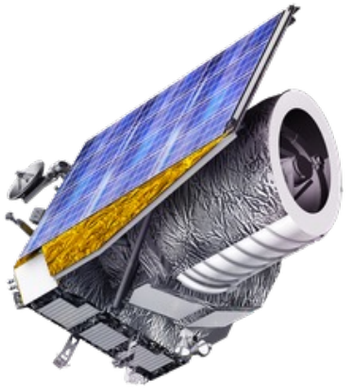
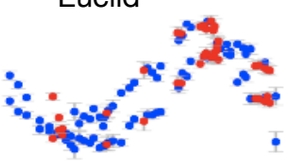
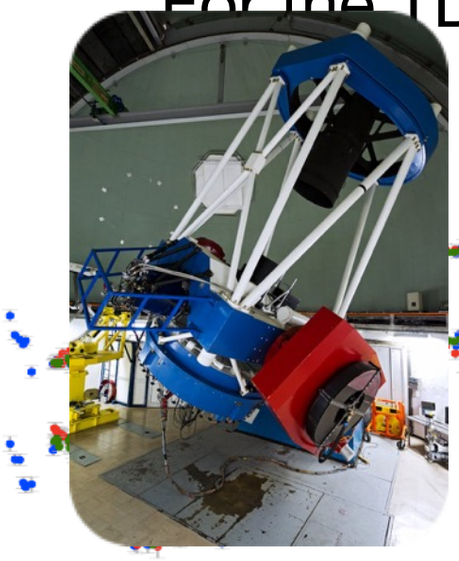
Measuring H_0 with time delays in strongly lensed quasars

Léon Koopmans (Kapteyn Astronomical Institute
University of Groningen)
For the TDCOSMO collaboration

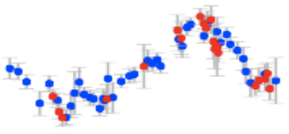


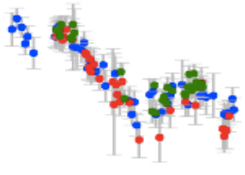
Euclid

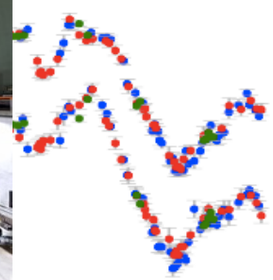


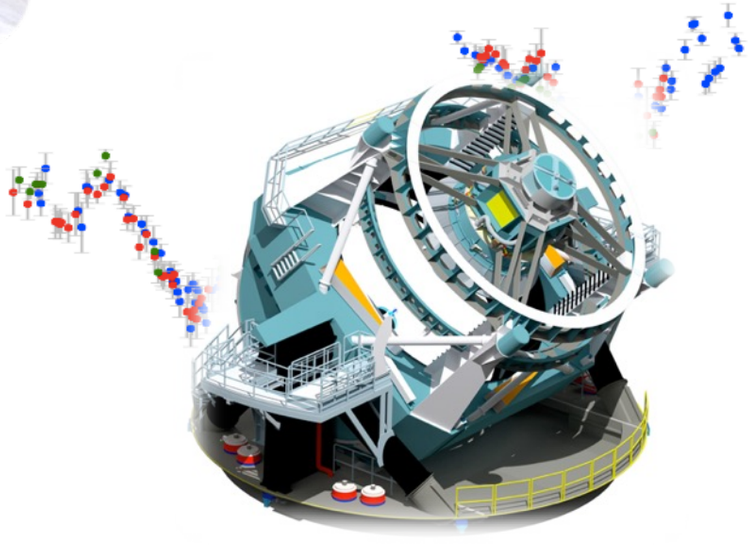


MPG 2.2m

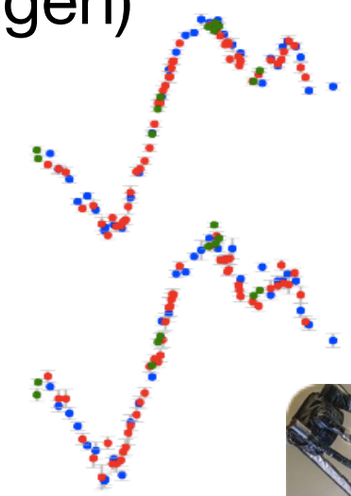


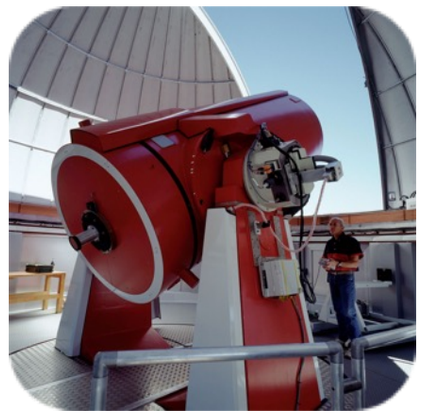






LSST





Euler 1.2m

JWST

ELT

COSMICLENS

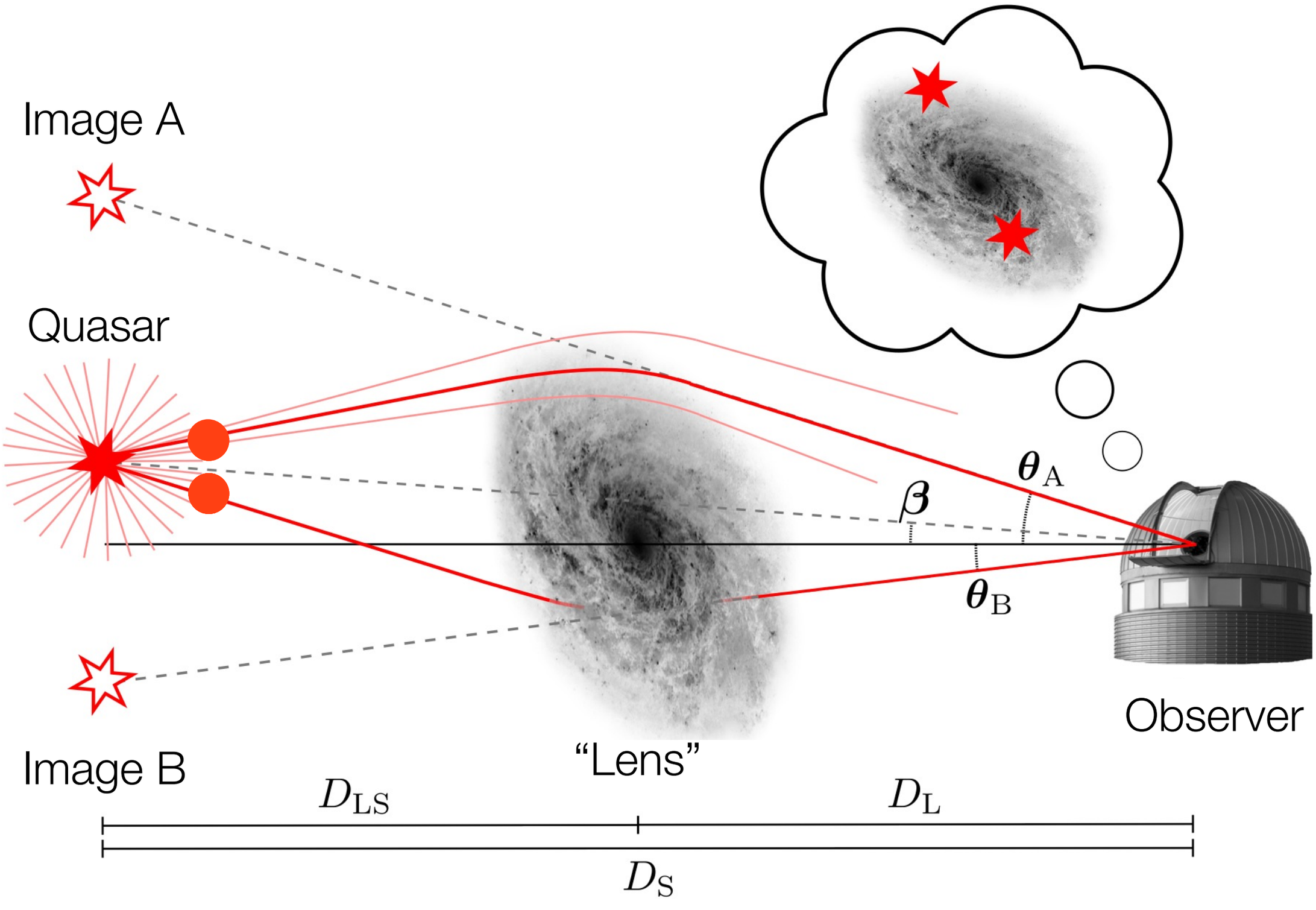
European Research Council
Established by the European Commission

FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

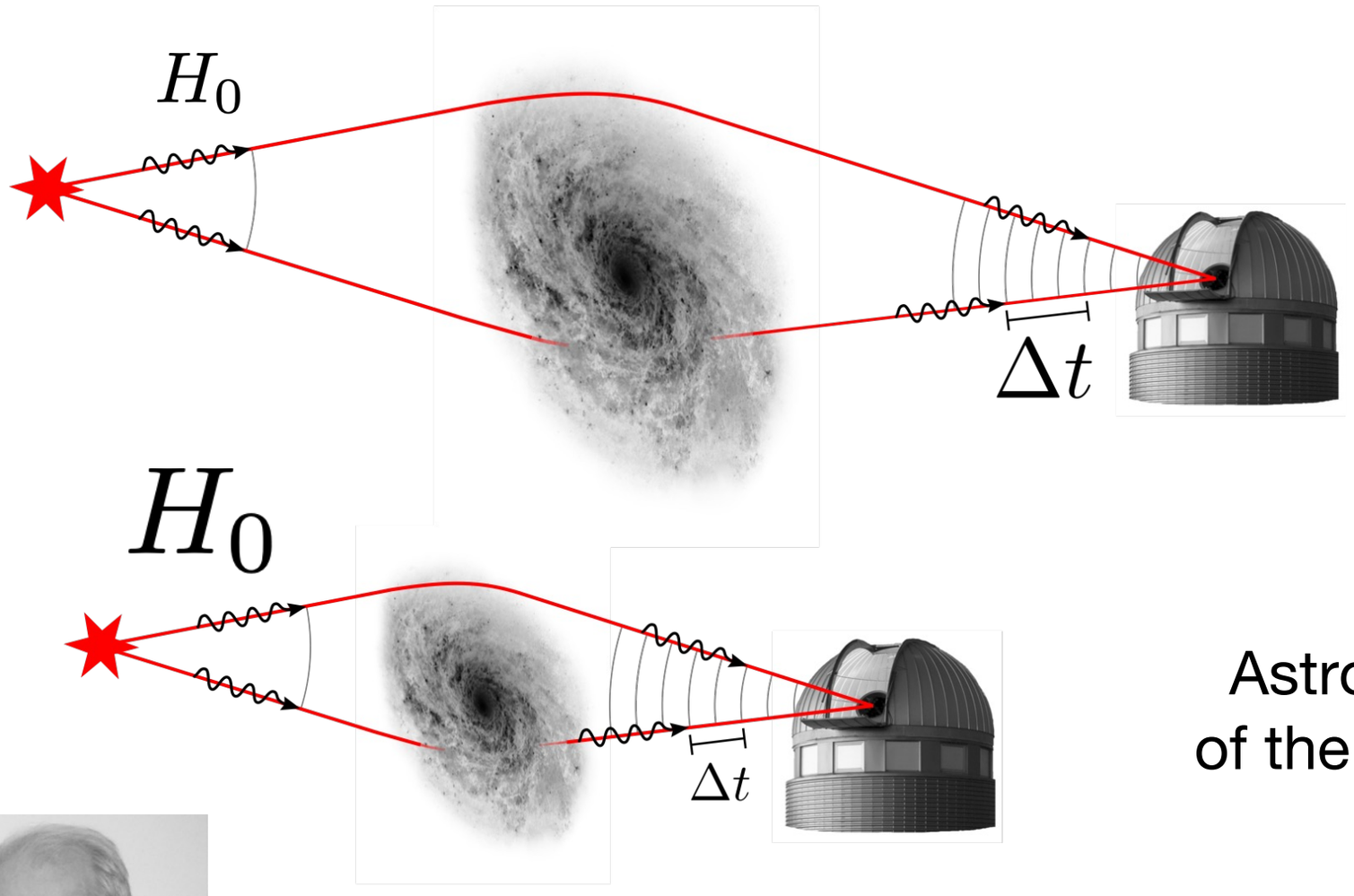
Corfu - September 2022

Time Delay Cosmography

Time Delays in Strongly Lensed Quasars



Time Delays Measure the Hubble Constant H_0



Sjur Refsdal

Lens potential at the images

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

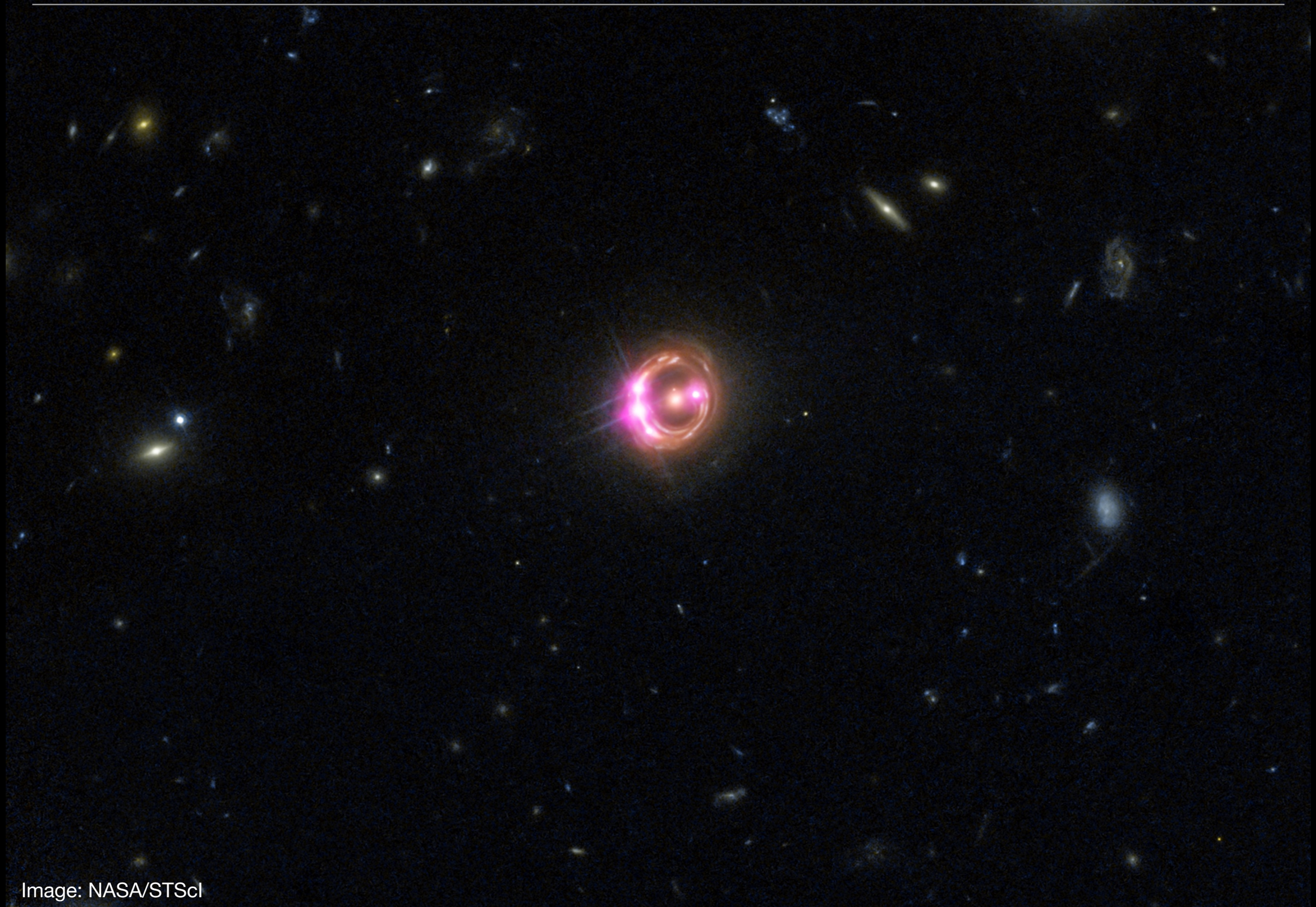


Image: NASA/STScI

Example of RX J1131-123

Mass in the Einstein ring
Mass slope at image position

Image: NASA/STScI

Example of RX J1131-123

Mass in the Einstein ring
Mass slope at image position

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

Image: NASA/STScI

What's Needed and State of the Art

	PAST	NOW
• **Time delays** measurements	15-30%	
• **Mass model** for the lens	- Simplistic models - Few constraints	
• **Environment** of the lens	- External shear	
• **Line of Sight** contribution	- External shear	
• **Lens dynamics**	- At best central vel. disp	

