Title: Astrophysics and cosmology with gravitationally lensed quasars

Speakers: Frederic Courbin

Series: Cosmology & Gravitation

Date: March 12, 2019 - 11:00 AM

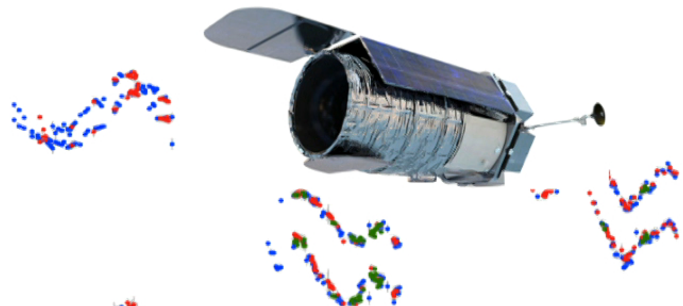
URL: http://pirsa.org/19030114

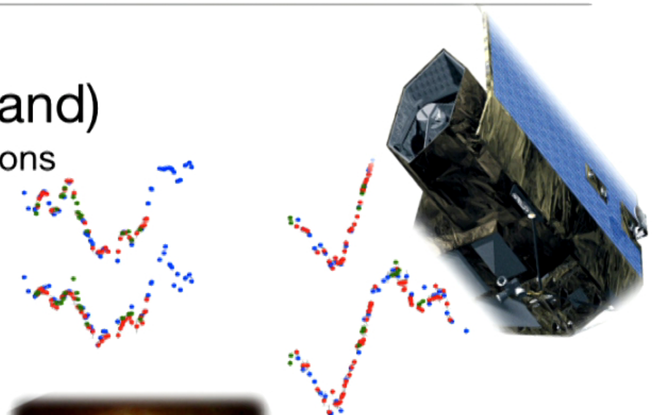
Abstract: Quasars are among the most powerful light sources in the universe and, as such, can be seen at cosmological distances. Is some rare occasions (although not that rare), a massive galaxy on their line of sight can act as a gravitational lens and produce multiple images of distant quasars. These can be used both for cosmology and astrophysics by measuring the so-called time delays between the lensed images from photometric monitoring, a quantity directly related to the Hubble-LemaÃ®tre parameter H0. The same data, affected by microlensing by stars in the lensing galaxy, can be used to measure the size and energy profile of quasar accretion disks on spatial scales of the order of the light-day, i.e. inaccessible to even the largest interferometers, including the SKA. The results in this talk are on behalf of the COSMOGRAIL and H0LiCOW collaborations.

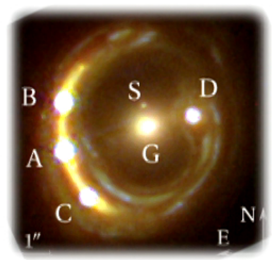
Cosmology with Quasar Time Delays

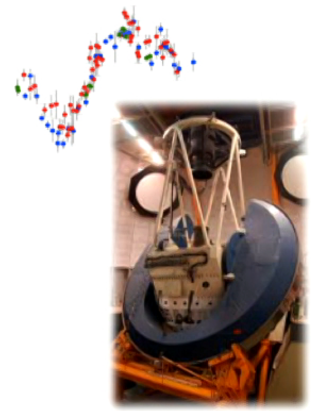
Frédéric Courbin (EPFL, Switzerland)

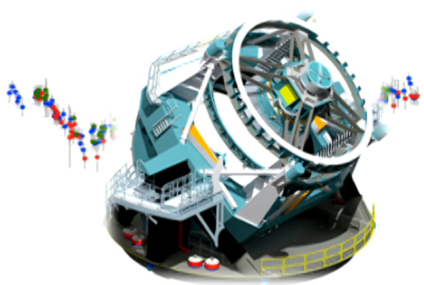
For the COSMOGRAIL and H0LICOW collaborations











COSMICLENS

erc

European Research Council

Established by the European Commission

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Laboratoire d'astrophysique http://lastro.epfl.ch

Ecole Polytechnique Fédérale de Lausanne (EPFL)

Perimeter Institute

March 2019

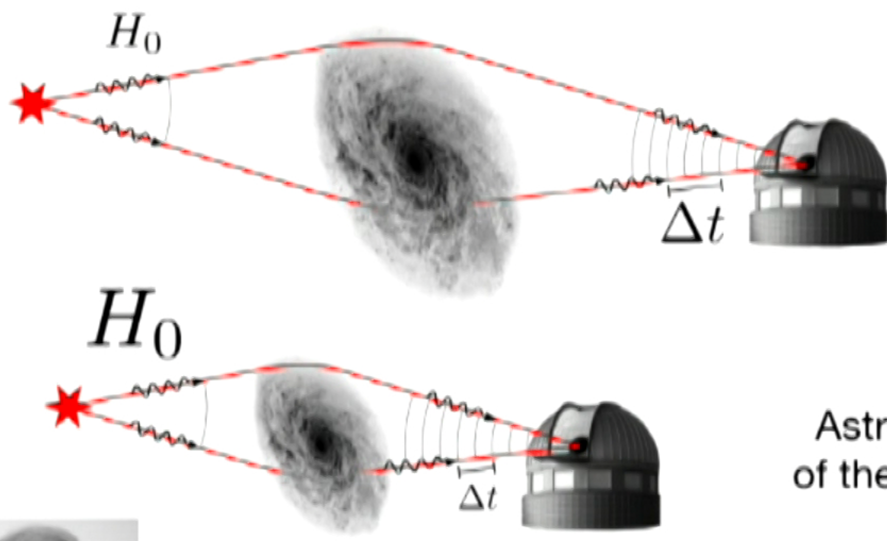
Main Cosmological Probes

- Standard **candles**: supernovae, Cepheids
- Standard **rulers**: masers, Baryonic Acoustic Oscillations (BAO)
- Cosmic Microwave Background (**CMB**)
- Galaxy **clusters**: number counts, Sunyaev-Zel'dovic effect
- **Weak** gravitational lensing
- **Strong** gravitational lensing

For recent reviews see e.g.

- Suyu, Chang, Courbin, Okumura 2018, arXiv:1801.07262
- de Grijs, Courbin, Martinez-Vazquez, Monelli, Oguri, Suyu, 2017, SSRv 212, 1743

Time Delays Probe (mostly) the Hubble Constant H_0



Lens potential at the images

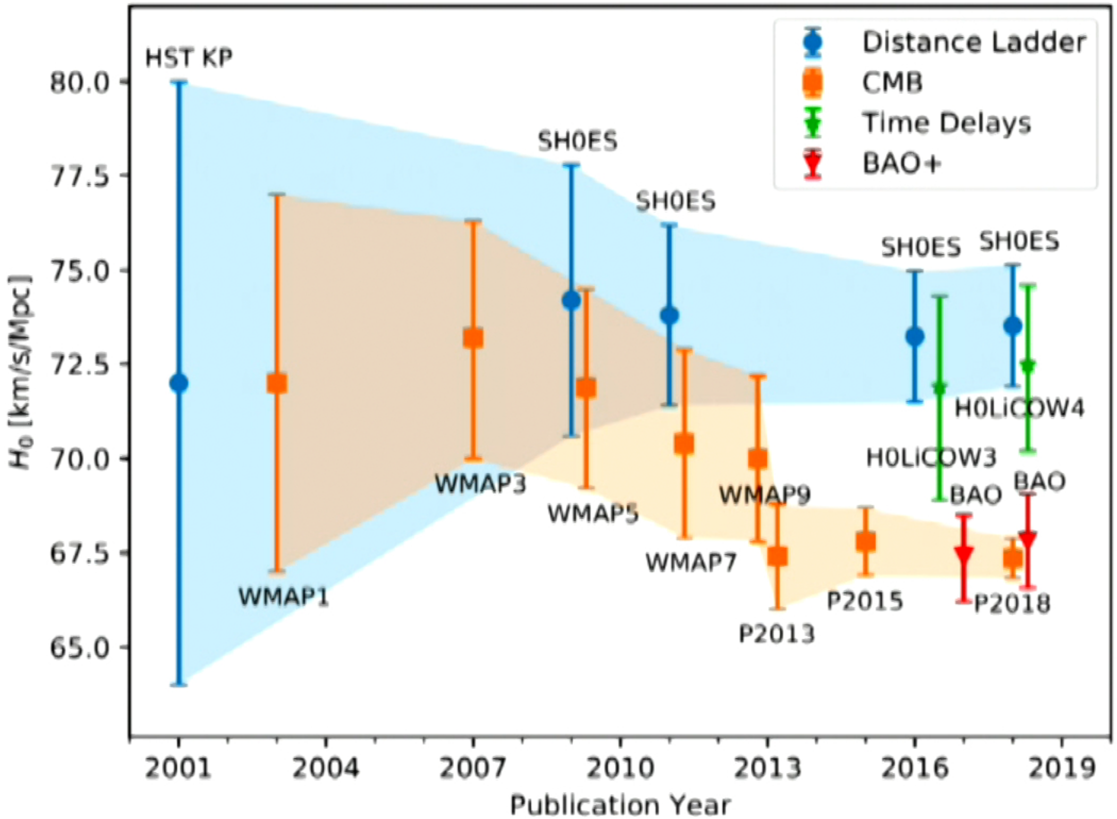
Source position (unconstrained)

Astrometry of the images

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

- Measured time delays provide *direct* and *independent* constraints on H_0.
- A percent-level determination of H_0 is highly complementary to other probes, and critical to constrain and test the ingredients of cosmological models.

Motivation : Why Bother About H_0 ?



From Tihhonova PhD thesis 2019 (EPFL)

Advantages

- One-step process
- Does not rely on any knowledge of a standard candle
- No need of secondary distance estimators
- Insensitive to local motions
- Insensitive to dust
- Independent of any other cosmological probe
- Can be combined with other probes: not really done so far !
- Does not need thousands of HST orbits

Ingredients

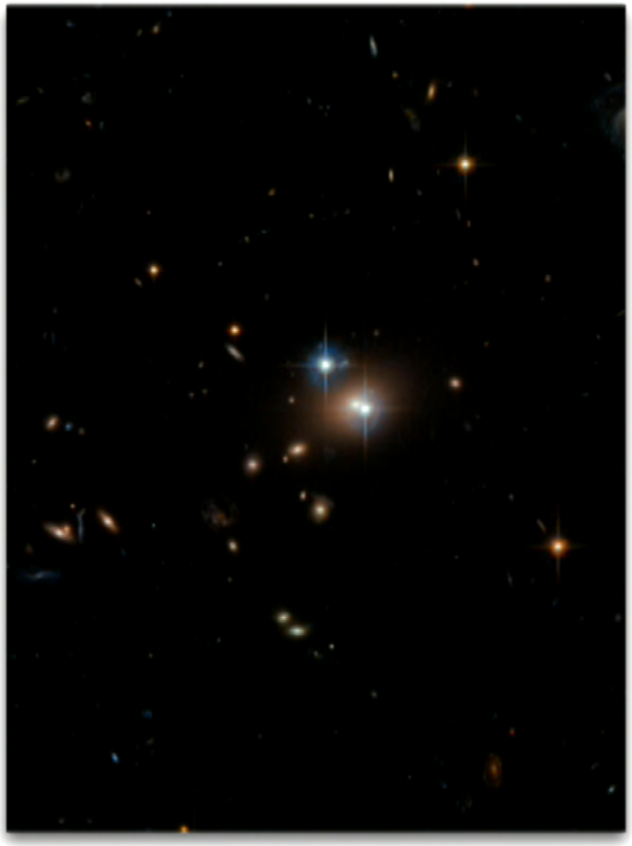
- **Time delays** are hard (but possible) to measure with high accuracy
- Historically, the field has suffered from the Q0957+561 time delay «controversy»
- Need a **mass model** for the lensing galaxy (mass-slope degeneracy)
- Need some knowledge of the **environment of the lens** (mass-sheet degeneracy)

First Measurements of Time Delays (1989-1992)

Based on photometric variations of the sources, seen shifted in time in each lensed image.

First photometric monitoring of **Q0957+561** by three groups led to contradictory results:

- **Vanderriest et al. 1989, A&A, 215, 1**: optical monitoring: $\Delta t = 415 \pm 20$ days
- **Schild 1990, AJ, 100, 1771**: optical monitoring: $\Delta t = 404 - 406$ days
- **Lehar et al. 1992, ApJ, 384, 453**: radio monitoring at the VLA leading to a delay of $\Delta t = 513 \pm 40$ days

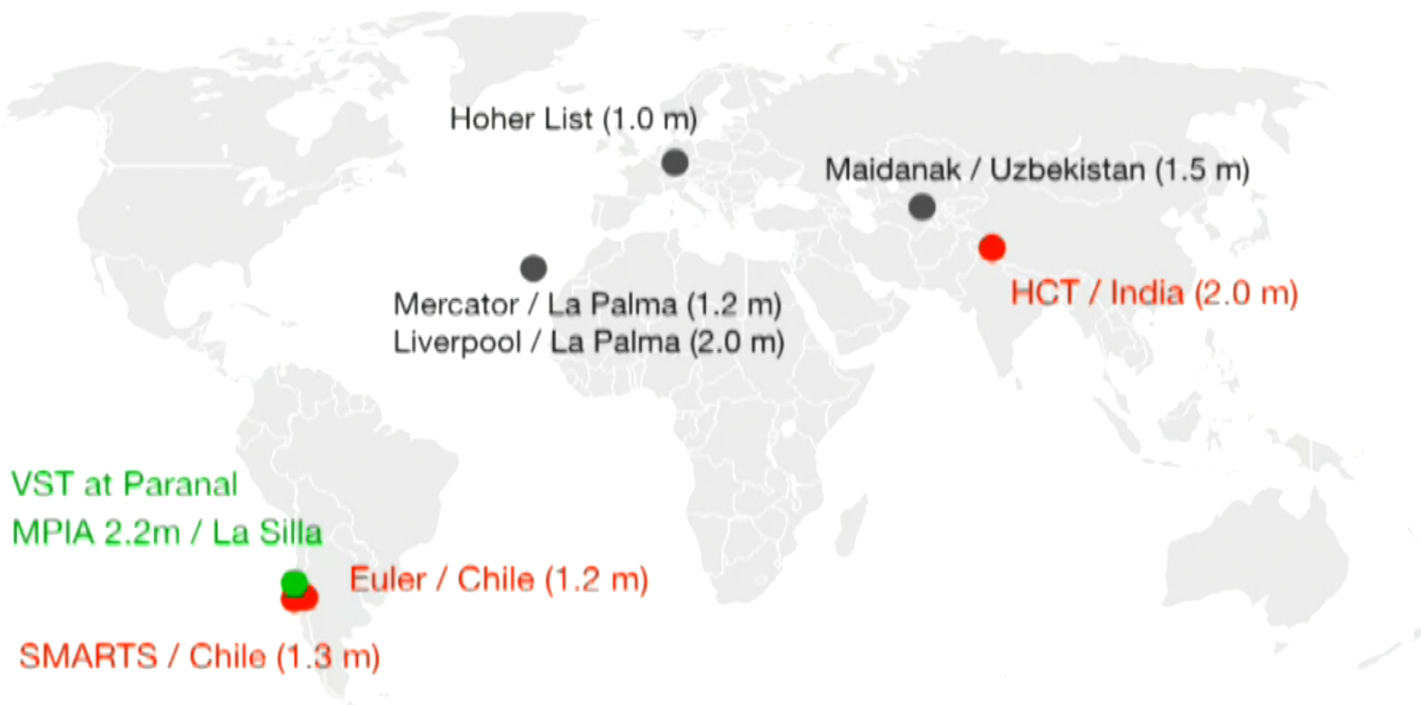


Need to Fix the Problem

Towards Lens Monitoring with Dedicated Telescopes

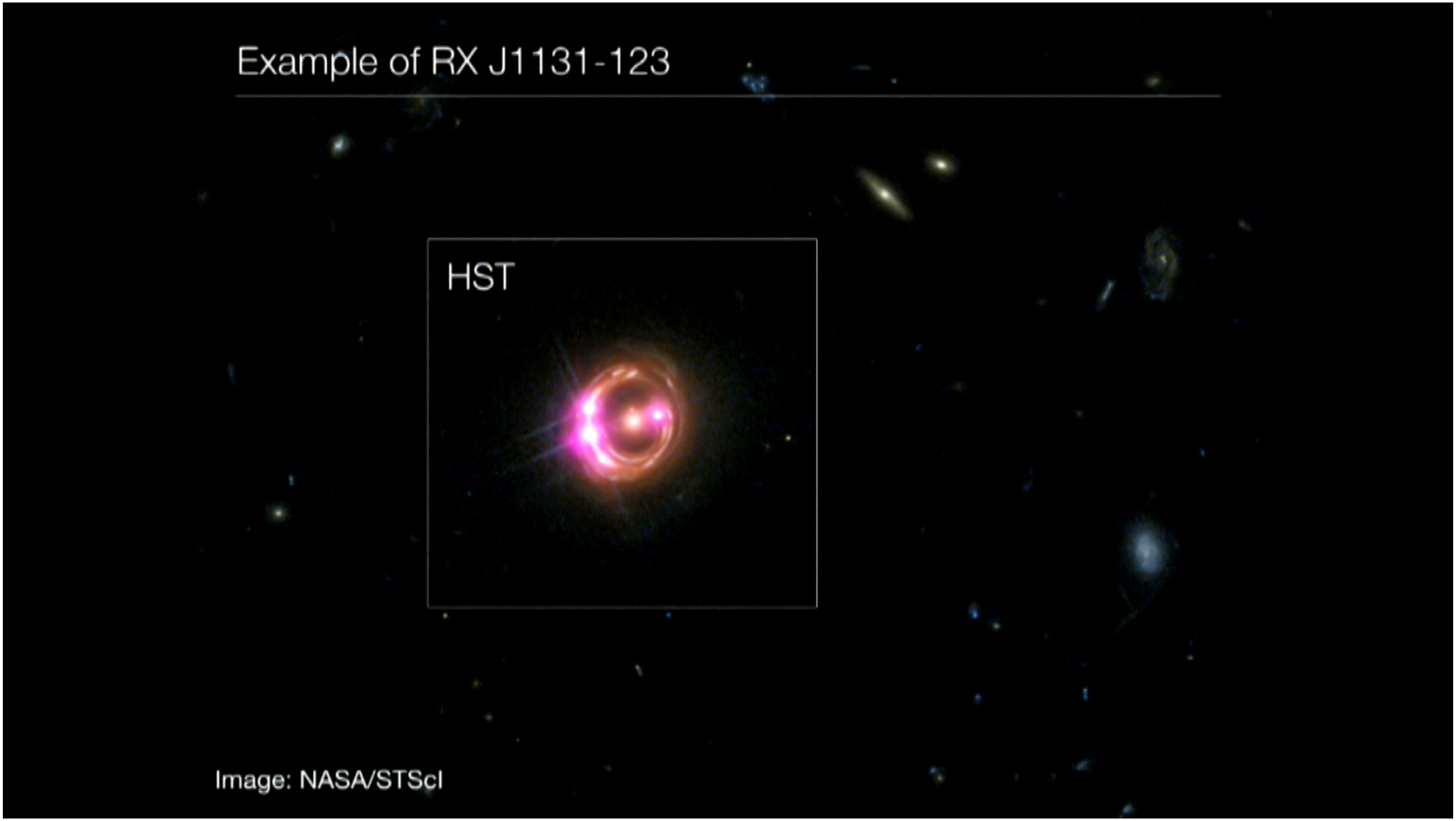
- Early days (80-90): deadly fights to get delays to 50%
- 1997: Paul Schechter's time delays of PG1115+080
- 2000: Chris Fassnacht's radio time delays of B1608+656
- 2001-2003: Ingunn Burud's optical time delays. Many time delays, mostly with the NOT and ESO, but with limited precision and accuracy (10-15%)
- 2004: Start of COSMOGRAIL and of Chris Kochanek lens monitoring programs
- 2014: H0 Lenses in COSMOGRAIL's Wellspring (H0LiCOW)
- 2018+ : High-cadence monitoring: COSMOGRAIL, H0LiCOW, STRIDES

