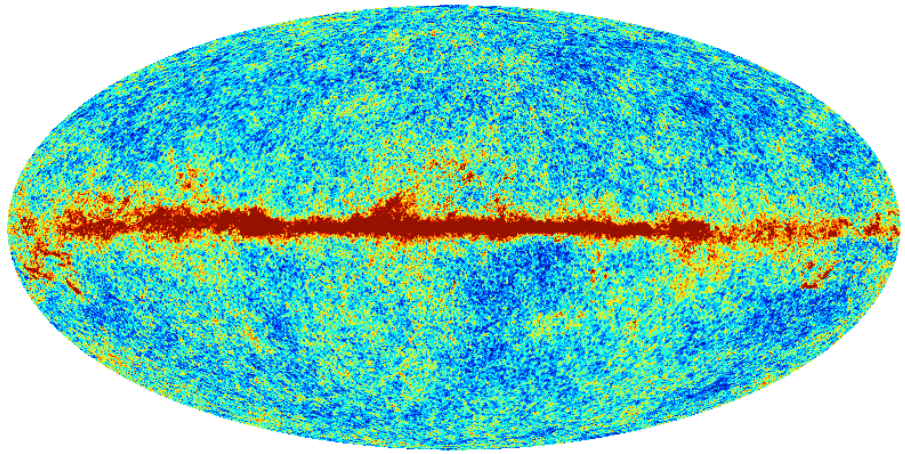
Future Prospects in Cosmology

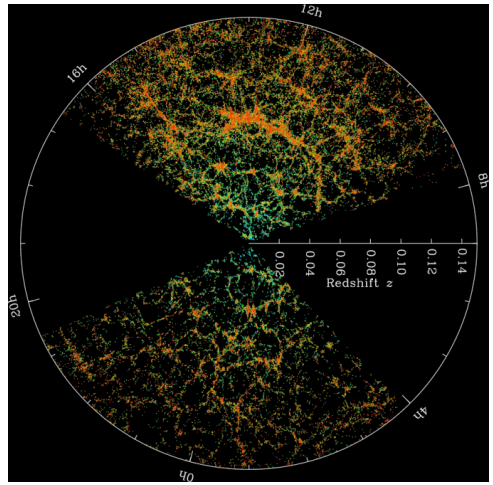
Raphael Flauger

Dark Interactions 2016, BNL, October 7, 2016

Current Status

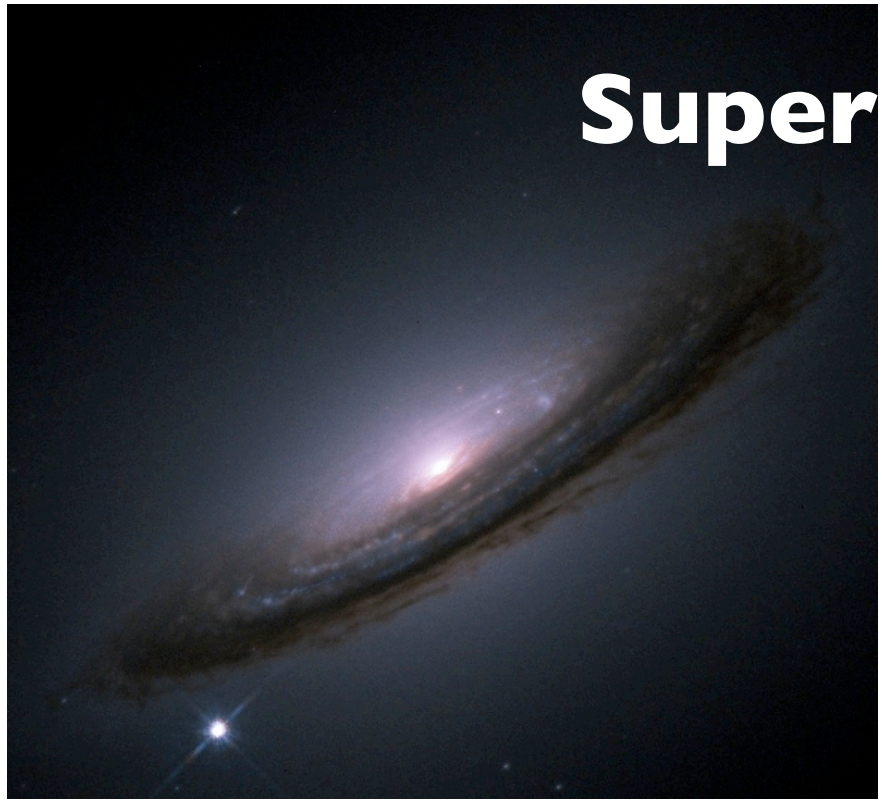
Current Status



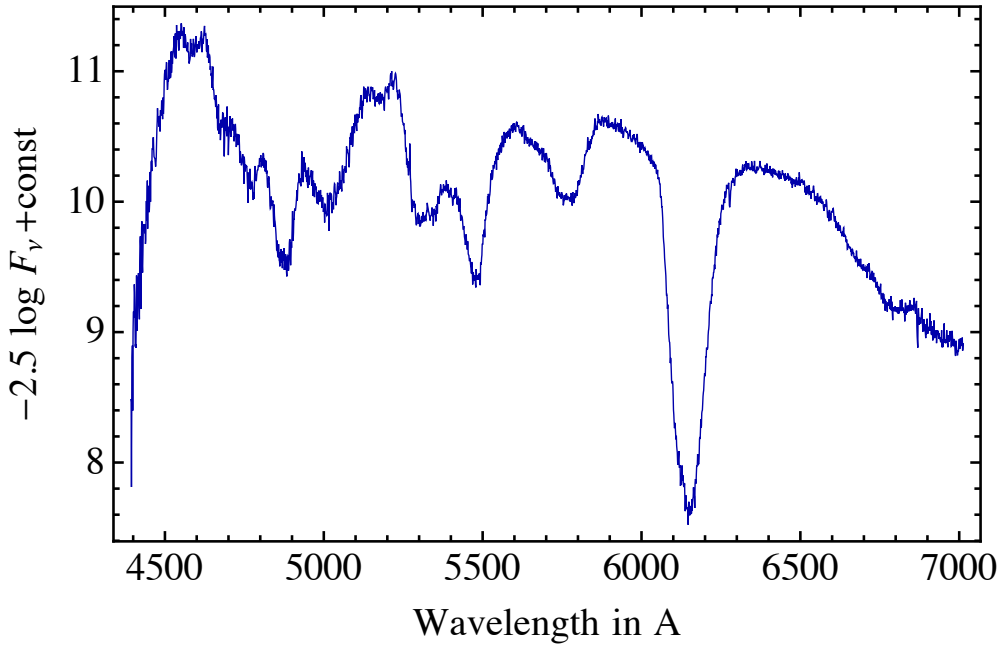


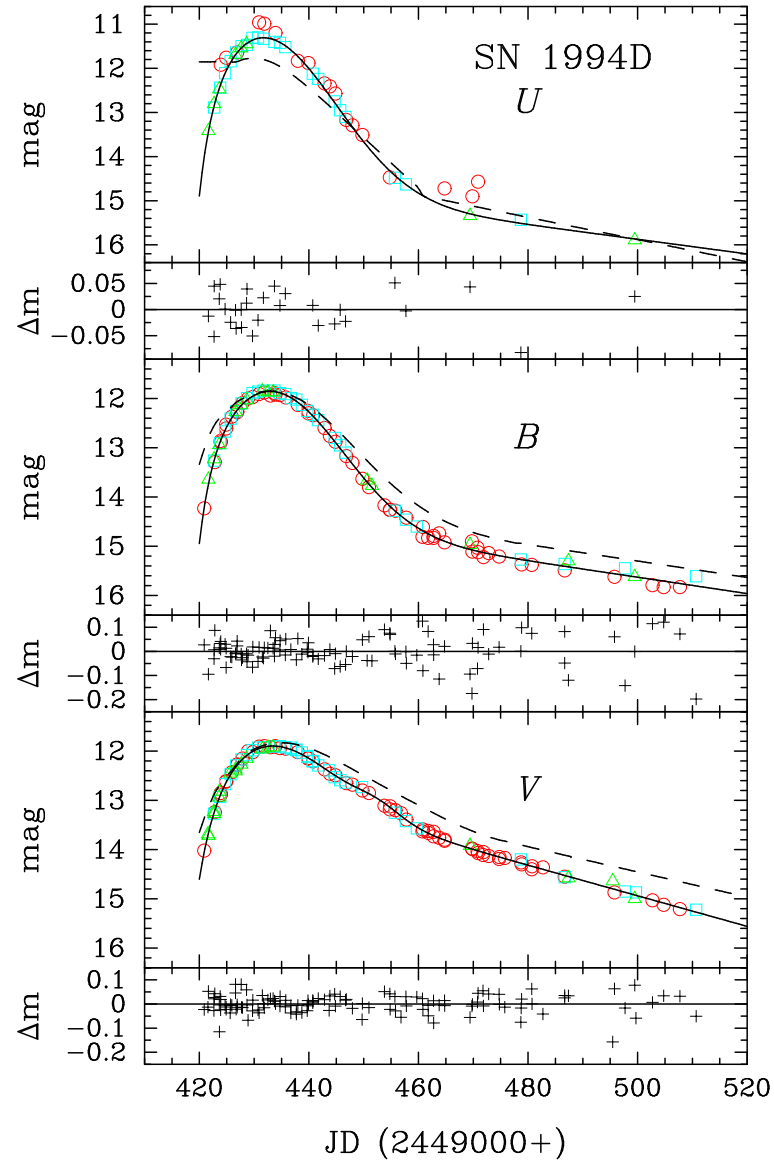
Observations of supernovae, cosmic microwave background, and galaxy redshift surveys are in good agreement with the simple six-parameter LCDM model.

Supernovae



(Vacca et al. 1996)





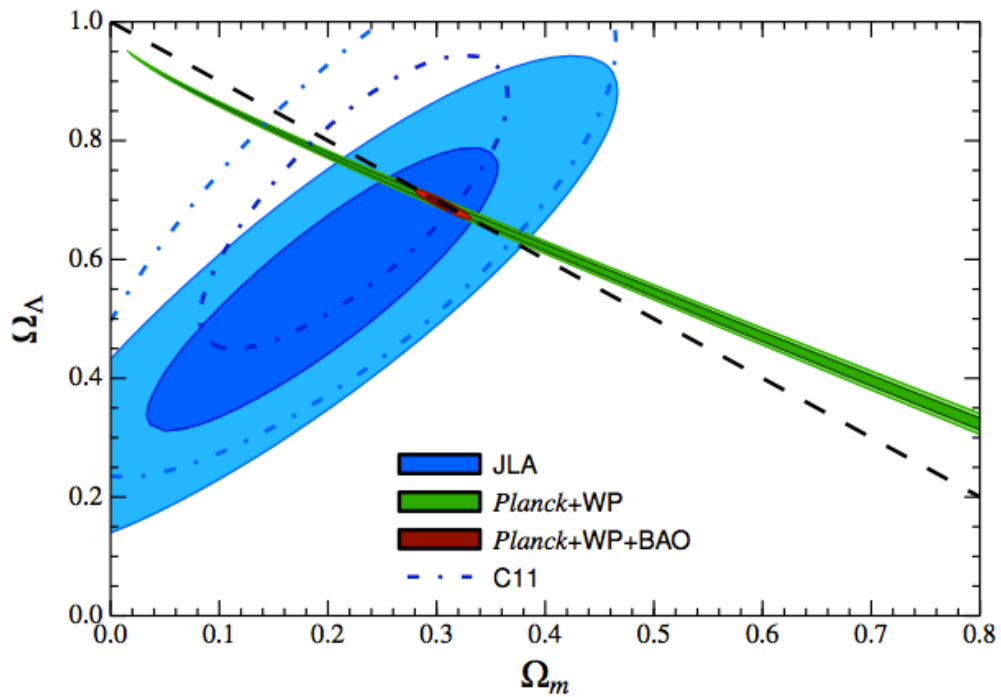
Supernovae

Provide measurement of

- Hubble rate

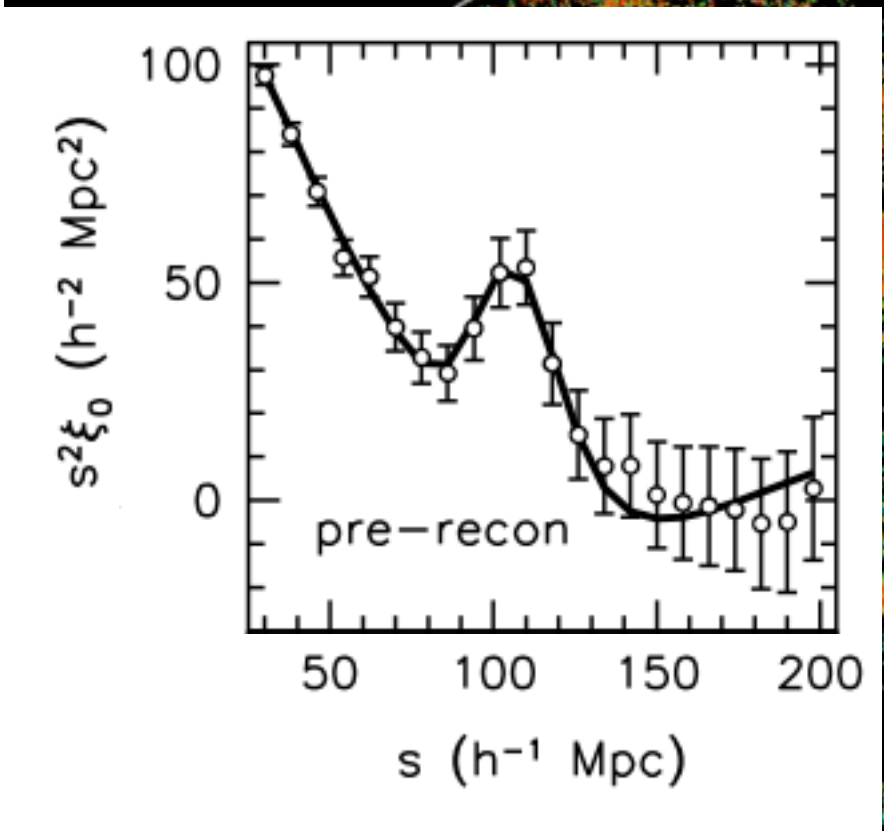
$$H_0 = 73.24 \pm 1.74 \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$$ **(Riess et al. 2016)**

