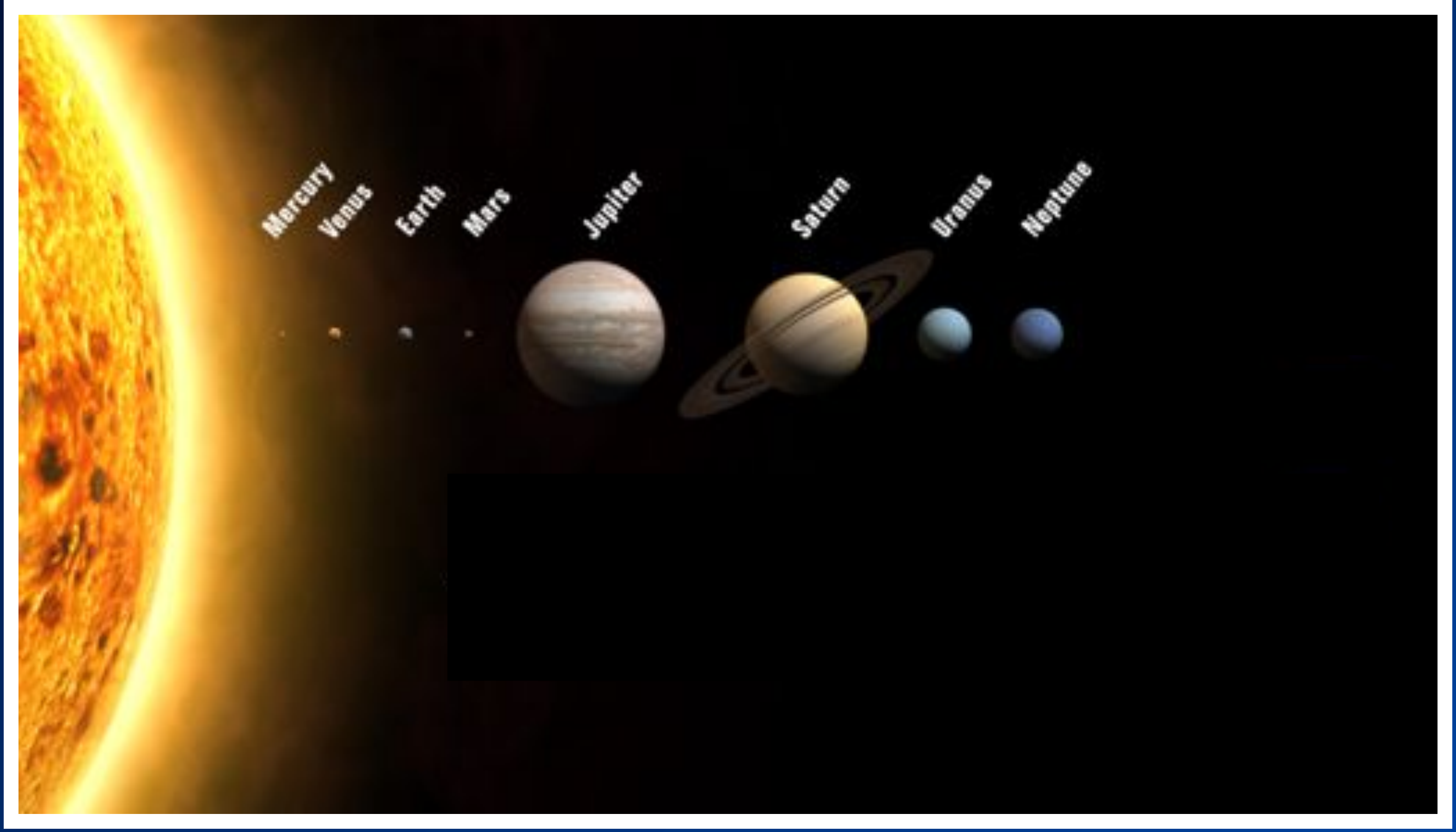
How to Conduct an Exoplanet Census.

Scott Gaudi
The Ohio State University

Backstory. Before 1995…



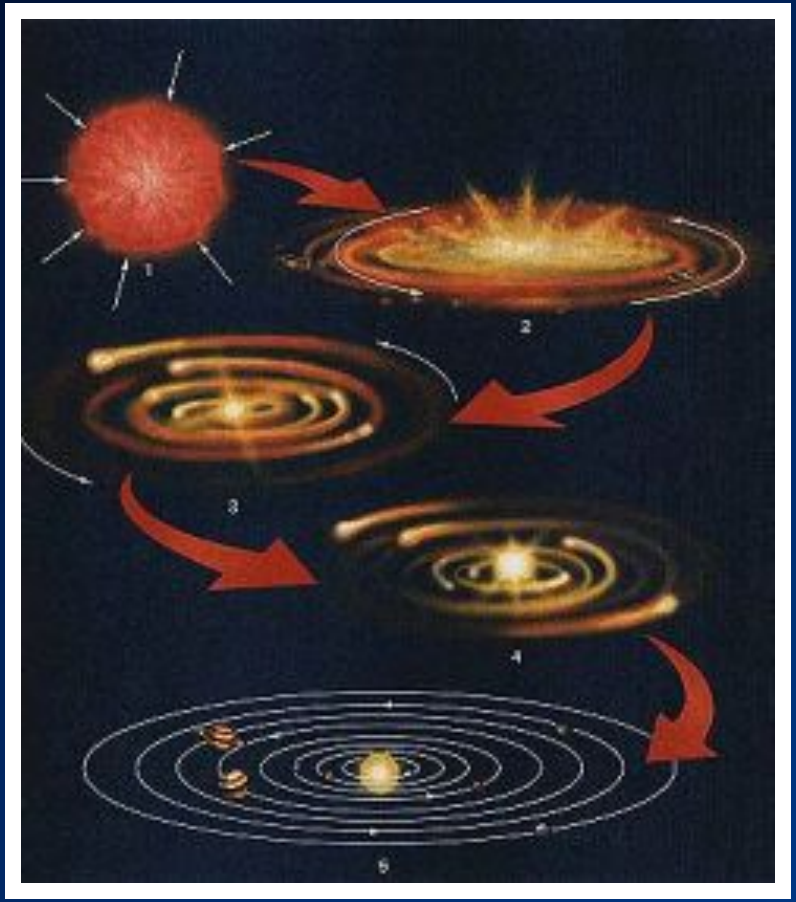
Planet Formation.

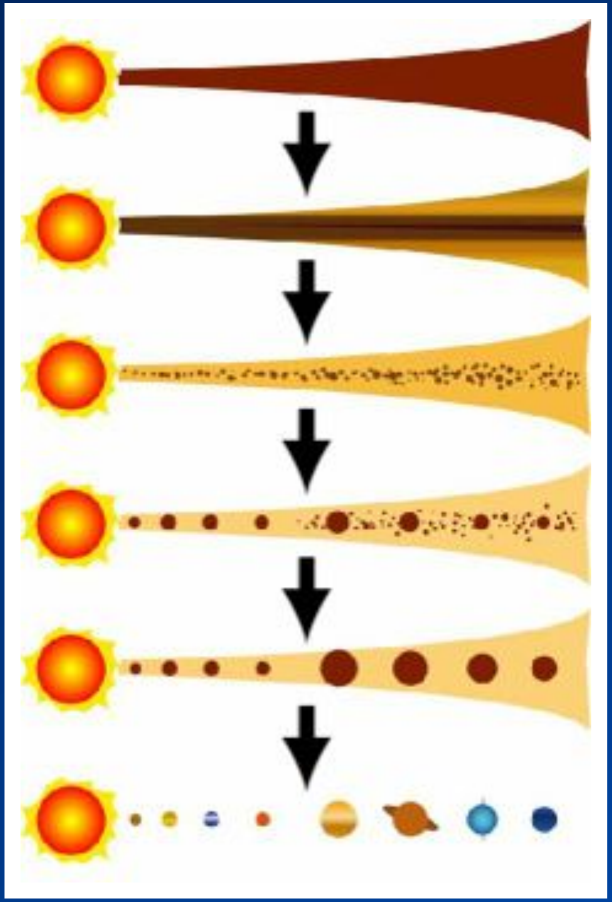
Must understand the physical processes by which micron-sized grains in protoplanetary disks grow by $10^{\sim 13\text{-}14}$ in size and $10^{\sim 38\text{-}41}$ in mass.

Hard!

A Fairy Tale.

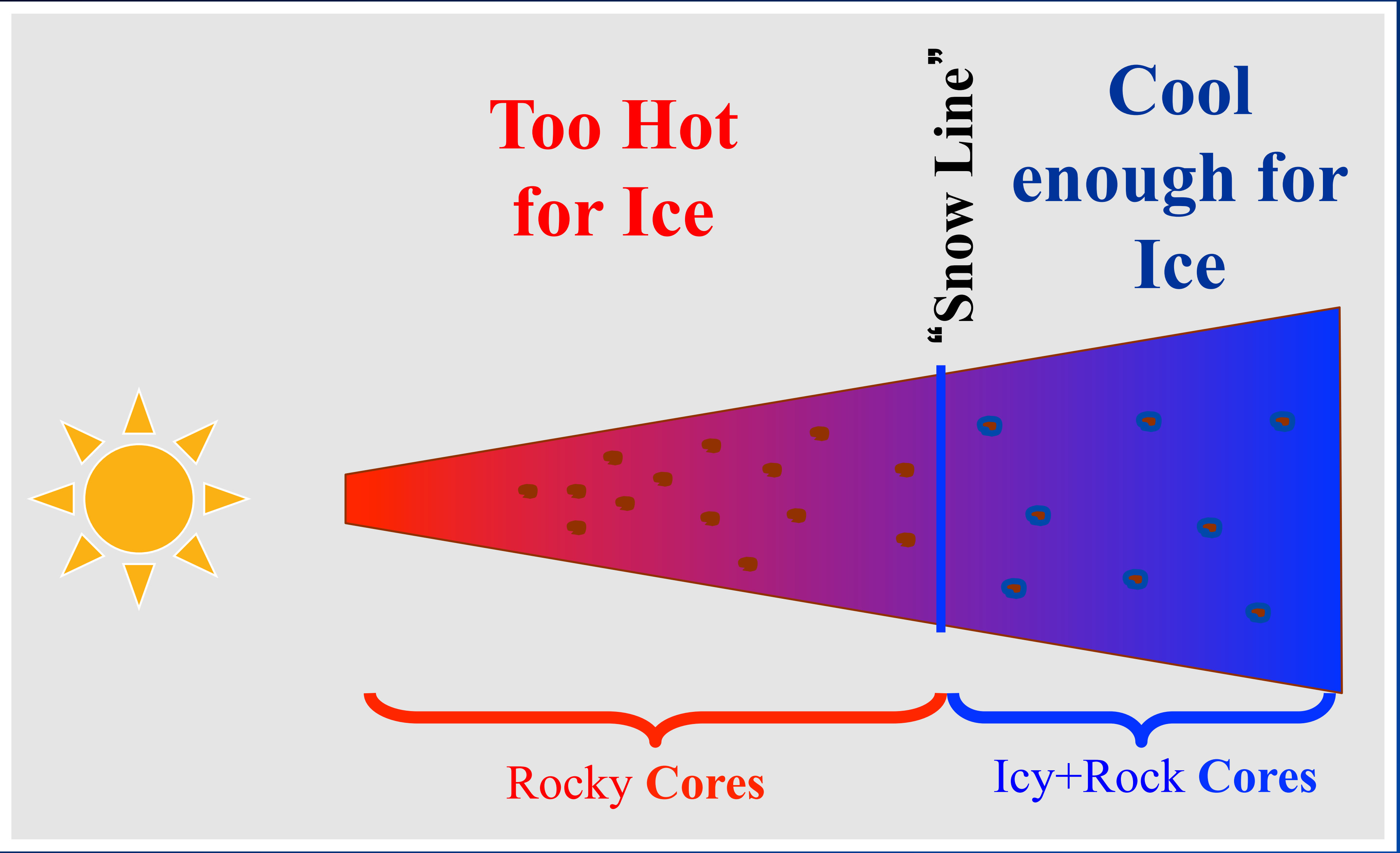
Bottom-Up Planet Formation.



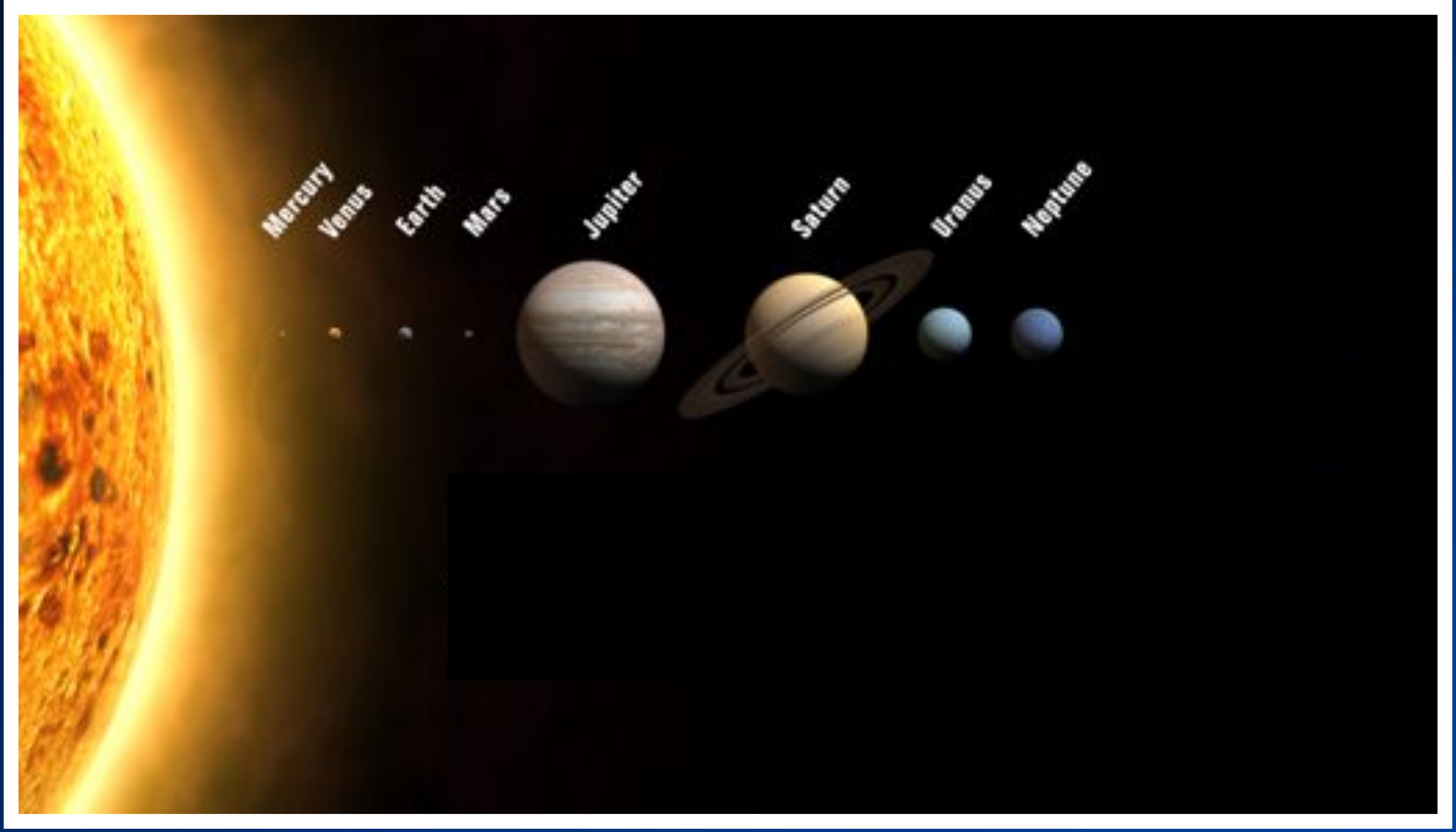


(e.g., Lissauer 1987; Ida & Lin 2004, 2005)

The Snow Line.



Matched Data Well.



