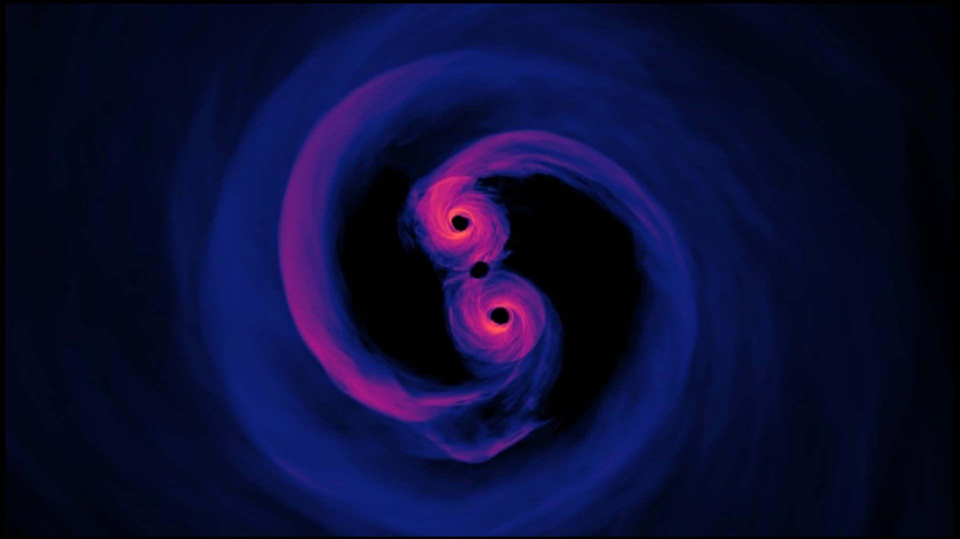
Evidence for a milli-parsec separation Supermassive Black Hole Binary with quasar microlensing



M. Millon, C. Dalang, C. Lemon, D. Sluse, E. Paic, J.H.H Chan, and F. Courbin

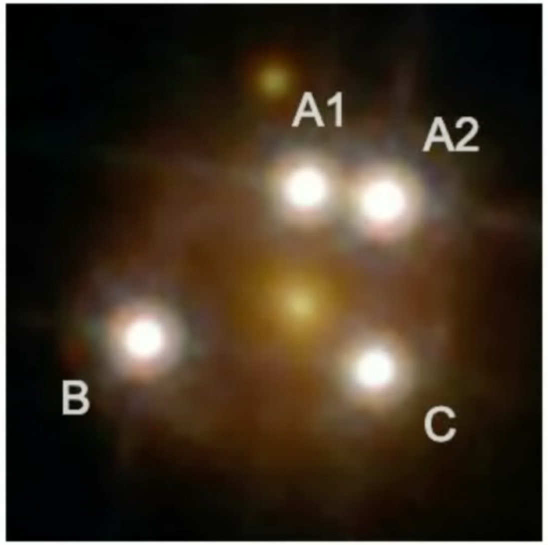
https://arxiv.org/abs/2207.00598

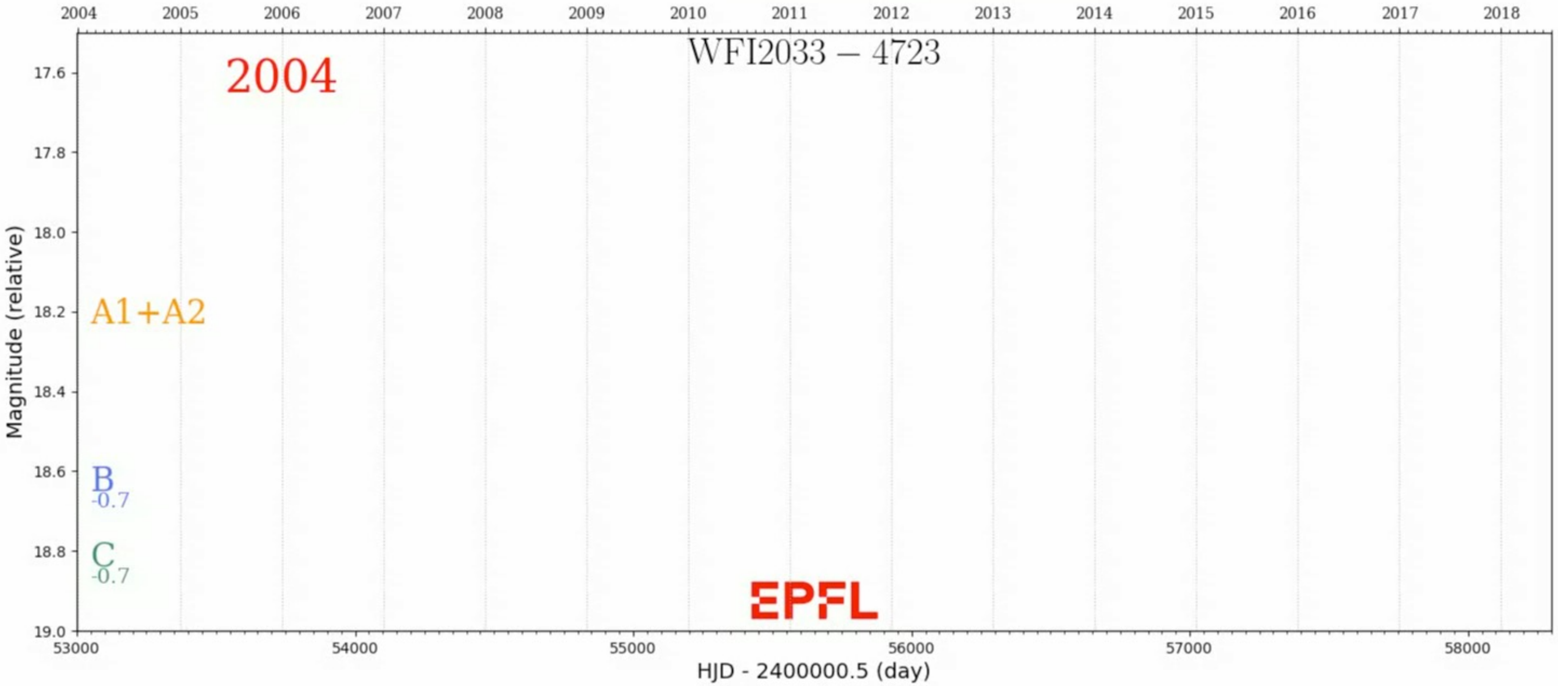
COSMICLENS

European Research Council
Established by the European Commission

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

EPFL


A1
A2
B
C


2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
WFI2033 − 4723
2004
A1+A2
B -0.7
C -0.7
Magnitude (relative)
17.6 17.8 18.0 18.2 18.4 18.6 18.8 19.0
53000 54000 55000 56000 57000 58000
HJD - 2400000.5 (day)
EPFL

