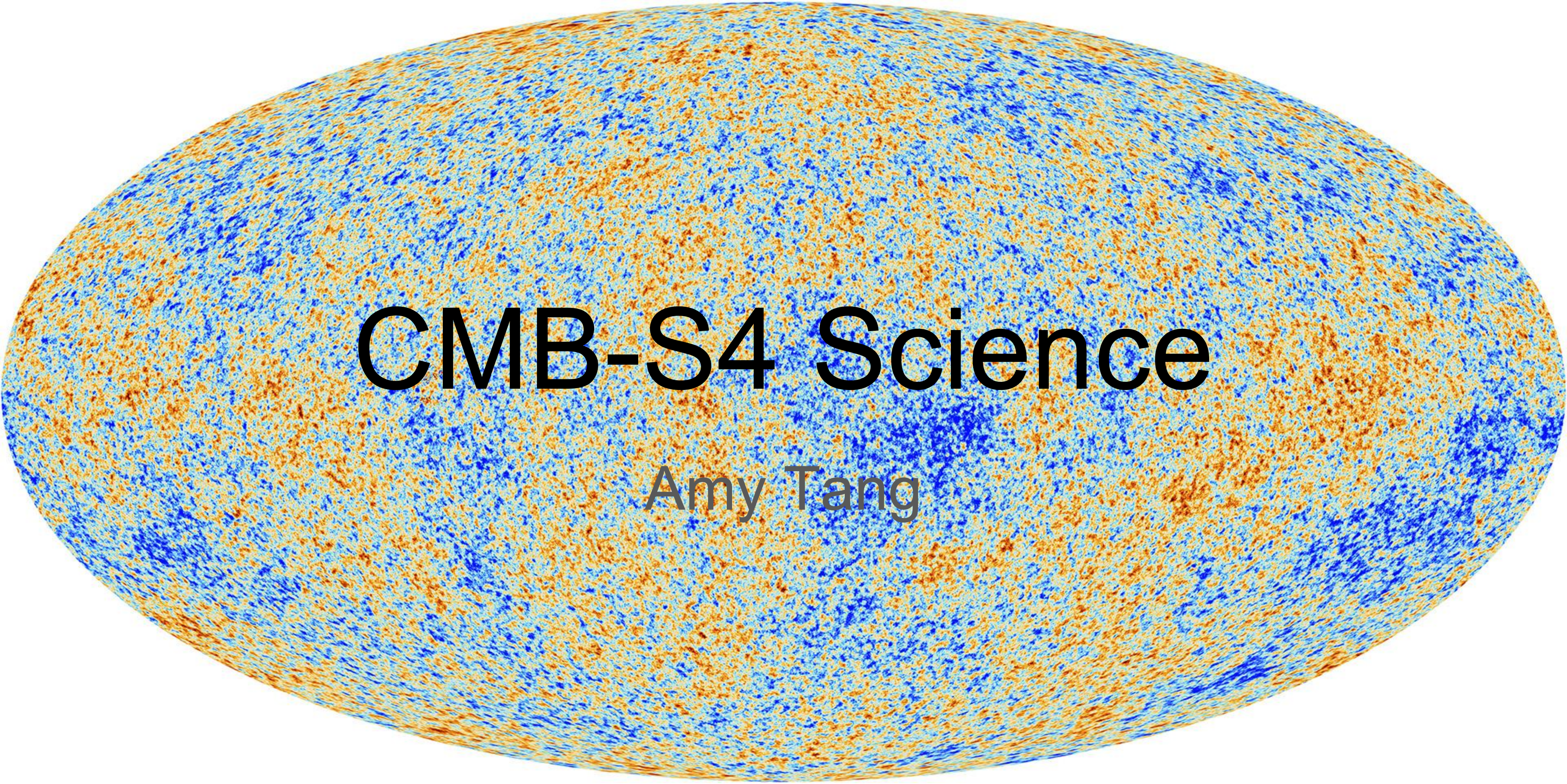
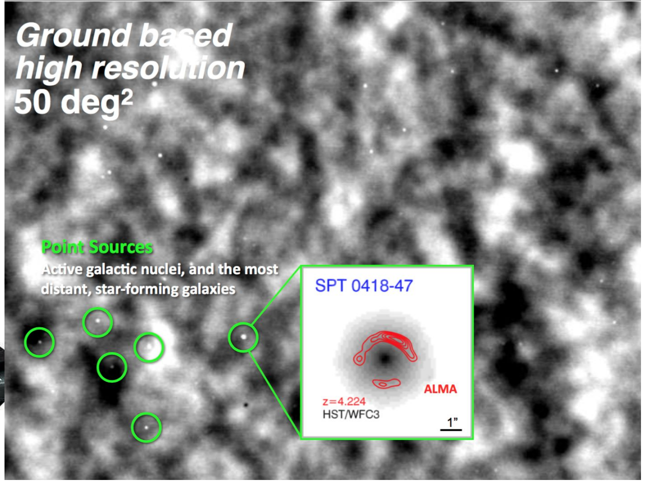
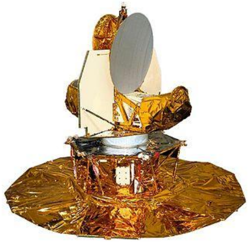


