Simulating Dithered Microlensing Astrometry for Roman Space Telescope

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What are alien planets like?

Exoplanets (Expectation)

Star Wars!!

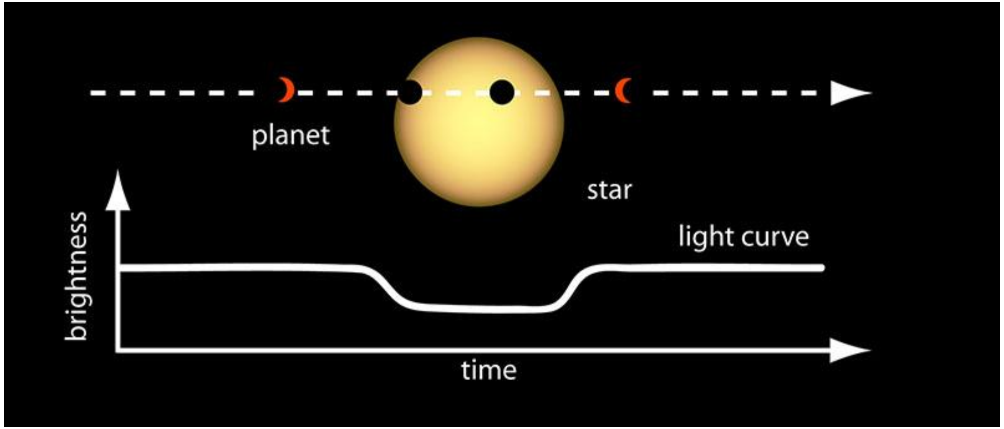
Obtained from cimsec.org, copyright Lucasfilm

Adventure!!

Obtained from comicyears.com, copyright Lucasfilm

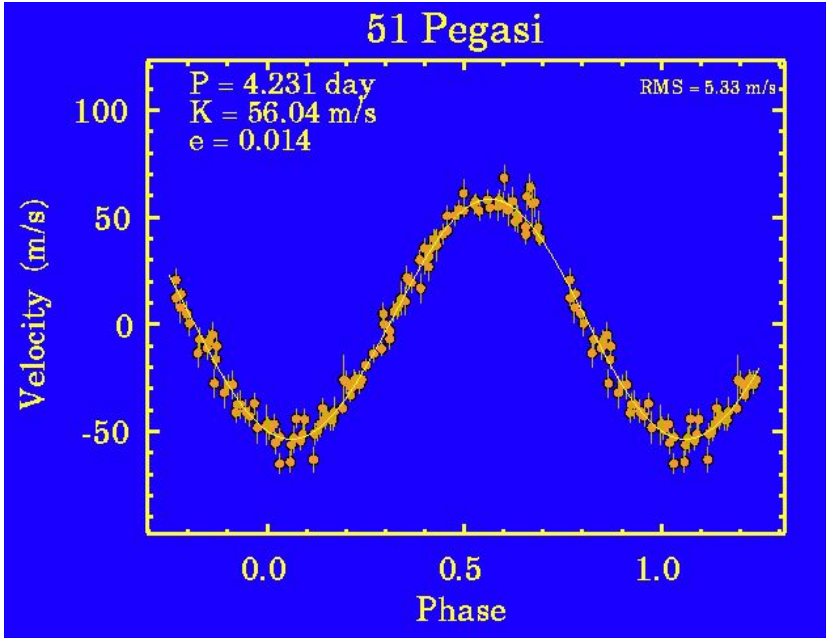
Exoplanets (Reality)

Example transit event



Credit [NASA]

Radial velocity graph of **51 Pegasi**



Credit exoplanets.org, obtained from the [Planetary Society]

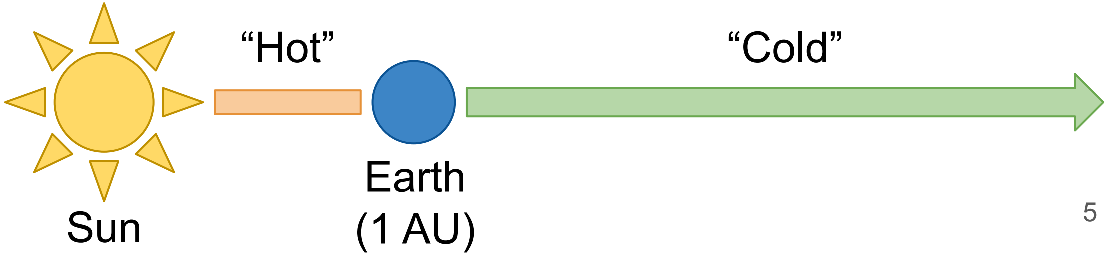
Detecting Exoplanets

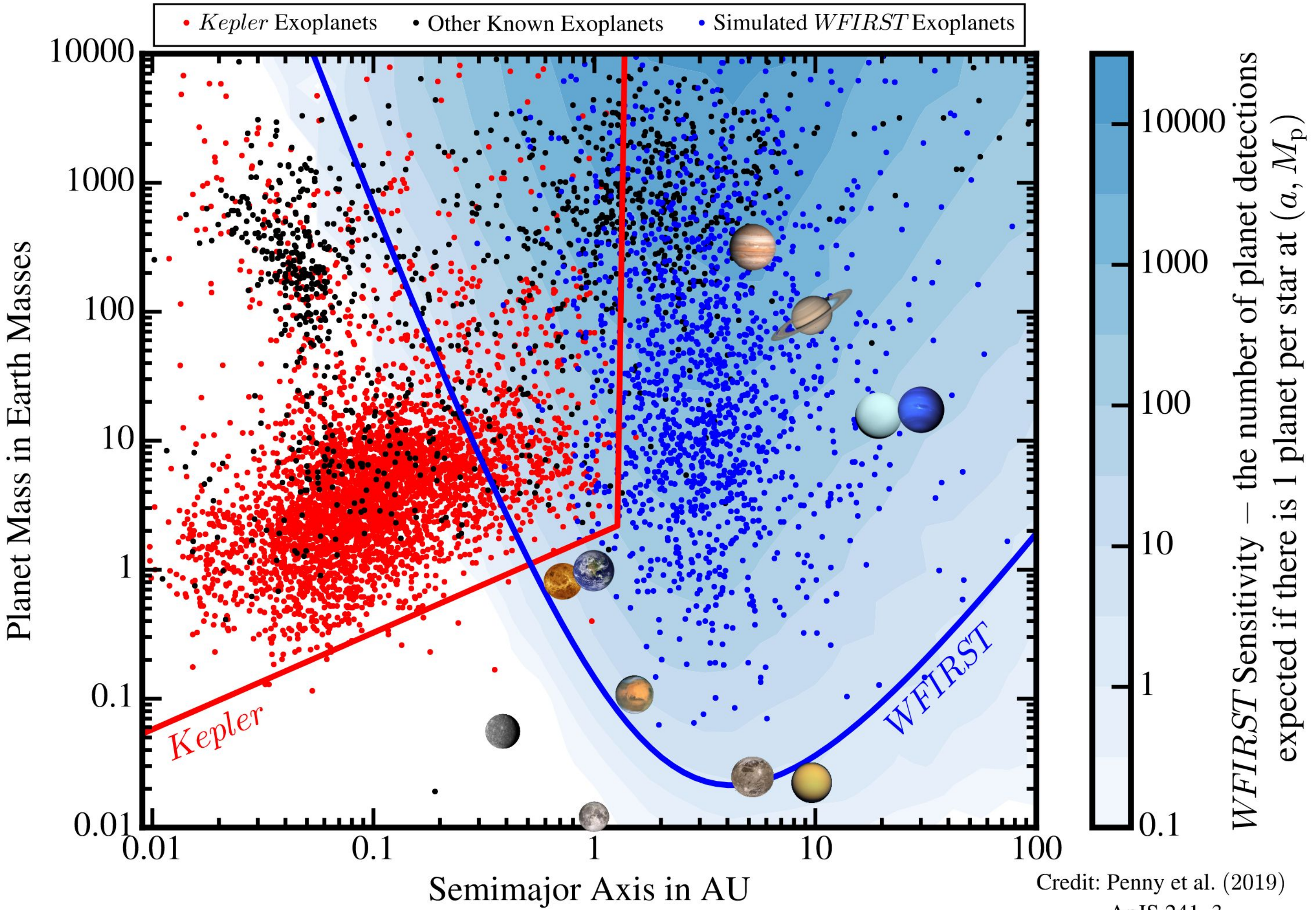
Exoplanet Parameter Space
(With Method of Discovery)

