Strong Lensing as a Probe of Cosmology

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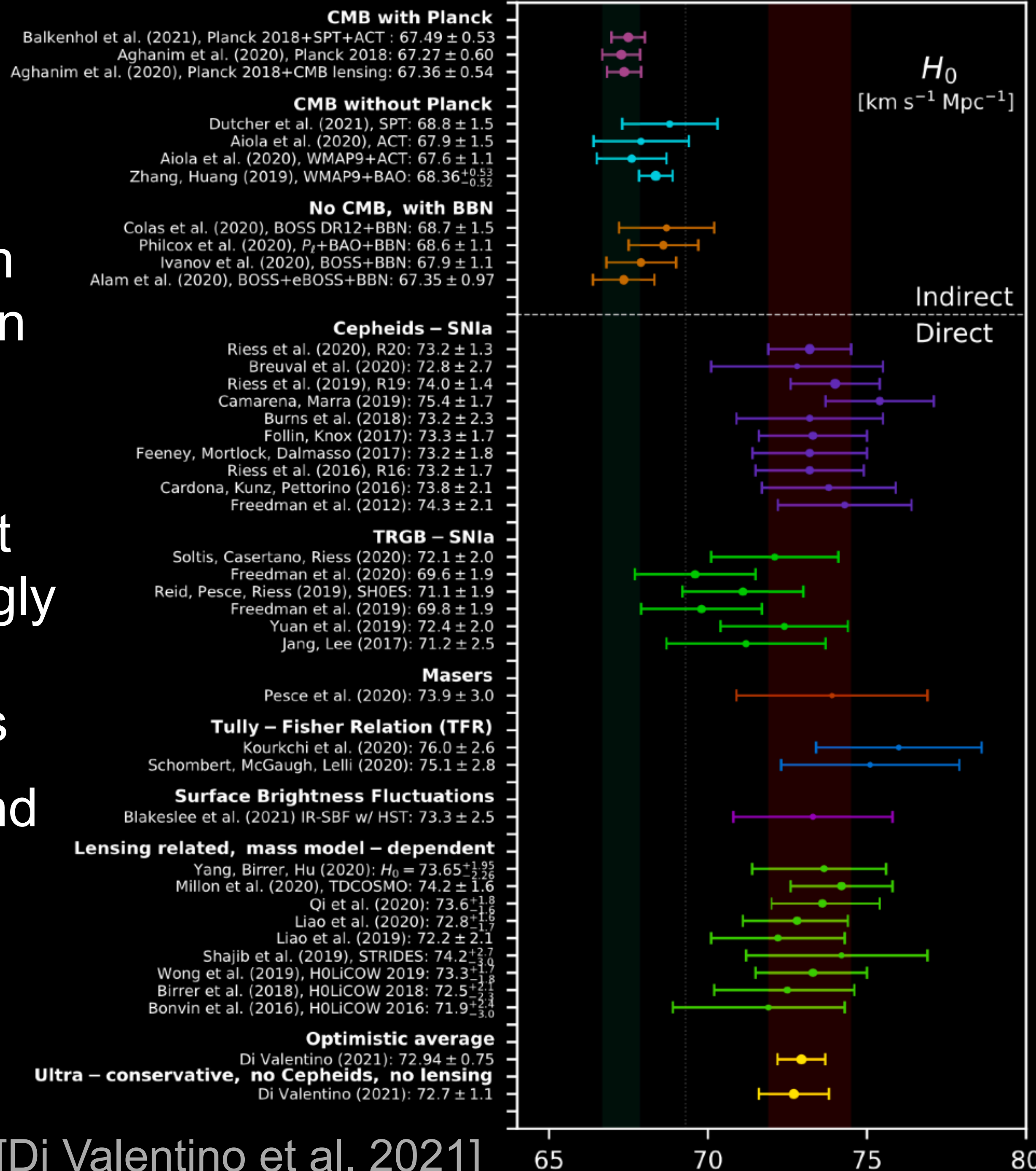
Cosmology in the Alps 2024 @ Les Diablerets

H_0 tension in flat ΛCDM

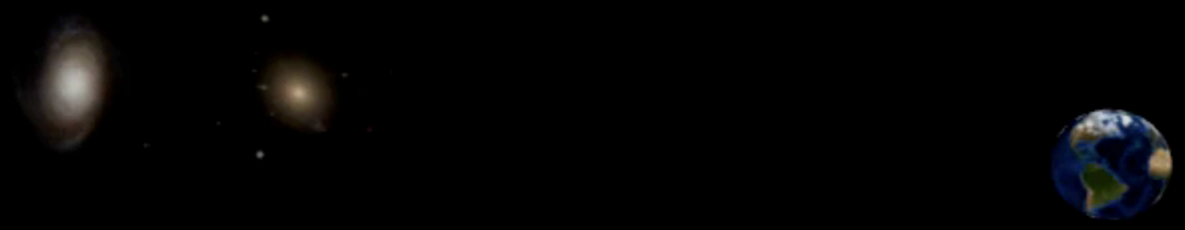
- 5σ tension between Planck collaboration (2020) and SH0ES (Riess et al. 2022)
- values from indirect methods rely strongly on cosmological model assumptions
- New physics beyond the standard flat ΛCDM model?

➜ ***Independent measurements are crucial***



[Di Valentino et al. 2021]

Strongly lensed supernova



[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:

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

Time-delay distance:

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

Obtain from lens mass model

Cosmography:

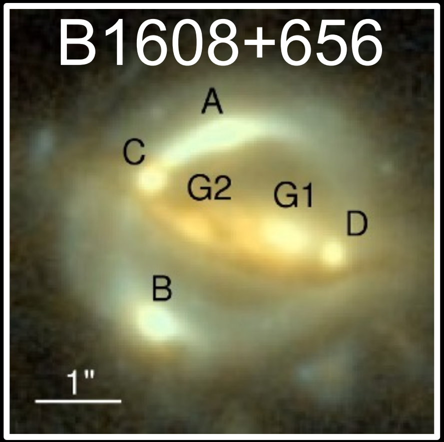
time delays Δt + mass model $\phi_{\rm lens}$

➜ time-delay distance $D_{\Delta t}$

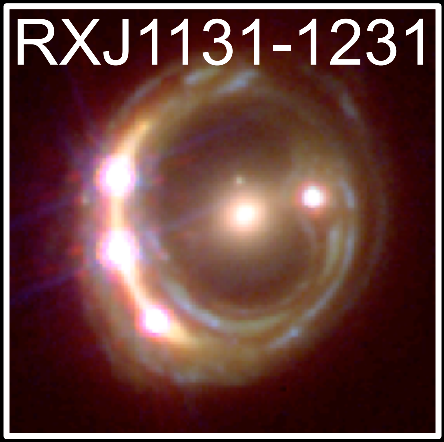
➜ Hubble constant H_0

[e.g., reviews by Suyu et al. 2024; Treu, Suyu & Marshall 2022; Liao et al. 2022]

H0LiCOW lensed quasars



[Suyu et al. 2010]

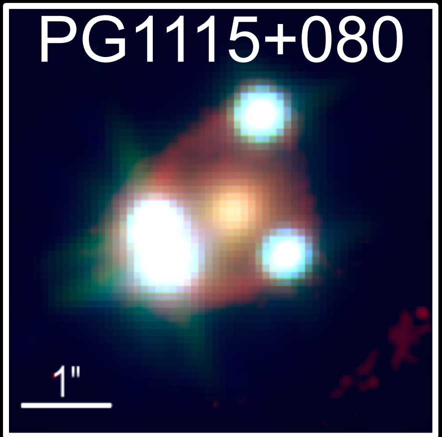


[Suyu et al. 2013, 2014; Tewes et al. 2013]

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

part of extended sample [Birrer et al. 2019]

