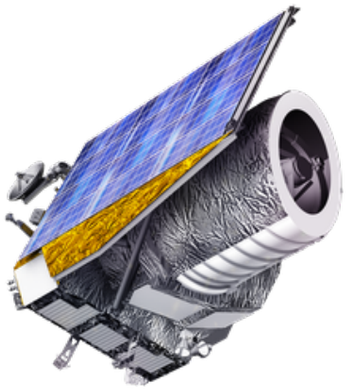
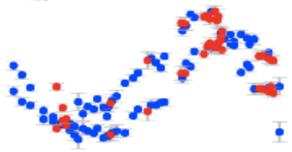
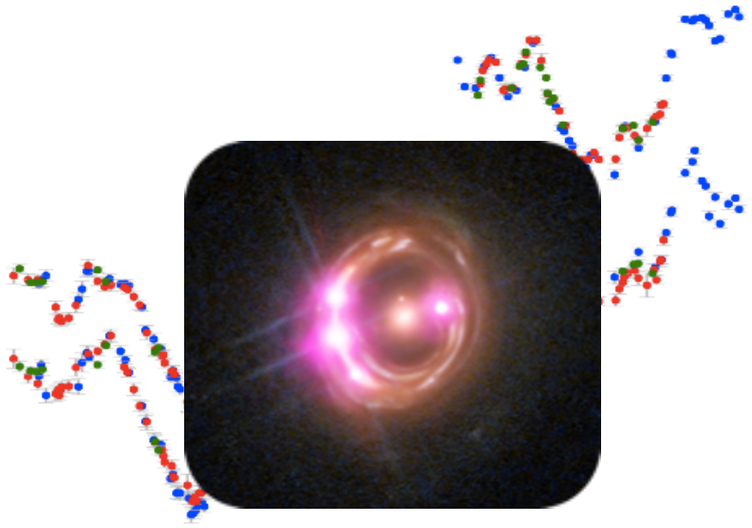
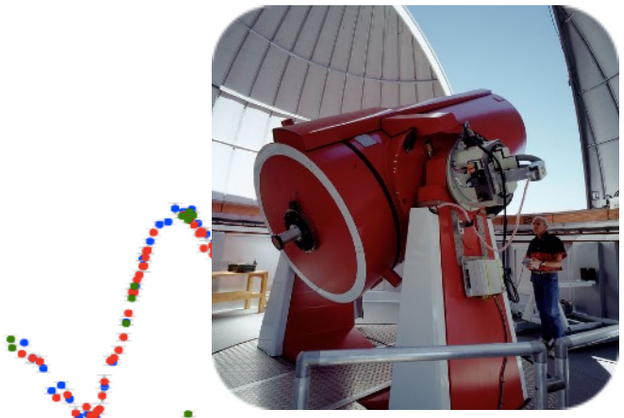
Time Delay Cosmography with Strongly Lensed quasars

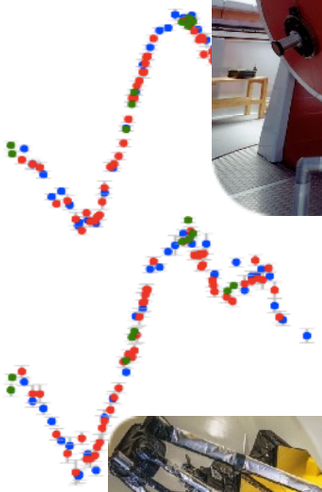
Frédéric Courbin (EPFL, Switzerland)
For the TDCOSMO collaboration











COSMICLENS

European Research Council
Established by the European Commission

FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
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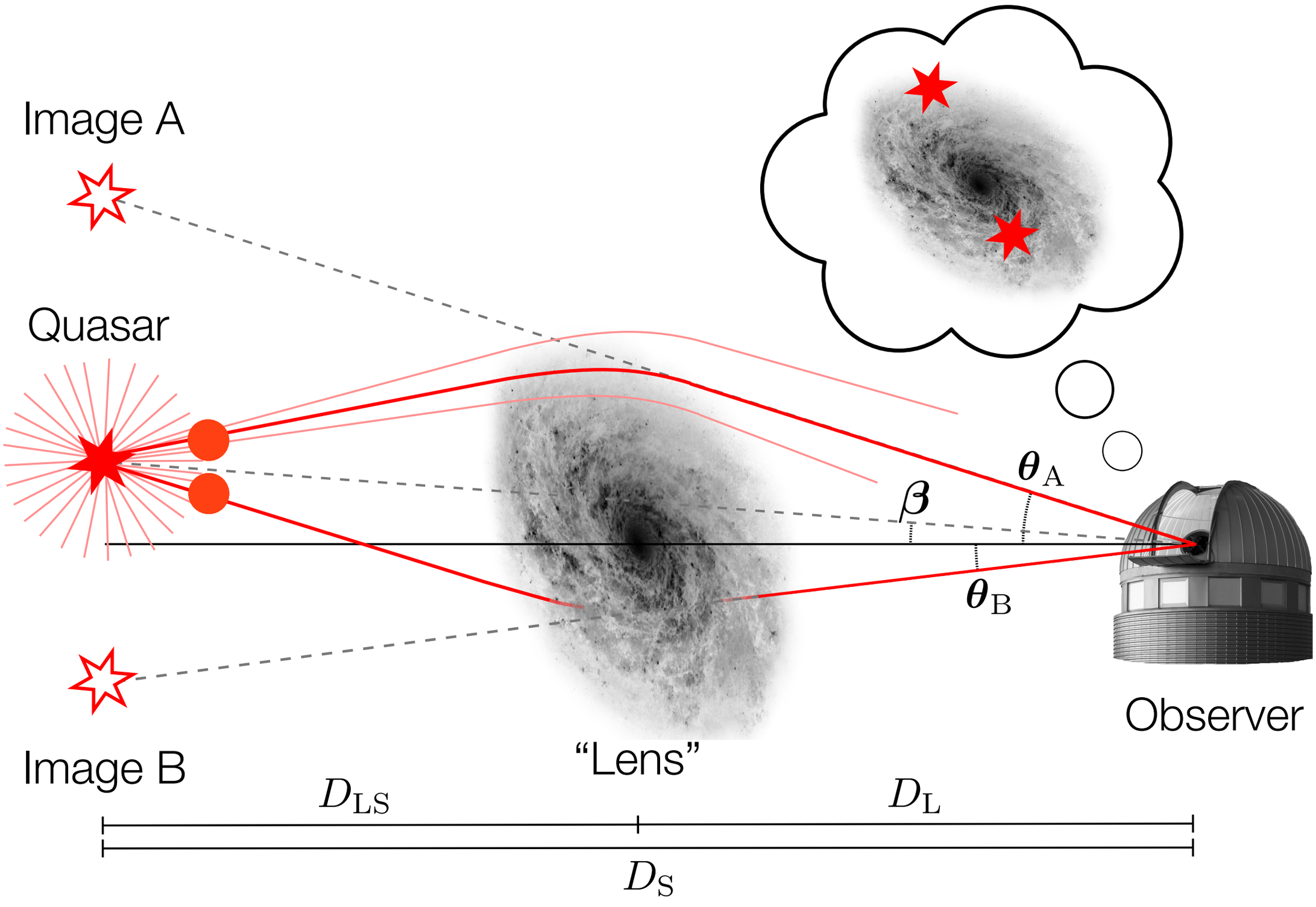
SWISS NATIONAL SCIENCE FOUNDATION

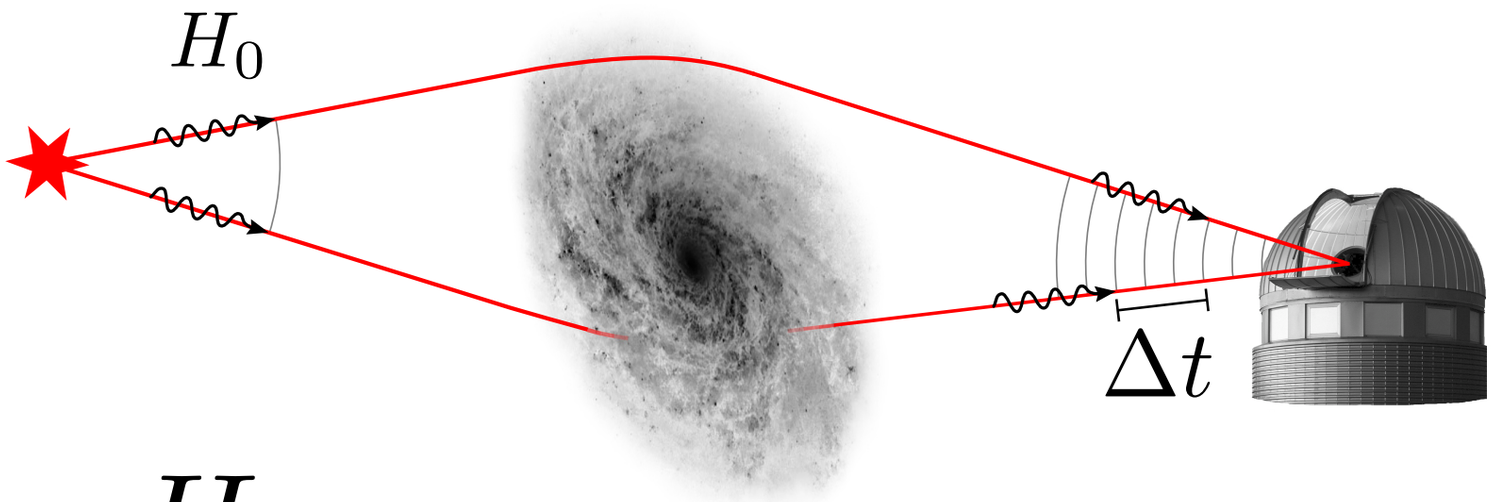
EPFL Laboratoire d'astrophysique http://lastro.epfl.ch
Ecole Polytechnique Fédérale de Lausanne (EPFL)

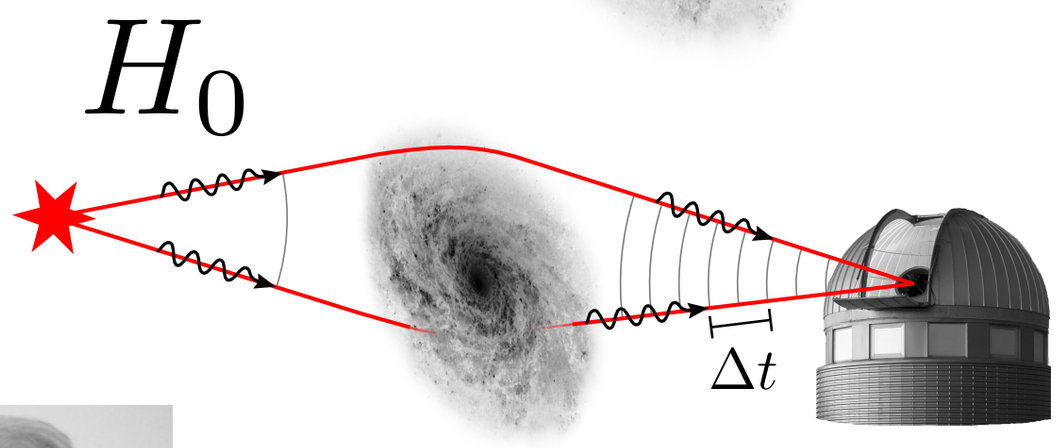
CosmoVeese - Lisbon - May 2023

Time Delays in Strongly Lensed Quasars



Time Delays Measure the Hubble Constant H_0





Sjur Refsdal

(1964)

Lens potential at image positions

Source position (unconstrained)

