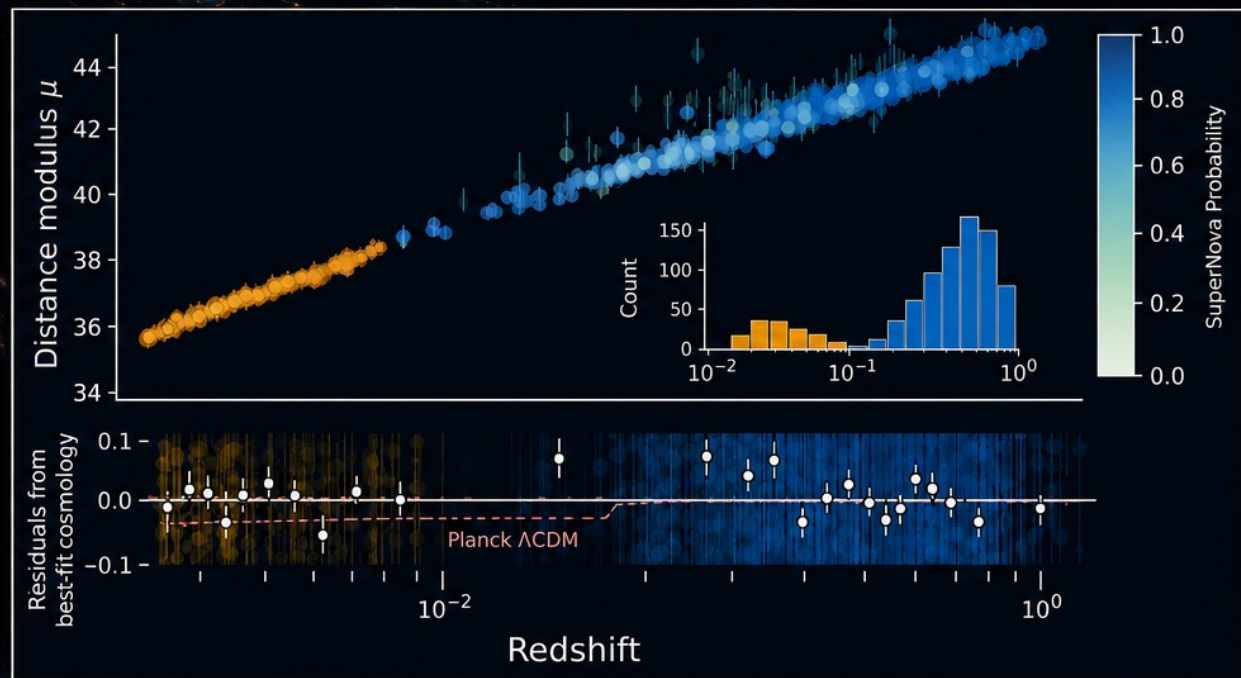
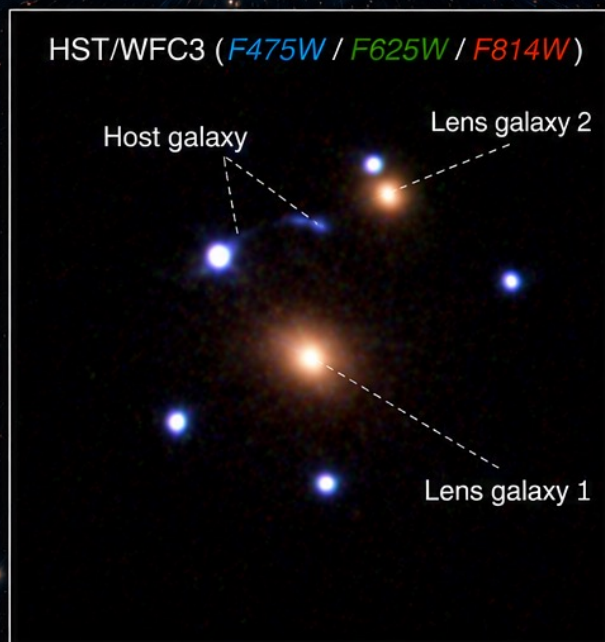
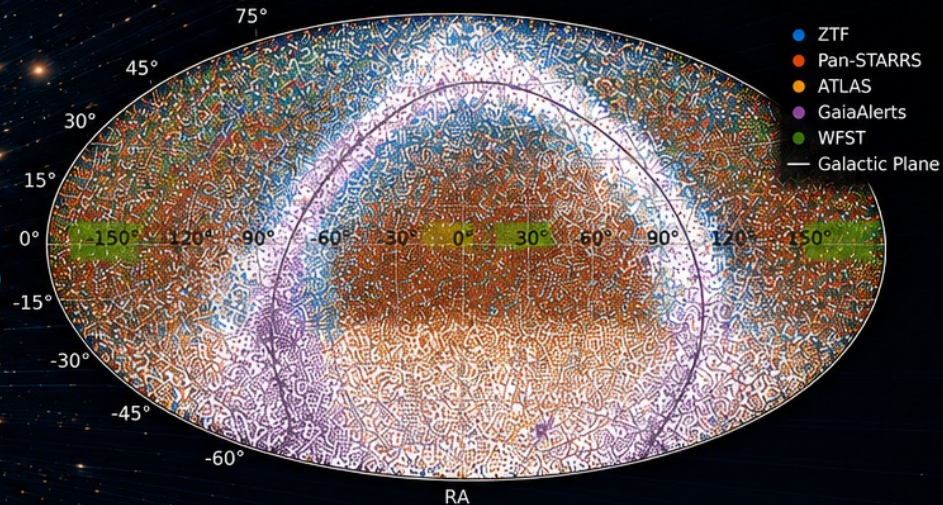


SN COSMOLOGY

IN THE ERA OF LARGE SURVEYS



Big Questions in Cosmology

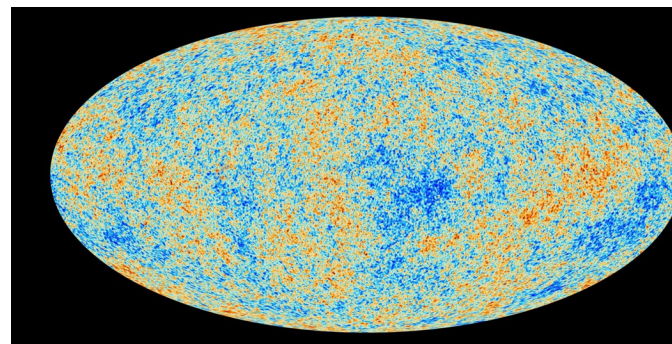
Spectacular developments in observations

- Initial condition of the Universe

- Dark matter

- Dark energy

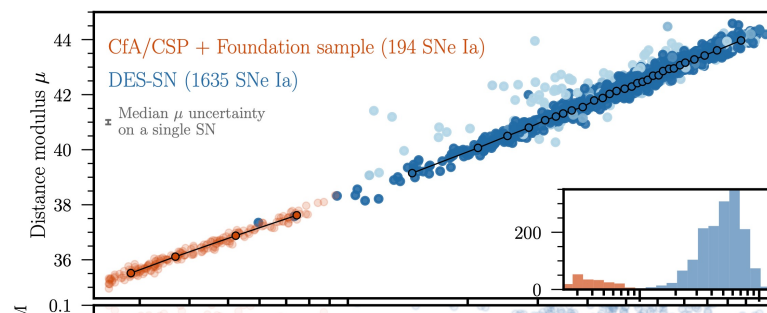
CMB



BAO



SNIa



Big Questions in Cosmology

Spectacular developments in observations
Limited guidance from fundamental theory

■ Initial condition of the Universe

- Inflation?

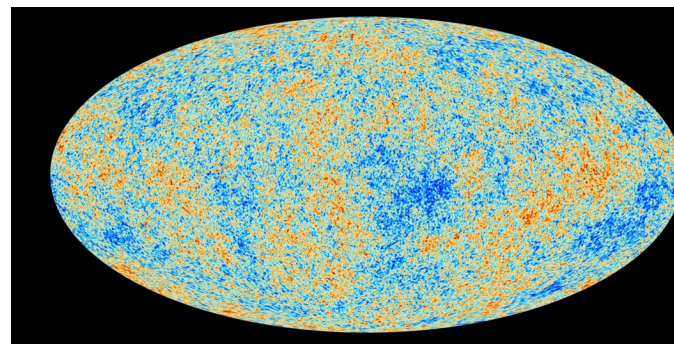
■ Dark matter

- Particle nature?
- Modified Gravity?

■ Dark energy

- Cosmological constant?
- Dynamical field?
- Modified gravity?