	"Hot"	"Cold"
"Large"	Transit Radial Velocity	Microlensing
"Small"	Transit	Microlensing
	Kepler	**Roman**

NASA Exoplanet Census

- Representative sample of all exoplanets
- Can reveal more about planet formation
- 2 stages
  - **Kepler** - "hot" planets
  - **Roman** - "cold" planets





Credit: Penny et al. (2019)
ApJS 241, 3

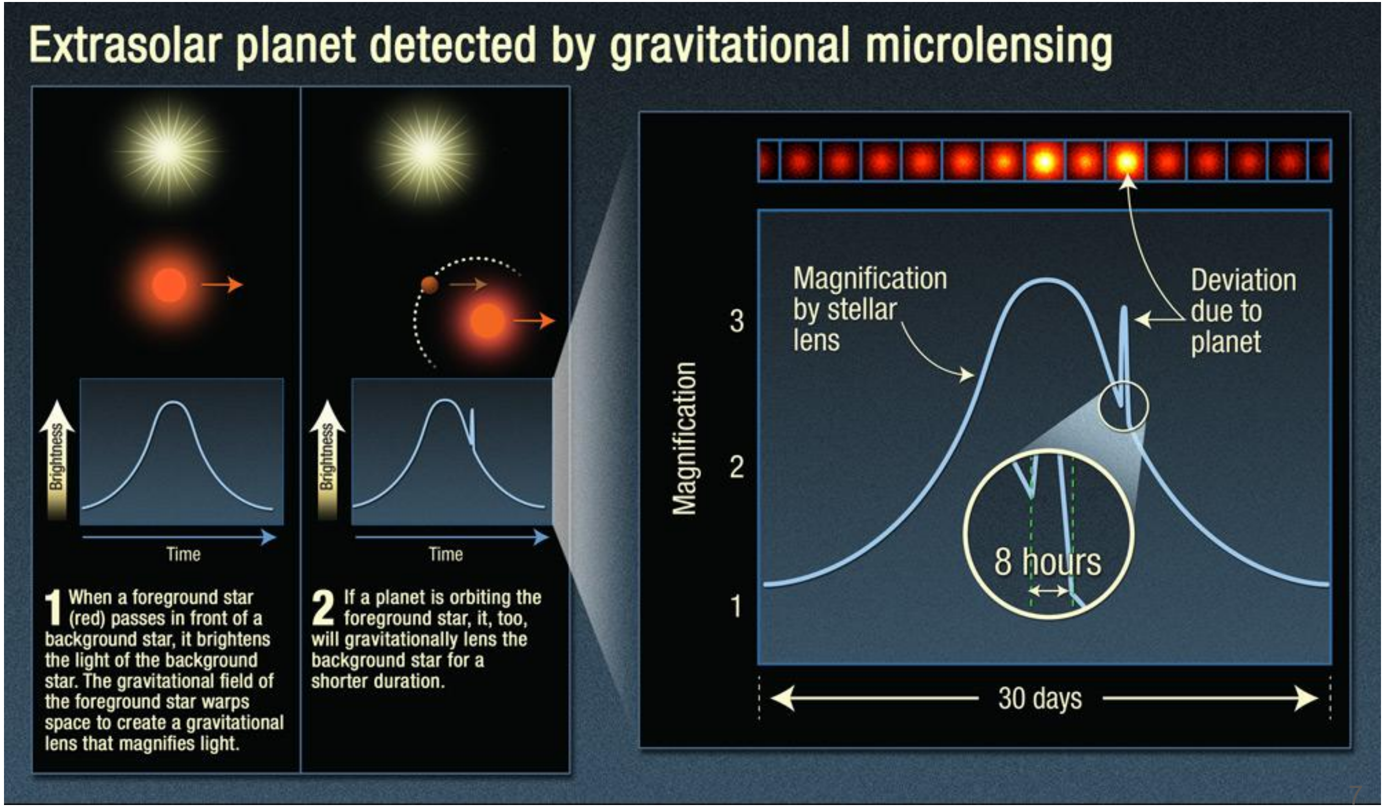
What is Microlensing?