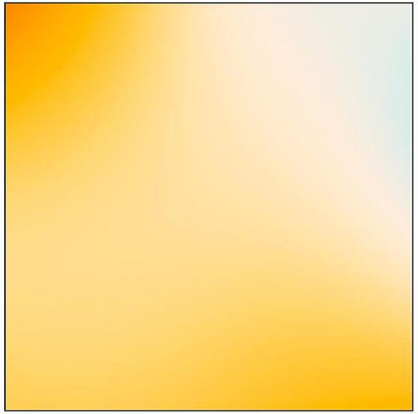
CMB-S4 Science

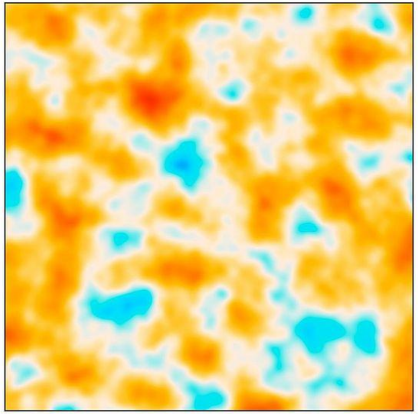
Amy Tang

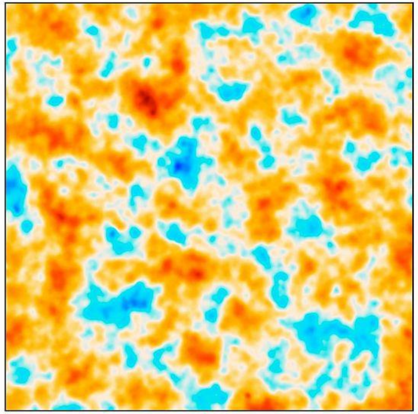
Progress in the CMB Detection











COBE

WMAP

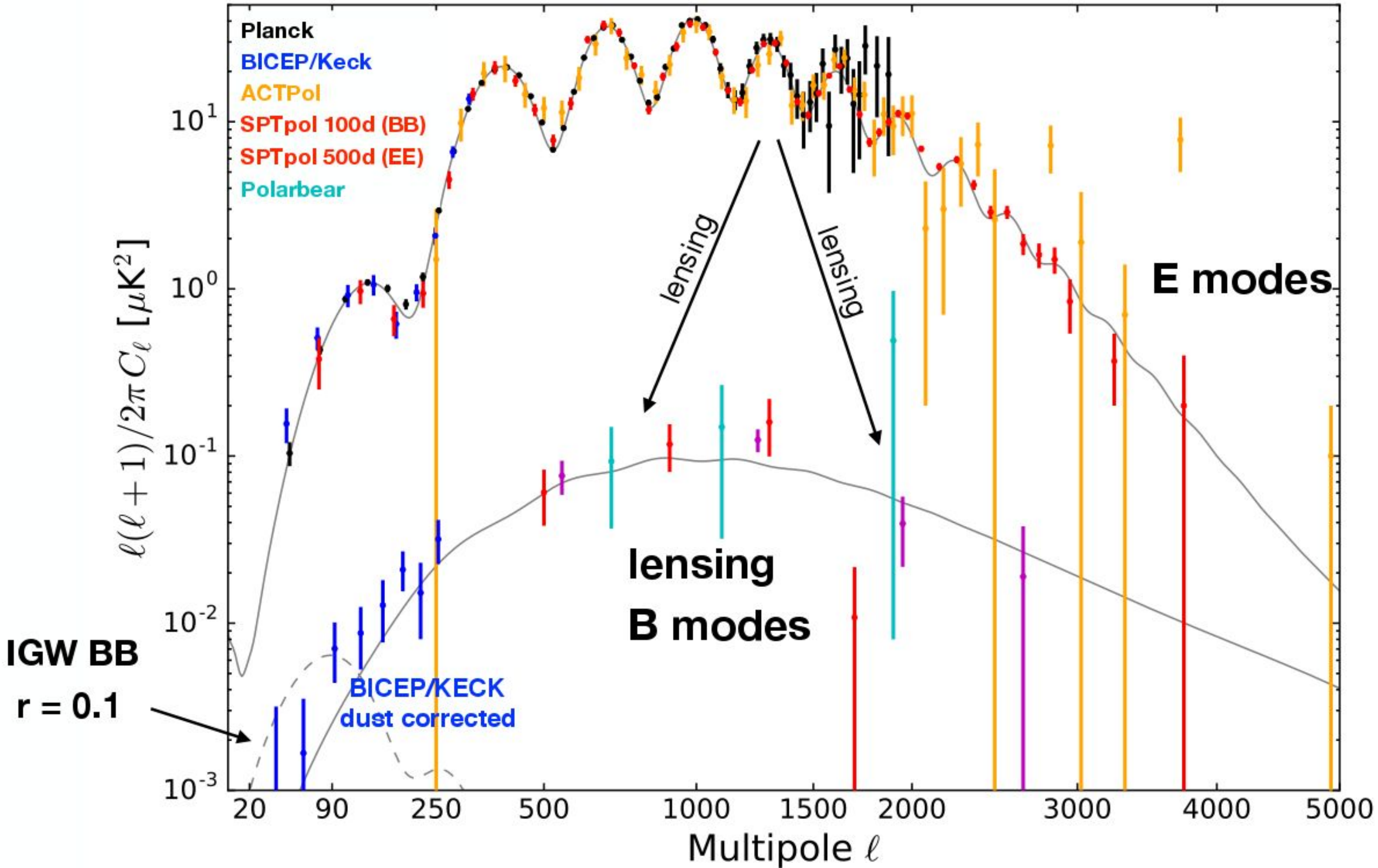
Planck

Is cosmology with CMB complete?

Cosmological parameters from 2015 *Planck* results[33][35]

Parameter	Symbol	TT+lowP 68% limits	TT+lowP +lensing 68% limits	TT+lowP +lensing+ext 68% limits	TT,TE,EE+lowP 68% limits	TT,TE,EE+lowP +lensing 68% limits	TT,TE,EE+lowP +lensing+ext 68% limits
Baryon density	$\Omega_b h^2$	0.022 22 ±0.000 23	0.022 26 ±0.000 23	0.022 27 ±0.000 20	0.022 25 ±0.000 16	0.022 26 ±0.000 16	0.022 30 ±0.000 14
Cold dark matter density	$\Omega_c h^2$	0.1197 ±0.0022	0.1186 ±0.0020	0.1184 ±0.0012	0.1198 ±0.0015	0.1193 ±0.0014	0.1188 ±0.0010
100x approximation to r_s / D_A (CosmoMC)	$100\,\theta_{MC}$	1.040 85 ±0.000 47	1.041 03 ±0.000 46	1.041 06 ±0.000 41	1.040 77 ±0.000 32	1.040 87 ±0.000 32	1.040 93 ±0.000 30
Thomson scattering optical depth due to reionization	τ	0.078 ±0.019	0.066 ±0.016	0.067 ±0.013	0.079 ±0.017	0.063 ±0.014	0.066 ±0.012
Power spectrum of curvature perturbations	$\ln(10^{10} A_s)$	3.089 ±0.036	3.062 ±0.029	3.064 ±0.024	3.094 ±0.034	3.059 ±0.025	3.064 ±0.023
Scalar spectral index	n_s	0.9655 ±0.0062	0.9677 ±0.0060	0.9681 ±0.0044	0.9645 ±0.0049	0.9653 ±0.0048	0.9667 ±0.0040
Hubble's constant (km Mpc^{-1} s^{-1})	H_0	67.31 ±0.96	67.81 ±0.92	67.90 ±0.55	67.27 ±0.66	67.51 ±0.64	67.74 ±0.46
Dark energy density	Ω_Λ	0.685 ±0.013	0.692 ±0.012	0.6935 ±0.0072	0.6844 ±0.0091	0.6879 ±0.0087	0.6911 ±0.0062
Matter density	Ω_m	0.315 ±0.013	0.308 ±0.012	0.3065 ±0.0072	0.3156 ±0.0091	0.3121 ±0.0087	0.3089 ±0.0062
Density fluctuations at 8h^{-1} Mpc	σ_8	0.829 ±0.014	0.8149 ±0.0093	0.8154 ±0.0090	[illegible]	[illegible]	0.8159 ±0.0086
Redshift of reionization	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$8.8^{+1.2}_{-1.1}$
Age of the Universe (Gy)	t_0	13.813 ±0.038	13.799 ±0.038	[illegible]	13.813 ±0.026	13.807 ±0.026	13.799 ±0.021
Redshift at decoupling	z_*	1 090.09 ±0.42	1 089.94 ±0.42	1 089.90 ±0.30	1 090.06 ±0.30	1 090.00 ±0.29	1 089.90 ±0.23
Comoving size of the sound horizon at z = z*	[illegible]	[illegible]	[illegible]	144.93 ±0.30	144.57 ±0.32	144.71 ±0.31	144.81 ±0.24
100× angular scale of sound horizon at last-scattering	$100\,\theta_*$	[illegible]	1.041 22 ±0.000 45	1.041 26 ±0.000 41	1.040 96 ±0.000 32	1.041 06 ±0.000 31	1.041 12 ±0.000 29
Redshift with baryon-drag optical depth = 1	z_{drag}	1 059.57 ±0.46	1 059.57 ±0.47	1 059.60 ±0.44	1 059.65 ±0.31	1 059.62 ±0.31	1 059.68 ±0.29
Comoving size of the sound horizon at z = z_{drag}	r_{drag}	147.33 ±0.49	147.60 ±0.43	147.63 ±0.32	147.27 ±0.31	147.41 ±0.30	147.50 ±0.24

