Hubble Constant at the Late Universe

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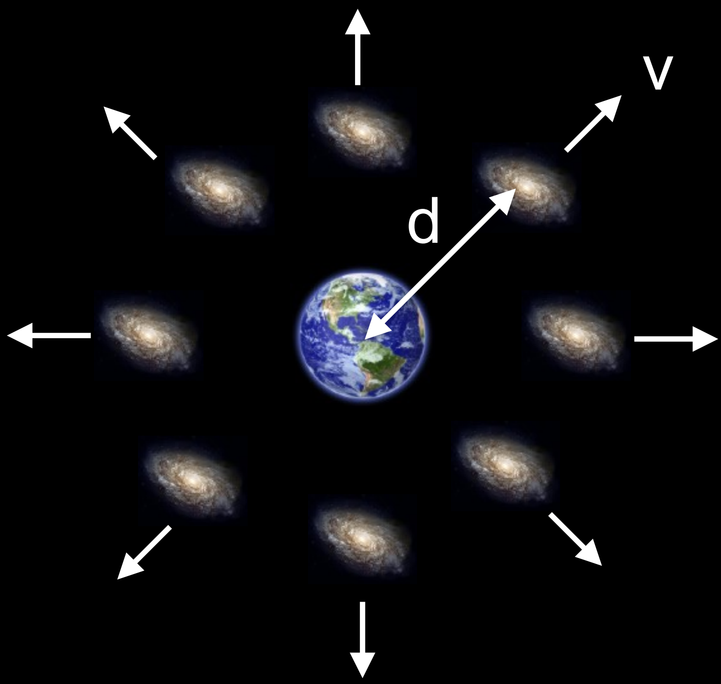
Expanding Universe

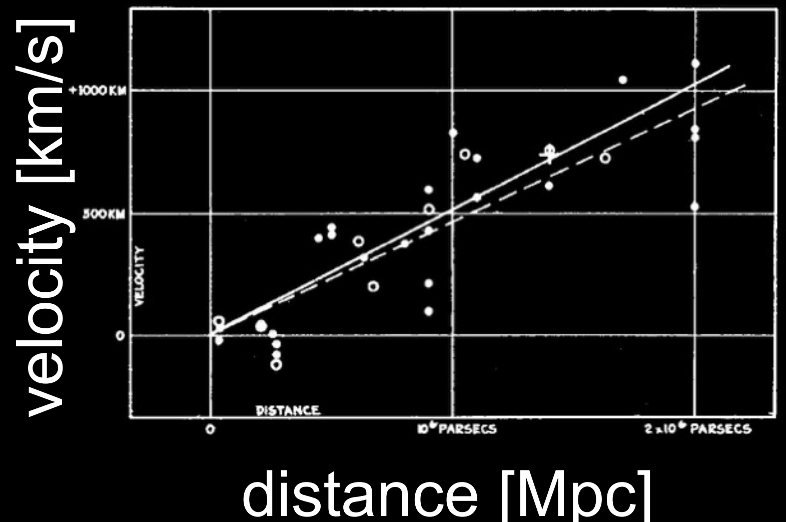
1920s Discovery



Lemaître & Hubble independently measured the expansion rate

$$v = H_0 \times d$$

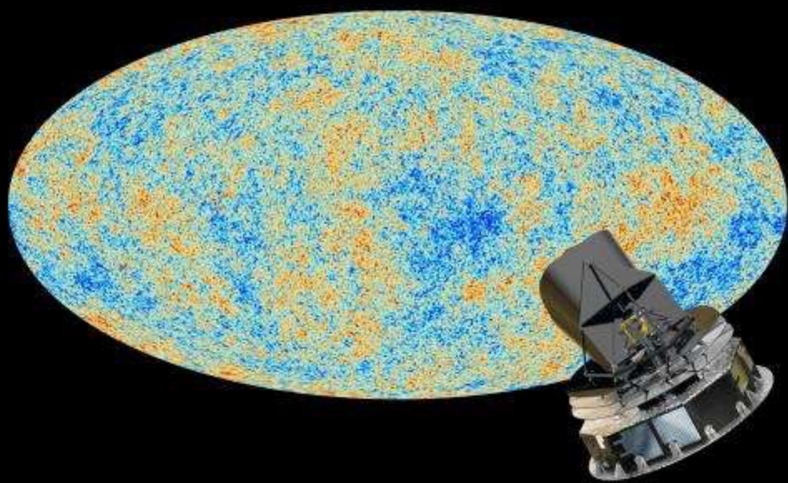
Hubble Constant



H_0 sets age and size of Universe! [Hubble 1929]

Tension in H_0

Measurement from early universe:
Cosmic Microwave Background



Measurement from local universe:
supernova distance ladder

Lucas Macri & Brent Tully's talks

[credit: NASA/JPL-Caltech]

[Planck collaboration 2020]

67.4 ± 0.5
assuming ΛCDM

69.6 ± 0.8 ± 1.7
CCHP [Freedman et al. 2020]

SH0ES [Riess et al. 2022]

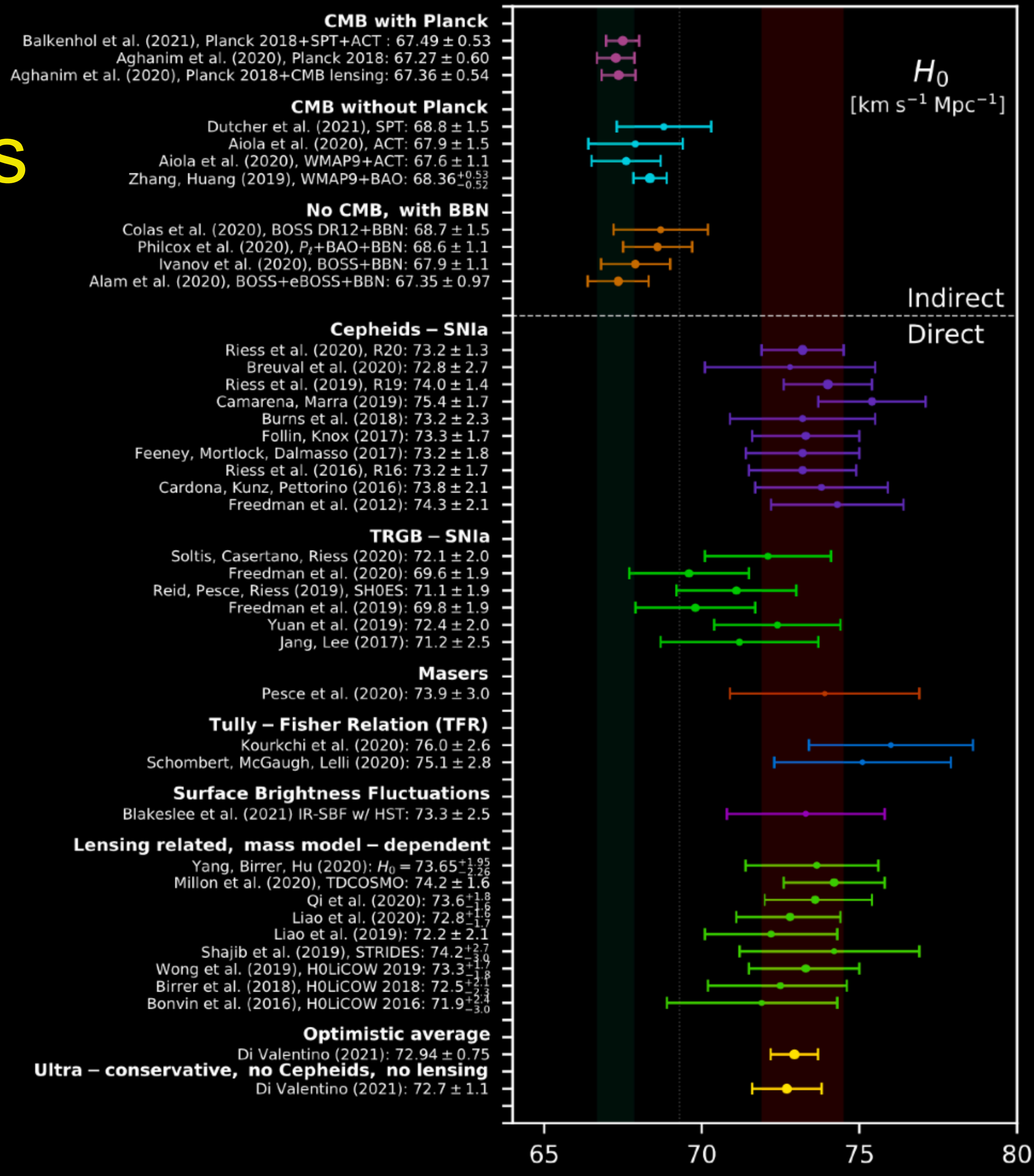
73.0 ± 1.0

New physics beyond standard cosmological model ΛCDM?

