

# Strong Lensing as a Probe of Cosmology

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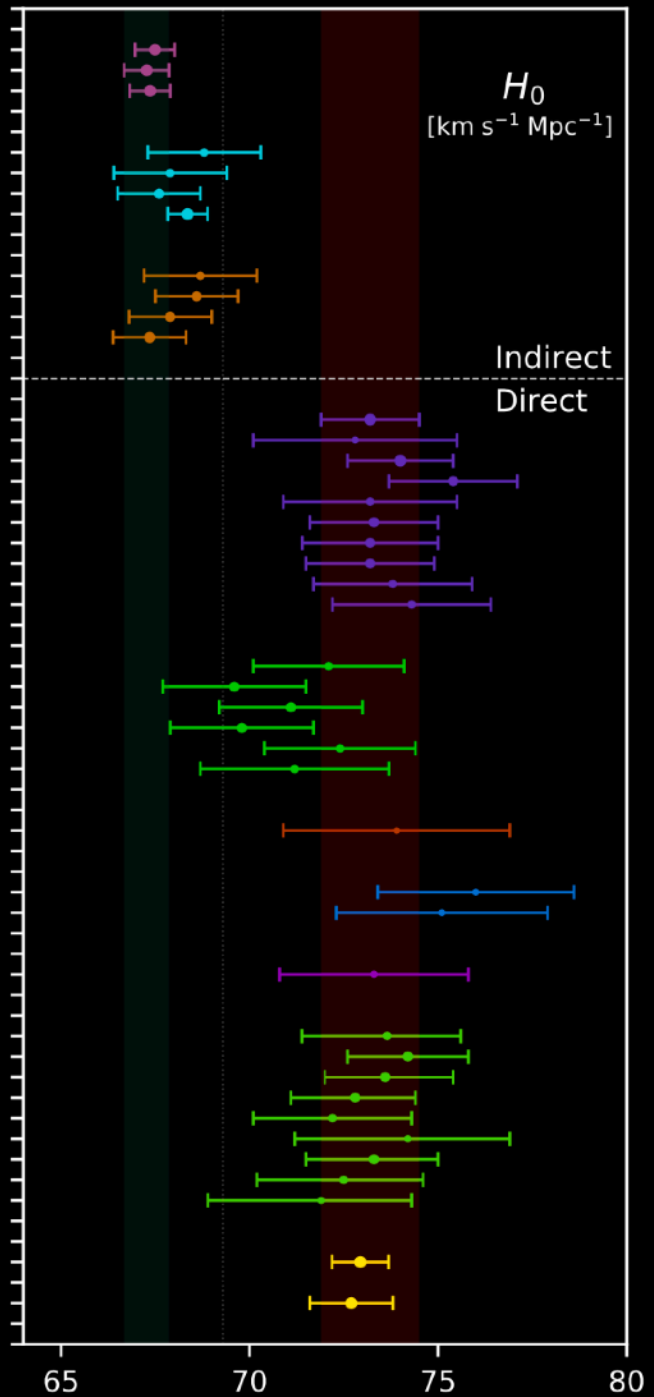
Cosmology in the Alps 2024 @ Les Diablerets

# $H_0$ tension in flat $\Lambda$ CDM

- $5\sigma$  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  $\Lambda$ CDM model?

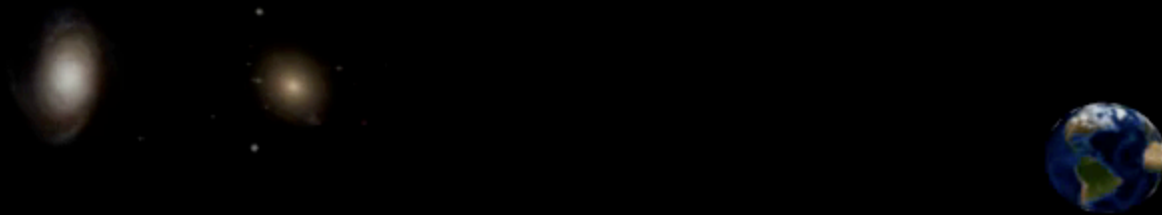
→ **Independent measurements are crucial**

<b>CMB with Planck</b>	
Balkenhol et al. (2021), Planck 2018+SPT+ACT	: $67.49 \pm 0.53$
Aghanim et al. (2020), Planck 2018	: $67.27 \pm 0.60$
Aghanim et al. (2020), Planck 2018+CMB lensing	: $67.36 \pm 0.54$
<b>CMB without Planck</b>	
Dutcher et al. (2021), SPT	: $68.8 \pm 1.5$
Aiola et al. (2020), ACT	: $67.9 \pm 1.5$
Aiola et al. (2020), WMAP9+ACT	: $67.6 \pm 1.1$
Zhang, Huang (2019), WMAP9+BAO	: $68.36^{+0.53}_{-0.52}$
<b>No CMB, with BBN</b>	
Colas et al. (2020), BOSS DR12+BBN	: $68.7 \pm 1.5$
Philcox et al. (2020), $P_z$ +BAO+BBN	: $68.6 \pm 1.1$
Ivanov et al. (2020), BOSS+BBN	: $67.9 \pm 1.1$
Alam et al. (2020), BOSS+eBOSS+BBN	: $67.35 \pm 0.97$
<b>Cepheids – SNIa</b>	
Riess et al. (2020), R20	: $73.2 \pm 1.3$
Breuval et al. (2020)	: $72.8 \pm 2.7$
Riess et al. (2019), R19	: $74.0 \pm 1.4$
Camarena, Marra (2019)	: $75.4 \pm 1.7$
Burns et al. (2018)	: $73.2 \pm 2.3$
Follin, Knox (2017)	: $73.3 \pm 1.7$
Feeney, Mortlock, Dalmaso (2017)	: $73.2 \pm 1.8$
Riess et al. (2016), R16	: $73.2 \pm 1.7$
Cardona, Kunz, Pettorino (2016)	: $73.8 \pm 2.1$
Freedman et al. (2012)	: $74.3 \pm 2.1$
<b>TRGB – SNIa</b>	
Soltis, Casertano, Riess (2020)	: $72.1 \pm 2.0$
Freedman et al. (2020)	: $69.6 \pm 1.9$
Reid, Pesce, Riess (2019), SH0ES	: $71.1 \pm 1.9$
Freedman et al. (2019)	: $69.8 \pm 1.9$
Yuan et al. (2019)	: $72.4 \pm 2.0$
Jang, Lee (2017)	: $71.2 \pm 2.5$
<b>Masers</b>	
Pesce et al. (2020)	: $73.9 \pm 3.0$
<b>Tully – Fisher Relation (TFR)</b>	
Kourkchi et al. (2020)	: $76.0 \pm 2.6$
Schombert, McGaugh, Lelli (2020)	: $75.1 \pm 2.8$
<b>Surface Brightness Fluctuations</b>	
Blakeslee et al. (2021) IR-SBF w/ HST	: $73.3 \pm 2.5$
<b>Lensing related, mass model – dependent</b>	
Yang, Birrer, Hu (2020): $H_0 = 73.65^{+1.95}_{-2.26}$	
Millon et al. (2020), TDCOSMO	: $74.2 \pm 1.6$
Qi et al. (2020)	: $73.6^{+1.8}_{-1.6}$
Liao et al. (2020)	: $72.8^{+1.6}_{-1.7}$
Liao et al. (2019)	: $72.2 \pm 2.1$
Shajib et al. (2019), STRIDES	: $74.2^{+2.7}_{-3.0}$
Wong et al. (2019), H0LICOW 2019	: $73.3^{+1.9}_{-1.8}$
Birrer et al. (2018), H0LICOW 2018	: $72.5^{+2.3}_{-3.0}$
Bonvin et al. (2016), H0LICOW 2016	: $71.9^{+2.4}_{-3.0}$
<b>Optimistic average</b>	
Di Valentino (2021)	: $72.94 \pm 0.75$
<b>Ultra – conservative, no Cepheids, no lensing</b>	
Di Valentino (2021)	: $72.7 \pm 1.1$



[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:

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

Time-delay  
distance:

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

Obtain from  
lens mass  
model

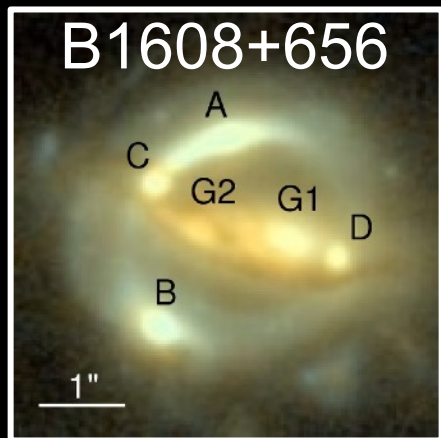
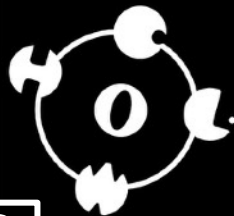
Cosmography:

time delays  $\Delta t$  + mass model  $\phi_{\text{lens}}$

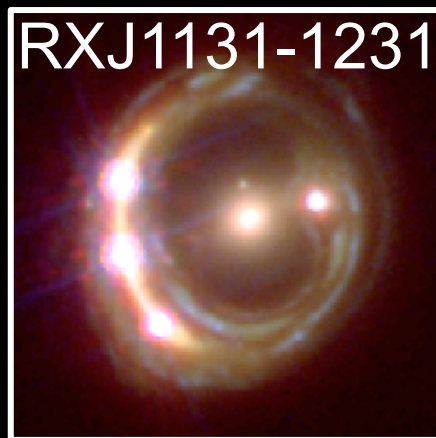
→ time-delay distance  $D_{\Delta t}$

→ Hubble constant  $H_0$

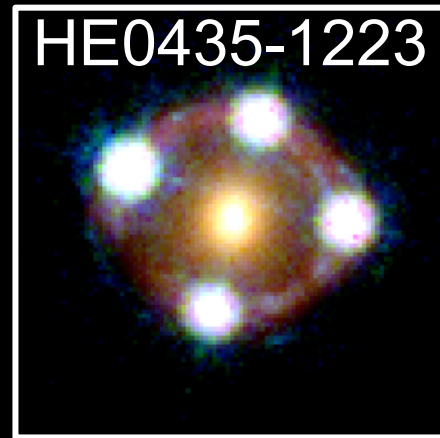
# H0LiCOW lensed quasars



[Suyu et al. 2010]



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



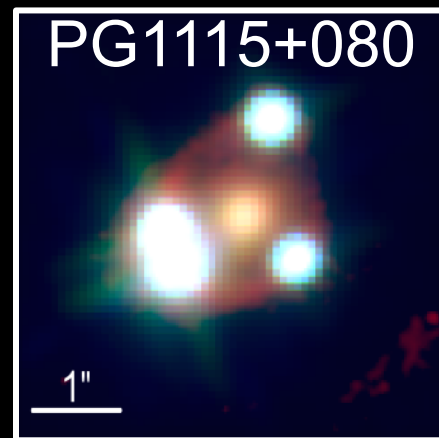
[Wong et al. 2017; Rusu  
et al. 2017; Sluse et al.  
2017; Bonvin et al. 2017]



part of extended sample  
[Birrer et al. 2019]



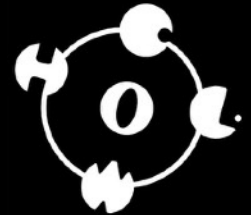
[Bonvin et al. 2019;  
Sluse et al. 2019;  
Rusu et al. 2020]



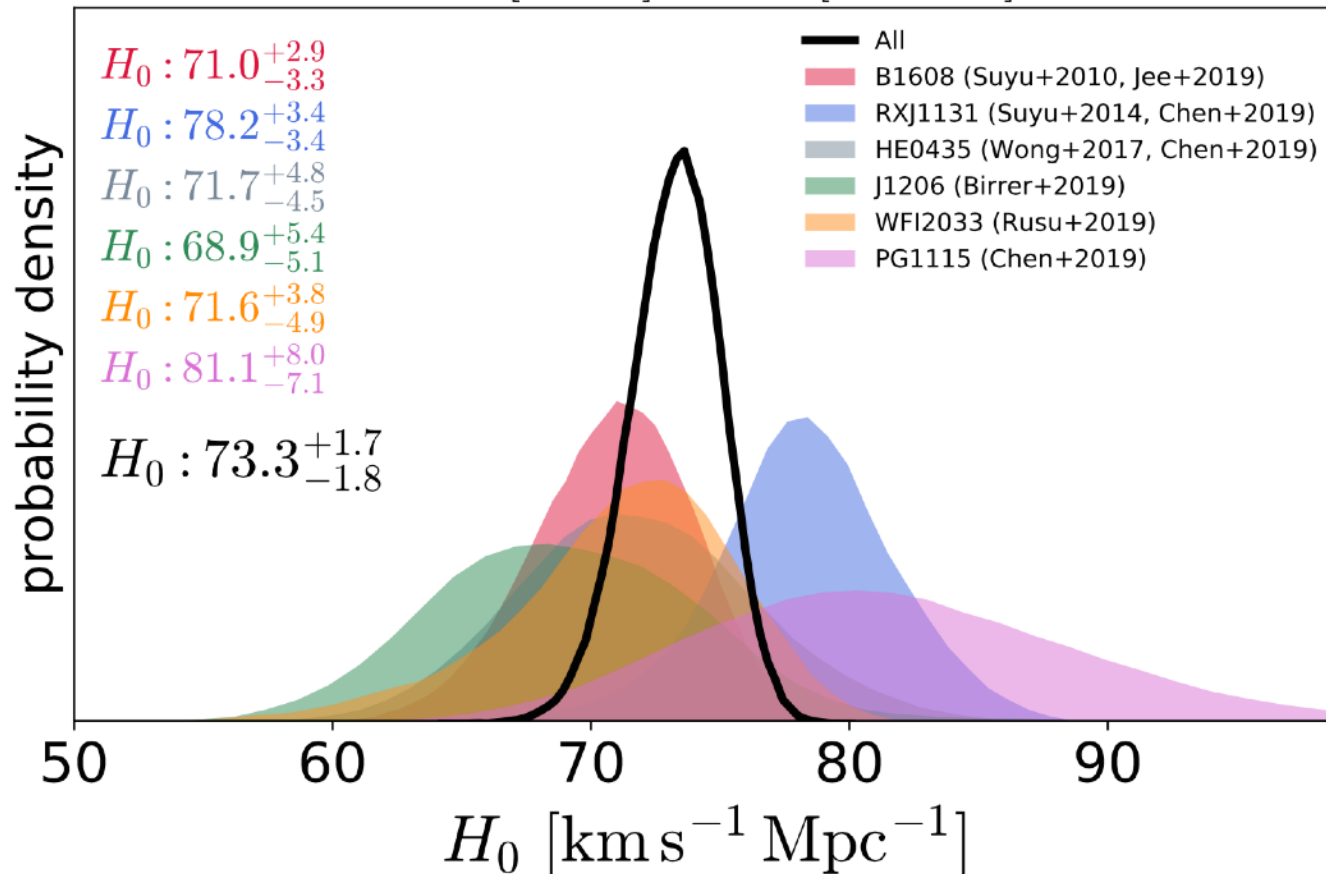
part of Keck AO sample  
of SHARP program  
[Chen et al. 2019]

# 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  $\Lambda$ CDM**

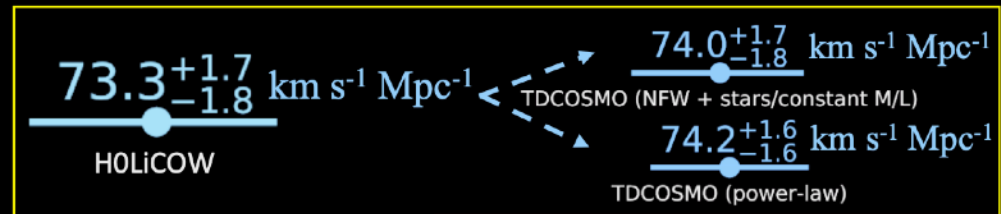
[Wong, Suyu, Chen et al. 2020]

# TDCOSMO $H_0$ measurements

TDCOSMO = COSMOGRAIL + HOLICOW + STRIDES + SHARP  
[Millon, Galan, Courbin et al. 2020; TDCOSMO I]

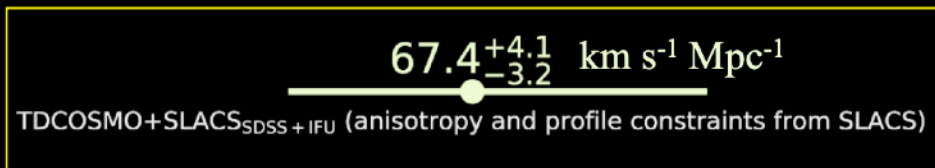
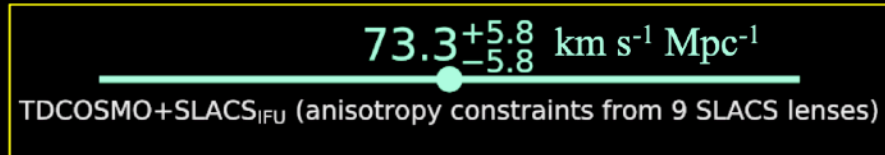
No assumption on the radial mass density profile of the lens galaxy

Galaxies are described by power law/stars+NFW mass profile



Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy and radial mass density property

