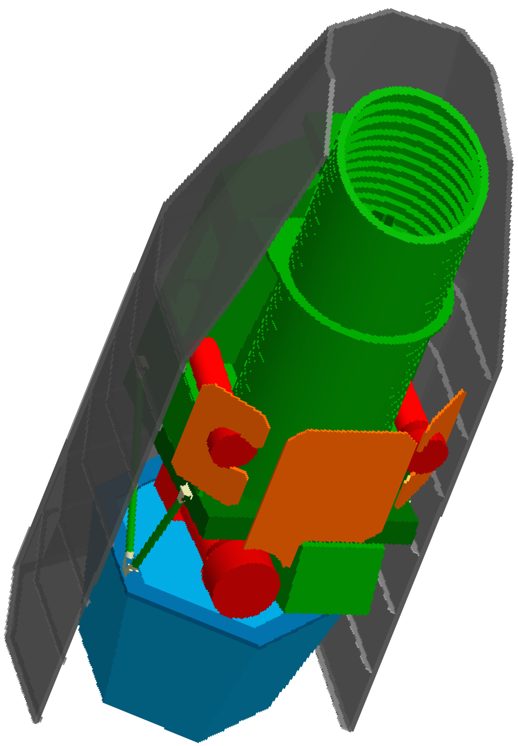
Exoplanet Microlensing Surveys with WFIRST and Euclid



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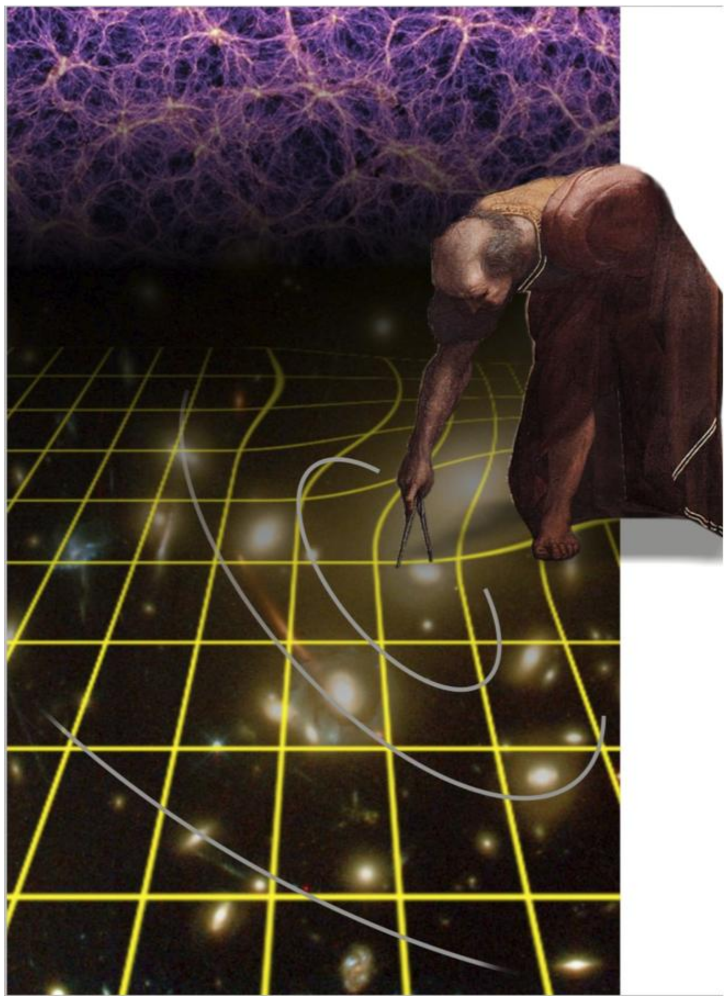


WFIRST
Wide-Field Infra-Red Survey Telescope

Why Space-based Microlensing?

- Space-based microlensing is critical for our understanding of exoplanet demographics
  - no other method covers 0.5 AU - ∞ at low masses (complements Kepler)
  - covers important region of habitable zone—snowline
  - future missions are likely to rely upon these statistics

- Microlensing requires extremely crowded fields
- Source stars only resolvable from space
- Ground-based surveys need high lensing magnification to resolve most source stars
  - Limits sensitivity to near the Einstein ring
- Space-based microlensing allows detection of most lens stars
  - Allows direct determination of star and planet masses

