Problems and Perspectives in Cosmology

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Astroparticule et Cosmologie – Université Paris Diderot

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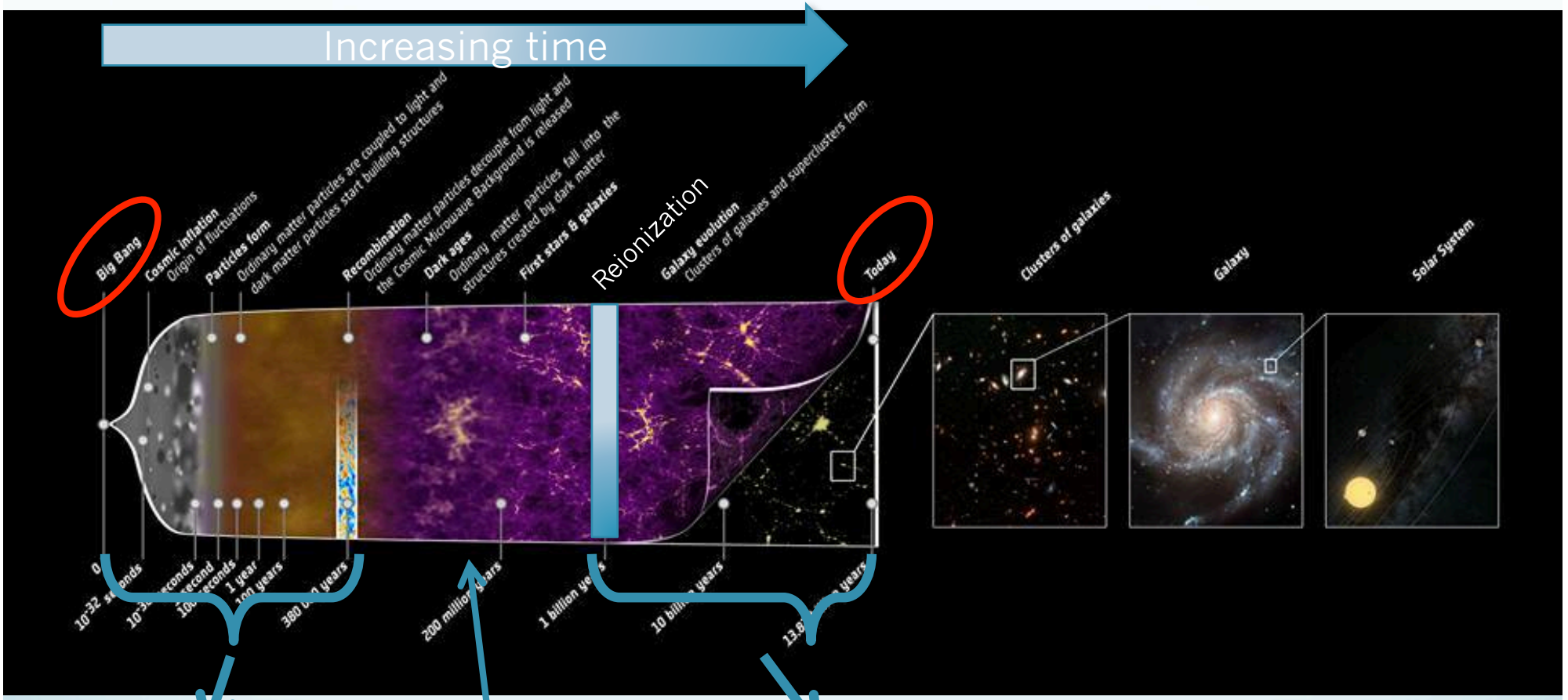
Problems and Perspectives

- Were we stand
  - The standard cosmological model
  - Possible tensions
- The path forward
  - Open questions
  - Observational campaign

Vista Point

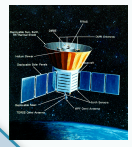


Early universe:
Inflation (z>1000)

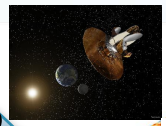
Dark ages

Late universe:
Dark sector, galaxy formation, reionization (z<15)

Standard Model



COBE

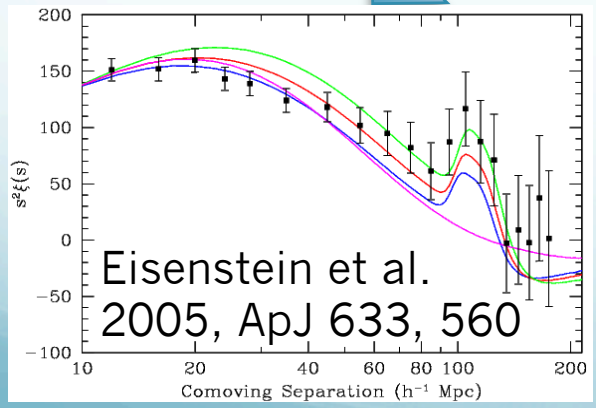


WMAP

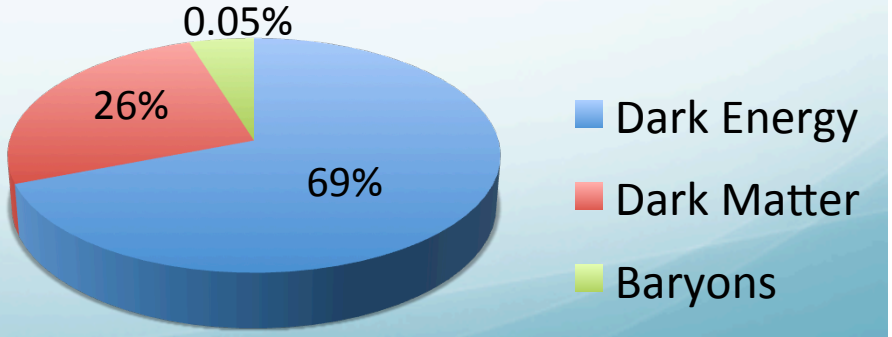
Planck

+ Lensing (and/or)

+ BAO



Flat ΛCDM 6 parameters



Standard Model Parameters

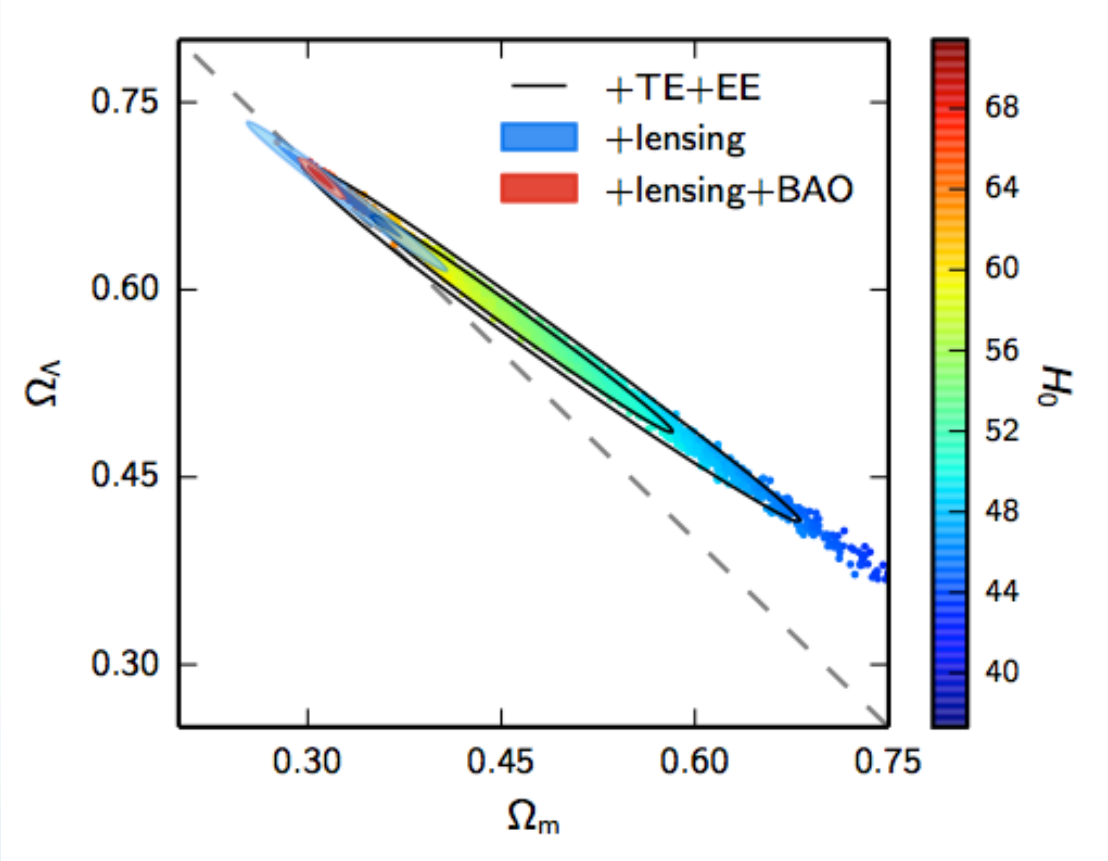
Planck CMB + *Planck* lensing: $\Omega_K = -0.004 \pm 0.015$