What's Needed and State of the Art

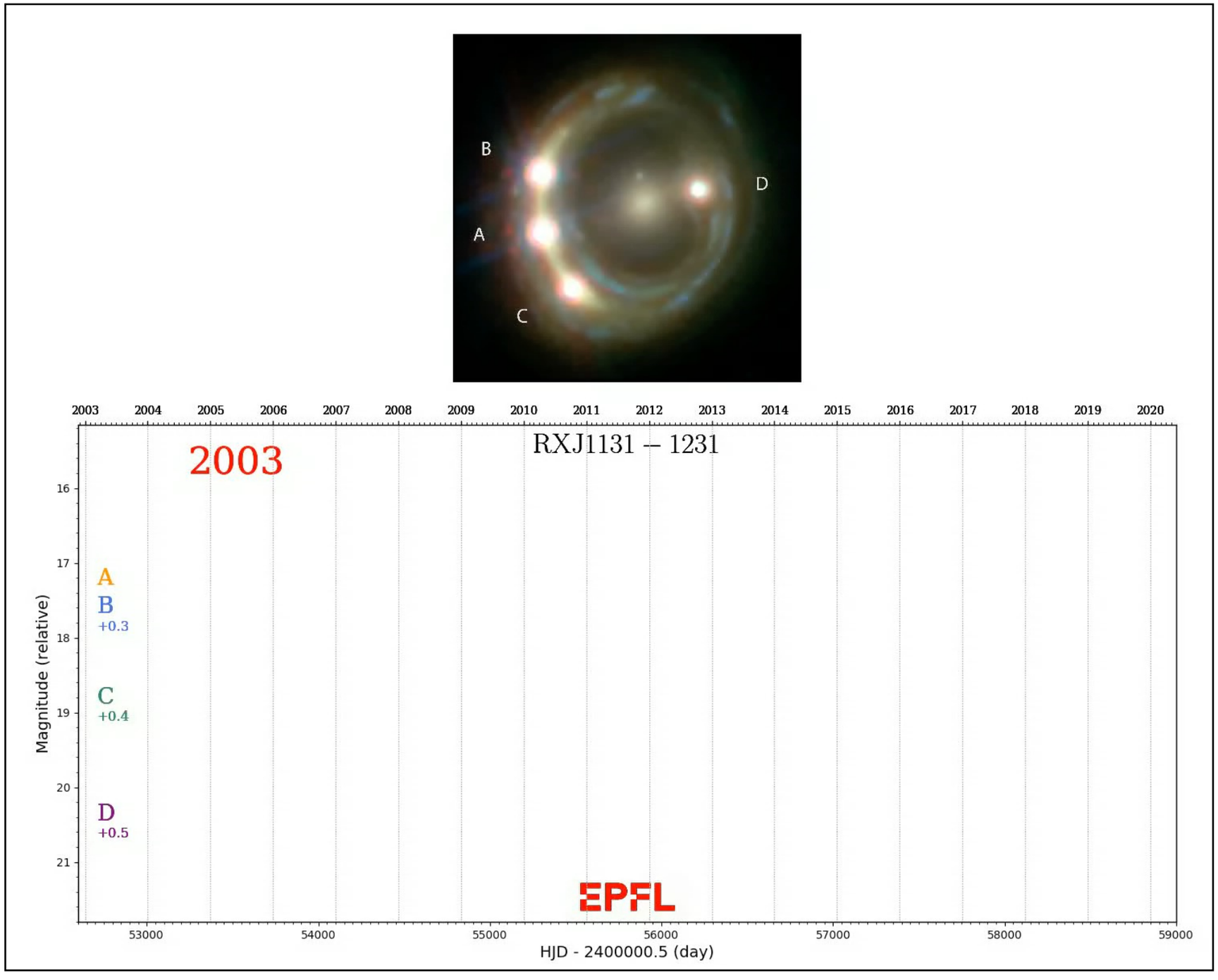
	PAST	NOW
• **Time delays** measurements	15-30%	1-5%
• **Mass model** for the lens	- Simplistic models - Few constraints	- Flexible elliptical models - Deep sharp HST/AO images - Lens dynamics
• **Environment** of the lens	- External shear	- Include nearby companions - Multiplane lensing - Photo and spectro z
• **Line of Sight** contribution	- External shear	- Galaxy counts - Cosmological simulations - Weak lensing
• **Lens dynamics**	- At best central vel. disp	- 2D kinematics (for some objects)
		- **BLIND Analysis** !

1- Time Delay Measurements

Photometry with image deconvolution

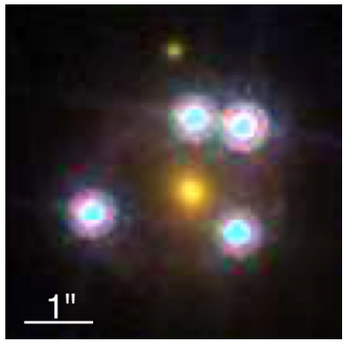
Deconvolution methods **with finite resolution** described in
Magain, Courbin, Sohy, 1998, ApJ 494, 472
Cantale, Courbin, et al. 2016, A&A 589, 81
NEW python+JAX code to be publicly released (Millon et al. 2022, JOSS, in prep)

