Astrometry and MicroLensing

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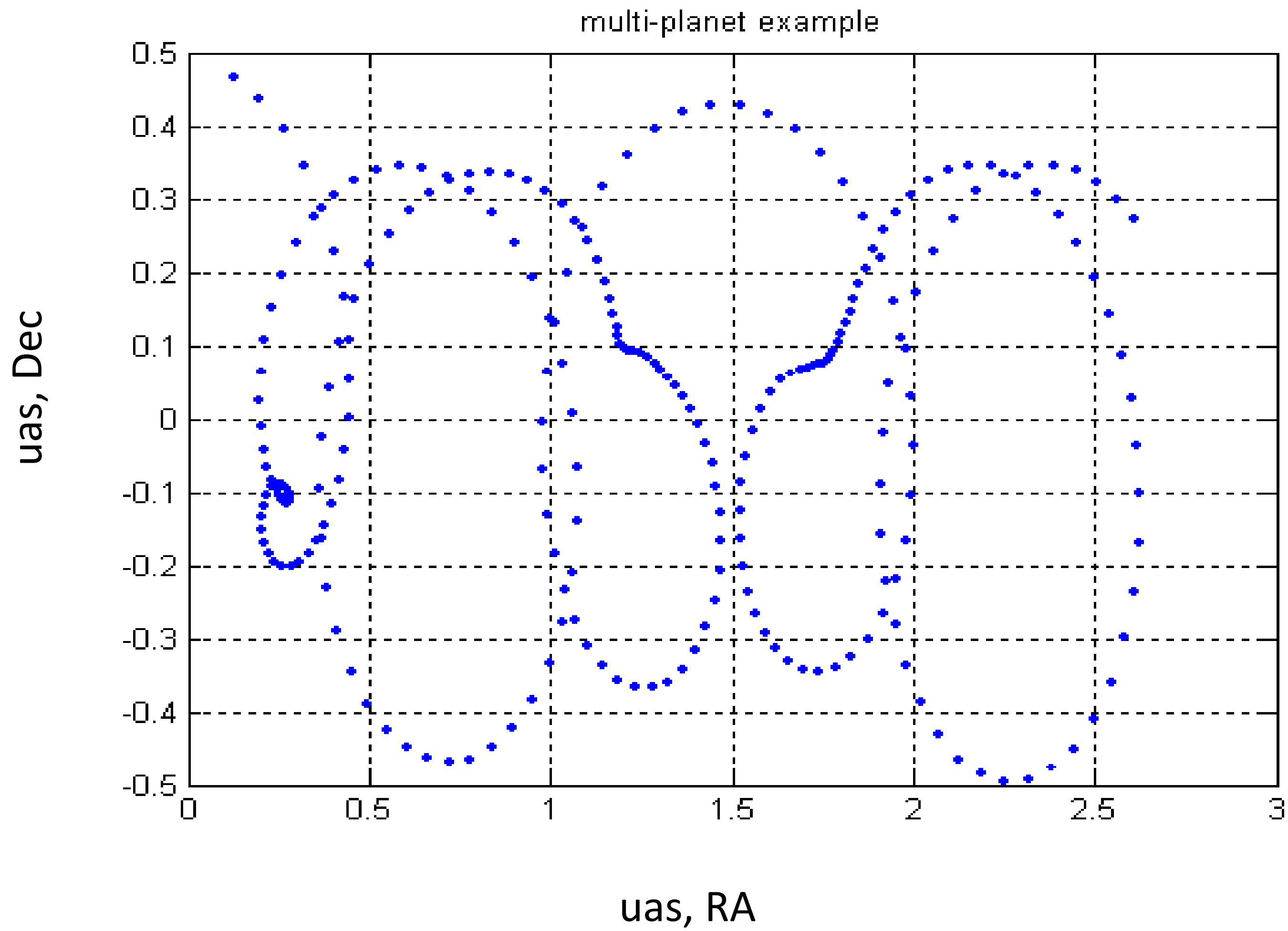
Outline

- Astrometry
  - Astrometric detection of planetary systems
    - Intro
    - Ground vs Space
    - GAIA and SIM-Lite
  - Synergy of astrometry and direct imaging (exo-Earths)
    - Identification of targets for direct imaging/spectroscopy

- uLensing detection of exoplanets
  - How does uLensing work?
  - Prospects, ground based, space based
  - Summary advantages, limitations