H_0
[km s^{-1}Mpc^{-1}]

Recent H_0 measurements

[Di Valentino et al. 2021]

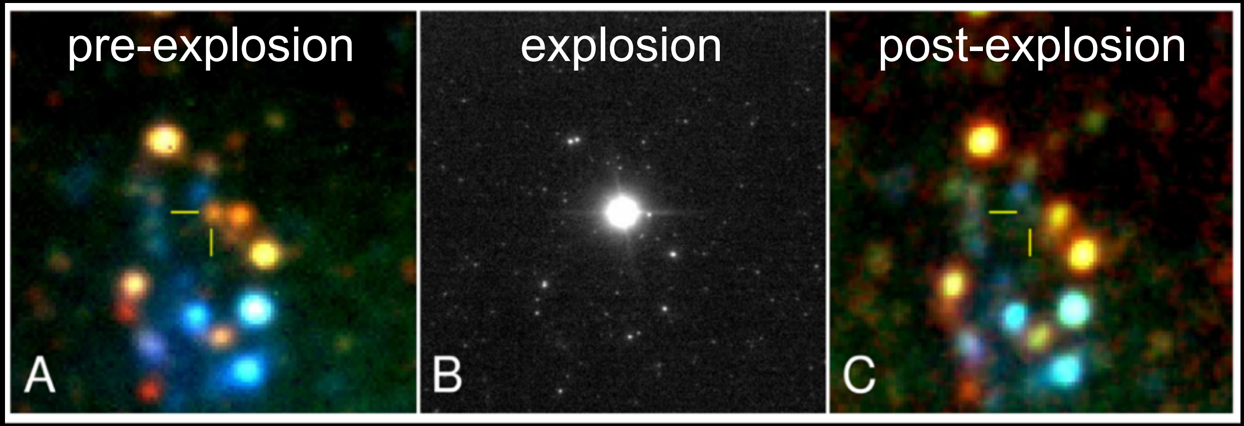


Two independent methods

- Type II supernovae
- Strong gravitational lensing

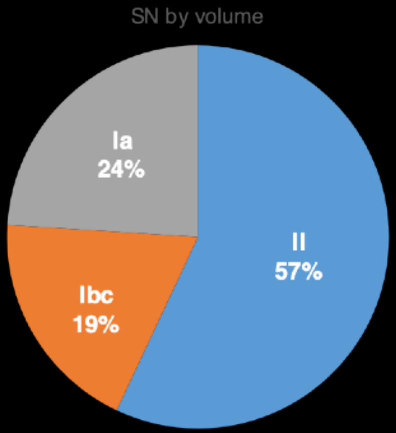
Type II supernovae

core-collapse explosions of massive red-supergiant stars



Mattila et al. 2010

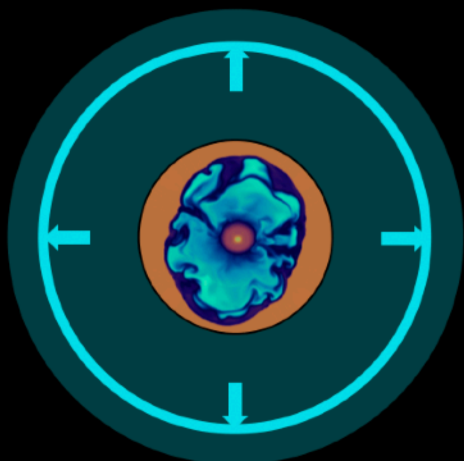
- Peak luminosity ~ 10^9 solar luminosity
  ➜ observable up to redshift z ~ 0.4
- Most common type of SN by volume
- Single-step distance measurement, independent of the distance ladder



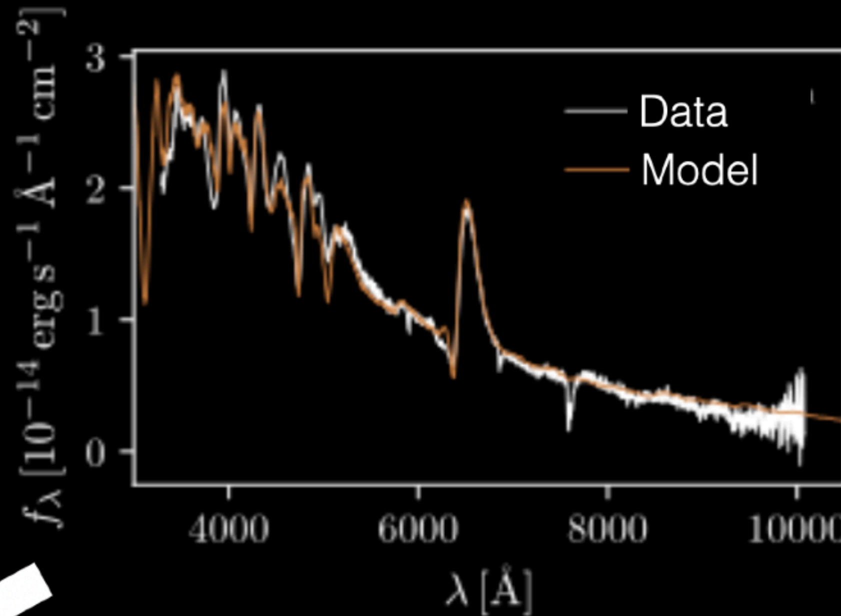
[Slide material courtesy of Stefan Taubenberger]

Type II supernovae

Radiation comes from photosphere in simple hydrogen-rich medium



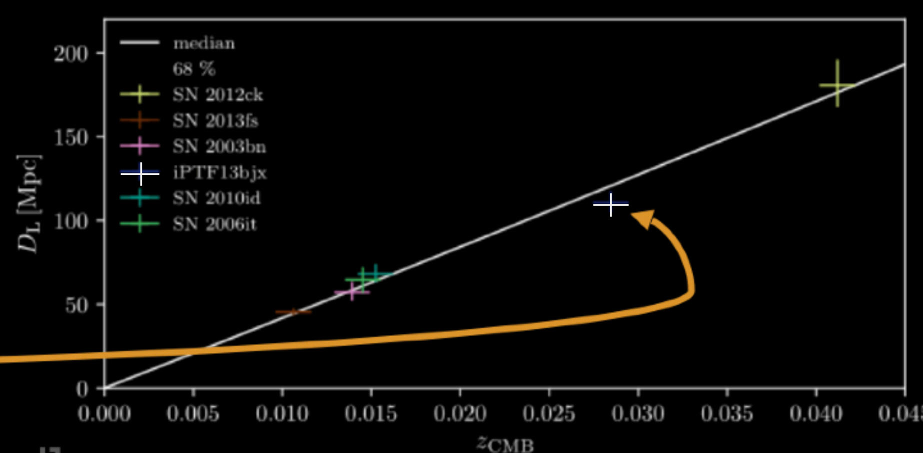
can be modeled accurately



Luminosity

Distance

Hubble constant



[slide material courtesy of Christian Vogl]

accurate determination of H_0 from core-collapse supernovae

$< 3\%$

$z < 0.15$

[Slide material courtesy of Stefan Taubenberger]

