Completing Exoplanet Census with Nancy Grace Roman Space Telescope

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Roman Galactic Time Domain Survey (Exoplanet Studies)

- 6 seasons – each of 72 days (expected)
- 6 seasons spread over 5 years including first 2 and last 2 bulge seasons
  - 3 early seasons, 3 late seasons
- 7 galactic bulge fields every 15 min
- 1.96 square deg field area
- Filters:
  - Wide band W149 (Each field once every 15 minutes) ~ 40000 images of each field
  - F184 or K band every 12 hours ~ 800 images of each field
  - Z087 or R062 (Red) every 12 hours ~ 800 images of each field

Look for Scott Gaudi talk tomorrow for more about these specifications and auxiliary science – S. Gaudi and Casey Lam talk.

Roman Galactic Time Domain Survey (Exoplanet Studies)

The exoplanets detected with microlensing wide orbit planets of different masses (Super Jupiter to Mars Mass) at beyond the snowline around G, K, M type stars.

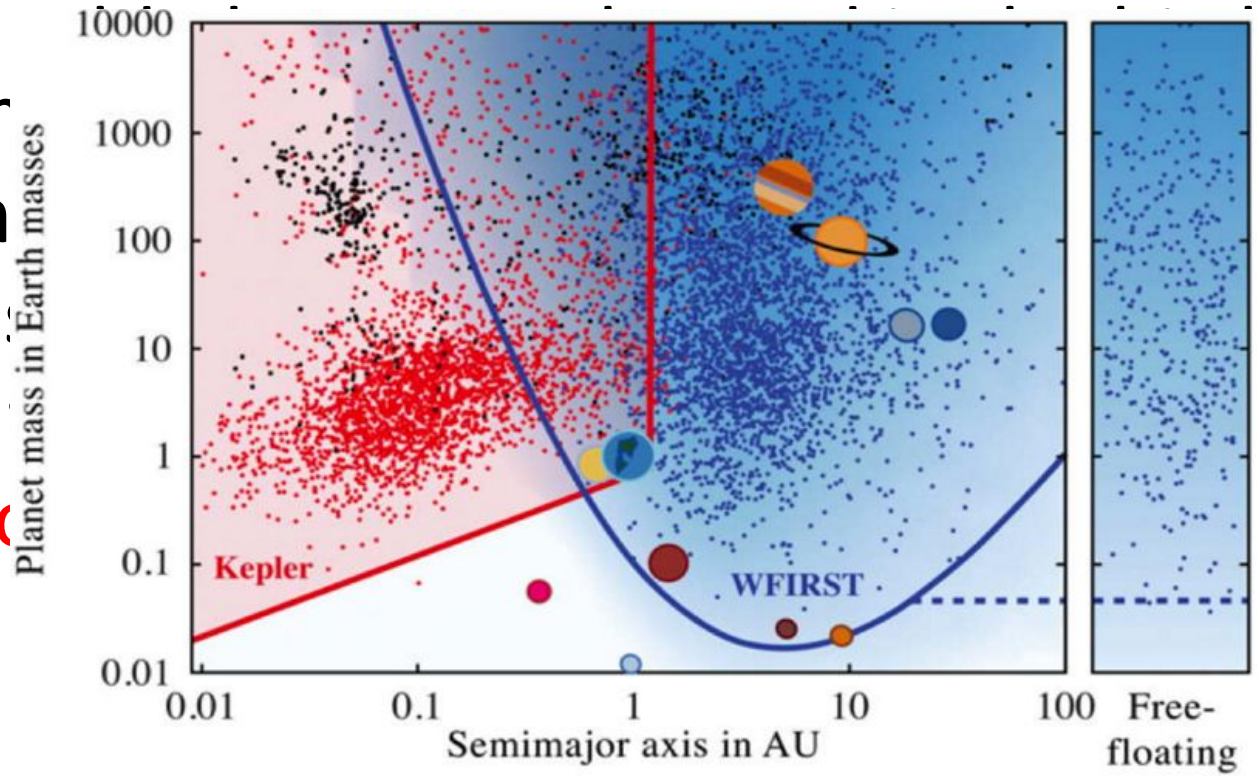
Predictions
1400+ exoplanets with mass as small as Mars mass (Penny+ 2019) and about 700+ mass measurements compared to 100 planets over 15+ years.

Time Domain data will:

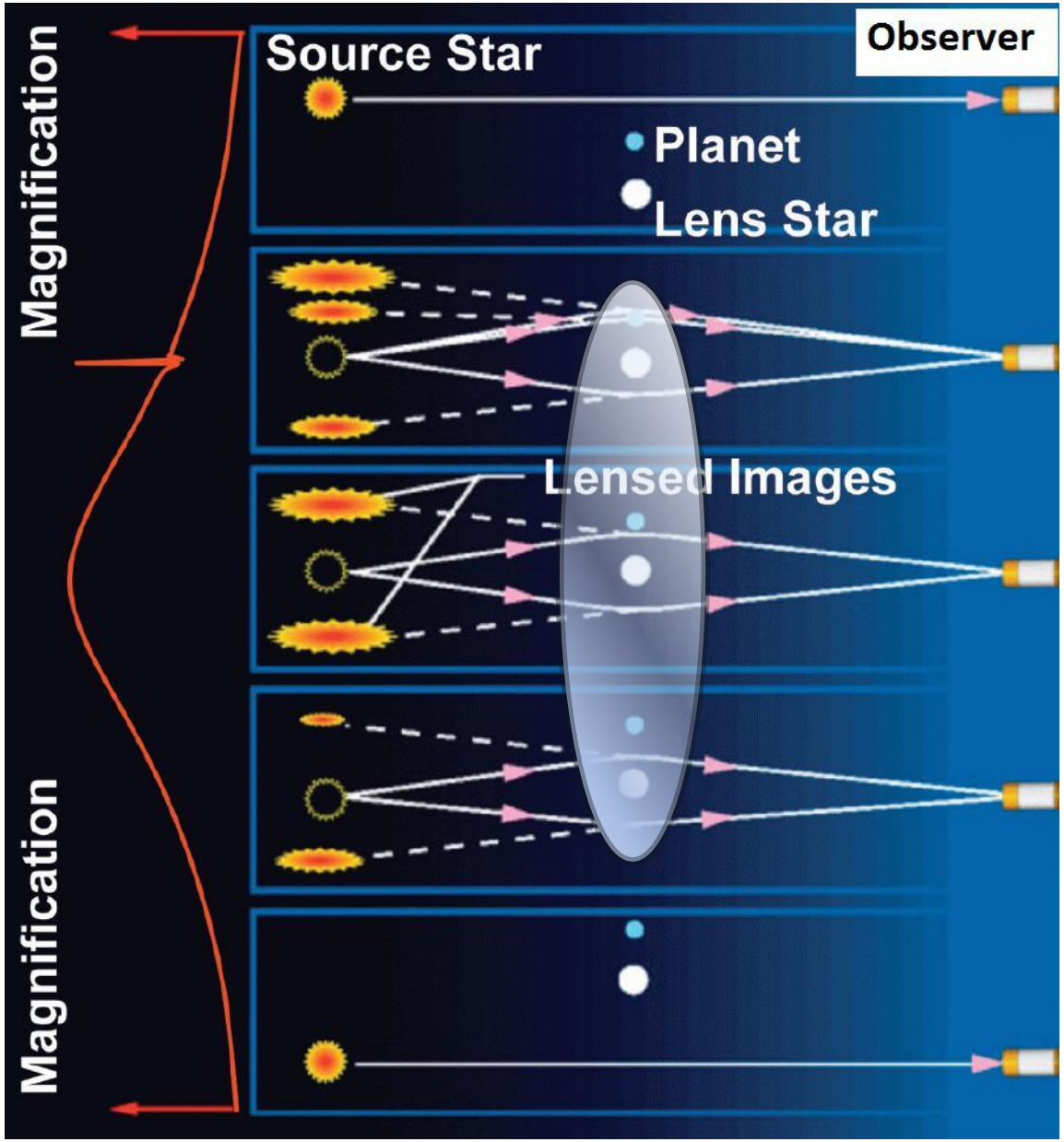
1. Detect the exoplanets
2. Measure the mass of the exoplanets.

The importance of cold low mass exoplanets

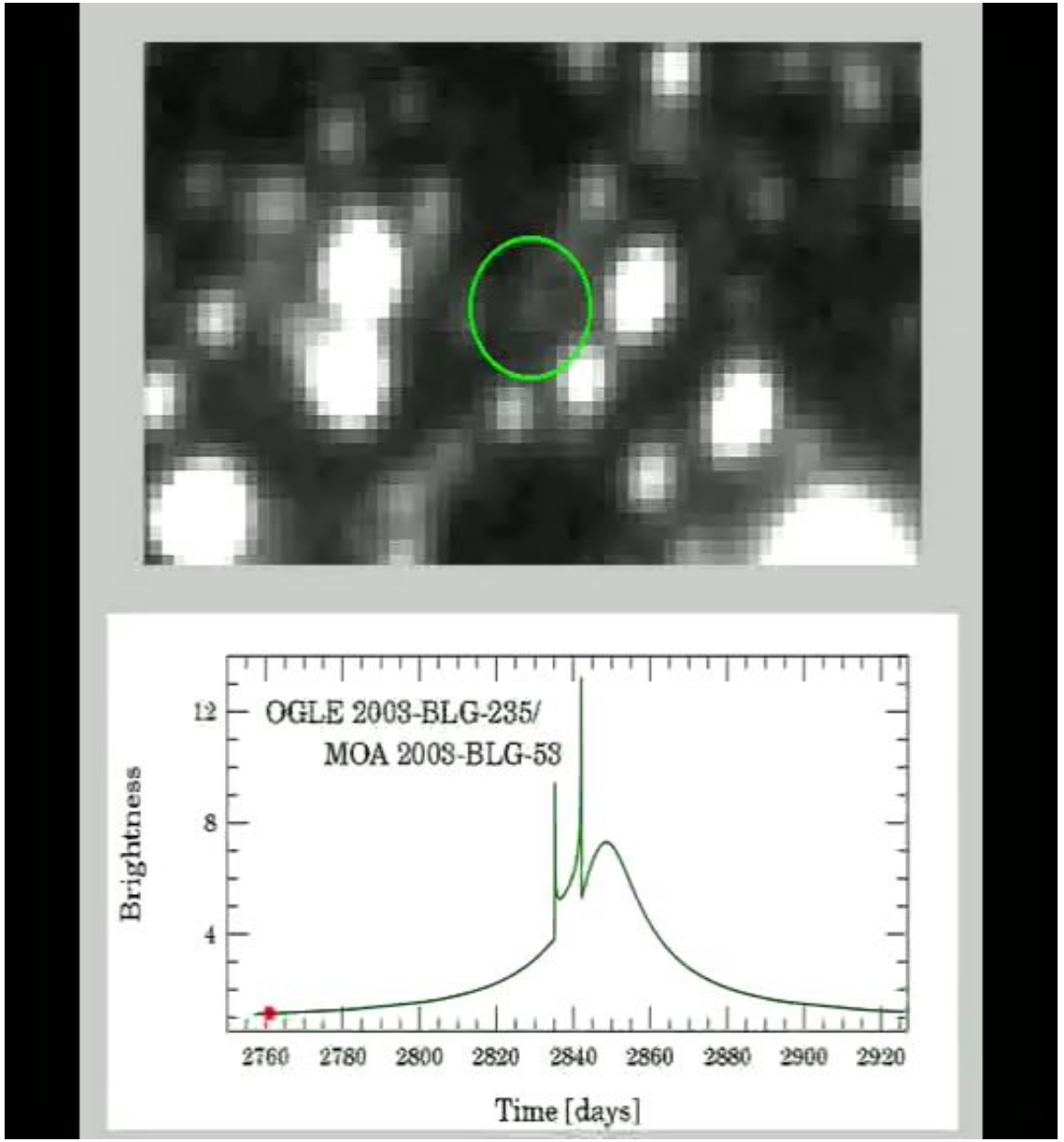
- Wide orbit … place of planet form…
- How comm…
- Where doe…
- Do planets … us?
- What kind … lly earth like planets?



Action: Detect the exoplanets, Build a statistics of exoplanet mass, their host star masses, their separations and their distances.



