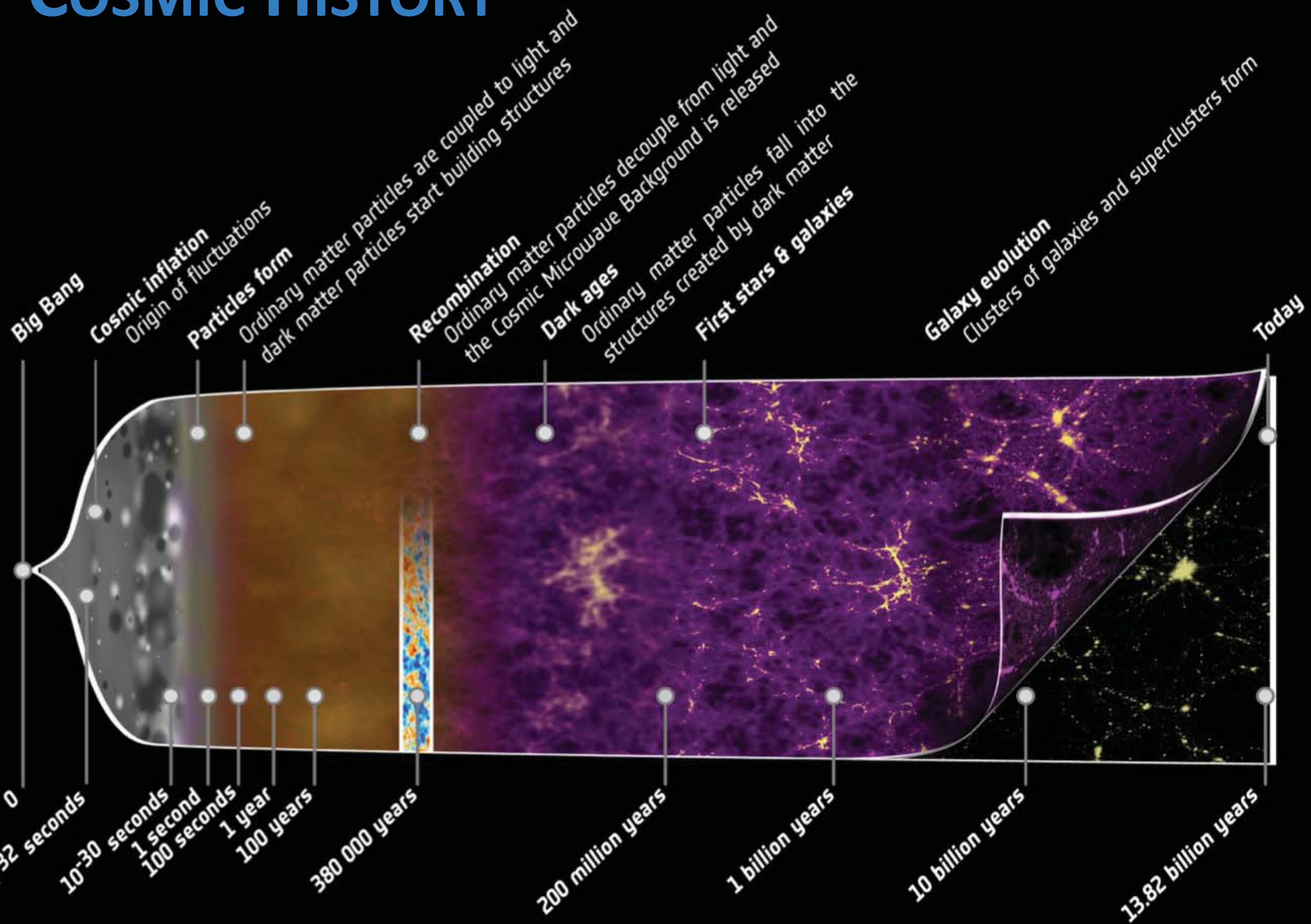
H_0 from Large-Scale Structure Surveys

Matthew Colless

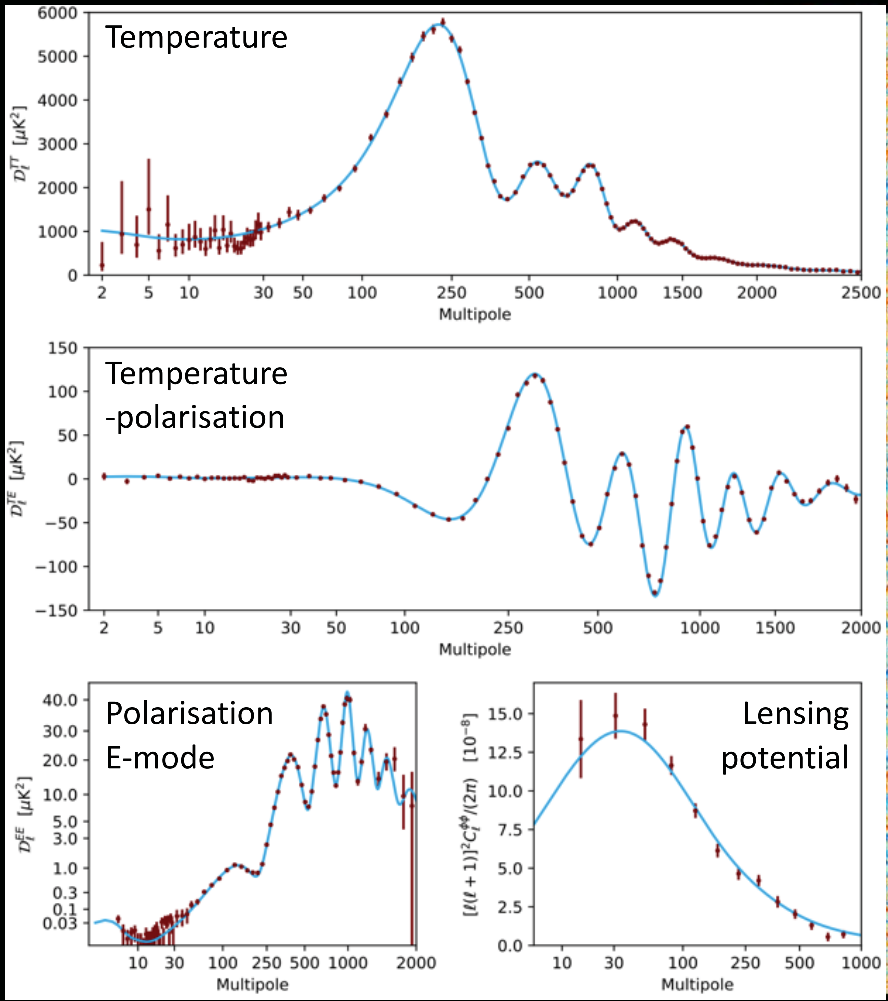
10 November 2018

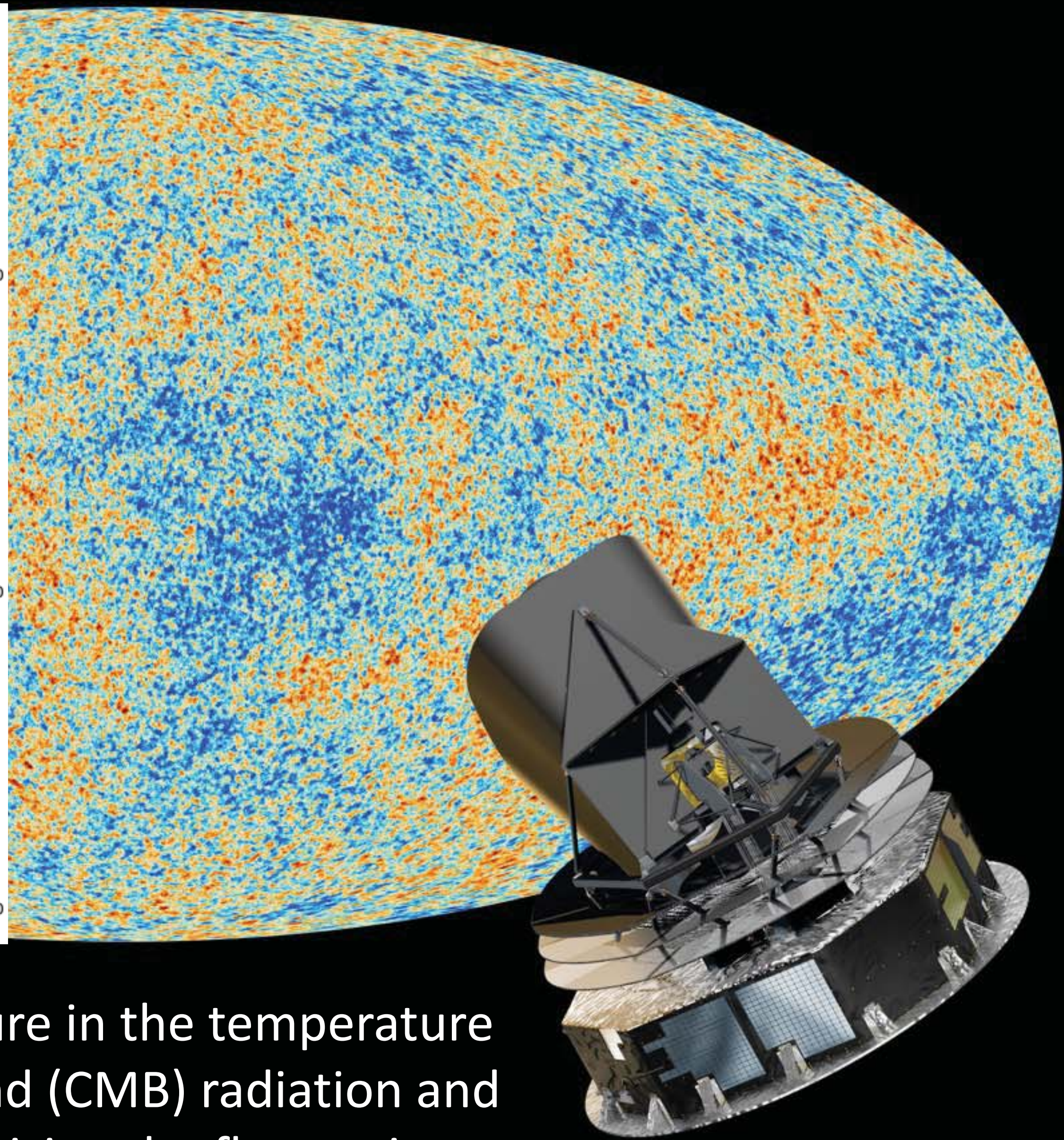
H_0 Symposium, Berlin

Cosmic History



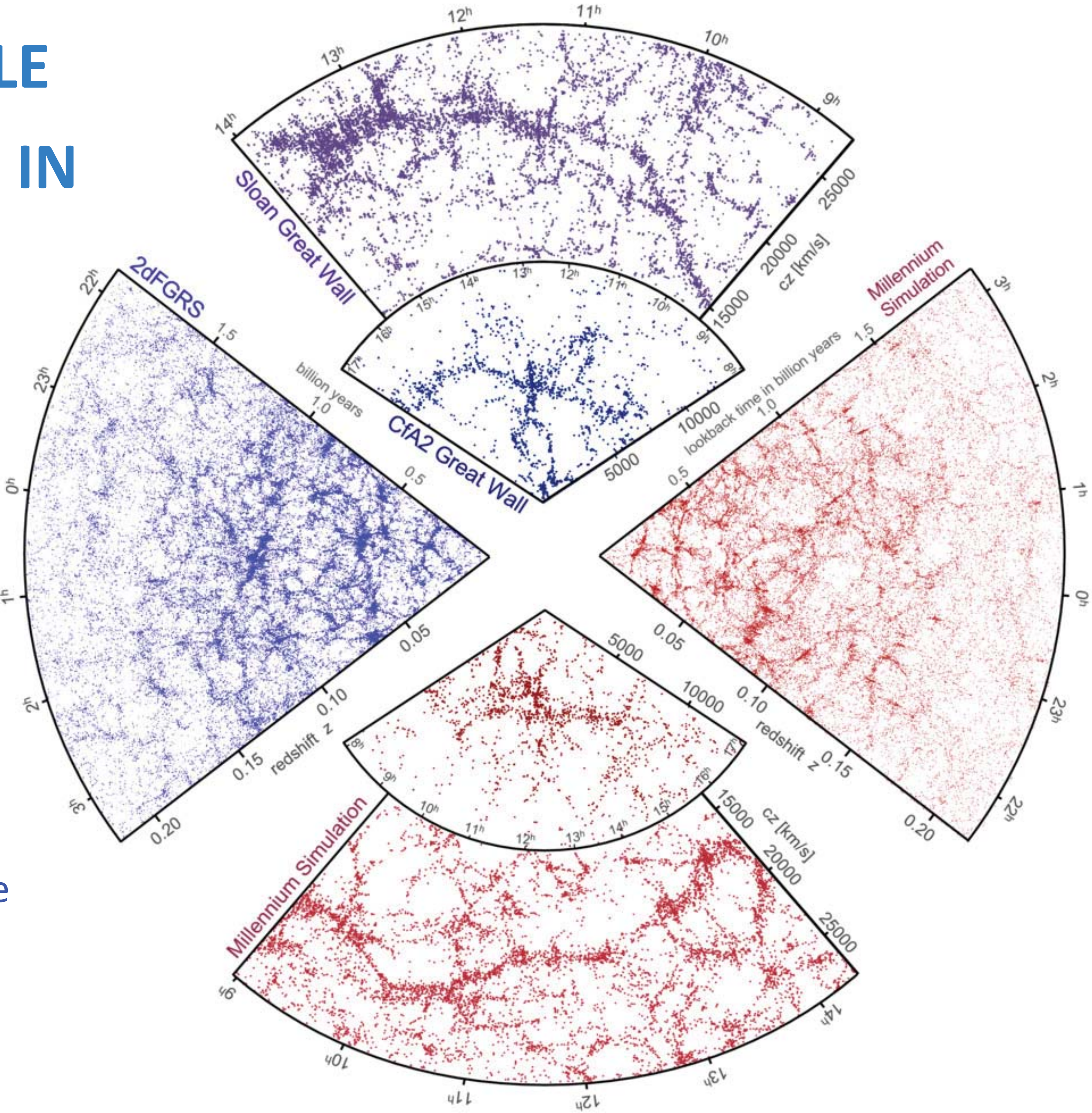
Cosmic Microwave Background





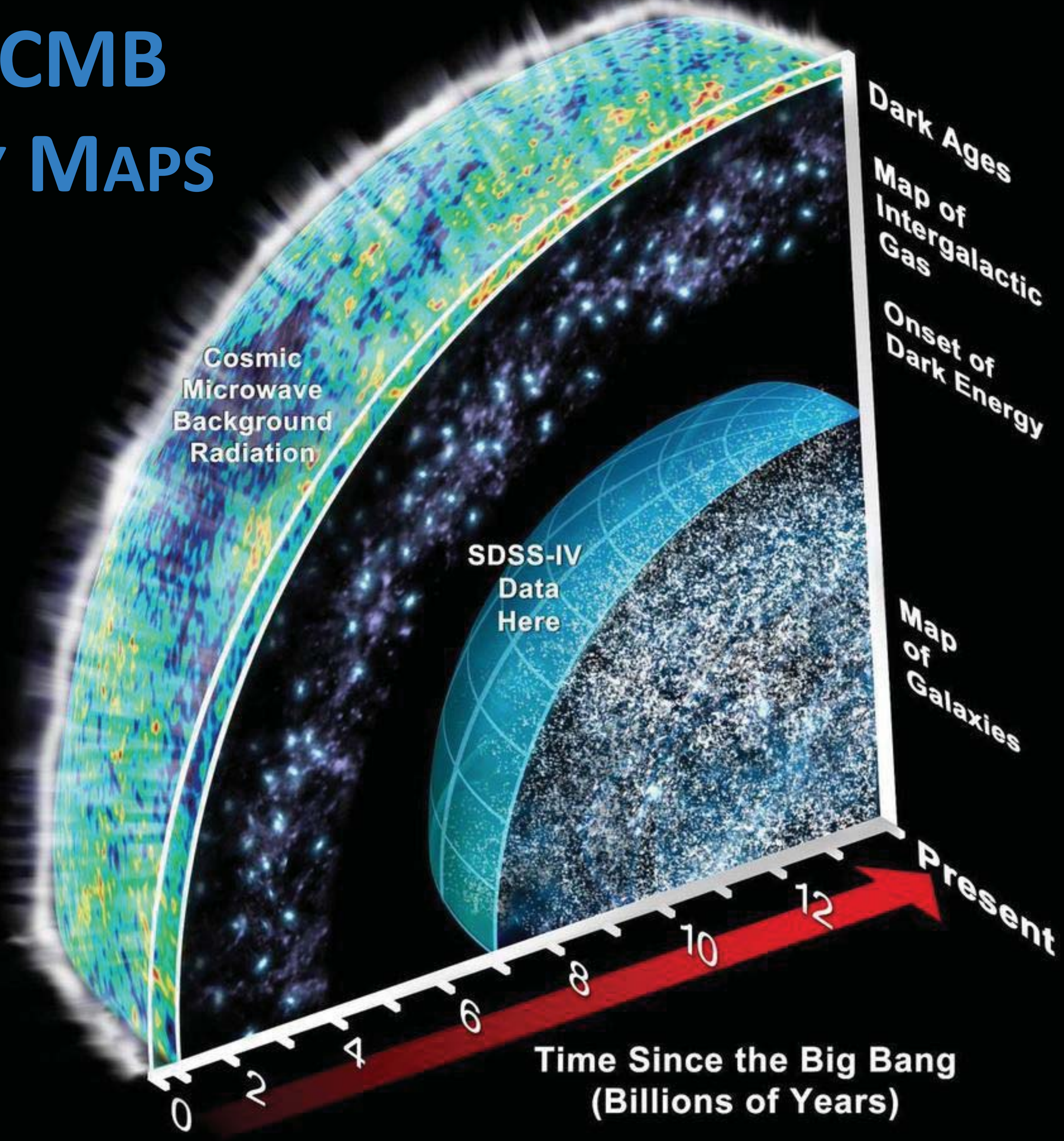
