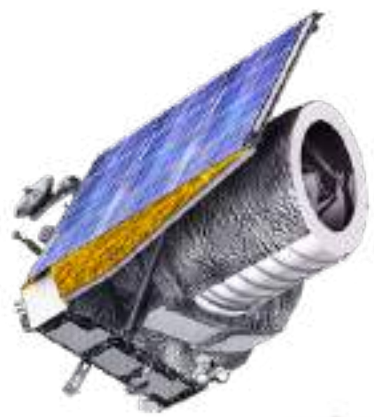
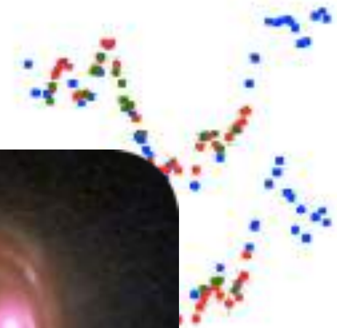
Time Delay Cosmography with Strongly Lensed quasars

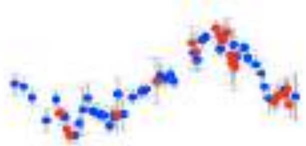
Frédéric Courbin (EPFL, Switzerland)
For the TDCOSMO collaboration













COSMICLENS

European Research Council
Established by the European Commission

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FONDS NATIONAL SUISSE
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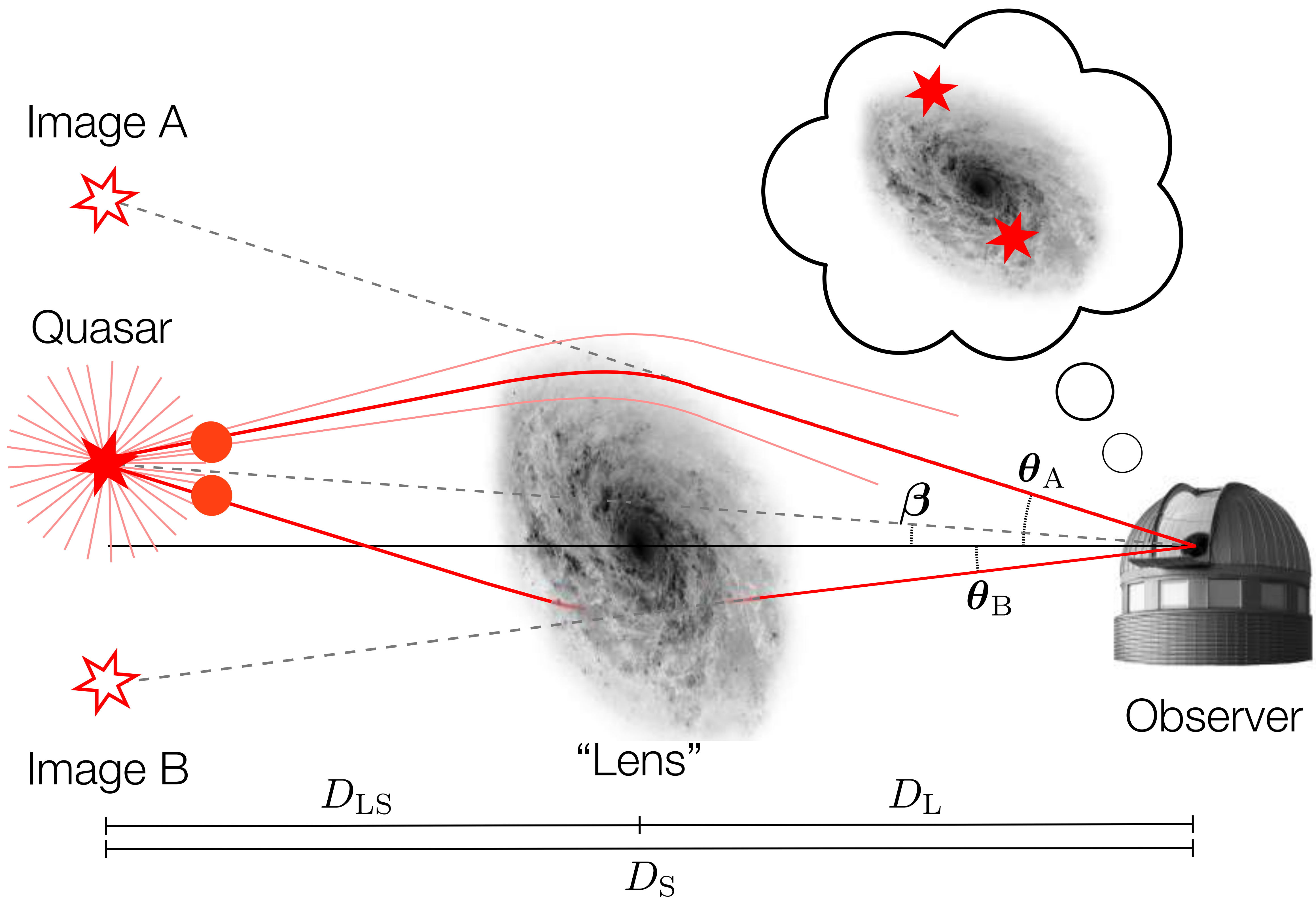
SWISS NATIONAL SCIENCE FOUNDATION

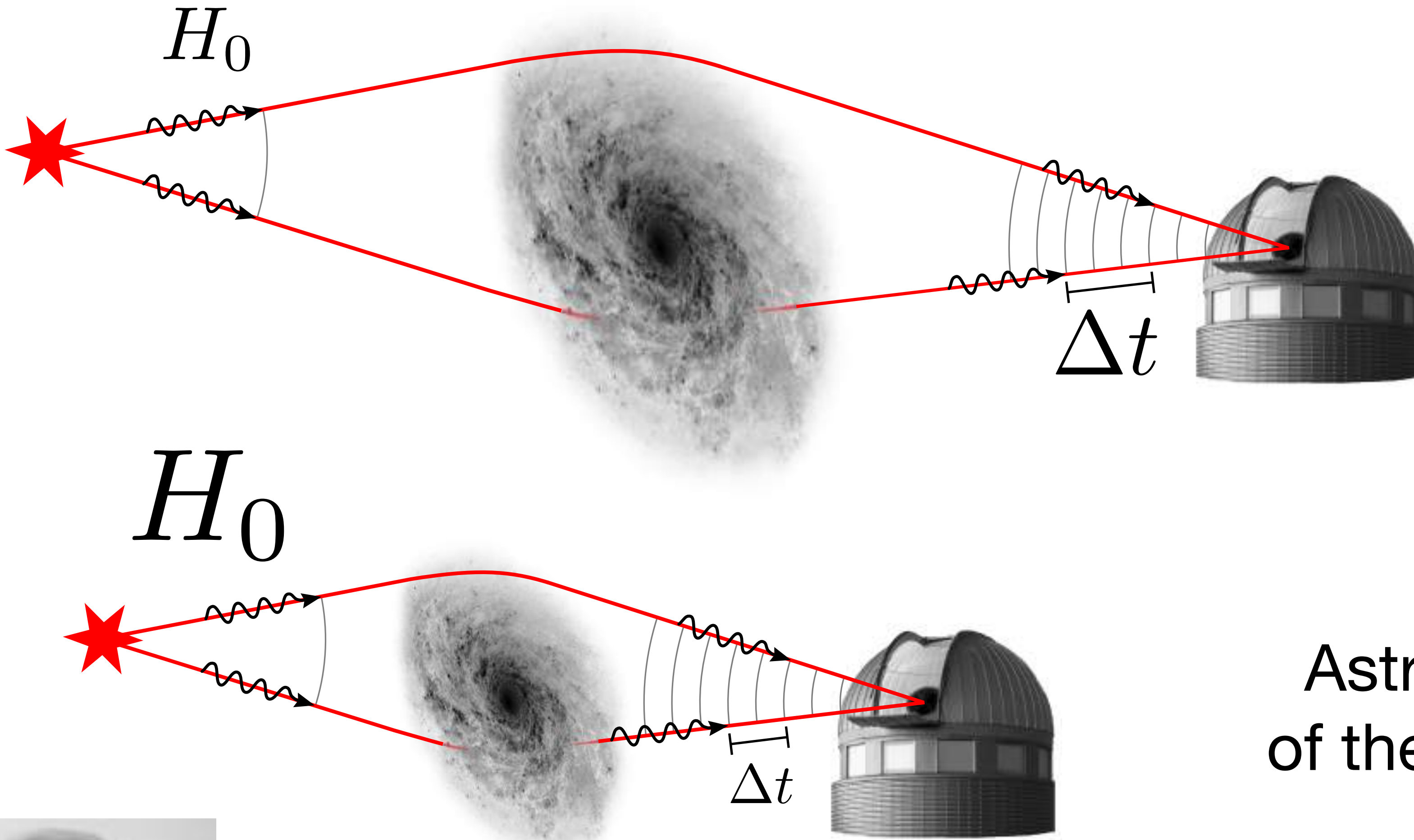
EPFL
Laboratoire d'astrophysique http://lastro.epfl.ch
Ecole Polytechnique Fédérale de Lausanne (EPFL)

CosmoVeese - Lisbon - May 2023

Time Delays in Strongly Lensed Quasars



Time Delays Measure the Hubble Constant H_0



Lens potential at image positions

Source position (unconstrained)

Astrometry of the images

$$\Delta t = \frac{1+z_{\mathrm{L}}}{c}\underbrace{\frac{D_{\mathrm{L}} D_{\mathrm{S}}}{D_{\mathrm{LS}}}}_{D_{\Delta t}\propto 1/H_0}\cdot\Delta\left(\frac{1}{2}|\vec{\theta}-\vec{\beta}|^2-\psi(\vec{\theta})\right)$$

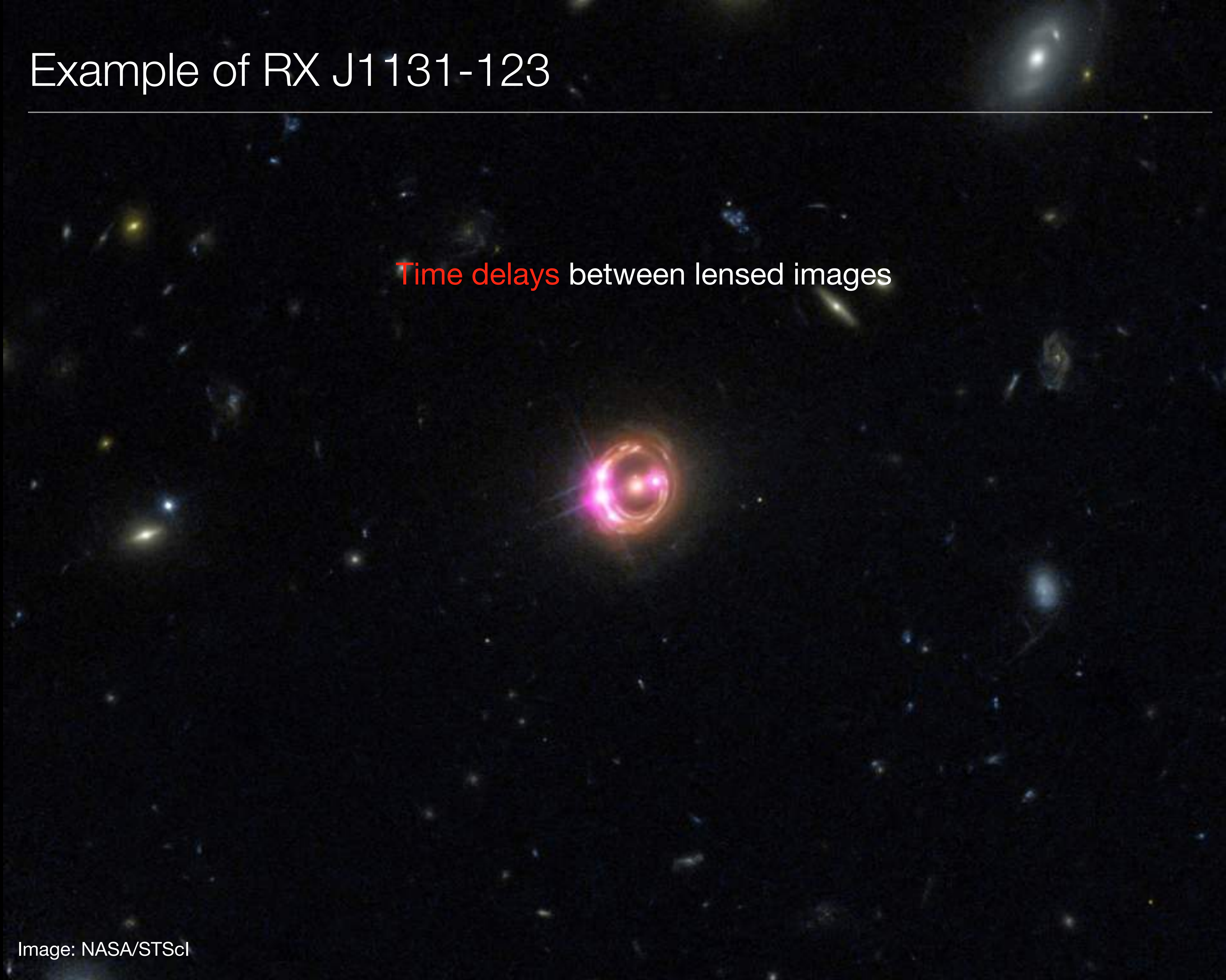
(1964)

Time delays provide a *single-step* and *independent* constraint on H_0.

