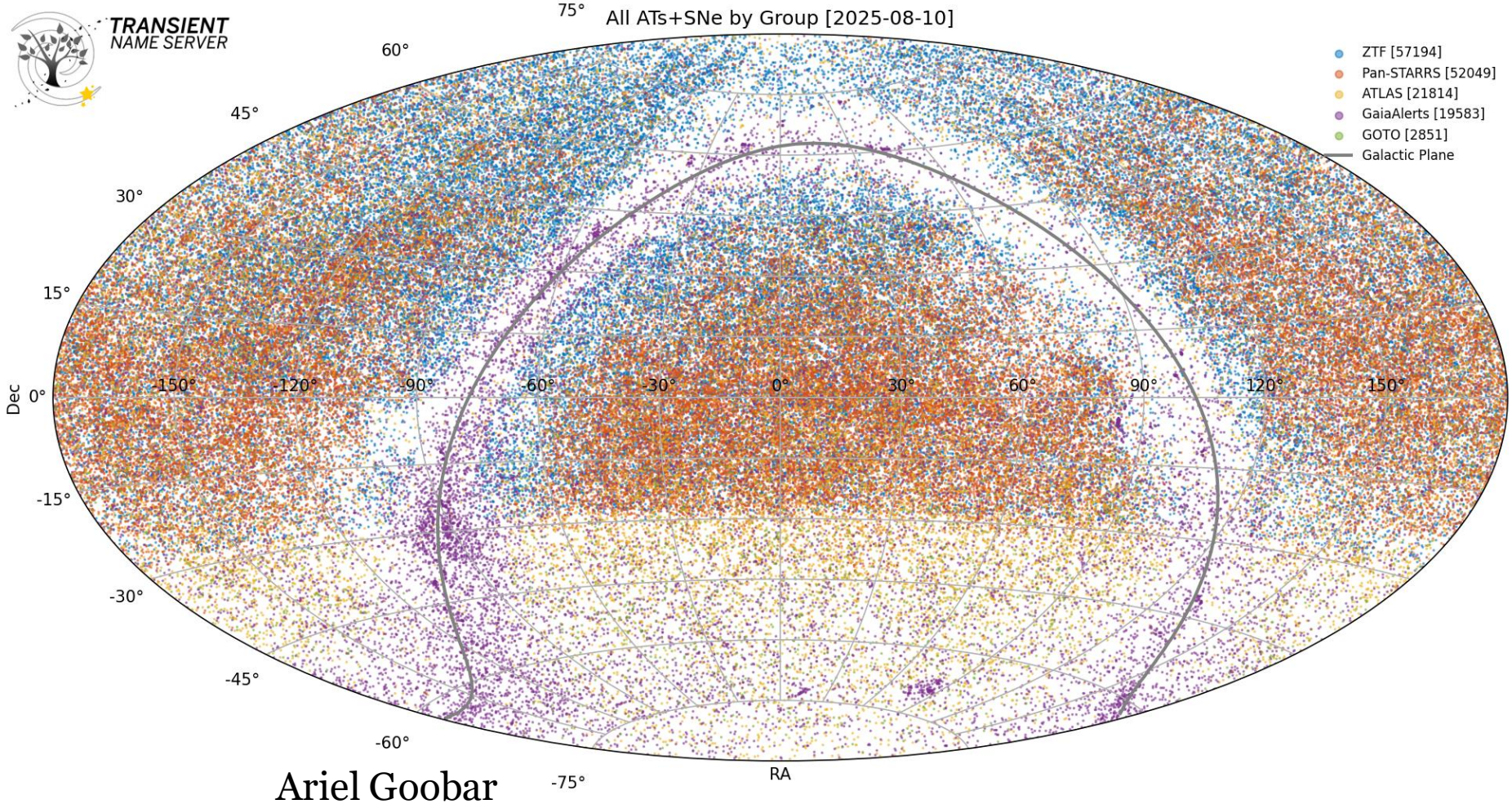
Time-domain Cosmology in the Era of Large Surveys



Ariel Goobar
The Oskar Klein Centre
Stockholm University

Since Jan 1, 2016:
151016 transients, 17345 confirmed supernovae

Cosmology at turning point?!

ΛCDM 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

Cosmology at turning point?!

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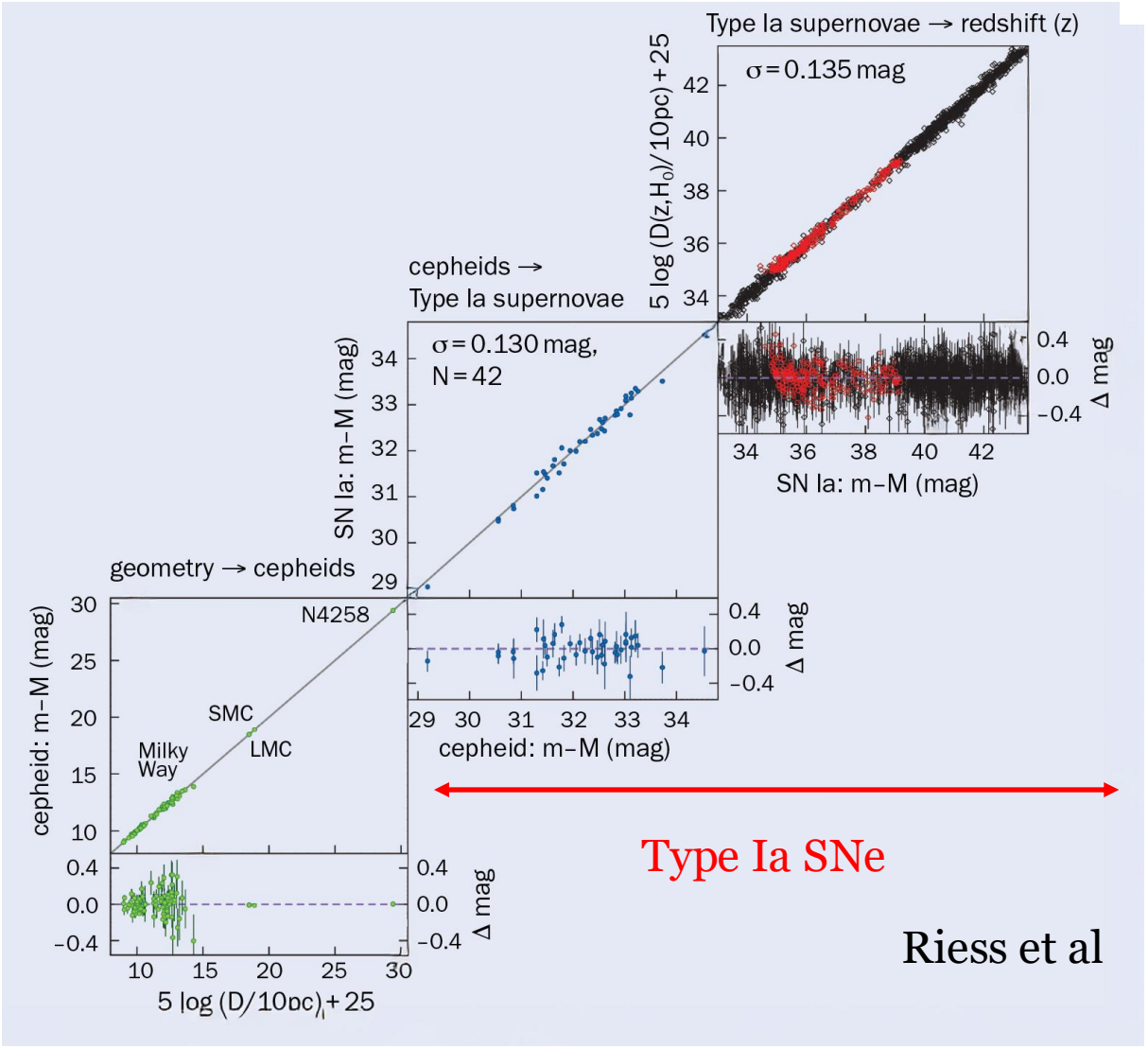
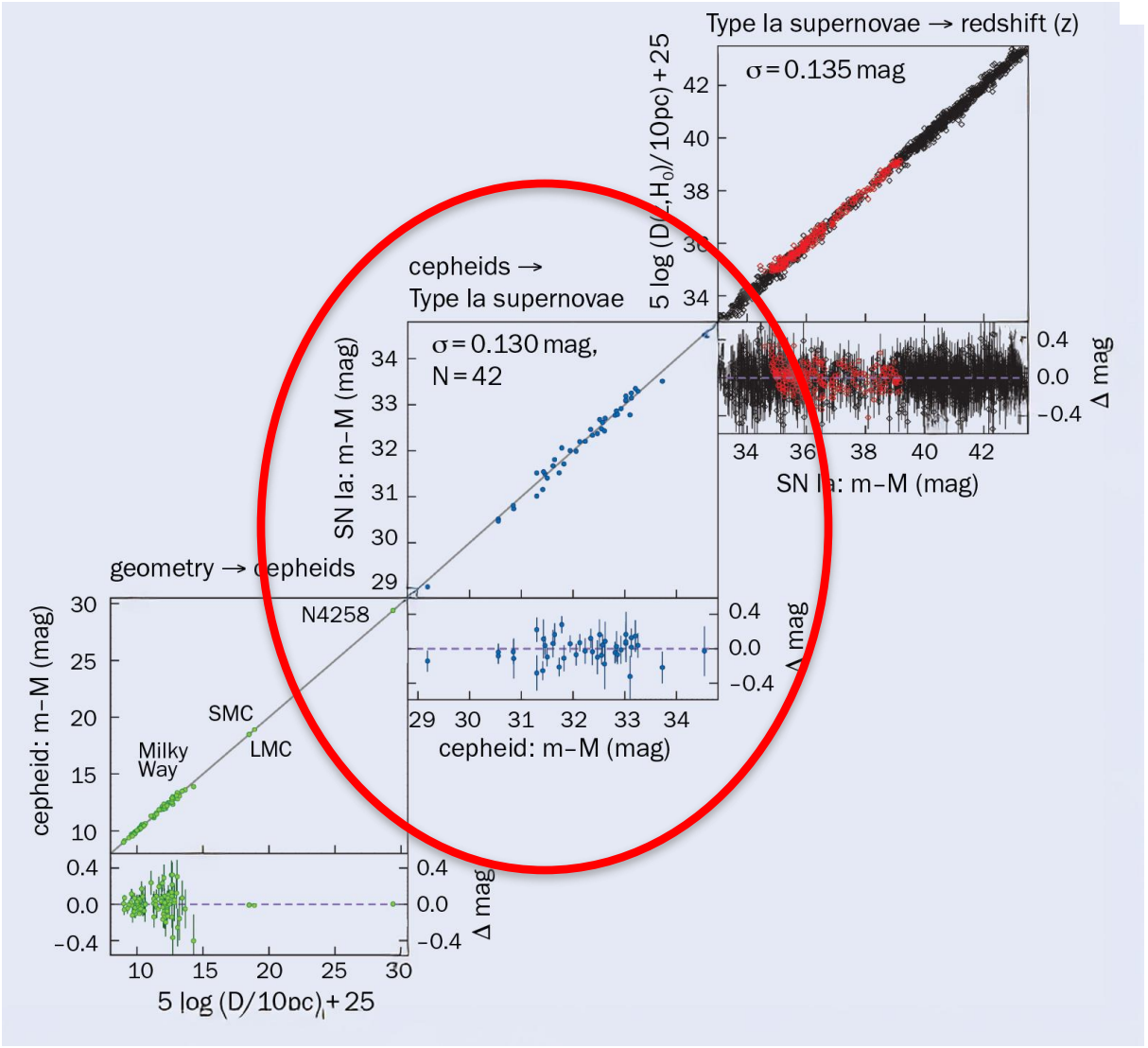
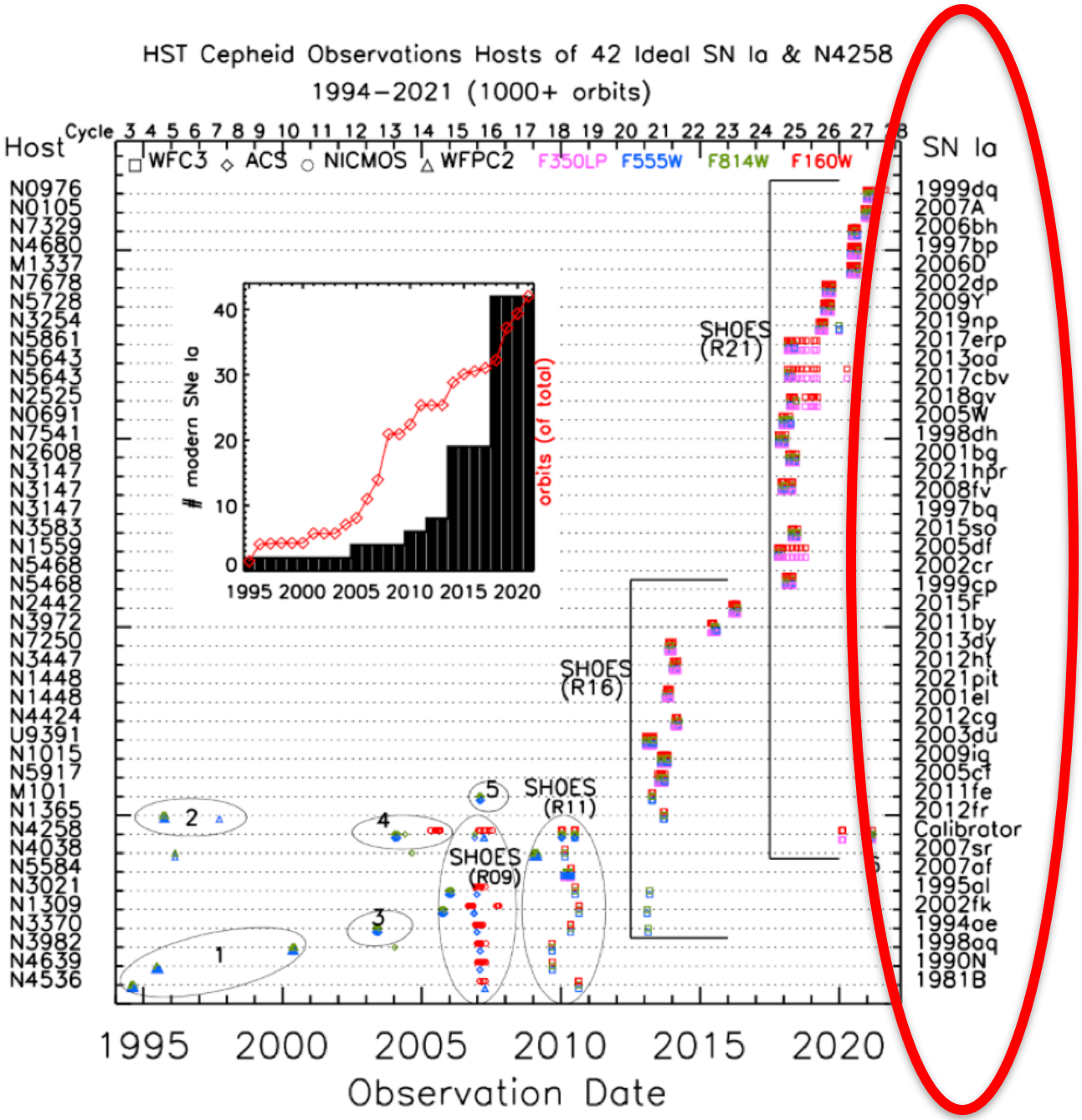
- Hubble tension: SNIa distance ladder calibrated with Cepheids by SH0ES team (Riess+22) finds 5σ deviation from early Universe inference of H_0
- DESI + CMB + SNe Ia, finds hints for *time-dependent dark energy equation of state, w(t)*, i.e., in possible tension with Cosmological Constant
- Both of these results rely on decades old Type Ia SN samples, especially at low redshifts, not always observed with precision cosmology in mind

