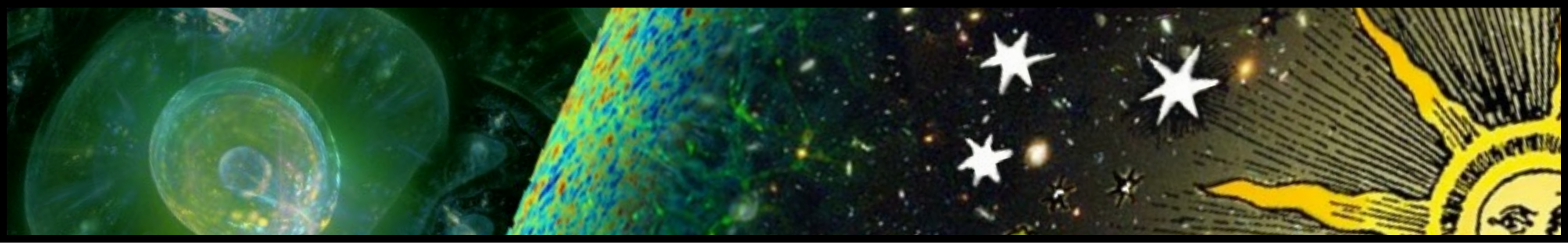


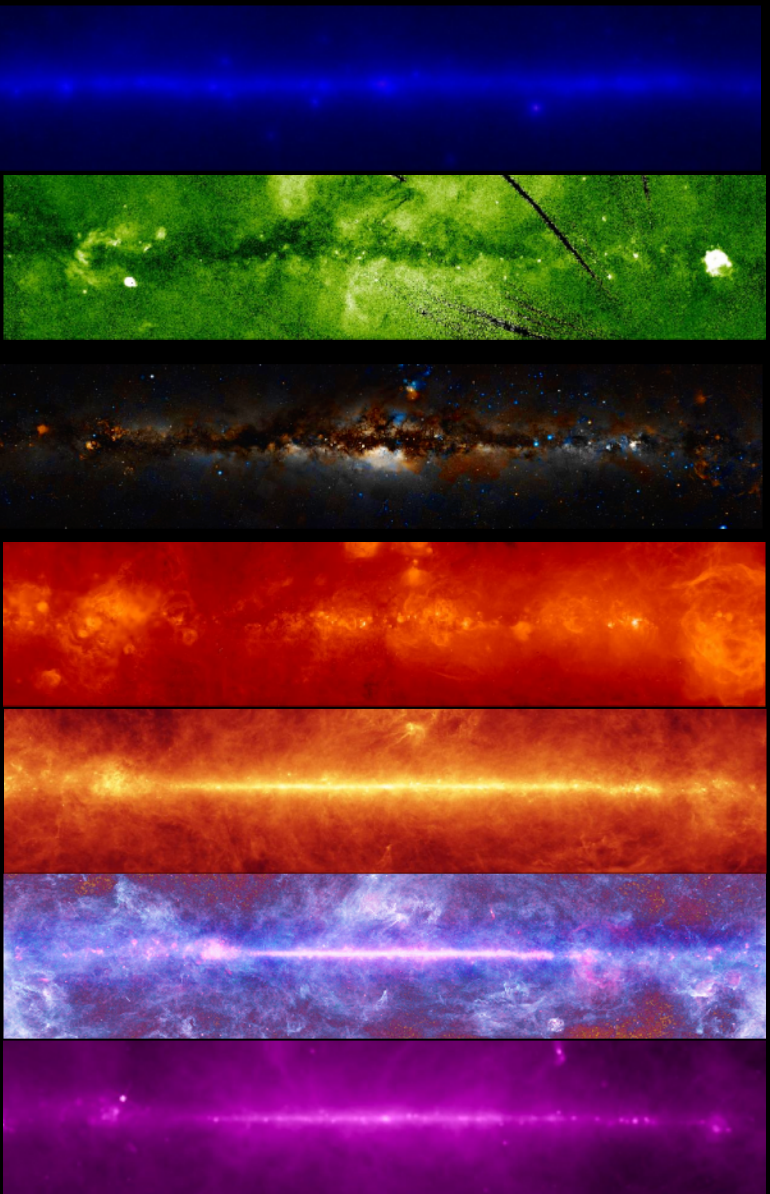
Survey cosmology in the multimessenger era

Hiranya V. Peiris

UCL and Oskar Klein Centre Stockholm

Oskar Klein centre
Knut och Alice Wallenbergs Stiftelse
erc European Research Council
VETENSKAPSRÅDET THE SWEDISH RESEARCH COUNCIL
UCL

The era of surveys



Gamma Ray (Fermi)

X Ray (ROSAT)

Optical (DSS)

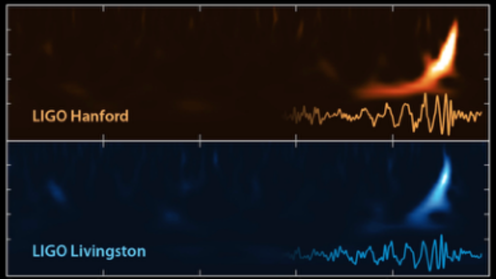
H-alpha

(WHAM/SHASSA/VTSS)

Far Infrared (IRAS)

Microwave (Planck)

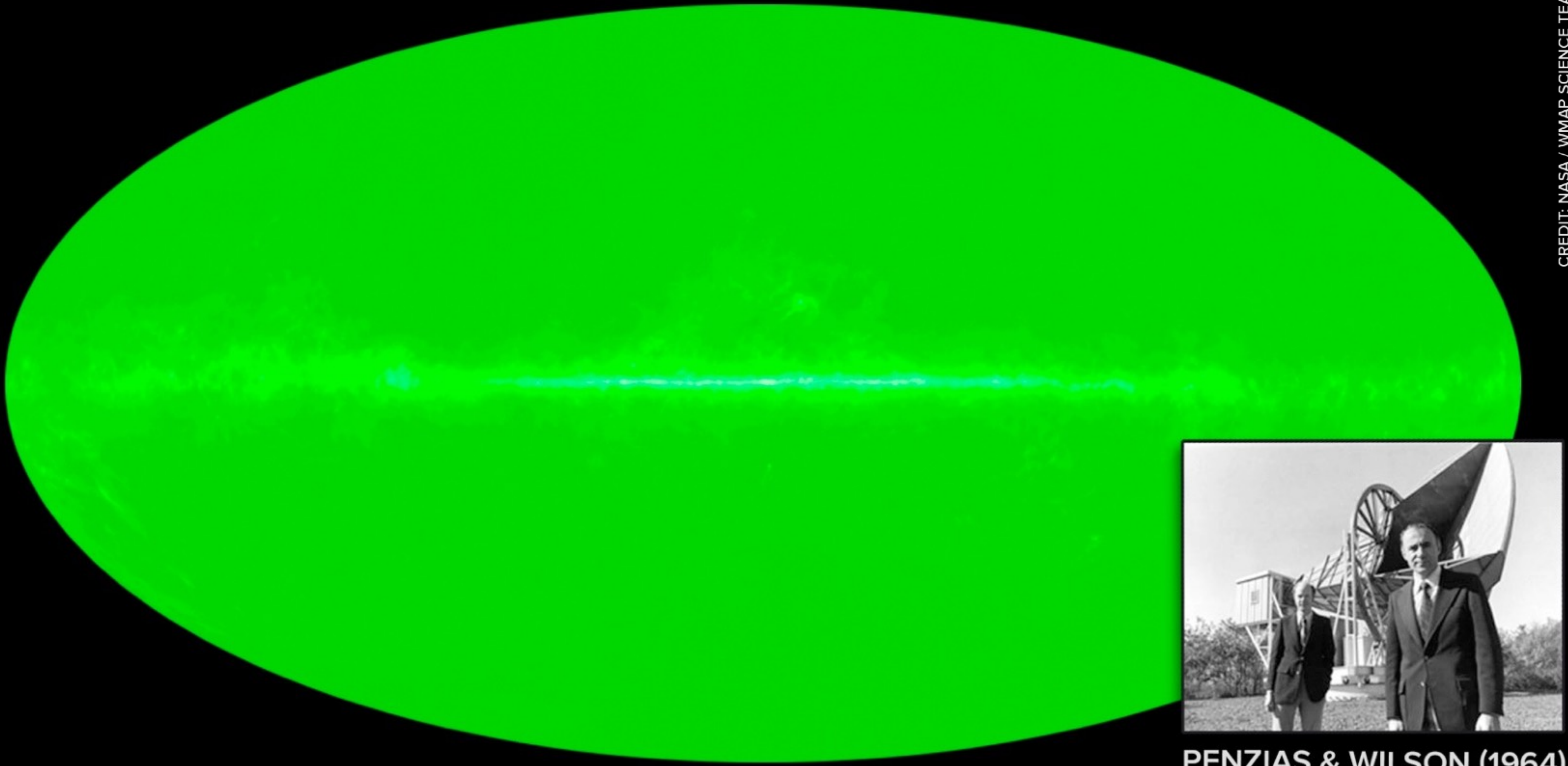
Radio (Haslam)



Gravitational Waves (LIGO)

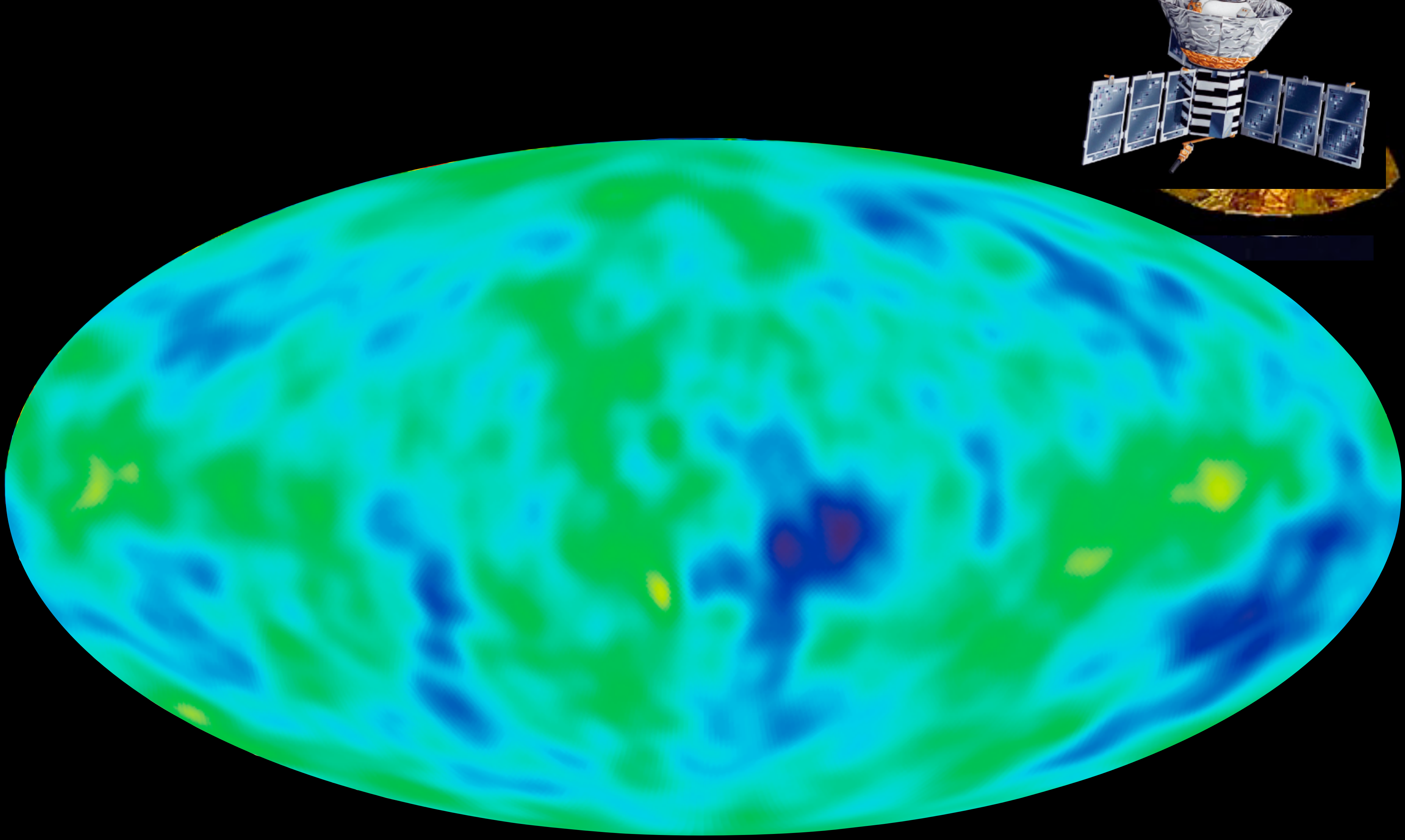
Credit: Chromoscope / Cardiff

Cosmic Microwave Background

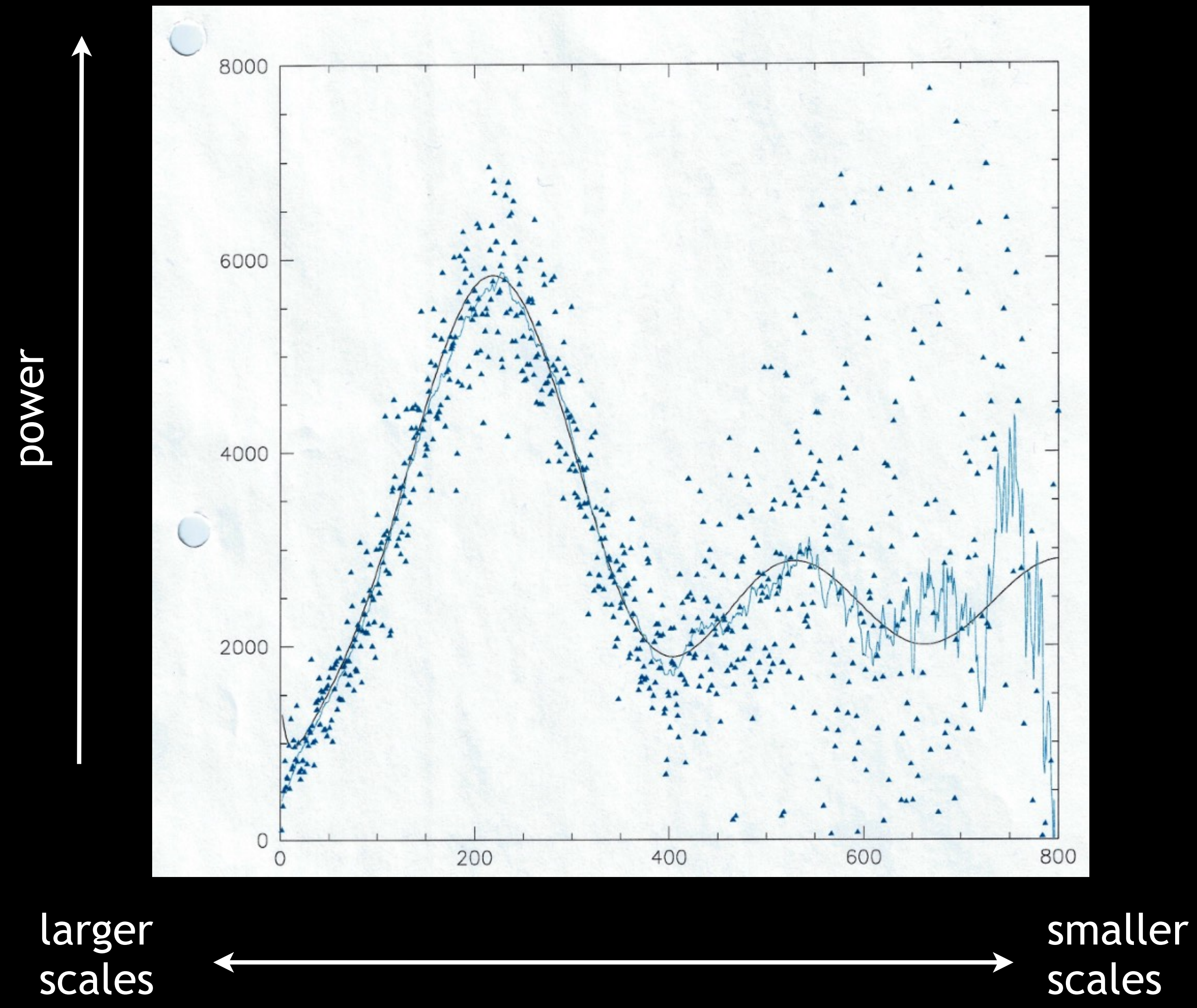


PENZIAS & WILSON (1964)

