Cosmic Tensions

A High Energy Physicist's Primer

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Introduction: Precision Cosmology and its Discontents

- Have well-and-truly entered an era of precision cosmology.
- Multiple independent observations allow us to constrain the parameters of our cosmological model.
- The Standard Model of Cosmology (ΛCDM) successfully explains a wide range of observations.
- However, increasing precision has revealed inconsistencies, or tensions, between different measurements.
- Are these tensions cracks in ΛCDM, hints of new physics, or simply measurement systematics?

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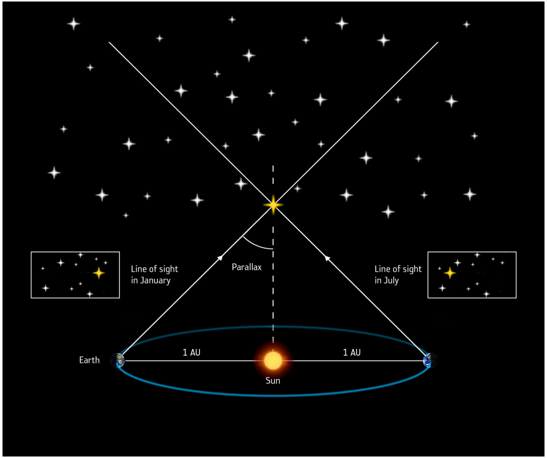

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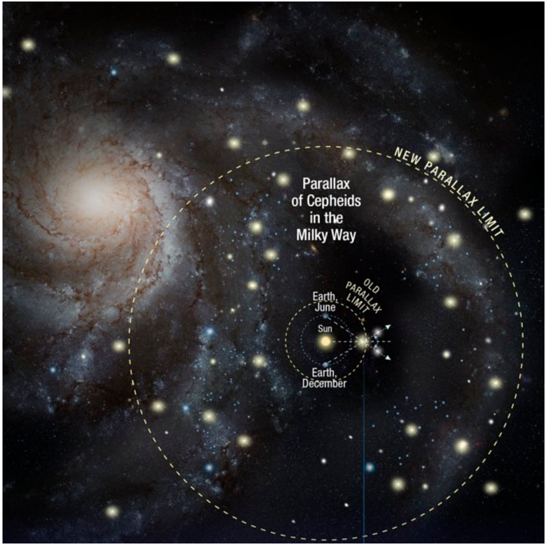
- . . . but it only gets you so far. [2208.00211]



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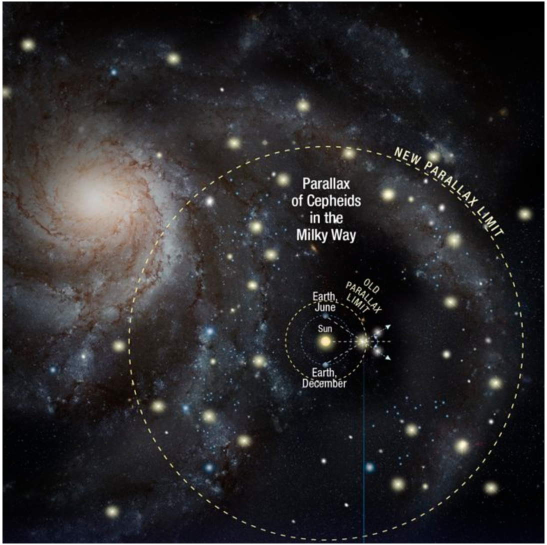
- Parallax is the archetypal cosmological **geometric** measurement. . .
- . . . but it only gets you so far. [2208.00211]
- To go beyond parallax you need:
  - a standardisable object that exists next to your geometric measurements. . .
  - . . . or some other way to measure distance, like standard rulers or sirens.