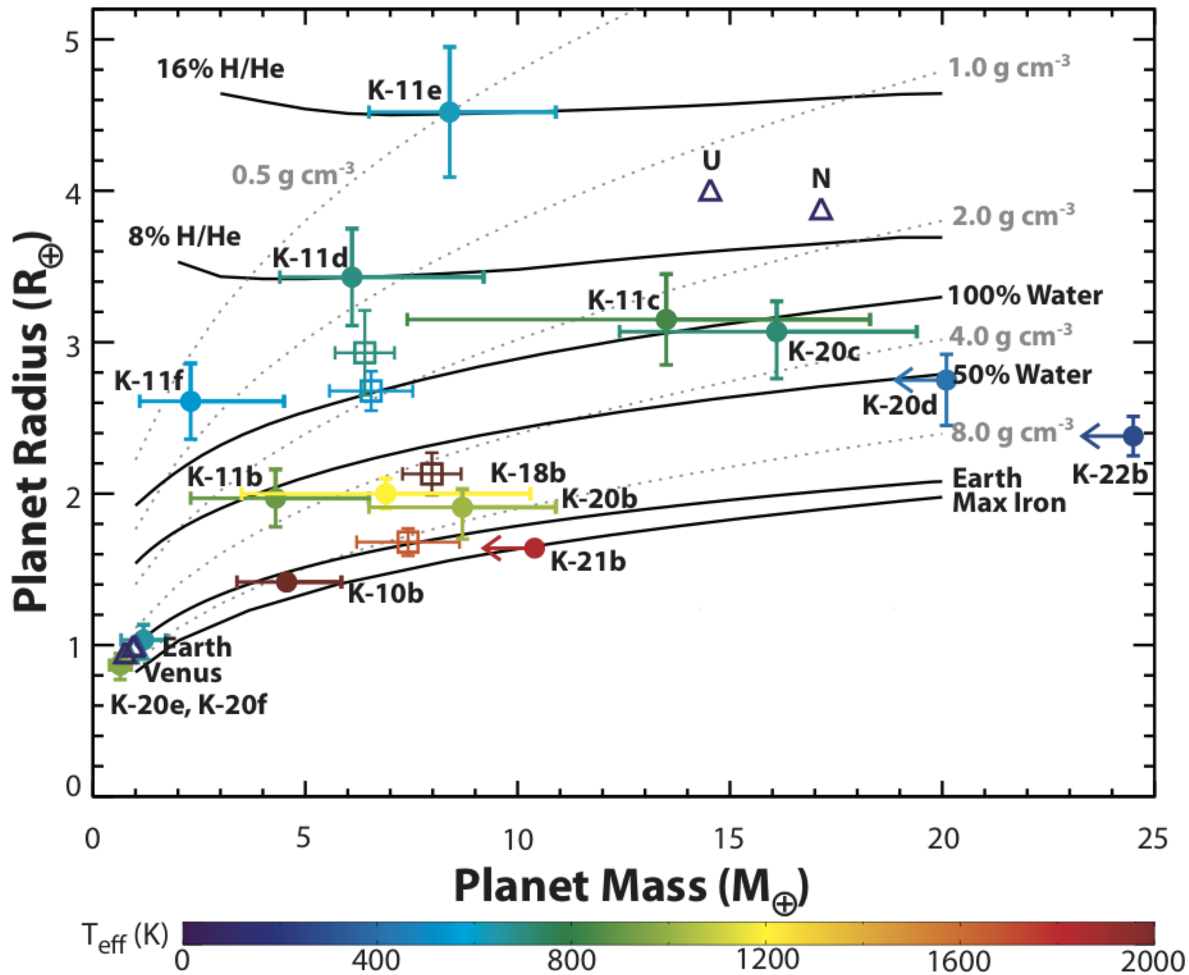
Unique Science from Space-based Survey

- ***Exoplanet Survey Question #1: How do planetary systems form and evolve?***
  - – complementary to Kepler
  - – Exoplanet sensitivity down to sub-Earth masses at 0.5 AU - ∞
  - – down to 0.1 Earth-masses over most of this range
  - – free-floating planets down to 0.1 Earth-masses
    - free-floating planet mass distribution is important for understanding planet formation.
- ***Exoplanet Survey Question #2: How common are potentially habitable worlds?***
  - – $\eta_{\oplus}$ = fraction of planetary systems with an earth-like planet in the habitable zone
  - – But what is earth-like?
  - – Kepler results imply: $\eta_{\oplus\text{-mass}}$ is not the same as $\eta_{\oplus\text{-radius}}$
  - – We need to answer question #1 to understand habitability

KEPLER IS EXPLORING THE PHASE SPACE BETWEEN EARTH AND NEPTUNE

Kepler
A Search for Earth-size Planets

low-mass planets in short period orbits can have low densities



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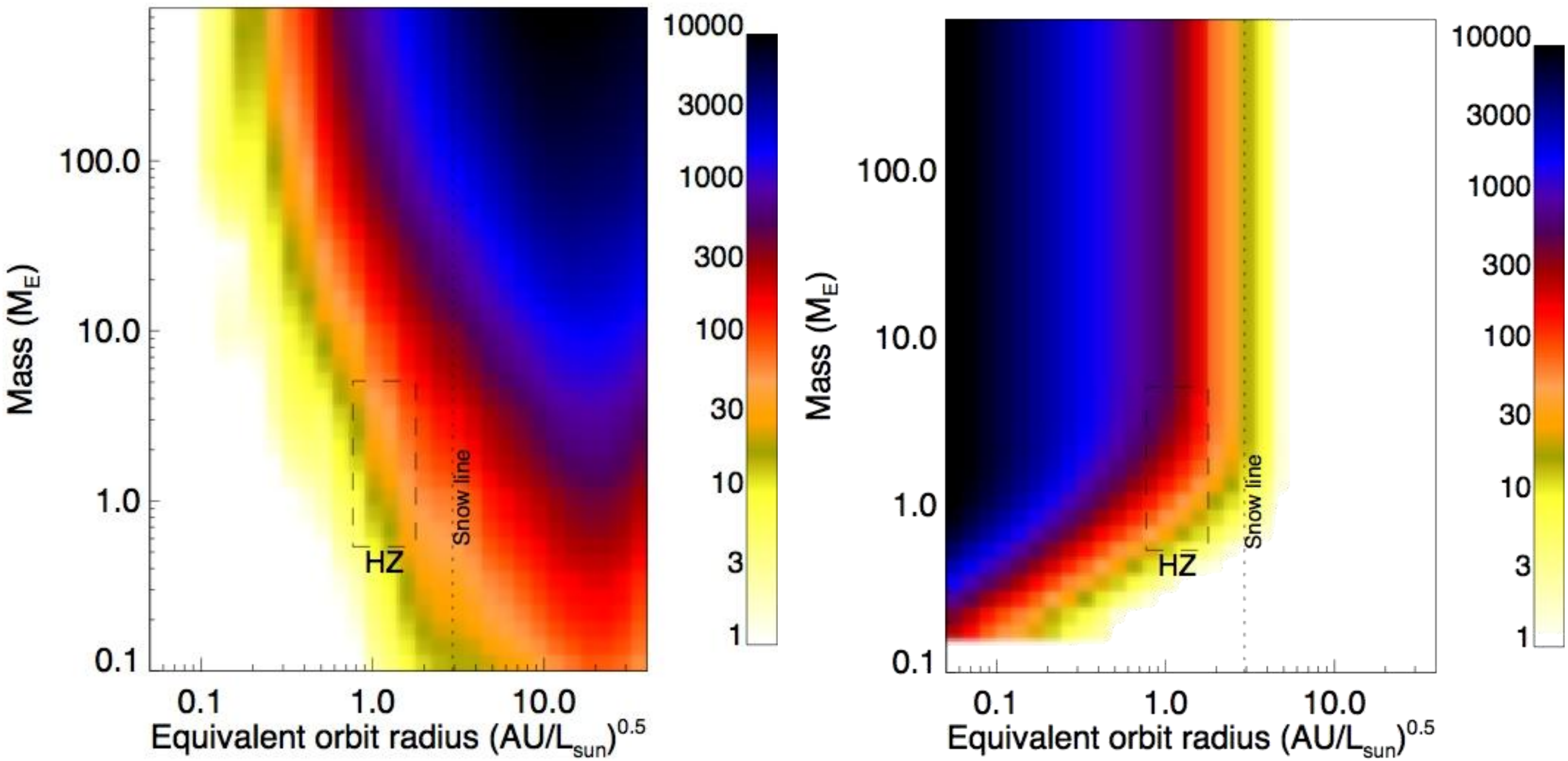
WFIRST vs. Kepler

