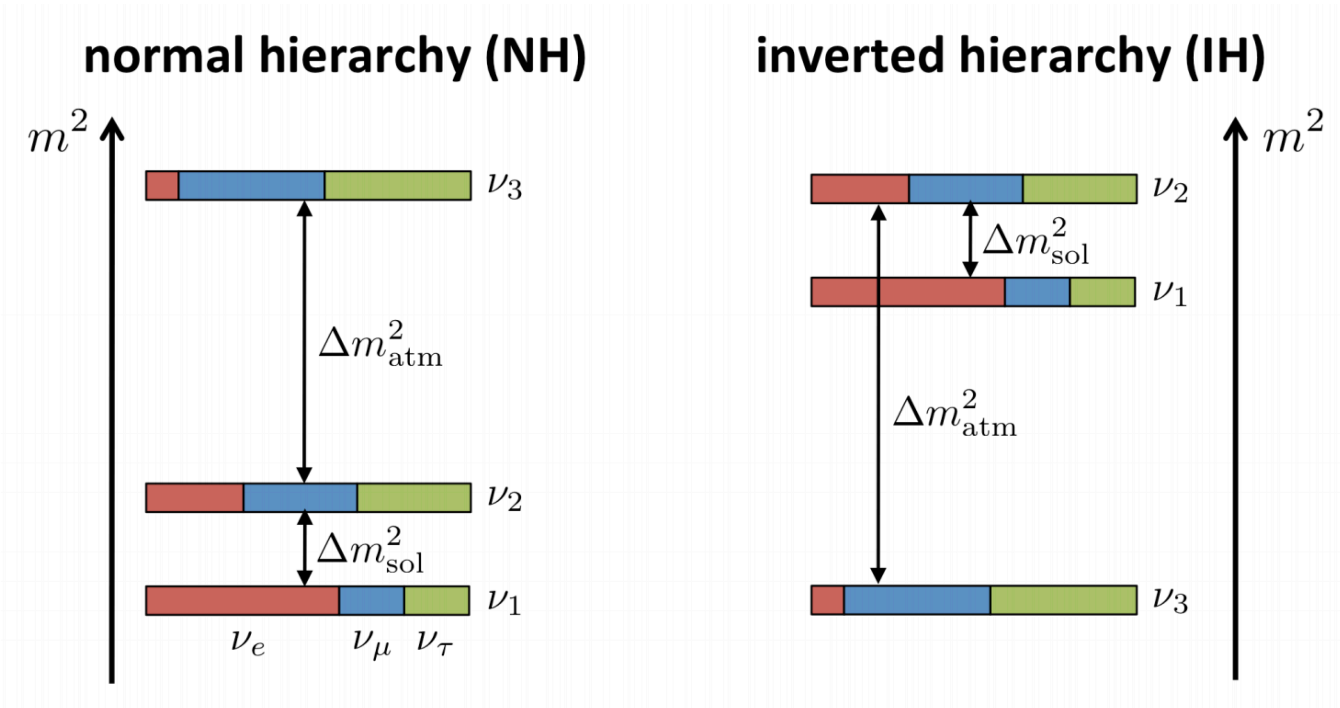
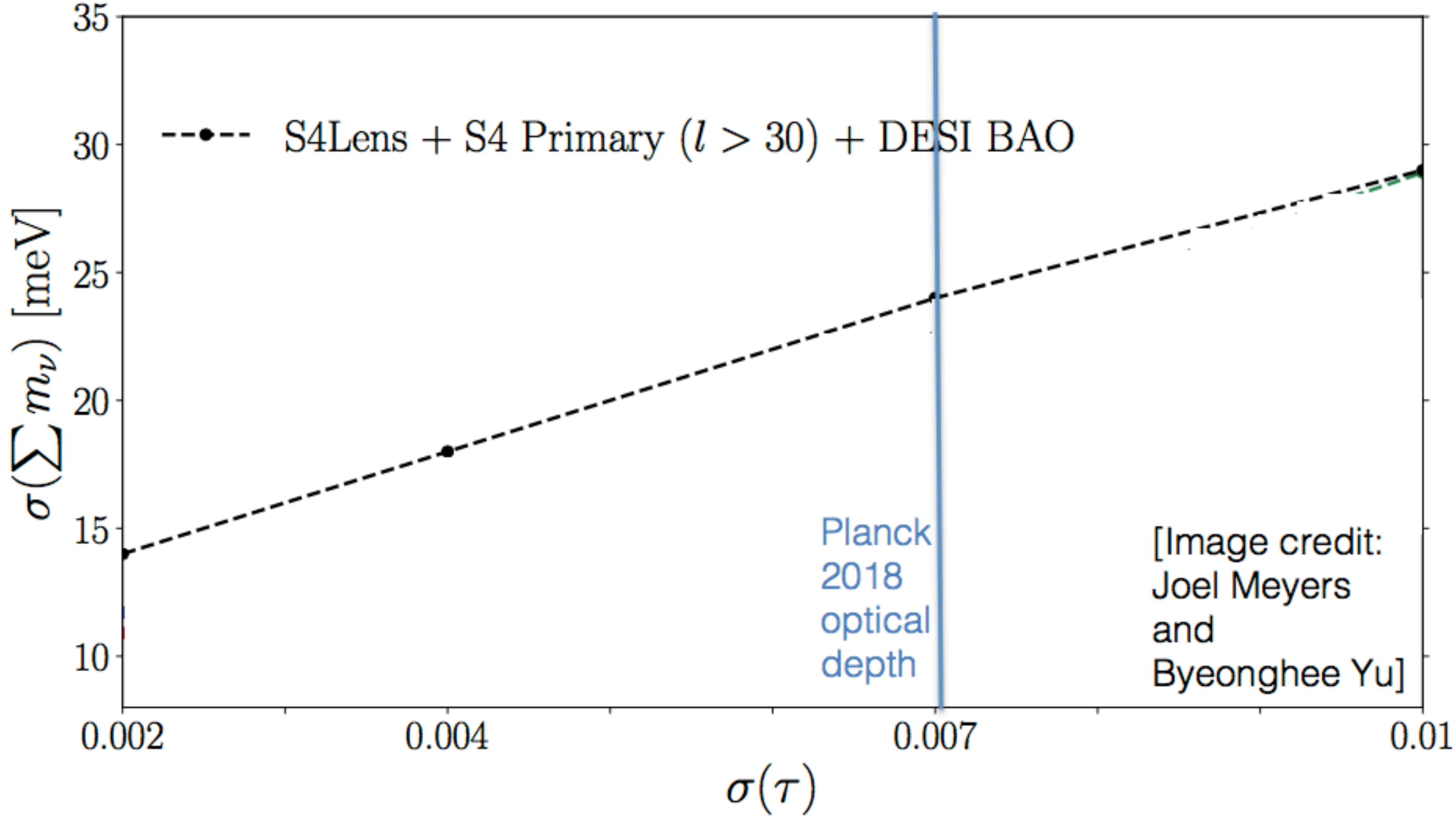
Neutrinos and cosmology

Simone Ferraro (UC Berkeley, LBNL)



290e seminar - UC Berkeley

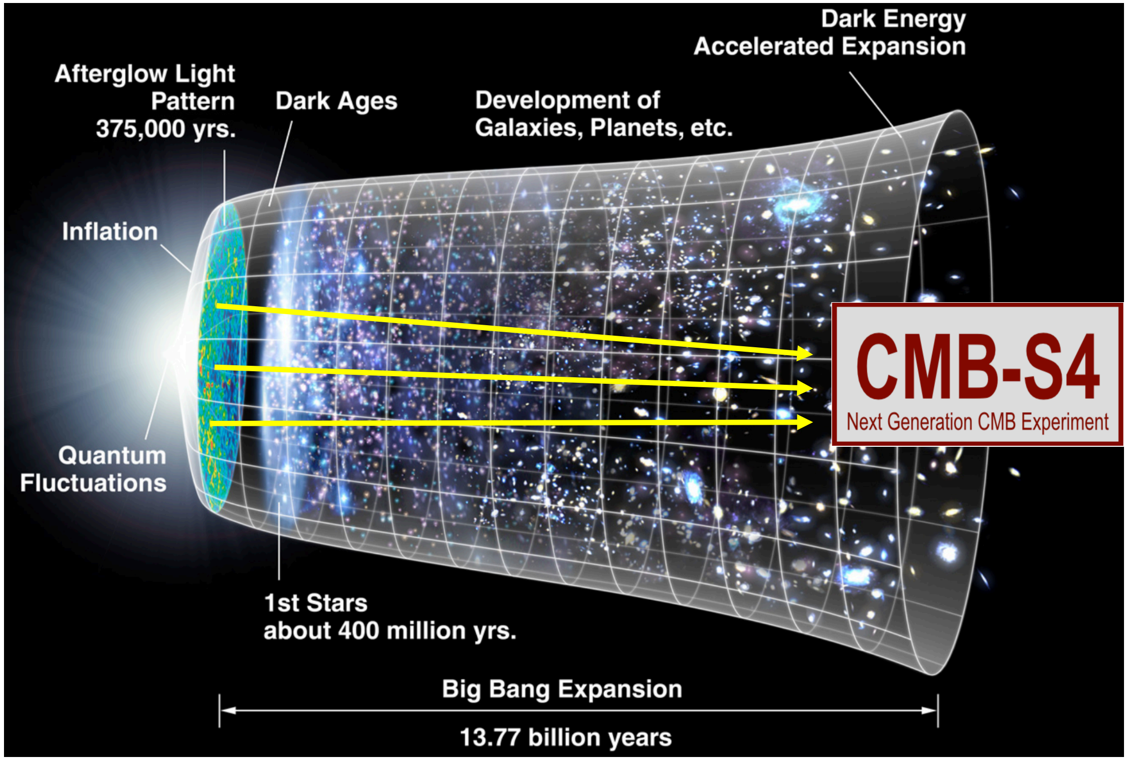
Goal: understand this plot!



