

Cosmic Tensions

A High Energy Physicist's Primer

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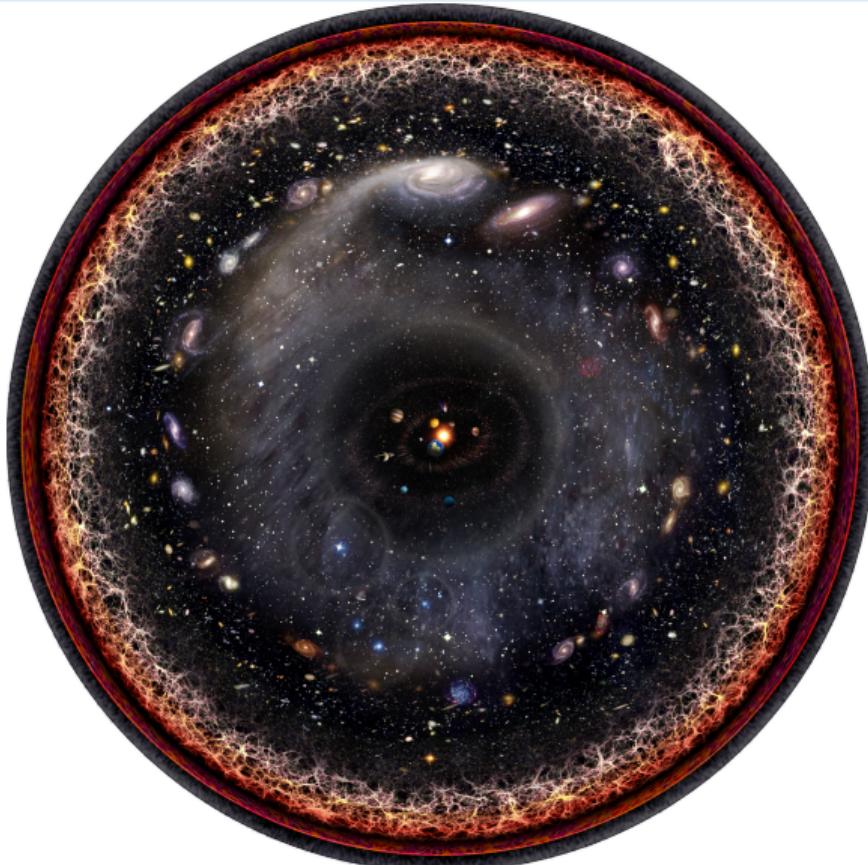


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Introduction: Precision Cosmology and its Discontents

- ▶ 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 (Λ CDM) successfully explains a wide range of observations.
- ▶ However, increasing precision has revealed inconsistencies, or tensions, between different measurements.
- ▶ Are these tensions cracks in Λ CDM, hints of new physics, or simply measurement systematics?



Measuring the Universe

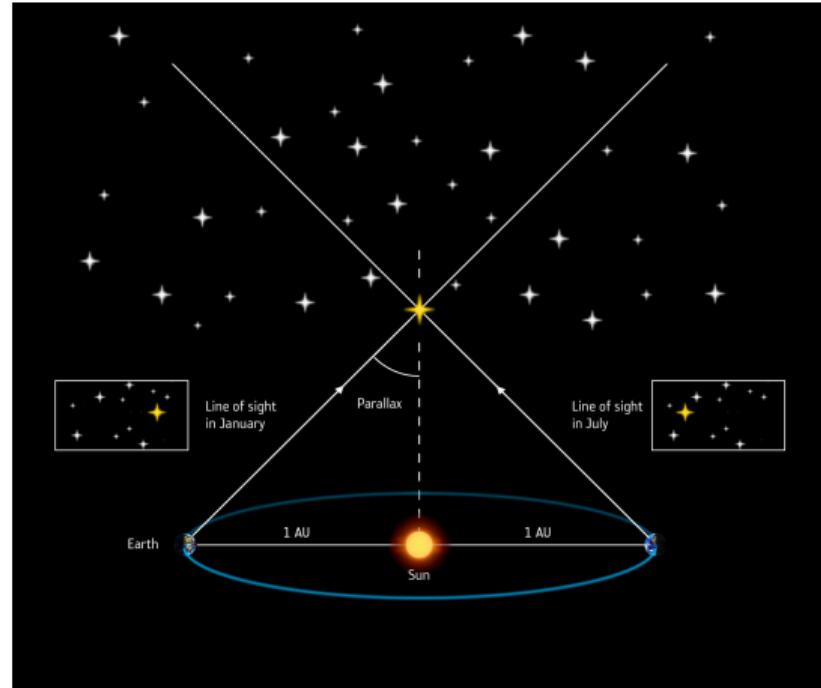
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Measuring the Universe

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 - ▶ Beyond our arms reach (where stereopsis fails), we rely on parallax between objects picked up by slight head motion.

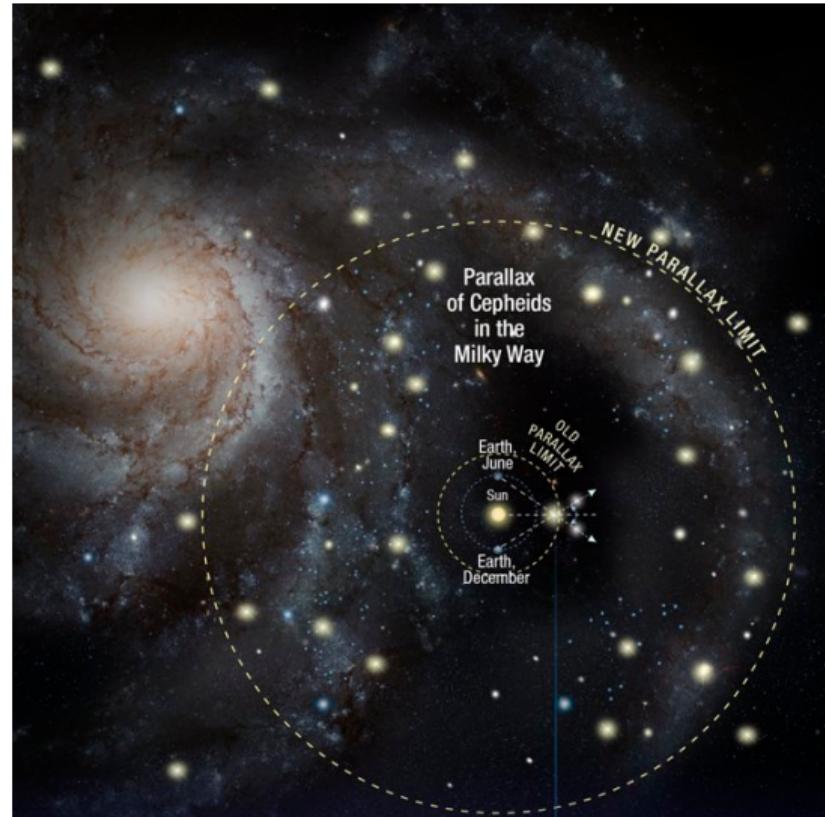
Measuring the Universe

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- ▶ Parallax is the archetypal cosmological **geometric** measurement...