1995: A Planetary Companion to 51 Peg

(Mayor & Queloz 1995)

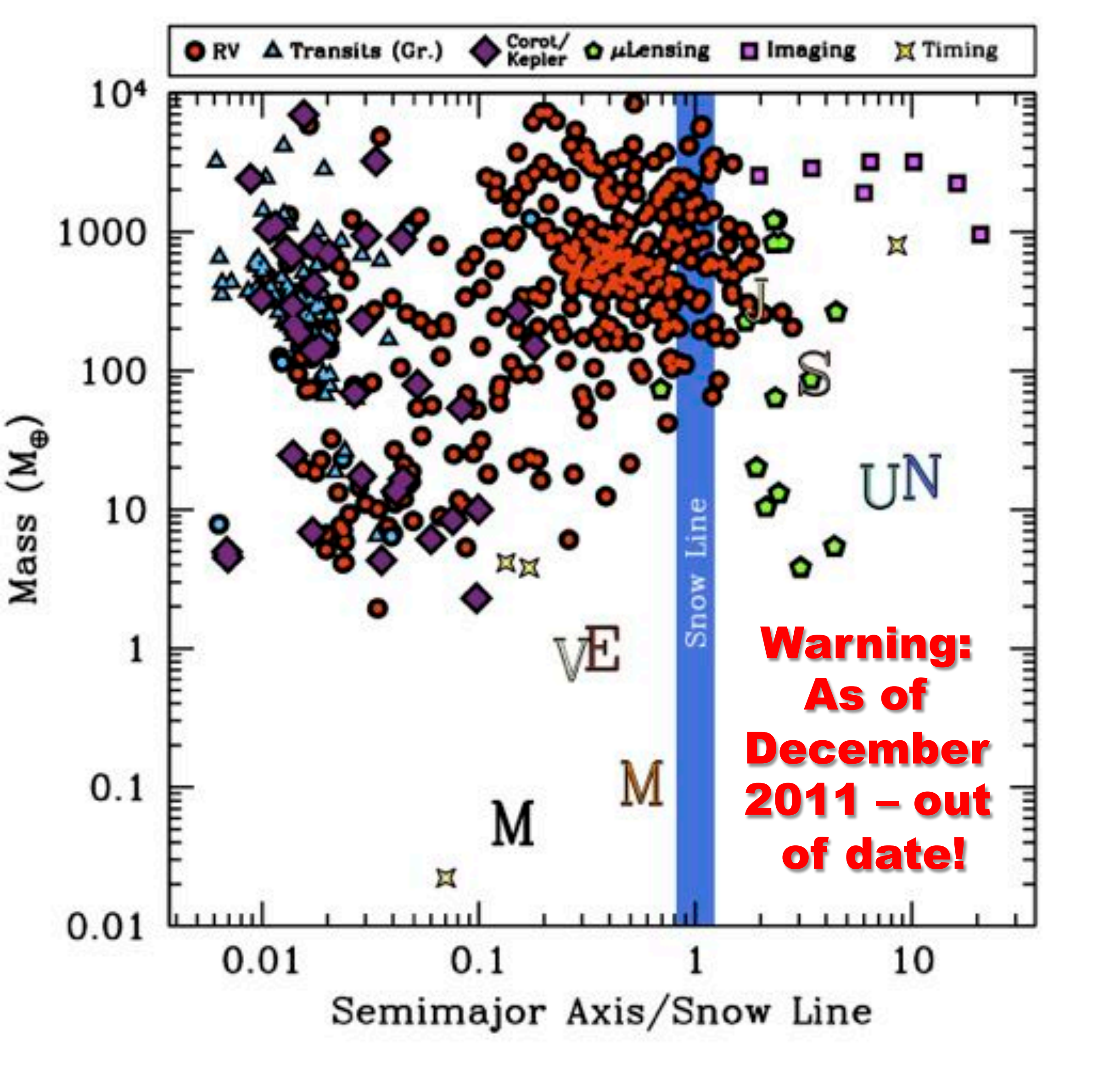
Planet formation is *really* hard!

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.



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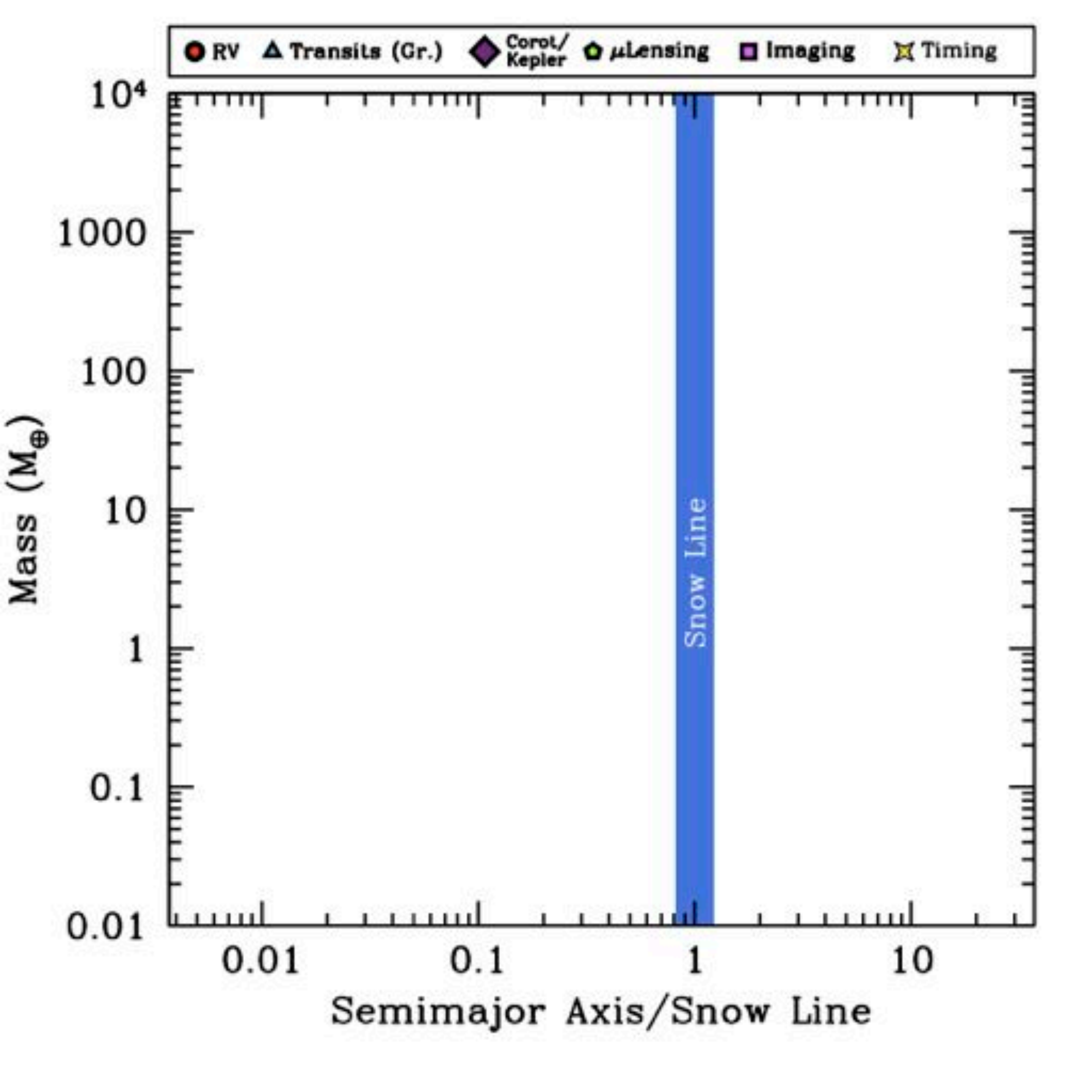

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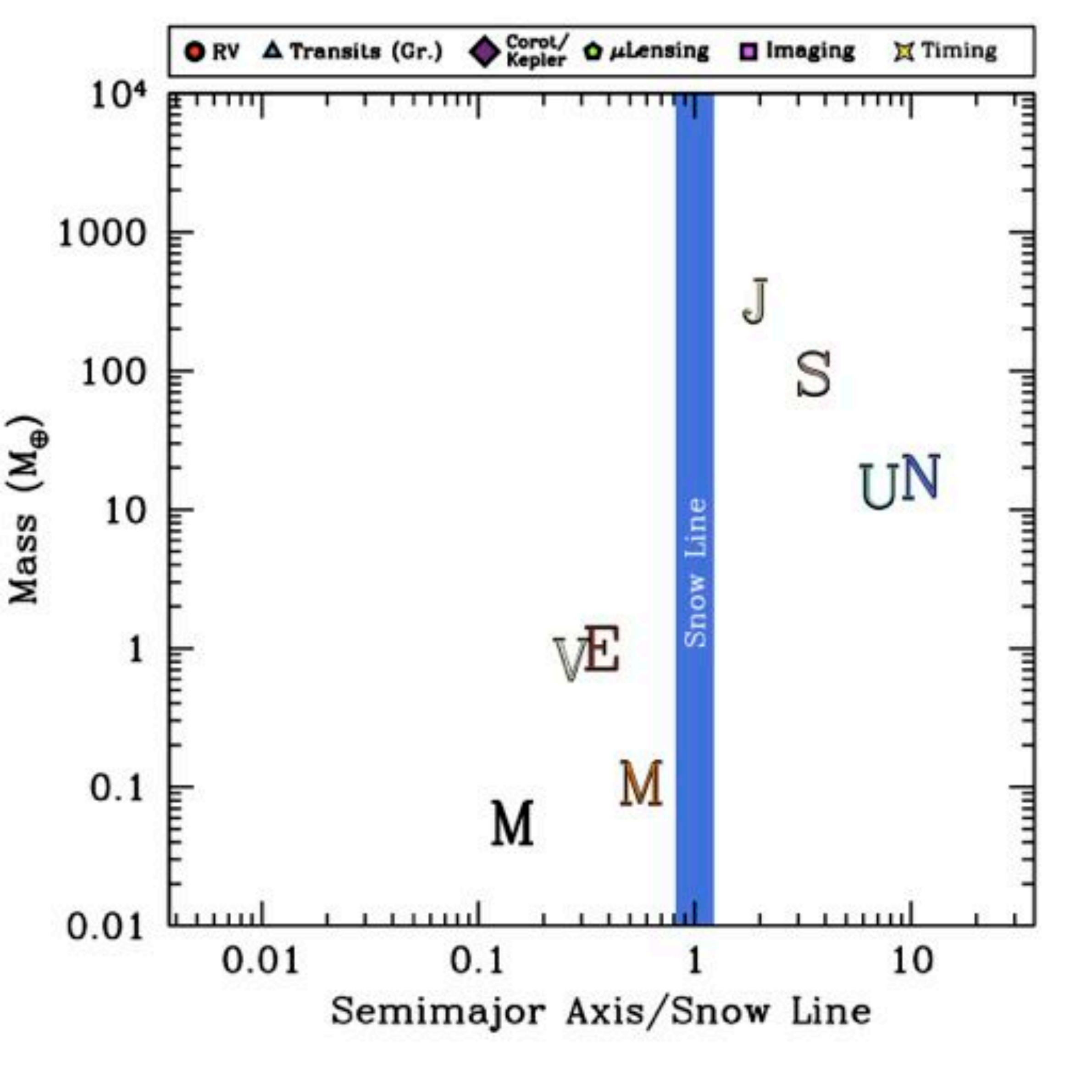

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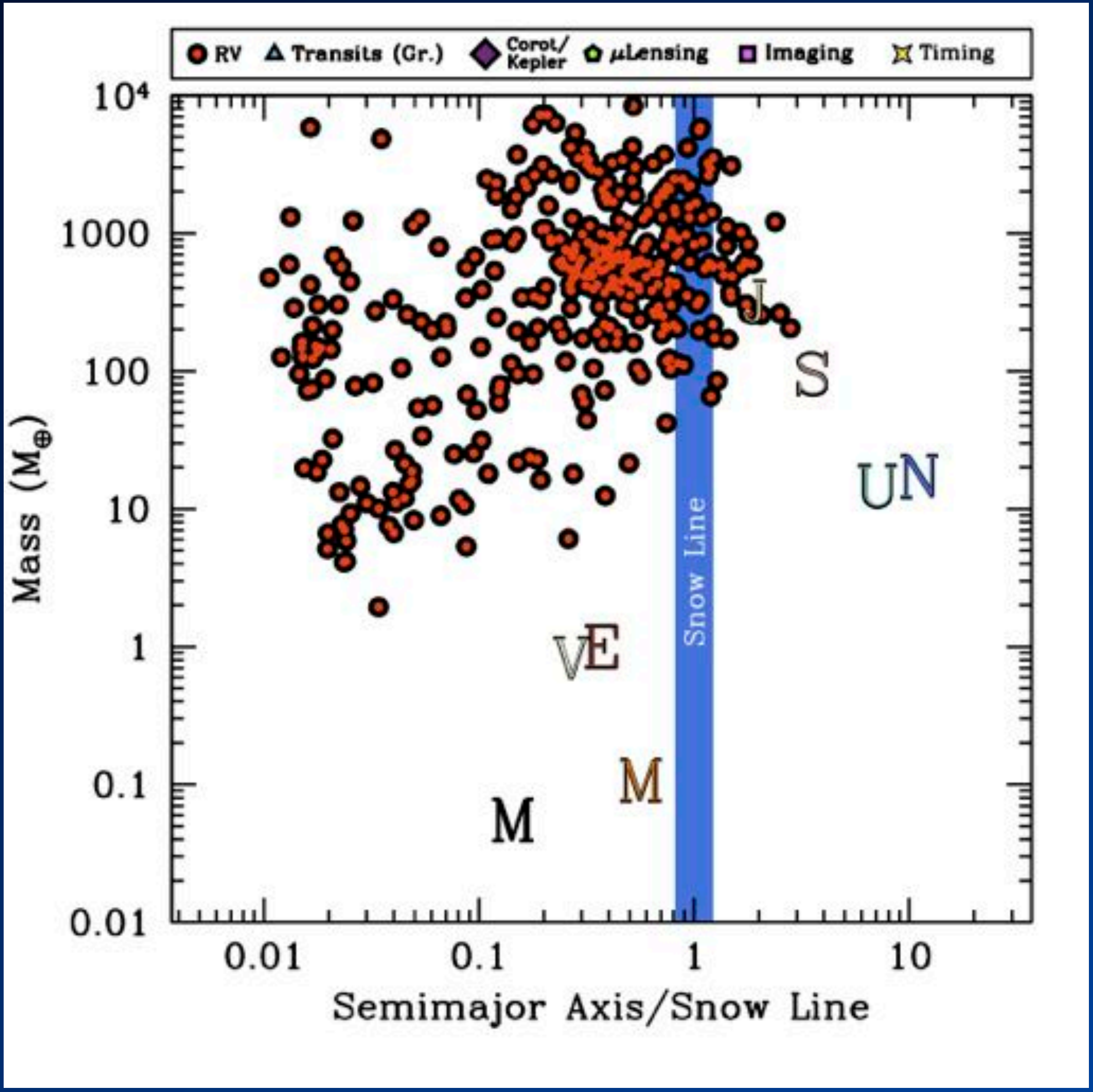

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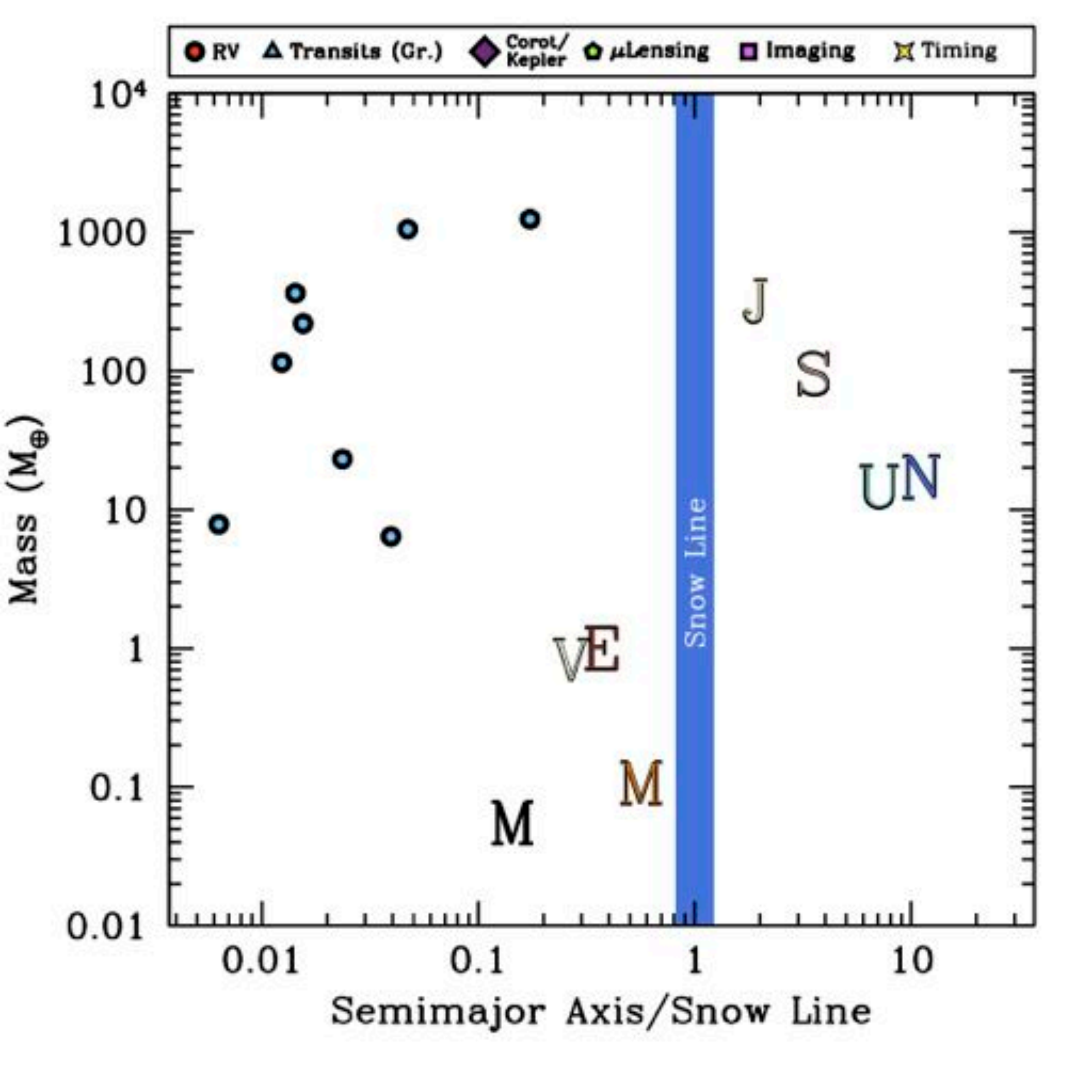

