MOA 2010-BLG-477Lb

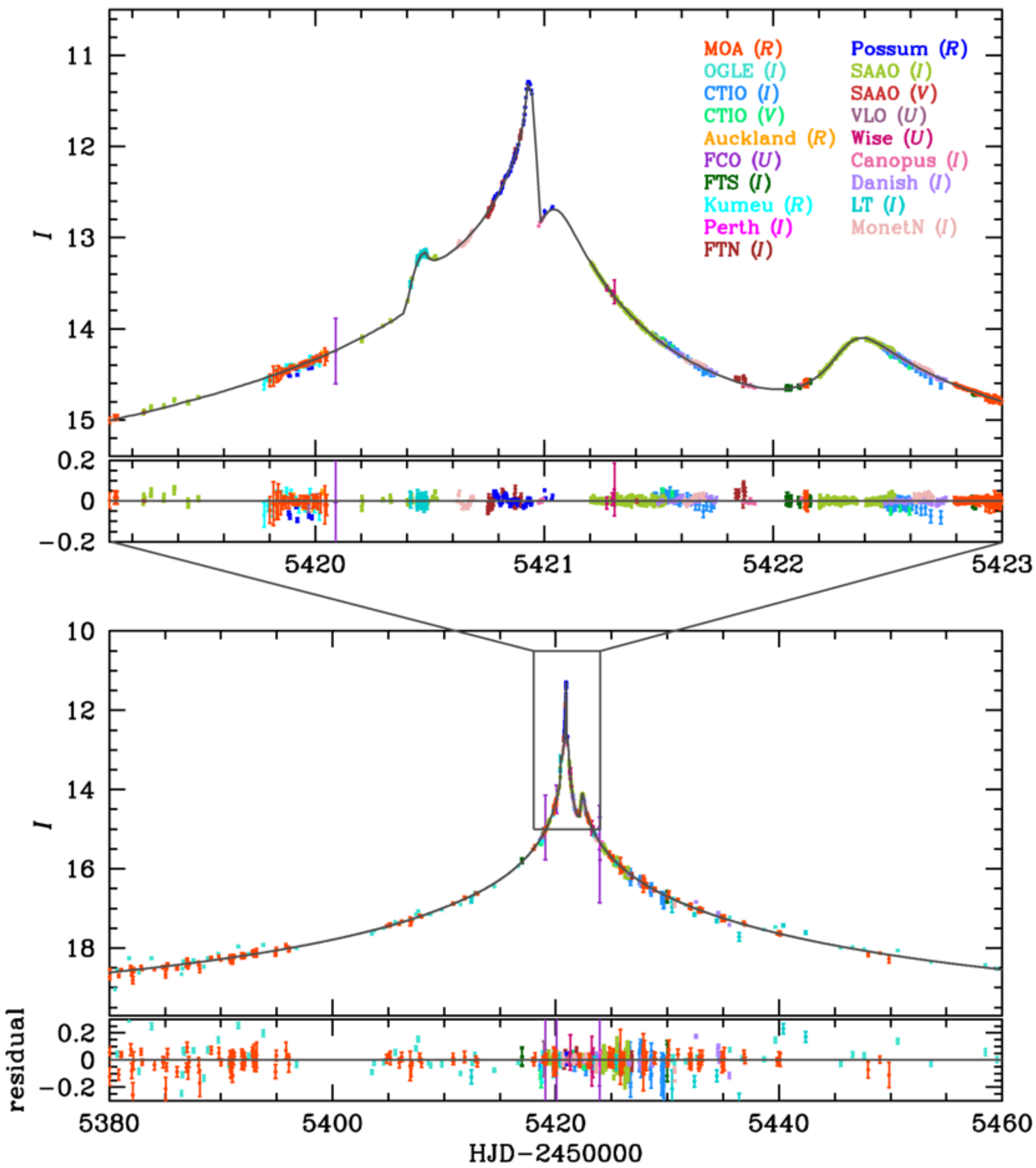
From planet detection to mass determination

Observations

- MOA August 2, 2010 (HJD′=5410.9)
- OGLE
- high magnification candidate
- follow-up: PLANET, μFUN, RoboNet, MiNDSTEp: >20 telescopes (⊃ASTEP Dome C)
- low-res spectrum at DuPont 2.5m
- IRSF and CTIO 2011

Image reduction

- off-line reduction with pySIS (image subtraction using numerical kernel) for 7 telescopes
- A_{max} = 400
- 2 spikes (5420.4, 5420.9), 2 bumps (5421.0, 5422.4)