Astrometry Tutorial



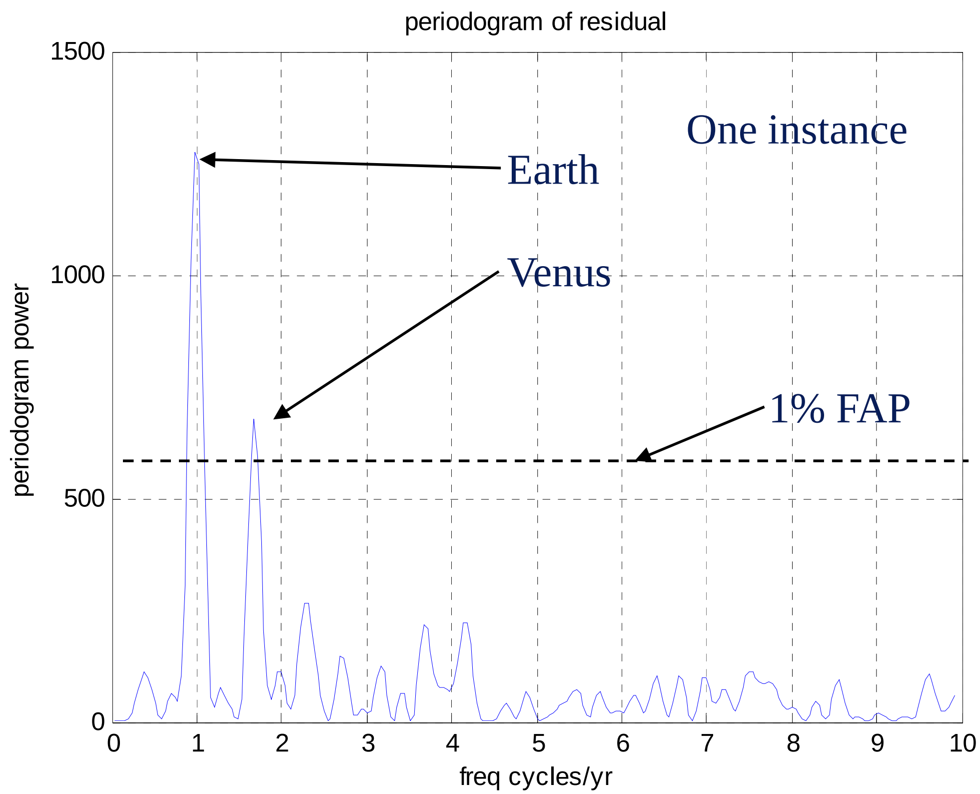
Motion of the Sun due only to the 4 inner planets, no parallax or proper motion (no noise)

Generic Algorithm (Used by all Teams)
Differences in approaches are at next level

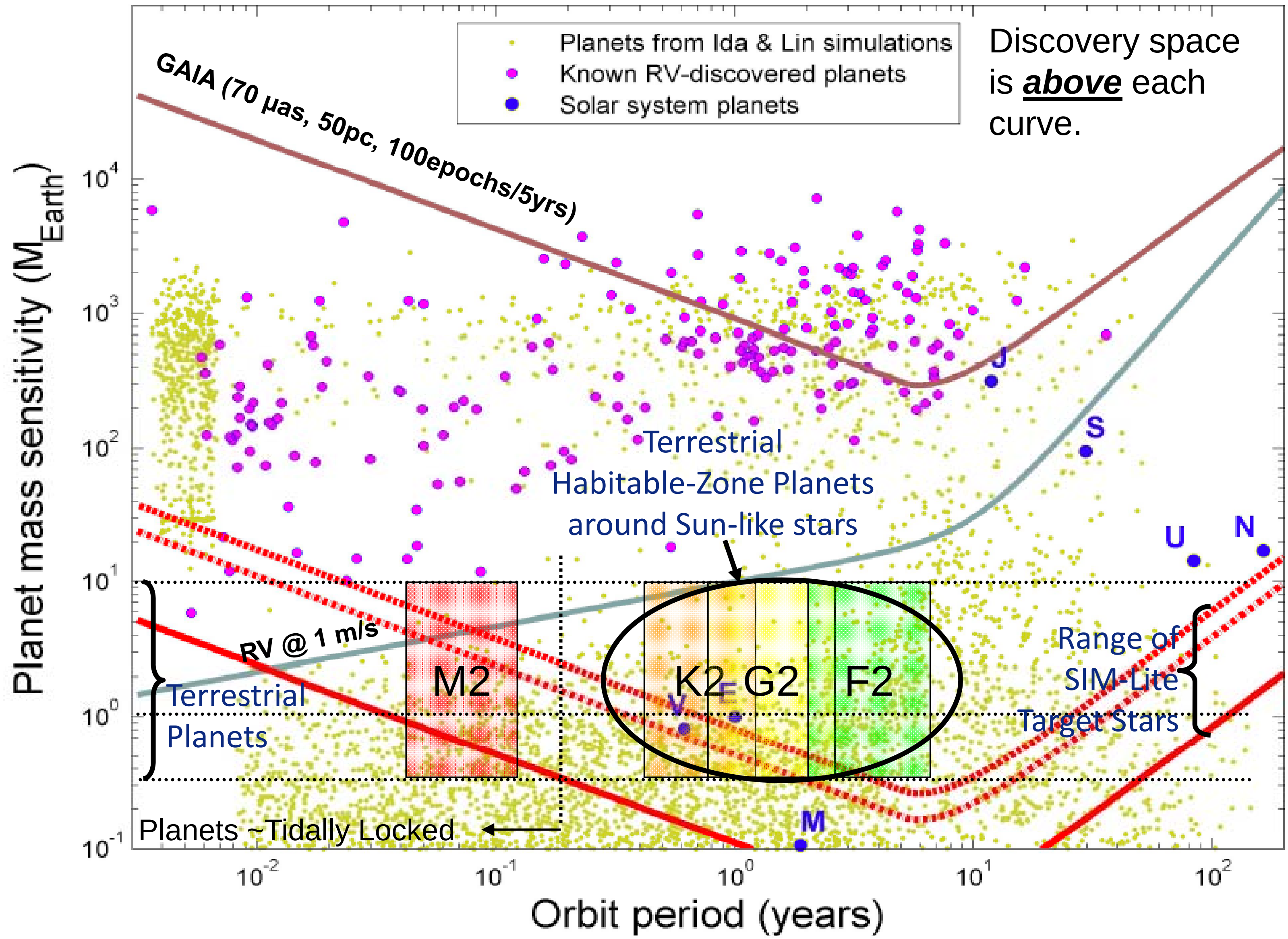
- Hierarchical approach to finding multiple planets
  - Identify the largest signal using a periodogram
  - Periodogram identifies the period and mass. Use this as a starting point for a non-linear least squares fit for the keplerian orbit of the planet.
  - Subtract the astrometric/RV signature of the fitted orbit from the data.
  - Use a periodogram of the residuals to find the 2nd biggest planet.
  - …
  - …