Astrometry of the images

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

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

Time delays between lensed images

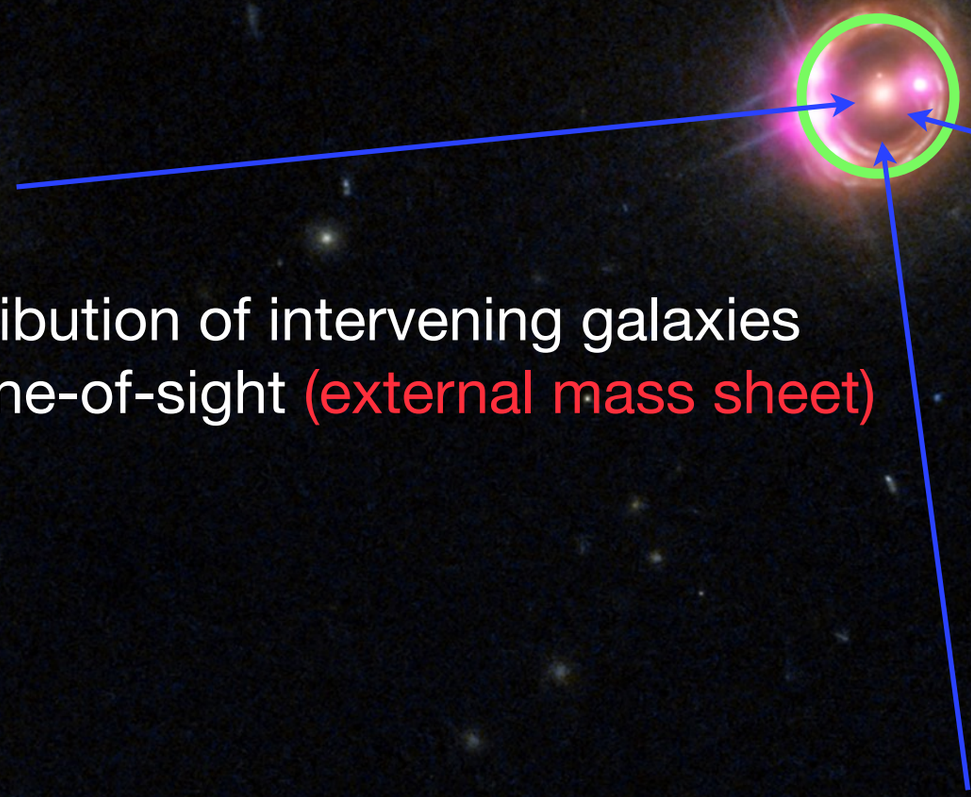
Mass in the Einstein ring
Mass slope at image position

Image: NASA/STScI

Example of RX J1131-123

Time delays between lensed images

Mass in the Einstein ring
Mass slope at image position



Mass contribution of intervening galaxies
along the line-of-sight (external mass sheet)

Image: NASA/STScI

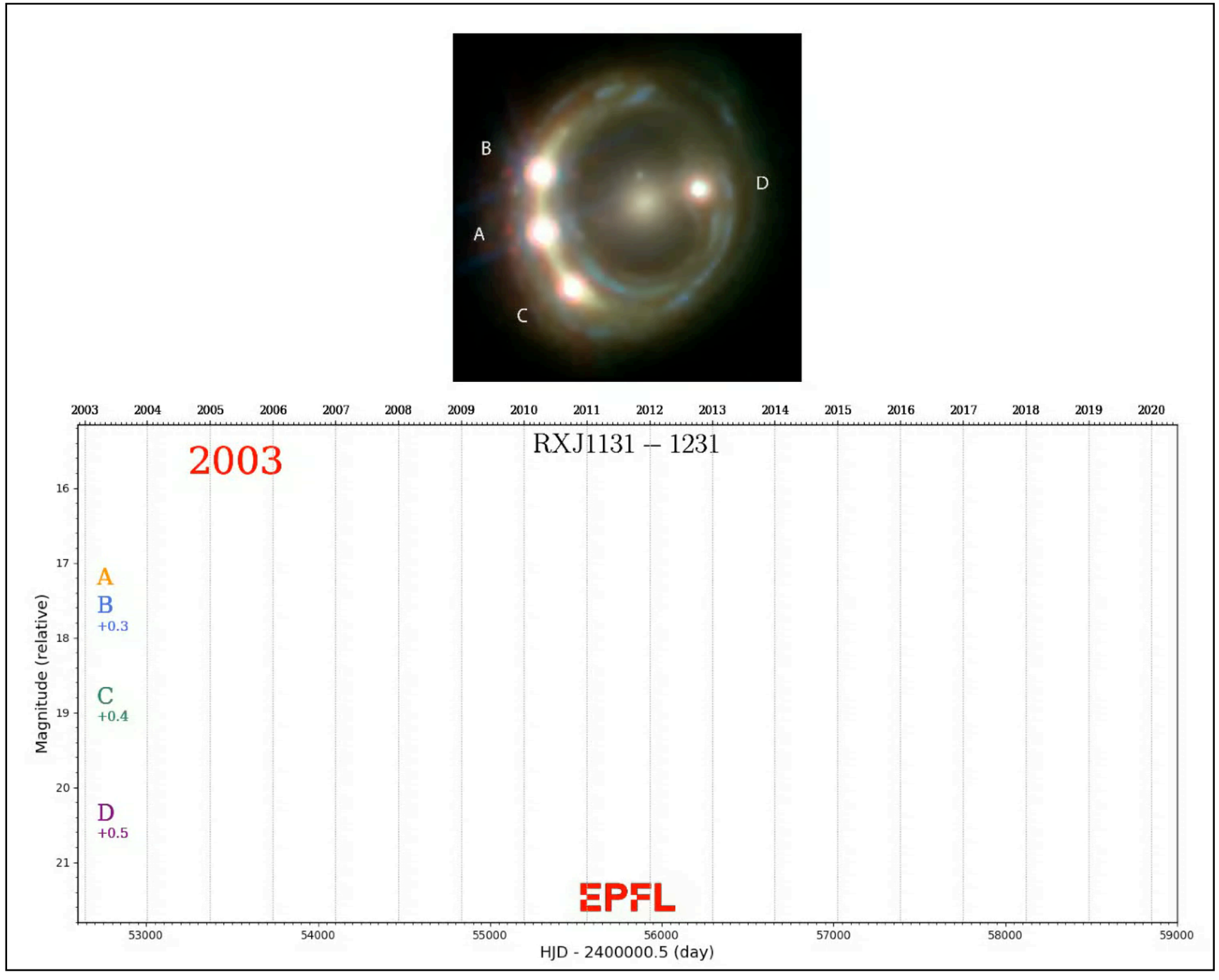
ALL ANALYSIS BLIND !

1- Time Delay Measurements

Photometry with image deconvolution

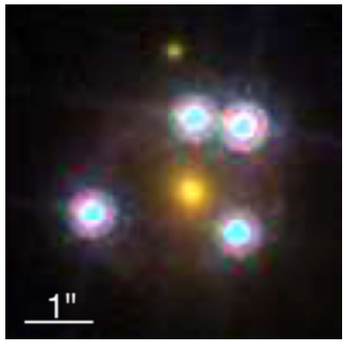
Deconvolution methods **with finite resolution** described in
Magain, Courbin, Sohy, 1998, ApJ 494, 472
Cantale, Courbin, et al. 2016, A&A 589, 81
Millon et al. 2023 in press : JAX version including wavelet regularization -> in Rubin-LSST pipeline