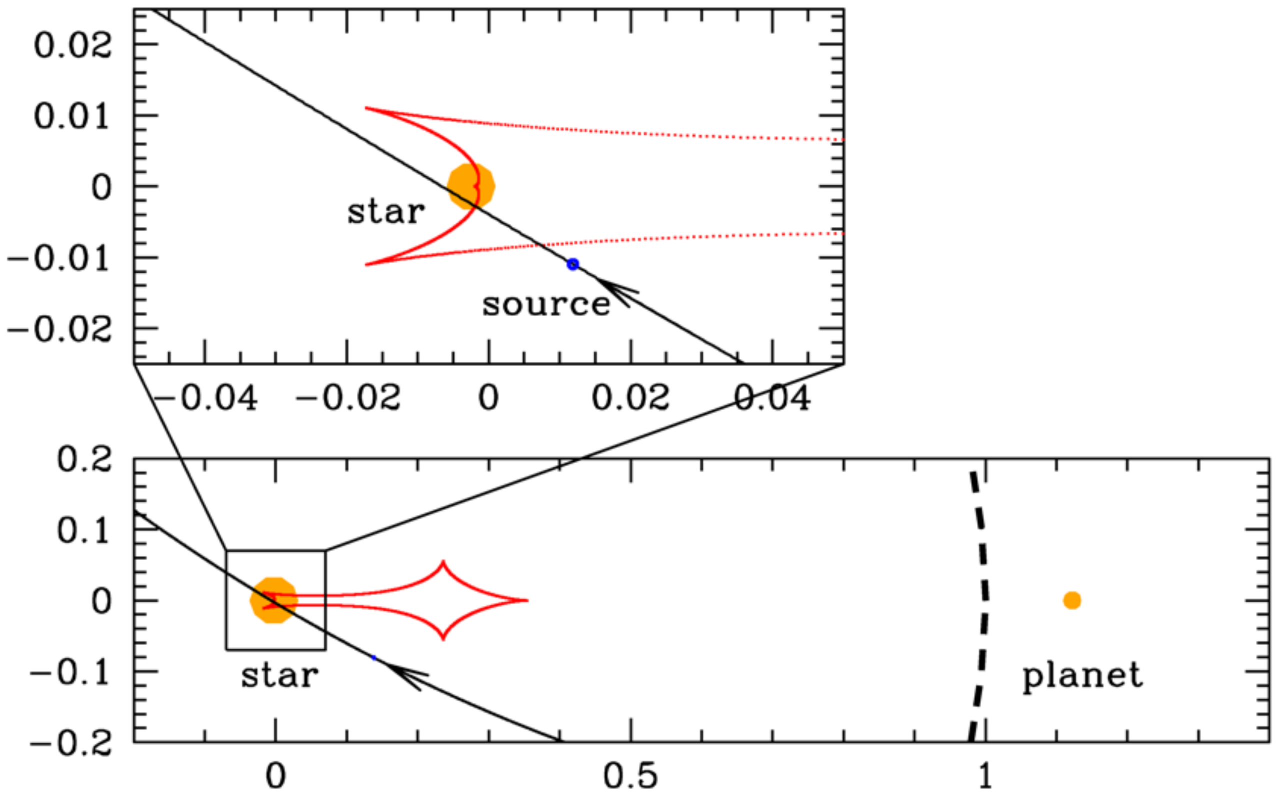
MOA (R)
OGLE (I)
CTIO (I)
CTIO (V)
Auckland (R)
FCO (U)
FTS (I)
Kumeu (R)
Perth (I)
FTN (I)
Possum (R)
SAAO (I)
SAAO (V)
VLO (U)
Wise (U)
Canopus (I)
Danish (I)
LT (I)
MonetN (I)
I
residual
HJD−2450000

Strategy for M

- Equations: $\theta_E^2 = \kappa\, \pi_{rel}\, M$ $\pi_E^2 = \dfrac{\pi_{rel}}{\kappa\, M}$
- As θ_E is well-determined, but not π_E, M cannot be well measured
- θ_E is large, so either M large or D_L small; both imply bright lens, but no detection; this gives upper limits both to M and D_L
- An upper limit on π_E provides lower limits on lens mass and distance