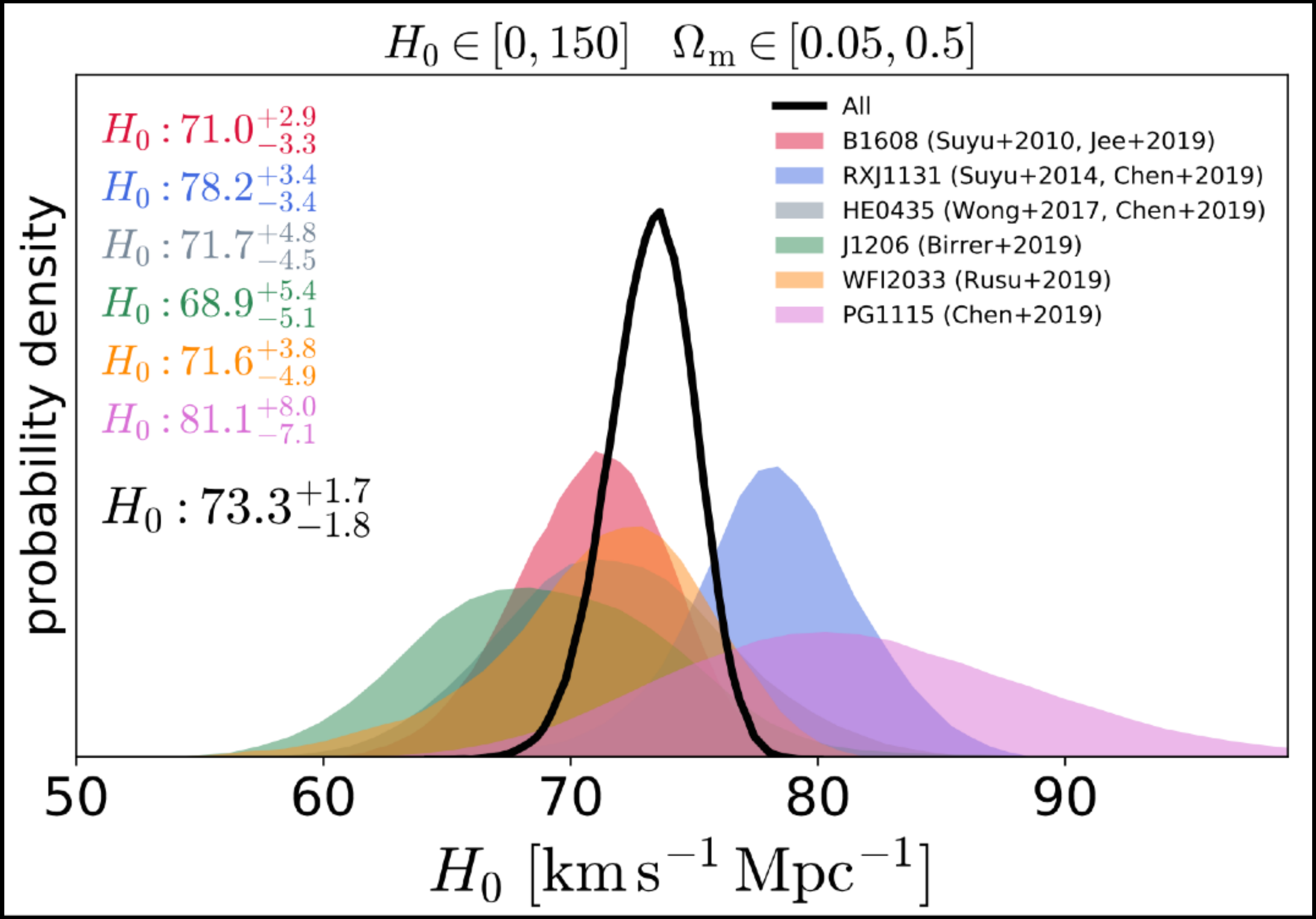
[Bonvin et al. 2019; Sluse et al. 2019; Rusu et al. 2020]



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



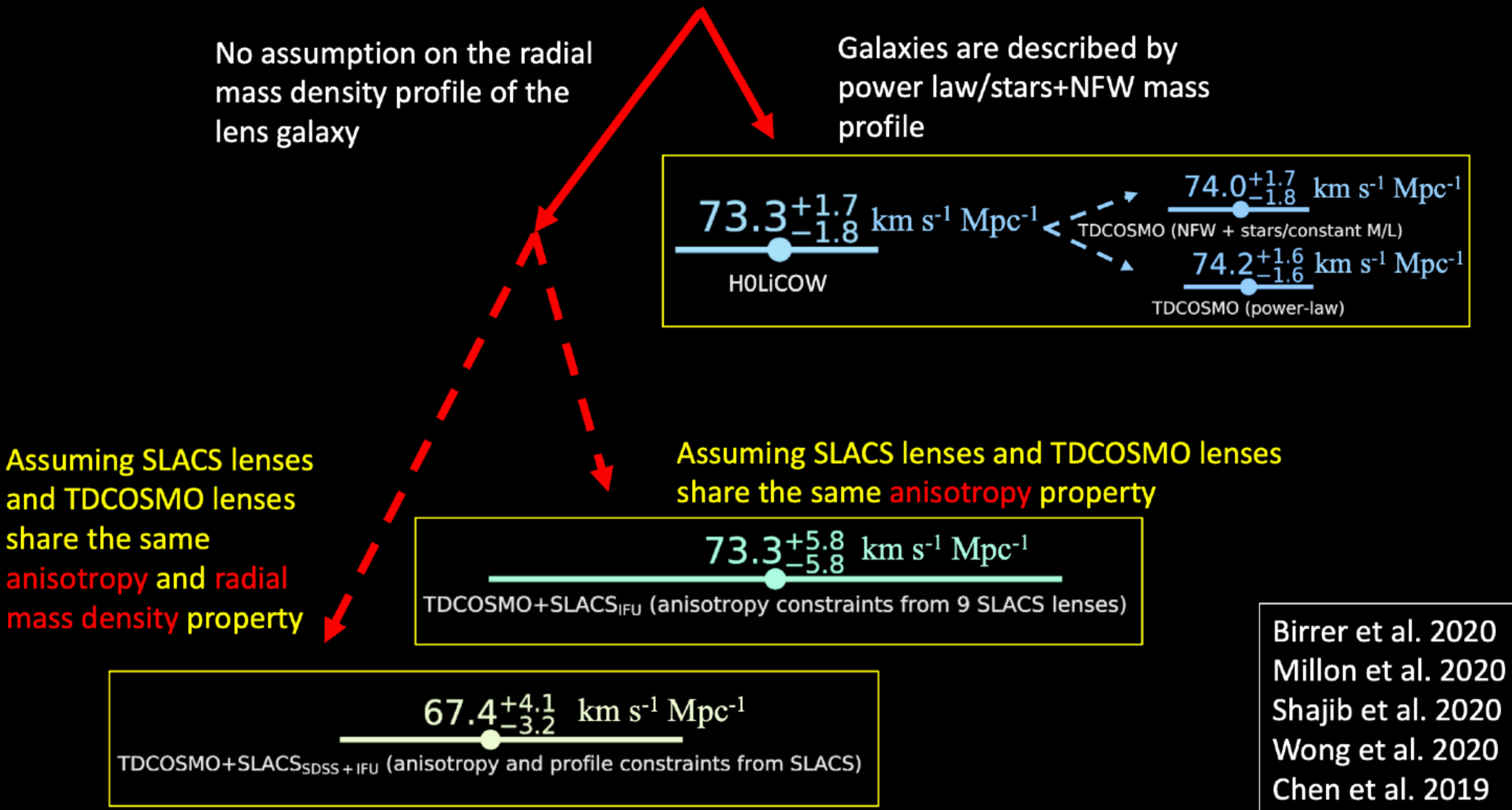
H_0 with 2.4% precision in flat ΛCDM

[Wong, Suyu, Chen et al. 2020]

TDCOSMO H_0 measurements

TDCOSMO = COSMOGRAIL + H0LiCOW + STRIDES + SHARP

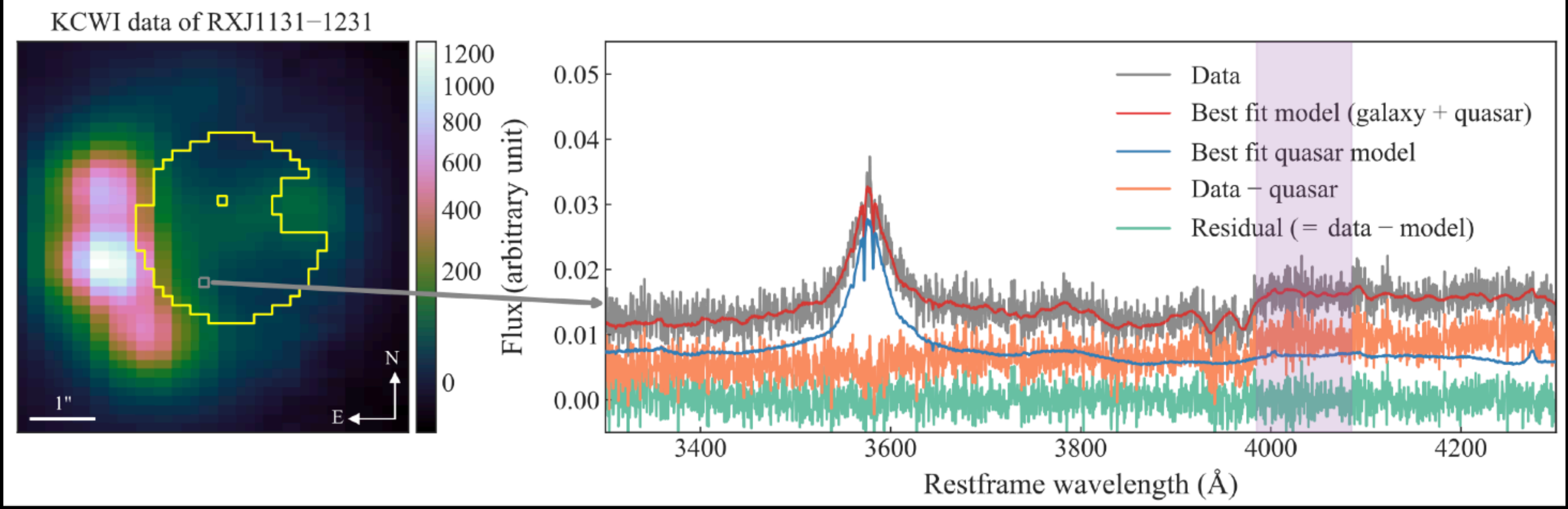
[Millon, Galan, Courbin et al. 2020; TDCOSMO I]



[Figure credit: Geoff C.-F. Chen]

Moving forward

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



[Shajib et al. 2023]