The Planck satellite's map of structure in the temperature of the cosmic microwave background (CMB) radiation and the various power spectra characterising the fluctuations

Large-Scale Structure in Galaxy Maps

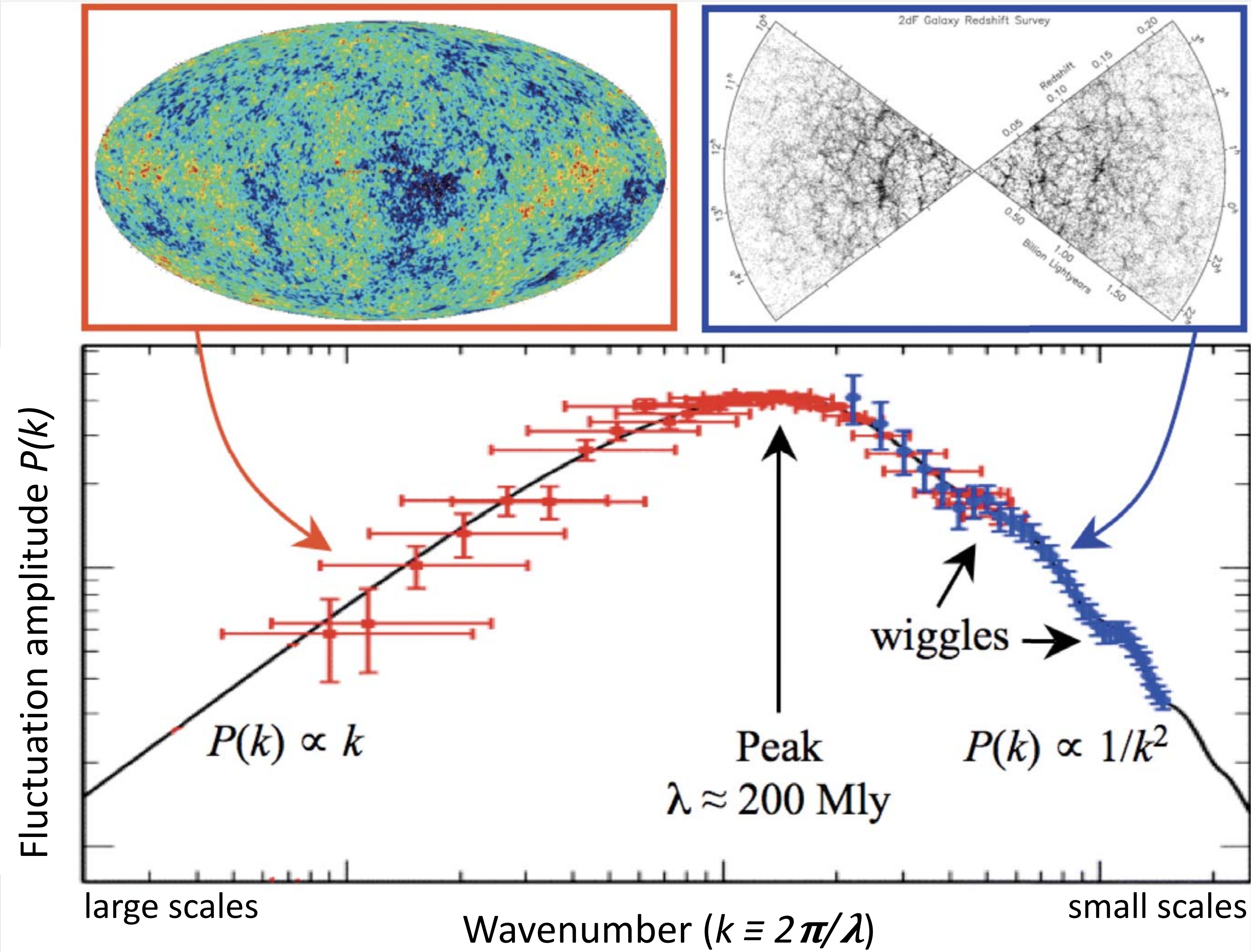


Observations in blue
(2dFGRS & SDSS)
Simulations in red
(Millennium Run)