Outline

- A brief history of the Universe
- Cosmological neutrinos
- Observables: CMB, Large Scale Structure
- Current status of neutrino cosmology
- Future experiments
- Number of neutrino species and other light relics

A brief history of the Universe

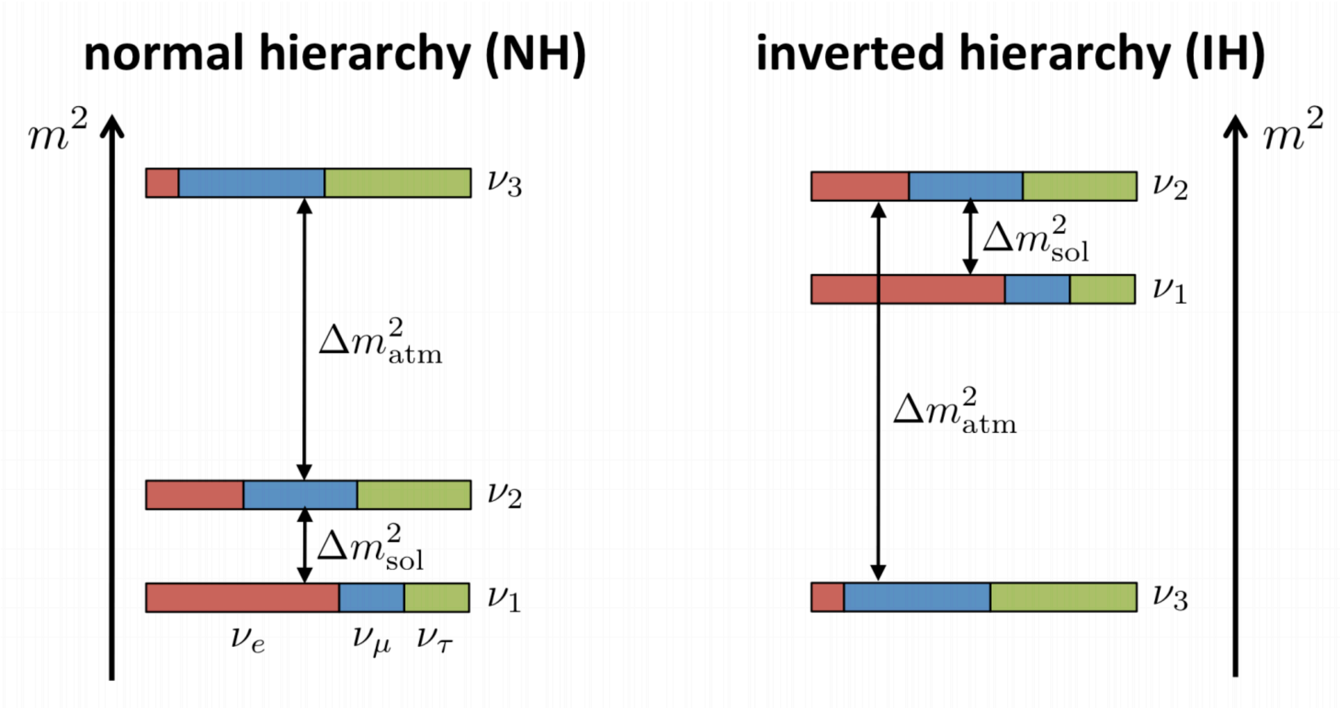


94% of photons travel from the CMB to us without scattering*

6% scatter with matter

*path slightly deflected by gravitational lensing

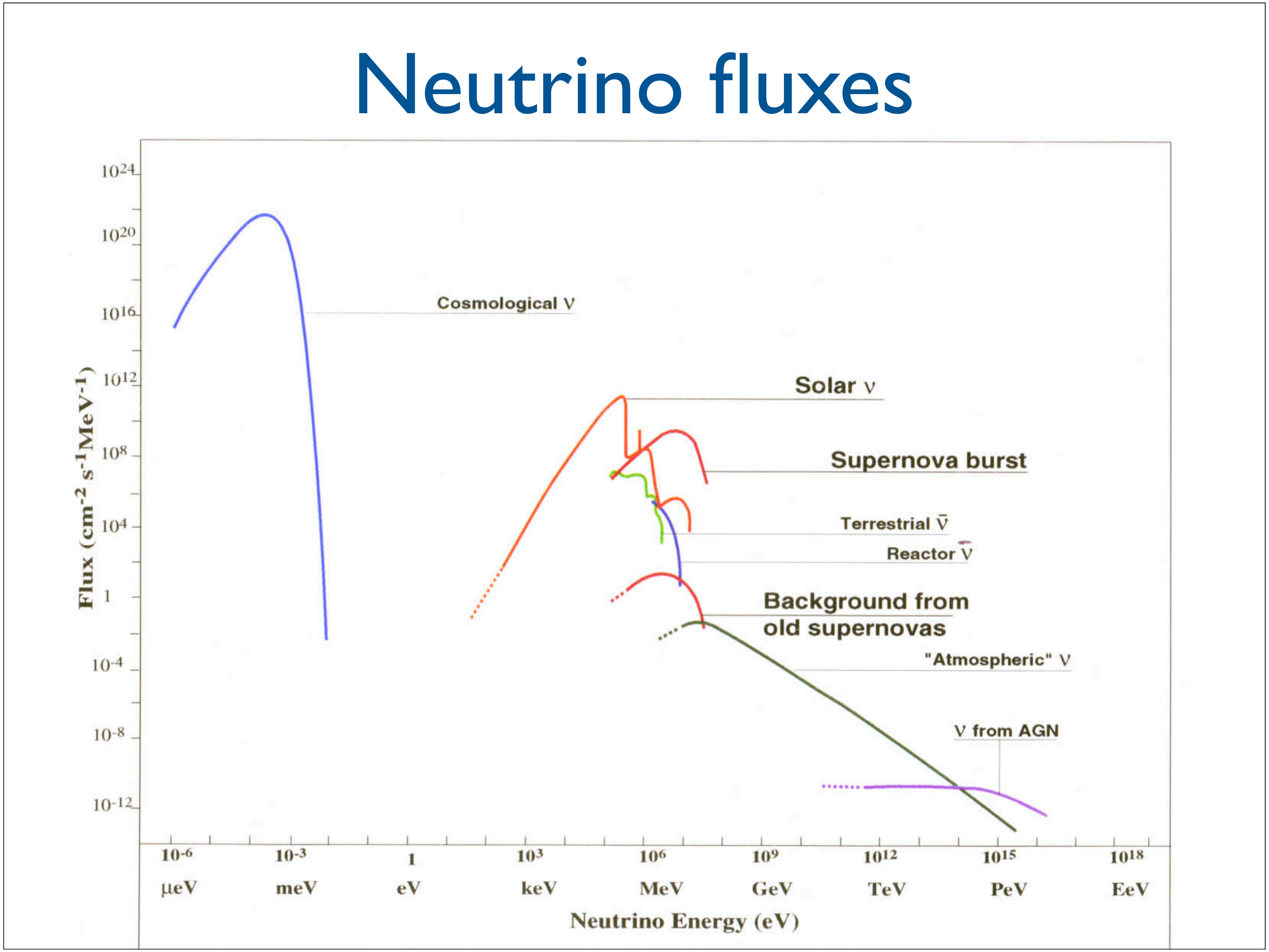
Neutrinos have mass!



$$\left(\sum m_\nu\right)_{\rm min} \approx 60 \text{ meV}$$

$$\left(\sum m_\nu\right)_{\rm min} \approx 100 \text{ meV}$$

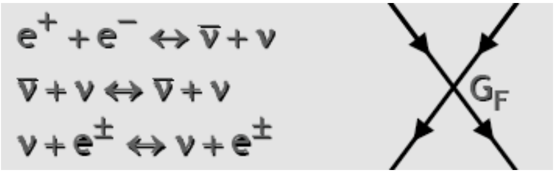
Cosmic neutrinos?