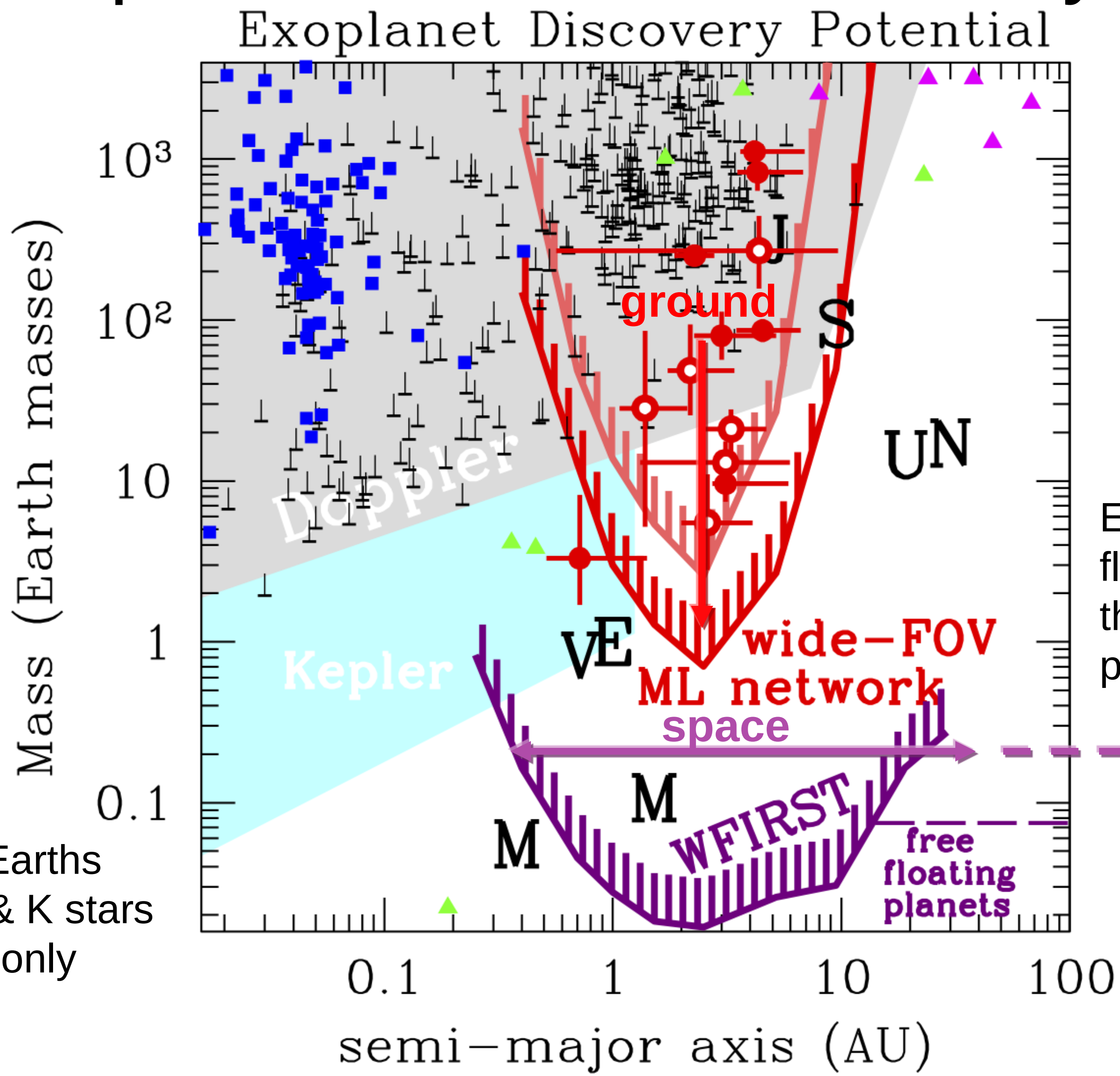
WFIRST – w/ extended mission

Kepler ~12 yr mission



Figures from B. MacIntosh of the ExoPlanet Task Force

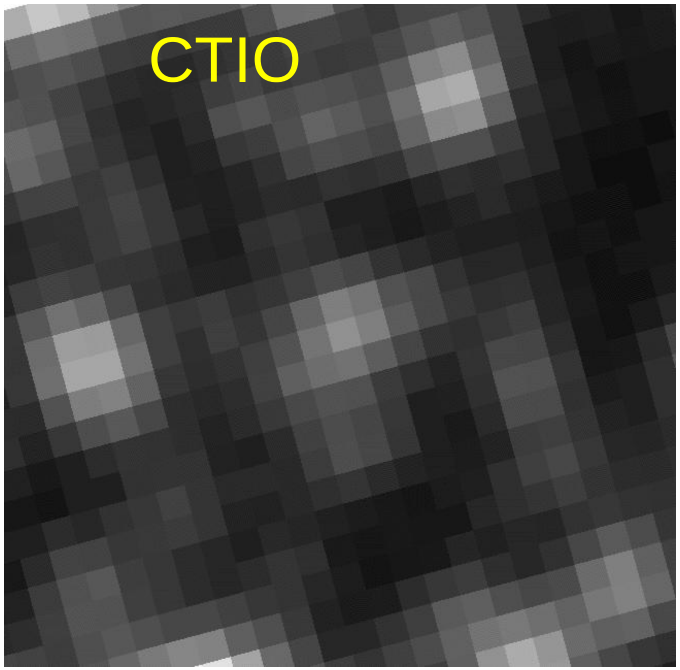
Space vs. Ground Sensitivity

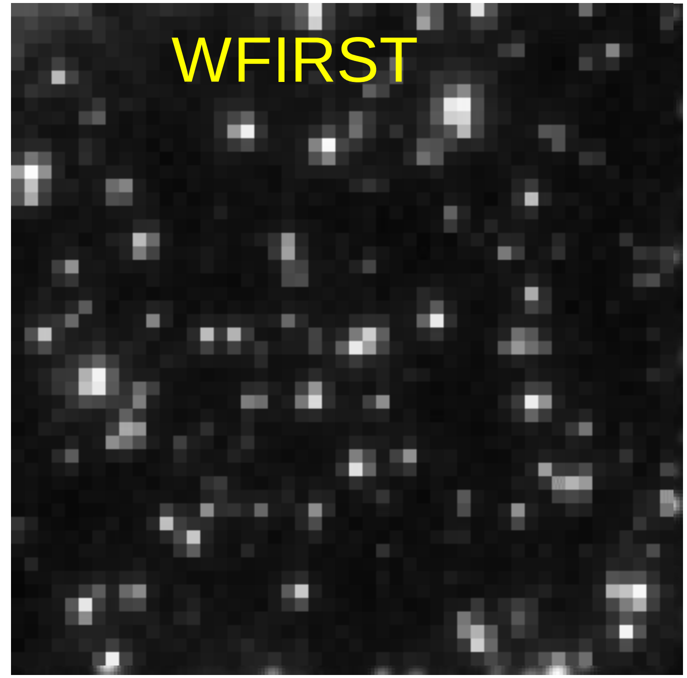


Expect 60 free-floating Earths if there is 1 such planet per star

Habitable Earths orbiting G & K stars accessible only from space

Ground-based confusion, space-based resolution





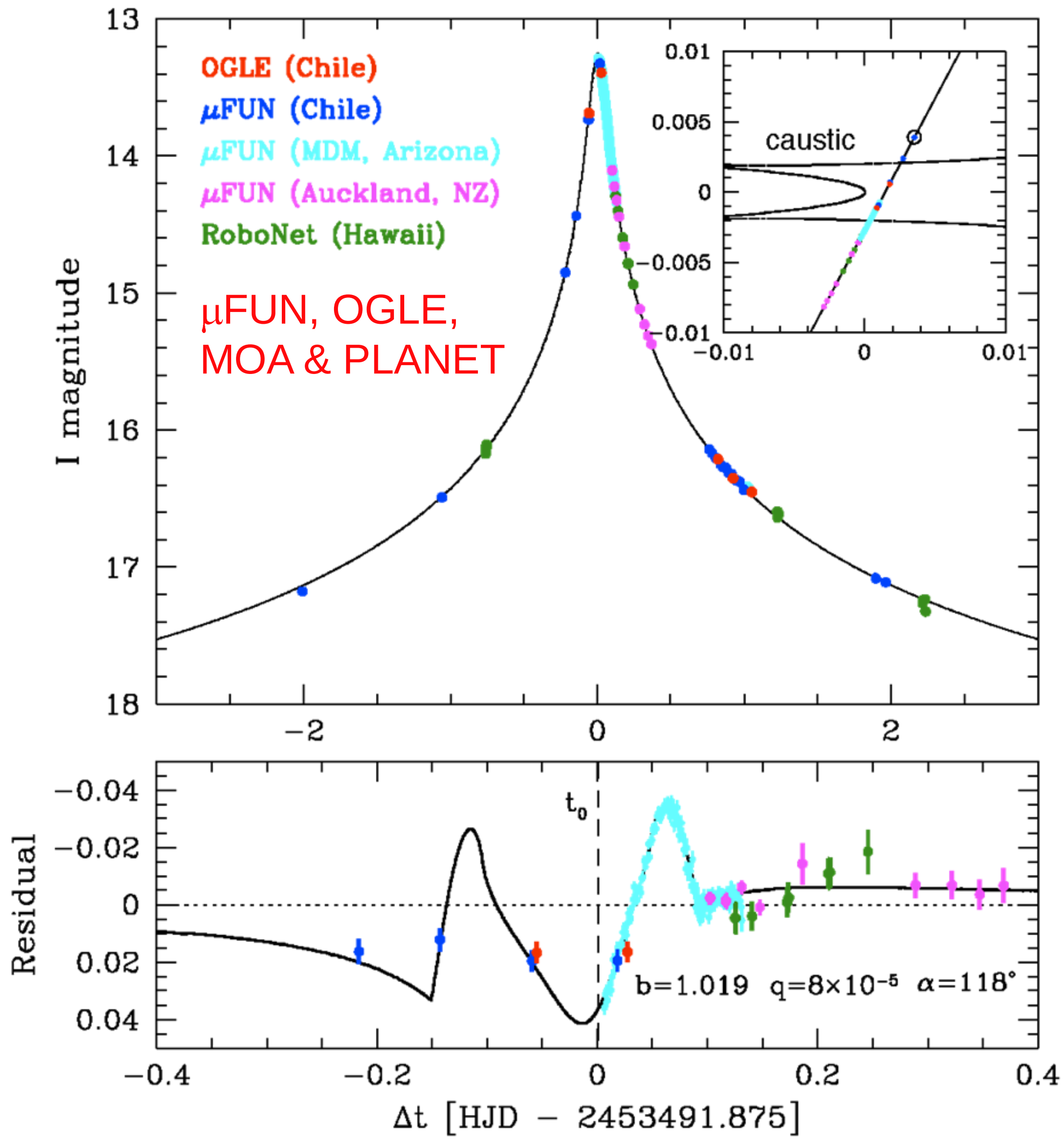
- Space-based imaging needed for high precision photometry of main sequence source stars (at low magnification) and lens star detection
