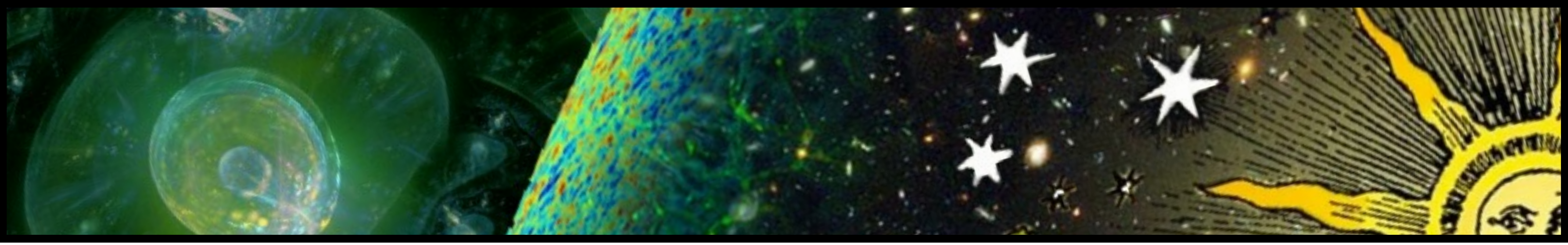


Pixels to physics: the promise and challenges of survey cosmology

Hiranya V. Peiris

UCL and Oskar Klein Centre Stockholm

Oskar Klein centre

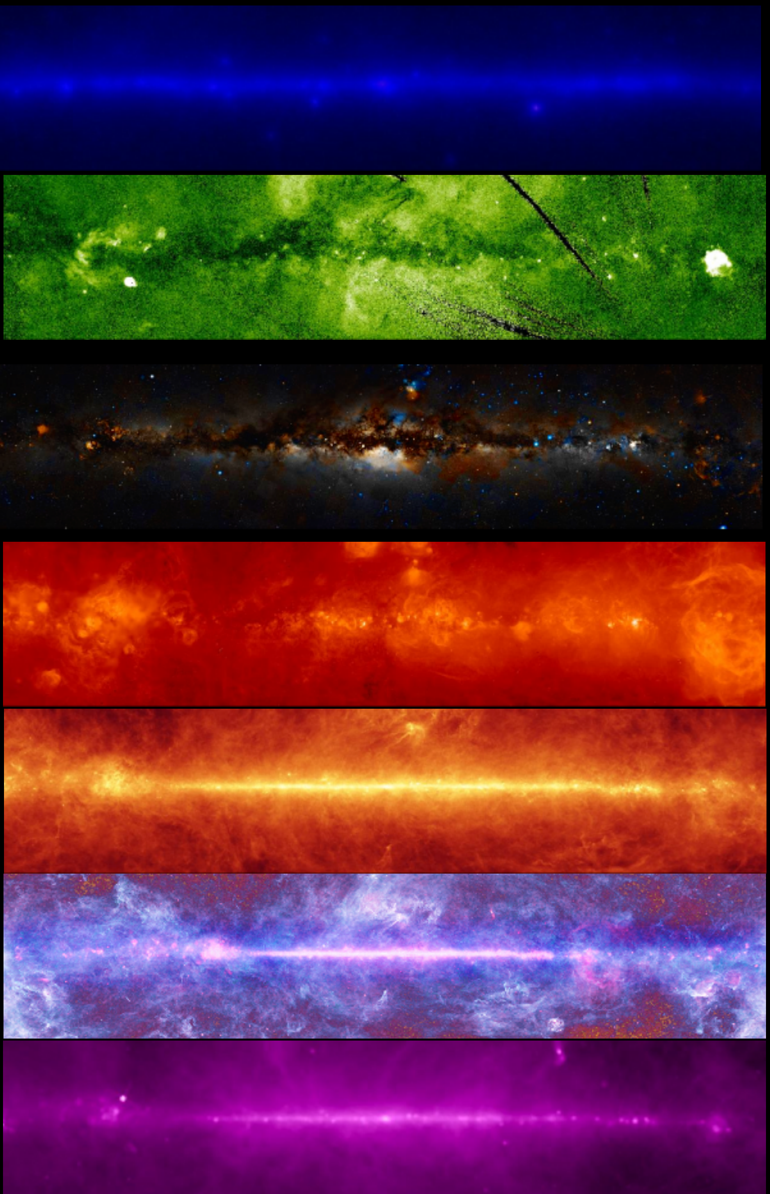
Knut och Alice Wallenbergs Stiftelse

erc European Research Council

VETENSKAPSRÅDET THE SWEDISH RESEARCH COUNCIL

UCL

The era of surveys



Gamma Ray (Fermi)

X Ray (ROSAT)

Optical (DSS)

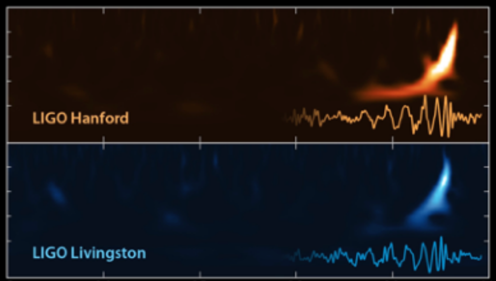
H-alpha

(WHAM/SHASSA/VTSS)

Far Infrared (IRAS)

Microwave (Planck)

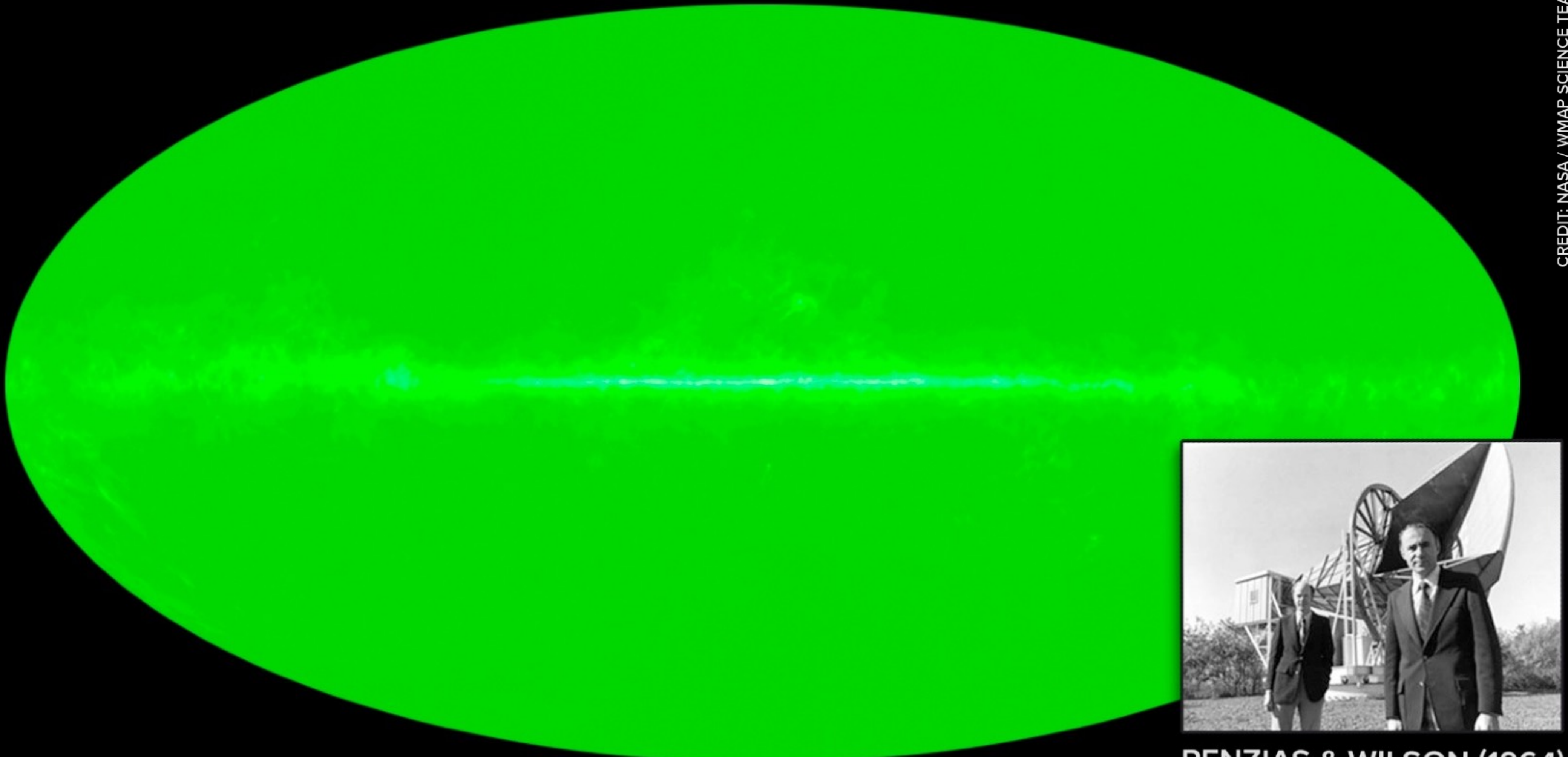
Radio (Haslam)



Gravitational Waves (LIGO)

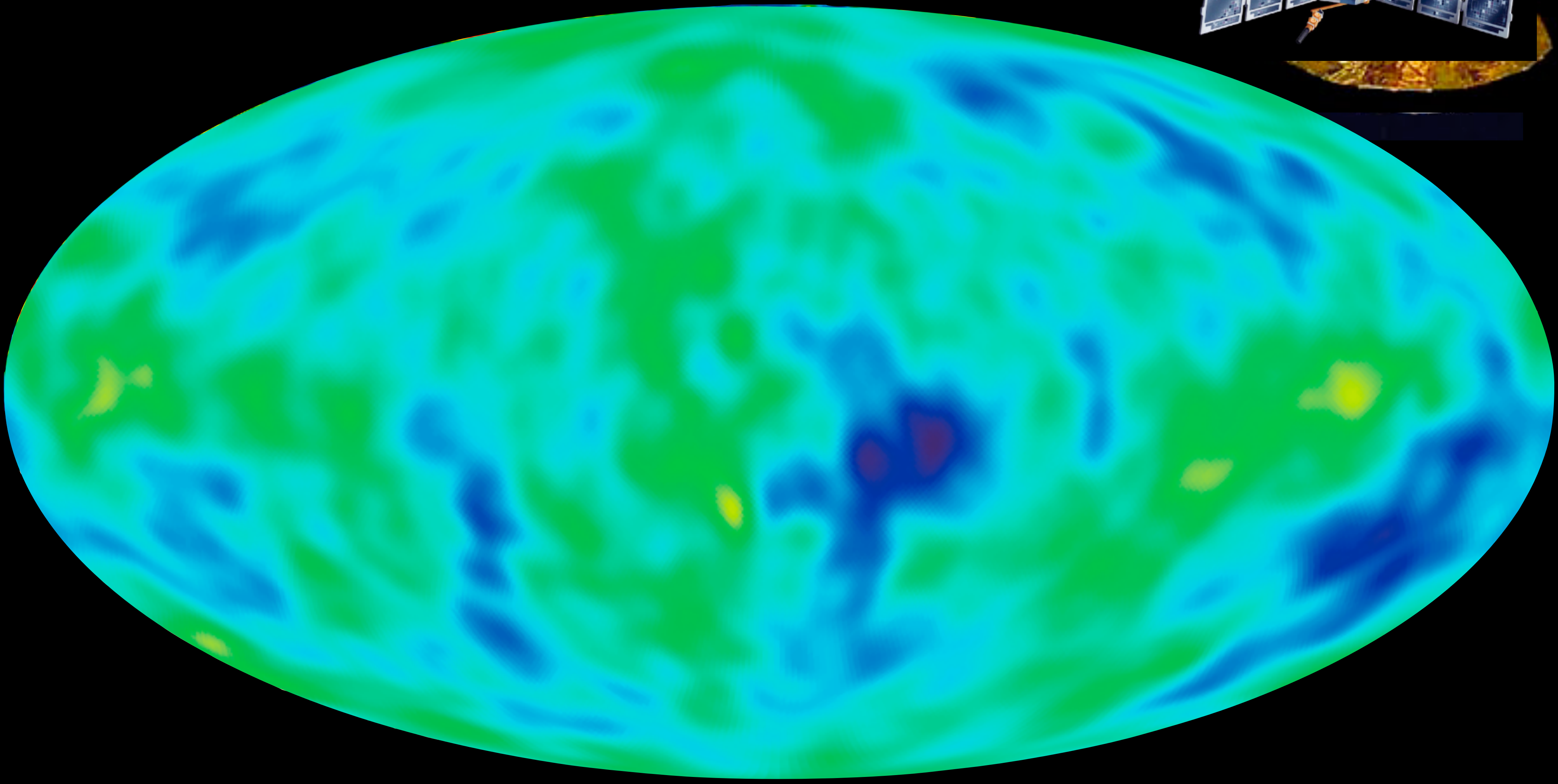
CREDIT: CHROMOSCOPE / CARDIFF

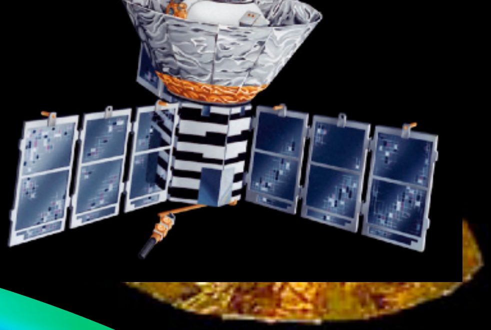
Cosmic Microwave Background



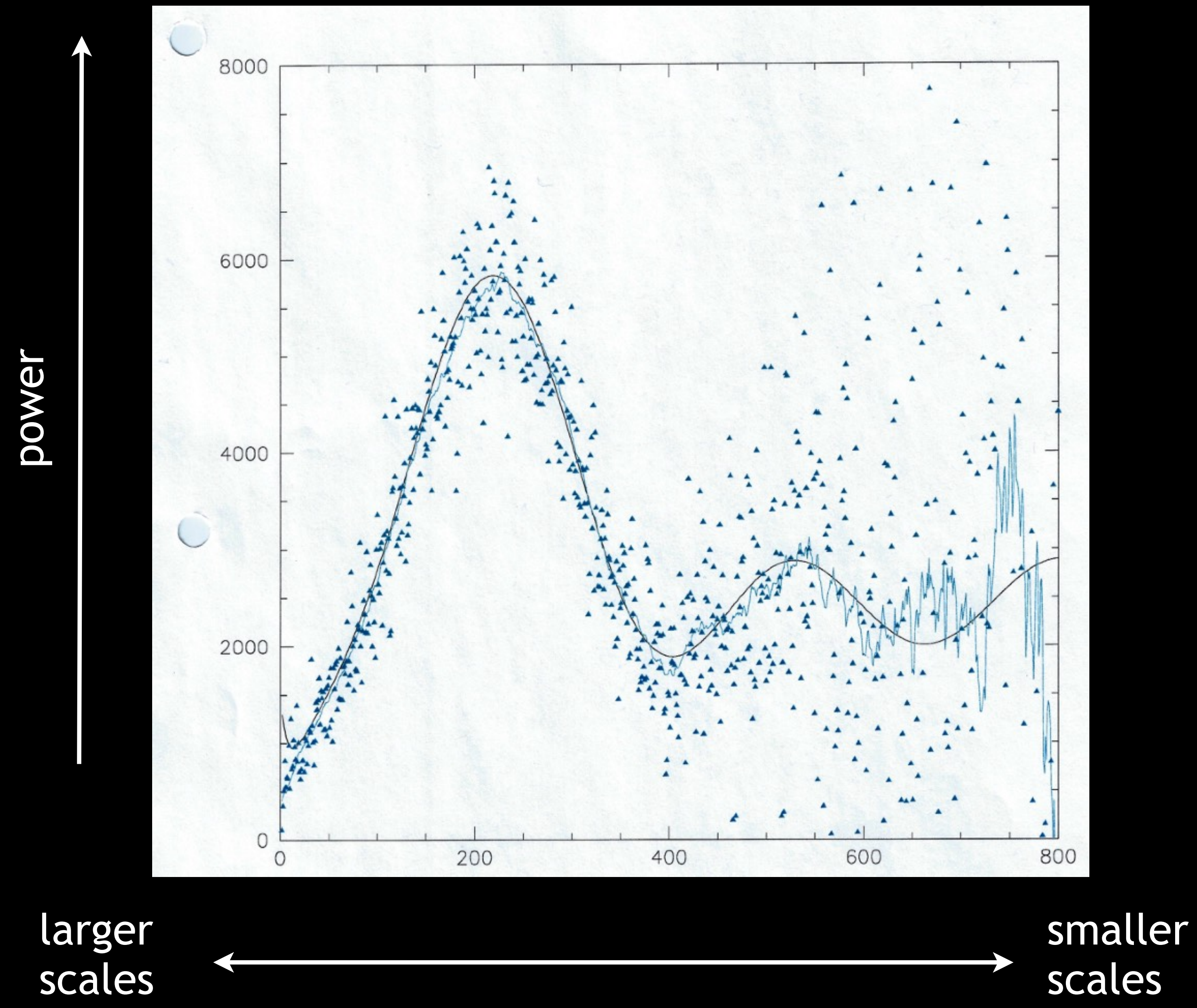
CREDIT: NASA / WMAP SCIENCE TEAM

PENZIAS & WILSON (1964)

