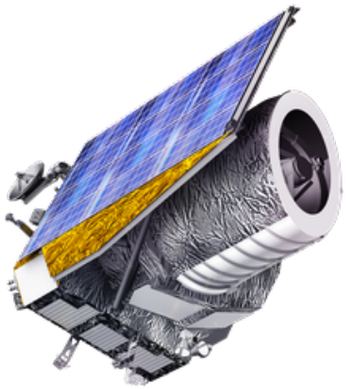
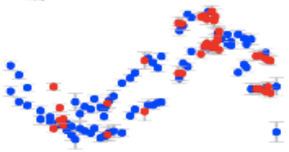
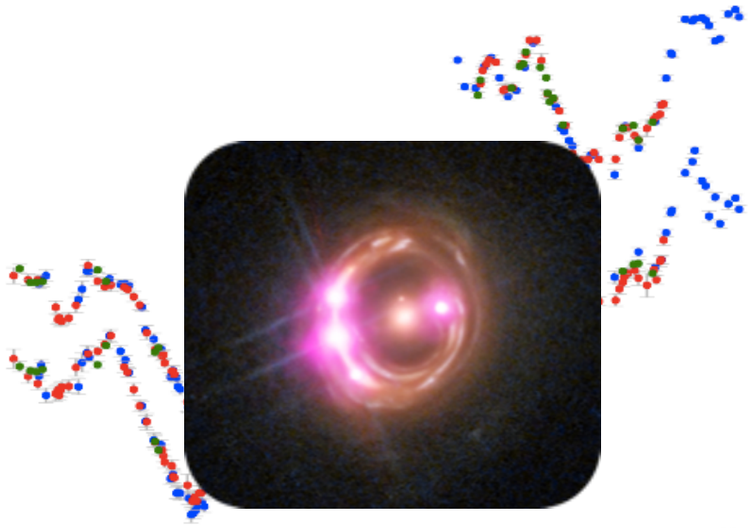
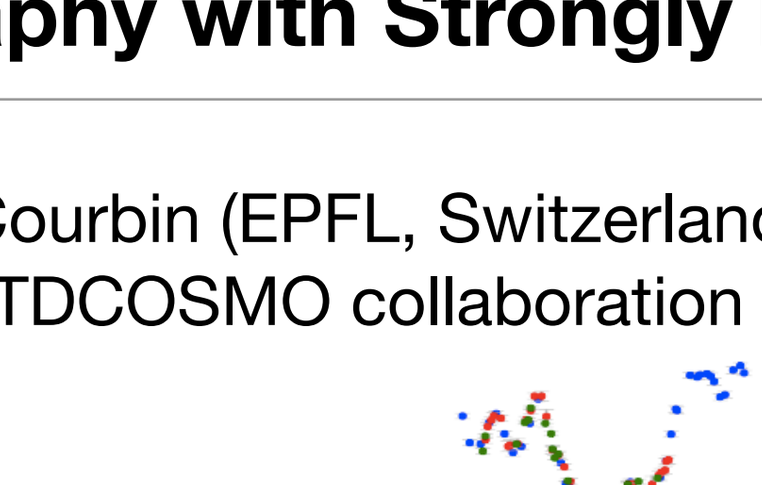
Time Delay Cosmography with Strongly Lensed quasars

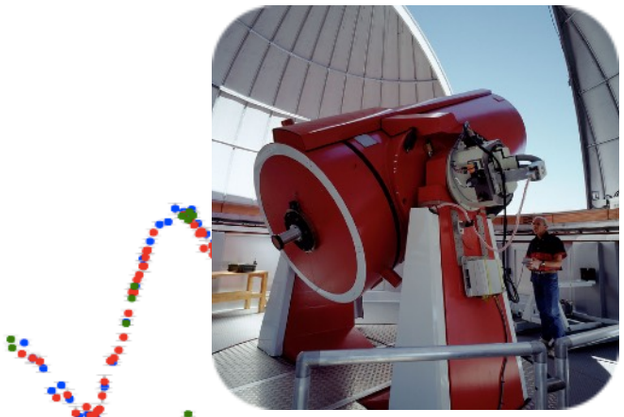
Frédéric Courbin (EPFL, Switzerland)
For the TDCOSMO collaboration

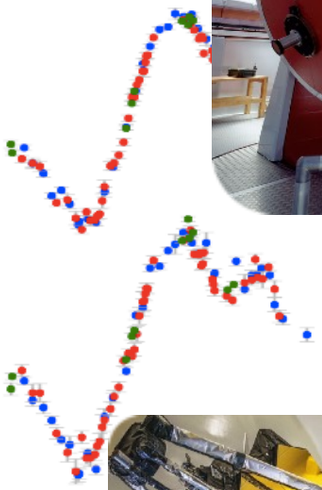












COSMICLENS

European Research Council
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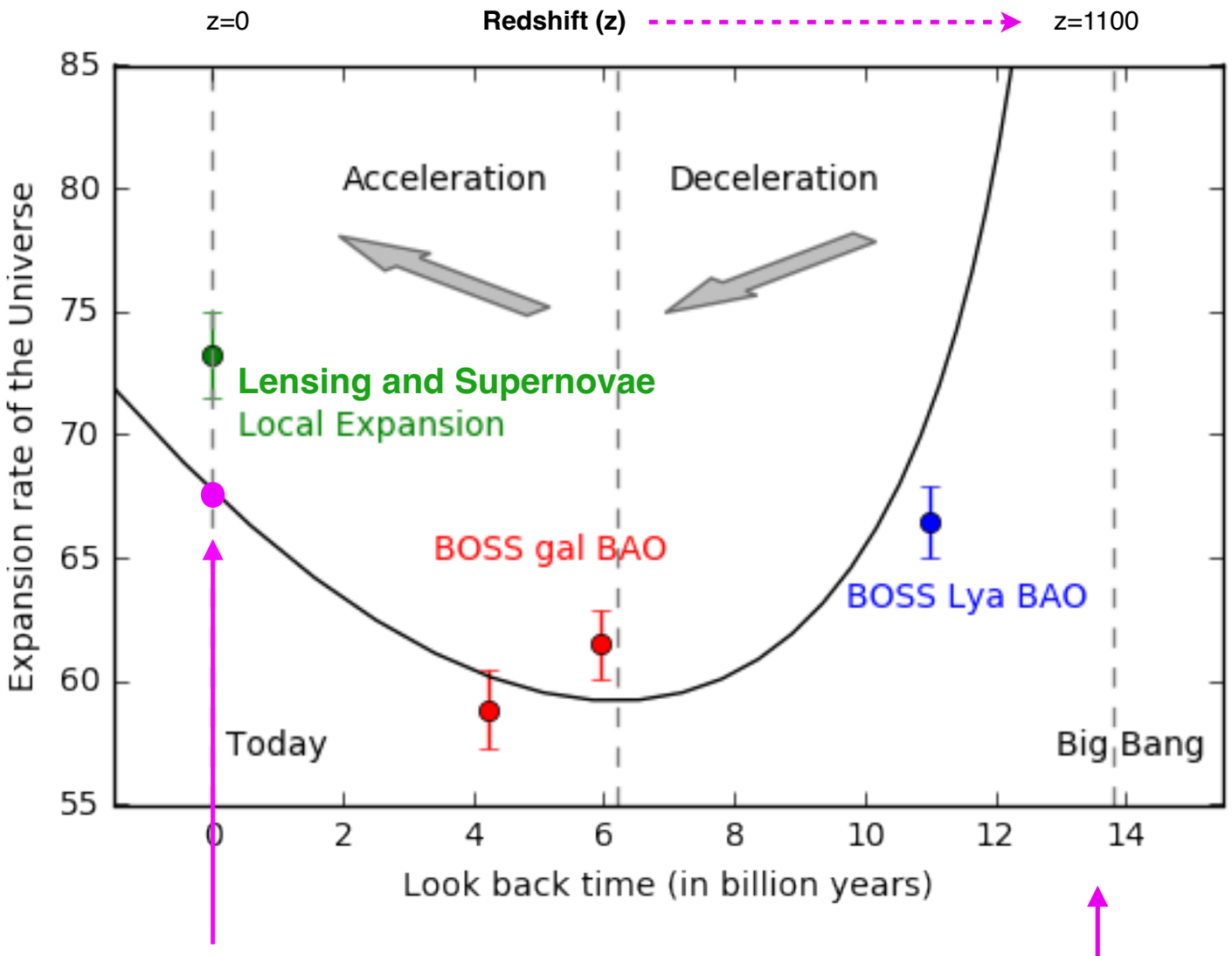
Ecole Polytechnique Fédérale de Lausanne (EPFL)

Frascati - September 2023

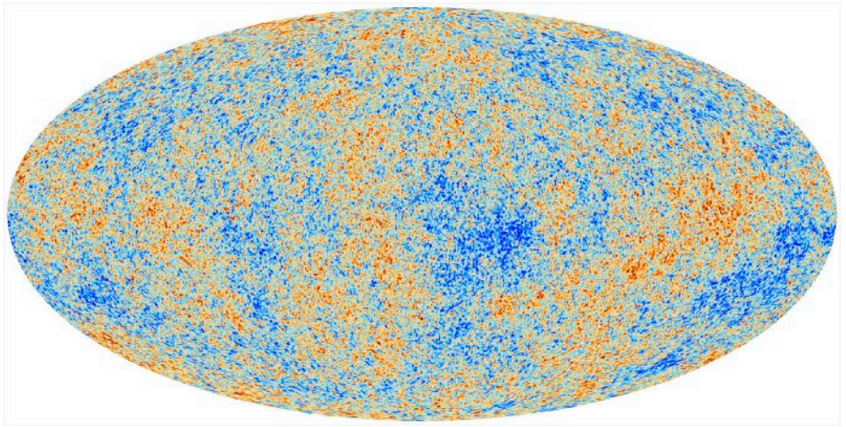
The H_0 Tension Between Early and Late Universe Probes

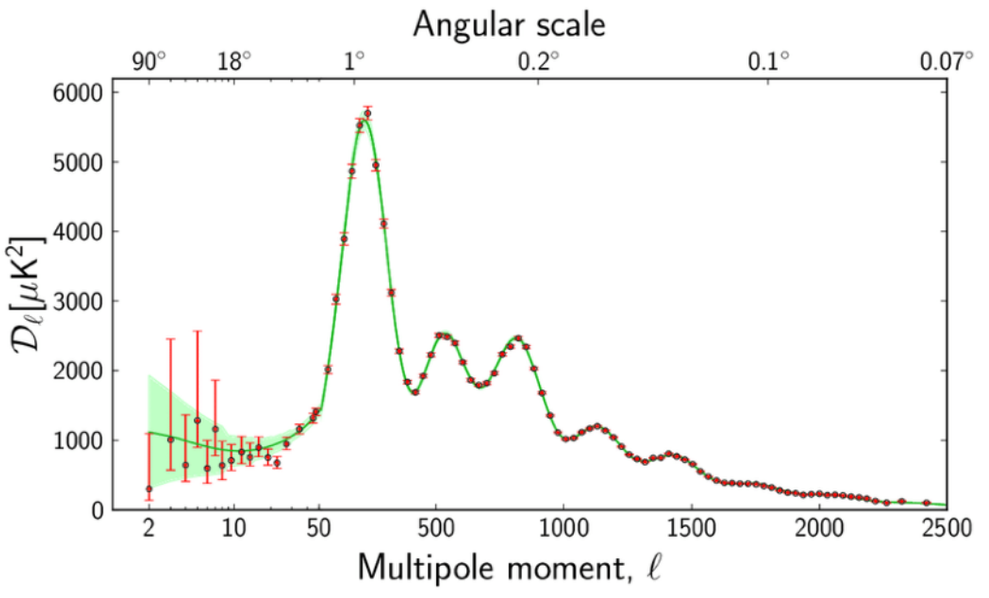
The tension/crisis means either **new physics or problems** with measurements



Value from Cosmic Microwave Background extrapolated (with cosmo model) to present epoch

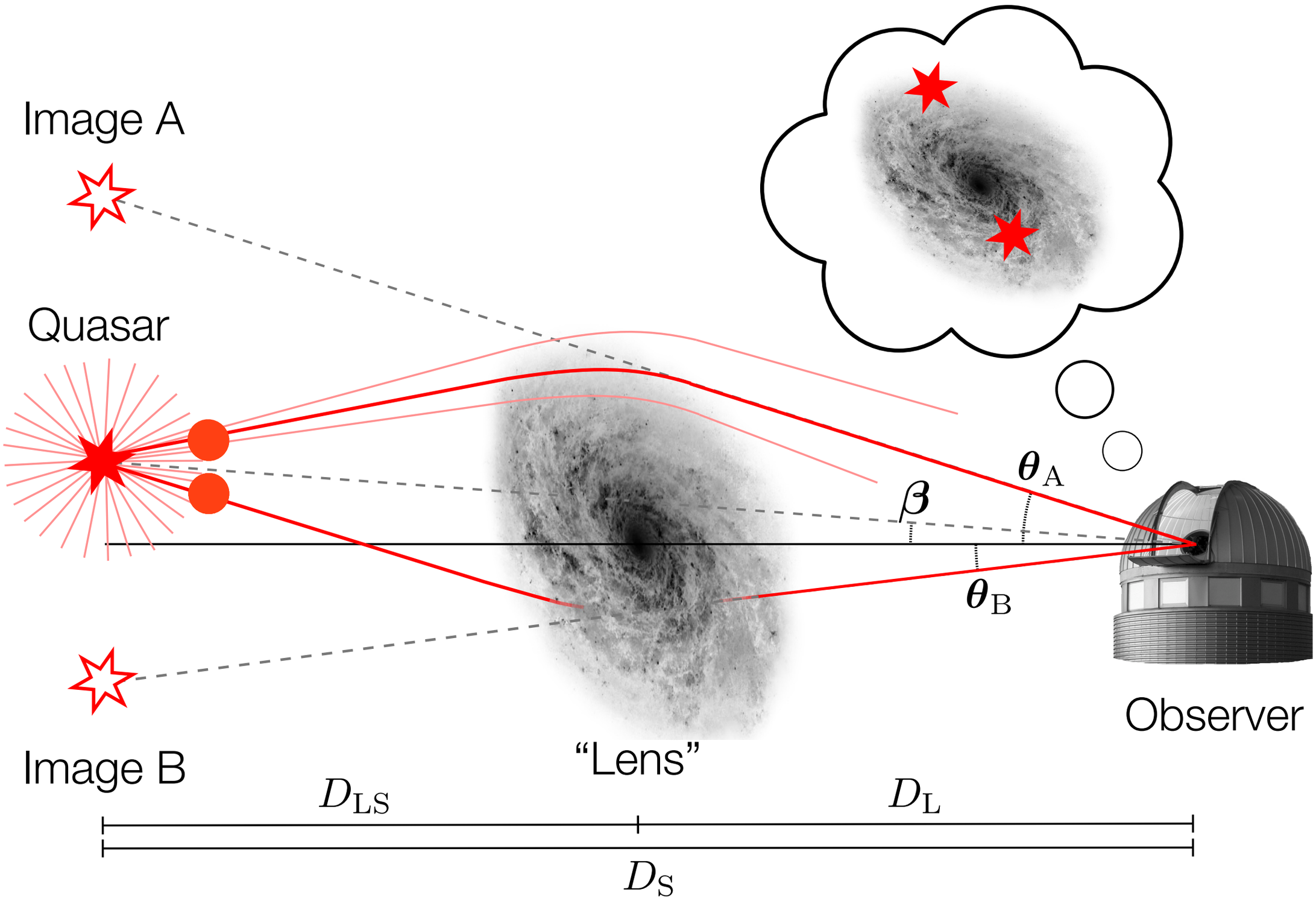
Cosmic Microwave Background from Planck satellite



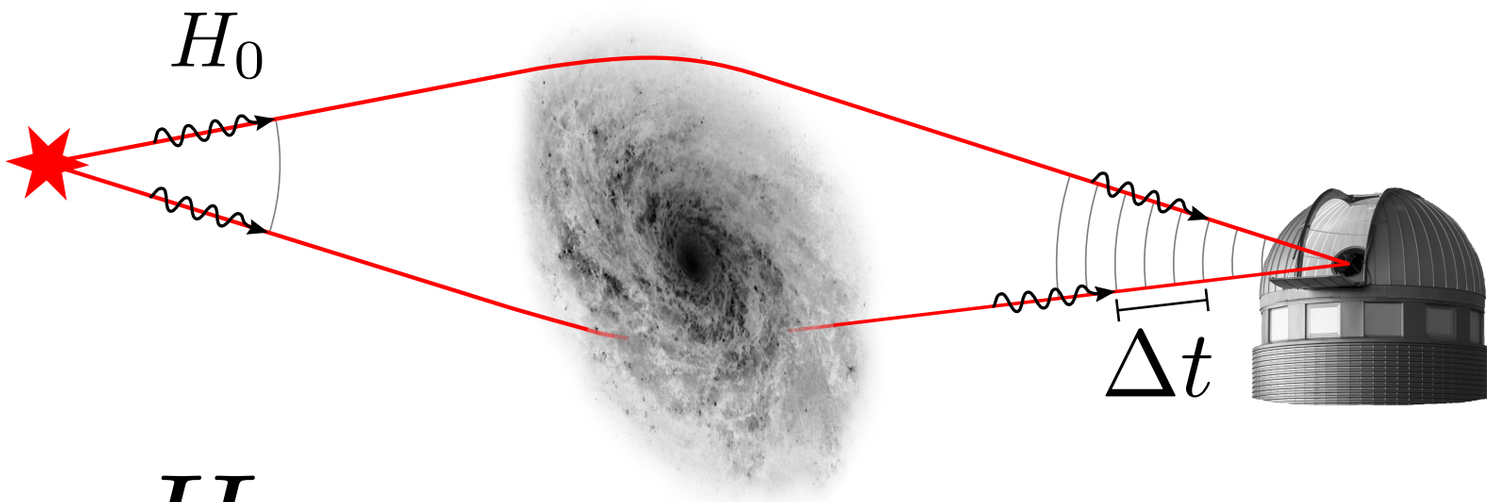


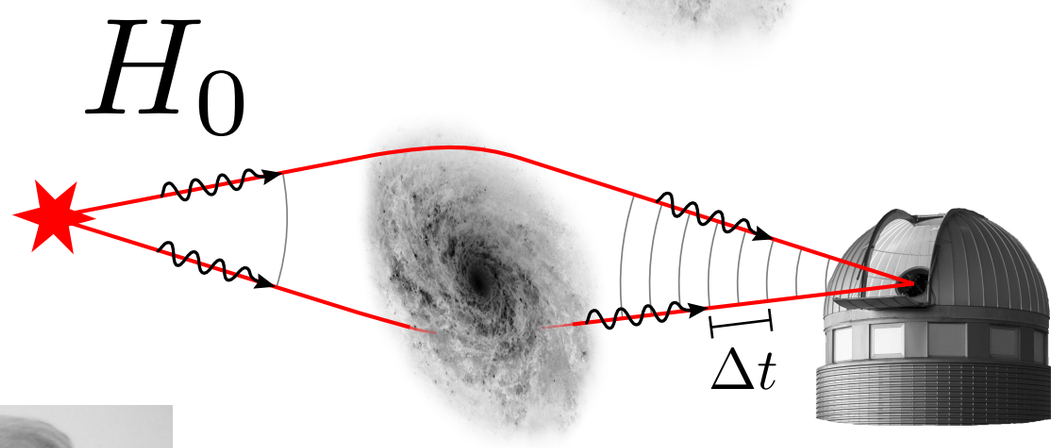
Cosmic Microwave Background measures H(z=1100) here !