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy property

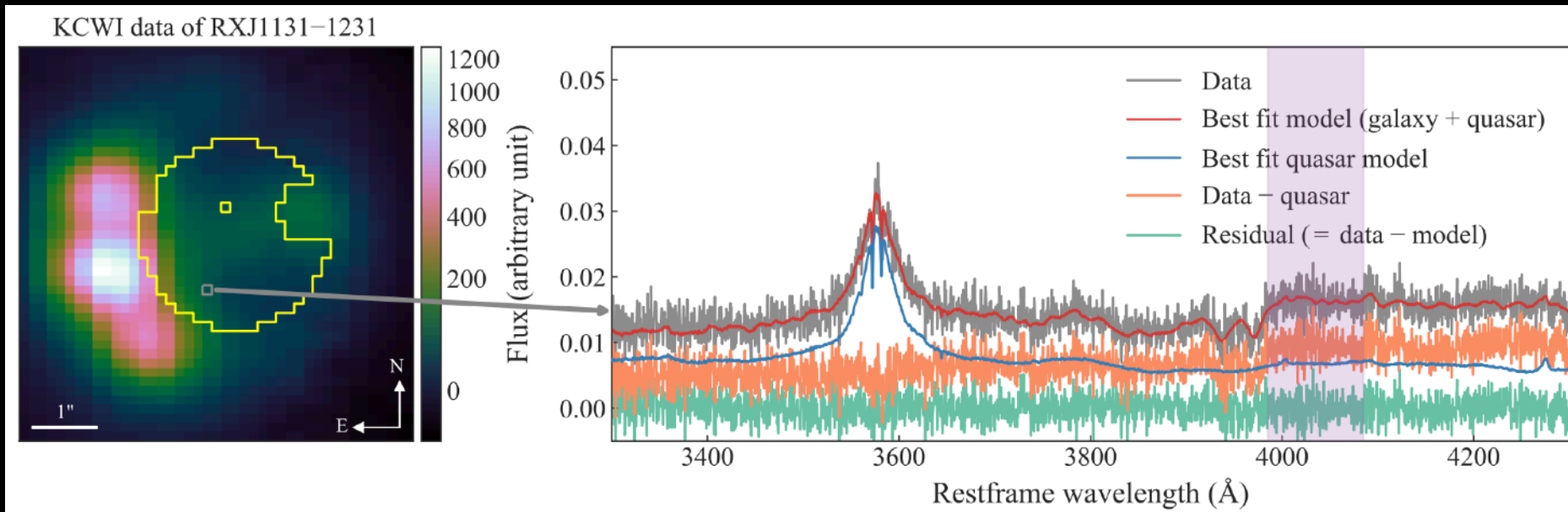


Birrer et al. 2020  
Millon et al. 2020  
Shajib et al. 2020  
Wong et al. 2020  
Chen et al. 2019

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

# Moving forward

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

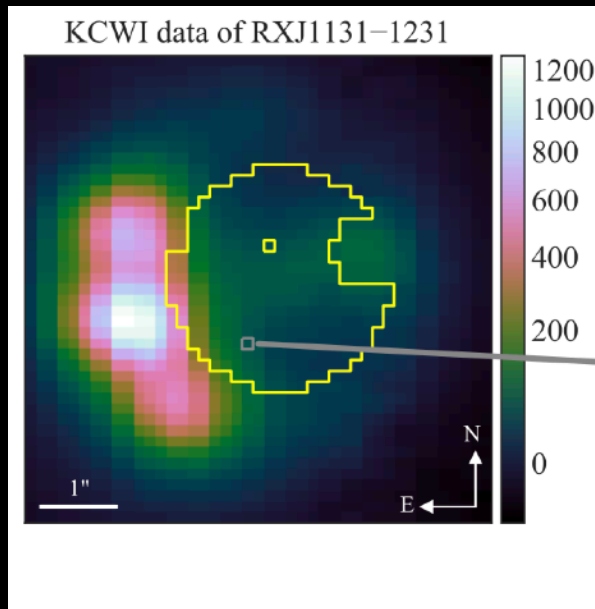


[Shajib et al. 2023]

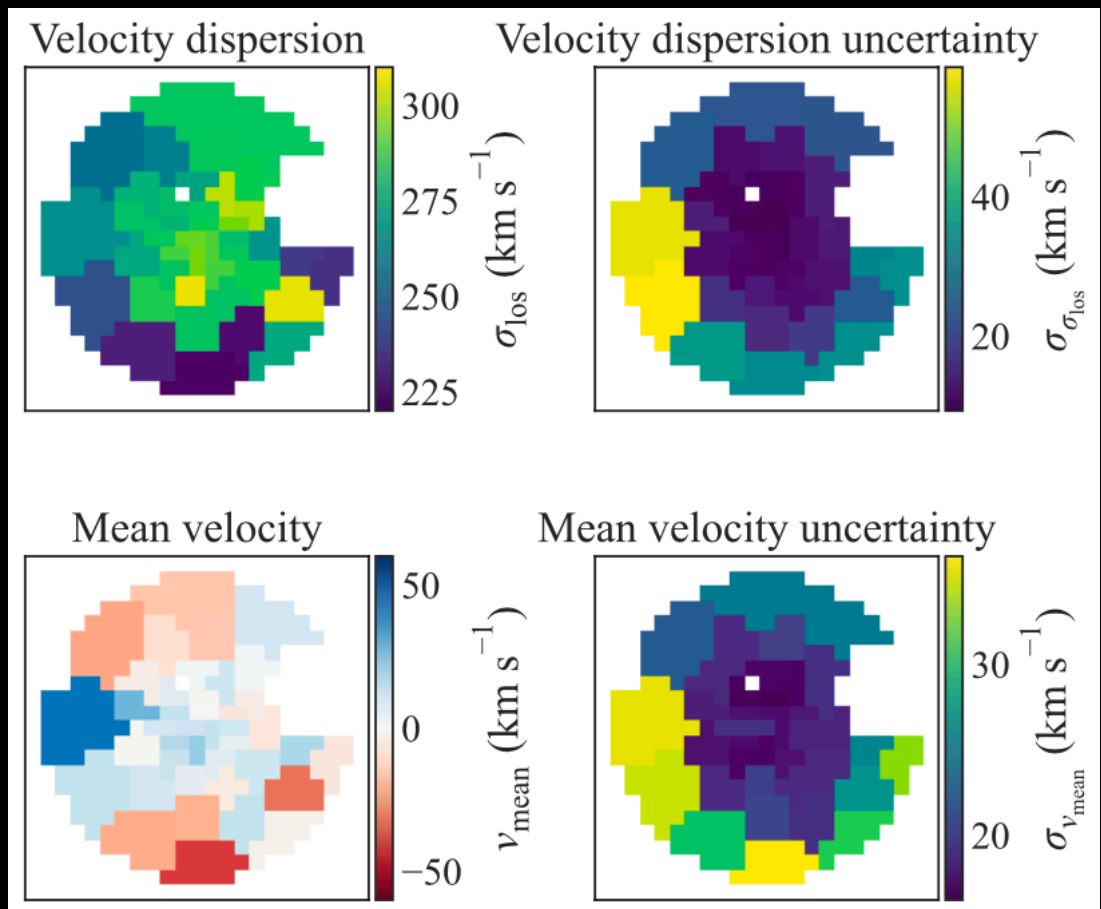


# Moving forward

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[Shajib et al. 2023]

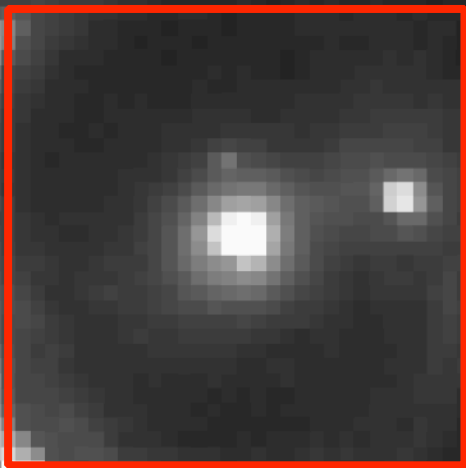


$H_0 = 77 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1}$  with flexible mass models