- functional relation between luminosity distance and redshift

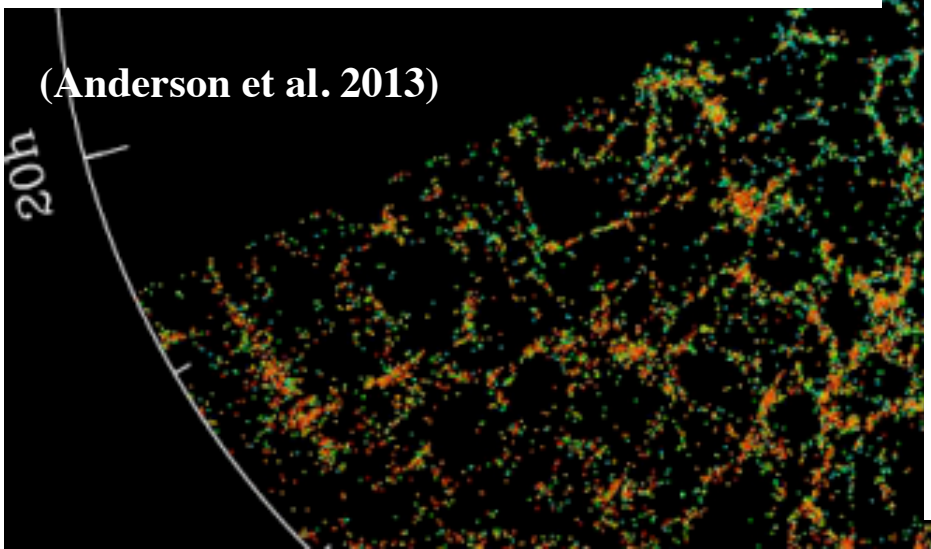


(Betoule et al. 2014)

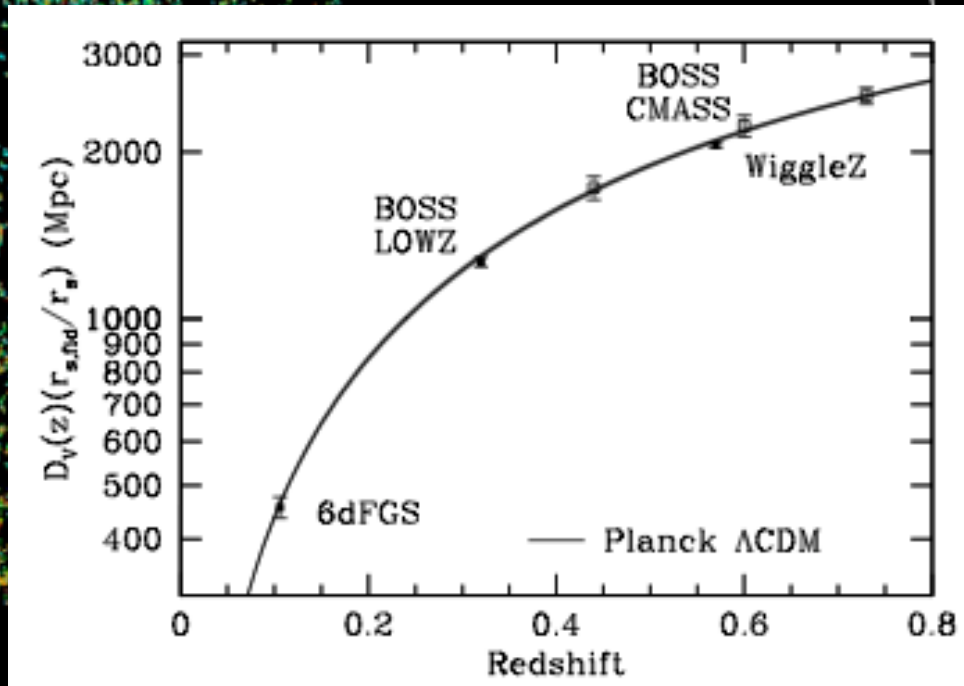
Baryon Acoustic Oscillations



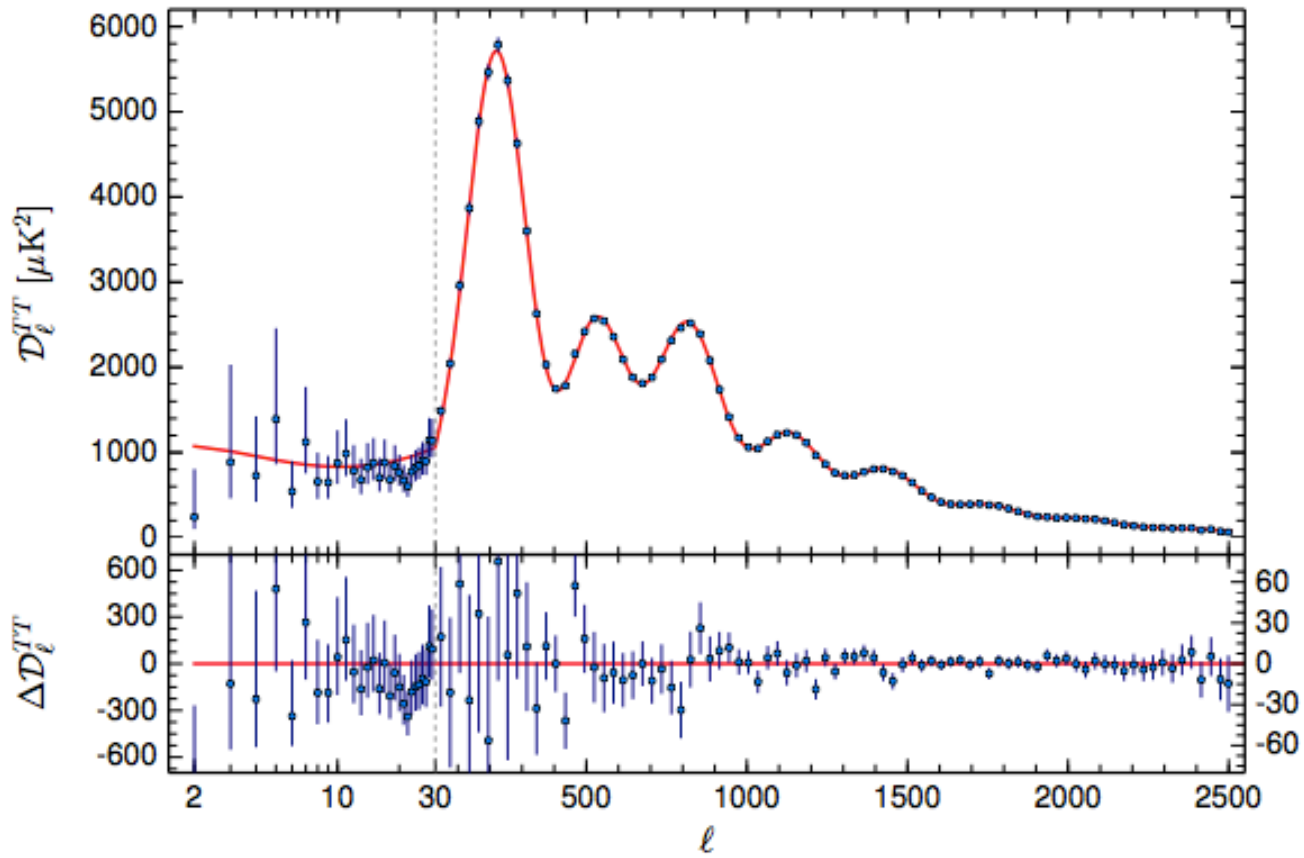
(Anderson et al. 2013)

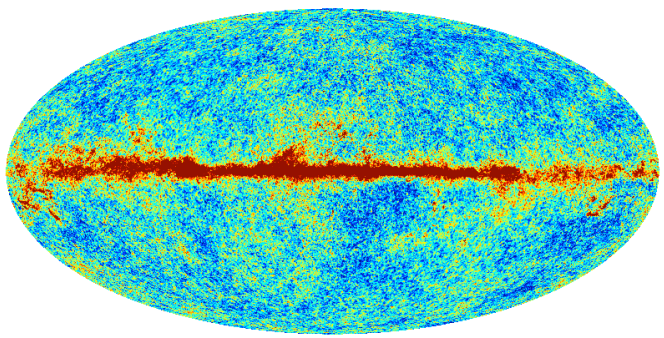


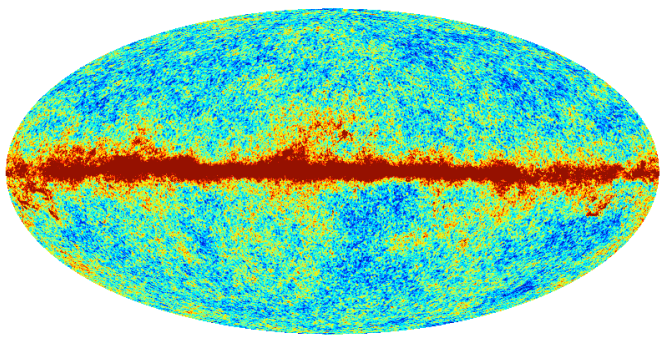
(Anderson et al. 2013)

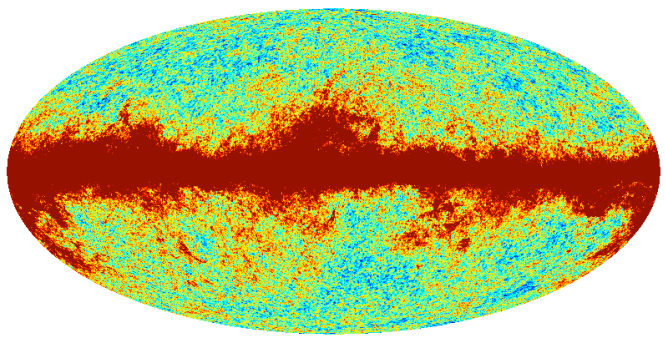


Cosmic Microwave Background





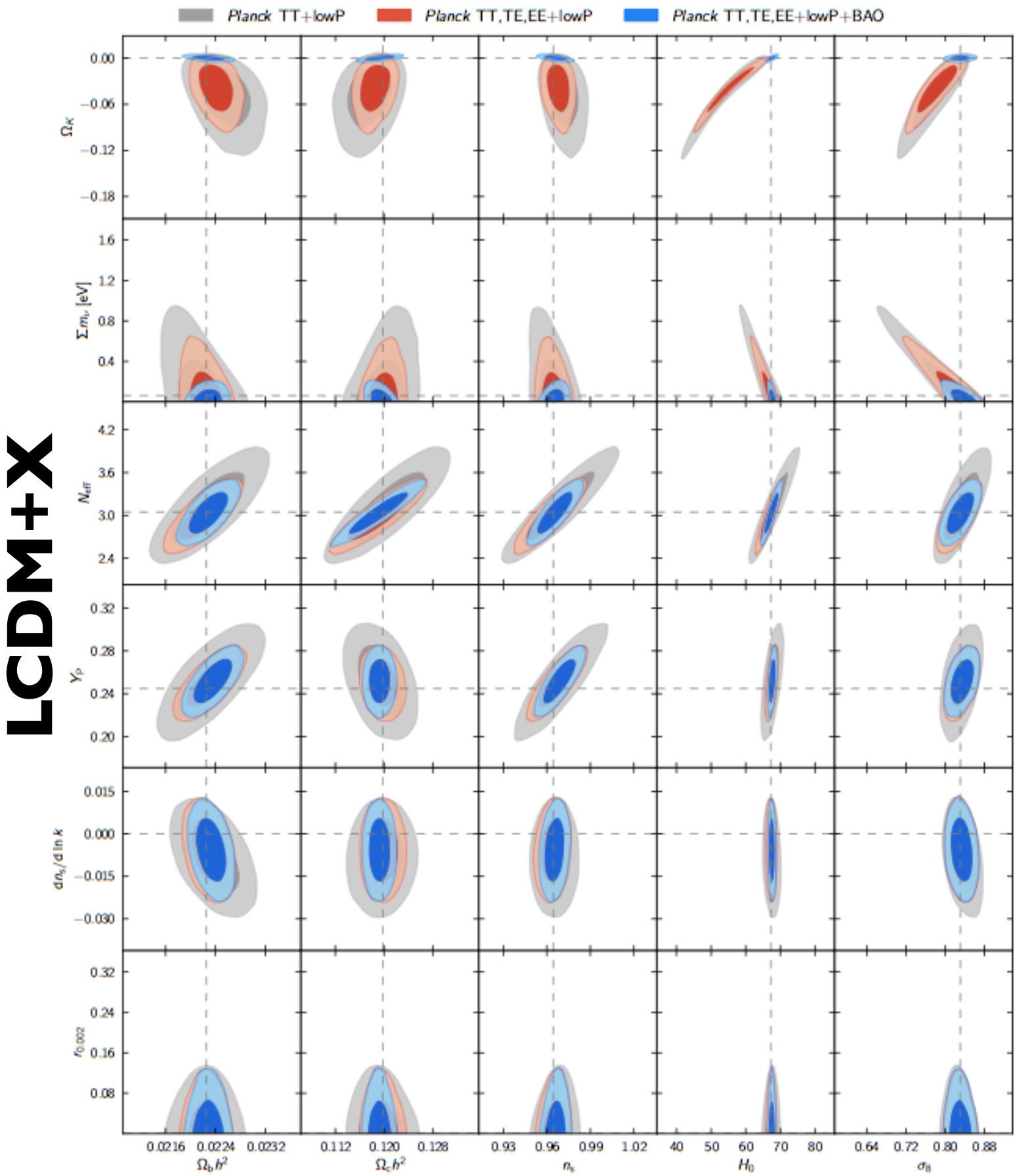




Parameter Constraints

Parameter	2015F(CHM)	2015F(CHM) (Plik)
$100\theta_{\rm MC}$	1.04094 ± 0.00048	1.04086 ± 0.00048
$\Omega_b h^2$	0.02225 ± 0.00023	0.02222 ± 0.00023
$\Omega_c h^2$	0.1194 ± 0.0022	0.1199 ± 0.0022
H_0	67.48 ± 0.98	67.26 ± 0.98
$n_{\rm s}$	0.9682 ± 0.0062	0.9652 ± 0.0062
$\Omega_{\rm m}$	0.313 ± 0.013	0.316 ± 0.014
σ_8	0.829 ± 0.015	0.830 ± 0.015
τ	0.079 ± 0.019	0.078 ± 0.019
$10^9 A_{\rm s} e^{-2\tau}$	1.875 ± 0.014	1.881 ± 0.014