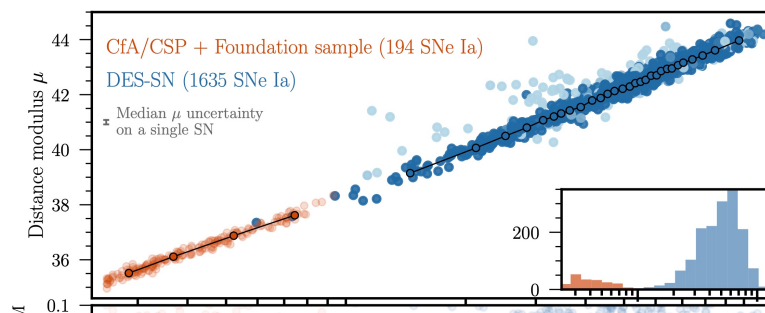
CMB



BAO



SN Ia



Big Questions in Cosmology

Spectacular developments in observations
Limited guidance from fundamental theory

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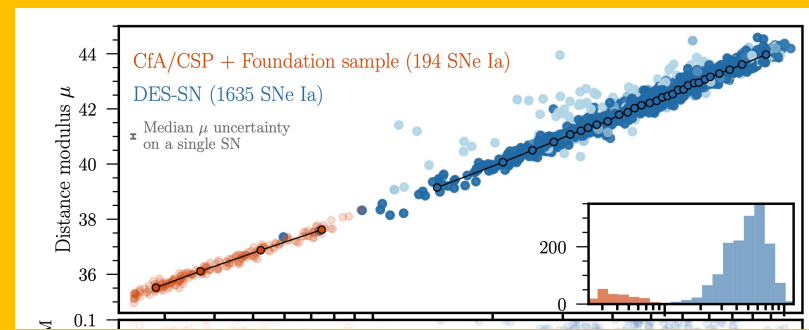
■ Dark matter

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SNIa

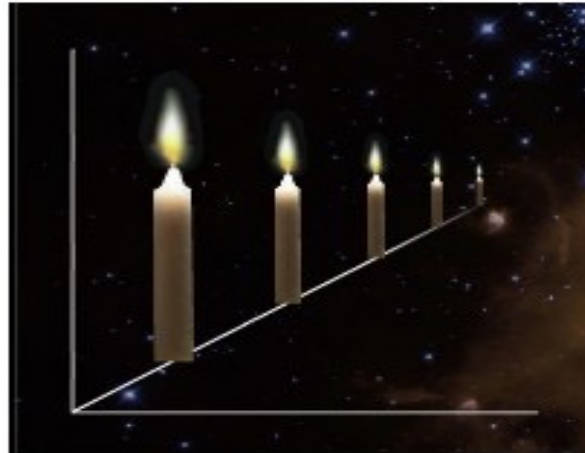


Tensions as pathfinders?

Λ CDM Standard model of cosmology challenged ?!

- **Hubble tension:** SNIa distance ladder calibrated with Cepheids by SH0ES team (Riess+22) finds 5σ deviation from early Universe inference of H_0
- DESI + CMB + SNe Ia, finds hints for *time-dependent dark energy equation of state, $w(t)$* , i.e., in possible tension with Cosmological Constant

Preamble: relative and absolute SNIa distances



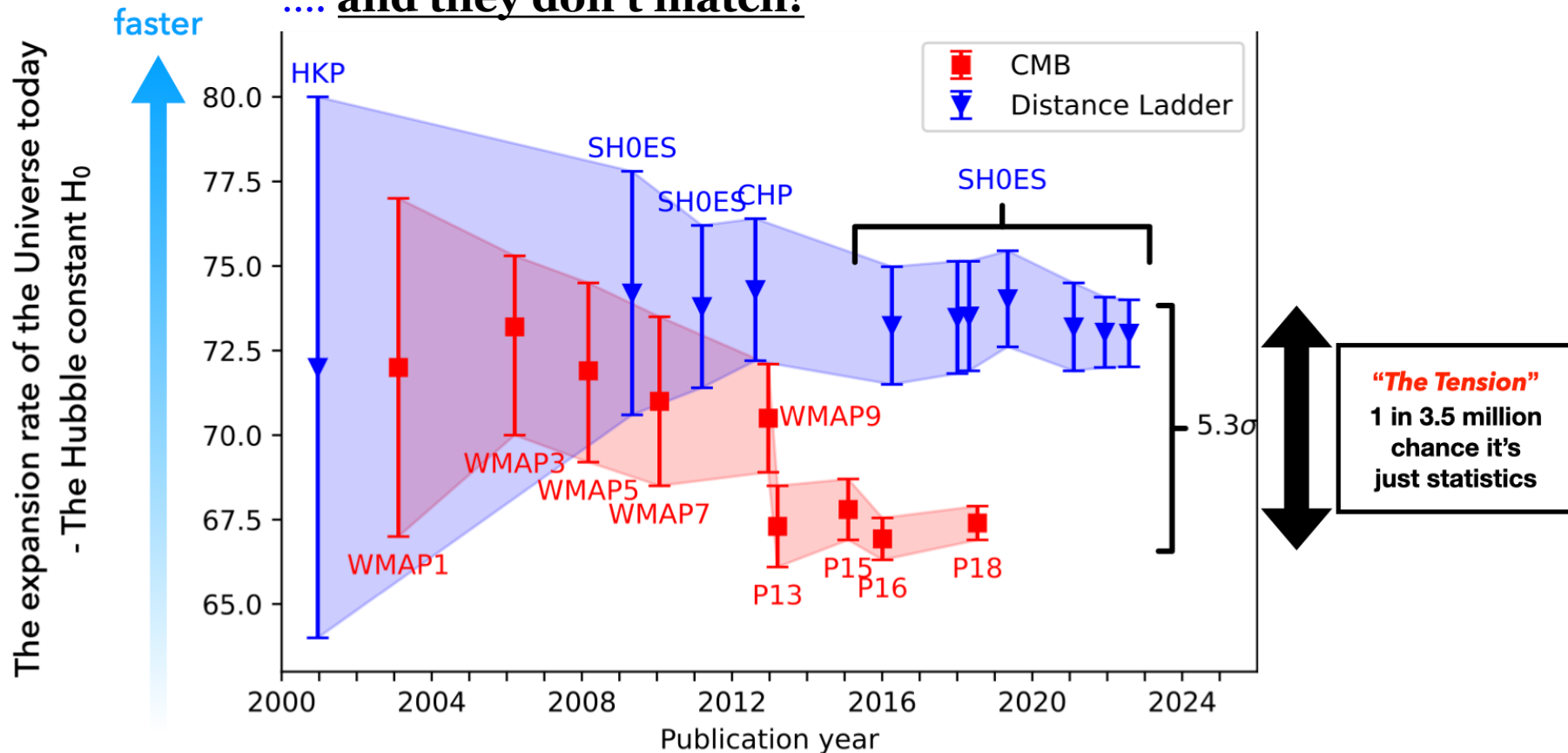
- Measuring H_0 involves measuring *absolute distances* (e.g., local distance ladder) or *time differences* (time-delay cosmography), i.e., *dimensionful quantities*
- Instead, the cosmic density parameters, Ω_M , Ω_Λ , Ω_K , w , are dimensionless, can therefore be inferred with *dimensionless measurements* i.e., relative distances vs redshift.

The *Hubble tension*

There are two ways to measure the current expansion rate, H_0

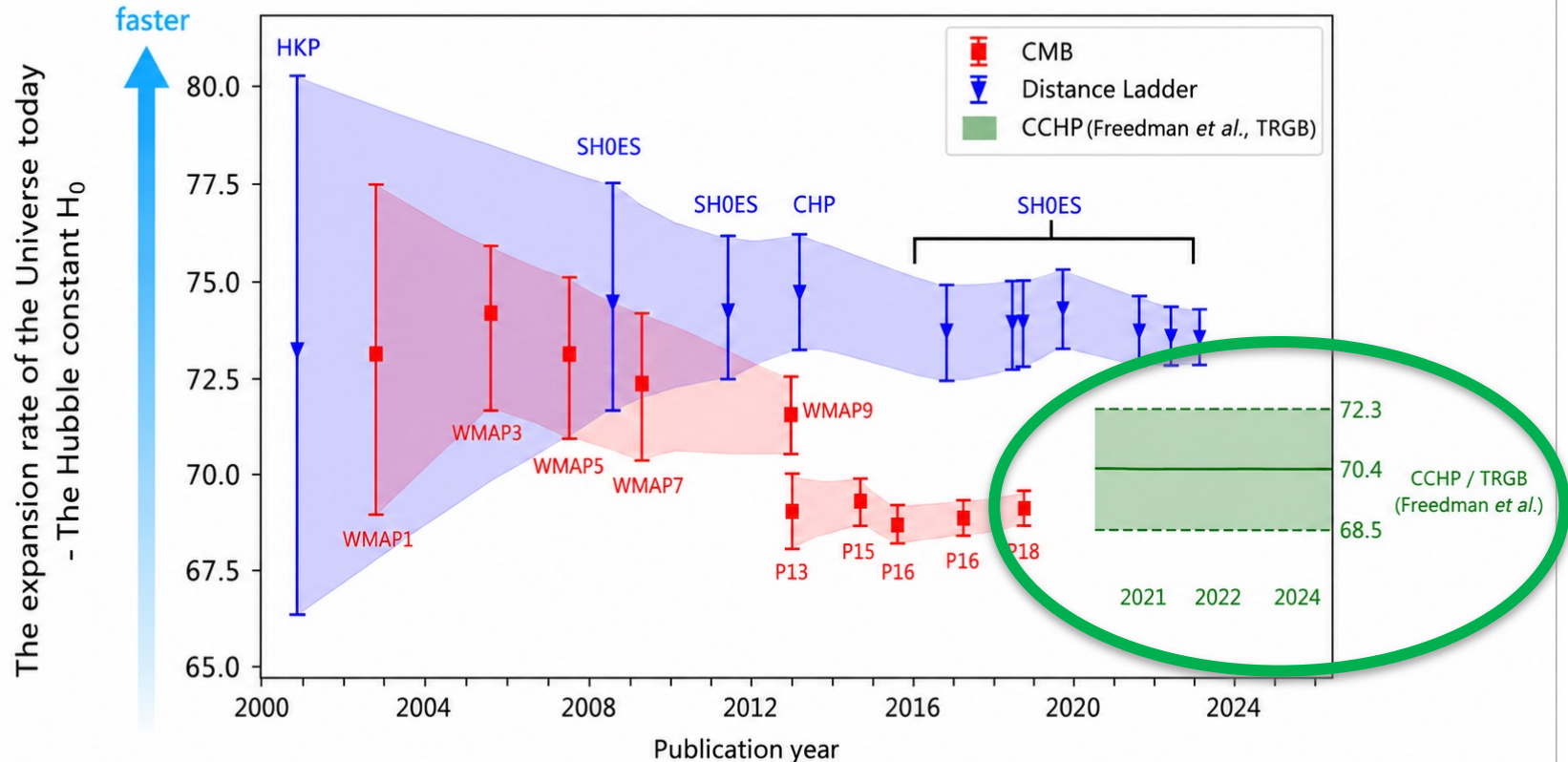
- 1) with the **local distance ladder**
- 2) From **early universe observations**, extrapolated to the present with **Λ CDM**