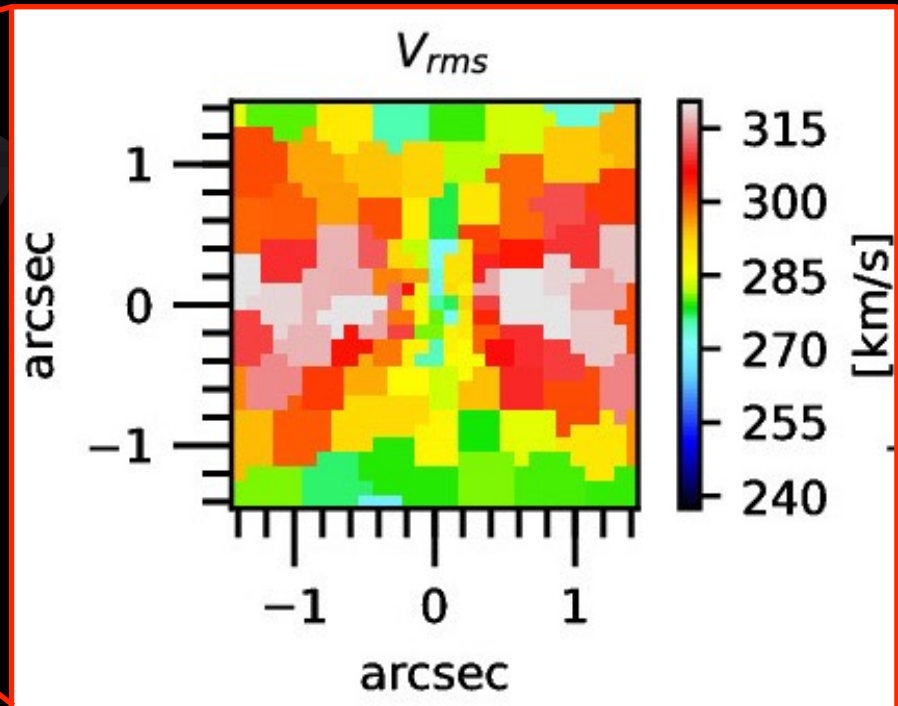
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[e.g., Shajib et al. 2023; Yıldırım et al. 2023]

JWST NIRSpec IFU



simulated stellar kinematic map  
from JWST NIRSpec observations



[Yıldırım, Suyu, Halkola 2019]

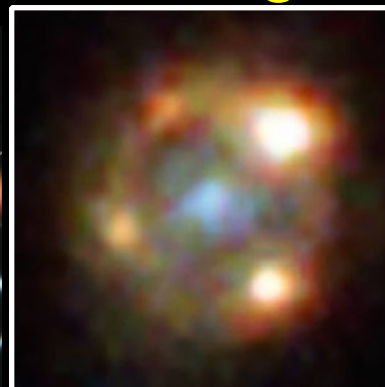
# Strongly lensed supernovae (SNe)

## SN Refsdal



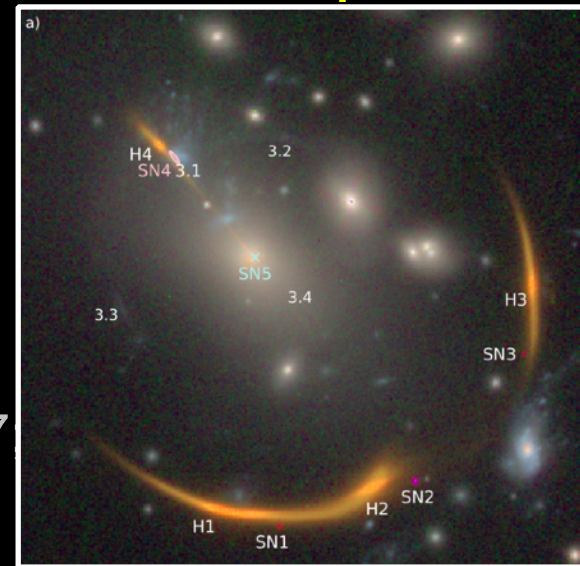
[Kelly et al. 2015]

## iPTF16geu



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

## SN Requiem



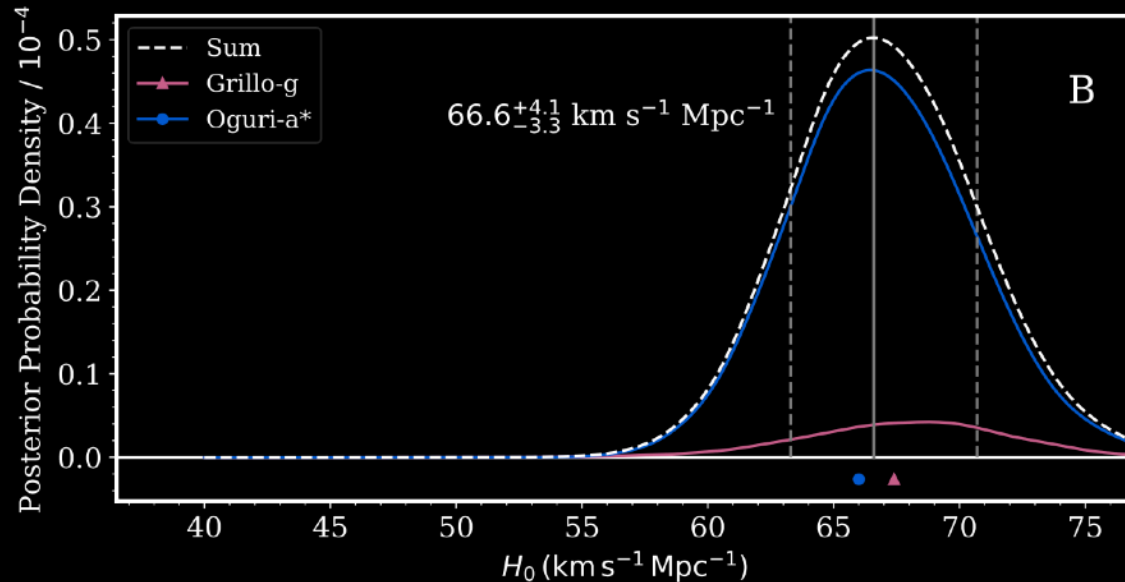
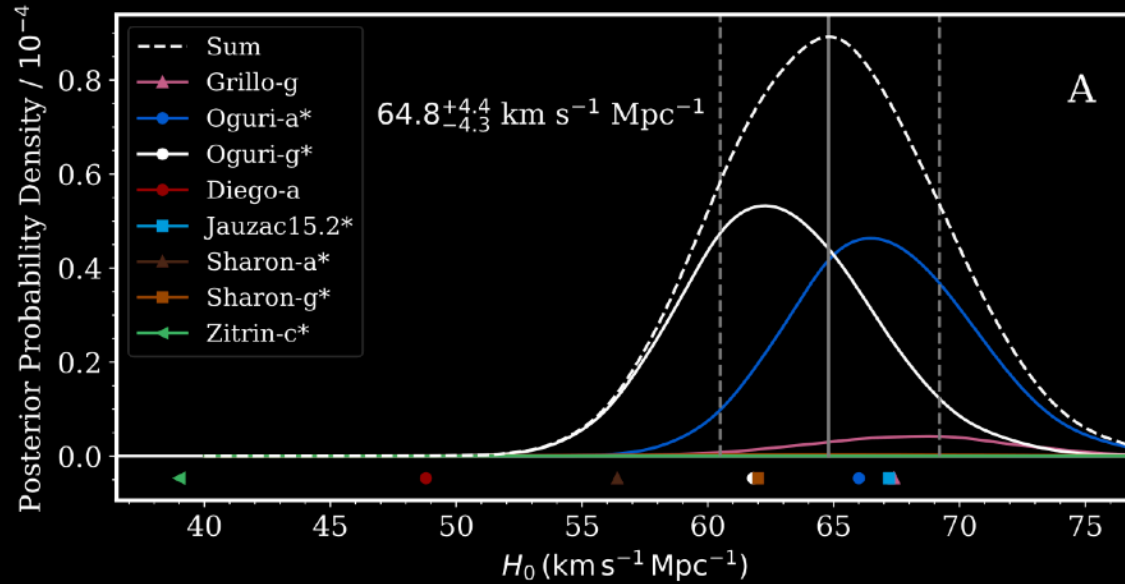
[Rodney et al. 2021]