H_0:the distance ladder

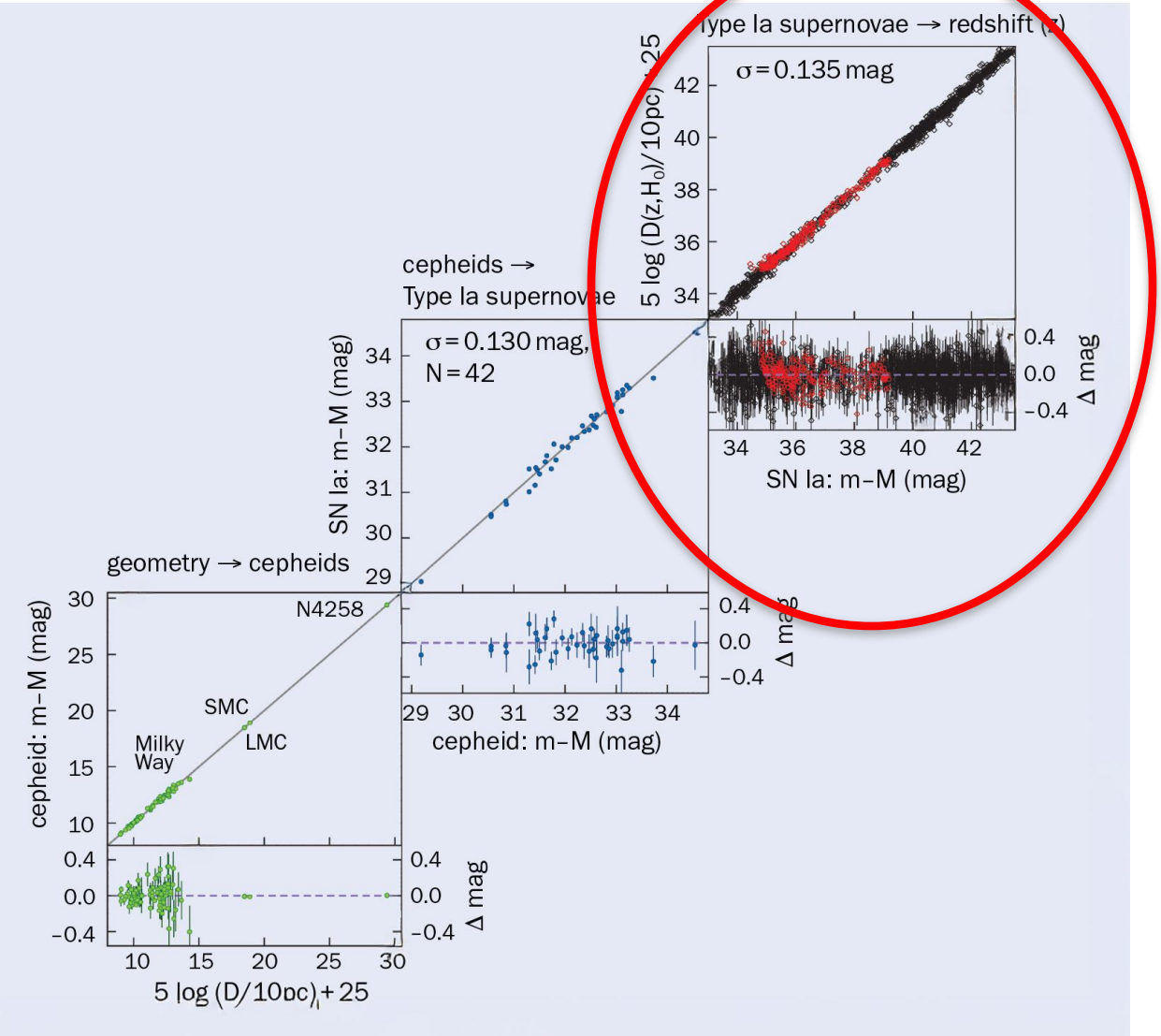


H_0:the distance ladder



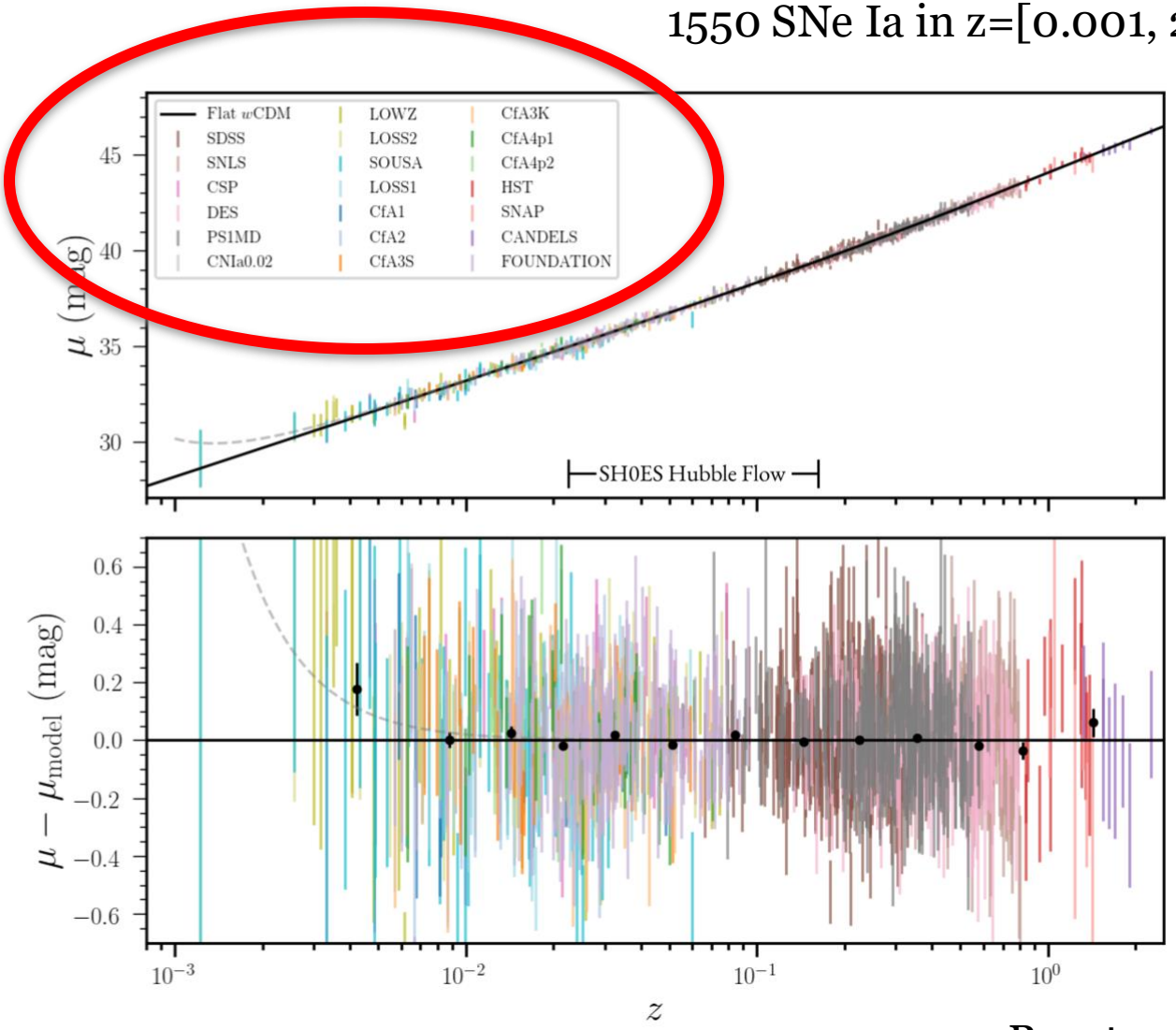

HST Cepheid Observations Hosts of 42 Ideal SN Ia & N4258
1994–2021 (1000+ orbits)
Cycle 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
Host
WFC3 ACS NICMOS WFPC2 F350LP F555W F814W F160W
SN Ia
N0976 N0105 N7329 N4680 M1337 N7678 N5728 N3254 N5861 N5643 N5643 N2525 N0691 N7541 N2608 N3147 N3147 N3147 N3583 N1559 N5468 N5468 N2442 N3972 N7250 N3447 N1448 N1448 N4424 U9391 N1015 N5917 M101 N1365 N4258 N4038 N5584 N3021 N1309 N3370 N3982 N4639 N4536
1999dq 2007A 2006bh 1997bp 2006D 2002dp 2009Y 2019np 2017erp 2013aa 2017cbv 2018gv 2005W 1998dh 2001bg 2021hpr 2008fv 1997bq 2015so 2005df 2002cr 1999cp 2015F 2011by 2013dy 2012ht 2021pit 2001el 2012cg 2003du 2009ig 2005cf 2011fe 2012fr Calibrator 2007sr 2007af 1995al 2002fk 1994ae 1998aq 1990N 1981B
modern SNe Ia
orbits (of total)
0 10 20 30 40
1995 2000 2005 2010 2015 2020
SHOES (R21)
SHOES (R16)
SHOES (R11)
SHOES (R09)
1 2 3 4 5
1995 2000 2005 2010 2015 2020
Observation Date