(Ade et al. 2015)

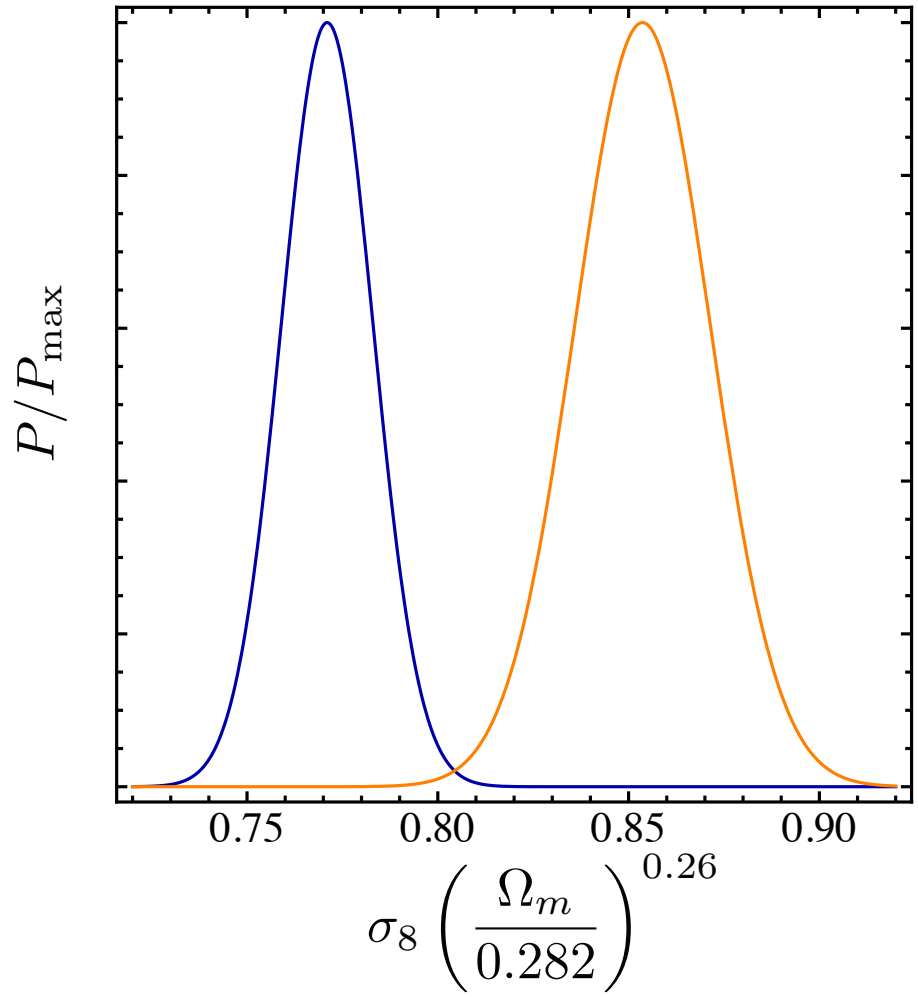


LCDM+X

Clustering

tSZ power spectrum
(Hill, Spergel 2013)

Planck 2015 TT+lowP
Paper XIII

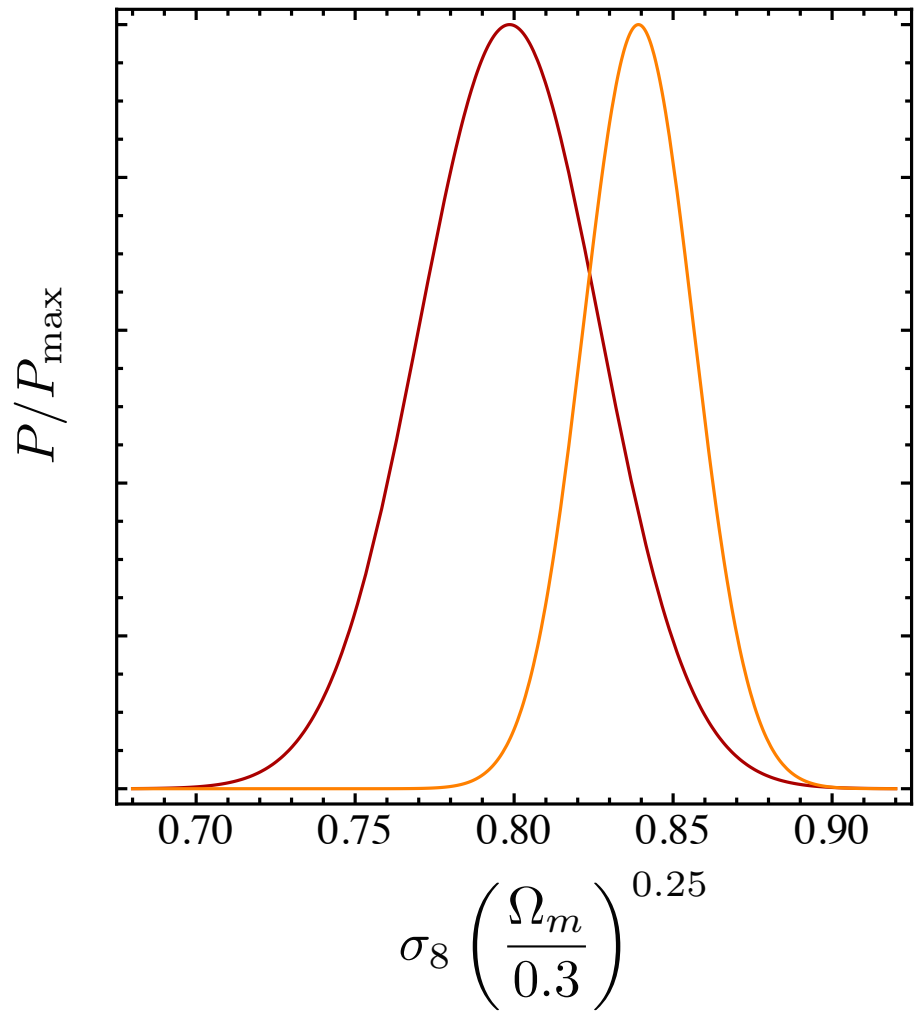


- Small tensions exist between the Planck TT data and a number of low redshift observations

Clustering

Planck 2015 TT+lowP

Planck 2015 lensing



- A milder tension also exists between Planck lensing and cosmology predicted by Planck TT

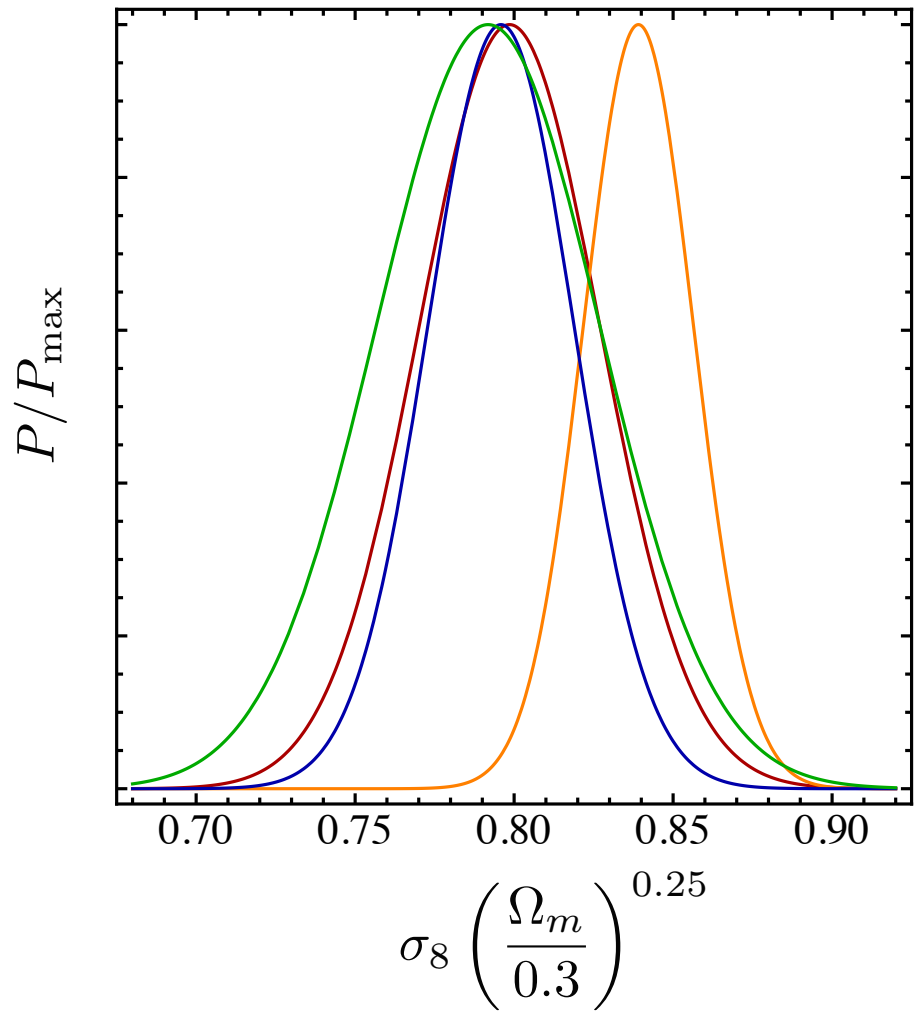
Clustering

Planck 2015 TT+lowP

Planck 2015 lensing

Planck 2015 TE+lowEB

Planck 2015 EE+lowEB



- Both Planck TE and Planck EE cosmologies in excellent agreement with Planck lensing