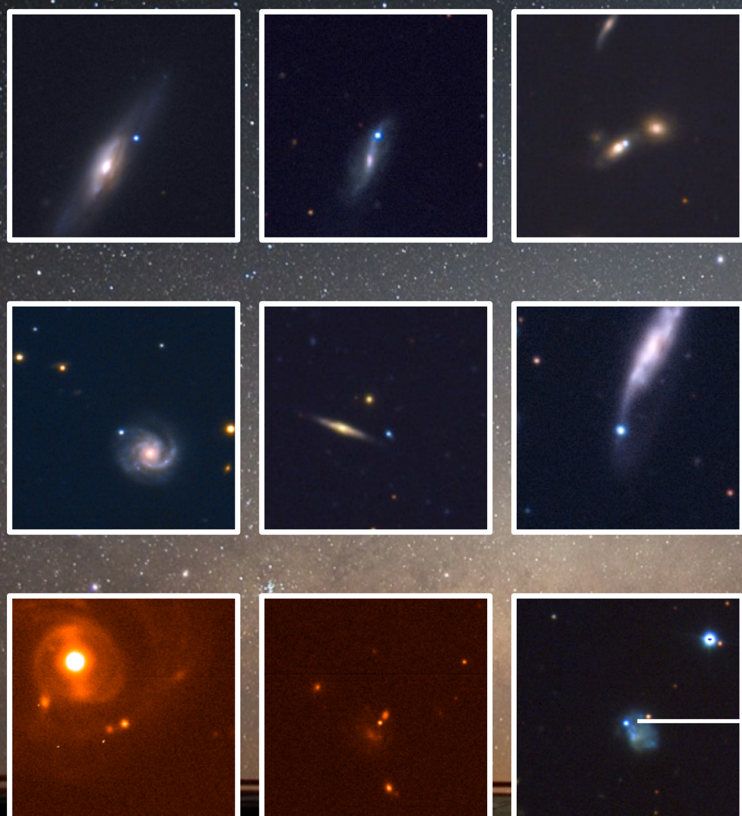
adH0cc

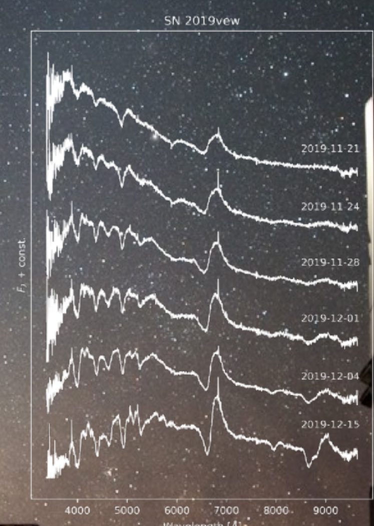
accurate determination of H_0 from core-collapse supernovae

https://adh0cc.github.io/

VLT large programme: ~150 hours over three semesters (PI: Leibundgut)

MPA, ESO, TUM, GSI, QUB, LAM, Turku, WIS, EPFL





Observations are finished:
26 objects at z > 0.03

→ H_0 to < 3%

[slide material courtesy of Christian Vogl & Stefan Taubenberger]

Image: ESO/Y. Beletsky

Two independent methods

- Type II supernovae
- **Strong gravitational lensing**

Strong Lensing

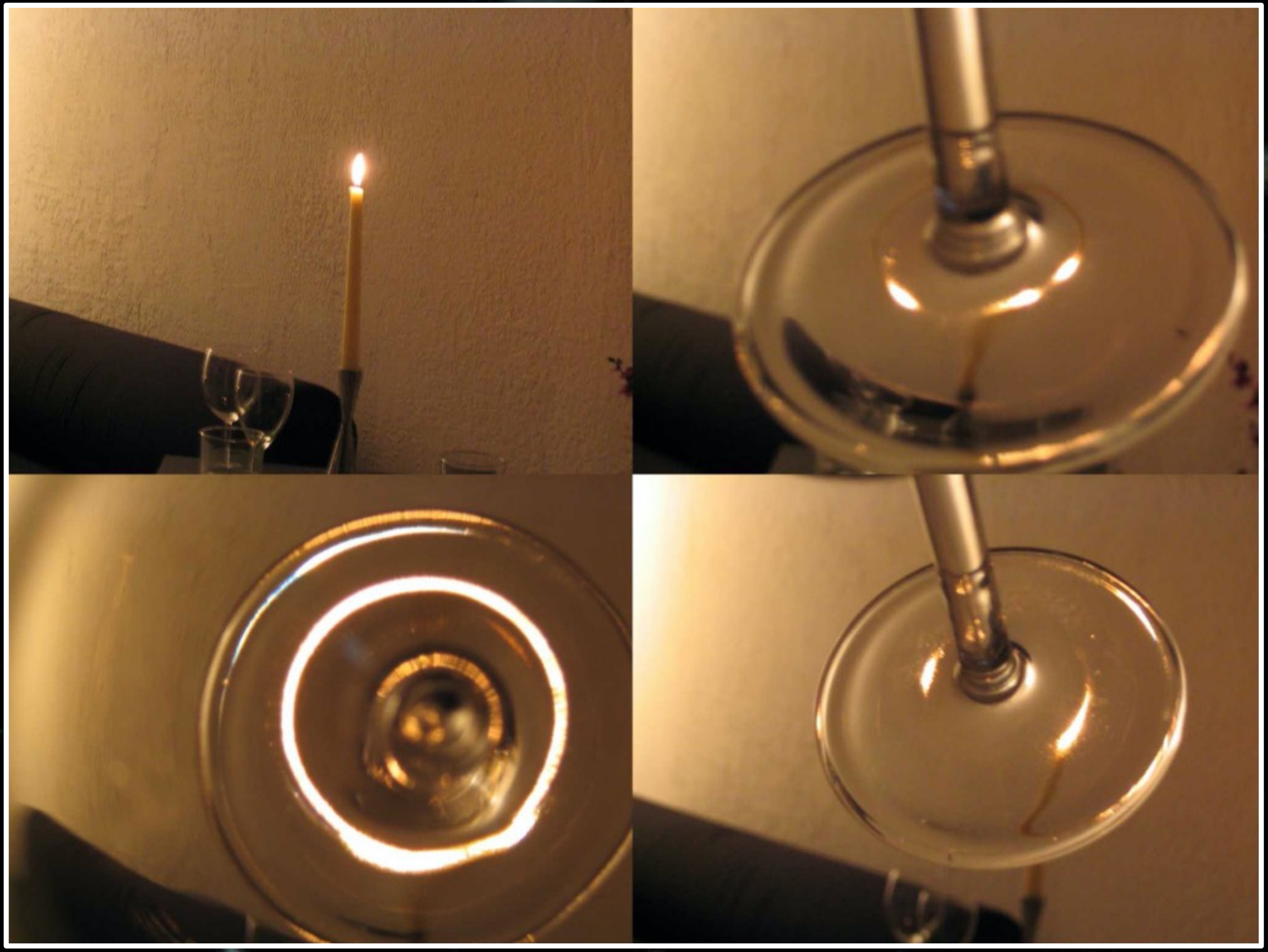
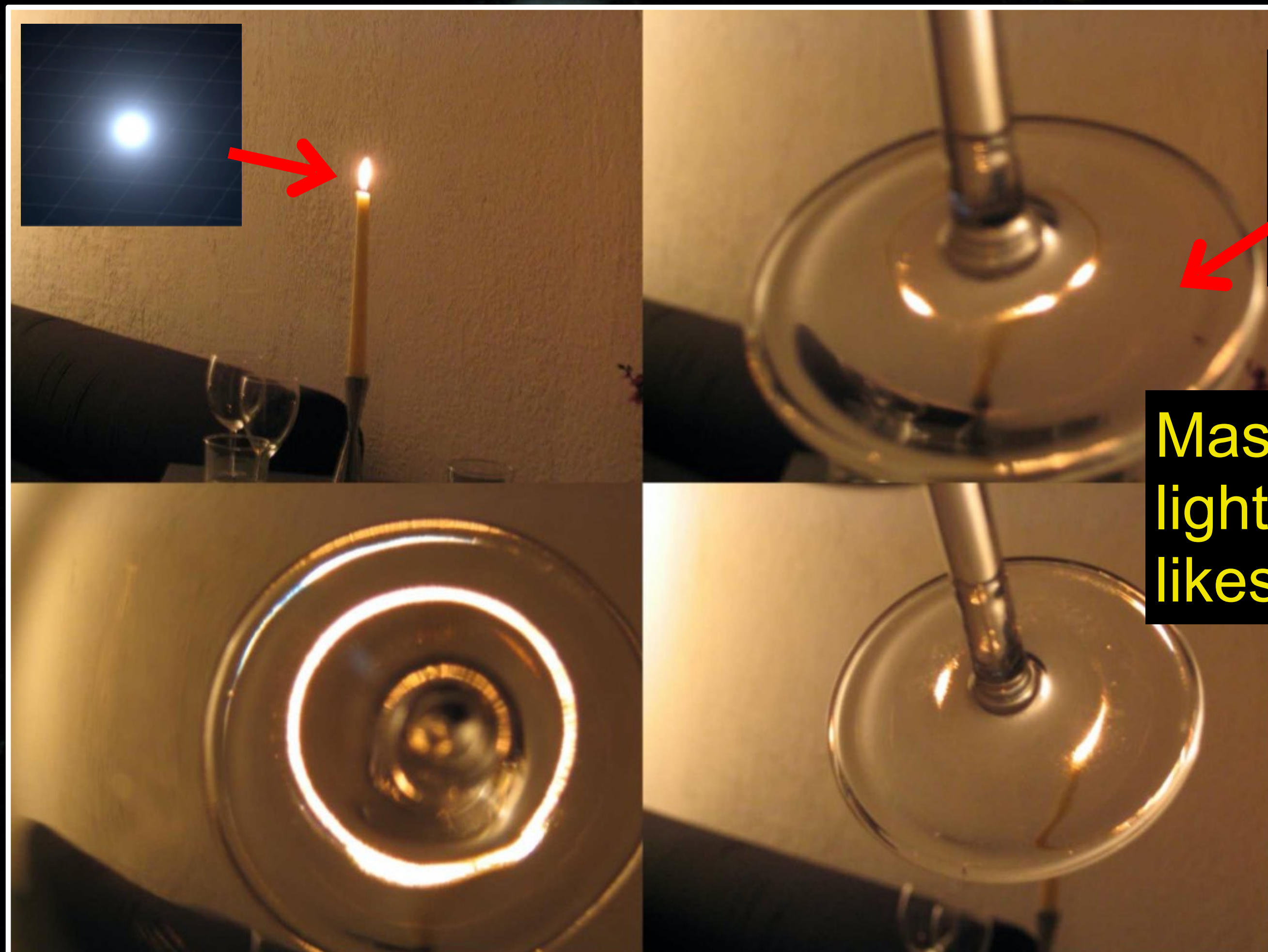


