

Time-delay cosmography: present and future

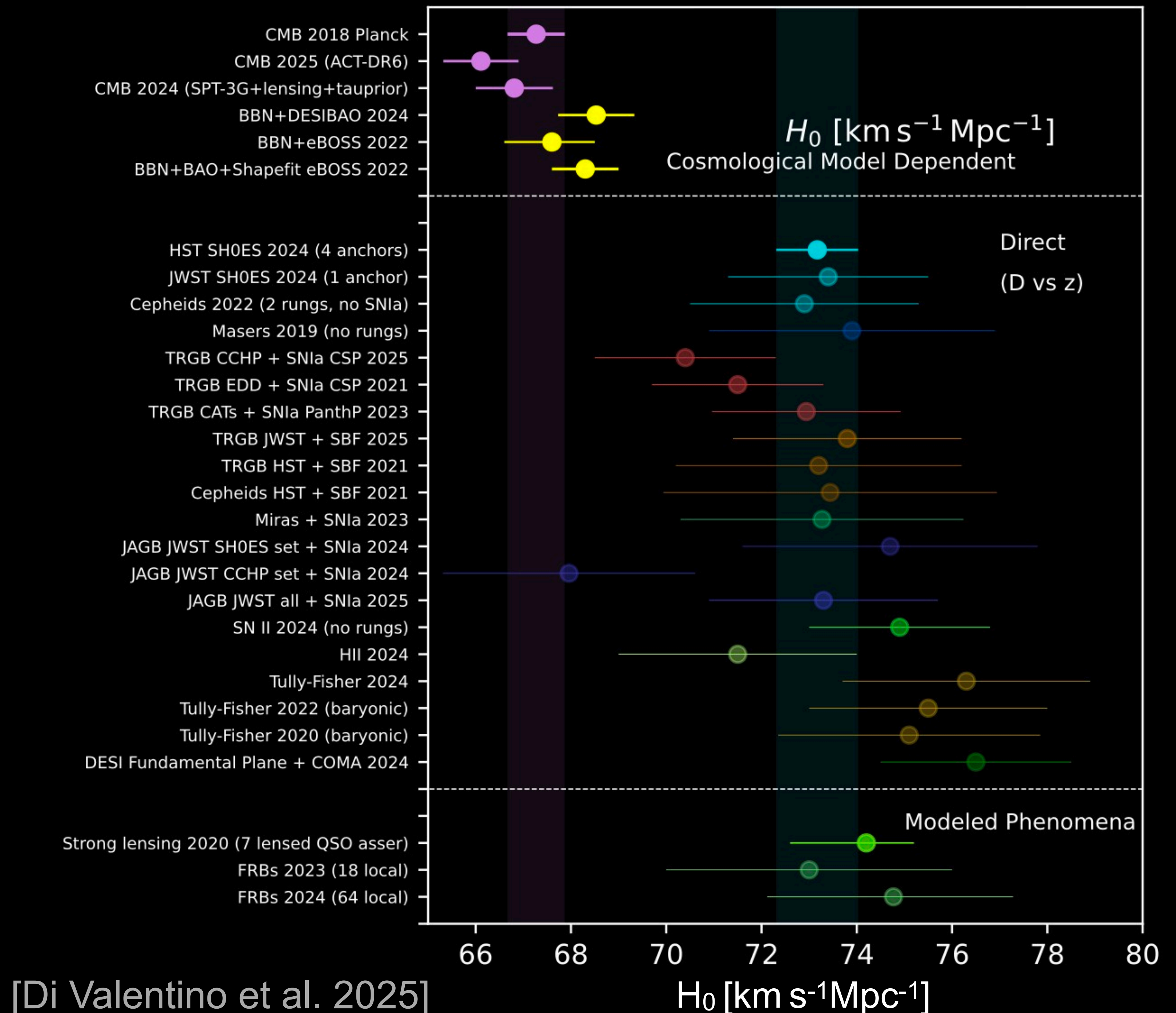
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Technical University of Munich
Max Planck Institute for Astrophysics

GGI workshop: Exploring New Frontiers in Cosmology
July 23, 2026 @ GGI, Florence

H_0 tension

- $\sim 6\sigma$ tension between Planck collaboration (2020) and SH0ES [Riess et al. 2025]
- New physics beyond the standard flat Λ CDM model?
- Need independent measurements of H_0



Strong Lensing

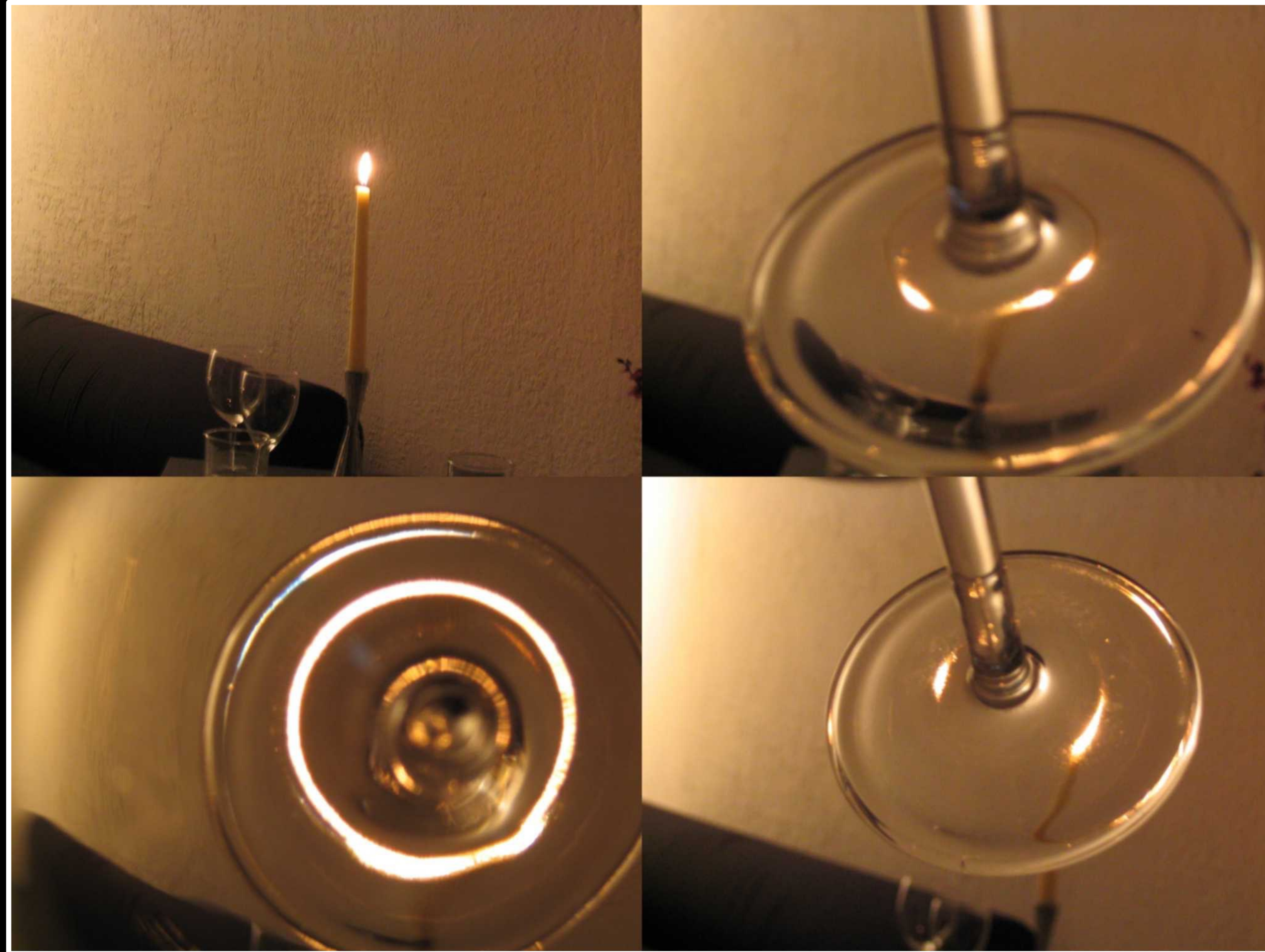


Image Credit: P. J. Marshall

Gravitational Strong[^]Lensing

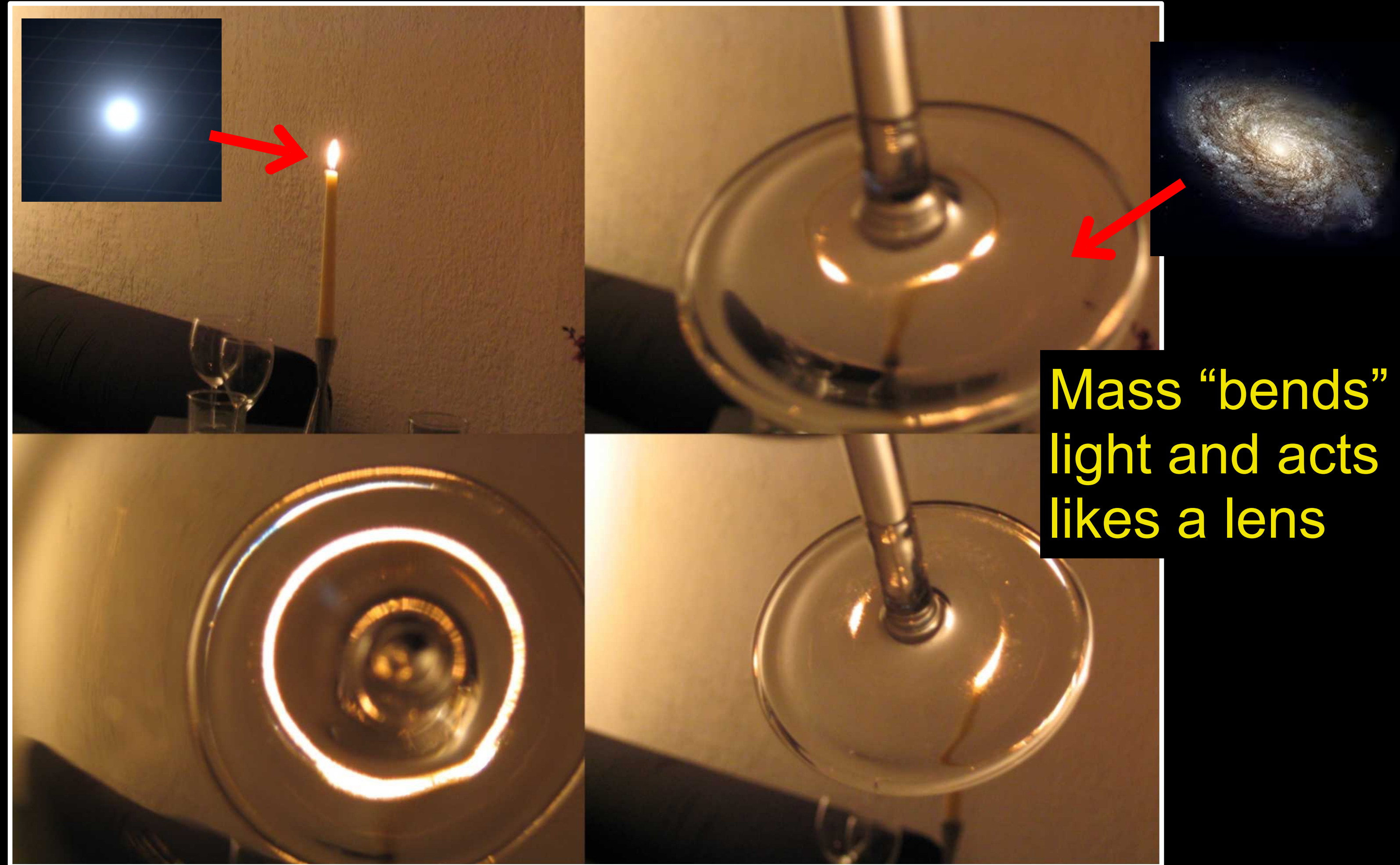


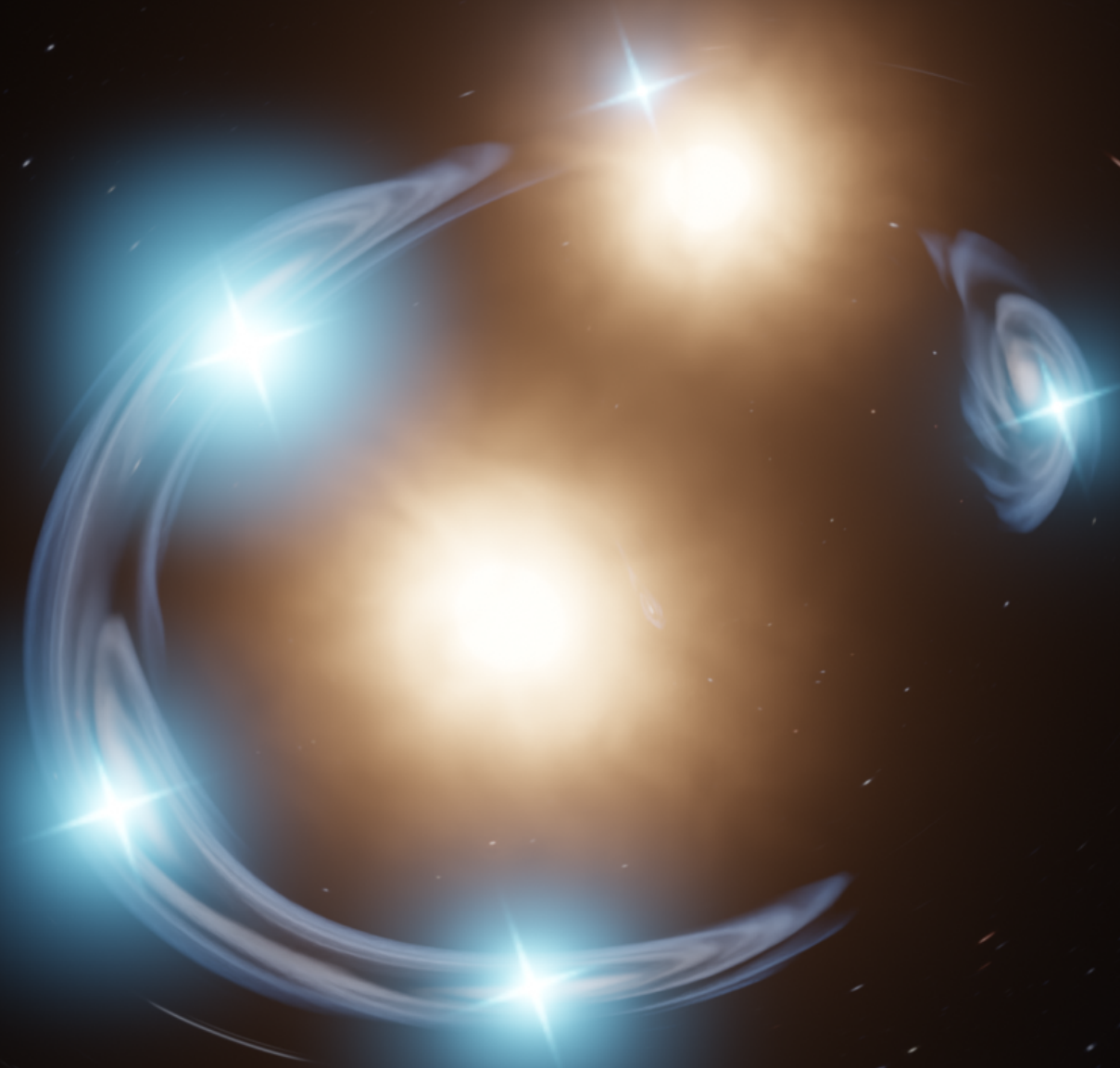
Image Credit: P. J. Marshall

Strongly lensed supernova



Cosmology with lensing delays

[Refsdal 1964]



[credit: E. Mamuzic]

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

To measure $D_{\Delta t}$ and H_0 , need:

- (1) time delays
- (2) lens mass model
- (3) mass along line of sight

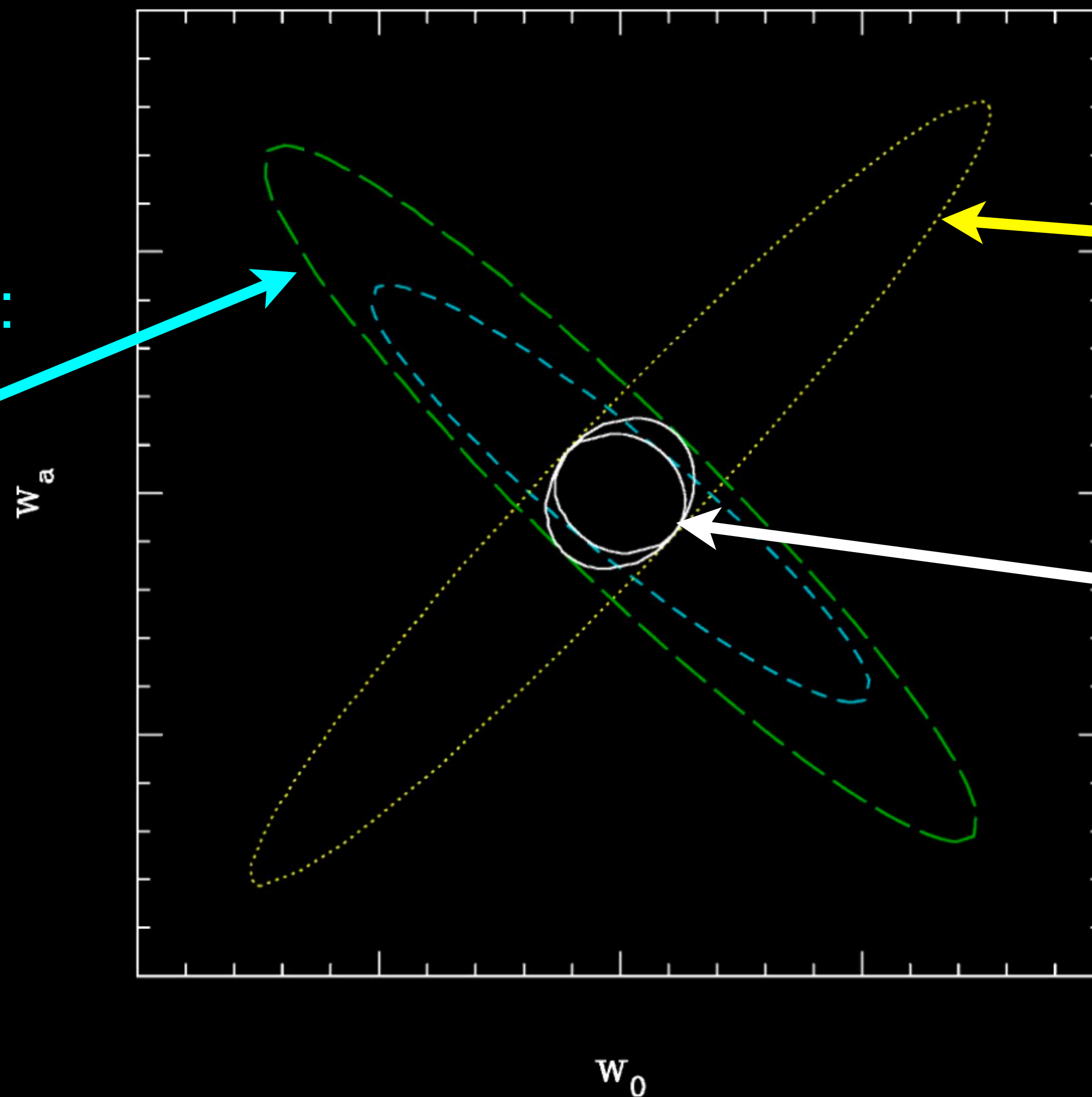
Cosmological complementarity of lensing time delays

Dark energy equation of state parameter:

$$w = w_0 + w_a (1 - a)$$

most distance probes:
anticorrelation of w_a
and w_0

- D_{ang} (e.g., BAO)
- D_{lum} (e.g., SN)



time-delay distance

$$D_{\Delta t} \sim D_{\text{lens}} D_{\text{sr}} / D_{\text{lens-sr}}$$

positive correlation for
 $z_{\text{lens}} \sim [0, 0.6]$

[Linder 2011]

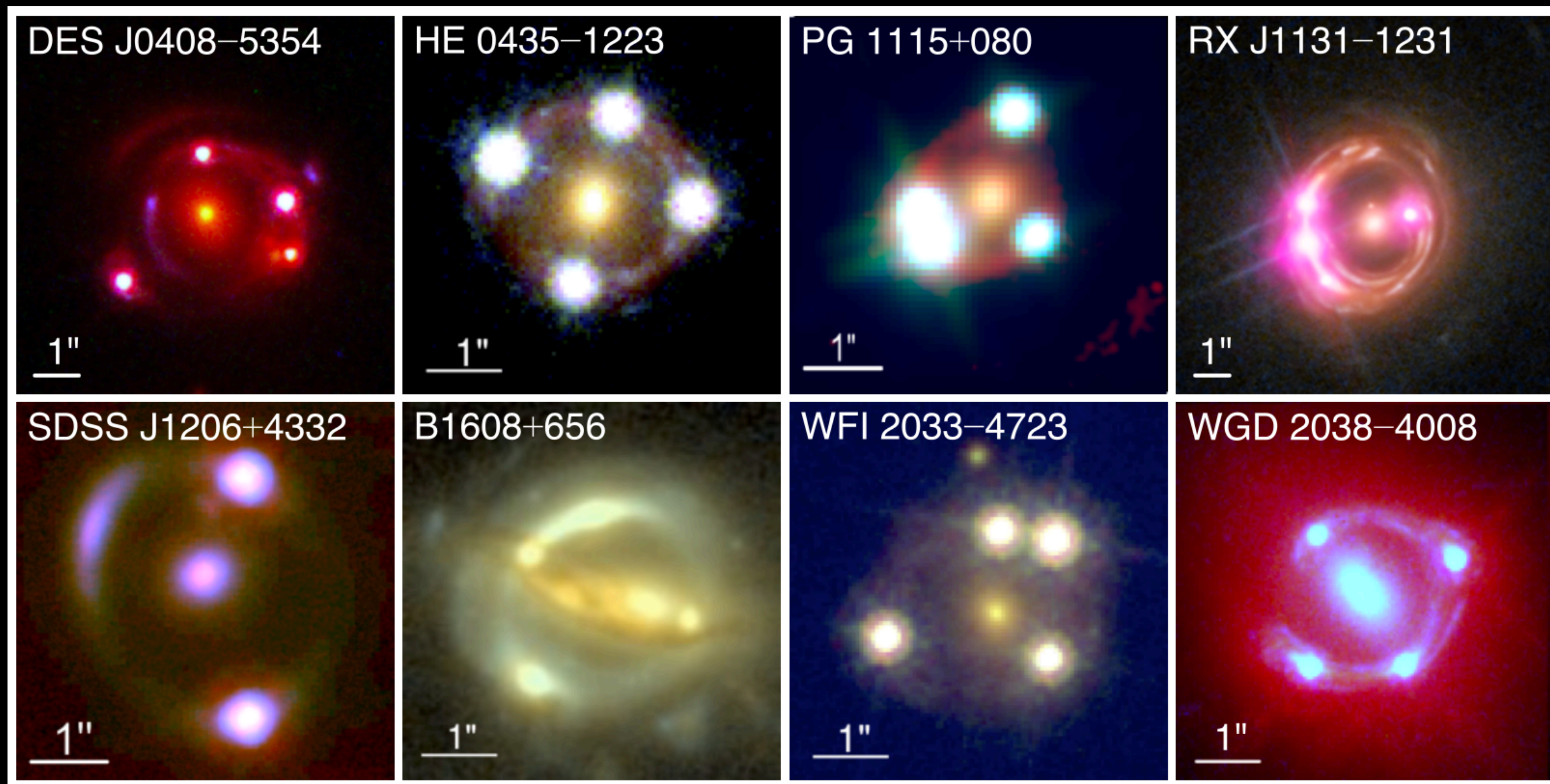
Combination of $D_{\Delta t}$ and
other distance probes:
powerfully breaking
parameter degeneracies

[Linder 2004]

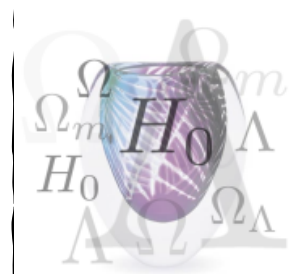
H_0 from lensed quasars

Lensed quasars

TDCOSMO (Time-Delay COSMOgraphy) sample in 2025

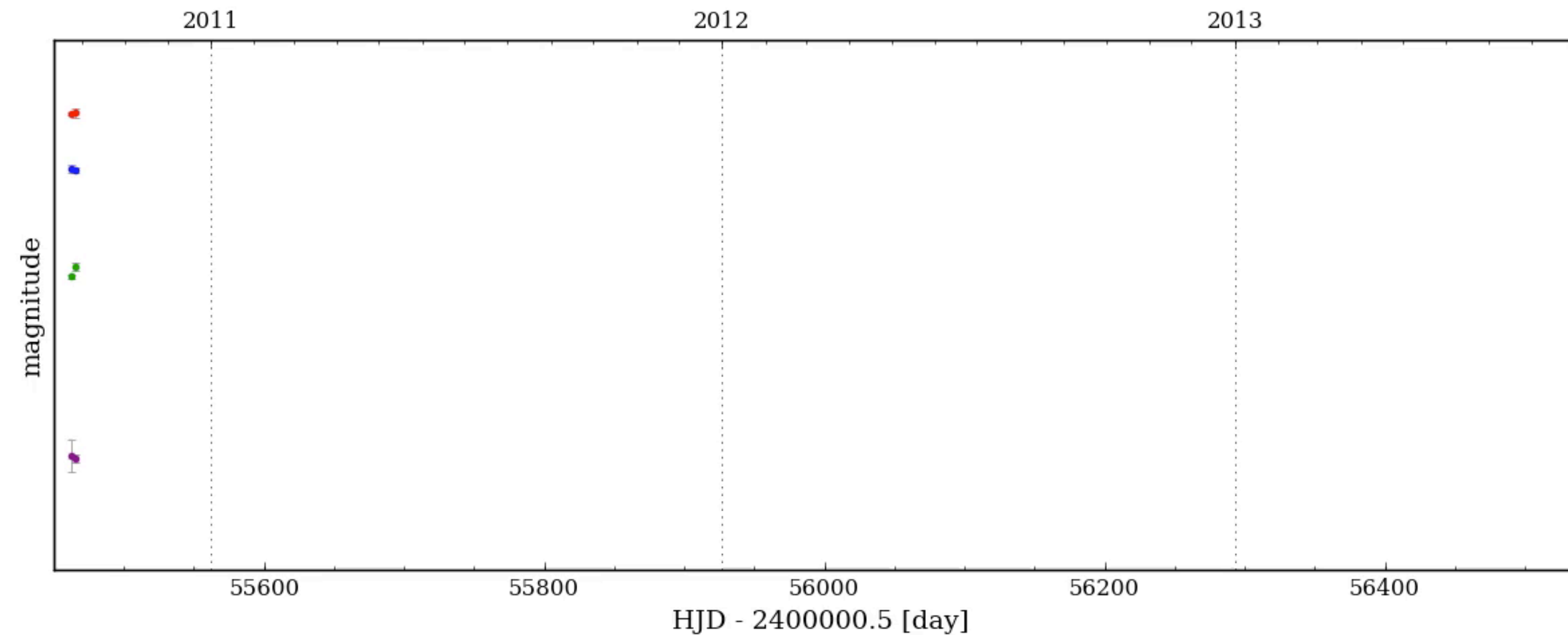
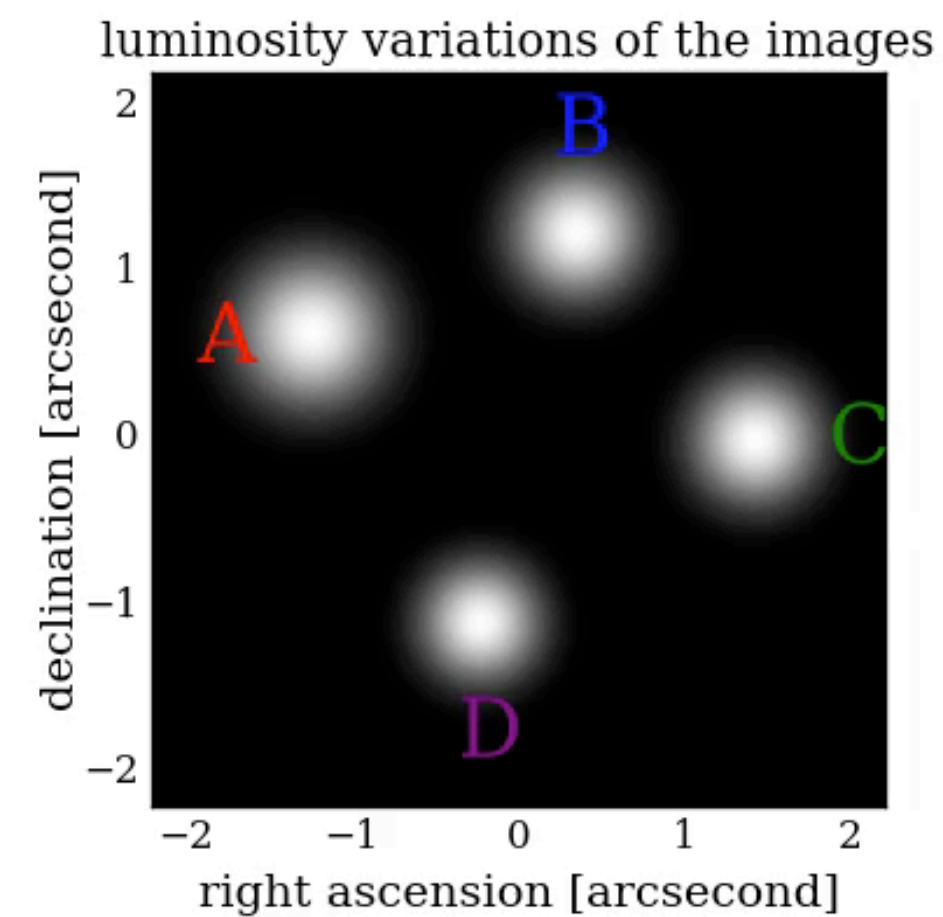