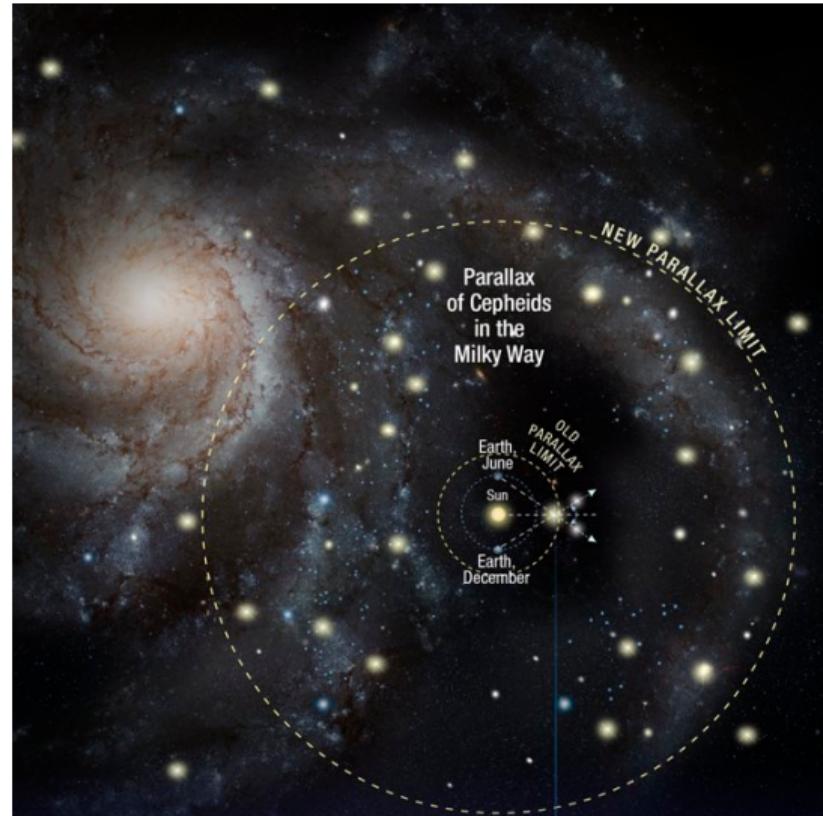
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- ▶ ...but it only gets you so far. [2208.00211]



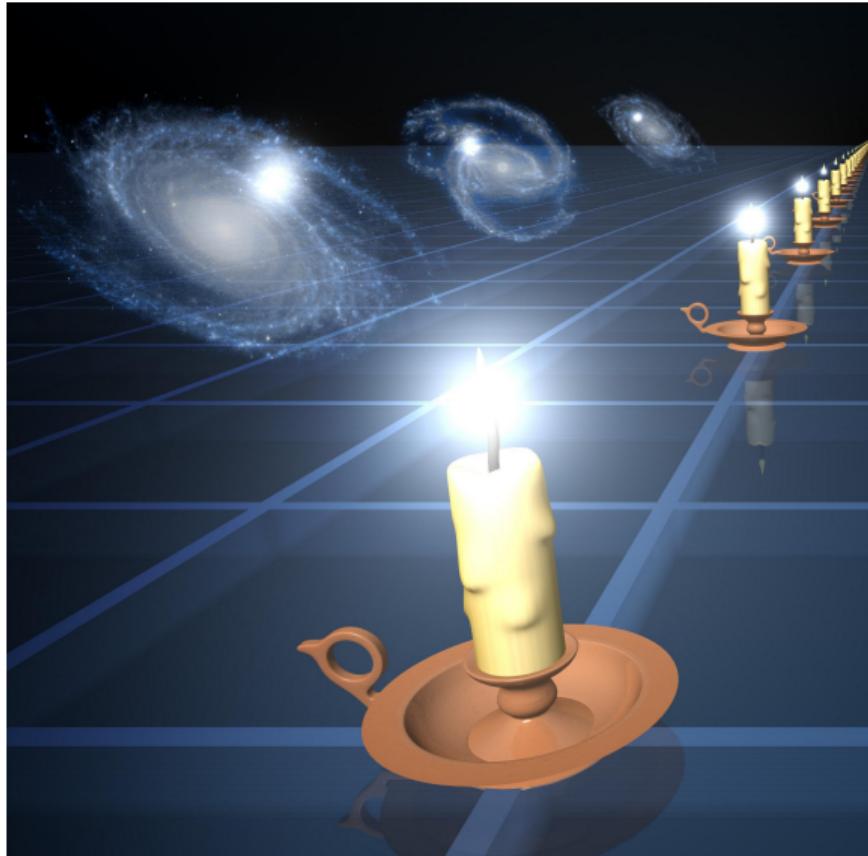
Measuring the Universe

- ▶ How do you know how far away anything is?
 - ▶ Beyond our arms reach (where stereopsis fails), we rely on parallax between objects picked up by slight head motion.
- ▶ 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.



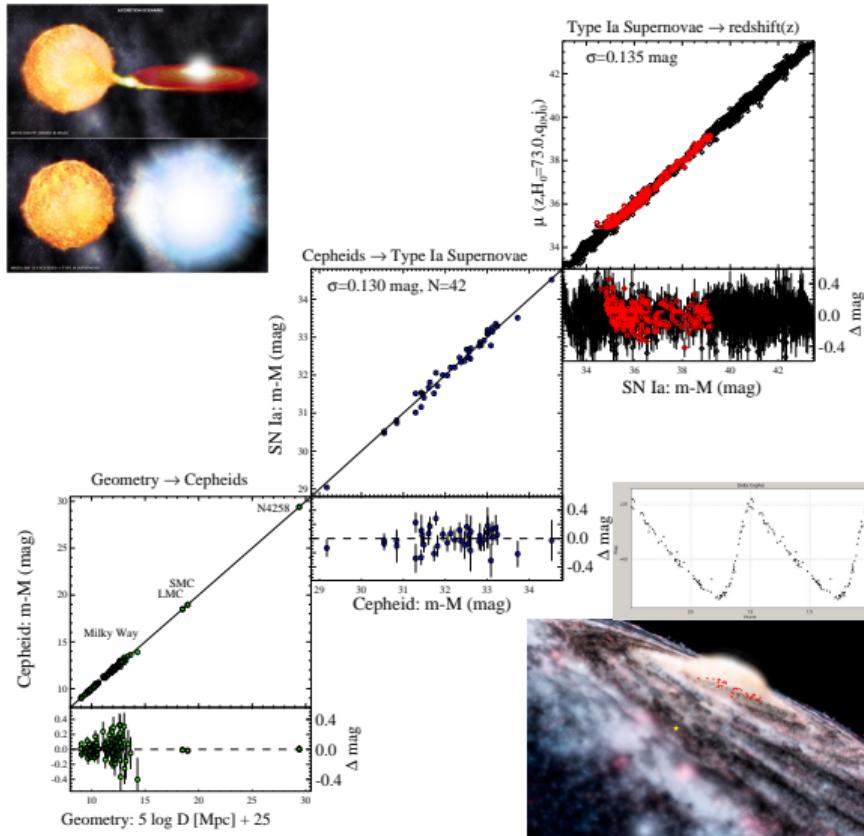
Standard Candles

- ▶ Standard Candles: Objects with known intrinsic luminosity.