Image Credit: P. J. Marshall

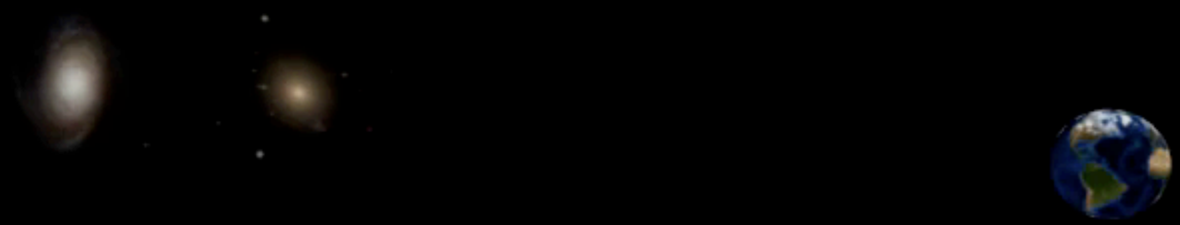
Gravitational
Strong^Lensing



Mass “bends” light and acts likes a lens

Image Credit: P. J. Marshall

Strongly lensed supernova event



[Credit: S. More]

multiple images of the SN event appear around the foreground lens galaxy, at ***different*** times

Cosmology with lensing delays

[Refsdal 1964]

Time delay:

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

Time-delay distance:

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

Obtain from lens mass model

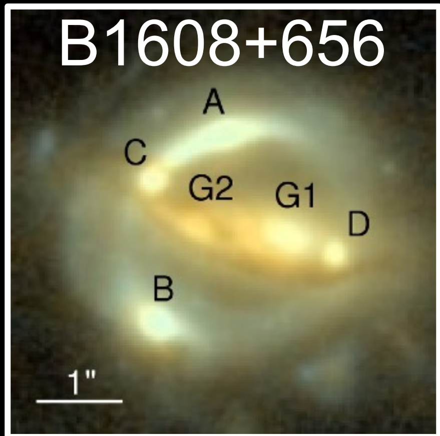
Cosmography:

time delays Δt + mass model ϕ_{lens}

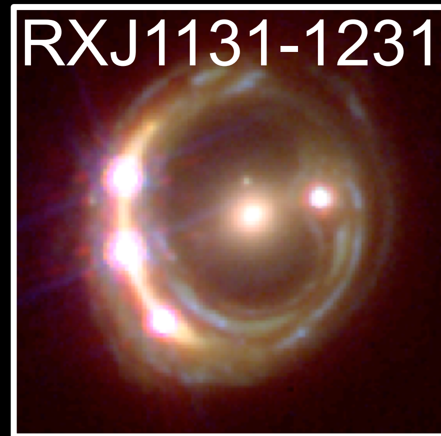
➜ time-delay distance $D_{\Delta t}$

➜ Hubble constant H_0

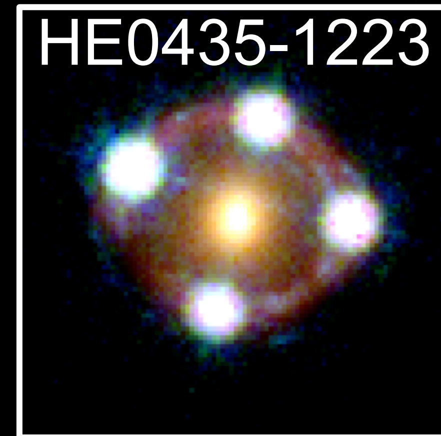
H0LiCOW lensed quasars



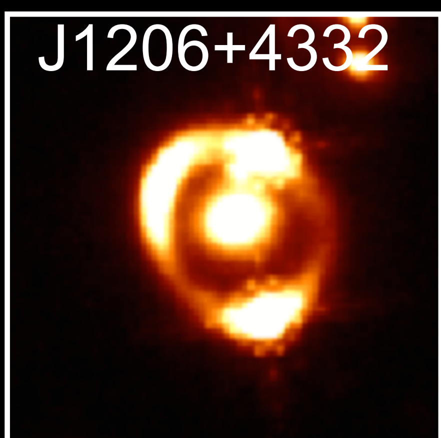
[Suyu et al. 2010]



[Suyu et al. 2013, 2014; Tewes et al. 2013]

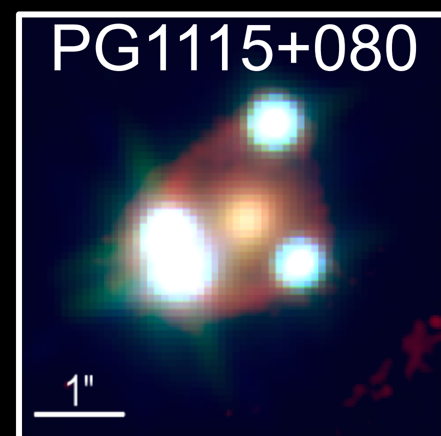


[Wong et al. 2017; Rusu et al. 2017; Sluse et al. 2017; Bonvin et al. 2017]



part of extended sample [Birrer et al. 2019]