Modeling

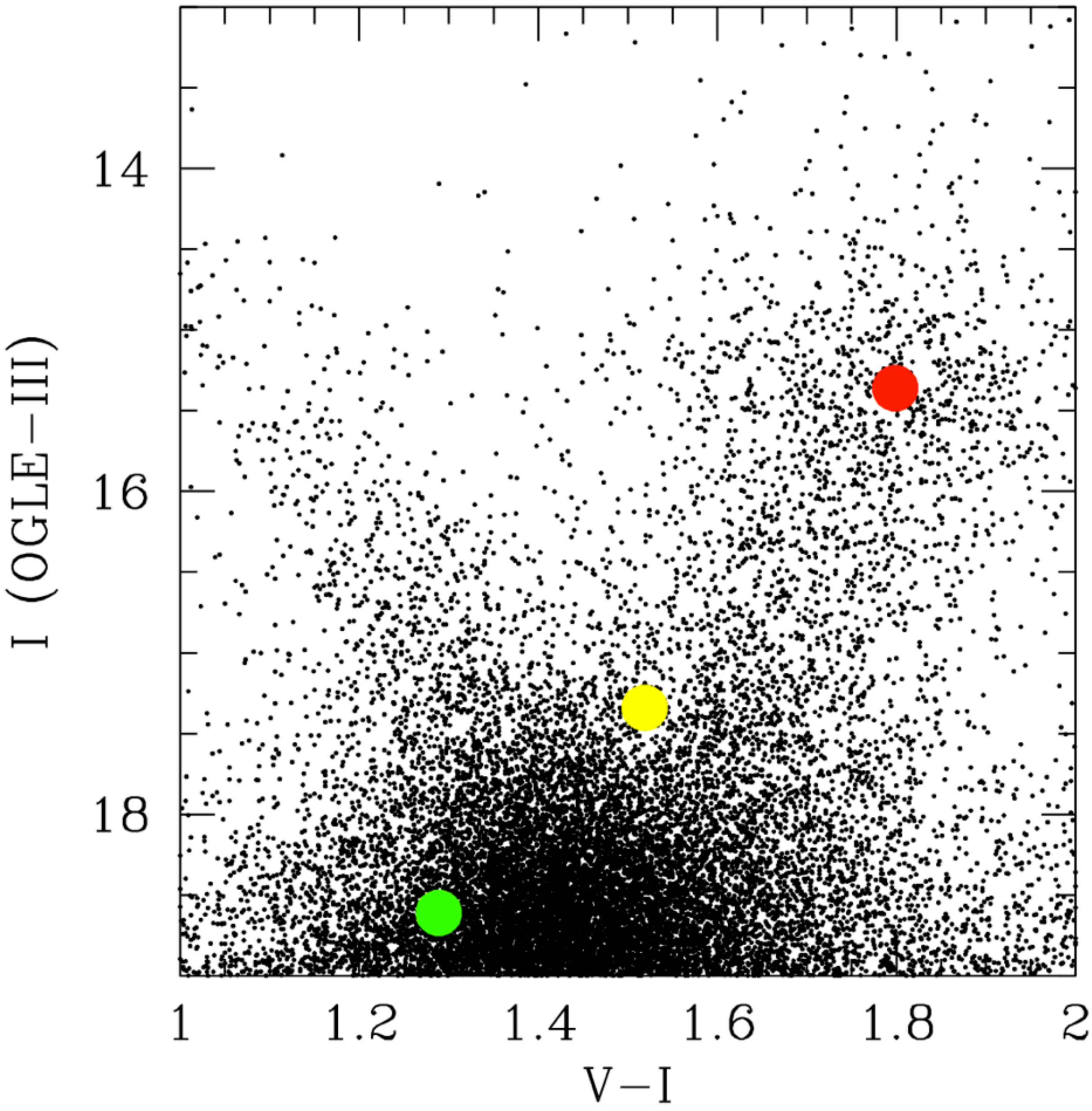
- Importance of a correct assessment of photometric errors: rescaling scheme
- Finite-source effect and limb darkening
- Static binary model: first step: grid search (s, q, α) + downhill χ^2 minimization (MCMC)
- Result: only one minimum: s=1.12, q=0.0024
- Second step: MCMC for all 7 parameters
- Second-order effects: microlensing parallax and orbital motion



0.02
0.01
0
−0.01
−0.02
star
source
−0.04
−0.02
0
0.02
0.04
0.2
0.1
0
−0.1
−0.2
star
planet
0
0.5
1

