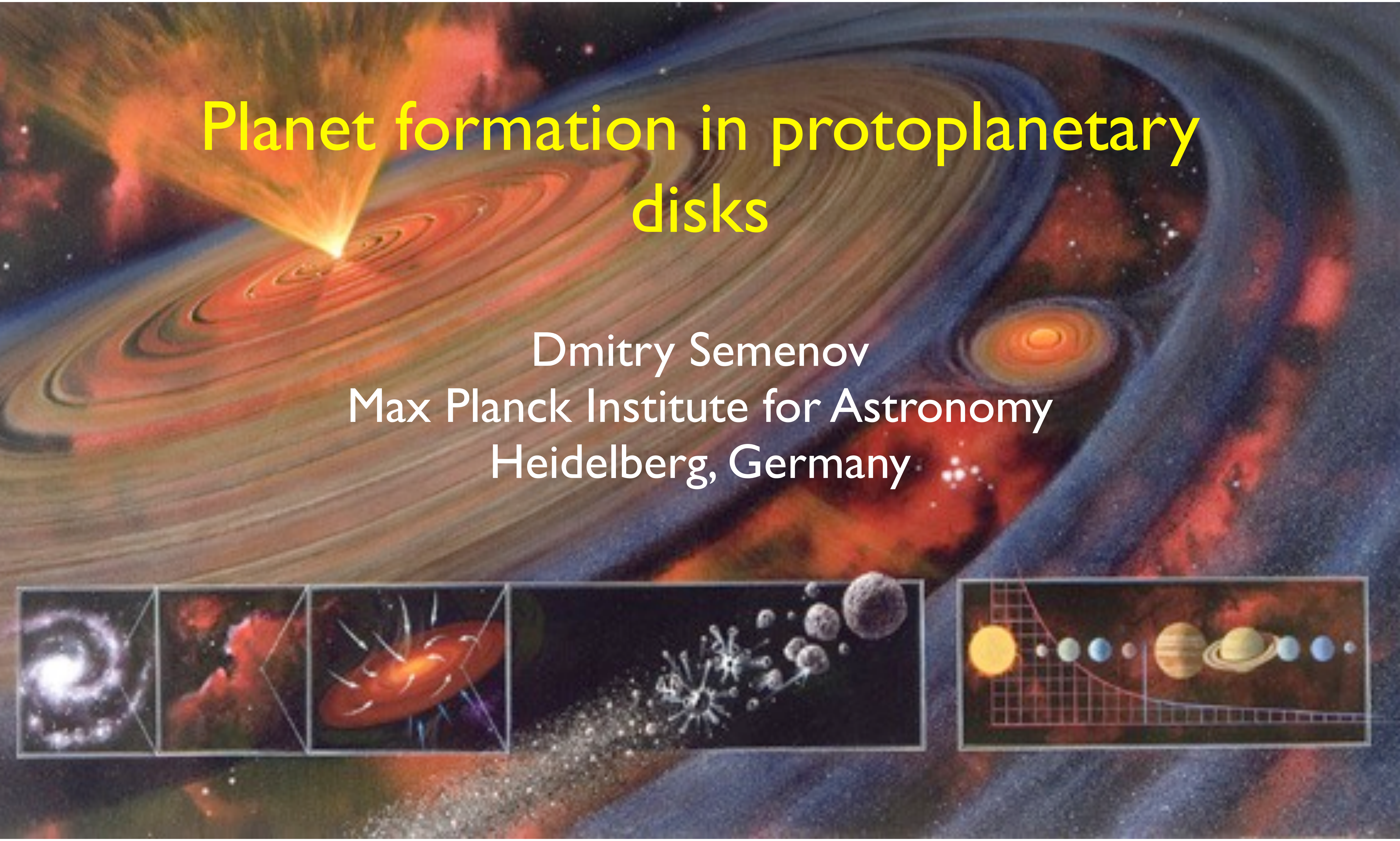
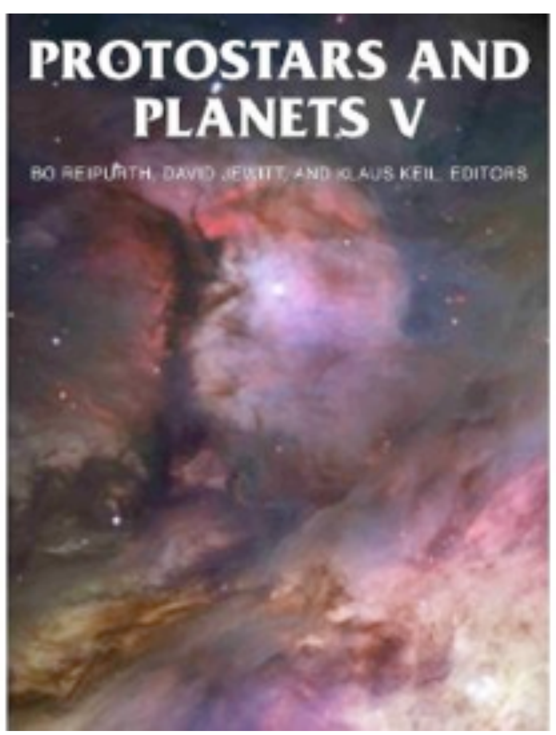
Planet formation in protoplanetary disks