## SN Zwicky

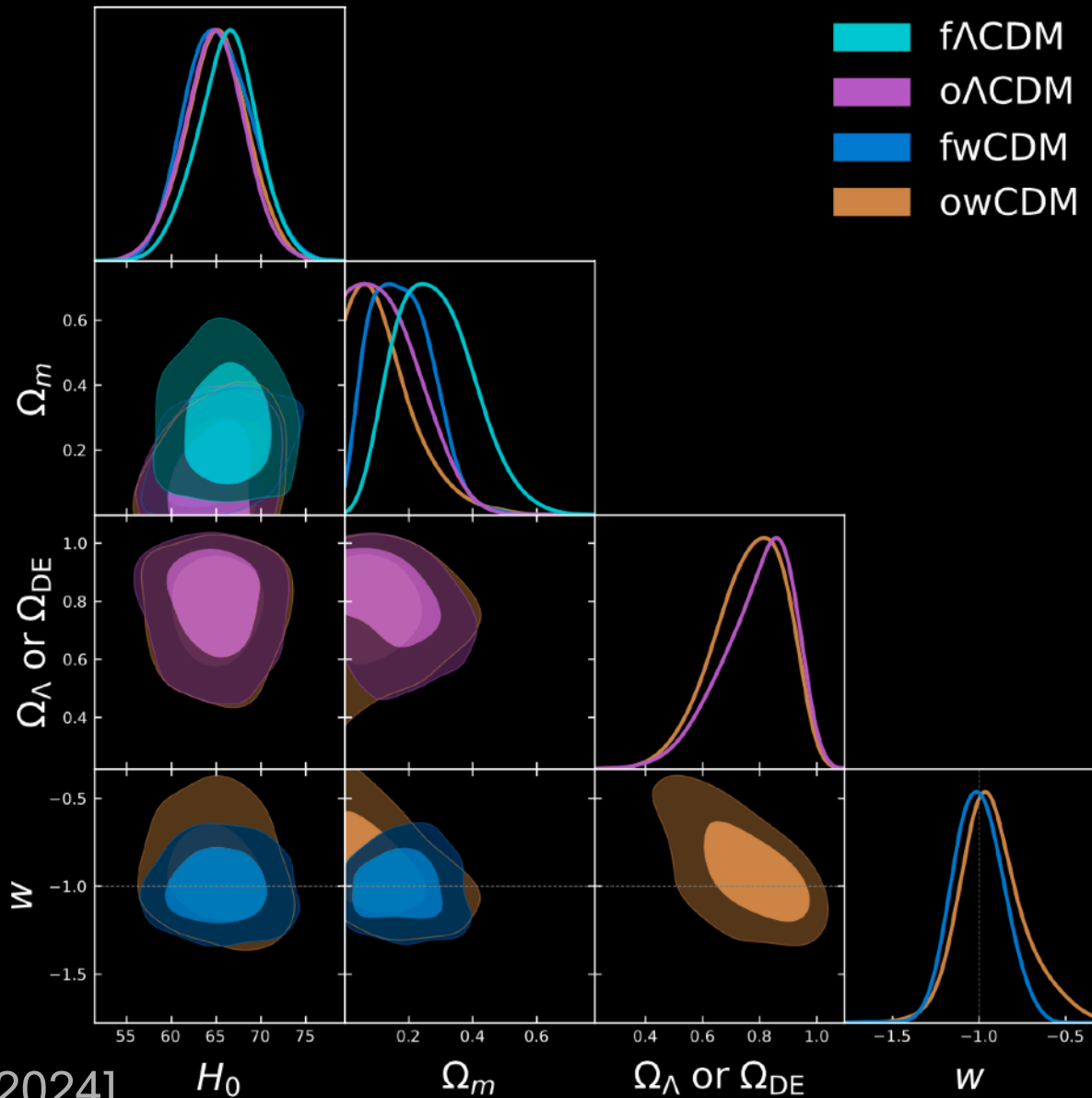


[Goobar et al. 2023;  
Pierel et al. 2023]

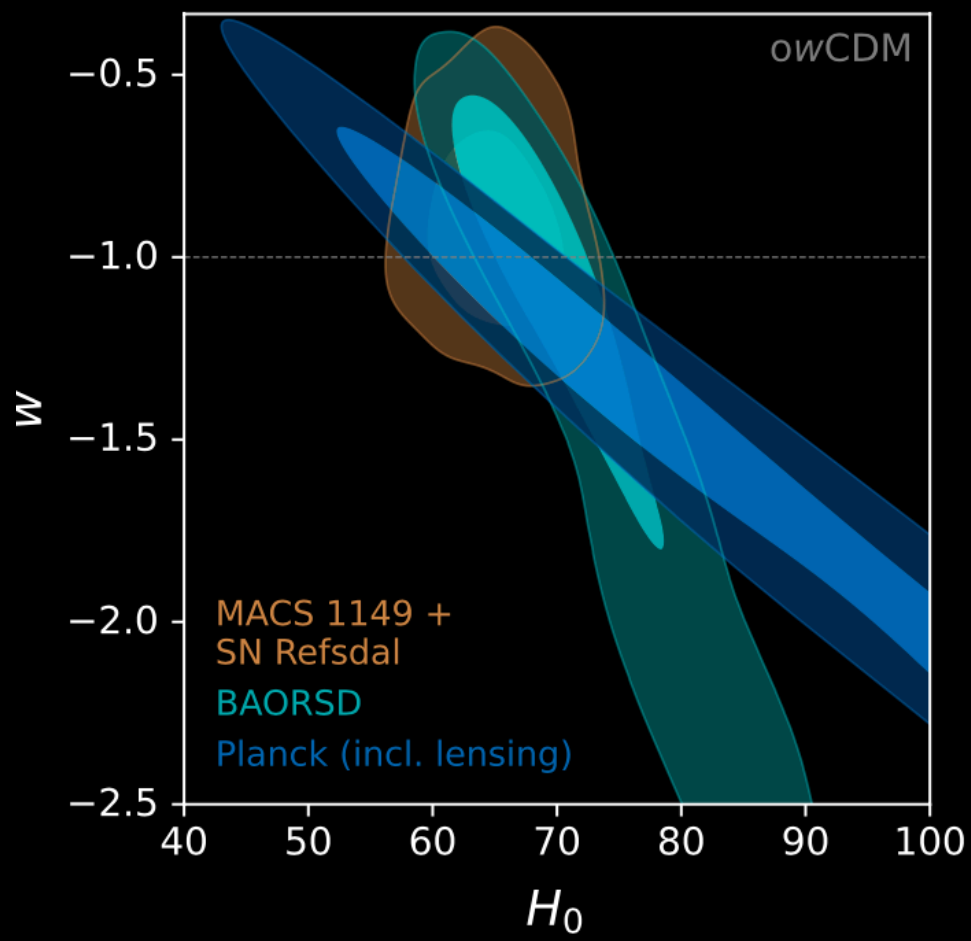
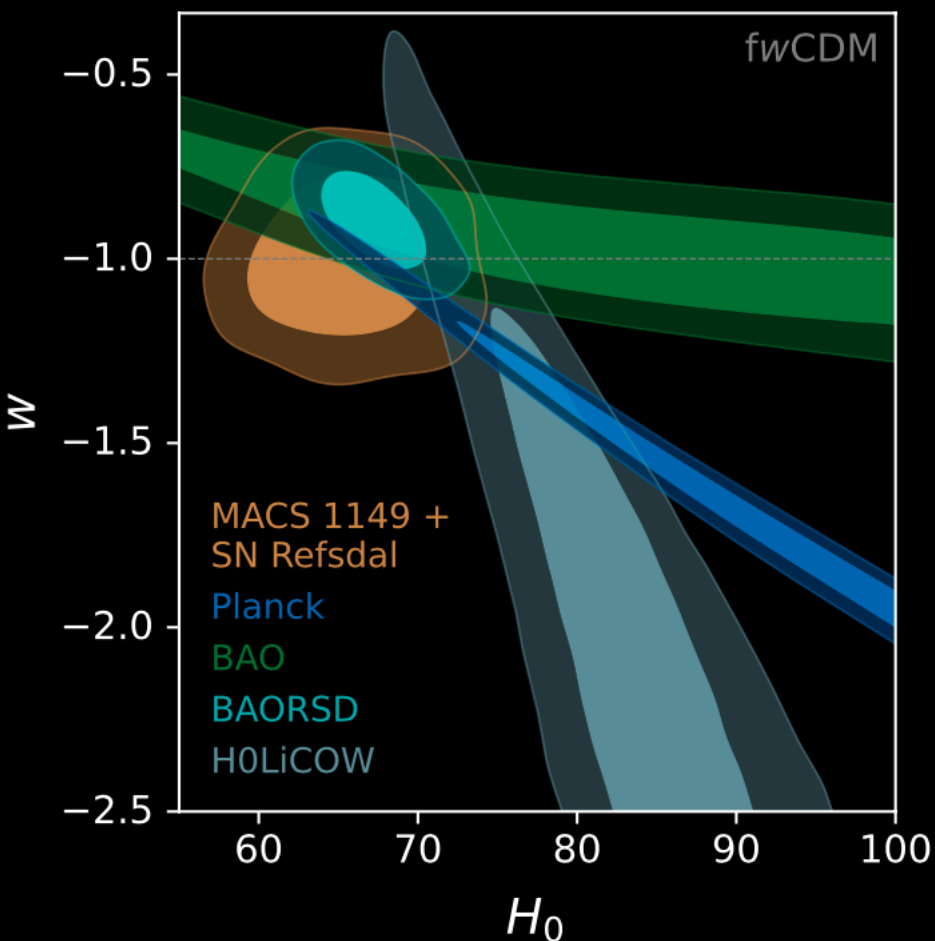
# $H_0$ from SN Refsdal in flat $\Lambda$ CDM



