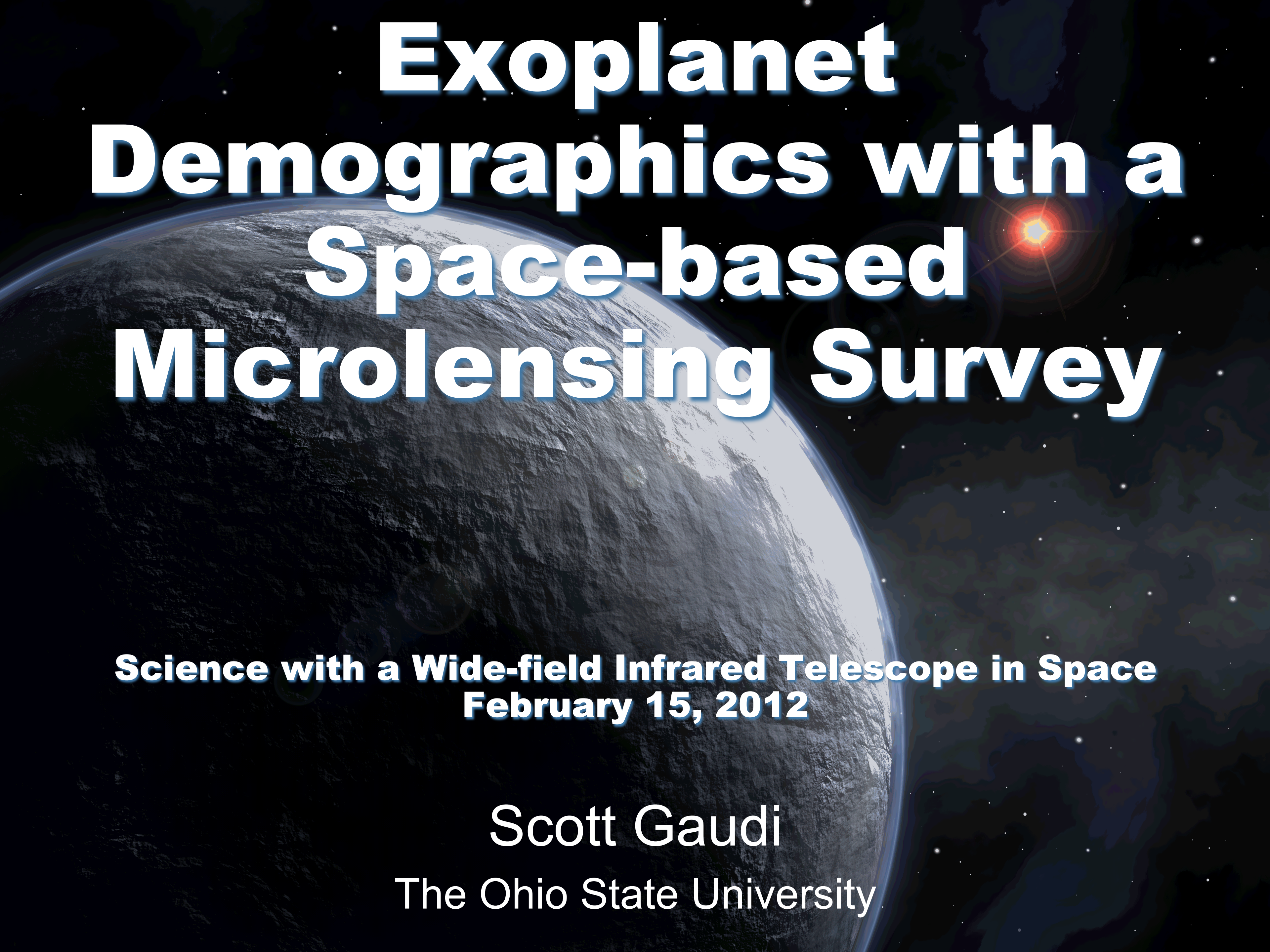
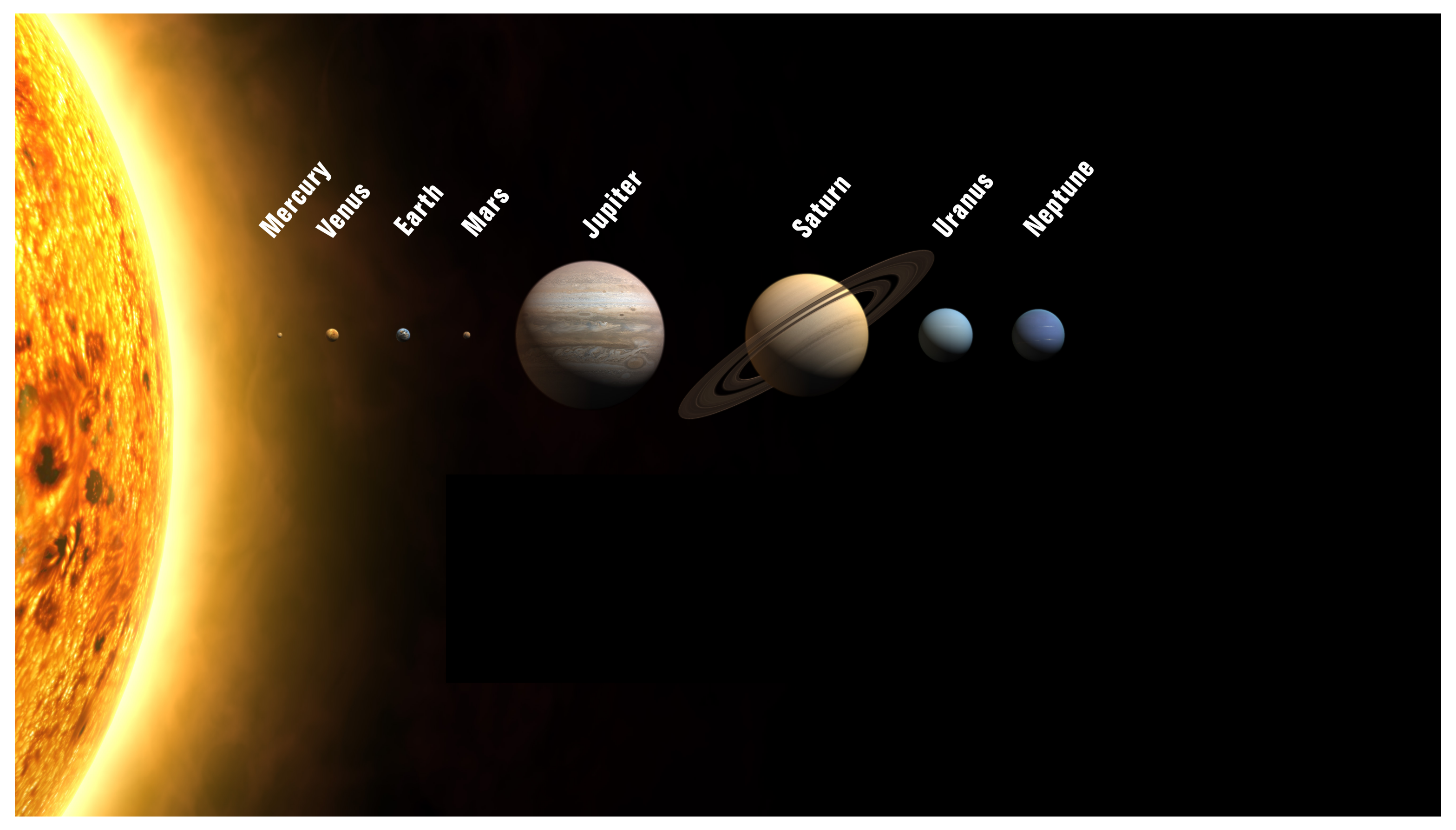


# Exoplanet Demographics with a Space-based Microlensing Survey

**Science with a Wide-field Infrared Telescope in Space**
**February 15, 2012**

Scott Gaudi
The Ohio State University

# Backstory. Before 1995...



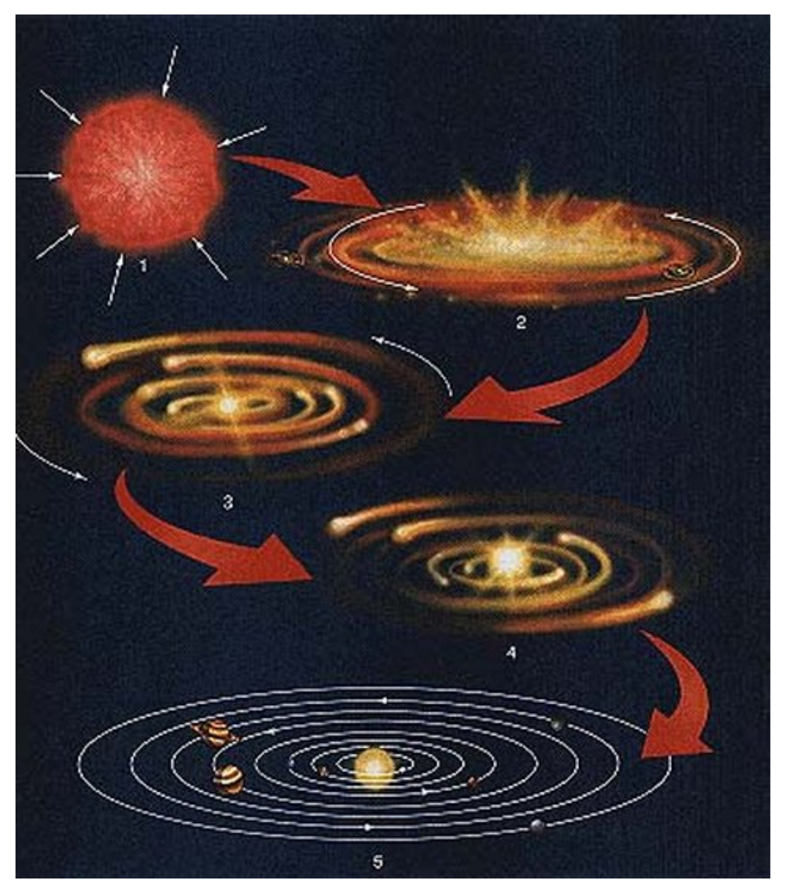
# Planet Formation.

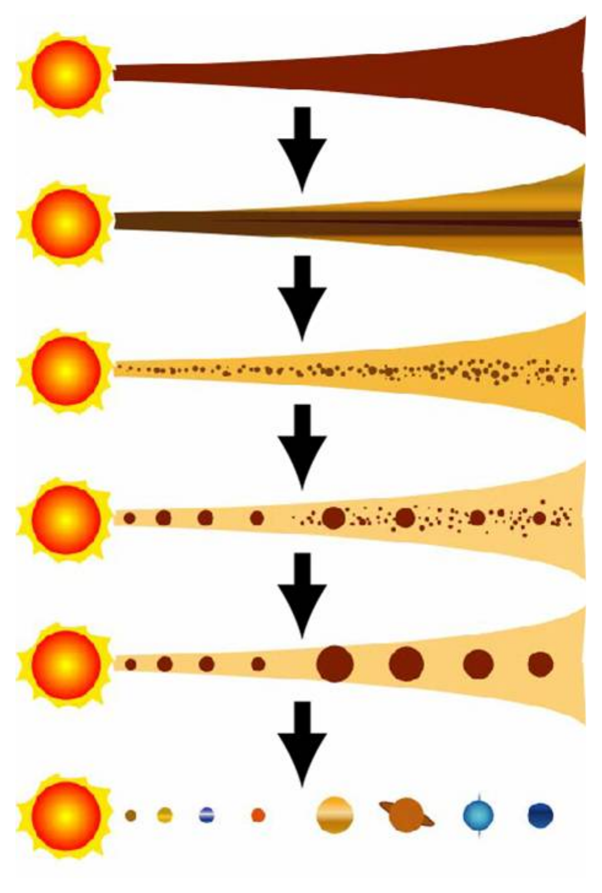
Must understand the physical processes by which micron-sized grains in protoplanetary disks grow by $10^{\sim 13\text{-}14}$ in size and $10^{\sim 38\text{-}41}$ in mass.

***Hard!***

# A Fairy Tale.

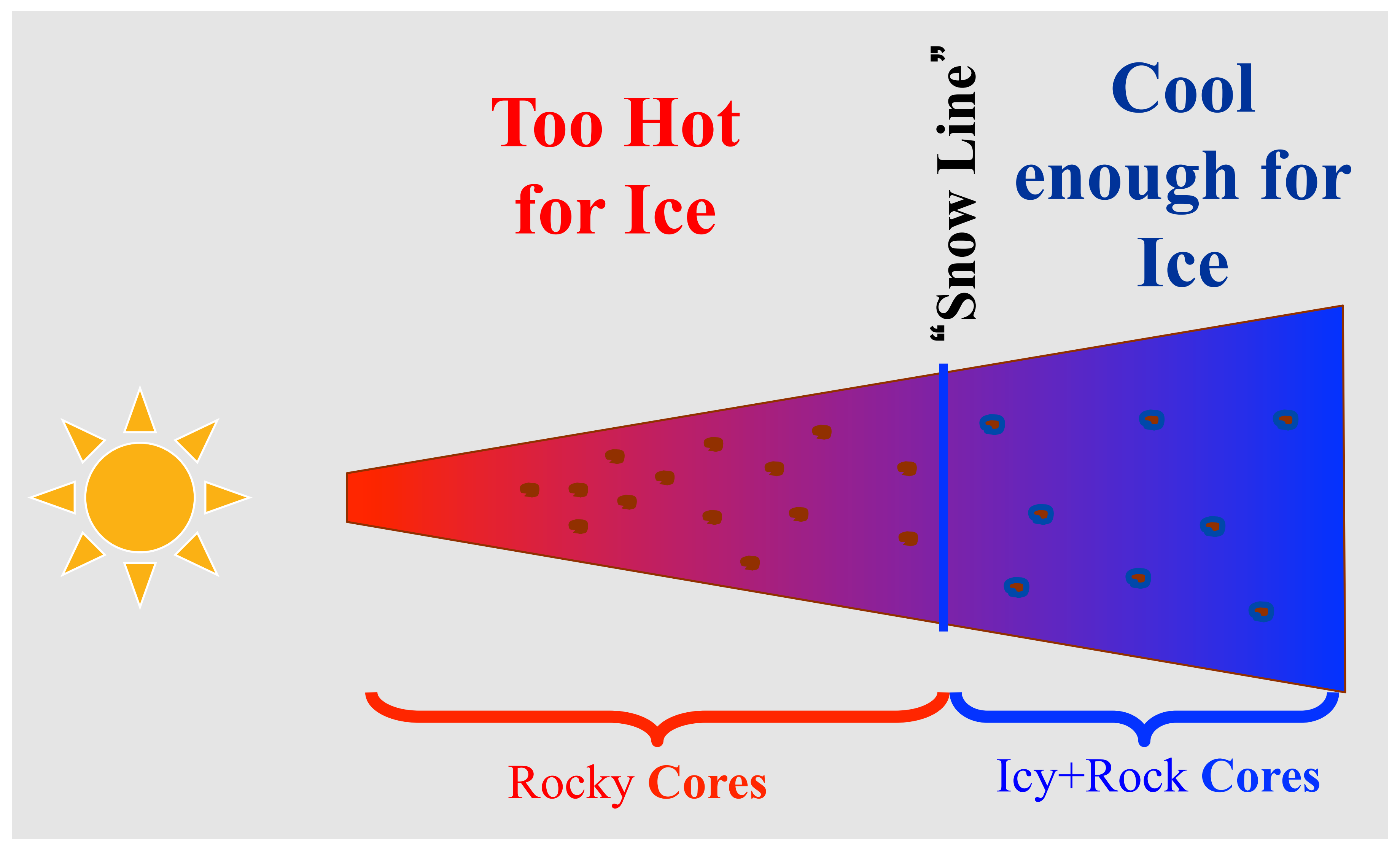
# Bottom-Up Planet Formation.



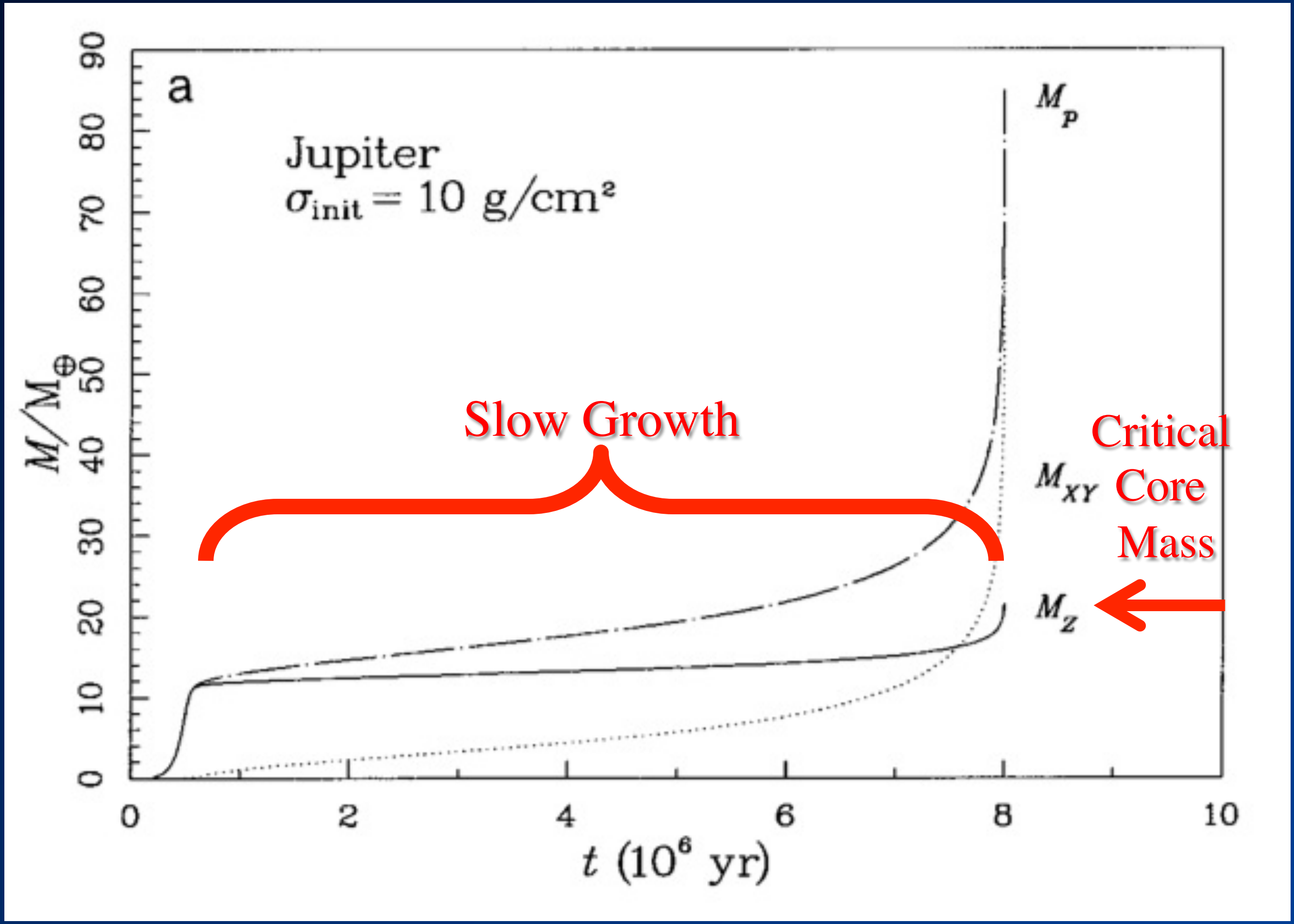


(e.g., Lissauer 1987; Ida & Lin 2004, 2005)

# The Snow Line.



# Core Accretion.

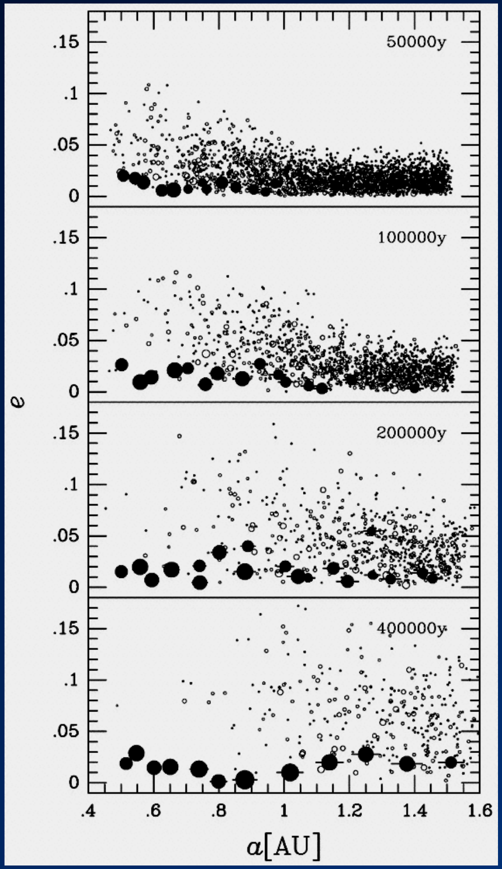


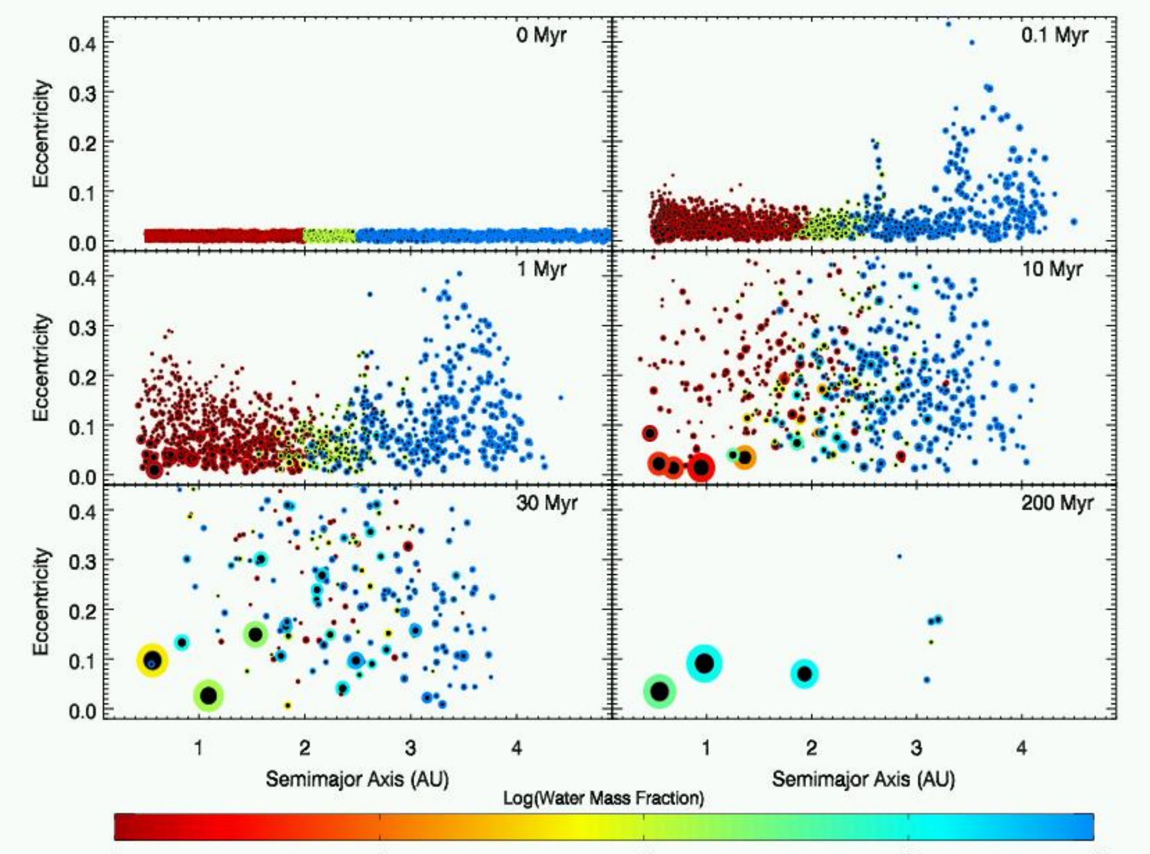
Slow Growth

Critical Core Mass

(Pollack et al. 1996)

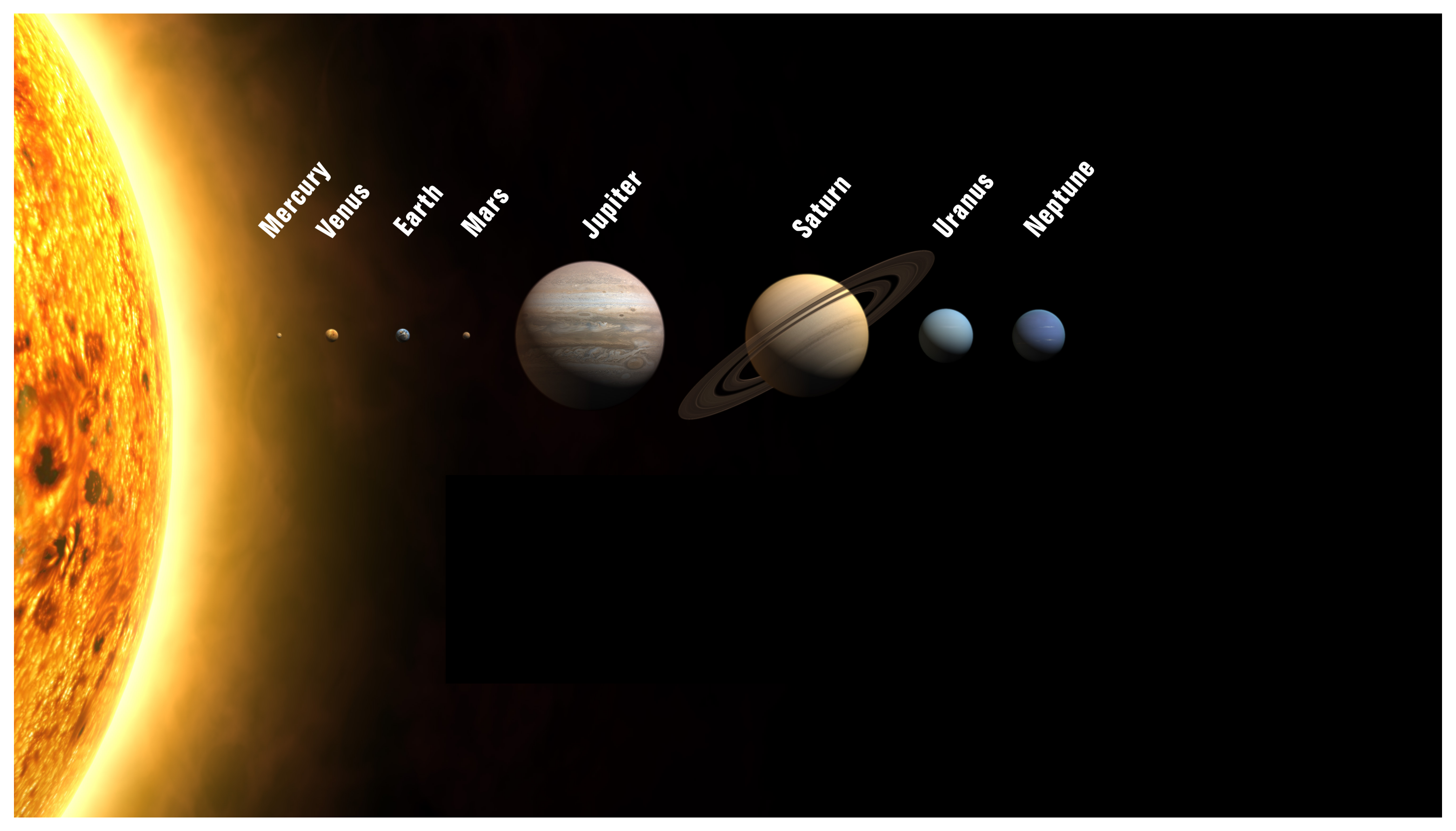
# Terrestrial Planet Formation.



