# Microlensing and MicroFUN Contributions to Star/Brown Dwarf/ Planet Formation Theories

2012 MicroFUN Workshop

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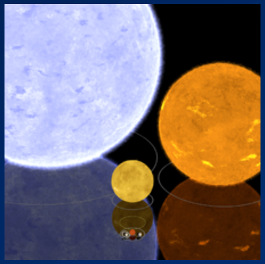
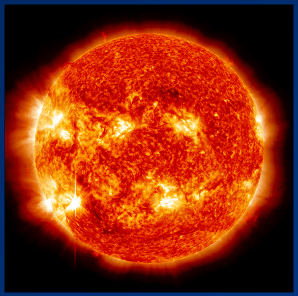
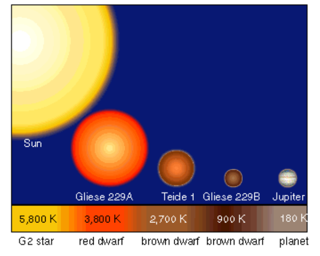
The Ohio State University

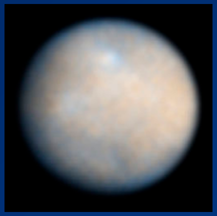
# Collapsed Objects.

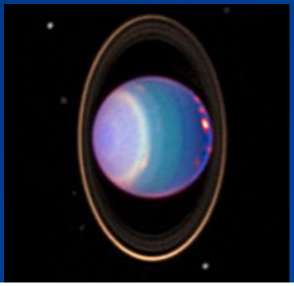
- Galaxy is populated with collapsed, self-gravitating objects.
- Broad range of masses:
    - Asteroids (0.02% Earth or 1% Moon)
    - Planets (6% Earth to $10^3$ Earth or 10× Jupiter)
    - Brown Dwarfs (~13× to 75× Jupiter)
    - Stars (7% Sun to 100× Sun)
- Broad range of compositions (Fe/O/Si/Mg to H/He).
- Range of isolation.
- How do these objects form?





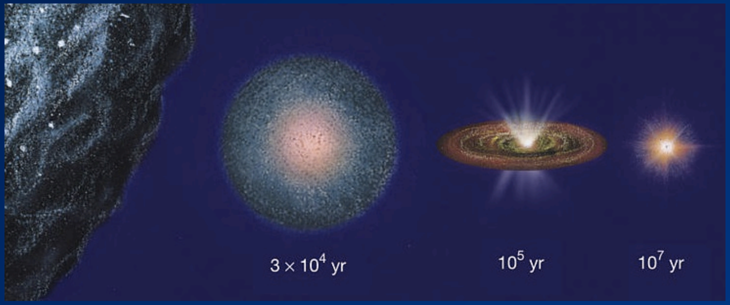




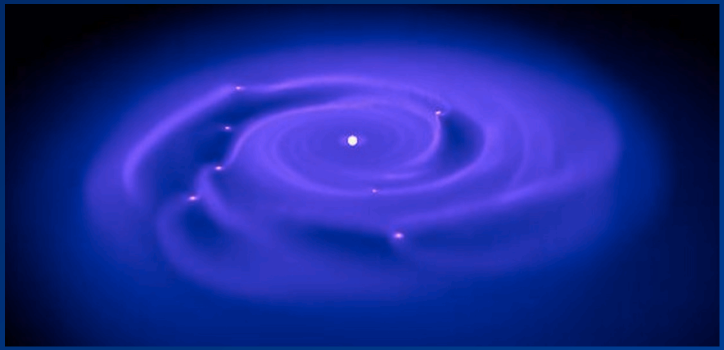


# Formation Theories.

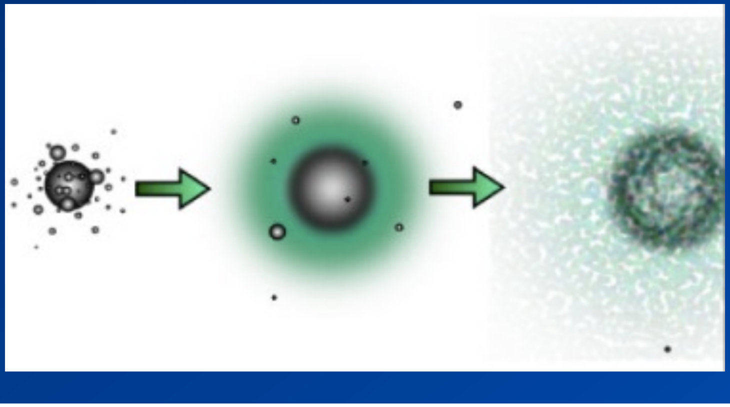
- Gravitational Collapse.



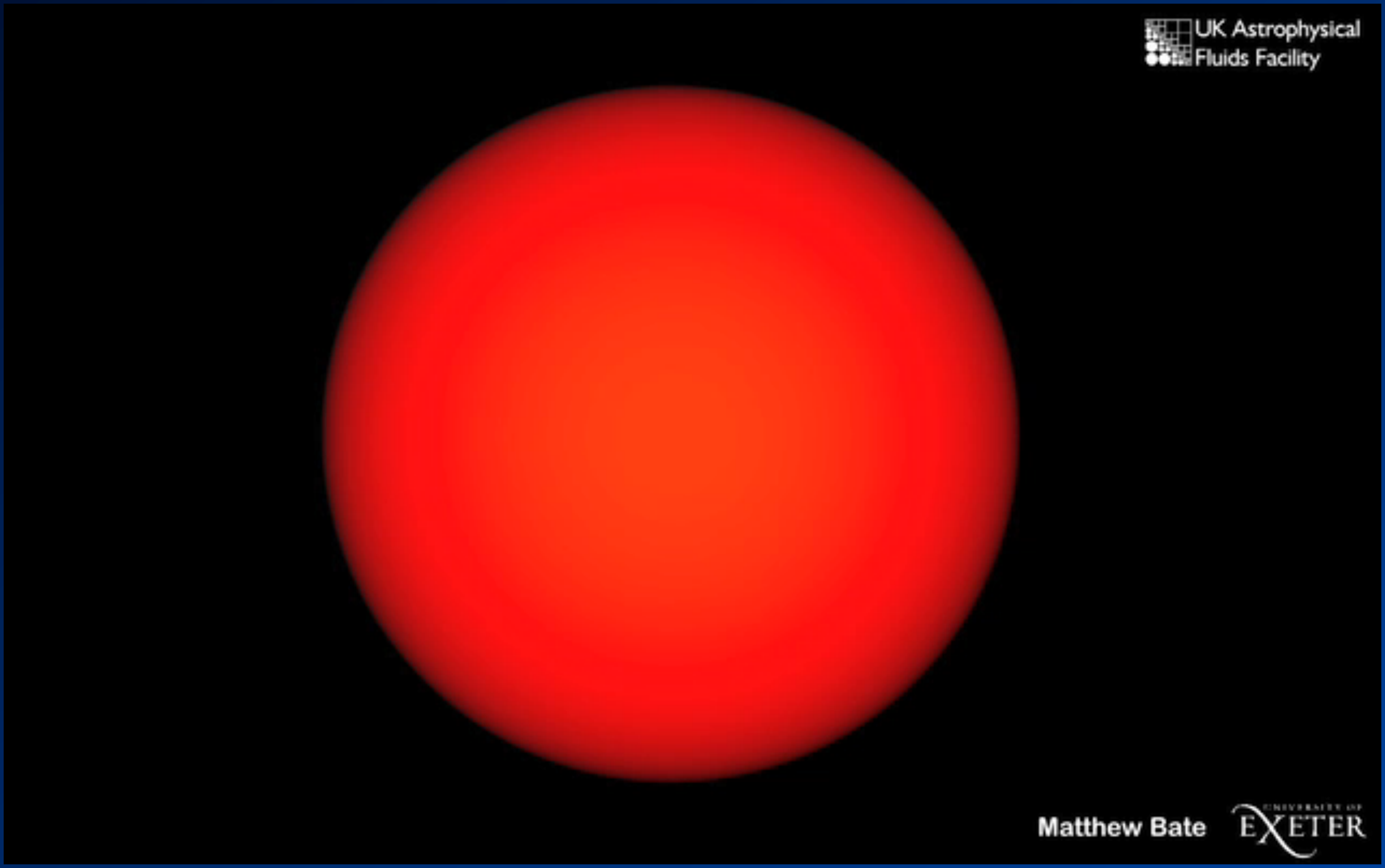
- Disk Fragmentation. (Disk: top down)



- Agglomeration and Core Accretion. (Disk: bottom up)

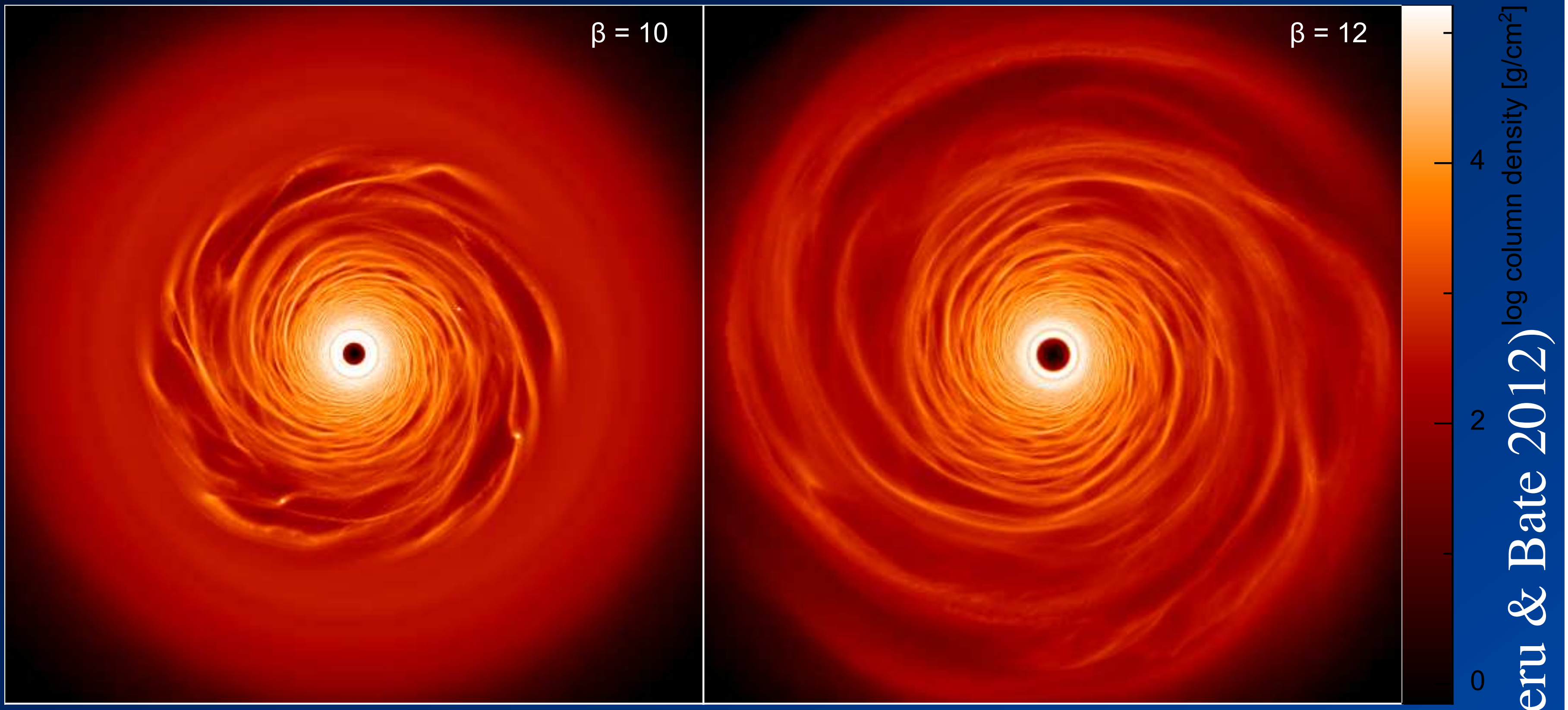


# Gravitational Collapse.



**Free-fall time < sound crossing time ➡ collapse**

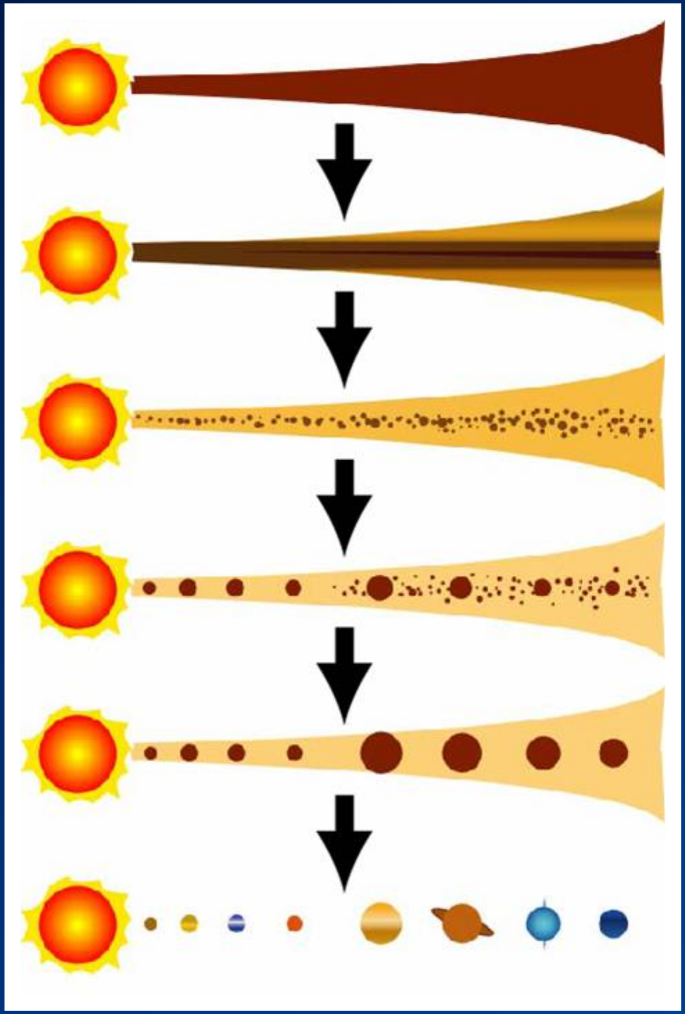
# Disk Instability.



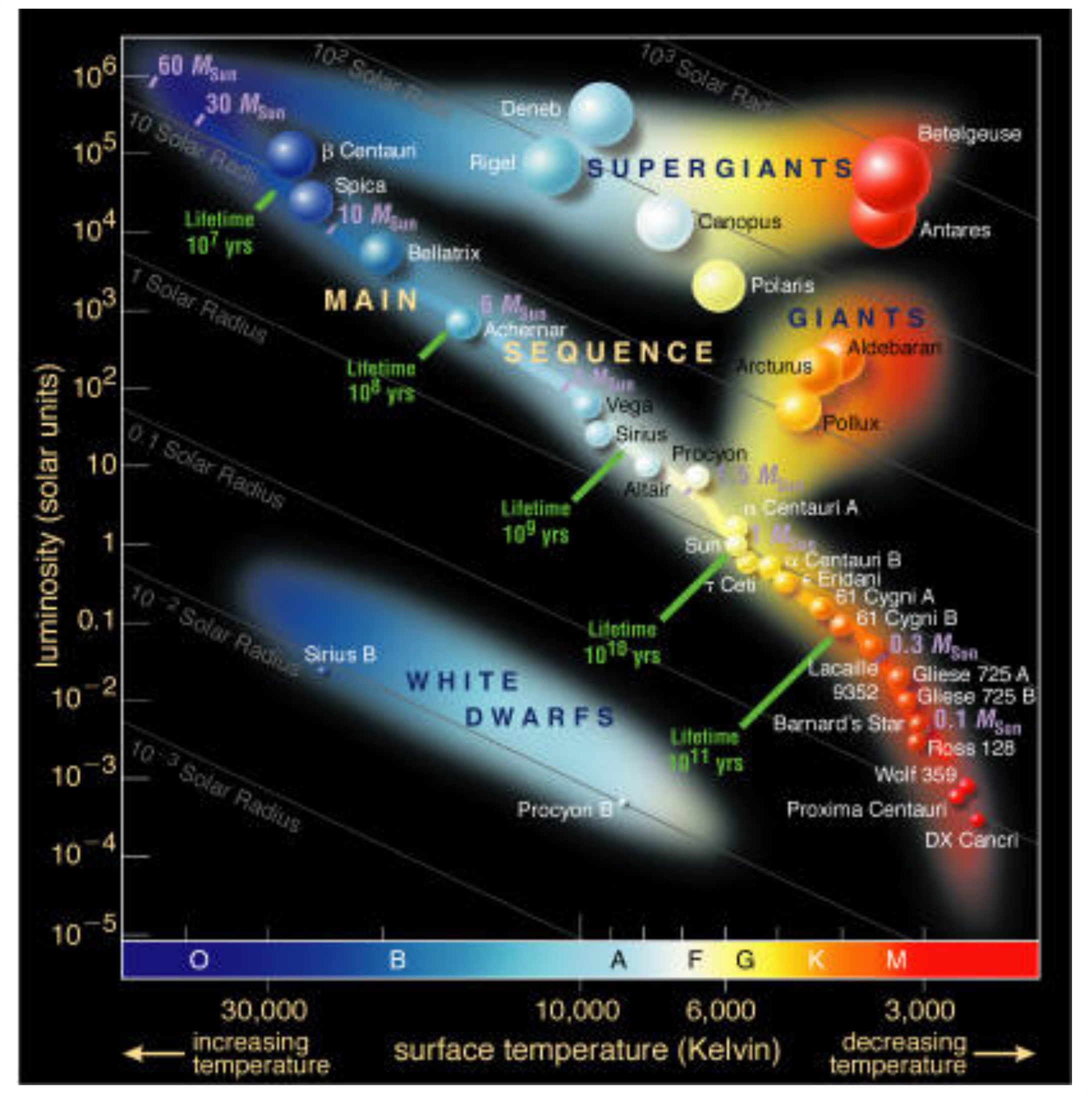
(Meru & Bate 2012)

**Thermal pressure + shear < gravity → collapse**

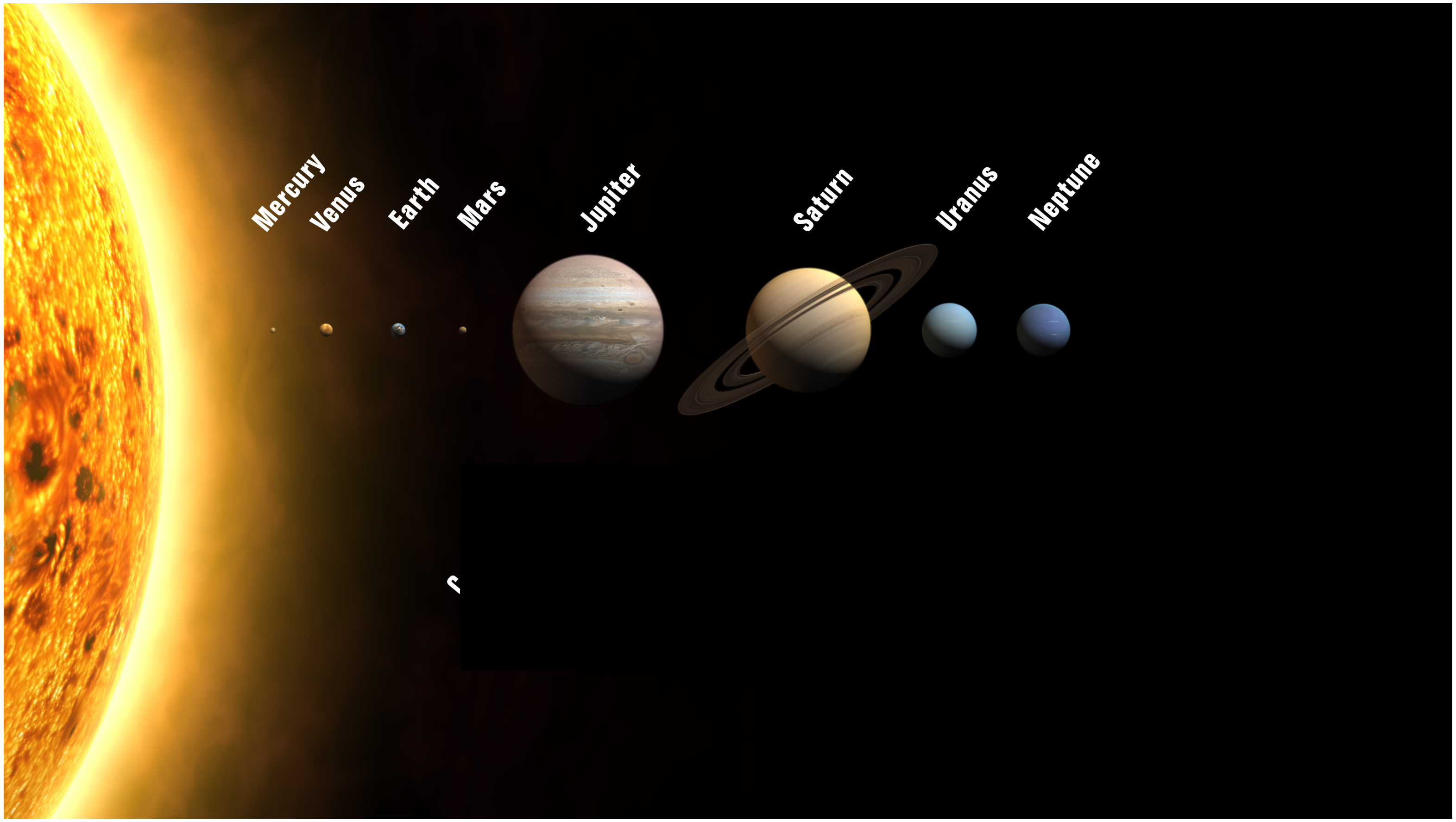
# Agglomeration and Core Accretion.

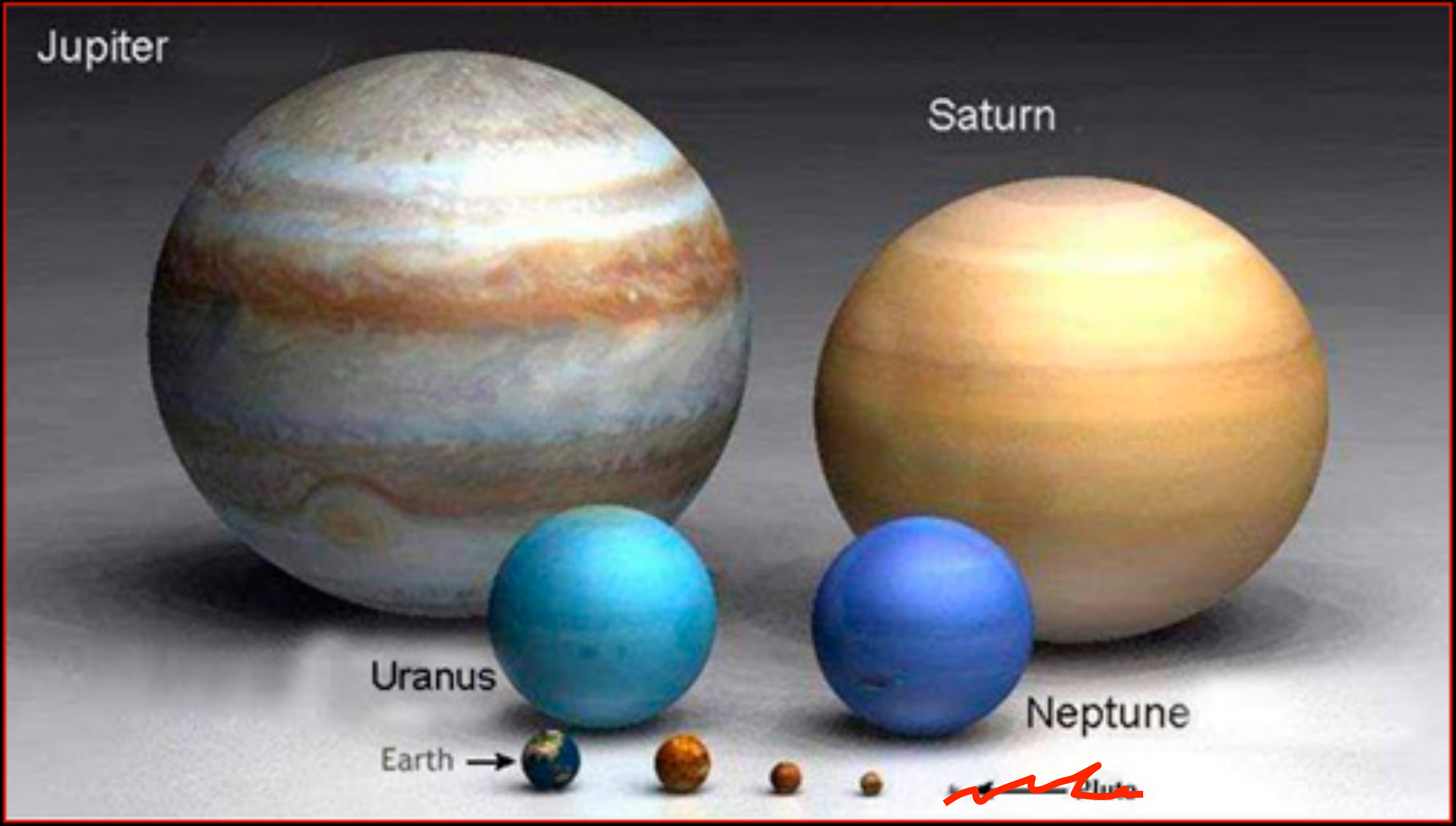


# Backstory. Before 1995...



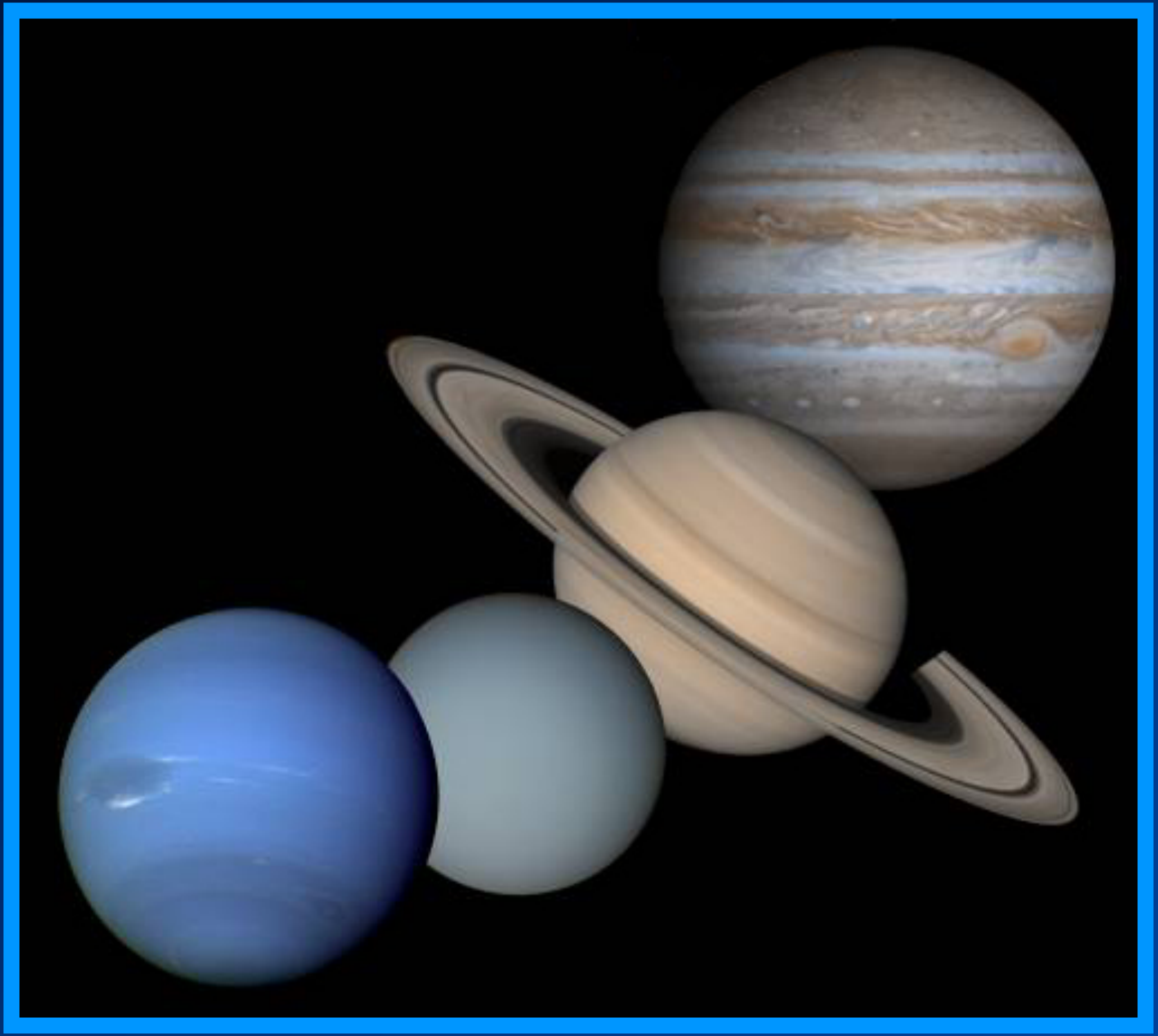
# Backstory. Before 1995...

