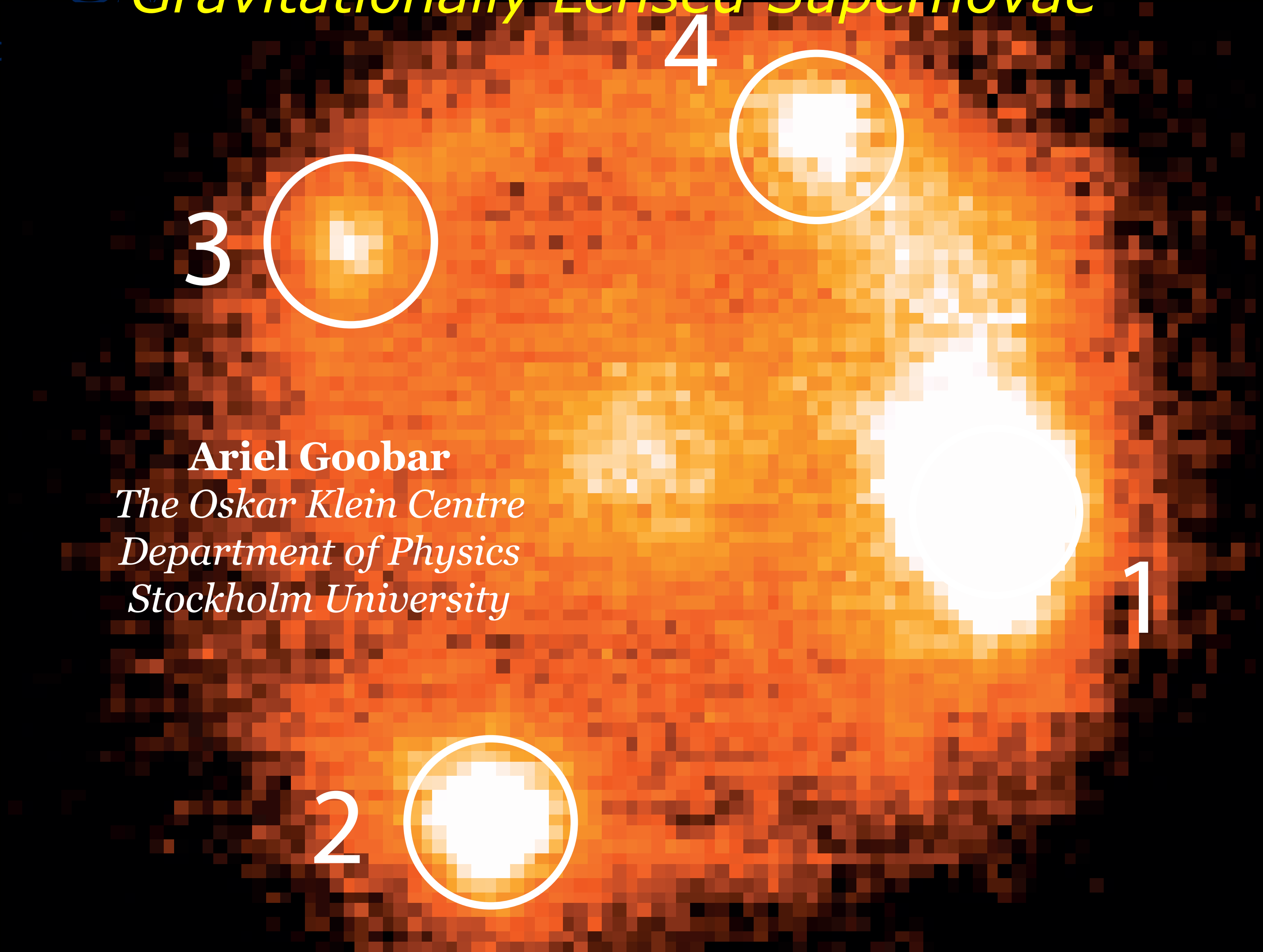
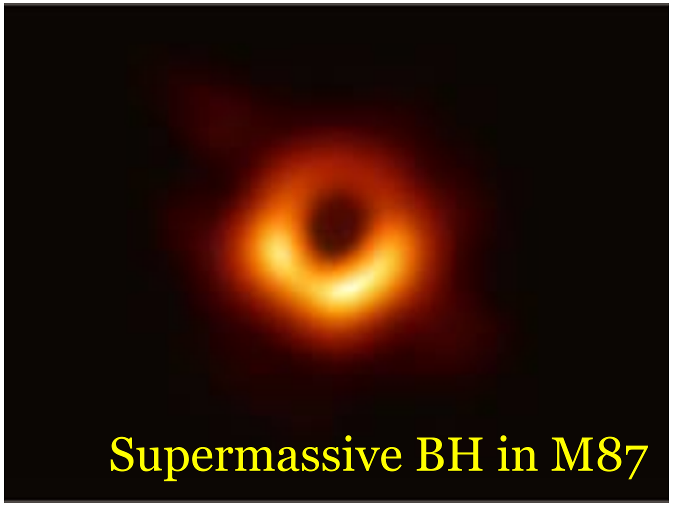
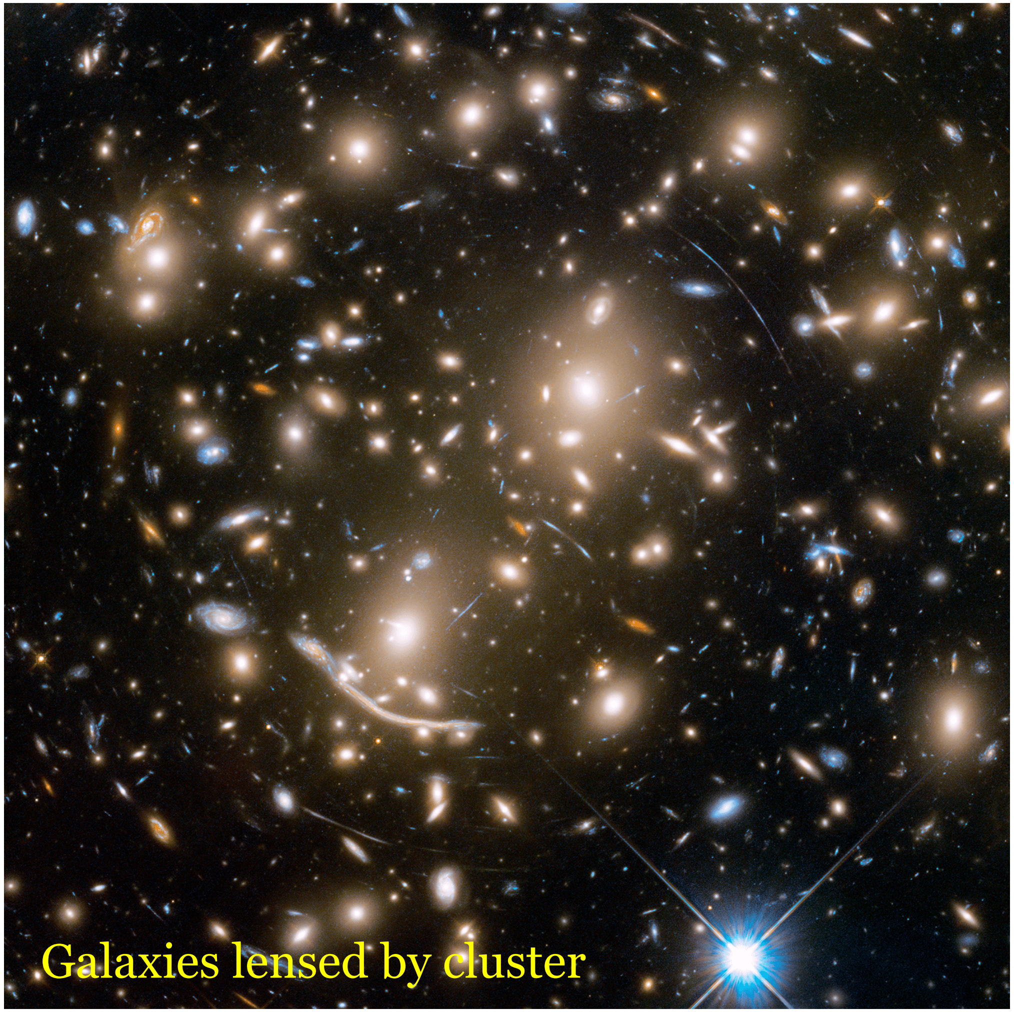
Spectrophotometric observations of Gravitationally Lensed Supernovae