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)

Ingredients

Time delays between lensed images

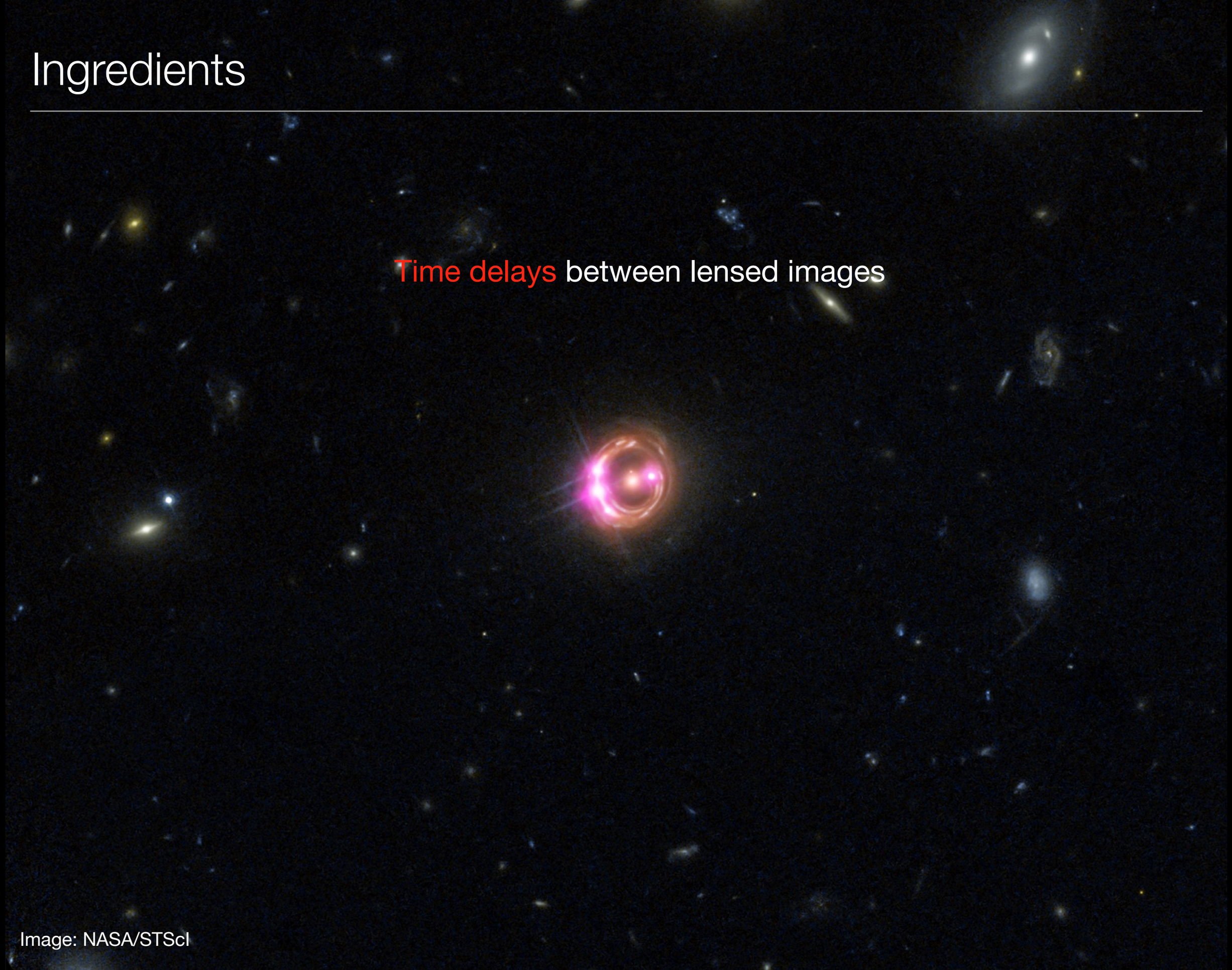


Image: NASA/STScI

Ingredients

Time delays between lensed images

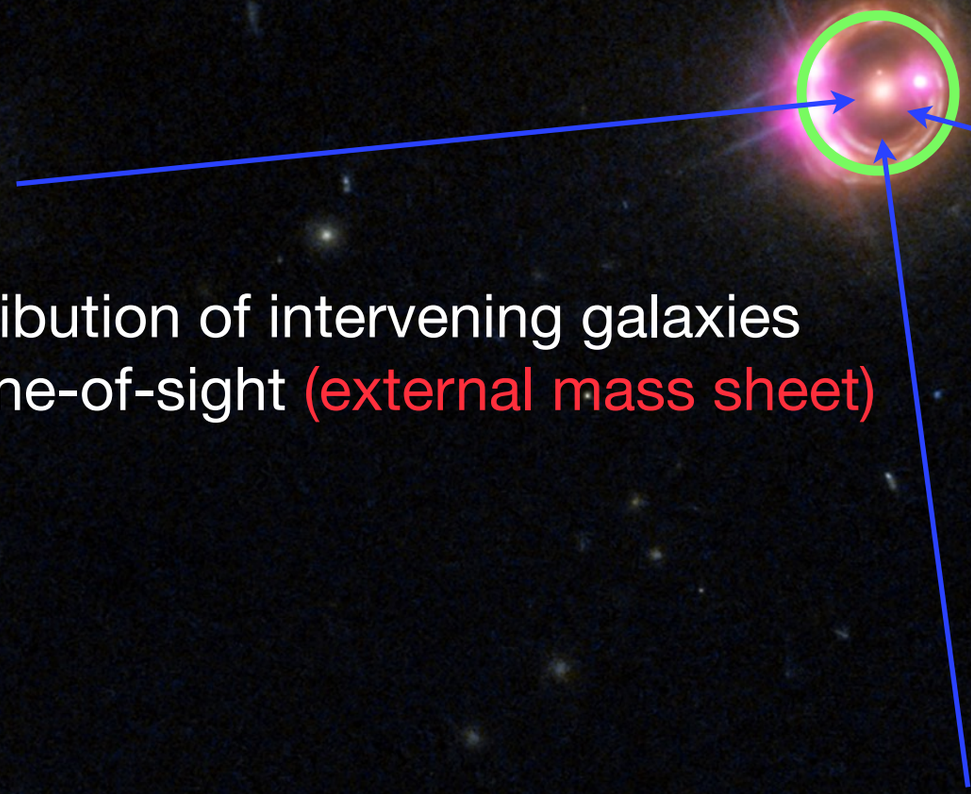
Mass in the Einstein ring
Mass slope at image position

Image: NASA/STScI

Ingredients

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

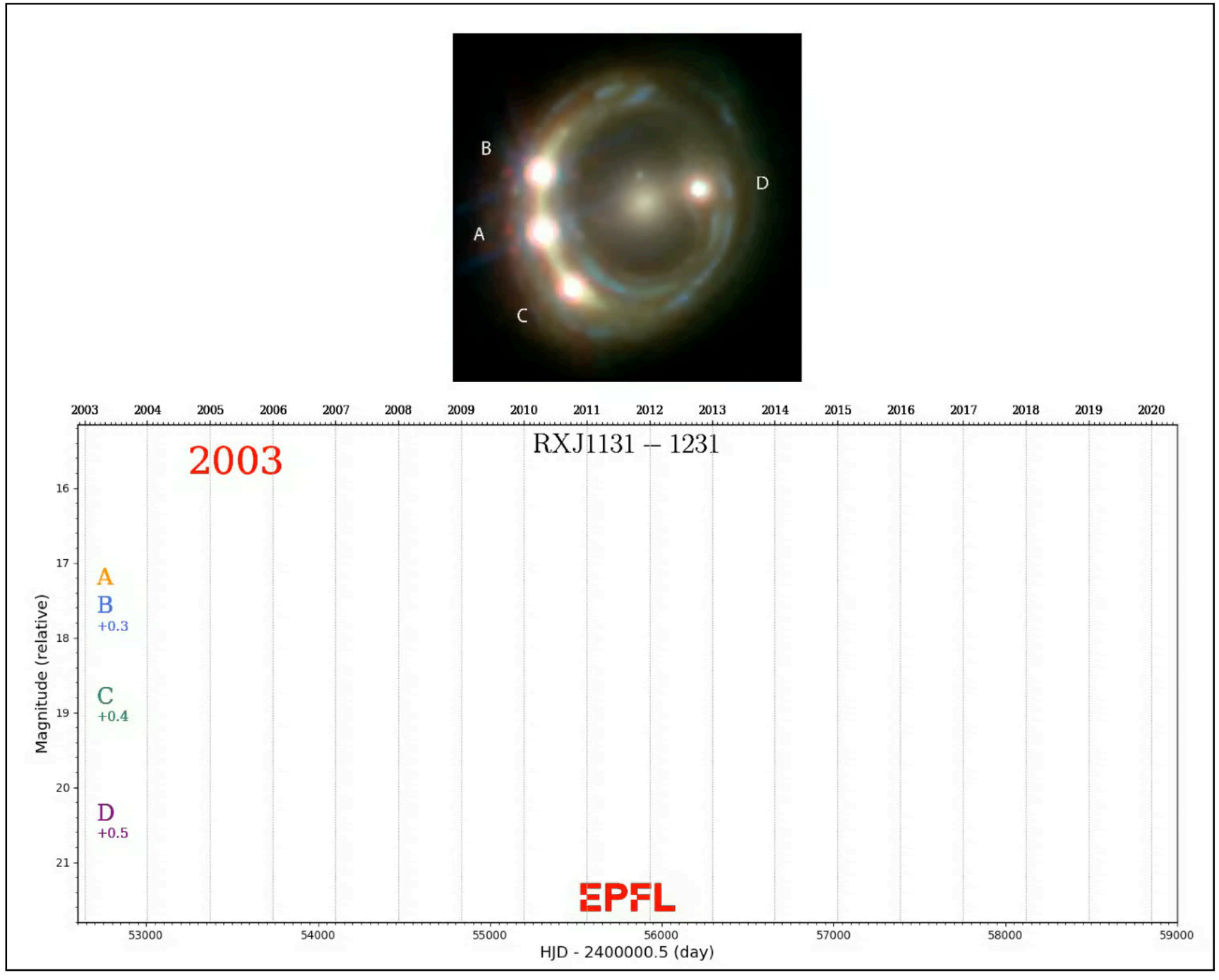
ALL ANALYSIS BLIND !

1- Time Delay Measurements

Photometry with image deconvolution

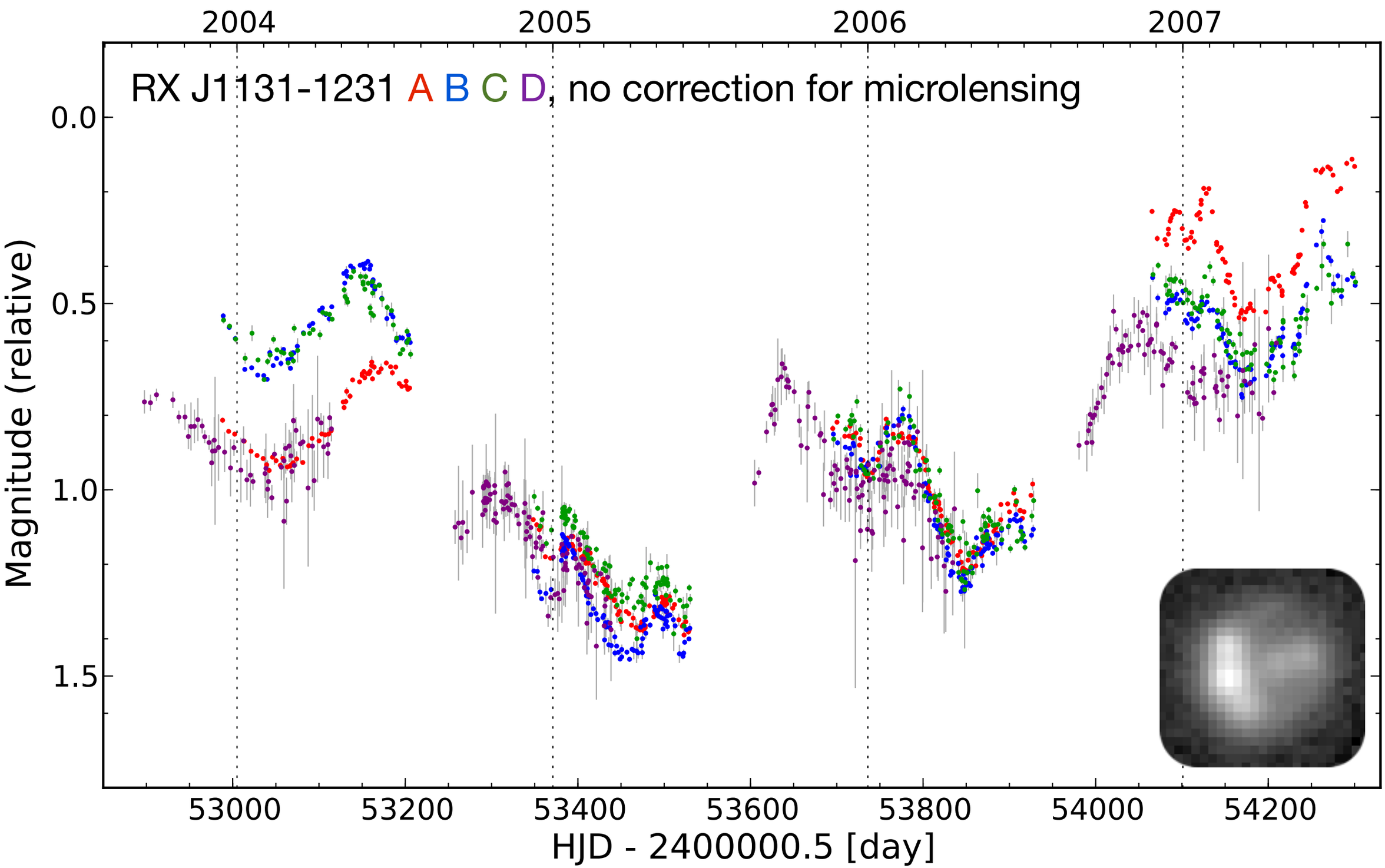
Deconvolution methods **with finite resolution** described in
Magain, Courbin, Sohy, 1998, ApJ 494, 472
Cantale, Courbin, et al. 2016, A&A 589, 81
Millon et al. 2023, JOSS 8, 5340: JAX version including wavelet regularization -> in Rubin-LSST pipeline

COSMOGRAIL Light Curves of RXJ1131-123

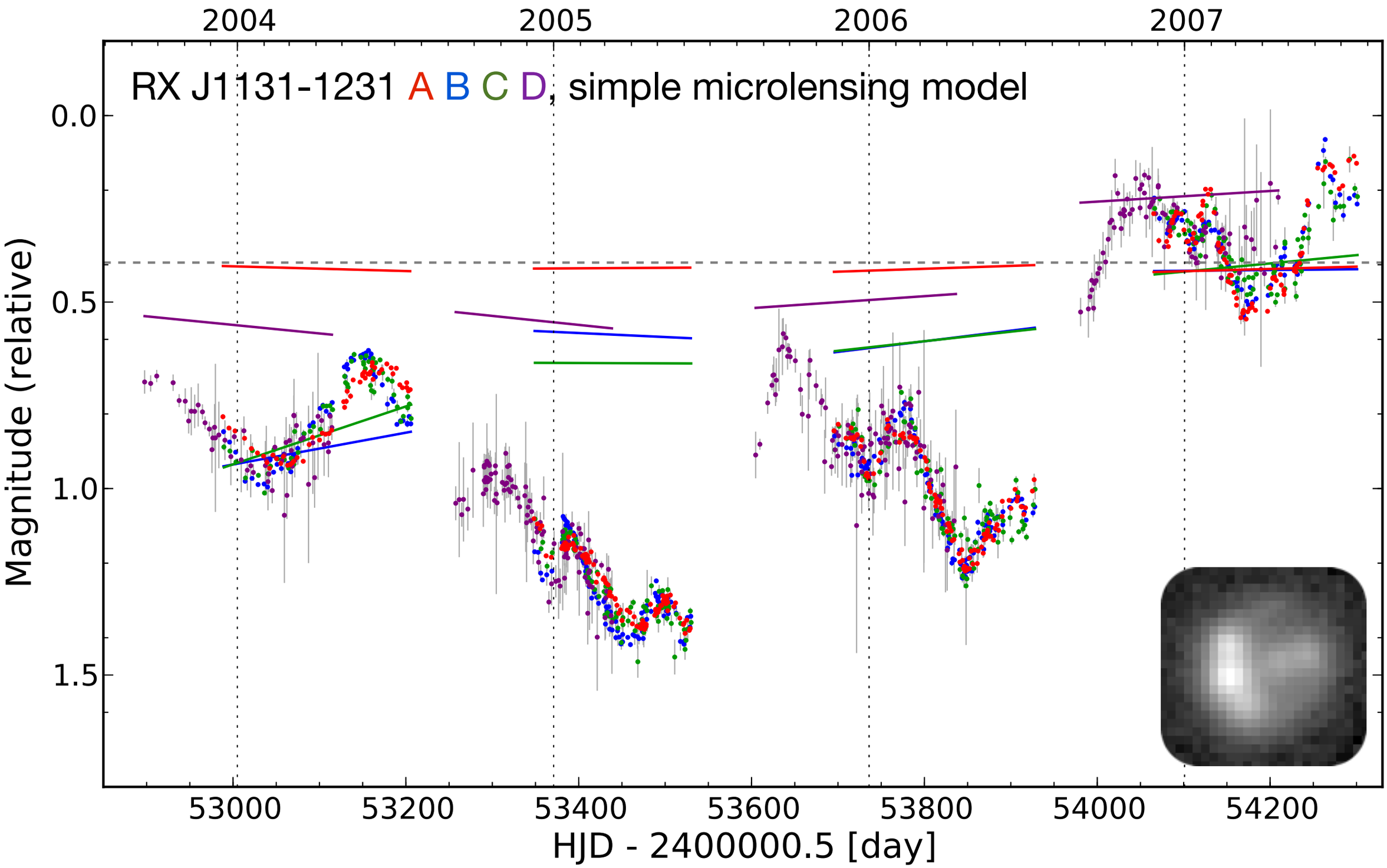


COSMOGRAIL collaboration

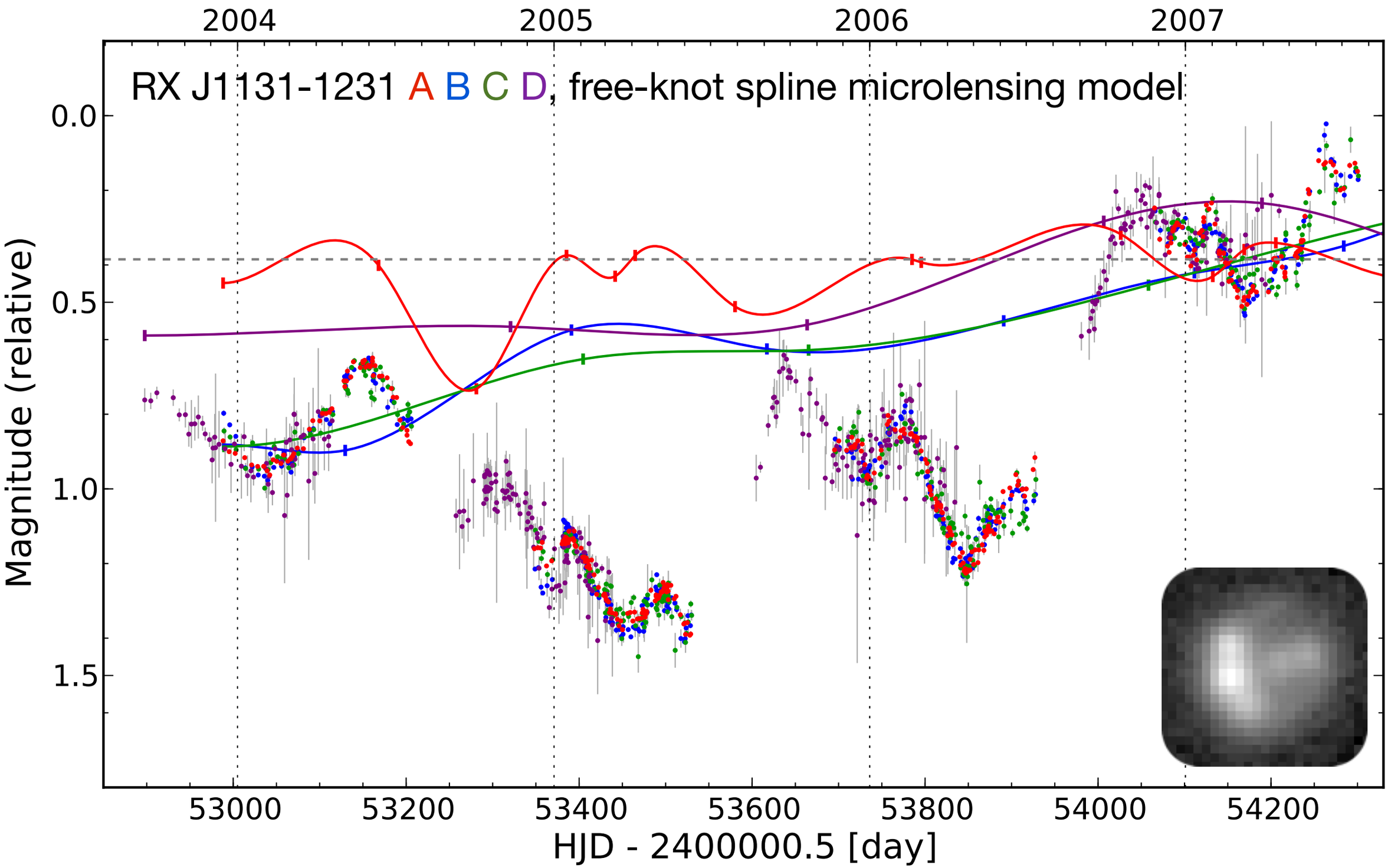
Microlensing Exacerbates Time Delay Measurements



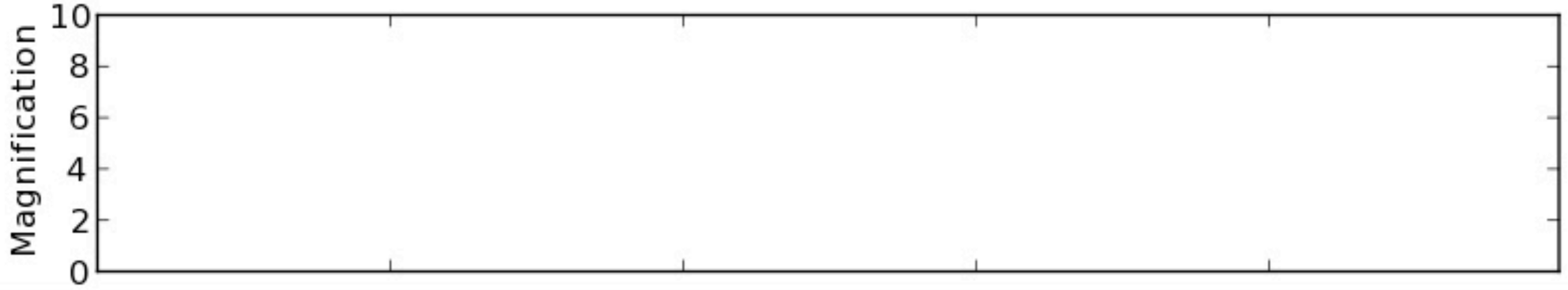
Microlensing Exacerbates Time Delay Measurements



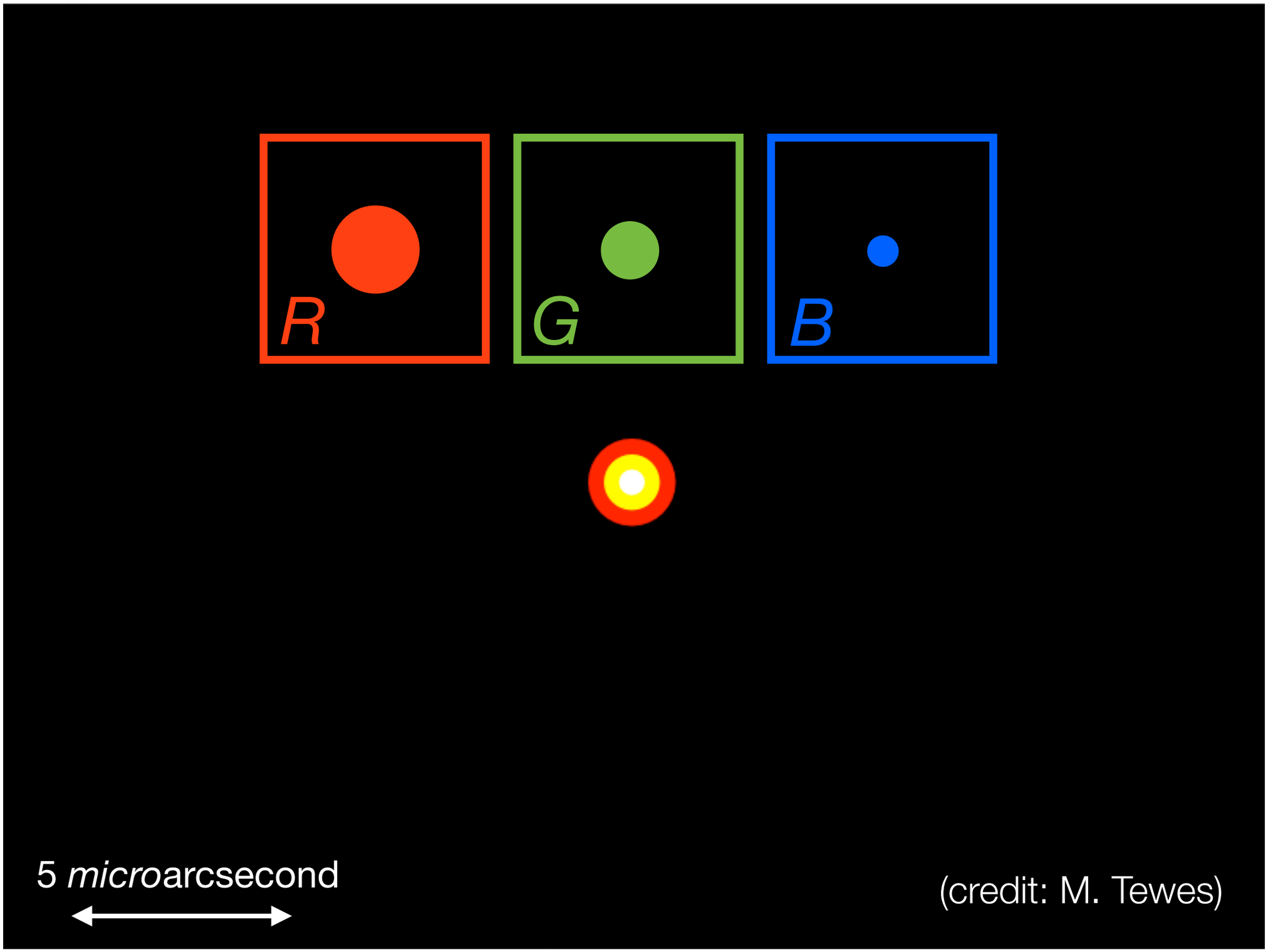
Microlensing Exacerbates Time Delay Measurements