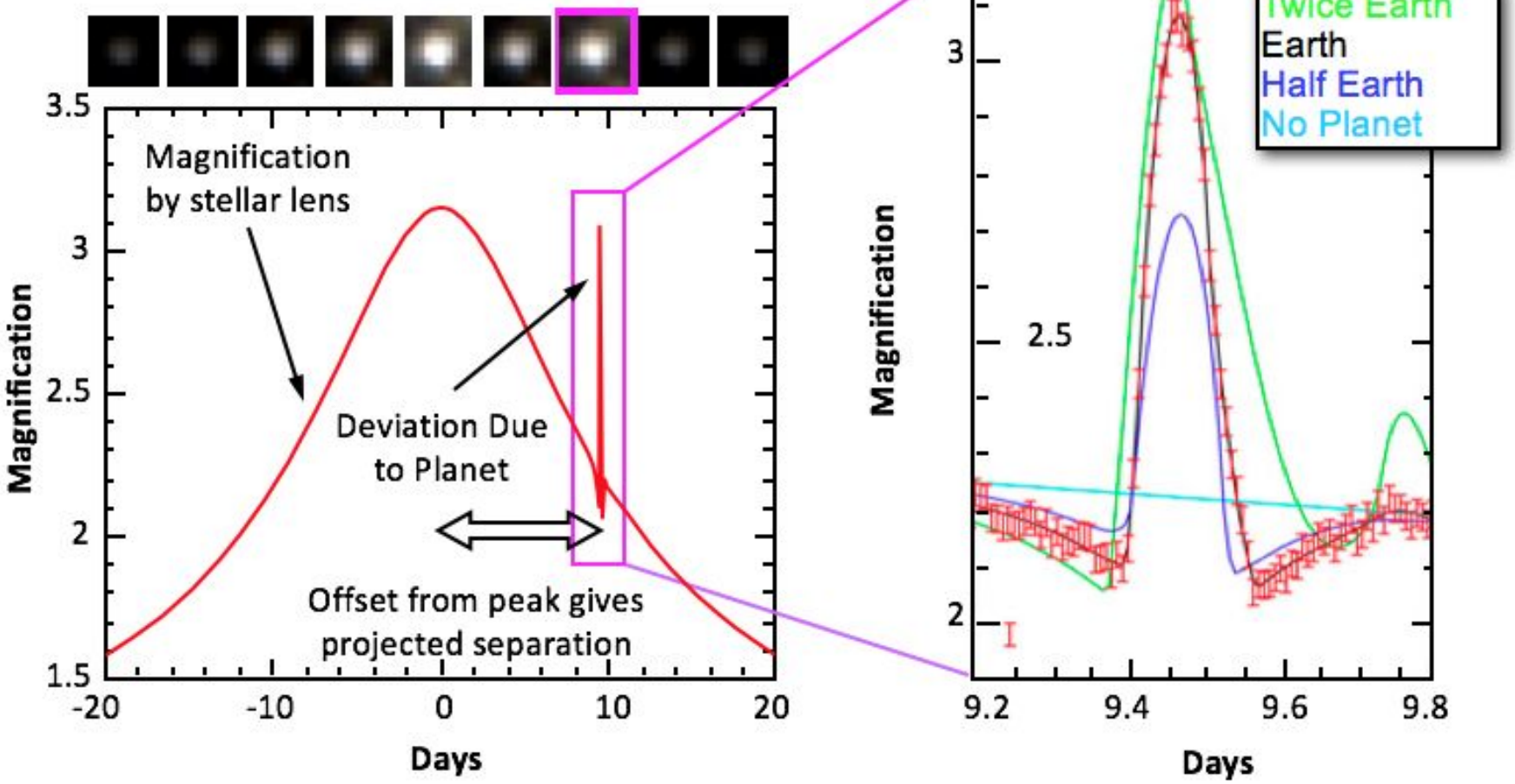
Since chances are small, we look at dense galactic field, but the signals are strong.



Most Light Curves give mass ratios of planet-host stars

Microlensing Exoplanet Detection

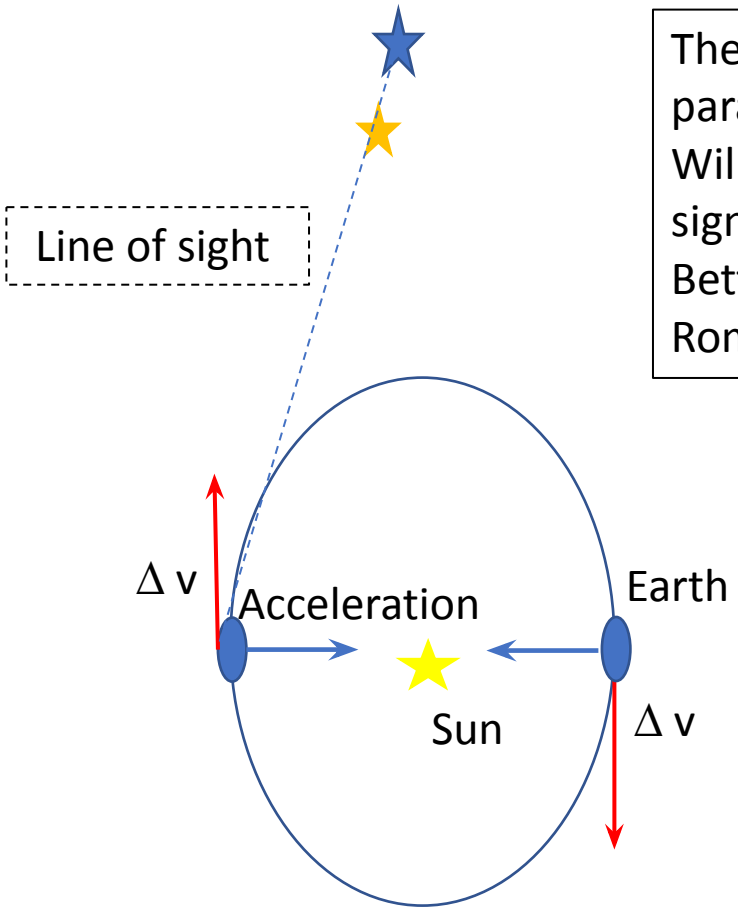
Light Curve



Muraki et al 2011, ApJ 741, 22

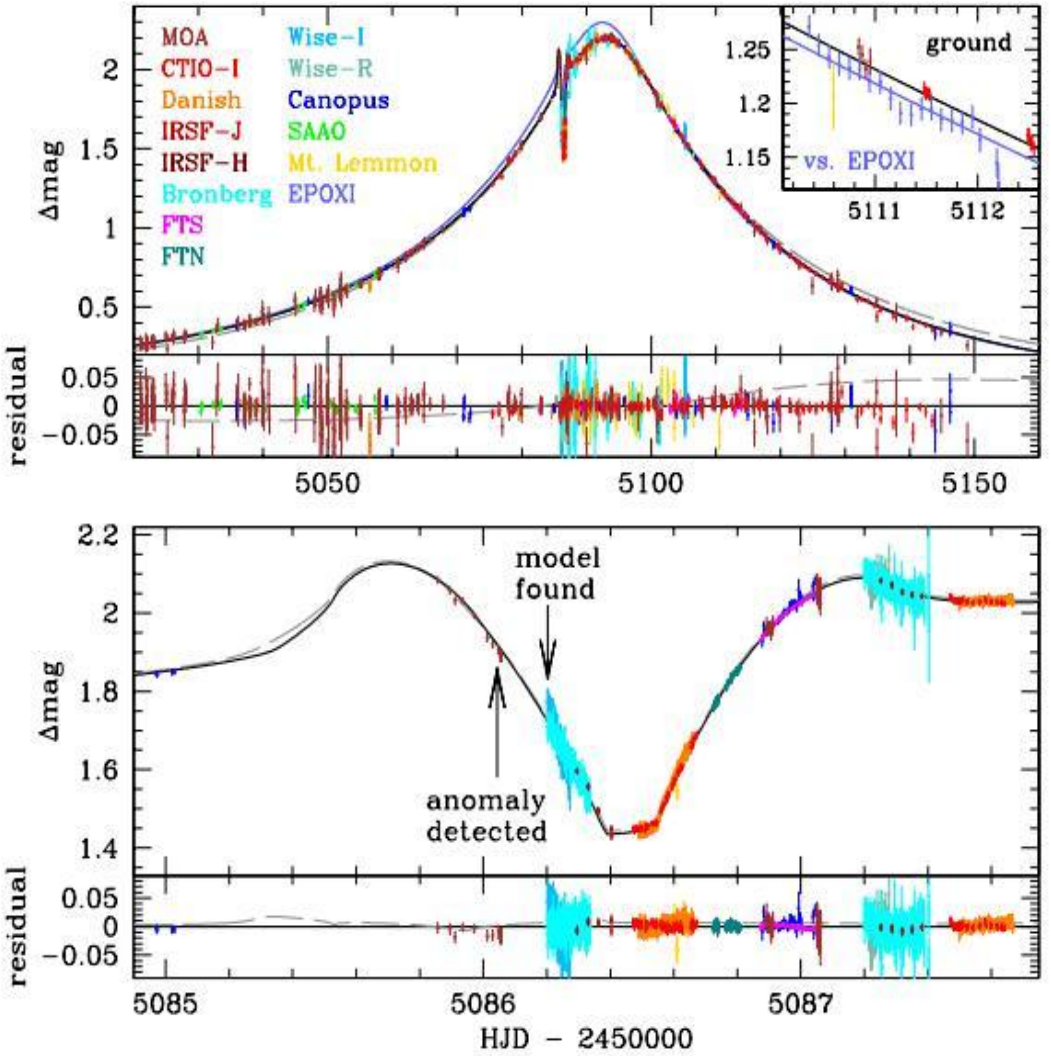
Mass measurement only from the light curve

Orbital Microlensing Parallax



Top View

The planet and parallax detection Will improve significantly due to Better photometry of Roman.



Sebastiano Calchi Novati talk today
For more on photometry analysis

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

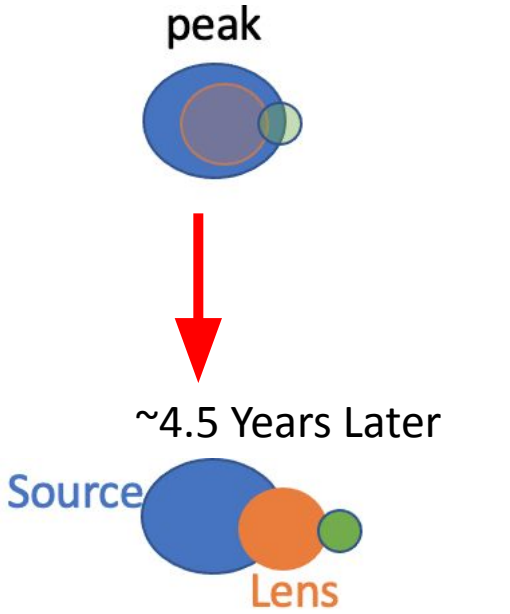
$M_P = 10.4 \pm 1.7\ M_\oplus$

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

Mass Measurement with Lens Detection

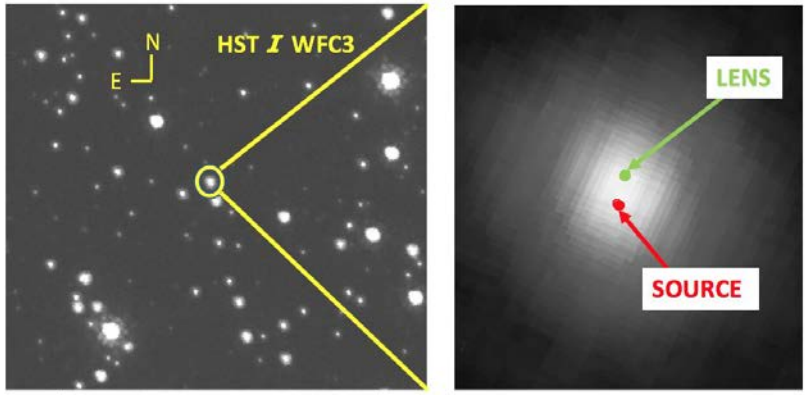
We need mass measurements of planet and its host stars and their separation to answer which stars are likely to host which type of planets.

The light curve planet detection gives planet-host mass ratio, we need high resolution follow up observations with Keck and Hubble for mass measurements (as precursor). Roman will observe multi epoch data in high resolution to measure mass.

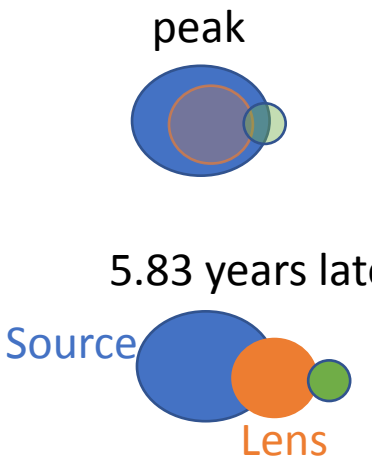


~ 10-30 mas separation

Mass Measurement by Lens Detection

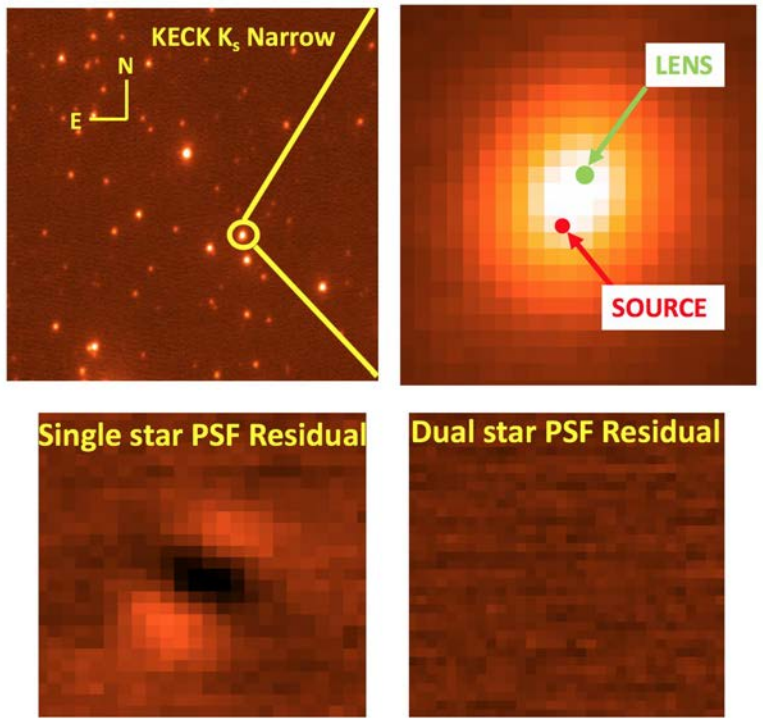


Follow-up taken with HST 5.83 years after the peak of the event on May 22, 2018



Separation = 34 mas

$M_H = 0.6 \pm 0.04\ M_{Sun}$
$M_P = 39 \pm 8\ M_E$
$D_L = 2.1 \pm 0.23$ kpc



Follow-up taken with Keck AO on May 23, 2018

Bhattacharya+ 2018

Getting physical parameters:

From microlensing planetary light curve fitting

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

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

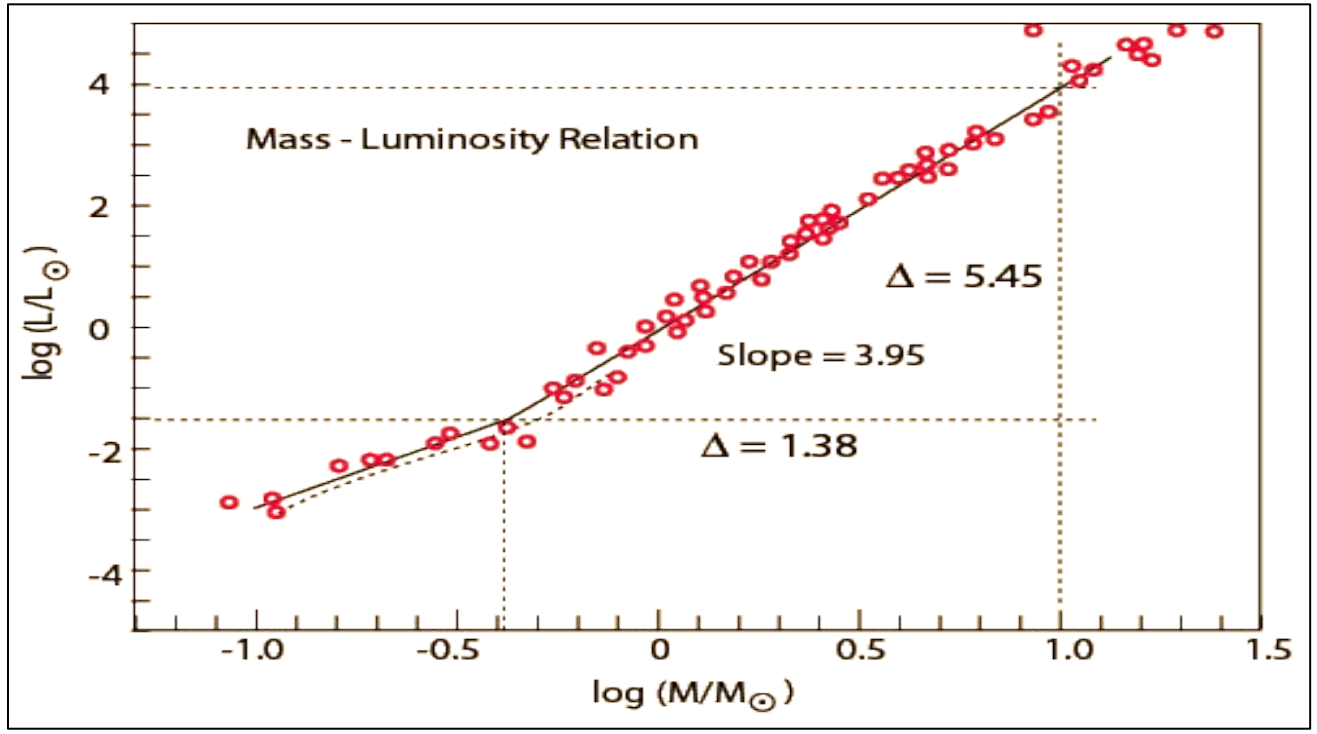
- Mass- distance from Einstein ring radius measurements (finite source effect)
- Mass-distance relation from microlensing parallax measurements
- Lens brightness from Follow-Up high angular resolution observations

Mass-Distance relations

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

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

$M_P = q \times M_L$



Needs High resolution image capability to detect the lens host star

Mass-Distance relations

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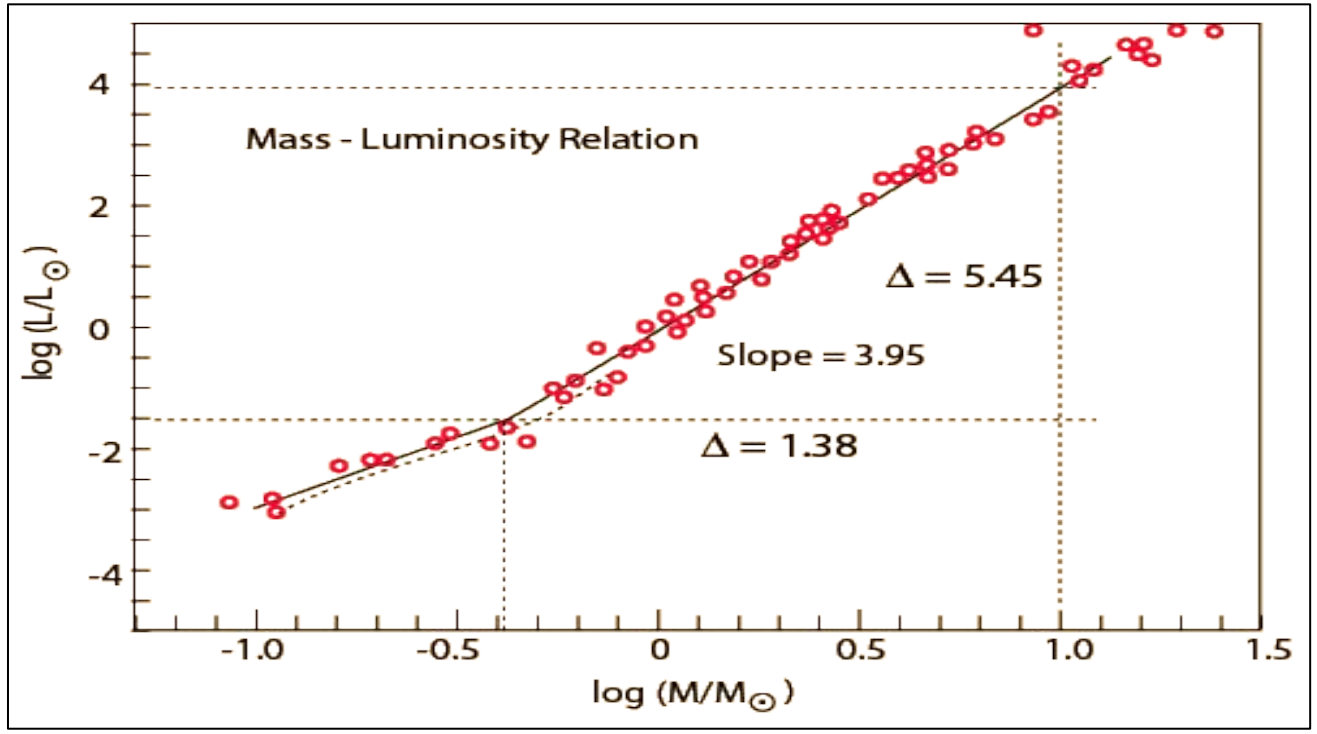

Roman with precise photometry will be able to measure for a lot of events.

Needs High resolution image capability to detect the lens host star

Mass-Distance relations

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

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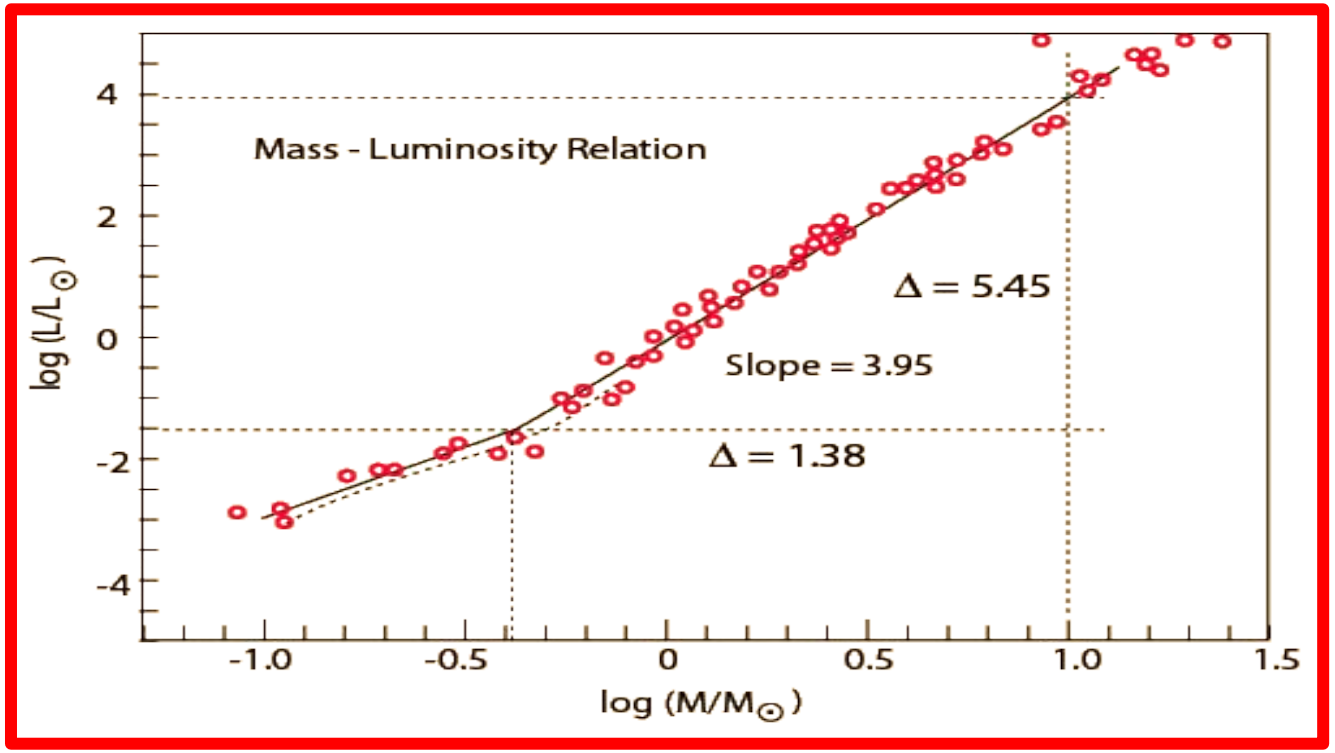
If we can measure only one of them, we can still measure mass with high resolution capability.



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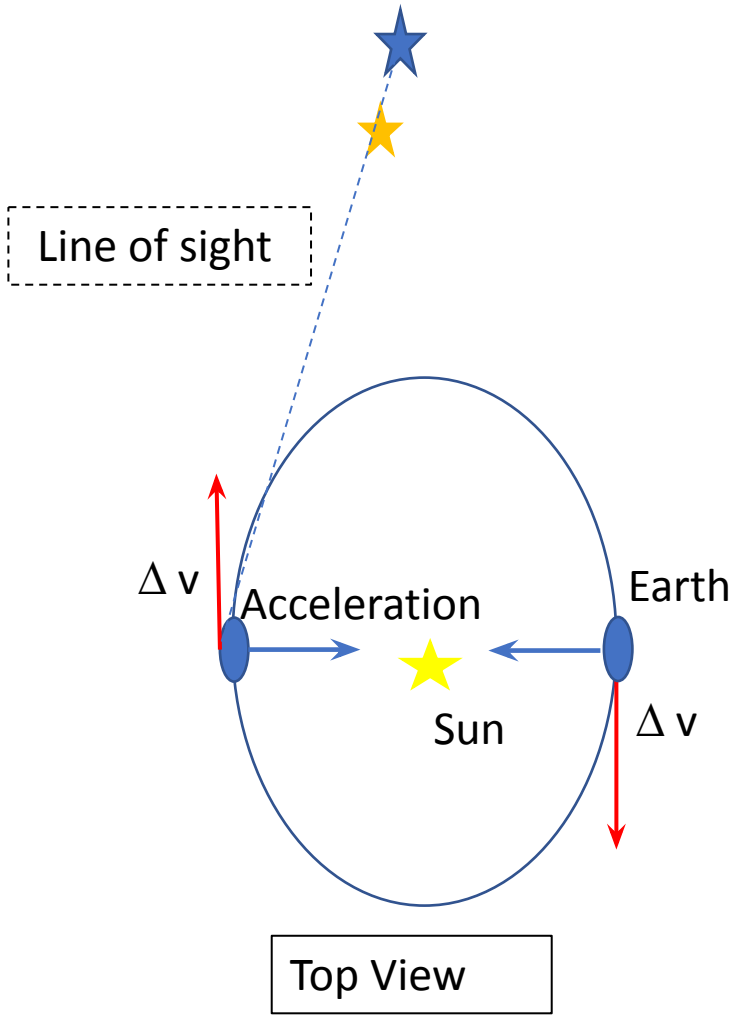
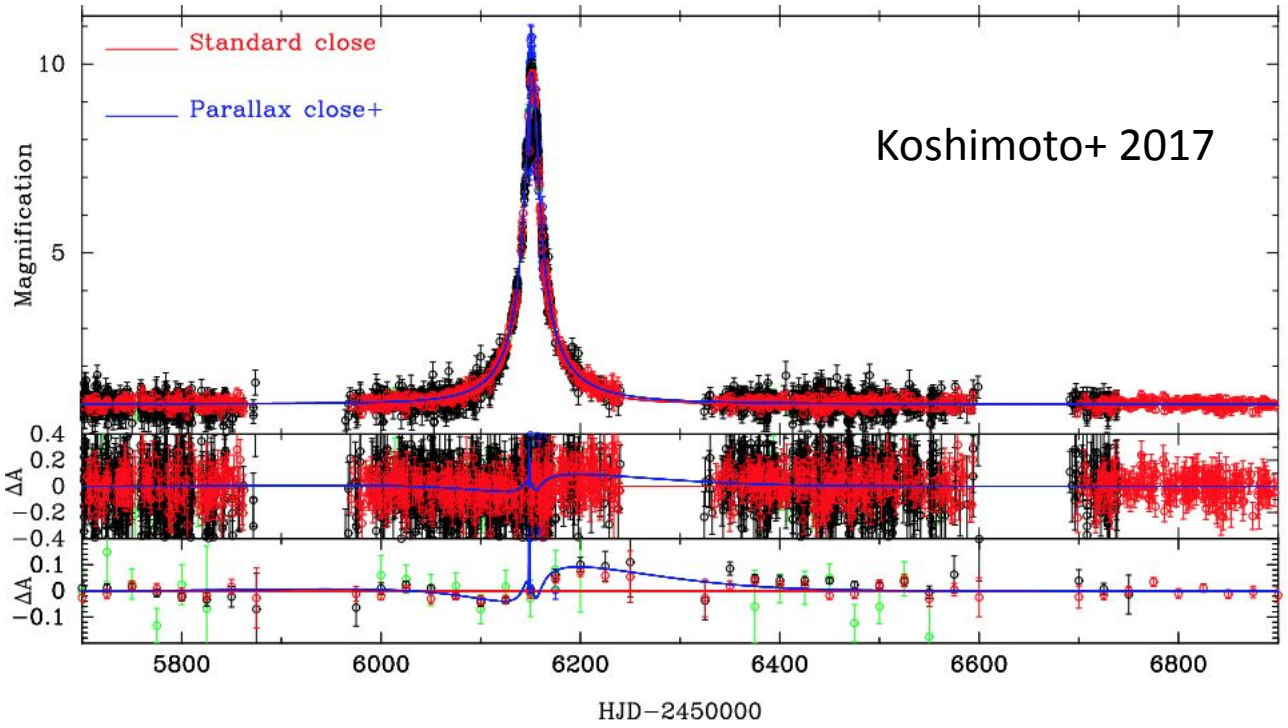
Orbital Microlensing Parallax