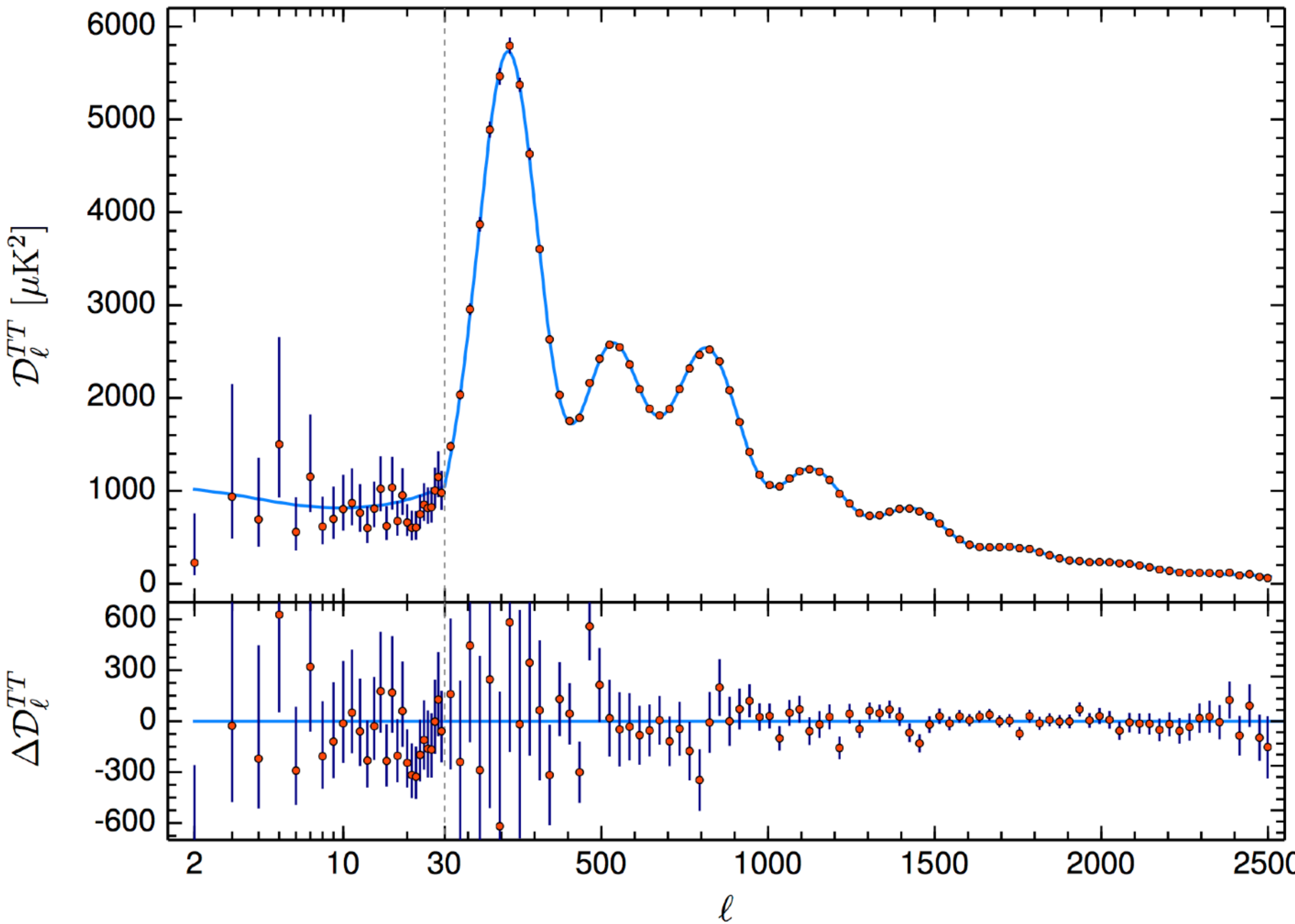
CREDIT: NASA / WMAP SCIENCE TEAM



WMAP "first light" spectrum

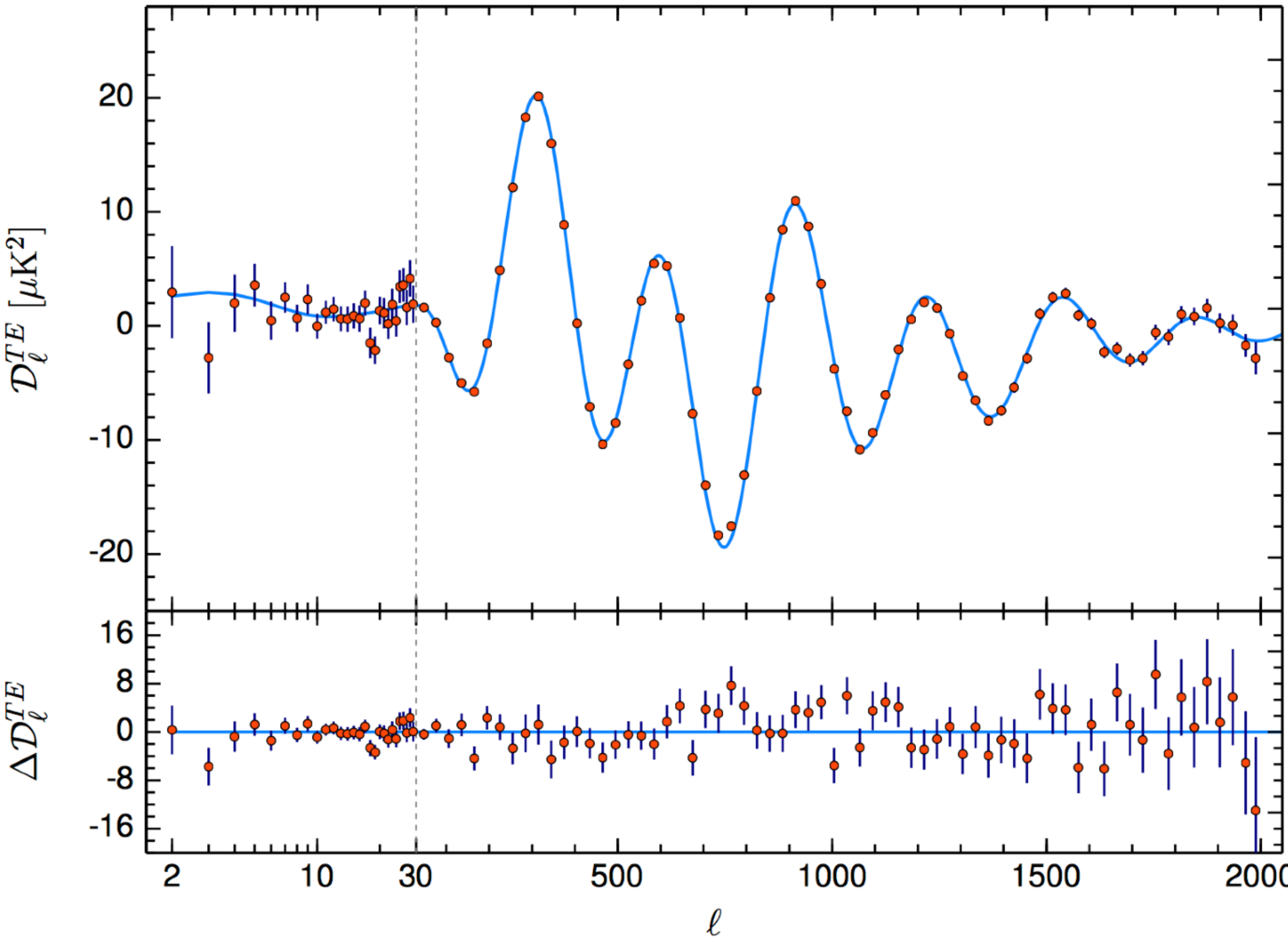


Planck 2018 Temperature



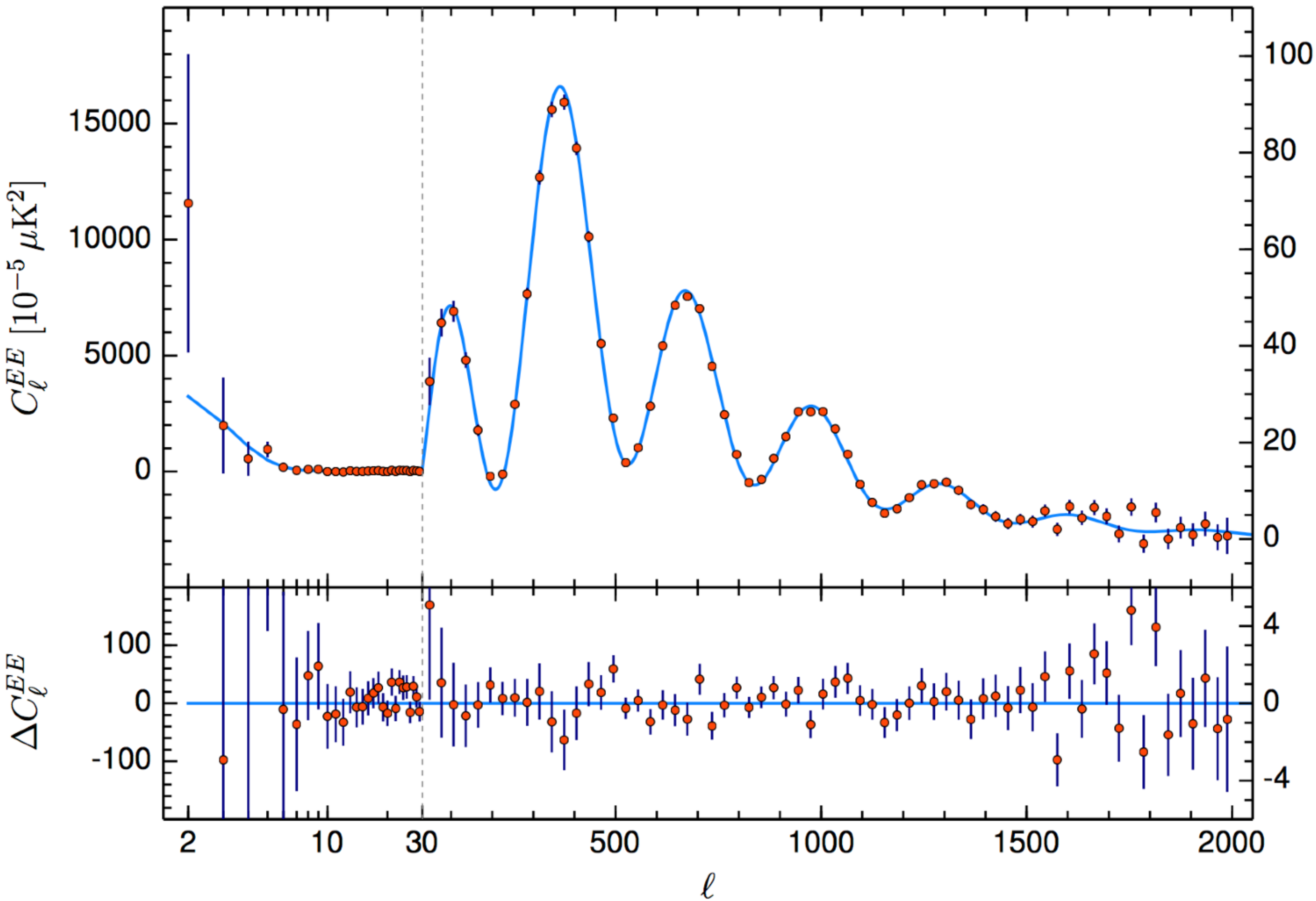
Planck Collaboration (2018)

Planck 2018 TE Polarisation



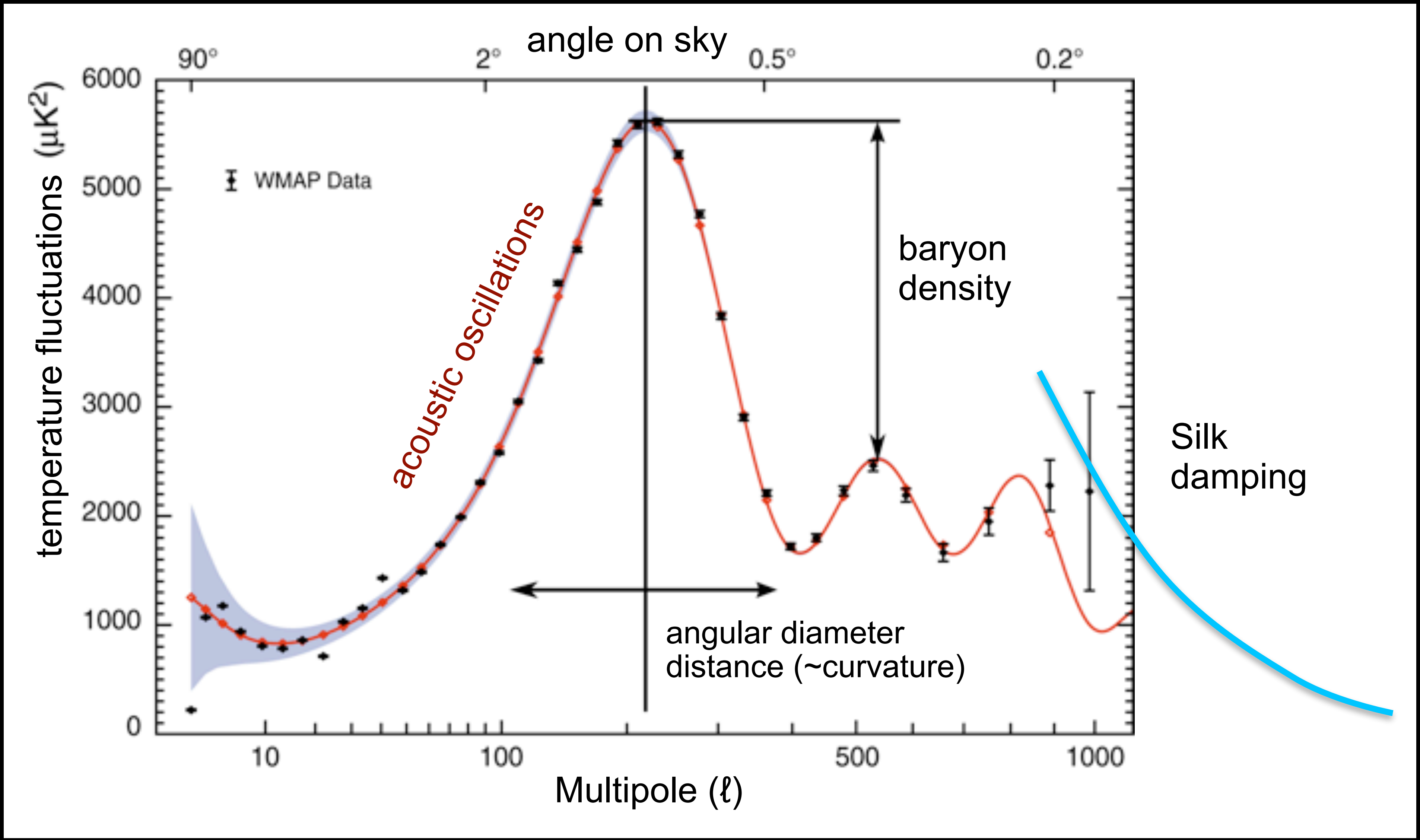
Planck Collaboration (2018)

Planck 2018 EE Polarisation



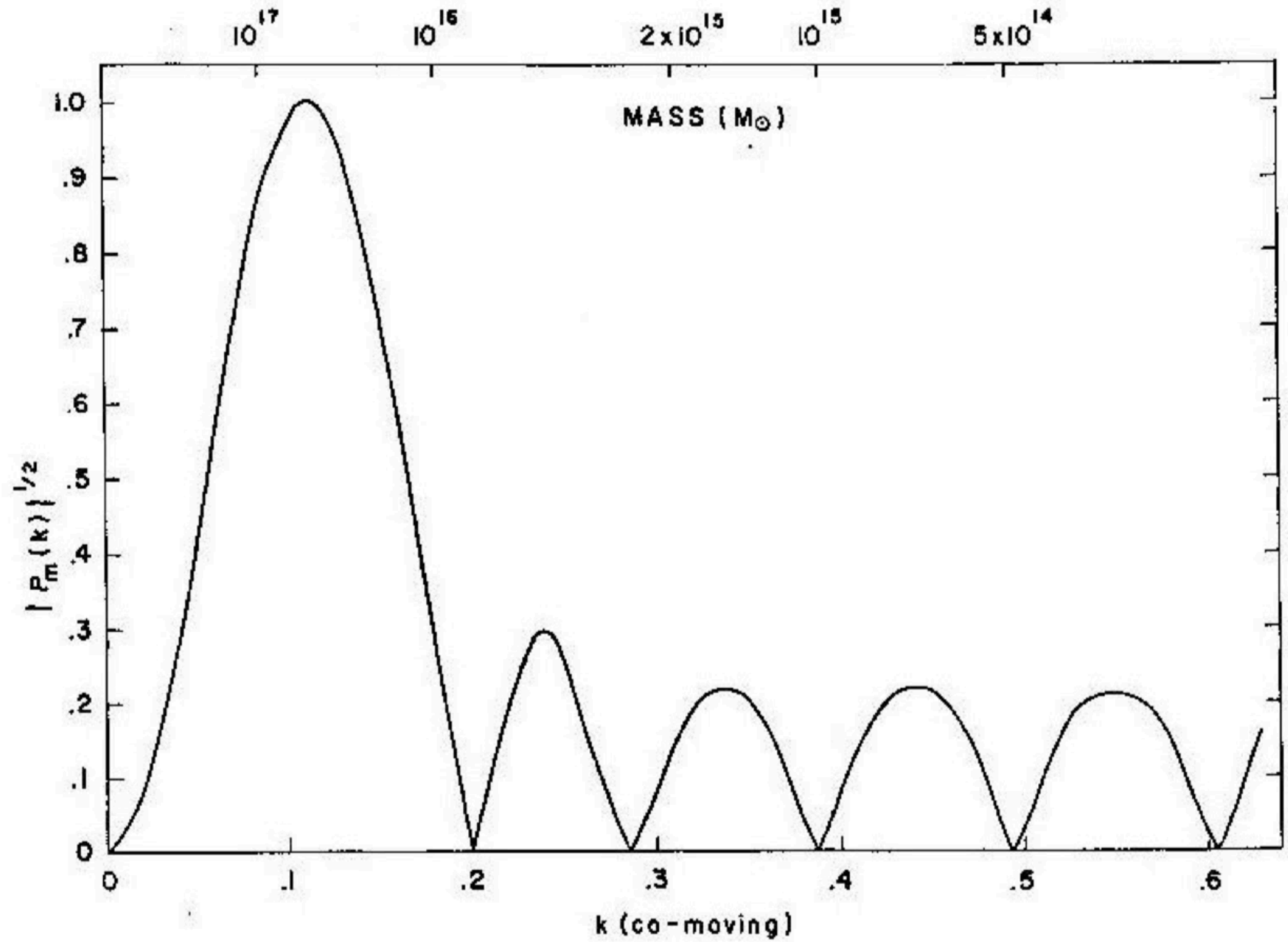
Planck Collaboration (2018)

Physics of the CMB power spectrum



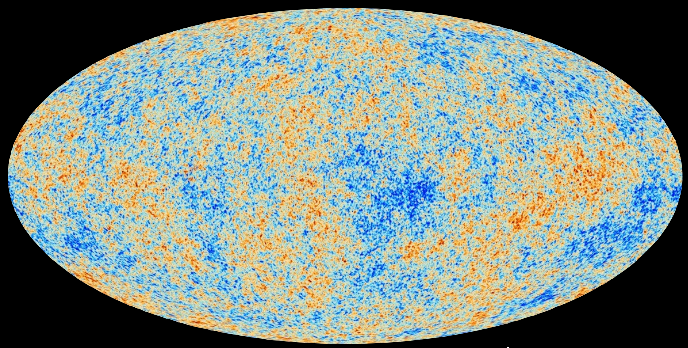
Peebles & Yu (1970), Sunyaev & Zel'dovich (1970), Sachs and Wolfe (1968), Silk (1968)

Credit: NASA/WMAP Science Team

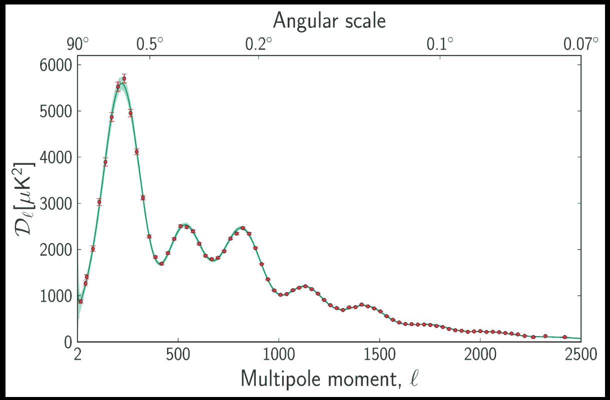


Peebles and Yu (1970)

Radical data compression!

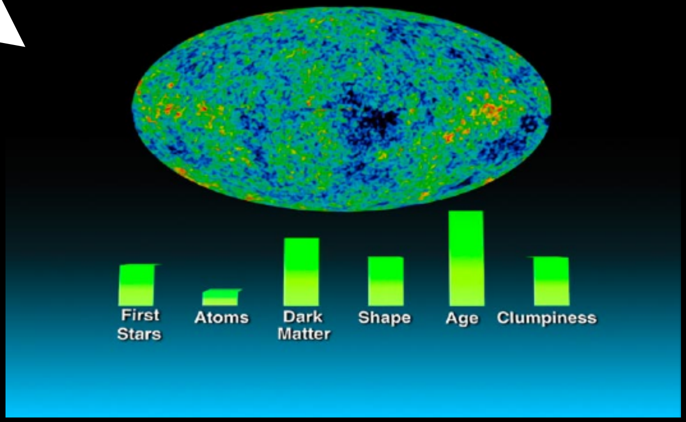


Raw data: *~quadrillion samples*
Maps: *~50 million pixels over 9 frequencies*

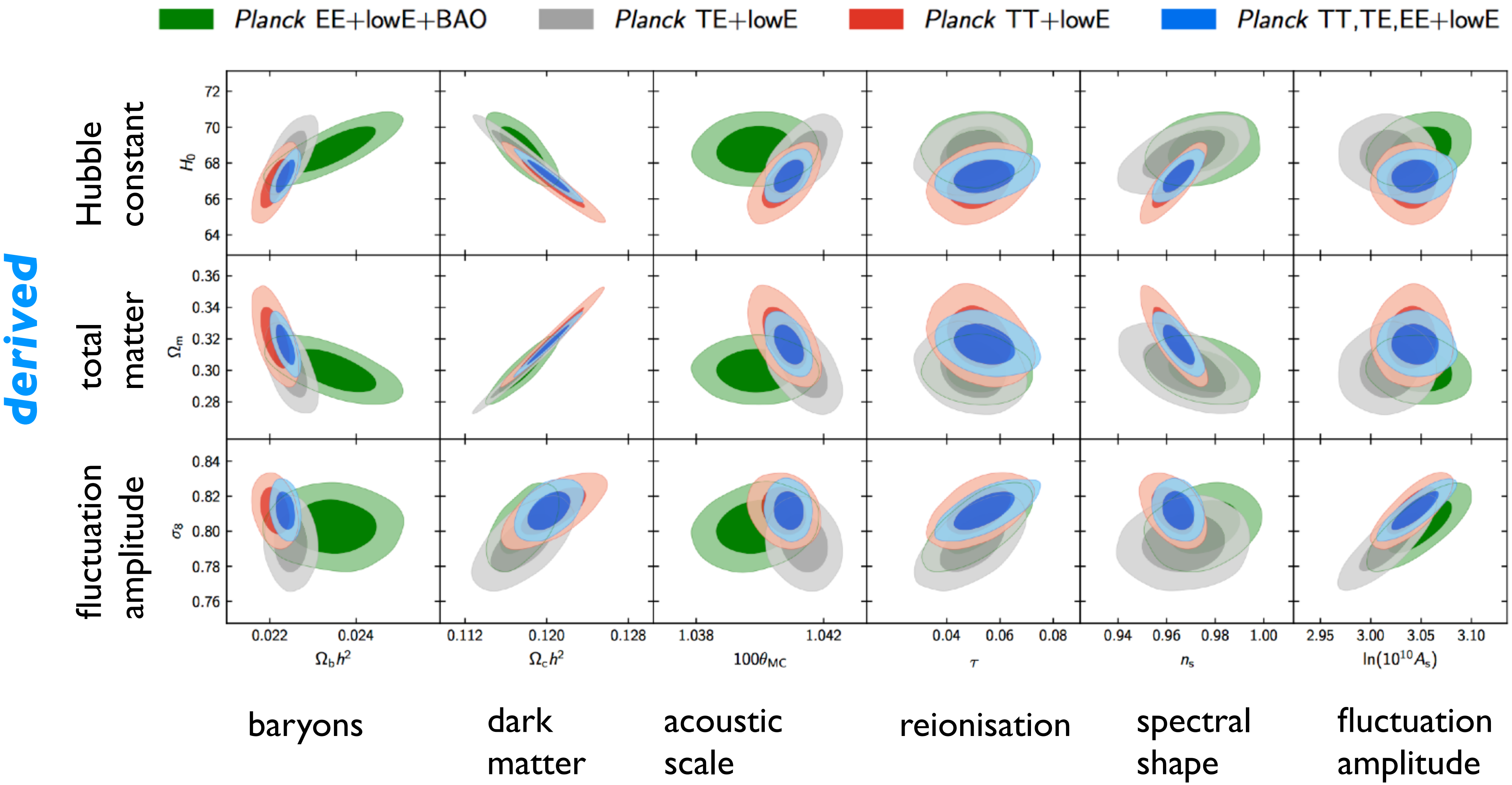


~2500 multipoles...

six cosmological parameters!



Planck's cosmological parameters

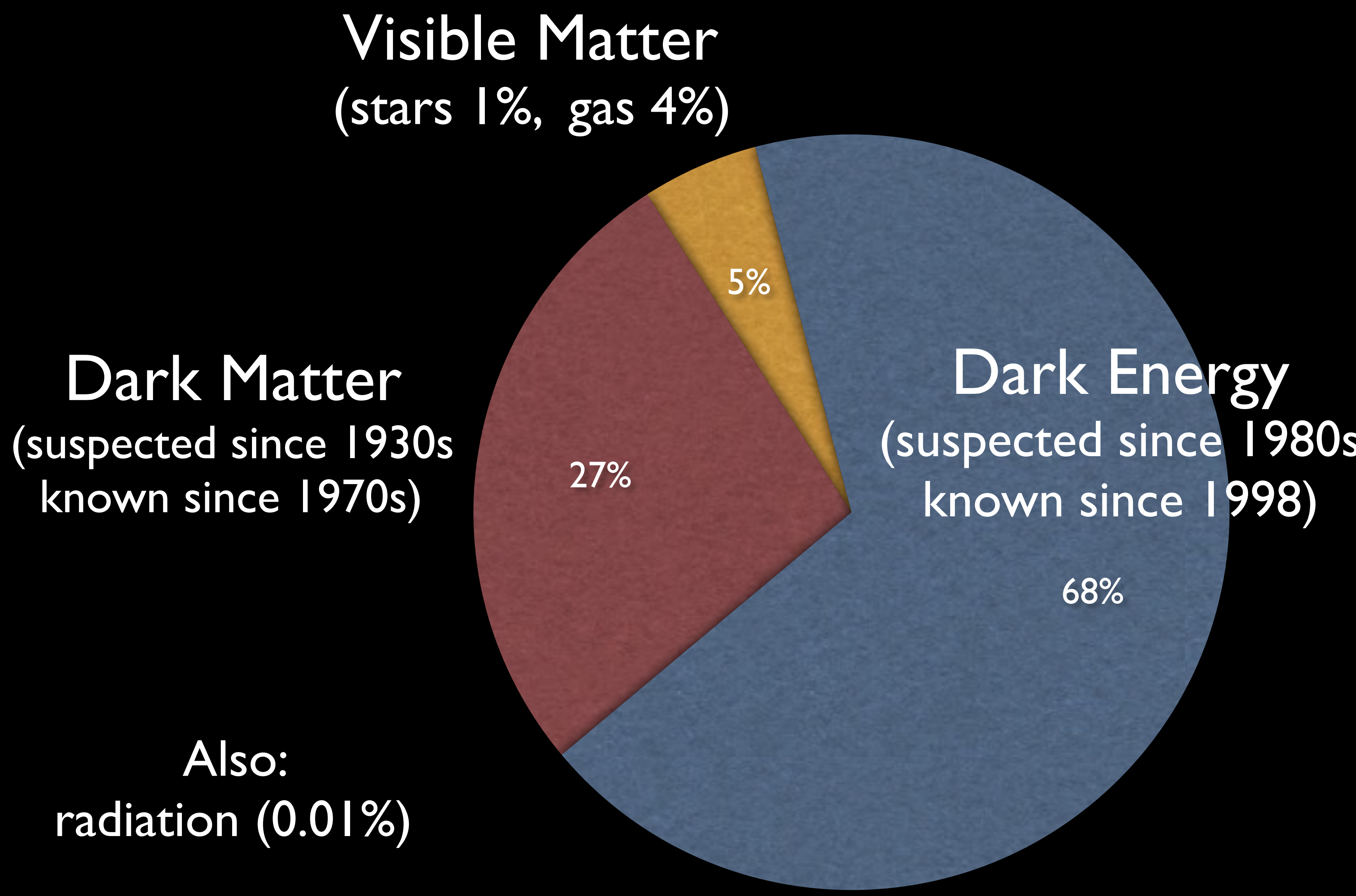


~directly measured

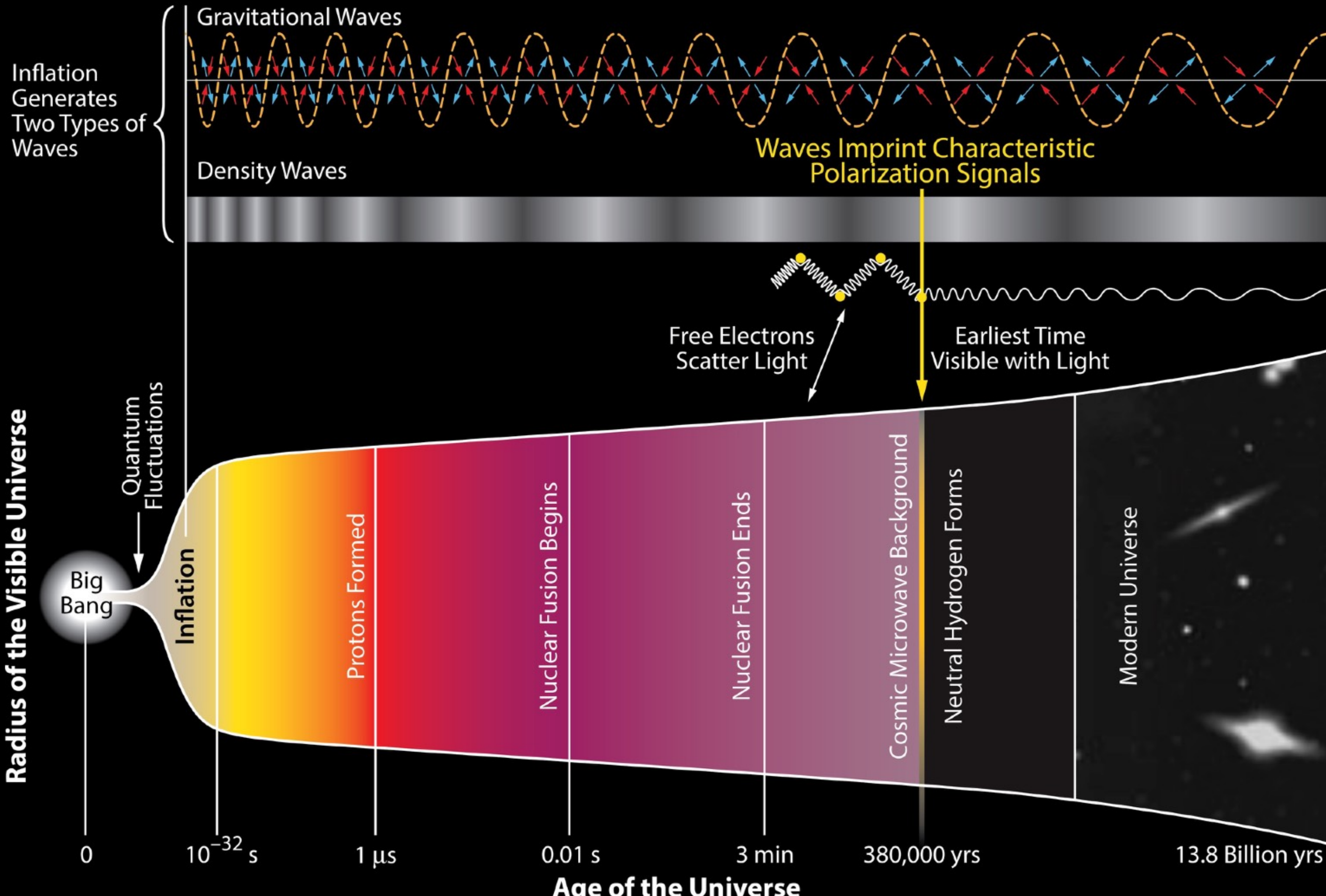
Planck Collaboration (2018)

Cosmological parameters not "directly measured"; details depend on models ["priors"]

What is Dark Matter? Dark Energy?