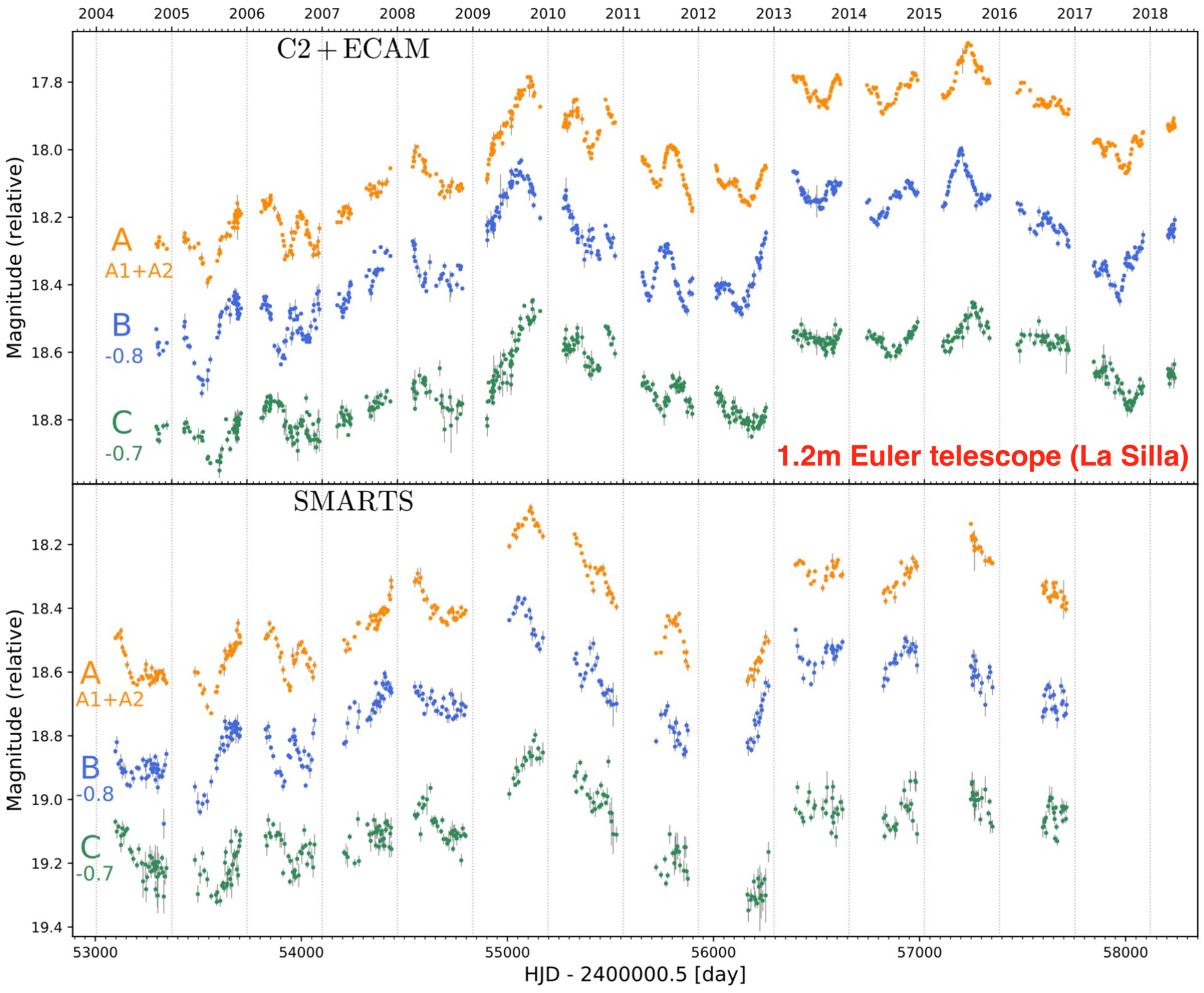
COSMOGRAIL Light Curves of RXJ1131-123



From PhD thesis of Martin Millon

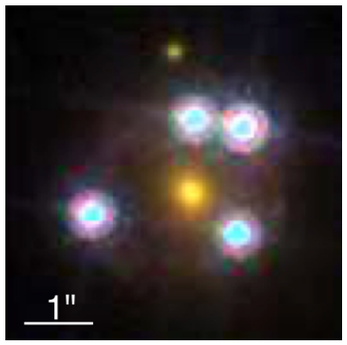
COSMOGRAIL Light Curves of WFI2033-4723

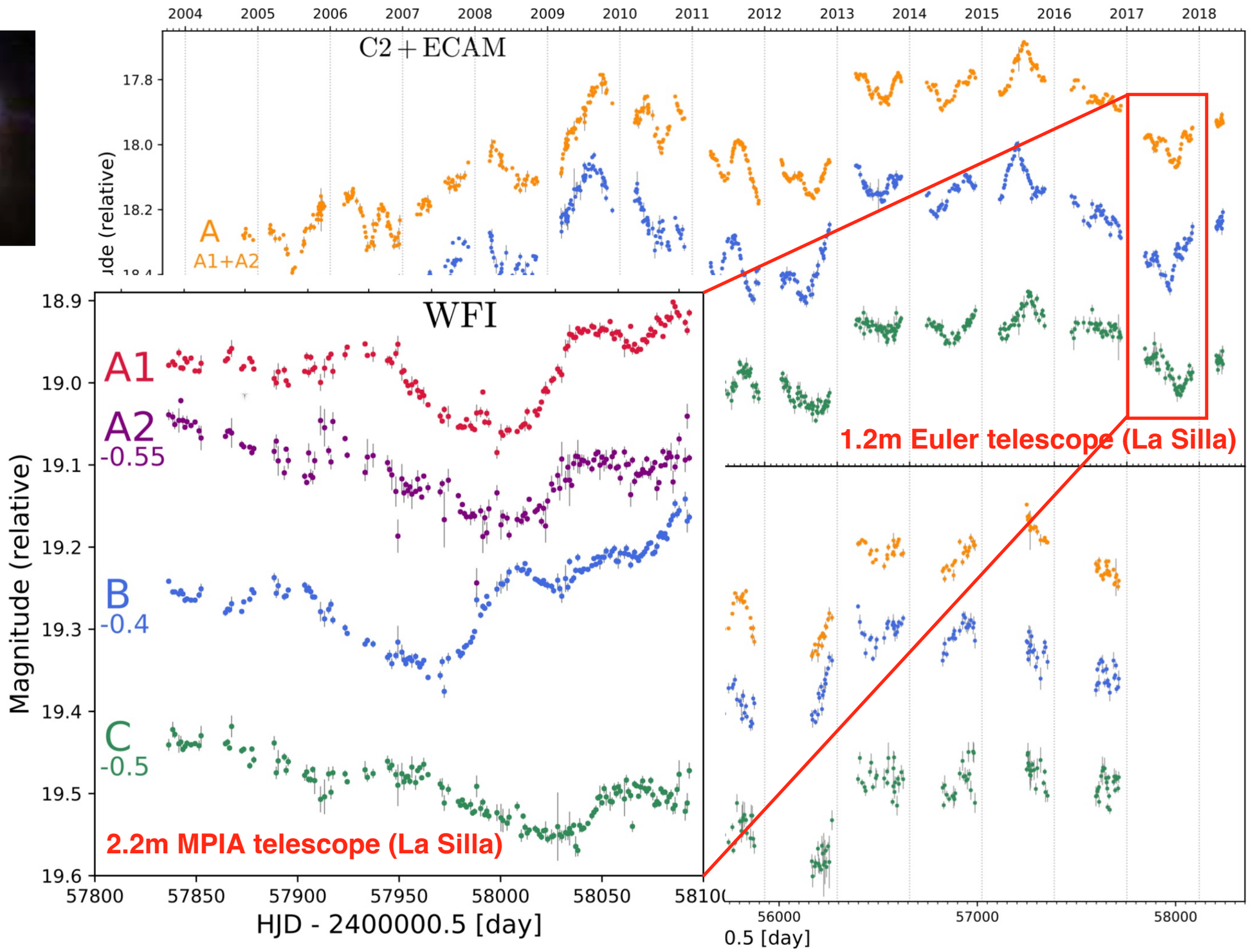




Bonvin et al. 2019, A&A 629, A97

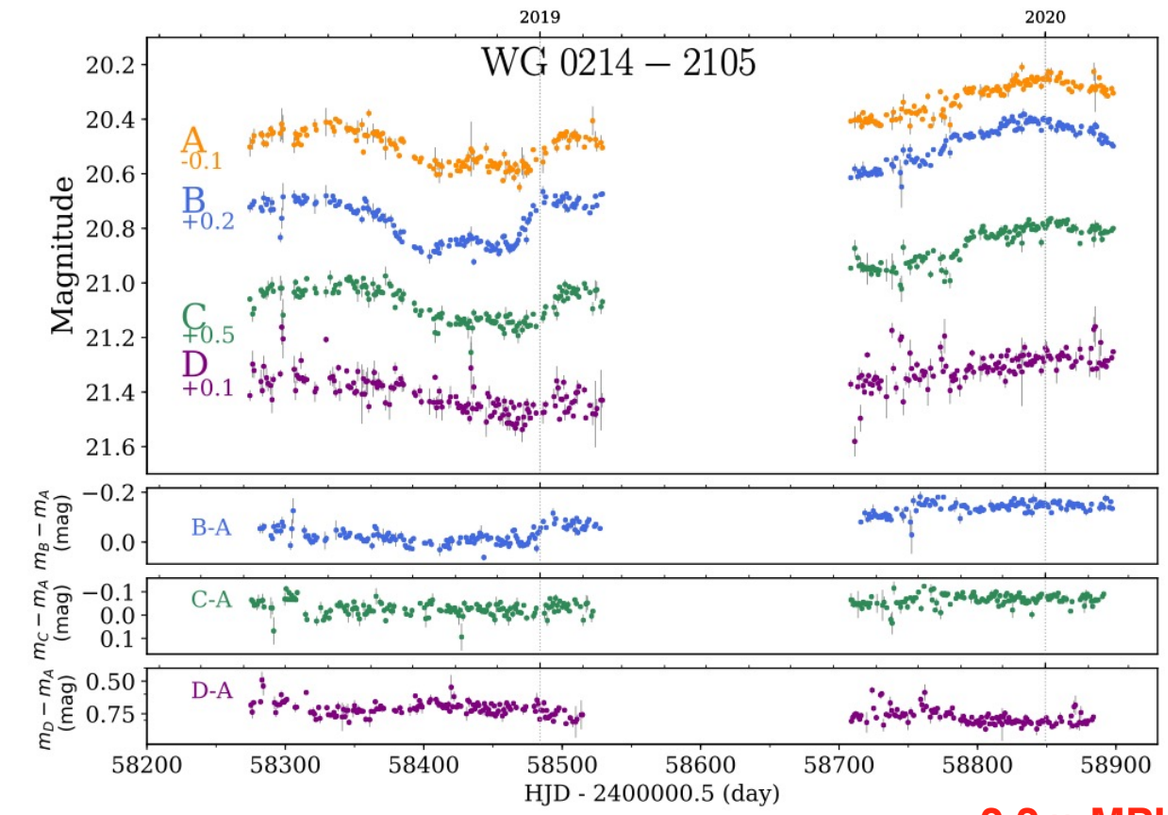
COSMOGRAIL Light Curves of WFI2033-4723

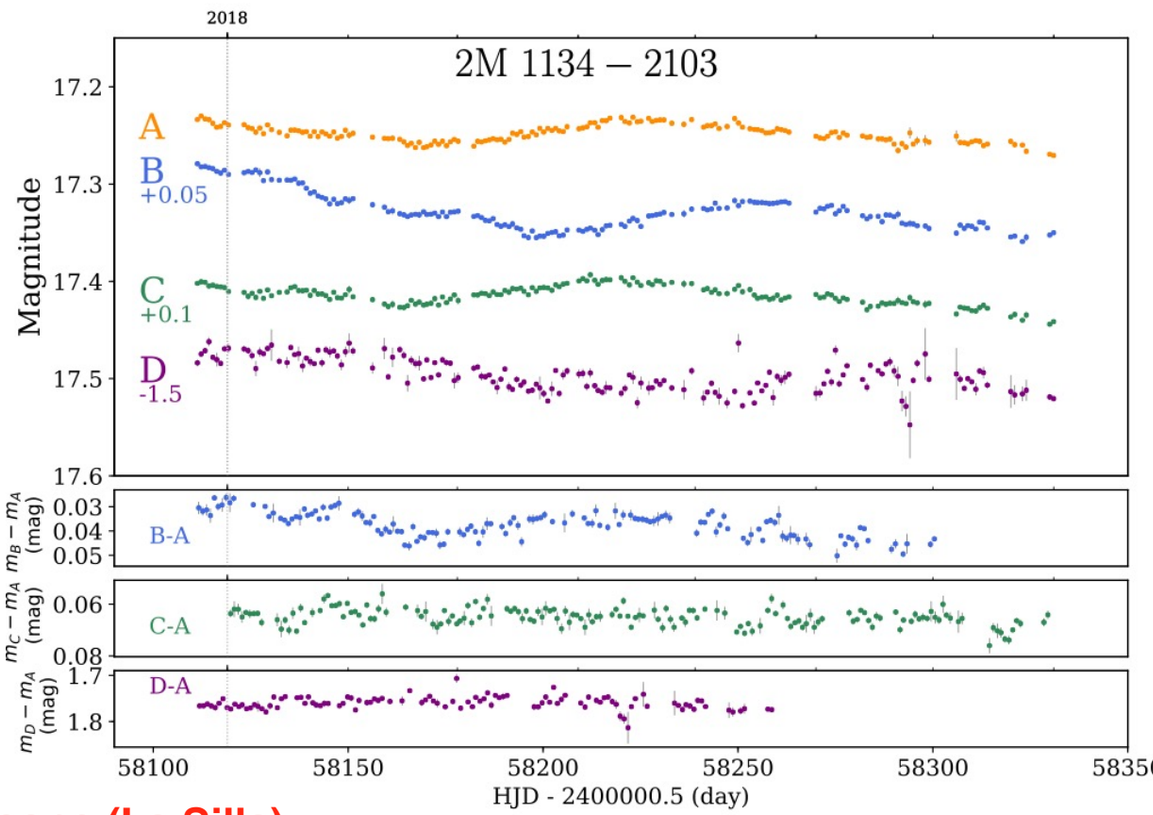




Bonvin et al. 2019, A&A 629, A97; Millon et al. 2020, 642, A193

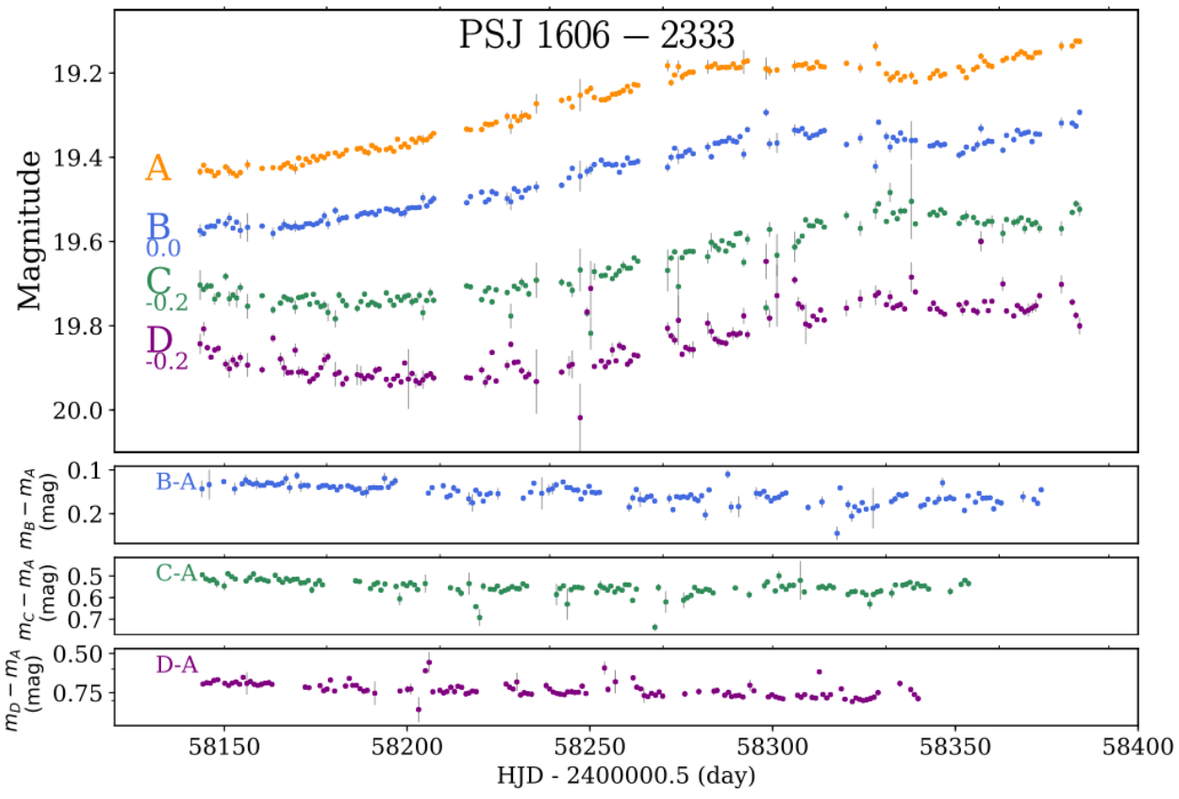
COSMOGRAIL: Mass Production of Time Delays





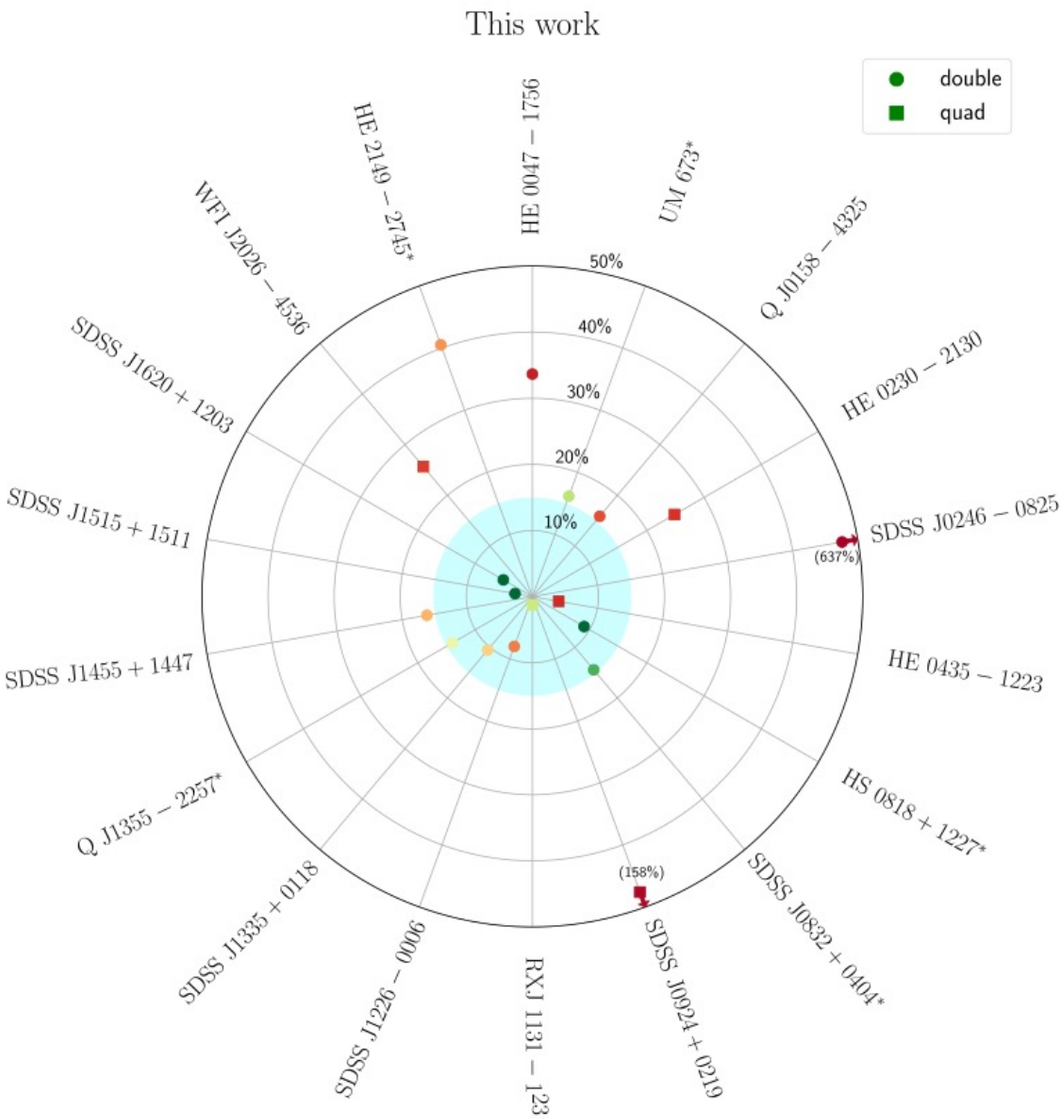
2.2m MPIA telescope (La Silla)

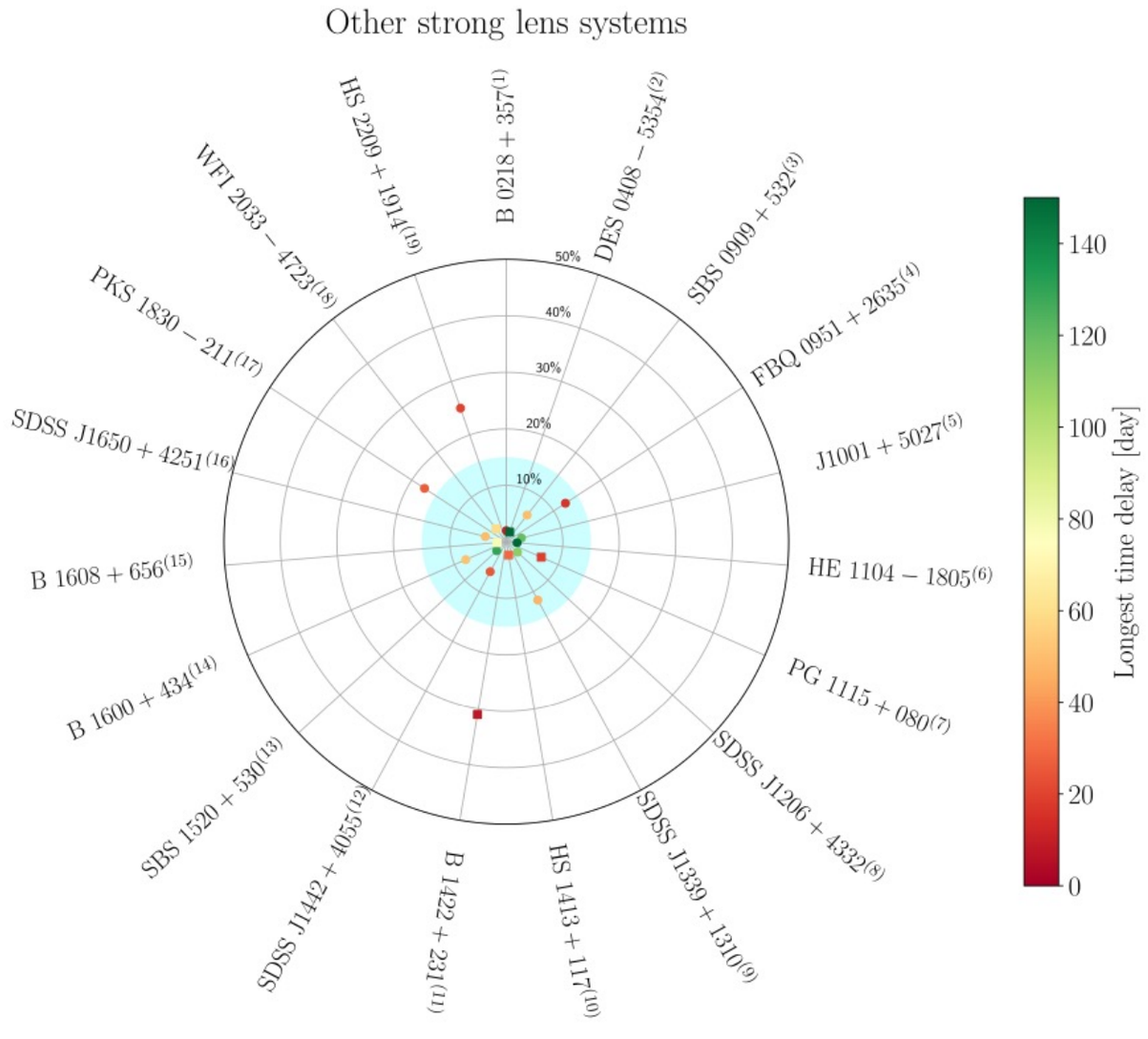
- 2m to 3m telescopes
- Daily cadence
- 30 min exposure per epoch
- 3 mmag precision per epoch
- Single-season measurement
- Better than LSST !



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

COSMOGRAIL: Mass Production of Time Delays





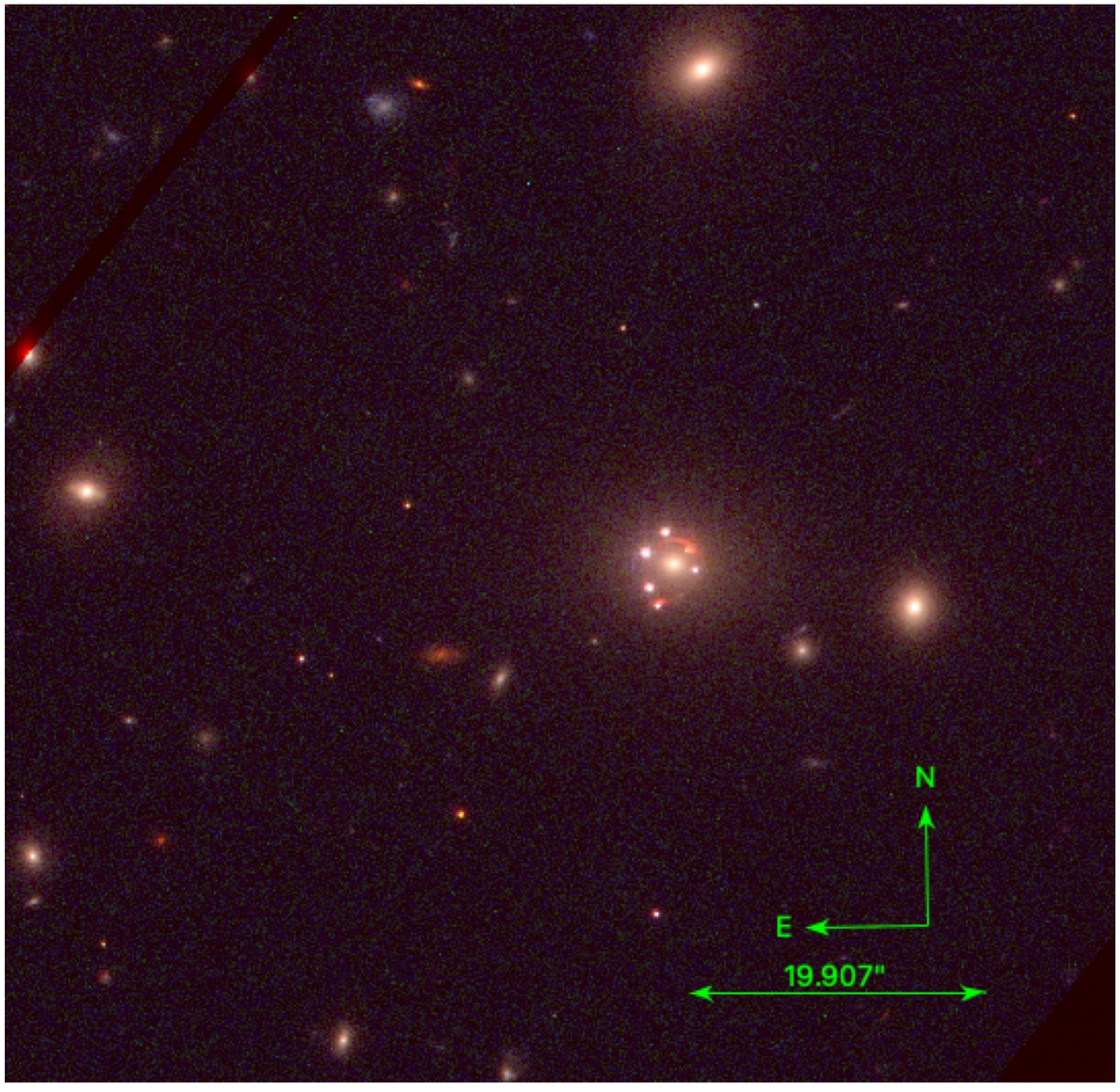
Millon et al. 2020, A&A 640, A105 (COSMOGRAIL XIX - final COSMOGRAIL paper)