OGLE-2012-BLG-0950



Red line shows the model without parallax

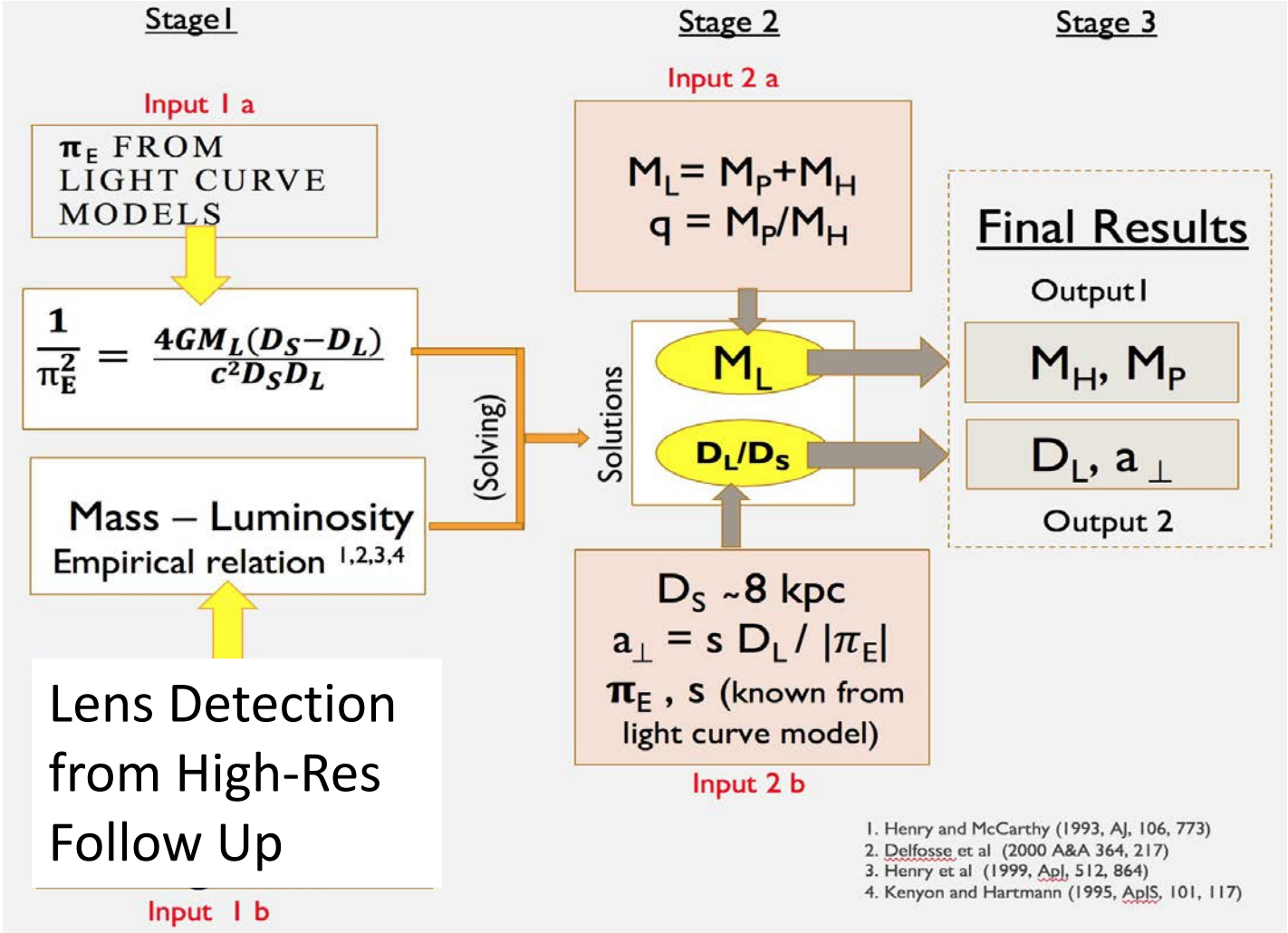
Mass measurement

from parallax

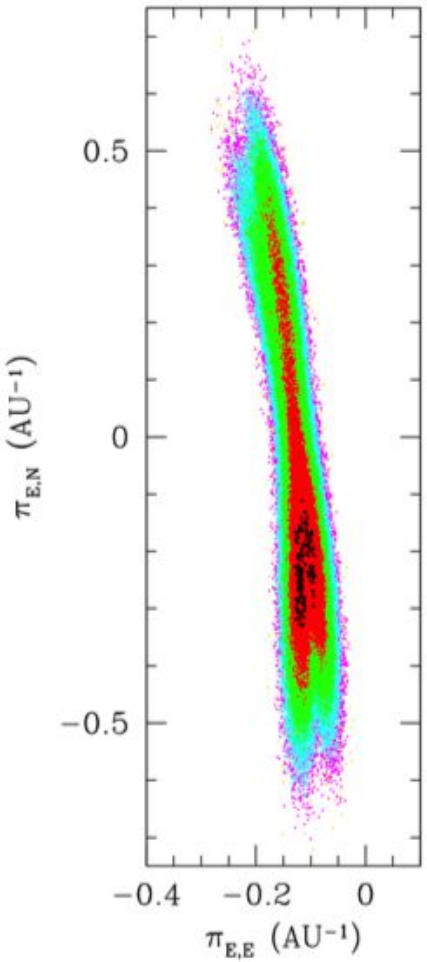
+

Lens Detection

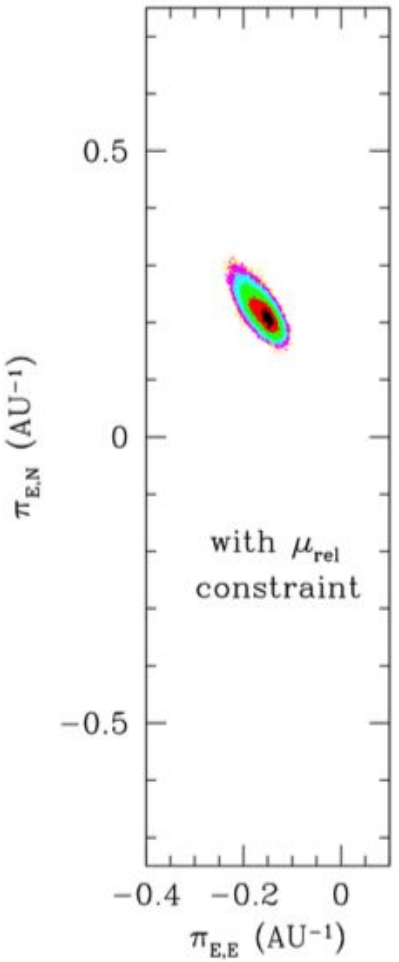
In case of finite source effect not well measured

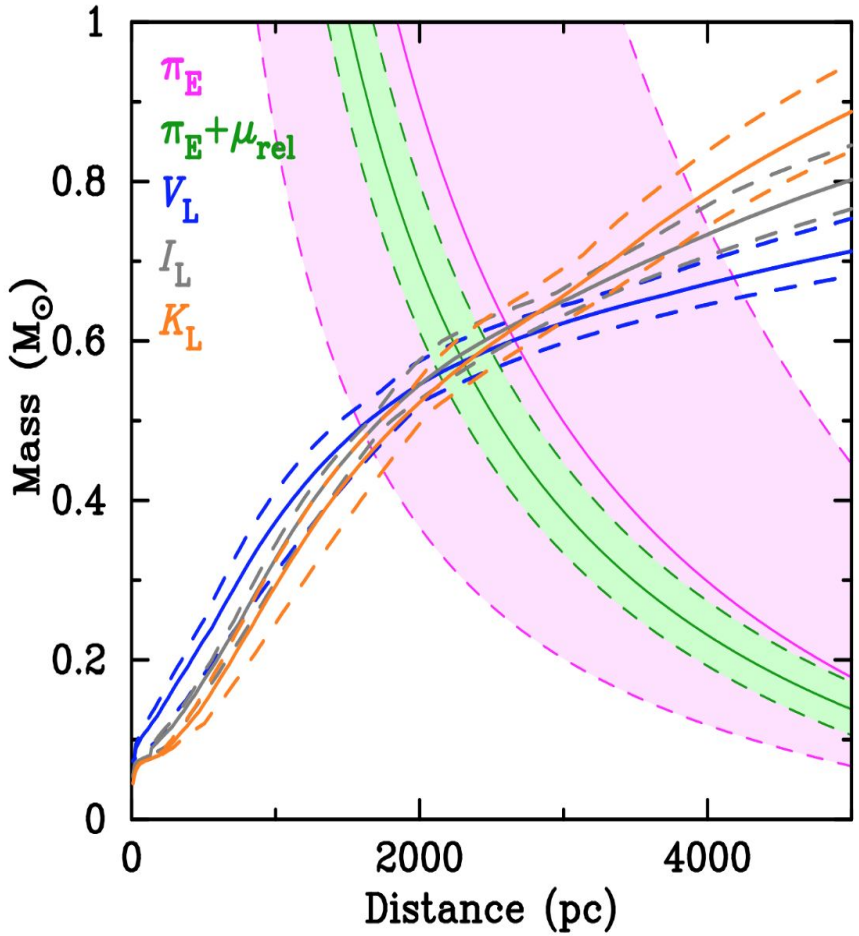


From Light Curve



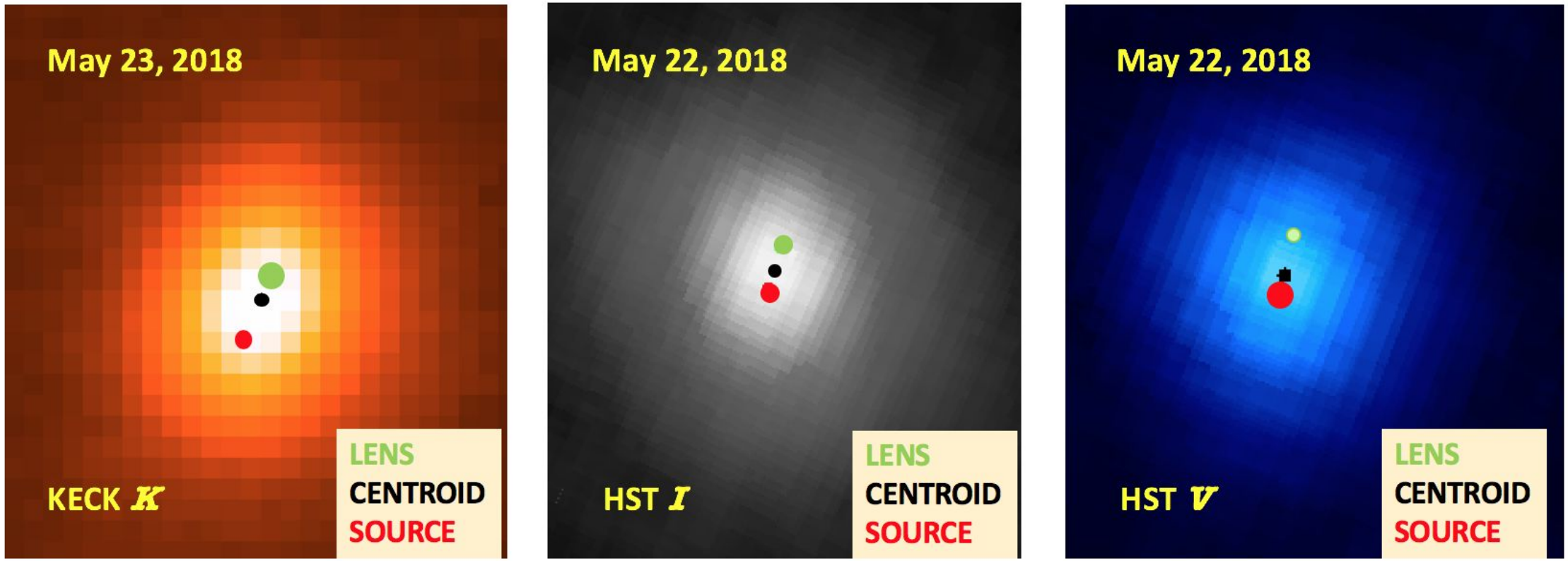
From High - Res





Roman will have both (data will be time domain+ images high resolution) +
Also observations will be taken in 2 different epochs

