H_0 with gravitational lenses in the next decade

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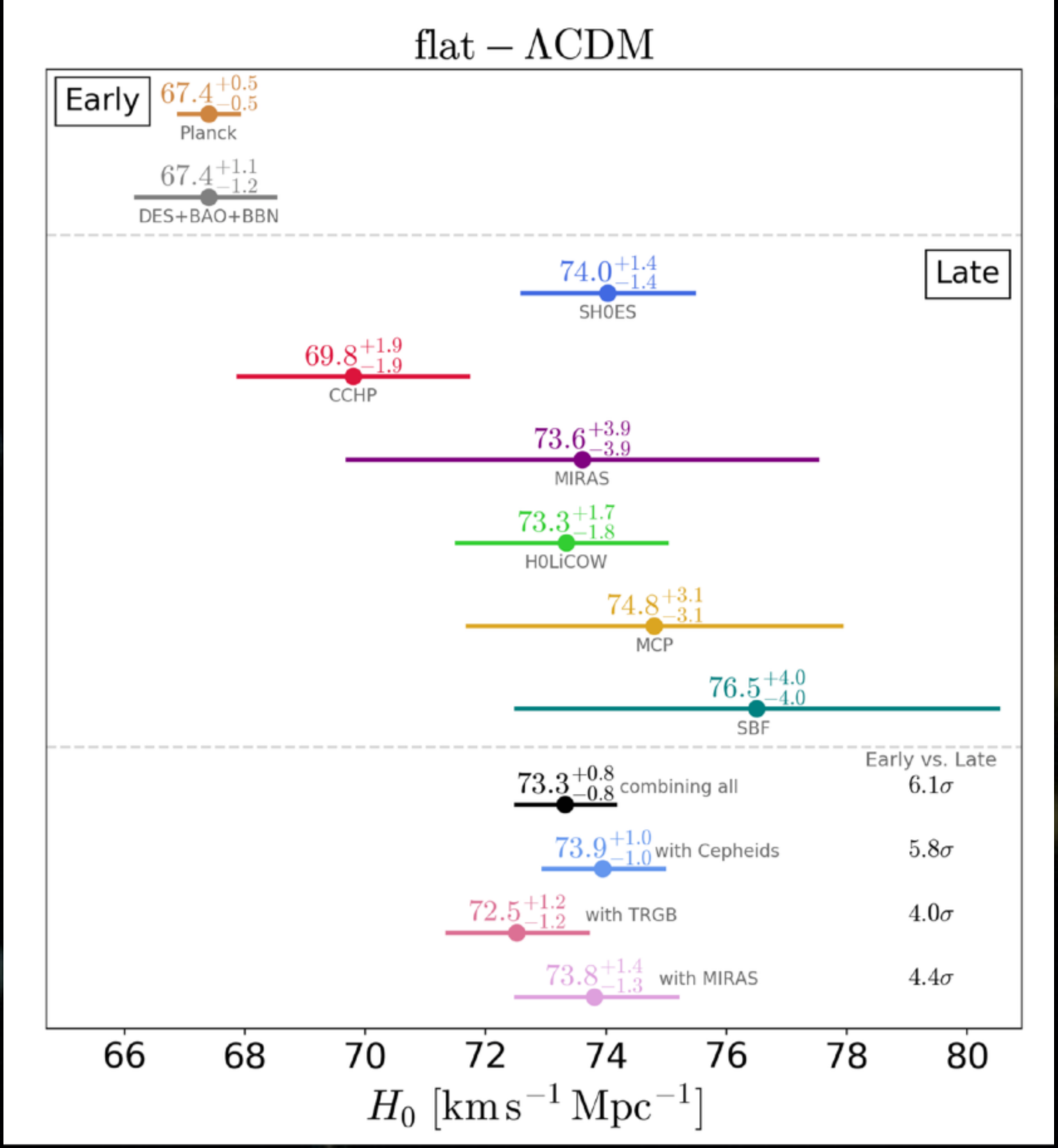
Snowmass Cosmic Frontier
CF4 Dark Energy and Cosmic Acceleration: The Modern Universe

Hubble tension



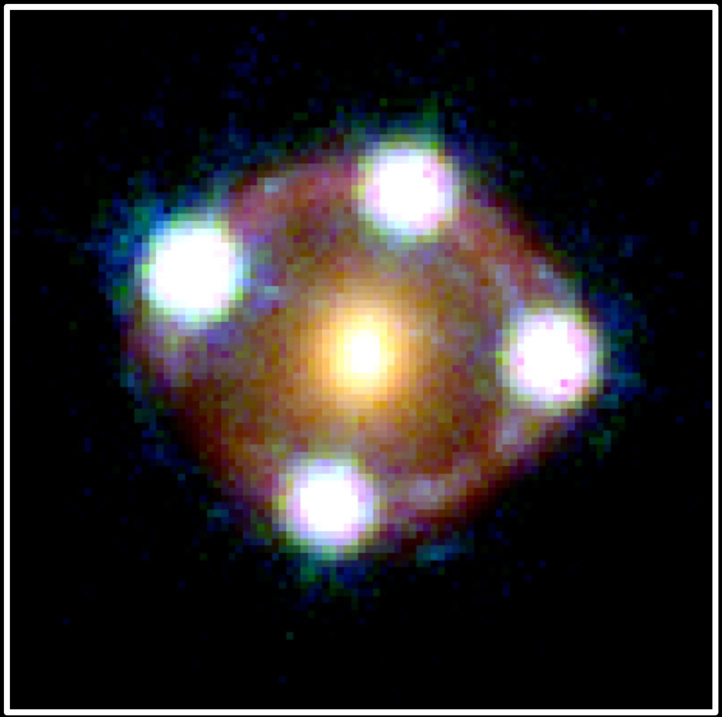
Tension? New physics?
➡ Need more precise & accurate H_0

Need independent methods to overcome systematics, especially the unknown unknowns

[Verde, Treu, Riess 2019; image credit: V. Bonvin]

Cosmology with time delays

HE0435-1223



[Suyu et al. 2017]

Time delay:

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

Time-delay distance:

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

Obtain from lens mass model

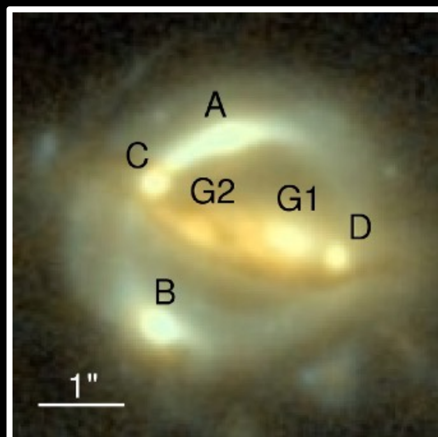
For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

Advantages:
- simple geometry & well-tested physics
- one-step physical measurement of a cosmological distance

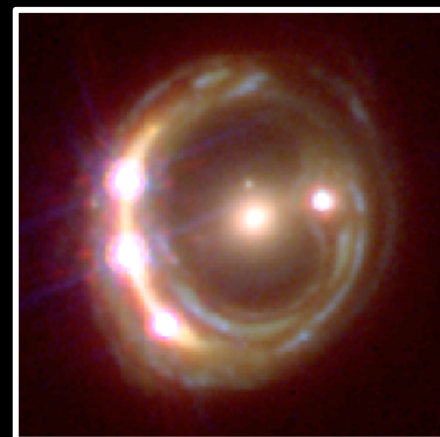
H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656

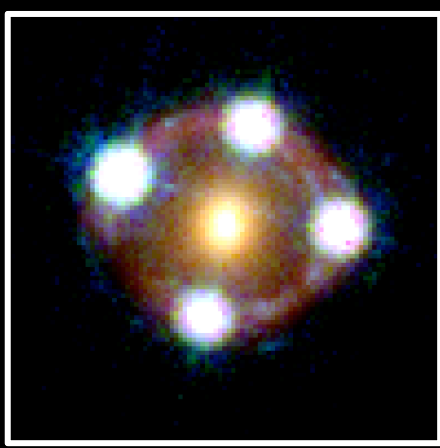


RXJ1131-1231

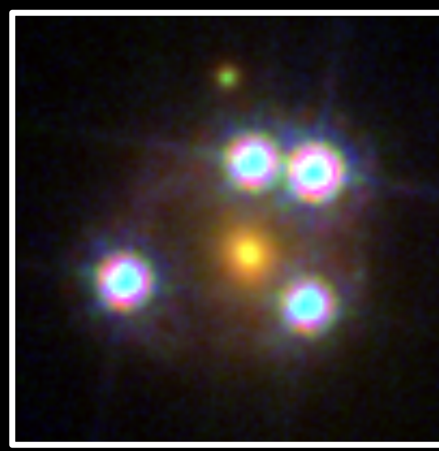


H_0 to <3.5% precision

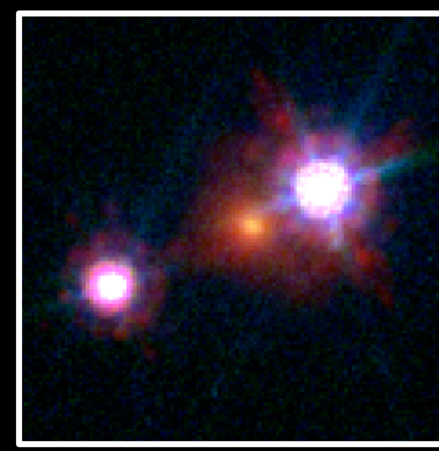
HE0435-1223



WFI2033-4723



HE1104-1805

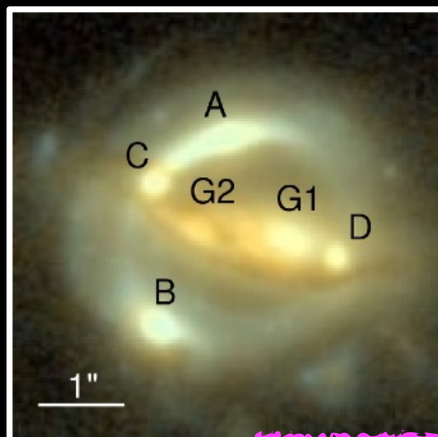


[Suyu et al. 2017]

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656



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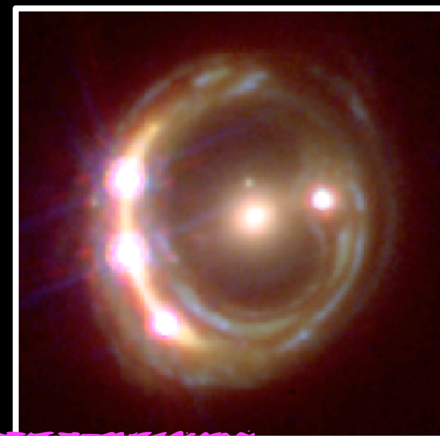

H_0 to <3.5% precision

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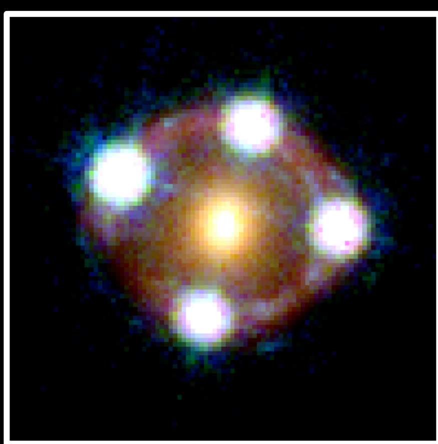