The Hubble flow sample



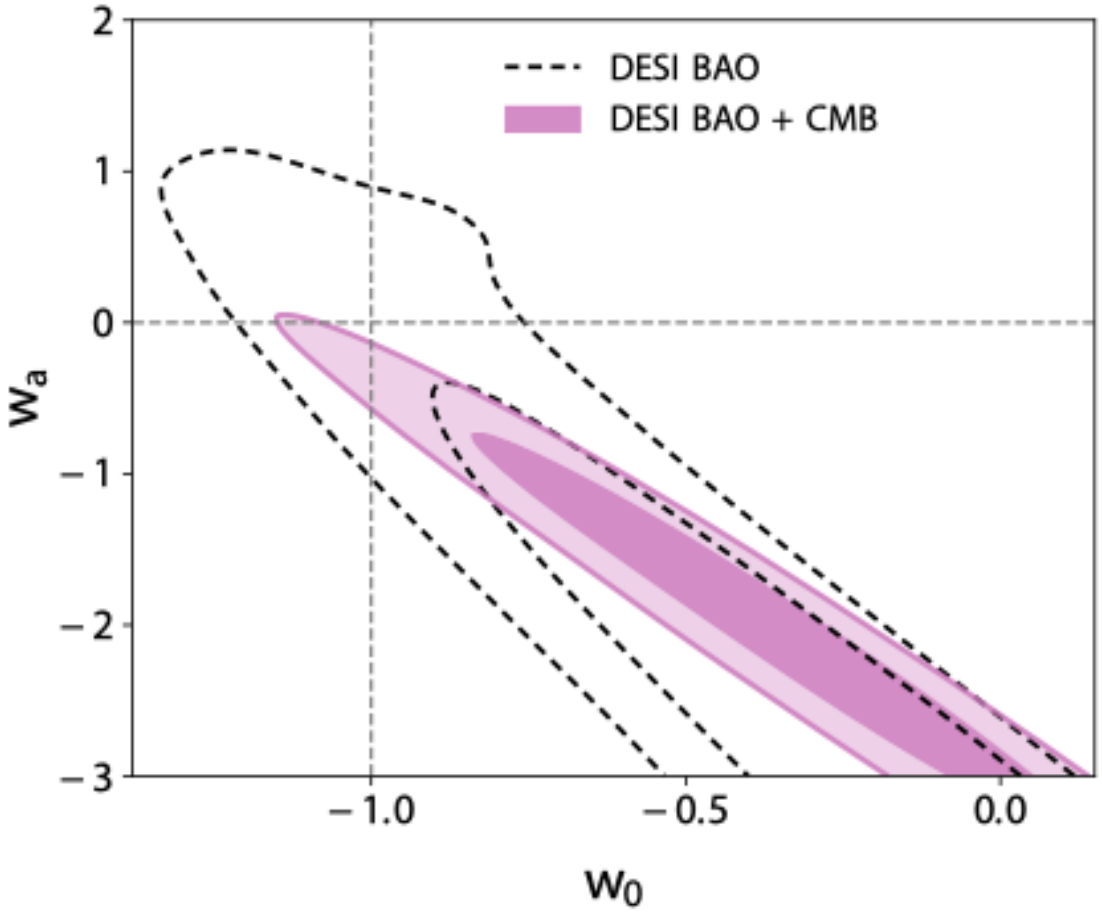
Pantheon+ compilation:
25 different photometric systems!