.... **and they don't match!**



Distance ladder tension?

Significance of tension challenged by the CCHP team, that uses TRGB distances to calibrate the SNe Ia luminosities
Is it a cosmology or an **astrophysics, selection effects, calibration, priors,..., issue?**



Jury still out...

Exploring evolution of the density of Dark Energy

- *Time dependent Dark Energy* equation of state,

$w(a) = \frac{p_{DE}}{\rho_{DE}}$, where a is the scale factor of expanding universe

$$\rho_{DE} = \rho_{DE}^0 a^{-3(1+w)}$$

for $w = -1$, constant density, i.e., compatible with Einstein's cosmological constant ($=\Lambda$). Alternative models of DE parametrized through $w \neq -1$.

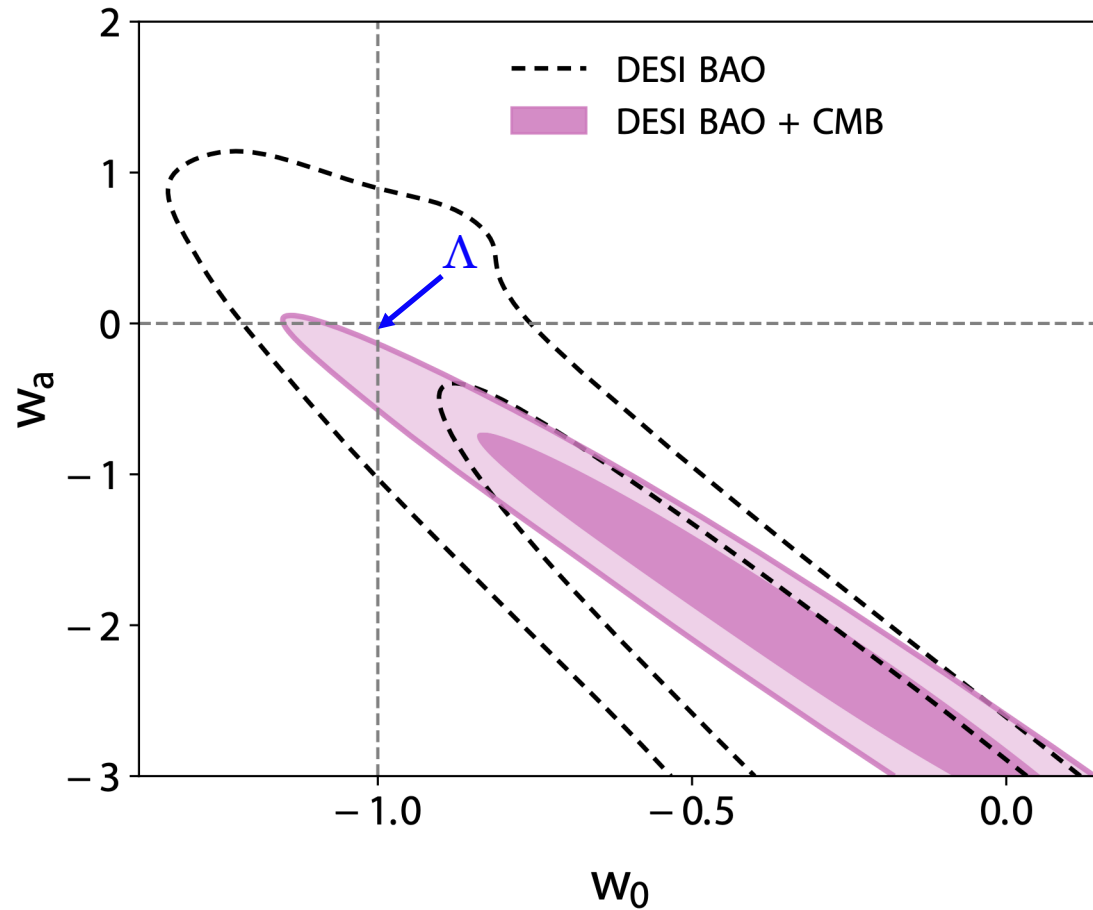
- It is customary to fit either a constant w , or give it more flexibility:

the CPL parametrization $w = w_0 + (1 - a)w_a$

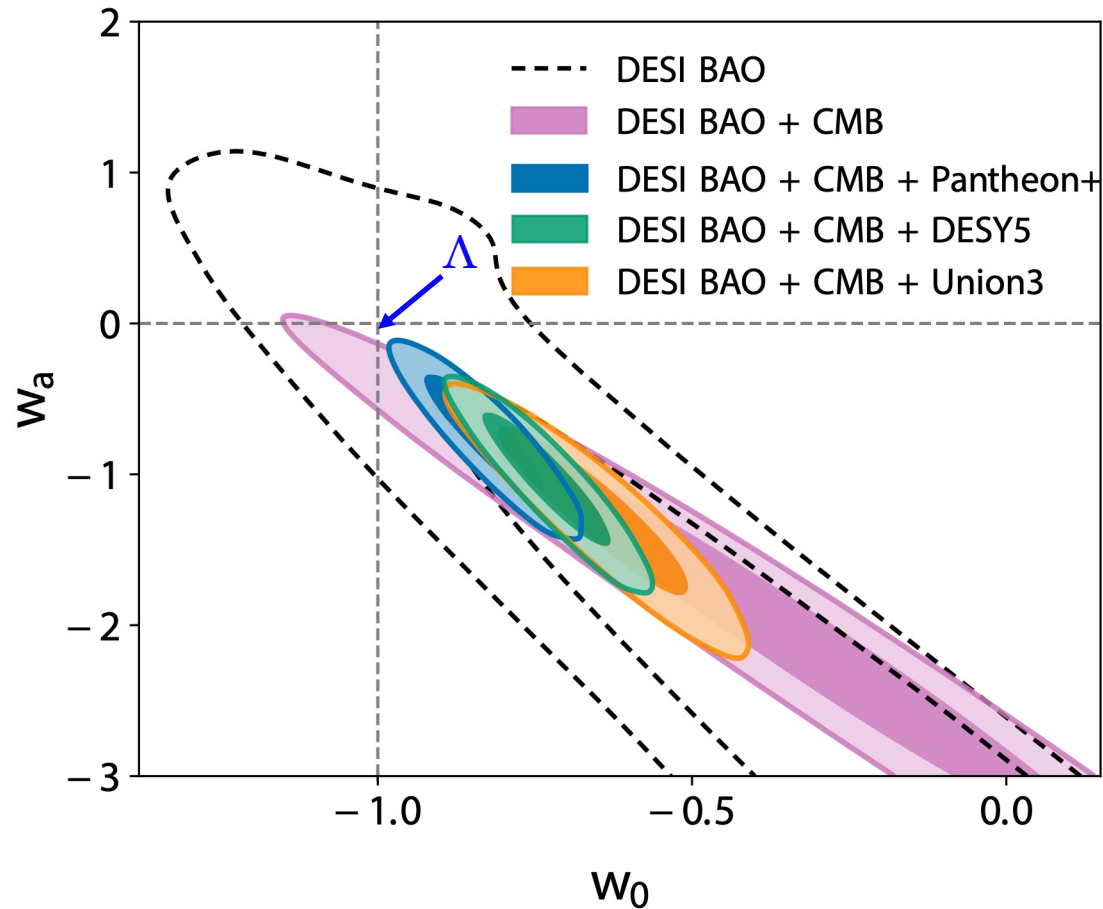
- CPL *has no direct physical motivation*, just simplicity

$w = w_0$ at present and $w = w_0 + w_a$ for $z \rightarrow \infty$

Evidence for dynamic dark energy?!