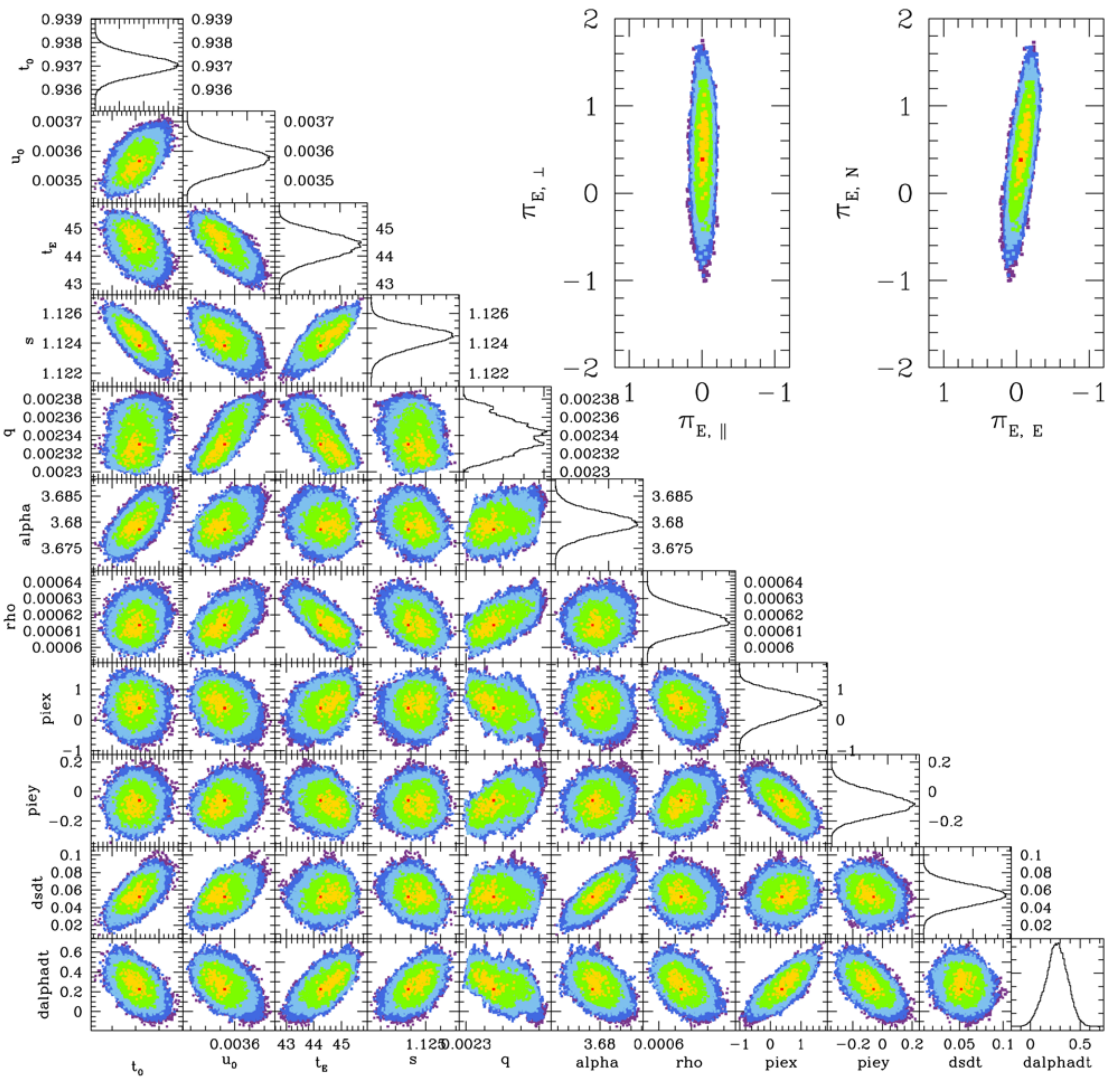
Measurement of θ_E

- spectrum: T_{eff} = 5950 ± 150 K, log g = 4.0 assuming solar metallicity; corresponds to $(V-I)_0 = 0.65 \pm 0.04$
- red clump method: $(V-I)_0 = 0.55 \pm 0.05$
- surface-brightness method then gives angular source radius: $\theta_* = 0.79 \pm 0.06$ μas
- model gives $\rho_* = 5.76\ (3)\ 10^{-4}$
- so $\theta_E = 1.38 \pm 0.11$ mas and $M\pi_{rel} = 0.233 \pm 0.036$