+ Ext (BAO, SN, H_0) : $\Omega_K = 0.0008 \pm 0.004$

For flat ΛCDM (base model):

Parameter	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
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
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
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
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
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
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086

Tensions: H_0



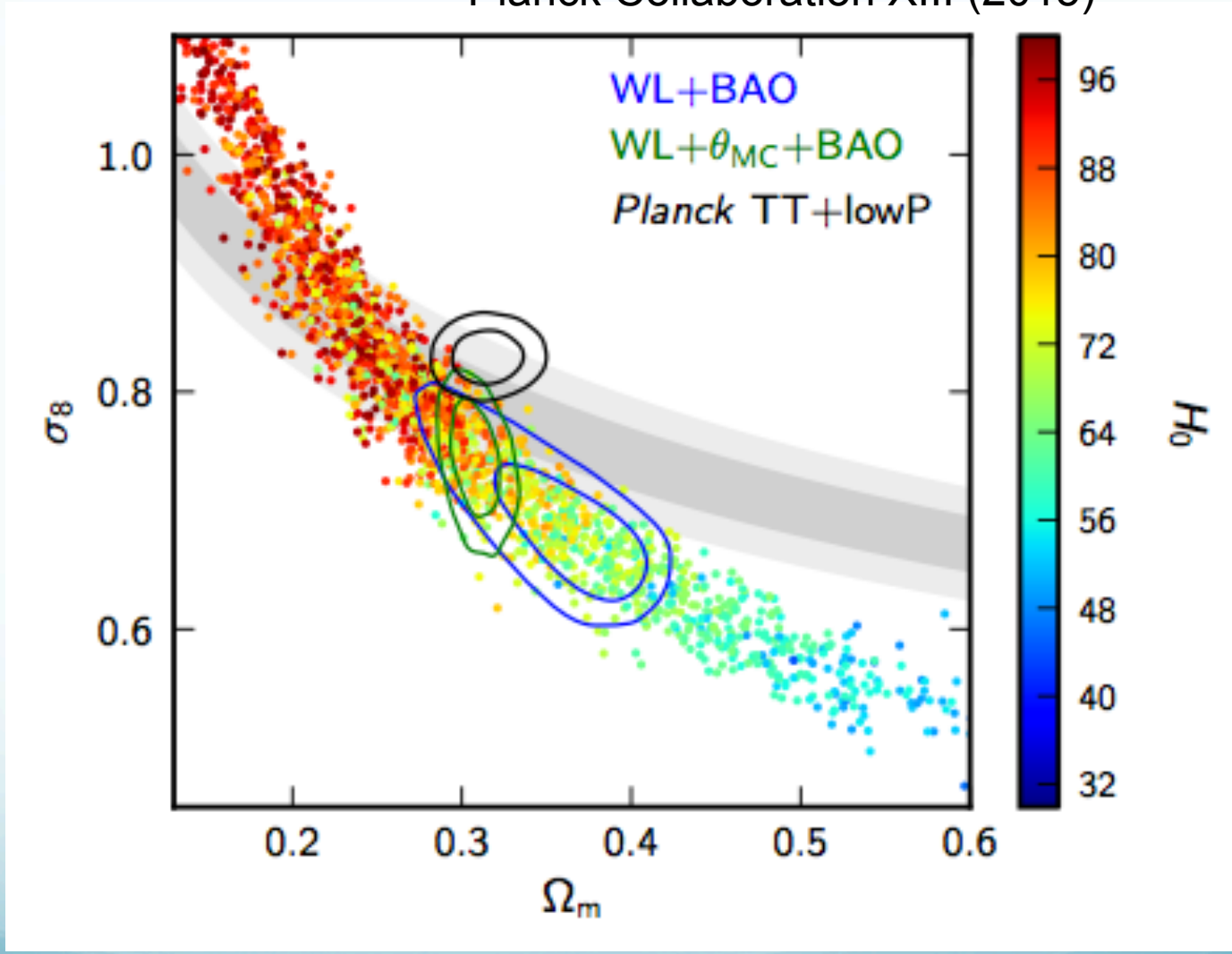
3.6σ
Tension between CMB and local H_0 determinations

$H_0 = (67.74 \pm 0.46)\,\mathrm{km\,s^{-1}Mpc^{-1}}$ Planck+BAO

$H_0 = (73.52 \pm 1.62)\,\mathrm{km\,s^{-1}Mpc^{-1}}$ Local (Riess+ 2018)

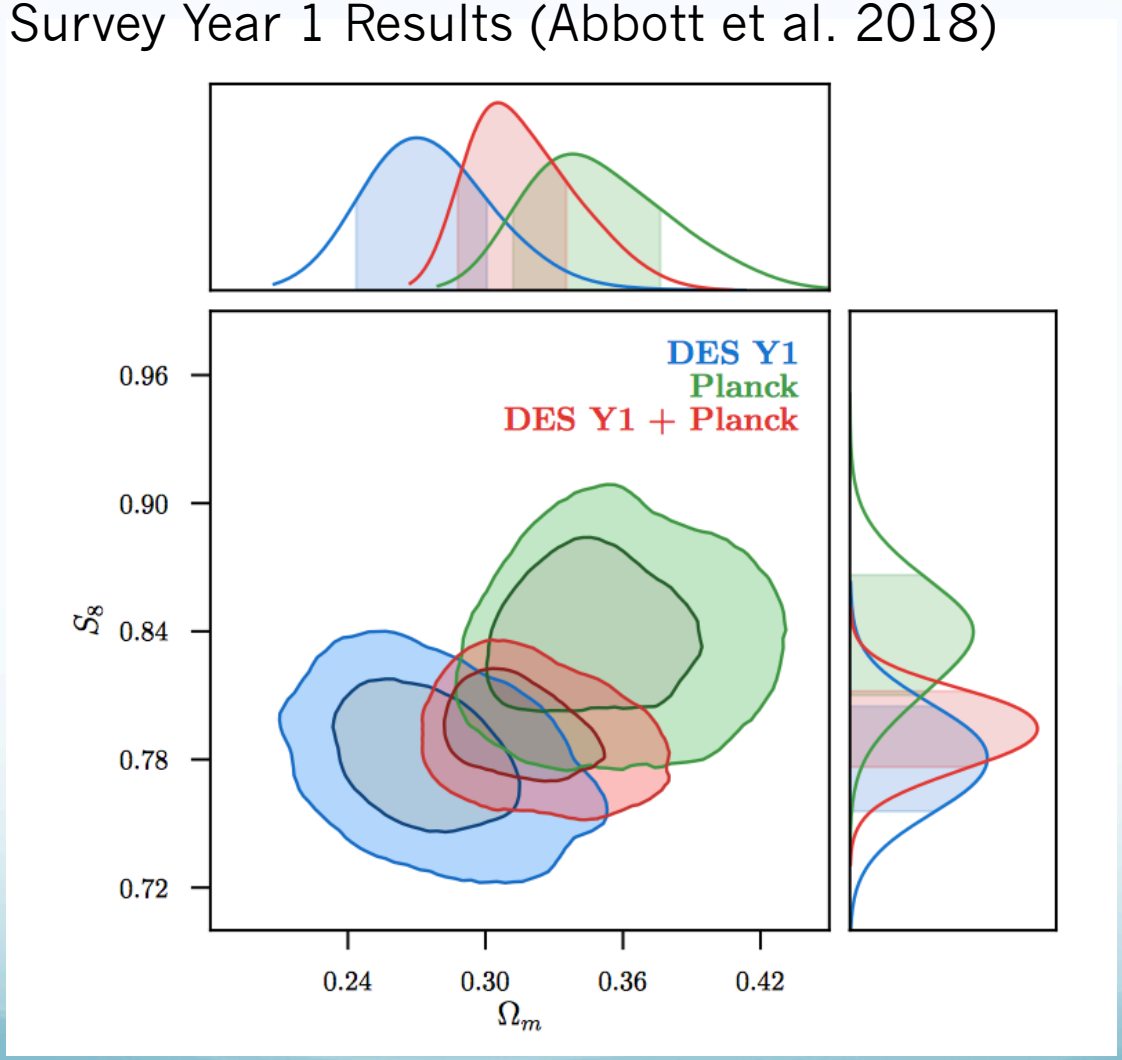
Tensions: σ_8

Planck Collaboration XIII (2015)