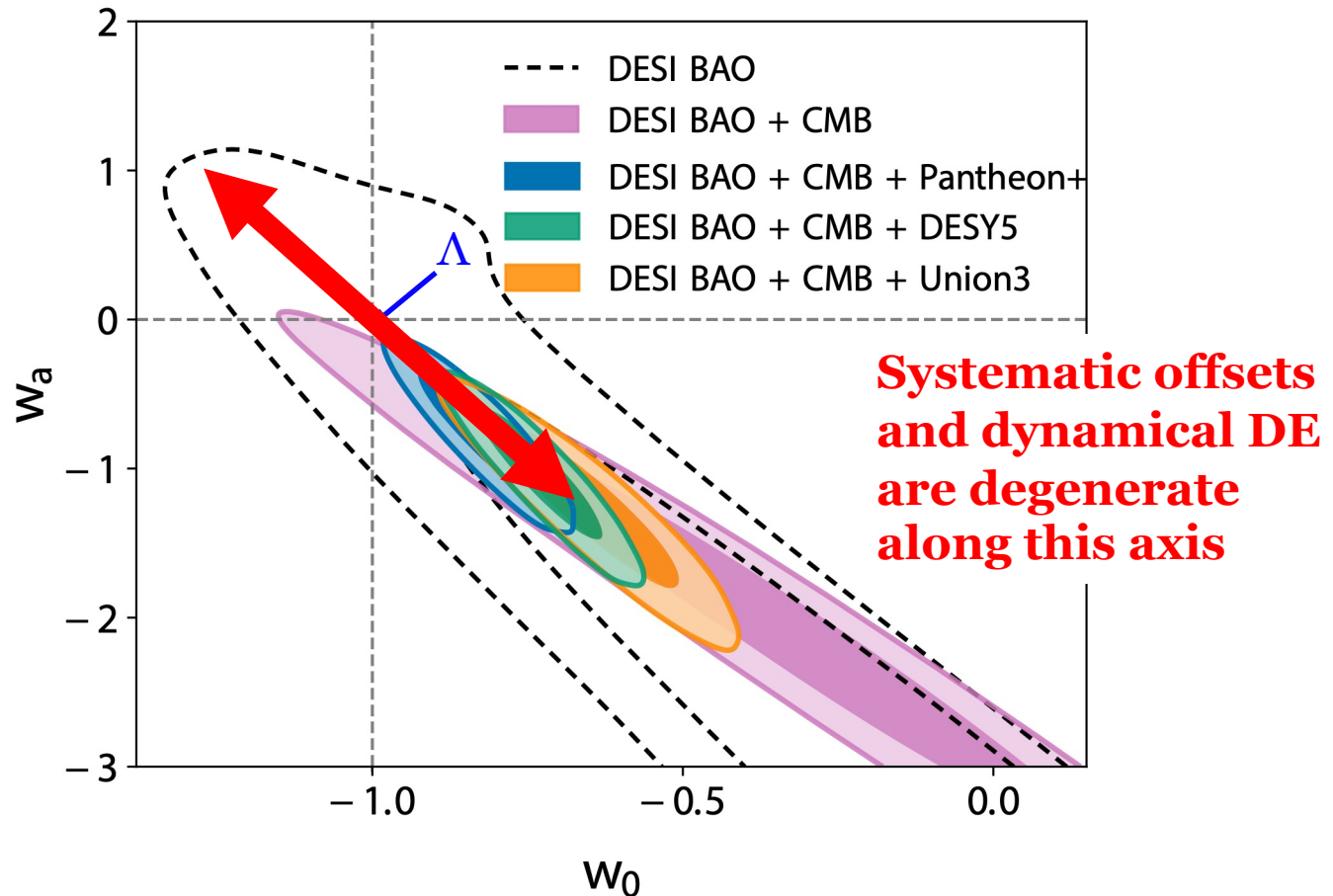


Evidence for dynamic dark energy?!

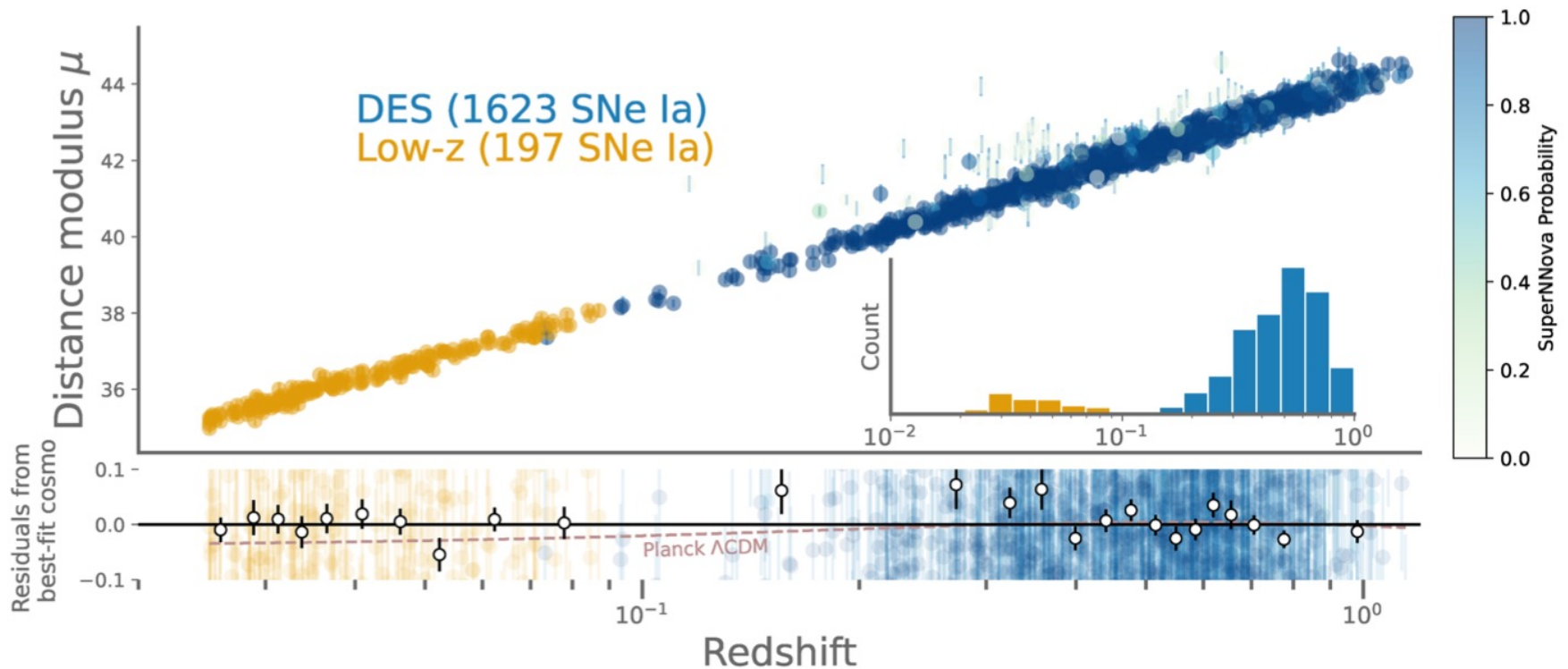


Shift from Λ CDM along the major axis
of uncertainties: any unaccounted
systematic effect will lead to bias along
that line

