Cosmology and Stellar Physics with Lensed Supernovae

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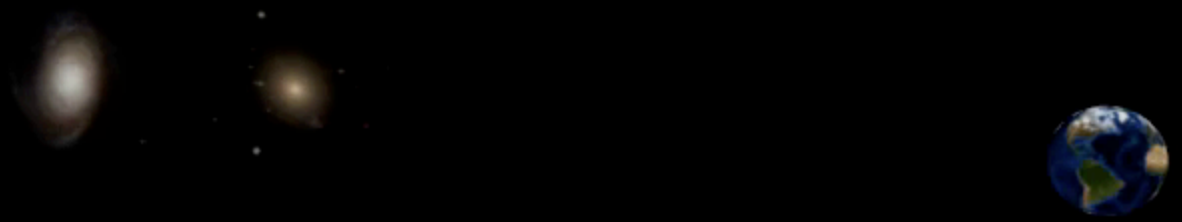
Time-Domain Cosmology with Strong Lensing workshop [online, Kavli IPMU]

Strongly lensed supernova event



[Credit: S. More]

How fast is our Universe expanding?

[Image Credit: NASA, ESA, A. James (STScI)]

- **Discord** between the H_0 measurements from the late-time Universe and early-time Universe
- if discrepancies in H_0 not due to measurement errors, then need ***new physics*** beyond the current standard ΛCDM cosmological model
- Independent methods necessary to assess tension

Cosmology with lensing delays

[Refsdal 1964]

Time delay:

$$t = \frac{1}{c} D_{\Delta t} \, \phi_{\text{lens}}$$

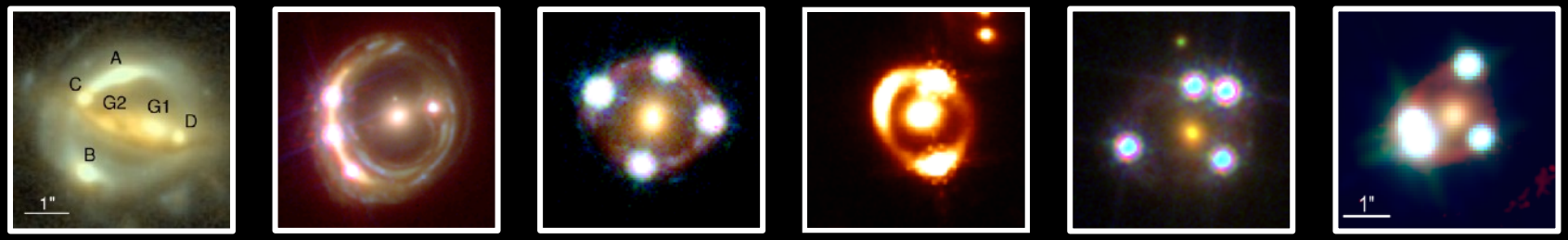
Time-delay distance:

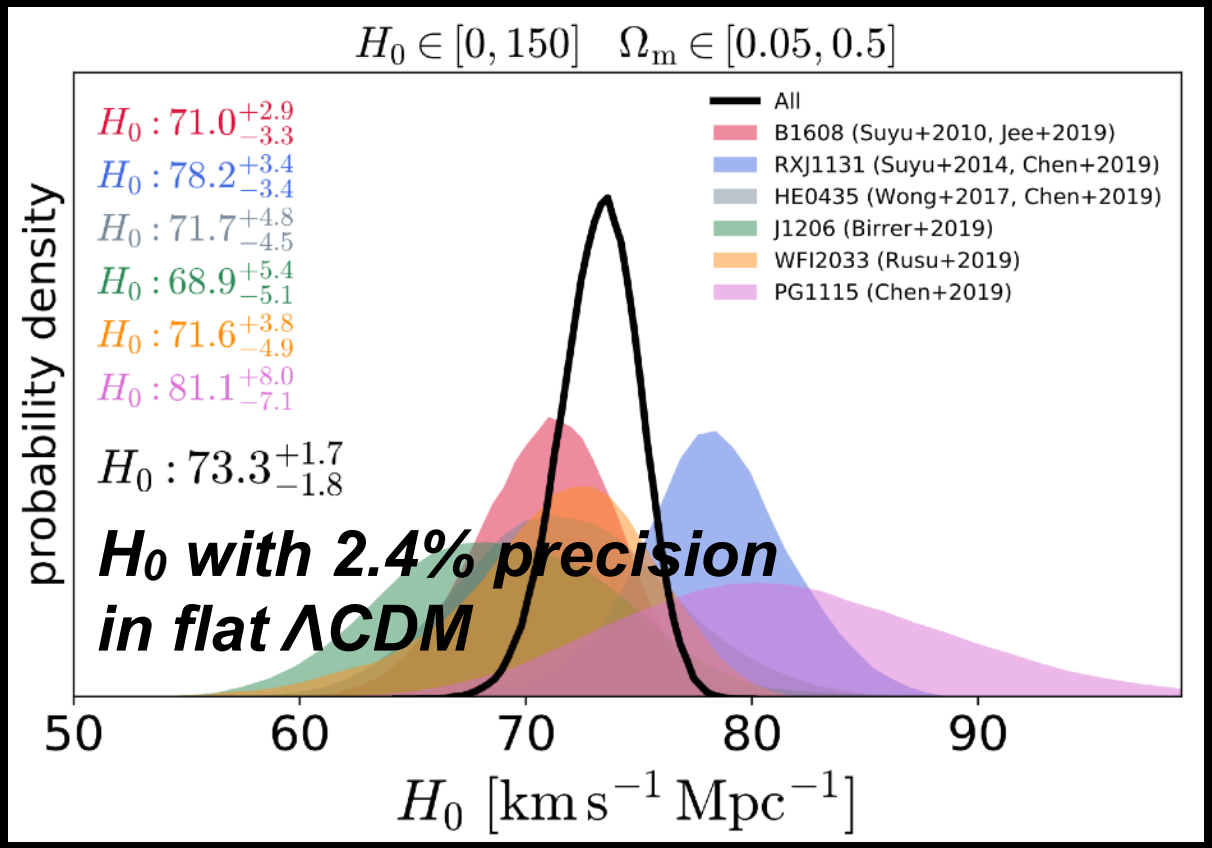
$$D_{\Delta t} \propto \frac{1}{H_0}$$

Obtain from lens mass model

For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

H0LiCOW: H_0 from 6 lensed quasars





Time delays:

- COSMOGRAIL
  ➜ ***M. Millon's talk***
- VLA [Fassnacht et al. 2002]