Microlensing

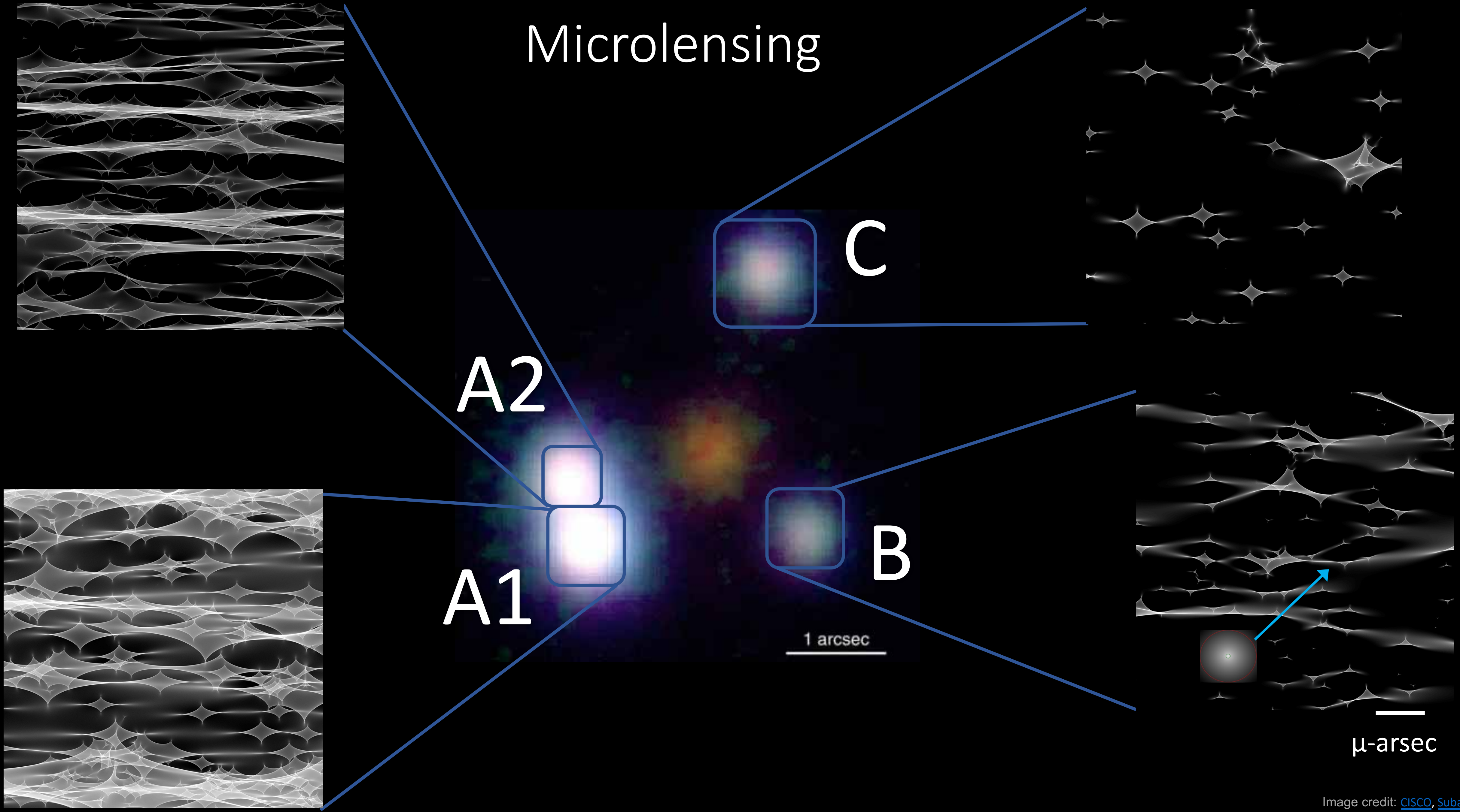
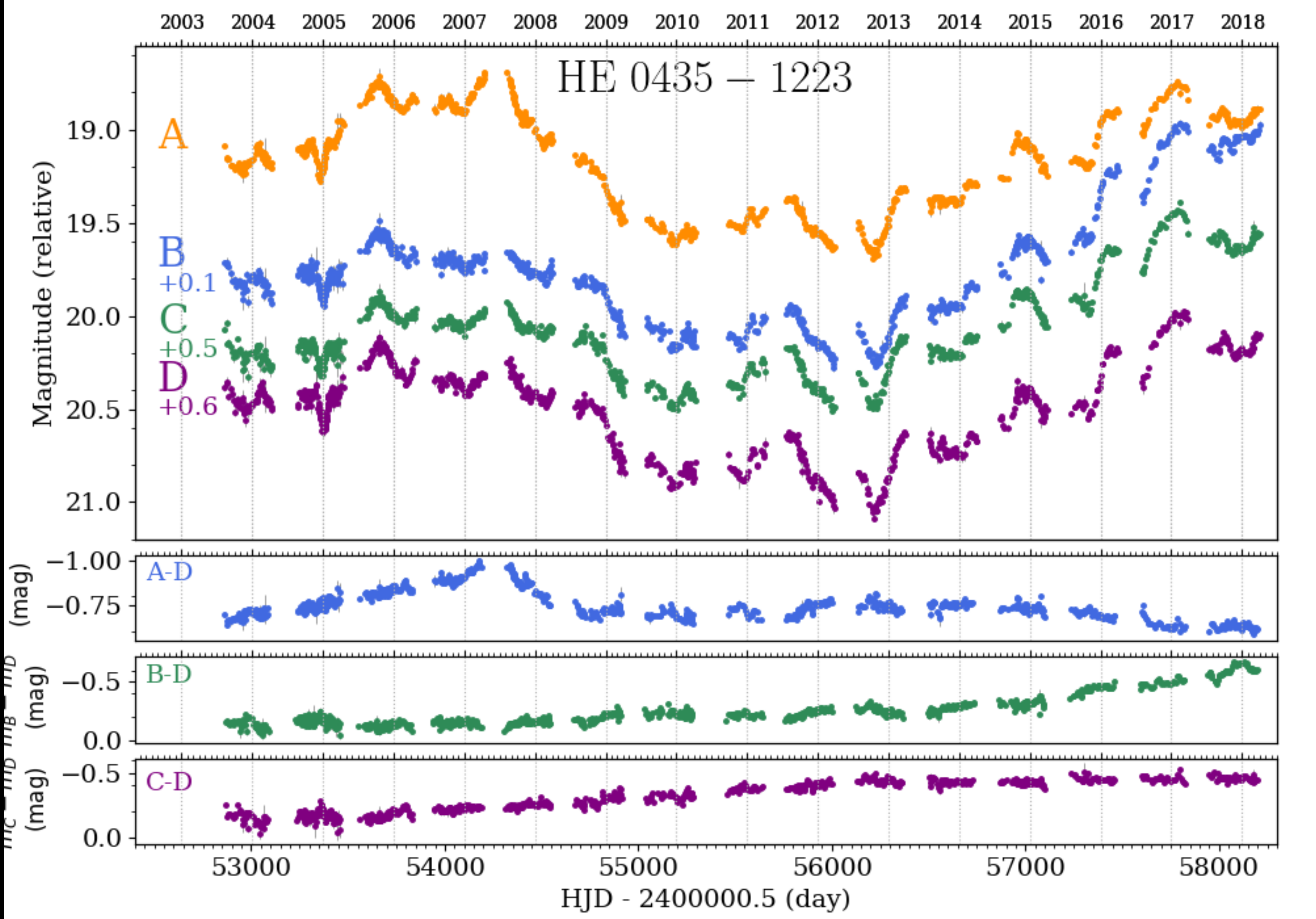
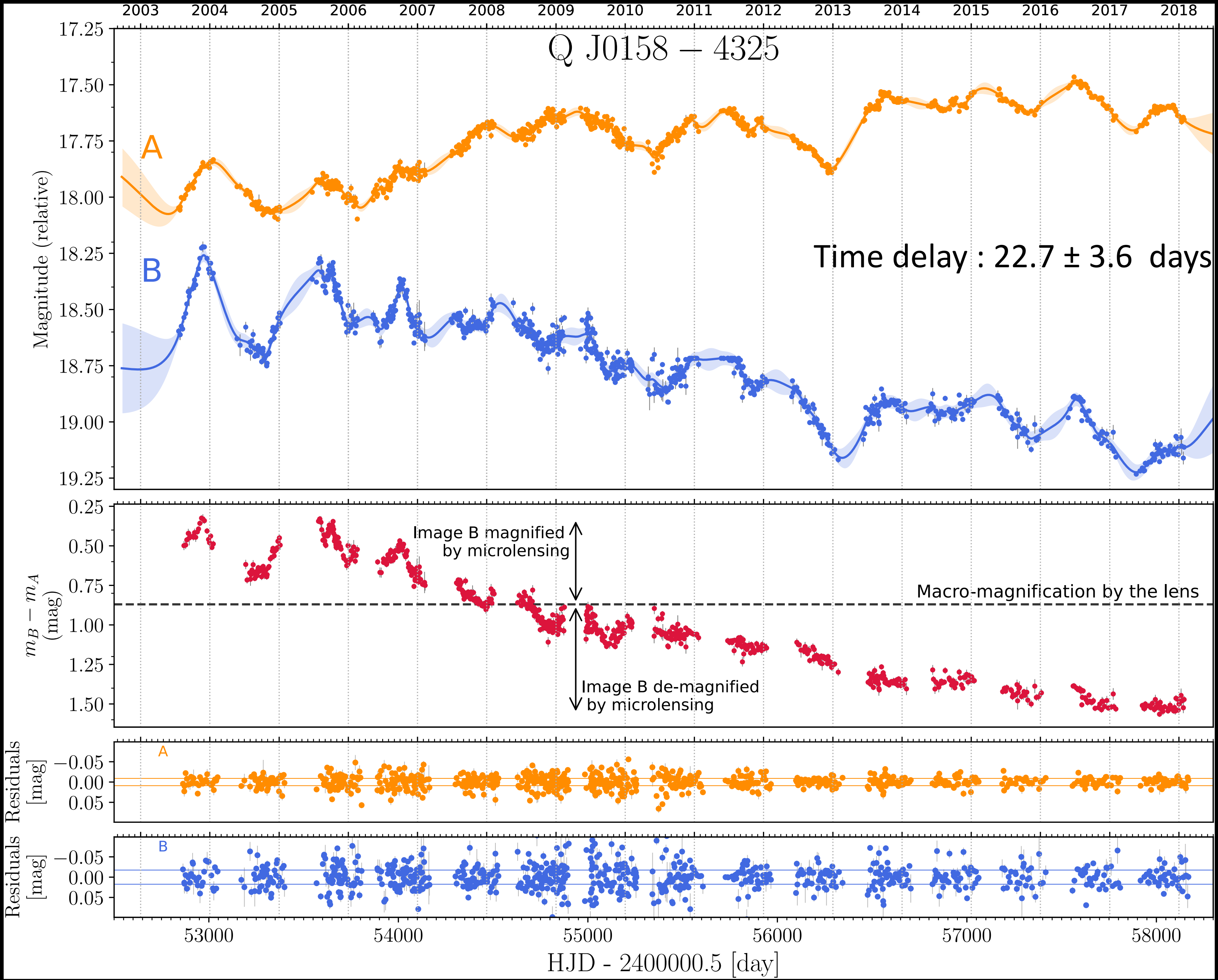
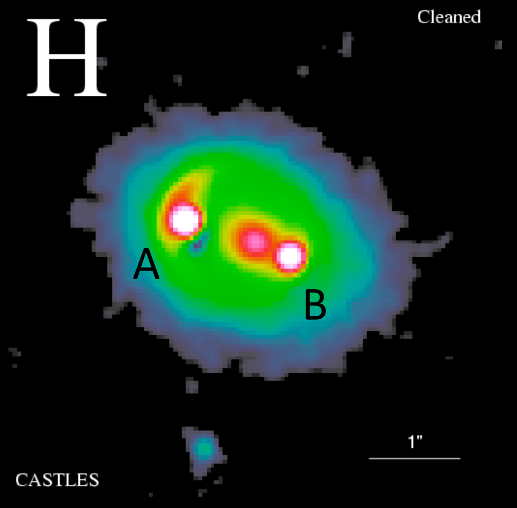
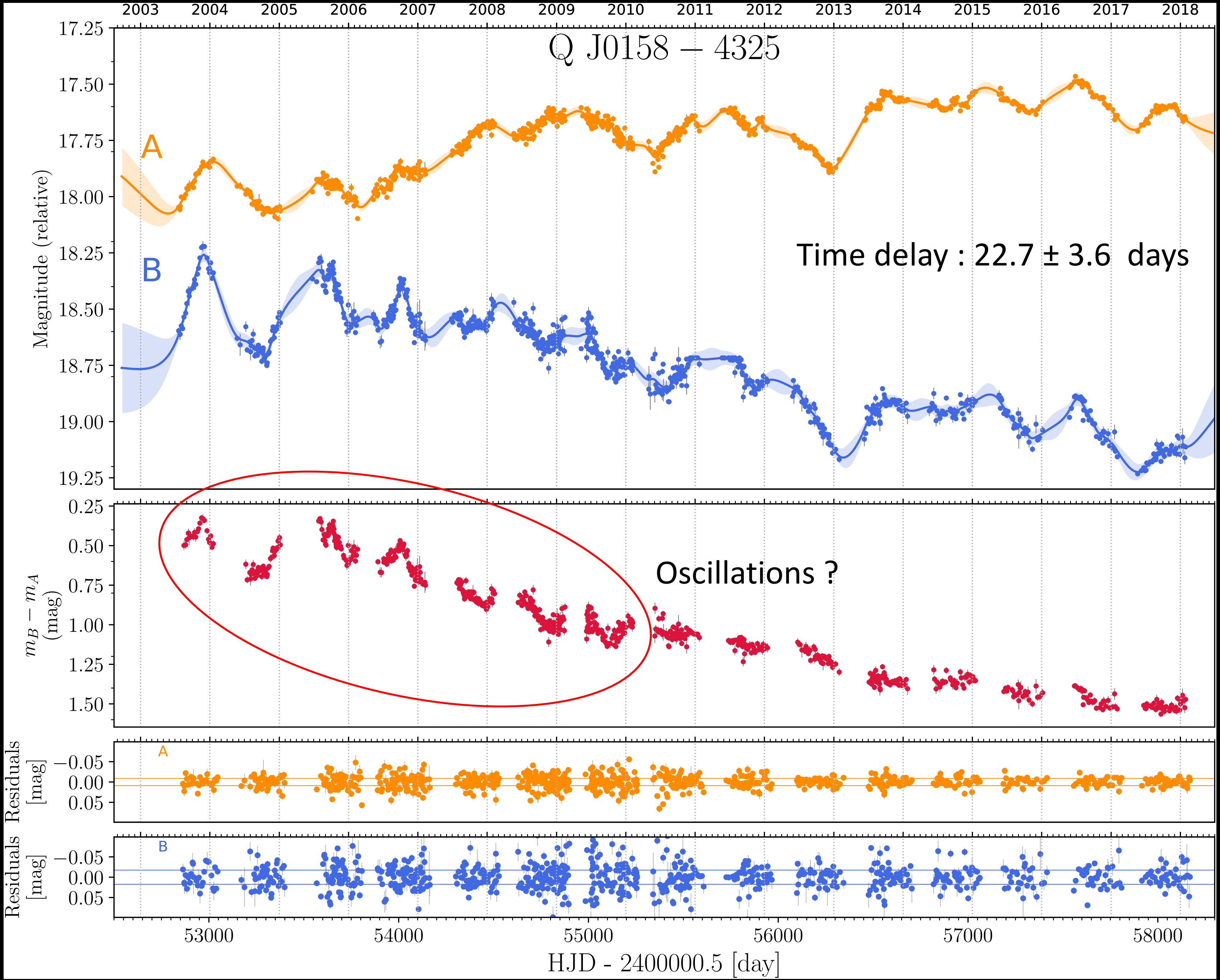