Pros

- Works on distant exoplanets
- Sensitive to small exoplanets

Cons

- One-time events
- Requires stellar separation to mass



Credit *NASA*

Roman Space Telescope (aka. WFIRST)

NASA's flagship astrophysics mission (2010 Decadal Survey)

Expected launch ~ **2026**

2.4 m main mirror

Image from NASA

Wide Field Instrument

- Infrared band
- Similar resolution to Hubble, but covering a field **x100** as large!
  - Undersampling

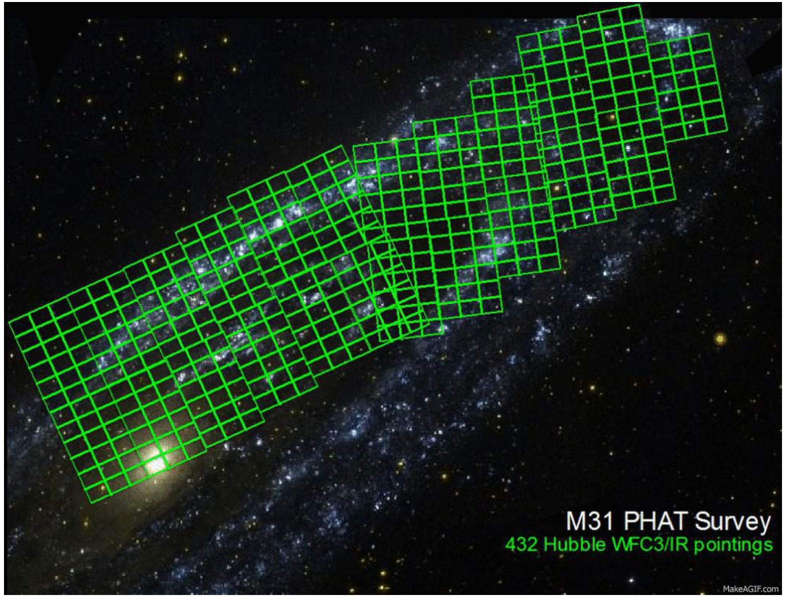
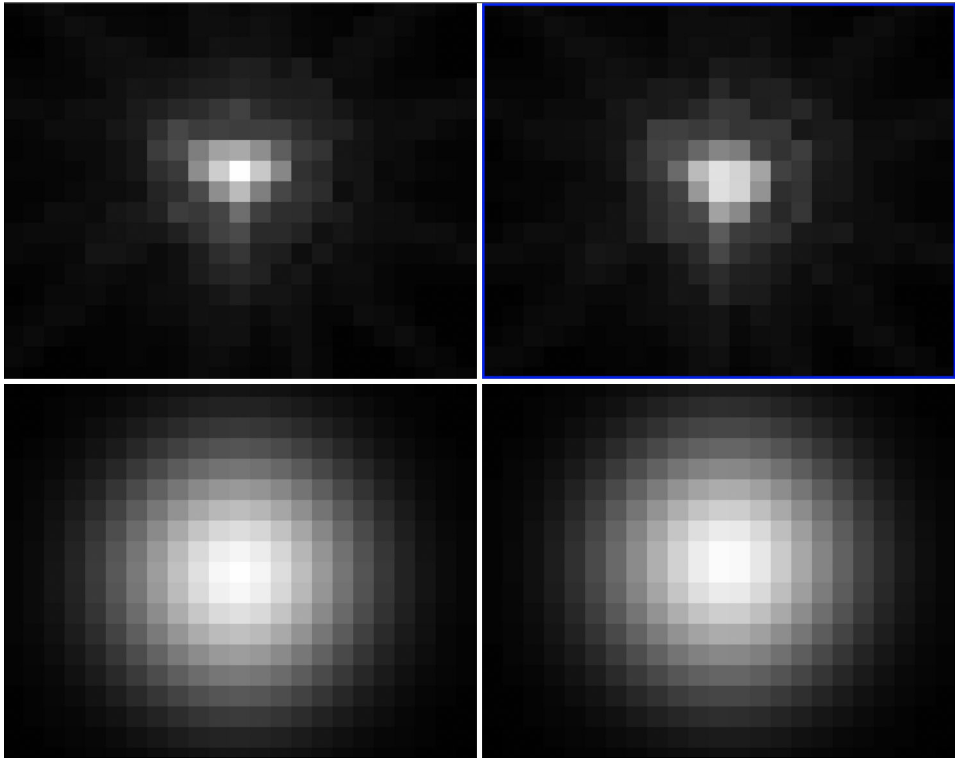


Image from NASA

The Undersampling Trade-Off



Images provided courtesy of Matthew Penny

Undersampling (top images) vs. regular sampling (bottom images)

Maximizes area, which increases exoplanet detection rates

Drawbacks:

- Lower resolution makes stellar separation harder
- Systematic errors in time domain make photometry more difficult

How good will Roman be at detecting exoplanet microlensing events?

GULLS Codebase

Developed by Penny, et al. (2013)

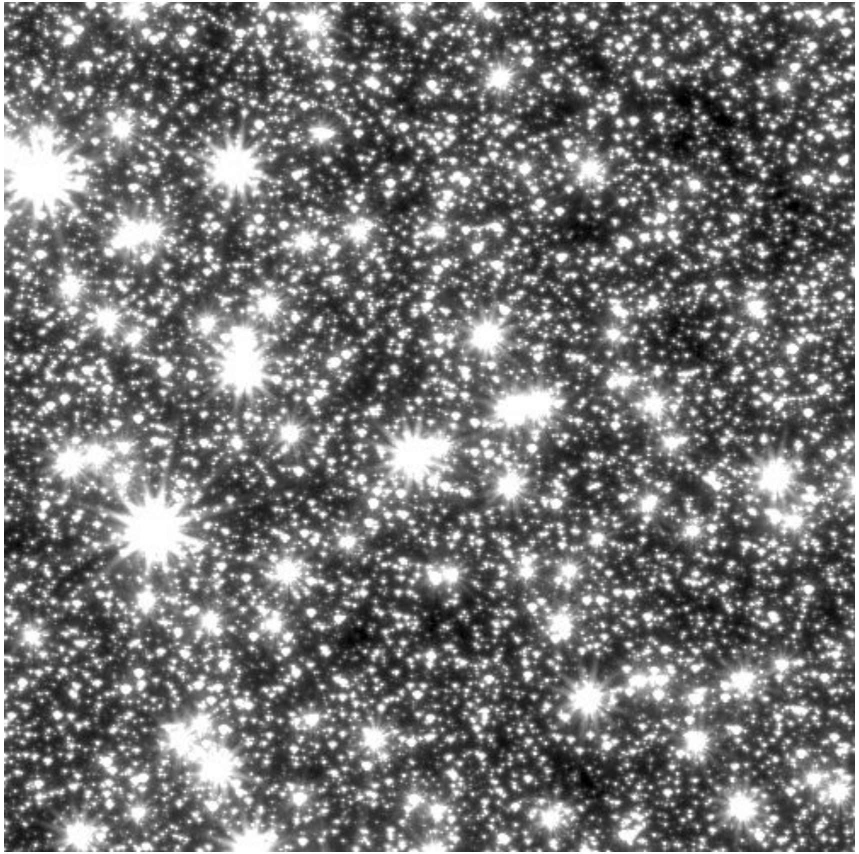
Simulates time-series microlensing data

Precisely models point spread functions (PSFs)