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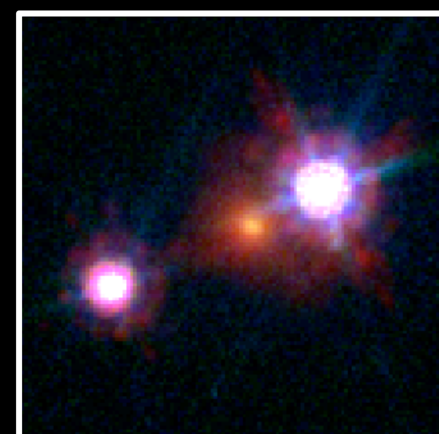
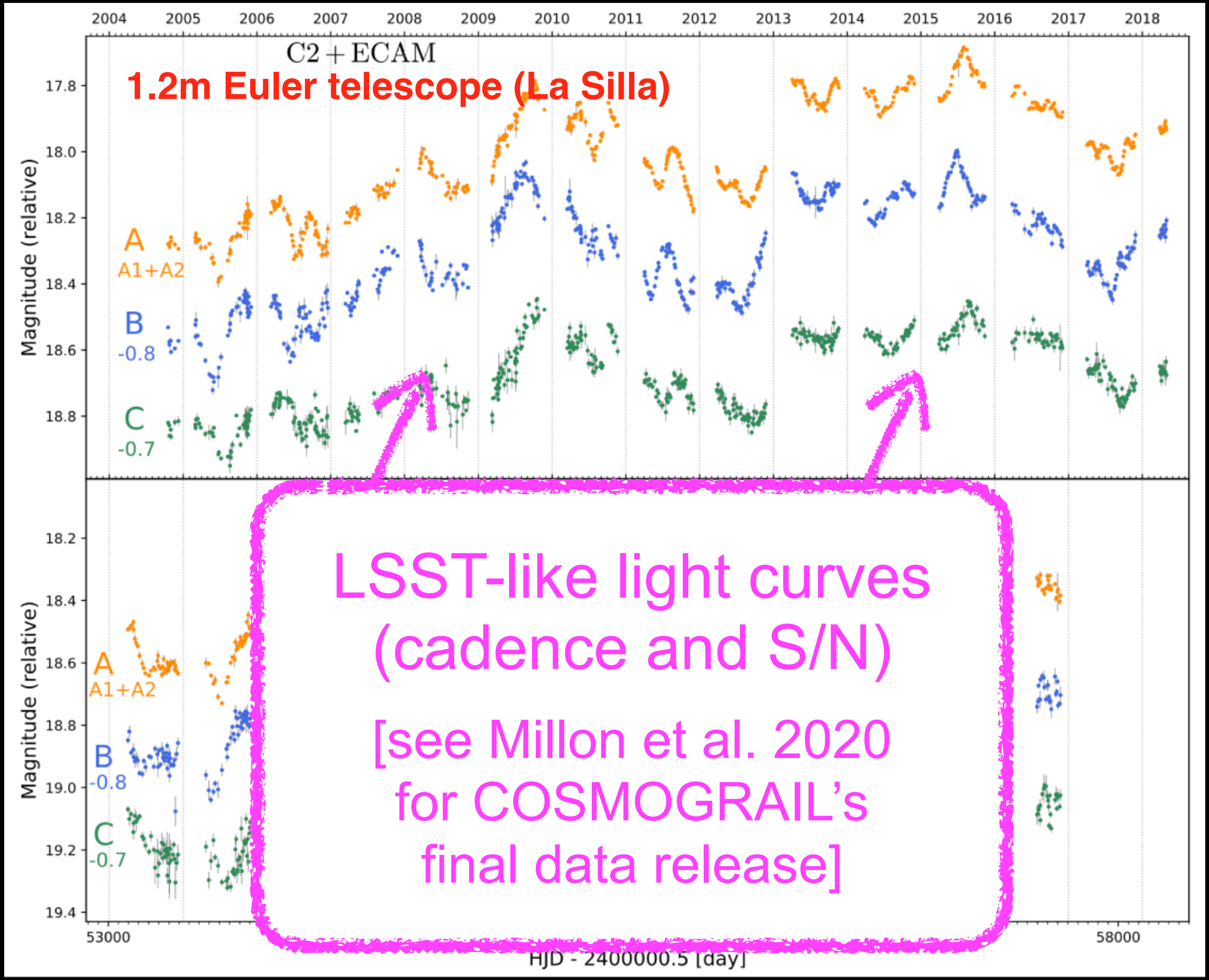


[Suyu et al. 2017]

Time Delays

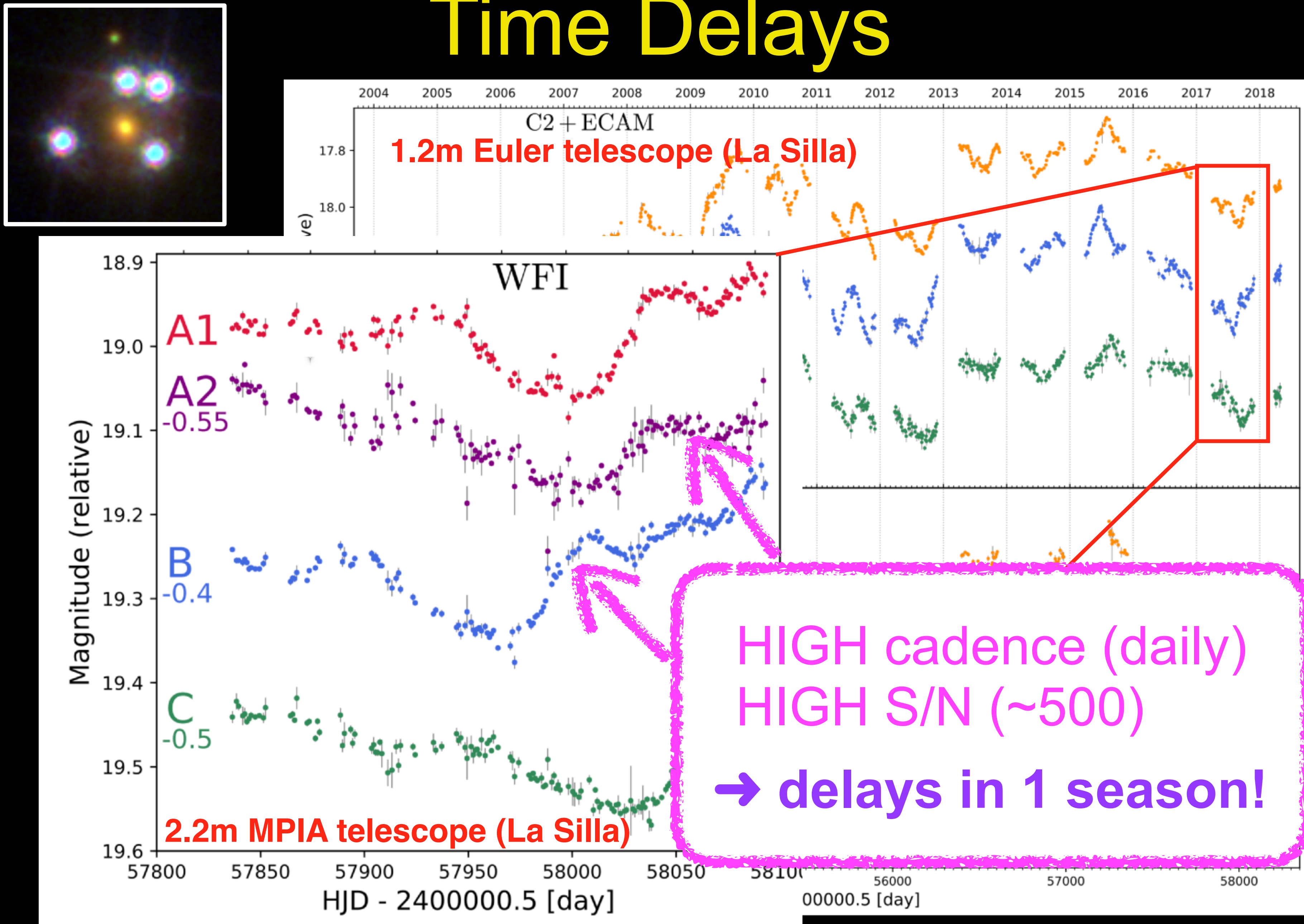
COSMOGRAIL
[Cosmological Monitoring of Gravitational Lenses]