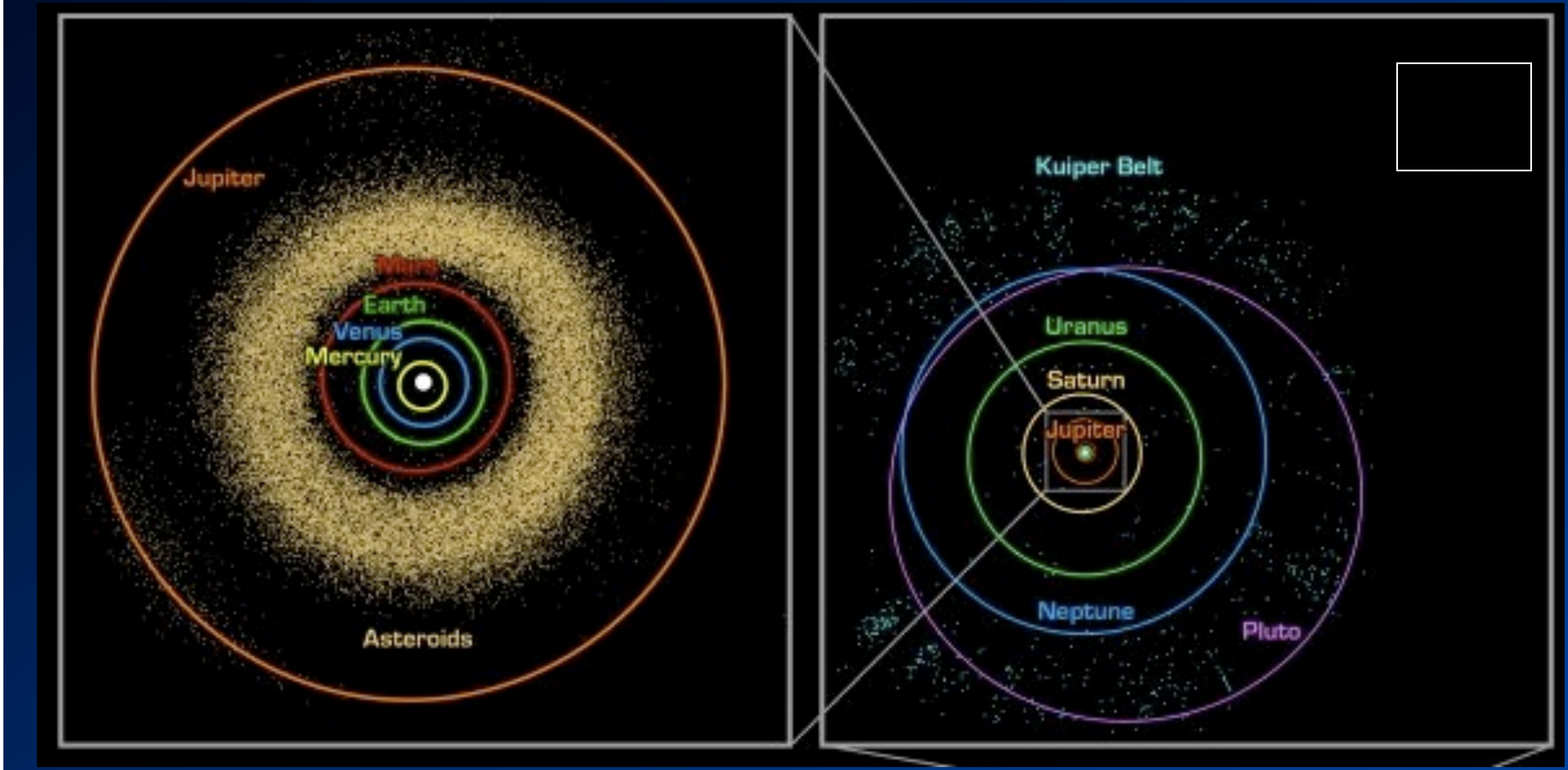



Jupiter
Saturn
Uranus
Neptune
Earth →
~~Pluto~~

# Terrestrial (“Rocky”) Planets.

# Gas/Ice Giants.




Jupiter
Mars
Earth
Venus
Mercury
Asteroids
Kuiper Belt
Uranus
Saturn
Jupiter
Neptune
Pluto

# Why does our solar system look like this?

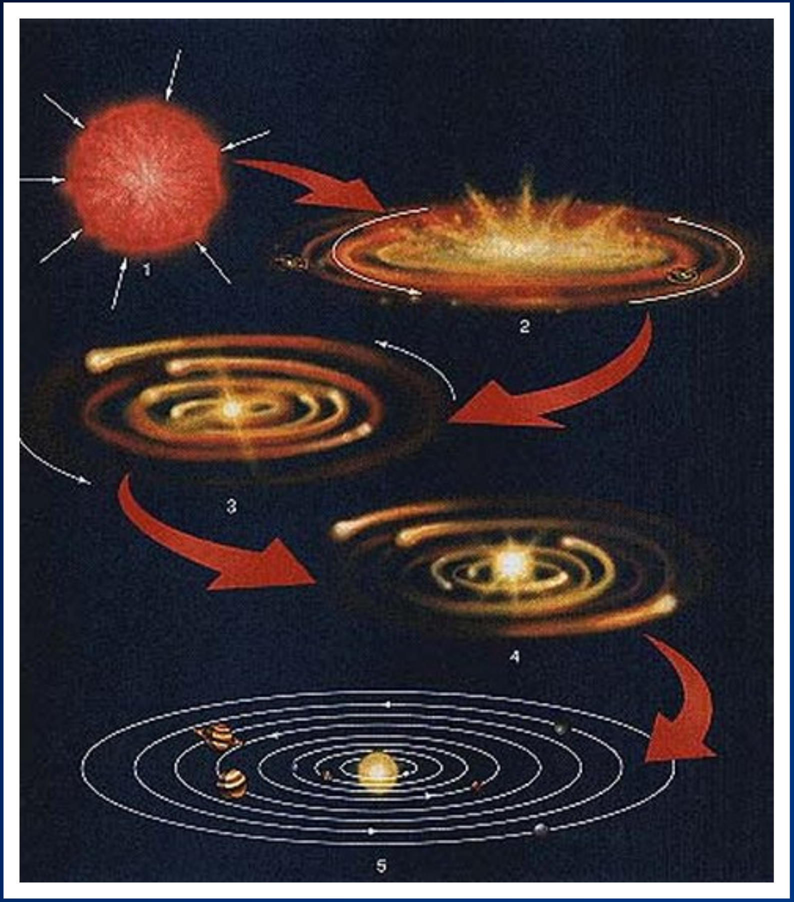
# A Fairy Tale.

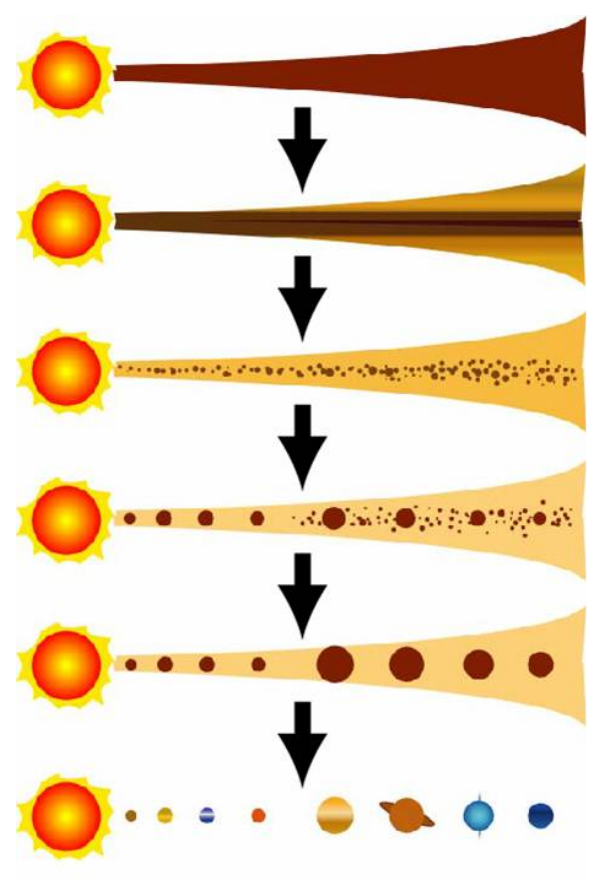
# Bottom-Up Planet Formation.

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

***Hard!***

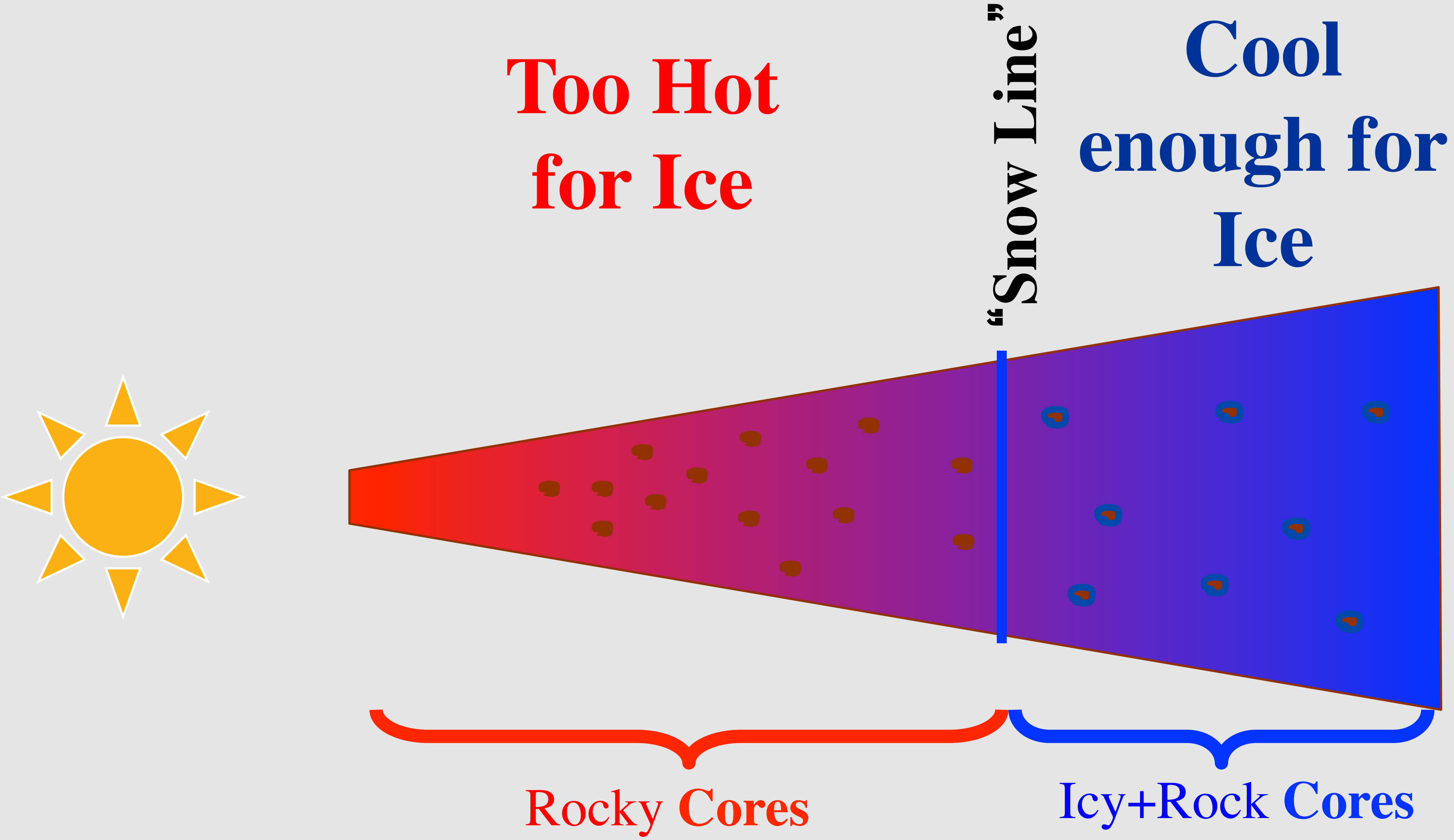
# Bottom-Up Planet Formation.





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

# The Snow Line.



Too Hot for Ice

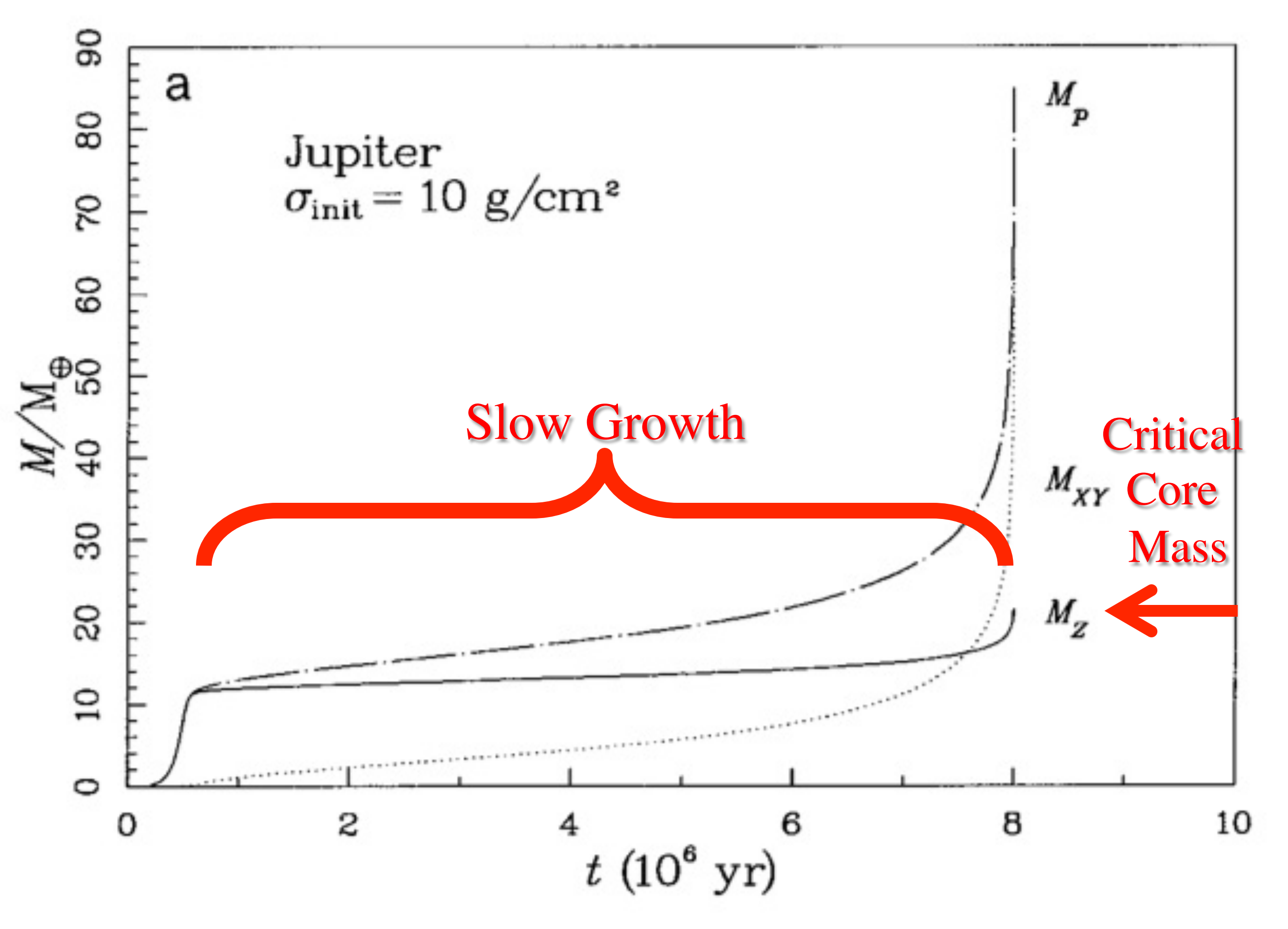
“Snow Line”

Cool enough for Ice

Rocky Cores

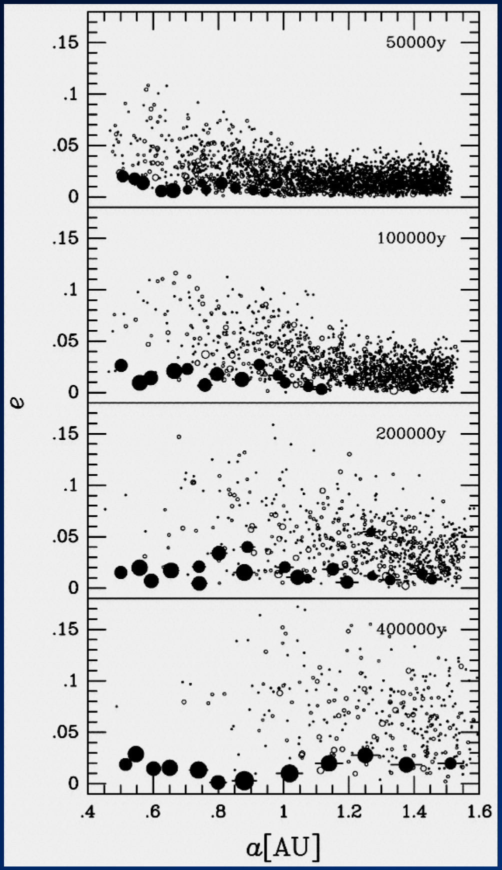
Icy+Rock Cores

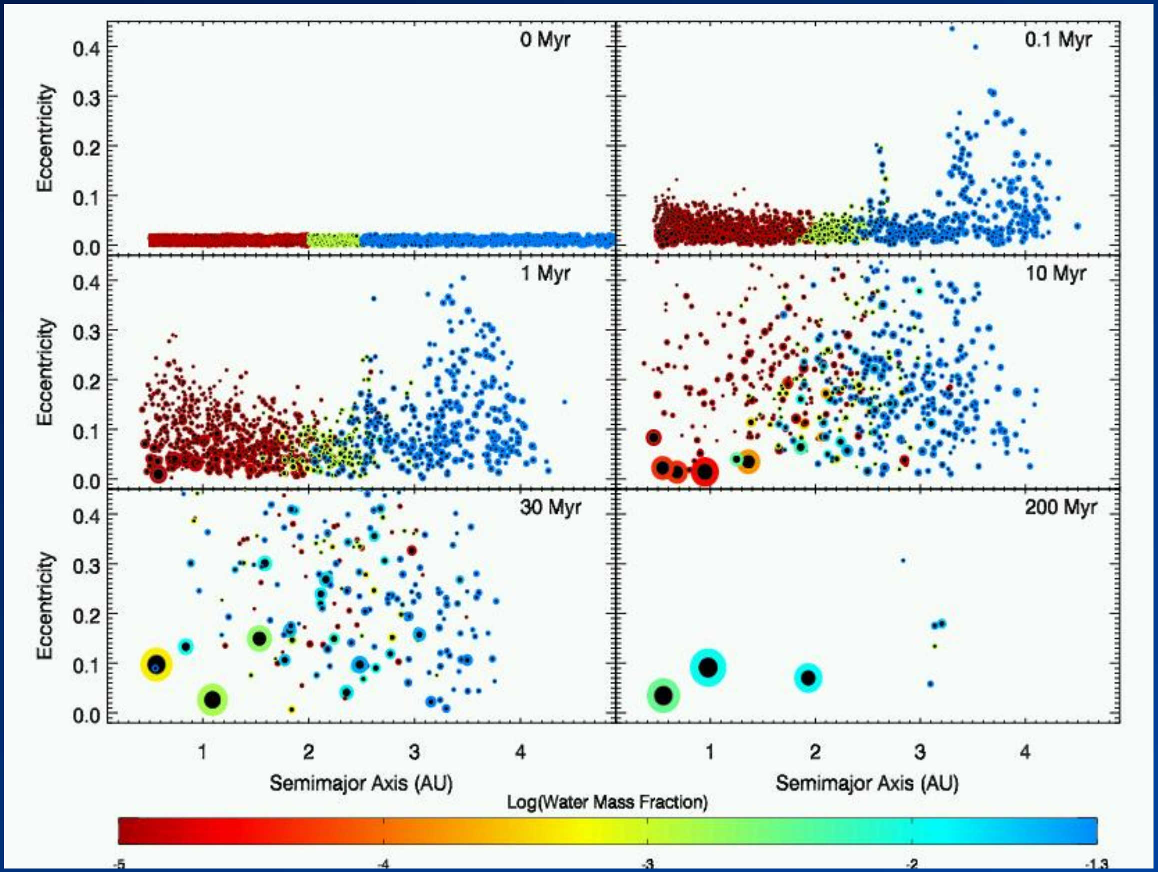
# Core Accretion.



(Pollack et al. 1996)

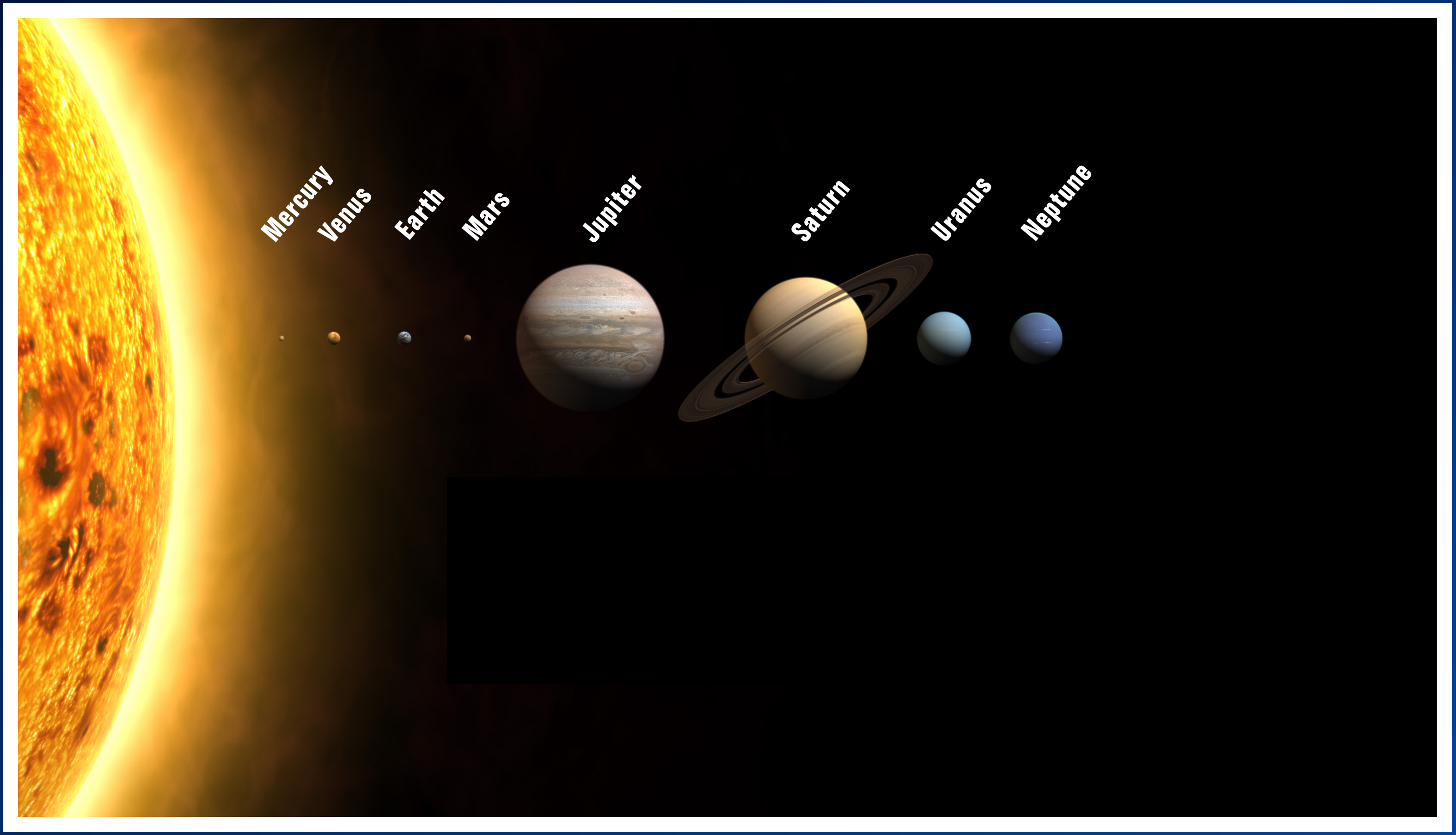
# Terrestrial Planet Formation.





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

# Matched Data Well.

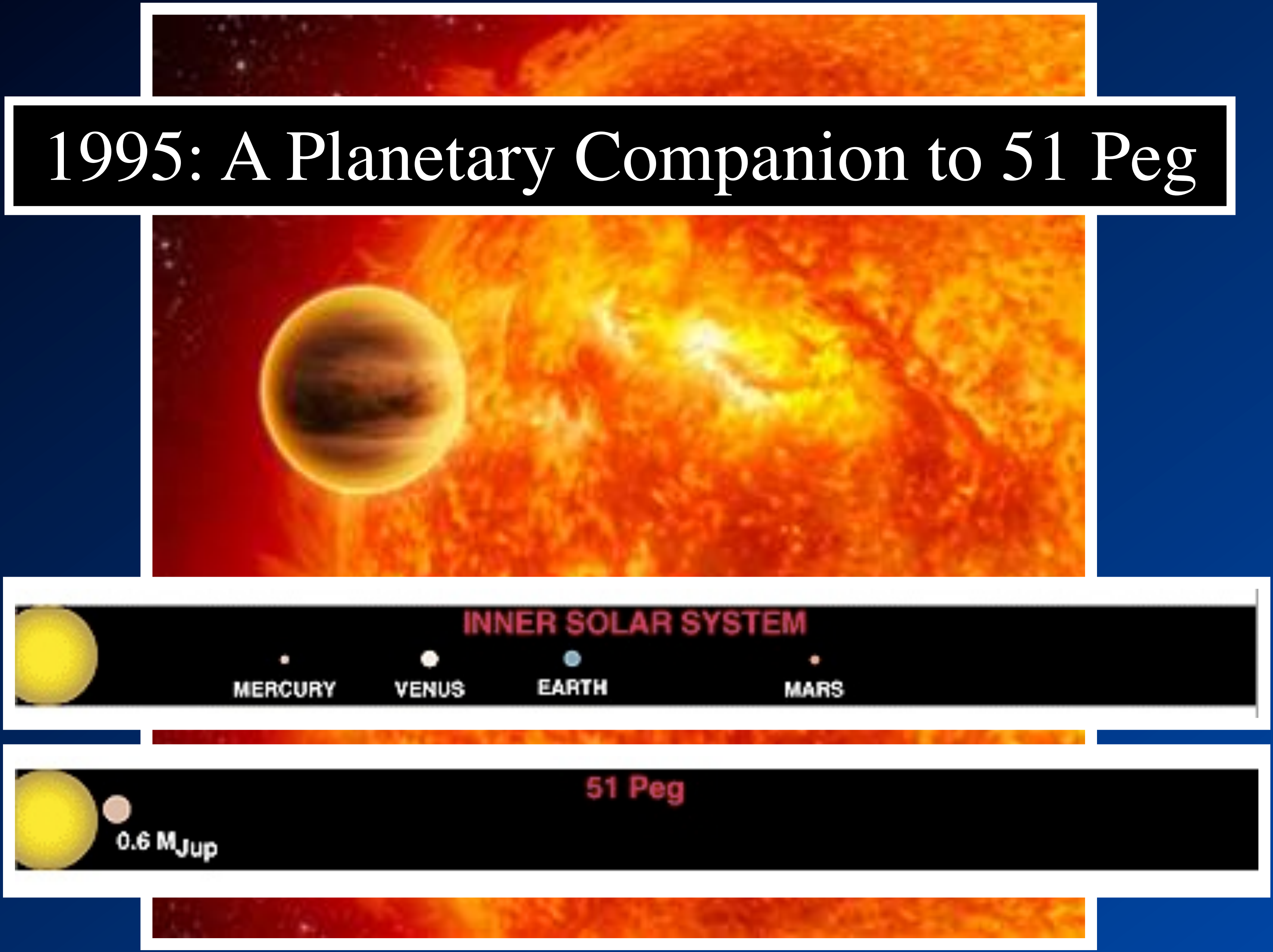


# Implications.

Consequences of this formation model:

- Compositional gradient in the types of planets.
- Massive, gas-giant planets beyond the “snow line”.
- Low-mass, rocky planets interior to the “snow line”.
- Cannot form gas-giant planets very close to the star.
- Low-mass stars cannot form gas giants easily.

# 1995: A Planetary Companion to 51 Peg



(Mayor & Queloz 1995)

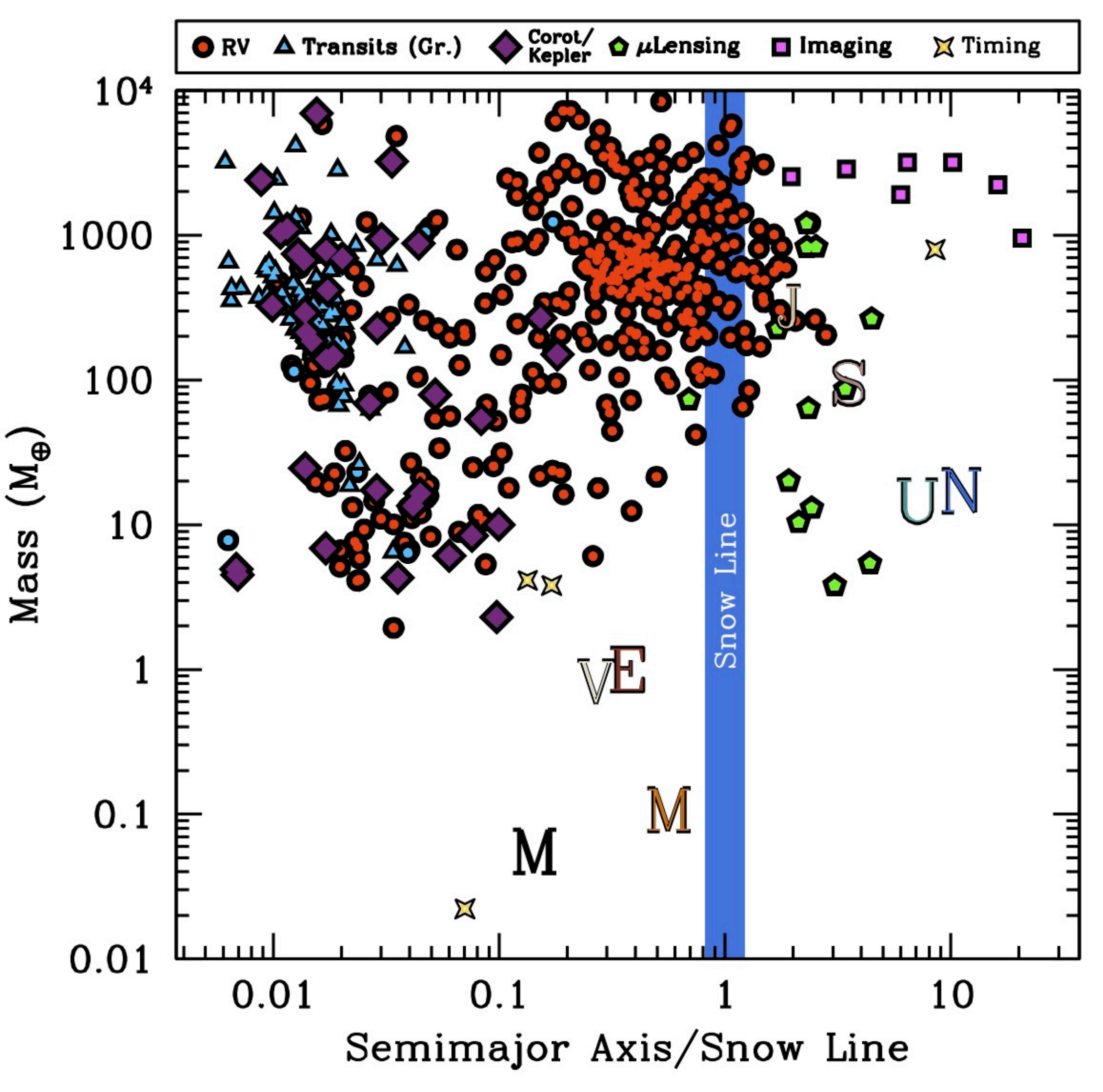
# Planet formation is *really* hard!