Image credit: CISCO, Subaru 8.3-m Telescope, NAOJ

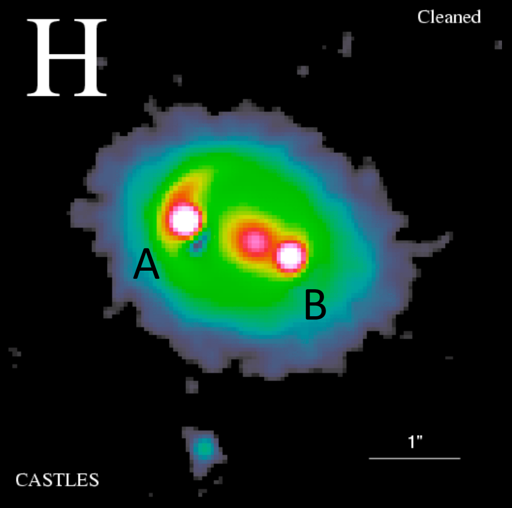
Slow microlensing in HE0435



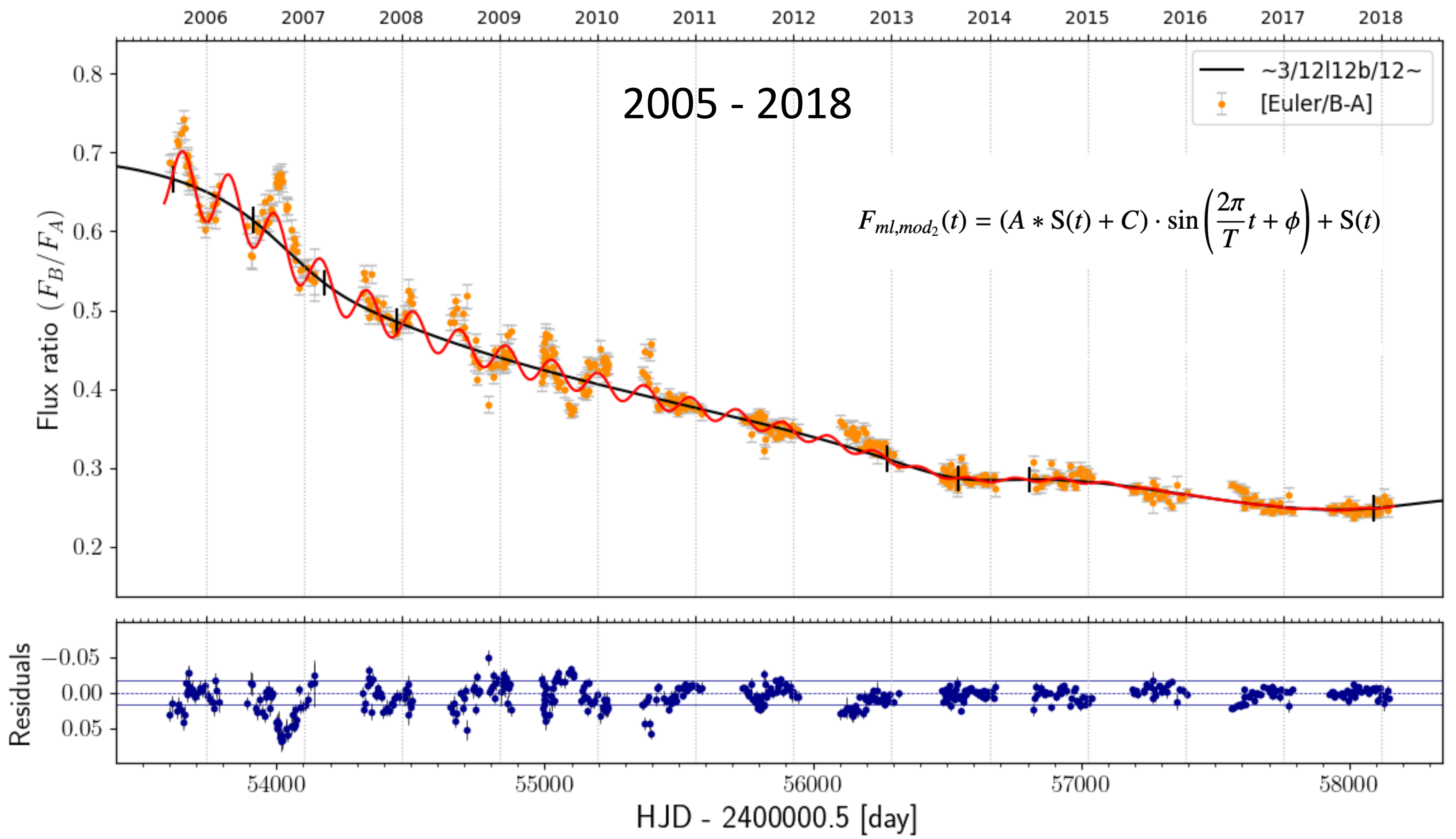

Q J0158 − 4325
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
A
B
Time delay : 22.7 ± 3.6 days
Magnitude (relative)
17.25
17.50
17.75
18.00
18.25
18.50
18.75
19.00
19.25
$m_B - m_A$ (mag)
0.25
0.50
0.75
1.00
1.25
1.50
Image B magnified by microlensing
Macro-magnification by the lens
Image B de-magnified by microlensing
Residuals [mag]
−0.05
0.00
0.05
53000
54000
55000
56000
57000
58000
HJD - 2400000.5 [day]