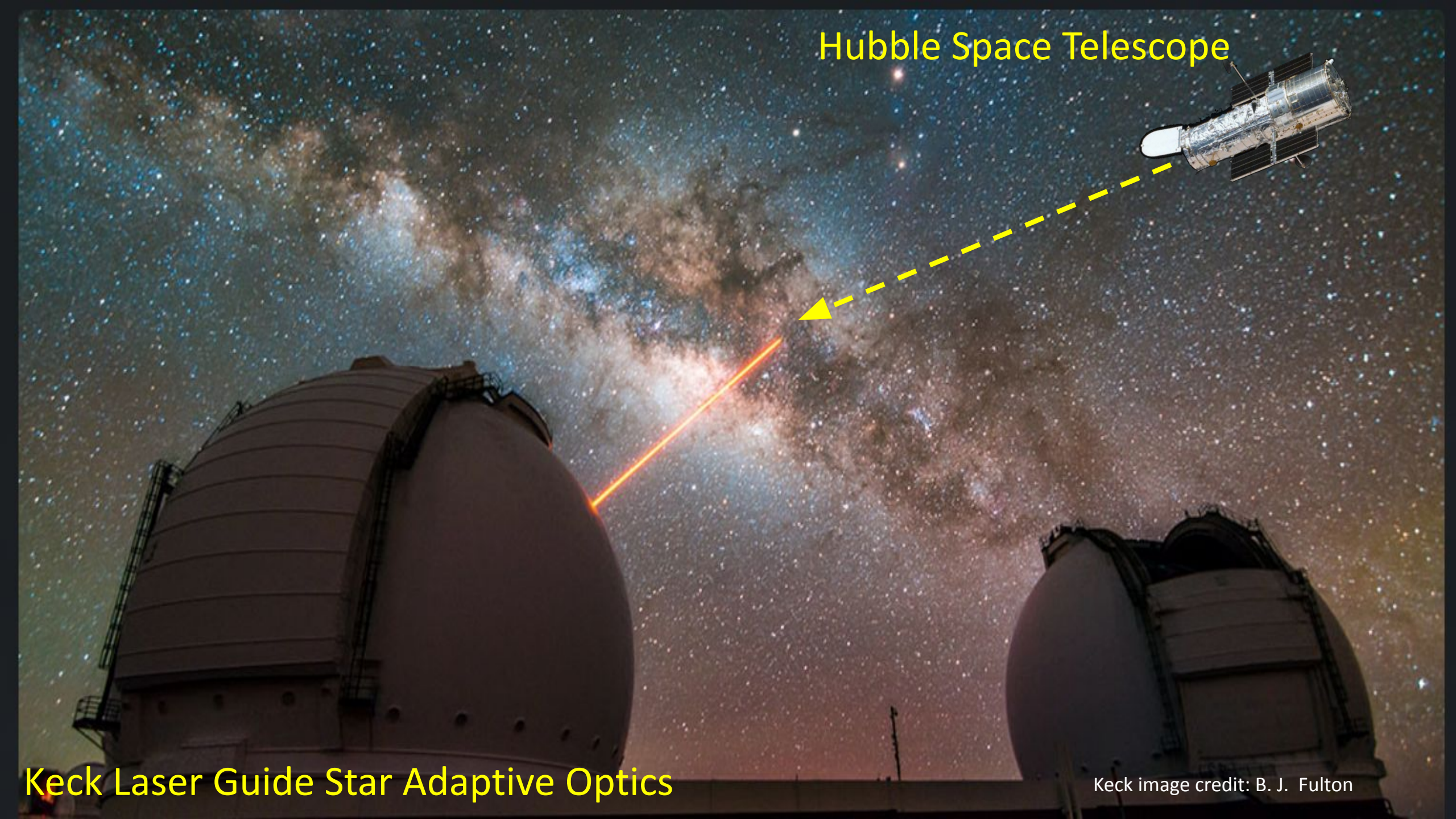
V vs K Color Dependent Centroid Shift



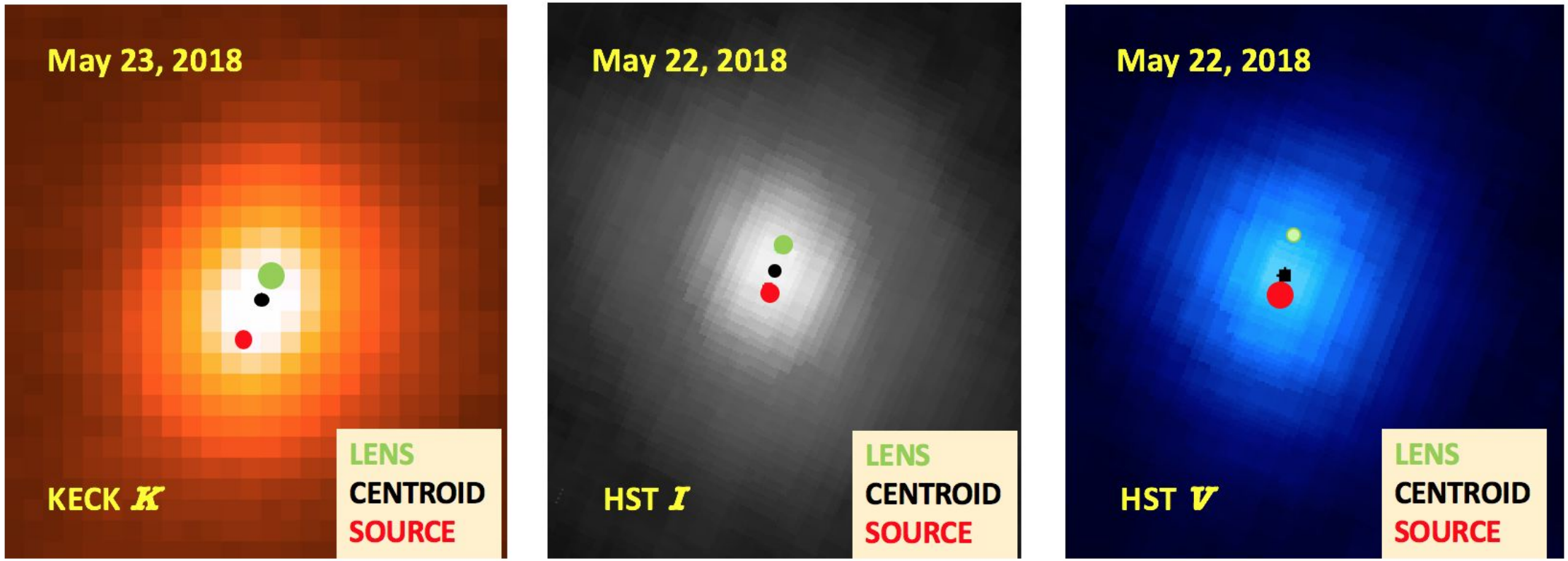
With color dependent centroid shift the lens can be detected in smaller separations 10-30 mas

Simultaneous Observations with Hubble and Keck

In Roman this will be done between different bands.


Hubble Space Telescope
Keck Laser Guide Star Adaptive Optics
Keck image credit: B. J. Fulton

V vs K Color Dependent Centroid Shift



With color dependent centroid shift the lens can be detected in smaller separations 10-30 mas

Simultaneous Observations with Hubble and Keck

In Roman this will be done between different bands.

Confirming centroid shift and Measured Masses

OGLE-2003-BLG-235

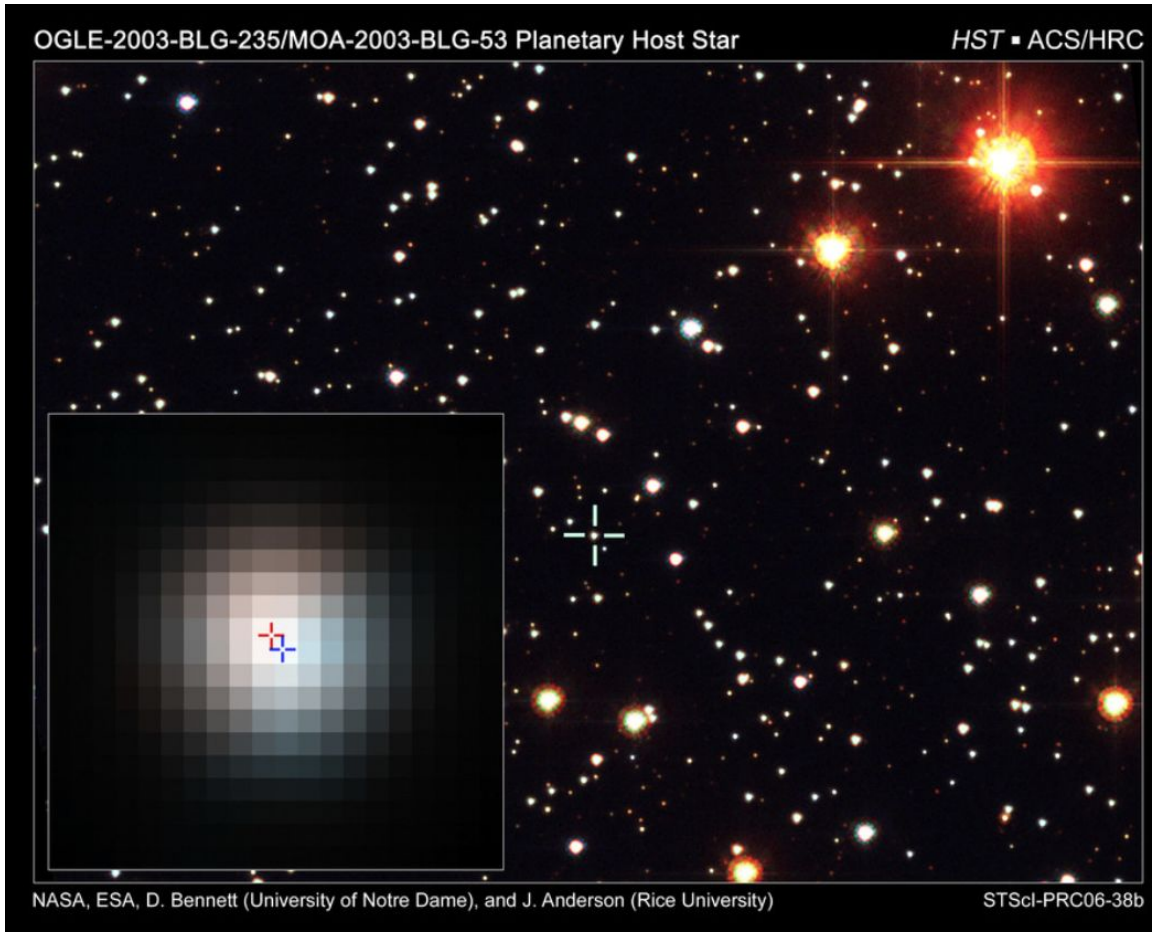
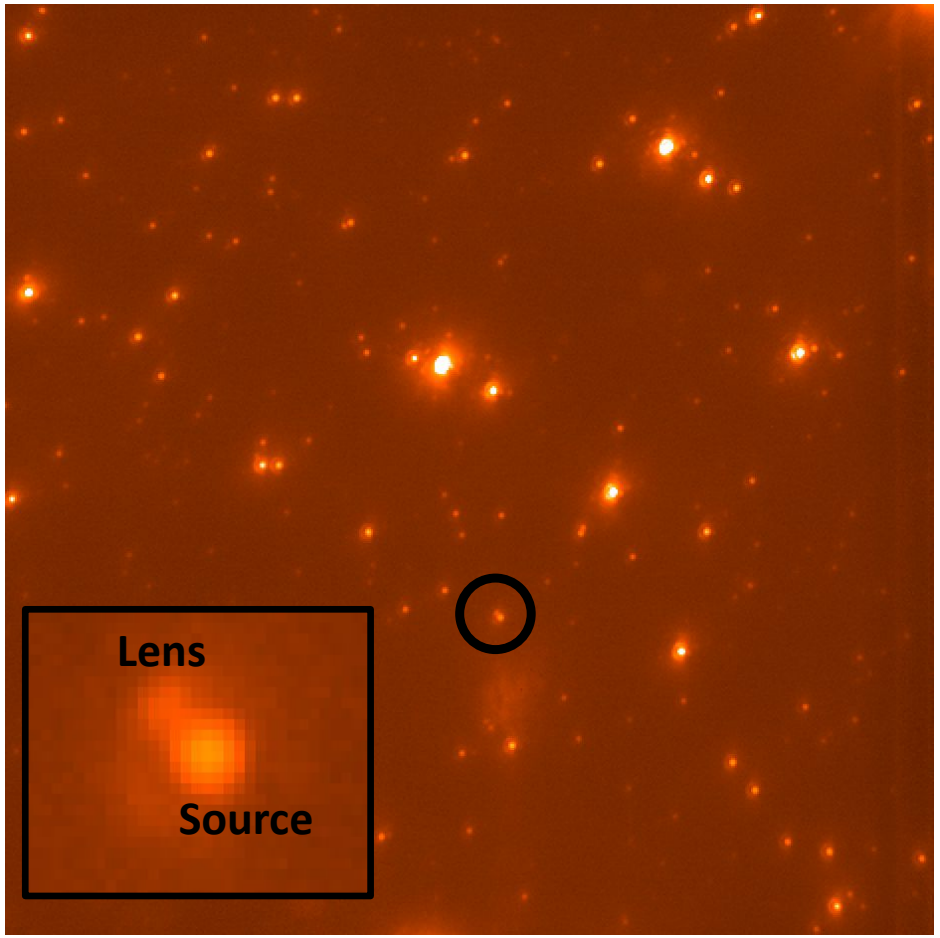