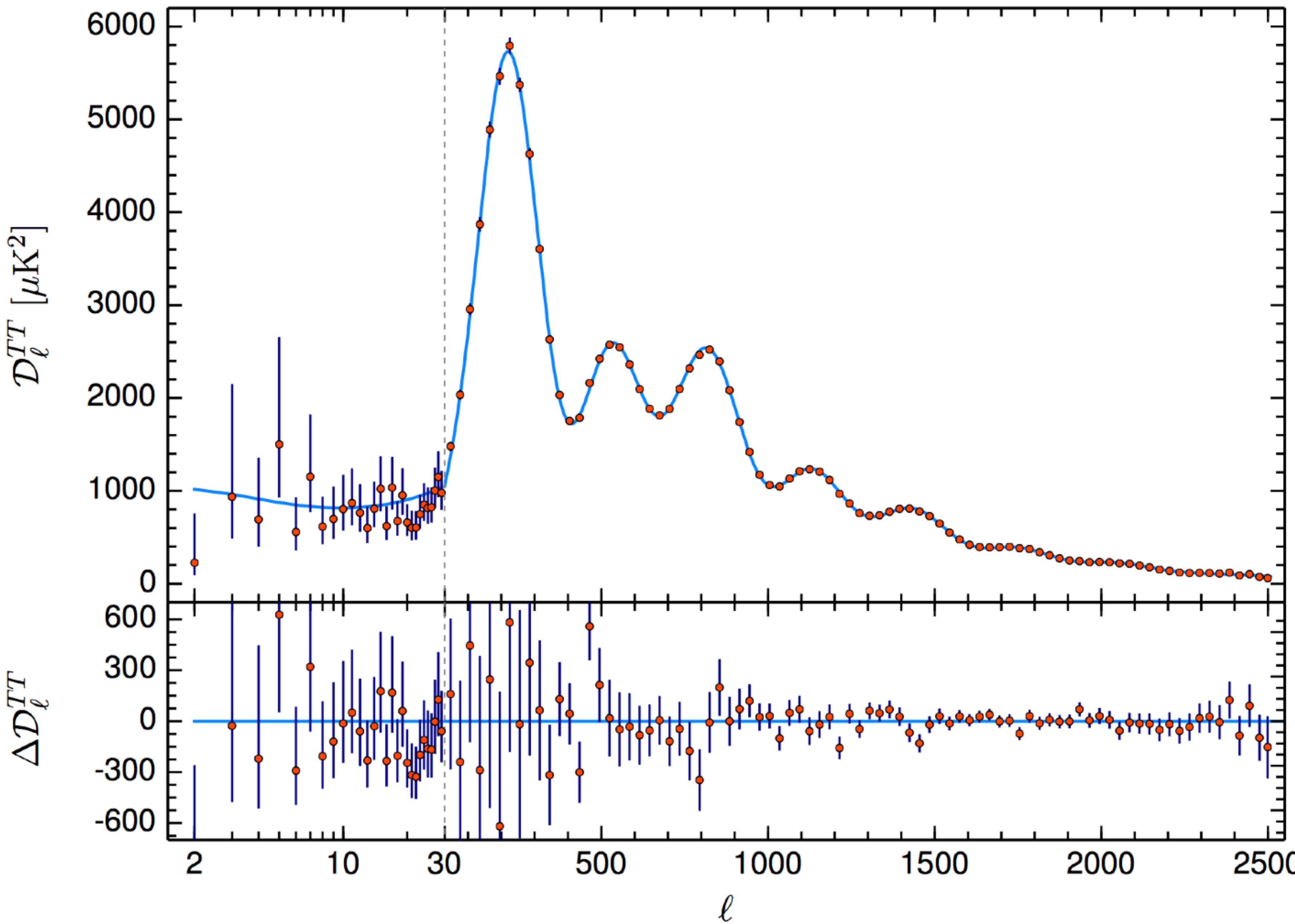




WMAP "first light" spectrum

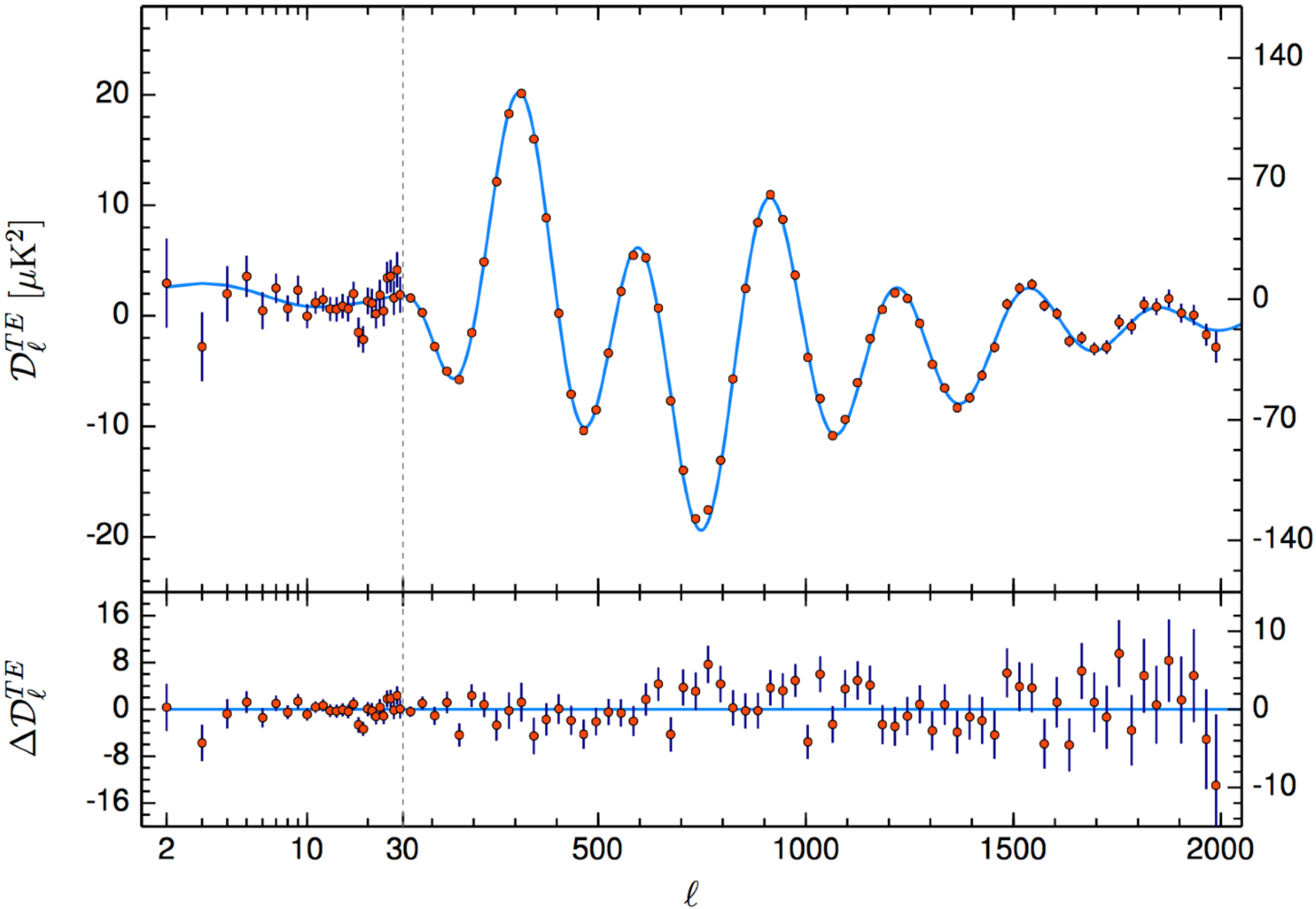


Planck 2018 Temperature



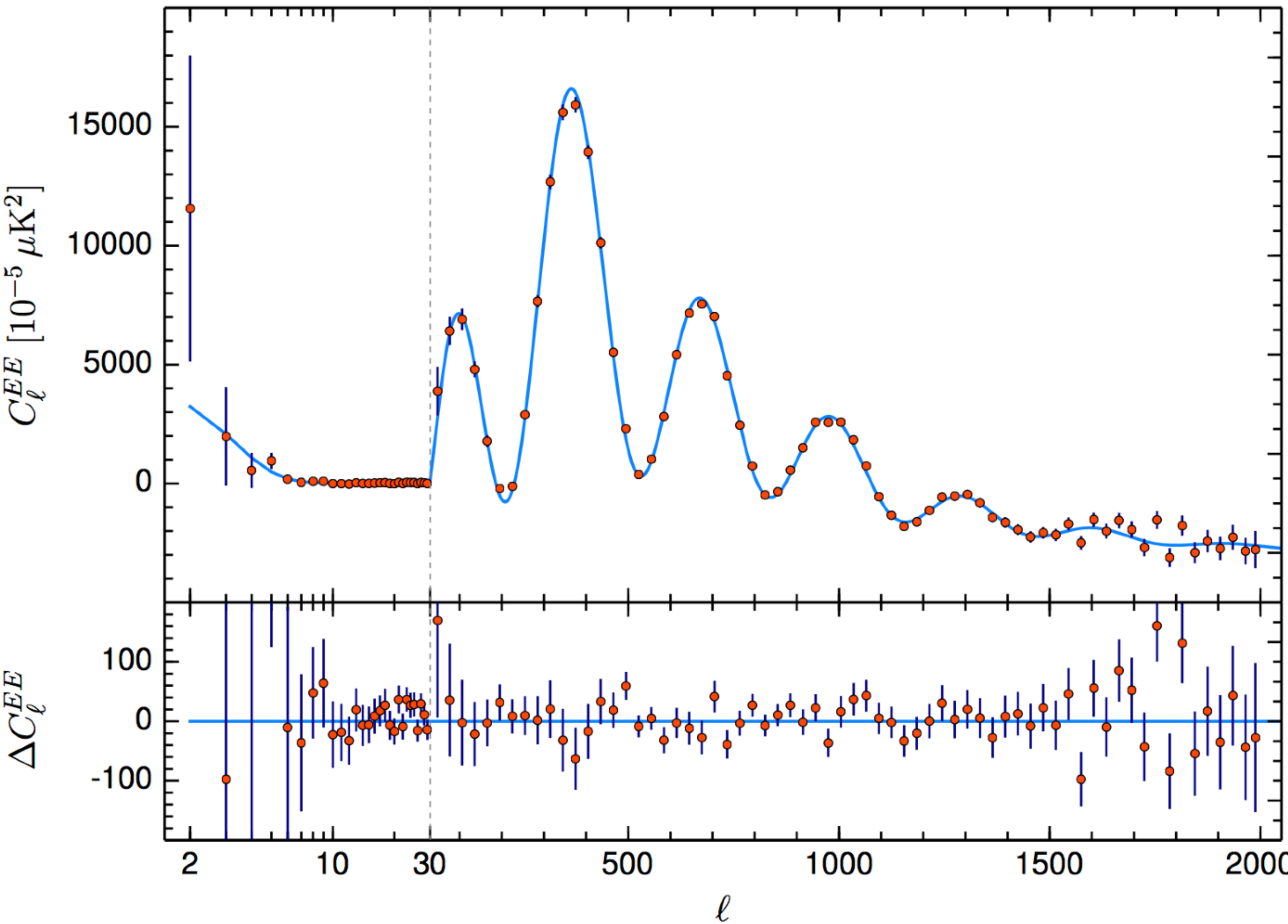
Planck Collaboration (2018)

Planck 2018 TE Polarisation



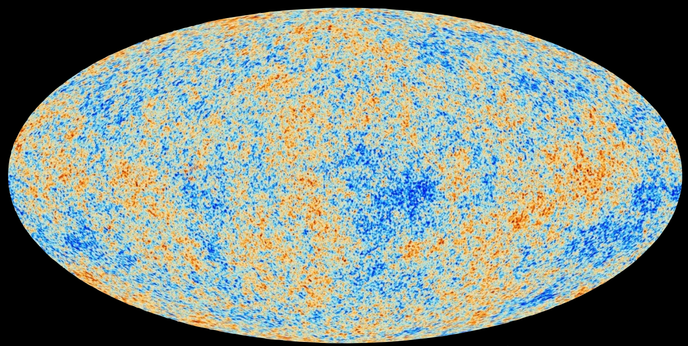
Planck Collaboration (2018)

Planck 2018 EE Polarisation



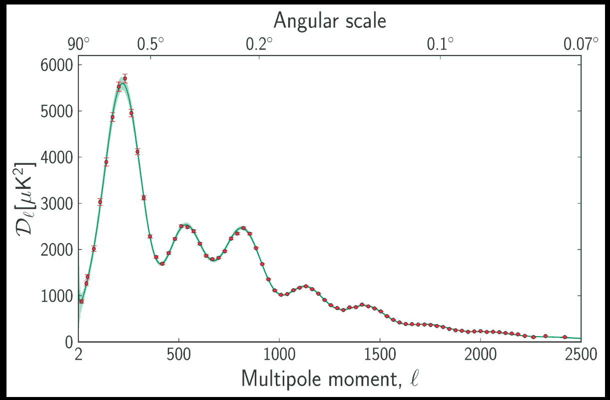
Planck Collaboration (2018)

Radical data compression!

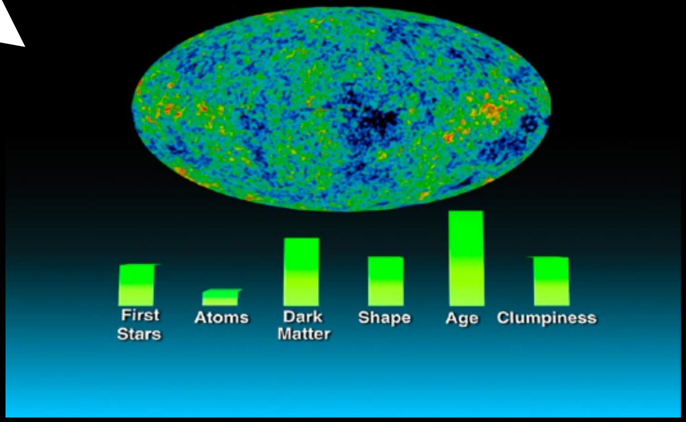


Raw data: *~quadrillion samples*

Maps: *~50 million pixels over 9 frequencies*

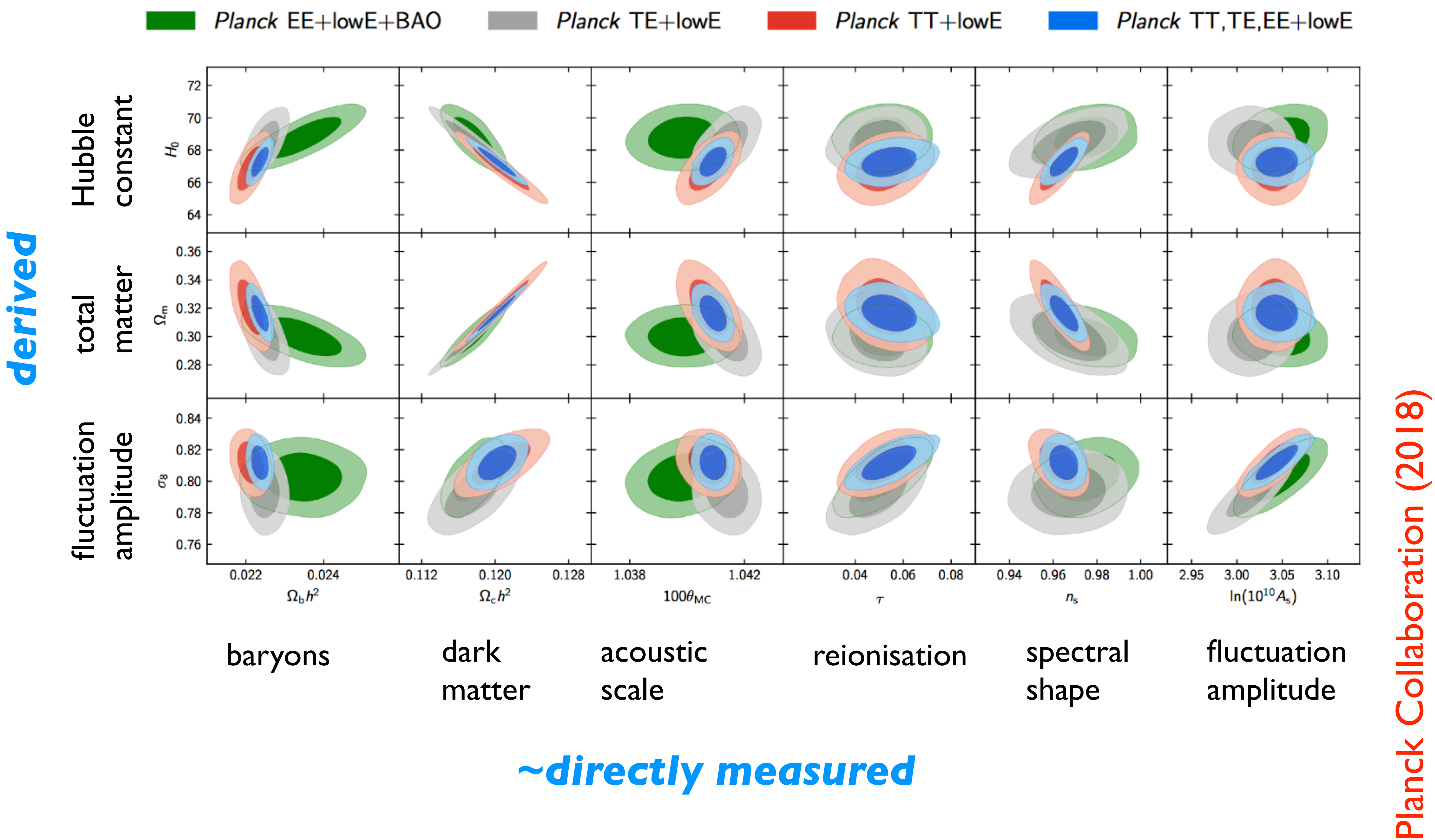


~2500 multipoles...



six cosmological parameters!

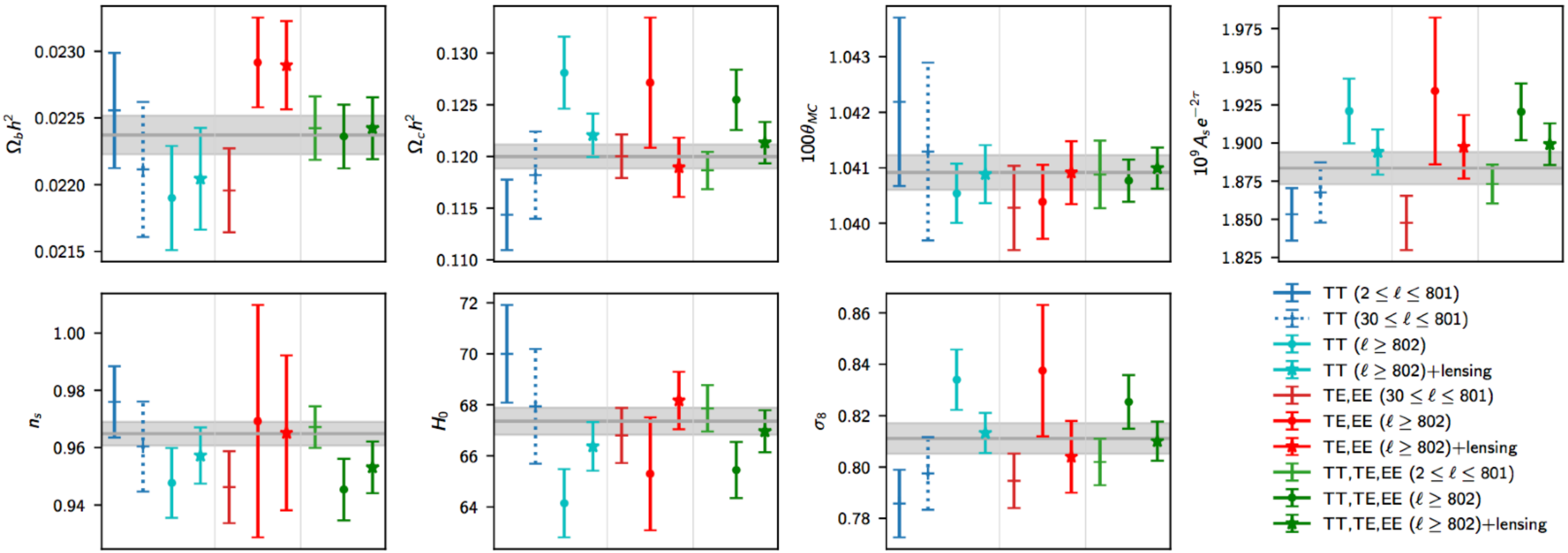
Planck's cosmological parameters



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

Internal Consistency of Planck parameters

baryons dark matter acoustic scale fluctuation amplitude



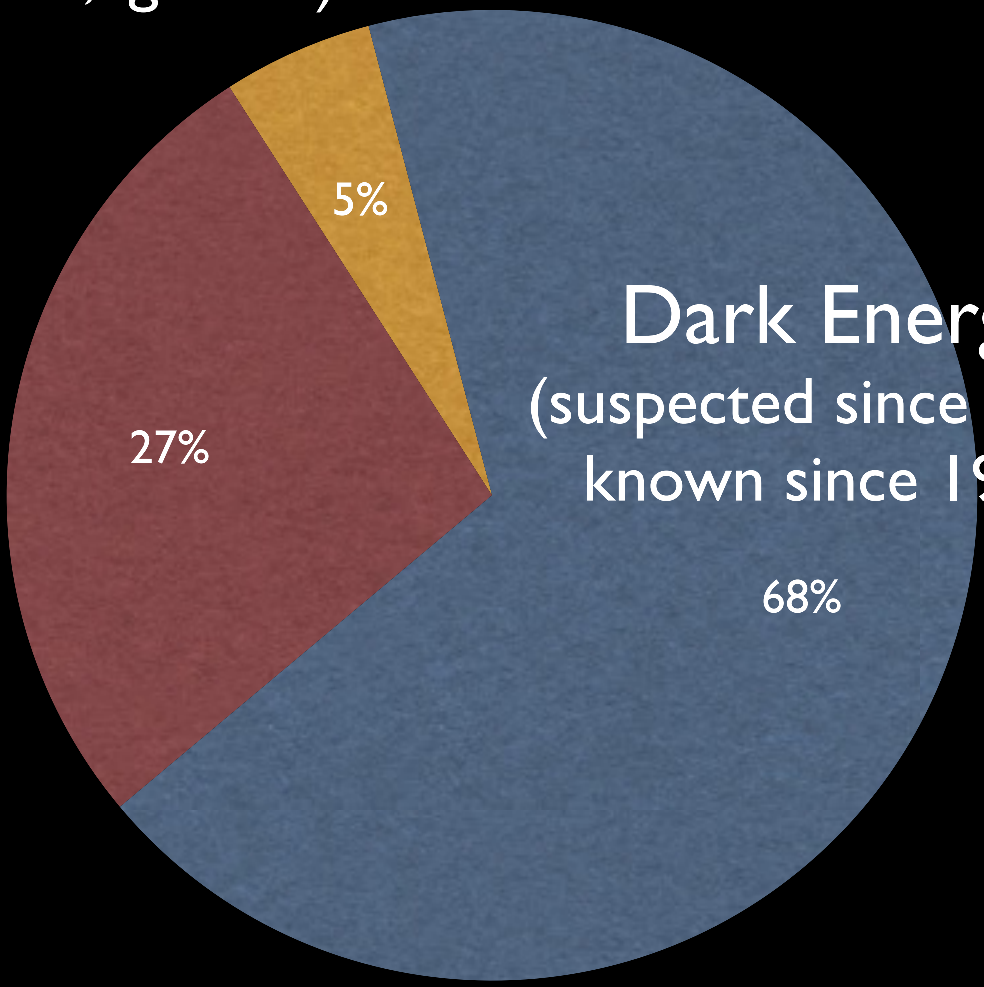
spectral shape Hubble constant fluctuation amplitude

Planck Collaboration (2018)

What is Dark Matter? Dark Energy?