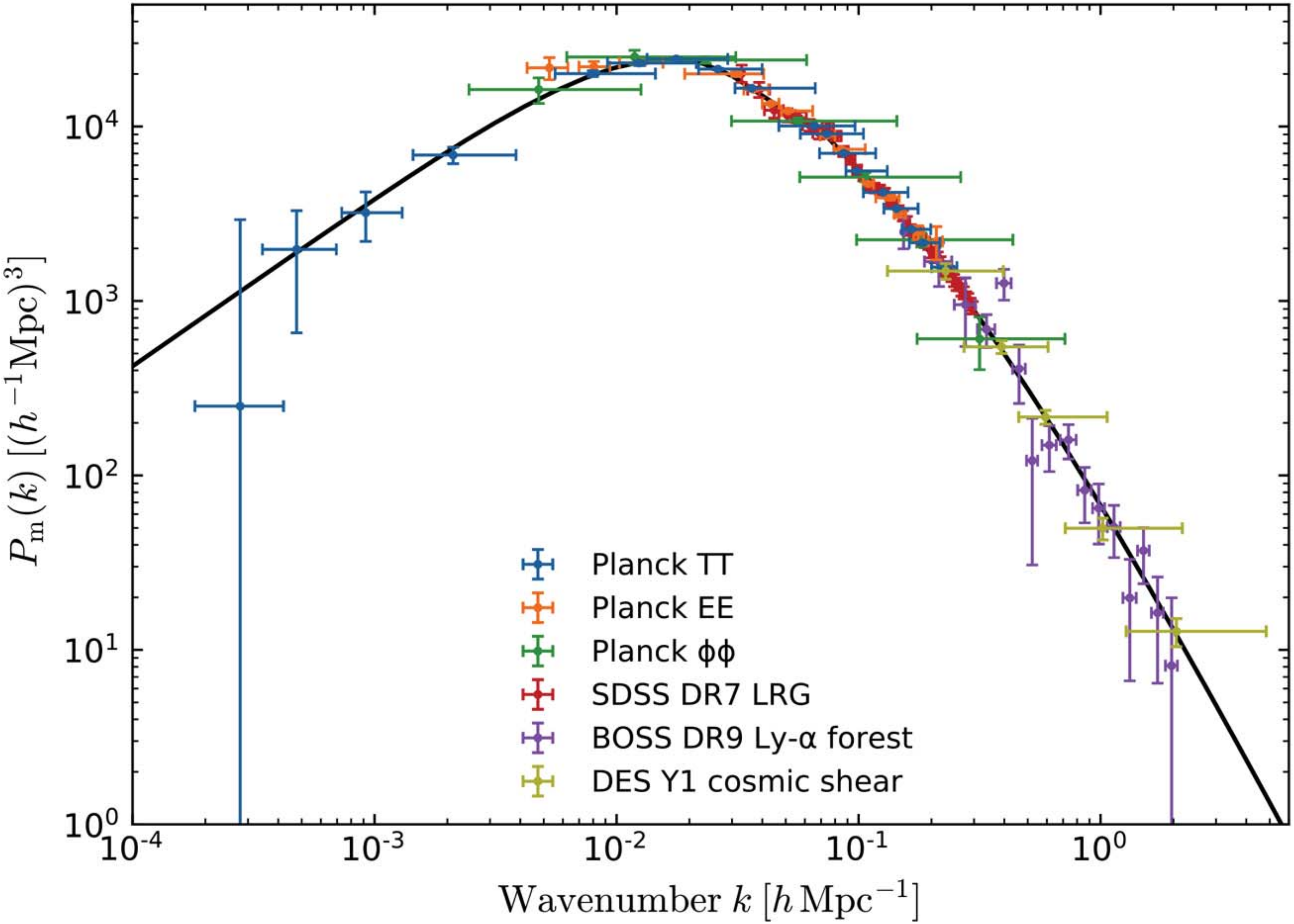
Combining CMB and Galaxy Maps



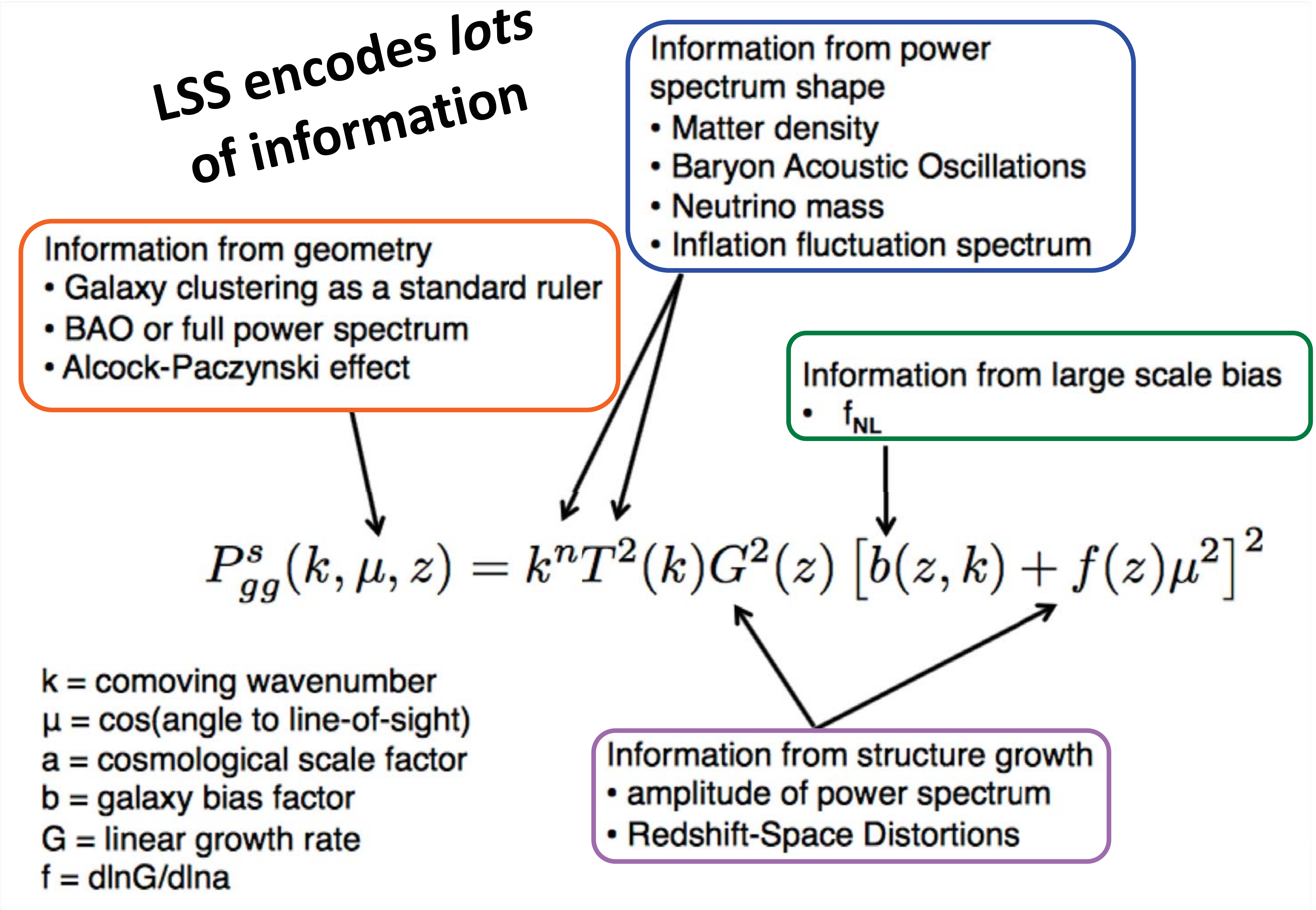
CMB + Galaxy Power Spectrum



CMB + Galaxy Power Spectrum



Physics from Large-Scale Structure



Cosmology Surveys Timeline

1980s	1990s	2000s	2010s	2020s

- CfA, 0, 4.0
- LCRS, 2.0, 4.4
- PSCz, 0, 4.2
- DEEP, ~2, 4.0
- 2dFGRS, 2.6, 5.3
- SDSS, 2.8, 5.9
- 6dFGS, 2.2, 5.1
- WiggleZ, 2.6, 5.5
- BOSS, 3.0, 6.2
- eBOSS, 3.0, 5.7
- Taipan, 2.5, 6.3
- DESI, 3.7, 7.5