- High Resolution + large field + 24hr duty cycle => Space-based Microlensing Survey
- Space observations needed for sensitivity at a range of separations and mass determinations

High-magnification: Low-mass planets

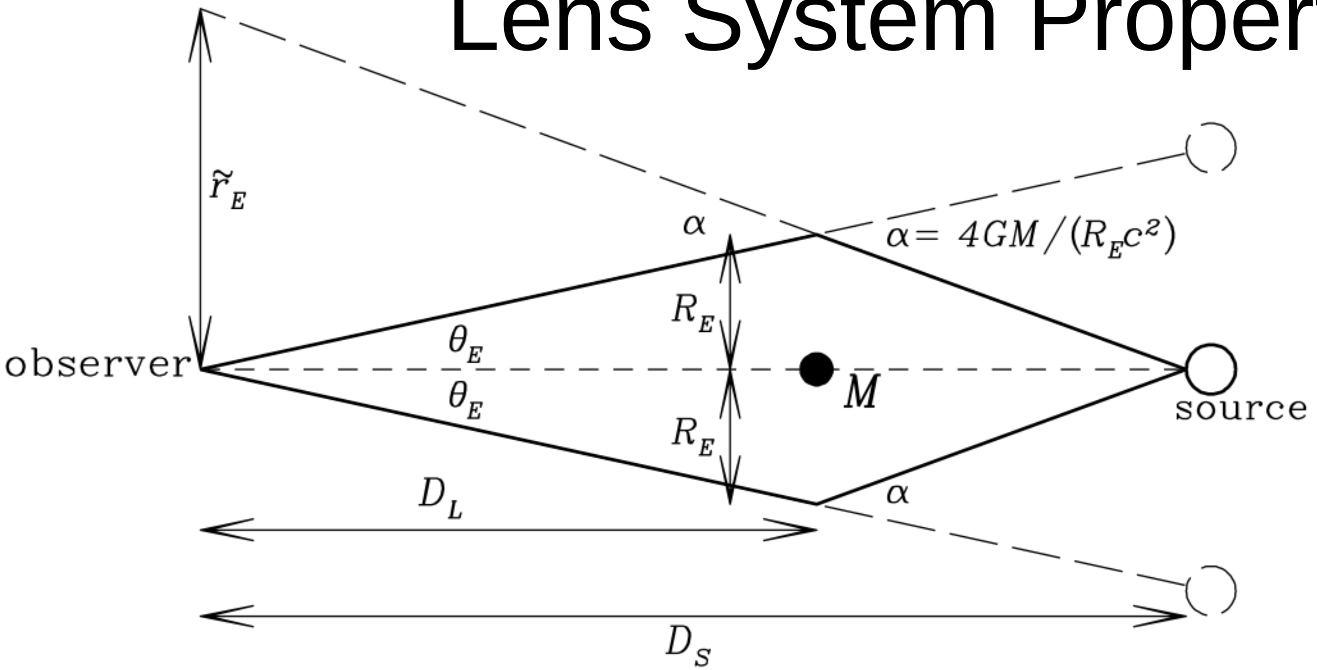
OGLE-2005-BLG-169Lb

- Detection of a ~17 $M_\oplus$ planet in a A_{max}= 800 event
- Caustic crossing signal is obvious when light curve is divided by a single lens curve.
- Detection efficiency for ~10 $M_\oplus$ planets is << than for Jupiter-mass planets

- Competing models with an Earth-mass planet had a signal of similar amplitude
- So, an Earth-mass planet could have been detected in this event!