Source trajectory

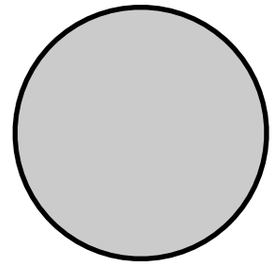


Quasar microlensing toy model



$z_{\mathrm{QSO}} = 0.658$
$z_{\mathrm{Lens}} = 0.295$
(RX J1131-1231)

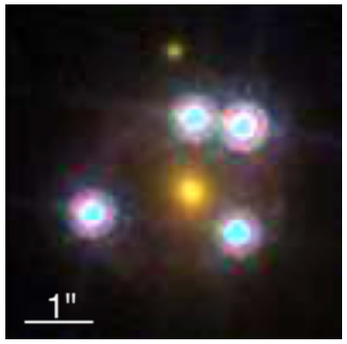
Einstein ring of $1 M_{\odot}$ - star in lens :

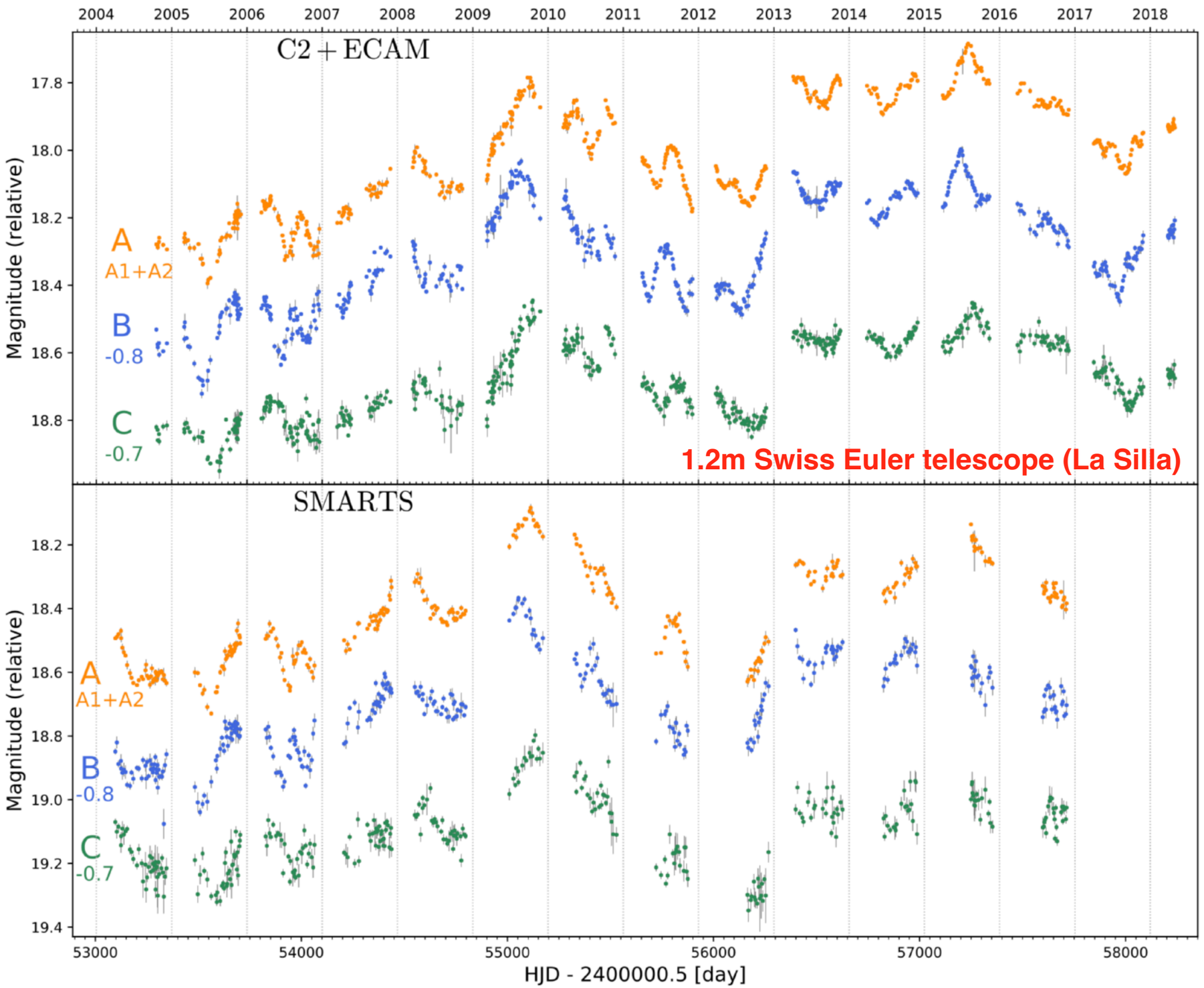


Macrolensed source :

Ø 1 light days
Ø 5 light days

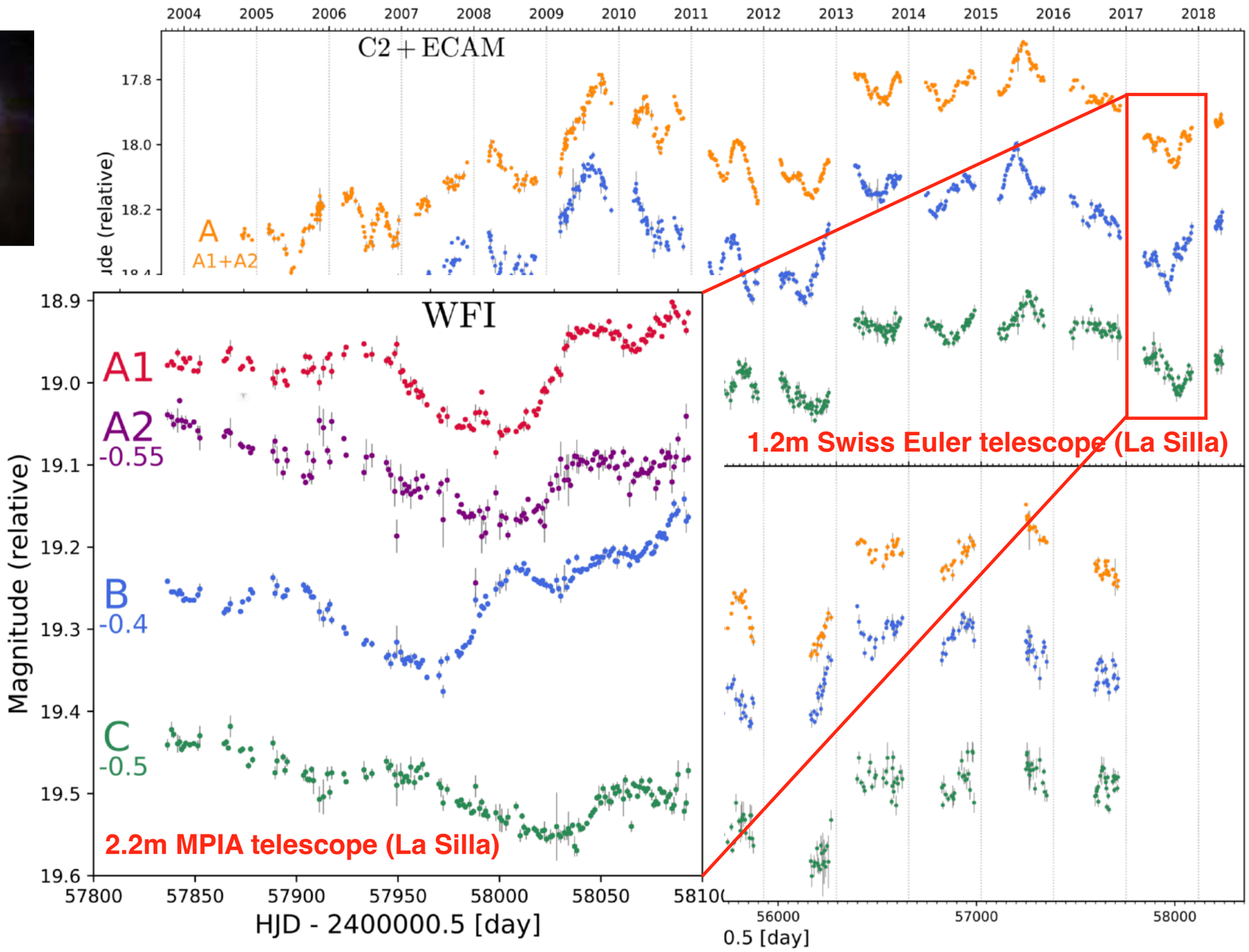
COSMOGRAIL Light Curves of WFI2033-4723





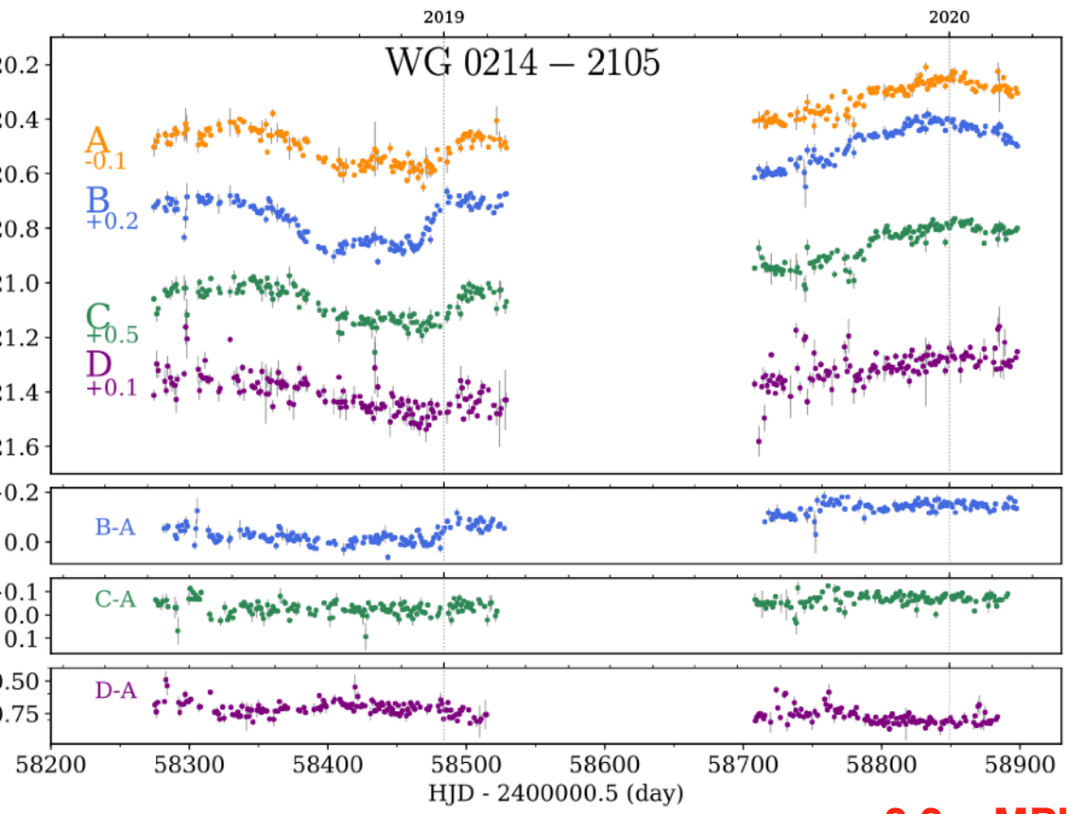
Bonvin et al. 2019, A&A 629, A97

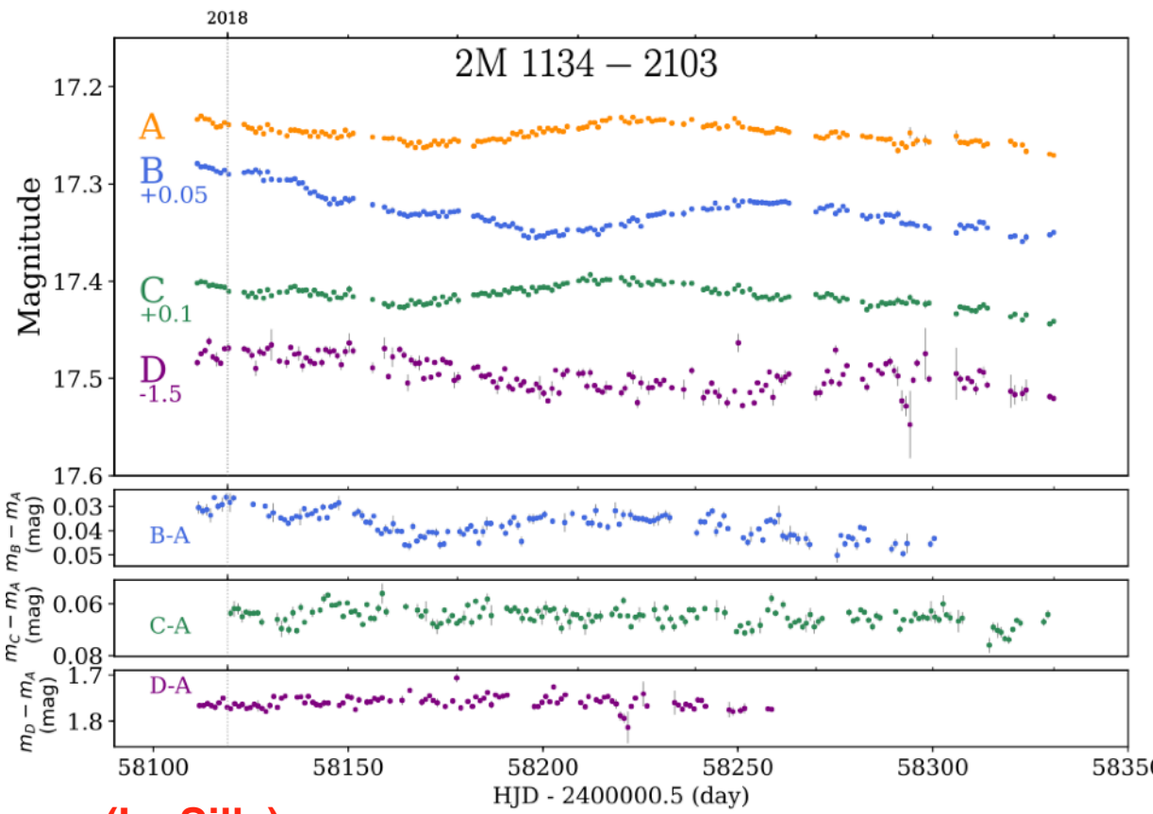
MPIA 2.2m Light Curves of WFI2033-4723



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

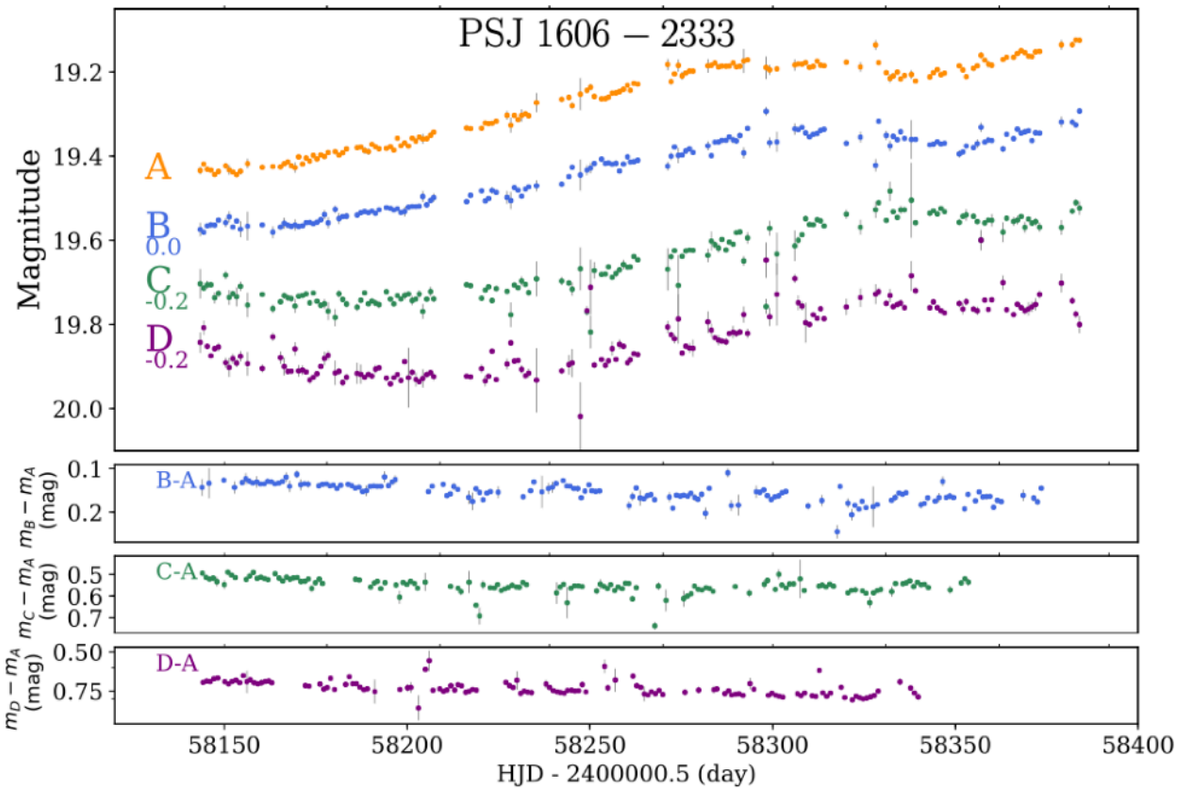
Mass Production of Time Delays





2.2m MPIA telescope (La Silla)

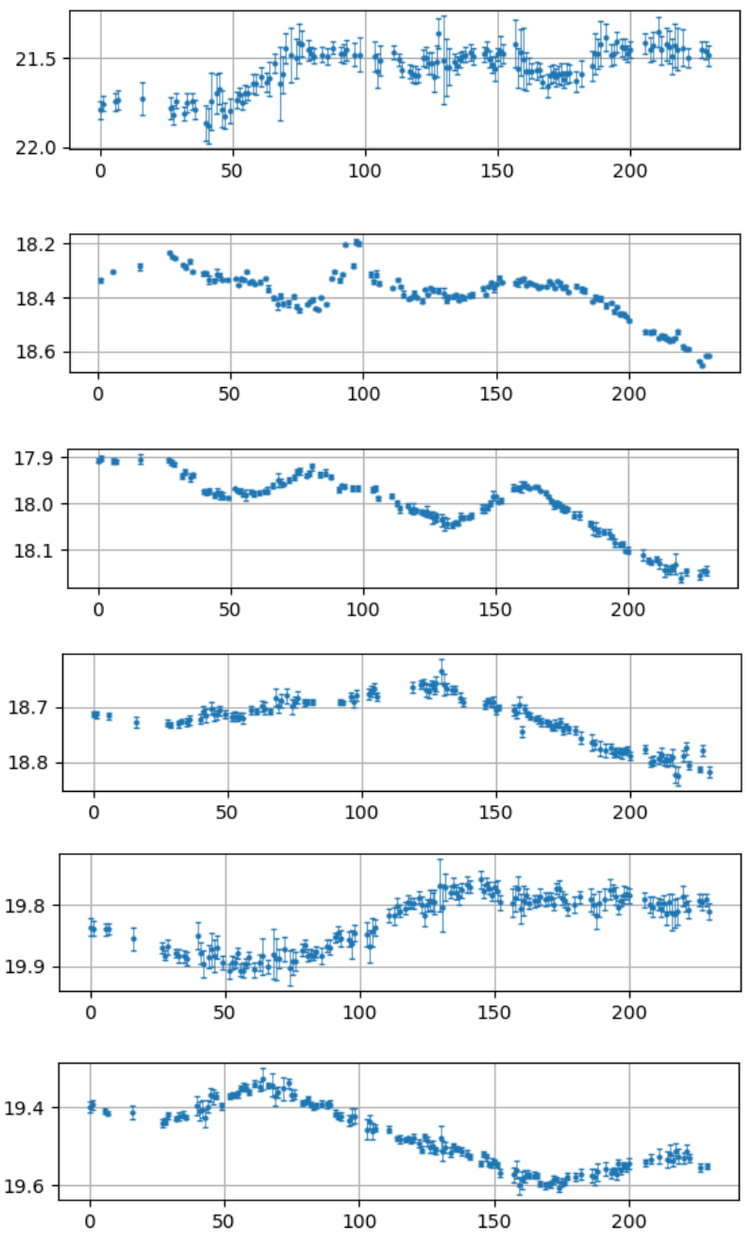
- 2m to 3m telescopes
- Daily cadence
- 30 min exposure per epoch
- 3 mmag precision per epoch
- Single-season measurement
- Better than LSST !
- ESO Large Program of 2000h on 2.6m VST



