

Hubble Constant at the Late Universe

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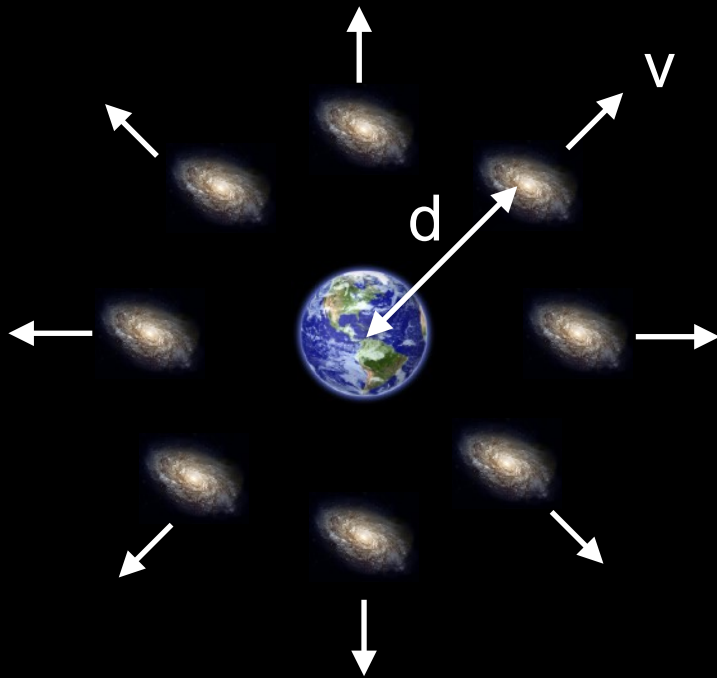
Academia Sinica Institute of Astronomy and Astrophysics

November 9, 2022

EDSU2022 @ La Réunion

Expanding Universe

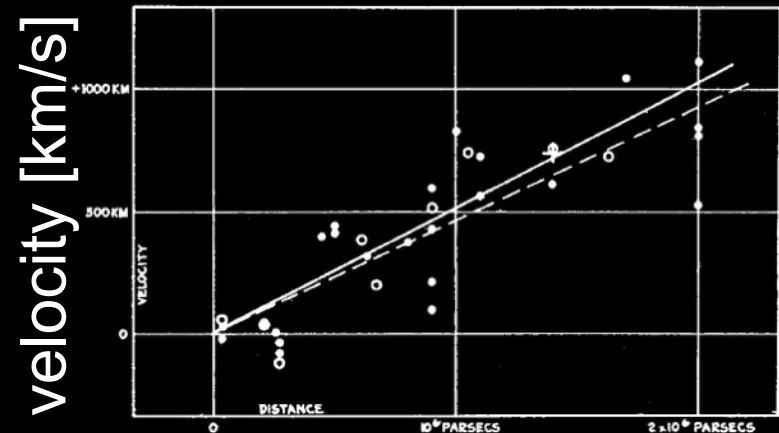
1920s
Discovery



Lemaître & Hubble
independently measured
the expansion rate

$$v = H_0 \times d$$

Hubble Constant

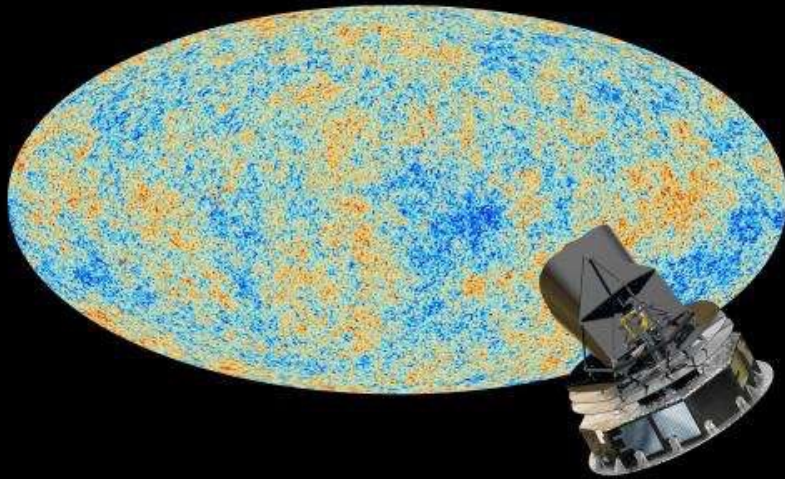


distance [Mpc]

H₀ sets age and size of Universe! [Hubble 1929]

Tension in H_0

Measurement from early universe:
Cosmic Microwave Background



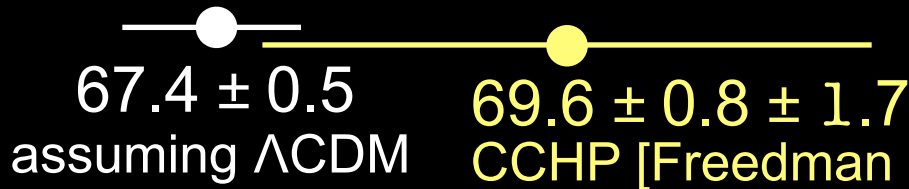
Measurement from local universe:
supernova distance ladder



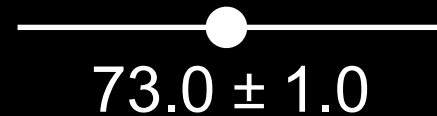
Lucas
Macri &
Brent
Tully's
talks

[credit: NASA/JPL-Caltech]

[Planck collaboration 2020]



SH0ES [Riess et al. 2022]



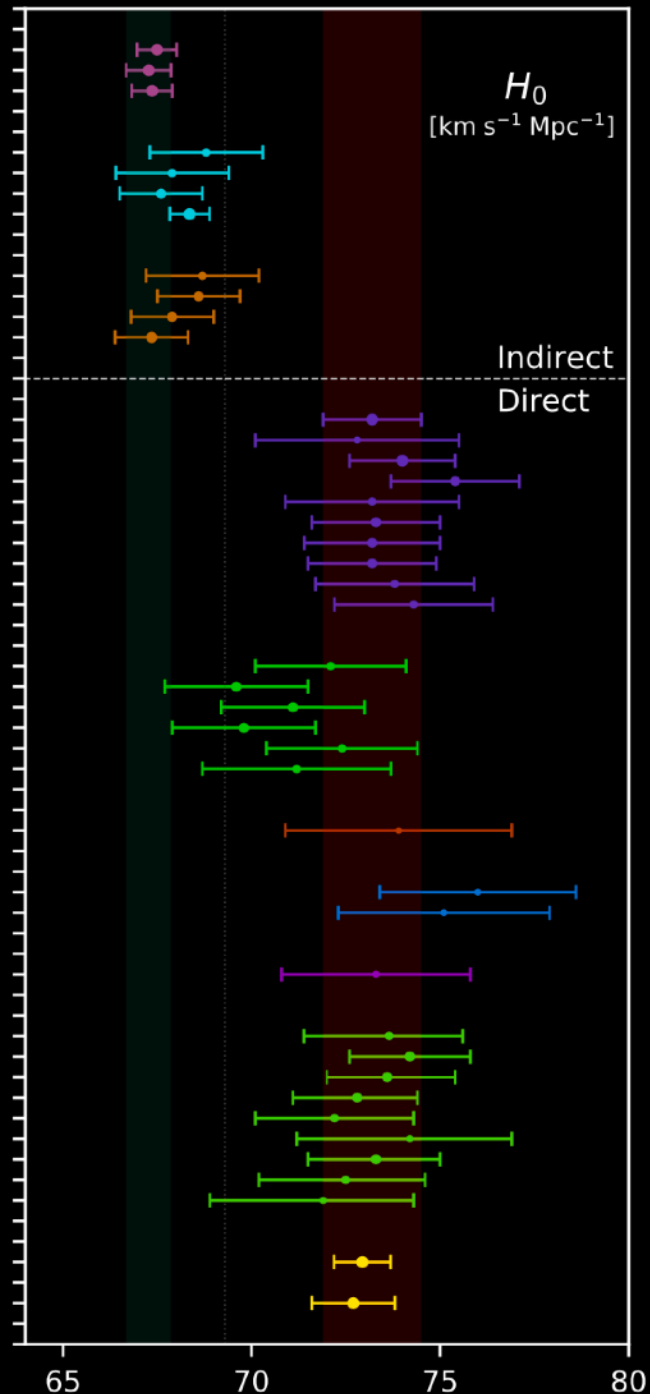
**New physics beyond standard
cosmological model Λ CDM?**