# $H_0$ from SN Refsdal: general cosmo. model

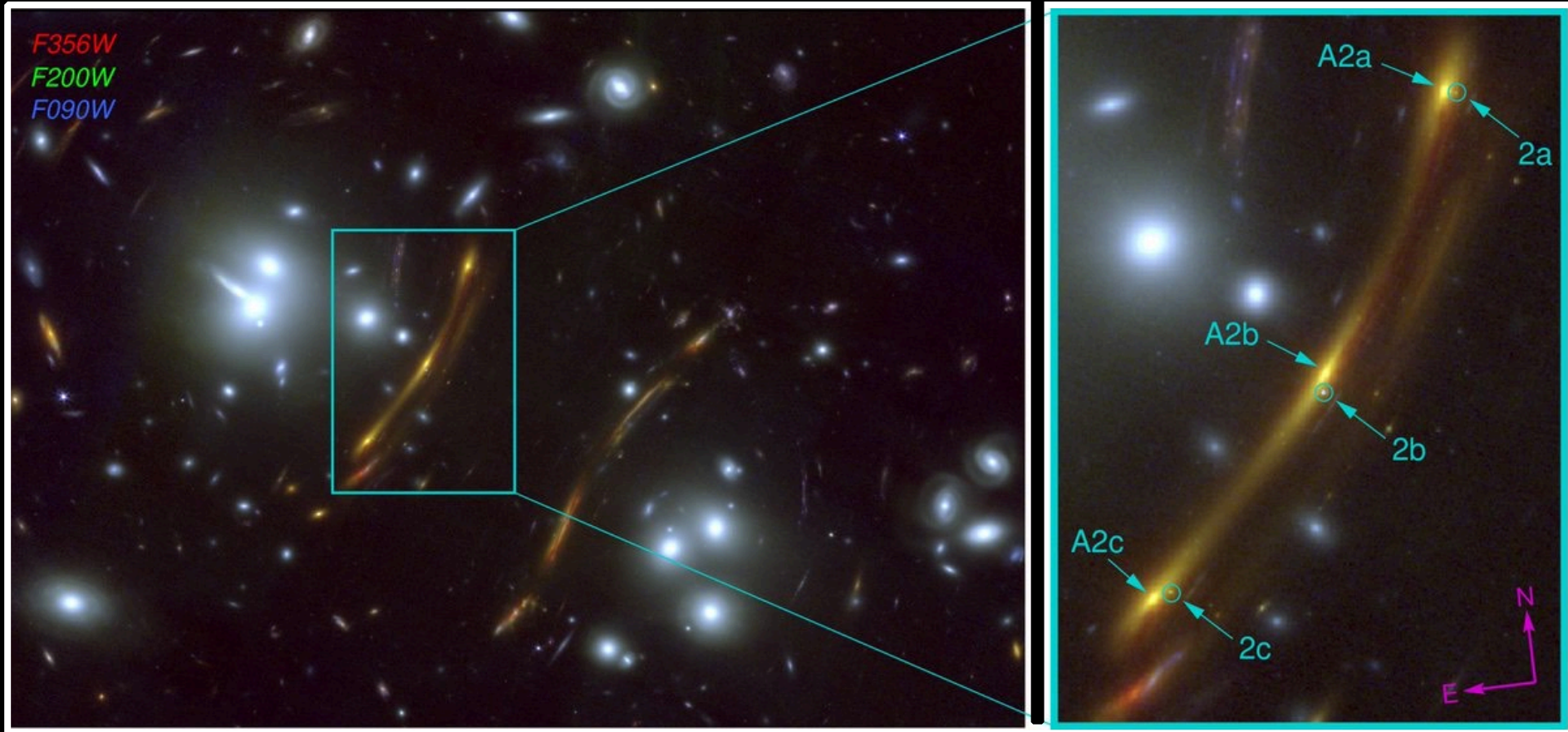


# Cosmological constraints from SN Refsdal



# 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.]



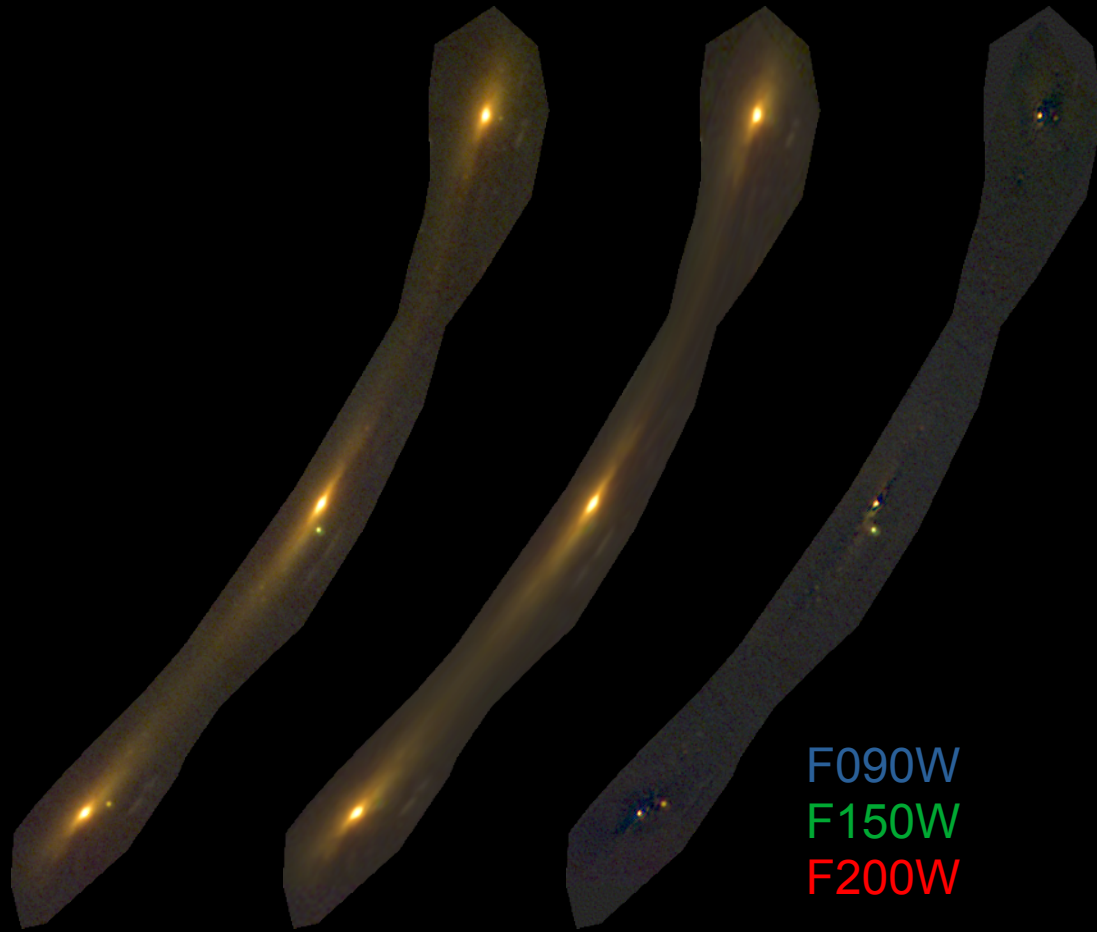
[Frye et al. 2024]

