Exoplanets: an Introduction

AST Special Topics course: Exoplanets

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What Is a Planet?

- No need to argue about this; it's been settled:
  - https://www.youtube.com/watch?v=xGoZZvfEd6A
- Or has it?
  - *I am happy to defend [QVC host Mizrahi]. I see no logical reason why large moons that are in hydrostatic equilibrium should not be considered planets too, and I call them that*. – Dr. Alan Stern, PI, *New Horizons* (NASA's Pluto flyby mission); NY Times, 1/20/15
  - *The vast majority of the international community has clearly accepted [the IAU's definition of a planet].* – Dr. Thierry Montmerle, IAU Secretary General; ibid.
- See also:
  - *Is Pluto a Planet?* (by David Weintraub)
  - *How I Killed Pluto, and Why It Had It Coming* (by Michael Brown)

What Is a Planet?

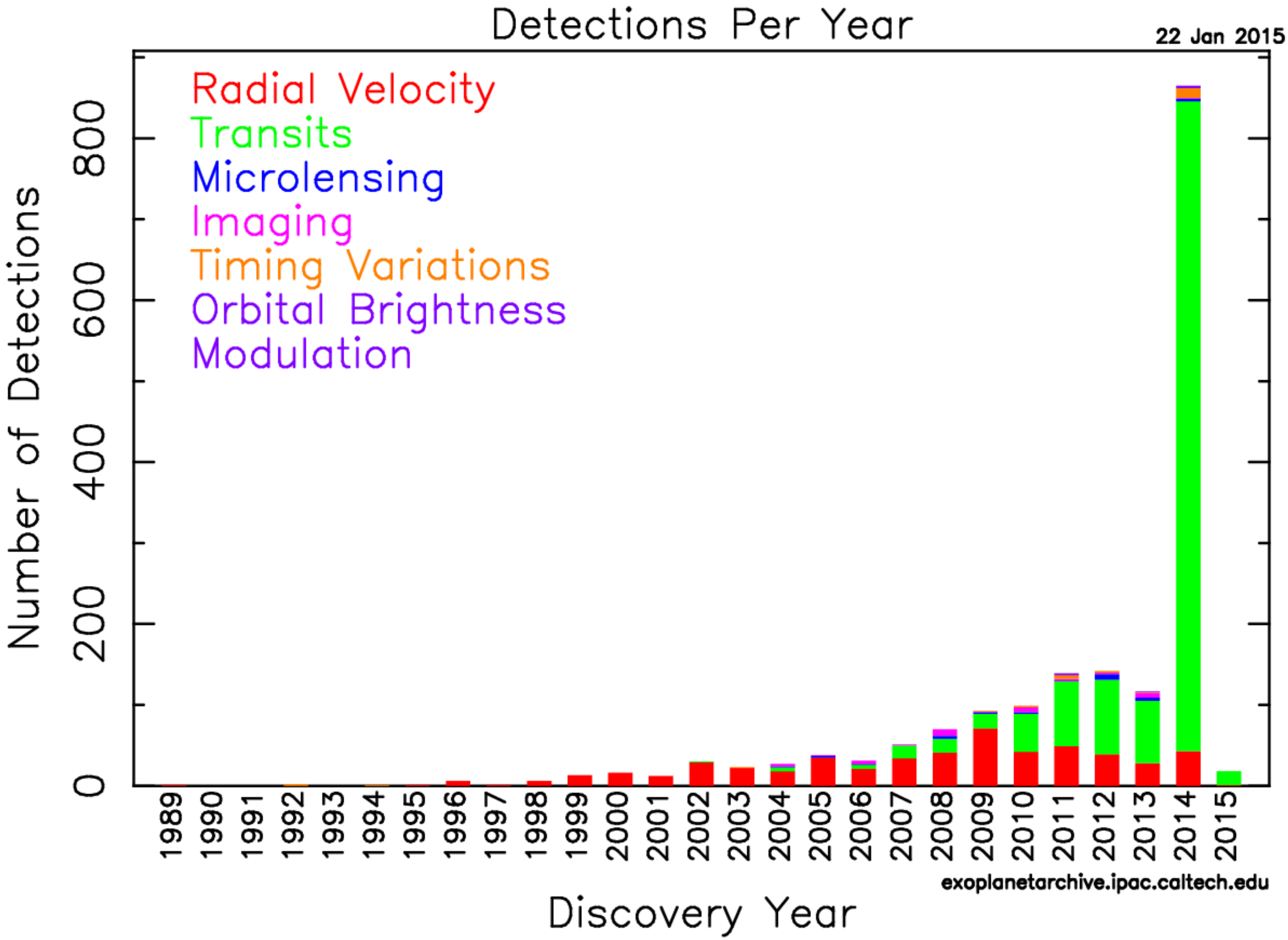
- Official IAU definition of a *planet* (in our solar system):
  - The IAU members gathered at the 2006 General Assembly agreed that a "planet" is defined as a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.
- IAU *working* definition of an *exoplanet* (a planet orbiting a star other than the Sun):
  1. Object w/ "true mass" below the limit for thermonuclear fusion of deuterium (presently estimated at 12-13 M_{Jup})
  2. Orbits a star or stellar remnant
  3. Has a "mass and/or size" larger than the low-mass limit established for planets in our solar system
  - Implications:
    - objects w/ masses between ~0.08 M_{sun} (~80 M_{jup}) and ~13 M_{jup} are *brown dwarfs*, regardless of how they formed or where they're located (i.e. a 14 M_{jup} object orbiting a star is a BD)
    - *Free-floating objects* with masses below ~13 M_{jup} are *not* planets, regardless of how they formed