PI: F. Courbin
G. Meylan



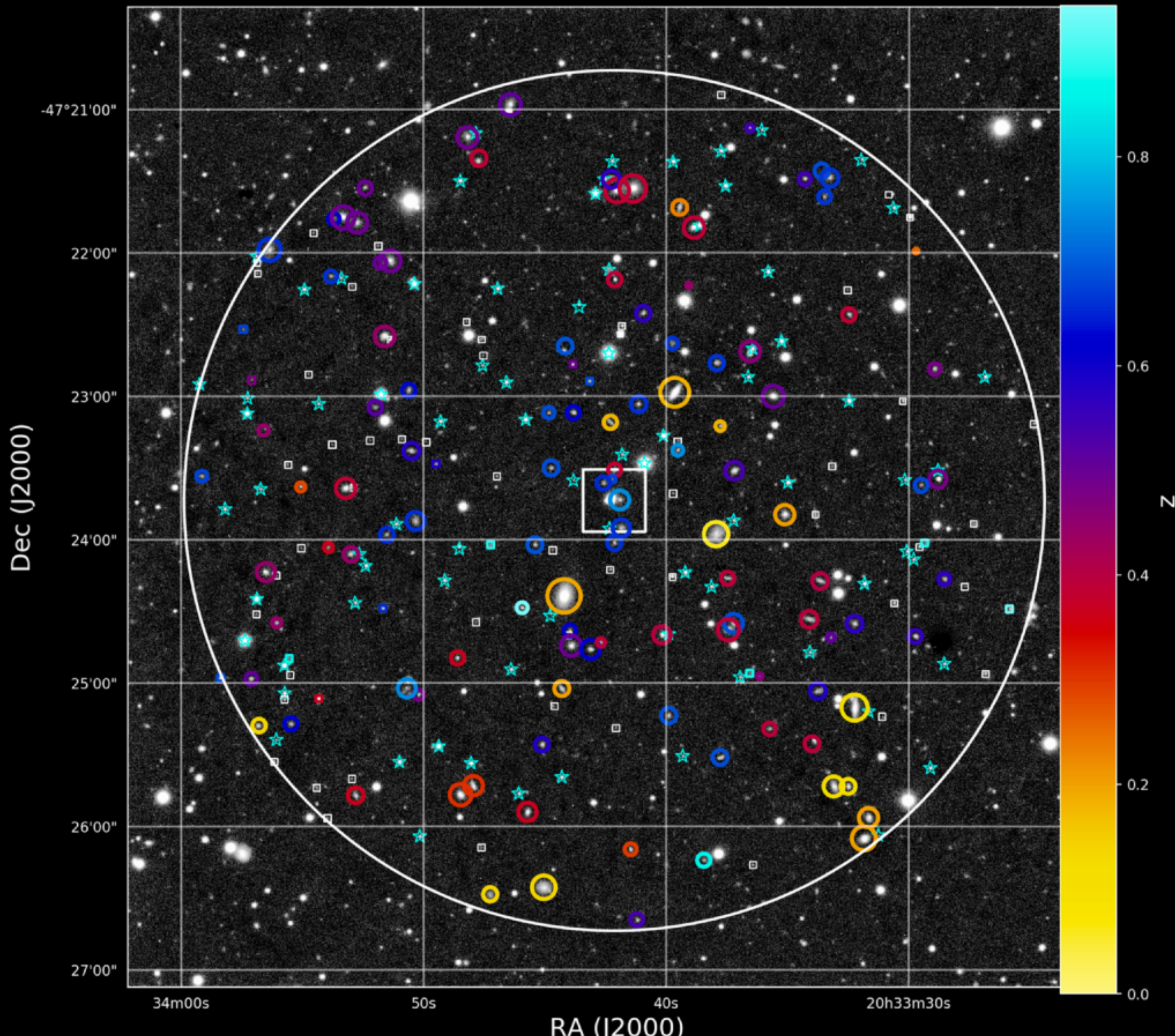
[Bonvin et al. 2019]

Time Delays



Delay (AB) with 2.1% precision [Bonvin et al. 2019]