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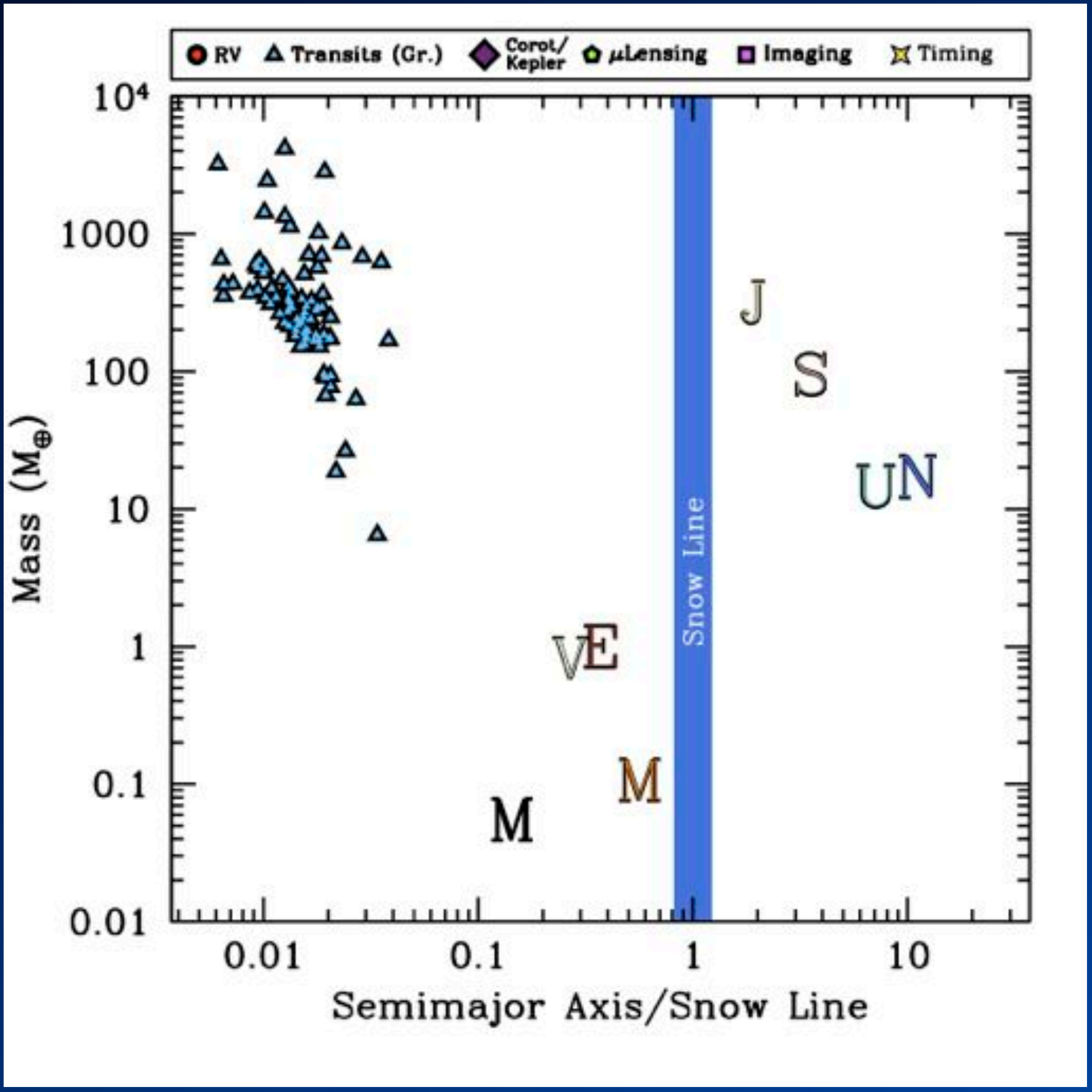

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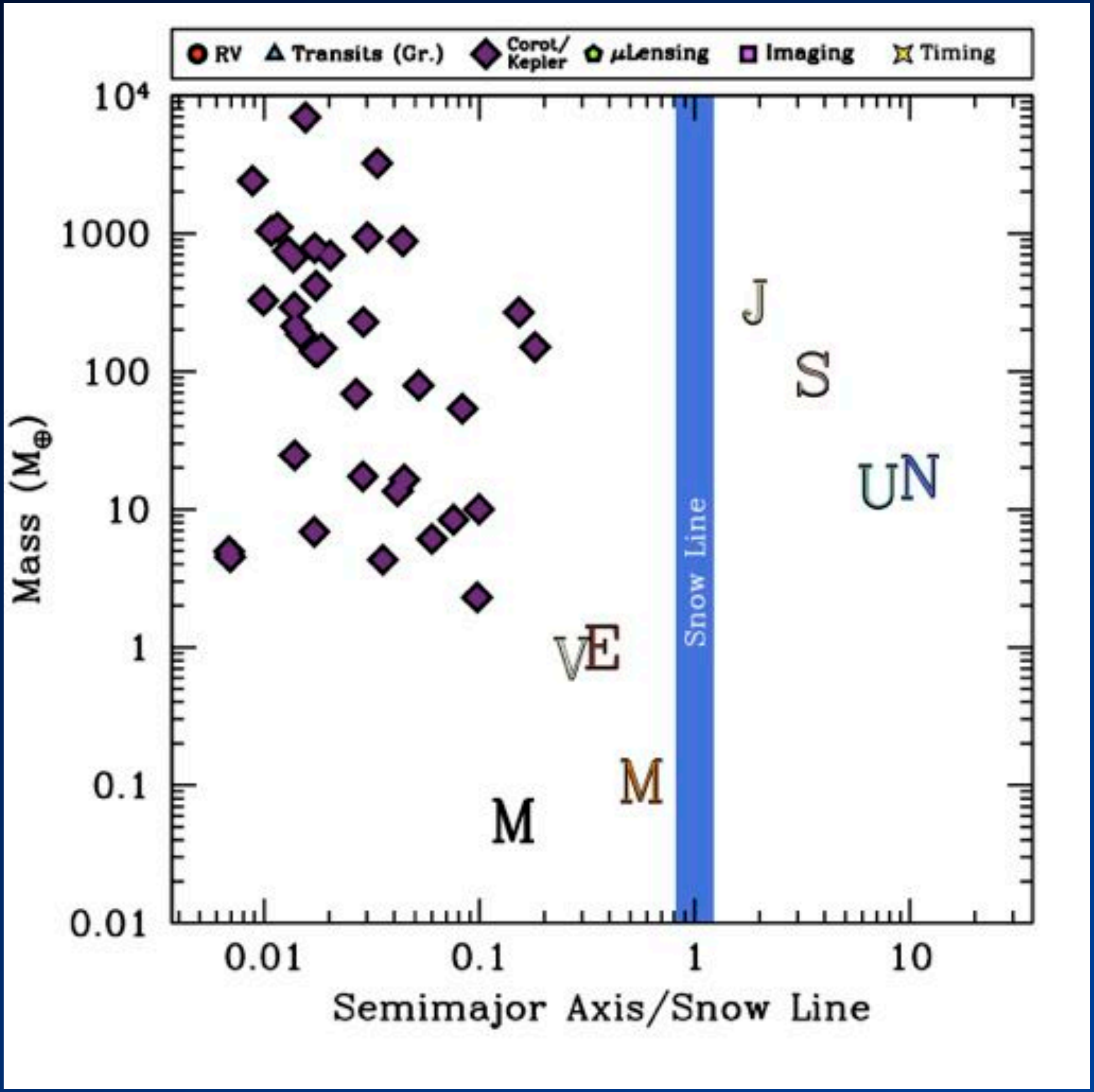

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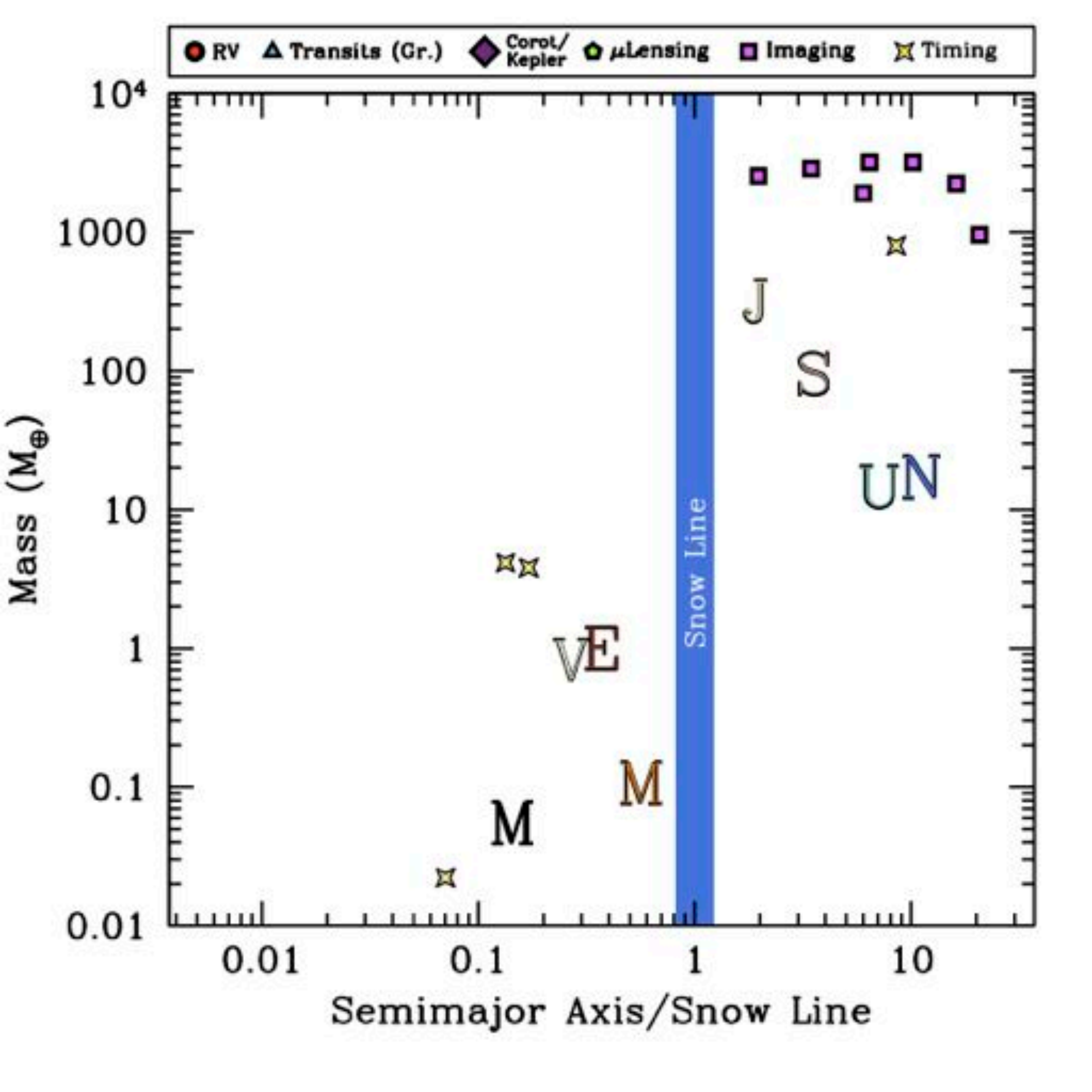

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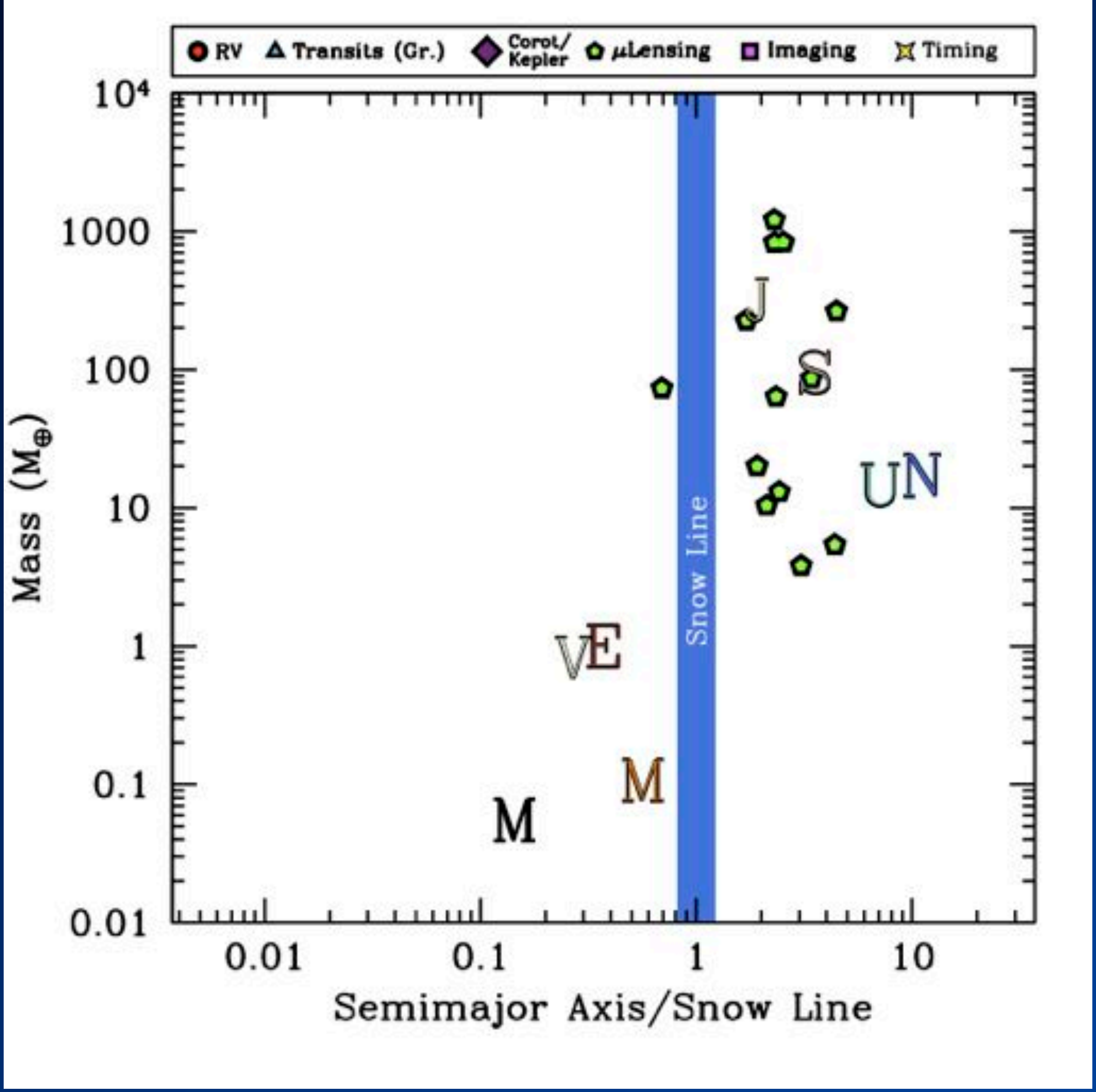

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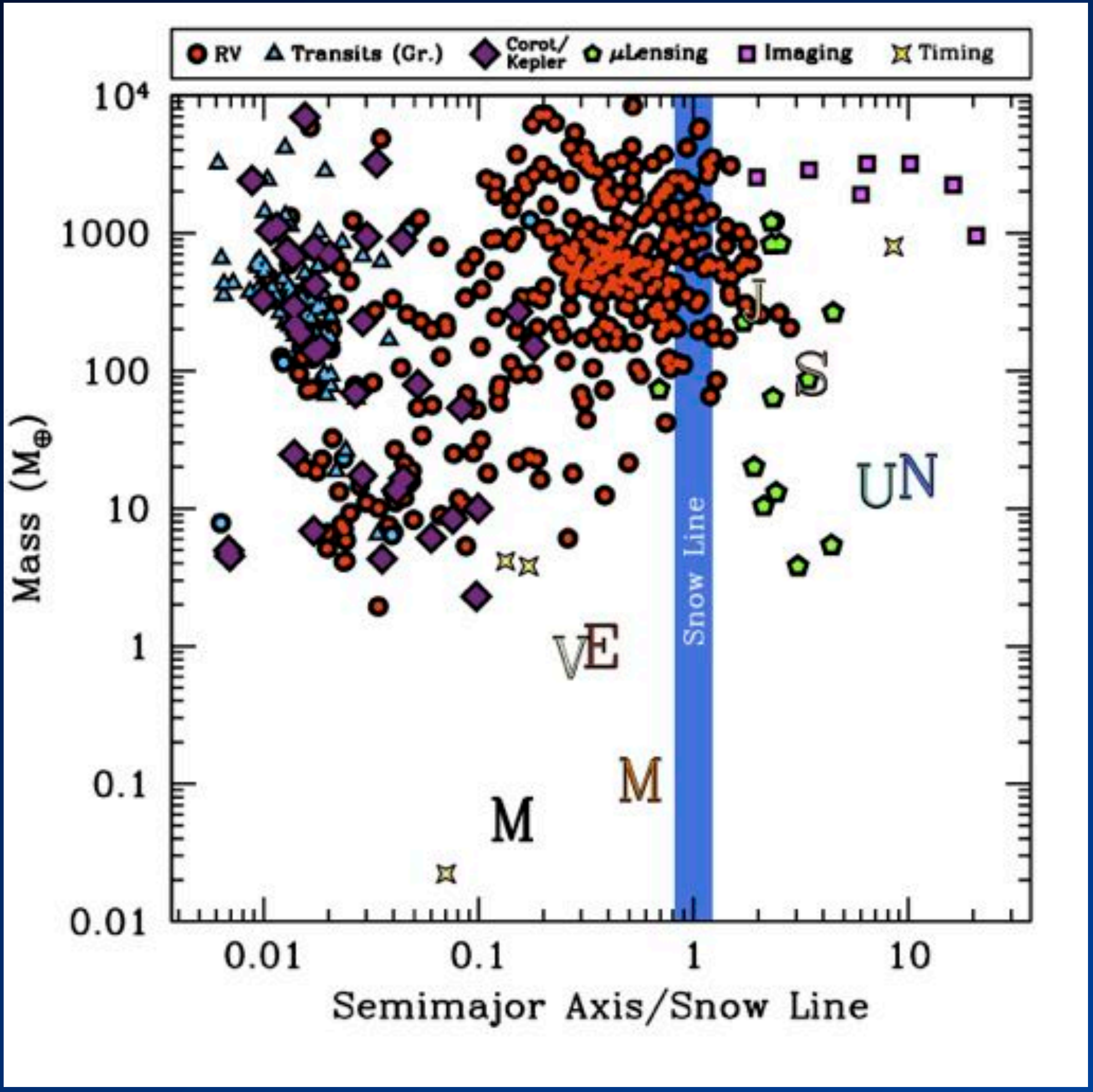