The Hubble Constant

Reid et al. 2013

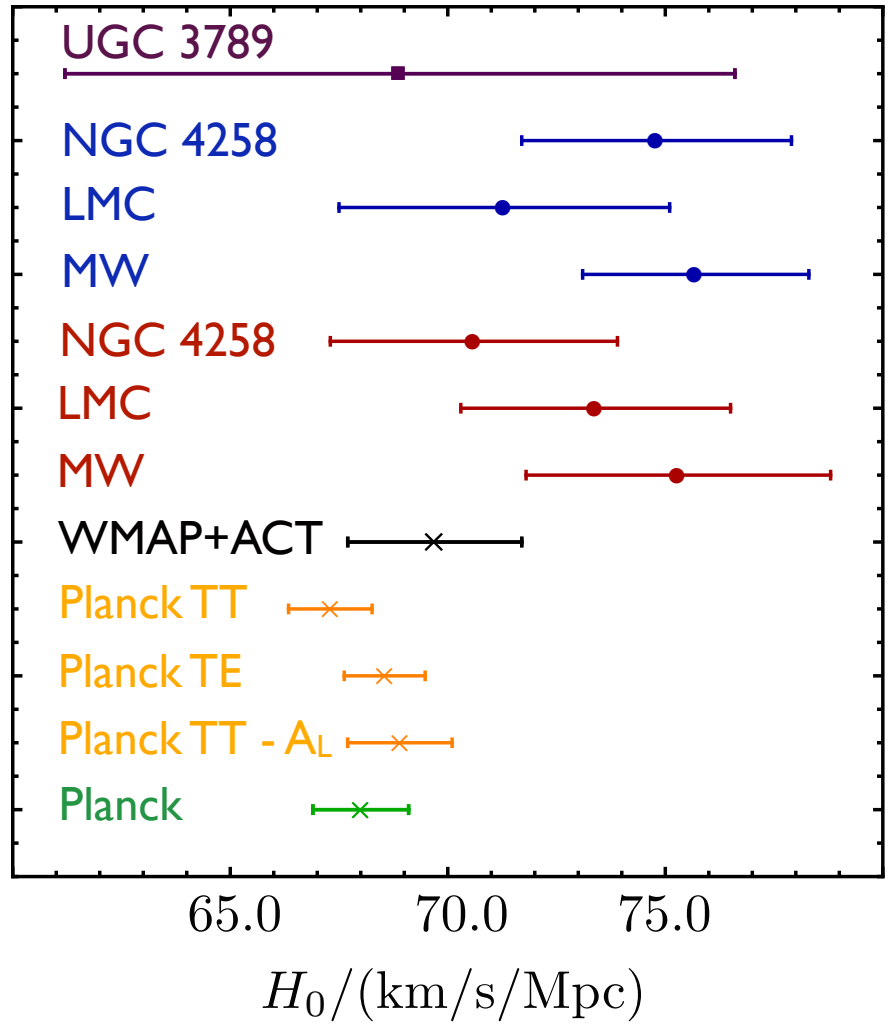
Riess et al. 2011

Efstathiou 2013

Hinshaw et al. 2013

Ade et al. 2015

Spergel, Flauger, Hlozek 2013



The Hubble Constant

Reid et al. 2013

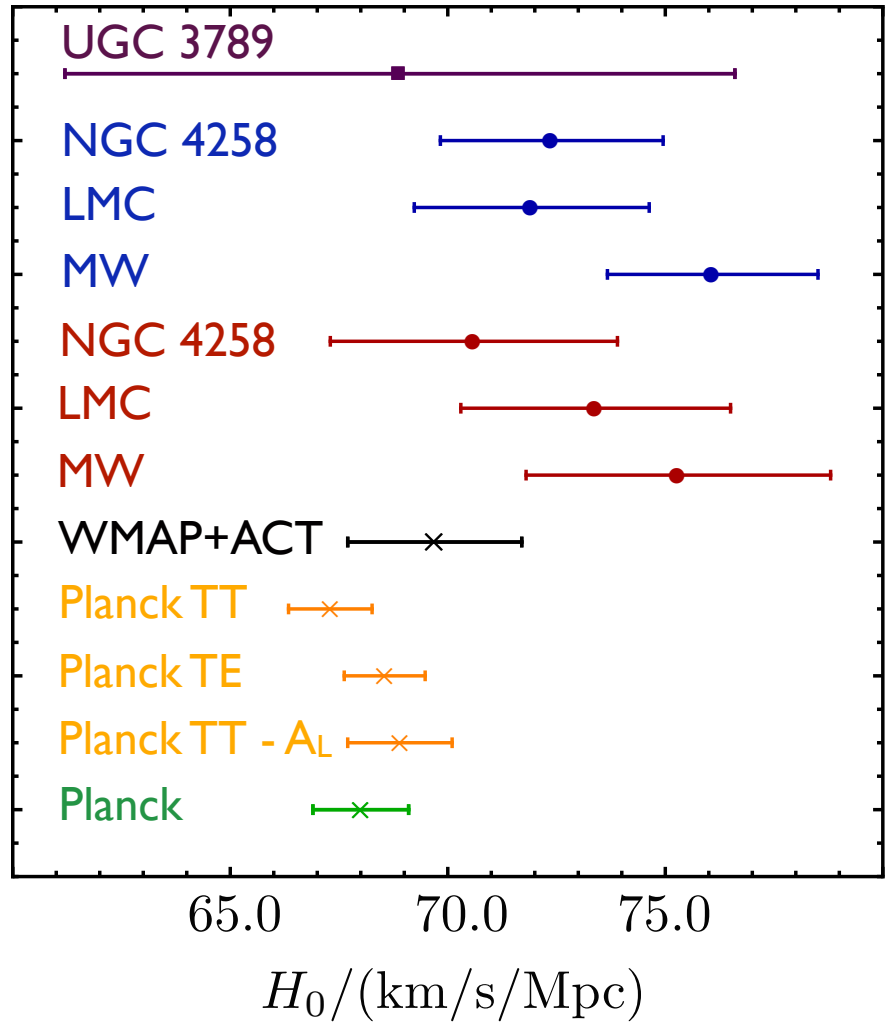
Riess et al. 2016

Efstathiou 2013

Hinshaw et al. 2013

Ade et al. 2015

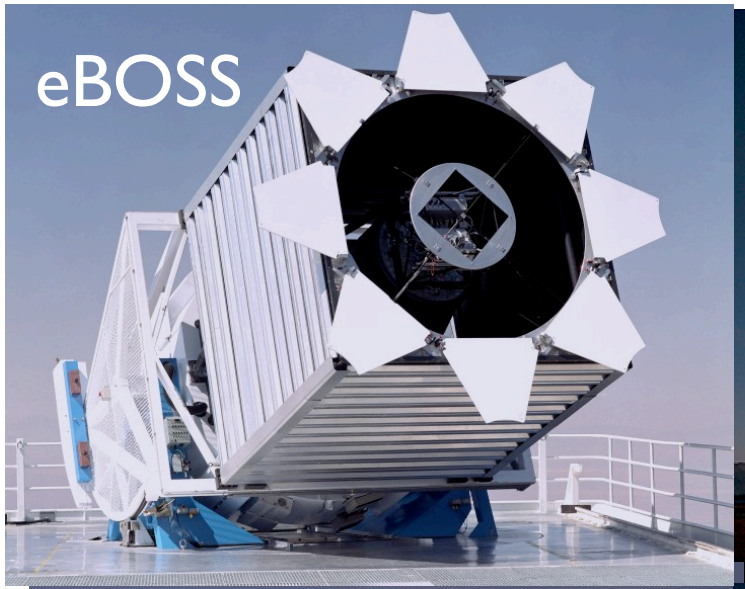
Spergel, Flauger, Hlozek 2013

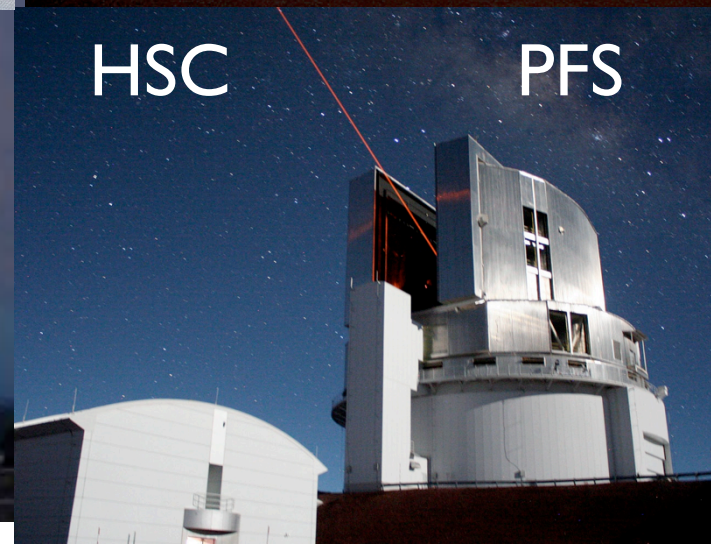


Upcoming and Future Experiments

Cosmic Surveys

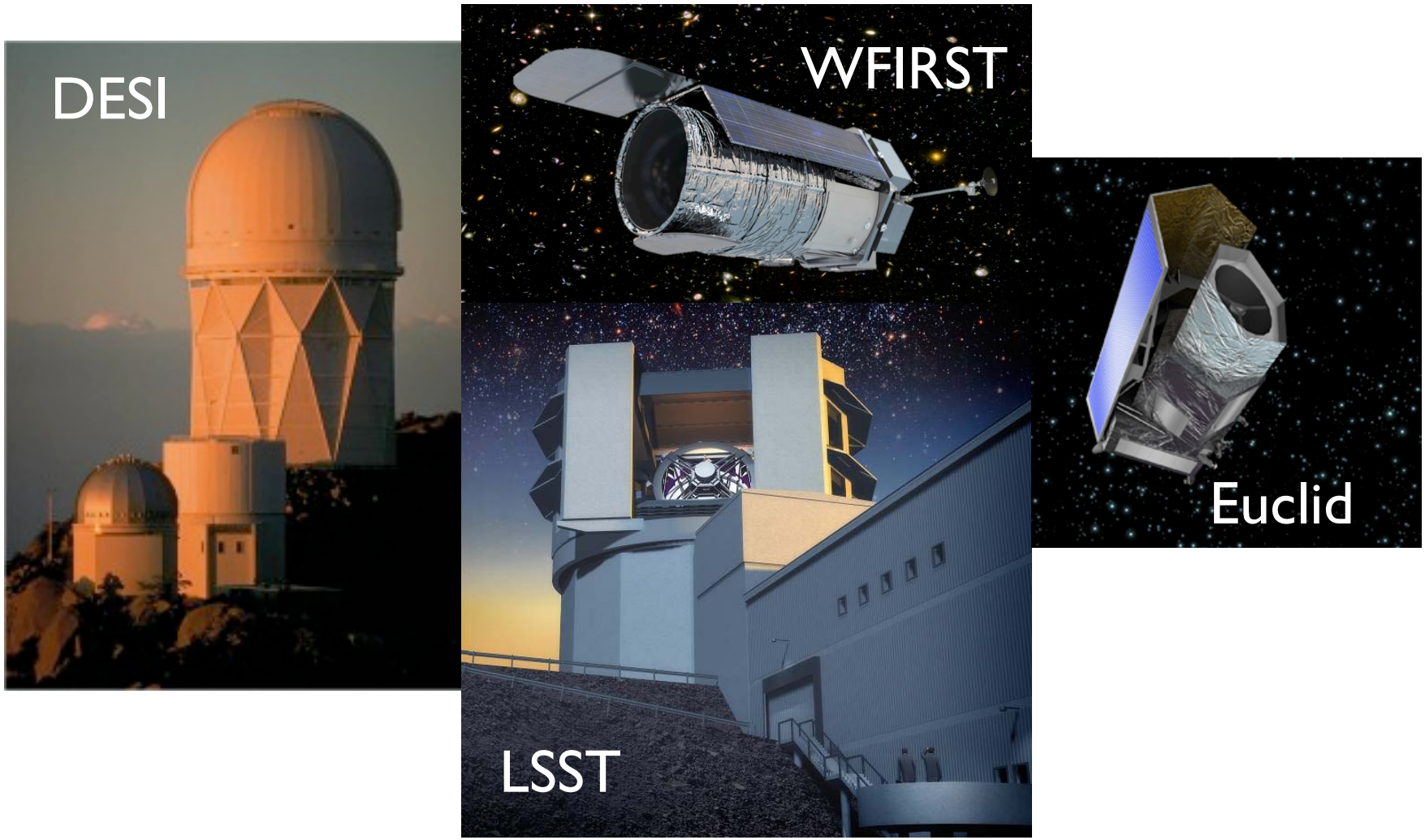
Stage III: now-2020





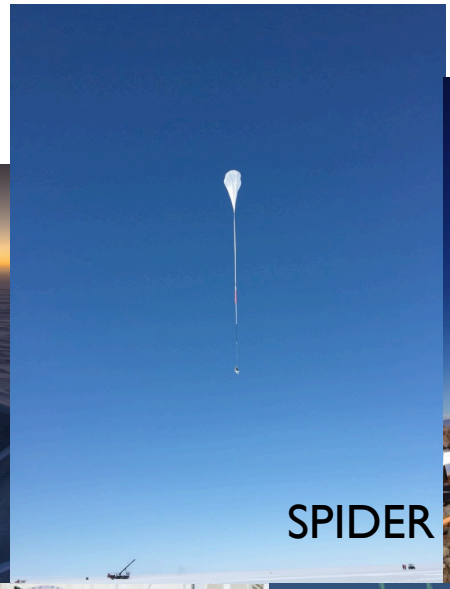
Cosmic Surveys

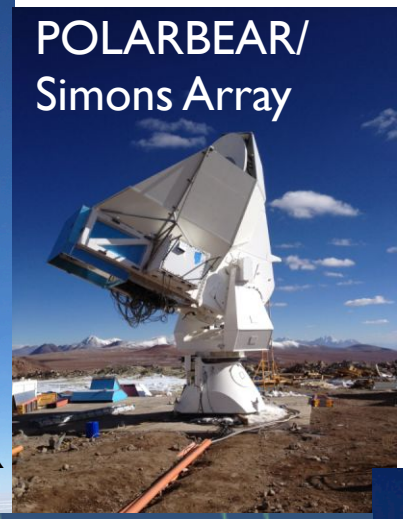
Stage IV: 2020-2030

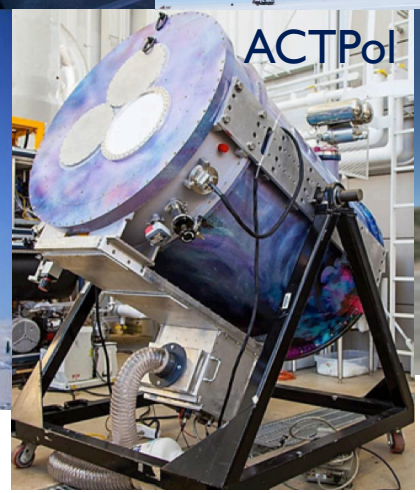


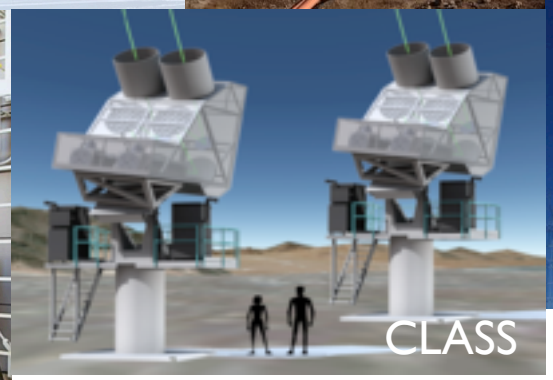
Cosmic Microwave Background

Stage III: now-2020









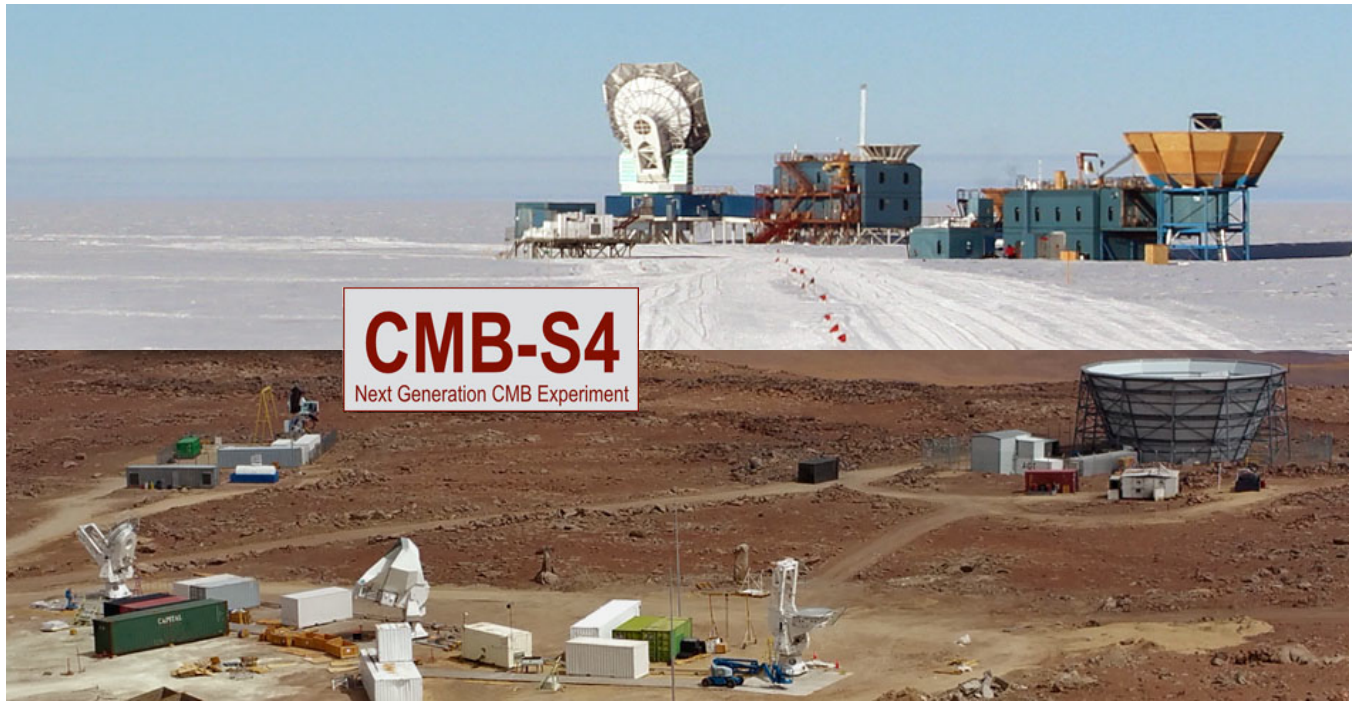
Cosmic Microwave Background

Stage III.5: soon-2020

BERKELEY LAB CONICYT Ministerio de Educación HEISING-SIMONS FOUNDATION NSF Penn University of Pennsylvania PRINCETON UNIVERSITY SIMONS FOUNDATION UNIVERSITY OF CALIFORNIA BERKELEY 1868 UNIVERSITY OF CALIFORNIA SAN DIEGO W

Cosmic Microwave Background

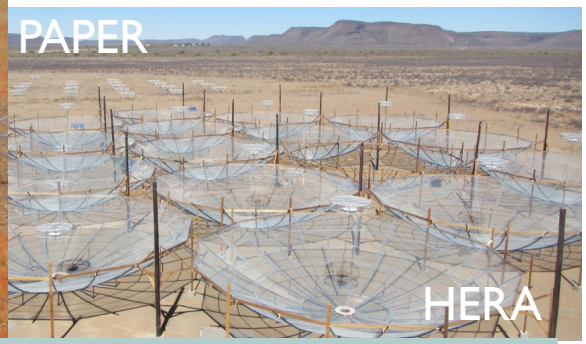
Stage IV: 2020-2030



Potentially Space Missions

LiteBIRD, PIXIE, COrE

Radio Interferometers



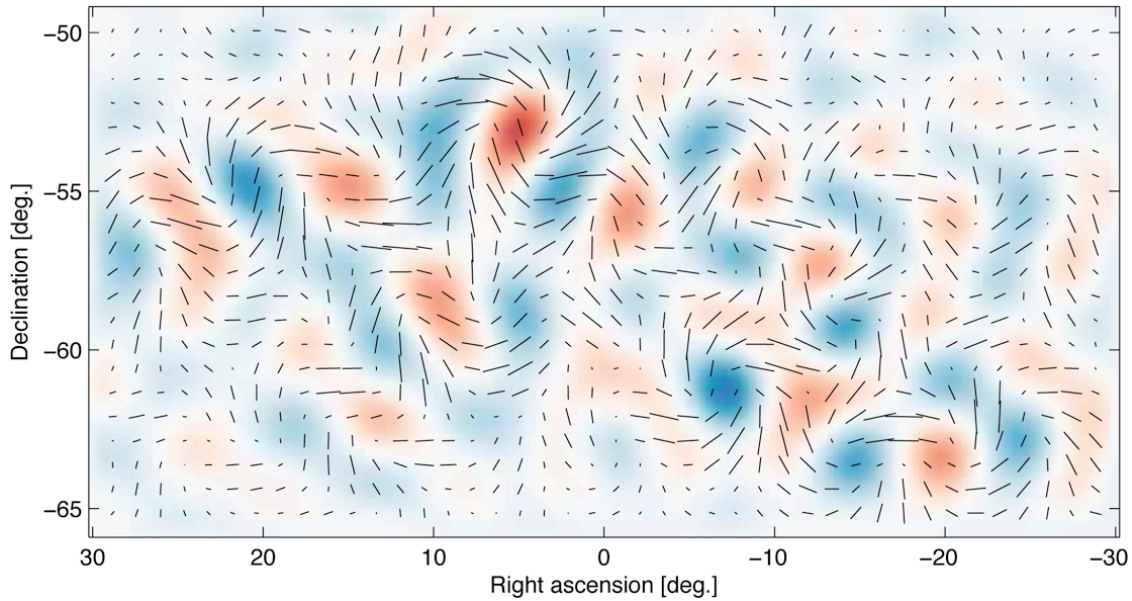
Future Prospects

Future Prospects

For this workshop, perhaps the most interesting topics are

- Primordial gravitational waves
- Light dark sector relics
- Neutrino mass
- Dark matter

Primordial B-modes



Detection of primordial B-modes would provide a measurement of the Hubble rate during inflation