Lens System Properties



- Einstein radius : $\theta_E = \theta_* t_E / t_*$ and projected Einstein radius, $\tilde{r}_E$
  - θ_* = the angular radius of the star
  - $\tilde{r}_E$ from the microlensing parallax effect (due to Earth's orbital motion).

$$R_E = \theta_E D_L, \text{ so } \alpha = \frac{\tilde{r}_E}{D_L} = \frac{4GM}{c^2 \theta_E D_L}. \text{ Hence } M = \frac{c^2}{4G} \theta_E \tilde{r}_E$$

Finite Source Effects & Microlensing Parallax Yield Lens System Mass

- If only θ_E or $\tilde{r}_E$ is measured, then we have a mass-distance relation.
- Such a relation can be solved if we detect the lens star and use a mass-luminosity relation
  - This requires HST or ground-based adaptive optics
- With θ_E, $\tilde{r}_E$, and lens star brightness, we have more constraints than parameters

mass-distance relations:

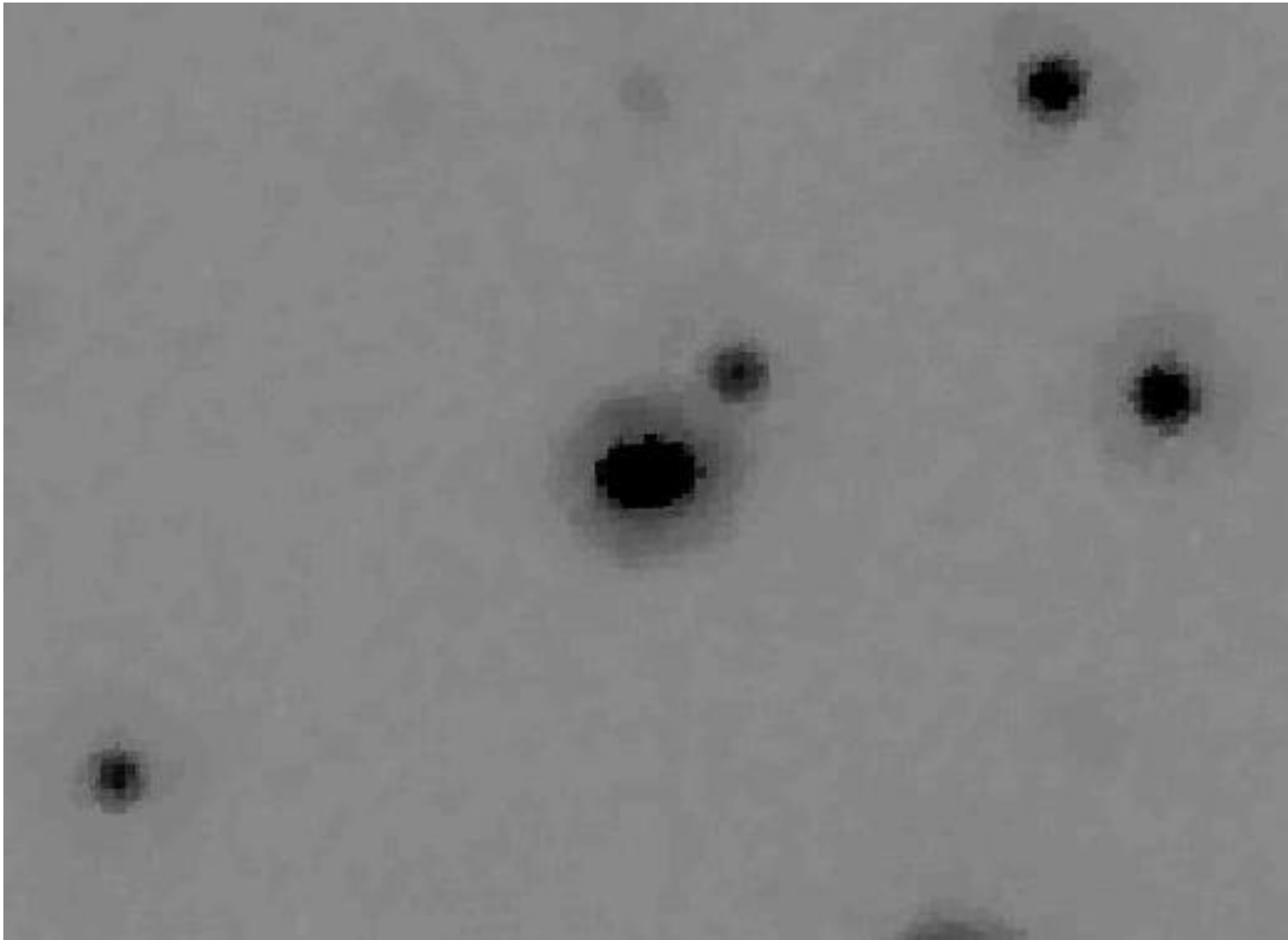
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

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

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

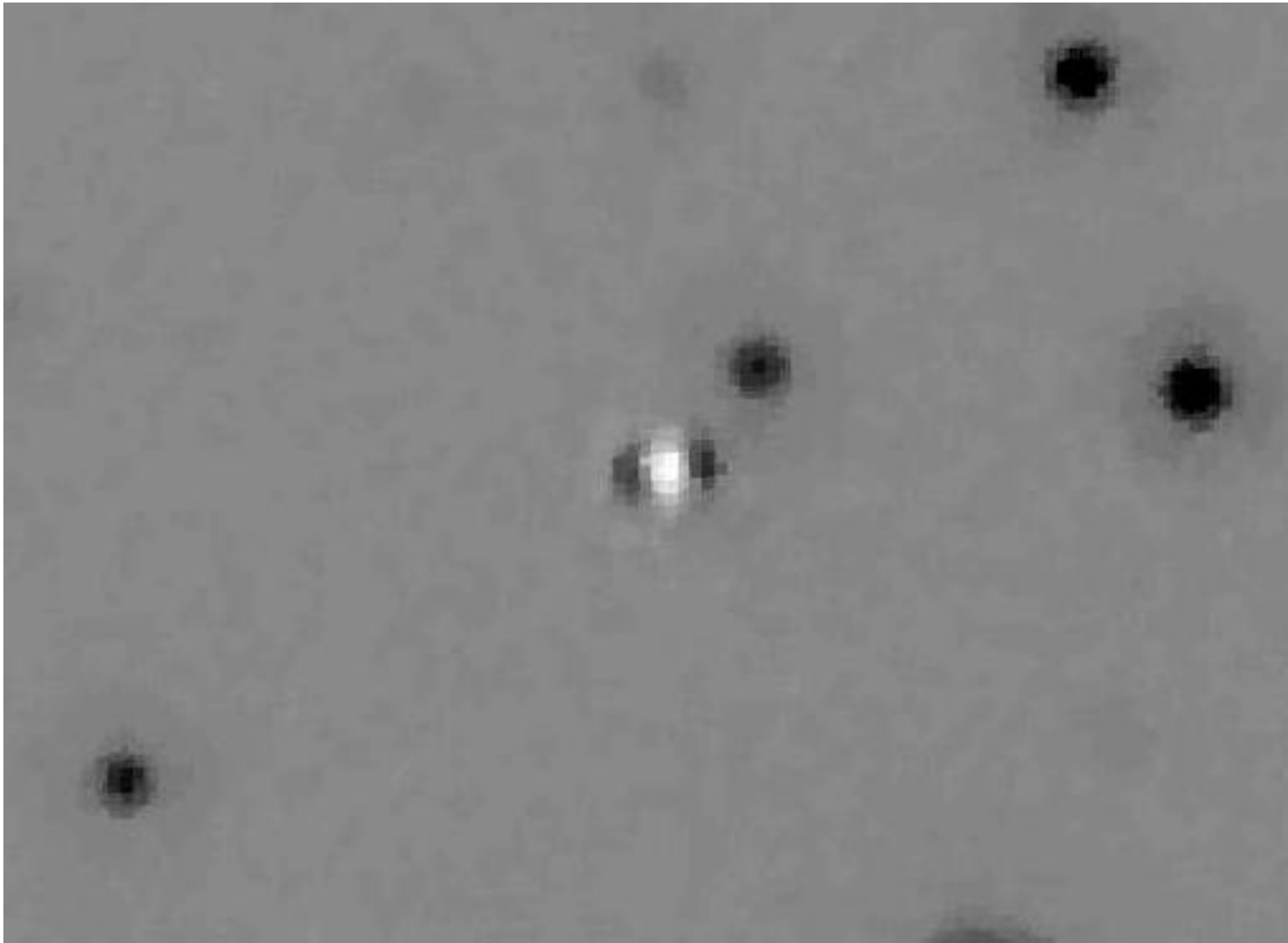
Stacked HST I-band Image of OGLE-2005-BLG-169 Source