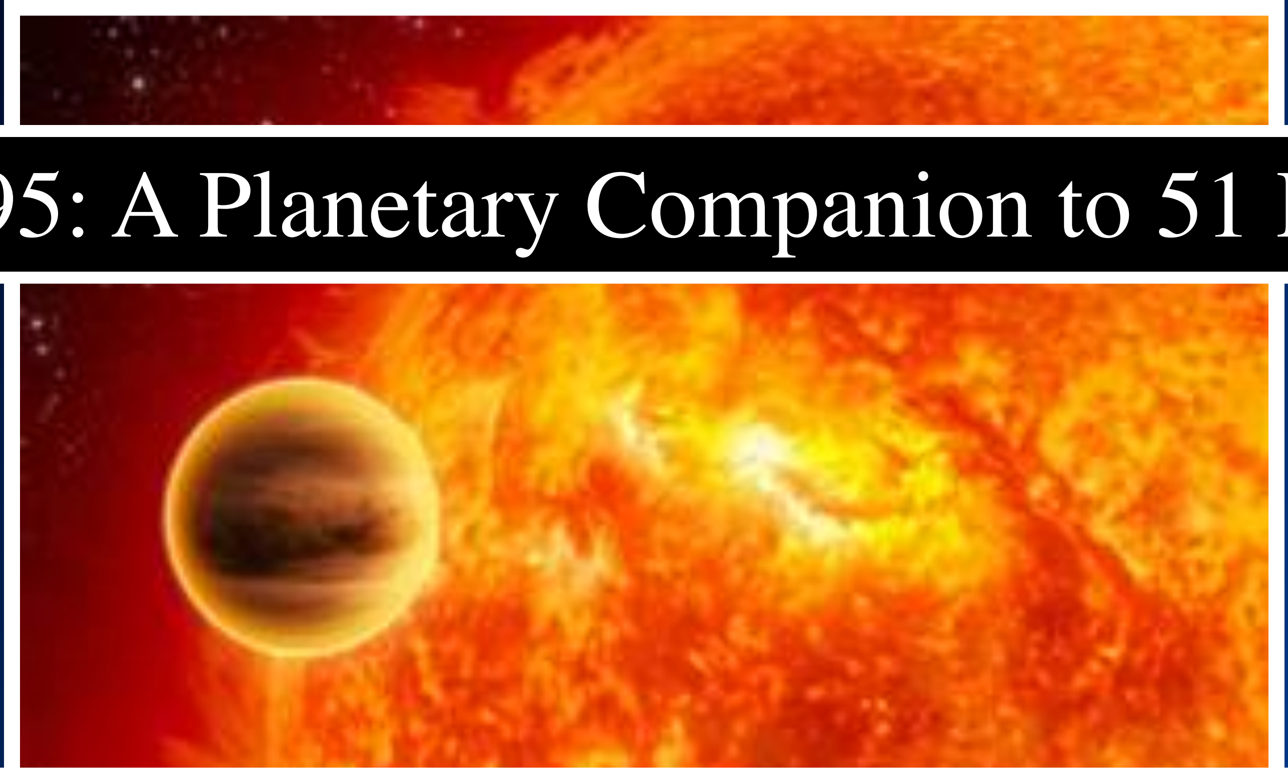


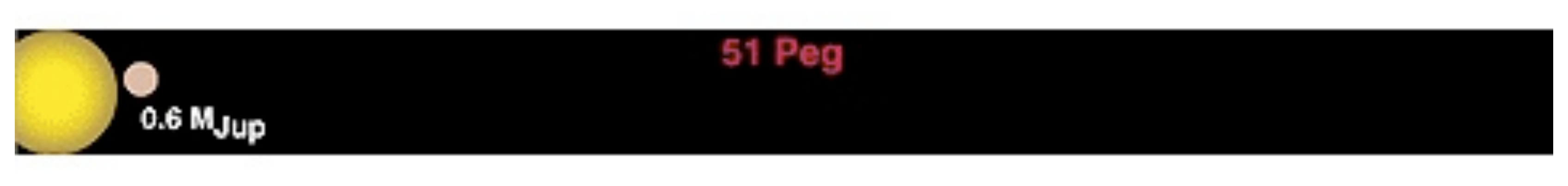
(Kokubo & Ida 2002, Raymond et al. 2006)

# Matched Data Well.



# 1995: A Planetary Companion to 51 Peg





(Mayor & Queloz 1995)

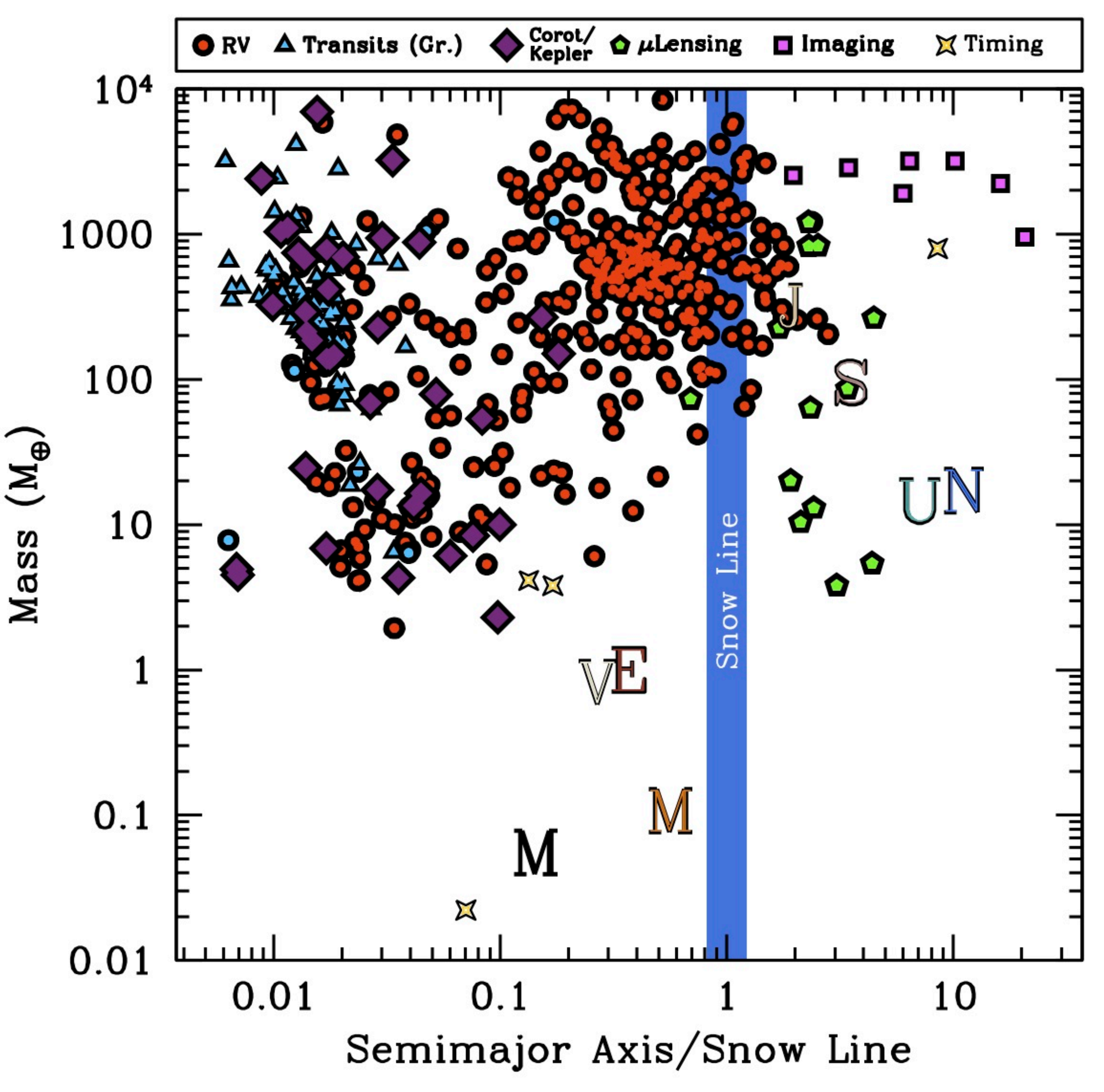
# Planet formation is *really* hard!

Additional physics, e.g.,

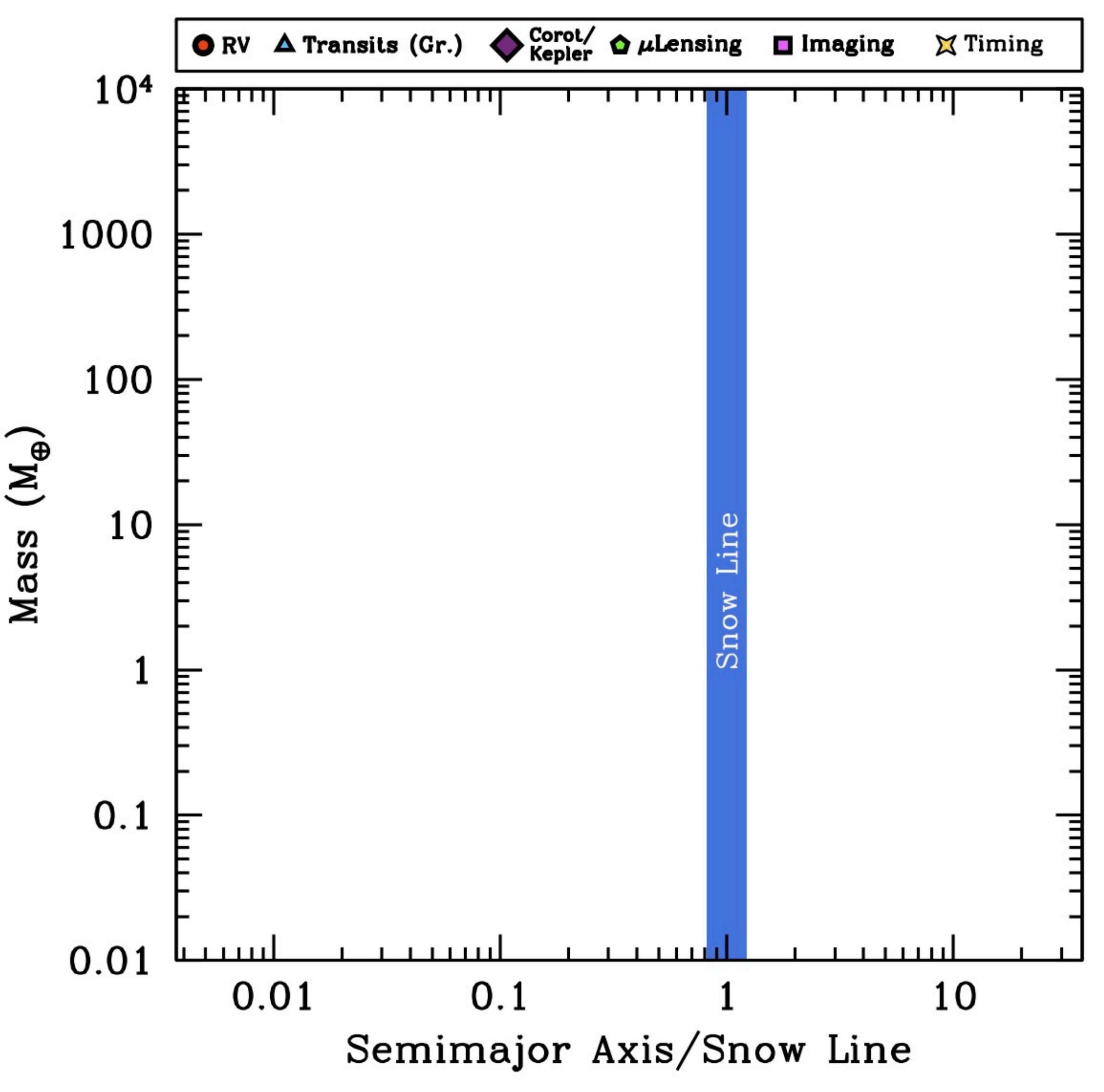
- Migration
- Influence of host star mass, metallicity
- Dynamical interactions
- Tides
- Disk properties
- Other models!  (e.g., disk instability)
- Etc.

# Meanwhile…

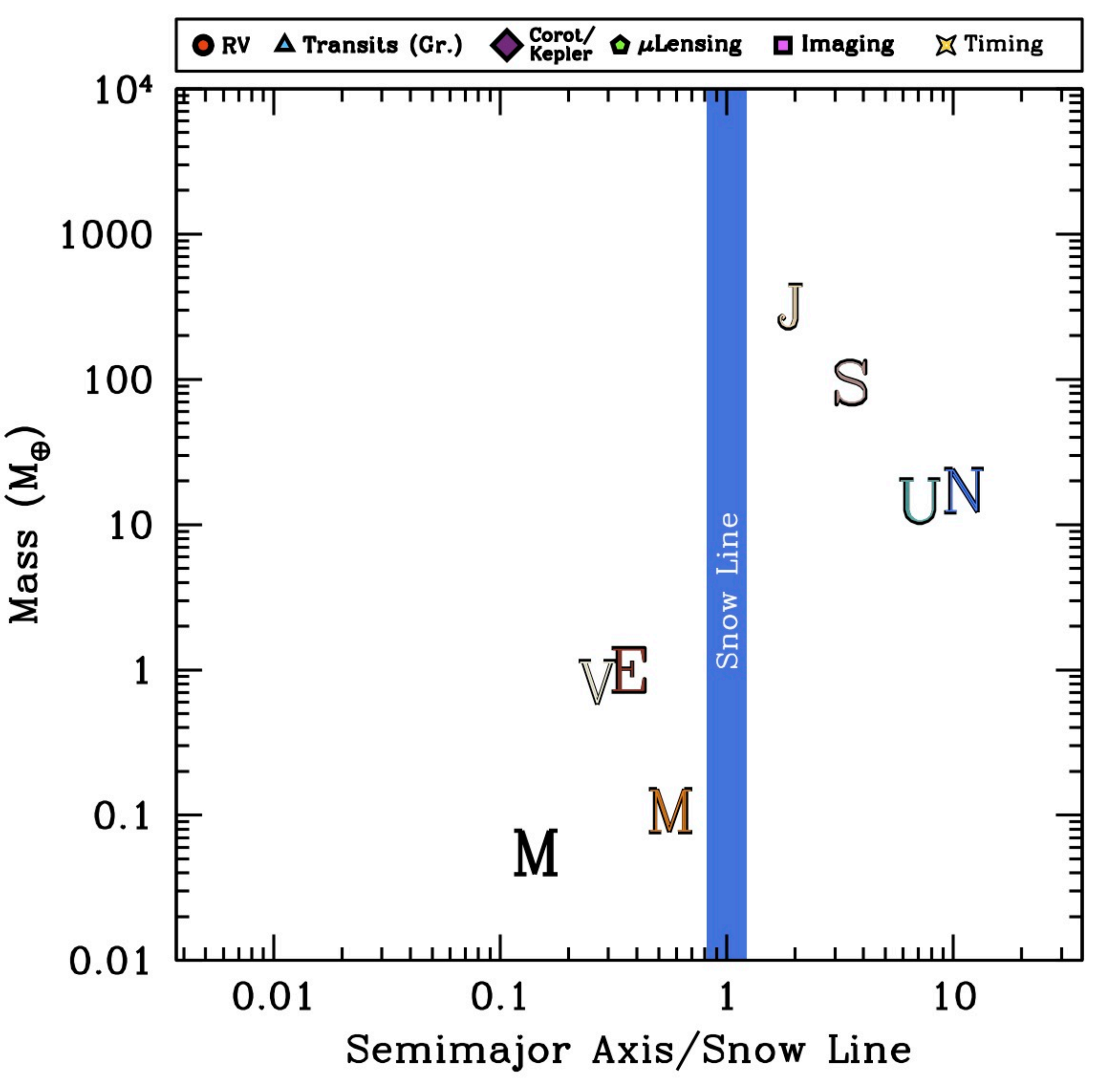
# Strange New Worlds.



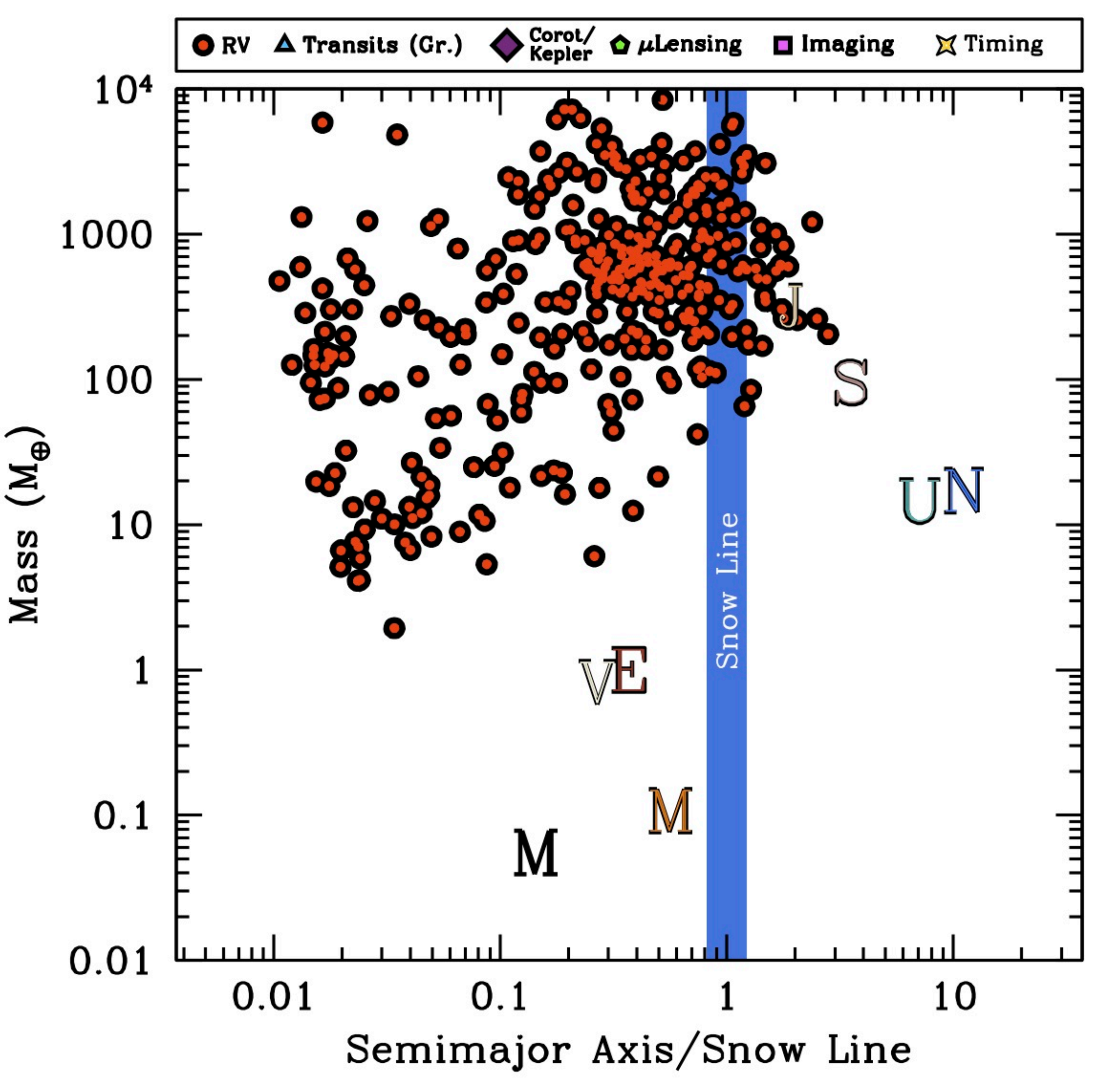
# Strange New Worlds.



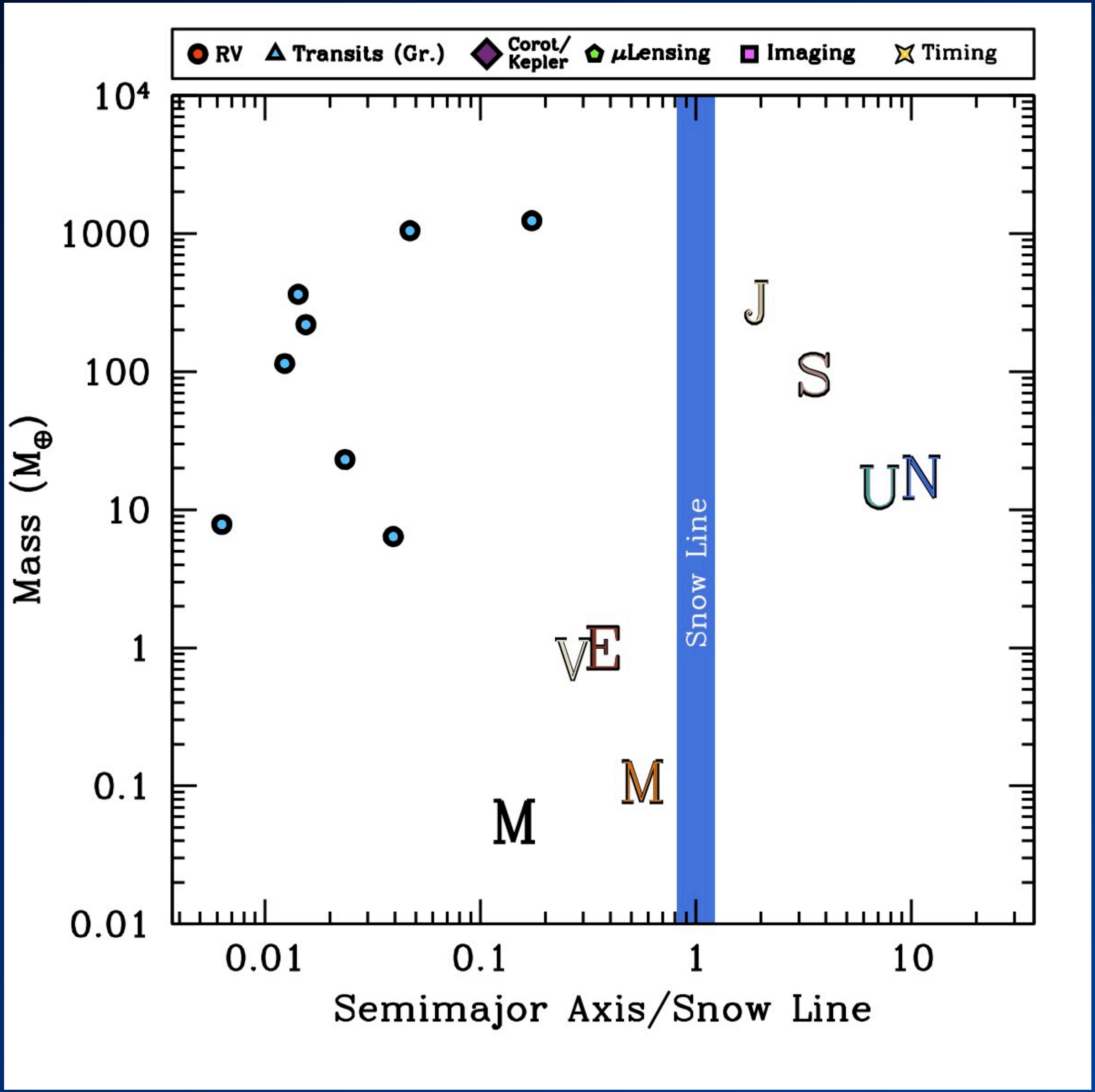
# Strange New Worlds.