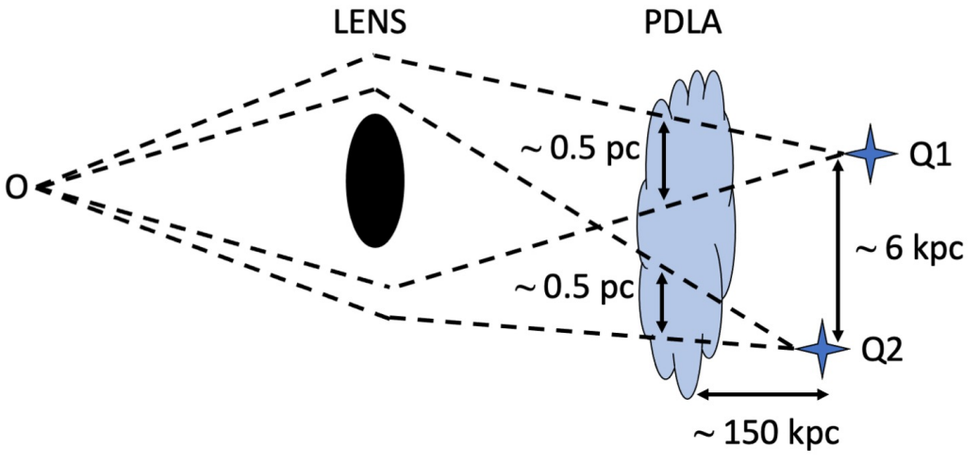
-> but many more from high-cadence monitoring with VST, NOT, 2.2m MPIA telescopes (Dux et al. 2022, in prep)

-> **more than 50 delays in total by 2023 as part of TDCOSMO**

Bonus - Lensing as a natural scanner: J1721+88

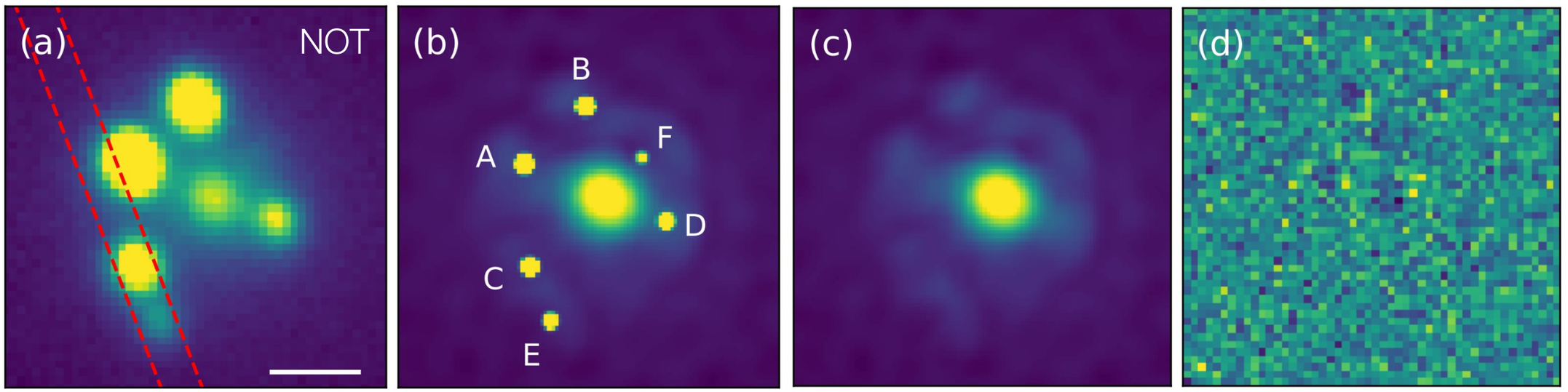
6 lines of sight probing 1- the lens, 2- a Proximate DLA

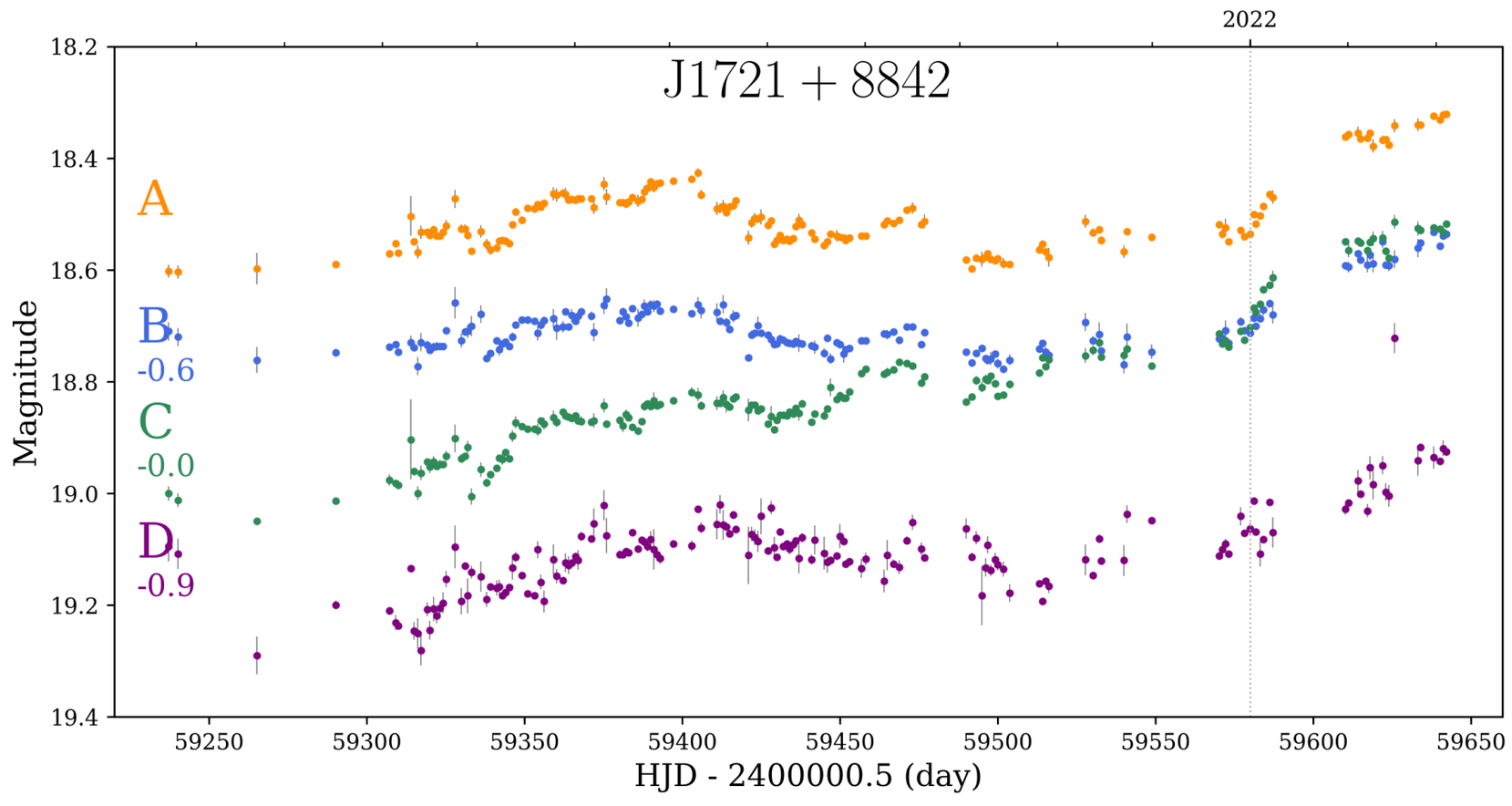




Lemon et al. 2022, A&A, 567, A113

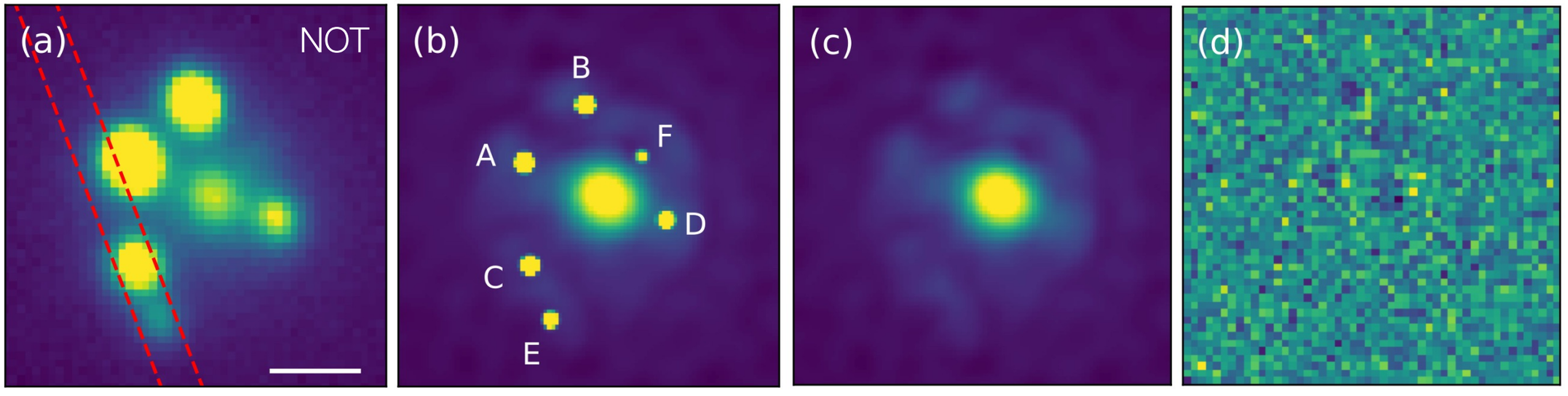
The 6-image quasar J1721+88 : NOT light curves