Time Delay Cosmography Collaborations

Now grouped as TDCOSMO : Time Delay COSMOgraphy (tdcosmo.org)
See also ERC project COSMICLENS (cosmiclens.epfl.ch)

Example of RX J1131-123



Time delays between lensed images

Image: NASA/STScI

Example of RX J1131-123

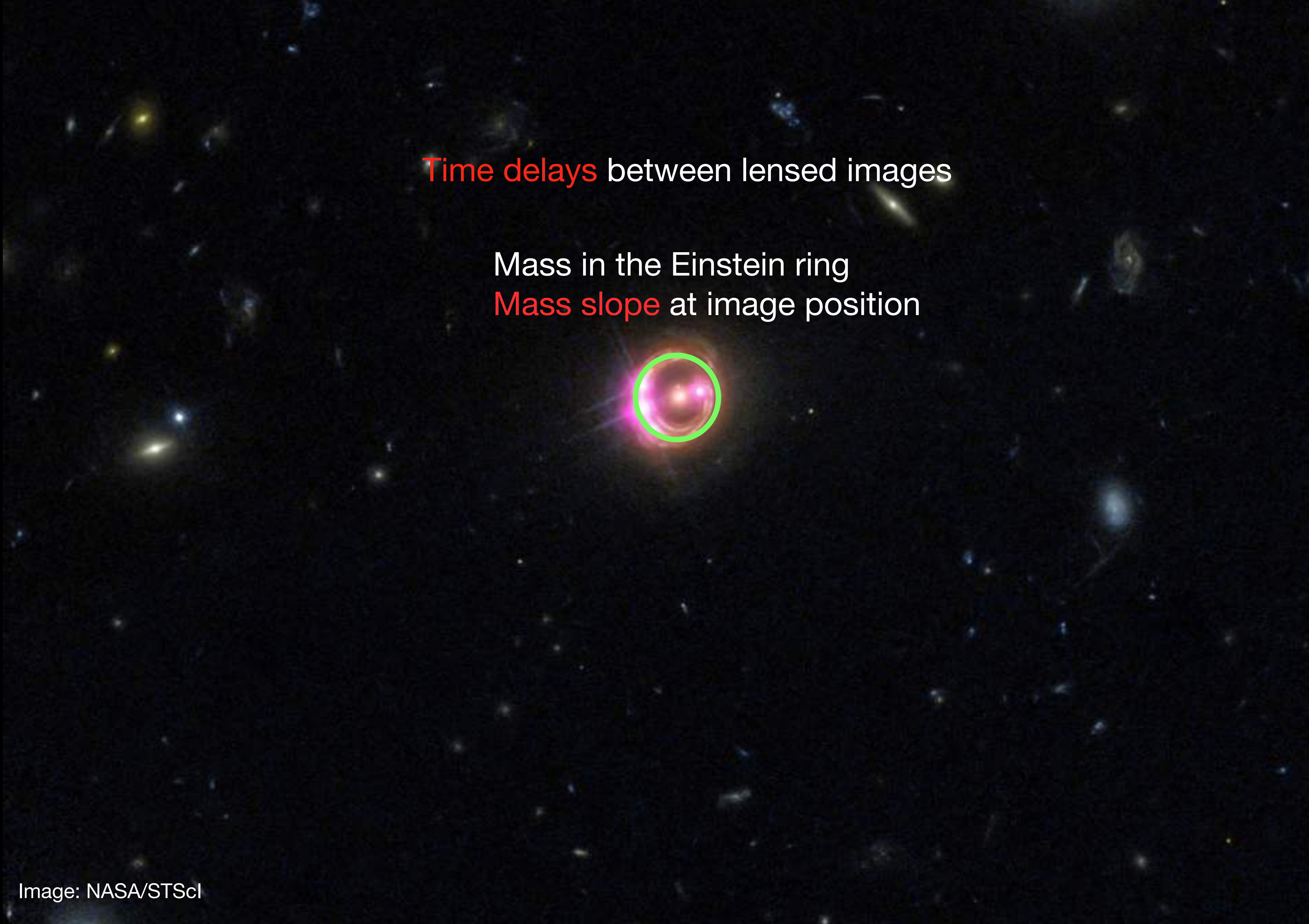


Image: NASA/STScI

Example of RX J1131-123

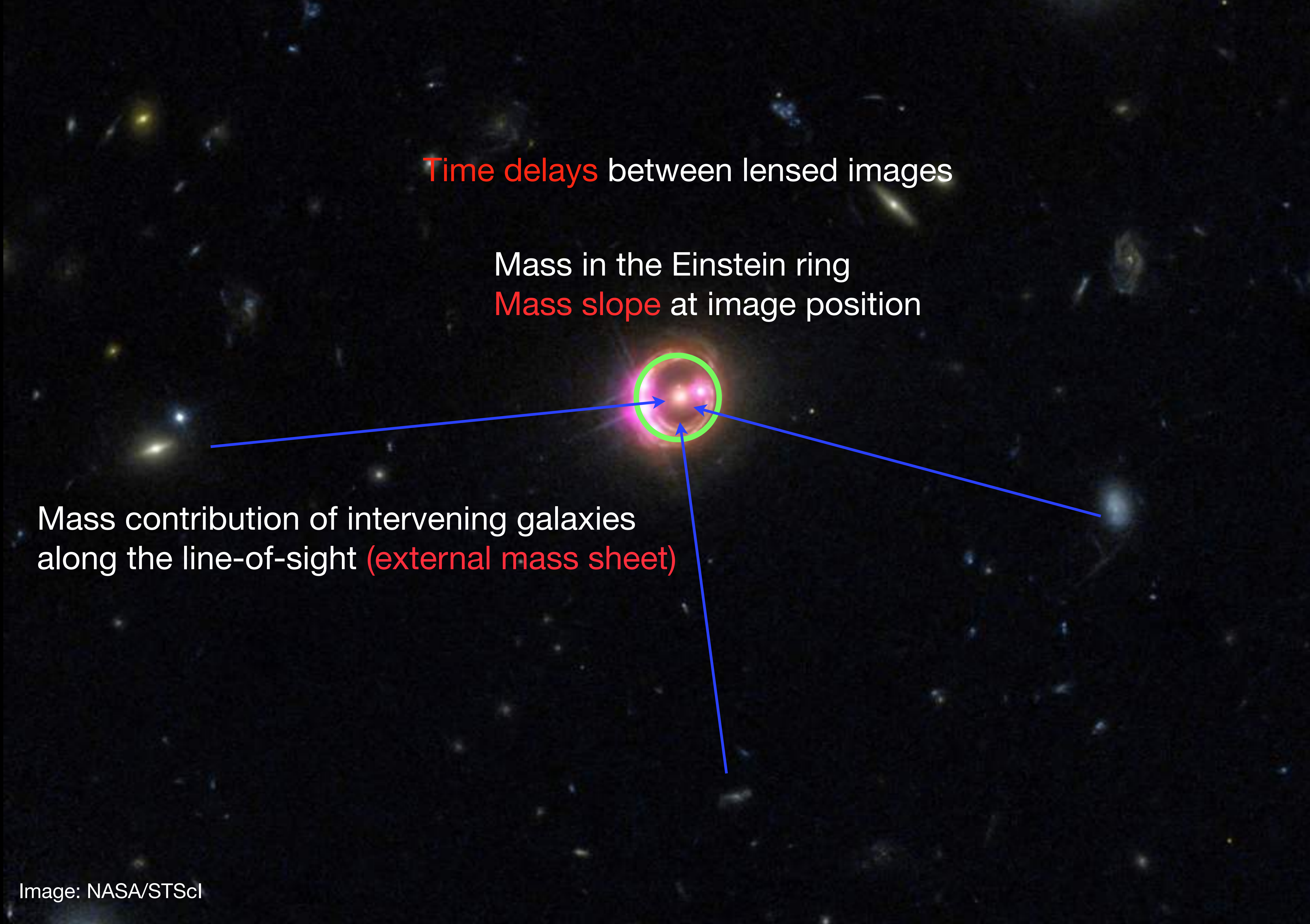


Image: NASA/STScI

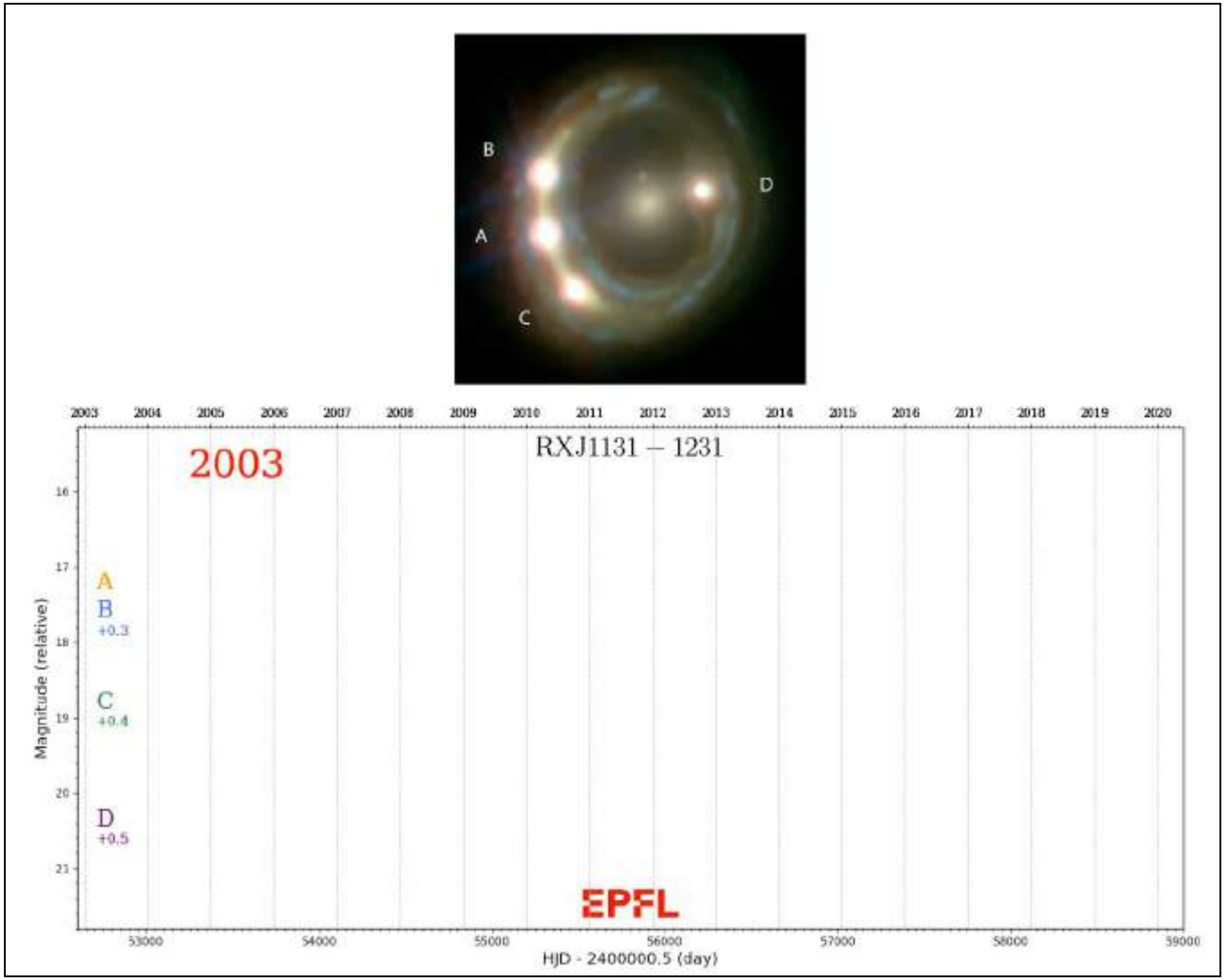
ALL ANALYSIS BLIND !