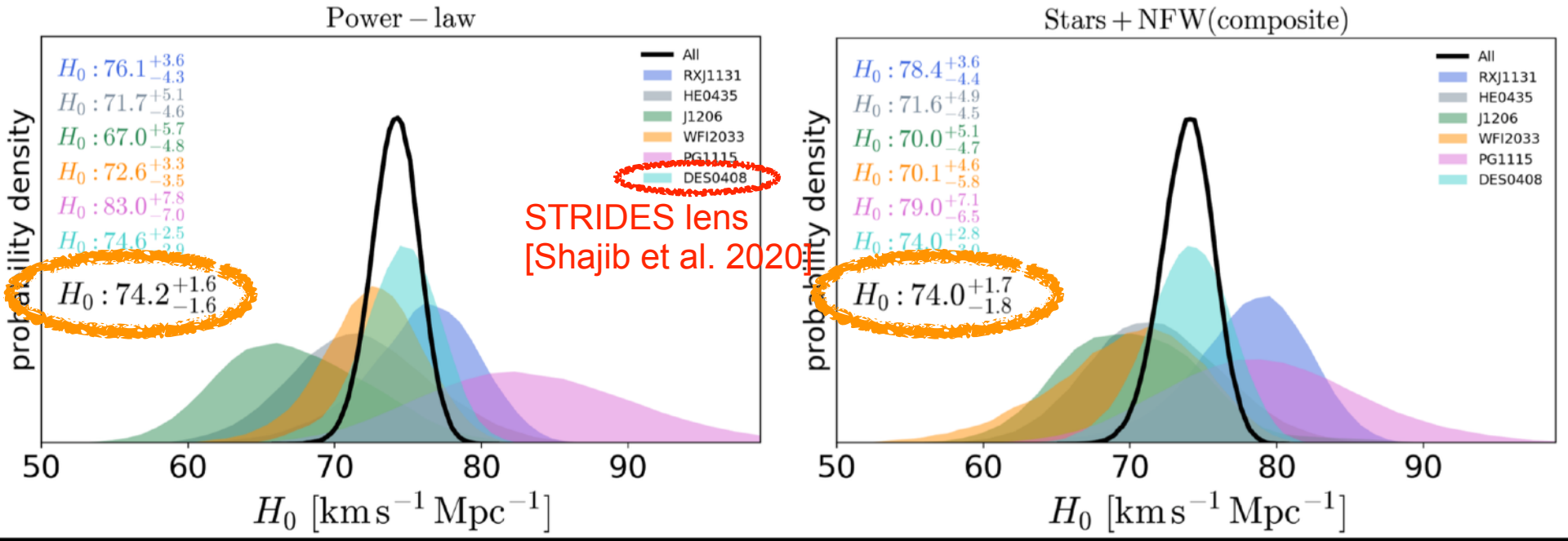
Modeling: HST & Keck AO [e.g., Wong et al. 2017; Chen et al. 2019; Birrer et al 2019]

LOS: wide-field imaging and spectroscopy [e.g., Sluse et al. 2019; Rusu et al. 2020]
➜ *also D. Gilman's talk*

Blind analysis!

[Wong, Suyu, Chen et al. 2020; H0LiCOW XIII]

Residual systematics?



[Millon, Galan, Courbin et al. 2020; TDCOSMO I]

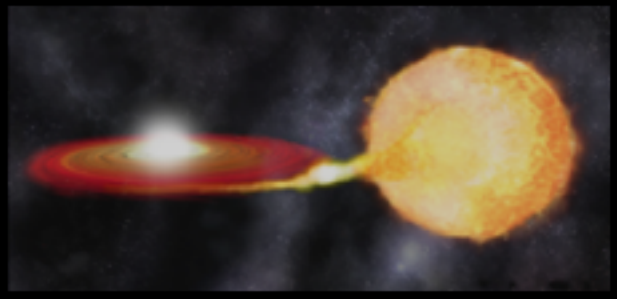
TDCOSMO = COSMOGRAIL + H0LiCOW + STRIDES + SHARP

Two different families of model yield same H_0 within 1%

➜ *also talks by A. Agnello, X. Ding, M. Gomer, N. Li, L. Van de Vyvere, D. Xu*
➜ *S. Birrer's talk for 1-parameter extension of mass-sheet transformation*
➜ *spatially-resolved kinematics of lens really help [Yıldırım et al. 2020, in prep.]*

Progenitors of Type Ia SN

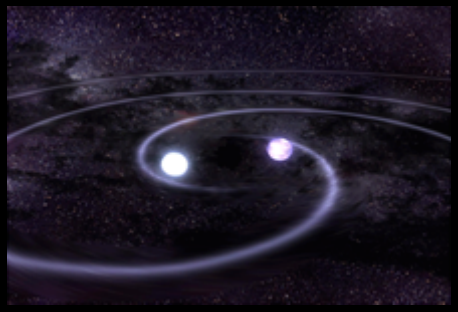
single degenerate



White dwarf (WD) accreting from non-degenerate companion

or

double degenerate



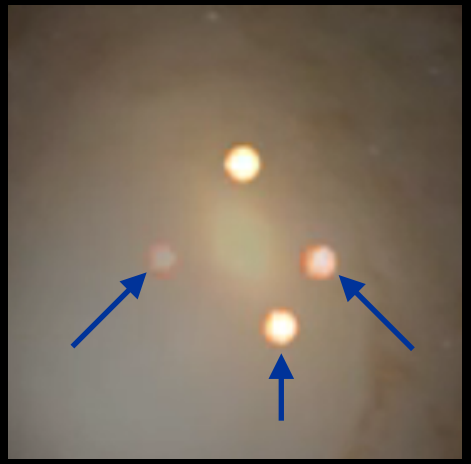
WDs merging

or something else? e.g. double detonation?

Unveiling SN Ia progenitors

Detect first
SN image

Predict location/time
of next SN image(s)