# Strange New Worlds.



# Strange New Worlds.



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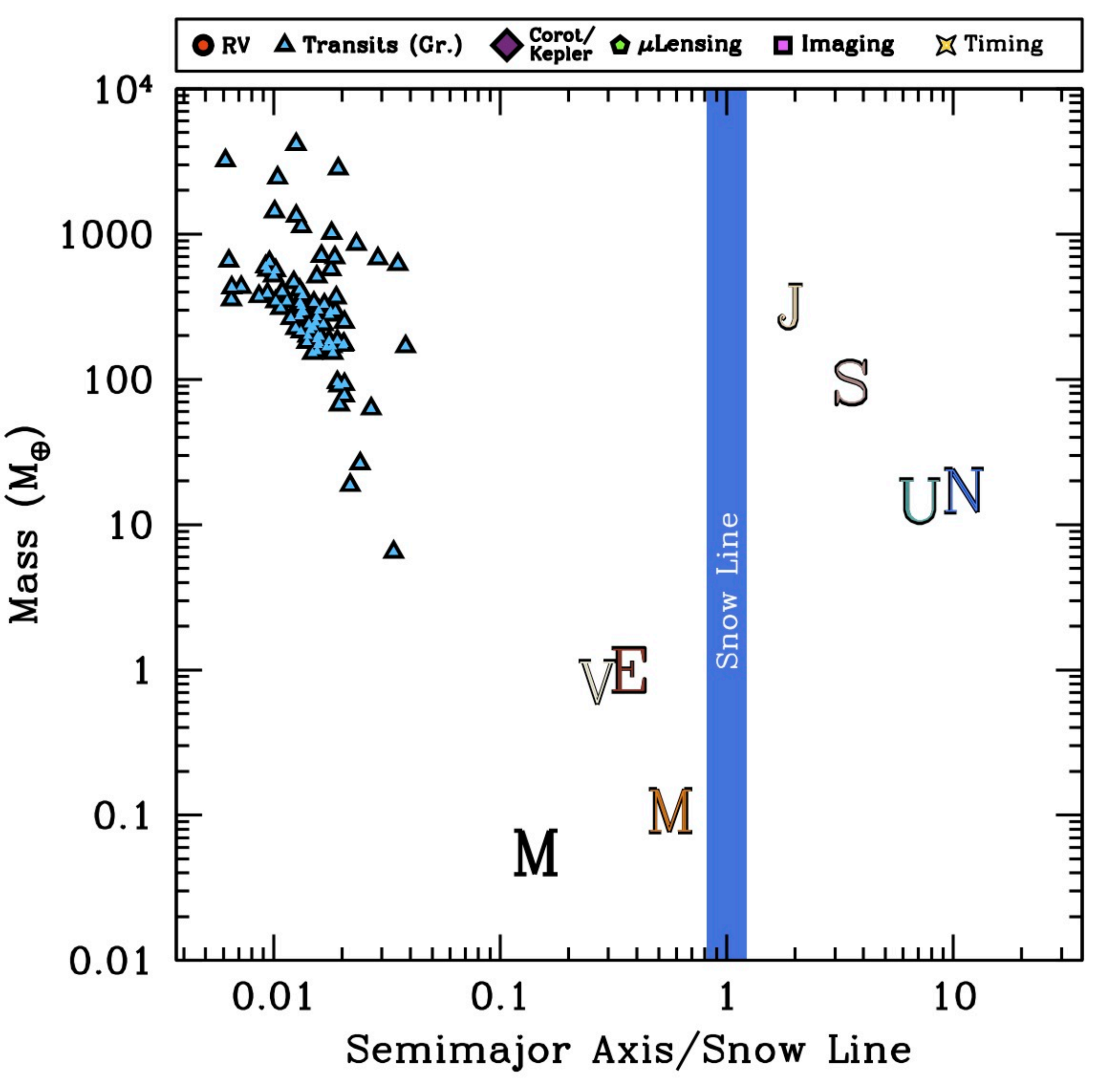

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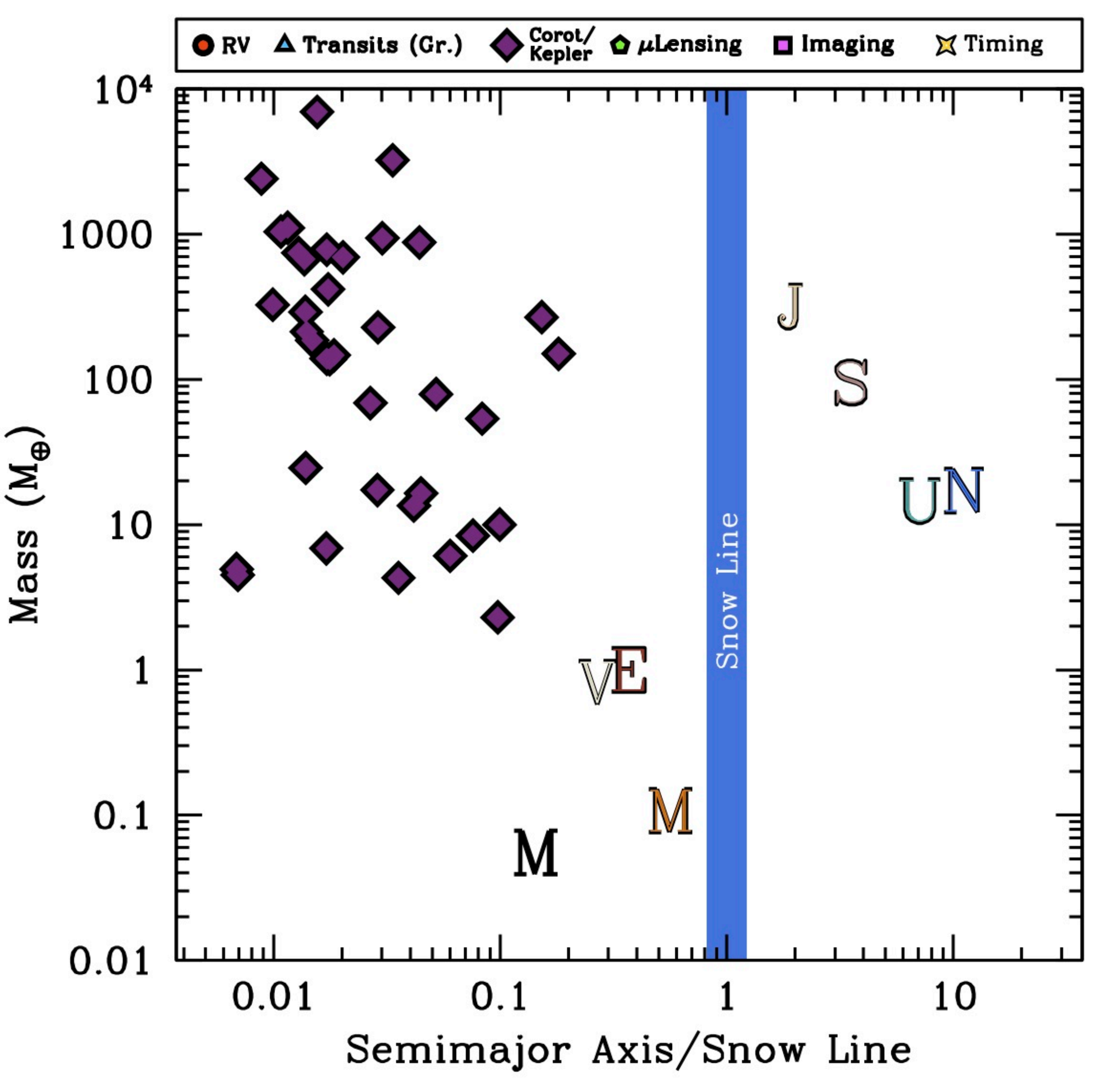

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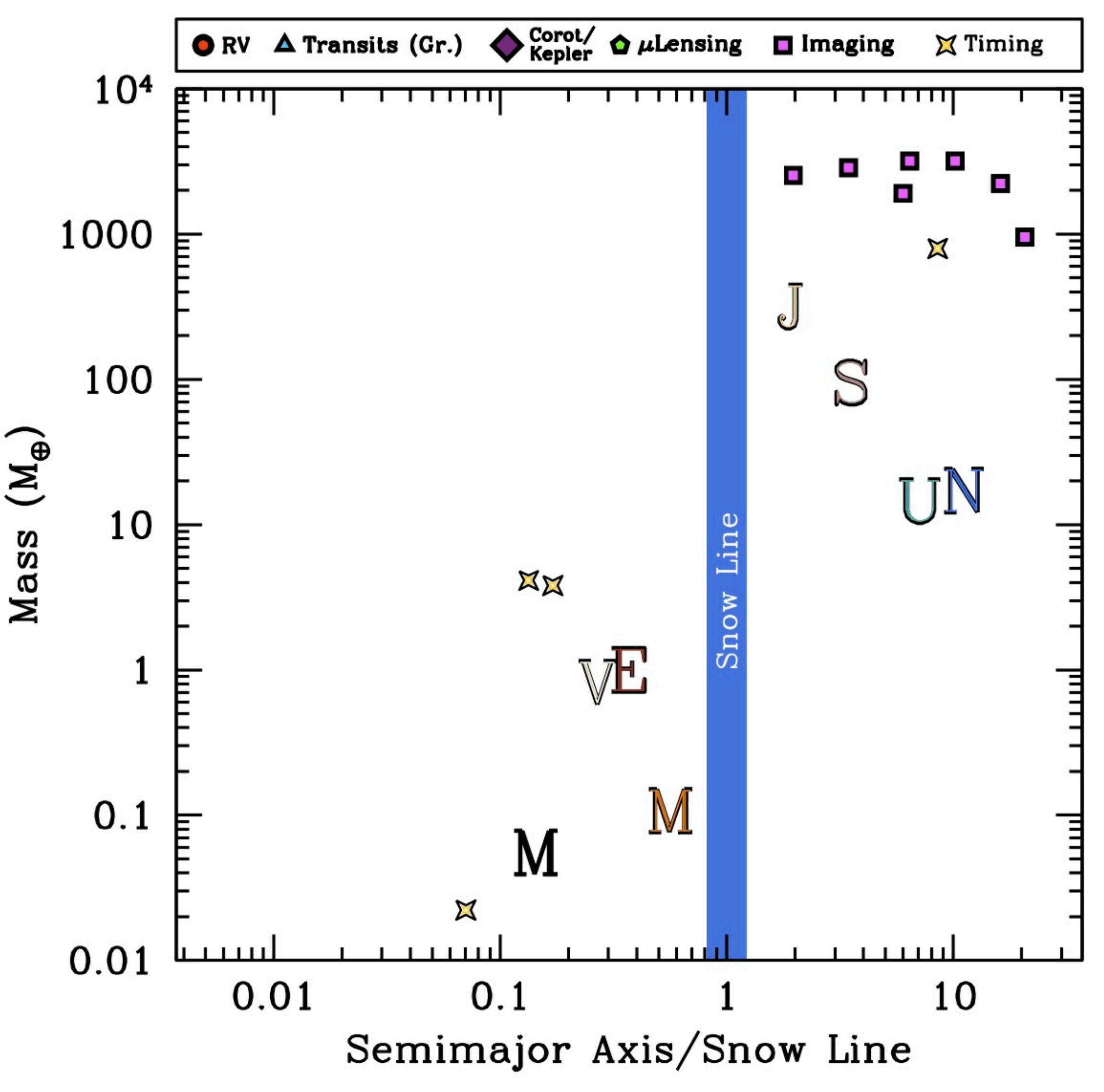
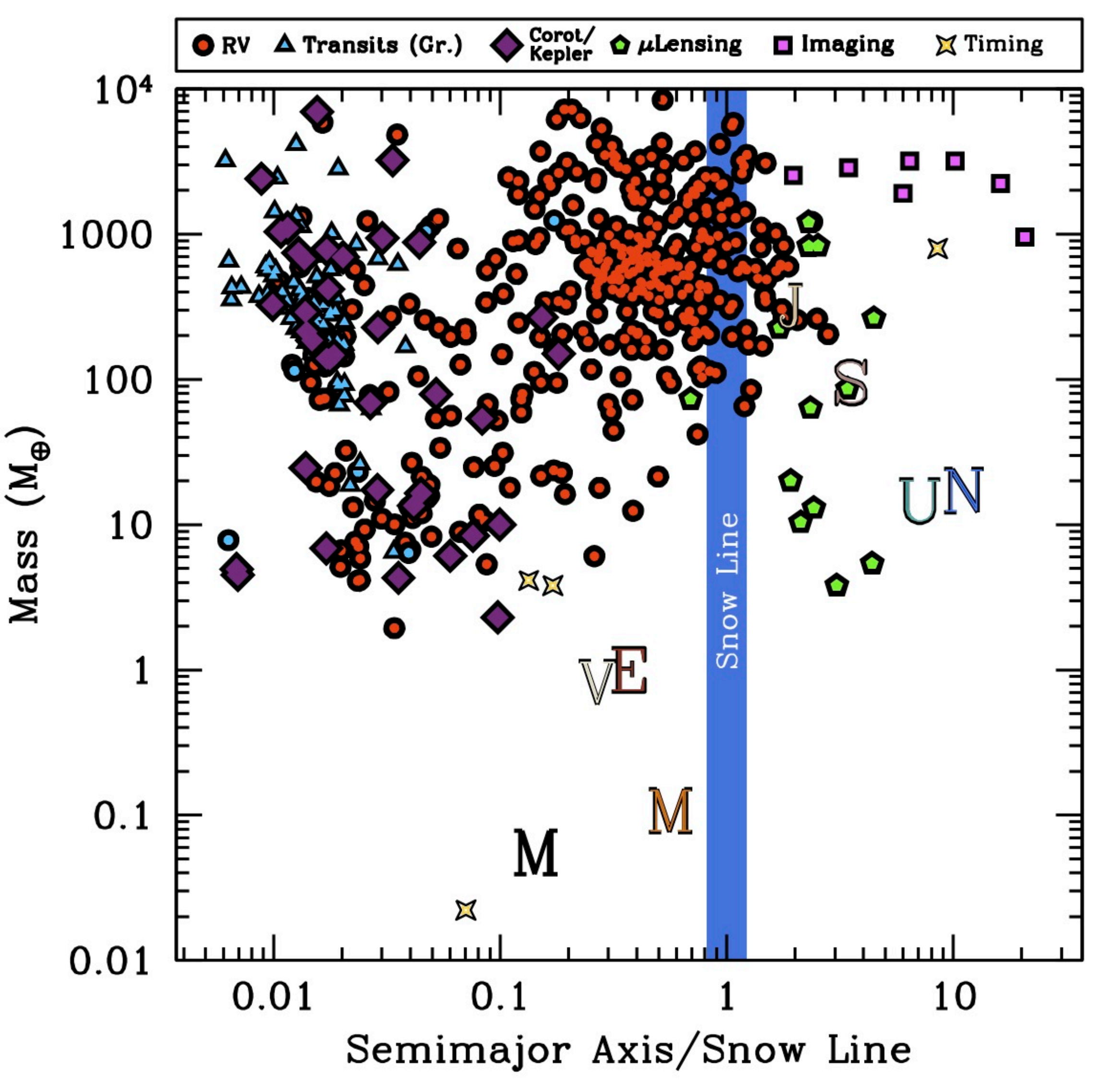
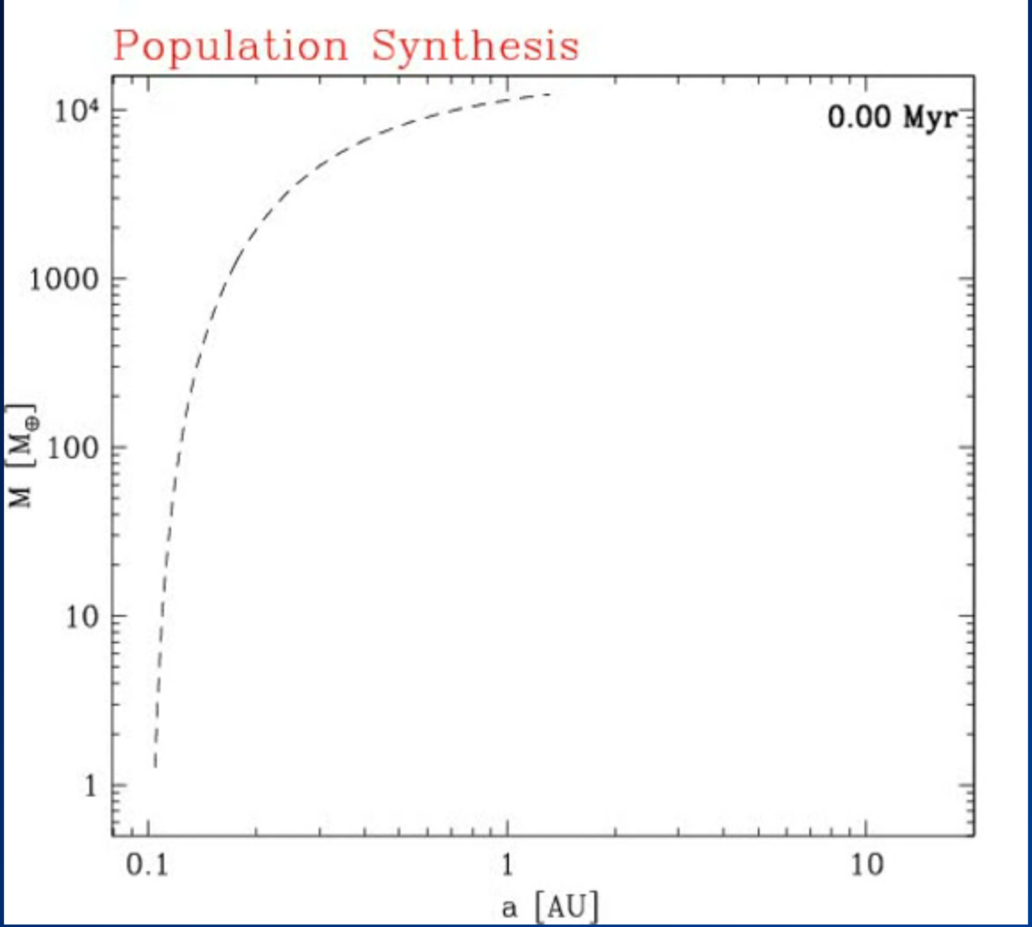


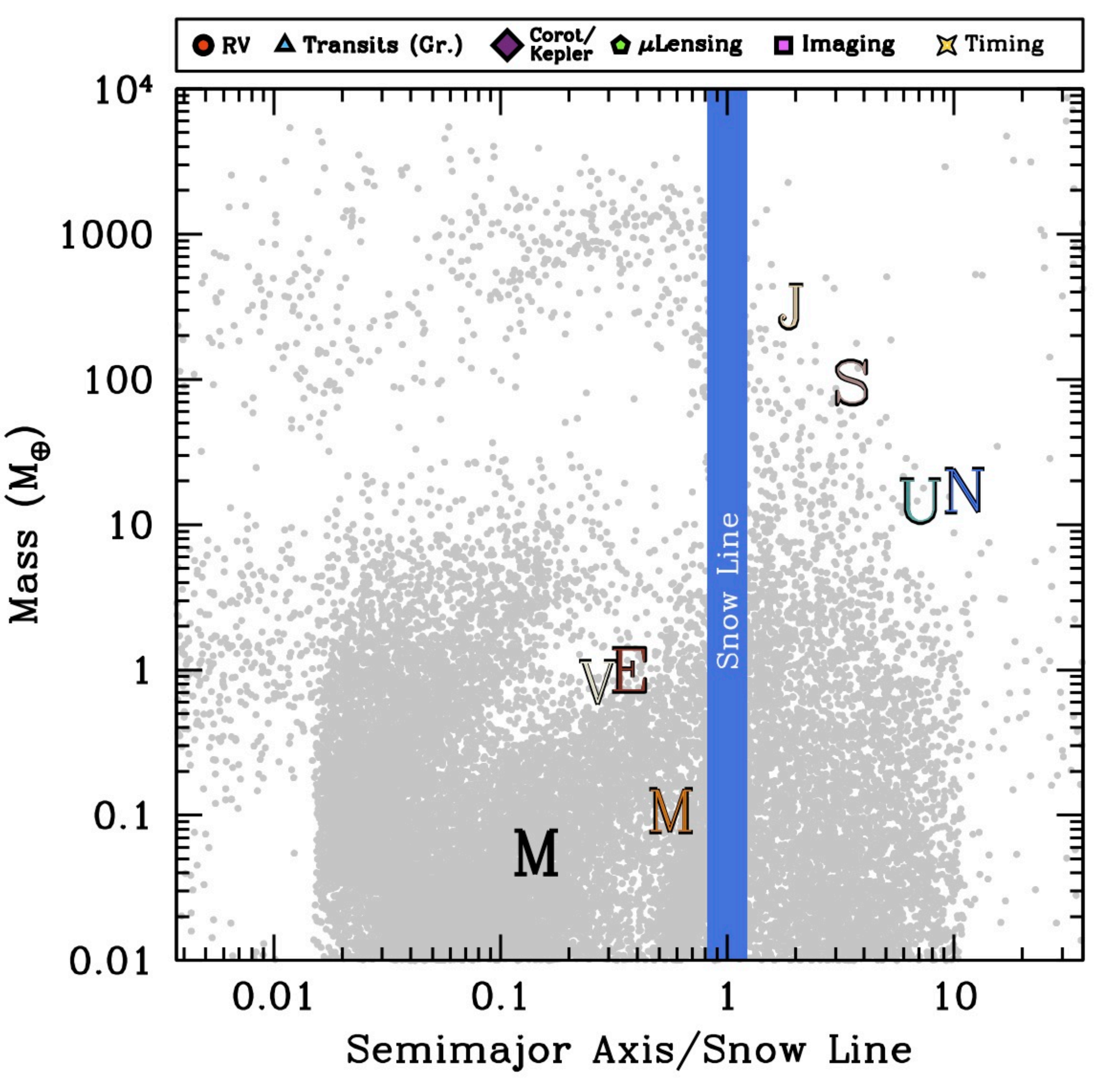
# Strange New Worlds.



# Semi-analytic planet formation.



(Mordasani et al. 2009)



● RV
▲ Transits (Gr.)
◆ Corot/ Kepler
⬟ μLensing
■ Imaging
✦ Timing
Mass ($M_\oplus$)
$10^4$
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
U
N
V
E
M
M

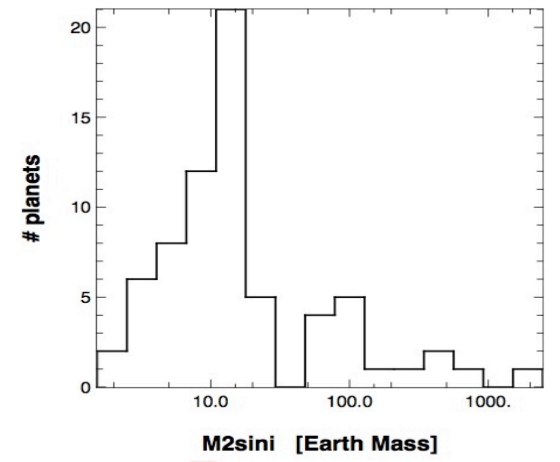
(Ida & Lin)

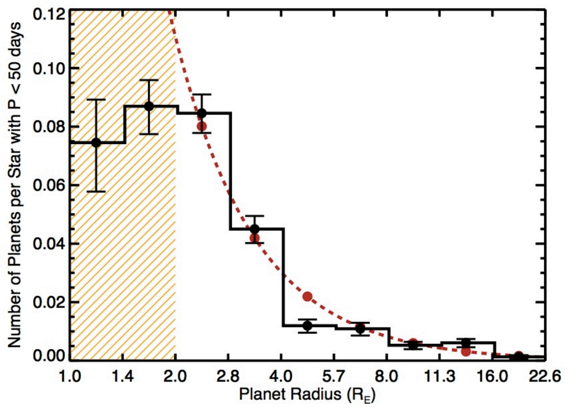
# Testing and Refining Theories.

- Physical processes at work during planet formation and evolution are imprinted in planet distributions.
- Examples:
  - Planet “desert”
  - Paucity of giant planets around low-mass stars
  - Free-floating planets
- The plan: *measure these distribution functions as accurately as possible over as broad a range of planet and host properties as possible.* (In other words, determine the **demographics** of exoplanets.)

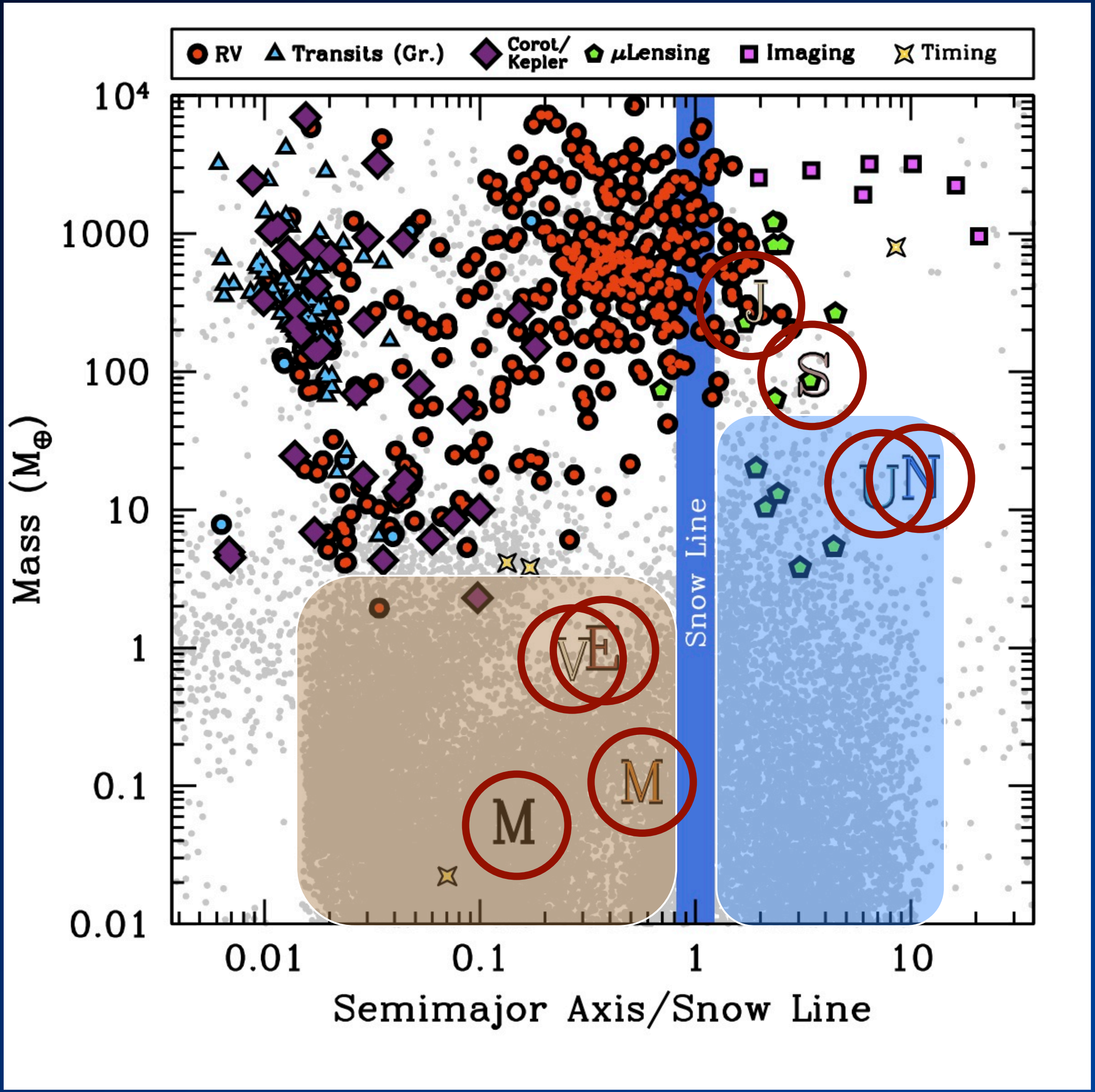
# Results from various methods.