H
Cleaned
A
B
1"
CASTLES

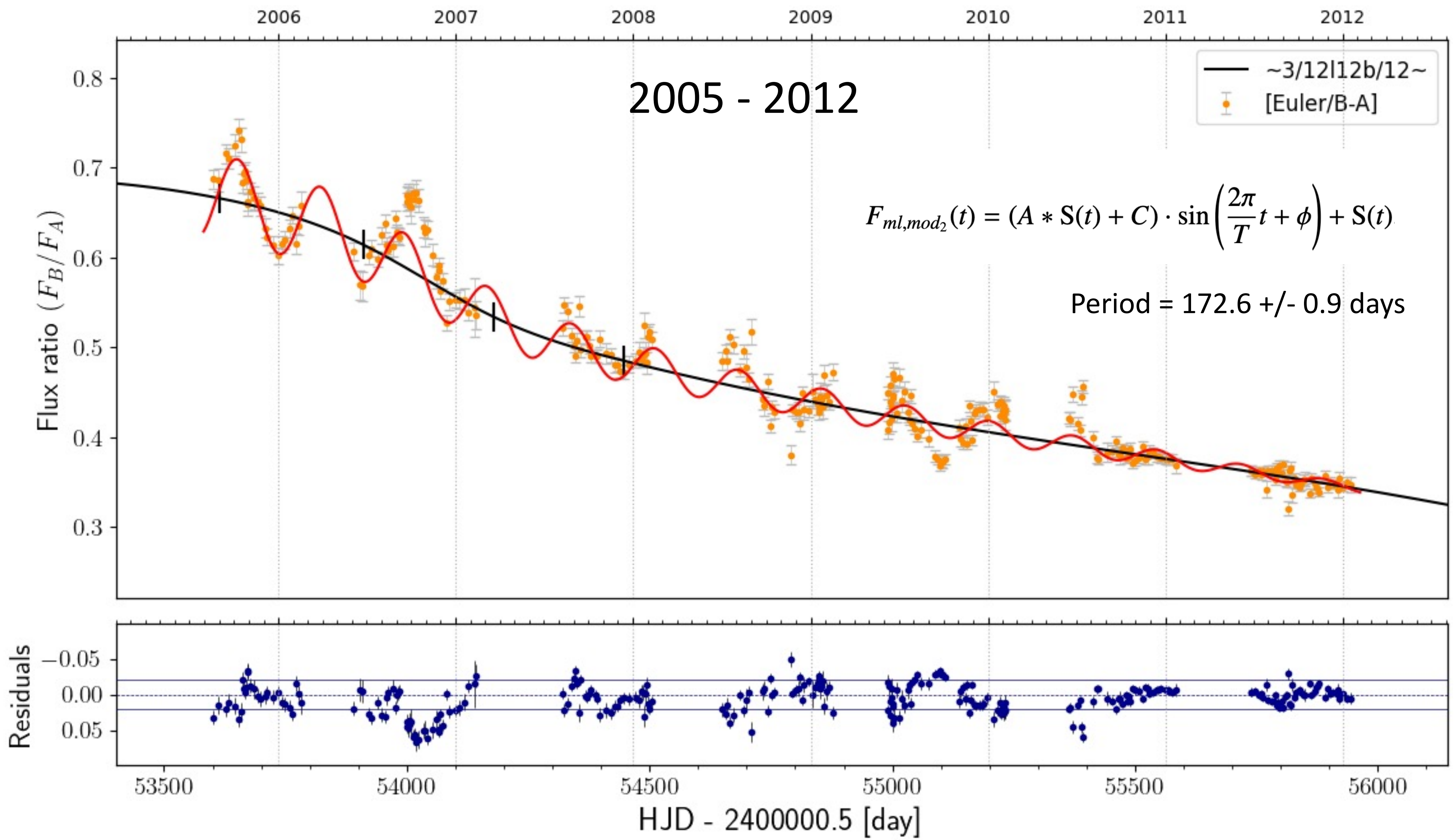


Q J0158 − 4325
Time delay : 22.7 ± 3.6 days
Oscillations ?
A
B
Magnitude (relative)
$m_B - m_A$ (mag)
Residuals [mag]
HJD - 2400000.5 [day]
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
53000
54000
55000
56000
57000
58000

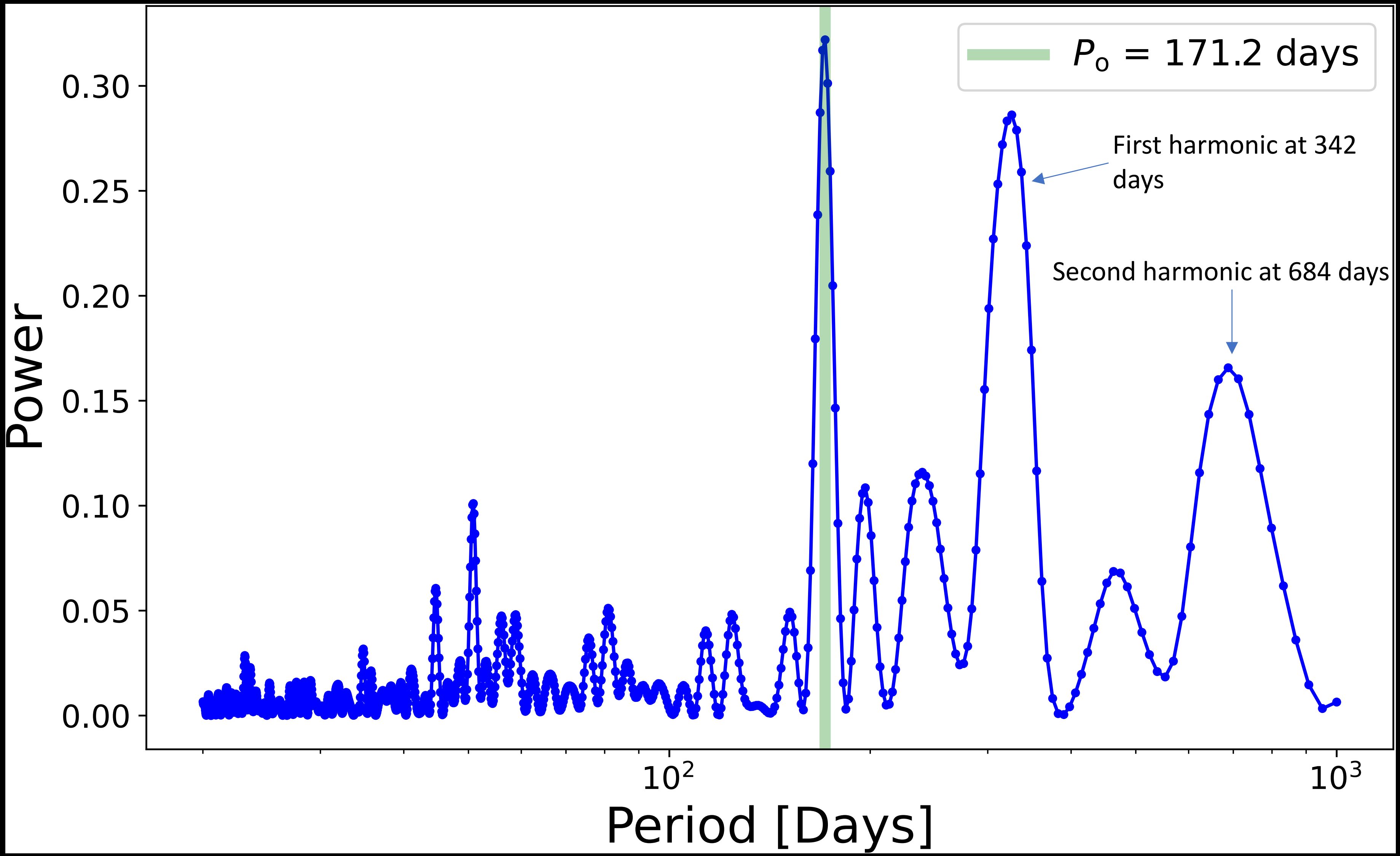


H
Cleaned
A
B
1"
CASTLES


2005 - 2018
$F_{ml,mod_2}(t) = (A * S(t) + C) \cdot \sin\left(\frac{2\pi}{T} t + \phi\right) + S(t)$
~3/12l12b/12~
[Euler/B-A]
Flux ratio (F_B/F_A)
Residuals
HJD - 2400000.5 [day]
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
54000
55000
56000
57000
58000


2005 - 2012
~3/12l12b/12~
[Euler/B-A]
$F_{ml,mod_2}(t) = (A * S(t) + C) \cdot \sin\left(\frac{2\pi}{T} t + \phi\right) + S(t)$
Period = 172.6 +/- 0.9 days
2006
2007
2008
2009
2010
2011
2012
Flux ratio (F_B/F_A)
Residuals
HJD - 2400000.5 [day]

Lomb-Scargle Periodogram



Origin of the periodic signal

- H0 : Binary microlenses (or planetary system acting as a microlens)
- H1 : Binary Supermassive Black Holes
- H2 : Relativistic “hotspot” in the accretion disk