After one subtracts out the orbital signature of Jupiter and Saturn The graph at right shows the periodogram of the residuals.

Venus is not always detectable.



Exo-Earth Search, Comparison



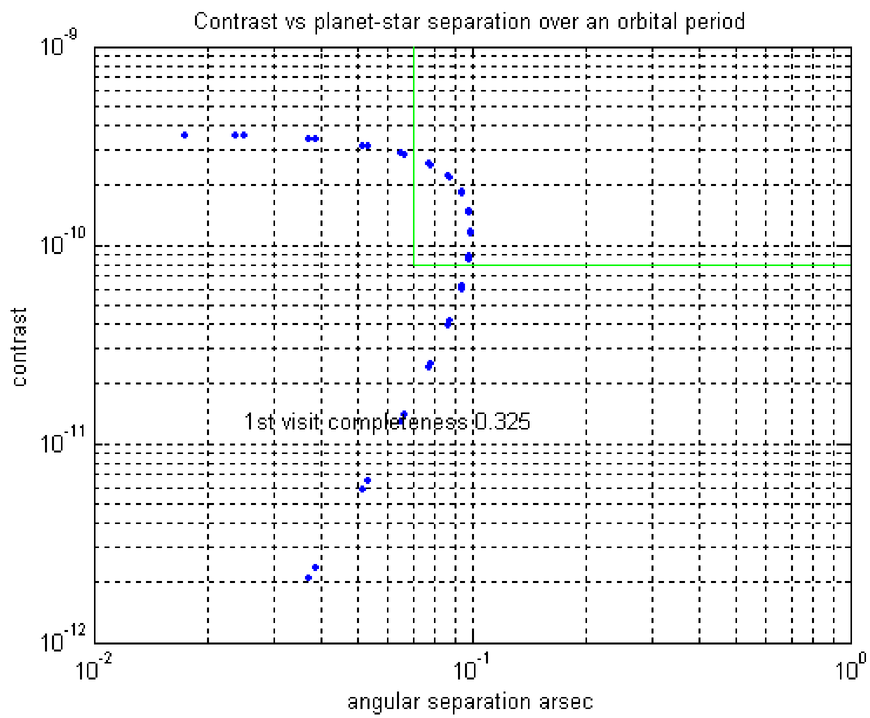
Identifying an Earth, when you've seen it

- An Earth-clone is a roughly Earth mass planet in the habitable zone of the parent star.
  - An Earth is clearly identified when it's mass is measured**, and** its orbit is measured to be in the HZ.
  - Astrometry measures the mass. Astrometry or direct imaging can measure its orbit.
- How many visits with an astrometric instrument, (or direct imaging instrument) are needed to get the orbit of an exo-Earth, in a multiplanet system? (say a hypothetical 4 planet system?)
  - With astrometry **> 70 visits** are needed. (4 planets ~ 28 unknowns, + 5 astrometric constants (position, proper motion parallax) = 33 unknowns. Want # measurements > 2 X the number of unknowns.
  - With Imaging need 4 images of the planet. If the 1st visit completeness is 30%, the system has to be imaged ~**12 times** on average to see the planet 4 times. (3 detections are needed to derive an orbit and a 4th detection at the right place at the right time is needed to verify that all 4 images are of the same planet. (See Confusion discussion later)
  - Imaging after planets are identified by astrometry. (assume eta_Earth is 10%) the number of direct imaging visits can be reduced by a factor of ~30

Measuring the Orbit

Imaging with/without Astrometry

- In direct detection, (internal or external coronagraphs), the exoplanet is detectable only when it is outside of the IWA (inner working angle)
- The planet's brightness varies by a factor 3~4 over a timescale of a few months.
- In a multiple planet system, there may be 0 Earths in the HZ, but you won't know there are zero until you have the orbits of the 3 planets that are present.
- One has to take 12 images of a multiple planet system to find out there are zero Earths-HZ.
- Assume 3 days/image *12 image *60 stars = 720 visits (**<u>720 epochs</u>**) over **<u>6 years</u>** of **<u>integration</u>** in the "search" phase before counting the time to take spectra of the planets.