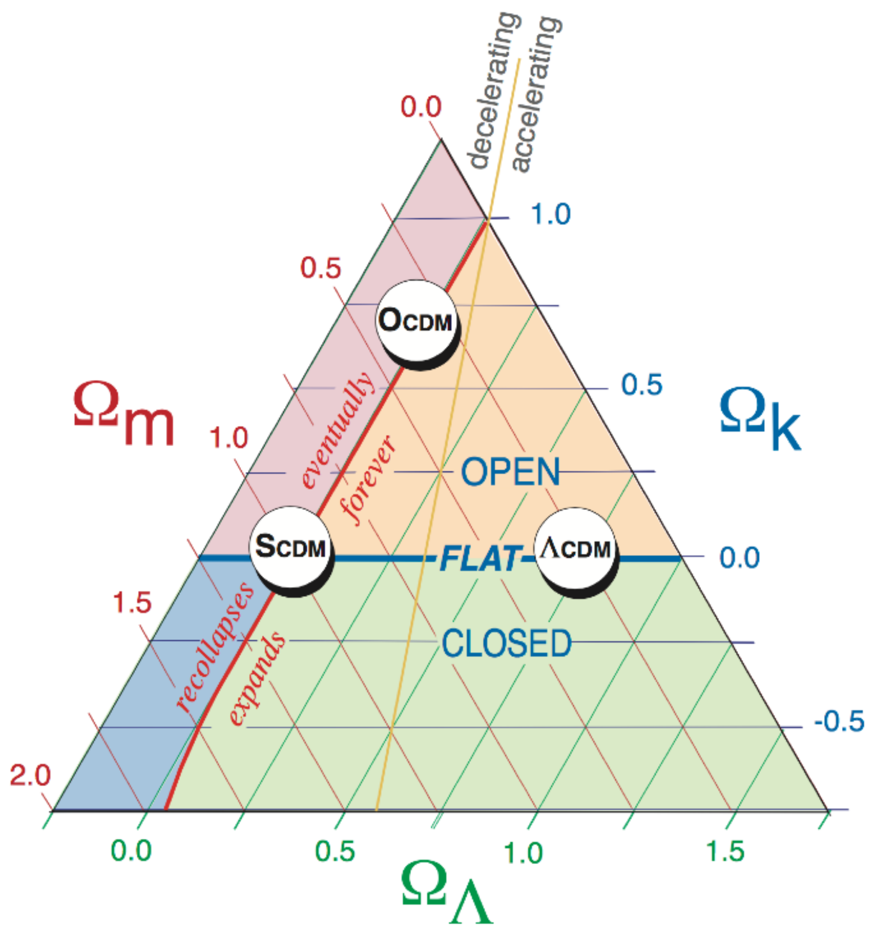


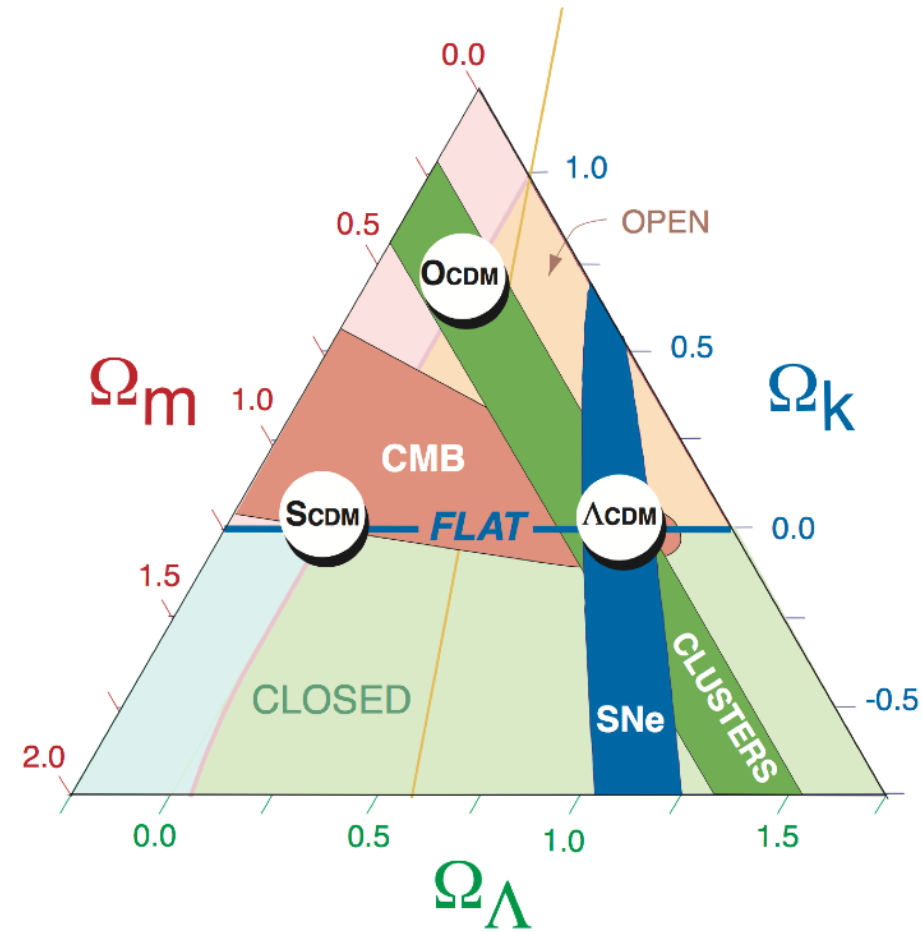
What is the origin of cosmic structure?



CREDIT: BICEP / KECK COLLABORATIONS

Concordance Cosmology





Bahcall, Ostriker, Perlmutter, Steinhardt (1999)

Cosmological Probes

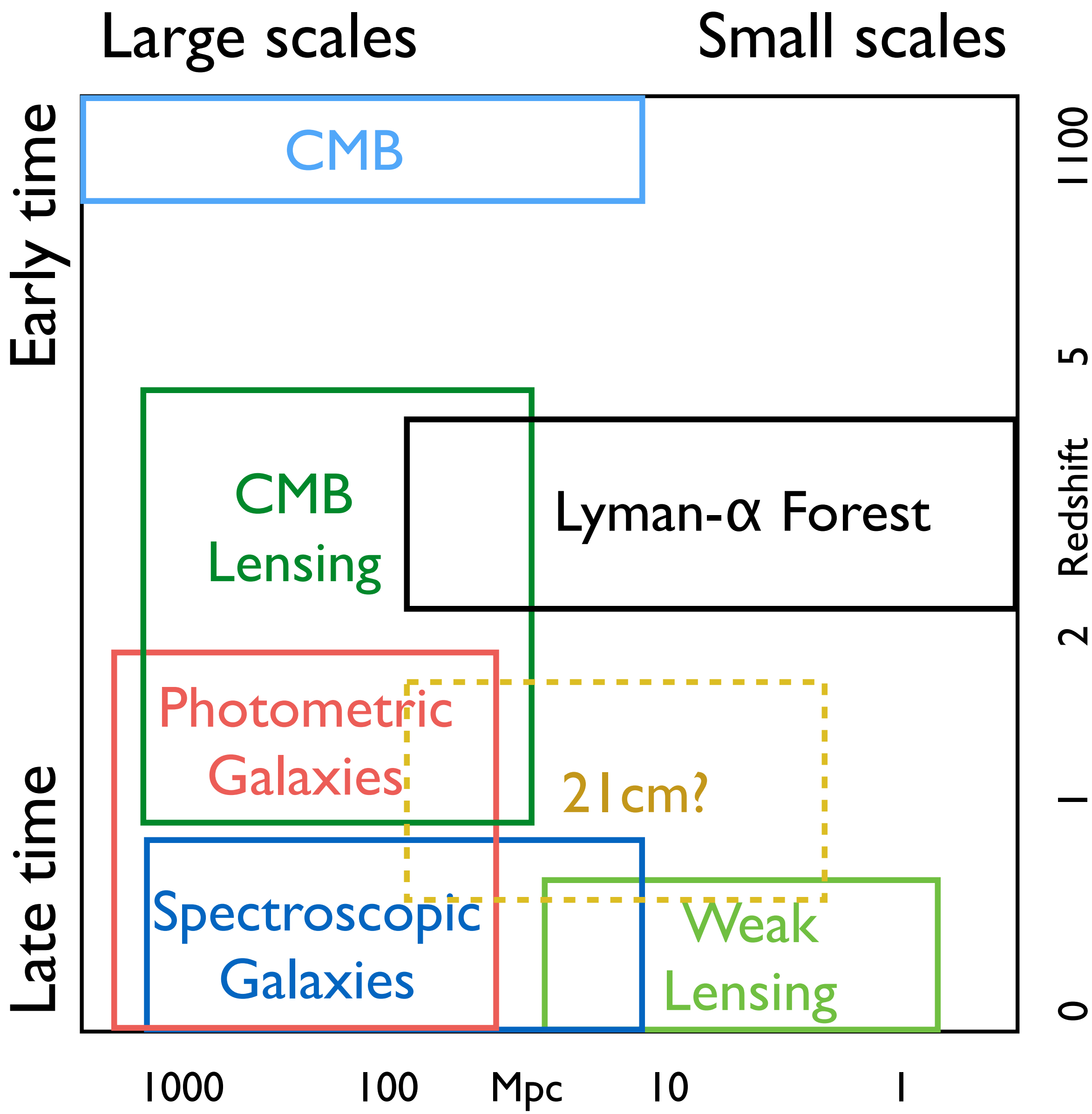
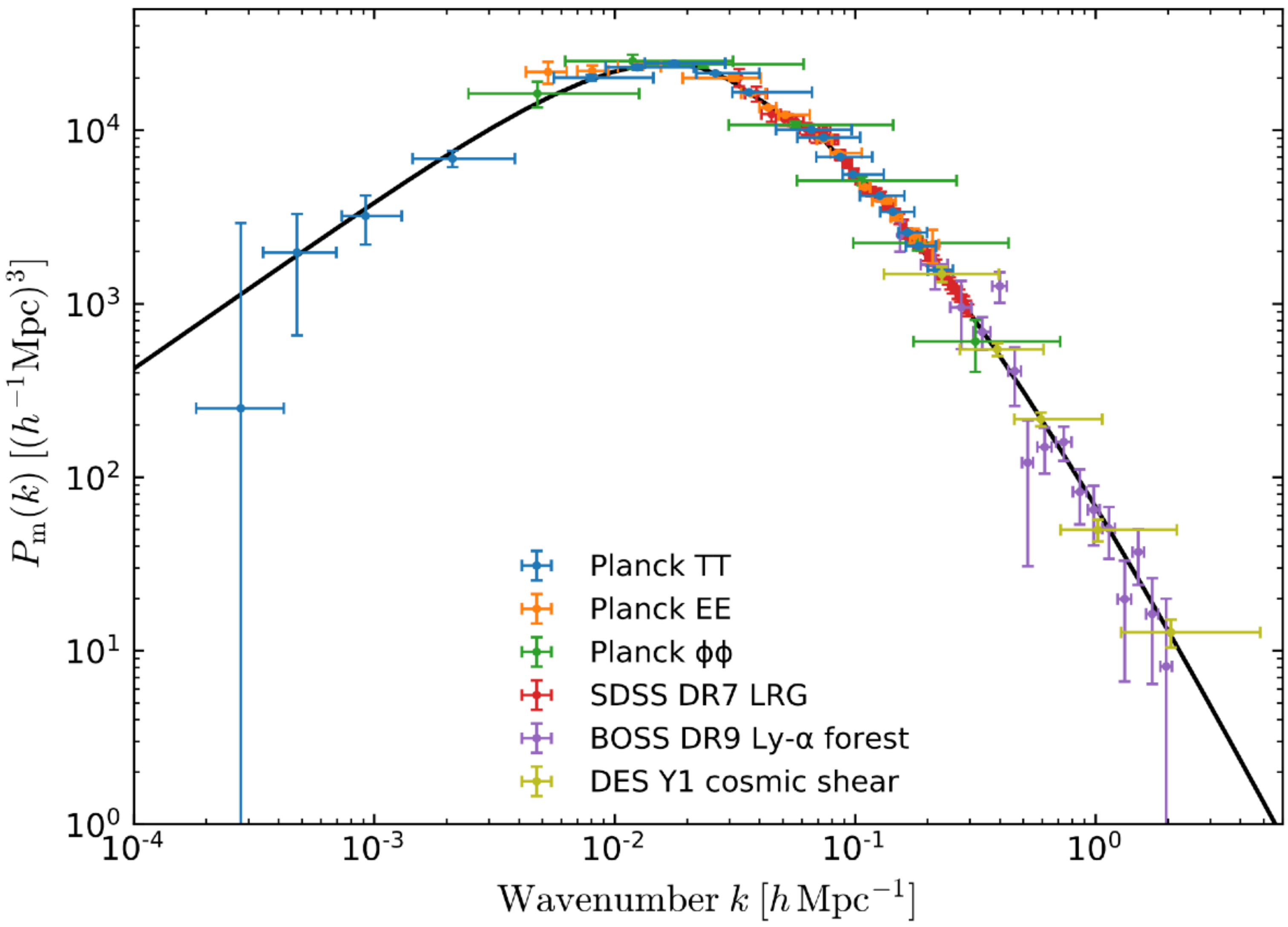


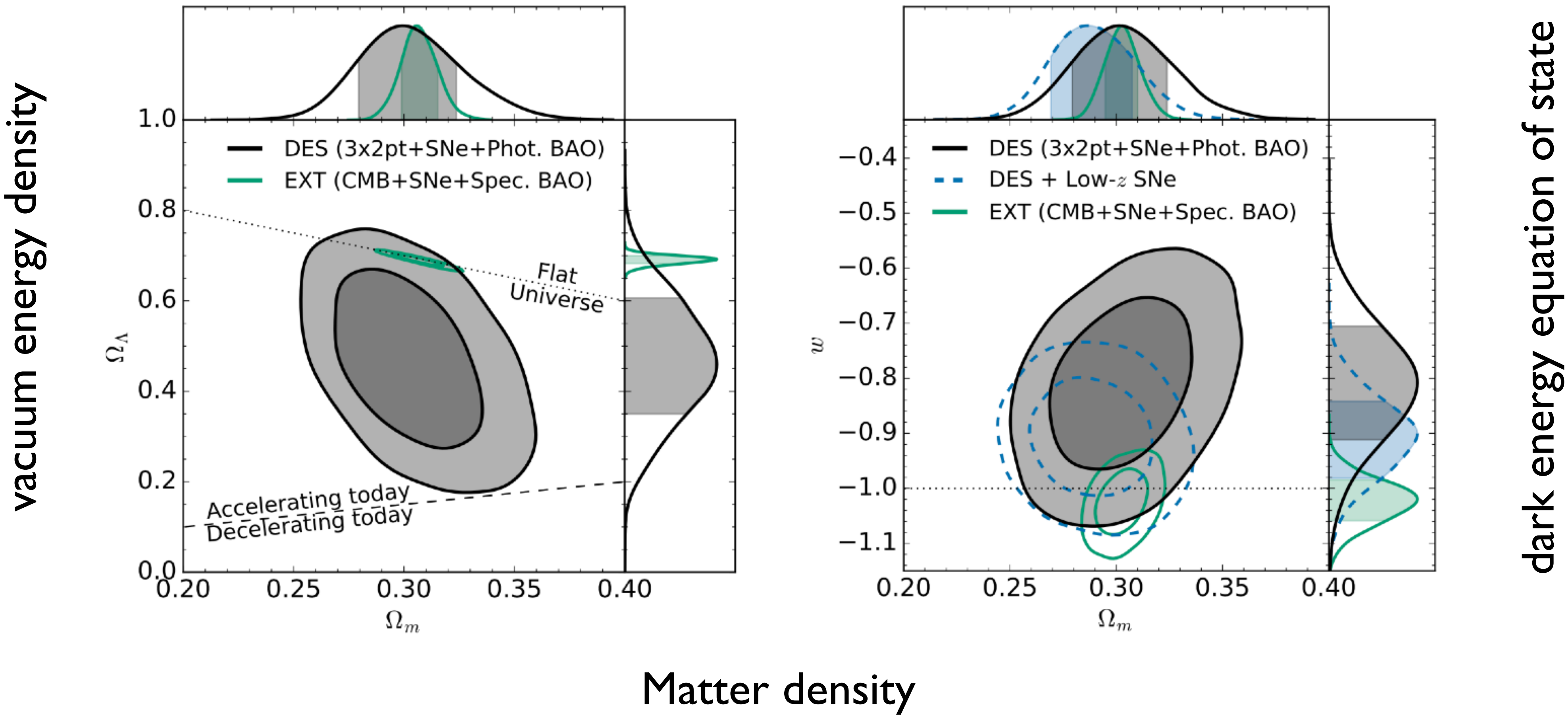
Figure: Andreu Font-Ribera

Cosmic consistency



Planck Collaboration (2018) summarising constraints on the matter power spectrum from a world collection of surveys spanning ~14 Gyr in time and 3 decades in scale

Cosmology from DES Y1 multi-probes



3x2pt: cosmic shear; galaxy-galaxy lensing; galaxy clustering
207 spectroscopically-confirmed SNe Type Ia lightcurves

DES Collaboration (2019)

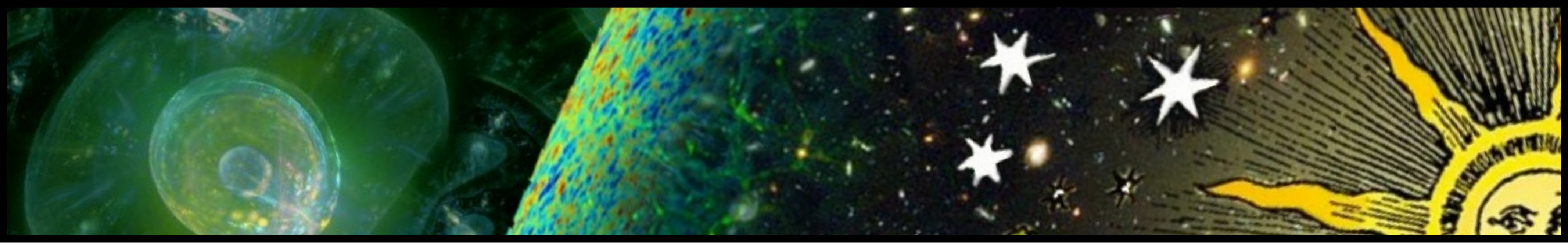
Observational cosmology in the next decade

- ***"Big Data" era***
  Very large datasets

- ***Small SNR***
  frontier research inevitably involves small signal-to-noise

- ***Large model space***

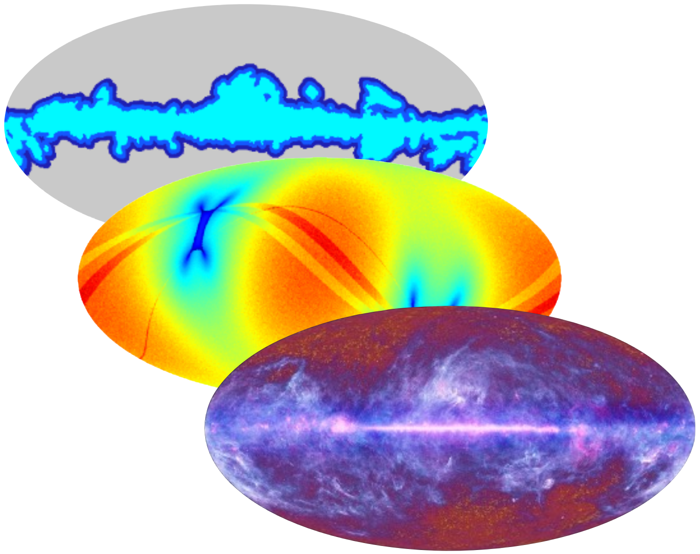
- ***Cosmic variance***
  a single realisation of an inherently random cosmological model
  (cf. quantum fluctuations)



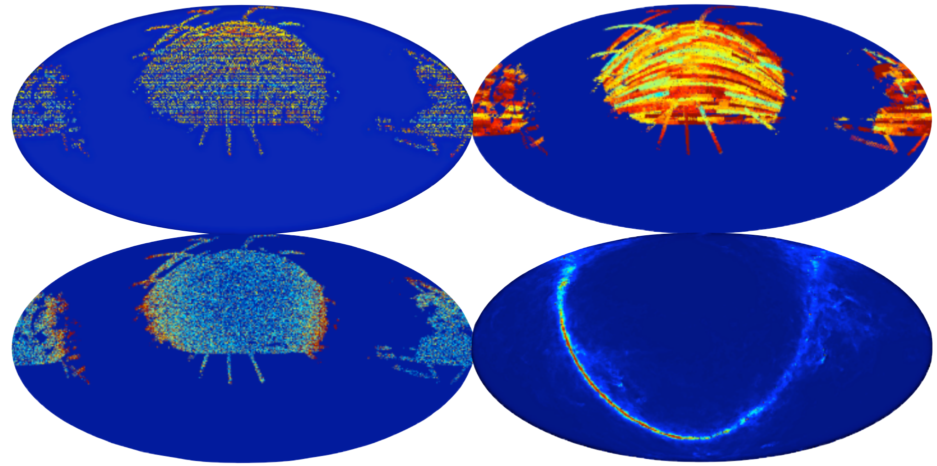
"No one trusts a model except the person who wrote it; everyone trusts an observation, except the person who made it".

paraphrasing H. Shapley

Known unknowns, unknown knowns, unknown unknowns



CMB: *complex sky mask, coloured / inhomogeneous noise, foregrounds...*



LSS: *seeing, sky brightness, stellar contamination, dust obscuration, spatially-varying selection function, Poisson noise, photo-z errors etc...*

Need thorough understanding of data & systematics for convincing detections of new physics.