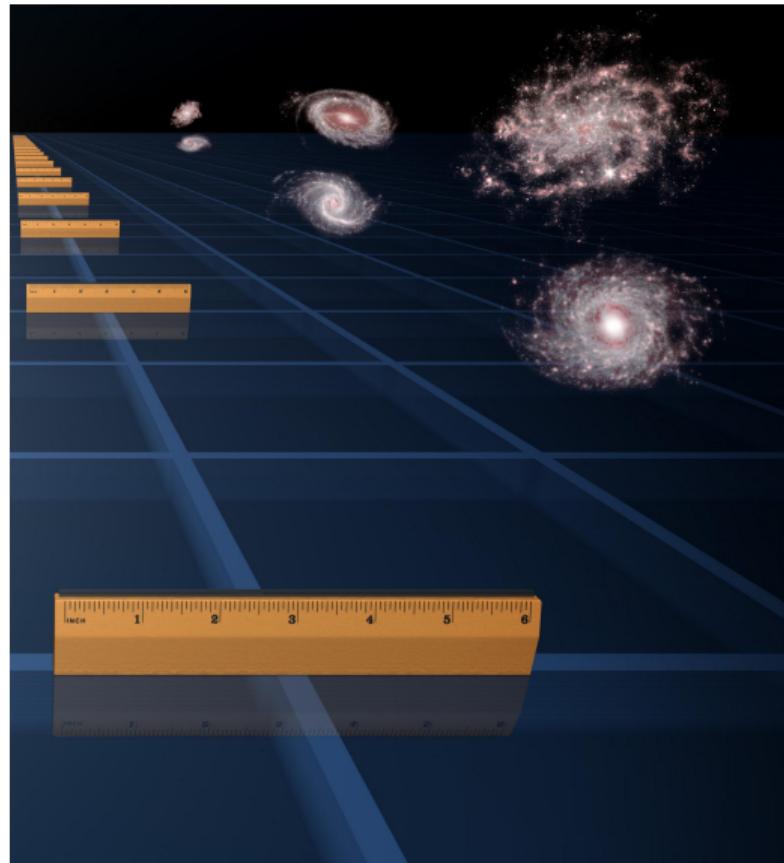
Standard Candles

- ▶ Standard Candles: Objects with known intrinsic luminosity.
- ▶ 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

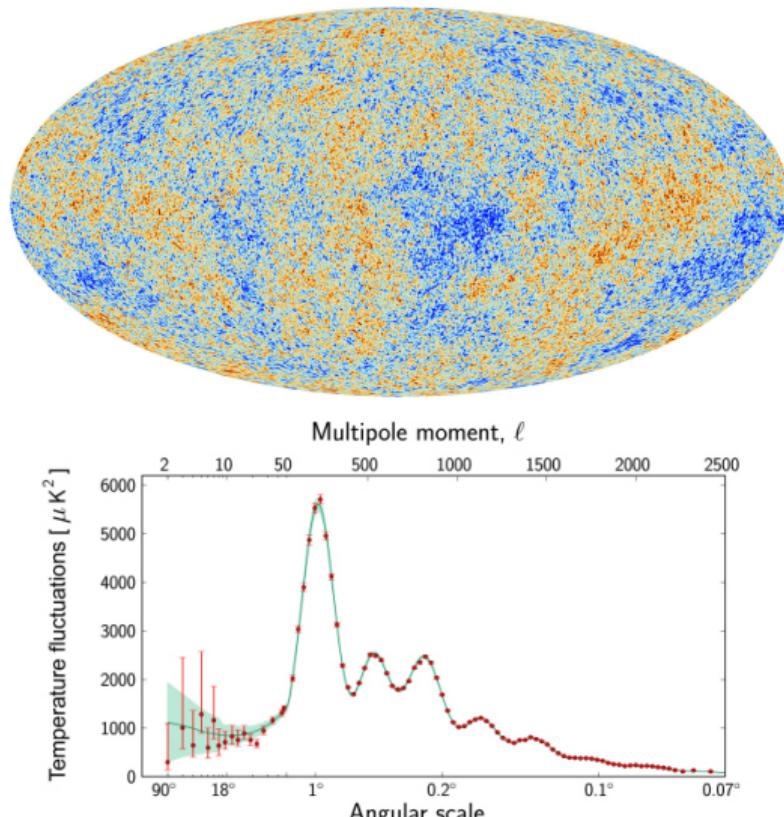
- ▶ Standard Rulers: Objects with known physical size.
- ▶ CMB: Cosmic Microwave Background, fluctuations give a standard ruler at $z \sim 1100$.
[[doi:10.1086/186504](https://doi.org/10.1086/186504)]
- ▶ BAO: Baryon Acoustic Oscillations, sound waves in early universe imprint a standard ruler on galaxy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

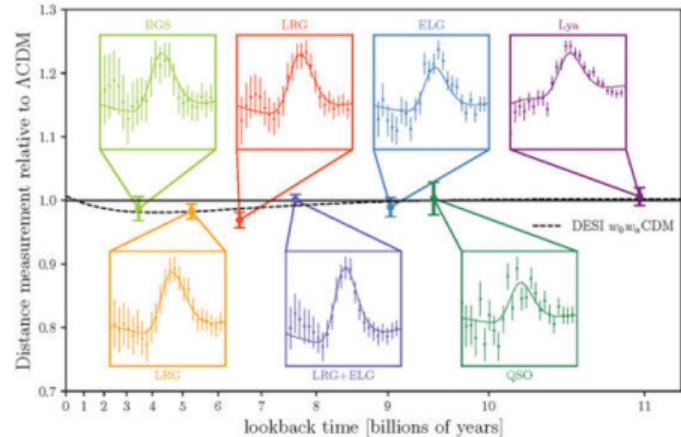
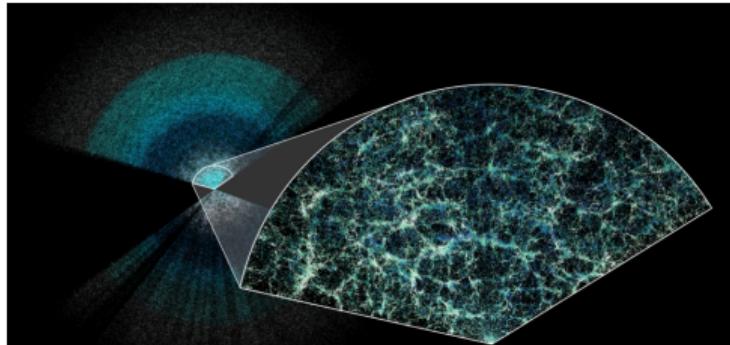
- ▶ CMB: "Surface of last scattering" at $z \sim 1100$.
Angular size of hot/cold spots gives a standard ruler.
[[doi:10.1086/186504](https://doi.org/10.1086/186504)]
- ▶ Temperature fluctuations: $\Delta T/T \sim 10^{-5}$.
[[doi:10.1086/186504](https://doi.org/10.1086/186504)]
- ▶ Polarization: E and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



