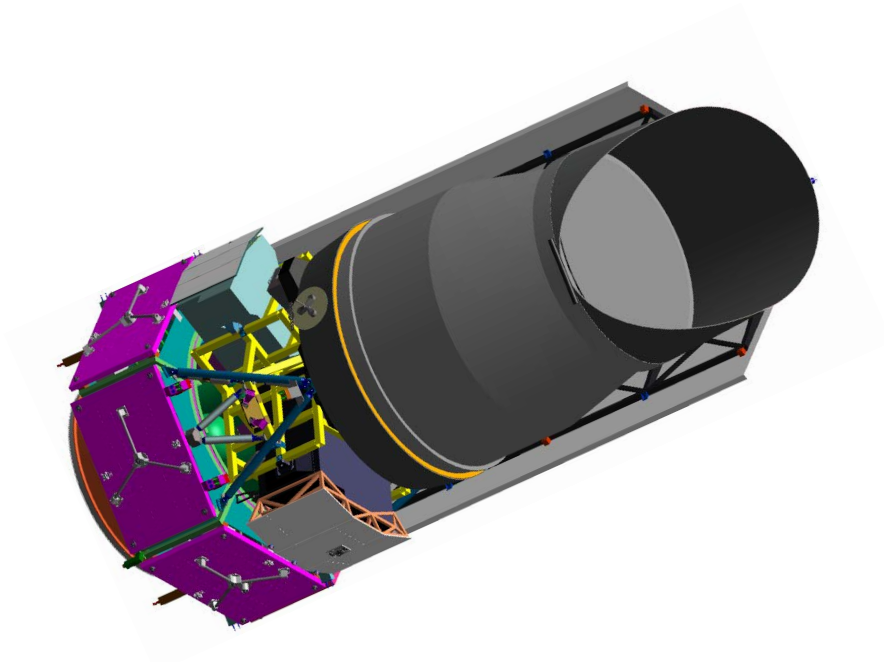
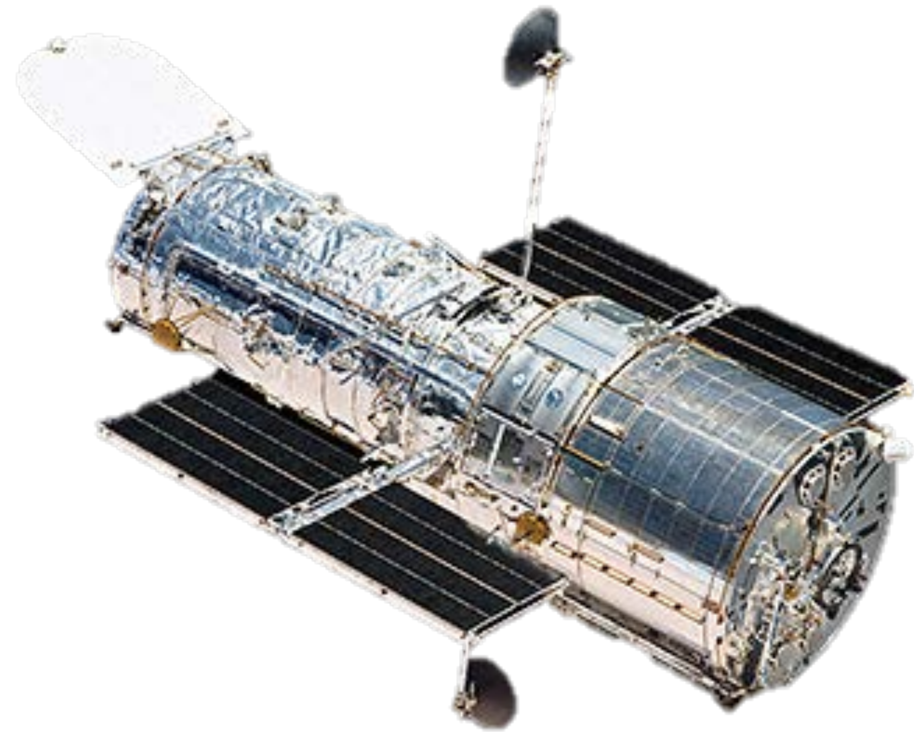
WFIRST & HST





David Bennett

NASA Goddard Space Flight Center

WFIRST Mission Schedule

- Feb., 2016 – enter Phase A – Mission Analysis
- Oct., 2017 – enter Phase B – Definition (System Design)
- Dec., 2018 – enter Phase C/D – Execution (Design, Development, Integration and Test)
- Late 2024 or early 2025, launch and Phase E

- Essentially no cost growth since Decadal Survey

These development phases do not map directly into probabilities that a mission will be successfully launched

- There are different categories of missions that have different risks at the same mission phase.

Cost Transparency

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
DARK ENERGY • EXOPLANETS • ASTROPHYSICS

Item	FY10 ($B)	FY15 ($B)	RY ($B)	Launch
NWNH WFIRST (2010)				
WFIRST	**1.61**	1.75	2.1	2020
+ New Worlds Technology	<0.2	<0.2	<.2	
Total	**1.6 - 1.8**	**1.8 - 2.0**	2.1-2.3	
SDT Report DRM (2015)				
WFIRST-AFTA w/o CGI+GO	1.4 - 1.7	1.6 - 1.9	1.9 – 2.3	2024
+ Coronagraph	0.32	0.35	0.42	
+ GO Program	0.09	0.1	0.12	
Total	1.8 - 2.1	**2.0 - 2.3**	**2.5 - 2.8**	
KDP-A (2016)				
WFIRST w/ CGI+GO	1.8 - 2.1	2.0 - 2.3	2.5 - 2.8	2025
+ New Changes Include	0.18	0.2	0.24	
1.) Launch vehicle cost increased,	0.068	0.075	0.09	
2.) Science team and industry funding,	0.045	0.05	0.06	
3.) Phase A extended (early start),	0.036	0.04	0.05	
4.) Reserves on items 1.) to 3.)	0.032	0.035	0.04	
+ WFI hardware changes*	0.045	0.05	0.06	
+ L2-related changes**	0.04	0.045	0.05	
+ Inefficient launch profile (2025 vs 2024)	0.18	0.2	0.24	
Total	2.1 - 2.4	2.6 - 2.8	**2.7 - 3.2†**	

Inflation Reminder:
$1.8B in 2010 (NWNH) = $2.0B in 2015 (*1.09x*)
$2.3B in 2015 = $2.8B in RY$ (*1.2x*)
$2.8B in 2015 = $3.2B in RY$

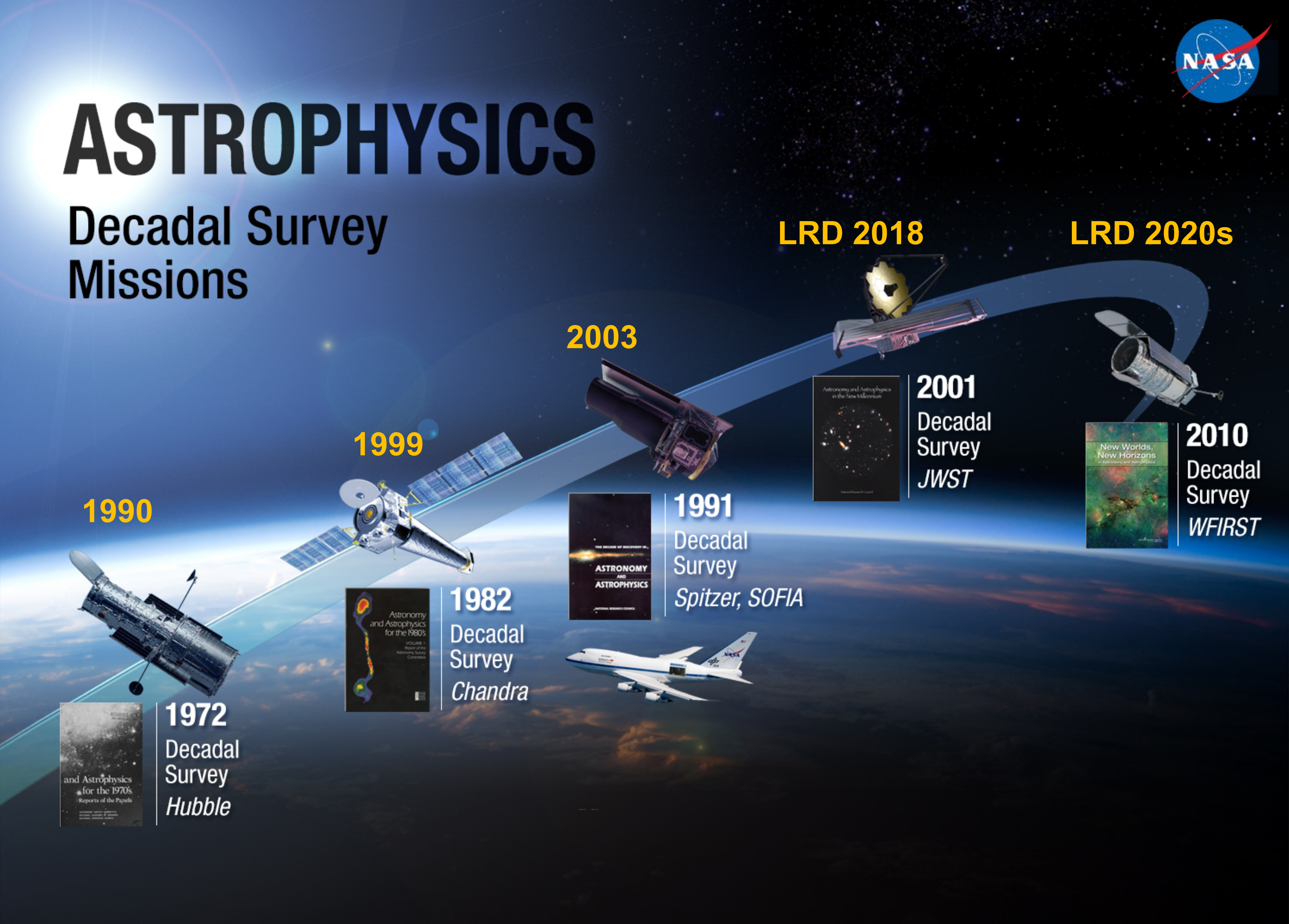
"Monetized launch risk"