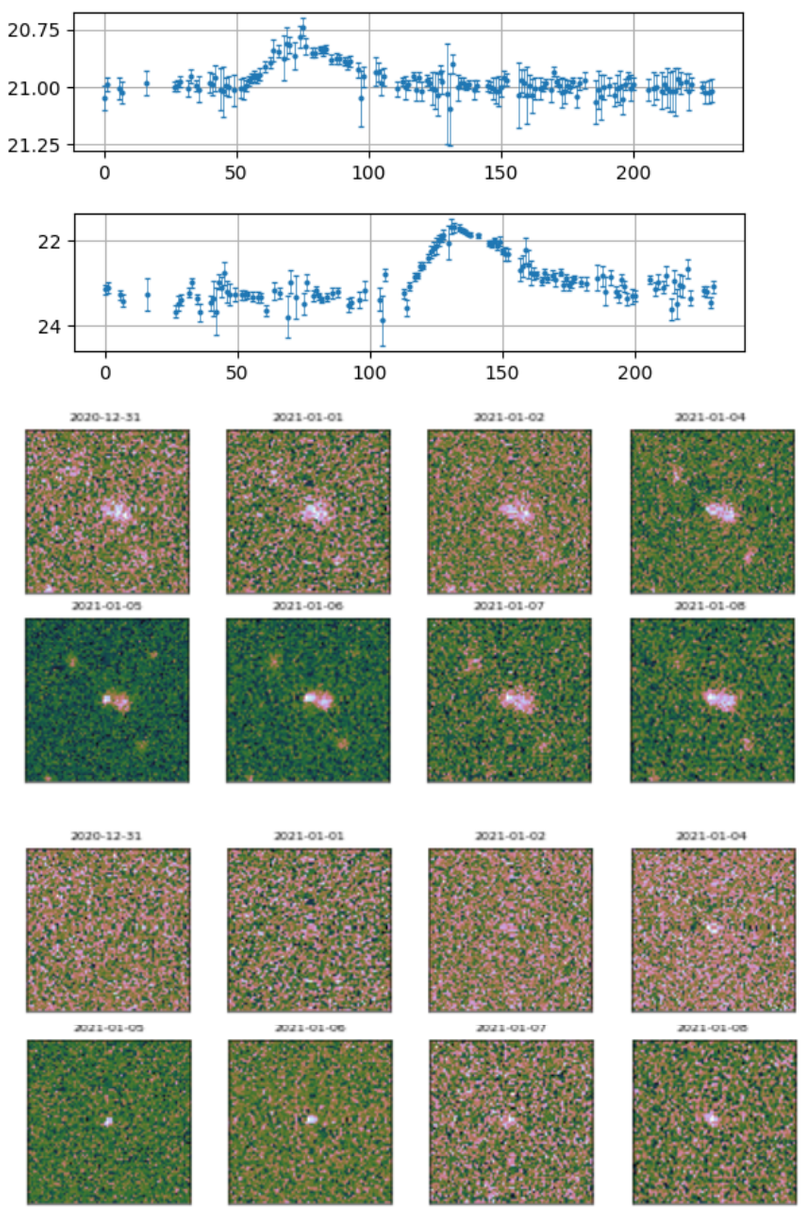
Millon et al. 2020, A&A 642, A193 (TDCOMOS II)

High-cadence monitoring at the 2.6m VST in Paranal

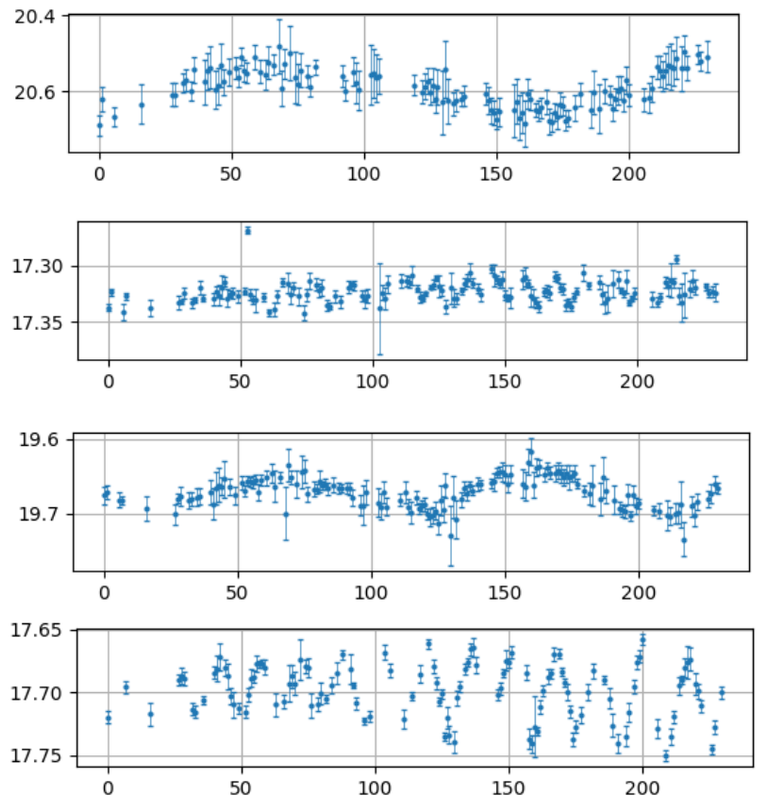
QUASARS



SUPERNOVAE



VARIABLE STARS



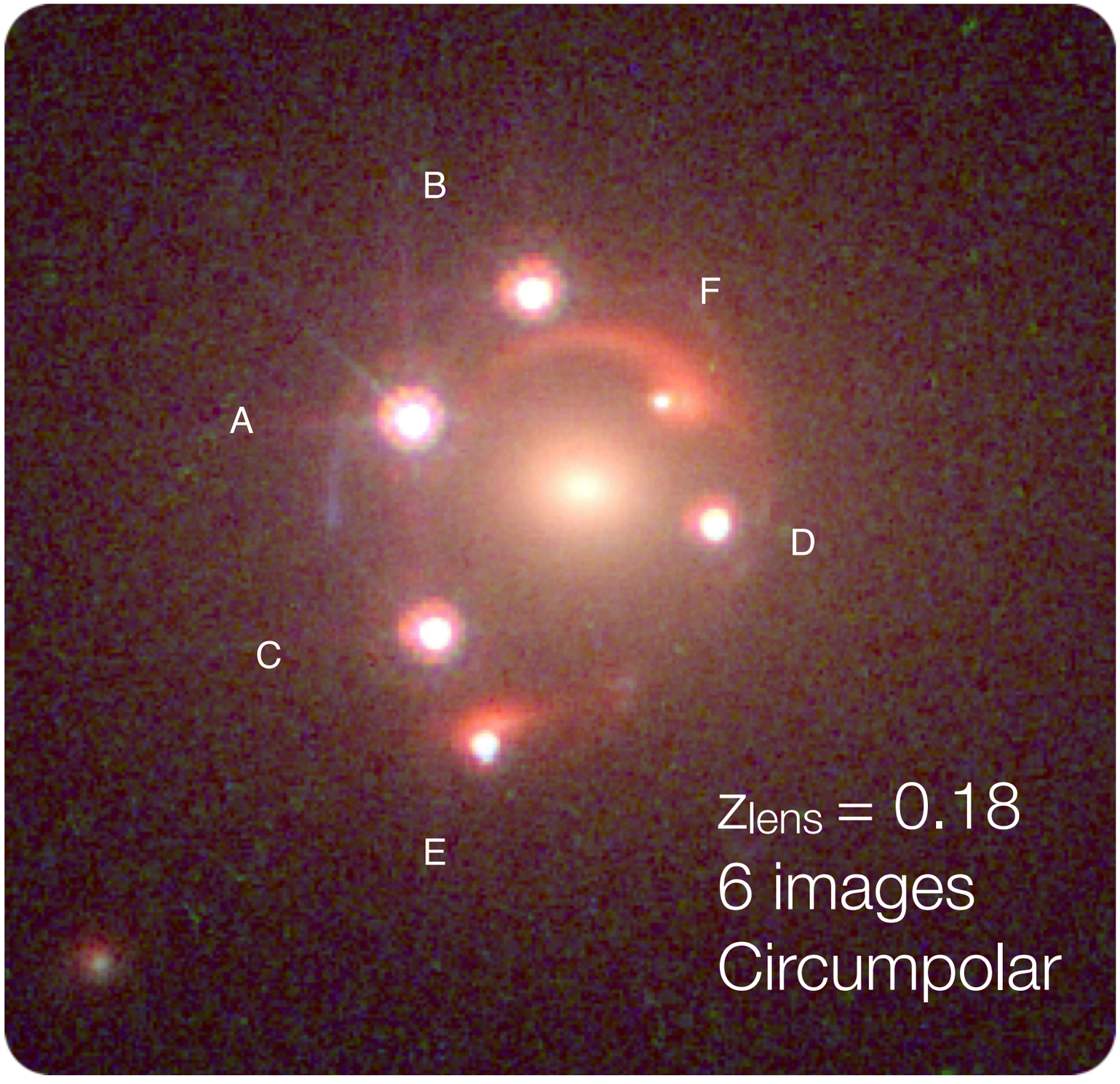
ESO Large program on the 2.6m VST

<u>2000 hours</u> over 2.5 years in the R-band
30 min daily exposure
Seeing ~0.5-0.8 arcsec
20 square degrees in total
Analysis with difference-image
Light curves from deconvolution photometry

Supernovae (maybe lensed!) to r~24.5
Discovery of quasars from variability
Discovery of faint halo variable stars

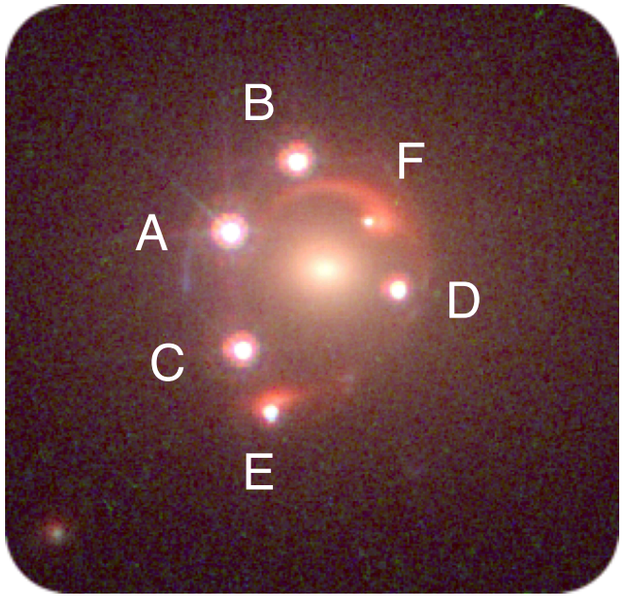
VST results from Lemon et al. 2023, in prep

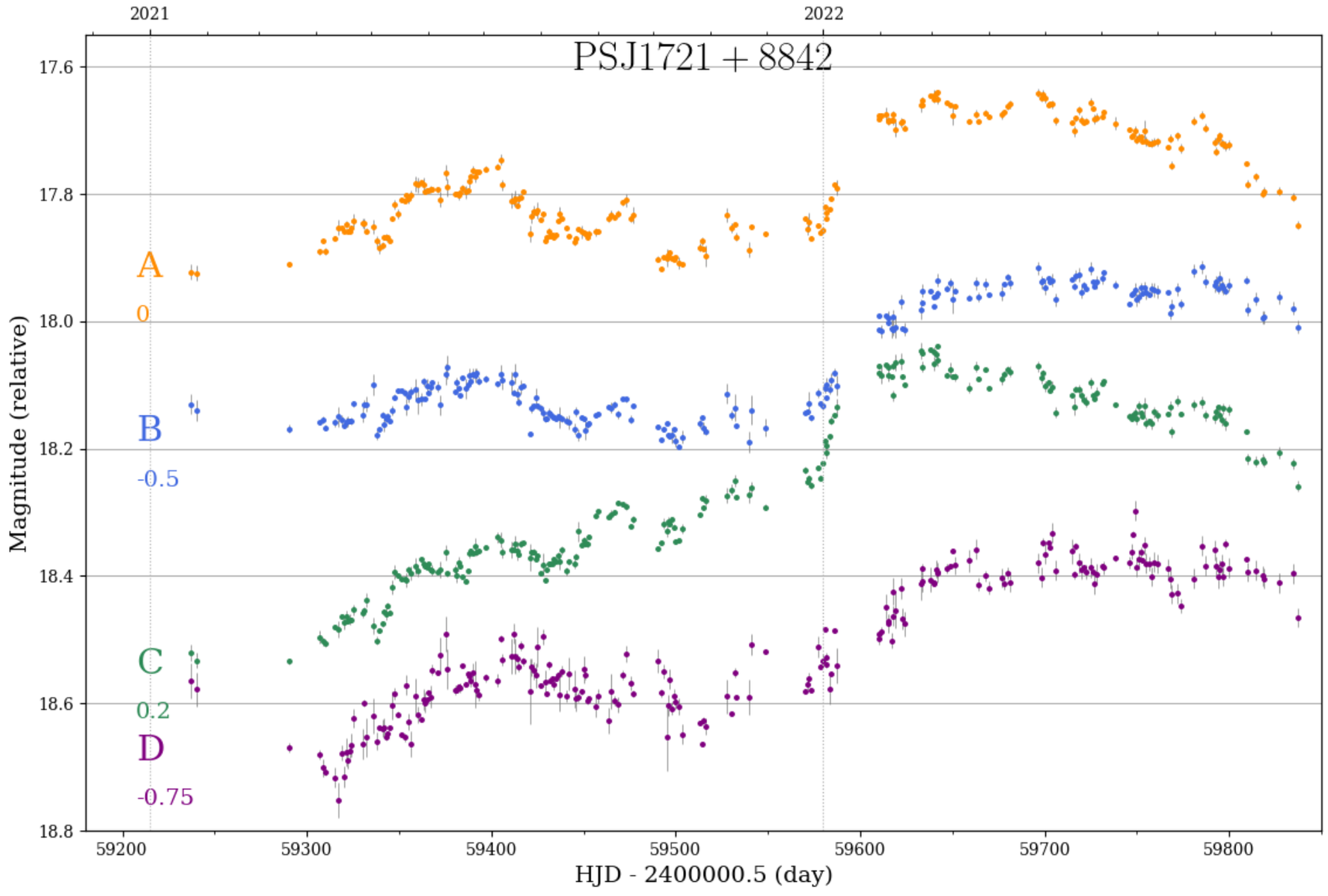
The 6-image quasar J1721+88 : NOT light curves



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

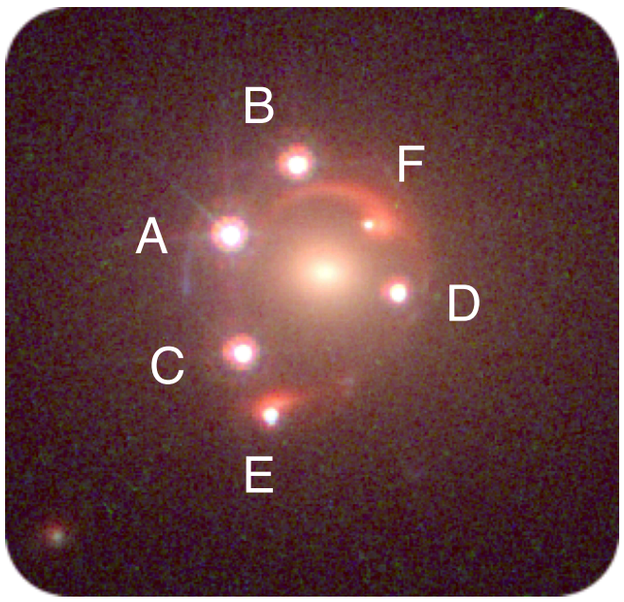
The 6-image quasar J1721+88 : NOT light curves



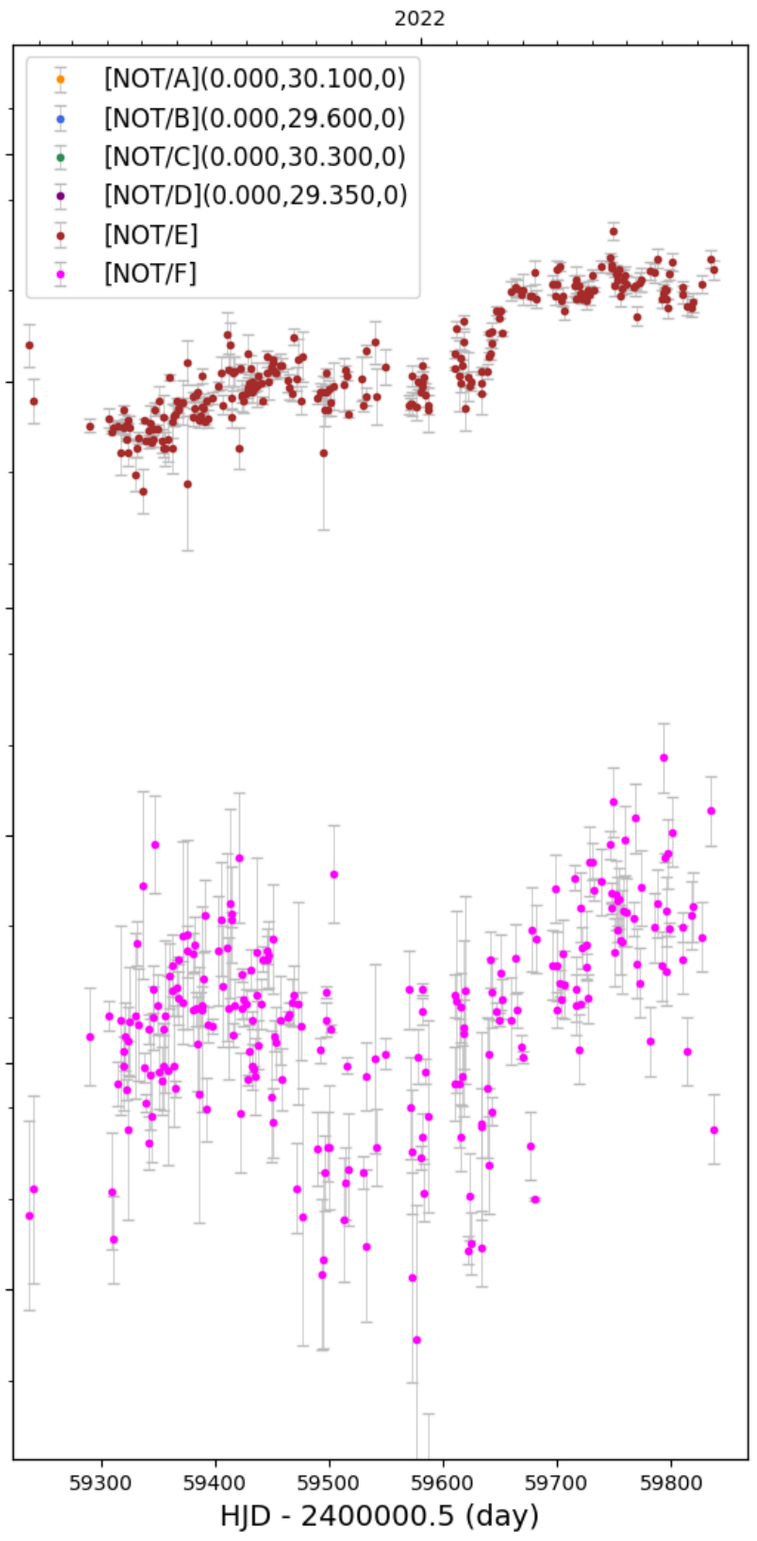


Eric Paic, FC, Martin Millon et al. 2023, in prep

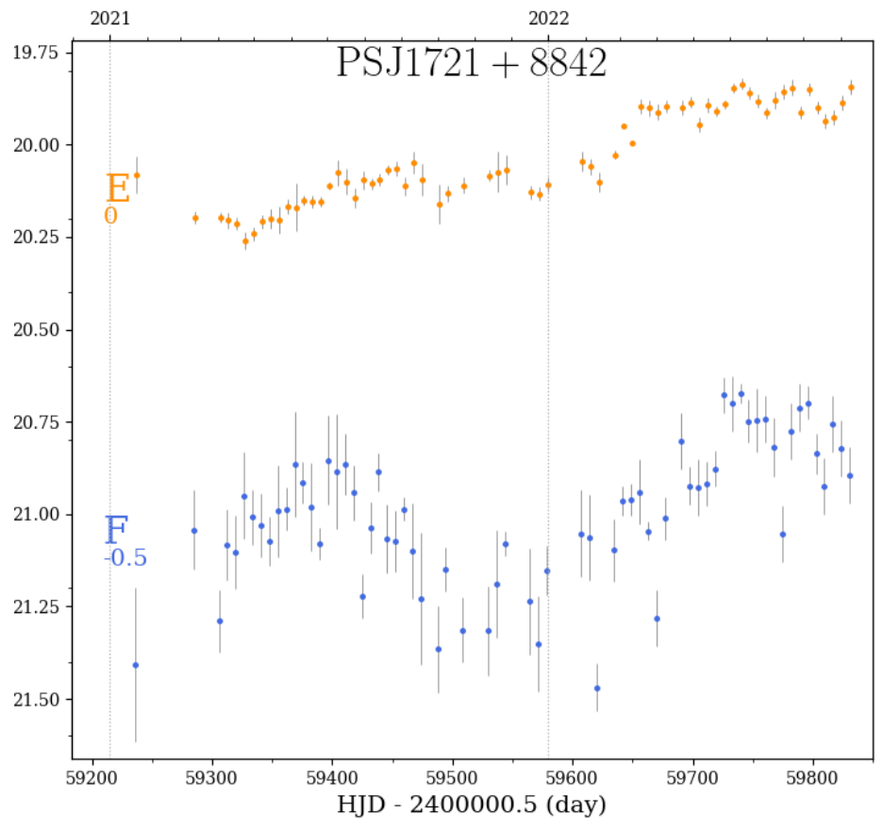
The 6-image quasar J1721+88 : NOT light curves