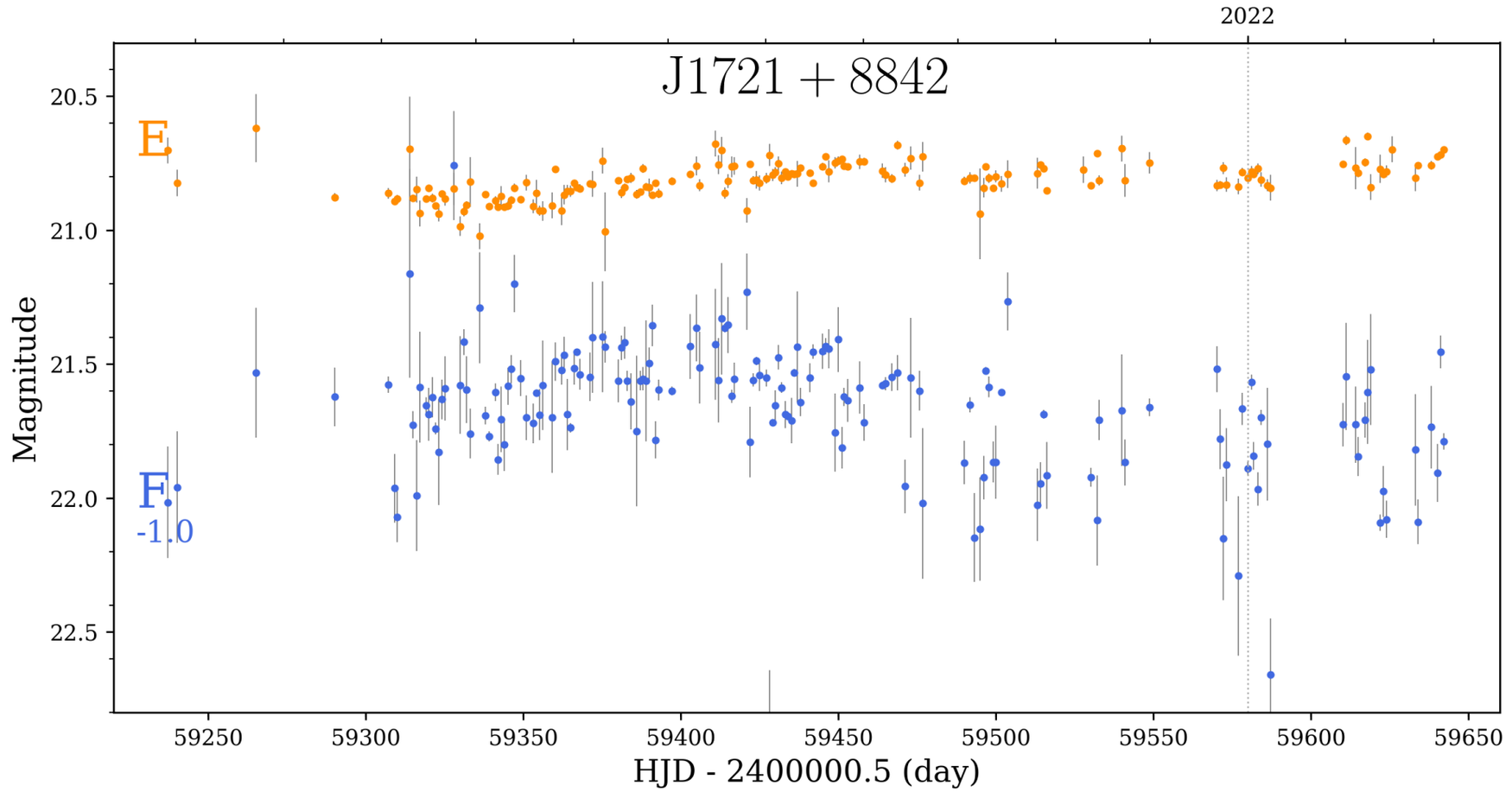




Light curves: Eric Paic & Martin Millon - daily monitoring until April 2023

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

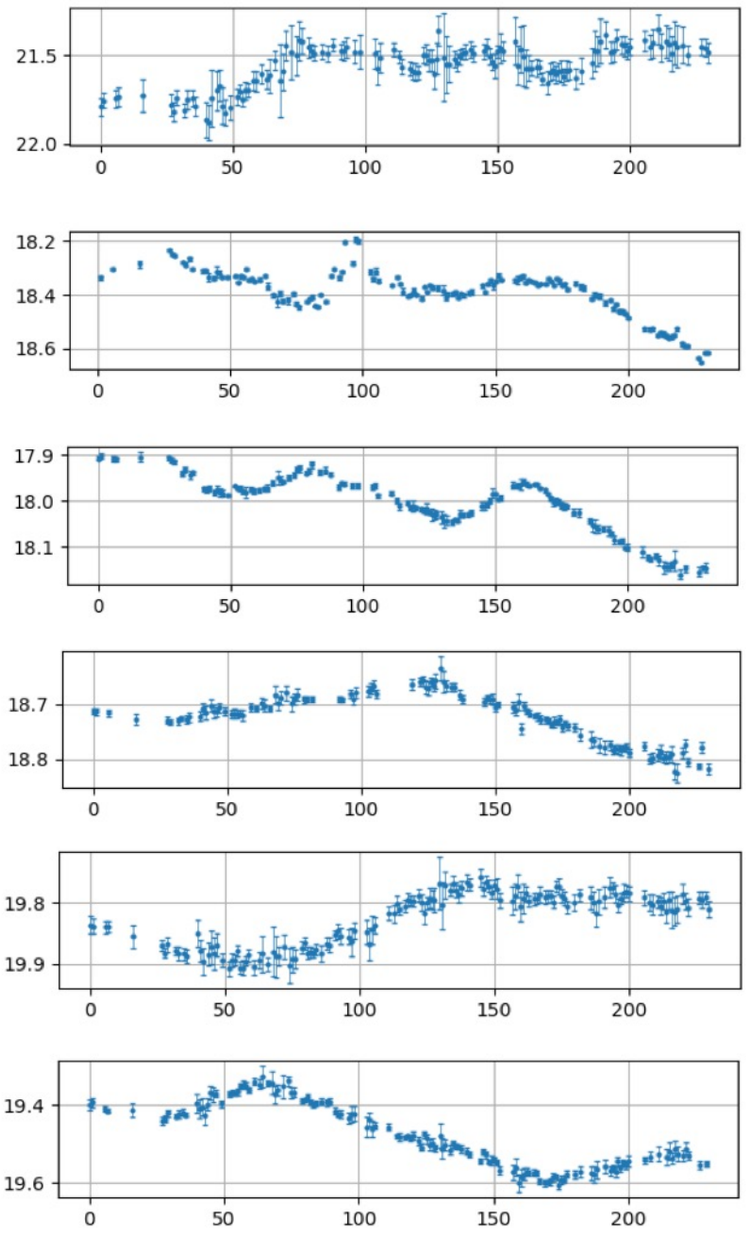




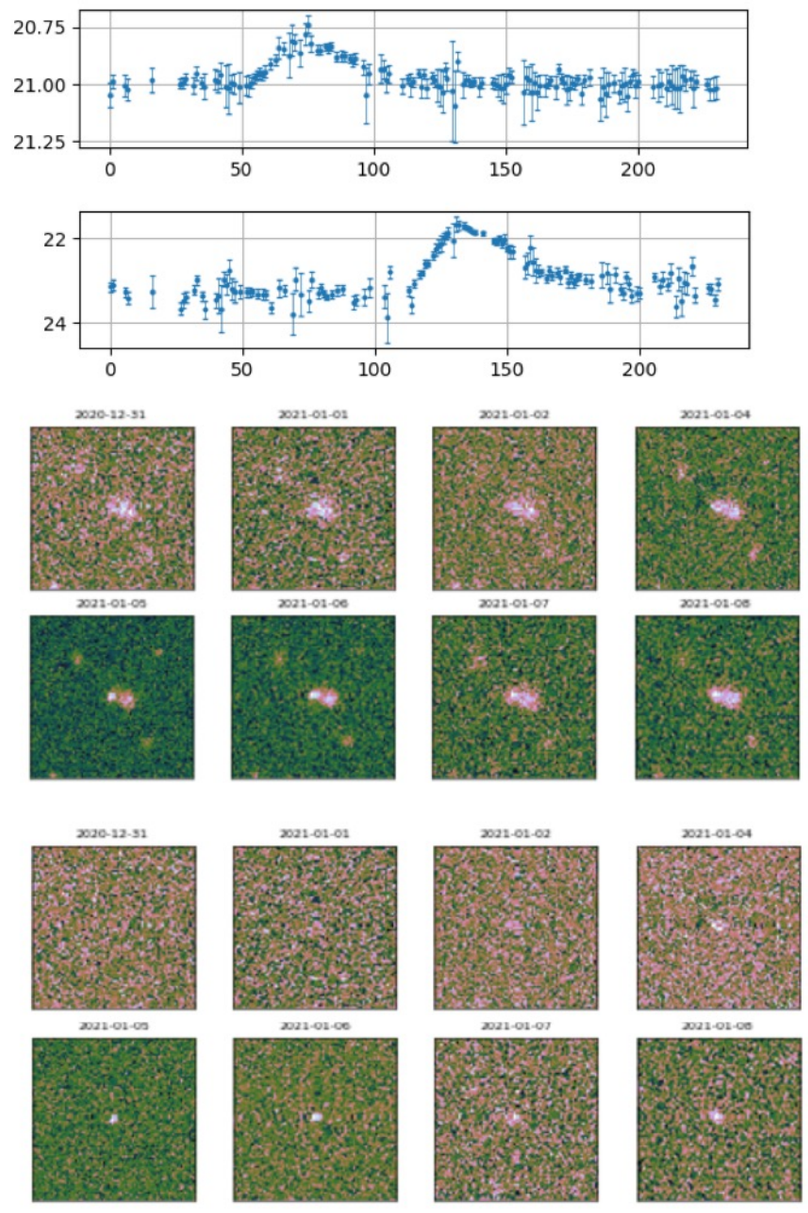
Light curves: Eric Paic & Martin Millon - daily monitoring until April 2023

High-cadence monitoring at the 2.6m VST in Paranal

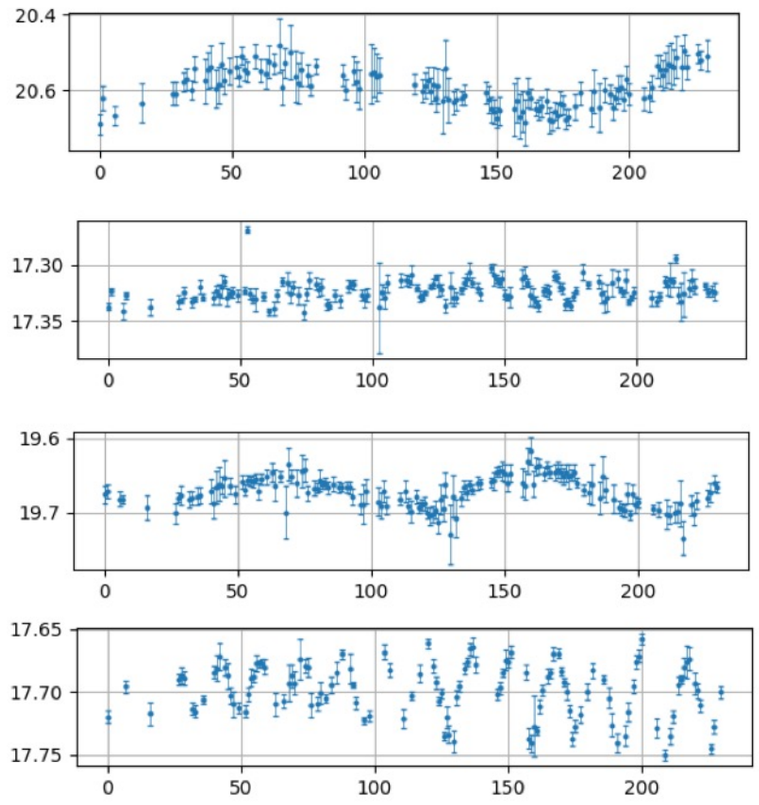
QUASARS



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

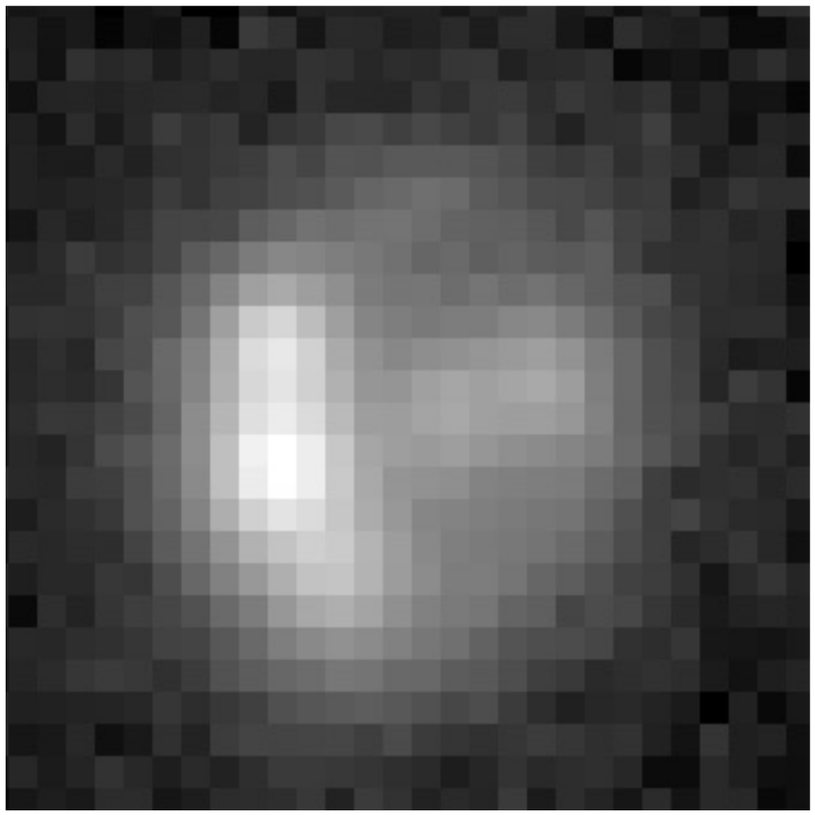
Supernovae (maybe lensed!) to r~24.5
Discovery of quasars from variability
Discovery of faint halo variable stars

PI: Courbin - VST results from Lemon et al. 2022, in prep

2- Constraining the Mass Slope

Imaging Data for RX J1131-123

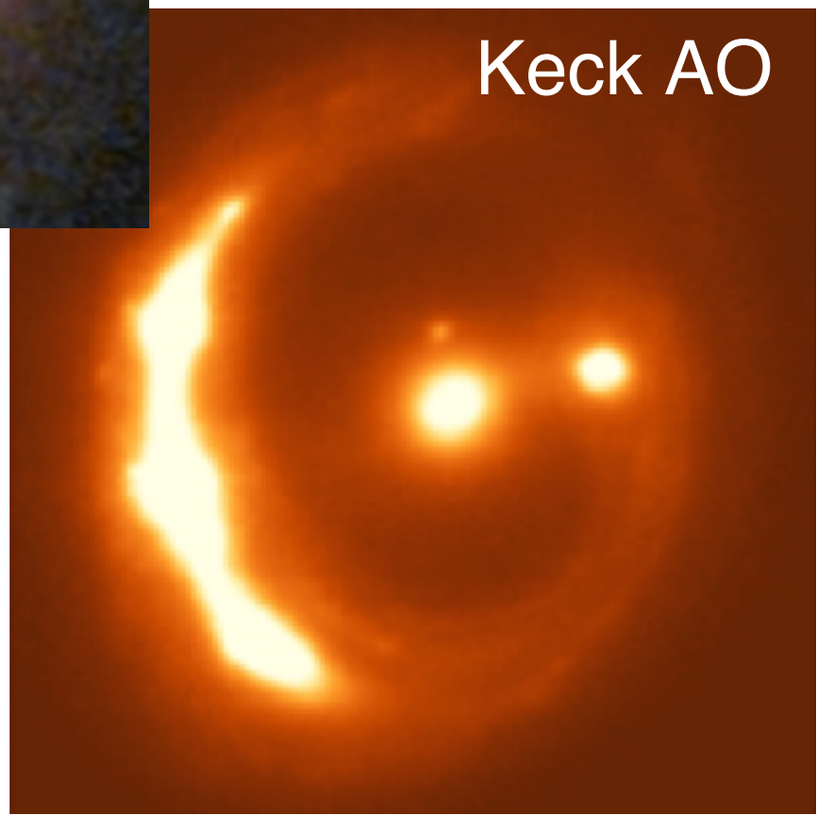
PAST



Ground-based seeing-limited

Lensing constraints restricted to astrometry of the lensed images

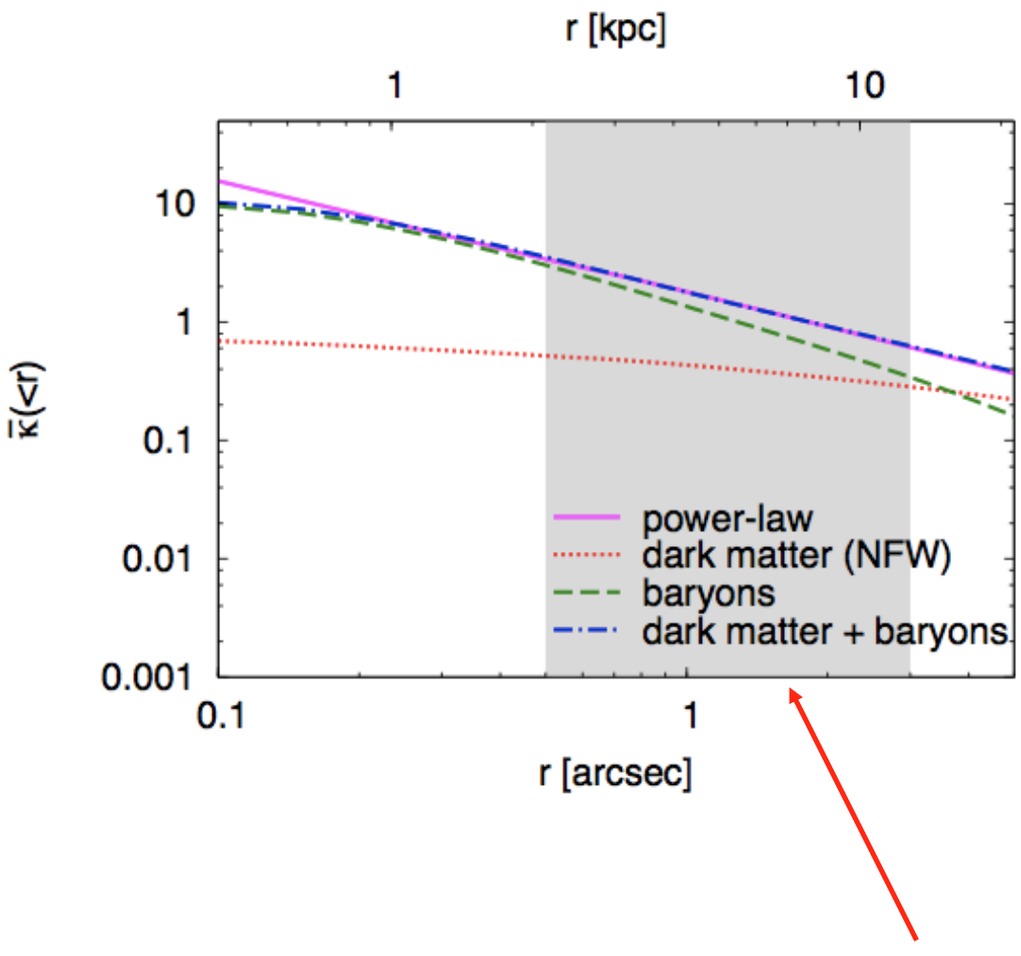
NOW

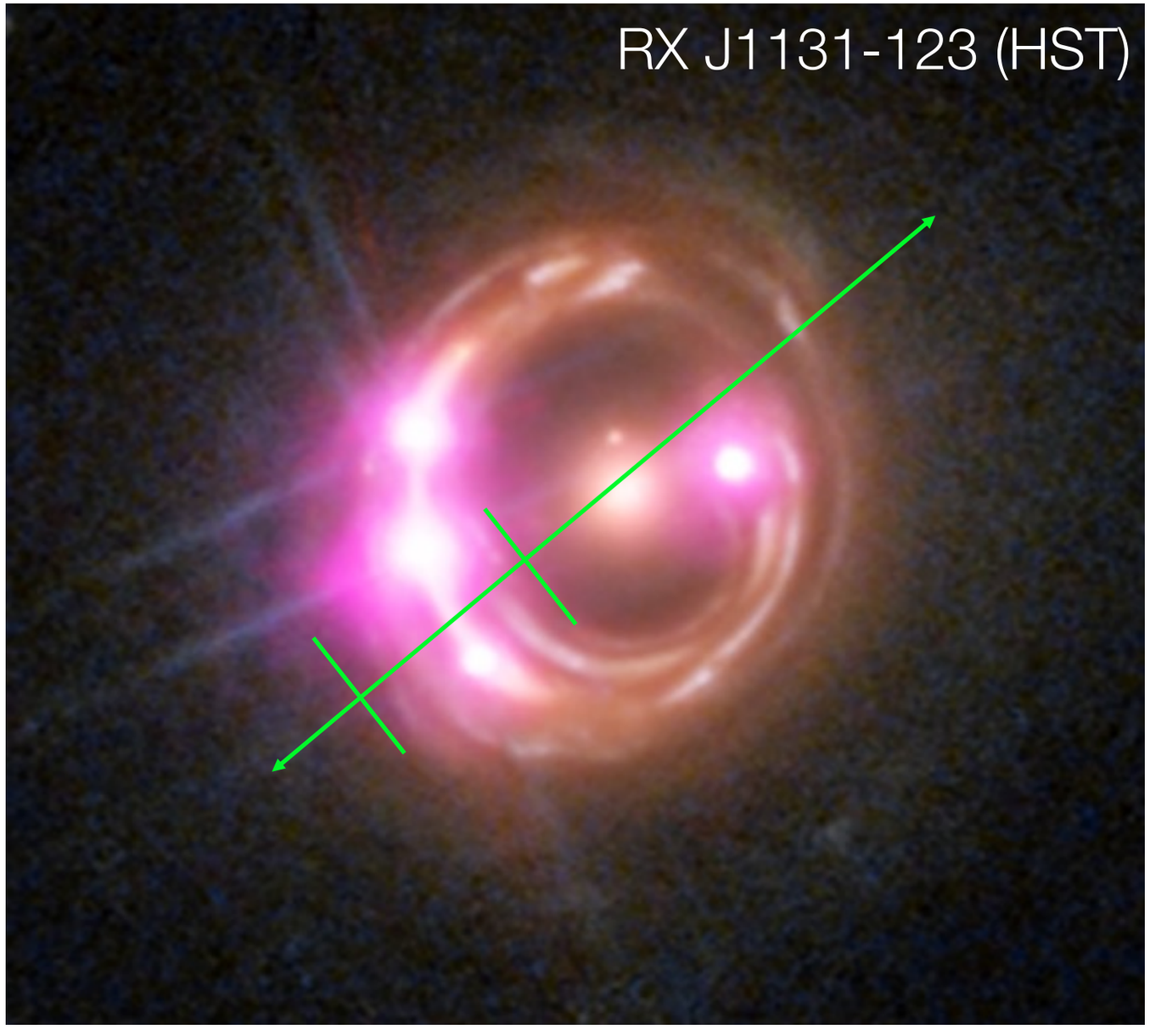


+ MUSE @VLT
+ OSIRIS @Keck
+ JWST (?)