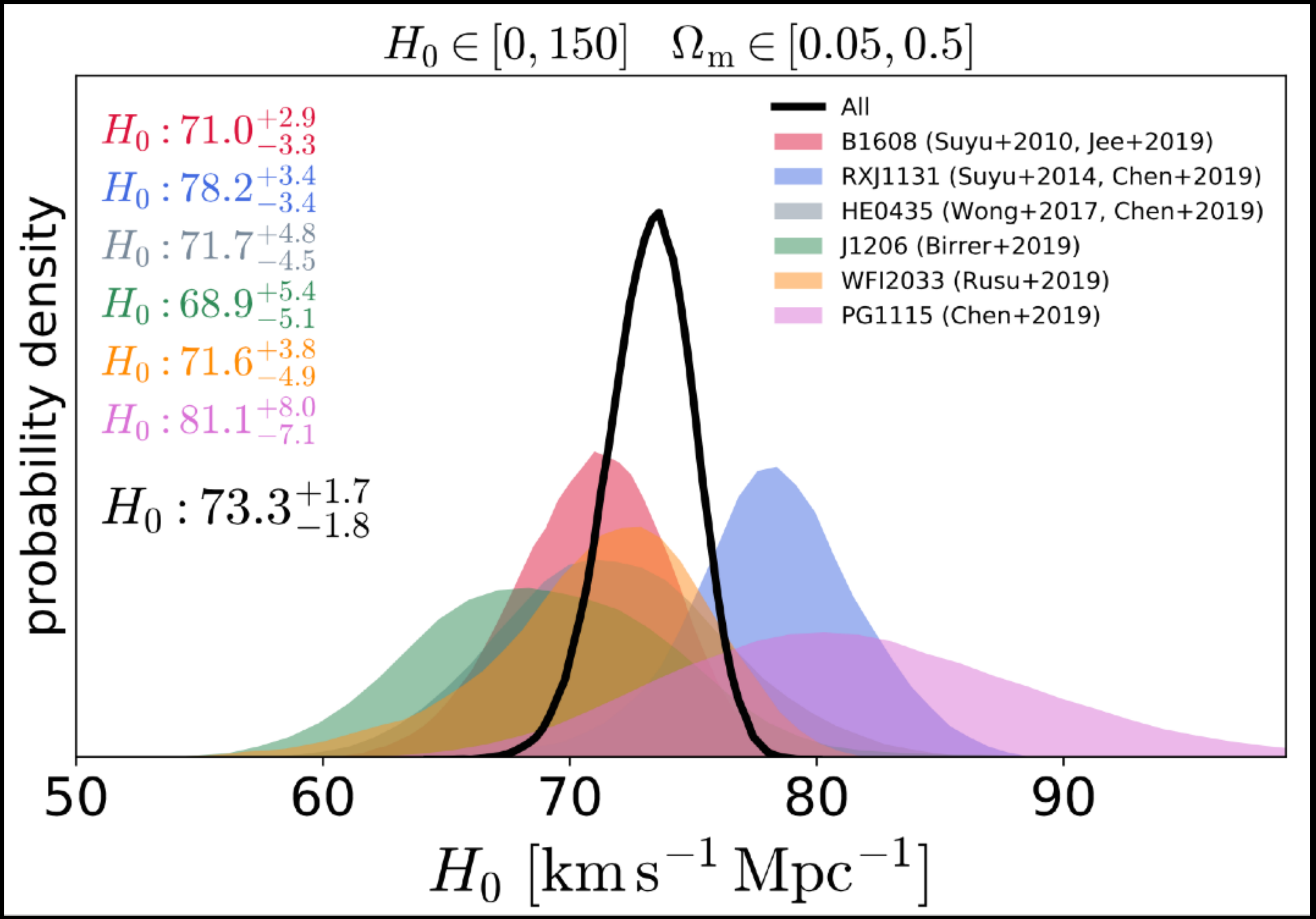
[Bonvin et al. 2019; Sluse et al. 2019; Rusu et al. 2020]



part of Keck AO sample of SHARP program [Chen et al. 2019]

H0LiCOW! H_0 from 6 strong lenses

- blind analysis to avoid confirmation bias
- well motivated lens mass models



[Wong, Suyu, Chen et al. 2020]

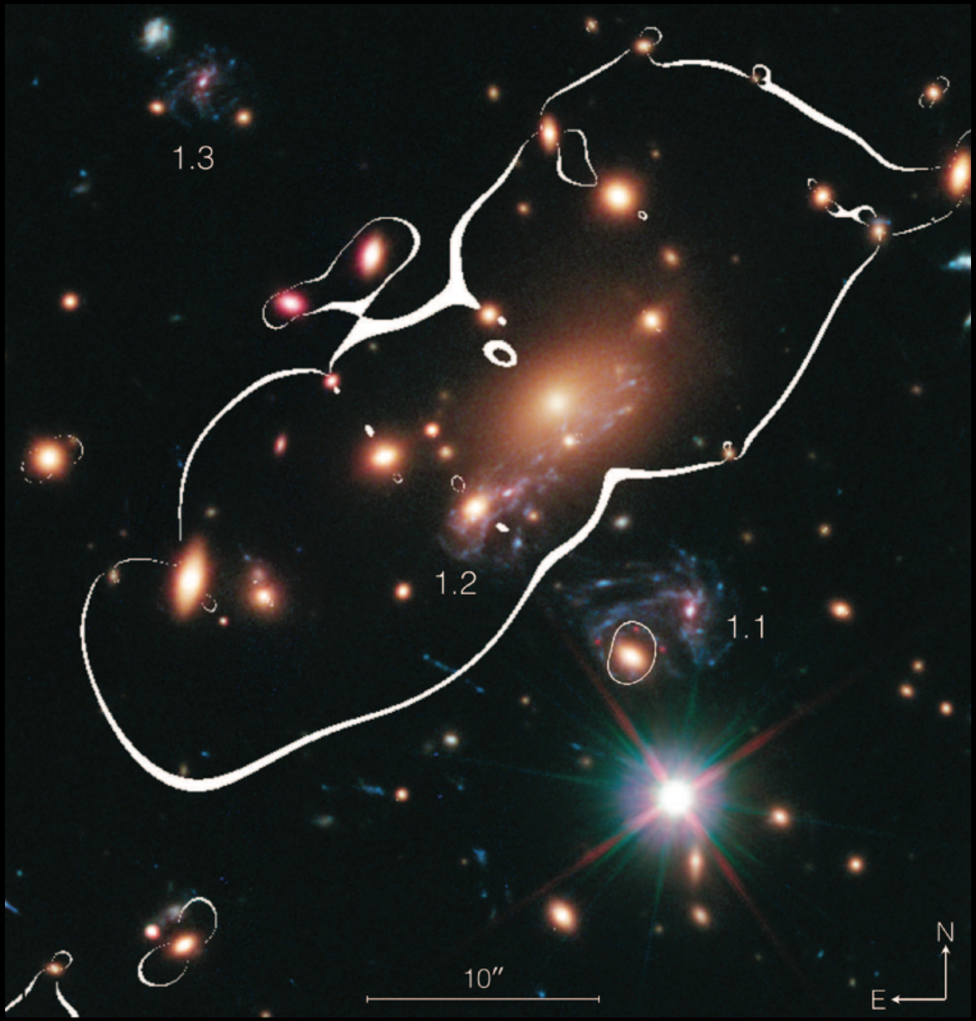
***H_0* with 2.4% precision in flat ΛCDM**

Observations

It took 50 years to observe the first strongly lensed SN event, after Refsdal proposed it in 1964