non-MOS

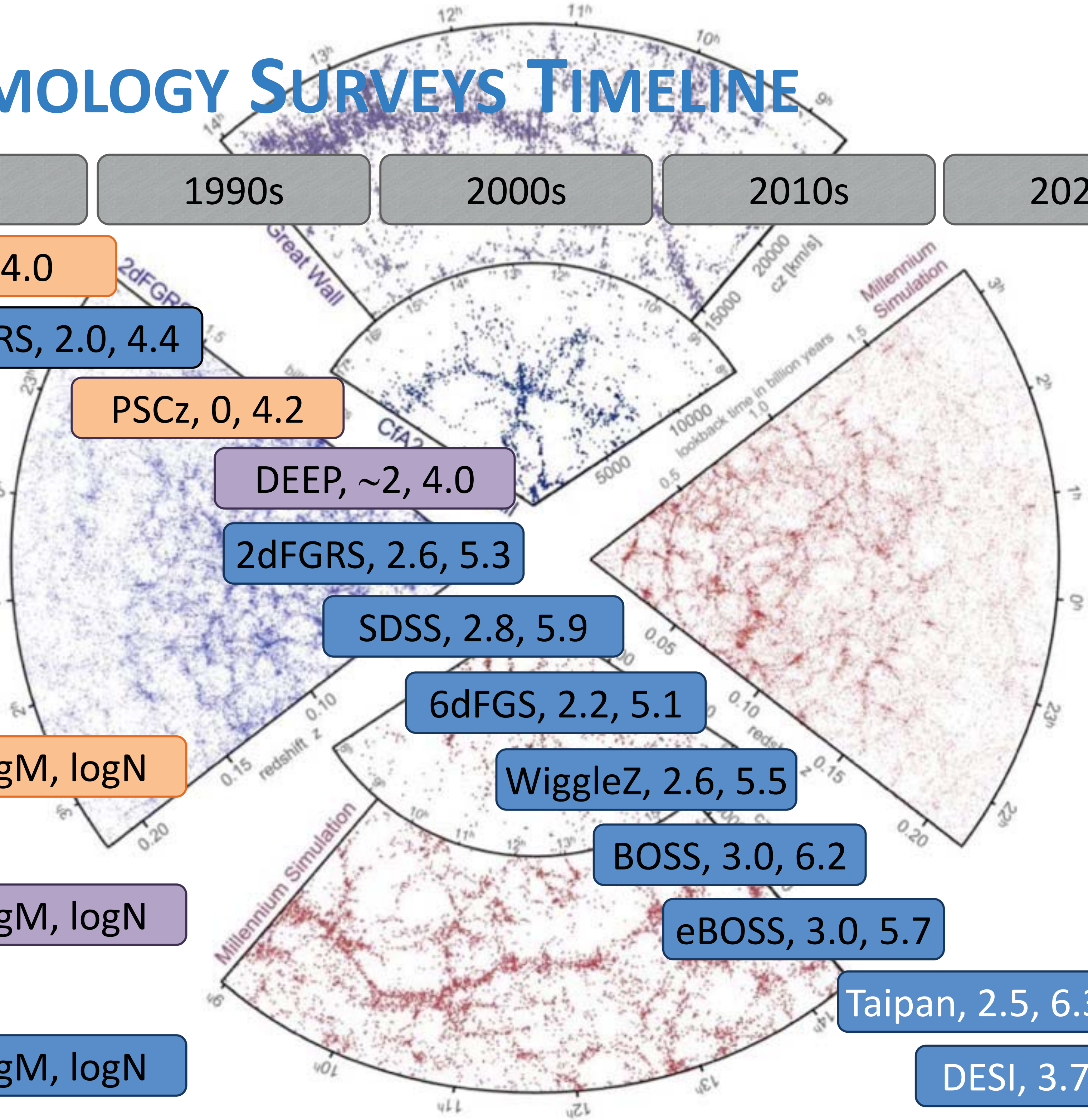
Survey, logM, logN

slit MOS

Survey, logM, logN

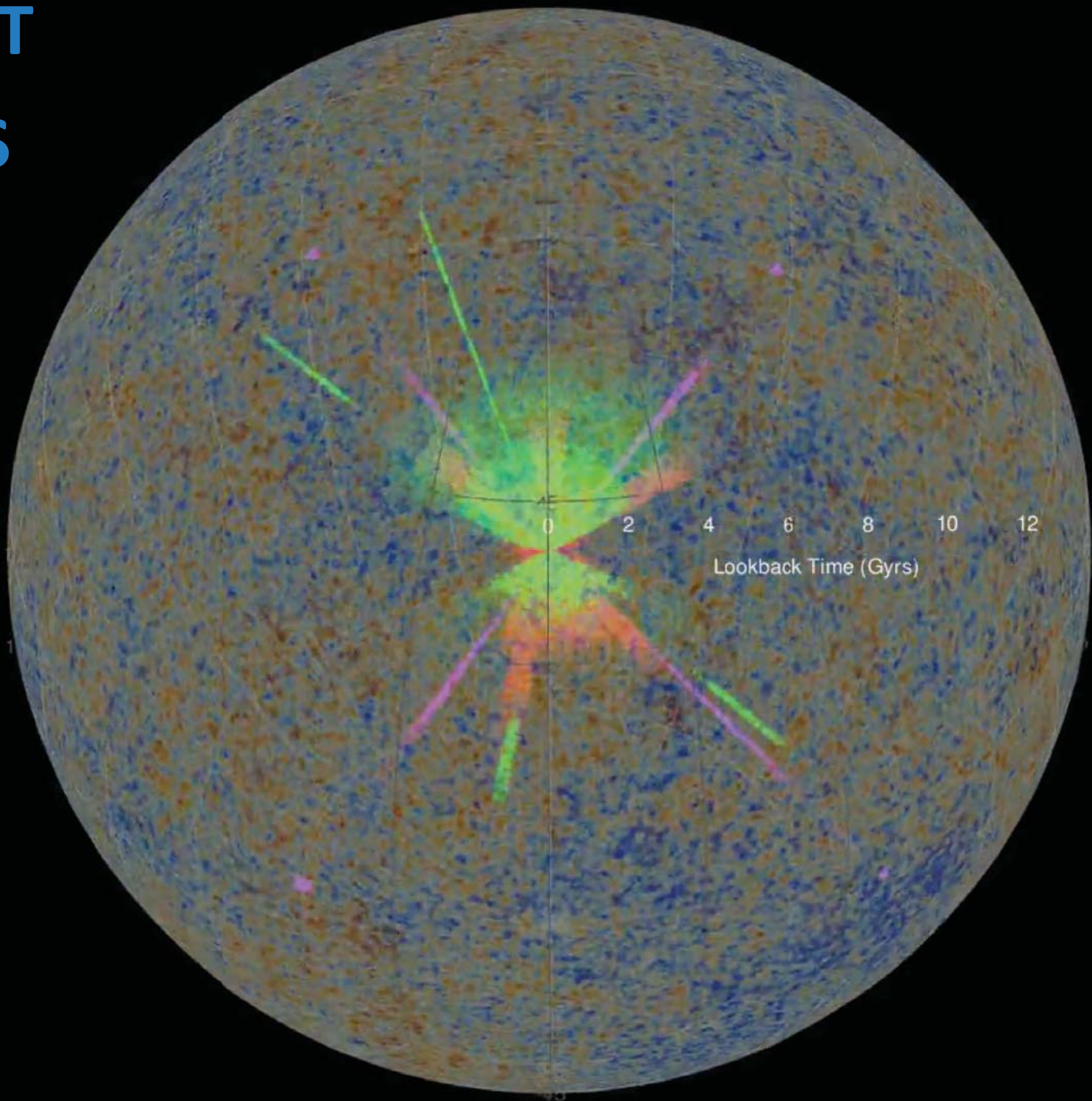
fibre MOS

Survey, logM, logN



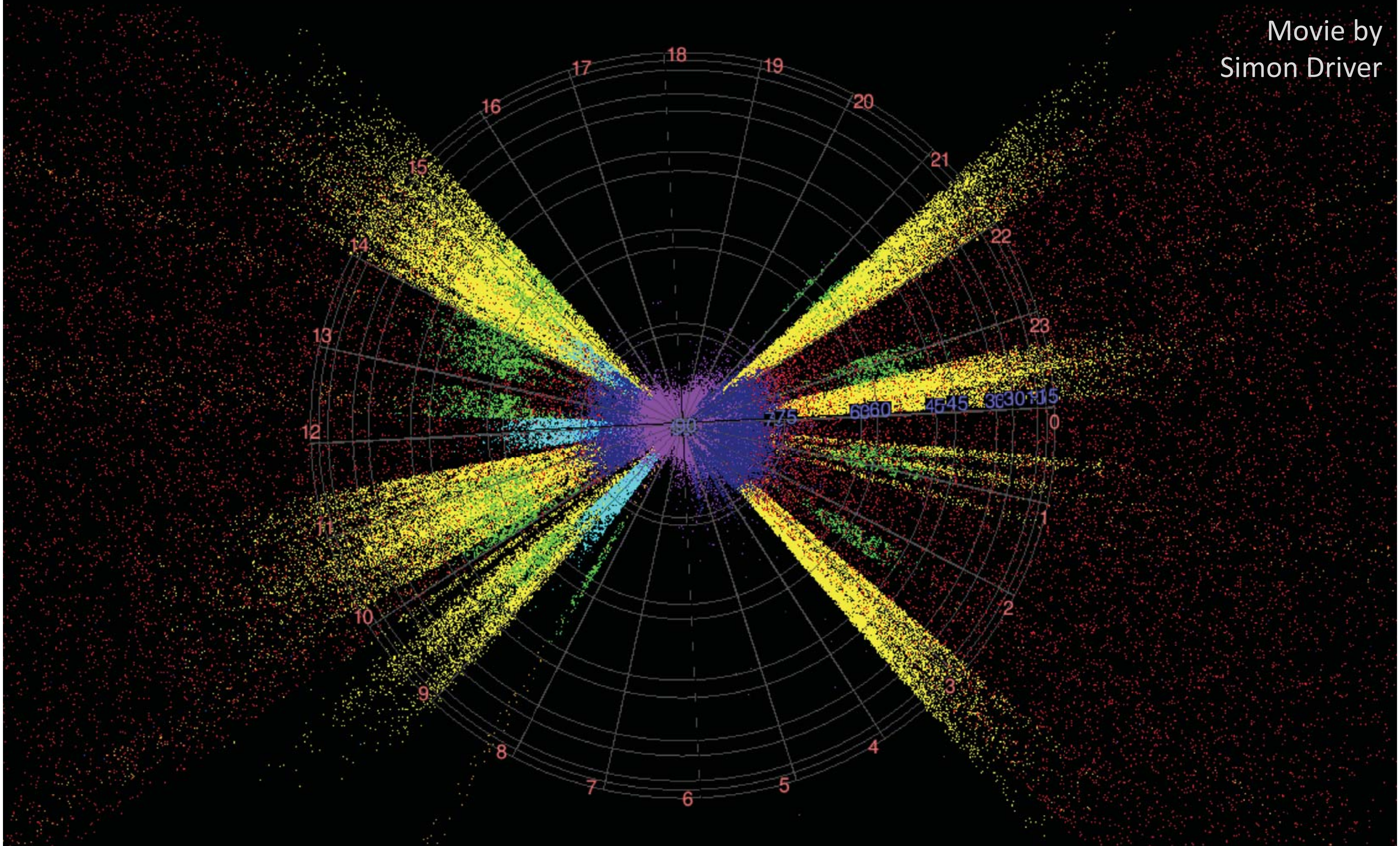
Redshift Surveys

Movie by
Simon Driver



US surveys, European surveys, Australian surveys
(celestial sphere is at CMB)

AUSTRALIAN REDSHIFT SURVEYS

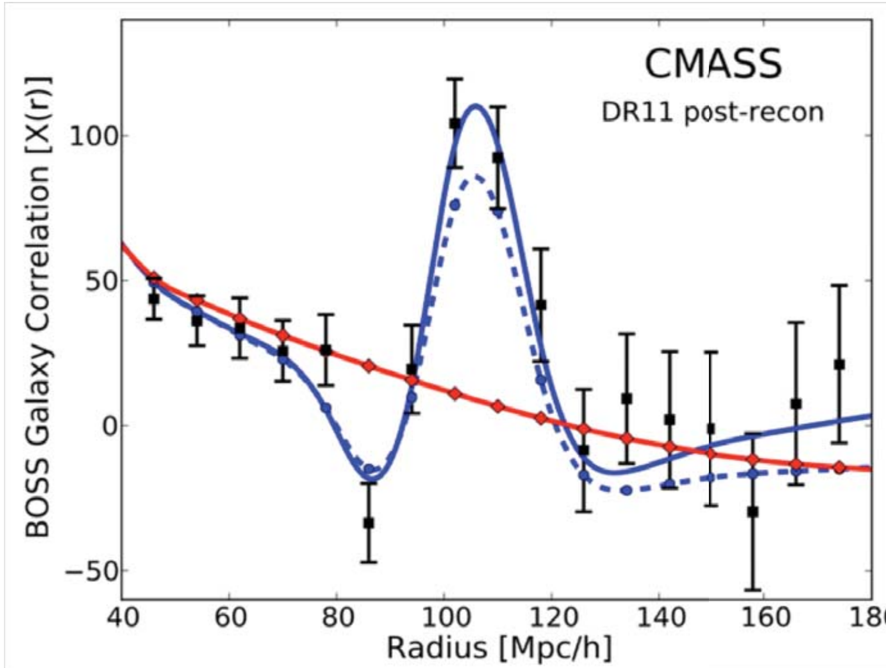


Movie by
Simon Driver

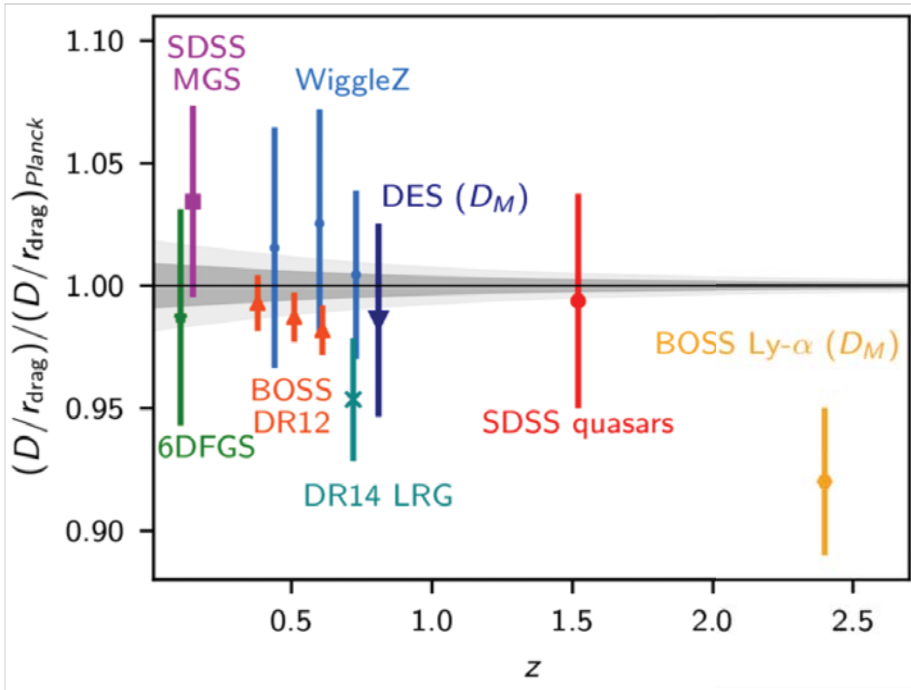
2dFGRS, 2QZ, 2SLAQ-LRG, 2SLAQ-QSO, 6dFGS, GAMA, WiggleZ
(celestial sphere at z=1)