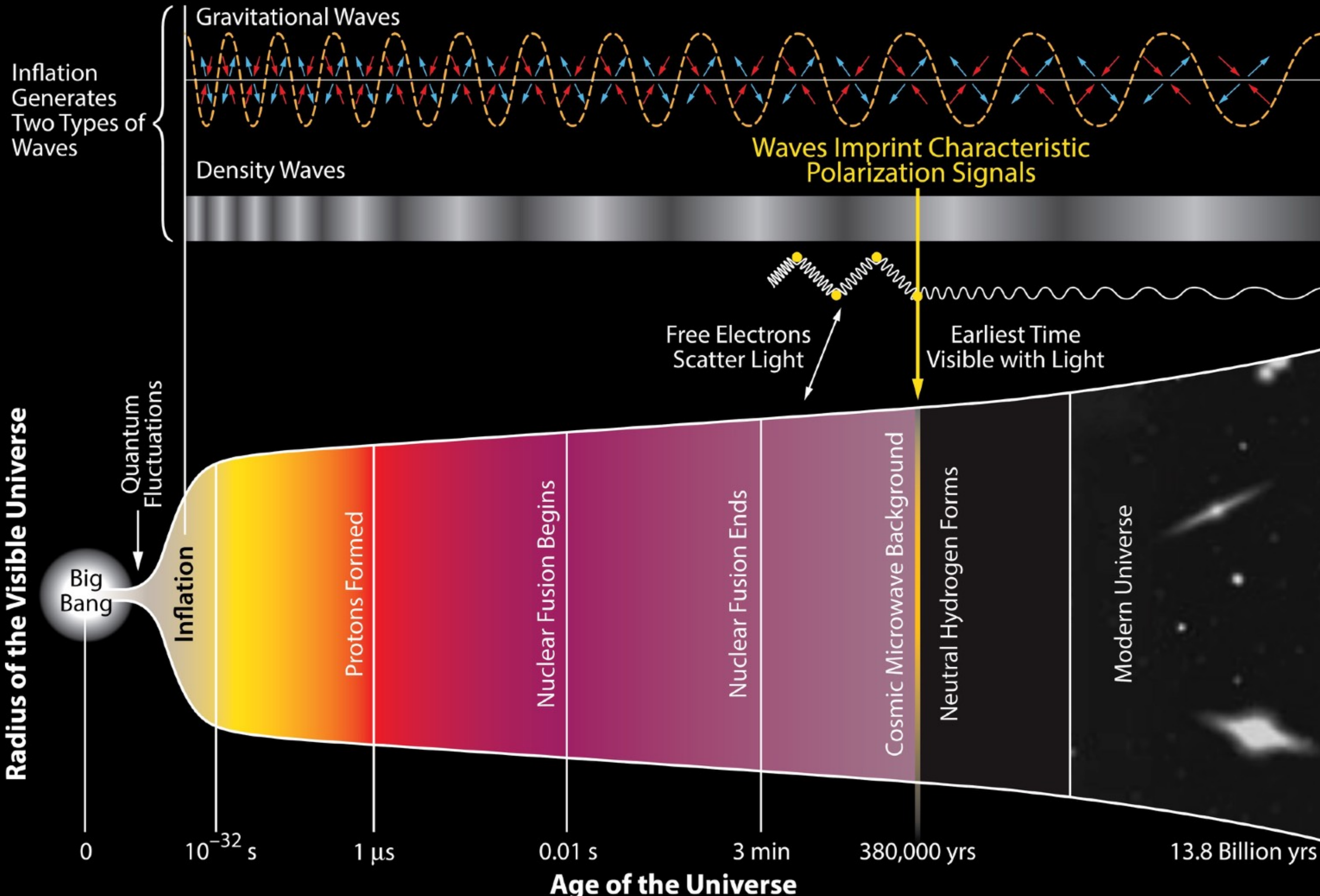
Visible Matter
(stars 1%, gas 4%)

Dark Matter
(suspected since 1930s
known since 1970s)



Also:
radiation (0.01%)

What is the origin of cosmic structure?



CREDIT: BICEP / KECK COLLABORATIONS

Life under a "standard model"

Standard cosmological model is phenomenological.

GR + broken time-translation invariance+ homogeneity + isotropy + initial conditions

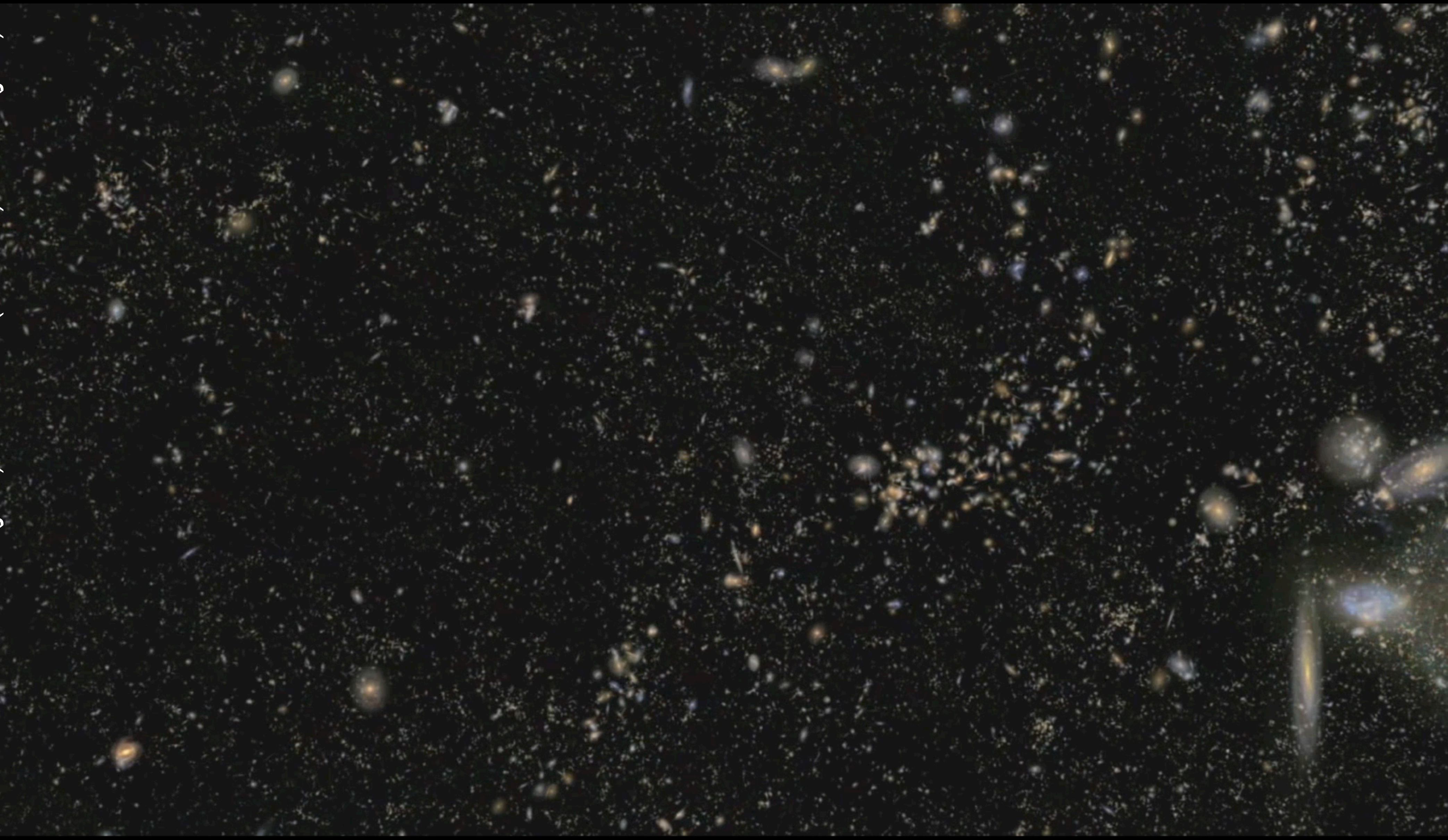
Two paths to a paradigm shift *cf John Wheeler*

Conservative Radicalism

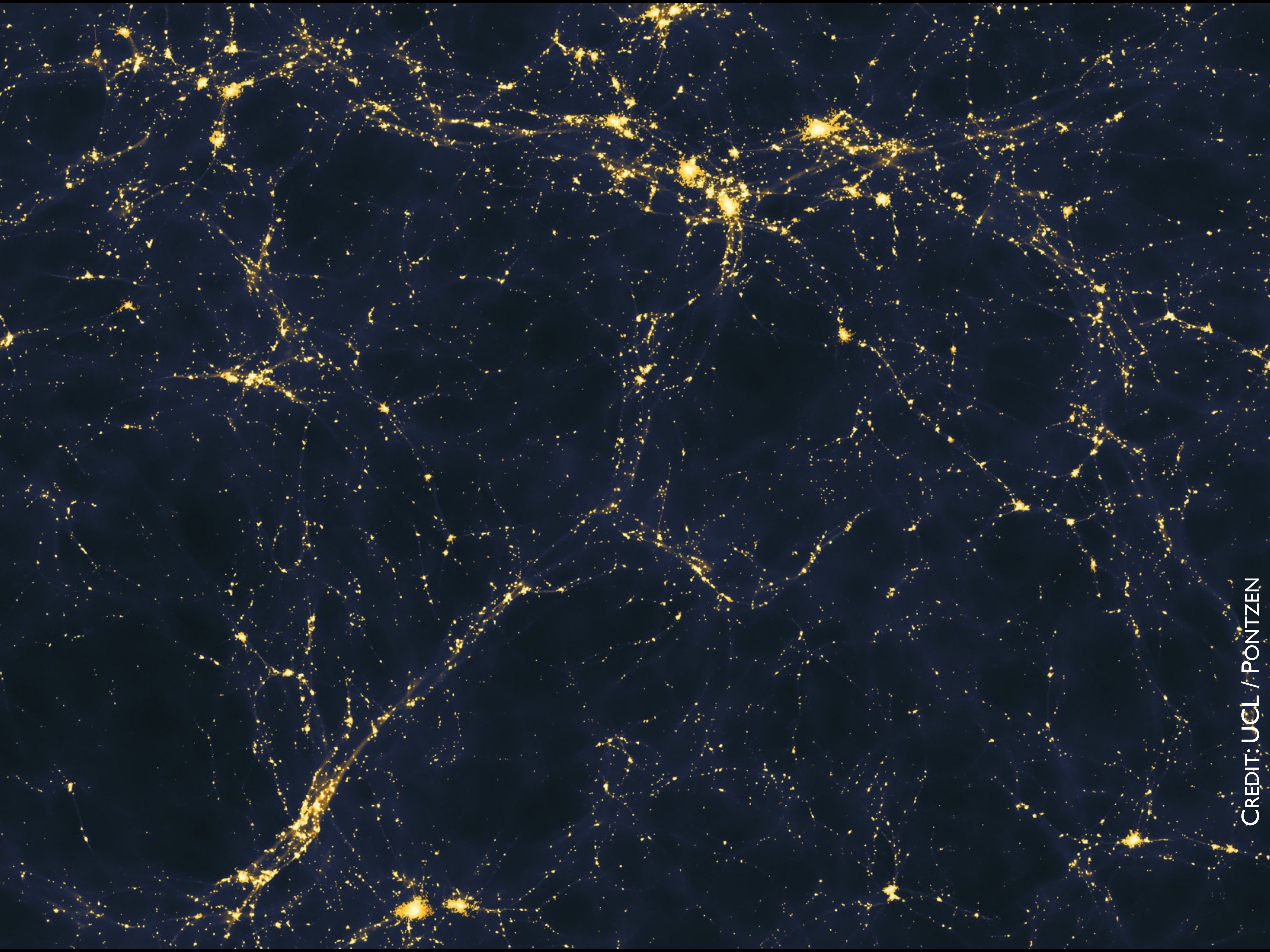
Give up principles / model assumptions one-by-one and explore consequences. Must be done rigorously - principles are precious - beware epicycles.

Radical Conservatism

Take the model seriously and explore its predictions in hitherto untested regimes. Eventually it will break. This is how paradigm shifts in physics have typically happened.

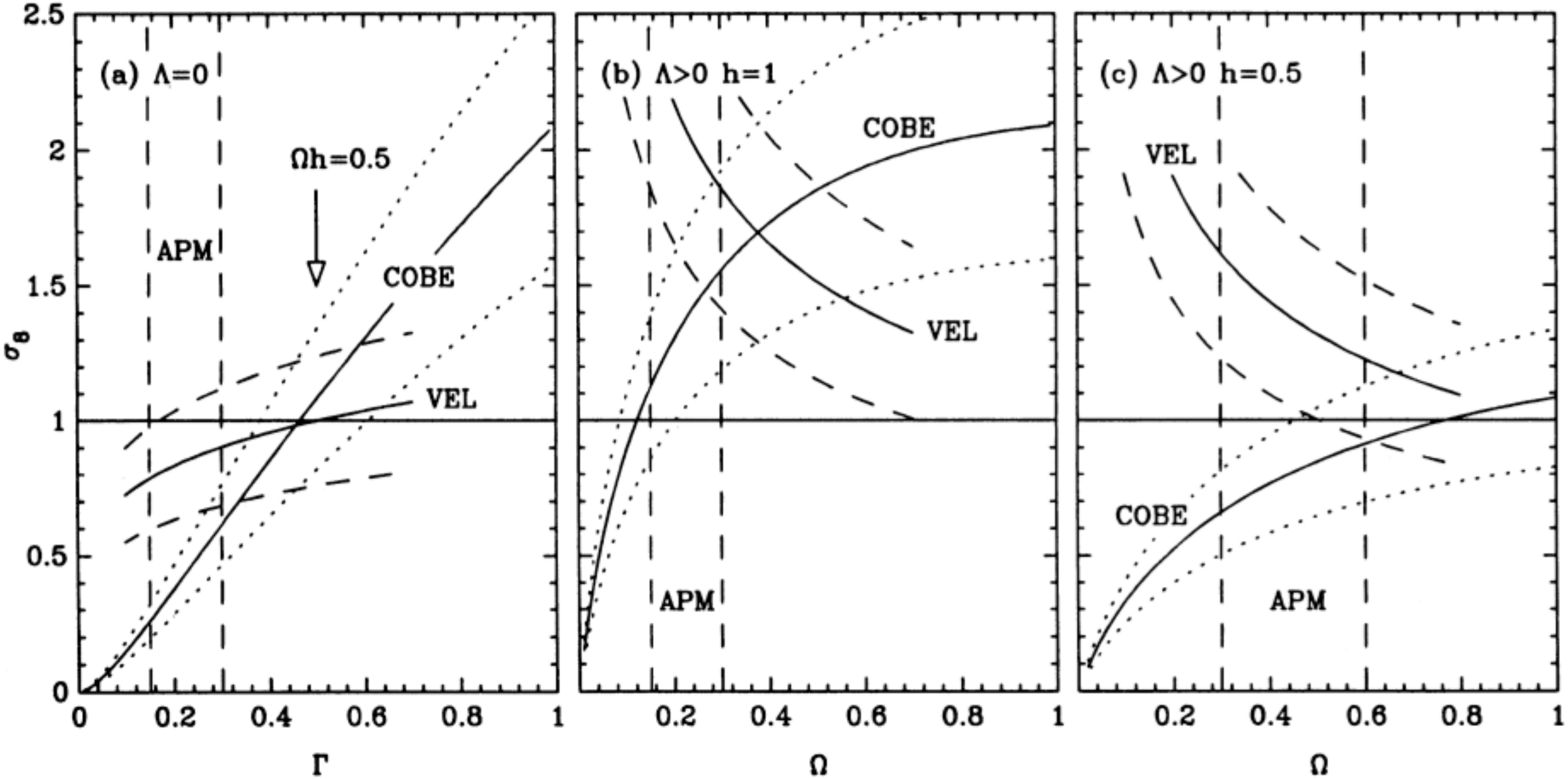


CREDIT: SDSS / ARAGON (JHU), SUBBARAO (ADLER P.), SZALAY (JHU)



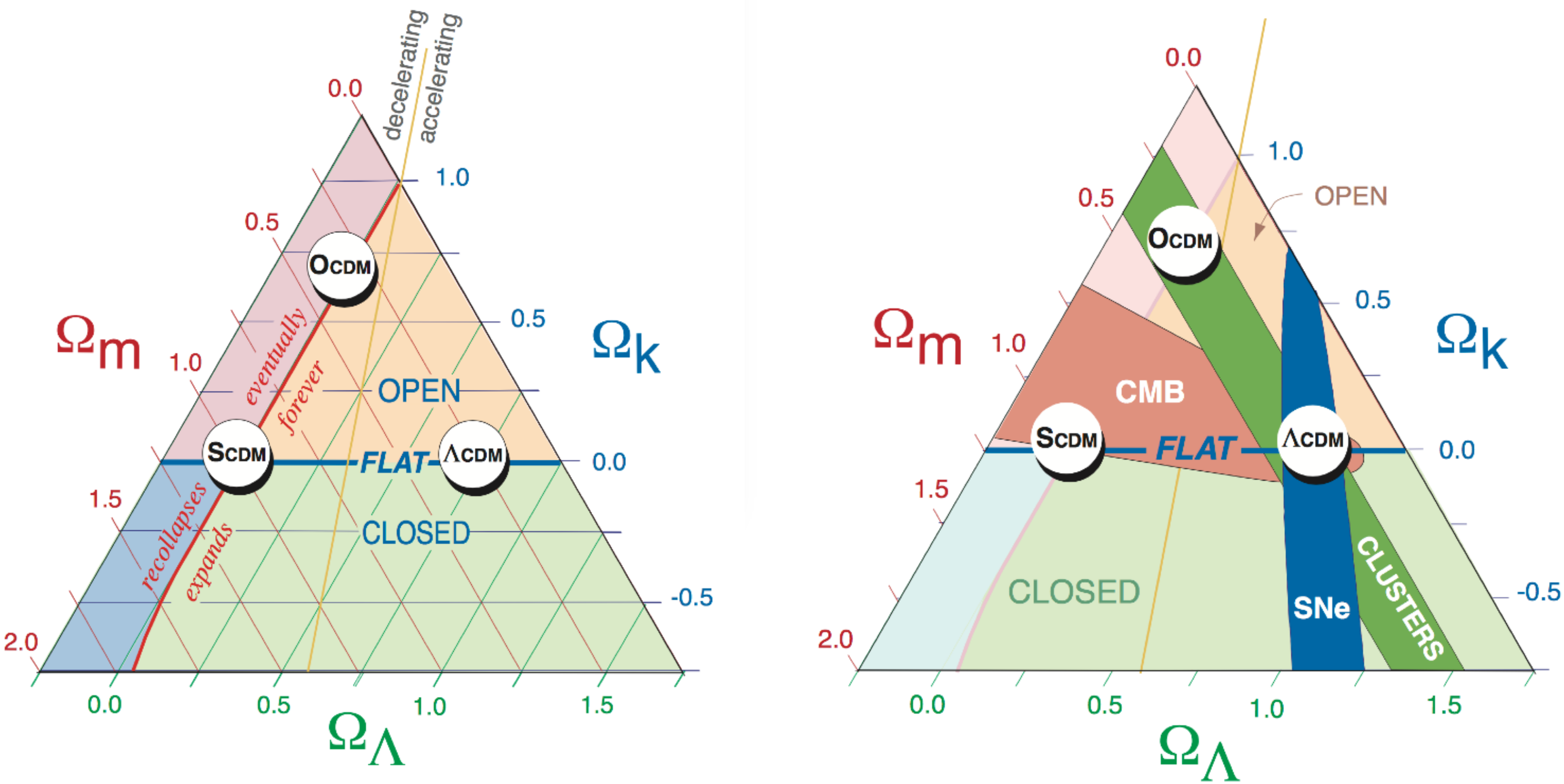
CREDIT: UCL / PONTZEN

Cosmic Consistency



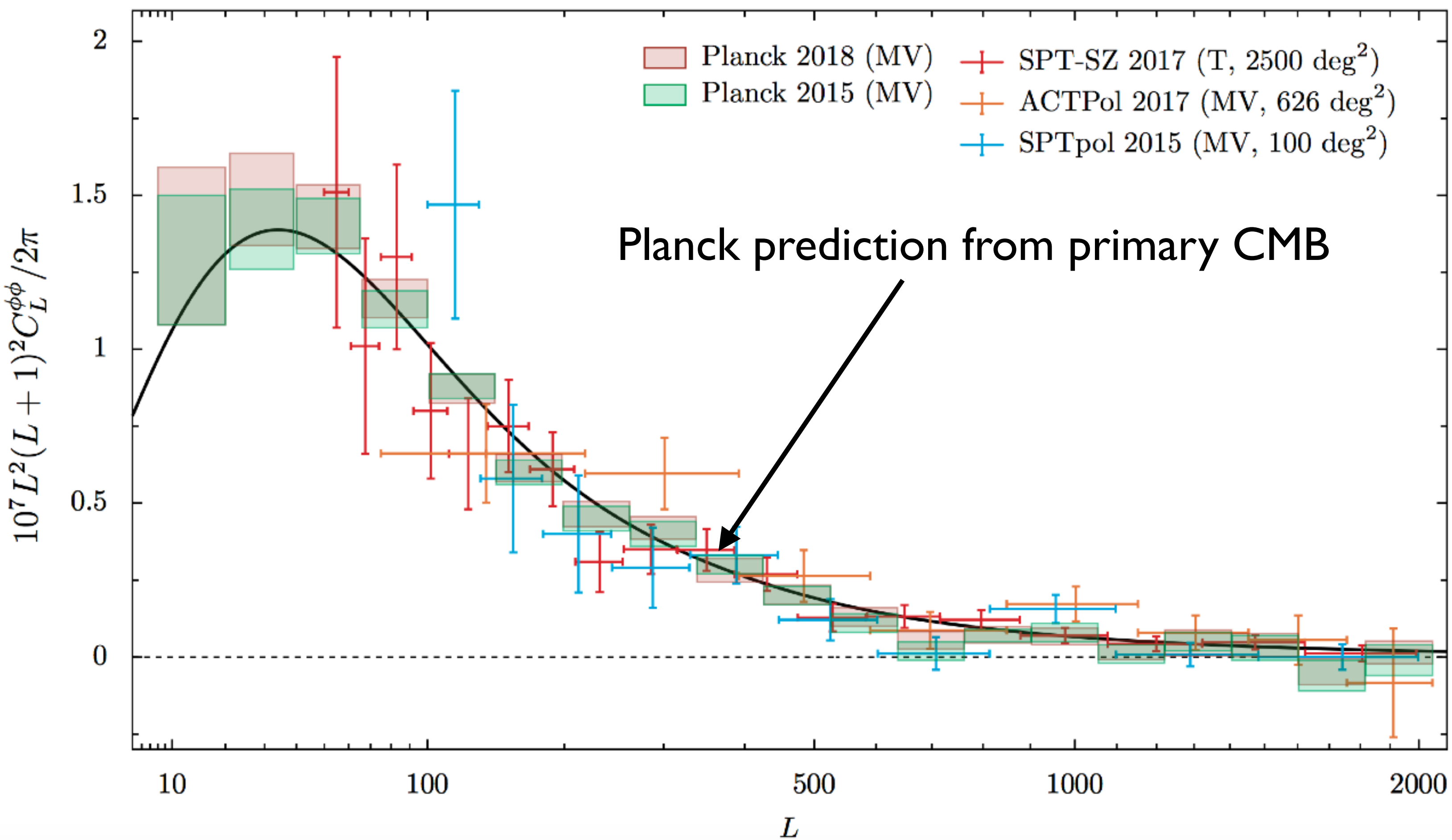
Efstathiou, Bond, White (1992)