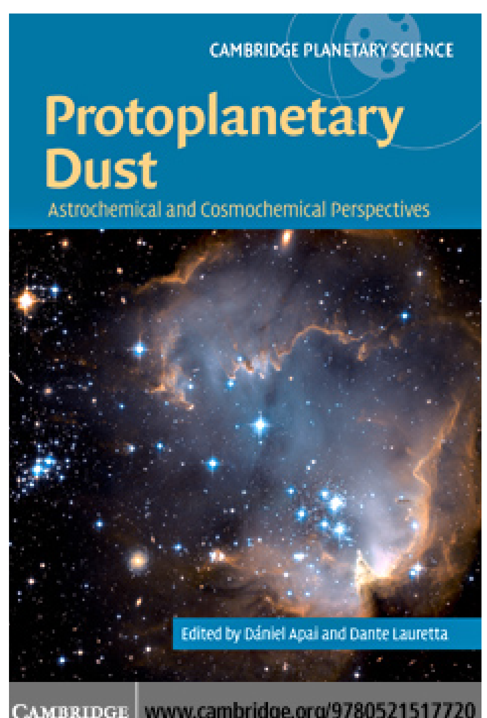
Dmitry Semenov
Max Planck Institute for Astronomy
Heidelberg, Germany

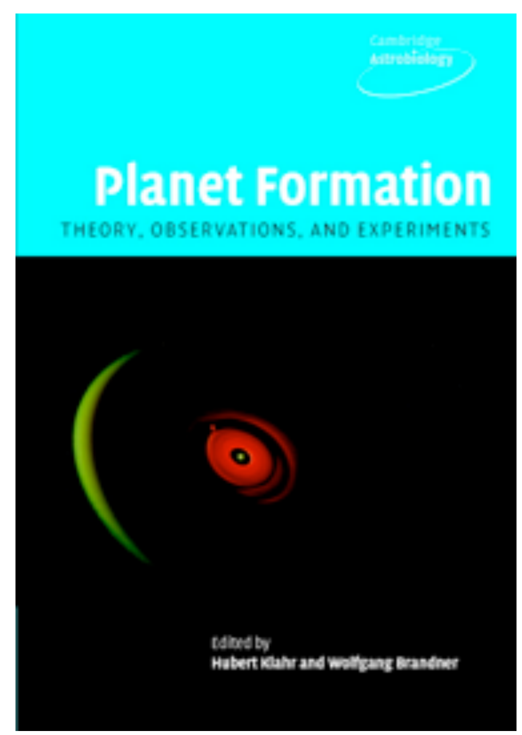


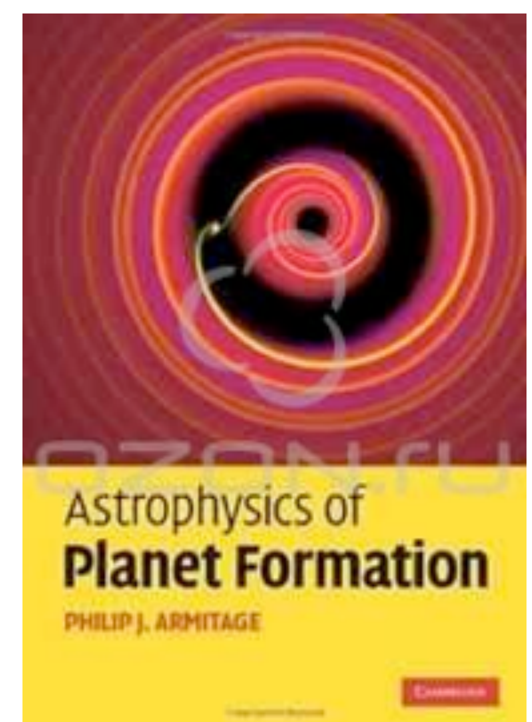
Suggested literature

- "Protoplanetary Dust" (2010), eds. D. Apai & D. Lauretta, CUP
- "Protostars & Planets V" (2005), Part VI, eds. B. Reipurt et al., Univ. Arizona P.