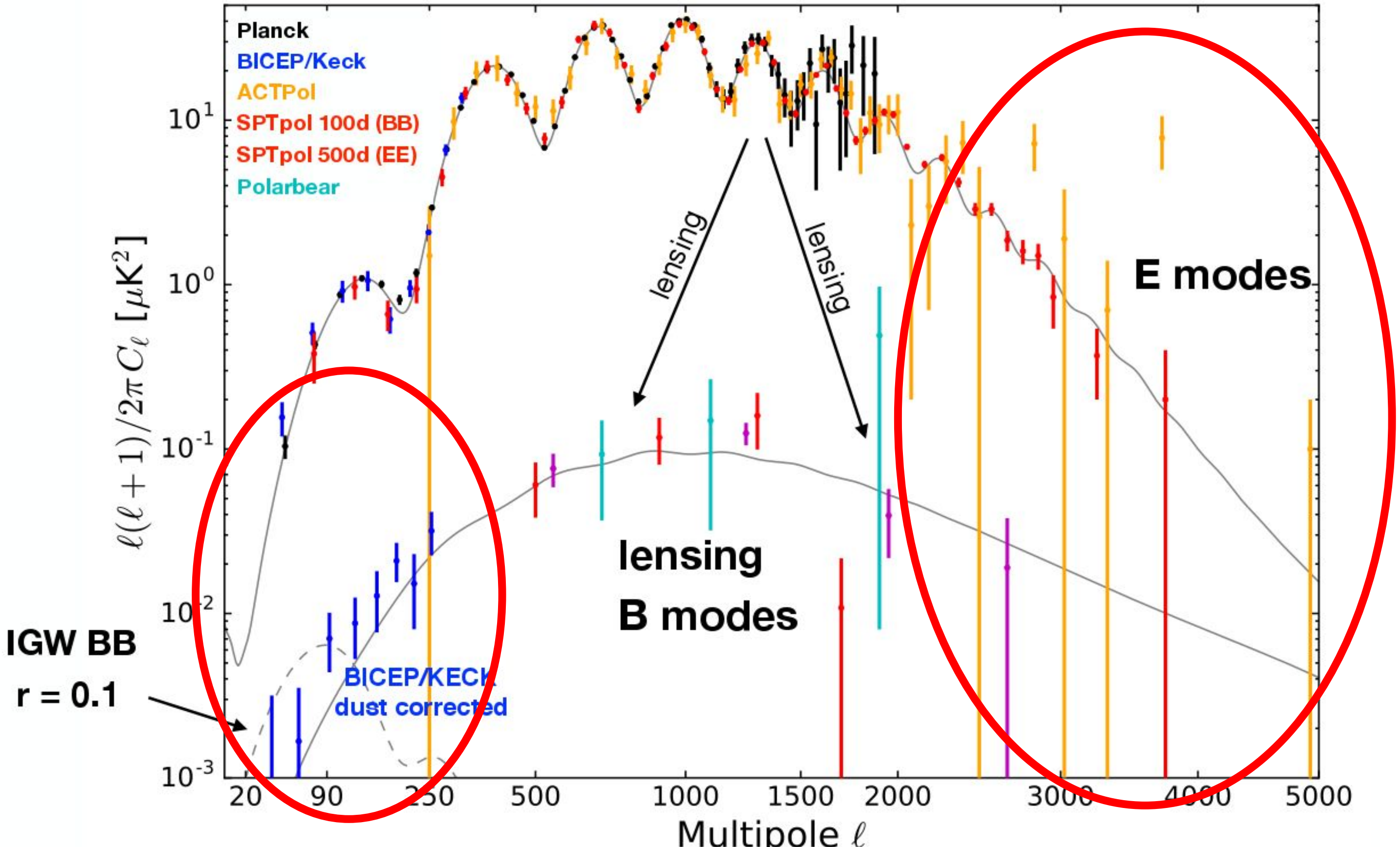
Current status of CMB Polarization



From Jeff McMahon talk (2016)