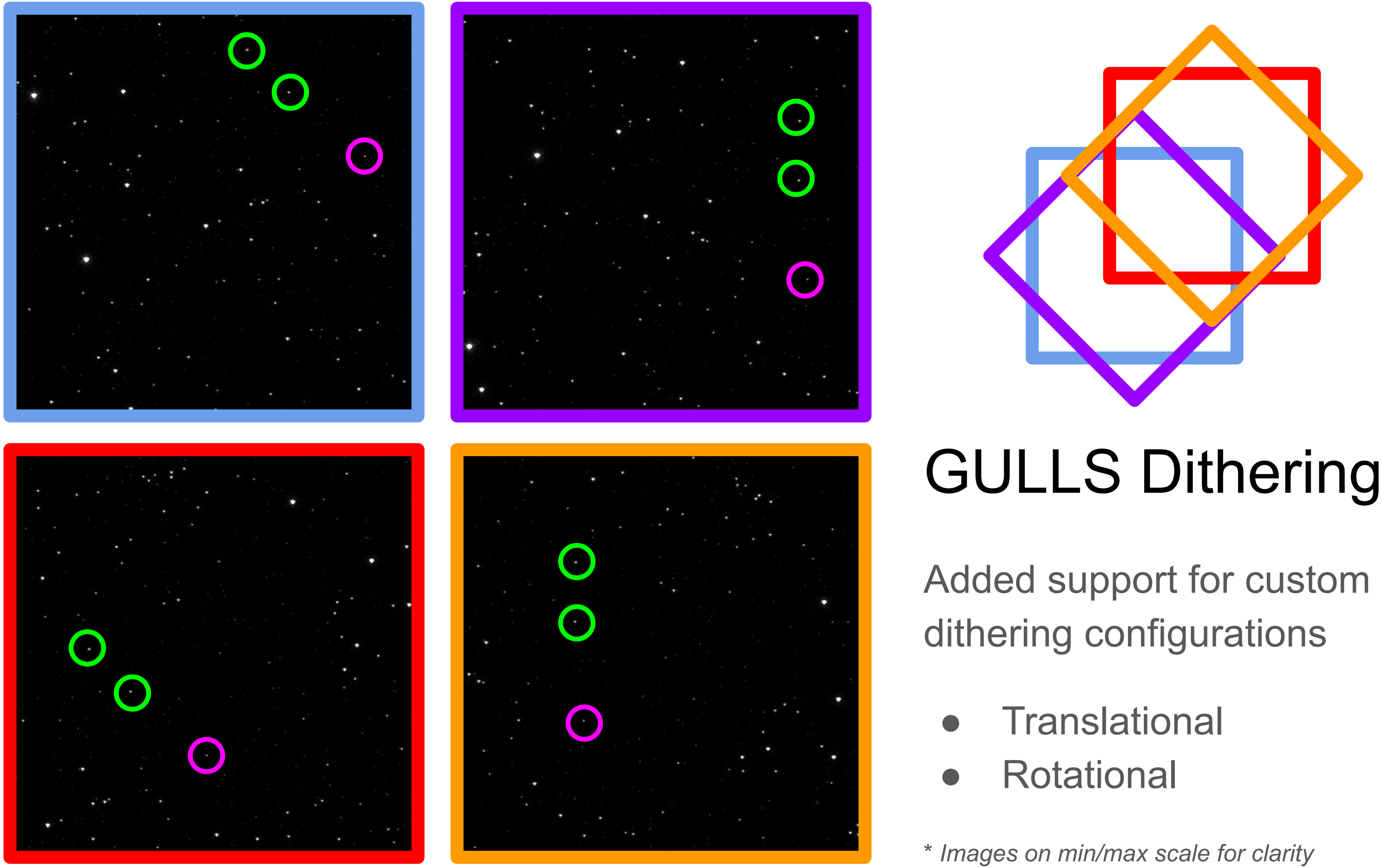
Generates singular images

Basic Improvements

- Poisson sampling of star lists
- Bug fixes



* *Images on **sqrt zscale** to show all faint stars*



GULLS Dithering

Added support for custom dithering configurations

- Translational
- Rotational

* *Images on min/max scale for clarity*

GULLS Proper Motion

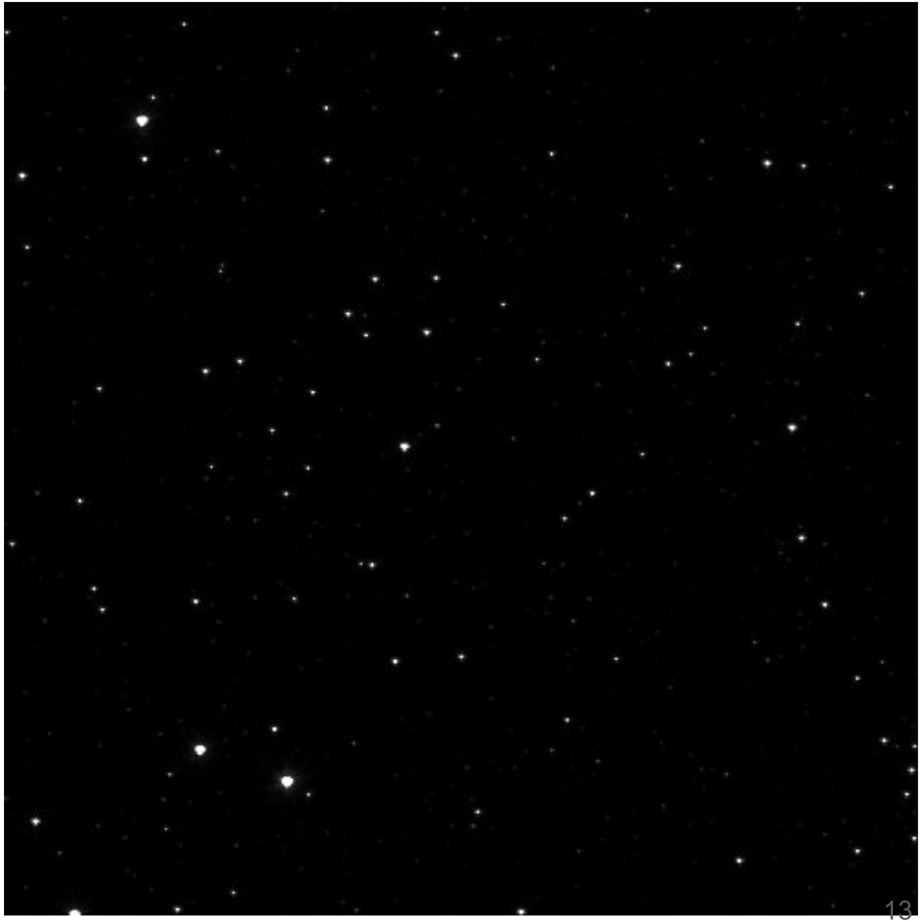
Added support for motion of stars over time