Gravitational Lens Time Delays



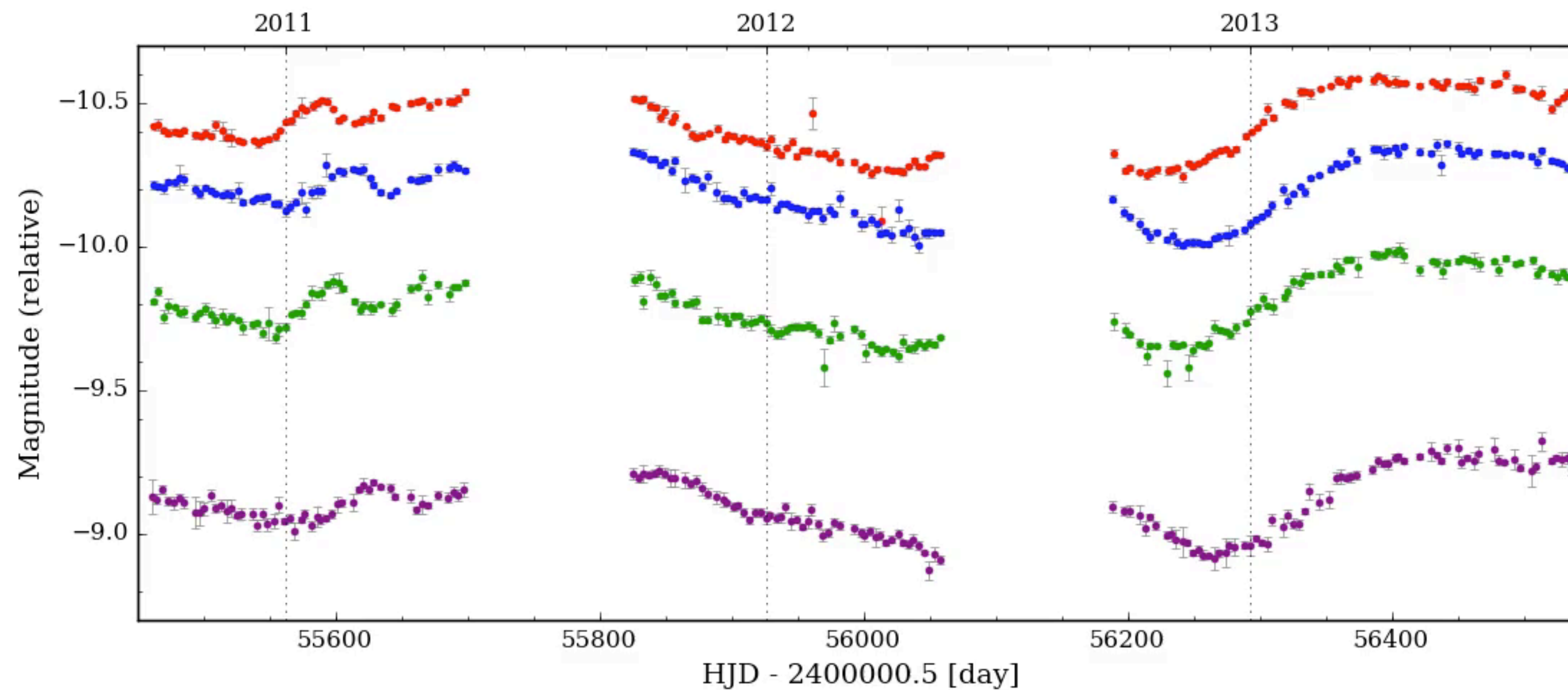
COSMOGRAIL

[COSmological
MONitoring of
GRAvitational
Lenses;
PI: F. Courbin,
G. Meylan]



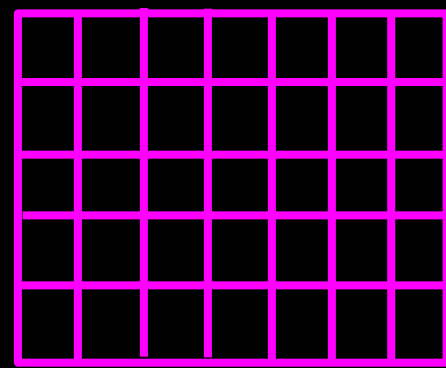
[Credit: V. Bonvin]

Measuring time delays



Lens galaxy mass modelling

light distribution
of extended source



mass distribution
of lens

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

light of
lensed
quasar

+
time delays

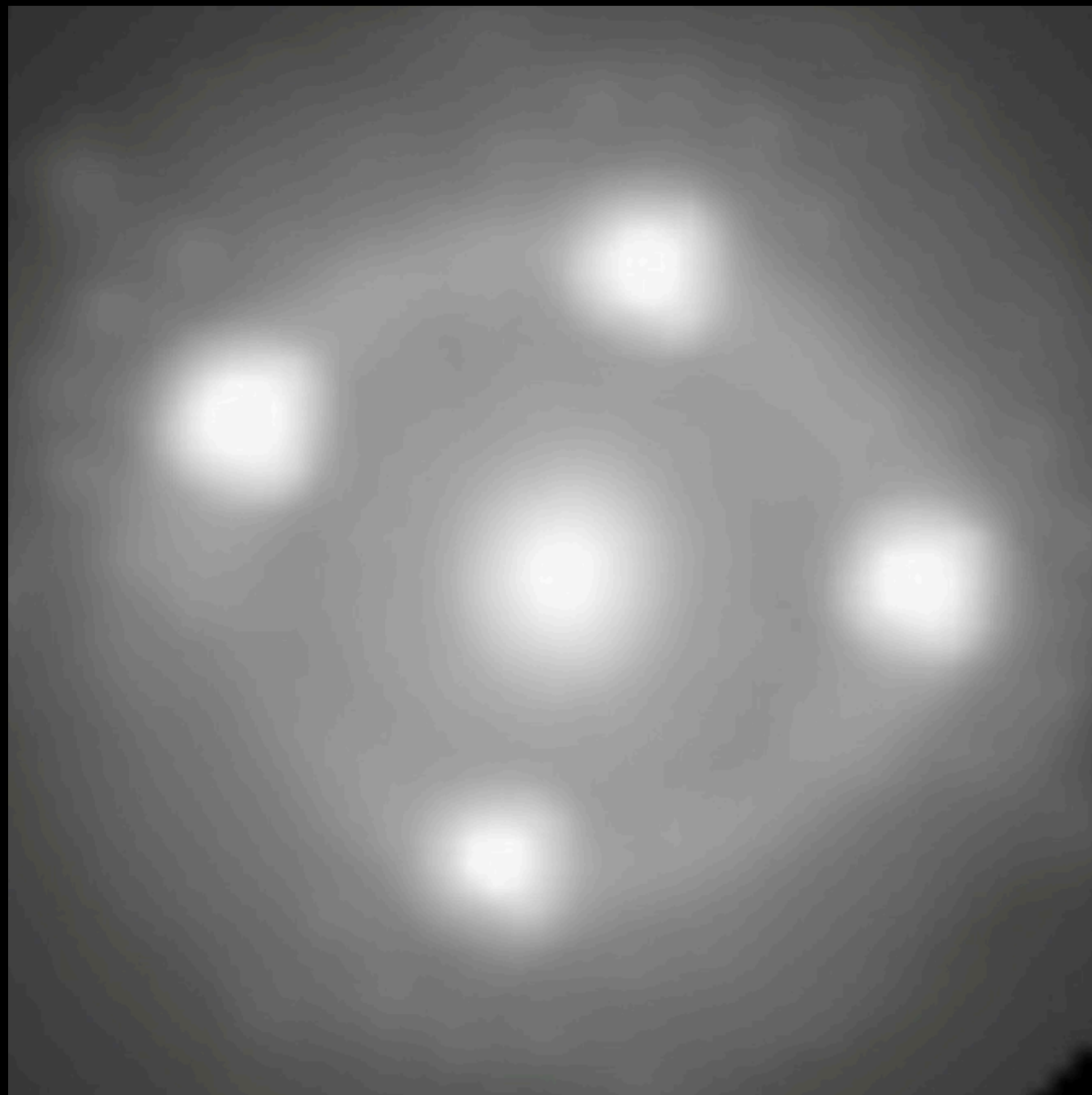
light of
lens
(Sersic)

Point-Spread-
Function (PSF)
reconstruction

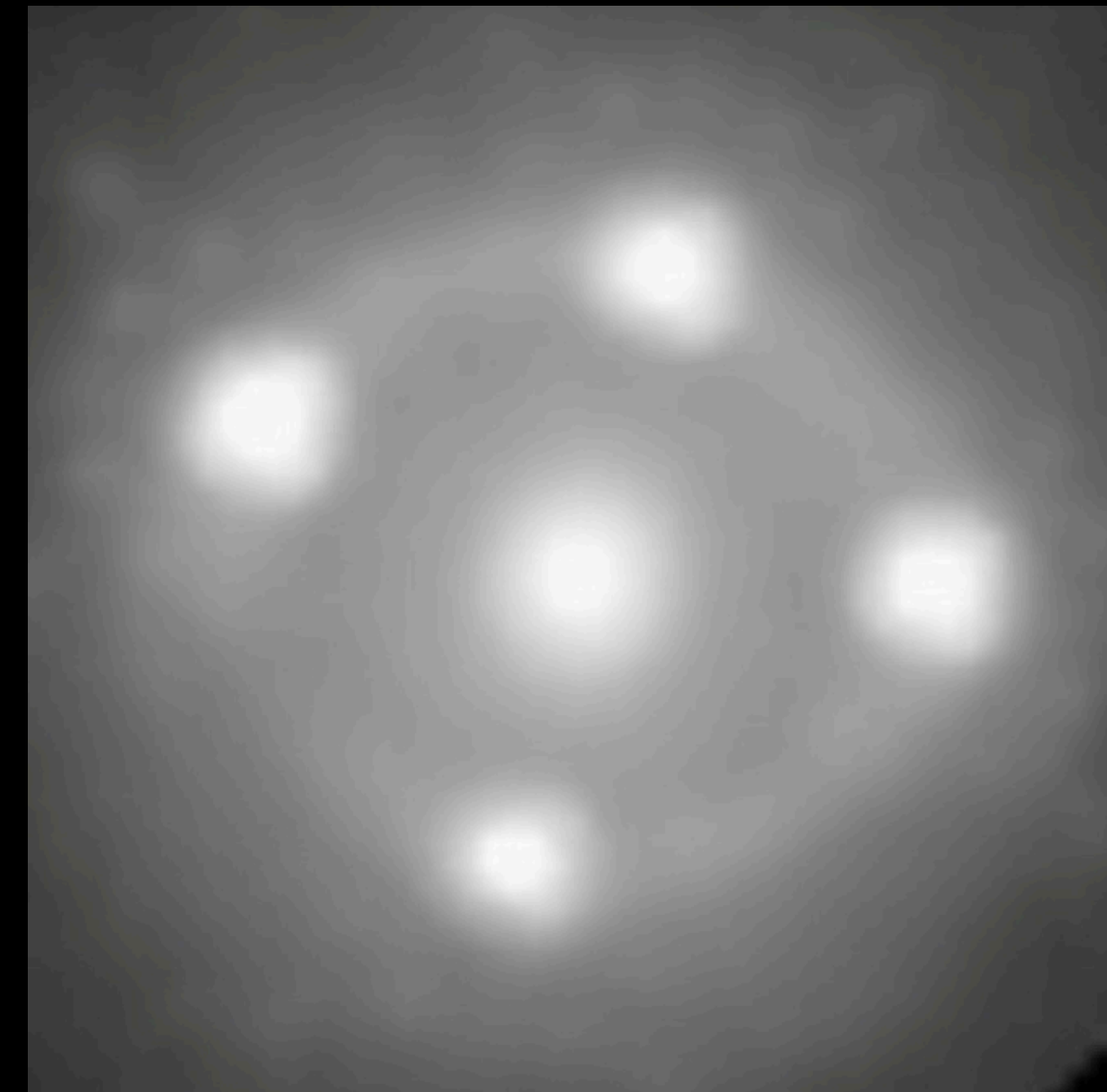
multi-lens plane
modelling including
nearby perturbers

Lens reconstruction

Which is our model and which is the Hubble Space Telescope observation?



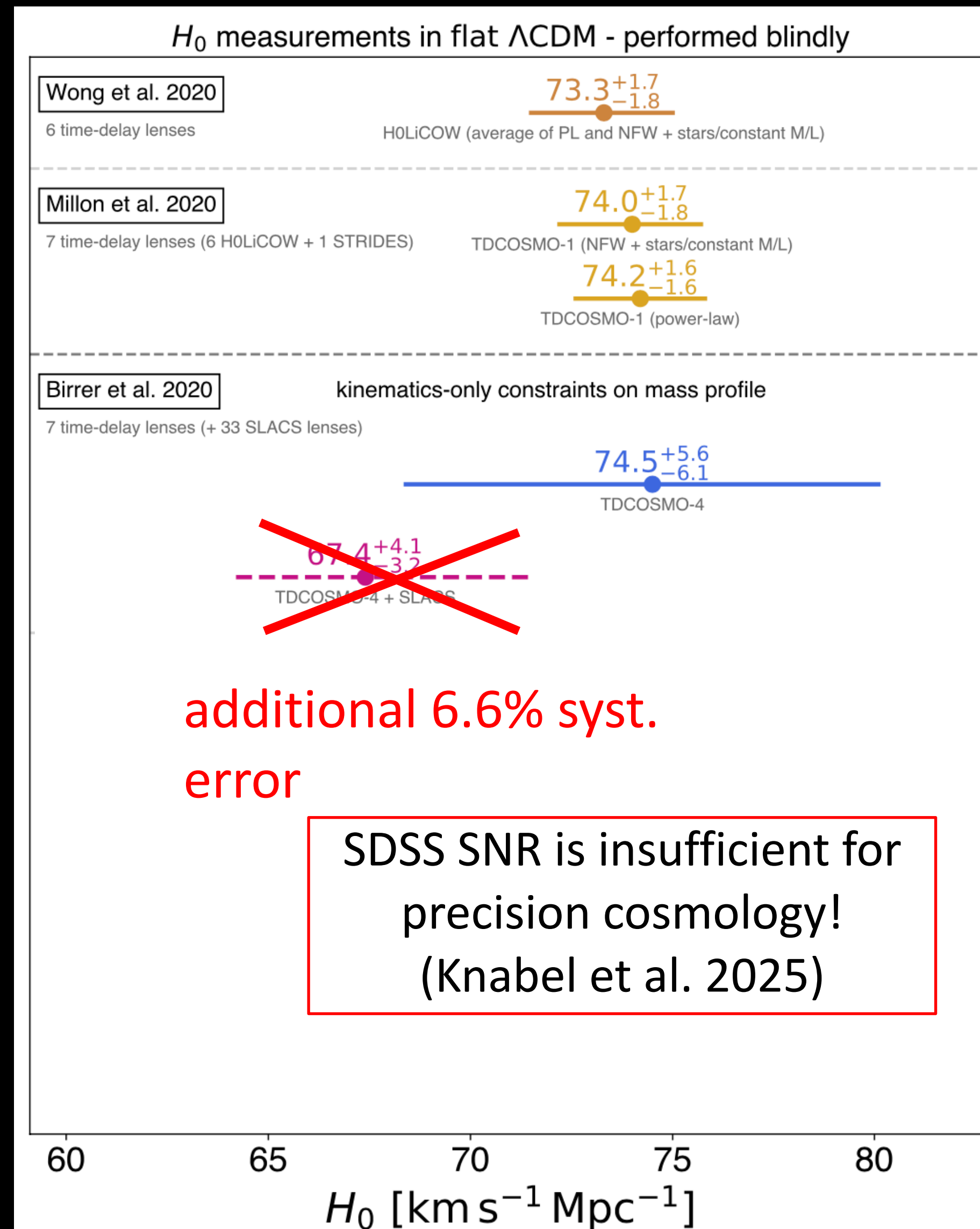
Model



HST observation

Latest H_0 measurements

H0LiCOW:
TDCOSMO-I:
TDCOSMO-IV:



Assertive model assumption

Conservative mass model assumption constrained with kinematic data

Latest H_0 measurements

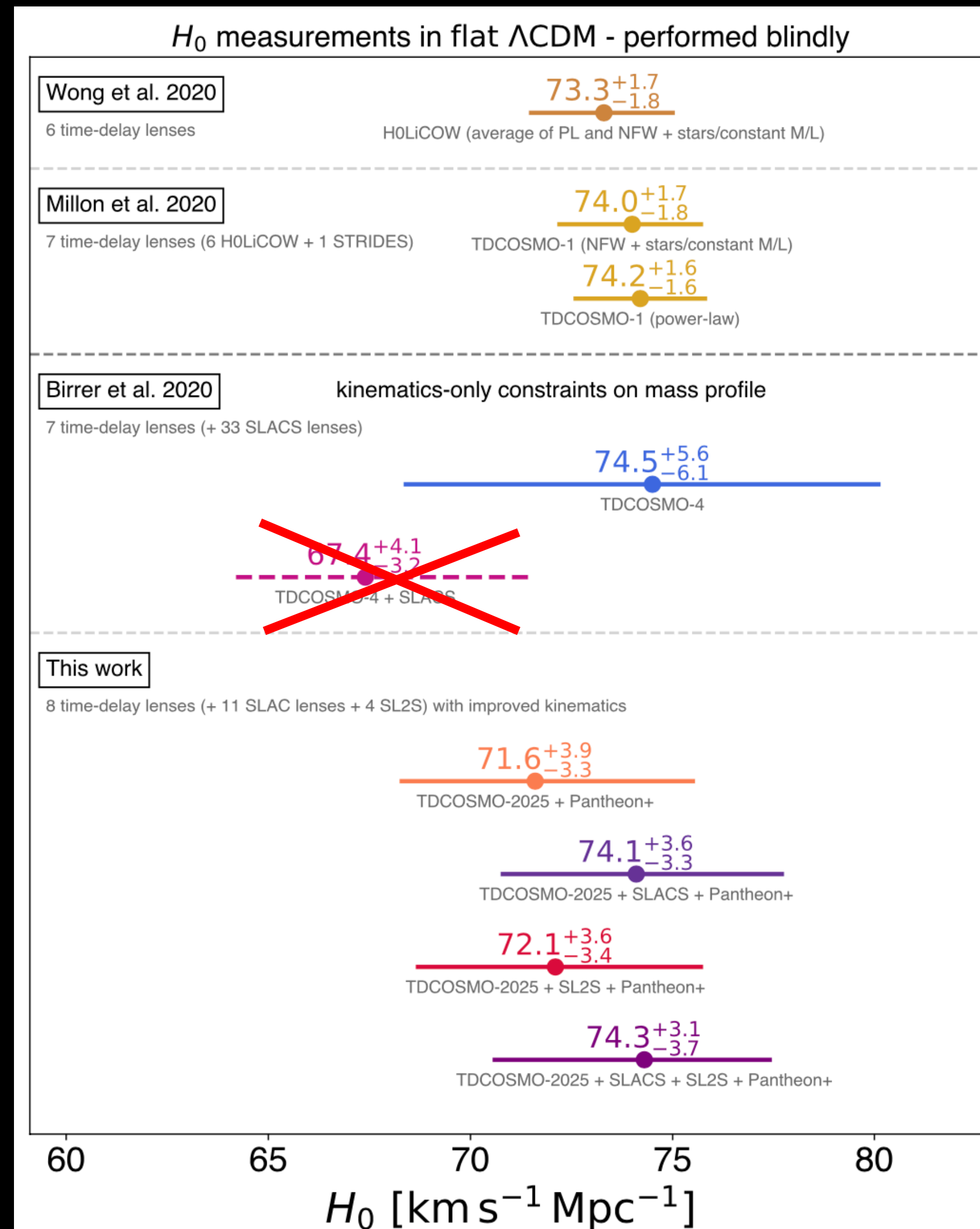
H0LiCOW:

TDCOSMO-I:

TDCOSMO-IV:

TDCOSMO 2025:

All but one
lens were
analyzed
blindly

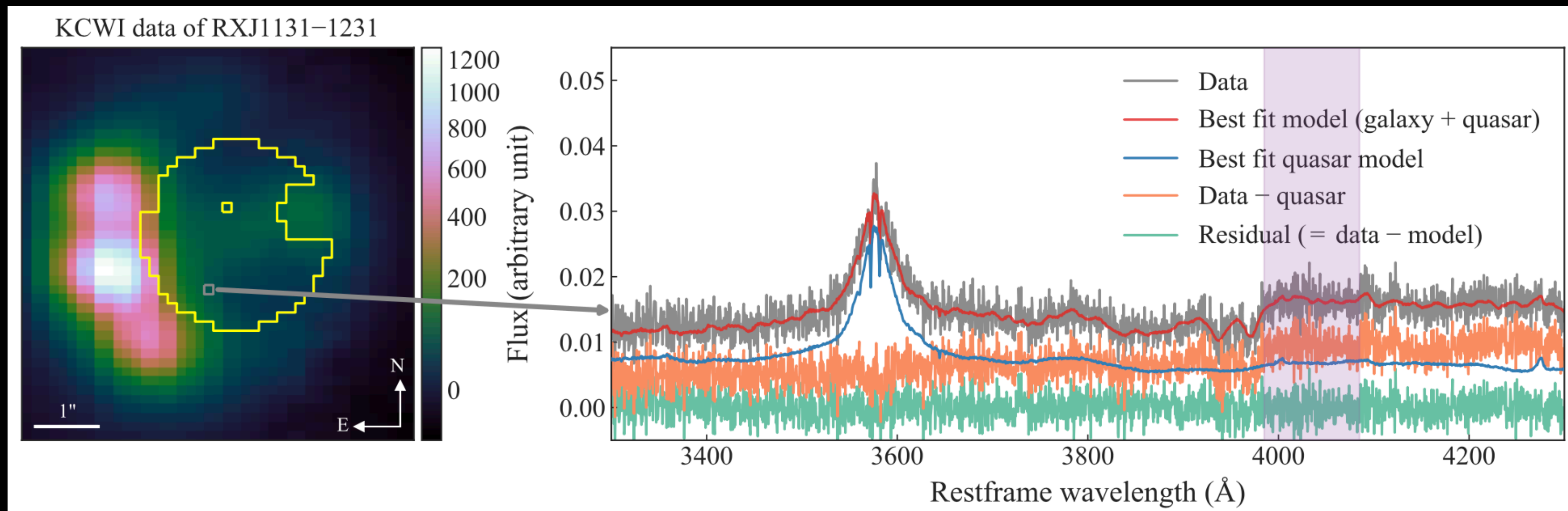


*Assertive model
assumption*

*Conservative
mass model
assumption
constrained
with kinematic
data*

Moving forward

- Spatially-resolved stellar kinematics are key to break model degeneracies and constrain $D_{\Delta t}$ and D_{lens}
[e.g., Shajib et al. 2023; Yıldırım et al. 2023; Wang et al. 2025]

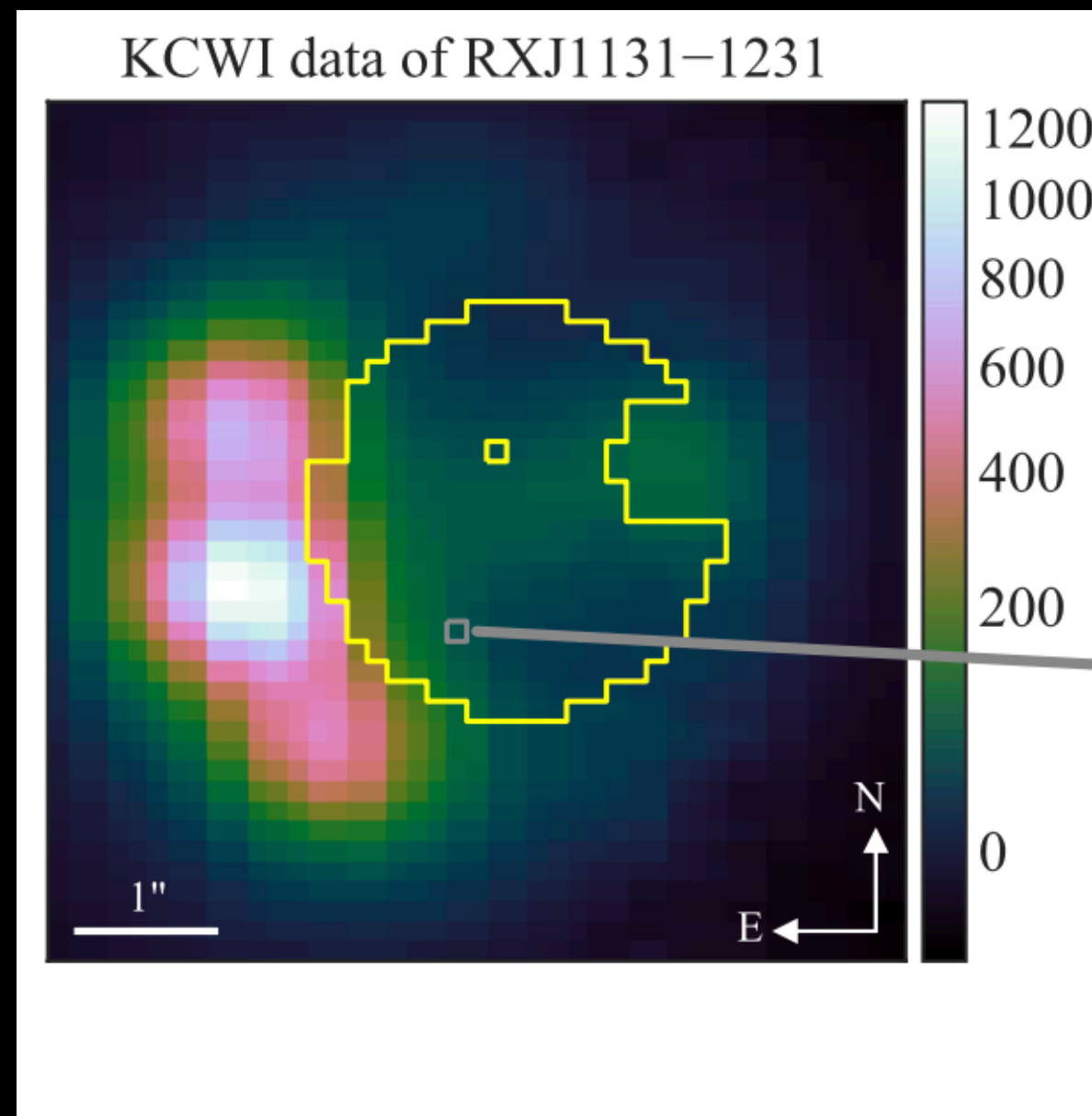


[Shajib et al. 2023]

Moving forward

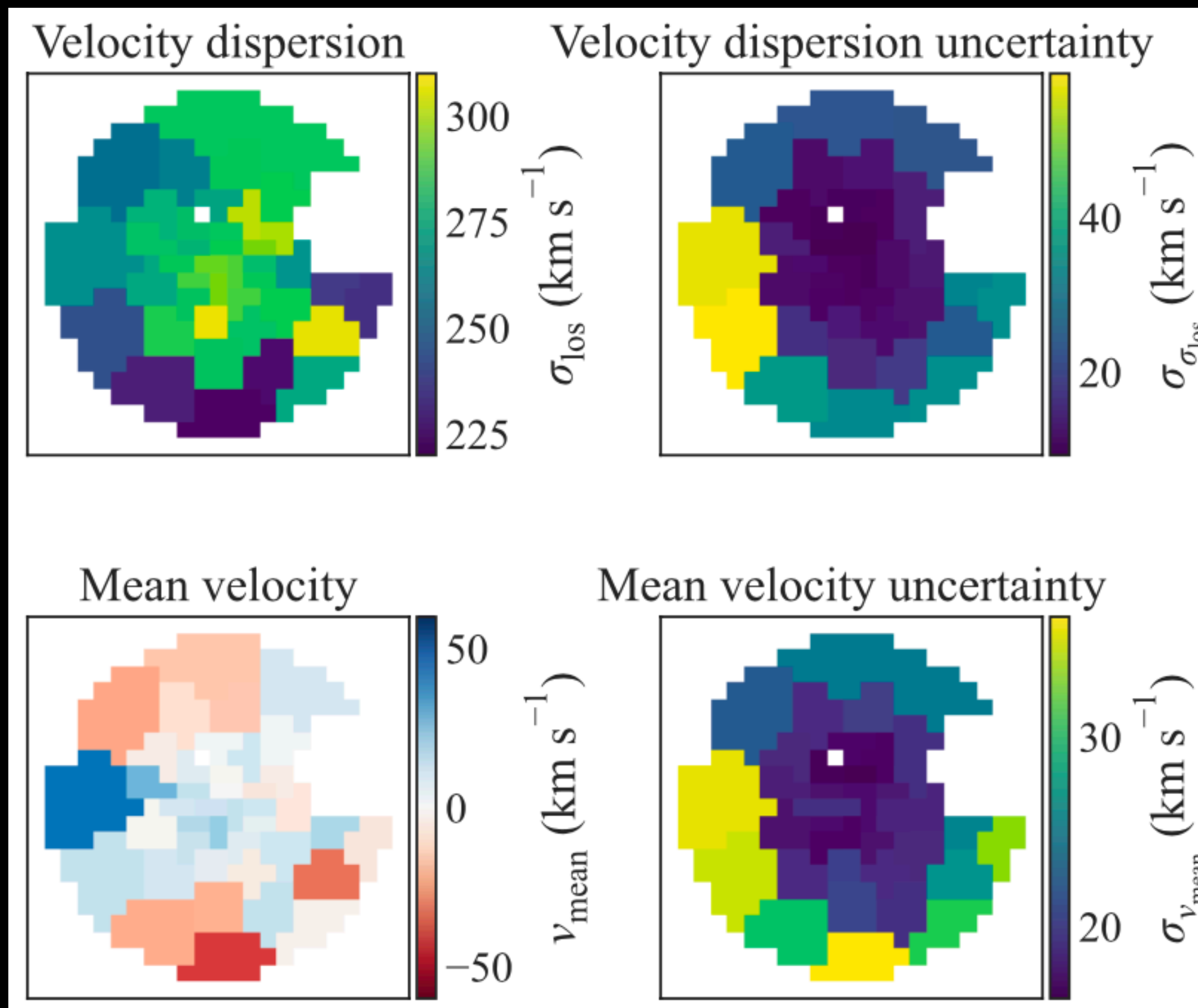
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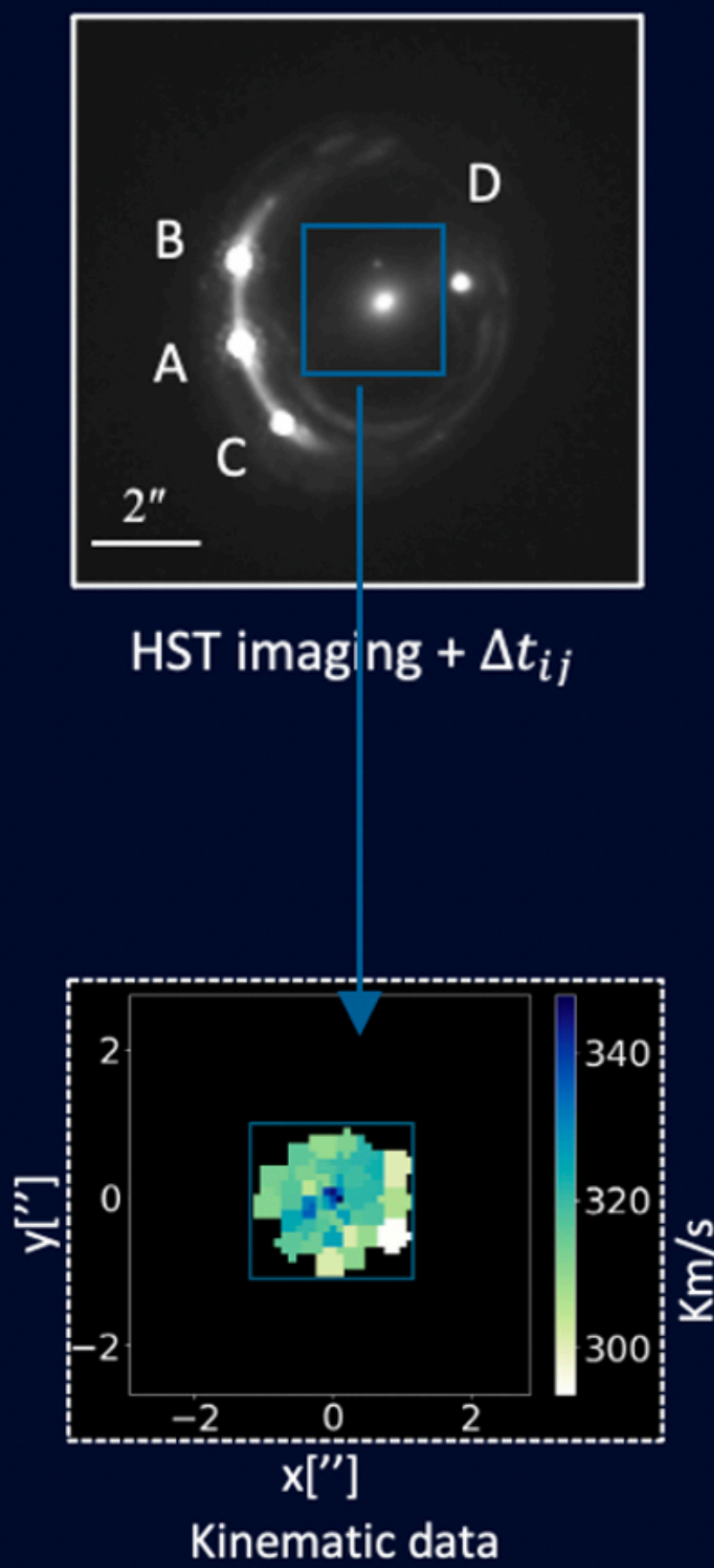
[Shajib et al. 2023]