- Radial velocity surveys, transits (*Kepler*), direct imaging, microlensing.
- Low-mass planets are much more common than high-mass planets
- Giant planet abundance scales with host star mass and metallicity.
- Almost all results are for planets interior to the snow line, or relatively massive planets.





(Howard et al. 2012, Mayor et al. 2012)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Snow Line
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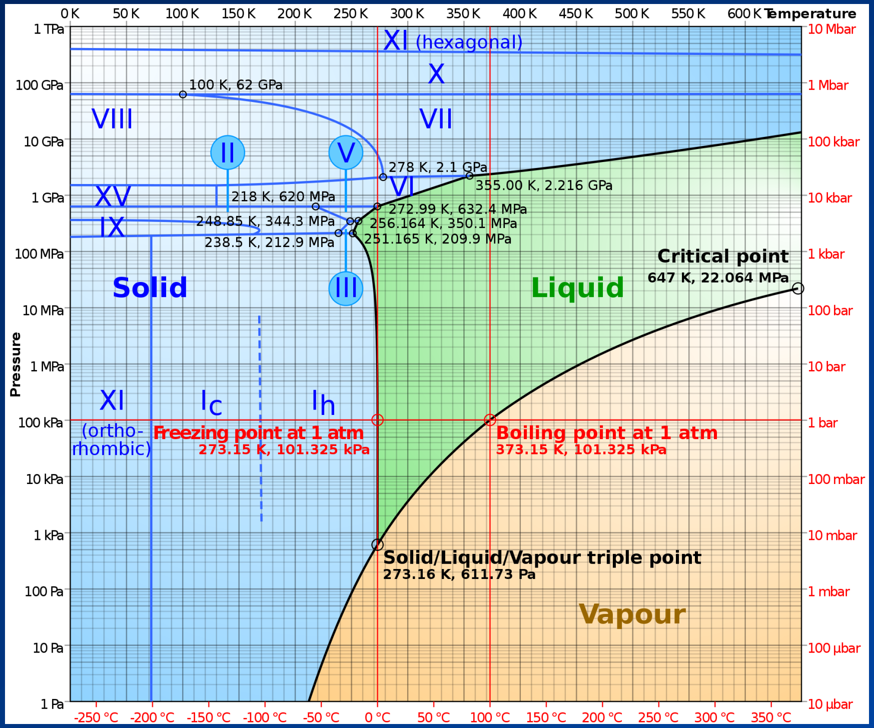
# Understanding Habitability.

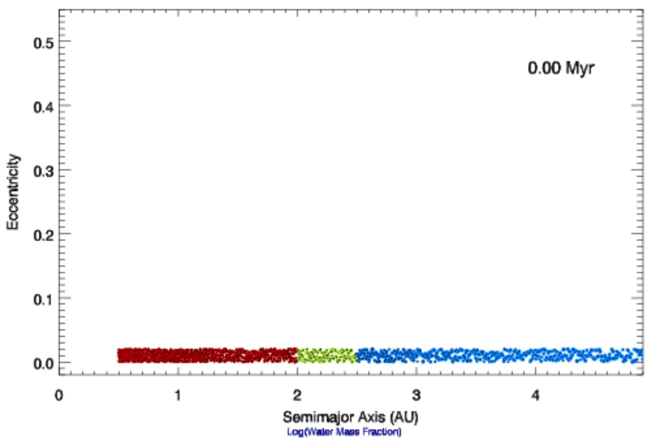
# Water, water, everywhere.

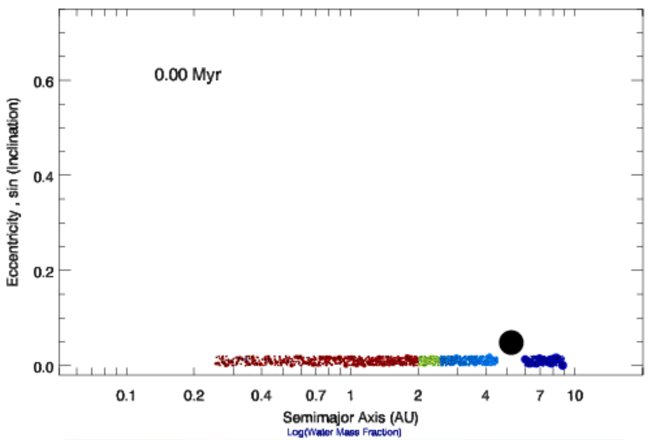
- For *in situ* formation, material that accreted to form rocky planets in the habitable zone was likely dry.
- Water was likely delivered from the outer solar system.



# Outer and Inner Regions Coupled.

- Giant planets likely formed first.
- Presence (or not) and properties of outer gas giants can effect
  - Terrestrial planet formation
  - Water delivery
- Migration of gas giants through terrestrial can result in small planets in the habitable zone.

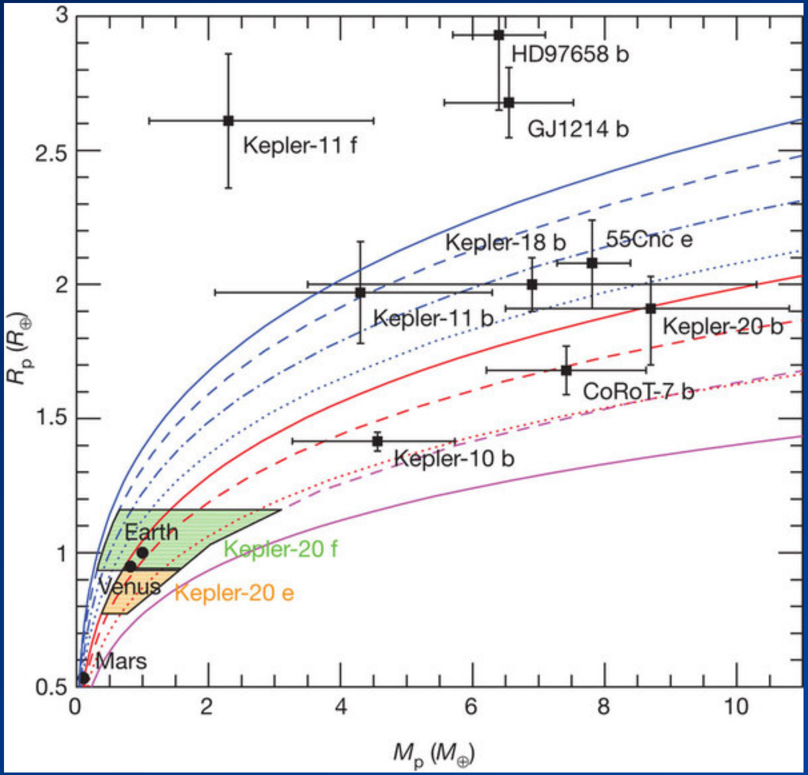




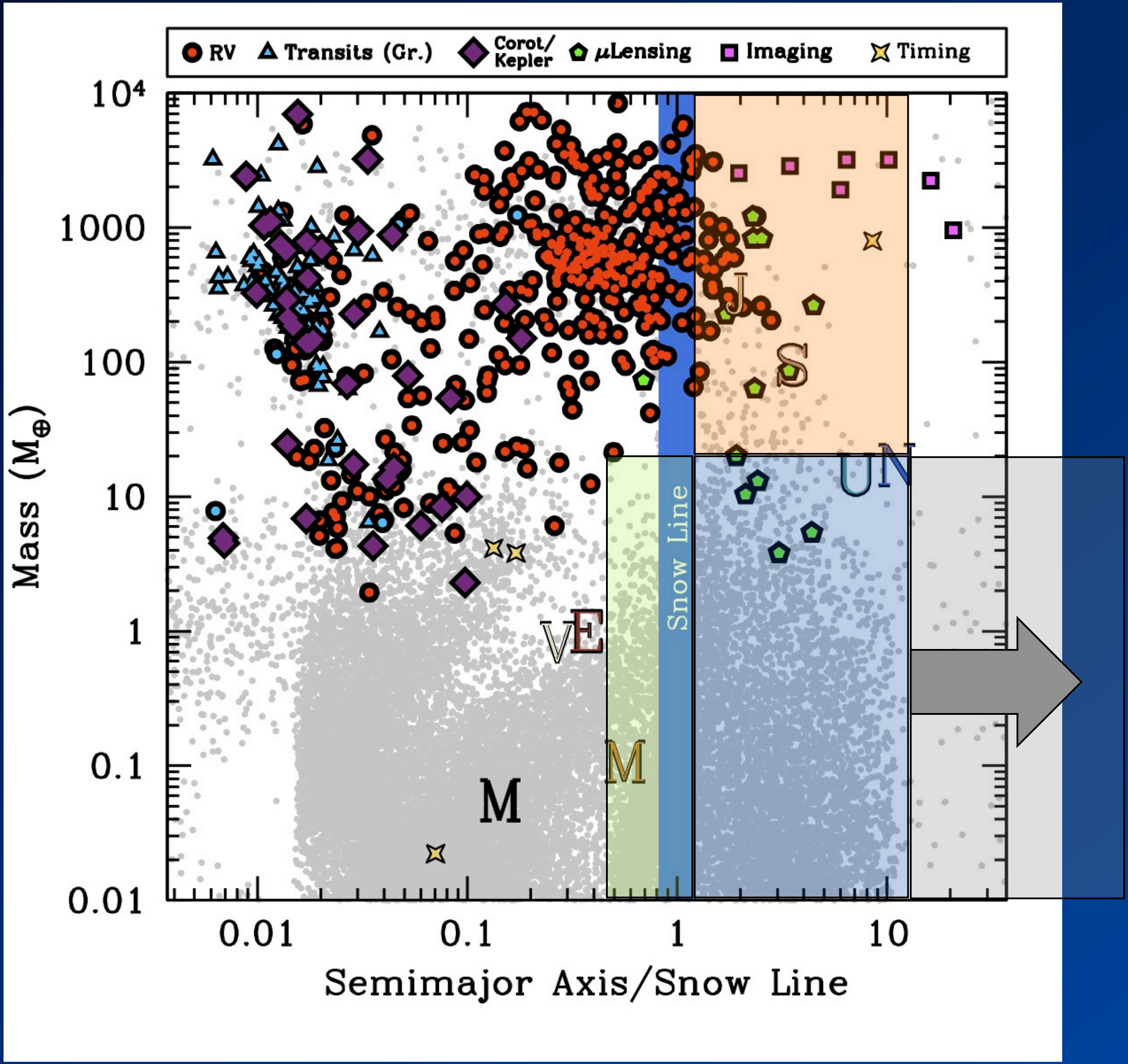
(Raymond et al. 2006, Mandell et al. 2007)

# Are small planets in the habitable zone, um, habitable?!?

- Migration can bring volatile-rich planets into habitable zone (Kuchner 2003).
- Water worlds, or rocky/icy bodies with very thick atmospheres.
- May or may not be habitable.
- Must disentangle the “natives” from the “immigrants”.
- Radii may not be sufficient.



(Fressin et al. 2012)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Semimajor Axis/Snow Line
Snow Line
J
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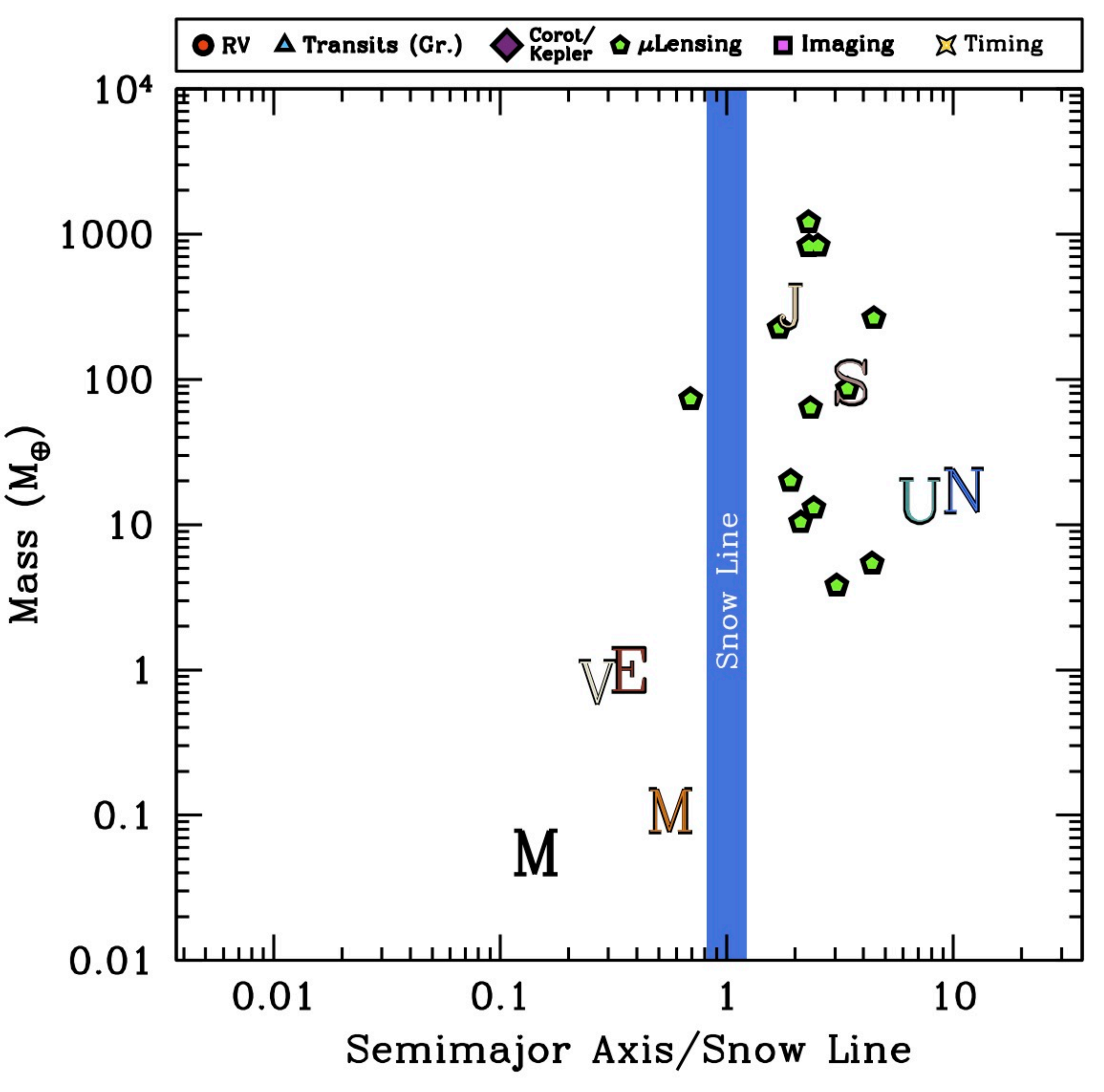
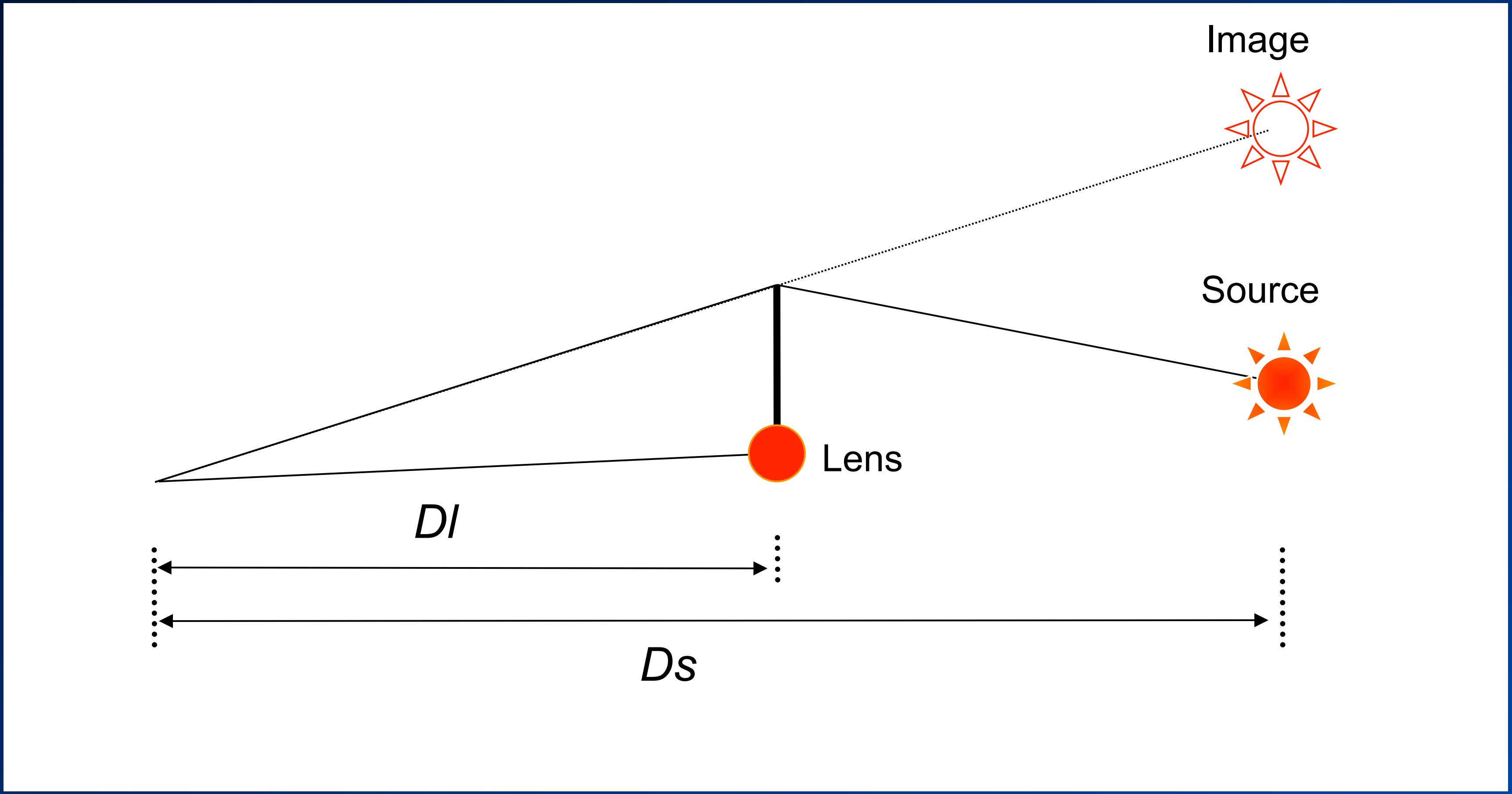
M

# To the snow line... and beyond!



# Microlensing.

# Microlensing Basics.



# Rings and Images.

$$\theta_{\mathrm{E}} = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_{OL}D_{OS}}} \sim 700\mu\mathrm{as}\left(\frac{M}{0.5M_{\odot}}\right)^{1/2}$$

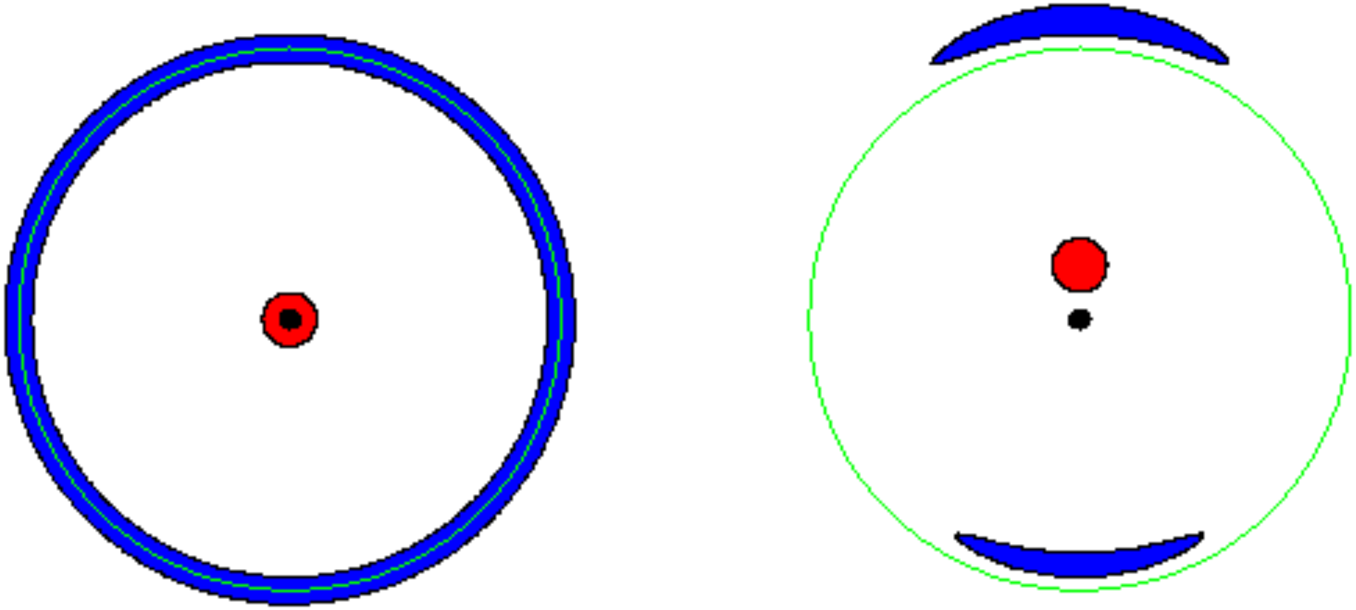
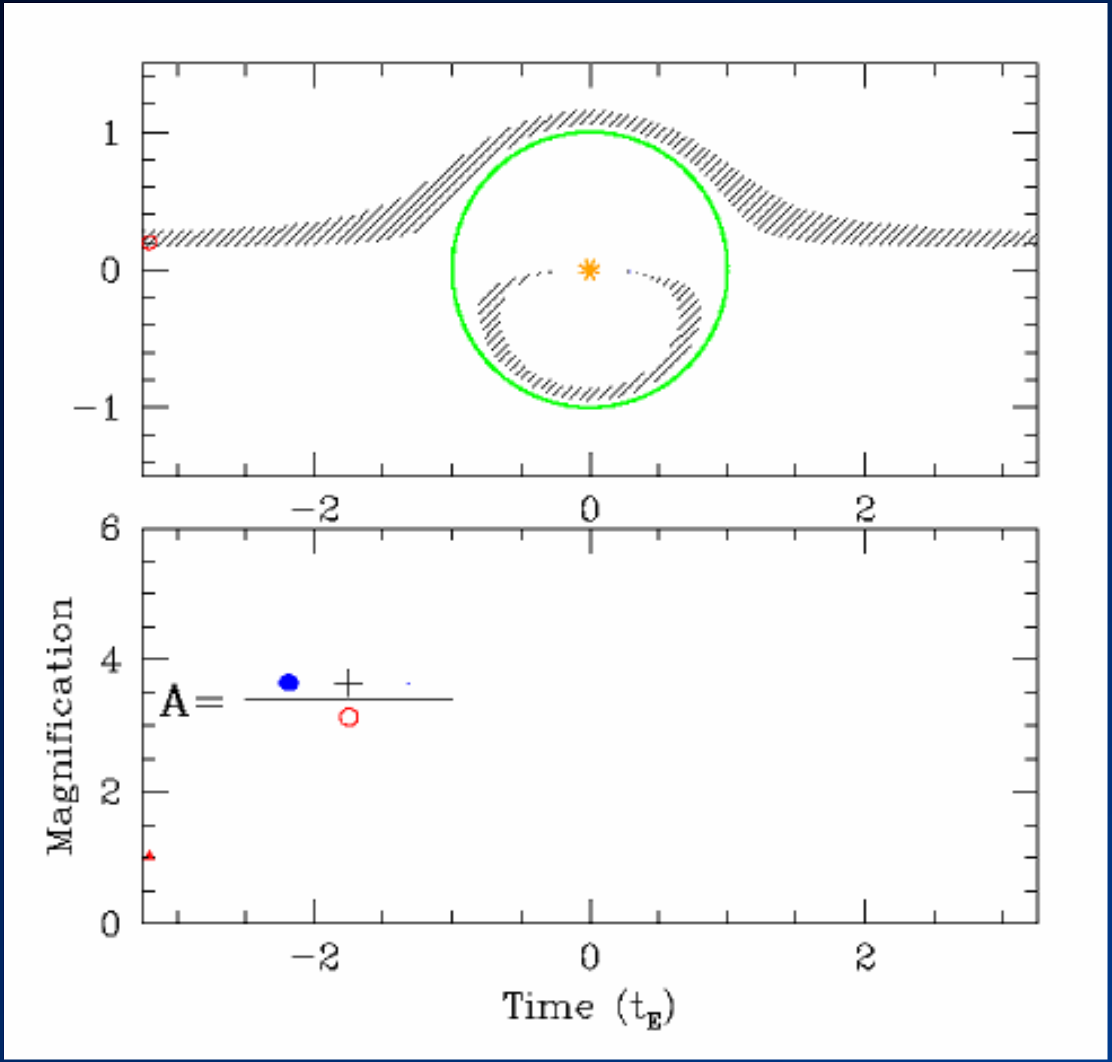


Image Separation $\approx 2\theta_{\mathrm{E}}$

Magnification $= \dfrac{\text{Area of Image}}{\text{Area of Source}}$

# Microlensing Events.

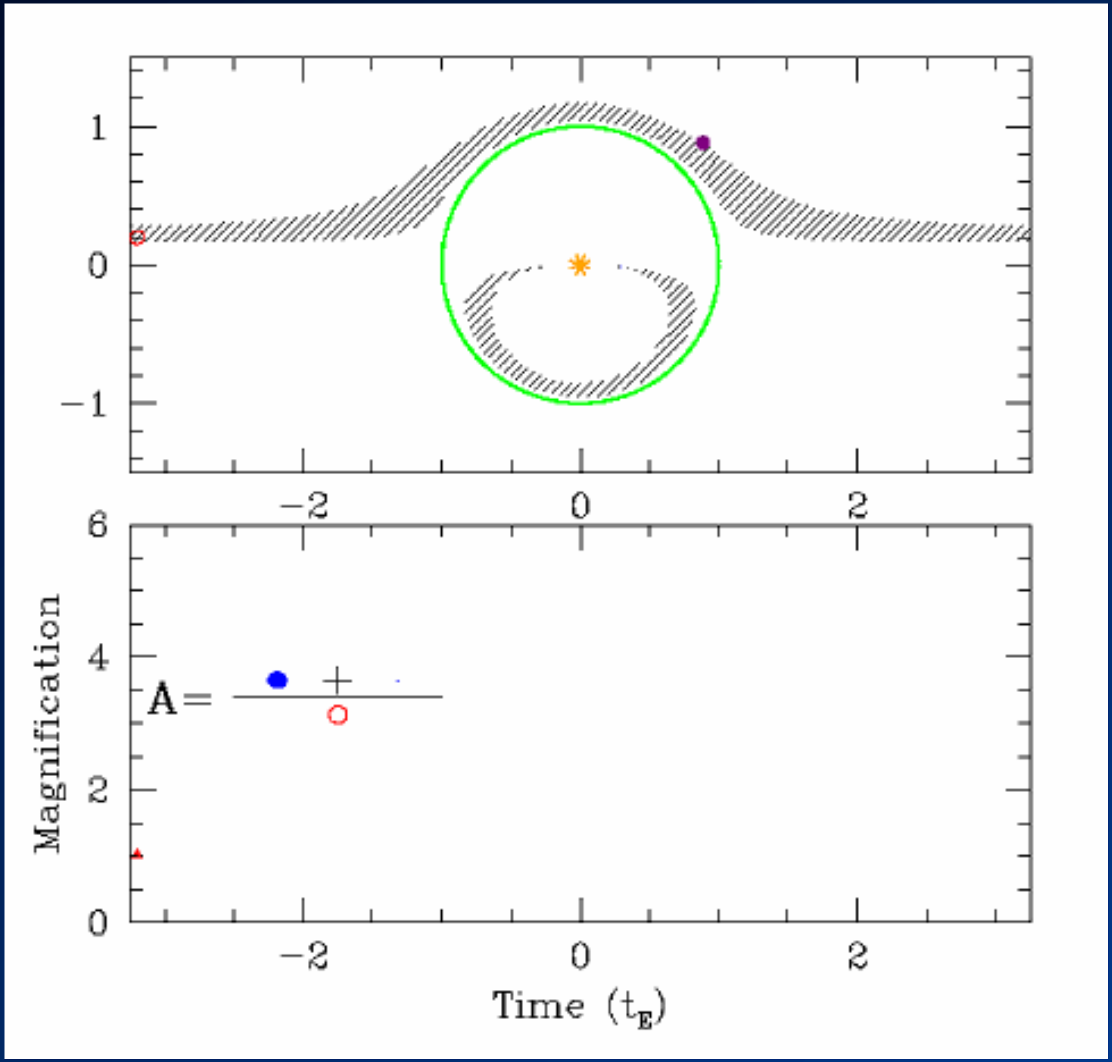


$$t_E = \frac{\theta_E}{\mu} \approx 25 \text{ days} \left(\frac{M}{0.5 M_\odot}\right)^{1/2}$$

$$\mu \sim 1-15 \text{ mas/year}, \theta_\text{E} \sim 0.1-2 \text{ mas}$$

- Timescales of a few to hundreds of days.
- Stochastic
- Degenerate combination of the mass, distance to lens and source, and relative lens-source proper motion.