Keplerian motion in the **lens plane**

H0 : Binary microlenses

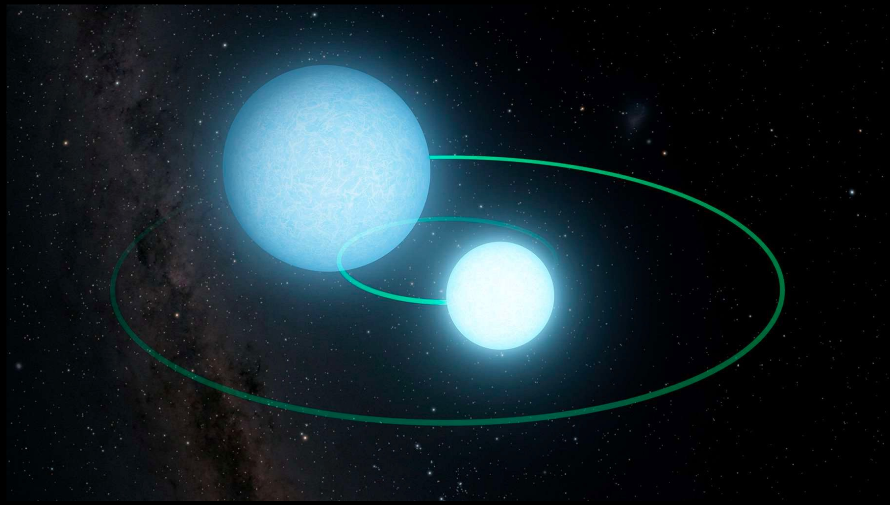
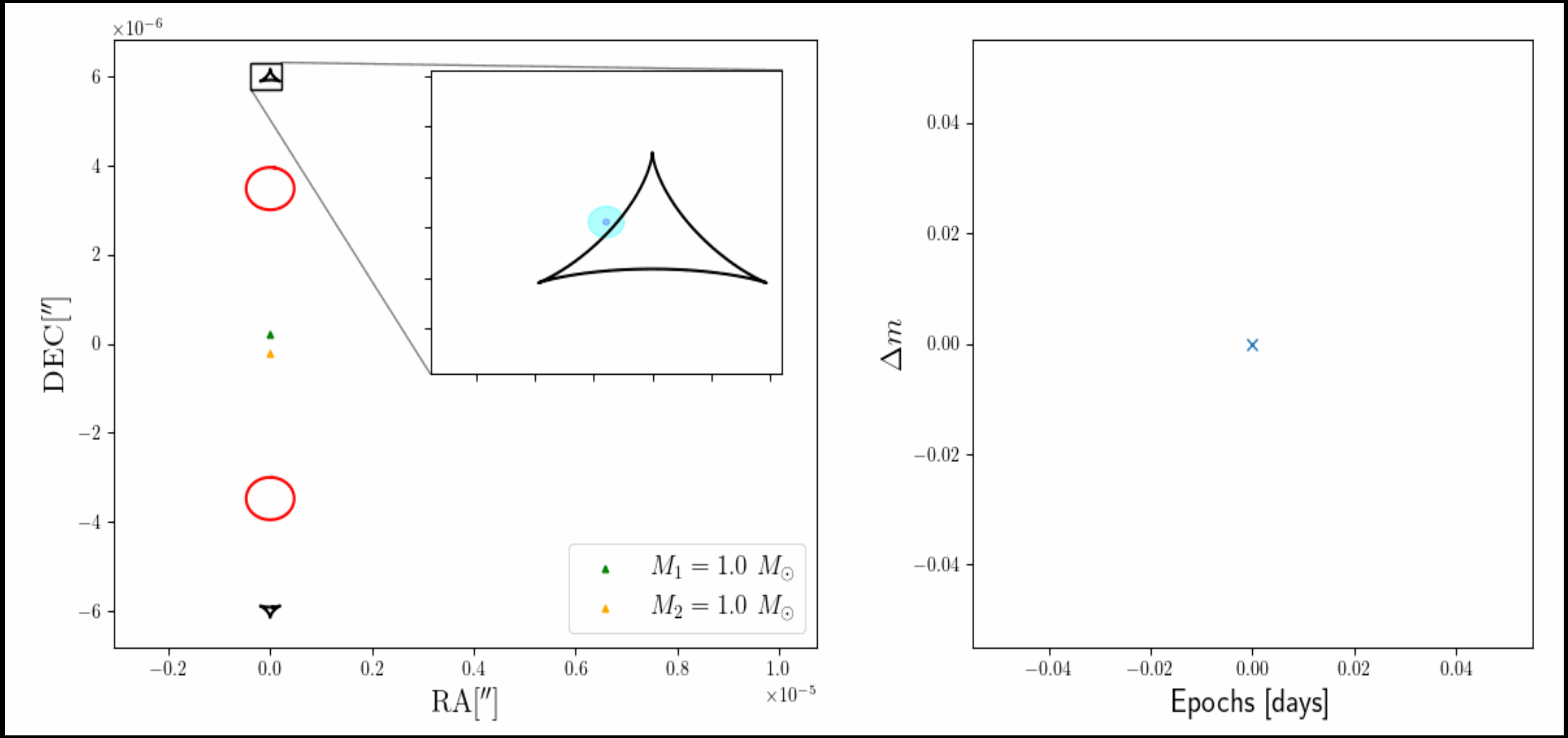


Image credit : Caltech, IPAC, R.Hurt

H0 : Binary microlenses

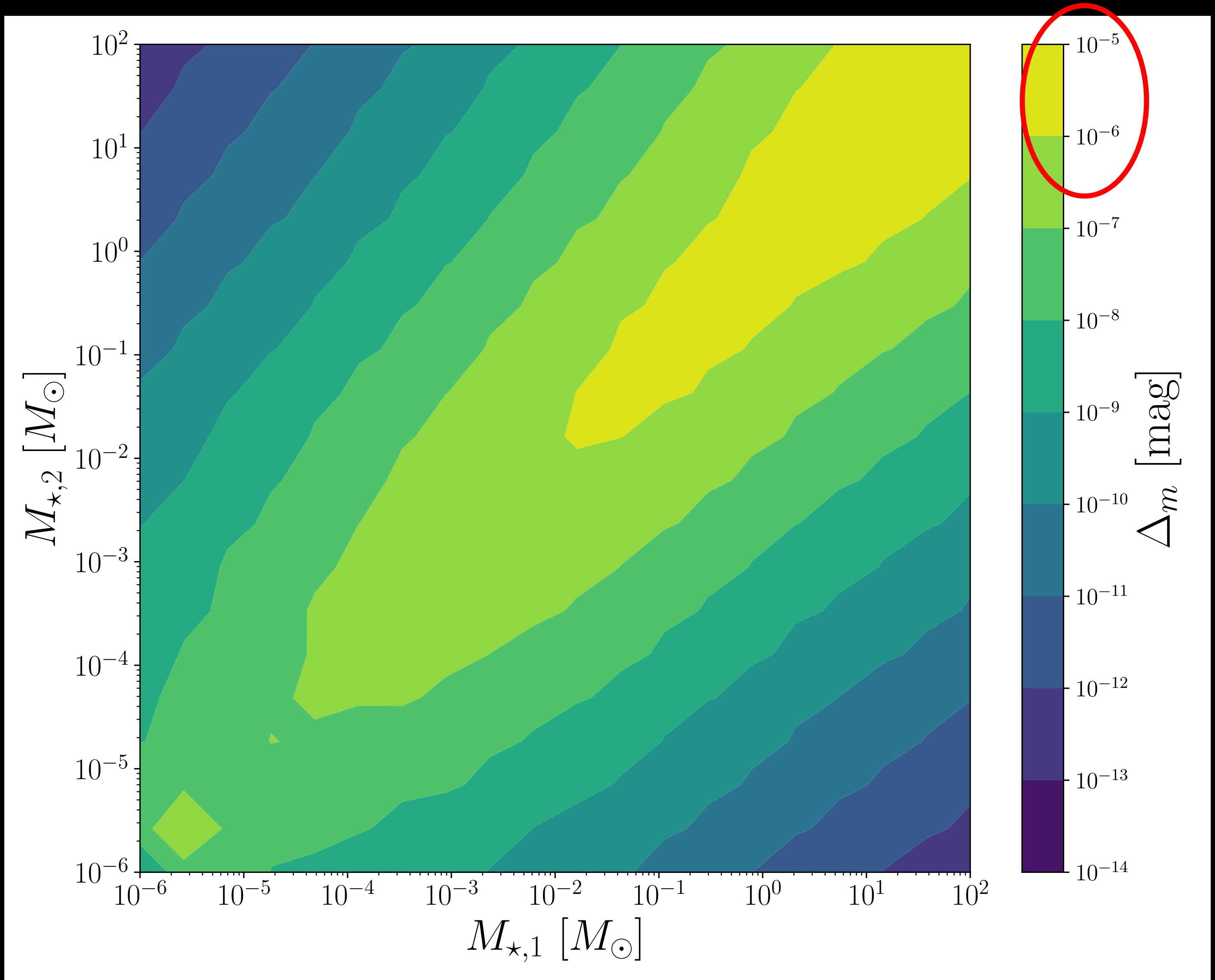
$M_1 = M_{sun}$
$M_2 = M_{sun}$
$a = 400$ AU
$R_0 = 7.9e14$ cm