1550 SNe Ia in z=[0.001, 2.26]

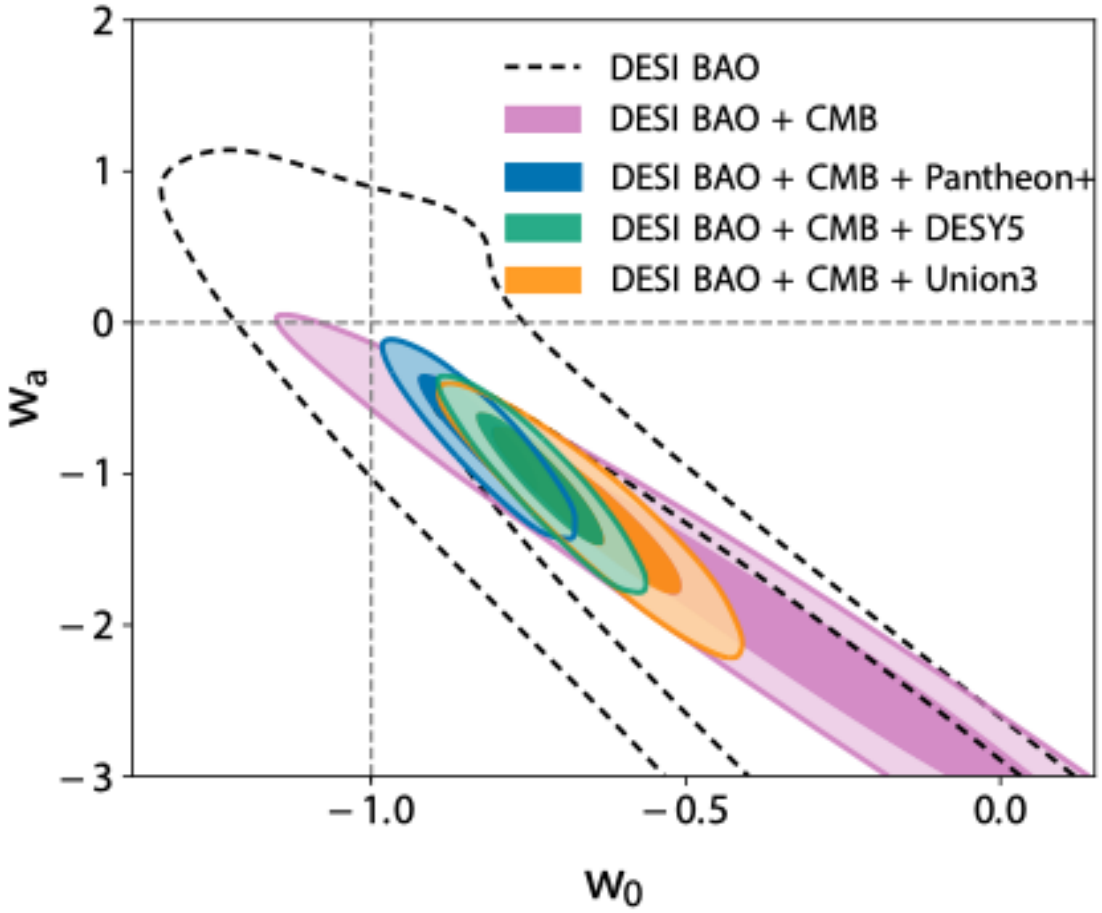


Brout+22

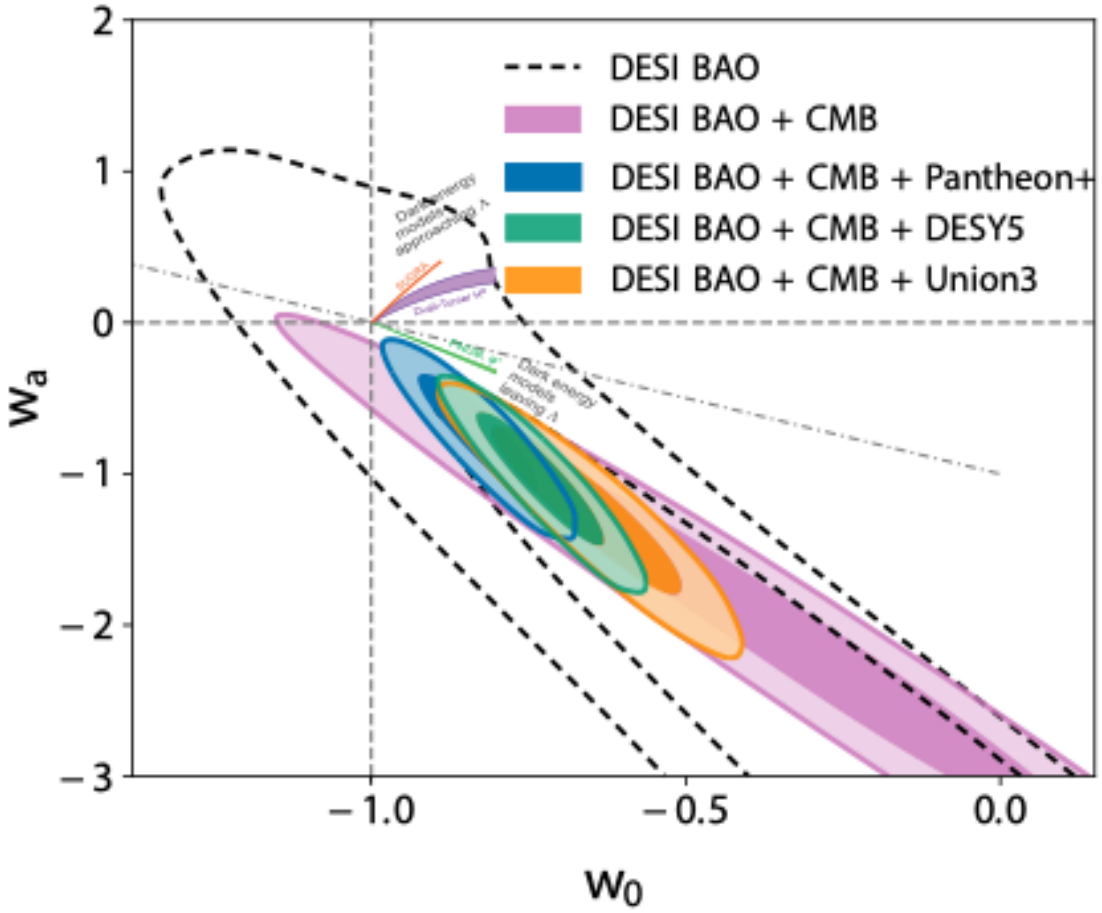
Evidence for dynamic dark energy



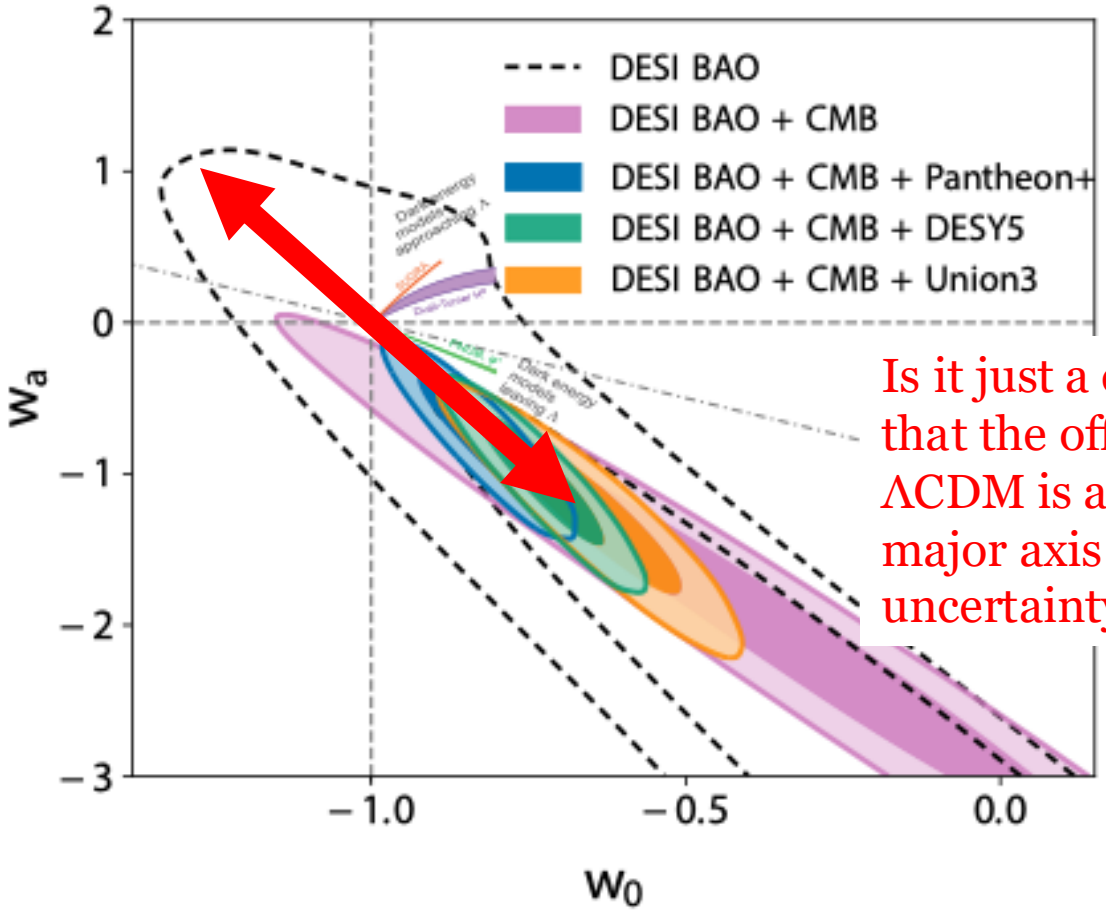
Evidence for dynamic dark energy



Evidence for dynamic dark energy

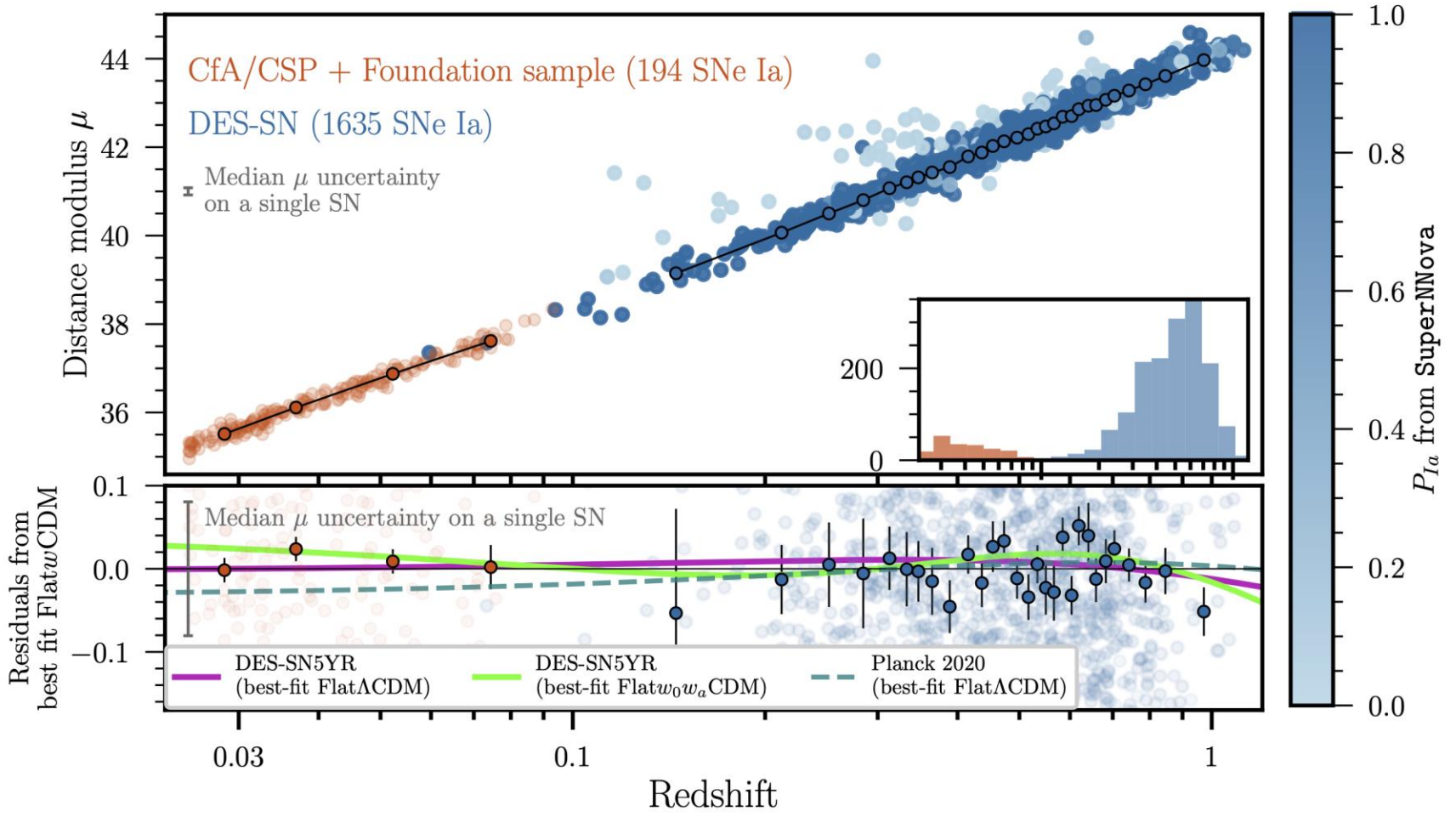


Evidence for dynamic dark energy

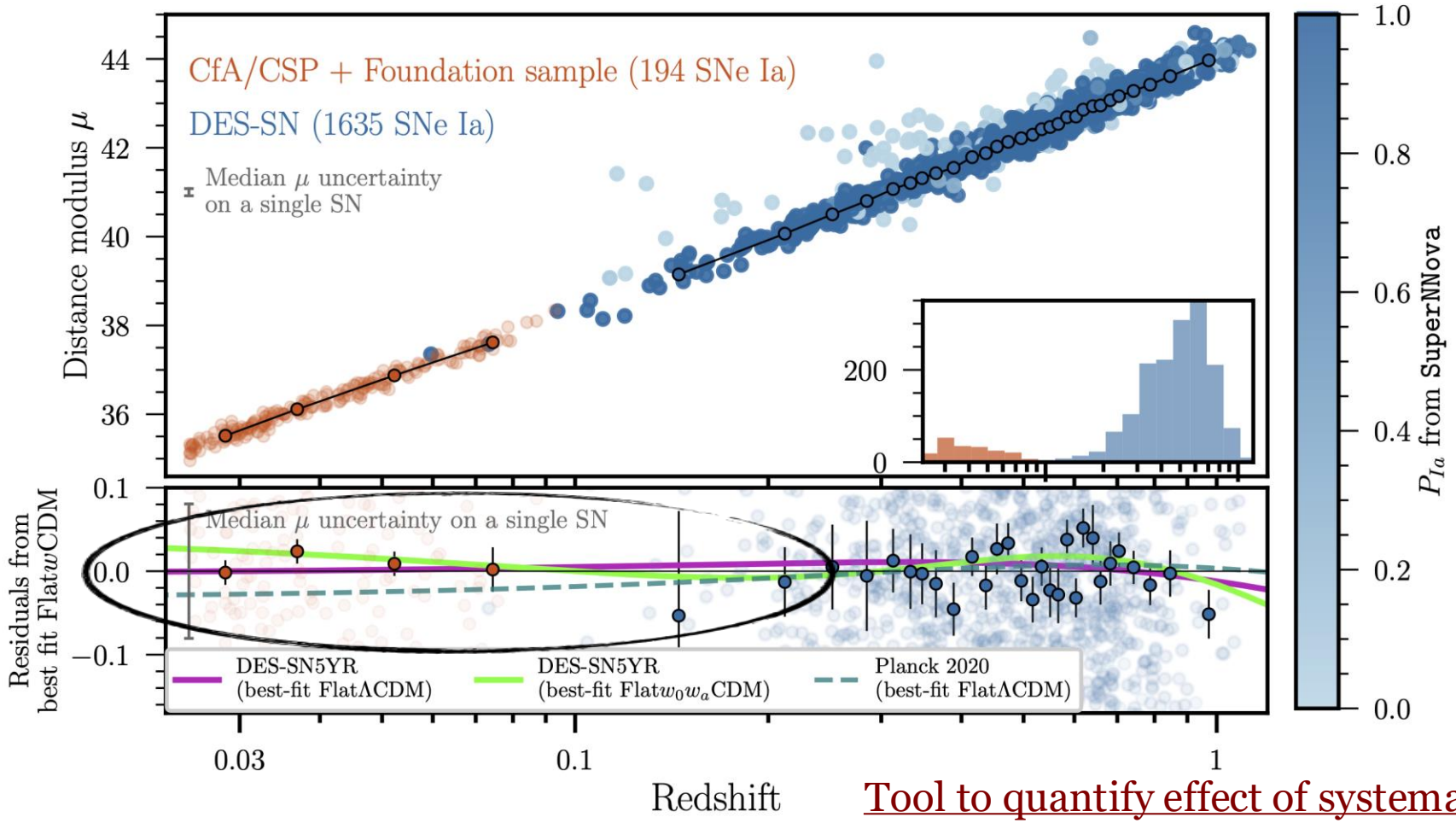


Is it just a coincidence that the offset from ΛCDM is along the major axis of the uncertainty ellips?

How robust is the low-z SNIa sample?



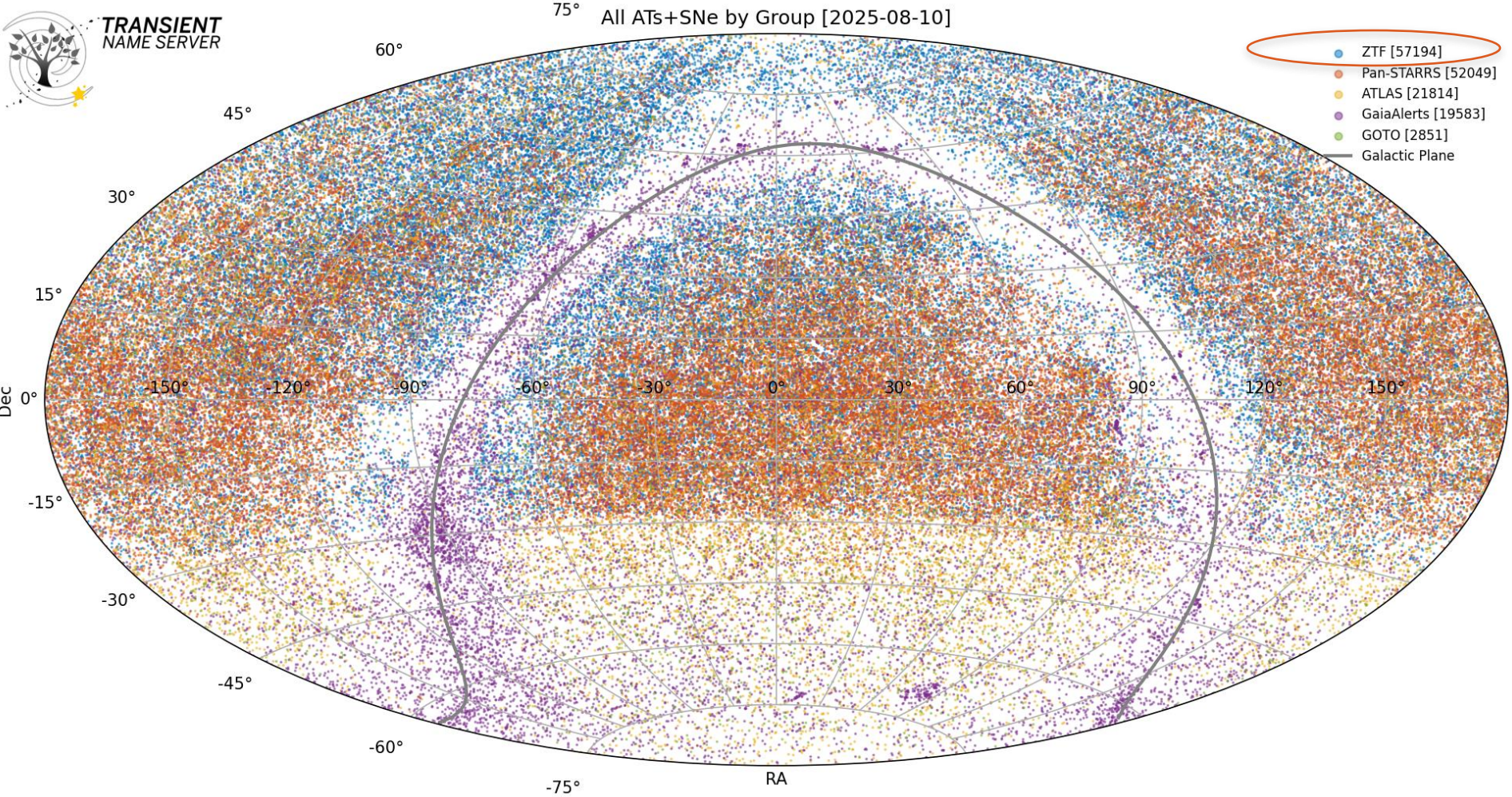
How robust is the low-z SNIa sample?



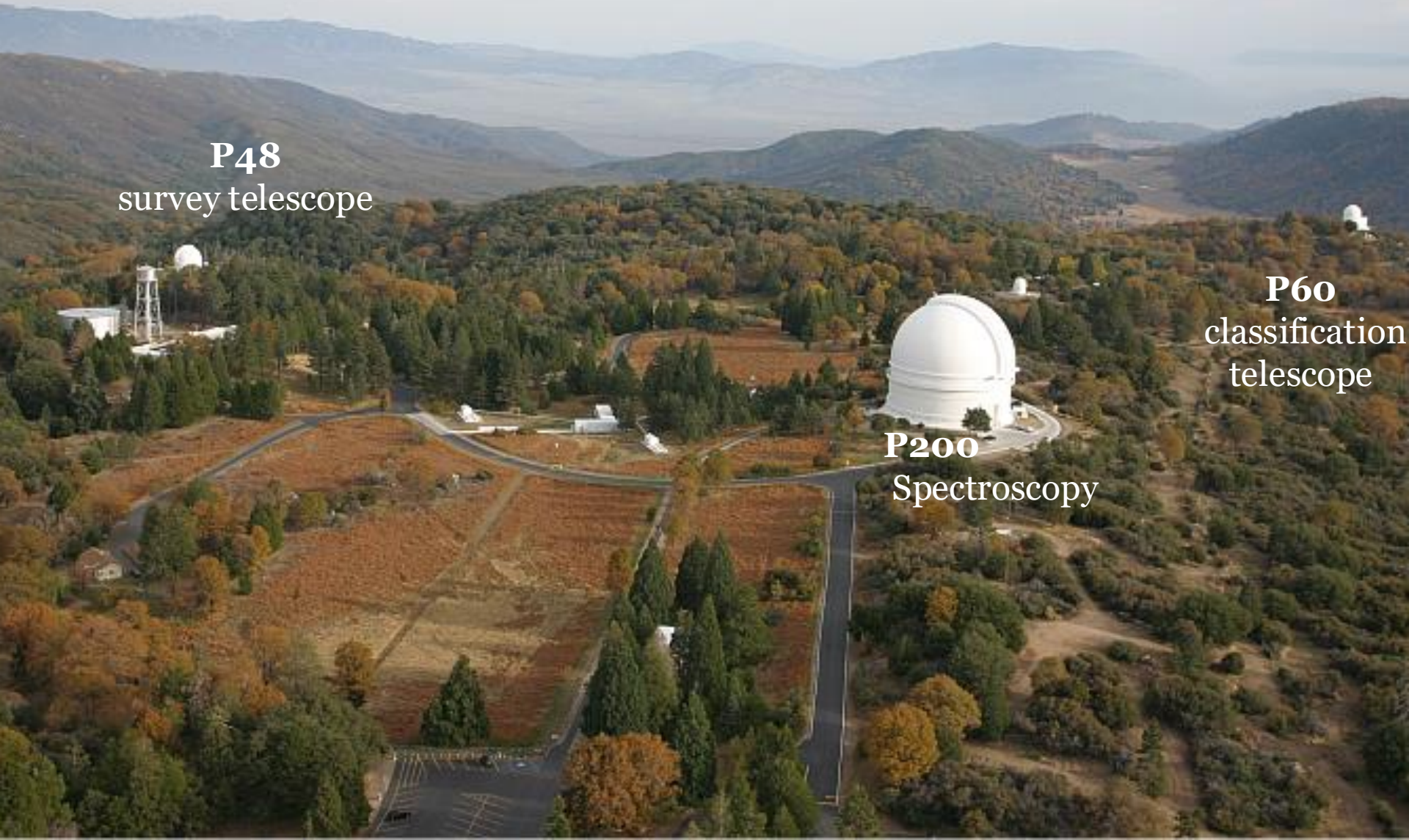
Tool to quantify effect of systematics!