In total, dither courses specify:

- **d** - timestamp (days)
- **x, y** - translation offset (pixels)
- **θ** - rotation (centered, degrees)

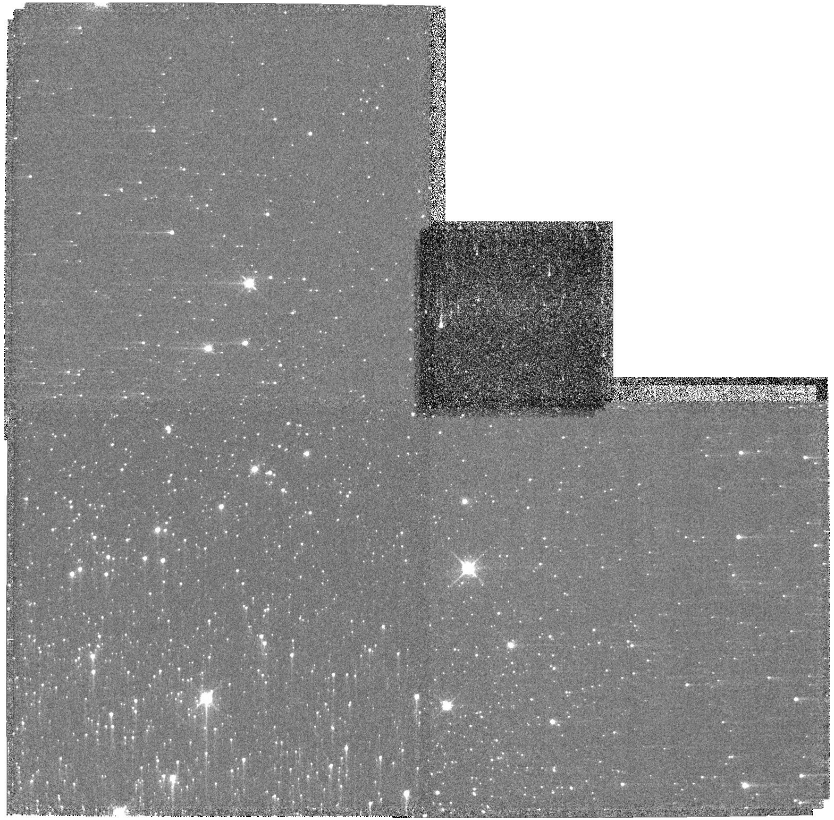
[Proper Motion Demo]

Frames at **0, 100, 200, 300 years**



* *Images on **linear min/max scale** for clarity*

Drizzle



* *Created using **Hubble MAST data** and STScI example notebooks for DrizzlePac*

Linear combination of aligned dithered images for high-resolution imaging

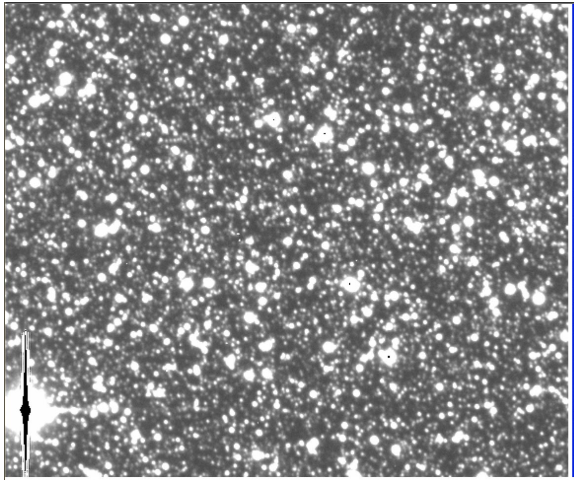
Potential for **noise correlation** among adjacent pixels

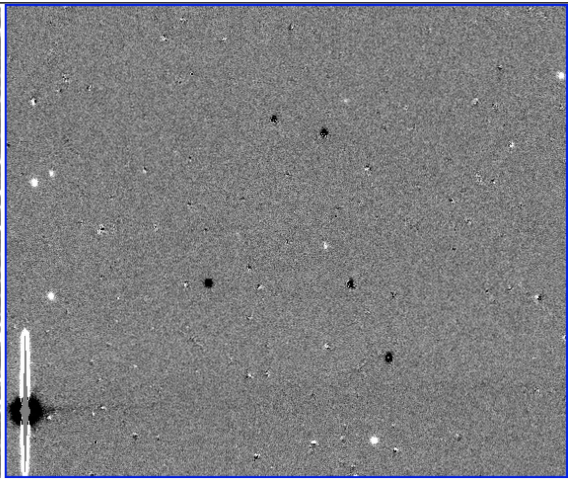
State-of-the-art implementation in DrizzlePac

DrizzlePac

- Python package from STScI
- Tailored almost exclusively for Hubble; **difficult to implement**
  - Work in progress

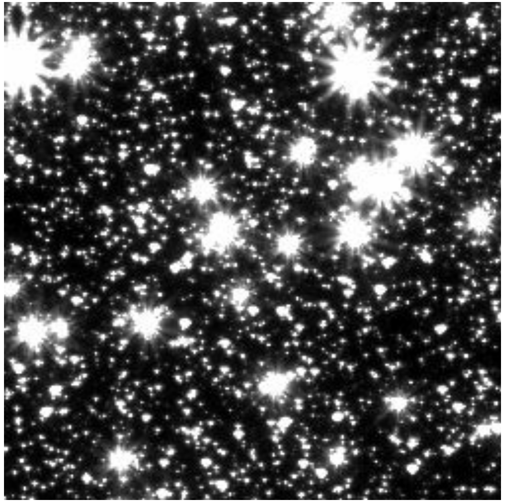
Ground-Based Difference Imaging (CFHT Microlensing Survey)

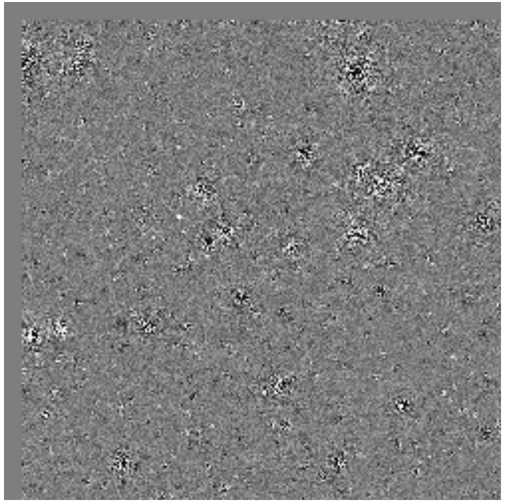




CFHT images provided courtesy of Matthew Penny

Roman Difference Imaging (GULLS/ISIS)