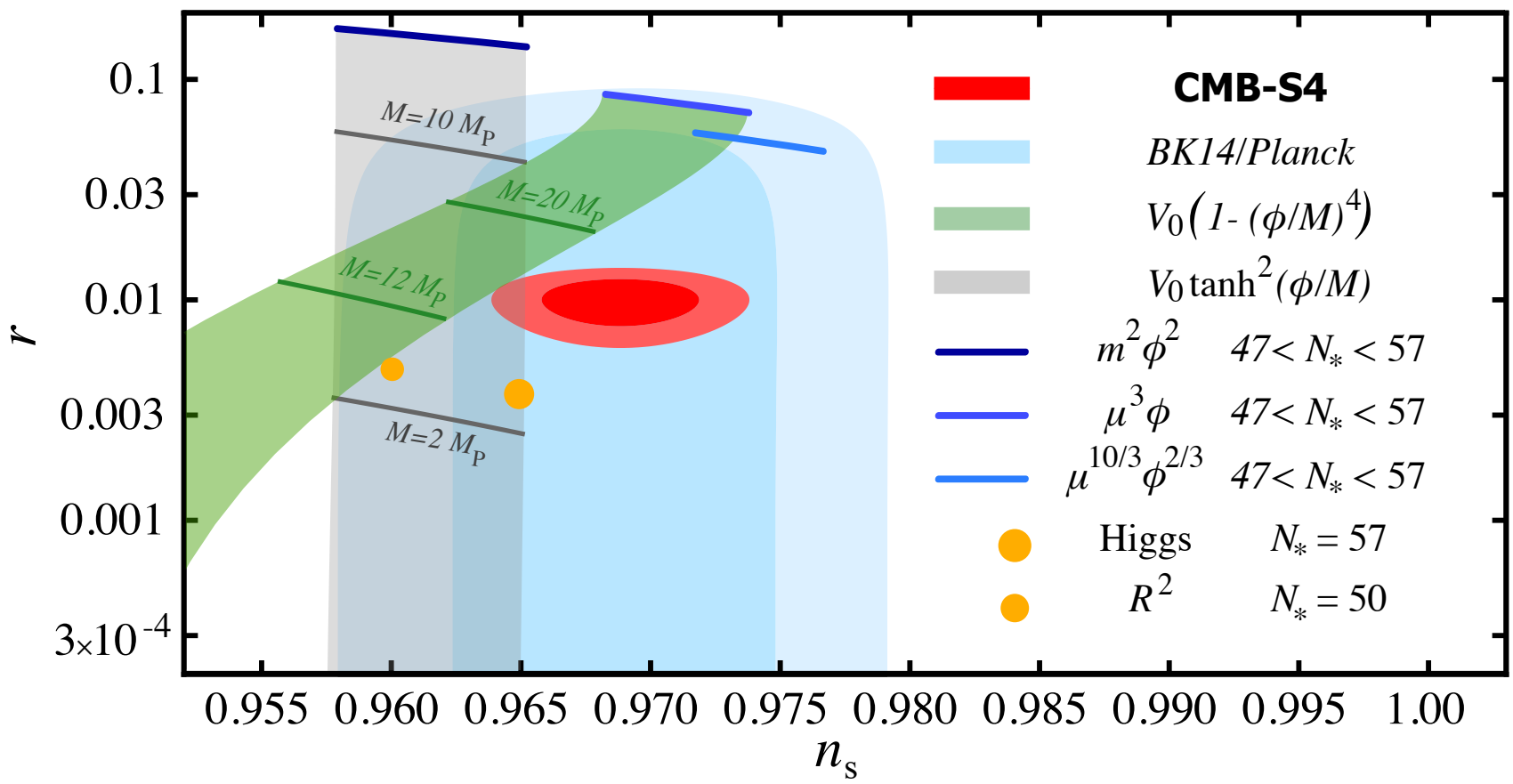
and via the Friedmann equation

$$V_{\rm inf}^{1/4} = 1.04 \times 10^{16}\,{\rm GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

Primordial B-modes

CMB-S4 could detect r=0.01 at high significance

CMB-S4 Science Book (http://www.cmbs4.org)



Primordial B-modes

Even an upper limit from CMB-S4 is interesting

If the inflationary model naturally explains the observed value of the spectral index, i.e.

$$n_{\rm s}(\mathcal{N}) - 1 = -\frac{p+1}{\mathcal{N}}$$

then the inflationary part of the potential is either

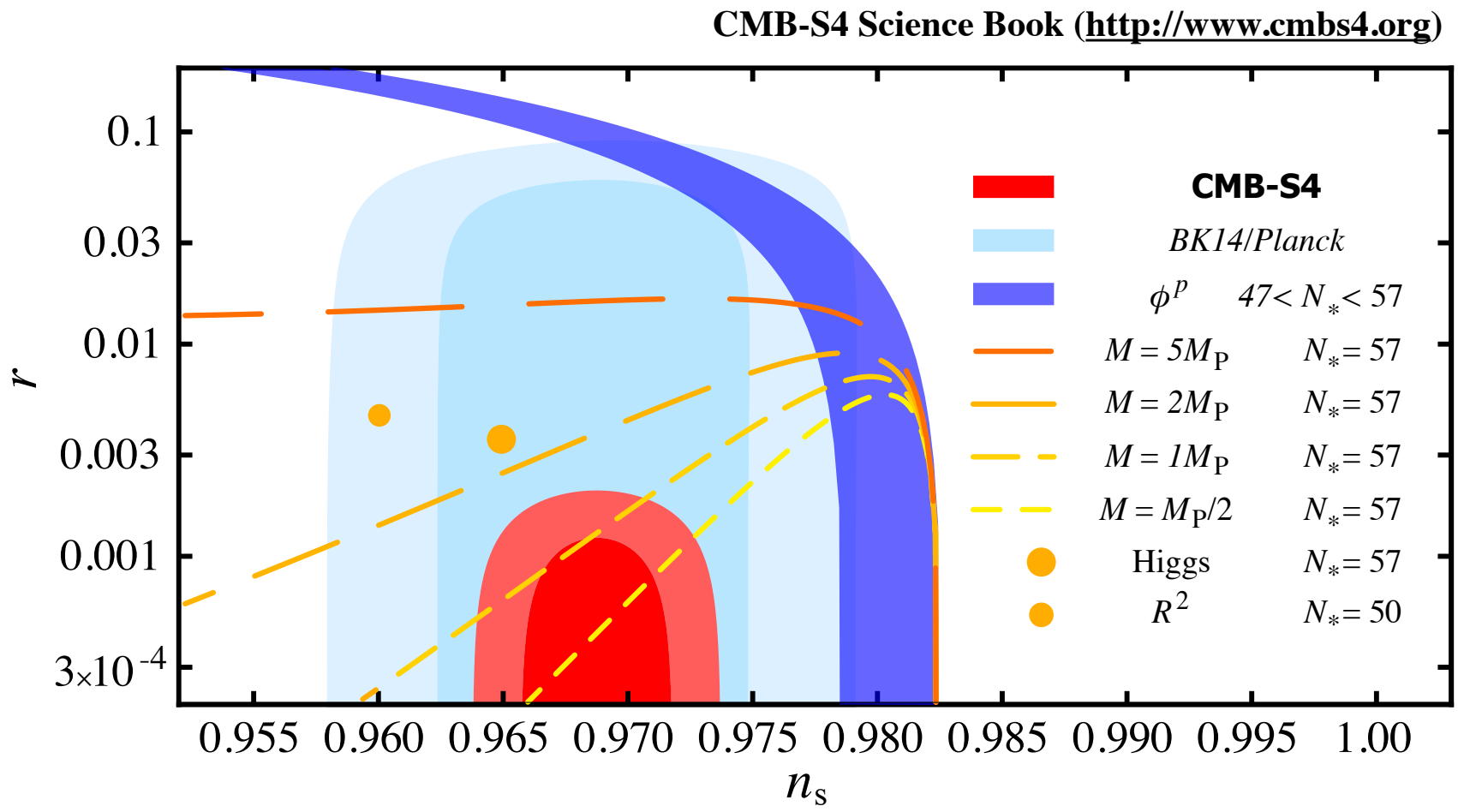
$$V(\phi) = \mu^{4-2p}\phi^{2p}$$

or

$$V(\phi) = V_0 \exp\left[-\left(\frac{\phi}{\Lambda}\right)^{\frac{2p}{p-1}}\right] \qquad (p \neq 1)$$

The characteristic scale in latter case is $M = \Lambda\dfrac{|1-p|}{p}$

Primordial B-modes



An upper limit with CMB-S4 would disfavor all models of inflation that naturally explain $n_{\rm S}$ with super-Planckian characteristic scale M

Light Relics

Light Relic

Particle that is stable on cosmological time scales and light enough to be relativistic at recombination

Contribute to the energy density in radiation

$$\rho_{\rm rad} = \frac{\pi^2 k_{\rm B}^4}{15\hbar^3 c^3}\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] T_\gamma^4$$

with $N_{\rm eff} = 3.046$ in the Standard Model

Light Relics

The CMB is sensitive to $N_{\rm eff}$ through

- the damping tail
- the phase of accoustic oscillations
- lensing

A detection of $\Delta N_{\rm eff} = N_{\rm eff} - 3.046 \neq 0$ would indicate physics beyond the Standard Model or a non-standard cosmology.