# Detecting Planets.



$$t_p = q^{1/2} t_E \approx 1 \text{ day} \left(\frac{M_p}{M_J}\right)^{1/2}$$

High-Magnification

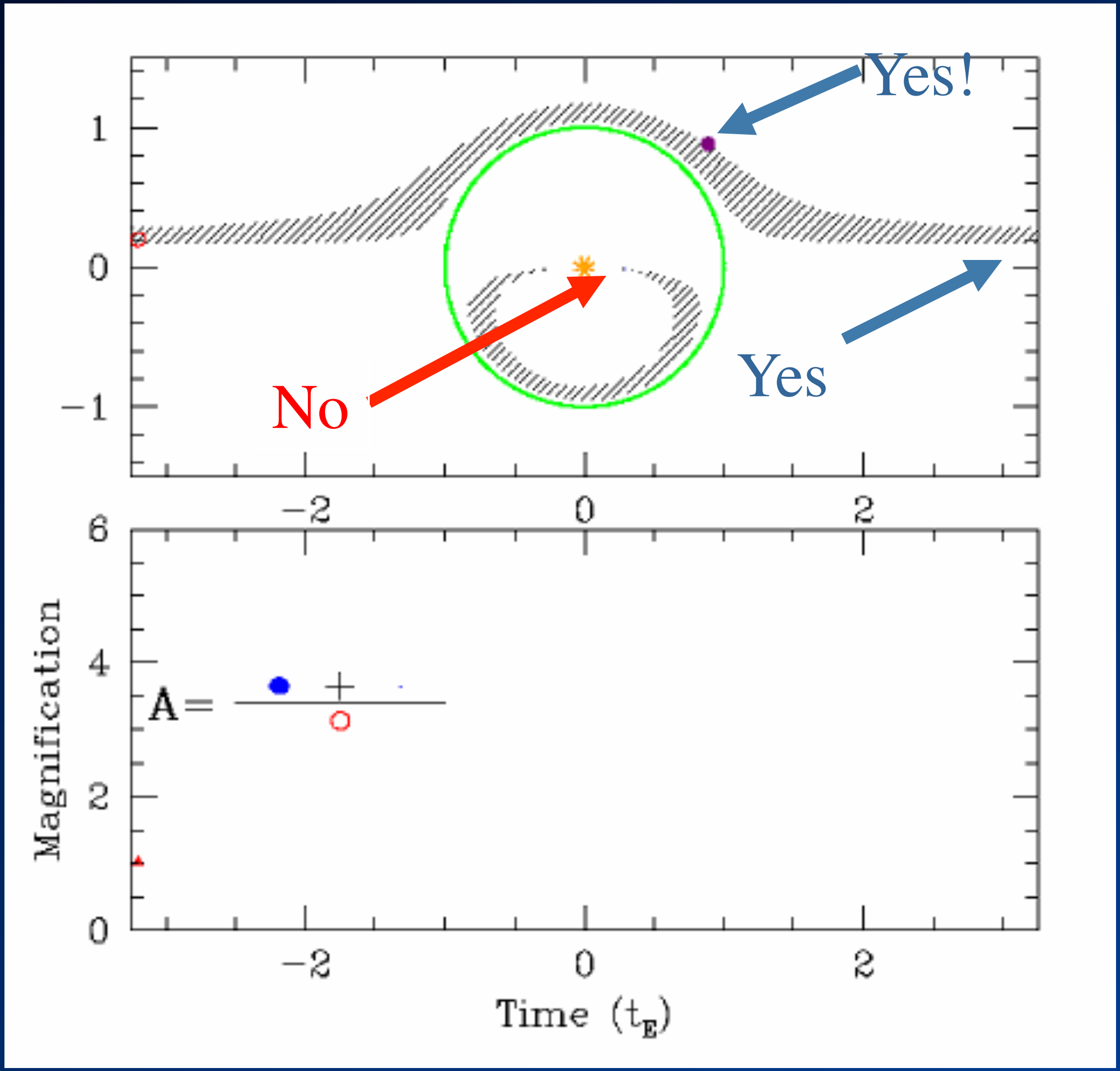
⇩

High Efficiency

Maximized when

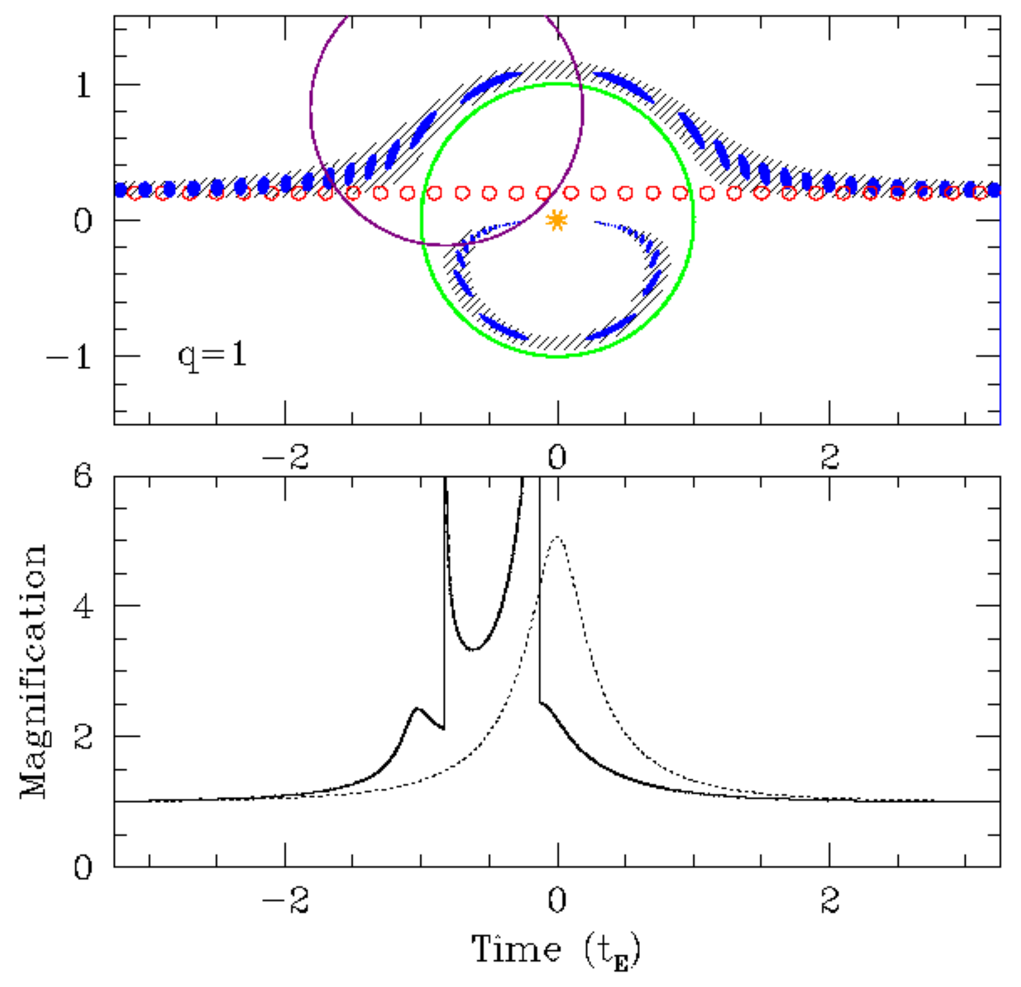
$$a \sim r_E = \theta_E D_l \sim 2.8\,\text{AU} \left(\frac{M}{0.5 M_\odot}\right)^{1/2}$$

# Microlensing is *directly* sensitive to planet mass.



- Works by perturbing images
- Does not require light from the lens or planet.
- Sensitive to planets throughout the Galaxy (distances of 1-8 kpc)
- Sensitive to wide or **free-floating** planets
- Not sensitive to very close planets

# Mass ratio dependence.



- Magnitude depends on separation of planet from image.
- Duration depends on mass ratio.

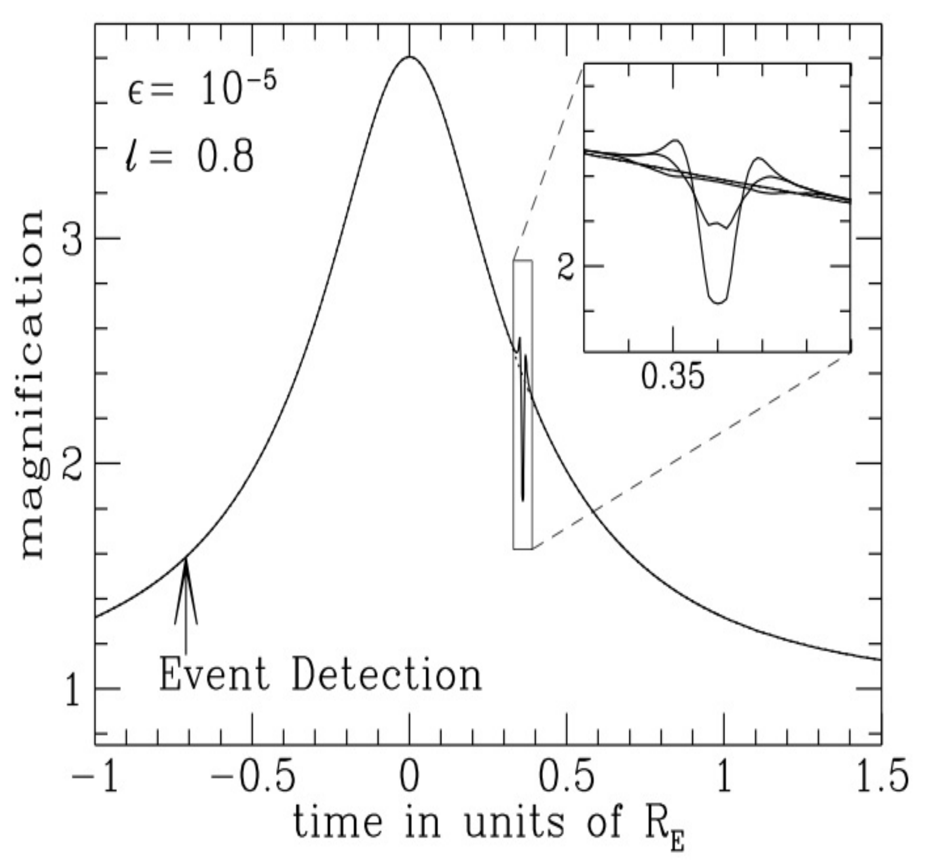
$$t_p = q^{1/2} t_E \approx 2 \text{ hrs} \left( \frac{q}{10^{-5}} \right)^{1/2}$$

- Detection probability depends on mass ratio.

$$P \sim A_0 \theta_p \sim \text{few } \% \left( \frac{q}{10^{-5}} \right)^{\sim 0.5}$$

Signal magnitude is *independent* of planet mass ratio, but signals get *rarer* and *briefer*.

# Lower Mass Limit.



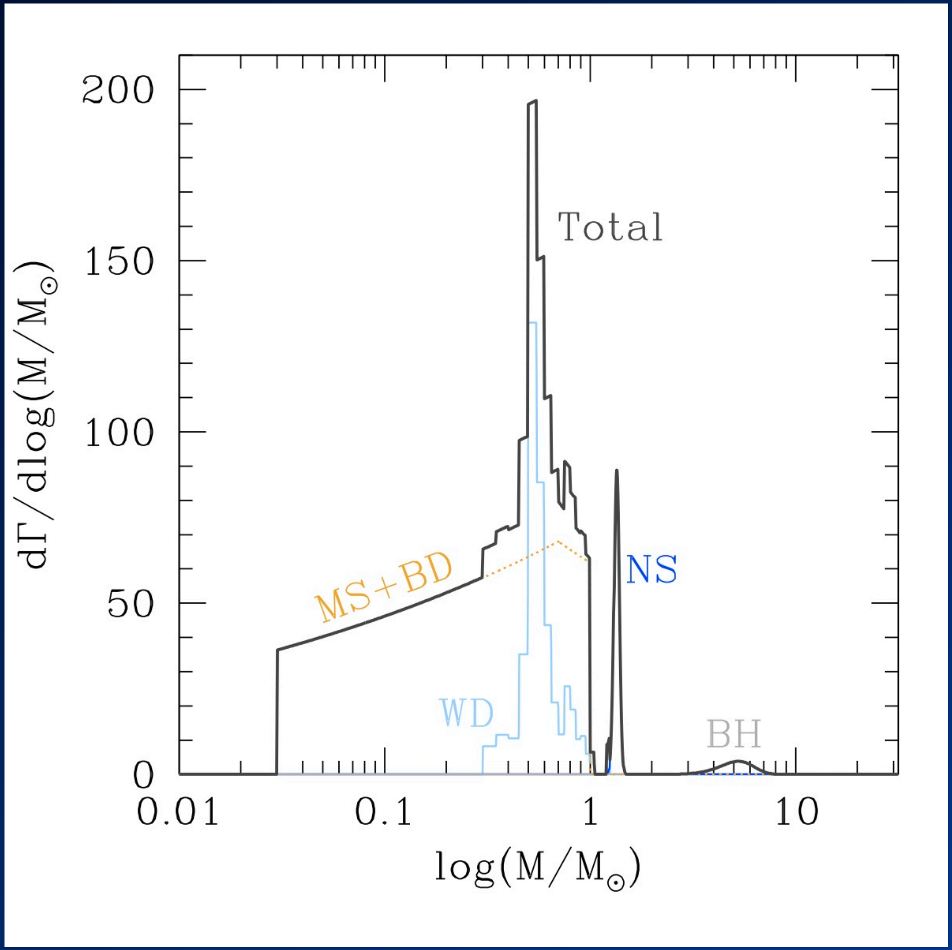
(Bennett & Rhie 1996)

$$\theta_E \approx \mu\text{as}\left(\frac{M_p}{M_\oplus}\right)^{1/2} \longleftrightarrow \theta_* \approx \mu\text{as}\left(\frac{R_*}{R_\odot}\right)$$

$$\rho_* = \frac{\theta_*}{\theta_E} \approx 1$$

- Detecting low-mass planets requires monitoring main-sequence sources.
- Mars-mass planets detectable!

# Microlensing Host Stars?



(Gould 2000)

Sensitive to planets around:

- Main-sequence stars with M < $M_{Sun}$
- Brown dwarfs
- Remnants

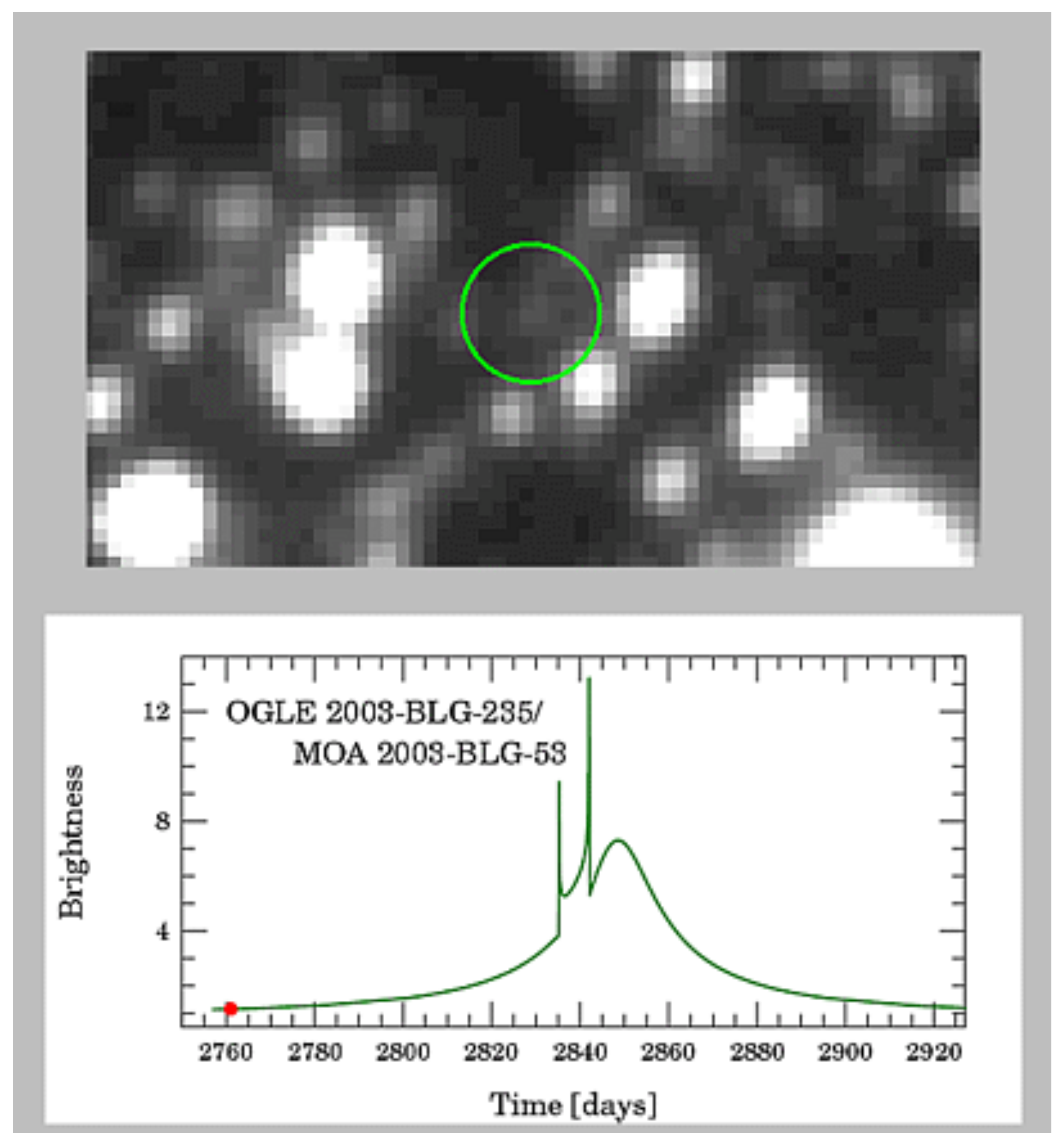
Faint Lenses:

- Most lenses are fainter than (and blended with) the sources.
- Lenses distributed along the line of sight (distances of 1-8 kpc)

# What do we measure?

- For nearly all events*:
  - mass ratio
  - projected separation in Einstein ring radius.

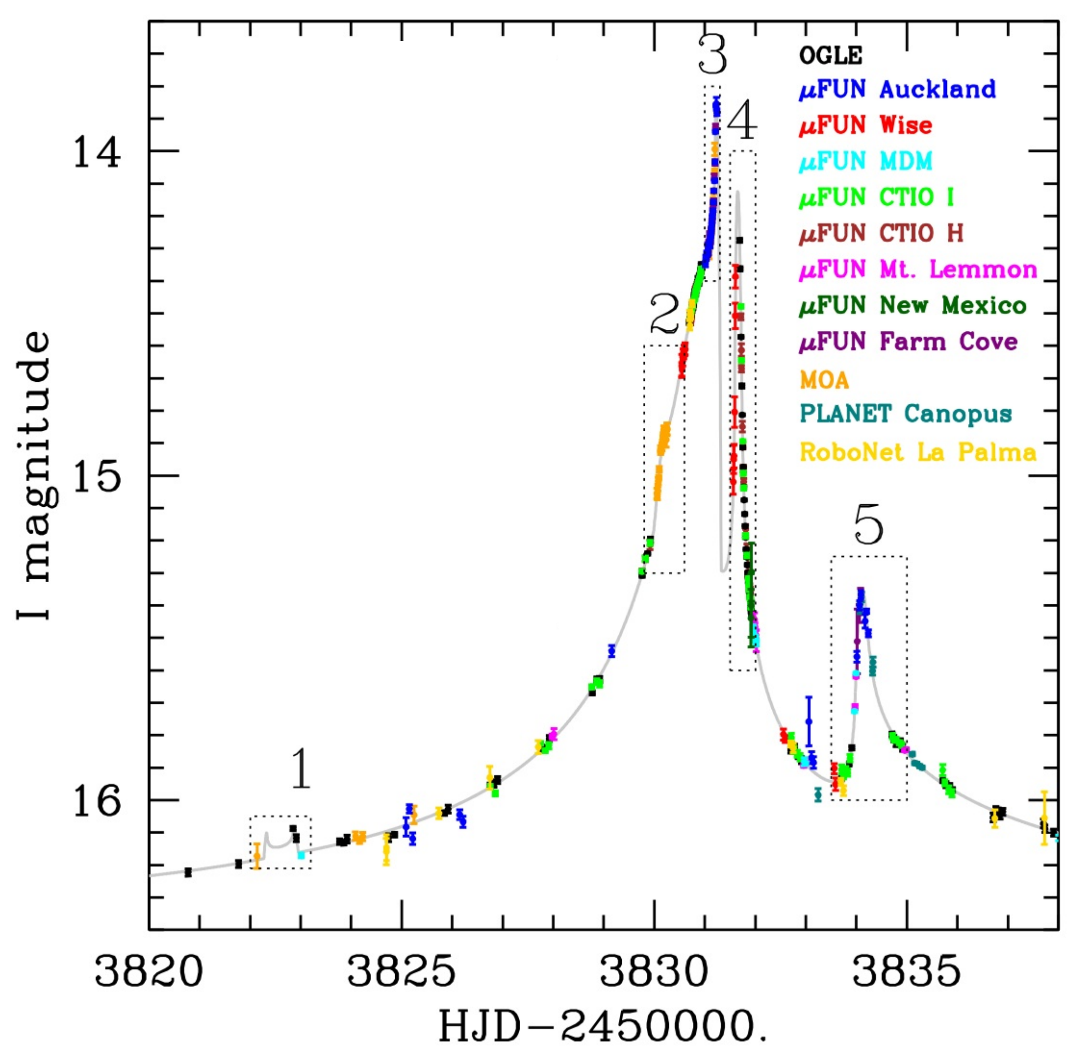
  *Need to measure primary event properties.
- For most low-mass planet detections (and a large subset of higher-mass detections)
  - Einstein ring radius through finite source effects.
  - Gives a relationship between mass and distance of lens.
- Finally measure mass through a number of ways:
  - Isolate flux from the lens
  - Measure microlens parallax
  - Both give different relationship between mass and distance



(Bond et al. 2004)

# Results!

# A Multiple-Planet System.



(Gaudi et al 2008; Bennett et al 2010)

- Single planet models fail.
- Two planets models work well.
- First multiple-planet system detected by microlensing.