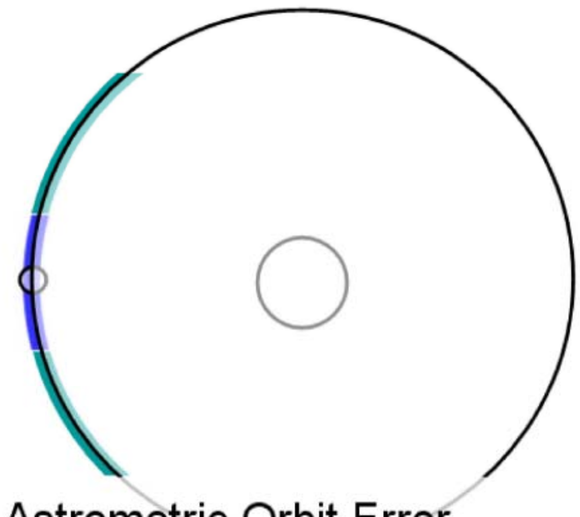


Sun-Earth @ 10pc,
IWA =70mas, Max S-P 100mas
Earth @ 90deg 1.2e-10
Detection threshold 8e-11
Prob of detection 32.5%

Measuring the Orbit
Imaging with/without Astrometry

- If an exo-Earth is detected astrometrically, some orbit parameters are measured very accurately (period/Semi-major axis ~3%, mass ~25%) But orbital phase precision degrades from 0.03AU at mid-epoch to ~ 1 AU 5yrs after the astrometric data is taken.
- But astrometric detection tells us 2 important things.
  - Which stars have Earths (don't visit those stars 12 times)
  - Only 2 images are needed to narrow the orbital phase uncertainty (vs 4)
- If Eta_Earth is 10% this **saves 95%** of the **mission time** for the direct detection mission. (from **6 yrs of integ to 4 months**)

Astrometric Detection of Exo-Earth @ SNR=6 FAP ~ 1%

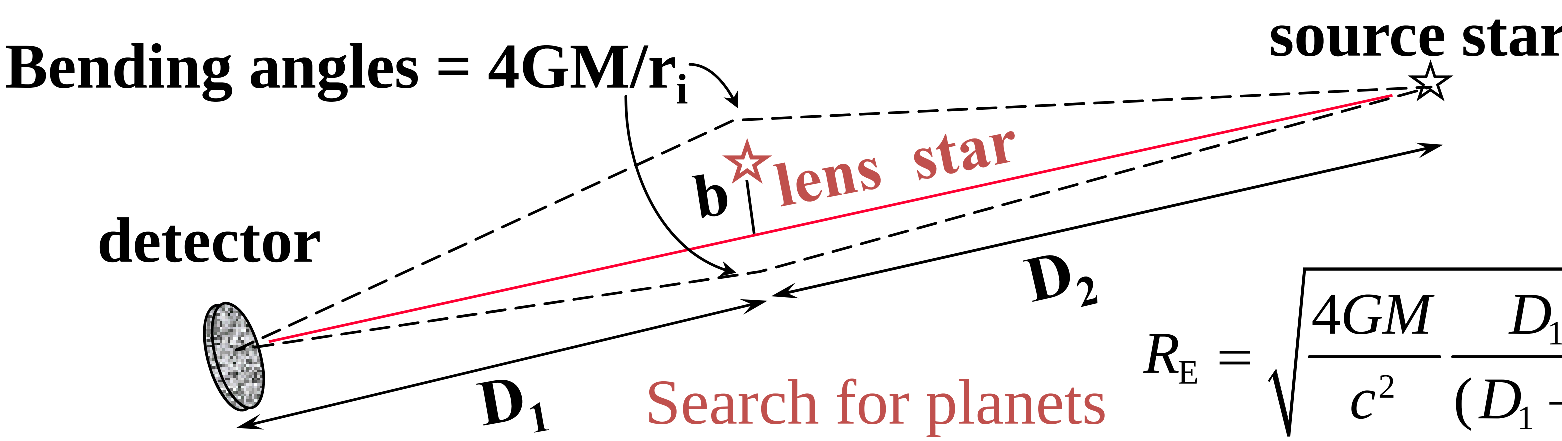


Astrometric Orbit Error
Blue – mid-epoch (σ_r~0.03 AU), (σ_θ ~0.25 radians)
Green – 5 yrs after mid-epoch

uLensing Tutorial

- Following charts from D. Bennet

The Principle (single lens case)



$$R_E = \sqrt{\frac{4GM}{c^2}\frac{D_1 D_2}{(D_1 + D_2)}}$$

Search for planets orbiting lens star

$$A(u = 1) = 1.34$$

and, if $u = \frac{b}{R_E}$, then

$$\Delta t \approx 3 \text{ days} \sqrt{\frac{M}{M_{\text{Jupiter}}}}$$

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

assumes $\sqrt{D}/v_\perp \approx \sqrt{2 \text{ kpc}}/(100 \text{ km/sec})$

How Likely is This?