CMB observational frontier: polarisation

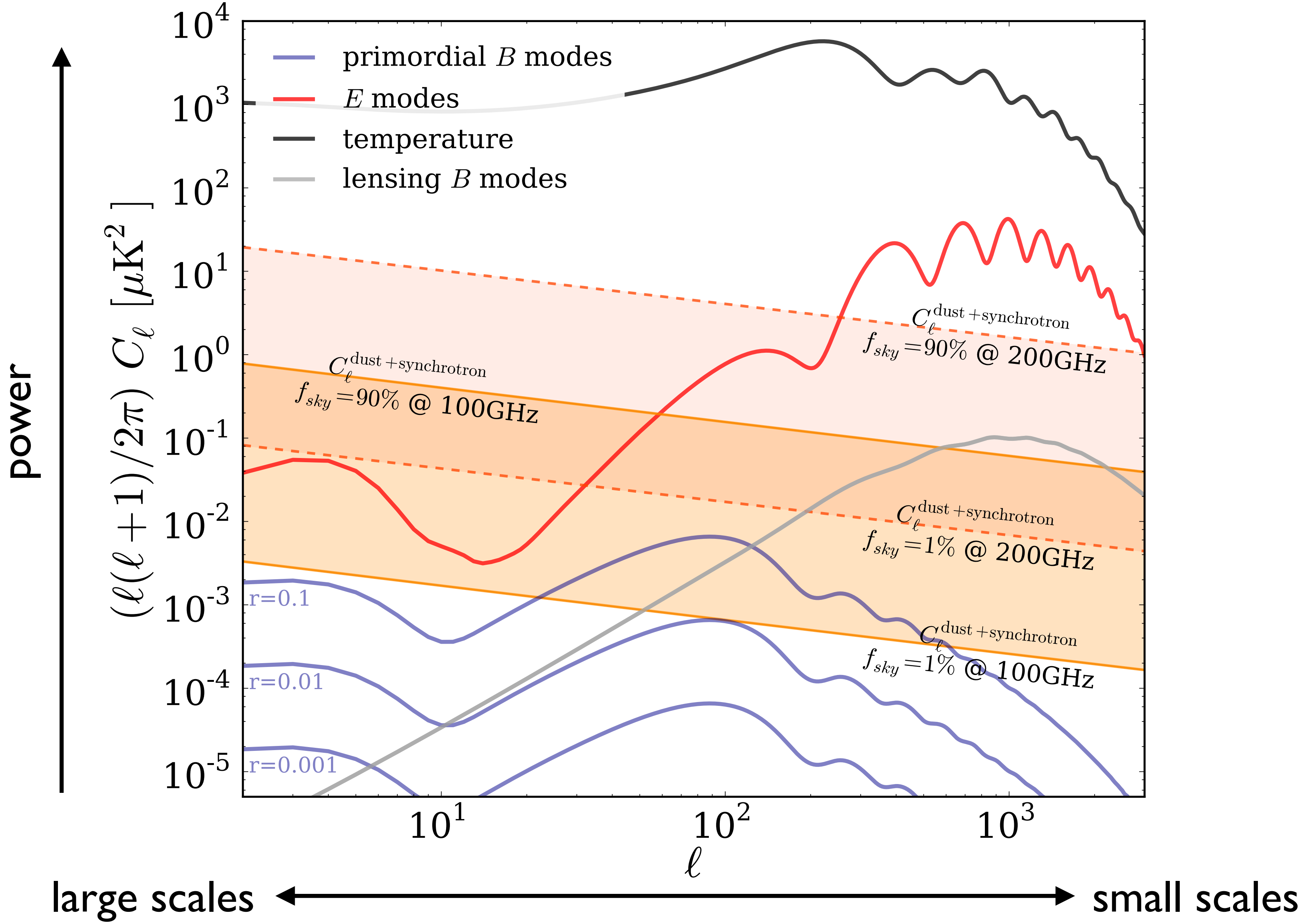
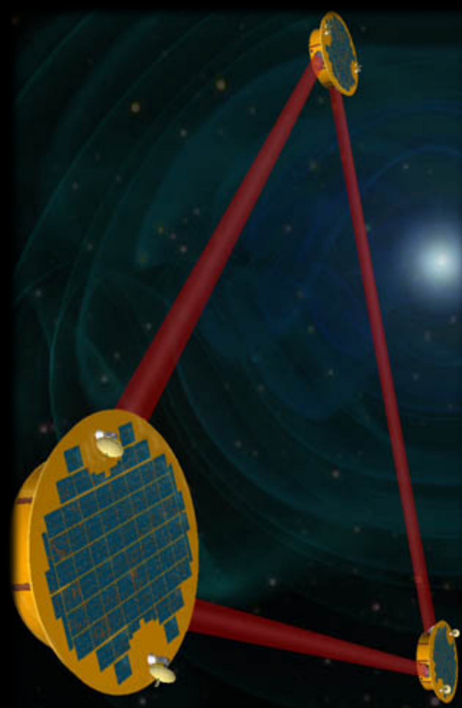
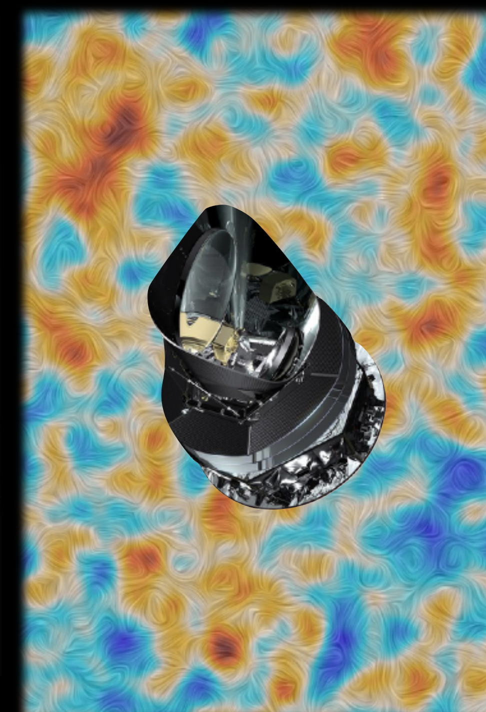


Figure: Errard, Feeney, Peiris, Jaffe (JCAP, 1509.06770)

Gravitational Wave Periods

Milliseconds	*Minutes to Hours*	*Years to Decades*	*Billions of Years*
			

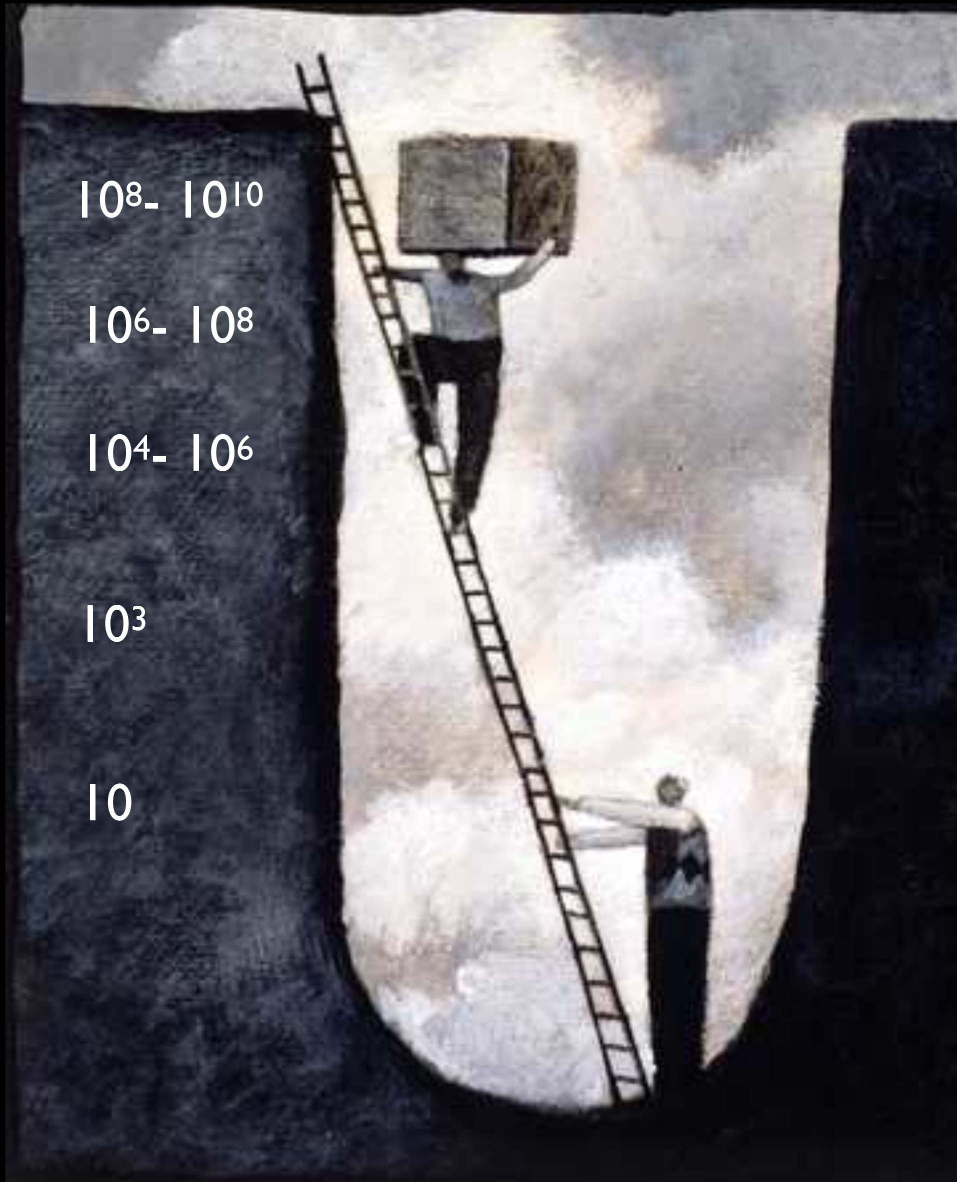
CREDIT: LIGO / KIP THORNE

The challenge

Typical degree-scale brightness fluctuations (150GHz)

T → P

Ground, Telescope mount etc	3-300 K	10^8- 10^{10}
Atmosphere	30 mK - 3 K	10^6- 10^8
Galaxy	0.3-30mK	10^4- 10^6
CMB T anisotropies	30μK	10^3
Lensing B modes (at arcmin)	300 nK	10
r=0.01 B-modes	30 nK	
noise you want to reach	<10 nK	



Adapted from C. Pryke

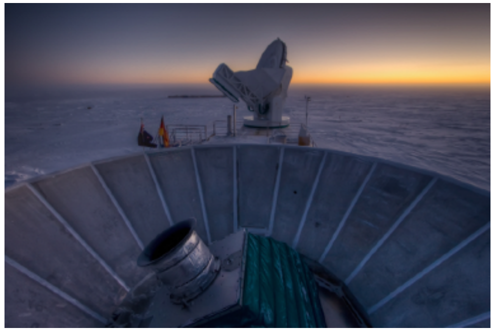
Next generation CMB polarisation experiments

- *Degree-scale B-modes: inflation*

- *Arc-minute scale B-modes: gravitational lensing*
  - *late-time physics: sum of neutrino masses*
  - *geometry: break geometric degeneracy, measure curvature*

- *Experimental frontier in the 2020s:*

  ground: *Simons Observatory (under construction), CMB-S4 (planning)*
  space: *LiteBIRD (JAXA, launch late 2020s)*

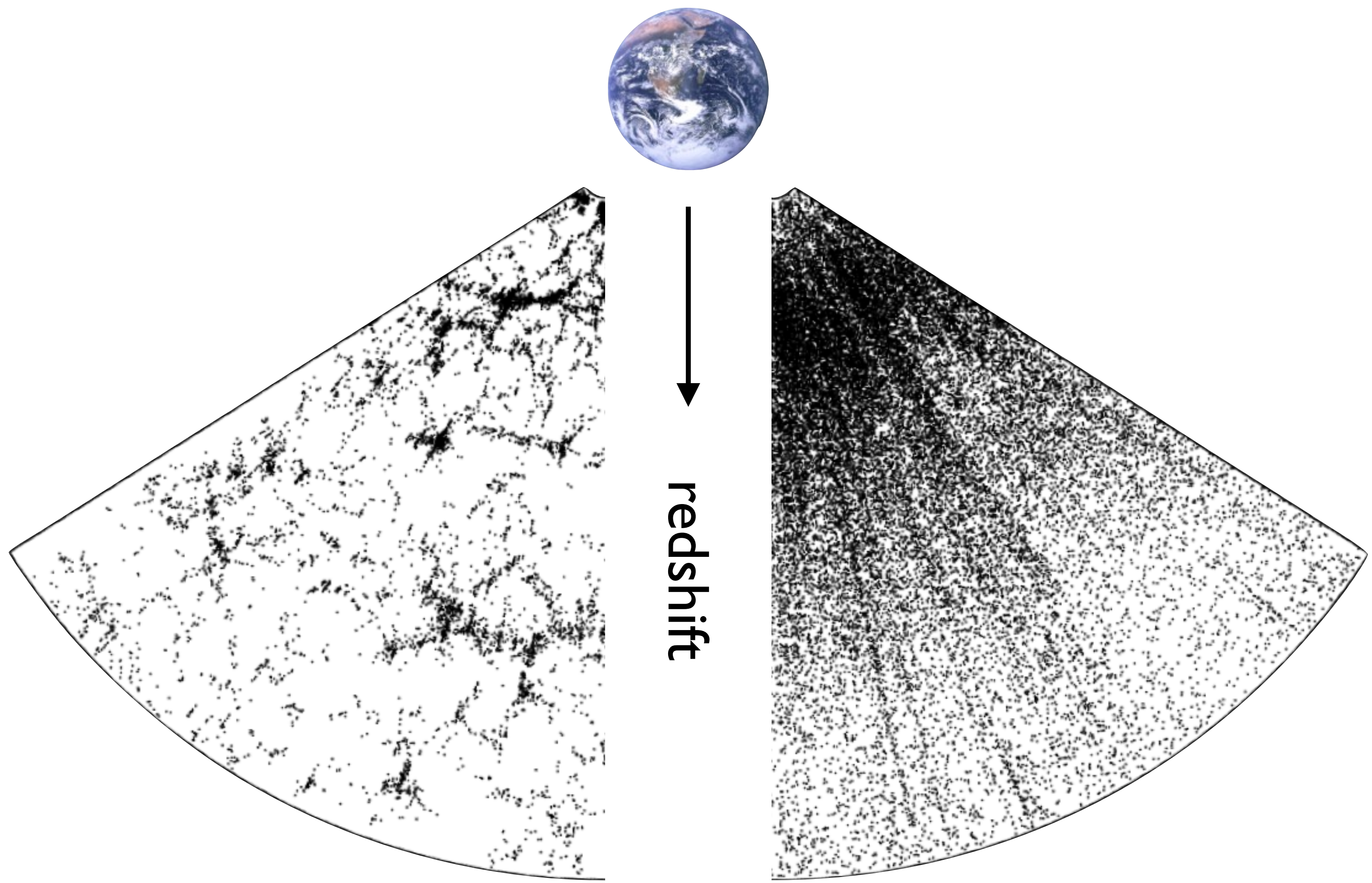


ground

balloon

satellite

Observational frontier with galaxy surveys

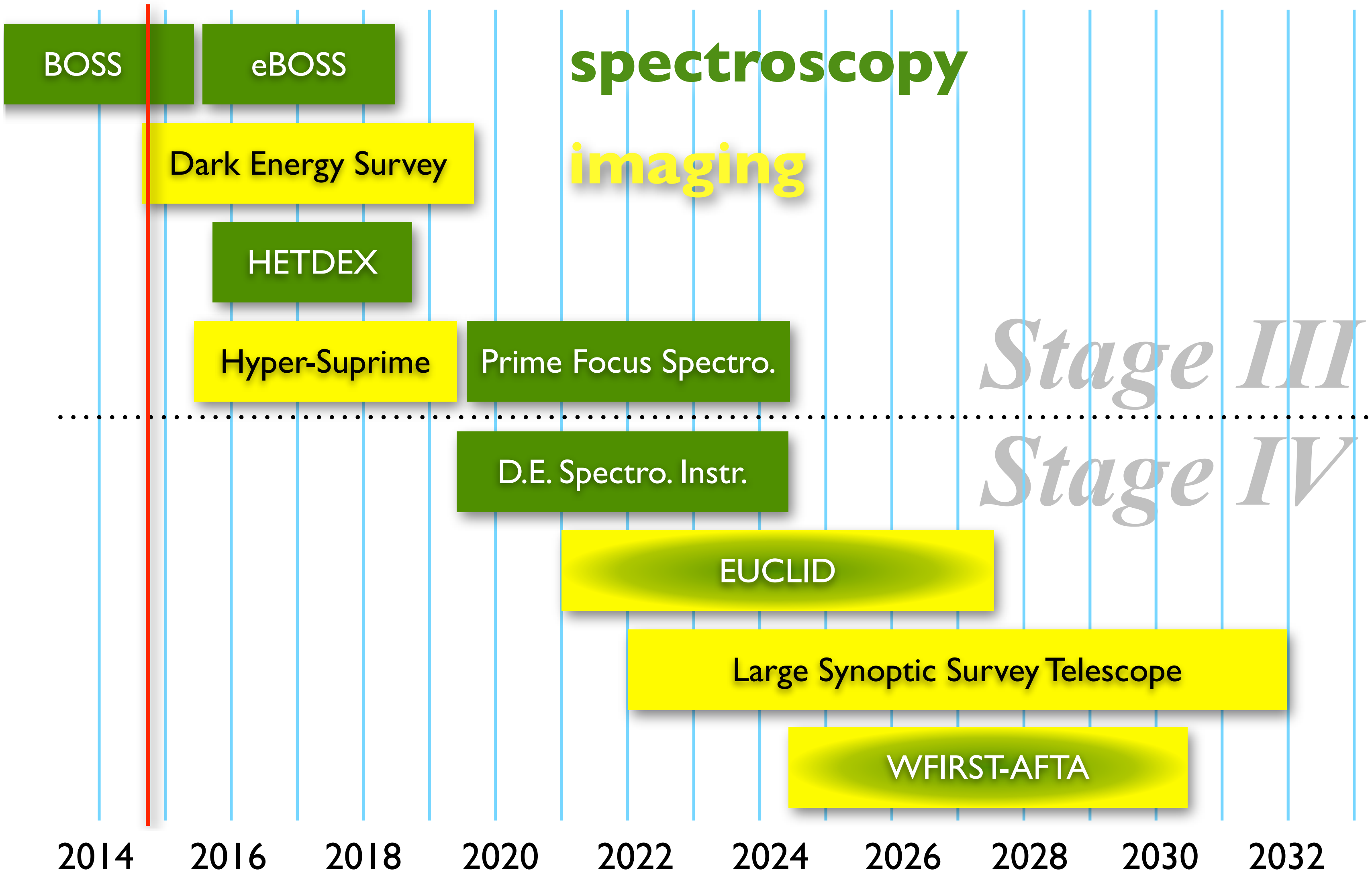


Spectroscopic
DESI (ground)

Photometric
LSST (ground), Euclid (space)