Current status of CMB Polarization

Need to fill out sparsely populated spots

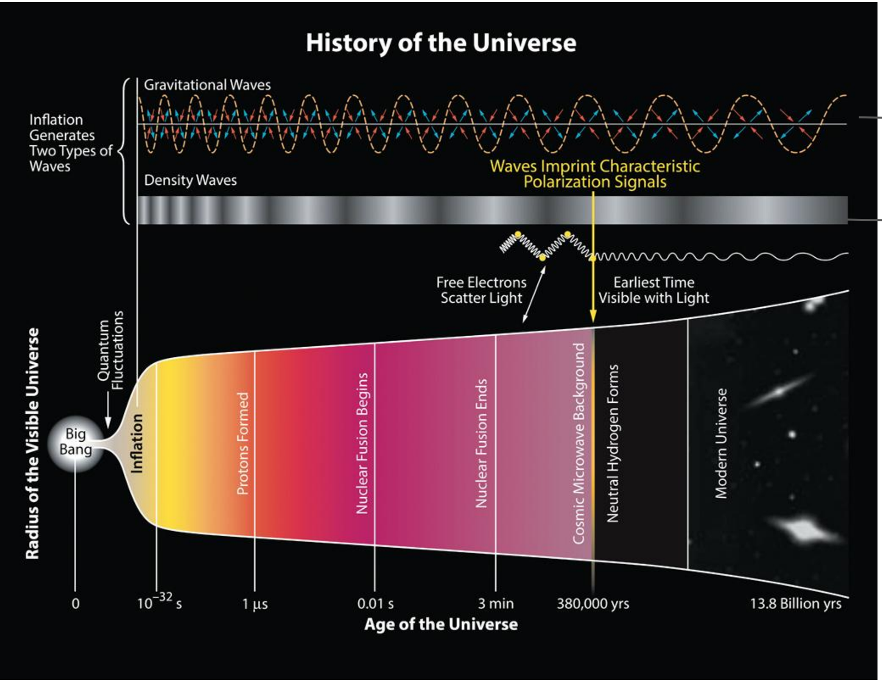


More Science to Come

- Inflation
- Neutrino
- Light relics
- Dark Matter
- Dark Energy
- CMB lensing

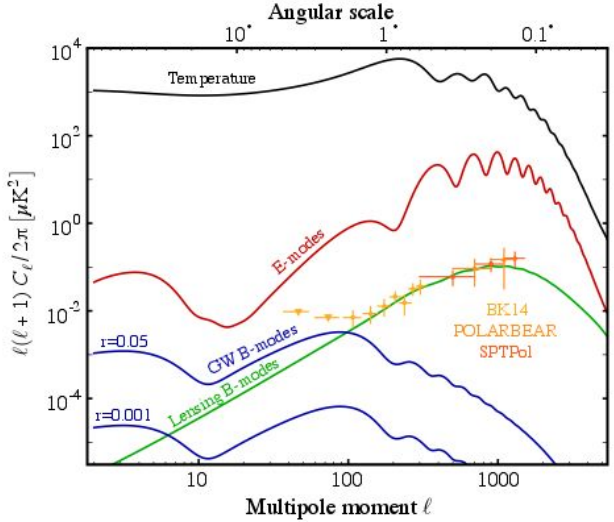
For more, CMB S4 Science Book:
arXiv:1610.02743

Inflation

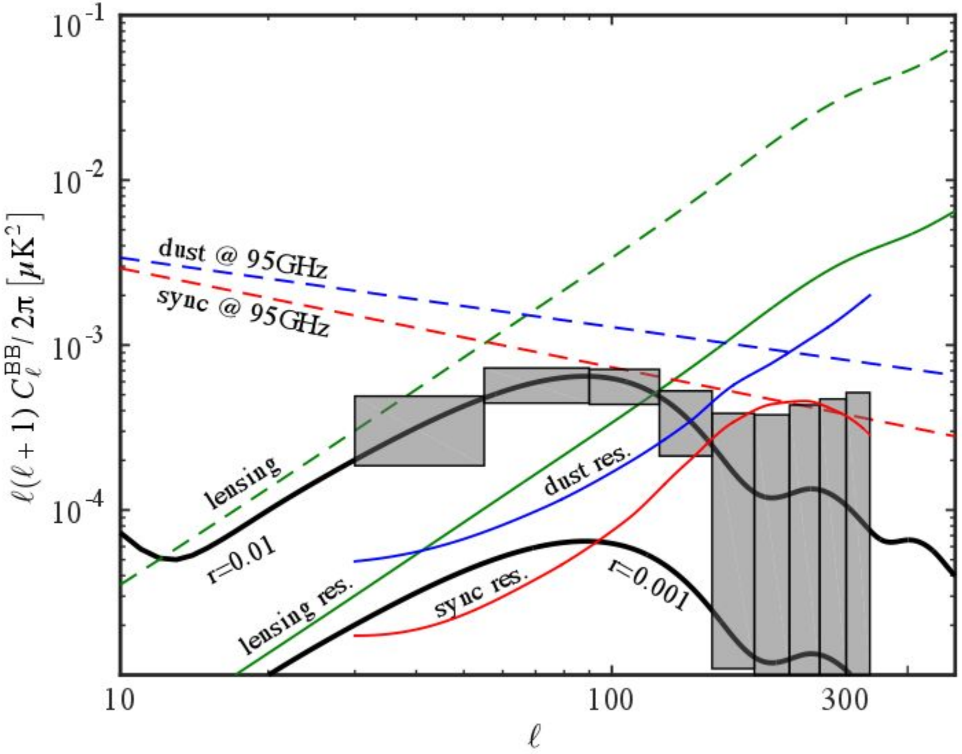


Tensor perturbations -> B-mode. ???????