Standard Candles

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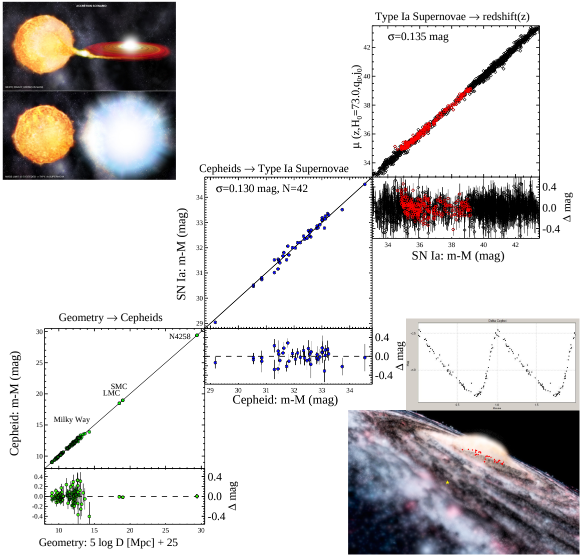
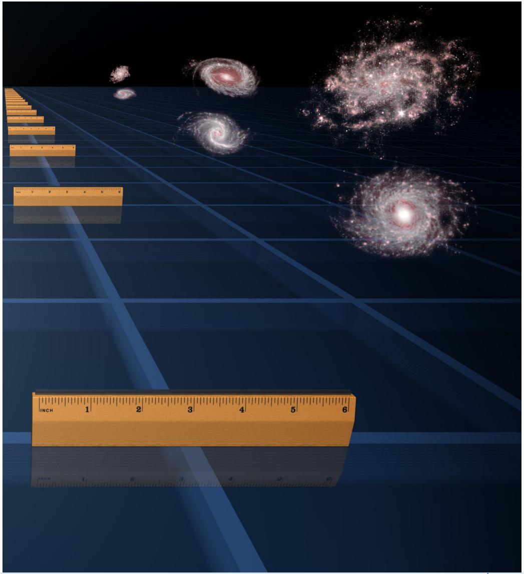
- Cepheids: Variable stars with period-luminosity relation. [2403.02801]
- Supernovae Type Ia (SNe Ia): Exploding white dwarfs, higher redshifts. [2202.04077]
- TRGB stars: Tip of the Red Giant Branch stars, Cepheid alternative. [2401.04776]
- JAGB stars: J-region Asymptotic Giant Branch stars, another [2401.04777]
- Two Prominent Teams: SH0ES (Riess) and CCHP (Freedman)



Standard Rulers

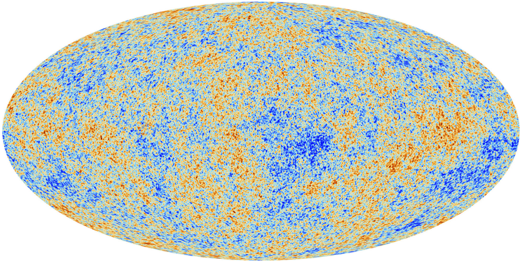
- Standard Rulers: Objects with known physical size.
- CMB: Cosmic Microwave Background, fluctuations give a standard ruler at z$\sim$1100. [doi:10.1086/186504]
- BAO: Baryon Acoustic Oscillations, sound waves in early universe imprint a standard ruler on galaxy distribution. [1201.2434]
- Strong lensing: Time delays between multiple images of a lensed object constrain distances. [doi:10.1093/mnras/128.4.307]
- Weak lensing: Distortion of galaxy shapes by intervening matter constrains the matter distribution.

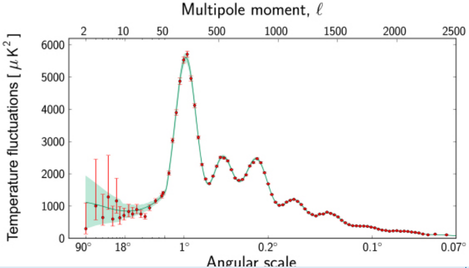


Standard Rulers

The cosmic microwave background

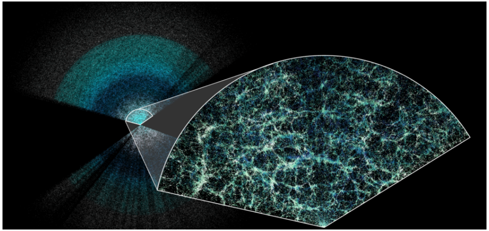
- CMB: "Surface of last scattering" at $z \sim 1100$. Angular size of hot/cold spots gives a standard ruler. [doi:10.1086/186504]
- Temperature fluctuations: $\Delta T/T \sim 10^{-5}$. [doi:10.1086/186504]
- Polarization: E and B modes. B-modes from primordial gravitational waves are a key target.