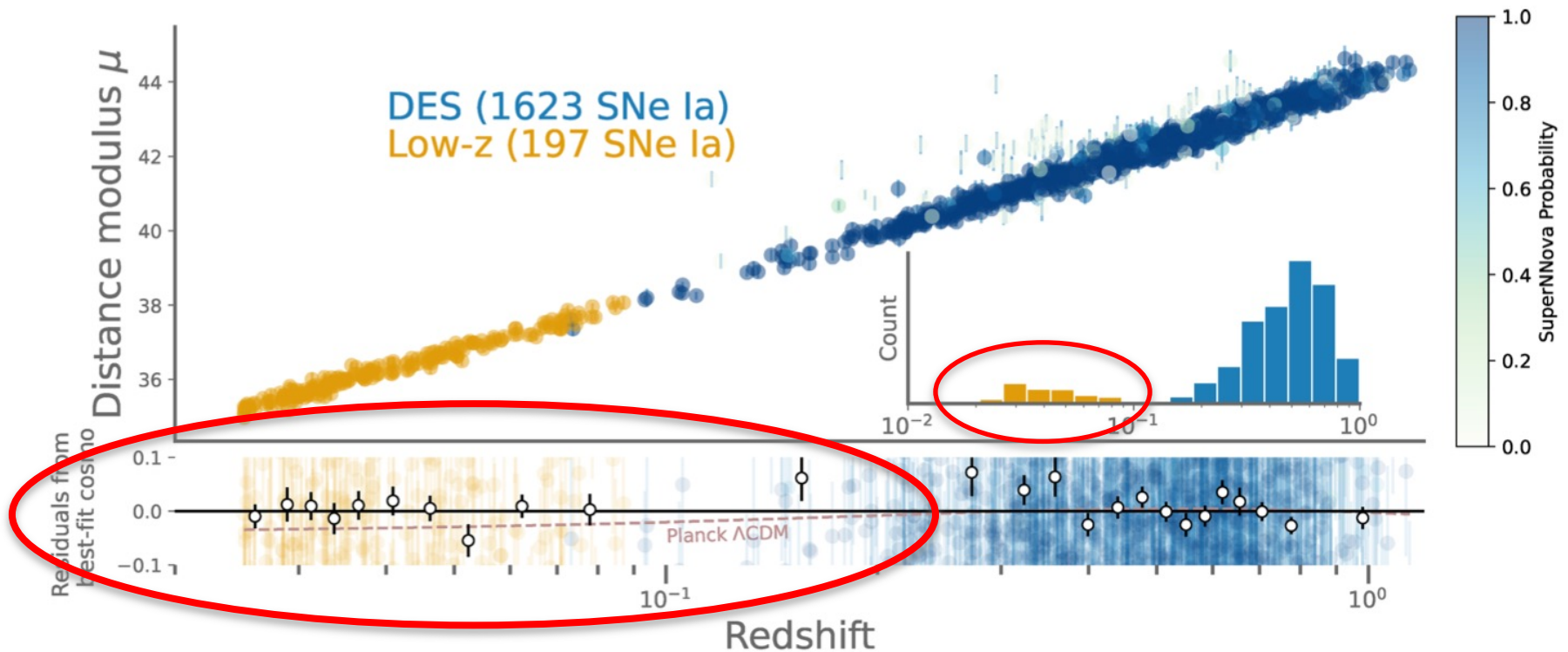
12



Very small effects – primarily at low- z where the sample is small
– and old!



Very small effects – primarily at low- z where the sample is small – and old!



~ 0.03 mag

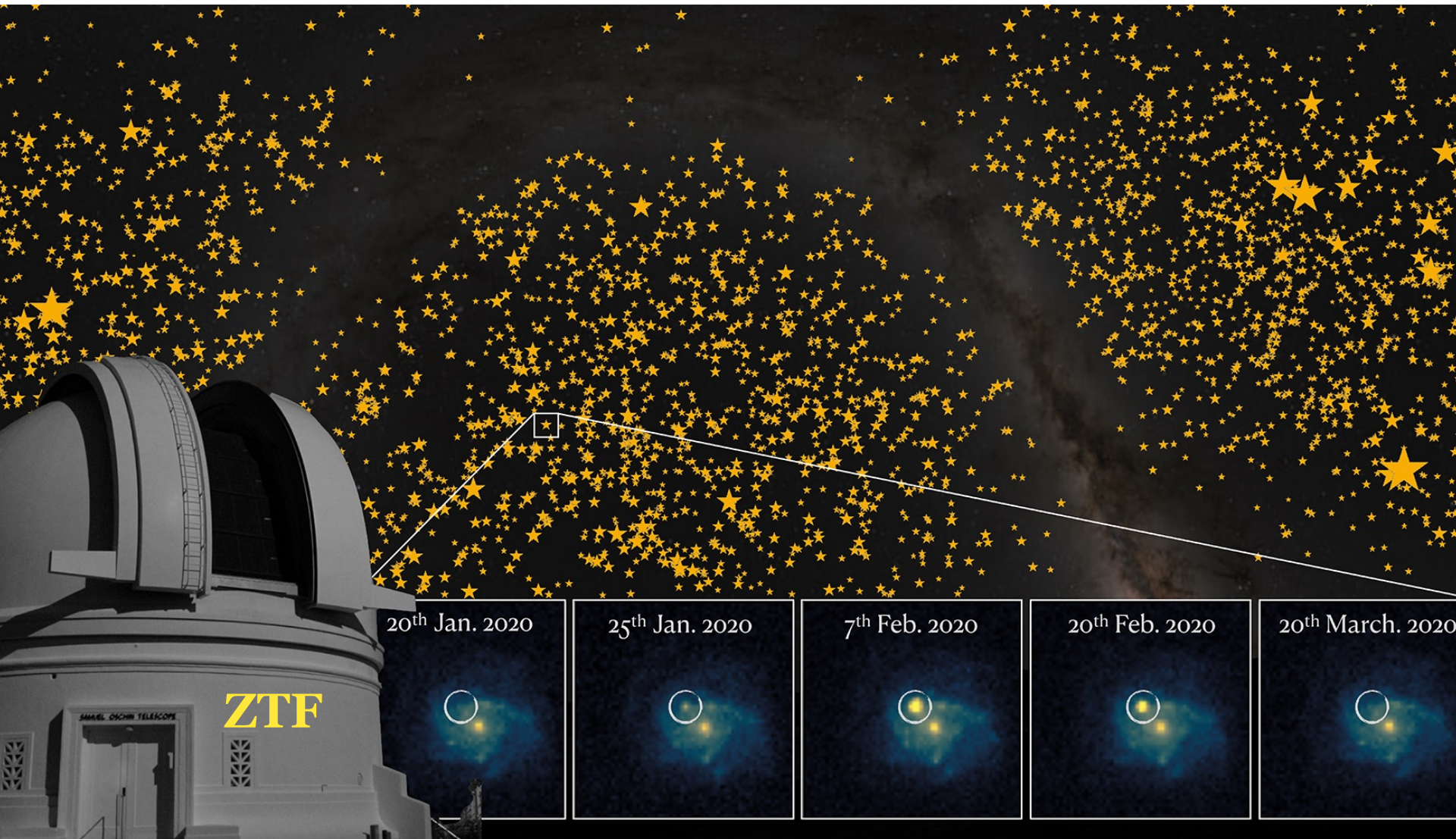
Popovic+25

Tensions as pathfinders?

Λ CDM Standard model of cosmology challenged ?!

- Both tensions rely on the same old low- z SNIa samples, not (all) collected with sub-% cosmology precision in mind!