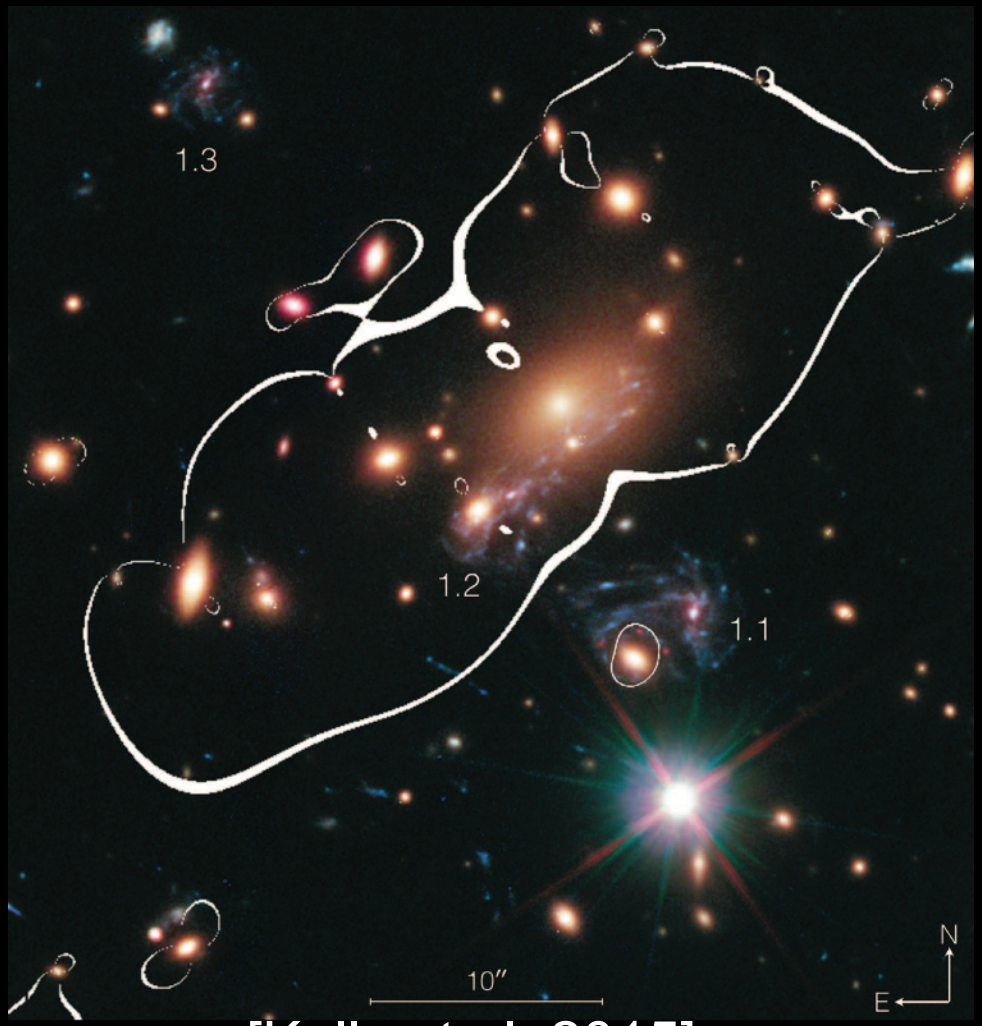


Observe early phase
of next SN image(s)

Strongly lensed SNe allow observations of early-phase light curves and spectra to constrain progenitor scenarios

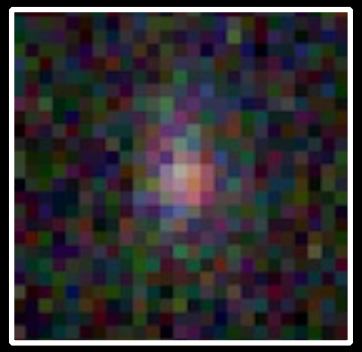
Strongly lensed supernova

SN Refsdal



[Kelly et al. 2015]

PS1-10afx



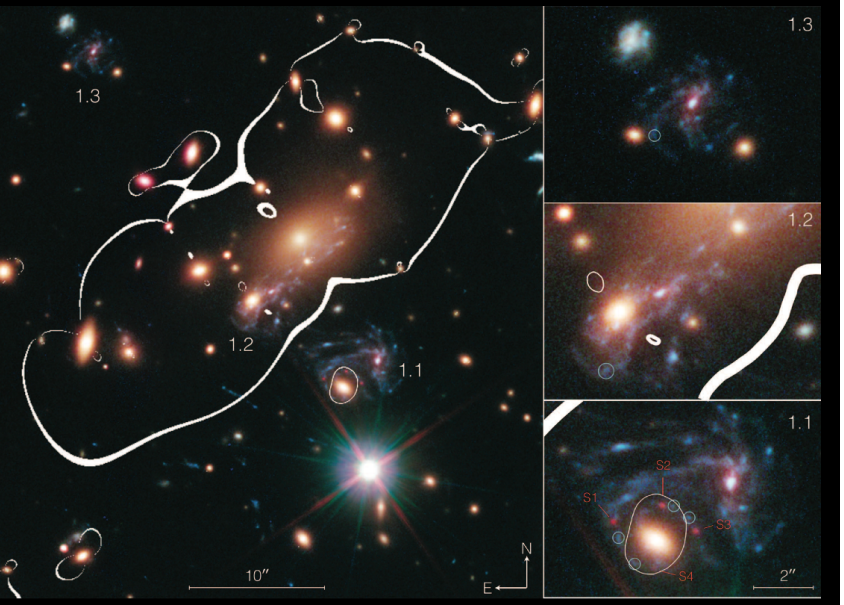
[Quimby, Oguri, More et al. 2014 image credit: CFHT]

iPTF16geu

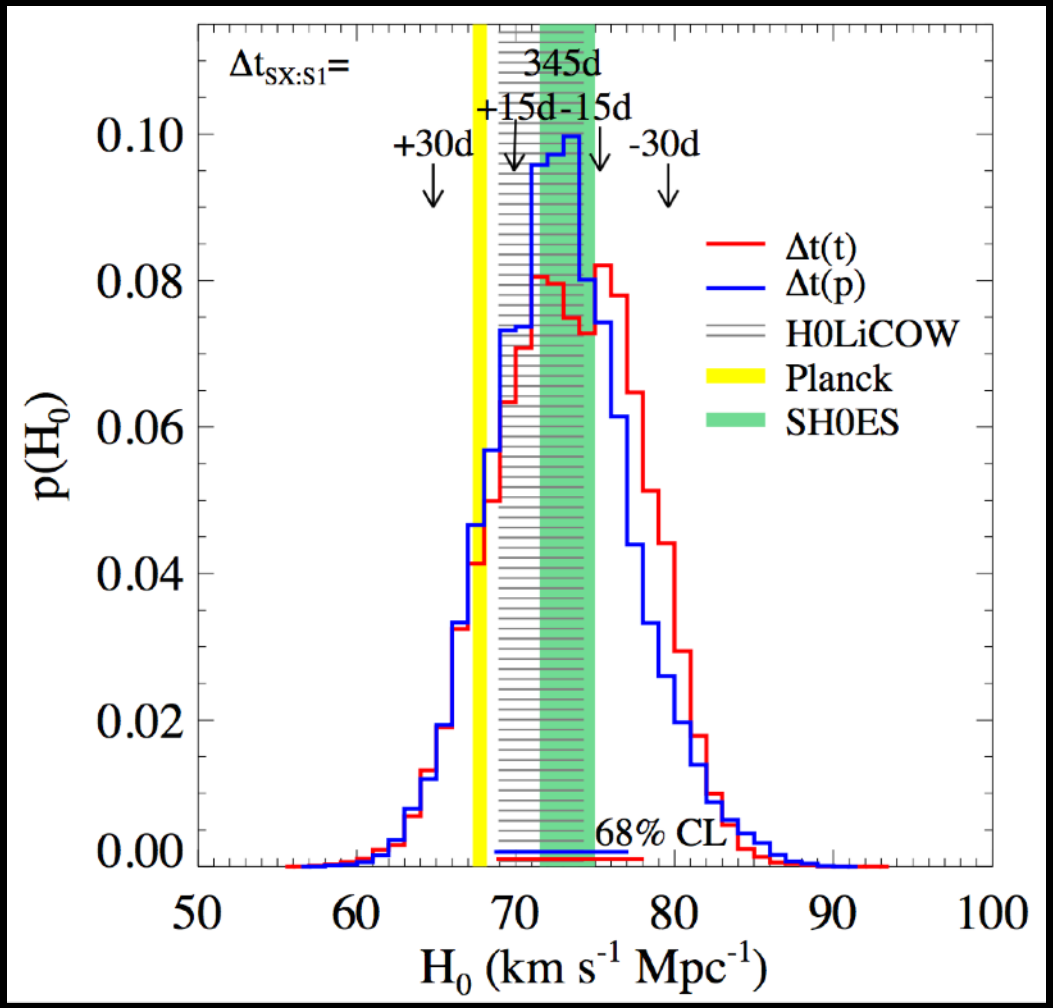
[Goobar et al. 2017; image credit: NASA/ESA]

H_0 à la Supernova Resfdal

feasibility study of using SN Refsdal for H_0 measurement



- S1-S2-S3-S4 delays from Rodney et al. (2016)
- SX-S1 delay estimated based on detection in Kelly et al. (2016)



[Grillo, Rosati, Suyu et al. 2018, 2020]

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HOLISMOKES!