Neutrino thermal equilibrium

- ★ In a gaseous ensemble of atoms or molecules, thermal equilibrium is obtained when the state of the system (# particles at a given energy) does not change with time
- ★ In an expanding universe the temperature is constantly changing and to be in equilibrium particles must adjust the energy faster than the time it takes to change the temperature, i.e. the interaction rate must be faster than the expansion rate of the universe:

$$\Gamma_{\rm int} > H(t)$$



- ★ Neutrinos interact only weakly
- ★ Interactions with nucleons were negligible when 1 MeV ≤ T_γ ≤ 100 MeV since the number density of nucleons was << density of relativistic e^+e^-
- ★ Interaction rate is $\Gamma_{int} \sim G_F^2 T^5$:
  - at small energies compared to the W mass, the cross section is ~ $G_F E^2$
  - the energy is of the order of the temperature T (relativistic particles)
  - the number density of relativistic particles is of the order of T^3

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Neutrino thermal equilibrium

- ★ The expansion rate (radiation dominated universe $\rho \sim T^4$) is $H \sim T_\gamma^2/M_{Pl}$
- ★ The condition for thermal equilibrium:

$$T_\gamma^{v-dec} \sim (M_{Pl} G_F^2)^{-1/3} \sim 1 \text{ MeV}$$

- ★ requires that $T \geq 1$ MeV (corresponding to $t \leq 1$ sec) for $M_{Pl} = 1.2 \times 10^{19}$ GeV
- ★ This coincides with the temperature where light element synthesis occur: observation of light elements abundances provide important information on ν's as well
- ★ It also means that neutrino decouple at a temperature slightly higher than the electron mass m_e, so that when e^+e^- annihilation occurs at $T \sim m_e/3$ the T_ν is not affected, while T_γ is heated by a factor $(11/4)^{1/3}$, since e^+e^- became non-relativistic and their entropy is transferred to photons, so that:

$$T_\nu / T_\gamma = (4/11)^{1/3} \simeq 0.71$$

- ★ This prediction is not yet been checked experimentally

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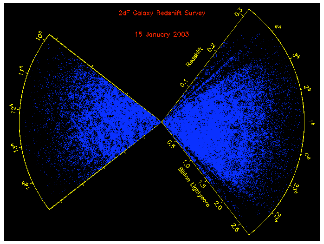
Cosmological data

★ Even though BBN provides interesting bounds on neutrino physics, observations of the late-time universe has provided very strong constraints on cosmological parameters and neutrino physics too

★ In particular neutrinos affect the growth of cosmic clustering and this clustering can be accurately measured combining data from:

- Large Scale Structures (LSS)
- Cosmic Microwave Background (CMB)
- The baryon acoustic peak (BAO)
- The Lyman-α forest
- Type Ia supernova



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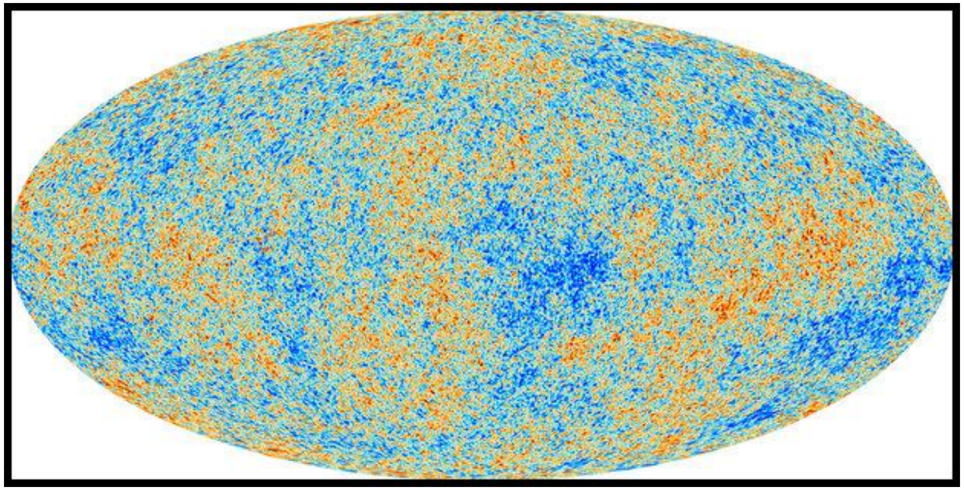
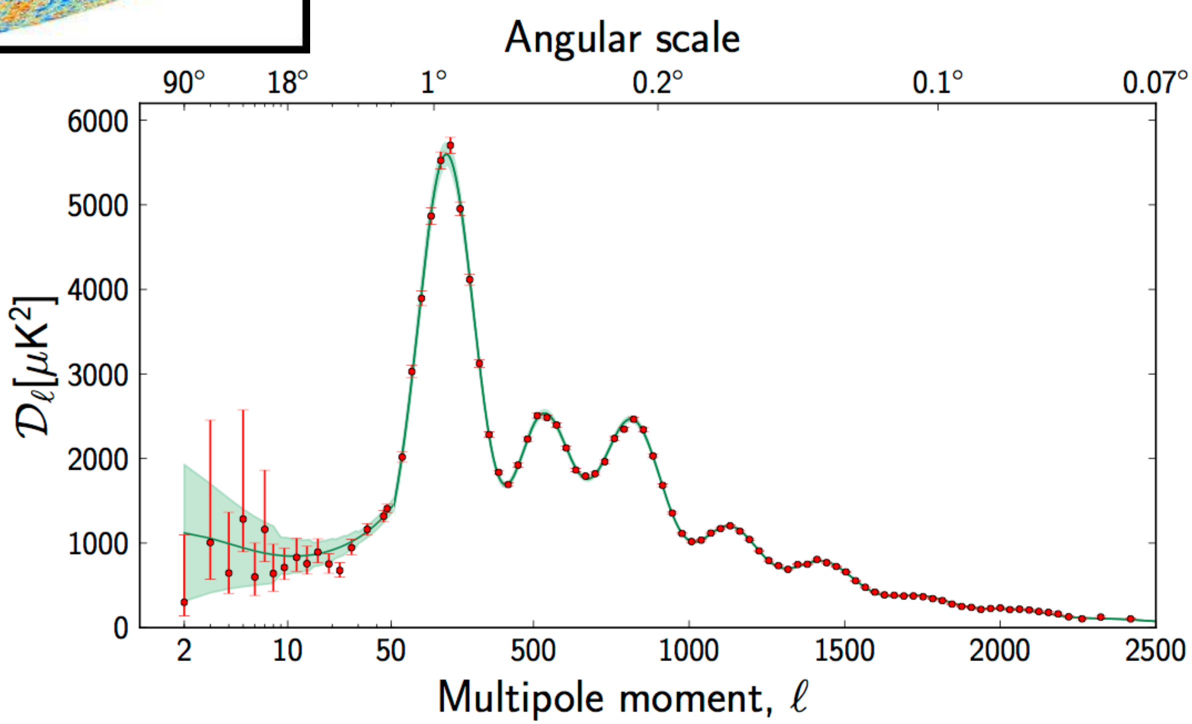
Cosmic microwave background (CMB)



Planck Satellite (2018)

[“primary fluctuations”]