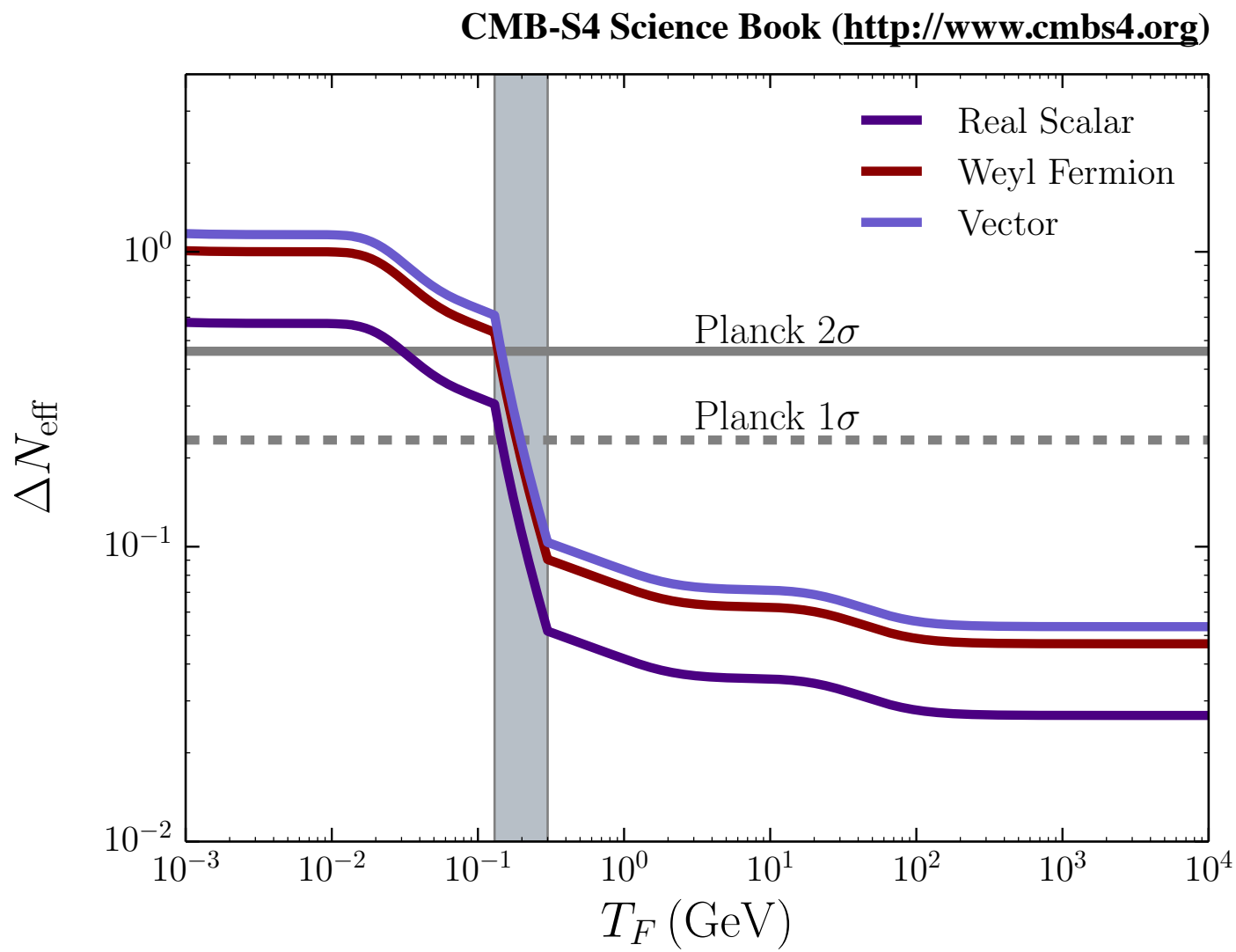
Light Relics

Many well-motivated models addressing open problems in particle physics lead to light relics

- Axions (spin-0)
- Sterile/Dark sector neutrinos (spin-1/2)
- Dark radiation (spin-1)
- Gravitinos (spin-3/2)

Light Relics

Contribution to $\Delta N_{\rm eff}$ from scalars, fermions, vectors that were in thermal equilibrium with the Standard Model and decoupled at T_F



Light Relics

Natural targets:

- Spin-1/2, 1, 3/2 particles predict*

$$\Delta N_{\rm eff} \geq 0.047$$

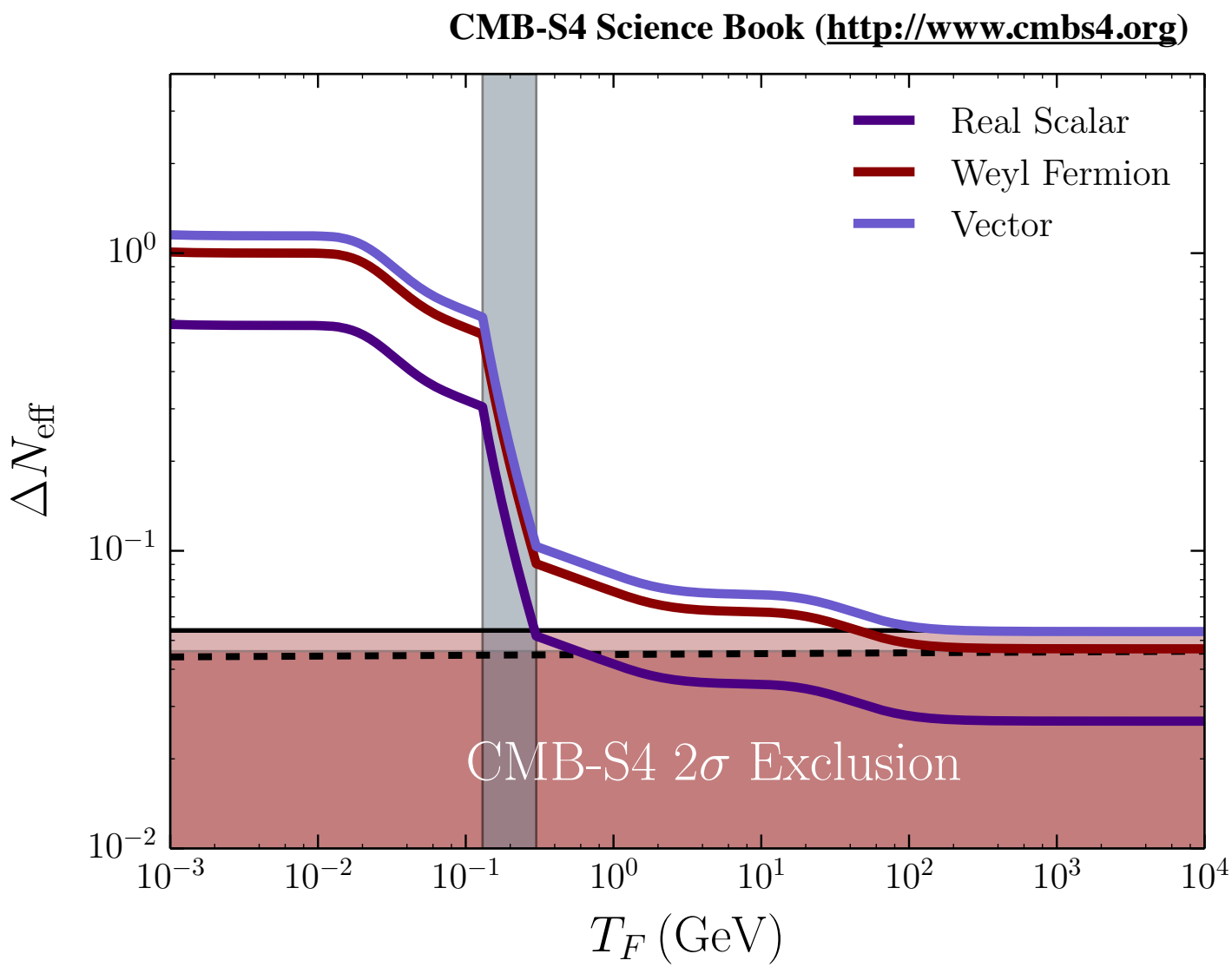
- Real scalars like the QCD axion predict*

$$\Delta N_{\rm eff} \geq 0.027$$

Currently studied configurations for CMB-S4 can achieve $\sigma(N_{\rm eff}) \approx 0.03$.

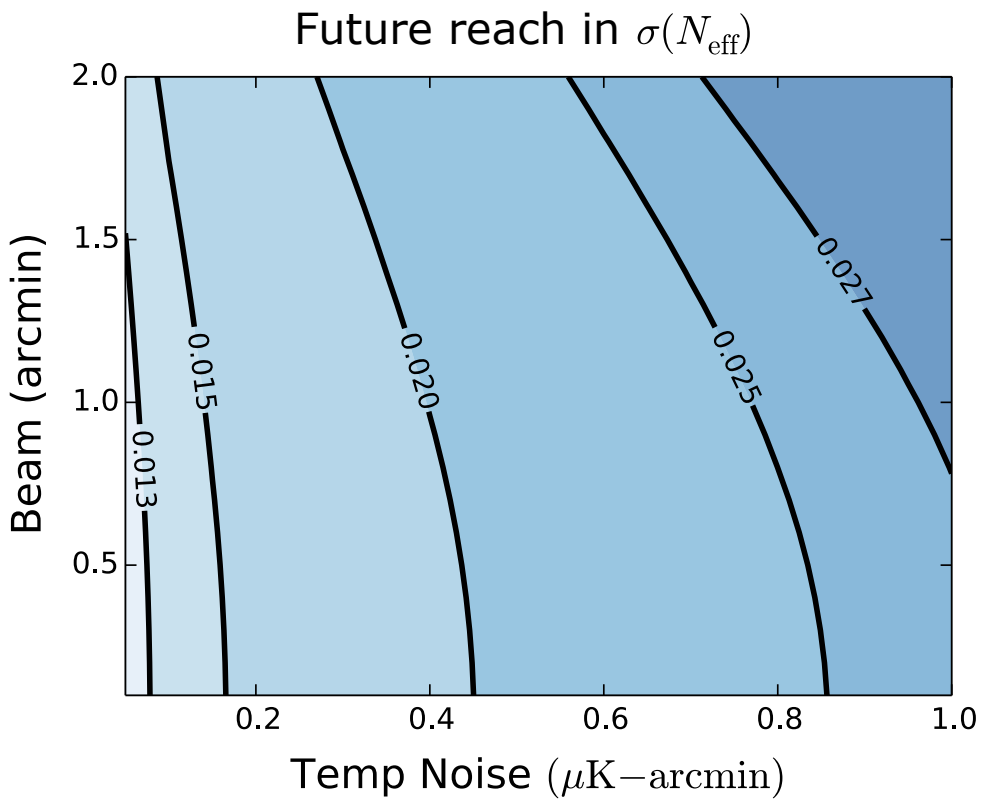
(*) assumes that there are no states that annihilate into standard model particles after freeze-out of the relic