Highly **O**ptimised **L**ensing **I**nvestigations of **S**upernovae, **M**icrolensing **O**bjects, and **K**inematics of **E**lliptical and **S**pirals

[Suyu, Huber, Cañameras et al. 2020]

HOLISMOKERS


Jana Bayer


Raoul Cañameras

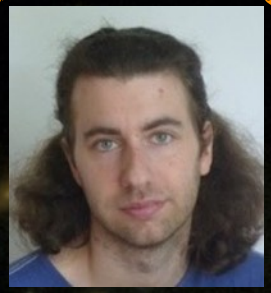

James Chan


Frédéric Courbin


Simon Huber


Markus Kromer


Uli Nöbauer


Stefan Schuldt


Yiping Shu


Stuart Sim


Dominique Sluse


Sherry Suyu (PI)

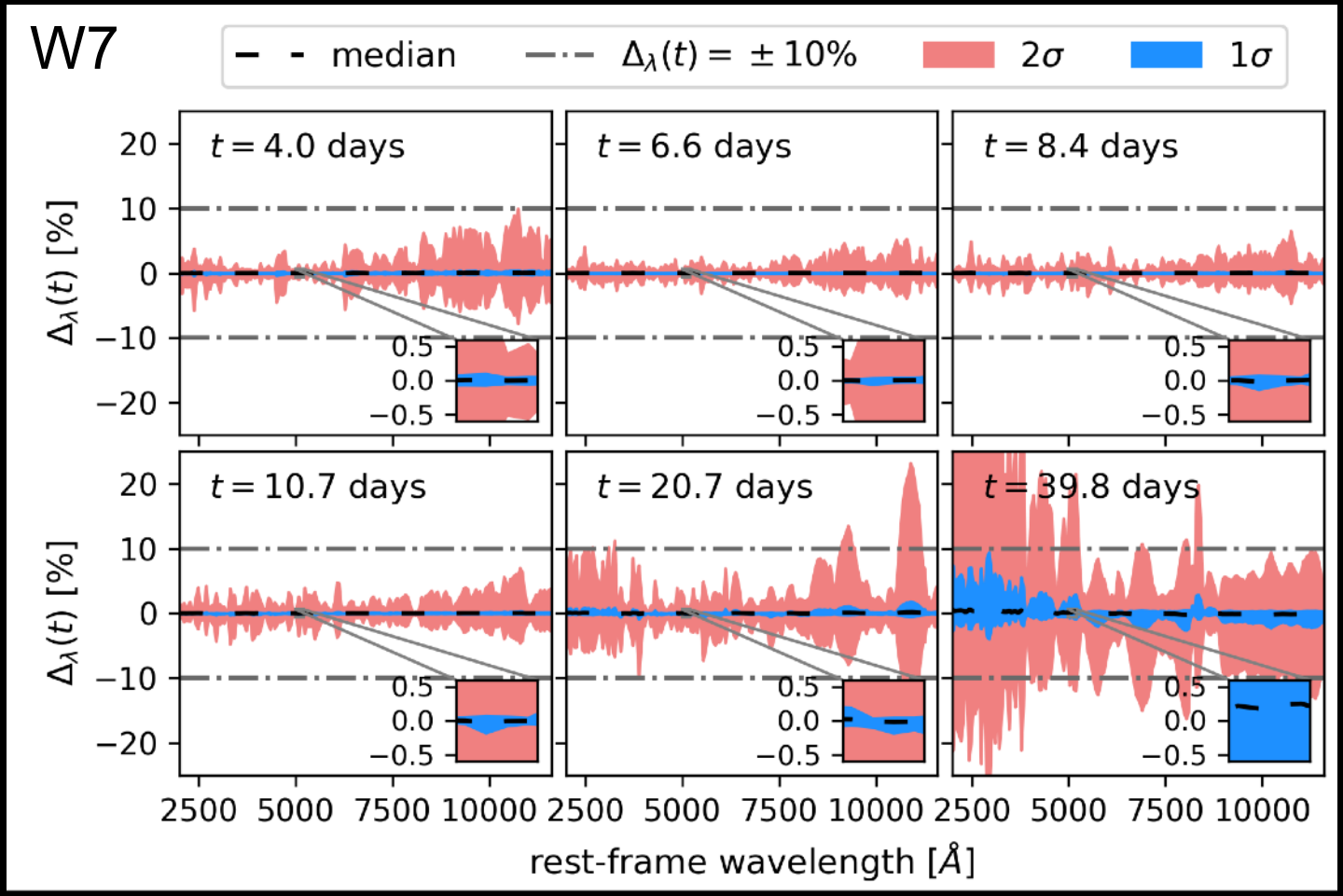

Stefan Taubenberger


Christian Vogl


Akın Yıldırım

Microlensing distortion on spectra

SN microlensed by stars in foreground lens galaxy ➜ spectra distortions



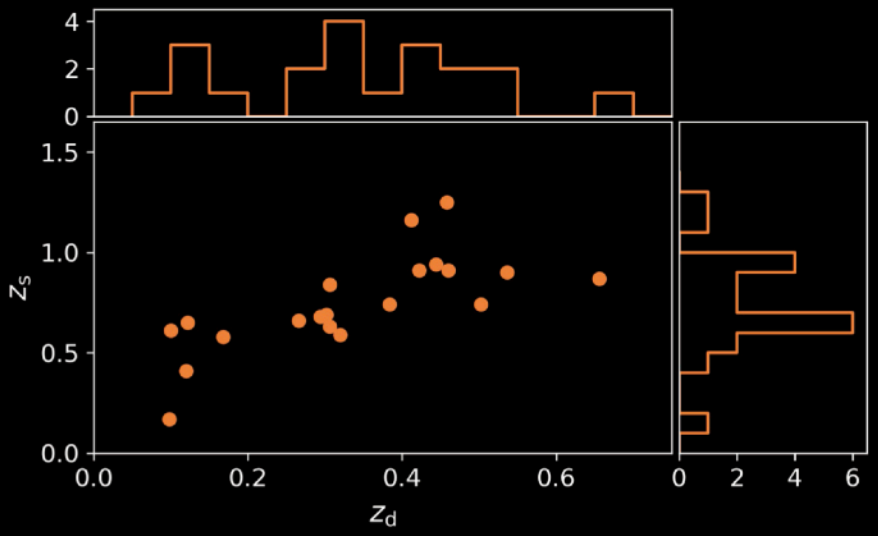
[Suyu, Huber, Cañameras et al. 2020; HOLI-SMOKES I]