Independent Cost and Technical Evaluation within ~10% of project estimate

Uncertainty in launch vehicle ~0.3B RY$

Independent Cost and Technical Evaluation within ~10% of project estimate

**auxillary guider, relative calibration system, IFU detector redundancy, structural mass*
***4 large propellant tanks, associated structure, SSR, TWTA, antenna, thermal hardware*
† Half of this uncertainty is due to range of launch vehicle costs


ASTROPHYSICS
Decadal Survey Missions
NASA
1990
1972 Decadal Survey Hubble
1999
1982 Decadal Survey Chandra
2003
1991 Decadal Survey Spitzer, SOFIA
LRD 2018
2001 Decadal Survey JWST
LRD 2020s
2010 Decadal Survey WFIRST
and Astrophysics for the 1970's
Astronomy and Astrophysics for the 1980's
ASTRONOMY AND ASTROPHYSICS
Astronomy and Astrophysics in the New Millennium
New Worlds, New Horizons

Canceled/Failed Astrophysics Missions

- FAME (Full sky Astrometric Mapping Explorer)
  - Failed at confirmation due to cost overruns, 0/24 CCDs delivered, failed optics… (MIDEX)
- SIM (Space Interferometry Mission)
  - 4th ranked medium program by 1991 Decadal Survey ($250M)
  - Heavy budget cuts in 2006-2008 put mission on hold
  - Rejected by 2010 Decadal Survey (due to cost of $1.8 billion)
  - Canceled because of higher priority missions
- GEMS (Gravity and Extreme Magnetism SMEX)
  - Failed at confirmation due to cost and schedule overruns
- IXO (International X-ray Observatory)
  - "canceled" in pre-phase-A by low ranking in 2010 decadal survey

Canceled/Failed Astrophysics Missions - 2

- HST (Hubble Space Telescope)
  - Considered failed due to large spherical aberration (1990-1993)
  - Rescued by 1st servicing mission
  - Failure of management, in part due to political pressure
    - Perkin-Elmer selected to build optics due to politics
    - Kodak builds back-up mirror, but testing of primary is left to Perkin-Elmer
    - Perkin-Elmer discovered spherical aberration, but hushed it up

There Is No Precedent for Canceling a Top-Rated Decadal Survey Mission

- Both HST and JWST had large cost overruns
- JWST Saved Despite
  - Goldin-era “Faster, Better, Cheaper” budget
  - NASA deliberately lying to Congress about over-runs (according to Congressional committee staff)
- WFIRST is a much simpler mission
  - Optics already exist
  - Detectors ready for production
  - Coronagraph is a “technology demonstration”, so requirements will be loosened, if need be, to avoid delaying launch.

High Risk HST Programs Are Often Approved

- The odds that WFIRST won’t launch are slim.
- Exoplanet transit spectroscopy proposals were considered high risk when first proposed – just 1 example
- I proposed GO-10544 in support of a SMEX MOO that was not yet approved, and it was conditionally approved
  - Why not allow conditional approval for WFIRST precursor observations? Say Cycle 25 observations if WFIRST is in phase B, or Cycle 26 observations if WFIRST is in phase C/D

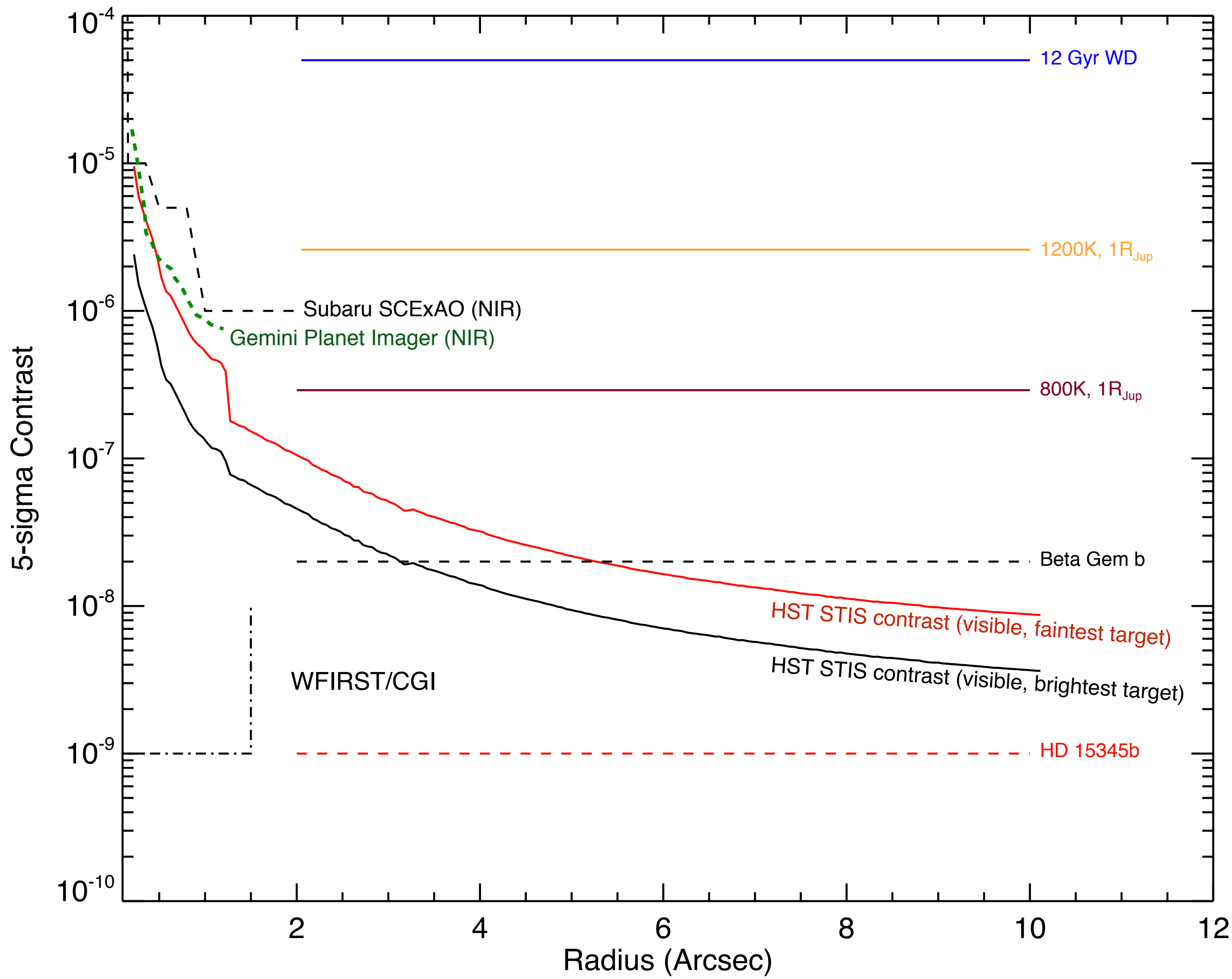
Example Programs

- WFIRST Coronagraph: Direct Imaging of Exoplanets vs. Cosmology
  - Exoplanets are as bright as faint galaxies – so confusion is an issue
  - Observe future locations of RV exoplanet hosts to search for background galaxies
  - Can polarization distinguish between the polarized reflected light from planets vs. unknown polarization of background galaxies
    - Should the WFIRST Coronagraph instrument include a polarizer?
- WFIRST Exoplanet microlensing
  - Develop lens mass and distance determination methods
    - Do we need data in more colors?
    - Should avoid the high extinction, high lensing rate fields?