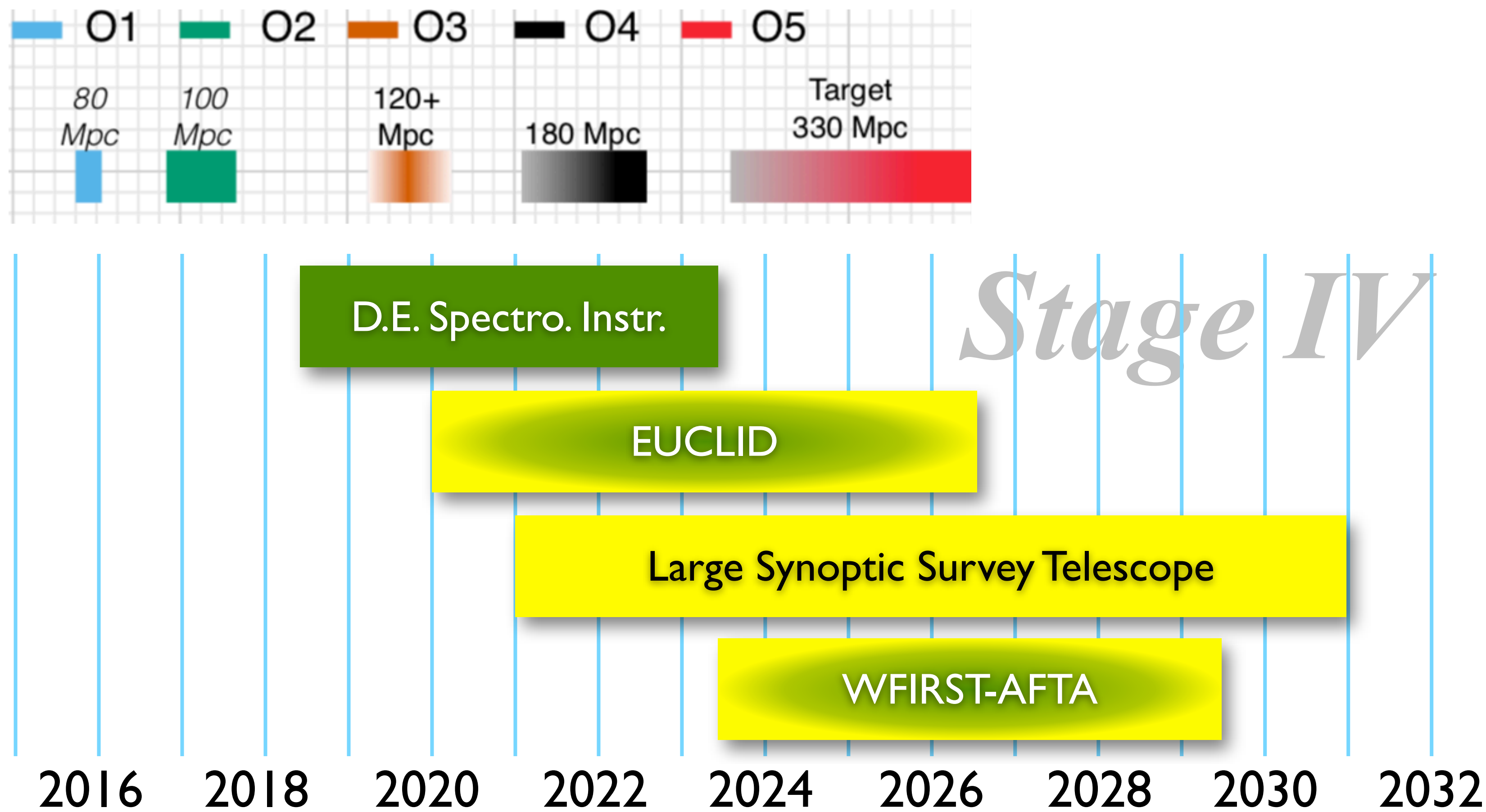
Image adapted from Boris Leistedt

Dark energy facilities roadmap



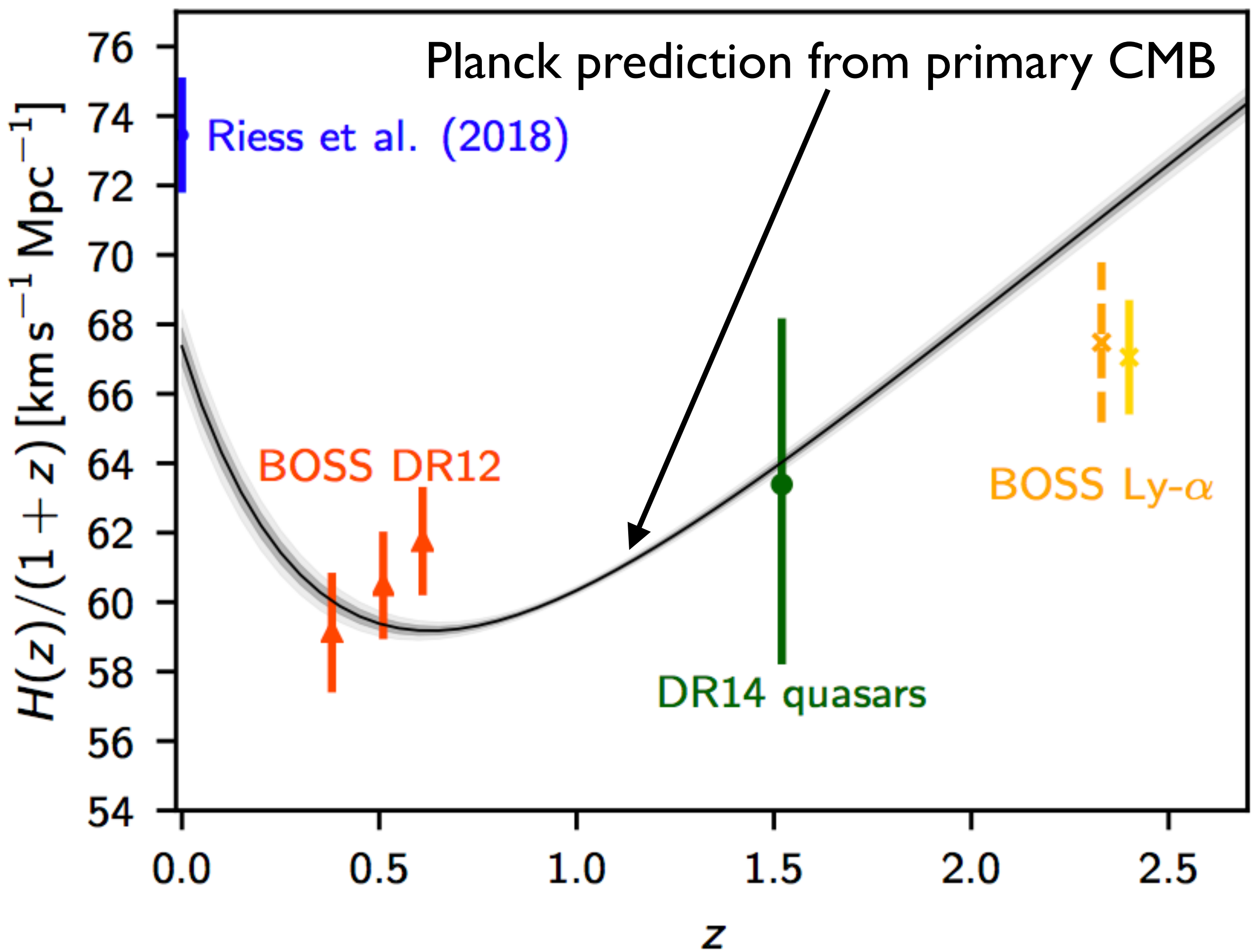
Adapted from: Ian Shipsey

Multimessenger survey roadmap



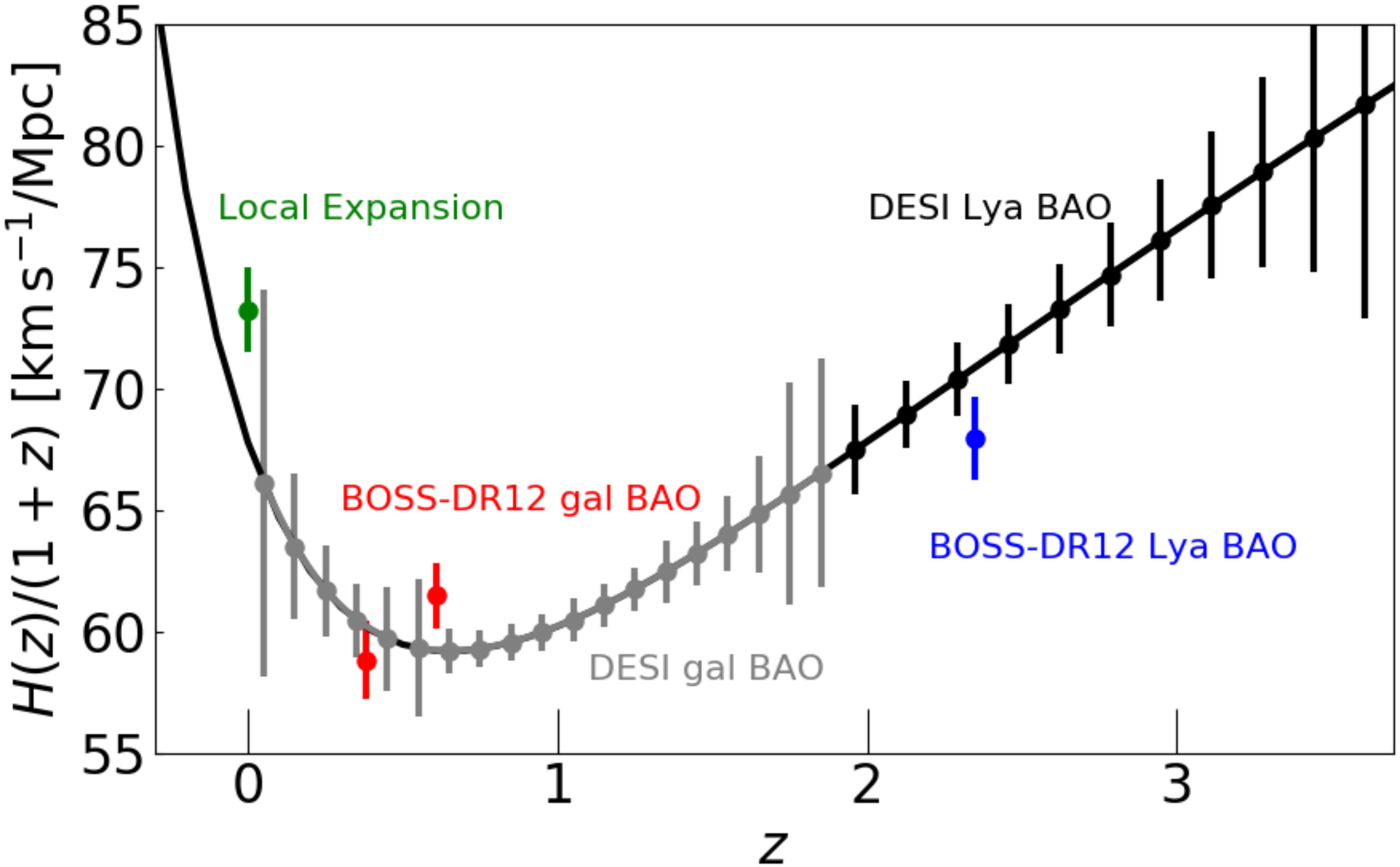
Adapted from: Ian Shipsey, LIGO Astro2020 whitepaper

Mapping the cosmic expansion history



H0 measurement (Riess et al. 2016)
DR12 BOSS Galaxy BAO (Alam et al. 2016)
DR14 BOSS Quasar BAO (Zarrouk et al 2018)
DR12 BOSS Lyman alpha forest BAO (Bautista et al 2017; du-Mas-des-Bourboux et al. 2017)

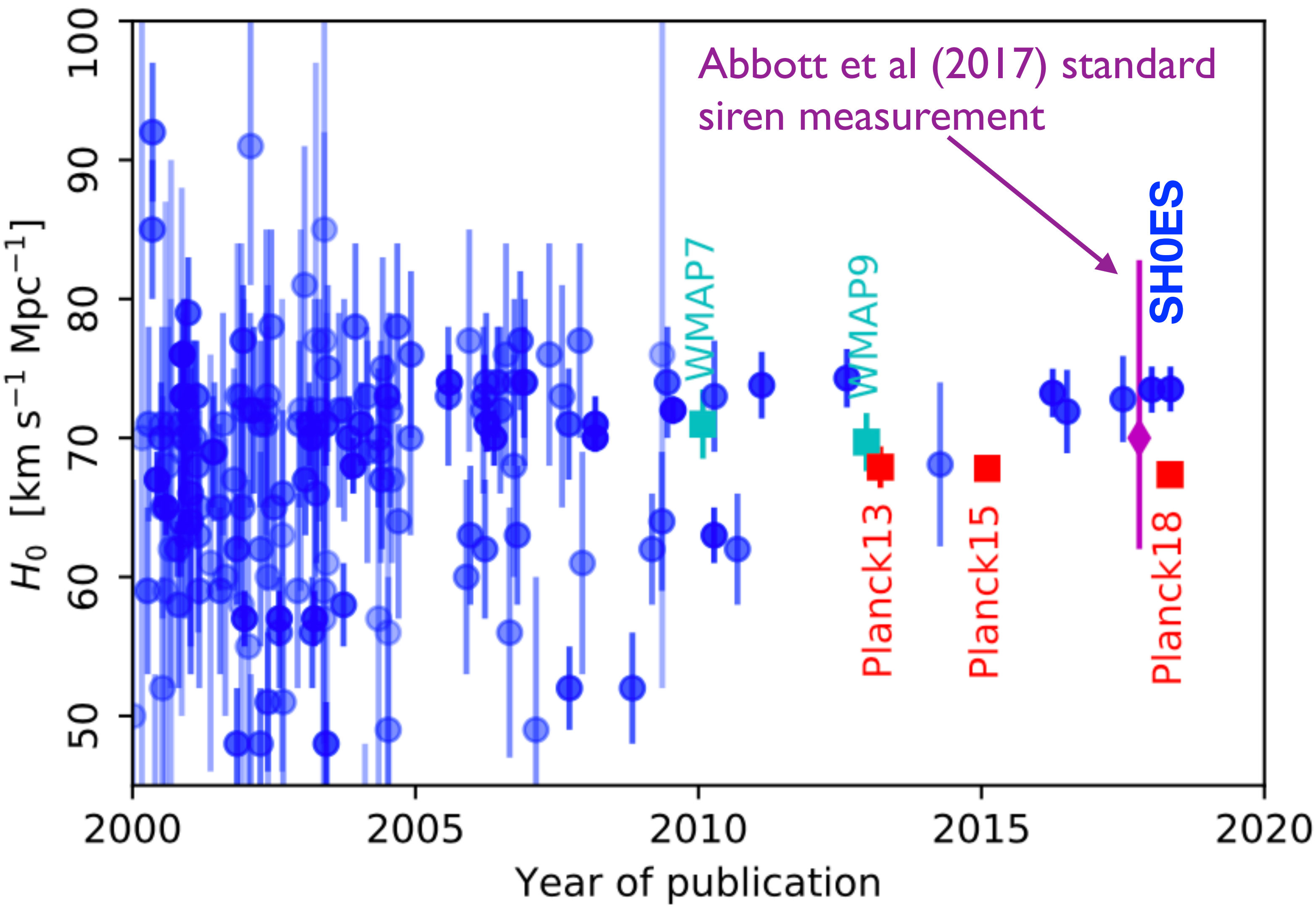
Measurements compiled by: Planck Collaboration (2018)



DESI (first light 2019)

Forecasts: Font-Ribera et al (2014)

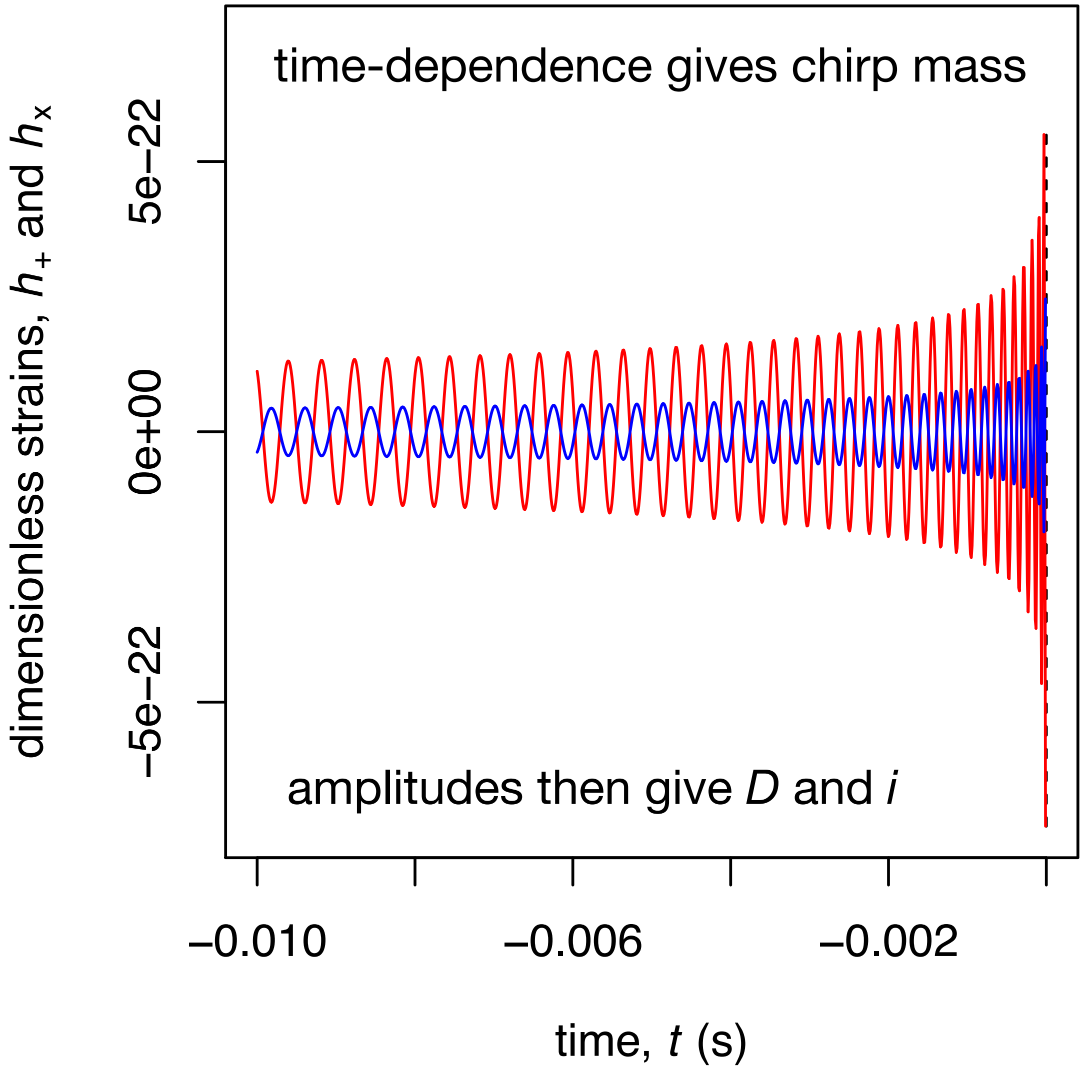
A sign of a crack in the model?

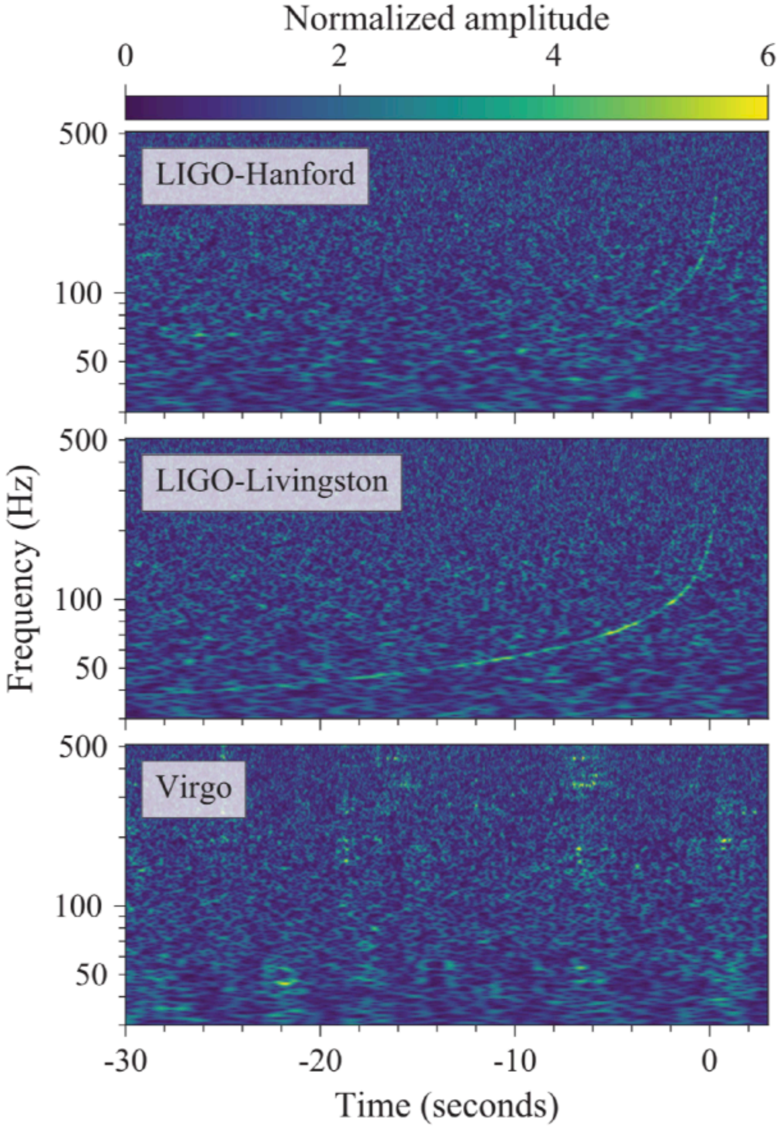


Hubble tension: currently ~4.4 σ

Compiled by Planck Collaboration (2018)

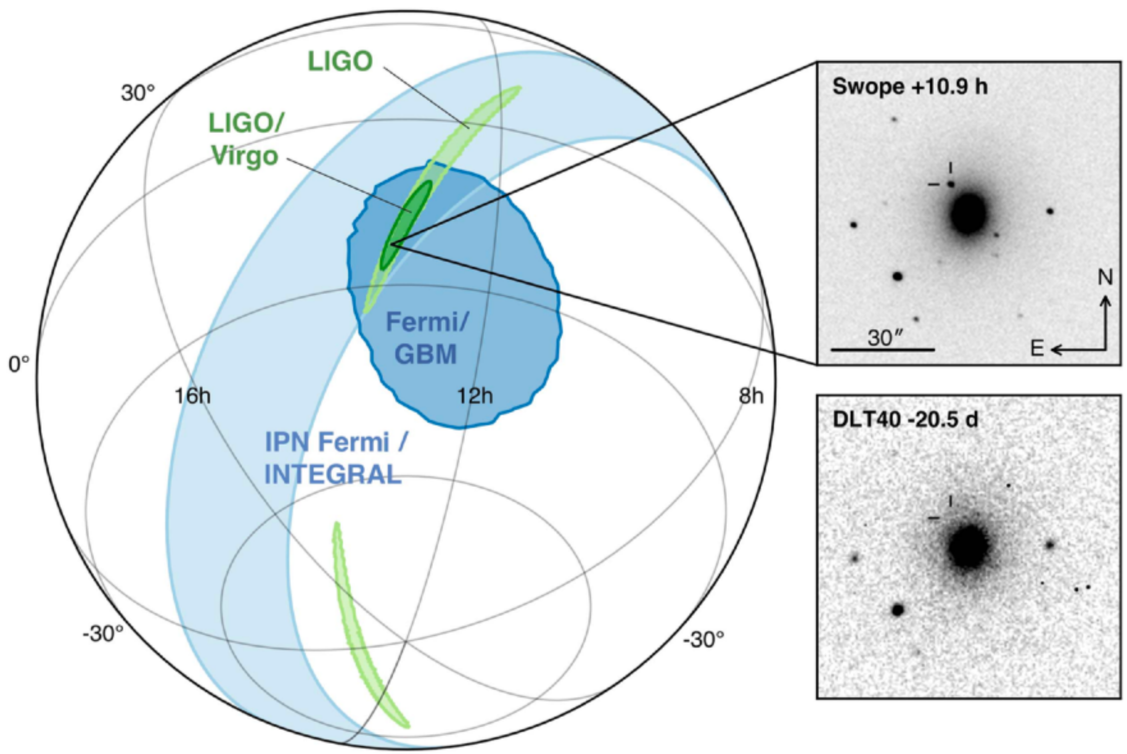
distance: GWs from BNS merger

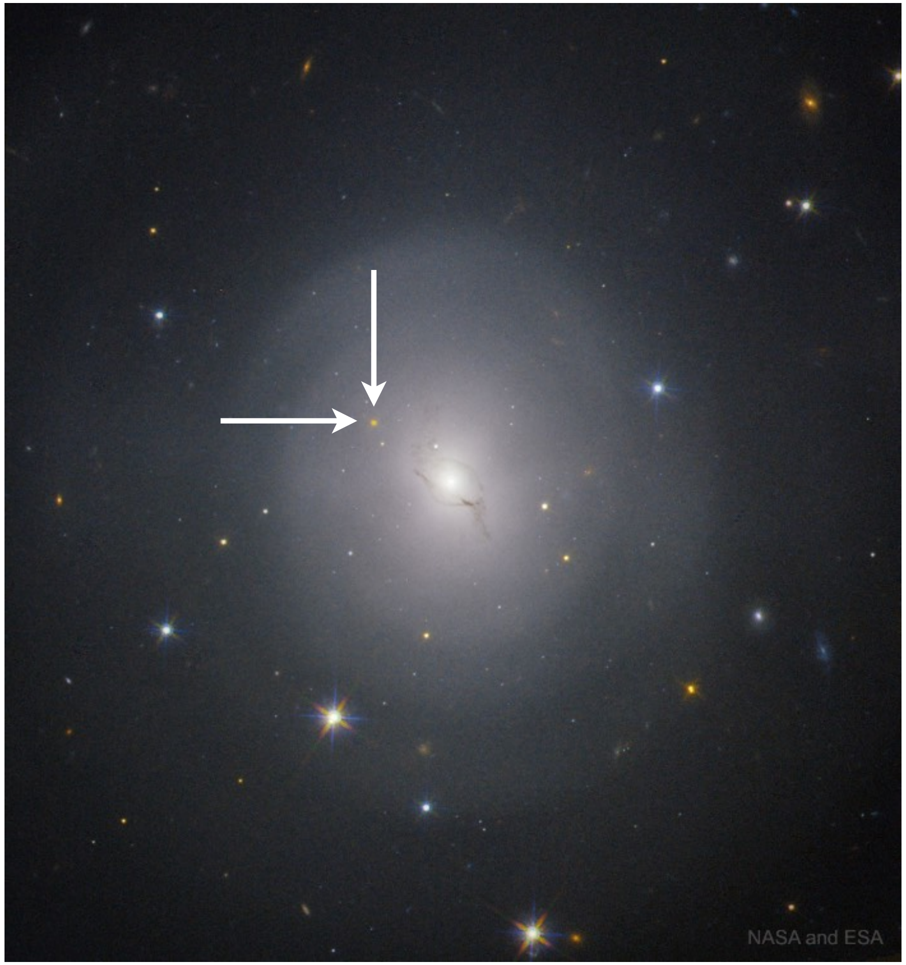




(Abbott et al. 2017)