COSMOGRAIL Monitoring Telescopes



Teams doing lens monitoring joined forces in 2010-13:

1) EPFL-led COSMOGRAIL team (started in 2004) : Lead time delay work
2) Group of C. S. Kochanek (Ohio), using SMARTS 1.3-m : Lead microlensing work
3) Creation of H0LiCOW, led by S. Suyu


Example of RX J1131-123
HST
Image: NASA/STScI

Example of RX J1131-123

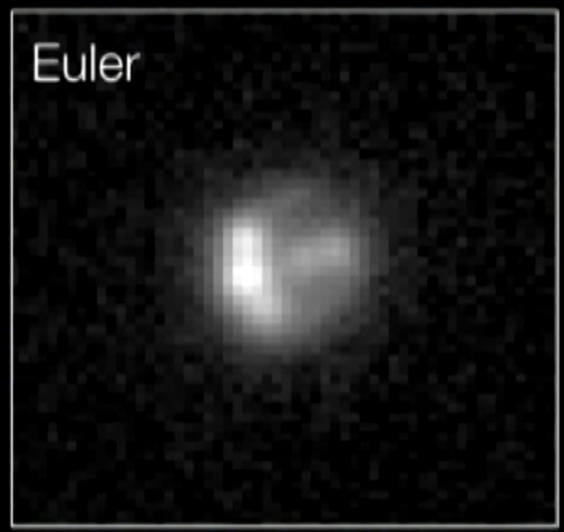


Image: NASA/STScI

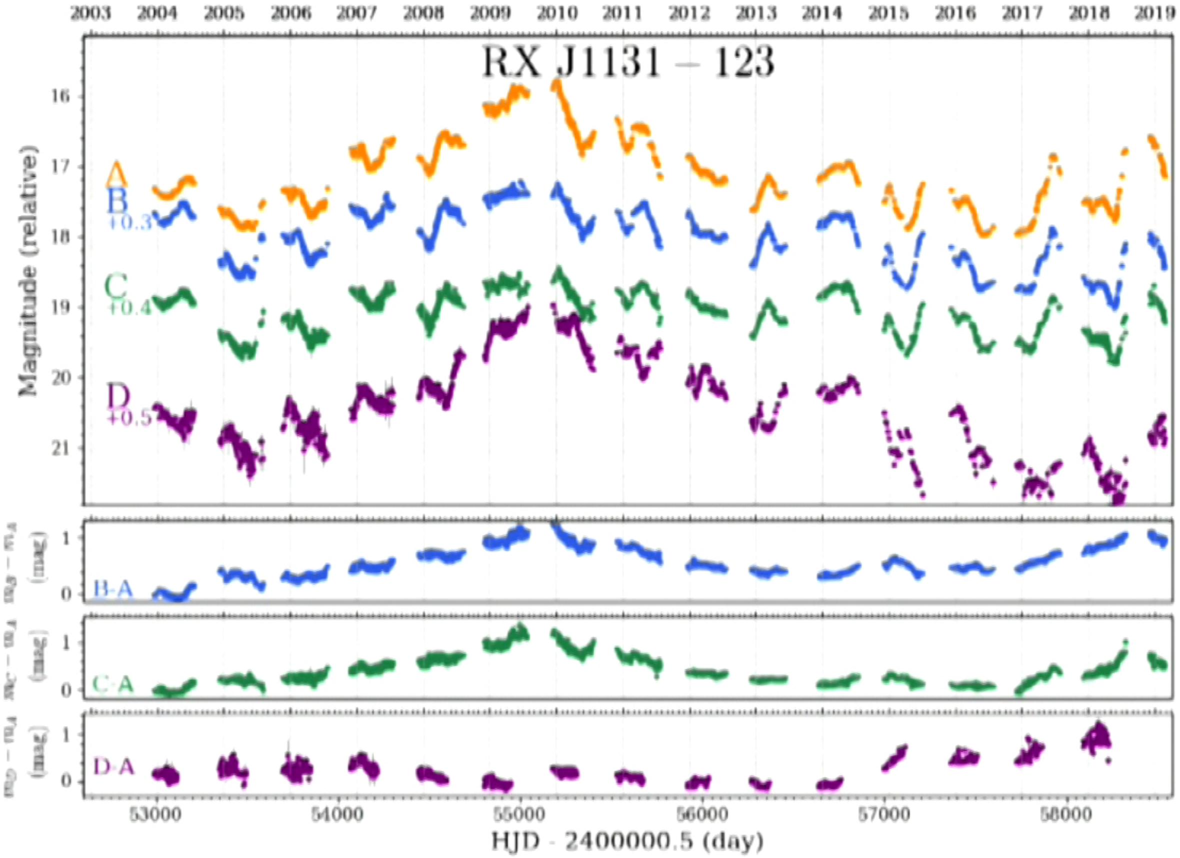
COSMOGRAIL Deconvolution Photometry Pipeline

Step 1 : characterize the point spread function (PSF) of each exposure

Step 2 : simultaneously fit one single model to all exposures

+ CCD calibrations, photometric normalizations (Tewes et al. 2013, Bonvin et al. 2018)

COSMOGRAIL lightcurves (2003-2019)



From Millon et al. 2019, in prep

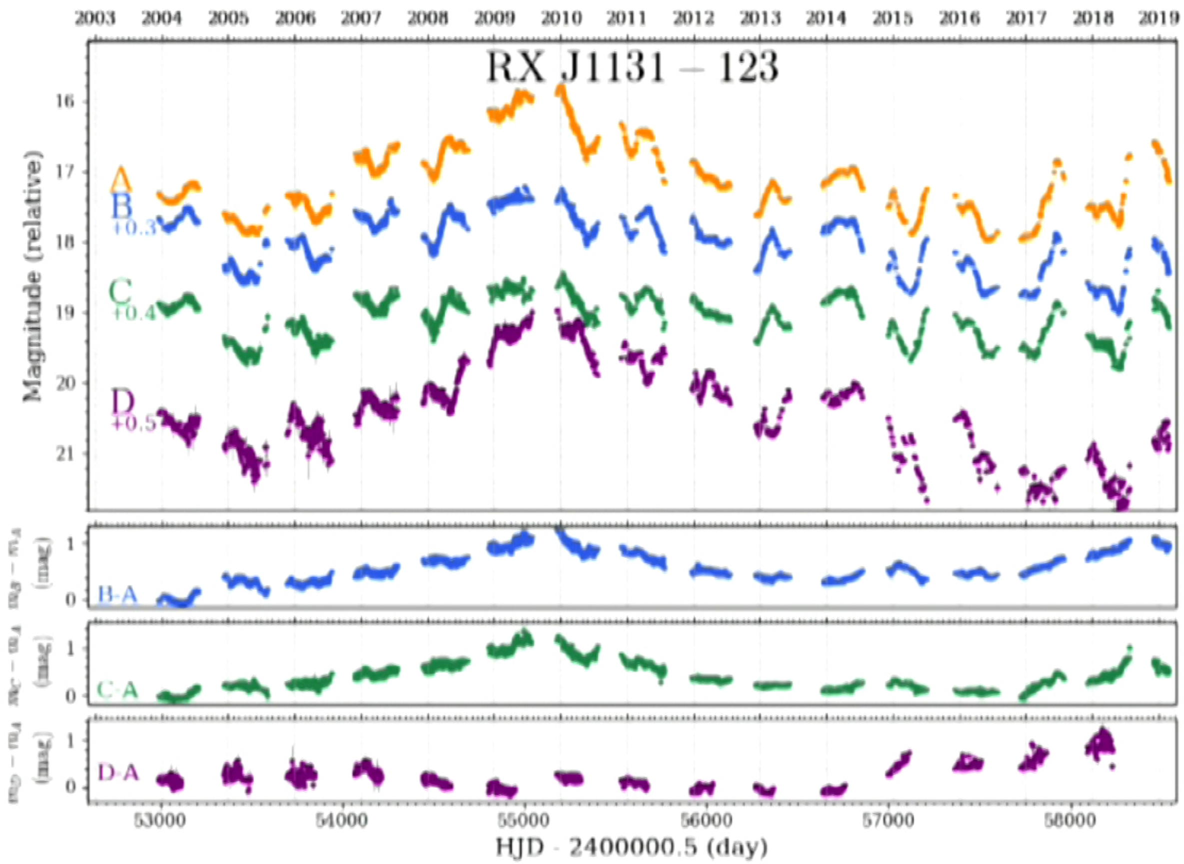
COSMOGRAIL Deconvolution Photometry Pipeline

Step 1 : characterize the point spread function (PSF) of each exposure

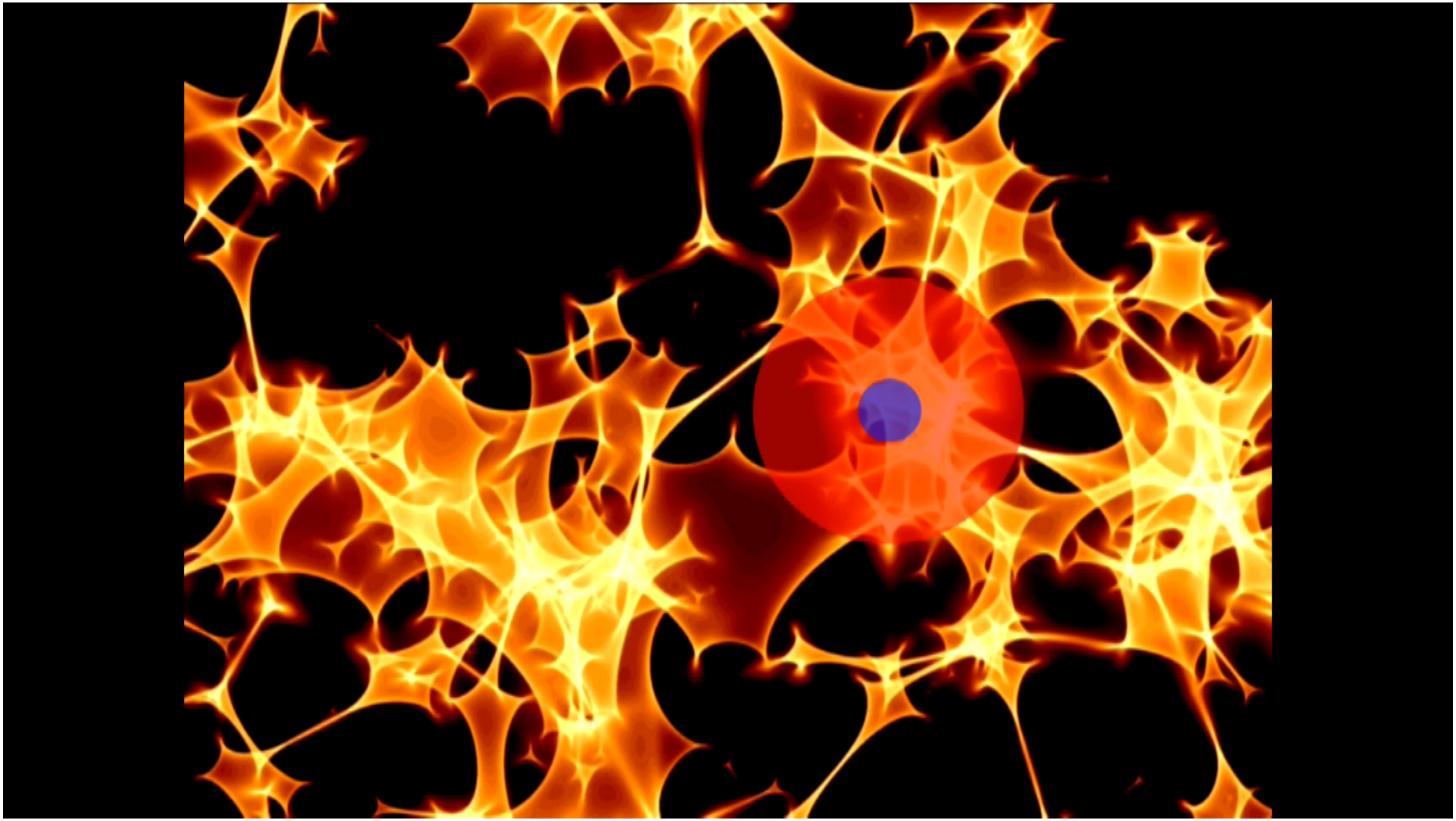
Step 2 : simultaneously fit one single model to all exposures

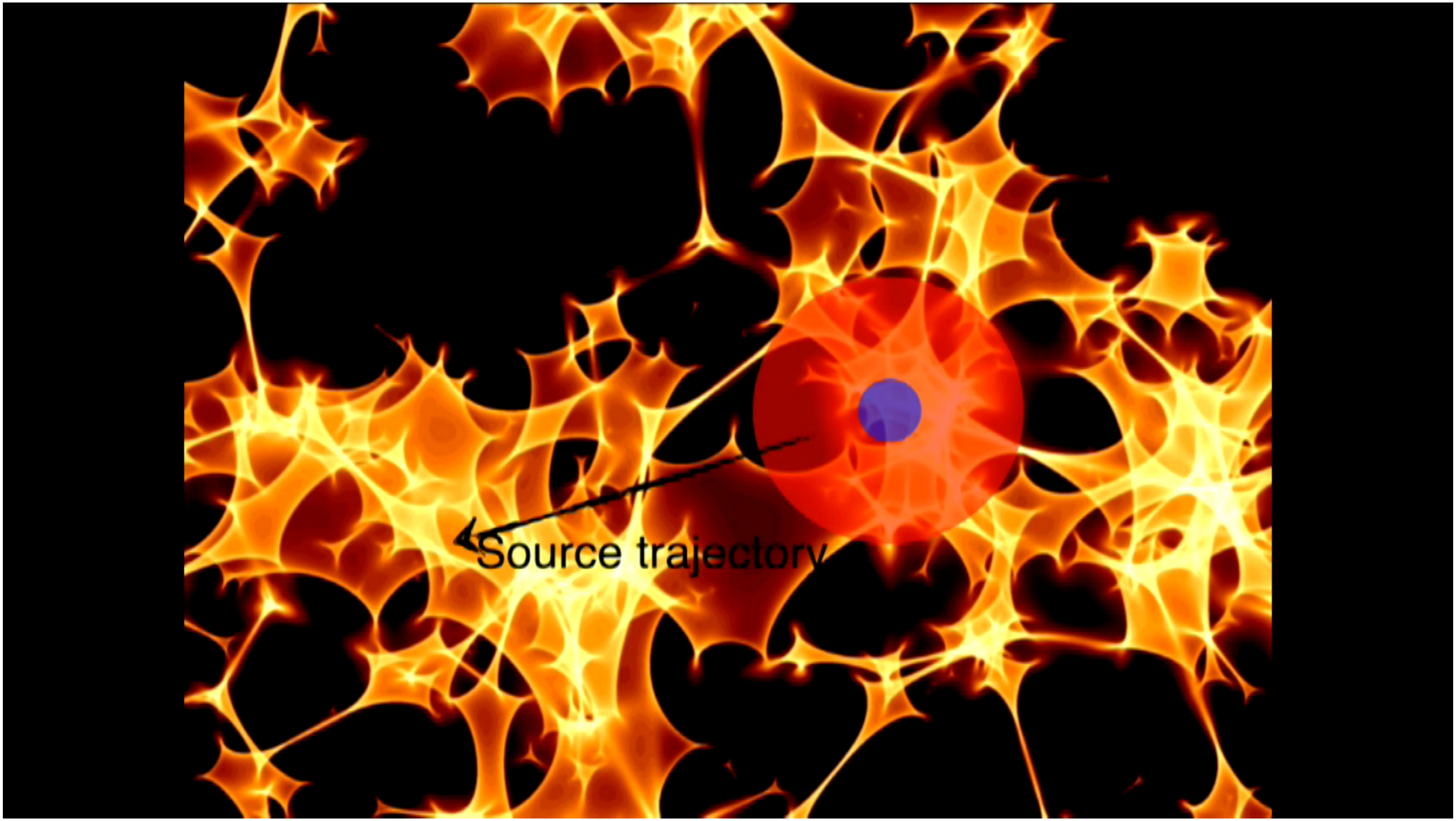
+ CCD calibrations, photometric normalizations (Tewes et al. 2013, Bonvin et al. 2018)

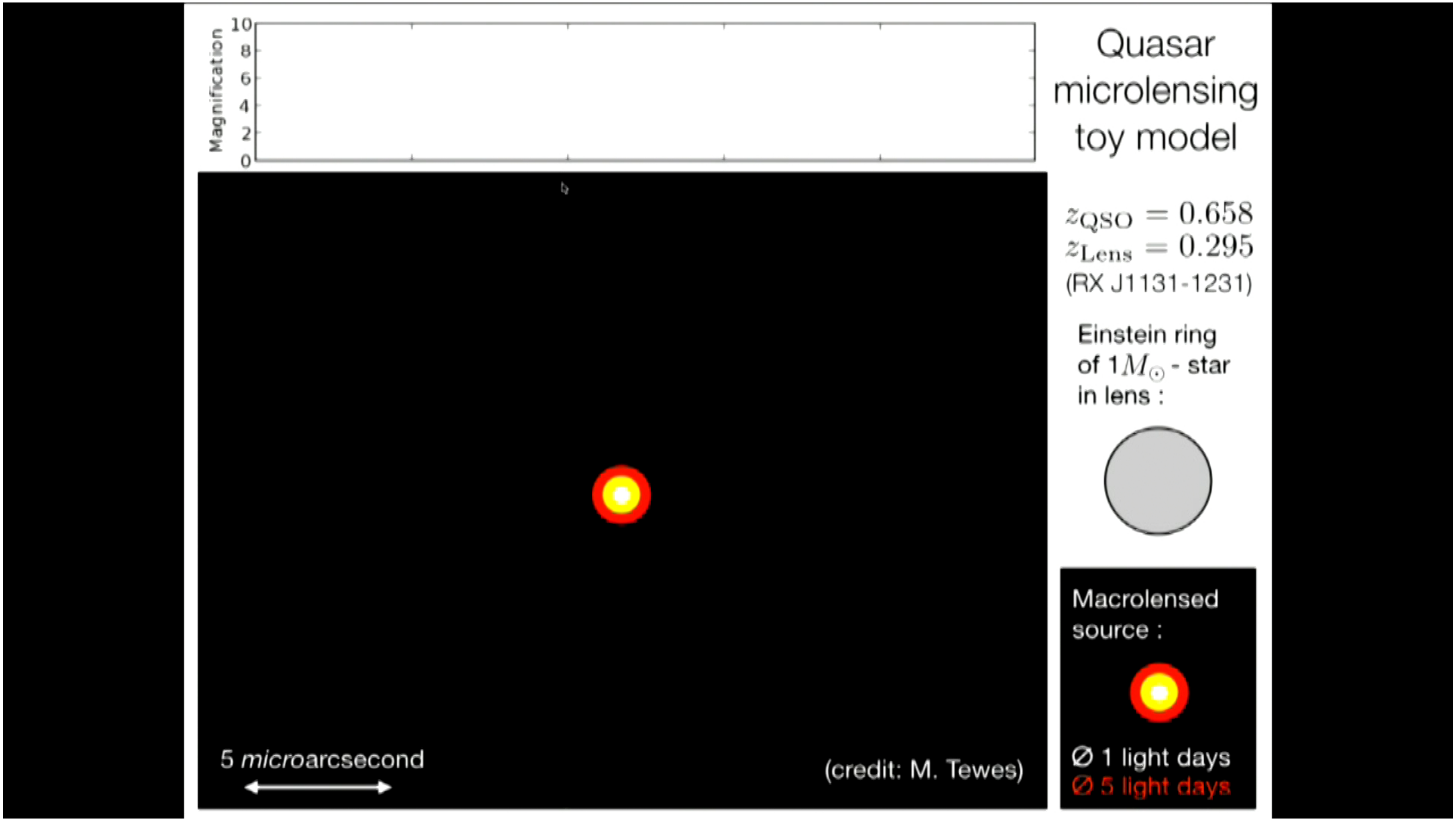
COSMOGRAIL lightcurves (2003-2019)



