Getting Physical Parameters and Mass Measurements

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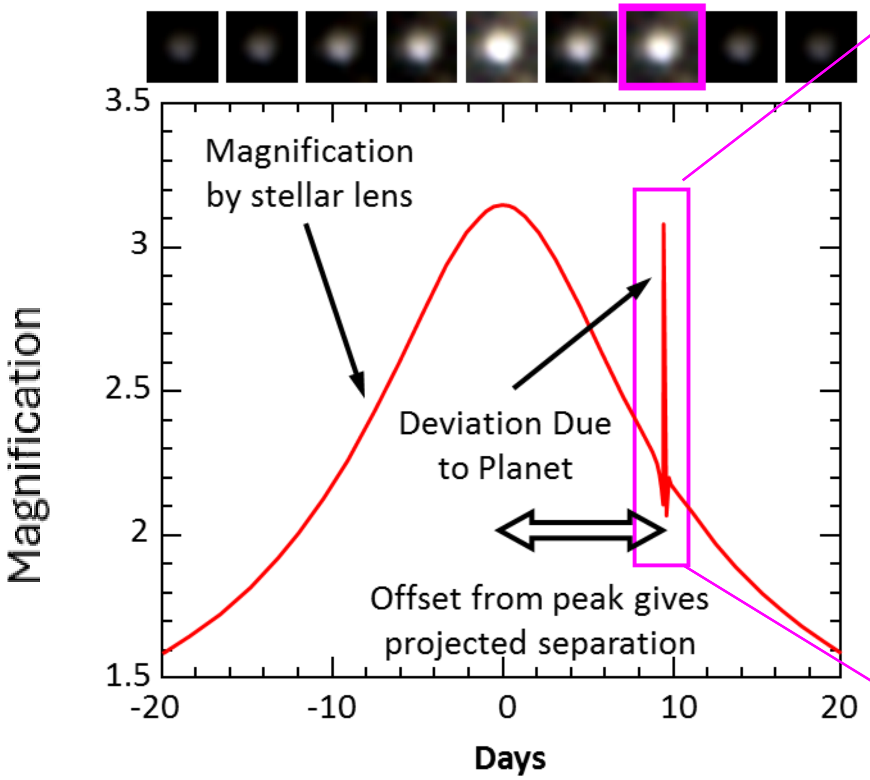
Sagan Workshop 2026

Extraction of Exoplanet Parameters: Part 1



Predicts q (planet-star mass ratio), s(projected separation between planet-star in Einstein radius), finite source effect, relative Lens-Source proper motion μ_{rel}, angular Einstein radius θ_E

Lens system is almost never seen from ground based survey data

Getting physical parameters:

- Mass ratio q
- Planet/star separation s in Einstein Ring radius units
- Einstein angular radius θ_E

From microlensing planetary light curve fitting

We need any 2 of these 3 relations to get physical parameters:

- Mass- distance from Einstein ring radius measurements (finite source effect)
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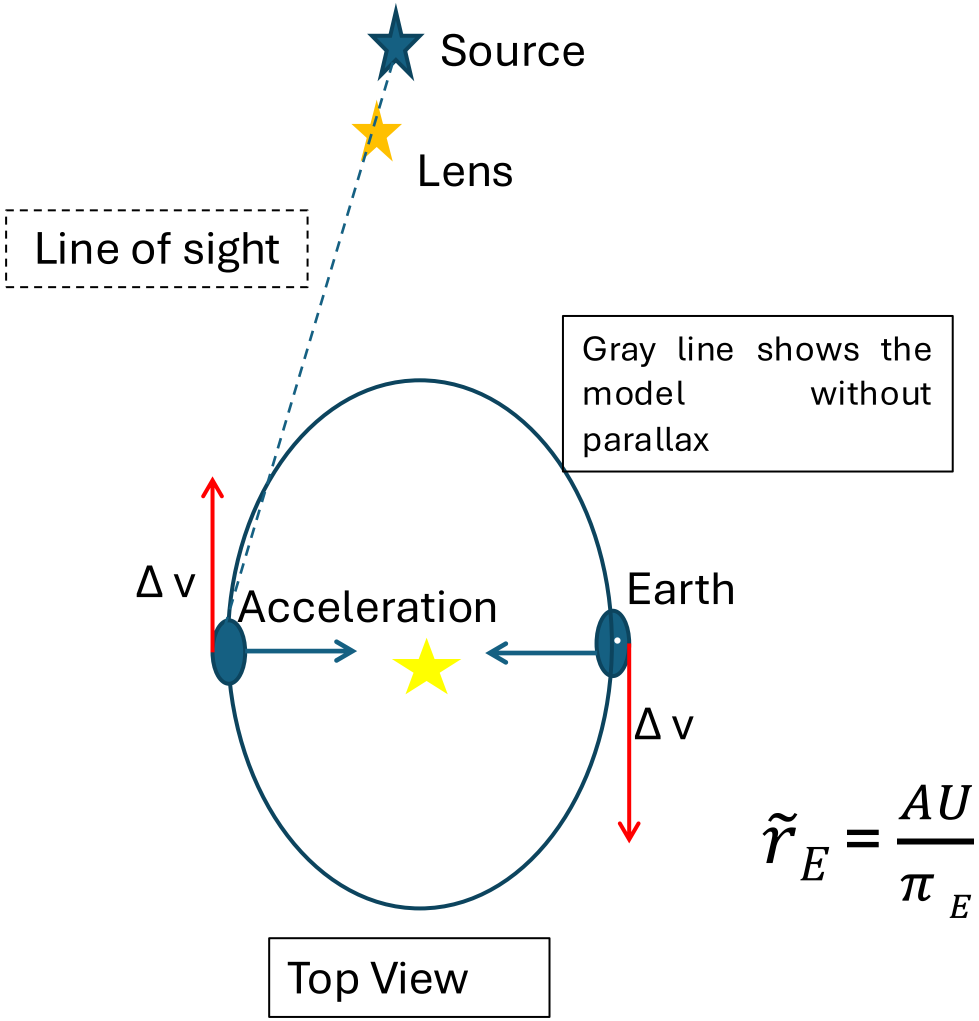
Extraction of Exoplanet Parameters: Annual Parallax



$$\tilde{r}_E = \frac{AU}{\pi_E}$$

$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

$$\times$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E \theta_E$$

$$M_P = q\ ML$$

Muraki et al 2011, ApJ 741, 22

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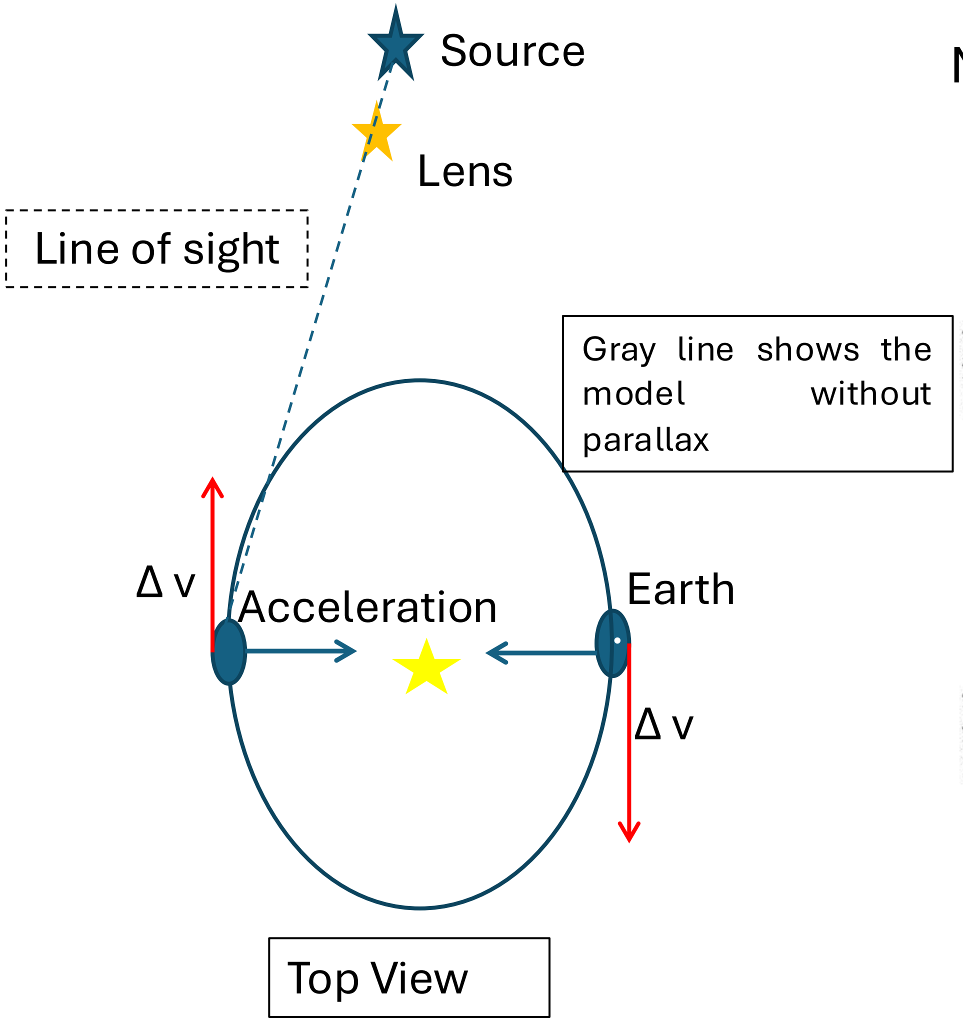
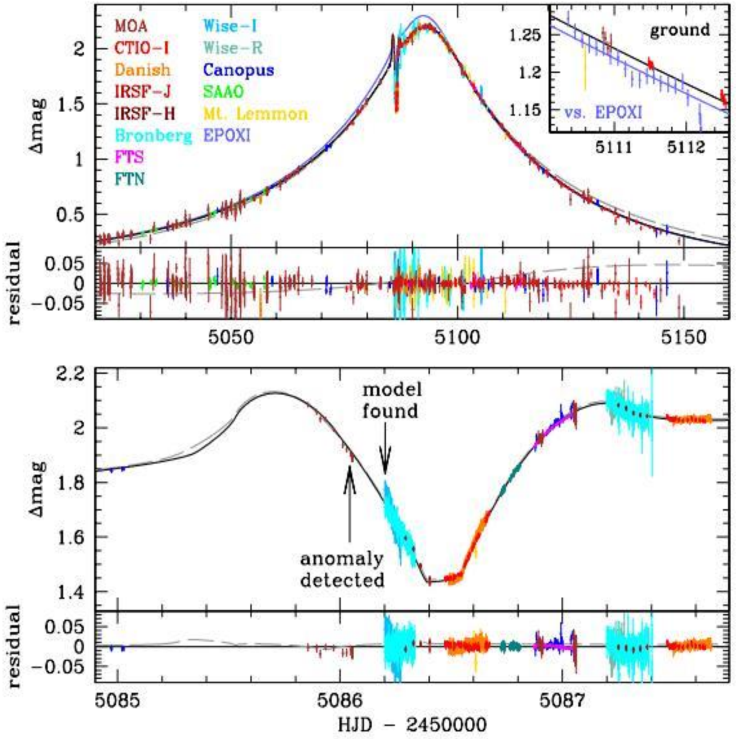