For detailed analyses of Keck AO imaging see Chen et al. (2019, MNRAS 490, 1743)

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)

3- Accounting for the Line of Sight

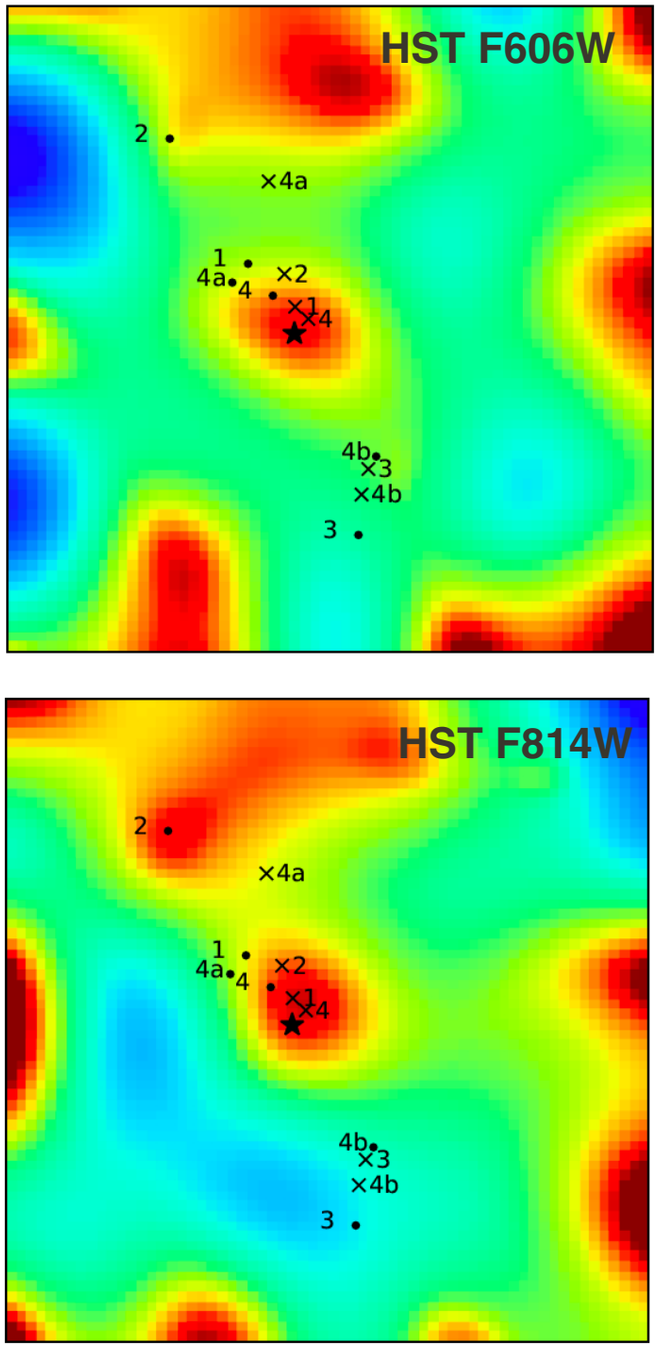
Mass-sheet Degeneracy (Line-of-Sight Contribution)

Mass along the line of sight brings extra mass inside the Einstein radius

This can be estimated in different ways:

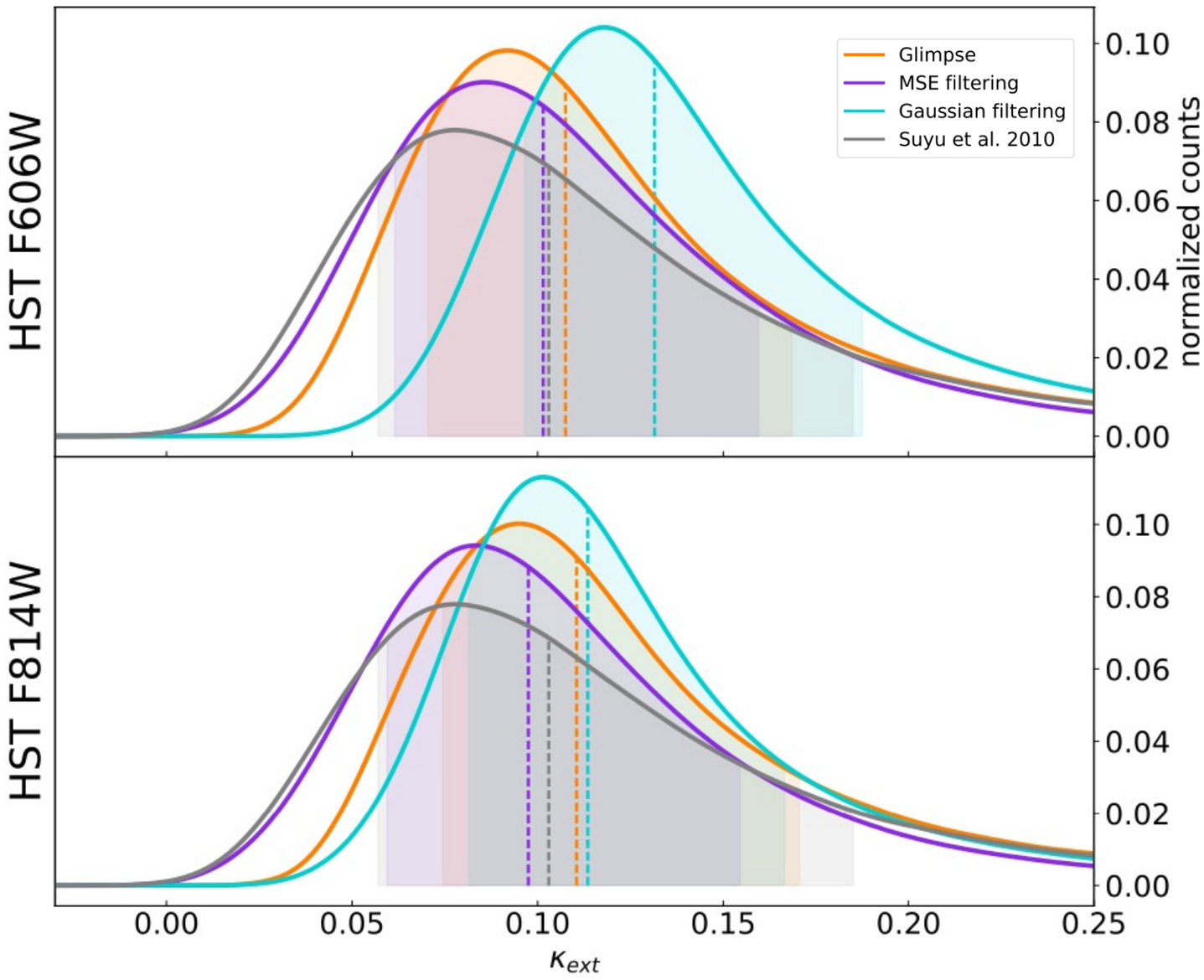
- Using galaxy counts in lens fields and compare with the general field (Fassnacht et al. 2006, ApJ, 642, 30)
- Using weighted galaxy counts (Collett et al. 2013, MNRAS 432, 679; Greene et al. 2013, ApJ, 768, 39)
- Calibrating with cosmological simulations (e.g. Suyu et al. 2013, ApJ, 766, 70)
- Using weak lensing maps (e.g. Tihhonova et al. 2020, MNRAS, 498, 1406)

LoS contribution: Galaxy Counts and Weak Lensing



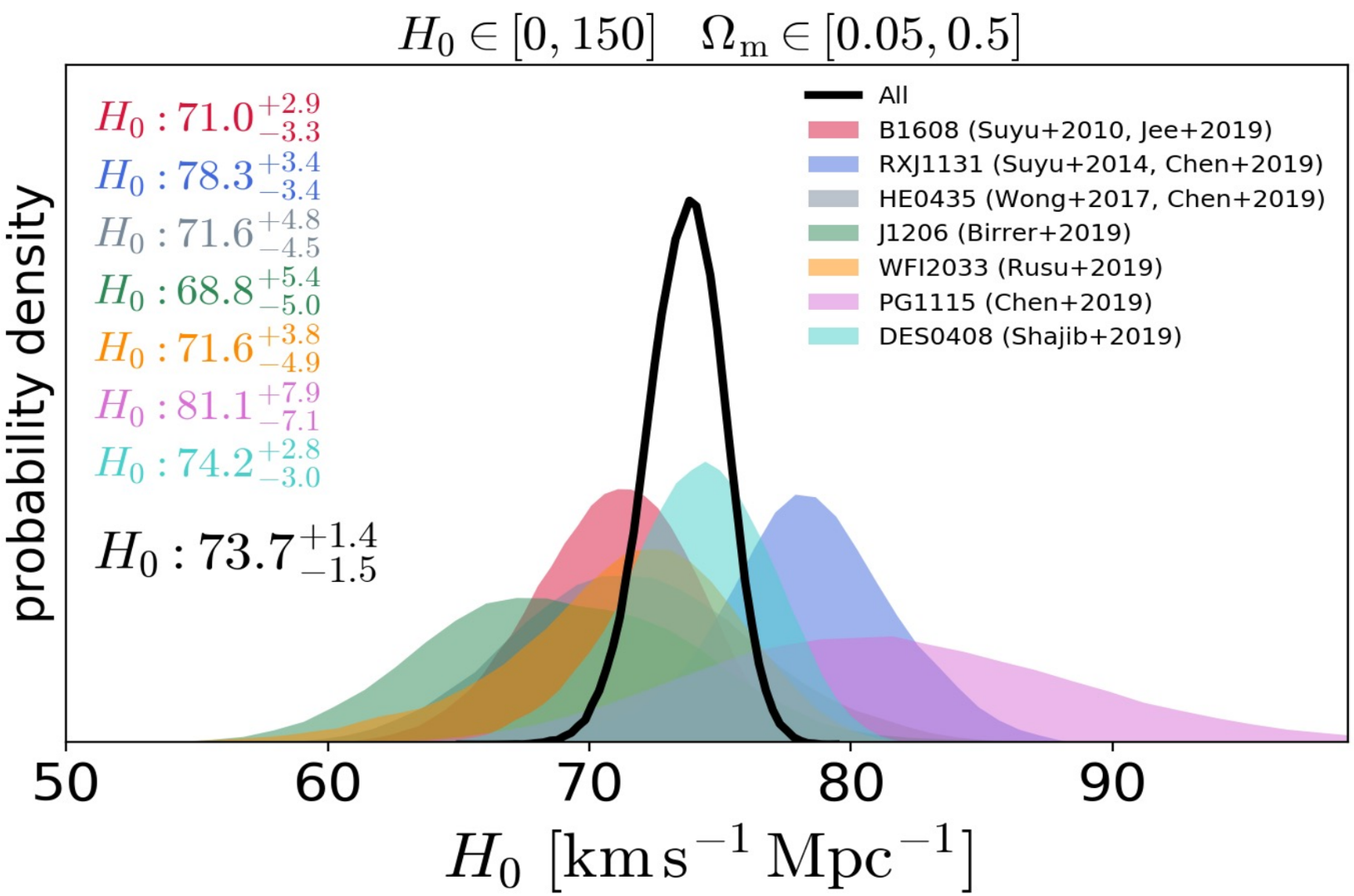
Galaxy counts and weak lensing agree !

Field of B1608: HST and Subaru imaging



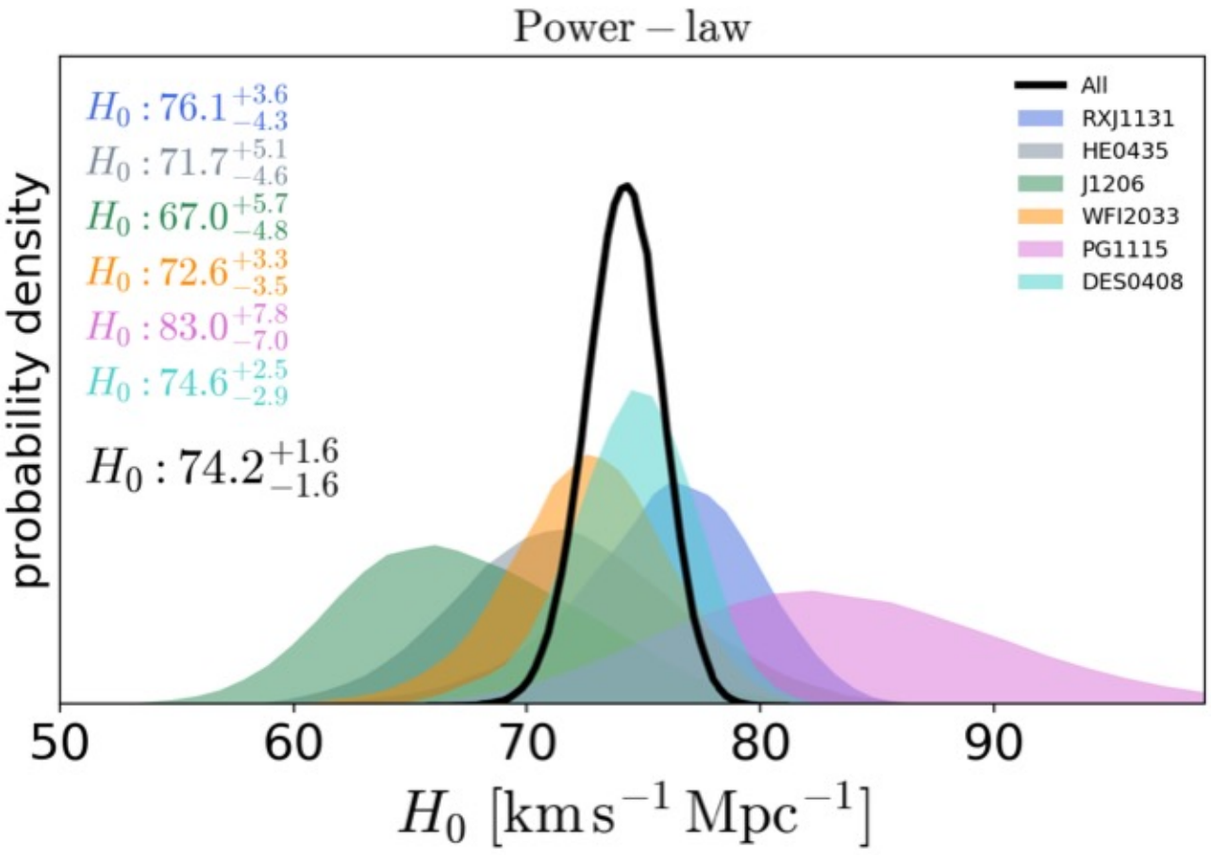
(Tihhonova et al. 2020, MNRAS, 498, 1406)