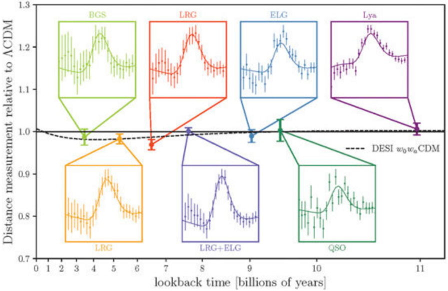




Standard Rulers

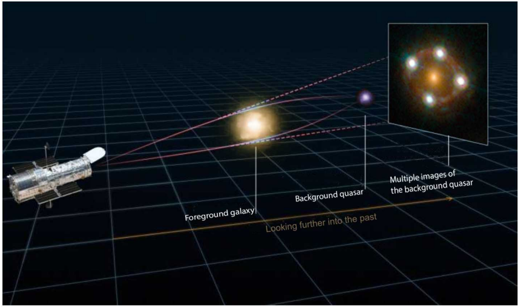
Baryon Acoustic Oscillations

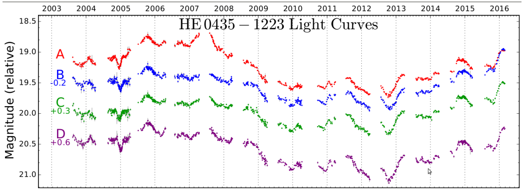




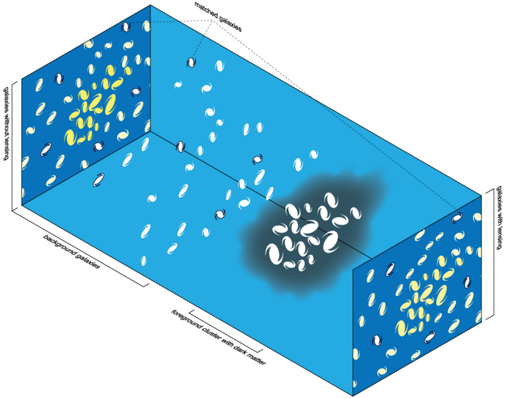
- BAO: Sound waves in the early Universe imprint a characteristic scale on the distribution of baryons (and galaxies). [1201.2434]
- SDSS: Sloan Digital Sky Survey, one of the first surveys to measure BAO. [astro-ph/0501171]
- DESI: Dark Energy Spectroscopic Instrument, current best BAO measurements. [2404.03001]

- Strong Lensing: Light from a distant object is bent by the gravity of a massive foreground object (e.g., a galaxy or galaxy cluster). [doi:10.1093/mnras/128.4.307]
- Time Delays: Differences in path lengths of multiple images lead to time delays, which can be used to measure distances. [2210.15794]



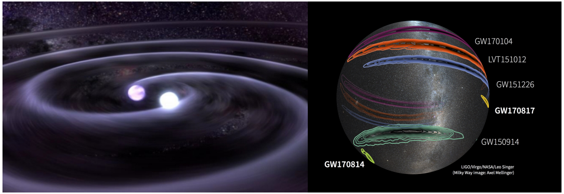


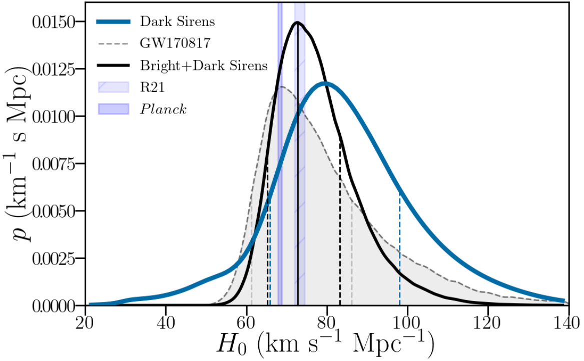
- Weak Lensing: Small distortions in the shapes of background galaxies caused by the gravitational lensing of intervening matter.
- Surveys like DES, KiDS, and HSC have used weak lensing to map the distribution of dark matter. [1610.04606][1910.05336]