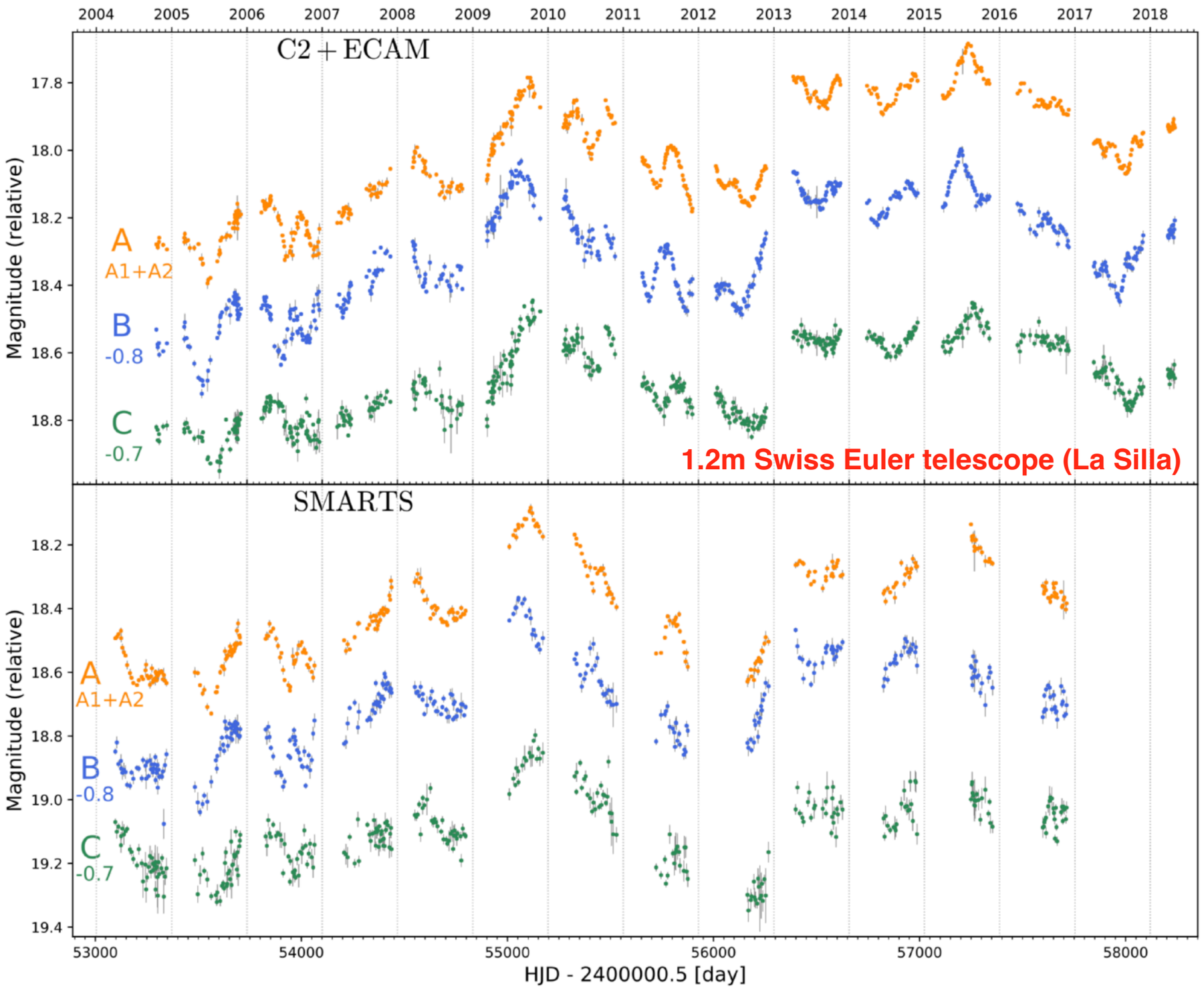
COSMOGRAIL Light Curves of RXJ1131-123



COSMOGRAIL collaboration

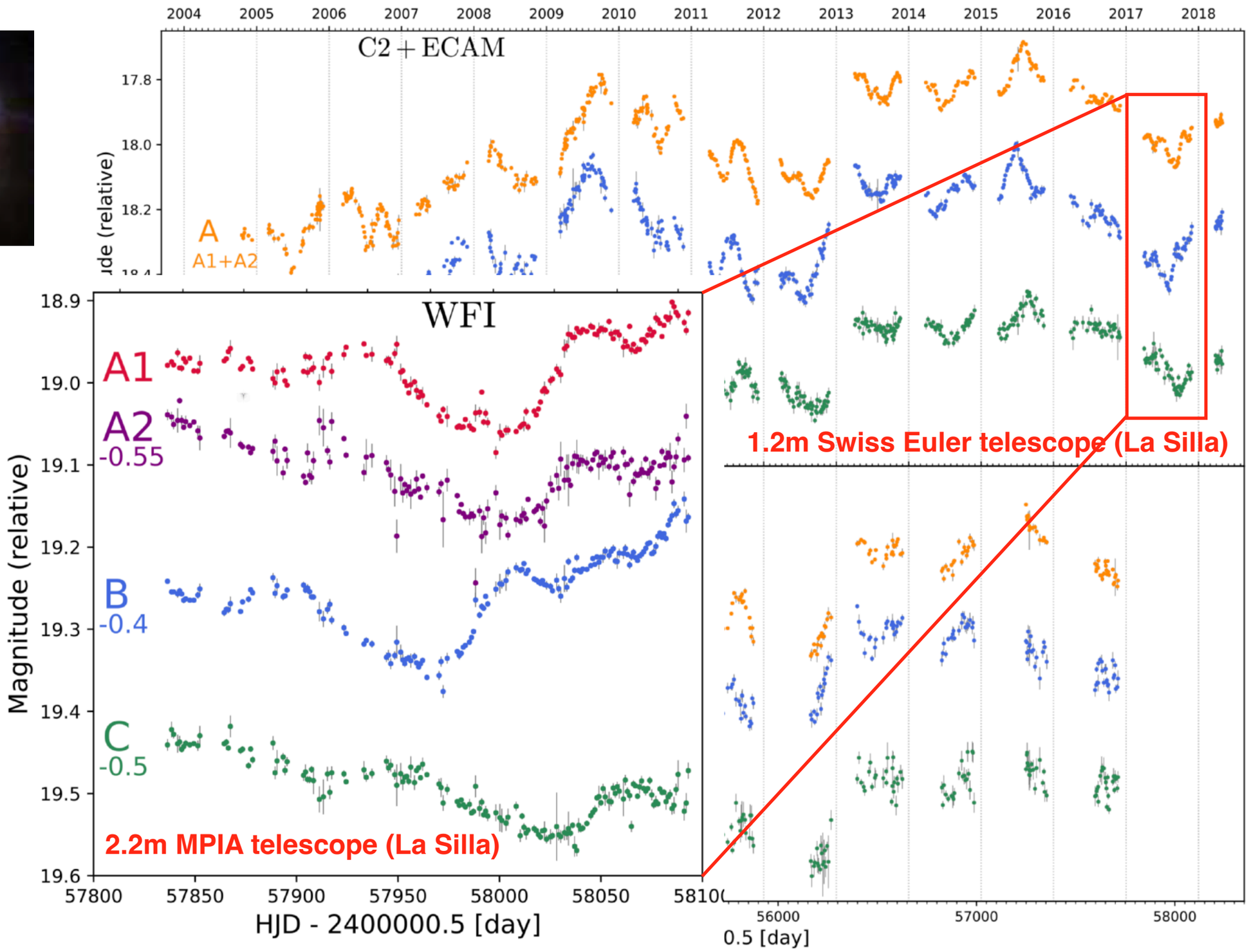
COSMOGRAIL Light Curves of WFI2033-4723





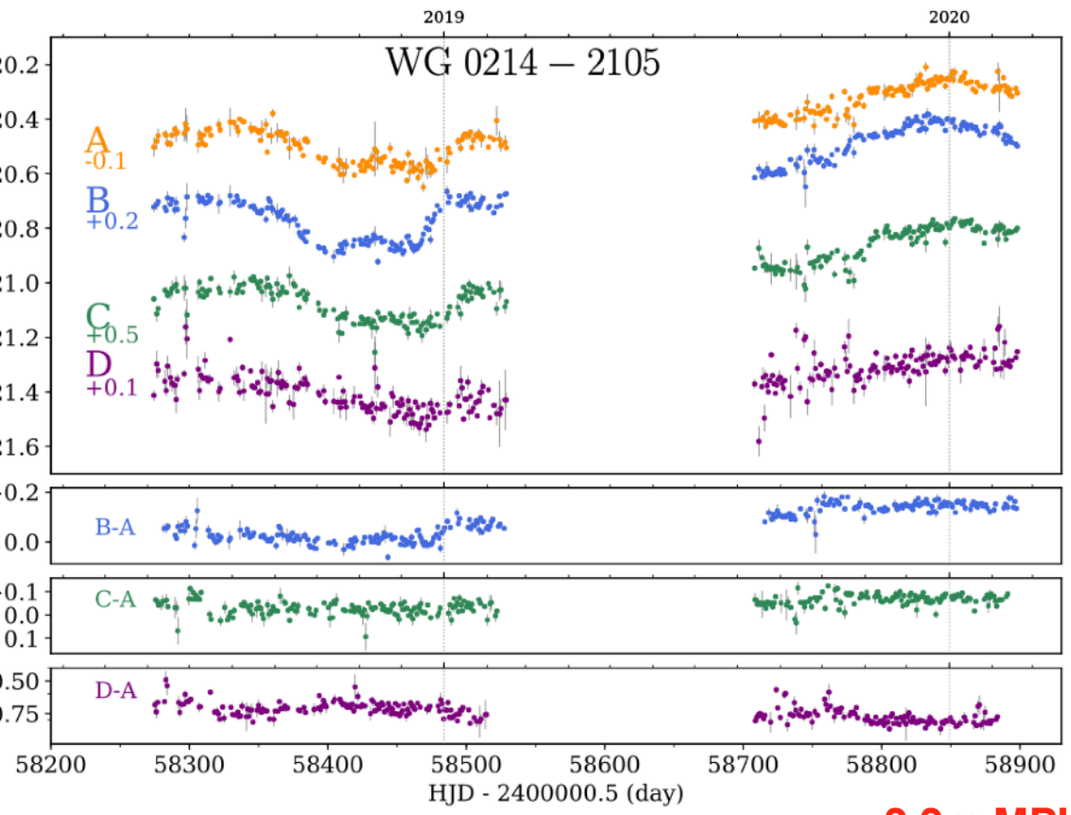
Bonvin et al. 2019, A&A 629, A97

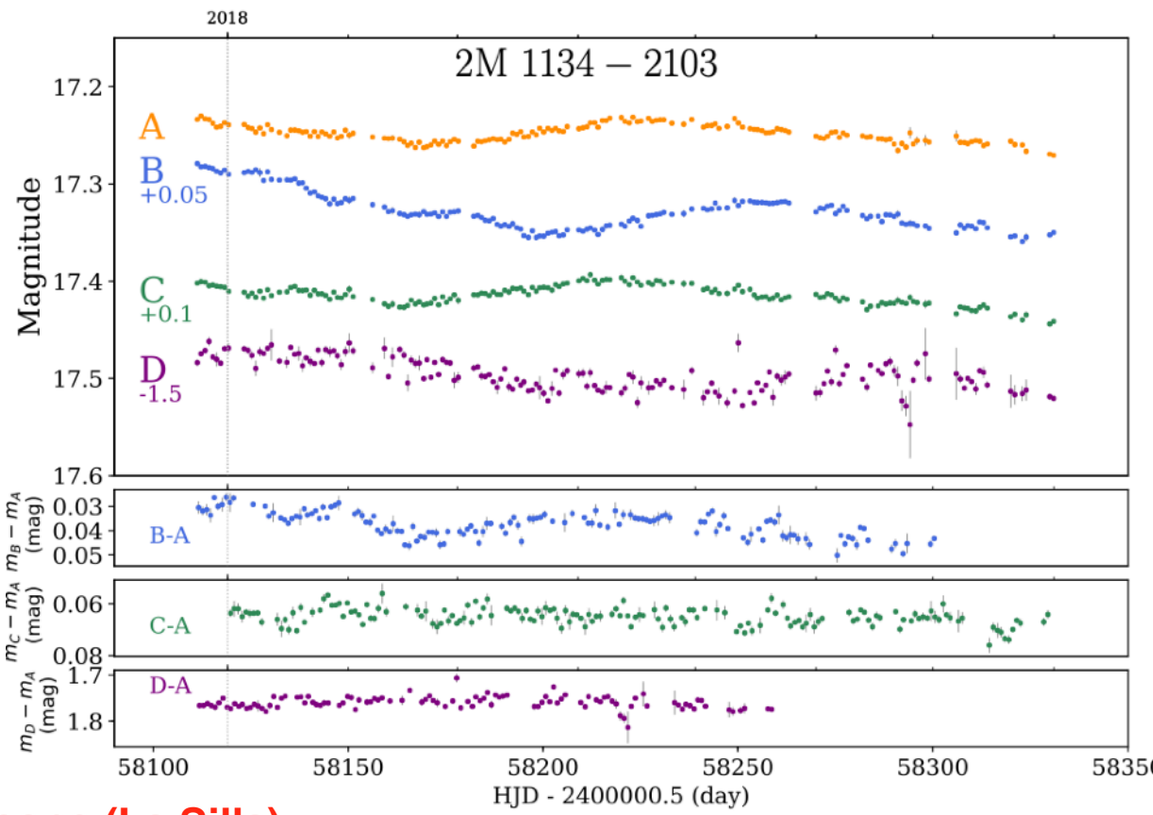
MPIA 2.2m Light Curves of WFI2033-4723



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

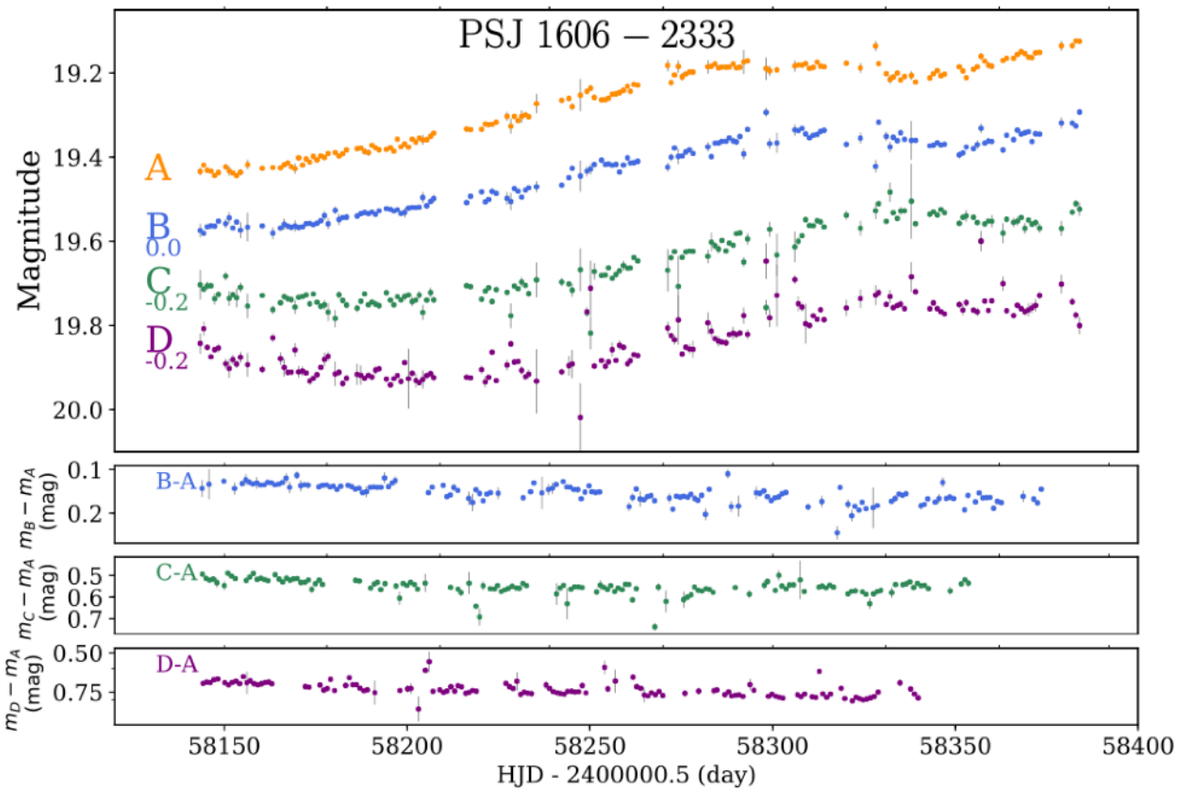
Mass Production of Time Delays





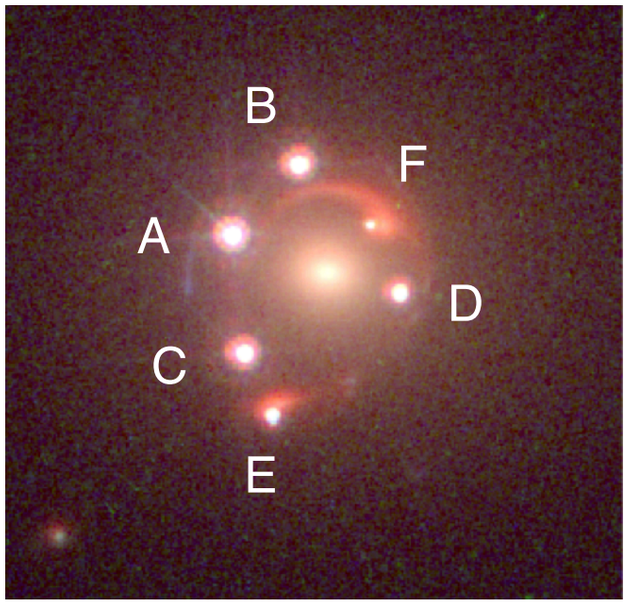
2.2m MPIA telescope (La Silla)