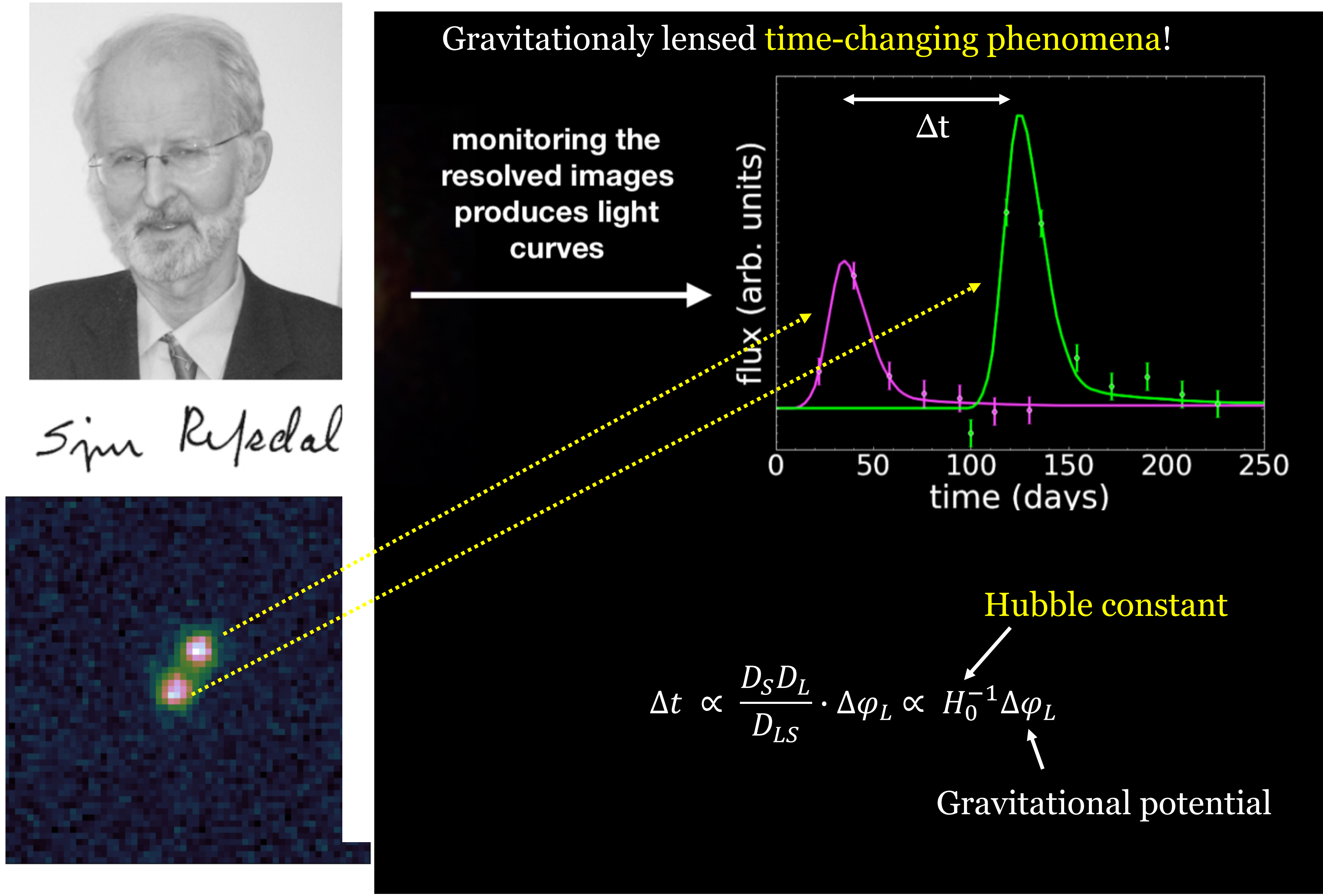


Ariel Goobar
The Oskar Klein Centre
Department of Physics
Stockholm University

Gravity in action:
strong lensing







Images take *different time to arrive* to us *depending on absolute distance scale*
Refsdal (1964): *Use SNe* as clocks to measure "time-delay", *measure Hubble constant!*

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In practice, until now, QSOs have been used instead of SNe

TDCOSMO. I. An exploration of systematic uncertainties in the inference of H_0 from time-delay cosmography

M. Millon[1], A. Galan[1], F. Courbin[1], T. Treu[2], S. H. Suyu[3,4,5], X. Ding[2], S. Birrer[6], G. C.-F. Chen[7], A. J. Shajib[2], K. C. Wong[8], A. Agnello[9], M. W. Auger[14,15], E. J. Buckley-Geer[20], J. H. H. Chan[1], T. Collett[17], C. D. Fassnacht[7], S. Hilbert[3], L. V. E. Koopmans[10], V. Motta[11], S. Mukherjee[12], C. E. Rusu[13], D. Sluse[12], A. Sonnenfeld[16], C. Spiniello[18,19], and L. Van de Vyvere[12]

(Affiliations can be found after the references)

December 18, 2019

ABSTRACT

Time-delay cosmography of lensed quasars has achieved 2.4% precision on the measurement of the Hubble Constant, H_0. As part of an ongoing effort to uncover and control systematic uncertainties, we investigate three potential sources: 1- stellar kinematics, 2- line-of-sight effects, 3- deflector mass model. To meet this goal in a quantitative way, we mimic closely the H0LiCOW/SHARP/STRIDES procedures (i.e., TDCOSMO), and we find the following. First, stellar kinematics cannot be a dominant source of error or bias given current uncertainties. Second, we find no bias arising from incorrect estimation of the line-of-sight effects. Third, we show that elliptical composite (stars + dark matter halo), power-law, and cored power-law mass profiles have the flexibility to yield a broad range in H_0 values. However, the TDCOSMO procedures to model the data with both composite and power-law mass profiles are informative. If the models agree, as we observe in real systems owing to the "bulge-halo" conspiracy, H_0 is recovered precisely by both models. If the two models disagreed, as in the case of some pathological models illustrated here, the TDCOSMO procedure would either be able to discriminate between them through the goodness of fit, or account for the discrepancy in the final error bars provided by the analysis. This conclusion is consistent with a reanalysis of the TDCOSMO (real) lenses: the composite model yields $H_0 = 74.2^{+1.6}_{-1.6}$ km s^{-1} Mpc^{-1}, while the power-law model yields $74.0^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}. In conclusion, we find no evidence of bias or errors larger than the current statistical uncertainties reported by TDCOSMO.

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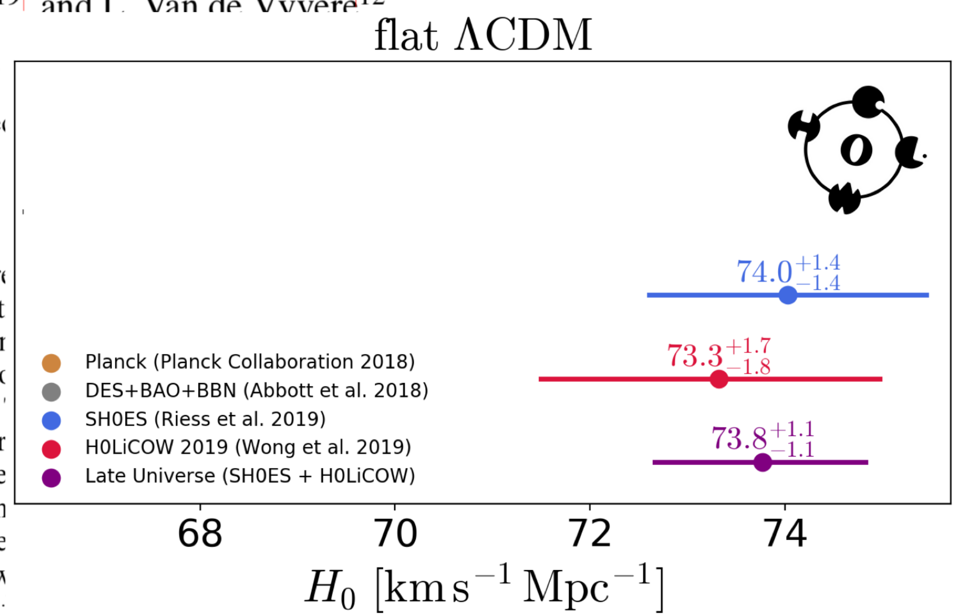