$H_0 = 77 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with flexible mass models



GLaD: Gravitational Lensing and Dynamical modeling

Measurements

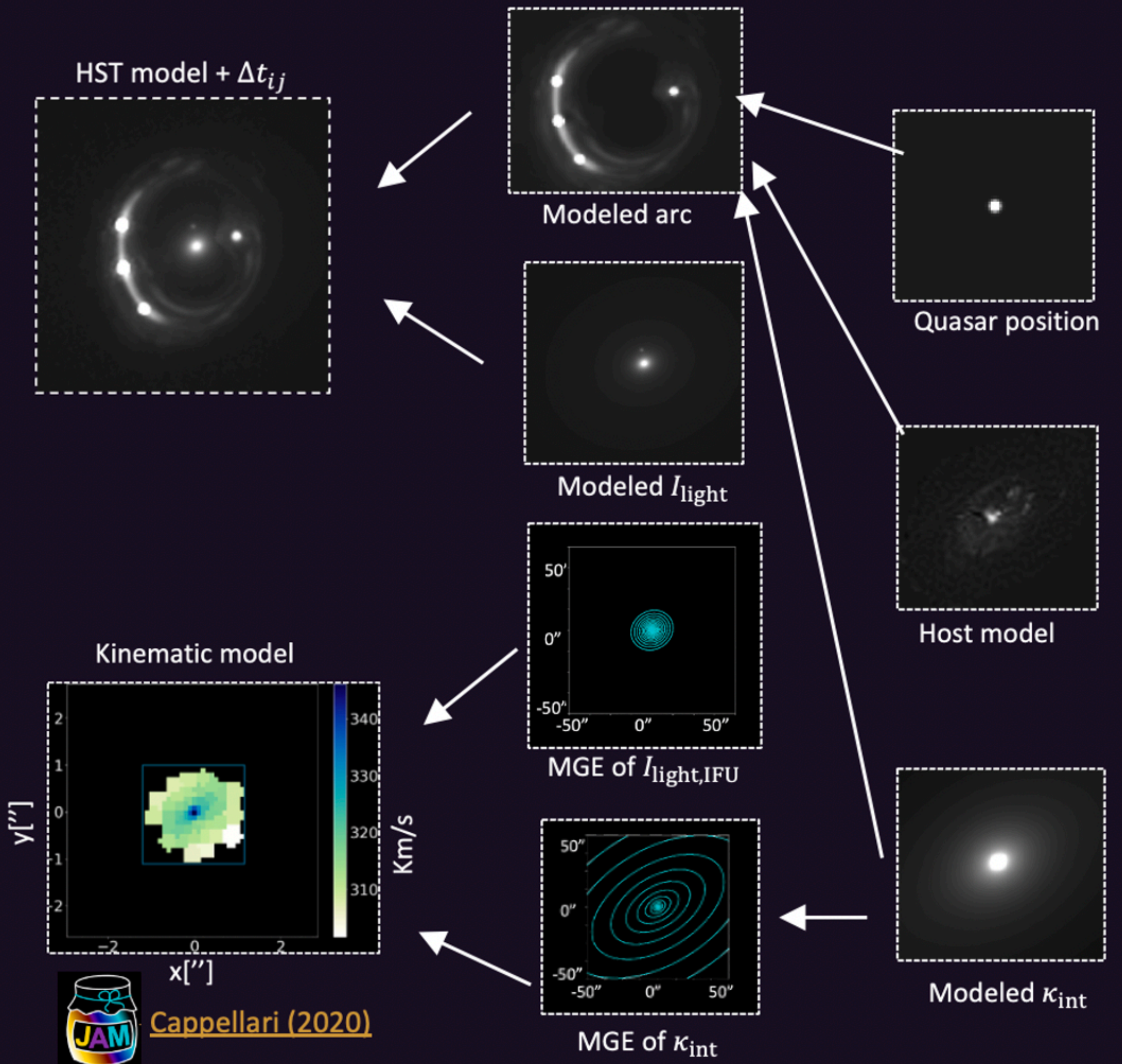


$$\mathcal{L}(\overrightarrow{d_{\text{lens}}})$$

+

$$\mathcal{L}(\overrightarrow{d_{\text{dyn}}})$$

Models



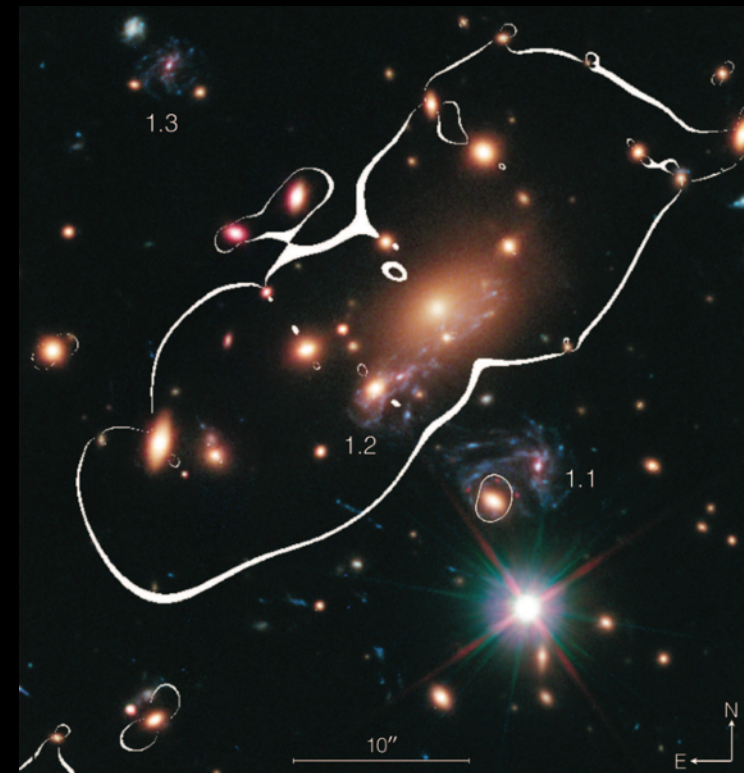
 [Cappellari \(2020\)](#)

[Wang, Suyu, Galan et al. 2025]

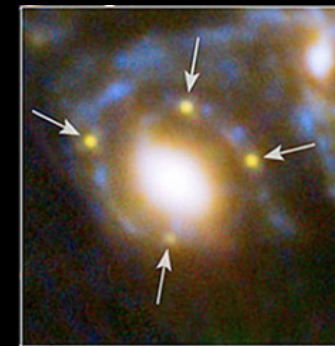
H_0 from lensed supernovae

Strongly lensed supernovae (SNe)