Planetary dynamics

- Planets in orbit about stars “obey” Kepler’s Laws:
  1. Planets move along elliptical paths, with the star at one focus
     - *Eccentricity of orbit*: ratio of half the distance between foci to semimajor axis (a)
  2. Line connecting planet & star sweeps out equal areas in equal times
  3. For a set of planets orbiting the same star, square of period is proportional to cube of semimajor axis
     - Star’s mass (& G) yield constant of proportionality
- Caveats: tides (for small separations), multiple-body interactions

Planet detection/characterization: Observational techniques

- Radial velocity
- Astrometry
- Timing
- Gravitational microlensing
- Transits
- Direct imaging



Detections Per Year
22 Jan 2015
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Number of Detections
0
200
400
600
800
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
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Discovery Year

Techniques that yield exoplanet masses and (in some cases) orbital semimajor axes

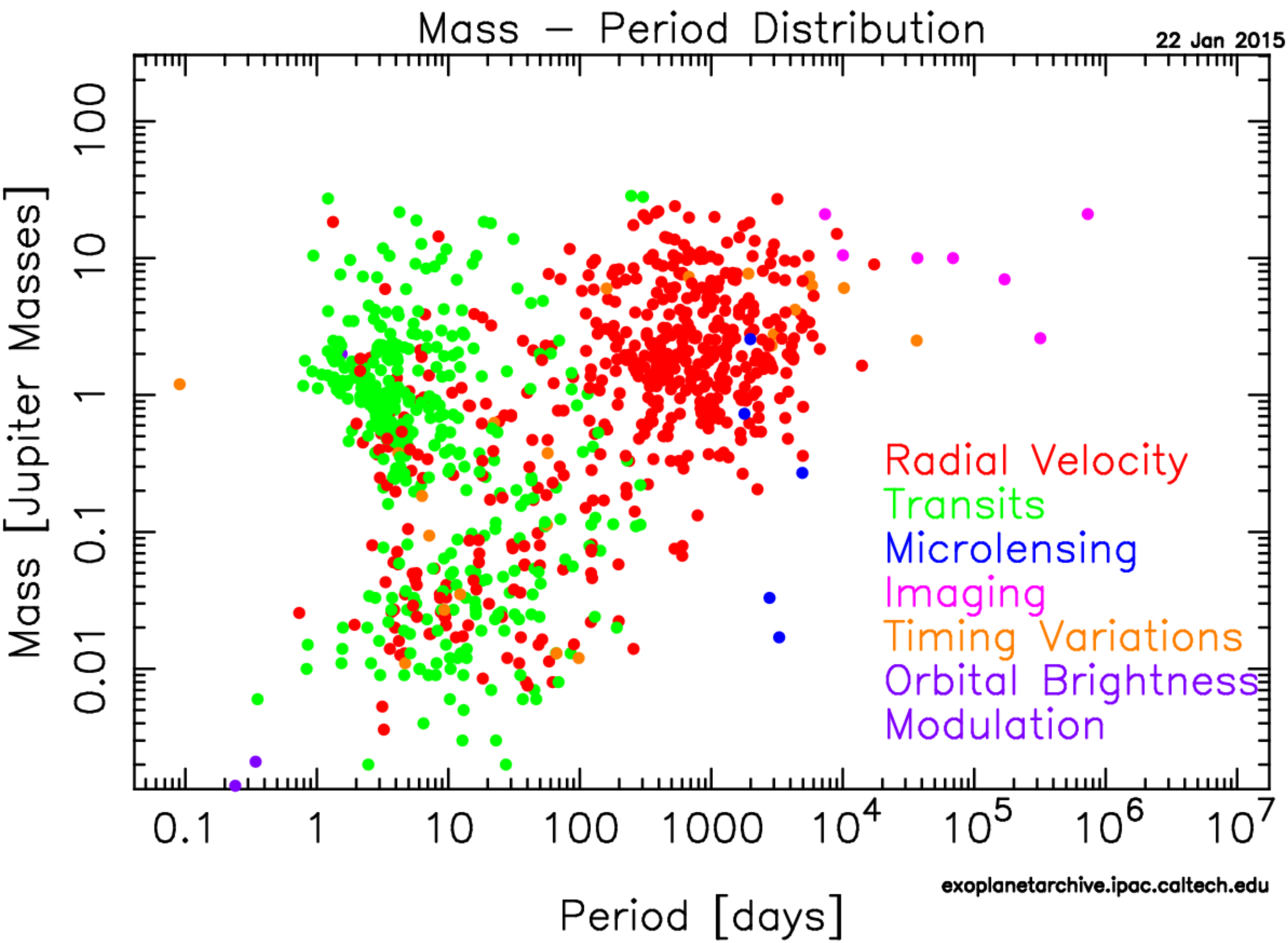
- Radial velocity
  - Determination of line-of-sight planet-induced reflex motion of star
    - Yielded first detection of planet around a "normal star"
      - 51 Peg, in 1995…but 51 Peg b is not a "normal" planet…
    - Can only yield minimum planet mass, $M_p \sin i$
      - i = inclination of orbital axis w/ respect to line of sight
    - Yields period (and eccentricity) hence semimajor axis, given determination/estimate of parent star's mass
- Astrometry
  - Measurement of periodic wobble in star's space (proper) motion by (unseen) planet
    - Can yield "true" mass (w/o "sin i" dependence)
    - Yields period (and eccentricity) hence semimajor axis, given determination/estimate of parent star's mass
  - No astrometric planet detections…yet…
    - ESO's *Gaia* mission is about to change that (and a lot of other things)!
      - Will be the *Kepler* of the astrometric planet detection world…