MOA-2009-BLG-266



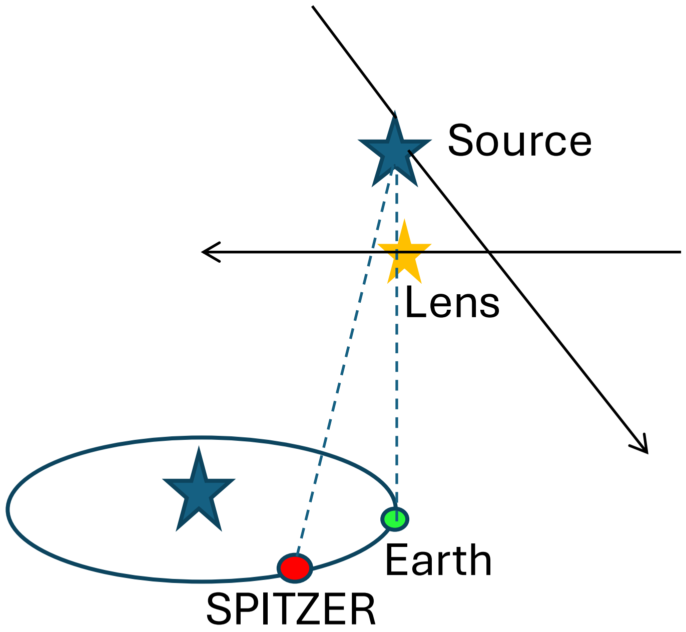
$M_H = 0.56 \pm 0.09\ M_\odot$

$M_P = 10.4 \pm 1.7\ M_\oplus$

$a_\perp = 3.2^{+1.9}_{-0.5}$ AU

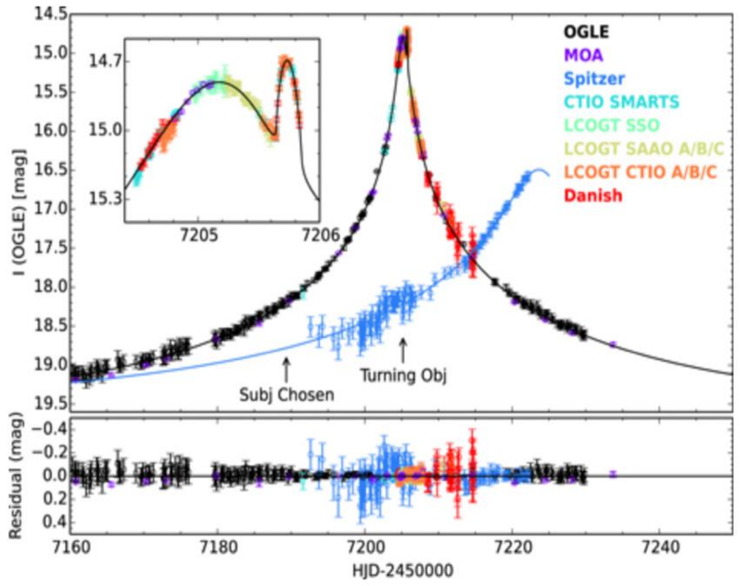
Muraki et al 2011, ApJ 741, 22

Microlensing with SPITZER



Satellite Parallax

OGLE-2015-BLG-0966



Results: $M_H = 0.38\ M_\odot$

$M_P = 21\ M_\oplus$

Street+, 2016, ApJ, 819

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Observation from High resolution Telescopes

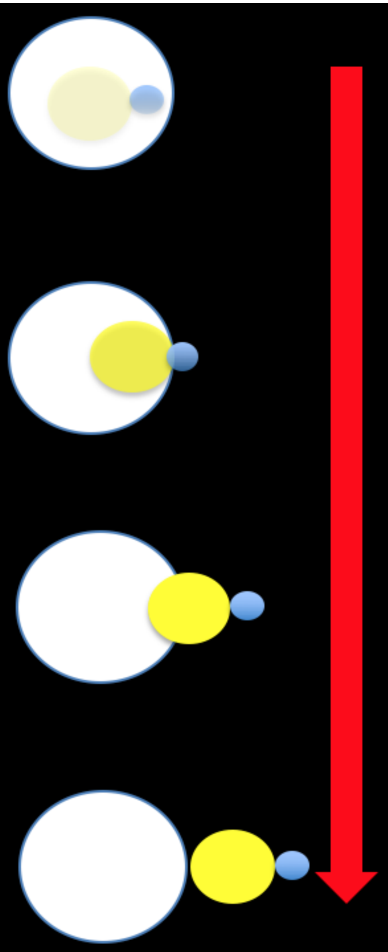
Light from source is still bent due to gravity

During the event

Few months after

5-6 years later

A decade later



Source

Lens Host Star

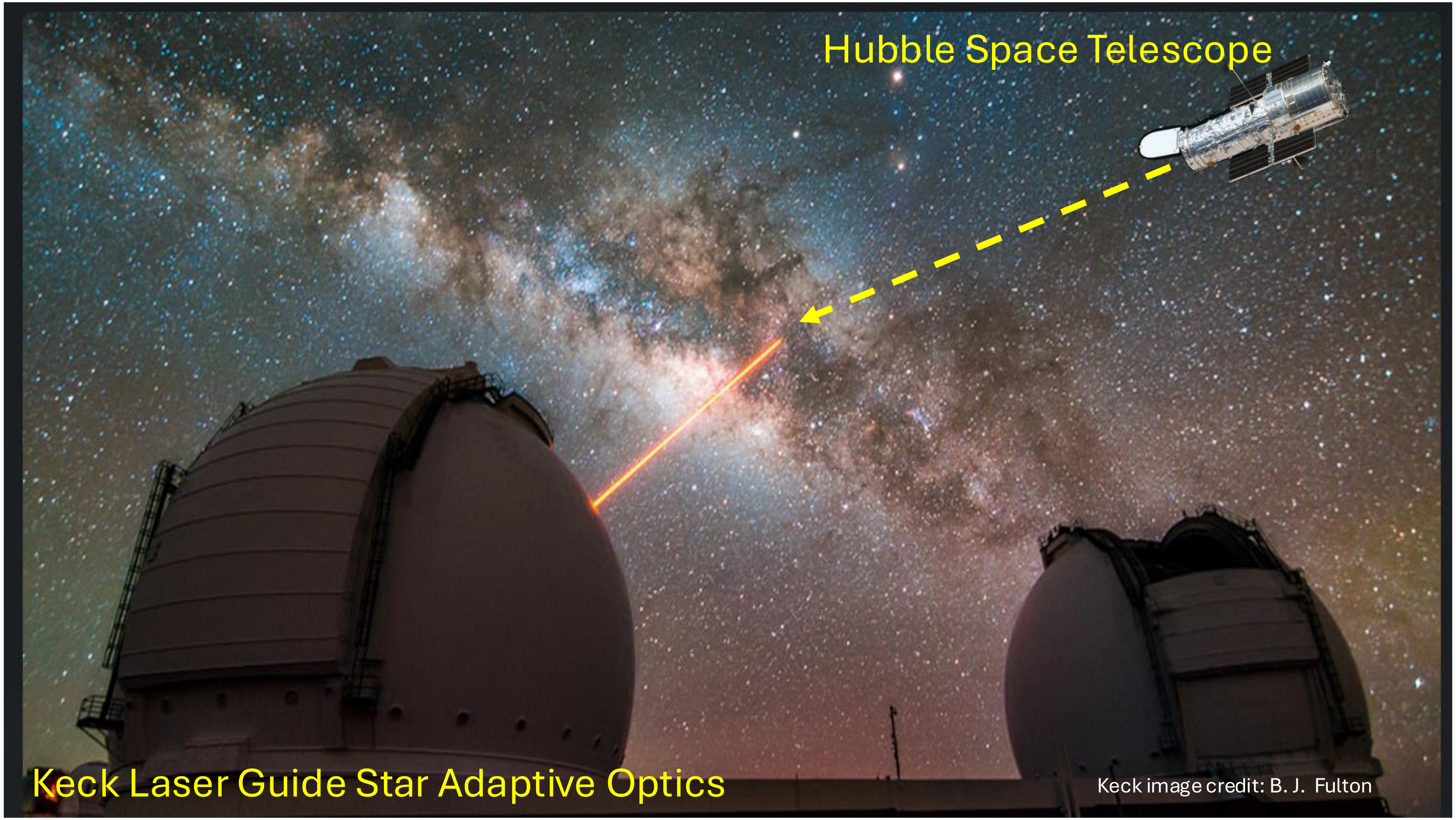
Planet

Time increasing

Roman will observe multi epoch data in multiple passbands high resolution to measure mass during the primary mission – no follow-up needed.