Cosmic Consistency



Bahcall, Ostriker, Perlmutter, Steinhardt (1999)

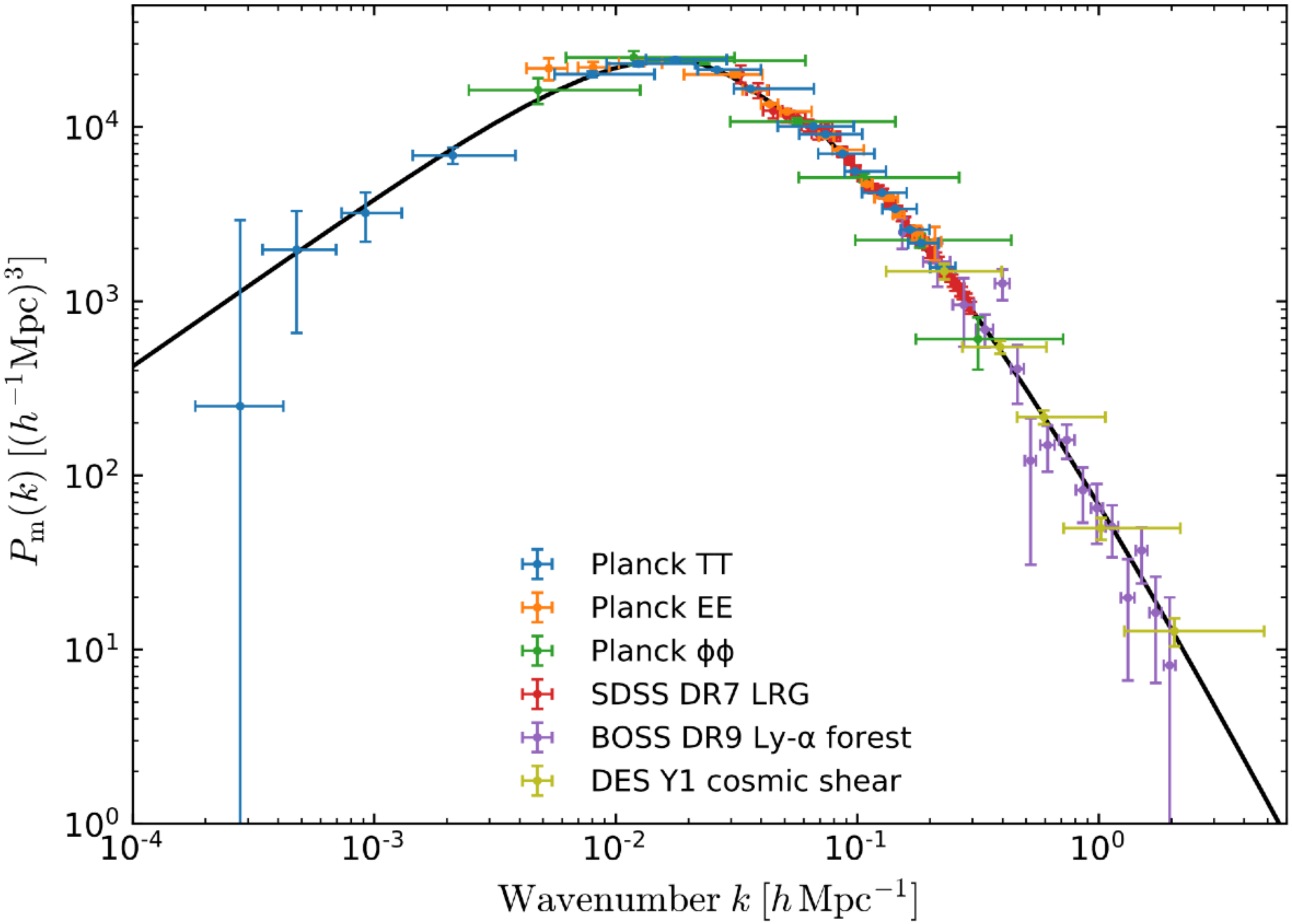
Cosmic Consistency



CMB lensing amplitude and scale dependence

Planck Collaboration (2018), ACTPol (Sherwin et al 2017), SPTPol (Story et al 2015), SPT-SZ (Simard et al 2017)

Cosmic consistency



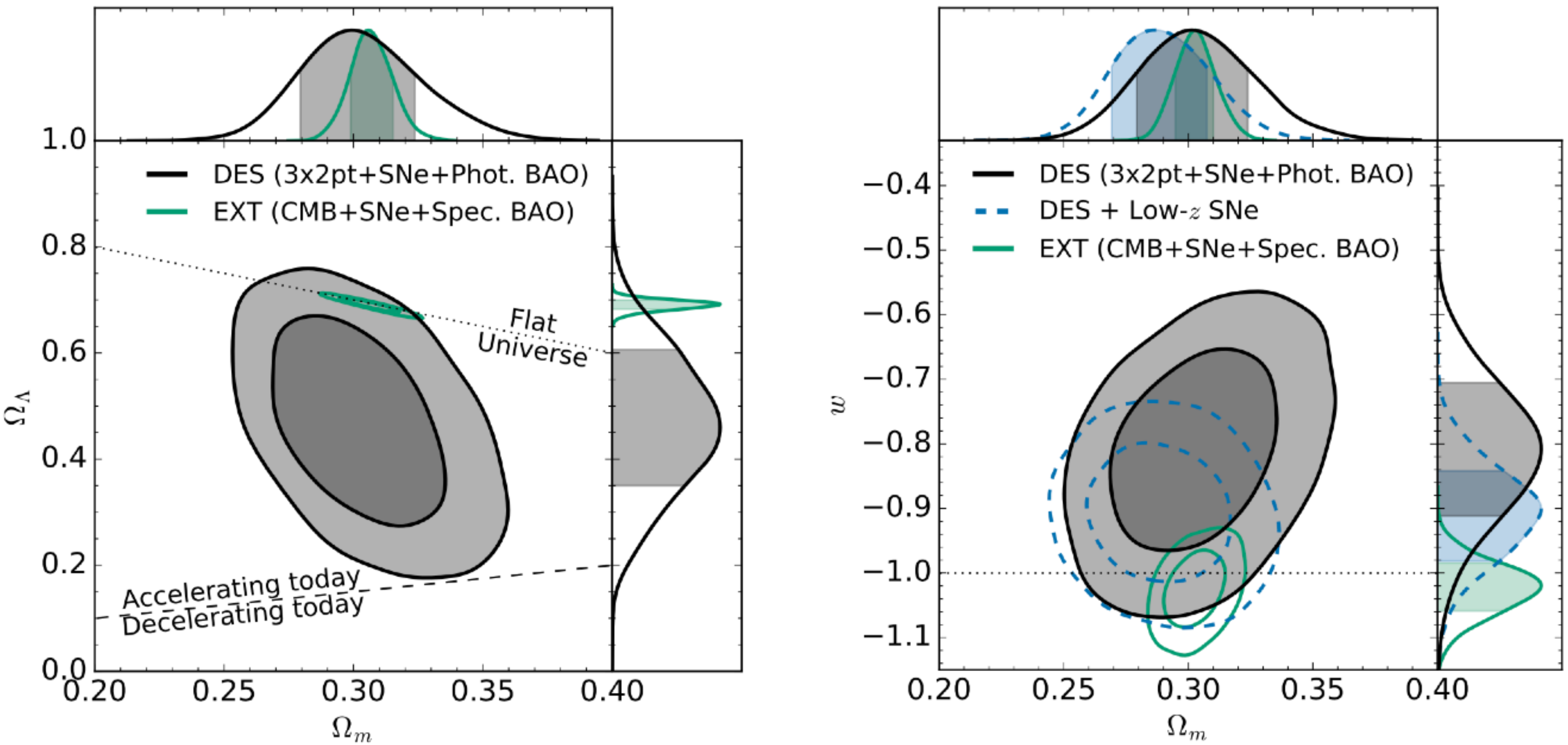
Planck Collaboration (2018) summarising constraints on the matter power spectrum from a world collection of surveys spanning ~14 Gyr in time and 3 decades in scale

The Dark Energy Survey

CREDIT: DARK ENERGY SURVEY / EPO TEAM

Cosmological constraints from multi-probes in DES

vacuum energy density



dark energy equation of state

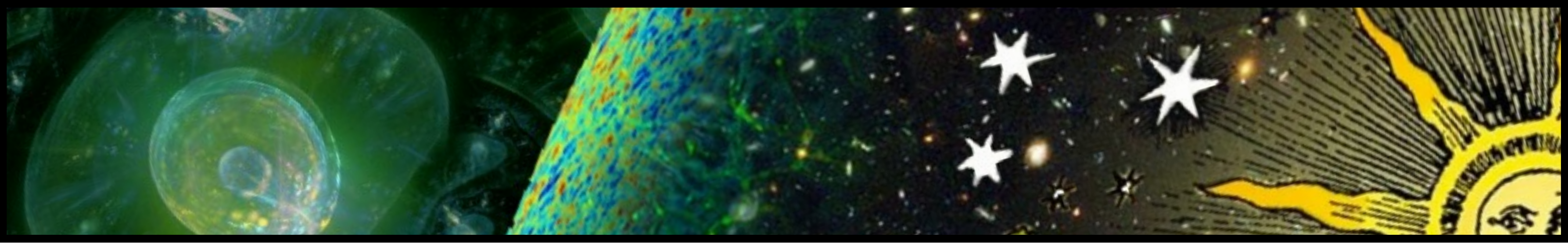
Matter density

DARK ENERGY SURVEY

3x2pt: cosmic shear; galaxy-galaxy lensing; galaxy clustering

DES Collaboration (2019)

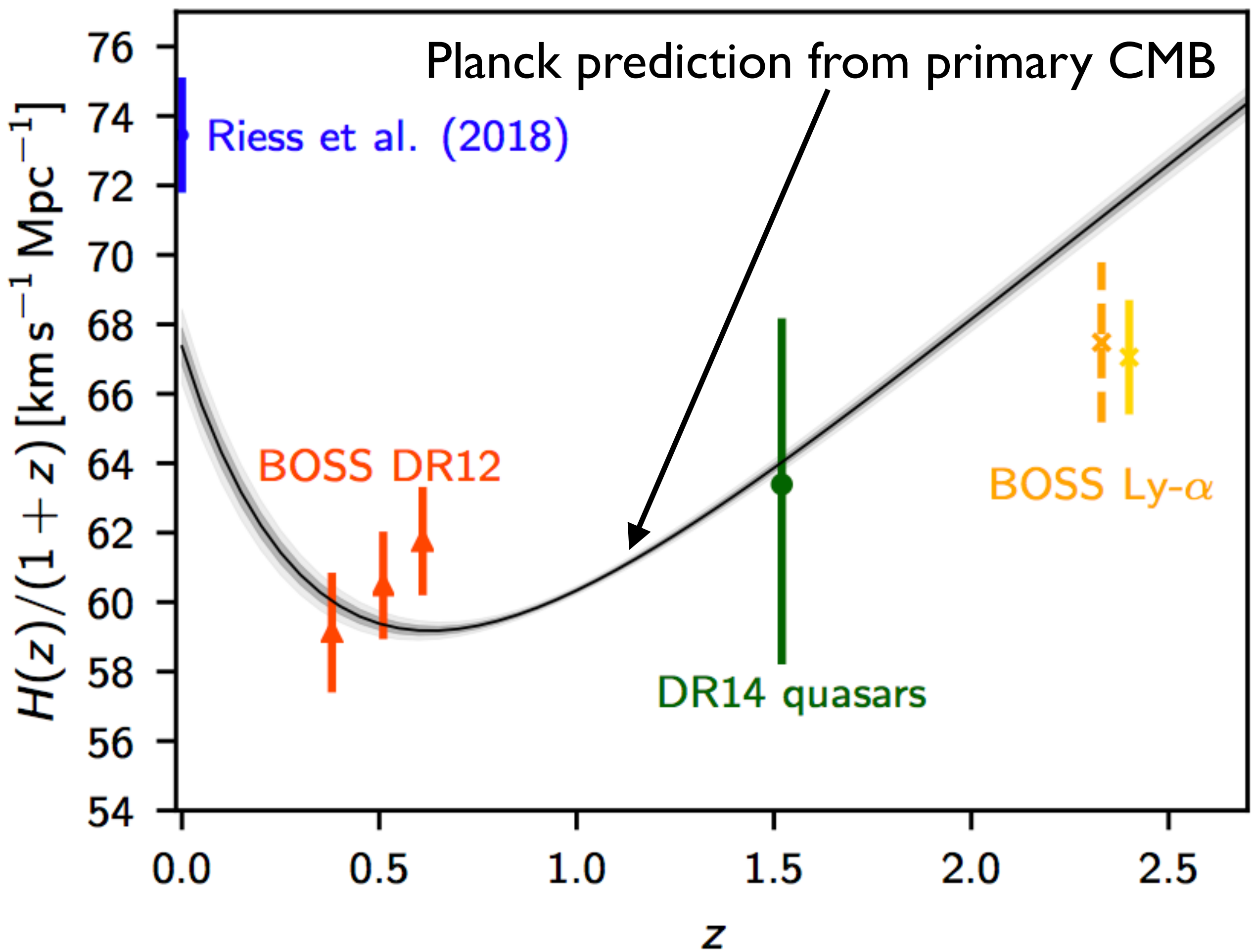
CREDIT: DARK ENERGY SURVEY / EPO TEAM



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

paraphrasing H. Shapley

Cosmic (in)consistency? 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)

The Hubble constant

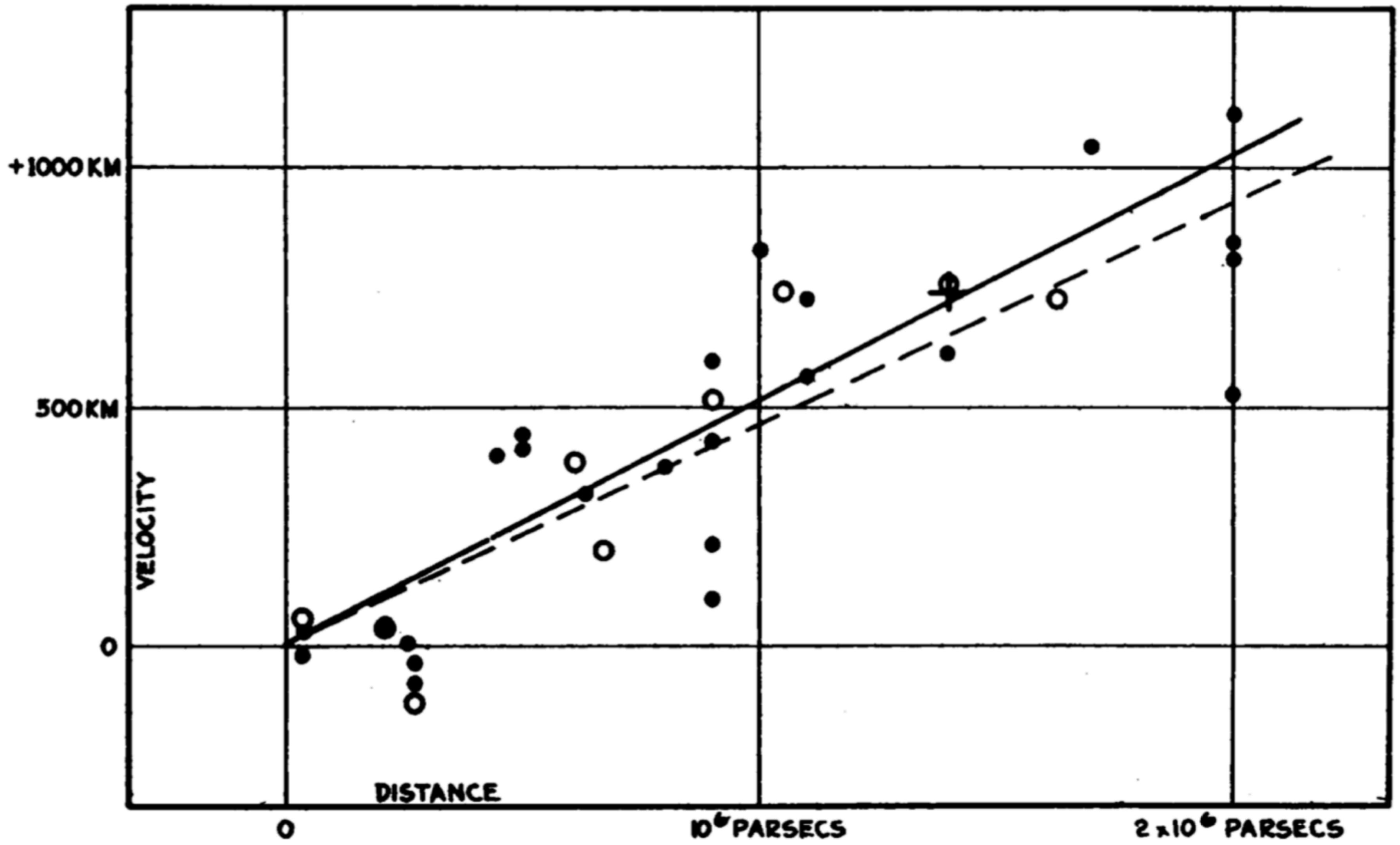
- Observations by Slipher, Hubble and Humason in the 1920s showed that galaxies were moving away from us with their speed, v, proportional to distance, D.
- The Hubble constant, H_0, is the constant of proportionality, defined such that $v = H_0 / D$.
- The Hubble constant defines the timescale of the Universe: $H_0 = 70$ km / s / Mpc implies $T = 14$ Gyr.

Measuring H_0

- Can estimate H_0 by measuring both the redshift, $z = v / c$, and distance, D, to a single astronomical object provided that:
  - it is in the Hubble(-Lemaître) flow;
  - its peculiar velocity can be estimated (or that it is sufficiently distant that it does not affect z);
  - it is not so distant that the cosmological expansion dynamics need to be accounted for.