Techniques that yield exoplanet masses and (in some cases) orbital semimajor axes (cont.)

- Timing
  - Measurement of perturbations of (otherwise stable) stellar rotation or pulsation periods
    - Yielded first detection of planets (around a pulsar) in 1992
    - Yields period (and eccentricity) hence semimajor axis, given determination/estimate of parent star's mass
- Gravitational microlensing
  - Focusing of background star's light by passage of foreground star/planet pair yields short-lived brightening of the background star
    - One-time event, but can yield star & planet masses and (instantaneous) star-planet separation

Techniques that yield other exoplanet properties

- Transits
  - Planet passes in front of star as seen from Earth
    - For low eccentricity and $R_p << R_*$, probability of transit is $p = R_*/a$
  - Yields planet radius
    - From depth of transit, given determination/estimate of parent star's radius
  - Multiple transits yield planet's period
    - hence semimajor axis, given determination/estimate of parent star's mass
  - NASA's *Kepler* mission has detected thousands of exoplanets and exoplanet candidates via this method!
- Direct imaging
  - Presently only feasible for exoplanets at large orbital semimajor axes
    - Note: 1" separation corresponds to 10 AU for a (nearby) star at 10 pc
  - Easiest for young, *self-luminous* planets
    - Can detect planet's heat (generated via ongoing gravitational contraction) via thermal infrared imaging
      - Poster children: HR 8799, beta Pic



Mass – Period Distribution
22 Jan 2015
Mass [Jupiter Masses]
100
10
1
0.1
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
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How do planets form?