Additional physics, e.g.,

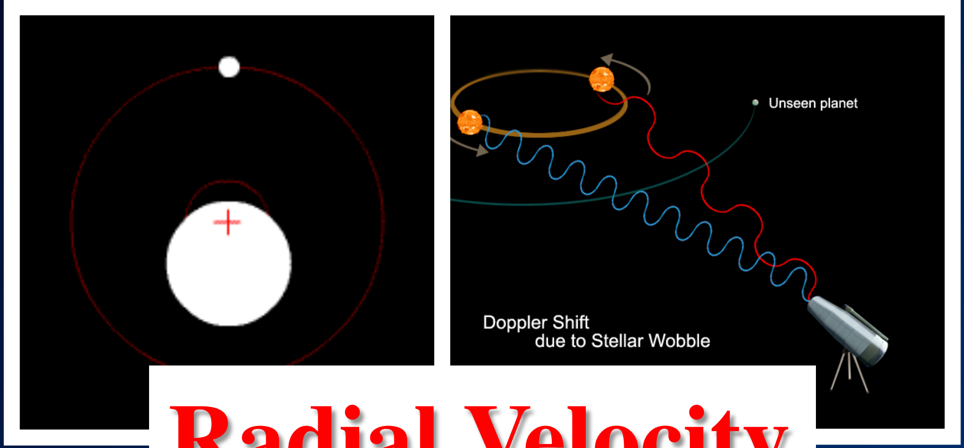
- Migration.
- Influence of host star mass, metallicity
- Dynamical interactions.
- Tides.
- Disk properties.
- Other models!  (e.g., disk instability)
- Etc.

# Meanwhile…

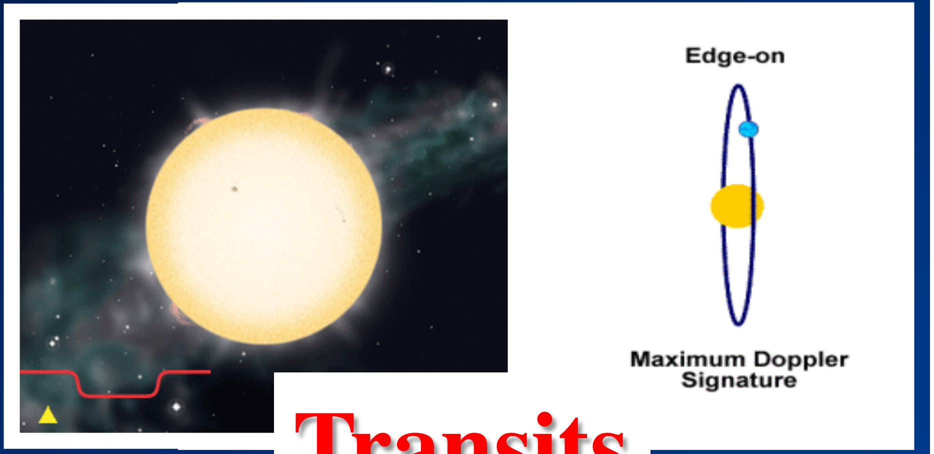
# Strange New Worlds.



# Detection methods.

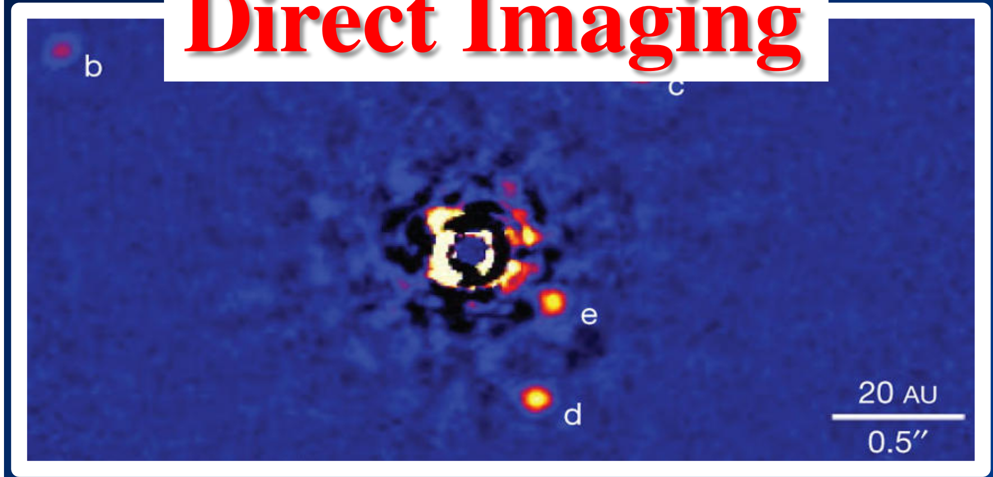


**Radial Velocity**

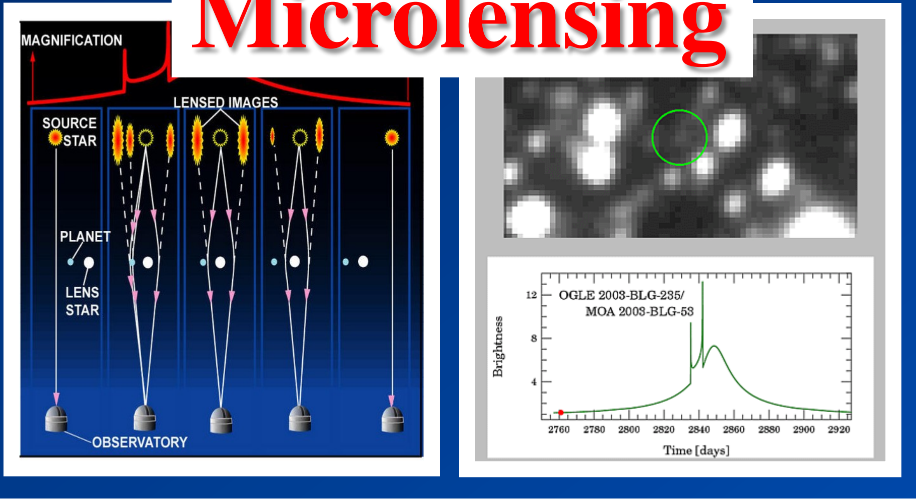


**Transits**

**Direct Imaging**



**Microlensing**



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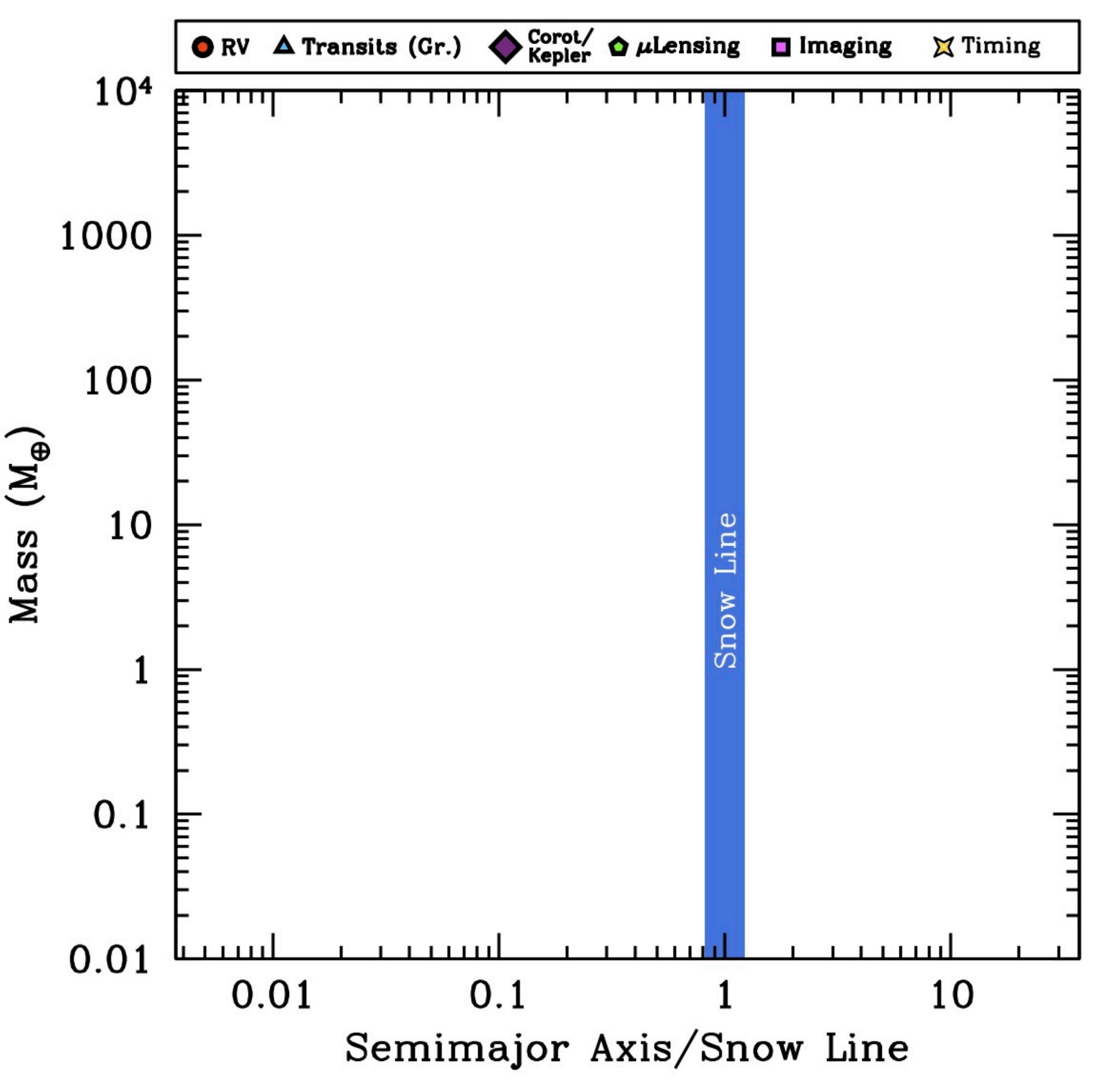

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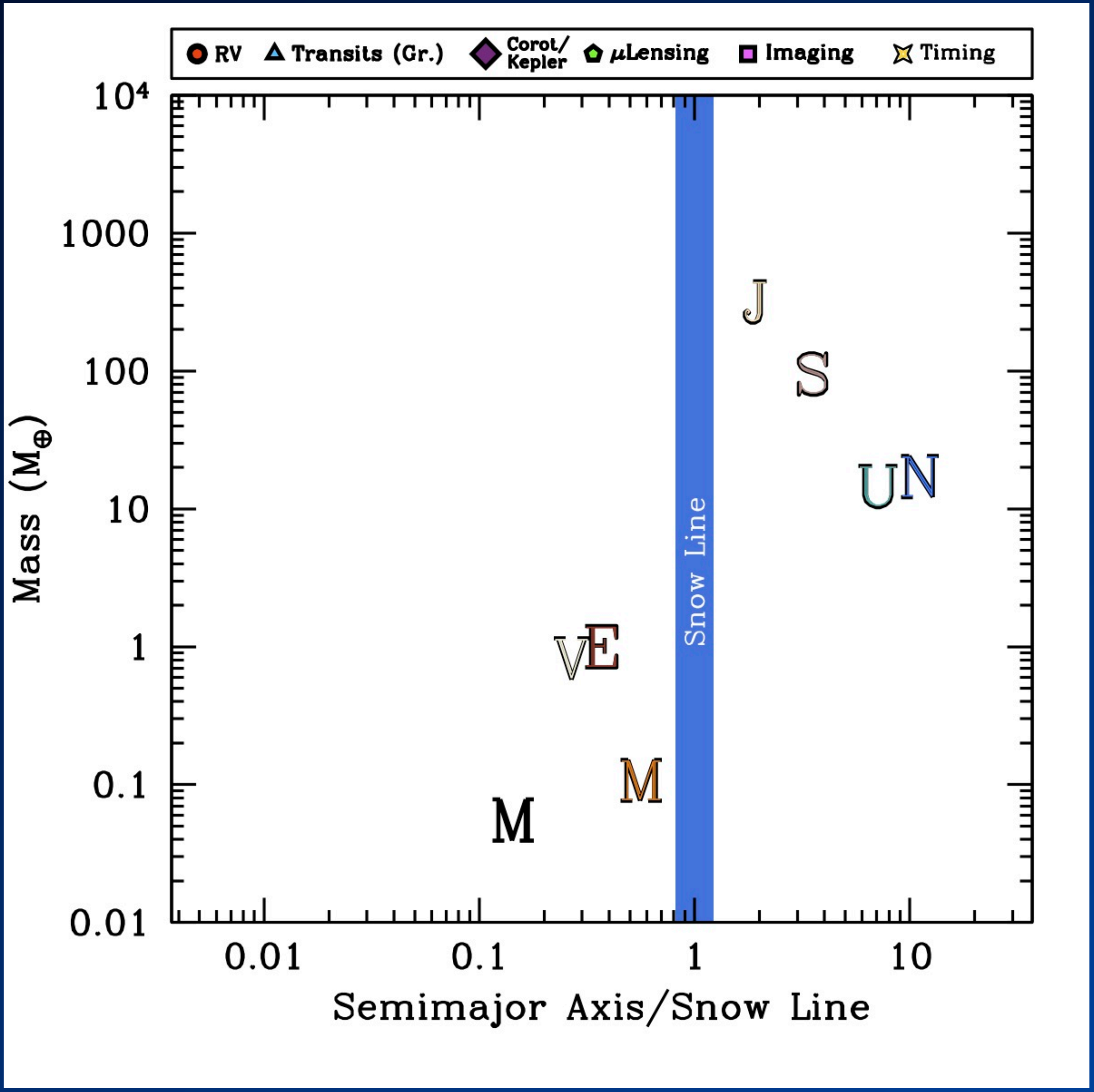

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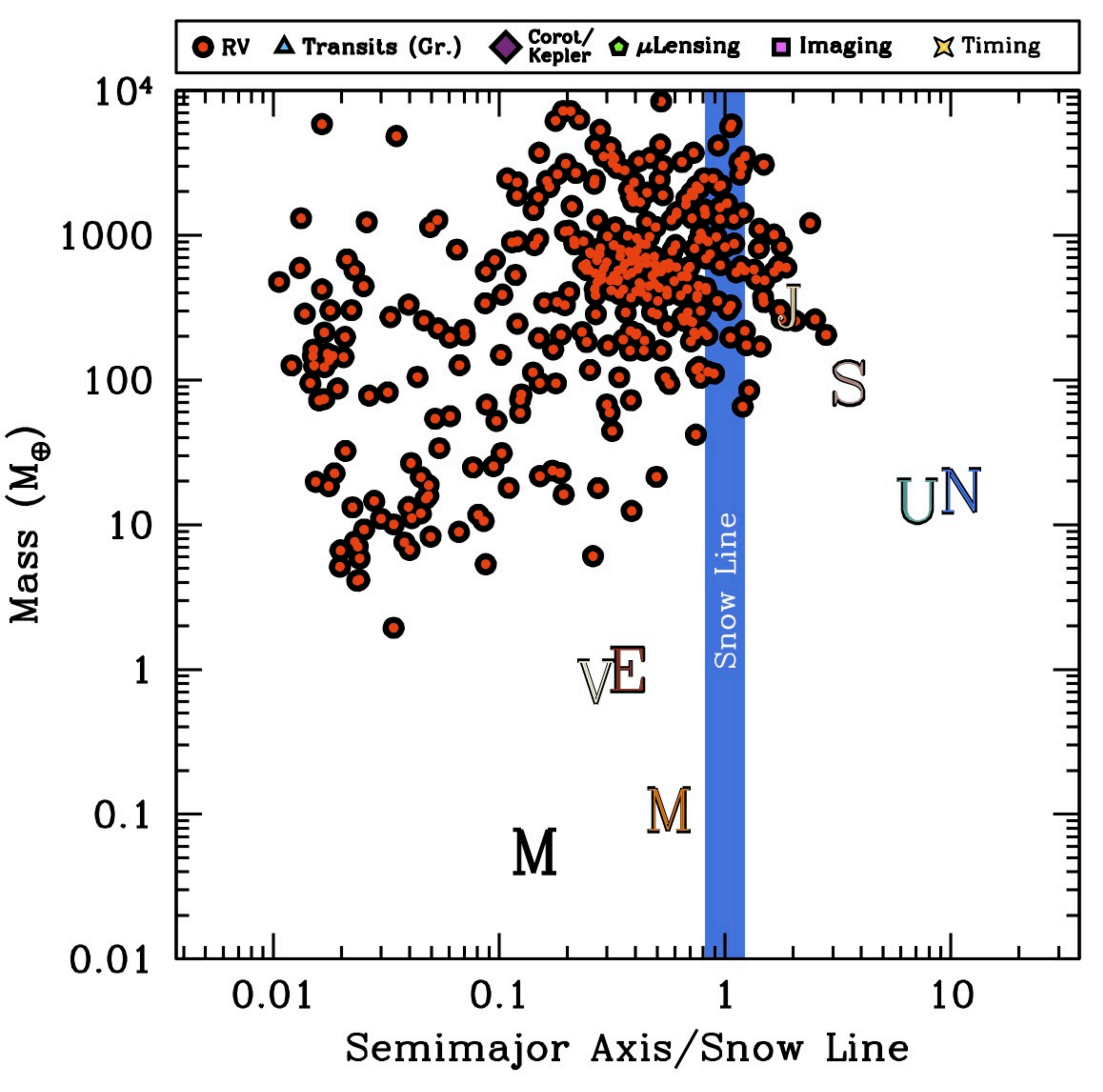

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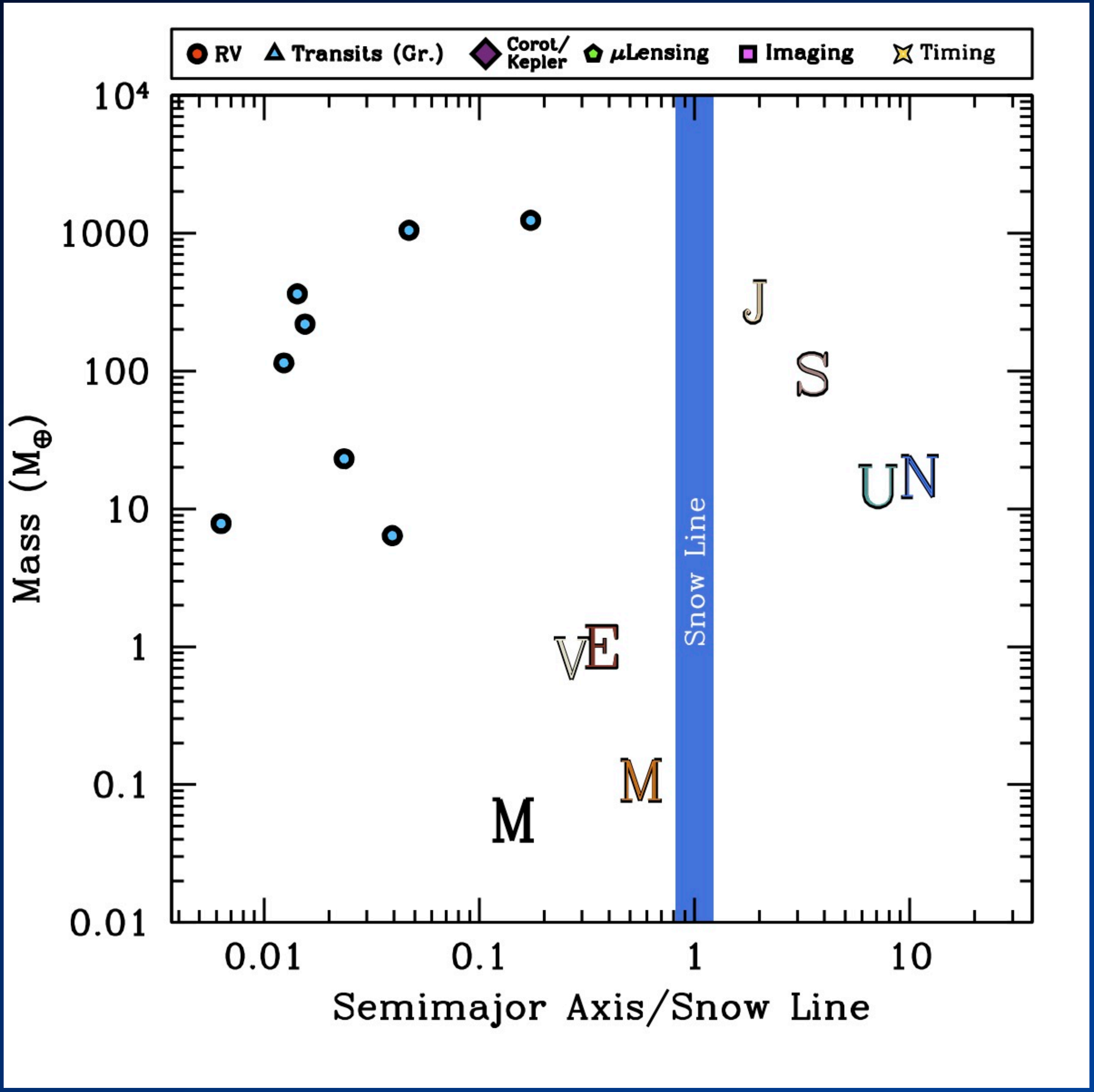

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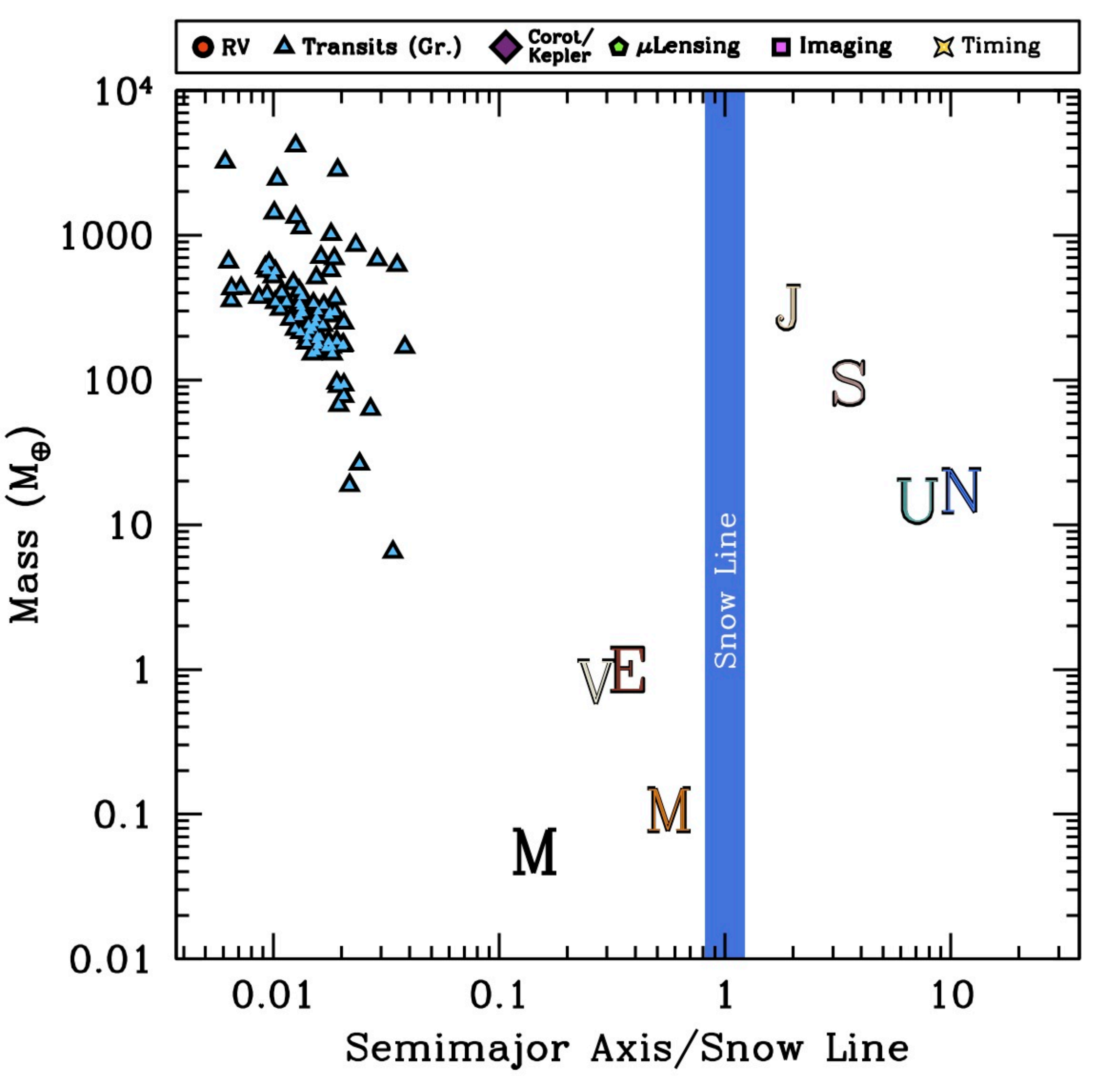

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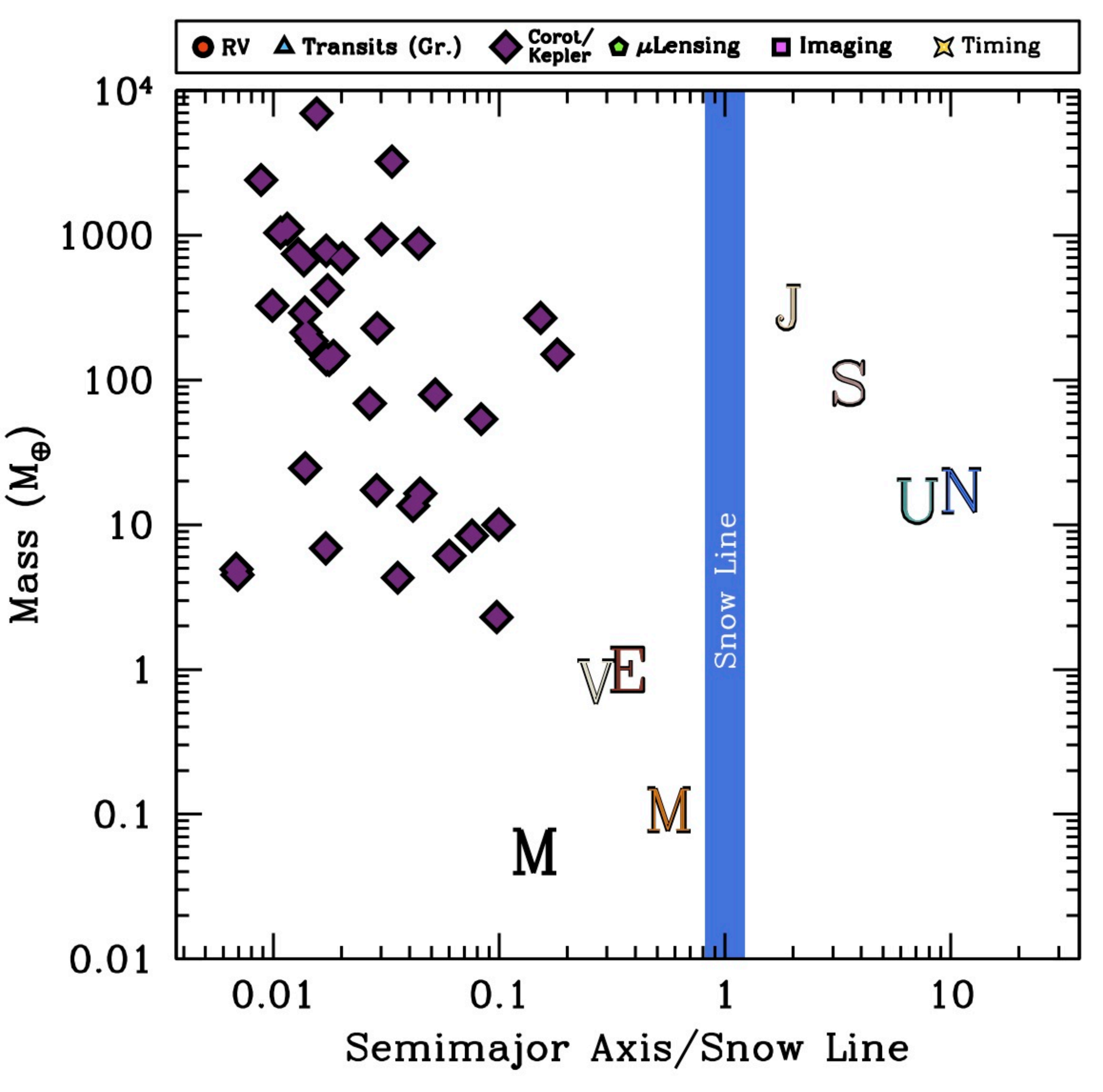

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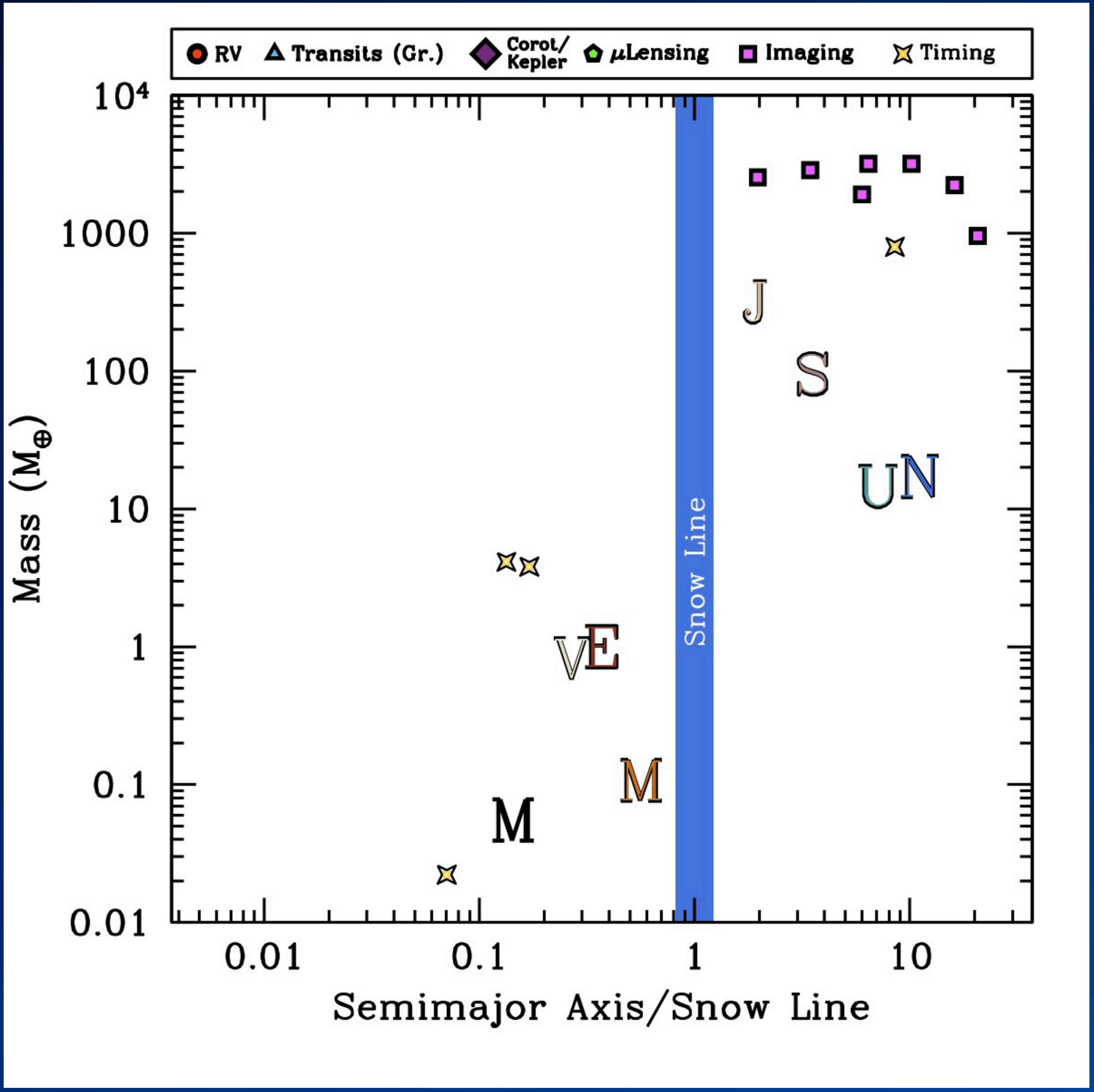