# SN H0pe: source reconstruction

observation

model

residual

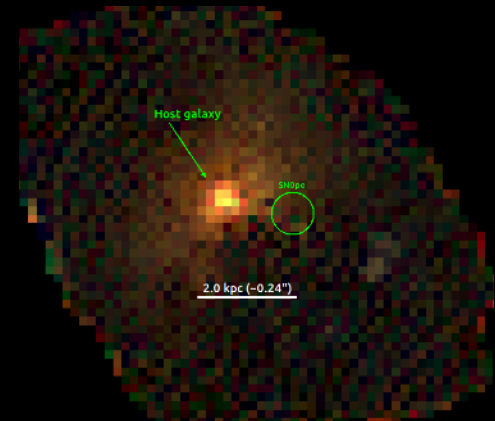


F090W  
F150W  
F200W



Gabriel Caminha

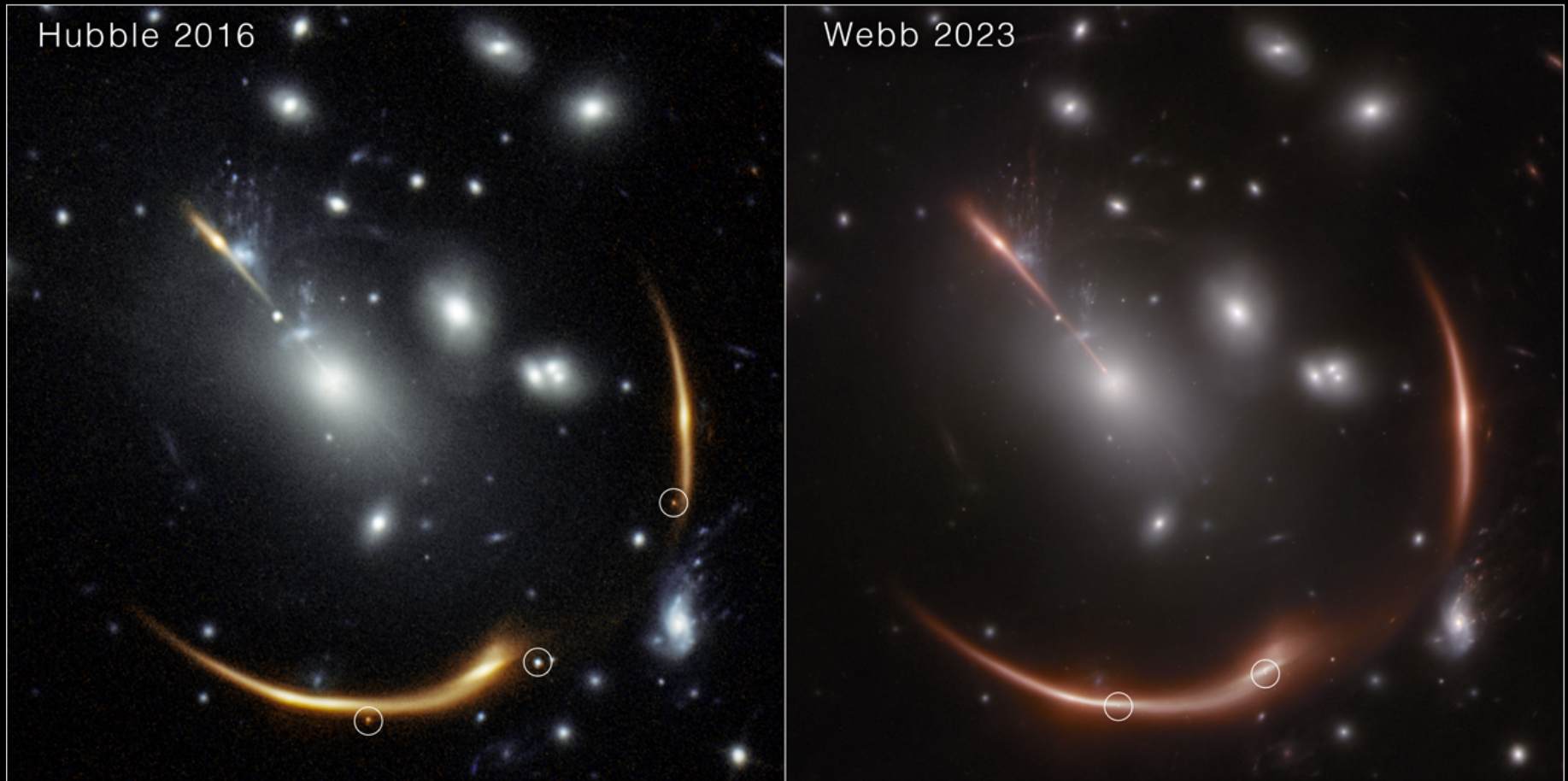
SN host galaxy reconstruction



[Caminha et al., in prep.]



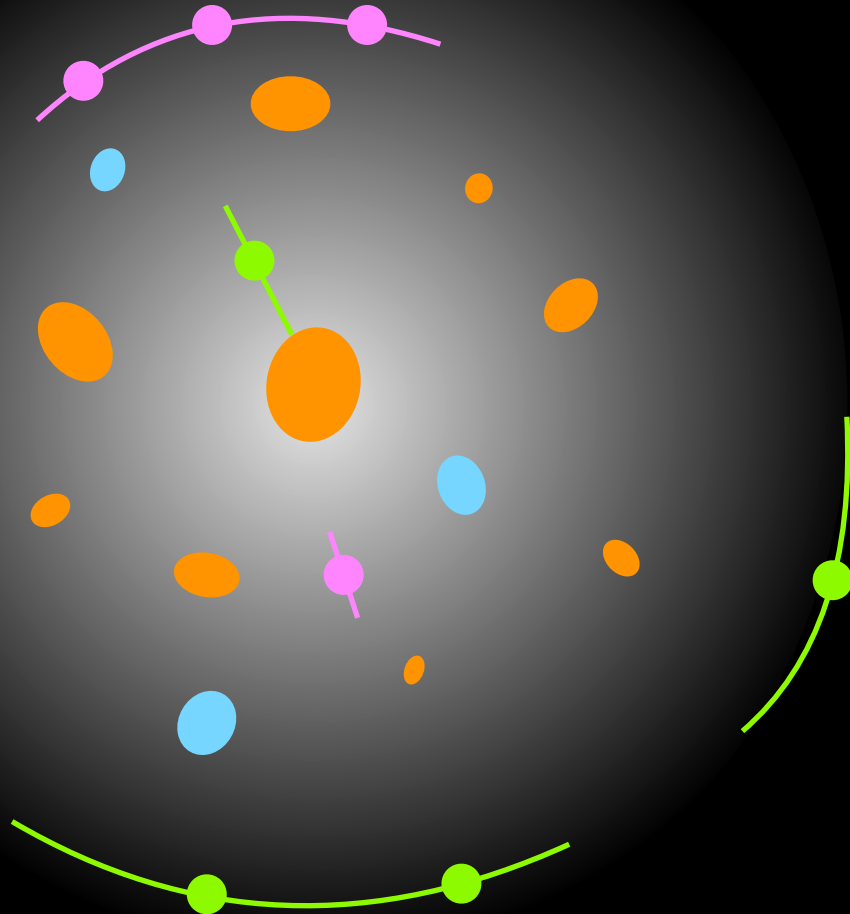
# SN Requiem and Encore!