1- Time Delay Measurements

Photometry with image deconvolution

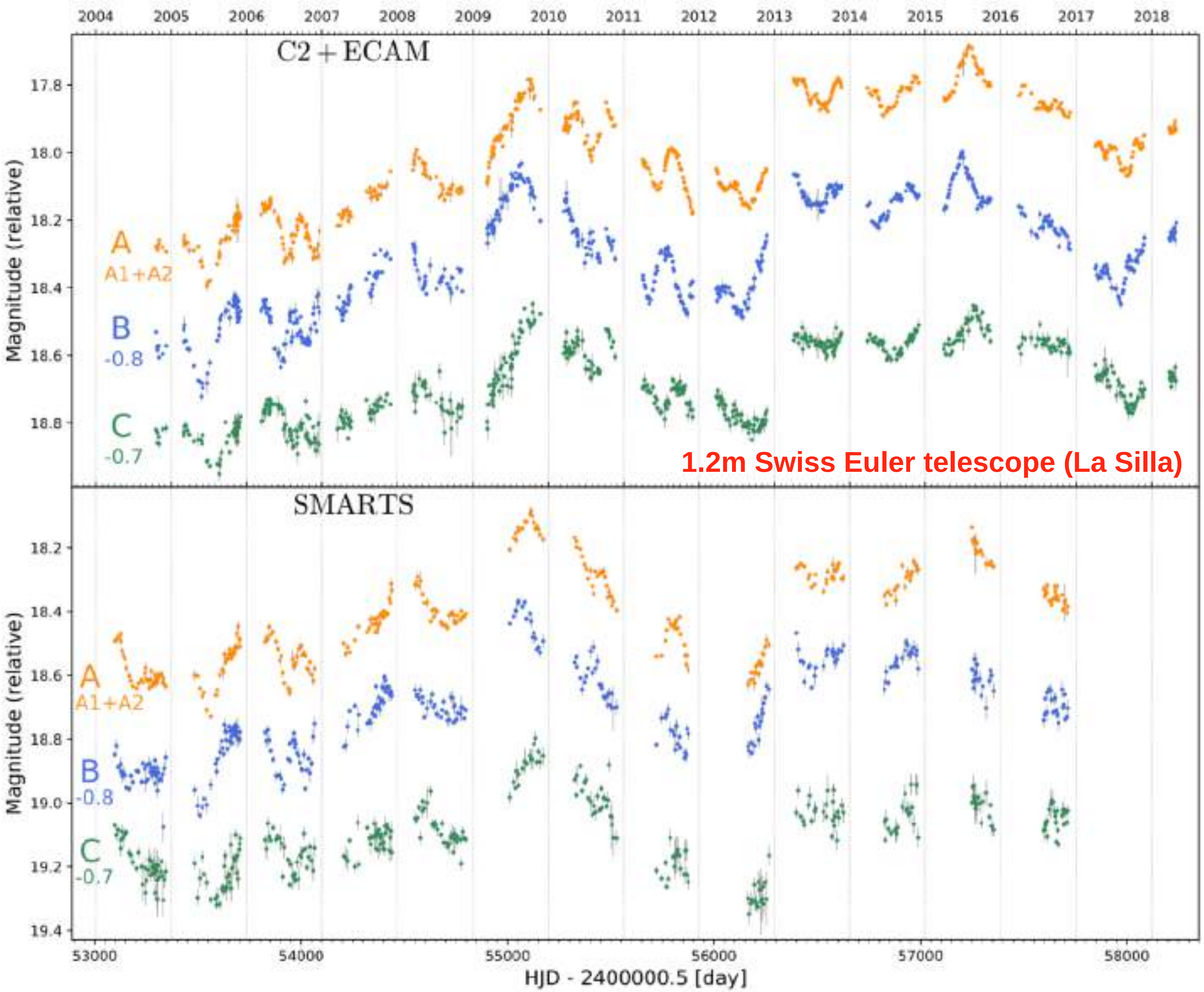
Deconvolution methods **with finite resolution** described in
Magain, Courbin, Sohy, 1998, ApJ 494, 472
Cantale, Courbin, et al. 2016, A&A 589, 81
Millon et al. 2023 in press : JAX version including wavelet regularization -> in Rubin-LSST pipeline