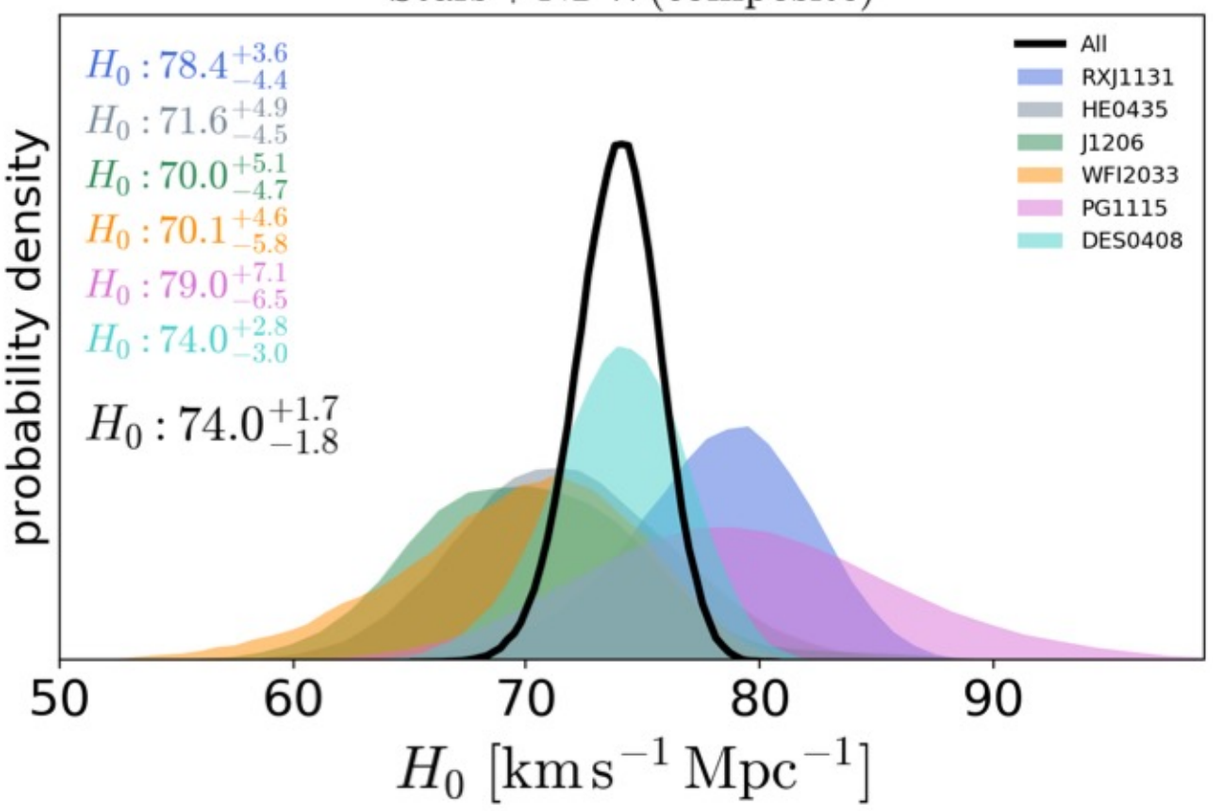
New Cosmology Results for 7 Lenses in flat lambda-CMD



H0LiCOW XIII milestone paper by Wong et al. (2020, MNRAS 498, 1420)
+ DES0408-5354 by Shajib et al. (2020, MNRAS 494, 6072)

No Significant Dependence on Lens Model

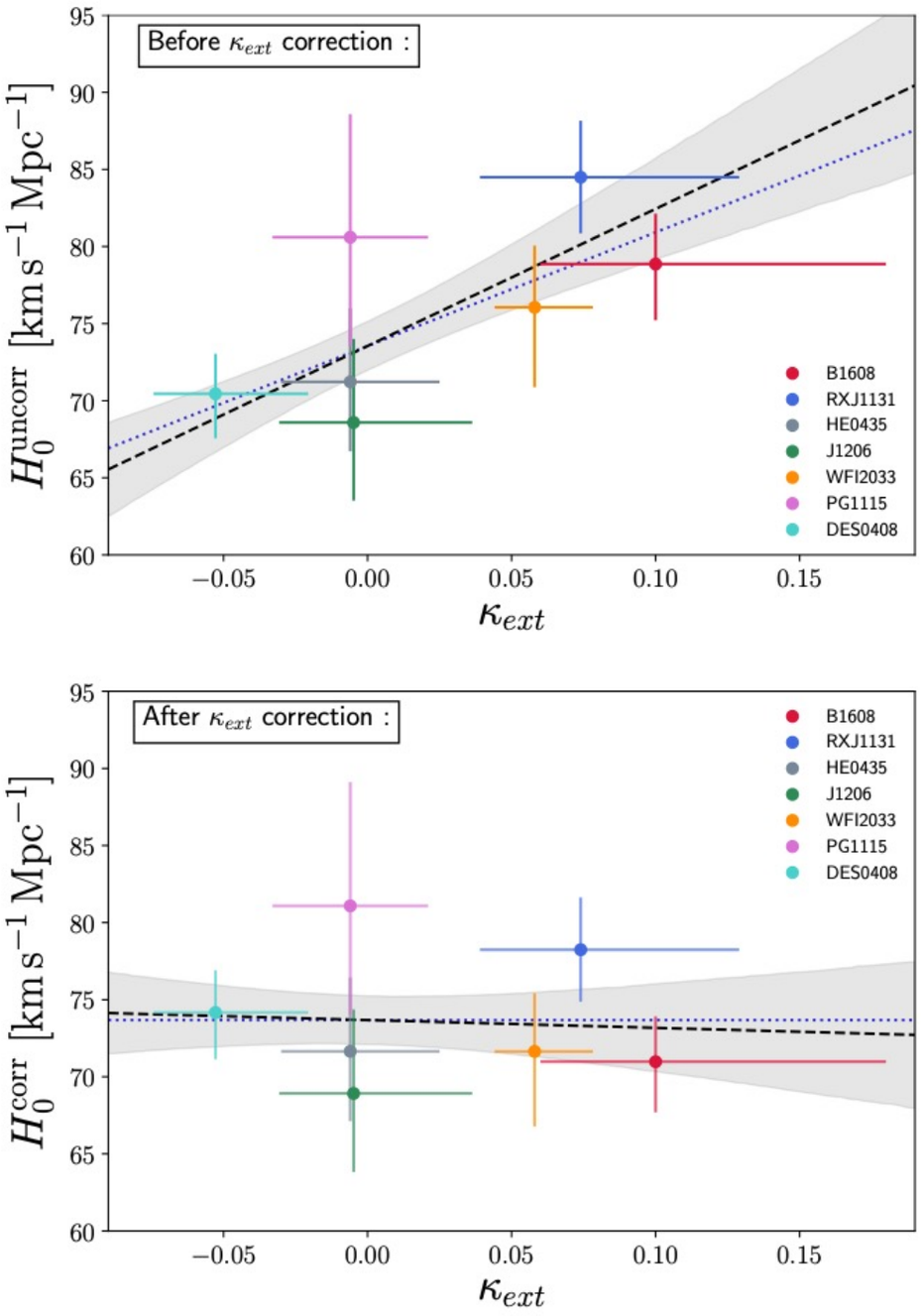




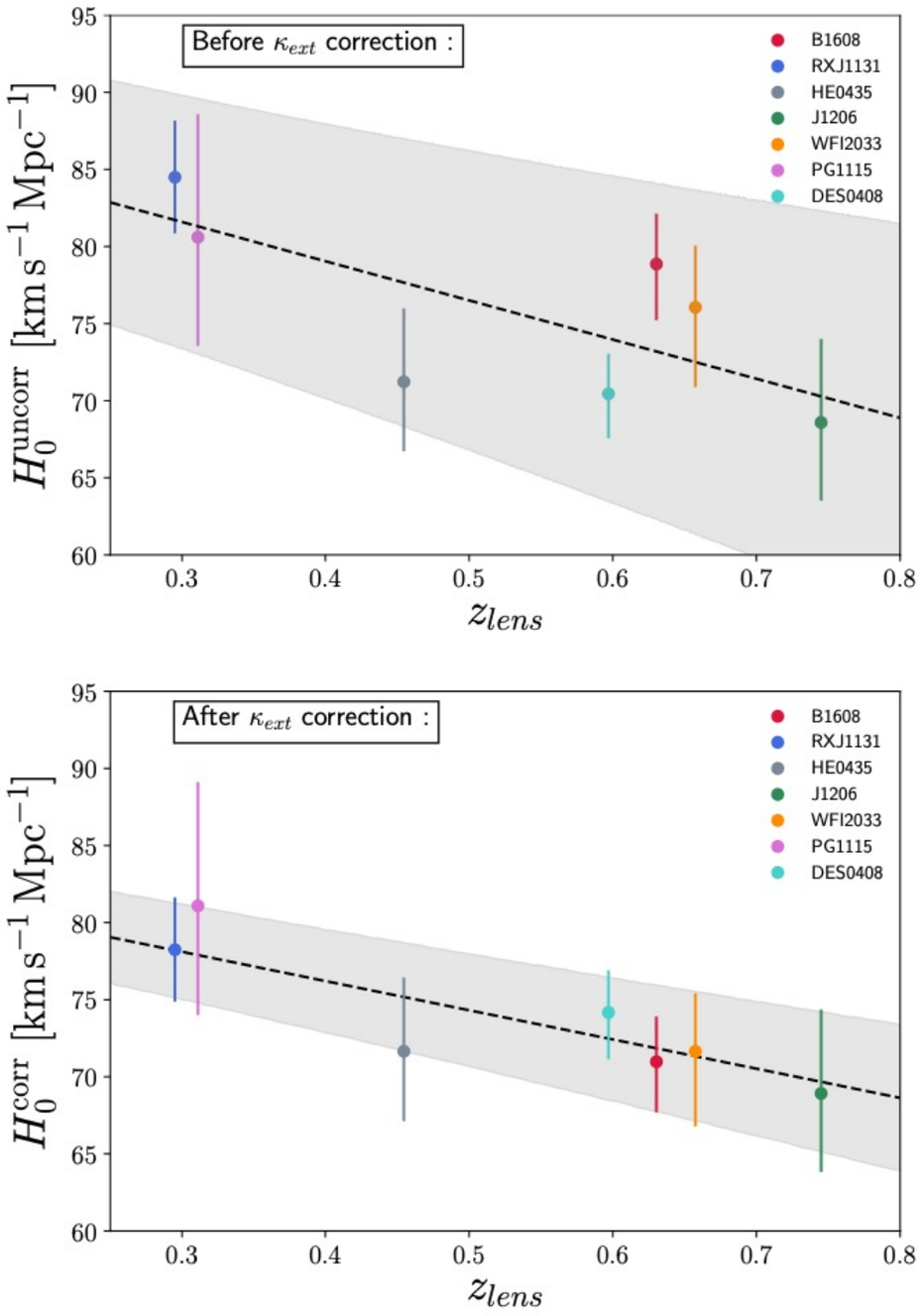
Millon et al. 2020, A&A 639, A101 (TDCOSMO I)

Dependence on External Convergence and Lens Redshift

No obvious correlation between H_0 and external convergence

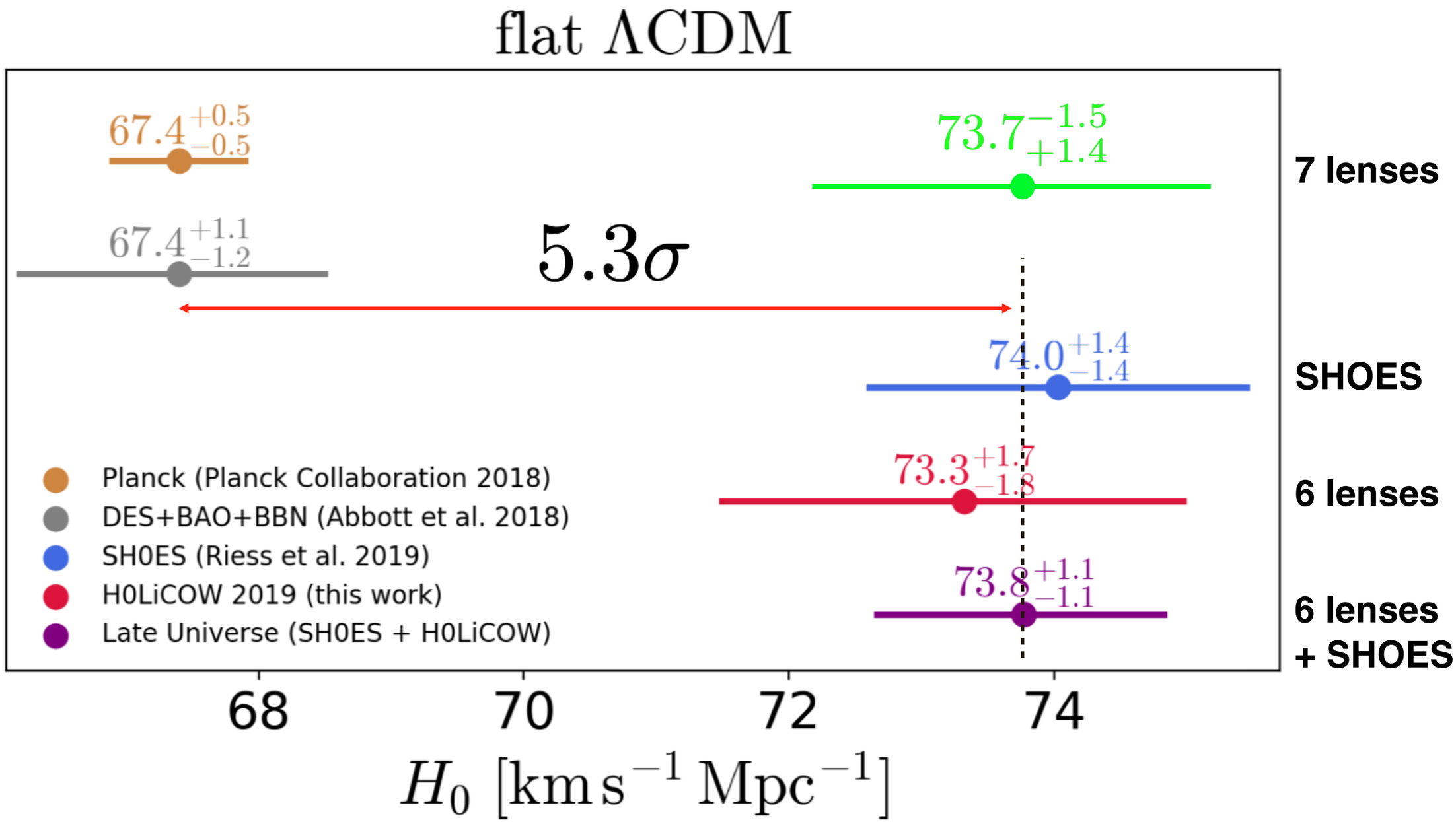


Some correlation between H_0 and lens redshift



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

Cosmology Results for 7 Lenses in flat lambda-CMD



H0LiCOW XIII milestone paper by Wong et al. (2020, MNRAS 498, 1420)
+ DES0408-5354 by Shajib et al. (2020, MNRAS 494, 6072)

Time delay cosmography and the the 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

