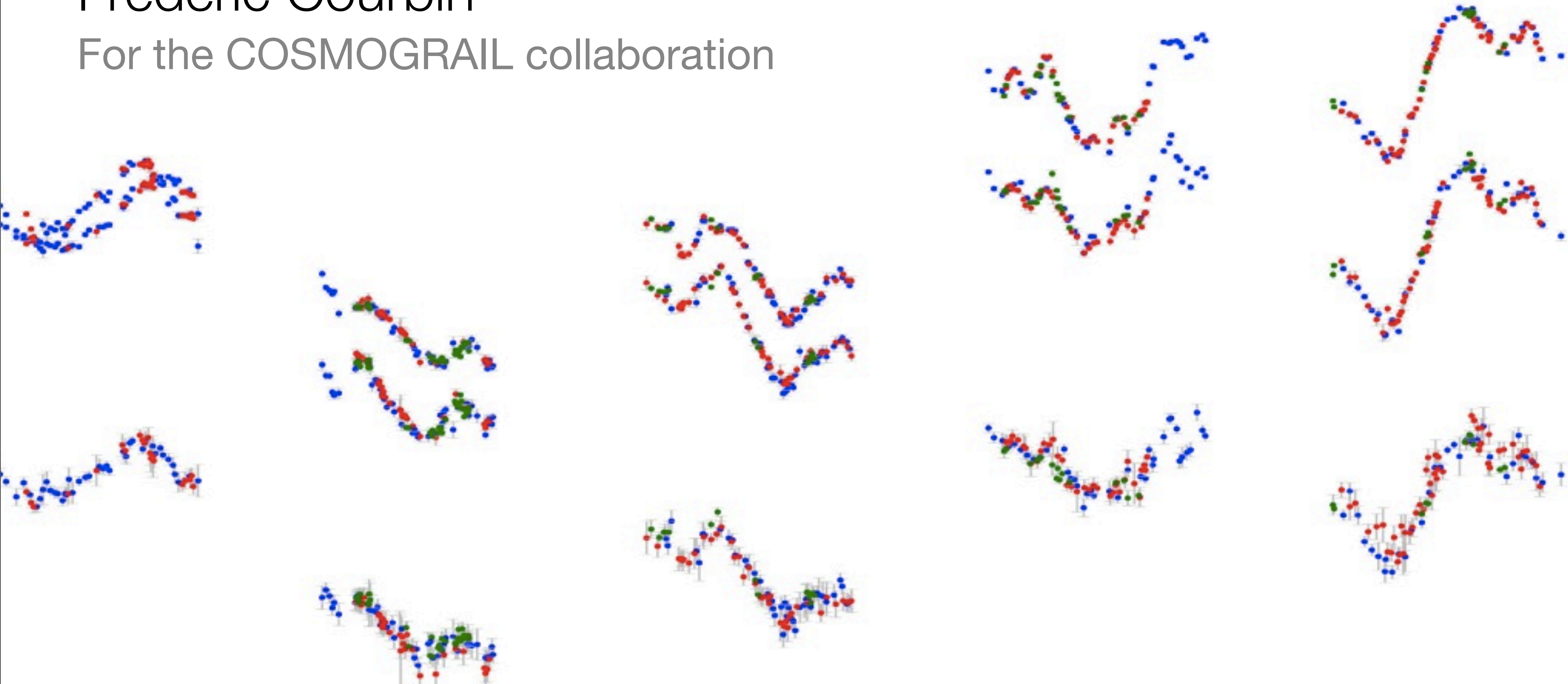
Strong lensing and quasar time delays

Frédéric Courbin
For the COSMOGRAIL collaboration



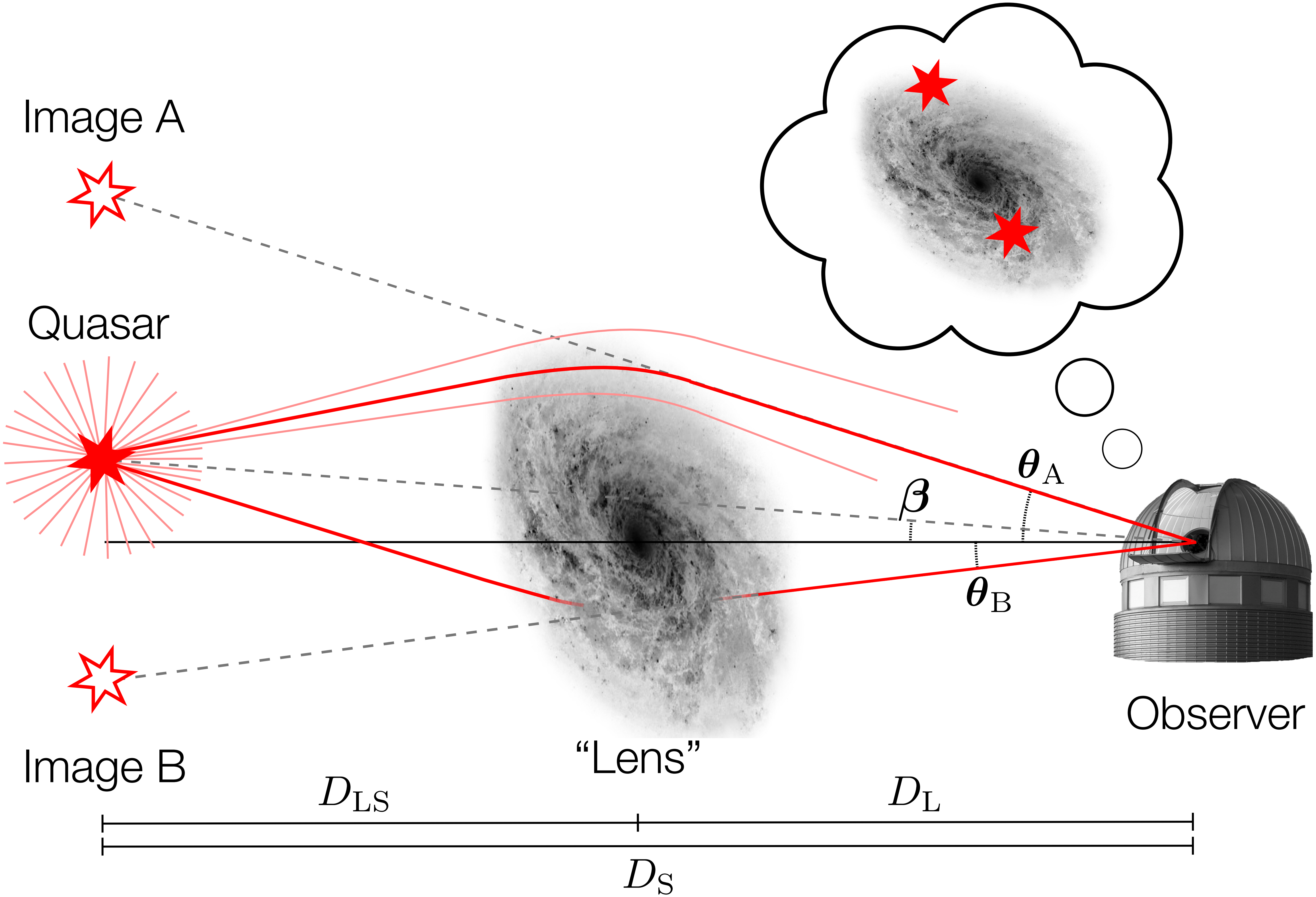
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
Laboratoire d'astrophysique http://lastro.epfl.ch
Ecole Polytechnique Fédérale de Lausanne (EPFL)

Ripples in Cosmos
Durham, July 2013

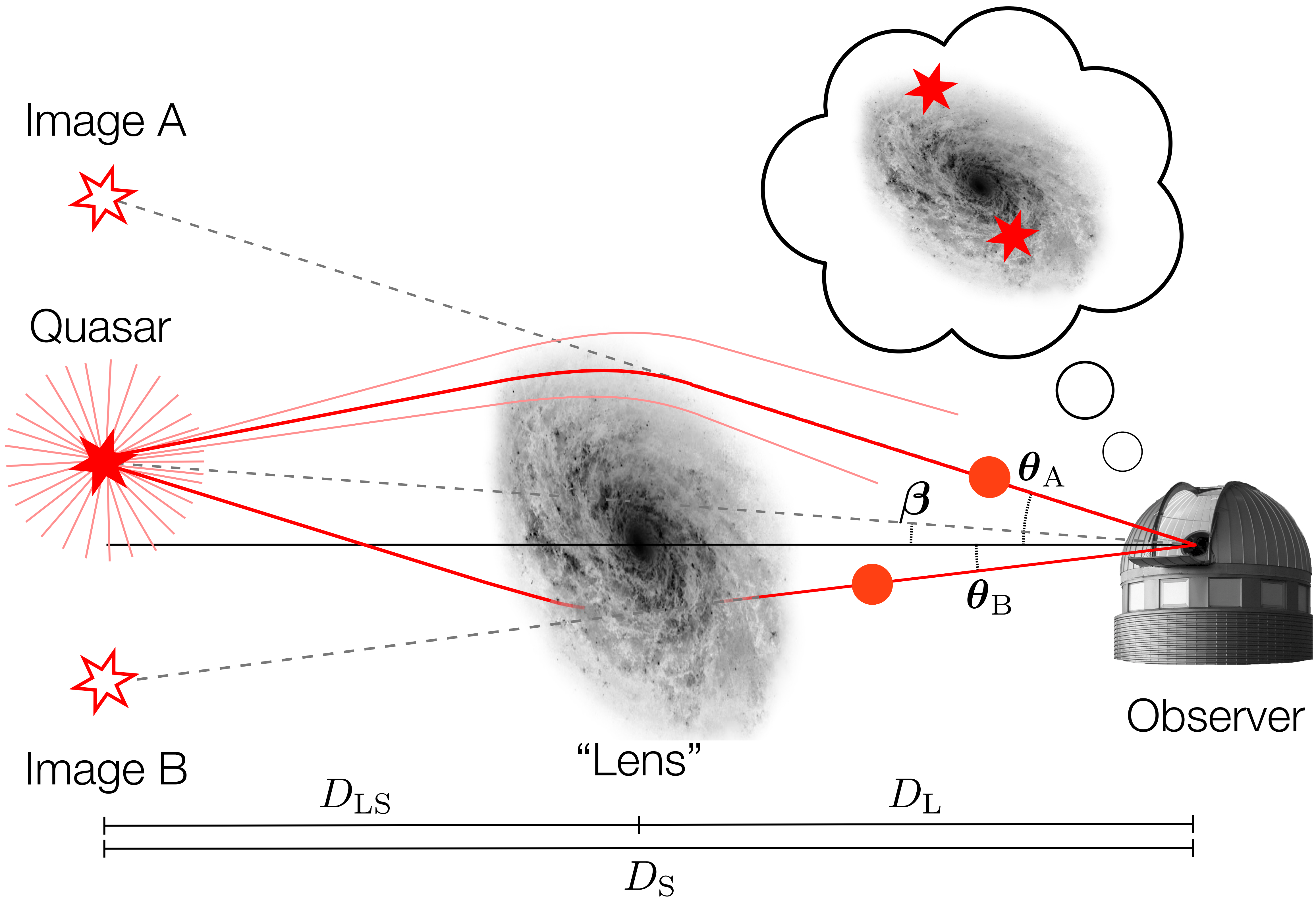
Main cosmological probes

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

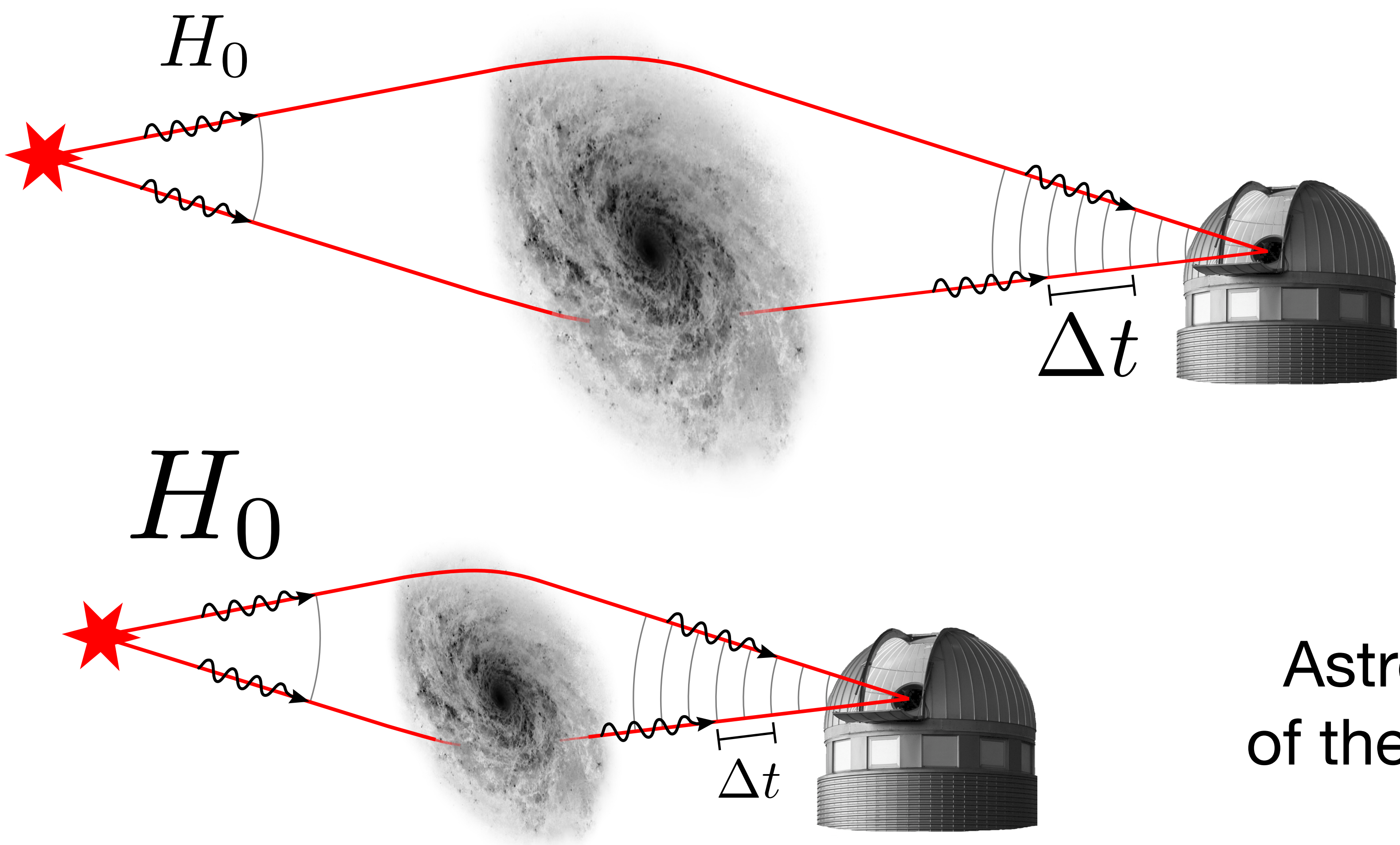
Strong gravitational lensing of quasars : multiple images



Strong gravitational lensing of quasars : multiple images



Time delays probe 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 ?