Measuring H_0

- Difficult to find such a class of objects, so other options needed:
- Cosmic microwave background observations give all cosmological parameters, but with assumptions to extrapolate to local *H*0 value.
- Distance ladder local but indirect:
  - measure distance to nearby object (e.g., using parallax);
  - obtain distance ratios to more distant objects in the Hubble-Lemaître flow (e.g., Cepheids, supernovae);
  - measure redshifts of host galaxies.


+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10^6 PARSECS
2 x 10^6 PARSECS

Hubble (1929)

H_0: Cosmological vs distance ladder measurements

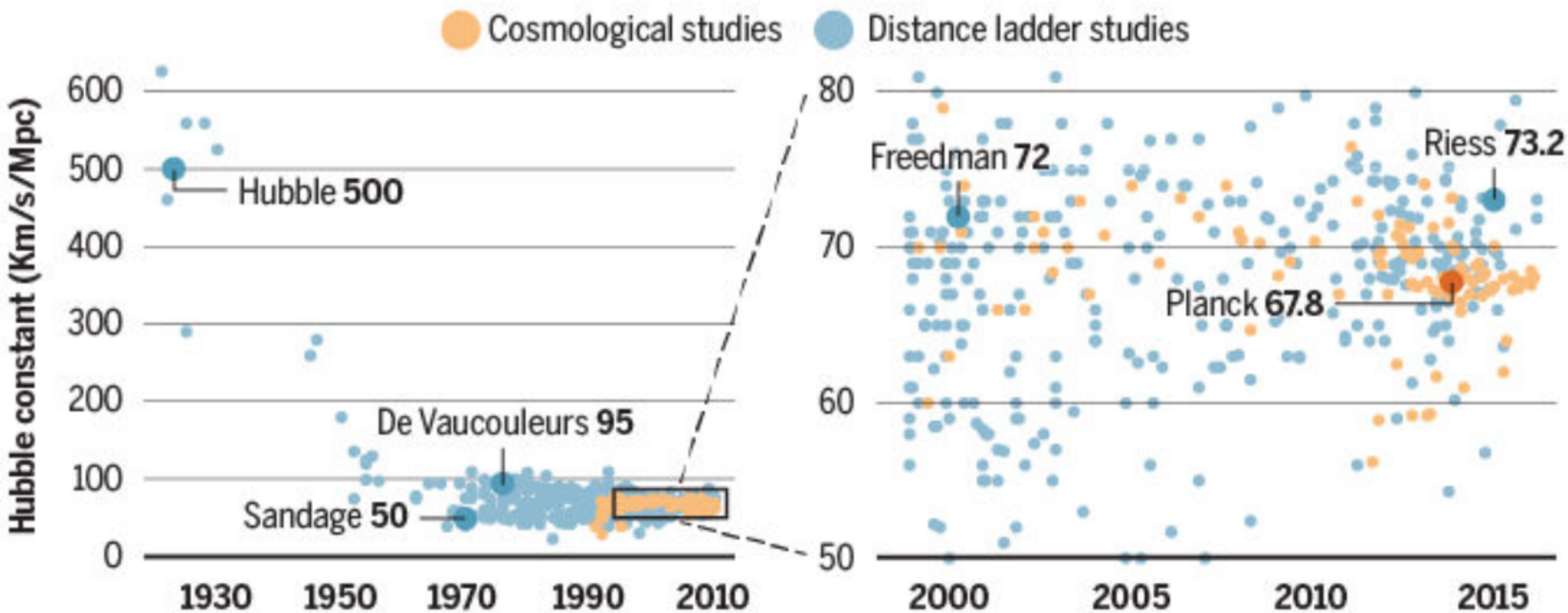
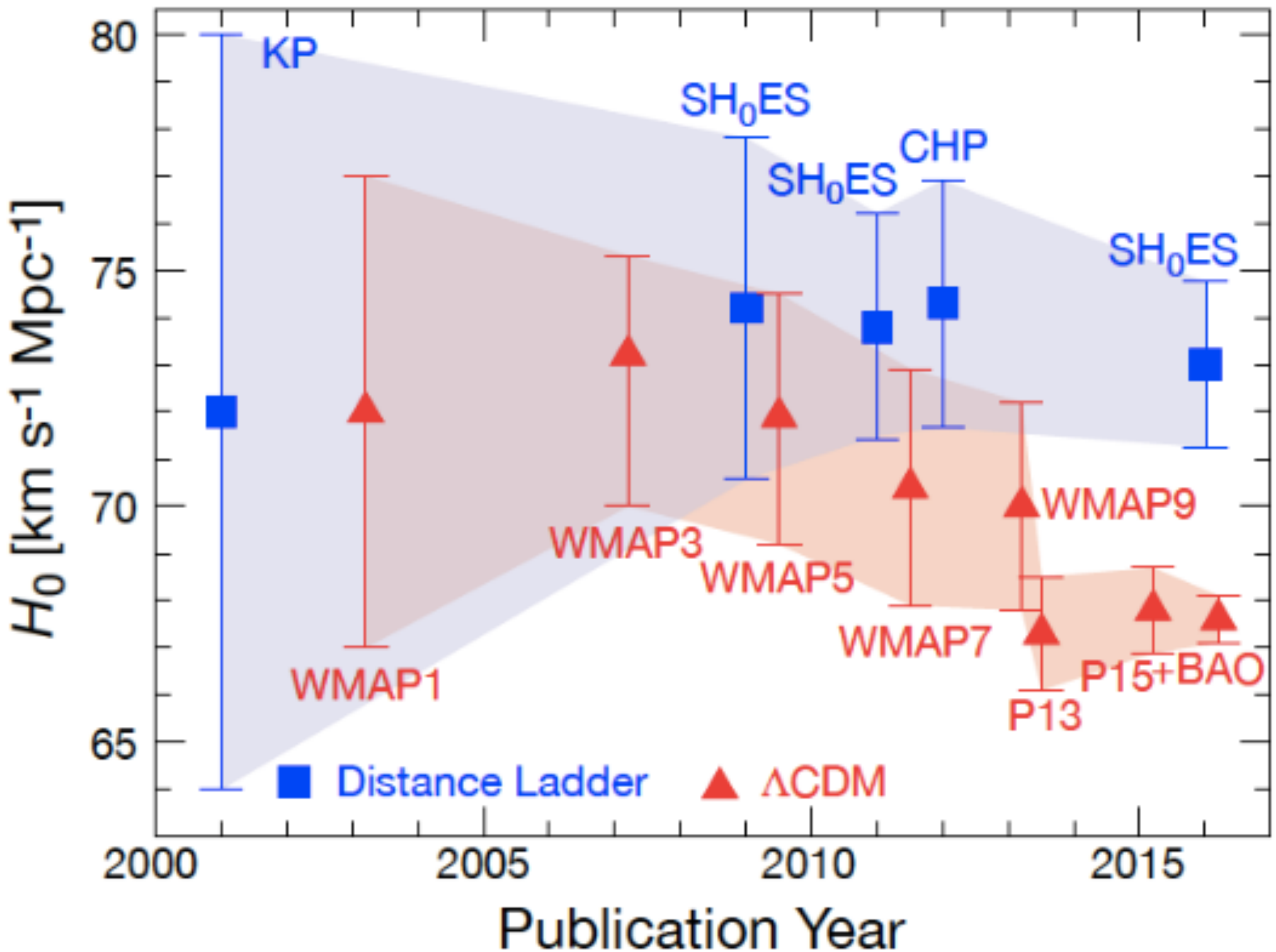


Figure: Science Magazine

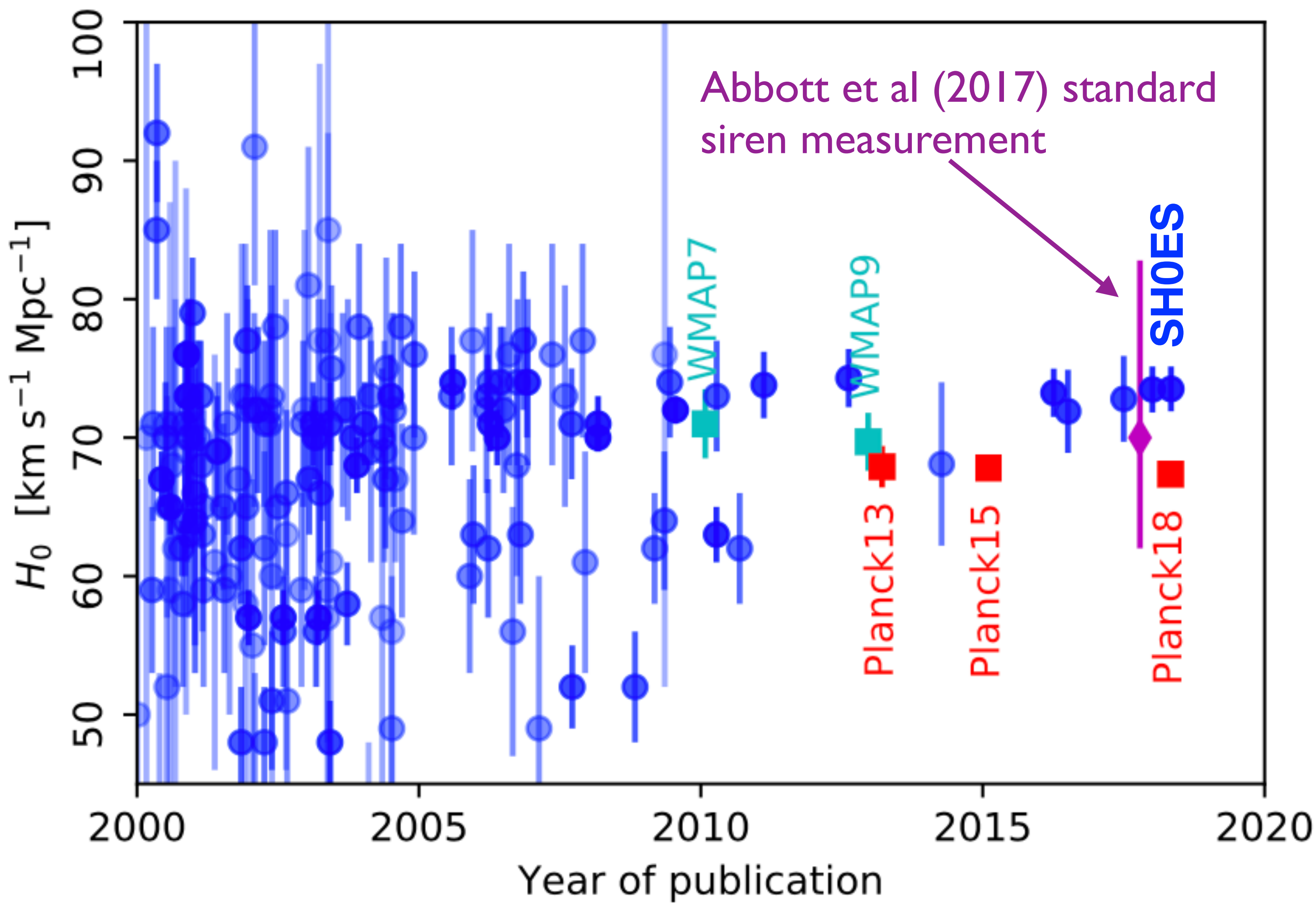
Hubble trouble?



Systematics? astrophysics? (new) physics?

Freedman (2017) adapted from Beaton et al (2016)

Cosmic (in)consistency: latest

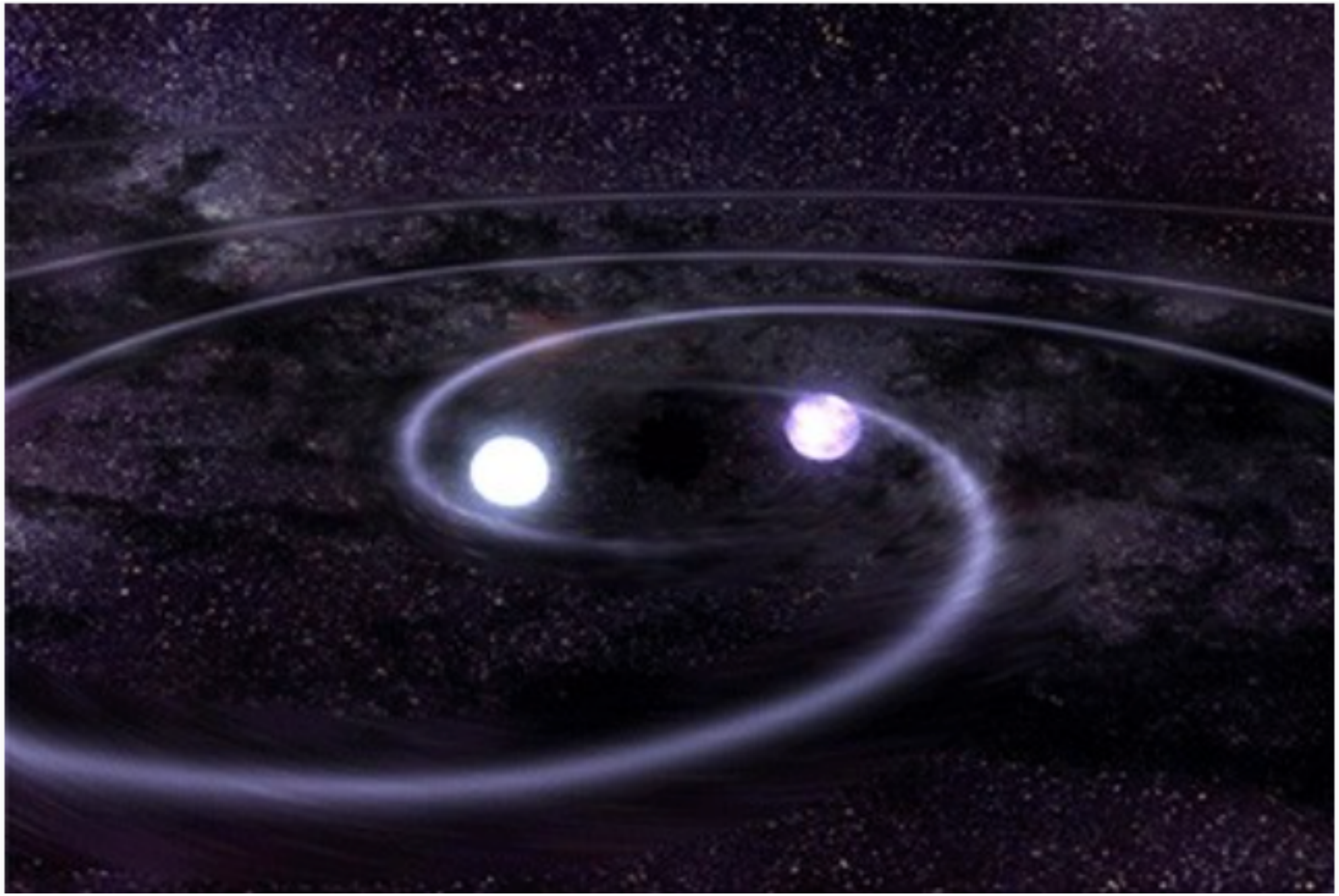


Currently a ~3.5σ tension

Compiled by Planck Collaboration (2018)

Binary neutron star mergers

- New independent data to arbitrate tension? GW standard sirens!

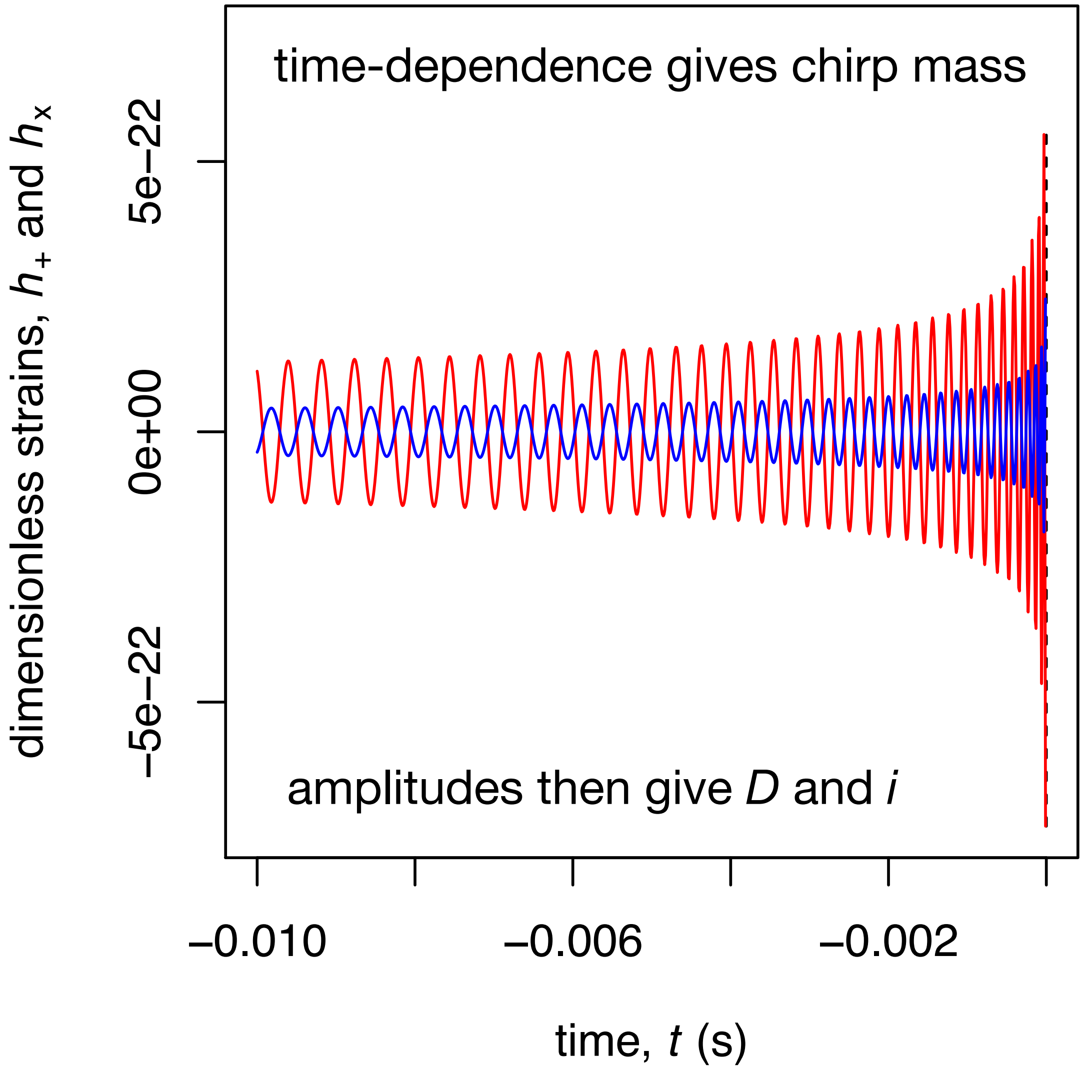


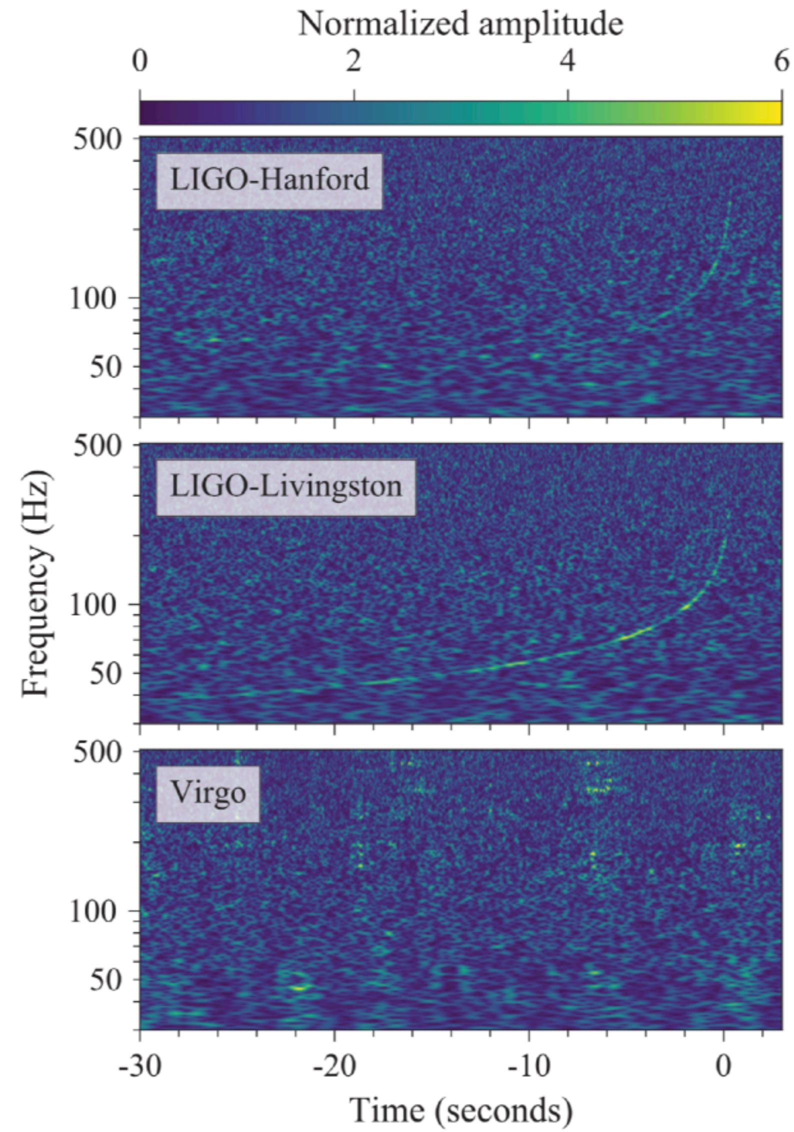
H_0 *from one BNS merger*

- GW 170817: LIGO+Virgo detected GWs from a merger event.
- GRB 170807A: A gamma-ray burst (GRB) <2 seconds later.
- Quick follow-up observations at (all?!) other wavelengths.
- GW (and other) data imply a binary neutron star (BNS) merger.
- Afterglow gives a precise location and host identification.
- GW data give "chirp mass" and (luminosity) distance D = 44(+7/-3) Mpc.
- Spectrum of host galaxy/group (and modelling of bulk flow towards the Great Attractor) gives z = 0.0101+/-0.0006.
- Hence Hubble constant estimate is $H_0 = c\, z\, /\, D$ = 70(+12/-8) km/s/Mpc.