I (OGLE−III)
14
16
18
1
1.2
1.4
1.6
1.8
2
V−I

Parallax and orbital motion

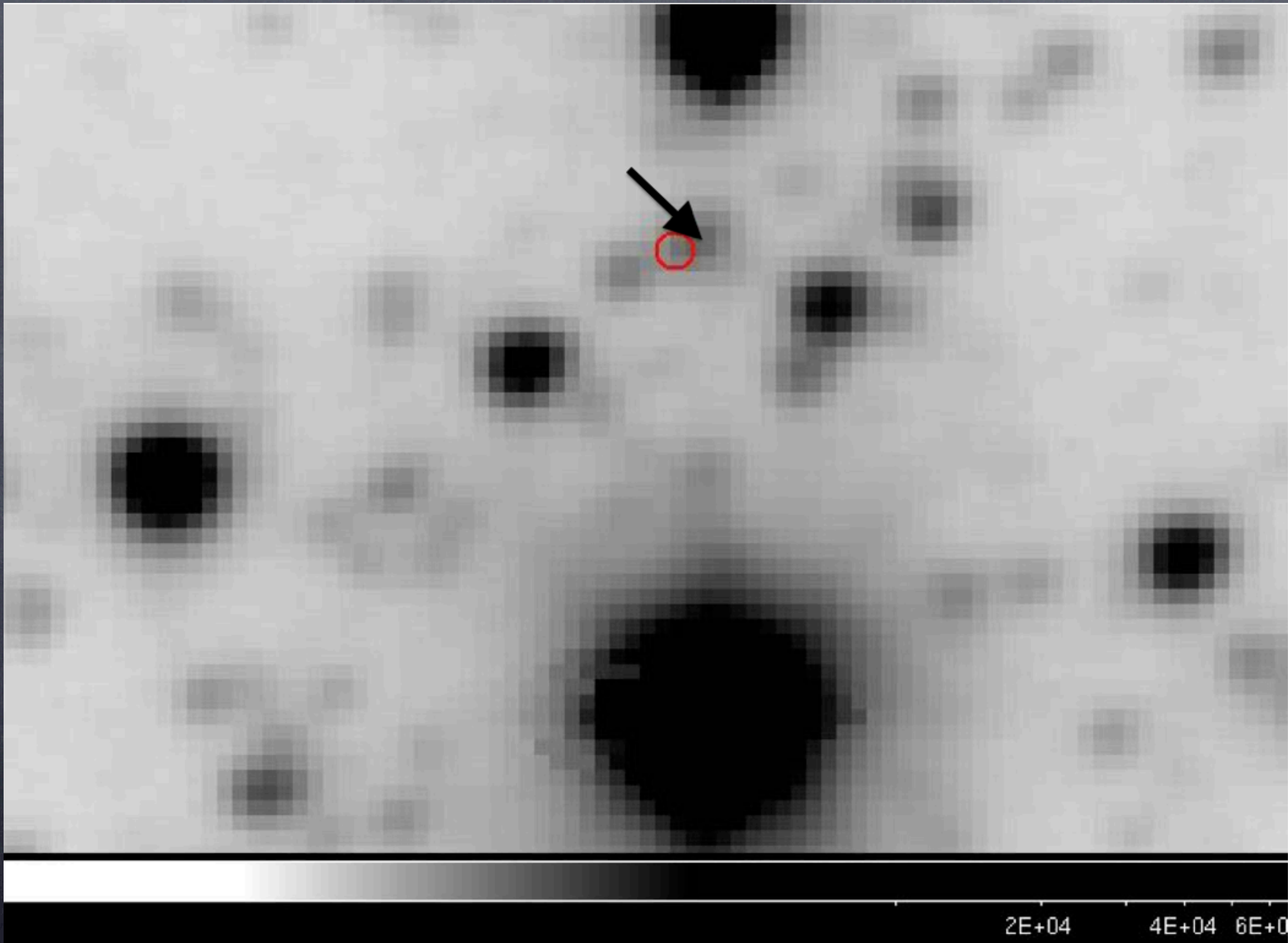
- Two independent modeling efforts: ours: ω, ds/dt and posterior check of bound orbit, vs. Bennett (circular orbit of period T_{orb})
- Post-bayesian analysis from raw MCMC adding Galactic model and Keplerian constraints



t_0
u_0
t_E
s
q
alpha
rho
piex
piey
dsdt
dalphadt
$\pi_{E,\perp}$
$\pi_{E,\parallel}$
$\pi_{E,N}$
$\pi_{E,E}$