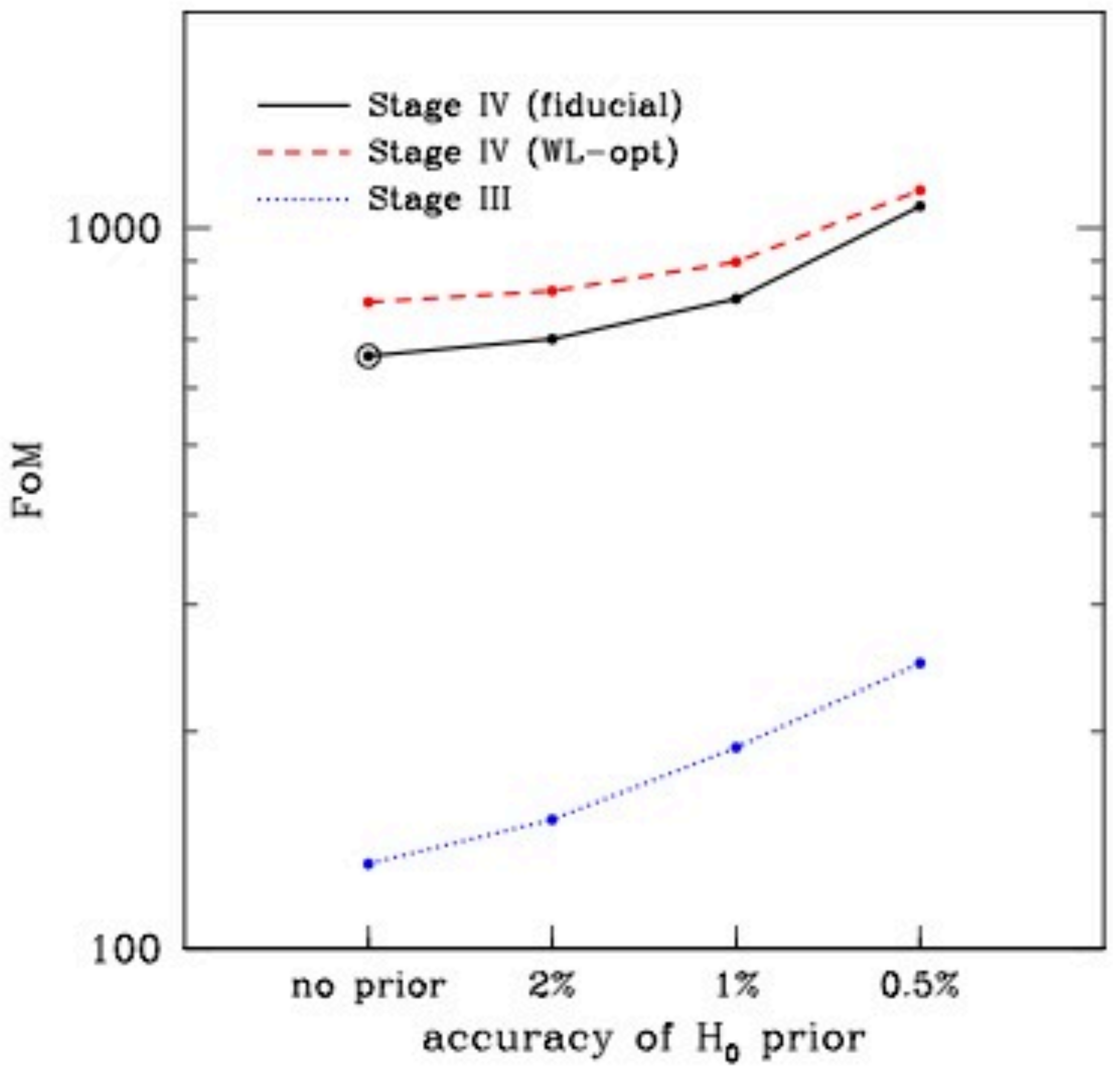


Figure 1. Dependence of the FoM from the DETF on the accuracy of independent measurements of the Hubble constant that would be used as priors in Stage III and IV forecasts from Weinberg et al. (2012). The fiducial Stage IV program with FoM= 664 is marked by an open circle. In all cases, adding a prior from an independent measurement of H_0 with ∼1% accuracy increases the FoM by ∼40%. The figure was extracted from Weinberg et al. (2012).

Advantages

- Do 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 !
- Do not need a 20m telescope in space

Drawbacks

- **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)

Cosmological Monitoring of Gravitational Lenses

... to measure "time delays", to constrain H_0, to learn about DE

EPFL: **G. Meylan, F. Courbin**, M. Tewes, Y. Revaz, N. Cantale, V. Bonvin, D. Paraficz

IIA Bangalore: T. Prabhu, C.S. Stalin, R. Kumar, D. Sahu

Univ. Bonn: D. Sluse

Univ. Liège: P. Magain, E. Eulaers, V. Chantry

UzAS Tashkent: I. Asfandiyarov

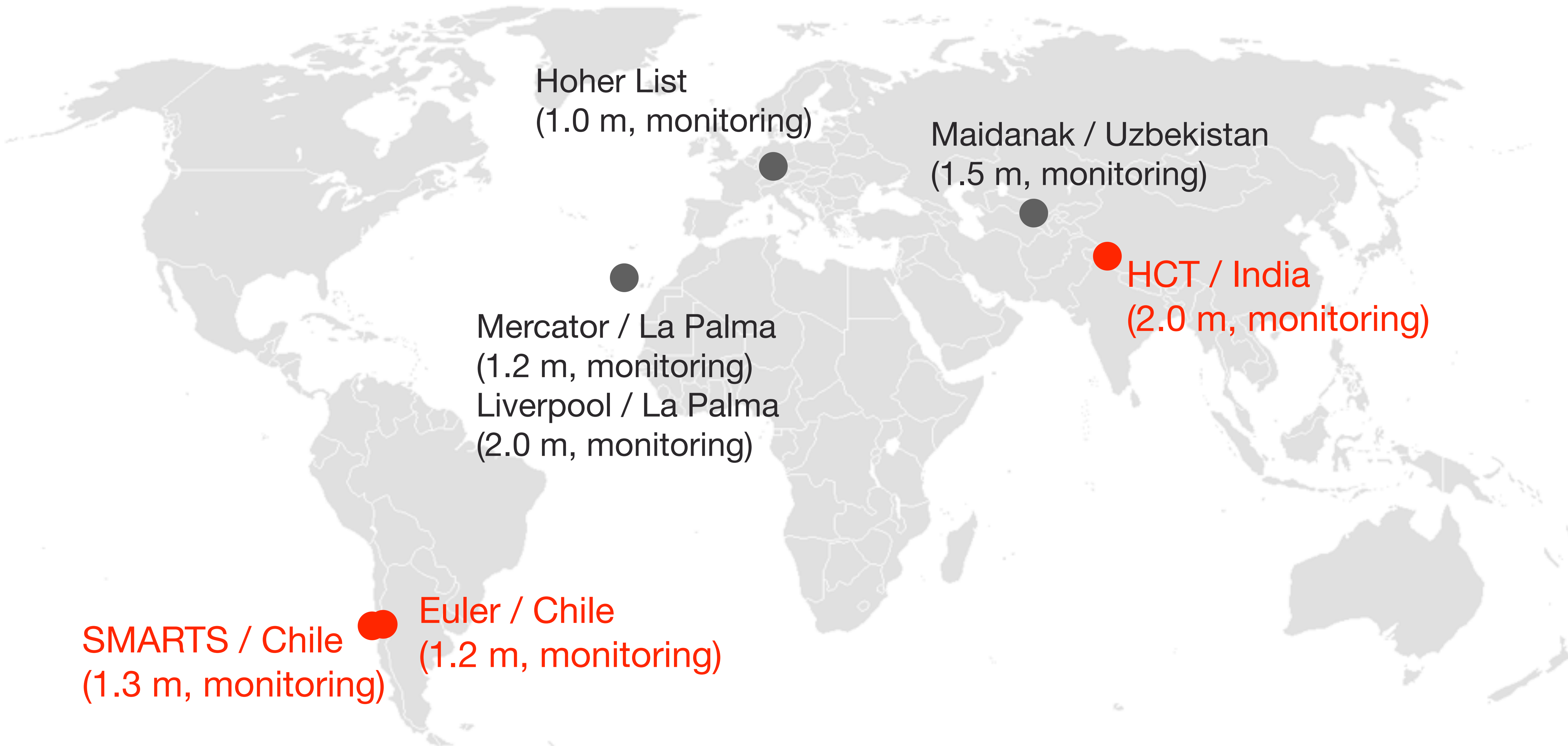
Univ. Zürich: P. Saha, J. Coles

Univ. Nottingham: S. Dye

Now also in close collaboration (monitoring, microlensing) with:
C. Kochanek, A. Mosquera (Ohio),
C. Morgan, C. MacLeod, L. Hainline (USNA)

And the lens modeling & cosmography experts :
S. Suyu (ASIAA), T. Treu (UC Santa Barbara), M. Auger (Cambridge), P. Marshall (Oxford), S. Hilbert (Stanford), L. Koopmans (Groningen), C. Fassnacht (UC. Davis), R. Blandford (KIPAC), T. Collett (Cambridge), S. Vegetti (MIT)

