MOA-2010-BLG-328: A SATURN, A NEPTUNE, OR A SUPER-EARTH?

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Collaborators: David Bennett, J.-P. Beaulieu, Sean Terry, Aparna Bhattacharya, Clément Ranc, Joshua Blackman, Andrew Cole, Natalia Rektsini + MOA collaboration

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HOW CAN WE USE LENS FLUX MEASUREMENTS TO BREAK DEGENERACIES OF MICROLENSING EVENTS THAT HAVE COMPLEX HIGHER ORDER EFFECTS LIKE PARALLAX, LENS ORBITAL MOTION, XALLARAP AND MAGNIFICATION OF A SECOND SOURCE.

Many events we work on are part of statistical studies like Suzuki+16 (e.g. MOA-2010-BLG-328) – which have used mass-ratios

It's a good technique for mass measurements that will stick around. So we need to get to know it.

Direct lens flux detections help with the modeling

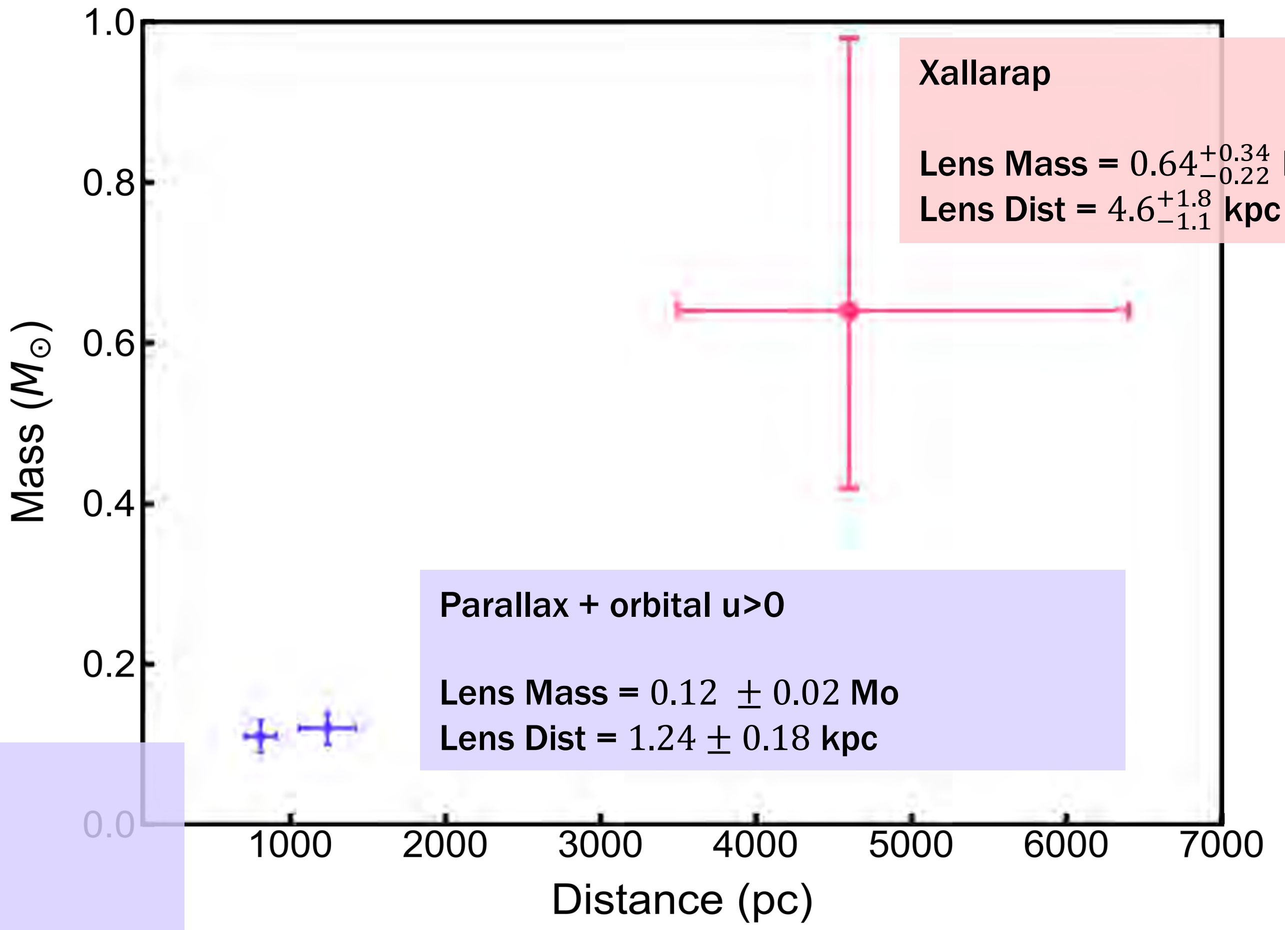
MOA-2010-BLG-328
Furusawa et al. 2013

Best fit solutions:

- Constrained Xallarap

- Parallax + orbital motion (u<0 and u>0)