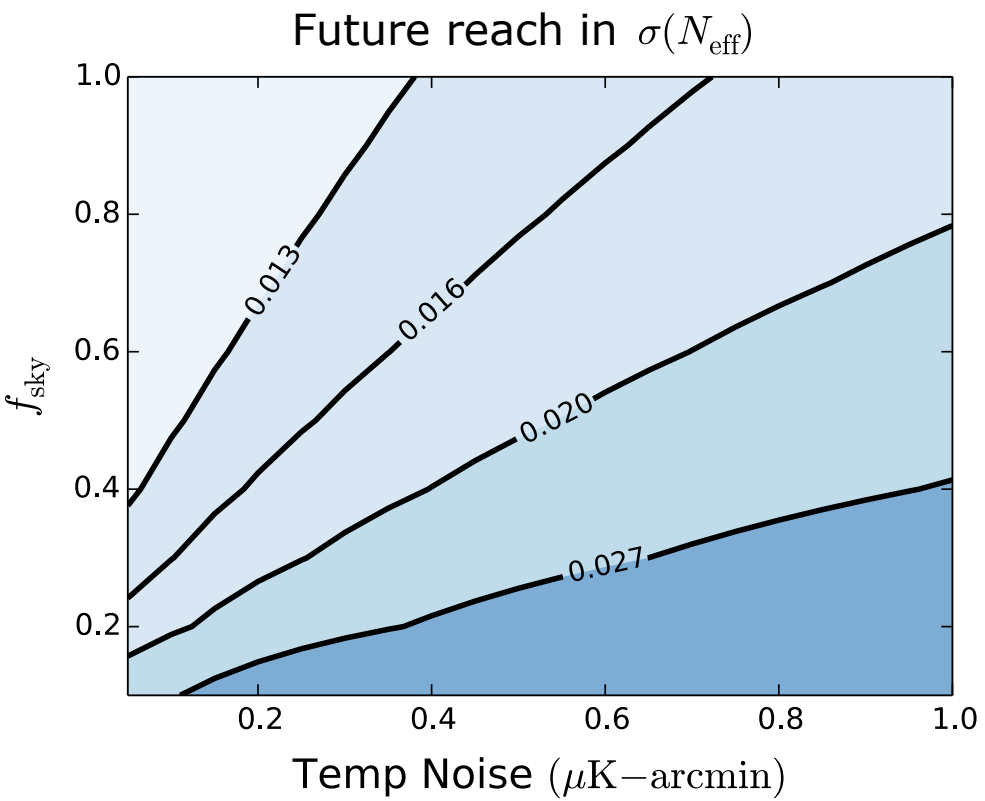
Light Relics



Light Relics

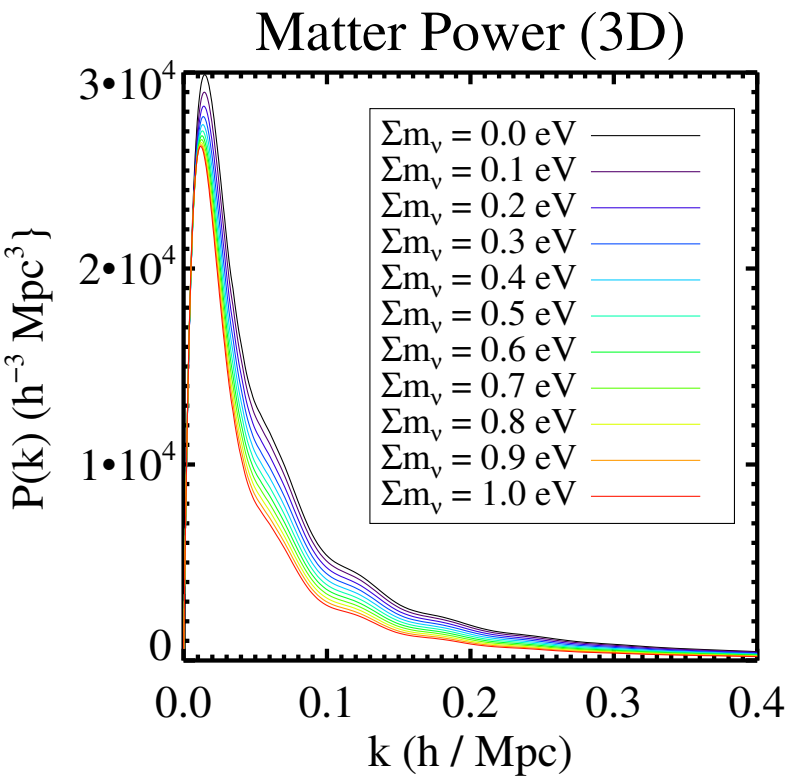
CMB-S4 Science Book (http://www.cmbs4.org)

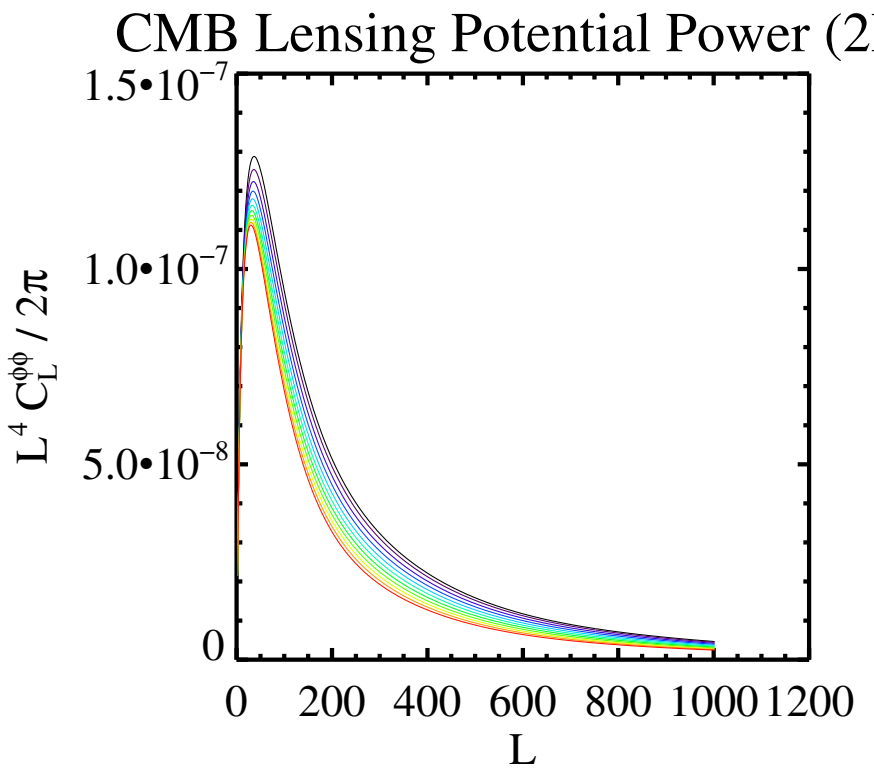




Neutrinos

Structure formation is suppressed on scales smaller than the free streaming scale. This can be detected in large scale structure surveys and through lensing of the cosmic microwave background.

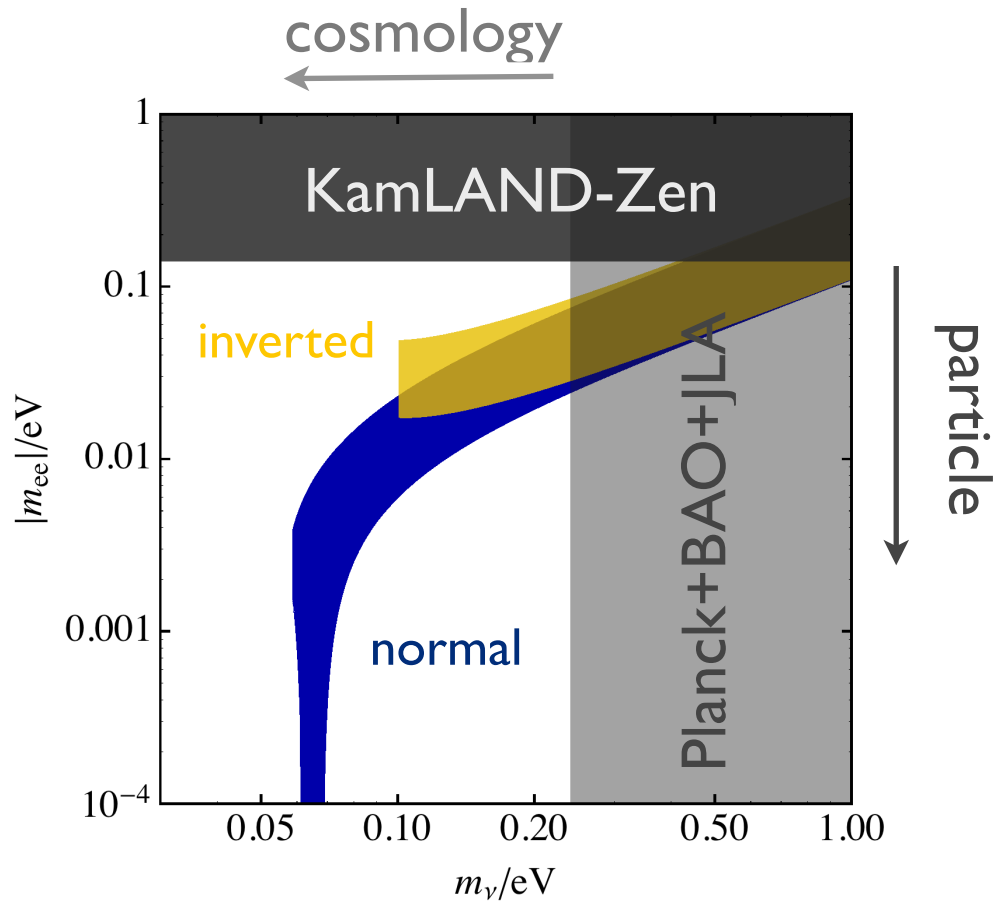




CMB-S4 Science Book (http://www.cmbs4.org)