The new era: ZTF ~ 10 classified SN/night¹⁶
since 2018, 2/3 are SNe Ia



>10000 classified SNe Ia to date

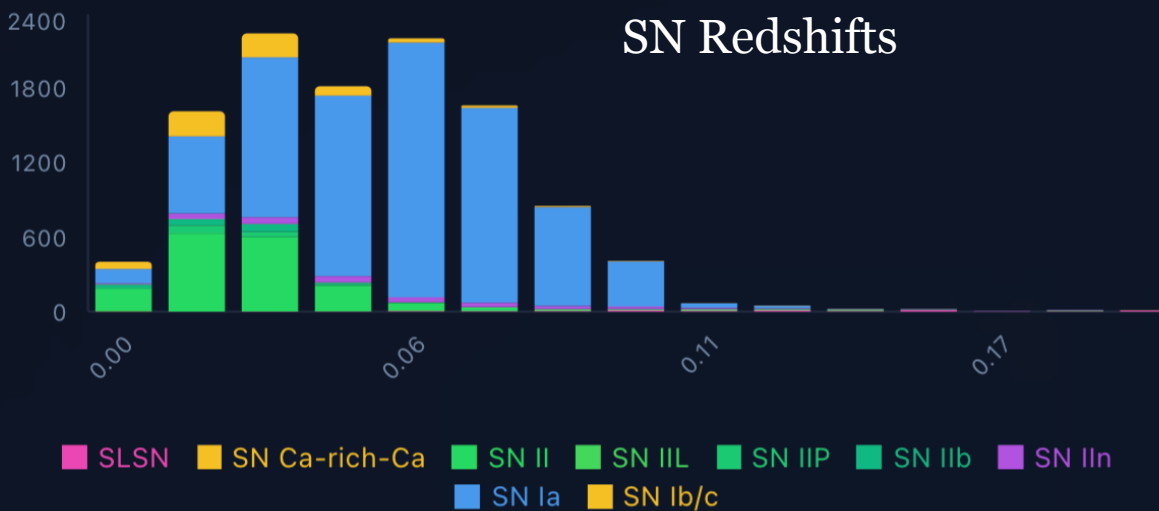
17



SN Types

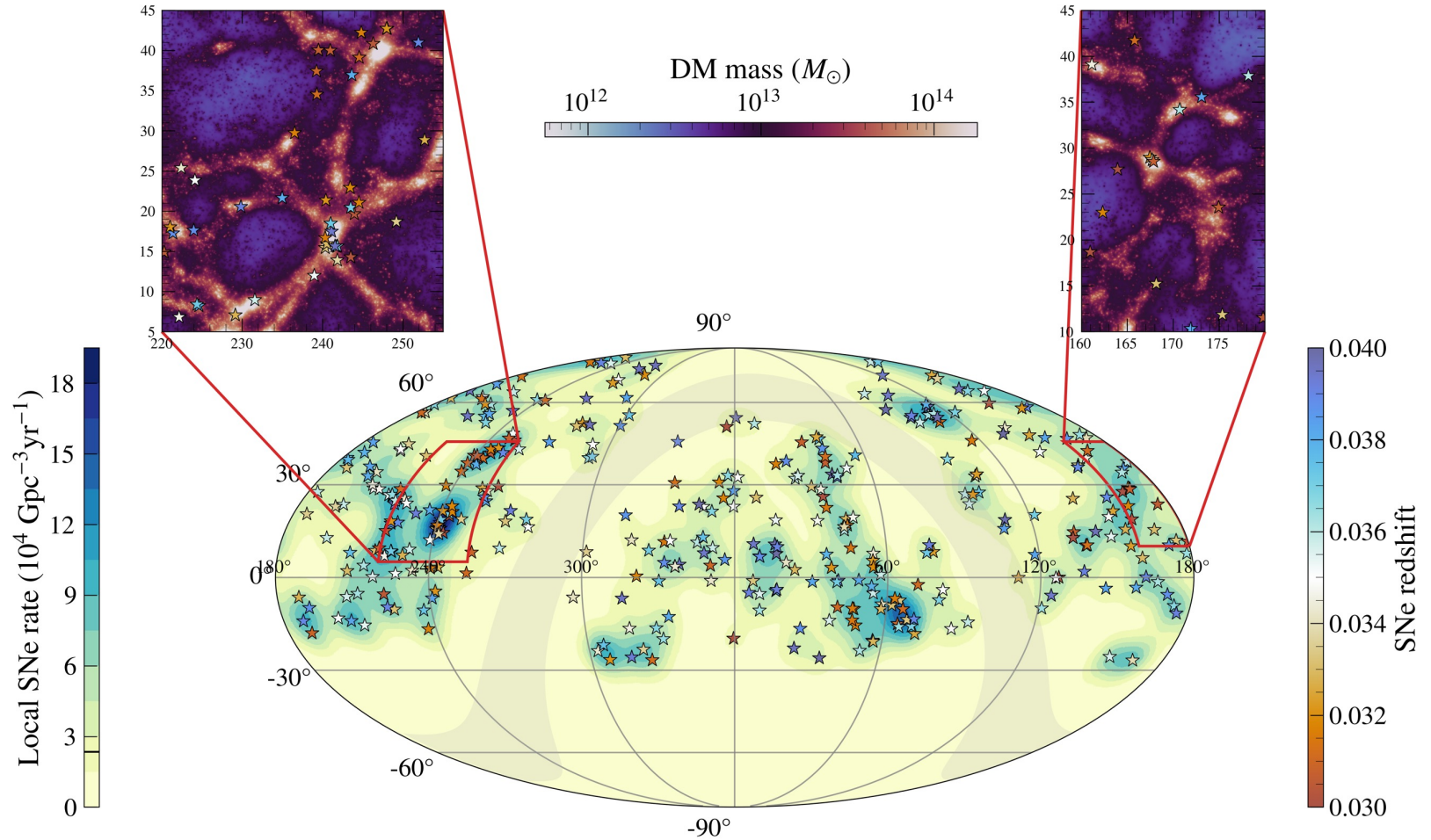


Today's count:
11462 classified SNe



We are even starting to resolve the LSS with SNe(Ia)!

18



Gilles Lordet+26

Closing in on precision cosmology... - stay tuned!

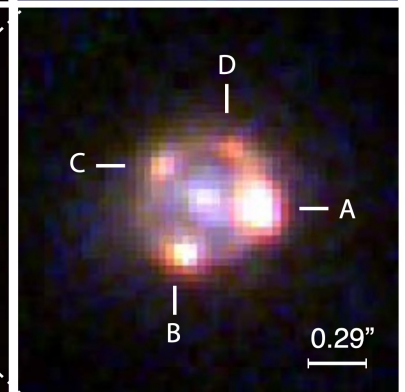
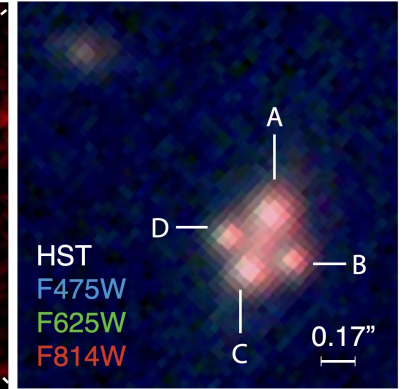
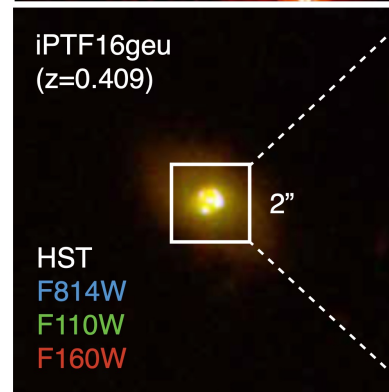
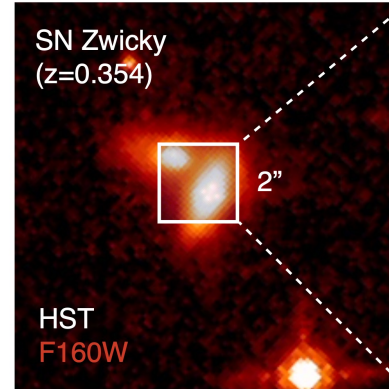
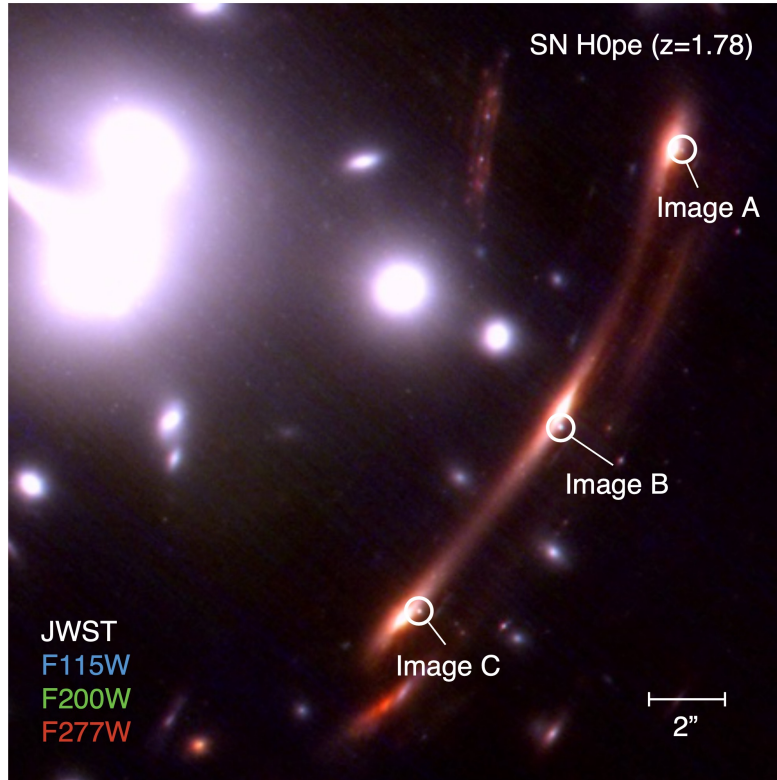
- ZTF team working on calibration to achieve better than 1% photometric accuracy.
- *Critical for precision cosmology, synergy with DESI spectroscopic survey for host galaxy redshifts!*
- Ongoing efforts to cross-calibrate with high- z samples (required): ZTF + DES5Y and separately, ZTF + Subaru + SNLS Yr5



Next: LSST and Roman From <21 mag to 26 mag!

- Great statistics at high- z , complementing ZTF low- z sample, *but limited spectroscopic follow-up*
- Systematics dominated: e.g., everything astrophysical that may not be constant over redshift:
 - * Properties of dust grains - requires excellent multi-band colors to verify/rule out
 - * Evolution of "standard candle"- *requires excellent spectroscopy* to verify/rule out
- Gravitational telescopes for *sub-samples* can help here!

A new frontier in the era of time-²¹ domain surveys: gravitationally lensed SNe

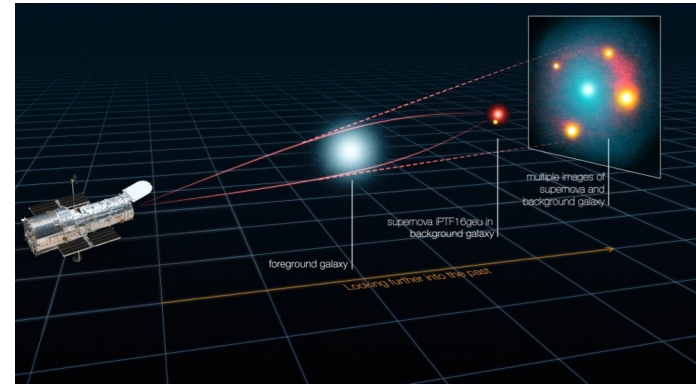


Why is it interesting?



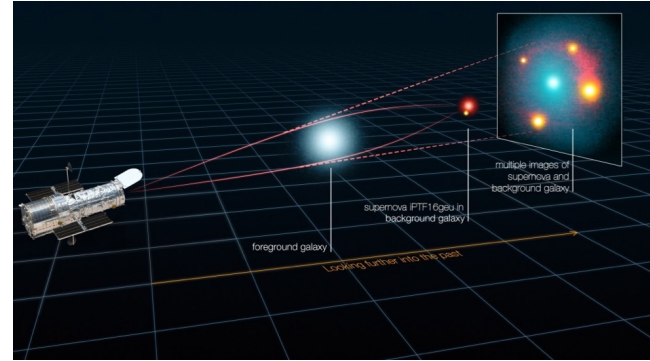
- Gravitational lensing provides huge magnifications that allow for **unique tests for astrophysics at high- z** , impossible to achieve with current man-made telescopes alone.