STIS Coronagraphic Imaging of the Vicinity of WFIRST RV Planet Targets

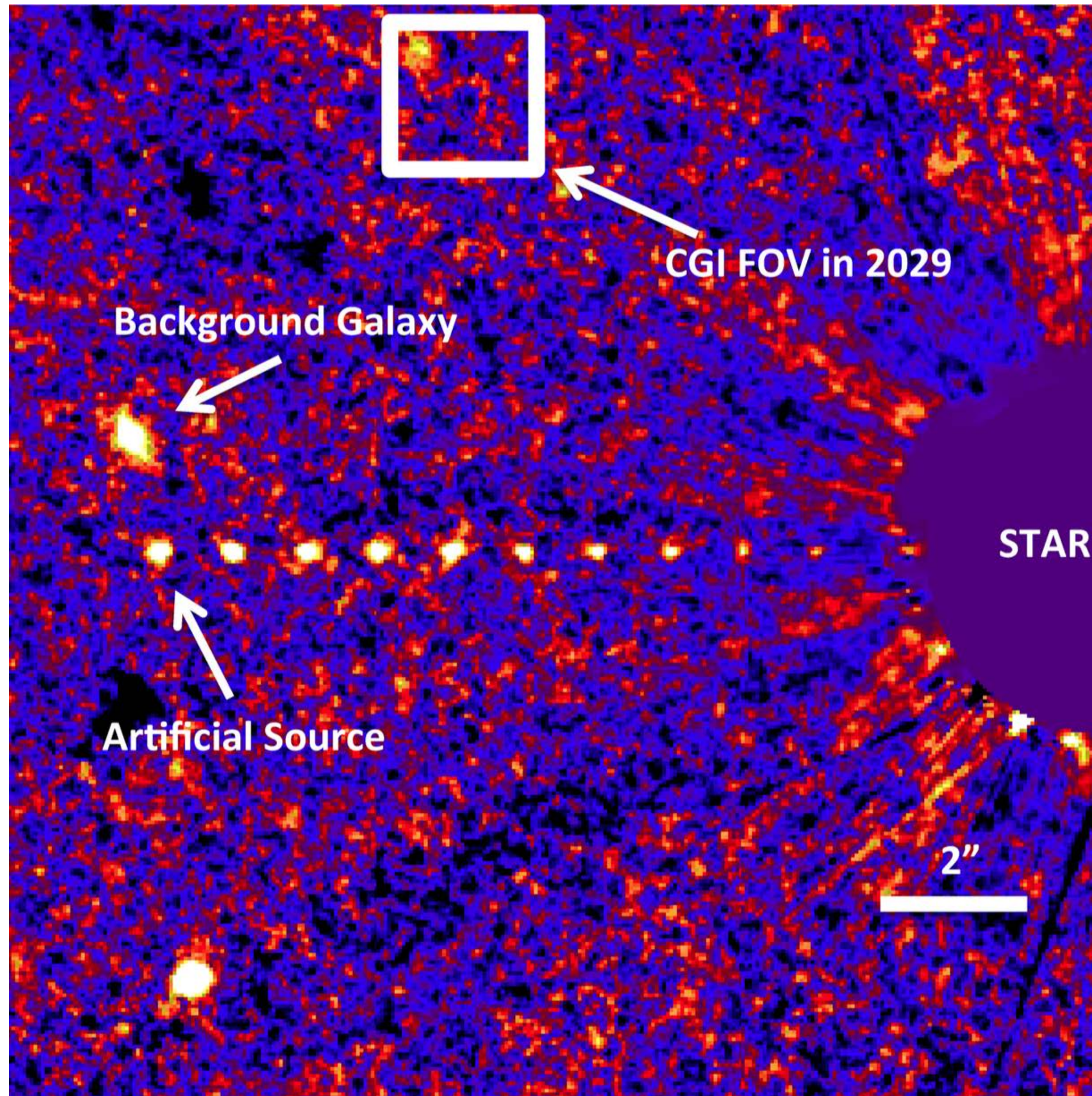
Many RV planet targets are expected to have contrasts of 1-2 × 10^{-8}

Motion of targets before WFIRST observations is ~3-10"



STIS Coronagraphic Imaging (2)

An image taken from classical ADI processing of HR 8799 with 6 spacecraft orientations at WEDGEB2.5. The scaling in the image shows S/N/pixel. These observations mimic what we propose. Several background objects are seen in the 15”×15” image. We have also implanted artificial sources with a contrast of $2{\times}10^8$ relative to the star. The narrow WFIRST dark hole extent is shown for scale, and is offset to mimic the location of observations that would be obtained in 2029 if the star had high proper motion.



ACS Imaging Polarimetry

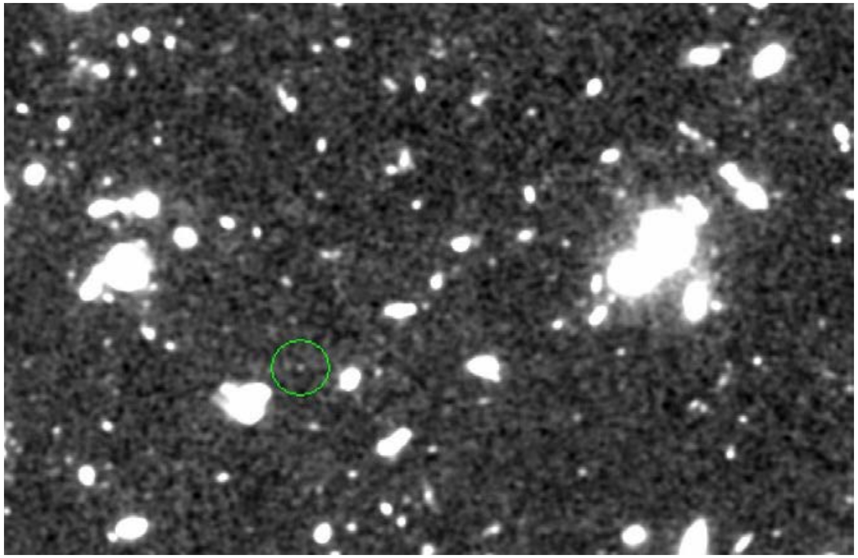
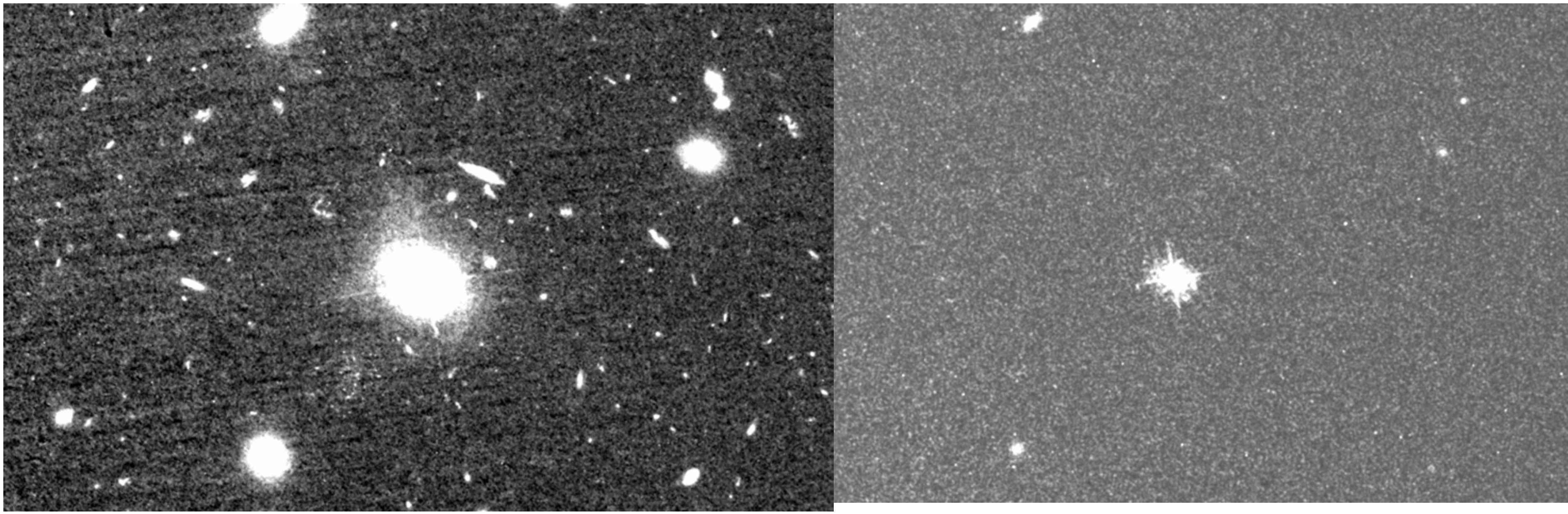


Fig. 1: 1arcmin^2 field of view at high galactic latitude, from the Hubble Extreme Deep Field (Illingworth et al. 2013). An object the brightness of a terrestrial exoplanet is indicated on the right (green circle) illustrating the confusion problem.

- Confusion with background galaxies is a serious problem for the direct imaging of exoplanets
- This could be much better in polarized light

ACS Imaging Polarimetry (2)



ACS images centered on quasar CSS 1150+497 in unpolarized and polarized light through filter F606W. The number density of sources in the polarized image is much smaller, suggesting that polarization might help to identify planets, but the nature of the polarized background sources in the polarized image is not known.

ExoPAG SAG-11 Report

NASA ExoPAG Study Analysis Group 11:

Preparing for the WFIRST Microlensing Survey

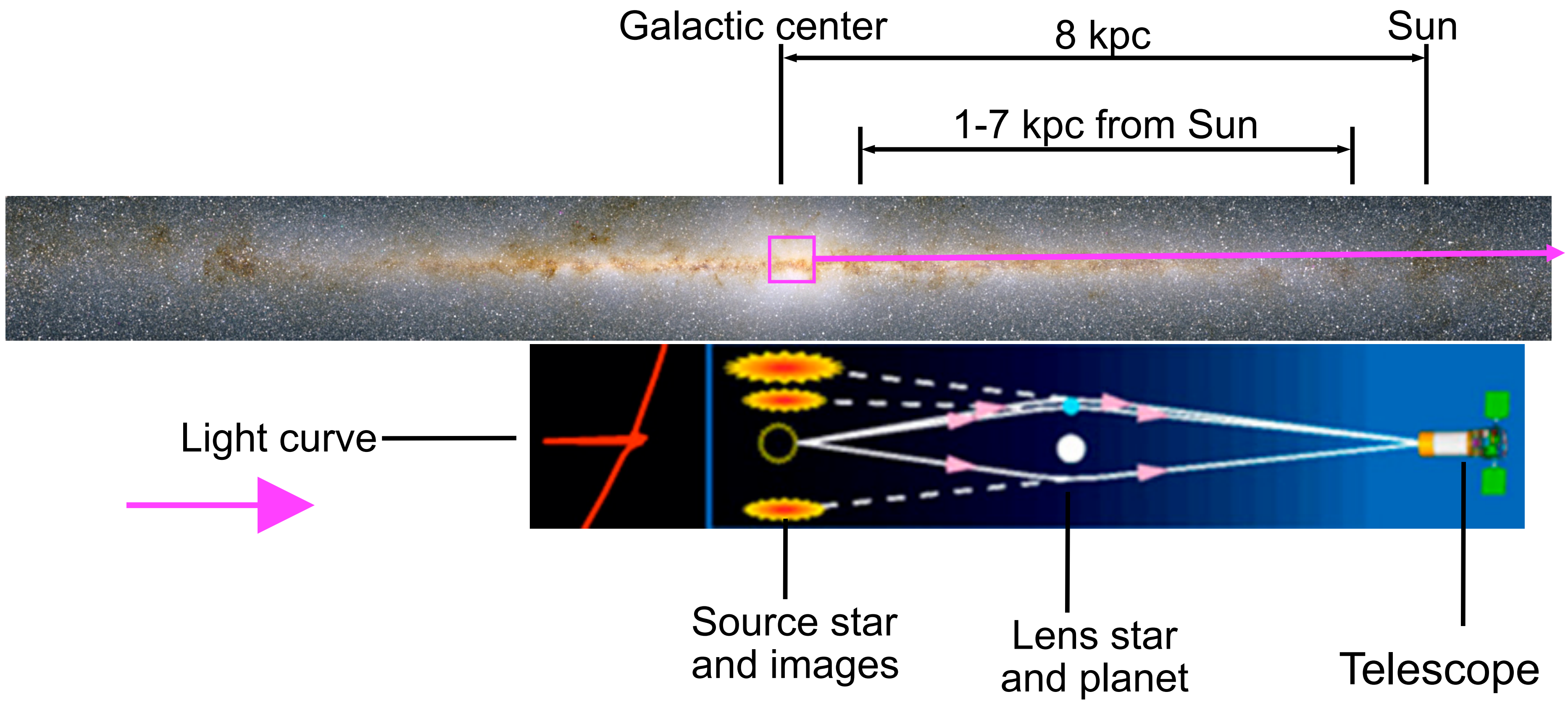
Jennifer C. Yee[1] (chair), Michael Albrow[2], Richard K. Barry[3], David Bennett[4], Geoff Bryden[5], Sun-Ju Chung[6], B. Scott Gaudi[7], Neil Gehrels[3], Andrew Gould[7], Matthew T. Penny[7], Nicholas Rattenbury[8], Yoon-Hyun Ryu[6,9], Jan Skowron[10], Rachel Street[11], Takahiro Sumi[12]