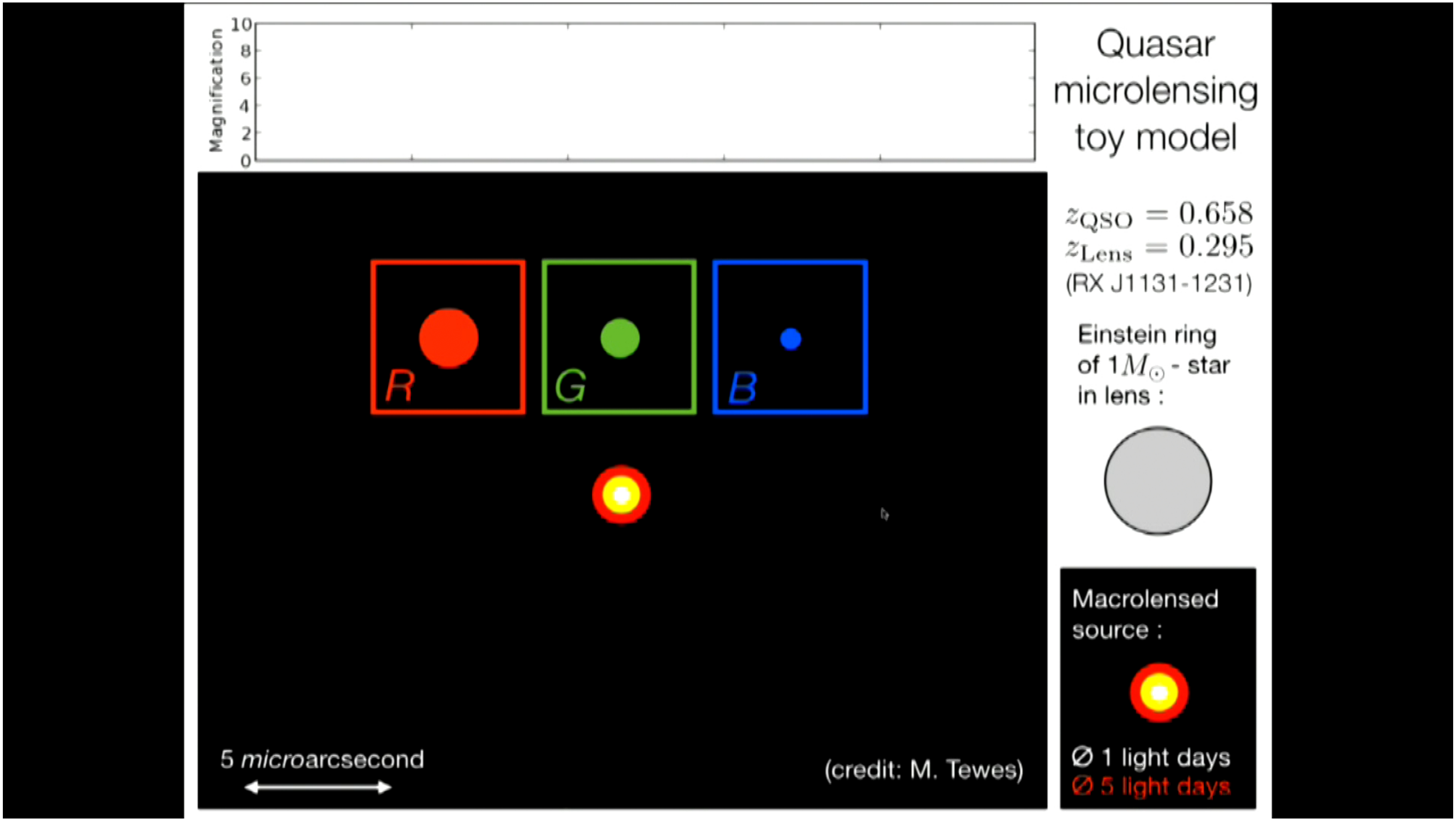
From Millon et al. 2019, in prep

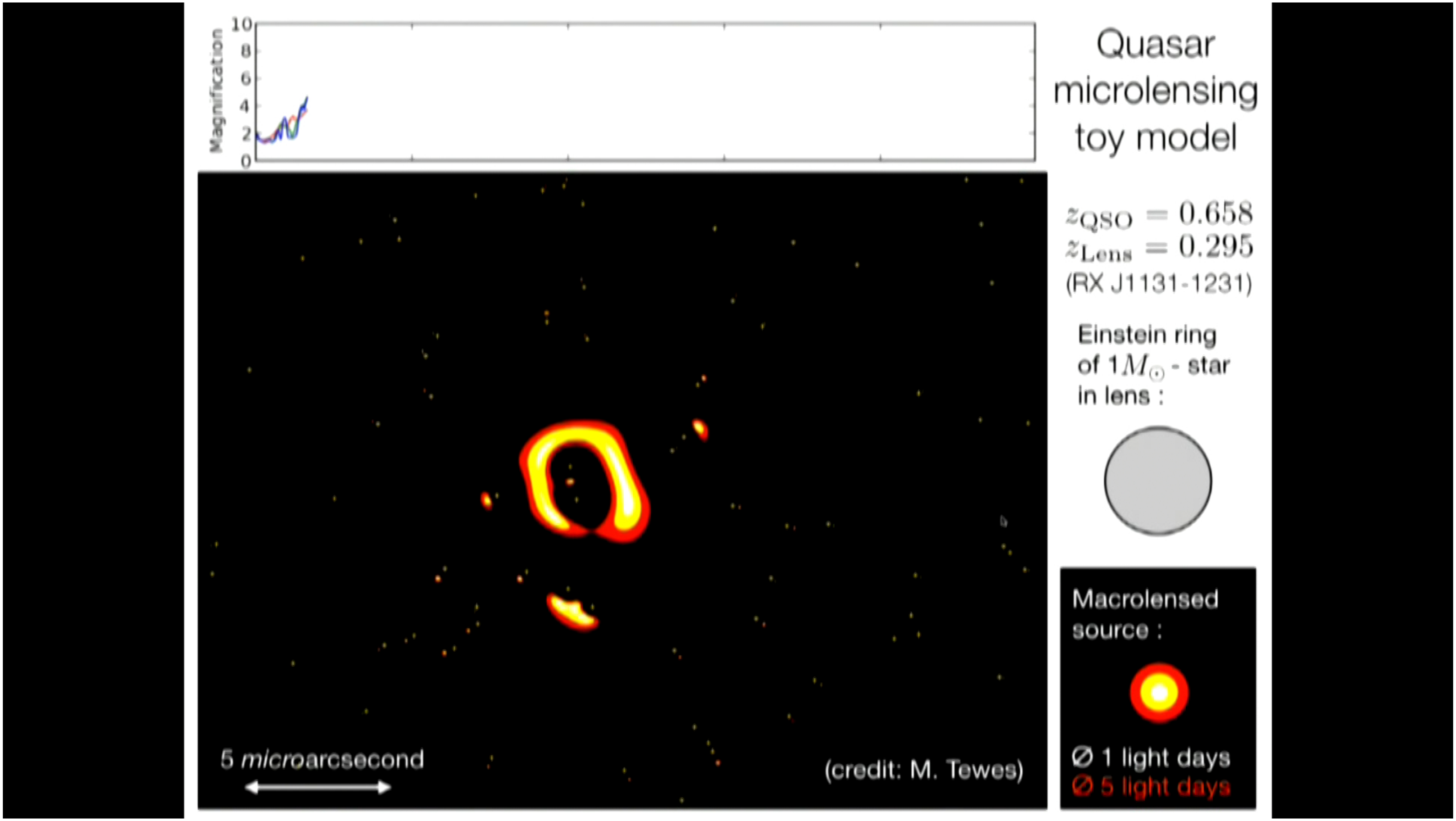


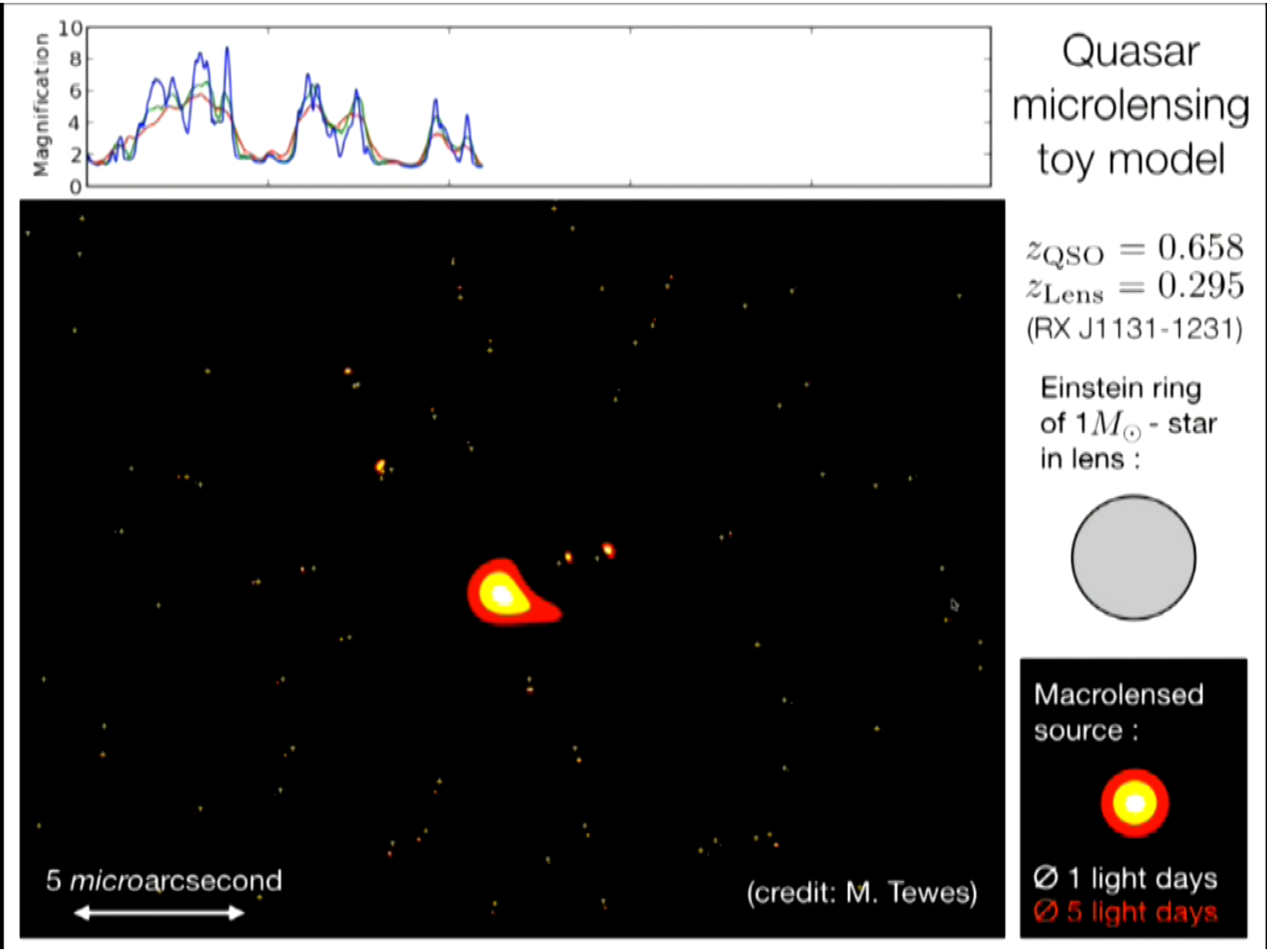

Source trajectory

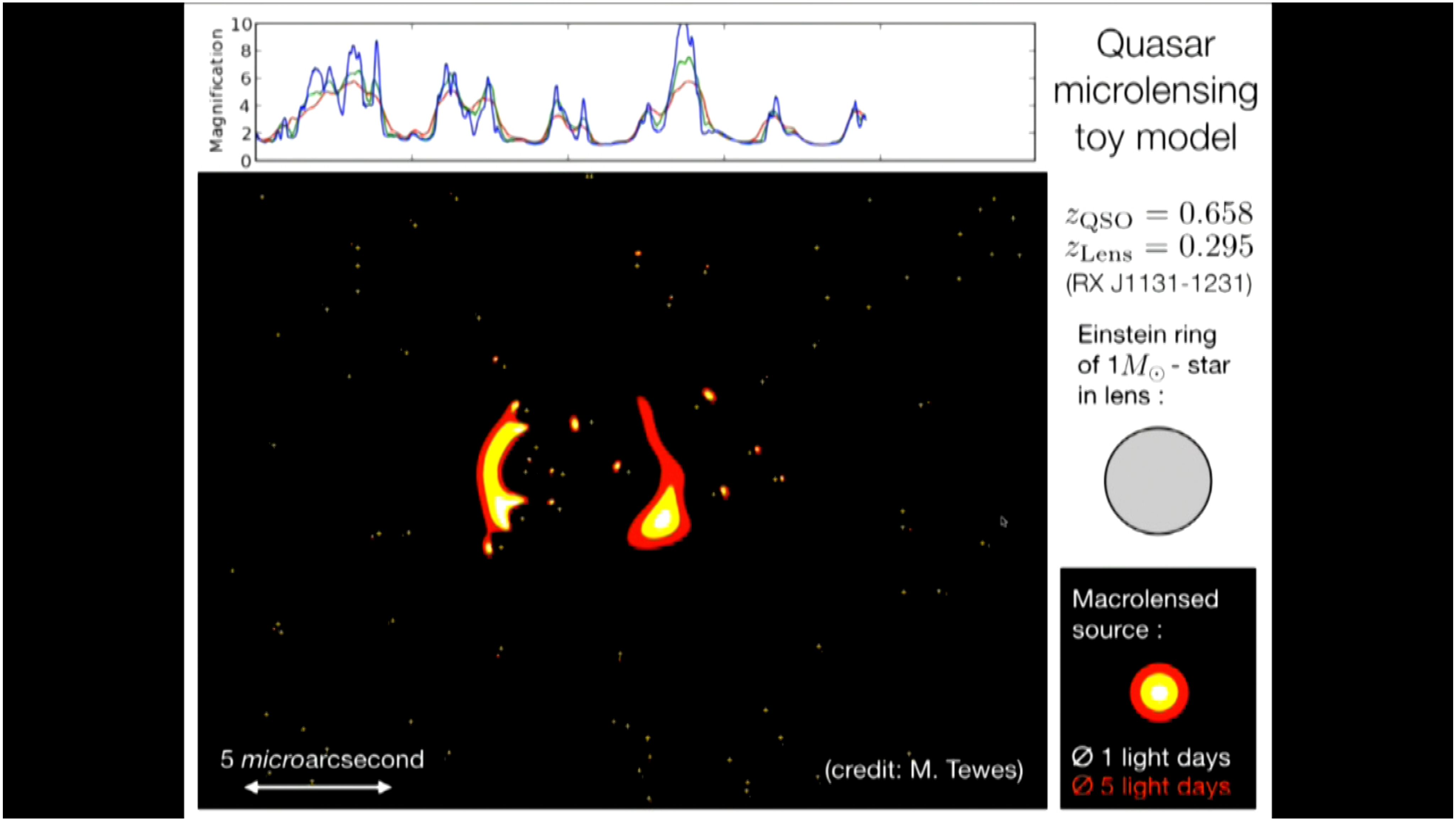


Magnification
0
2
4
6
8
10
Quasar microlensing toy model
$z_{\rm QSO} = 0.658$
$z_{\rm Lens} = 0.295$
(RX J1131-1231)
Einstein ring of $1M_\odot$ - star in lens :
Macrolensed source :
Ø 1 light days
Ø 5 light days
5 *micro*arcsecond
(credit: M. Tewes)

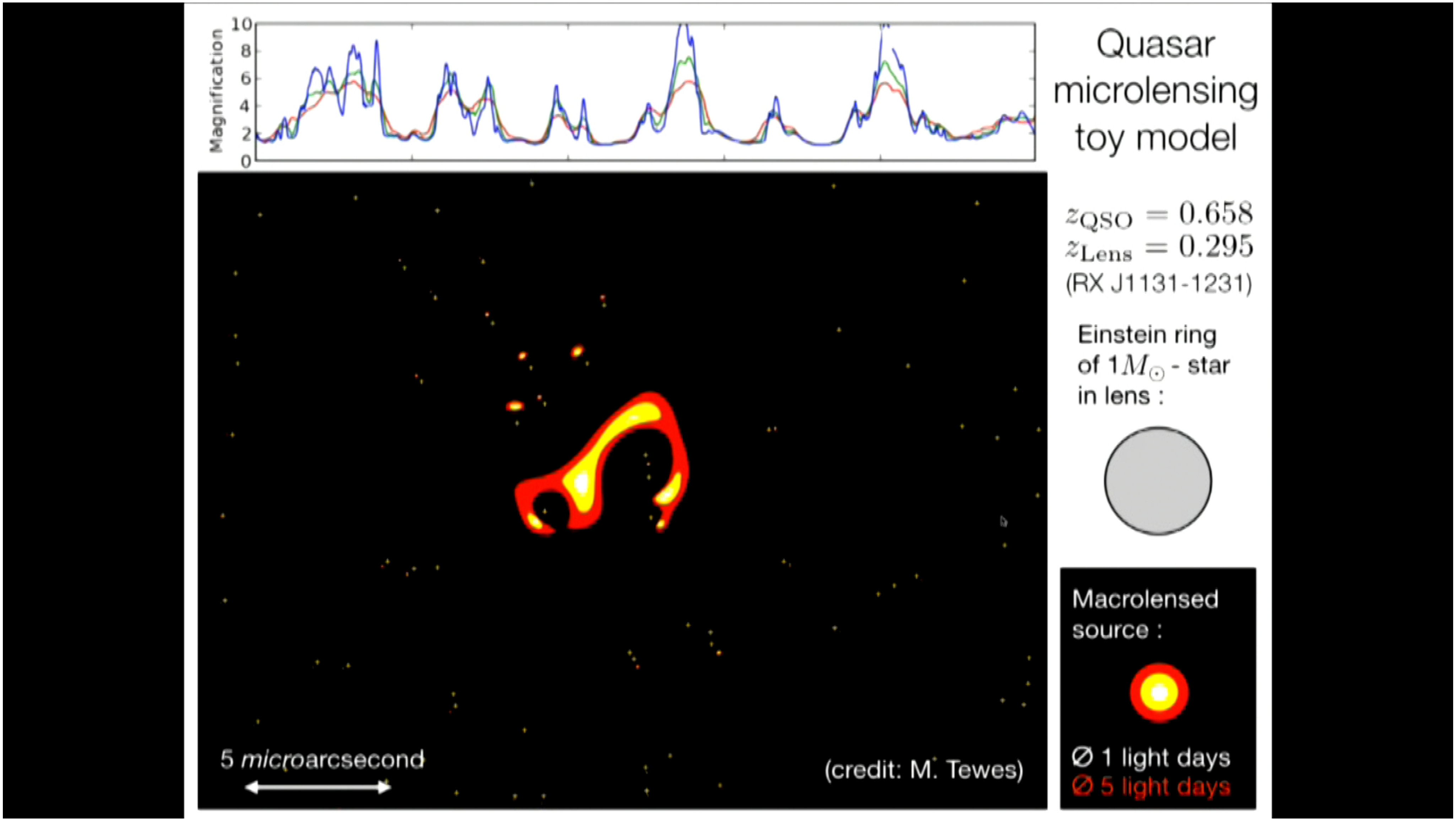

Quasar microlensing toy model
Magnification
0
2
4
6
8
10
R
G
B
$z_{QSO} = 0.658$
$z_{Lens} = 0.295$
(RX J1131-1231)
Einstein ring of $1M_\odot$ - star in lens :
Macrolensed source :
Ø 1 light days
Ø 5 light days
5 *micro*arcsecond
(credit: M. Tewes)