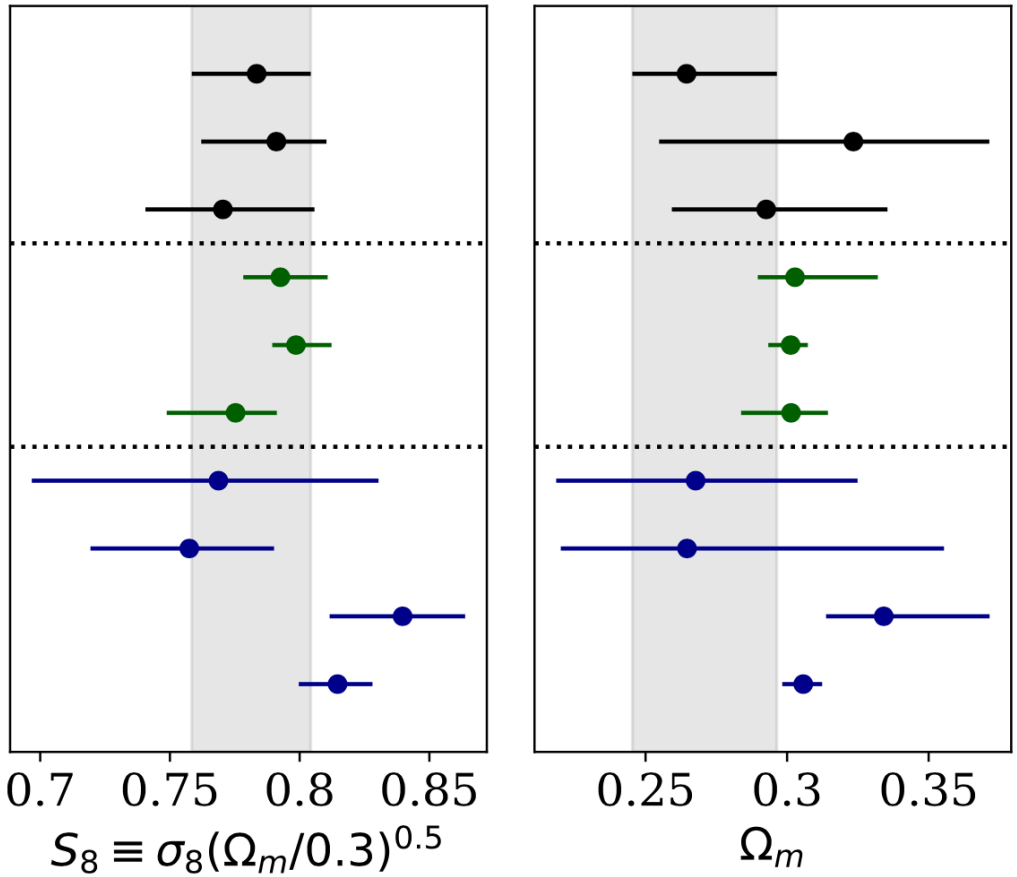
Tensions: σ_8

Dark Energy Survey Year 1 Results (Abbott et al. 2018)



Tensions: σ_8

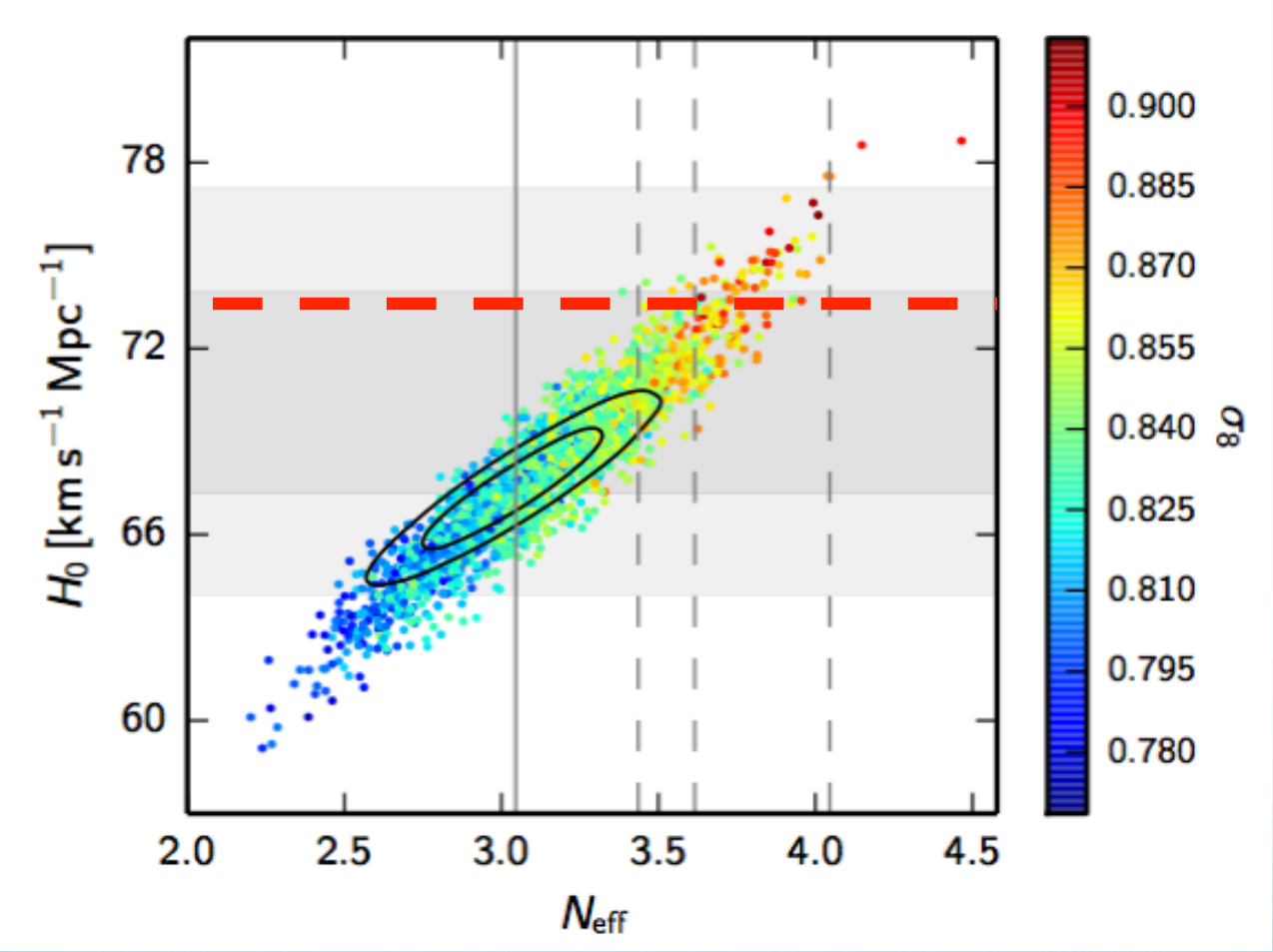
Dark Energy Survey Year 1 Results (Abbott et al. 2018)



DES Y1 All
DES Y1 Shear
DES Y1 $w + \gamma_t$
DES Y1 All + Planck (No Lensing)
DES Y1 All + Planck + BAO + JLA
DES Y1 All + BAO + JLA
DES SV
KiDS-450
Planck (No Lensing)
Planck + BAO + JLA

H_0, N_{eff} and σ_8

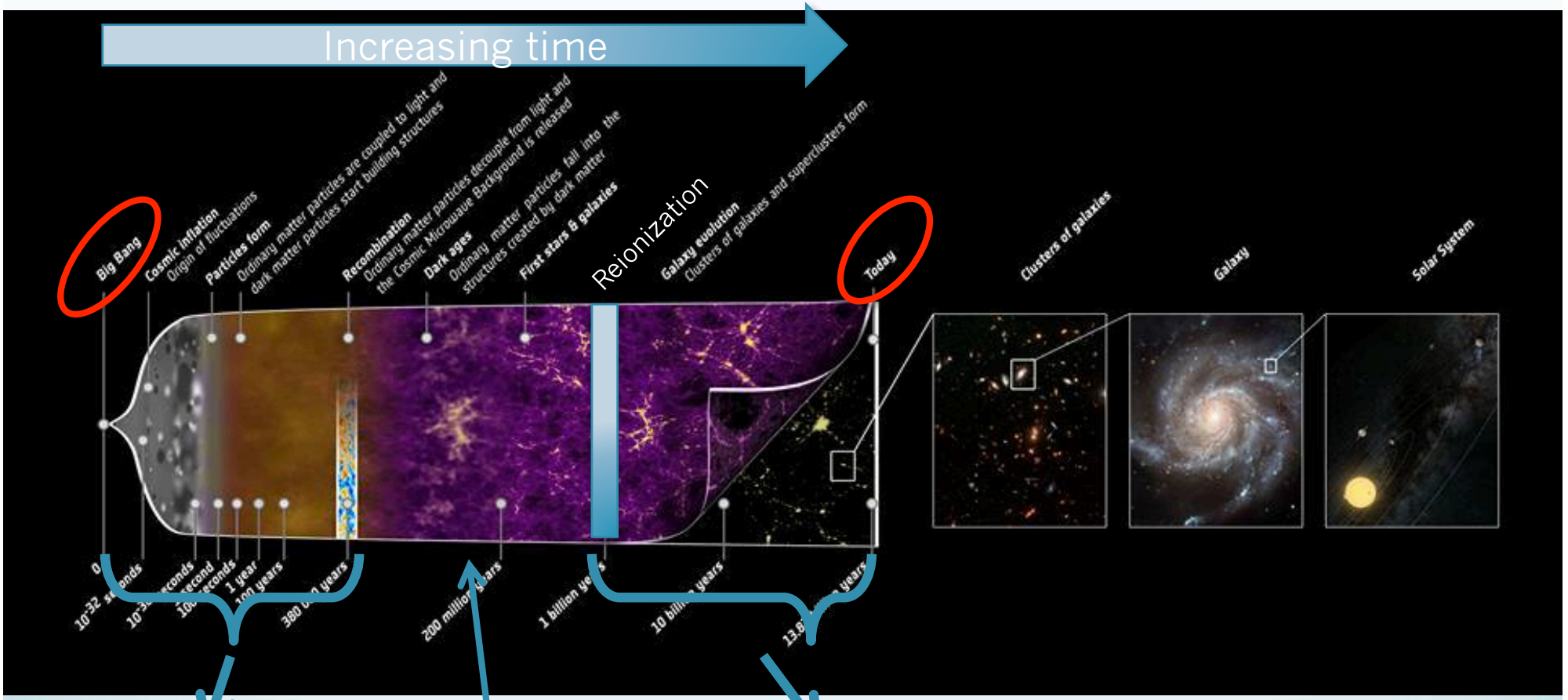
Planck Collaboration XIII (2015)