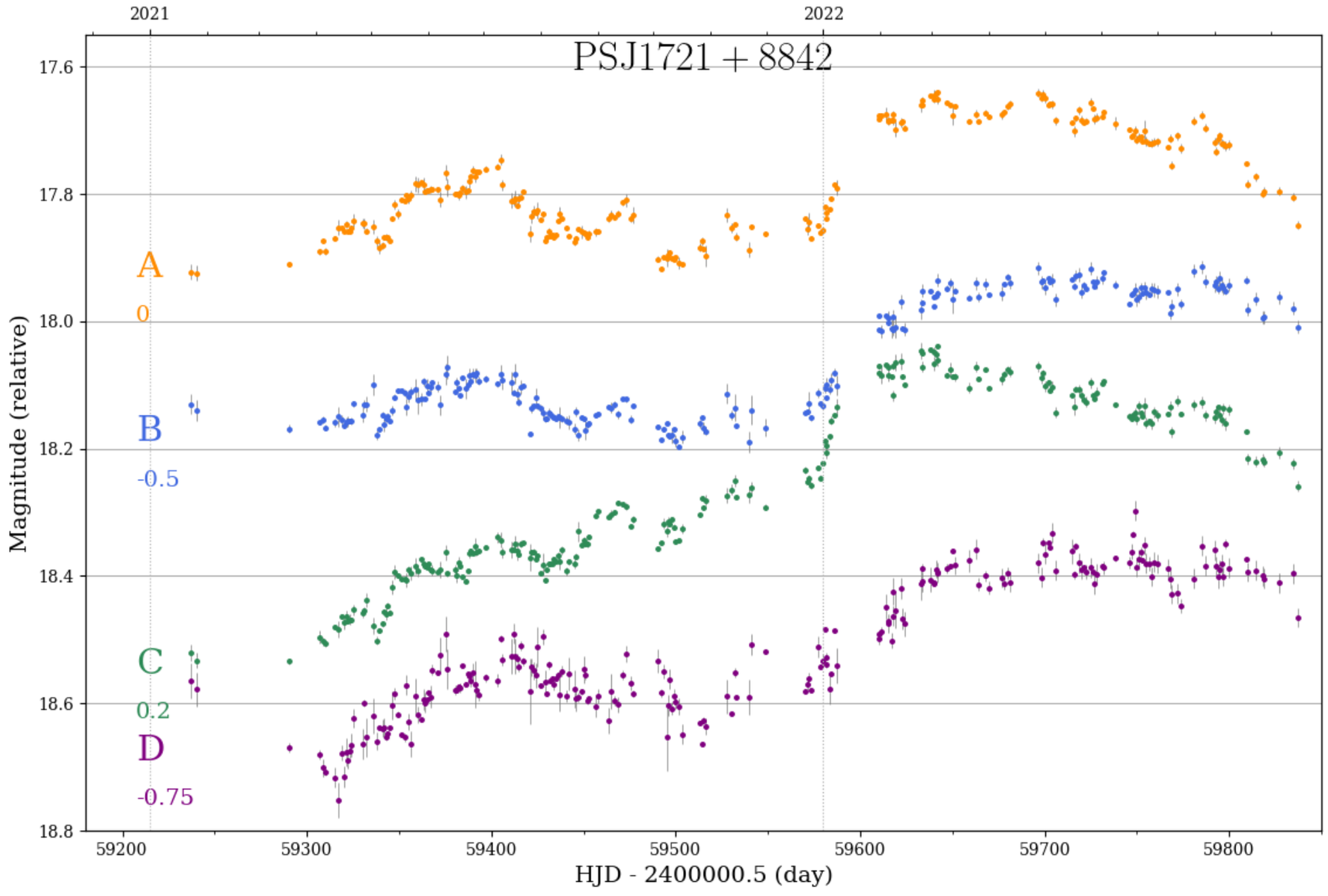
- 2m to 3m telescopes
- Daily cadence
- 30 min exposure per epoch
- 3 mmag precision per epoch
- Single-season measurement
- Better than LSST !
- More to come with 2000h of 2.6m VST



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

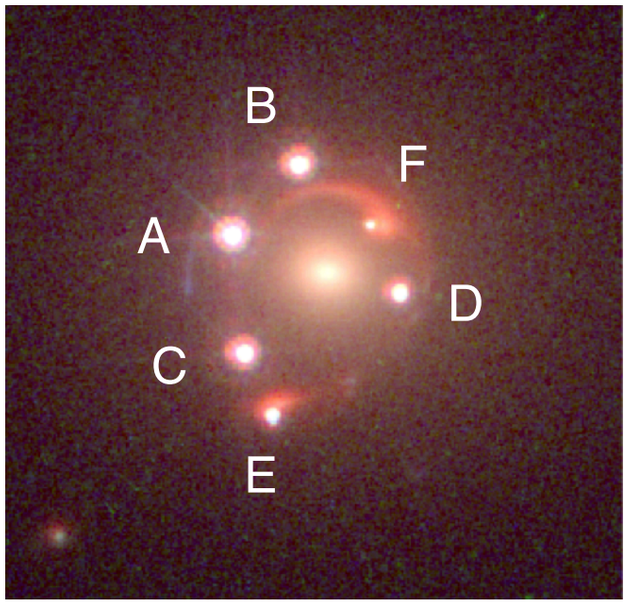
The 6-image quasar J1721+88 : NOT light curves



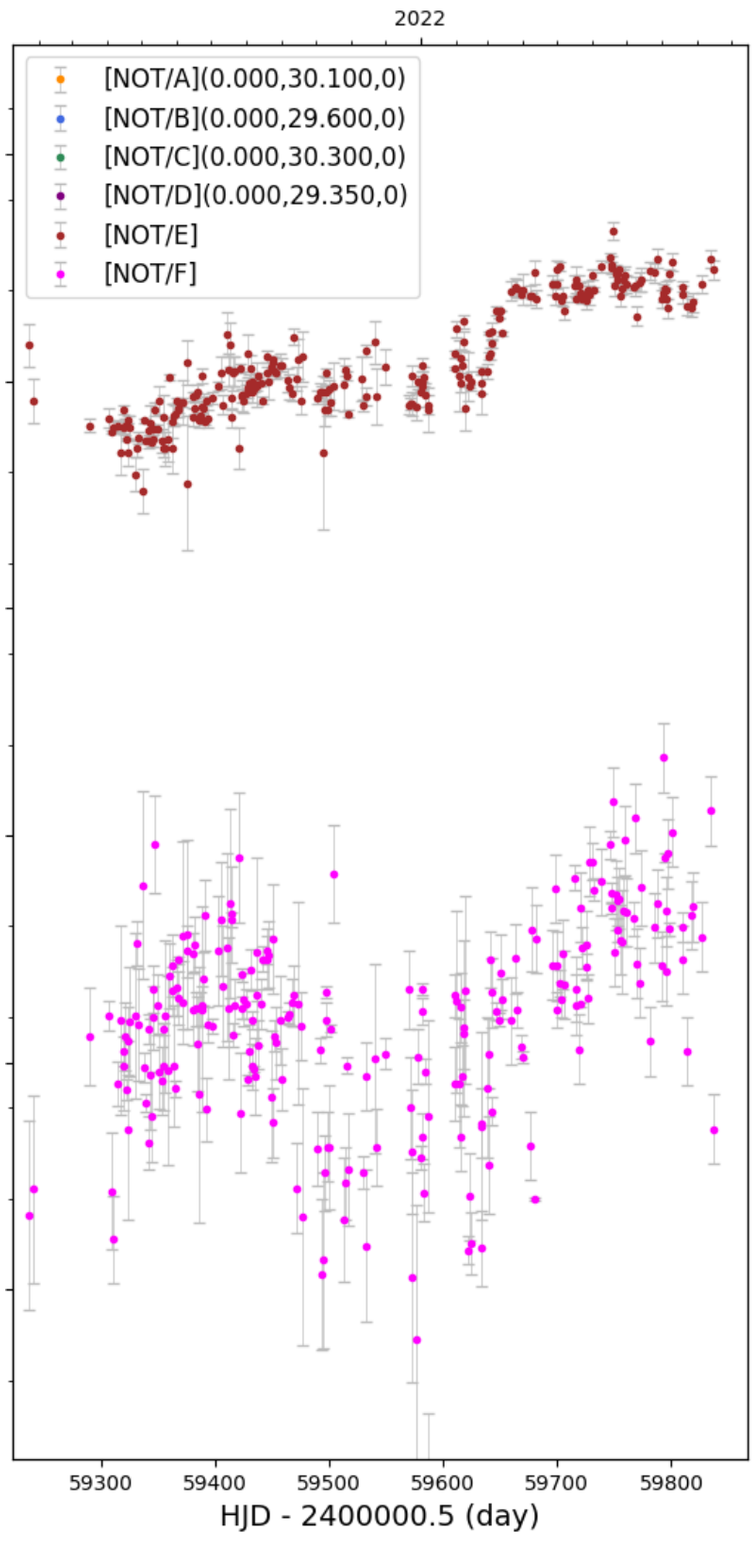


Eric Paic, FC, Martin Millon et al. 2023, in prep

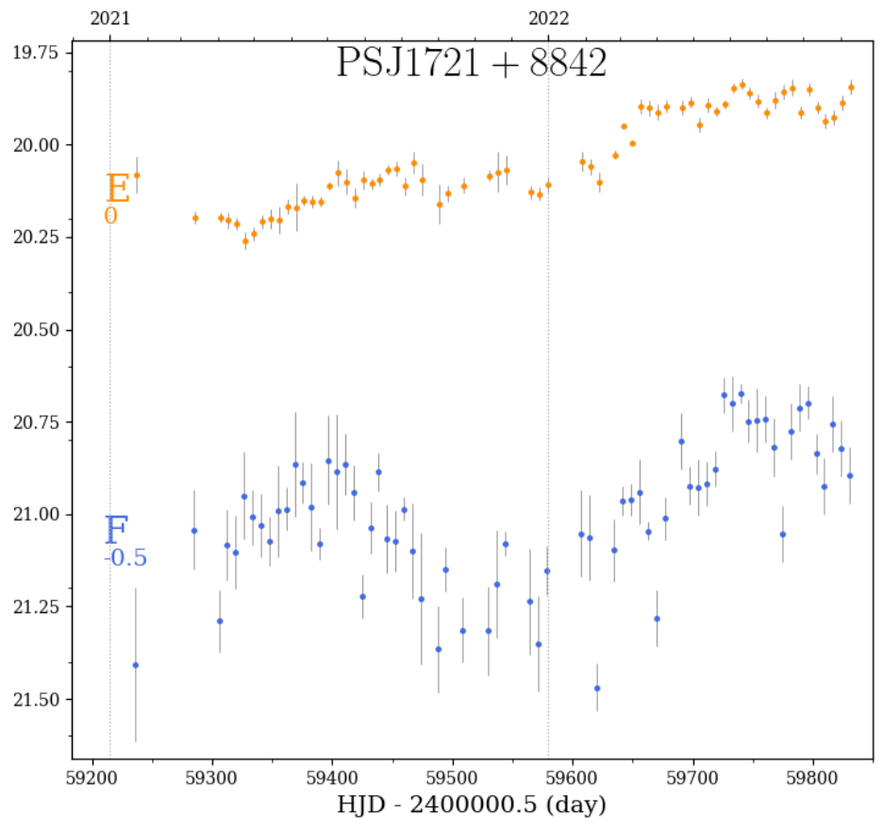
The 6-image quasar J1721+88 : NOT light curves