- Led by Jennifer Yee (arXiv:1409.2759)
- Not a detailed study, but a description of several important precursor programs

Recommended HST Precursor Observations

- Develop WFIRST Exoplanet Microlens Mass Measurement Methods
  - Should we selected WFIRST fields with low extinction or very high microlensing rates?
- HST/WFC3/UVIS + ACS observations for pre-WFIRST astrometry
- HST/WFC3/IR time series observations for photometry/astrometry pipeline code development
- Development of Microlensing Expertise
  - Microlensing workforce is currently too small for WFIRST
  - Public HST data will help encourage participation

Microlensing Target Fields are in the Galactic Bulge



100s of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.

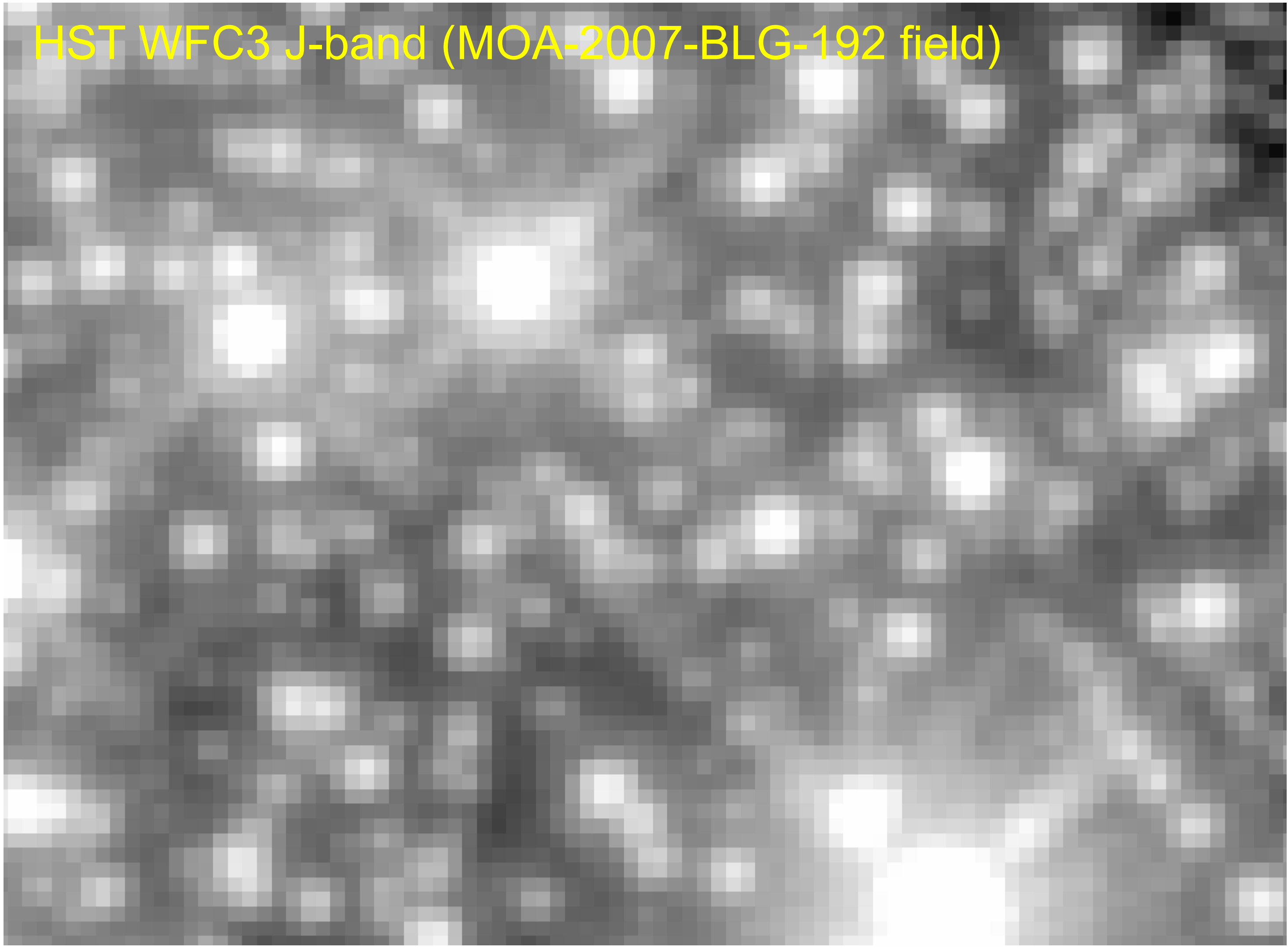
WFIRST Bulge Images Are Crowded!

Most stars are not completely blended, but the images overlap.

High precision photometry (~1 mmag) needed with overlapping images

Proper motion of neighbors must be accounted for:

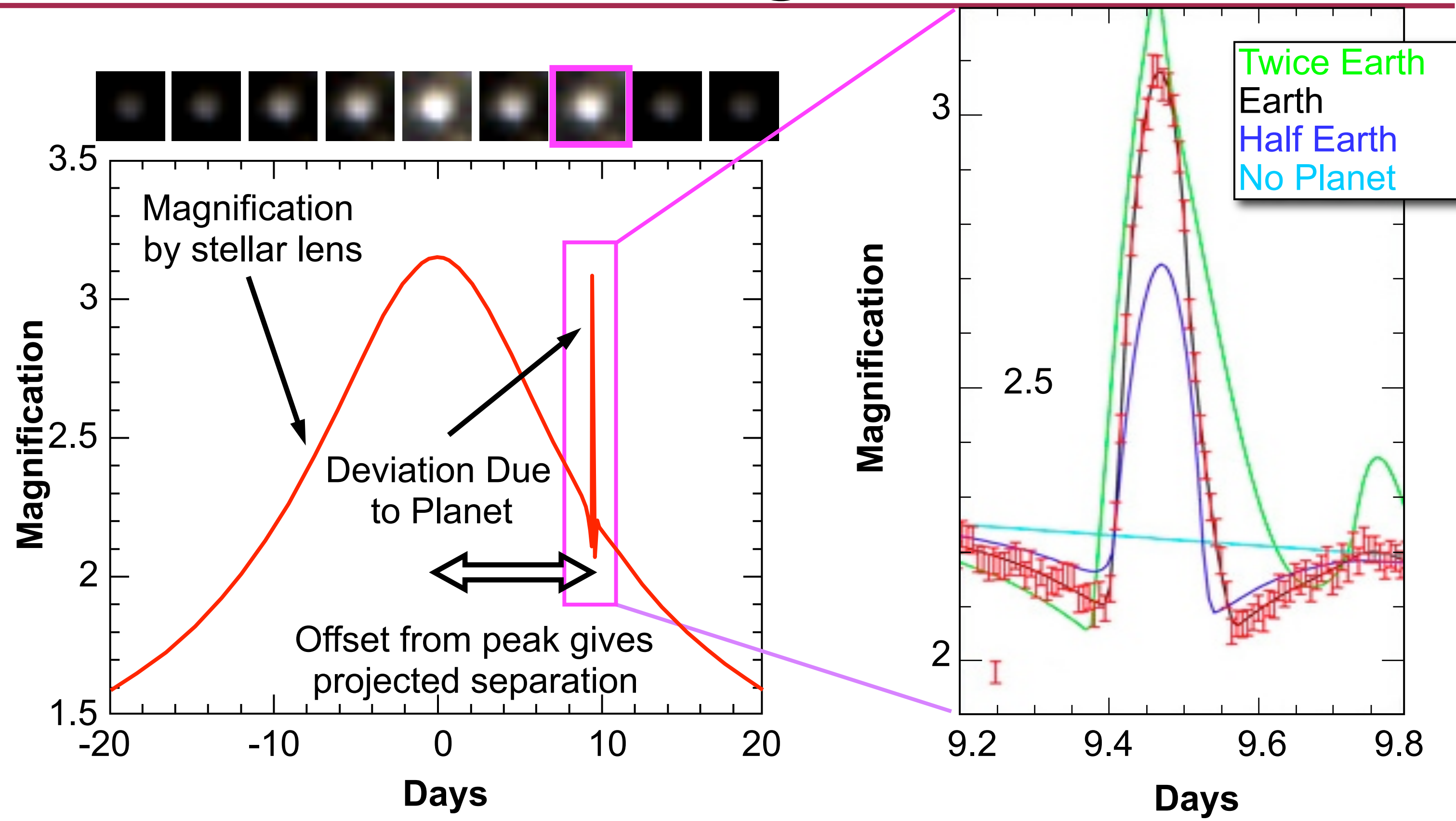
Precision photometry requires precision astrometry



This field has 1.5-2× smaller star density than WFIRST fields

Extraction of Exoplanet Light Curve Signal

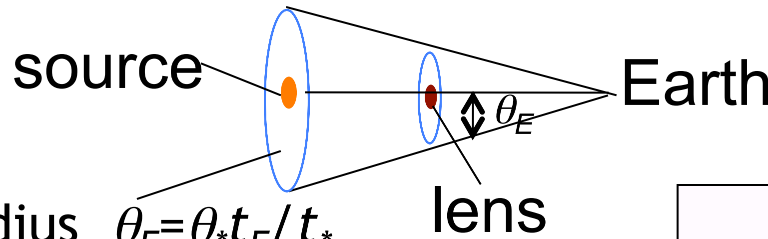
Time-series photometry is combined to uncover light curves of background source stars being lensed by foreground stars in the disk and bulge.