COSMOLOGY FROM BAO

- Baryon acoustic oscillations (BAO) are a cosmological *standard ruler* derived from large-scale structure
- BAO result from pressure waves in the pre-recombination photon-baryon fluid imprinting the sound horizon scale on the matter distribution
- BAO can map cosmic expansion both *along* and *across* the line of sight, and can probe both dark energy & gravity
- Galaxy z-surveys can measure BAO as a function of redshift, and so give the evolution of the angular diameter distance $D_A(z)$ and expansion rate H(z)
- BAO are a precise and (supposedly) well-understood tool, but require very large-scale surveys, in both #s & size



Anderson+ (2014)



Planck+ (2018)

DEVELOPMENT OF BAO SURVEYS

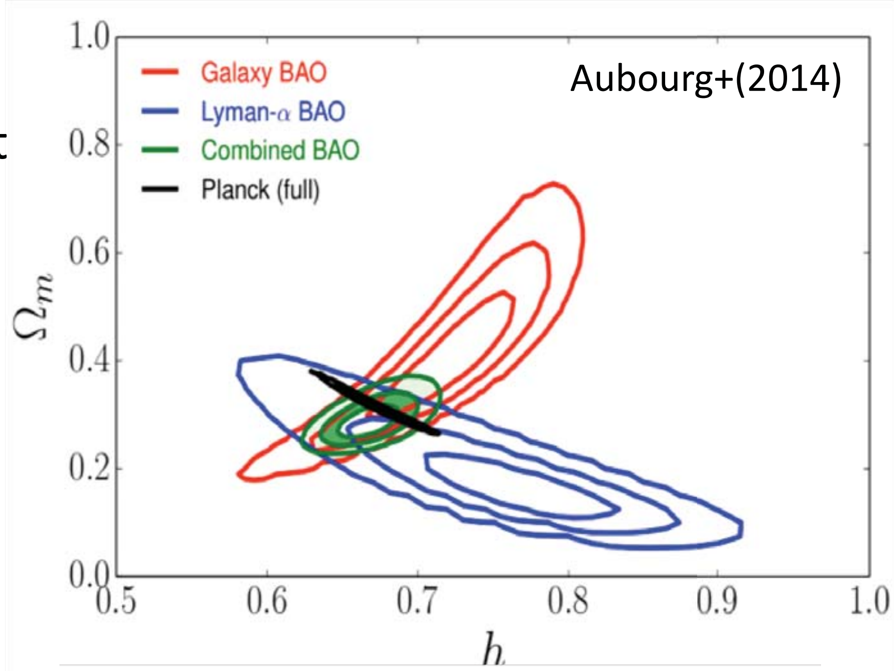
- 2dFGRS & SDSS – BAO were first detected in the galaxy distribution (at 2.5σ) by 2dFGRS and SDSS (Cole+ 2005, Eisenstein+ 2005)
- SDSS-LRG – Kazin+ (2010) used the full LRG sample from SDSS DR7 to obtain a 3.5% measurement of the BAO scale at $z = 0.35$
- 2dFGRS+SDSS – Percival+ (2010) used 900,000 galaxies from the 2dFGRS and SDSS DR7/LRG samples to obtain the BAO scale at $z=0.27$ with 2.7% precision
- 6dFGS – obtained a fiducial low-redshift ($z\sim0.1$) BAO distance measurement with 4.5% precision (Beutler+ 2011, Carter+ 2018)
- WiggleZ survey – observed 2×10^5 emission-line galaxies and measured BAO at $0.5<z<1$ with 3.8% precision (Blake+ 2011)
- BAO reconstruction – Padmanabhan+ (2012) showed that BAO measurements can be improved by about a factor of 2 through reconstruction of the density field

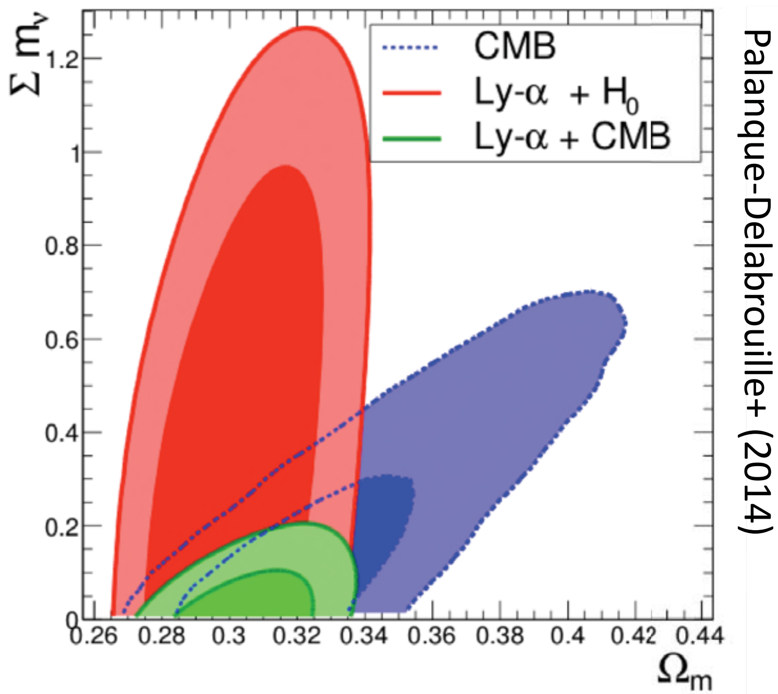
LSS Surveys - the State of the Art

- BOSS survey (part of SDSS-III) detects BAO feature at 7σ in galaxies and 5σ in Lyα forest
- BAO alone yield a high-confidence detection of dark energy and, with the CMB acoustic scale, BAO imply a nearly flat universe
- BAO+CMB+SNe data jointly give an estimate H_0 = 67.3 ± 1.1 km/s/Mpc (1.7%), robust to assumptions about dark energy & curvature
- For constant dark energy (Λ), combining BAO+CMB+SNe yields

  $\Omega_m = 0.301 \pm 0.008$ (2.7%)

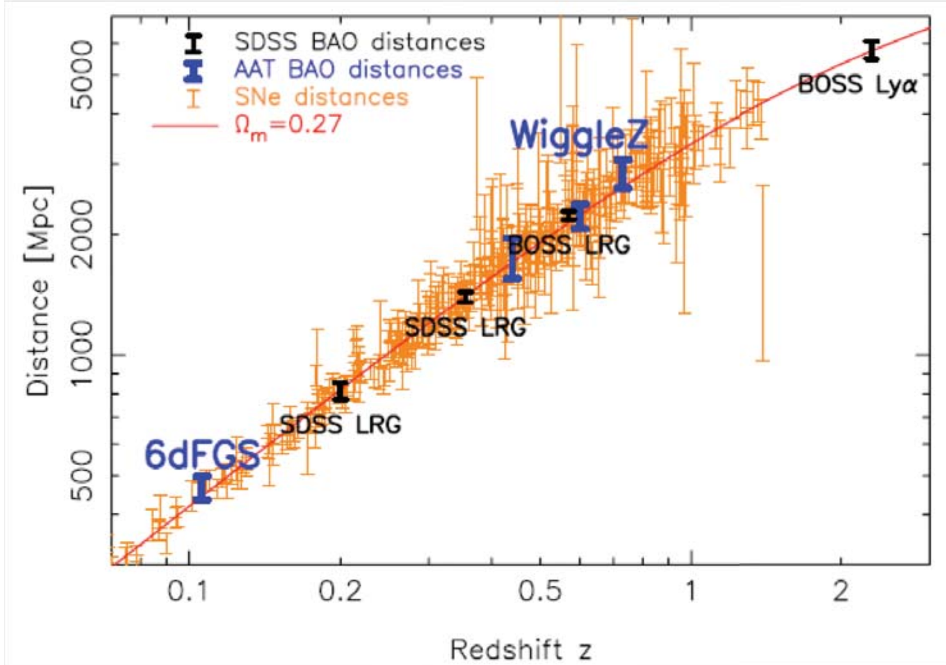
  $\Omega_k = -0.003 \pm 0.003$
- For evolving forms dark energy, combined BAO+CMB+SNe data are always consistent with flat ΛCDM at about the 1σ level
- BAO+CMB+WL give a summed mass for neutrino species of $\Sigma m_\nu < 0.25$ eV
- eBOSS (part of SDSS-IV) is mapping 0.5x10^6 QSOs to map the BAO feature over 0.8<z<2.

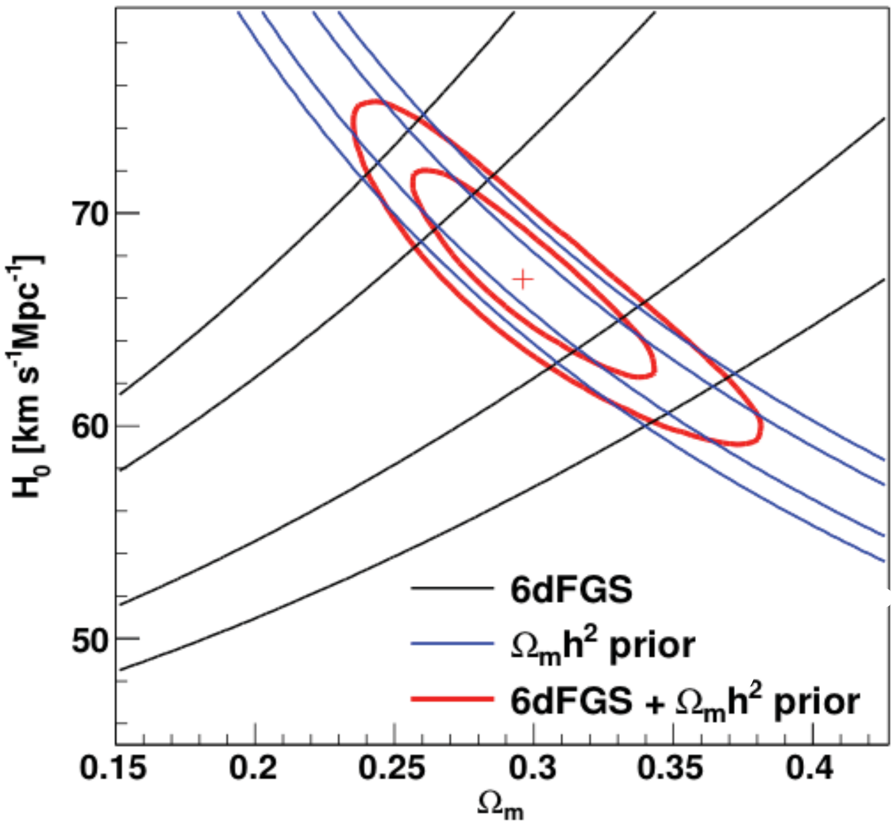




H_0 FROM THE 6DF GALAXY SURVEY (6DFGS)