Daily cadence



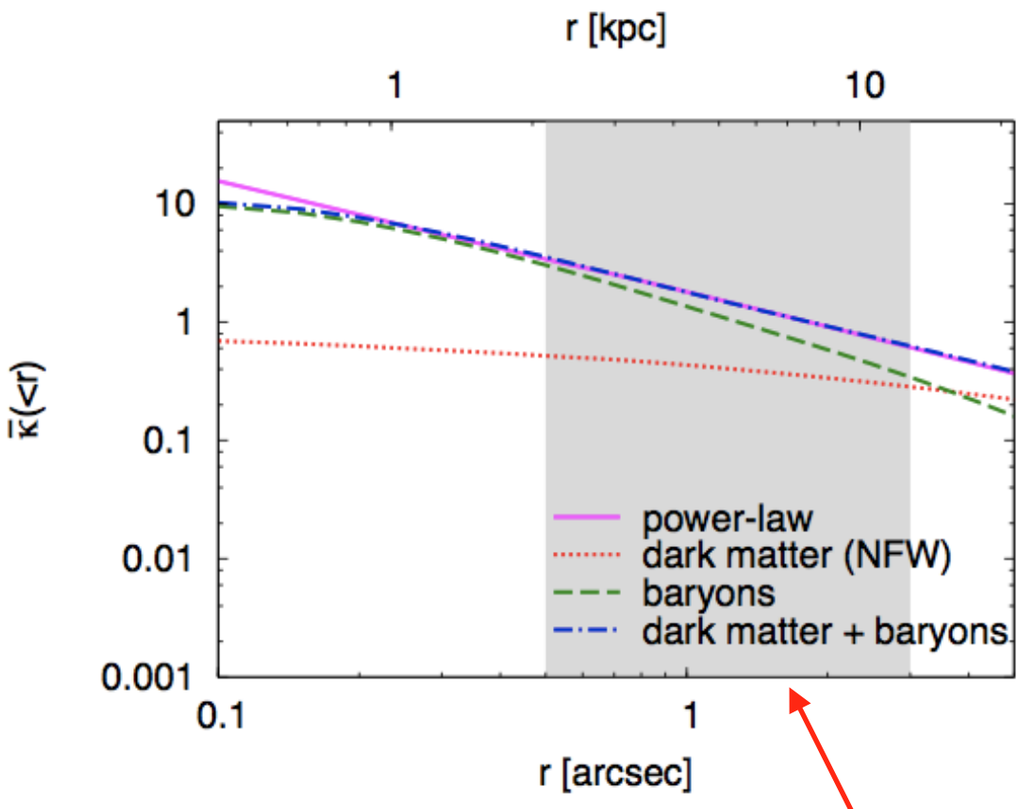
1-week binning

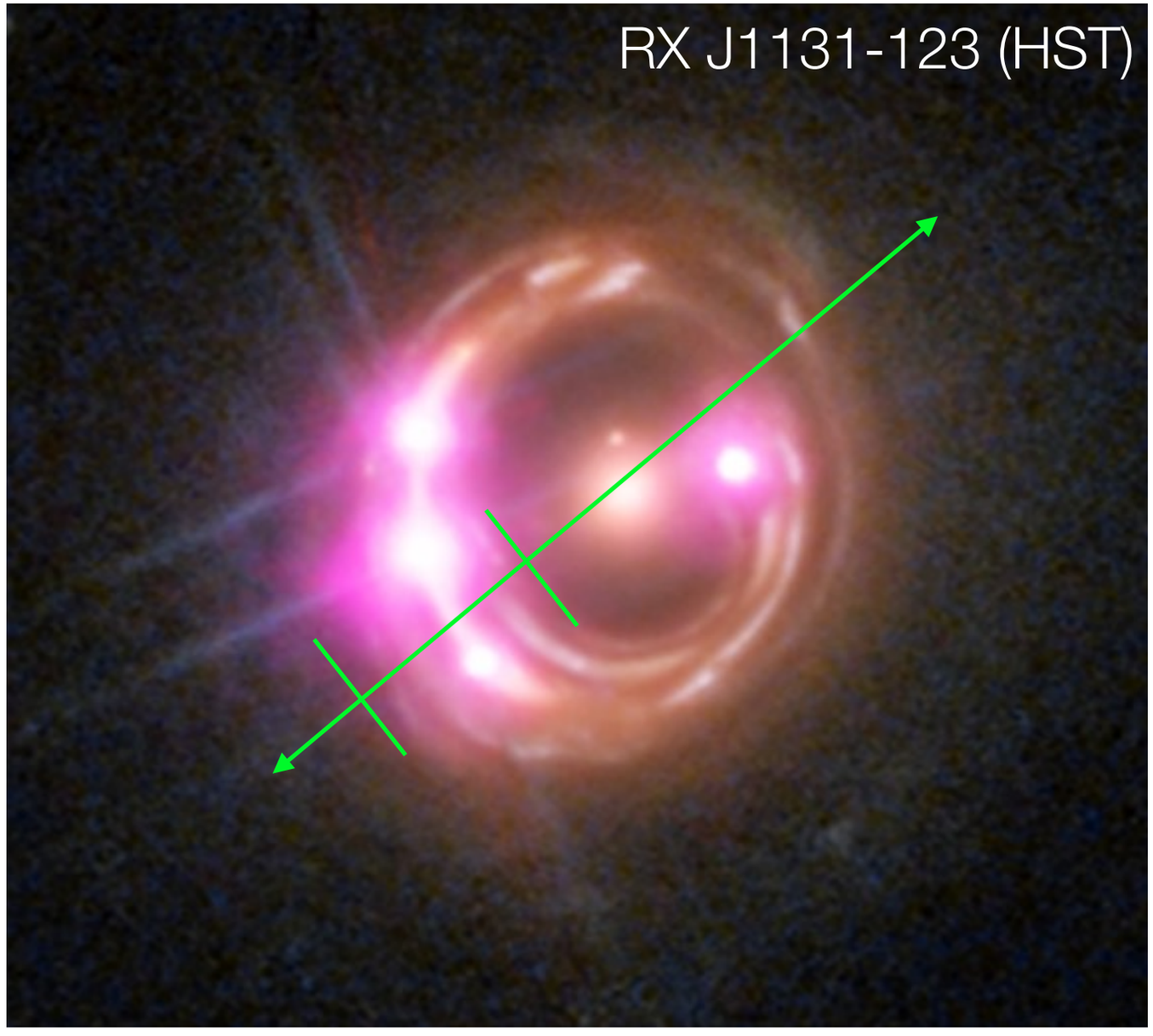


Eric Paic, FC, Martin Millon et al. 2023, in prep

2- Constraining the Mass Slope

Constraining Models with Thick Rings



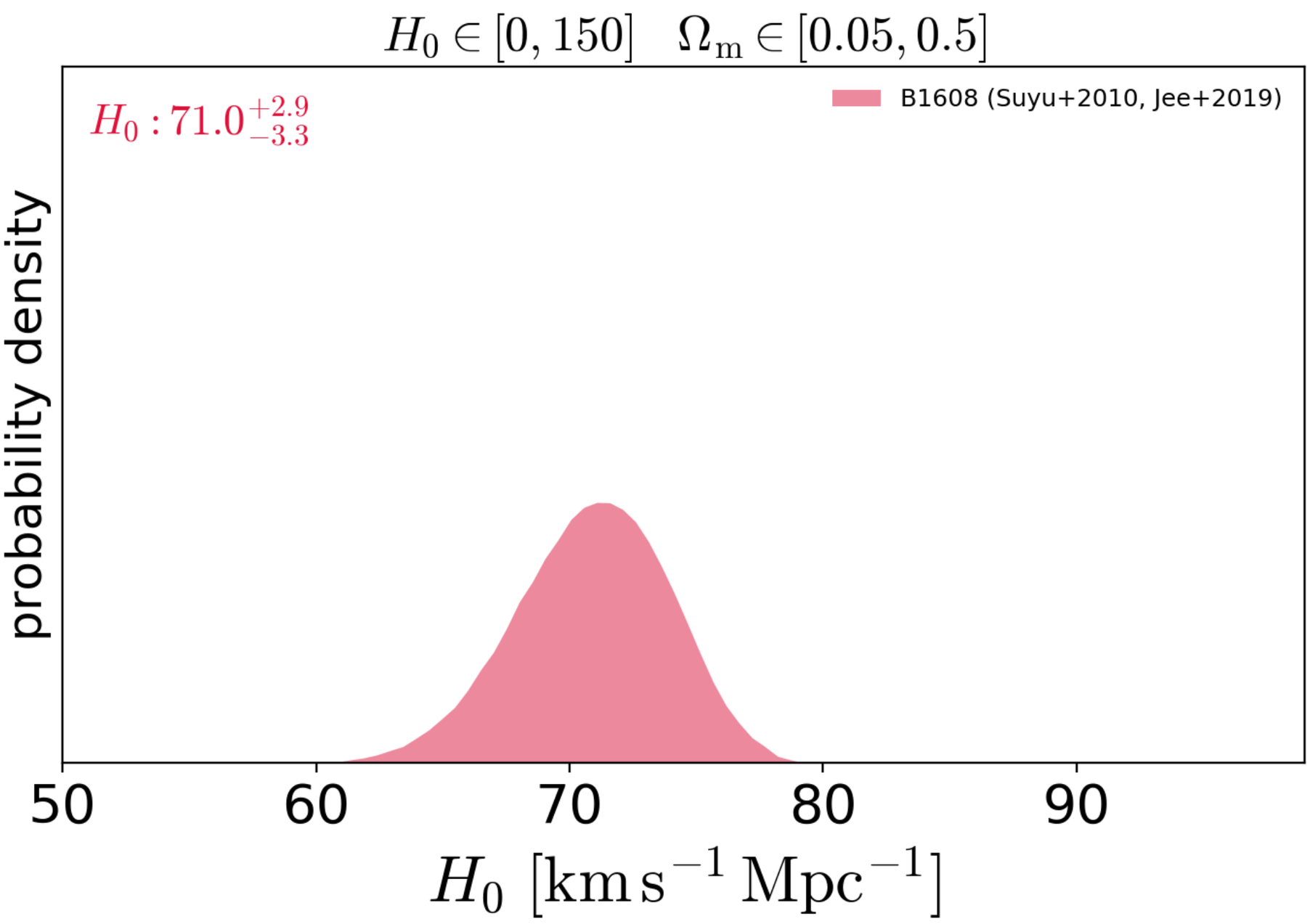


Lensing constraints come from all pixels covered by the Einstein ring formed by the quasar host

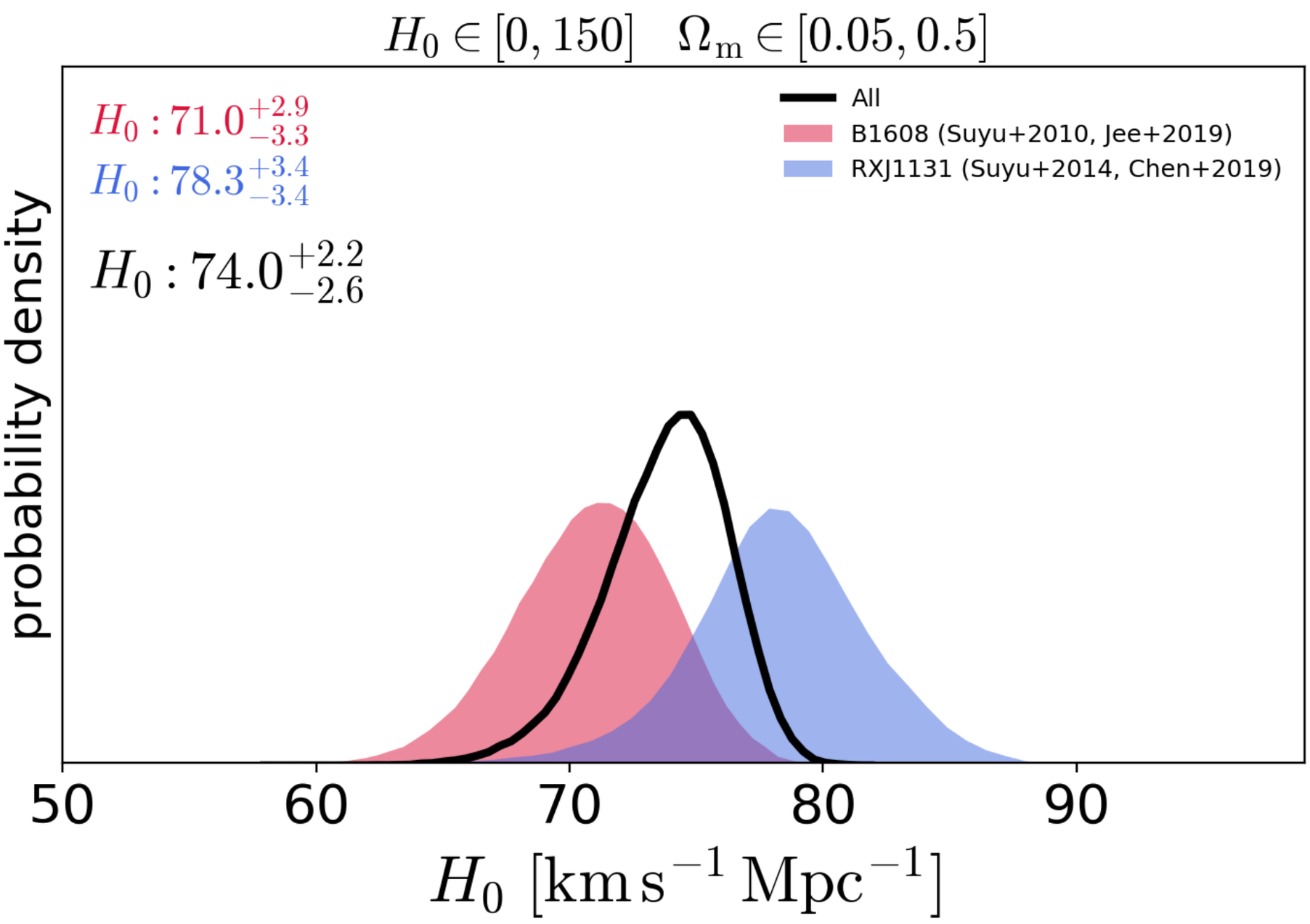
More complex models and simple power-law converge to the same mass slope

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

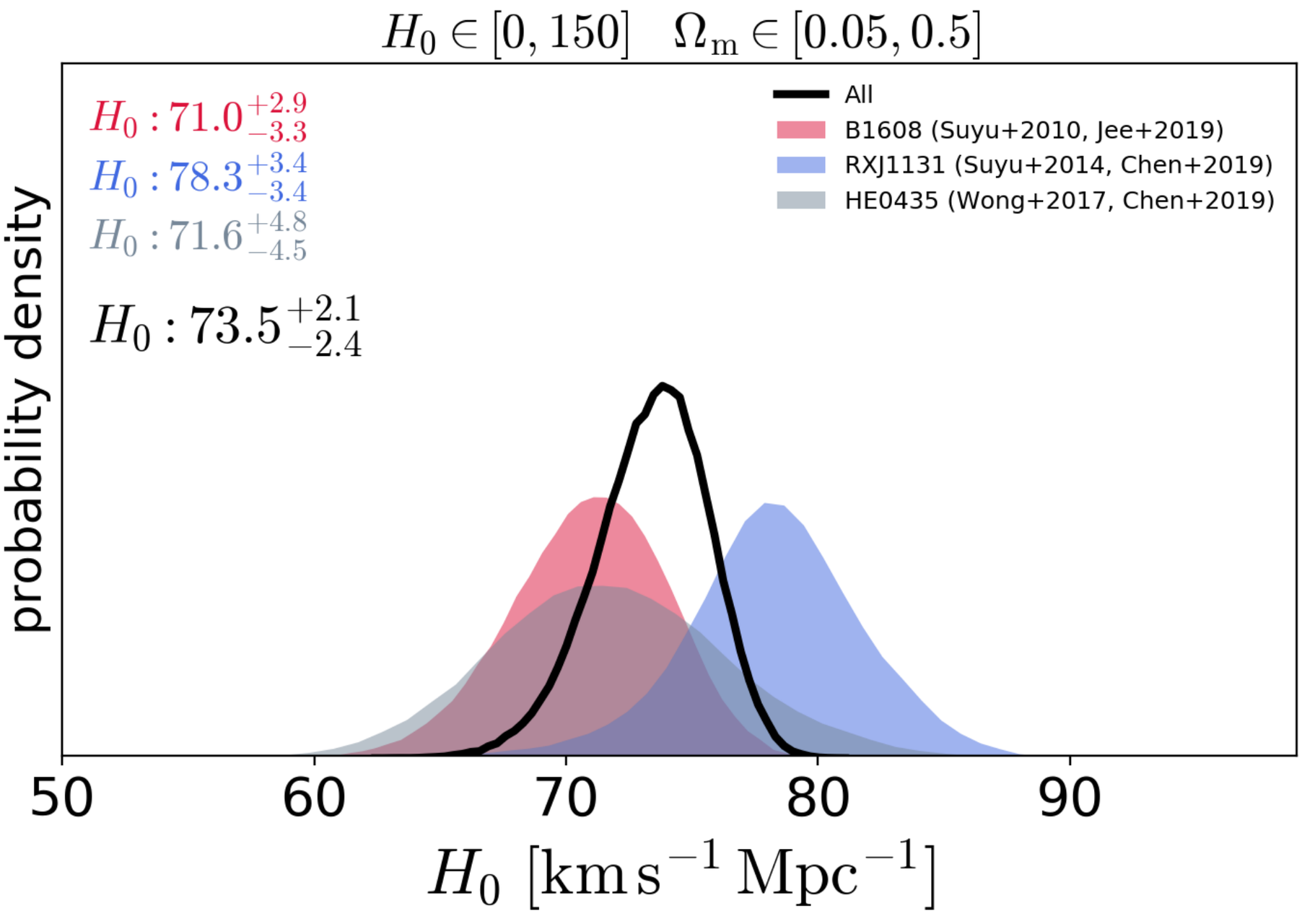
Cosmology Results for 1 Lens in flat lambda-CMD



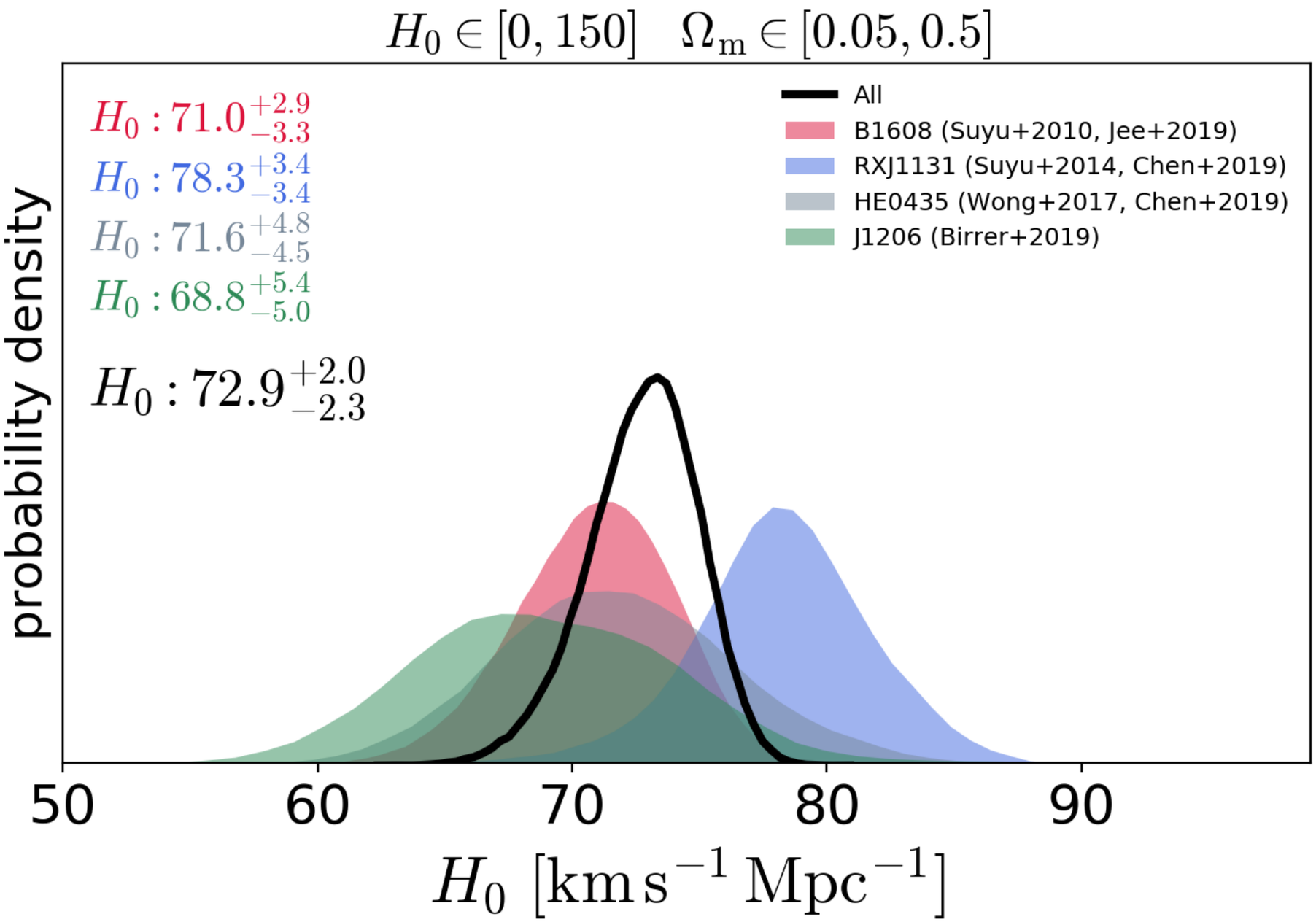
Cosmology Results for 2 Lenses in flat lambda-CMD



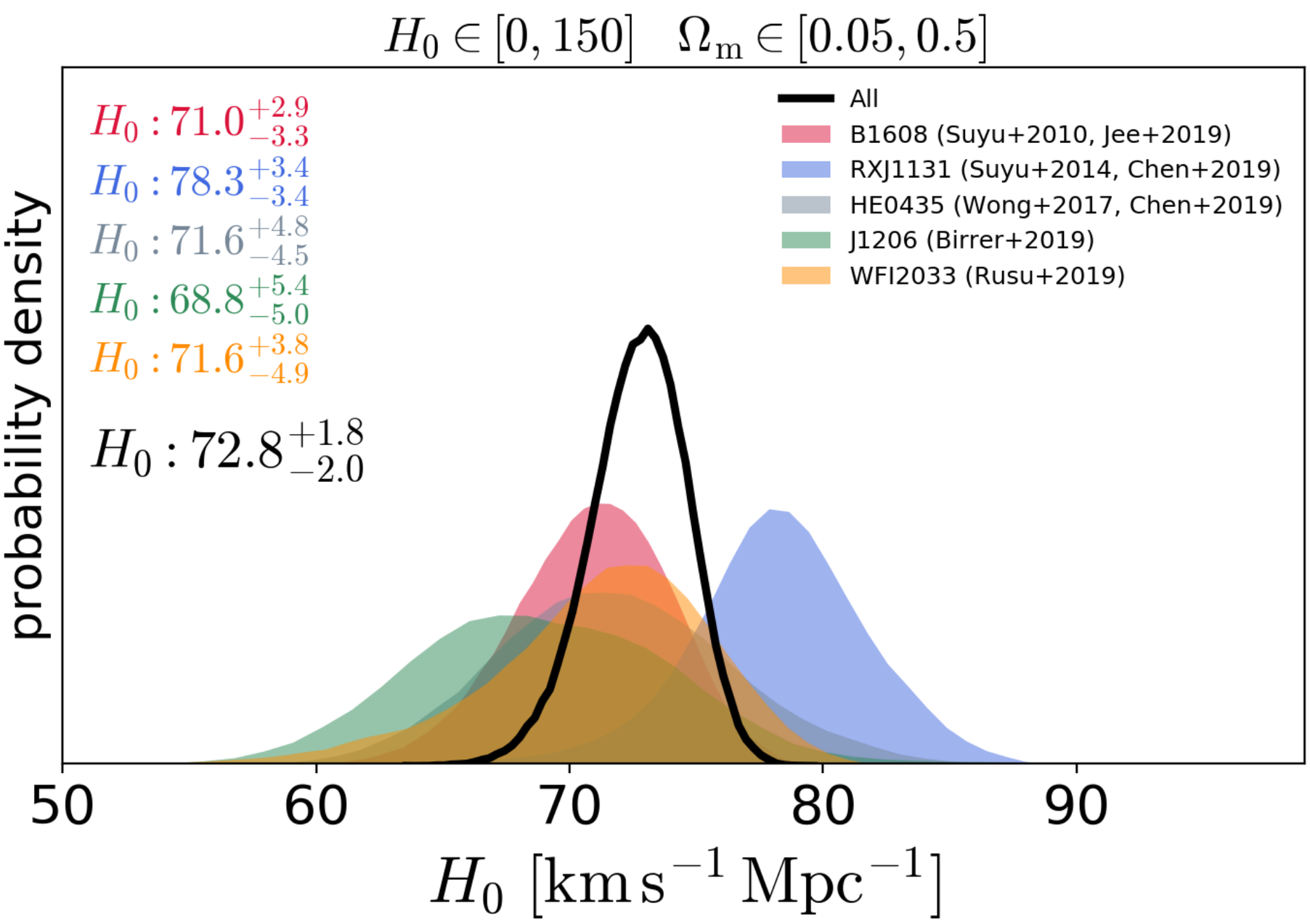
Cosmology Results for 3 Lenses in flat lambda-CMD