- "Exoplanets: Detection, Formation, ..." (2010), ed. J. Mason, Springer
- Ph. J. Armitage: "Astrophysics of Planet Formation" (2010), CUP
- "Planet Formation: Theory, Observations & Experiments" (2006), eds. H. Klahr & W. Brandner, CUP



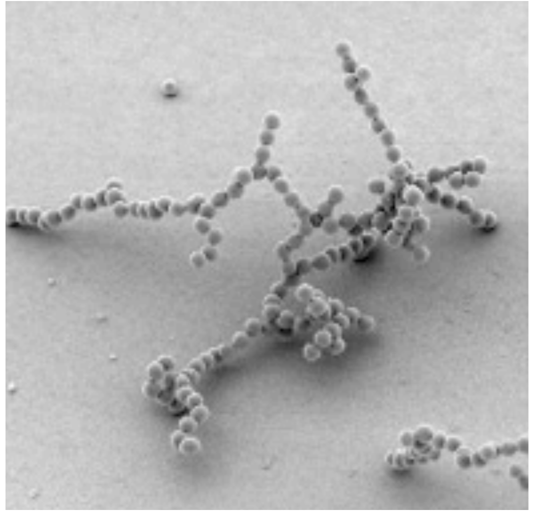
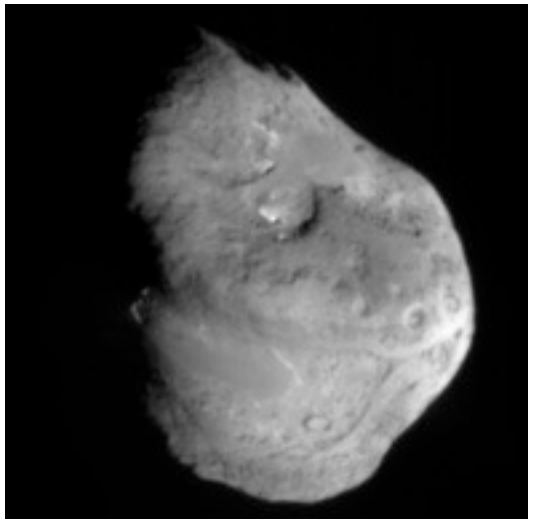
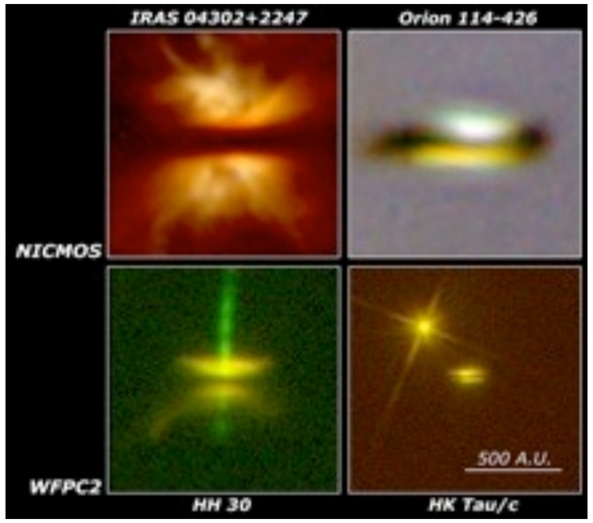