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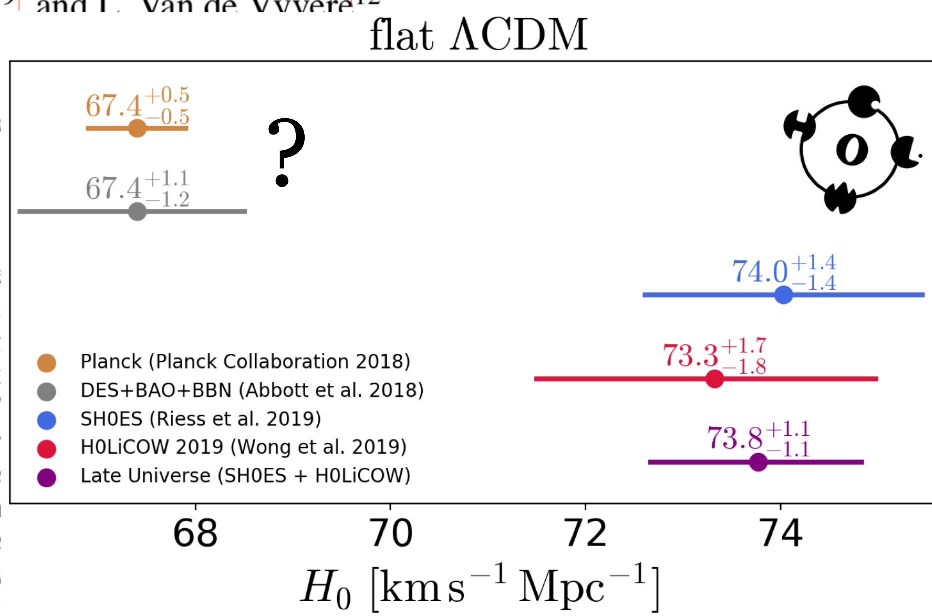
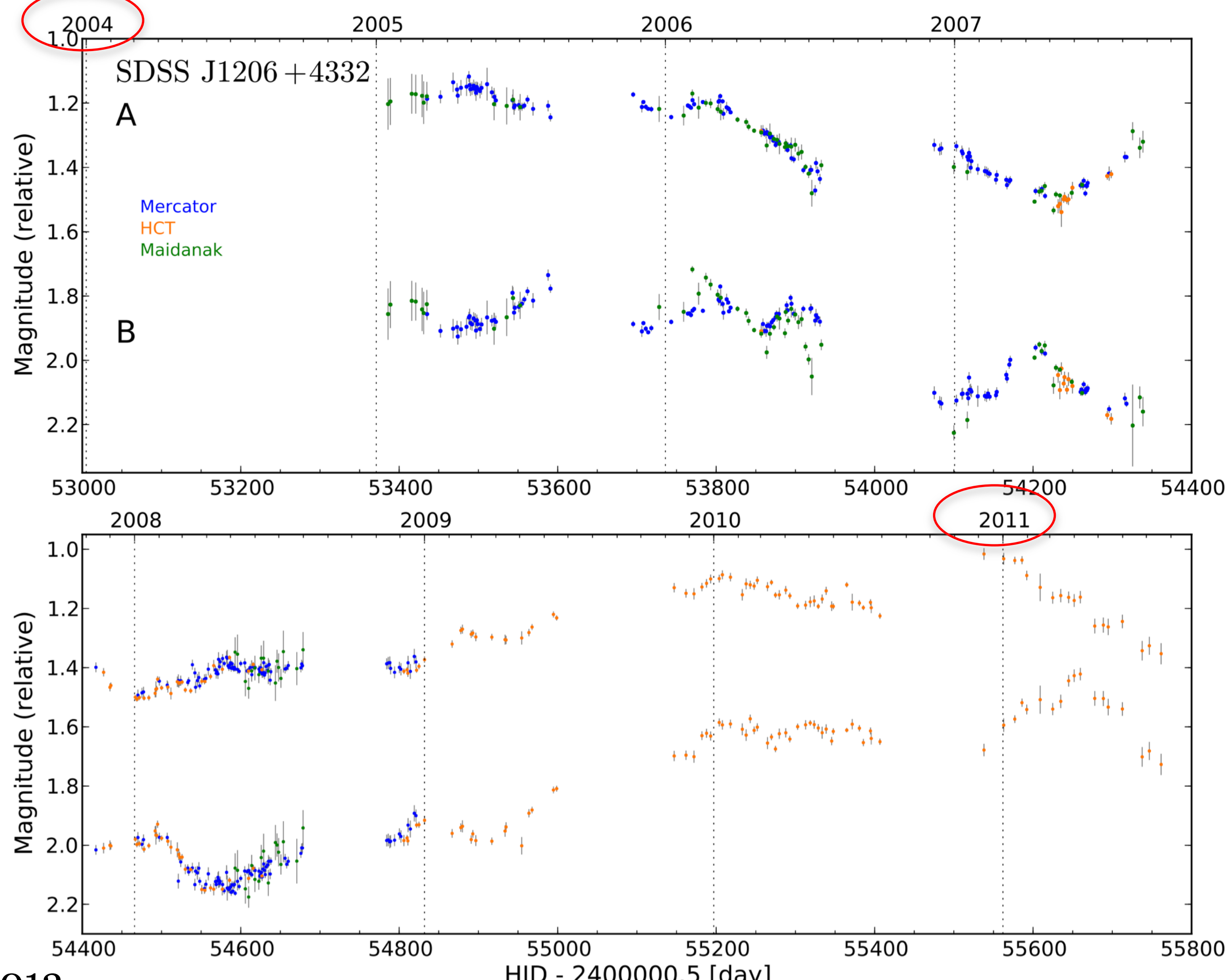
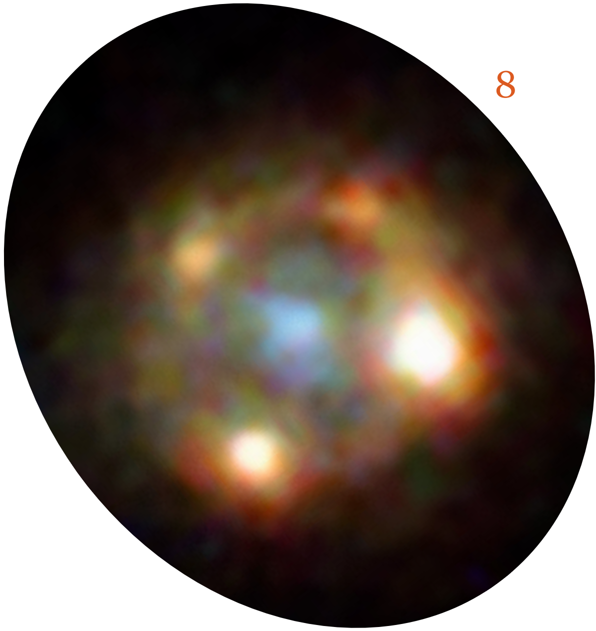


The "Hubble tension"