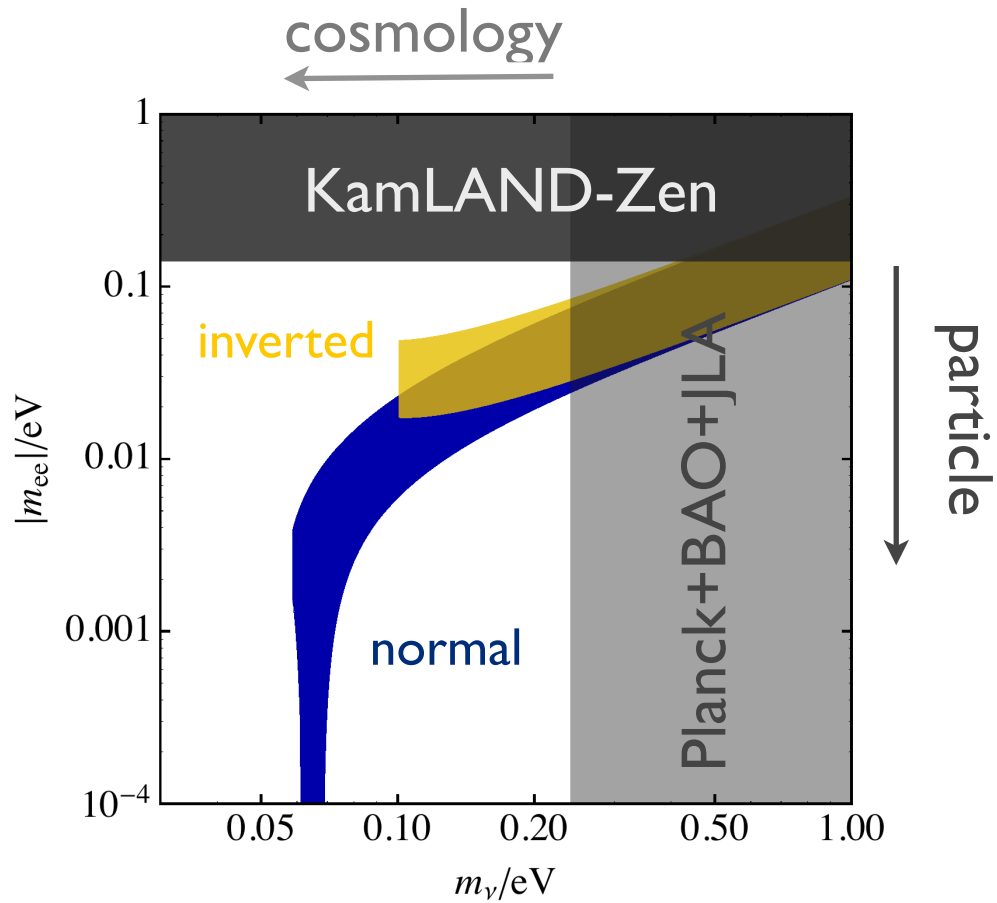
Neutrinos

Complementary to lab experiments



Neutrinos

Complementary to lab experiments

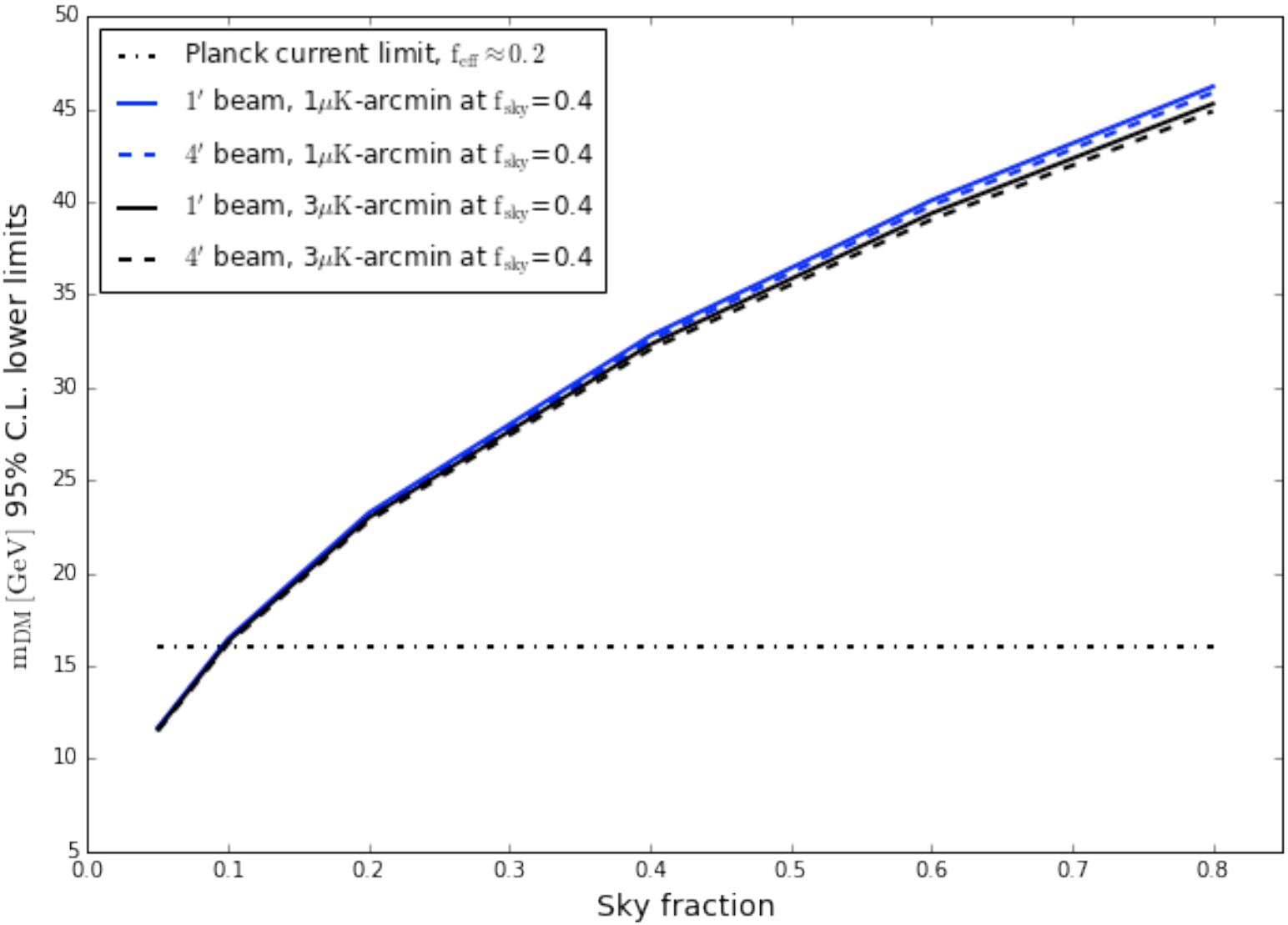


DESI+CMB-S4: $\sigma(m_\nu) \approx 0.02\,\mathrm{eV}$

3σ measurement even for normal hierarchy

Dark Matter

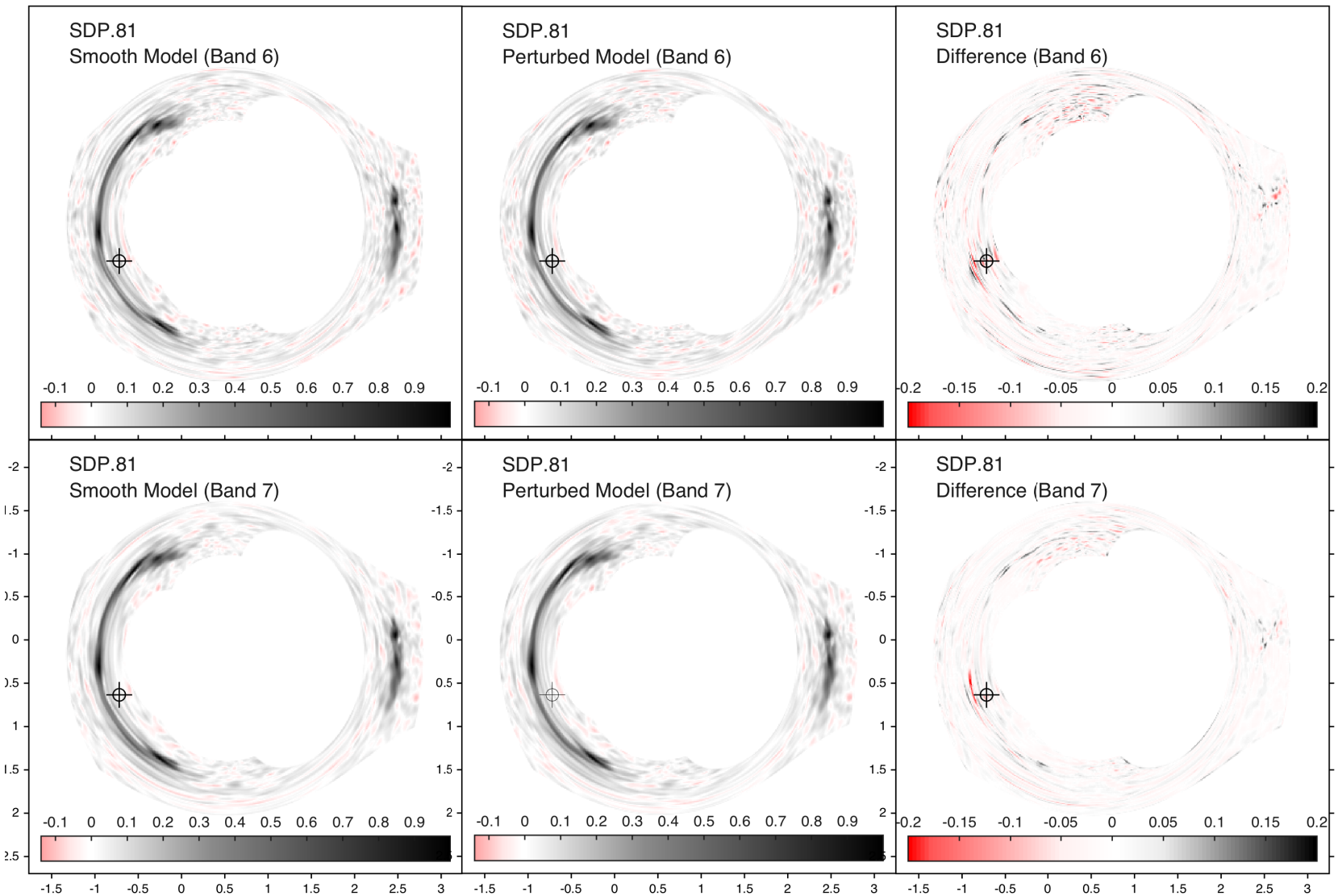
CMB-S4 Science Book (http://www.cmbs4.org)



(only applies to s-wave annihilation)

Dark Matter

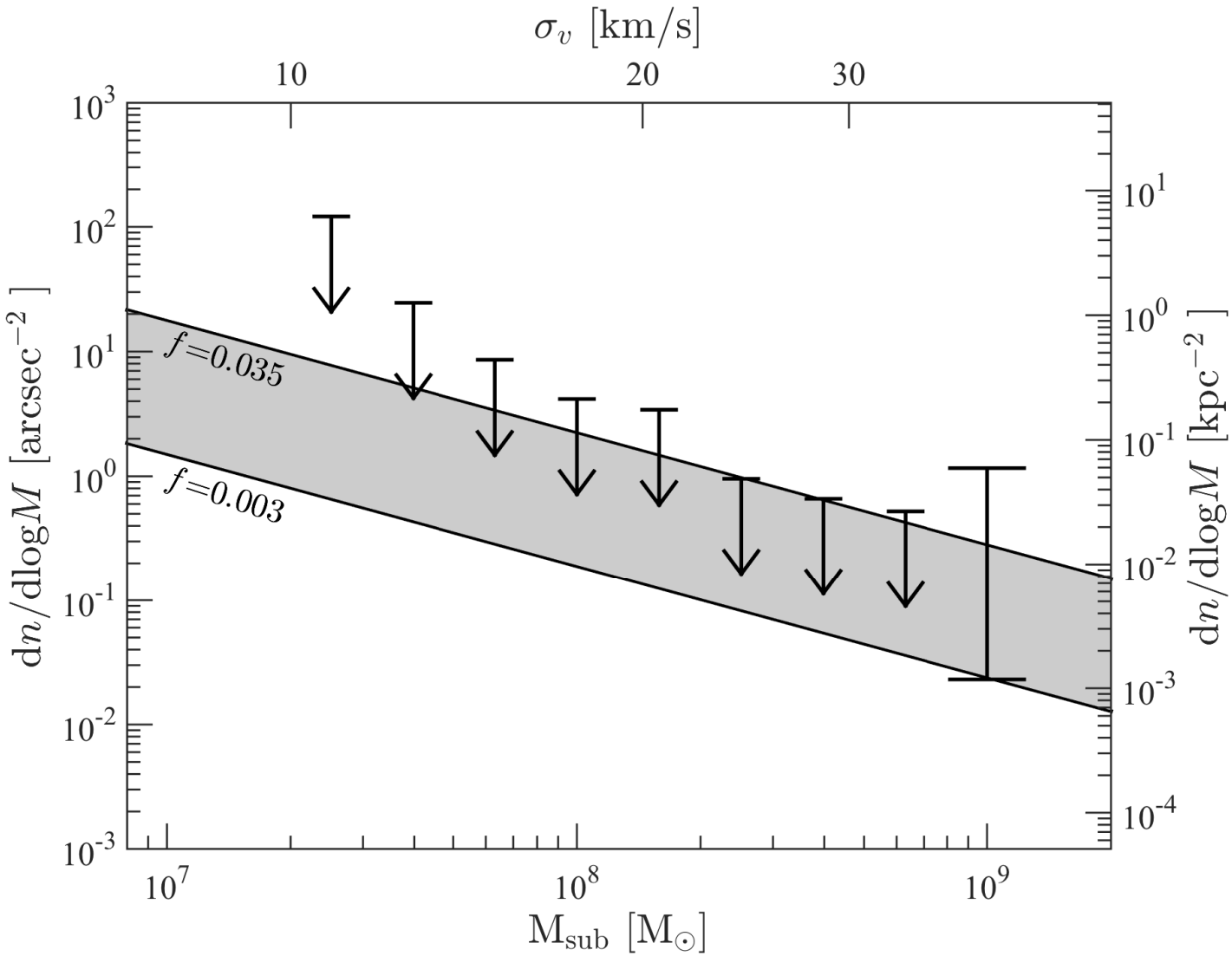
Abundance of substructure from lensing, here from ALMA



(Hezaveh et al. 2016)

Dark Matter

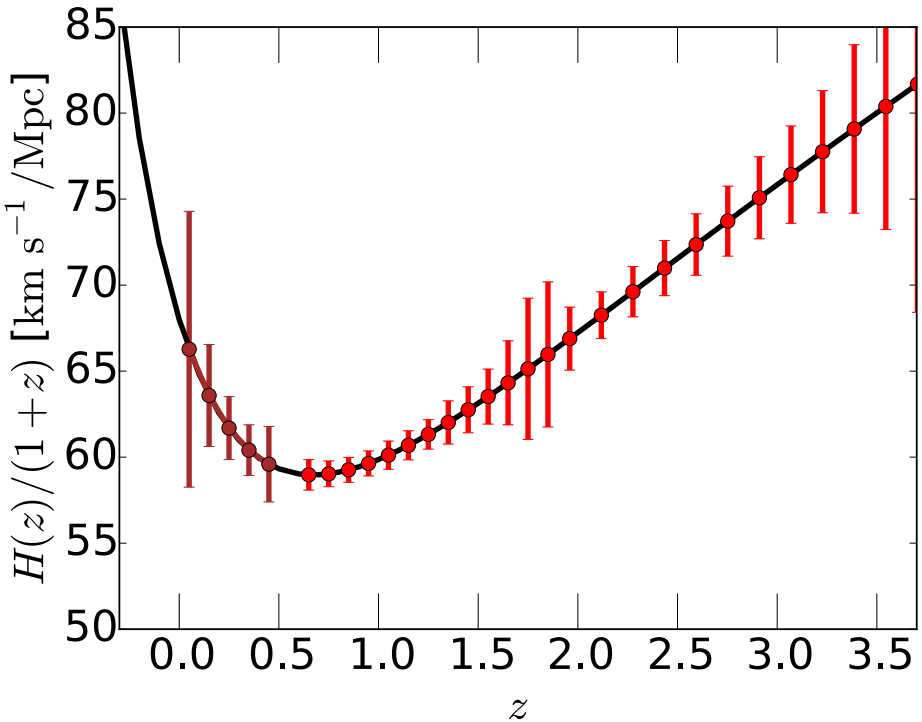
Abundance of substructure from lensing, here from ALMA

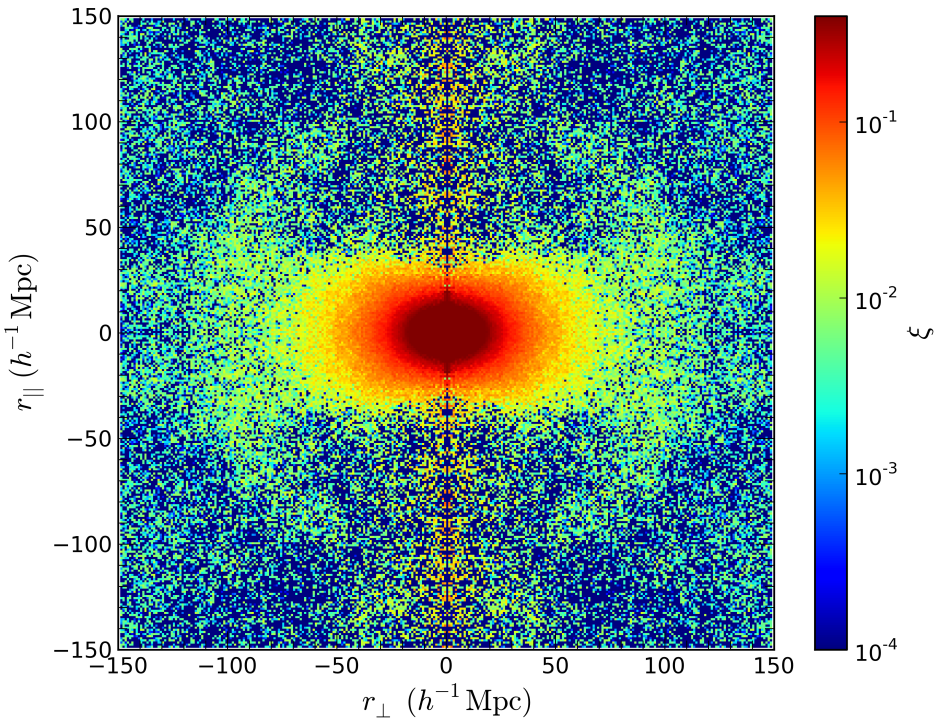


(Hezaveh et al. 2016)

Dark Energy, Modified Gravity,...

- BAO will map the expansion history extremely well and constrain any departures from a cosmological constant





- Redshift space distortions will allow to measure the growth of structure and provide stringent tests of general relativity

- ...

Conclusions

- Our understanding of the early universe has improved significantly over the past two decades
- Although there are small tensions, all data remains consistent with the simple LCDM model
- Many experiments are already taking data, many will soon come online and will constrain light relics, neutrinos, dark matter, ...
- How they can best be used to constrain dark interactions has likely not been fully explored
- The next decade will be eventful and we should continue to learn a lot about the early universe

Thank you