Dhawan, Popovic, AG, 2025

The Era of Large Surveys and precision cosmology



Zwicky Transient Facility: since 2018



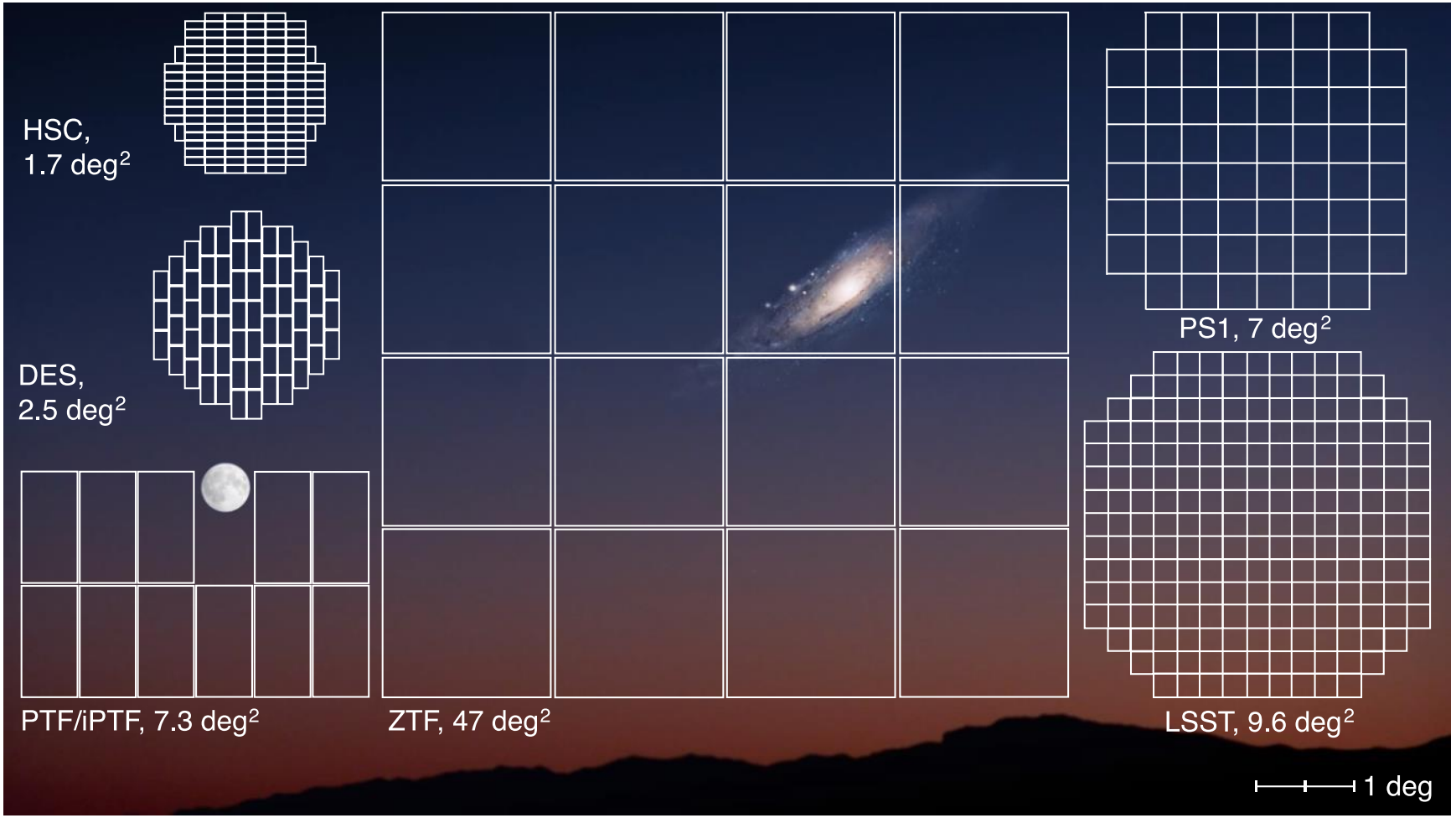
Zwicky Transient Facility: since 2018

P48
survey telescope

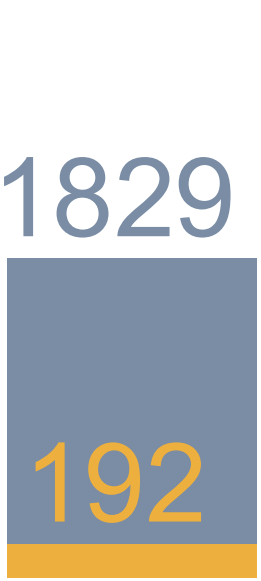
P60
classification telescope

P200
Spectroscopy

The Zwicky Transient Facility

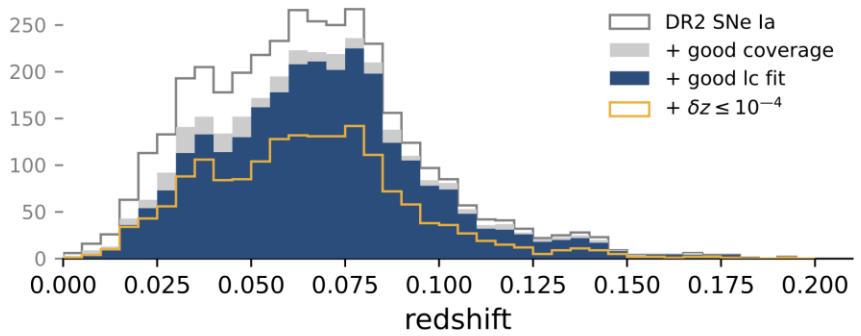


ZTF DR2 spectroscopically classifed SNe Ia for *low-z* cosmology



DES 2024 SNIa

ZTF DR2 SNIa



2.5 years worth of data out of 7!

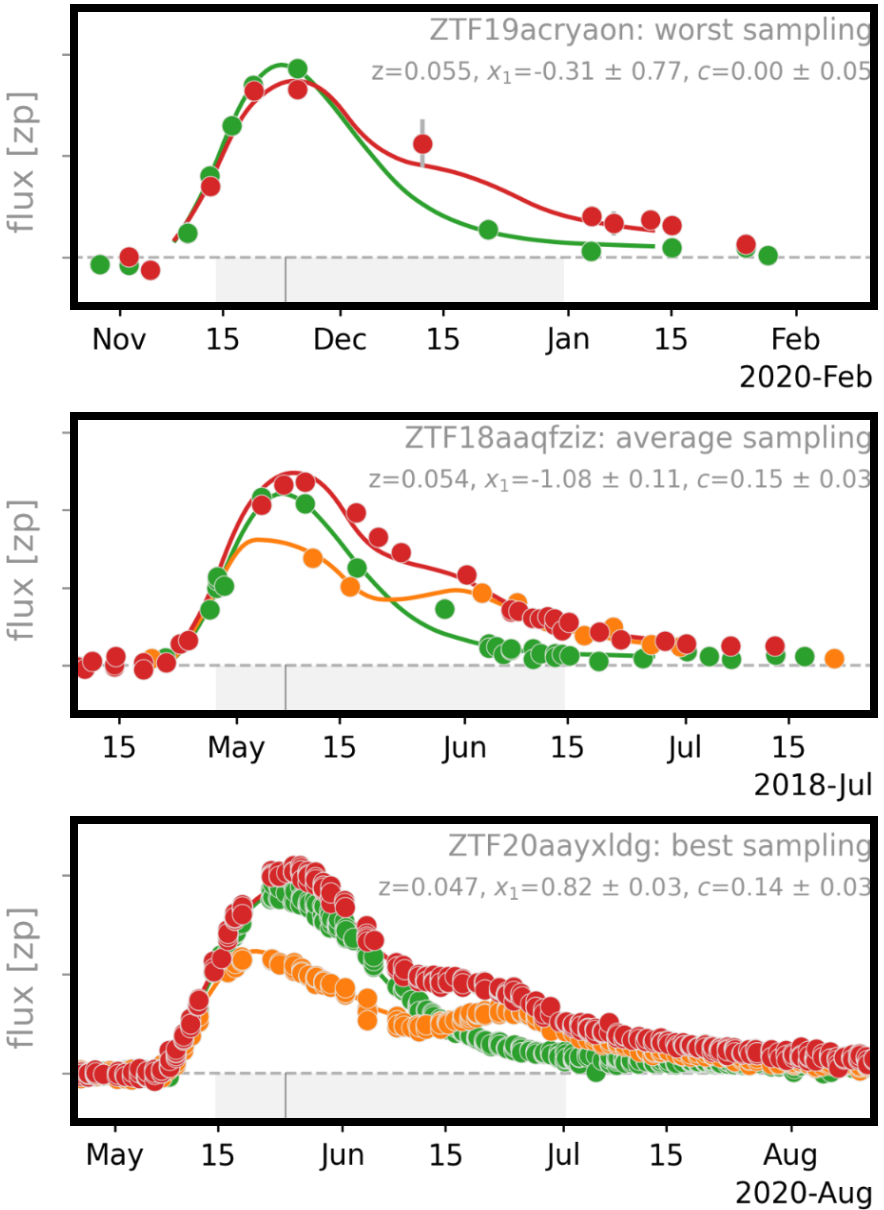
ZTF SN Ia DR2 Papers

(+ more in prep…)