This is when high res follow up obs taken

Near Simultaneous HST-Keck observation program (May 22-23, 2018)

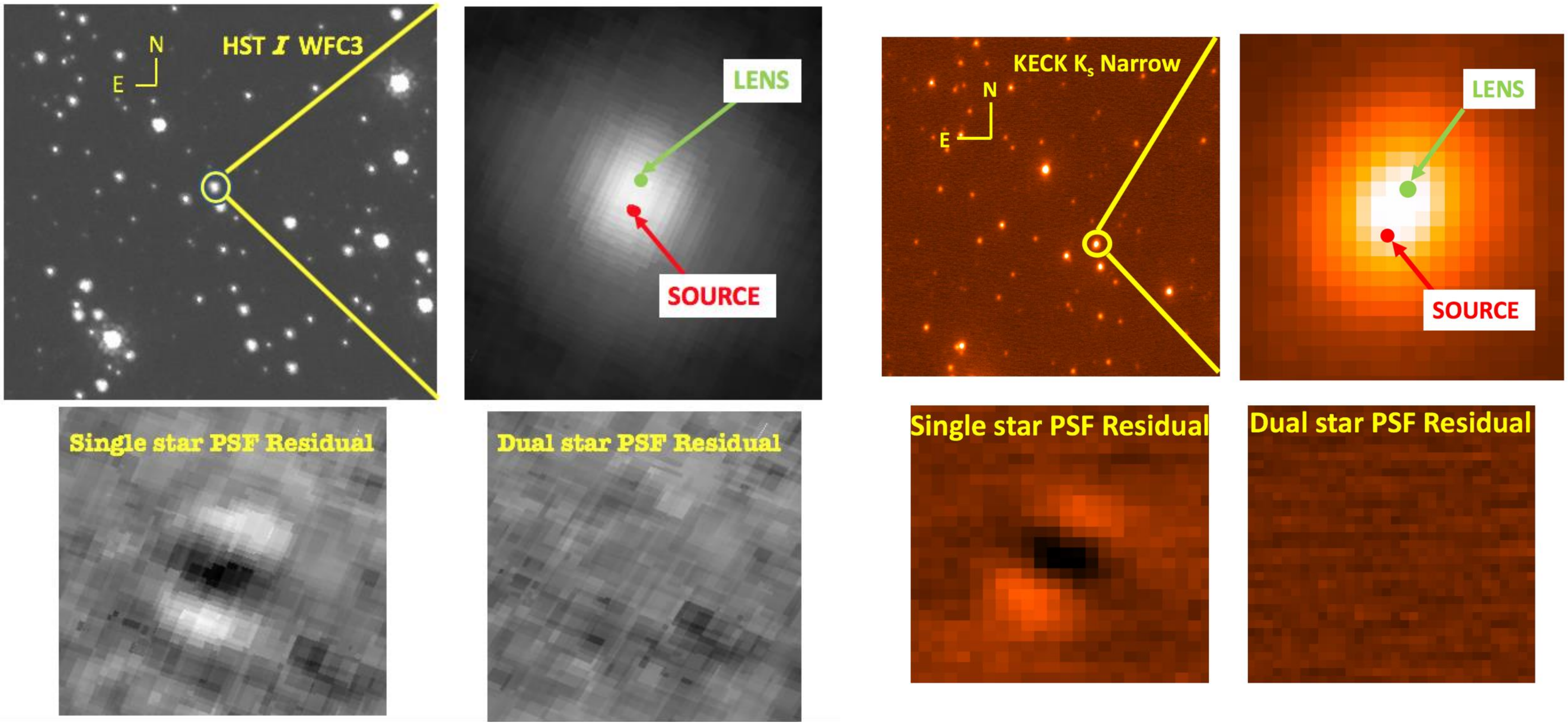


HST and Keck :

Two different methods to detect lens and measure Lens-Source Proper motion, μ_{rel} :

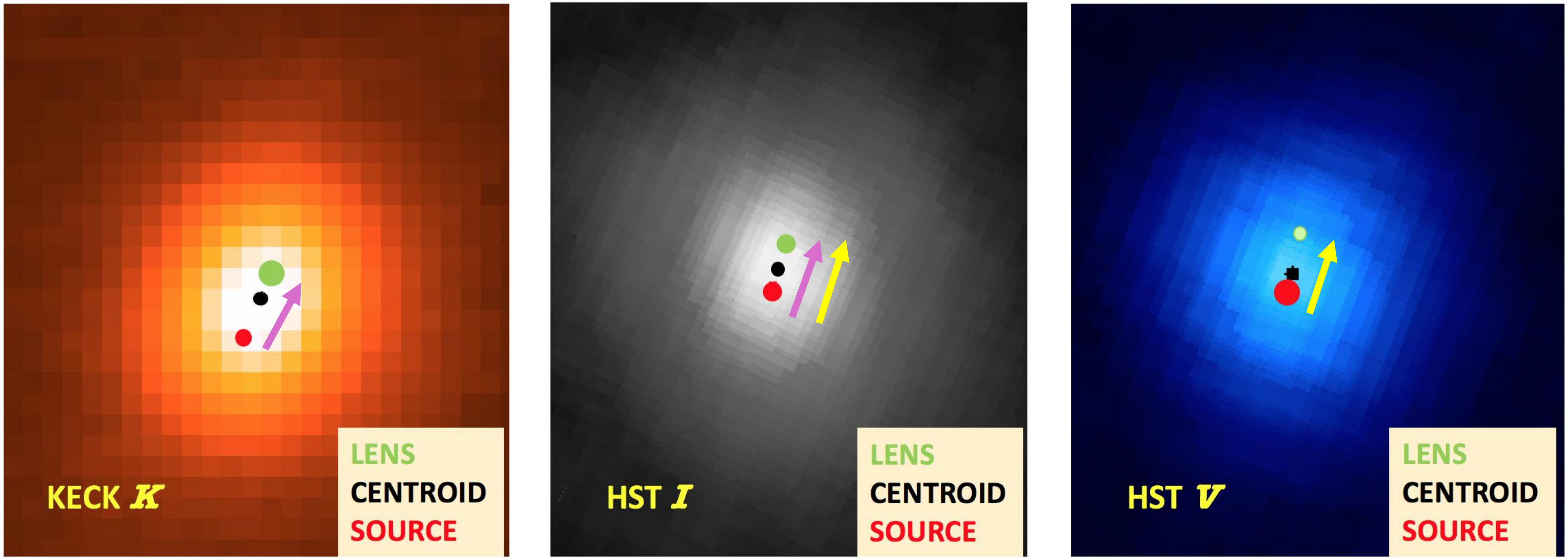
- Color Dependent Centroid shift
  - If lens and source have different colors, the centroid of the blended image will depend on the color
- Image Elongation:
  - Blended image will be elongated in the μ_{rel} direction
  - works if lens and source have the same color
  - Stable PSF allows clear detection of PSF elongation signal

PSF = Point Spread Function


HST I WFC3
N
E
LENS
SOURCE
Single star PSF Residual
Dual star PSF Residual
KECK K_s Narrow
N
E
LENS
SOURCE
Single star PSF Residual
Dual star PSF Residual