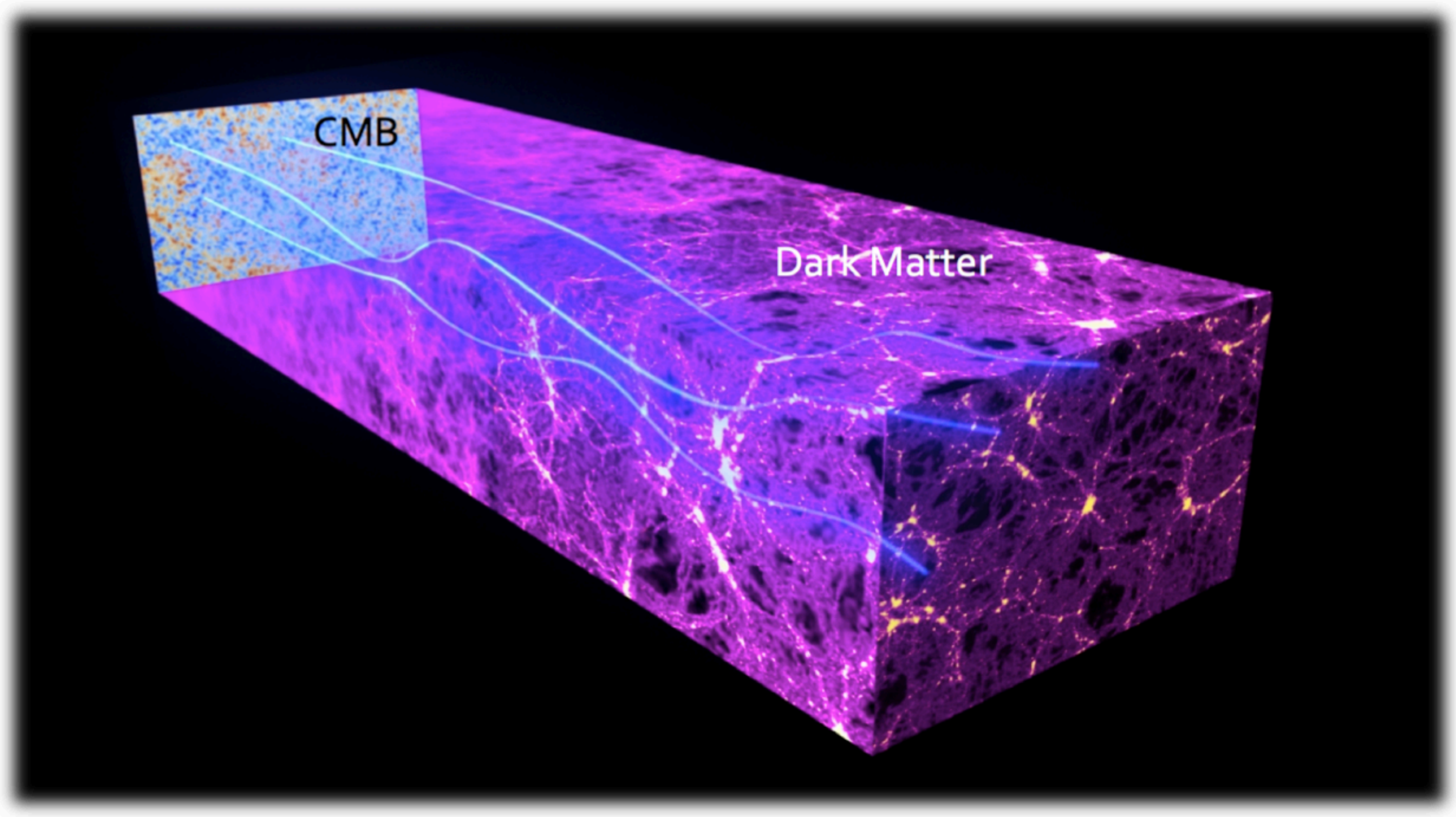


Not enough information from the CMB alone!

Need CMB + low-redshift tracer of matter

CMB lensing

Paths of CMB photons deflected by matter → create statistical anisotropy



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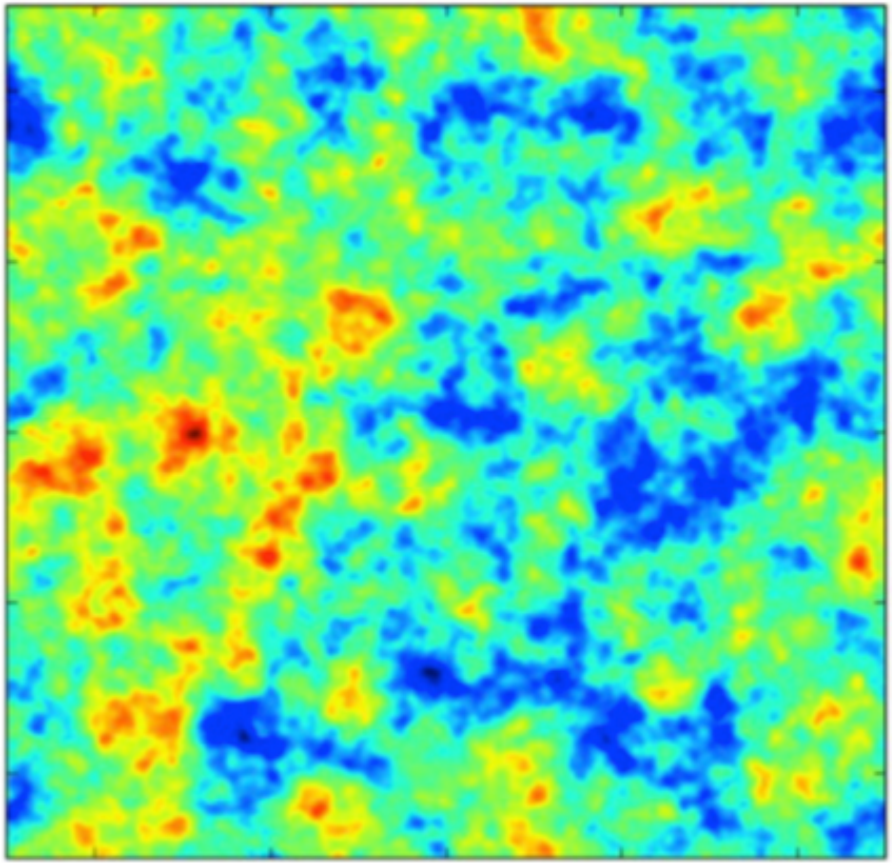

CMB lensing

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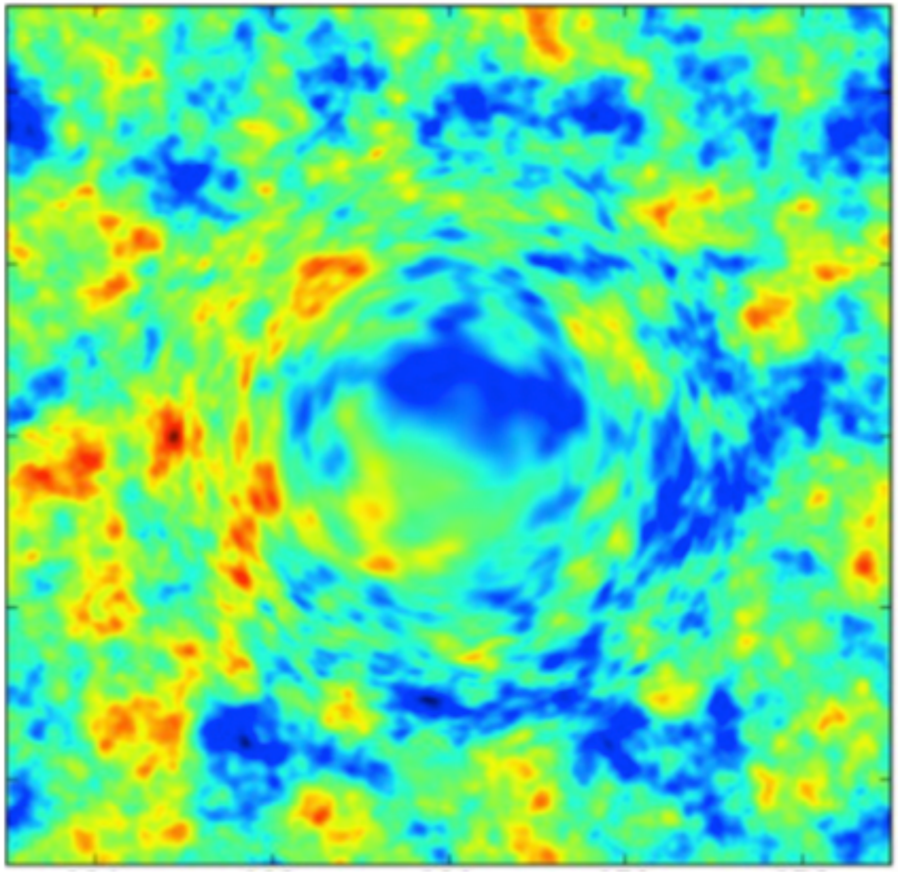
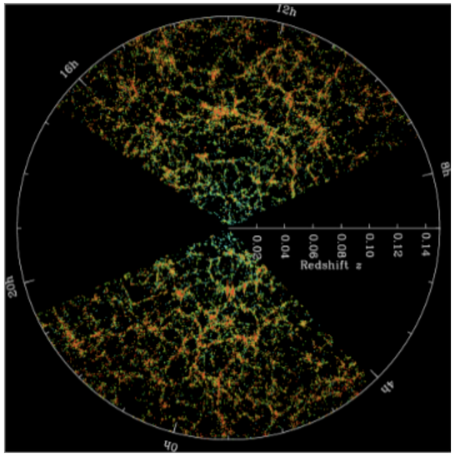