Strongly lensed supernovae

SN Refsdal

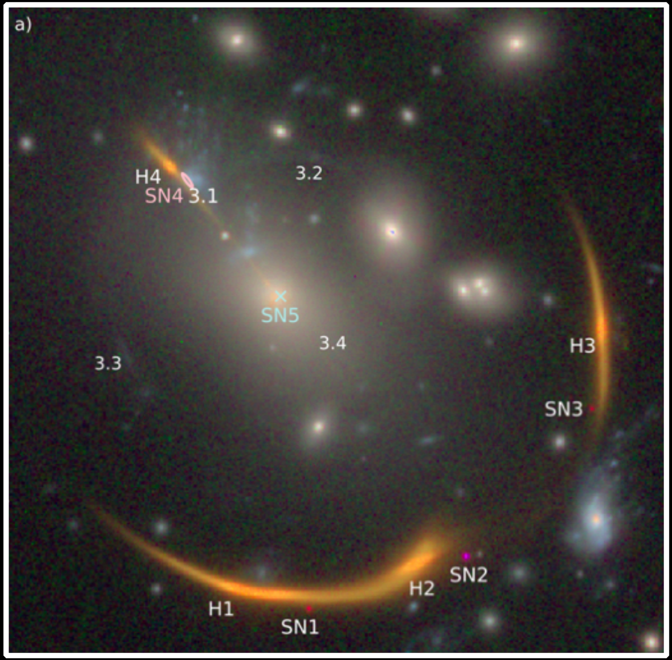


[Kelly et al. 2015]

iPTF16geu

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

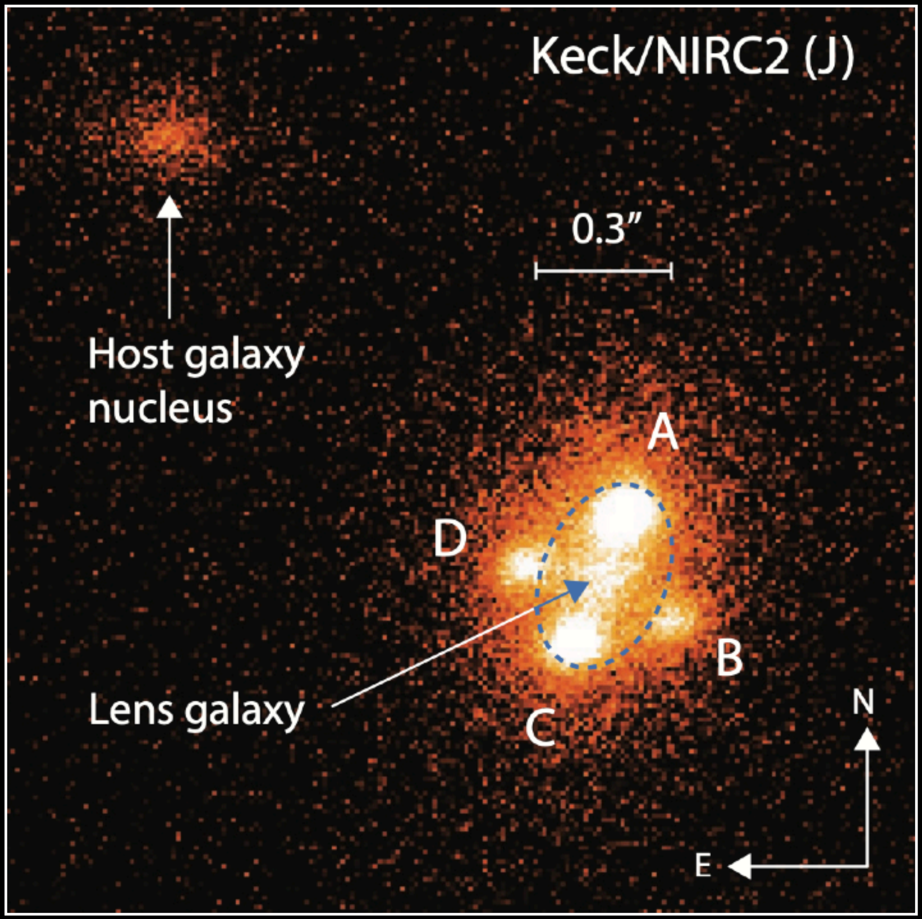
SN Requiem



[Rodney et al. 2021]

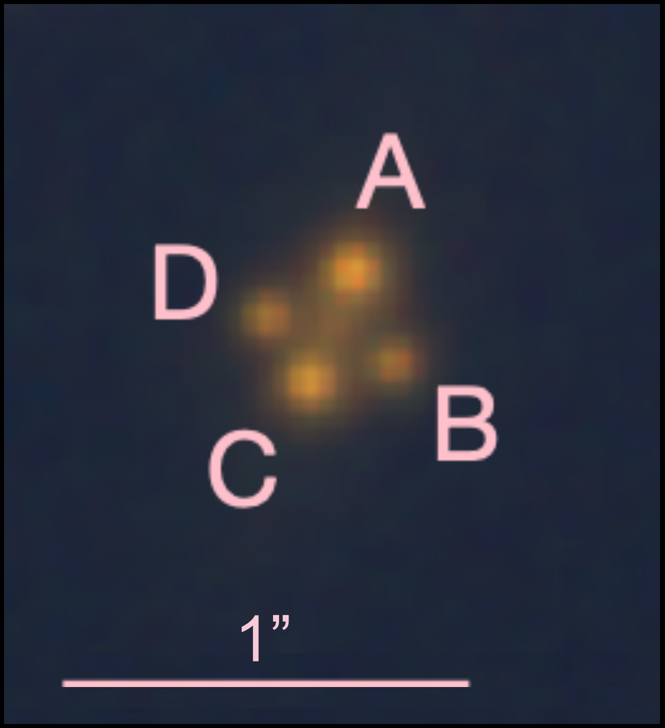
Strongly lensed supernovae

SN Zwicky



[Goobar et al. 2022; arXiv:2211.00656]

HST WFC2/UVIS



[Pierel et al. 2022; arXiv:2211.03772]

HOLISMOKES!

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

[Suyu, Huber, Cañameras et al. 2020; Paper I]
www.holismokes.org

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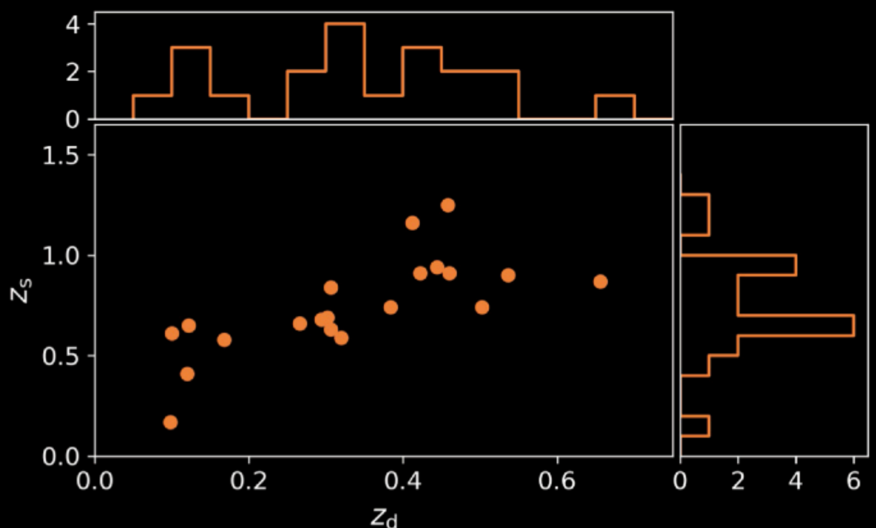
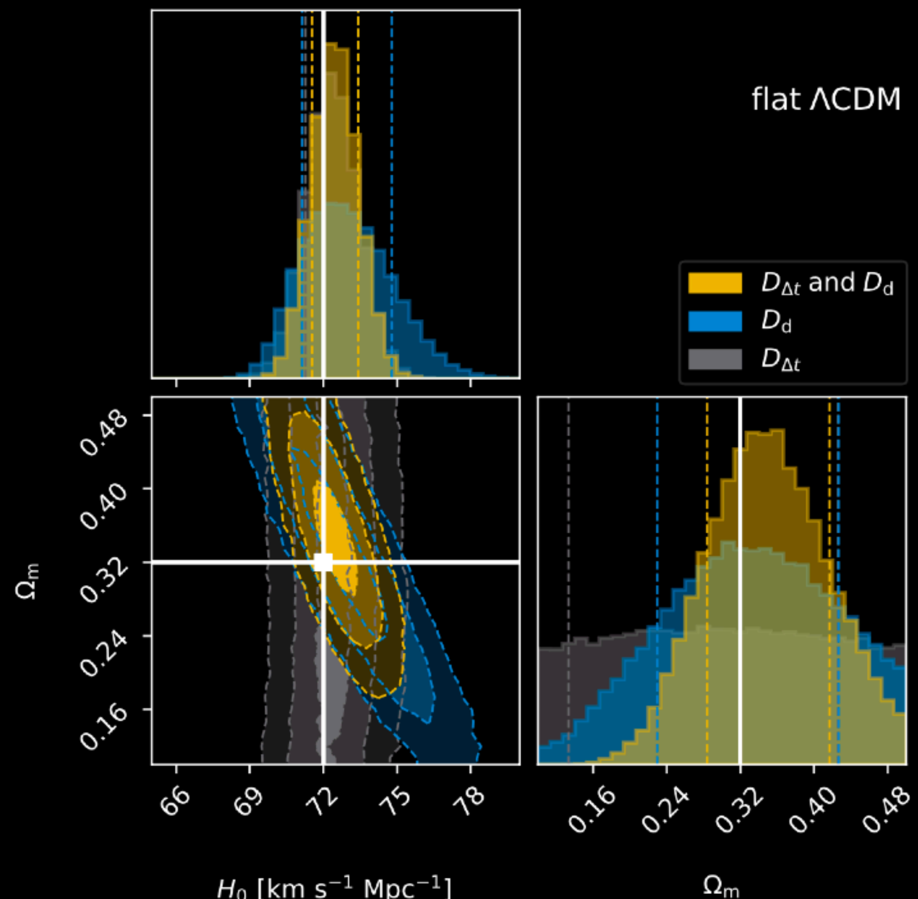
Stefan Taubenberger