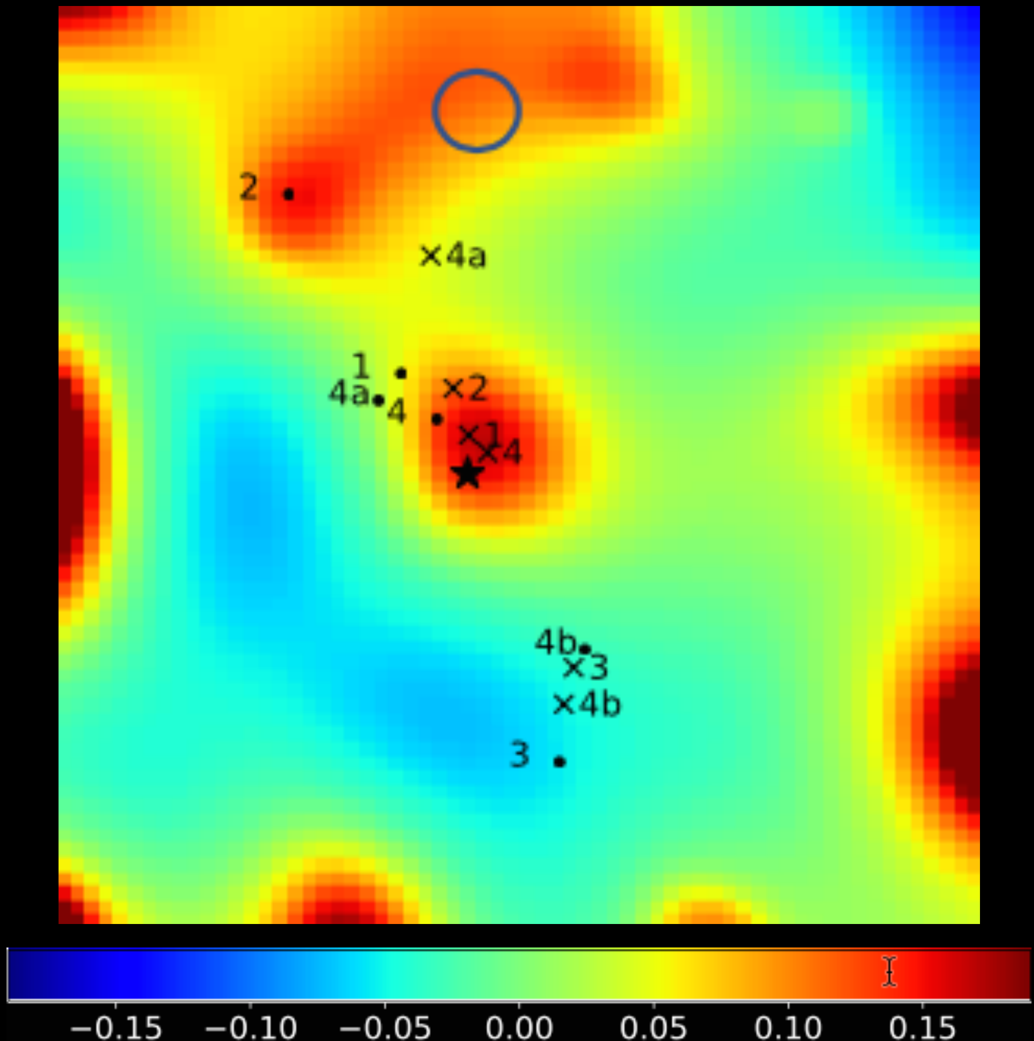
Lens environment



Wide-field spectroscopy and imaging for:

- redshift measurements and galaxy group identification [Sluse et al. 2019 (H0LiCOW X)]
- quantifying the amount of external mass along the line of sight through galaxy counts [Rusu et al 2020 (H0LiCOW XII)]

Lens environment



underdense overdense

Wide-field spectroscopy and imaging for:

- weak lensing mass maps [Tihhonova et al.2020; (H0LiCOW XI)]

LSST will provide external mass measurements from:

- weak lensing
- galaxy counts

Lens mass modeling

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

Modeling with GLEE :)