Open Questions

- **Tensions?**
- **Primordial perturbations**
  - **Primordial gravity waves from inflation (CMB surveys)**
  - Non-Gaussianity (Galaxy surveys)
- Neutrino sector (CMB and galaxy surveys)
  - Mass scale
  - Neff
- **Dark sector (Galaxy surveys)**
  - Dark matter
  - **Dark energy**
  - Modified gravity
- Baryon physics
  - Galaxy formation and evolution
  - Reionization

Vista Point



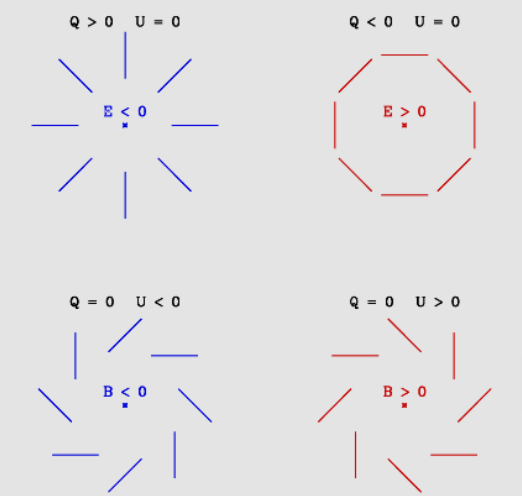
Early universe:
Gravity waves - CMB polarization surveys

Dark ages

Late universe:
Dark Energy – SNIa, BAO/RSD, lensing, clusters

Primordial Grav. Waves

Polarization anisotropy patterns

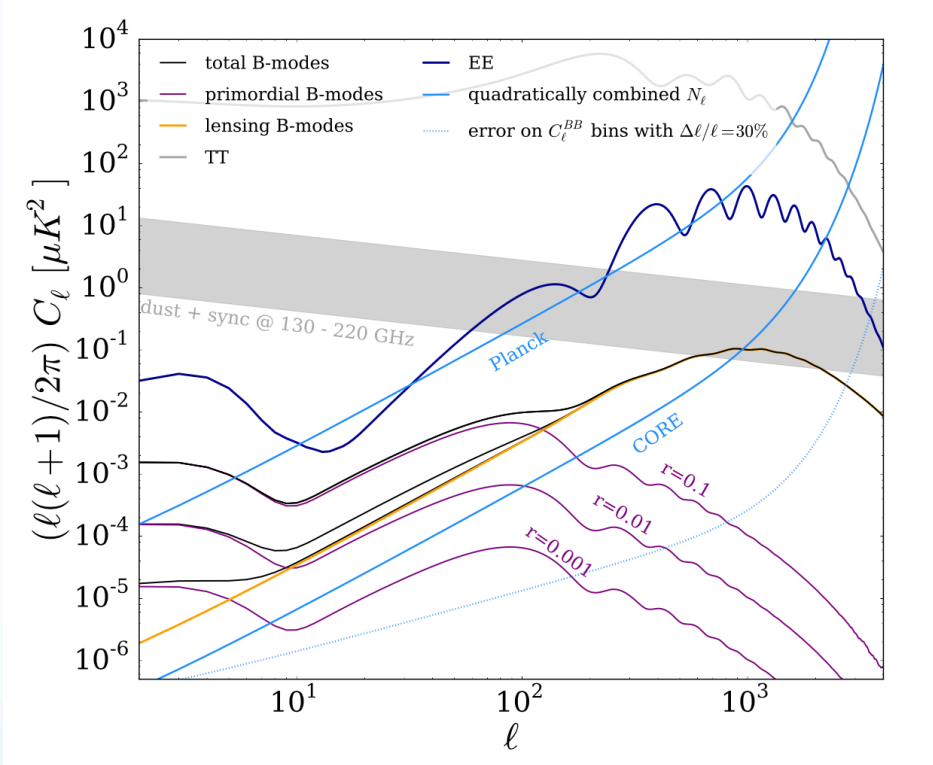


Zaldarriaga

E-mode

B-mode: only grav. waves & lensing (loss of axial symmetry)

Finelli et al. (2017)

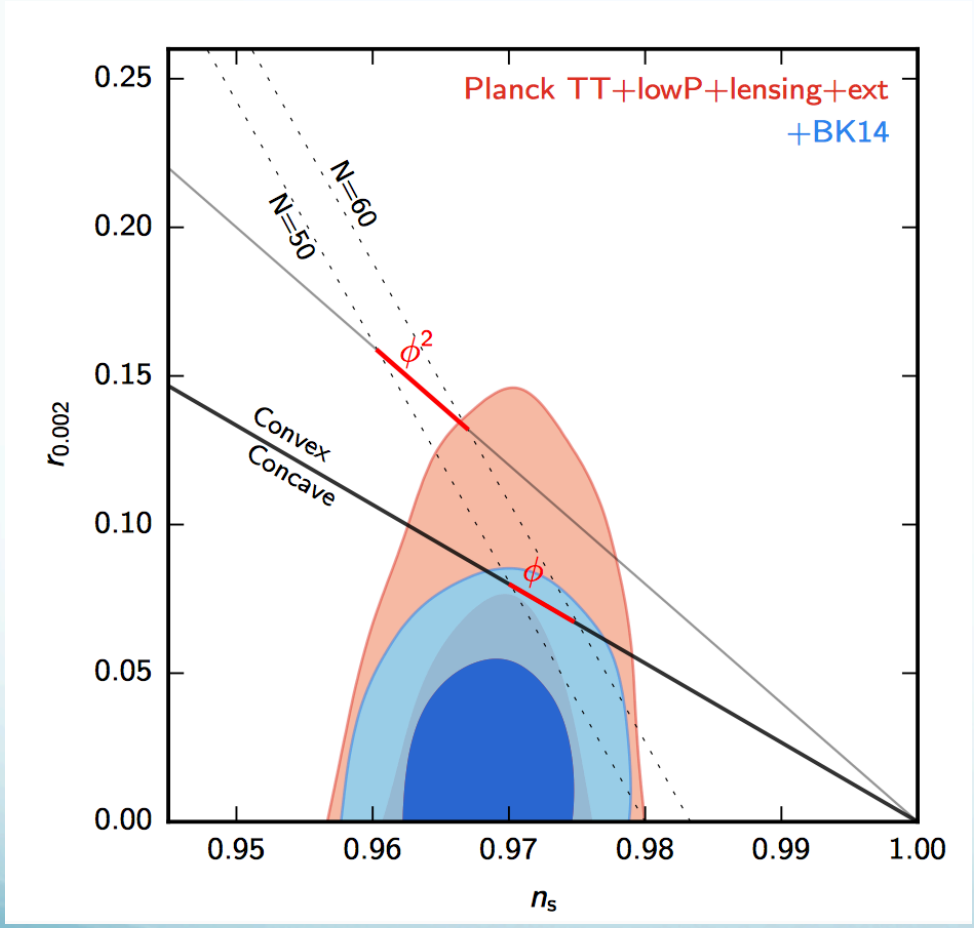


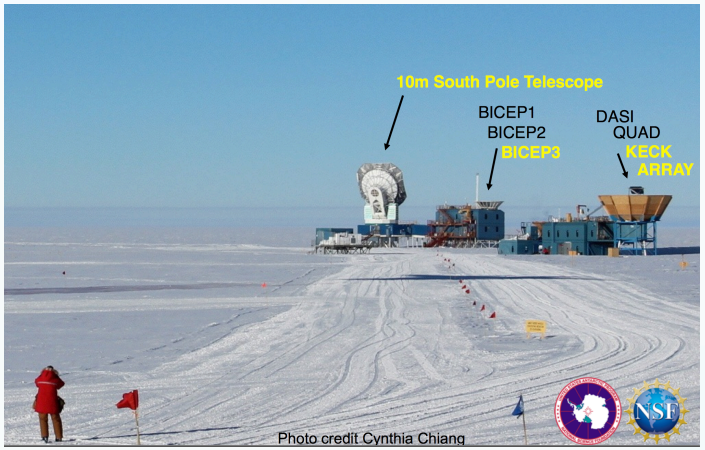
Inflation "smoking gun" & energy scale: $\Delta^2 h_{+,x} = \frac{1}{2\pi^2}\left(\frac{H}{M_{pl}}\right)^2$

$$r \sim 0.07(E/1.8\times 10^{16}\,\mathrm{GeV})^4$$ Lyth (1997)