H_0
[km s⁻¹Mpc⁻¹]

Recent H_0 measurements

[Di Valentino et al. 2021]

CMB with Planck	
Balkenhol et al. (2021), Planck 2018+SPT+ACT	: 67.49 ± 0.53
Aghanim et al. (2020), Planck 2018	: 67.27 ± 0.60
Aghanim et al. (2020), Planck 2018+CMB lensing	: 67.36 ± 0.54
CMB without Planck	
Dutcher et al. (2021), SPT	: 68.8 ± 1.5
Aiola et al. (2020), ACT	: 67.9 ± 1.5
Aiola et al. (2020), WMAP9+ACT	: 67.6 ± 1.1
Zhang, Huang (2019), WMAP9+BAO	: $68.36^{+0.53}_{-0.52}$
No CMB, with BBN	
Colas et al. (2020), BOSS DR12+BBN	: 68.7 ± 1.5
Philcox et al. (2020), P_z +BAO+BBN	: 68.6 ± 1.1
Ivanov et al. (2020), BOSS+BBN	: 67.9 ± 1.1
Alam et al. (2020), BOSS+eBOSS+BBN	: 67.35 ± 0.97
Cepheids – SNIa	
Riess et al. (2020), R20	: 73.2 ± 1.3
Breuval et al. (2020)	: 72.8 ± 2.7
Riess et al. (2019), R19	: 74.0 ± 1.4
Camarena, Marra (2019)	: 75.4 ± 1.7
Burns et al. (2018)	: 73.2 ± 2.3
Follin, Knox (2017)	: 73.3 ± 1.7
Feeney, Mortlock, Dalmaso (2017)	: 73.2 ± 1.8
Riess et al. (2016), R16	: 73.2 ± 1.7
Cardona, Kunz, Pettorino (2016)	: 73.8 ± 2.1
Freedman et al. (2012)	: 74.3 ± 2.1
TRGB – SNIa	
Soltis, Casertano, Riess (2020)	: 72.1 ± 2.0
Freedman et al. (2020)	: 69.6 ± 1.9
Reid, Pesce, Riess (2019), SHOES	: 71.1 ± 1.9
Freedman et al. (2019)	: 69.8 ± 1.9
Yuan et al. (2019)	: 72.4 ± 2.0
Jang, Lee (2017)	: 71.2 ± 2.5
Masers	
Pesce et al. (2020)	: 73.9 ± 3.0
Tully – Fisher Relation (TFR)	
Kourkchi et al. (2020)	: 76.0 ± 2.6
Schombert, McGaugh, Lelli (2020)	: 75.1 ± 2.8
Surface Brightness Fluctuations	
Blakeslee et al. (2021) IR-SBF w/ HST	: 73.3 ± 2.5
Lensing related, mass model – dependent	
Yang, Birrer, Hu (2020): $H_0 = 73.65^{+1.95}_{-2.26}$	
Millon et al. (2020), TDCOSMO	: 74.2 ± 1.6
Qi et al. (2020)	: $73.6^{+1.8}_{-1.7}$
Liao et al. (2020)	: $72.8^{+1.6}_{-1.7}$
Liao et al. (2019)	: 72.2 ± 2.1
Shajib et al. (2019), STRIDES	: $74.2^{+2.7}_{-2.7}$
Wong et al. (2019), H0LICOW 2019	: $73.3^{+1.7}_{-1.8}$
Birrer et al. (2018), H0LICOW 2018	: $72.5^{+2.3}_{-2.3}$
Bonvin et al. (2016), H0LICOW 2016	: $71.9^{+2.4}_{-3.0}$
Optimistic average	
Di Valentino (2021)	: 72.94 ± 0.75
Ultra – conservative, no Cepheids, no lensing	
Di Valentino (2021)	: 72.7 ± 1.1

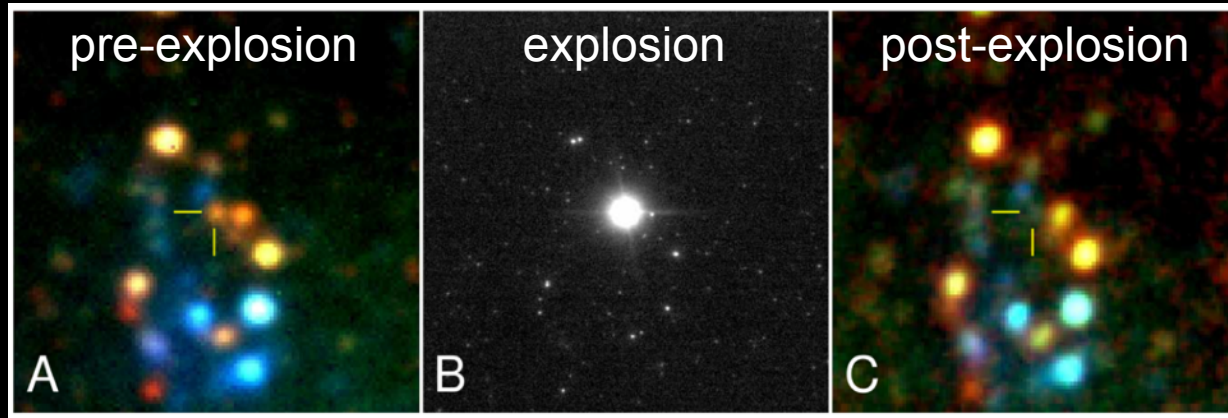


Two independent methods

- Type II supernovae
- Strong gravitational lensing

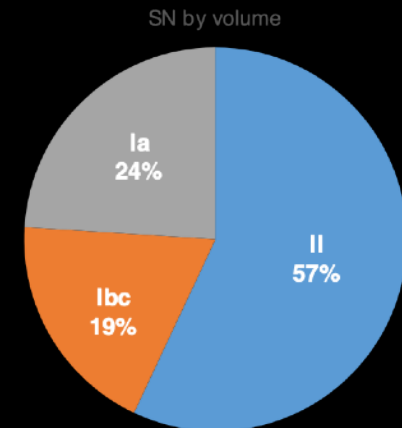
Type II supernovae

core-collapse explosions of massive red-supergiant stars



Mattila et al. 2010

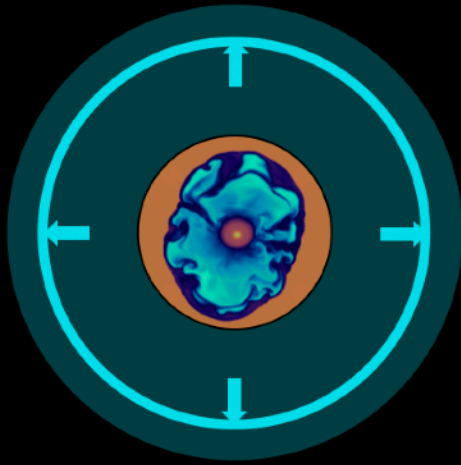
- Peak luminosity $\sim 10^9$ solar luminosity
→ observable up to redshift $z \sim 0.4$
- Most common type of SN by volume
- Single-step distance measurement, independent of the distance ladder