(LIGO+Virgo 2017)

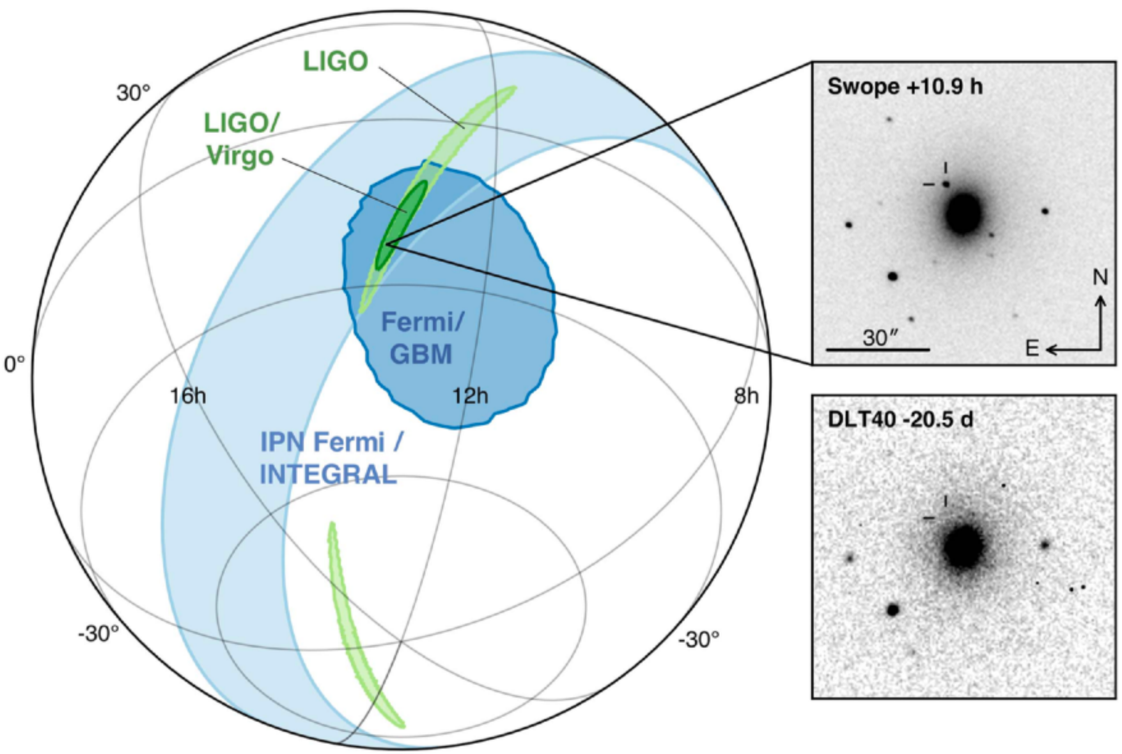
distance: GWs from BNS merger

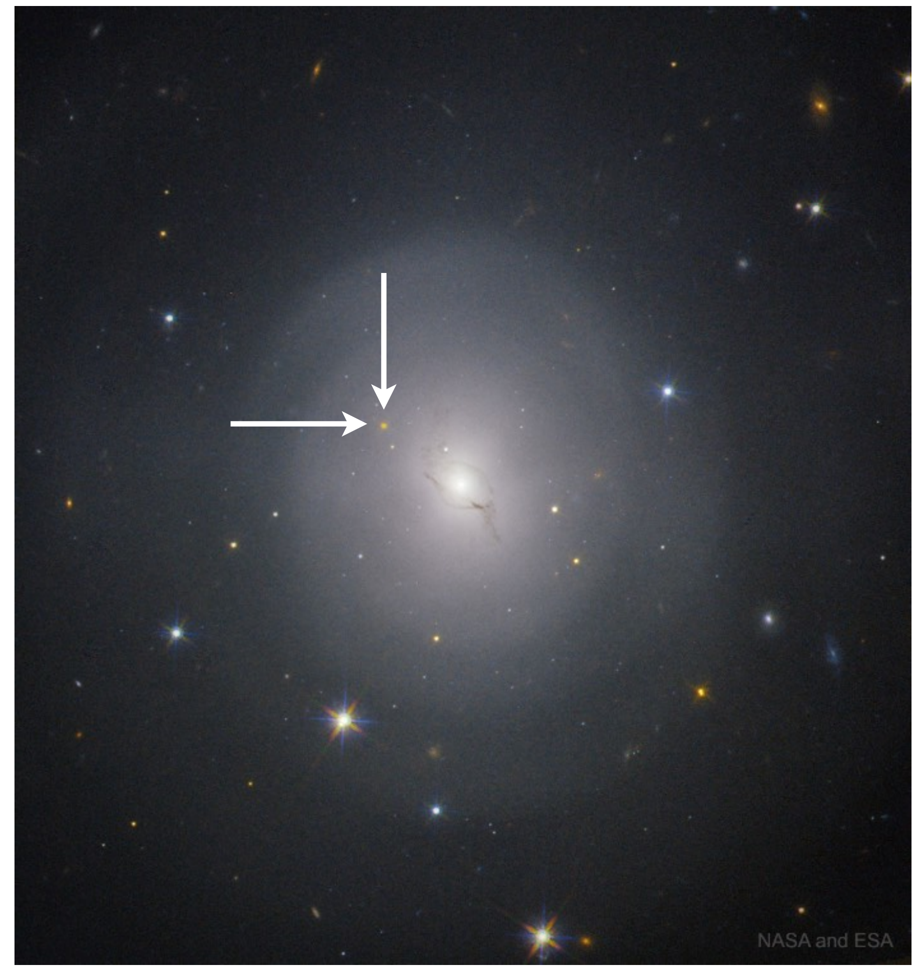




(Abbott et al. 2017)

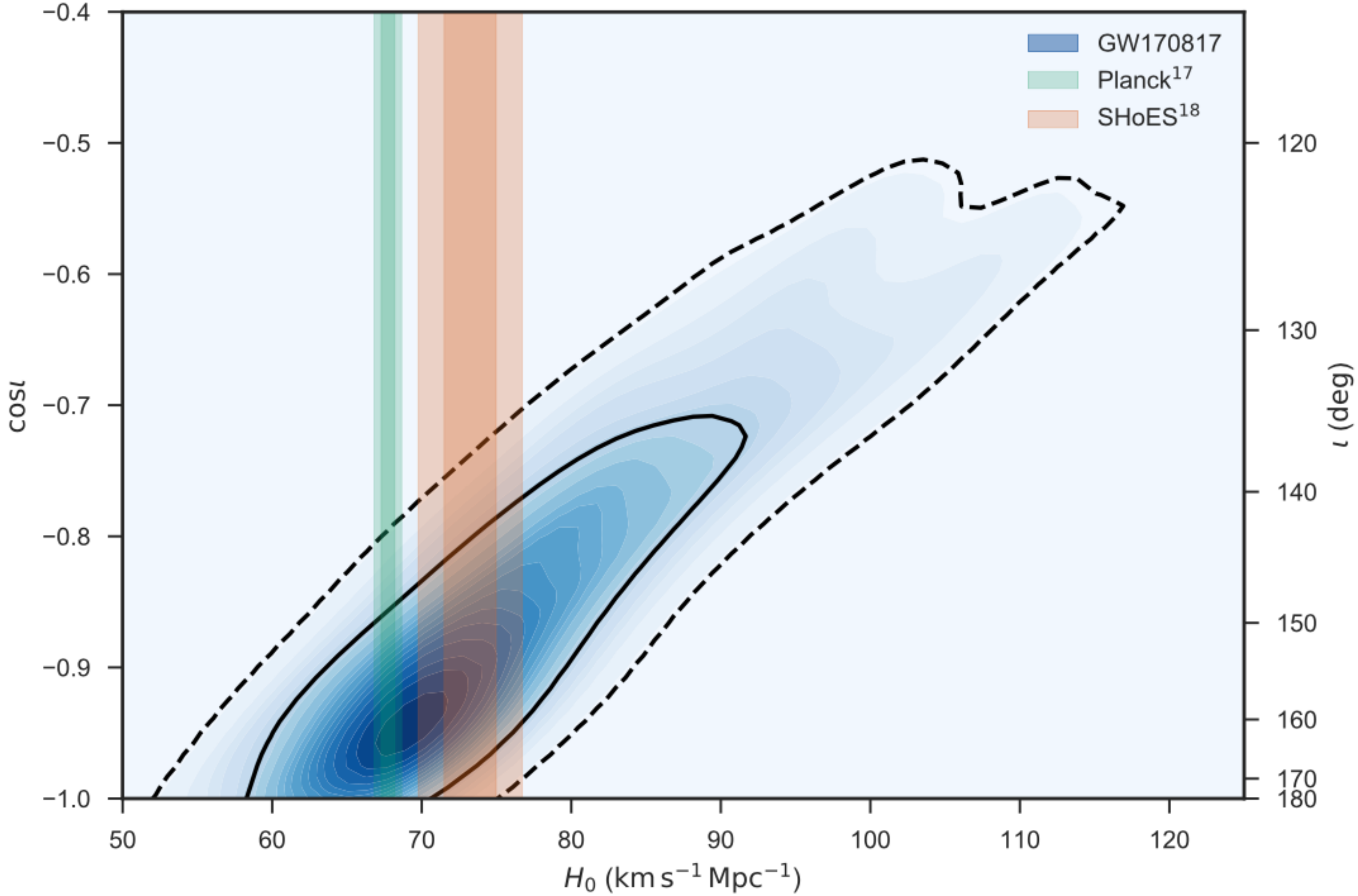
host identification: EM emission / “kilonova”





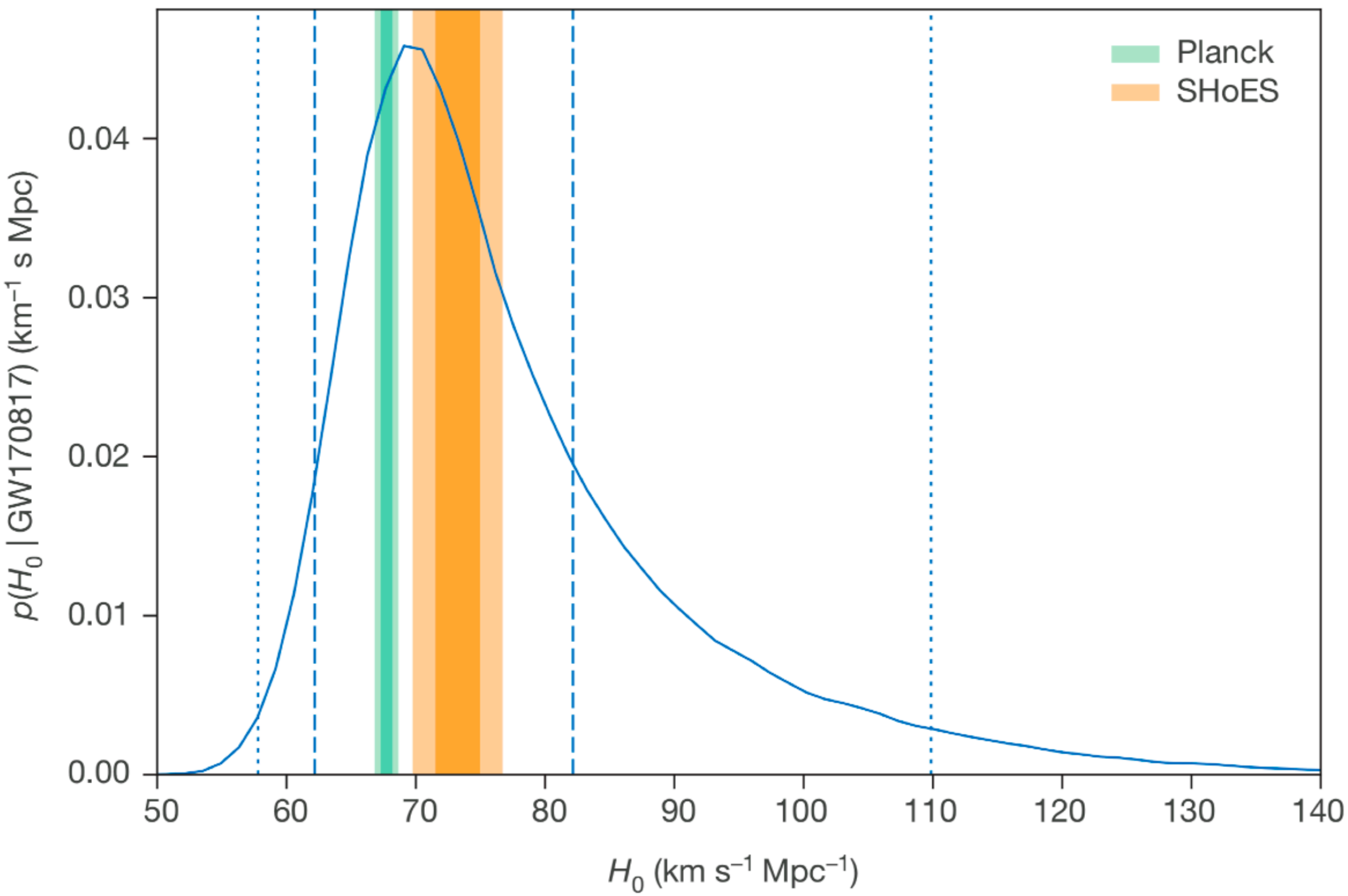
(3600 physicists and astronomers et al. 2017)

H_0 from one BNS merger



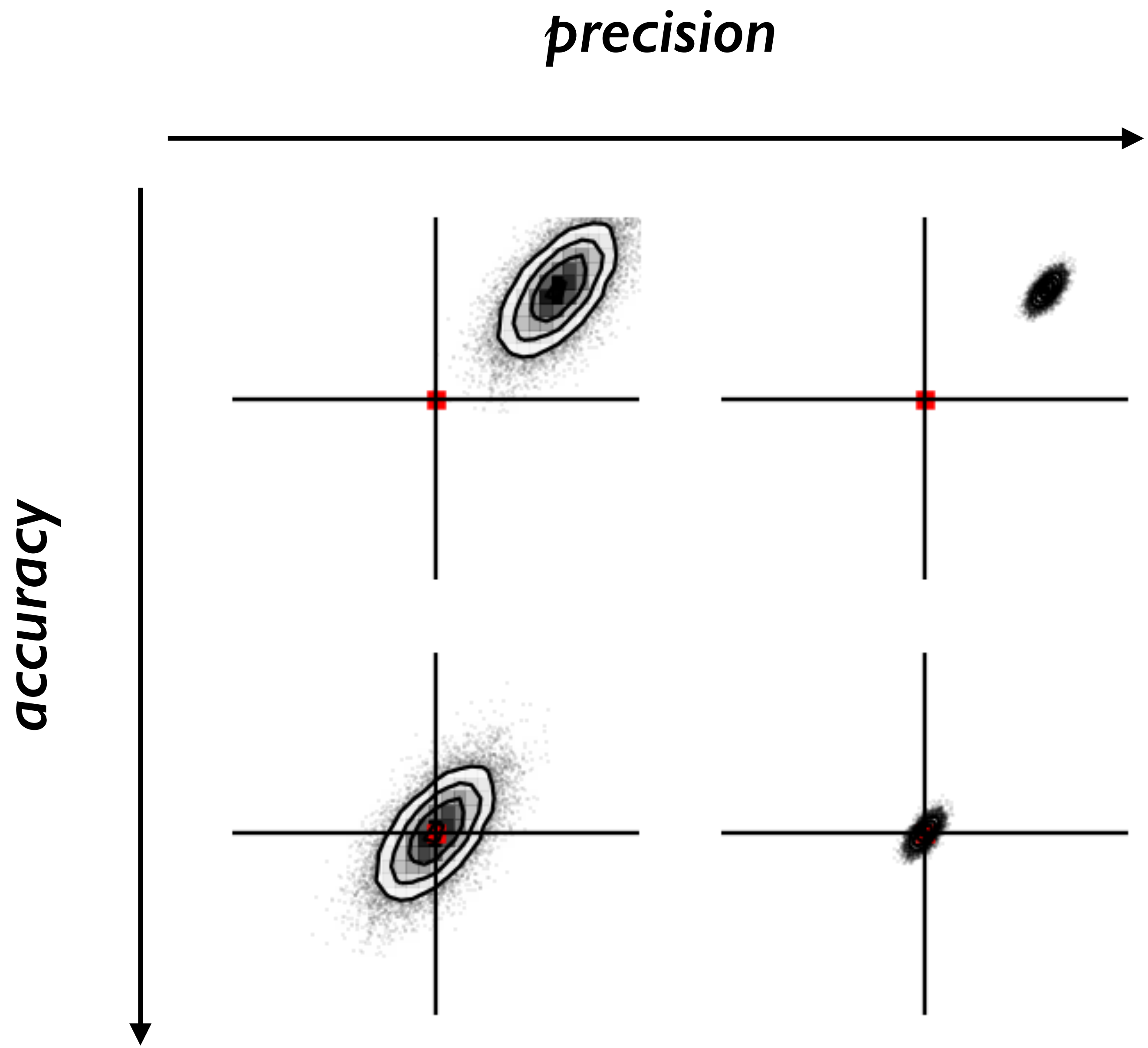
(LIGO+Virgo 2017)