Hard measurement to do! Multi-year follow-up needed



Eulaers+2013

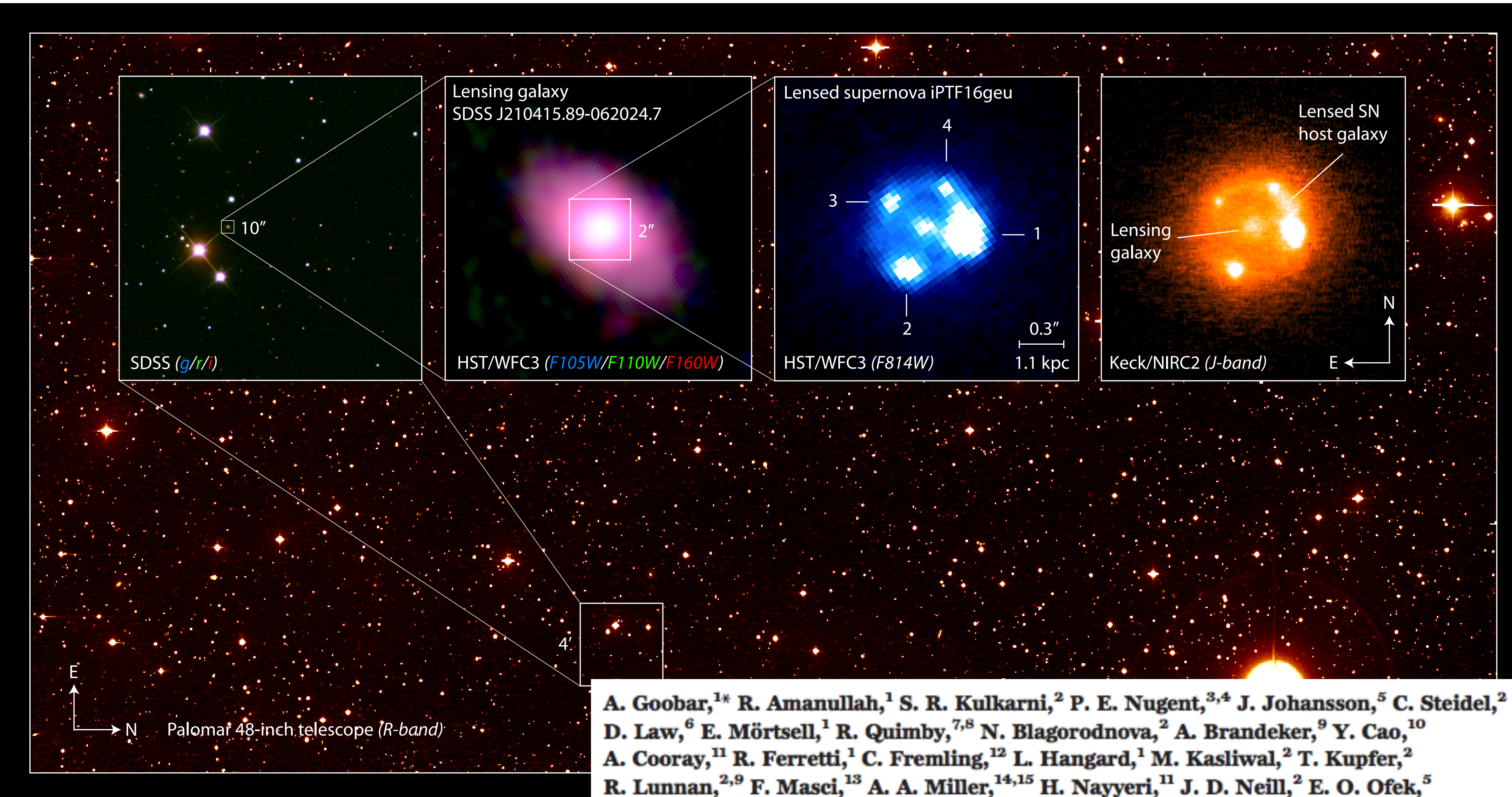


Strongly lensed Supernovae:

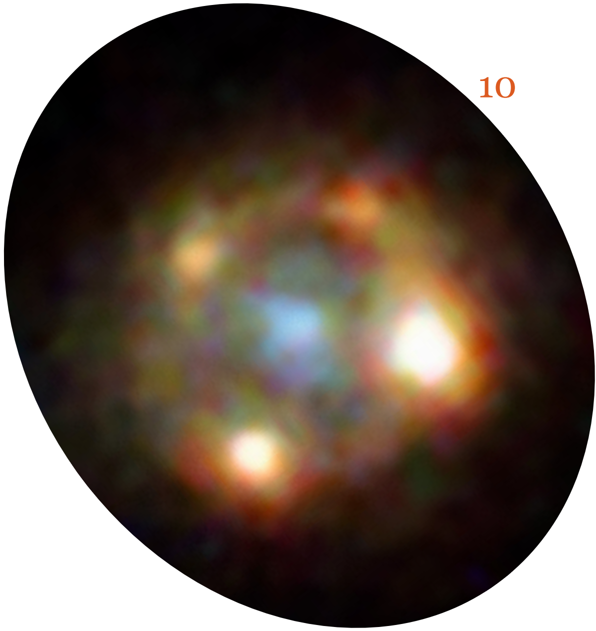
- Wide field time-domain surveys (ZTF, LSST) sample enough volume to find gravitationally lensed SNe (gLSNe)

- Follow-up with 10-m class telescopes over *a few weeks* can yield high-precision measurements of H_0 + it can probe a few more things:
sub-structures in inner core of lensing galaxies, mass fraction in compact objects, dust content in lens ISM, …

First resolved strongly lensed SNIa



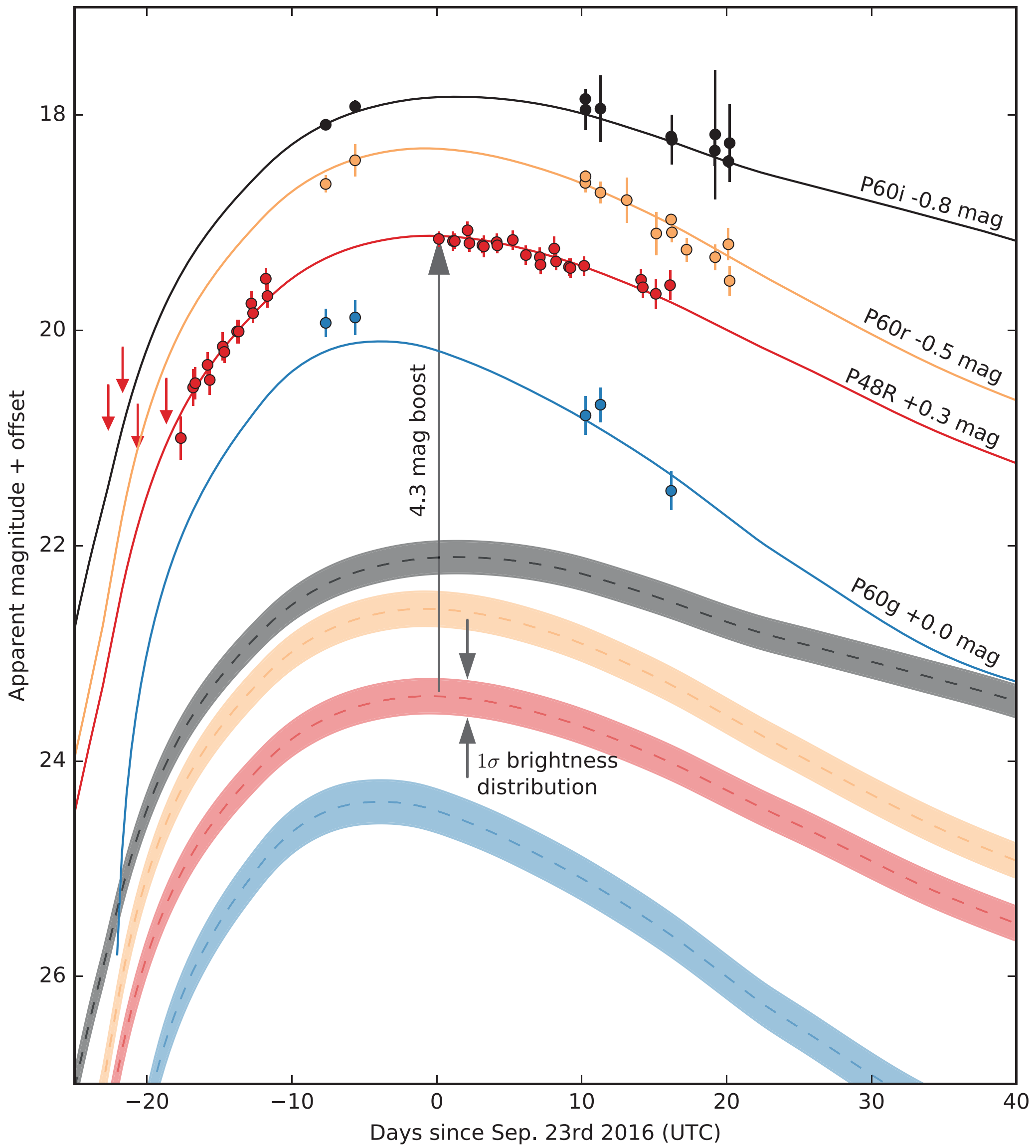
A. Goobar,[1*] R. Amanullah,[1] S. R. Kulkarni,[2] P. E. Nugent,[3,4] J. Johansson,[5] C. Steidel,[2] D. Law,[6] E. Mörtsell,[1] R. Quimby,[7,8] N. Blagorodnova,[2] A. Brandeker,[9] Y. Cao,[10] A. Cooray,[11] R. Ferretti,[1] C. Fremling,[12] L. Hangard,[1] M. Kasliwal,[2] T. Kupfer,[2] R. Lunnan,[2,9] 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]