Standard Sirens

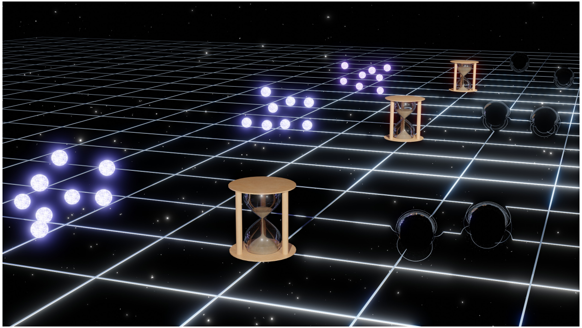
- Standard Sirens: Gravitational wave sources with known intrinsic "loudness". [doi:10.1038/323310a0] [astro-ph/0504616]
- Bright sirens: GW events with an electromagnetic counterpart, allowing redshift measurement. [1710.05835]
- Dark sirens: GW events without an electromagnetic counterpart; statistical redshift information is used. [1901.01540]
- Spectral sirens: Redshift is inferred statistically from the mass distribution of merging black holes. [1908.09084]





Standard Clocks

- Standard Clocks: Objects or phenomena whose time evolution can be used to measure time or distances.
- Cosmic Chronometers: Passively evolving galaxies whose age can be measured, giving dH/dz. [astro-ph/0106145]
- Pulsar timing arrays: Variations in the arrival times of pulsar signals can be used to detect gravitational waves and measure distances.

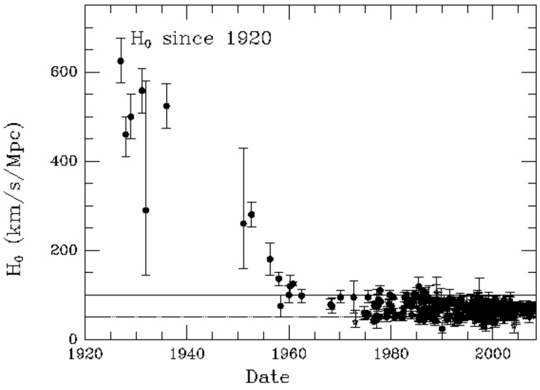


The Hubble tension

- CMB: $H_0 = 67.4 \pm 0.5$ km/s/Mpc. [1807.06209]
- SH_0ES: $H_0 = 73.2 \pm 1.3$ km/s/Mpc. [2112.04510]
- Exciting if not measurement error
  - People trust the CMB measurement, but perhaps not the ΛCDM model assumptions.
  - Measurements of H_0 from supernovae are notoriously challenging (crowding, dust, metallicity, etc.)
- As of 2024, Hubble three ways (Cepheids, TRGB, JAGB) show some convergence:

CCHP (Freedman)	$(72.0, 69.8, 67.96) \pm 1.8$
SH0ES (Riess)	$(73.4, 72.1, 72.2) \pm 2.2$

[2408.06153][2408.11770]



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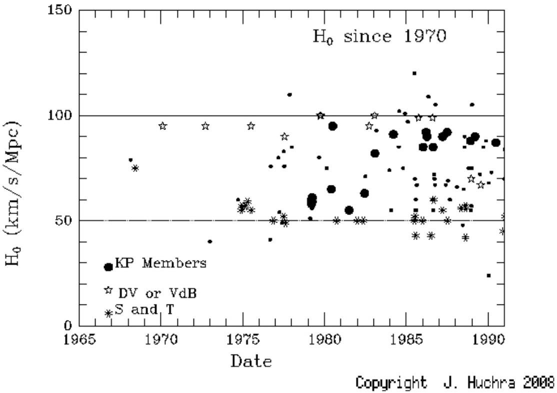

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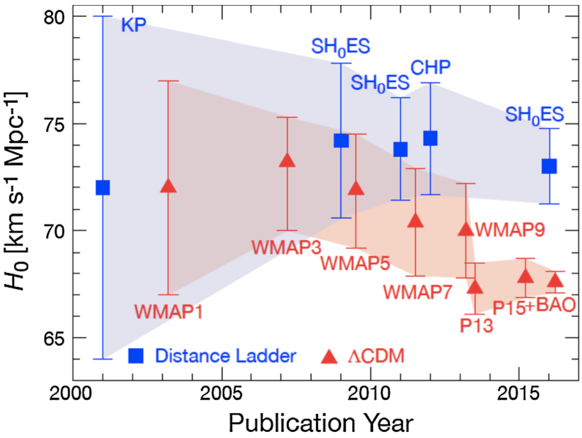