- At low z, distance measures only constrain H_0 – but such local H_0 estimates are nearly independent of the cosmological model
- 6dFGS BAO gives low H_0 consistent with CMB, unlike local distance ladder estimates





low-z

Beutler+ 2011 (6dFGS, BAO)
H_0 = 67 ± 3.2 km/s/Mpc

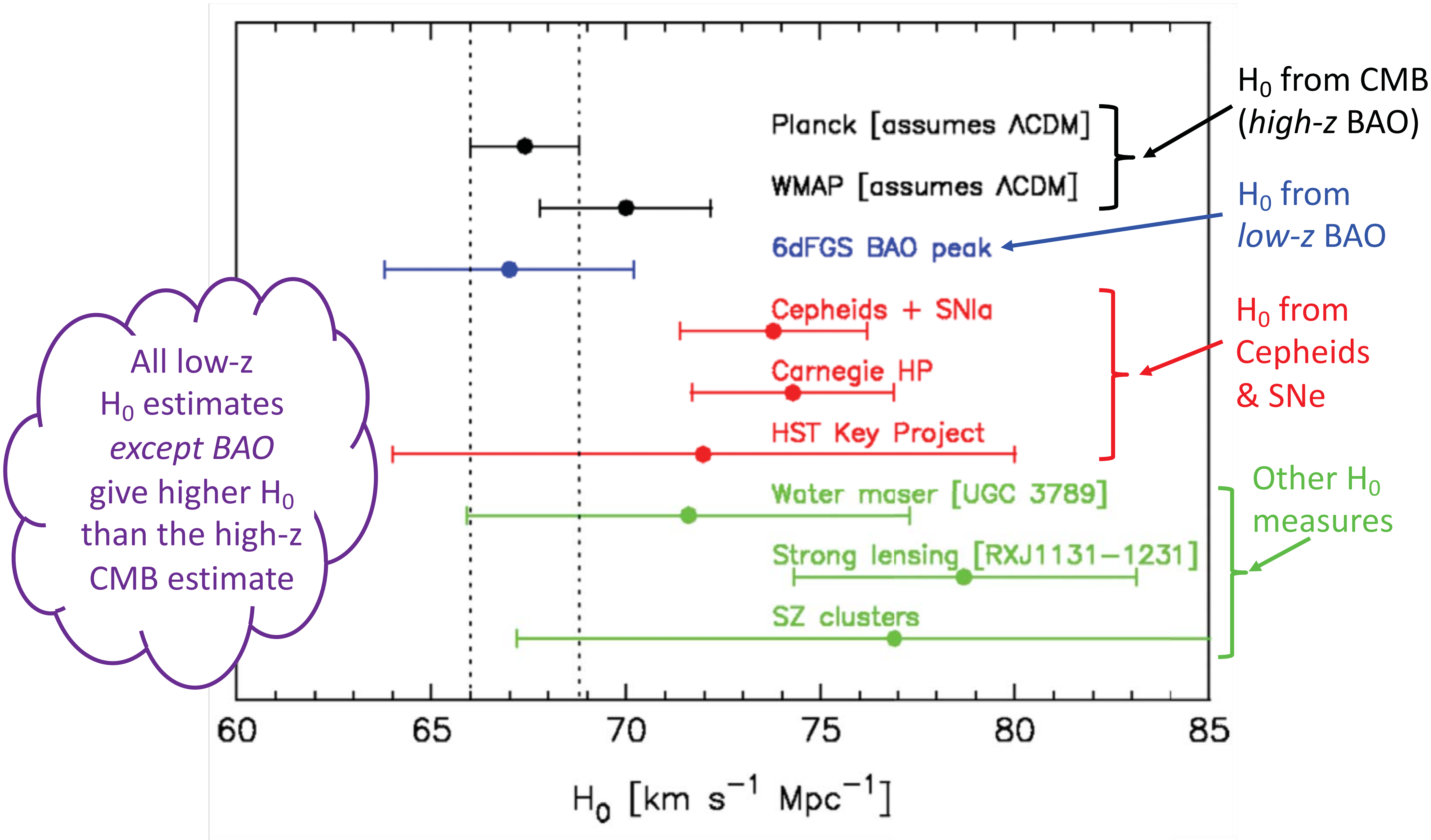
Riess+ 2018 (Cepheids, SNe)
H_0 = 73.5 ± 1.6 km/s/Mpc

high-z

Planck 2018 (CMB, BAO)
H_0 = 67.4 ± 0.5 km/s/Mpc
(model-dependent)

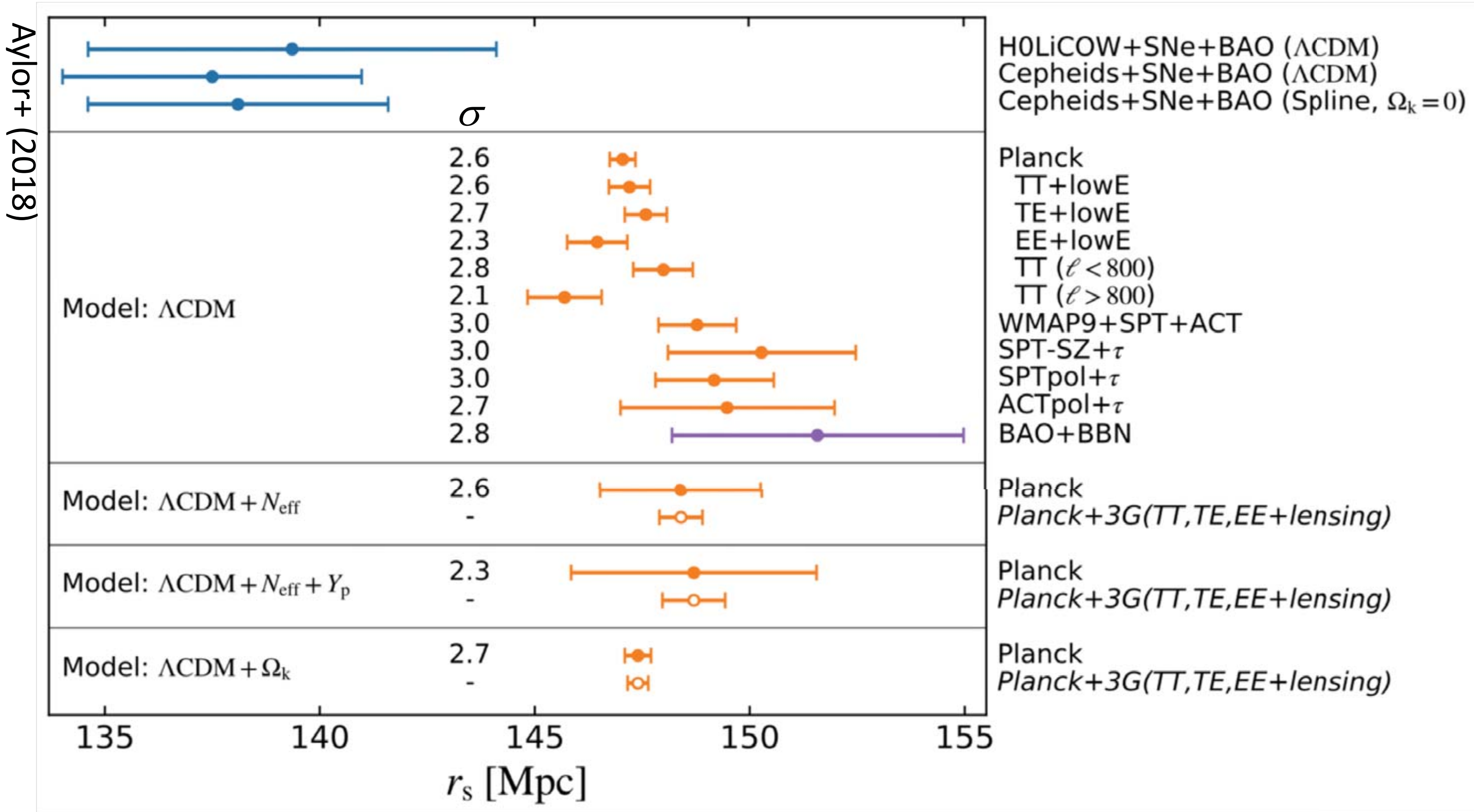
3.6σ tension

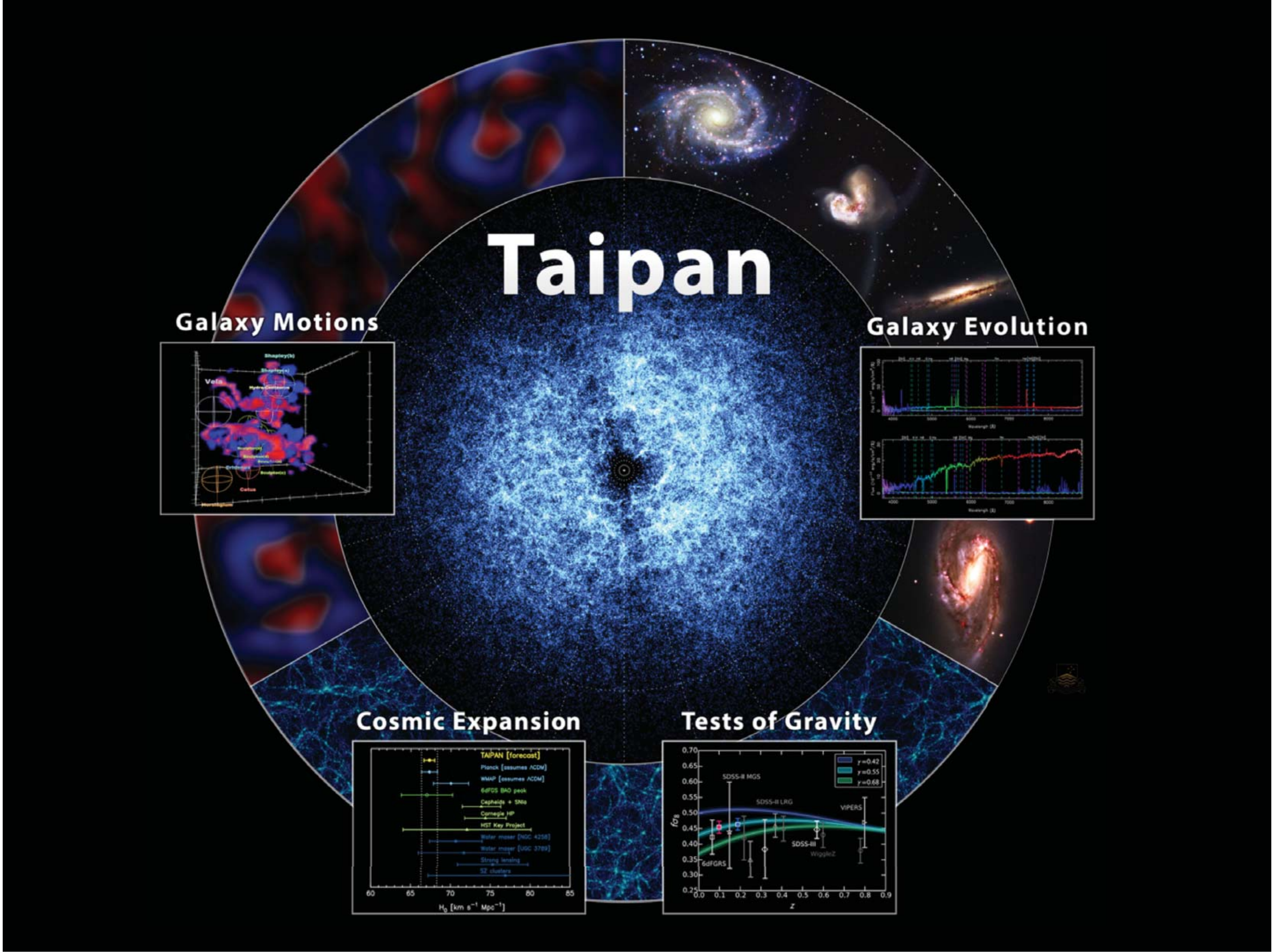
Local & CMB H_0 are Discrepant



BAO Scale Discrepancy

- The H_0 discrepancy is equivalent to (can be interpreted as) a discrepancy in the BAO scale (the sound horizon scale at the drag epoch, r_s)