Daily cadence



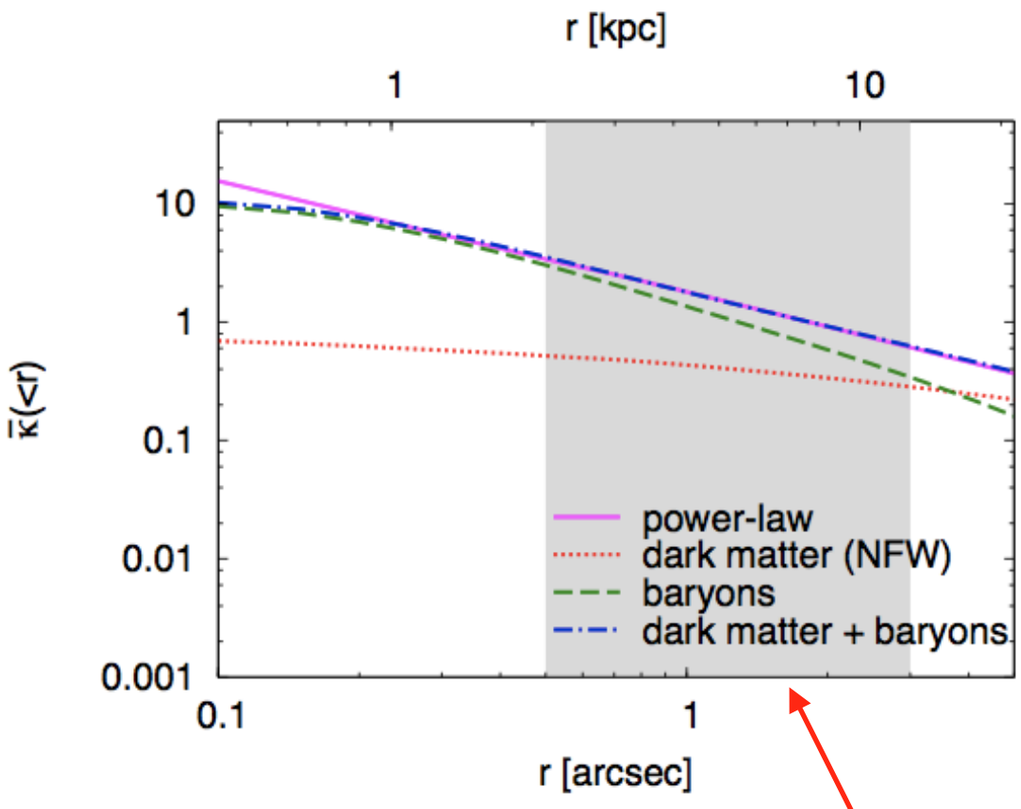
1-week binning

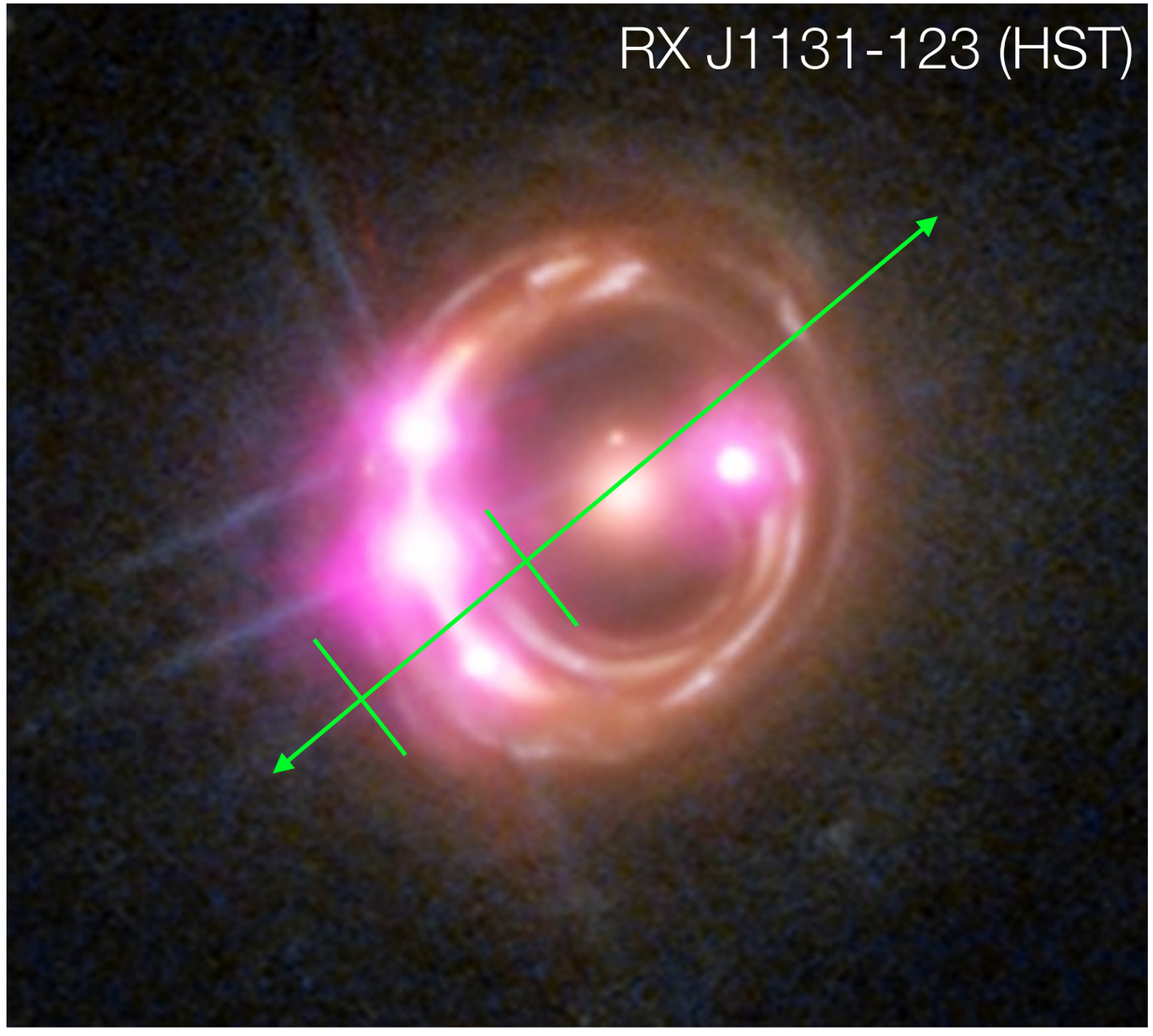


Eric Paic, FC, Martin Millon et al. 2023, in prep

2- Constraining the Mass Slope

Constraining Models with Thick Rings



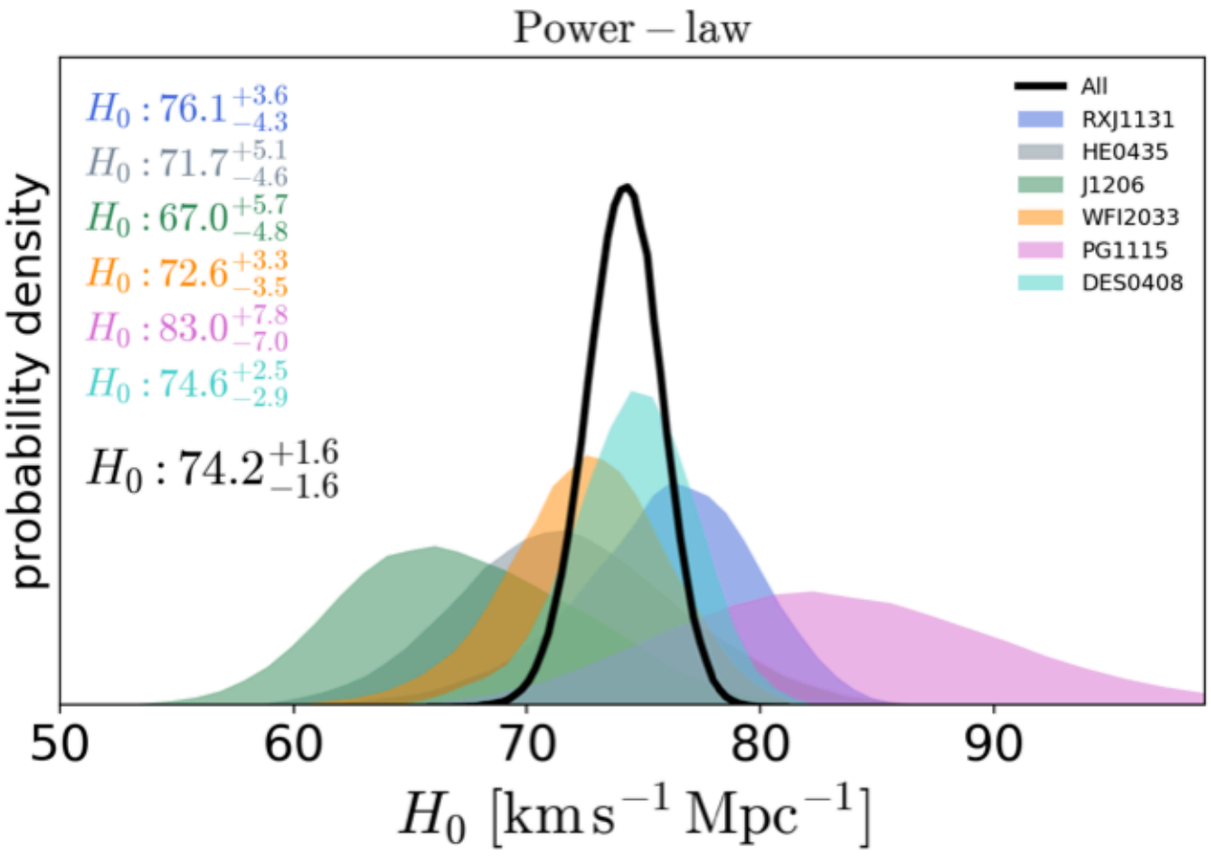


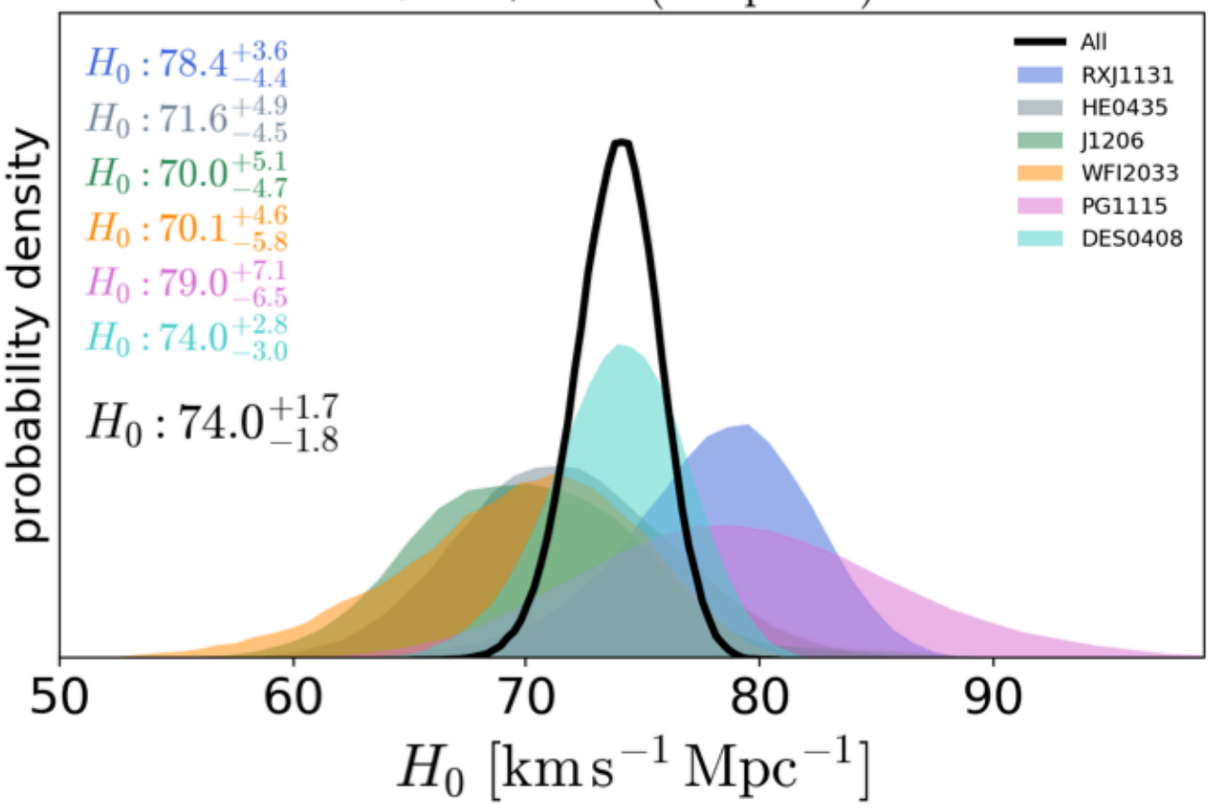
Lensing constraints come from all pixels covered by the Einstein ring formed by the quasar host