Why is it interesting?

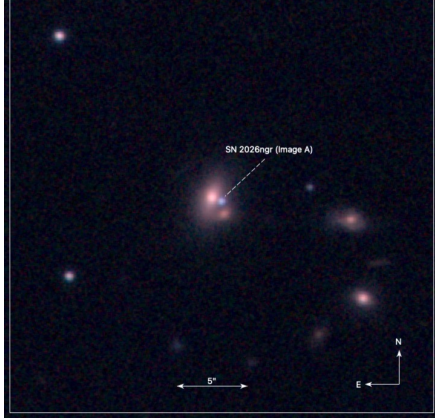


- Gravitational lensing provides huge magnifications that allow for **unique tests for astrophysics at high- z** , impossible to achieve with current man-made telescopes alone.
- Time delay between SN images provides an independent measurement of the **Hubble constant**

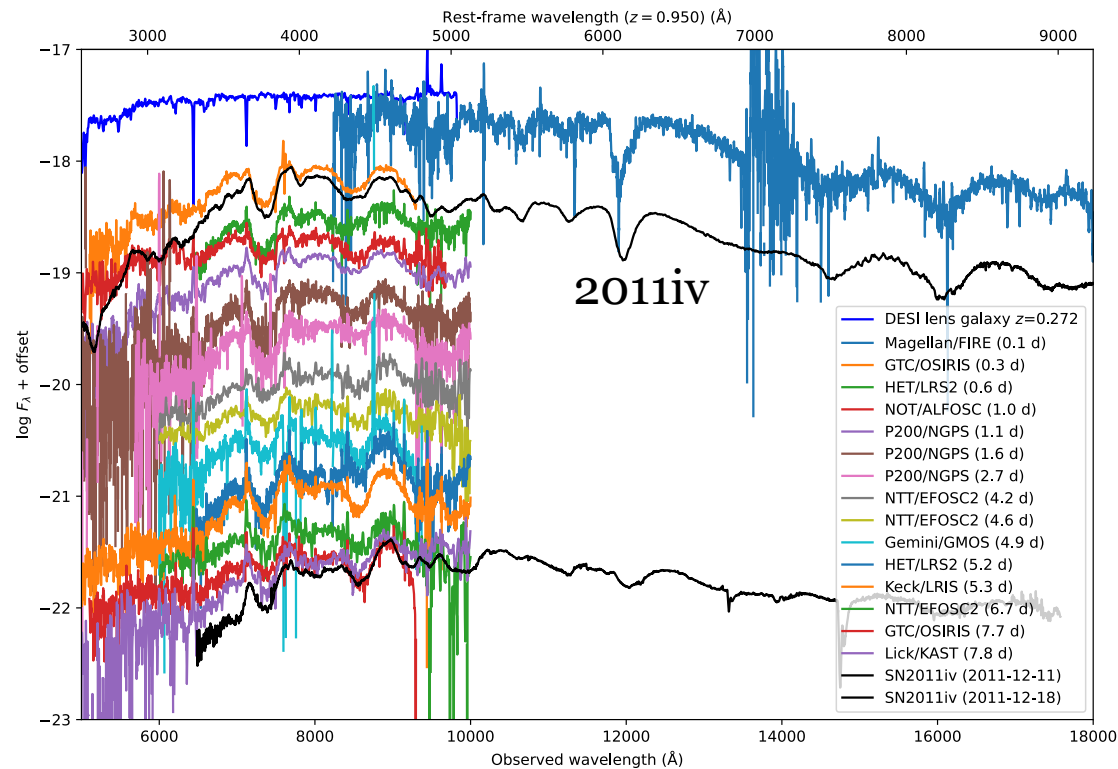
Recent developments...



- Bottleneck has been spectroscopic screening
- Critical synergies with DESI spectroscopic survey – *compensates (partially) the lack of transient spectroscopy*
- We have found 3 new lensed SNe in ZTF thanks to availability of galaxy redshifts from DESI: look for transients too bright to be hosted by the nearest galaxy
 - > “Nearest galaxy” is a lens, not the host!
- *LSST Era: up to one lensed SN every week (!) -> % level on H_0 realistic in first few years of survey.*

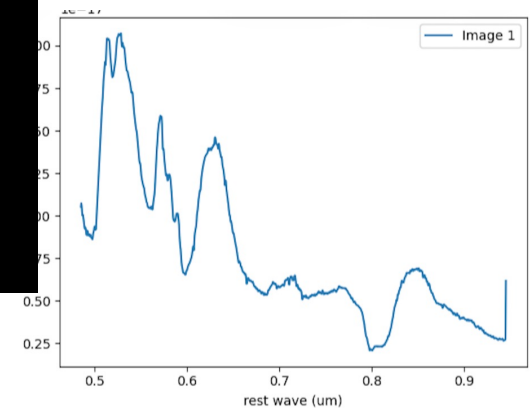
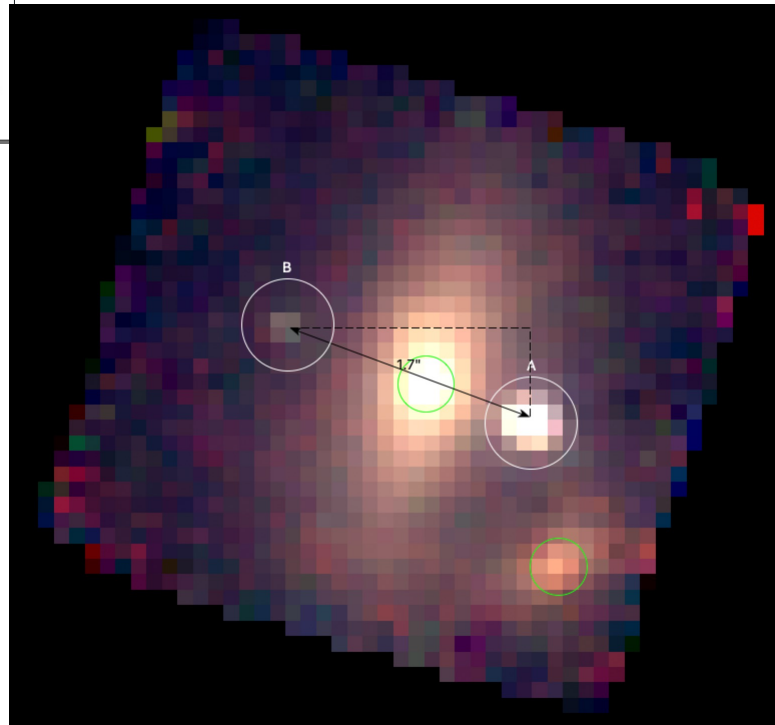
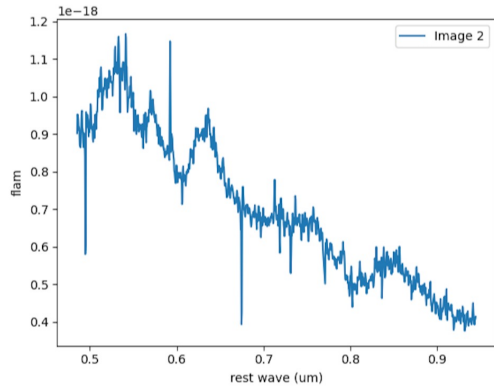