OGLE-2012-BLG-0950

Bhattacharya+ 2018



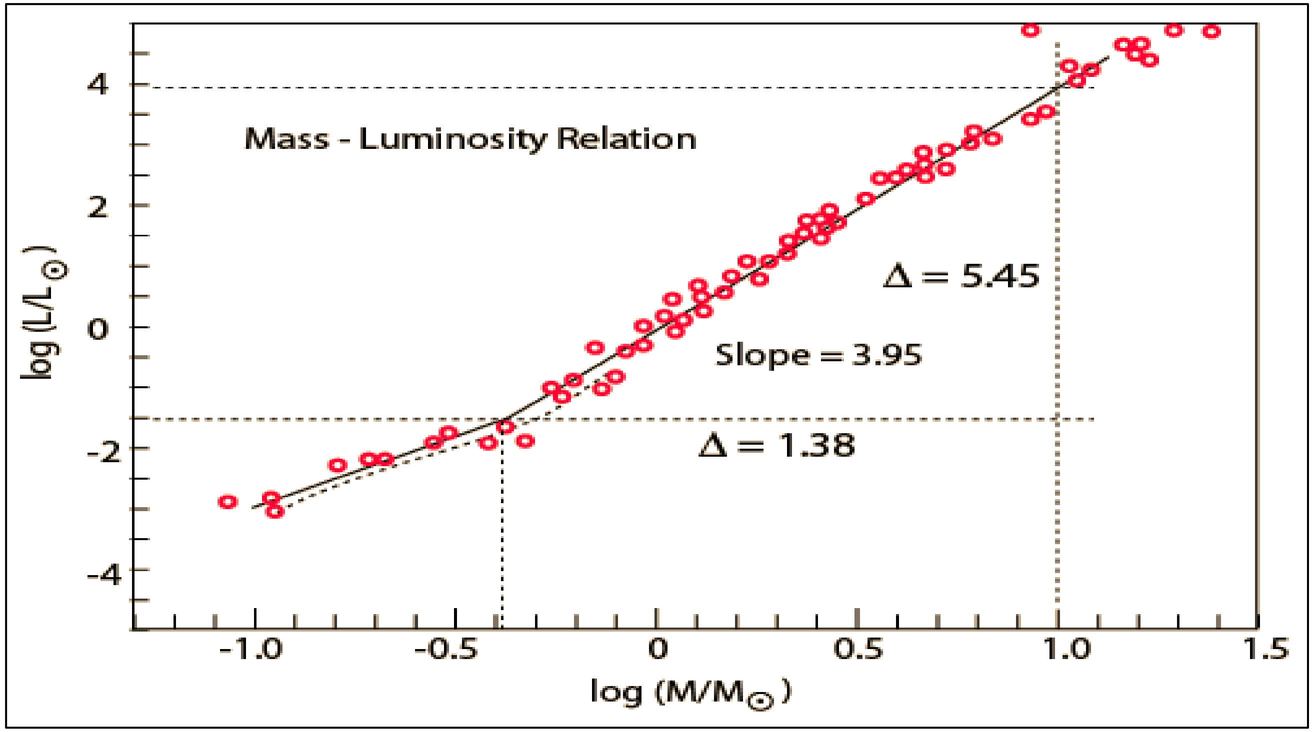
Near Simultaneous HST & Keck Program

Color dependent Centroid shift + image elongation
Mu_rel = lens – source separation/ yr
We also know the direction which constrains the direction of the parallax

Mass-Distance relations

$$\theta_E^2 = \frac{4GM_L(D_S - D_L)}{c^2 D_S D_L}$$

$$\frac{1}{\pi_E^2} = \frac{4GM_L D_S D_L}{c^2(D_S - D_L)}$$



Roman with precise photometry will be able to measure for a lot of events.

Needs High resolution image capability to detect the lens host star

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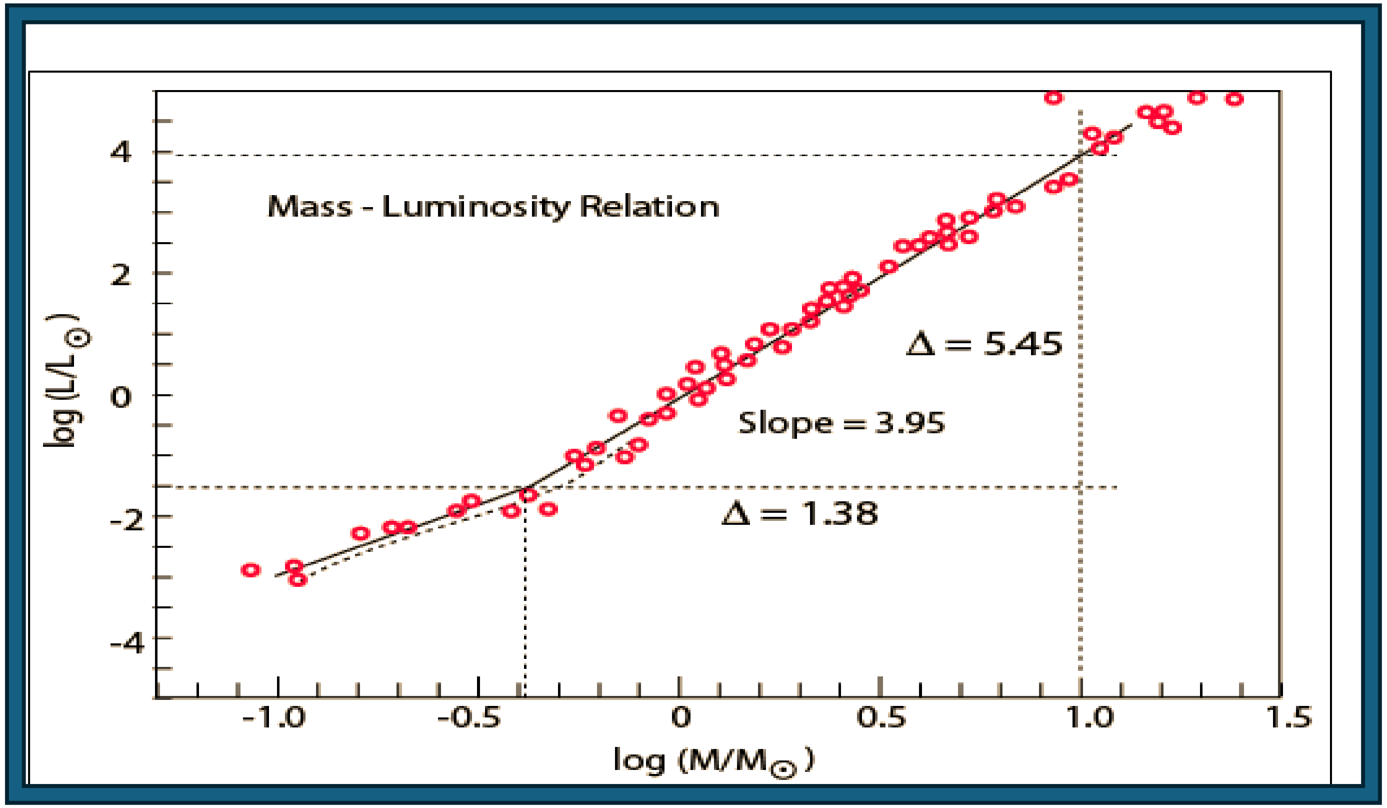

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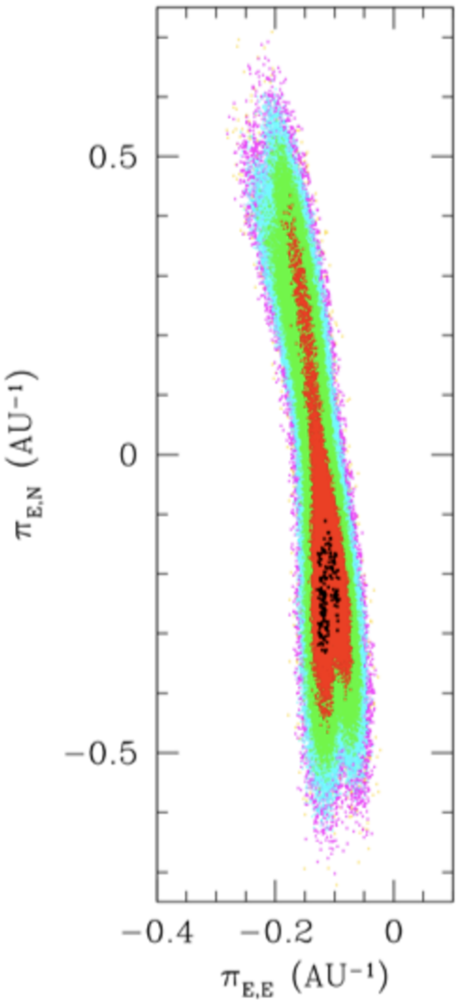
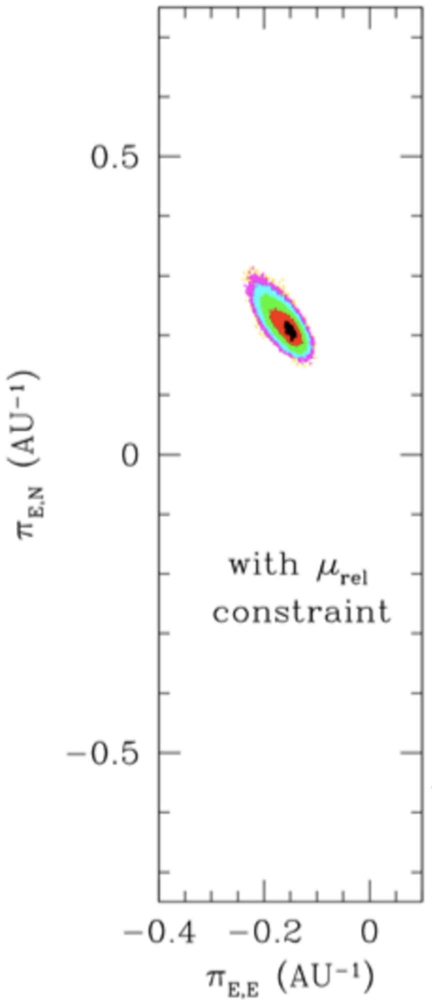
OGLE-2012-BLG-0950