Christian Vogl

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 in flat ΛCDM from this sample

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

Lens Search

(Papers II, VI, VIII)

Follow-up Observations

(Paper III)

HOLI SMOKES

Time Delays

(Papers V, VII)

Lens Modelling

(Papers IV, IX, X)

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Search for lensed SNe

Zwicky Transient Facility (ZTF):

Combine ZTF + Pan-STARRS to search for lensed SNe

New lenses in Pan-STARRS

- Find lensed galaxies in Pan-STARRS as potential hosts of SN
- Use Deep Learning to cope with huge data volume
- $3x10^9$ sources in Pan-STARRS 3π survey

➜ $2.3x10^7$ after simple photometric cuts, star removal

➜ $1.0x10^6$ after apply neural network on photometric measurements

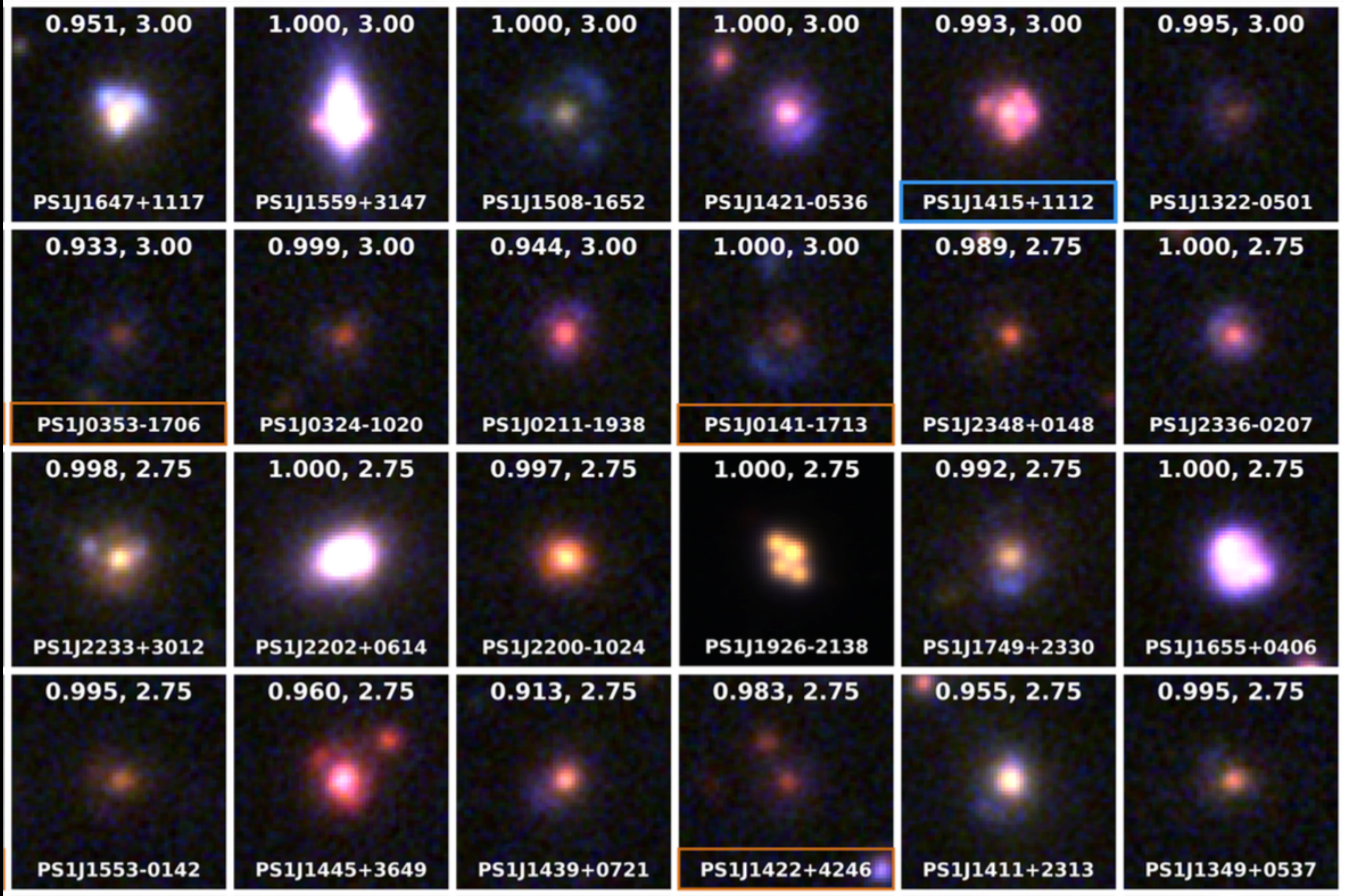
➜ $1.2x10^4$ after apply convolutional neural network (CNN) on g, r, i-band image cutouts of systems

➜ 330 high-quality candidates after visual inspection

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

New lenses in Pan-STARRS

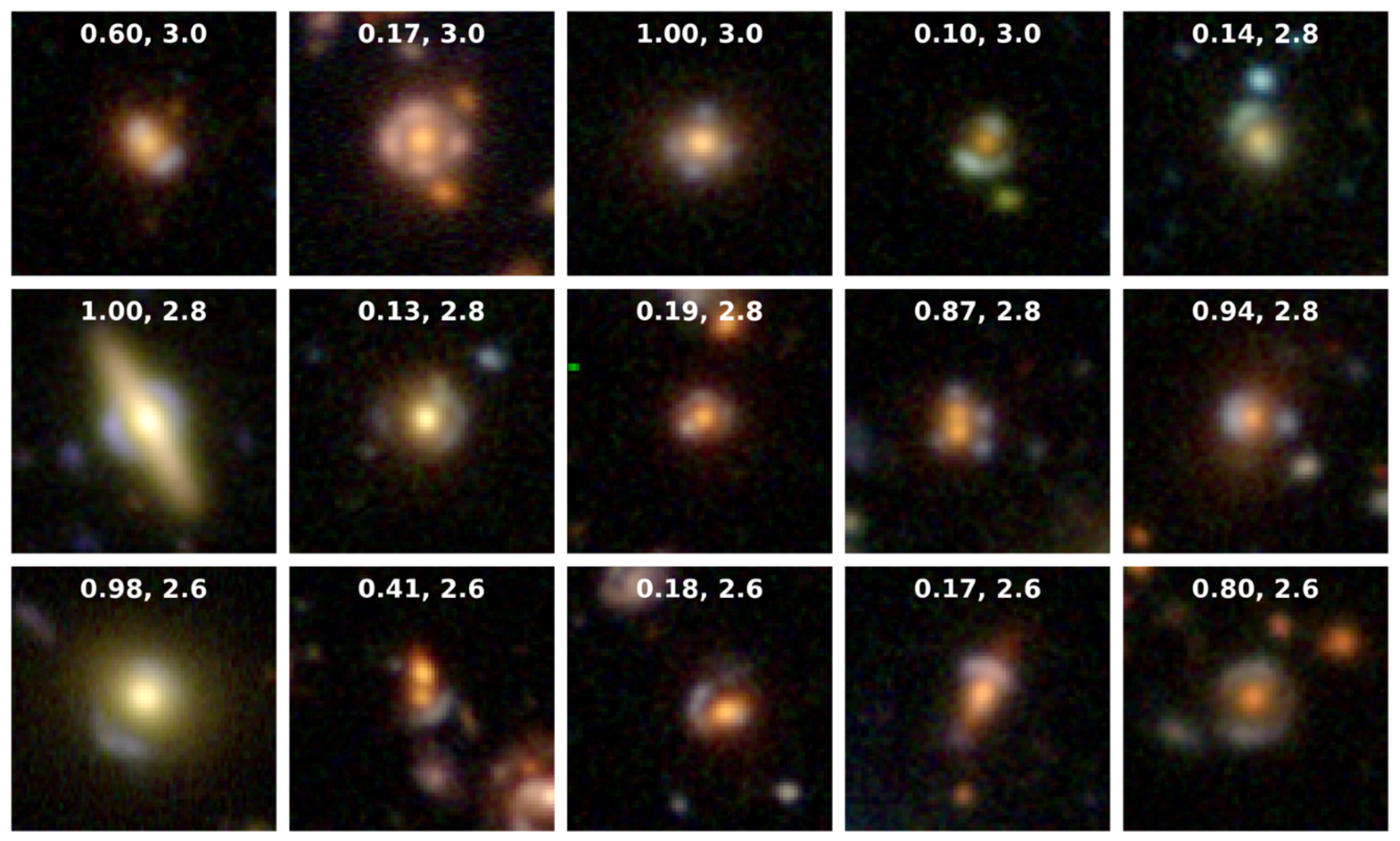
We found 330 new lens candidates in Pan-STARRS!