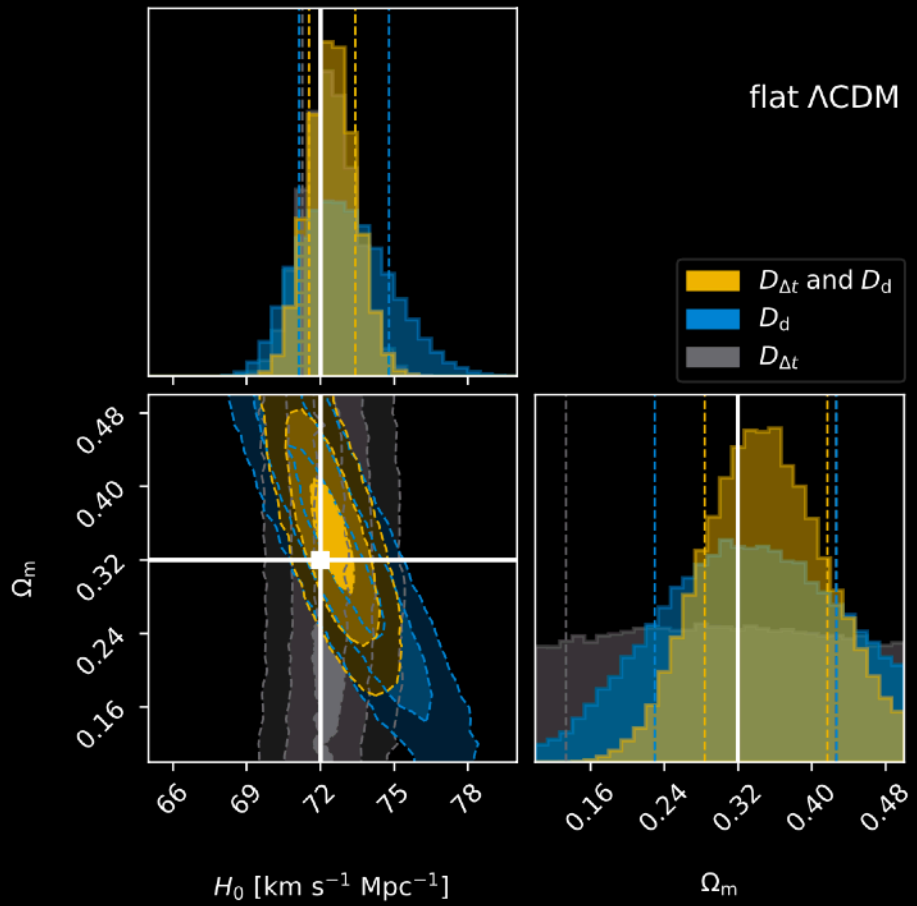
<1% deviation (1σ) of early-phase SN spectra due to microlensing for 4 SN progenitor scenarios (W7, N100, subCh, merger)

➜ lensed SNe allow observations of early-phase for progenitor studies

Forecast: H_0 measurement

sample of 20 lensed SN Ia from LSST that we can have precise and accurate time-delay measurements





➜ anticipate H_0 constraints with 1.3% precision from this sample

[Suyu, Huber, Cañameras et al. 2020; HOLISMOKES I]

Search for lensed SNe

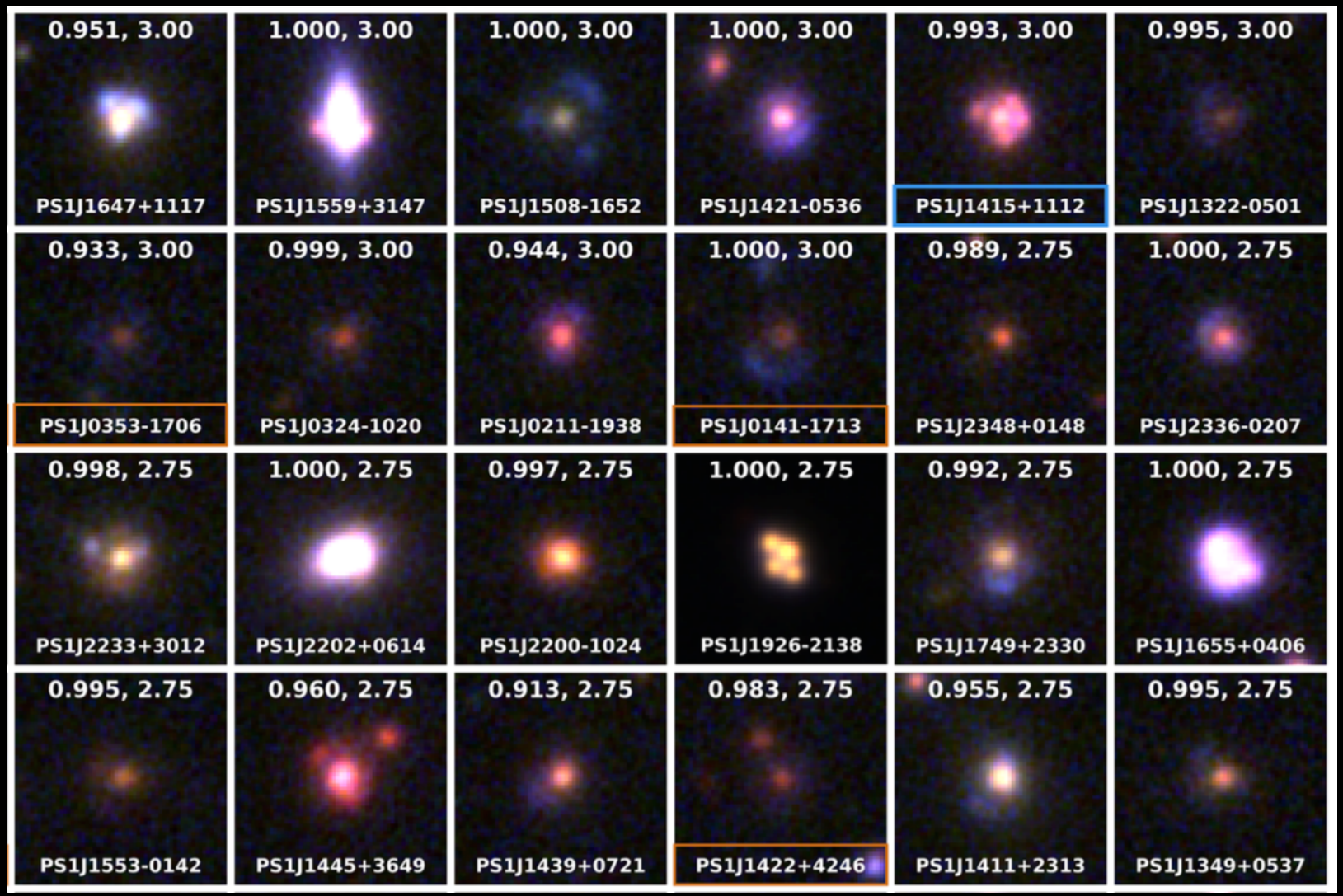
Zwicky Transient Facility (ZTF):