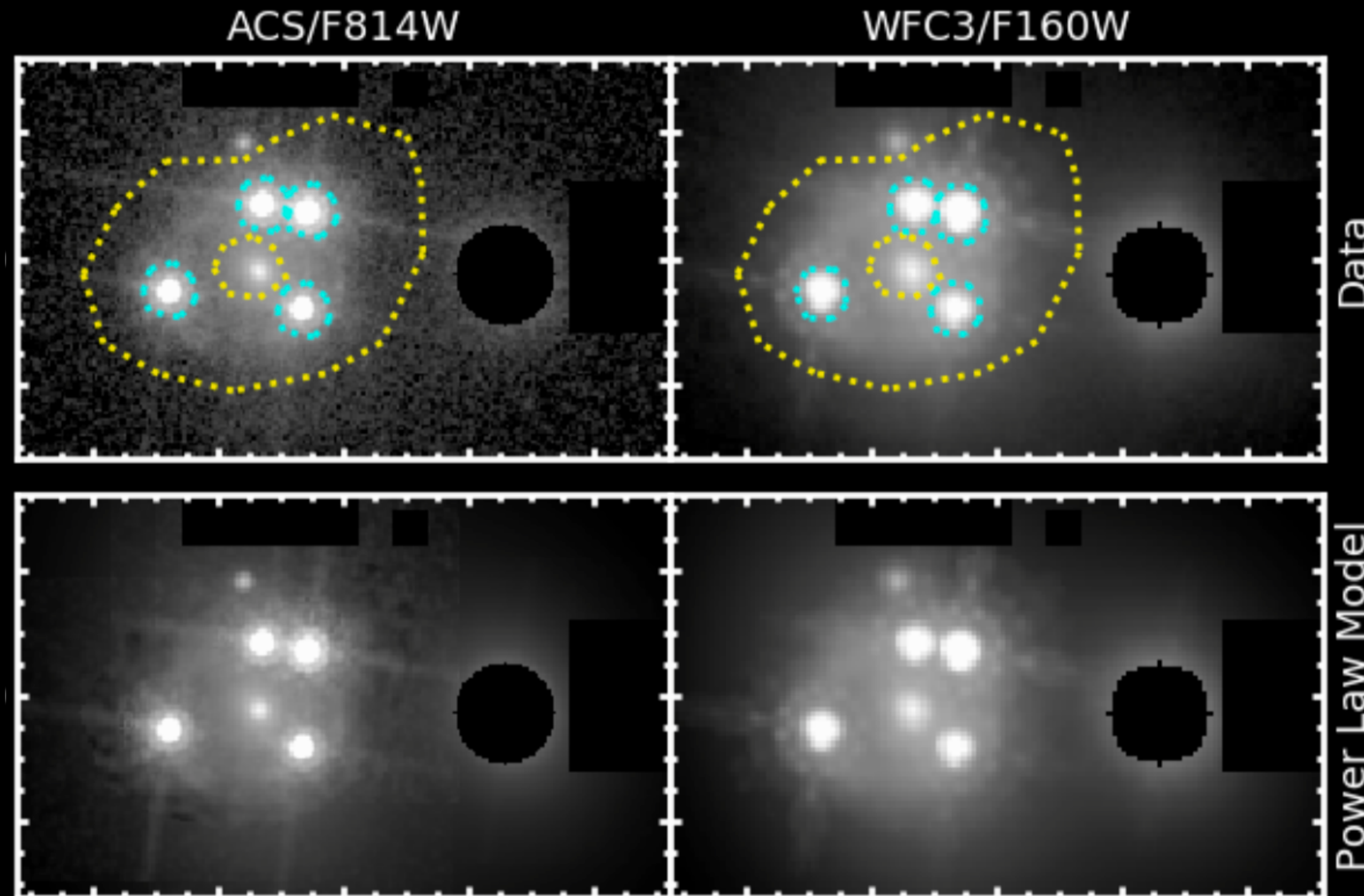
Gravitational
Lens
Efficient
Explorer

[Suyu & Halkola 2010]

and

Lenstronomy
[Birrer & Amara 2018]

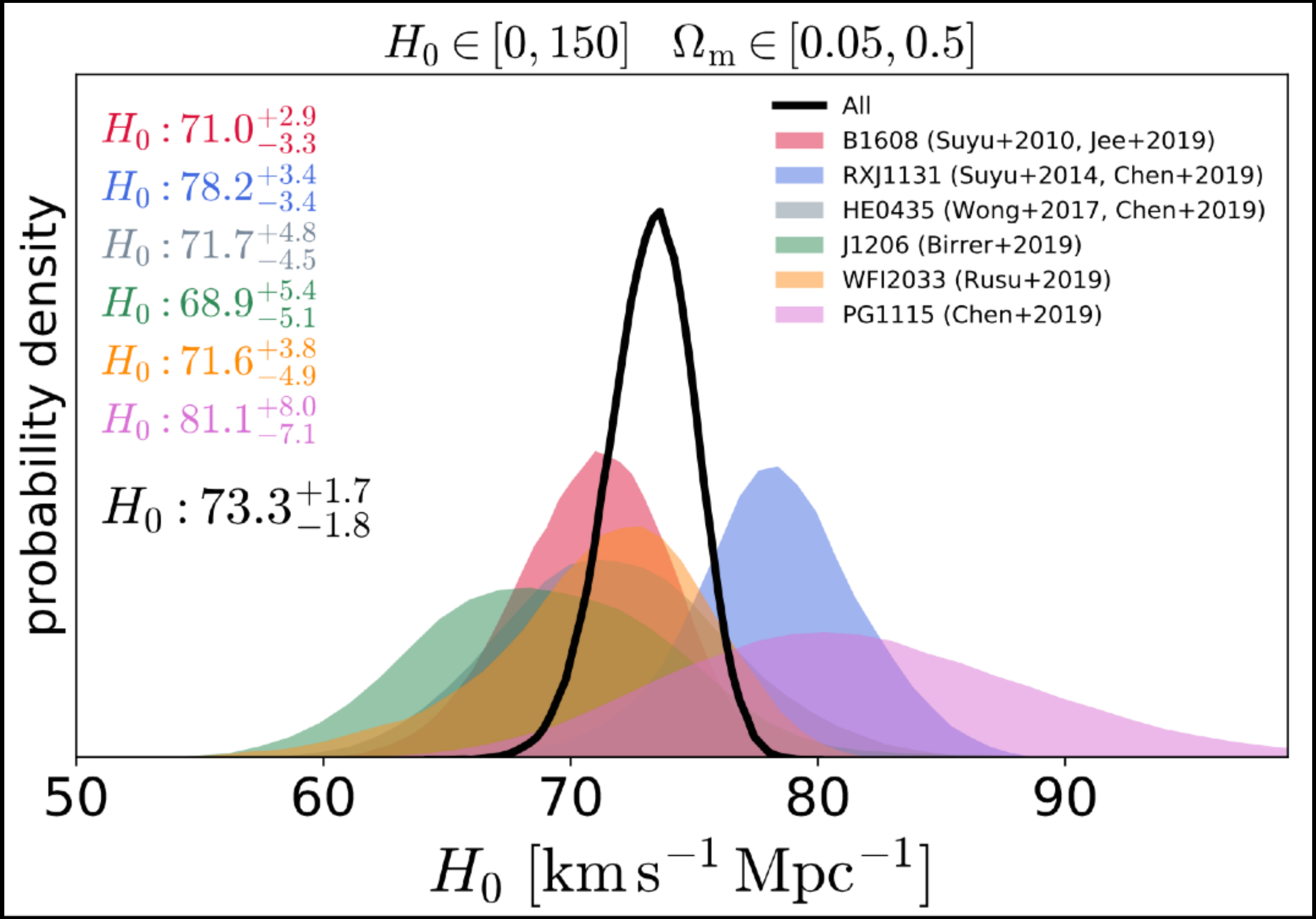
Lens reconstruction



[Rusu, Wong, Bonvin et al 2020 (H0LiCOW XII)]

H0LiCOW: H_0 from 6 strong lenses

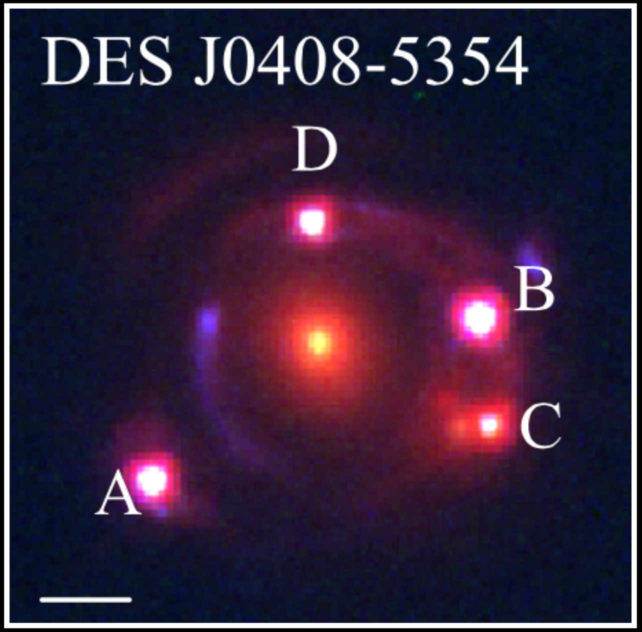
Blind analysis to avoid confirmation bias