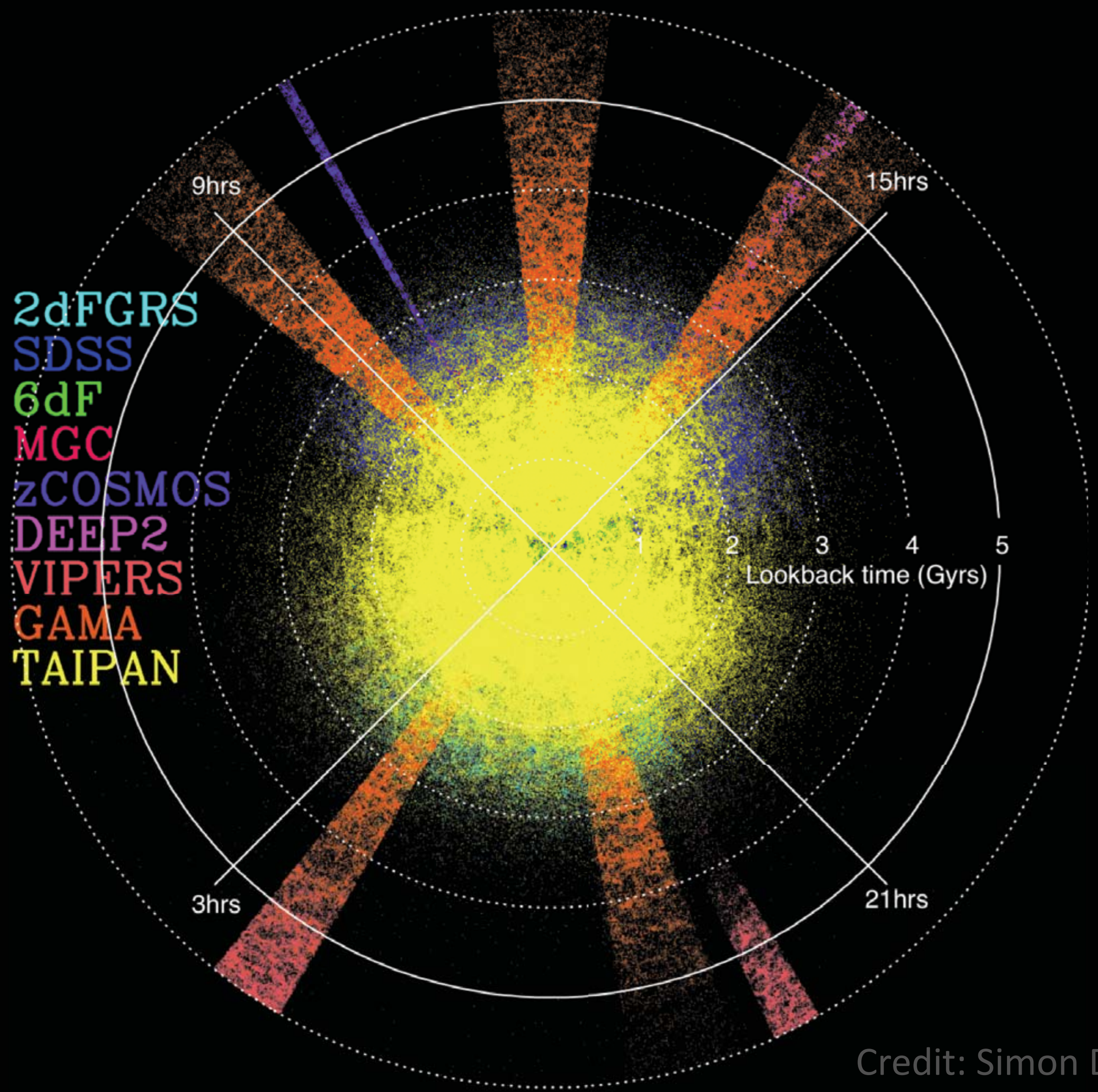



Taipan
Galaxy Motions
Shapley(b)
Vela
Galaxy Evolution
Cosmic Expansion
TAIPAN [forecast]
Planck [assumes ΛCDM]
WMAP [assumes ΛCDM]
6dFGS BAO peak
Cepheids + SNIa
Carnegie HP
HST Key Project
Water maser [NGC 4258]
Water maser [UGC 3789]
Strong lensing
SZ clusters
60 65 70 75 80 85
H0 [km s−1 Mpc−1]
Tests of Gravity
γ=0.42
γ=0.55
γ=0.68
SDSS-II MGS
SDSS-II LRG
VIPERS
SDSS-III
WiggleZ
6dFGRS
fσ8
z

THE TAIPAN SURVEY

- Taipan is a spectroscopic galaxy survey covering 2π steradians (Dec < +10°, b>|10°|) using 1.2-metre UK Schmidt Telescope
- Redshifts for 2×10^6 galaxies: a complete sample of 1.2×10^6 galaxies to $i = 17$ & a sample of 0.8×10^6 luminous red galaxies
- Effective redshift $\langle z_{eff} \rangle \approx 0.17$; effective volume $V_{eff} \approx 1.3$ Gpc^3
- Observing program will take 4.5 years, starting March 2019
- A key science goal for Taipan is measuring H_0 to 1% precision
- Survey description: da Cunha et al., 2017, PASA, 34, 47 https://doi.org/10.1017/pasa.2017.41
- More details about the Taipan survey available on website https://www.taipan-survey.org/

Redshift Surveys

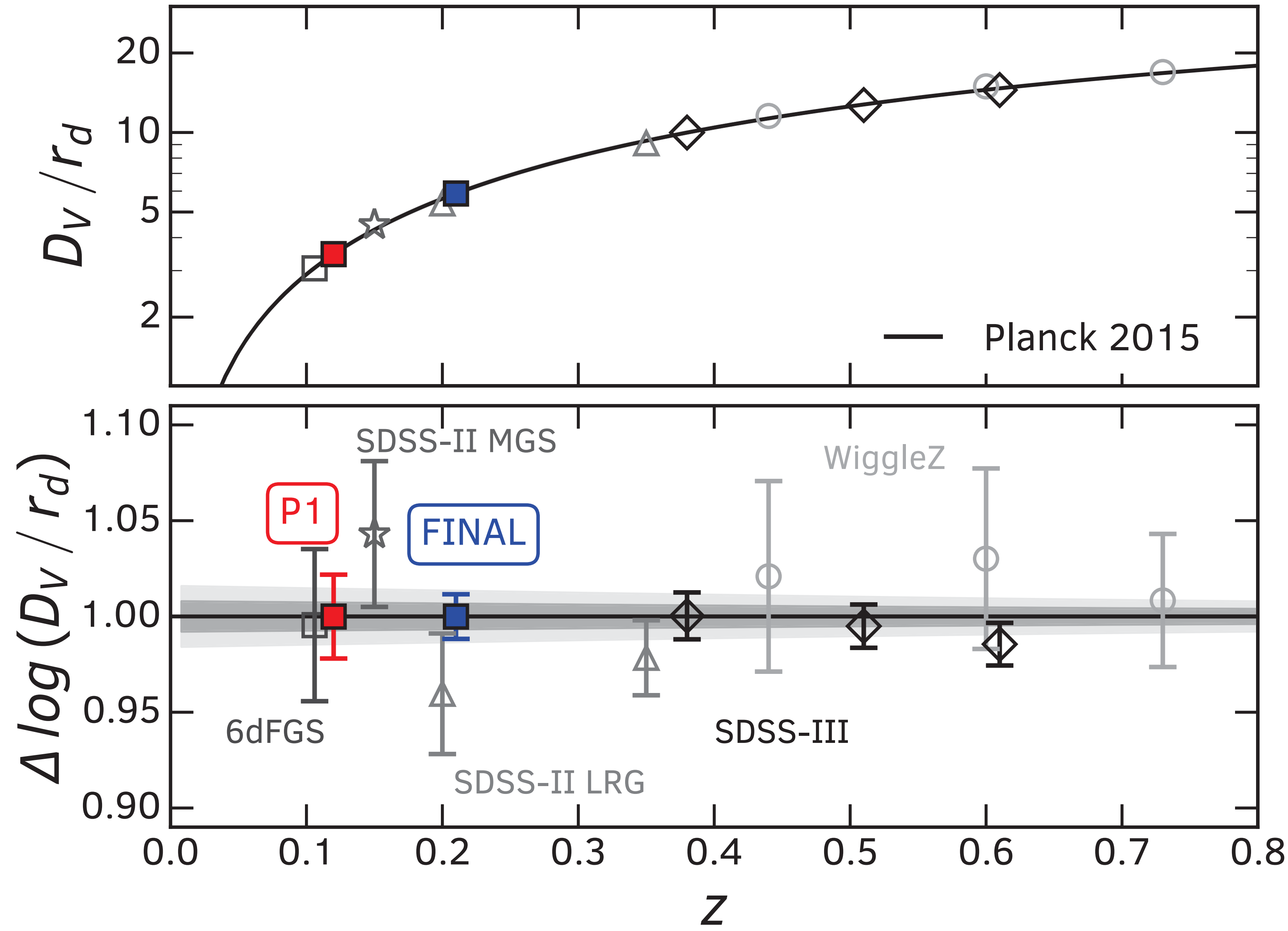


Credit: Simon Driver (UWA)

Taipan Survey Components & Phases

- The Taipan galaxy survey has three components:
  - BAO survey – large-volume z-survey optimized for cosmology
  - Peculiar velocity survey – Fundamental Plane survey optimized for nearby early-type galaxies & measuring peculiar velocities
  - Legacy survey – an i-band magnitude-limited sample with high completeness optimized for galaxy studies & legacy value
- The survey will be carried out in two phases:
  - Taipan Phase 1 [first ~15 months] will be based on 2MASS (BAO survey), 6dFGS (PV survey) & KiDS-S (i-band survey); these are the best available sources at the start of the survey
  - Taipan Final [next ~3 years] will be based on SkyMapper and PanSTARRS (all surveys); best input sources by end of Phase 1