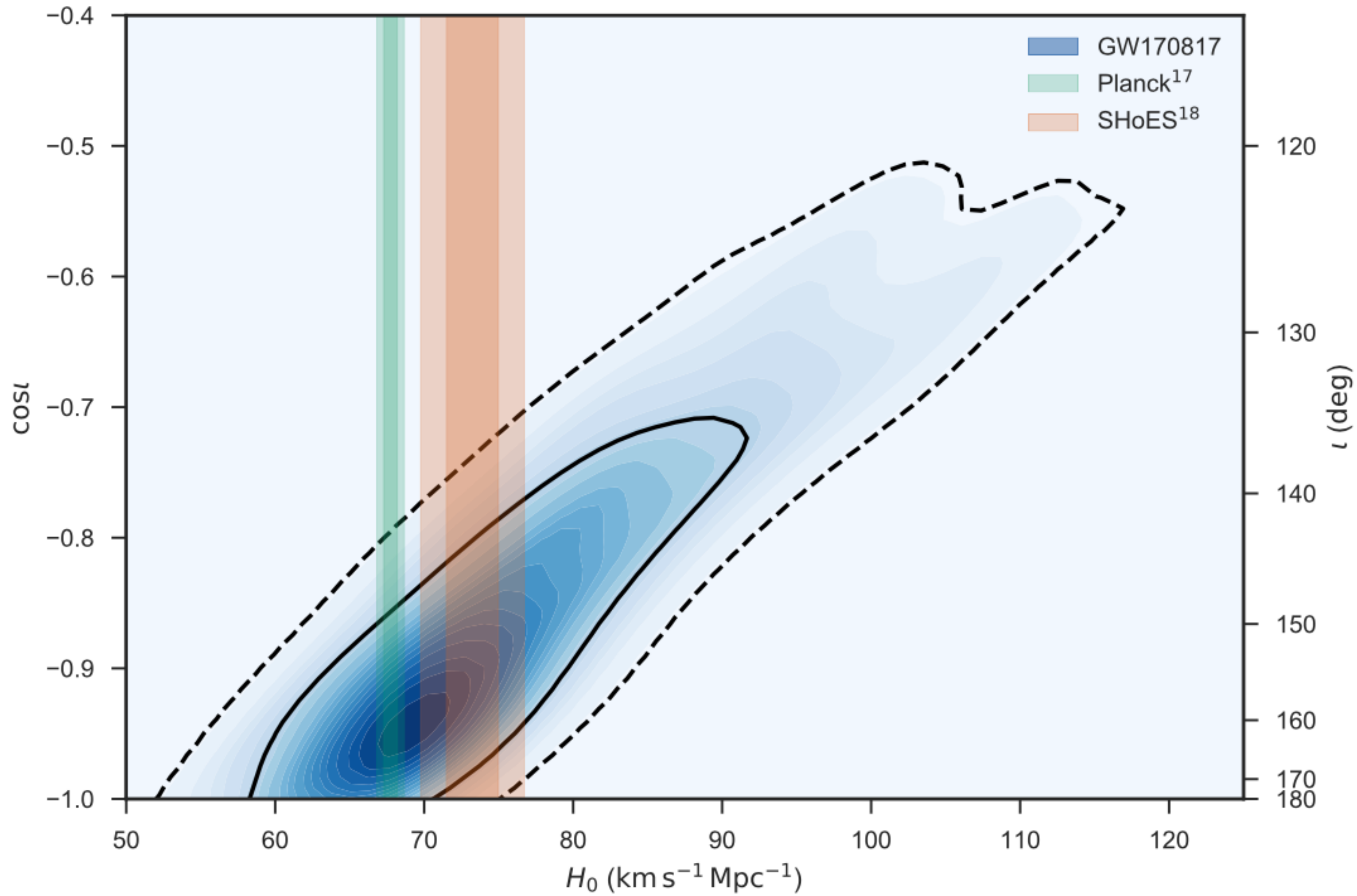
host identification: EM emission / "kilonova"





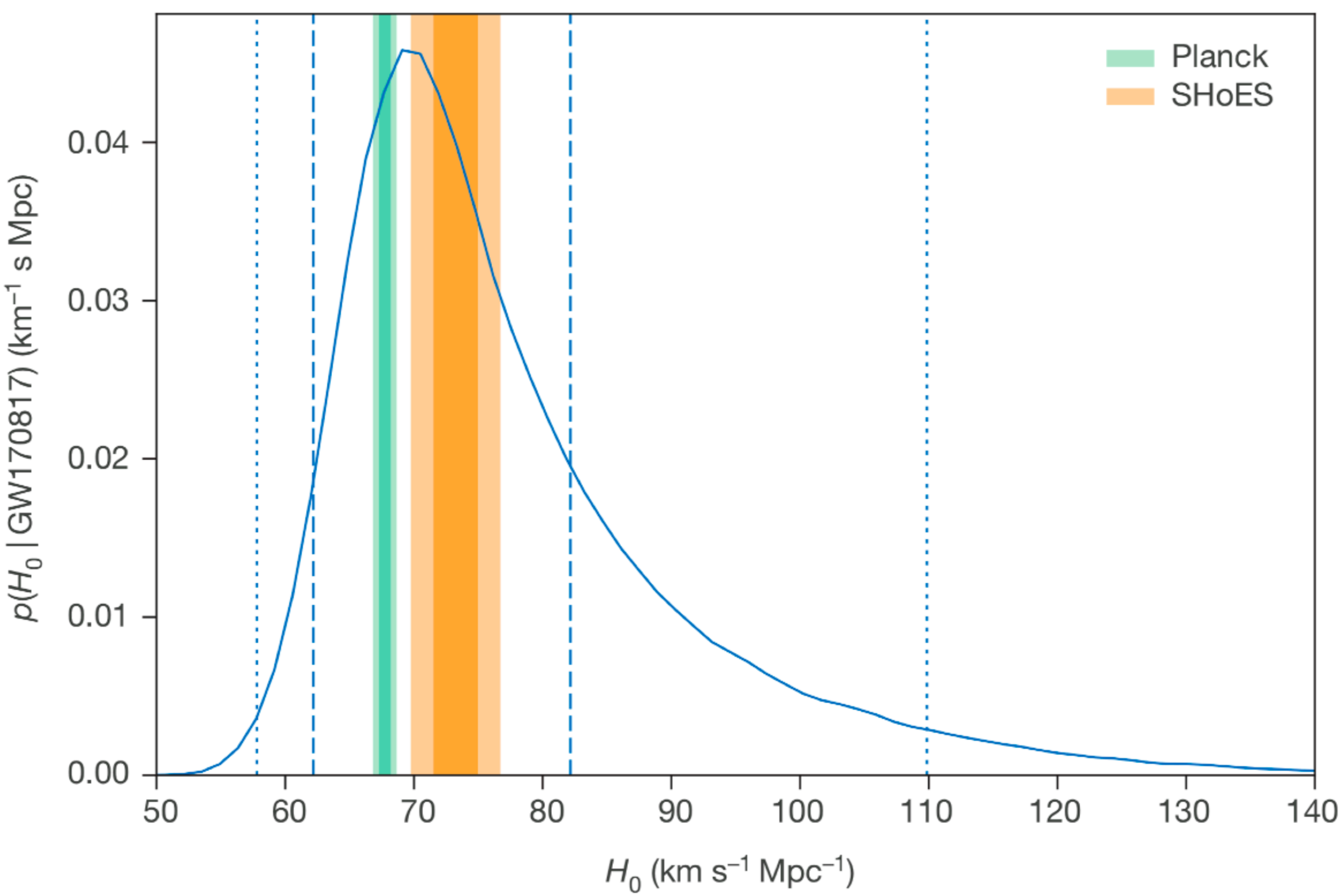
(3600 physicists and astronomers et al. 2017)

H_0 from one BNS merger



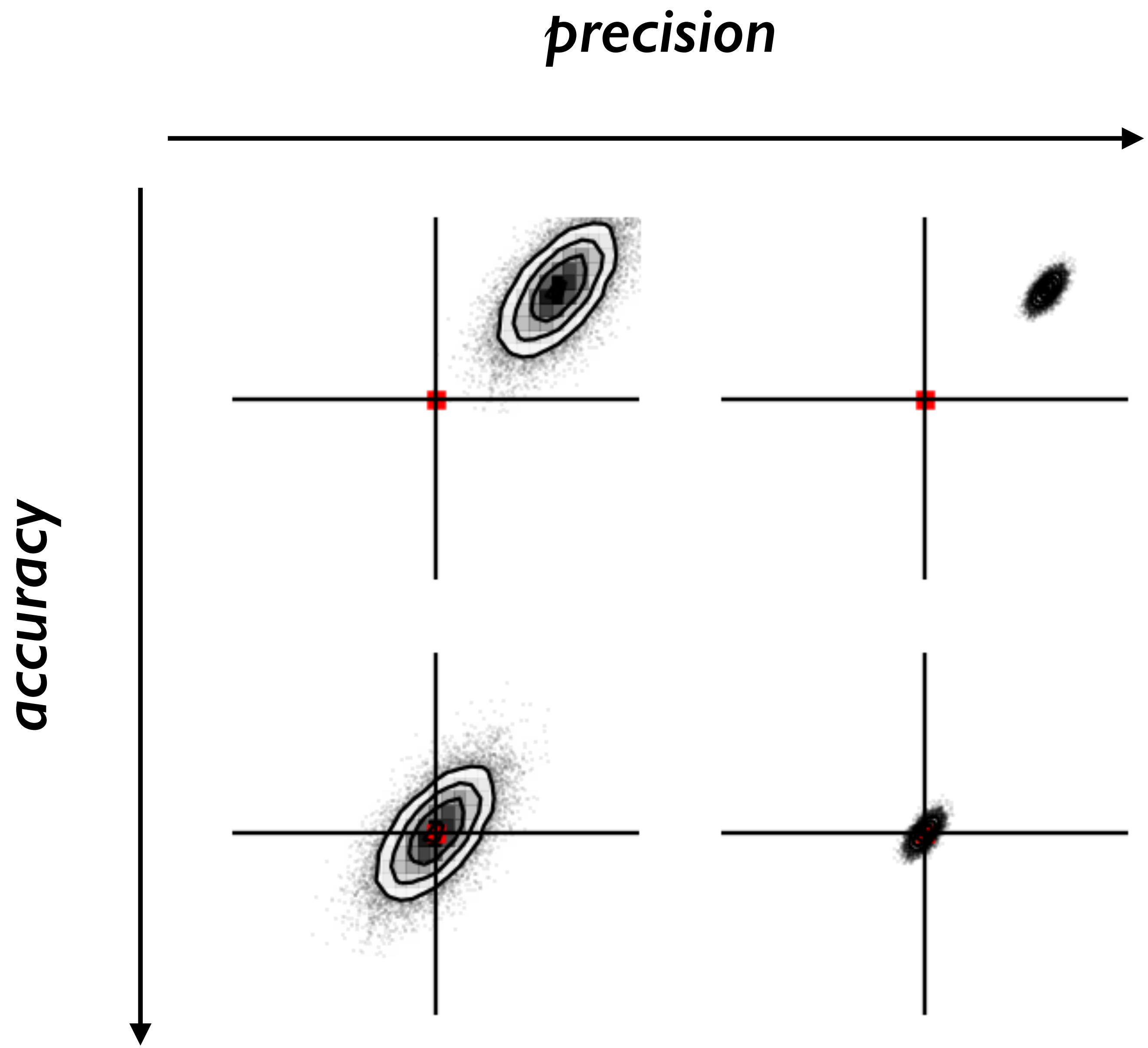
(LIGO+Virgo 2017)

H_0 from one BNS merger



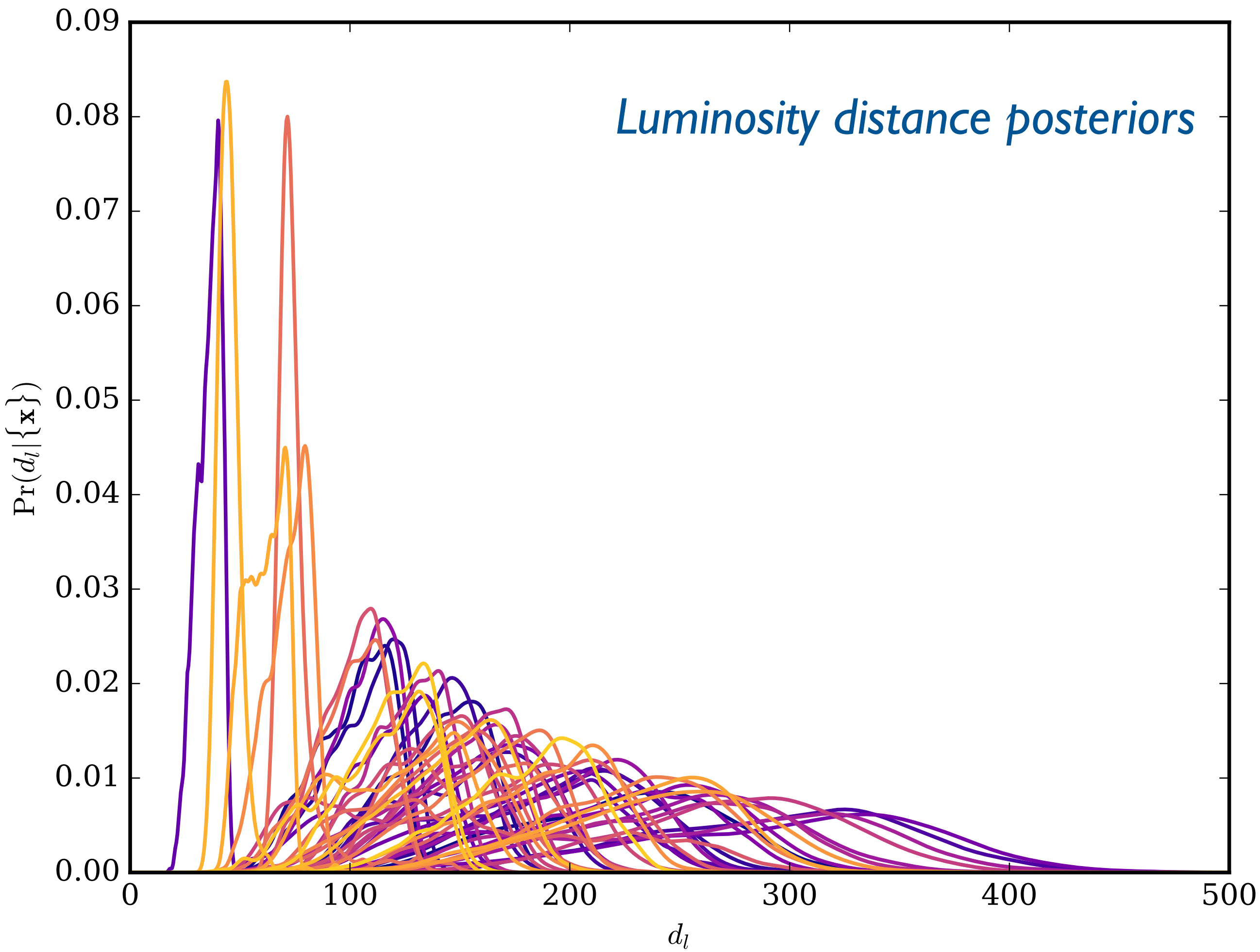
(LIGO+Virgo 2017)

"Fast vs exact methods" (Research In Progress)


precision
accuracy

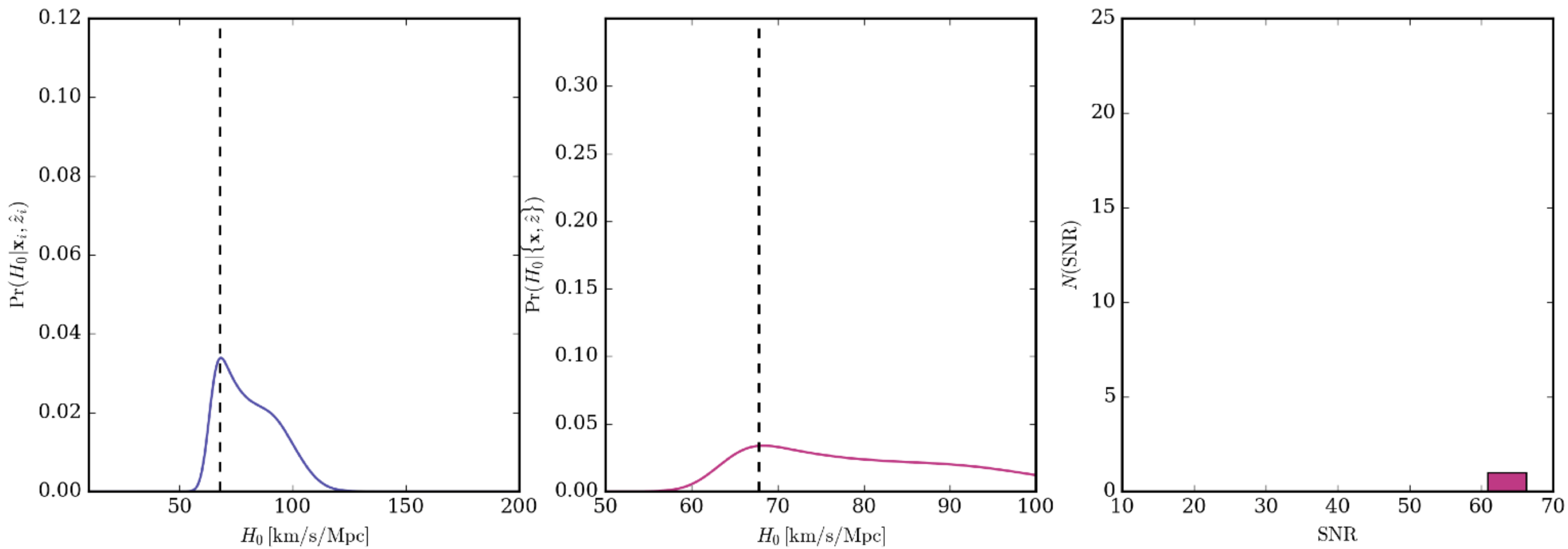
Arbitrating H_0 tension with GW standard sirens

- Simulate binary neutron star mergers w/ EM counterparts (angular position and redshift known)
- Four years of LIGO/ Virgo, assuming R_{BNS}=1500/Gpc^3/yr
- Waveforms injected in coloured noise, analysed with lalinference_mcmc (Veitch+:1409.7215)
- 51 **detectable** events



Feeney, Peiris, Williamson, Nissanke, Mortlock, Alsing, Scolnic (2019, Phys. Rev. Lett.)

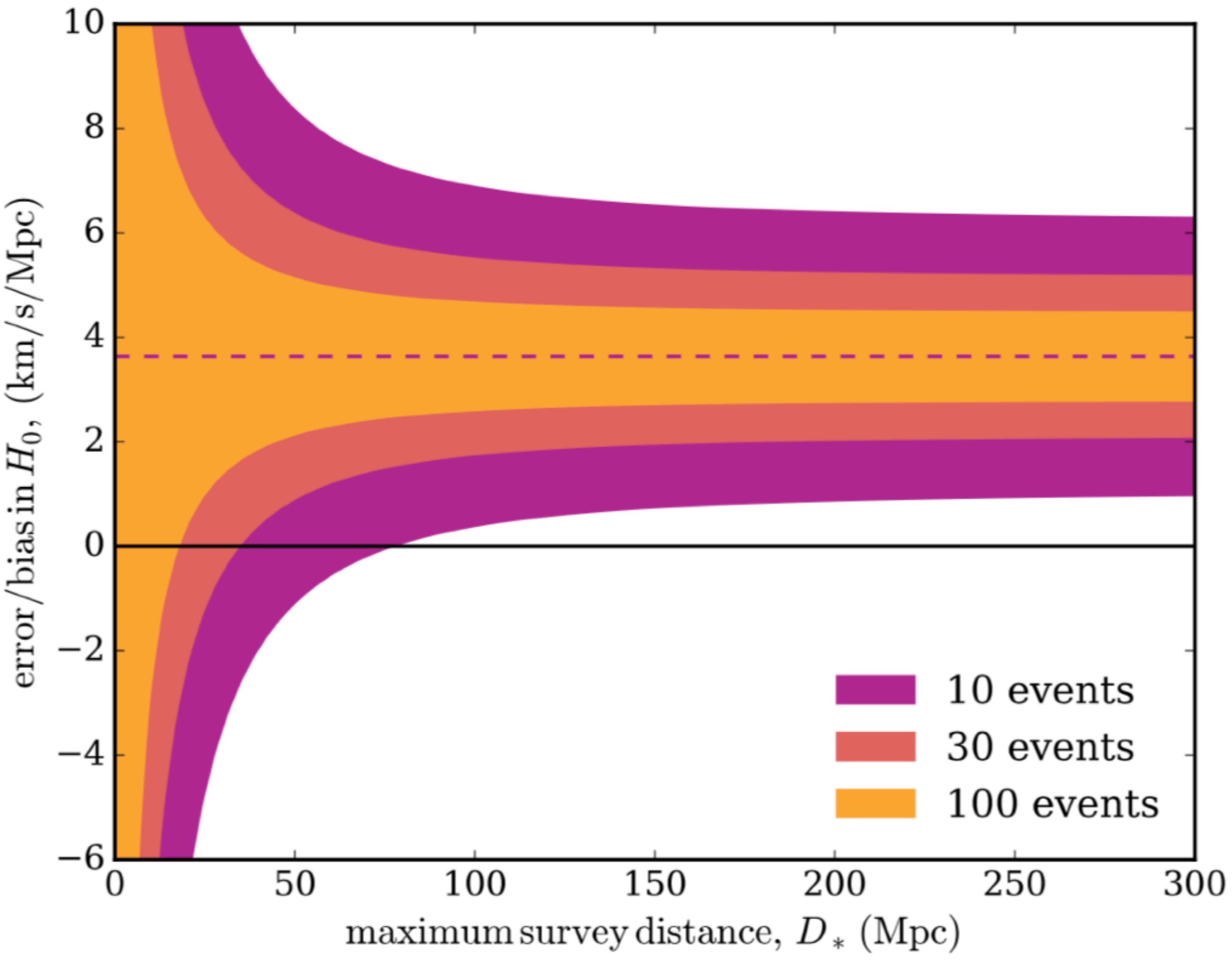
Arbitrating H_0 tension with GW standard sirens



- Compute H_0 posterior assuming perfect redshift measurements + Gaussian peculiar velocity likelihoods
- Sample of 51 mergers sufficient to arbitrate tension (though sample variance important)

Feeney, Peiris, Williamson, Nissanke, Mortlock, Alsing, Scolnic (2019, Phys. Rev. Lett.)