Lens flux limits

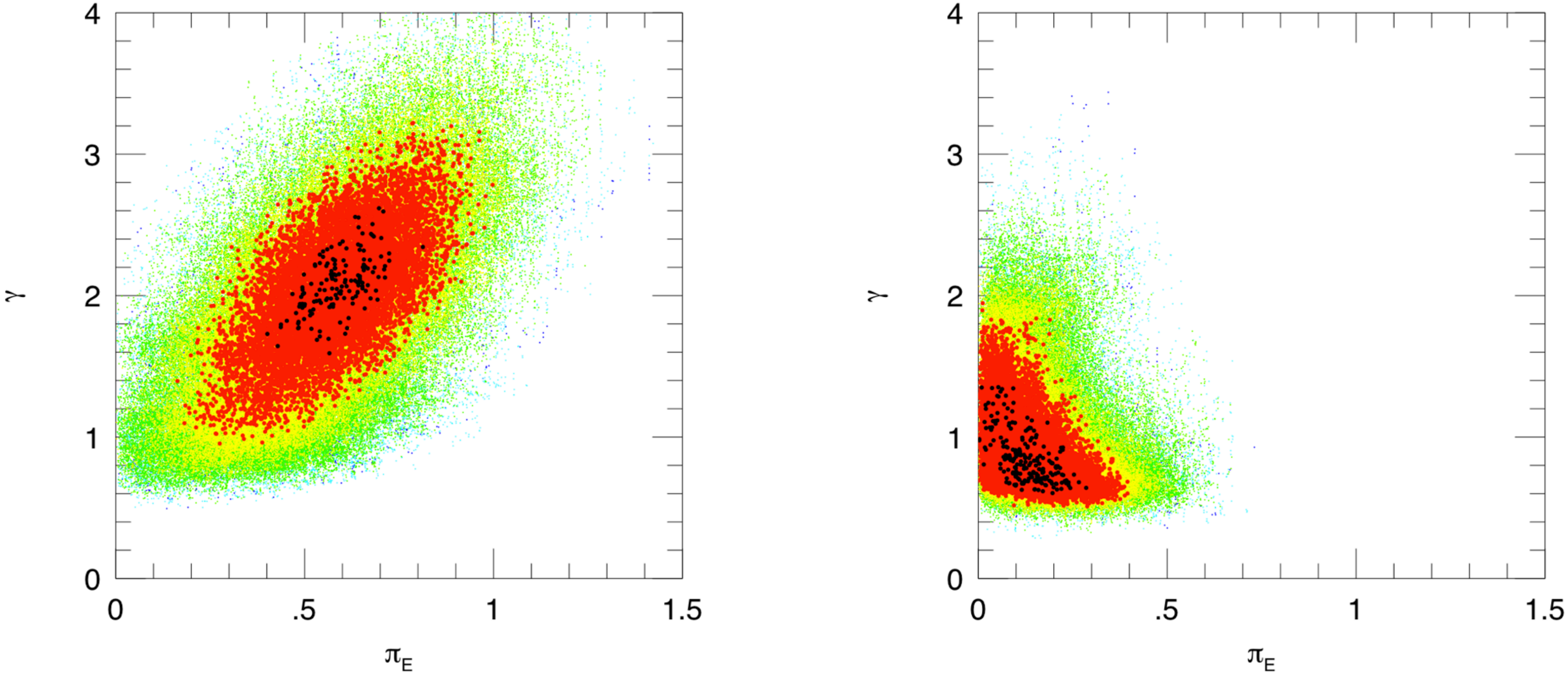
- measured blend corresponds exactly to an OGLE-III star: I=17.446±0.052 vs. I_b=17.443±0.031: no contribution from lens
- analysis of good-seeing OGLE-III images spanning 3.3 yr shows no residual at target position: given the large relative proper motion (10.3±0.8 mas/yr), this again proves the faintness of the lens
- conclusion: $M < 1\ M_{sun}$, so $D_L < 2.8$ kpc