H_0 from one BNS merger



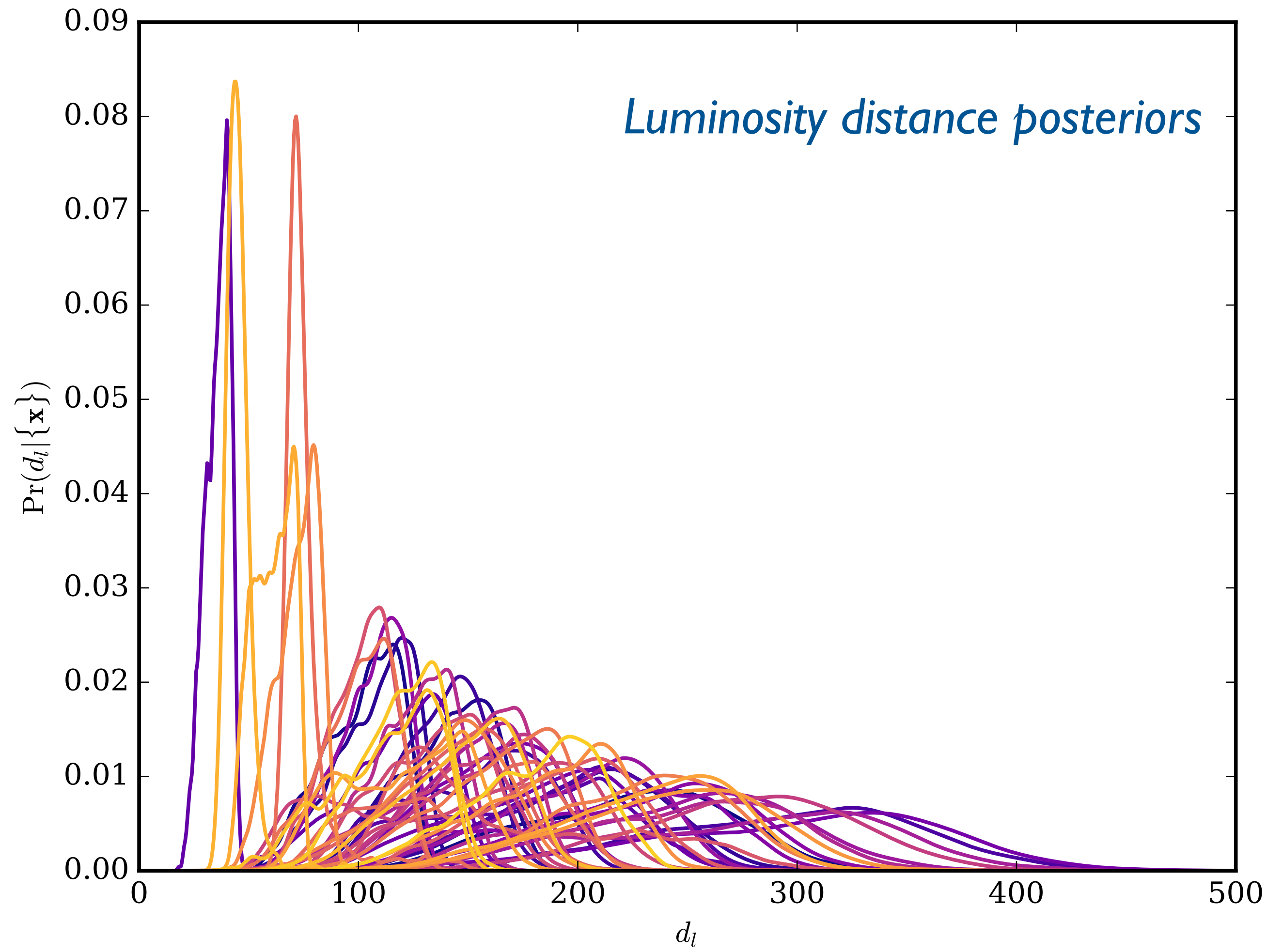
(LIGO+Virgo 2017)

“Fast vs exact methods” (Research In Progress)


precision
accuracy

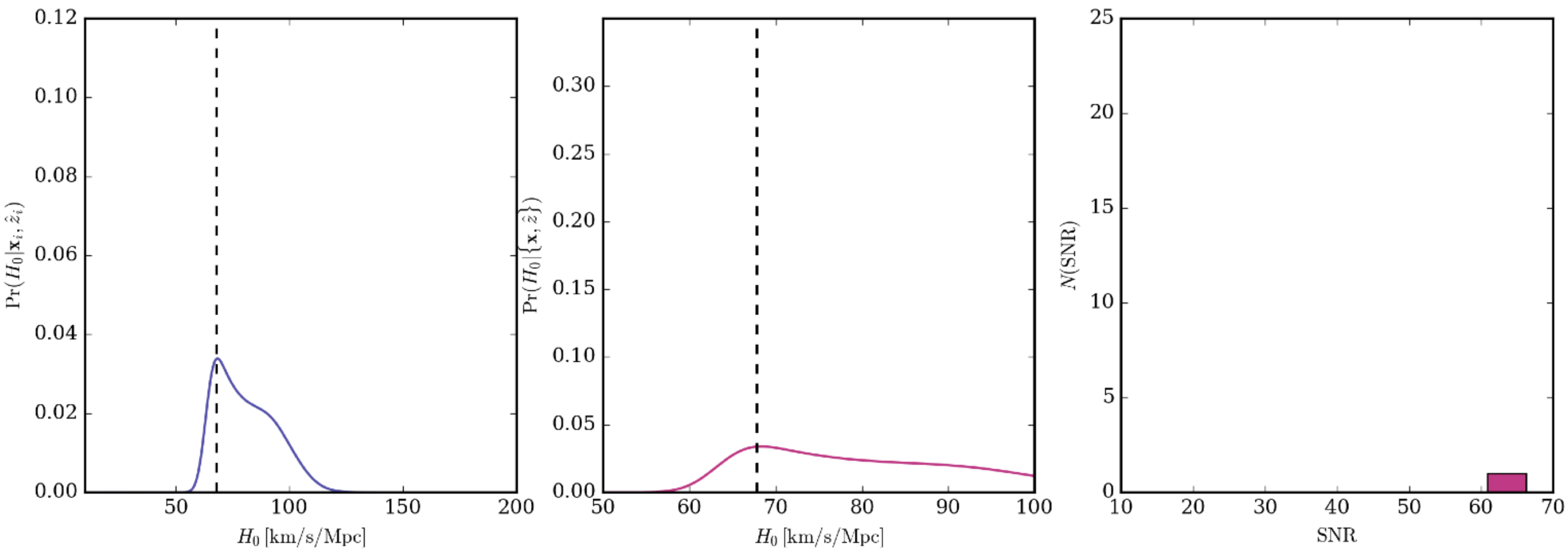
Arbitrating H_0 tension with GW standard sirens

- 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 et al (2018, Phys. Rev Lett.)

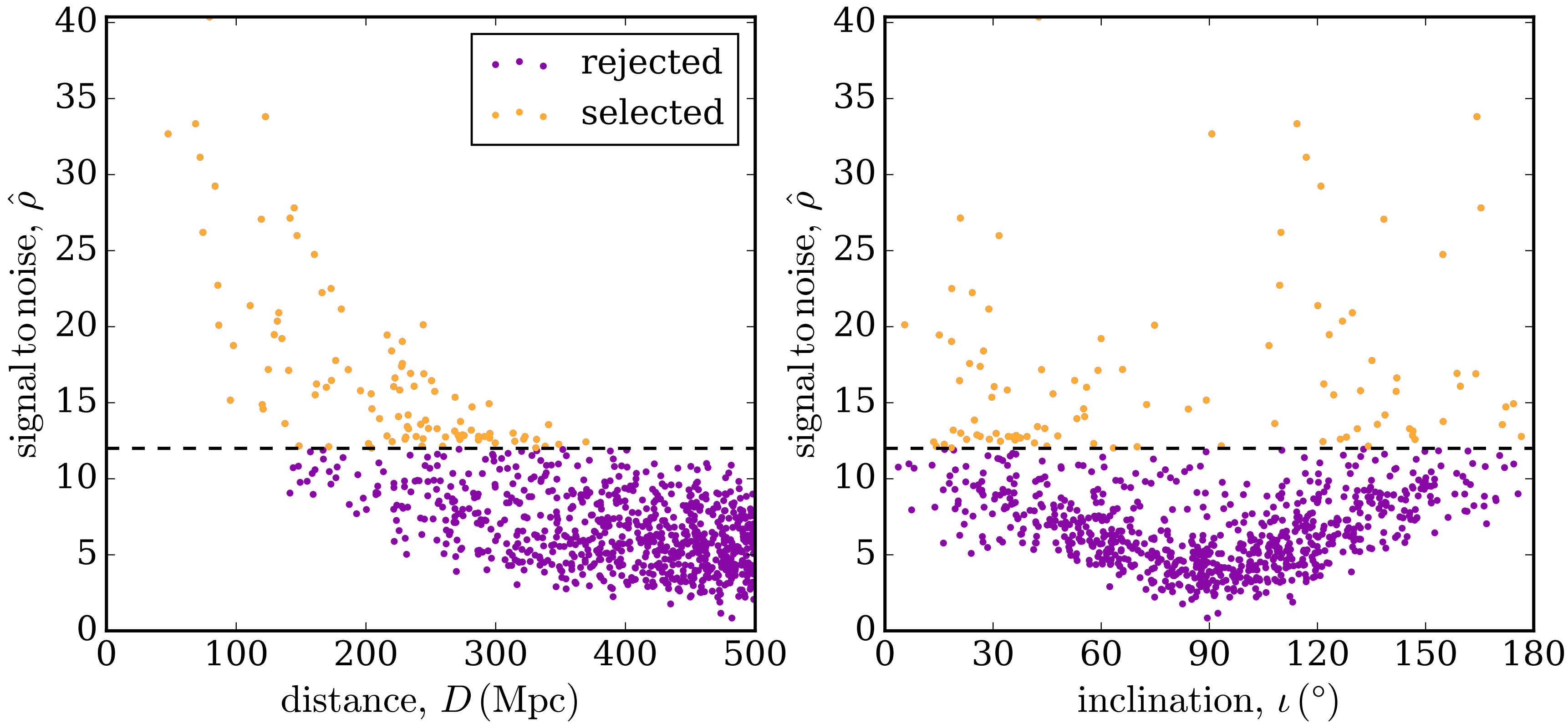
Arbitrating H_0 tension with GW standard sirens



- 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 et al (2018, Phys. Rev Lett.)

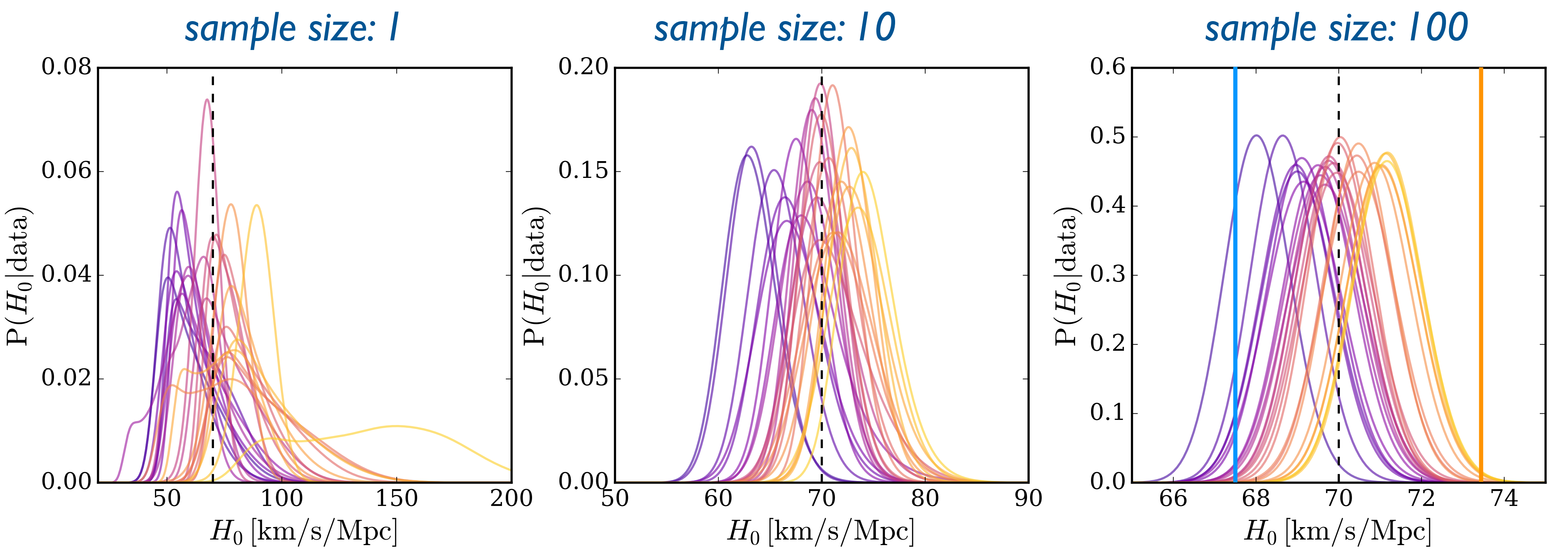
Are H0 estimates from std siren samples unbiased?



- 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 et al (2018)

Simulation results



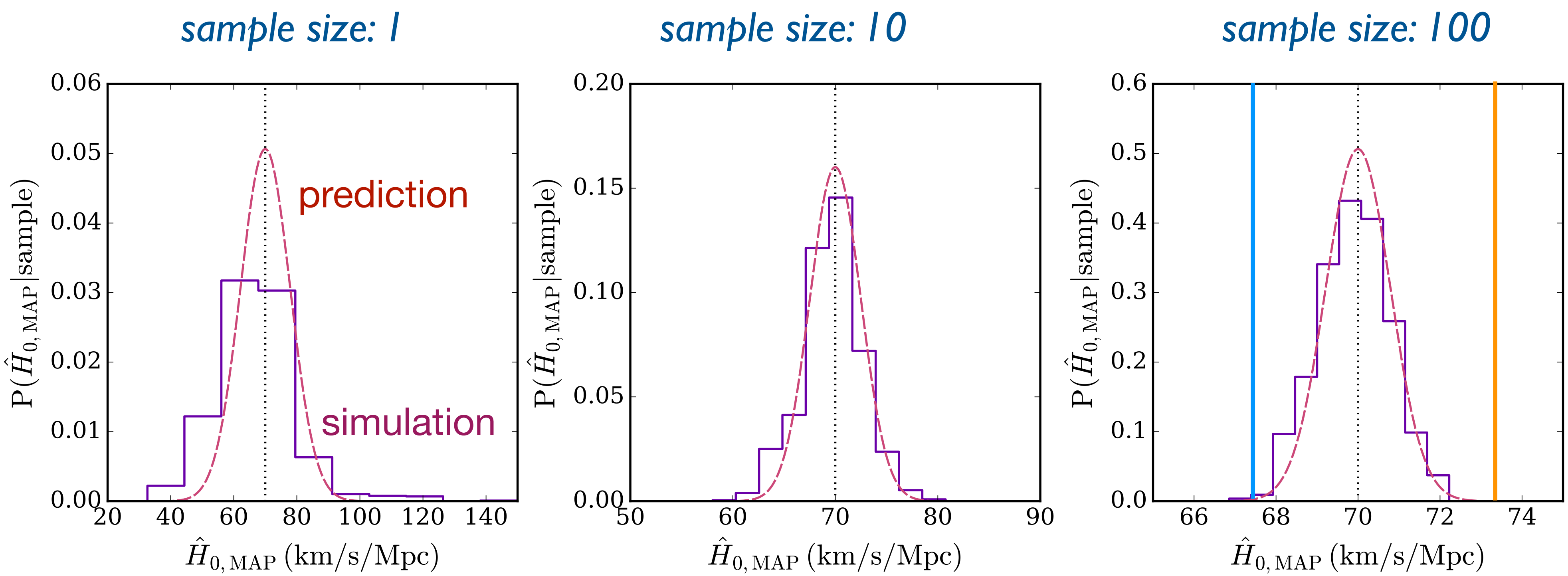
Posterior distributions in H_0 from 25 simulations of samples of N BNSs

N = 1: Posteriors have range of shapes; difficult to assess error/bias

N = 100: Posteriors all Gaussian; into asymptotic regime

Mortlock et al (2018)

Simulation results



Distribution of MAP estimate of H_0 from simulations of samples of N BNSs

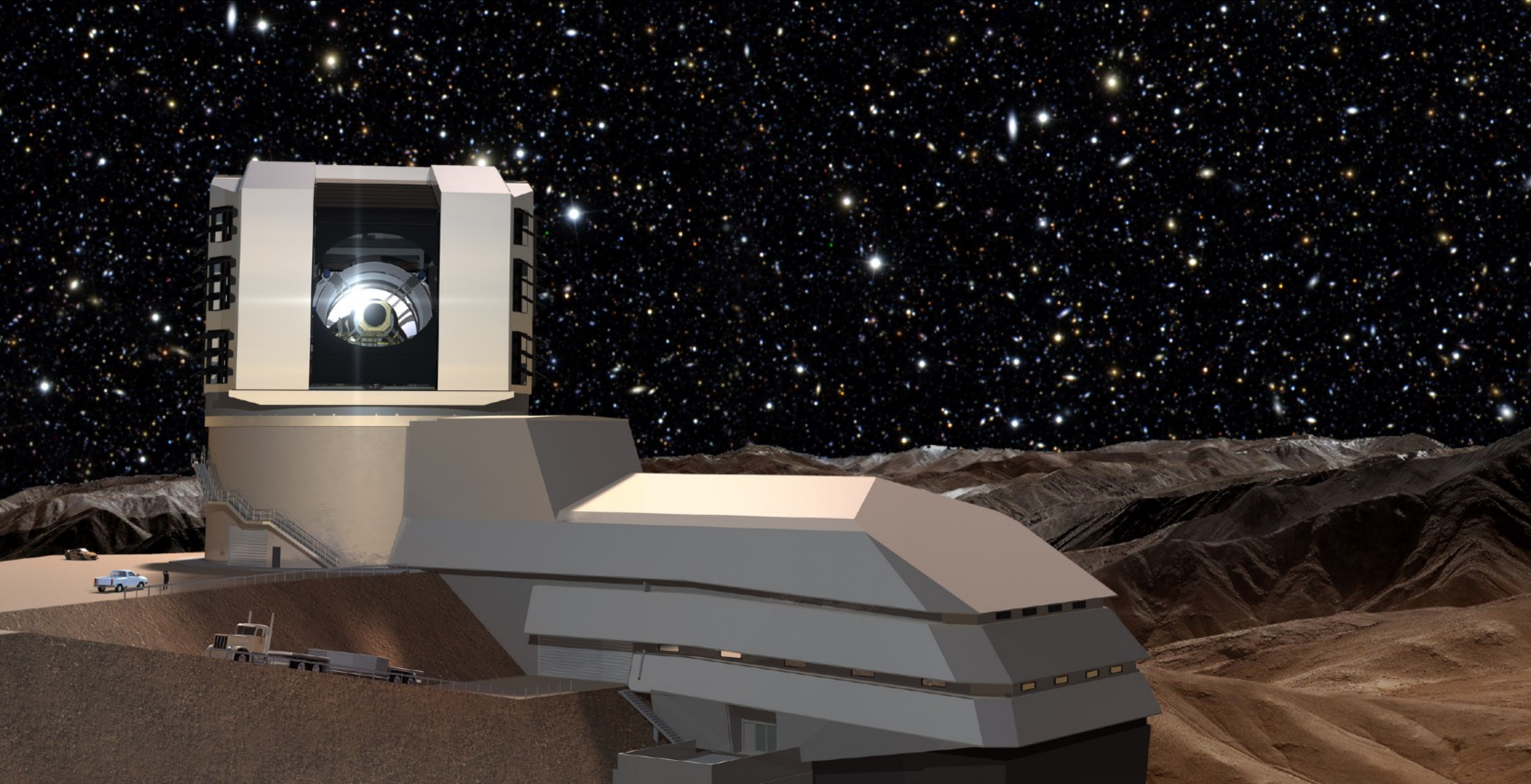
N = 1: Distribution has a high-H_0 tail; difficult to assess error/bias

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

Mortlock et al (2018)

A dedicated survey telescope

- Wide (half-sky), deep (24-27 mag), fast (every ~3 days) images
- Beginning in 2020, LSST will survey the sky for 10 years
- Involves scientists in 23 countries (US, Chile and International Partners)



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!