Scalar perturbations -> E-mode. DETECTED



Predictions for CMB-S4

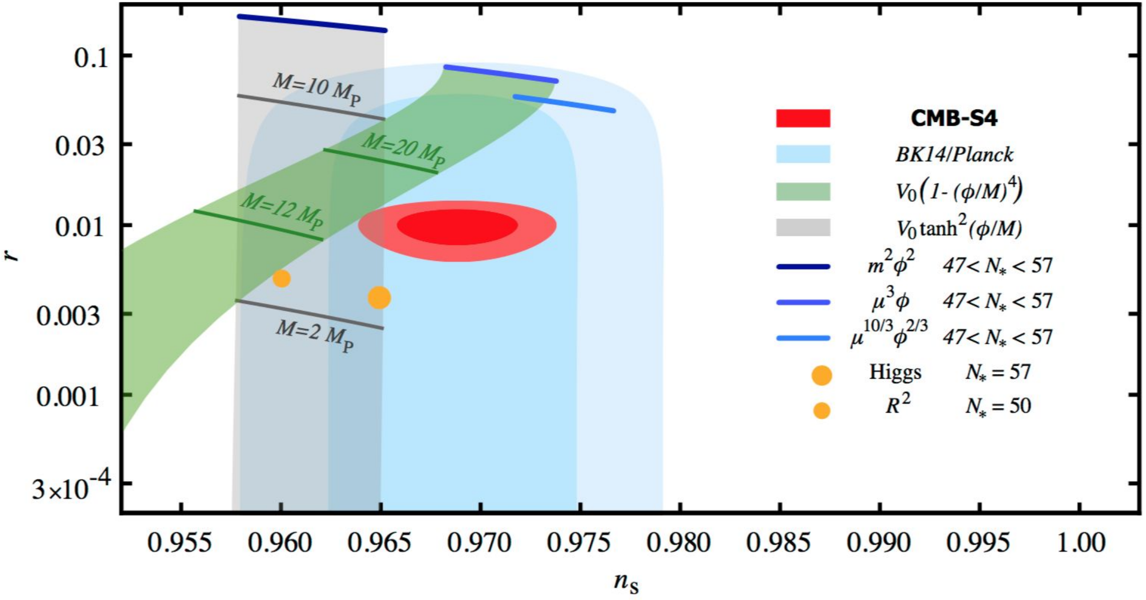


- Sensitivity ~ 1uK arcmin needed to reach σ(r) ~10^{-3}
- Target bump at l~80
  - Reionization bump difficult to reach from ground
- Multi-band to separate foregrounds
- Large aperture telescope delensing (constructed from E-mode maps) effort needed

Implications of B-mode Detection

- Final check of inflation
- Probes the energy scale of inflation ~ 10^{16} GeV
- Evidence that quantum gravity must accommodate Planckian field range

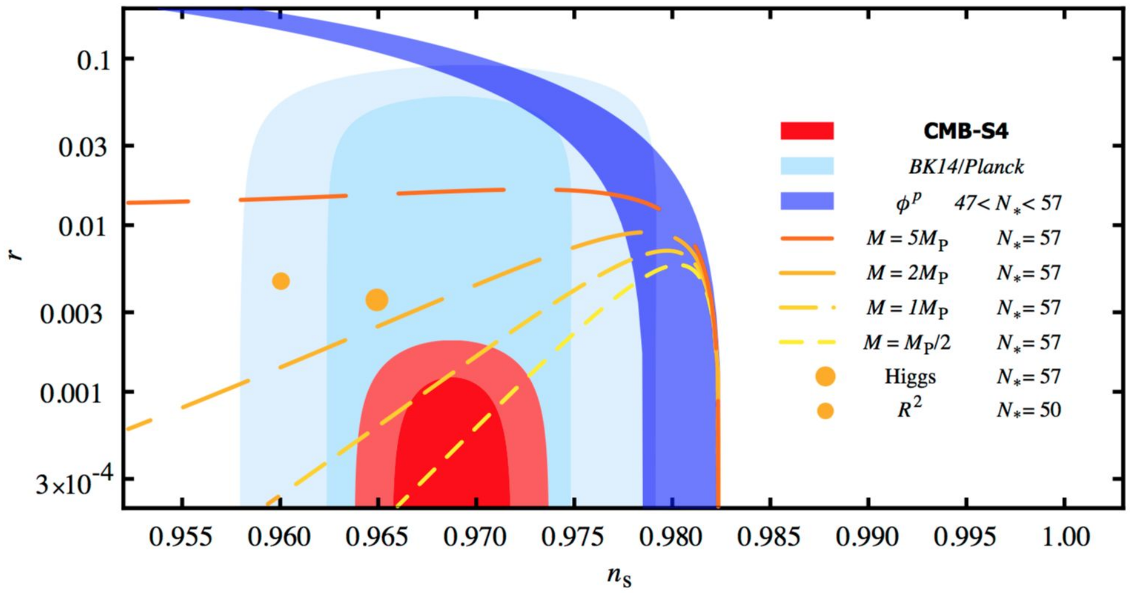
$$\frac{\Delta\phi}{M_{\rm P}} \gtrsim \left(\frac{r_*}{8}\right)^{1/2} \mathcal{N}_* \gtrsim \left(\frac{r}{0.01}\right)^{1/2}$$



Implications of an Improved Upper Limit

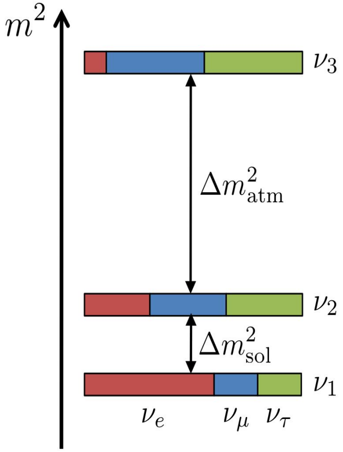
Models that explain observed value of n_s naturally with $\Delta\Phi$ >~ M_P would be excluded

- Give up on inflation?



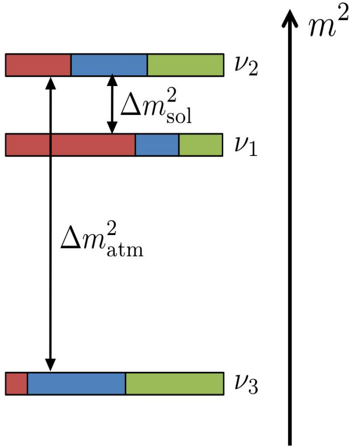
Neutrinos

normal hierarchy (NH)