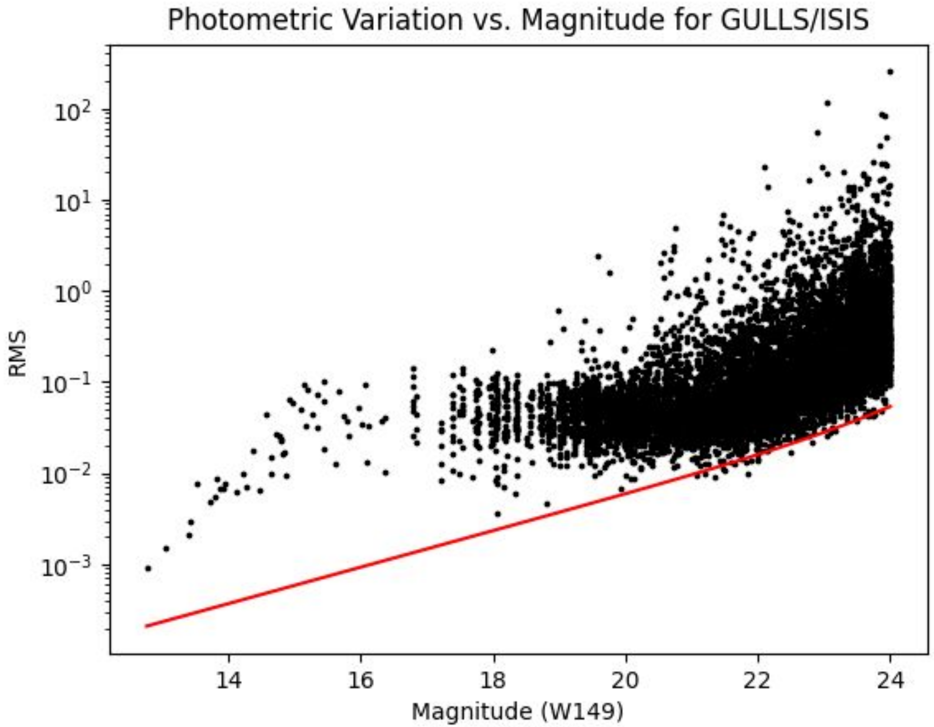
Difference Imaging Analysis

ISIS - *Alard & Lupton 1998, ApJ, v. 503, p. 325*

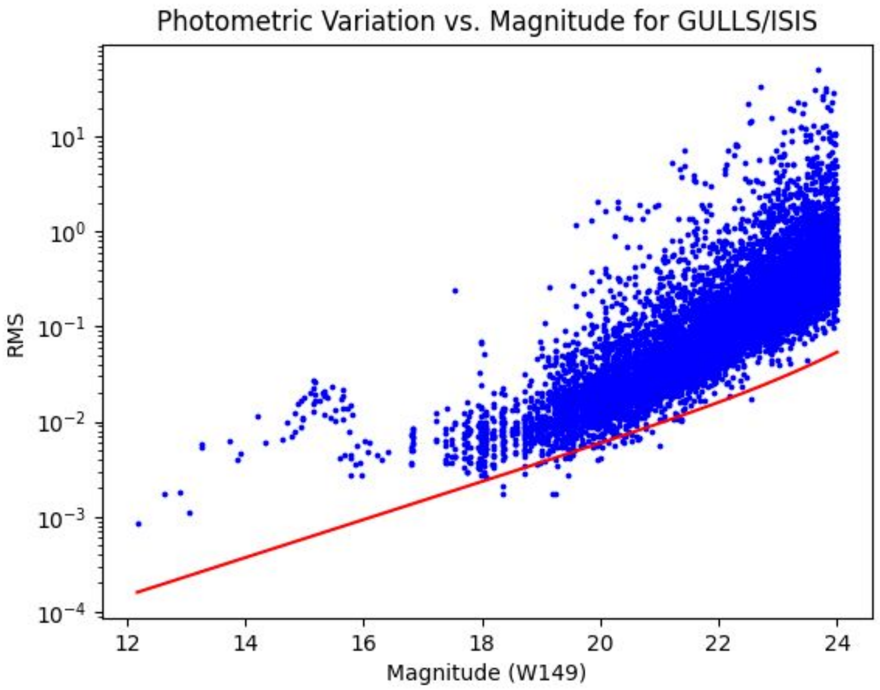
Generates light curves from **image subtraction**

Very flexible, relatively simple implementation

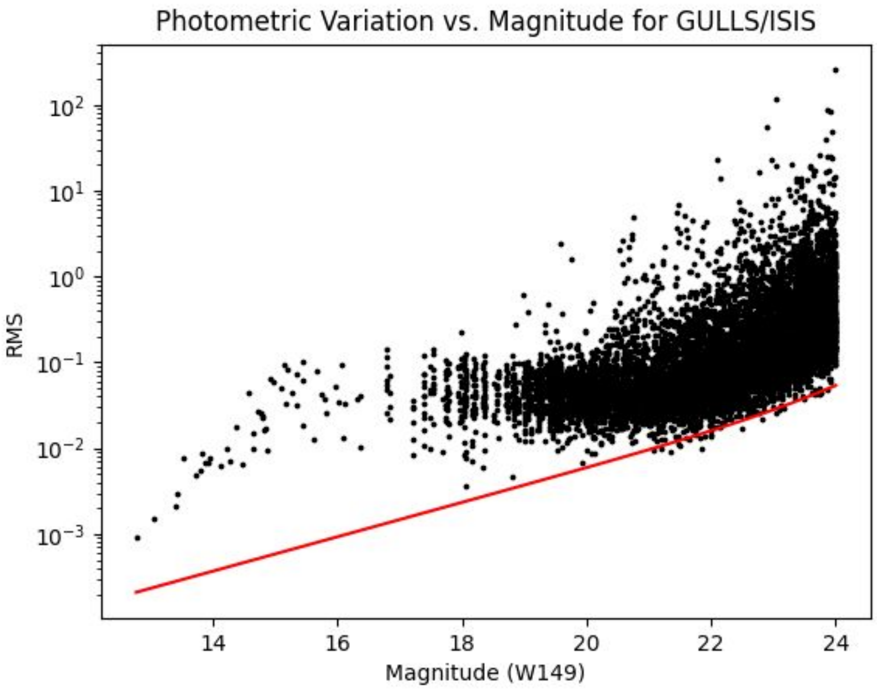
Systematic error arises from undersampling and physical design