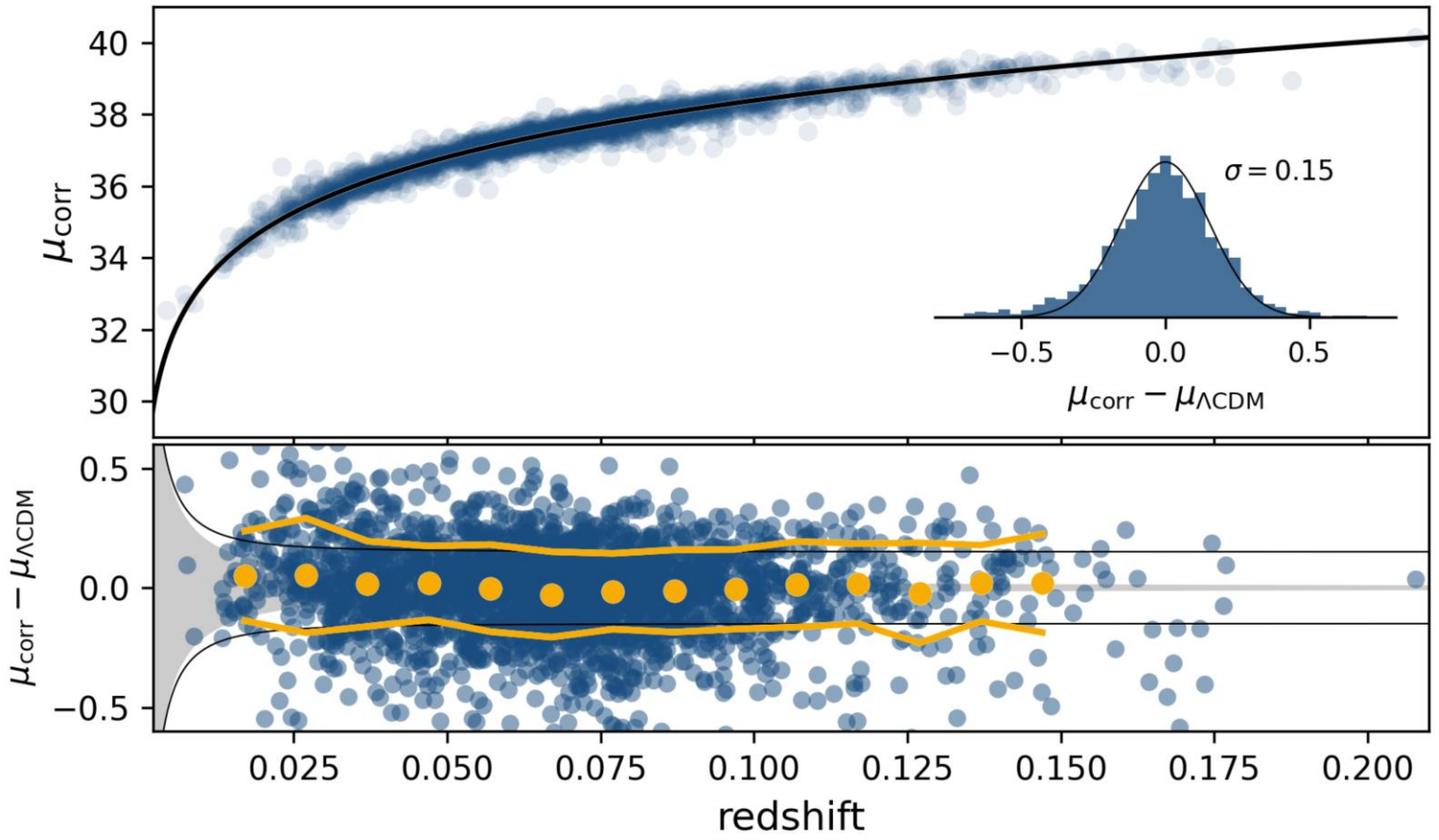
A&A Special edition

- ZTF SN Ia DR2: Overview — Rigault, M., Smith, M., Goobar, A., et al.
- ZTF SN Ia DR2: Study of Type Ia supernova light-curve fits — Rigault, M., Smith, M., Regnault, N., et al.
- ZTF SN Ia DR2: Simulations and volume-limited sample — Amenouche, M., Rosnet, P., Smith, M., et al.
- ZTF SN Ia DR2: Colour standardisation of type Ia supernovae and its dependence on the environment — Ginolin, M., Rigault, M., Copin, Y., et al.
- ZTF SN Ia DR2: Evidence of changing dust distribution with redshift using type Ia supernovae — Popovic, B., Rigault, M., Smith, M., et al.
- ZTF SN Ia DR2: Impact of the galaxy cluster environment on the stretch distribution of Type Ia supernovae — Ruppin, F., Rigault, M., Ginolin, M., et al.
- ZTF SN Ia DR2: Exploring SN Ia properties in the vicinity of under-dense environments — Aubert, M., Rosnet, P., Popovic, B., et al.
- ZTF SN Ia DR2: Peculiar velocities' impact on the Hubble diagram — Carreres, B., Rosselli, D., Bautista, J. E., et al.
- ZTF SN Ia DR2: Improved SN Ia colors through expanded dimensionality with SALT3+ — Kenworthy, W. D., Goobar, A., Jones, D. O., et al.
- ZTF SN Ia DR2: The spectral diversity of Type Ia supernovae in a volume-limited sample — Burgaz, U., Maguire, K., Dimitriadis, G., et al.• ZTF SN Ia DR2: The diversity and relative rates of the thermonuclear supernova population — Dimitriadis, G., Burgaz, U., Deckers, M., et al.
- ZTF SN Ia DR2: Searching for late-time interaction signatures in Type Ia supernovae from the Zwicky Transient Facility — Terwel, Jacco H., Maguire, Kate, Dimitriadis, Georgios, et al.
- ZTF SN Ia DR2: Secondary maximum in type Ia supernovae — Deckers, M., Maguire, K., Shingles, L., et al
- ZTF SN Ia DR2: Properties of the low-mass host galaxies of Type Ia supernovae in a volume-limited sample — Burgaz, U., Maguire, K., Dimitriadis, G., et al.
- ZTF SN Ia DR2: An environmental study of Type Ia supernovae using host galaxy image decomposition — Senzel, R., Maguire, K., Burgaz, U., et al.
- ZTF SN Ia DR2: Environmental dependencies of stretch and luminosity for a volume-limited sample of 1000 type Ia supernovae — Ginolin, M., Rigault, M., Smith, M., et al.
- ZTF SN Ia DR2: High-velocity components in the Si IIλ6355 — Harvey, L., Maguire, K., Burgaz, U., et al.

ZTF DR2: Worst, average, best quality



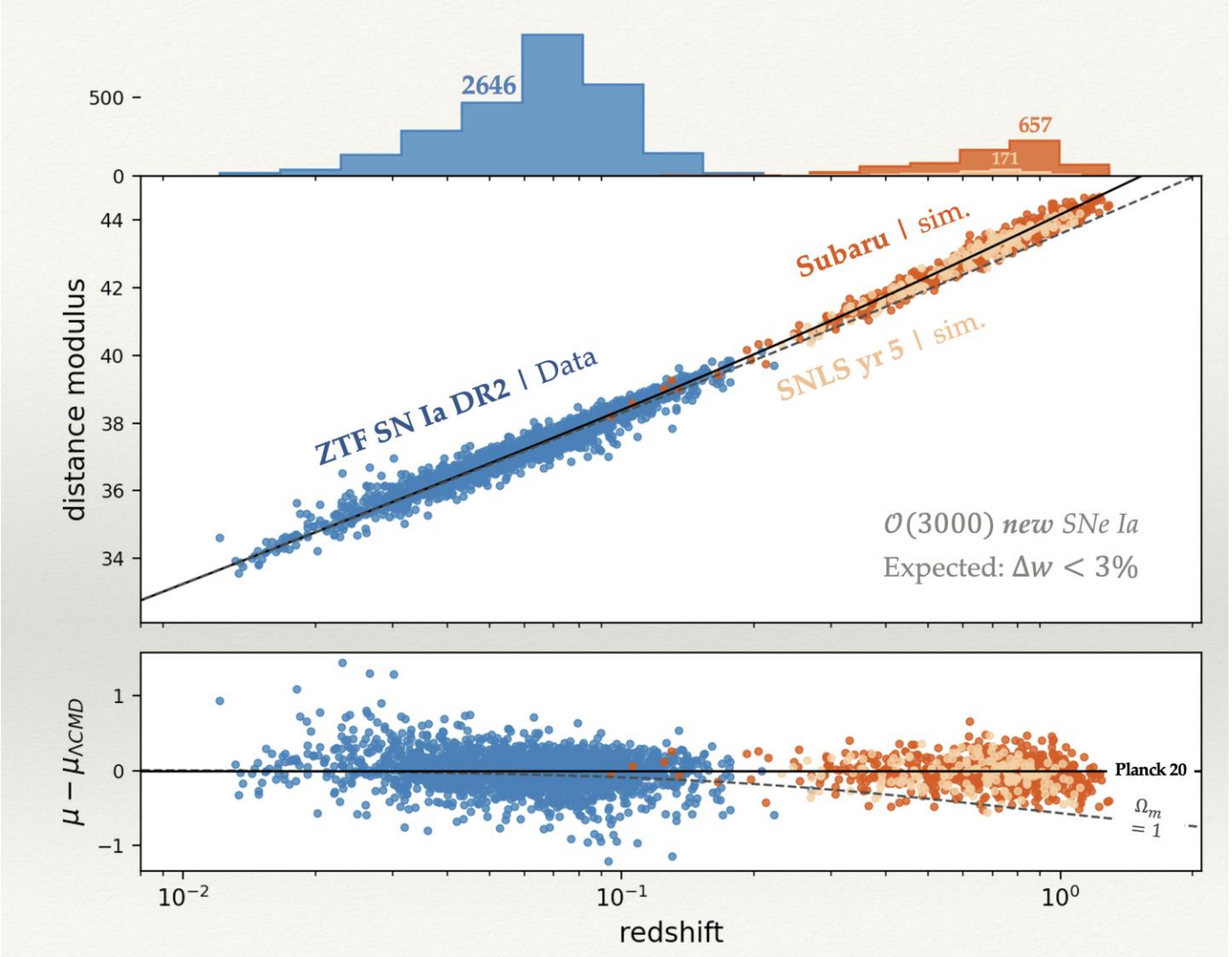
After standardization



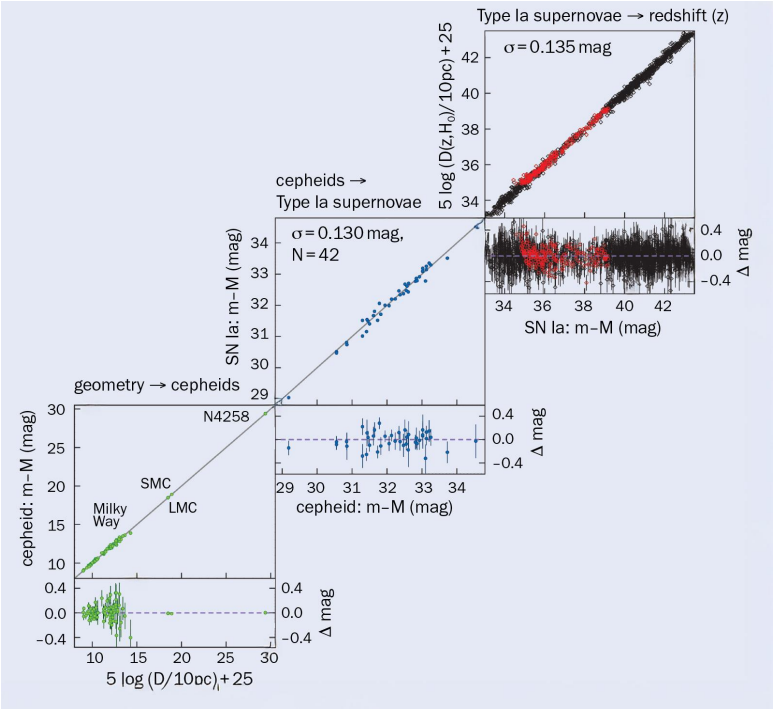
But! Not quite ready for precision cosmology…

- Working on calibration of system to achieve better than 1% photometric accuracy + scene modeling photometry
- DE equation of state: two ongoing efforts to cross-calibrate with high-z samples (required): ZTF + DES5Y and separately, ZTF + Subaru + SNLS Yr5
- *ZTF + Subaru + SNLS Yr5 data have not been used in any cosmological analysis before, hence all data completely independent from previous results – blinded data.*
- Ultimately, add LSST + Roman!

Work in progress…



H_0: distance ladder revisited



Known issues:

- Combines SNe measured with multiple instruments that need cross-calibration
- Cepheids only in a subset of all SNIa host galaxies, environmental differences
- Cepheids suffer significant crowding/extinction – hard to validate corrections

A simplified distance ladder

Volume limited ZTF SNIa both in the Hubble diagram as well as in anchoring galaxies with the Tip of the Red Giant Branch (TRGB) technique, avoid selection effects and cross-calibration issues.

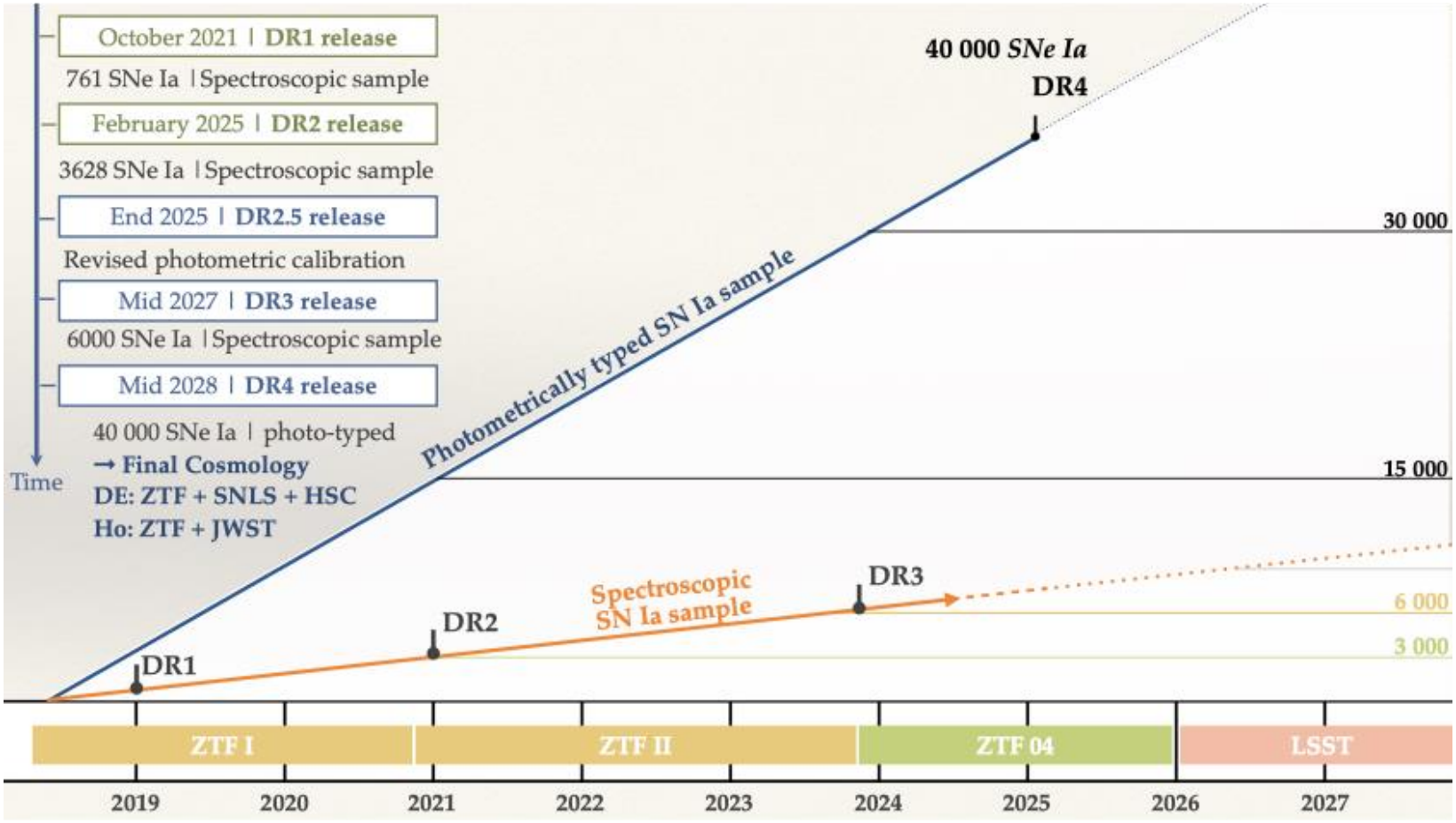
There are already ~40 SNe Ia in the ZTF sample within ~50 Mpc