Image by HST ACS in 2005 Bennett+ 2006



Keck NIRC2 Narrow camera image in 2018
Bhattacharya+ 2022

Confirming centroid shift and Measured Masses

OGLE-2003-BLG-235

Centroid shifts

prediction: dE_(B-I), dN_(B-I) = -0.5179 +- 0.0559, -0.5388 +- 0.0584
observation: dE_(B-I), dN_(B-I) = -0.2643 +- 0.3637, -0.6214 +- 0.2396

prediction: dE_(B-V), dN_(B
0.0378, -0.1454 +- 0.0393
observation: dE_(B-V), dN_(B-V) = -0.2125 +- 0.2859, -0.6094 +- 0.2166

prediction: dE_(V-I), dN_(V-I) = -0.3782 +- 0.0408, -0.3934 +- 0.0426
observation: dE_(V-I), dN_(V-I) = -0.0518 +- 0.2669, -0.0120 +- 0.2196

Predictions of 2005 data based on 2018 Keck detections and
Observations are shifts observed in 2005

They are consistent

Host Masses

2018: 0.550 +- 0.018 M_{sun}
2005: 0.63 +0.07/-0.09 M_{sun}

Planet Masses

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

Bhattacharya+ in prep, 2021

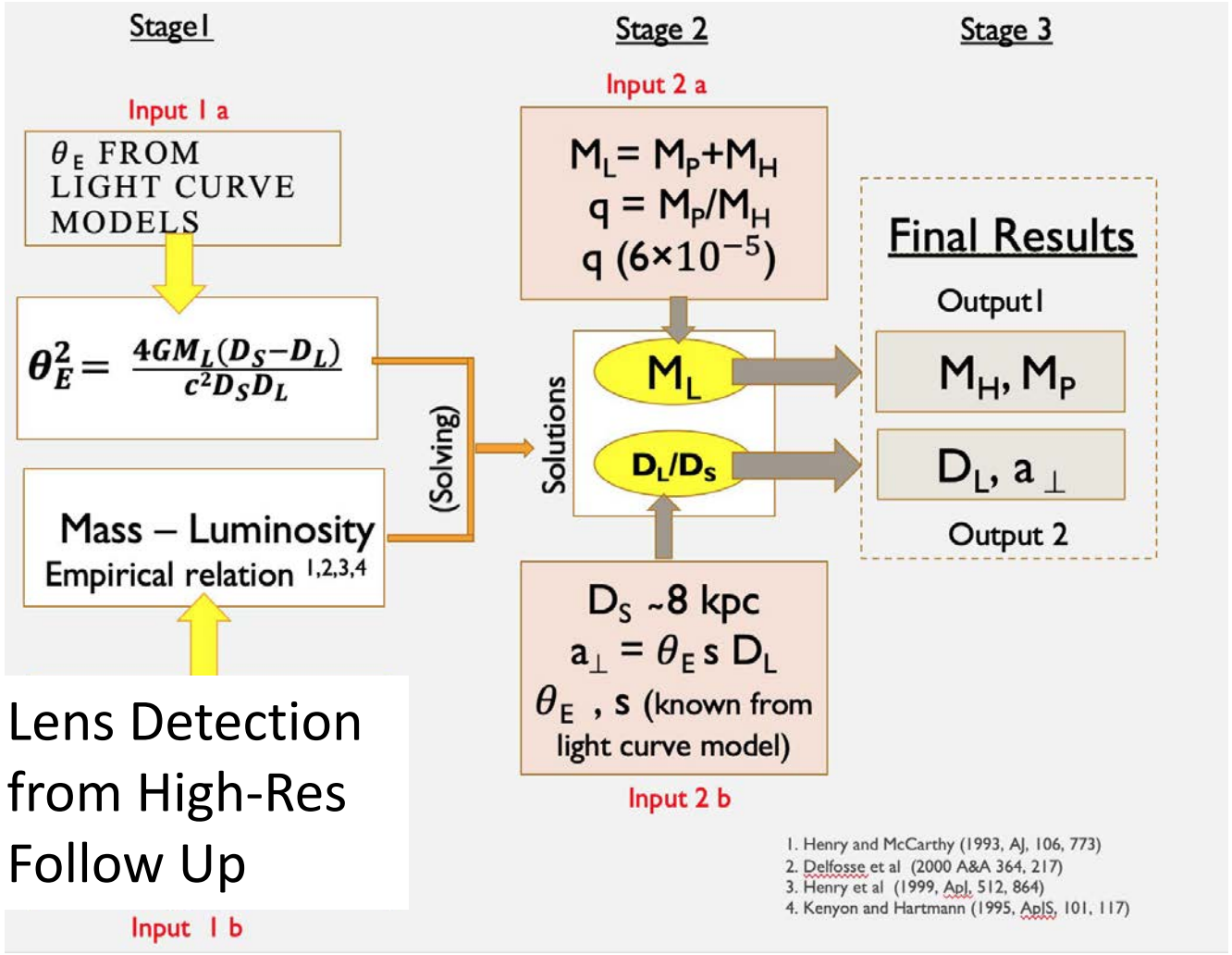
Mass measurement

from finite source effect

+

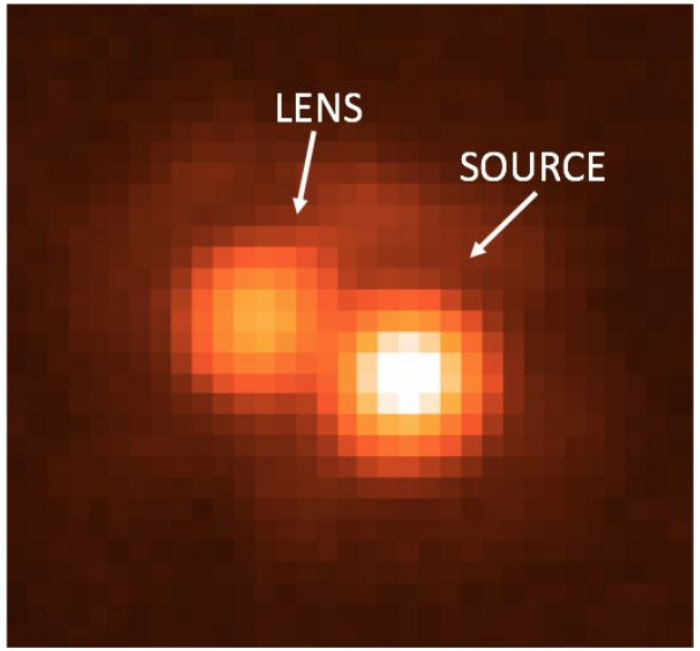
Lens Detection

In case of parallax not well measured



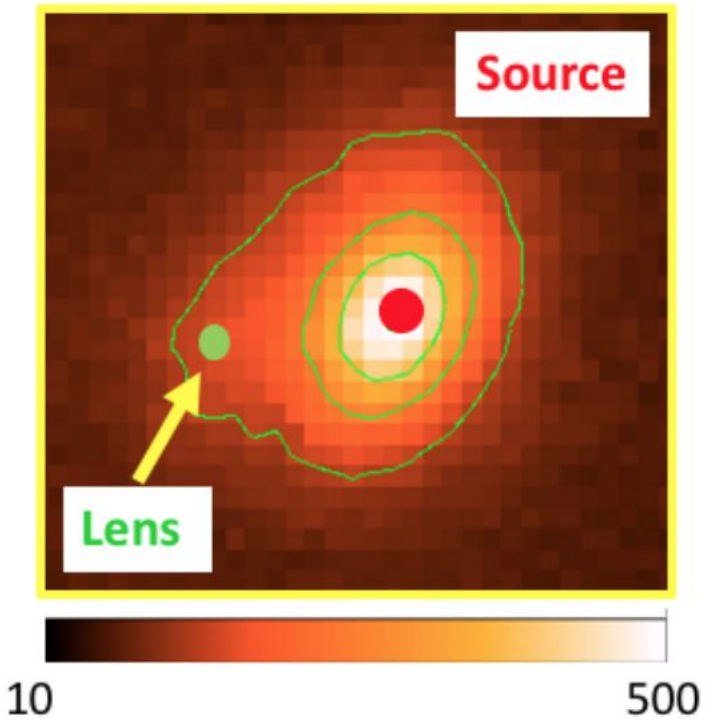
Planet Mass Measurements in Galactic Bulge

2019



MOA-2013-BLG-220:
Vandorou et al. 2020.
$M_L = 2.74 \pm 0.17\ M_J$
$M_H = 0.88 \pm 0.05\ M_S$
$D_L = 6.72 \pm 0.59$ kpc

2018



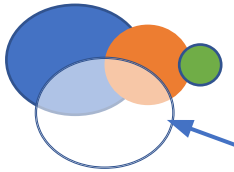
MOA-2007-BLG-400:
Bhattacharya et al. 2021.
$M_L = 1.71 \pm 0.27\ M_J$
$M_H = 0.69 \pm 0.04\ M_S$
$D_L = 6.89 \pm 0.77$ kpc
Lens ~ 10 x fainter than source

Koshimoto et al. 2021 showed planet frequency does not depend on galactic distance implying galactic bulge DOES have planets. ROMAN will find planets in galactic bulge.

Both events seem to suggest that more massive stars tend to host more massive planets. Roman will provide way more data on this.