Source *looks* elongated relative to neighbors



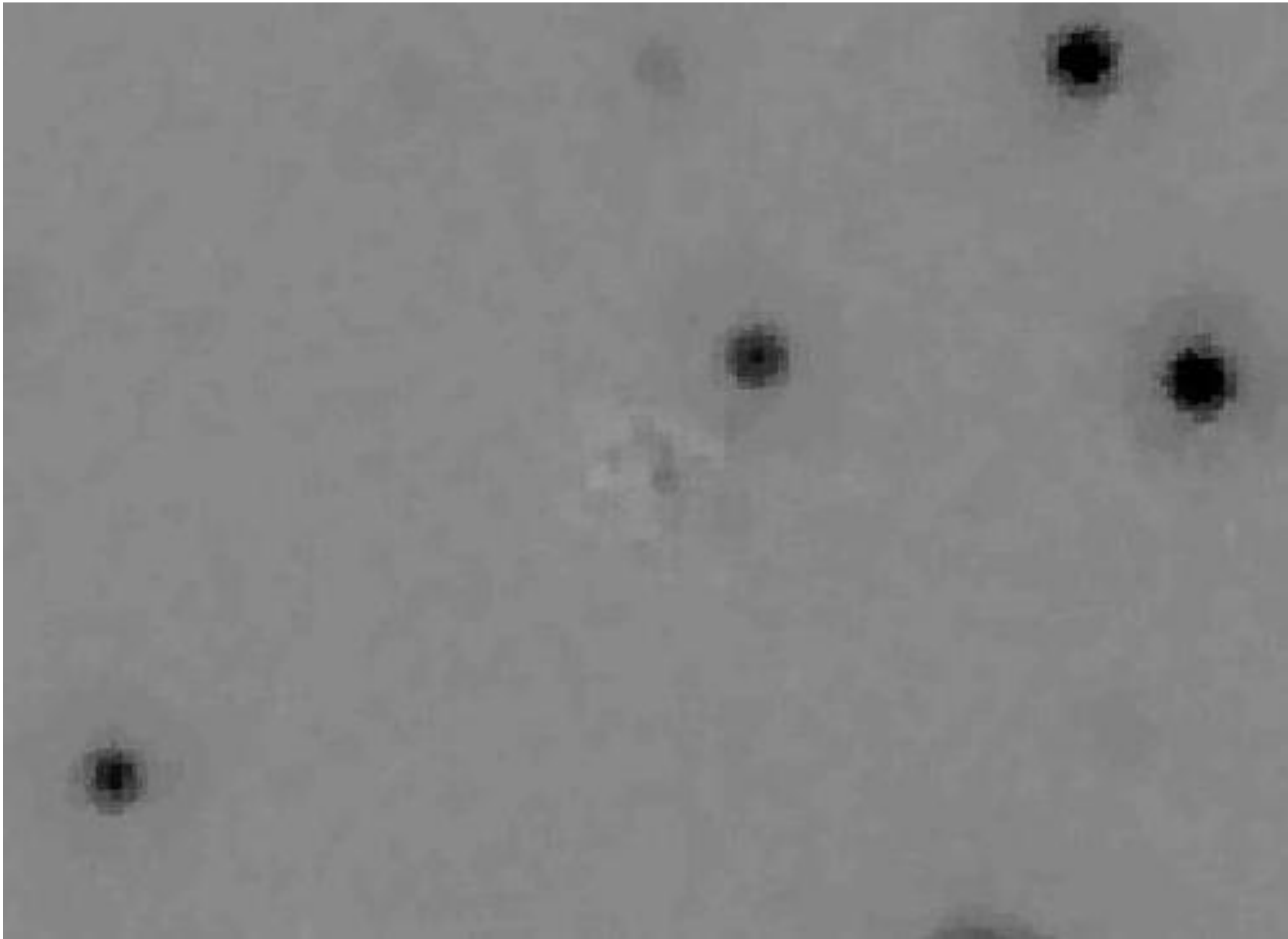
PSF for a Single Star Subtracted

Residuals in X when we subtract a PSF from each image and stack…



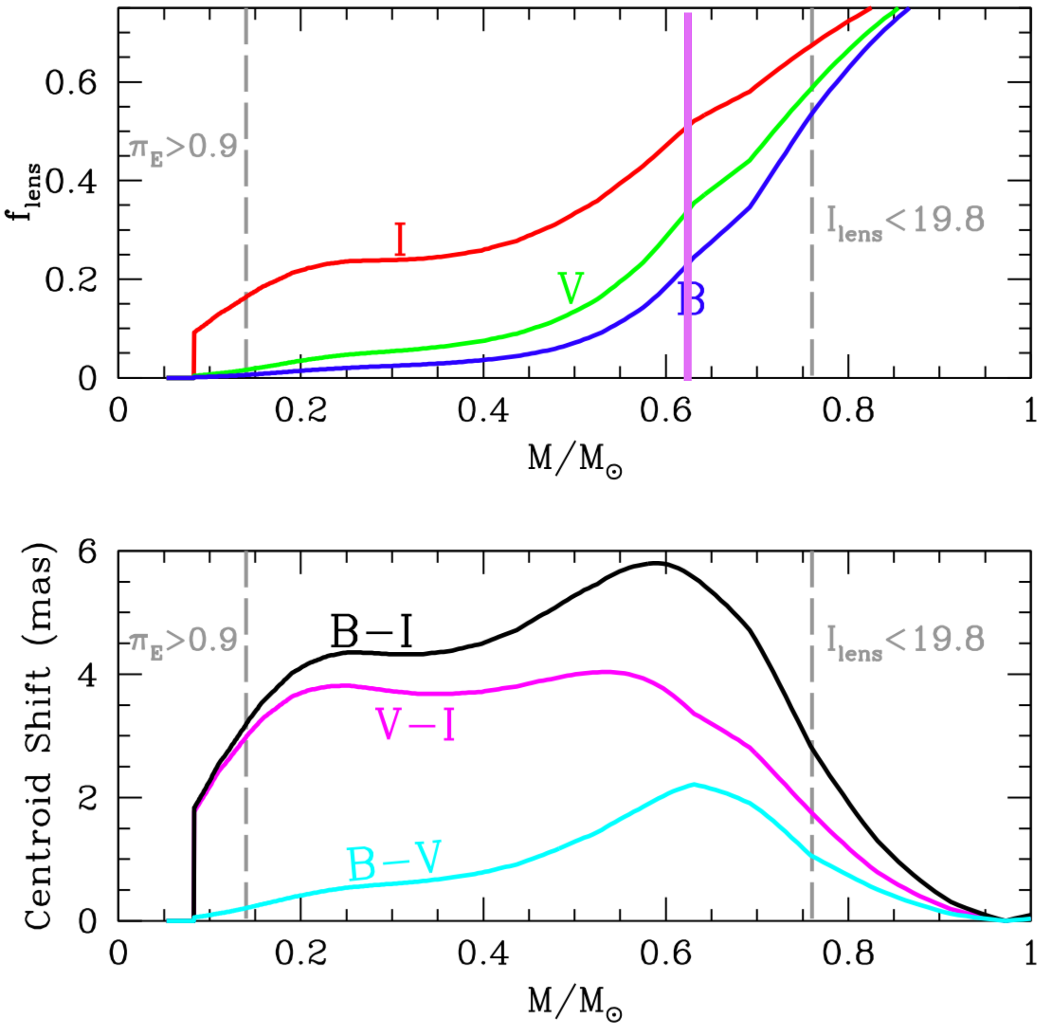
Fit and Subtract Two Stars: Source & Lens