H_0 with 2.4% precision in flat ΛCDM

[Wong, Suyu, Chen et al. 2020]

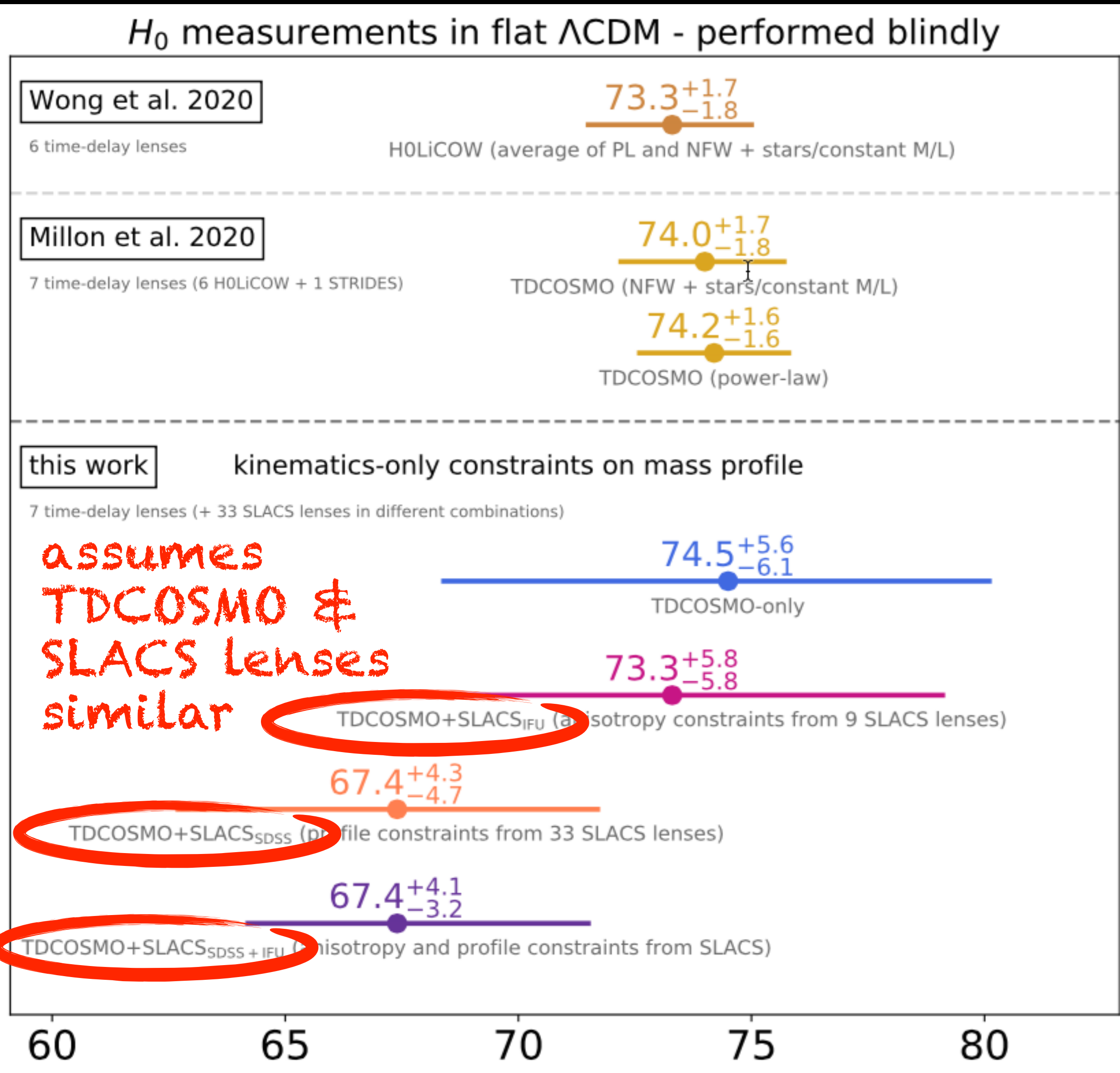
STRIDES: new lensed quasars



[Shajib et al. 2018]

- STRong-lensing Insights into the Dark Energy Survey (STRIDES) collaboration [Treu et al. 2018] has discovered ~100 new lensed quasars
- Follow-up data of the best lenses being acquired
- First STRIDES lens analysed
  - Distance and H_0 measurement from modeling [Shajib et al. 2020]
  - Environment characterisation [Buckley-Geer et al. 2020]

TDCOSMO



[Birrer et al. 2020]

TDCOSMO =
COSMOGRAIL
+ H0LiCOW
+ STRIDES + SHARP

H0LiCOW used physical and well-motivated lens mass profiles

TDCOSMO Paper IV [Birrer et al. 2020]
➜ relax assumptions on lens mass profile
➜ use lens kinematic measurements
➜ use info of galaxy properties from SLACS lens systems