COSMOGRAIL Light Curves of RXJ1131-123



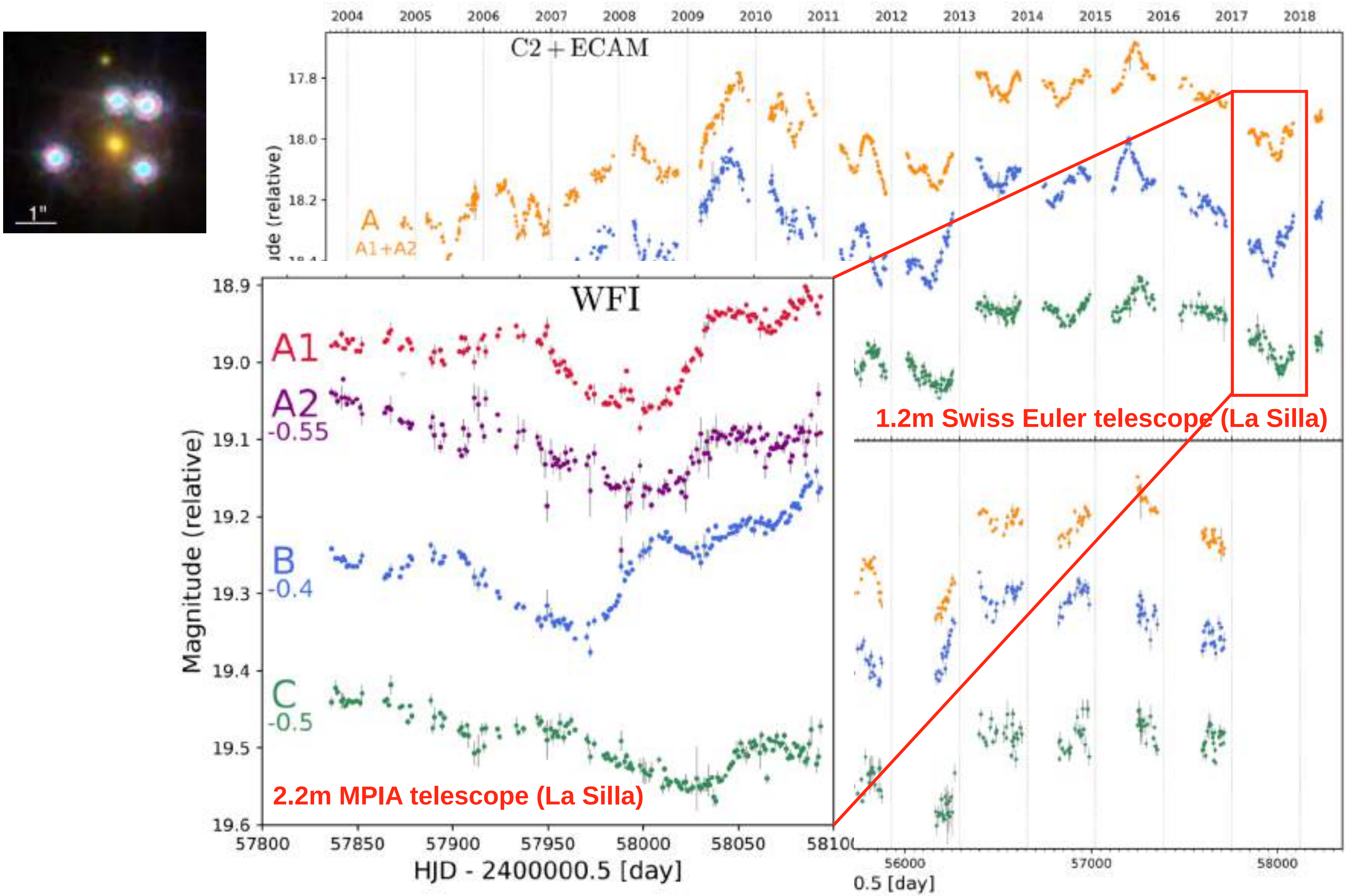
COSMOGRAIL collaboration

COSMOGRAIL Light Curves of WFI2033-4723



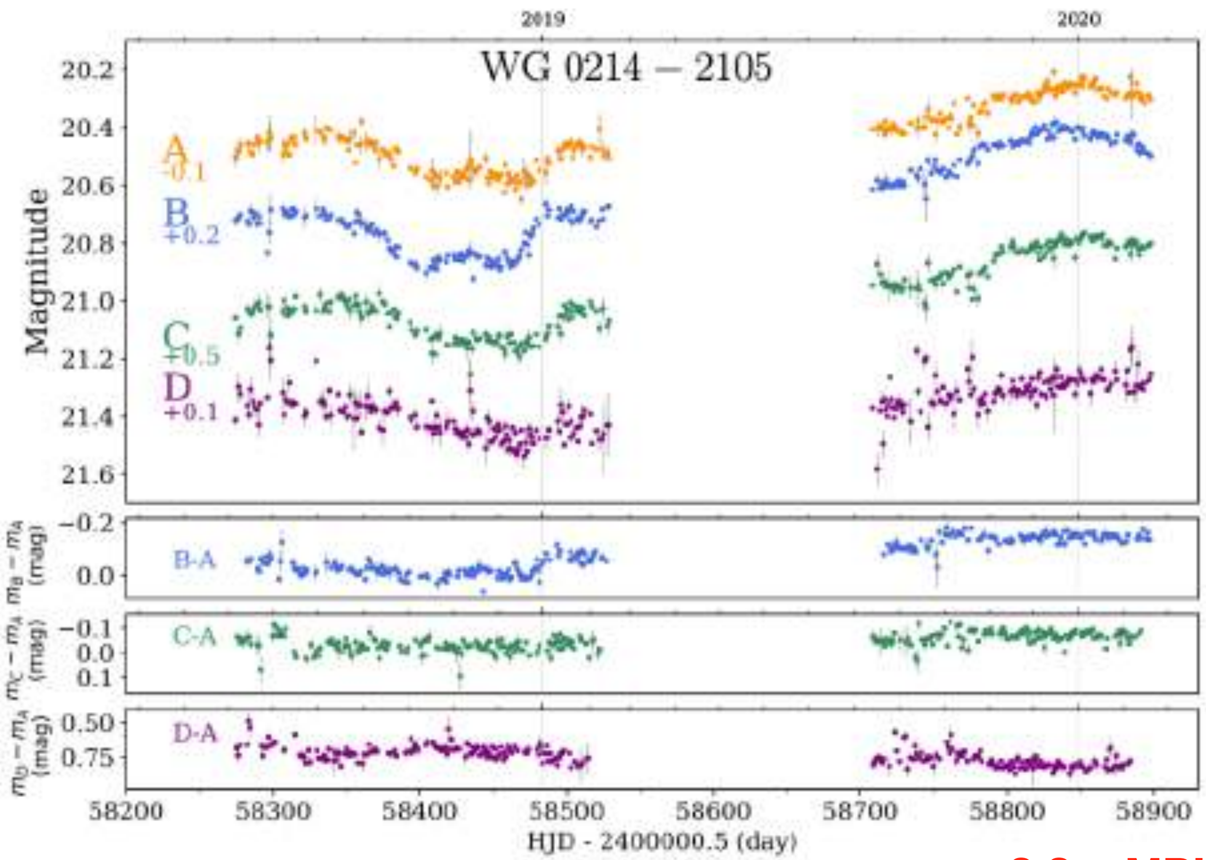
Bonvin et al. 2019, A&A 629, A97

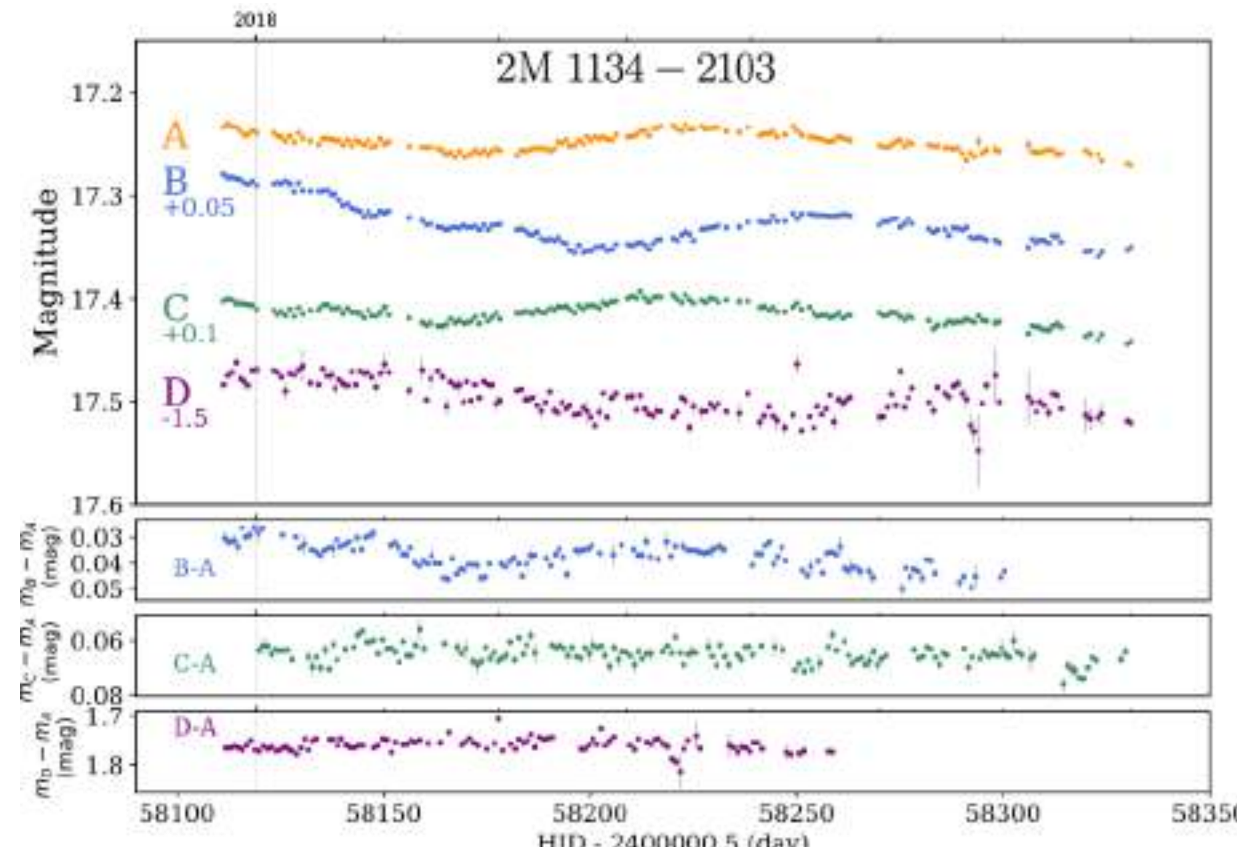
MPIA 2.2m Light Curves of WFI2033-4723



Bonvin et al. 2019, A&A 629, A97; Millon et al. 2020, 642, A193

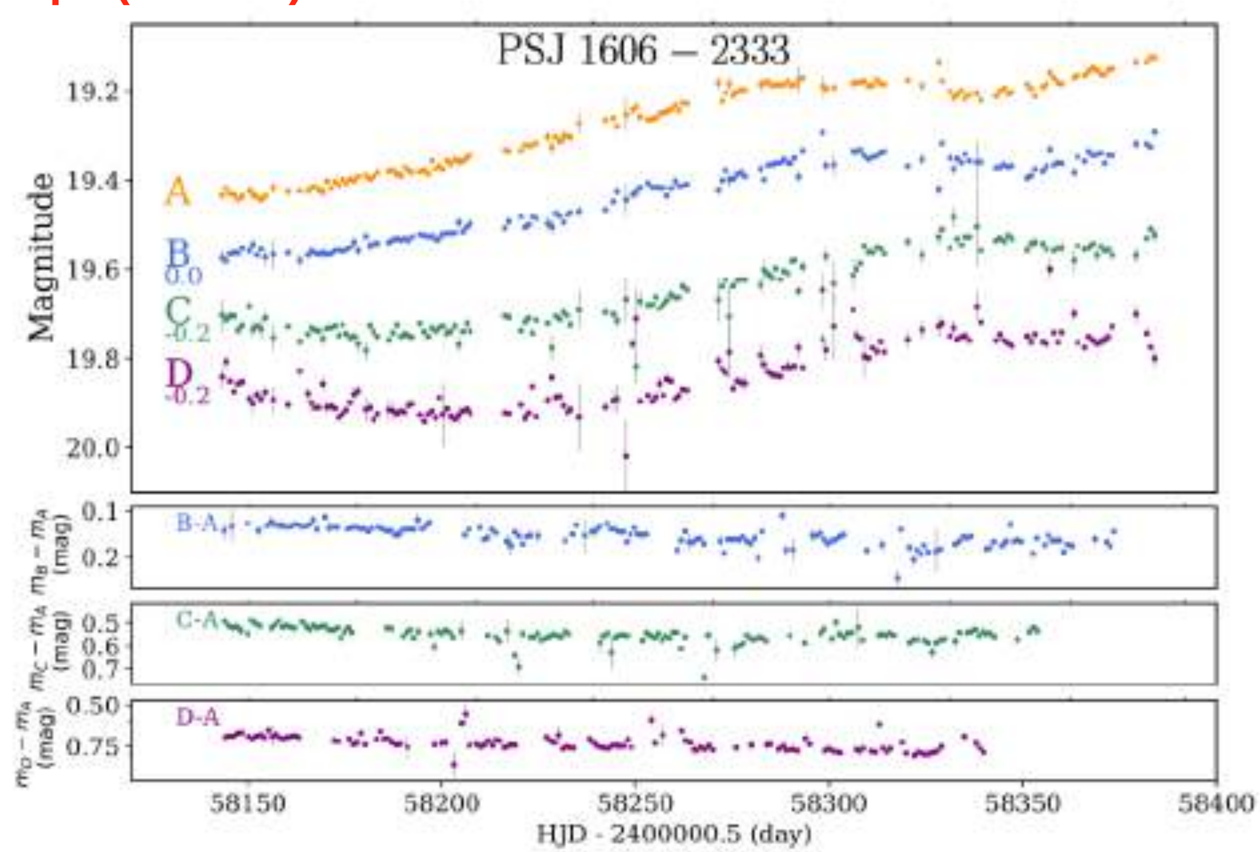
Mass Production of Time Delays





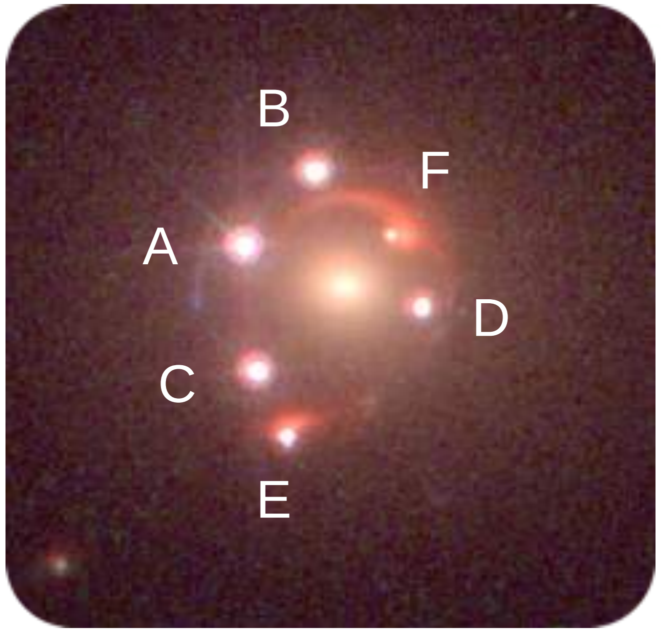
2.2m MPIA telescope (La Silla)

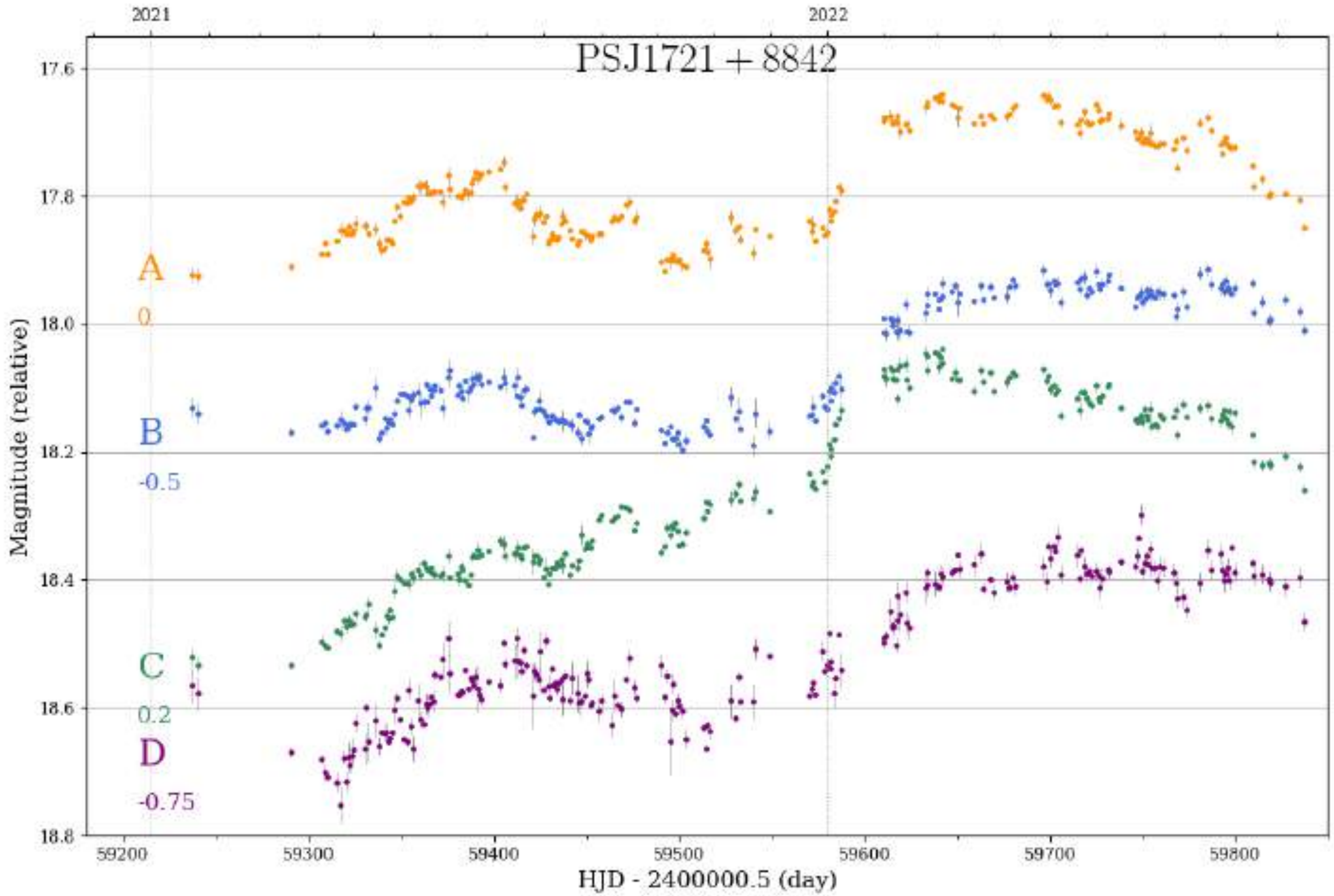
- 2m to 3m telescopes
- Daily cadence
- 30 min exposure per epoch
- 3 mmag precision per epoch
- Single-season measurement
- Better than LSST !
- More to come with 2000h of 2.6m VST



Millon et al. 2020, A&A 642, A193 (TDCOMOS II)

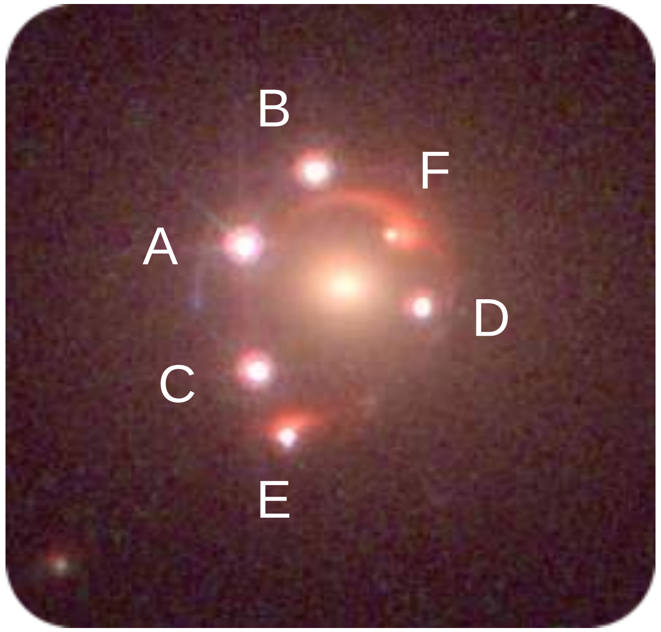
The 6-image quasar J1721+88 : NOT light curves