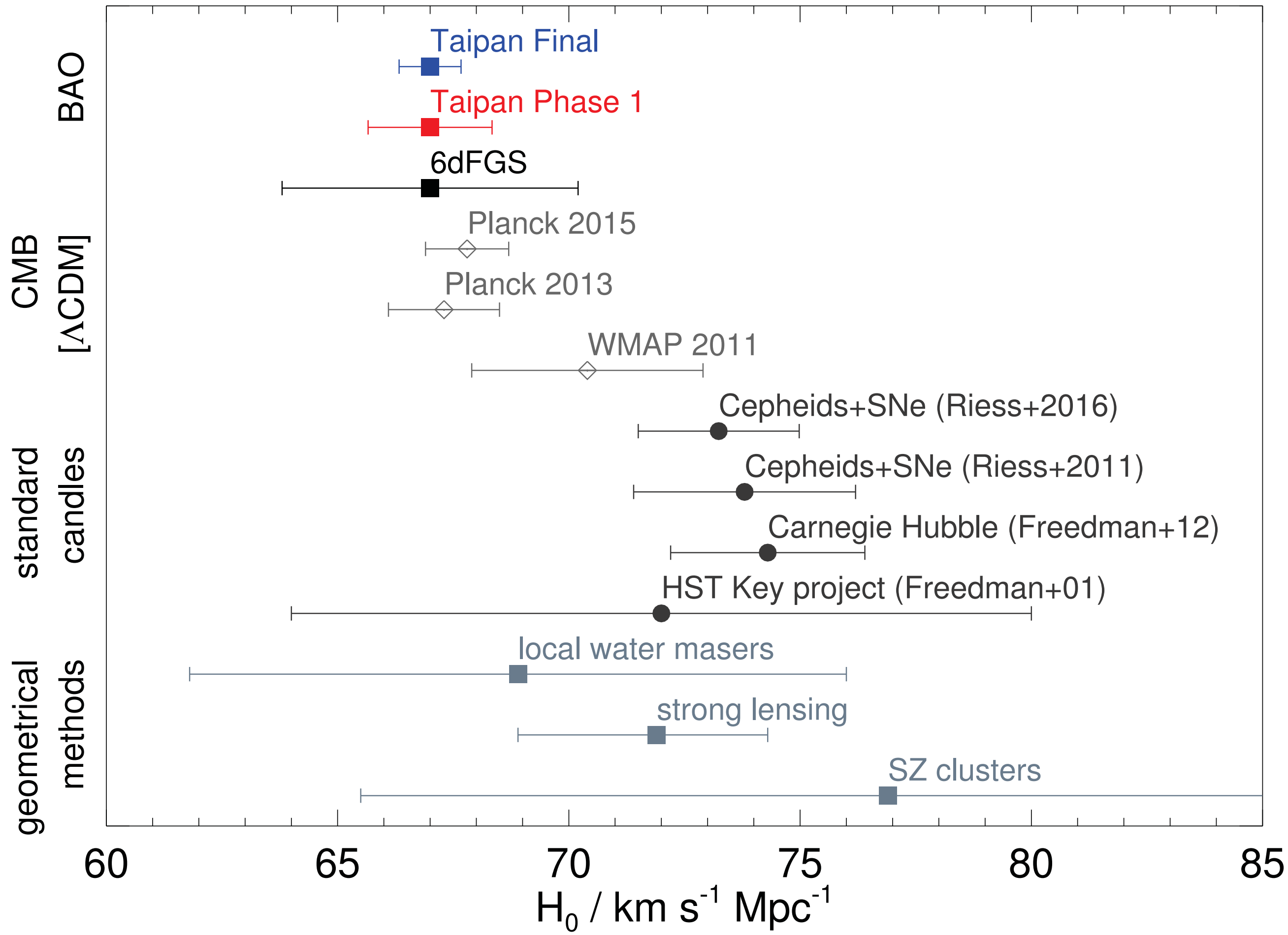
Taipan BAO Distances



HUBBLE CONSTANT FROM TAIPAN

- With 2×10^6 galaxies at $\langle z_{eff} \rangle \approx 0.17$ over $V_{eff} \approx 1.3$ Gpc^3, simulations show that Taipan Final will measure H_0 to 0.9% precision, with 2.1% precision already by the end of Taipan Phase 1 (da Cunha+ 2017)

- Taipan Final gives H_0 with 5x the precision of 6dFGS:
  - o Gain ~2.5x from larger sample size and volume of Taipan *cf.* 6dFGS
  - o Gain another ~2x from better BAO reconstruction



H_0 Tensions

- Taipan will test the tension in H_0 measurements between high-redshift CMB (=BAO) and low-redshift distance ladder estimates by providing a 1% BAO measurement at low redshift
    - 2018 status: high-*z* Planck CMB and low-*z* SNe distance ladder estimates are in >3σ tension
    - 2022 case A: Taipan supports the *Planck CMB* estimate with a BAO-derived low-*z* 1% H_0 measurement...
    - 2022 case B: Taipan supports the *distance ladder* estimate with a BAO-derived low-*z* 1% H_0 measurement...
- Less interesting intermediate cases are of course also possible!

2018 status	BAO measure	Distance ladder
High redshift (z~1100)	Planck (2018) CMB 67.4 +/- 0.5	N/A
Low redshift (z<0.1)	6dFGS (2011) BAO 67.0 +/- 3.2	Riess+(2018) SNe 73.5 +/- 1.6

2018 status ⇒ 3.6σ tension between BAO (CMB) and distance ladder (SNe) results

2022 Case A	BAO measure	Distance ladder
High redshift (z~1100)	Planck (2018) CMB 67.4 +/- 0.5	N/A
Low redshift (z<0.1)	Taipan (2022) BAO 67.4 +/- 0.6	Riess+(2022) SNe 73.5 +/- 0.7

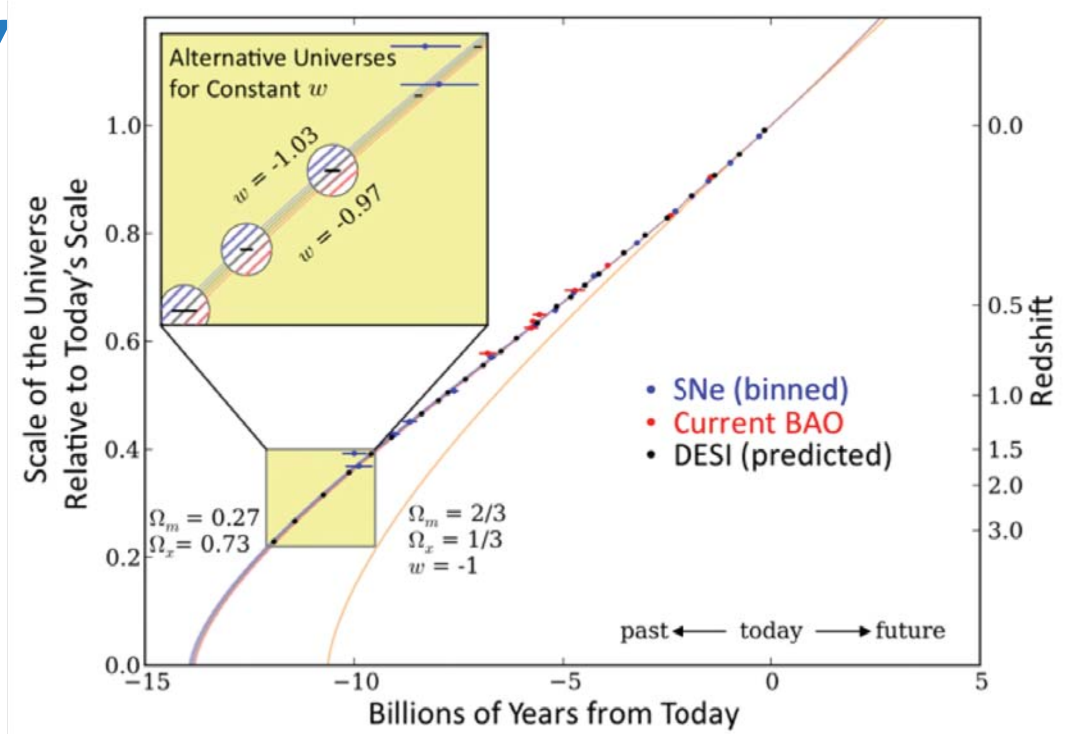
2022 Case A ⇒ 7.1σ discrepancy between the low-z results of two methods ⟹ problem with distance ladder or BAO scale?

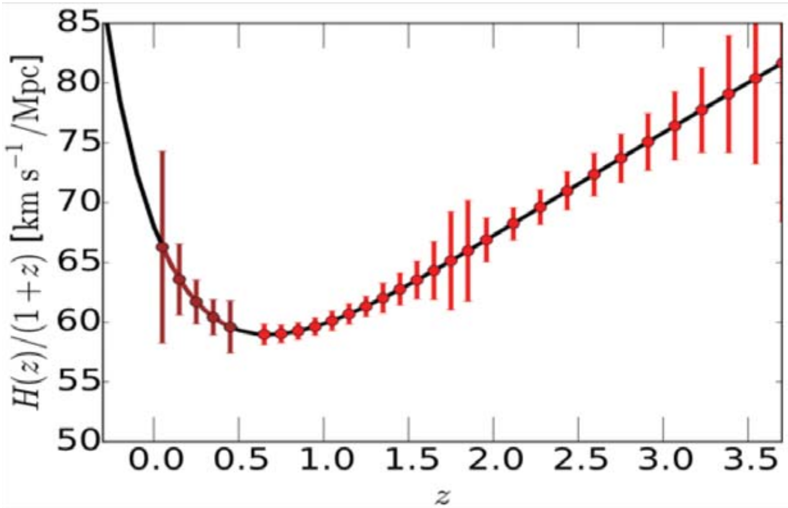
2022 Case B	BAO measure	Distance ladder
High redshift (z~1100)	Planck (2018) CMB 67.4 +/- 0.5	N/A
Low redshift (z<0.1)	Taipan (2022) BAO 73.5 +/- 0.7	Riess+(2022) SNe 73.5 +/- 0.7

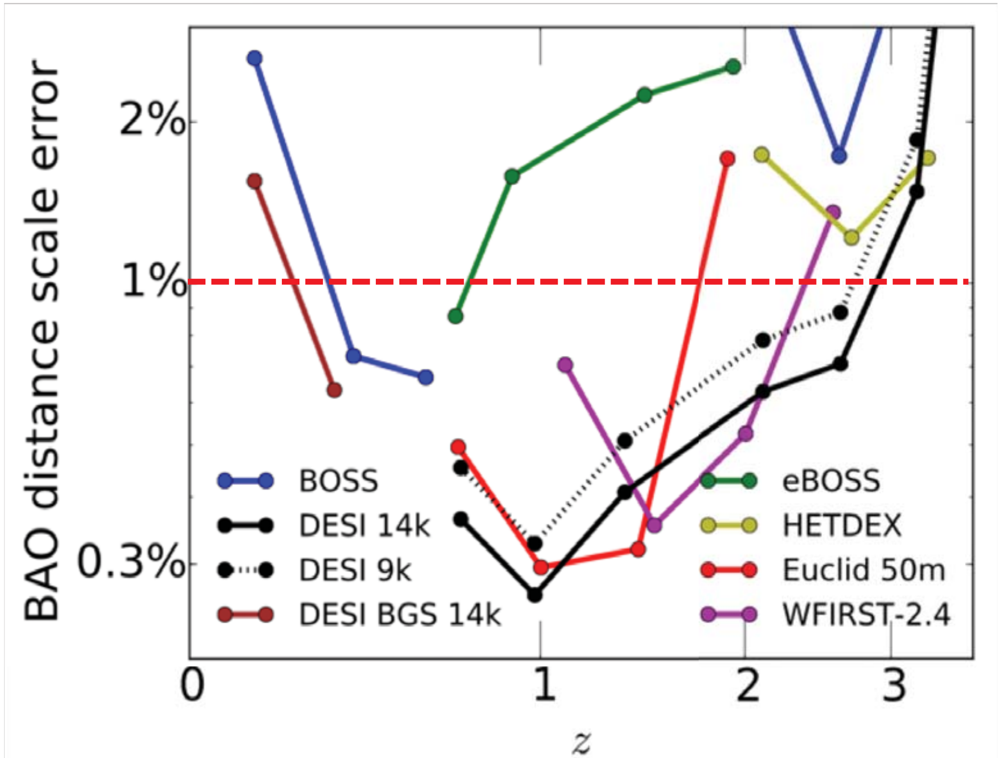
2022 Case B ⇒ 7.1σ discrepancy between low-z and high-z BAO results ⟹ problem with cosmological model at z<1100?

Dark Energy Survey Instrument (DESI)

- DESI is a Stage IV dark energy experiment to study BAO with a wide-area galaxy & QSO z-survey
- Four target samples observed:
  - Luminous red galaxies up to z=1.0
  - [OII] emission-line galaxies to z=1.7
  - QSOs at 2.1<z<3.5 and their Ly-α forest neutral hydrogen absorption
  - A magnitude-limited Bright Galaxy Survey of ~10^7 galaxies with z≈0.2
  - In total, 3×10^7 galaxy and QSO z's







Conclusions – H_0 from LSS Surveys

- Is there just tension or a real discrepancy in H_0 measurements?
  - Taipan and the DESI Bright Galaxy Survey will measure H_0 from BAO at low redshift to <1% precision, each giving >7σ significance (>10σ jointly) *if* the current size of the discrepancy is maintained
  - DESI (and the EUCLID and WFIRST satellite missions) will also give <1% precision measurements of H(z) for most redshifts z<3
- If real, what is the origin of the discrepancy?
  - Late-time (z<3, esp. DE-dominated era) deviations from ΛCDM will be tracked directly (hard to reconcile with other cosmological constraints)
  - If all H(z) from H_0 to H(z=3) are low in proportion, issue may be with BAO scale (r_s), implying problems in z>1100 physics or early-time cosmology
- Planned large-scale structure surveys can address, refine and potentially resolve this controversy!