Very good subtraction residuals when we fit for *two* sources



Two-source Solution:

- Offset consistent in the F814W, F555W, and F438W data:
  - Δx = 1.25 pixels = 50 mas
  - Δy = 0.25 pixel = 10 mas
  - FLUX: (left) (right)
    - F814W 3392 e^- 3276 e^-
    - F555W 2158 e^- 3985 e^-
    - F438W 338 e^- 1029 e^-
    - $f_I = 0.51$
    - $f_V = 0.35$
    - $f_B = 0.25$



HST BVI observations imply

$M_* = 0.63\ M_\odot$

$M_p = 17\ M_\oplus$

Q1: What is your assessment of Euclid microlensing capabilities?

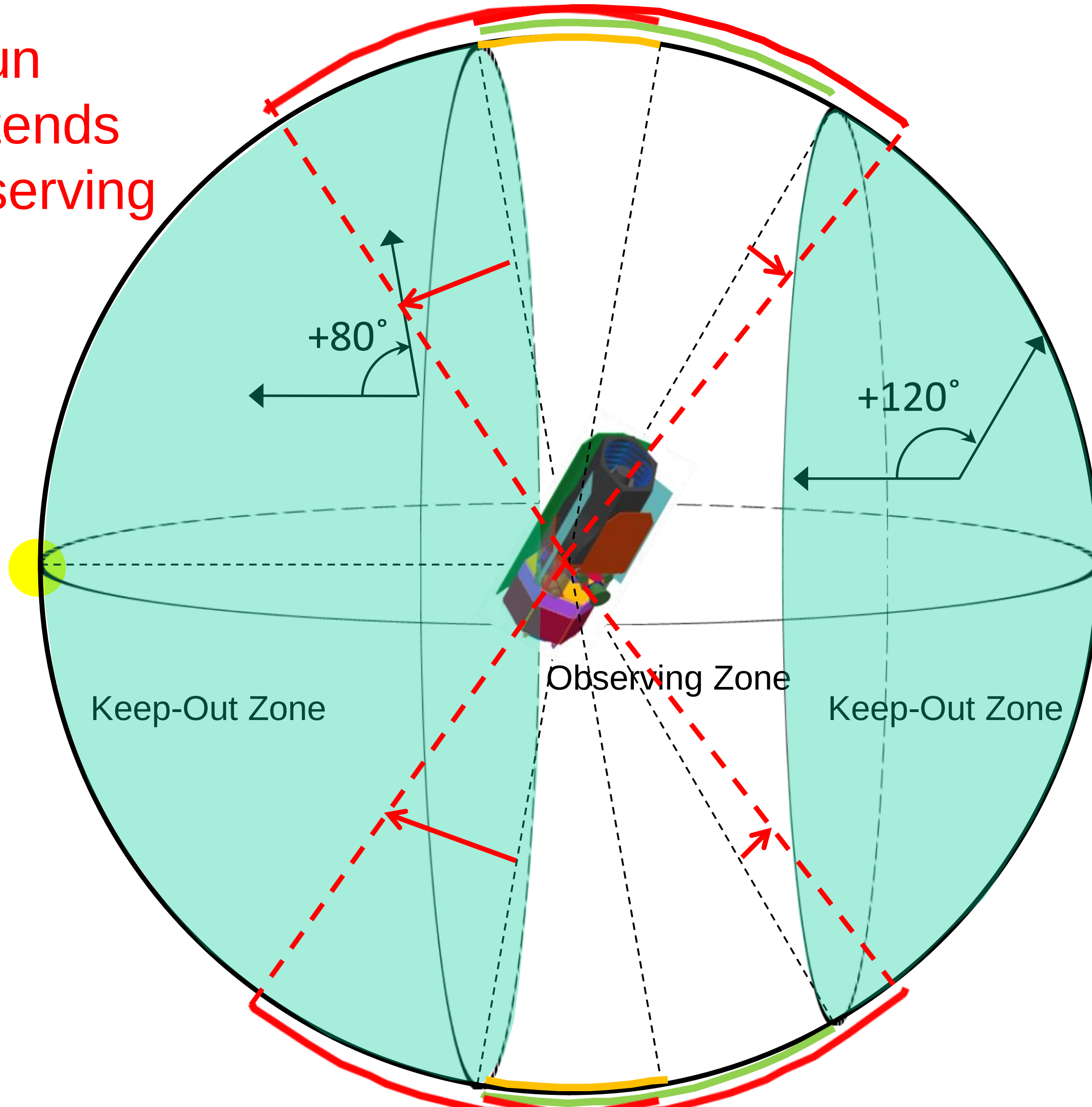
- Main Drawback of Euclid is programmatic
  - Exoplanet program is not core science, so microlensing observing time is sharply limited for a small reduction in cost
    - 2 1-month observing windows per year
    - DE program requirements are generally tighter than microlensing ones
- Photometry is limited by crowding
  - trade between crowding and FOV is optimized at courser resolution than WFIRST
  - Euclid IR channel has about the same photometric detection rate as WFIRST IDRM (due to wider FOV)
    - only difference is for inner planets (near HZ) where low amplitude signals occur at low magnification
  - Based on detailed simulations (Penny et al., in preparation; independently by DPB – not yet compared)

Q1: Euclid microlensing capabilities? (cont.)