Planets are revealed as short-duration deviations from the smooth, symmetric magnification of the source due to the primary star.

Detailed fitting to the photometry yields the parameters of the detected planets.

Finite Source Effects & Microlensing Parallax Yield Lens System Mass



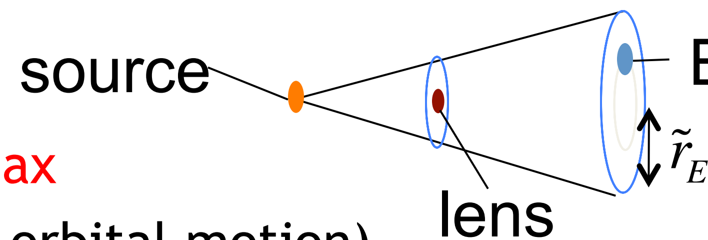
- Finite source effects

  Angular Einstein radius $\theta_E = \theta_* t_E / t_*$

  θ_* = source star angular radius

  D_L and D_S are the lens and source distances

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



- Microlensing Parallax

  (Effect of Earth's orbital motion)

  Einstein radius projected to Observer $\tilde{r}_E$

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

OR

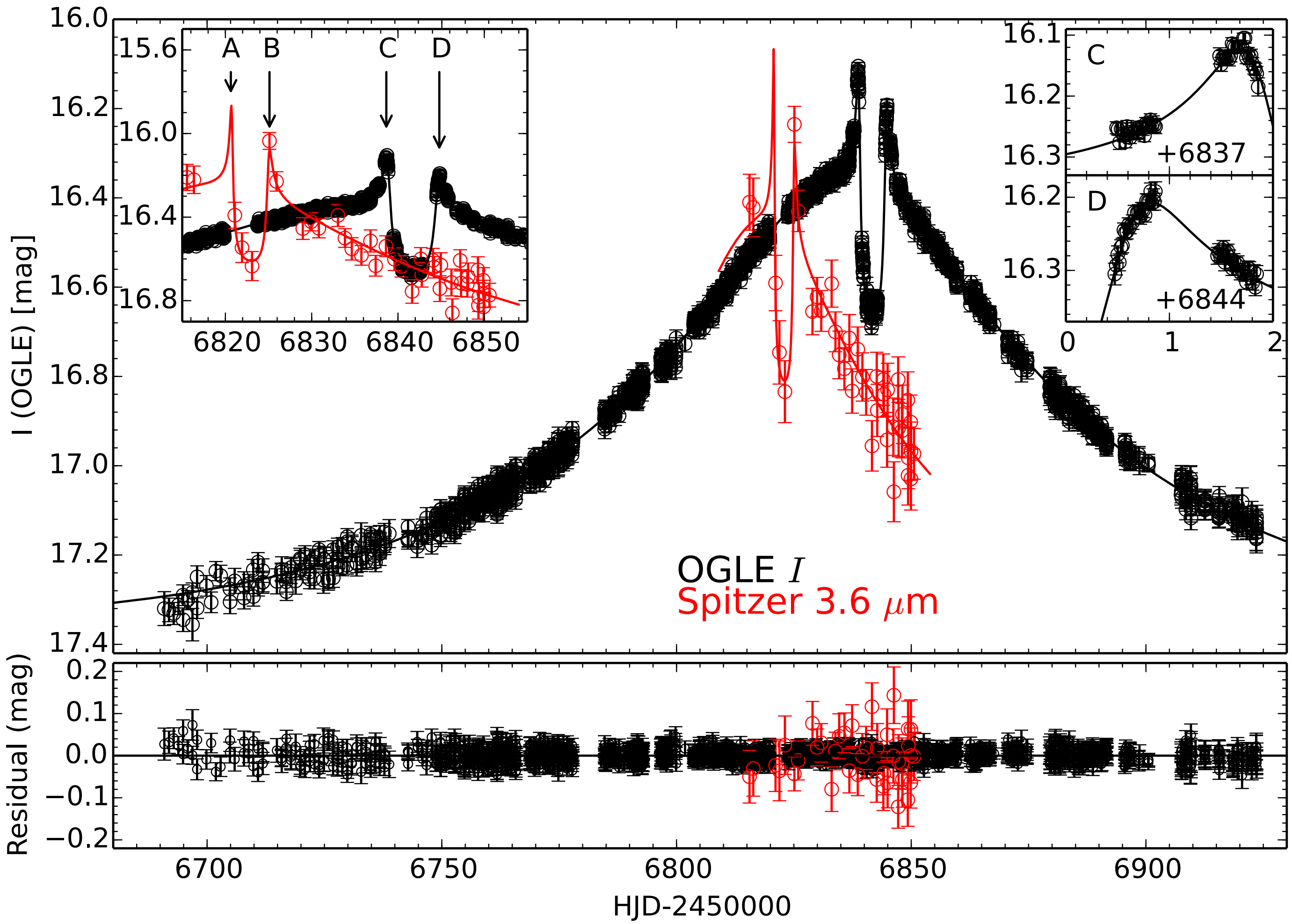
- One of above +

  Lens brightness & color(AO,HST)

  mass-distance relation → D_L

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

Spitzer & OGLE observations of OGLE-2014-BLG-0124



(Udalski et al. 2014)

Parallax and Relative Proper Motion or Astrometric Microlensing

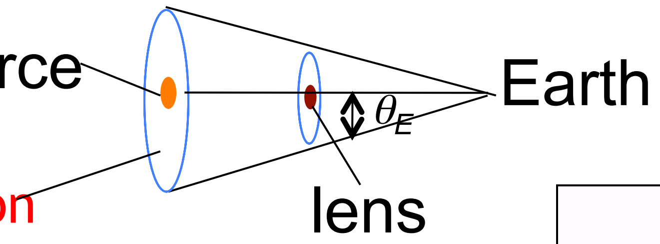
- Microlensing parallax $\pi_E = \dfrac{1}{\tilde{r}_E}$ and
- relative proper motion $\mu_{\rm rel} = \dfrac{\theta_E}{t_E} = \dfrac{\theta_*}{t_*}$
- are both 2-d vectors – and they are parallel
- π_E is often measured more precisely in 1 direction (Earth's acceleration direction) than the other
- A measurement of $\boldsymbol{\mu}_{\rm rel}$ improves the precision of $|\pi_E|$

- Astrometric microlensing yields the same information as $\boldsymbol{\mu}_{\rm rel}$: θ_E and direction of lens-source motion

Lens-Source Relative Proper Motion Plus 1-d Microlensing Parallax

- WFIRST microlensing observing seasons in spring and fall are when Earth's (and WFIRST's) acceleration is perpendicular to line-or-sight
- One dimension of 2-d microlensing parallax vector, $\boldsymbol{\pi}_E$, can often be measured from WFIRST light curves
  - Since $\boldsymbol{\pi}_E$ || is parallel to lens-source relative proper motion, $\boldsymbol{\mu}_{\mathrm{rel}}$, we can determine the 2-d microlensing parallax from a 1-d parallax measurement and a $\boldsymbol{\mu}_{\mathrm{rel}}$ measurement.

Finite Source Effects & Lens Brightness Measurement Yield Lens System Mass



- Finite source effect or lens-source proper motion

  Angular Einstein radius $\theta_E = \theta_* t_E / t_*$

  θ_* = source star angular radius

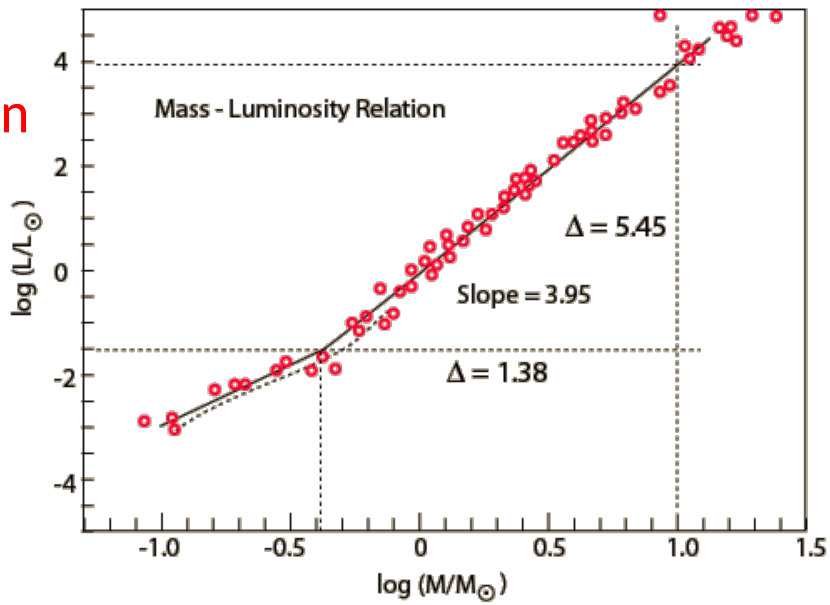
  D_L and D_S are the lens and source distances