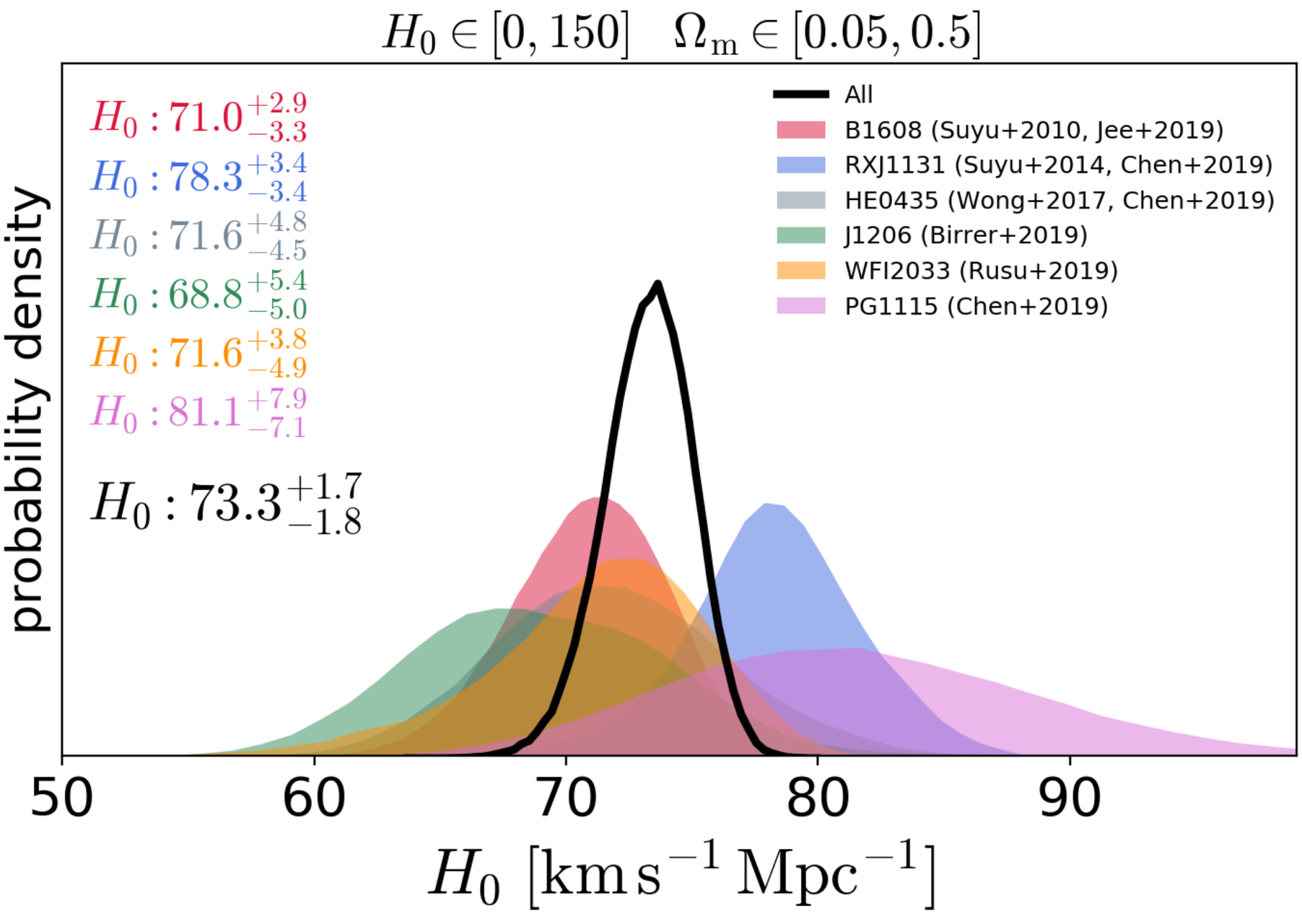
Cosmology Results for 4 Lenses in flat lambda-CMD



Cosmology Results for 5 Lenses in flat lambda-CMD

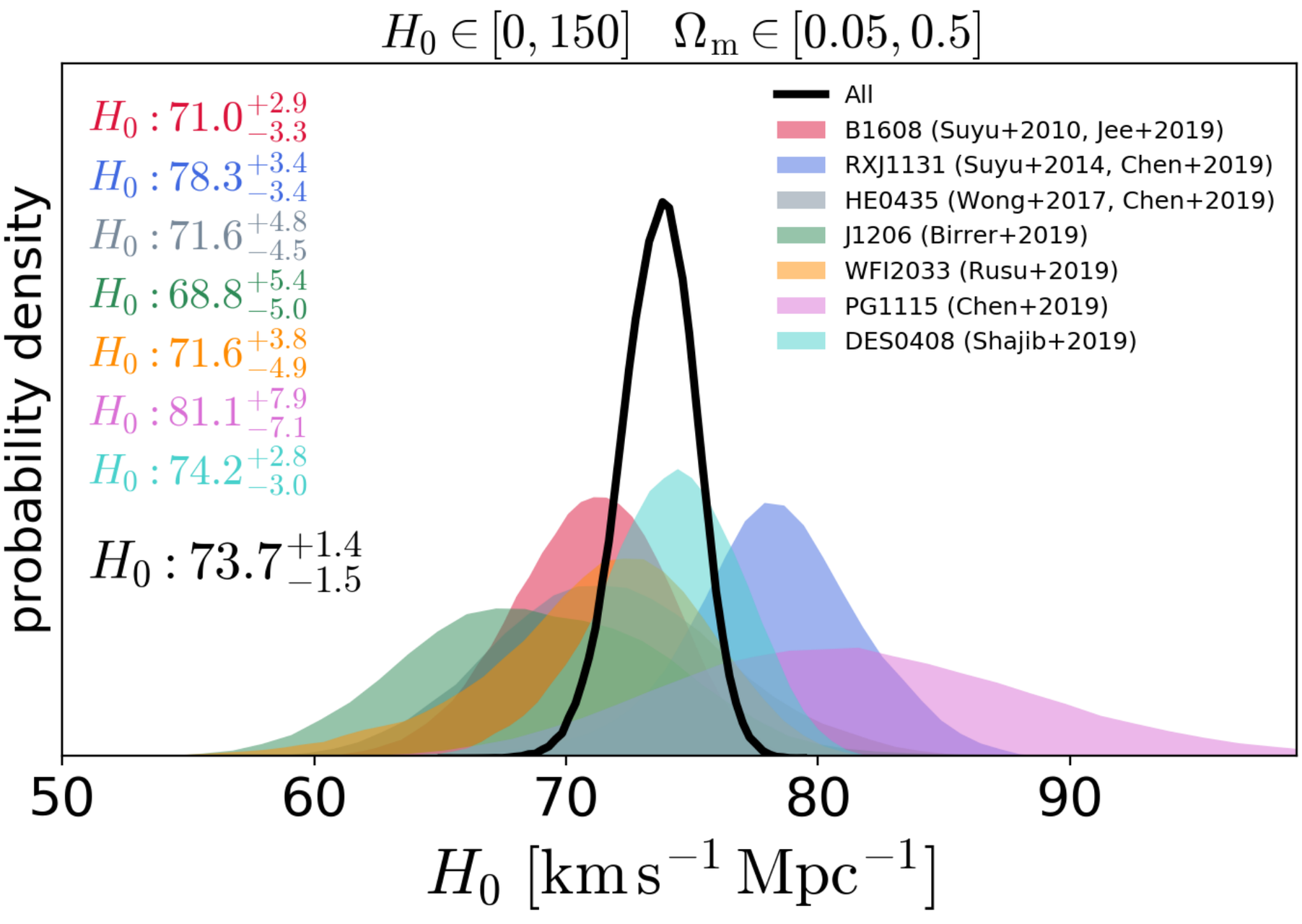


Cosmology Results for 6 Lenses in flat lambda-CMD



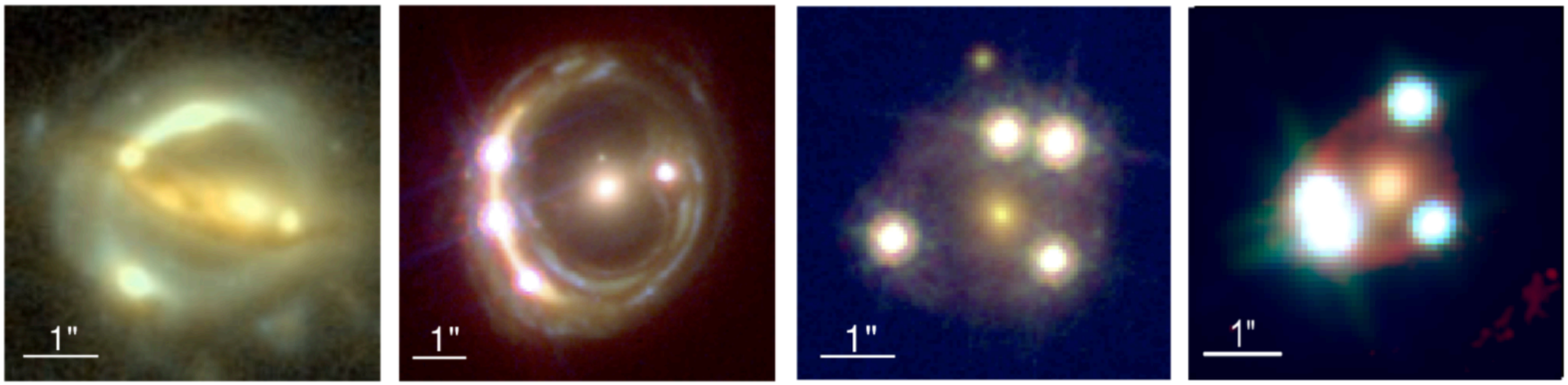
H0LiCOW XIII: milestone paper (Wong et al. 2020)

Cosmology Results for 7 Lenses in flat lambda-CMD

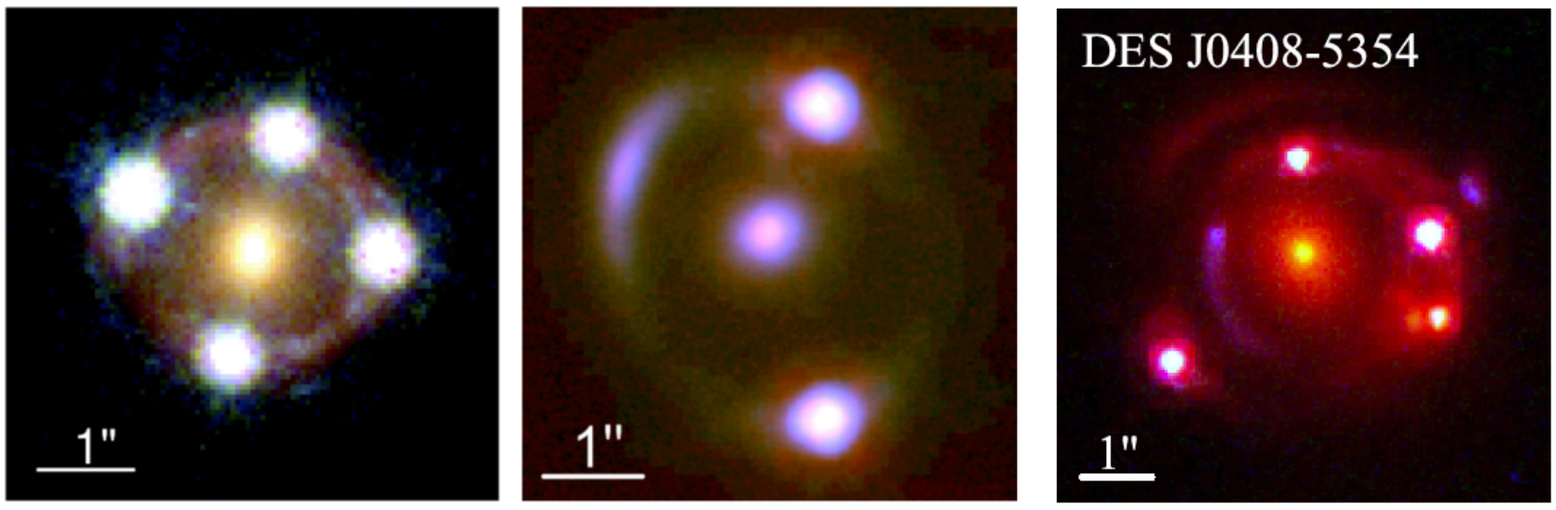


Latest lens by (Shajib et al. 2020)

Each Lens is Unhappy in its Own Way !



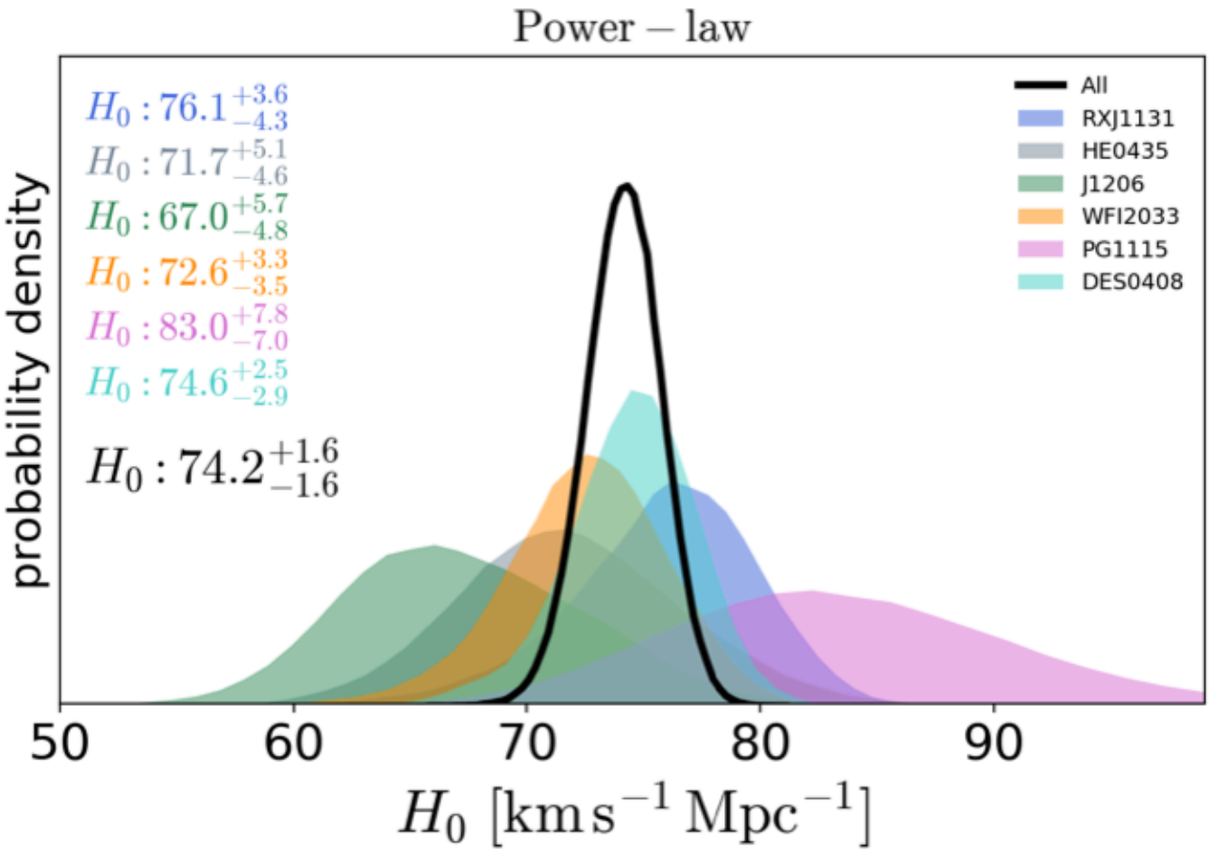
(a) B1608+656 (b) RXJ1131−1231 (e) WFI2033−4723 (f) PG 1115+080

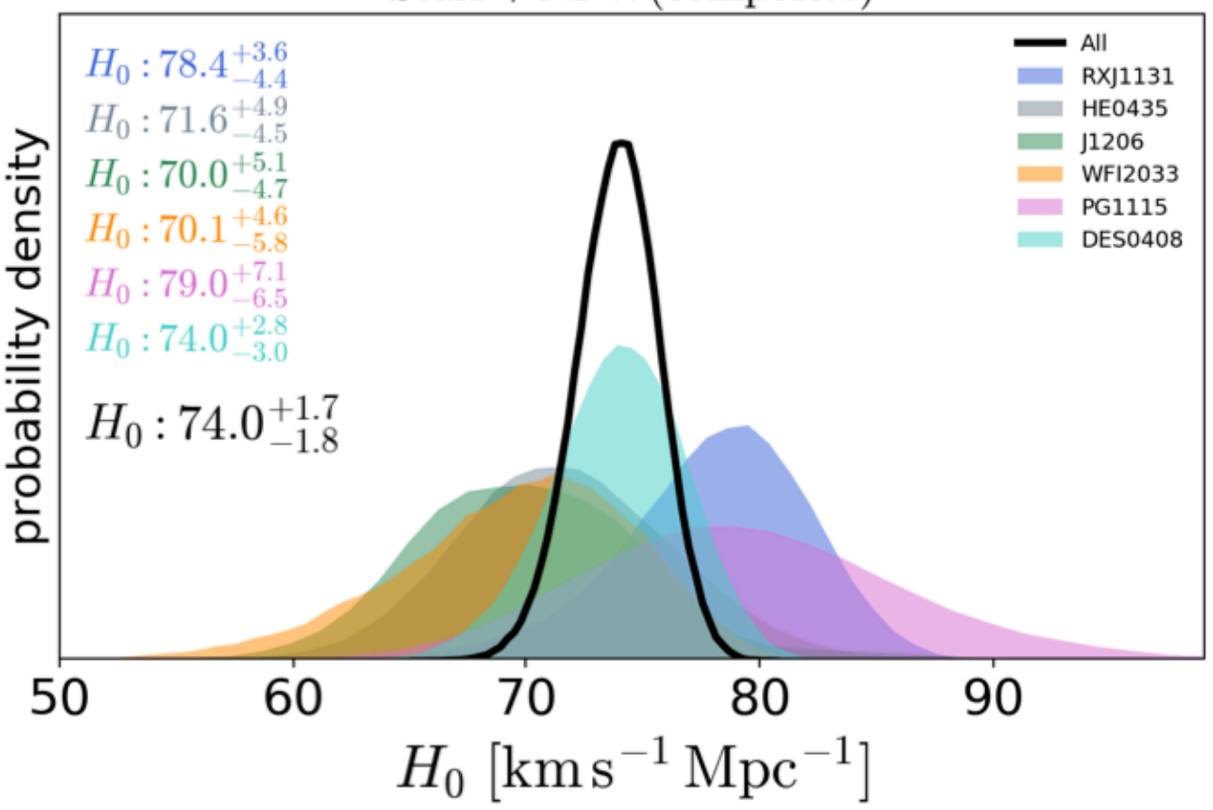


(c) HE 0435−1223 (d) SDSS 1206+4332

H0LiCOW XIII: milestone paper (Wong et al. 2019, arXiv1907.04869)