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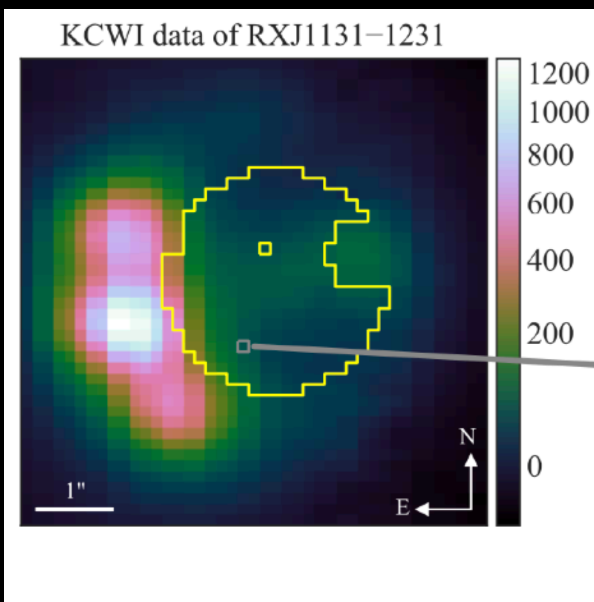
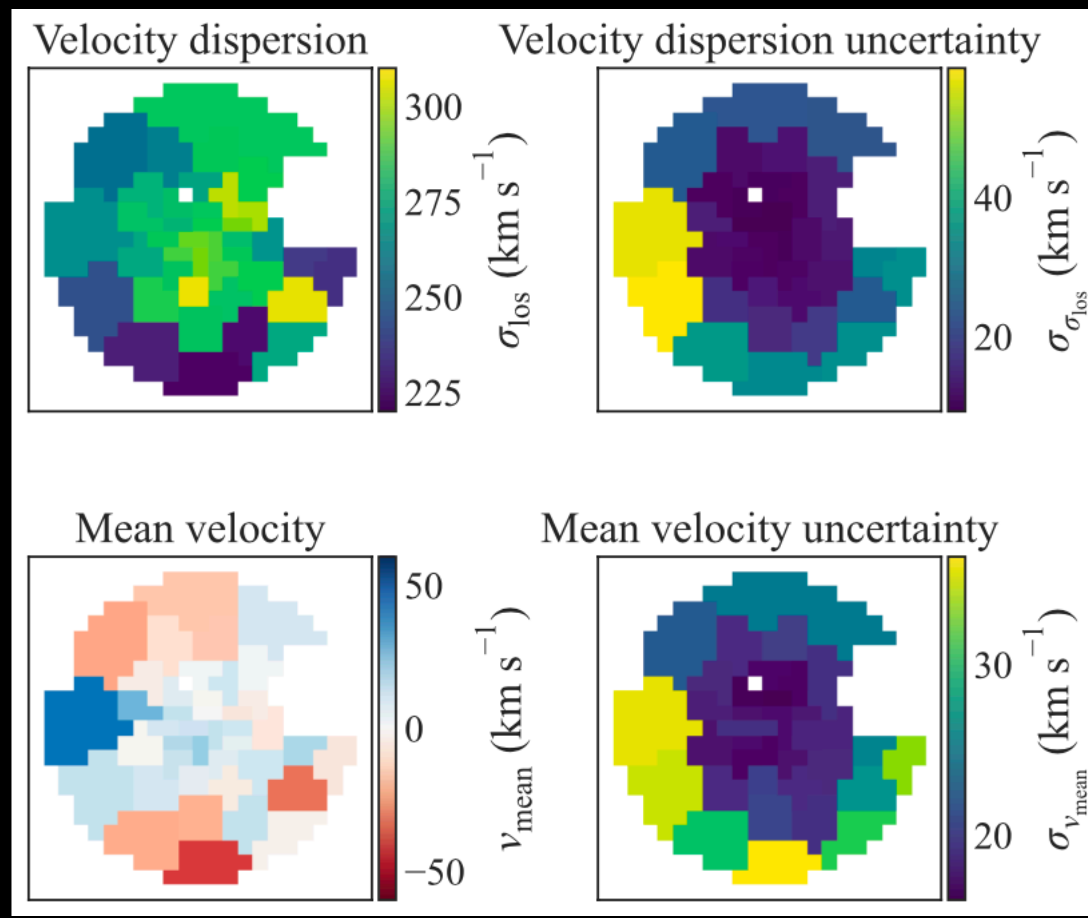


[Shajib et al. 2023]



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

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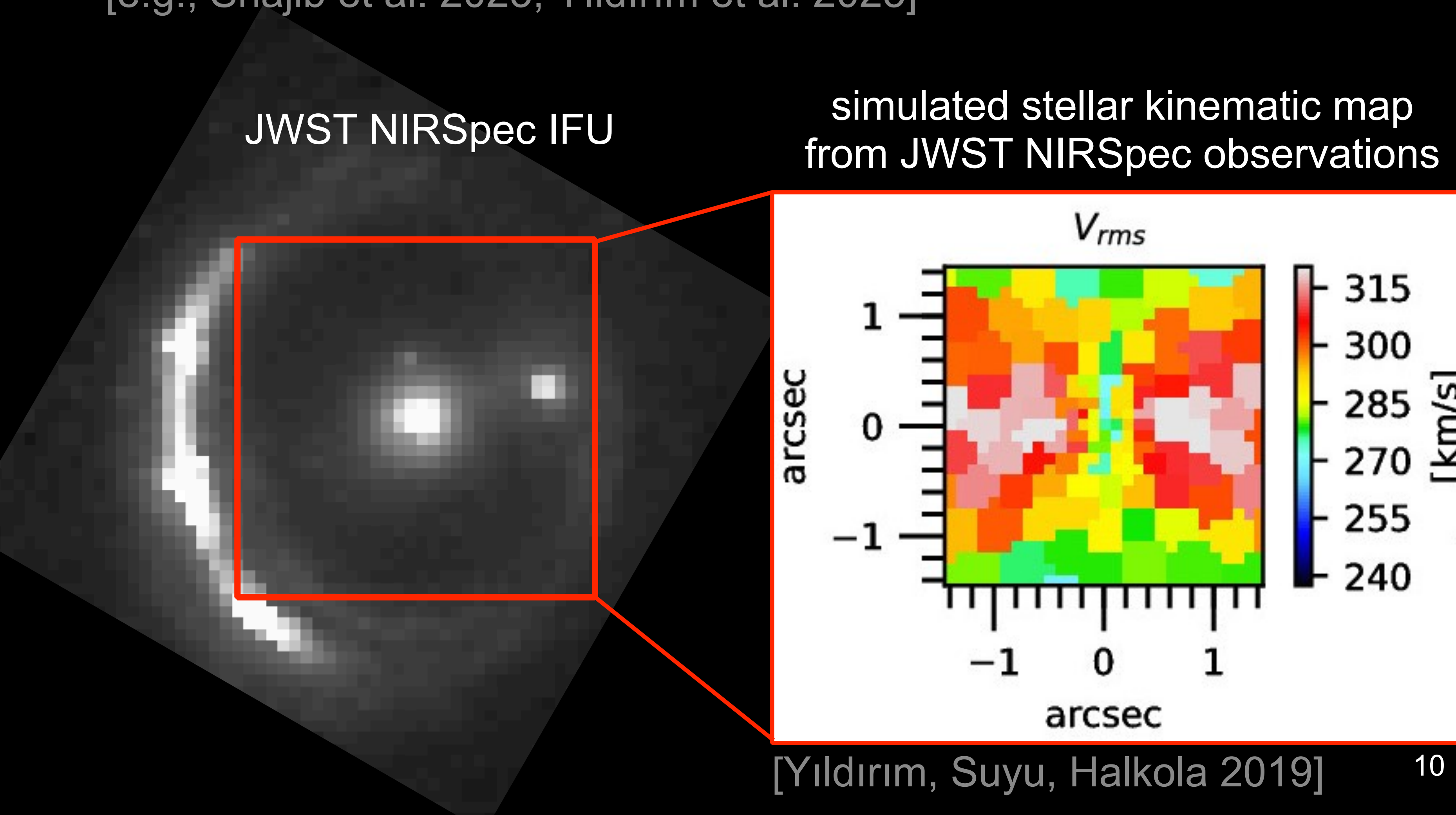


[Yıldırım, Suyu, Halkola 2019]

Strongly lensed supernovae (SNe)

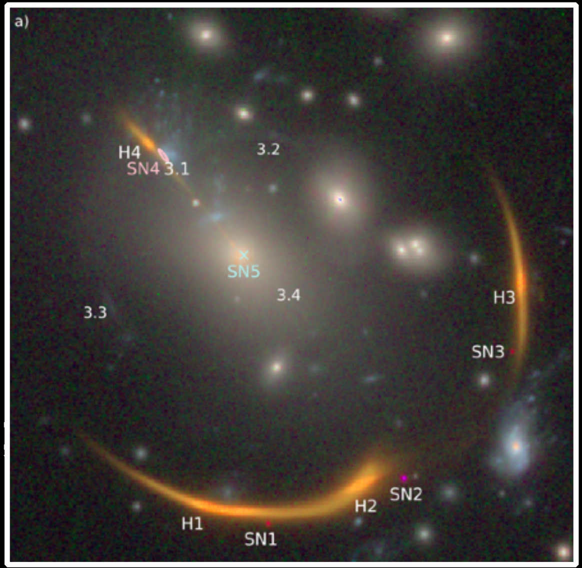
SN Refsdal

[Kelly et al. 2015]