  => **Mass-distance relation**

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

\+

- Lens brightness + Mass-Luminosity relation + Mass-Distance relation ➔ D_L , M_L



- But, we need to ensure that we are correctly identifying the lens
- Measure lens-source relative proper motion: $\mu_{rel} = \theta_*/t_* = \theta_E/t_E$

HST Relative Proper Motion for OGLE-2005-BLG-169 Lens-Source

Source *looks* elongated relative to neighbors at 6.5 years after event

$$M_* = 0.69 \pm 0.02 M_\odot$$

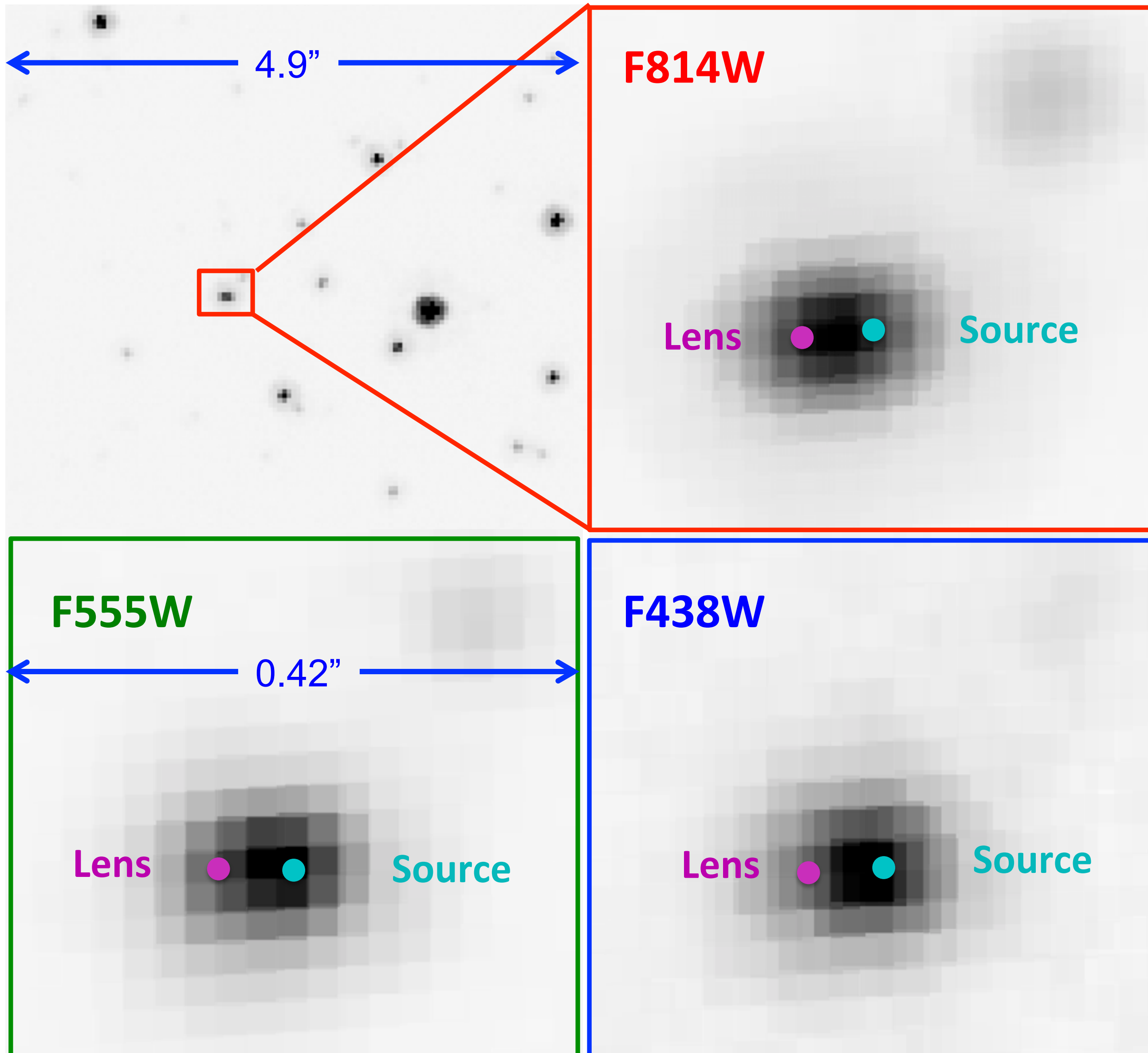
$$m_p = 14.1 \pm 0.9 M_\oplus$$

$$a_\perp = 3.5 \pm 0.3 \text{ AU}$$

$$a_{3d} = 4.0^{+2.2}_{-0.6} \text{ AU}$$

$$D_L = 4.1 \pm 0.4 \text{ kpc}$$

Bennett et al. 2015
Keck result:
Batista et al. 2015

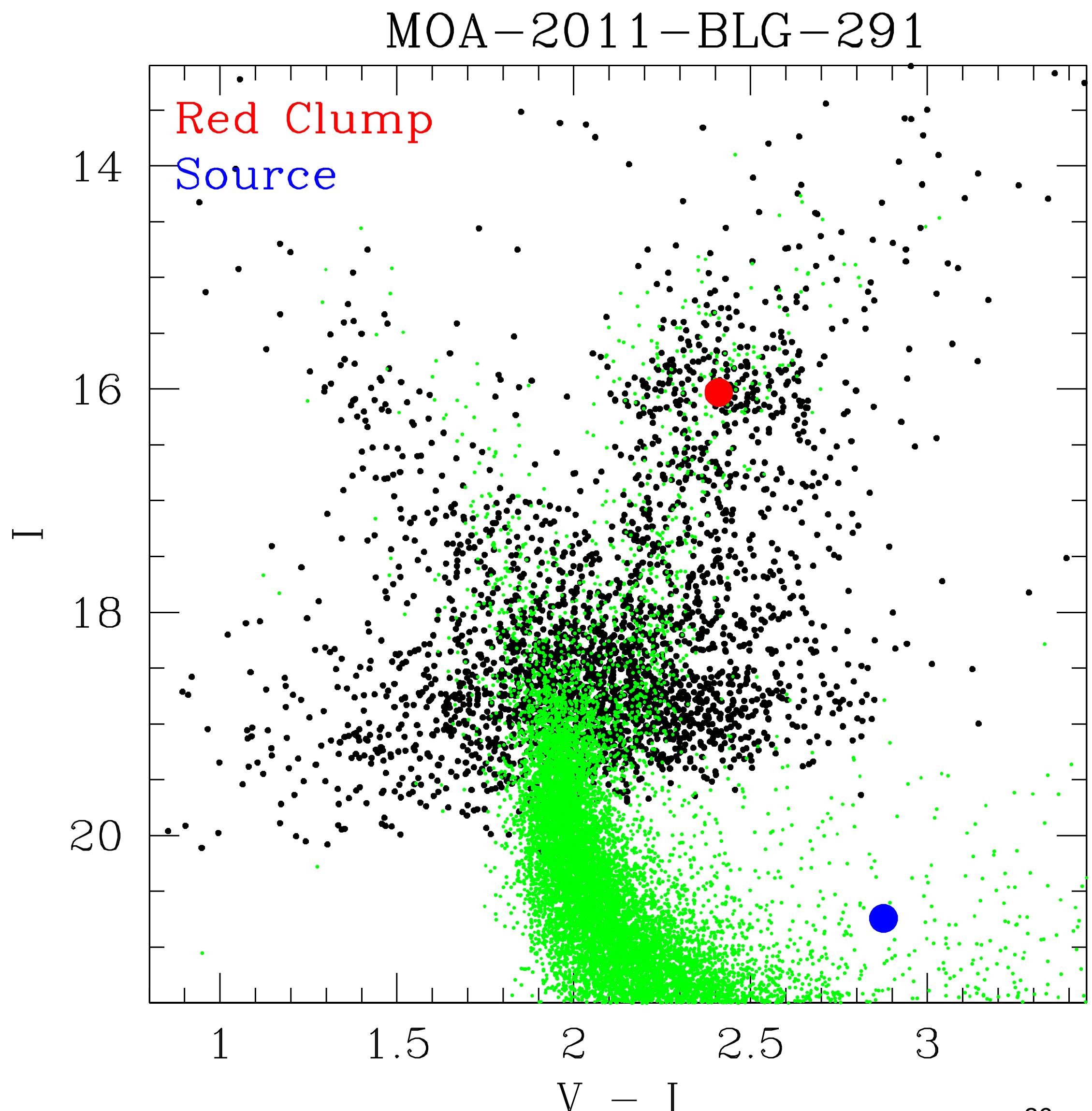


Lens-Source Relative Proper Motion

- Lens and source are not resolved at the time of the microlensing event
- Need to distinguish lens star from companion to the source or lens, or an unrelated star.
- 2 methods to measure $\boldsymbol{\mu}_{rel}$:
  - Color Dependent Centroid shift
    - If lens and source have different colors, the centroid of the blended image will depend on the color
    - Precision scales as t
  - Image Elongation:
    - Blended image will be elongated in the $\boldsymbol{\mu}_{rel}$ direction
    - works if lens and source have the same color
    - Precision scales as t^2
  - In practice, fit for lens and source location with constraints from light curve model

Potential Problem at Low Galactic Latitude

- Source much redder than predicted bulge main sequence
  - Not likely to have the average bulge extinction
- At *b* = -1.97°, in nominal WFIRST fields
- Source may be on far side of bulge at $D_S >> D_{bulge}$
- Can we estimate D_S from μ_S ?
- Should we avoid high lensing rate fields with high extinction in order to get optical colors to estimate extinction