Parameters	Standard	Parallax	Unconstrained xallarap	Constrained xallarap	Orbital	Parallax + Orbital ($u_0 < 0$)	Parallax + Orbital ($u_0 > 0$)
t_0 (HJD′)	5378.641 0.015	5378.717 0.017	5378.723 0.015	5378.706 0.013	5378.776 0.036	5378.683 0.014	5378.694 0.017
t_E (day)	57.2 0.3	70.3 0.7	62.9 0.3	61.8 0.3	75.1 0.9	62.6 0.6	64.2 0.6
u_0	0.0816 0.0005	0.0644 0.0007	−0.0722 0.0005	−0.0741 0.0004	0.0596 0.0007	−0.0721 0.0008	0.0716 0.0007
$q \times 10^4$	8.16 0.11	4.46 0.07	5.17 0.08	5.16 0.06	11.63 0.92	2.60 0.53	3.68 1.26
s	1.243 0.001	1.192 0.002	1.216 0.001	1.220 0.001	1.310 0.012	1.154 0.016	1.180 0.028
α (rad)	0.1694 0.0005	0.1976 0.0010	−0.1740 0.0005	−0.2024 0.0004	0.1385 0.0081	−0.2743 0.0087	0.1965 0.0151
$\rho \times 10^3$	1.91 0.02	1.09 0.02	1.31 0.02	1.35 0.01	1.66 0.06	0.93 0.10	1.09 0.17
$\pi_{E,N}$	...	0.35 0.01	...	...	...	1.01 0.06	0.72 0.05
$\pi_{E,E}$	...	−0.13 0.03	...	...	...	−0.51 0.04	−0.39 0.03
$\xi_{E,N}$	...	...	−2.58 ...	0.02 ...	...	...	...
$\xi_{E,E}$	...	...	−1.86 ...	0.04 ...	...	...	...
R.A.$_\xi$ (deg)	...	...	256.07 ...	255.77 ...	...	...	...
Decl.$_\xi$ (deg)	...	...	−23.44 ...	−0.89 ...	...	...	...
P_ξ (day)	...	...	475.53 ...	155.66 ...	...	...	...
ϵ	...	...	0.17 ...	0.20 ...	...	...	...
$\omega \times 10^3$ (rad day^{-1})	...	...	...	...	−0.93 0.26	−7.39 0.39	−1.39 0.60
$ds/dt \times 10^3$ (day^{-1})	...	...	...	...	−5.67 0.56	2.51 0.63	1.41 1.16
χ^2 dof	6037.32 5664	5684.47 5662	5651.69 5658	5652.59 5658	5716.16 5662	5657.75 5660	5660.31 5660



Xallarap

Lens Mass = $0.64^{+0.34}_{-0.22}$ **Mo**
Lens Dist = $4.6^{+1.8}_{-1.1}$ **kpc**

Parallax + orbital u>0

Lens Mass = 0.12 ± 0.02 **Mo**
Lens Dist = 1.24 ± 0.18 **kpc**

Parallax + orbital u<0

Lens Mass = 0.11 ± 0.02 **Mo**
Lens Dist = 0.81 ± 0.10 **kpc**

Higher order effects are often only added if they are required to fit the data.

Even if there is no significant signal on the light curve though, parallax should not be ignored.

Setting parallax to 0 could lead to wrong error bars on t_E and source brightness.

BUT you would also want a prior to exclude highly unlikely parallax values as these are sensitive to systematic errors.

WHEN a significant parallax signal is detected, then orbital motion can interfere with parallax.

So, orbital motion should be included to get accurate parallax values and errors.

Lastly…

Binary source stars are common.

Their separation is often too large to affect the light curve, although they can still add brightness that is unresolved from the source.

Both xallarap and magnification of the second source are still relatively common.

Events with excess flux at the source should be modeled with these effects.

MOA-2010-BLG-328

They considered:

Just Parallax

Parallax & orbital motion

Just Xallarap

Just orbital motion

See poster by Zhecheng Hu on event OGLE-2015-BLG-0845 for another xallarap + parallax event

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t_E	57.2	70.3	62.9	61.8	75.1	62.6	64.2
(day)	0.3	0.7	0.3	0.3	0.9	0.6	0.6
u_0	0.0816	0.0644	−0.0722	−0.0741	0.0596	−0.0721	0.0716
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	0.001	0.002	0.001	0.001	0.012	0.016	0.028
α	0.1694	0.1976	−0.1740	−0.2024	0.1385	−0.2743	0.1965
(rad)	0.0005	0.0010	0.0005	0.0004	0.0081	0.0087	0.0151
$\rho \times 10^3$	1.91	1.09	1.31	1.35	1.66	0.93	1.09
	0.02	0.02	0.02	0.01	0.06	0.10	0.17
$\pi_{E,N}$	...	0.35	...	...	...	1.01	0.72
		0.01				0.06	0.05
$\pi_{E,E}$	...	−0.13	...	...	...	−0.51	−0.39
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R.A.$_\xi$	...	...	256.07	255.77	...	...	...
(deg)			...	...			
Decl.$_\xi$	...	...	−23.44	−0.89	...	...	...
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(day)			...	...			
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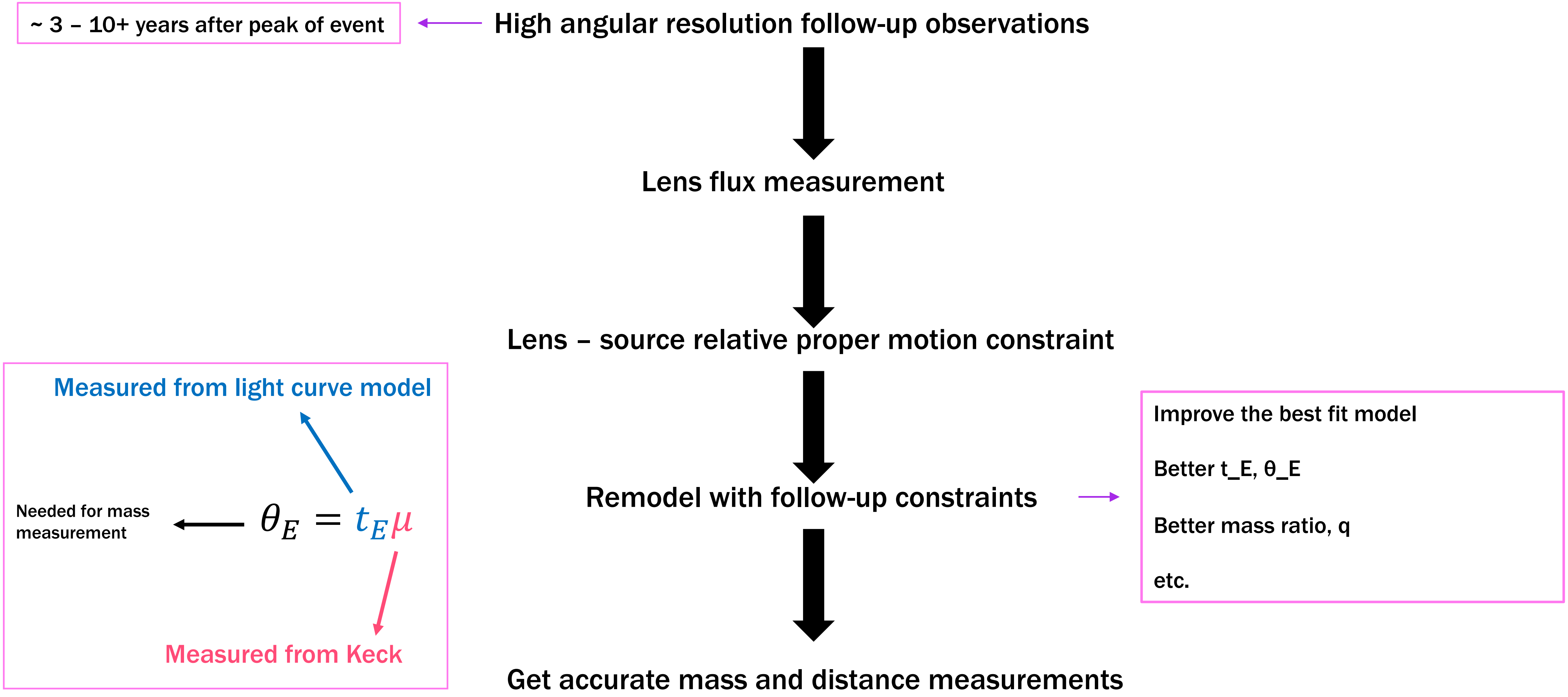
dof	5664	5662	5658	5658	5662	5660	5660