Combine ZTF + Pan-STARRS to search for lensed SNe

Find lensed galaxies in Pan-STARRS as potential hosts of SN

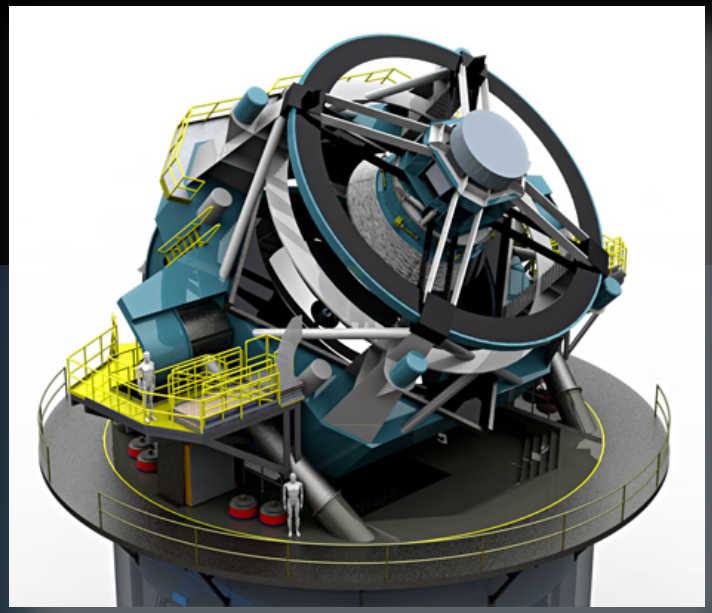
New lenses in Pan-STARRS

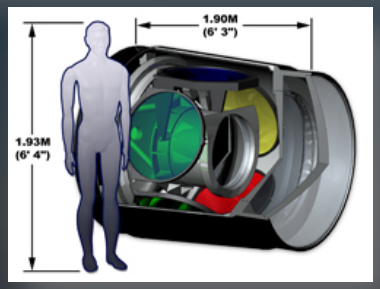
Discovered 330 high-quality lens candidates in Pan-STARRS



[Cañameras, Schuldt, Suyu, Taubenberger et al. 2020; HOLISMOKES II]

Rubin Observatory
Legacy Survey of Space and Time (LSST)





High etendue survey telescope:

- **6.7m effective aperture**
- **10 sq degree field**
- **24 mag in 30 seconds**

Visible sky mapped **every few nights**
Cerro Pachon, Chile: **0.7" seeing**

Ten year movie of the entire Southern sky

120 Petabytes of data
(1Pb = every book ever published)

First light ~2021, survey starts ~2023

Expect hundreds of lensed SNe in the 10-year LSST survey
[Oguri & Marshall 2010; Goldstein et al. 2017; Wojtak et al. 2019]

[slide material courtesy of P. Marshall]

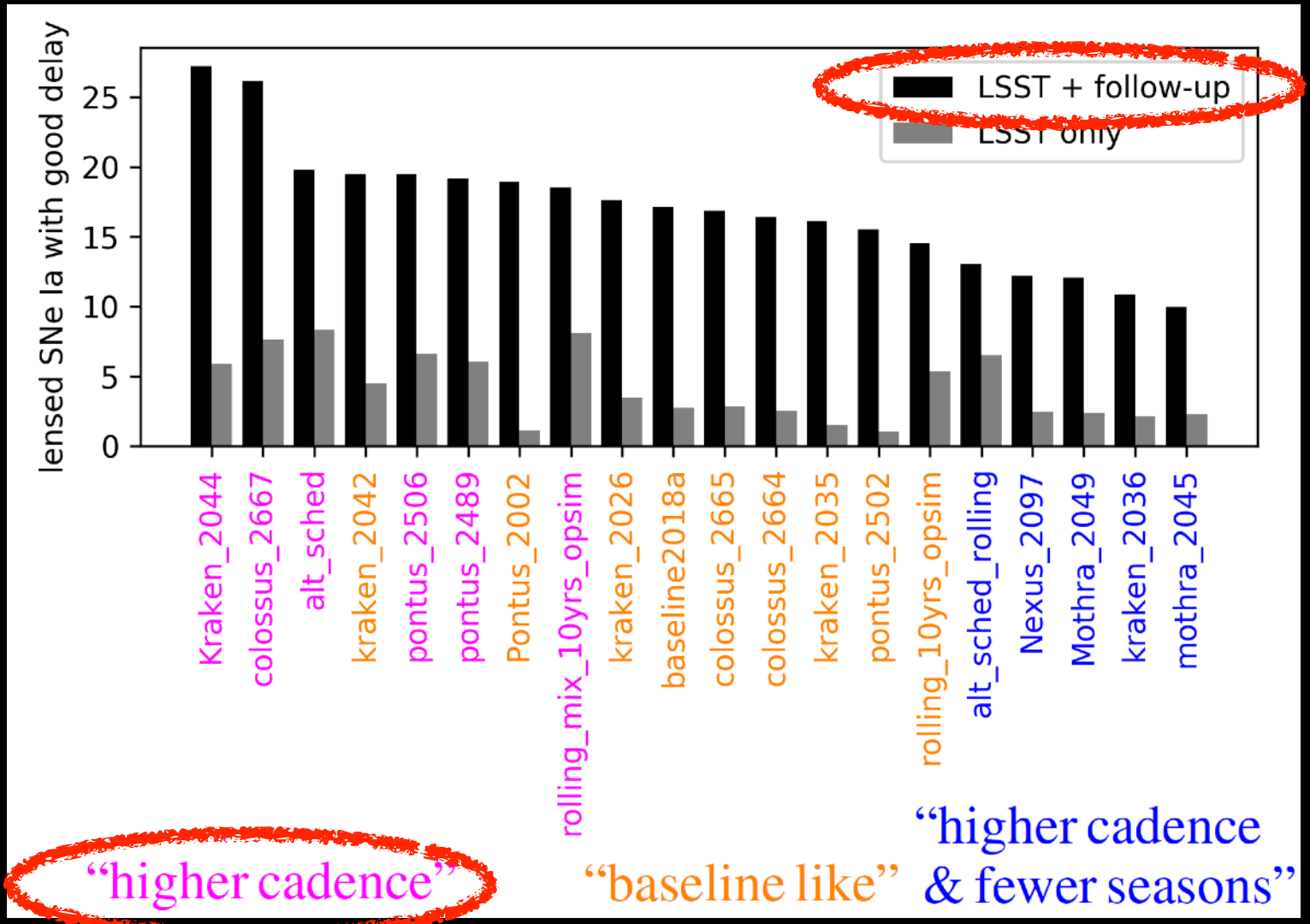
Cadence Strategy for Lensed SNe

When, where, which filter to observe?