Outline

- Detections and characteristics of exoplanets
- Formation & migration of planets
- Signatures of planet formation to be detected with ALMA

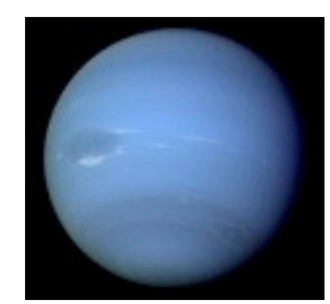
1. Detection & characteristics of exoplanets

Definitions

- Planet: a gravitationally bound body that is not massive to enable thermonuclear fusion of D
- 1 M_{Earth} = 6 10^{27} gm = 3 10^{-6} M_{Sun}
- Upper mass limit: ~13 M_{Jp} (317 M_{Earth})
- Extrasolar planet: a planet orbiting (a) star(s) or stellar remnants
- Terrestrial: Mercury, Venus, Earth, Mars (0.06–1 M_{Earth})
- Gas giants: Jupiter, Saturn, Uranus, Neptune (14–317 M_{Earth})





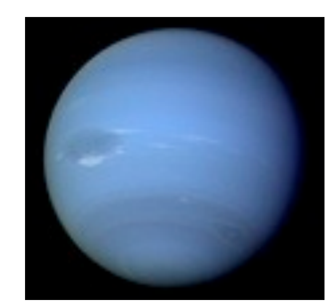



Planets of the Solar System