Area on the sky covered

by Einstein disks: $A = \underbrace{\pi R_E^2}_{\sigma} \underbrace{\left[\frac{M_{\text{Gal}}}{M_{\text{Lens}}}\right]}_{\text{\# of lenses}}$

Fractional area covered:

$$\tau \approx \frac{\pi\left(\frac{4GM_{\text{Lens}}}{c^2}\right)\left(\frac{R_{\text{Gal}}}{2}\right)\left(\frac{M_{\text{Gal}}}{M_{\text{Lens}}}\right)}{4\pi R_{\text{Gal}}^2}$$

(assume that lenes dominate the total mass of the Galaxy)

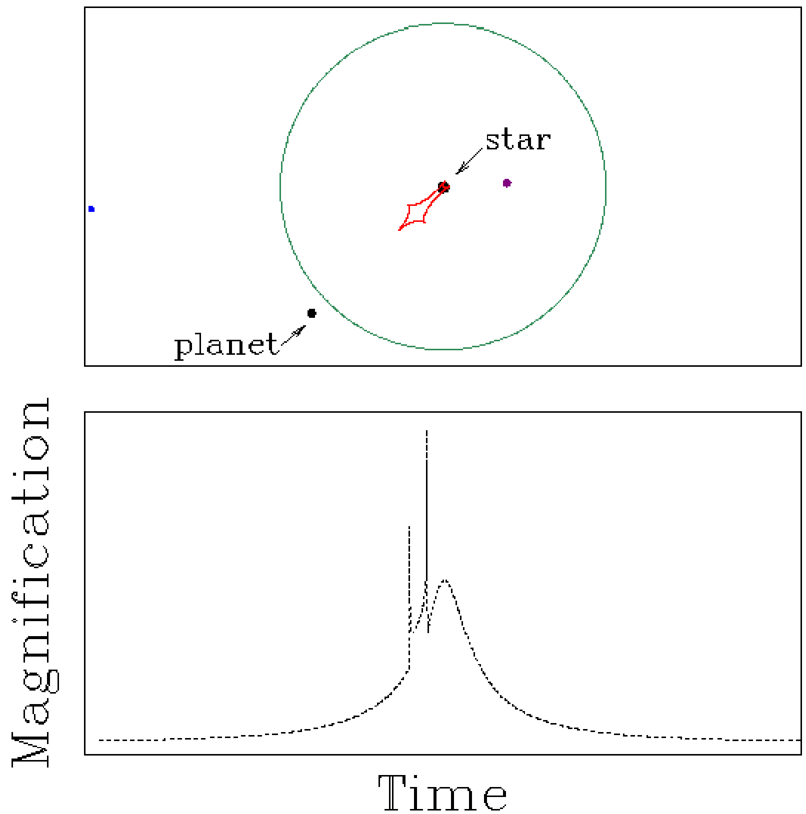
$$\tau \approx \frac{GM_{\text{Gal}}}{R_{\text{Gal}}c^2}$$, but recall that $v_c^2 \approx \frac{GM_{\text{Gal}}}{R_{\text{Gal}}}$, so

$$\tau \approx \frac{v_c^2}{c^2} \approx \left(10^{-3}\right)^2 \approx 10^{-6}$$

(Paczynski 1986)

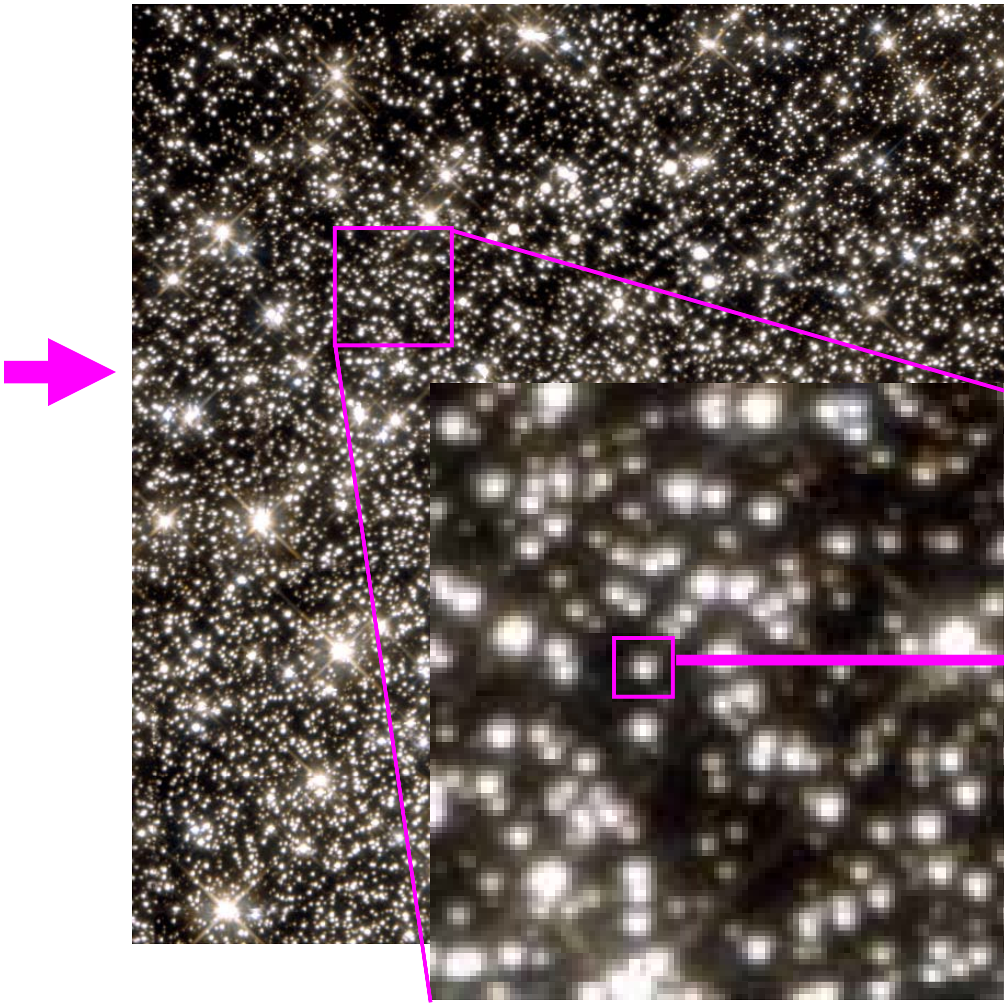
Need to monitor >10^6 stars!
Or > 10^8 stars to find planets!