4 galaxy scale systems
6 cluster-scale systems



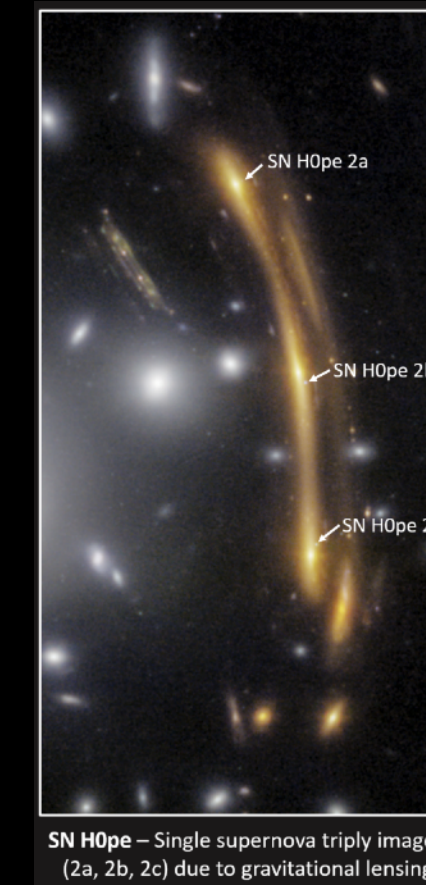
SN
Refsdal



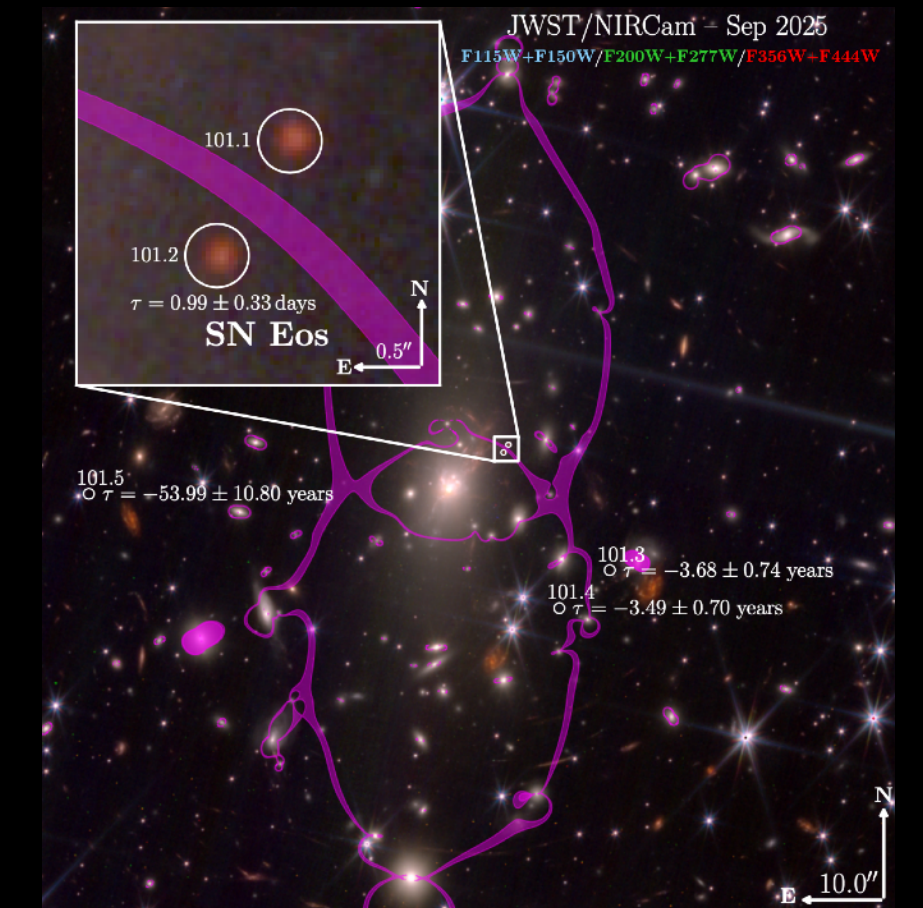
SN
Requiem



SN Zwicky



SN H0pe



SN Eos

1964

2016

2022

2025

2026

2014

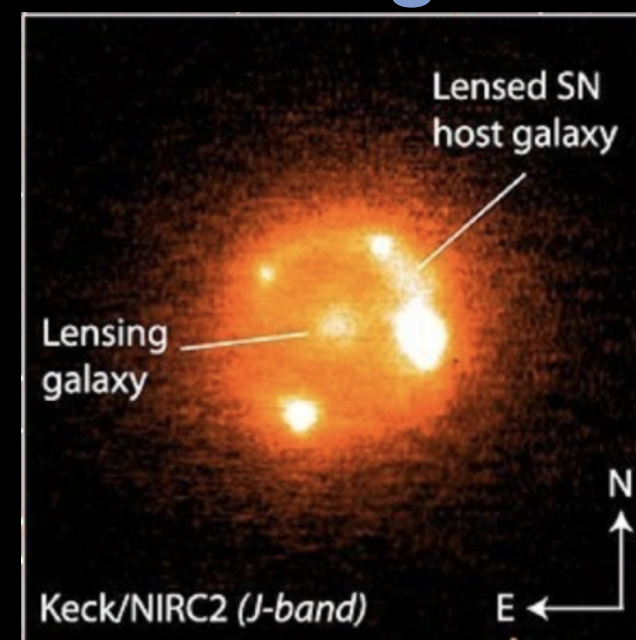
2021

2023

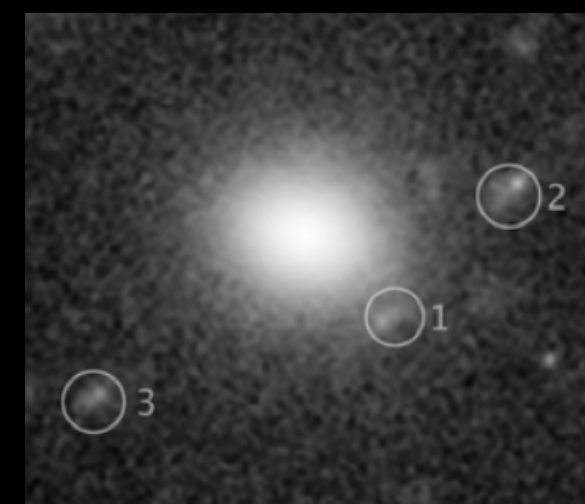
2026

Prediction
by
Refsdal

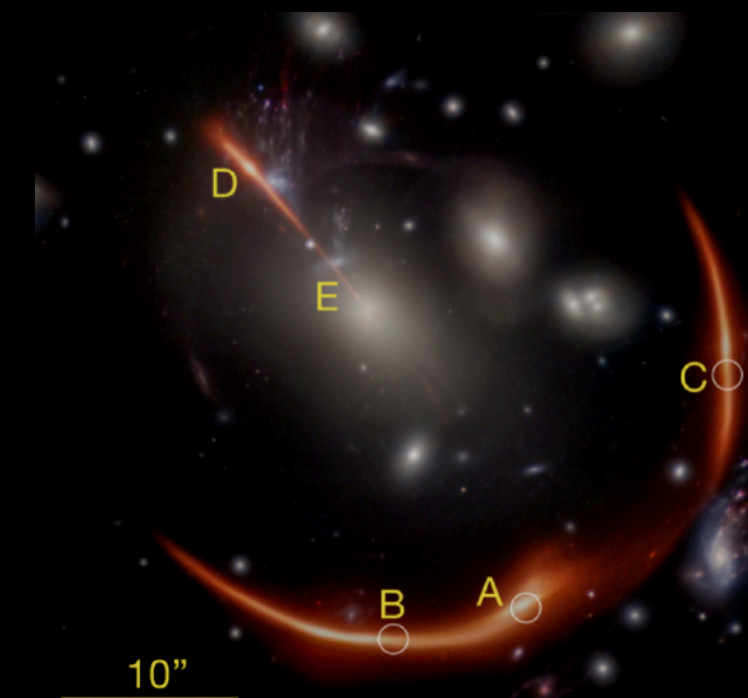
iPTF16geu



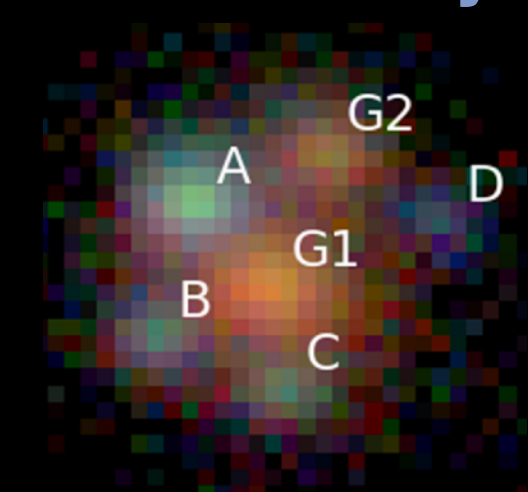
Abell 370



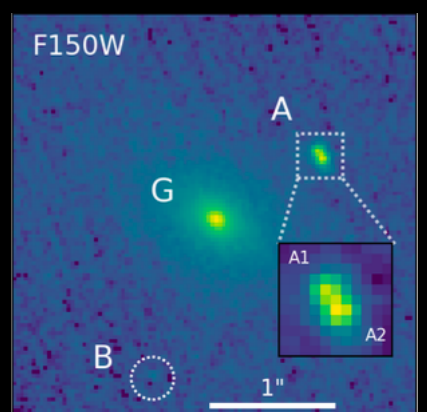
SN Encore



SN Winny



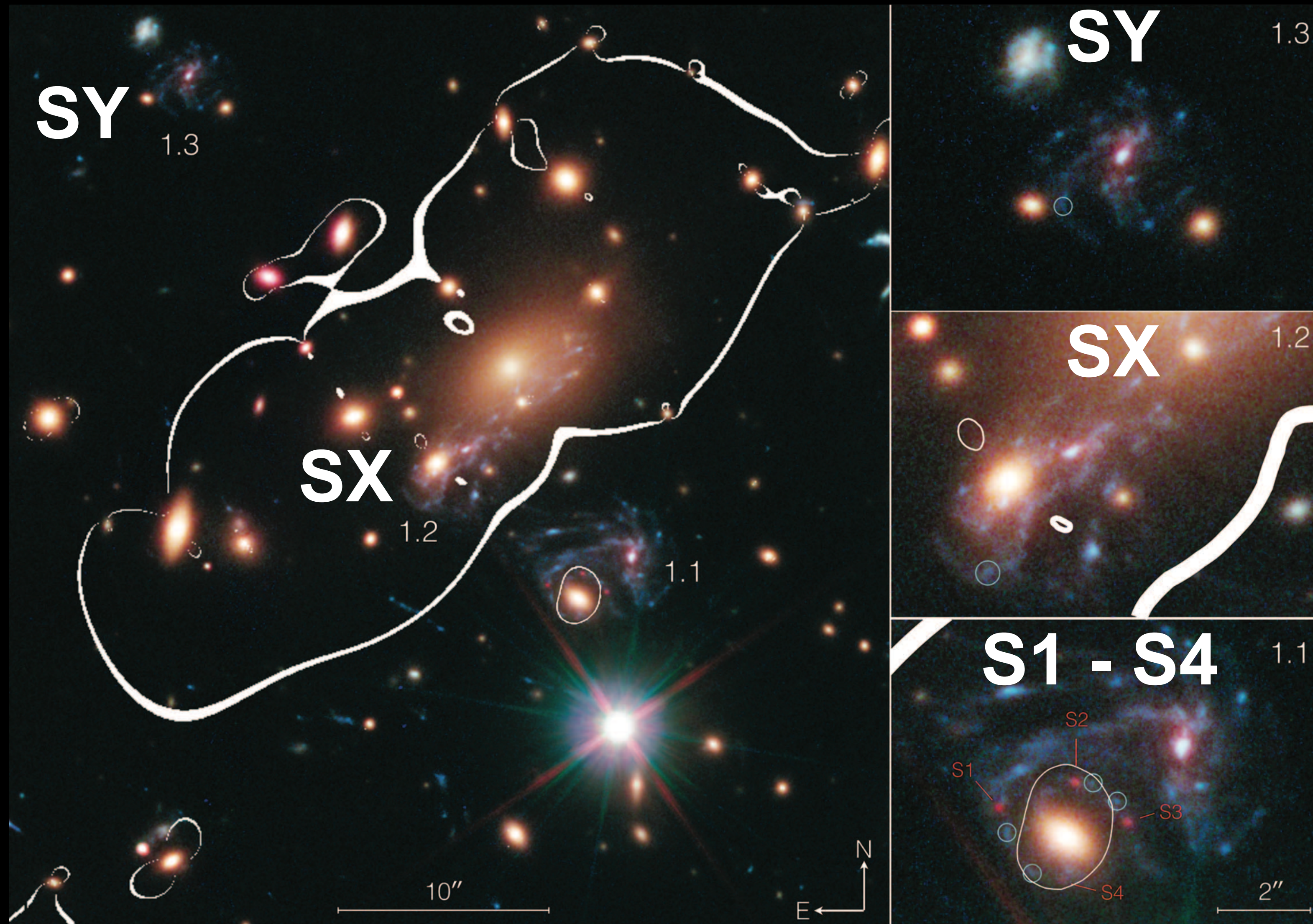
SN 2025mkn



[Kelly et al. 2015; Goobar et al. 2017; Rodney et al. 2021; Chen et al. 2022; Goobar et al. 2023; Frye et al. 2024; Pierel et al. 2024; Taubenberger et al. 2025; Johansson et al. 2025; Coulter et al. 2026; Lemon et al. 2026]

[credit: slide from A. Melo and modified]

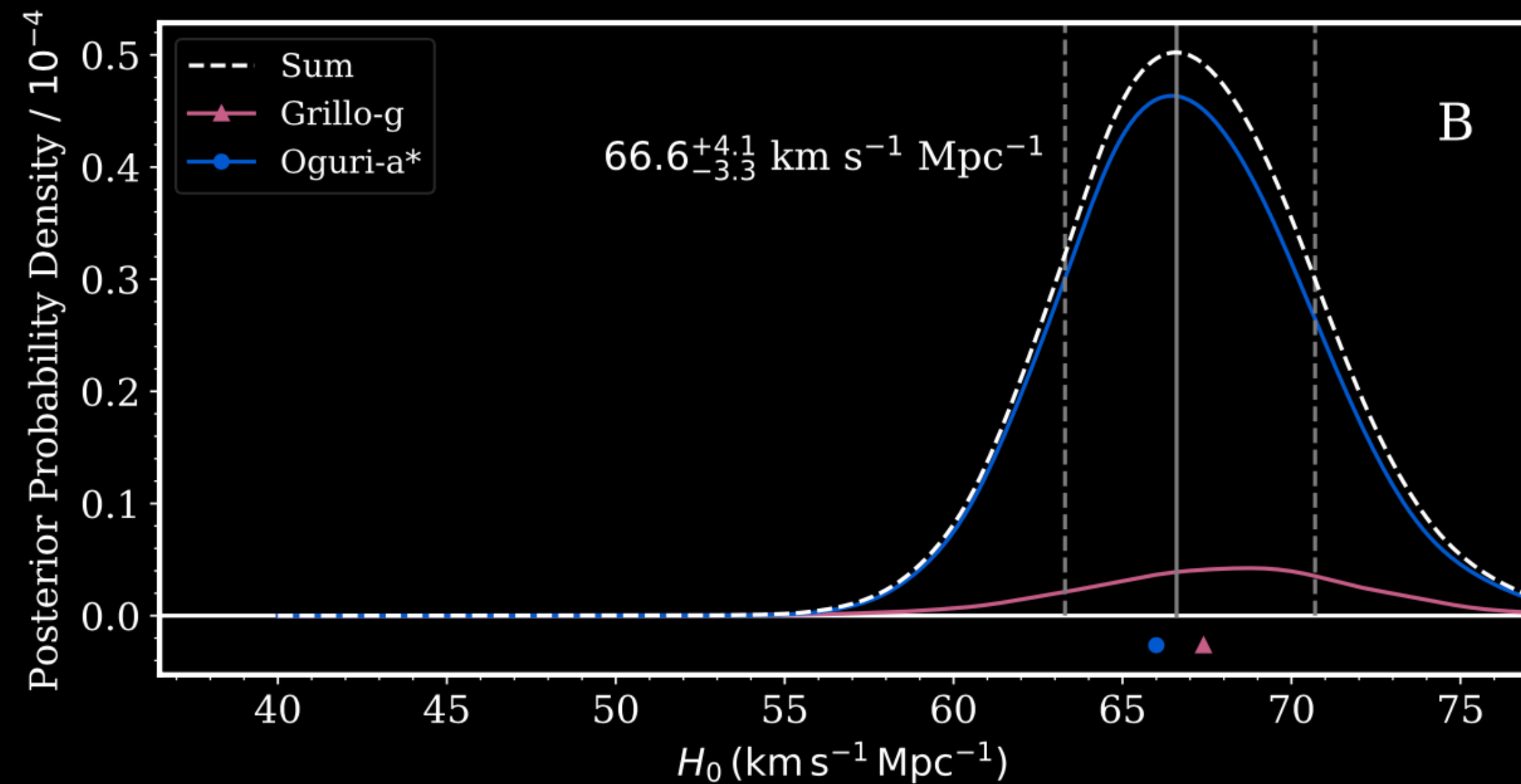
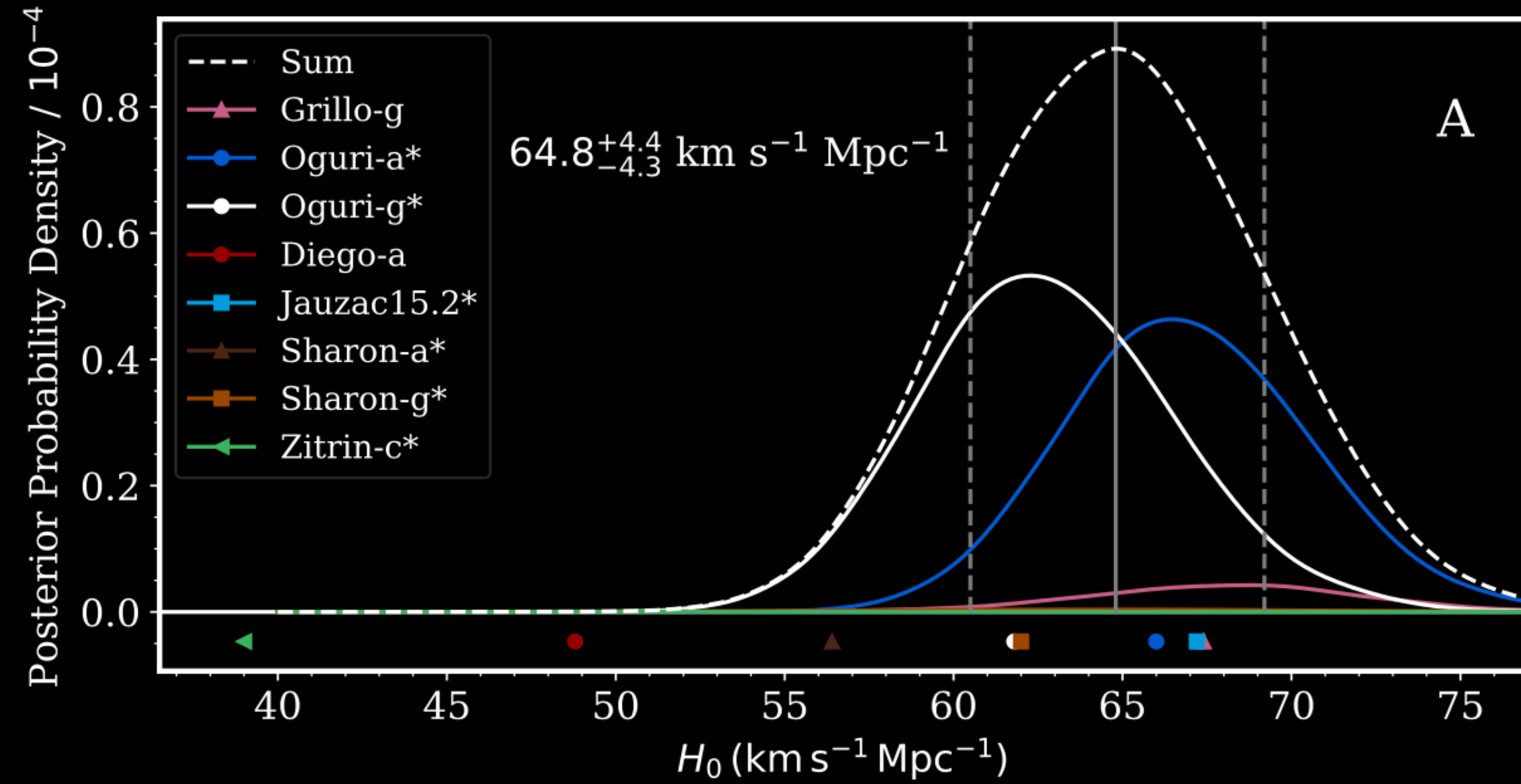
SN Refsdal