Large Scale Structures (LSS)

★ The Sloan Digital Sky Survey (SDSS) has observed almost 1 million galaxies and measured the red-shifts, which results in the most detailed map of the Universe

★ Another important survey is the 2dFGRS (2 degrees Field Galaxy Redshift Survey)



SDSS Galaxy map

★ The analysis of large scale structures (comparison of models to observational data by constructing the power spectrum of density fluctuation P(k), i.e. the variance of the fluctuations in Fourier space) allows to study the properties of dark matter and the spectrum of primordial density fluctuations and in particular to put more stringent bounds on the neutrino mass

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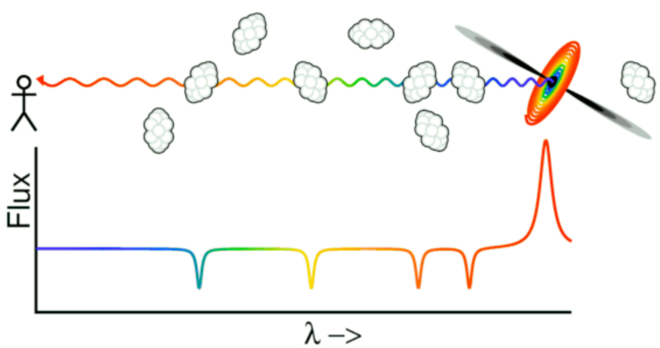
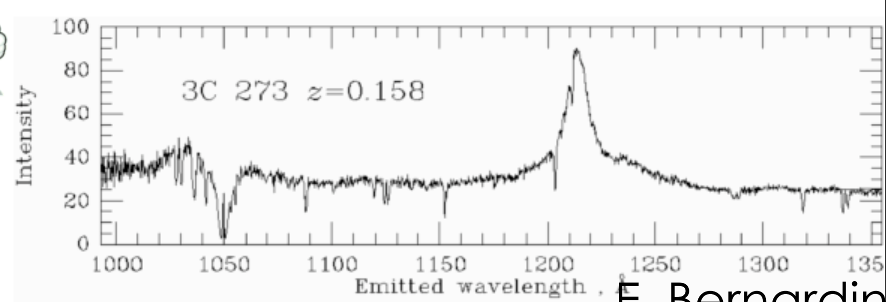
The Lyman-α forest

- ★ Lyman-α forest: absorption lines in the spectrum of distant quasars due to intermediate hydrogen clouds which absorb the Lyman-α line (λ_α=1215.67 Å)
- ★ If the quasar is at redshift z_q, the Lyman -α emission line has observed wavelength $\lambda_\alpha{}^q=(1+z_q)\lambda_\alpha$
- ★ Since the absorption clouds are at different redshifts, smaller than z_q, it is common to observe a "forest" of absorption lines, below the Lyman -α emission line of the quasar
- ★ From the characteristics of the absorption lines it is possible to infer the power spectrum of density fluctuations for relatively small λ





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Global fits of cosmological data

- ★ It is assumed that galaxies trace dark matter up to a constant factor b (the "bias") which implies that the galaxy power spectrum $P_g(k)$ is related to the dark matter power spectrum $P_{DM}(k)$ by:

$$p_g(k) = b^2 P_{DM}(k)$$

- ★ The bias is extracted from fits to the data in the framework of specific cosmological models

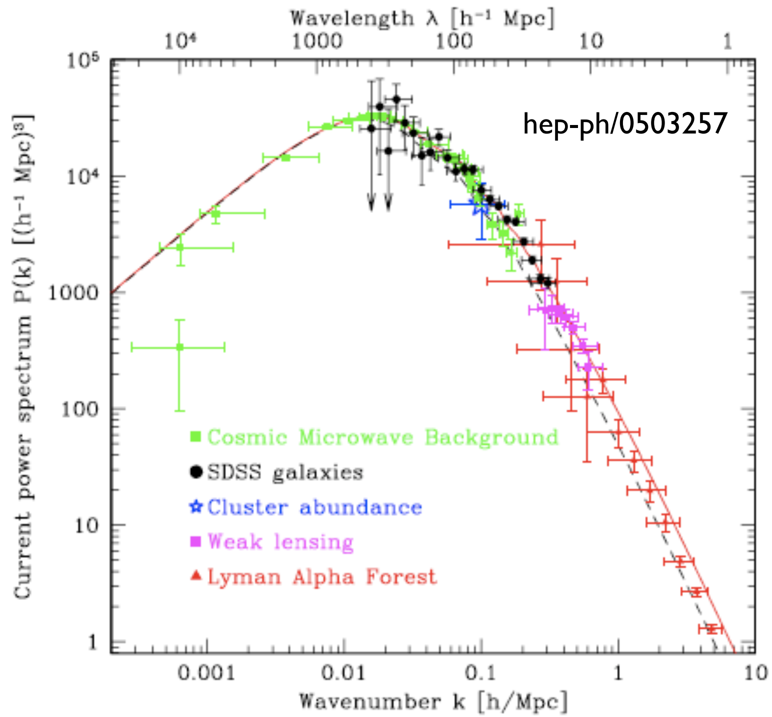

FIG. 1: Cosmological constraints on the current matter power spectrum $P(k)$ reprinted from [26]. See [26] for details about the modeling assumptions underlying this figure. The solid curve shows the theoretical prediction for a "vanilla" flat scalar scale-invariant model with matter density $\Omega_m = 0.28$, Hubble parameter $h = 0.72$ and baryon fraction $\Omega_b/\Omega_m = 0.16$. The dashed curve shows that replacing 7% of the cold dark matter by neutrinos, corresponding to a neutrino mass sum $M_\nu = 1$ eV, suppresses small-scale power by about a factor of two.

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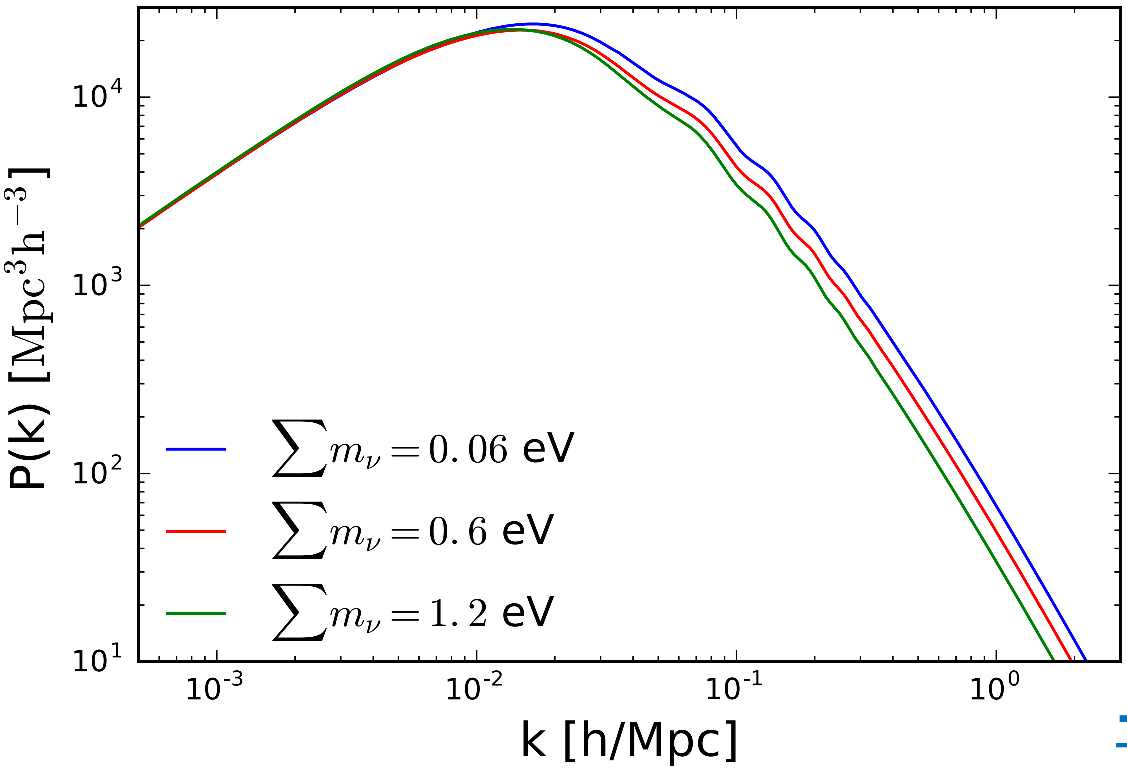
Neutrino mass effect on LSS

The small-scale matter power spectrum, $k>k_{fs}$, is reduced in presence of massive neutrinos:

- On larger scales νs cluster in the same way as cold dark matter
- Free-streaming νs do not cluster
- The growth rate of CDM and baryon fluctuations is reduced

$$k_{\rm fs} \simeq 0.018\ \Omega_m^{1/2} \left(\frac{M_\nu}{1\rm eV}\right)^{1/2}\ h\ \rm Mpc^{-1}$$



Power suppression at small scales

$$\frac{\Delta P(k)}{P(k)} \sim -8 f_\nu$$

$$f_\nu = \omega_\nu / \omega_{\rm m}$$
= 0.5%

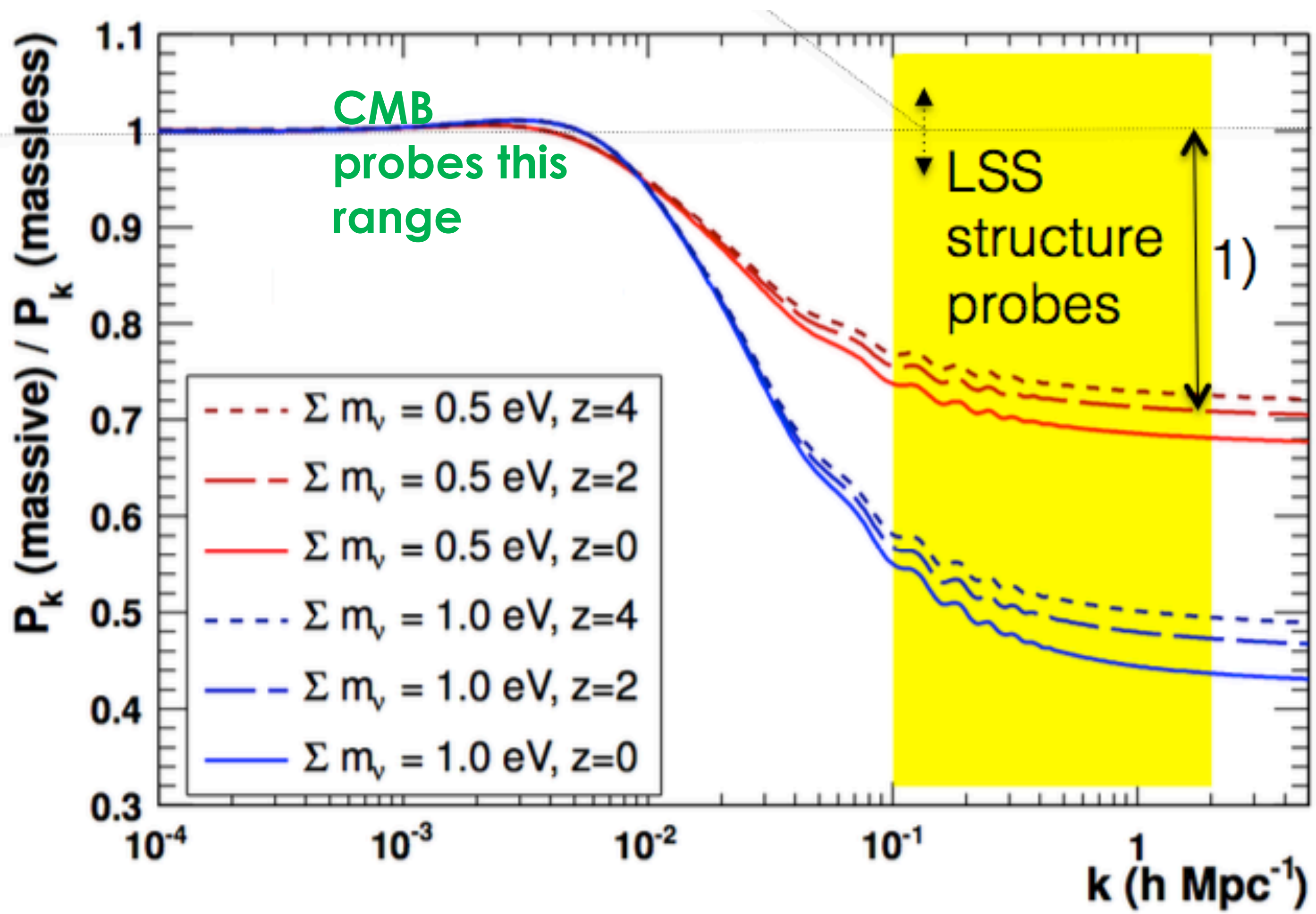
→ 4% suppression minimum!

+ non-linear calculations: additional suppression at large k
see Villaescusa-Navarro et al. 2013

Neutrino mass

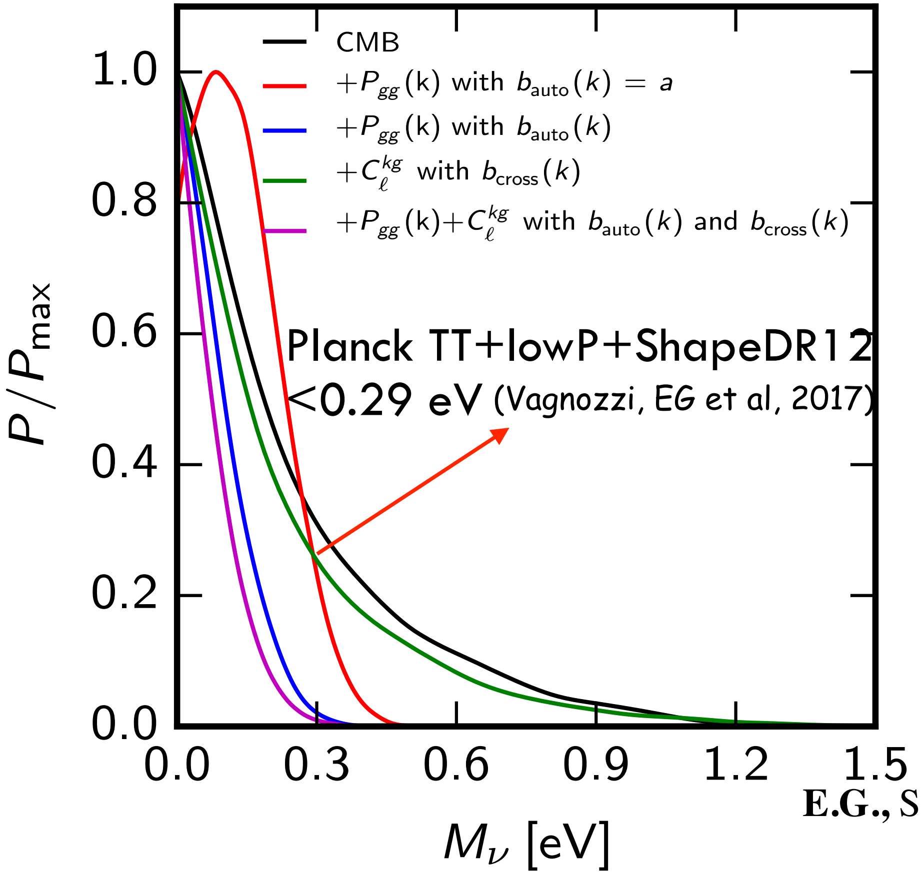
Compare CMB to LSS amplitudes and look for a suppression!

Inferred from CMB, which probes $A_s e^{-2\tau}$



Results: Cosmological constraints

Dataset	a (68% C.L.)	c (68% C.L.)	d (68% C.L.)	M_ν [eV] (95% C.L.)
$CMB \equiv PlanckTT{+}lowP$				< 0.72
$CMB{+}C_\ell^{\kappa g}$	1.45 ± 0.19	2.59 ± 1.22		**0.06**
	1.50 ± 0.21	2.97 ± 1.42		< 0.72
$CMB{+}P_{gg}(\mathrm{k})$	1.97 ± 0.05		-13.76 ± 4.61	**0.06**
	1.98 ± 0.08		-14.03 ± 4.68	< 0.22
$CMB{+}P_{gg}(\mathrm{k}){+}C_\ell^{\kappa g}$	1.95 ± 0.05	0.45 ± 0.87	-13.90 ± 4.17	**0.06**
	1.95 ± 0.07	0.48 ± 0.90	-14.13 ± 4.02	< 0.19 eV



Currently best constraint!