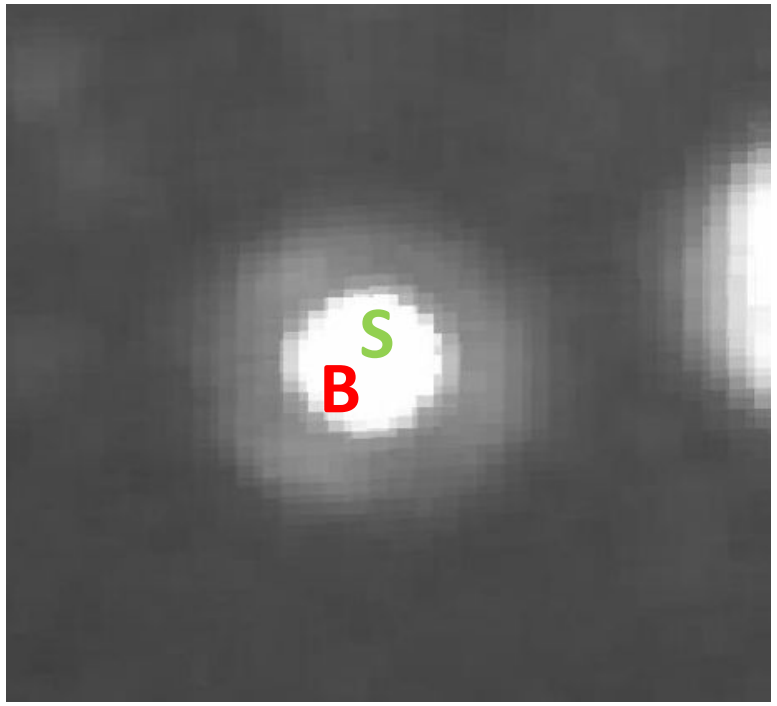
Two star fit –> Three Star Fit

MOA-2008-BLG-310



NEARBY UNRELATED STAR

2012 HST F814W

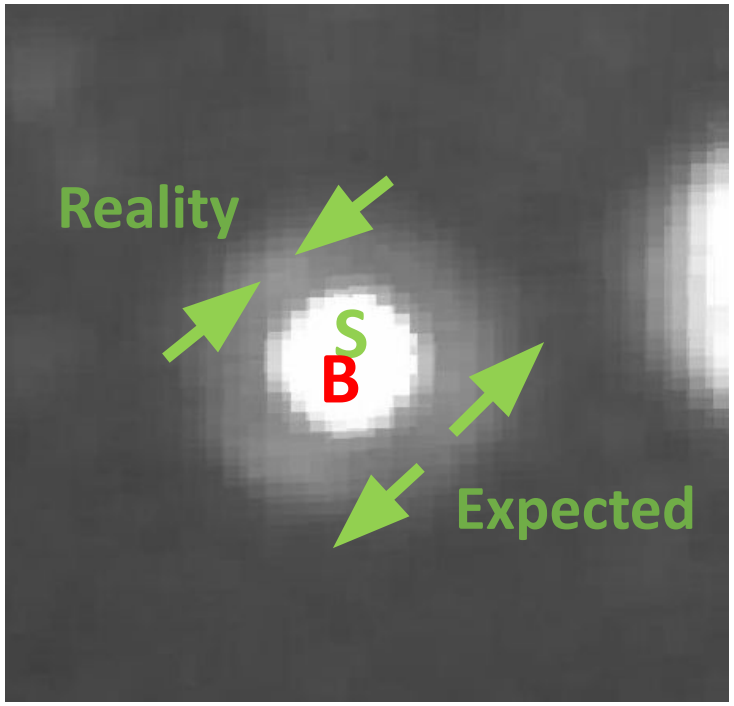


Source

Blend Star

Source Flux constrained from light curve fitting

2014 HST F814W

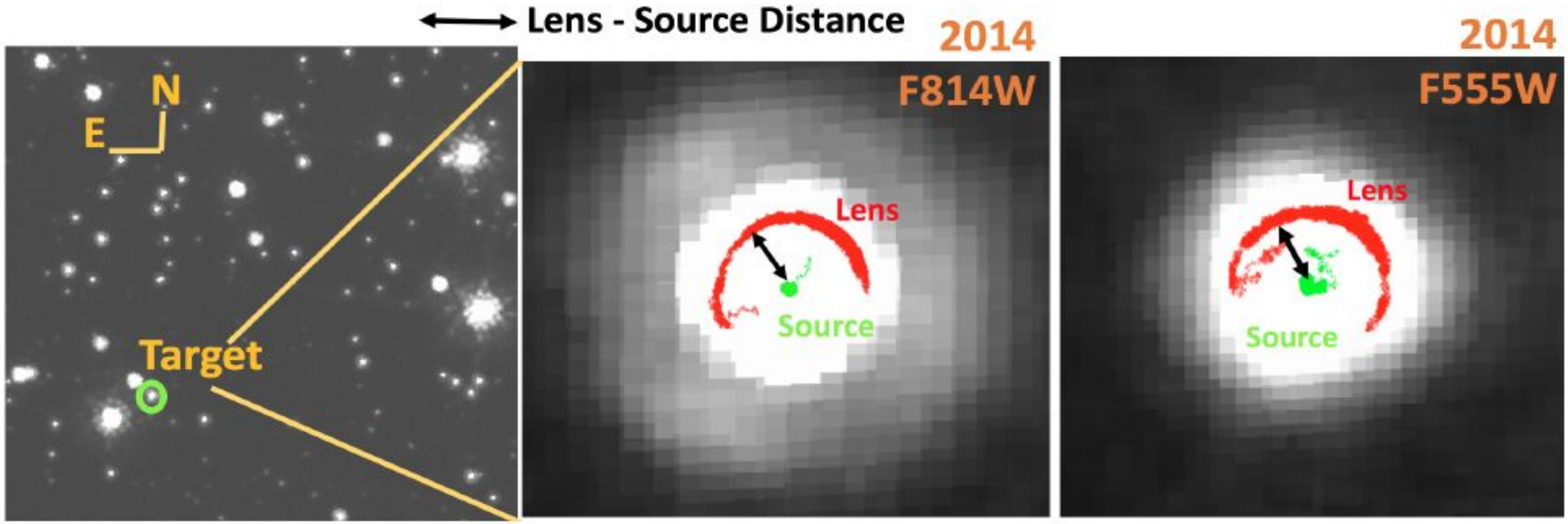


Three star fit – Upper Limit on Lens Mass

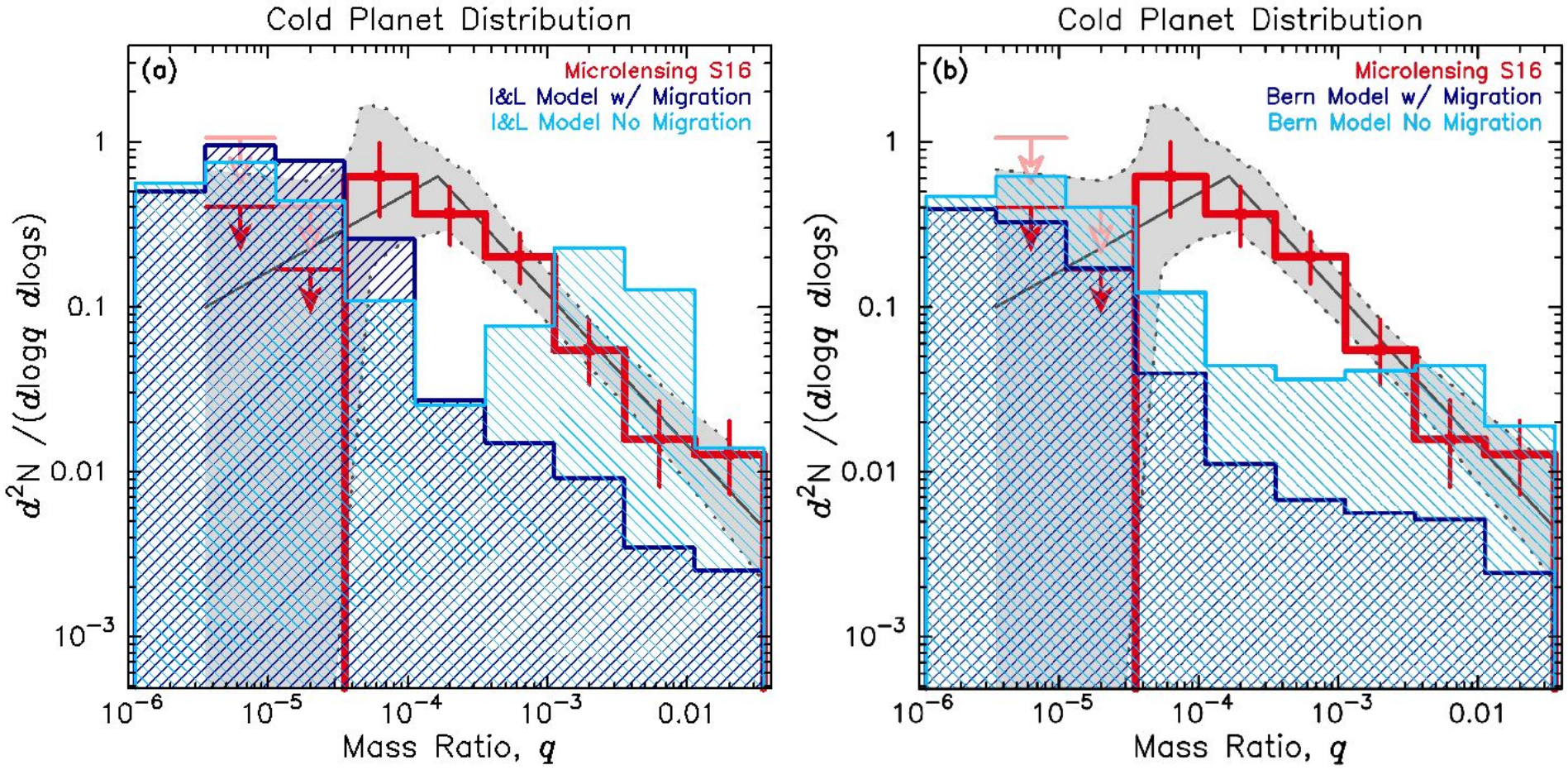
Bhattacharya et al. 2017

MOA-2008-BLG-310

Three star fit – Upper Limit on Lens Mass



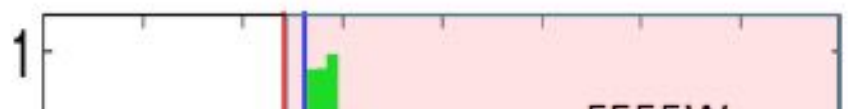
Core Accretion predicts lack of 20-80 M_E mass planets



Suzuki+ 2018

MOA-2008-BLG-310

Three star fit – Upper Limit on Lens Mass

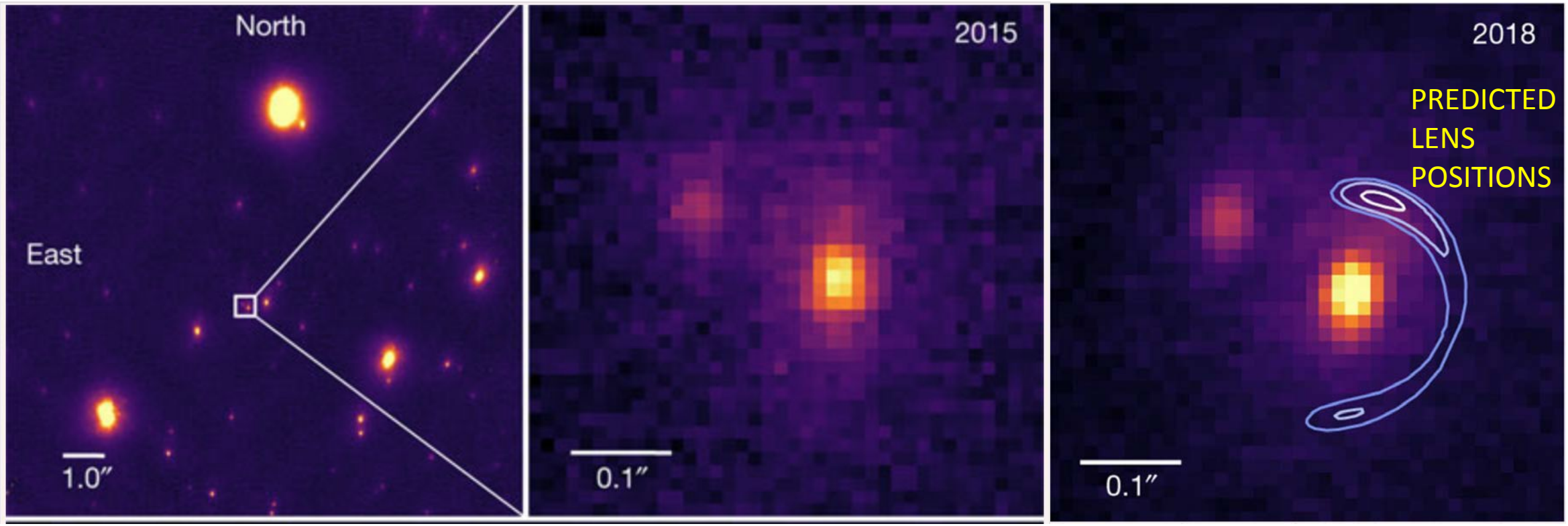


parameter	units	99% confidence		95% confidence	
		I	V	I	V
Host star mass, M_*	$M_\odot$	0.64	0.73	0.61	0.72
Planet mass, $m_{\rm P}$	$M_\oplus$	72	82	69	81
Host star - Planet 2D separation, $a_\perp$	AU	1.1	1.1	1.1	1.1
Lens distance, $D_{\rm L}$	kpc	7.8	7.8	7.8	7.8

$I = 22.15, V = 23.41$ (99% confidence)

$I = 22.44, V = 23.62$ (95% confidence)

Jovian Analog planet around white dwarf



D_L ~ 2 kpc

MOA -2010-BLG-477

Blackman et al 2021, Nature

Highlights

- About 30+ events with mass measurements, 10+ published. Lot of these events are part of Hubble and Keck KSMS program as part of Roman precursor study. Develop the method.
- Challenge – Closer to galactic plane higher chance of microlensing, less mass measurements due to higher extinction – where's the balance?

- We have also confirmed a planet around white dwarf host star (Blackman+ 2021)
- We have shown that even for stars with companions, it is possible to get upper limits on planet and host masses (Bhattacharya+ 2017)
- Mass measurements will help breaking degeneracies and understand the planet formation better

Highlights

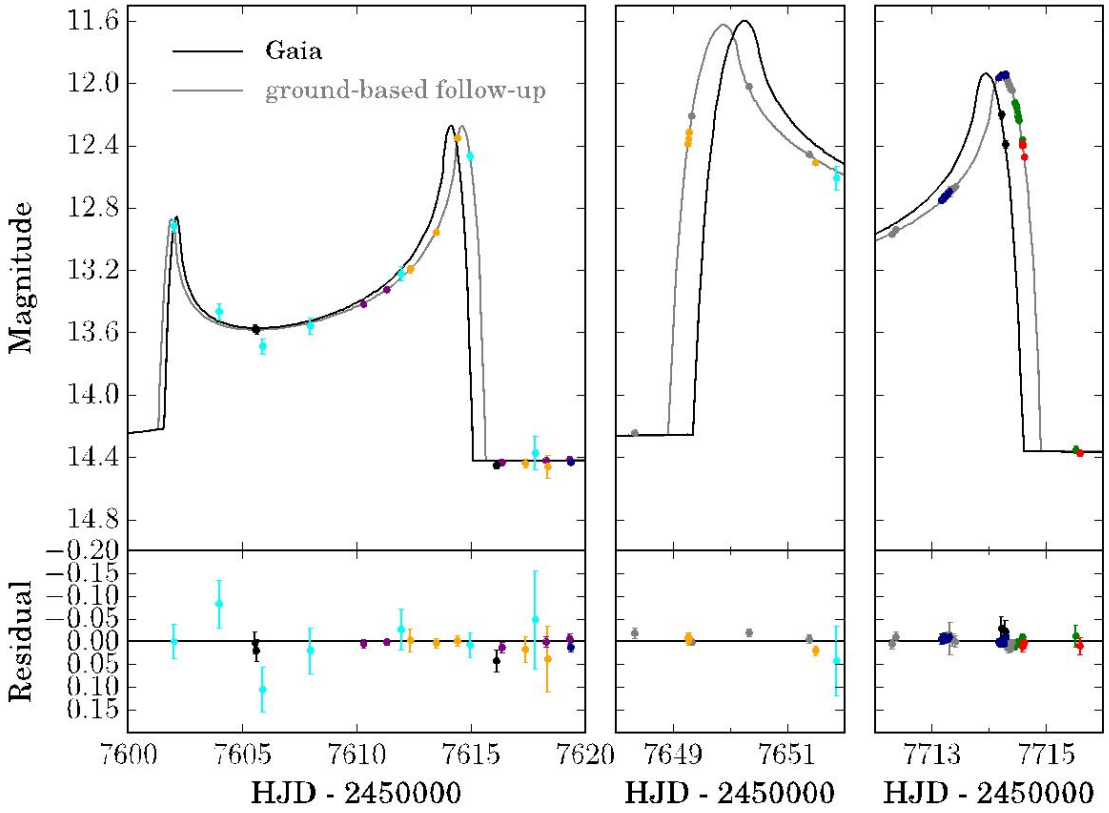
We can detect free floating planets using this method since we do not need to depend on the light from the host.