Quasar microlensing toy model
Magnification
10
8
6
4
2
0
$z_{\mathrm{QSO}} = 0.658$
$z_{\mathrm{Lens}} = 0.295$
(RX J1131-1231)
Einstein ring of $1 M_{\odot}$ - star in lens :
Macrolensed source :
Ø 1 light days
Ø 5 light days
5 *micro*arcsecond
(credit: M. Tewes)

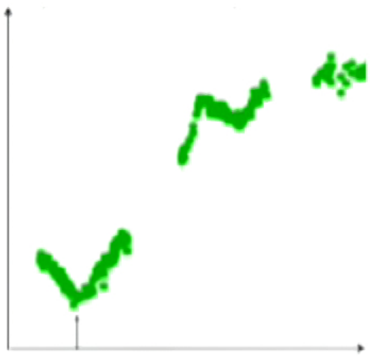

Quasar microlensing toy model
$z_{\rm QSO} = 0.658$
$z_{\rm Lens} = 0.295$
(RX J1131-1231)
Einstein ring of $1 M_\odot$ - star in lens :
Macrolensed source :
∅ 1 light days
∅ 5 light days
Magnification
10
8
6
4
2
0
5 *micro*arcsecond
(credit: M. Tewes)

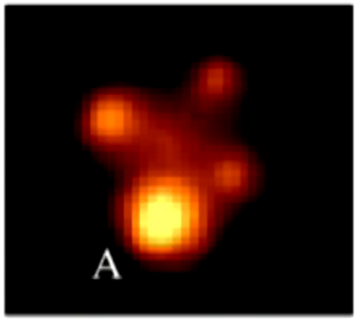


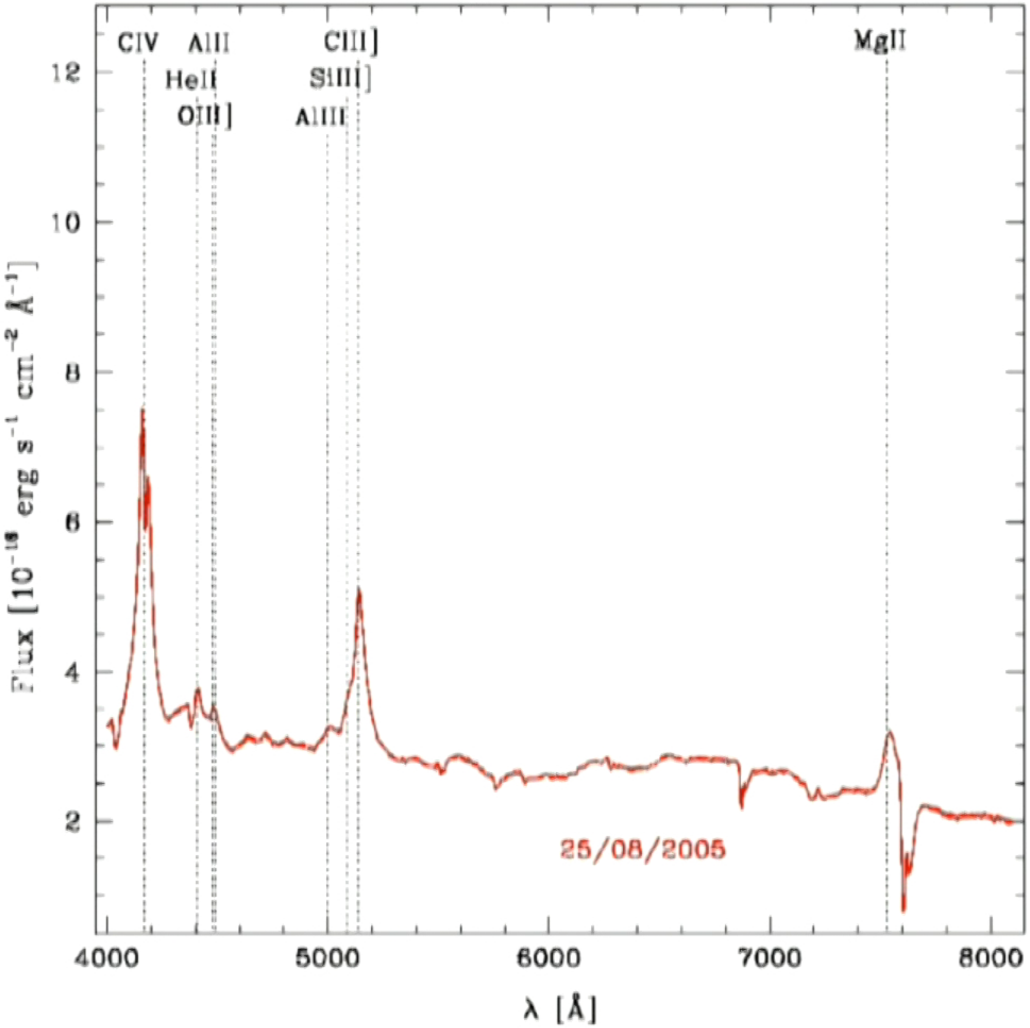
Magnification
0
2
4
6
8
10
Quasar microlensing toy model
$z_{\rm QSO} = 0.658$
$z_{\rm Lens} = 0.295$
(RX J1131-1231)
Einstein ring of $1 M_\odot$ - star in lens :
Macrolensed source :
Ø 1 light days
Ø 5 light days
5 *micro*arcsecond
(credit: M. Tewes)


Quasar microlensing toy model
Magnification
$z_{\rm QSO} = 0.658$
$z_{\rm Lens} = 0.295$
(RX J1131-1231)
Einstein ring of $1 M_\odot$ - star in lens :
Macrolensed source :
Ø 1 light days
Ø 5 light days
5 *micro*arcsecond
(credit: M. Tewes)

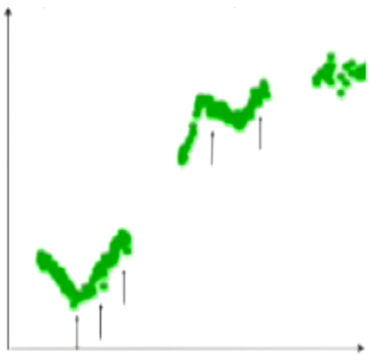
Microlensing in the Einstein Cross (Eigenbrod et al. 2008)

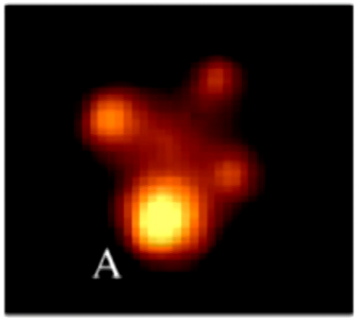


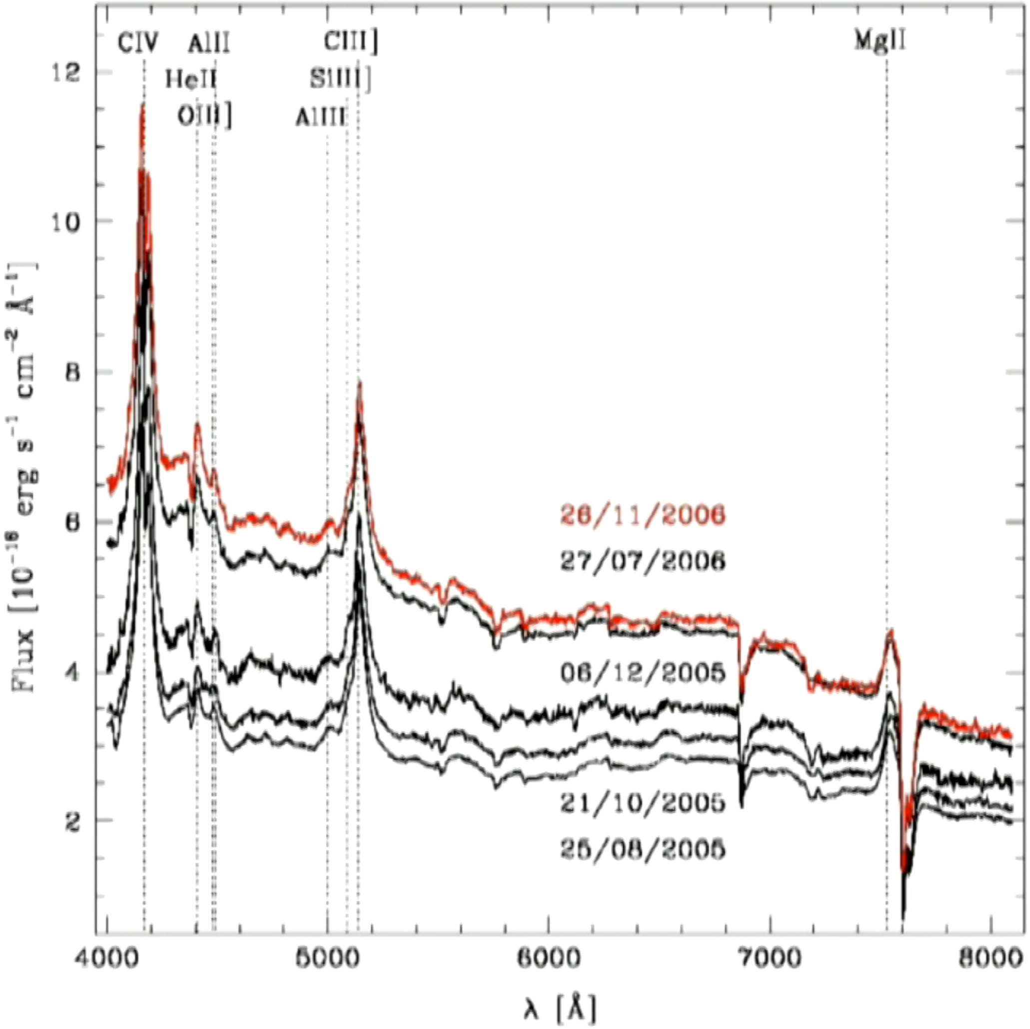




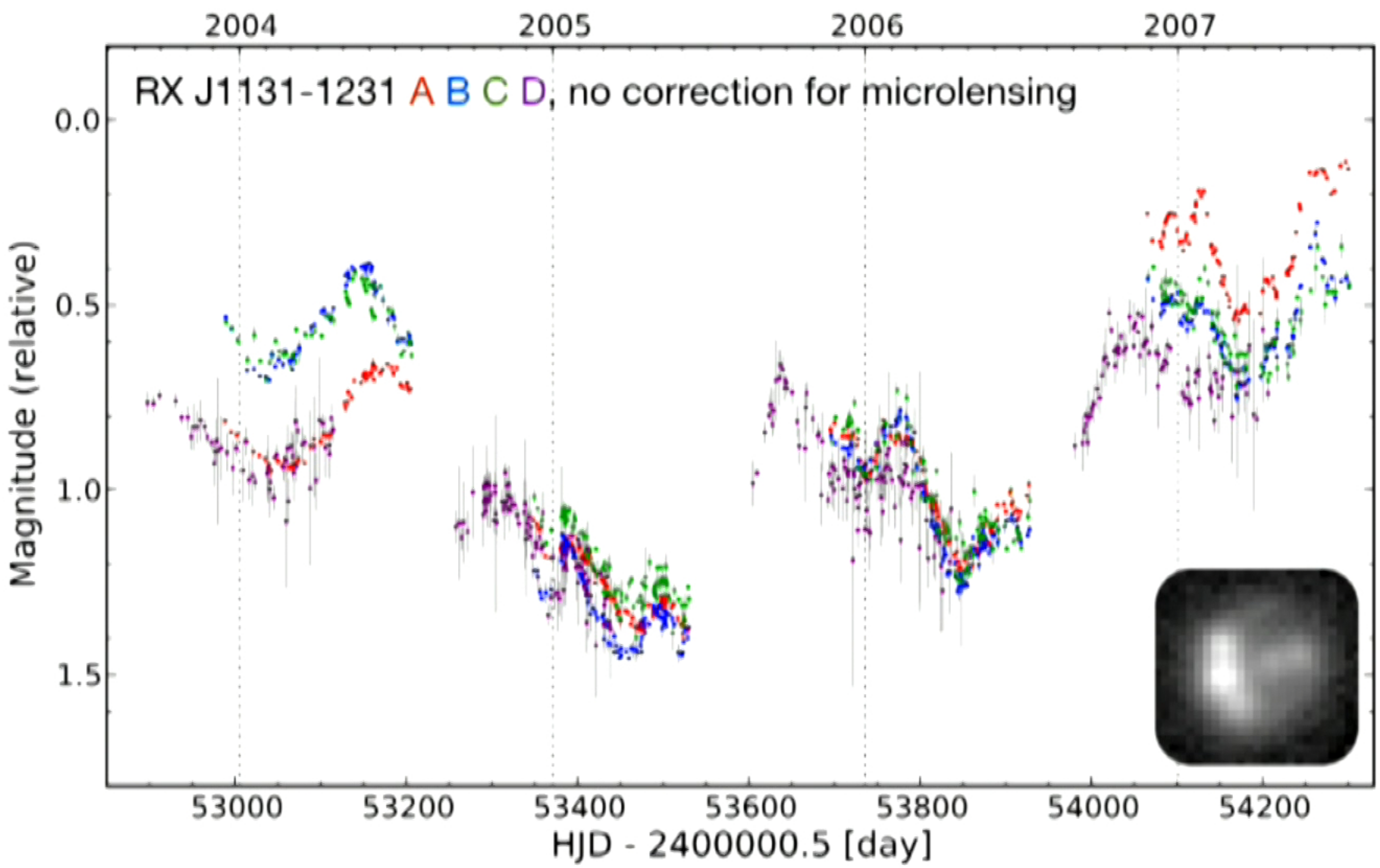
Microlensing in the Einstein Cross (Eigenbrod et al. 2008)





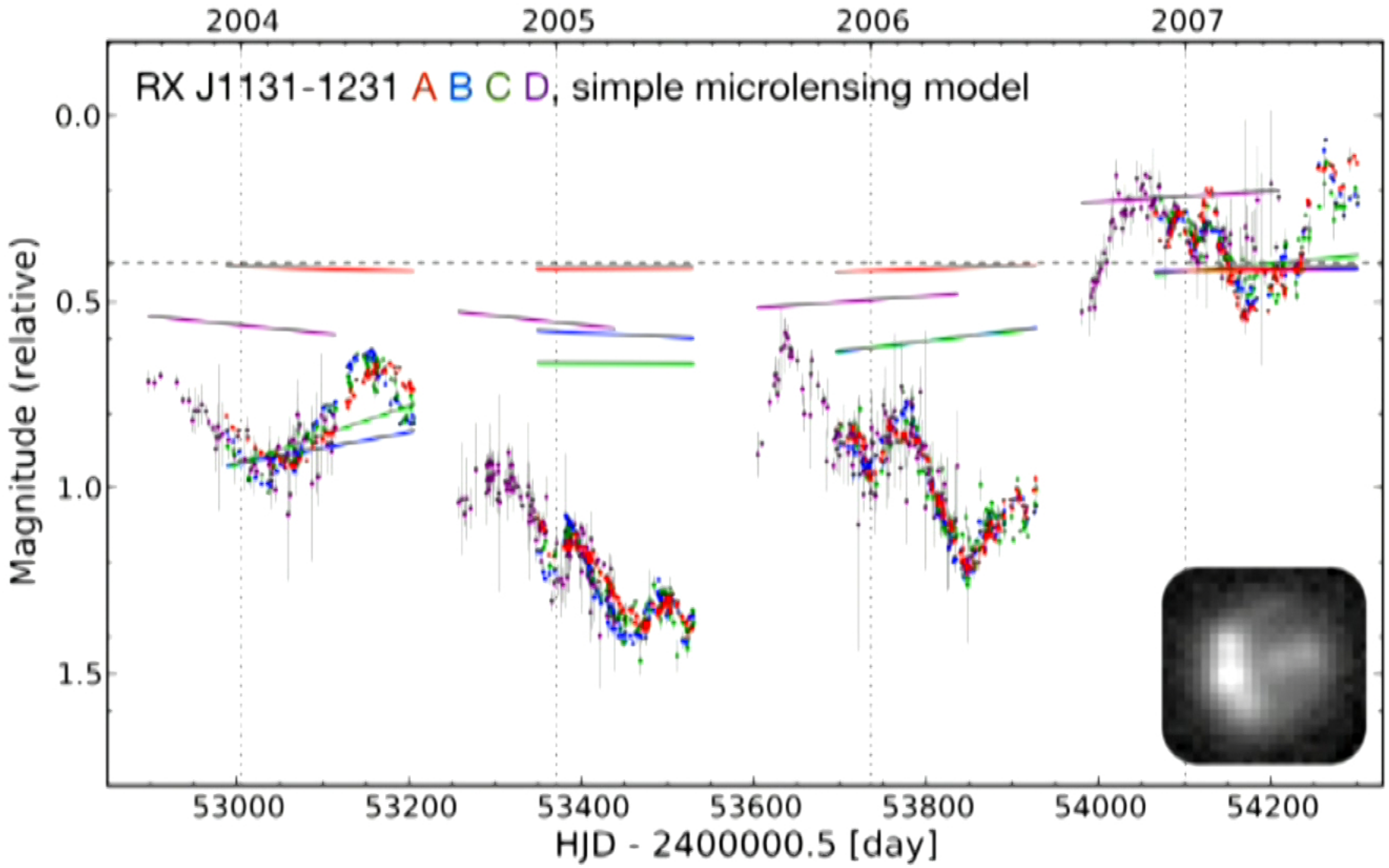


Microlensing Exacerbates Time Delay Measurements



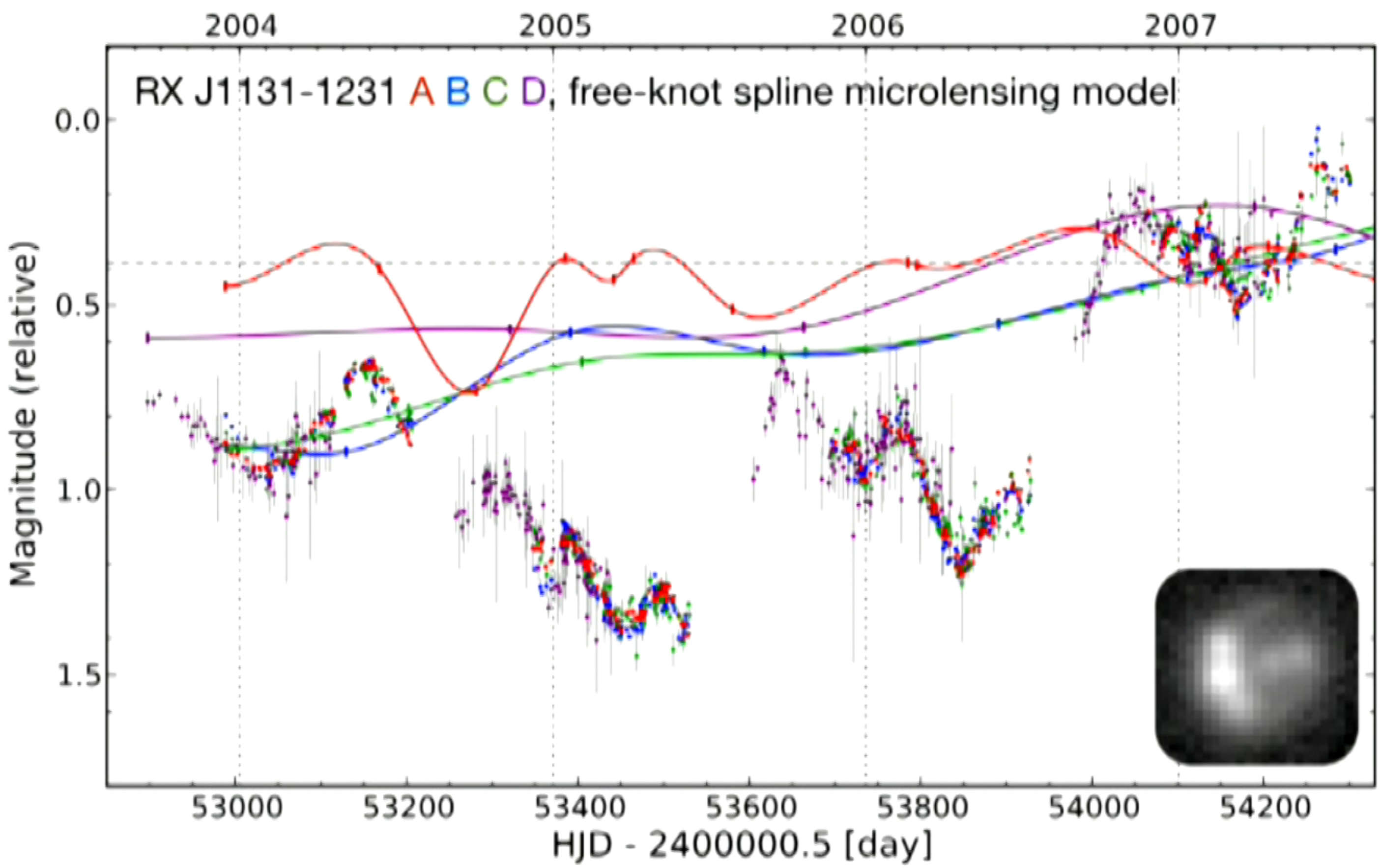
Tewes et al. (2013)