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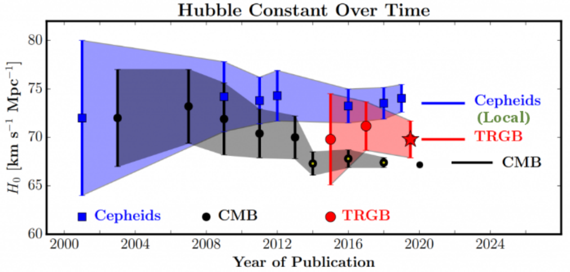

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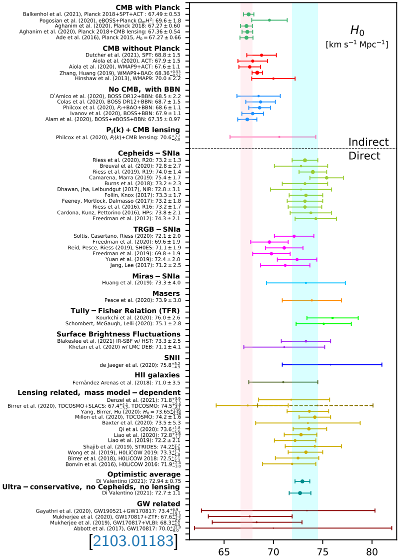
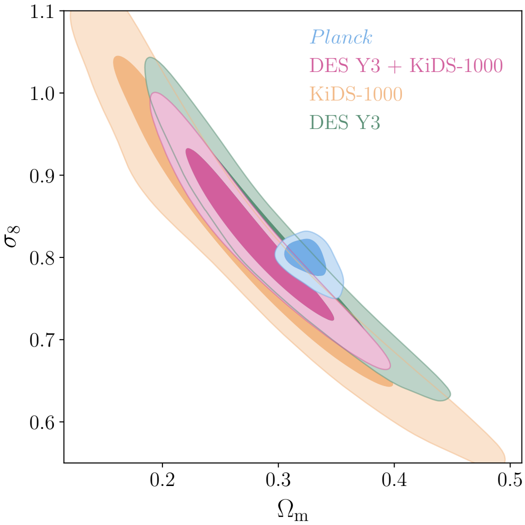


[2103.01183]

The S_8 tension

aka σ_8/weak lensing tension

- S_8 quantifies the amplitude of matter fluctuations on large scales.
- $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$.
- CMB: $S_8 \approx 0.834$. [1807.06209]
- Weak lensing: $S_8 \approx 0.76$. [1610.04606][1910.05336]
- Tension at the $2-3\sigma$ level.
- Possible systematics in weak lensing or new physics?



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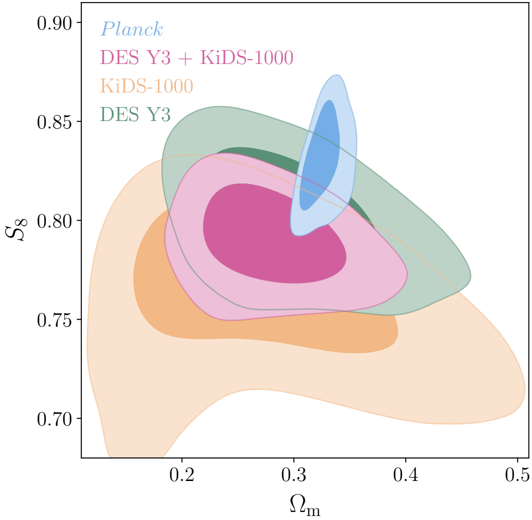