iPTF16geu

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

SN Requiem

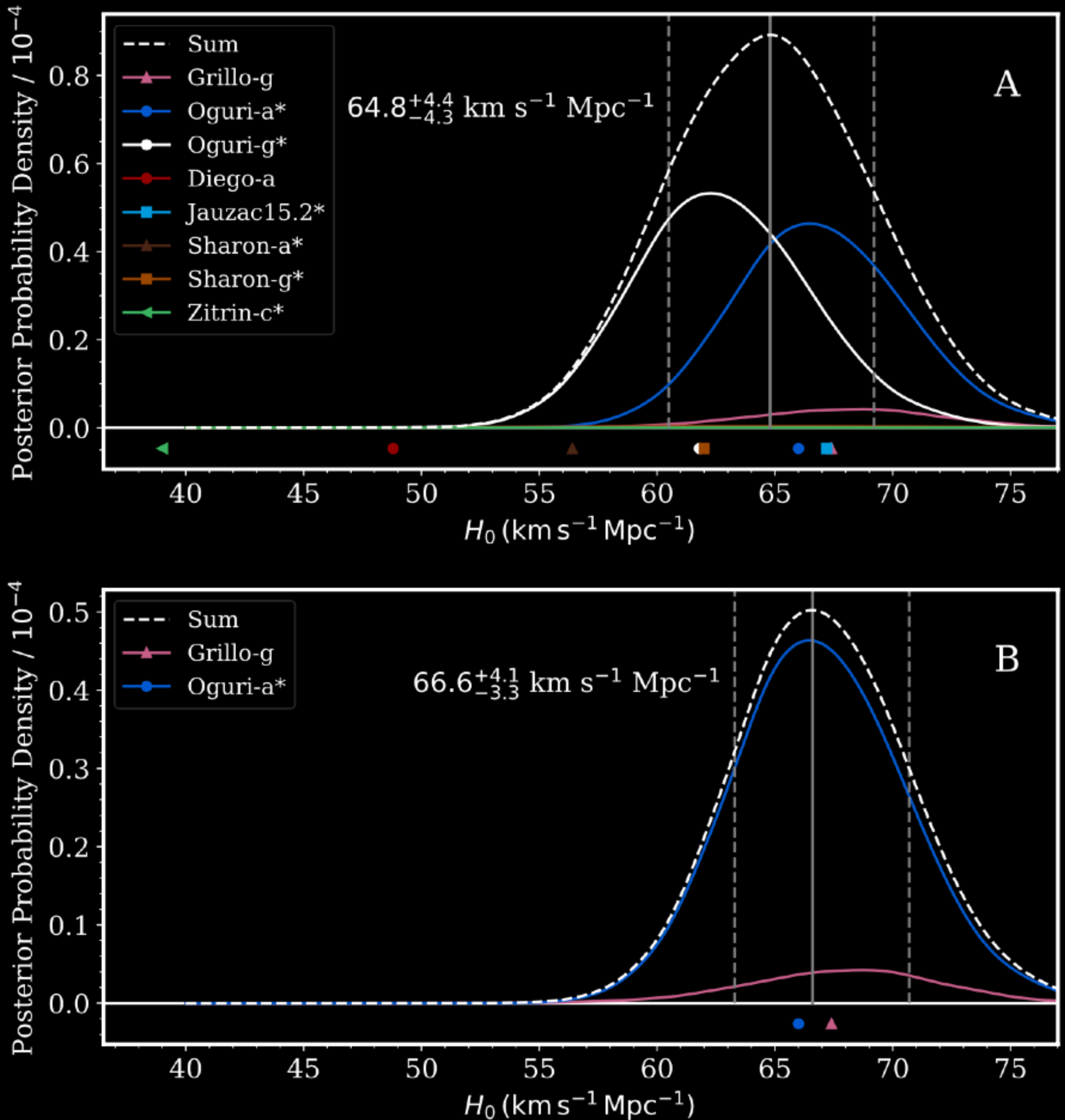


[Rodney et al. 2021]

SN Zwicky

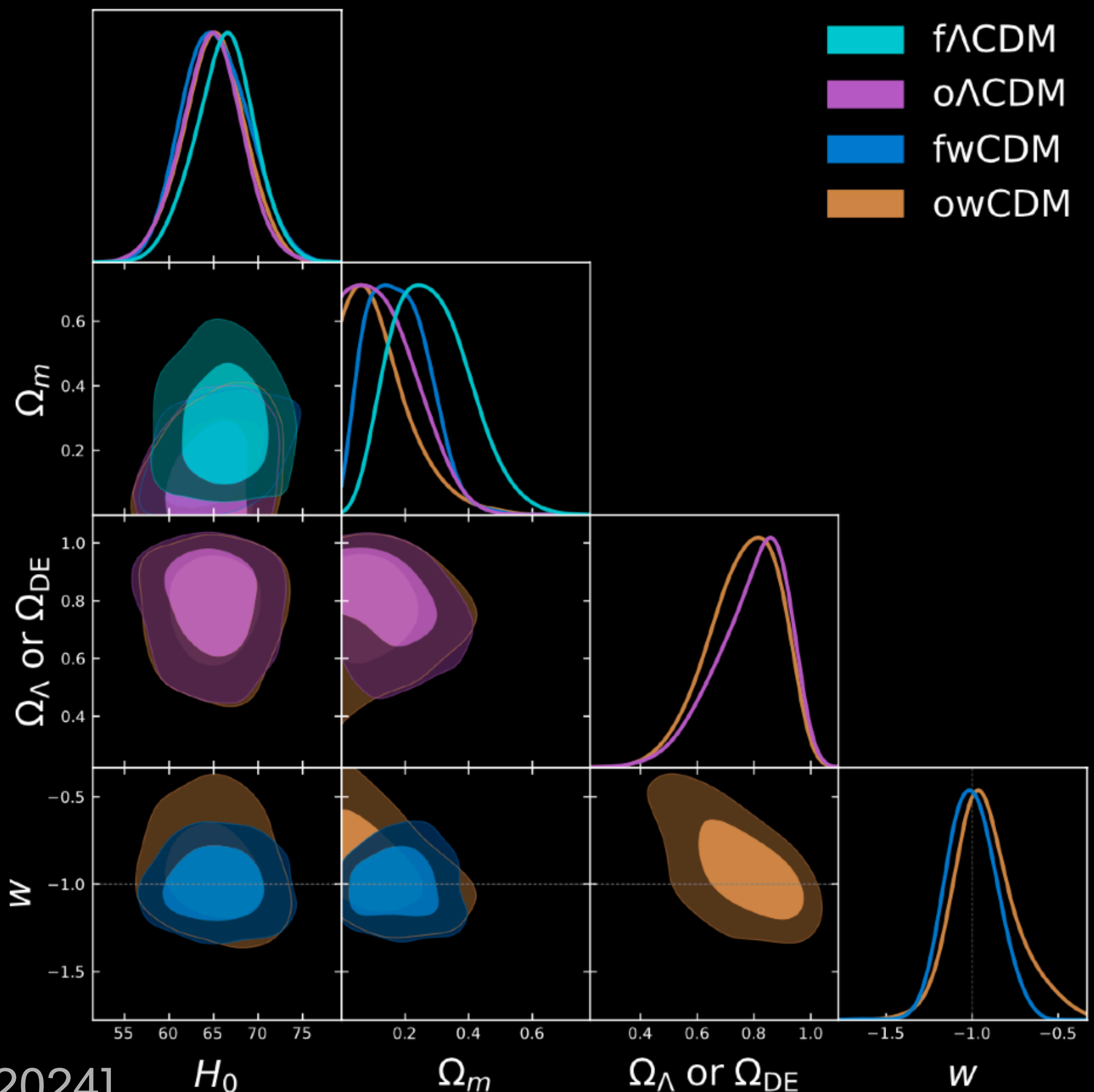
[Goobar et al. 2023; Pierel et al. 2023]

H_0 from SN Refsdal in flat ΛCDM



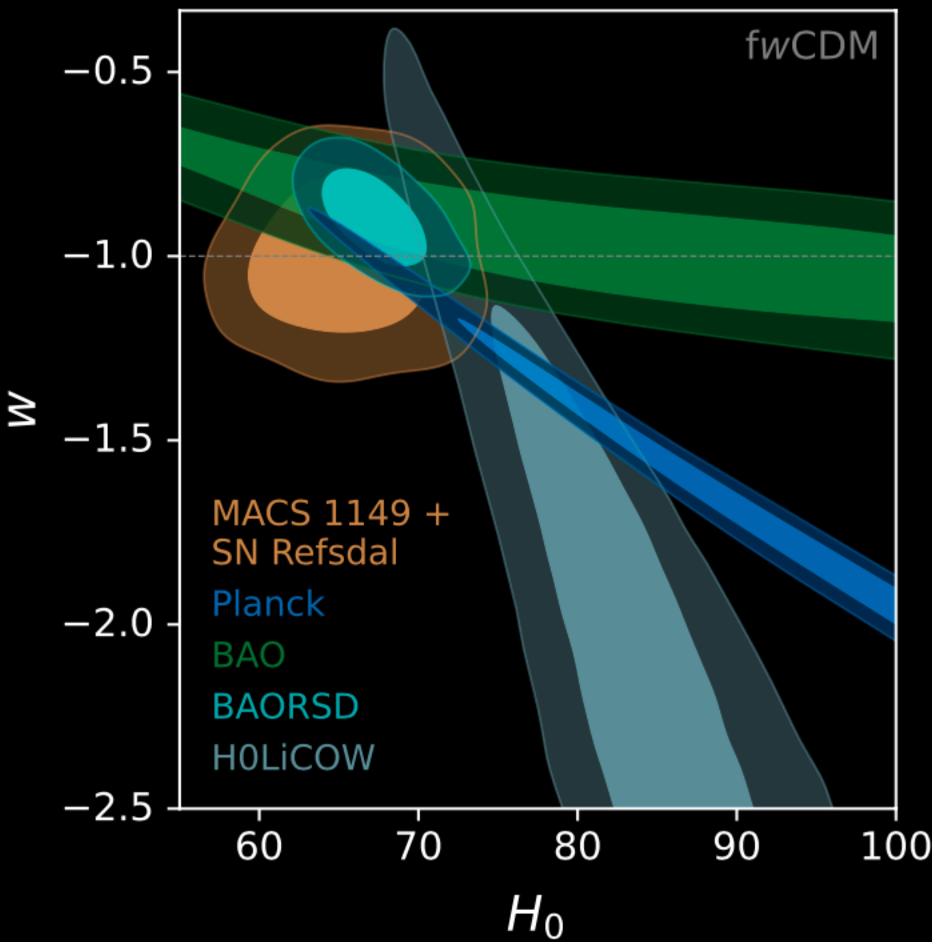
[Kelly et al. 2023a]