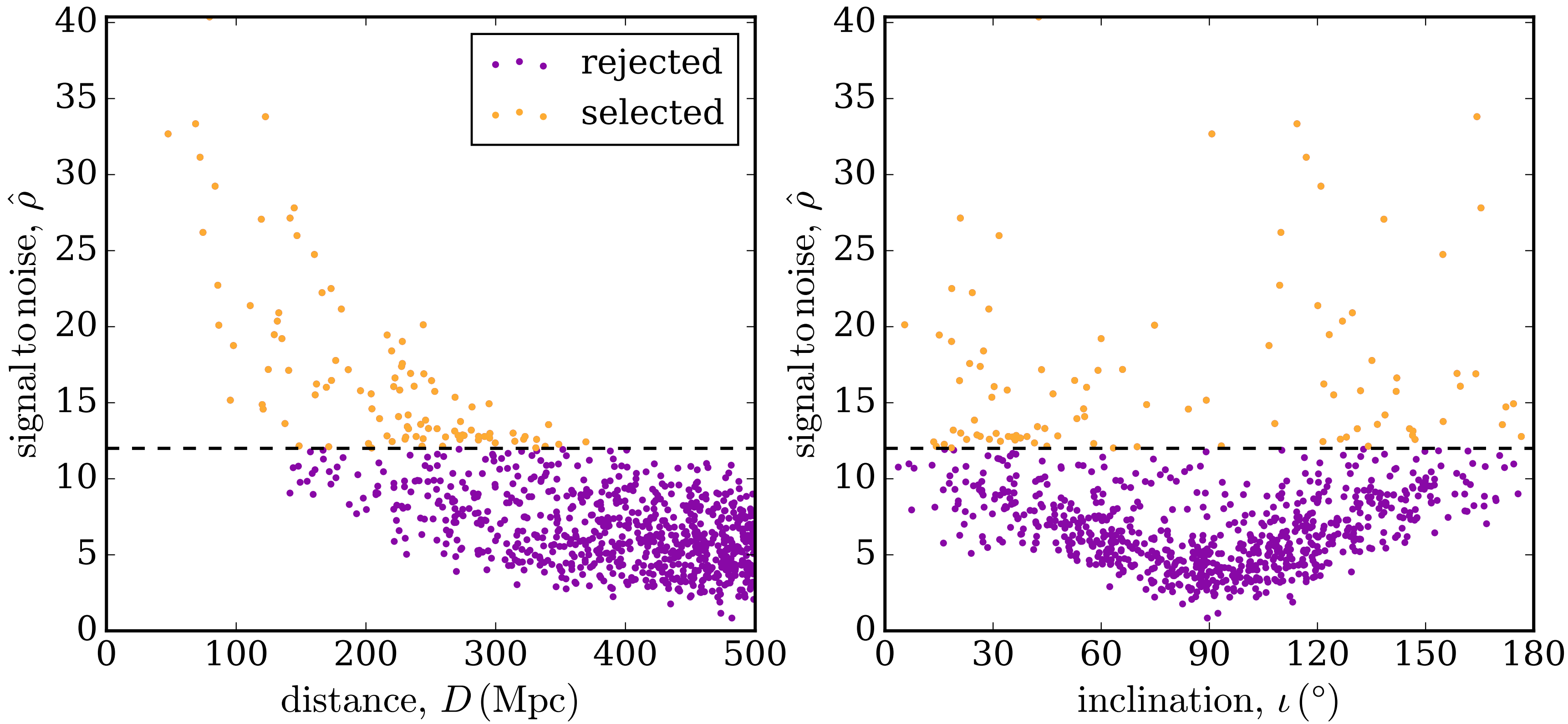
Potential selection biases in std siren samples



The potential bias due to selection effects, which would dominate over sample variance for N > 10 and D > 70 Mpc.

Mortlock, Feeney, Peiris et al (2019, Phys. Rev. D in press, arXiv:1811.11723)

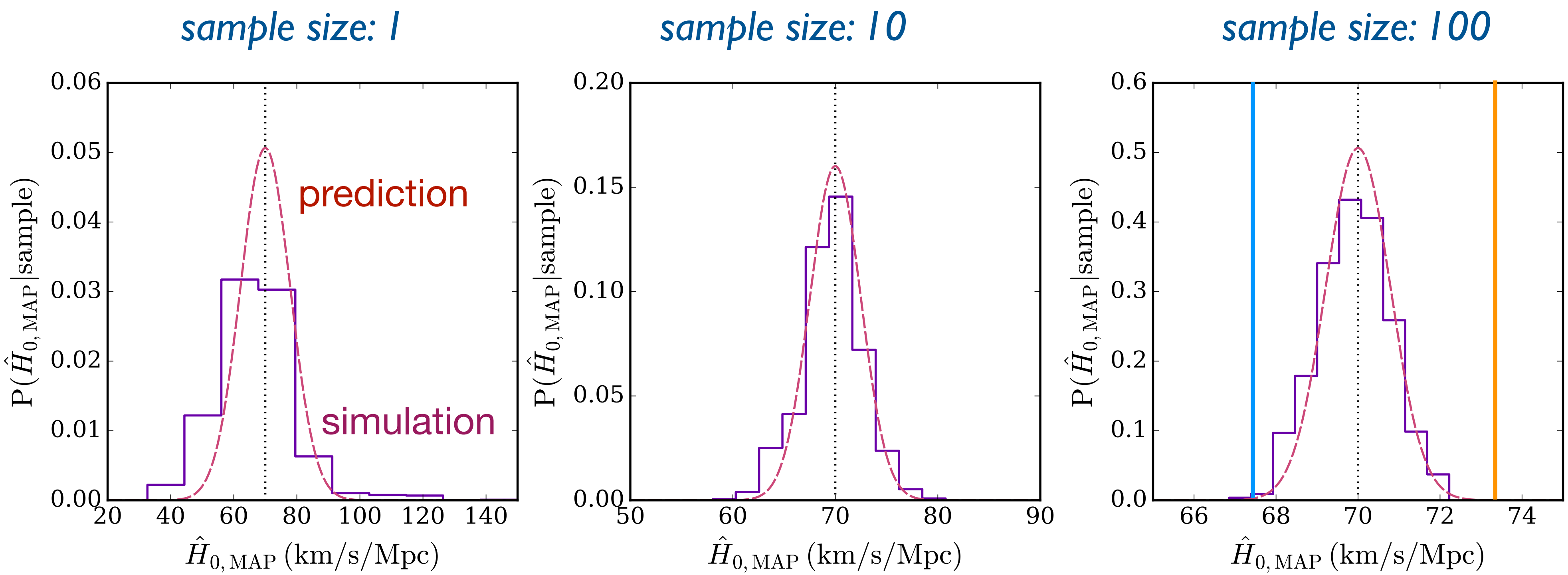
Are H0 estimates from std siren samples unbiased?



- Full models too slow to do large number numbers of realisations.
- Use linearised general relativity which includes only: “chirp mass”, *M*; distance, *D*; and inclination *i*.
- Includes self-consistent selection on *observed* quantities.

Mortlock, Feeney, Peiris et al (2019, Phys. Rev. D in press, arXiv:1811.11723)

Are H0 estimates from std siren samples unbiased?



Distribution of MAP estimate of H_0 from simulations of samples of N BNSs applying GW selection

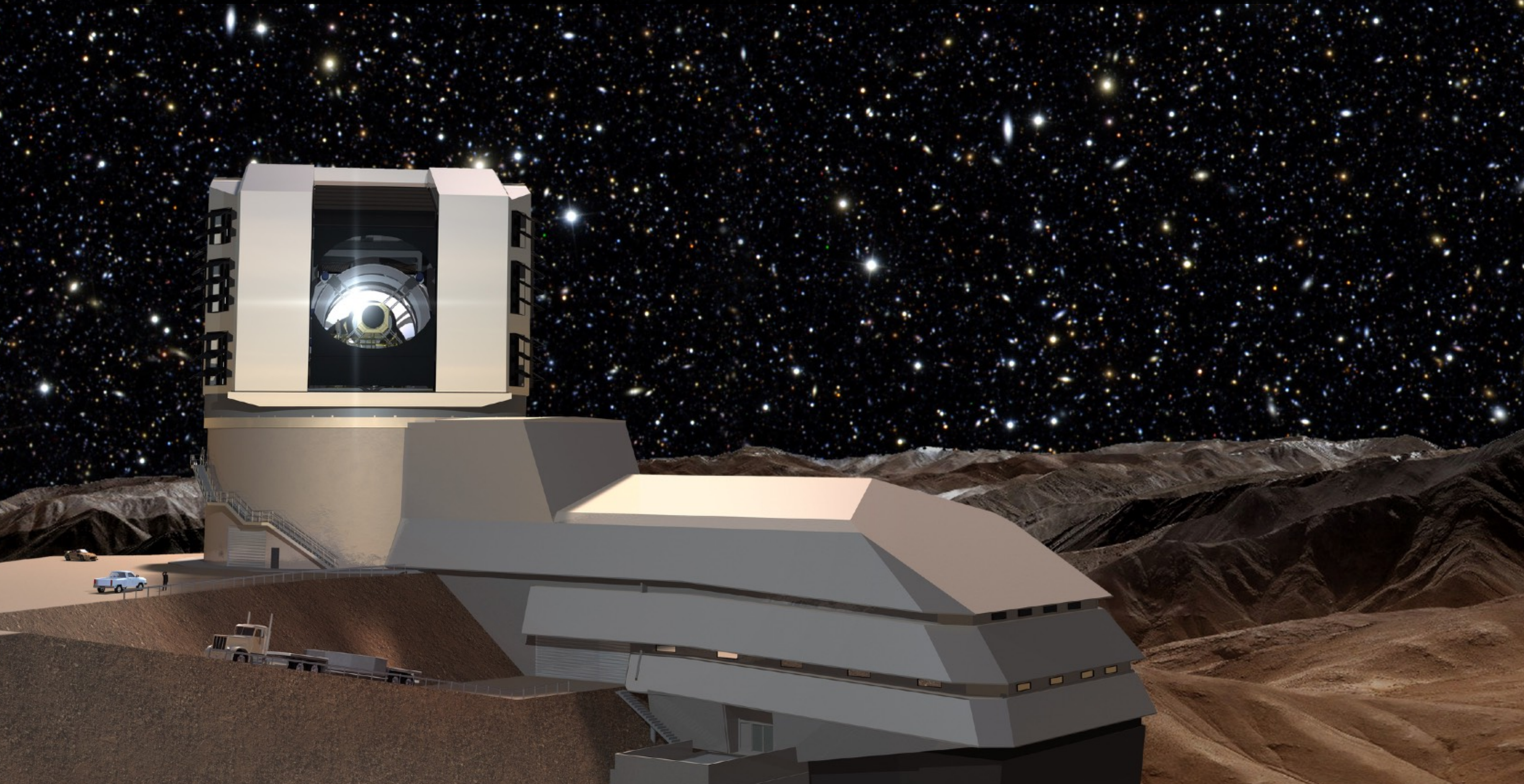
N = 1: Distribution has a high-H_0 tail; difficult to assess error/bias

N = 100: Distribution Gaussian; into asymptotic regime; unbiased

Mortlock, Feeney, Peiris et al (2019, Phys. Rev. D in press, arXiv:1811.11723)

A dedicated survey telescope

- Wide (half-sky), deep (24-27 mag), fast (every ~3 days) images
- Beginning in 2020, LSST will survey the Southern sky for 10 years
- Expand space-time volume a 1000 times over current surveys



Large Synoptic Survey Telescope

10 year survey of 18,000 sq deg (southern sky) every ~ 3 days

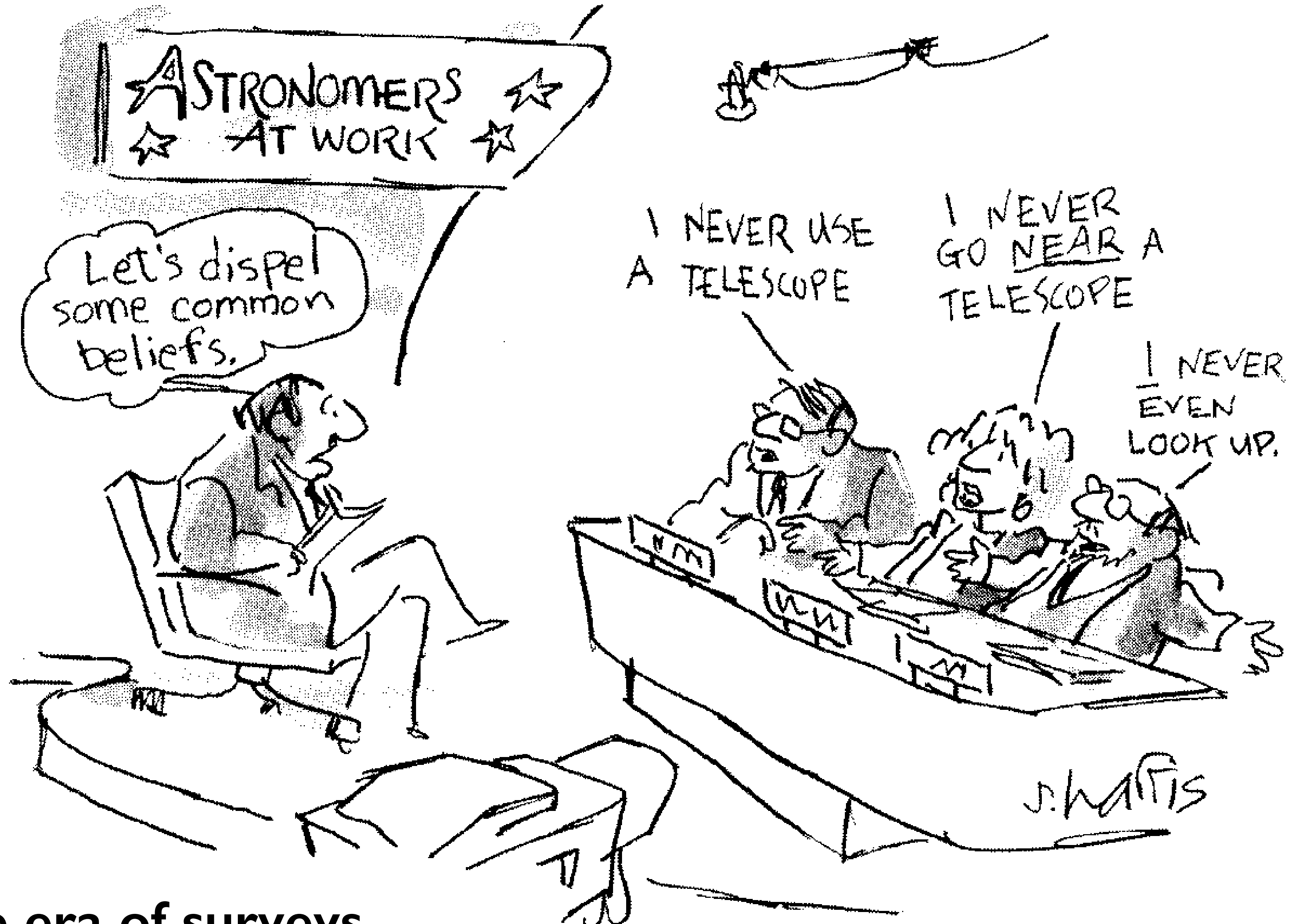
- 4 billion galaxies (with photo-z)
- Time domain:
  - 5 million asteroids
  - 1 million supernovae
  - 1 million gravitational lenses
  - 100 million variable stars

+ new phenomena

survey of 37 billion objects in space and time

Expand space-time volume a thousand times over current surveys!

From Zeljko Ivezic

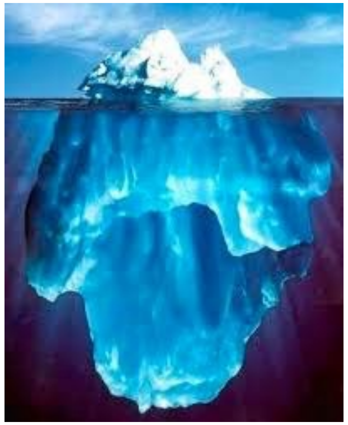


The era of surveys…

“Ask Not What Data You Need To Do Your Science, Ask What Science You Can Do With Your Data.”

LSST 4 science missions

Dark matter-Dark energy



Multiple investigations into the nature of the dominant components of the Universe.

Solar system inventory

Find 90% of hazardous NEOs down to 140m over 10 years; test theories of Solar System formation.

"Movie of the Universe"

Discovering the transient and unknown over time scales days to years

Mapping the Milky Way

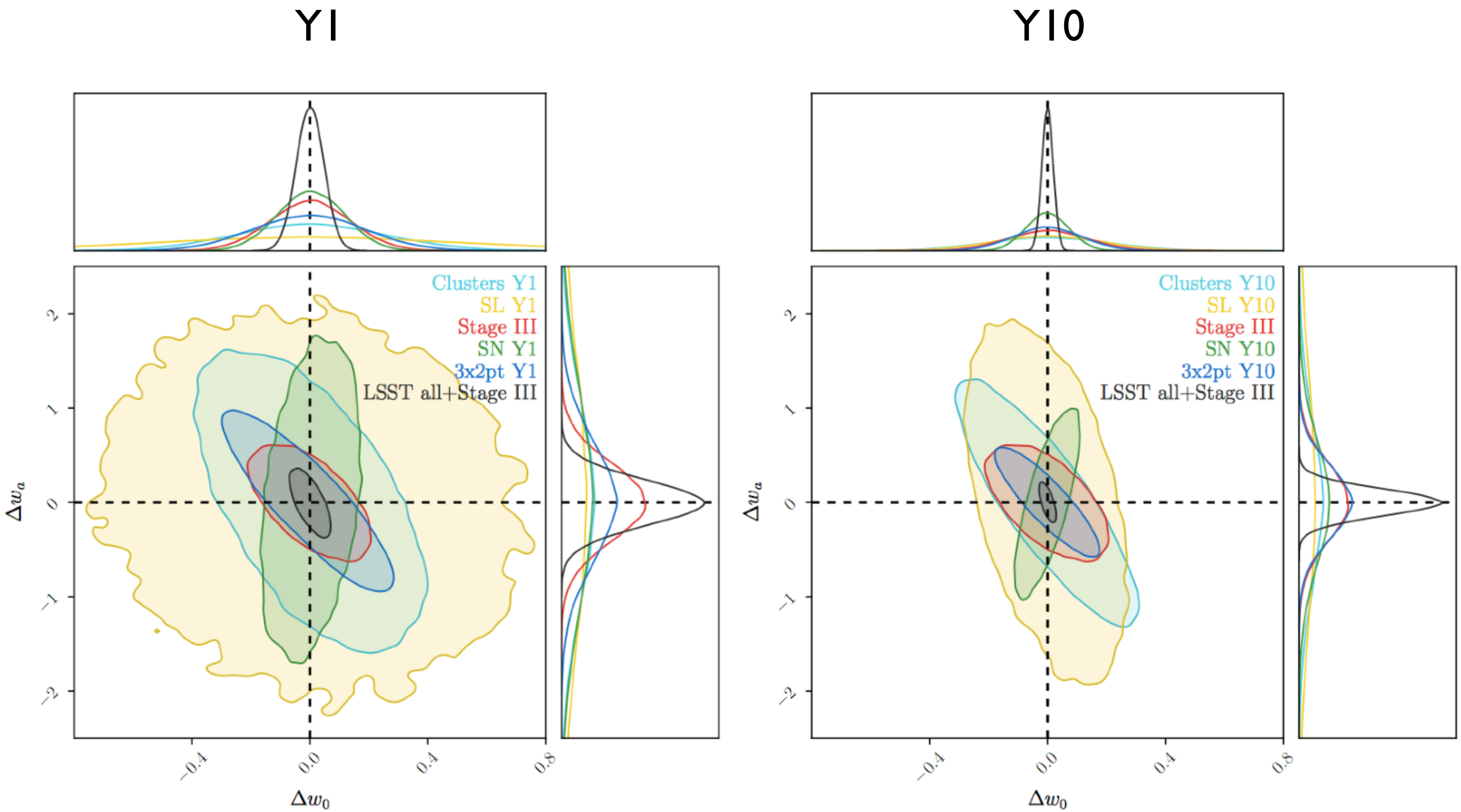
Map the rich and complex structure of the Milky Way in unprecedented detail [test-beds for dark matter physics]

All missions conducted in parallel.

Adapted from Ian Shipsey

BACKGROUND IMAGE CREDIT: UCL / PONTZEN

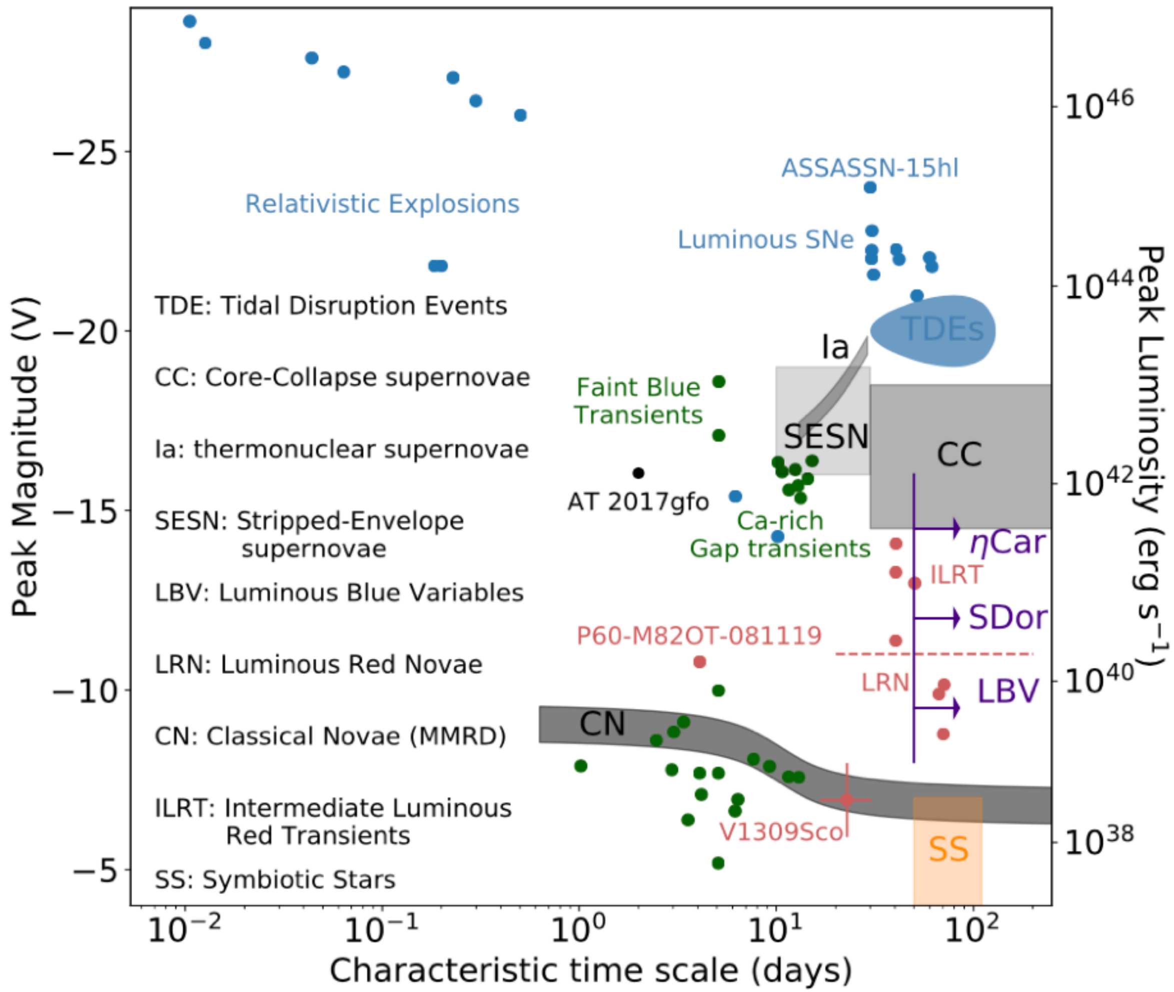
LSST and Dark Energy Science



Measuring if / how dark energy evolves with time

DESC Science Requirements Document V1 (ArXiv: 1809.01669)