- Mass Measurements are probably more difficult with Euclid
  - High angular resolution more important for relative astrometry than for photometry
    - This is where microlensing benefits most from higher WFIRST angular resolution in the IR
  - light curves give mass ratios
  - poor IR angular resolution makes relative proper motion measurement difficult
  - Euclid optical data is probably better than IR data for this.
  - no detailed simulations have been done for either mission
- 1-month Euclid observing seasons make microlensing parallax measurements difficult

JDEM ➔ WFIRST Transformation Expands Field of Regard

Larger Sun shield extends bulge observing window



SNe FoR

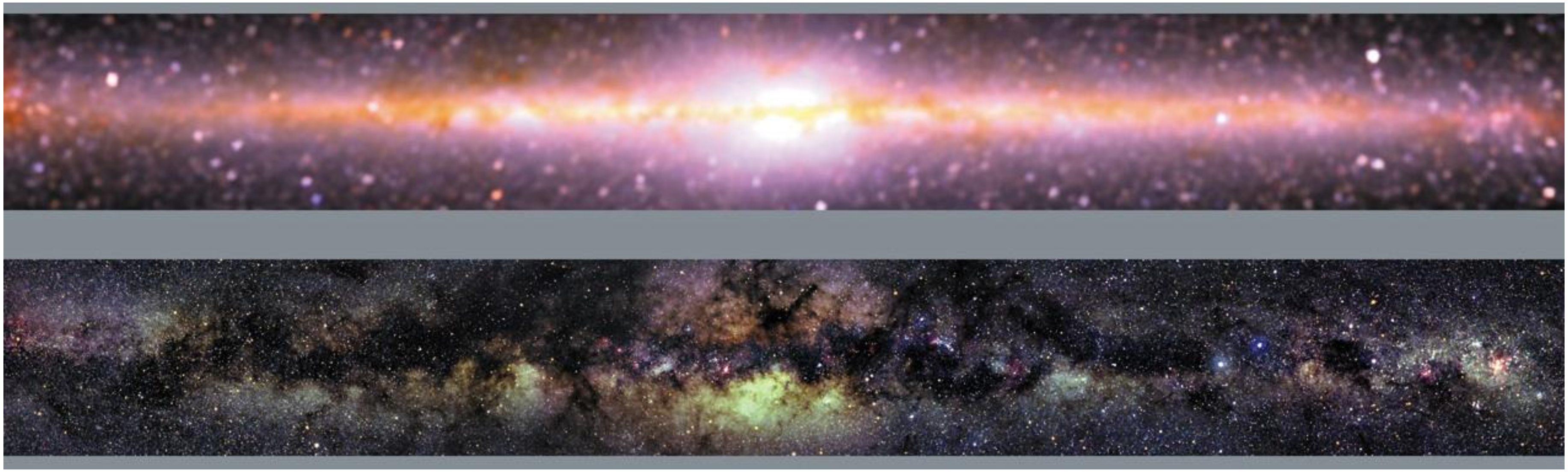
WL/BAO FoR

JDEM had 40-day bulge observing season vs. 30-days for Euclid. WFIRST has 72-days seasons

Q2: How essential are the HgCdTe detectors for the microlensing program?

The central Milky Way:

near infrared



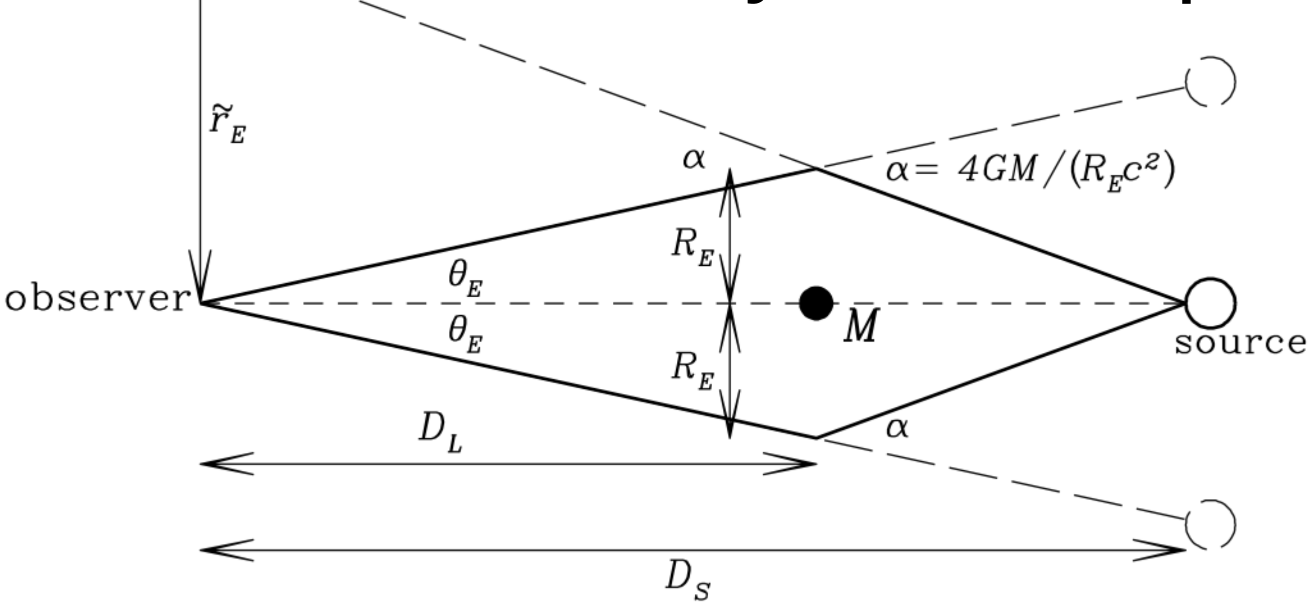
optical

The optimal microlensing fields are highly obscured, and we detect 4× more photons in the IR. HgCdTe detectors are much better than CCDs, but not absolutely required. 2 deg^2 CCD FOV would be ok (i.e. GEST)

Q3: What are the synergies/overlaps between the two missions as currently conceived?

- More statistics will be better, particularly if they come sooner
  - Euclid will not likely allow more than 1-month of early microlensing observations, when the cosmology fields are available
  - Field of regard restrictions cut both ways as Euclid will run out of cosmology fields observable during the bulge seasons
- Early Euclid observations will provide a long time baseline for relative proper motion measurements => mass measurements
  - But detailed simulations have not been done
- If Euclid & WFIRST fly at the same time, then simultaneous observations of microlensing events will yield some microlensing parallax measurements if they are out of phase by π
  - WFIRST-Euclid separation ~ planetary Einstein radius
  - Only mass measurements for free-floating Earths
  - Can't be required

Lens System Properties



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Q4: If US scientists have access to Euclid data, what is most important for the exoplanet/microlensing community?

- If Euclid doesn’t do a microlensing program, then Euclid data is of little interest!
- Early microlensing data would be helpful to improve mass measurements for a large fraction of all WFIRST and Euclid discoveries
- L2—L2 microlensing parallax is an interesting possibility, but we can’t make realistic plans for something that depends on the timing of missions run by different agencies