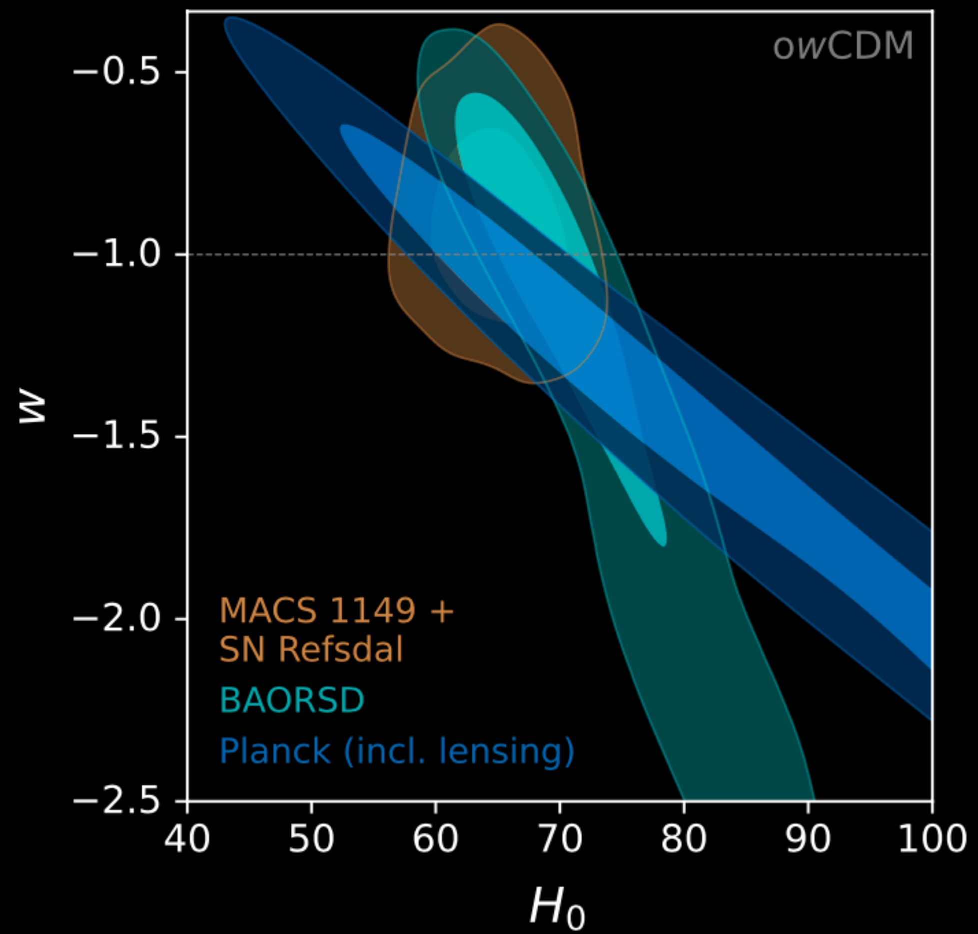
H_0 from SN Refsdal: general cosmo. model



[Grillo et al. 2024]

Cosmological constraints from SN Refsdal

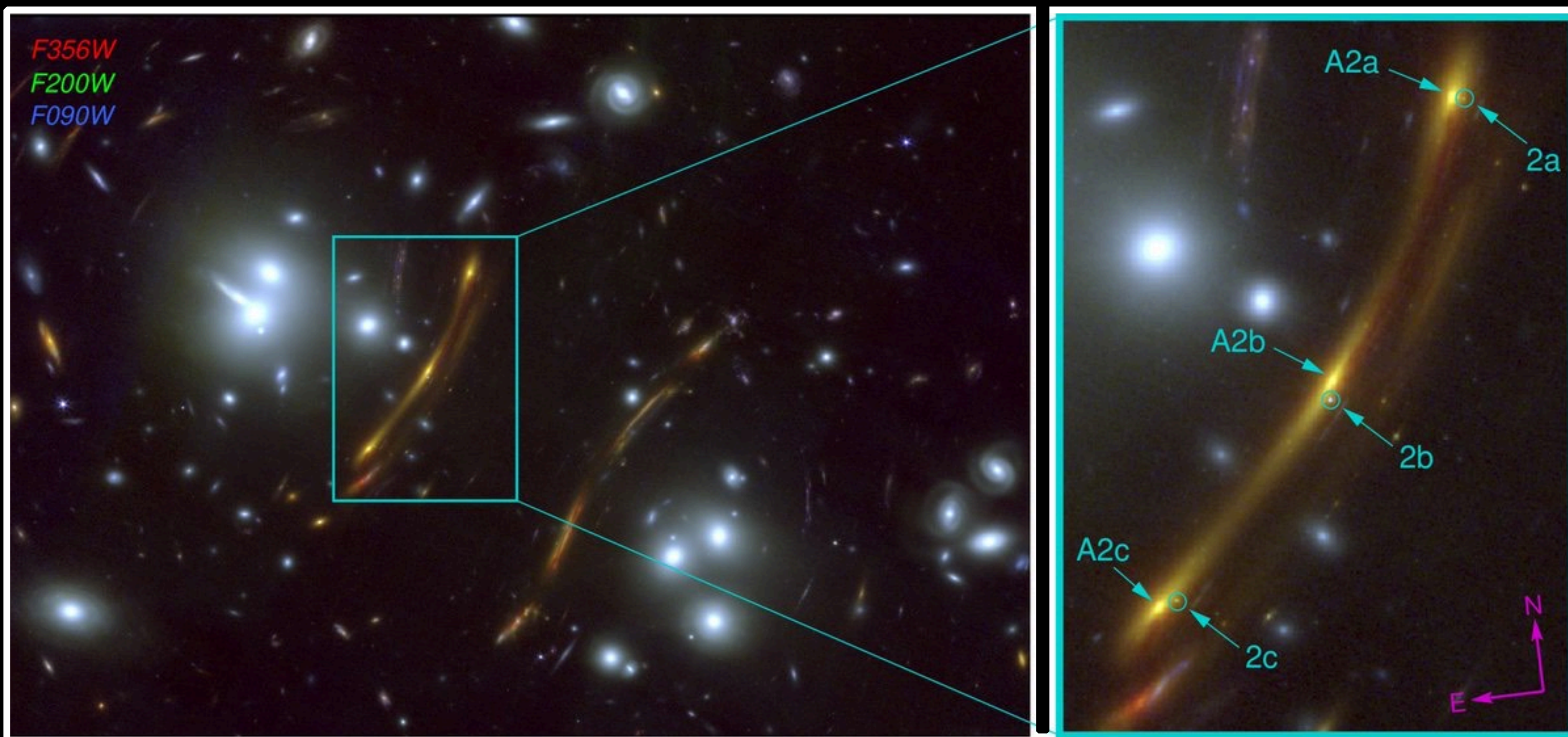




[Grillo et al. 2024]