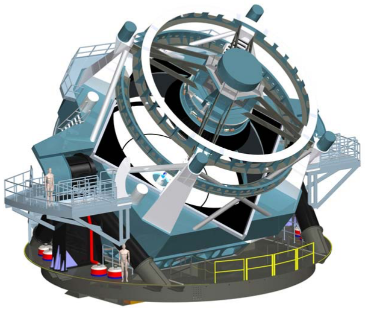
(conservative)

We are not that far from the minimum mass allowed

E.G., S. Vagnozzi, S. Ho et al. 2018, arXiv:1802.08694

What's next? Large scale structure

LSST



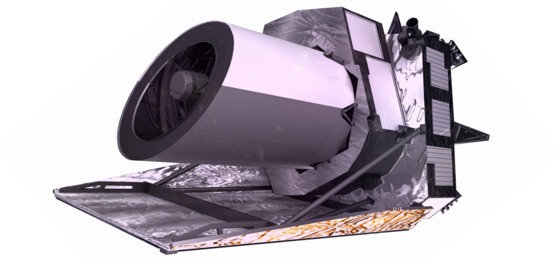
DESI

+ 4-MOST, HSC/PFS, HETDEX, MSE, …

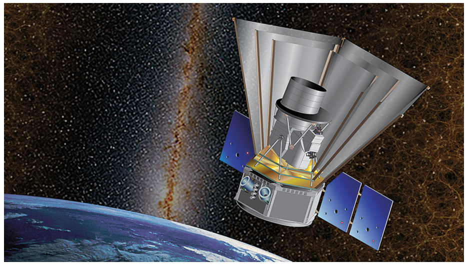
Also: 21cm (Chime, HIRAX)

WFIRST

EUCLID



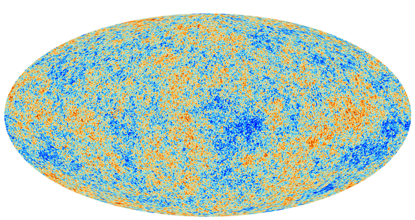
SPHEREx



The CMB landscape – state of the art

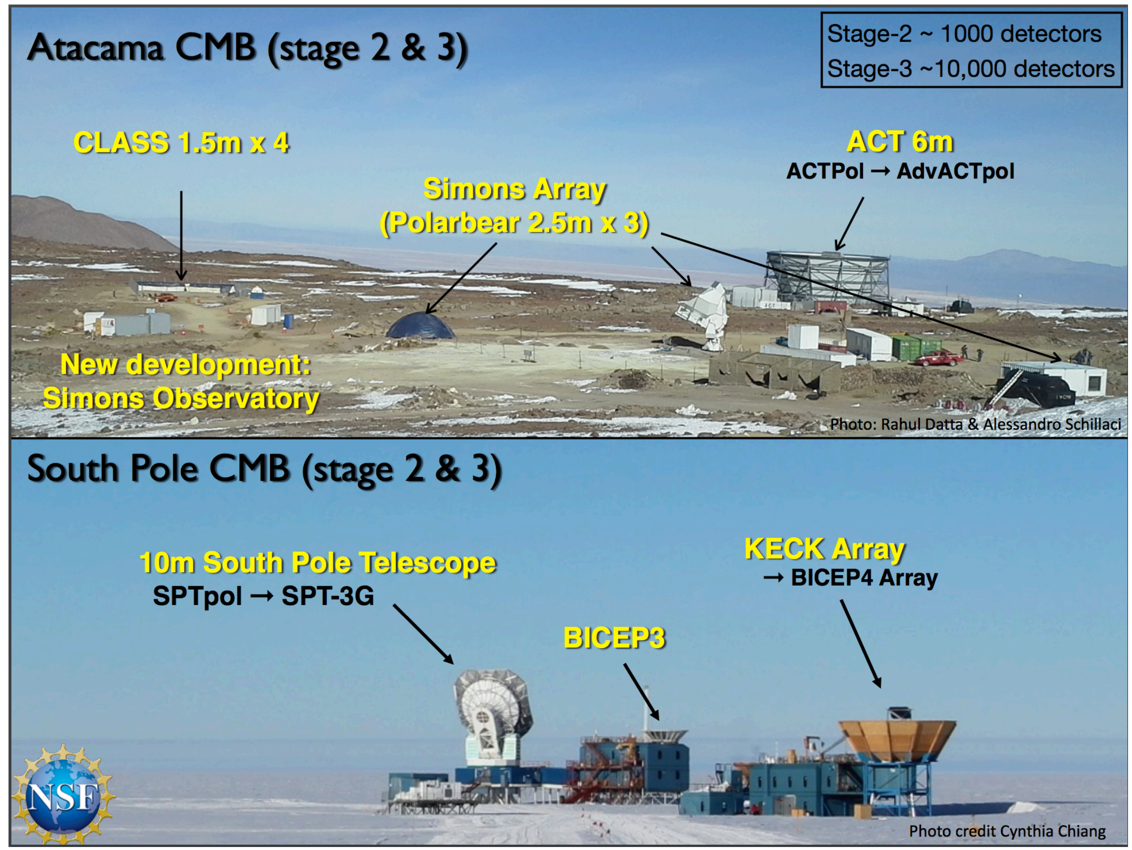
SPACE

Planck satellite

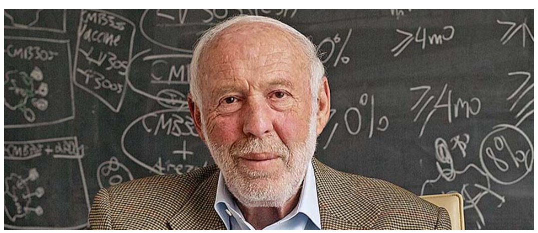


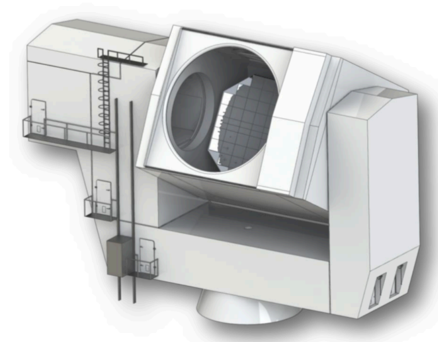
+ **BALLOON** experiments

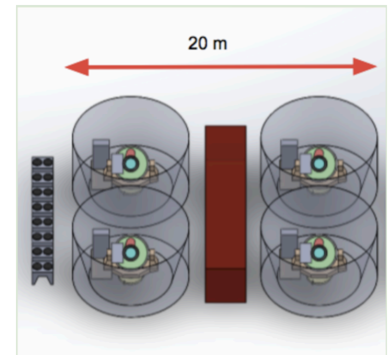
GROUND



The CMB landscape – early 2020s







Large Aperture Telescope
one 6 meter in diameter

Small Aperture Telescopes
~four 42 cm refractors

Large frequency coverage (30 – 270 GHz)

- 10 Countries
- 40+ institutions
- Key LBL participation

Fully funded
6-year program
First light in 2021!

The CMB landscape – mid-2020s

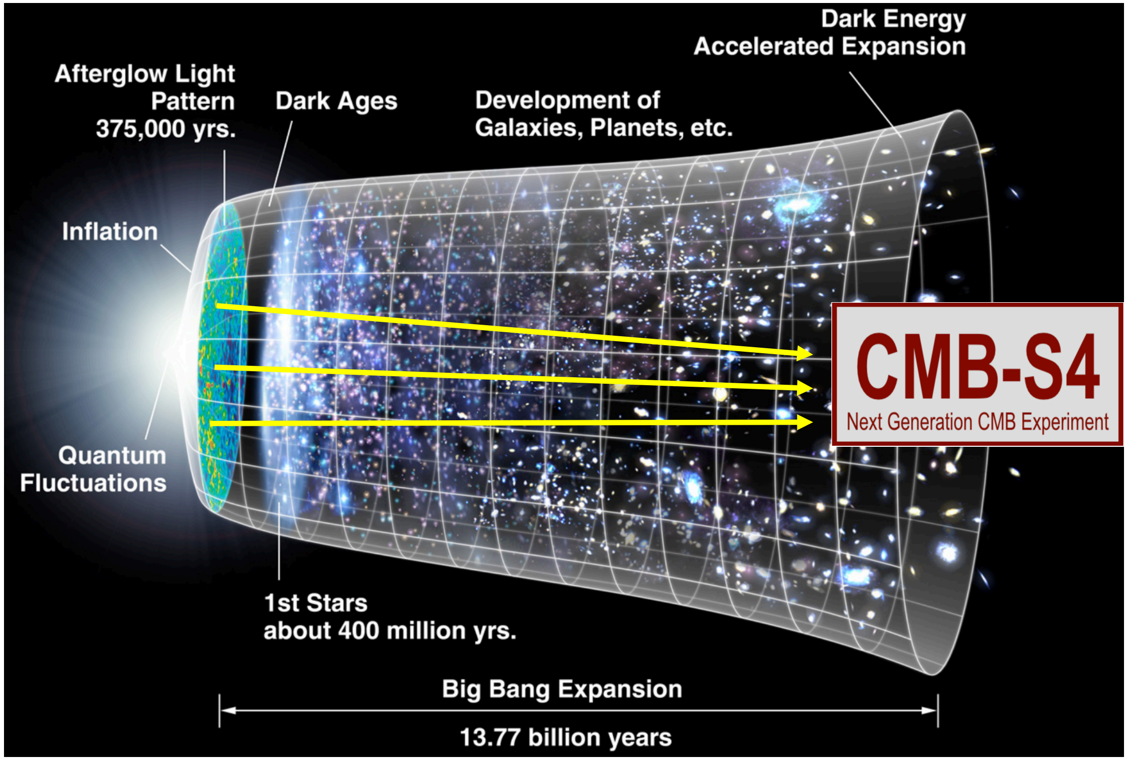
- **CMB S4:** next generation ground based experiment
- Factor of ~10 increase in sensitivity

- Multi-agency effort (DOE & NSF)
- LBL/UCB will play a leading role

Can we improve?