SN2026ngr – SNIa @ $z=0.95$ 4:th lensed SN found with ZTF



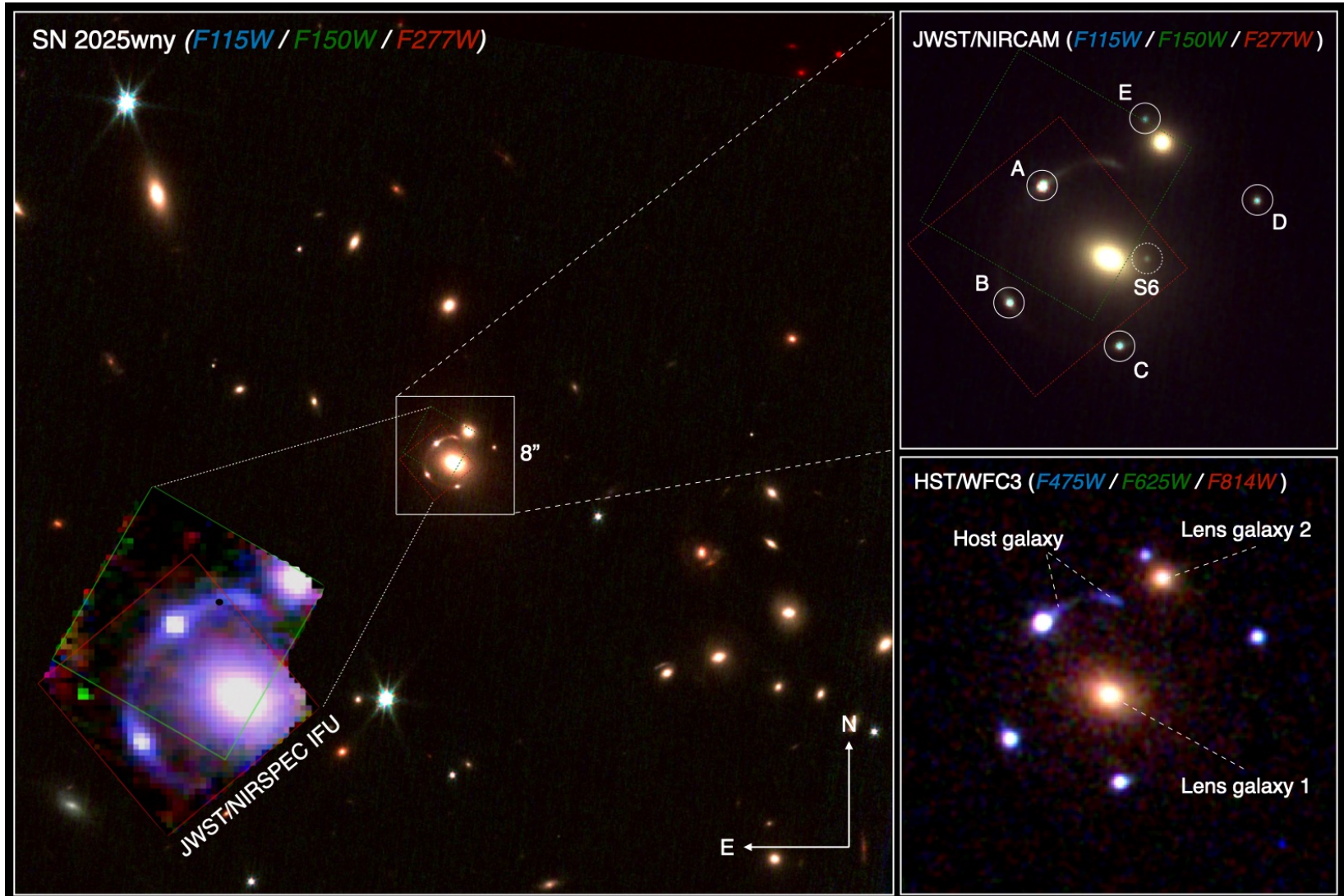
**High SNR
restframe daily
UV spec with
2m+ class
telescopes
thanks to **$\sim 150\times$
magnification****

Just off the STScI archive: NIRSPec

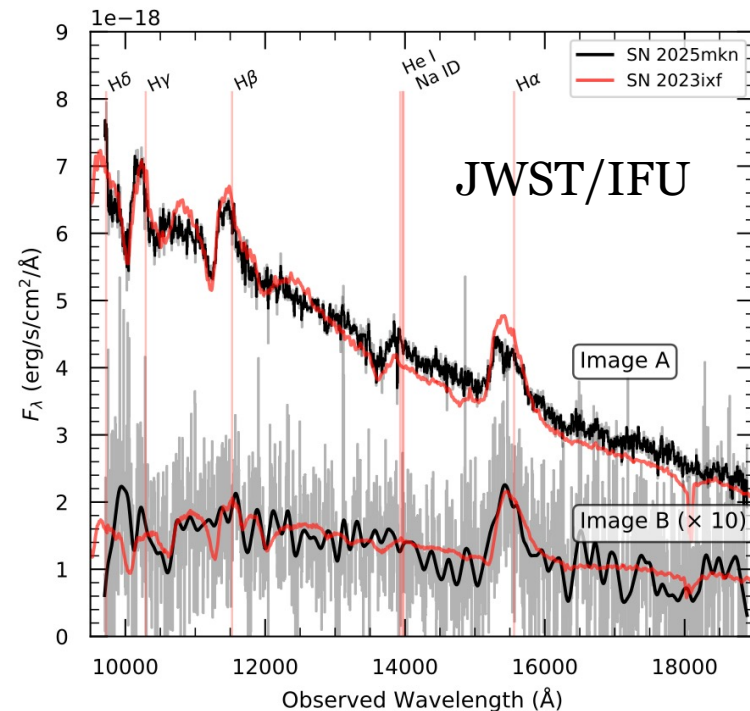
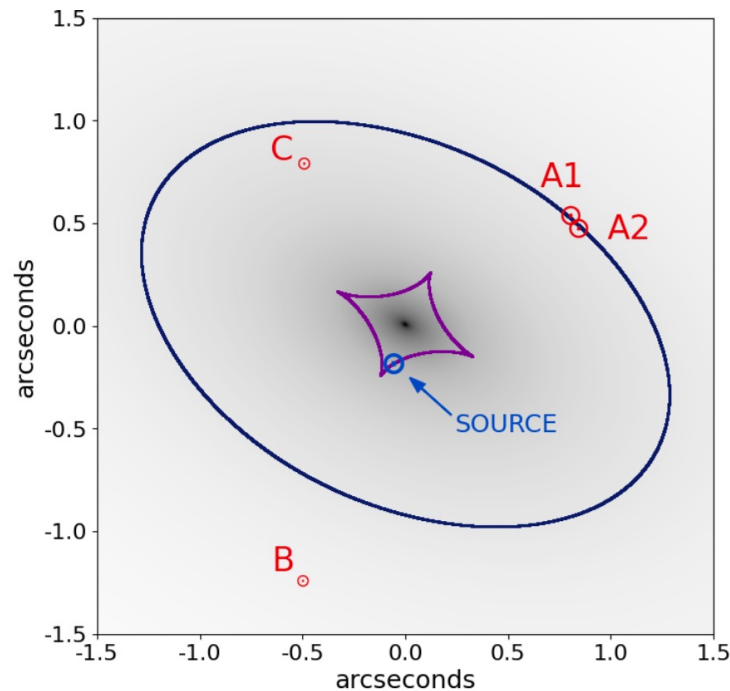


SN2025wny – SLSN at $z=2$, Largest time-delay ~ 2 months $\rightarrow$ great for H_0 !

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SN2025mkn: by comparison with
spectral time sequence of
SN2023ixf we can measure time
delays...



Lemon+26

Time-delay measurement in progress!

Great synergies ground+ ²⁹space missions!

+ Lazuli!



JWST

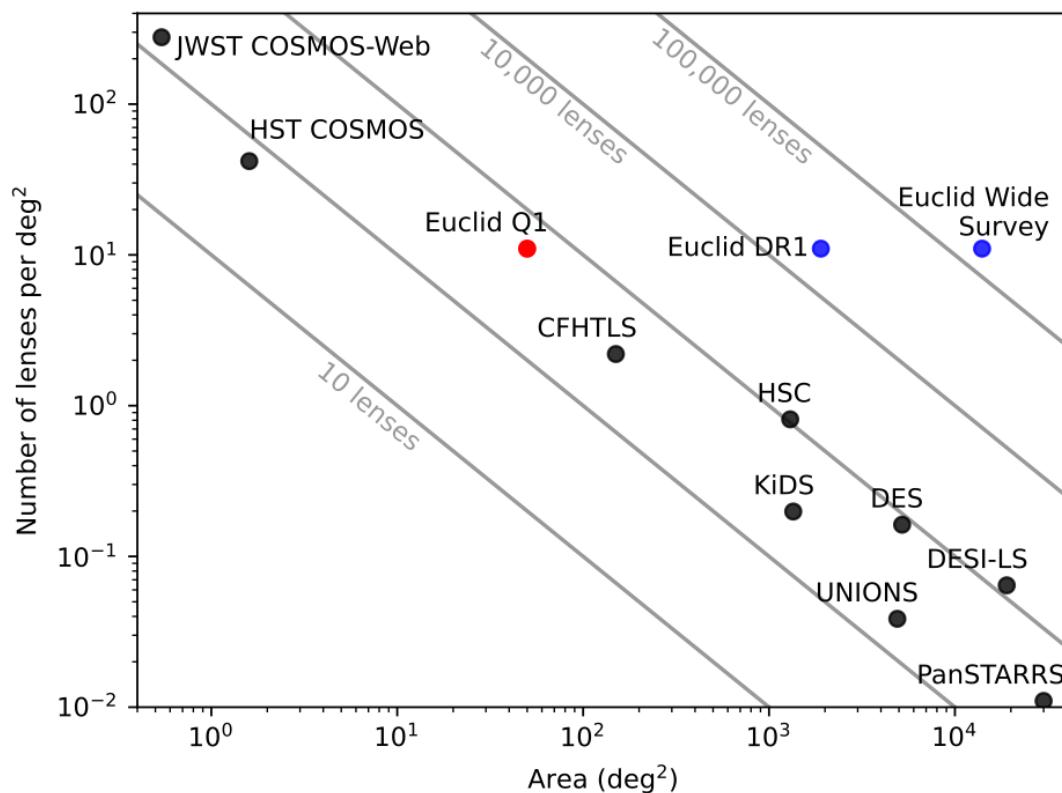


Euclid



Roman

LSST to search for lensed SNe in the 10^4 lenses found by EUCLID by start of survey and ultimately 10^5



Wamsley+25

Lines+ 2025

Summary & Outlook

- Hubble tension and evidence for evolving DE at the focus for contemporary cosmology. Key SN components.
- New fundamental physics?
- Ruling out systematic uncertainties in SN distances is essential for confirming potential breakthrough(s).
- Bottleneck is transient spectroscopy
- Synergies between ground and space missions + static spectroscopic surveys are key to observational success.
- Strong gravitational lensing emerging as a powerful tool in the era of large surveys!