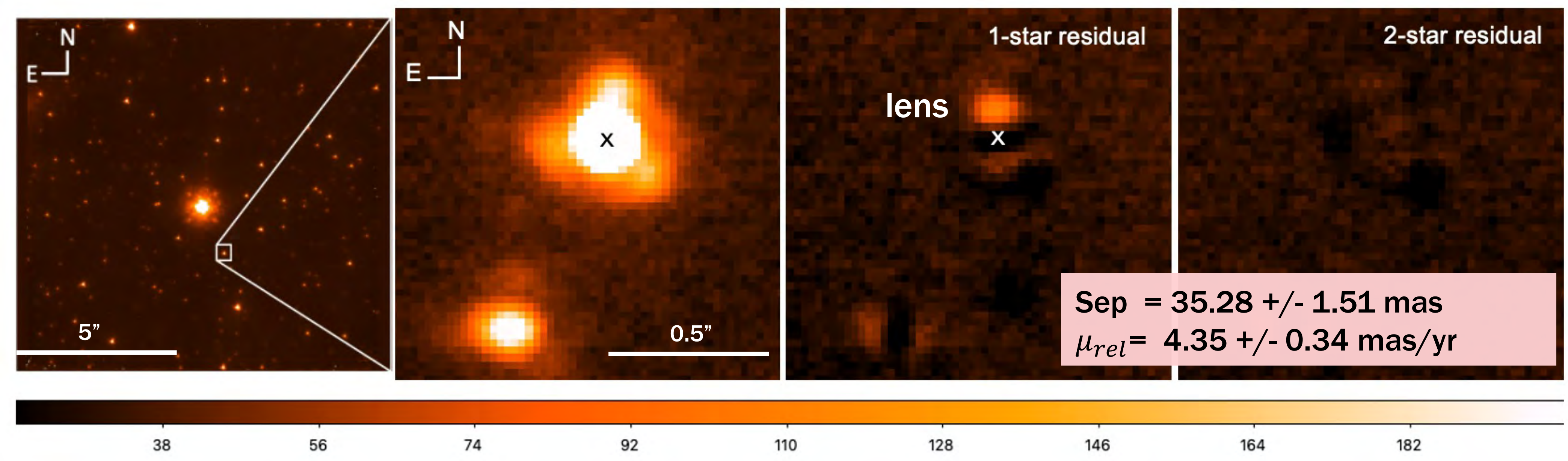

~ 3 – 10+ years after peak of event
High angular resolution follow-up observations
Lens flux measurement
Lens – source relative proper motion constraint
Remodel with follow-up constraints
Get accurate mass and distance measurements
Improve the best fit model
Better t_E, θ_E
Better mass ratio, q
etc.
Measured from light curve model
Needed for mass measurement
$\theta_E = t_E \mu$
Measured from Keck