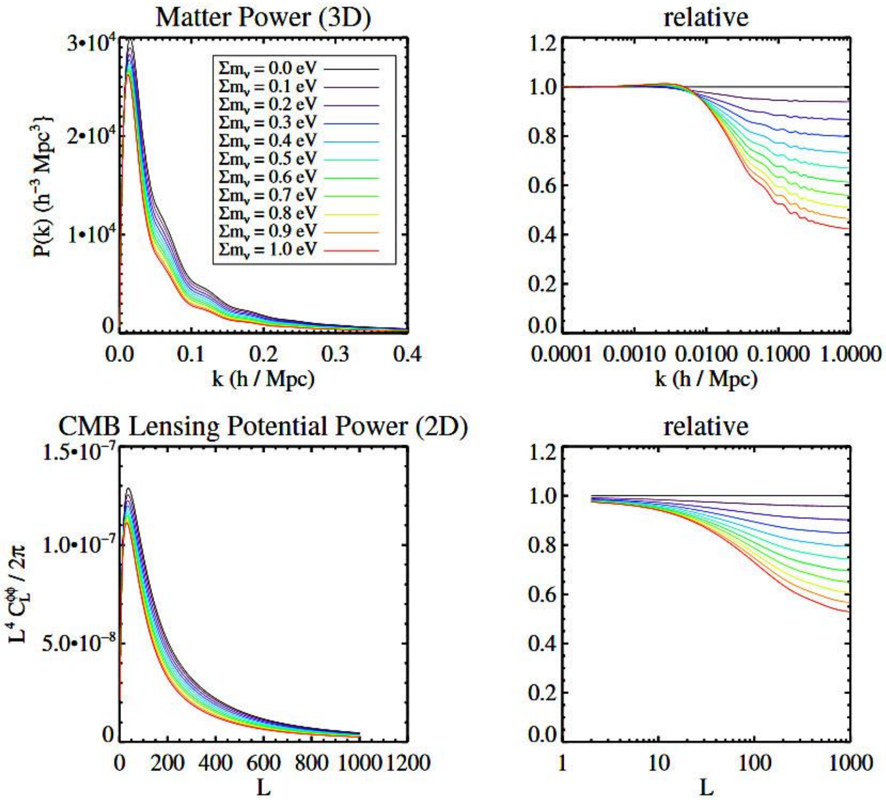


$$\sum m_\nu \gtrsim 58 \text{ meV}$$

inverted hierarchy (IH)



$$\sum m_\nu \gtrsim 105 \text{ meV}$$



Probing Neutrino Mass

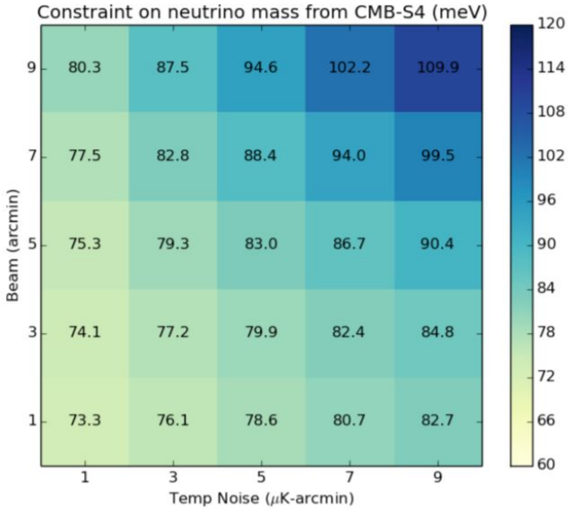
CMB Lensing

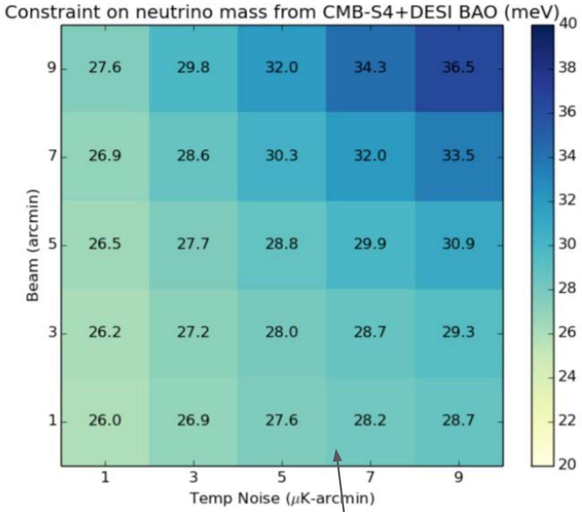
- CMB directly sensitive to matter spectrum, largely free of astrophysical uncertainties
- Challenges: degeneracy with τ at above $l \sim 20$, and with Ω_m (can be broken with DESI BAO expansion history)

Galaxy Cluster Abundance

- Free streaming neutrinos slow growth of structure and suppresses abundance
- Expects nearly mass limited sample (140000 for 1’ resolution)
- Limited by cluster mass estimation (X-ray observations and galaxy-cluster weak lensing can help)
- Synergy with LSST, sensitive to galaxy clusters at different epochs

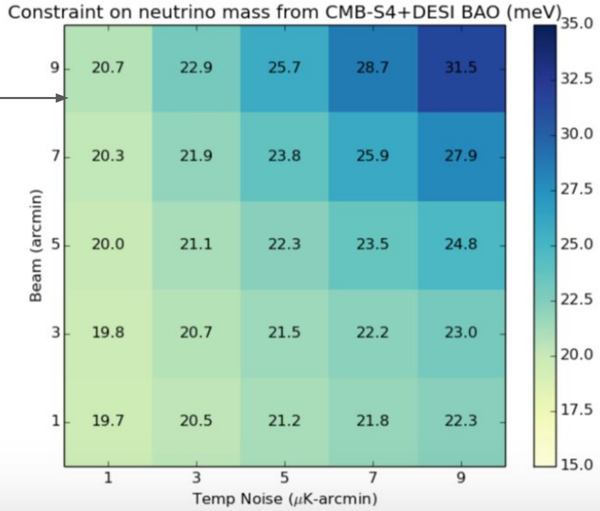
Forecast





Sensitivity caps out ~ 26meV, strongly dependent on τ!

With prior τ = 0.06+/- 0.01



Can expect stronger τ constraints from Stage 3, can push $\sigma(\Sigma m_v) <$ 15meV corresponding to 4σ detection for Σm_v=58meV