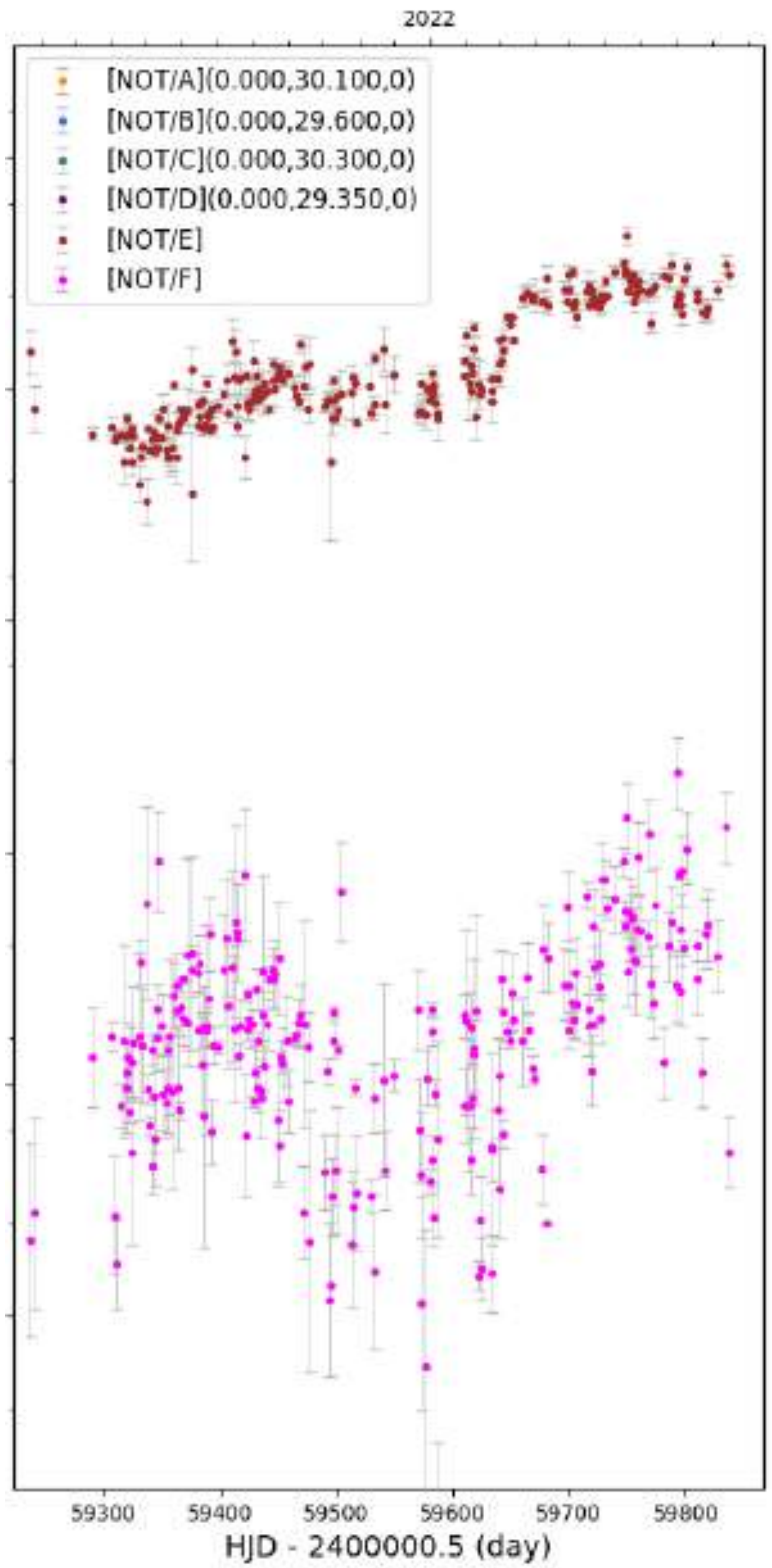


Eric Paic, FC, Martin Millon et al. 2023, in prep

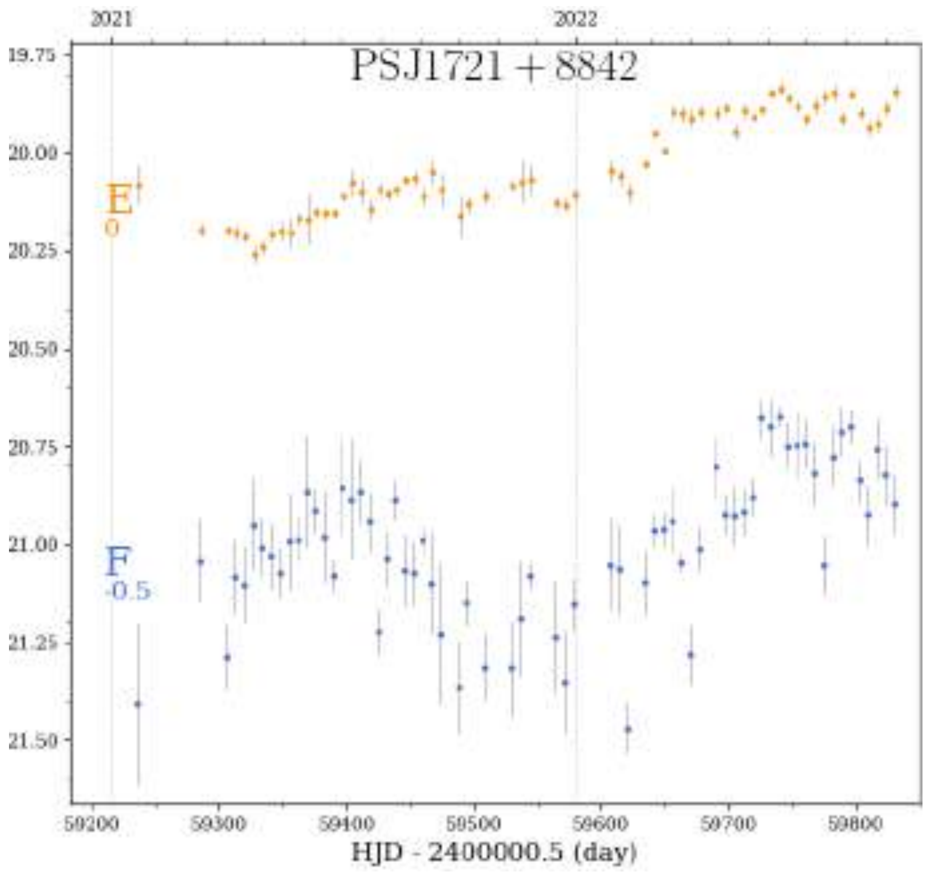
The 6-image quasar J1721+88 : NOT light curves