Standard Rulers

Baryon Acoustic Oscillations

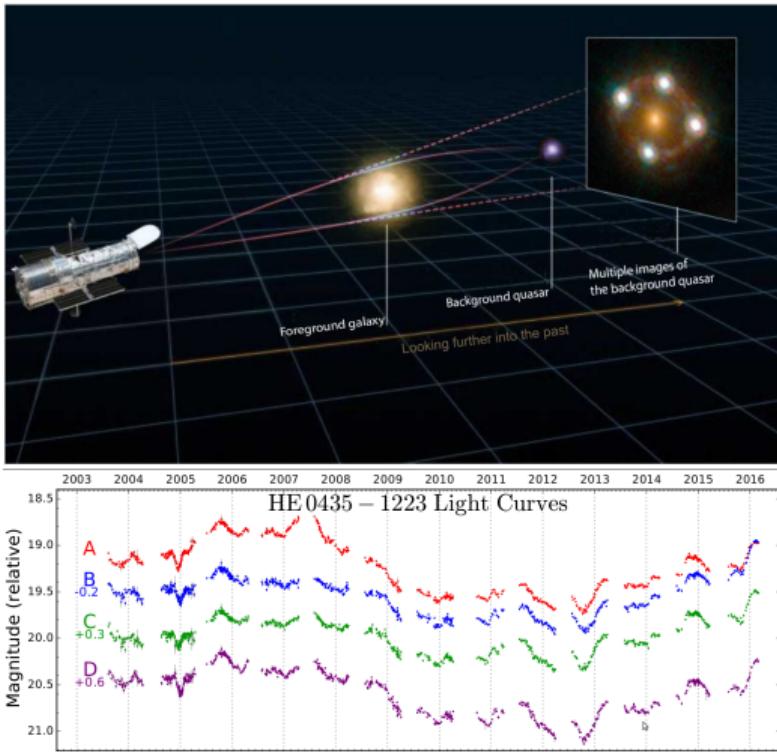
- ▶ BAO: Sound waves in the early Universe imprint a characteristic scale on the distribution of baryons (and galaxies). [1201.2434]
- ▶ SDSS: Sloan Digital Sky Survey, one of the first surveys to measure BAO. [astro-ph/0501171]
- ▶ DESI: Dark Energy Spectroscopic Instrument, current best BAO measurements.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



Standard Rulers

Strong Lensing

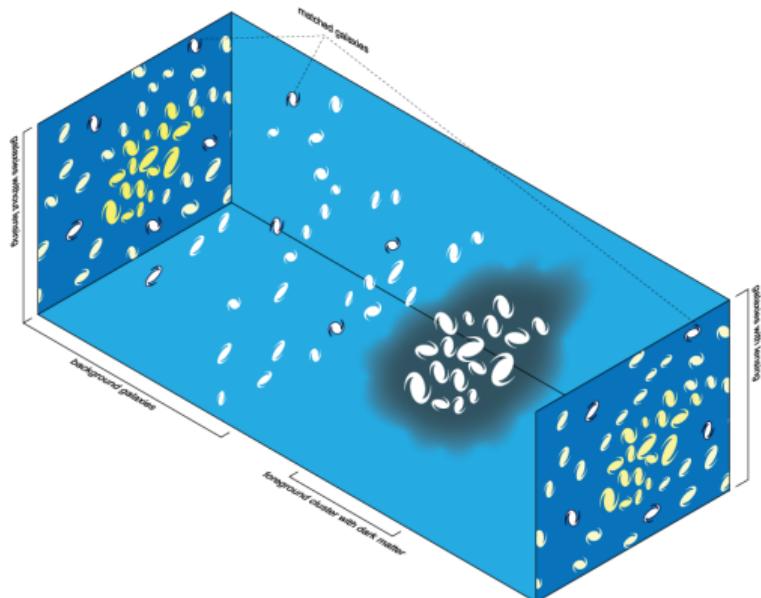
- ▶ Strong Lensing: Light from a distant object is bent by the gravity of a massive foreground object (e.g., a galaxy or galaxy cluster).
[\[doi:10.1093/mnras/128.4.307\]](https://doi.org/10.1093/mnras/128.4.307)
- ▶ Time Delays: Differences in path lengths of multiple images lead to time delays, which can be used to measure distances.
[\[2110.15794\]](https://arxiv.org/abs/2110.15794)



Standard Rulers

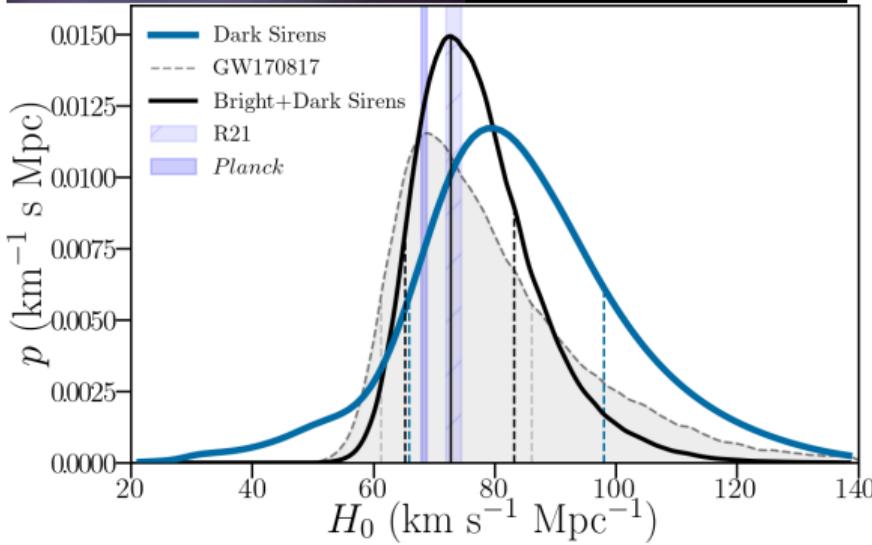
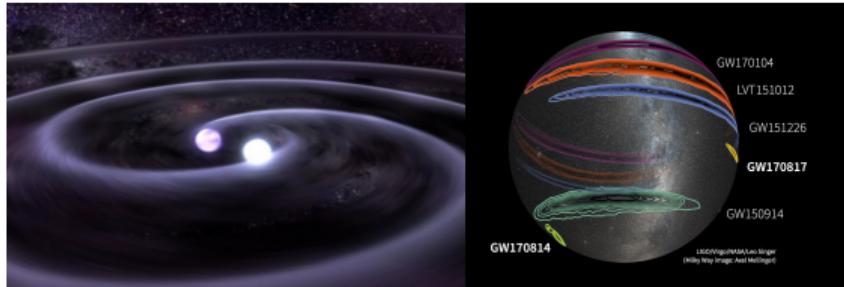
Weak Lensing

- ▶ 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]



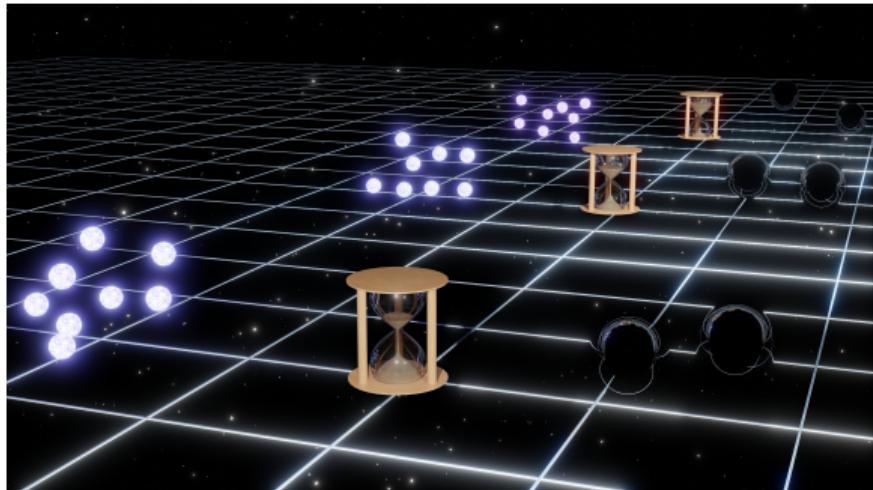
Standard Sirens

- ▶ 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]