Microlensing Exacerbates Time Delay Measurements

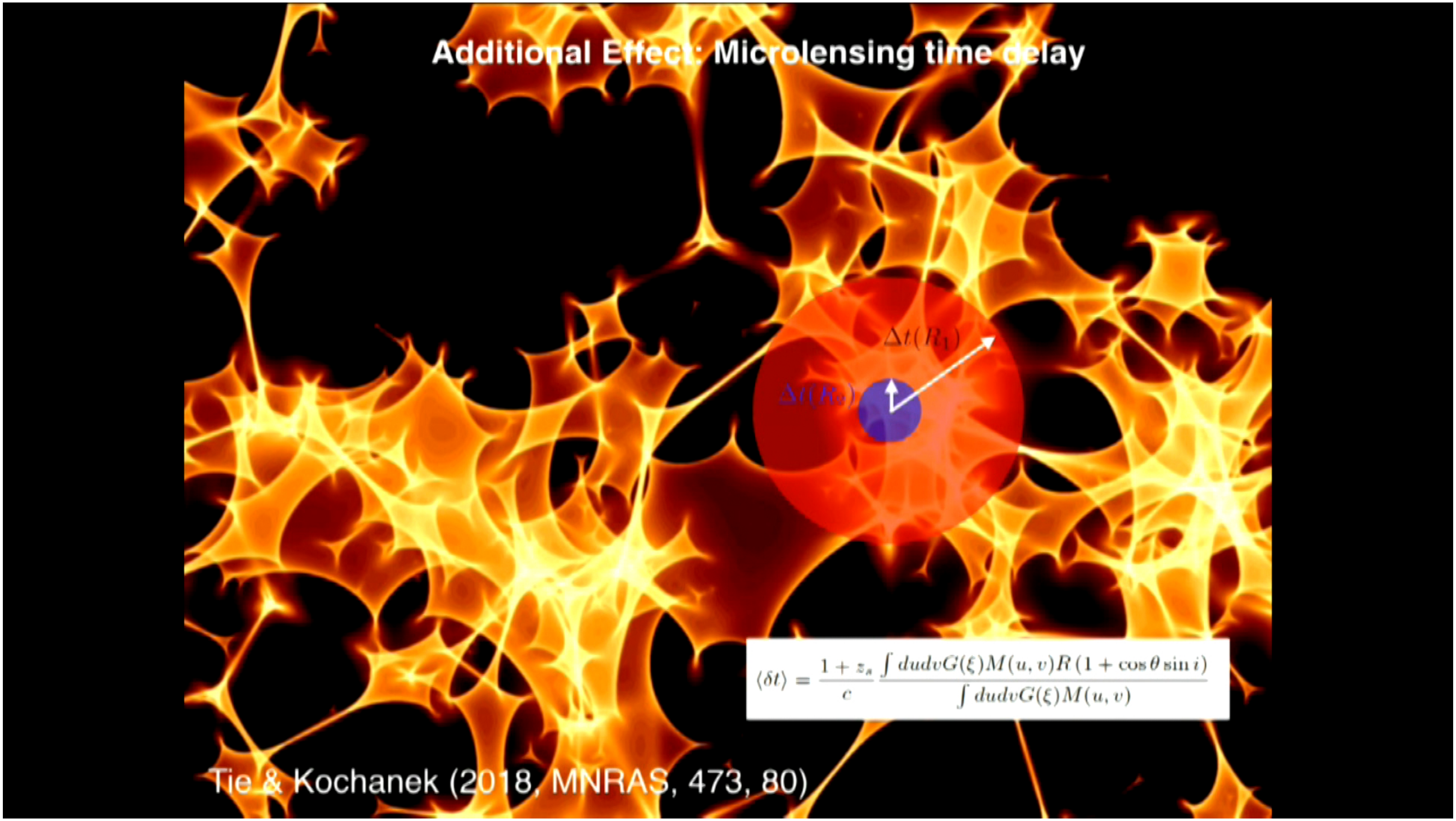


Tewes et al. (2013)

Microlensing Exacerbates Time Delay Measurements

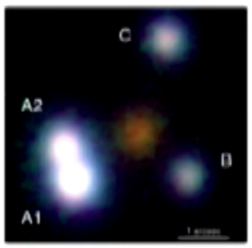


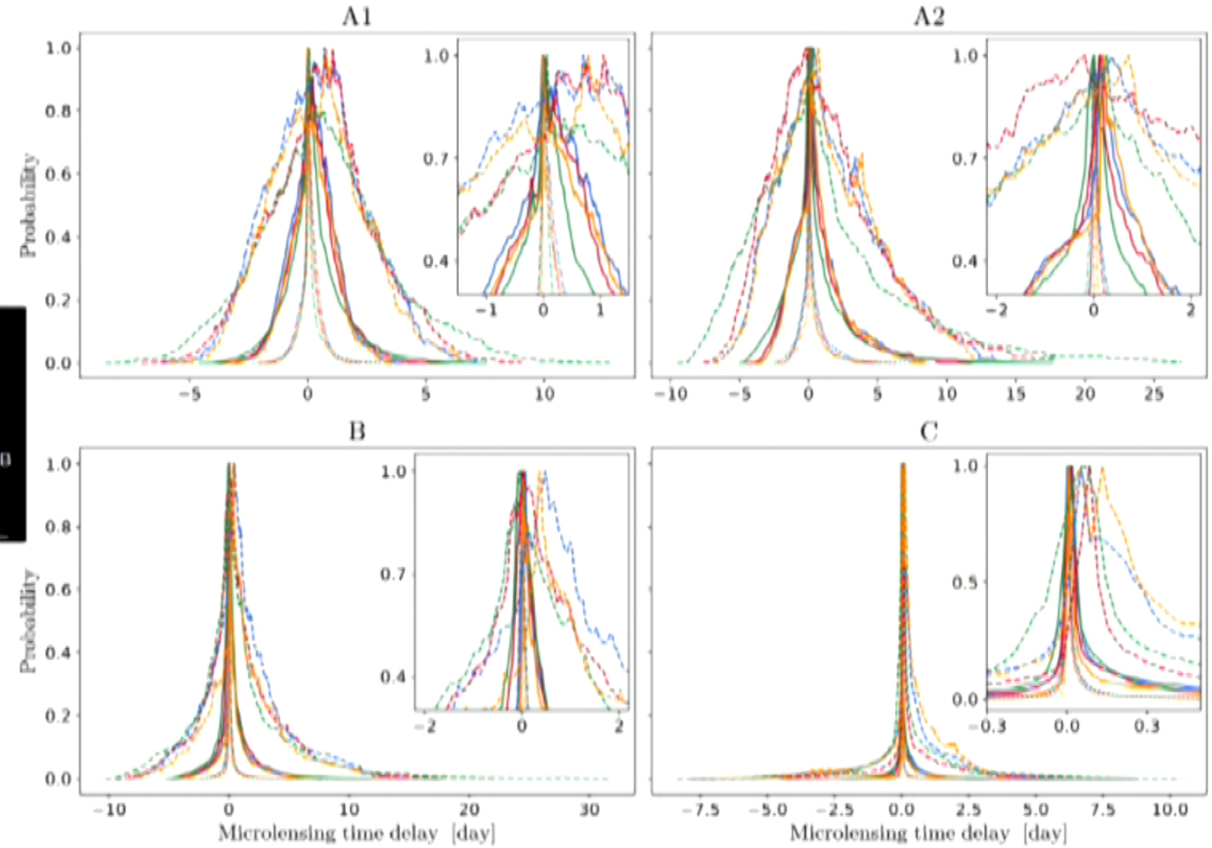
Tewes et al. (2013)



Additional Effect: Microlensing time delay
$\Delta t(R_1)$
$\Delta t(R_0)$
$\langle \delta t \rangle = \frac{1+z_s}{c} \frac{\int du dv G(\xi) M(u,v) R (1 + \cos\theta \sin i)}{\int du dv G(\xi) M(u,v)}$
Tie & Kochanek (2018, MNRAS, 473, 80)

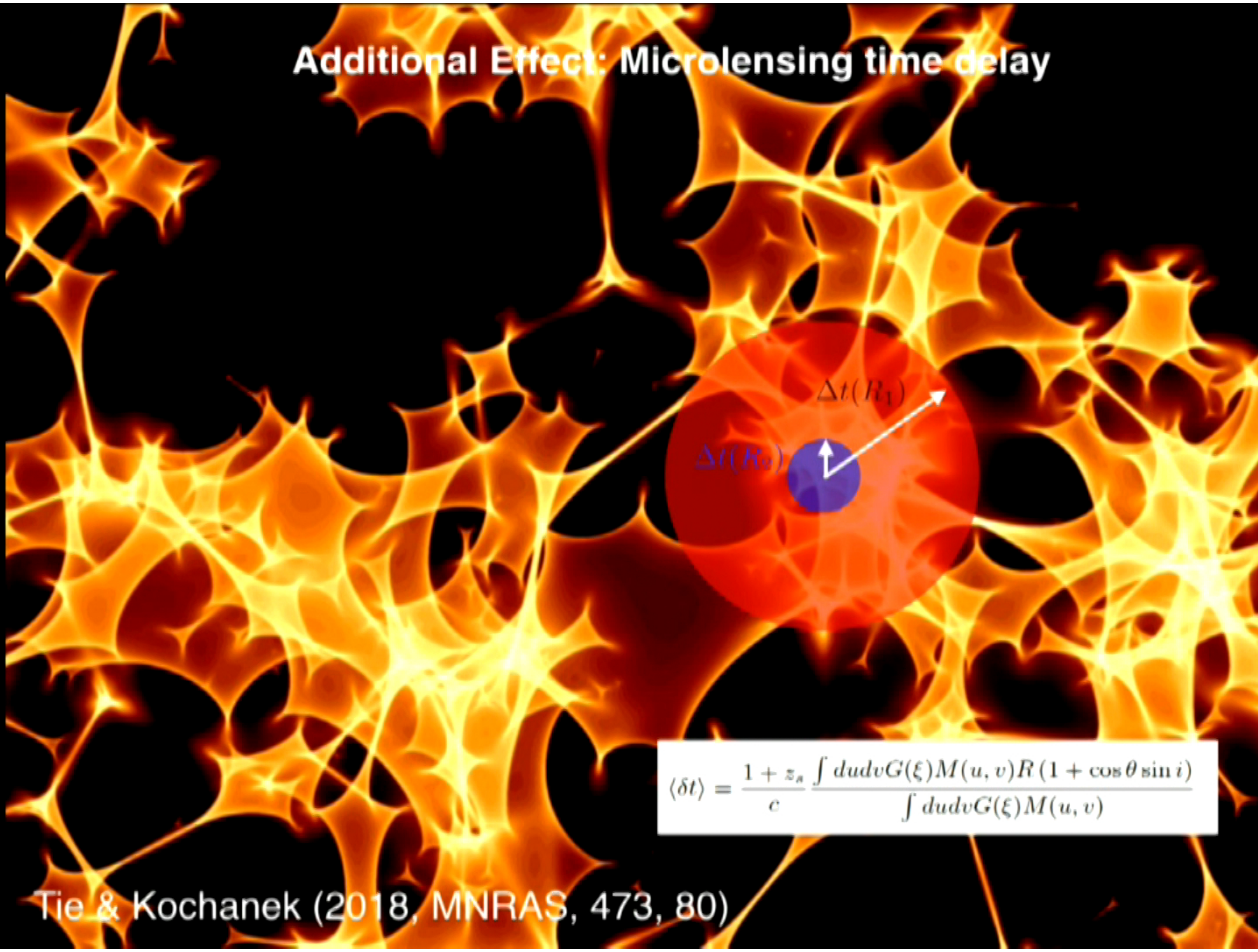
Typical (theoretical) microlensing time delay for PG1115+080





Bonvin et al. (2018, A&A 616, A183)

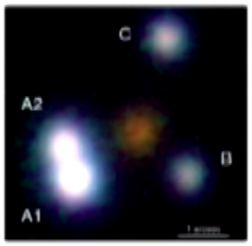
Additional Effect: Microlensing time delay

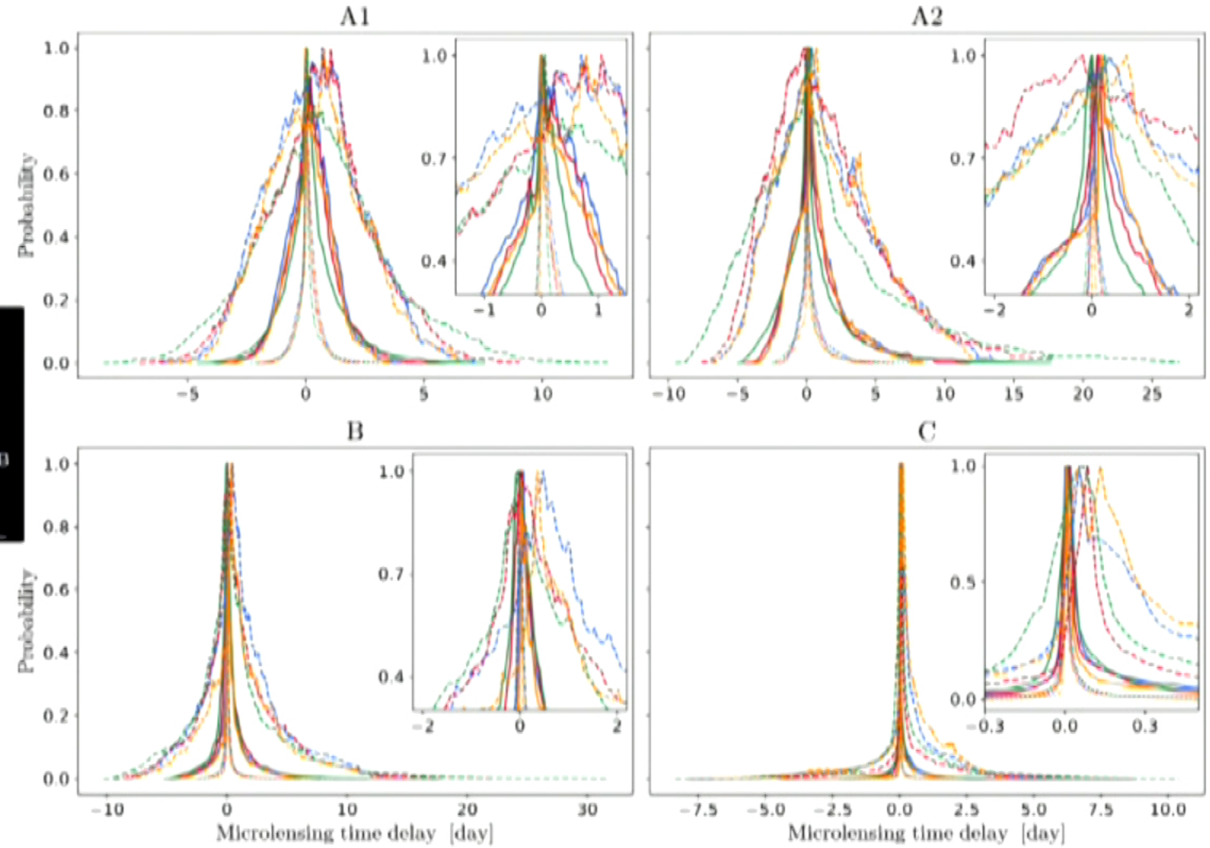


$$\langle \delta t \rangle = \frac{1+z_s}{c} \frac{\int du dv G(\xi) M(u,v) R \left(1 + \cos\theta \sin i\right)}{\int du dv G(\xi) M(u,v)}$$

Tie & Kochanek (2018, MNRAS, 473, 80)

Typical (theoretical) microlensing time delay for PG1115+080



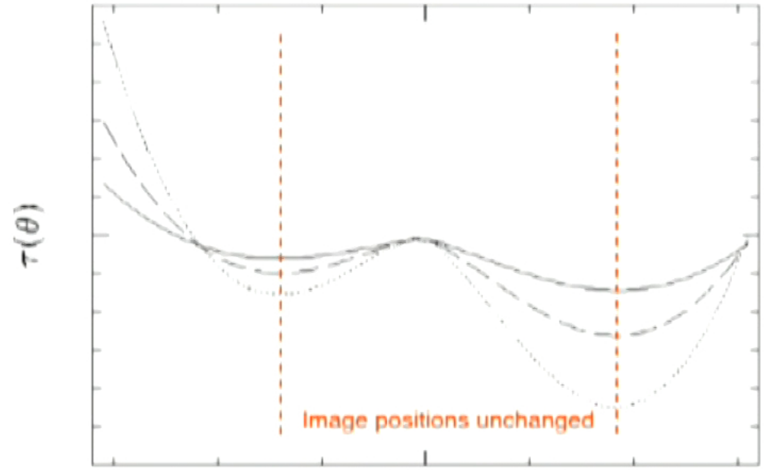


Bonvin et al. (2018, A&A 616, A183)

Mass Slope of Lens Galaxy

H_0 from time delays is all about estimating the mass slope of lens galaxy and the external convergence from intervening objects.