MOA-2010-BLG-328

Keck

2018

K-band

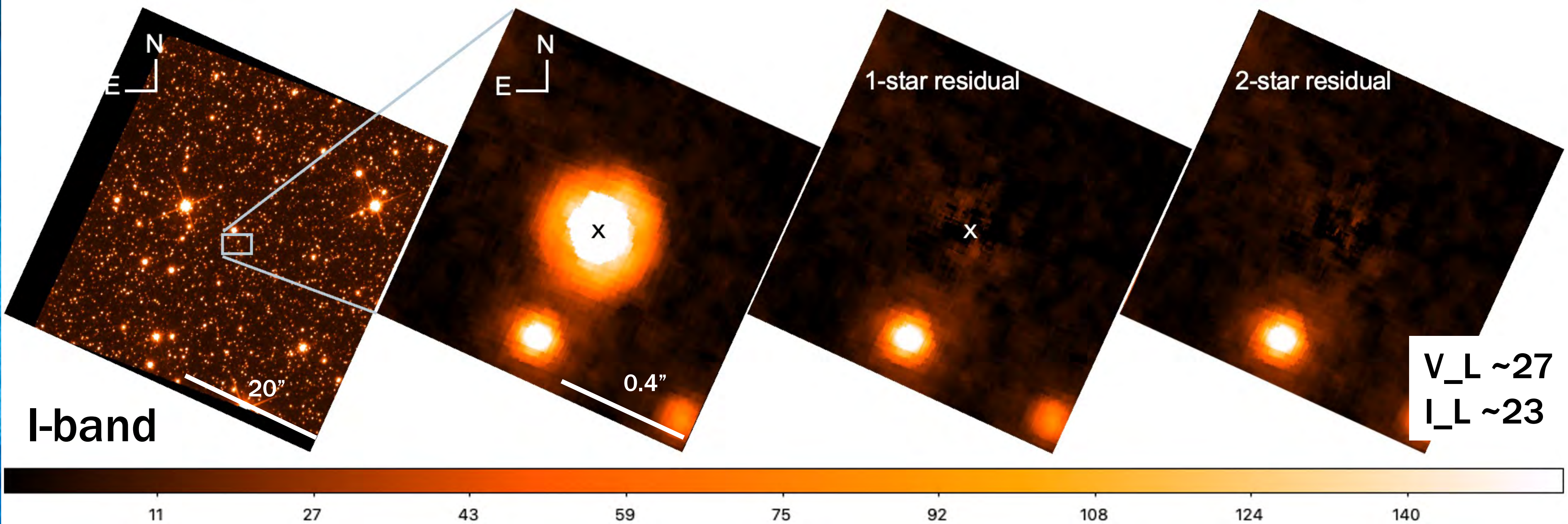


HST

2018

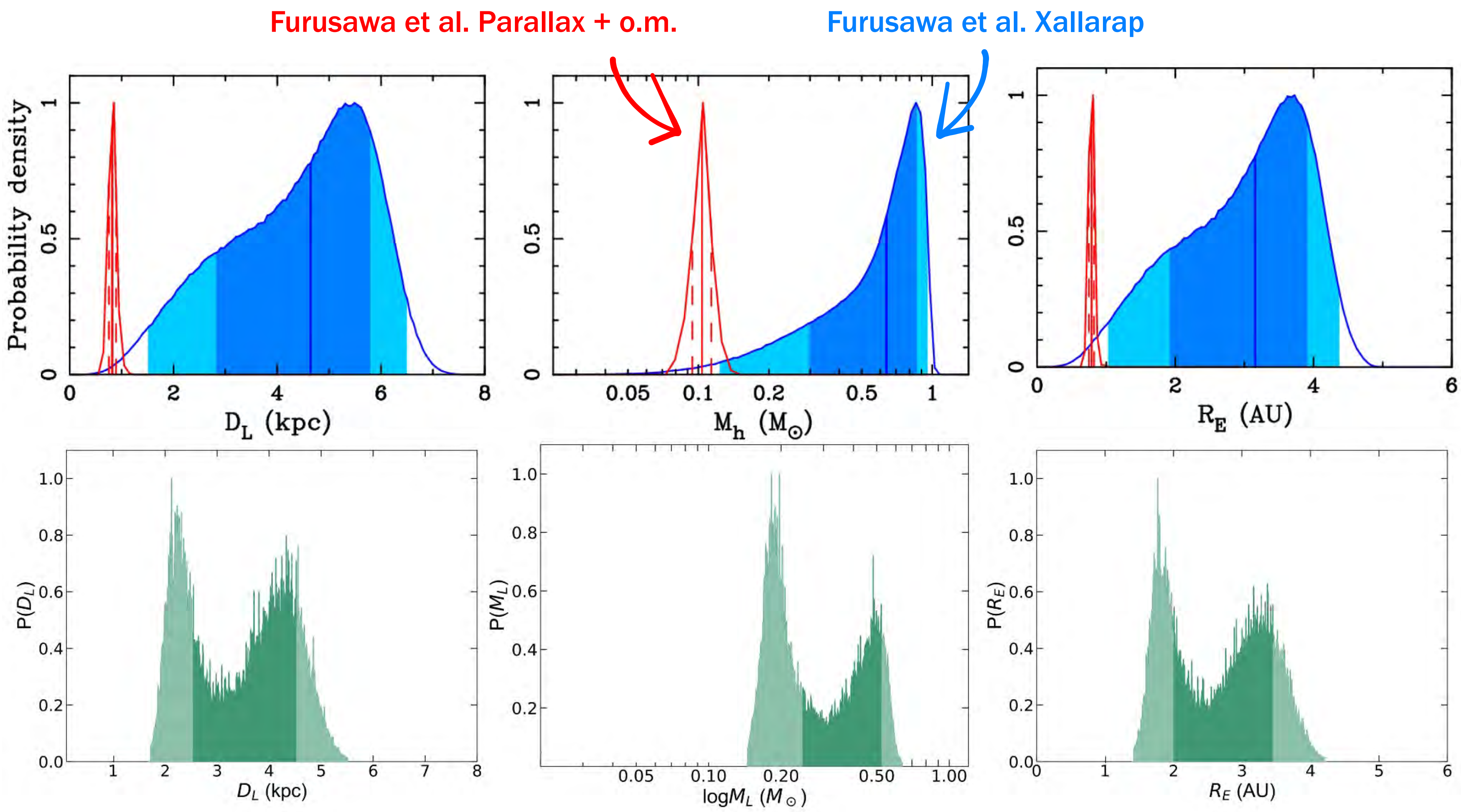
I-band

V-band

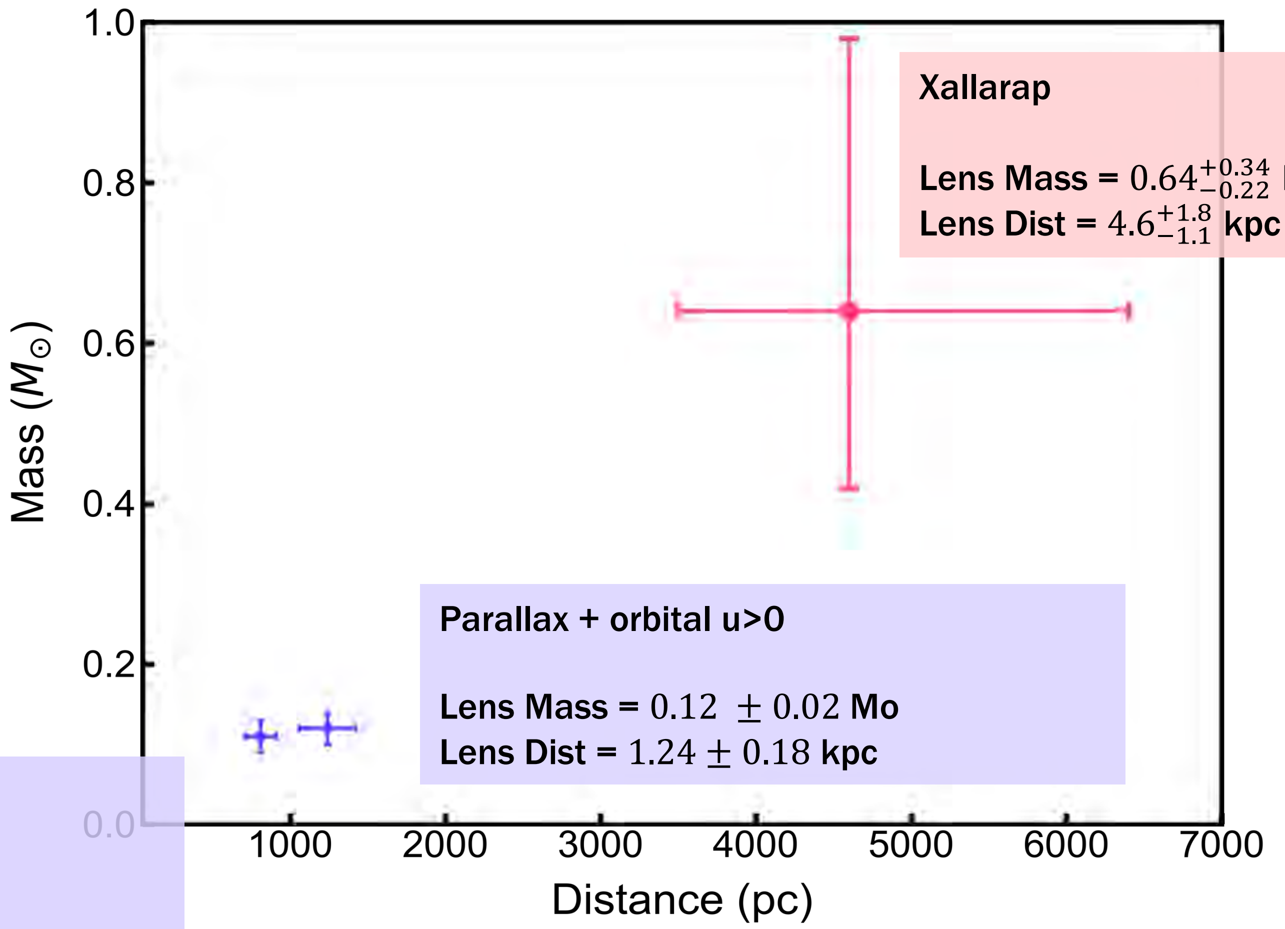


	Parallax + o.m. u<0	Parallax + o.m. u>0	Xallarap	Keck
Source K (mag)	17.14 +/- 0.25	17.14 +/- 0.26	17.13 +/- 0.26	16.12 +/- 0.16
Lens K (mag)	18.76 +/- 0.36	19.42 +/- 0.47	$18.50^{+1.25}_{-0.81}$	18.56 +/- 0.13
Mu_rel (mas/yr)	5.71 +/- 0.70	4.72 +/- 0.79	4.03 +/- 0.26	4.35 +/- 0.34