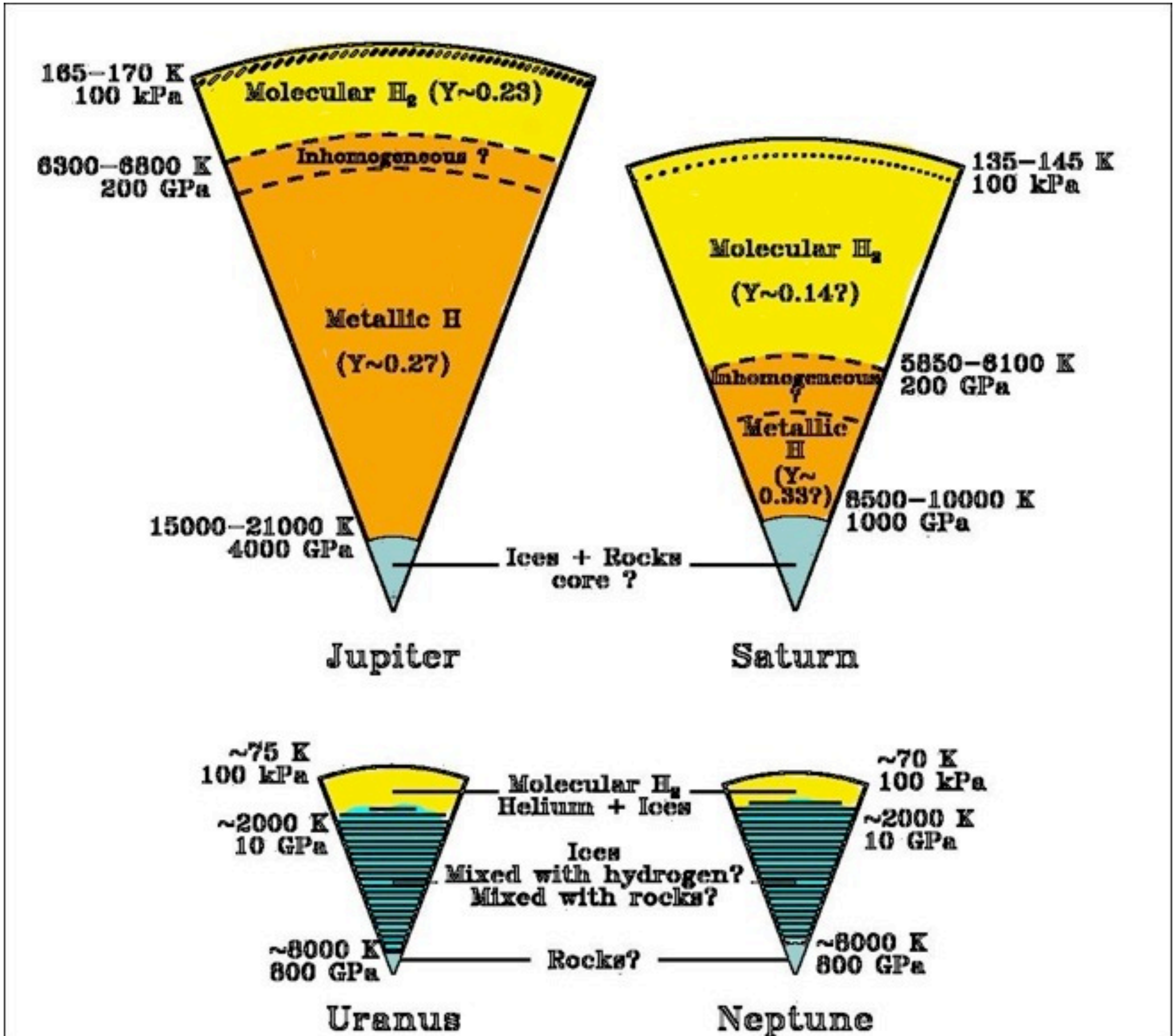
- Major semi-axes: 0.4–30 AU (1 AU = $1.5\ 10^{13}$ cm)
- Low eccentricities: 0.07–0.2 (0 - circular orbit, 1 - parabolic orbit)
- Rotate in one plane
- Terrestrial planets: rocky materials (high-T condensates), ~5 g/cm^3
- "Ice" planets (Uranus, Neptune): ~10 M_{Earth} rock-ice core + gas, ~1.5 g/cm^3
- Gas giants (Jupiter, Saturn): ~10–20 M_{Earth} rock-ice core + gas, ~1 g/cm^3
- Stable orbital configuration: ~10 Gyr





Planets of the Solar System



Lissauer (2004)

Extrasolar planets: detection

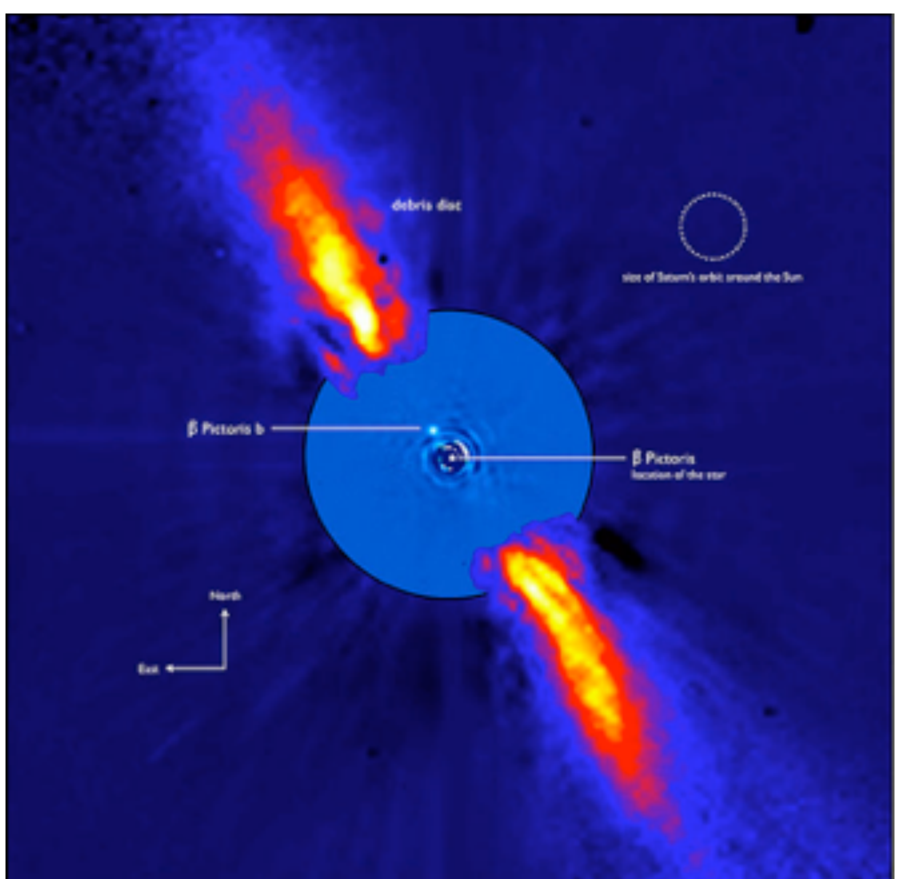
- $M_{planet}/M_* \sim 10^{-6}–10^{-2}$, $R_{planet}/R_* \sim 10^{-2}–10^{-1}$, $L_{planet}/L_* < 10^{-5}$ (IR)