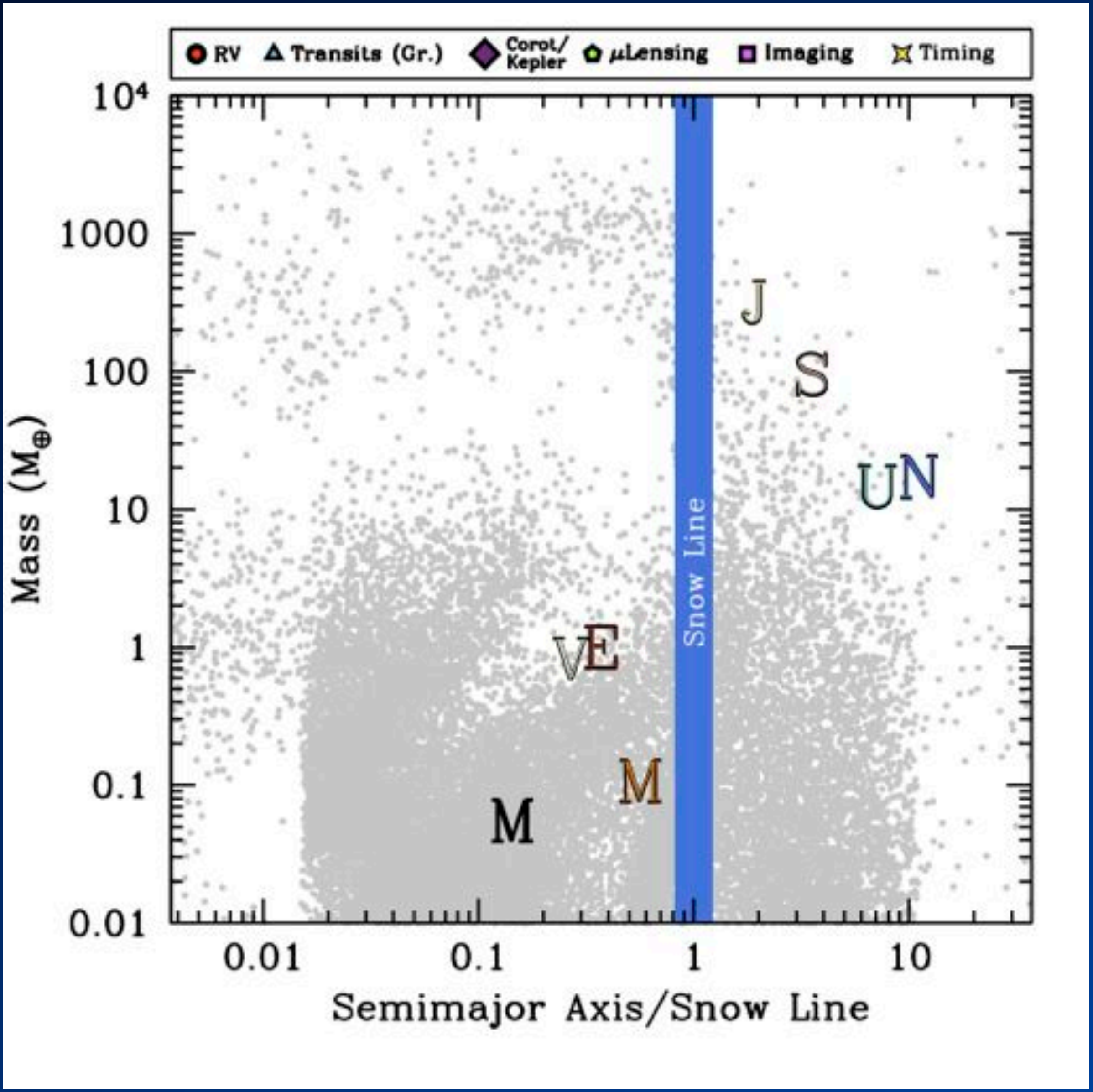
RV
Transits (Gr.)
Corot/ Kepler
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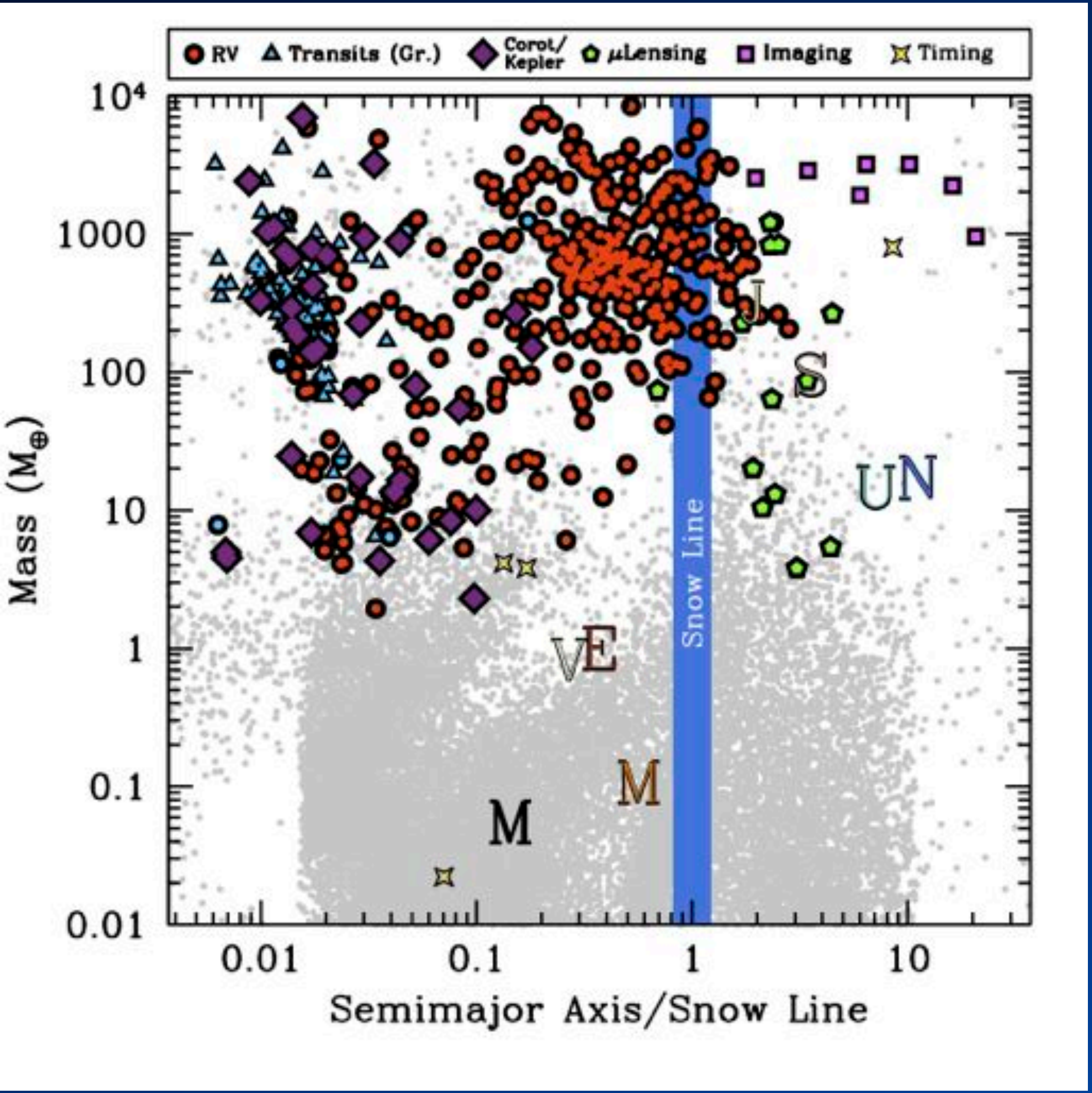
(Ida & Lin)



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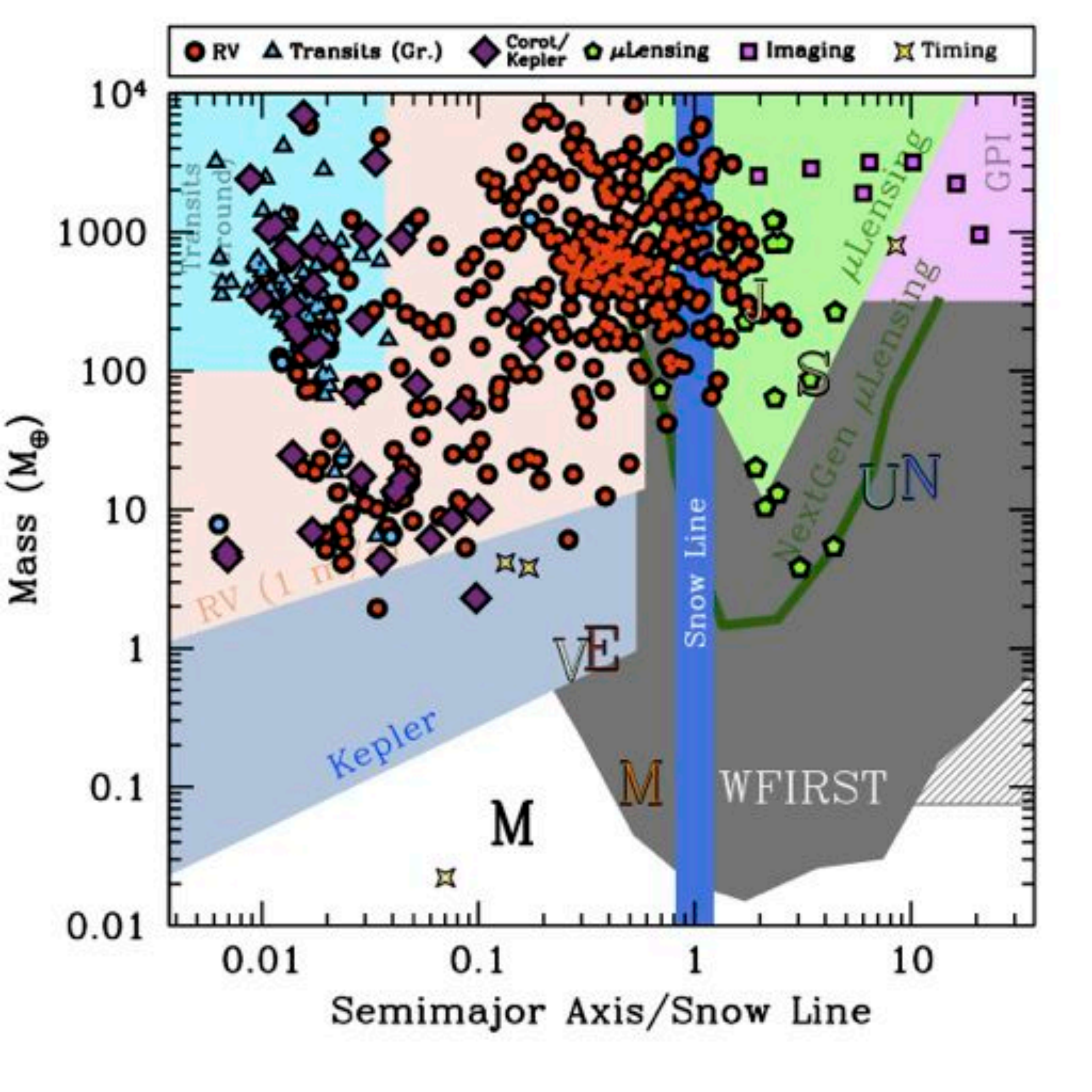
Taking the Census of Exoplanets.

- Physical processes at work during planet formation and evolution are imprinted in planet distributions.
- 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, take the ***census*** (or determine the ***demographics***) of exoplanets.
- Must employ all the detection methods at our disposal!

Synergy of Detection Methods!



Plethora of Methods.

- Timing.
- Radial velocities.
- Transits.
- Microlensing.
- Direct Imaging.
- Astrometry.

Confusing at first, but: the underlying physics of all of these methods is relatively simple; this physics dictates their sensitivity.

The Physics of Exoplanet Detection.

Physical Principles.

- Properties of light.
- Interaction of matter and light.
- Gravity.
- (…and conservation laws.)

Light.

- Particle and wave.
- Speed of light is constant in vacuum.
- Characterized by wavelength or frequency or energy -> electromagnetic spectrum.
- Luminosity is the total amount of light emitted by a body per unit time: intrinsic.
- Flux is the apparent amount of light at a given distance.
  - $F=L/4\pi d^2$

Matter and Light.

- Matter can reflect light.
- Matter can absorb light.
- Matter can emit light.
- Temperature -> internal energy.
  - Absorb light -> higher energy -> higher temperature.
  - Emit light -> lower energy -> lower temperature.
- Blackbody radiation.
  - Anything with a finite temperature emits light.
  - Total amount depends on T^4xArea.

Gravity.

- Orbits.
  - P^2 is proportional to a^3
    - More distant planets orbit more slowly and take longer to complete an orbit.
  - Planets and stars orbit common center of mass.
    - $a_{\star}M_{\star}=a_p m_p$
- Deflection of light.
  - Light is a particle, so gravity deflects light.

Planet Detection Methods, Generalized.

Planet Detection Methods.

- What are the ways in which we can detect the presence of planets?
- Direct detection: planets emit light.
- Indirect detection: planets affect the observed properties of stars.

Direct Detection.

- Planets reflect light from star.
- Planets absorb light from star, then emit light.

Indirect Detection.

- Center of mass motion.
  - Astrometry.
  - Radial velocity.
  - Timing.

- Planet passing in front of a star.
  - Transits – planets block star’s light.
  - Microlensing – planets bend star’s light.

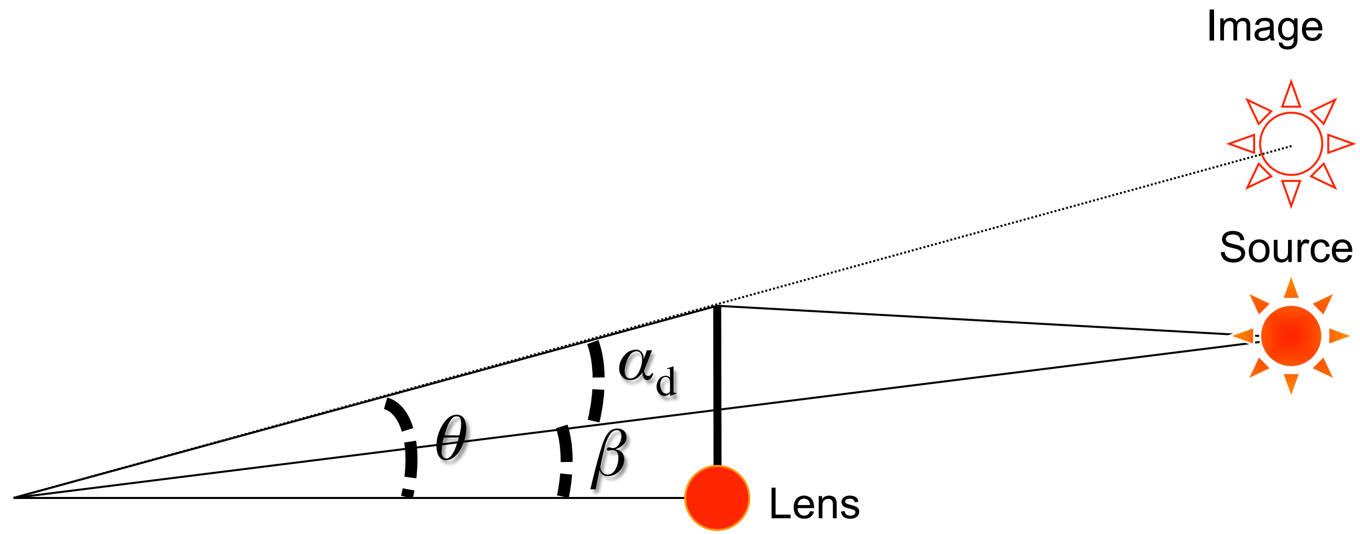
Understanding the Sensitivities of the Methods.

Example: Doppler & Astrometry.

- Stars orbit around center of mass.
  - What is the value for Earth/Sun?
  - Roughly $(M_{Earth}/M_{Sun}) \times AU \sim 450$ km
- Stars move along the line-of-sight.
  - What is the speed for the Earth/Sun?
  - $2\pi \times 450$km/year ~ 10 cm/s
- Stars move perpendicular to the line-of-sight.
  - What is the angular shift?
  - 450km/10pc ~ 0.3 μarcseconds

Microlensing.

Microlensing Basics.