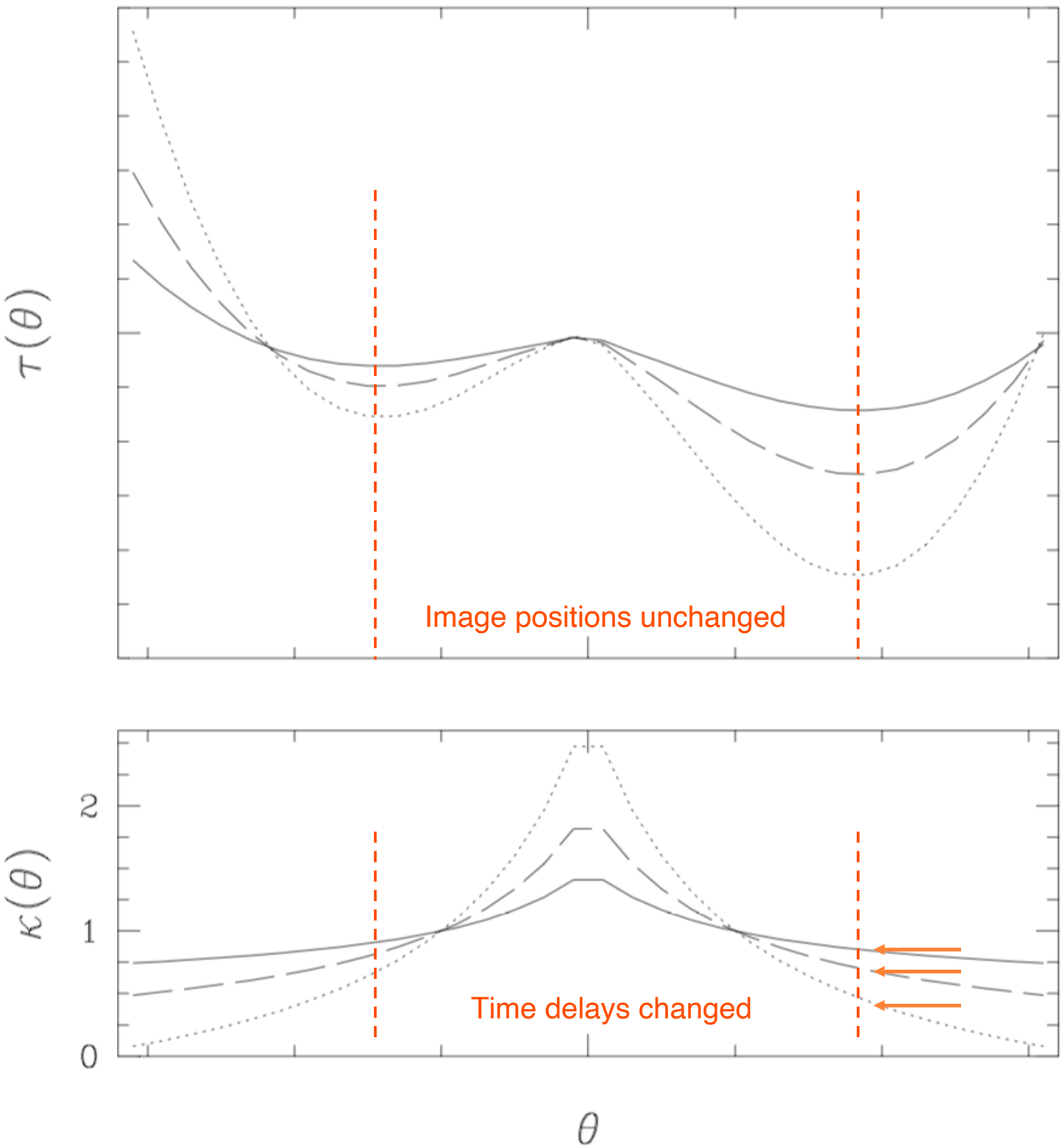
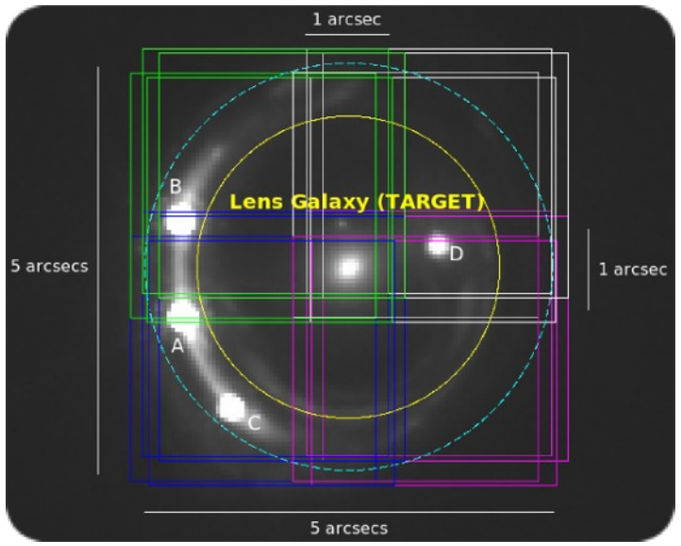


Figure adapted from Saha, 2000, AJ 120, 1654

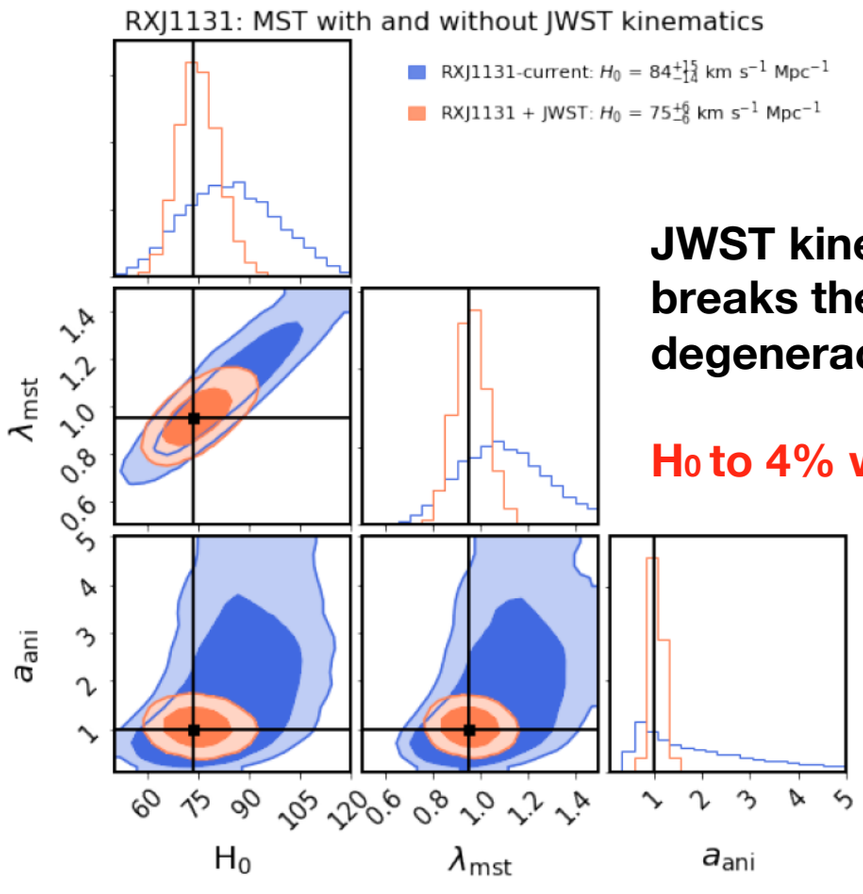
Future avenues

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



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

Yildirim et al. 2020, MNRAS 493, 4783



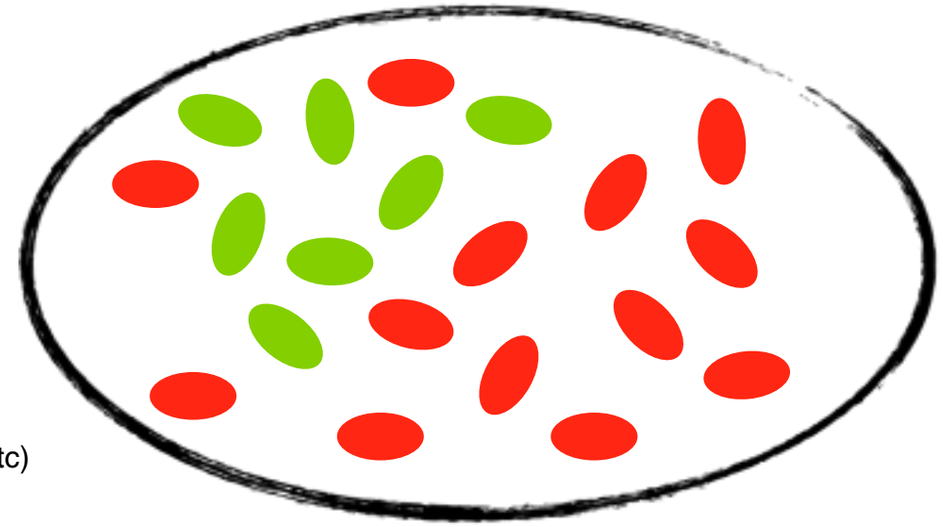
JWST kinematics breaks the Mass-sheet degeneracy

H_0 to 4% with 1 single lens

Hierarchical Bayesian Analysis for
both cosmology and galaxy evolution

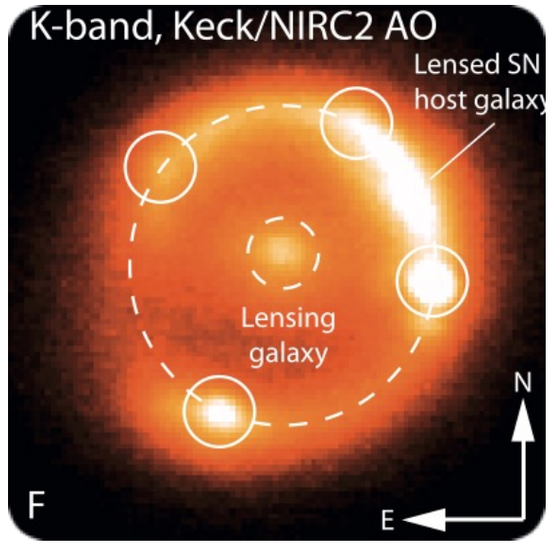
Time-delay lenses (TDCOMOS)

Non-time-delay lenses (Euclid, LSST, etc)



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

Lensed supernovae



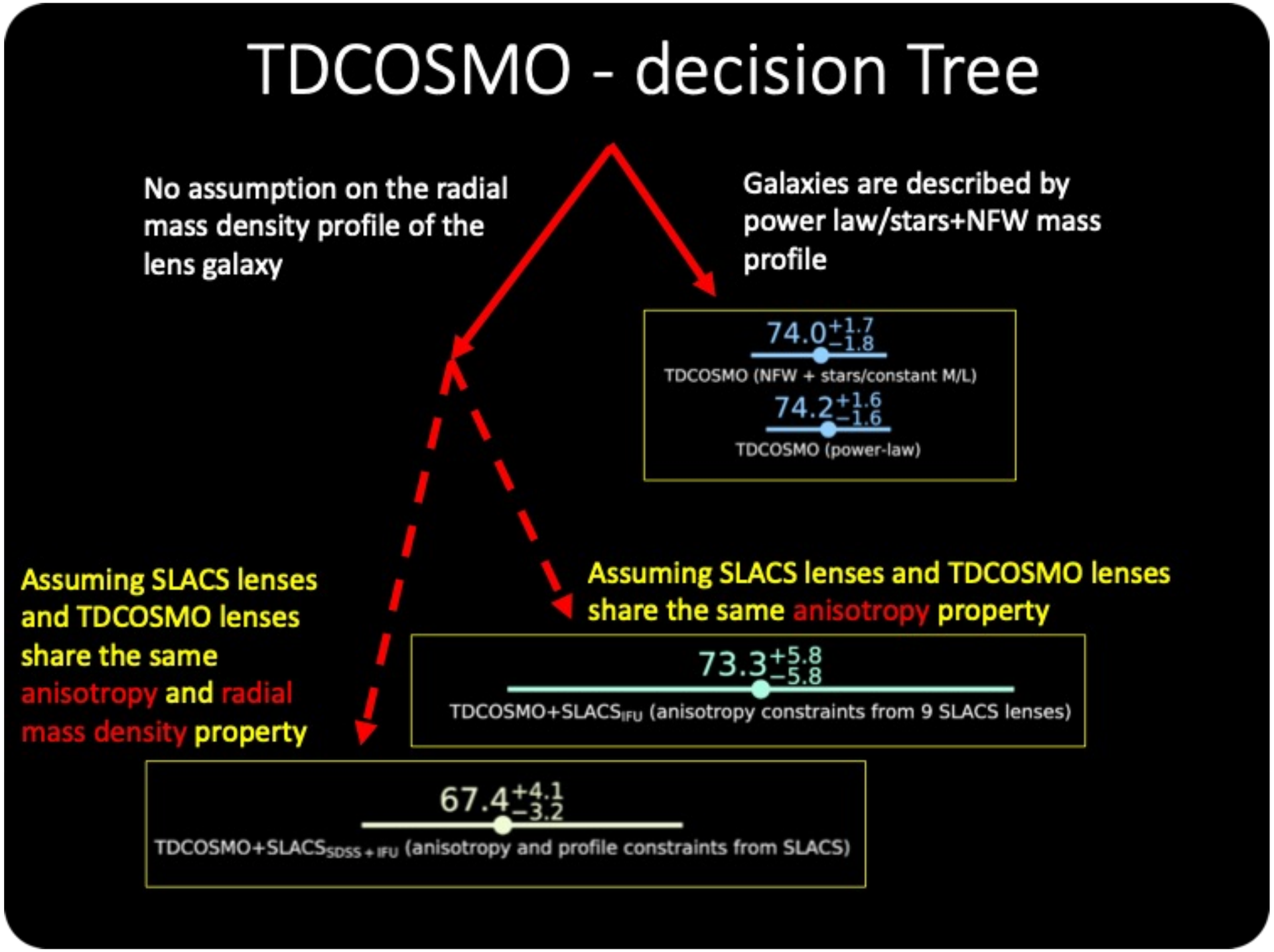
Ongoing search

- 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)

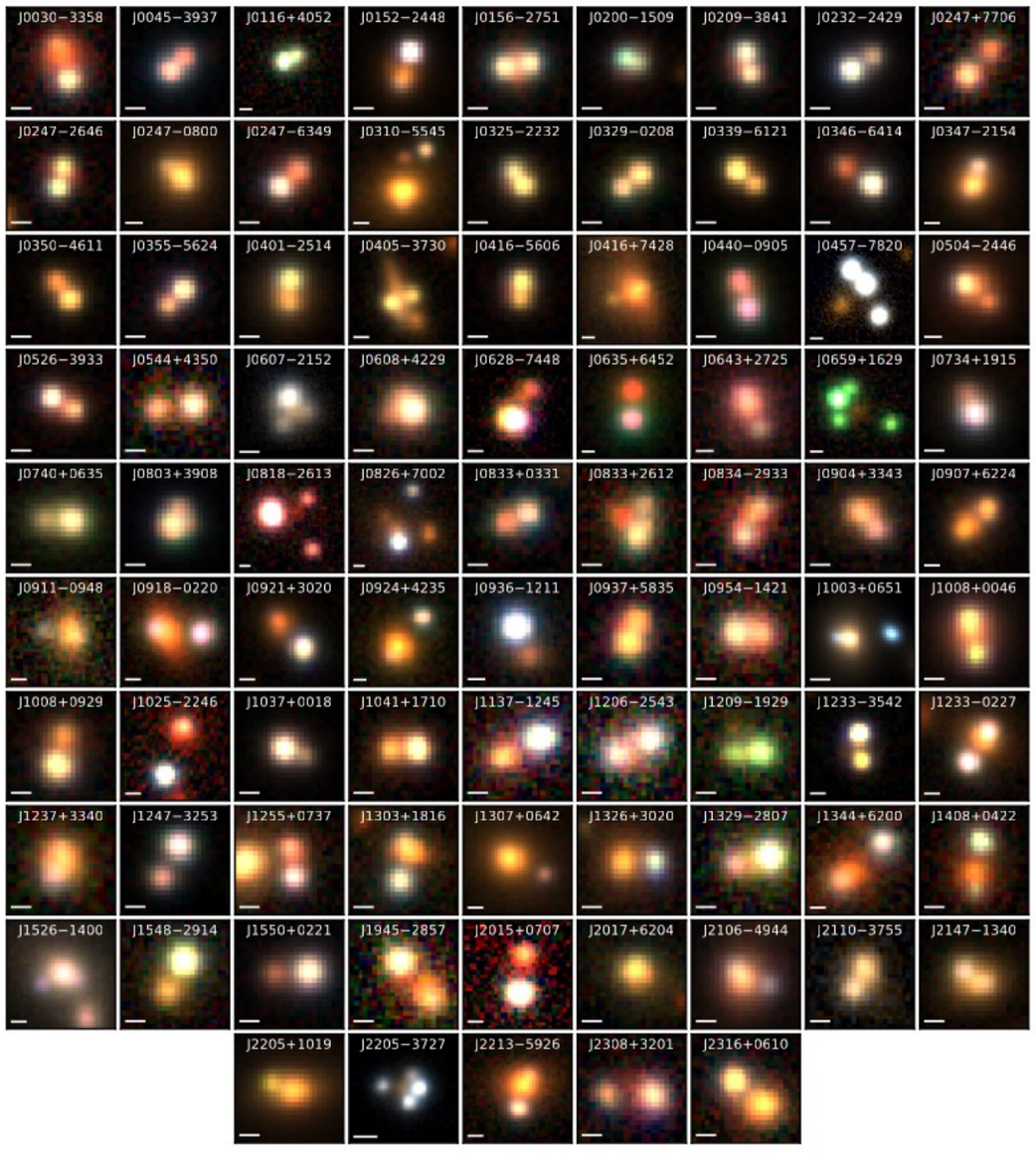
Hierarchical Bayesian Analysis



Birrer et al. 2020, A&A 643, A165 (TDCOSMO IV); "TDCOSMO X: A key test of systematics in the hierarchical method of time-delay cosmography" Gomer et al. 2022 (accepted) - **combing lenses in one H0 analysis => more precise and more accurate (general property of non-linear models)**

Summary

- Strong lensing time delays consist in an **absolute distance indicator**
- Time delays are measured to a few percents within **1 single season**
- **We will have >50 time delays by September 2023**
- DES, KIDS, HSC, PanSTARSS, EUCLID, LSST, Gaia, will discover **hundreds of new suitable targets**
- 7 lenses give H_0 with accuracy and precision comparable to supernovae and are **independent**
- **In flat lambda-CDM and power-law models H_0 = 74.0 +/- 1.7 km.s^{-1}.Mpc^{-1}**
- **Future avenue 1:** spatially resolved lens kinematics
- **Future avenue 2:** hierarchical analysis



85 new confirmed lenses from WISE + Gaia !
(Lemon et al. 2022, arXiv2206.07714)