➜ Affects both number and time-delay measurements of lensed SNe

Cadence Strategy for Lensed SNe

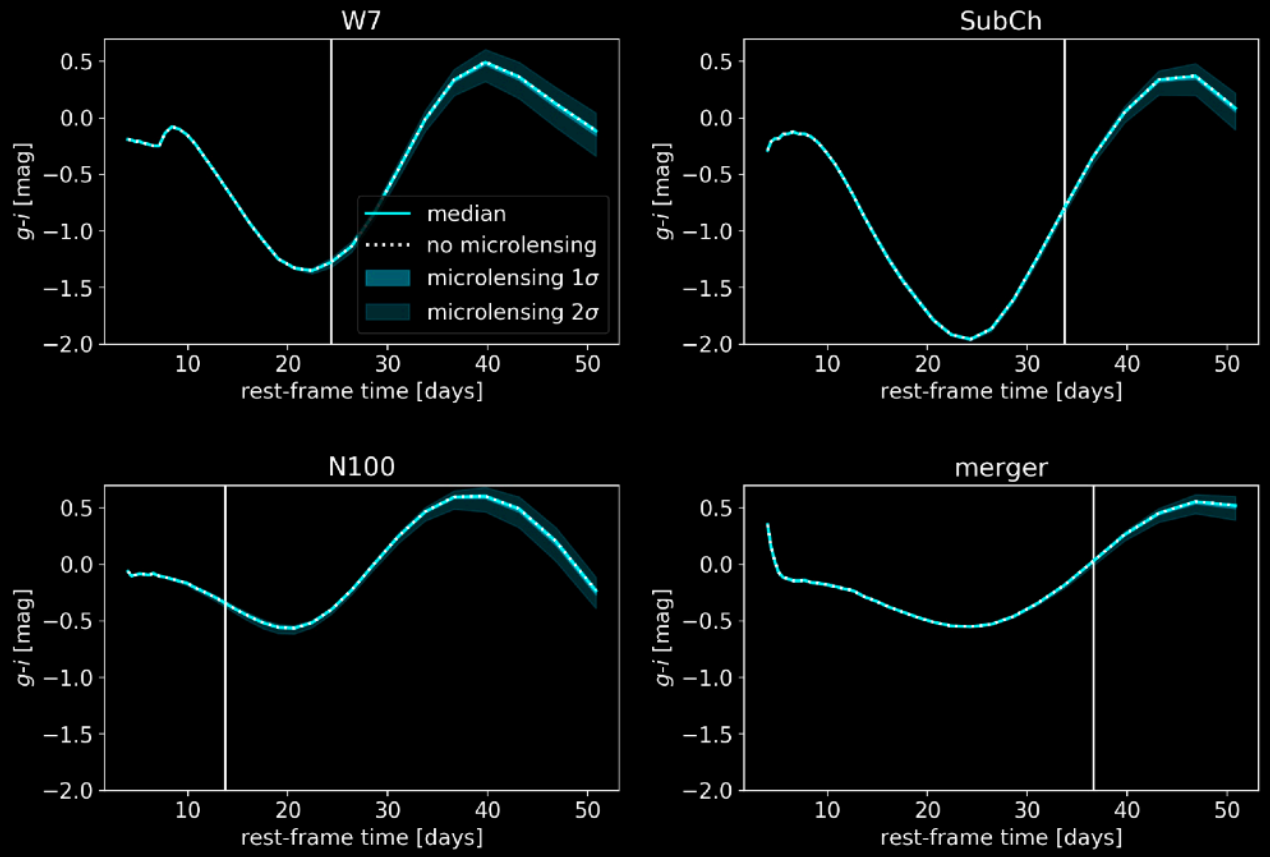
quantitatively compare LSST observing strategies



[Huber, Suyu, Nöbauer et al. 2019]

Follow-up observations

Which filters to observe light curves and color curves for time-delay measurements?



developing new method to measure time delays from light curves [Huber et al., in prep]

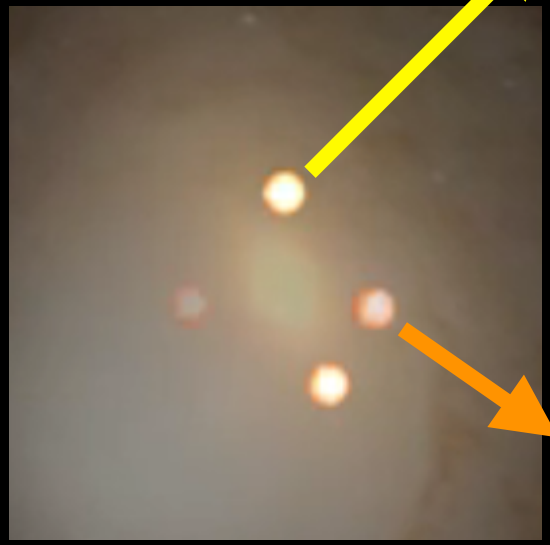
For typical system, at least r, i and z bands

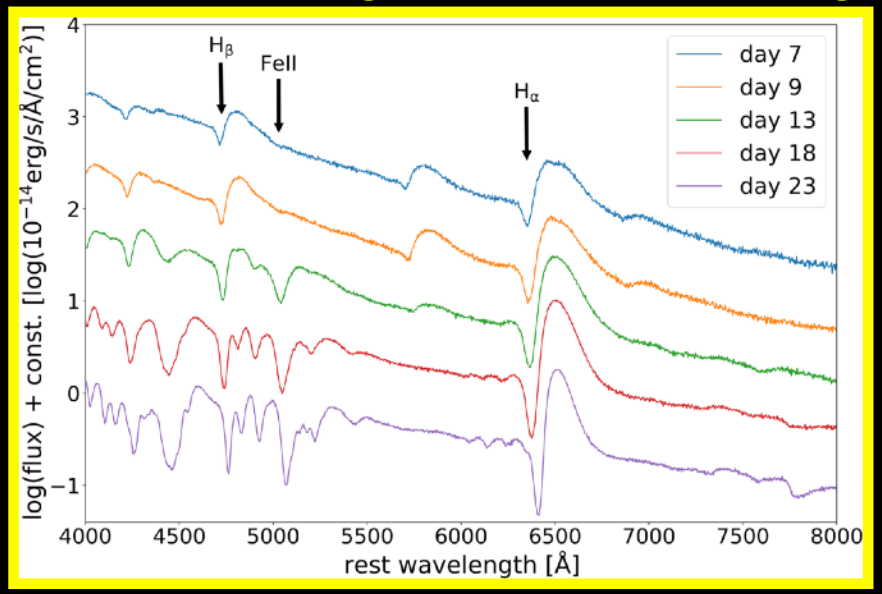
[Huber, Suyu, Nöbauer et al. 2020; HOLISMOKES III]

Time delay through spectra

Can we use spectra to measure time delays? ➜ YES!

first appearing supernova image

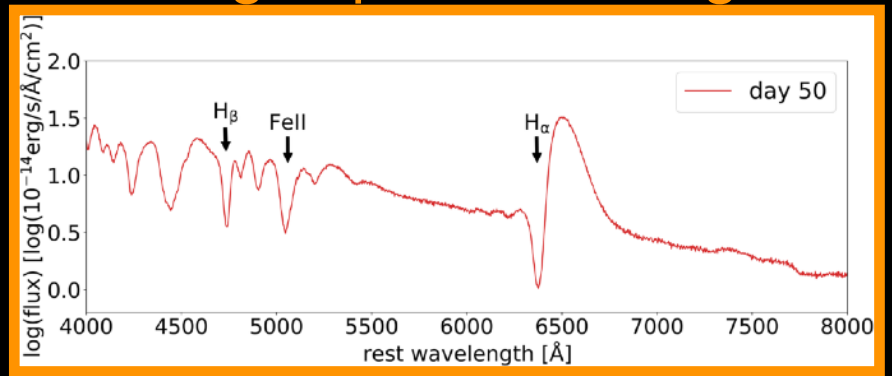




can measure delays with uncertainties of ±2 days!