Strongly lensed Supernovae:

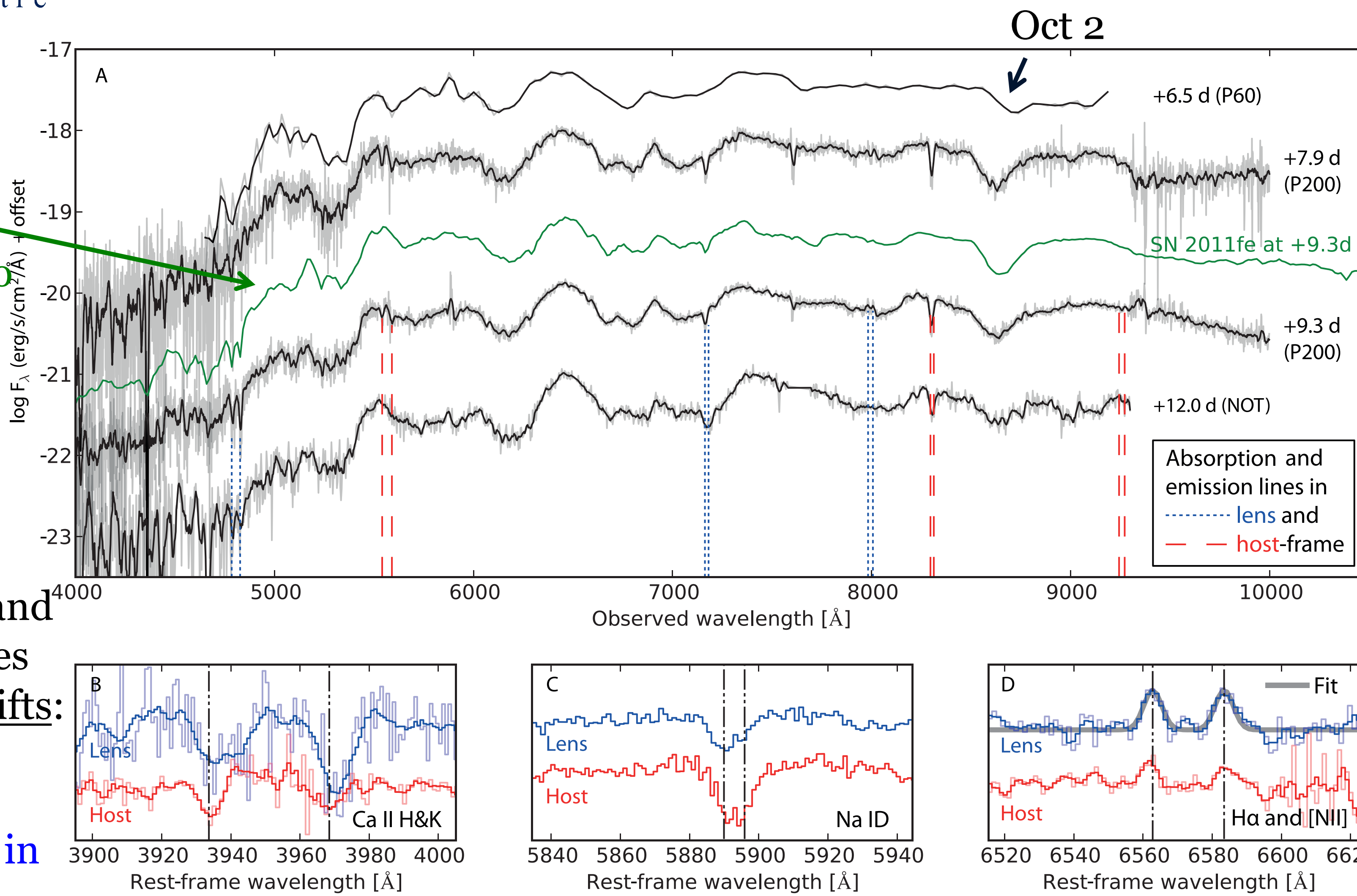
- How do we find them?
- Where does spectroscopy come in?

Much brighter than normal SNIa at z~0.4: >30σ outlier!



Perfect match to a z_s=0.409 SN Ia + intervening galaxy at z_l=0.216

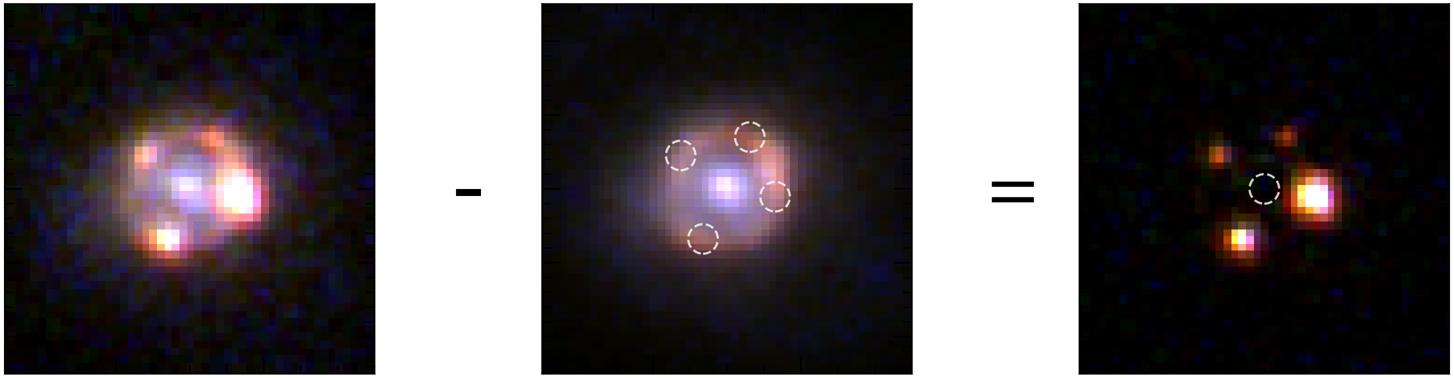
"Typical" SNIa redshifted to z=0.409



Absorption and emission lines at <u>two redshifts</u>: the SN host galaxy and other galaxy in line-of-sight

AG+17

Something you *cannot* do with lensed QSOs: get a clean shot at the lens after the SN faded!