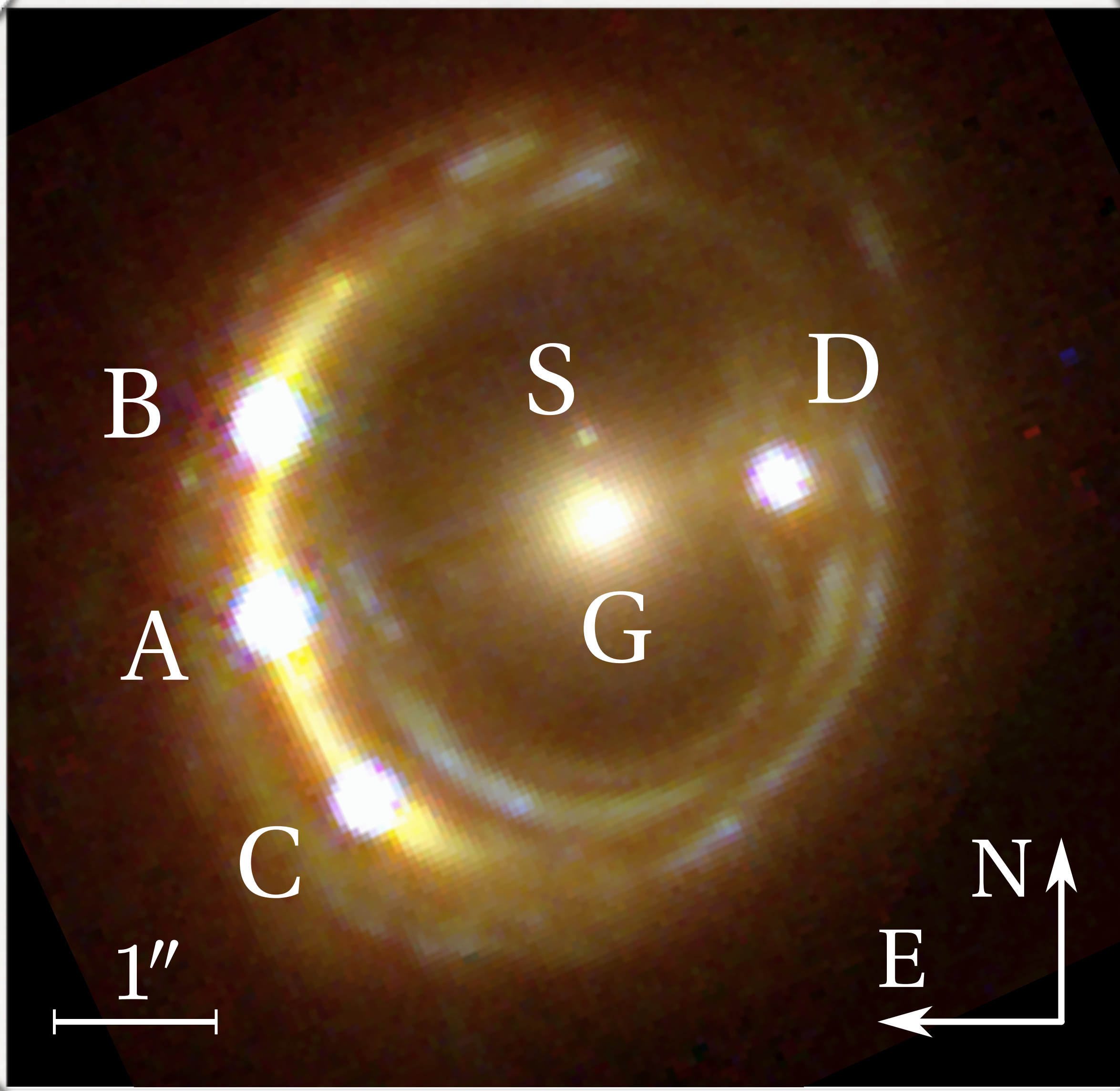
COSMOGRAIL monitoring telescopes

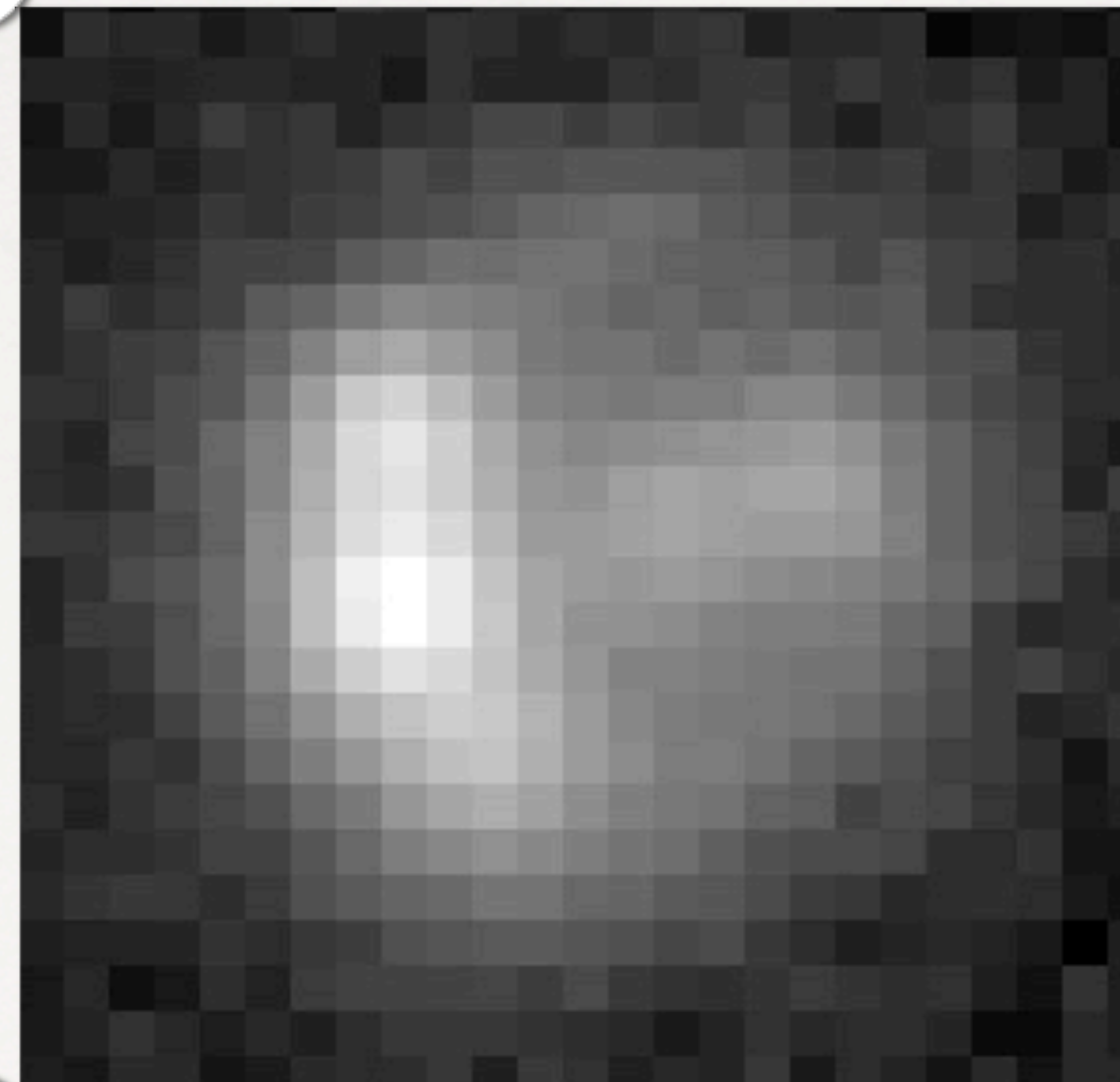


Main teams doing lens monitoring joined forces in 2010 :

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

RX J1131-1231, seen from space and ground





Hubble Space Telescope

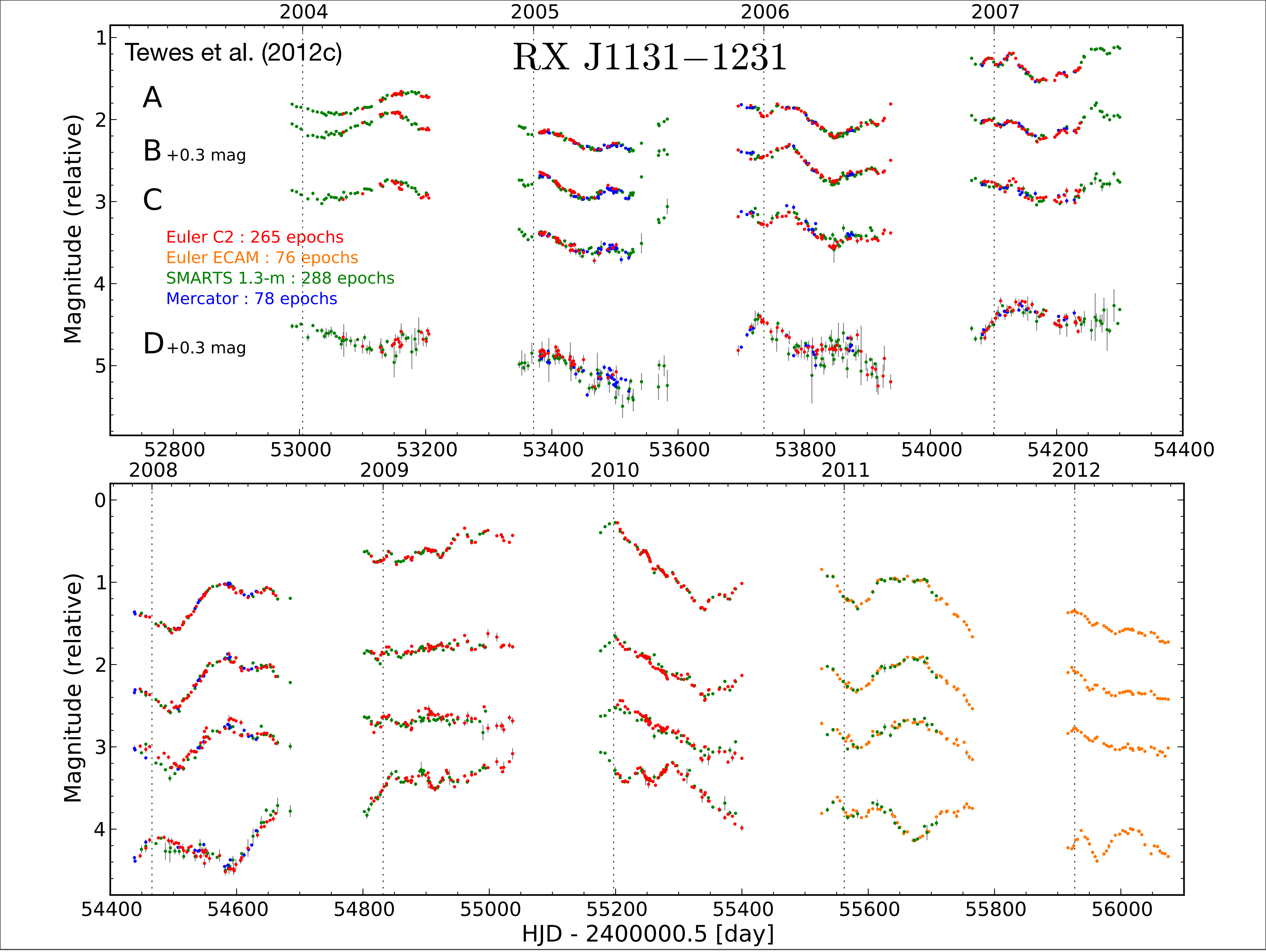
Data from CASTLES, PI C. S. Kochanek
ACS + NICMOS2

Euler

1.2 m Swiss Euler Telescope T_{exp} = 360 s
Camera C2, FWHM 1.0 arcsec R filter

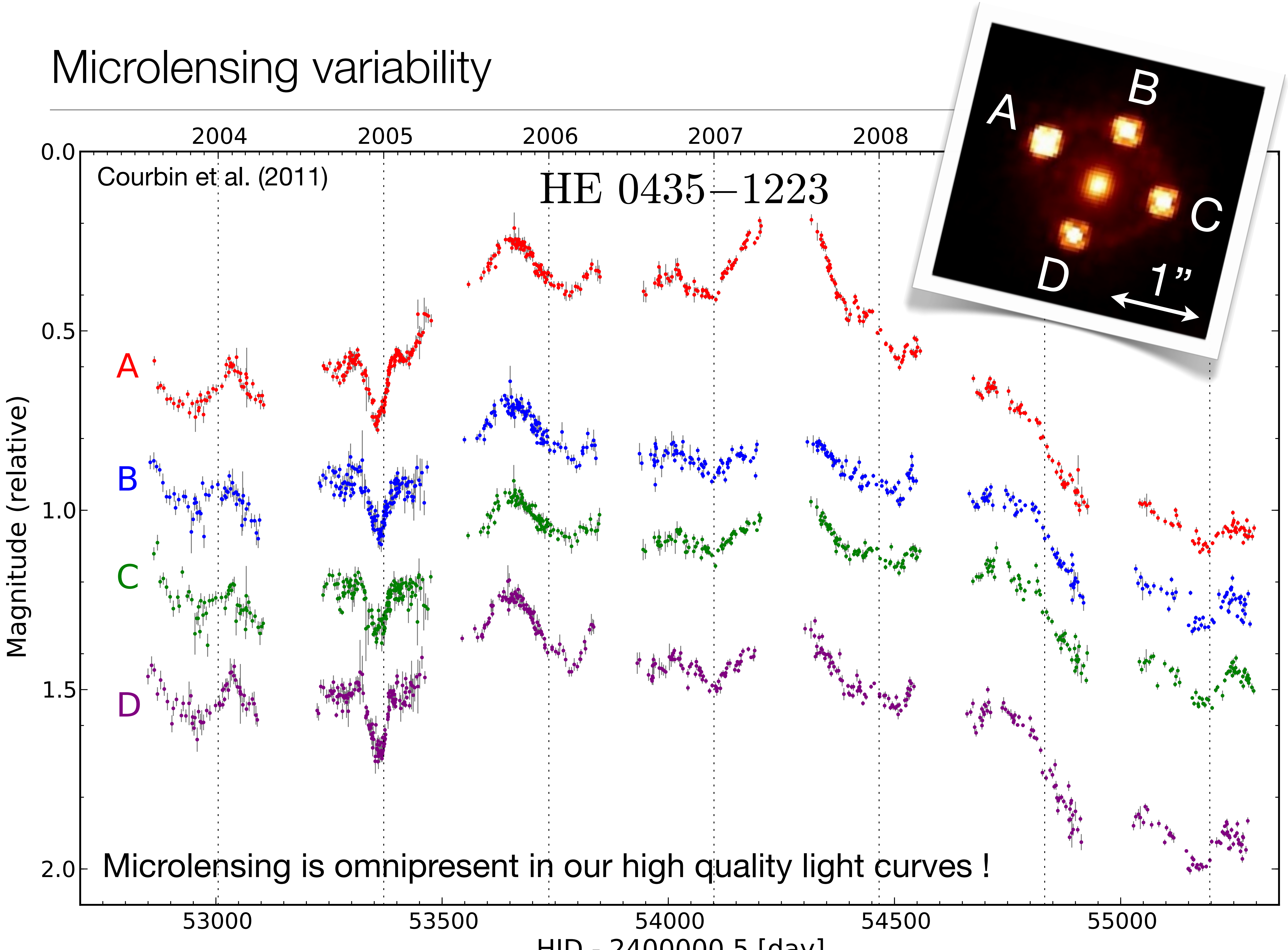
COSMOGRAIL Deconvolution Photometry Pipeline