TDCOSMO future

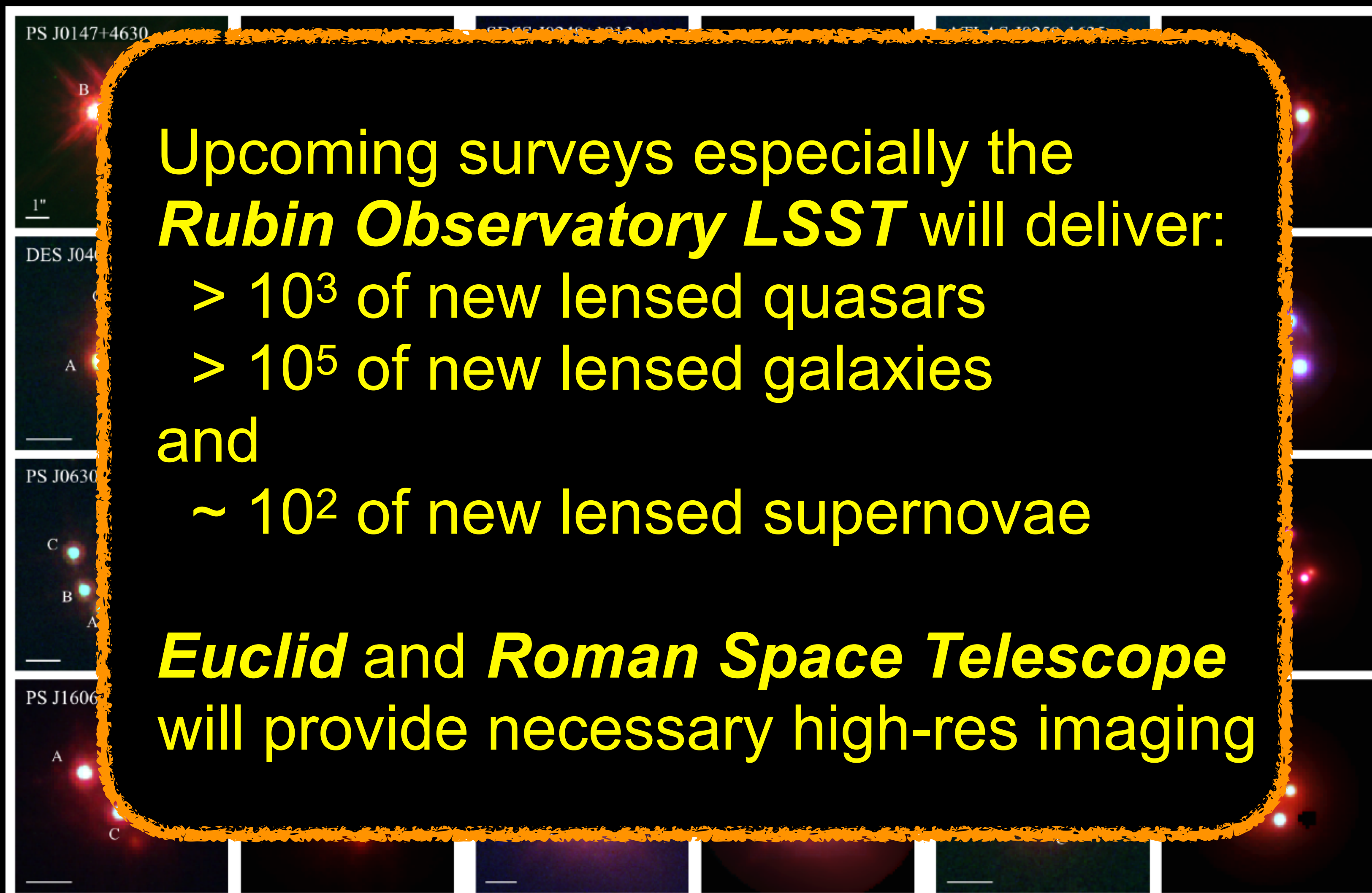
Aim: independent H_0 measured with 1% uncertainty

- More lensed quasars with time-delay measurements and high-resolution imaging/spectroscopy
  ➜ ~40 lensed quasars
  (~10 with high-quality spatially resolved kinematics)

- Large population of lensed galaxies to inform us about the mass profiles of galaxies
  ➜ ~100s lensed galaxies

New lenses imaged with HST

New lens systems discovered in DES, Pan-STARRS, SDSS, ATLAS:



Upcoming surveys especially the ***Rubin Observatory LSST*** will deliver:

- $> 10^3$ of new lensed quasars
- $> 10^5$ of new lensed galaxies

and

- $\sim 10^2$ of new lensed supernovae

Euclid and ***Roman Space Telescope*** will provide necessary high-res imaging

[Shajib et al. 2018]

HOLISMOKES

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

PI: S. H. Suyu

European Research Council
Established by the European Commission

Lensed supernovae provide great opportunities for

1) Measuring H_0, complementary to lensed quasars
2) Constraining the progenitor of Type Ia supernova

With hundreds of lensed supernovae expected from LSST

➜ **follow-up observations necessary for both cosmology and supernova progenitor studies**

[Suyu, Huber, Cañameras et al. 2020]

High priority: Imager on a 4m telescope

- Efficient time-delay measurement (i.e., within 1 season) for cosmology require ***dedicated high cadence and high S/N monitoring***, as demonstrated by COSMOGRAIL
  - LSST does not have sufficient cadence and S/N

- Desired specs:
  - good seeing to resolve the multiple lensed images (ideally better than 0.8”)
  - multi-band to mitigate/study microlensing of lensed SNe and quasars
    (optical + J + H)
  - high-quality camera and image, with at least 10’x10’ FoV (to monitor both galaxy-scale and cluster-scale lenses)

Complementary facilities for spectroscopy (funded by other sources)

- Spectroscopy of lens systems needed to:
  - measure lens/source redshifts
  - measure redshifts of neighboring galaxies

- Complementary spectroscopic facilities include:
  - DESI
  - 4MOST
  - MOONS
  - PFS
  - Blue MUSE

Development of Imagers and IFU with AO (funded by other sources)

- Accurate and precise lens mass modeling require:
  - Spatially-resolved stellar kinematics of lens galaxies
  - High angular resolution images

- early 2020s:
  - optical spectroscopy: MUSE@VLT; KCWI or MOS @Keck
  - high resolution imaging: NIRCAM@JWST; OSIRIS@Keck
  - spatially resolved kinematics: NIRSPEC@JWST; OSIRIS/ LIGER @ Keck All-Sky Precision Adaptive Optics

- late 2020s/2030s
  - optical spectroscopy: ELTs. Within US-ELT Program: WFOS@TMT and GMACS@GMT
  - high resolution imaging: ELTs. Within US-ELT Program: IRIS@TMT GMTIFS@GMT
  - spatially resolved kinematics: ELTs. Within US-ELT Program: IRIS@TMT and GMTIFS@GMT

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TDCOSMO

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Summary

- Time-delay lenses are an independent and competitive probe of cosmology
- Euclid, LSST and Roman Space Telescope expected to deliver thousands of lensed quasars and hundreds of lensed supernovae
- Follow-up observations crucial for time-delay cosmography
  - **Dedicated 4m-telescope with optical/NIR multi-band (7-10) for daily monitoring of lenses**
  - Other ancillary data from complementary spectroscopic and imaging facilities