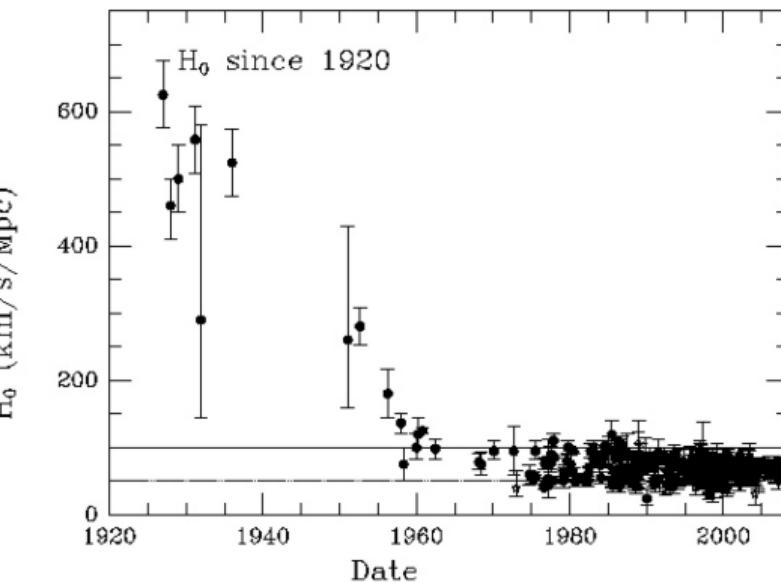
Standard Clocks

- ▶ 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: $H_0 = 67.4 \pm 0.5 \text{ km/s/Mpc}$.
[1807.06209]
- ▶ SH₀ES: $H_0 = 73.2 \pm 1.3 \text{ km/s/Mpc}$.
[2112.04510]
- ▶ Exciting if not measurement error
 - ▶ People trust the CMB measurement, but perhaps not the Λ CDM 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) ± 1.8
SH0ES (Riess) (73.4, 72.1, 72.2) ± 2.2
[2408.06153][2408.11770]



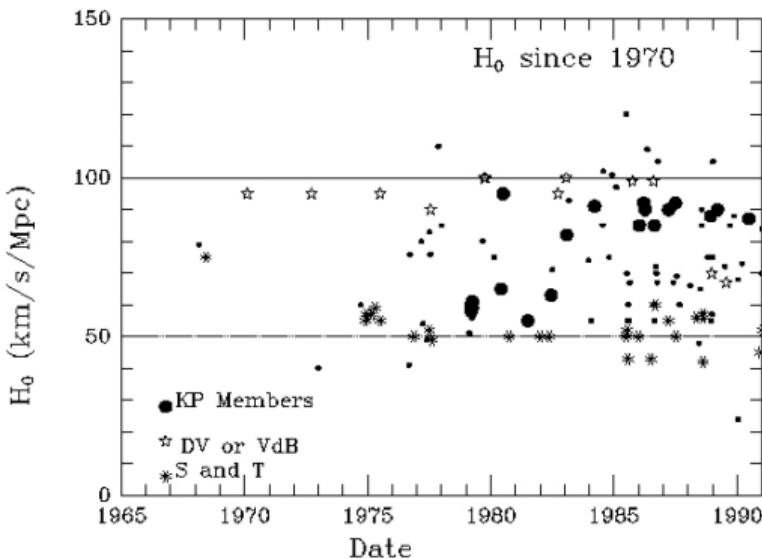
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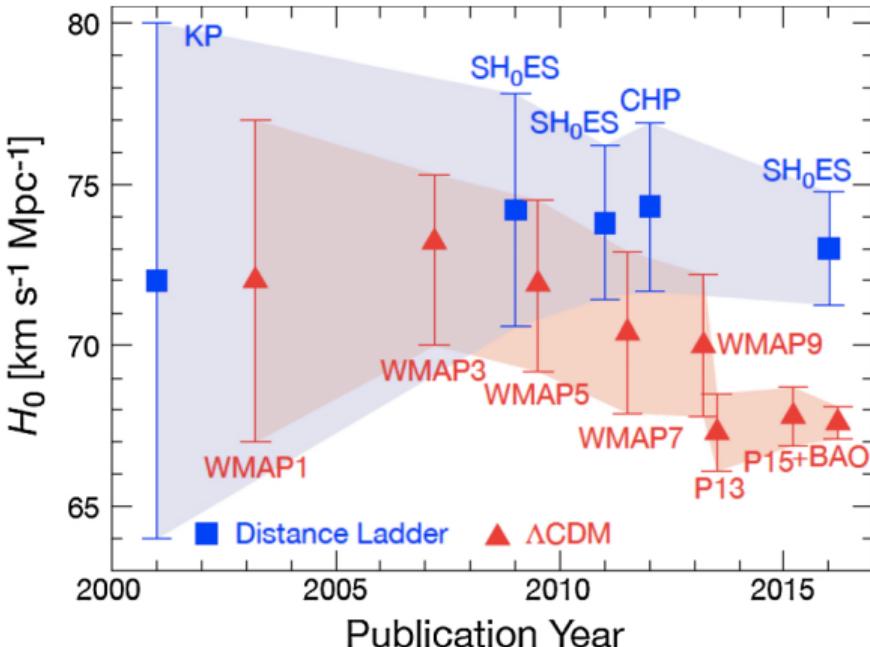
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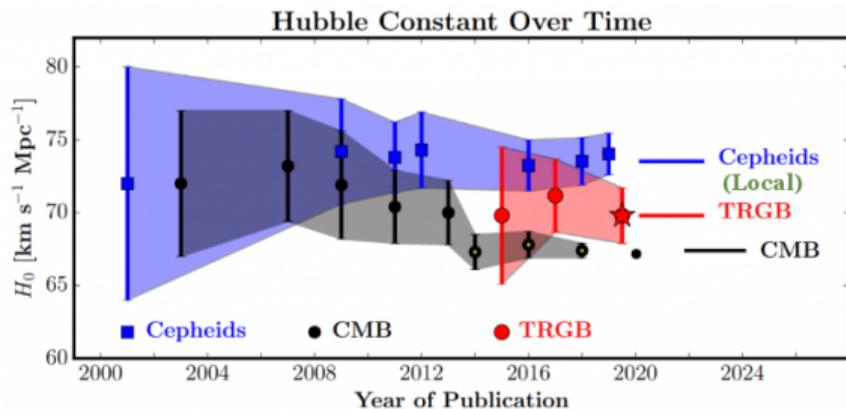
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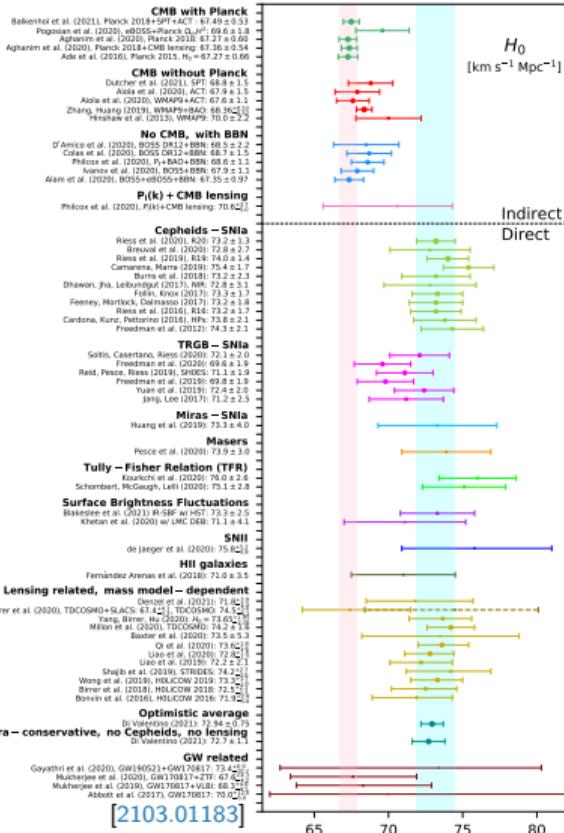
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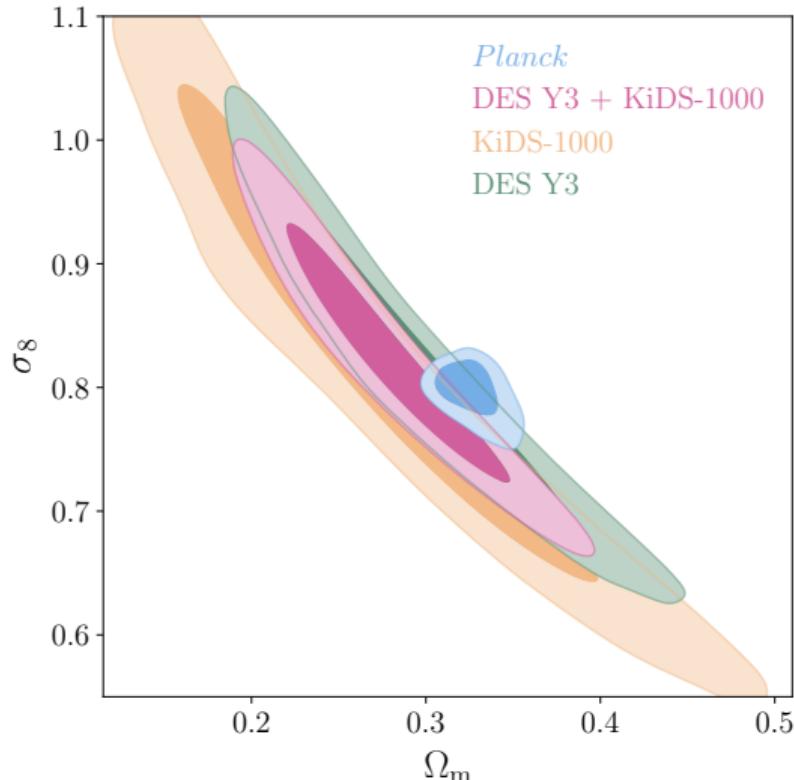
[<wh260@cam.ac.uk>](mailto:wh260@cam.ac.uk)