- See Samson Johnson talk tomorrow.

We can get mass measurements even for free floating planets using the parallax/ finite source method using Rubin – ROMAN

(Etienne Bachelet Talk)

- The only method in which we can get mass measurements of free floating planets.



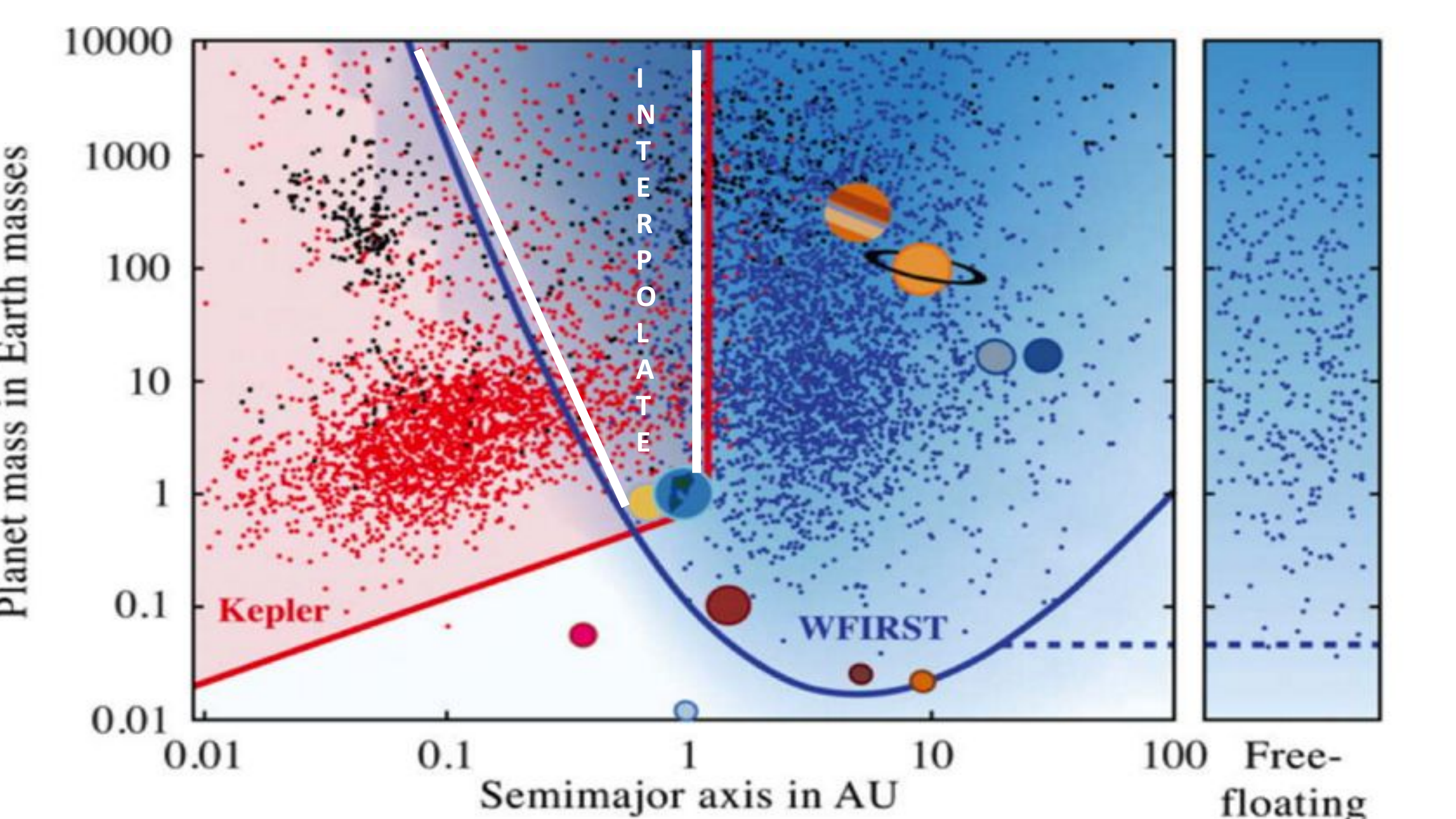
Wyrzykowski+ 2020

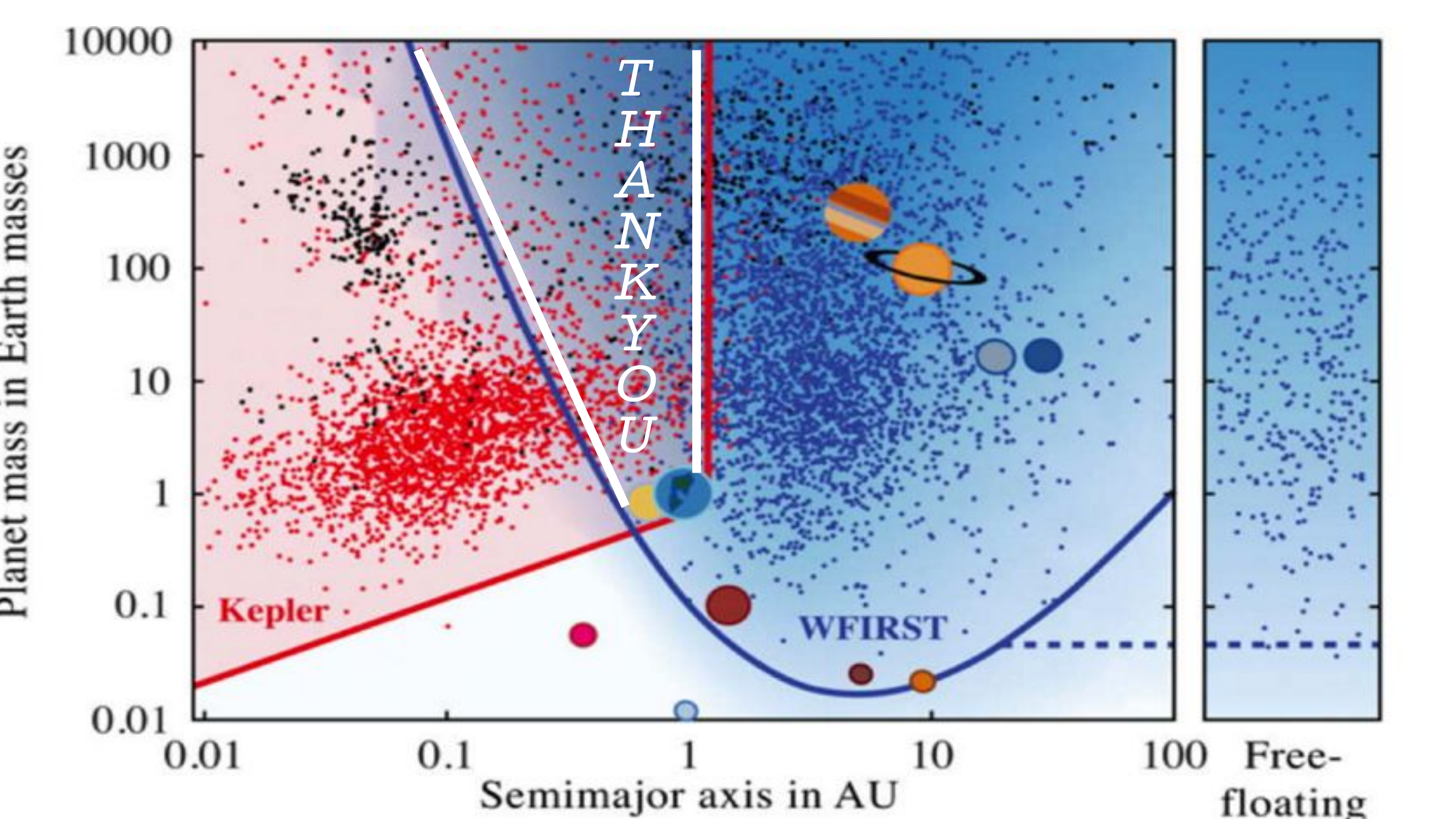
With 1400+ cold low mass exoplanets and 700+ mass measurements around G,K,M stars

- Wide orbit cold planets are located in the birthplace of planet formation –just beyond the snowline
- How common is our solar system?
- Where does the water on earth come from?
- Do planets form in the same way even far from us?
- What kind of stars host earth like planets?

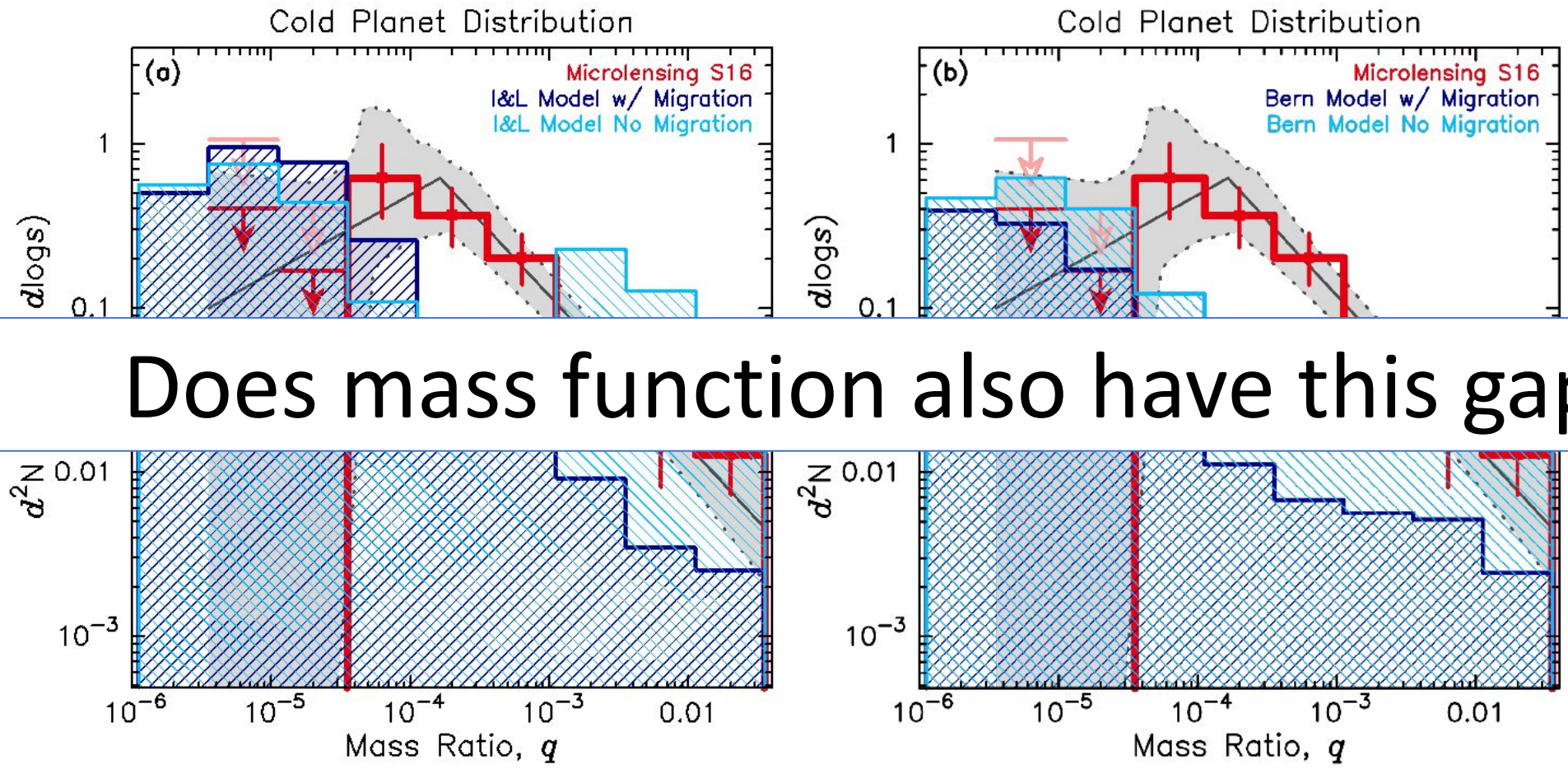
(500+ planets in 10ME and 180 planets in 1 ME (Penny 2019))

- The only way to get mass measurements of free-floating planets


10000
1000
100
10
1
0.1
0.01
Planet mass in Earth masses
0.01
0.1
1
10
100
Free-floating
Semimajor axis in AU
INTERPOLATE
Kepler
WFIRST


10000
1000
100
10
1
0.1
0.01
Planet mass in Earth masses
0.01
0.1
1
10
100
Free-floating
Semimajor axis in AU
Kepler
WFIRST
THANKYOU

Core Accretion predicts lack of 20-80 M_E mass planets



Does mass function also have this gap ?

Suzuki+ 2018, in prep

Ultimate Goals with KSMS

- Expanding mass ratio function to mass function with the mass measurements
- Test planet formation theories with the mass function
- Applying these algorithms to build WFIRST microlensing exoplanet data reduction pipeline – WFIRST will simultaneously observe in high resolution as well as discover the planets with thousands of images.