2016 2018 Difference

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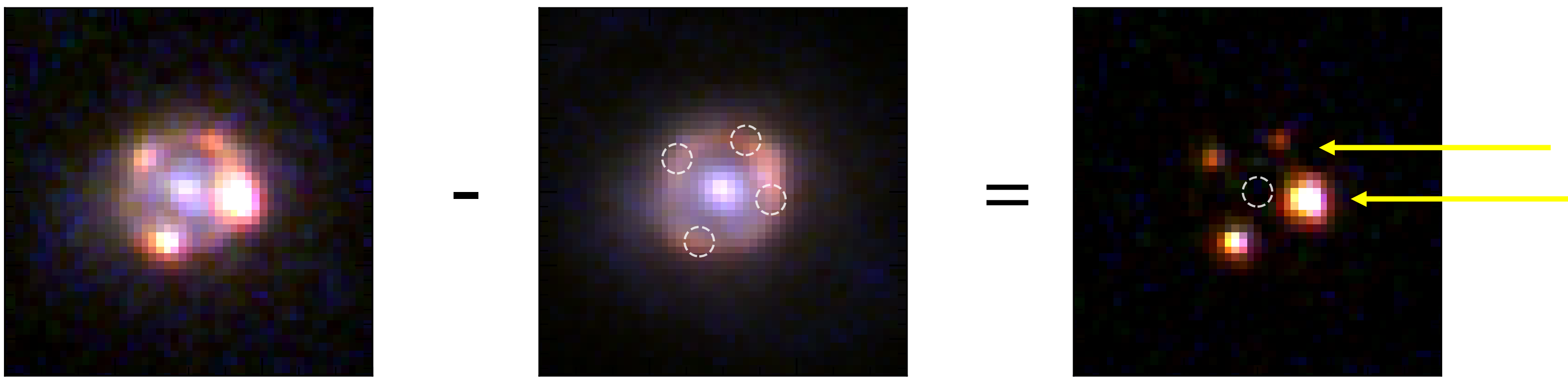


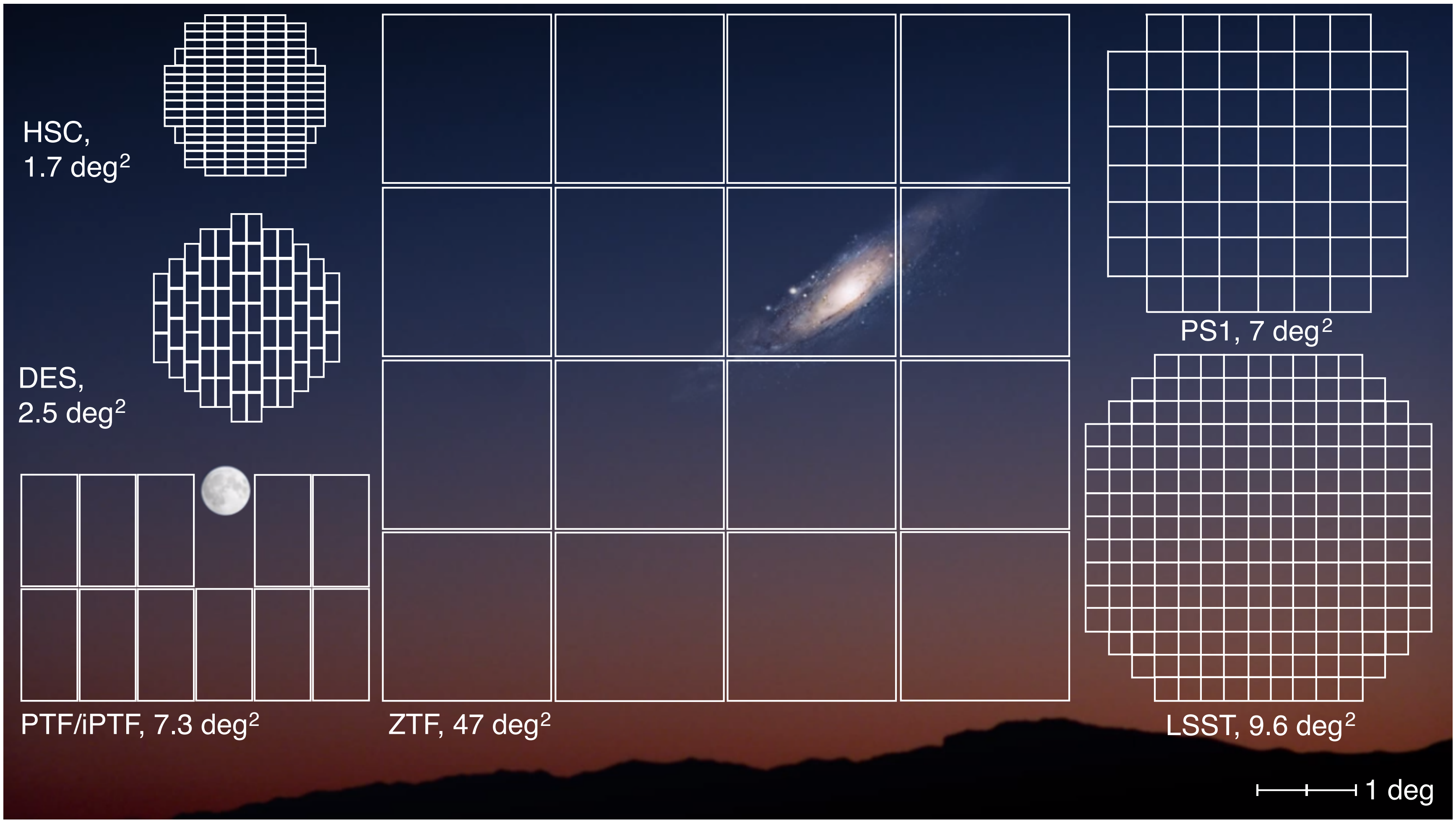
2016 2018 Difference

Surprisingly different brightness, in spite of symmetry:

1) Differential dimming by dust in the lens +
2) evidence for sub-structures milli/microlensing some of the images

The MAAT@GTC era: discoveries from ZTF-II & LSST

Huge search volumes!



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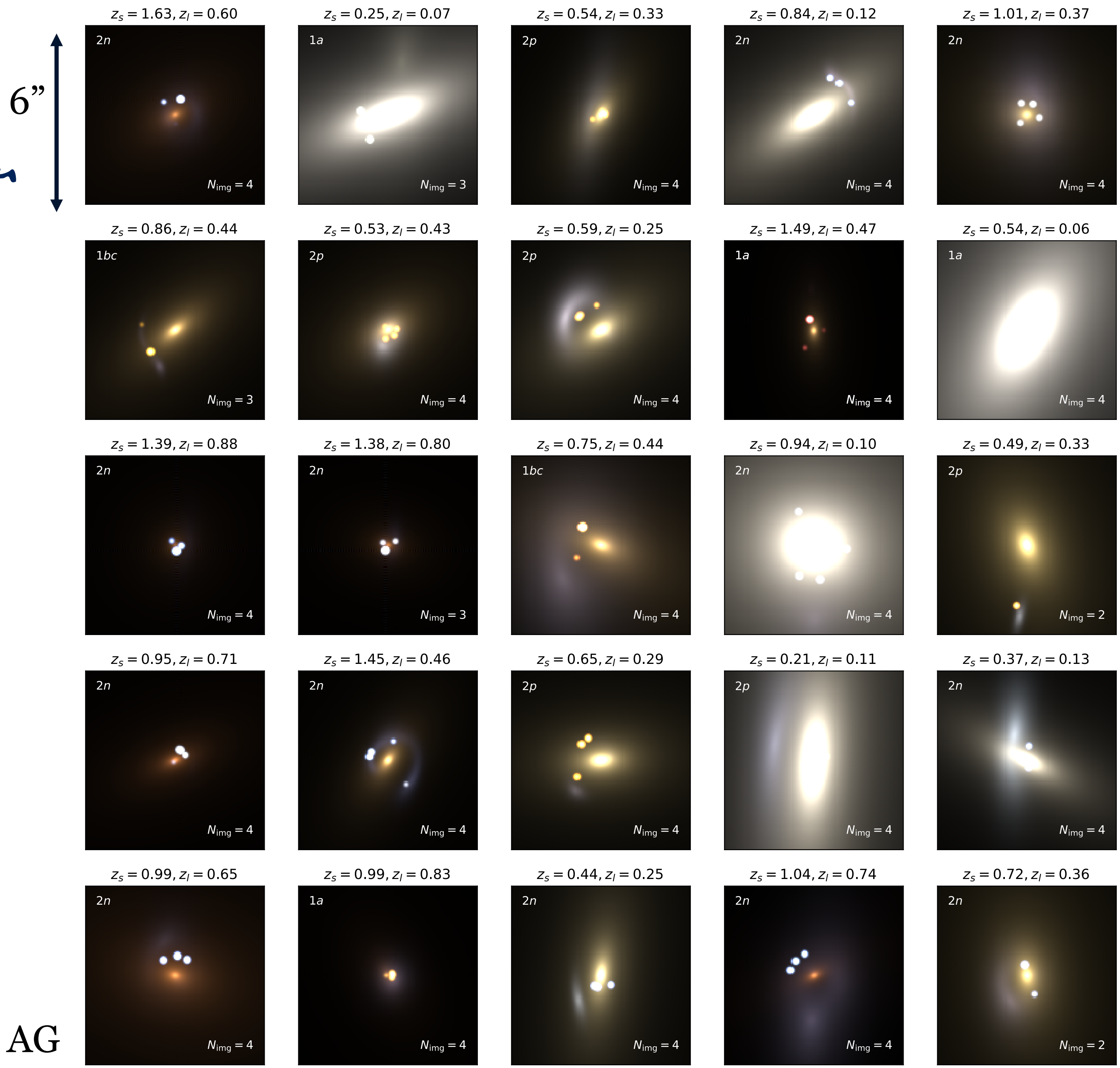
Simulated strongly lensed SNe discovered by ZTF-II:

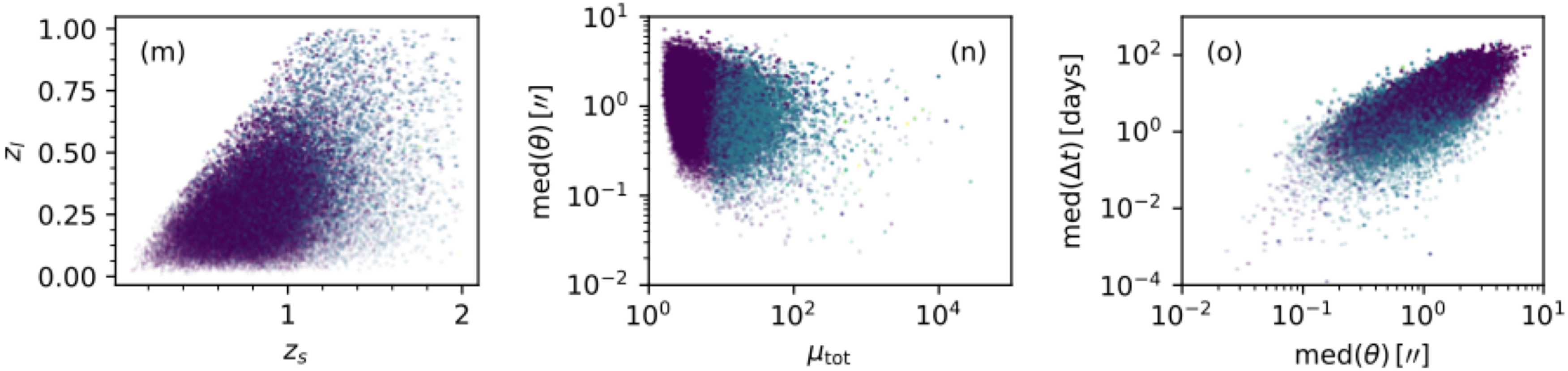
Should find a few (1/4 Ia’s)

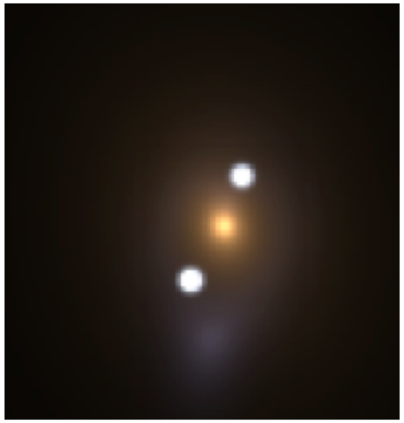
Nearly 400 with LSST!

Goldstein, Nugent, AG 2019



gLSNIa characteristics: LSST





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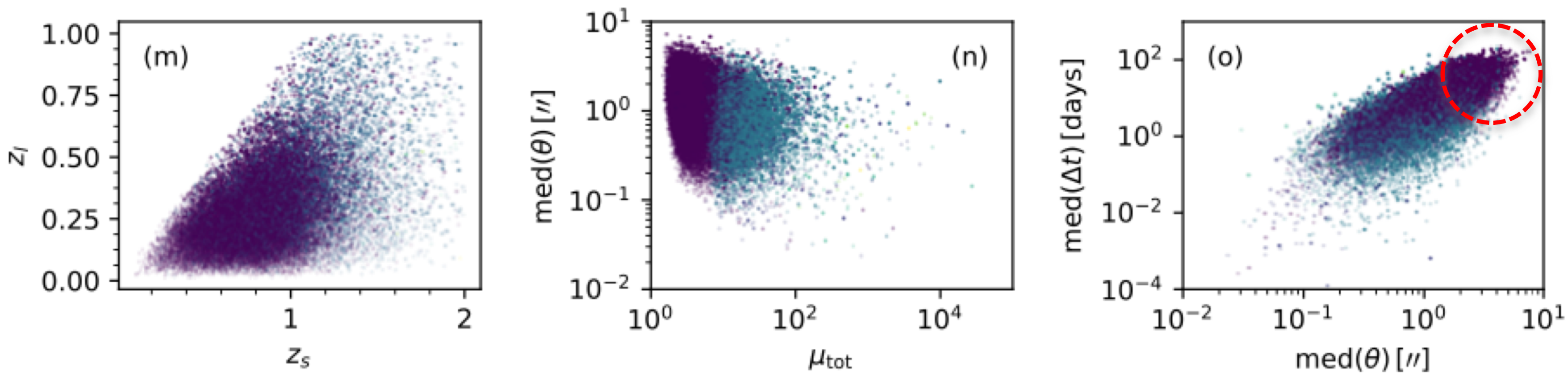
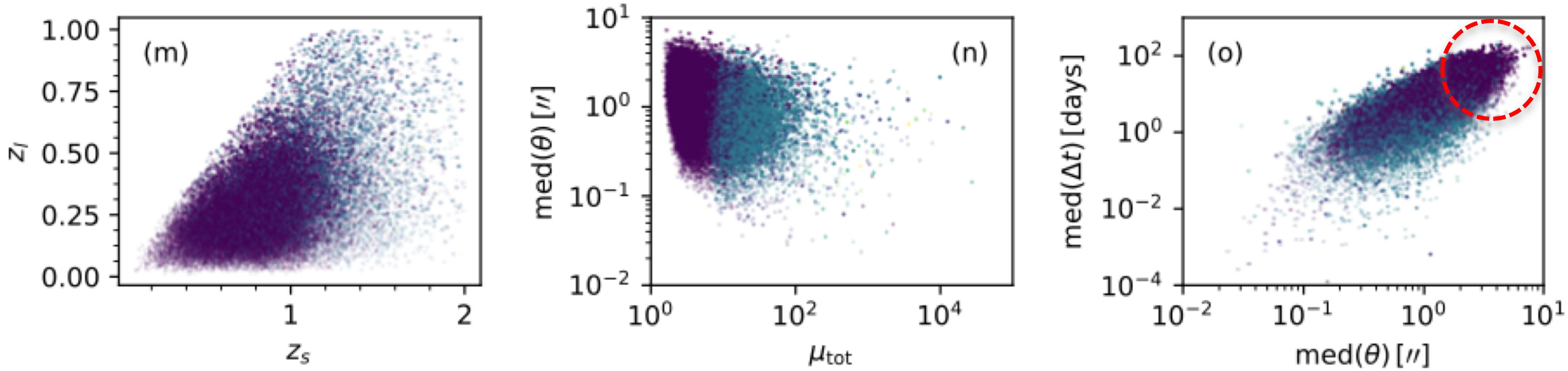
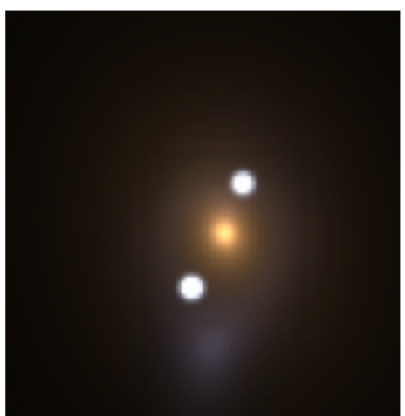
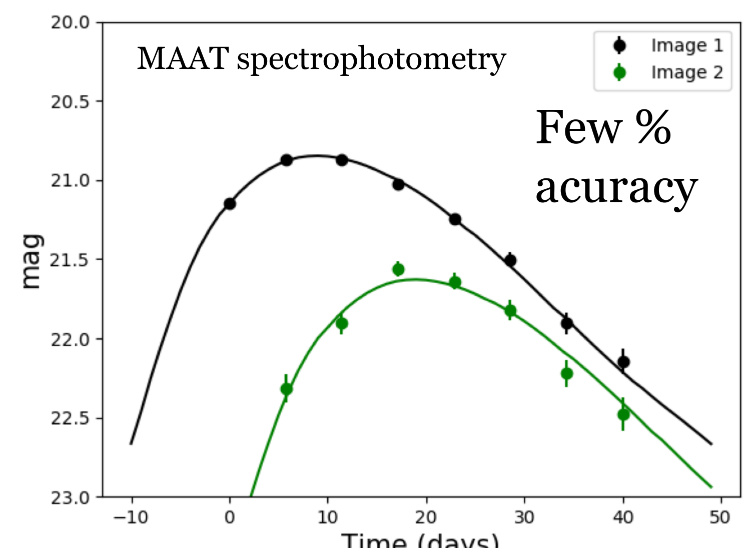