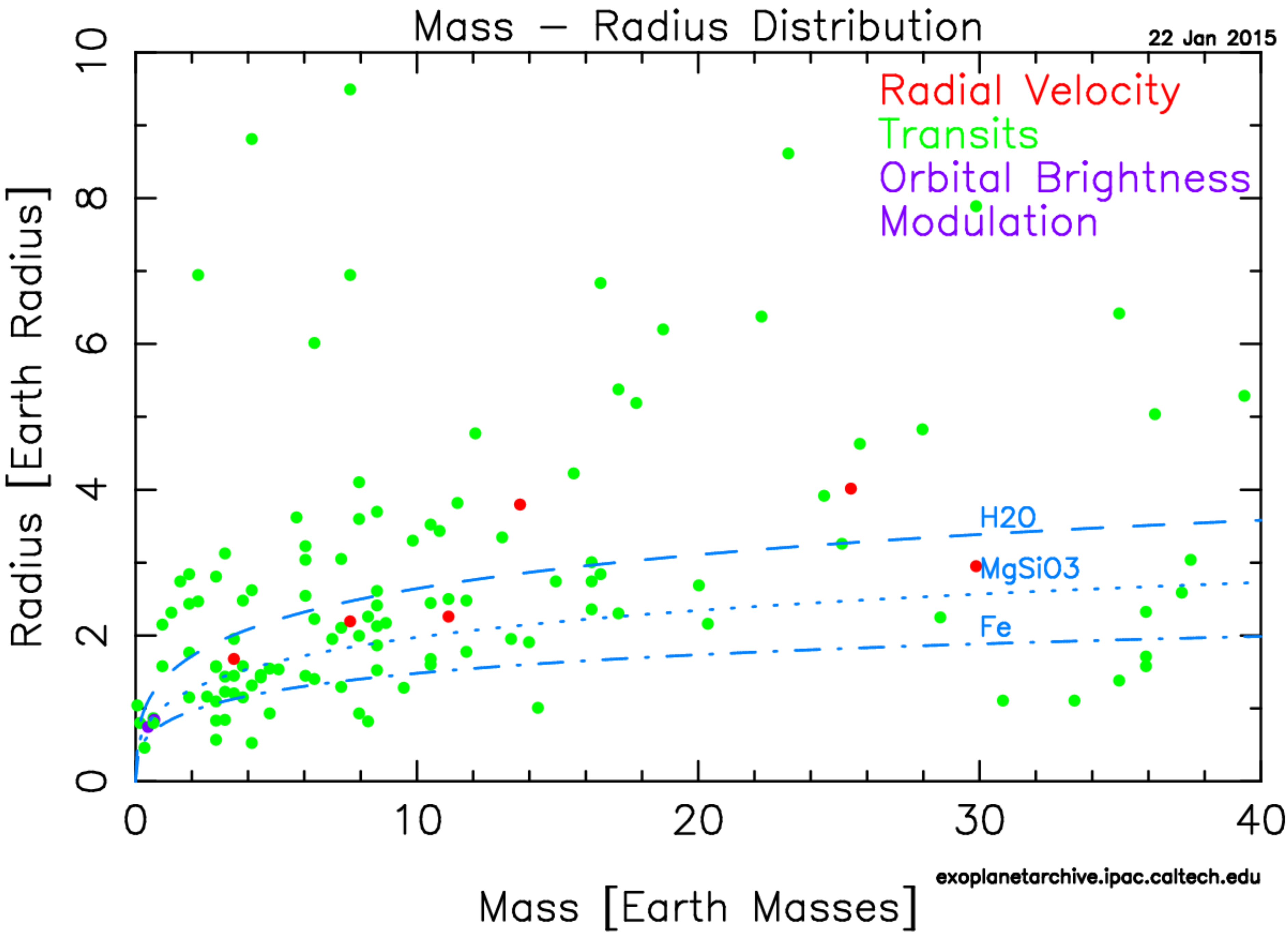
- If you figure it out, tell me…but, all seriousness aside…
- Planets form in *circumstellar disks* that are a necessary byproduct of star formation
  - Necessary to understand disk origin & evolution – so disk structure, composition, shaping & dispersal processes, etc, etc…
    - Entire field in itself
- Giant planet formation may be rapid
  - Timescale <10 Myr? (e.g., Zuckerman, Forveille, & Kastner 1995)
- Terrestrial planet formation likely requires 10s-100s of Myr

Giant planet formation & migration

- Giant planet formation: competing models
  - agglomeration of solid core + accretion of disk gas ("core accretion"; slower)
  - disk gravitational instability (faster)
- – Giant planets likely migrate
  - Poster child is 51 Peg b (first exoplanet discovered around normal star): a giant planet in a few-day orbit
  - – Type I migration: gravitational interaction between planet & massive disk
  - – Type II migration: massive planet exerts torques on (& opens gap within) disk

Exoplanet structure: interiors

- Planets can be “decomposed” in terms of rock, ice, & gas (mass) components
  - E.g., in our solar system, M, V, E, M: rocky; J, S: massive gas envelopes (surrounding ~10 M_{earth} rock/ice cores?); U, N: massive ice/rock cores w/ gas envelopes?
- Requires measurements of planet mass *and* radius…plus modeling



Mass – Radius Distribution
22 Jan 2015
Radial Velocity
Transits
Orbital Brightness
Modulation
H2O
MgSiO3
Fe
Radius [Earth Radius]
Mass [Earth Masses]
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Exoplanet structure: atmospheres

- Origins in circumstellar disk gas (massive, gas giant planets) vs. outgassing (terrestrial planets)
- How to probe atmospheric composition?
  - direct imaging/spectroscopy
    - Only feasible for the brightest & widest-separation exoplanets
  - Transmission spectroscopy
    - Feasible for transiting exoplanets orbiting bright stars
      - Requires excellent calibration stability => initial attempts mostly by space telescopes (HST, Spitzer)
  - Major goal for the field of astrobiology!
    - Hunt for *biomarkers* in exoplanet atmospheres

NASA Exoplanets Archive

http://exoplanetarchive.ipac.caltech.edu/

Assignment(s) #1:

- Browse to familiarize yourself with the available data & plots
- Note trends in the planet data available (exoplanet table columns) as functions of *planet discovery method*
- Note trends in the planet data available as functions of *host star's designation*