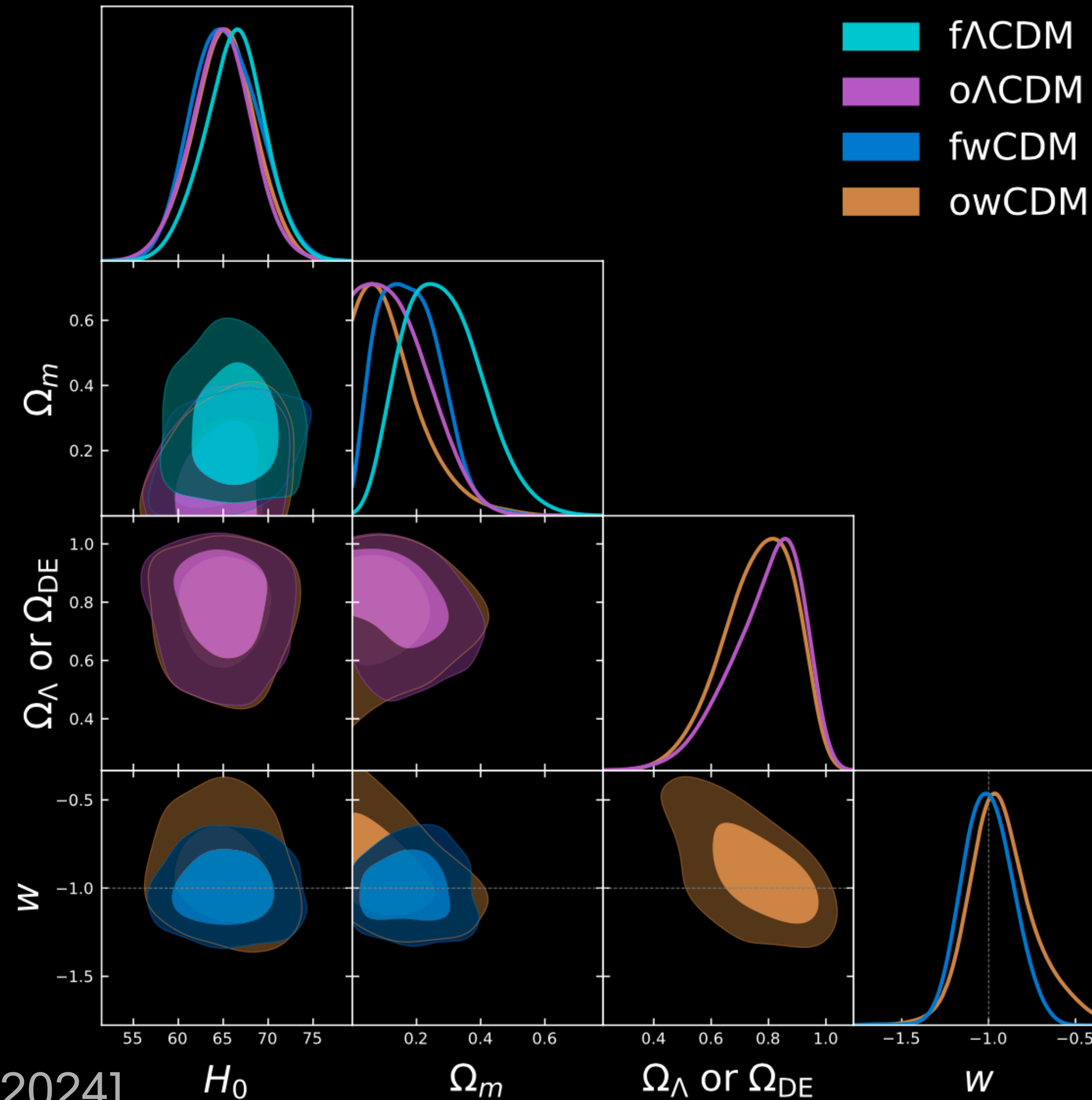
MACS 1149.6+2223

[Kelly et al. 2015] ²¹

H_0 from SN Refsdal in flat Λ CDM

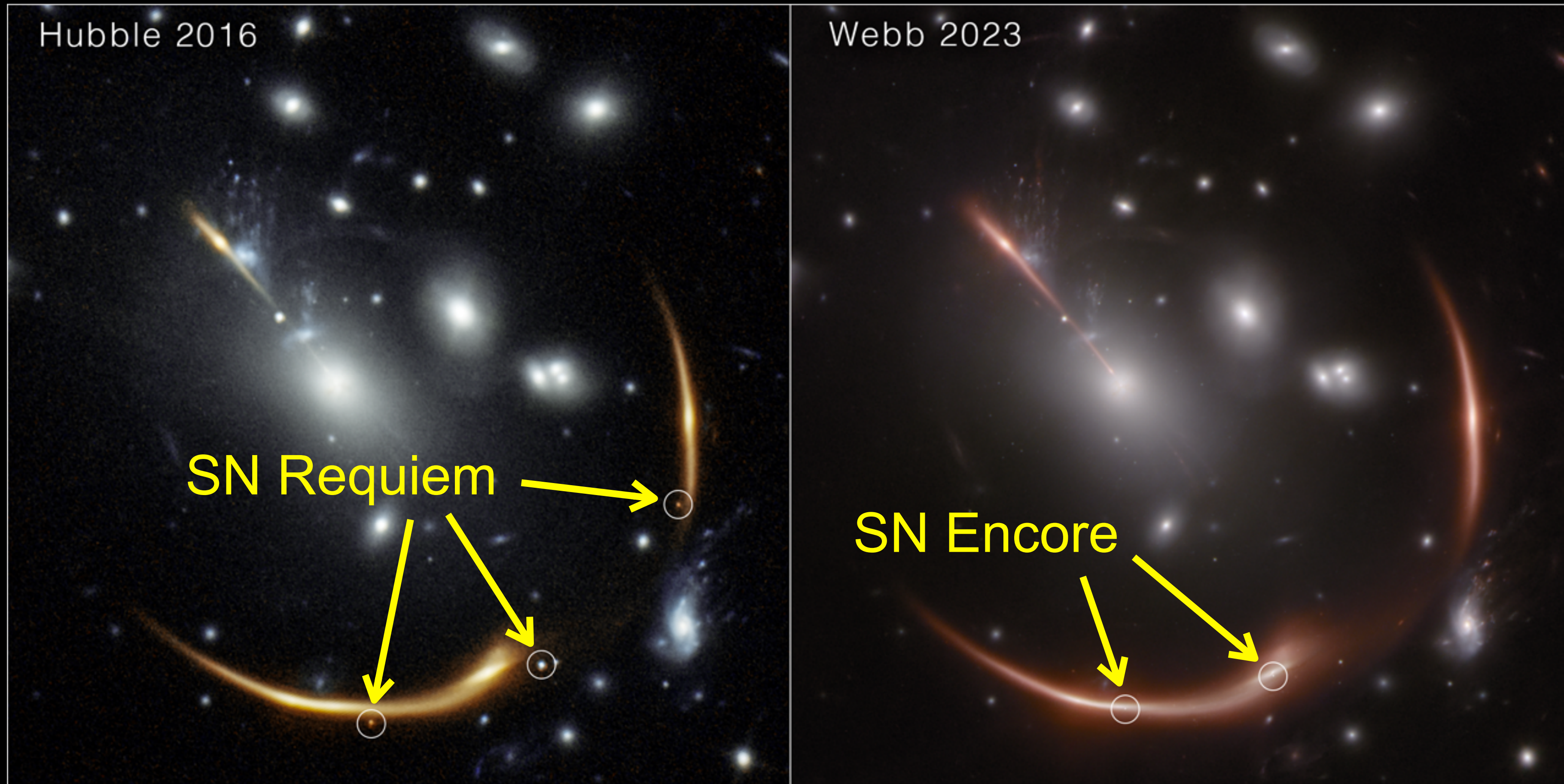


H_0 from SN Refsdal: general cosmo. model



[Grillo et al. 2024]

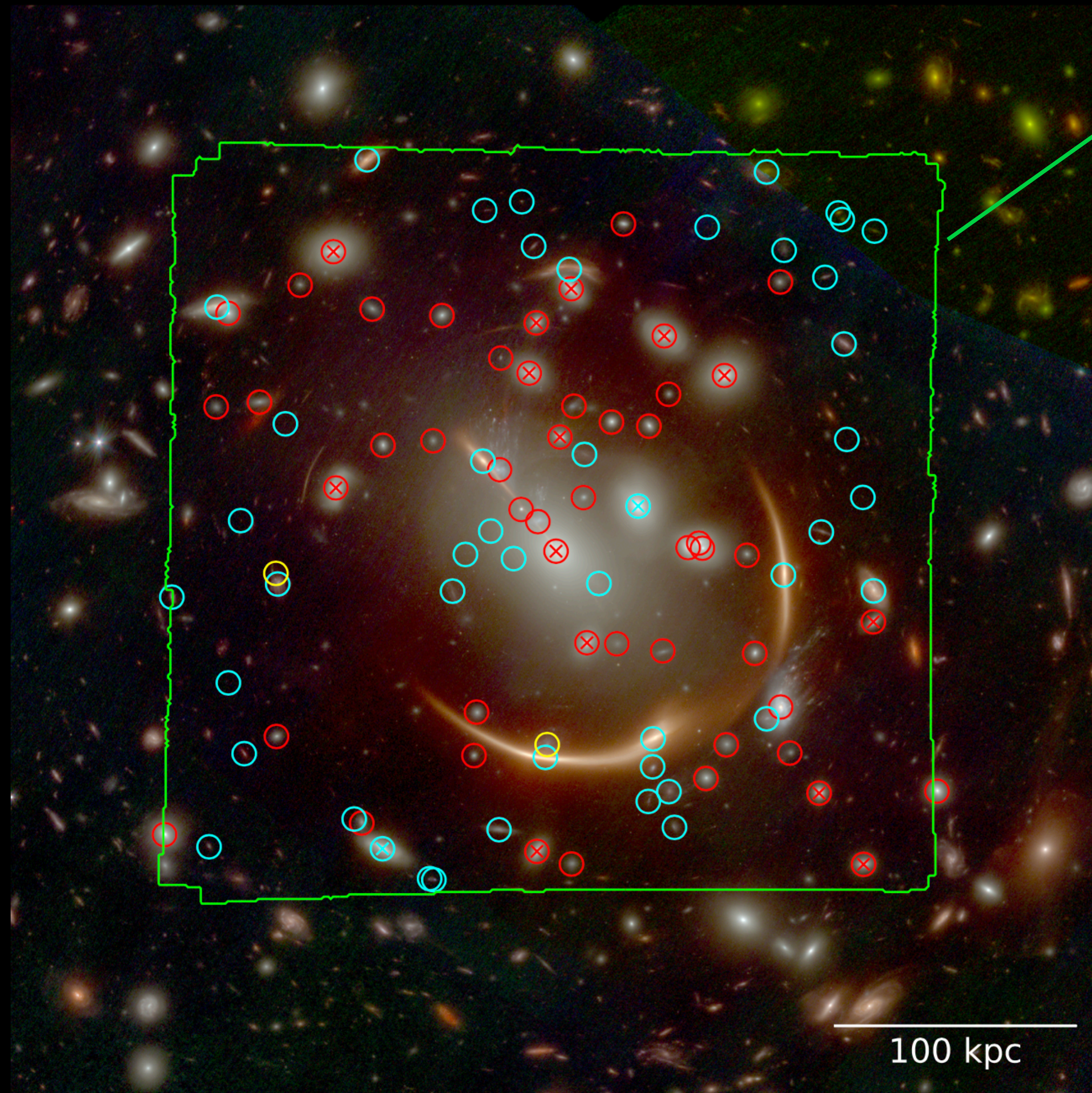
SN Requiem and Encore!



[Image credits: Hubble image: NASA, ESA, STScI, Steve A. Rodney (University of South Carolina) and Gabriel Brammer (Cosmic Dawn Center/Niels Bohr Institute/University of Copenhagen). JWST image: NASA, ESA, CSA, STScI, Justin Pierel (STScI) and Andrew Newman (Carnegie Institution for Science).]

[Pierel et al. 2024]

Crucial spectroscopy



MUSE spectrograph
field of view

○ foreground
galaxies

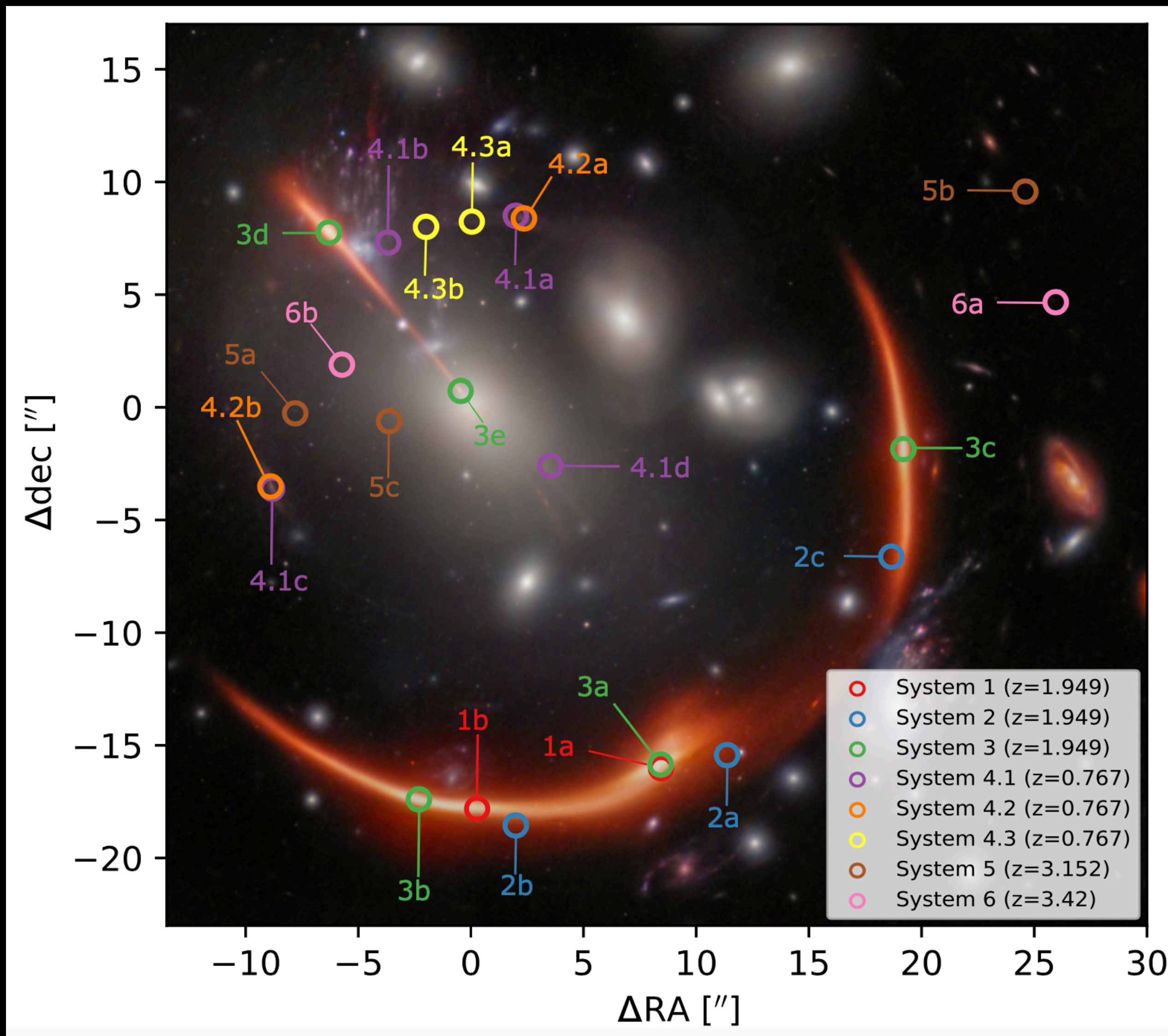
○ cluster
members

○ background
galaxies

spectroscopy enables
accurate mass model

[Granata et al. 2024]

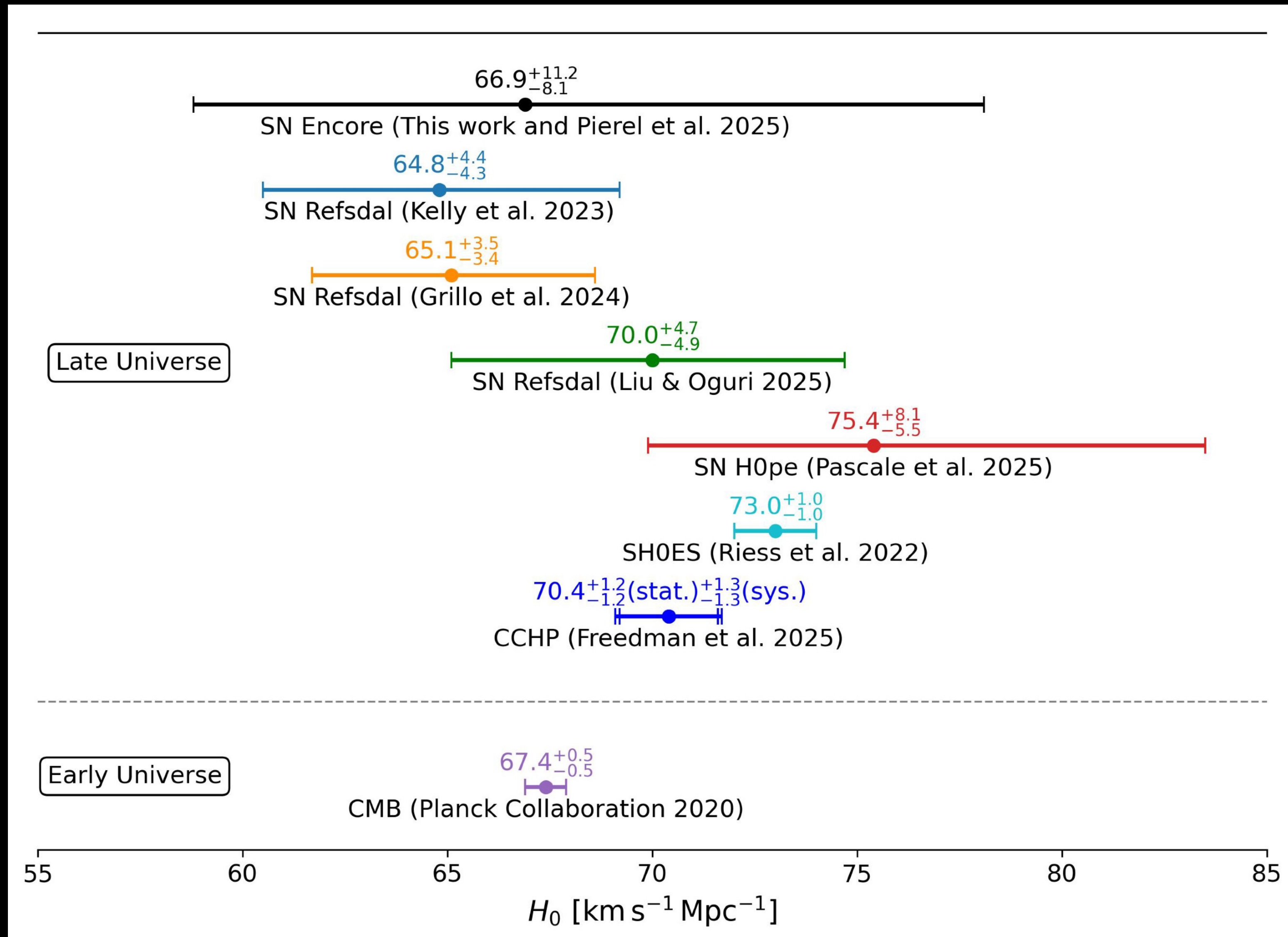
Lensed multiple images



7 independent modeling teams vetted JWST, HST and MUSE data, identifying:

- 84 galaxy cluster members
- 8 lensed image systems from 4 distinct redshifts

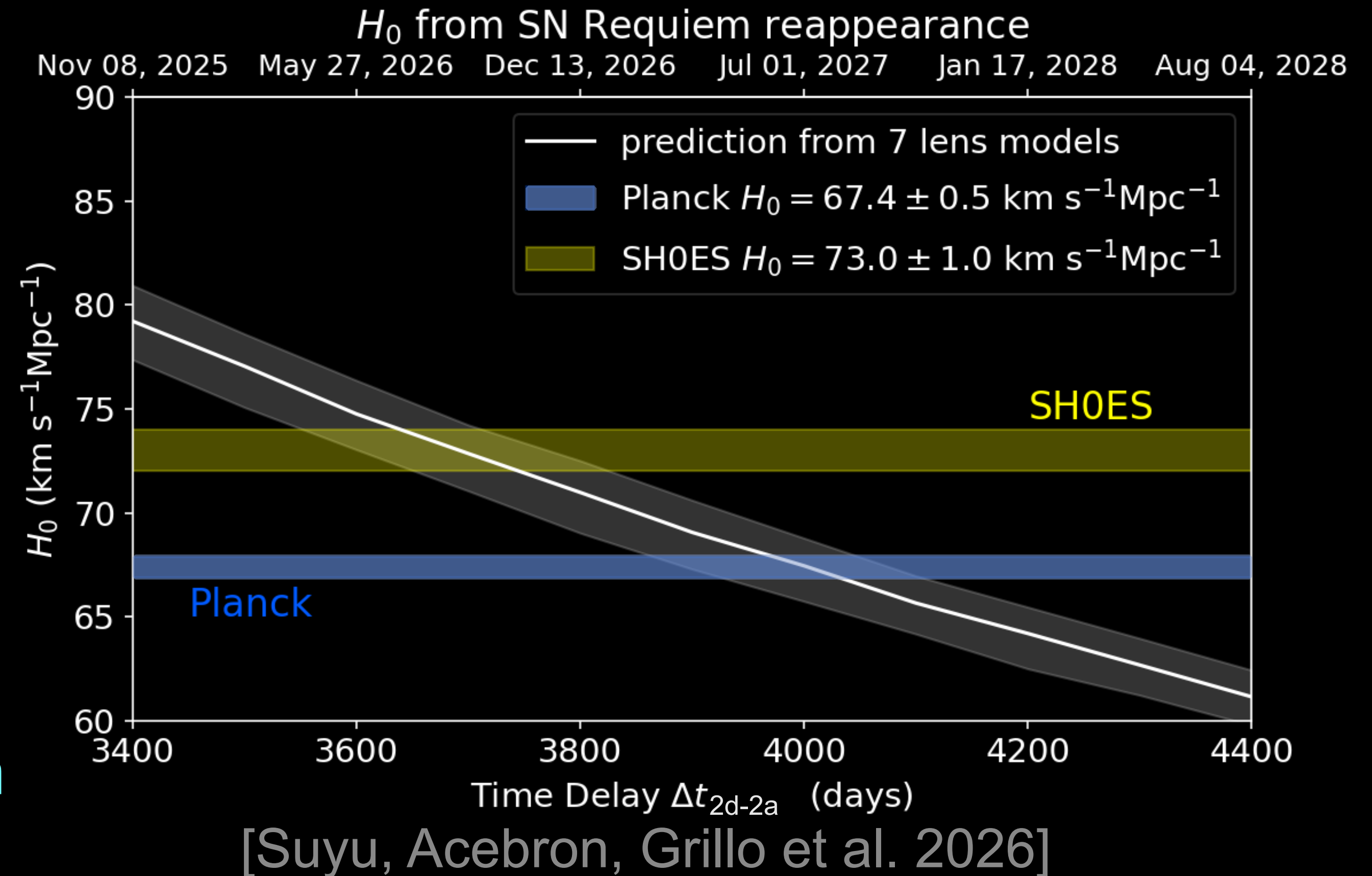
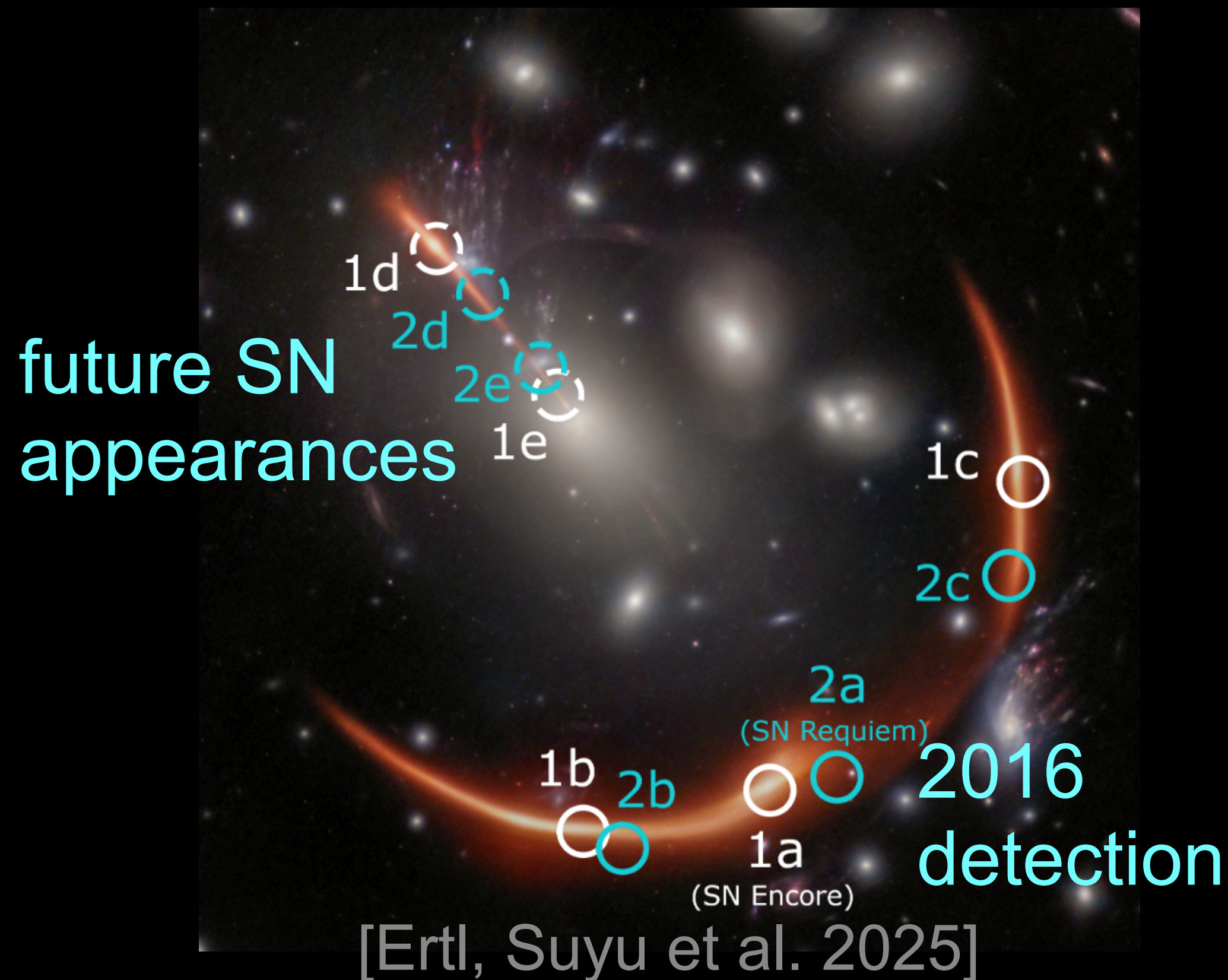
H_0 from SN Encore



- H_0 uncertainty of SN Encore dominated by delays
- Difficult photometric measurement of SN Encore near the core of host
- New JWST template image (after SN faded)

Strong-lensing time machine: H_0 to 2-3%

predict SN Requiem will reappear in ~2026-2027 after 10-year hiatus



- Approved JWST and HST programs to catch SN Requiem reappearance
- Detection of SN Requiem reappearance will yield H_0 with 2-3% uncertainty!

HOLISMOKES!

Highly Optimised Lensing Investigations
of Supernovae, Microlensing Objects,
and Kinematics of Ellipticals and Spirals

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

HOLISMOKERS



Satadru
Bag



Stéphane
Blondin



Raoul
Cañameras



James
Chan



Janet
Chen



Frédéric
Courbin



Jana
Grupa



Simon
Huber



Elias
Mamuzić



Alejandra
Melo



Stefan
Schuldt



Yiping
Shu



Stuart
Sim



Dominique
Sluse



Sherry
Suyu (PI)



Stefan
Taubenberger



Christian
Vogl

Lens Search

(Papers II, VI, VIII, XI, XIII,
XV, XVI, XVII, XIX, XXI)

Follow-up Observations

(Paper III)



Time Delays

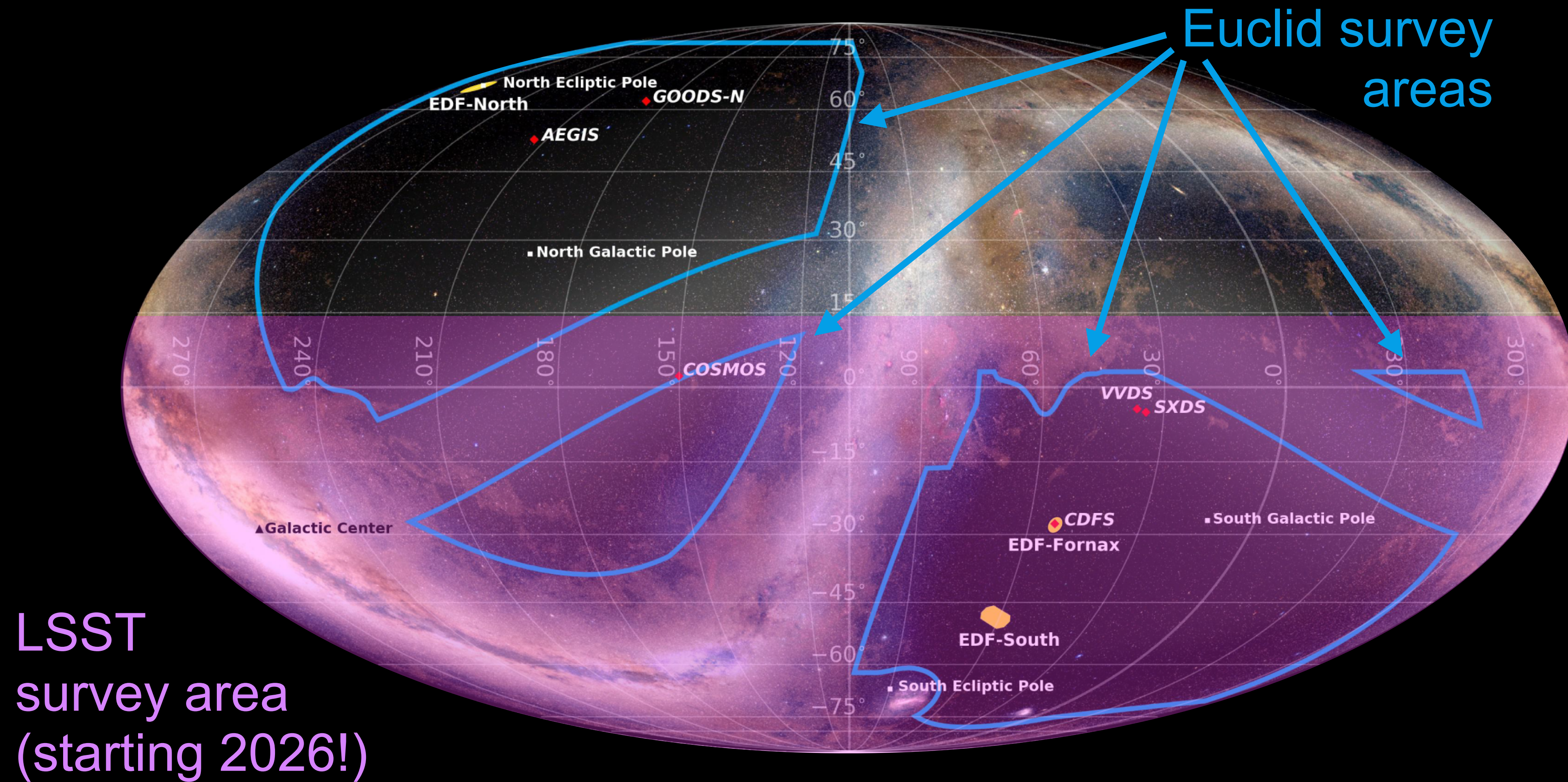
(Papers V, VII, XII,
XIV, XVIII)

Lens Modelling

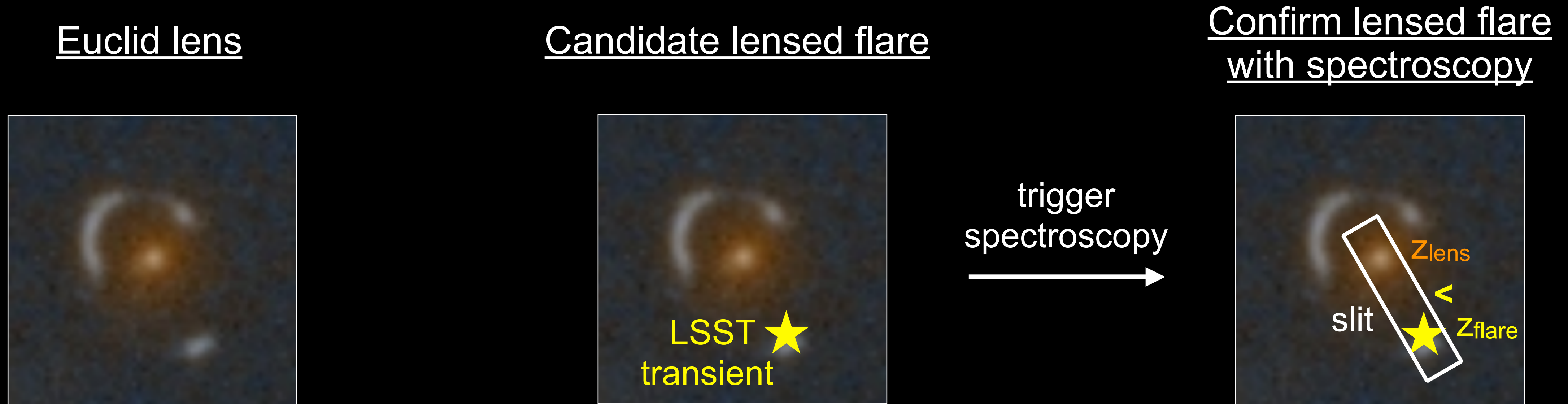
(Papers IV, IX, X
XX)

- 1. measure H_0 with 1% uncertainty***
- 2. obtain unprecedented constraints on SN progenitors***

Euclid+LSST: treasure trove of lensed flares



Euclid+LSST: treasure trove of lensed flares



Expect thousands of lensed AGNs and hundreds of lensed SNe
in the 10-year LSST survey

[e.g., Oguri & Marshall 2010; Goldstein et al. 2017; Wojtak et al. 2019]

→ ***Golden era for lensed transients***

Summary

- Lensed quasars and supernovae are powerful probes of cosmology, especially in measuring H_0
- Lensed quasars delivering competitive H_0 measurements
- Exciting time with the first lensed SNe being discovered and providing H_0 measurements
- SN Requiem expected to reappear in ~2026-2027
- HOLISMOKES program to study cosmology and SN progenitors
- Upcoming cadenced surveys especially LSST in combination with Euclid will augment lens sample by at least an order of magnitude - a bright future ahead!