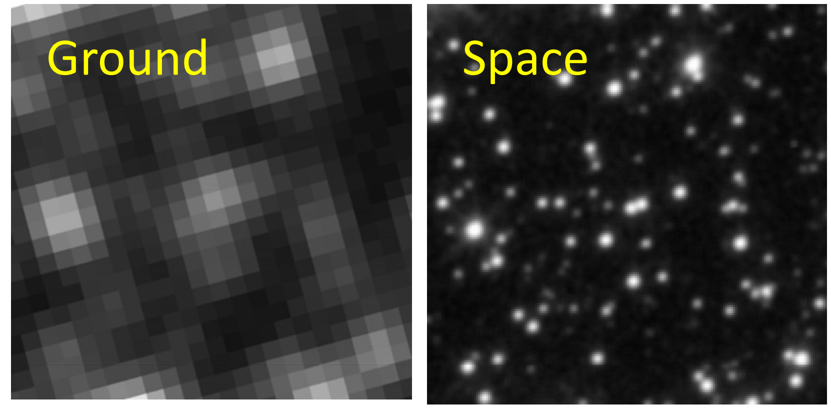
Lensed images at μarcsec resolution



A planet can be discovered when one of the lensed images approaches its projected position.

MPF Observes Bulge Main Sequence Stars





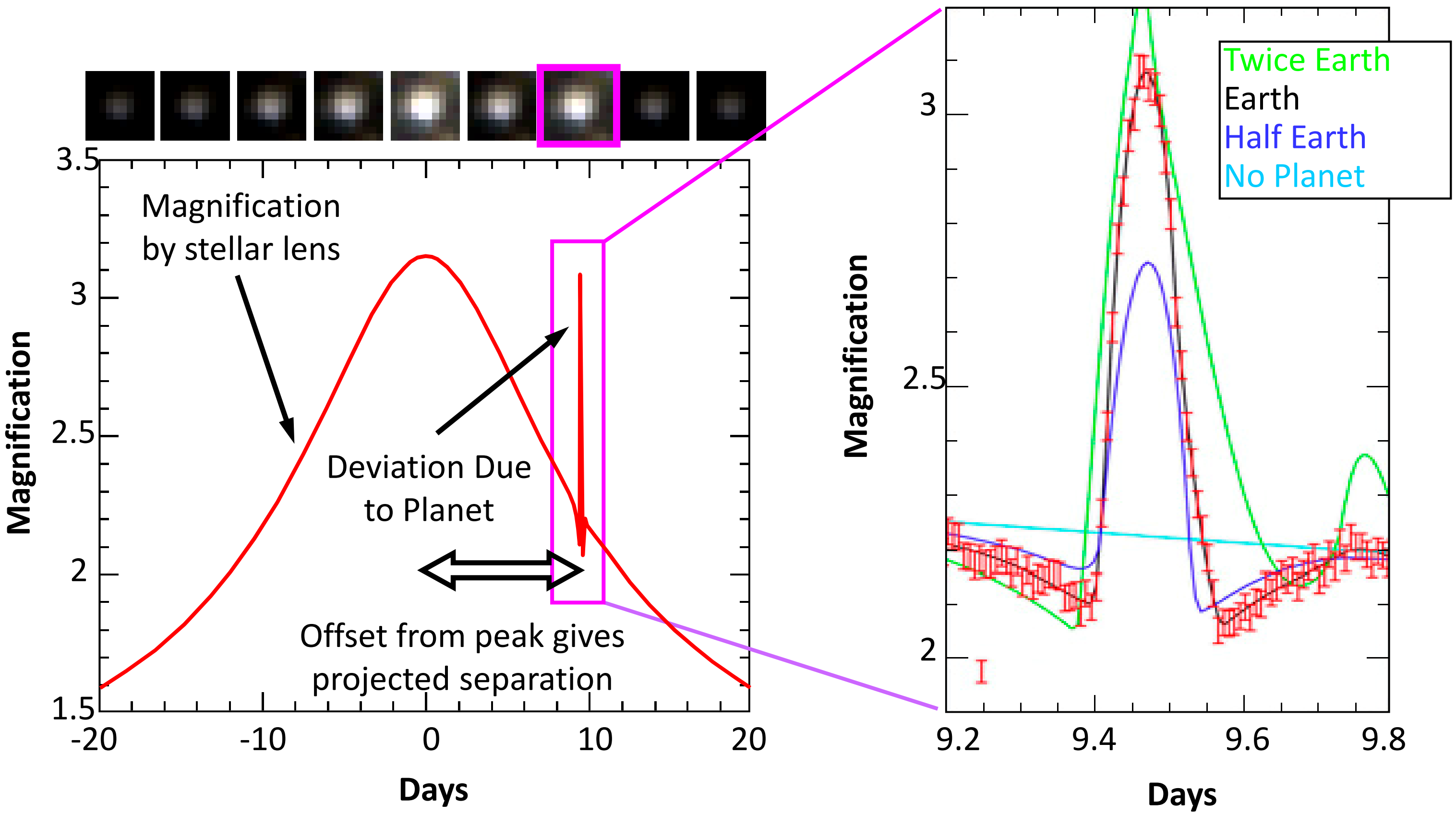
The field of microlensing event MACHO 96-BLG-5 as seen from CTIO and at MPF resolution.