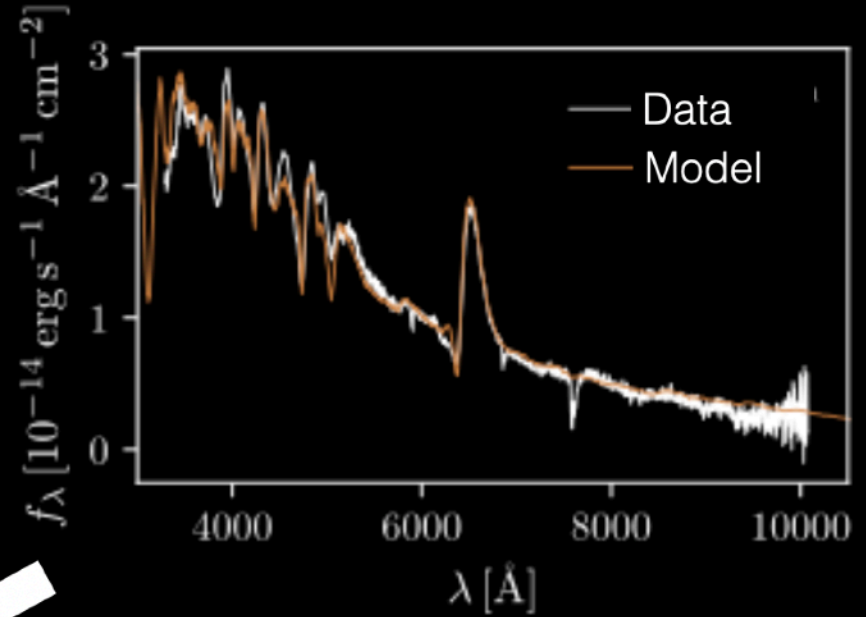
[Slide material courtesy of Stefan Taubenberger]

Type II supernovae

Radiation comes from photosphere in simple hydrogen-rich medium



can be modeled accurately

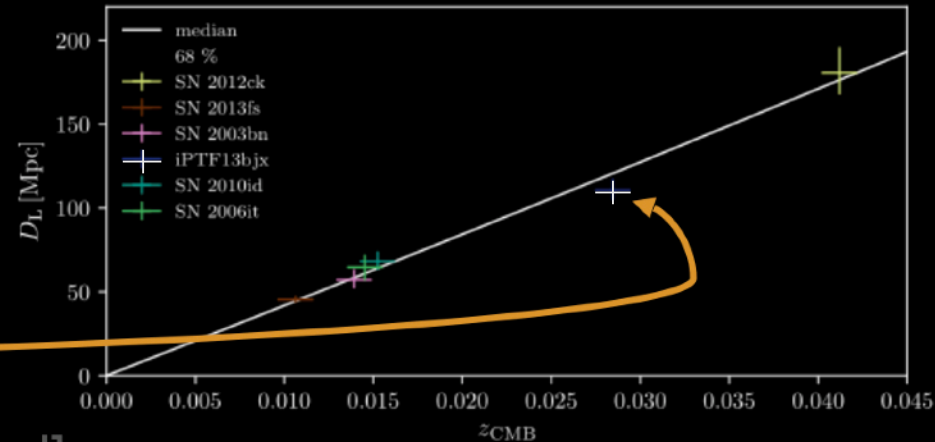


Luminosity



Distance

Hubble constant



[slide material courtesy of Christian Vogl]



< 3%



$z < 0.15$



accurate
determination

of H_0

from core-

collapse

supernovae

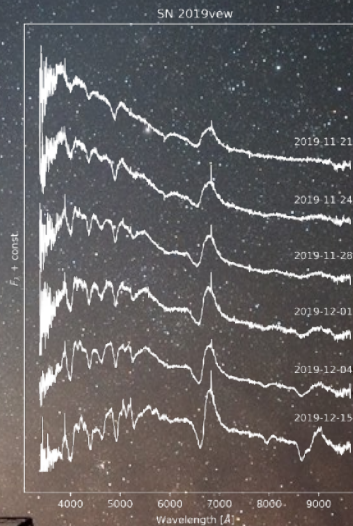
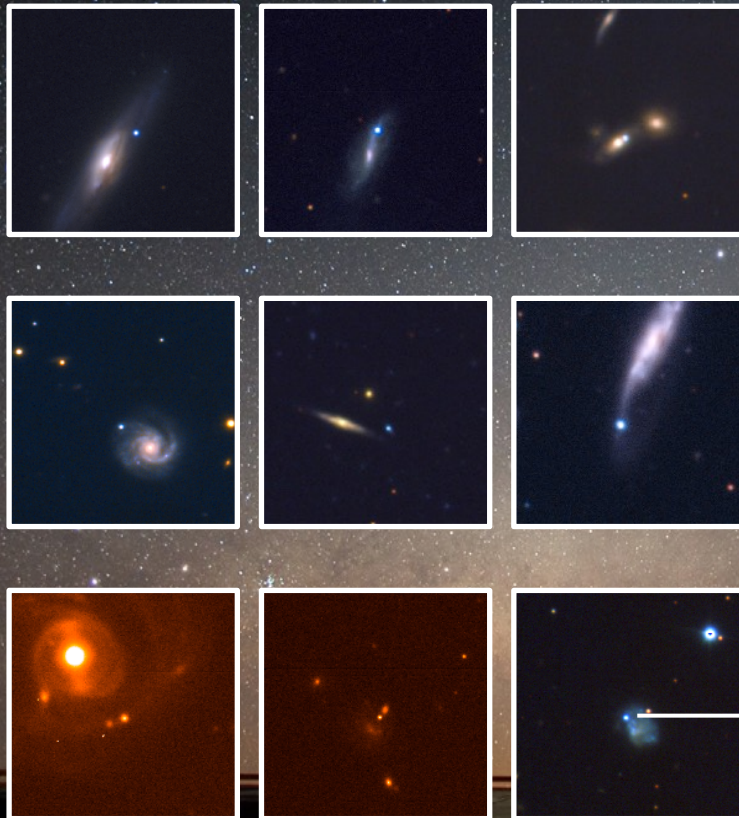