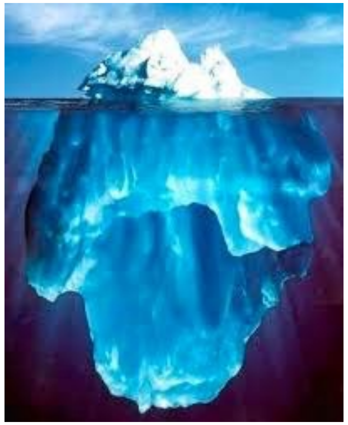
From Zeljko Ivezic

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

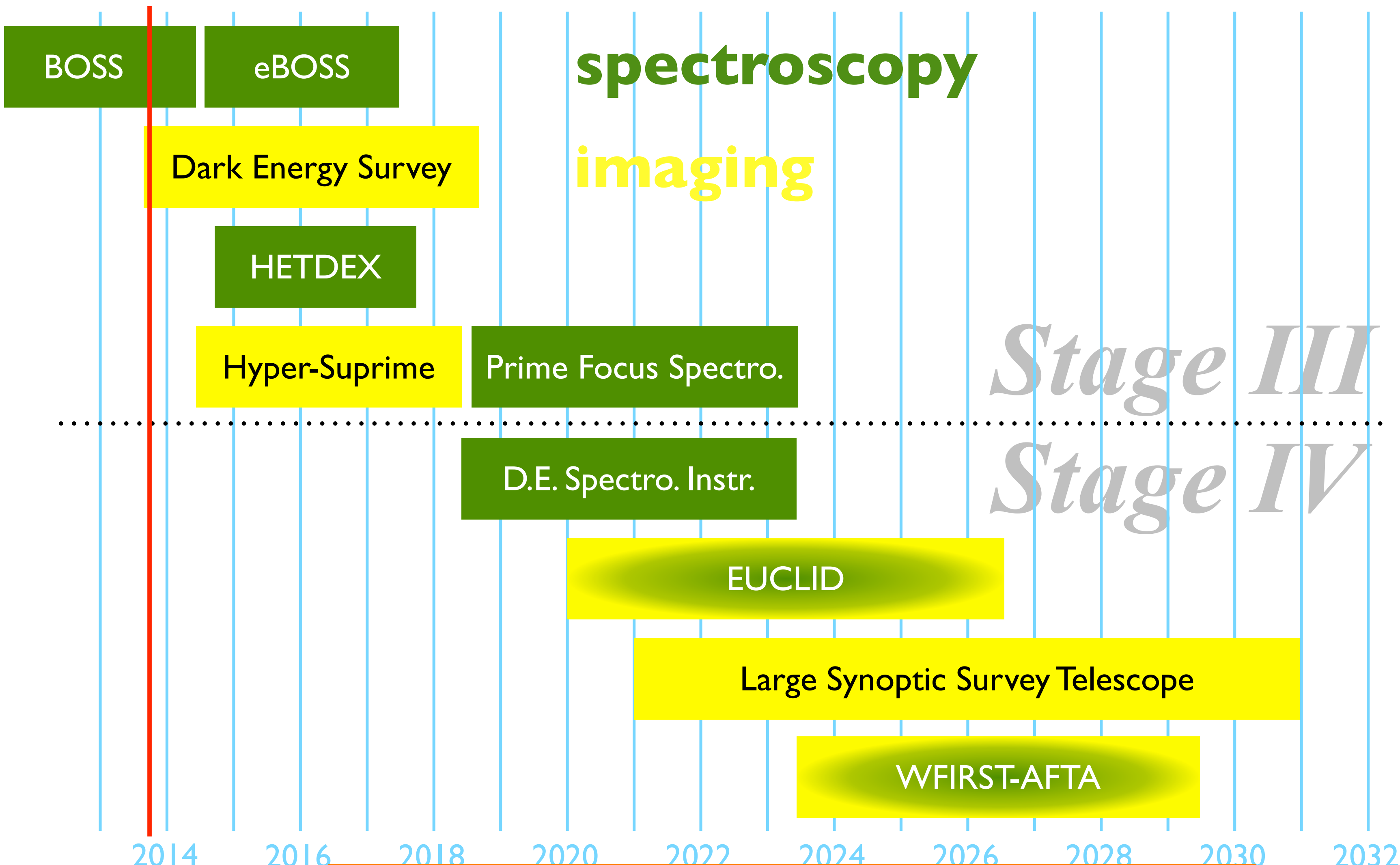
Mapping the Milky Way

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

Dark Energy Facilities Roadmap

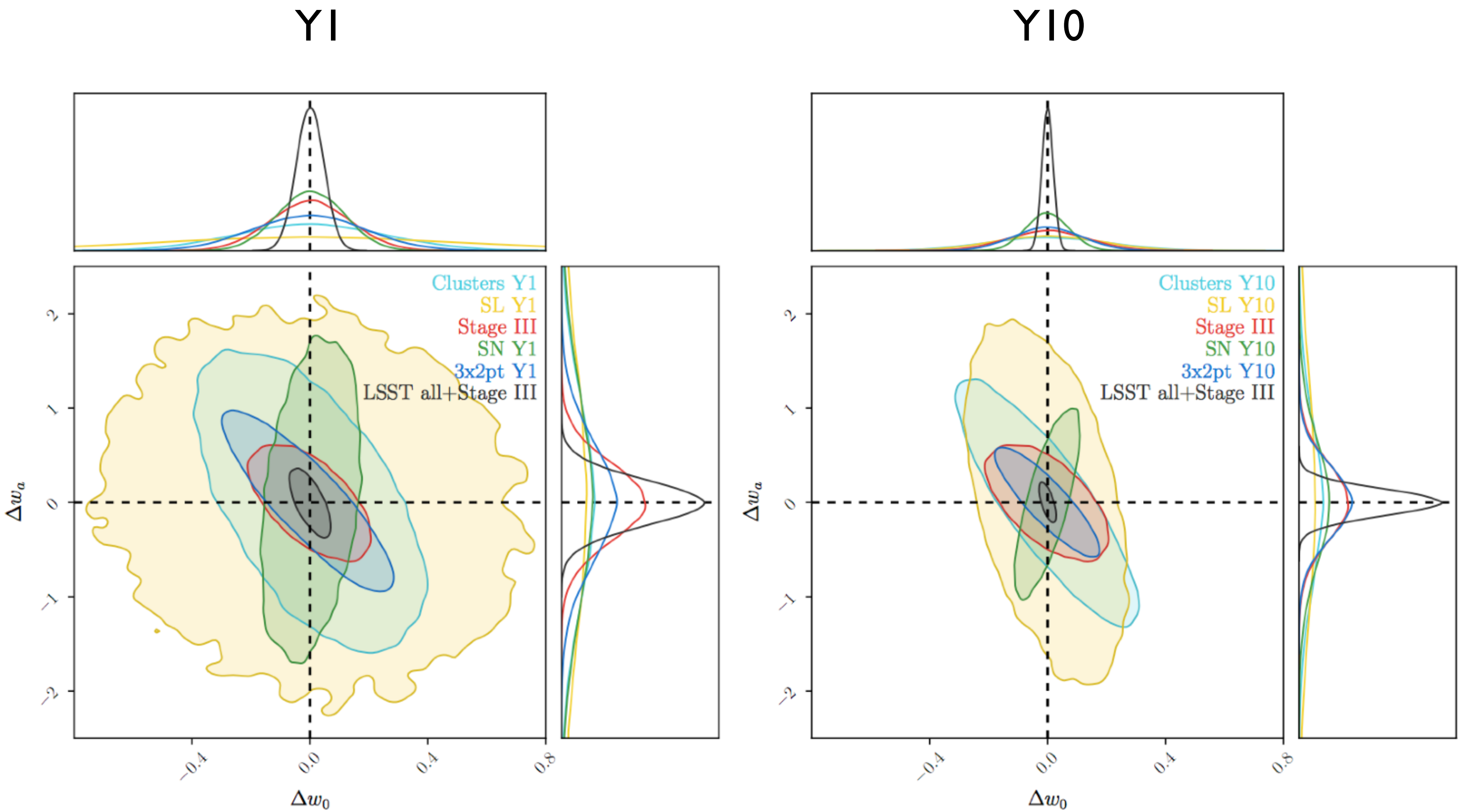


High degree of complementary between missions

Image: Ian Shipsey

Background Image Credit: UCL / Pontzen

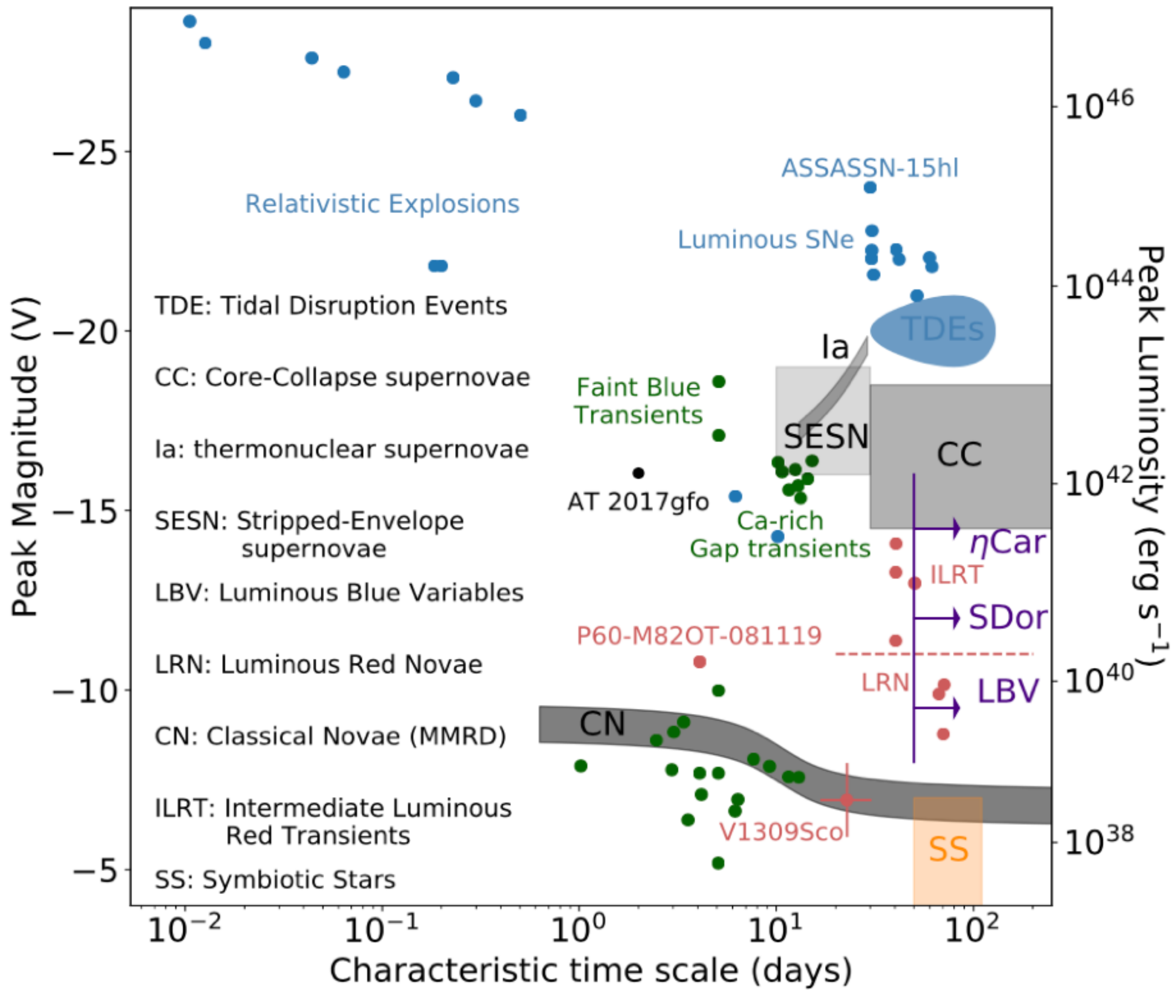
LSST and Dark Energy Science



Forecast dark energy constraints at Y1 and Y10 from each probe individually and the joint forecast including Stage III priors.

DESC Science Requirements Document V1 (arXiv: 1809.01669)

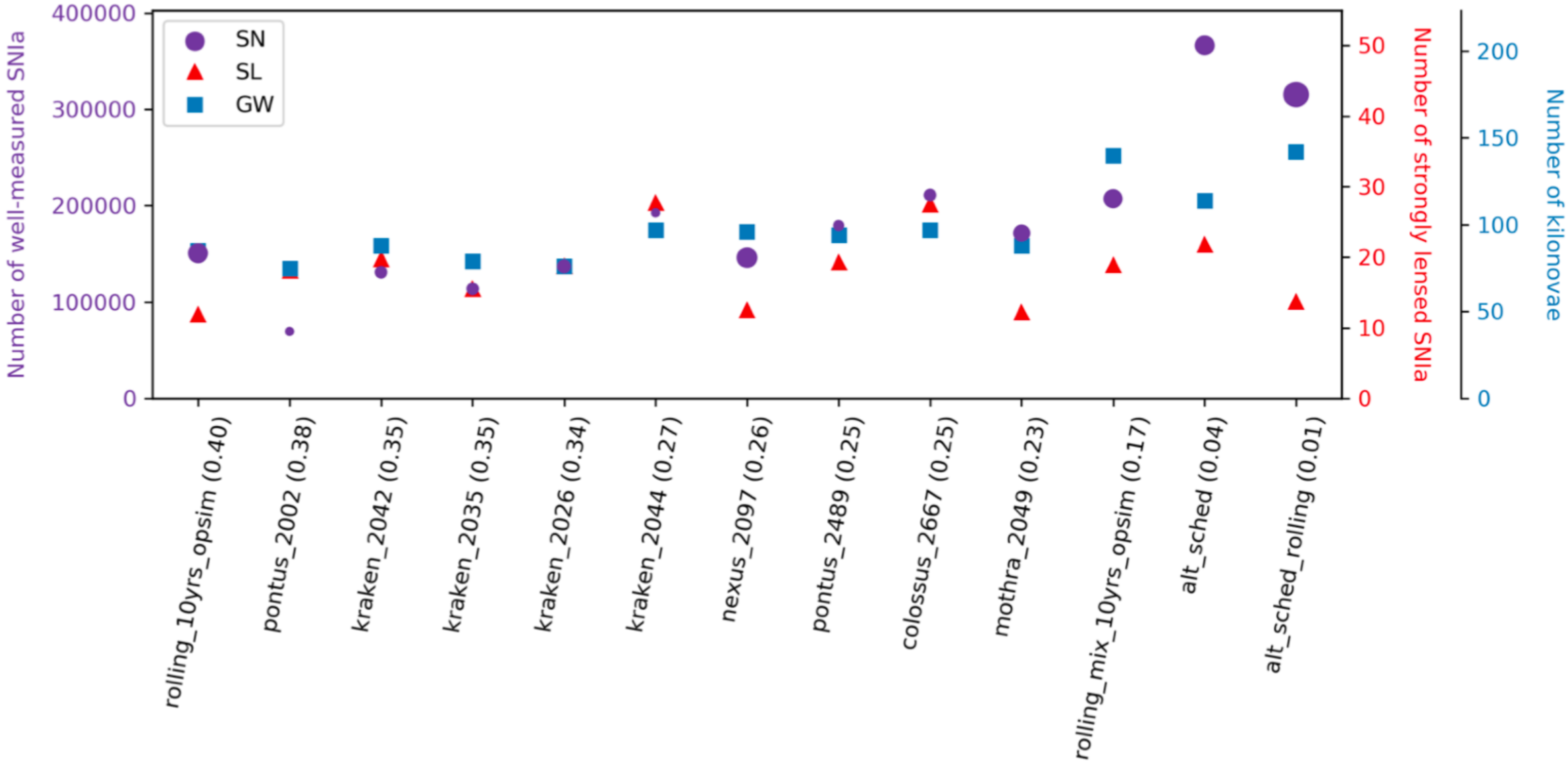
LSST and the transient universe



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)

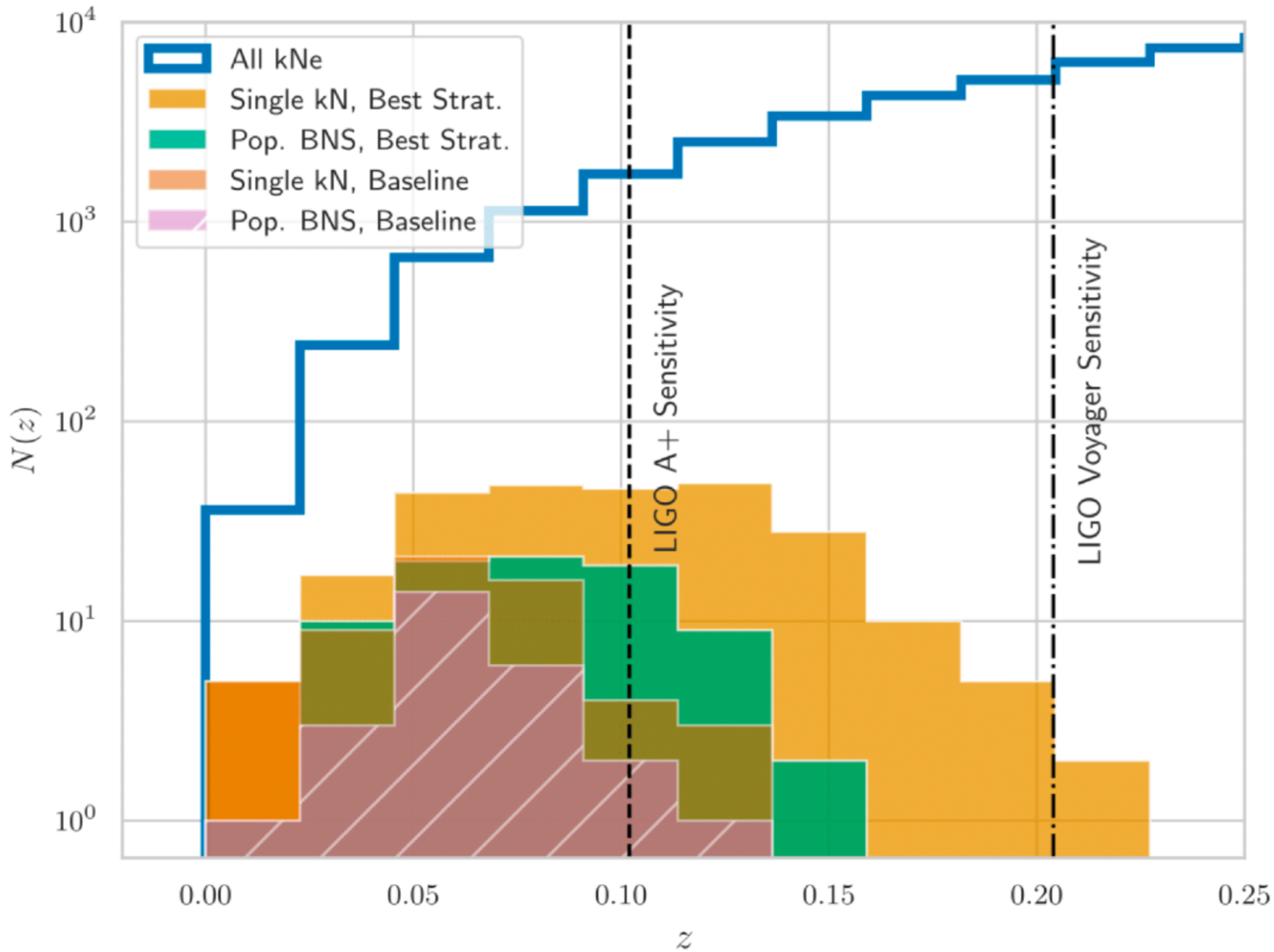
LSST and the transient universe



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

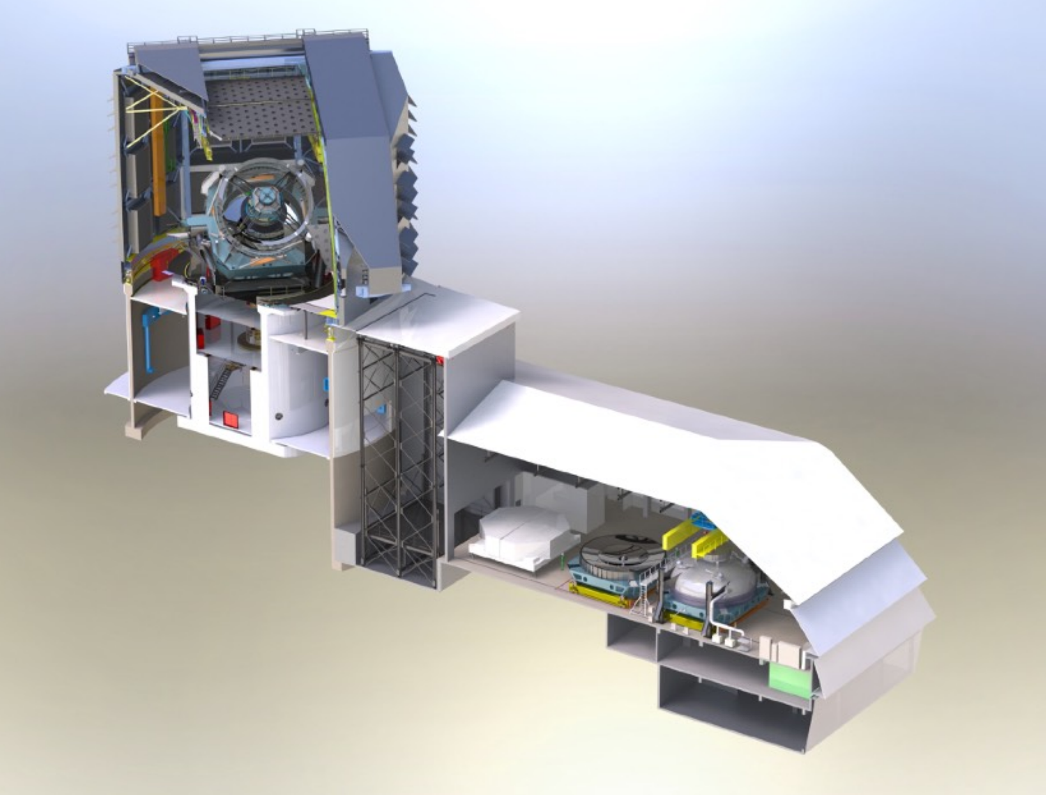
Serendipitous detections of kilonovae in LSST



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

SETZER ET AL (LSST DESC, MNRAS IN PRESS, ARXIV:1812.10492)

First light: 2019



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