Primordial Grav. Waves

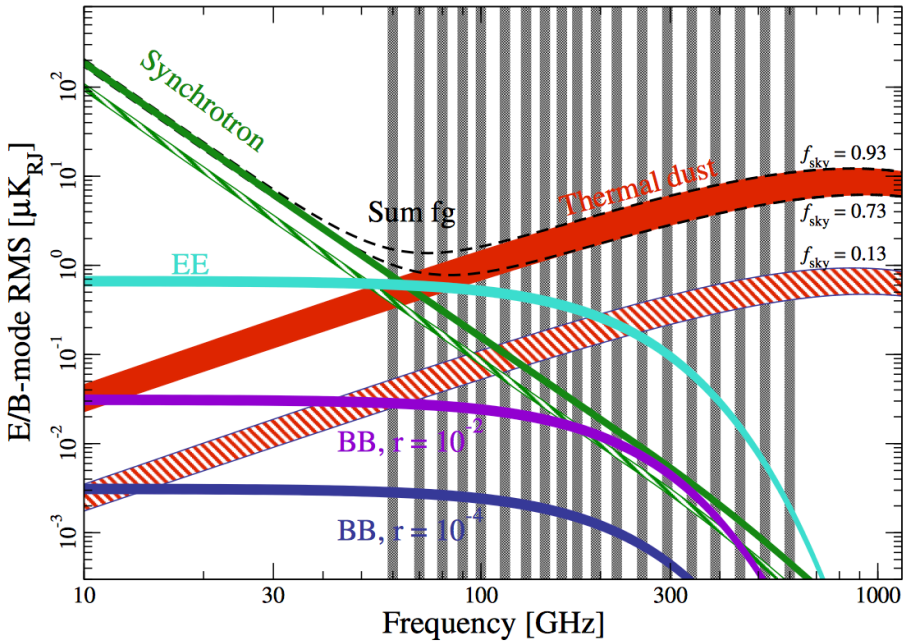
Keck Array and BICEP2 Collaborations (2016)





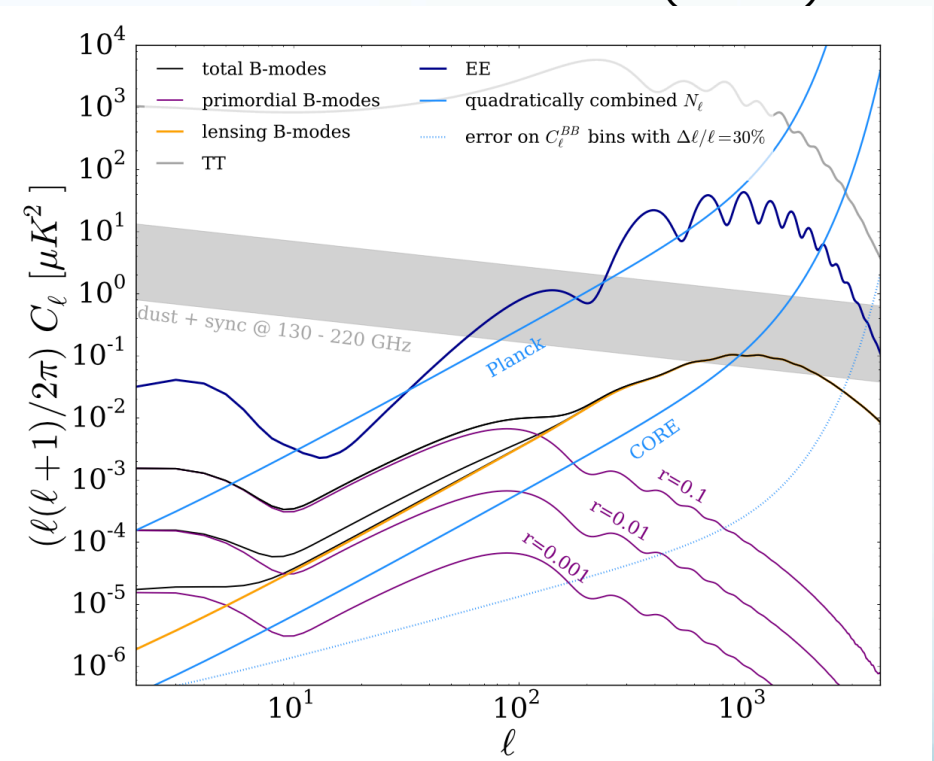
$$r_{0.05} < 0.07 \quad 95\%$$

The Challenge



Remazeilles et al. (2017)

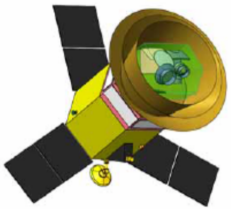
Finelli et al. (2017)



The CMB Program

Simons Observatory: Atacama

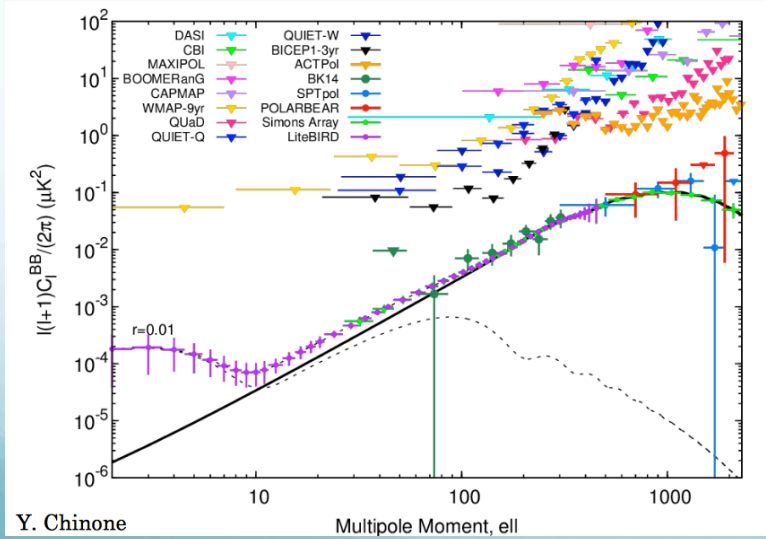
CMB-S4 2025: South Pole + Atacama



LiteBIRD
2027

PICO / ? ~2030?

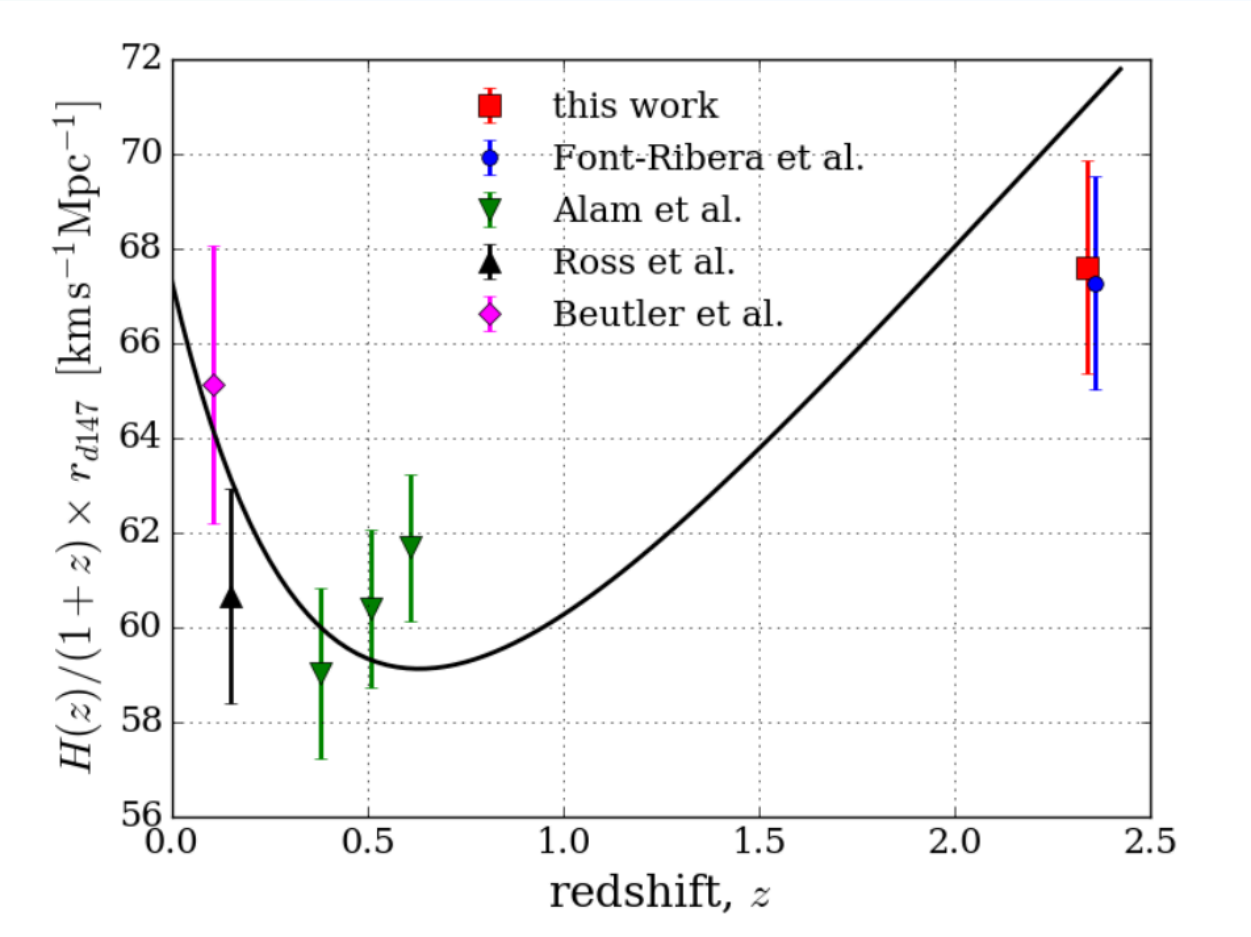
E.g. LiteBIRD



$$\sigma_r = 5 \times 10^{-4}$$

Dark Energy

Bautista et al. (2017)



What is Λ?