There is excess flux, likely due to a second source



New model – including parallax, orbital motion, xallarap, high-res constraints



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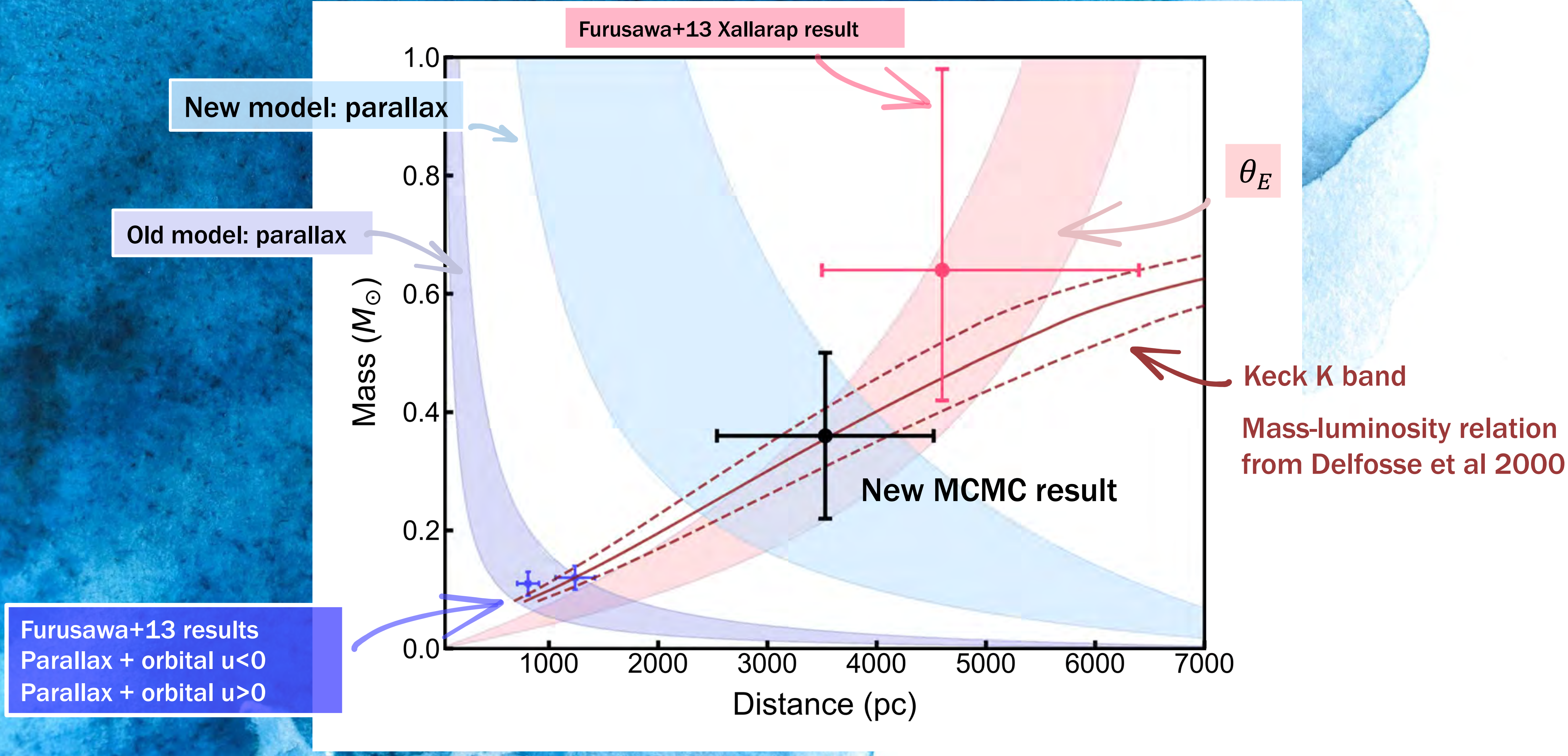
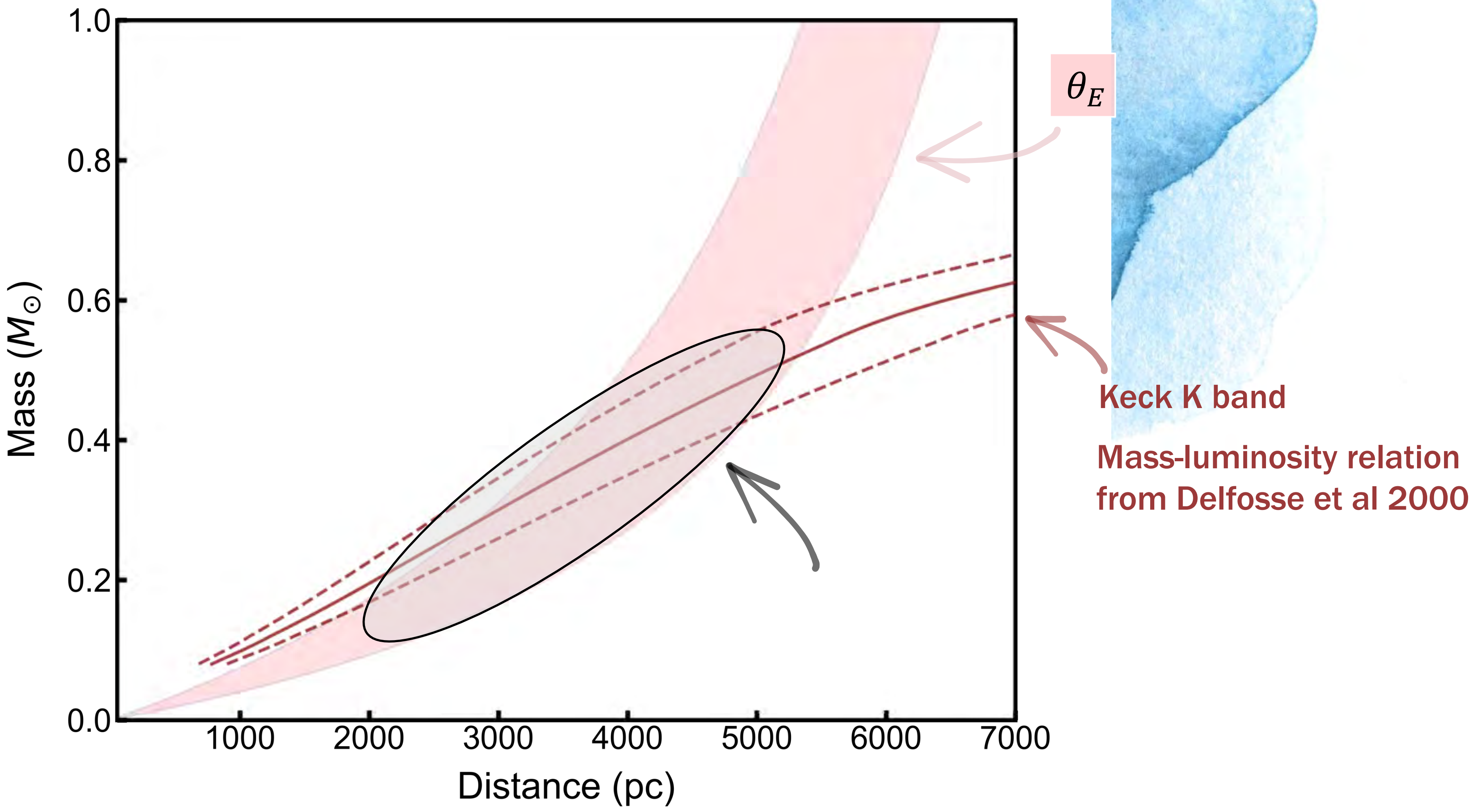