- Future surveys will measure the amplitude on the sky to better than 0.5% (both CMB and LSS)
- We are looking for a 4% suppression (or larger)
- So, no problem??
- Reionization is the limiting factor in getting measuring the amplitude from CMB!

CMB and reionization



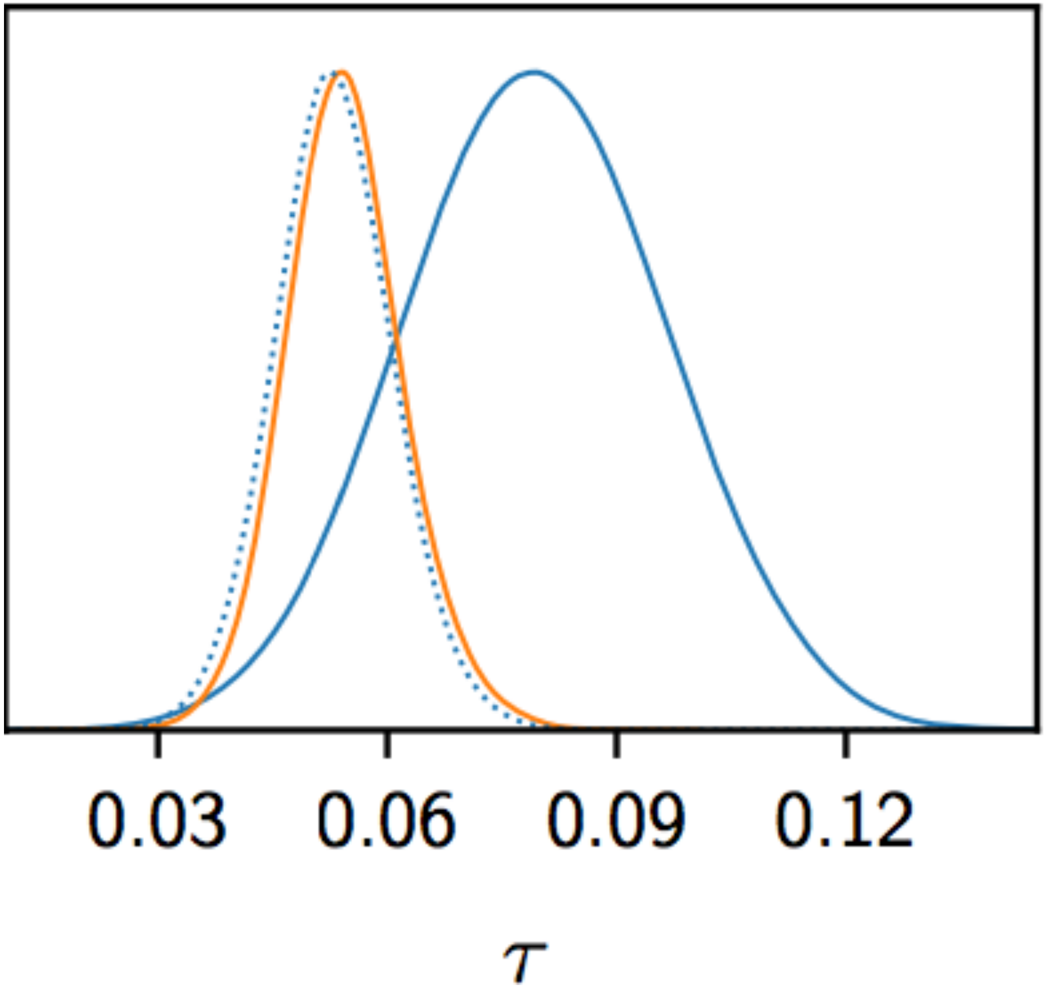
~94% of photons travel from the CMB to us without scattering*

~6% scatter with matter

Optical depth τ = fraction of CMB photons that scatter with matter

CMB actually measures $\text{Amplitude} \times e^{-2\tau}$

Current best measurements



Planck 2018

$$\tau = 0.0544^{+0.0070}_{-0.0081}$$

↓

Amplitude

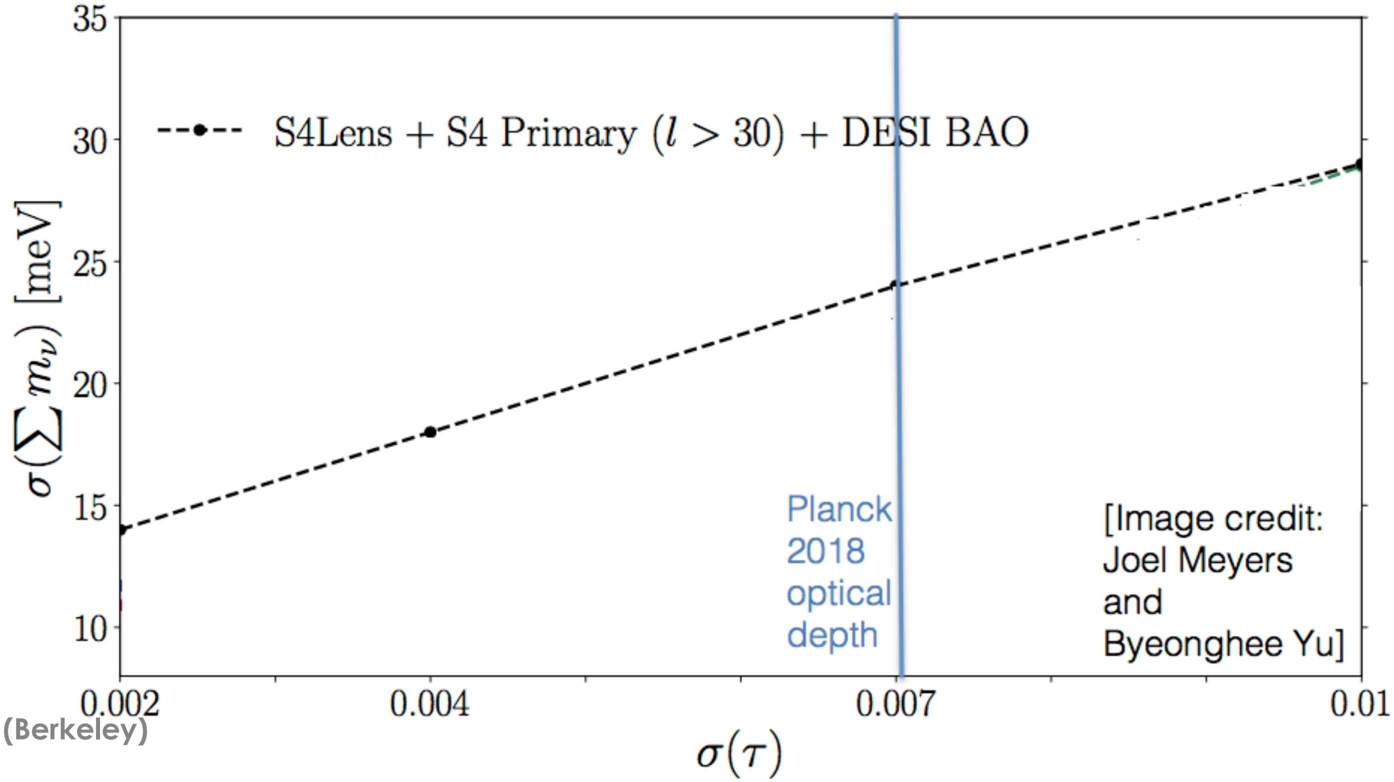
$$A_s = (2.101^{+0.031}_{-0.034}) \times 10^{-9}$$

known to 1.5%

Not limited by surveys, but by knowledge of τ!

Better τ measurements?

- Measure from the large-scale polarization of the CMB. Not accessible by the ground → need to go to space!
- Current proposed missions: LiteBird (UCB/LBL + Jaxa), CORE (ESA), PICO (NASA)
- New ideas?



BACKUP

Light relics

- Each phase transition/annihilation conserve entropy