adH0cc

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

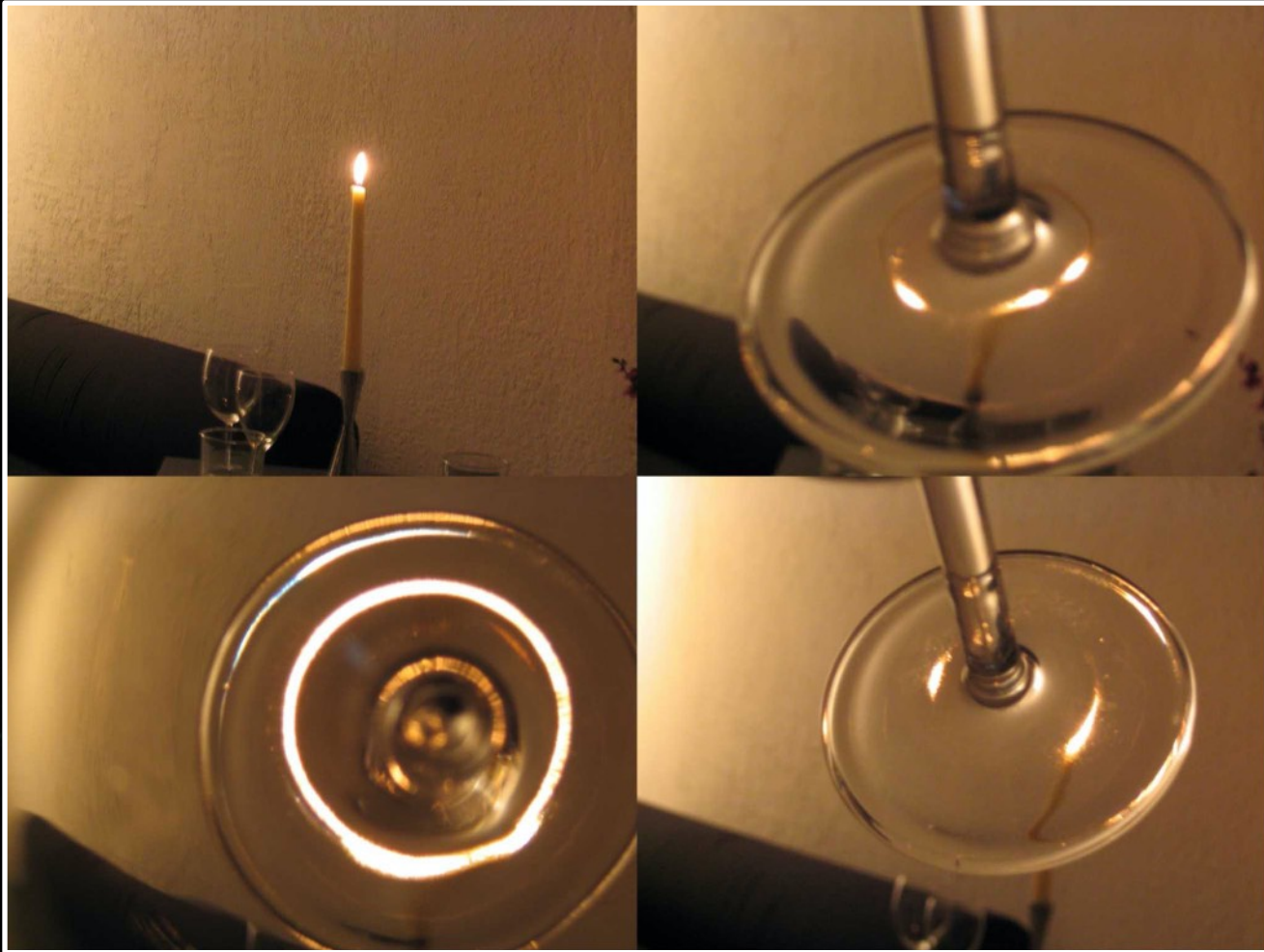
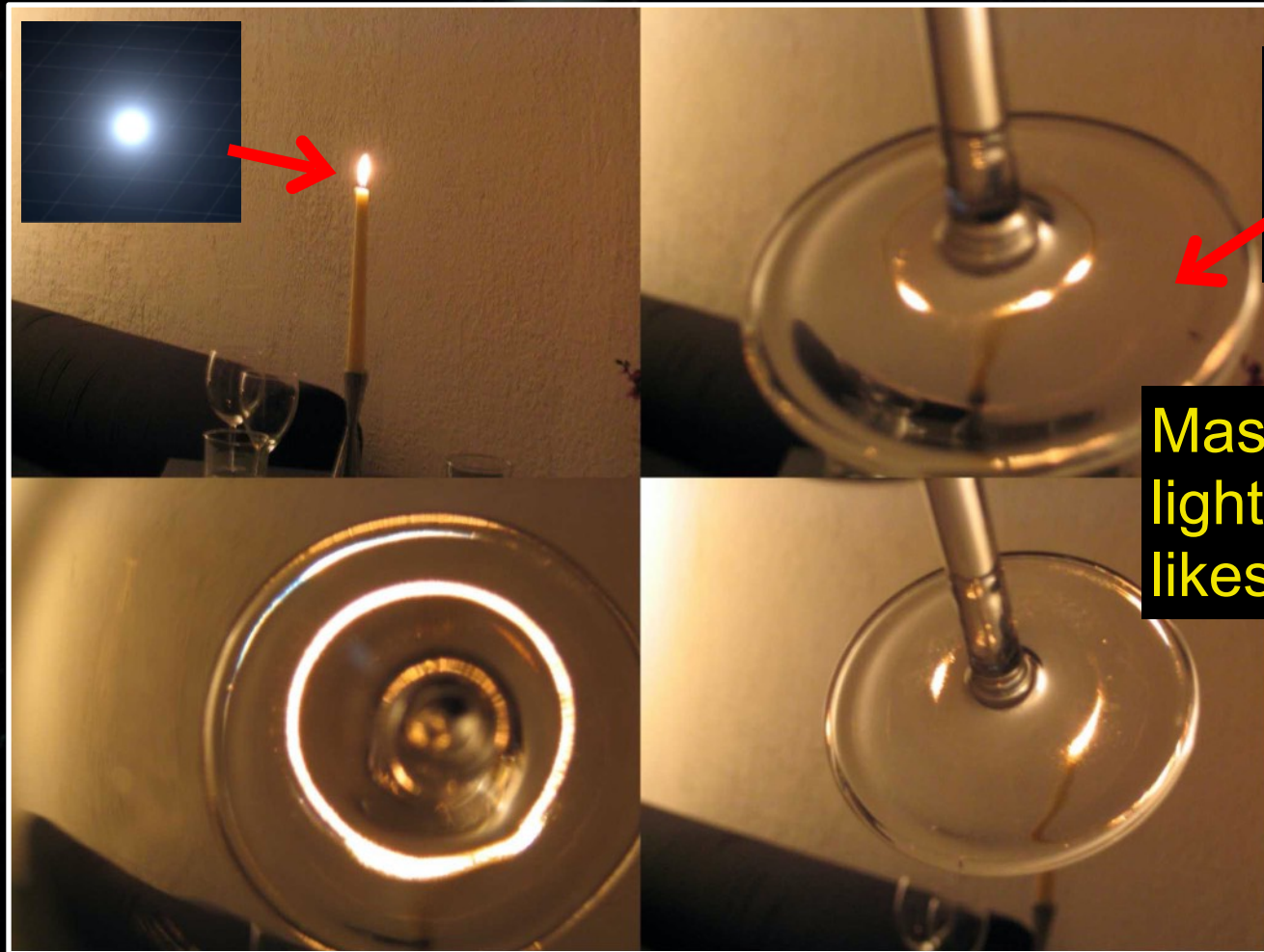


Image Credit: P. J. Marshall

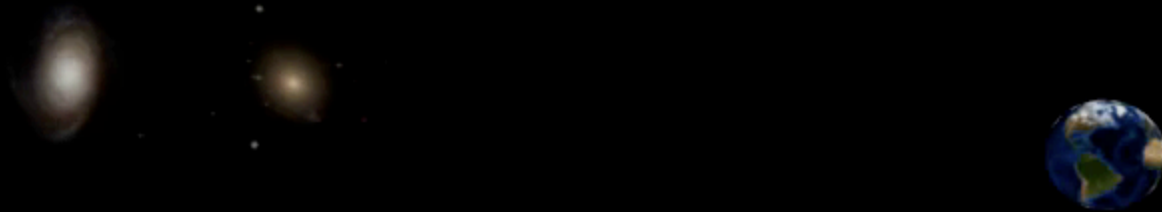
Gravitational Strong[^]Lensing



Mass “bends”
light and acts
like 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:

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

Time-delay
distance:

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

Obtain from
lens mass
model

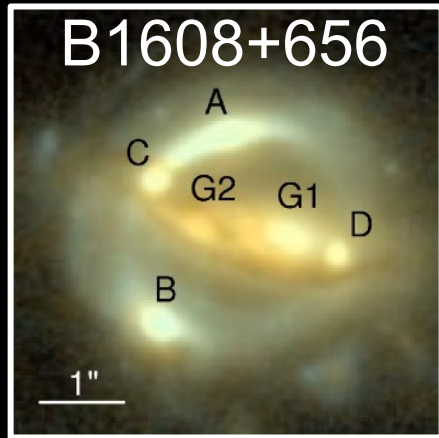
Cosmography:

time delays Δt + mass model ϕ_{lens}

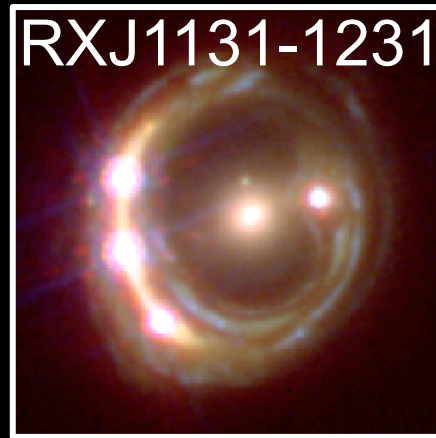
→ time-delay distance $D_{\Delta t}$

→ Hubble constant H_0

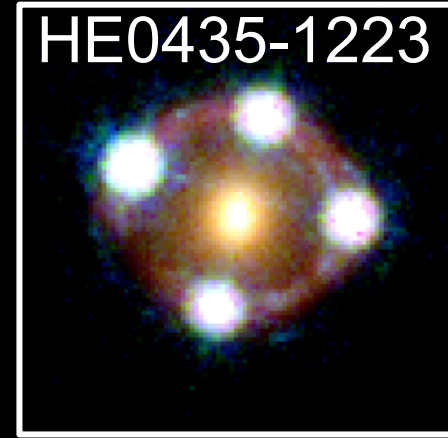
H0LiCOW lensed quasars



[Suyu et al. 2010]



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



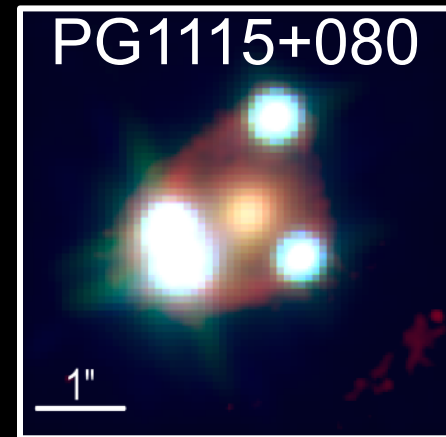
[Wong et al. 2017; Rusu
et al. 2017; Sluse et al.
2017; Bonvin et al. 2017]



part of extended sample
[Birrer et al. 2019]



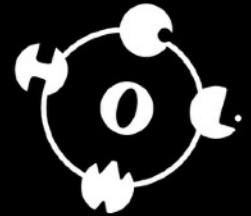
[Bonvin et al. 2019;
Sluse et al. 2019;
Rusu et al. 2020]



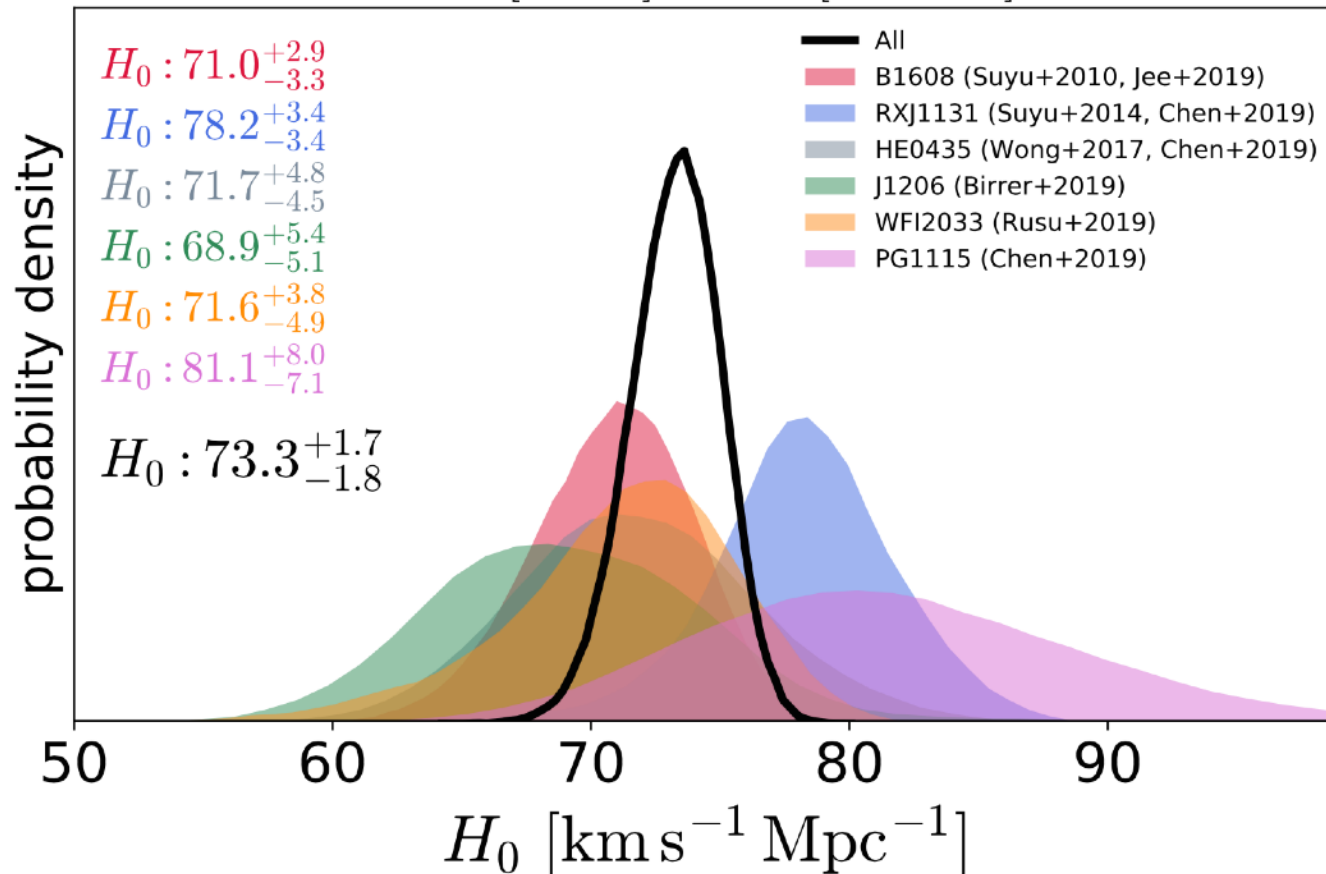
part of Keck AO sample
of SHARP program
[Chen et al. 2019]

H0LiCOW! H_0 from 6 strong lenses

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



$H_0 \in [0, 150]$ $\Omega_m \in [0.05, 0.5]$



**H_0 with 2.4%
precision in
flat Λ CDM**

[Wong, Suyu, Chen et al. 2020]

Observations

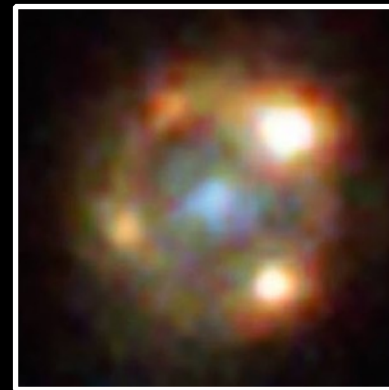
It took 50 years to observe the first strongly lensed SN event, after Refsdal proposed it in 1964