MPF's high angular resolution is required to resolve the brightest main sequence stars for accurate photometry.

~1.5×10^{8} main-sequence stars will be observed every 15 minutes continuously for 9 months per year for the entire four-year mission.

Extraction of Exoplanet Signal

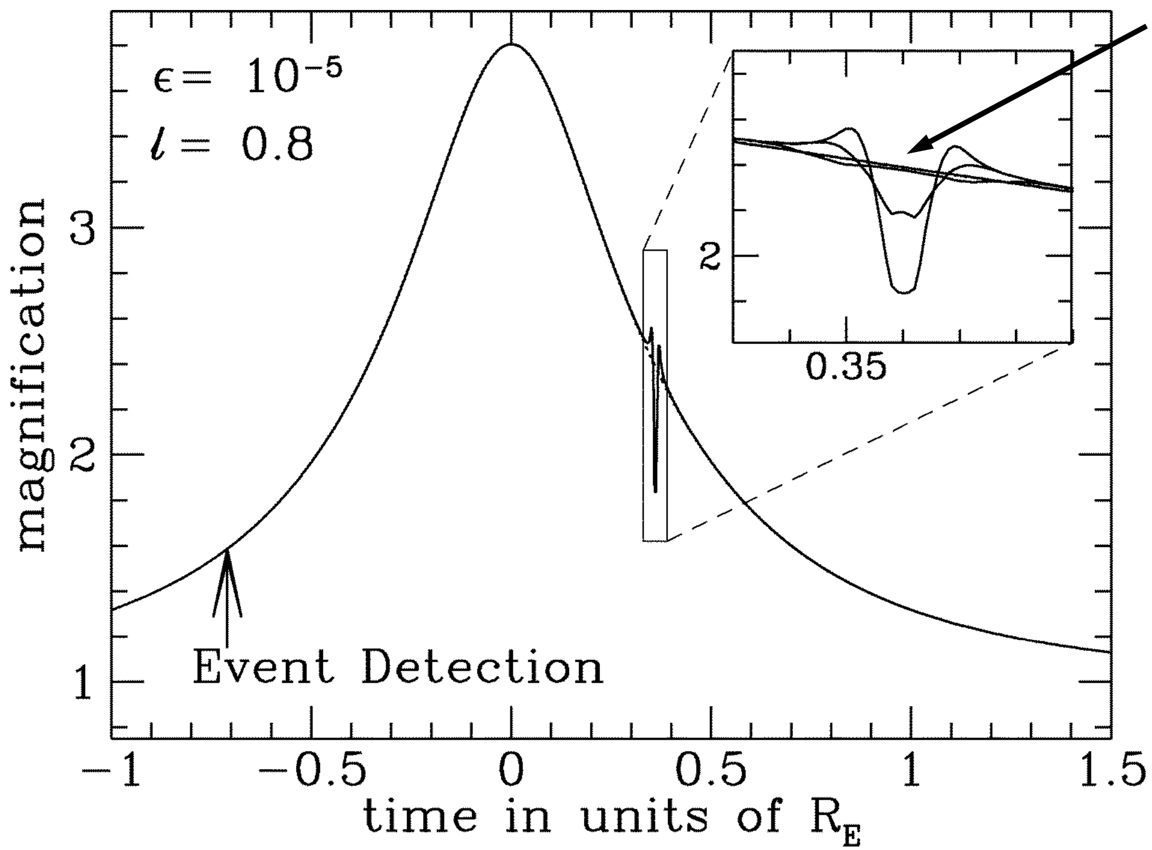
Time-series photometry is combined to uncover light curves of background source stars being lensed by foreground stars in the disk and bulge.