More complex models and simple power-law converge to the same mass slope

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)

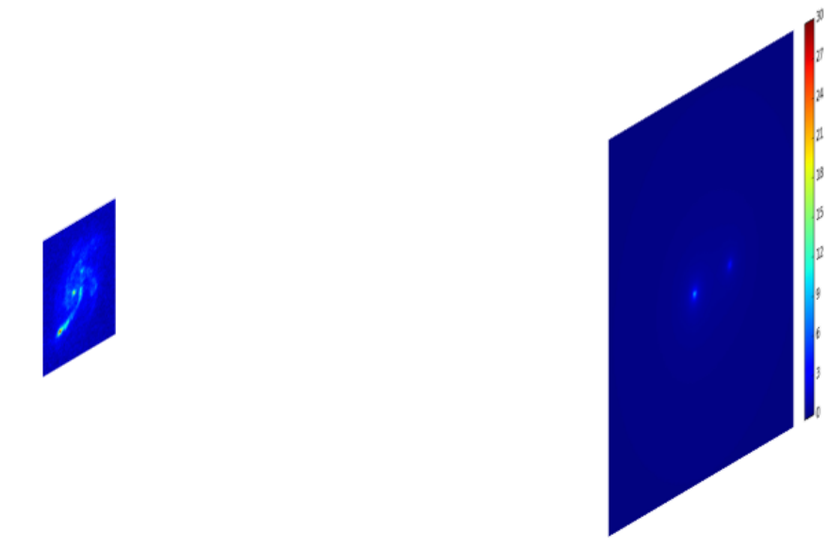
Source plane

Mass

Lensed images

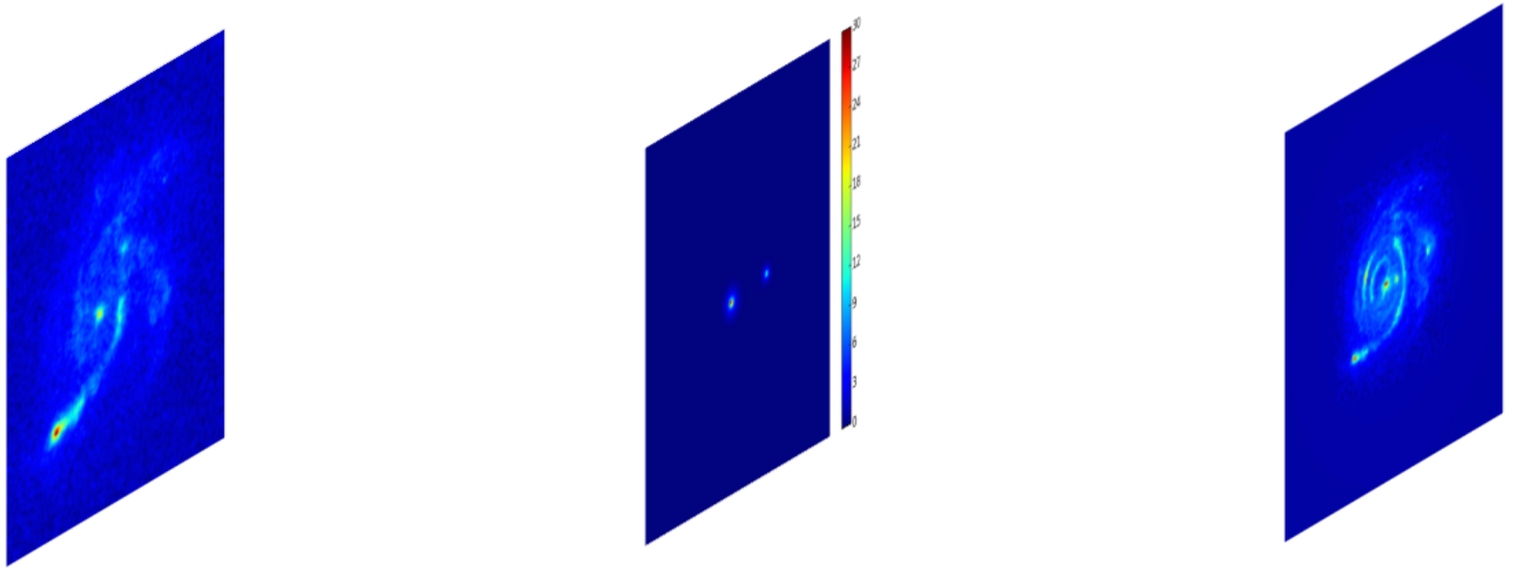
$\underline{\beta}$

κ



$\lambda\underline{\beta}$

$\lambda\kappa + (1-\lambda)$



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

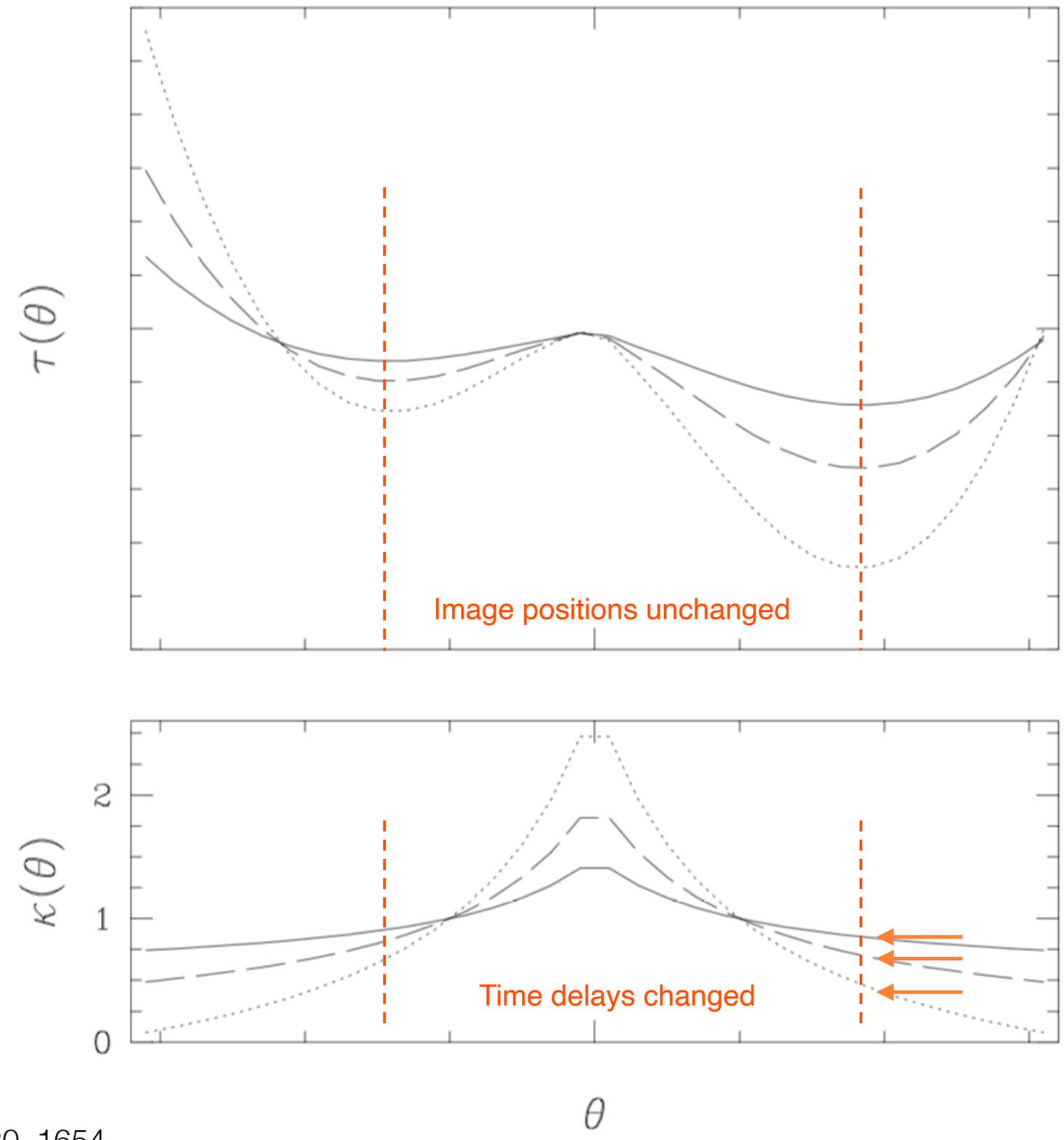
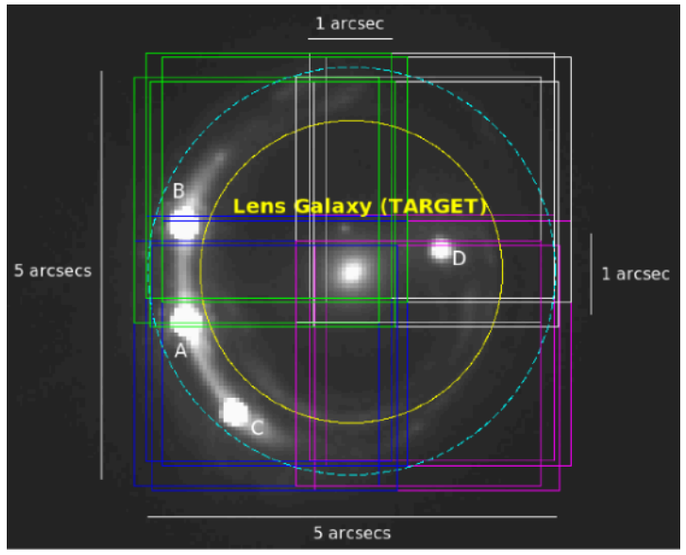