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. 2012)

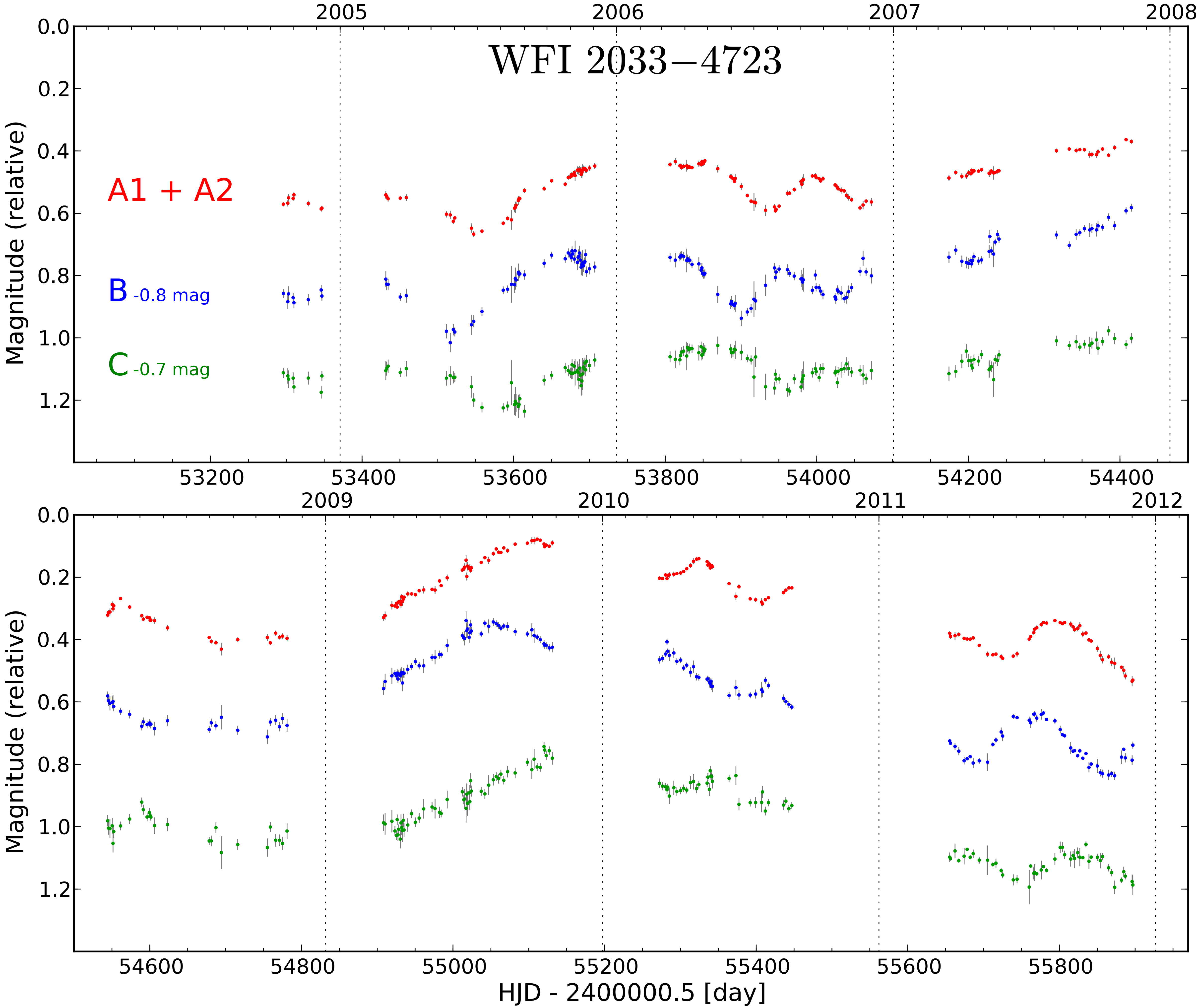


mardi, 23 juillet 2013

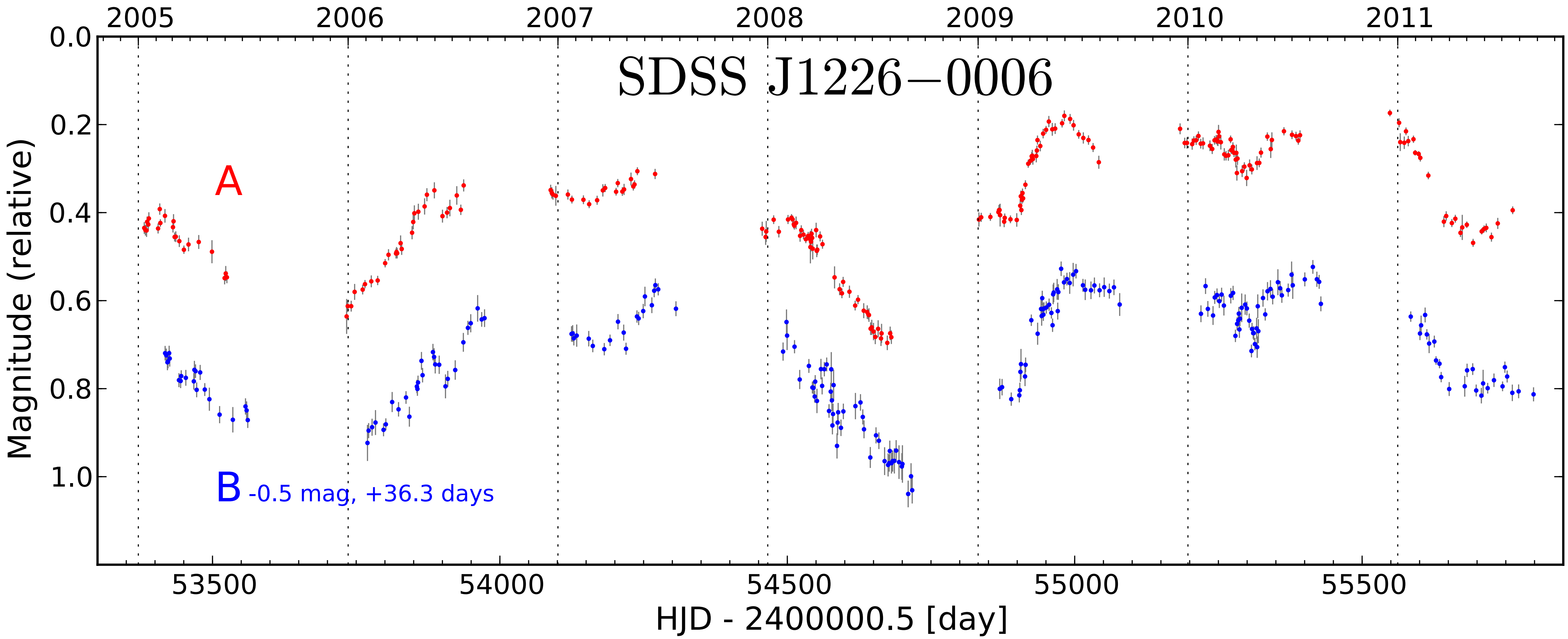
Microlensing variability

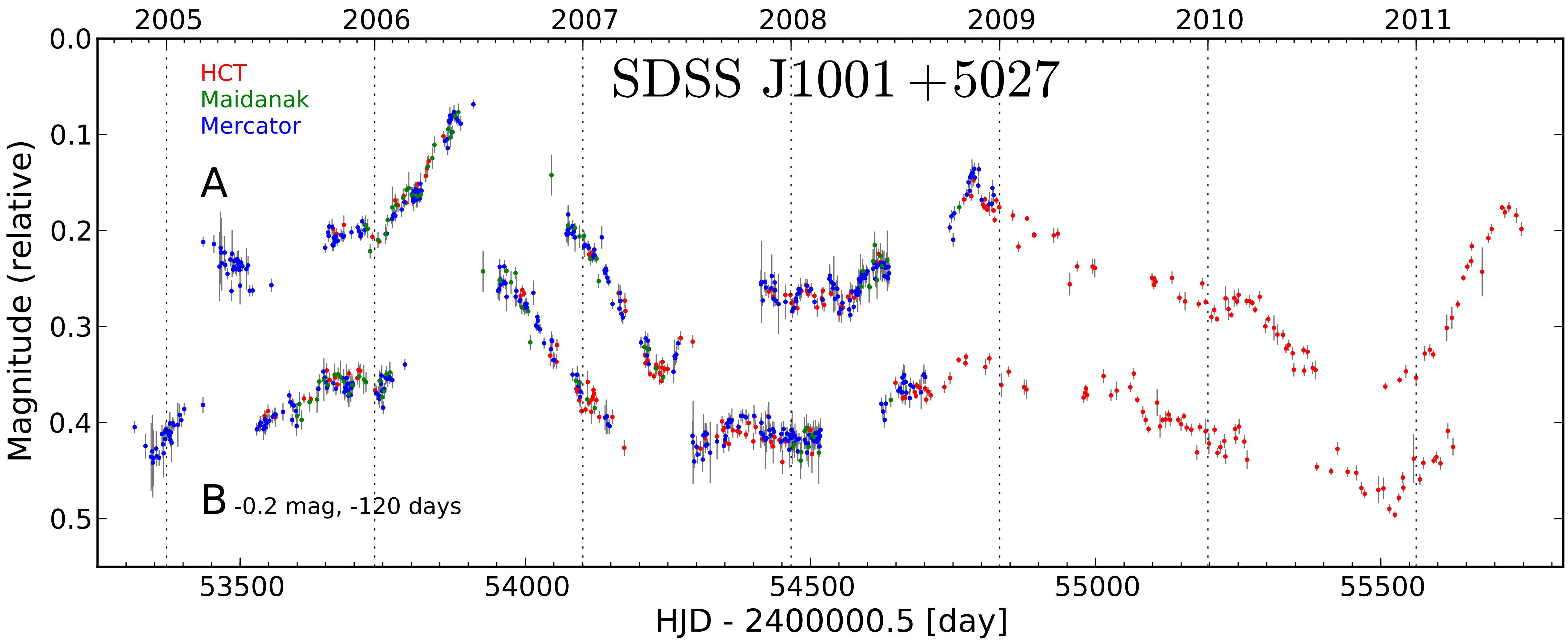


Microlensing is omnipresent in our high quality light curves !