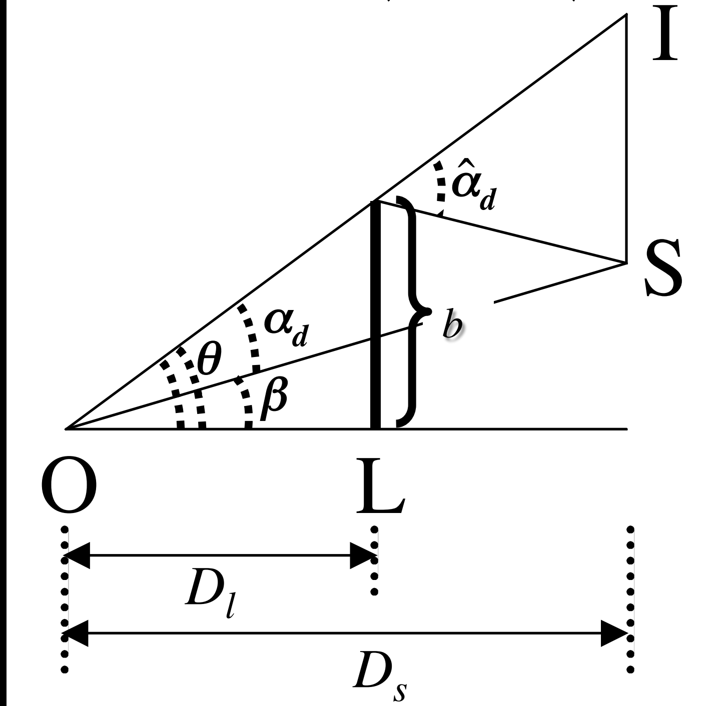
$$\beta = \theta - \alpha_d \text{ (Lens Equation)}$$

Deflection of Light.

- Light ray from the source passing by the lens gets bent by an angle
  $\hat{\alpha}_d$
- Heuristically, this can be estimated by assuming a photon will feel a velocity kick:

$$\hat{\alpha}_d \sim \frac{\delta v}{c} \sim \left(\frac{GM}{b^2}\right) \times \left(\frac{2b}{c}\right) \times \left(\frac{1}{c}\right) = \frac{2GM}{bc^2} = \frac{4GM}{\theta D_l c^2}$$

$$\beta = \theta - \alpha_d = \theta - \left(\frac{D_s - D_l}{D_s}\right)\hat{\alpha}_d$$



$$\beta = \theta - \alpha_d(\theta) = \theta - \left(\frac{D_s - D_l}{D_s}\right)\hat{\alpha}_d(\theta) = \theta - \left(\frac{D_s - D_l}{D_s D_l}\right)\frac{4GM}{c^2\theta} = \theta - \frac{4GM}{Dc^2\theta}$$

Einstein Ring Radius.

- Define the angular Einstein ring radius:

$$\theta_{\mathrm{E}}^2 = \frac{4GM}{Dc^2}$$

- The lens equation for a single lens is then:

$$\beta = \theta - \frac{\theta_{\mathrm{E}}^2}{\theta}$$

Rings and Images.

$$\beta = \theta - \theta_E^2 / \theta$$

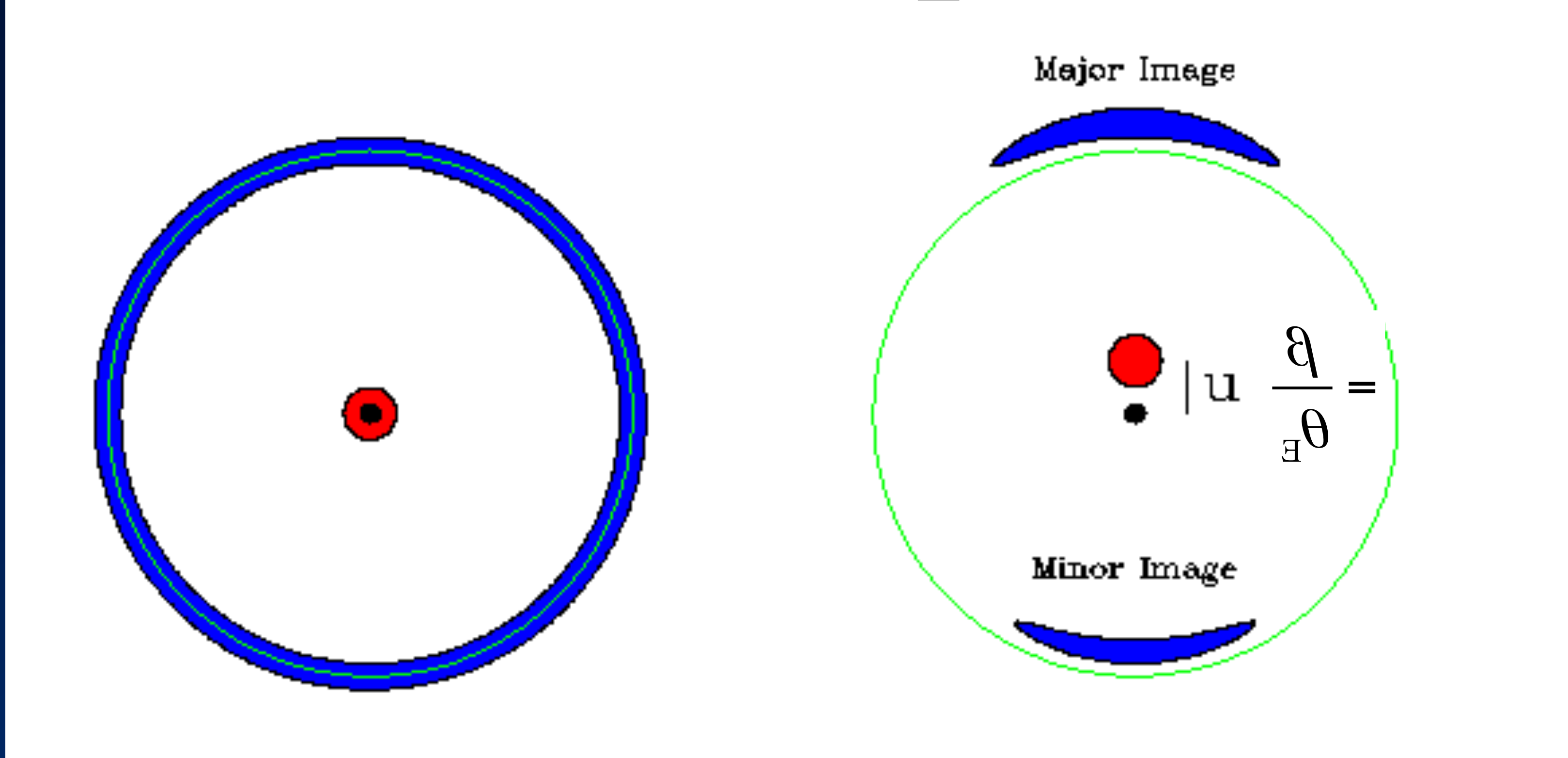
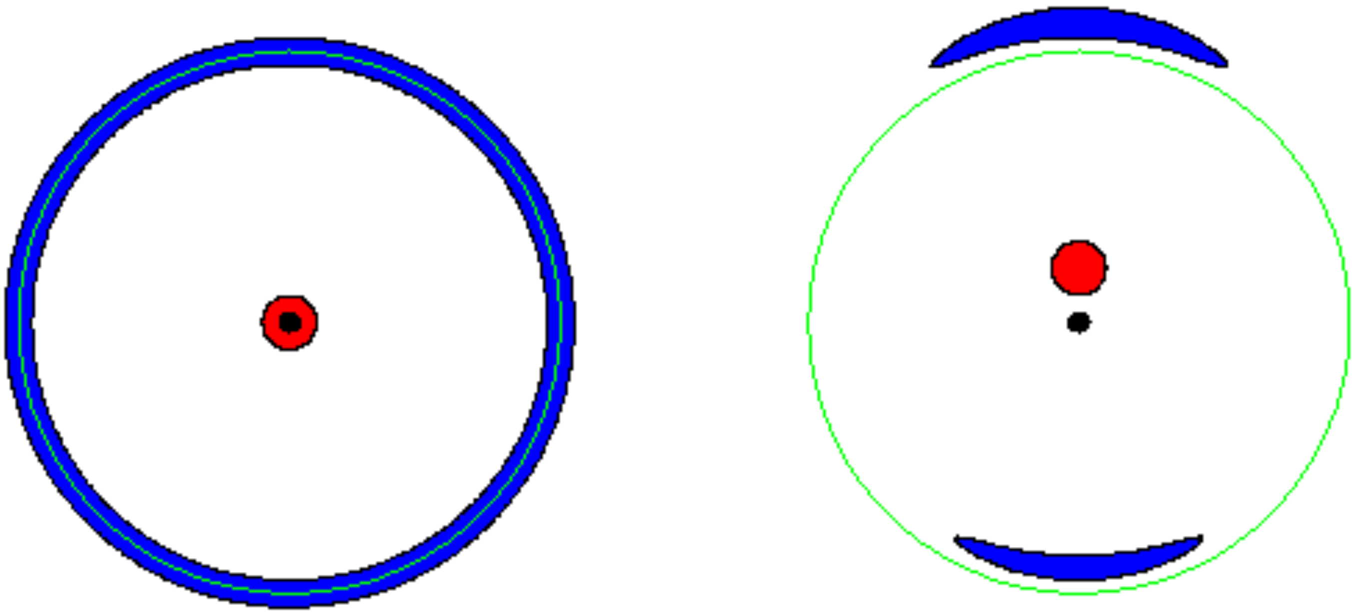


Image Separation $\approx 2\theta_E$

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

Rings and Images.

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



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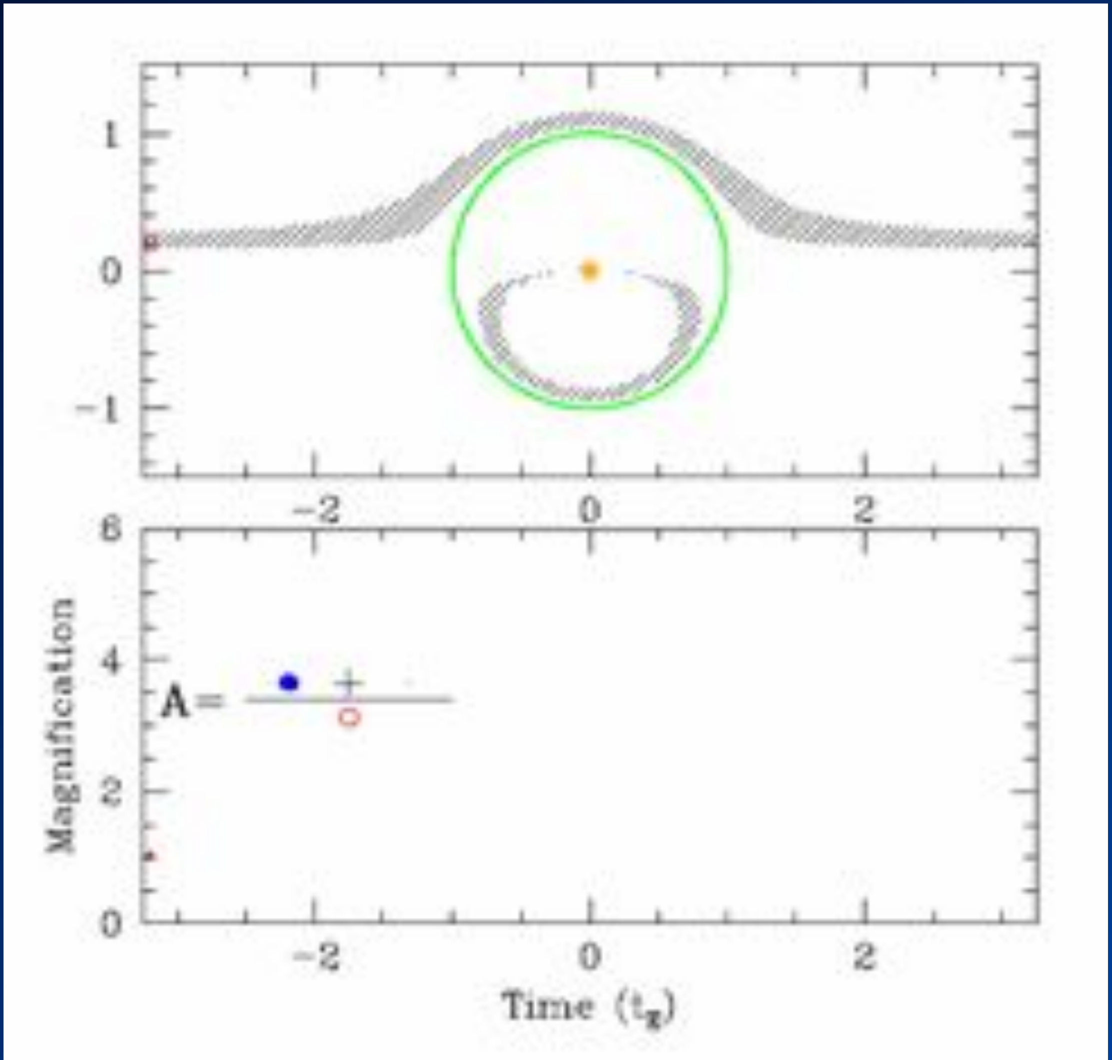
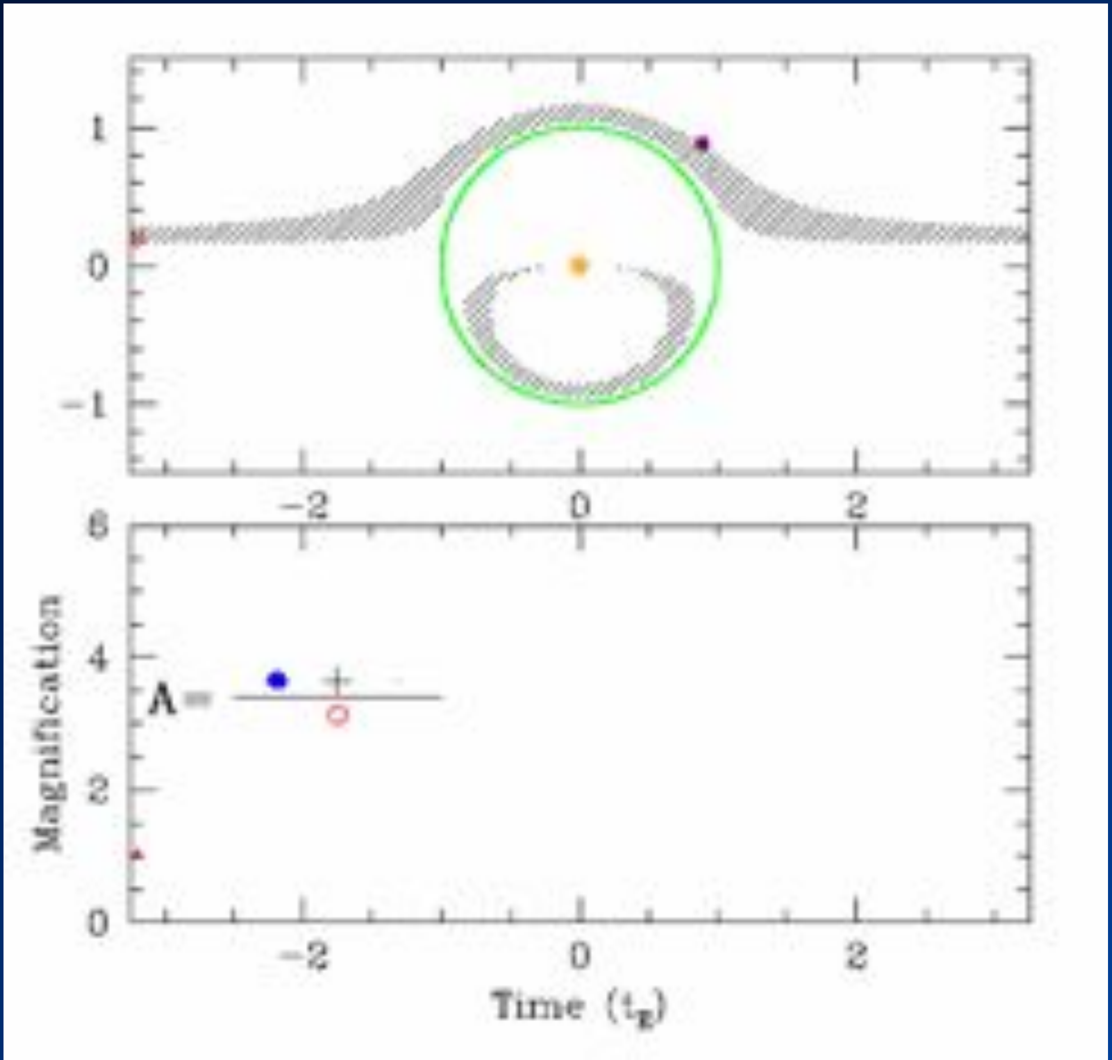
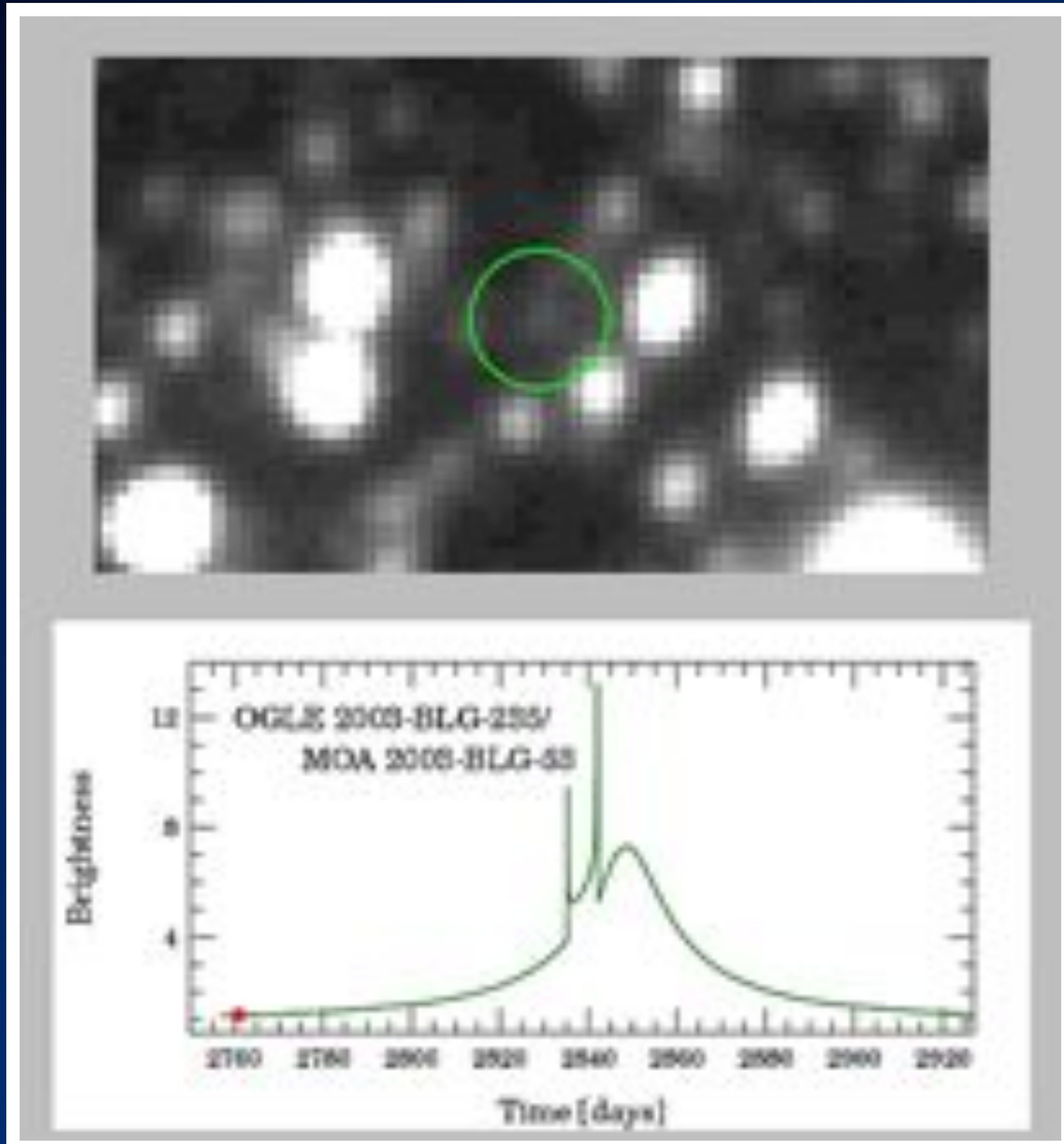
Microlensing Events.