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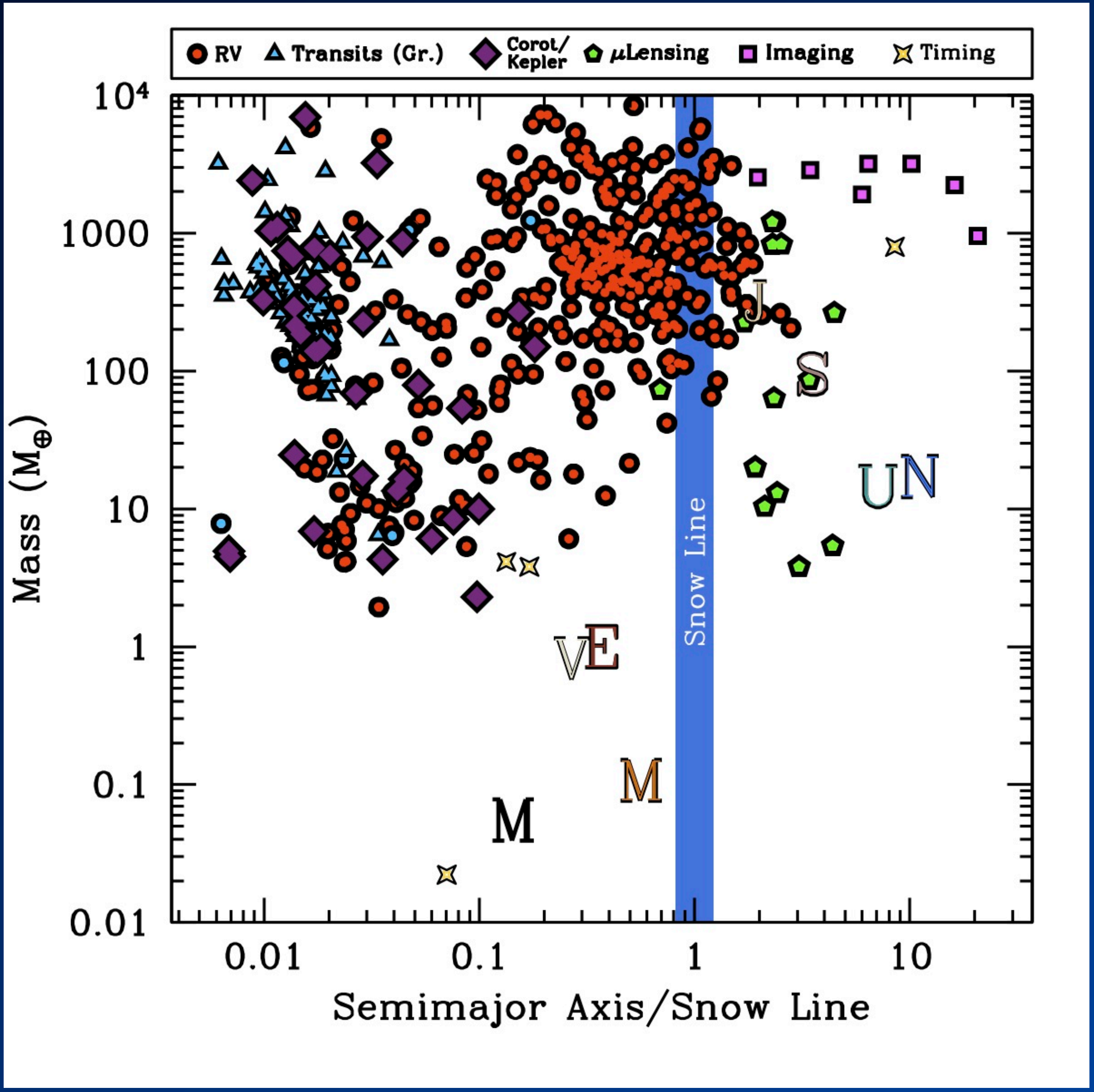
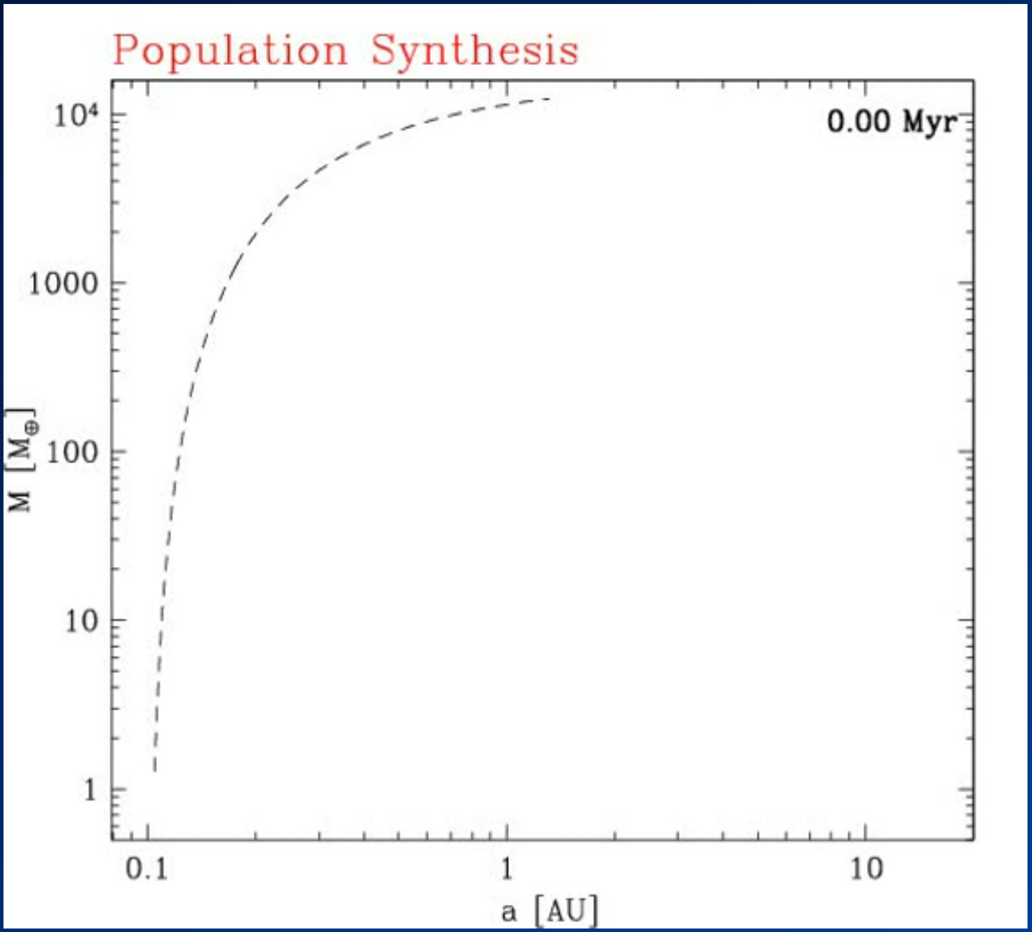
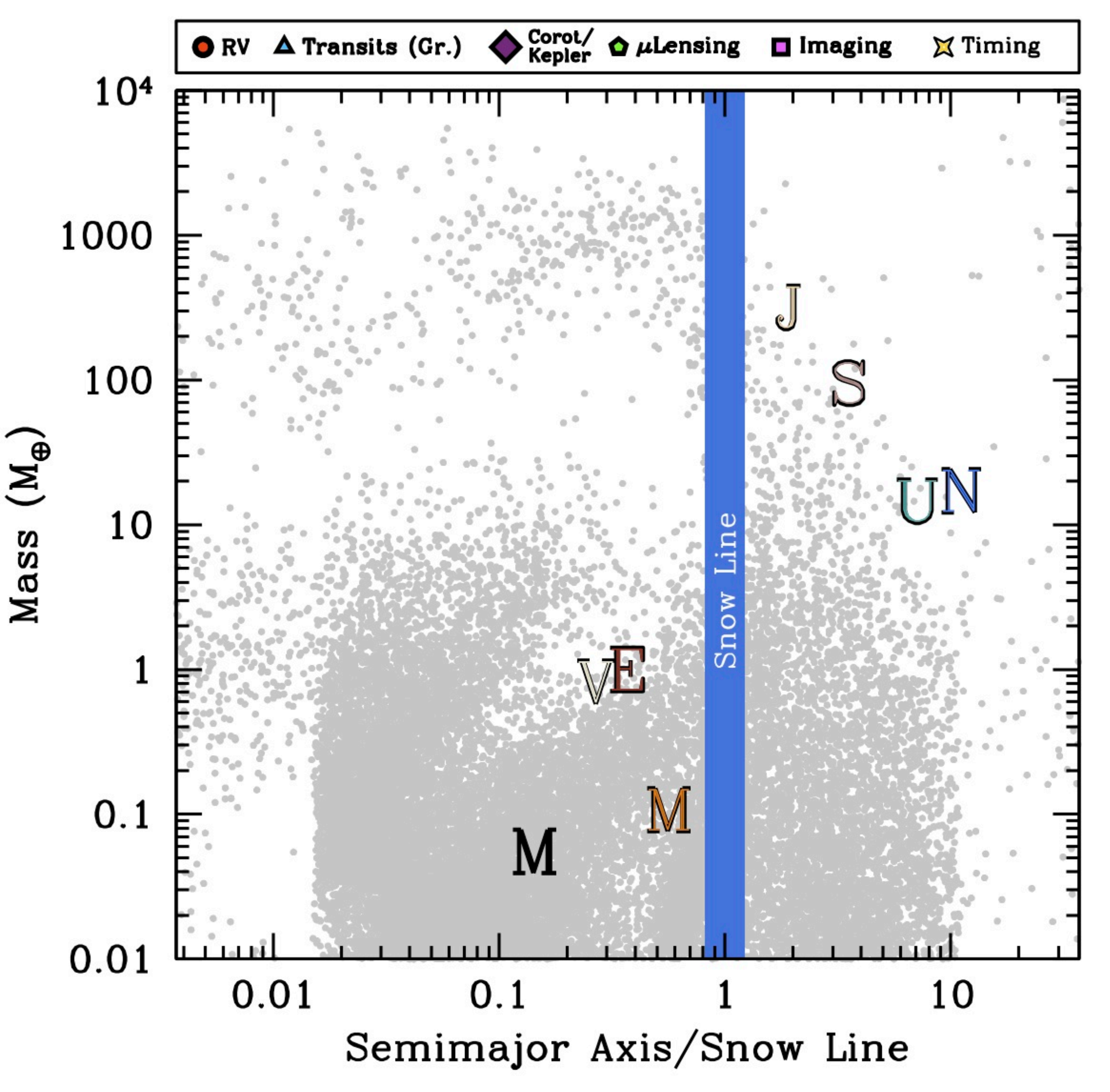


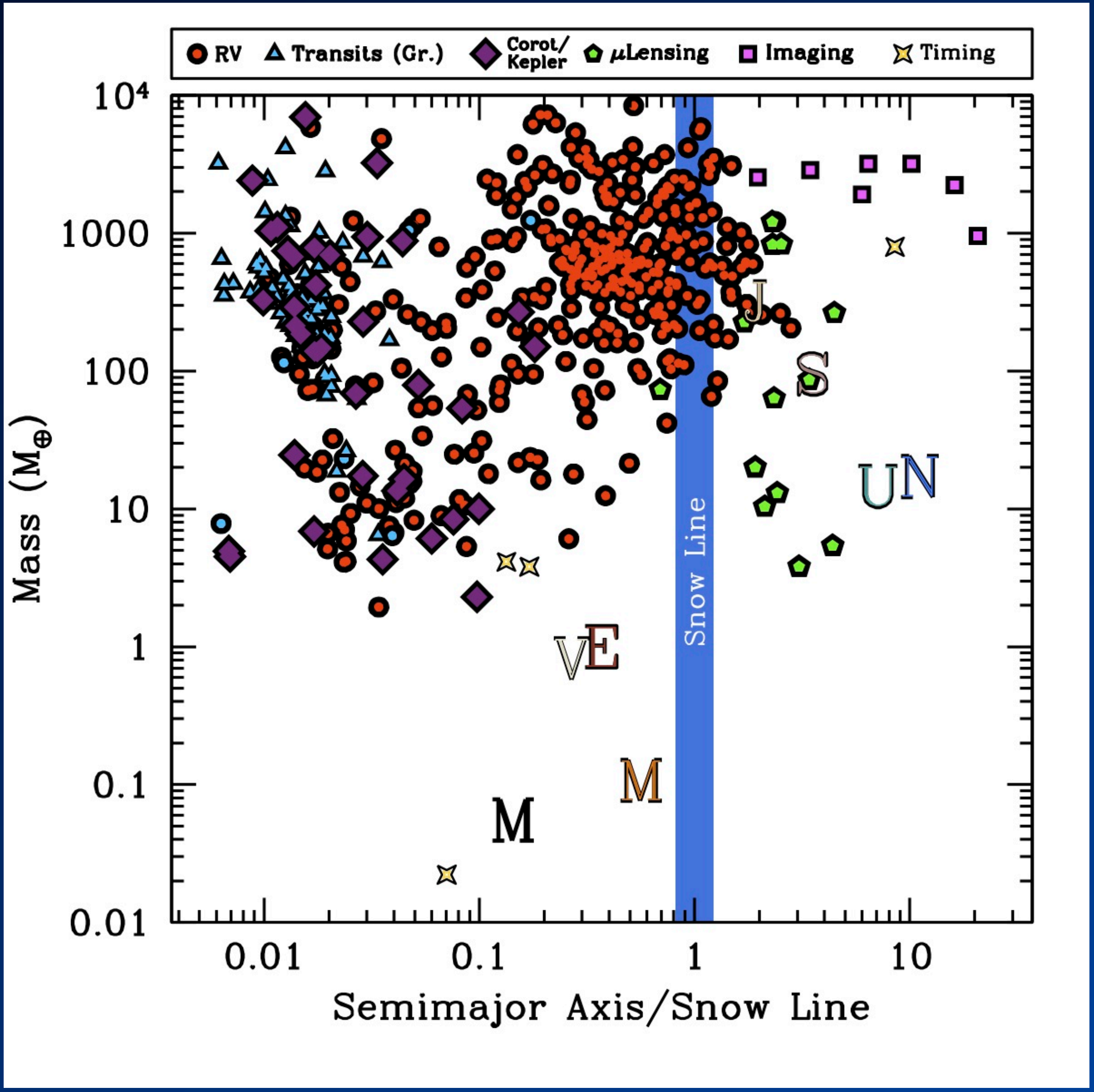
# Semi-analytic planet formation.



(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
Semimajor Axis/Snow Line
0.01
0.1
1
10
Snow Line
J
S
U
N
V
E
M
M

(Ida & Lin)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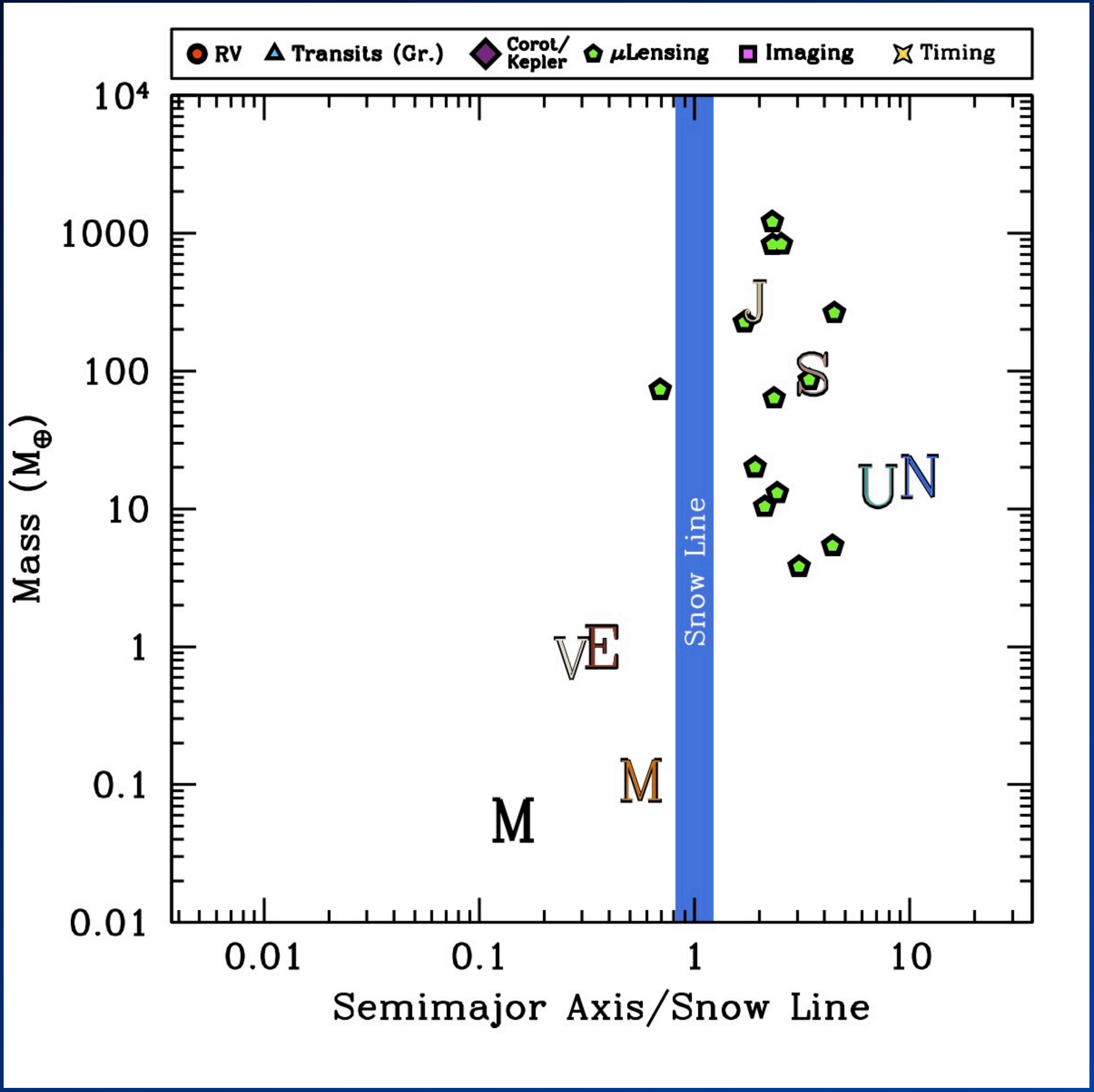
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
M
V
E
M
J
S
U
N

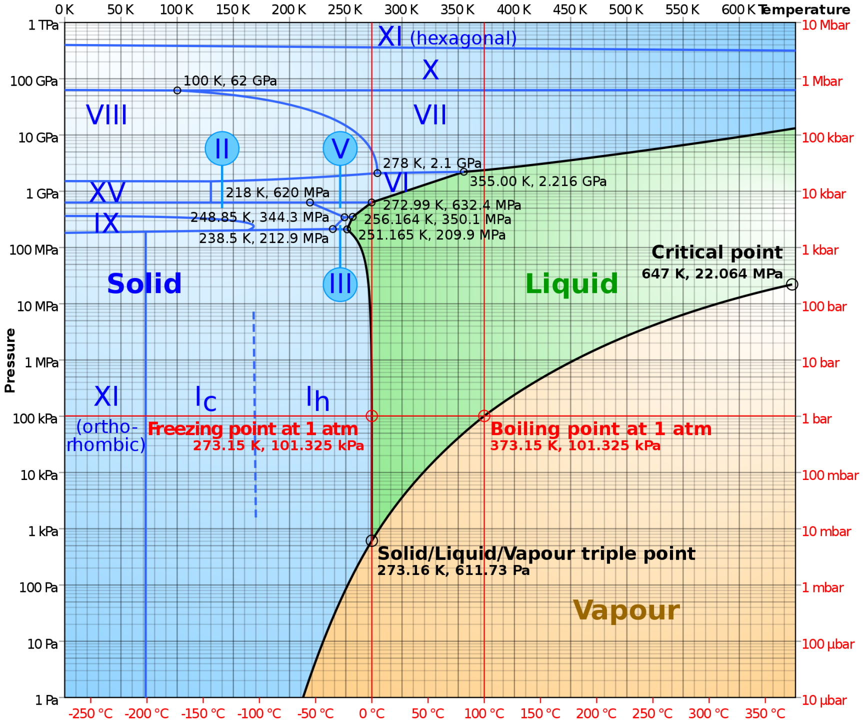
# To the snow line… and beyond!



# Understanding Habitability.

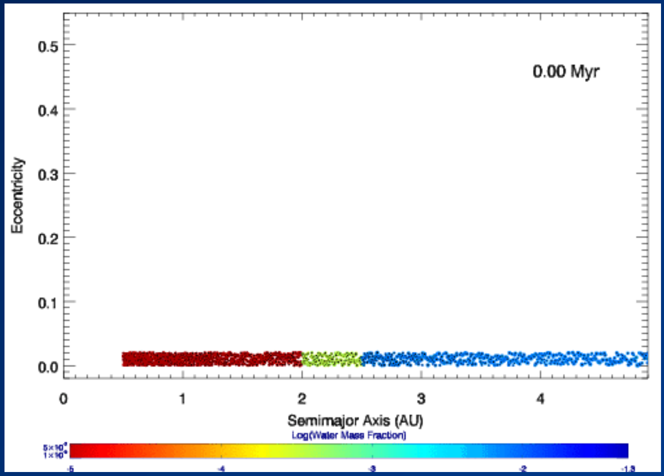
# Water, water, everywhere.

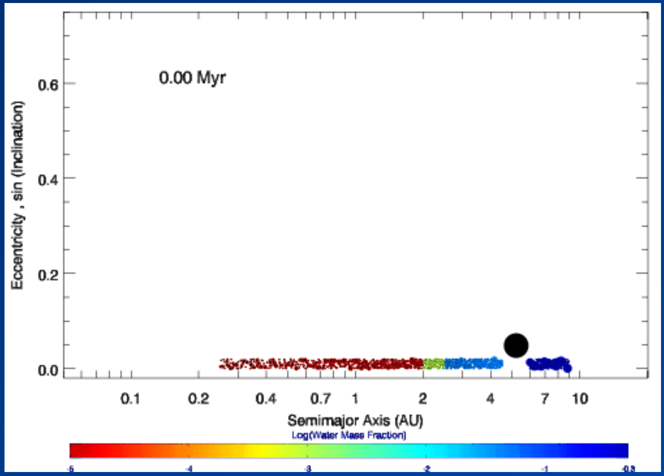
- For *in situ* formation, material that accreted to form rocky planets in the habitable zone was likely dry.
- Water was likely delivered from the outer solar system.



# 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.





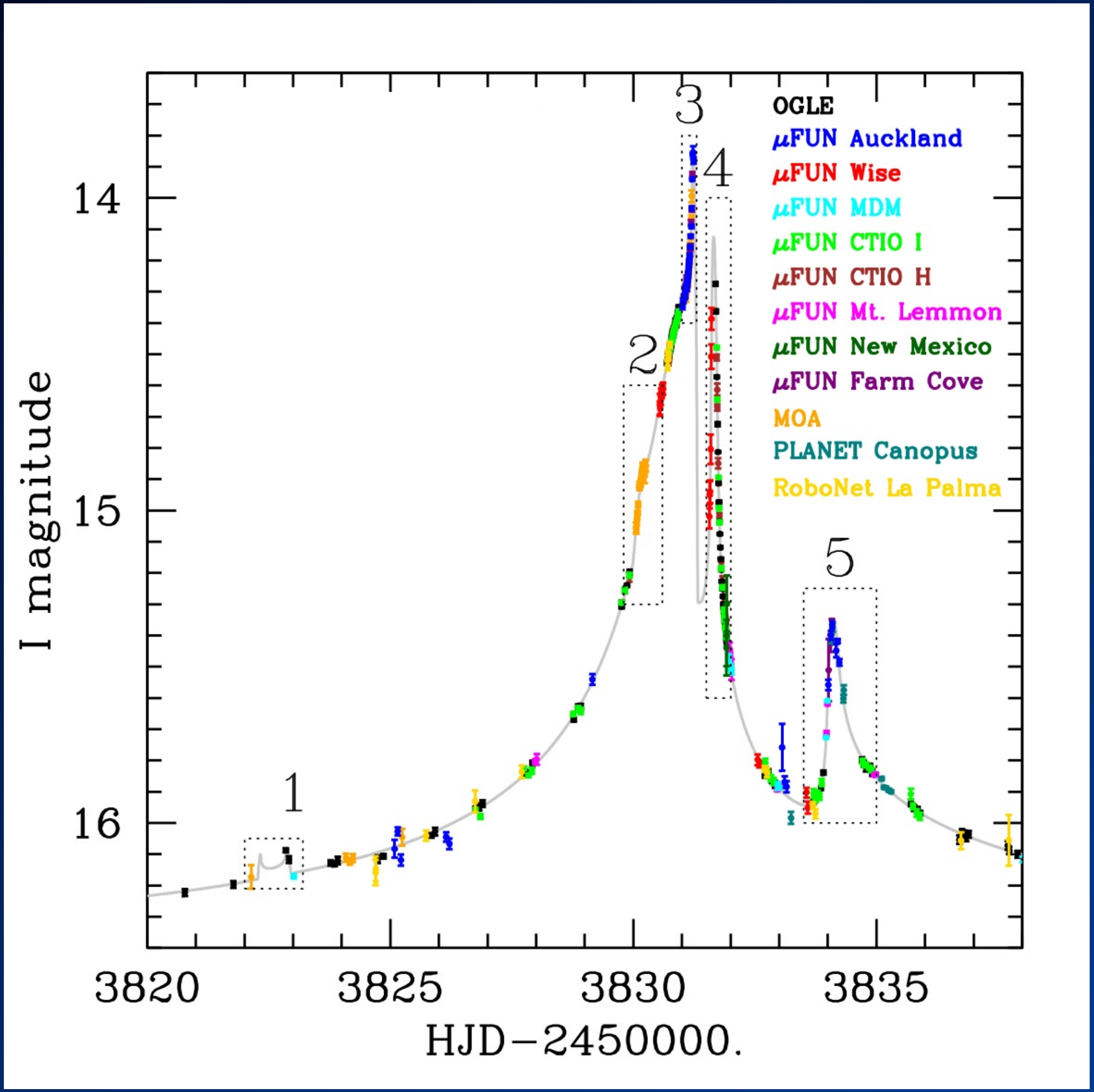
(Raymond et al. 2006, Mandell et al. 2007)

# Why Microlensing is Important.

- Planets beyond the snow line.
  - Most sensitive at ~few × $a_{snow}$
  - Where most planets likely form, where gas giants likely form, source of water.
- Multiple-planet systems beyond the snow line.
  - Jupiter/Saturn analogs.
- Long-period and free-floating planets.
  - 0.5 AU – ∞
- *Very* low-mass planets.
  - $>$10% Mars.
- Directly sensitive to mass.
  - Low-luminosity or dark lenses.
- Wide range of host masses.
  - BD, $M<M_{Sun}$, remnants
  - Typically 0.5 $M_{Sun}$
- Planets throughout the Galaxy.
  - 1-8 kpc