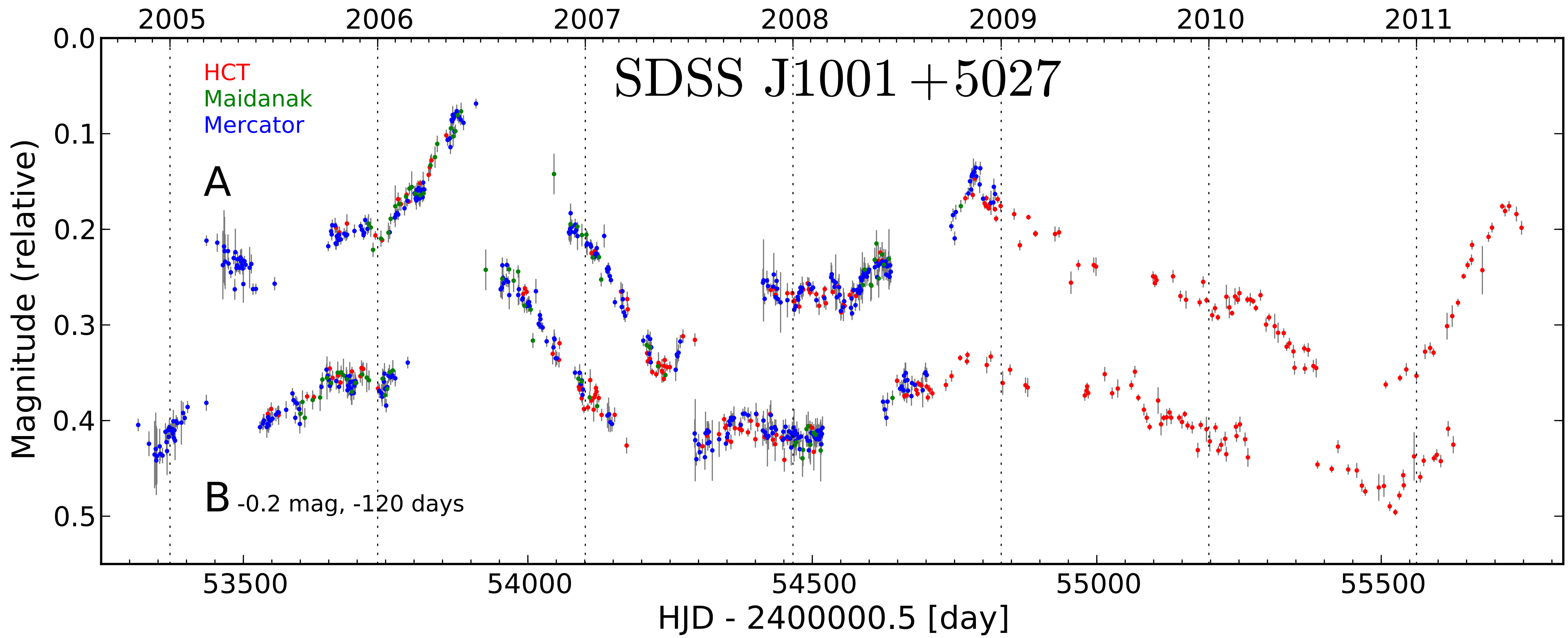


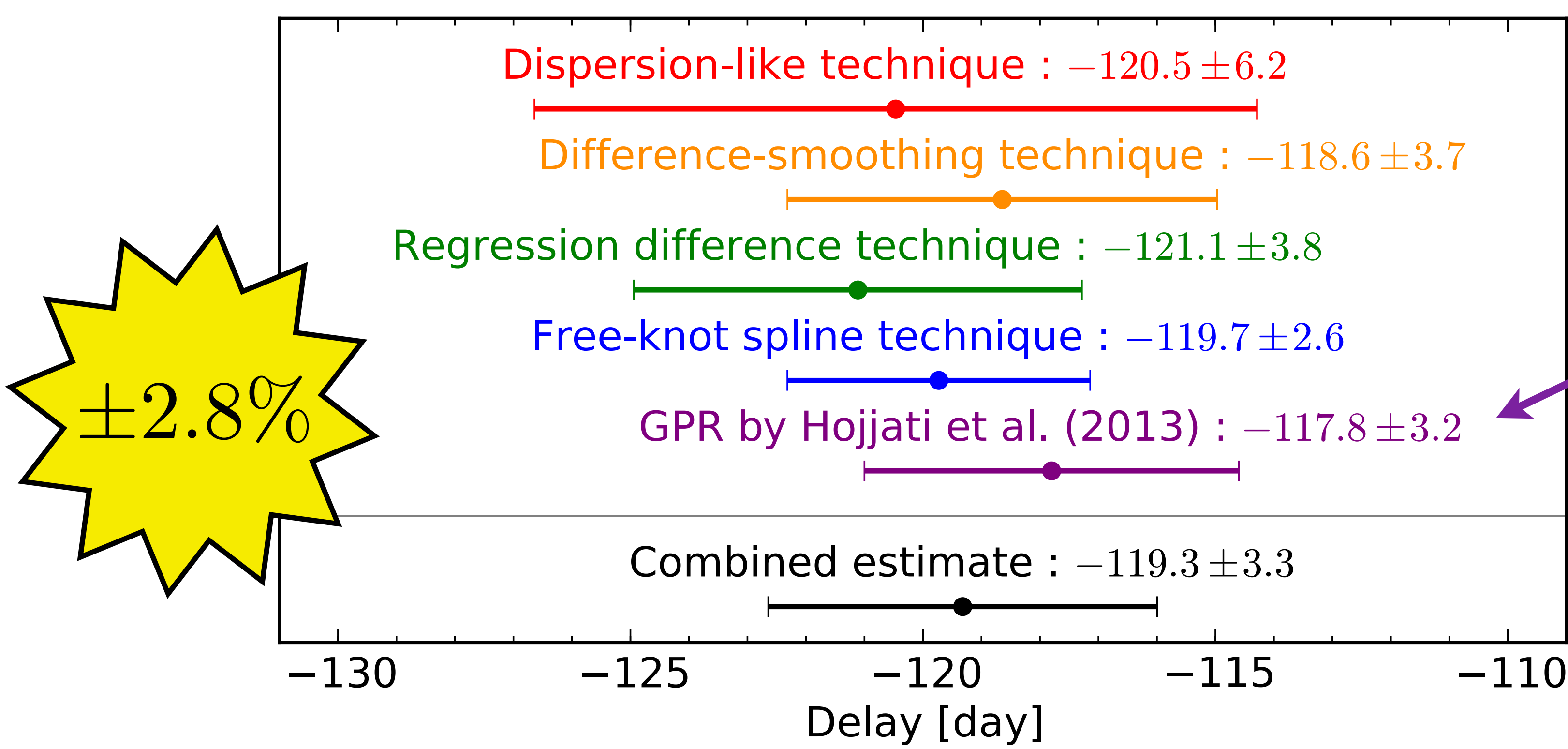
WFI 2033−4723
A1 + A2
B -0.8 mag
C -0.7 mag
Magnitude (relative)
HJD - 2400000.5 [day]
2005
2006
2007
2008
2009
2010
2011
2012


2005
2006
2007
2008
2009
2010
2011
SDSS J1226−0006
A
B -0.5 mag, +36.3 days
Magnitude (relative)
0.0
0.2
0.4
0.6
0.8
1.0
53500
54000
54500
55000
55500
HJD - 2400000.5 [day]


2005
2006
2007
2008
2009
2010
2011
SDSS J1001+5027
HCT
Maidanak
Mercator
A
B -0.2 mag, -120 days
Magnitude (relative)
0.0
0.1
0.2
0.3
0.4
0.5
53500
54000
54500
55000
55500
HJD - 2400000.5 [day]

Blind comparison with a newly developed technique

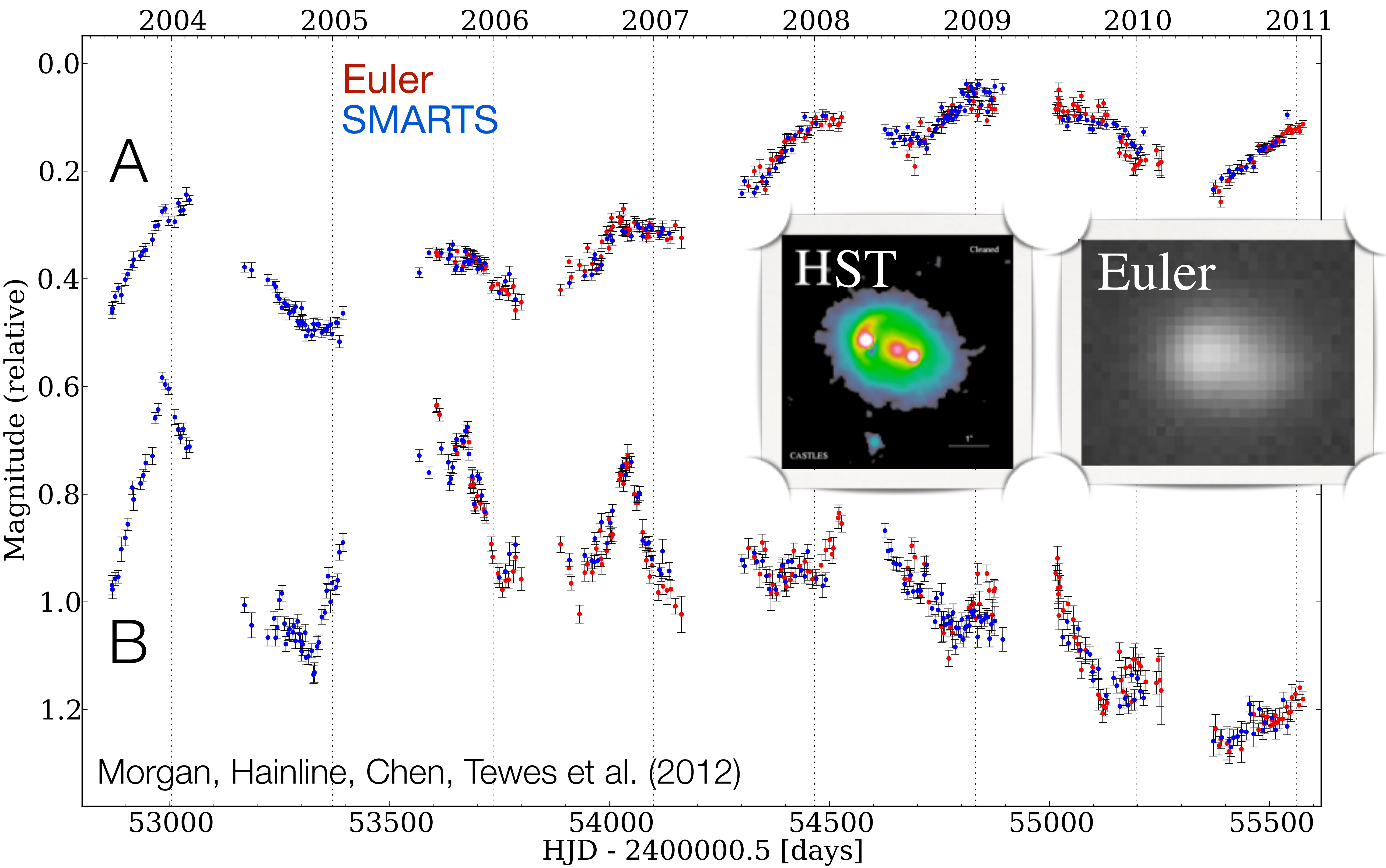




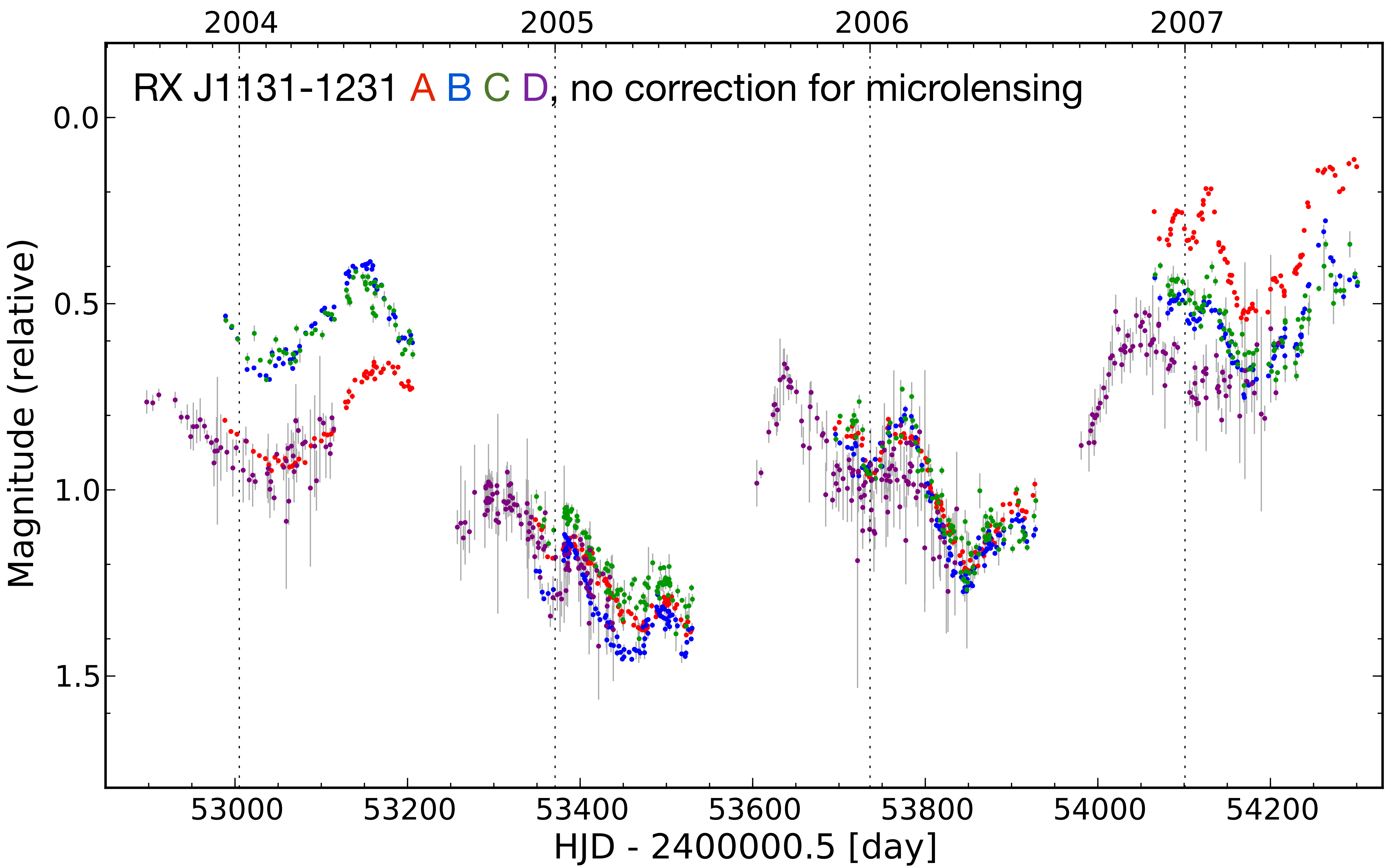
Blind test by
Hojjati, Kim, Linder (2013)
arXiv:1304.0309

Rathna Kumar, Tewes et al.
in press in A&A (arXiv1306.5105)