Furusawa+13 Xallarap result
New model: parallax
Old model: parallax
θ_E
Keck K band
Mass-luminosity relation
from Delfosse et al 2000
New MCMC result
Furusawa+13 results
Parallax + orbital u<0
Parallax + orbital u>0
Mass ($M_\odot$)
Distance (pc)
1.0
0.8
0.6
0.4
0.2
0.0
1000
2000
3000
4000
5000
6000
7000



1.0
0.8
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Mass ($M_\odot$)
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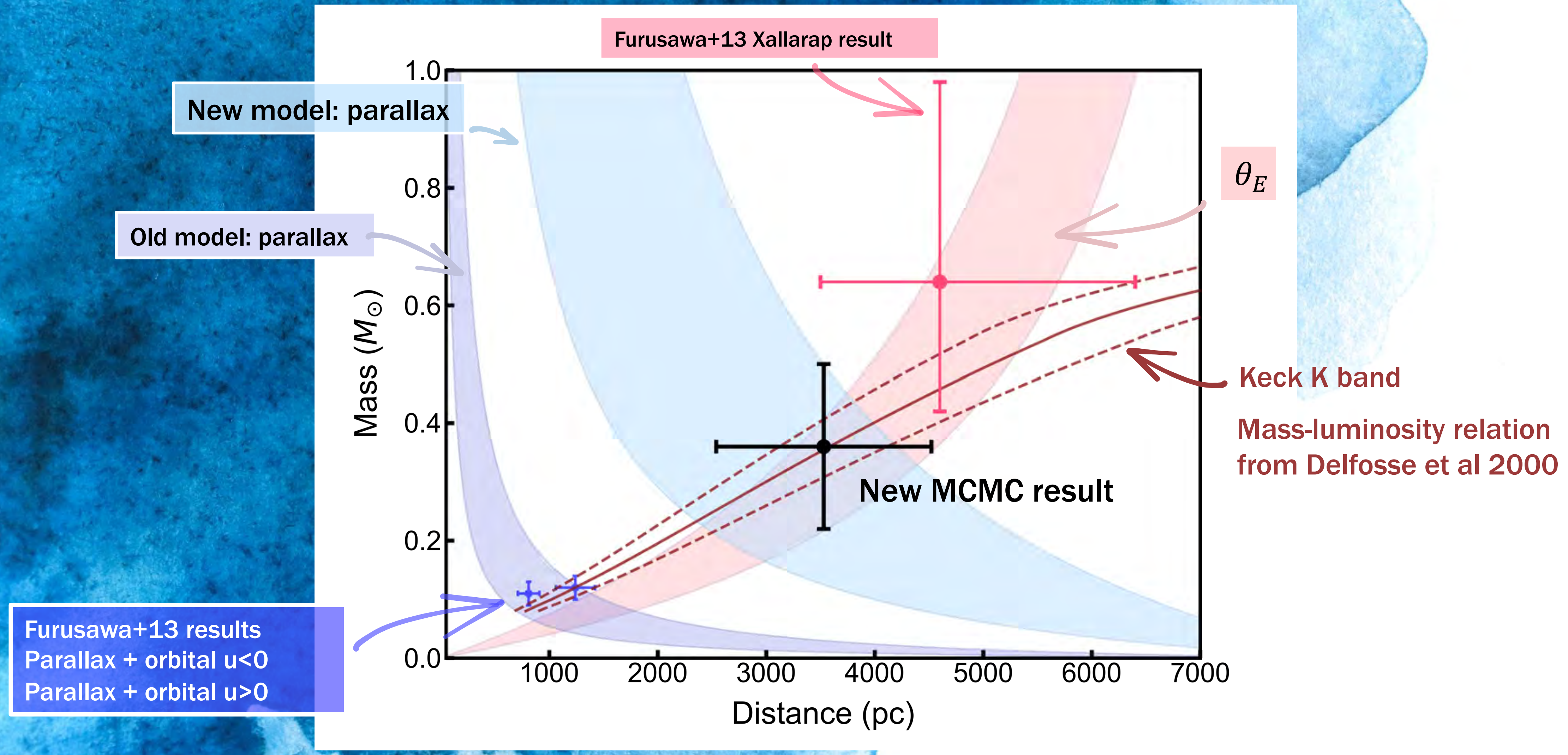