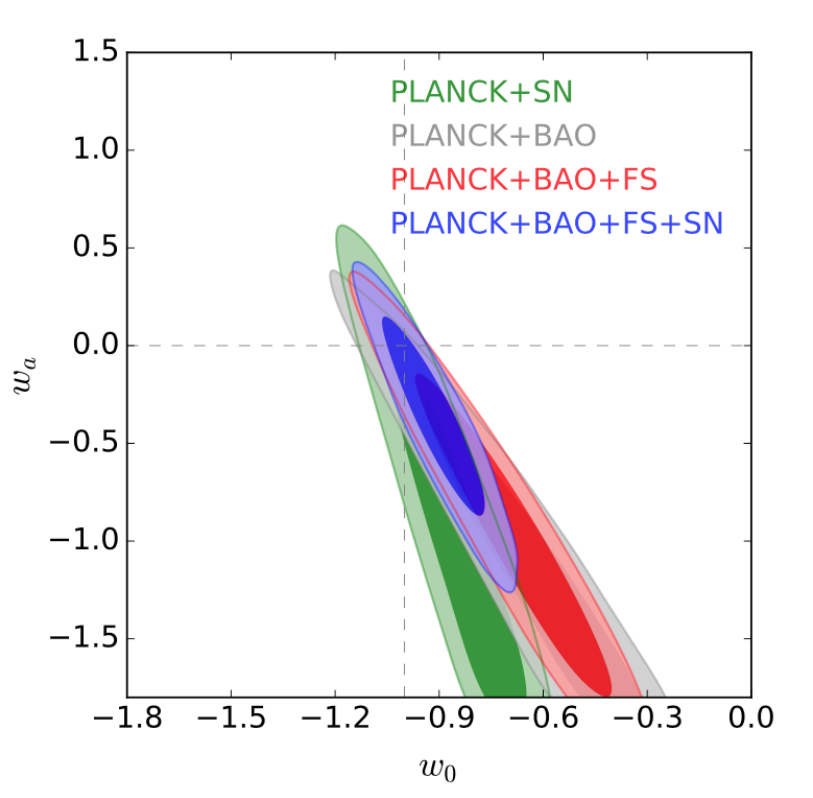
- Does it evolve?
- Generic EoS

$$p = w(a)\rho$$

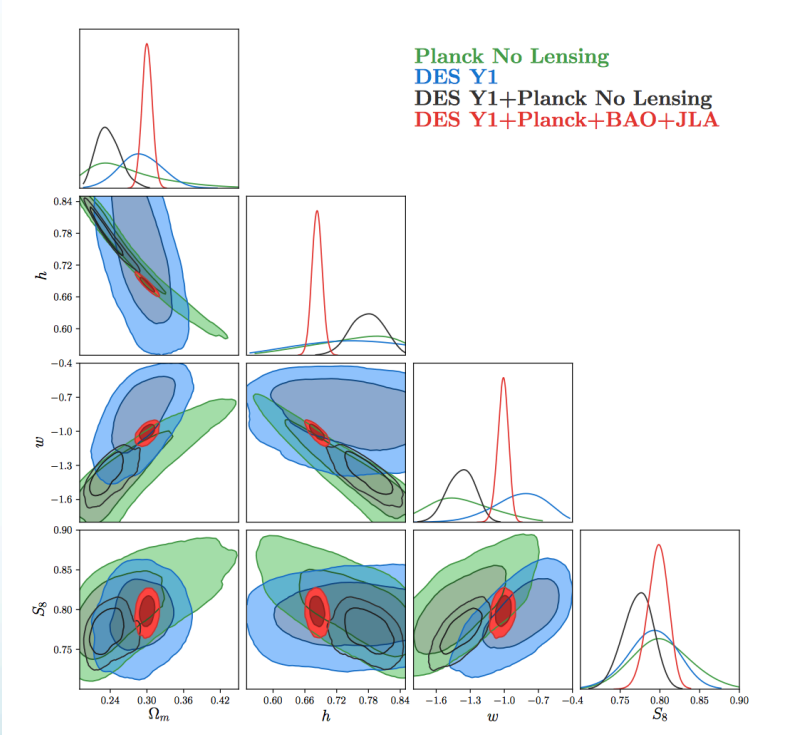
$$w = w_0 + (1-a)w_a$$

Dark Energy Status

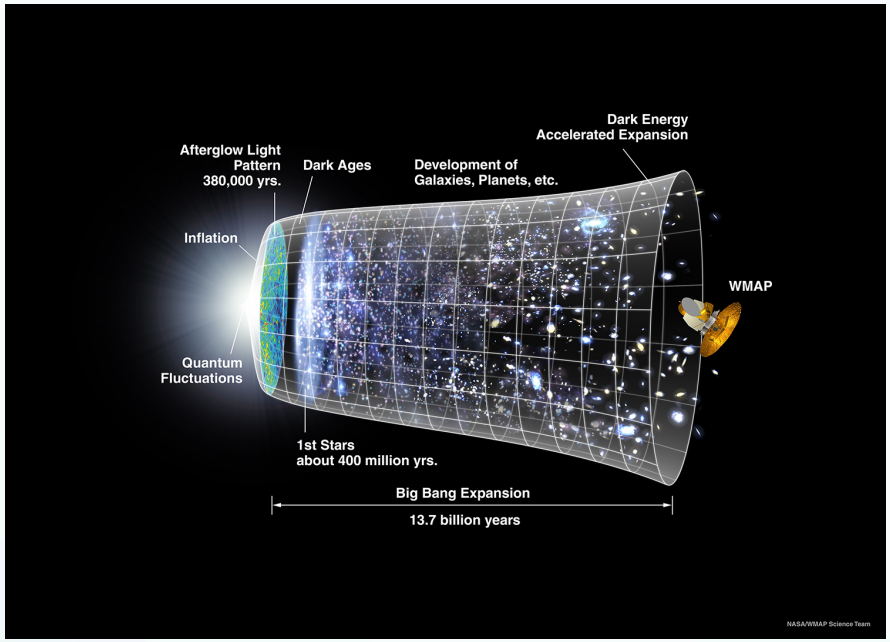
SDSS BOSS (DR12, Alam et al. 2017)



DES Year 1 Results (Abbott et al. 2018)



The Dark Energy Program



Dark energy begins to dominate late (around *z=1*)

Wide Field Surveying in optical/NIR

- Imaging
- Spectra

Dark energy probes:

- Baryon acoustic oscillations (geometry)
- Galaxy cluster evolution (dynamics, geometry)
- Cosmic shear (dynamics, geometry)
- SNIa distance measurements (geometry)