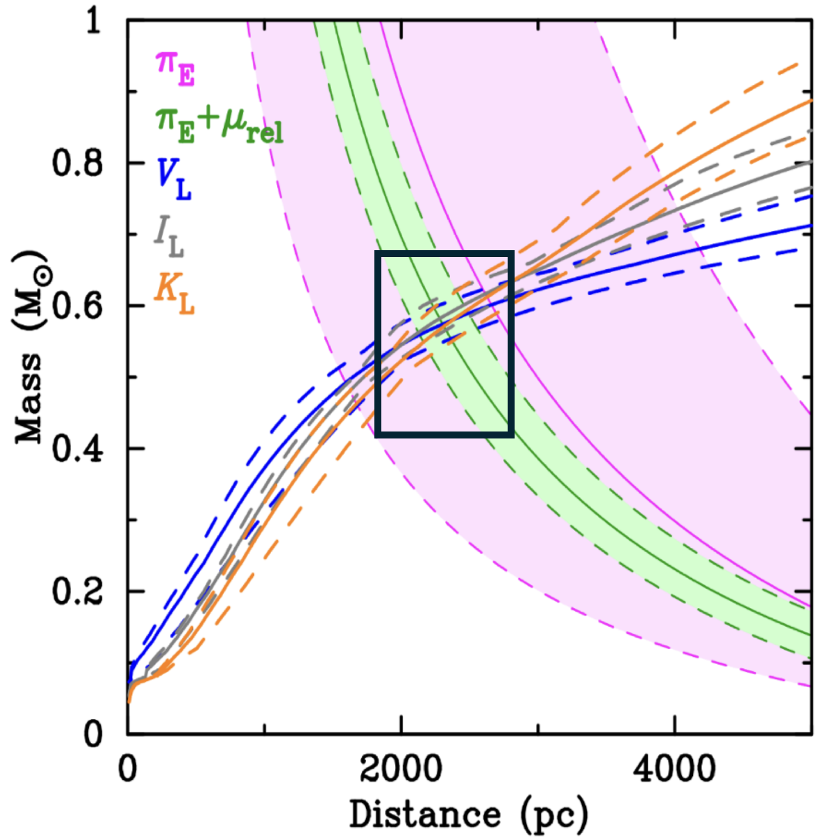
Bhattacharya+ 2018



From light curve



From high-res



$M_H = 0.58 \pm 0.04\ M_S$

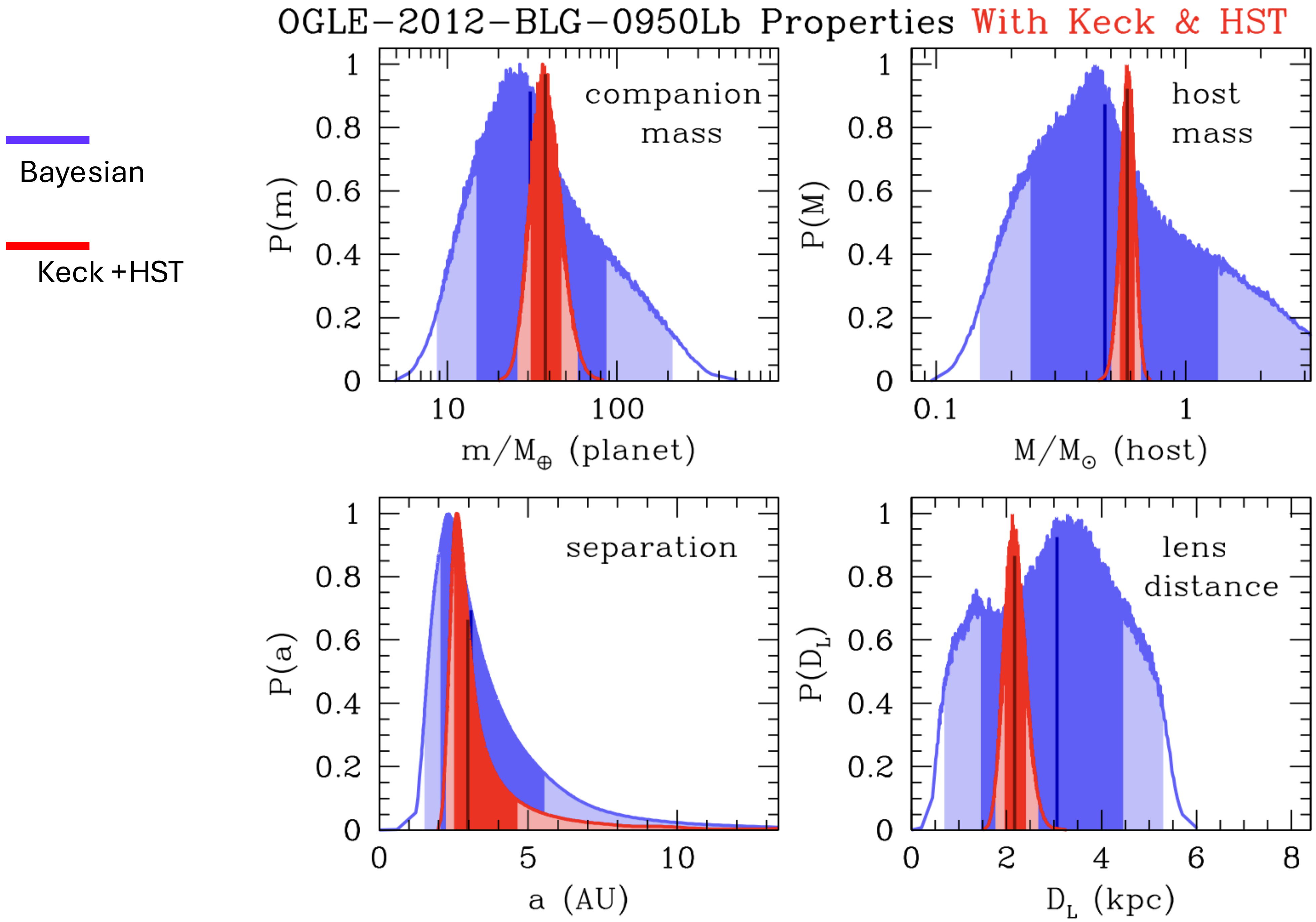
$M_P = 39 \pm 0.8\ M_E$

$a_{2D} = 2.54 \pm 0.23$ AU

$D_S = 2.19 \pm 0.23$ kpc

Sep = 33 ± 2 mas

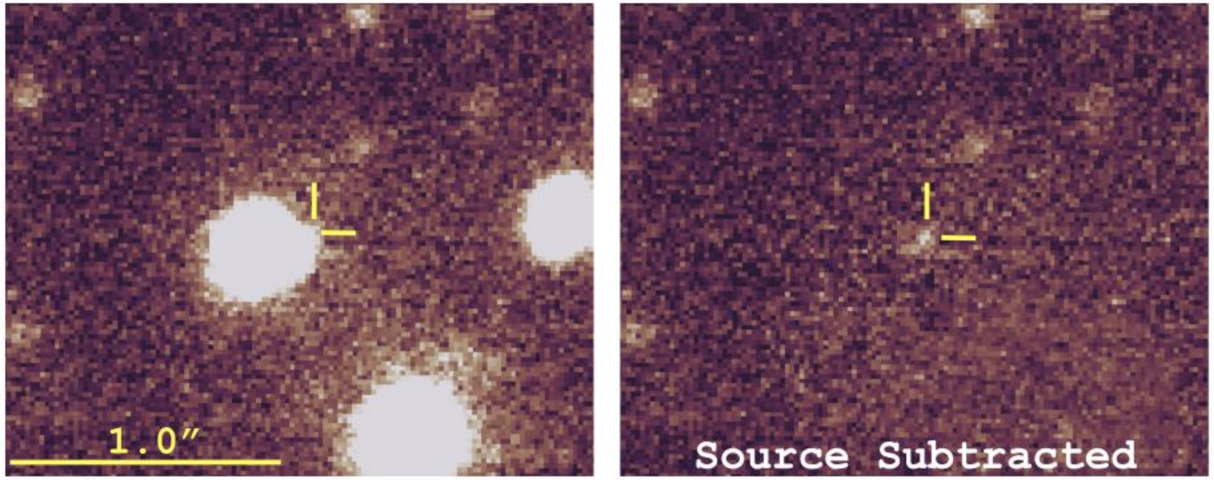
Roman will have both

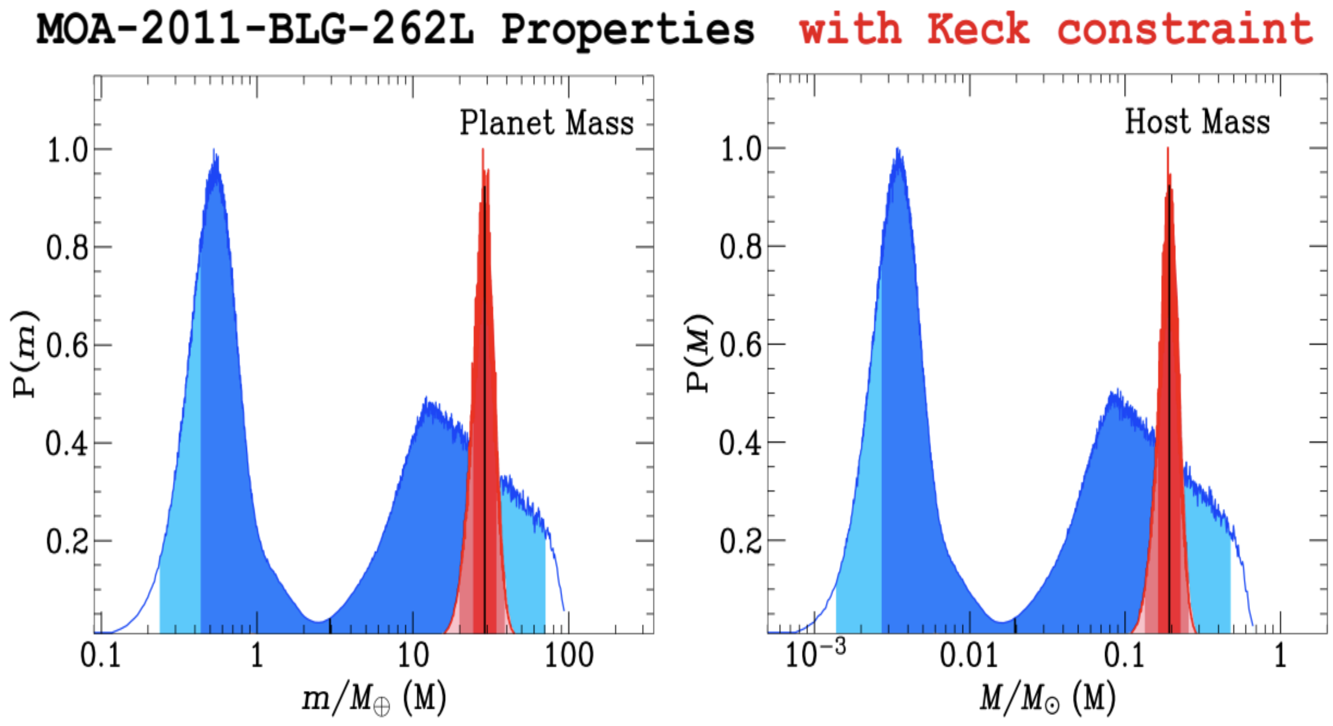


OGLE-2012-BLG-0950Lb Properties With Keck & HST
Bayesian
Keck +HST