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

New lenses in HSC

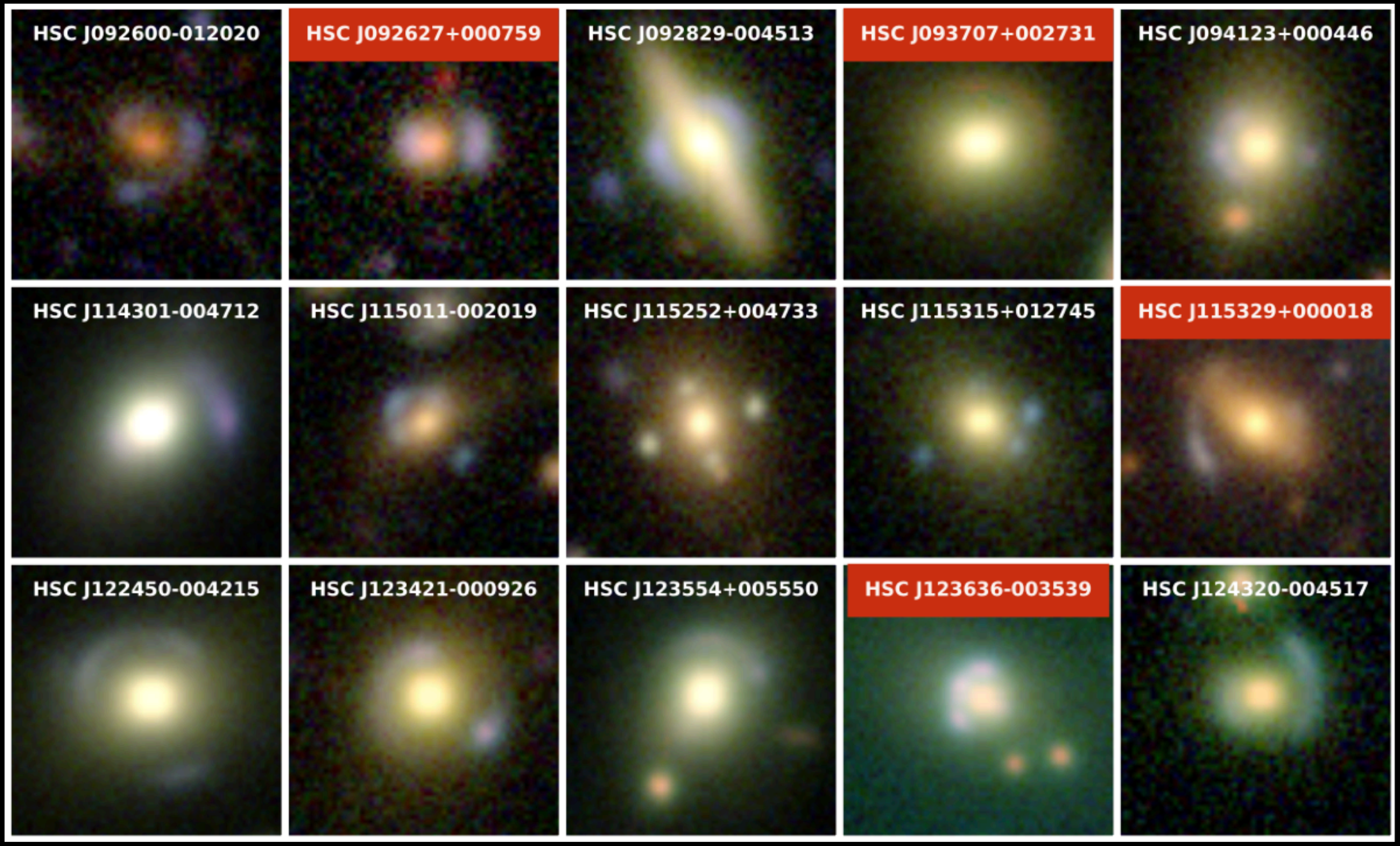
ResNet ***reduced false-positive rate to ~0.01%!***



[Cañameras et al. 2021; HOLISMOKES VI]

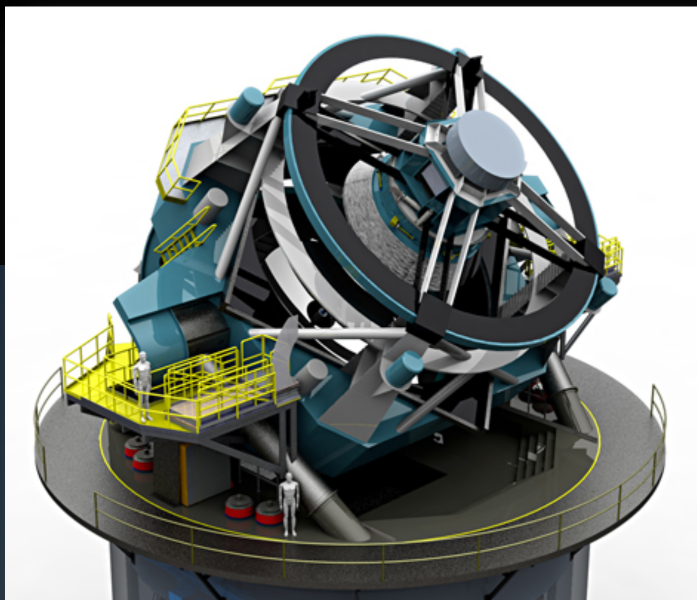
High-z lenses in HSC

Trained additional ResNet for high-z lenses and searched in Hyper Suprime Cam (HSC) Public Data Release 2
➜ >700 lens candidates (~40% are newly discovered)



[Shu et al. 2022; HOLISMOKES VIII]

Rubin Observatory
Legacy Survey of Space and Time (LSST)



High etendue survey telescope:

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

Ten year movie of the entire Southern sky

Survey starts ~2024

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

[Part of slide material courtesy of Phil Marshall]

Summary

- Intriguing tension in the measurements of H_0 from the late Universe and the early Universe
- Independent measurements of H_0 are crucial to validate or refute the tension
- adH0cc program to measure H_0 with <3% uncertainty from a sample of 20+ Type II supernovae
- HOLISMOKES program to establish lensed supernovae as a new and competitive probe of cosmology in the era of the Rubin Observatory
- >700 new lens candidates in Pan-STARRS and HSC as potential SN hosts