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.

Sensitivity to Earths Depends on Source Size

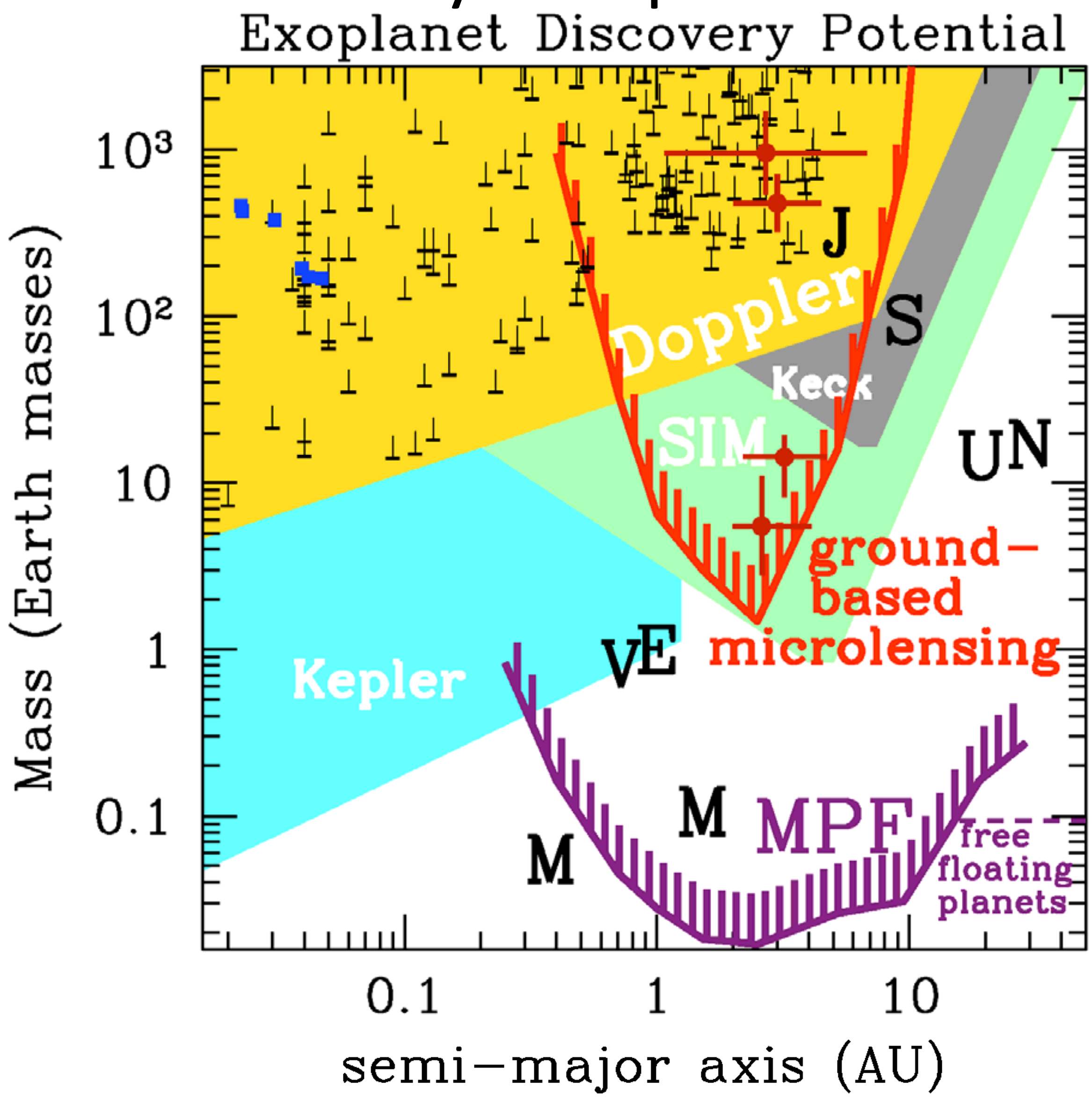


Earth mass planet signal is washed out for giant source stars

- If planetary Einstein Ring < source star disk: planetary microlensing effect is washed out (Bennett & Rhie 1996)
- For a typical bulge giant source star, the limiting mass is ~10 $M_\oplus$
- For a bulge, solar type main sequence star, the limiting mass is ~ 0.1 $M_\oplus$

Planet Detection Sensitivity Comparison

- Sensitivity to all Solar System-like planets
  - –Except for Mercury & Pluto
- most sensitive technique for a ≥ 1 AU
- Good sensitivity to “outer” habitable zone (Mars-like orbits) where detection by TPF is easiest
- Mass sensitivity is 1000 × better than v_{rad}
- Assumes $\Delta\chi^2 \geq 80$ detection threshold
- Can find moons and free planets



Updated from Bennett & Rhie (2002) ApJ 574, 985