Daily cadence



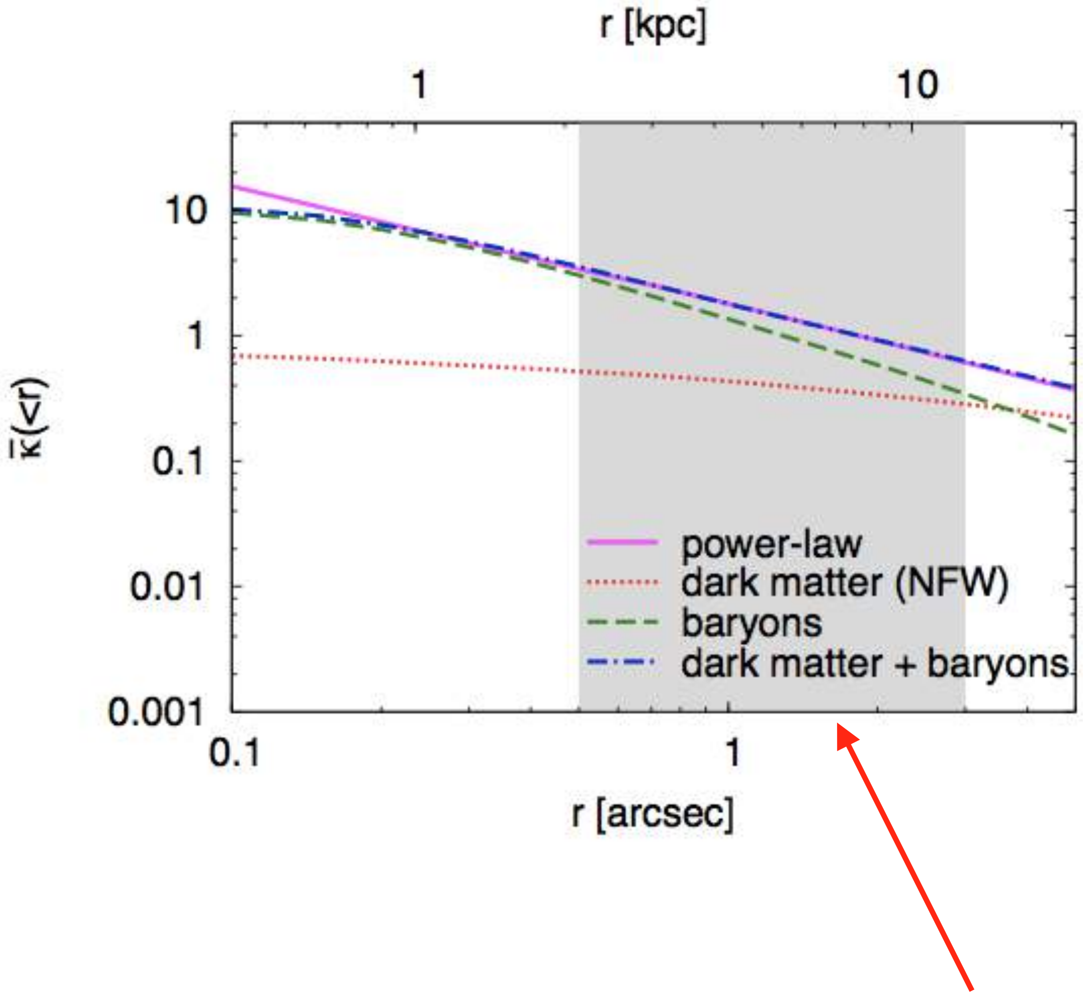
1-week binning

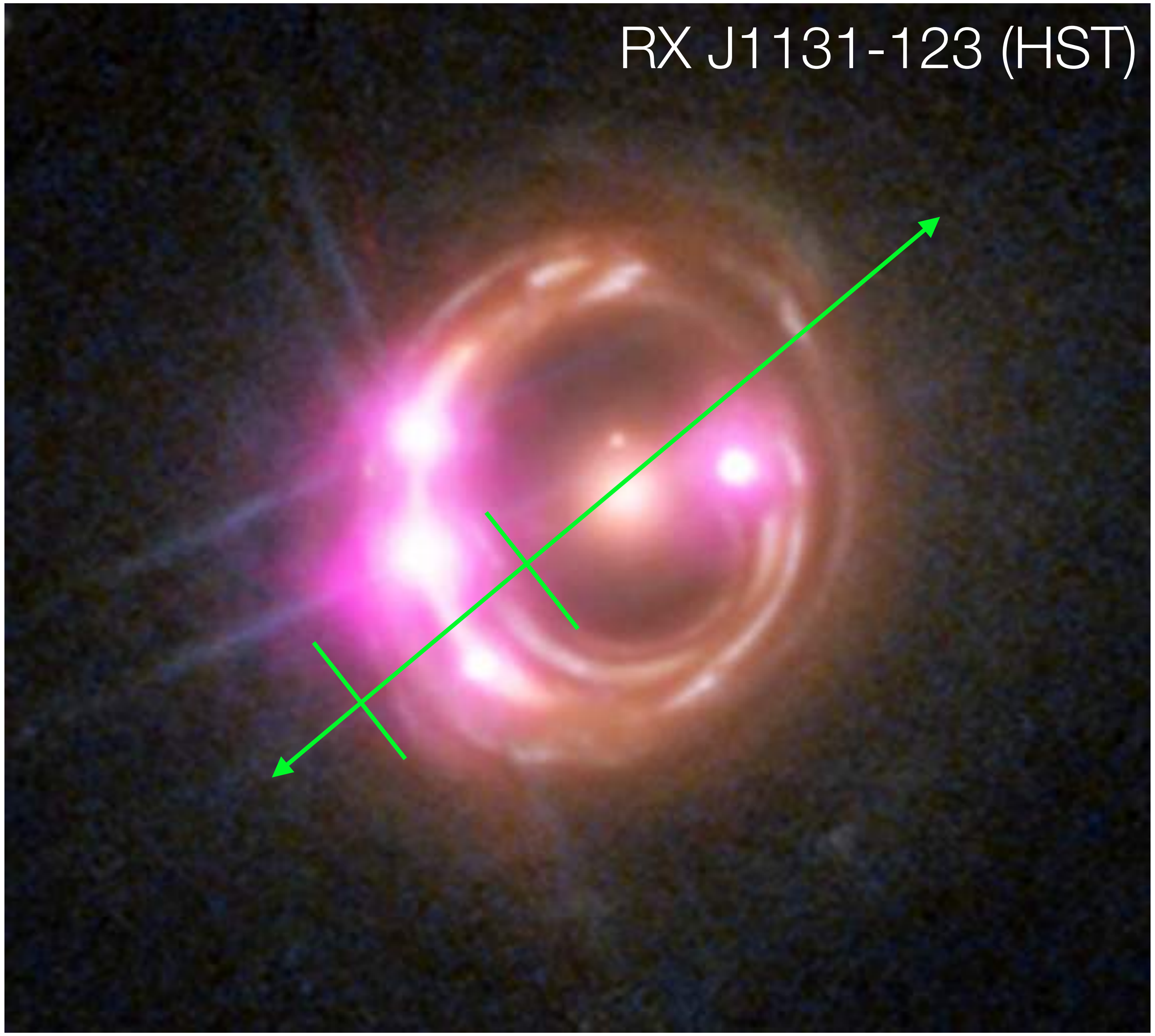


Eric Paic, FC, Martin Millon et al. 2023, in prep

2- Constraining the Mass Slope

Constraining Models with Thick Rings



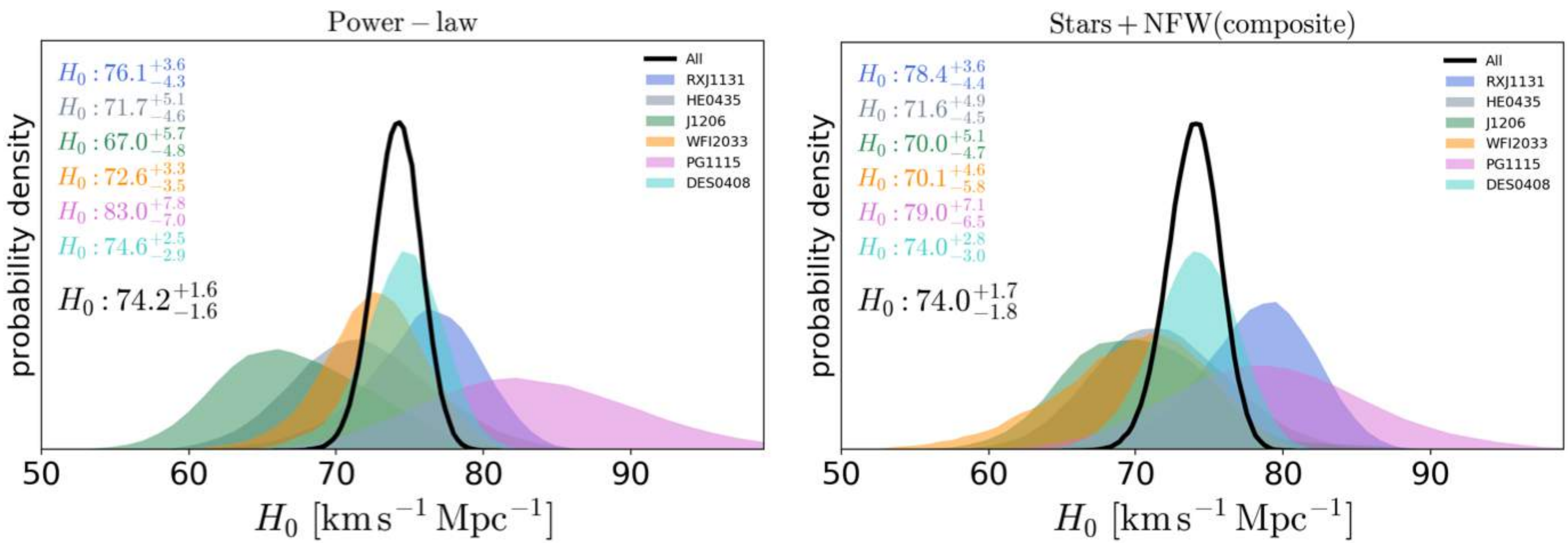


Lensing constraints come from all pixels covered by the Einstein ring formed by the quasar host

<u>More complex models and simple power-law converge to the same mass slope</u>

Suyu et al. (2014, ApJ, 788, L35)

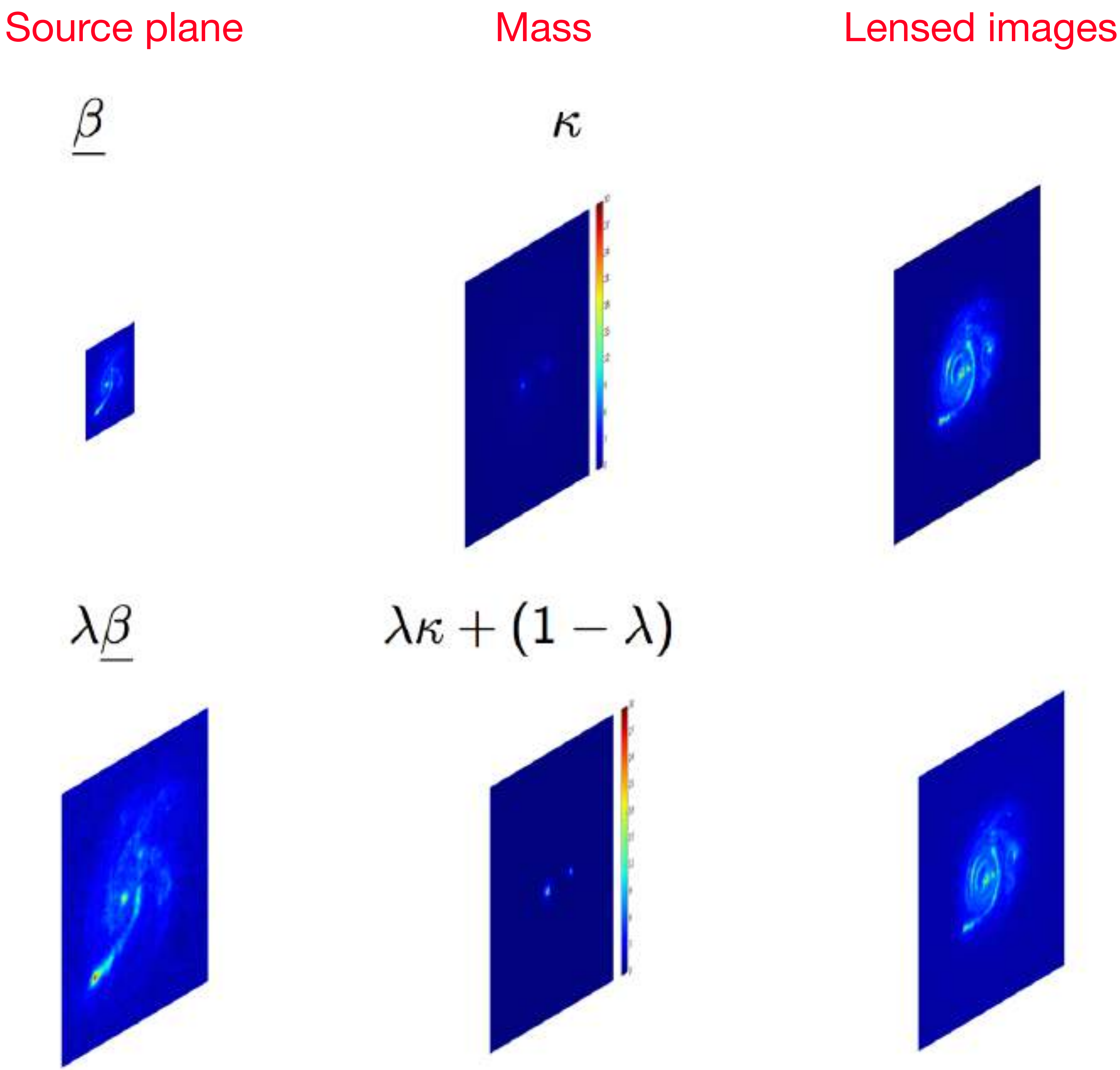
No Significant Dependence on Lens Model



Millon et al. 2020, A&A 639, A101 (TDCOSMO I)

3- The Mass-sheet Transform (MST)

Model Degeneracies: Mass Sheet Transform (MST)



Mass Sheet Transform (MST)

$$\kappa_\lambda(\vec{\theta}) = \lambda\kappa(\vec{\theta}) + 1 - \lambda$$
$$\vec{\beta}_\lambda = \lambda\vec{\beta},$$

Arrival time surfaces
in the image plane

Normalized mass profile
κ = projected mass density
in units of the critical mass

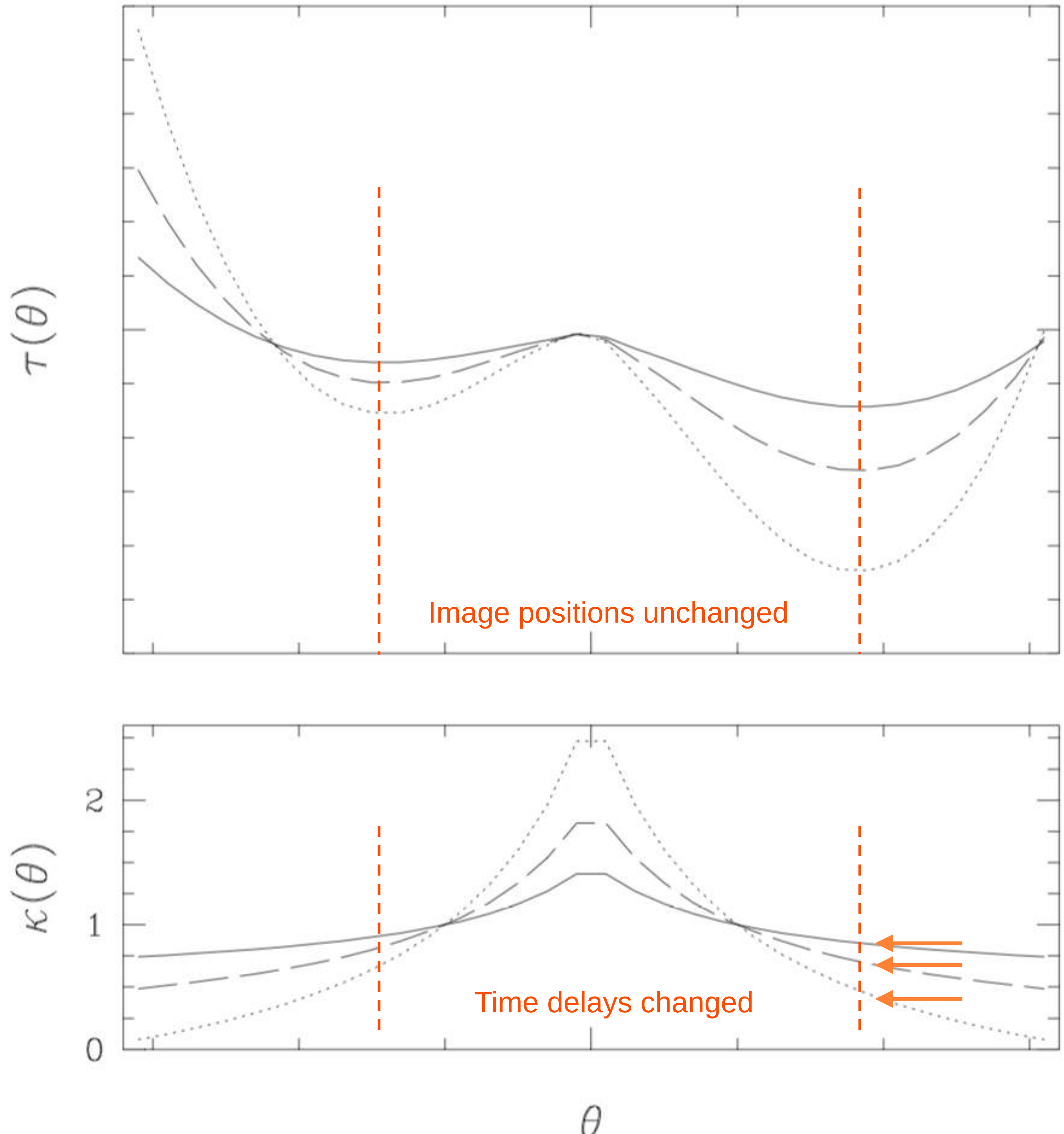
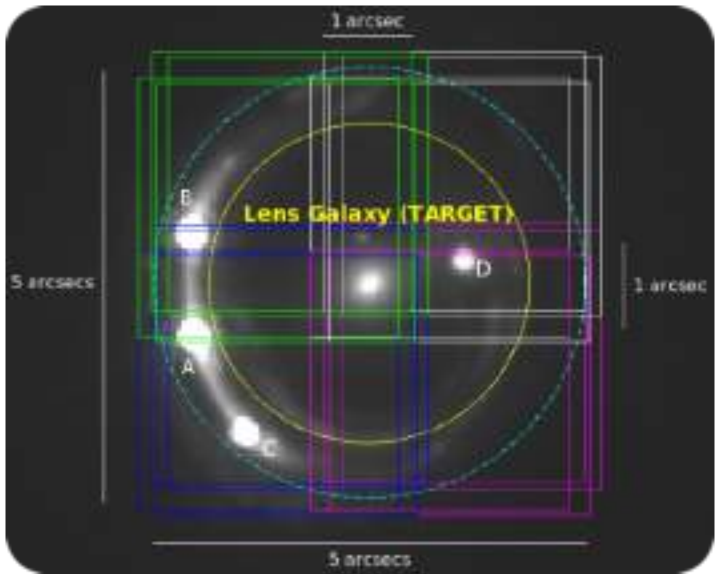