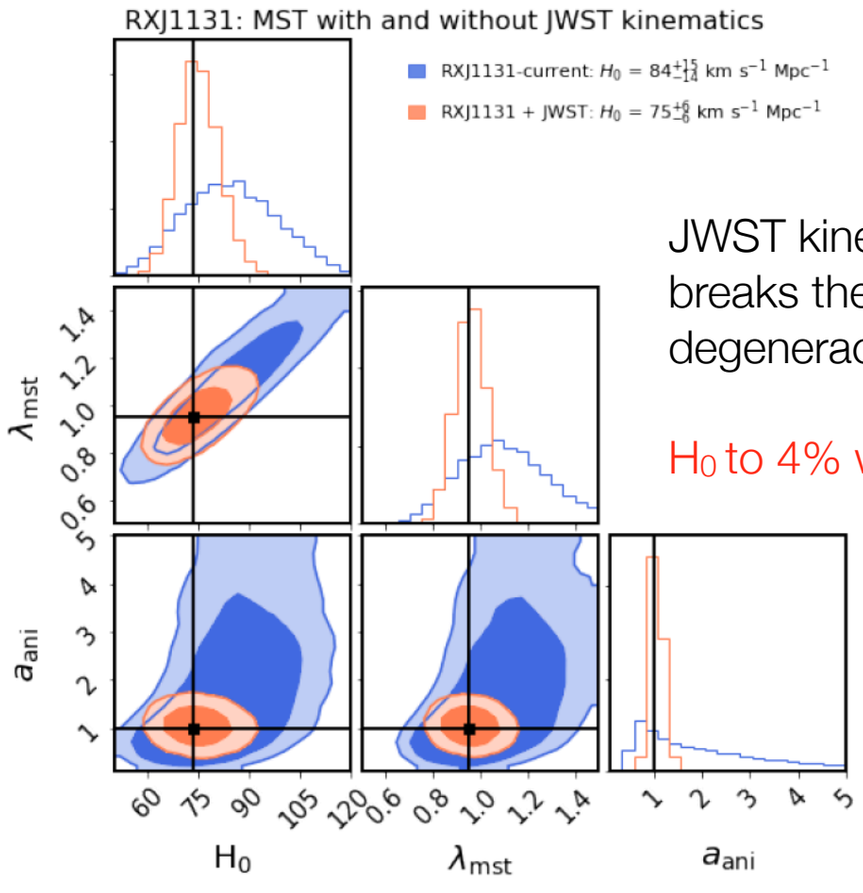
Figure adapted from Saha, 2000, AJ 120, 1654

Future Avenues

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



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

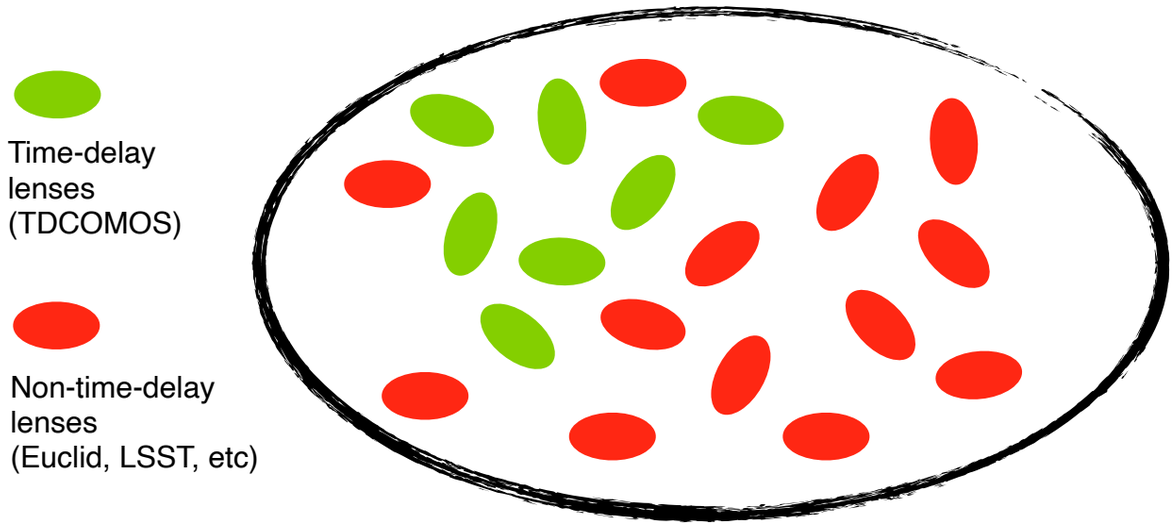


JWST kinematics breaks the Mass-sheet degeneracy

H_0 to 4% with 1 single lens

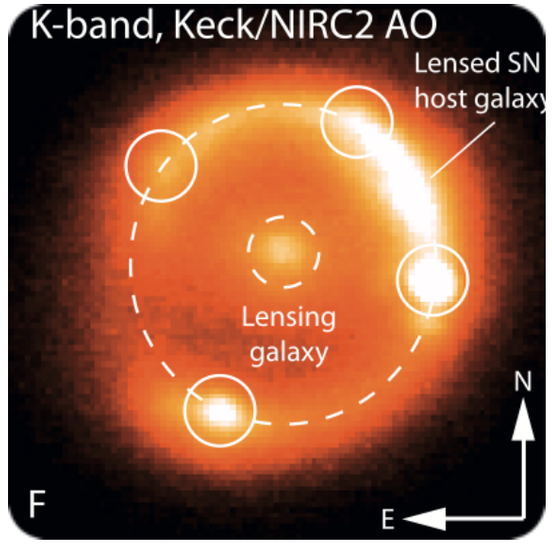
TDCOSMO collaboration

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 (Euclid is a key-player here !)

Lensed supernovae



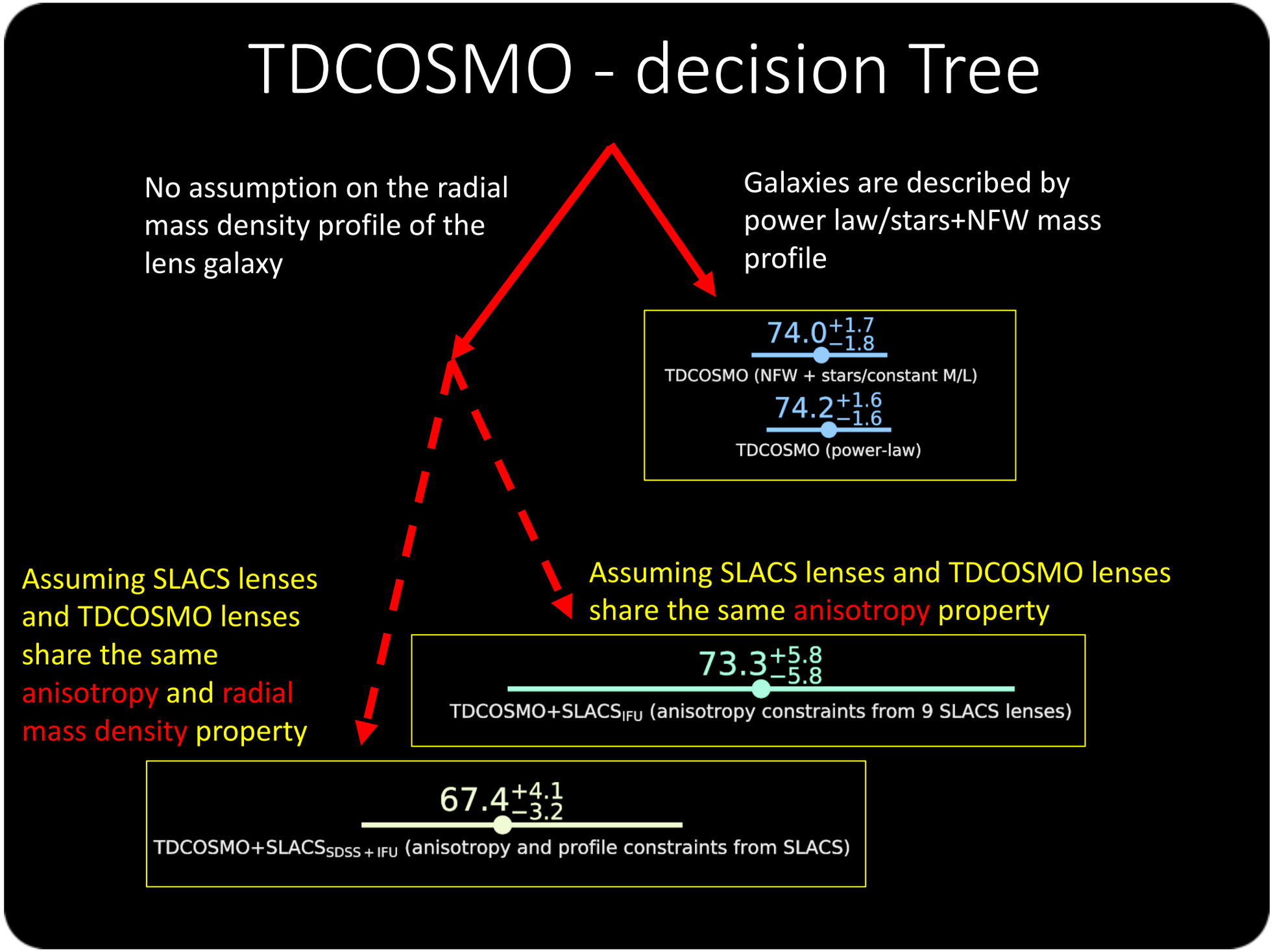
Ongoing search

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

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

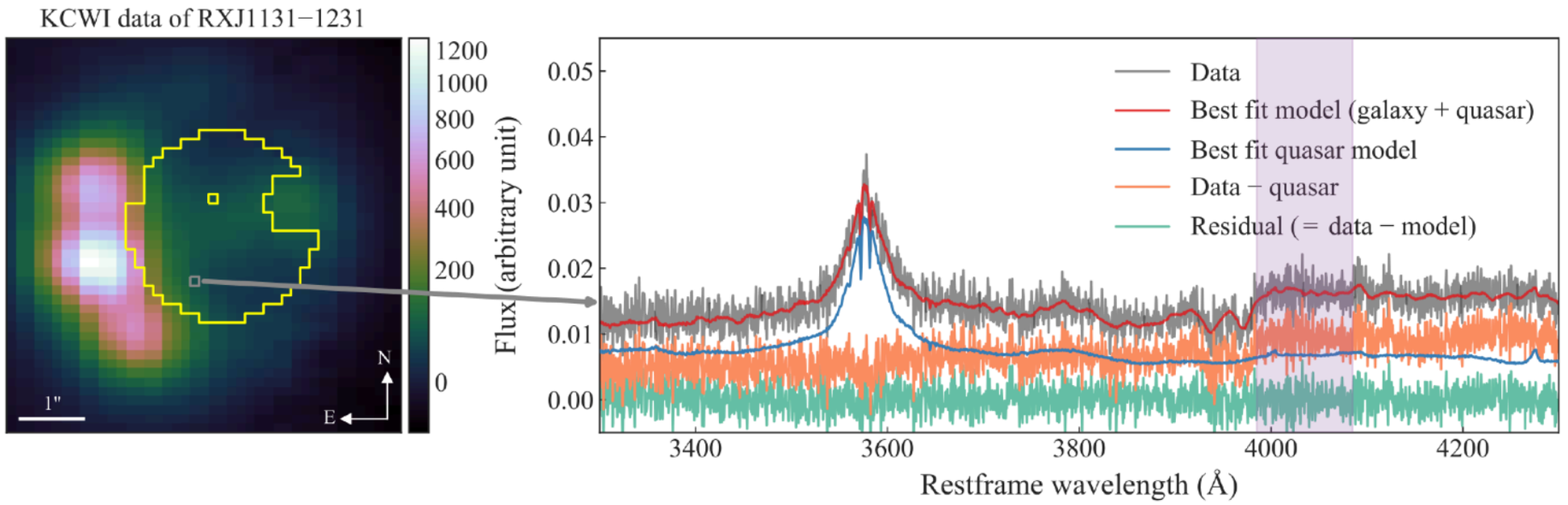
Goobar et al. (2017, Science 356, 291)