JWST observations can provide independent distances to their host galaxies by means of TRGB measurements that can be used to calibrate SNIa luminosity

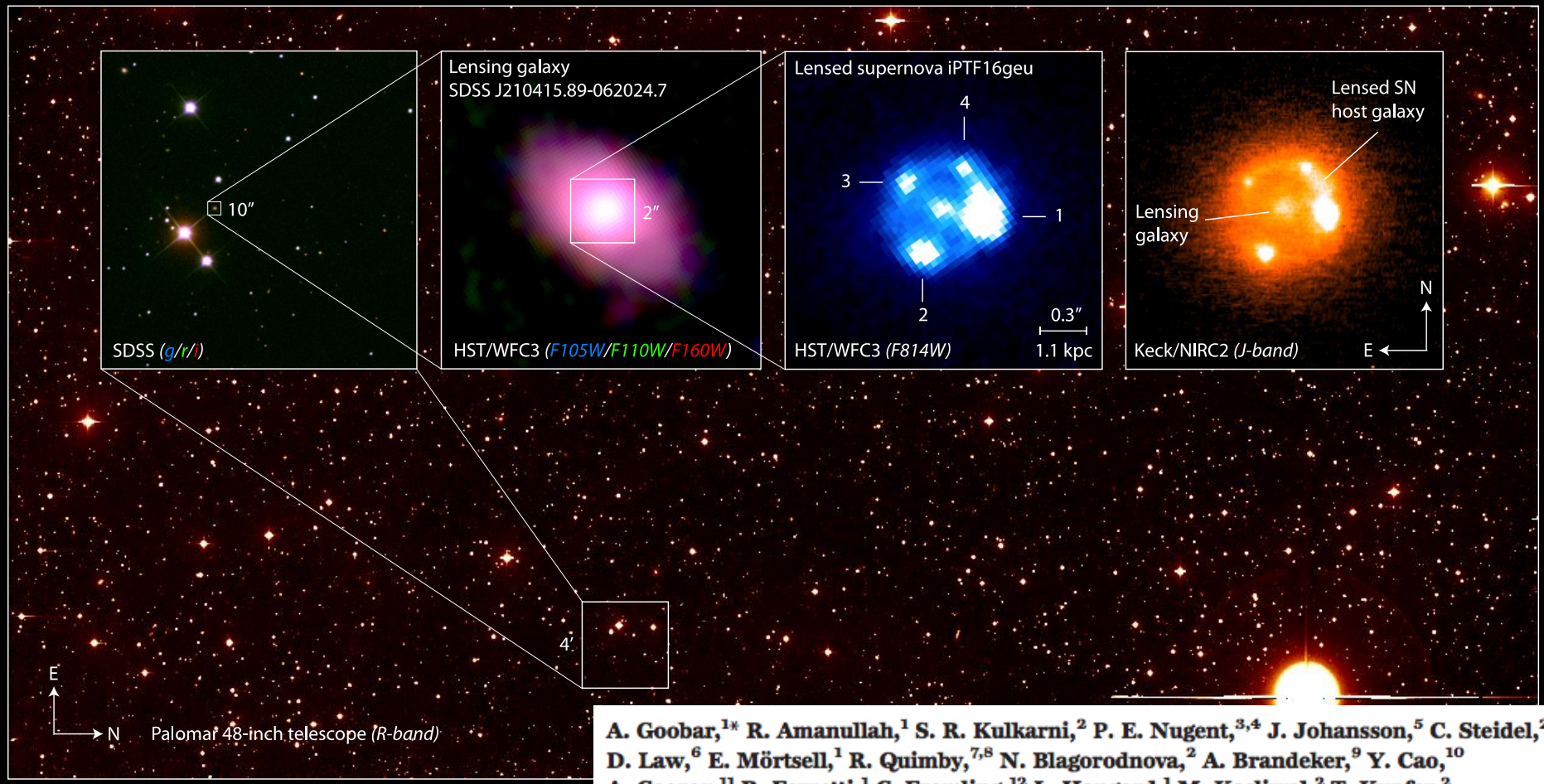
➔ All SNe observed with *single* instrument

+ TRGB technique avoids crowding/reddening issues + can be used for all host galaxy types, unlike Cepheids, only found in young, star-forming galaxies.

ZTF-Timeline



Strongly lensed SNe: a new window to cosmology



A. Goobar,[1*] R. Amanullah,[1] S. R. Kulkarni,[2] P. E. Nugent,[3,4] J. Johansson,[5] C. Steidel,[2] D. Law,[6] E. Mörtsell,[1] R. Quimby,[7,8] N. Blagorodnova,[2] A. Brandeker,[9] Y. Cao,[10] A. Cooray,[11] R. Ferretti,[1] C. Fremling,[12] L. Hangard,[1] M. Kasliwal,[2] T. Kupfer,[2] R. Lunnan,[2,9] F. Masci,[13] A. A. Miller,[14,15] H. Nayyeri,[11] J. D. Neill,[2] E. O. Ofek,[5] S. Papadogiannakis,[1] T. Petrushevska,[1] V. Ravi,[2] J. Sollerman,[12] M. Sullivan,[16] F. Taddia,[12] R. Walters,[2] D. Wilson,[11] L. Yan,[2] O. Yaron[5]

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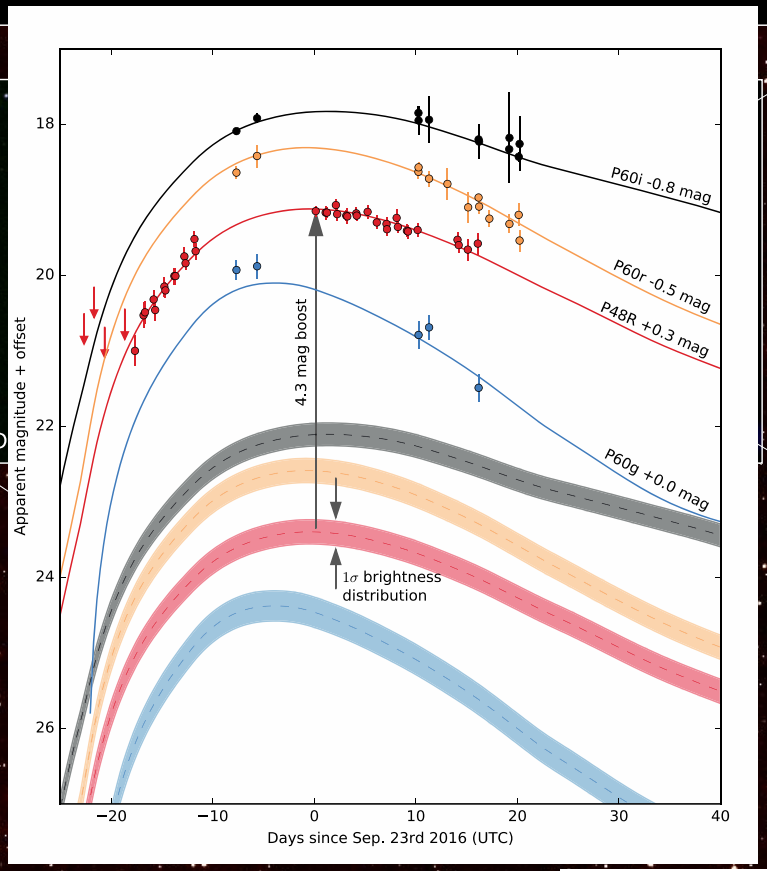
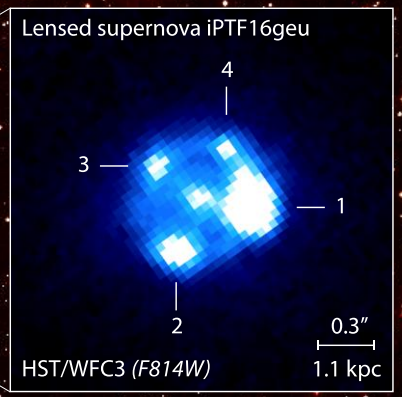
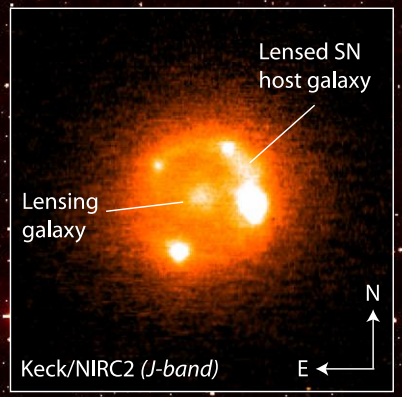