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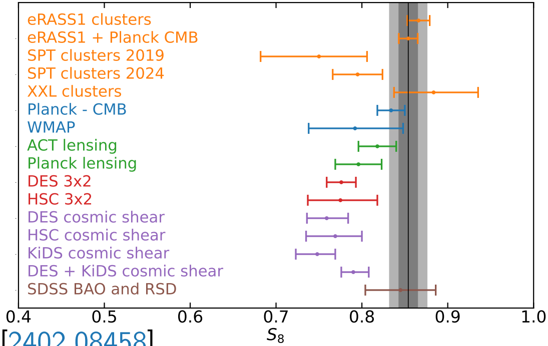
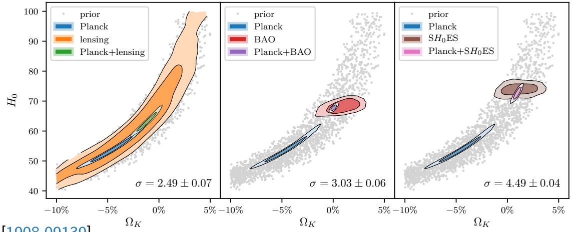


[2402.08458]

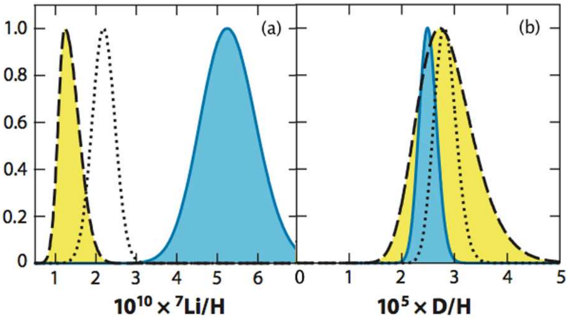
[2305.17173]

Other Tensions and Anomalies

- A_{lens} anomaly: CMB lensing amplitude higher than expected. [1807.06209]
- Non-zero curvature: Some data hints at a closed universe. [1902.04029]
- CMB anisotropic anomalies: Large-scale features that challenge statistical isotropy. [1510.07929]
- BBN anomalies: Discrepancies in light element abundances. [1912.01132]

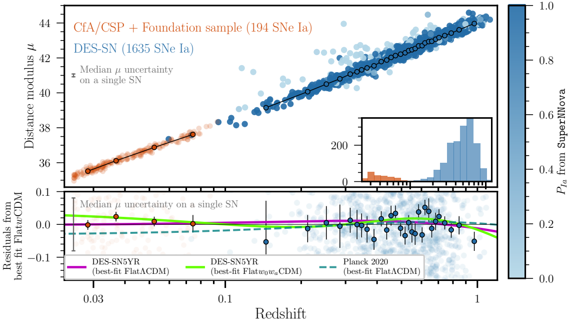


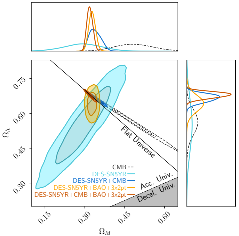
[1908.09139]

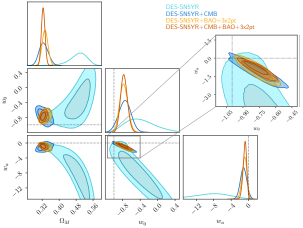


- 2024 was a big year for cosmology, with new data releases from multiple surveys:

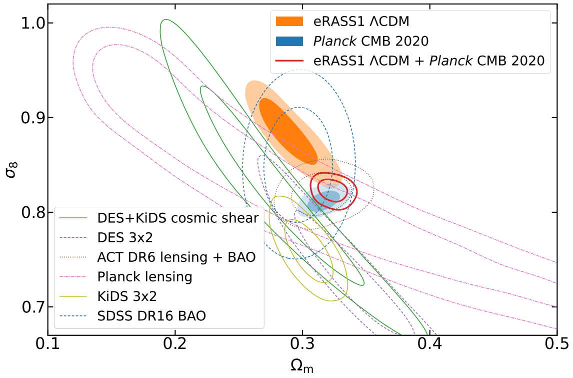
Jan	DESY5 SNe: Improved supernova measurements from the Dark Energy Survey. [2401.02929]
Feb	eROSITA: First all-sky survey results from the extended ROentgen Survey with an Imaging Telescope Array. [2402.08458]
Mar	DESI: First year cosmology results from the Dark Energy Spectroscopic Instrument. [2404.03002]