Arrival time surfaces in the image plane



Normalized mass profile

κ = projected mass density in units of the critical mass

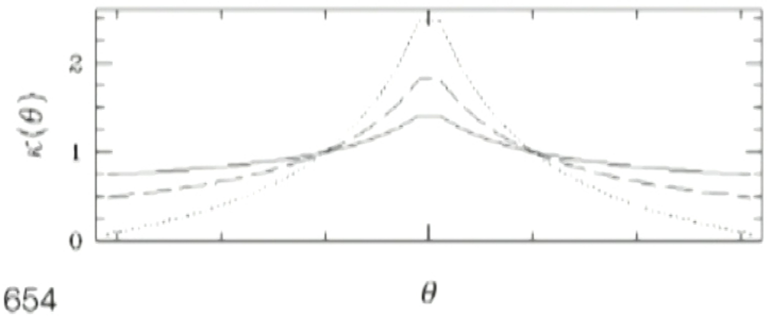
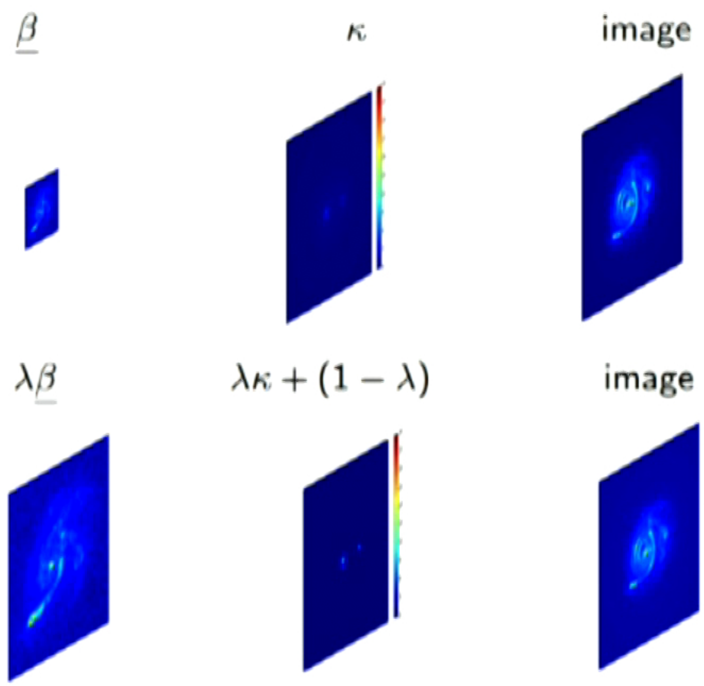
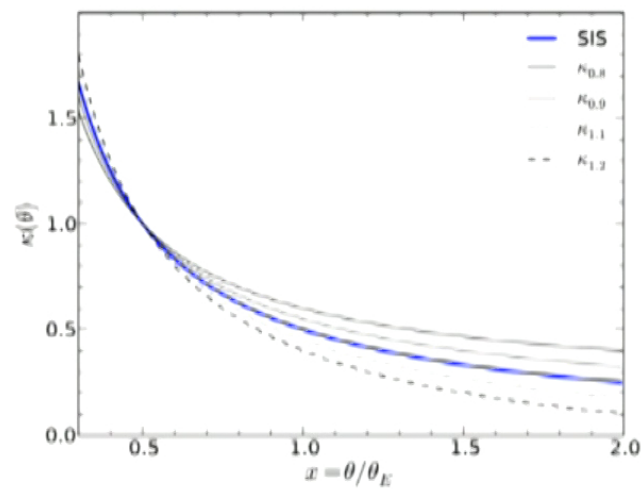


Figure from Saha, 2000, AJ 120, 1654

Model degeneracies: Mass Sheet Transform (MST)

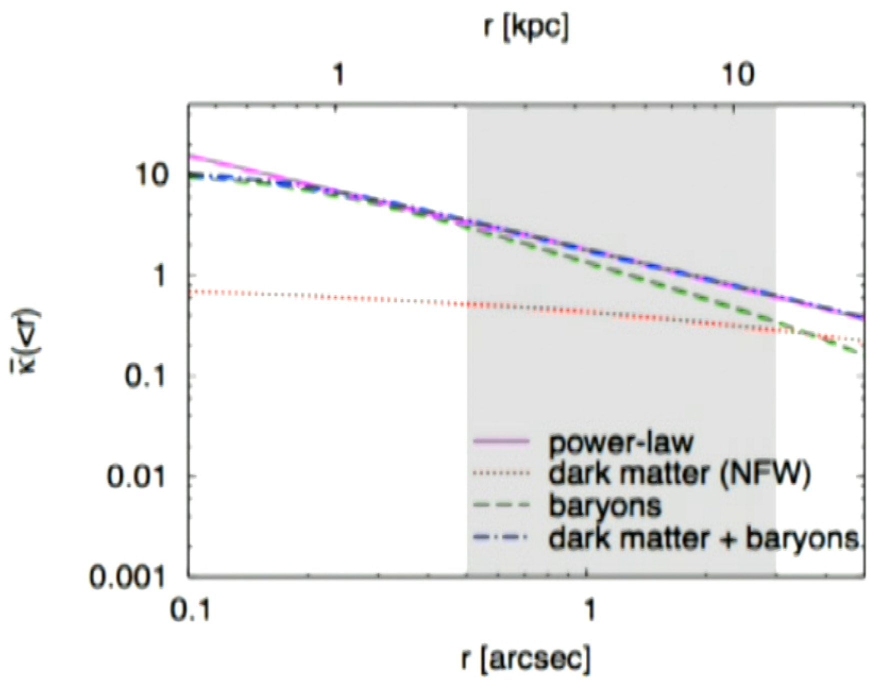


Different mass profiles that all fit the lensing data (except the time delays)



Schneider & Sluse (2013, A&A, 559, A37)
Schneider & Sluse (2014, A&A, 564, A103)

Mass-slope Degeneracy

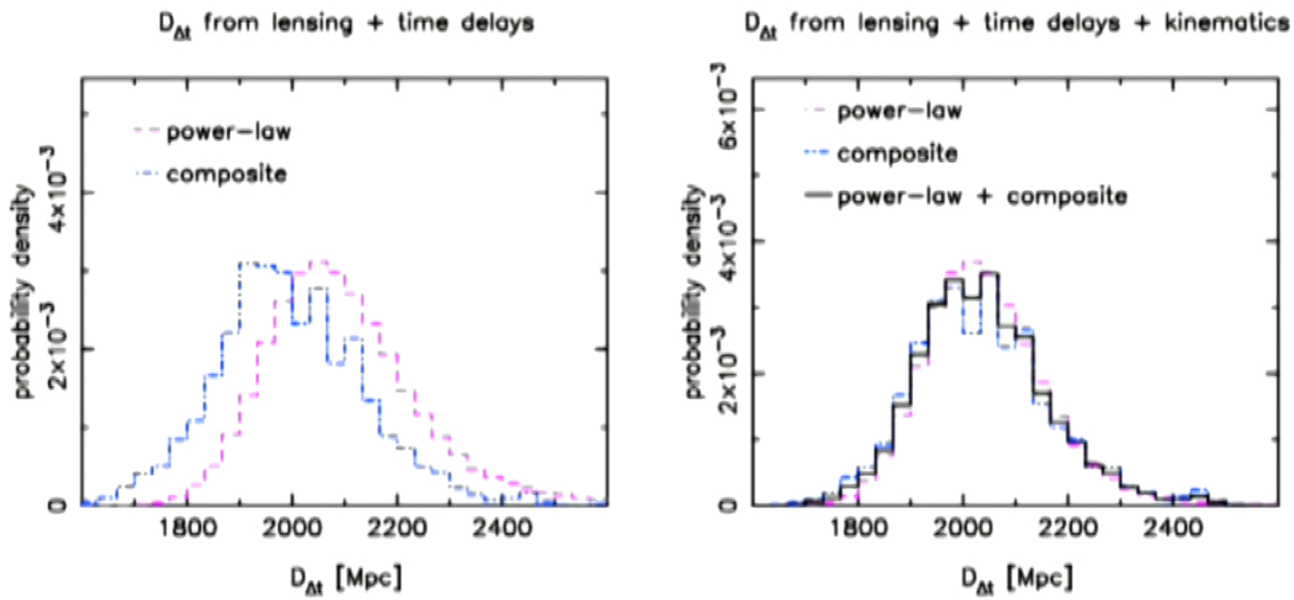


Different mass models give the same lensing observables but different time delays.

Using the **dynamical** information on the lensing galaxy breaks this degeneracy.

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

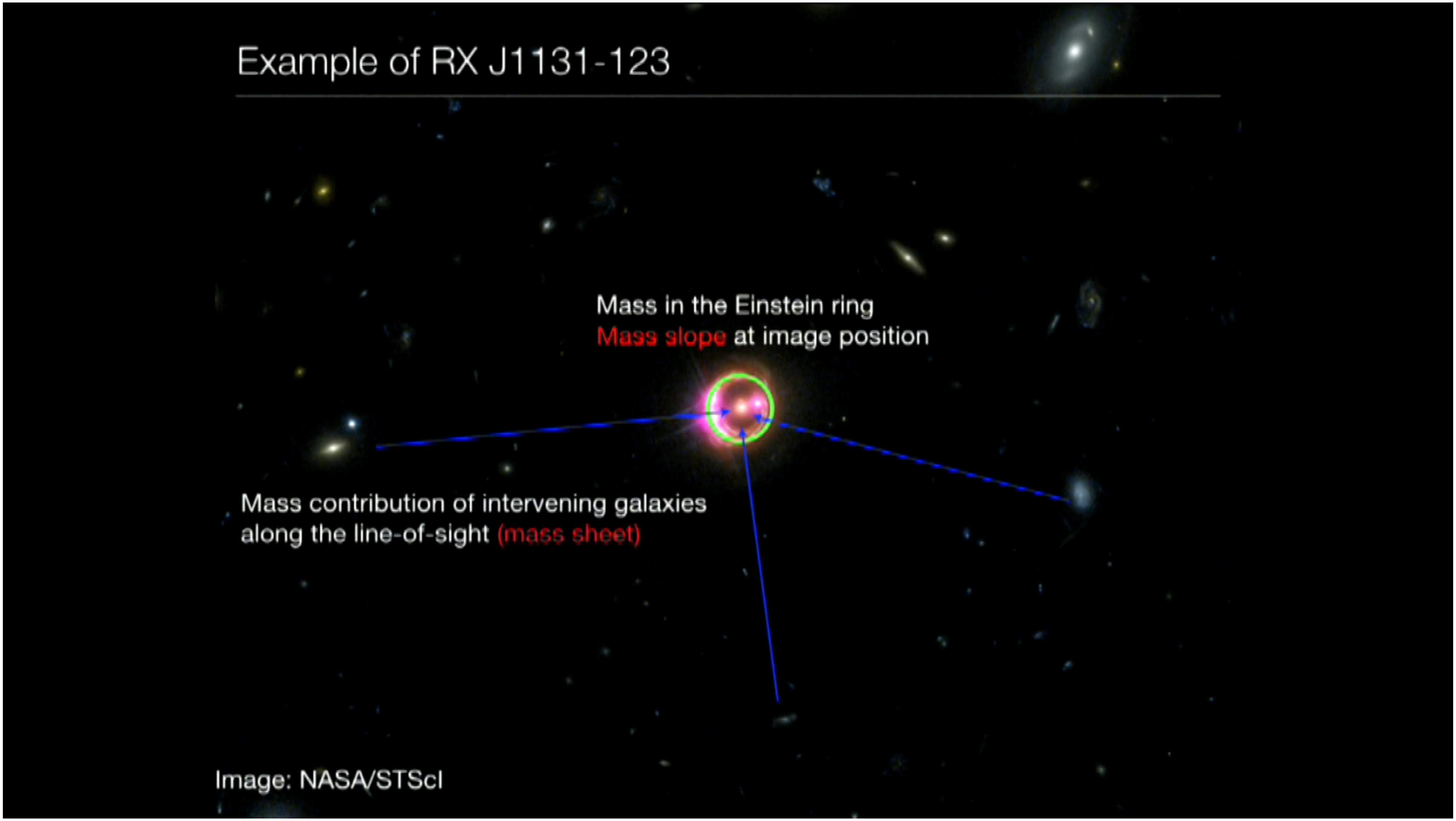
Mass-slope Degeneracy



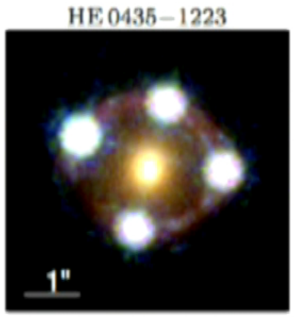
Different mass models give the same lensing observables but different time delays.

Using the **dynamical** information on the lensing galaxy breaks this degeneracy.

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

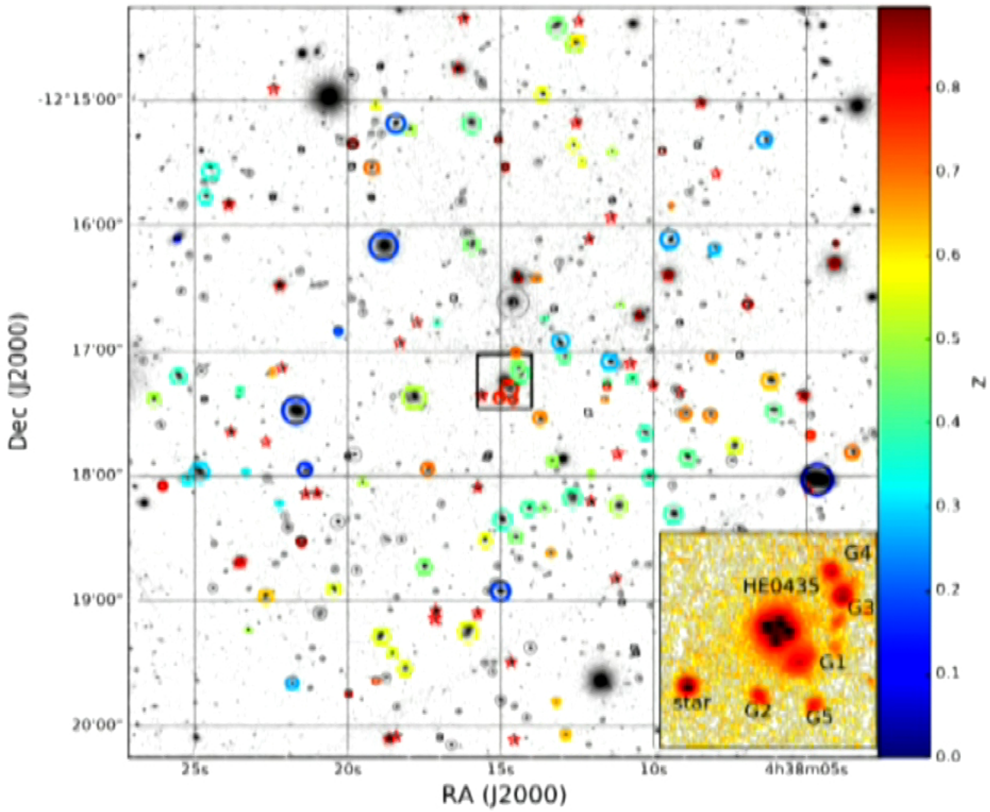

Example of RX J1131-123
Mass in the Einstein ring
Mass slope at image position
Mass contribution of intervening galaxies
along the line-of-sight (mass sheet)
Image: NASA/STScI

The case of HE 0435-1223



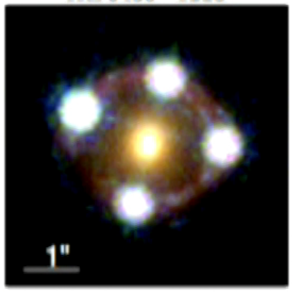
Suyu et al. 2017
(Paper I; MNRAS 468, 2590)
Project overview

Sluse et al. 2017
(Paper II; MNRAS 470, 4838)
Spectroscopy



The case of HE 0435-1223

HE 0435 − 1223

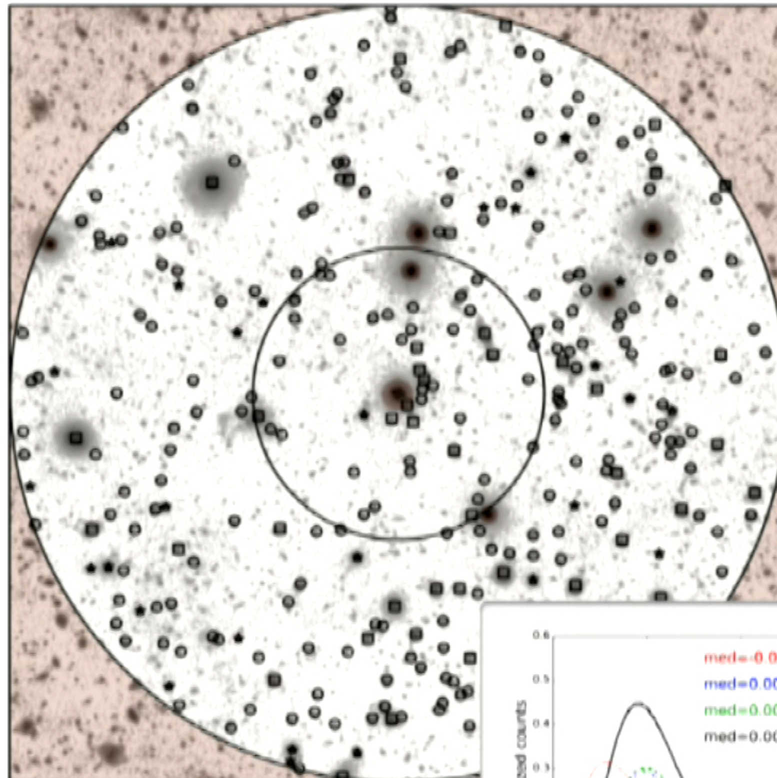


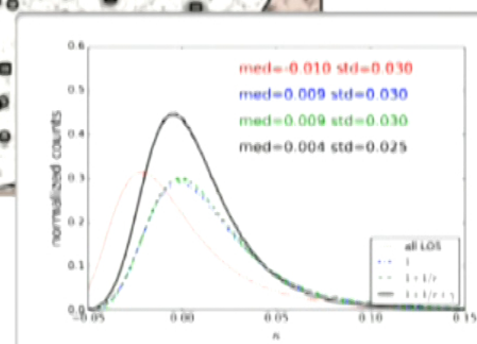
Suyu et al. 2017
(Paper I; MNRAS 468, 2590)
Project overview

Sluse et al. 2017
(Paper II; MNRAS 470, 4838)
Spectroscopy

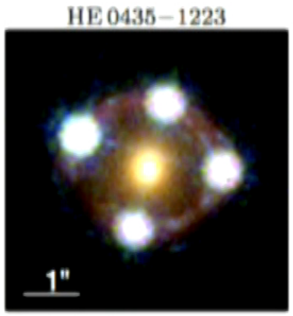
Rusu et al. 2017
(Paper III; MNRAS 467, 4220)
Photo-z and external convergence

4 arcmin





The case of HE 0435-1223

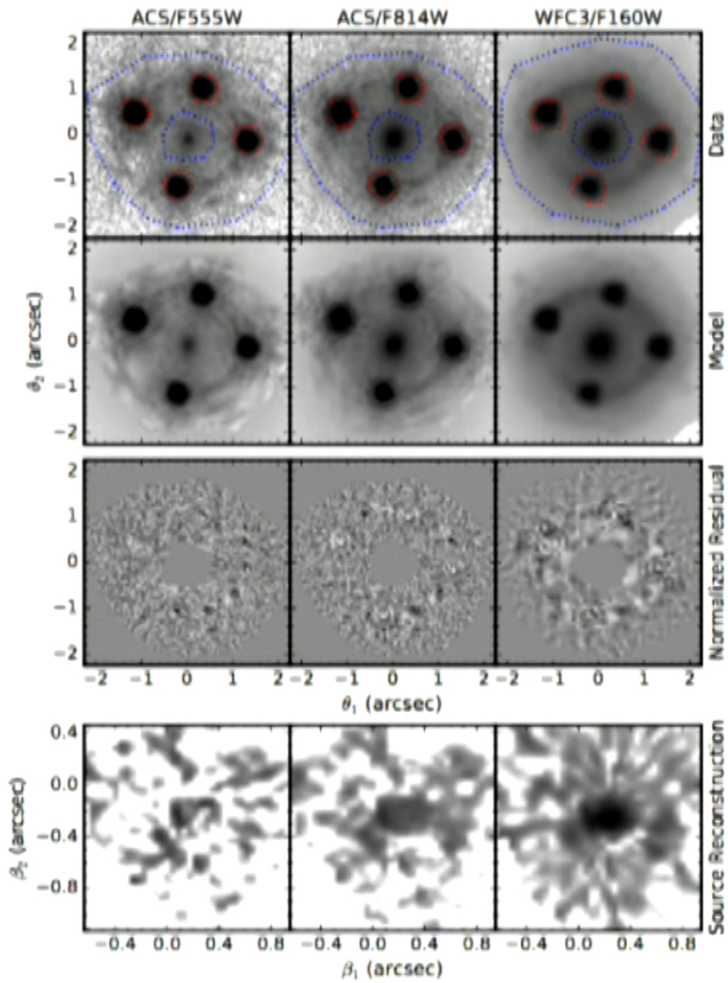


Suyu et al. 2017
(Paper I; MNRAS 468, 2590)
Project overview

Sluse et al. 2017
(Paper II; MNRAS 470, 4838)
Spectroscopy

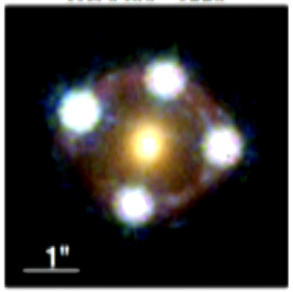
Rusu et al. 2017
(Paper III; MNRAS 467, 4220)
Photo-z and external convergence