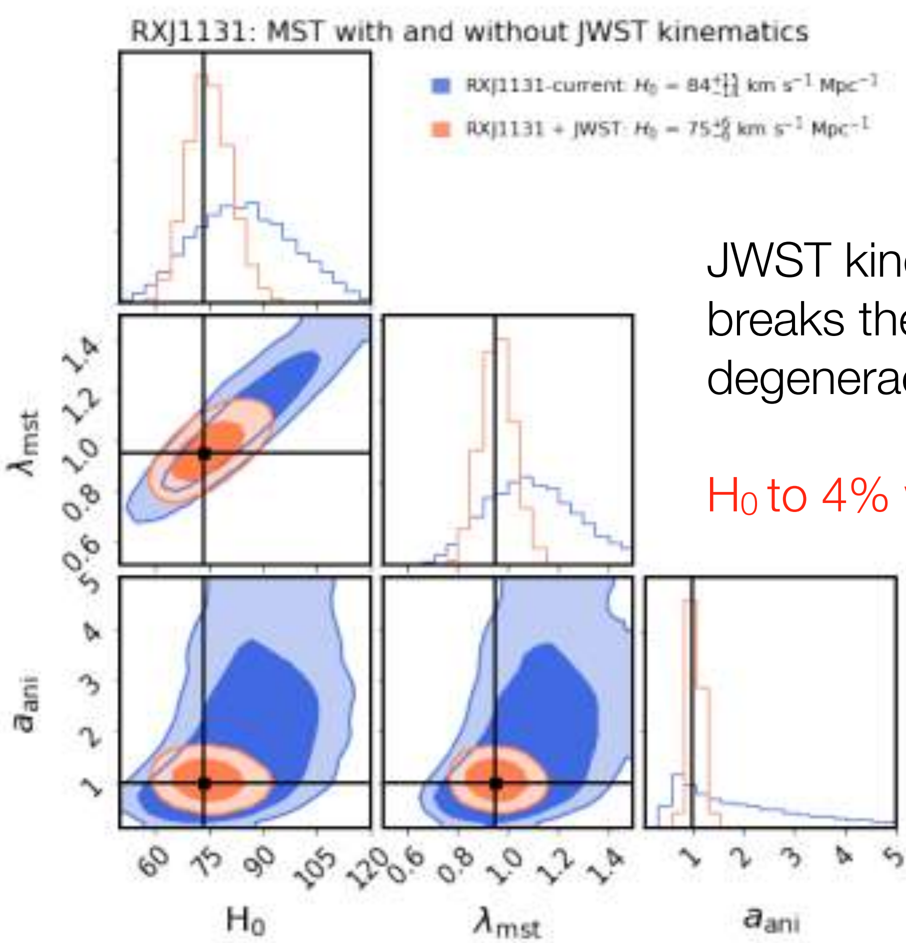
Figure adapted from Saha, 2000, AJ 120, 1654

Future Avenues

Spatially resolved kinematics
(ongoing with VLT/MUSE, Keck KCWI, JWST pending)



Accepted JWST dithers with NIRSpec (exp. time: 6.5h)

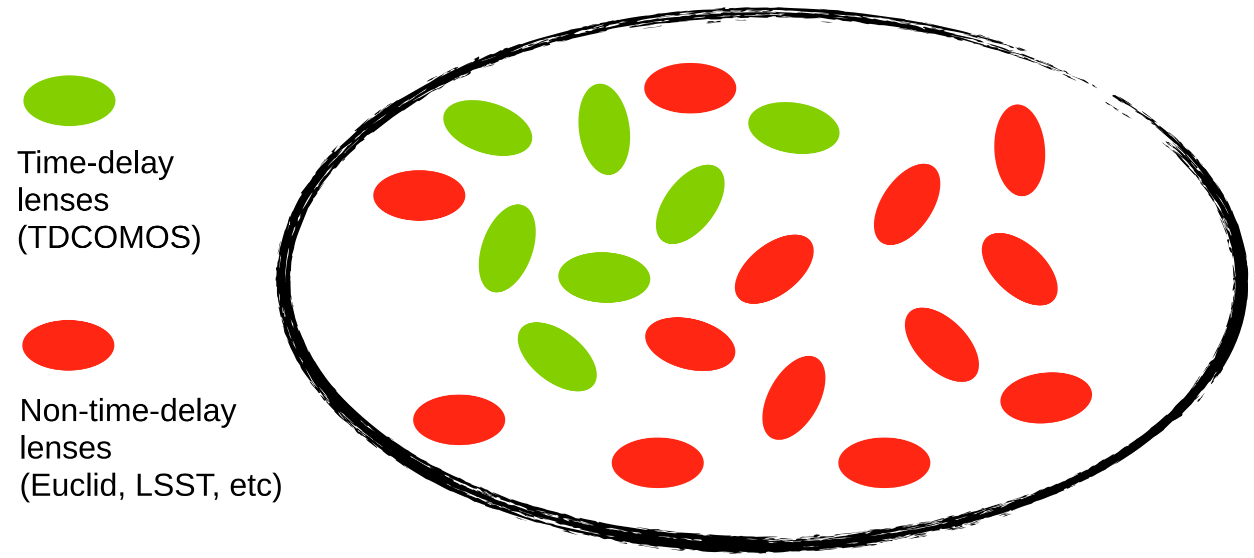


JWST kinematics breaks the Mass-sheet degeneracy

H_0 to 4% with 1 single lens

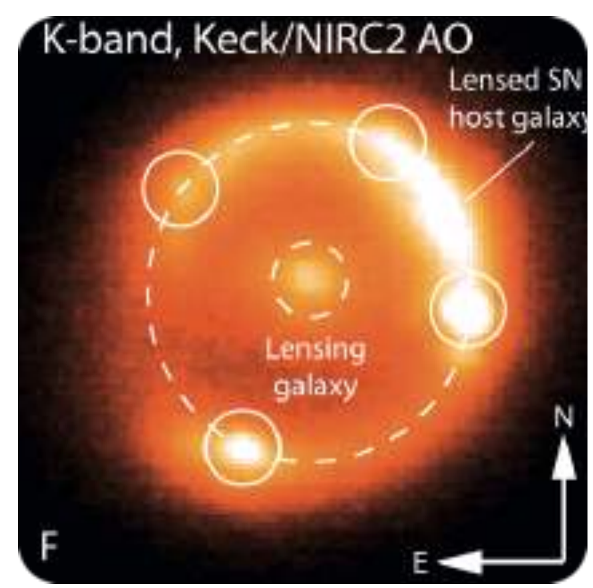
TDCOSMO collaboration

Hierarchical Bayesian Analysis for both cosmology and galaxy evolution



H_0 to 1.2% with 40 delays + 200 lenses with no time delay but resolved kinematics <u>(Euclid is a key-player here !)</u>

Lensed supernovae



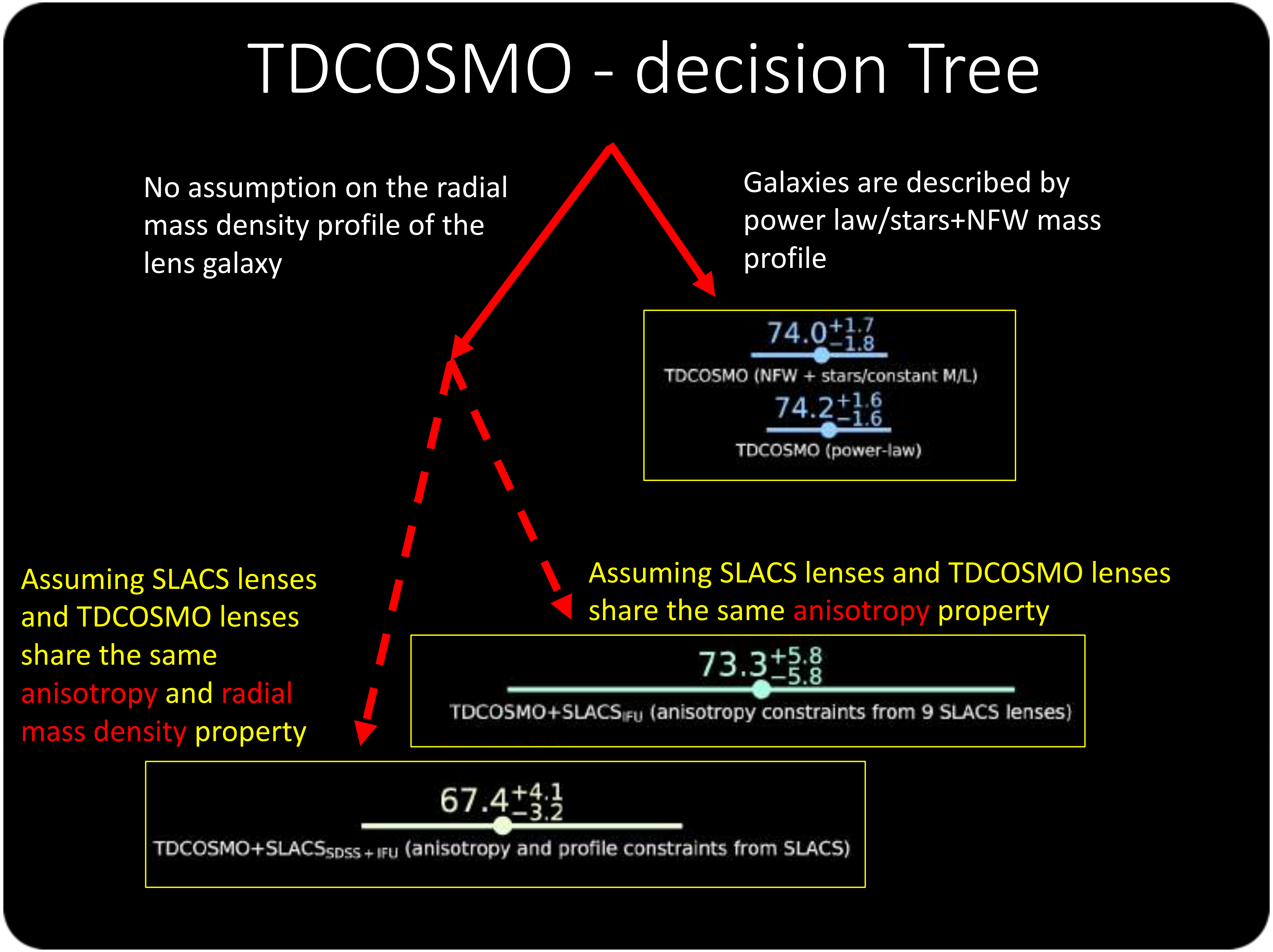
Ongoing search

- in ZTF alerts
- by monitoring monthly know lenses
- in ongoing VST large program

Approved ToO follow-up at VLT (MUSE + XShooter)