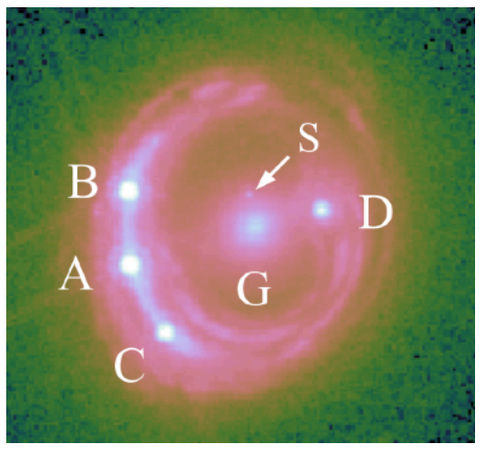
Avenue #1 - Hierarchical Bayesian Analysis

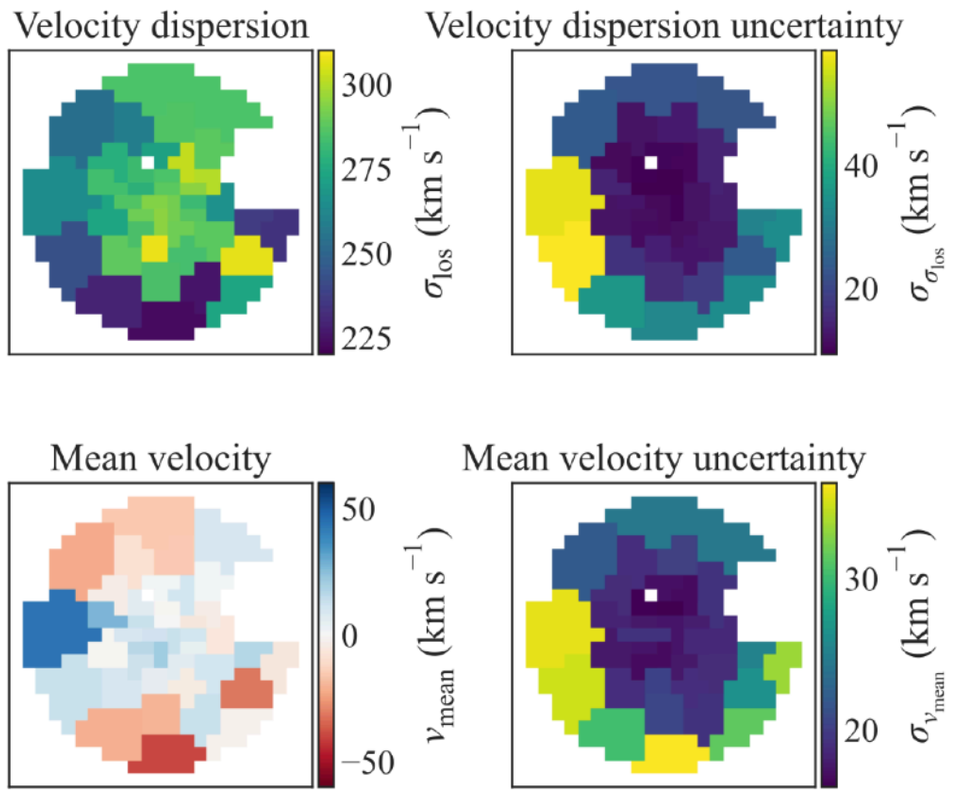


Birrer et al. 2020, A&A 643, A165 (TDCOSMO IV)

Avenue #2 - Dynamics of Time-Delay Lens Galaxies





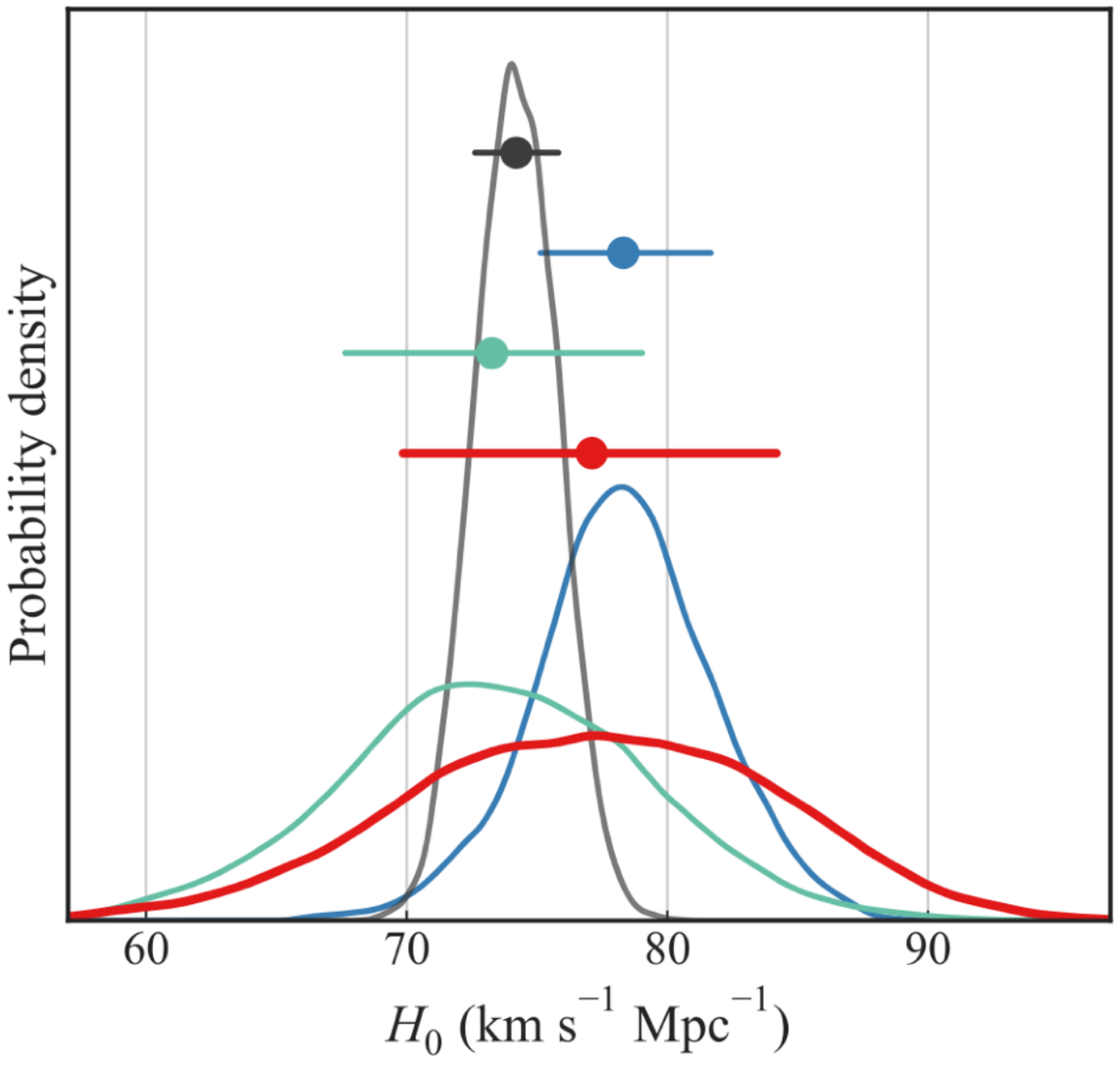


4h of Keck KCWI IFU spectroscopy (no-AO)

More to come with VLT-MUSE, Keck, JWST

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

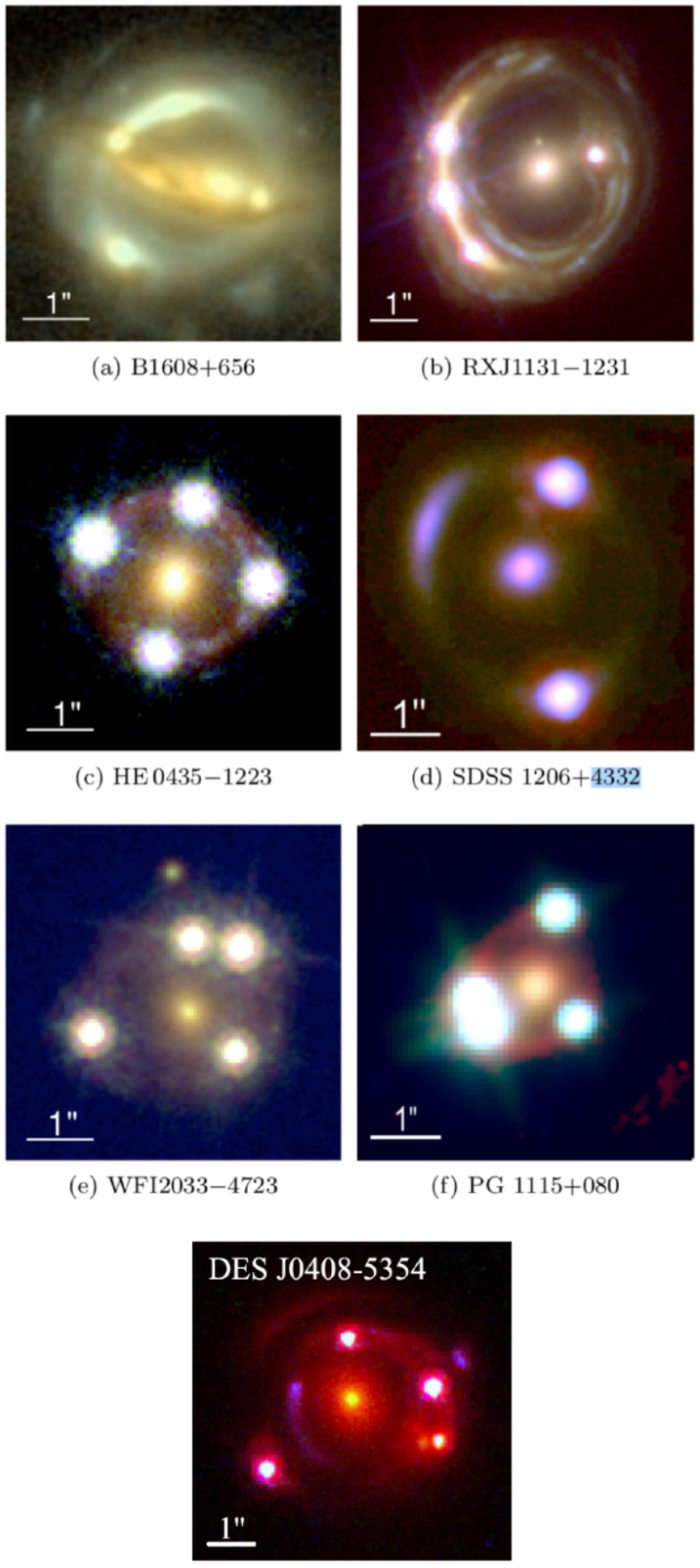
Avenue #2 - Dynamics of Time-Delay Lens Galaxies



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