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The S_8 tension

aka σ_8 /weak lensing tension

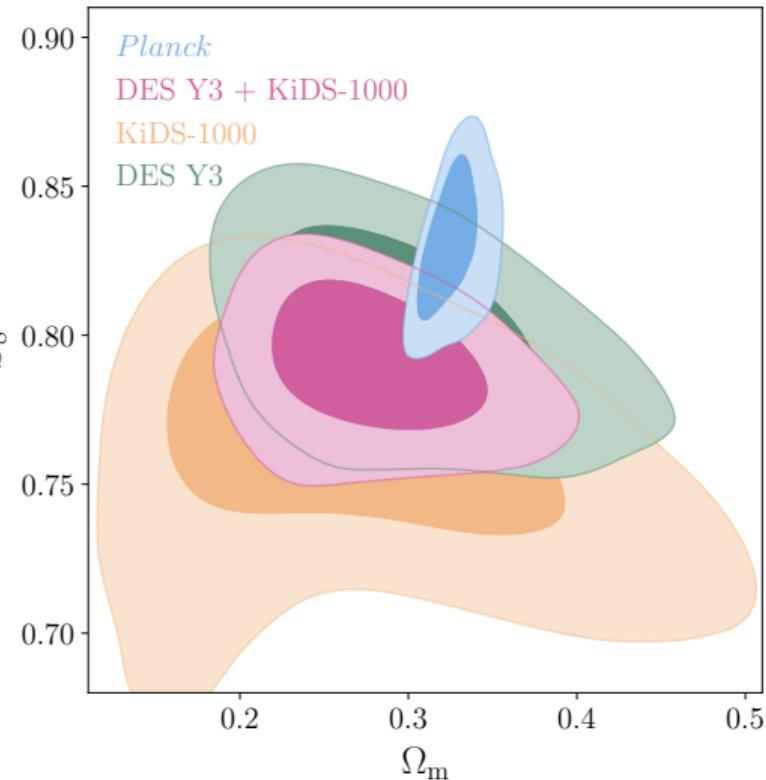
- ▶ S_8 quantifies the amplitude of matter fluctuations on large scales.
- ▶ $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$.
- ▶ CMB: $S_8 \approx 0.834$. [1807.06209]
- ▶ Weak lensing: $S_8 \approx 0.76$. [1610.04606][1910.05336]
- ▶ Tension at the $2 - 3\sigma$ level.
- ▶ Possible systematics in weak lensing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



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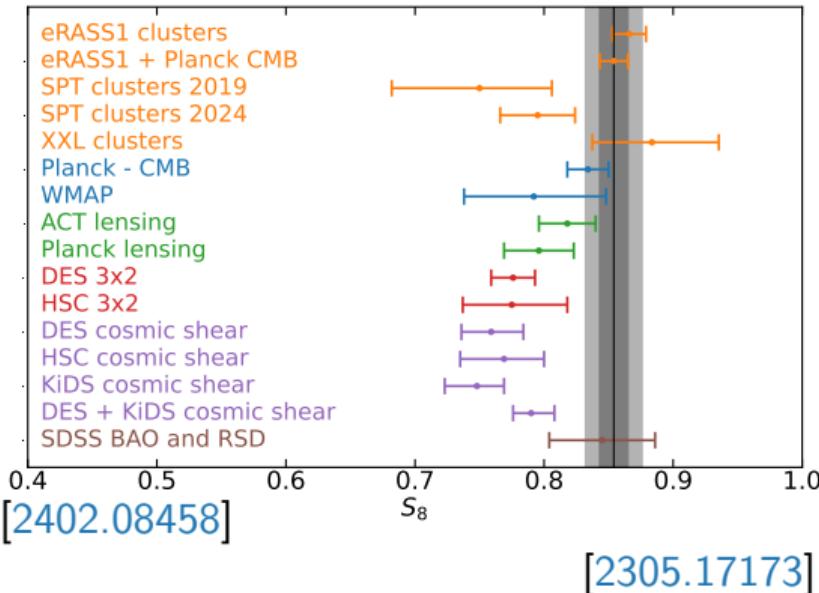
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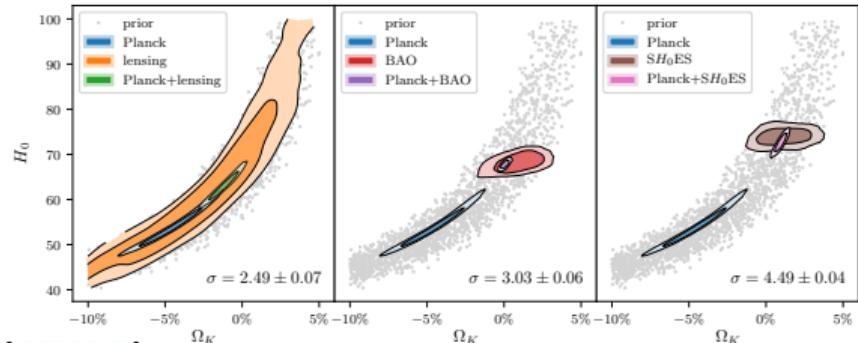
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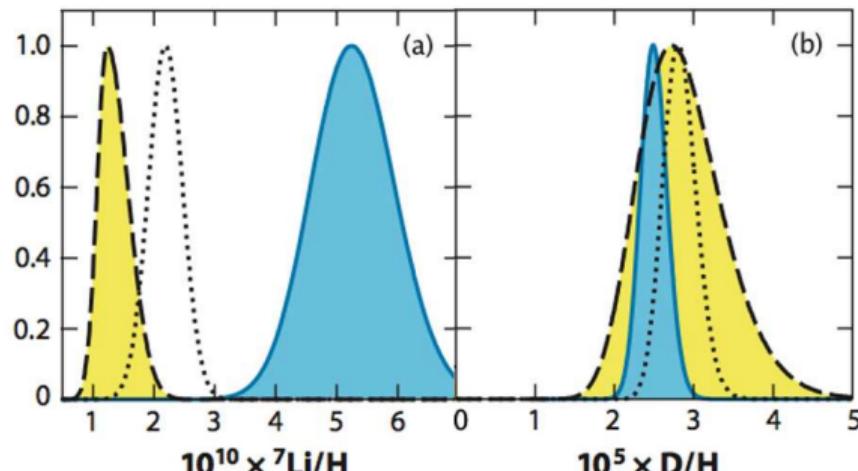