2E+04
4E+04
6E+0

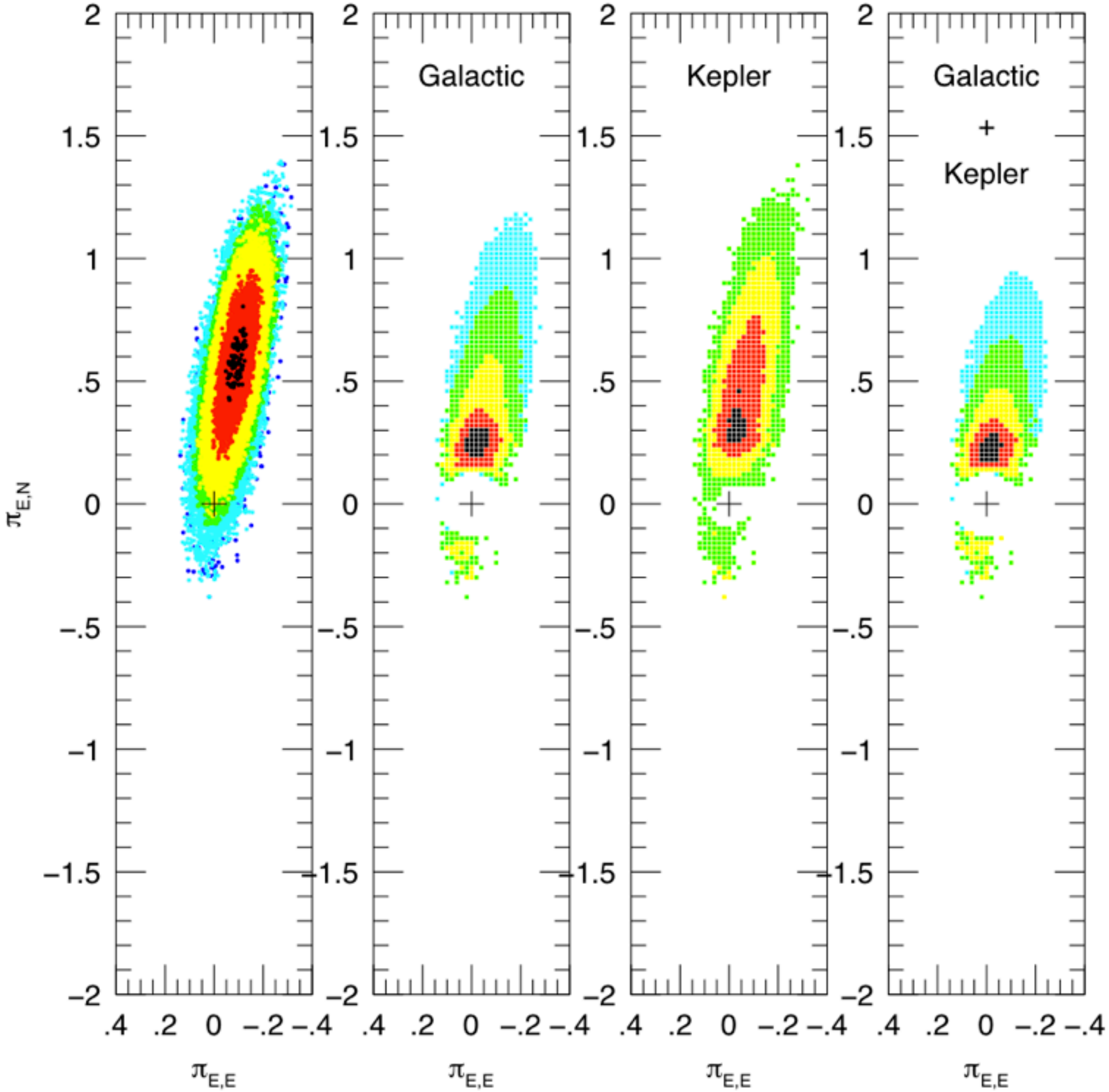
Constraints from parallax

- parallax-only model improves χ^2 by 8.6 only
- parallax and orbital motion model improves it by 54.4: second-order effects are detected
- confirmed by differences between $u_0>0$ and $u_0<0$ solutions
- but difficult to disentangle: degeneracy $\pi_{E,perp}$ and ω: both correspond to a trajectory curvature
- lightcurve excludes $\pi_E > 1.3$, so $M > 0.13\ M_{sun}$ and $D_L > 0.5$ kpc


4
3
2
1
0
γ
0
.5
1
1.5
π_E
4
3
2
1
0
γ
0
.5
1
1.5
π_E

Post-bayesian analysis

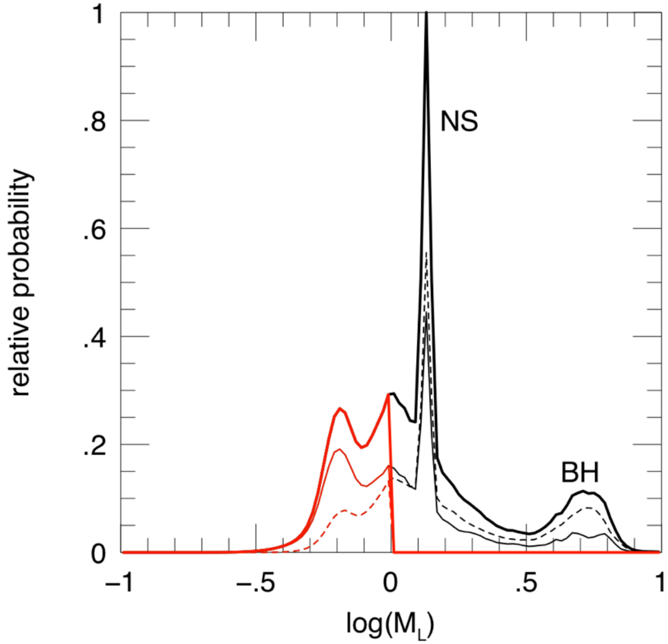
- Galactic model, Jacobian transformations and Keplerian constraints as used in Batista et al. (2011)
- Independently favor large lens mass and distance, but must remain compatible with lens flux limits