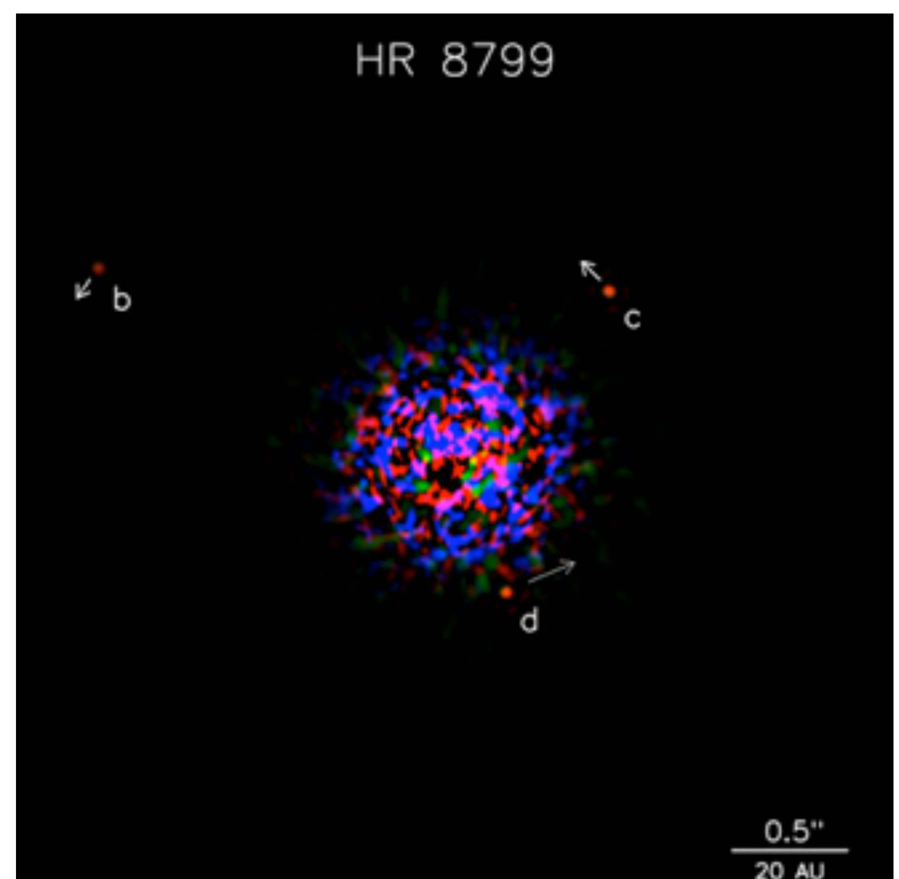
- First 2 exoplanets: PSR B1257+12 by Wolszcsan & Frail in 1992