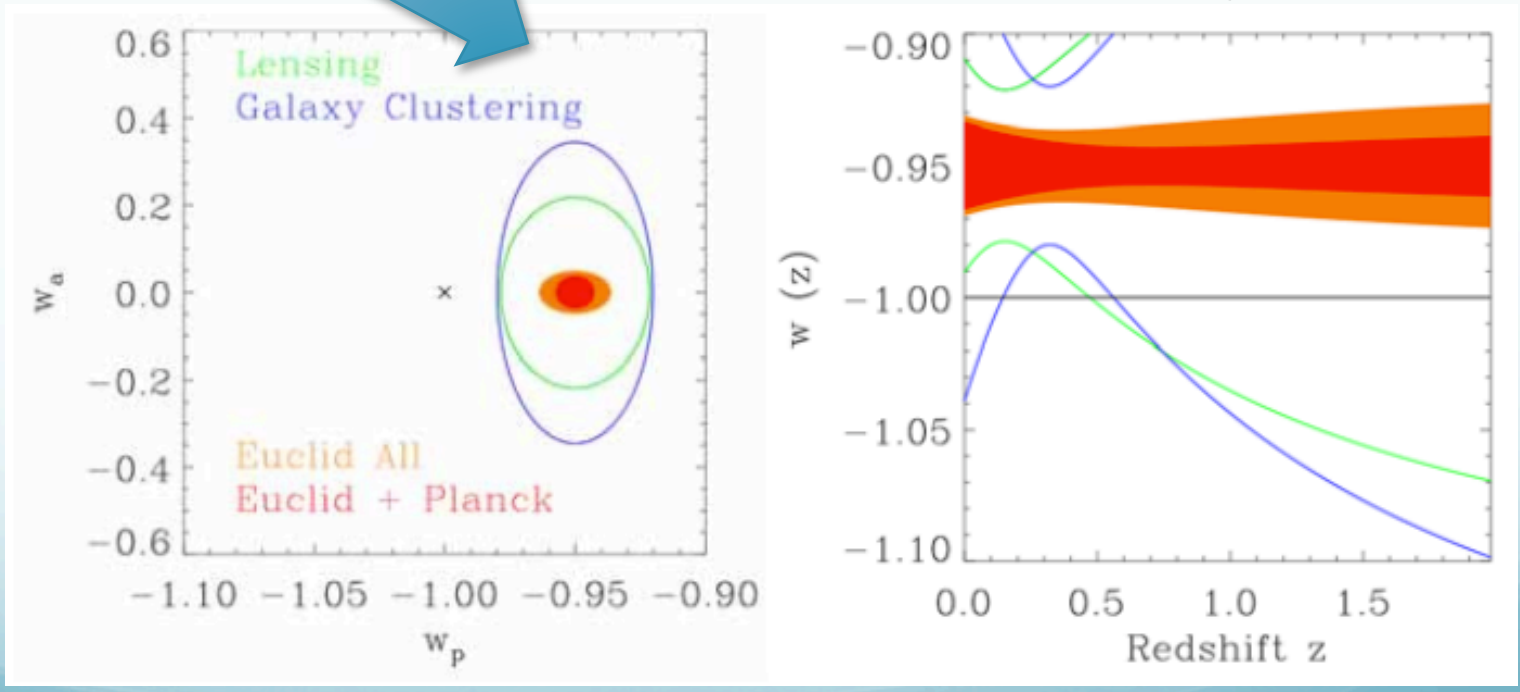
The Dark Energy Program

DESI (2018 start)

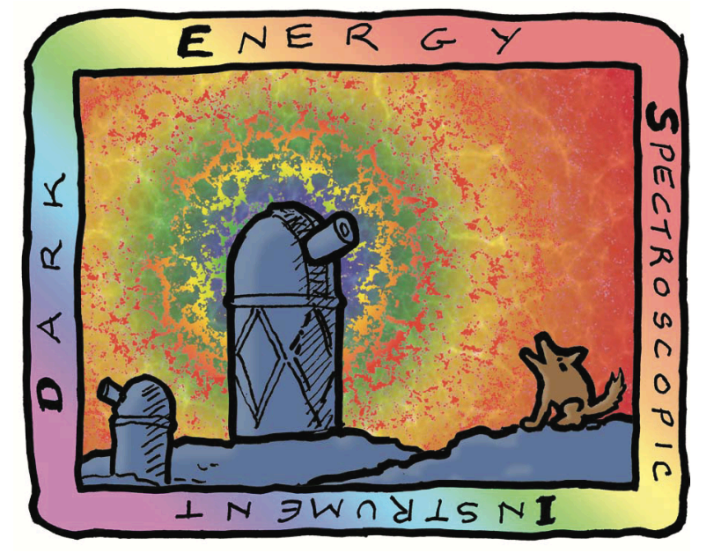
Euclid/LSST (early 2020s start, 6-10 year operation)

WFIRST (2025?)