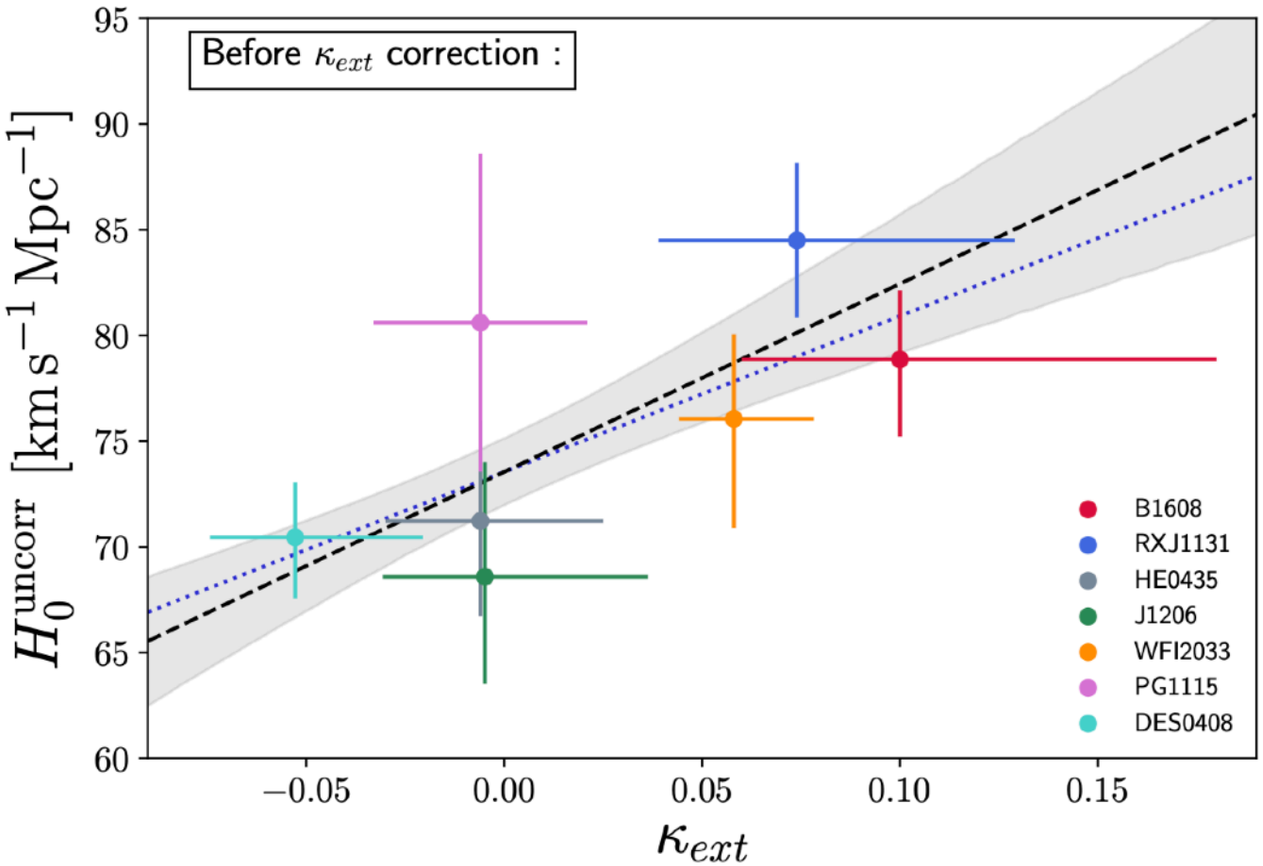
No Significant Dependence on Lens Model

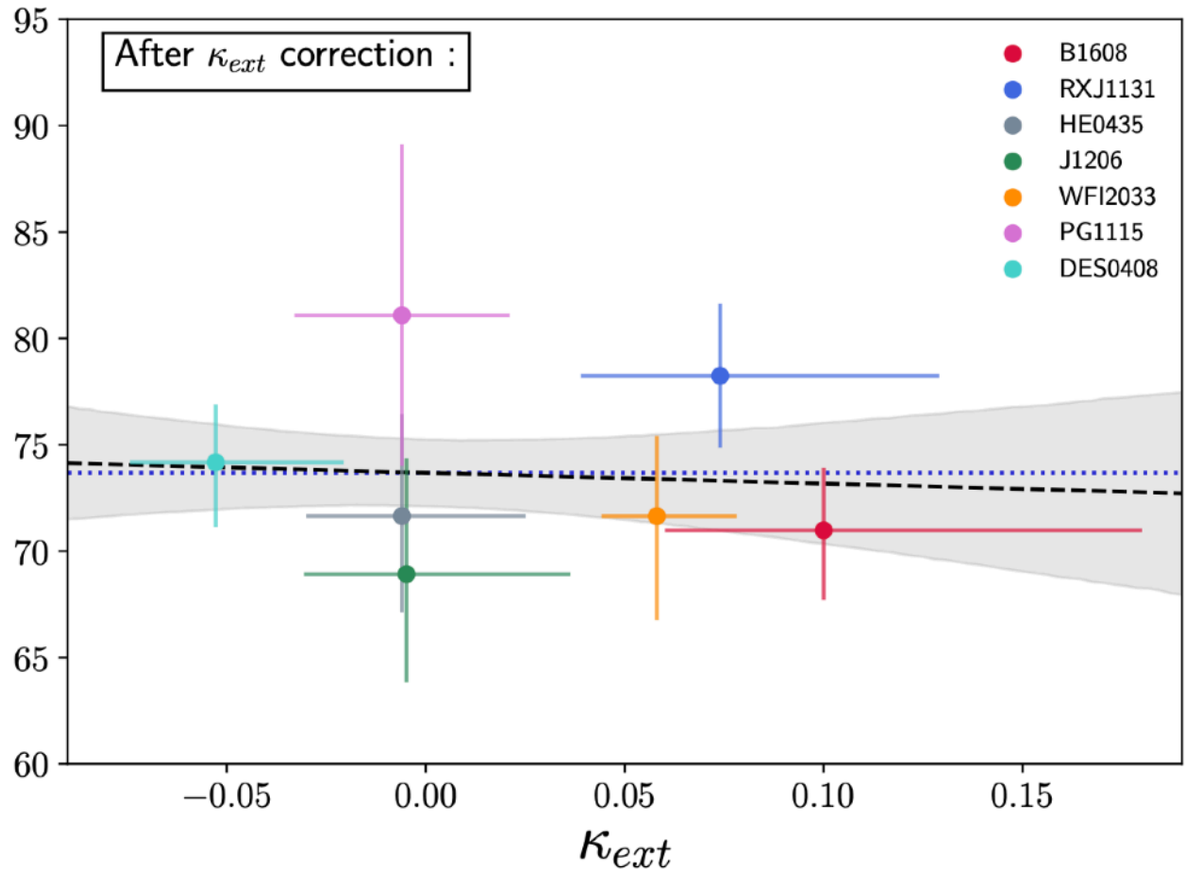




Millon et al. 2020, A&A 639, A101 (TDCOSMO I)

Excellent Correction for Environment and Line of Sight





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

3- The Mass-sheet Transform (MST)

(also known as MSD)

Model Degeneracies: Mass Sheet Transform (MST)

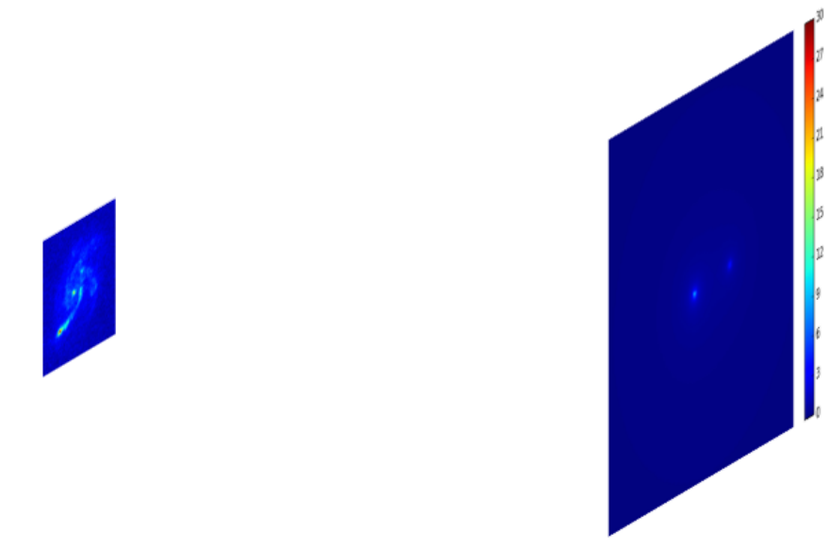
Source plane

Mass

Lensed images

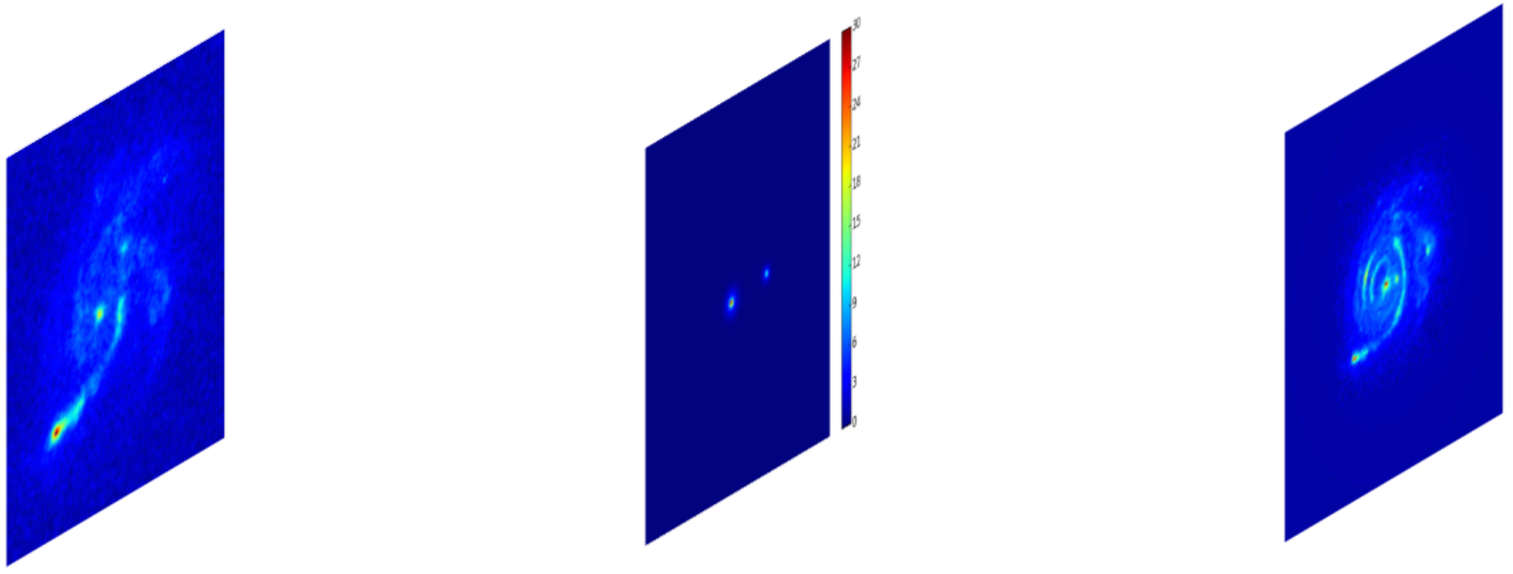
$\underline{\beta}$

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

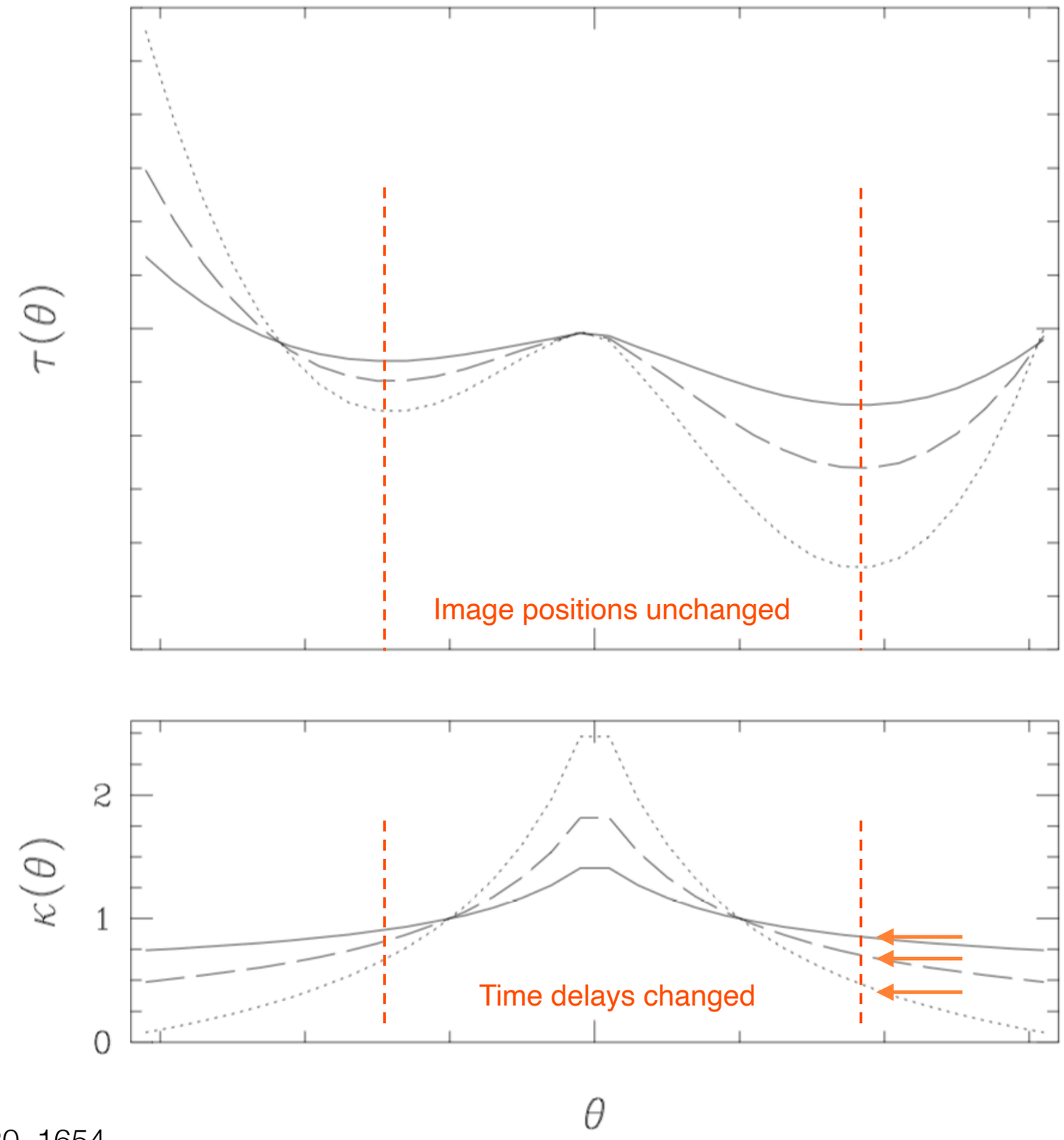
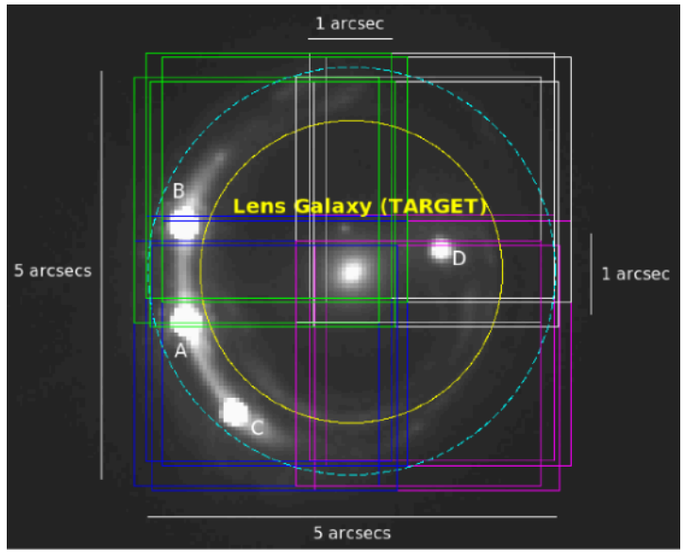


Figure adapted from Saha, 2000, AJ 120, 1654

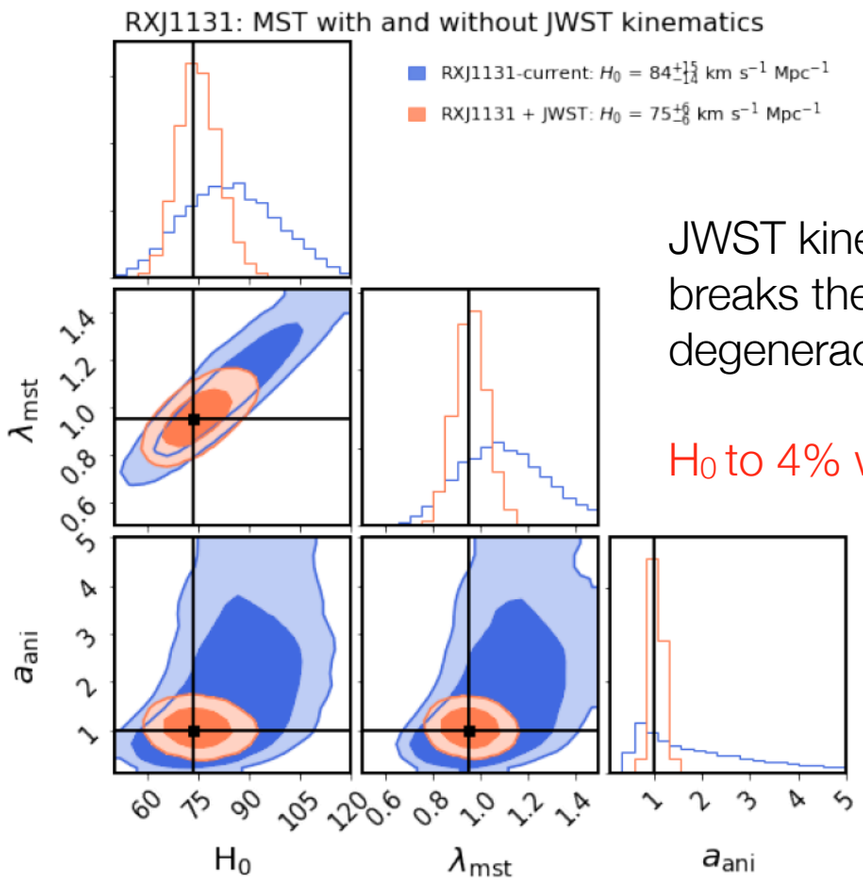
Future Avenues - Relaxing Assumptions !

Spatially resolved kinematics

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



JWST dithering with NIRSpec (exp. time: 6.5h)

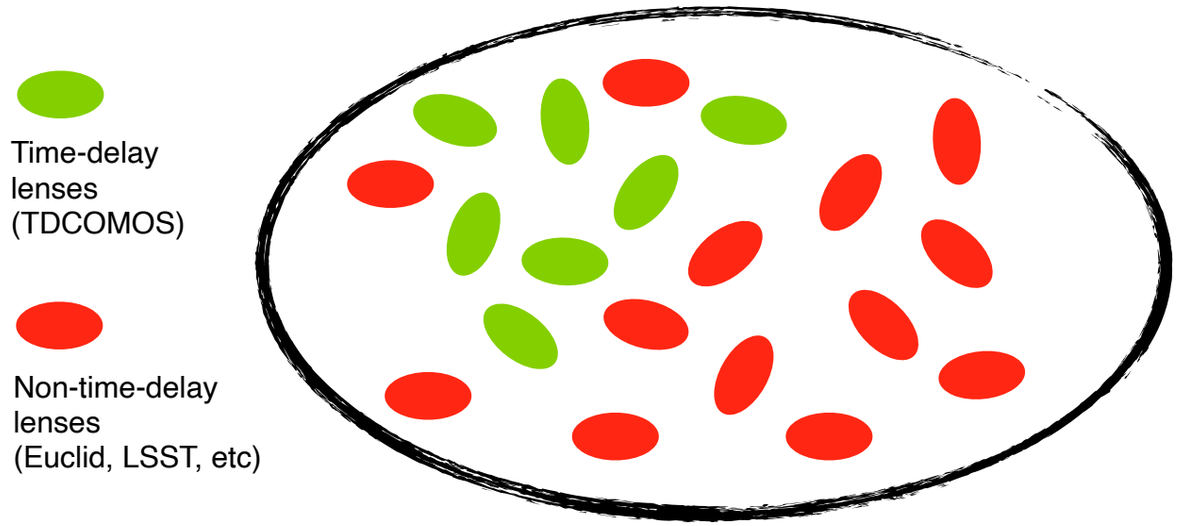


JWST kinematics breaks the Mass-sheet degeneracy

H_0 to 4% with 1 single lens

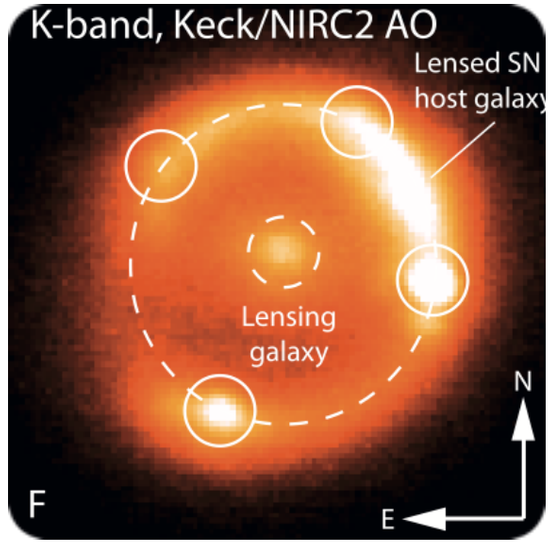
TDCOSMO collaboration

Hierarchical Bayesian Analysis



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

Time Delay Cosmography (TDCOSMO) – H_0 determination

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

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

$73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}
H0LiCOW

$74.0^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}
TDCOSMO (NFW + stars/constant M/L)

$74.2^{+1.6}_{-1.6}$ km s^{-1} Mpc^{-1}
TDCOSMO (power-law)

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

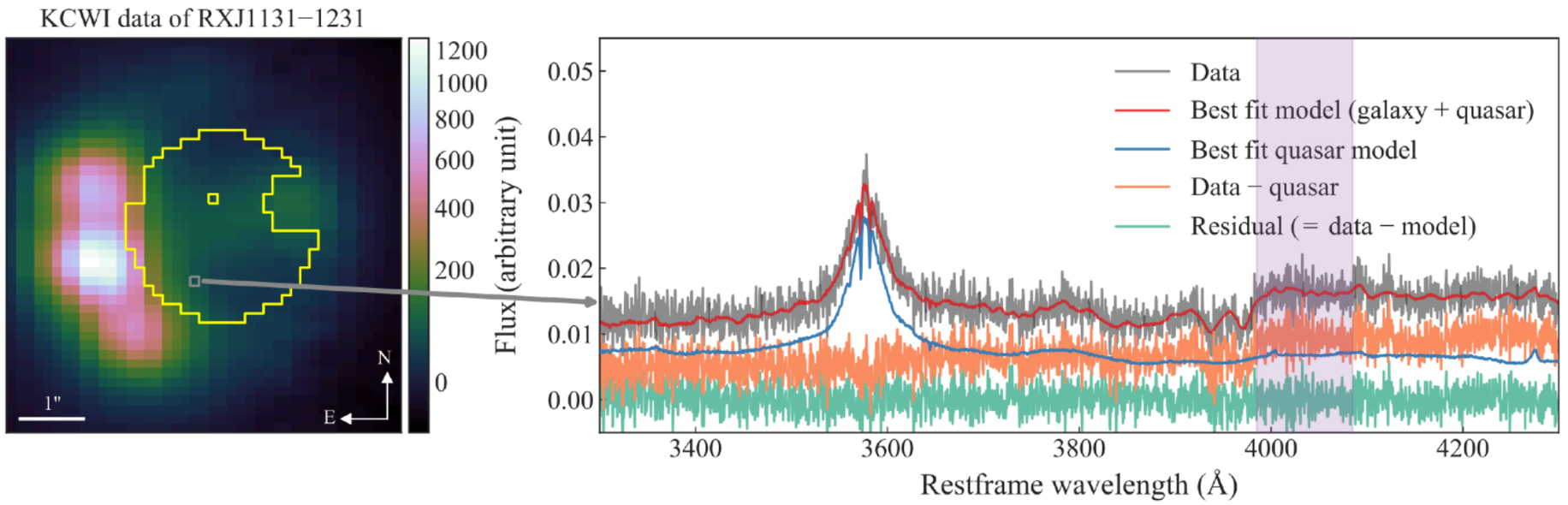
Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy property