With Gaussian Convolution



Naive Implementation



Conclusions

Roman is poised to play a crucial role in the **NASA exoplanet census**

GULLS is a powerful simulation tool which can be applied to Roman imaging

Improvements made are more reflective of **real world observing conditions**

Drizzle is a **promising technique in theory**, but difficult to implement in practice

ISIS is relatively simple to implement, and has **promising preliminary photometry**

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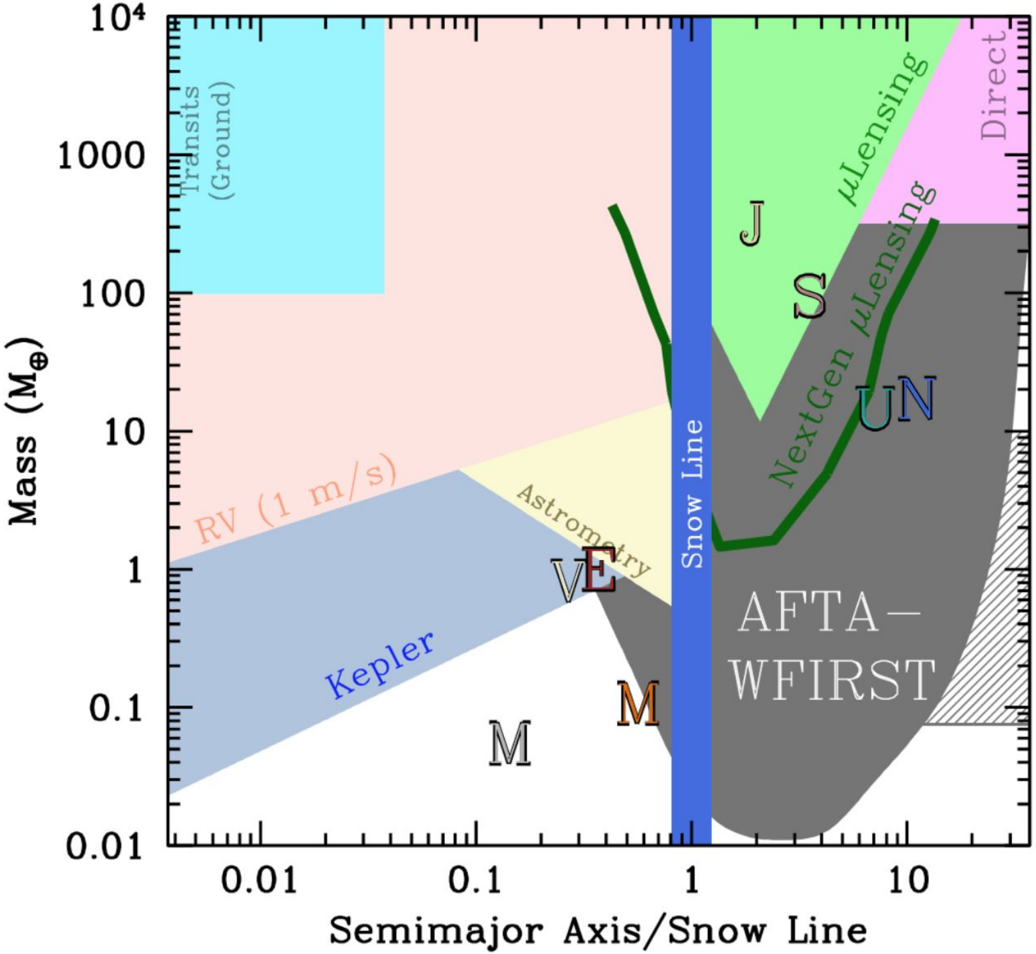
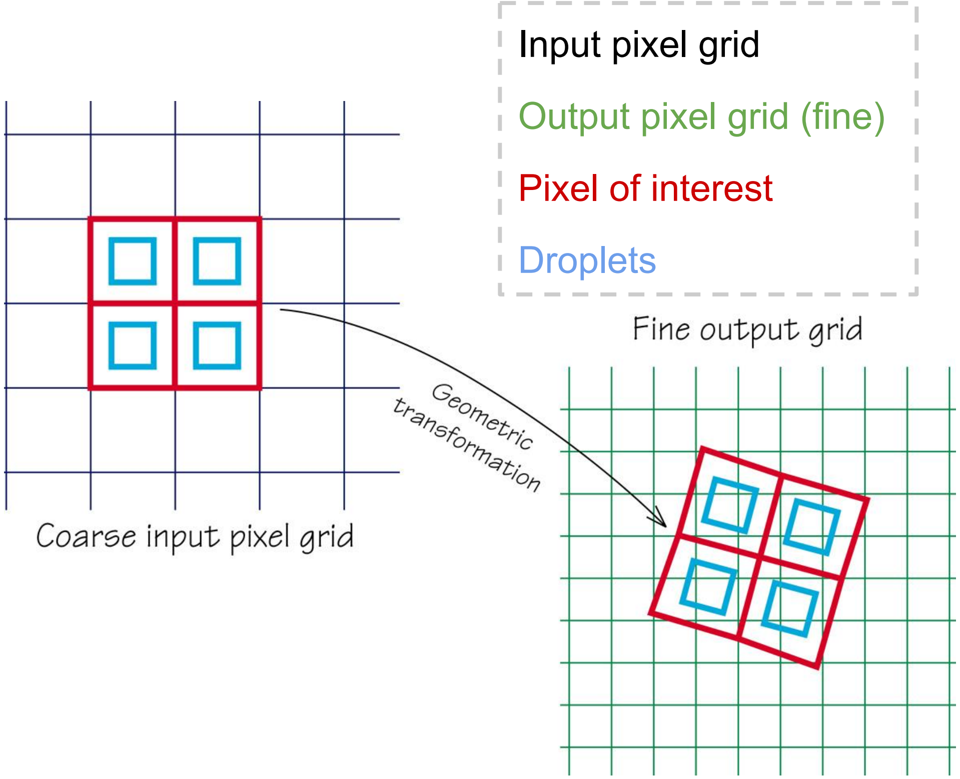
The University of Texas at Dallas Department of Physics

Questions?