Detecting Planets.



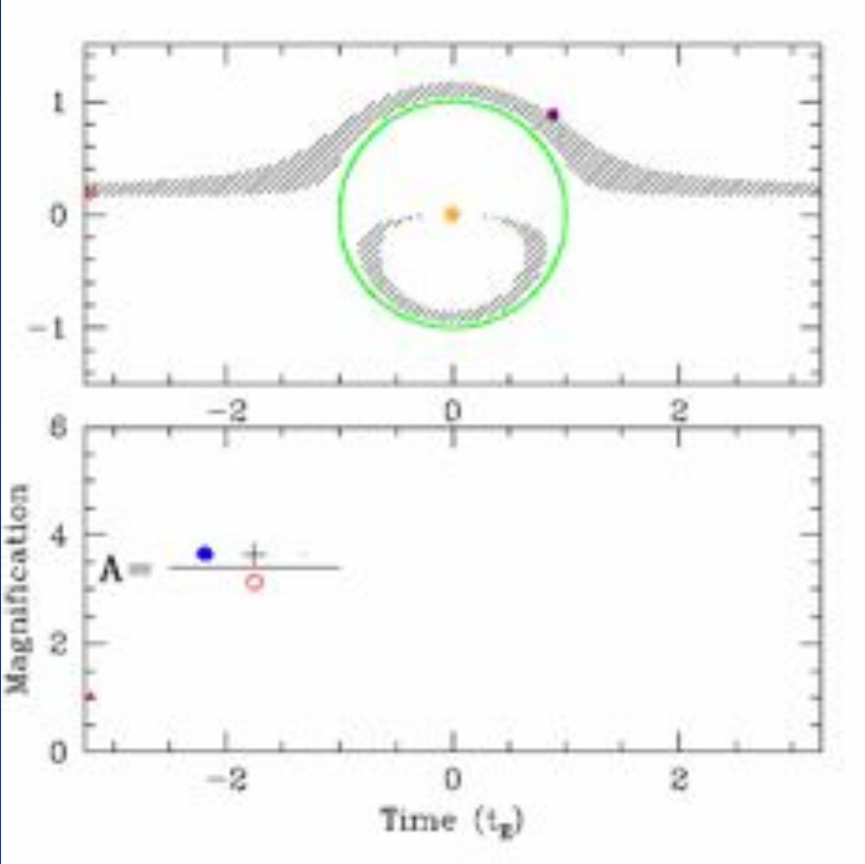


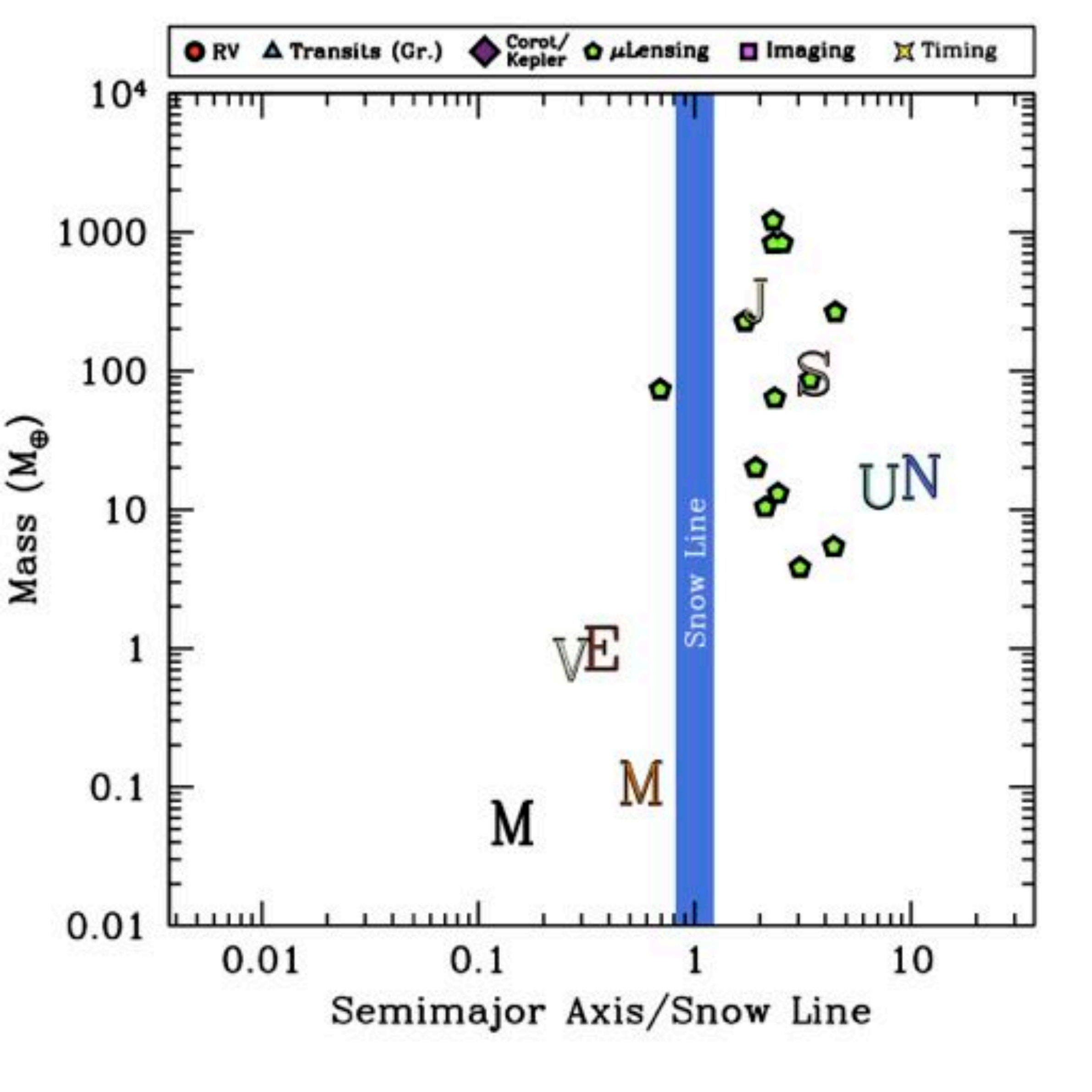
(Bond et al. 2004)

Which planets?

- Most sensitive to planets near the Einstein ring radius.

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





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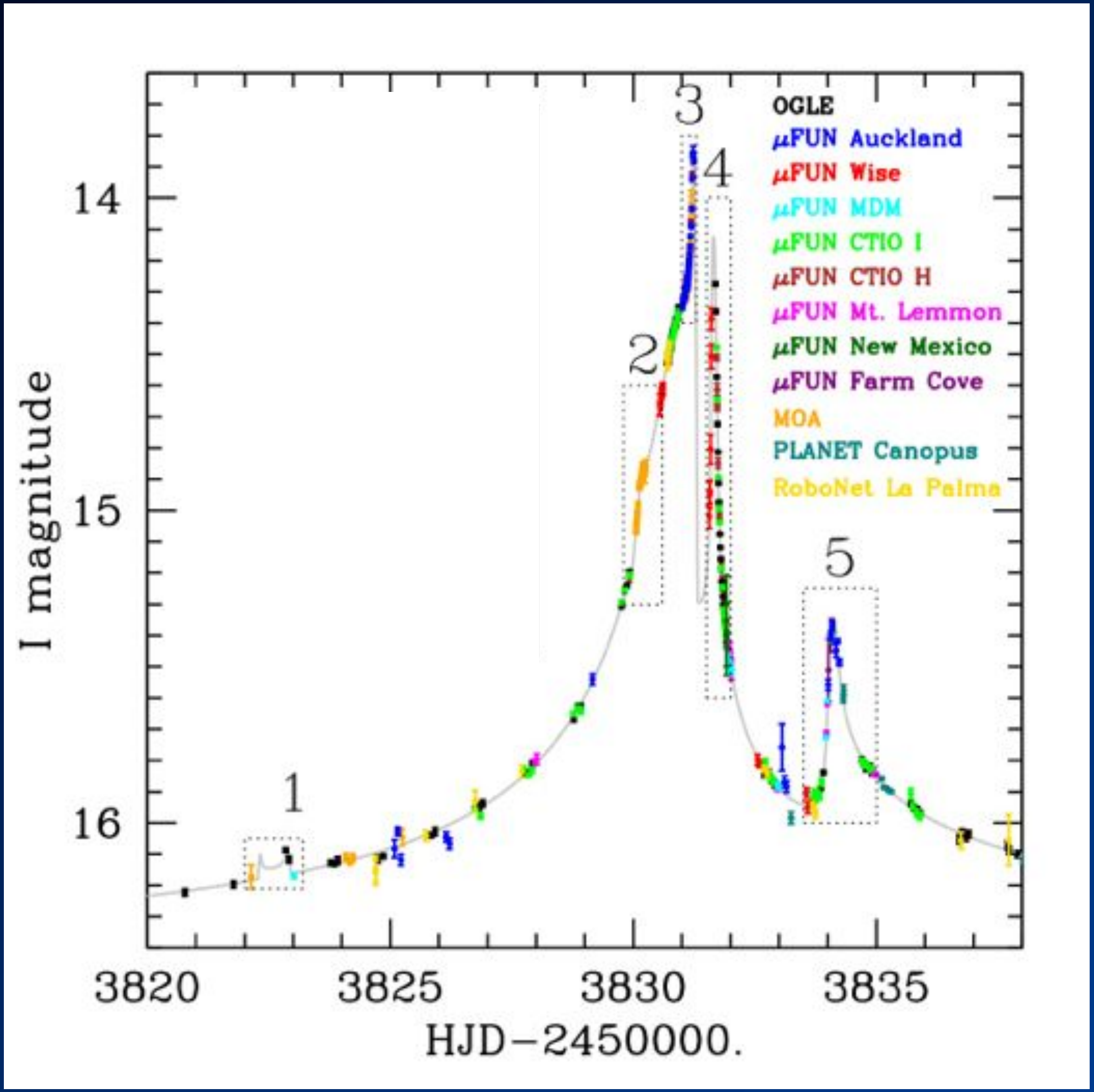
Example.

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}

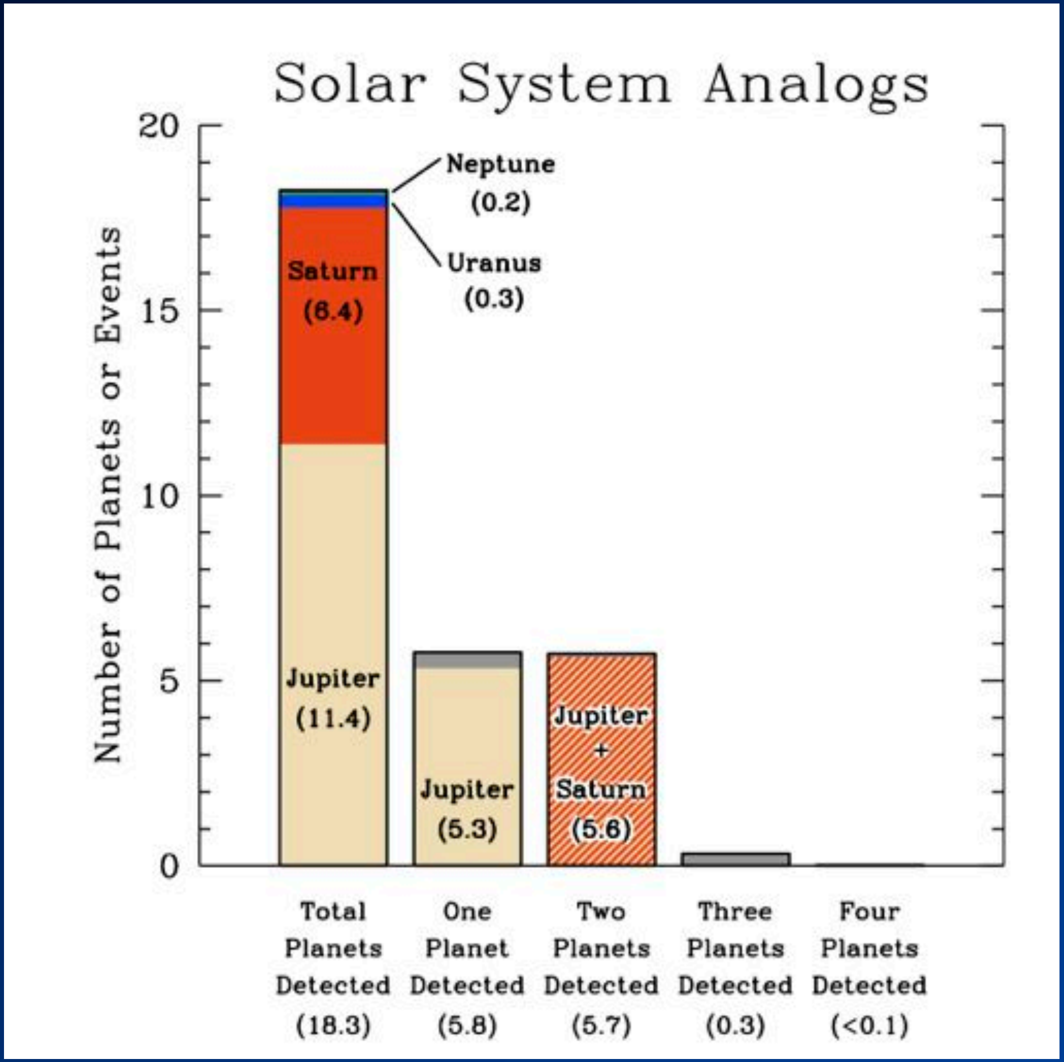
Semimajor Axis = 2.3 +/- 0.5 AU

Planet c:

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

Semimajor Axis = 4.6 +/- 1.5 AU

No Place Like Home?