Other Tensions and Anomalies

- ▶ 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]



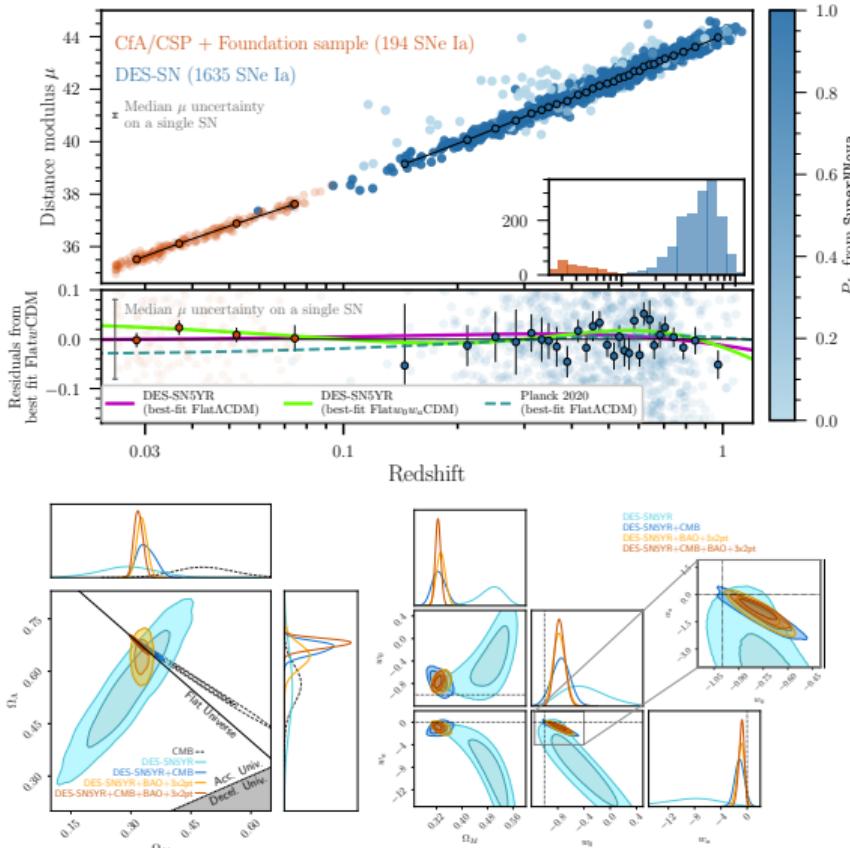
Cosmology in 2024

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

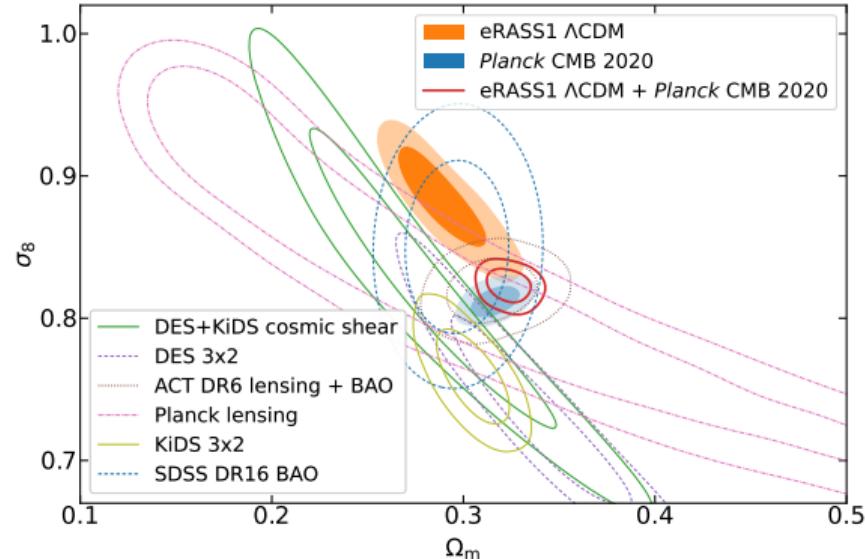
Jan DESY5 SNe: Improved supernova measurements from the Dark Energy Survey.
[2401.02929]

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 $\sim 12,000$ galaxy clusters, providing a powerful new dataset for cosmology.
- ▶ Results broadly consistent with Λ CDM, but with some hints of tension in σ_8 , but in the wrong direction! [2402.08458]



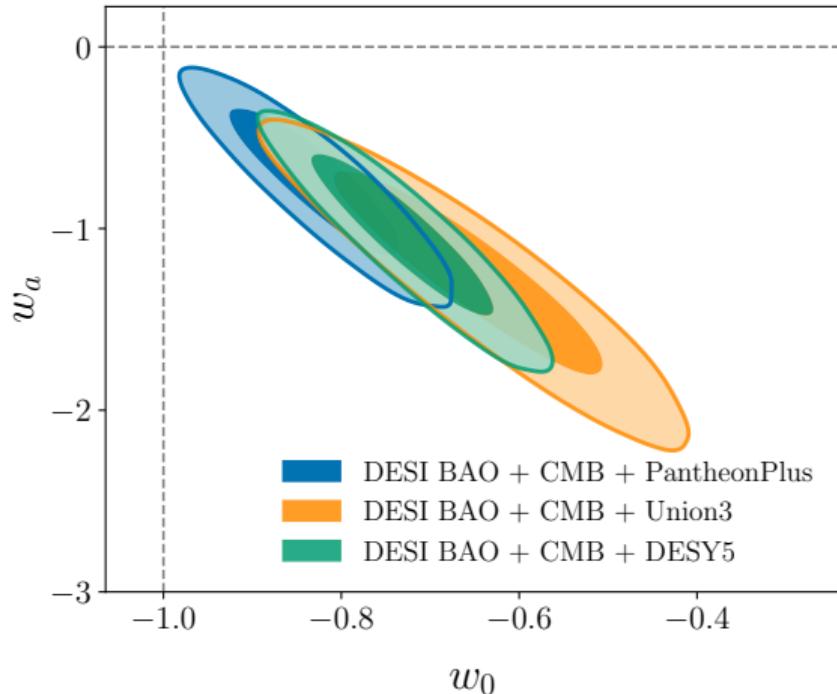
DESI

- ▶ DESI is a BAO survey, so measures $r_d H_0$, not H_0 directly, but agrees with other ‘early time’ probes.
- ▶ Full BAO and BBN analysis yields $H_0 = 68.53 \pm 0.80 \text{ km/s/Mpc}$ (independent of CMB). [2404.03000]
- ▶ First year cosmology results have tentatively exciting results – possible evidence for evolving dark energy. [2404.03002]