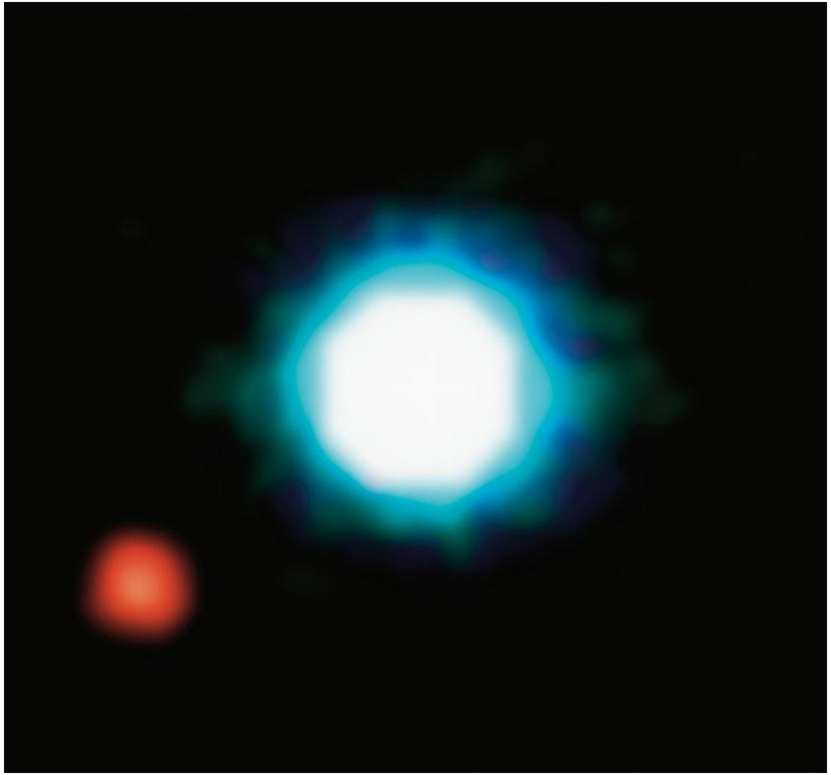


Obtained from Fischer, et al. (2014), figure courtesy of B. Scott Gaudi and Matthew Penny



Fruchter and Hook (2002), obtained from [STScI]

Incredibly clear direct image of **2M1207b**



Credit ESO, obtained from NASA

Roman Specifications (Cycle 7 Design)

Table 1
Adopted Parameters of Each Mission Design

	IDRM		DRM1		DRM2		AFTA		*WFIRST* **Cycle 7**	
Reference	Green et al. (2011)		Green et al. (2012)		Green et al. (2012)		Spergel et al. (2015)		…[a,b]	
Mirror diameter (m)	1.3		1.3		1.1		2.36		**2.36**	
Obscured fraction (area, %)	0		0		0		13.9		**13.9**	
Detectors	7 × 4 H2RG-10		9 × 4 H2RG-10		7 × 2 H4RG-10		6 × 3 H4RG-10		**6 × 3 H4RG-10**	
Plate scale (″/pix)	0.18		0.18		0.18		0.11		**0.11**	
Field of view (deg^2)	0.294		0.377		0.587		0.282		**0.282**	
Fields	7		7		6		10		**7**	
Survey area (deg^2)	2.06		2.64		3.52		2.82		**1.97**	
Avg. slew and settle time (s)	38		38		38		38		**83.1**	
Orbit	L2		L2		L2		Geosynchronous		L2	
Total survey length (day)	432		432		266		411[c]		**432**	
Season length (day)	72		72		72		72		**72**	
Seasons	6		6		3.7		6		**6**	
Baseline mission duration (yr)	5		5		3		6		**5**	
Primary bandpass (μm)	1.0–2.0 (W149)		1.0–2.4 (W169)		1.0–2.4 (W169)		0.93–2.00 (W149)		**0.93–2.00** (**W149**)	
Secondary bandpass (μm)	0.74–1.0 (Z087)		0.74–1.0 (Z087)		0.74–1.0 (Z087)		0.76–0.98 (Z087)		**0.76–0.98** (**Z087**)	
	W149	Z087	W169	Z087	W169	Z087	W149	Z087	**W149**	**Z087**
Zeropoint[d] (mag)	26.315	25.001	26.636	24.922	25.990	24.367	27.554	26.163	**27.615**	**26.387**
Exposure time (s)	88	116	85	290	112	412	52	290	**46.8**	**286**
Cadence	14.98 min	11.89 hr	14.35 min	12.0 hr	15.0 min	12.0 hr	15.0 min	12.0 hr	**15.16 min**	**12.0 hr**
Bias (counts/pix)	380	380	1000	1000	1000	1000	1000	1000	**1000**	**1000**
Readout noise[e] (counts/pix)	9.1	9.1	7.6	4.2	9.1	9.1	8.0	8.0	**12.12**	**12.12**
Thermal + dark[f] (counts/pix/s)	0.36	0.36	0.76	0.76	0.76	0.76	1.30	0.05	**1.072**	**0.130**
Sky background[g] (mag/arcsec^2)	21.48	21.54	21.53	21.48	21.52	21.50	21.47	21.50	**21.48**	**21.55**
Sky background (counts/pix/s)	2.78	0.79	3.57	0.77	1.99	0.45	3.28	0.89	**3.43**	**1.04**
Error floor (mmag)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	**1.0**	**1.0**
Saturation[h] (10^3 counts/pix)	65.5	65.5	80	80	80	80	679	2037	**679**	**679**

Penny et al. (2019)

Roman Specifications (Cycle 7 Design)

Table 2
The *WFIRST* Microlensing Survey at a Glance

Area	1.96 deg^2
Baseline	4.5 yr
Seasons	6×72 days
$W149$ Exposures	$\sim$41,000 per field
$W149$ Cadence	15 min
$W149$ Saturation	$\sim$14.8
Phot. Precision	0.01 mag @ $W149 \sim 21.15$
$Z087$ Exposures	$\sim$860 per field
$Z087$ Saturation	$\sim$13.9
$Z087$ Cadence	$\lesssim$12 hr
Stars ($W149 < 15$)	$\sim 0.3 \times 10^6$
Stars ($W149 < 17$)	$\sim 1.4 \times 10^6$
Stars ($W149 < 19$)	$\sim 5.8 \times 10^6$
Stars ($W149 < 21$)	$\sim 38 \times 10^6$
Stars ($W149 < 23$)	$\sim 110 \times 10^6$
Stars ($W149 < 25$)	$\sim 240 \times 10^6$
Microlensing events $\lvert u_0 \rvert < 1$	$\sim$27,000
Microlensing events $\lvert u_0 \rvert < 3$	$\sim$54,000
Planet detections (0.1–10^4 $M_\oplus$)	$\sim$1400
Planet detections (<3 $M_\oplus$)	$\sim$200

Penny et al. (2019)