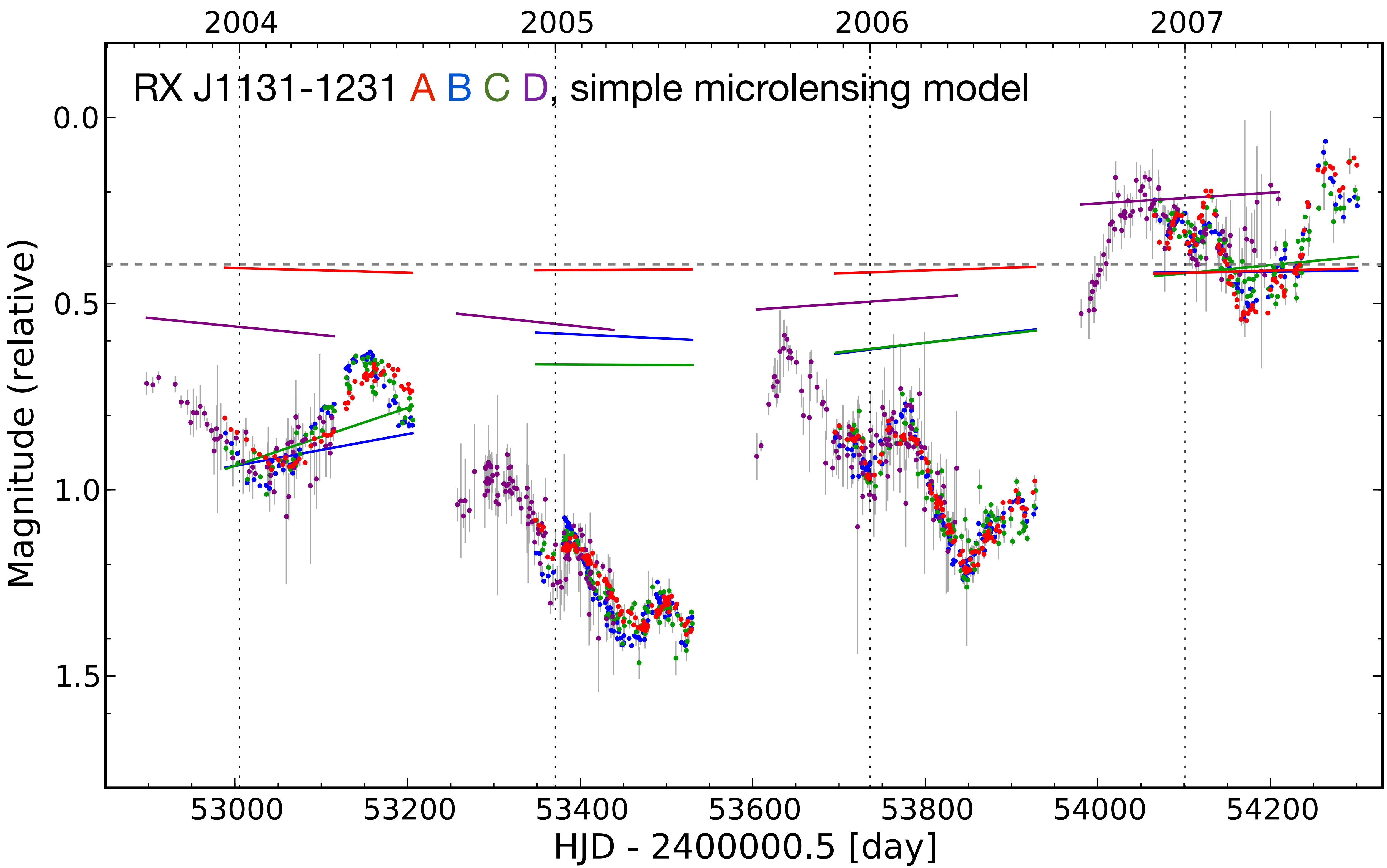
J0158-4325 : *dominated* by microlensing variability



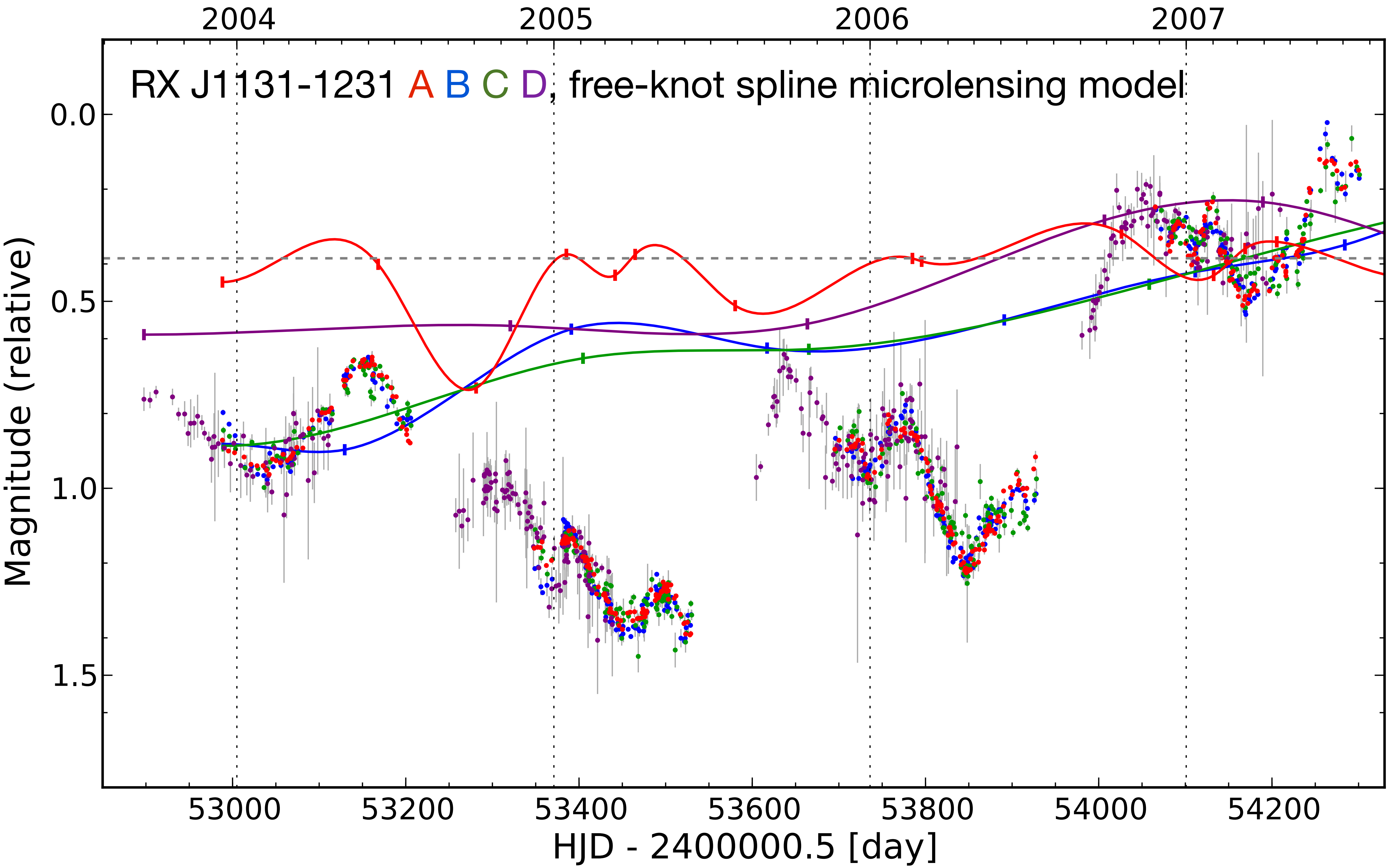
Microlensing exacerbates time delay measurements



Microlensing exacerbates time delay measurements

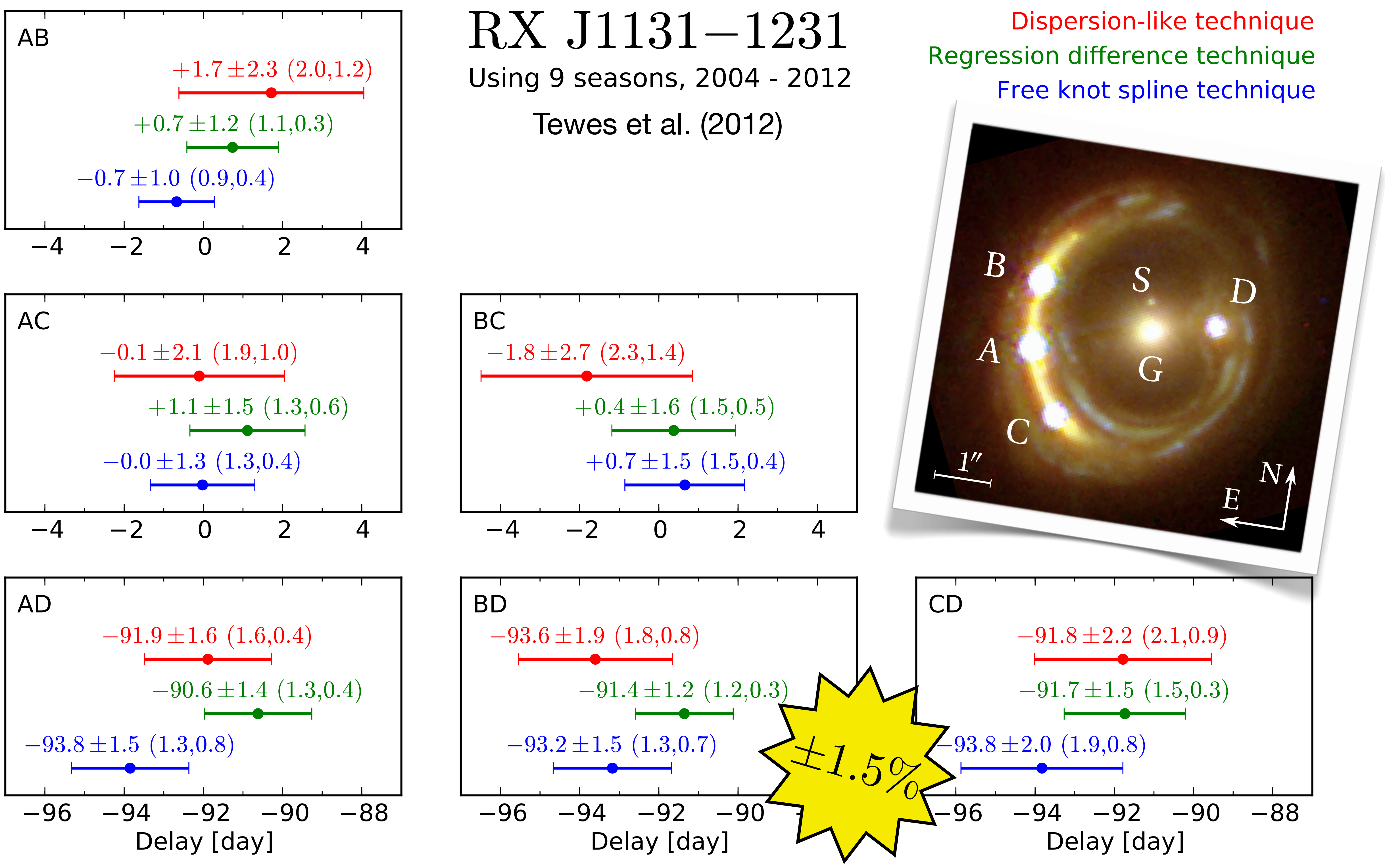


Microlensing exacerbates time delay measurements



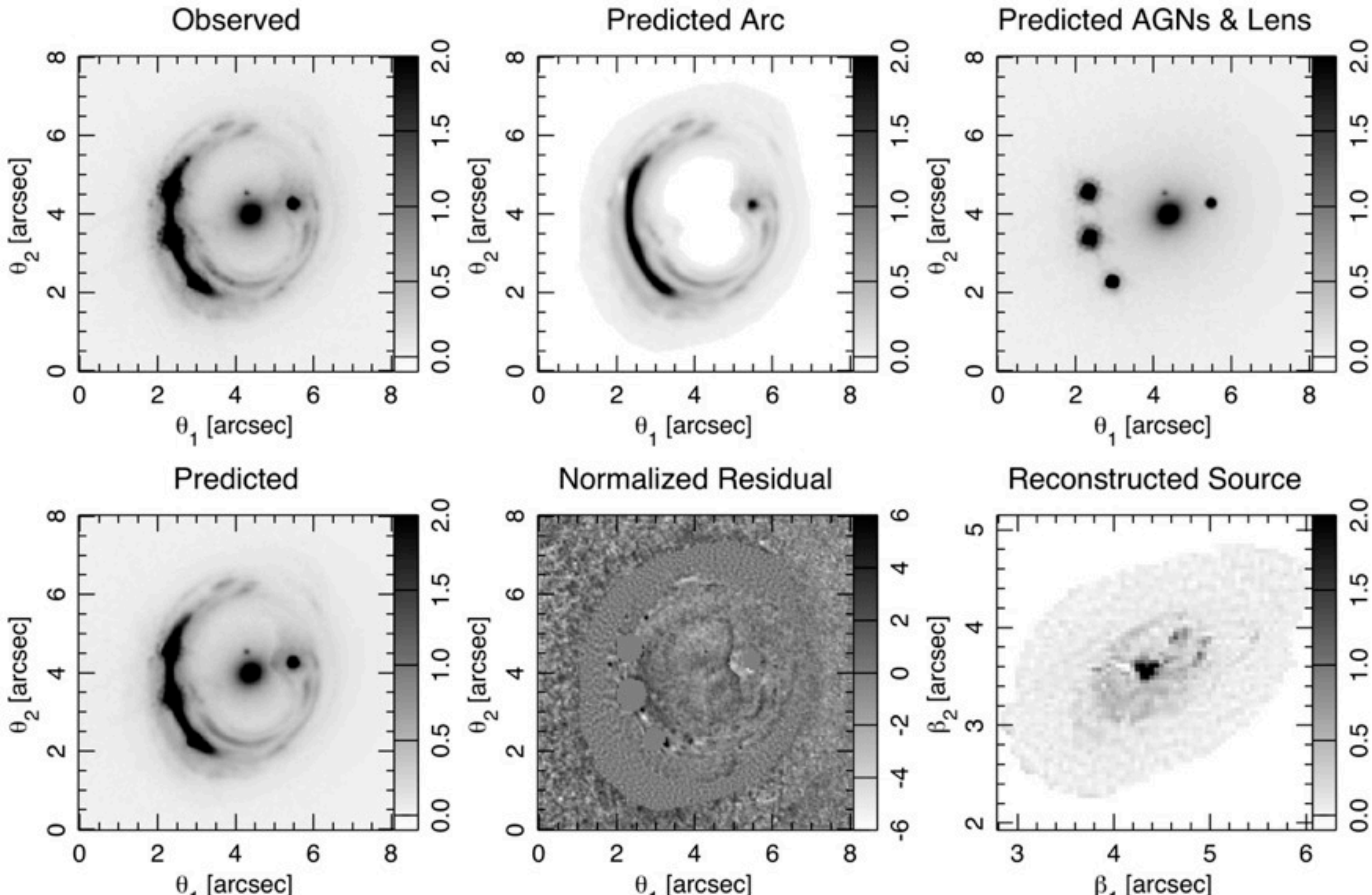
Time delay measurements by 3 different techniques

... from the real observations – only the error bars make use of the simulations.