[Bayer, Huber, Vogl et al. 2021; HOLISMOKES V]

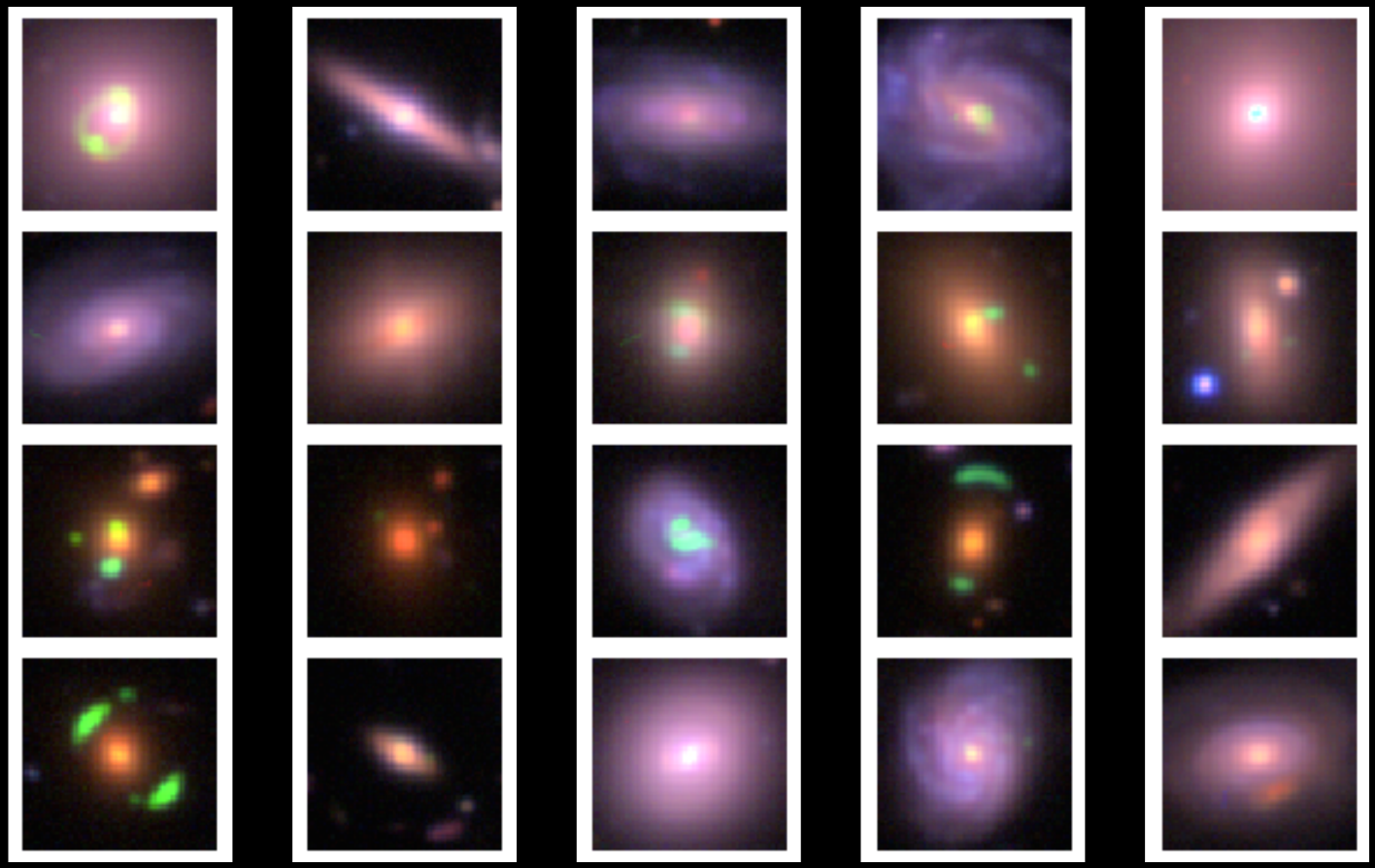
a trailing supernova image



see also Johansson et al. 2020 and A. Goobar's talk

Lens modeling with machine learning

- simulate realistic lenses
- train neural network to infer lens mass parameters
  [Hezaveh et al. 2017; Perreault Levasseur et al. 2017]



➜ *S. Schuldt's talk*

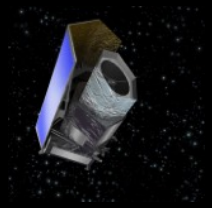
➜ *see also J. Park's talk*

[Schuldt, Suyu, Meinhardt et al. 2020; HOLISMOKES IV]

Future Prospects

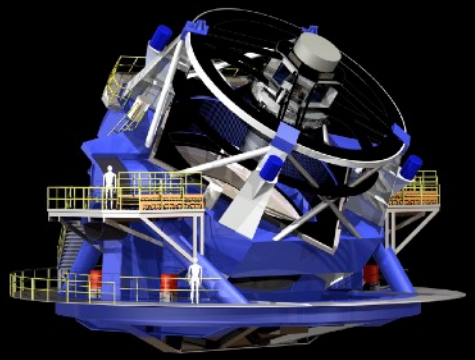
Experiments and surveys in the 2020s including Euclid, Rubin, and Roman observatories will provide ~100 lensed supernovae and thousands of lensed quasars
[Oguri & Marshall 2010; Goldstein et al. 2019; Wojtak et al 2019; Pierel et al. 2020]

Euclid



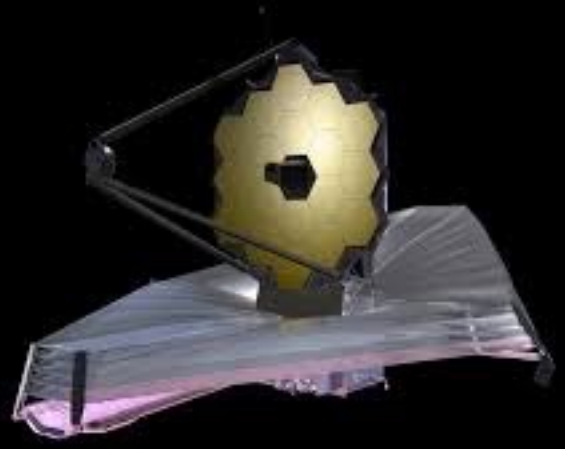
Discovery
Imaging
Spectroscopy

LSST



Discovery
Time delays
Imaging

JWST



High-resolution imaging
& spectroscopy

Many thanks to

HOLISMOKES

Jana Bayer
Raoul Cañameras
James Chan
Frédéric Courbin
Simon Huber
Markus Kromer
Uli Nöbauer
Stefan Schuldt
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Christian Vogl
Akın Yıldırım

H0LiCOW & TDCOSMO

Adriano Agnello
Timo Anguita
Matt Auger
Bohdan Bidenko
Simon Birrer
Roger Blandford
Vivien Bonvin
Liz Buckley-Geer
James Chan
Chih-Fan Chen
Tom Collett
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Alessandro Sonnenfeld
Chiara Spiniello
Sherry Suyu
Stefan Taubenberger
Olga Tihhonova
Tommaso Treu
Georgios Vernardos
Lyne Van de Vyvere
Patrick Wells
Ken Wong
Akın Yıldırım

Summary

- Lensed SNe provide great opportunities to constrain SN progenitors and cosmology
- HOLISMOKES! New program on lensed SN
- Microlensing of SN in early phases is negligible for SN progenitor studies
- >300 new lens candidates in Pan-STARRS as potential SN hosts
- LSST cadence strategy: higher cadence and longer season
- New methods to measure time delays
- Lens modeling with machine learning yields huge gain in speed
- Current and future surveys will have hundreds of new lensed supernovae, making lensed SN a competitive probe of SN progenitors and cosmology


Virtual meetings are basically modern seances.
"Elizabeth are you here?"
"Make a sound if you can hear us."
"Is anyone else with you?"
"We can't see you. Can you hear us?"
Yore Mamm