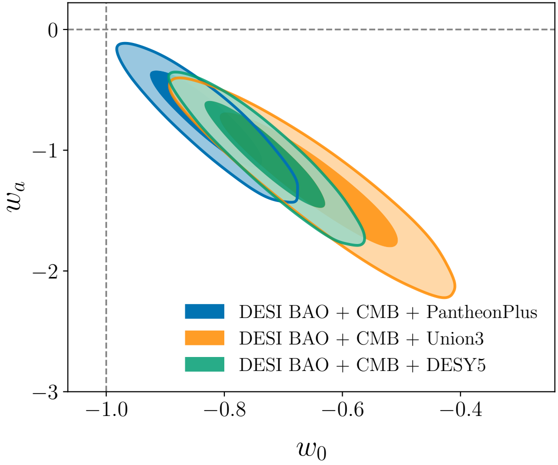


- eROSITA performed the first all-sky survey in X-rays since ROSAT.
- Detected ∼12,000 galaxy clusters, providing a powerful new dataset for cosmology.
- Results broadly consistent with ΛCDM, but with some hints of tension in σ_8. [2402.08458]



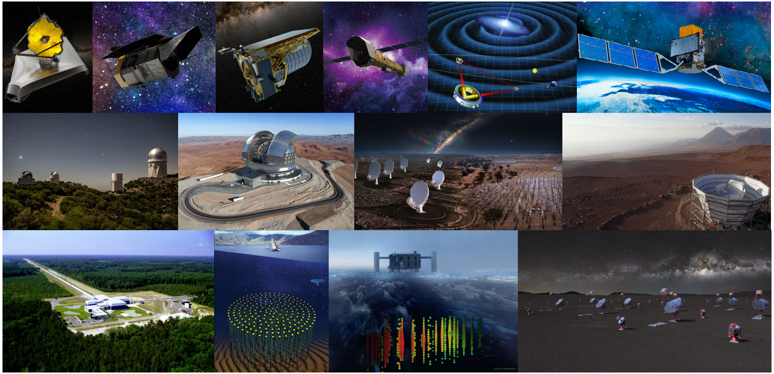
DESI

- DESI is mapping millions of galaxies and quasars to measure BAO and redshift-space distortions.
- First year cosmology results strengthen evidence for dark energy, but do not resolve the H_0 tension. [2404.03002]
- Full BAO and BBN analysis yields $H_0 = 68.53 \pm 0.80$ km/s/Mpc (independent of CMB). [2404.03000]



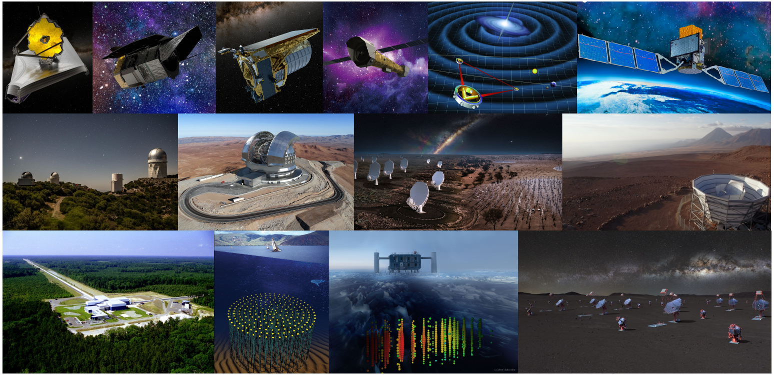
What to watch out for

- In 2025:
  - DESI: Year 3 BAO results with increased precision.
  - DES/Euclid: Improved weak lensing measurements with larger sky coverage.
  - eROSITA: Further analysis of X-ray cluster data, including mass calibration.
  - ACT: Final data release with improved CMB polarization measurements.
  - LVK: Continued gravitational wave observations, potentially increasing the number of standard sirens.



What to watch out for

- Next 5 years:
  - Simons Observatory: High-precision CMB observations, targeting primordial B-modes.
  - Rubin: First light and early strong lensing discoveries.
  - Roman: Hubble 3.0 with improved Cepheid measurements.
  - IPTA: Improved pulsar timing array data, constraining the stochastic gravitational wave background.



What to watch out for

- Next 10-20 years:
  - LISA/Einstein Telescope: Next-generation gravitational wave observatories, probing the early Universe.
  - SKA: Large FRB surveys, constraining cosmological parameters and the intergalactic medium.
  - LiteBird: Space-based CMB polarization measurements, targeting primordial B-modes.
  - ATHENA: High-resolution X-ray observations of galaxy clusters, mass calibration.