H0 : Binary microlenses

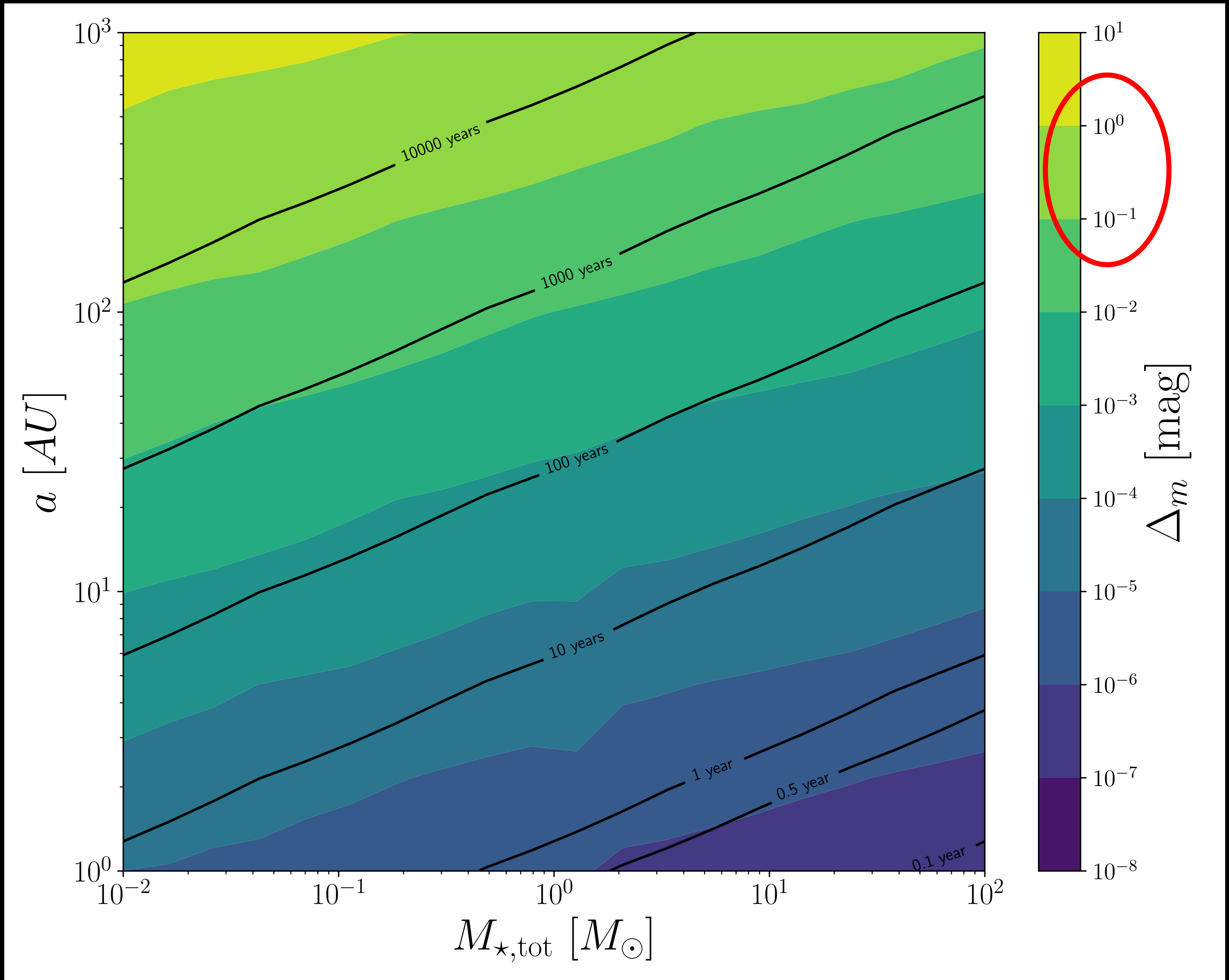
4 orders of magnitude
too small !

Fixed orbital period to :
P = 172 /(1+z_l) *2 = 260 days



H0 : Binary microlenses

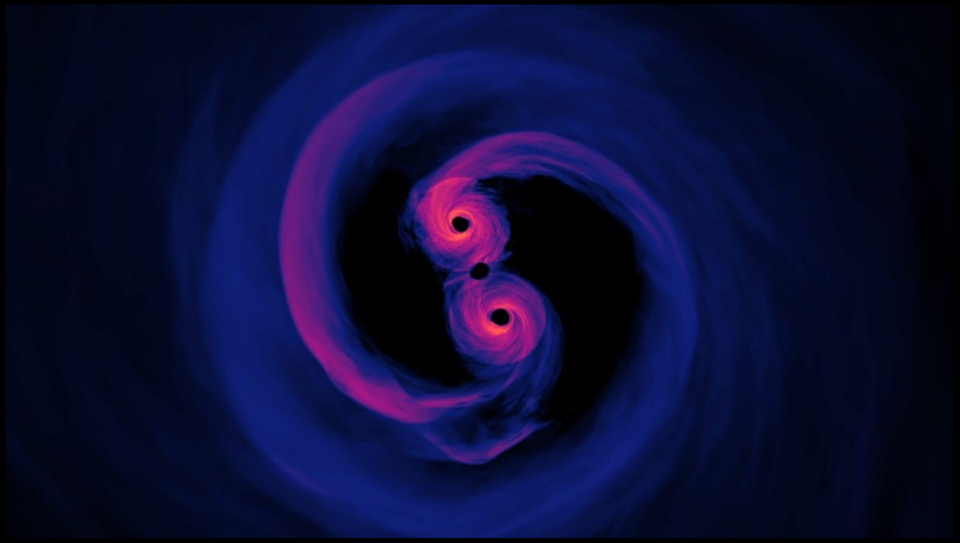
Free orbital period :



Observed amplitude

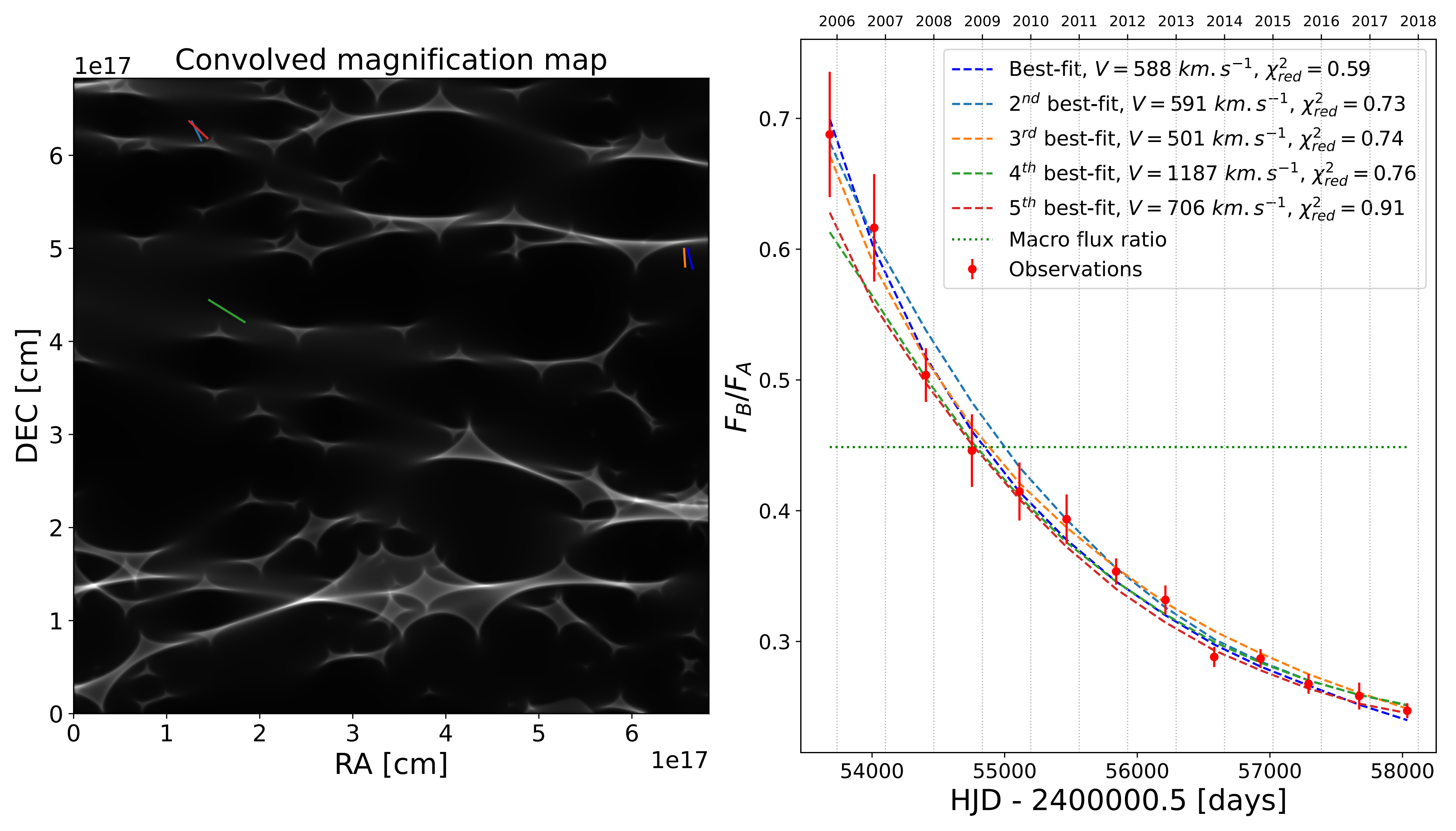
Keplerian motion in the **source plane**

H1 : Binary Supermassive Black Holes

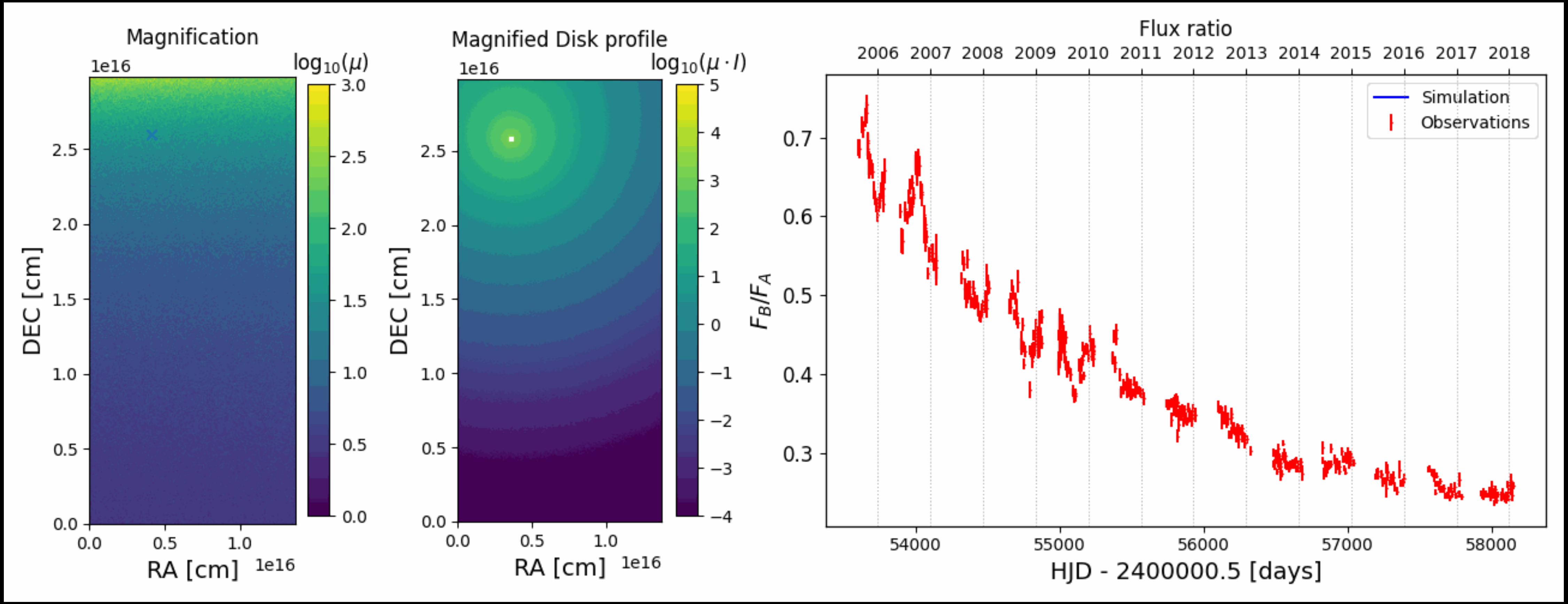


H1 : Binary SMBH

Long-term microlensing trend :