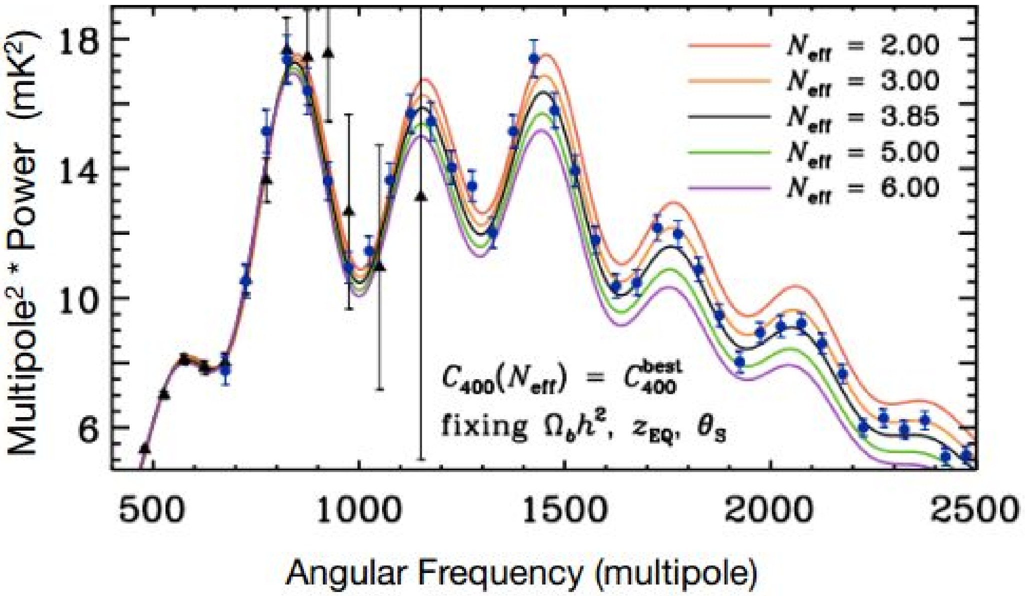
Light Relics

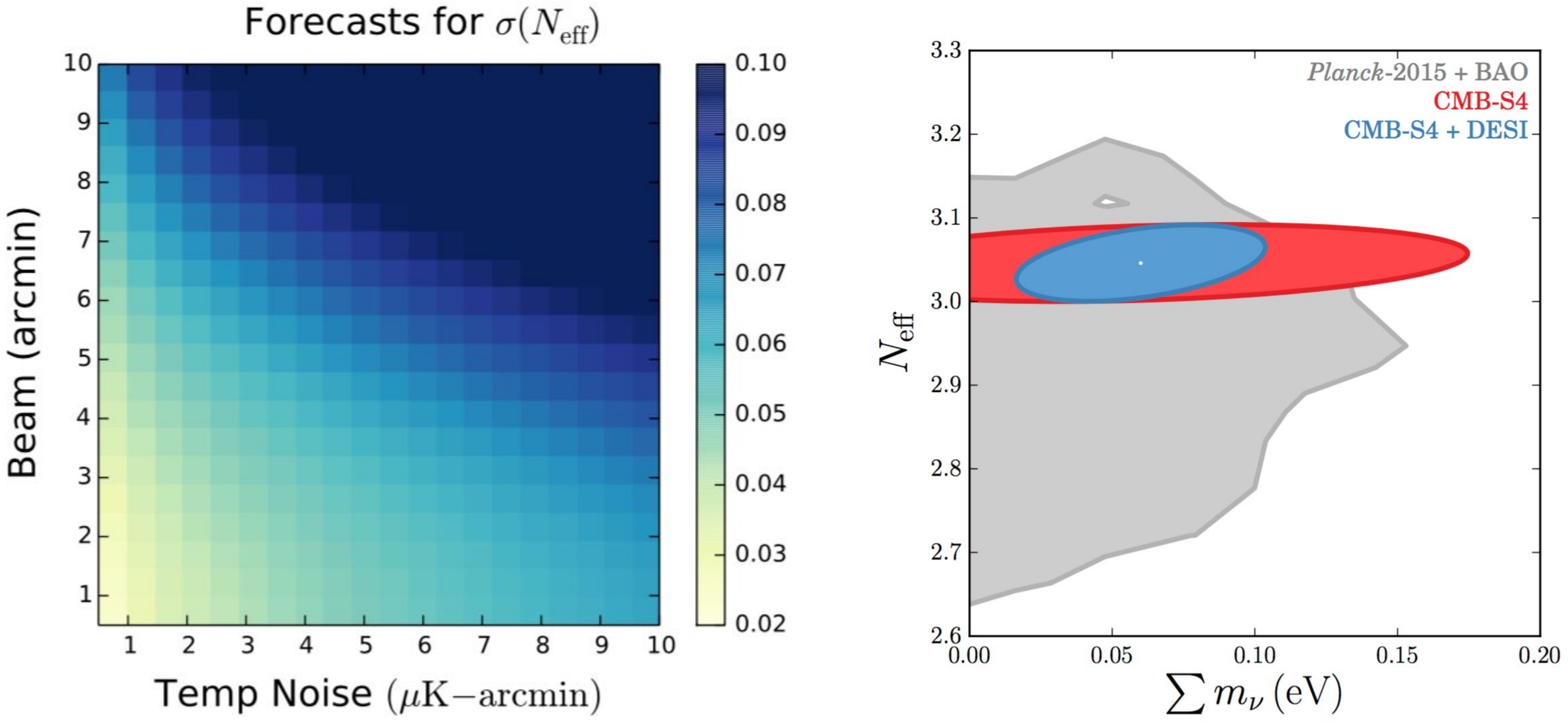
- N_{eff}: total energy density in radiation prior to recombination (SM: N_{eff}=3.046)
  - Measure of the gravitational influence of free streaming radiation that is decoupled from the photon-baryon fluid
- Possible sources of dark radiation: axions, sterile neutrinos, gravitational waves, dark photons, etc.
- $\Delta N_{eff} \geq 0.047$ predicted for models with additional light particles of spin 1/2,1, and/or 3/2
- $\Delta N_{eff} \geq 0.027$ predicted for models with particles of spin 0
- $\sigma(N_{eff}) \sim 0.02$-$0.03$ will probe this at 2σ and 1σ

Observational Signatures

- Change in radiation energy density which controls the expansion and thus the damping tail of power spectrum
- Fluctuations also produces a shift in phase of peaks

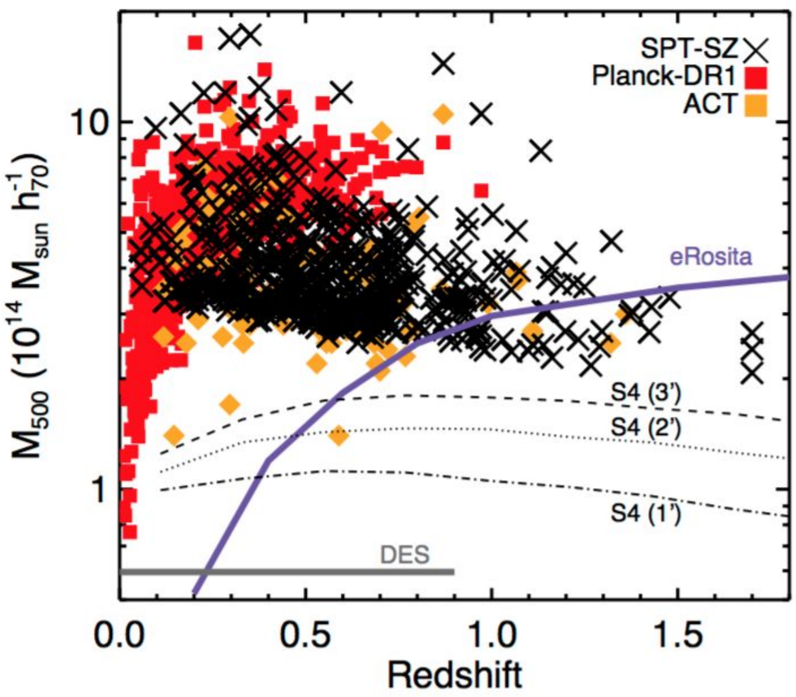
Constraints sensitive to l_{max} (~5000?)