Strongly lensed supernovae

SN Refsdal



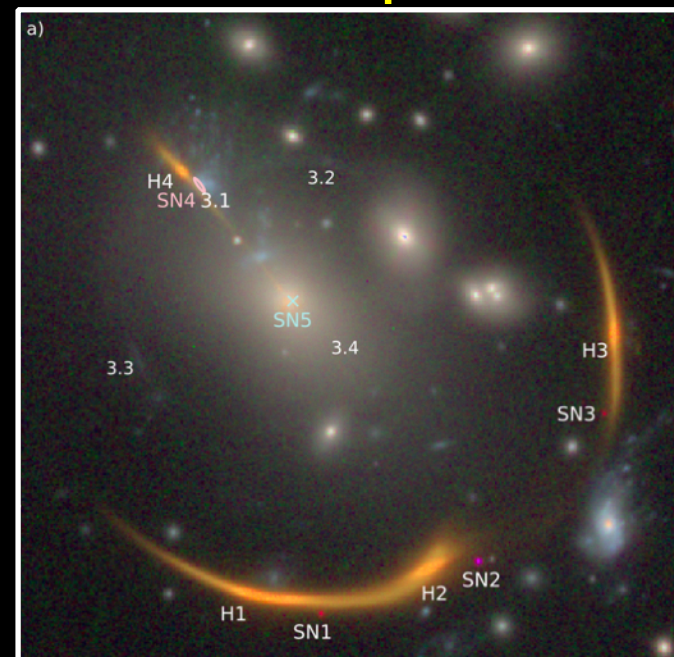
[Kelly et al. 2015]



iPTF16geu

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

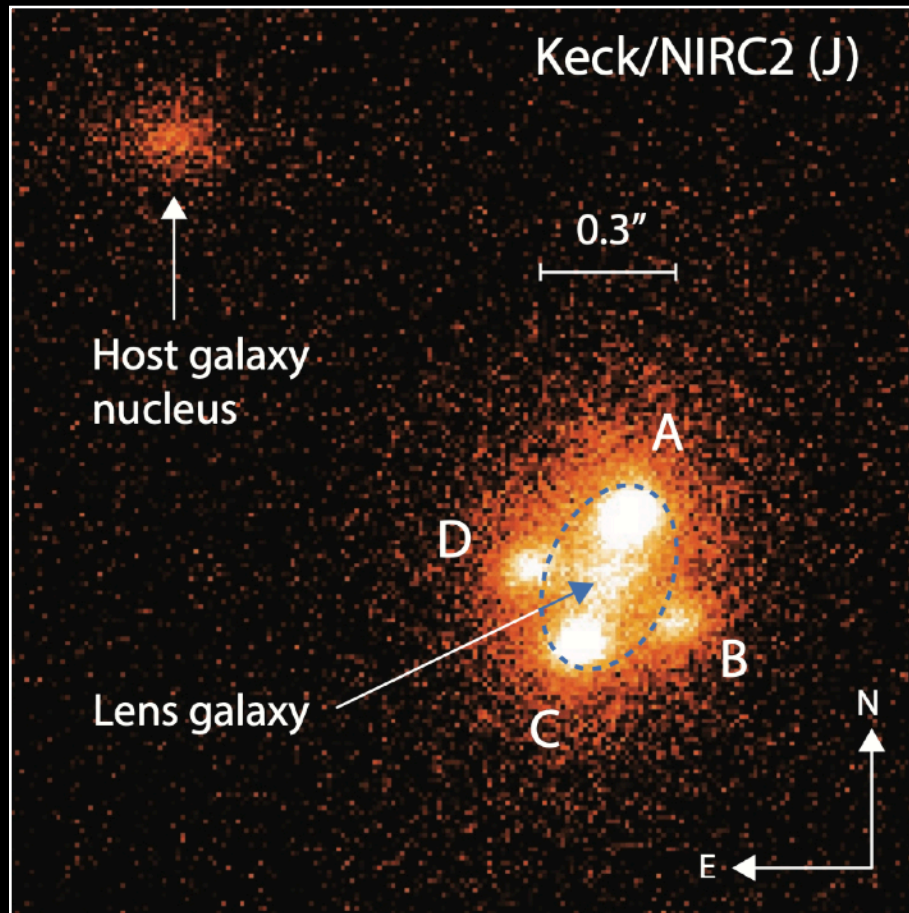
SN Requiem



[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

HOLISMOKERS



Jana
Bayer



Raoul
Cañameras



James
Chan



Frédéric
Courbin



Simon
Huber



Markus
Kromer



Alejandra
Melo Melo



Uli
Nöbauer



Stefan
Schuldt



Yiping
Shu



Stuart
Sim



Dominique
Sluse



Sherry
Suyu (PI)



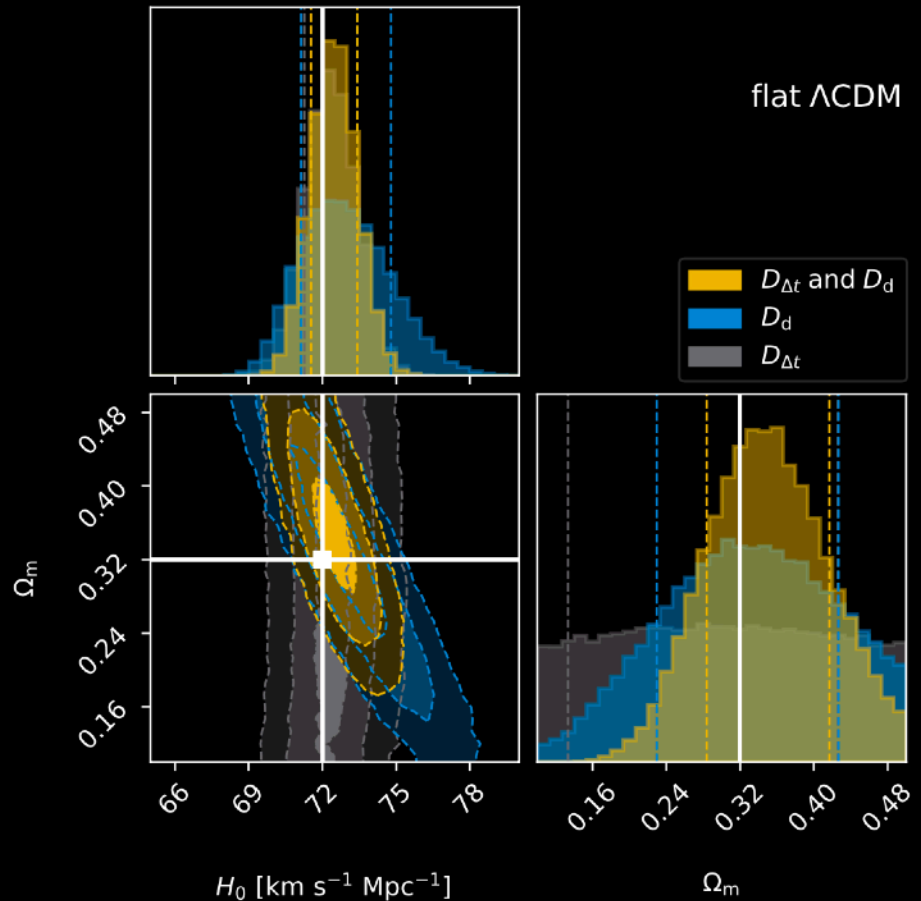
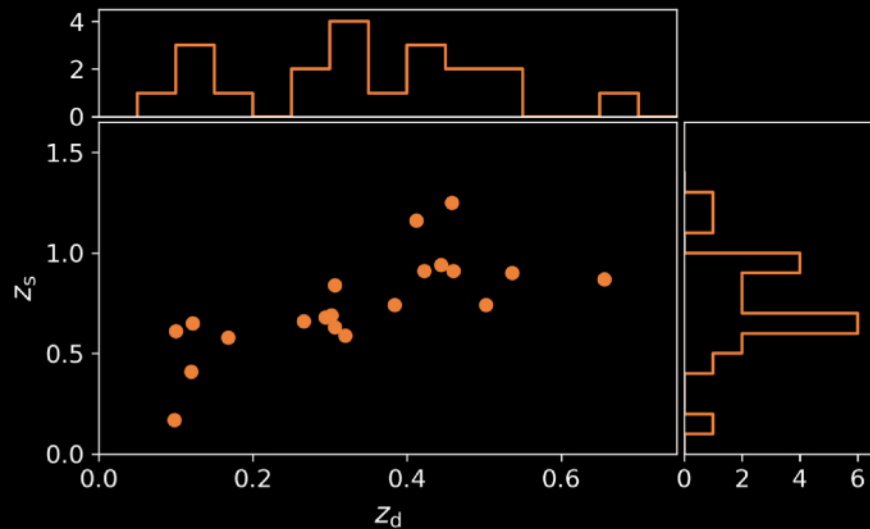
Stefan
Taubenberger