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

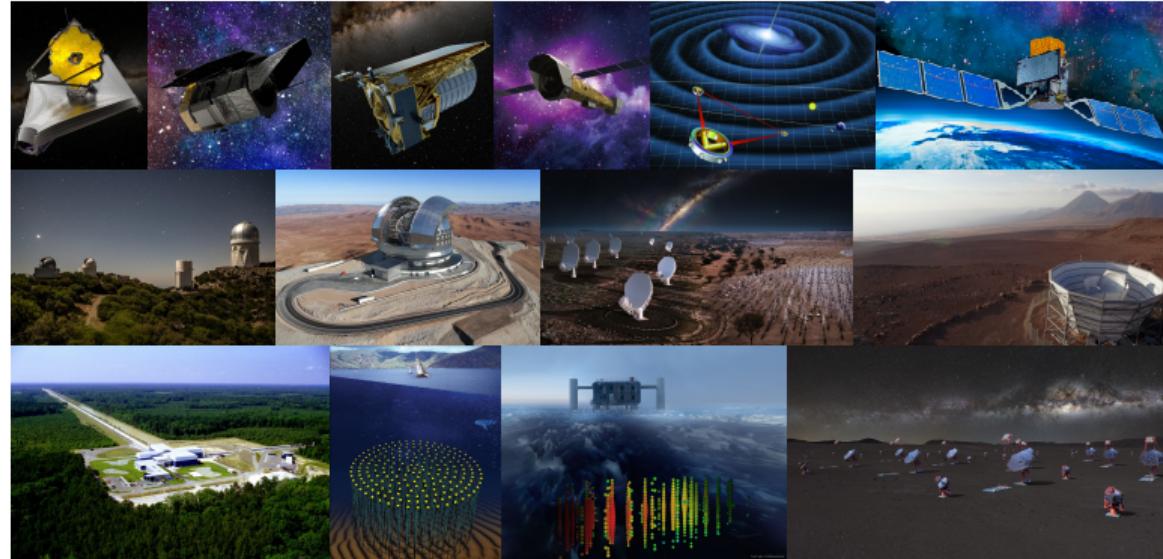
$$w_a \neq 0, \quad w_0 \neq -1$$

- ▶ Watch this space in 2025!



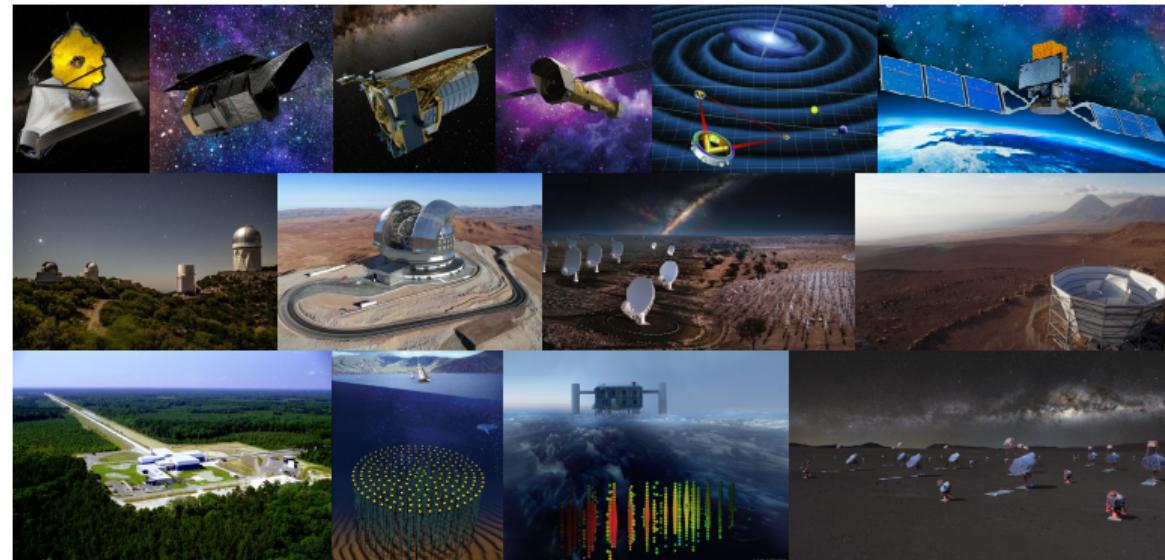
What to watch out for

- ▶ 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.



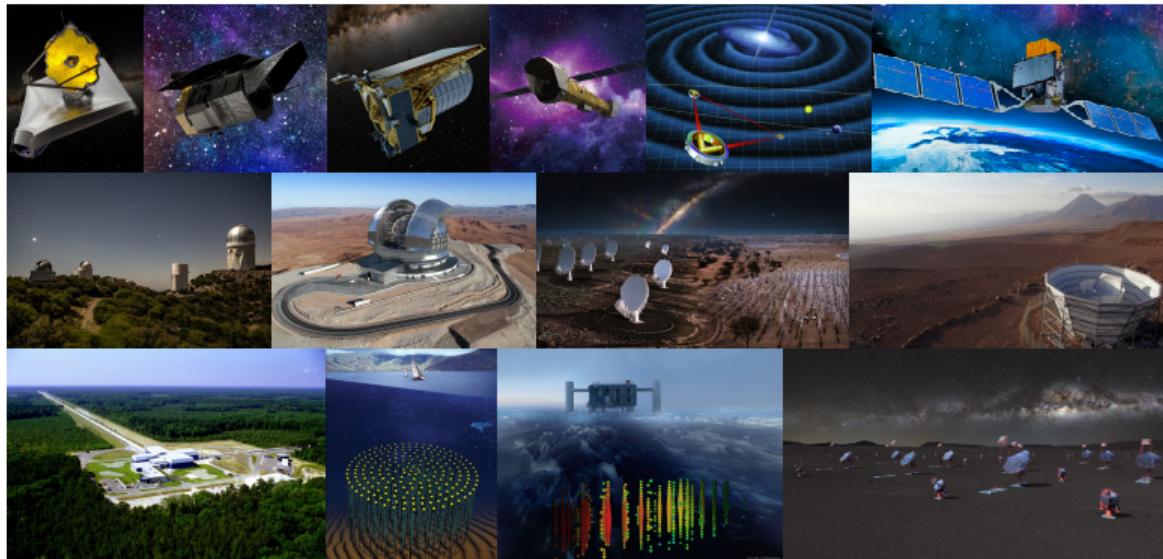
What to watch out for

- ▶ 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.



Where do I fit



github.com/handley-lab/group

- ▶ I was on *Planck*
- ▶ I'm an astrostatistician
- ▶ My model comparison theory & codes underpin several of the teams pipelines above
- ▶ My current research interest is into trying to remove “modelling systematics” with Simulation Based Inference
- ▶ Also developing tools that are flexible enough to be able to combine the next generation of data at speed (e.g. GPU/jax capable cosmology codes).
- ▶ I have a side-line interest in theory (in particular Poincare Gauge Theory gravities).