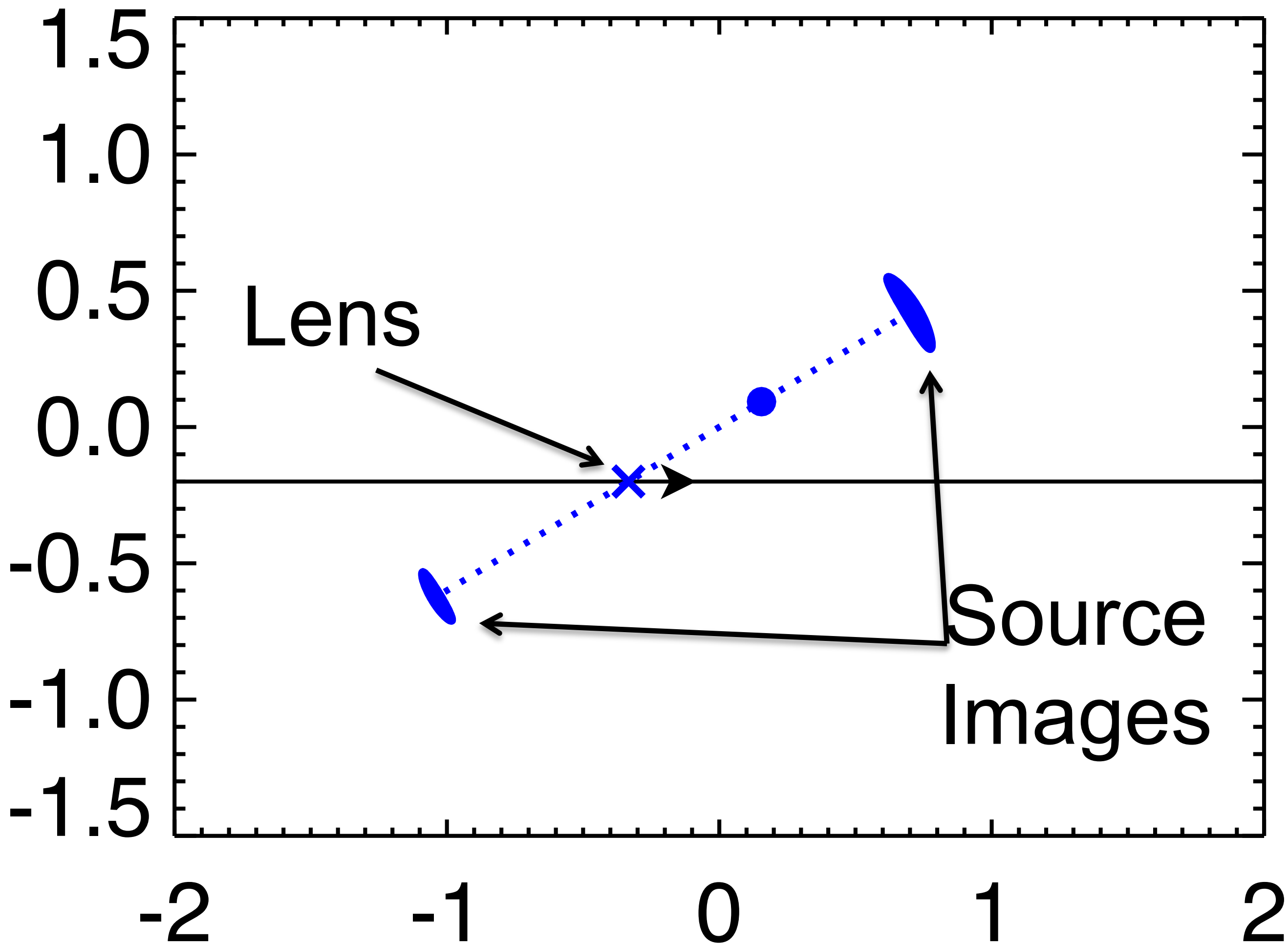


Masses for Dark Lens Systems

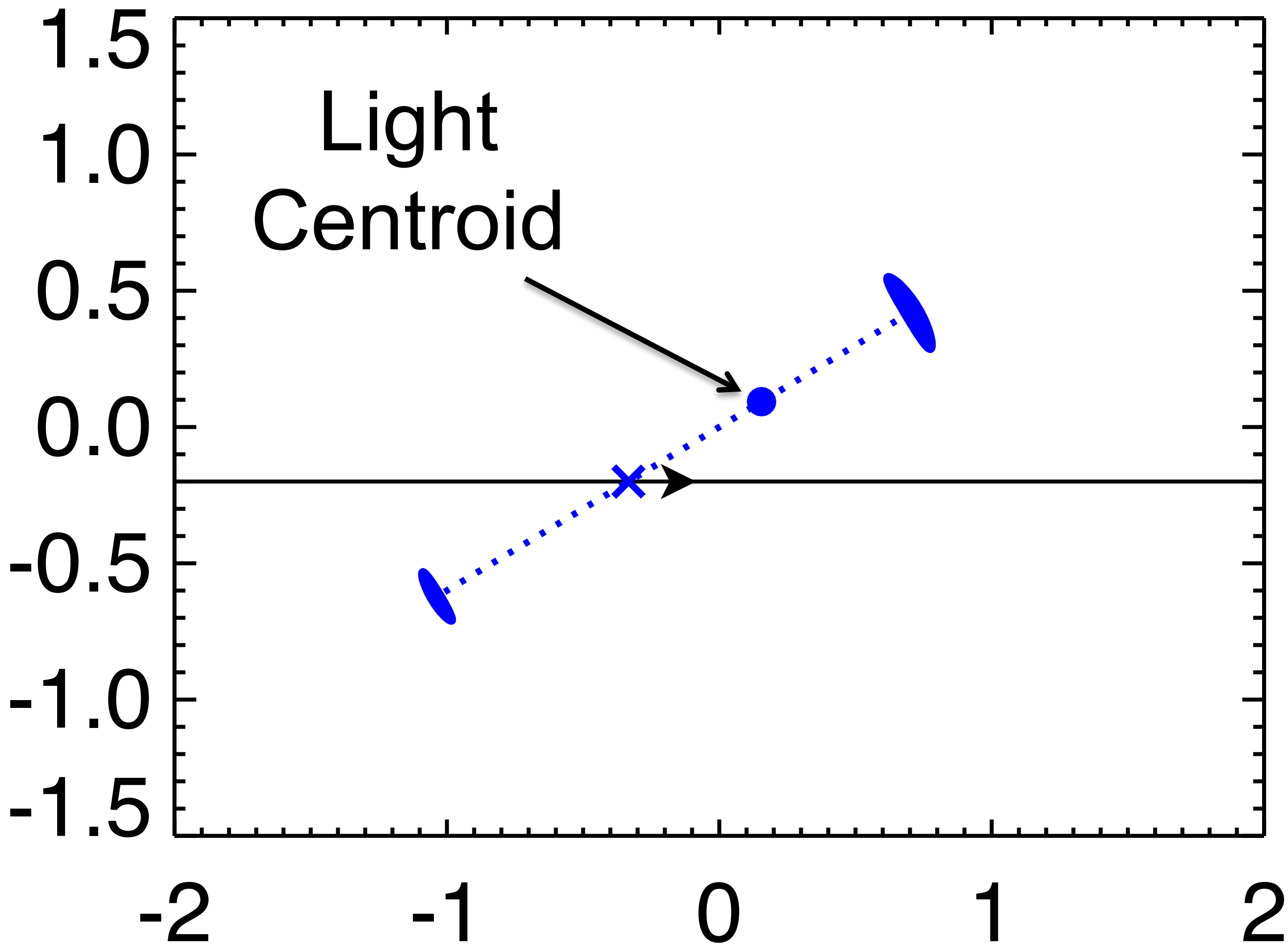
- Astrometric microlensing
  - centroid of lensed images is displaced as a function of time
- Yields mass when combined with 1-d microlensing parallax
- Straight forward for stellar mass black holes (Sahu's program)
- Challenging for low mass stars and brown dwarfs
  - Well within WFIRST photon noise limits

- Precision needed for low mas stars and brown dwarfs will also yield parallaxes for many bulge stars (in fields too crowded for GAIA)