H1 : Binary SMBH



Best-fit for a mass ratio of ~4.5

H1 : Binary SMBH

Orbital parameters :

M_1 = 1.3e8 M_{sun}
M_2 = 2.6e7 M_{sun}
P = 75 days in source plane
a = 189 AU (~ 10^{-3} pc)
Velocity : 0.09c

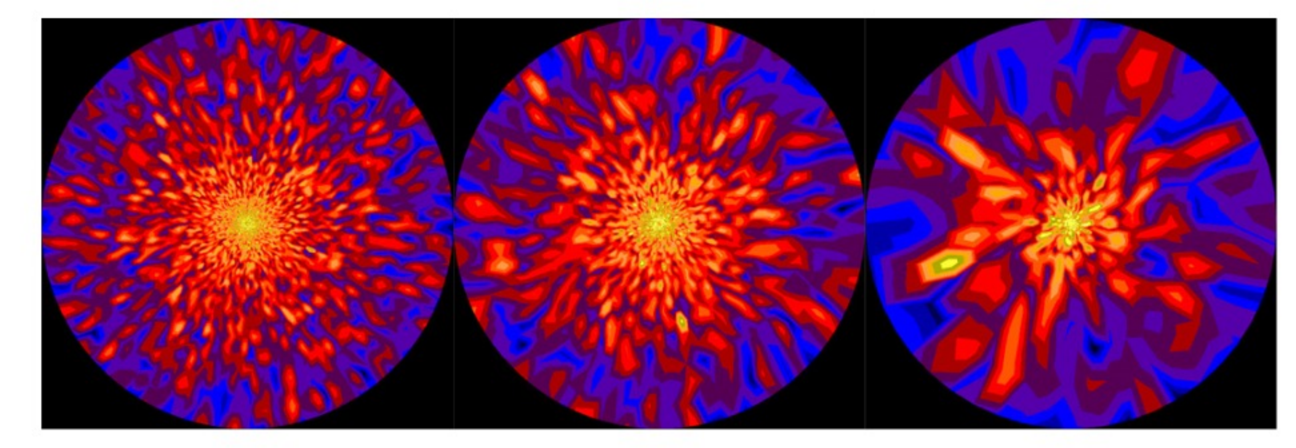
Coalescence time-scale :

$$t_{\rm coal} = \frac{5}{256} \frac{a^4 c^5}{G^3 M_1 M_2 (M_1 + M_2)}$$

t_{coal} ~ 1000 years

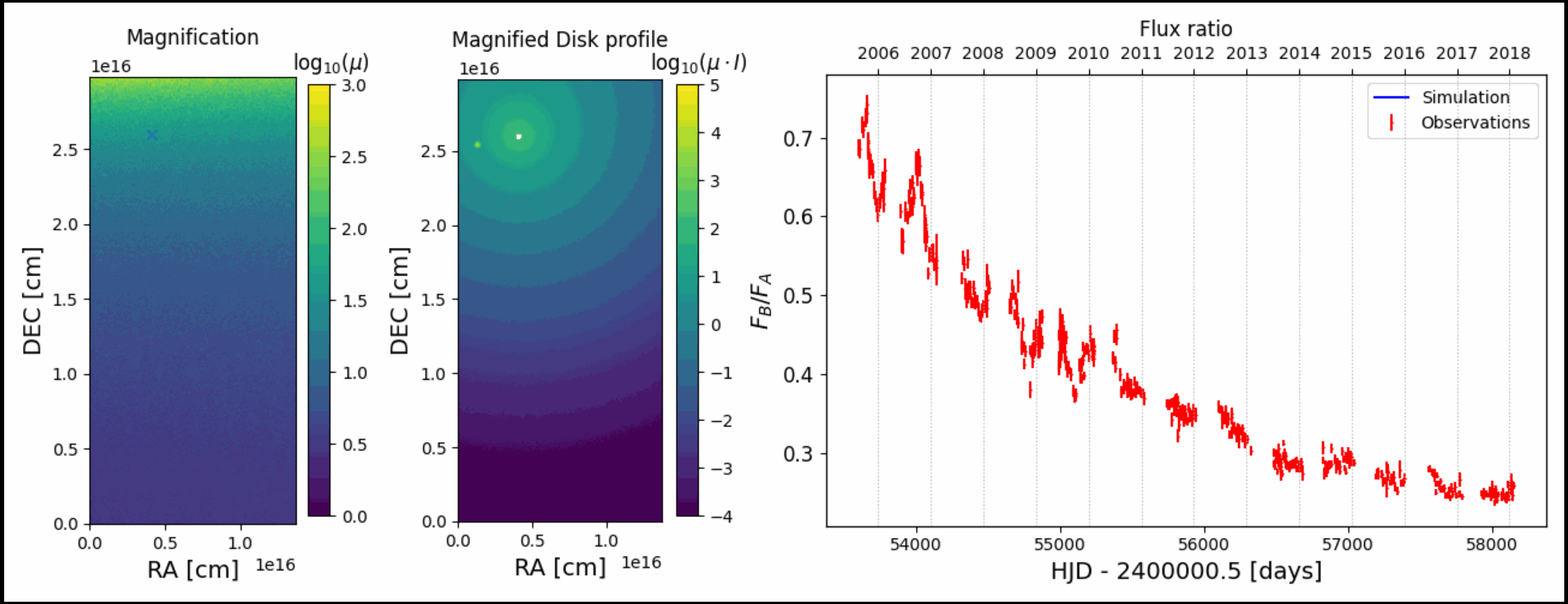
Inhomogeneous accretion in the **source plane**

H2 : relativistic “hotspot” in the accretion disk



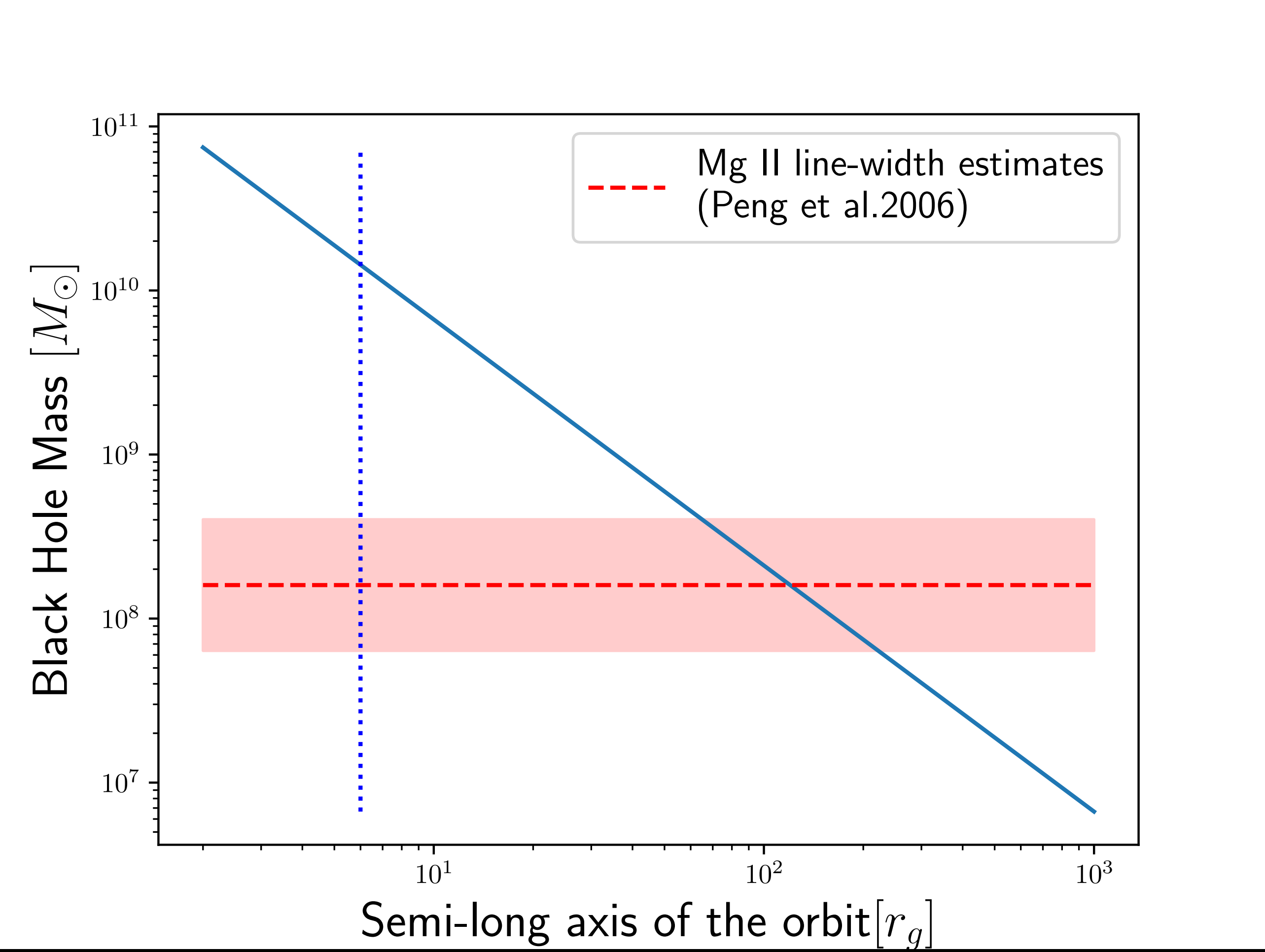
Dexter and Agoll (2011)