# Physical Properties.

## Host:

Mass = 0.51 +/- 0.05 $M_{Sun}$

Luminosity ~ 5% $L_{Sun}$

Distance = 1510 +/- 120 pc

## Planet b:

Mass = 0.73 +/- 0.06 $M_{Jup}$

Semimajor Axis = 2.3 +/- 0.5 AU

## Planet c:

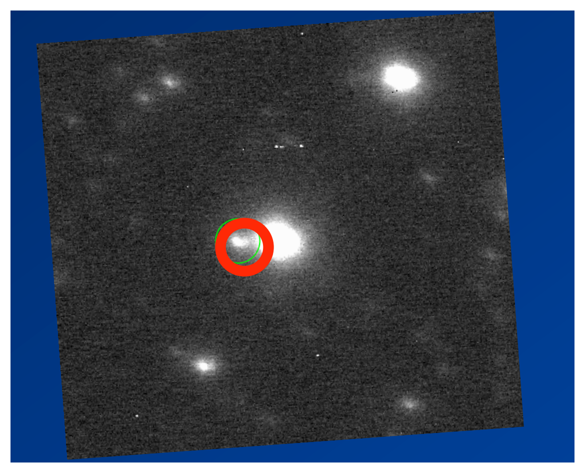
Mass = 0.27 +/- 0.02 $M_{Jup}$ = 0.90 $M_{Sat}$

Semimajor Axis = 4.6 +/- 1.5 AU

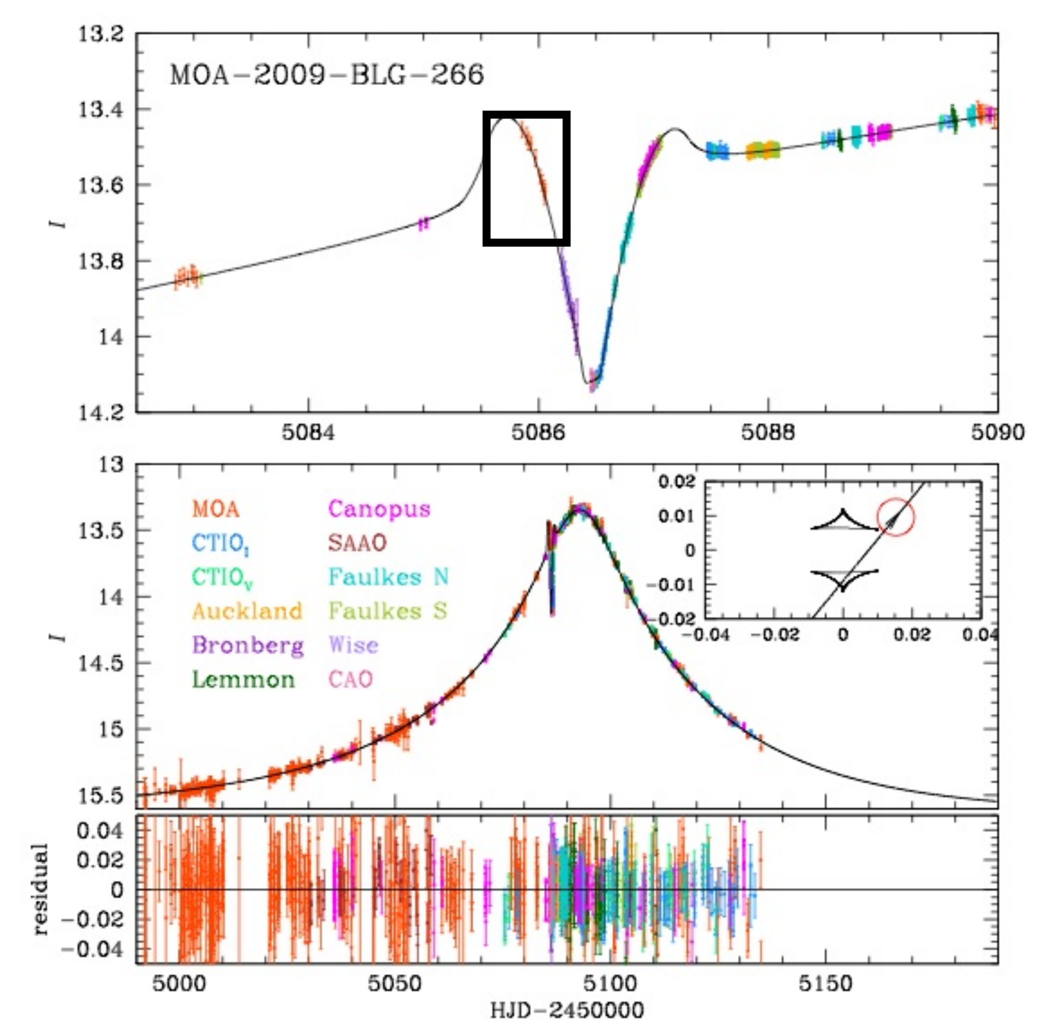
Eccentricity = 0.15+0.17-0.10

Inclination = 64+4-7 degrees

AO Imaging from Keck



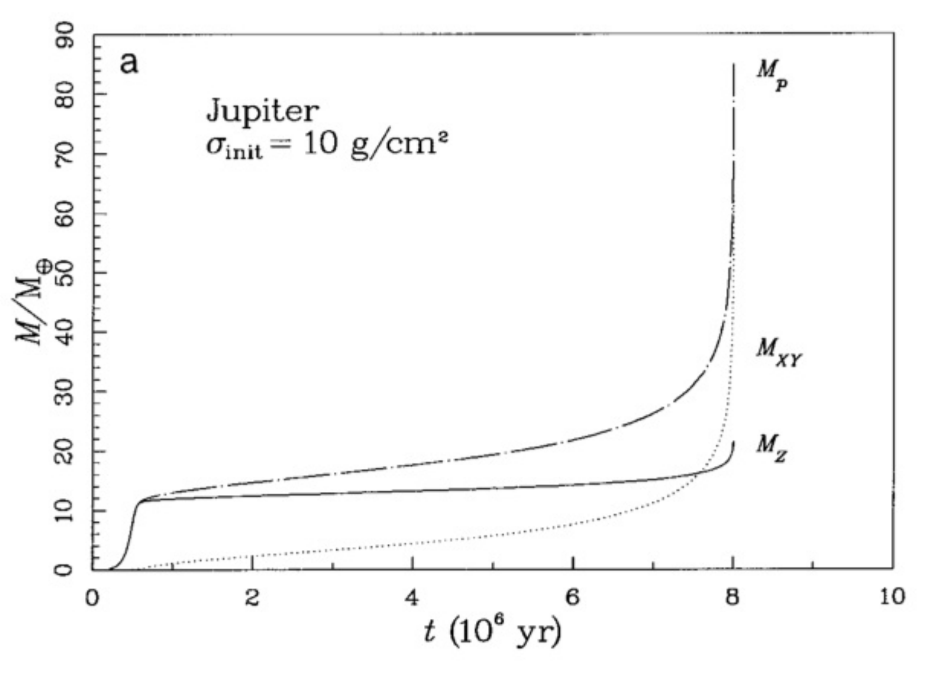
# ~10 $M_{\rm Earth}$ Planet.



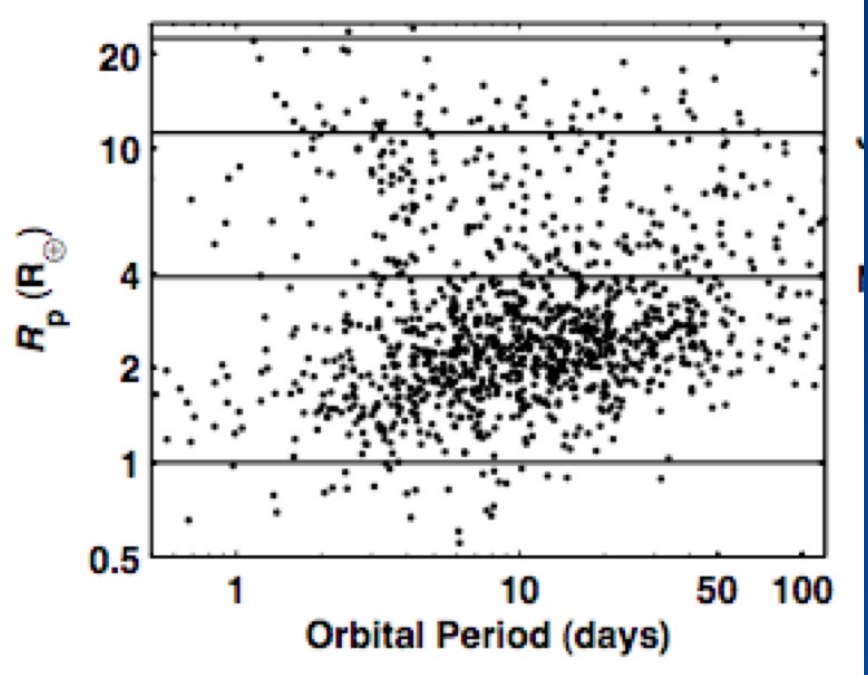
(MOA, $\mu$FUN, PLANET, RoboNET, Muraki et al. 2011)

# Failed Jupiter Core?

$$\text{Planet mass} = 10.4 \pm 1.7\, M_{\text{Earth}}$$

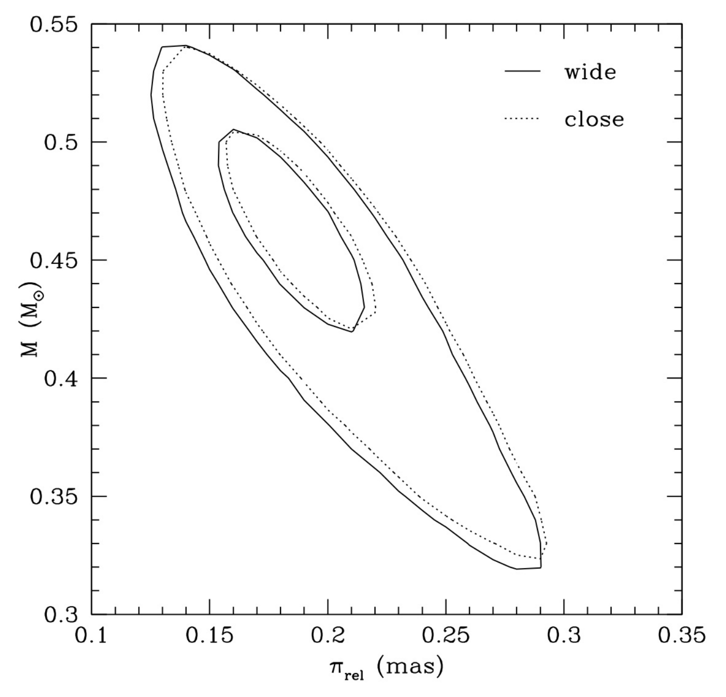


(Pollack et al. 1996)

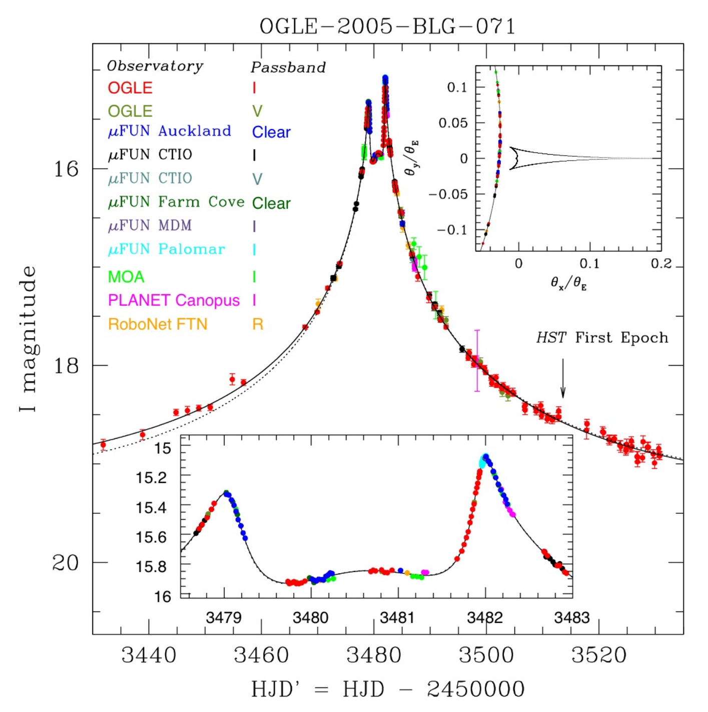


(Borucki et al. 2011)

# A Massive M Dwarf Planet.



(Dong et al. 2008)



$$M = 0.46 \pm 0.04\, M_\odot$$

$$D_l = 3.2 \pm 0.4 \text{ kpc}$$

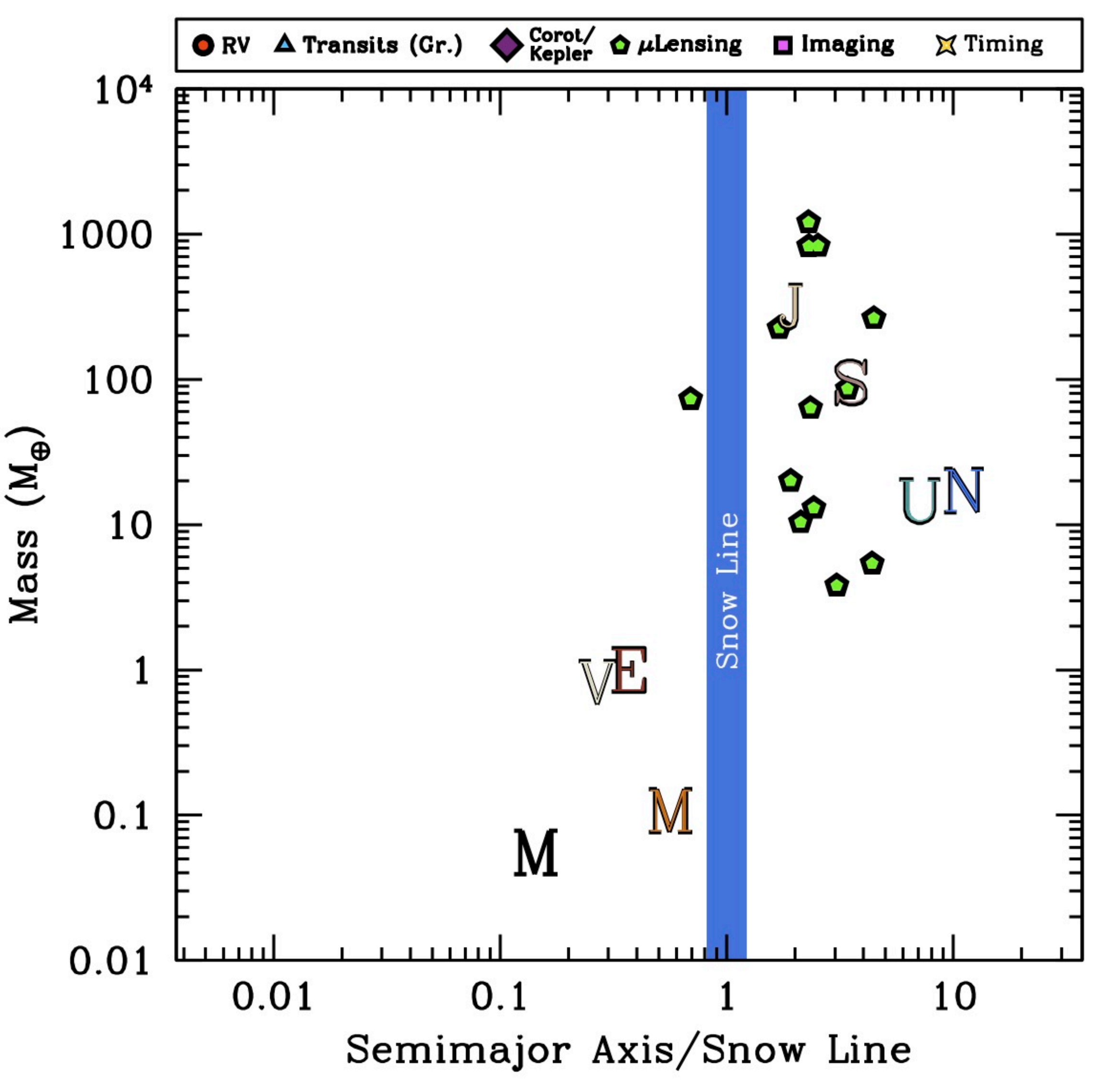
$$v_{\rm LSR} = 103 \pm 15 \text{ km s}^{-1}$$

$$m = 3.8 \pm 0.4\, M_{\rm Jup}$$

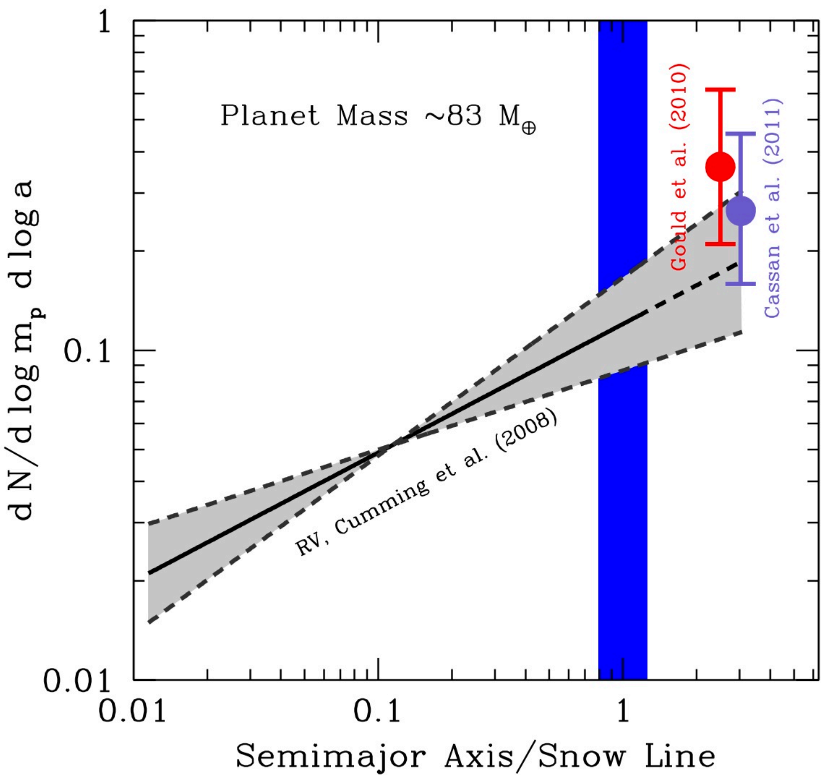
$$r_\perp = 3.6 \pm 0.2 \text{ AU}$$

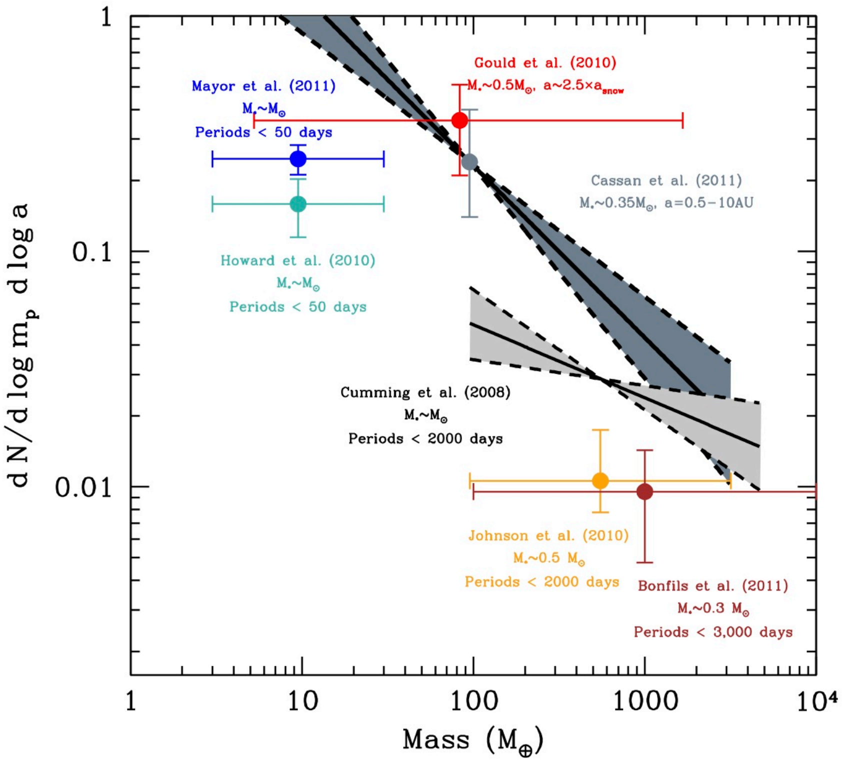
$$T_{eq} \sim 50K$$

# Demographics Beyond the Snow Line:



# An Inconvenient Truth.

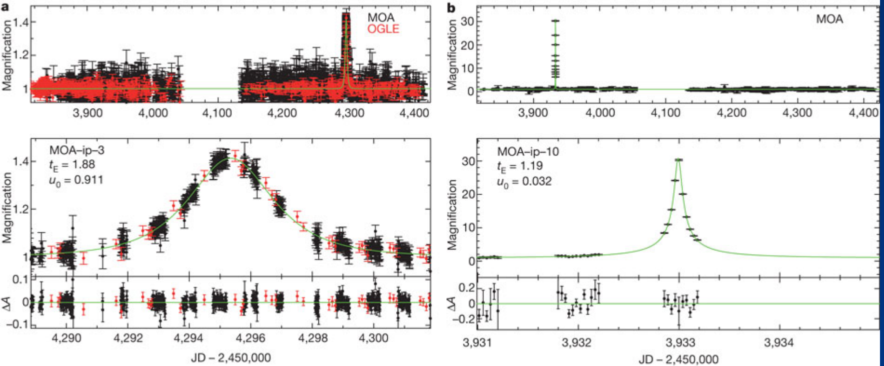


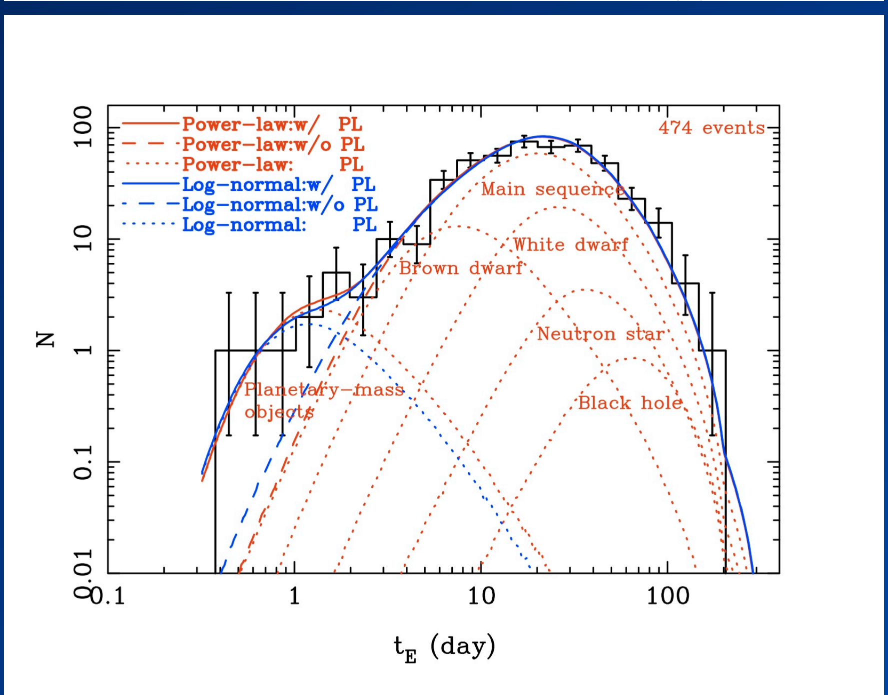


(Gould et al. 2010, Sumi et al. 2009, Cassan et al. 2012)

# Free Floating Planets.

- Excess of short time scale events relative to expected stellar/ brown dwarf contribution.
- Unbound or wide-separation planets.
- Implies roughly 2 Jupiter-mass free-floating planets per star.





(Sumi et al. 2011; MOA + OGLE Collaborations)

# Next Generation Surveys.

# Microlensing Event Rates.

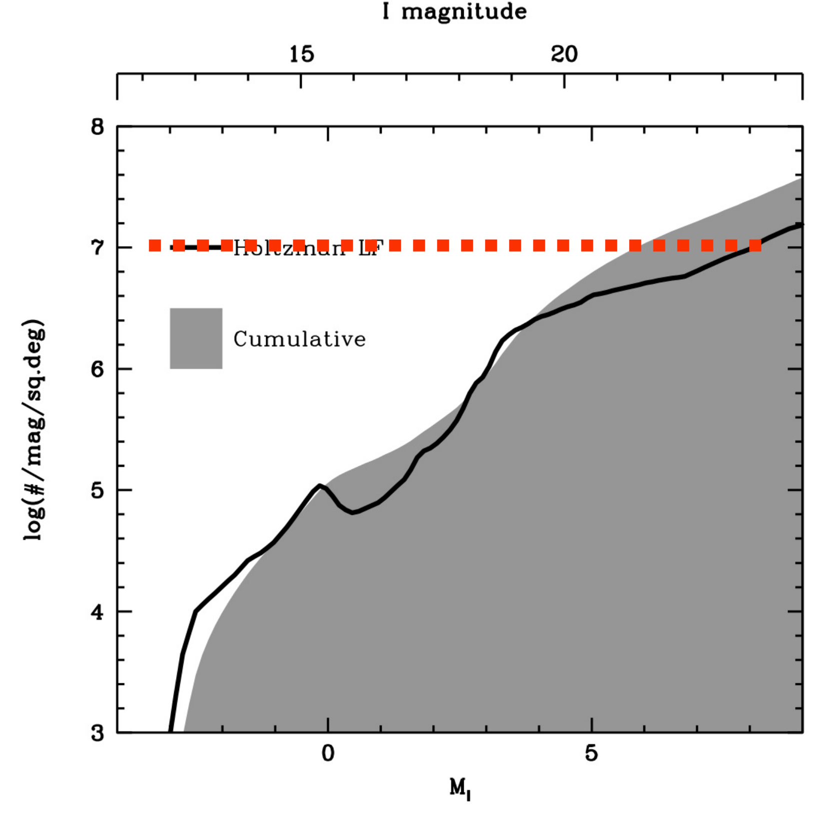
- Require a close alignment of ~1 mas.
- The event rate depends on the density distribution of masses along the line of sight.
- Event rate highest for stars in Galactic bulge.

$$\Gamma \approx 10^{-5}\,\mathrm{yr}^{-1}$$

- Total numbe ends on the luminosity function of bulge sources.