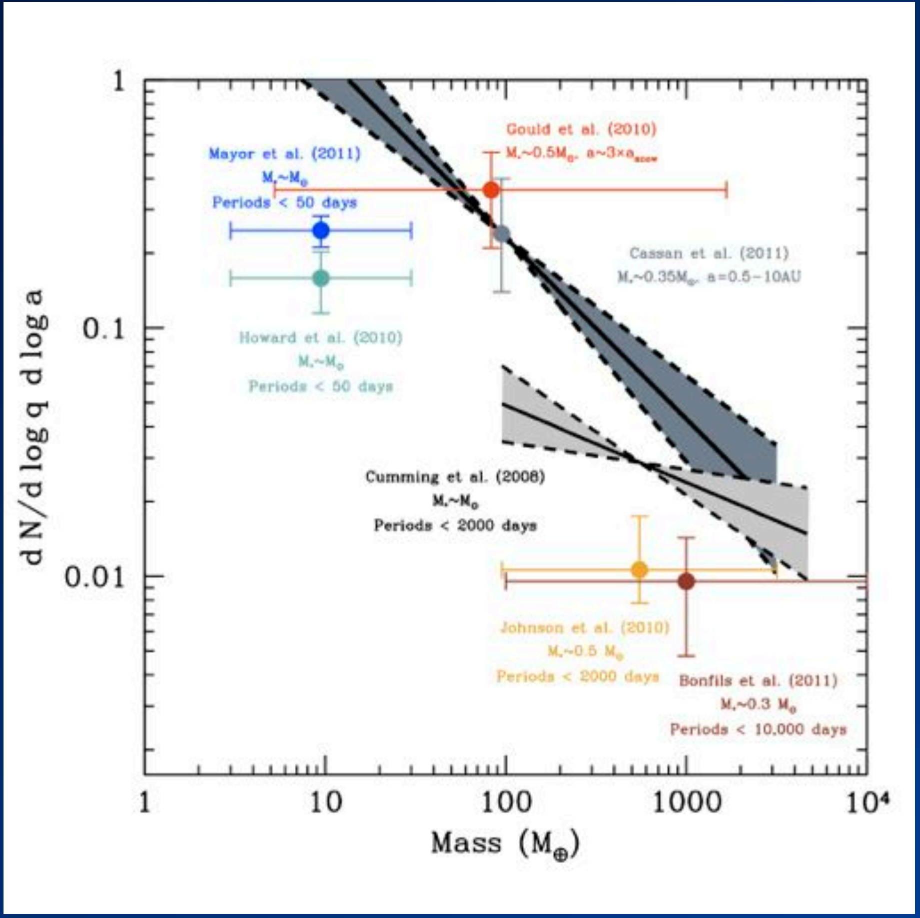


(Gould et al. 2010)

Frequency of Solar System Analogs:

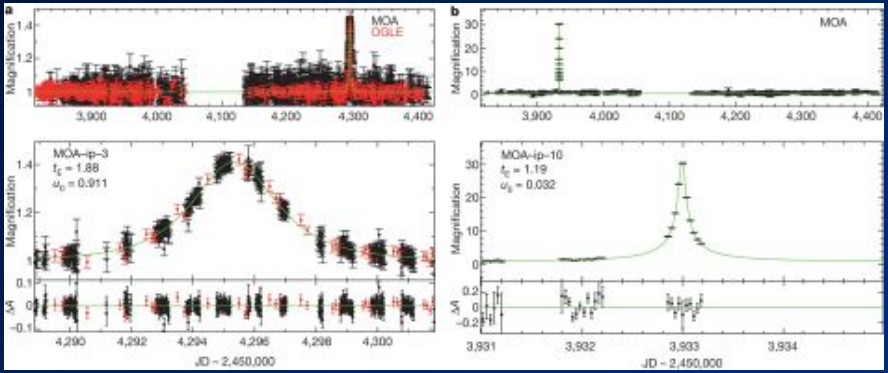
~15%

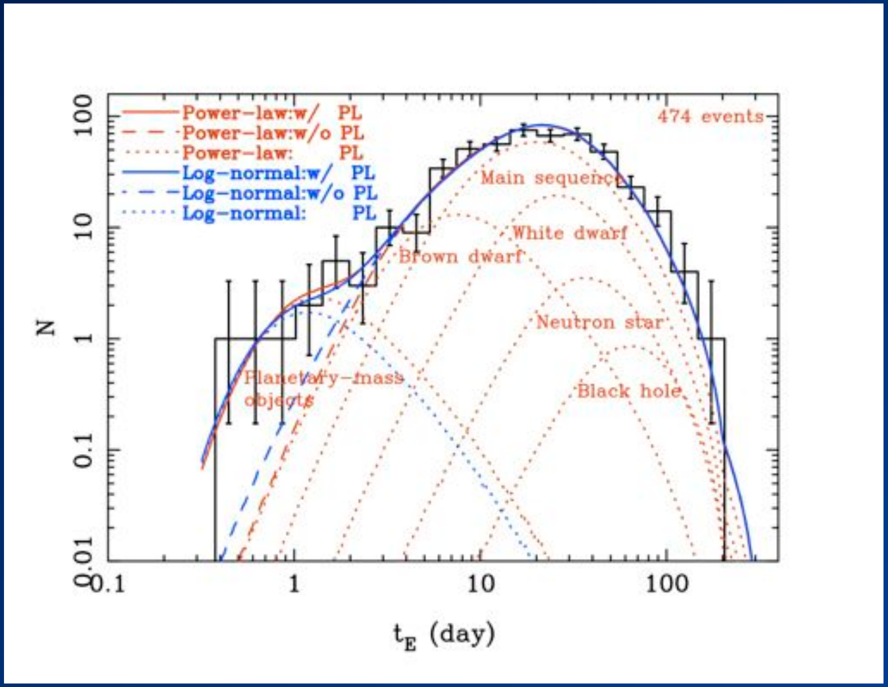
Demographics of Planets.



(Gould et al. 2010, Sumi et al. 2009, Cassan et al. 2011)

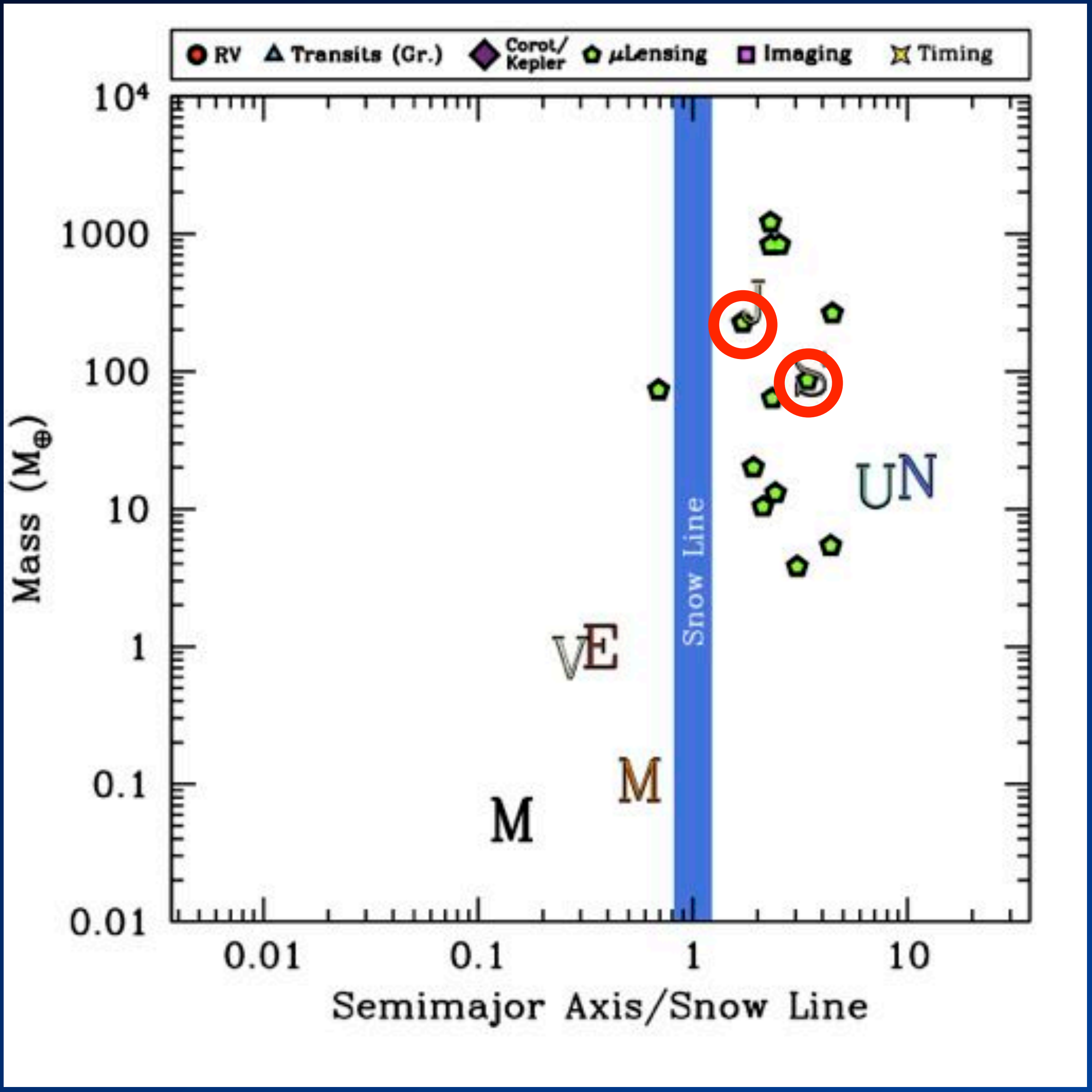
Free Floating Planets





Roughly one free-floating planet per star!

(Sumi et al. 2011; MOA + OGLE Collaborations)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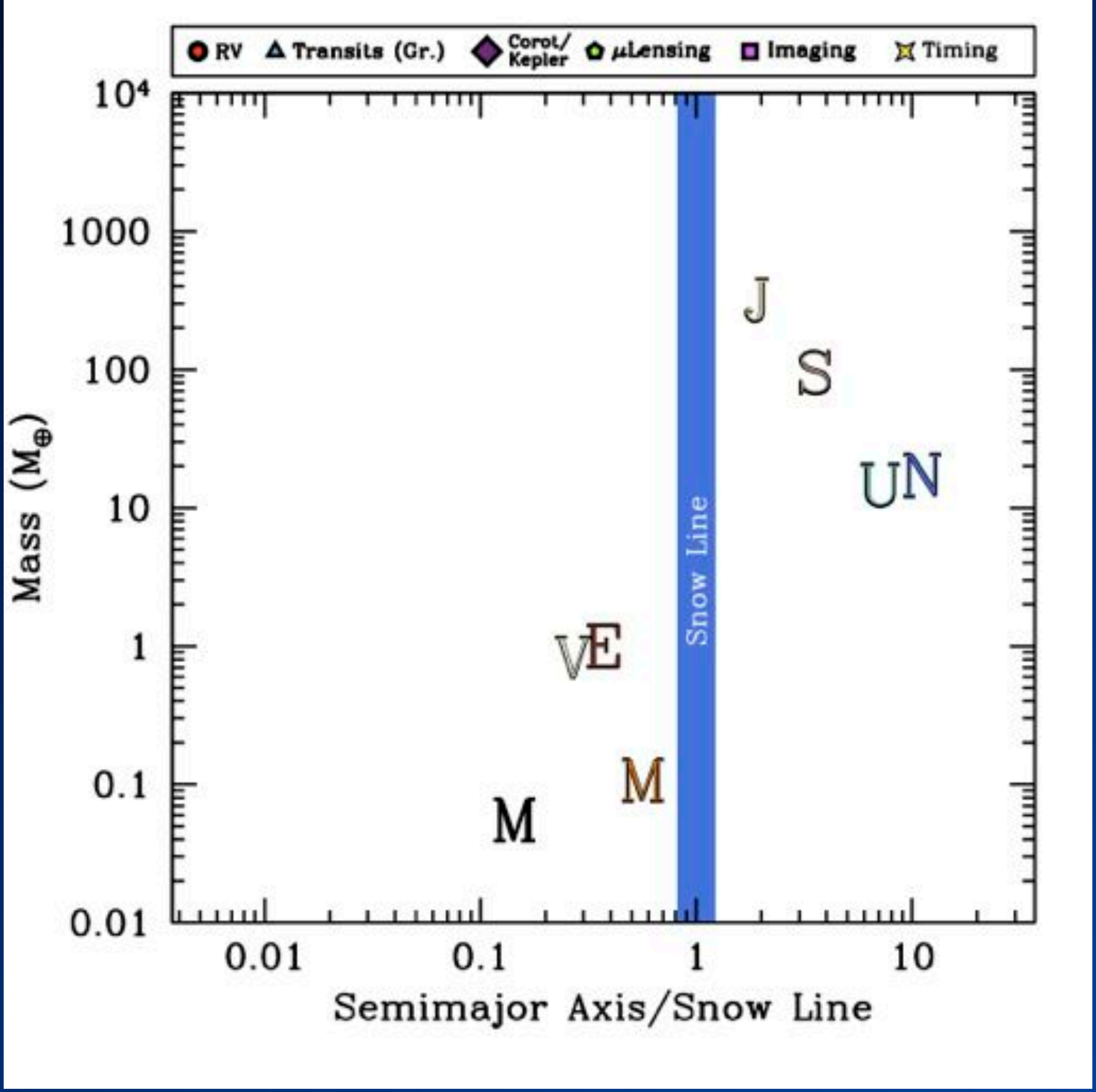
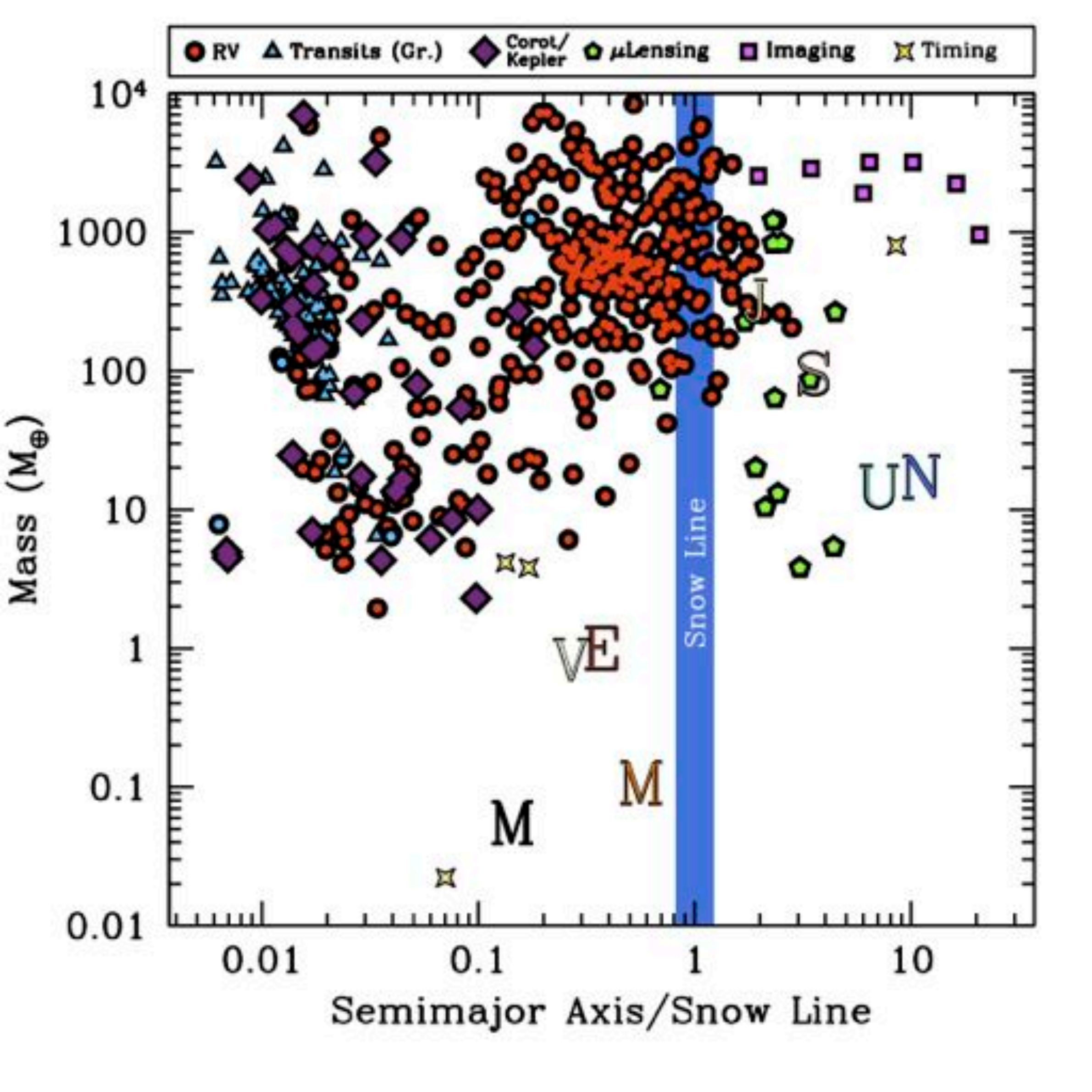
Planet Search Synergy!



A Census of Exoplanets.

Planet Search Synergy!