companion mass
P(m)
m/M⊕ (planet)
host mass
P(M)
M/M⊙ (host)
separation
P(a)
a (AU)
lens distance
P(D_L)
D_L (kpc)

MOA-2011-BLG-262

Bayesian   Keck





Lens: 50 x fainter lens than the source

Terry et al. 2025

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Confirming centroid shift and Measured Masses

OGLE-2003-BLG-235 (discovery in Bond+ 2004)

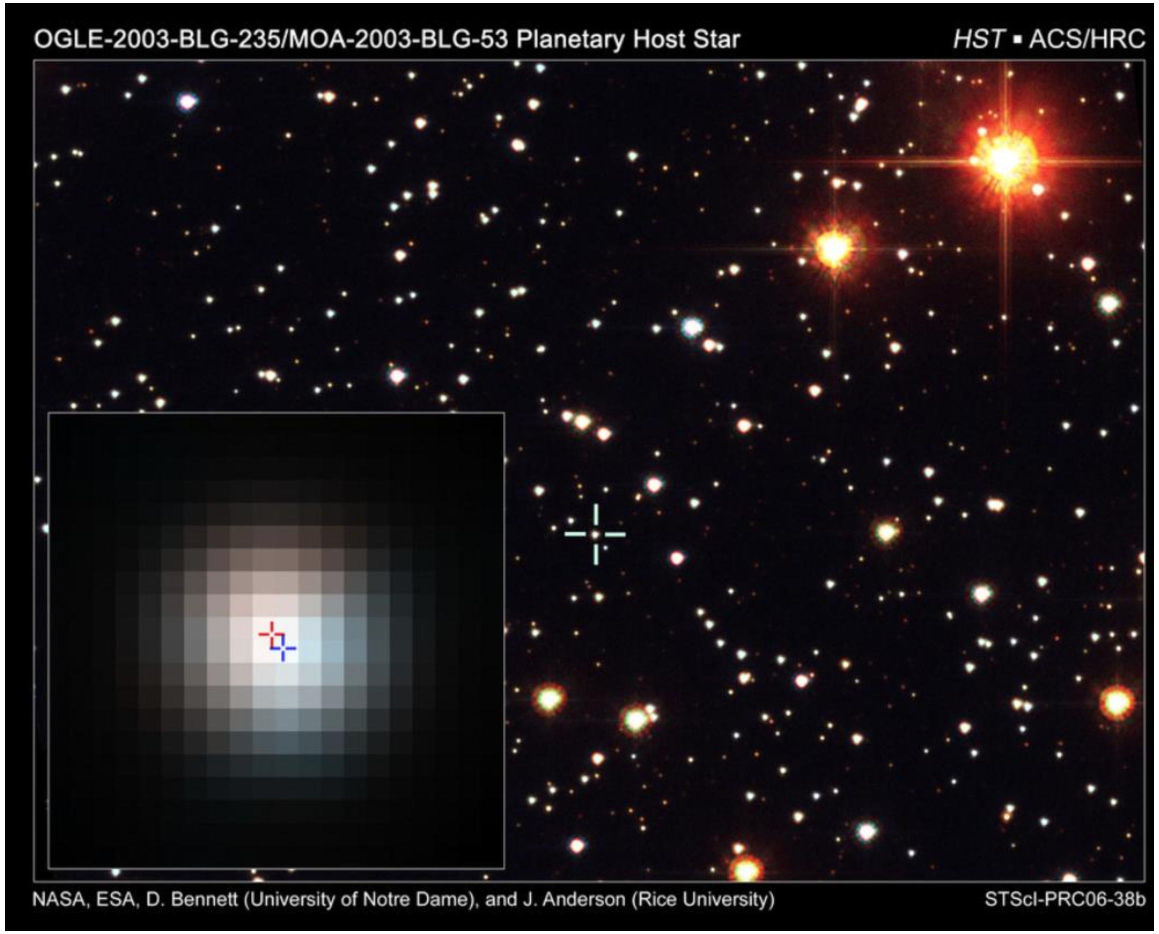
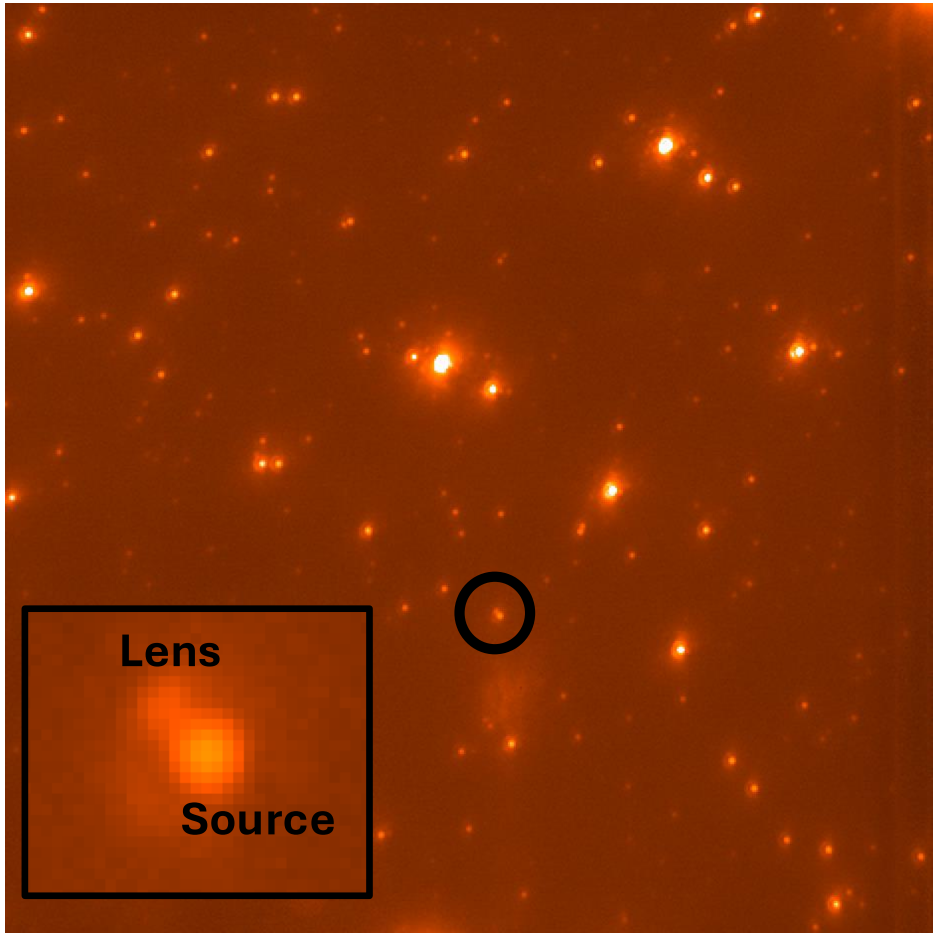