# Bulge Luminosity Function.

- Fainter → more sources
- Fainter → smaller sources
- Fainter ↔ FOV
- Longer wavelength → smaller sources, more extincted regions, higher event rates, but also more crowded



(mean separation ~0.5” for *I*<25)

# Requirements.

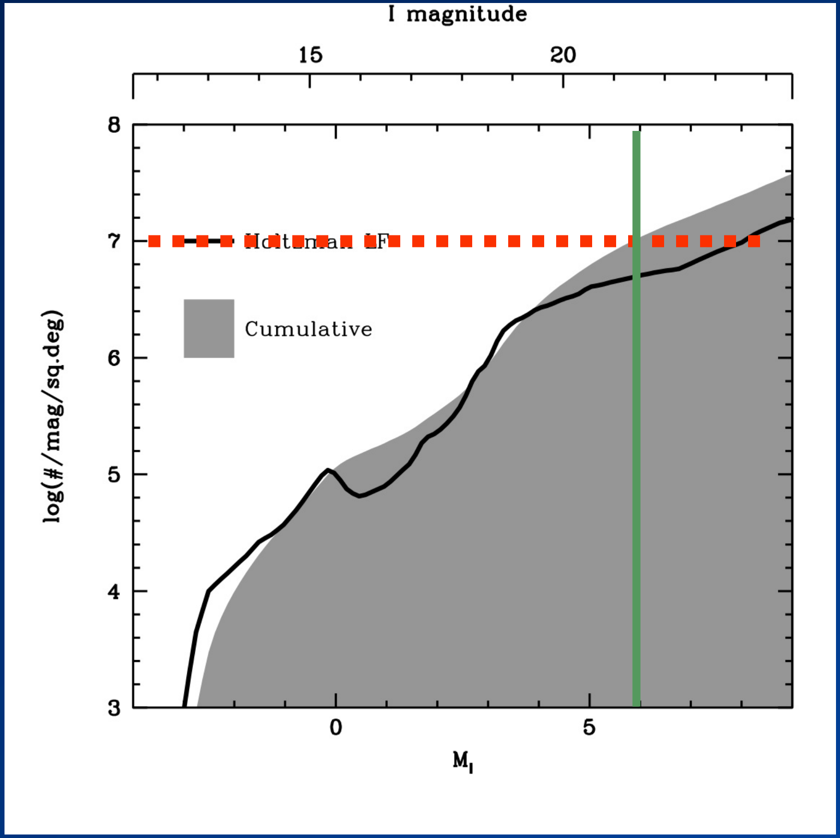
- Event Rate
  - Primary Event Rate

$$\Gamma \approx 10^{-5}\,\mathrm{yr}^{-1}$$

  - Detection Probability

$$P \approx A_0\theta_p \approx 1\%\left(\frac{M_p}{M_{Earth}}\right)^{1/2}$$

  - Detections Per Year



$$N \approx n_F\Omega\Phi\Gamma P \approx 10\ \mathrm{yr}^{-1}\left(\frac{\Omega}{10\square^\circ}\right)\left(\frac{\Phi}{10^7/\square^\circ}\right)\left(\frac{\Gamma}{10^{-5}\,\mathrm{yr}^{-1}}\right)\left(\frac{P}{1\%}\right)$$

# Requirements Part 2.

Detecting the Perturbations from Earth-mass Planets

- Sampling rate ~ 10 minutes

$$t_{E,p} = 2\mathrm{hrs}\left(\frac{M_p}{M_E}\right)^{1/2}$$

- Photometric Accuracy ~ 1% at I~21
  - Signal Magnitude

$$\frac{\Delta F}{F} \approx 1\%\left(\frac{M_p}{M_{\male}}\right)\left(\frac{R_*}{R_\odot}\right)^{-2}$$

  - Photometric Uncertainty

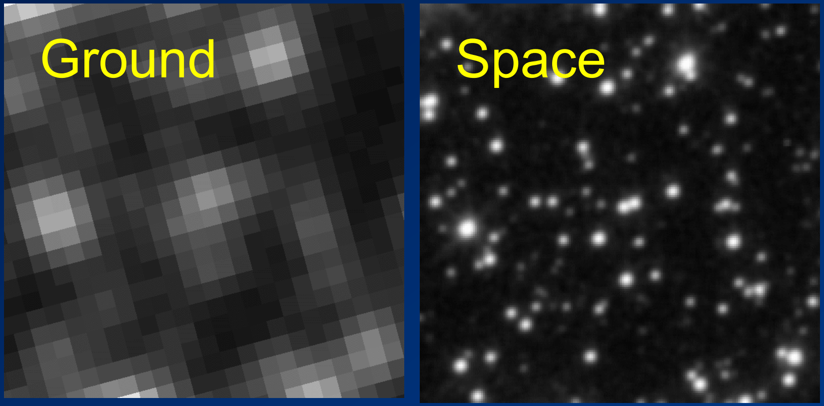
$$\sigma = 1\%\left(\frac{D}{2\mathrm{m}}\right)^{-1}\left(\frac{t_{\exp}}{120\mathrm{s}}\right)^{-1/2} 10^{0.2(I-21)}$$

# What sets the lower mass limit?

- The finite size of the sources sets the ultimate lower mass limit for detection.
- The source crossing time sets the minimum required cadence of ~10 minutes.
- Small sources allow the detection of smaller planets
  - Late type stars - fainter, IR.
- Source size more important for closer planets.

# Ground vs. Space.

- Infrared.
  - More extincted fields -> higher event rates.
  - Smaller sources -> smaller planets, close-in planets.
- Resolution
  - Low-magnification events with main-sequence sources -> higher event rates, smaller planets.
  - Isolate light from the lens star -> Host mass characterization for the majority of events.
- Coverage
  - Complete coverage -> Better characterization

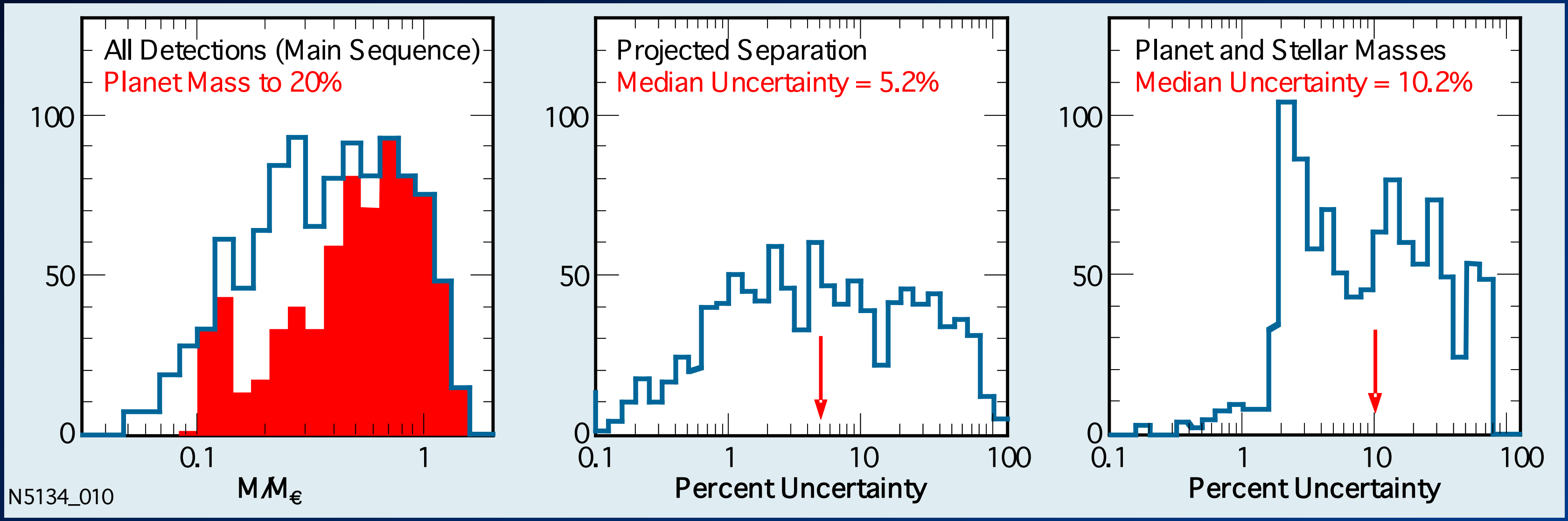


The field of microlensing event MACHO 96-BLG-5 (Bennett & Rhie 2002)

- Smaller systematics
  - Better characterization of parameters, more robust quantification of efficiencies.

Science enabled from space: sub-Earth mass planets, habitable planets, free-floating Earth-mass planets, mass measurements.

# Lens Detection Provides Accurate Mass Estimate.



(Bennett et al. 2007)

- Lens will be detected for the majority of main-sequence lenses.
- Host star masses will be measured to 10% for half of the events.
- Projected separations will be measured to 5% for half of the events.

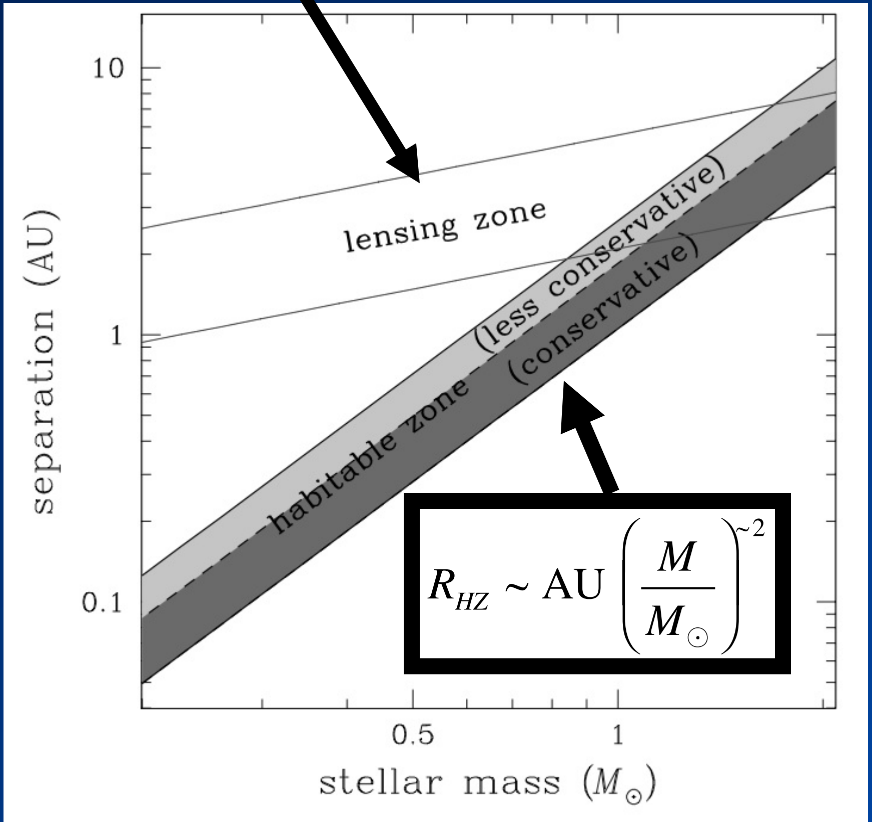
# Habitable Planets?

- Habitable zone is well interior to the Einstein ring radius for most lenses.

$$\frac{R_{HZ}}{R_E} \sim 0.3 \left(\frac{M}{M_\odot}\right)^{\sim 3/2} [x(1-x)]^{1/2}$$

- Minor image perturbations.
- More sensitive to source size.
- Require better precision.
- Can be made up by more time through the "*x*" factor.

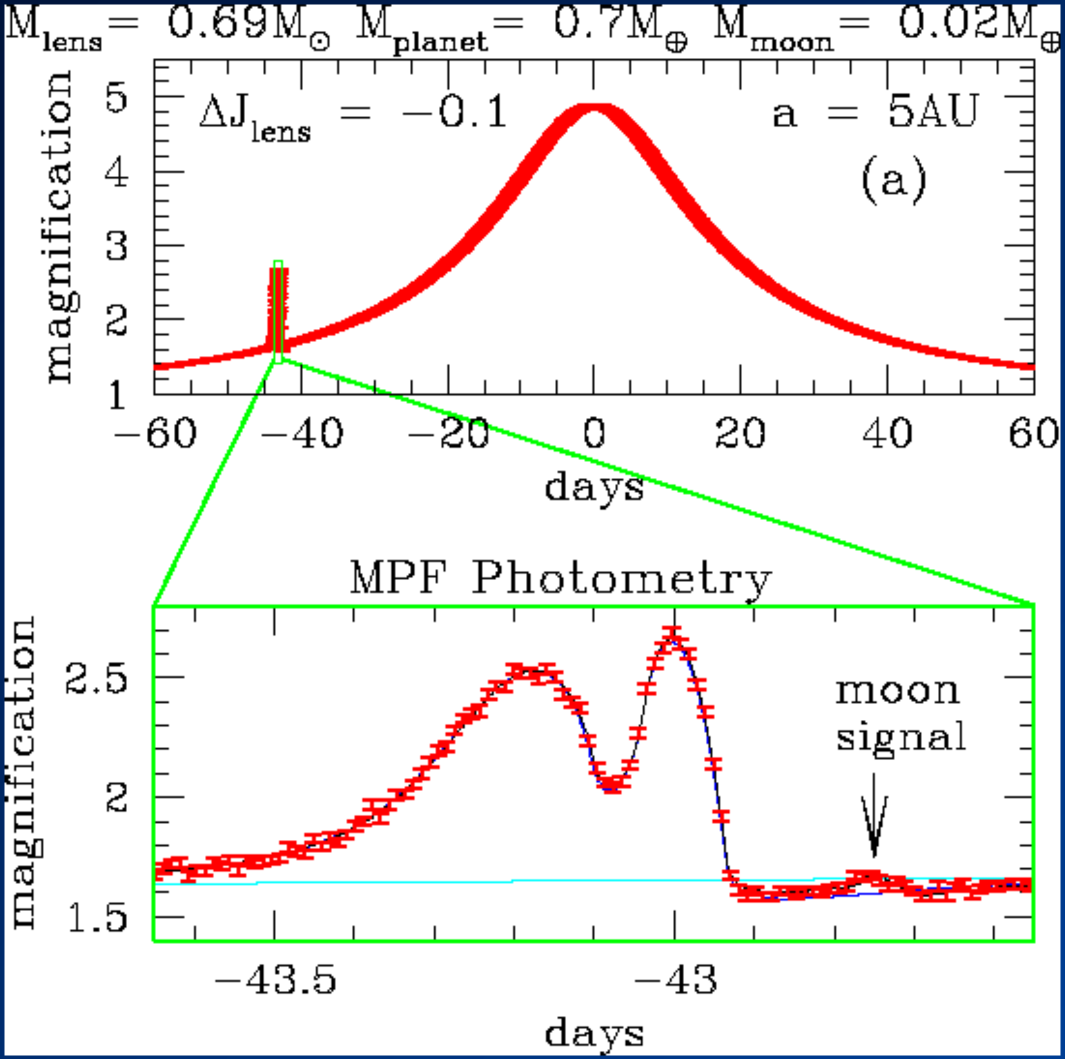
$$R_E = \theta_E D_l \sim 3.5\,\mathrm{AU} \left(\frac{M}{M_\odot}\right)^{1/2} [x(1-x)]^{1/2}, \quad x \equiv \frac{D_{ol}}{D_{os}}$$



$$R_{HZ} \sim \mathrm{AU} \left(\frac{M}{M_\odot}\right)^{\sim 2}$$

(Park et al. 2006)

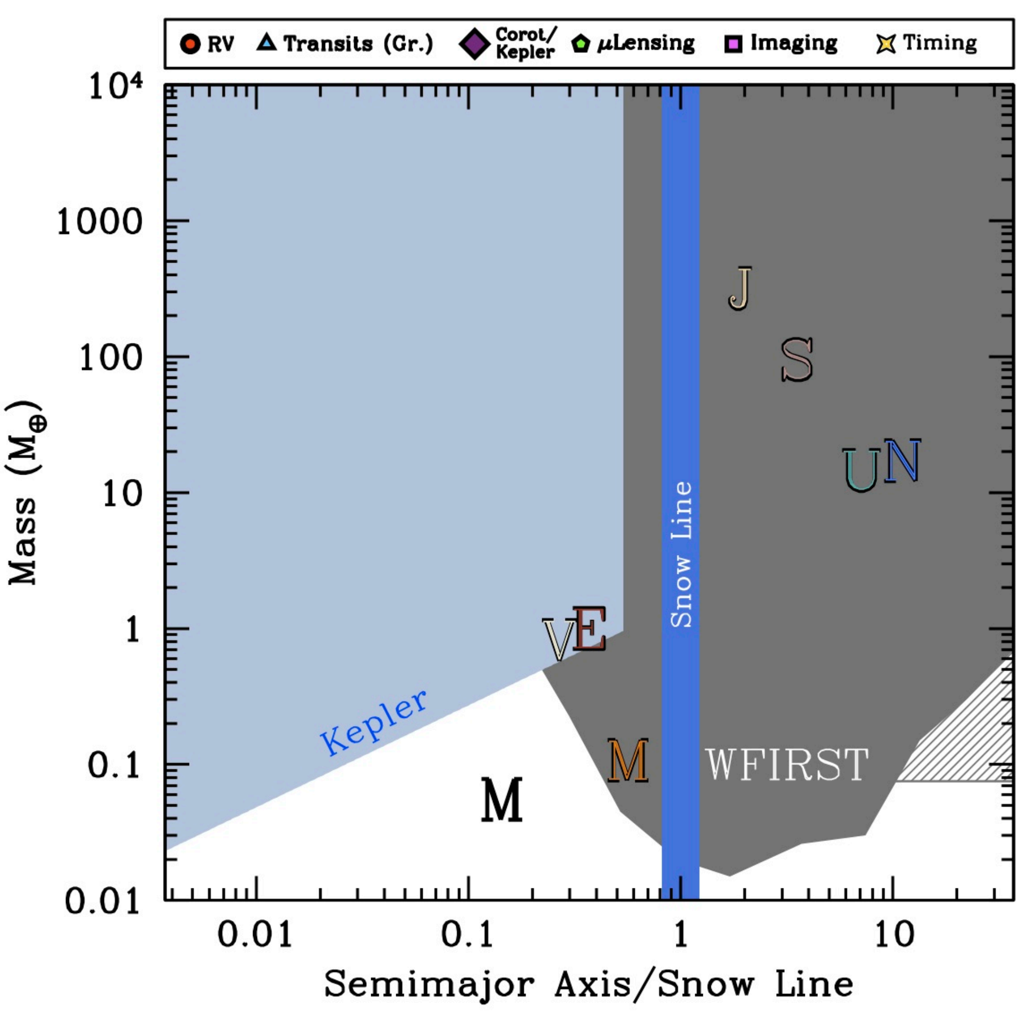
# Detailed Simulations.



(Bennett & Rhie 2002)

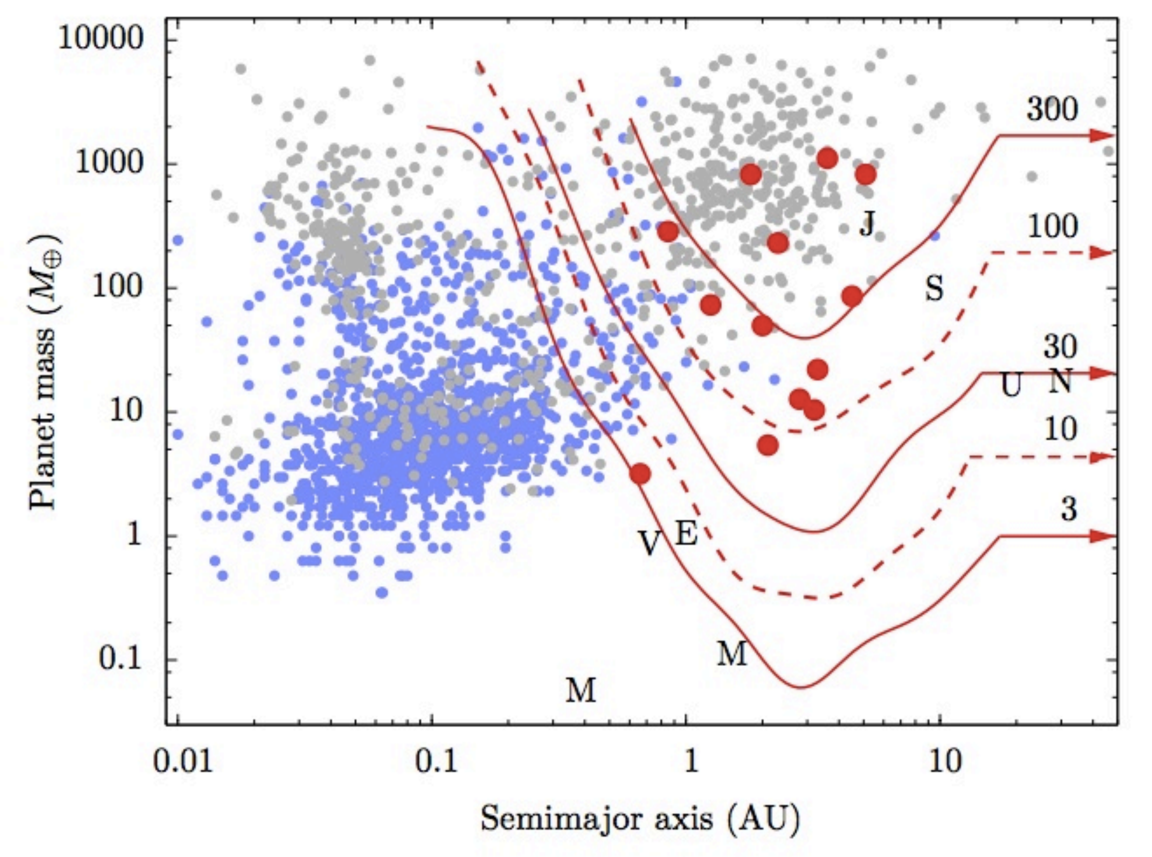
# Space Discovery Potential.

- With Kepler, “completes the census” of planets.
- Sensitivity to all Solar System-analogs except Mercury
- Good sensitivity to “outer” habitable zone (Mars-like orbits).
- Free-floating planets down to ~Mars mass.
- WFIRST IDRM estimated yields:
  - Roughly 3300 bound planets (0.1-40 AU)
  - 320 < Earth, 1500 < 10xEarth
  - Roughly 2000 free-floating planets
  - Solar system analogs:
    - 280 terrestrial
    - 3200 gas giants
    - 84 ice giants.
- Euclid has similar *potential*.



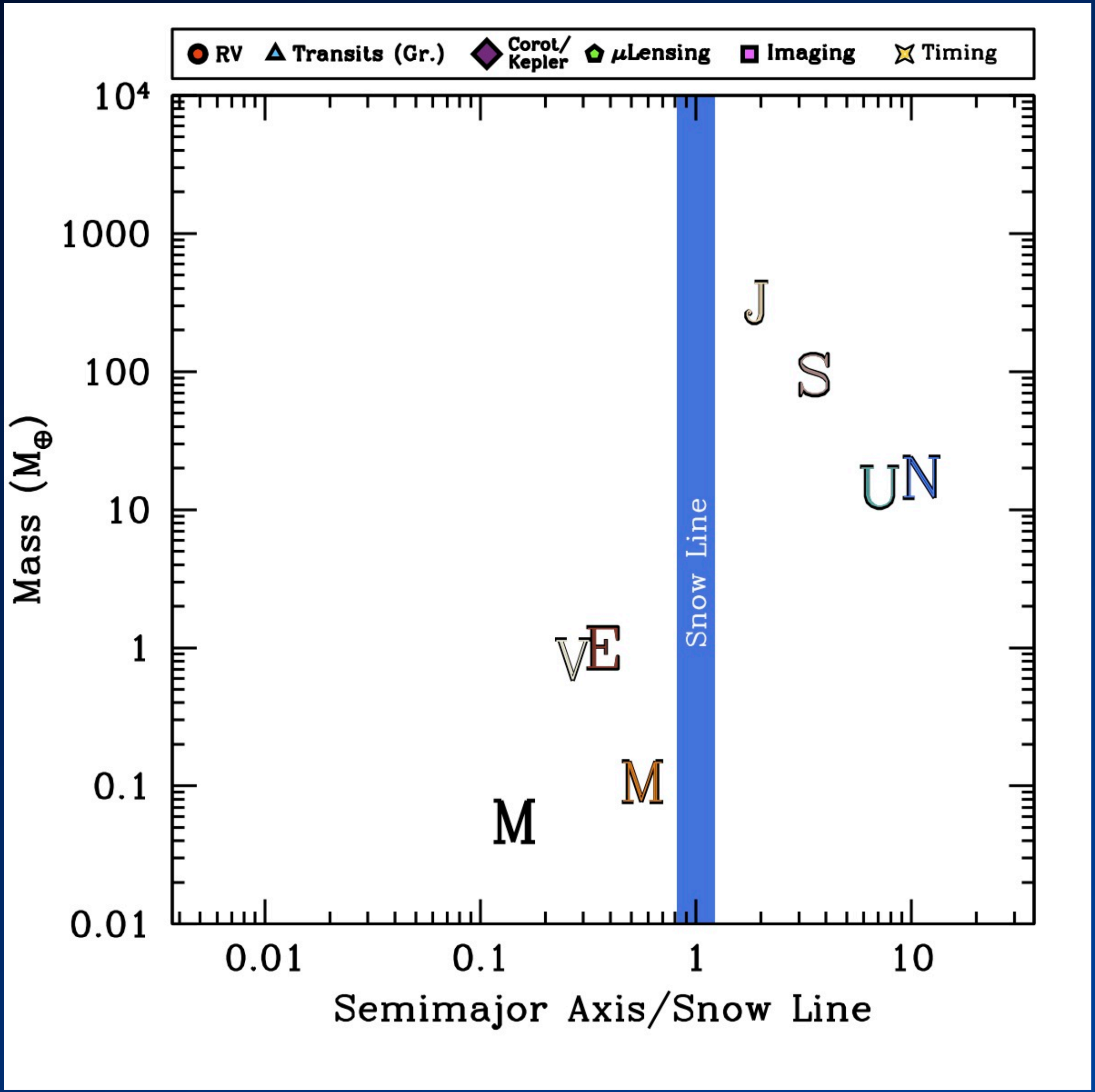
(Green et al, WFIRST Interim Report)