Wong et al. 2017
(Paper IV; MNRAS 465, 4895)
HST imaging and lens models



The case of HE 0435-1223

HE 0435 − 1223



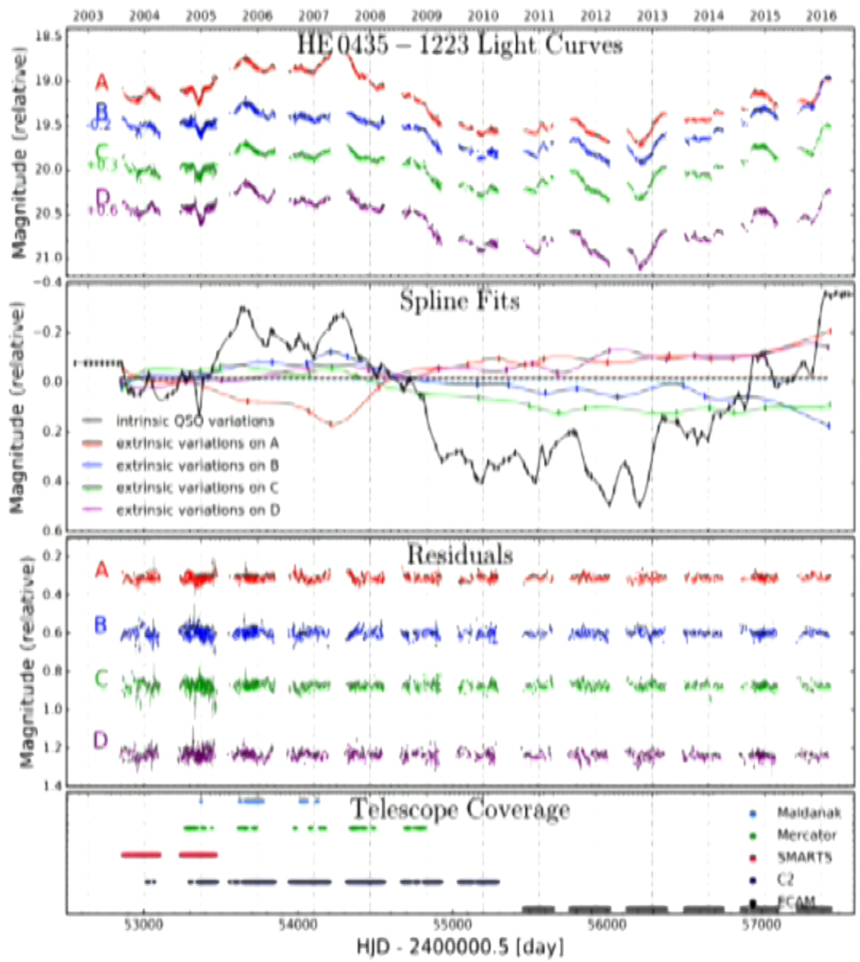
Suyu et al. 2017
(Paper I; MNRAS 468, 2590)
Project overview

Sluse et al. 2017
(Paper II; MNRAS 470, 4838)
Spectroscopy

Rusu et al. 2017
(Paper III; MNRAS 467, 4220)
Photo-z and external convergence

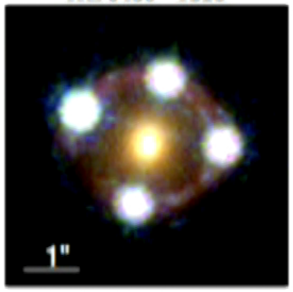
Wong et al. 2017
(Paper IV; MNRAS 465, 4895)
HST imaging and lens models

Bonvin et al. 2017
(Paper V; MNRAS 465, 4914)
Cosmology results for 3 lenses



The case of HE 0435-1223

HE 0435 − 1223



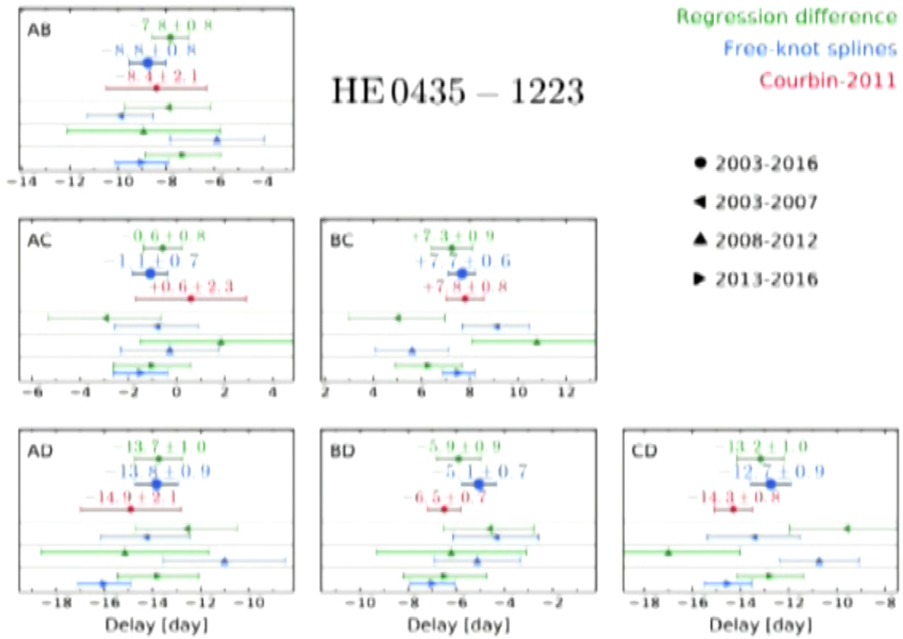
Suyu et al. 2017
(Paper I; MNRAS 468, 2590)
Project overview

Sluse et al. 2017
(Paper II; MNRAS 470, 4838)
Spectroscopy

Rusu et al. 2017
(Paper III; MNRAS 467, 4220)
Photo-z and external convergence

Wong et al. 2017
(Paper IV; MNRAS 465, 4895)
HST imaging and lens models

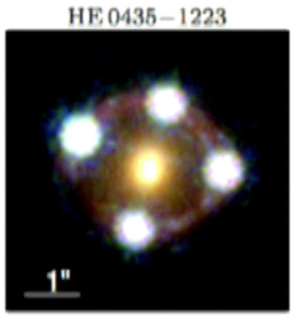
Bonvin et al. 2017
(Paper V; MNRAS 465, 4914)
Cosmology results for 3 lenses



Curve-shifting methods tested (blindly) on the **Time Delay Challenge (TDC)** data

Dobler et al 2015, ApJ, 799, 168; presentation of the challenge
Liao et al. 2015, ApJ, 800, 11; results of the challenge
Bonvin et al. 2015, A&A, 585, A88: performance of the COSMOGRAIL methods

The case of HE 0435-1223



Suyu et al. 2017
(Paper I; MNRAS 468, 2590)
Project overview

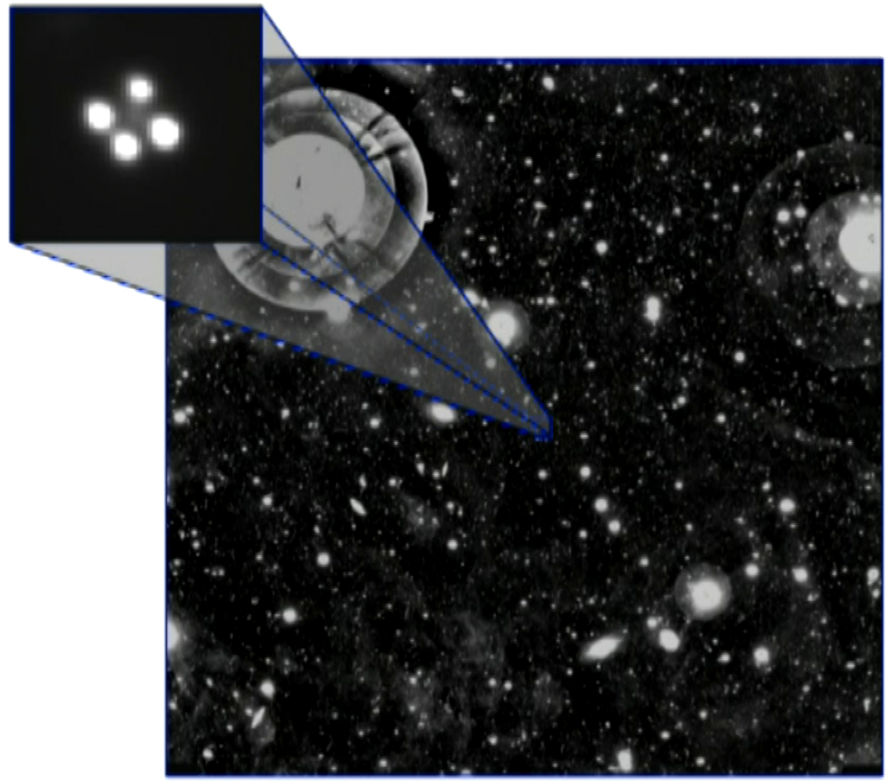
Sluse et al. 2017
(Paper II; MNRAS 470, 4838)
Spectroscopy

Rusu et al. 2017
(Paper III; MNRAS 467, 4220)
Photo-z and external convergence

Wong et al. 2017
(Paper IV; MNRAS 465, 4895)
HST imaging and lens models

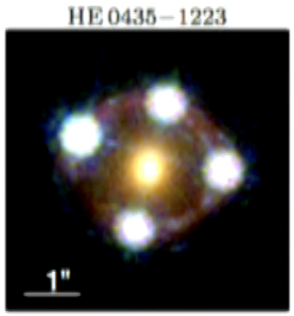
Bonvin et al. 2017
(Paper V; MNRAS 465, 4914)
Cosmology results for 3 lenses

Tihhonova et al. 2017
(Paper VIII; MNRAS 477, 5657)
Weak lensing study of the field (Subaru data)



Deep r-band Subaru Suprime-Cam data (PI: Fassnacht):
- 1.5h on-target
- 15 galaxies per sq acrmin at r=25.8
- 0.5" seeing

The case of HE 0435-1223



Suyu et al. 2017
(Paper I; MNRAS 468, 2590)
Project overview

Sluse et al. 2017
(Paper II; MNRAS 470, 4838)
Spectroscopy

Rusu et al. 2017
(Paper III; MNRAS 467, 4220)
Photo-z and external convergence

Wong et al. 2017
(Paper IV; MNRAS 465, 4895)
HST imaging and lens models

Bonvin et al. 2016
(Paper V; MNRAS 465, 4914)
Cosmology results for 3 lenses

Tihhonova et al. 2017
(Paper VIII; MNRAS 477, 5657)
Weak lensing study of the field (Subaru data)

External convergence at lens position:

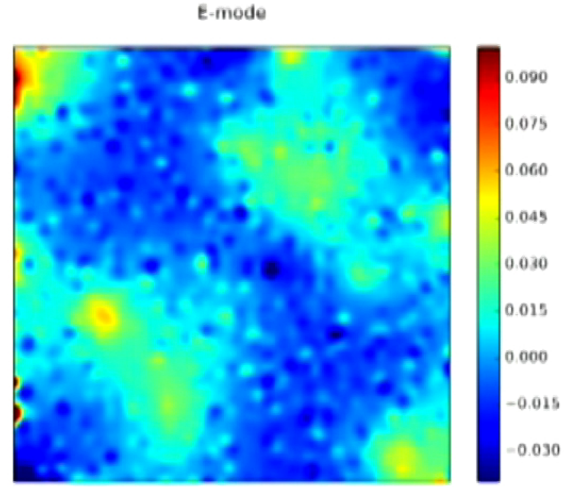
$\kappa = -0.007 \pm 0.01$

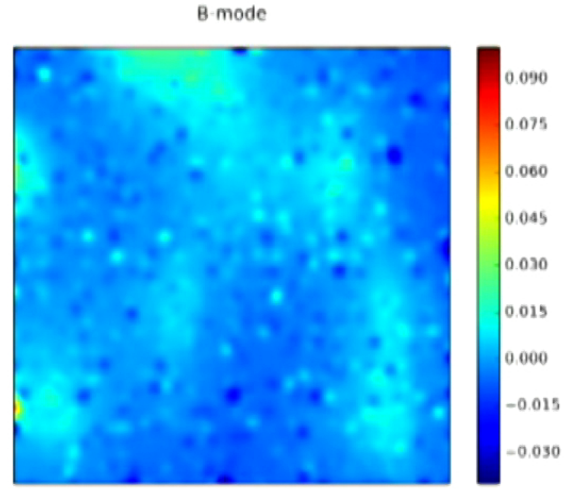
Maximum convergence in 2' aperture:

$\sigma(\kappa) \sim 0.03$

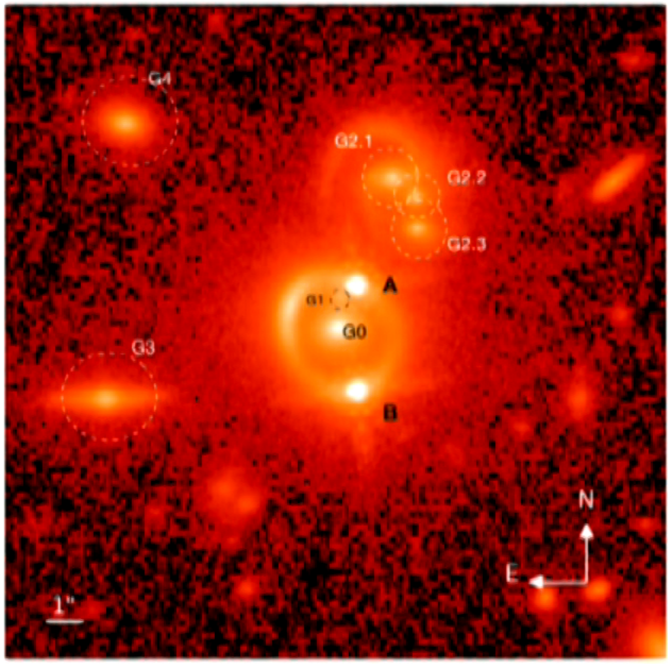
2D map reconstruted:

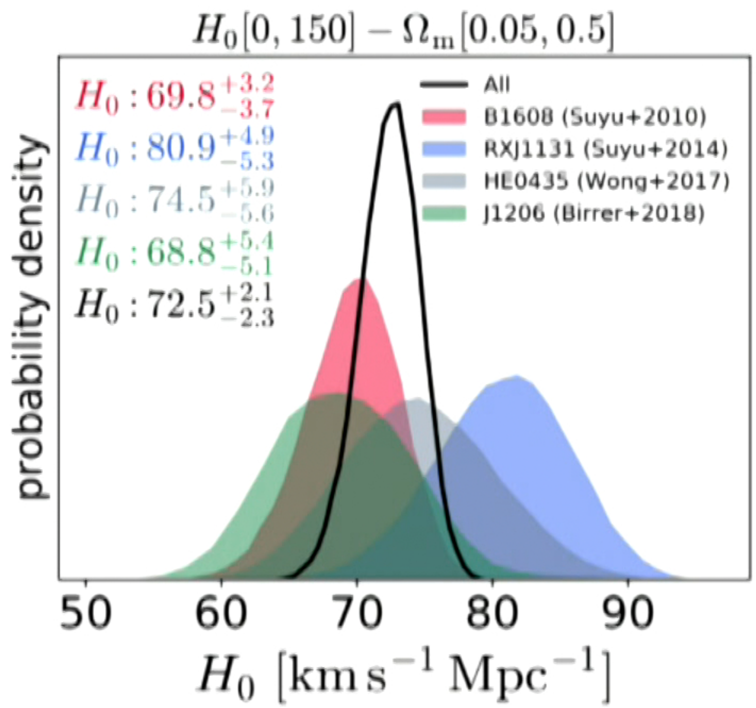
- **Step 1:** inpainting of shear map using `FASTlens` (Pires et al. 2009)
- **Step 2:** `mrlens` turns shear into convergence using marlins based on wavelet reconstruction (Starck et al. 2006).





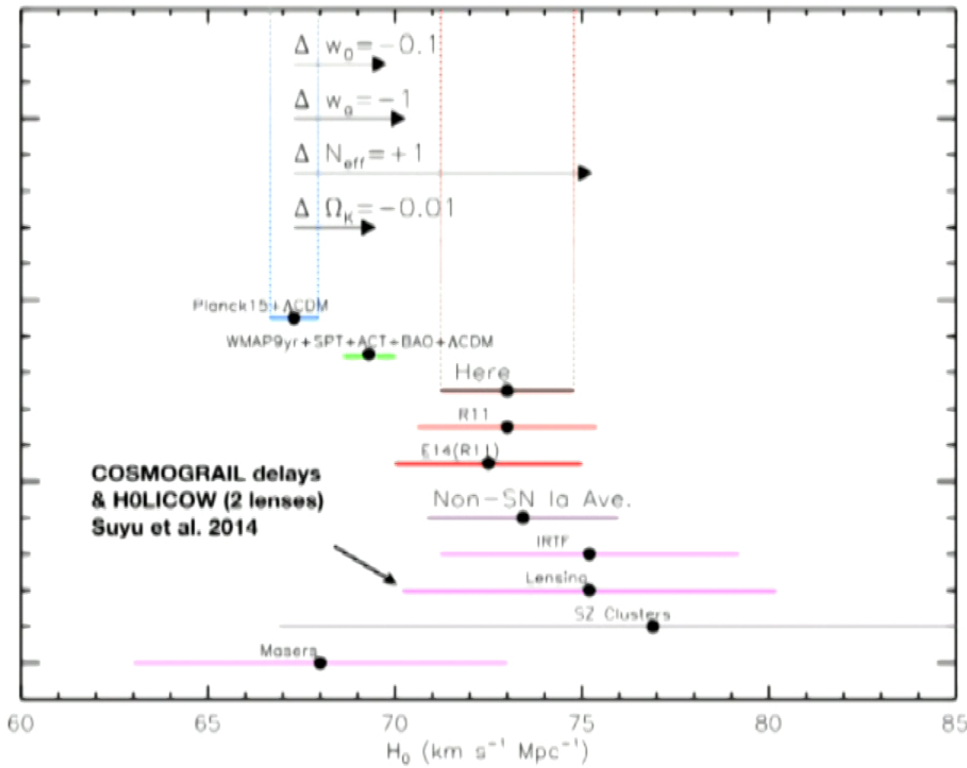
Cosmology Results with 4 Lenses - updated 2019