# Results!

# OGLE 2006-BLG-109Lb,c



(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 $M_{Jup}$

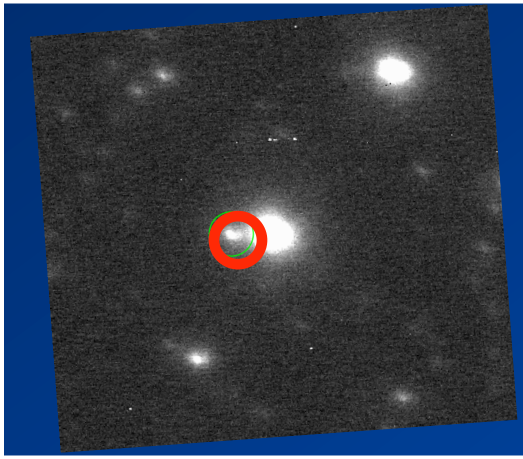
Semimajor Axis = 2.3 +/- 0.5 AU

## Planet c:

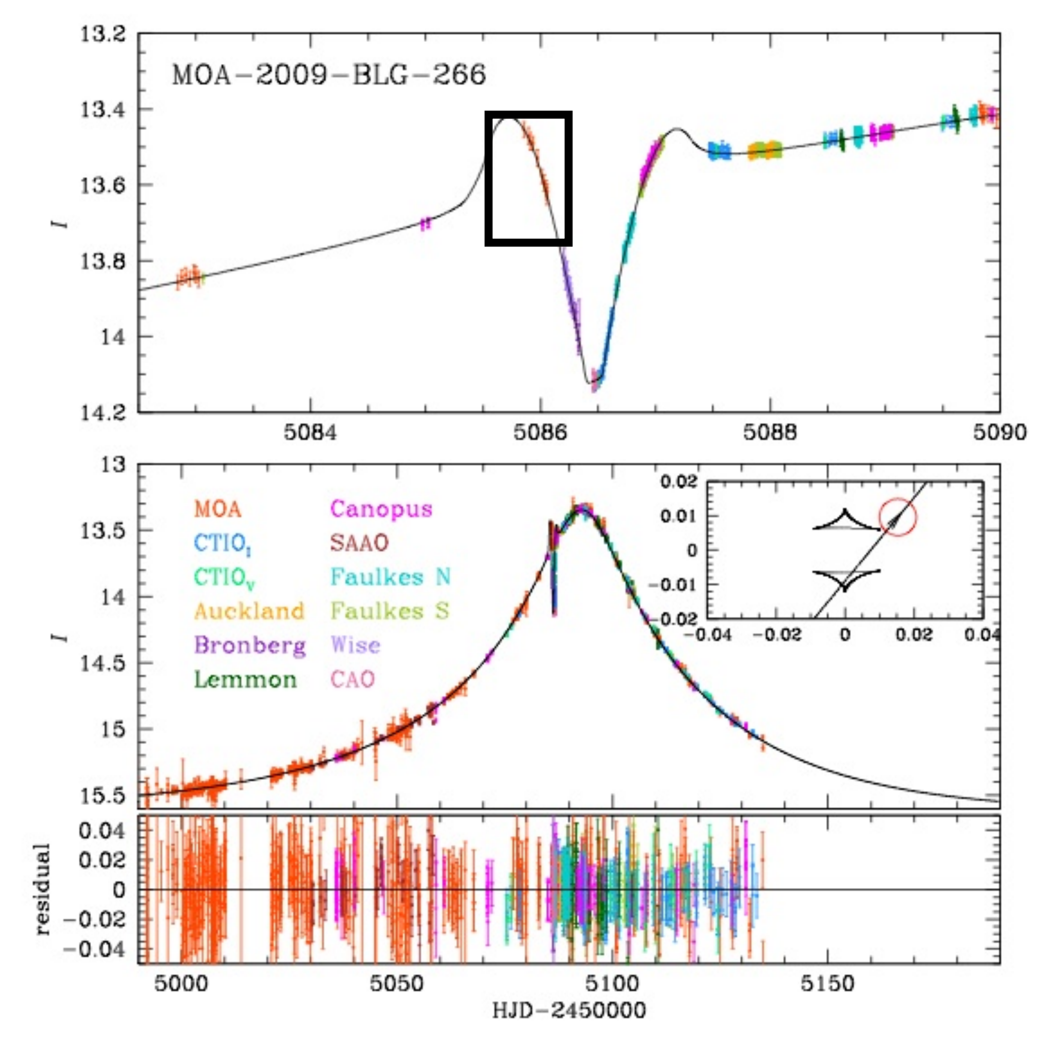
Mass = 0.27 +/- 0.02 $M_{Jup}$ = 0.90 $M_{Sat}$

Semimajor Axis = 4.6 +/- 1.5 AU

AO Imaging from Keck



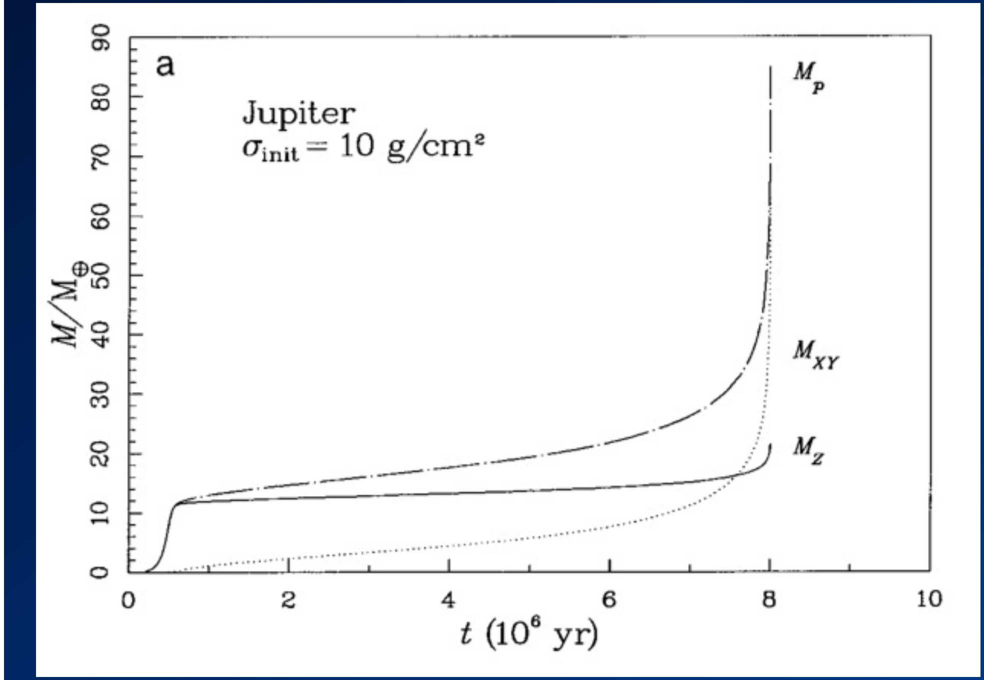
# ~10 $M_{Earth}$ Planet.



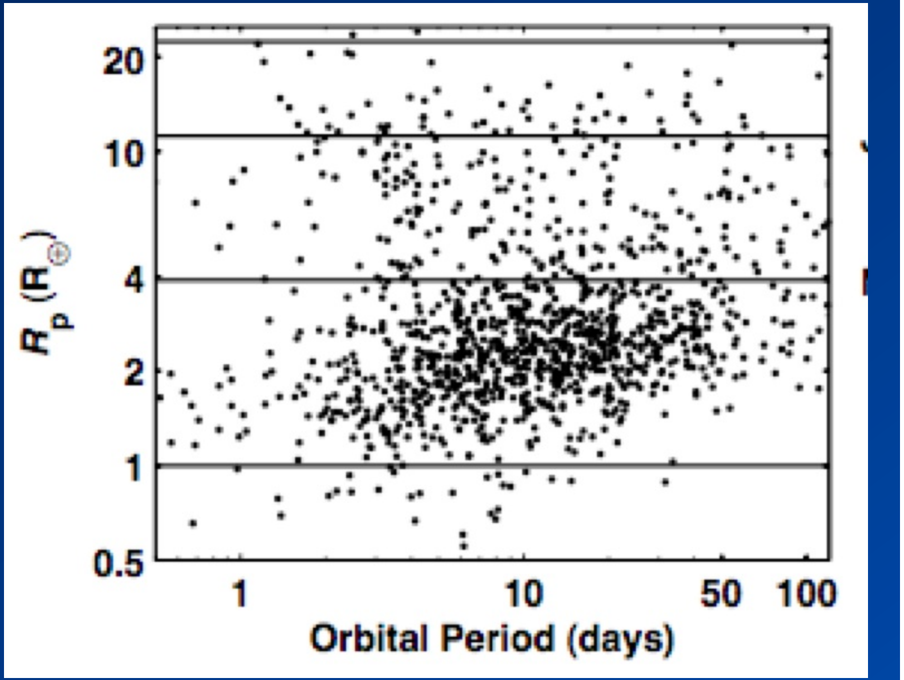
(MOA, $\mu$FUN, PLANET, RoboNET, Muraki et al. 2011)

# Failed Jupiter Core?

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

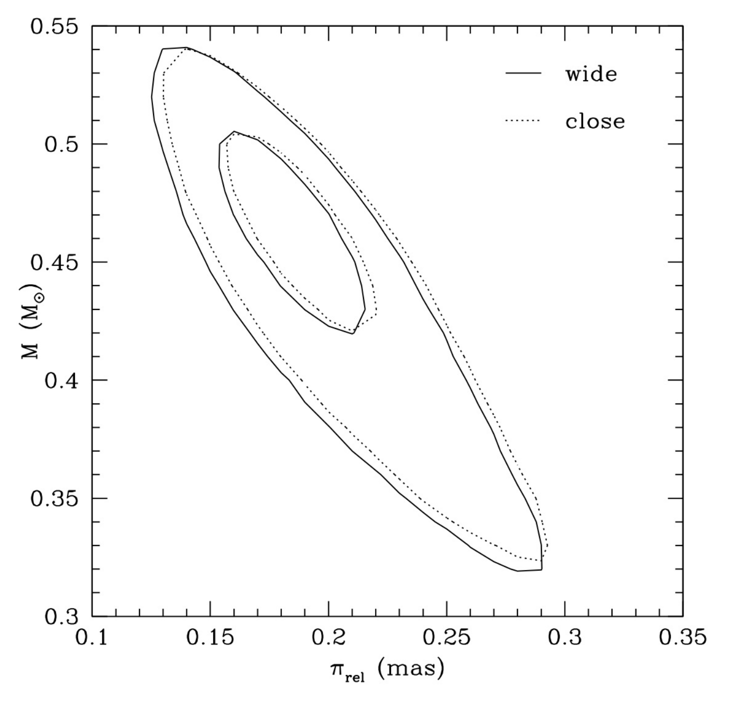


(Pollack et al. 1996)

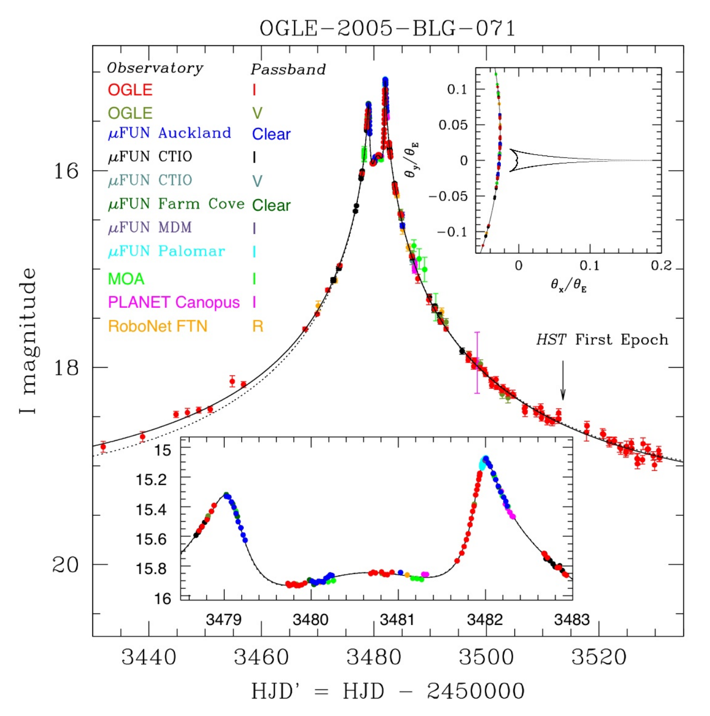


(Borucki et al. 2011)

# A Massive M Dwarf Planet.



(Dong et al. 2008)



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

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

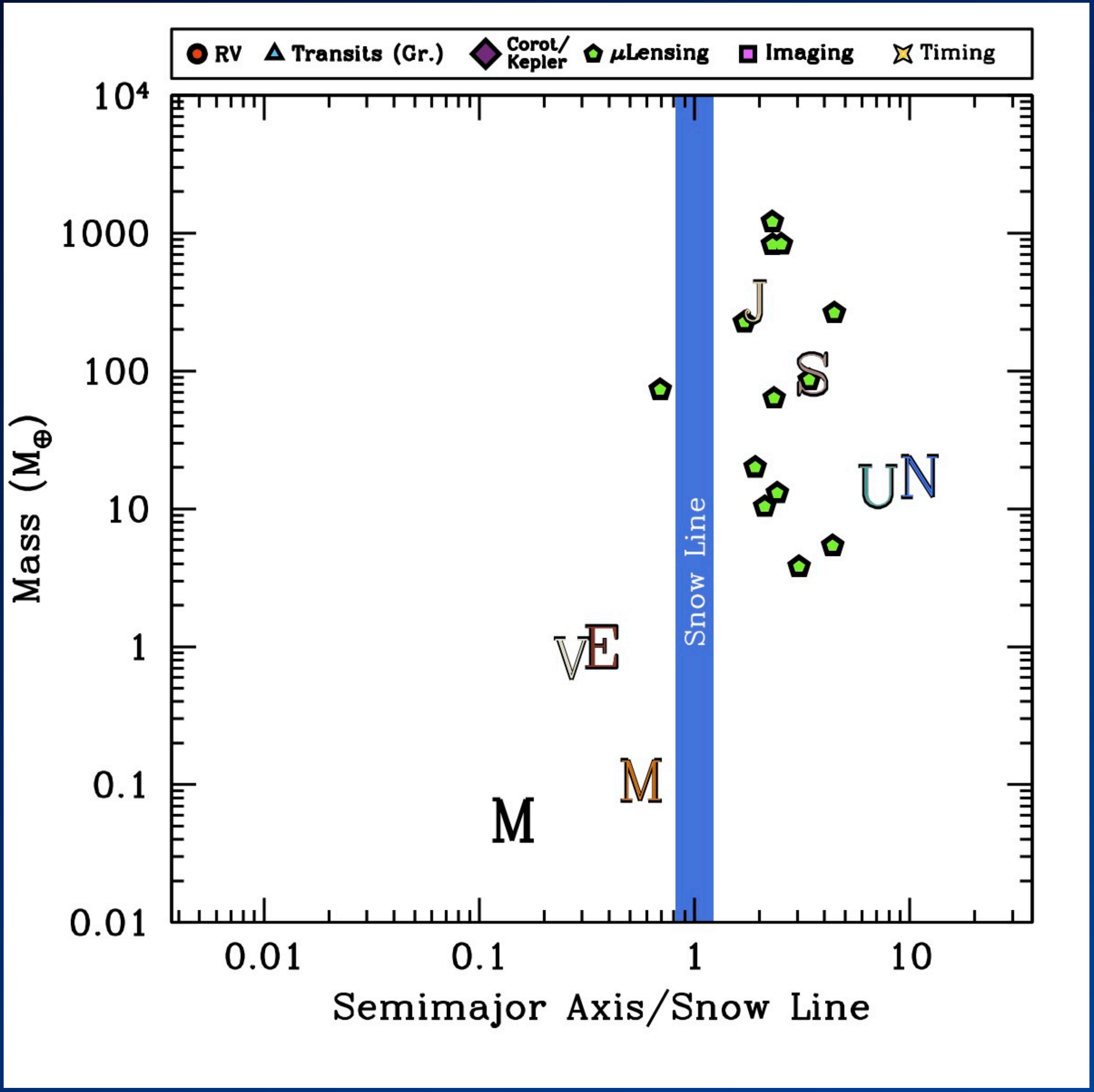
$$v_{\rm LSR} = 103 \pm 15 \text{ km s}^{-1}$$

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

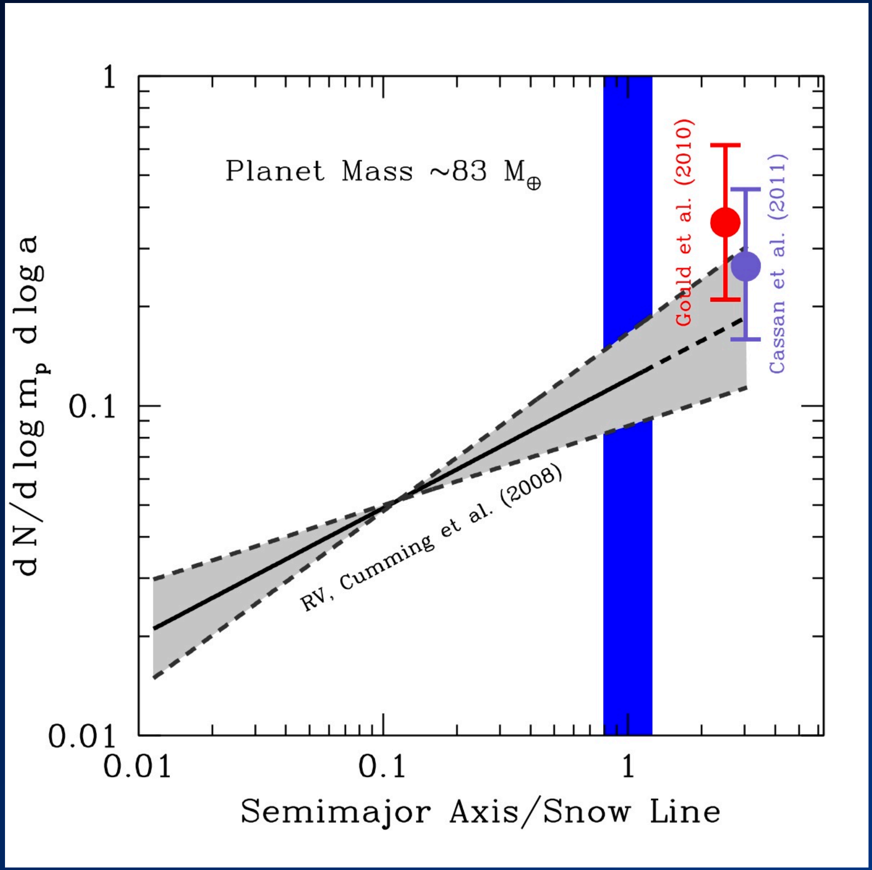
$$r_\perp = 3.6 \pm 0.2 \text{ AU}$$

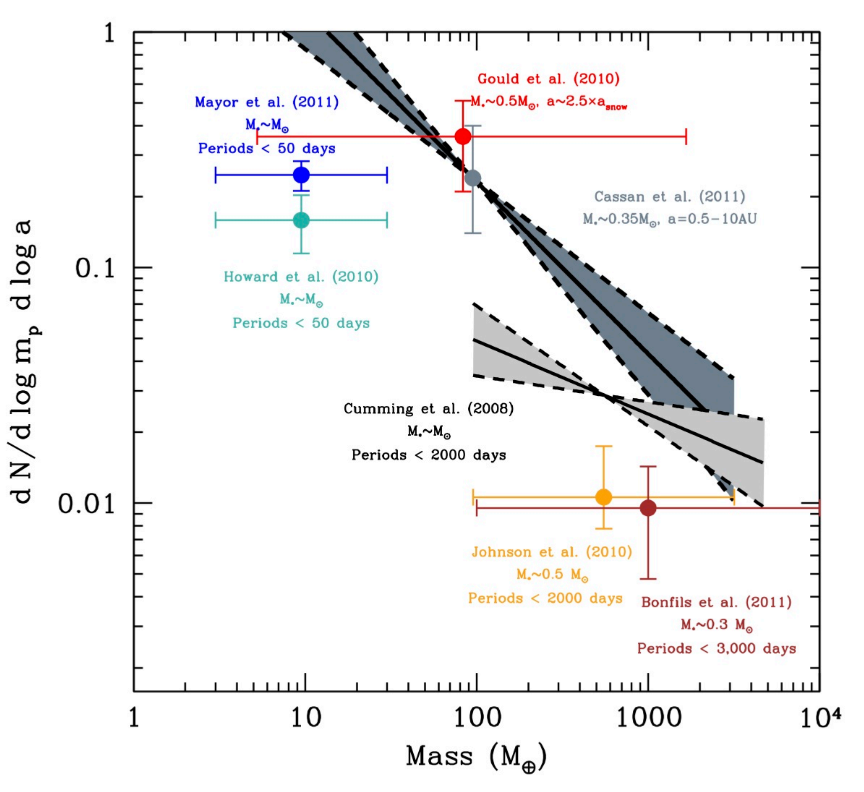
$$T_{eq} \sim 50K$$

# Demographics Beyond the Snow Line:



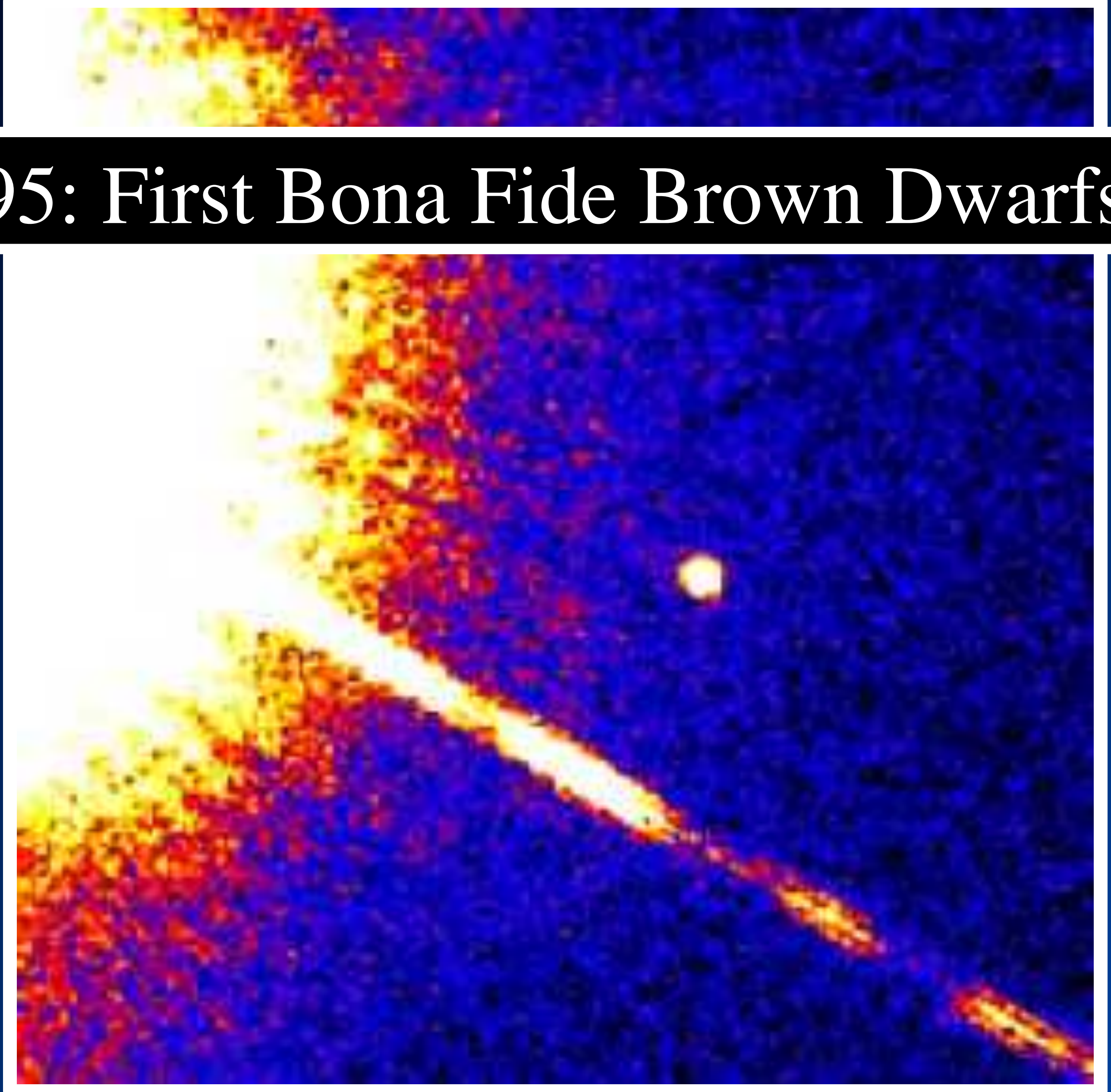
# An Inconvenient Truth.





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

# 1995: First Bona Fide Brown Dwarfs.



(Nakajima et al. 1995)

# Brown Dwarfs.

Direct Imaging Surveys:

- Young clusters.
- Near–IR field surveys.
- Wide companions to stars.

Indirect Surveys:

- Radial velocity.
- Transits.

# Brown Dwarfs Formation Scenarios.

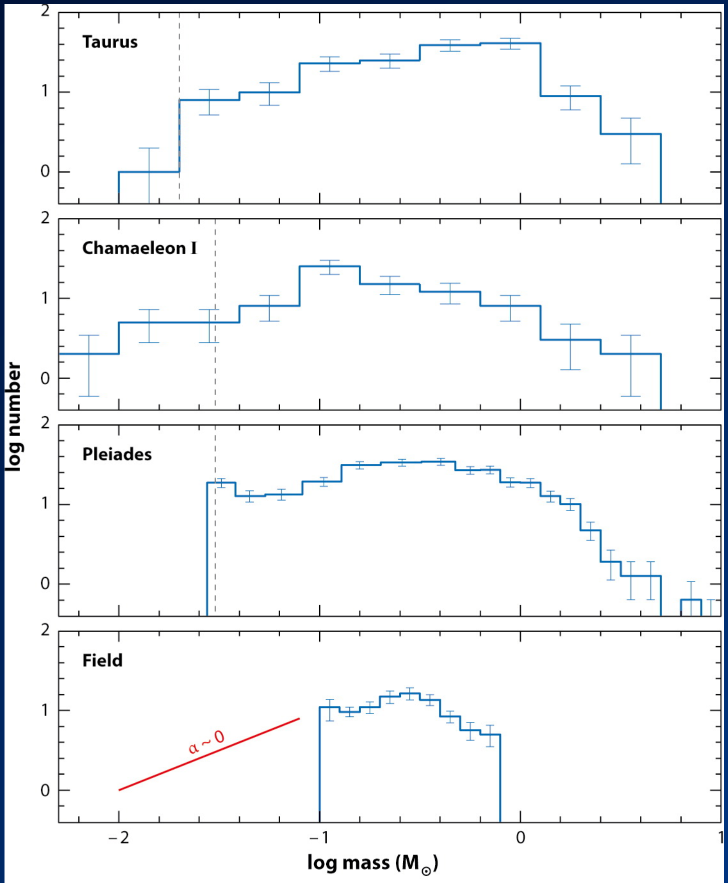
Proposed models:

- Direct collapse and fragmentation:
  - Low-mass end of star formation?
  - Truncated growth?
    - Irradiation.
    - Ejection.
- Disk Fragmentation.
- Core accretion.

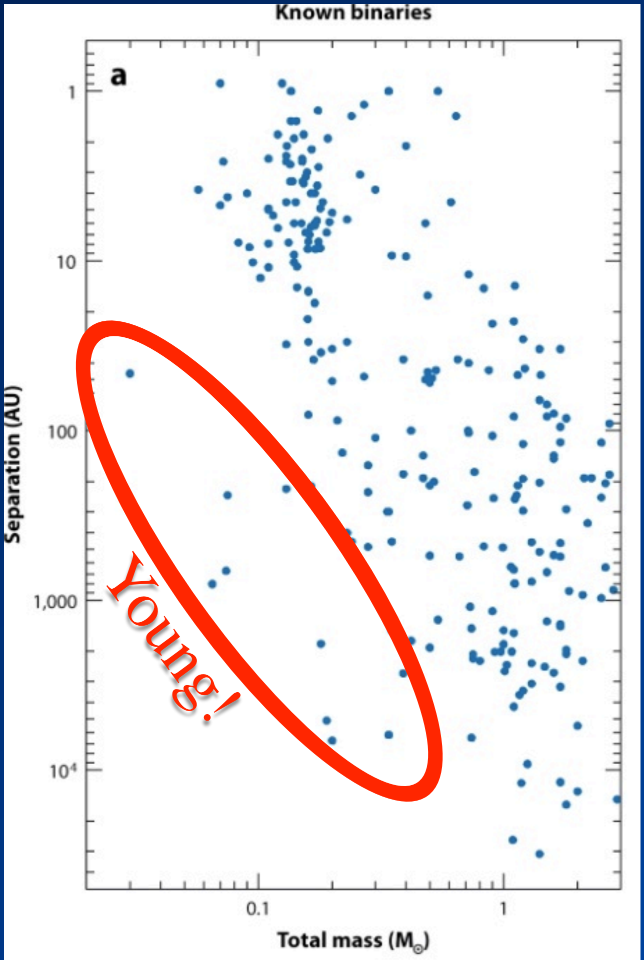
Tests: Mass function, Binary properties, Disks.