SN H0pe

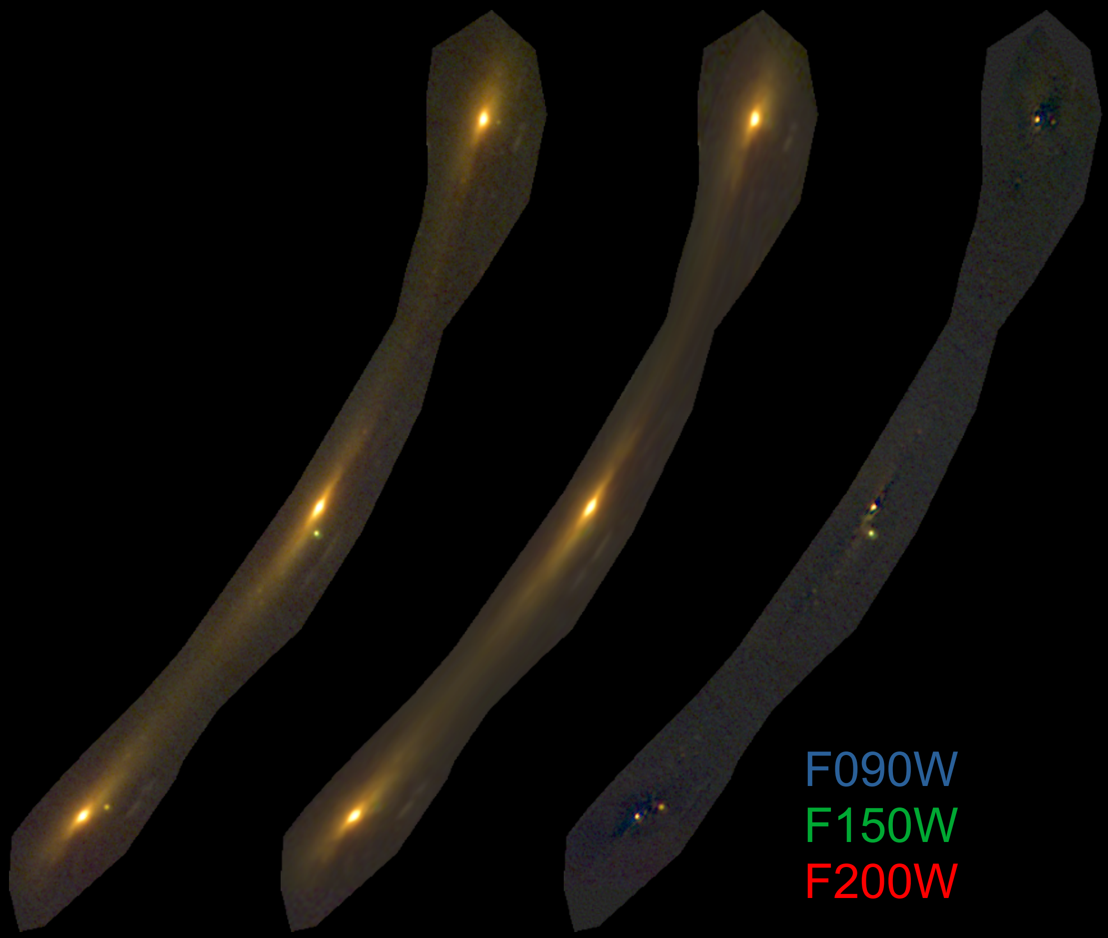
discovered by the PEARLS team in JWST imaging [Frye et al. 2024, Pierel et al. (accepted), Chen et al., Pascale et al., Caminha et al. in prep.]



[Frye et al. 2024]

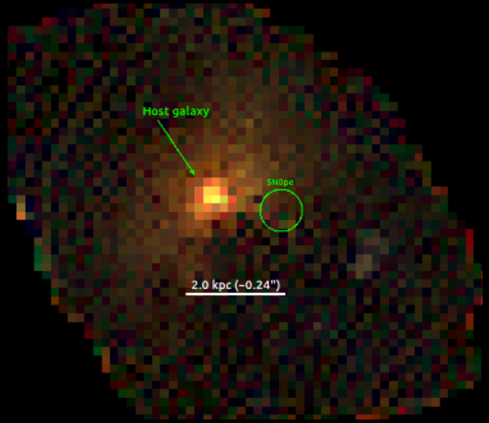
SN H0pe: source reconstruction

observation model residual



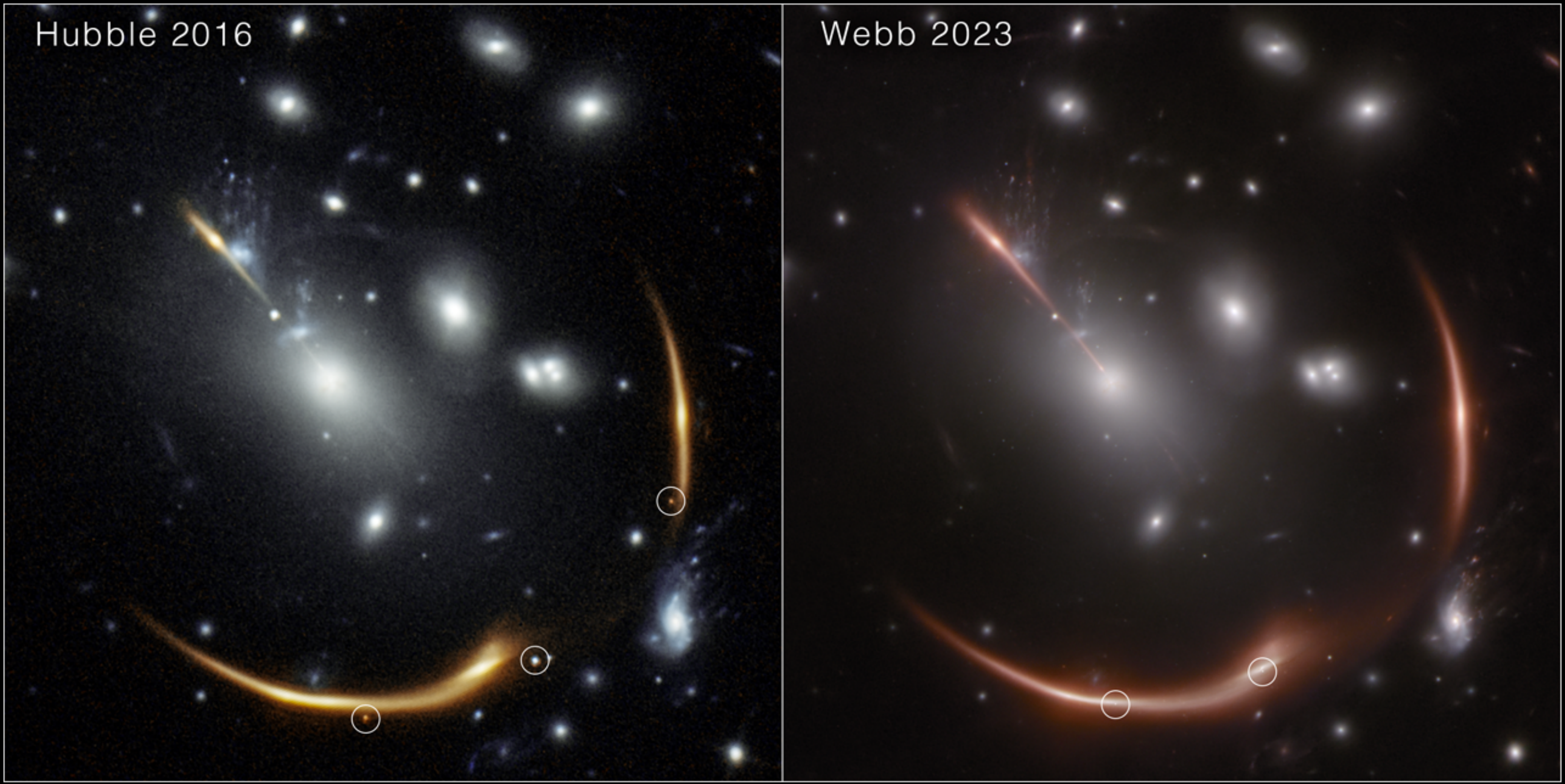
Gabriel Caminha

SN host galaxy reconstruction



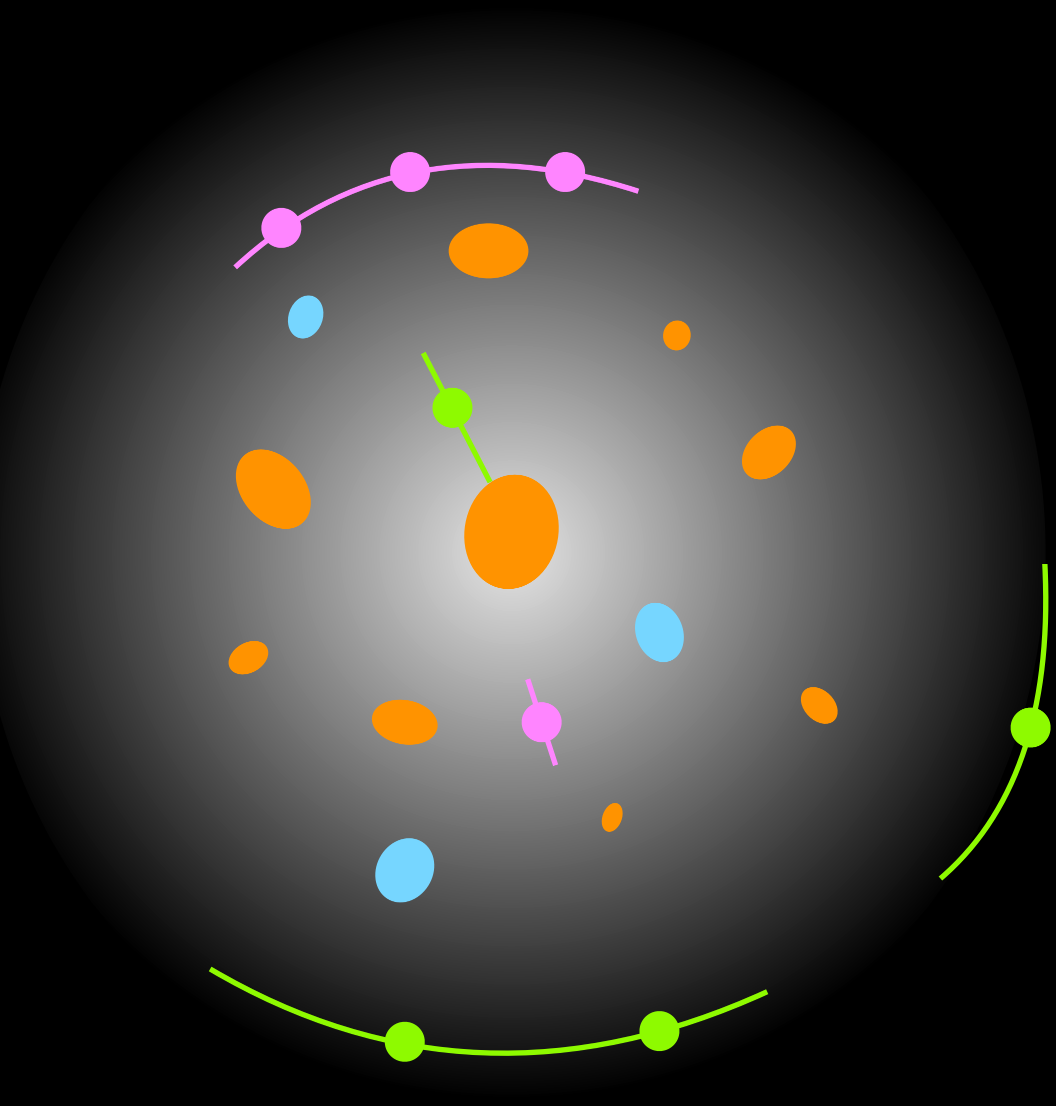
[Caminha et al., in prep.]