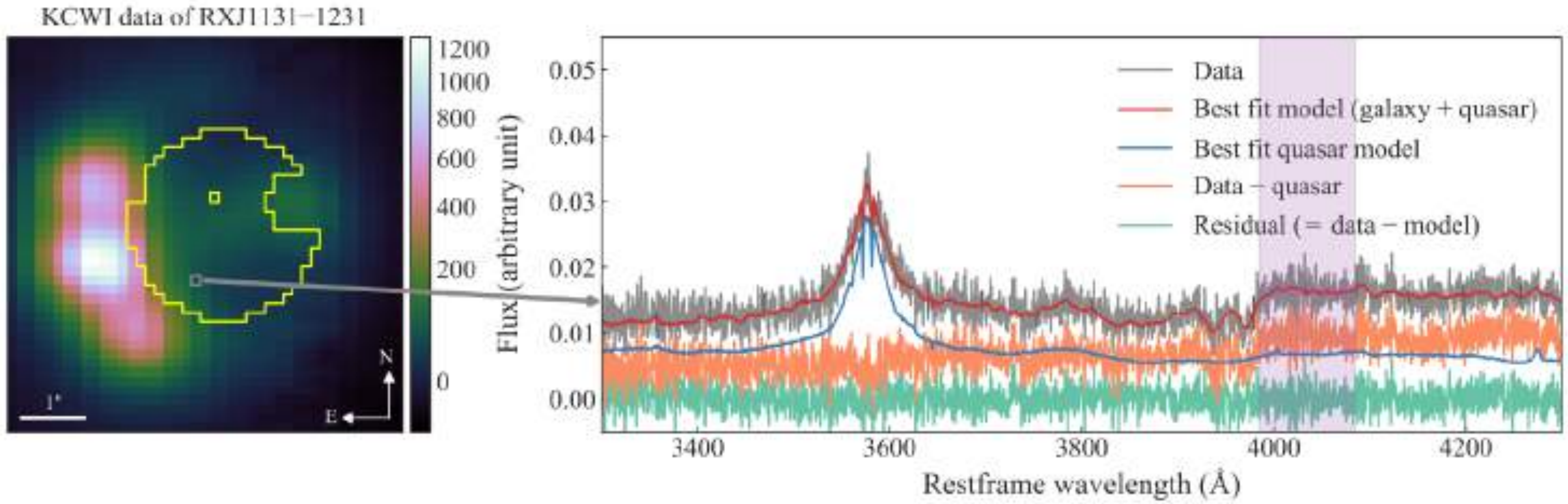
Goobar et al. (2017, Science 356, 291)

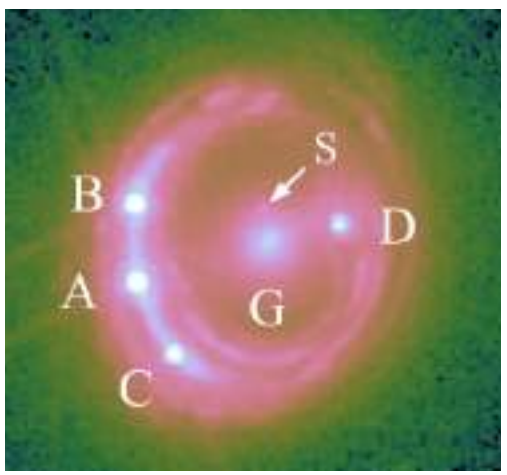
Avenue #1 - Hierarchical Bayesian Analysis

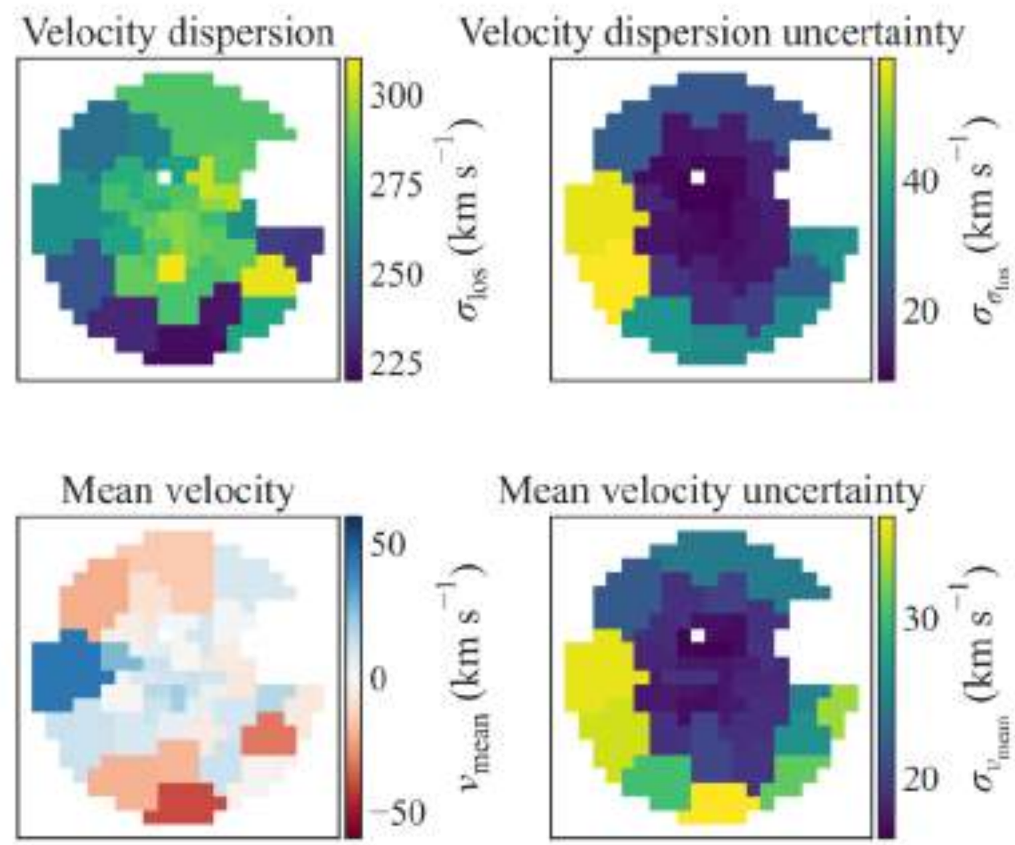


Birrer et al. 2020, A&A 643, A165 (TDCOSMO IV)

Avenue #2 - Dynamics of Time-Delay Lens Galaxies





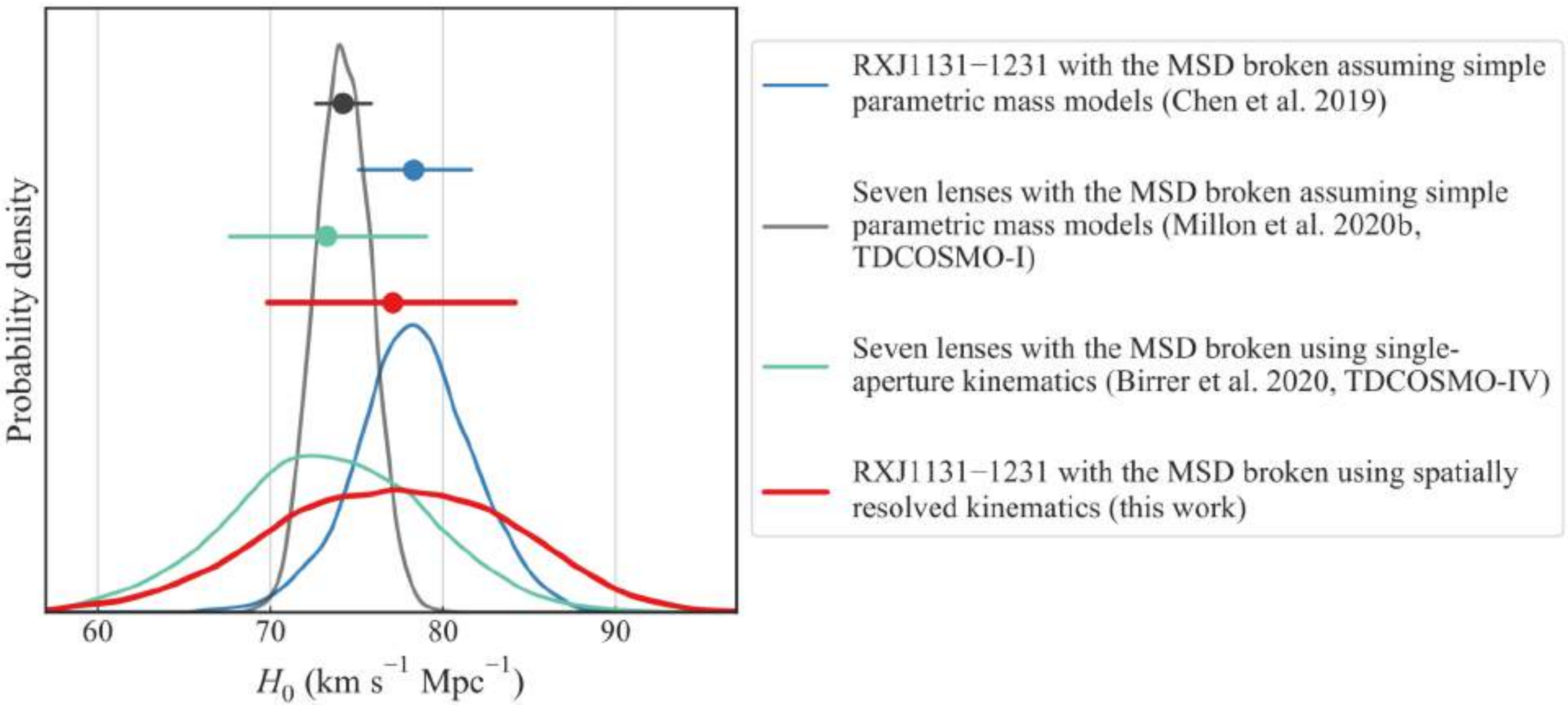


4h of Keck KCWI IFU spectroscopy (no-AO)

More to come with VLT-MUSE, Keck, JWST

Shajib et al. 2023, A&A 673, A9 (TDCOSMO XII)

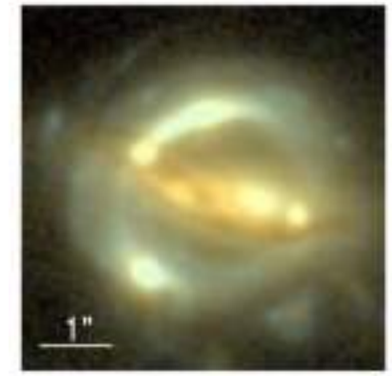
Avenue #2 - Dynamics of Time-Delay Lens Galaxies



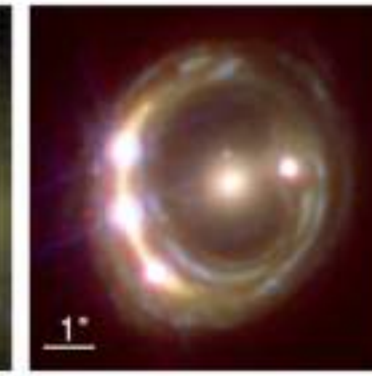
Shajib et al. 2023, A&A 673, A9 (TDCOSMO XII)

Summary

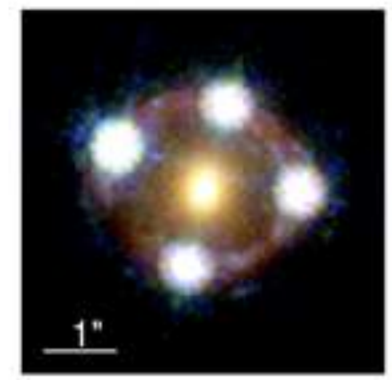
- Strong lensing time delays consist in an **absolute distance indicator**
- Time delays are measured to a few percents within **1-2 seasons**
- **7 lenses** give H_0 with accuracy and precision comparable to supernovae and are **independent**
- **In flat lambda-CDM H_0 = 74.0 +/- 1.8 km.s^{-1}.Mpc^{-1}**
- The **Mass-Sheet-Degeneracy** needs to be addressed
- Avenue #1: **Hierarchical analysis: more work needed**
- Avenue #2: **Resolved kinematics: supports previous analysis**



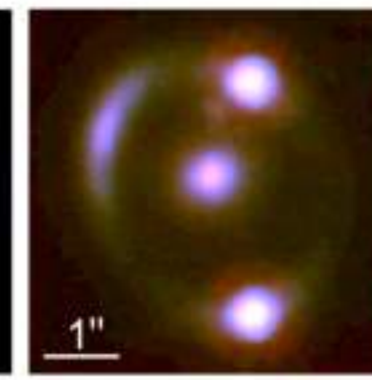
(a) B1608+656



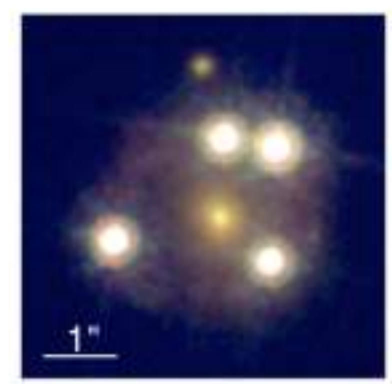
(b) RXJ1131−1231



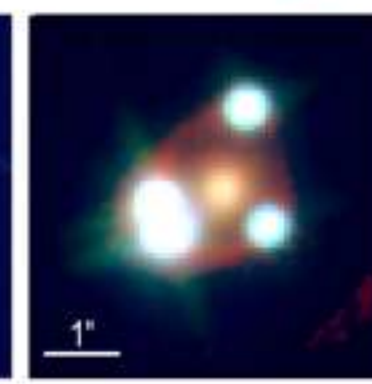
(c) HE 0435−1223



(d) SDSS 1206+4332



(e) WFI2033−4723



(f) PG 1115+080