# “Isolated” Brown Dwarfs.

Luhman 2012

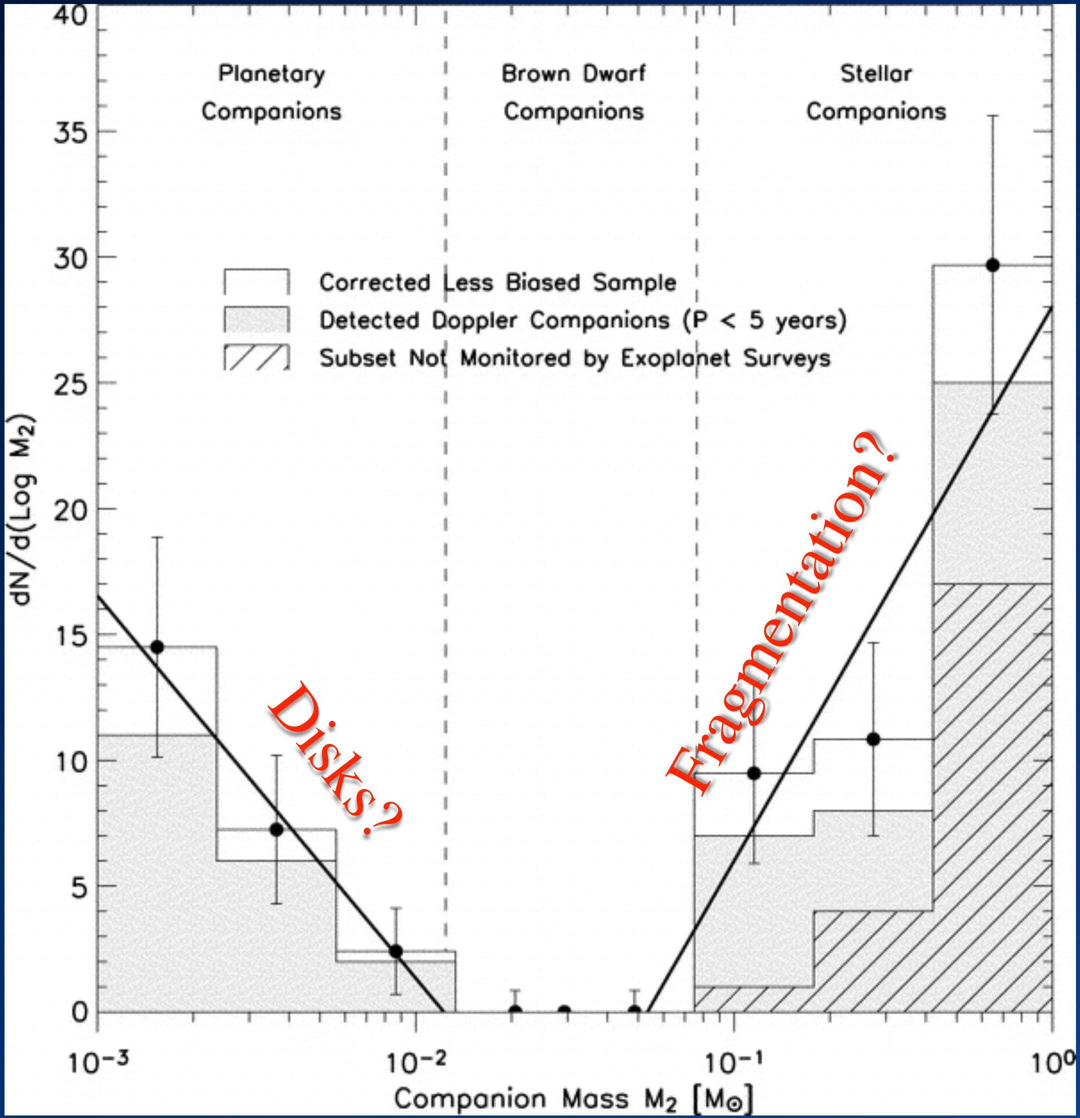


Luhman KL. 2012.
Annu. Rev. Astron. Astrophys. 50:65–106



# Brown Dwarf Companions.

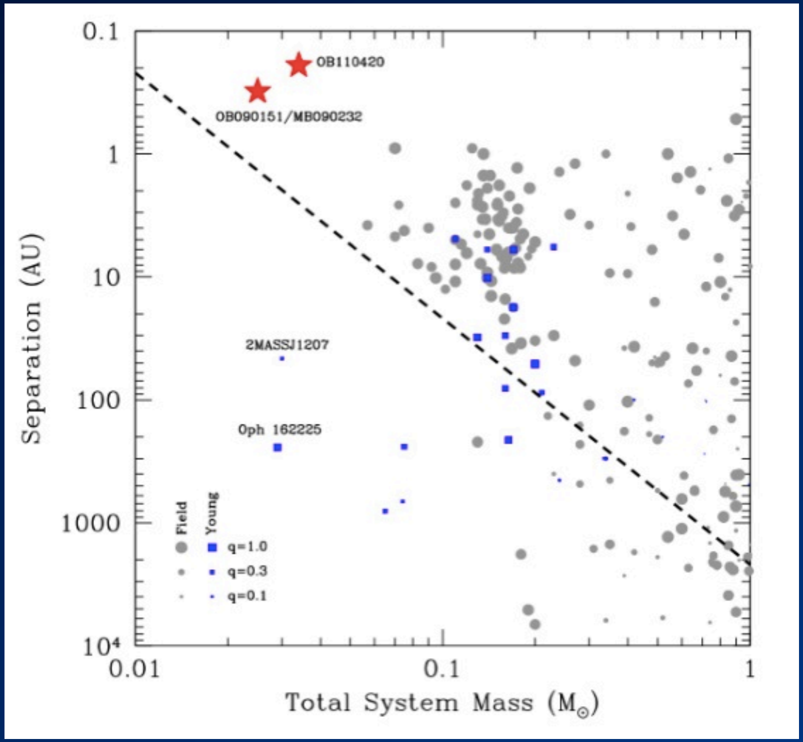
Grether & Lineweaver 2006

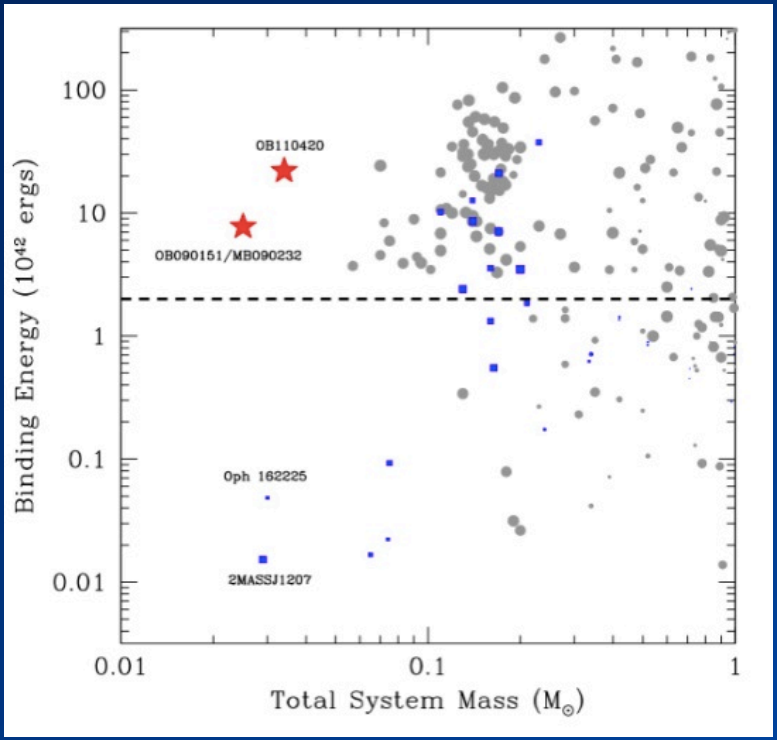


# Results!

# Microlensing Tight Brown Dwarf Binaries.

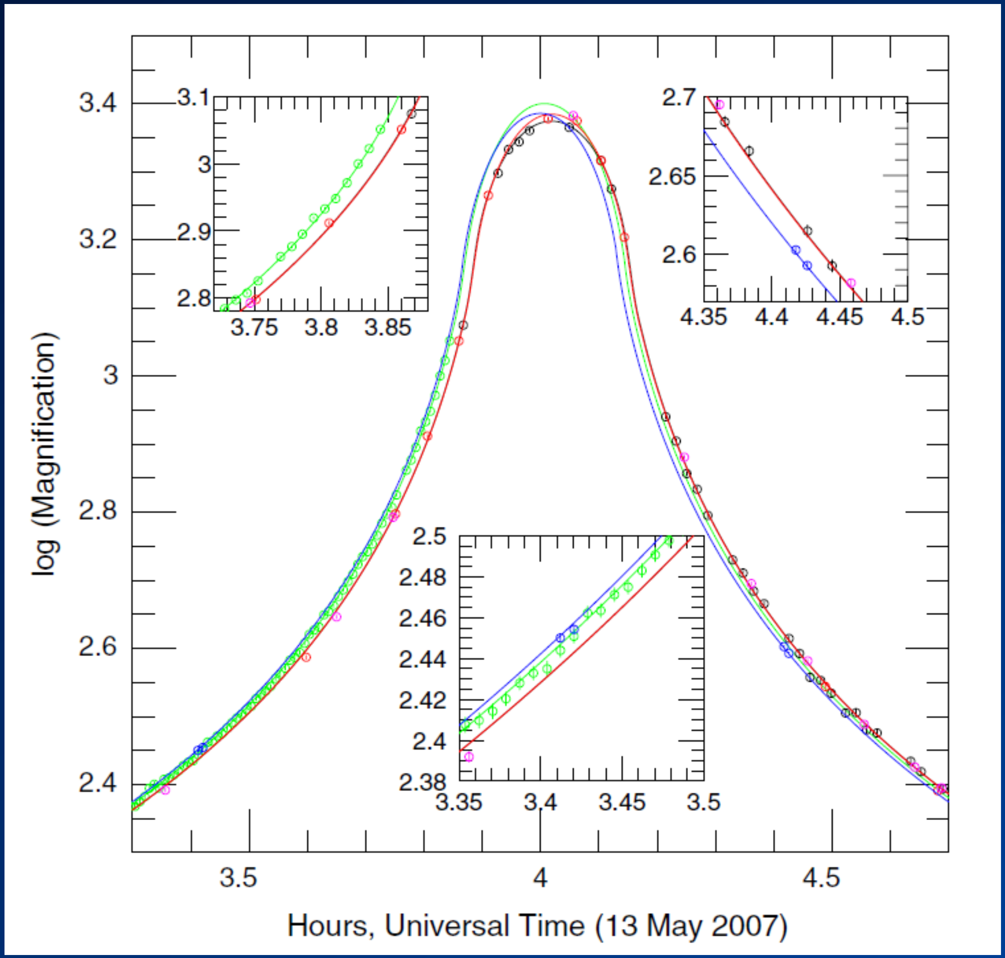
Han et al., to be submitted.





# Isolated Brown Dwarfs.

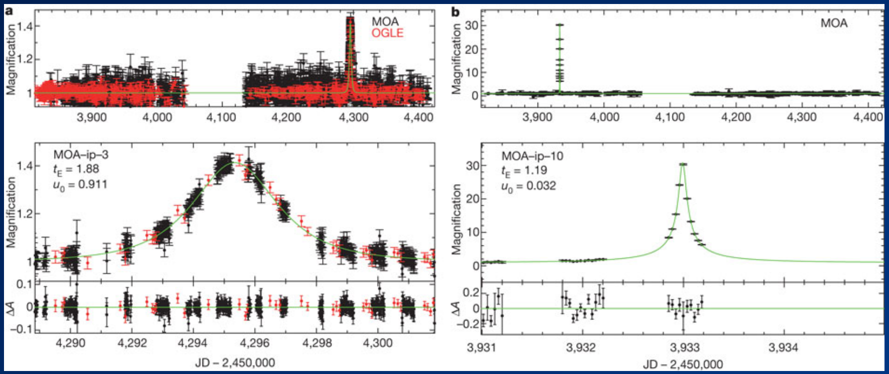
Gould et al. 2009

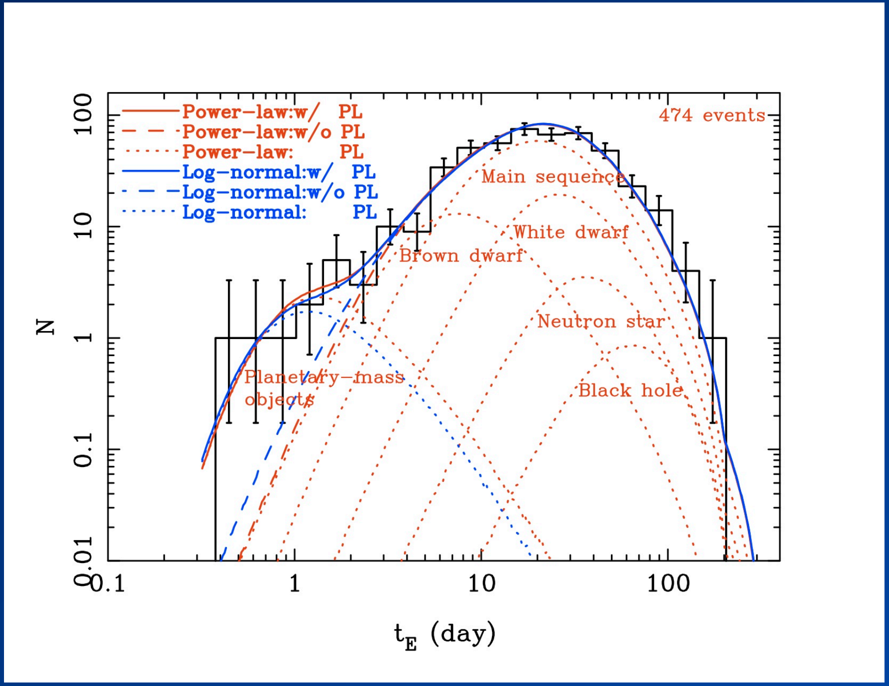


OGLE-2007-BLG-224

# 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)

# 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 is crucial component of our arsenal of planet detection methods.
- Microlensing results (many by MicroFUN!) have already provided important (and surprising) new information about planets.
- High-magnification events play an important role by providing qualitatively different information.

# Space Surveys.

# Requirements.

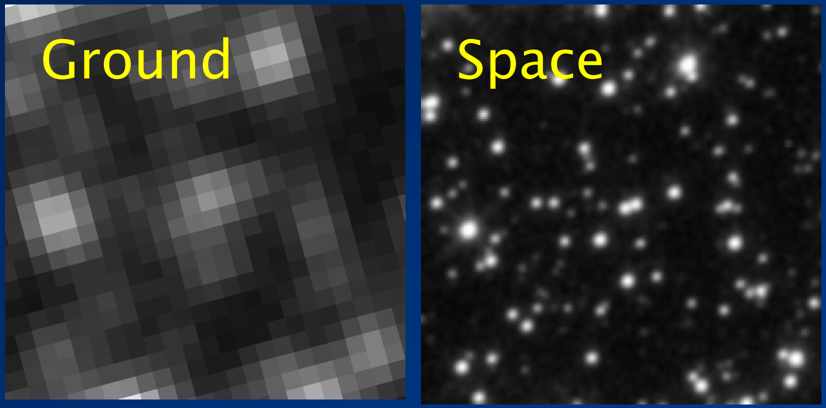
- Monitor hundreds of millions of bulge stars continuously on a time scale of ~10 minutes.
  - Event rate ~$10^{-5}$/year/star.
  - Detection probability ~0.1–1%.
  - Shortest features are ~30 minutes.
- Relative photometry of a few %.
  - Deviations are few – 10%.
- Main sequence source stars for smallest planets.
- Resolve background stars for primary mass determinations.

# 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 versus Space.

- Infrared.
  - More photons.
  - More extincted fields.
  - Smaller sources.
- Resolution.
  - Low-magnification events.
  - Isolate light from the lens star.
- Visibility.
  - Complete coverage.
- Smaller systematics.
  - Better characterization.
  - Robust quantification of sensitivities.



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

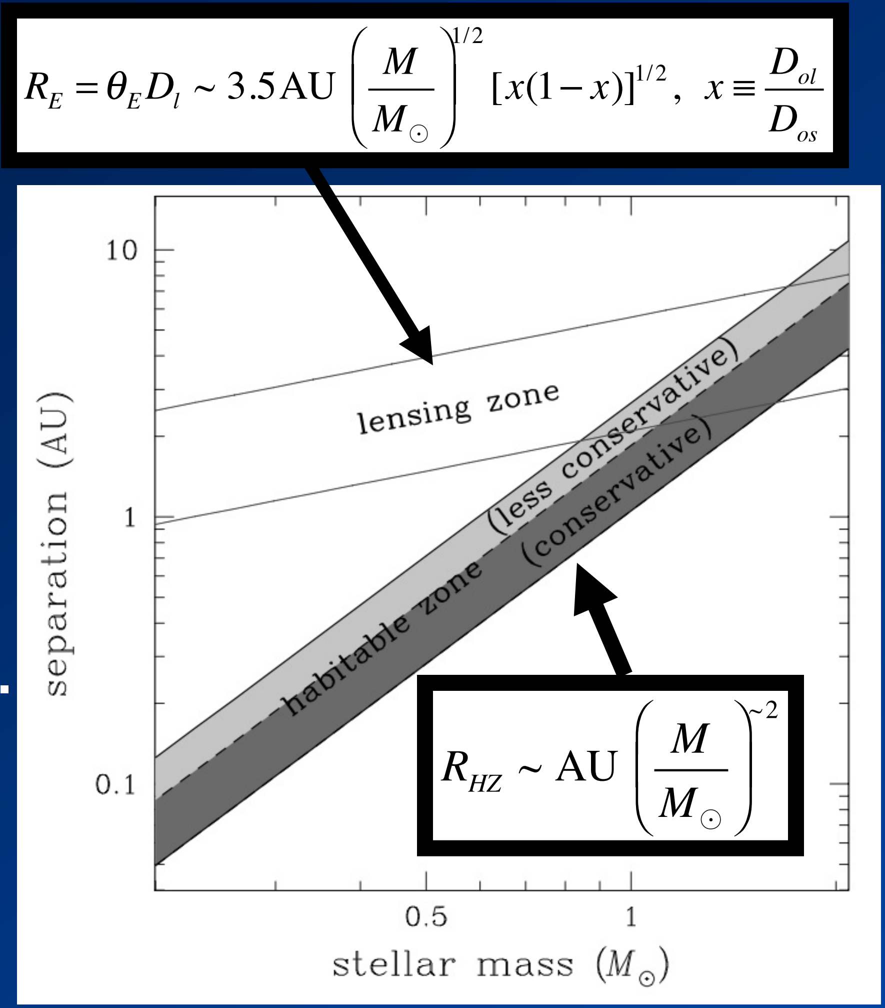
Science potentially enabled from space: sub-Earth mass planets, habitable zone planets(?), free-floating Earth-mass planets, host star characterization.

# 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.



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

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

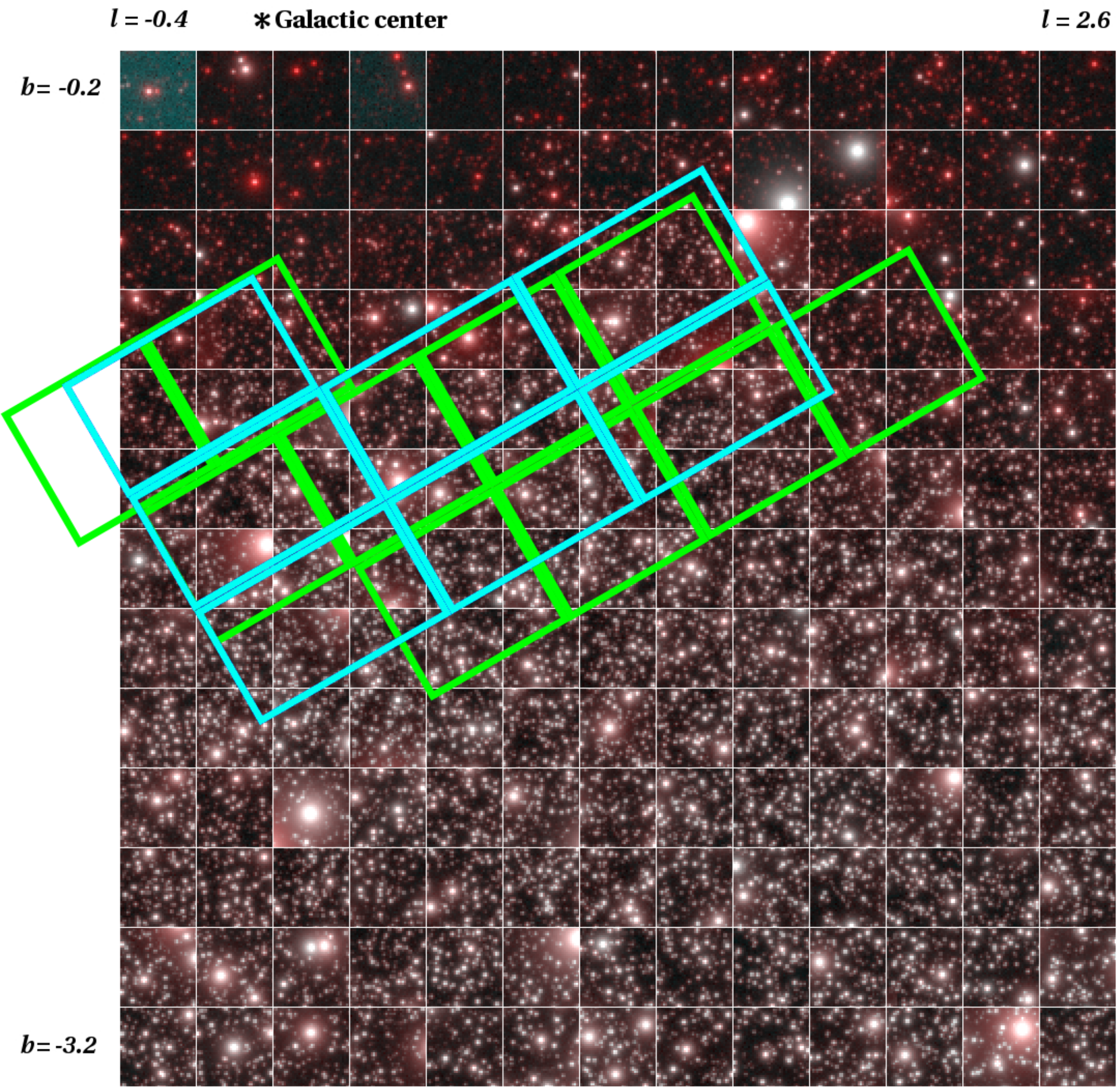
(Park et al. 2006)

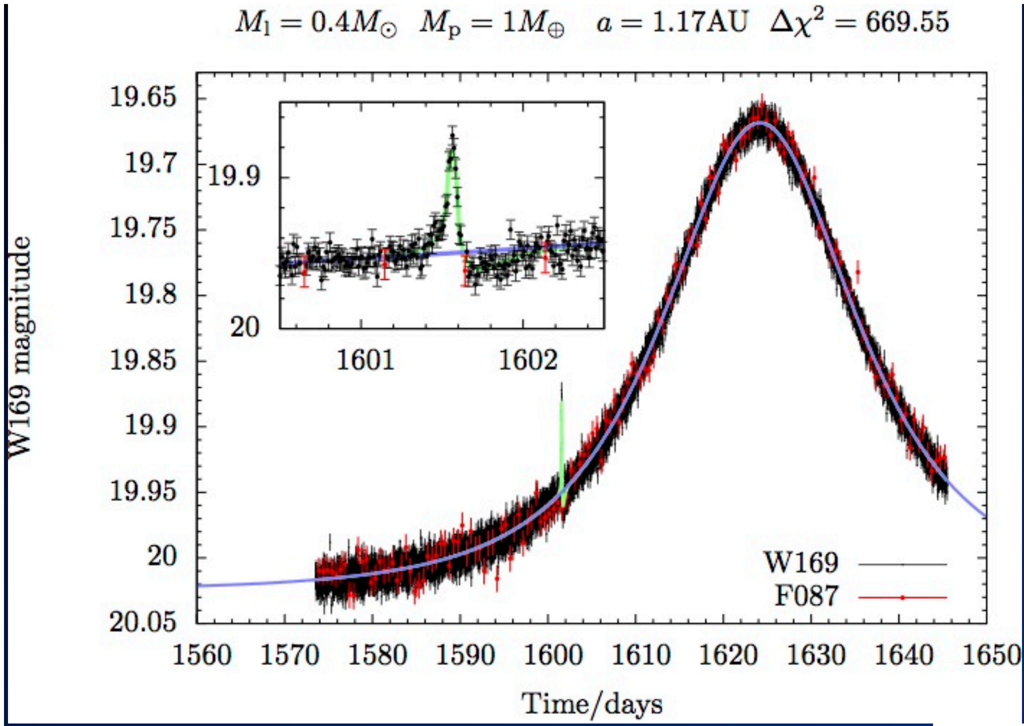
# Potential/Proposed Space Missions.

- Microlensing Planet Finder (Bennett)
  - Dedicated Near-IR Microlensing Mission.
  - Submitted to NASA as a Discovery proposal, turned down.
  - Submitted as a white paper to Decadal Survey.
- Wide-Field InfraRed Survey Telescope.
  - Creation of Decadal survey.
  - Combined MPF, JDEM-Omega, other NIR wide-field missions (following a suggestion by Gould).
  - Several versions: IDRM (1.5m), DRM1 (1.3m), DRM2 (1.1m).
- AFTA-WFIRST.
  - NRO donated two 2.4m telescopes to NASA.

# Yields.

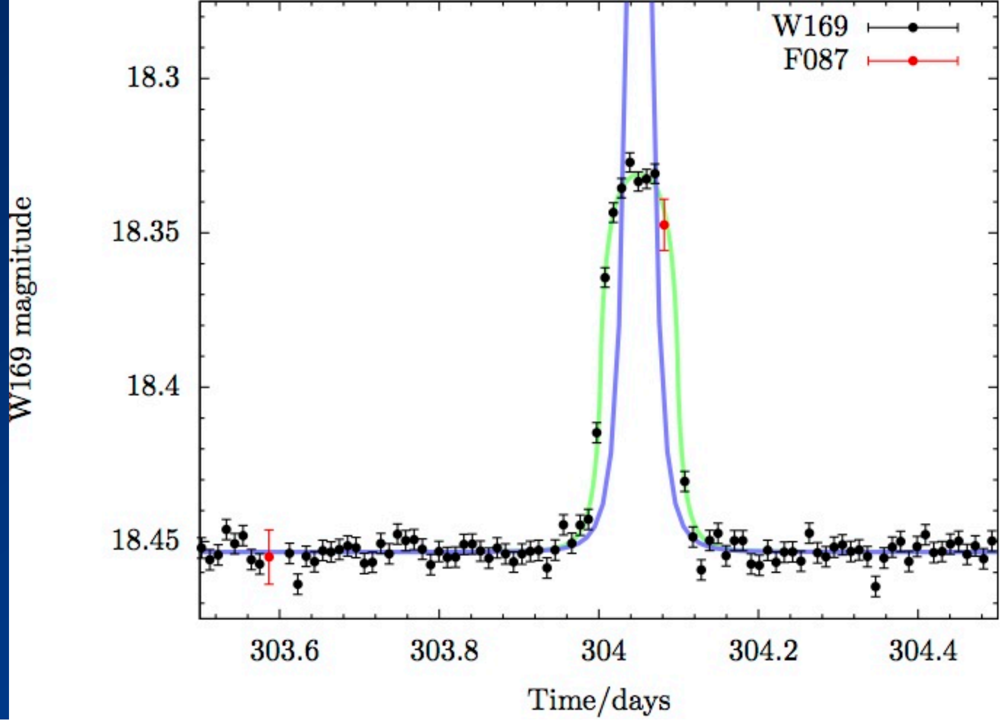
- Yields determined by:
  - Total number of stars monitored (FOV, aperture).
  - Photon rate (Aperture, wavelength).
  - Total observing time.
  - Matthew Penny.
- Primary hardware dependencies:
  - FOV.
  - Aperture.
  - Bandpass (total throughput + red cutoff).
  - Resolution (background).
  - Pointing constraints.
- Secondary hardware dependencies:
  - Data downlink.


l = -0.4
∗Galactic center
l = 2.6
b= -0.2
b= -3.2



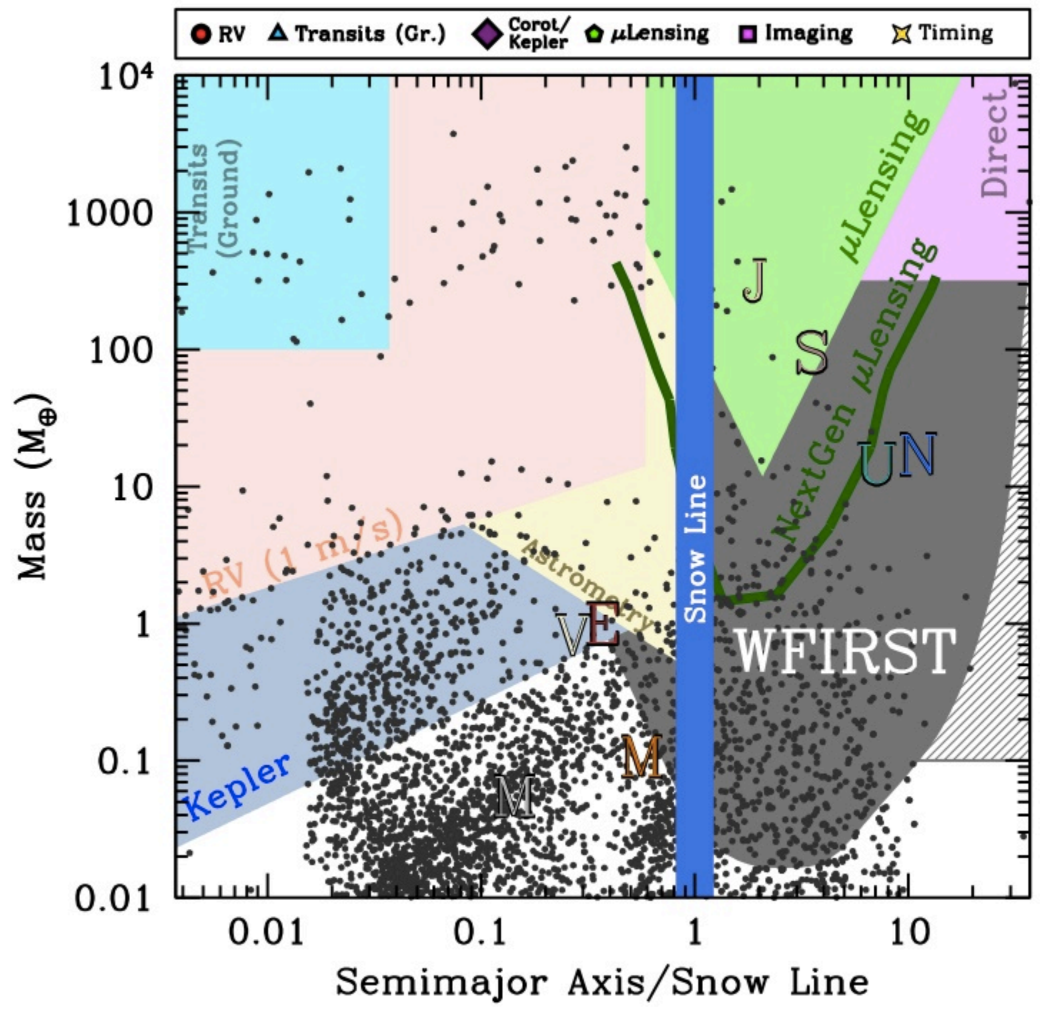
**Earth-mass Planet**

**Free Floating Earth**



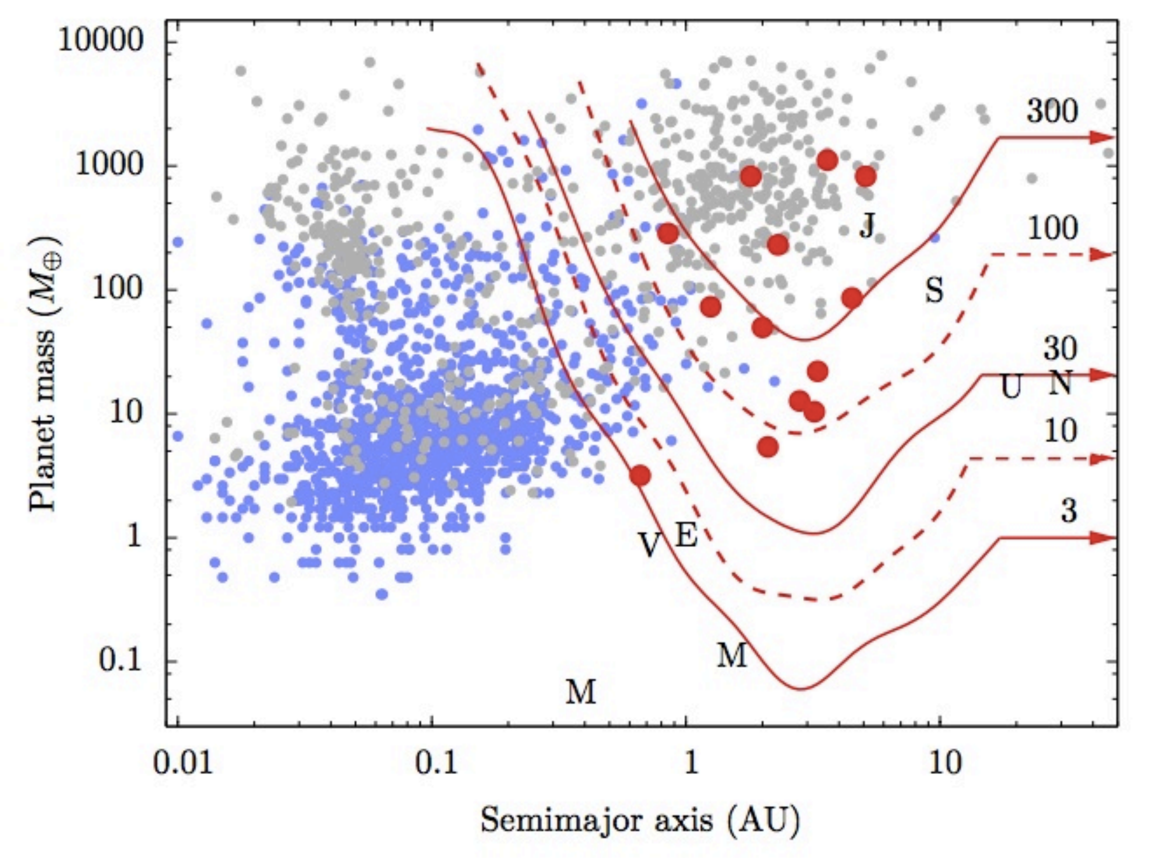
# Space Discovery Potential.