[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

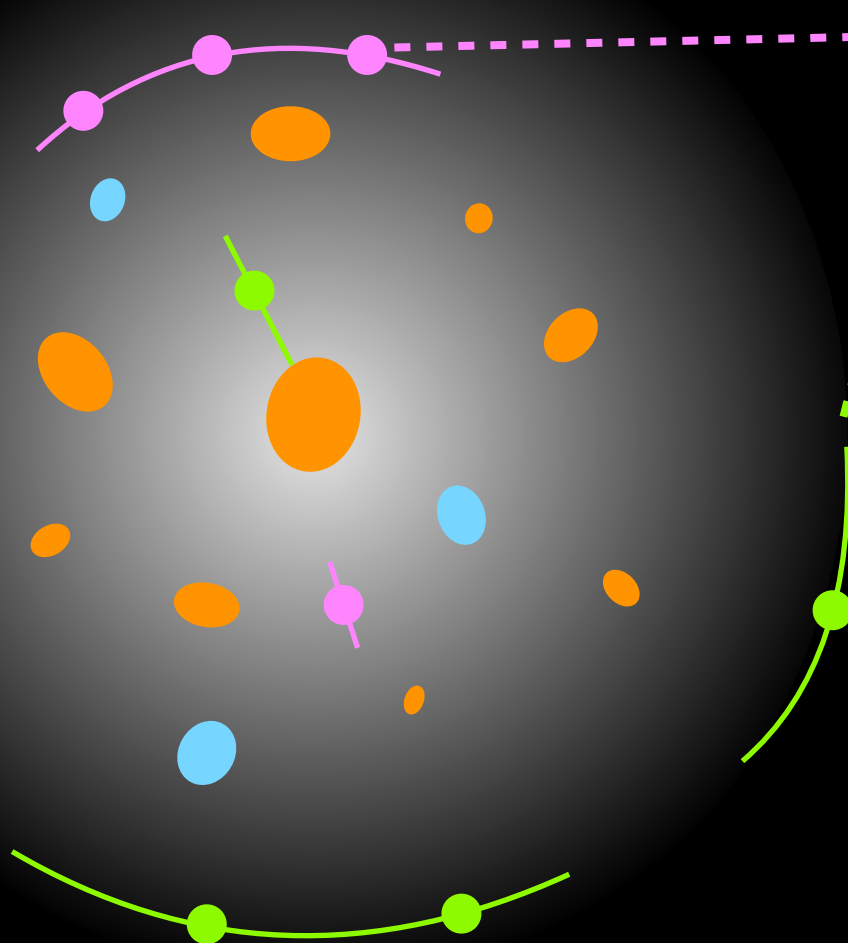
line-of-sight (LOS) galaxies

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

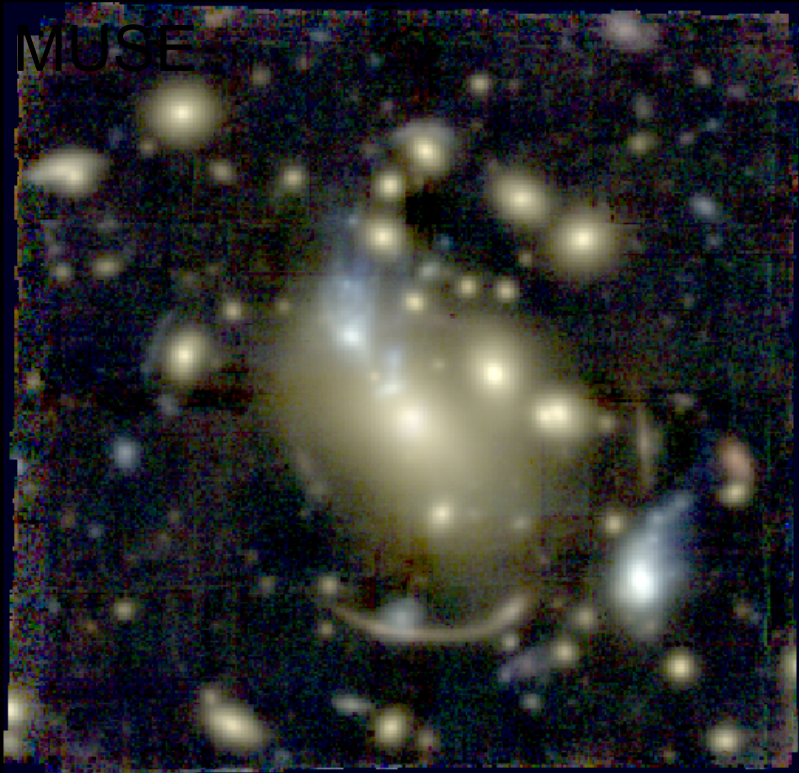
Total exposure on target 3.74 hours

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



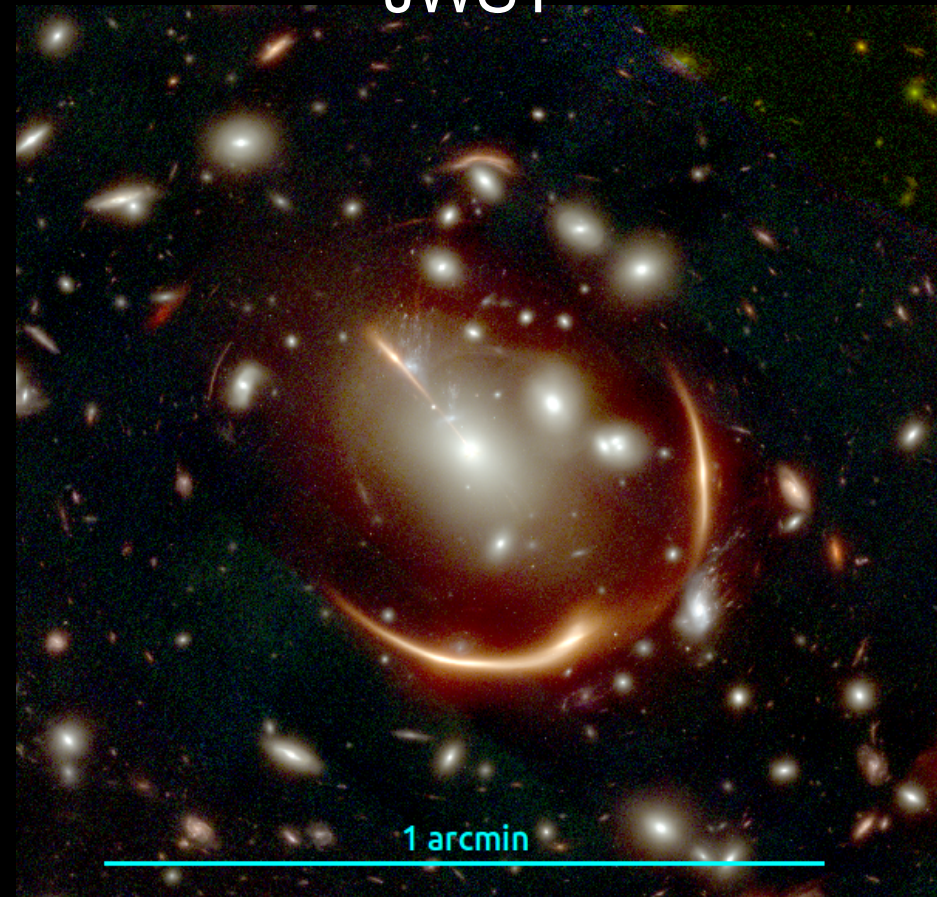
Gabriel  
Caminha

MUSE



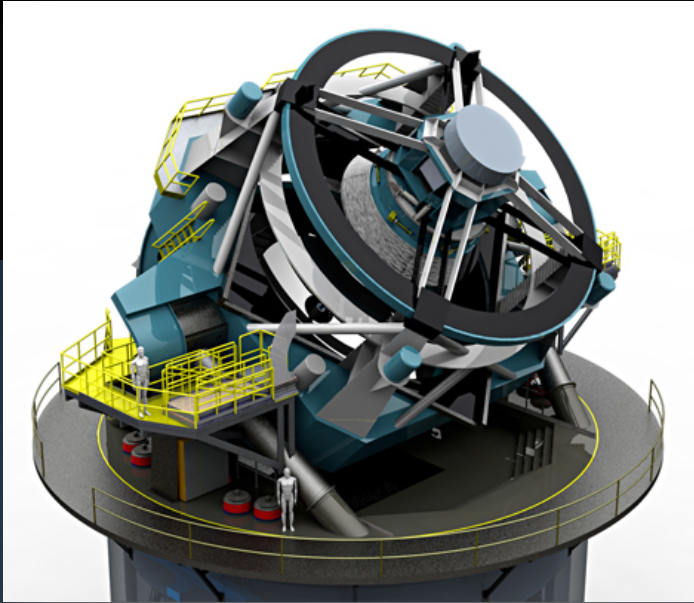
1 arcmin

JWST



1 arcmin

# 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

# HOLISMOKES!

**H**ighly **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](http://www.holismokes.org)

# HOLISMOKES

PI: S. H. Suyu

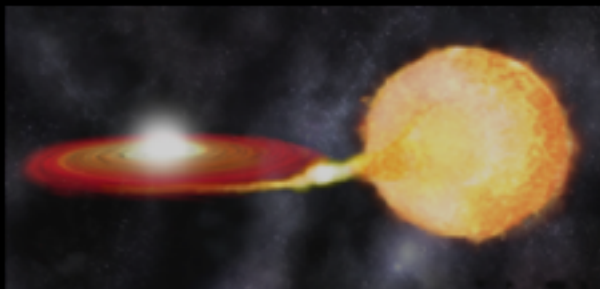


**Lensed supernovae provide great opportunities for**

1) Measuring  $H_0$

2) Constraining the progenitor of Type Ia supernova

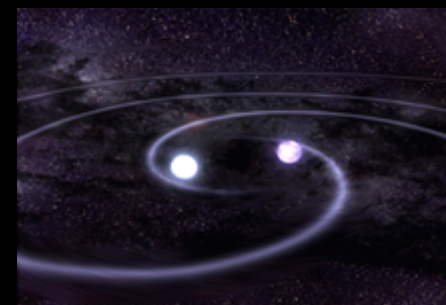
single degenerate



White dwarf (WD) accreting from non-degenerate companion

or

double degenerate



WDs merging



# HOLISMOKERS



Jana  
Grupa



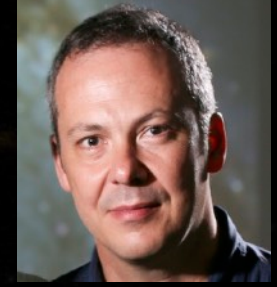
Stéphane  
Blondin



Raoul  
Cañameras



James  
Chan



Frédéric  
Courbin



Simon  
Huber



Markus  
Kromer



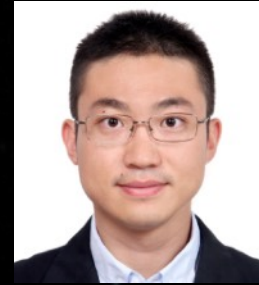
Alejandra  
Melo Melo



Uli  
Nöbauer



Stefan  
Schuldt



Yiping  
Shu



Stuart  
Sim



Dominique  
Sluse



Sherry  
Suyu (PI)



Stefan  
Taubenberger



Christian  
Vogl

## Lens Search

(Papers II, VI, VIII, XI)

## Follow-up Observations

(Paper III)

The logo for HOLISMOKES features the word "HOLI" in white, uppercase letters above the word "SMOKES" in white, uppercase letters. The letter "O" in "SMOKES" is replaced by a stylized orange smoke ring. The text is set against a background of wispy, grey smoke. A small orange dot is positioned above the "O" in "HOLI", with two thin orange lines extending downwards from it to the top of the "O" in "SMOKES".

HOLI  
SMOKES

## Time Delays

(Papers V, VII, XII)

## Lens Modelling

(Papers IV, IX, X)

# 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!