SN Requiem and Encore!

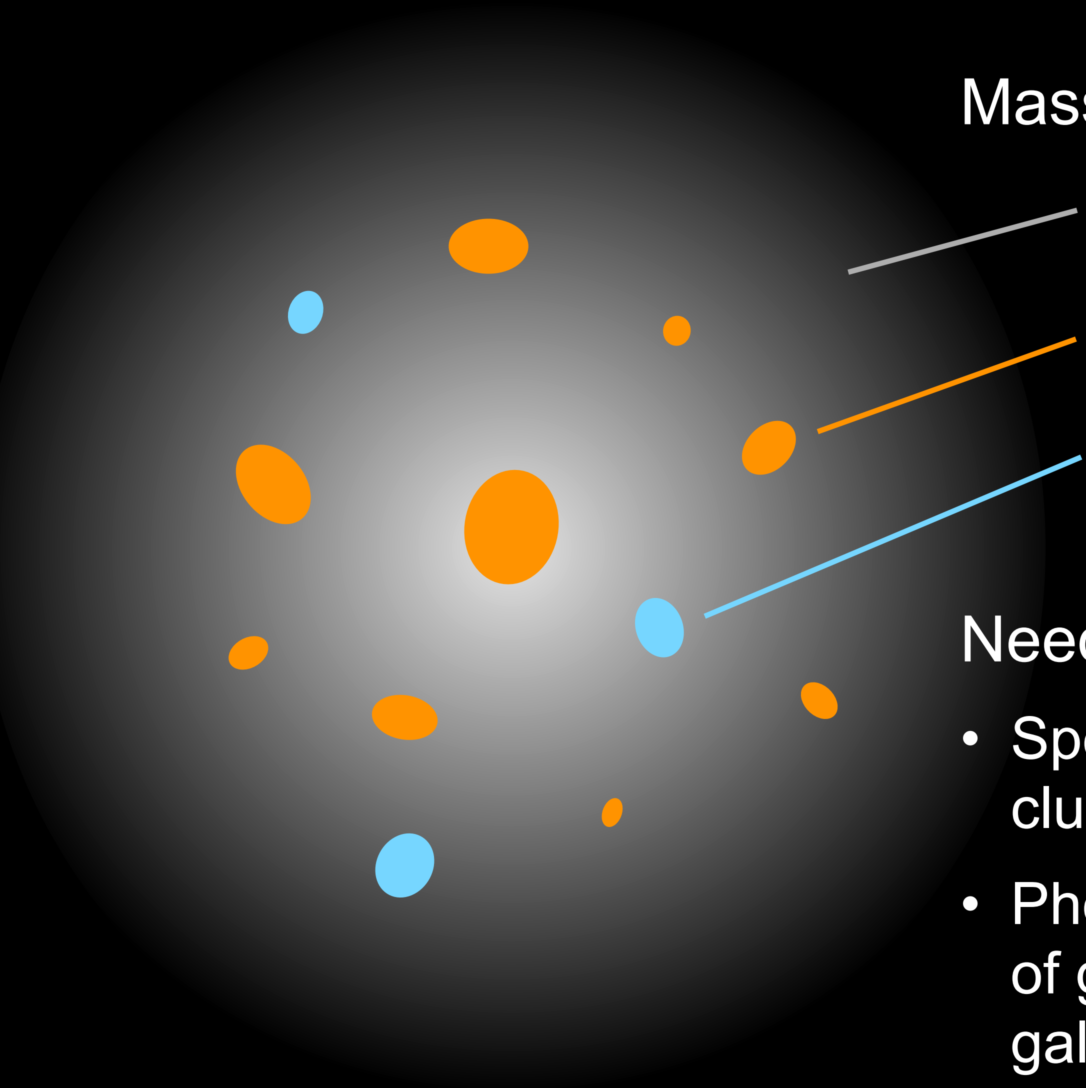


[Image credits: Hubble image: NASA, ESA, STScI, Steve A. Rodney (University of South Carolina) and Gabriel Brammer (Cosmic Dawn Center/Niels Bohr Institute/University of Copenhagen).
JWST image: NASA, ESA, CSA, STScI, Justin Pierel (STScI) and Andrew Newman (Carnegie Institution for Science).]

Cluster mass modelling



Cluster mass modelling



Mass components:

dark matter halo of cluster

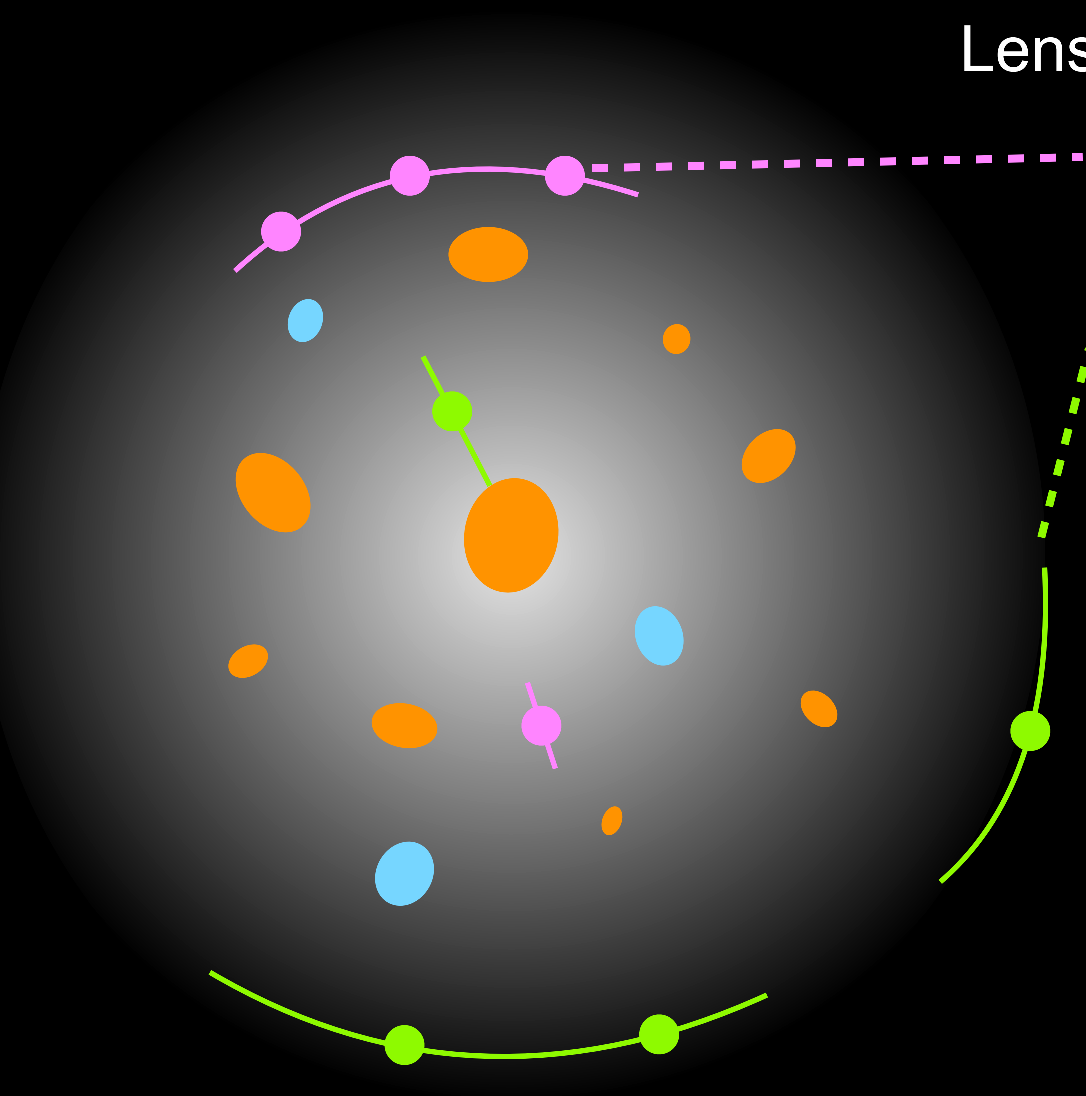
member galaxies of cluster

line-of-sight (LOS) galaxies

Need:

- Spectroscopy to disentangle cluster member and LOS galaxies
- Photometry and stellar kinematics of galaxies to scale masses of galaxies

Cluster mass modelling



Lensing constraints on masses:

positions of multiple images of lensed background sources

surface brightness distribution of strongly lensed background sources (arcs)

Need:

- Photometry to identify lensed sources
- Spectroscopy to confirm lensed images and measure their redshifts
- Surface brightness measurements