Image by HST ACS in 2005 Bennett+ 2006

Second shortest time gap between peak and follow-up – 1.78 years

Sep = ~ 5 mas



Keck NIRC2 Narrow camera image in 2018 Bhattacharya+ 2023

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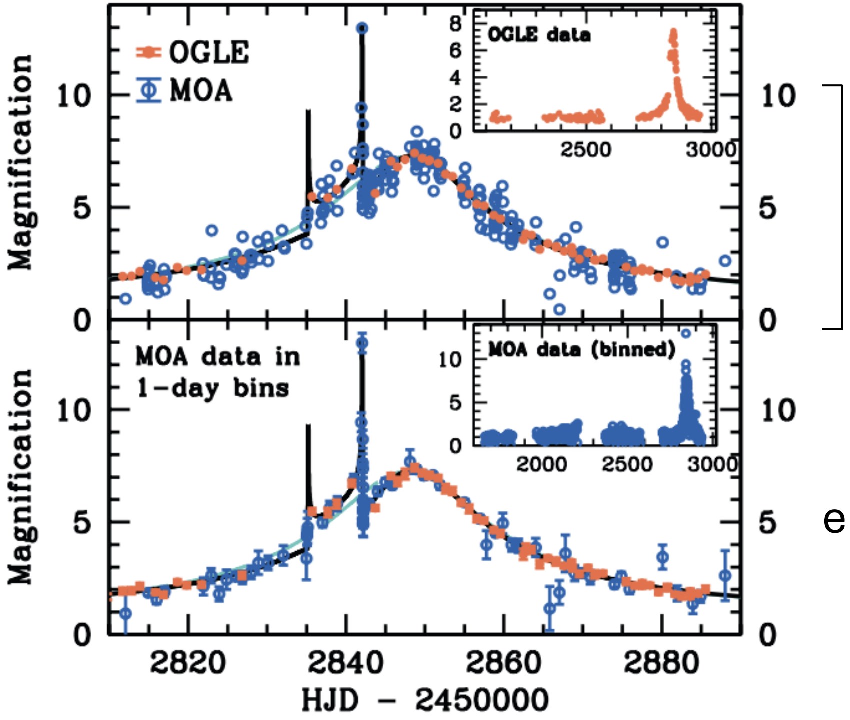
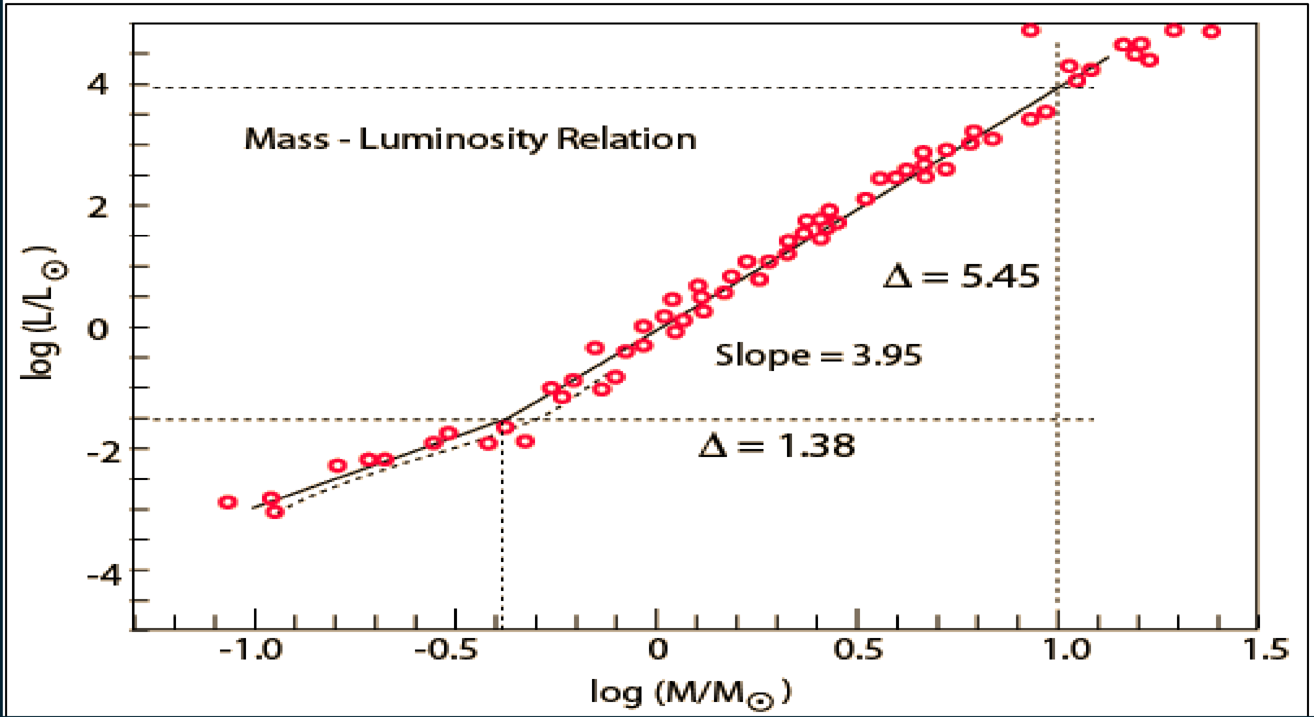


Ro e to measure
for



Needs High resolution image capability to detect the lens host star

Confirmation of centroid shifts

Host Masses

2018: $0.550 \pm 0.018\ M_{sun}$ 2005: $0.63\ ^{+0.07}_{-0.09} M_{sun}$

Planet Masses

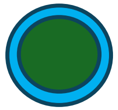
2018: $2.33 \pm 0.43\ M_J$ 2005: $2.6\ ^{+0.8}_{-0.06}\ M_J$

Distance to Lens

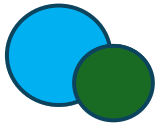
2018: 5.37 ± 0.71 kpc 2005: $5.8\ ^{+0.6}_{-0.7}$ kpc