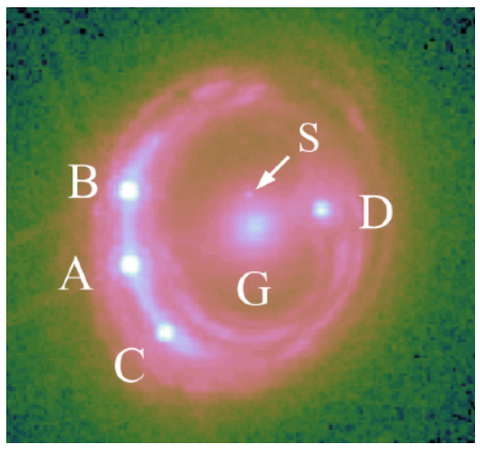
$73.3^{+5.8}_{-5.8}$ km s^{-1} Mpc^{-1}
TDCOSMO+SLACS$_{IFU}$ (anisotropy constraints from 9 SLACS lenses)

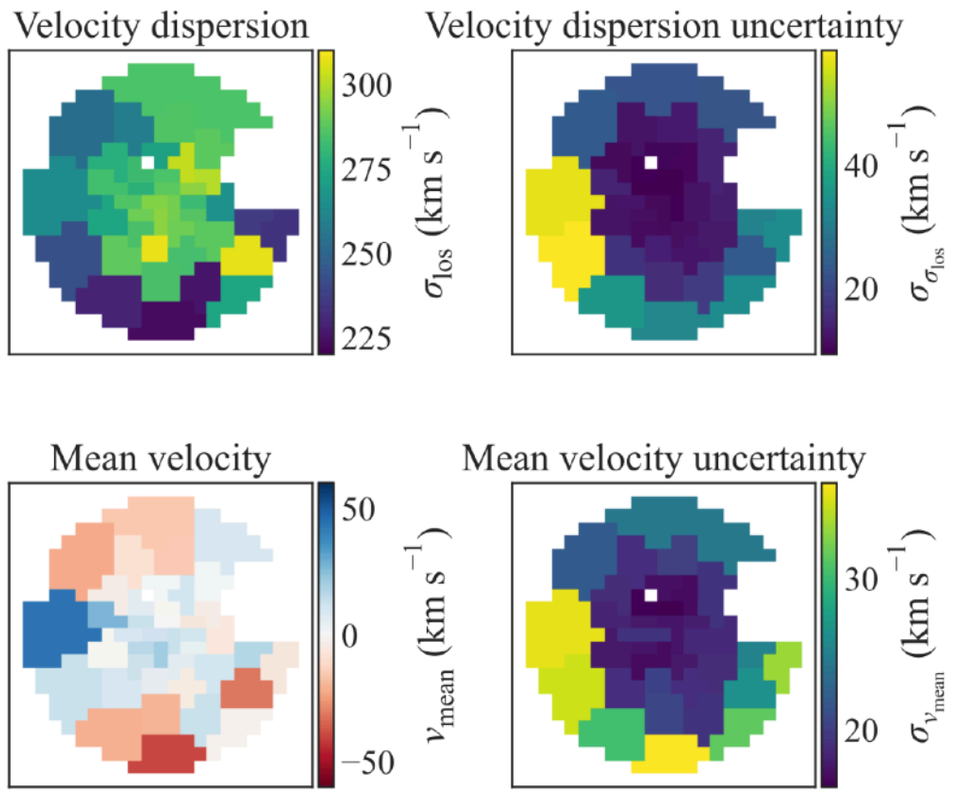
$67.4^{+4.1}_{-3.2}$ km s^{-1} Mpc^{-1}
TDCOSMO+SLACS$_{SDSS+IFU}$ (anisotropy and profile constraints from SLACS)

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

Avenue #2 - Dynamics of Time-Delay Lens Galaxies





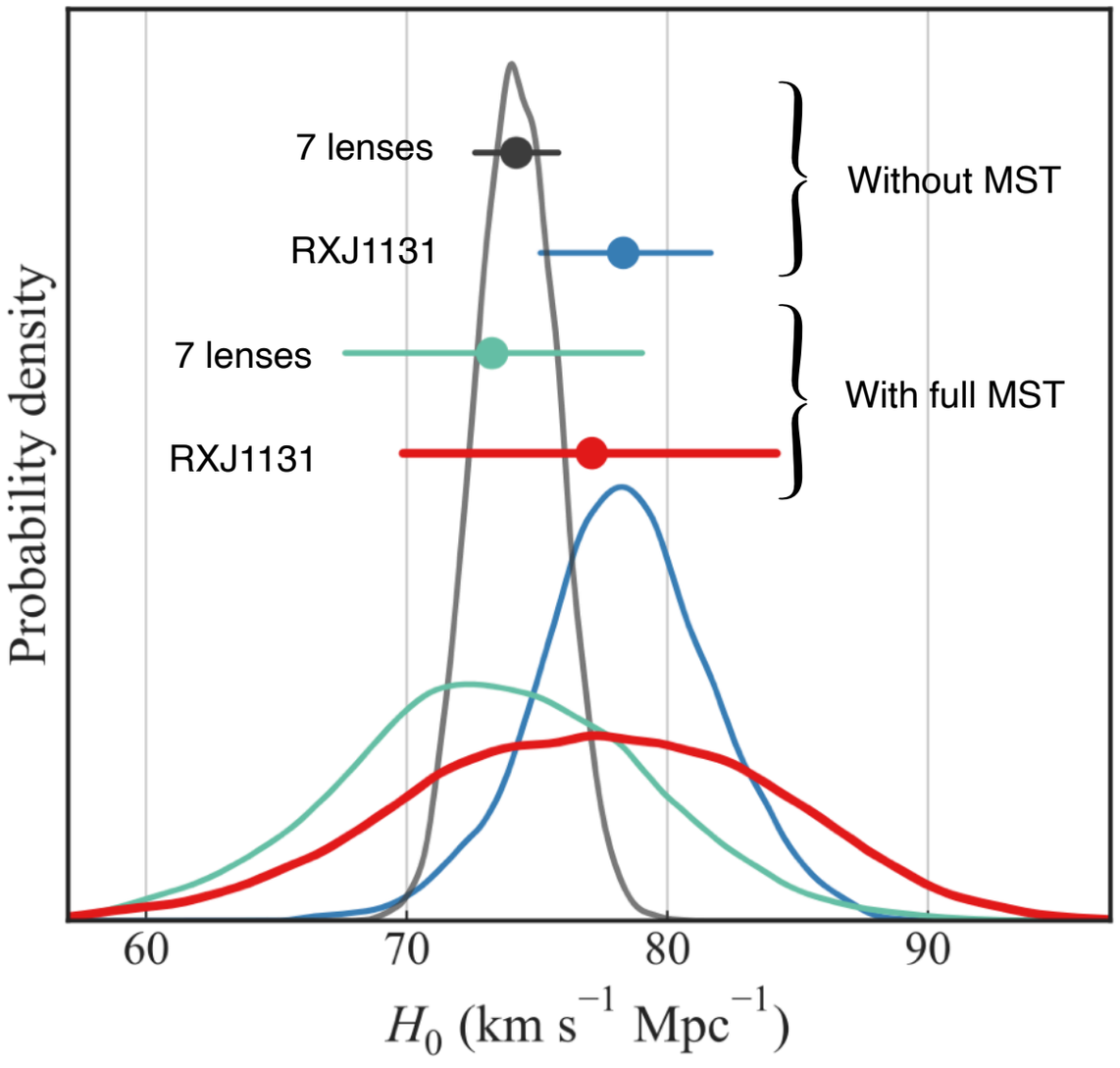


4h of Keck KCWI IFU spectroscopy (no-AO)

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



RXJ1131−1231 with the MSD broken assuming simple parametric mass models (Chen et al. 2019)

Seven lenses with the MSD broken assuming simple parametric mass models (Millon et al. 2020b, TDCOSMO-I)

Seven lenses with the MSD broken using single-aperture kinematics (Birrer et al. 2020, TDCOSMO-IV)

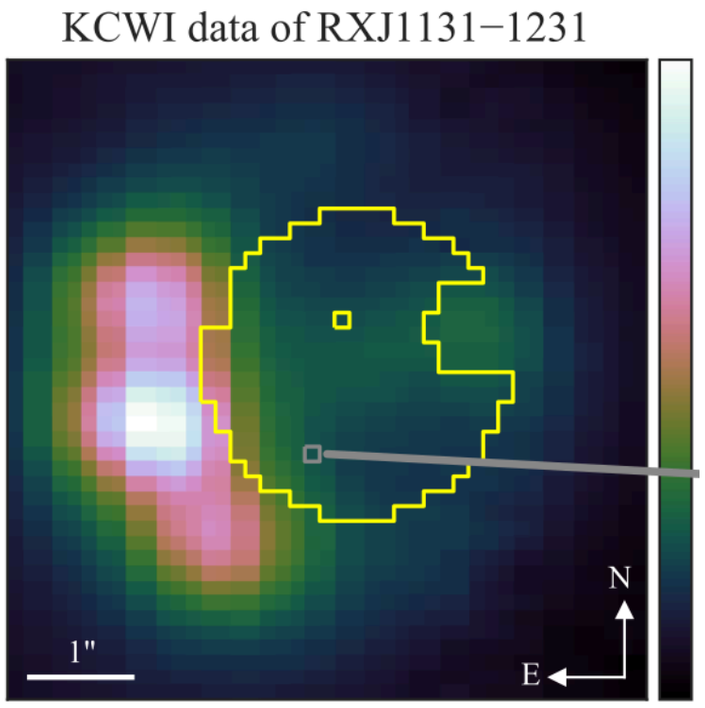
RXJ1131−1231 with the MSD broken using spatially resolved kinematics (this work)

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

Avenue #2 - Dynamics of Time-Delay Lens Galaxies

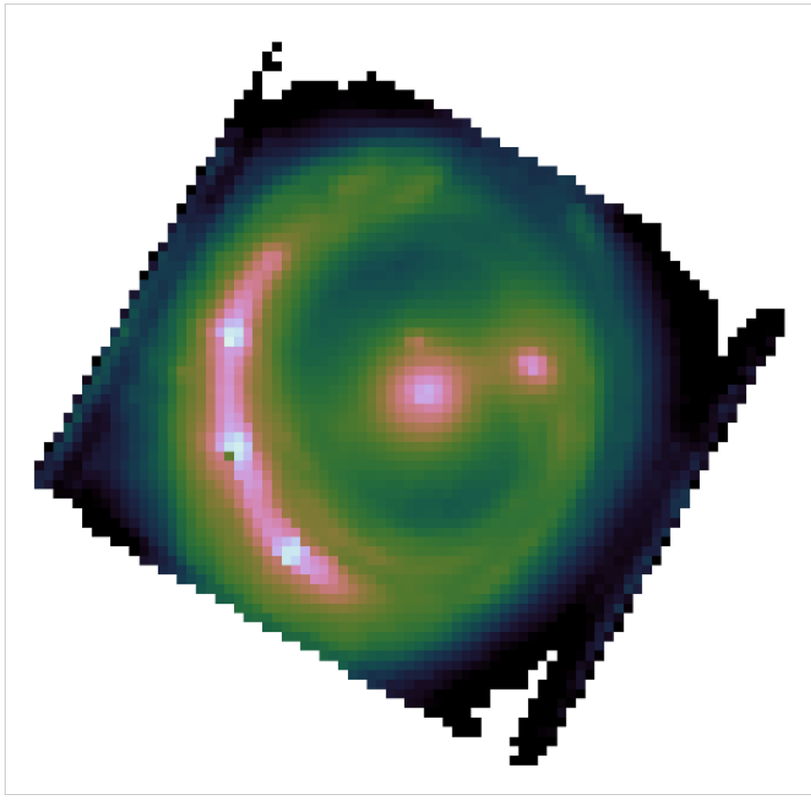
New JWST Cycle 1 NIRspec IFU + accepted Cycle 2 program

HST optical imaging



Keck IFU (no-AO)

9% precision

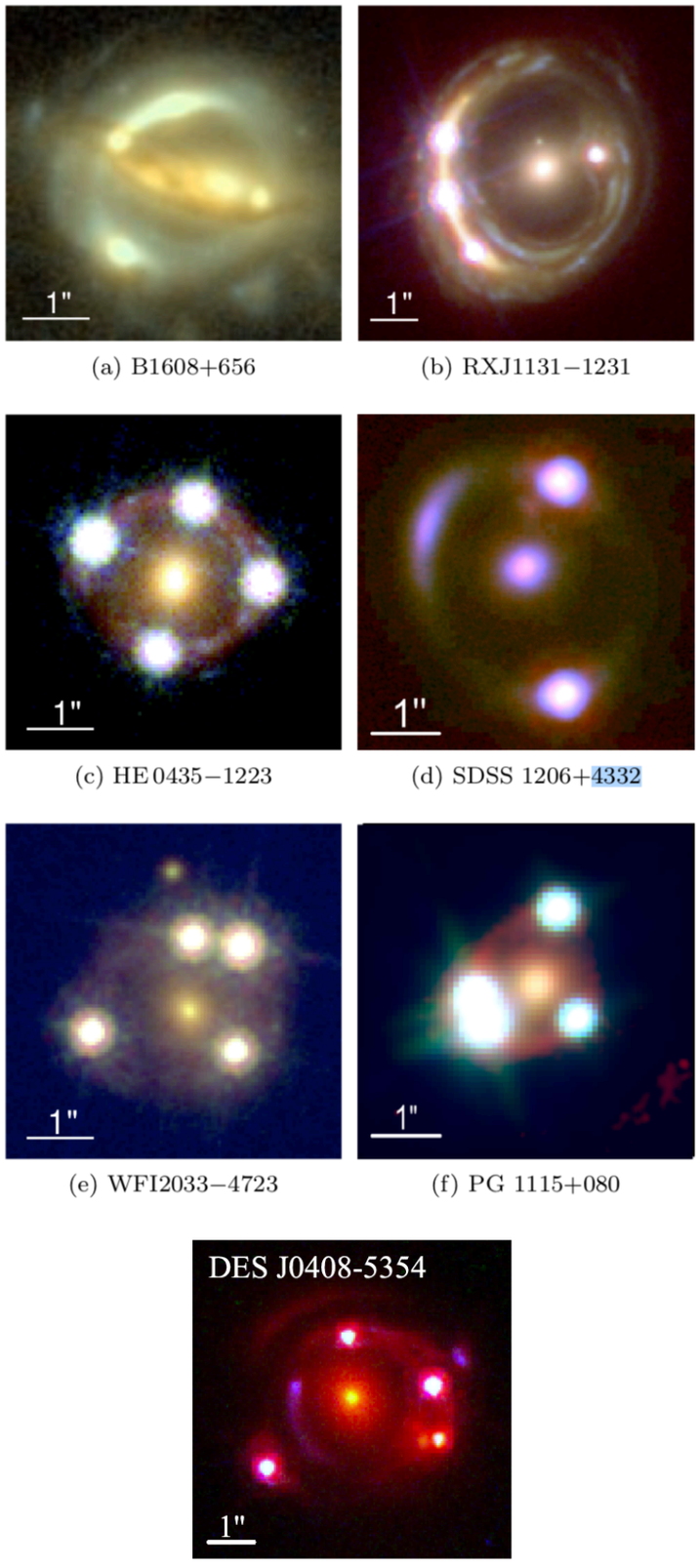


JWST NIRspec (white-light image)

Expected 4% precision

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**

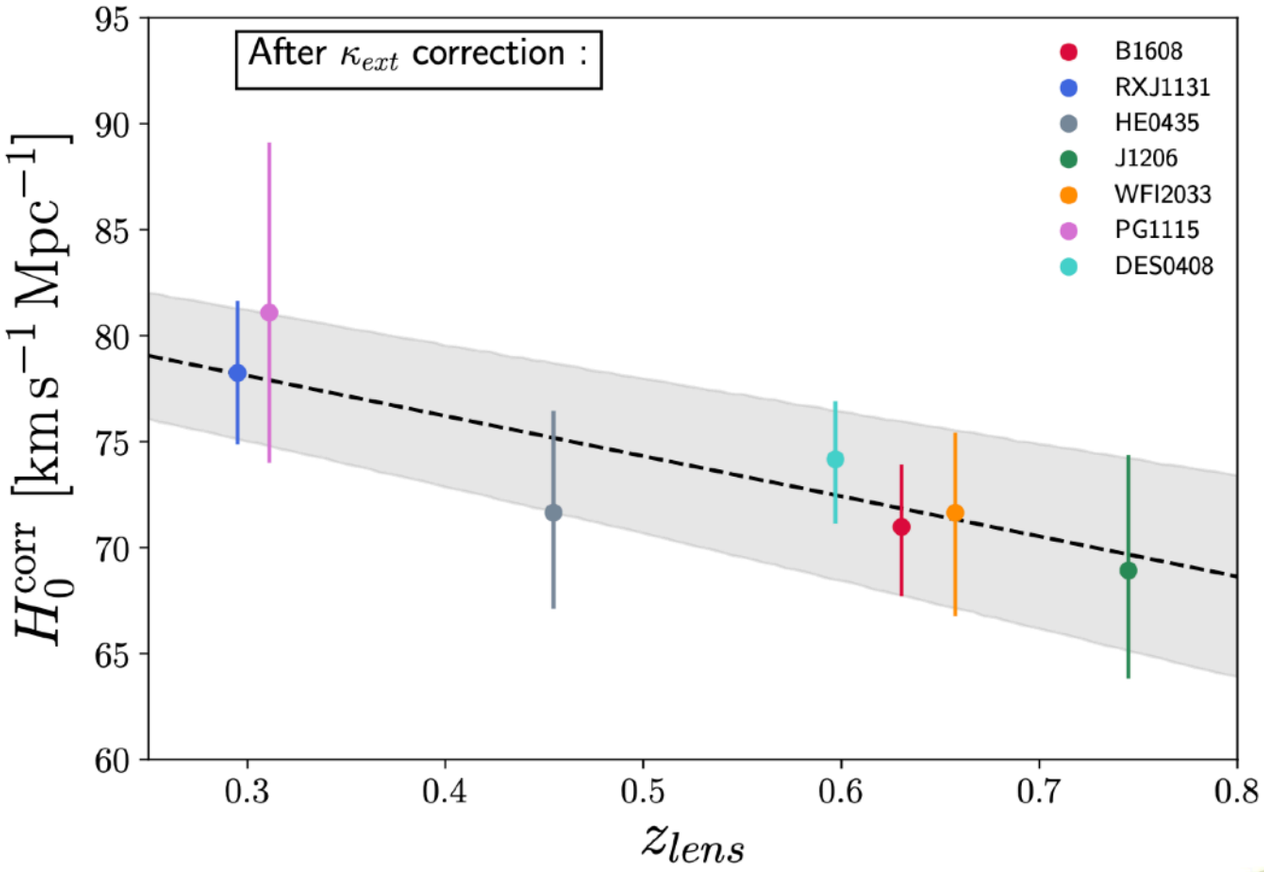


(a) B1608+656 (b) RXJ1131−1231

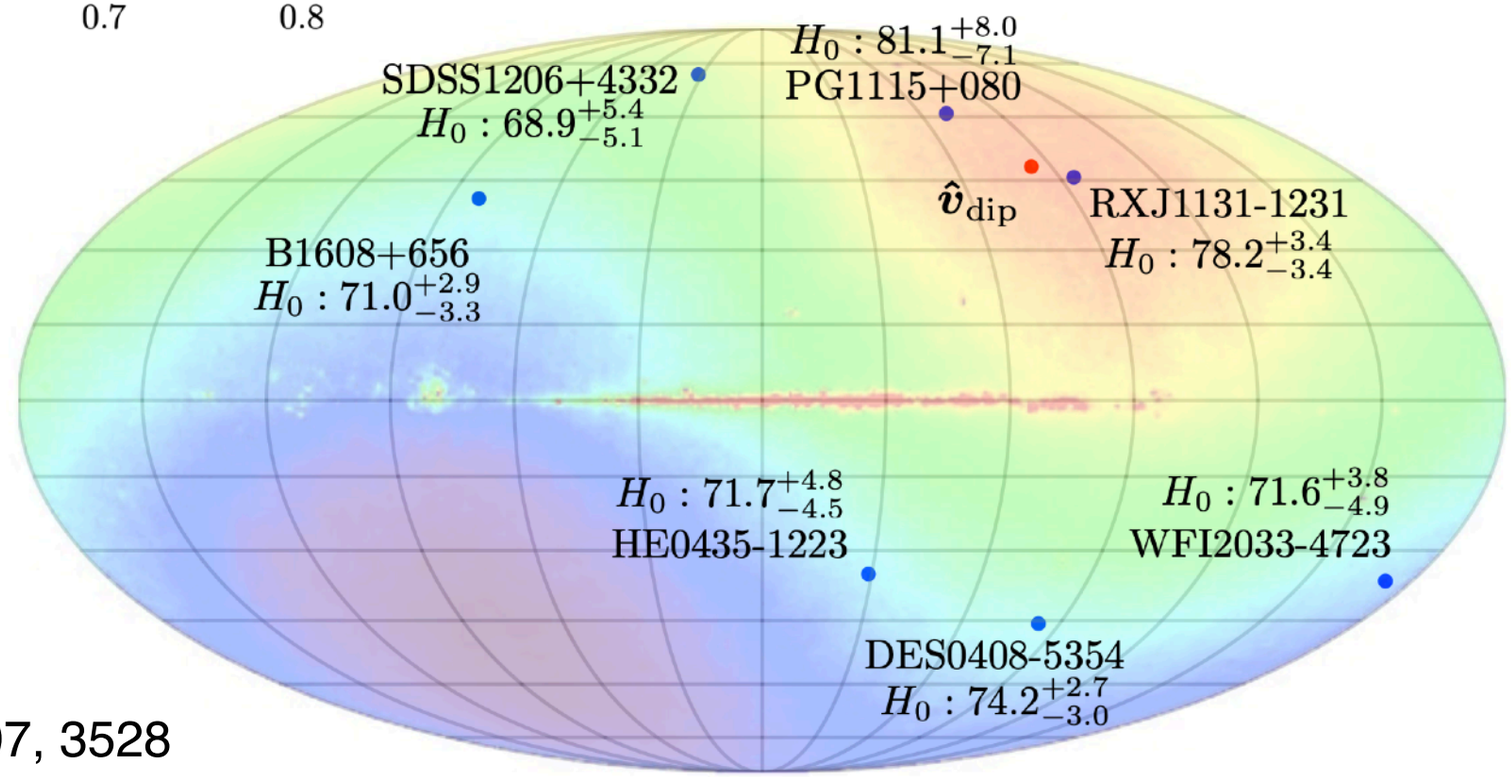
(c) HE 0435−1223 (d) SDSS 1206+4332

(e) WFI2033−4723 (f) PG 1115+080

Bonus puzzles



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



Dalang, Millon & Baker, 2023, PHRvD, 107, 3528