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 Λ CDM from this sample

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

Lens Search
(Papers II, VI, VIII)

**Follow-up
Observations**
(Paper III)

The logo for HOLI SMOKES features the word "HOLI" in a clean, white, sans-serif font above the word "SMOKES" in a white, hand-drawn, sketchy font. A small orange dot is positioned above the letter "O" in "HOLI", with two thin orange lines extending downwards from it to the top of the letter "O" in "SMOKES". The letter "O" in "SMOKES" is filled with a brown, smoky, circular gradient, giving it a glowing, smoky appearance. The background behind the text is a dark, smoky, ethereal glow.

**HOLI
SMOKES**

Time Delays
(Papers V, VII)

Lens Modelling
(Papers IV, IX, X)

Search for lensed SNe

Zwicky Transient Facility (ZTF):



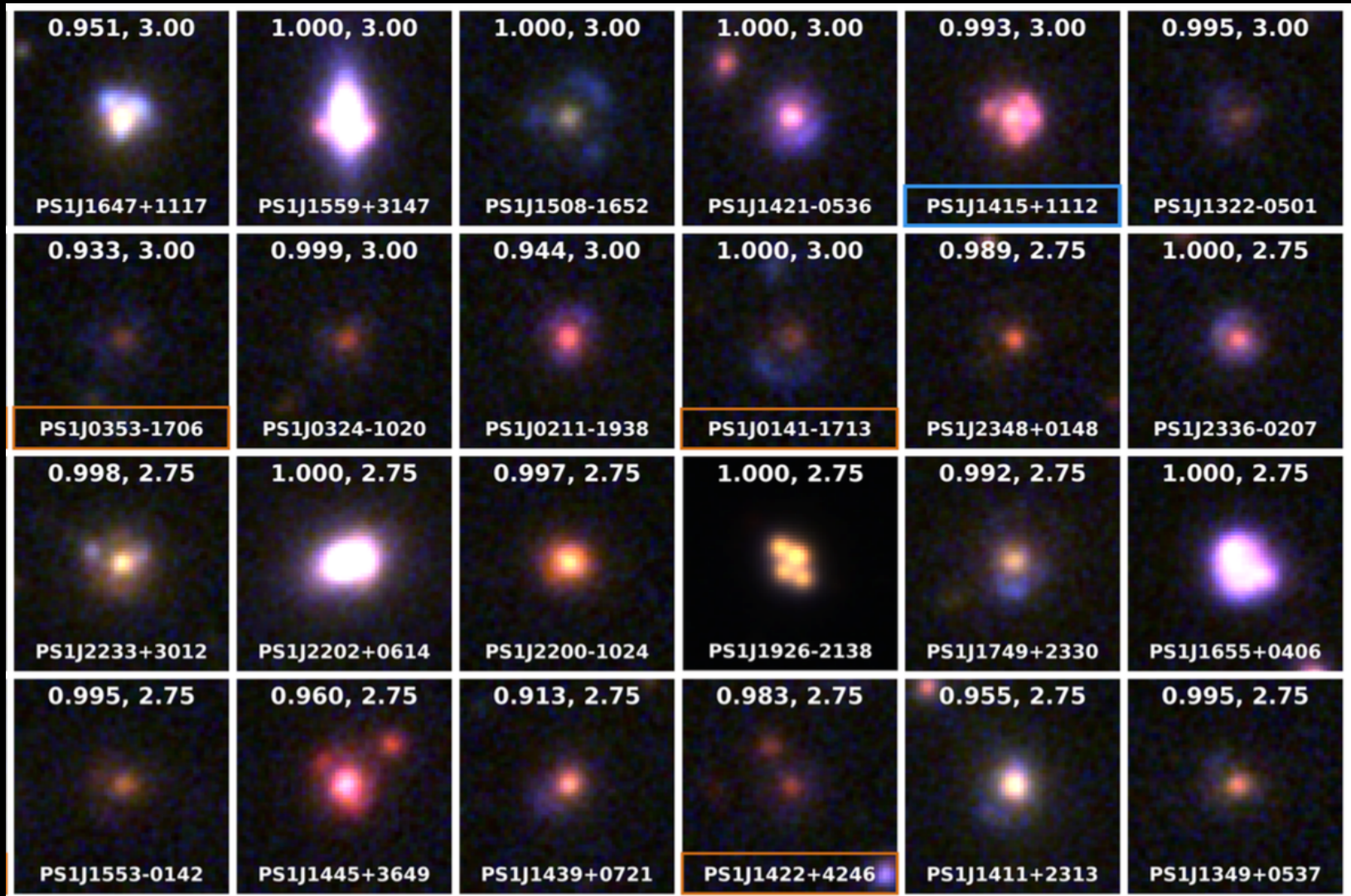
Combine ZTF + Pan-STARRS to search for lensed SNe

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
- 3×10^9 sources in Pan-STARRS 3π survey
 - 2.3×10^7 after simple photometric cuts, star removal
 - 1.0×10^6 after apply neural network on photometric measurements
 - 1.2×10^4 after apply convolutional neural network (CNN) on g, r, i-band image cutouts of systems
 - 330 high-quality candidates after visual inspection