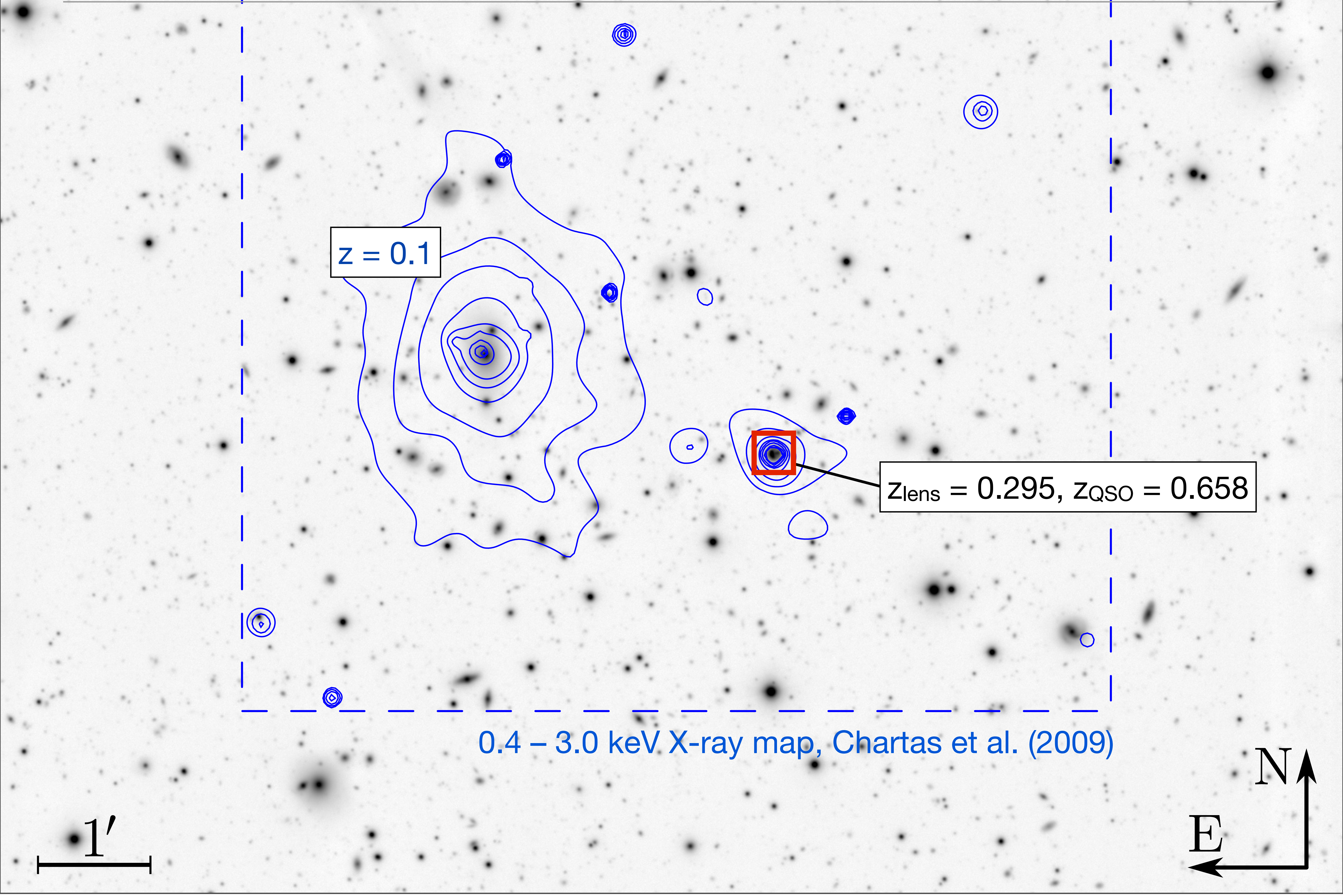


Lens models, fighting degeneracies (Suyu et al. 2012)

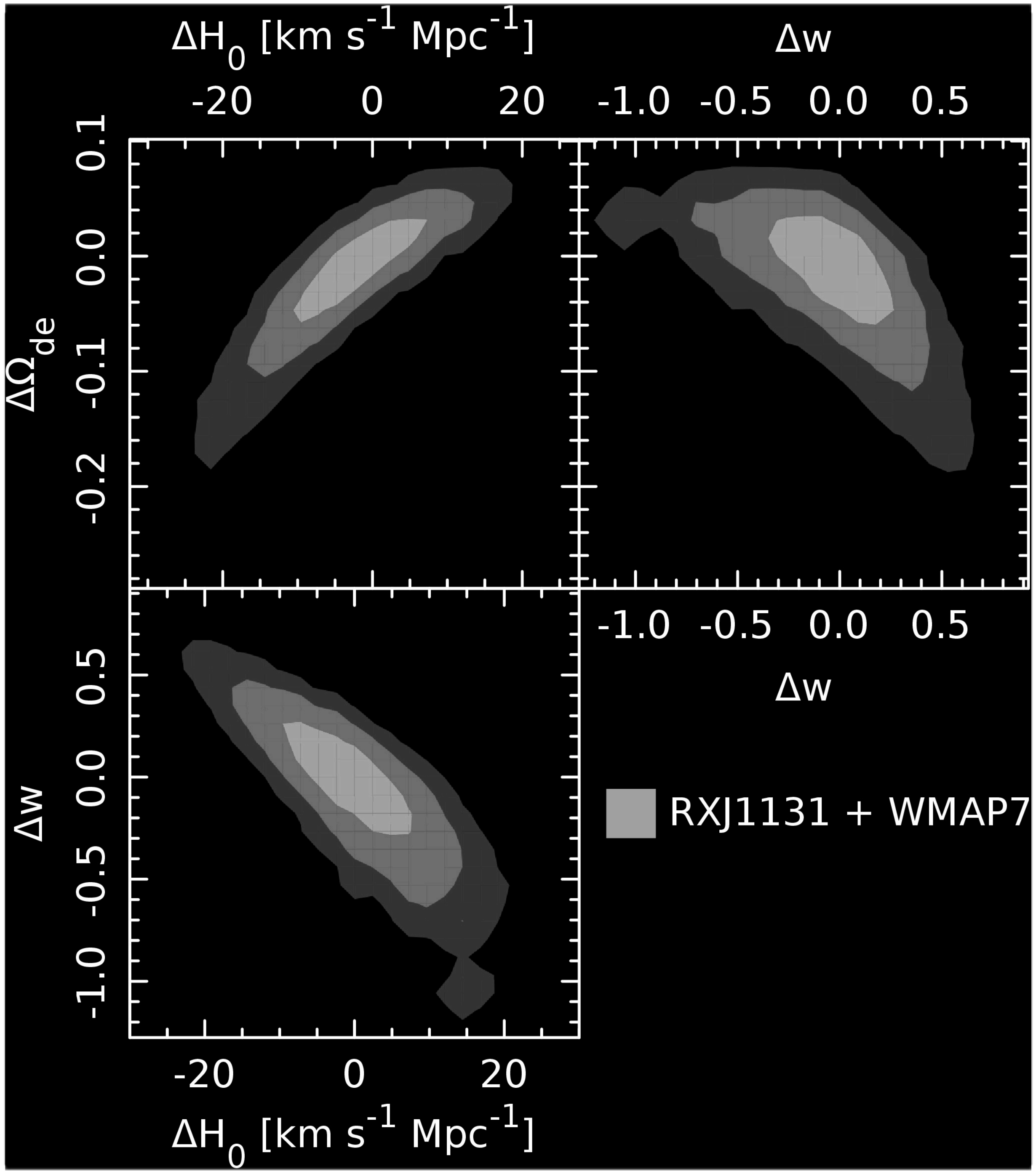
- Fully exploit the Einstein ring from HST images + measured velocity dispersion
- Characterization of the LOS structures via observations of the environment