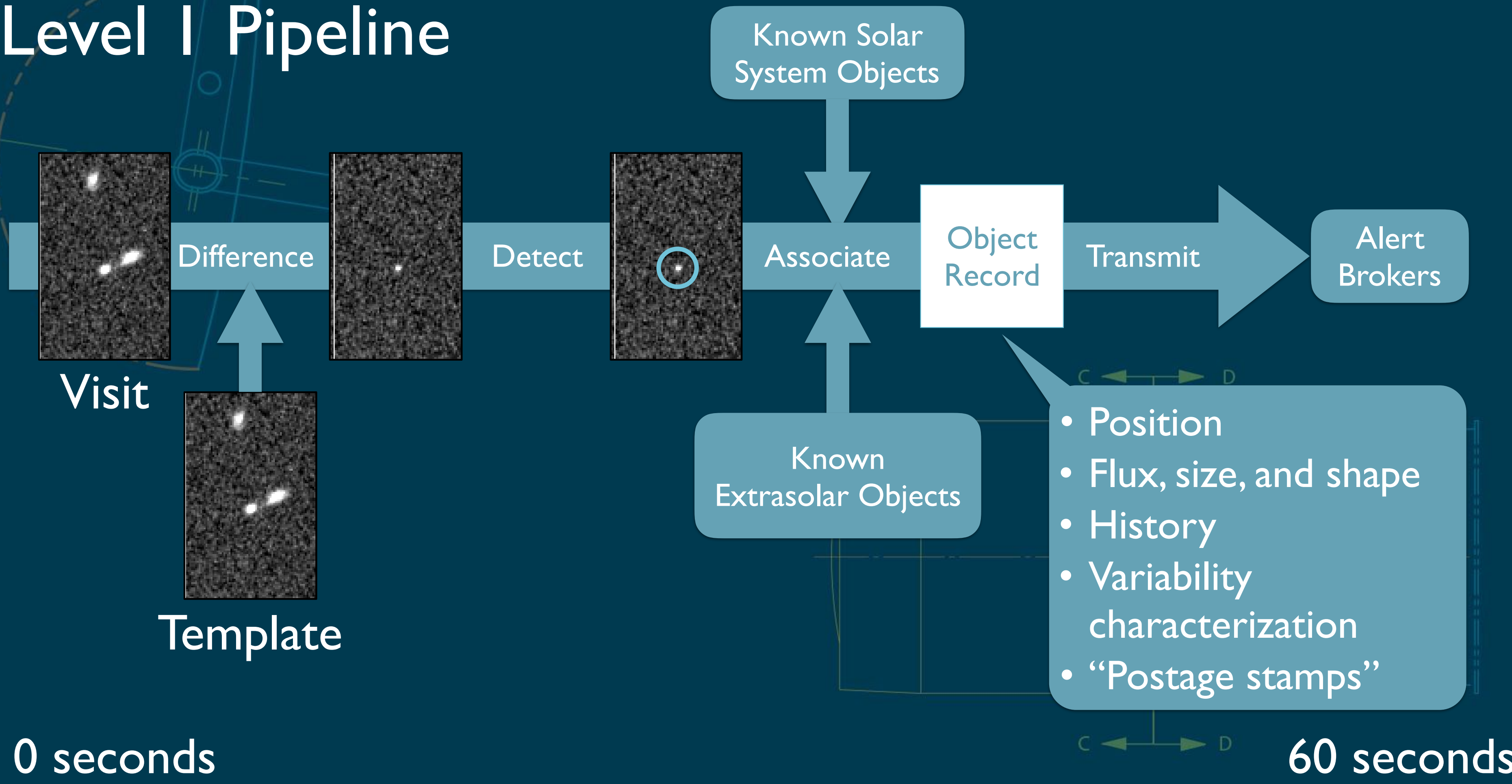
LSST and the transient universe



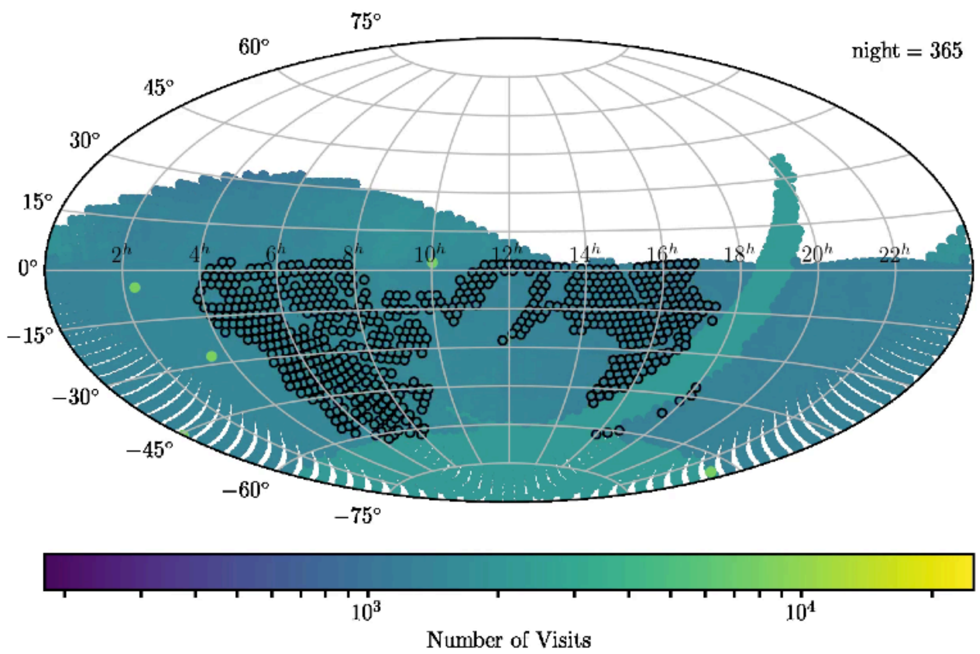
The phase space of cosmic explosive and eruptive transients represented by absolute V band peak brightness and event timescale, adapted from Kulkarni et al. (2007) and Kasliwal (2011). LSST will open up large regions of this phase space for systematic exploration.

FIGURE: IVEZIC ET AL (ARXIV: 0805.2366V5, LIVING REFERENCE DOCUMENT)

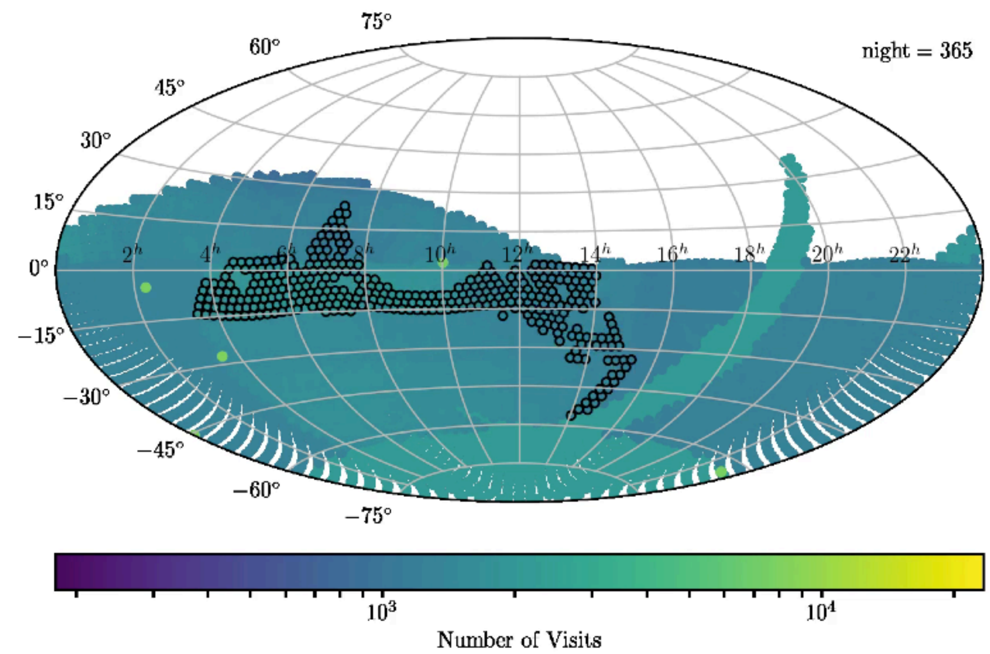
Level 1 Pipeline



LSST cadence



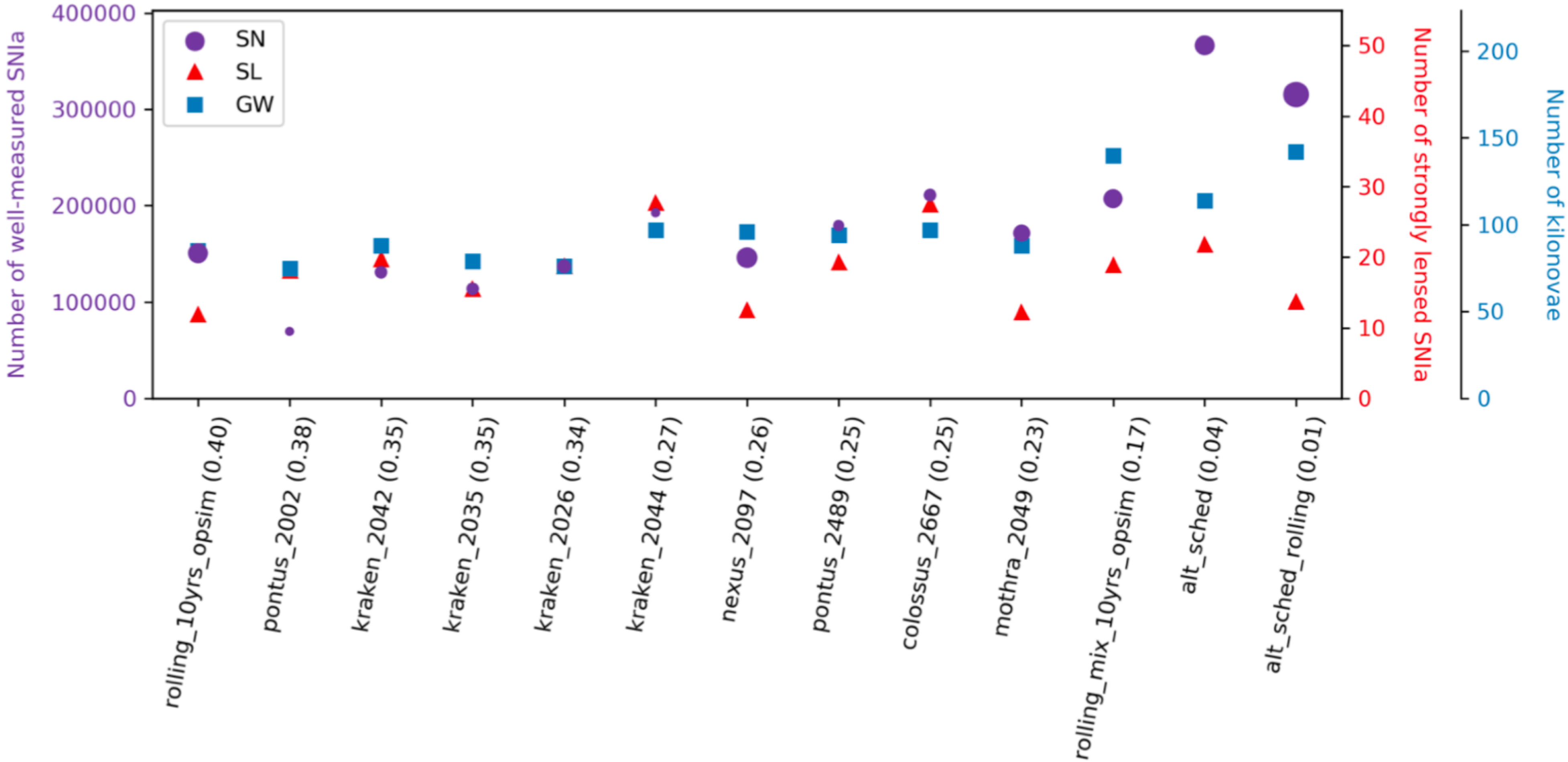
WFD baseline strategy



A rolling WFD proposal

MOVIES: ROB FIRTH

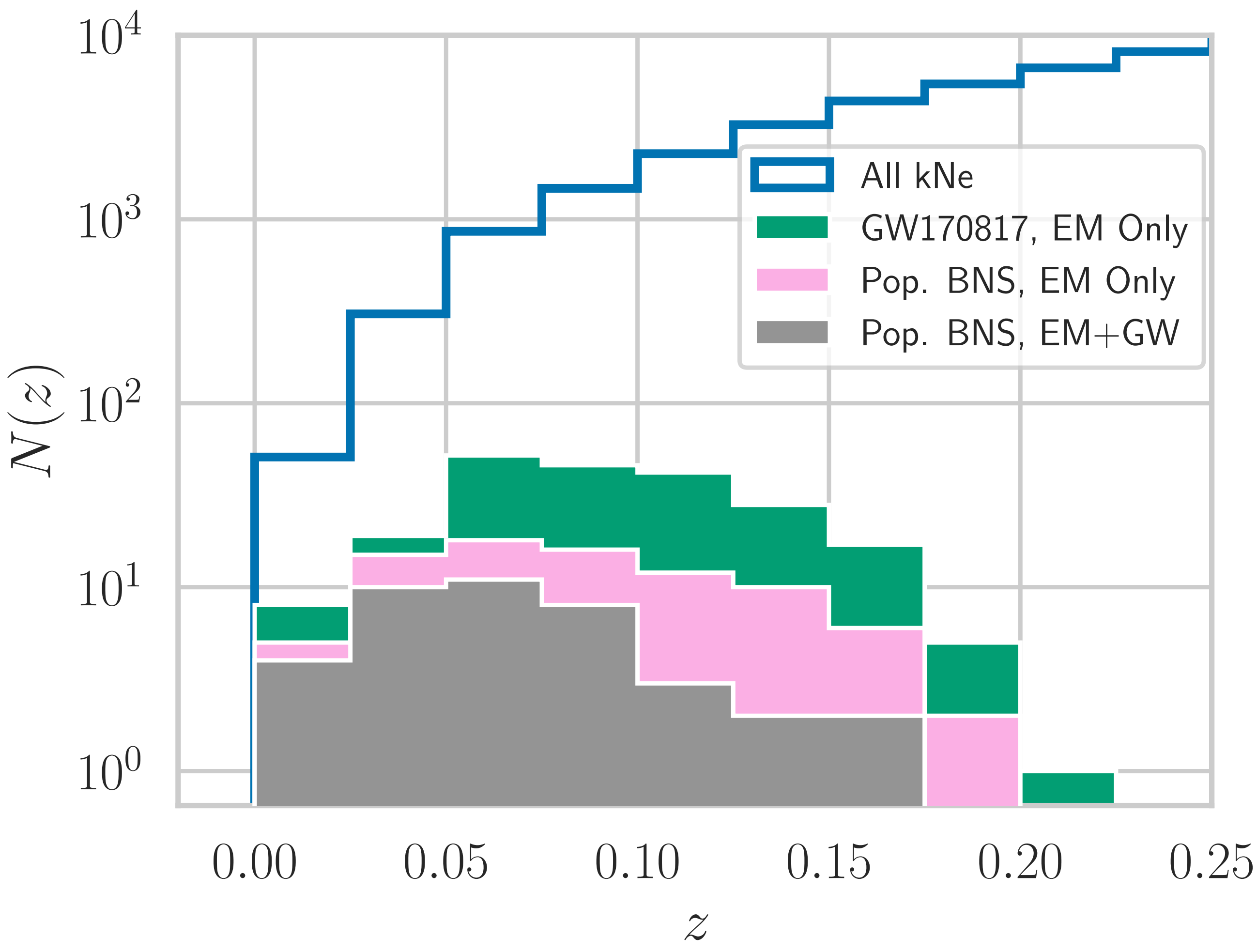
LSST and the transient universe



Number of kilonovae, strongly lensed type Ia supernovae with well-measured time delays (both assuming follow-up with other telescopes) and well-measured type Ia supernovae for Y10 as a function of observing strategy, ordered by percentage of visits in r-band separated by more than 15 days (in brackets).

LSST DESC WFD (ArXiv:1812.00515) and DDF (ArXiv:1812.00516) white papers

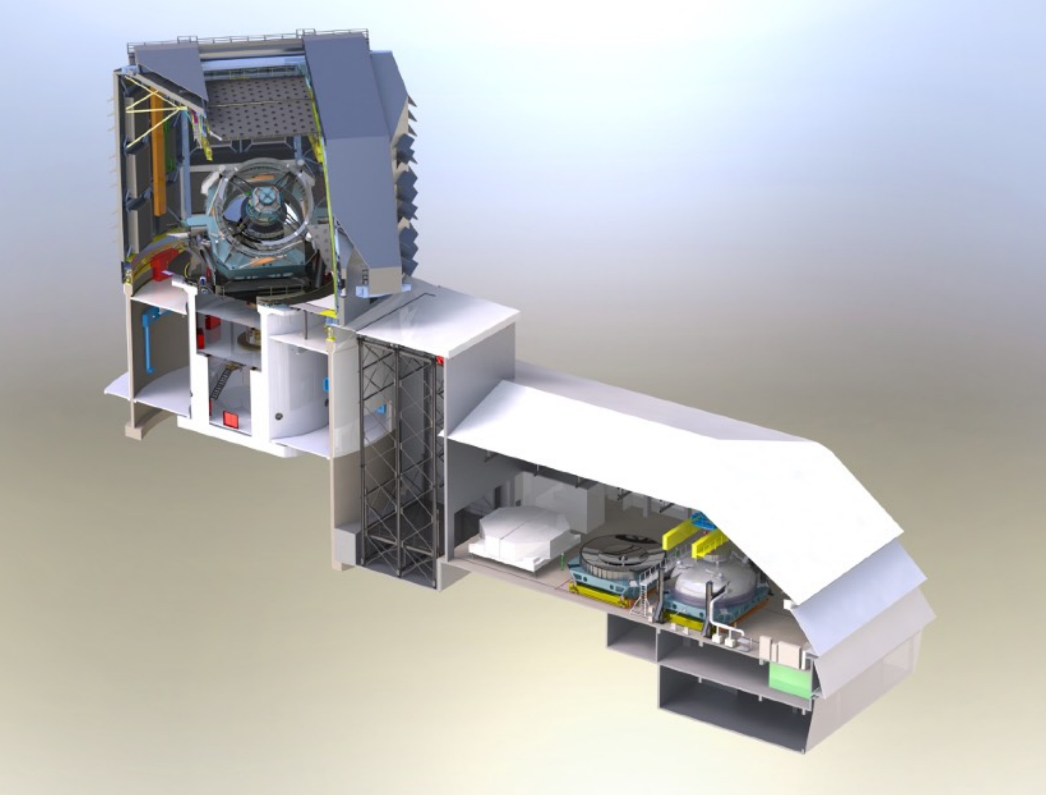
Serendipitous detections of kilonovae in LSST

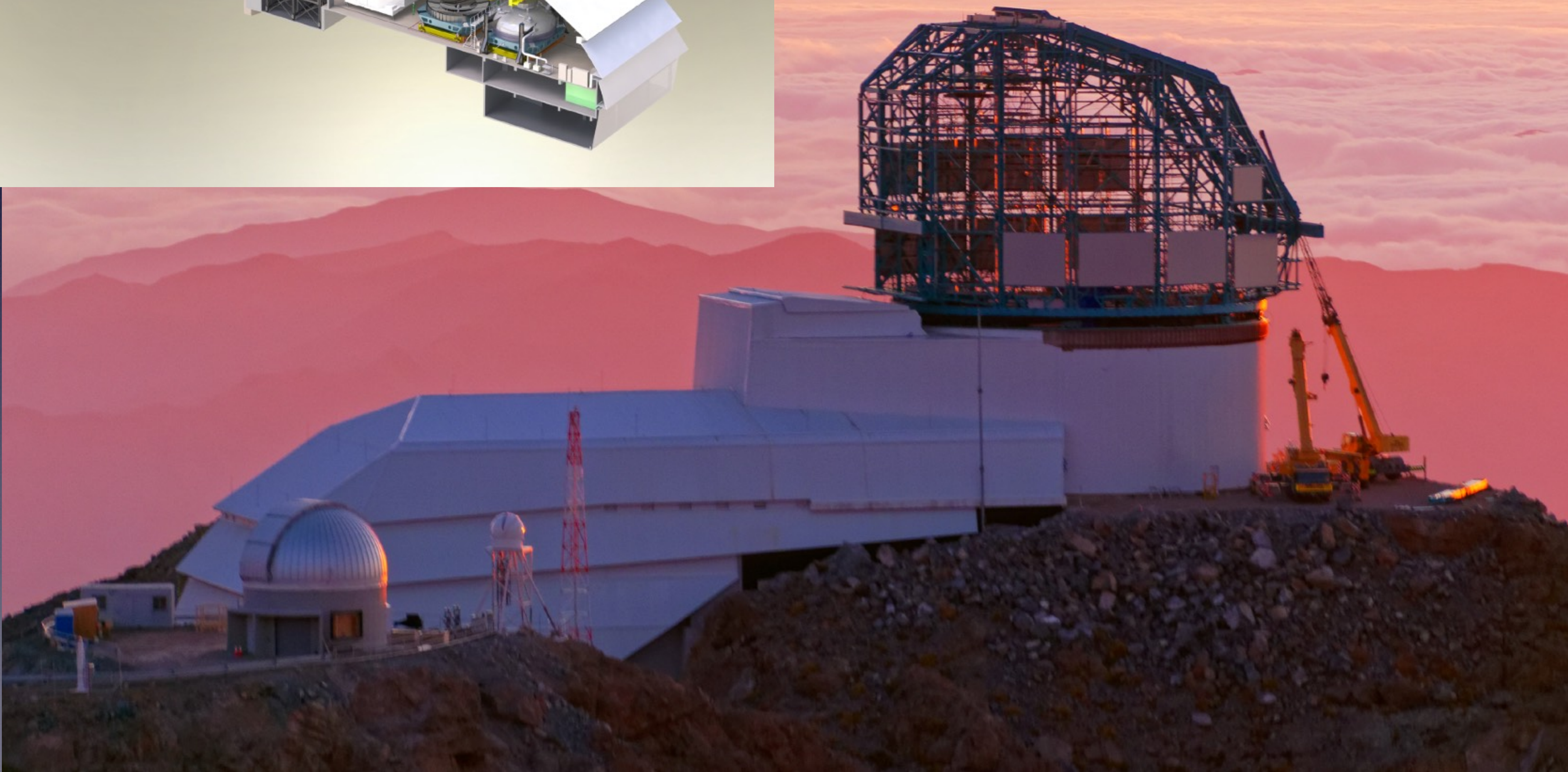


Can optical kilonovae detections be used to "reverse-trigger" searches for sub-threshold GW events in archival data?

Setzer et al (LSST DESC, MNRAS 2019, 1812.10492)

First light: 2020





What might we learn in the next decade?

- ***Smoking gun of inflation?***
  primordial B-mode polarisation

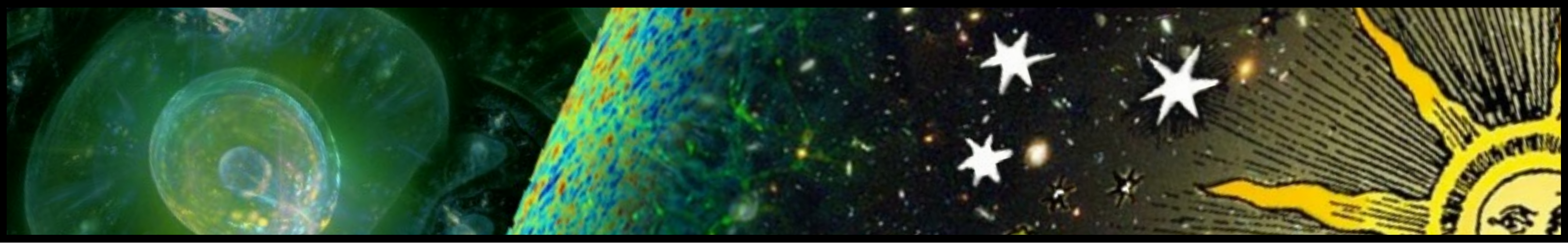
- ***Nature of dark energy and dark matter***
  DE equation of state, properties of dark matter

- ***Is GR the correct theory of gravity?***
  tests of gravity at cosmological scales

- ***Neutrino sector***
  mass, hierarchy

- ***Thermal history ~1 sec after the Big Bang***
  relativistic degrees of freedom

- ***Discovery space!***



More mysteries of the universe remain hidden. Their discovery awaits the adventurous scientists of the future — Vera Rubin

Stephen Feeney
(UCL)

Christian Setzer
(Stockholm)

G.R.E.A.T. @ Stockholm

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