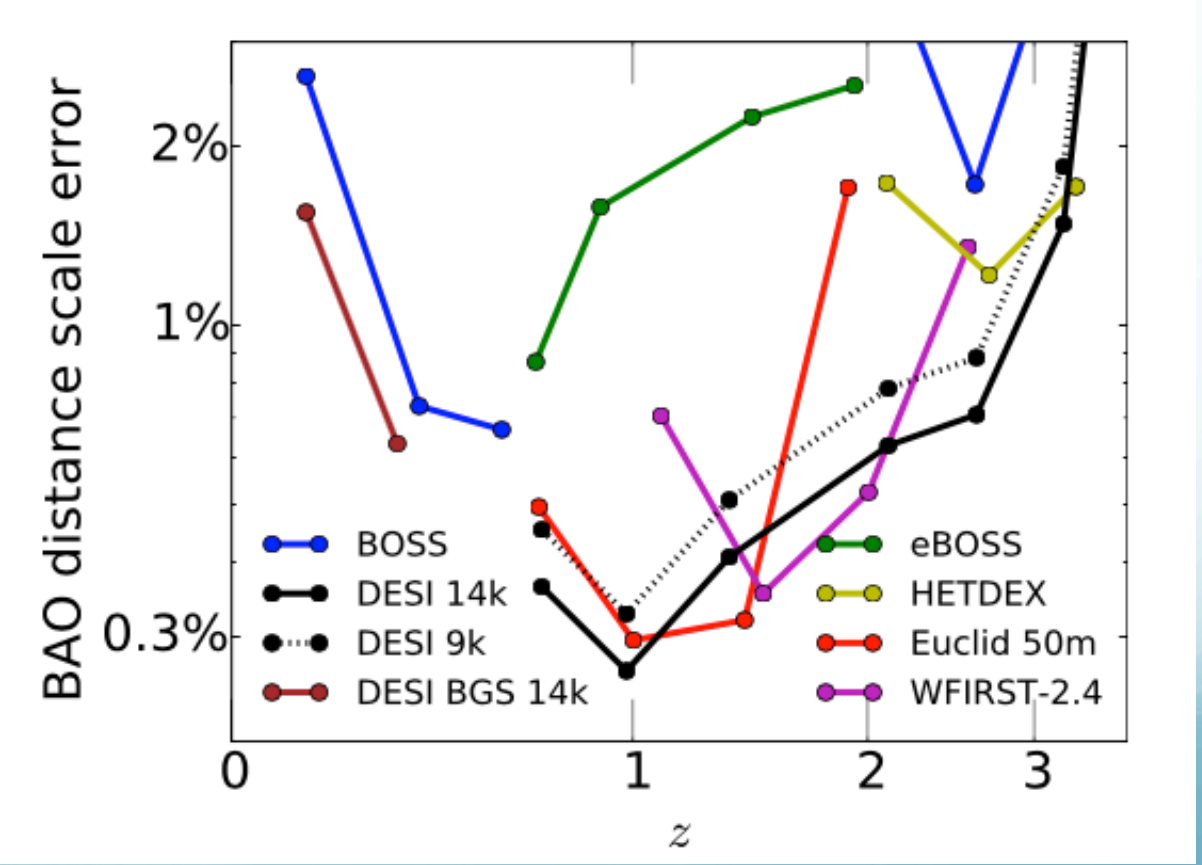
E.g. Euclid



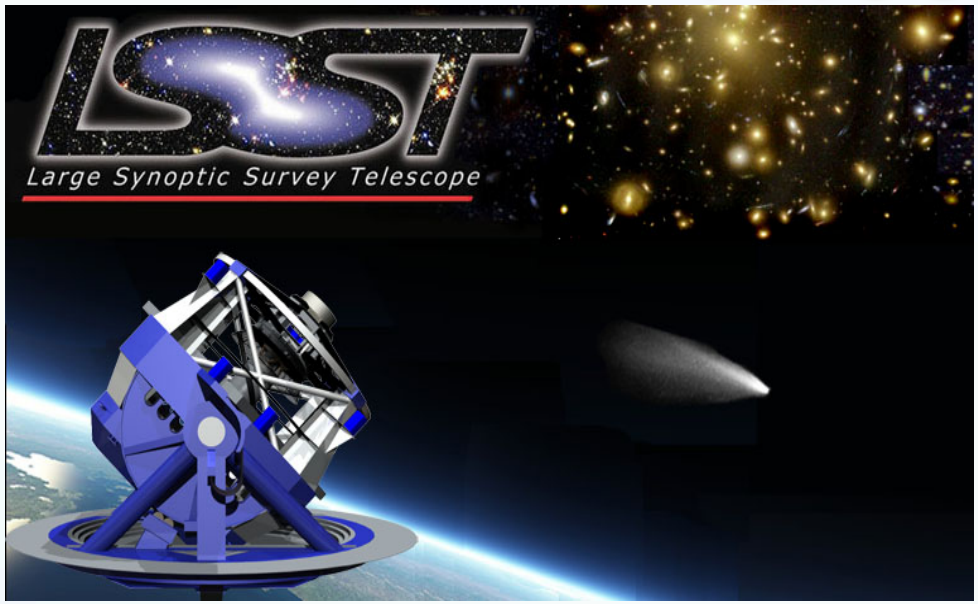
Dark Energy Spectroscopic Instrument



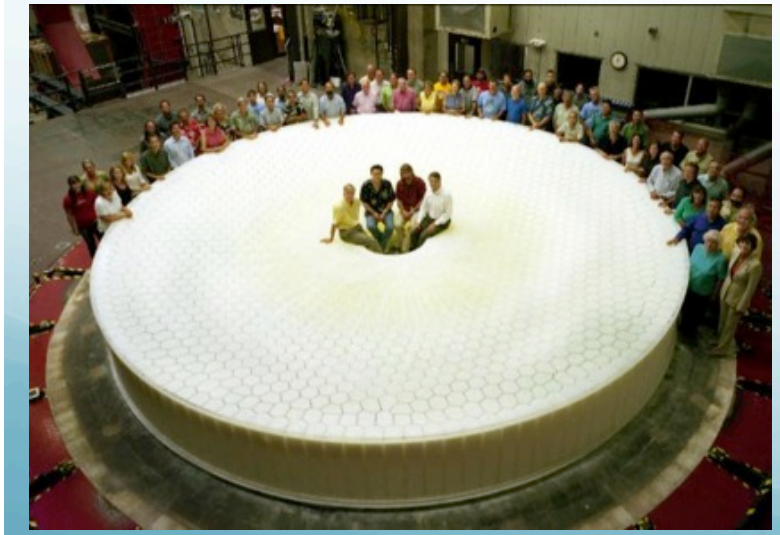
DESI FDR



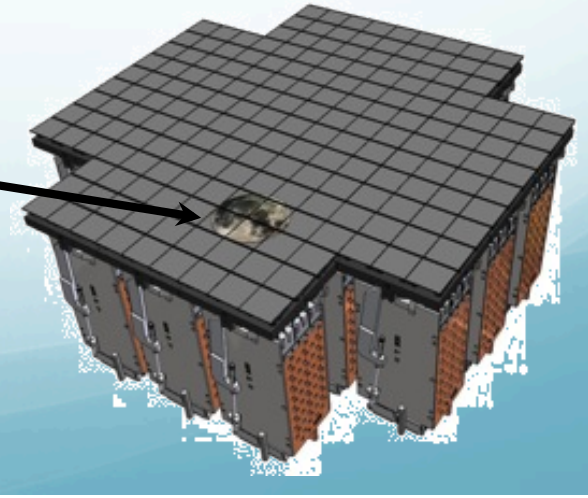
Large Synoptic Survey Telescope



- 8.4 m primary
- 10 sq. deg. FOV
- 6 bands (ugrizY)
- Single visit (2x15s) to r ≈24.5 mag
- 10-year survey (full southern sky every few days) to r≈27.5 mag
- All 4 dark energy probes
- Construction start 2014; Operations 2023-2033

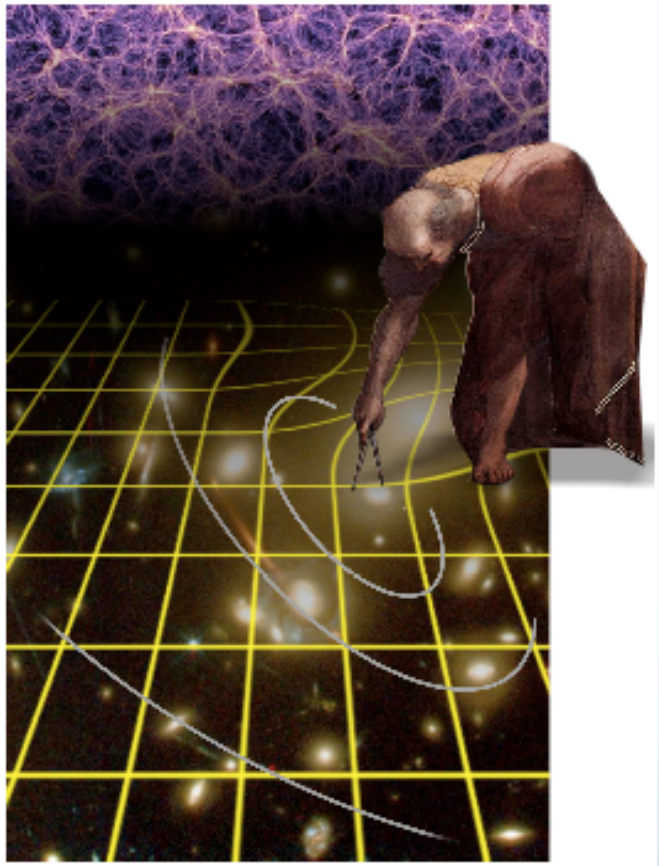


Moon image

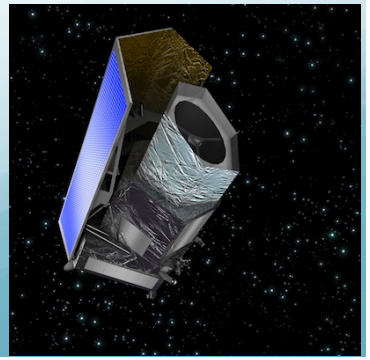


189 science CCD (21 rafts)
3024 Channels
>3 10^9 pixels
Readout: 2s

Space: Euclid

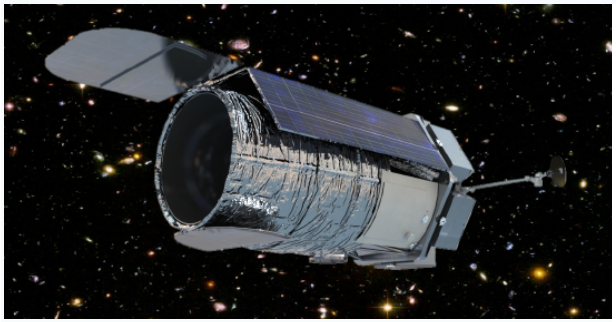


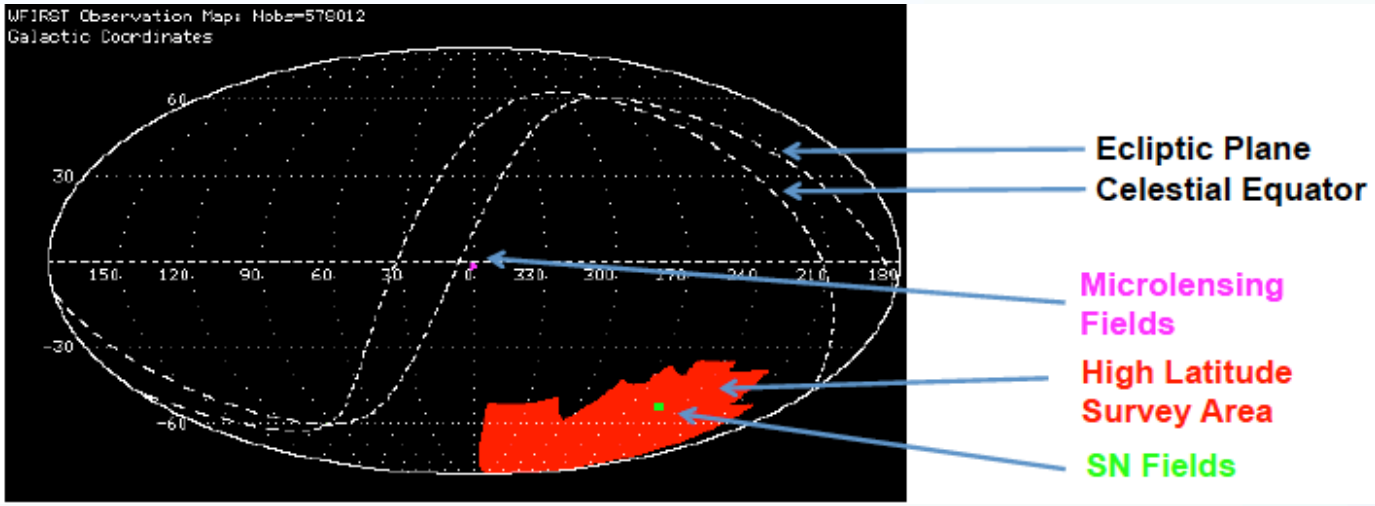
- Optimized for BAO and cosmic shear
  - Other probes: Clusters, z-distortions, ISW
- 1.2m survey telescope at L2
- Two instruments
  - Imaging: Visible RIZ-band to 24.5 mag (shapes) + NIR photometry YJH-bands to 24 mag
  - NIR Spectroscopy
- Tremendous Legacy Science
- Launch 2021



esa space for europe European Space Agency

Space: WFIRST





- Cosmic shear, BAO, Supernovae + Clusters, RSD, ISW (& Exo-planets)
- 2.4m survey telescope at L2
- Wide Field Instrument
- Wide field channel: NIR imaging, Grism spectro (R=645-900)
- Integral Field Unit
- Launch 2025

Conclusions

- Tensions?
- Primordial perturbations
  - Primordial gravity waves from inflation (CMB surveys)
  - Non-Gaussianity (Galaxy surveys)
- Neutrino sector (CMB and galaxy surveys)
  - Mass scale
  - Neff

$$\sigma(\sum m_\nu) = 0.02\,\mathrm{eV}$$

- Dark sector (Galaxy surveys)
  - Dark matter
  - Dark energy
  - Modified gravity
- Baryon physics
  - Galaxy formation and evolution
  - Reionization

Vigorous observational program over next 10-15 years