Euler field of view around RX J1131-1232

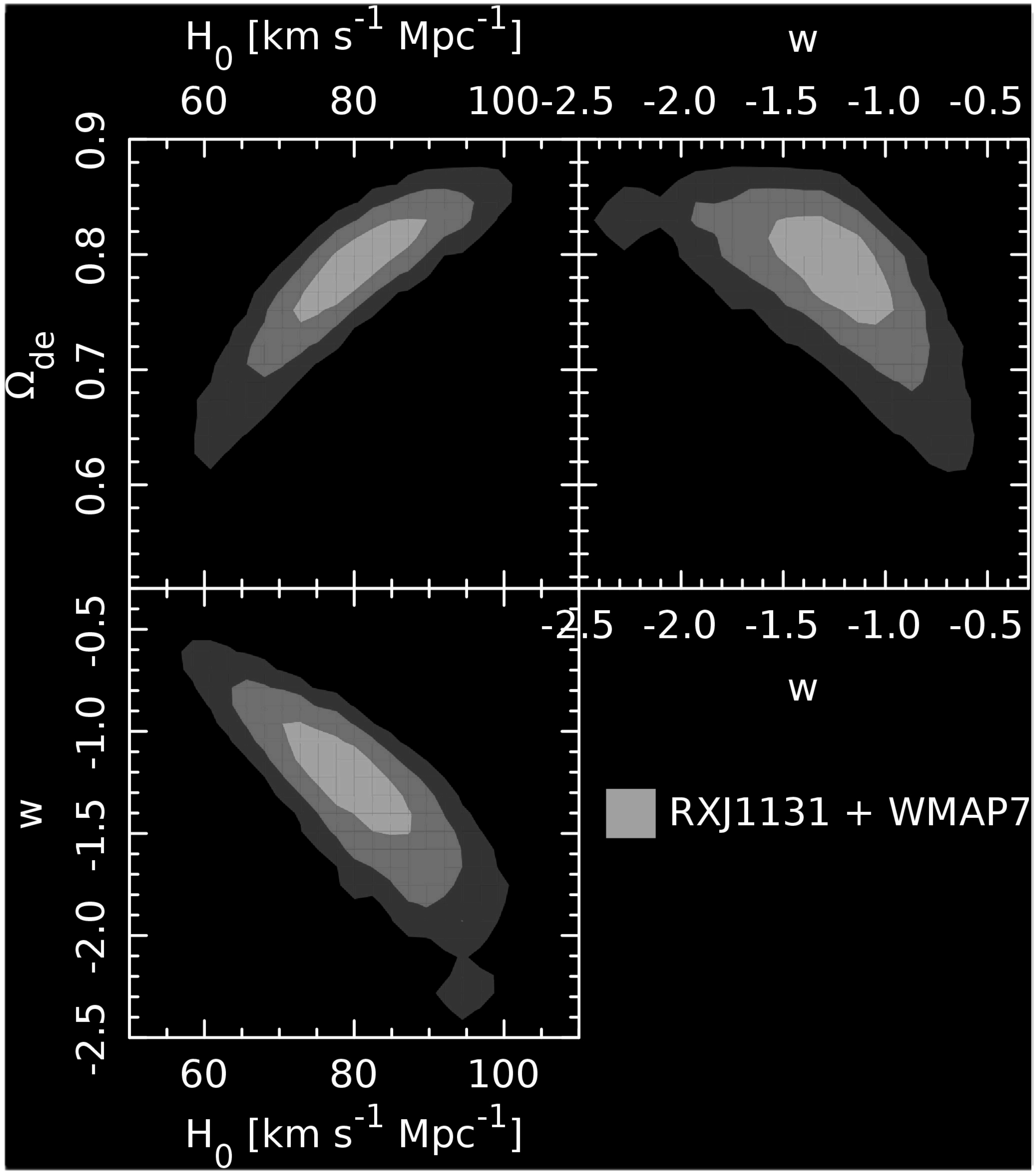


Cosmological results with RX J1131-1232



In combination with WMAP7 in flat wCDM cosmology: **blind analysis**

Cosmological results with RX J1131-1232



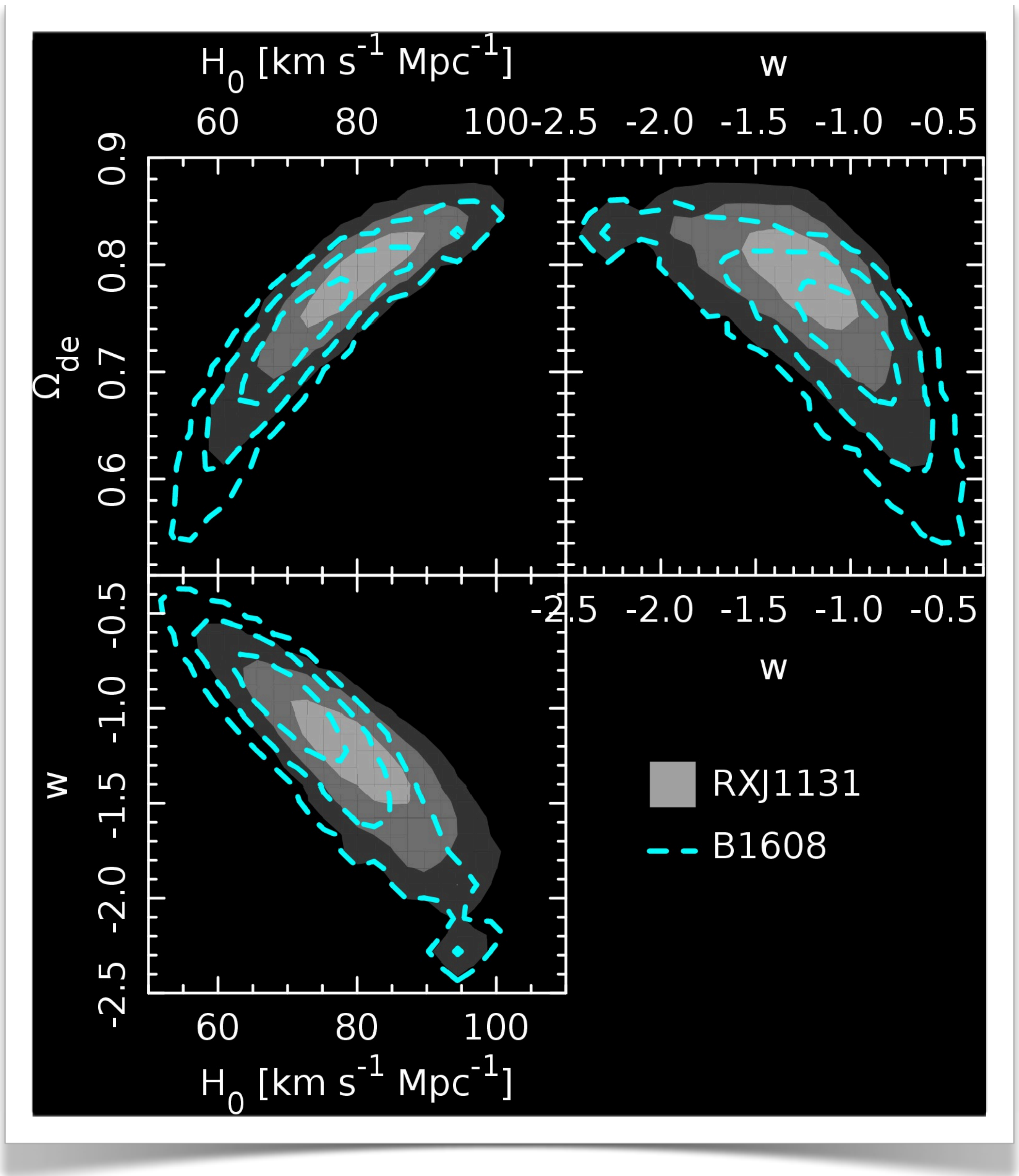
$$H_0 = 80.0^{+5.8}_{-5.7}\ \mathrm{kms^{-1}Mpc^{-1}}$$

$$\Omega_{de} = 0.79 \pm 0.03$$

$$w = -1.25^{+0.17}_{-0.21}$$

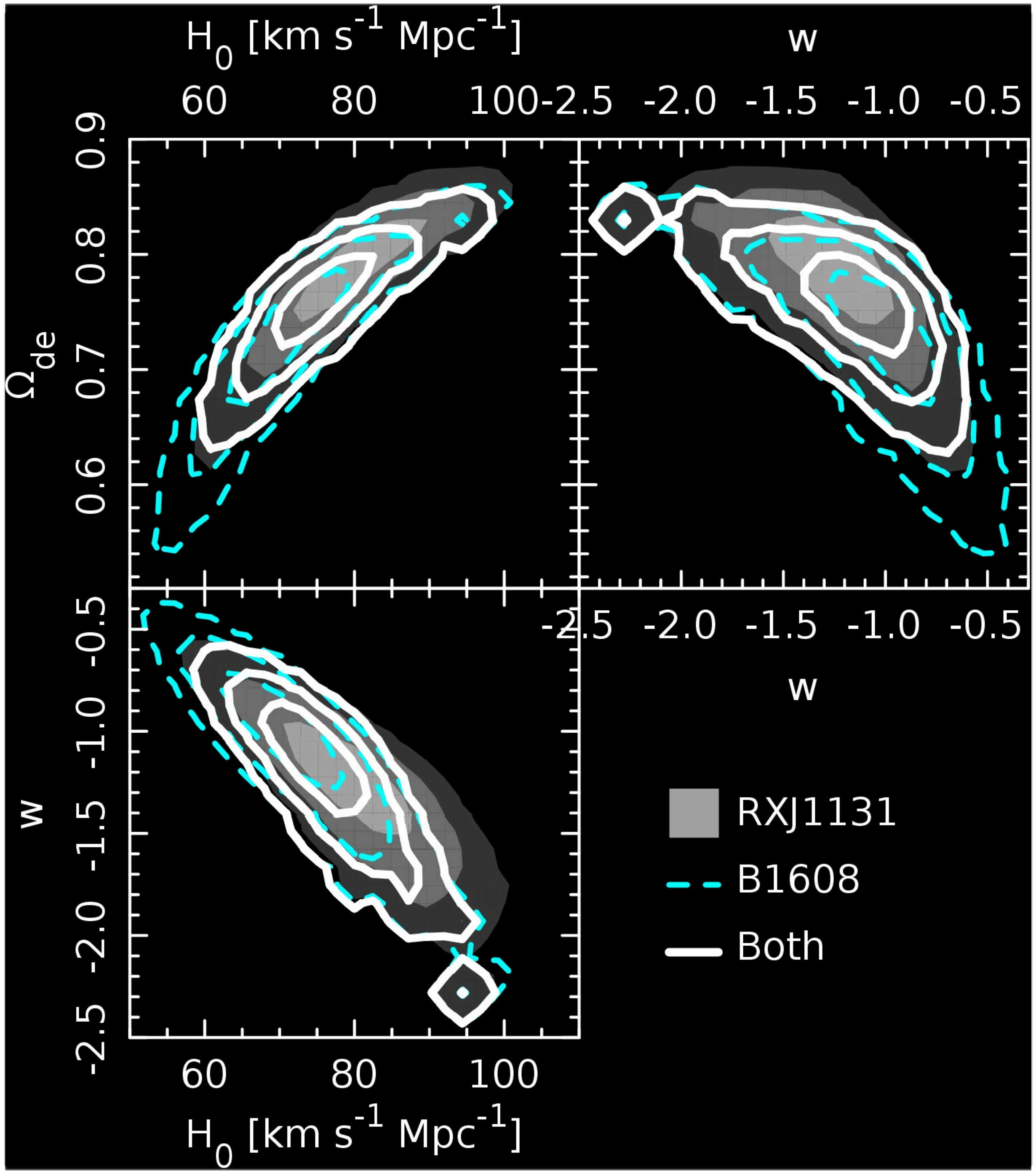
In combination with WMAP7 in flat wCDM cosmology: **un-blinding the analysis !**

Cosmological results with RX J1131-1232



Compatible with previous results using a different system (B1608)

Cosmological results with RX J1131-1232 and B1608



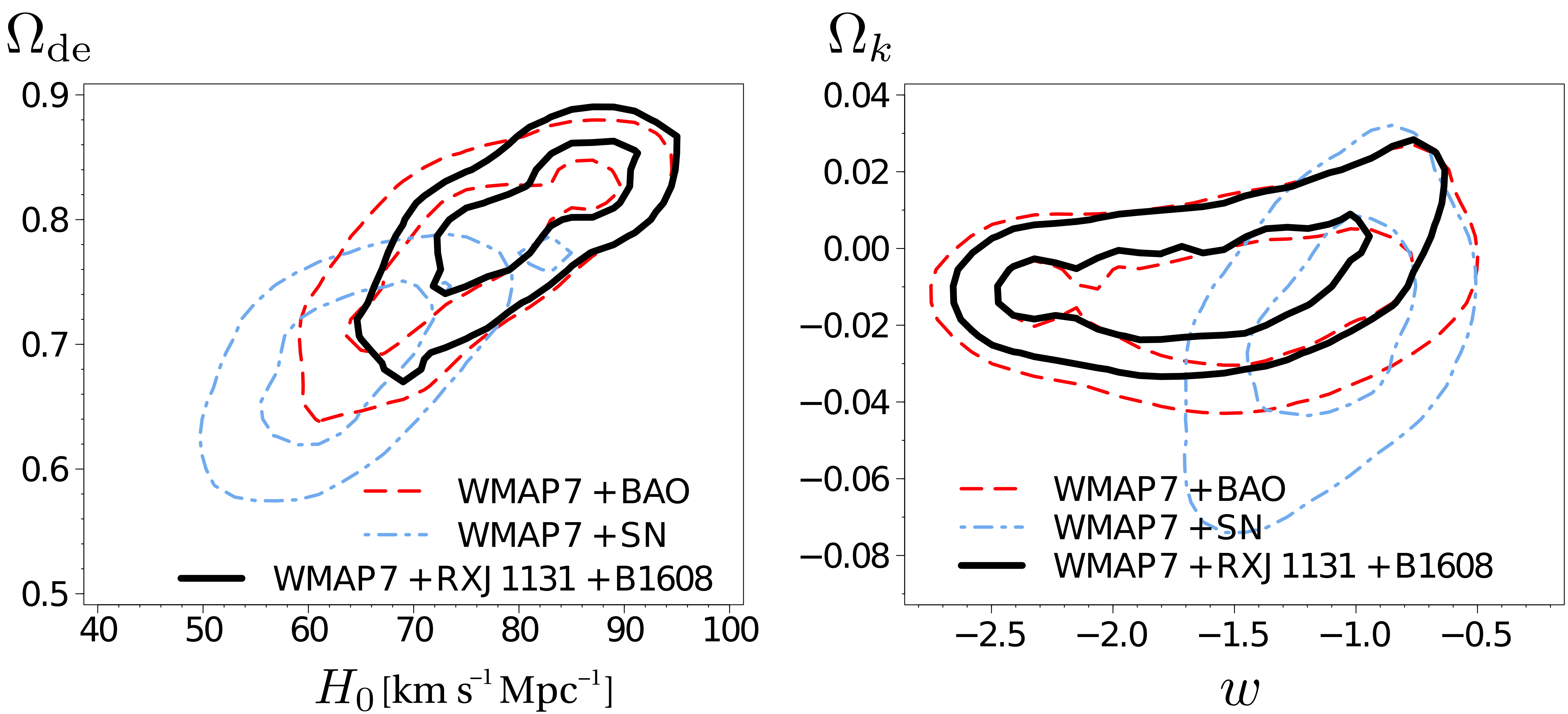
$$H_0 = 75.2^{+4.4}_{-4.2}\ \mathrm{kms^{-1}Mpc^{-1}}$$

$$\Omega_{de} = 0.76^{+0.02}_{-0.03}$$

$$w = -1.14^{+0.17}_{-0.20}$$

Combining the two lenses

Inference on dark energy and curvature from 2 lenses



Time delay work (COSMOGRAIL): Tewes et al. (2013 A&A, in press, arXiv:1208.6009)
Curve shifting methods: Tewes et al. (2013, A&A, in press, arXiv:1208.5508)
Lens modeling: Suyu et al. (2013, ApJ 766, 70)

Update using Planck results

The marginalized joint constraints in open ΛCDM are

$$\begin{cases} H_0 = 79.0^{+4.7}_{-5.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \\ \Omega_{\mathrm{k}} = 0.012^{+0.006}_{-0.007} \end{cases} \quad \text{(WMAP9 + RXJ1131)}$$

and

$$\begin{cases} H_0 = 63.9^{+8.9}_{-7.7}\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \\ \Omega_{\mathrm{k}} = -0.01 \pm 0.02 \end{cases} \quad \text{(Planck + RXJ1131).}$$

The marginalized joint constraints in the flat wCDM model are

$$\begin{cases} H_0 = 82.5^{+6.5}_{-6.3}\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \\ w = -1.36^{+0.20}_{-0.22} \end{cases} \quad \text{(WMAP9 + RXJ1131)}$$

and

$$\begin{cases} H_0 = 85.3^{+6.5}_{-5.9}\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \\ w = -1.55^{+0.19}_{-0.21} \end{cases} \quad \text{(Planck + RXJ1131).}$$

Suyu et al. (2013, arXiv1306.4732)

Summary

- COSMOGRAIL has demonstrated that time delays can be accurately measured
- H0LiCOW: H_0 Lenses in COSMOGRAIL Wellspring
  --> turn time delays into cosmology
- DES, KIDS, LSST, Euclid will bring hundreds of new targets
- Long and well-sampled light curves are crucial to handle microlensing properly
- The mass-slope degeneracy can be broken at least in some cases
- The mass-sheet (line of sight) degeneracy can be minimized