- With Kepler, “completes the census” of planets.
- Sensitivity to all Solar System-analogs except Mercury.
- Some sensitivity to massive, “outer” habitable zone (Mars-like orbits).
- Free-floating planets down to ~Mars mass.
- WFIRST DRM1 estimated yields:
  - Roughly 2200 bound planets (0.1-40 AU)
  - 250 < 3xEarth, 1000 < 30xEarth
  - Roughly 30 free-floating Earths
- Euclid is less capable per unit time.



(Green et al, WFIRST Final Report)

# Euclid.



(Penny et al, 2012)

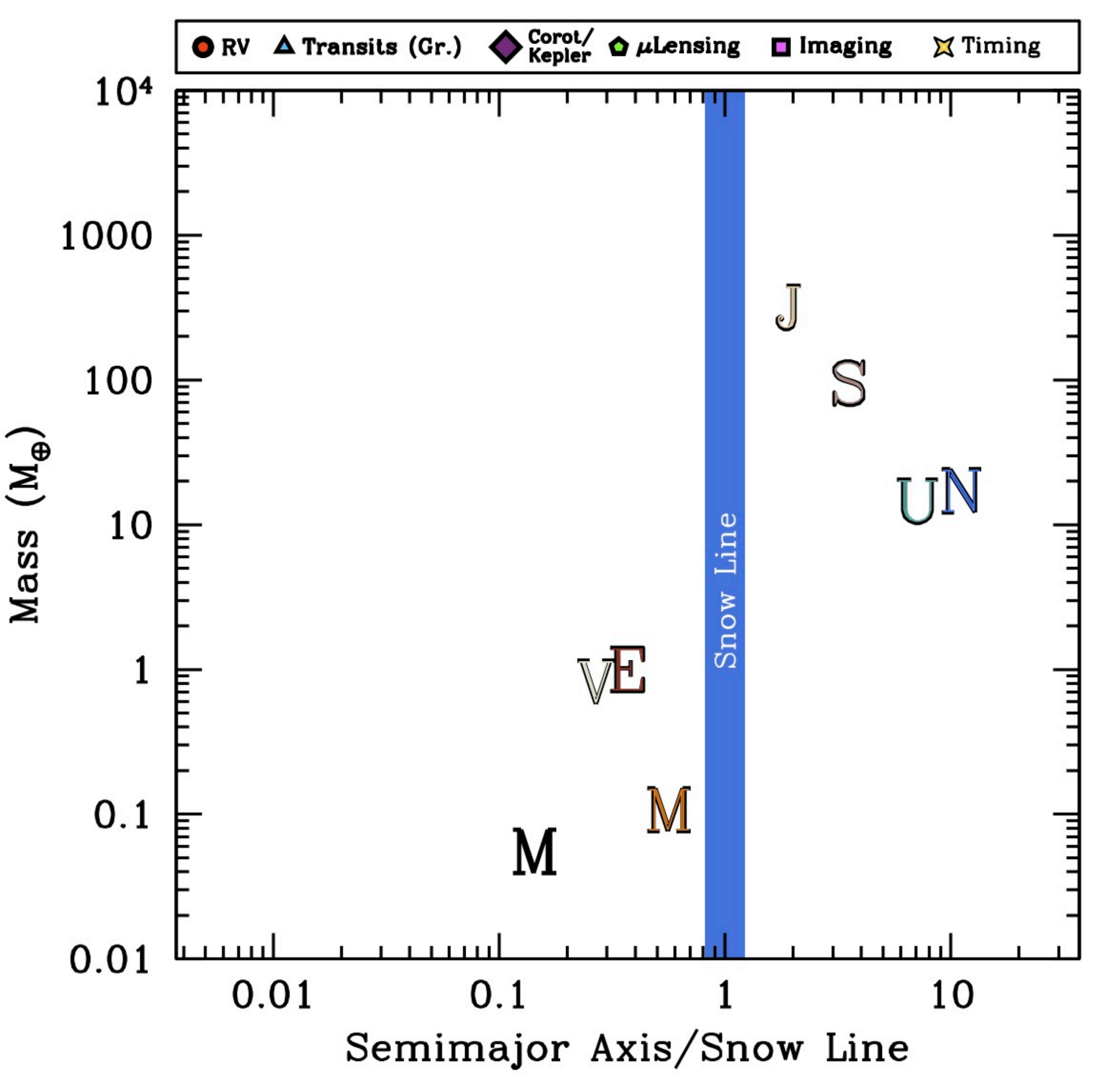
# Politics.

- Microlensing is not part of Euclid’s core science.
  - Degradation of CCDs means it won’t happen early in the mission, if it happens at all.
- NASA does not get a new ‘large start’ until JWST is launched.
  - ‘Punishment’ for JWST cost overruns.
- WFIRST is not very popular amongst many US astronomers.
  - They see it as a ‘dark energy’ mission, along with LSST.

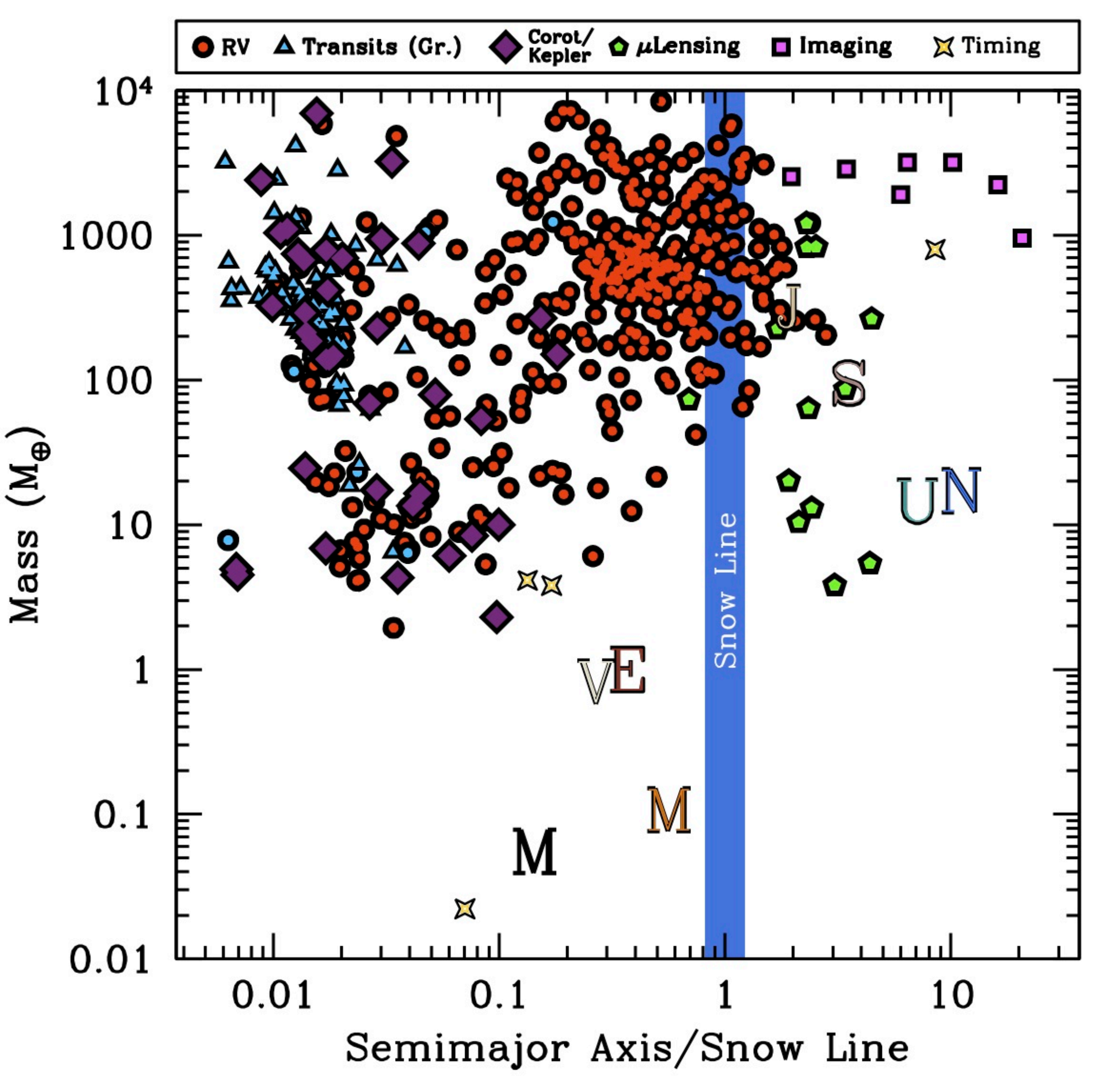
# Summary.

- Space-based surveys enable qualitatively new, exciting science:
  - Sub-Earth-mass planets.
  - Low-mass free-floating planets.
  - Outer habitable zone planets.
  - Mass measurements.
- Unclear if/when one will happen.

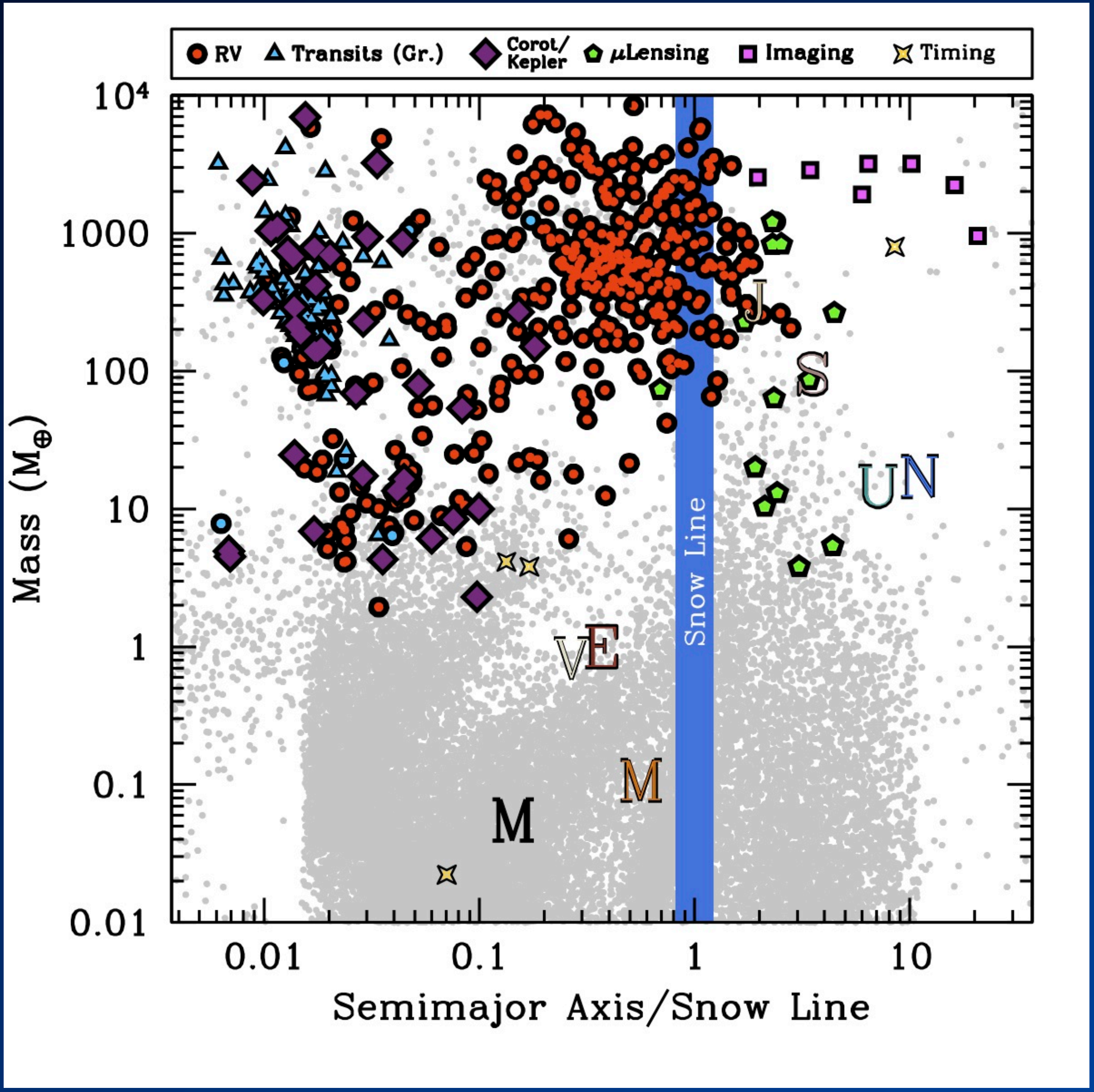
# Planet Search Synergy!



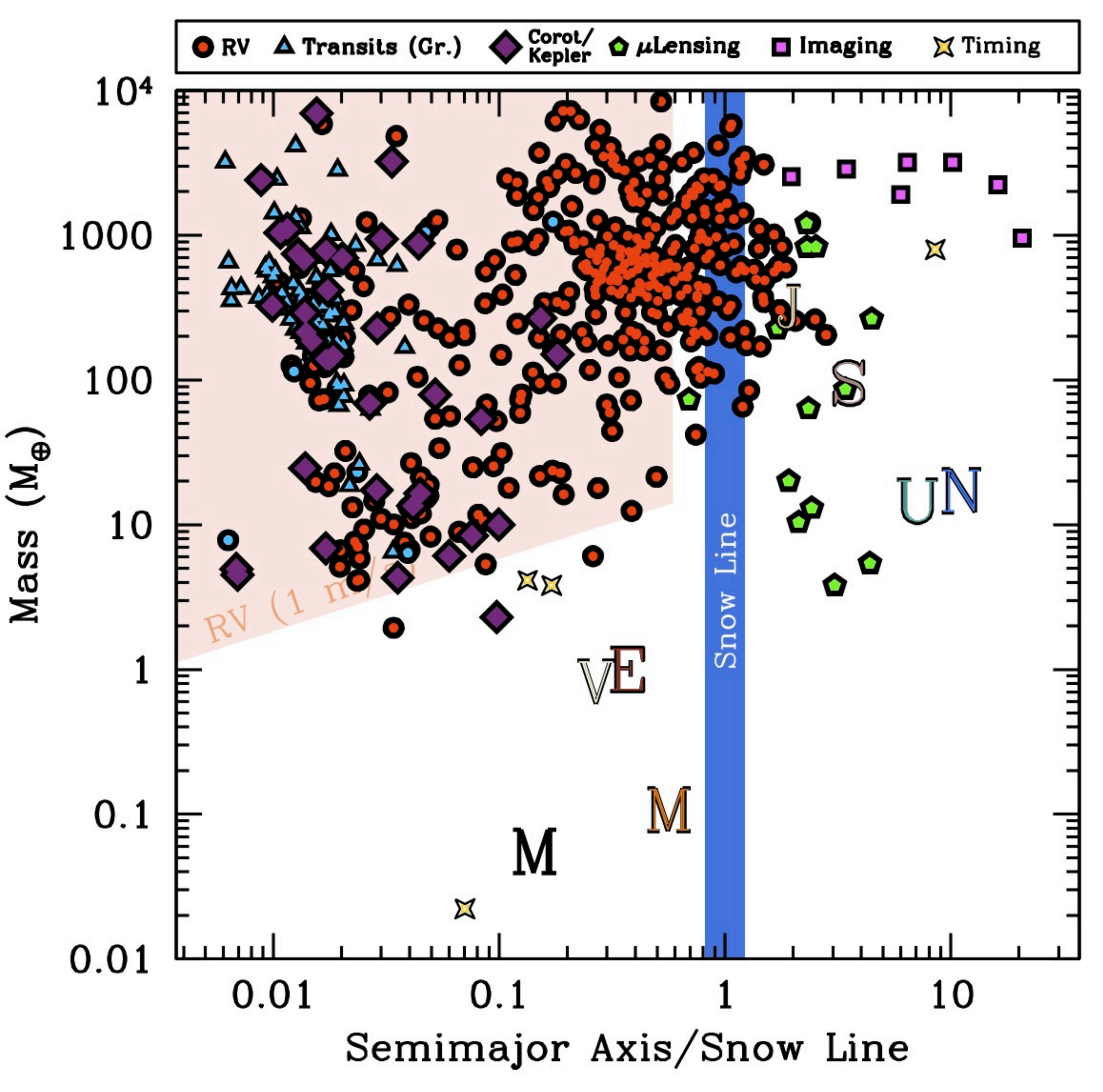
# Planet Search Synergy!



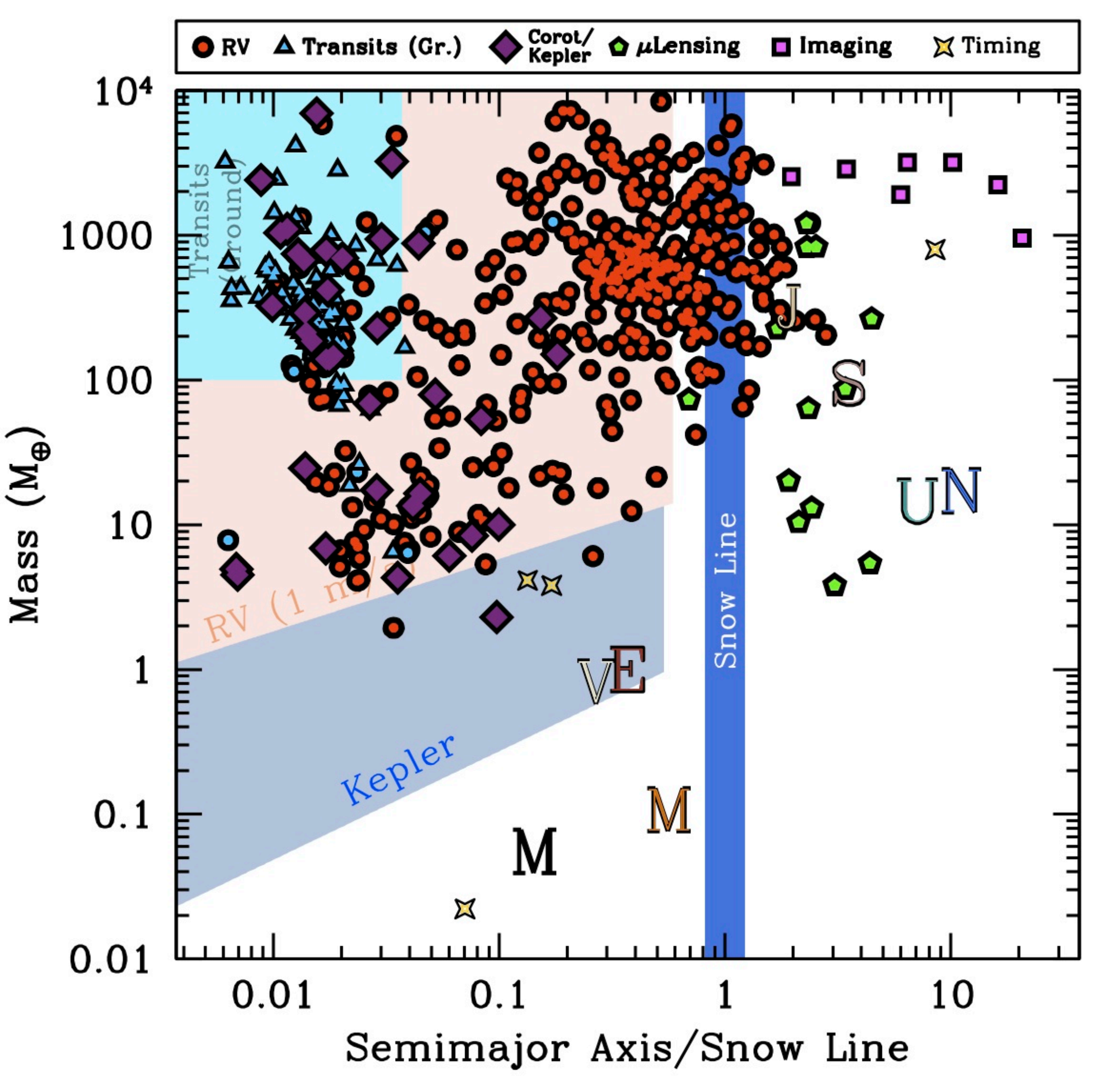
# Planet Search Synergy!



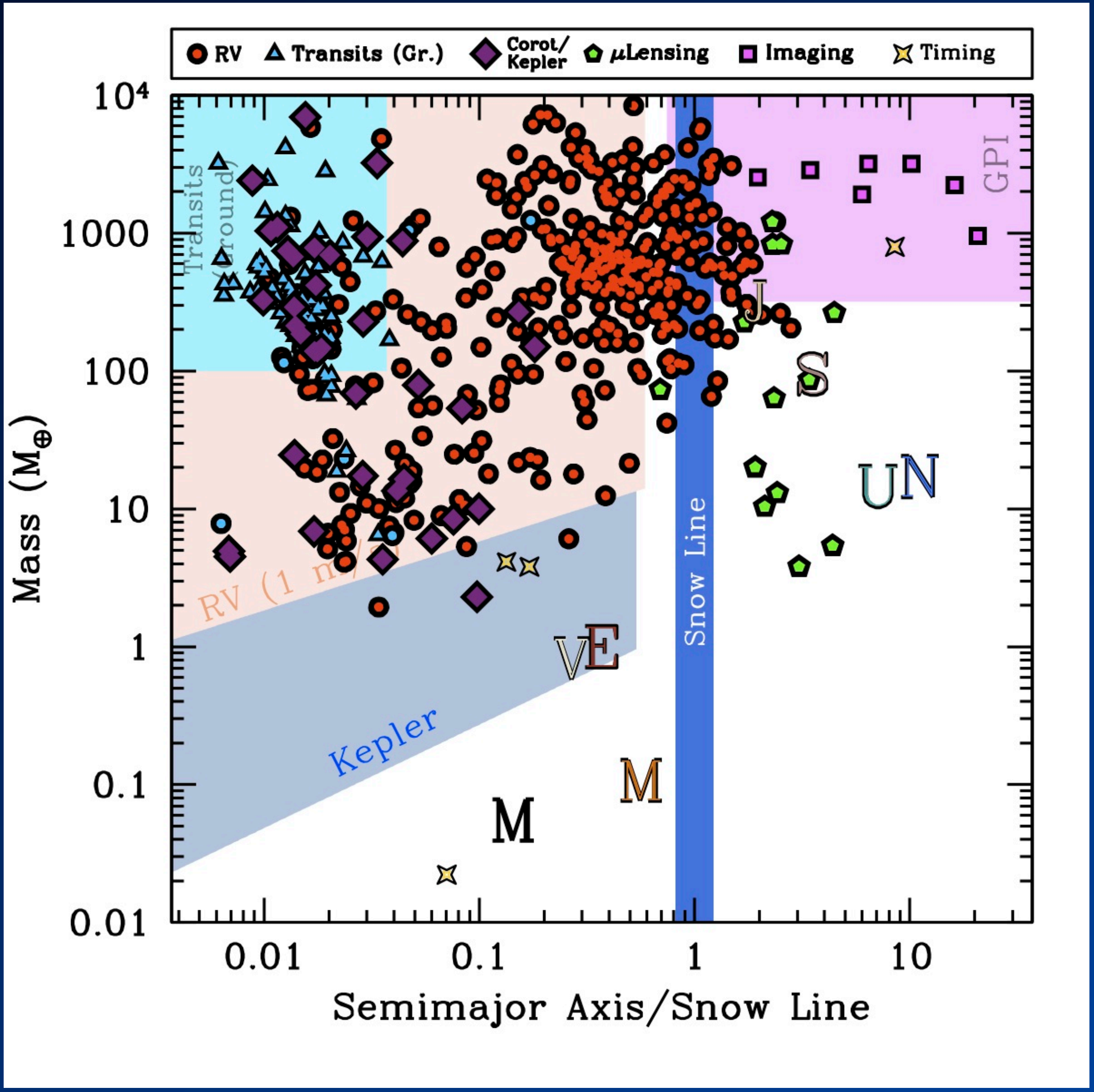
# Planet Search Synergy!



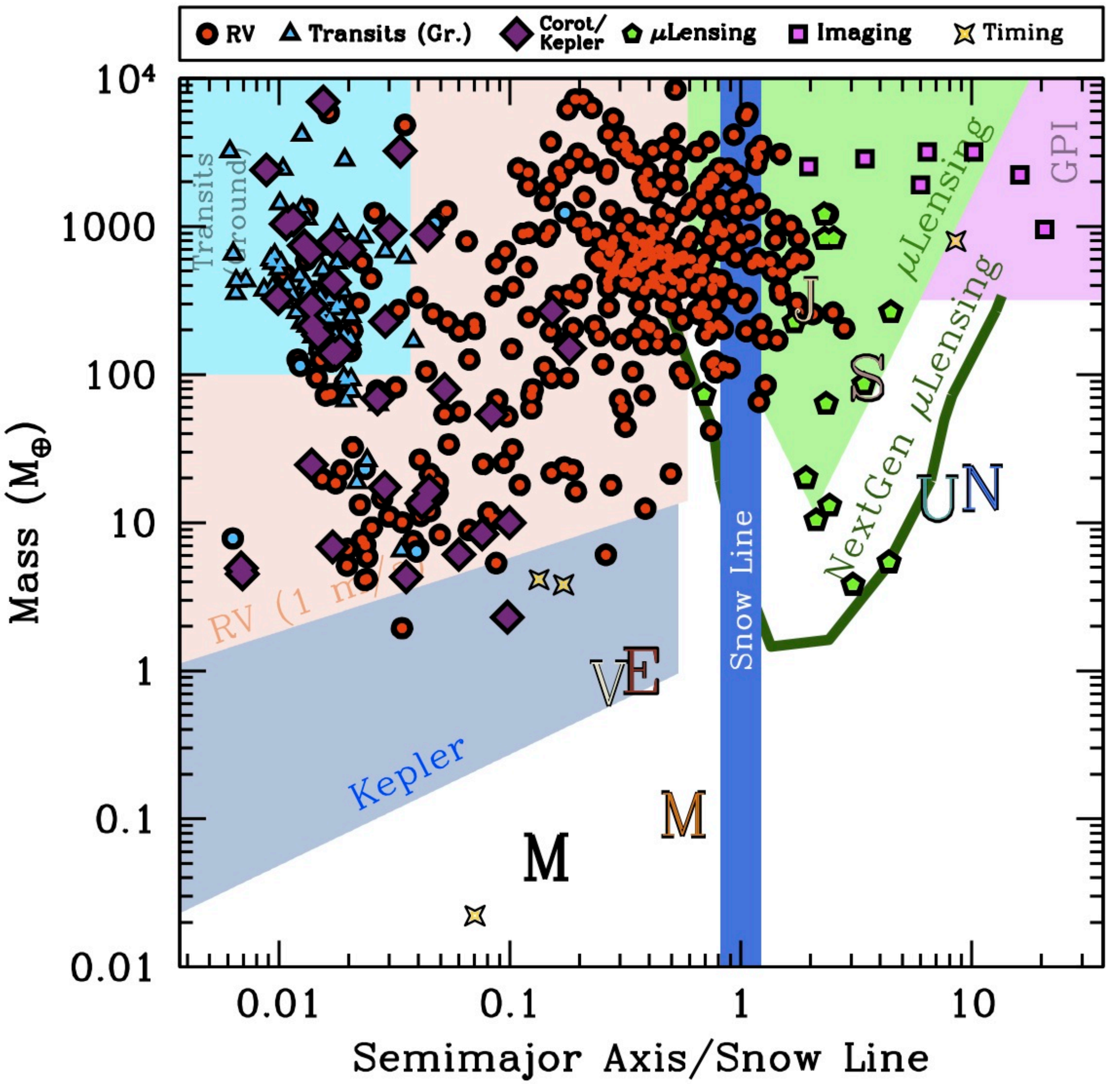
# Planet Search Synergy!



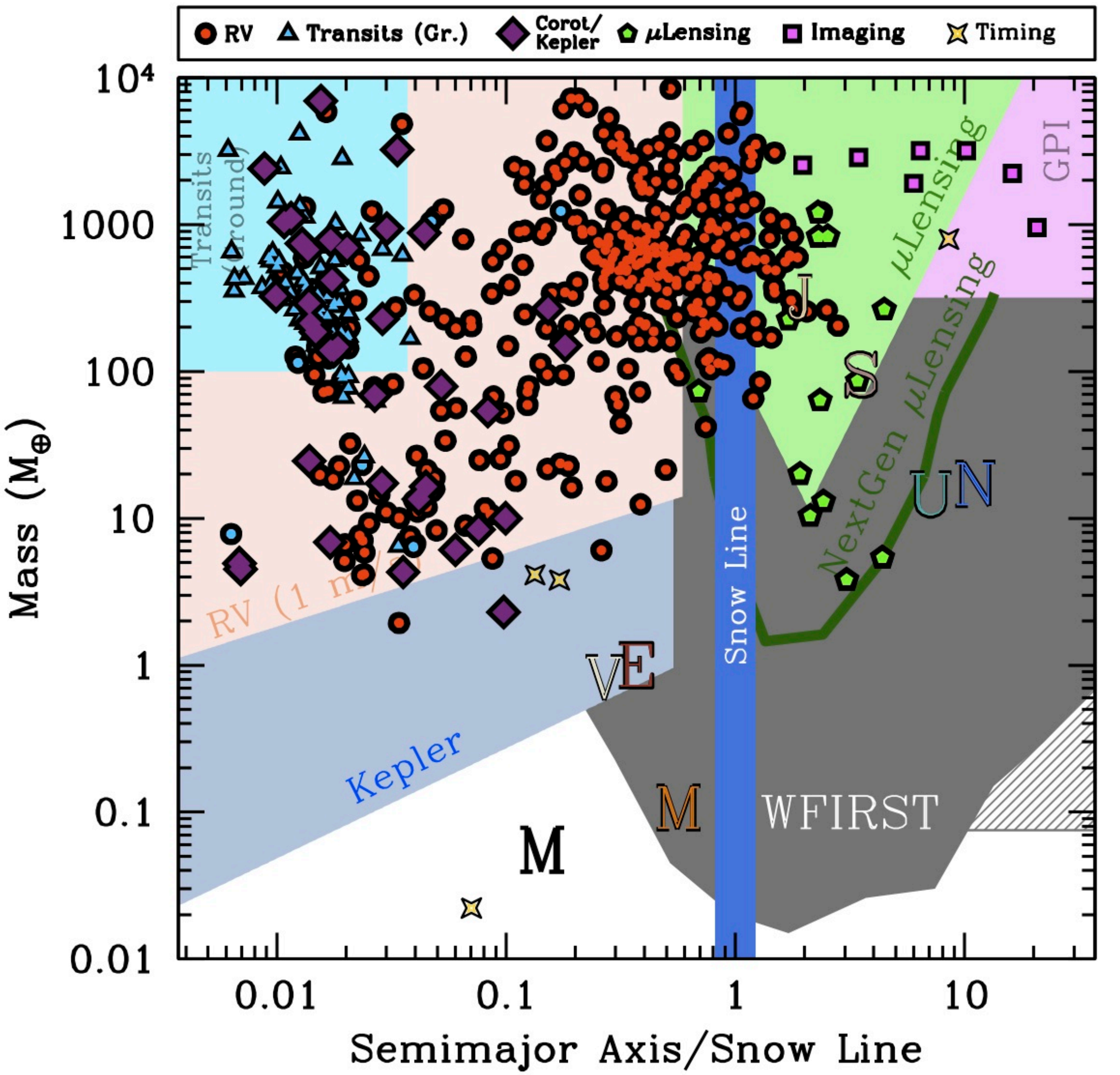
# Planet Search Synergy!