# Euclid.

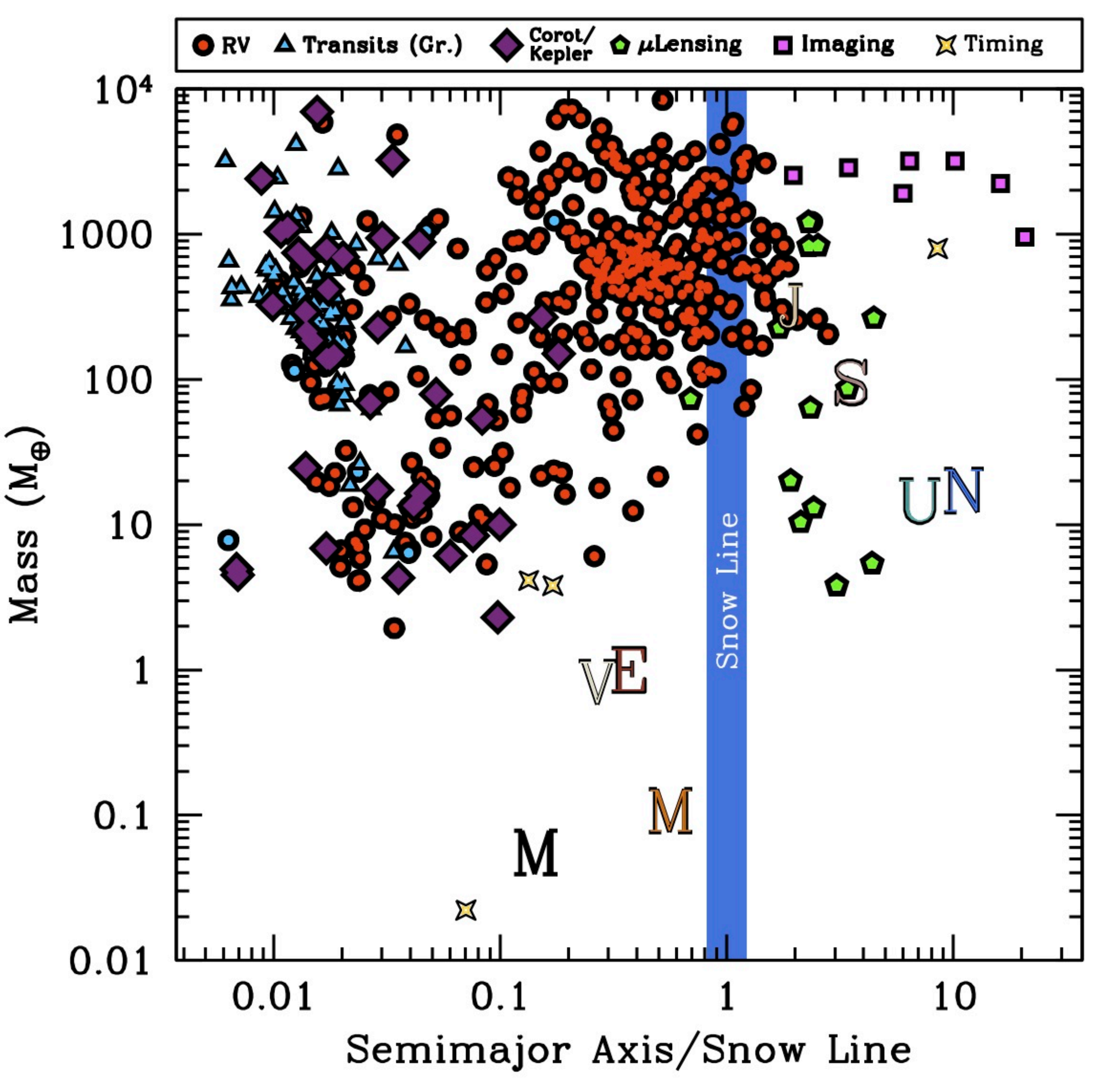


(Penny et al, 2012)

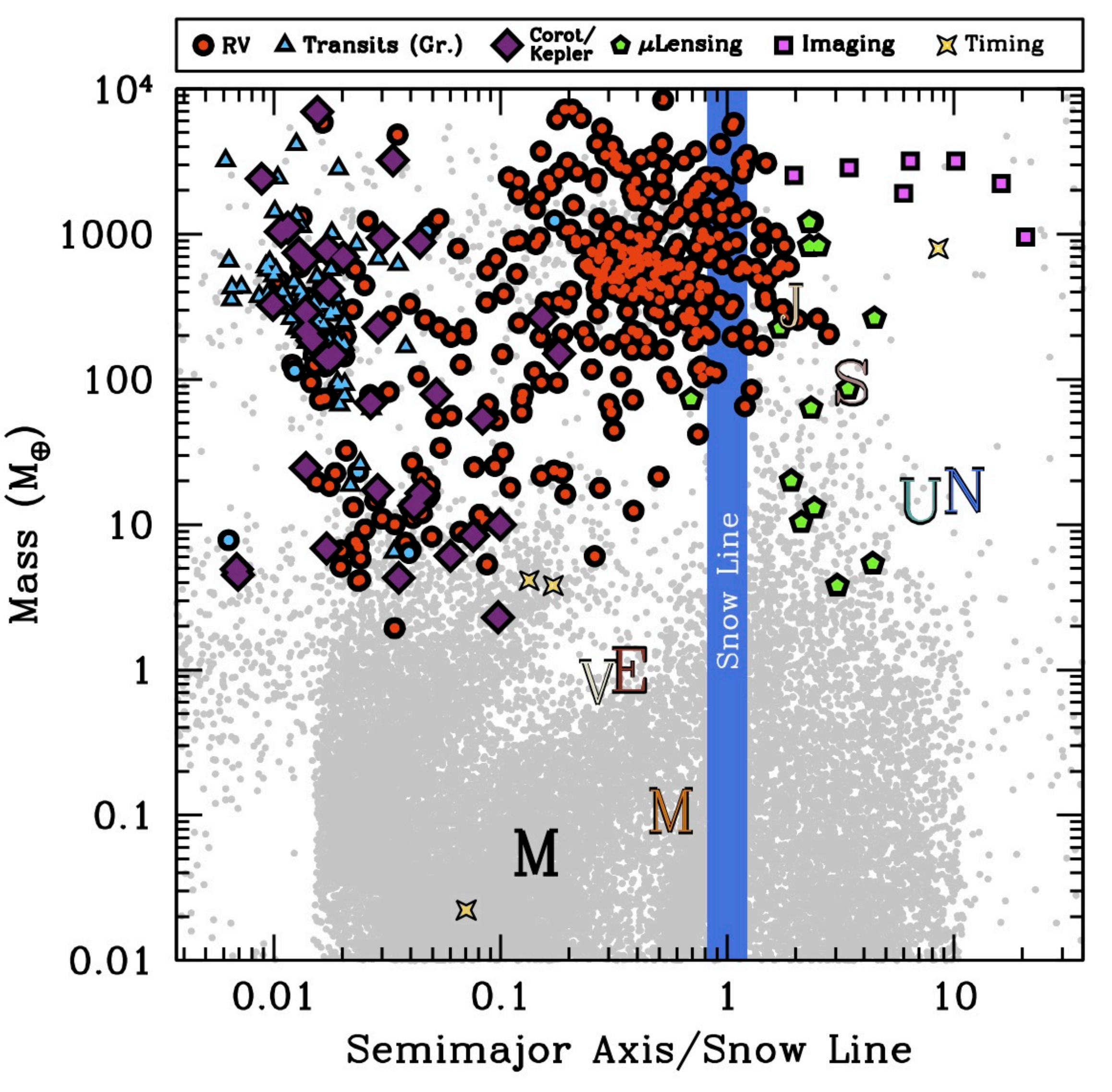
# Planet Search Synergy!



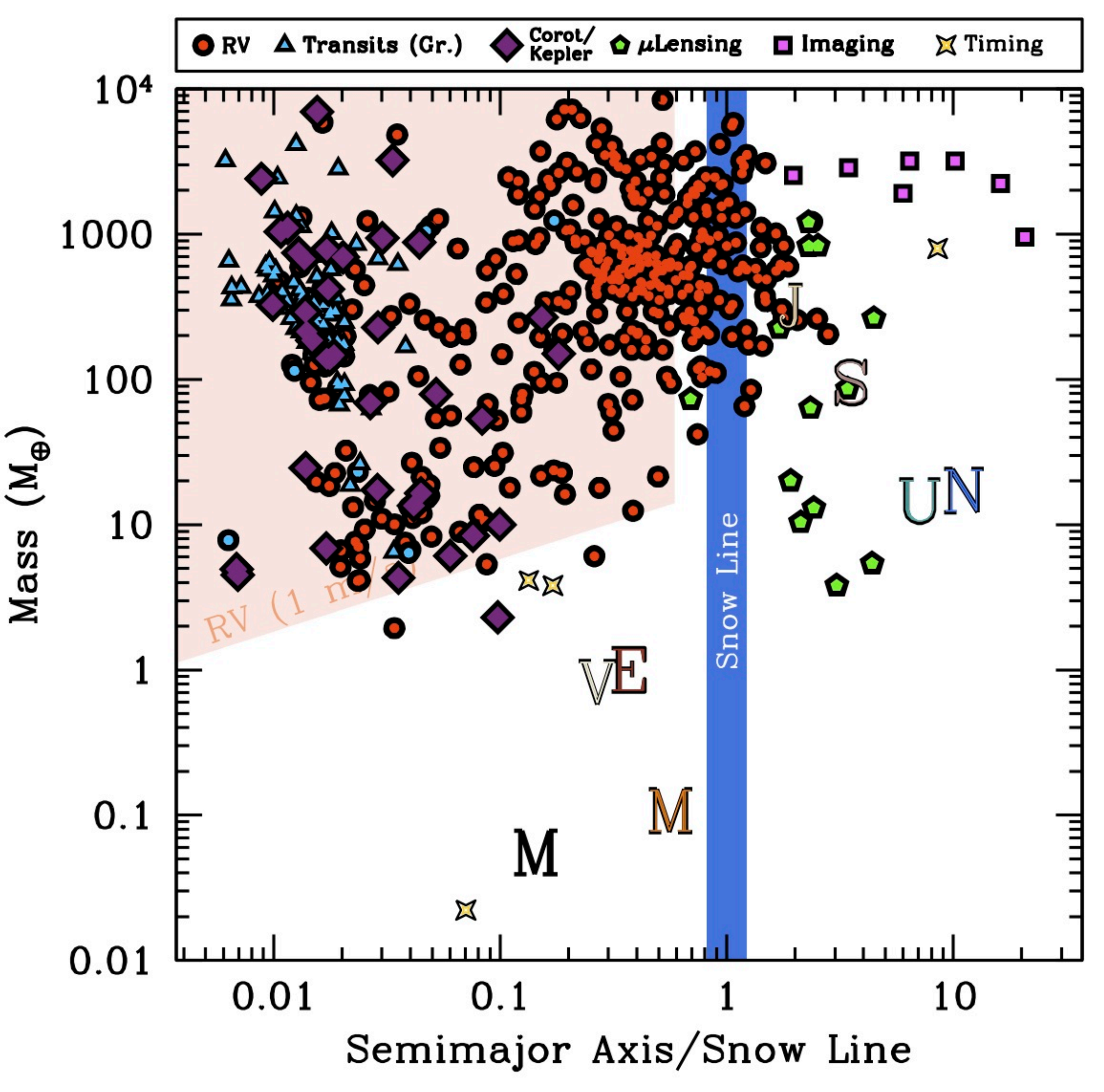
# Planet Search Synergy!



# Planet Search Synergy!



# Planet Search Synergy!



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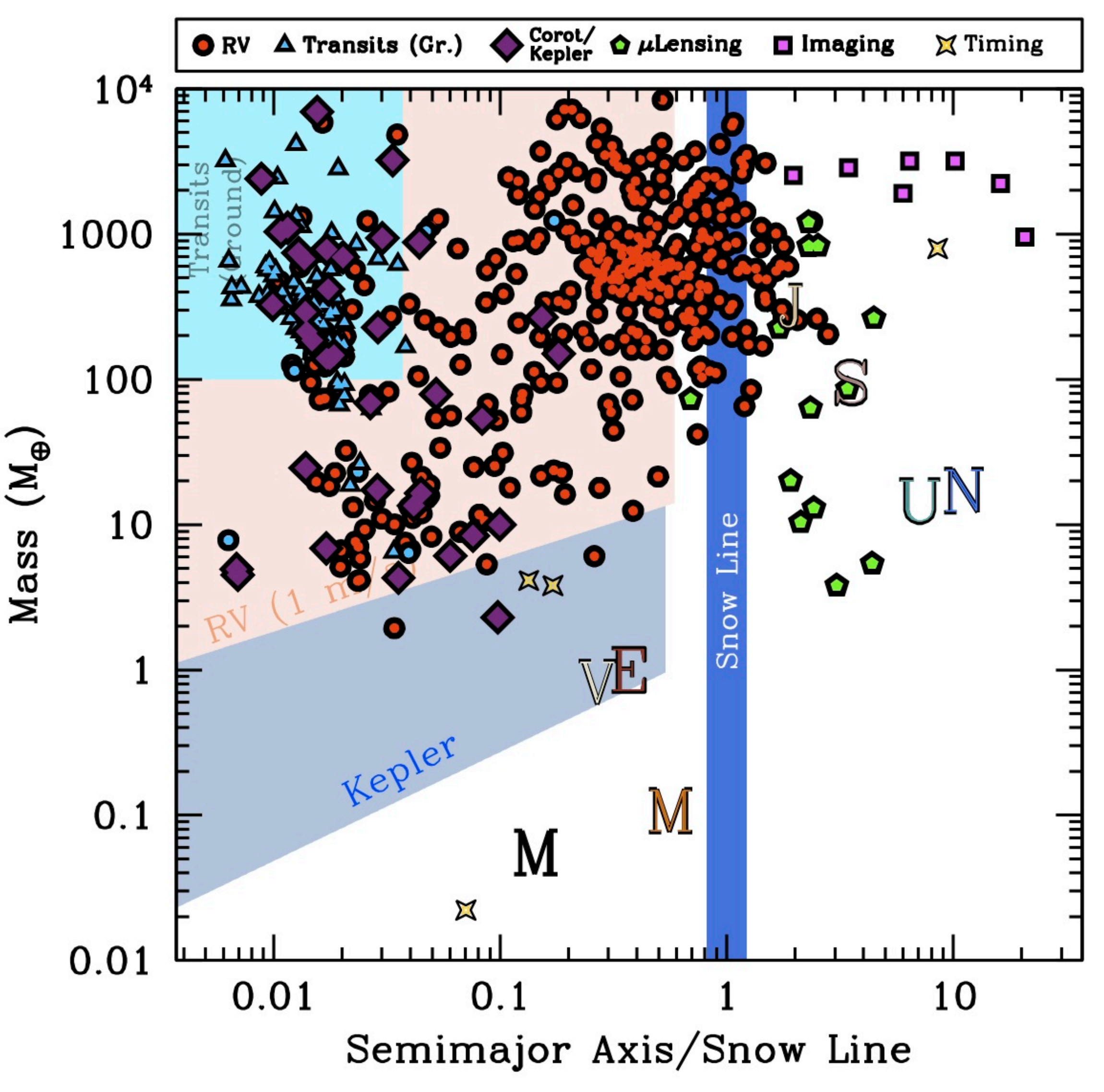

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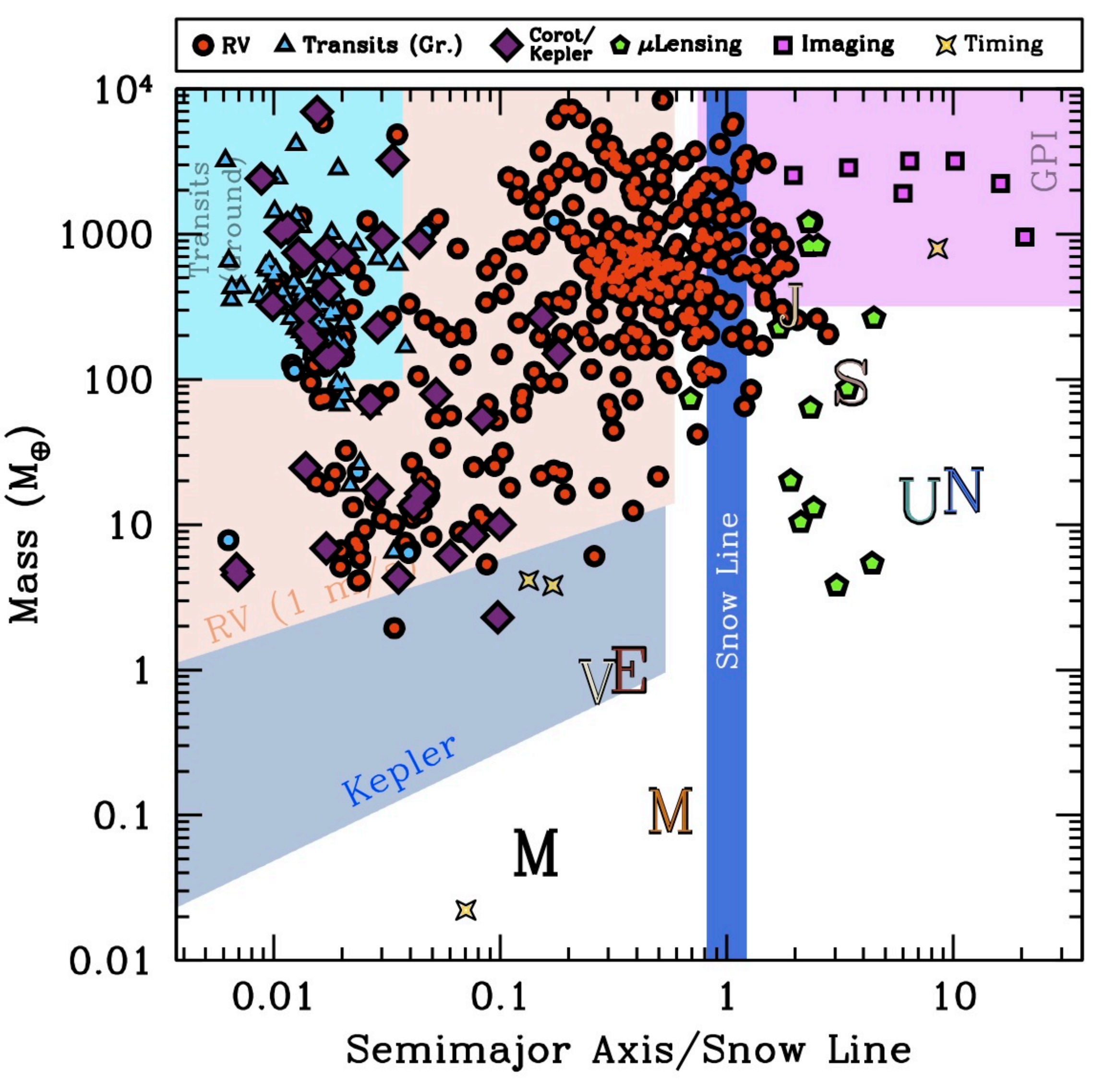

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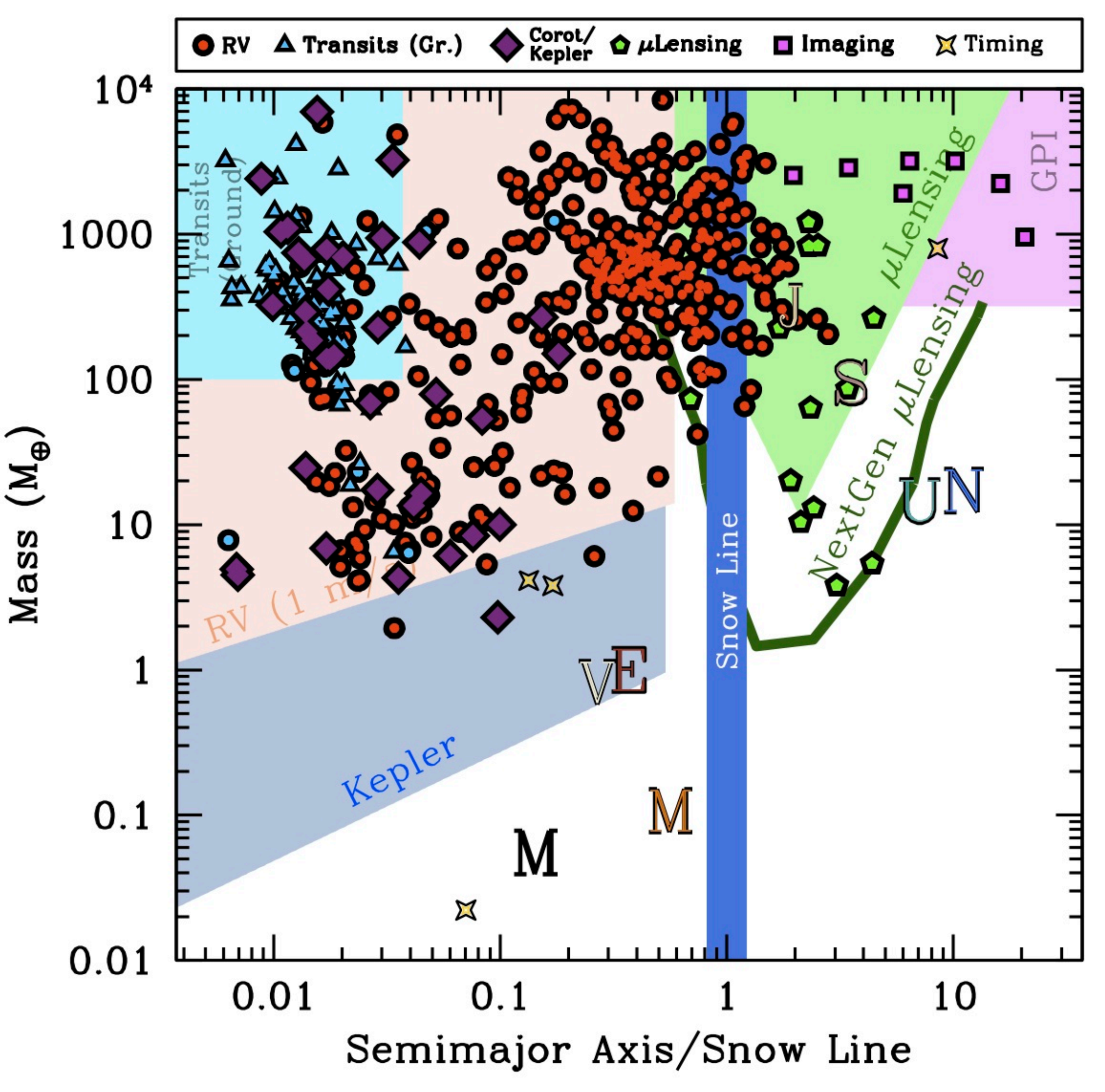

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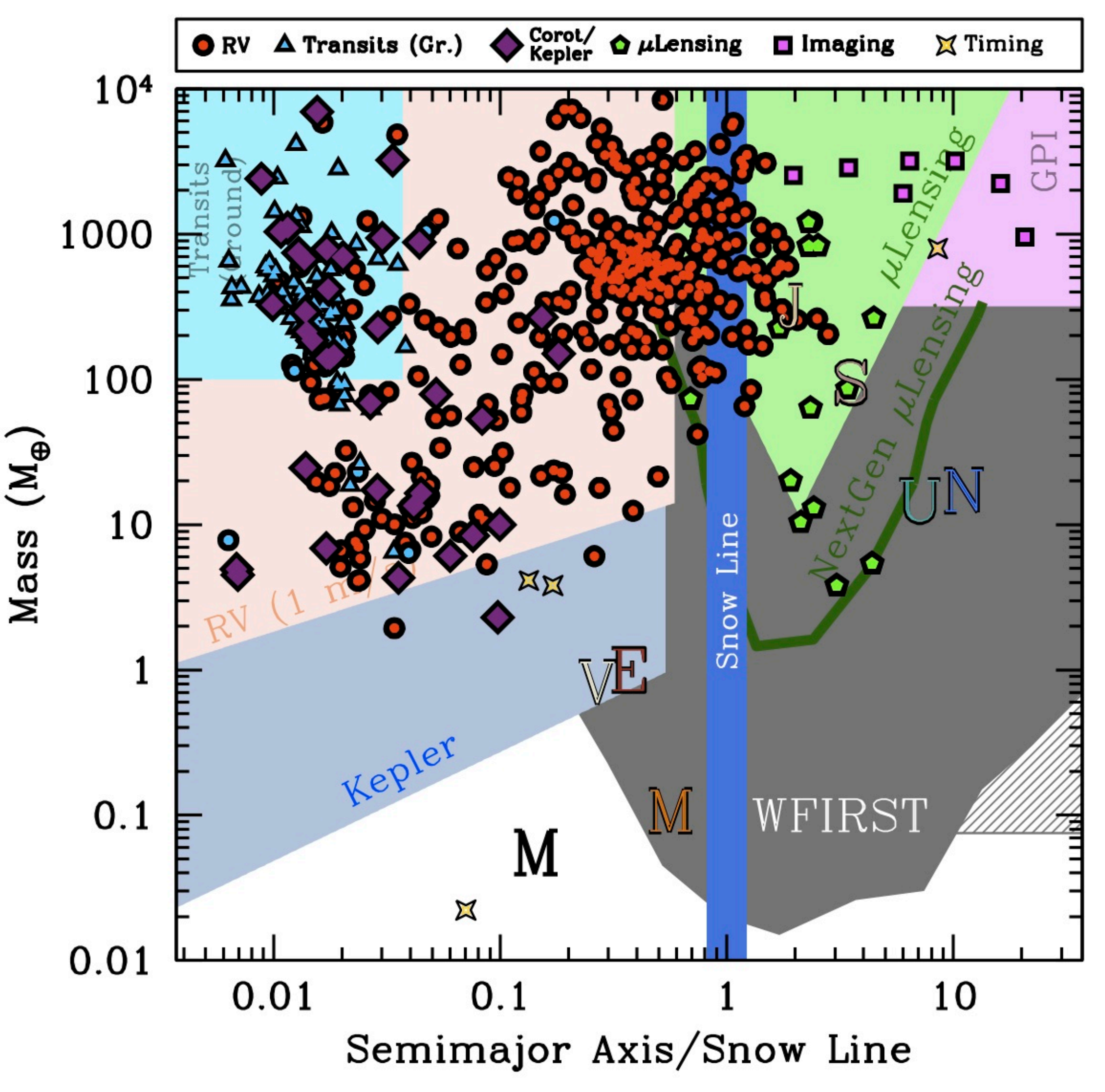

# Summary.

- Planet formation is hard.
- The demographics of planets beyond the snow line provides crucial constraints on planet formation theories.
- Understanding habitability likely requires a broad picture of exoplanet demographics.
- Microlensing surveys have already provided intriguing information about planets beyond the snow line.
- Space-based surveys enable qualitatively new, exciting science: sub-Earth-mass planets, free-floating planets, outer habitable zone planets, mass measurements.