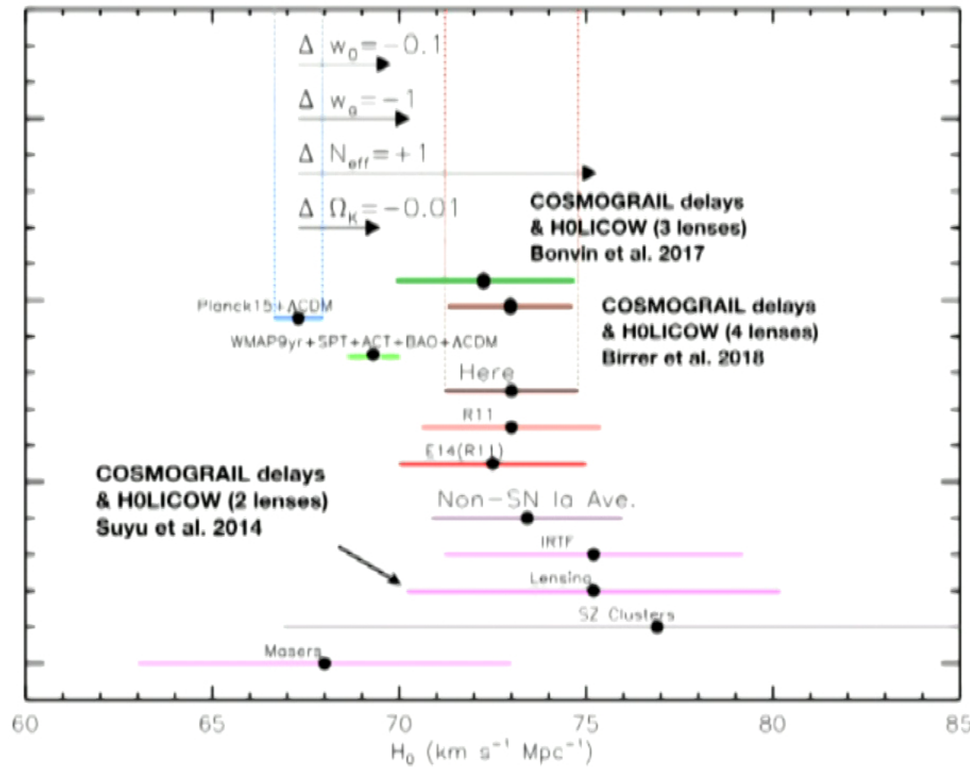
Birrer et al. 2019, MNRAS 484, 4726
(Paper IX)
Cosmology results for 4 lenses

Comparison with other Cosmological Probes



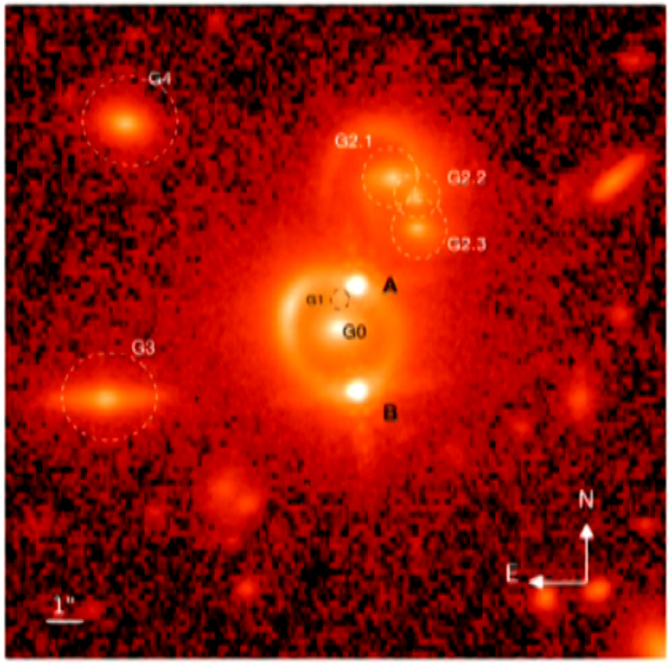
Adapted From Riess et al. (2016)

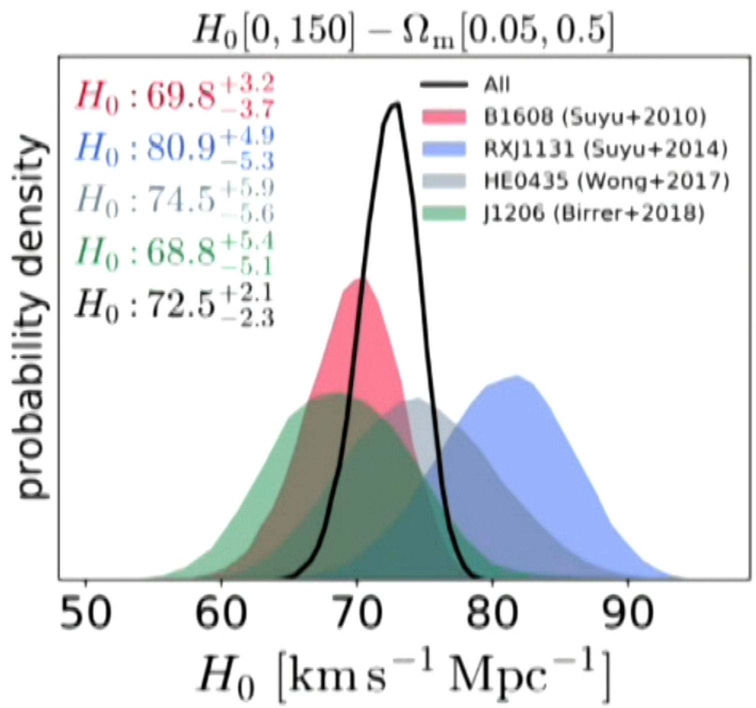
Comparison with other Cosmological Probes



Adapted From Riess et al. (2016)

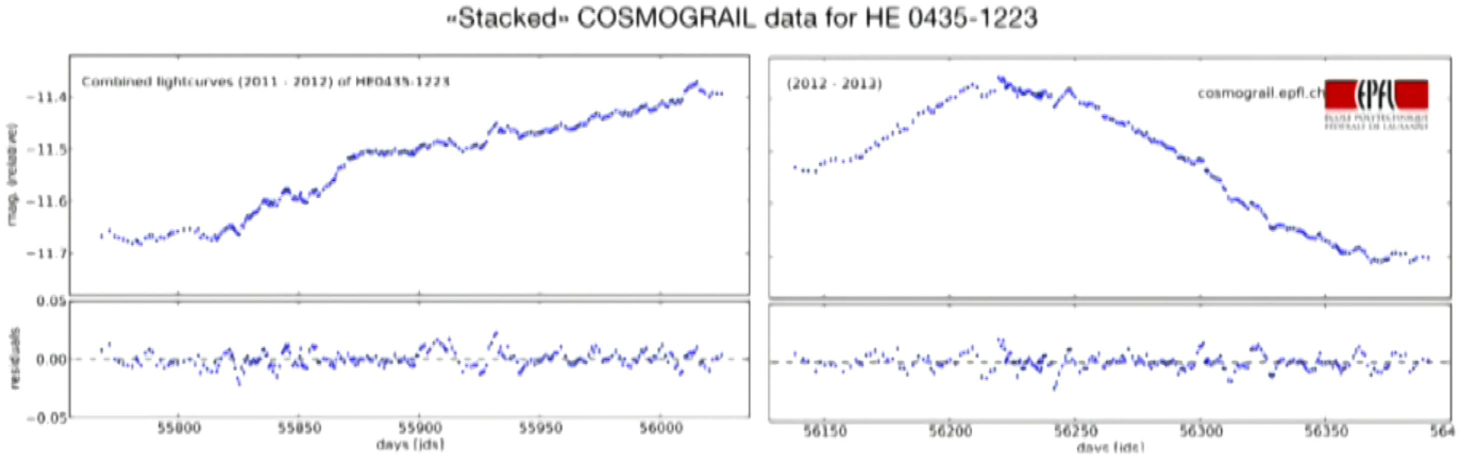
Cosmology Results with 4 Lenses - updated 2019





Birrer et al. 2019, MNRAS 484, 4726
(Paper IX)
Cosmology results for 4 lenses

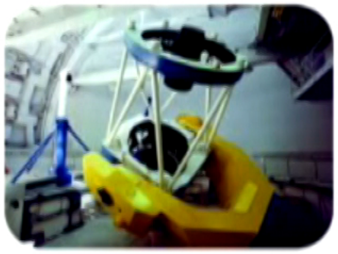
Future: High Cadence Monitoring at High SNR (>1000)



Use small (mmag) variations, shorter than microlensing

Go to larger telescopes WITH flexible scheduling capability

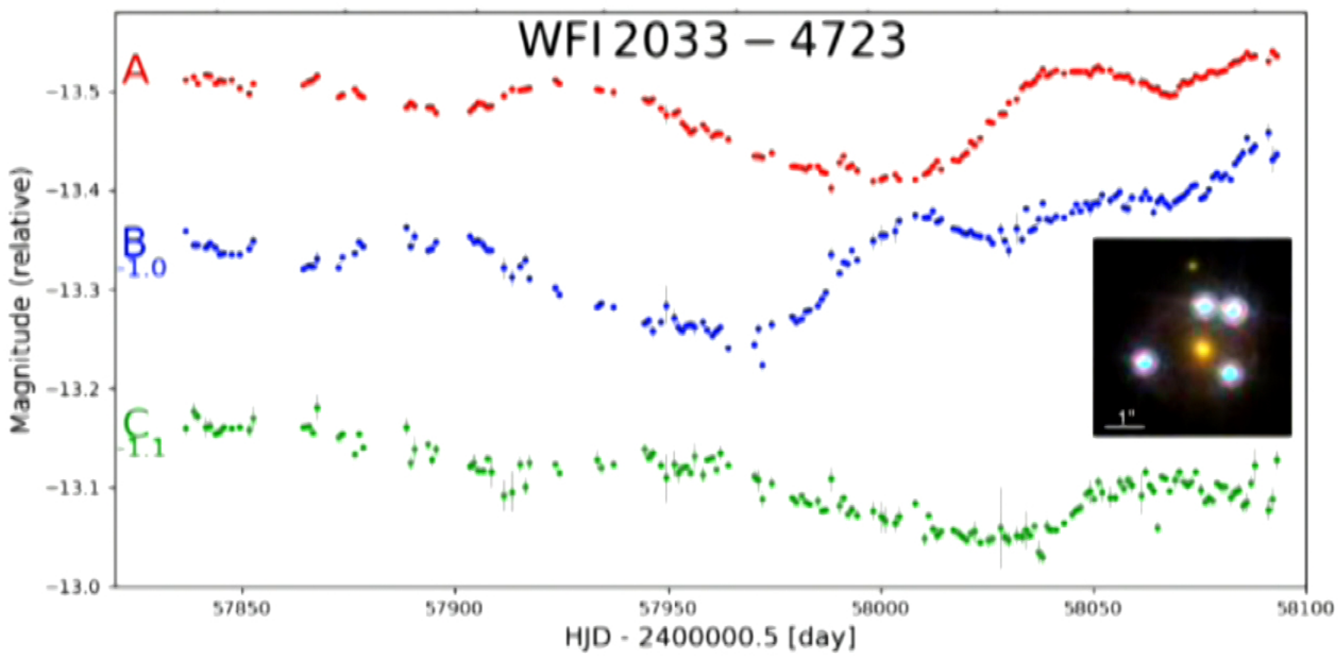
Goal: time delays to 1% or below in 1 observing season



New consortium (EPFL, UCLA, MPA, Stanford, Chicago, UCDavis) to use 20% of the MPIA 2.2m telescope at La Silla Observatory for this project: **Oct. 2016 - Oct. 2019**

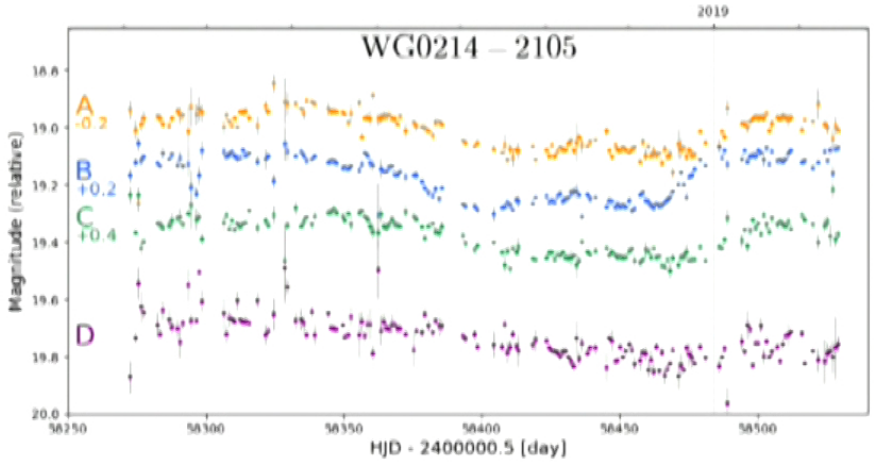
Oct 2019 - Oct 2023: ERC-funded

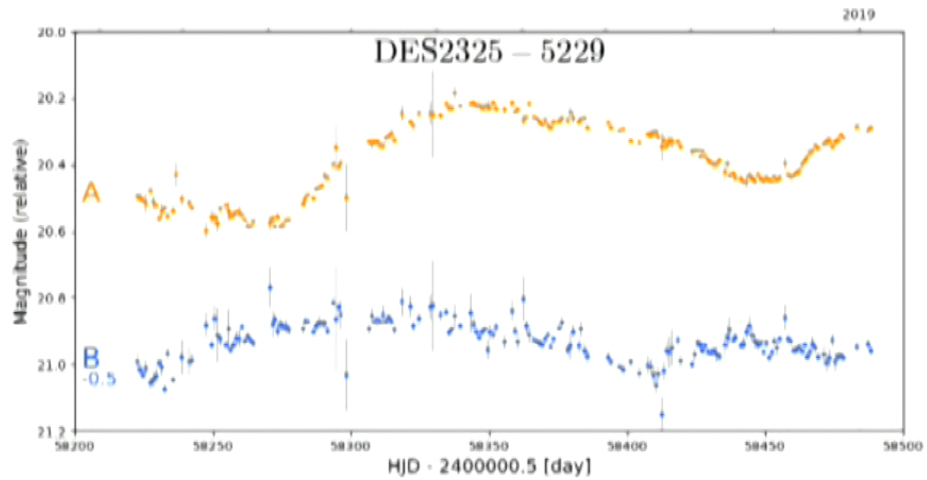
Recent Light Curves with the MPIA 2.2m



Next H0LiCOW target!
Bonvin et al. 2019, in prep

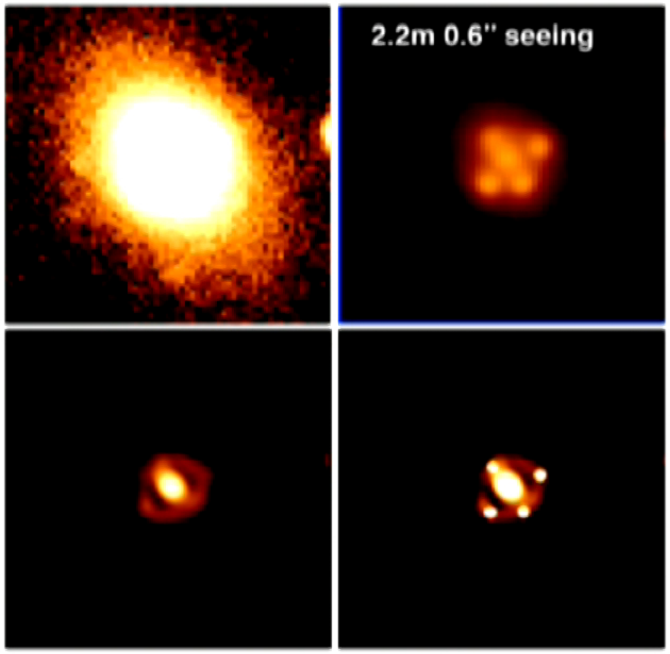
Recent Light Curves with the MPIA 2.2m

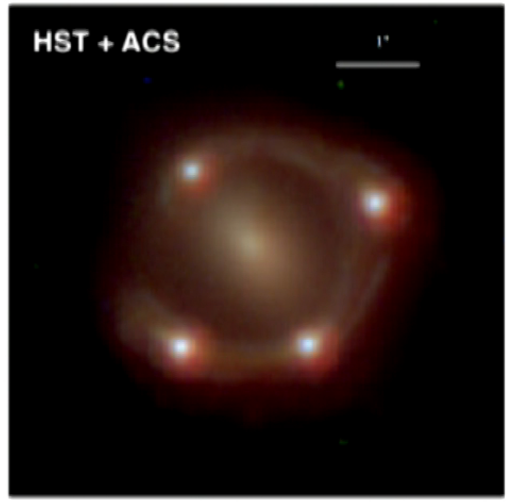




Millon et al. 2019, in prep

Recent Light Curves with the MPIA 2.2m



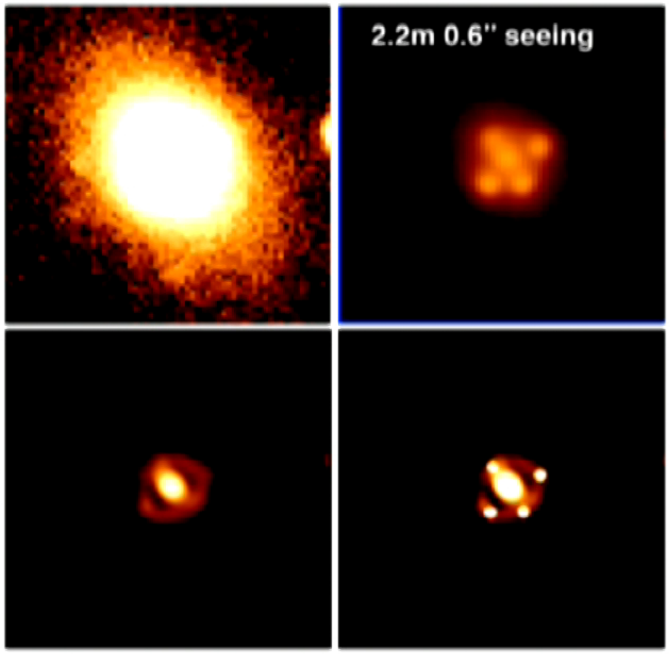


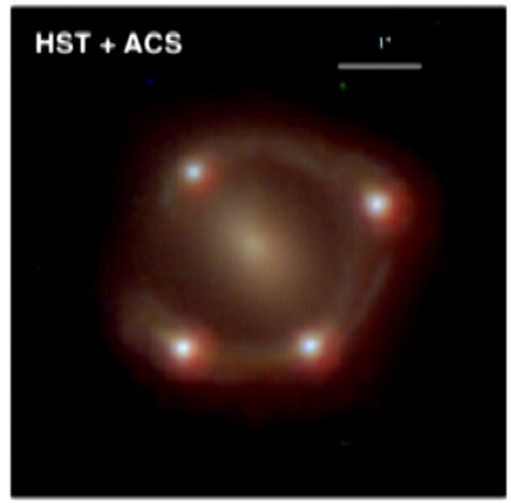
HST C25 image courtesy of Tommaso et al.

Summary

- COSMOGRAIL is measuring time delays accurately
- H0LiCOW: **H_0 L**enses **in CO**SMOGRAIL's **W**ellspring
  --> turns time delays into cosmology
- Strong lensing time delays consist in an **absolute** distance indicator
- DES, KIDS, HSC, EUCLID, LSST, will discover hundreds of new targets
- Long and well-sampled light curves are crucial to handle microlensing properly
- 4 lenses give H_0 with accuracy and precision comparable with BAO
- Still needs to evaluate in detail the impact of model degeneracies and how to mitigate them (e.g. with 2D dynamics with MUSE, OSIRIS and JWST)
- High-cadence (multi-band?) monitoring is the future (see talk by Martin Millon)!
- All analysis done blind!

Recent Light Curves with the MPIA 2.2m





HST C25 image courtesy of Tommaso et al.

Summary

- COSMOGRAIL is measuring time delays accurately
- H0LiCOW: **H_0 L**enses **in CO**SMOGRAIL's **W**ellspring
  --> turns time delays into cosmology
- Strong lensing time delays consist in an **absolute** distance indicator
- DES, KIDS, HSC, EUCLID, LSST, will discover hundreds of new targets
- Long and well-sampled light curves are crucial to handle microlensing properly
- 4 lenses give H_0 with accuracy and precision comparable with BAO
- Still needs to evaluate in detail the impact of model degeneracies and how to mitigate them (e.g. with 2D dynamics with MUSE, OSIRIS and JWST)
- High-cadence (multi-band?) monitoring is the future (see talk by Martin Millon)!
- All analysis done blind!