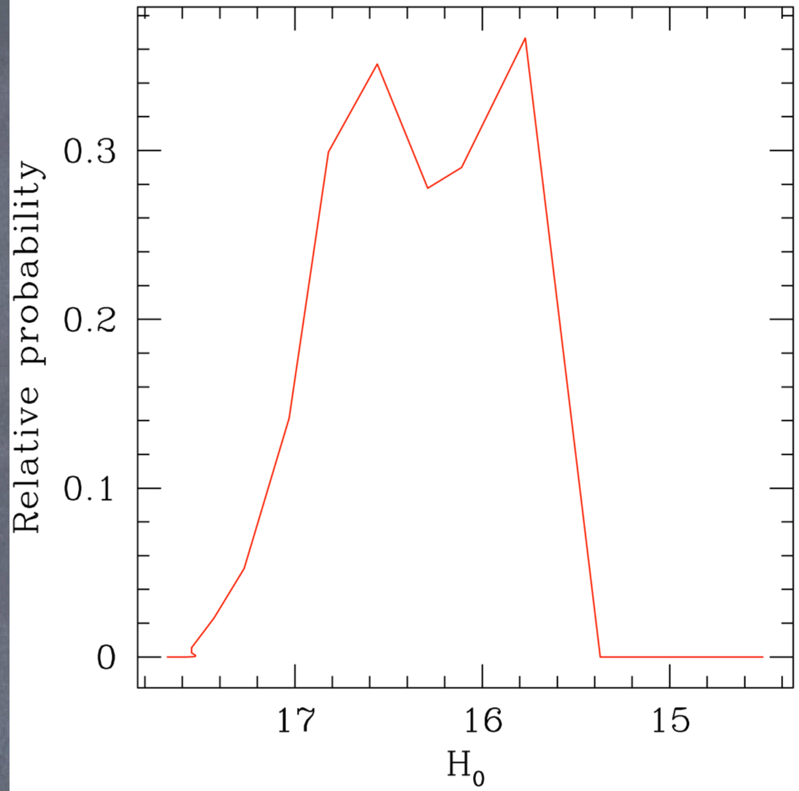


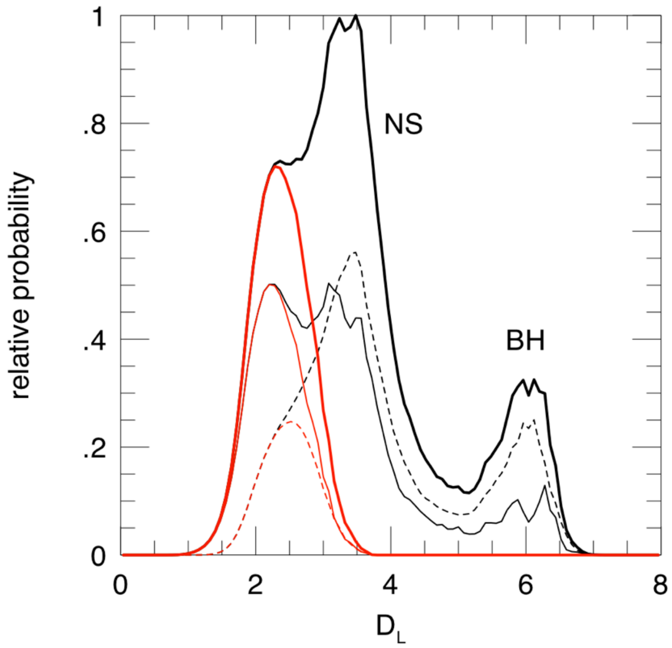
Galactic
Kepler
Galactic
+
Kepler
$\pi_{E,N}$
$\pi_{E,E}$

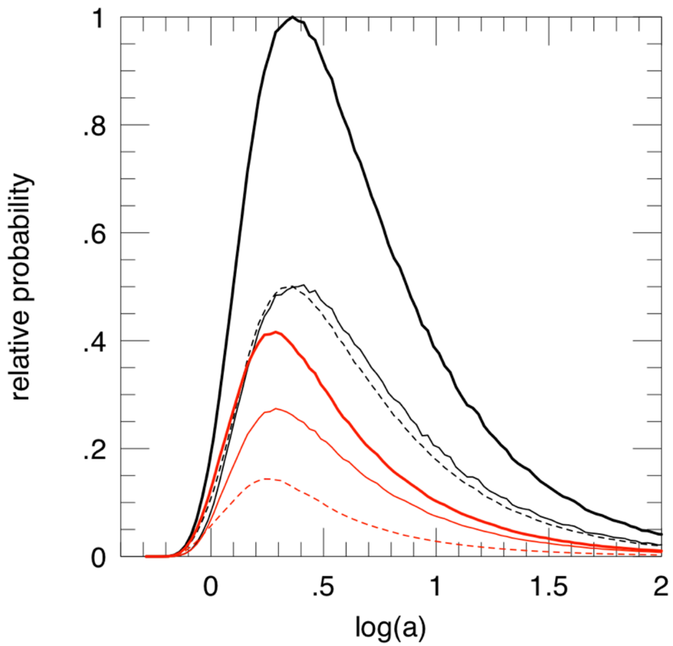
Conclusions

- mass distribution peaks at $M_L=0.67^{+0.33}_{-0.13}$ corresponding to $M_p=1.5^{+0.8}_{-0.3}$ M_{JUP}
- lens distance: $D_L=2.3\pm0.6$ kpc
- semi-major axis a between 1 and 5 AU


NS
BH
relative probability
log(M_L)


Relative probability
H_0


NS
BH
relative probability
D_L


relative probability
log(a)

Perspectives

- adaptive optics telescope time obtained at Keck, VLT and Subaru to measure the lens +source flux: 0.5 M_{sun} lens as bright as source, 0.1 M_{sun} lens produces 0.5 mag additional light
- very sensitive to third body (similar to OGLE 2006-BLG-109Lbc)
- second-order effects degeneracy shows the need of very accurate photometry, probably only obtainable from space (WFIRST, EUCLID)