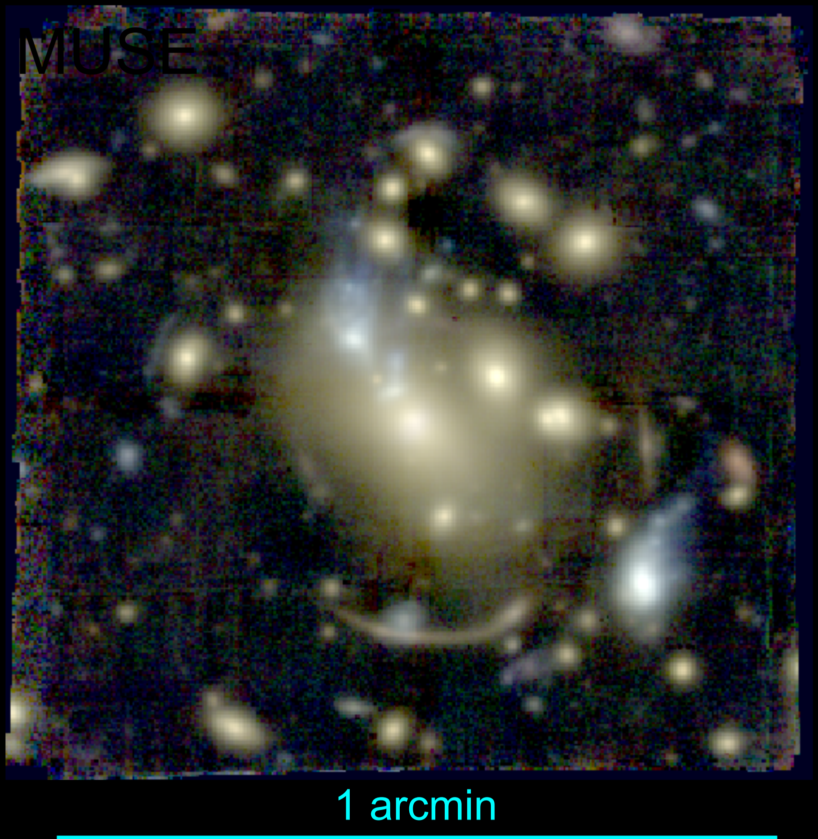
SN Encore with MUSE

Total exposure on target 3.74 hours

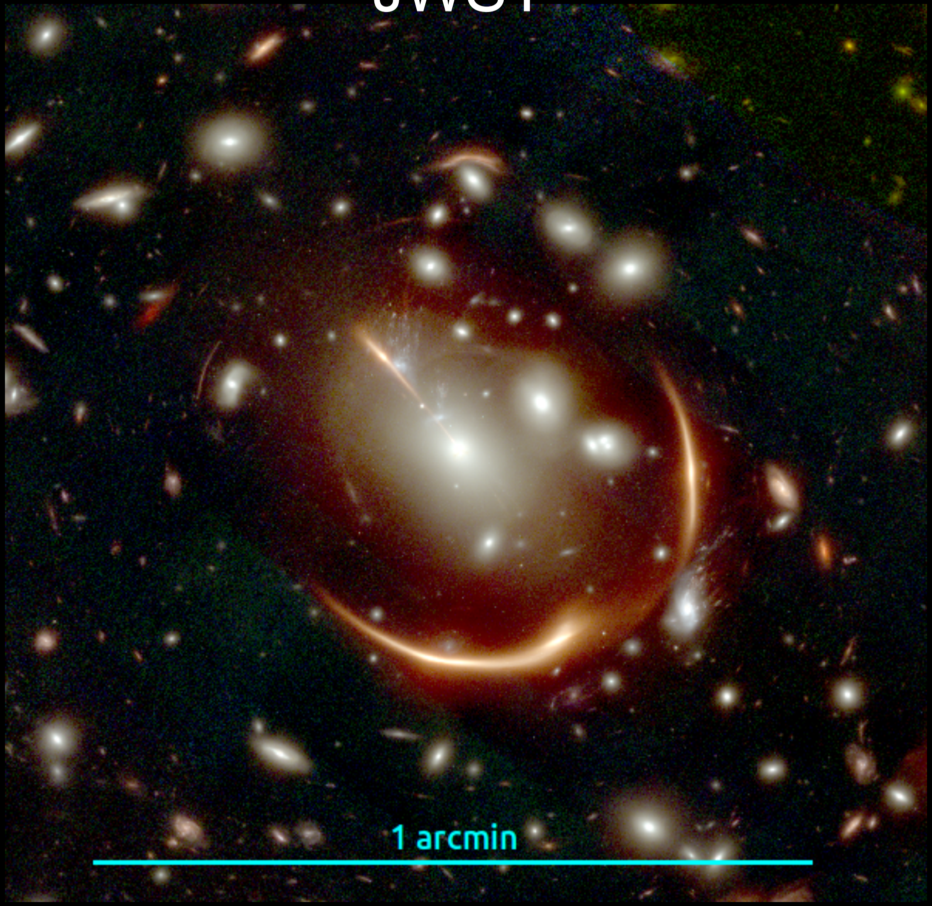
- 0.81 hr of archival data (2019/09), P.I. Edge
- 2.93 hr proprietary ToO (2023/12), P.I. Suyu

Gabriel Caminha

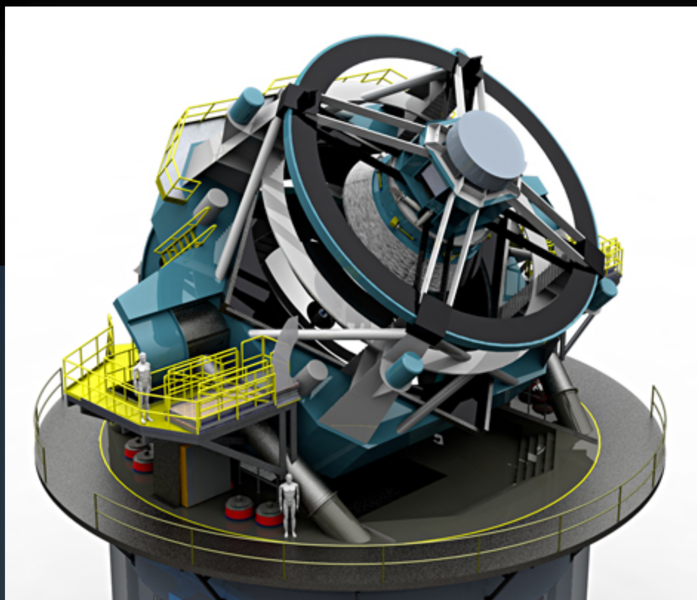
MUSE



JWST



Rubin Observatory Legacy Survey of Space and Time (LSST) and Euclid



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 ~2025

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

Euclid will provide high-resolution images for a large fraction of these systems

[Part of slide material courtesy of Phil Marshall]

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

HOLISMOKES

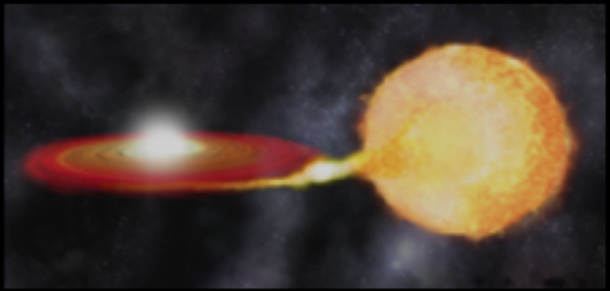
PI: S. H. Suyu

Lensed supernovae provide great opportunities for

1) Measuring H_0

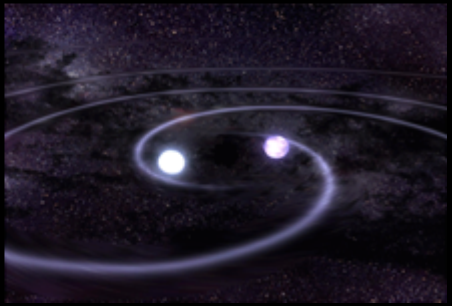
2) Constraining the progenitor of Type Ia supernova

single degenerate | double degenerate



White dwarf (WD) accreting from non-degenerate companion

or



WDs merging

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

HOLISMOKERS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James Chan


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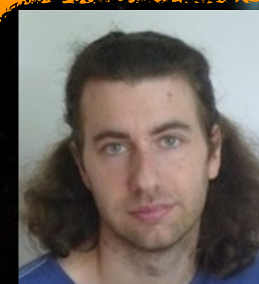
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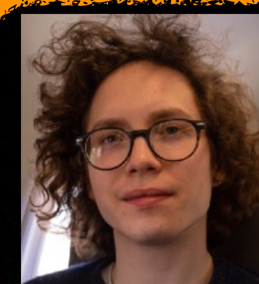
Yiping Shu


Stuart Sim


Dominique Sluse


Sherry Suyu (PI)


Stefan Taubenberger


Christian Vogl

Lens Search

(Papers II, VI, VIII, XI)

Follow-up Observations

(Paper III)

HOLI SMOKES

Time Delays

(Papers V, VII, XII)

Lens Modelling

(Papers IV, IX, X)

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Summary

- Strongly lensed transients with time delays are a competitive probe of cosmology
- Exciting time with the first lensed SNe being discovered
- Analyses of SN H0pe and SN Encore ongoing
- HOLISMOKES program to study cosmology and SN progenitors through lensed SNe
- Upcoming surveys especially LSST and Euclid will yield dozens of lensed SNe with high-resolution imaging - a bright future ahead!