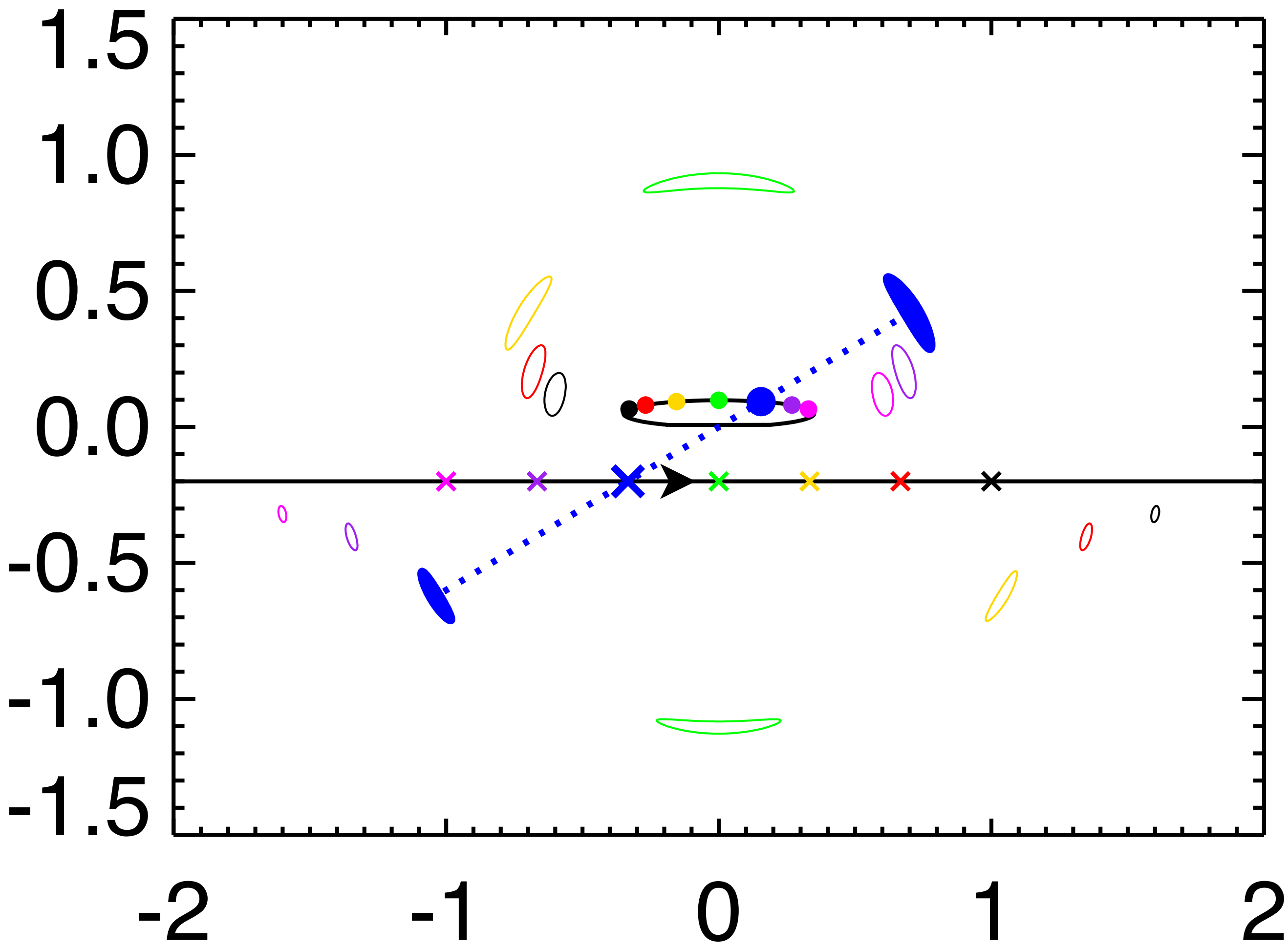
Astrometric Microlensing



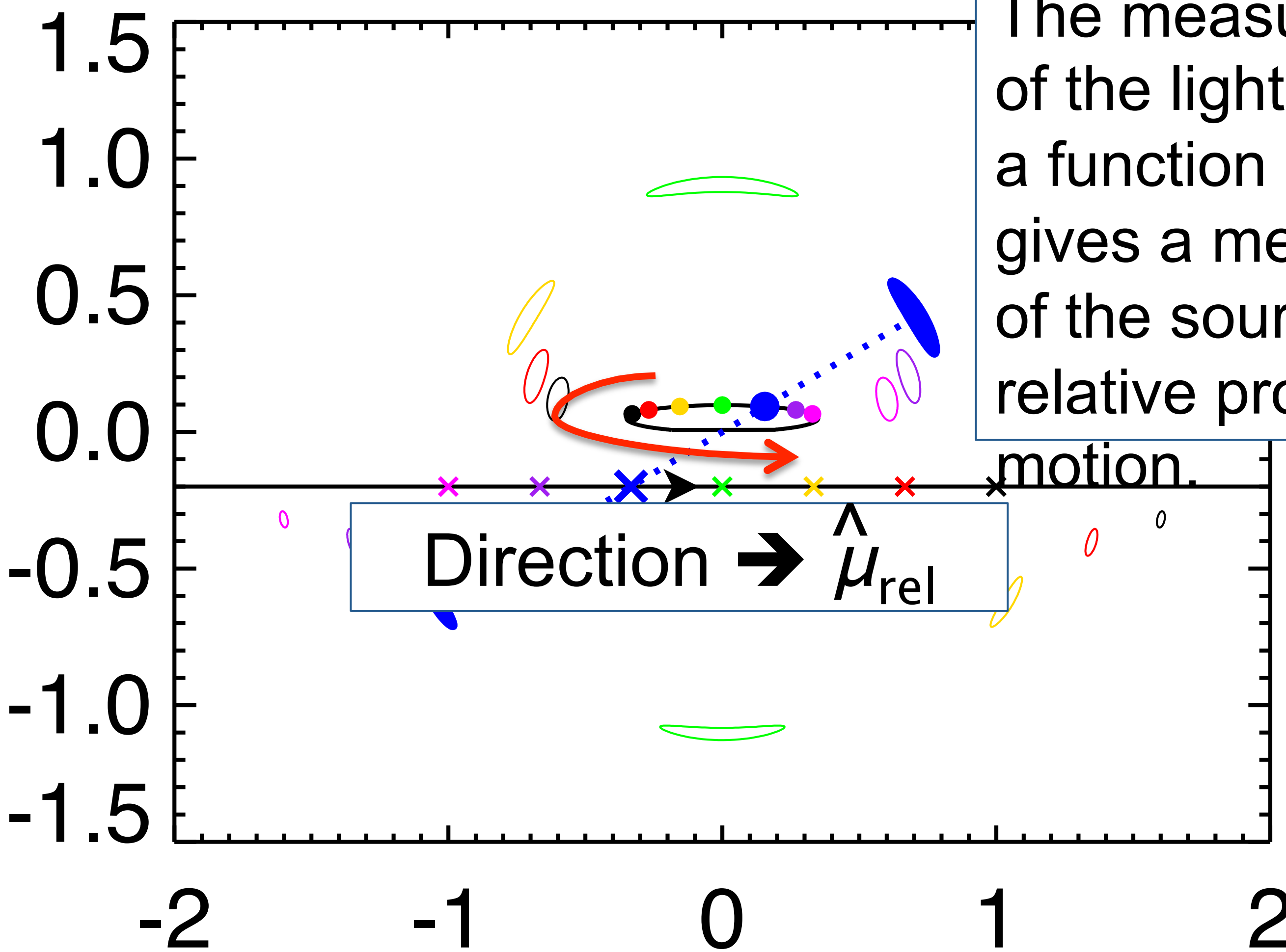
Astrometric Microlensing



Astrometric Microlensing

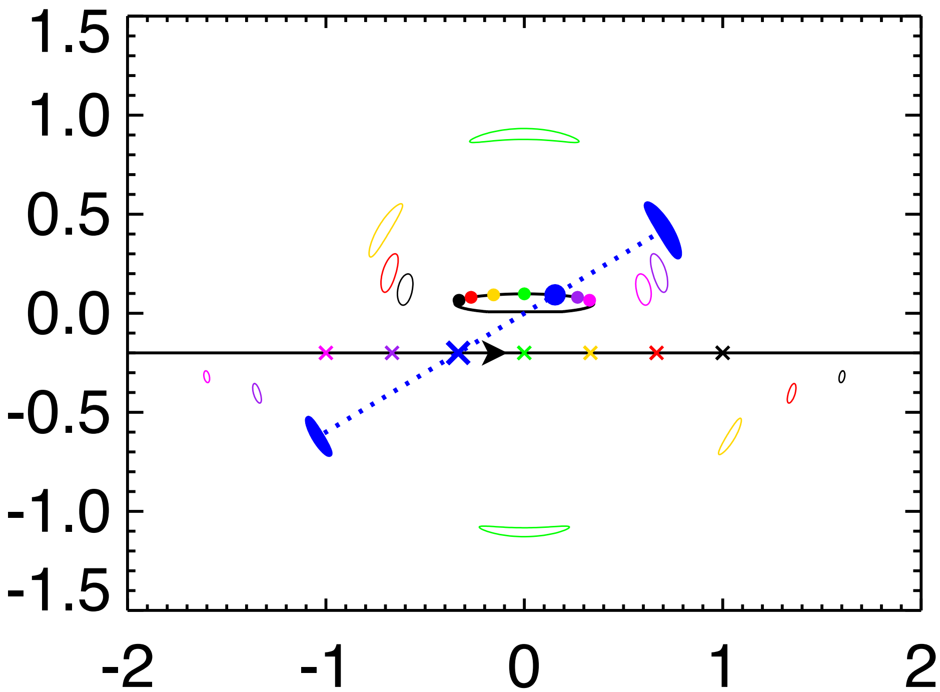


Astrometric Microlensing



The measured motion of the light centroid as a function of time gives a measurement of the source-lens relative proper motion.

Microlens Astrometry of Black Holes



The astrometric microlensing effect for stellar mass black holes is large enough to measure with current capabilities.

Astrometric Microlensing

- A long baseline greatly reduces uncertainties because it allows proper motions to be measured precisely
  - Early HST observations can provide the baseline
  - 400 orbits of simultaneous ACS and WFC3 observations can cover 71% of the WFIRST microlensing fields without much inefficiency
  - 50-100 orbits would cover 9-18% of the WFIRST fields and would robust comparisons to WFIRST astrometry (with its huge number of detected photons).

WFIRST Precursor Observation Timing Considerations

- Some precursor observations may affect WFIRST hardware, like filter choices
  - Changing filters after phase B can be expensive. Cost risk is much higher than the risk that WFIRST won’t fly.
- The value of some observations degrades with time
  - S/N of observations of coronagraph target locations degrades as target approaches its position
  - Bulge proper motion measurements have lower S/N the longer that we wait.
- Earlier microlensing precursor observations may help to develop the microlensing workforce.

Recommendations

- Allow a category of WFIRST precursor observations in cycle 25 – possibly a joint category with JWST
  - Give special priority to observations that may influence hardware decisions or requirements.
  - The TAC should consider the complete science enabled by the proposed observations, including the WFIRST science that is enabled by the proposed HST observations.
  - The probability that WFIRST won't fly can also be considered, but this should be a realistic estimate – not something just based on the mission phase.
  - For the microlensing precursor observations, at least, NASA's goals would probably be best served by requiring or encouraging no proprietary time.