H2 : relativistic “hotspot” in the accretion disk



Best-fit for a luminosity ratio of ~5

H2 : relativistic “hotspot” in the accretion disk



1) What mechanism can produce **1/5th of the total UV-luminosity** of the disk and **stay compact on an orbit at 15-25 R_{ISCO} ?**

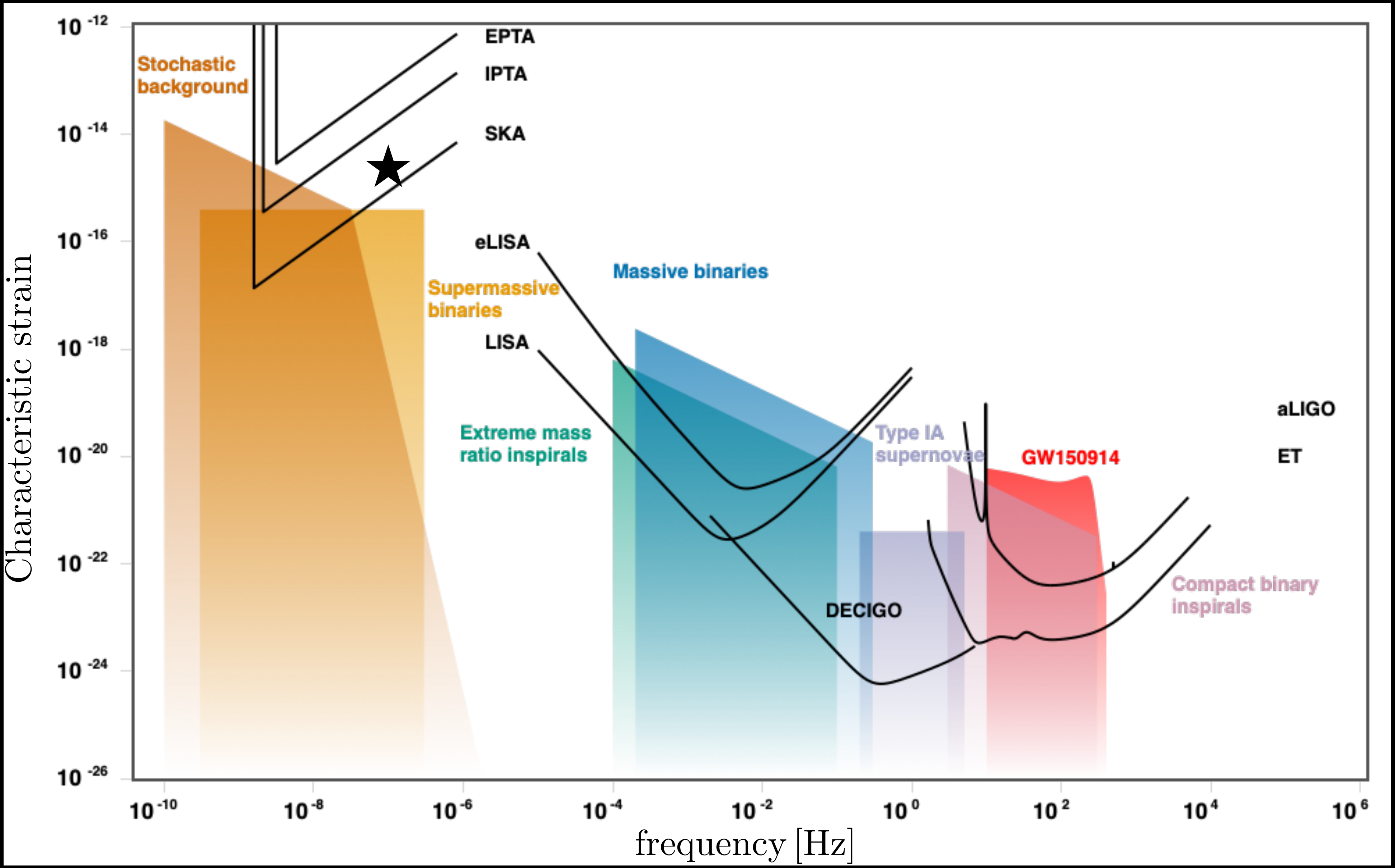
- Disk instability ? Turbulent accretion ?
- Accretion on secondary BH ?

2) These “hotspots” would be disrupted by Keplerian shear on a timescale of :

$$\tau_{shear} \sim 15yr$$

Conclusion

- Binary microlenses : Seems impossible to reproduce both the period and amplitude of the signal.
- Binary SMBH : Reproduces the observation **but such systems should be extremely rare unless angular momentum is transported from the circumbinary disk.**
- Hotspot in the disk : Also reproduces the observation. **Can a hotspot emits or absorb ~1/5th of the total luminosity and stay compact in an accretion disk ?** It would be disrupted by Keplerian shear if not bound by gravity.



EPTA
IPTA
SKA
Stochastic background
Supermassive binaries
eLISA
LISA
Massive binaries
Extreme mass ratio inspirals
Type IA supernovae
GW150914
aLIGO
ET
DECIGO
Compact binary inspirals
Characteristic strain
frequency [Hz]
10 -12
10 -14
10 -16
10 -18
10 -20
10 -22
10 -24
10 -26
10 -10
10 -8
10 -6
10 -4
10 -2
10 0
10 2
10 4
10 6

So far no detection of SMBH from current PTA experiments, BUT:

- We know where J0158-43 is
- VLT follow-up (wobbling)
- Current sensitivity is already ok !
- Rubin-LSST should find even more !

NANOGrav array sensitivity map

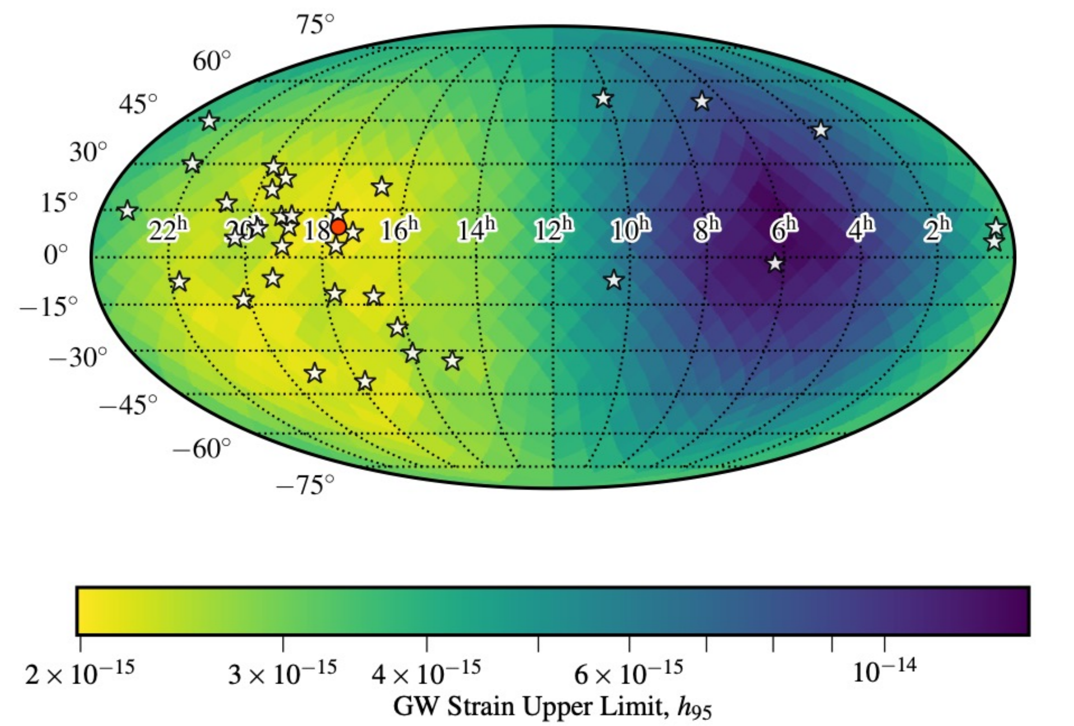


Figure 5. The 95% upper limit on the GW strain amplitude from a circular SMBHB with $f_{gw} = 8$ nHz as a function of sky position from an analysis of the 11-year data set, plotted in equatorial coordinates using the Mollweide projection. We used the DE436 ephemeris model with BayesEphem to model uncertainty in the SSB. The positions of pulsars in our array are indicated by stars, and the most sensitive sky location is indicated by a red circle. The 95% upper limit ranged from $2.0(1) \times 10^{-15}$ at our most sensitive sky location to $1.34(4) \times 10^{-14}$ at our least sensitive sky location.

Aggarwal et al. 2020 ApJ, 889, 38