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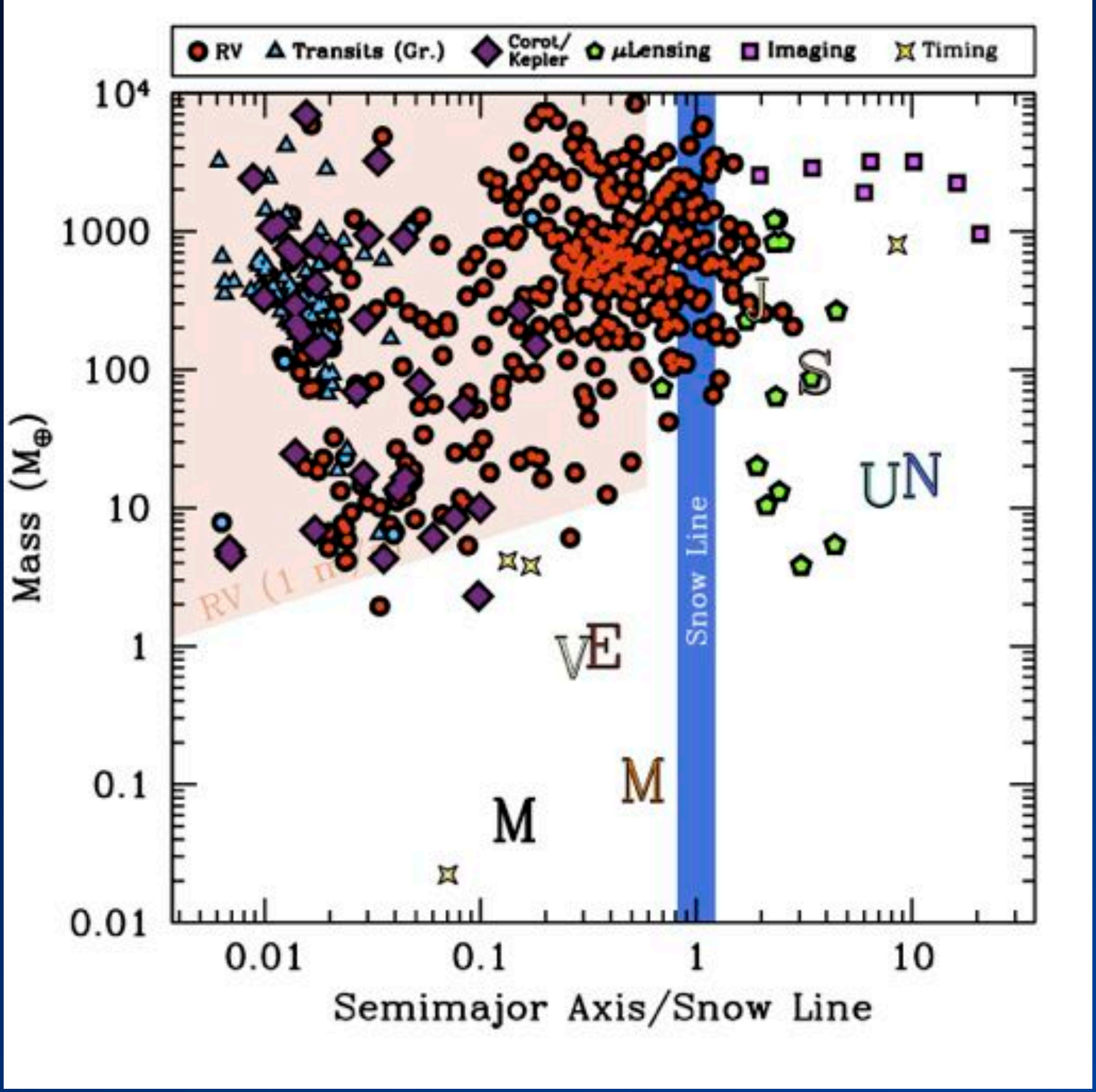

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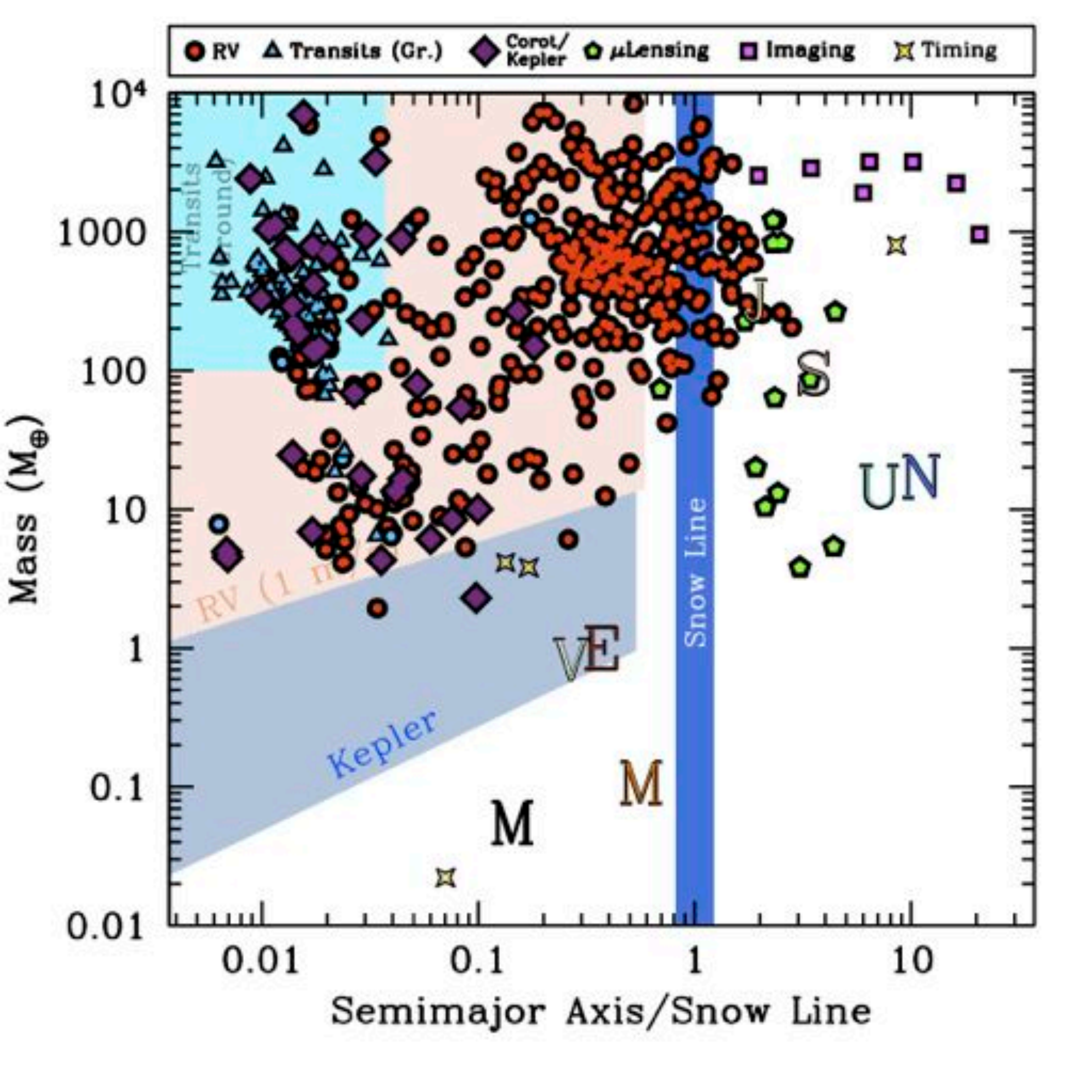

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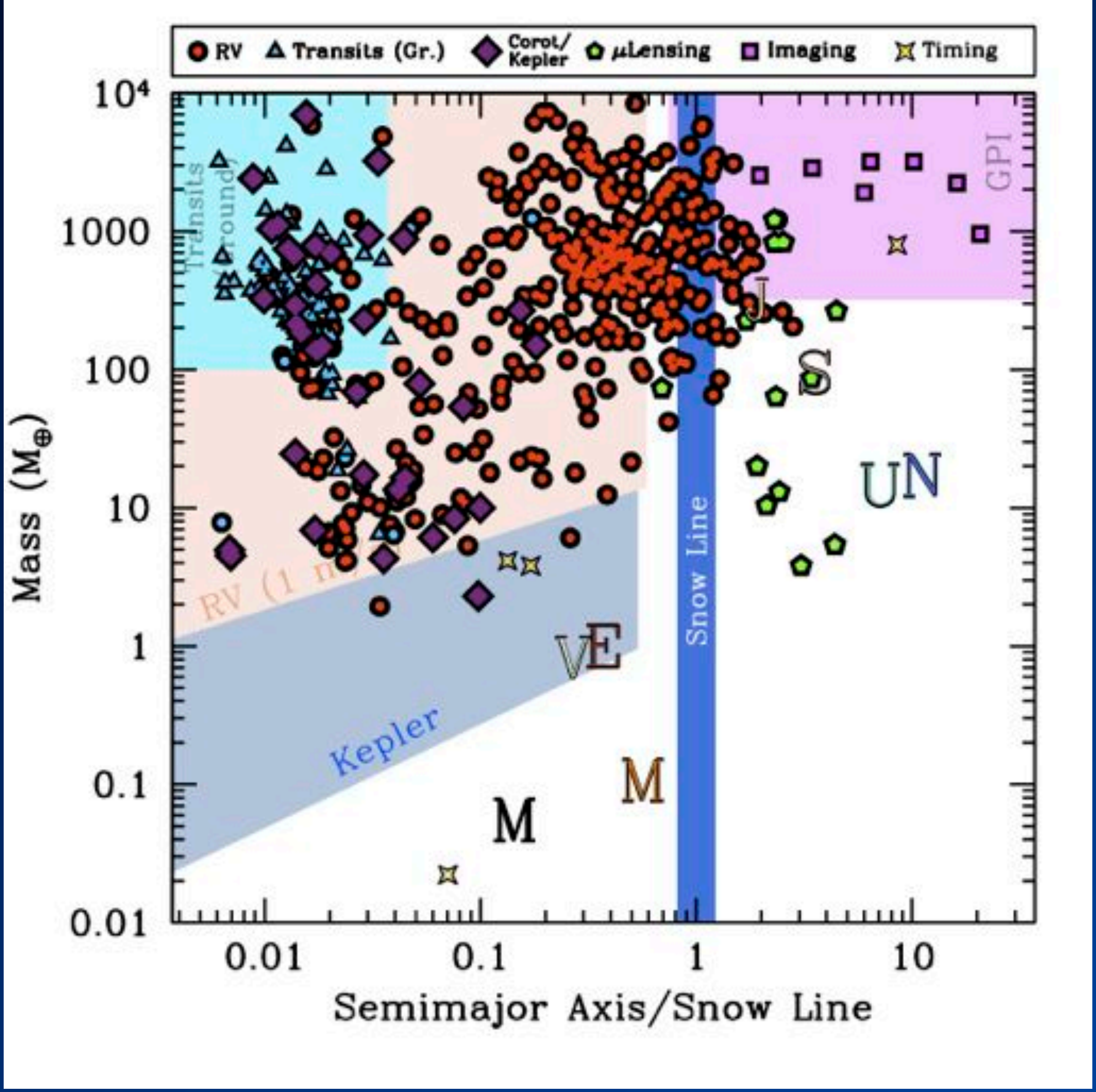

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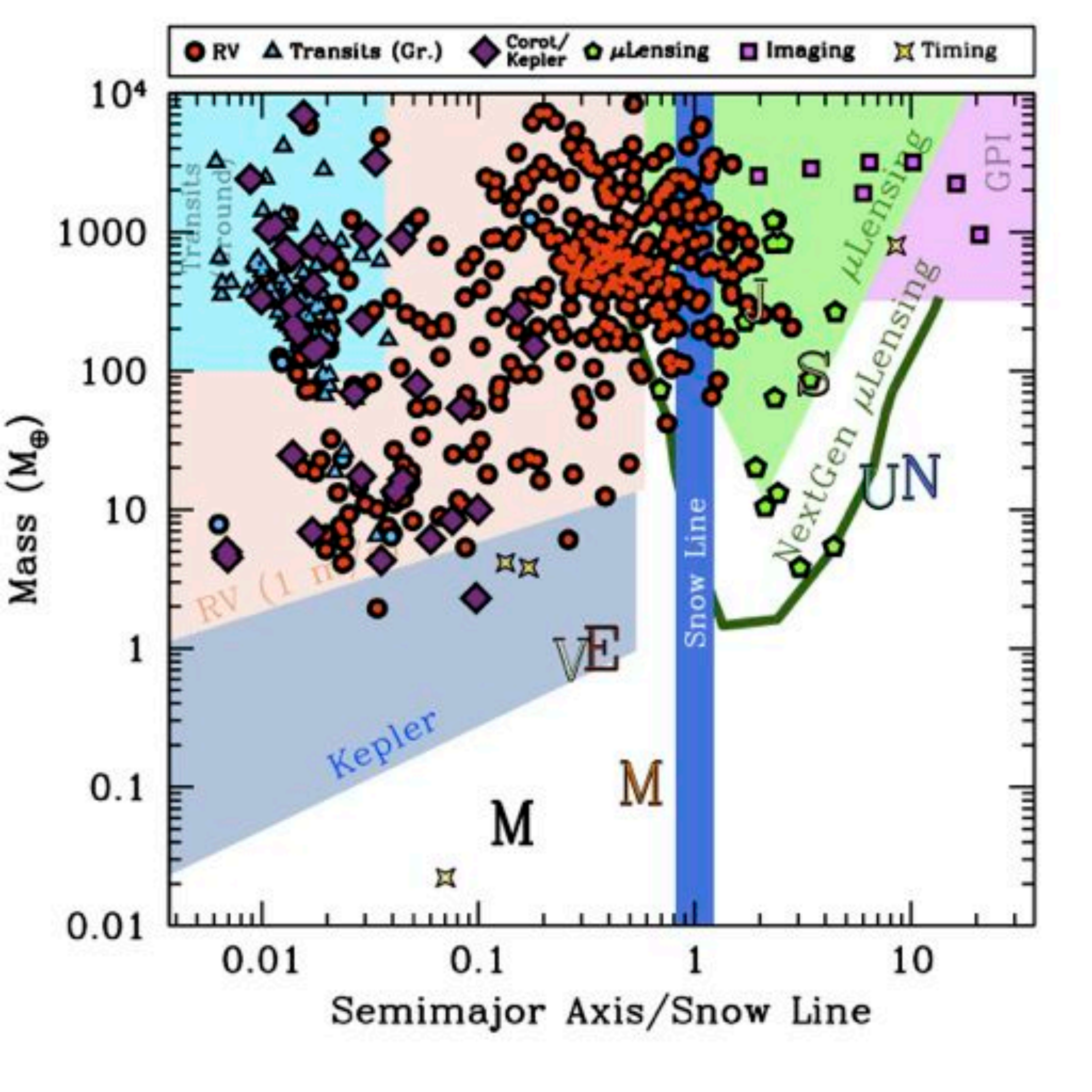

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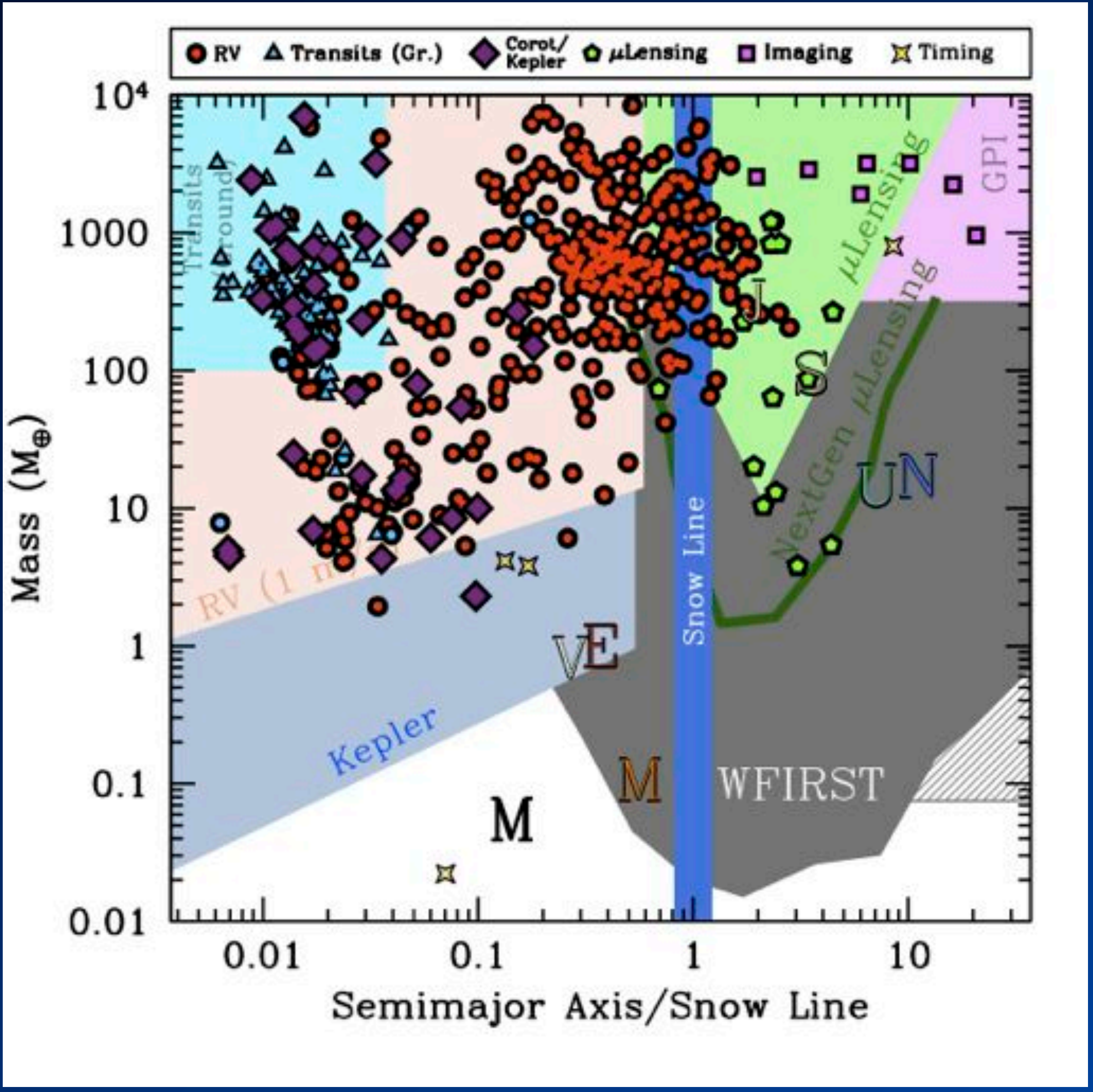

Summary.

- Physics of planet formation is hard.
- A complete census of planets is needed to understand planet formation.
- Requires multiple planet detection methods.
- Physics of planet detection is easy.