The spatially resolved systems we can study with MAAT are the ones which are best for measuring H_0!

gLSNIa characteristics: LSST





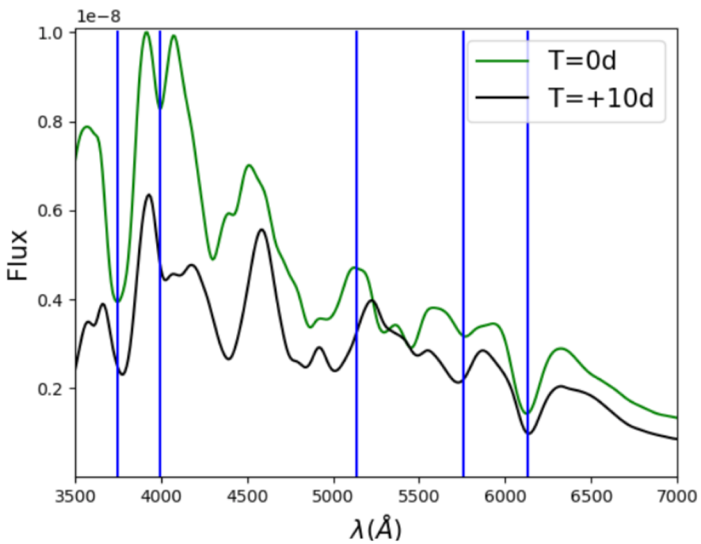


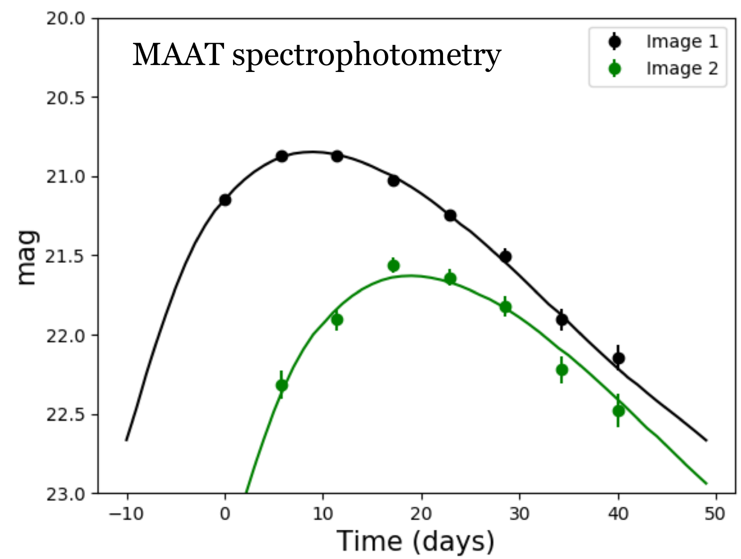
gLSNIa characteristics: LSST

Unique for supernovae: measure time-delays ***also*** from evolution of spectral features!

Demonstrated for iPTF16geu in Johansson+20

3% accuracy on time-delays very feasible





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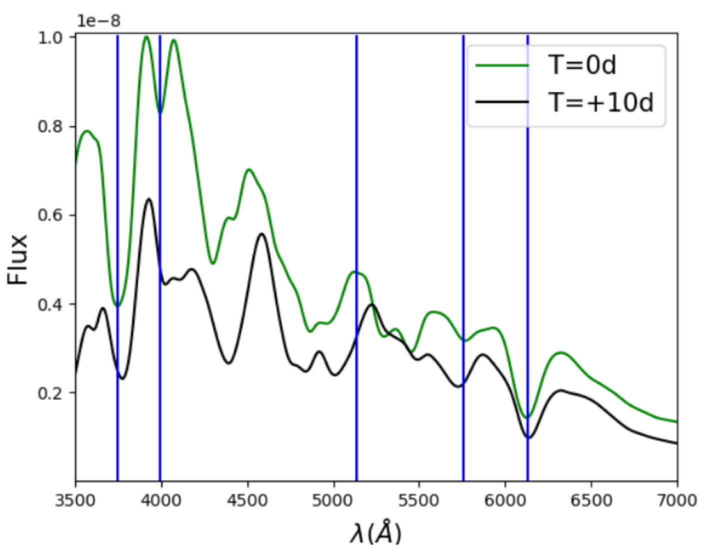

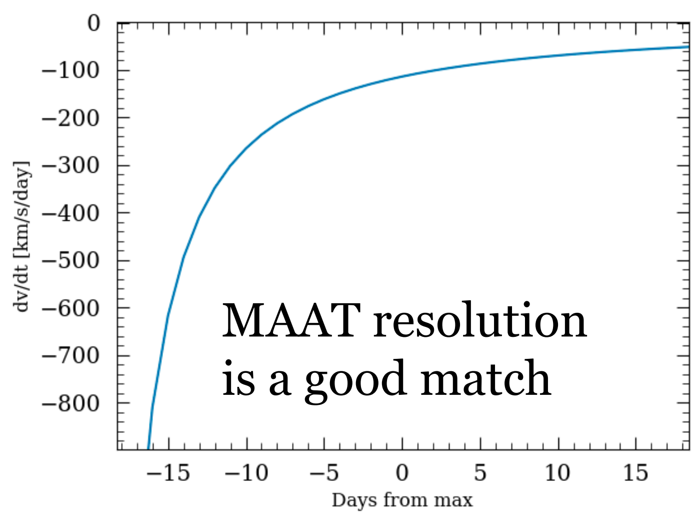

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Summary & Outlook

- Wide FoV transient surveys offer good means to find lensed supernovae, we have found one already!
- *ZTF-II should find a handful, LSST should find hundreds!*
- Spectrophotometric follow-up observations with MAAT@GTC could be a game changer: each system ”done” within just a couple of months and yield H_0 measurements of a few percent/system.
- Exploration of sub-structures: milli/microlensing affects magnification, but also perturbs later time spectral features.
- Unique insight into dust properties in inner cores of lensing galaxies
- Also to be presented here: how the observations aid the lens modelling

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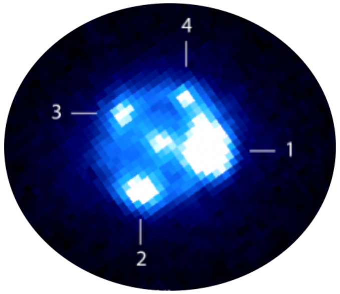

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