# Planet Search Synergy!

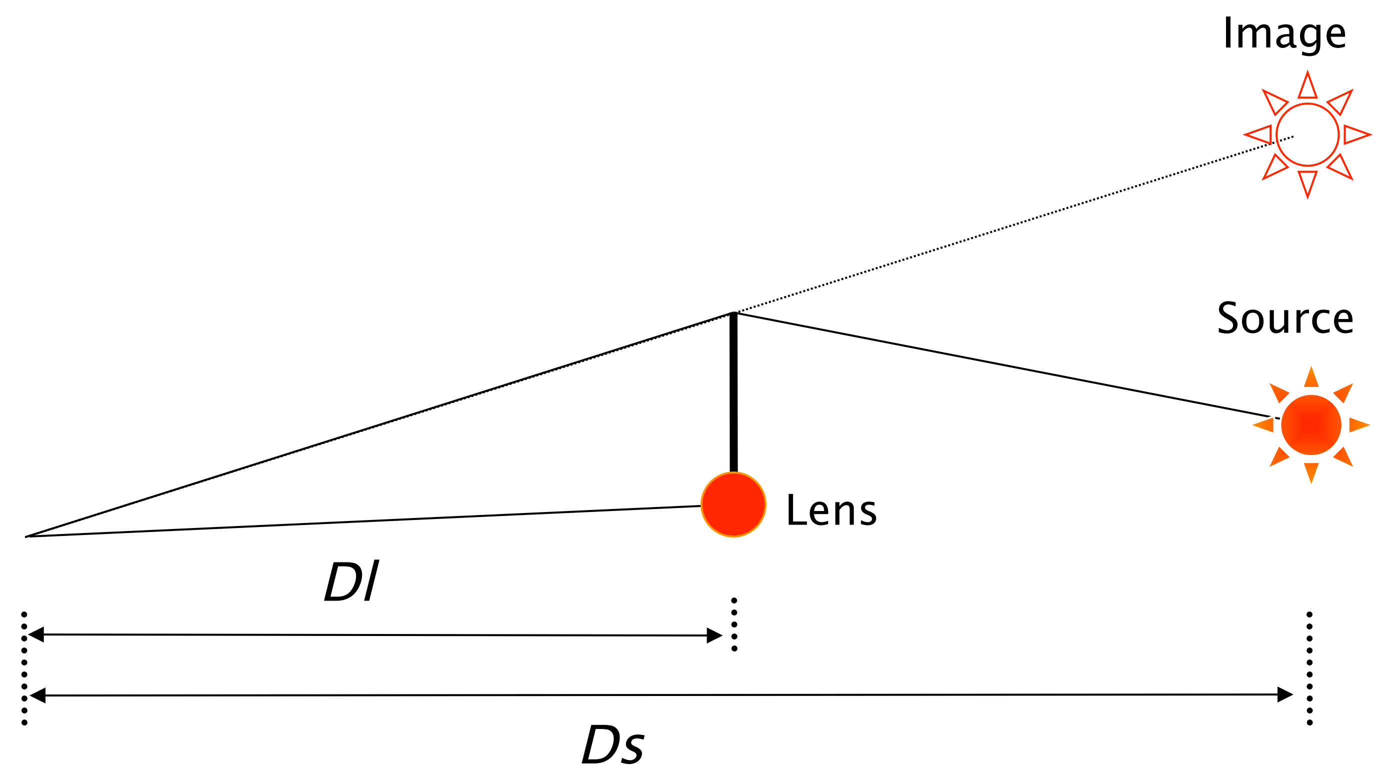


# Planet Search Synergy!



# Microlensing.

# Microlensing Basics.



# Rings and Images.

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

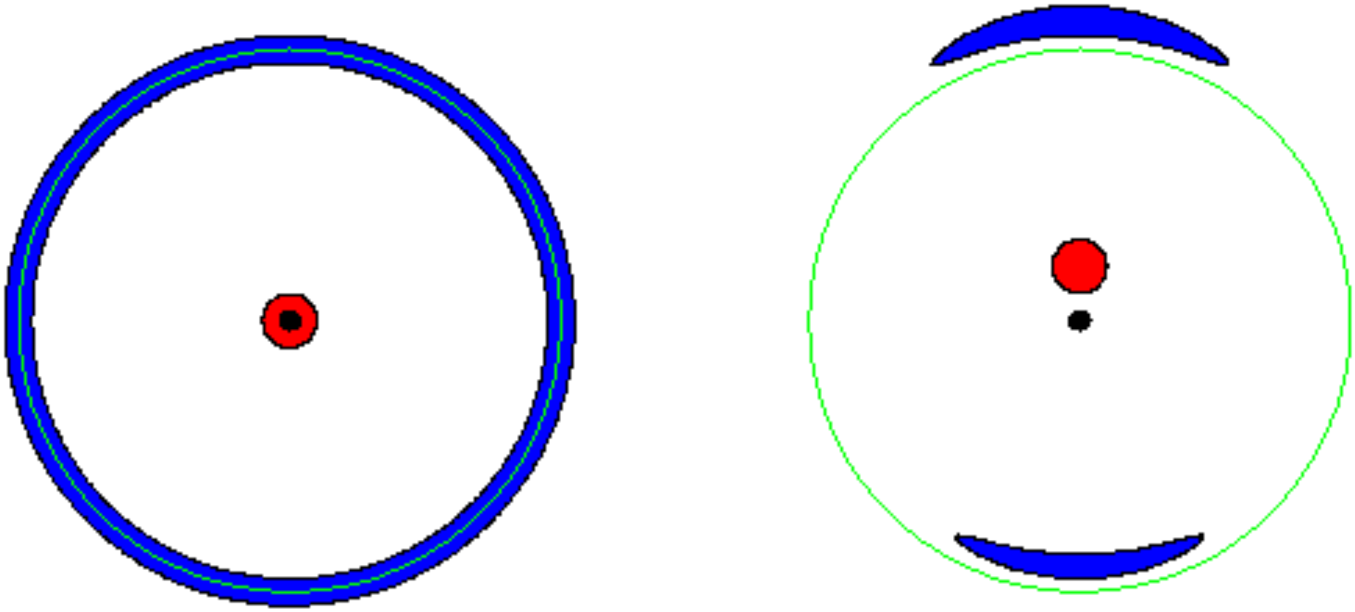
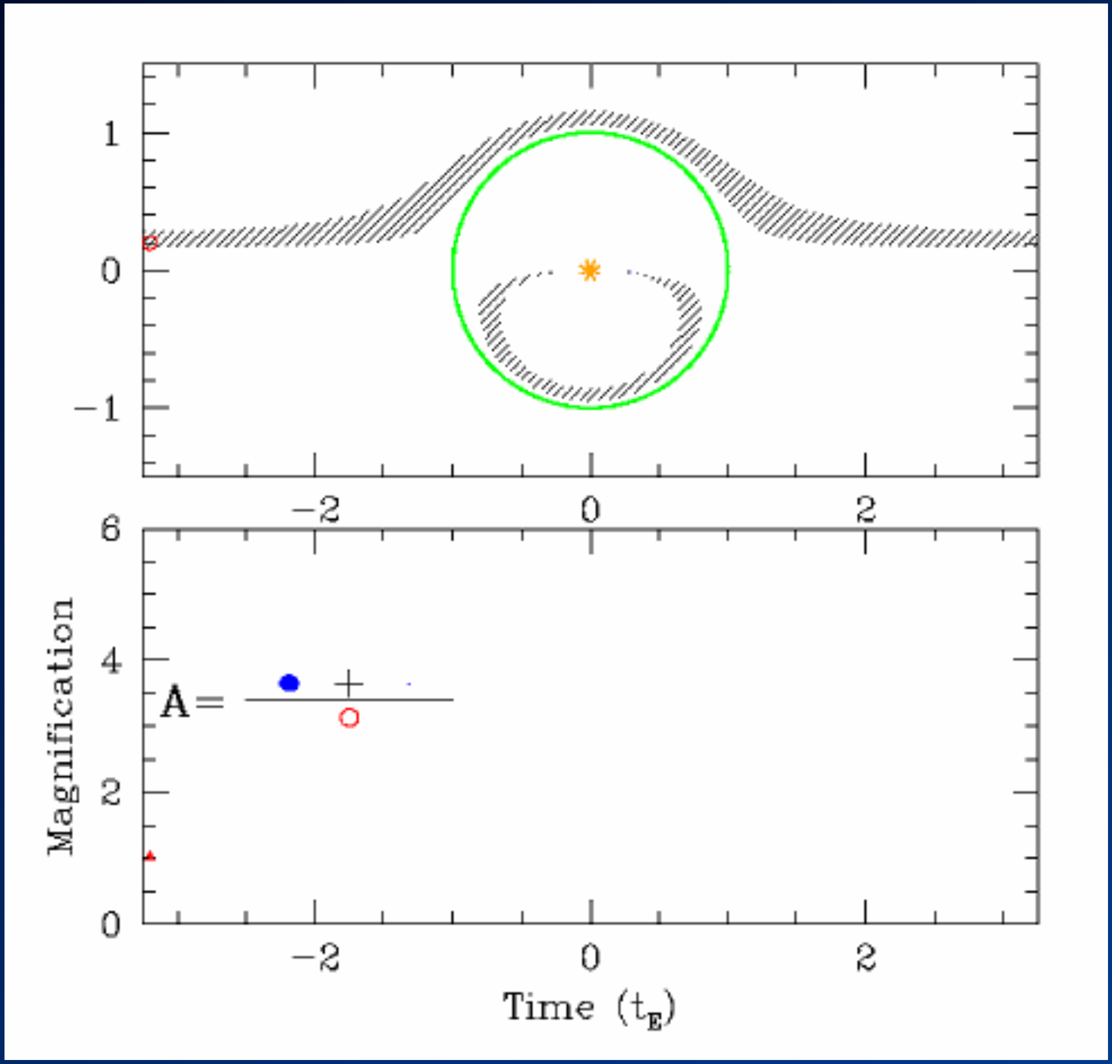


Image Separation $\approx 2\theta_E$

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

# Microlensing Events.

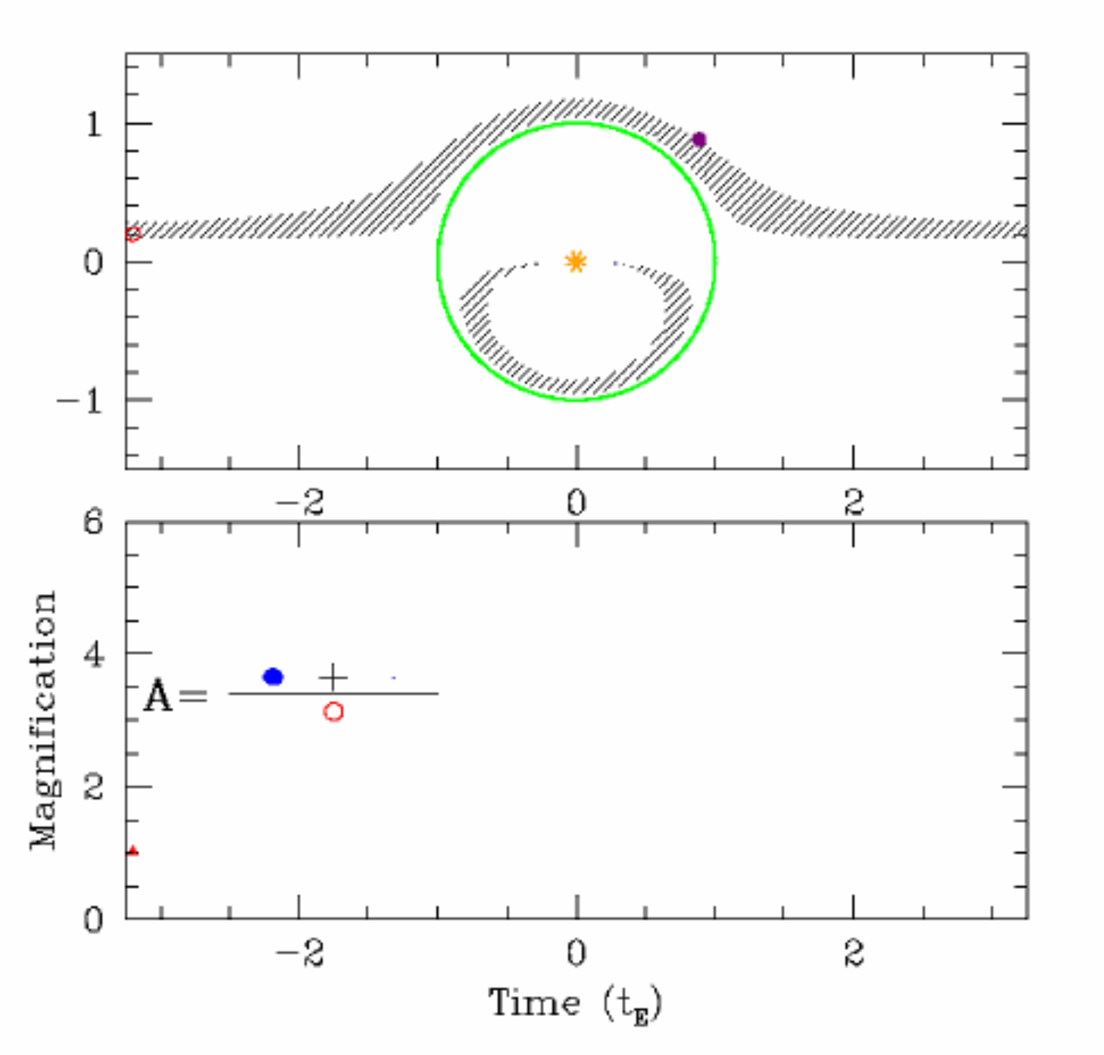


$$t_E = \frac{\theta_E}{\mu} \approx 25 \text{ days} \left( \frac{M}{0.5 M_\odot} \right)^{1/2}$$

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

- 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

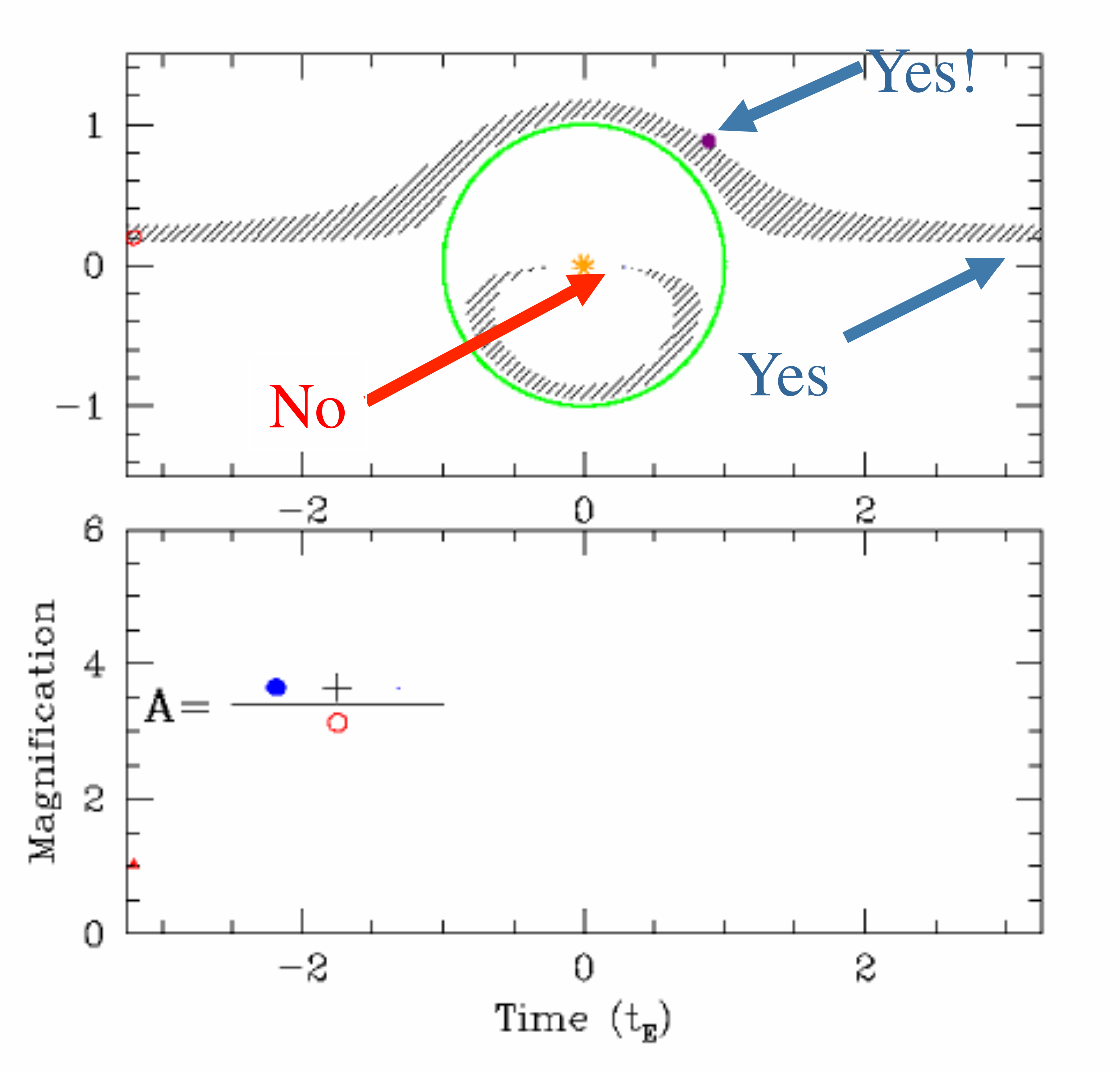
⇓

High Efficiency

Maximized when

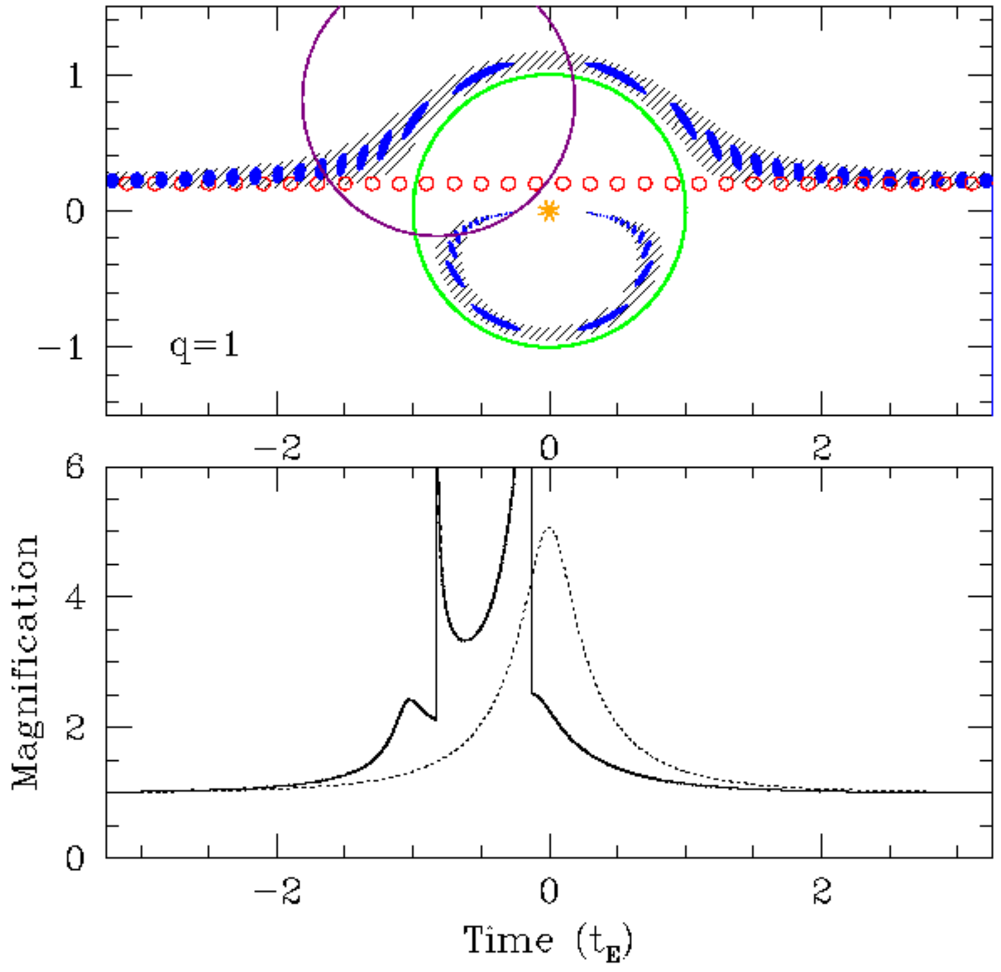
$$a \sim r_E = \theta_E D_l \sim 2.8\,\text{AU} \left(\frac{M}{0.5\,M_\odot}\right)^{1/2}$$

# 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.

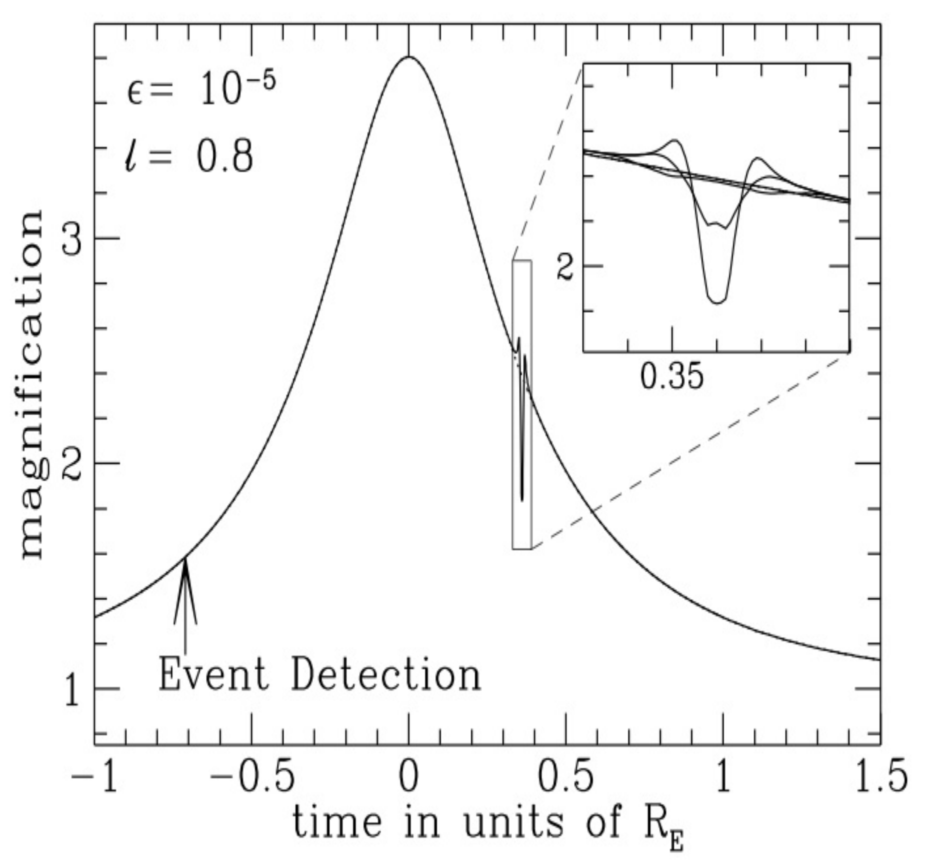
$$t_p = q^{1/2} t_E \approx 2 \text{ hrs} \left( \frac{q}{10^{-5}} \right)^{1/2}$$

- 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.



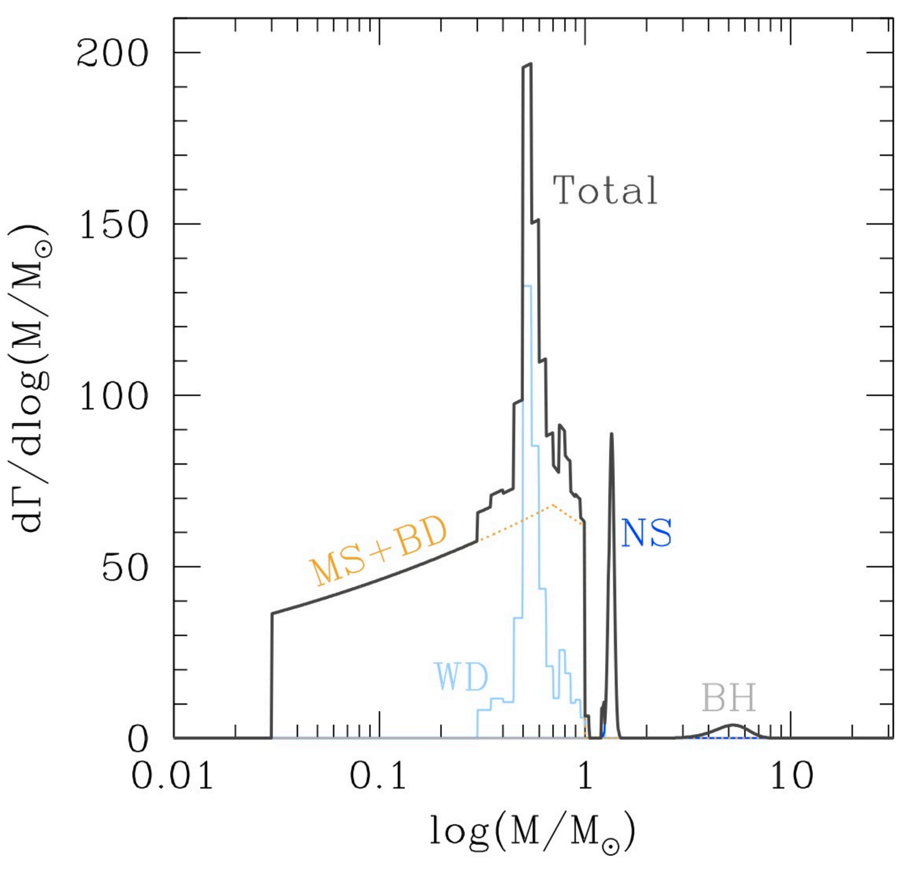
(Bennett & Rhie 1996)

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

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

- 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

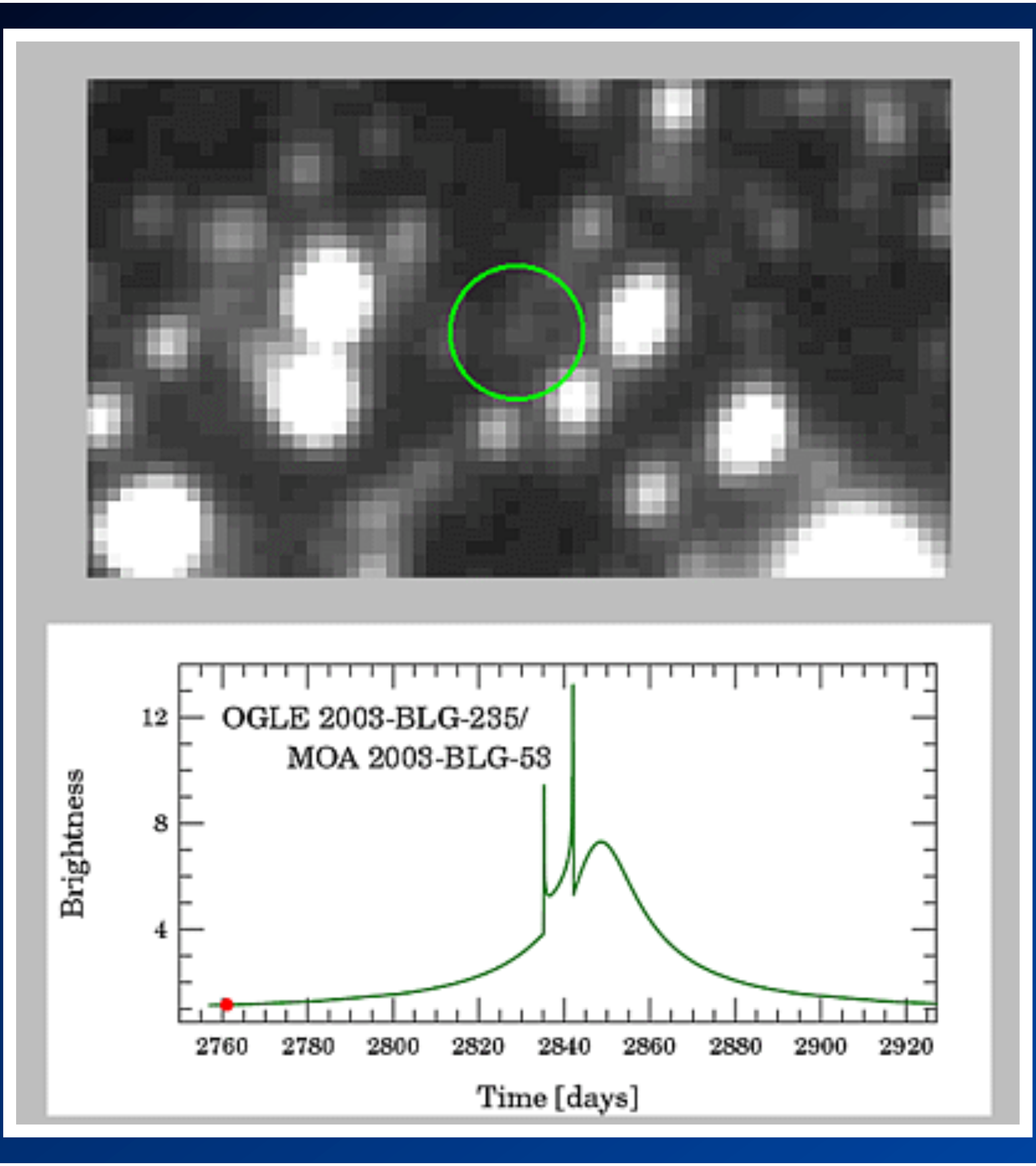
Faint Lenses:

- 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)