Ideal condition of Follow up Observations for Mass Measurement

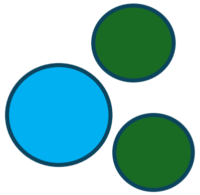
Source
Lens



Cannot confirm
the lens– too early



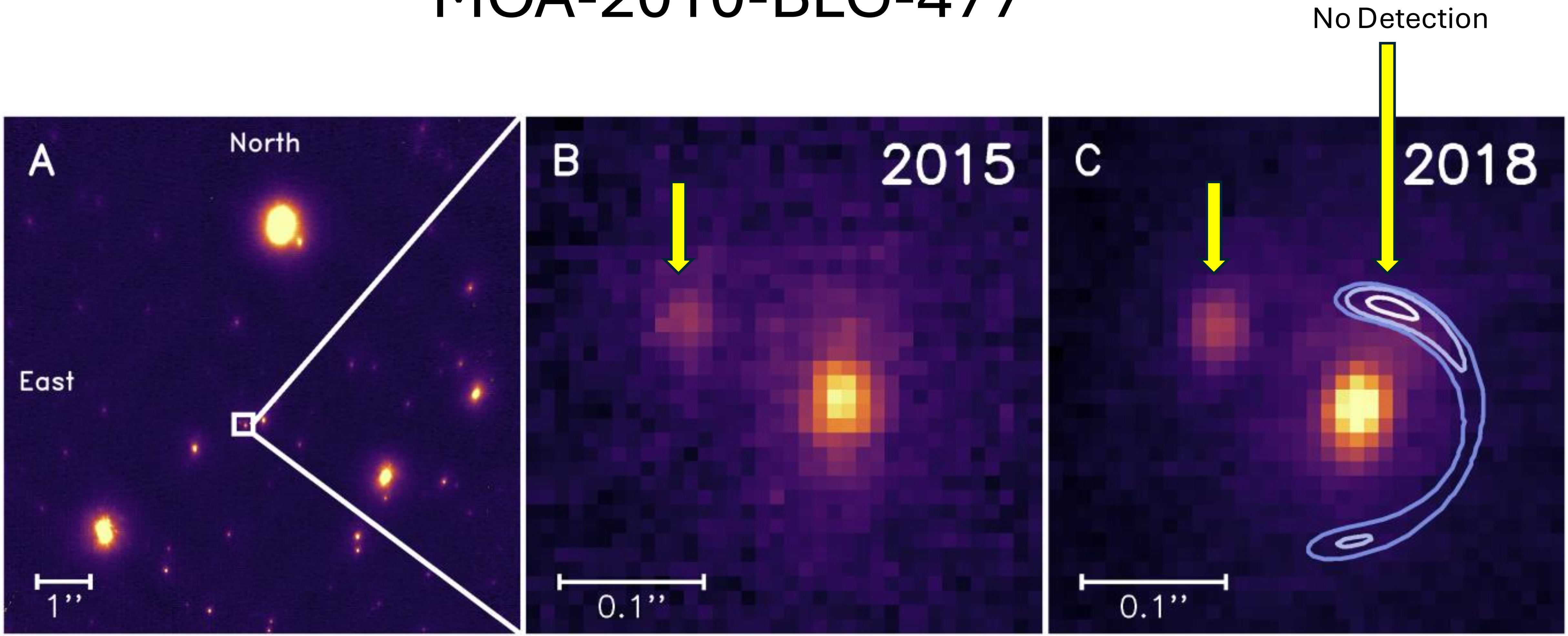
Best
Condition



Which one is lens ?
Lens or ambient
star? too late

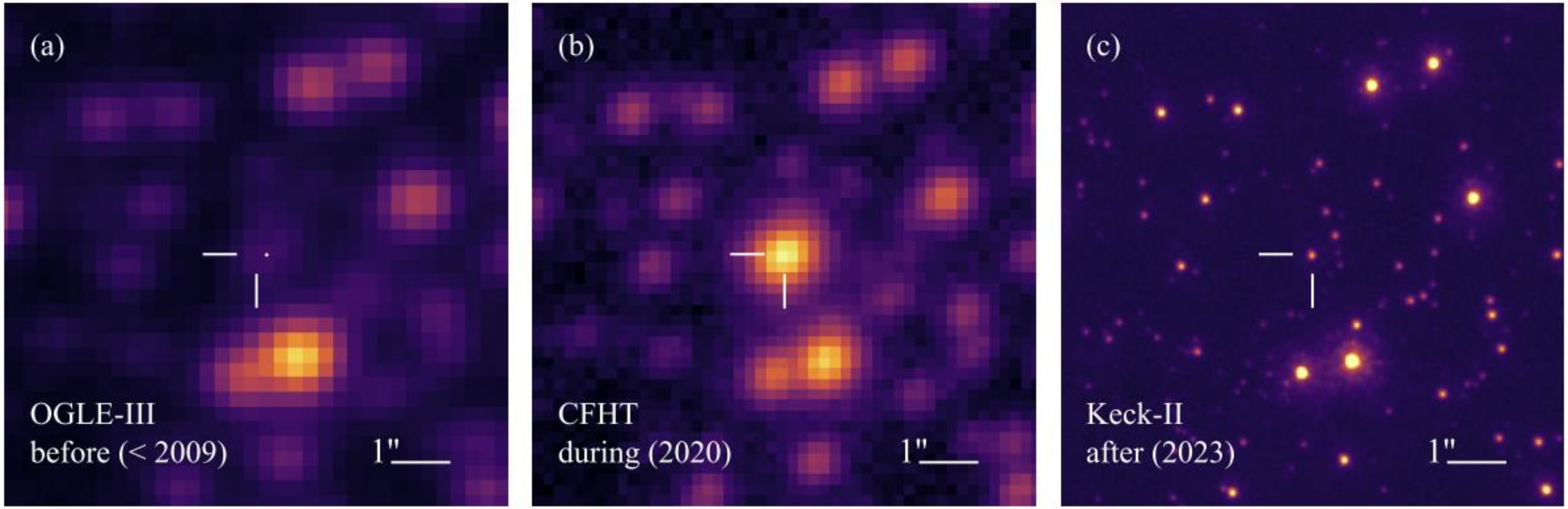
Let's go to example

MOA-2010-BLG-477



Blackman et al. including *D.Bennett, A. Bhattacharya, S.Terry*, Nature, 2021

KMT-2020-BLG-0414



Zhang et al.,including *S.Gaudi, S. Terry*, Nature, 2024

KMT-2020-BLG-0414

Parameter	Unit	Close-NE	Wide-NE
WD mass	$M_\odot$	$0.51^{+0.08}_{-0.05}$	$0.49^{+0.06}_{-0.03}$
Distance	kpc	$1.27^{+0.19}_{-0.12}$	$1.33^{+0.16}_{-0.12}$
WD flux (K_s)	mag	$23.8^{+0.7}_{-0.6}$	$24.0^{+0.6}_{-0.8}$
Proper motion	mas yr^{-1}	$7.74^{+1.52}_{-0.63}$	$7.77^{+1.29}_{-0.76}$
Proper motion direction	deg	$62.9^{+21.4}_{-21.7}$	$68.5^{+15.4}_{-20.2}$
Planet mass	$M_\oplus$	$1.75^{+0.31}_{-0.18}$	$1.87^{+0.27}_{-0.16}$
Planet projected separation	au	$2.17^{+0.30}_{-0.17}$	$2.07^{+0.22}_{-0.11}$
Planet physical separation ($e < 0.2$)	au	$\gtrsim 10$	$2.07^{+0.24}_{-0.09}$
BD mass	M_J	$32.4^{+4.8}_{-2.6}$	$27.0^{+4.0}_{-3.1}$
BD projected separation	au	$0.20^{+0.03}_{-0.02}$	$22.3^{+2.4}_{-1.5}$

More and more planets around White Dwarf in few AU distances will show up with Roman data.

Zhang et al.,including *S.Gaudi, S. Terry*, Nature, 2024

Mass Measurement with Nancy Grace Roman Space Telescope

Roman will take images with multiple passbands every 12 minutes for 72 days ~ 8000 images in each season in F146, a few hundreds in Z087 and F213 - would be able to detect a lot of the lens hosts and provide mass measurements

- hundreds to thousands images instead of 16 frames – higher SNR
- higher PSF stability due to L2 orbit
- lens detection can happen both before and after the peak of the event

Build a statistic of planets around their host stars

-Answer questions about planet formation and habitability: which stars are more likely to host earth like planets and why?

- Build the first WD planetary demographics

Observation with Roman vs High resolution follow up

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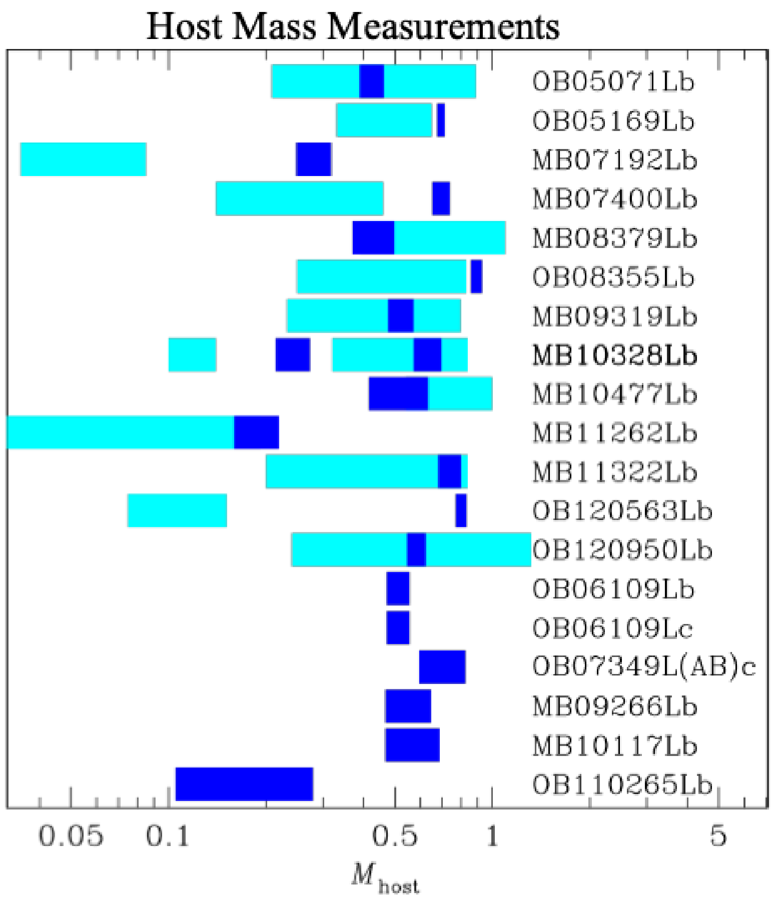
Cool Planet Host Mass Dependence

Bennett+26 (in preparation)

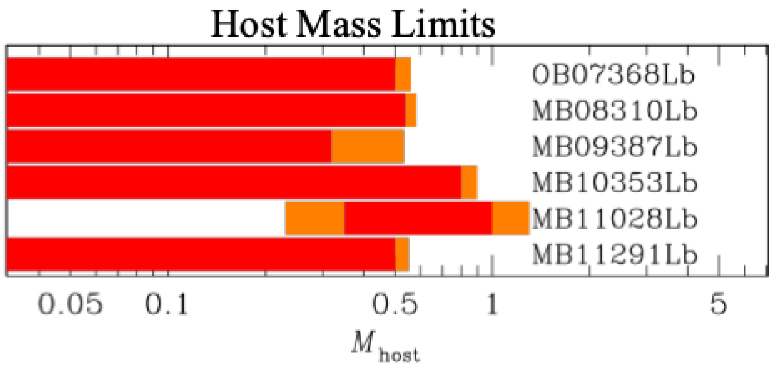
- 29 planets (in 28 events)
- 19 planets with mass measurements
- 6 planets with mass limits
- 4 planets without limits due to giant source and no π_E measurement

Host mass dependence at fixed mass ratio, q, scales as $\sim M_{\mathrm{host}}^{1.0\pm0.3}$ for $q \geq 5\times10^{-5}$

- implies more mass measurements for Roman due to brighter host stars and more π_E measurements



Discovery paper estimated host mass in cyan, and measured mass in blue.



Allowed mass range in red, and 1-σ mass range in orange

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Pedagogical References :

Microlensing Equations
Gould 2000 arXiv:astro-ph/0001421
Gaudi 2010 arXiv:1002.0332

PSF fitting
Anderson and King 2000 arXiv:astro-ph/0006325

Mass Measurement with HST and Keck
Batista et al. 2015, Bennett et al. 2015, Bhattacharya et al. 2017, 2018
Look for Beaulieu and Terry talks.

Light Curve modeling:
Bennett 2010, Bozza 2024
Look for Bennett and Ishitani Silva talk.