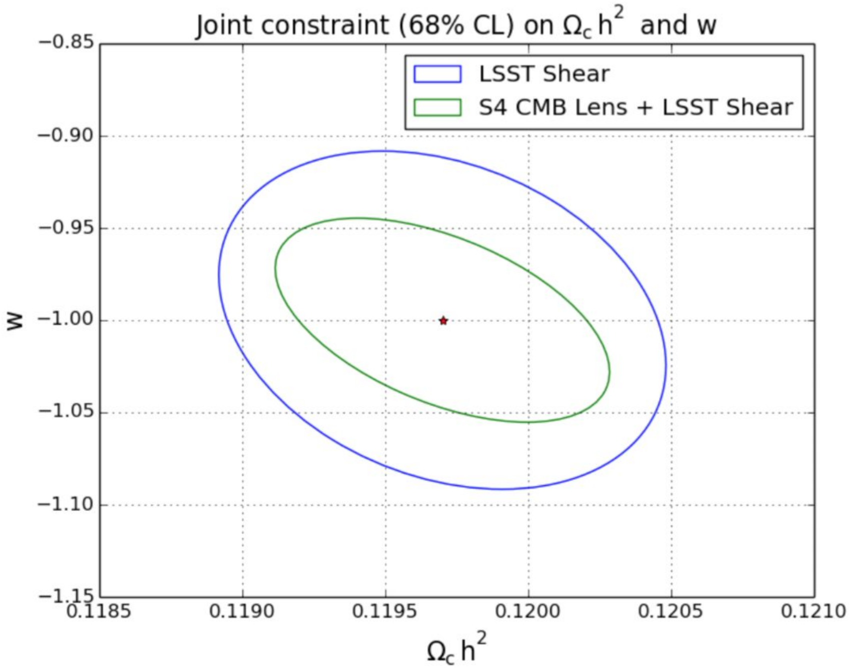




Forecasts for $\sigma(N_{\rm eff})$
Beam (arcmin)
Temp Noise (μK$-$arcmin)
Planck-2015 + BAO
CMB-S4
CMB-S4 + DESI
$N_{\rm eff}$
$\sum m_\nu$ (eV)

Dark Energy





~ 140000 clusters for 1’

Photon noise limited

NEP = $6 \times 10^{-17} W^2/(Hz)^{½}$

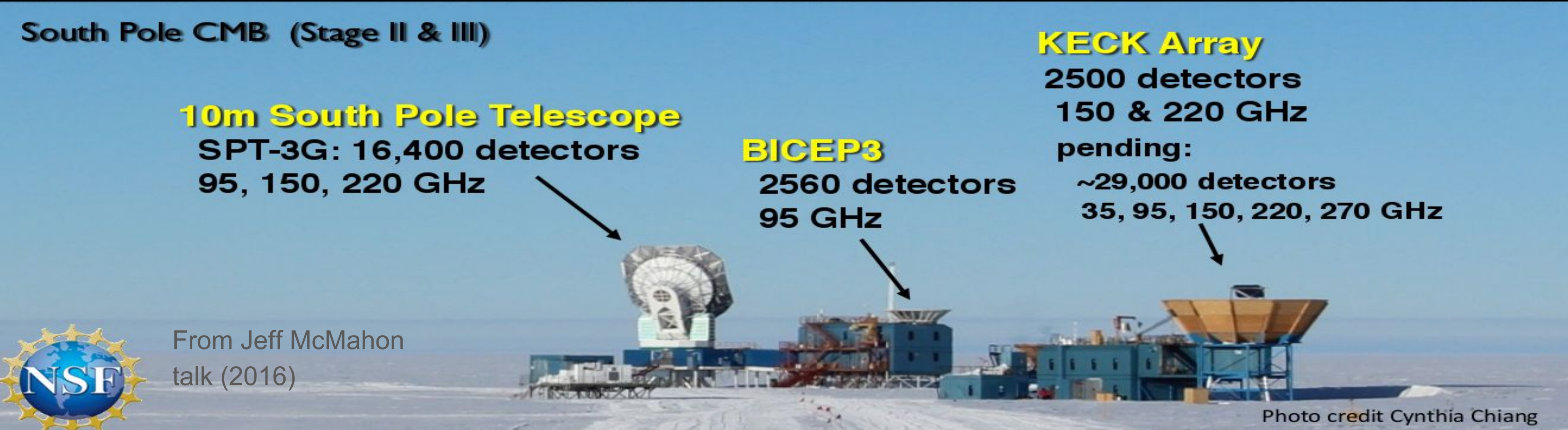
NET ~ $300 uK\ s^{1/2}$

Assume temperature noise of 3 nK deg, 4 year survey with 25% efficiency, f_{sky} ~ 0.05

$N_{bolo} = (300 uK\ s^{1/2}/0.003\ uK\ deg)^2 \times (2000\ deg^2/3 \times 10^7 s) \sim 5 \times 10^5$ bolometers needed

Years	Stage	Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015–2016	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	0.15eV (Boss BAO prior)	~180 (DES+BOSS SPT clusters)
2017–2020	Stage 3 10,000 detectors	10^{-6}	0.006	0.06	0.06eV (Boss BAO prior)	~300-600 (DES + DESI SZ Clusters)
2021–2023, **Target**	Stage 4 CMB-S4 ~500,000 detectors	**10^{-8}**	**0.0005**	**0.027**	**0.015eV** (DESI BAO $+\tau_e$ prior)	**1250** (DESI +LSST S4 Clusters)


Atacama CMB (Stage II & III)
CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz
Simons Array
(Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz
ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz
Photo: Rahul Datta & Alessandro Schillaci


South Pole CMB (Stage II & III)
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz
BICEP3
2560 detectors
95 GHz
KECK Array
2500 detectors
150 & 220 GHz
pending:
~29,000 detectors
35, 95, 150, 220, 270 GHz
NSF
From Jeff McMahon
talk (2016)
Photo credit Cynthia Chiang

Current status

- Fleshing out CMB-S4 Instrumentation Book. What could we do to achieve the goals from Science Book?
- Figuring out how to control systematics, especially removing foreground
- Start building telescopes and detectors