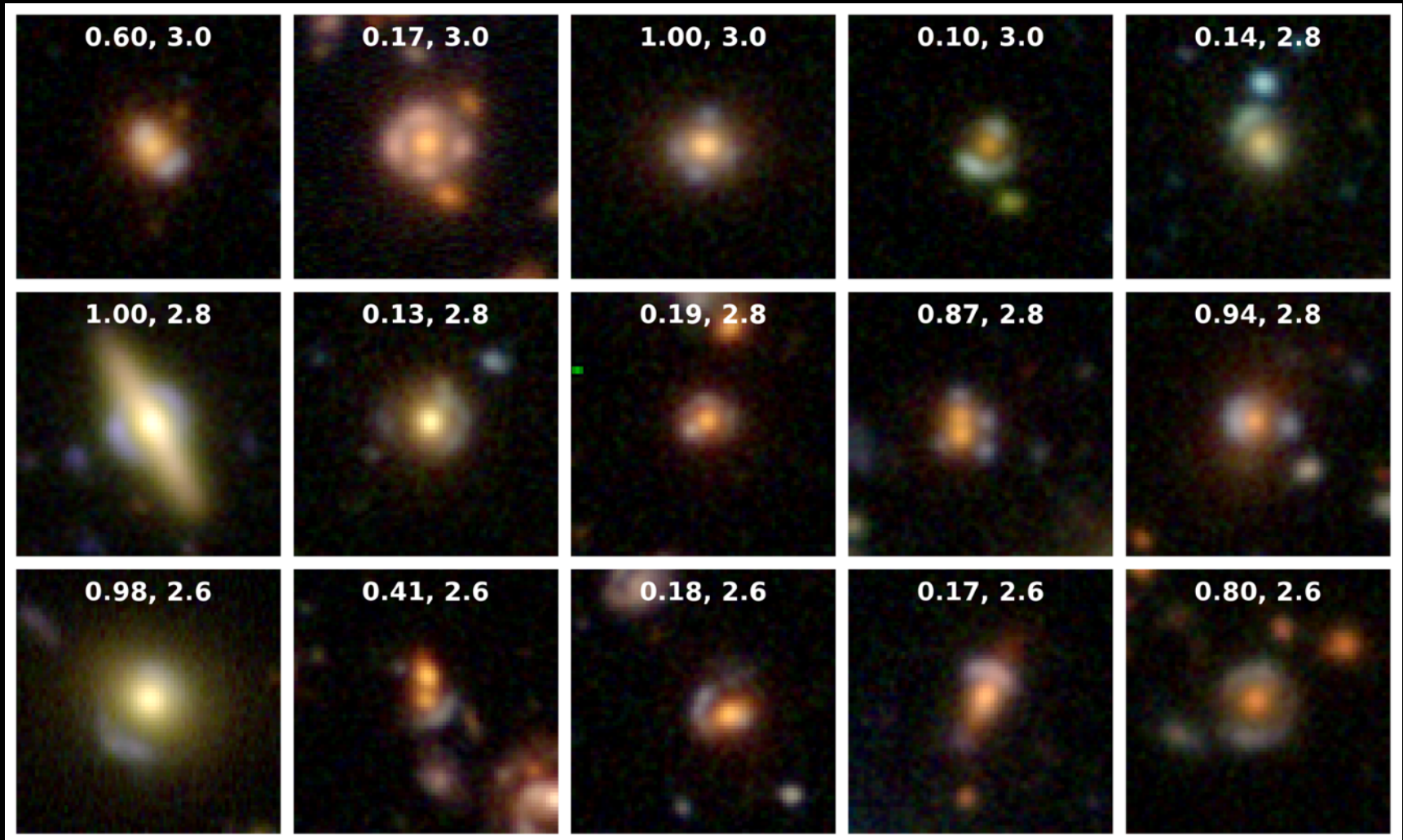
New lenses in Pan-STARRS

We found 330 new lens candidates in Pan-STARRS!



New lenses in HSC

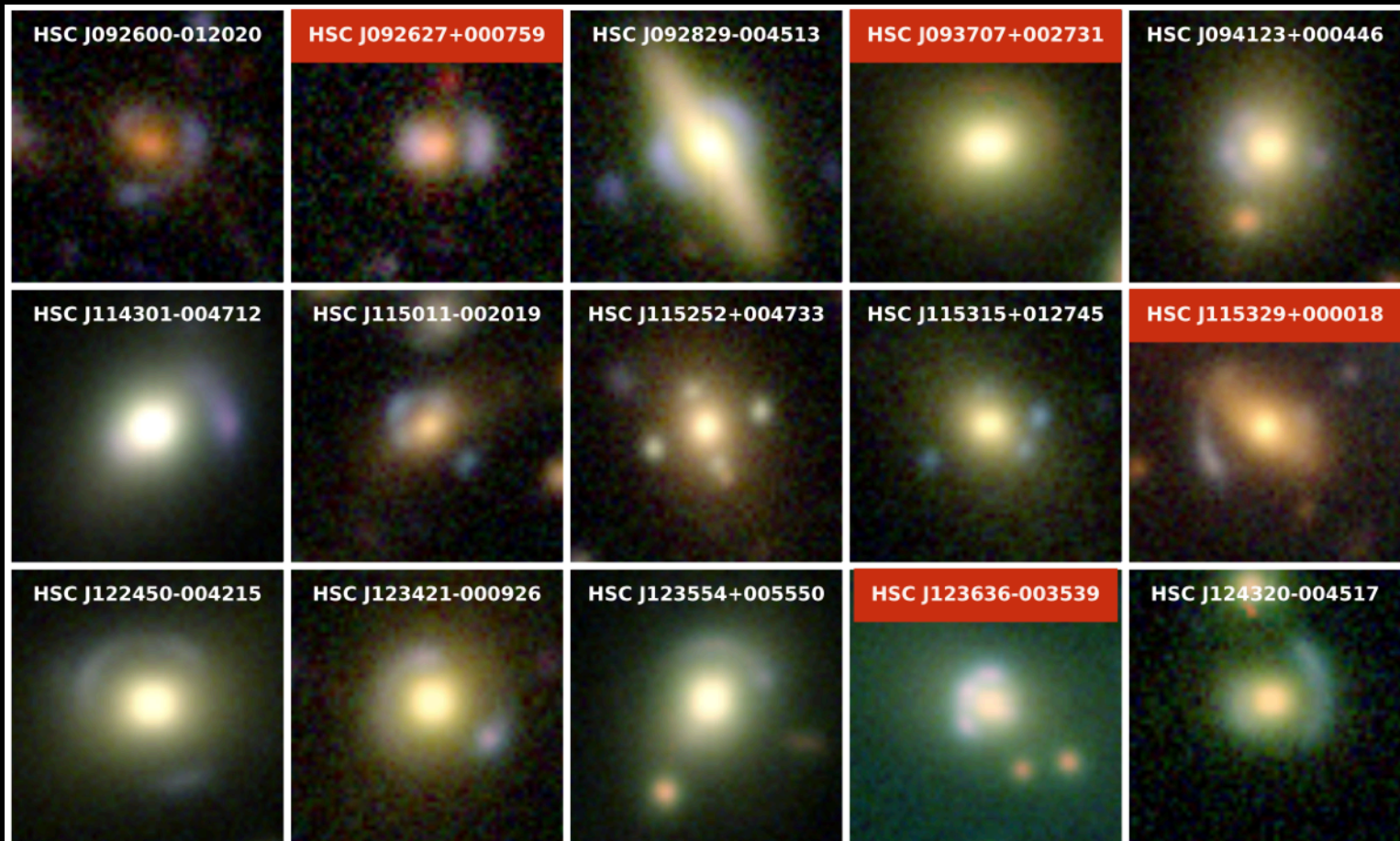
ResNet *reduced false-positive rate to ~0.01%!*



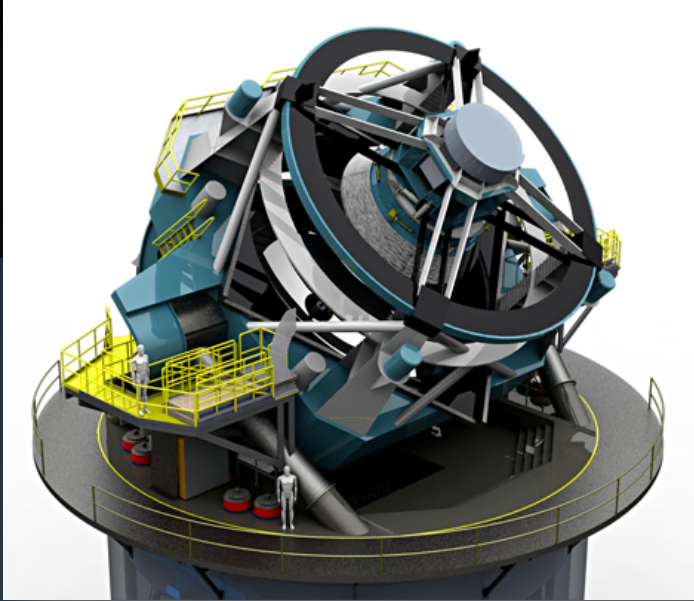
High-z lenses in HSC

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)



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