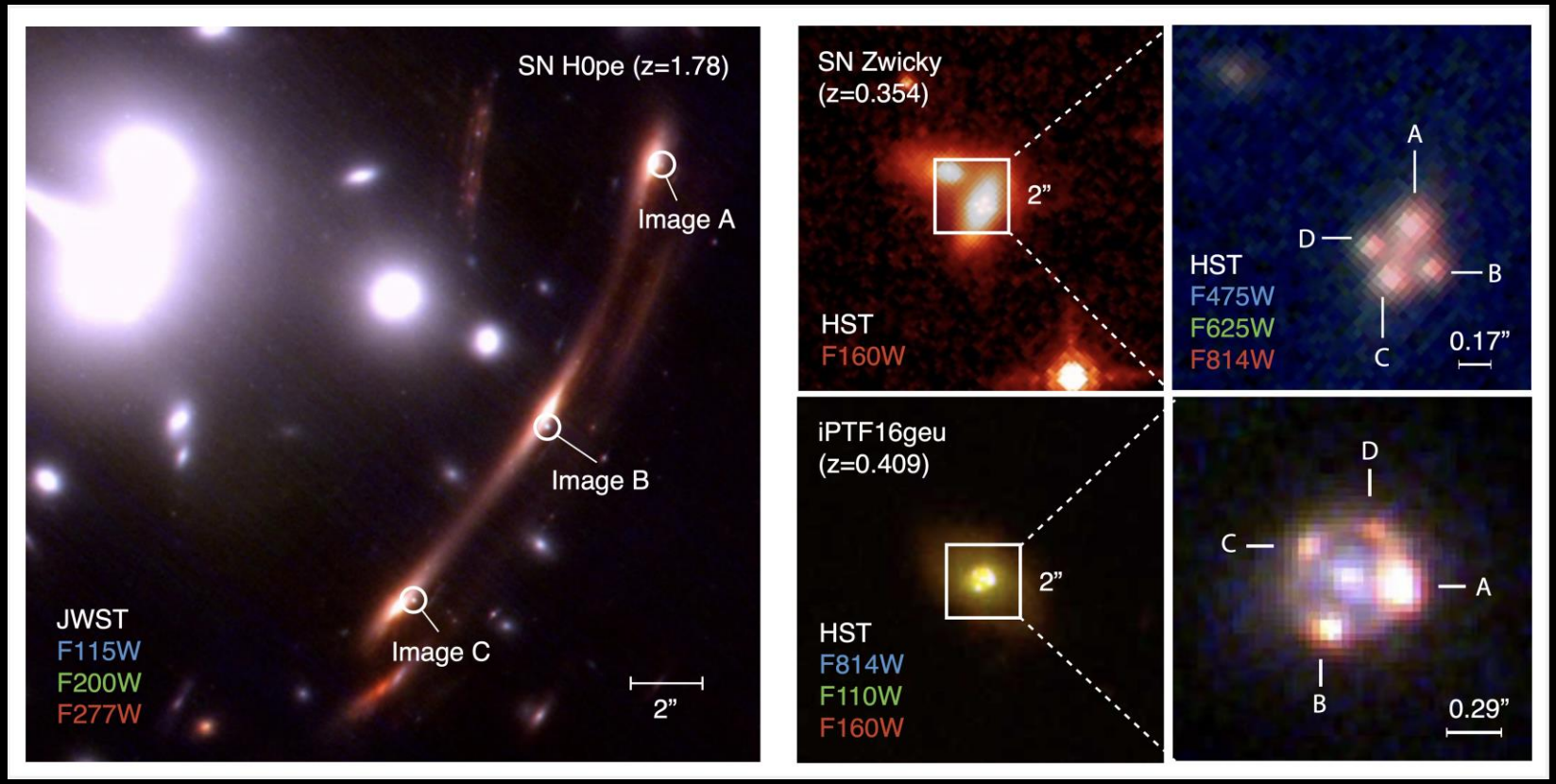




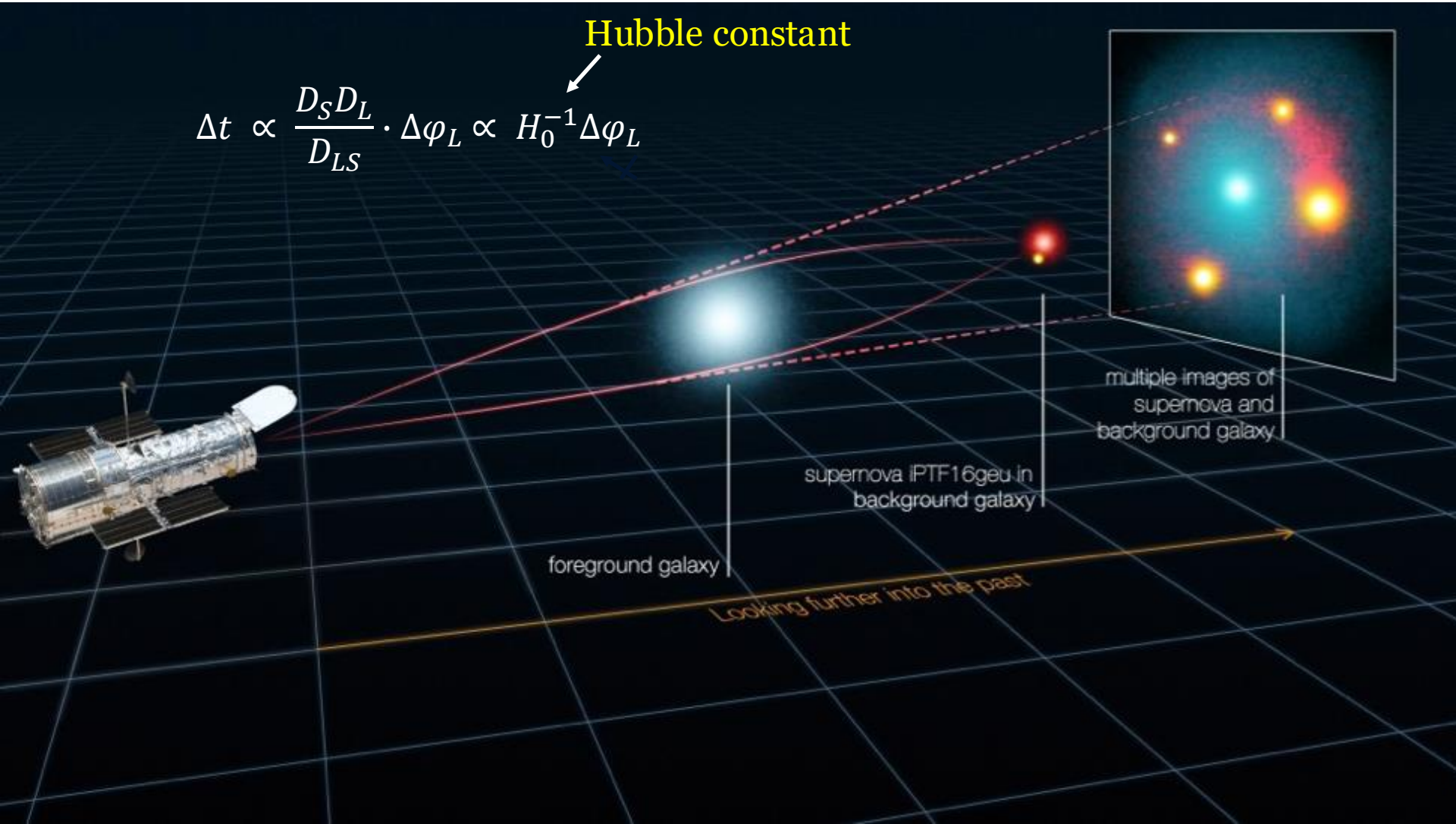
E
N
Palomar 48-inch telescope (*R-band*)

A. Goobar,[1*] R. Amanullah,[1] S. R. Kulkarni,[2] P. E. Nugent,[3,4] J. Johansson,[5] C. Steidel,[2] D. Law,[6] E. Mörtsell,[1] R. Quimby,[7,8] N. Blagorodnova,[2] A. Brandeker,[9] Y. Cao,[10] A. Cooray,[11] R. Ferretti,[1] C. Fremling,[12] L. Hangard,[1] M. Kasliwal,[2] T. Kupfer,[2] R. Lunnan,[2,9] F. Masci,[13] A. A. Miller,[14,15] H. Nayyeri,[11] J. D. Neill,[2] E. O. Ofek,[5] S. Papadogiannakis,[1] T. Petrushevska,[1] V. Ravi,[2] J. Sollerman,[12] M. Sullivan,[16] F. Taddia,[12] R. Walters,[2] D. Wilson,[11] L. Yan,[2] O. Yaron[5]

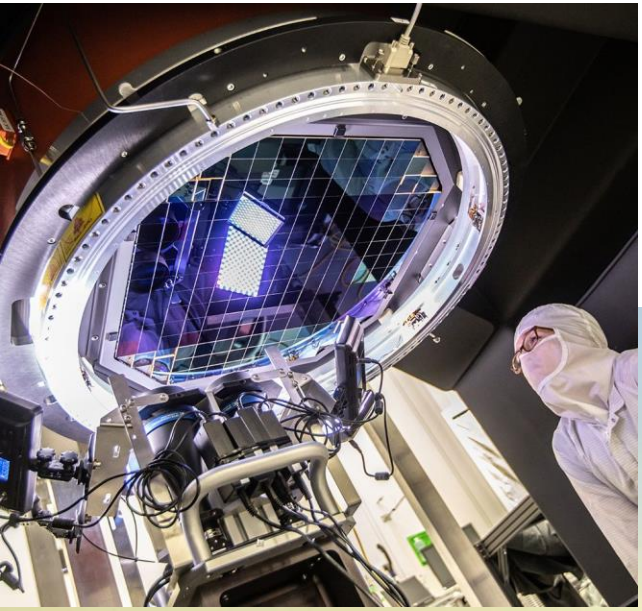
A new frontier in the era of time-domain surveys: gravitationally lensed supernovae



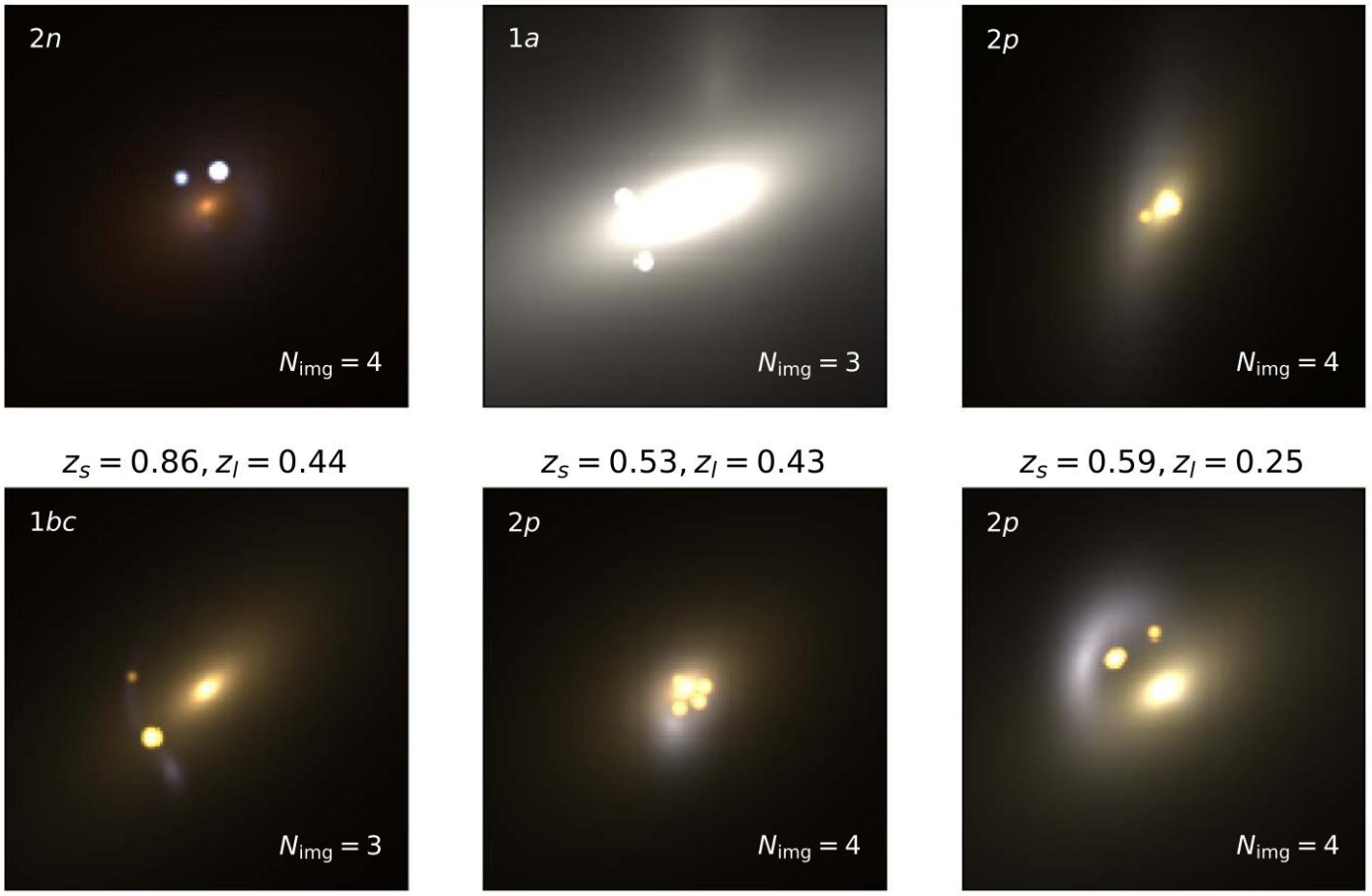
Time-delay cosmography



LSST: a discovery machine for lensed SNe!



Simulated events:
New lensed SNIa every *week*
New lensed CC SN every *day*?!!



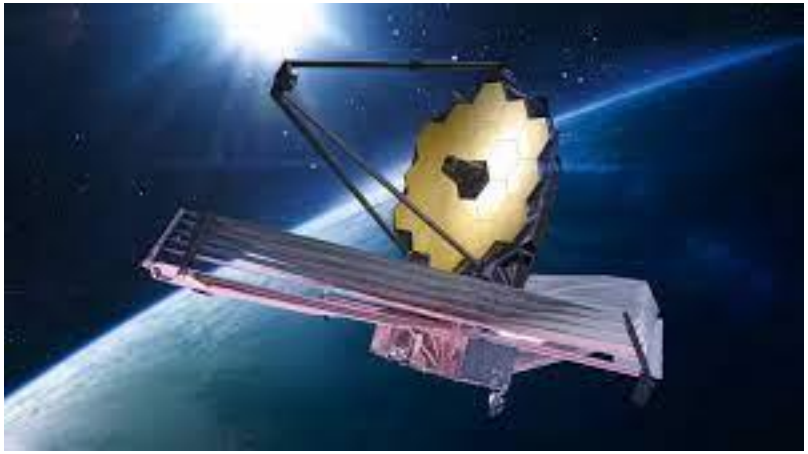
6”

Expect to achieve 1-2 % accuracy on H_o within first few years of operations

Goldstein, Nugent, AG 2019

Also Wojtak+19, Arendse+24

Great synergies with space missions!



JWST

Euclid

Roman – planned launch in 2027?

Summary

- Important challenges to ΛCDM depend critically on SNIa distances: the *low-redshift sample* limiting factor today
- ZTF is providing new key low-redshift SNIa data – single instrument, superior statistics, control of selection effects, special attention to calibration, etc.
- Expect big impact on precision cosmology – stay tuned!
- Opportunity to do a ZTF+JWST measurement of local H_0 that circumvents some of the issues with e.g., SH0sES
- Emerging technique in view of great sky coverage: *strongly lensed SNe* – independent test of Hubble tension.
- The golden era of time-domain surveys is here – LSST just saw first light….combination with ZTF + static data from EUCLID and DESI should revolutionatize the field!

Cảm ơn!