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Parallax + orbital u<0
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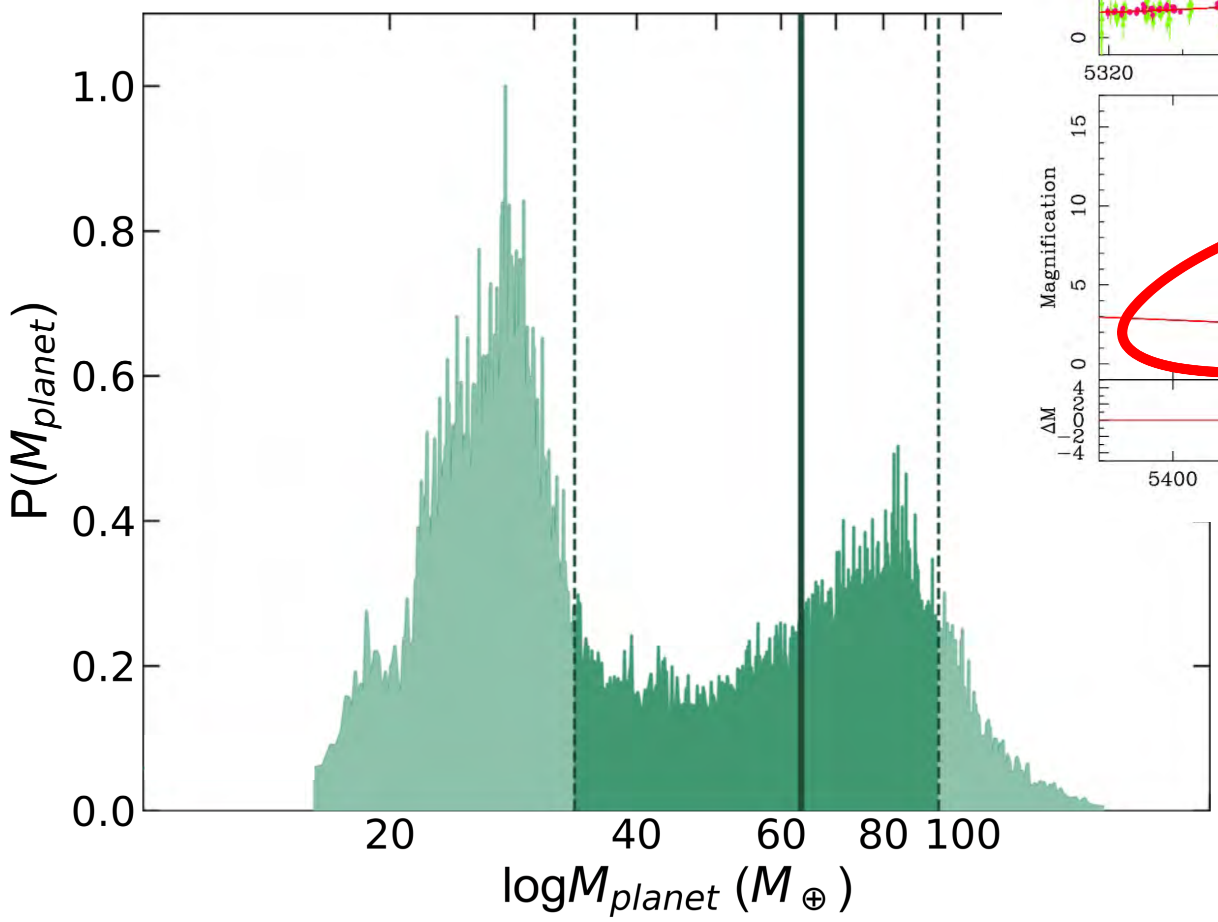
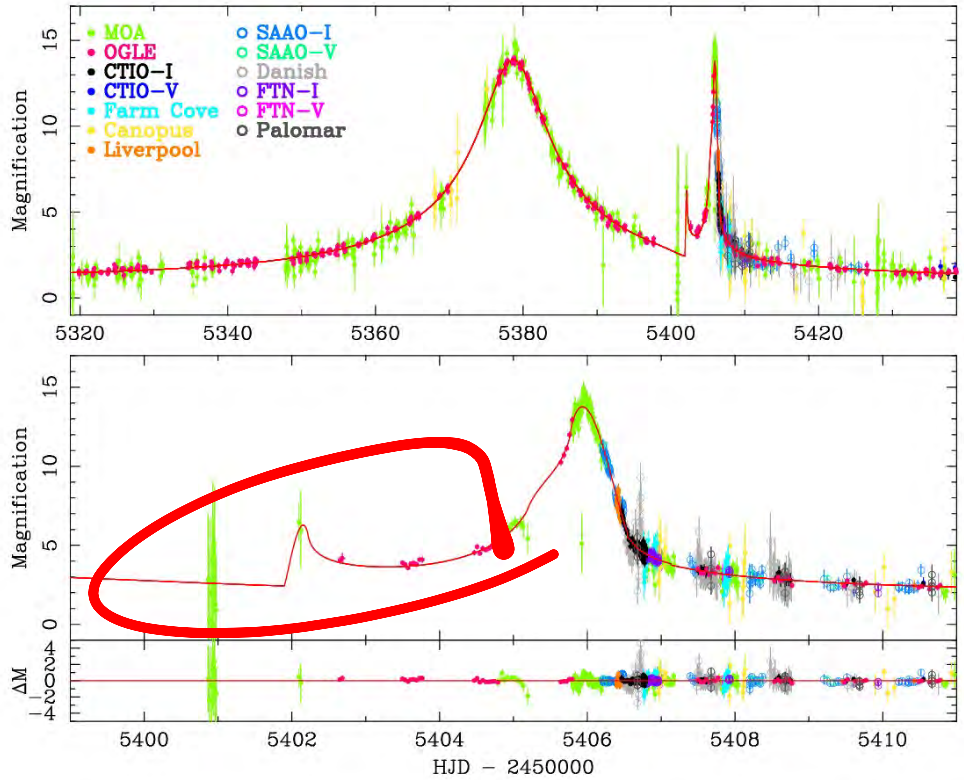
Distance (pc)

Furusawa et al. 2013





SUMMARY

- ✓ Modeling is important (but you already knew that)
- ✓ Higher order effects are important.
- ✓ Follow-ups and modeling together can give accurate mass/distance measurements.

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