- First exoplanet around MS star: 51 Peg by Mayor & Queloz in 1995

- June 15, 2011: 471 planetary systems, 562 planets, 57 multiple planet systems

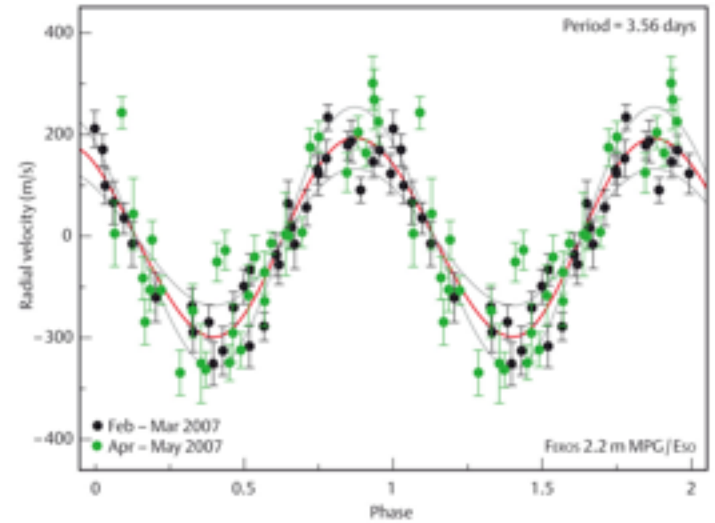
http://exoplanet.eu



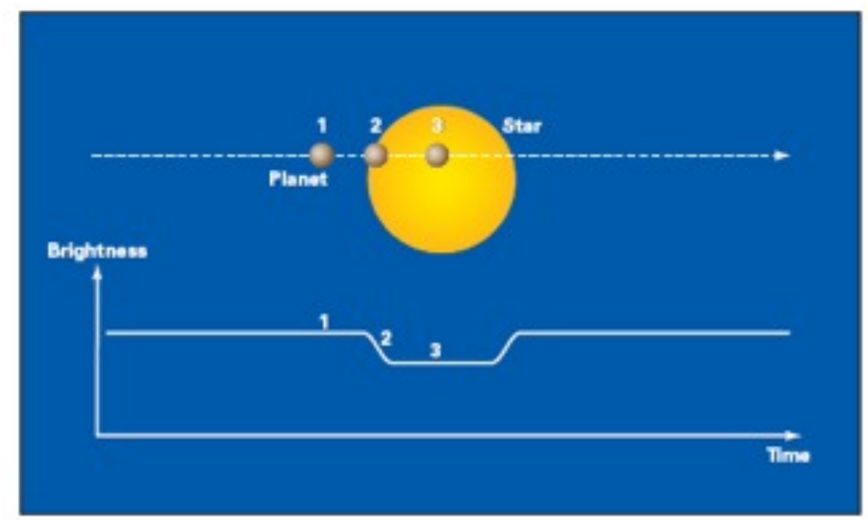


Detection techniques

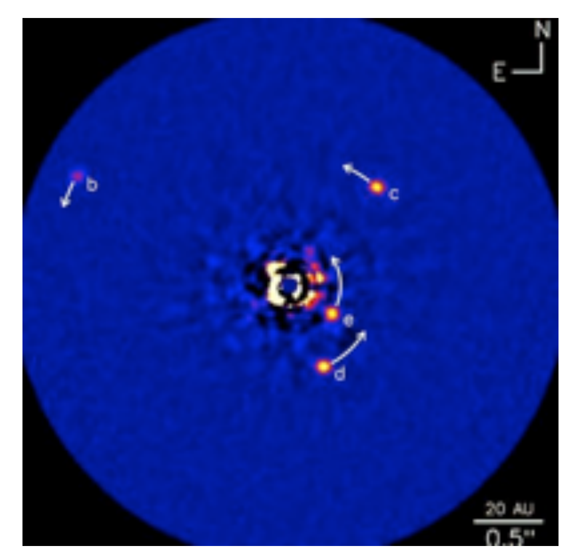
- Radial velocities:
  - periodic Doppler shifts (Jupiter = 13m/s),
  - current limit is 1m/s,
  - not restricted by distance
  - Msin(i), a



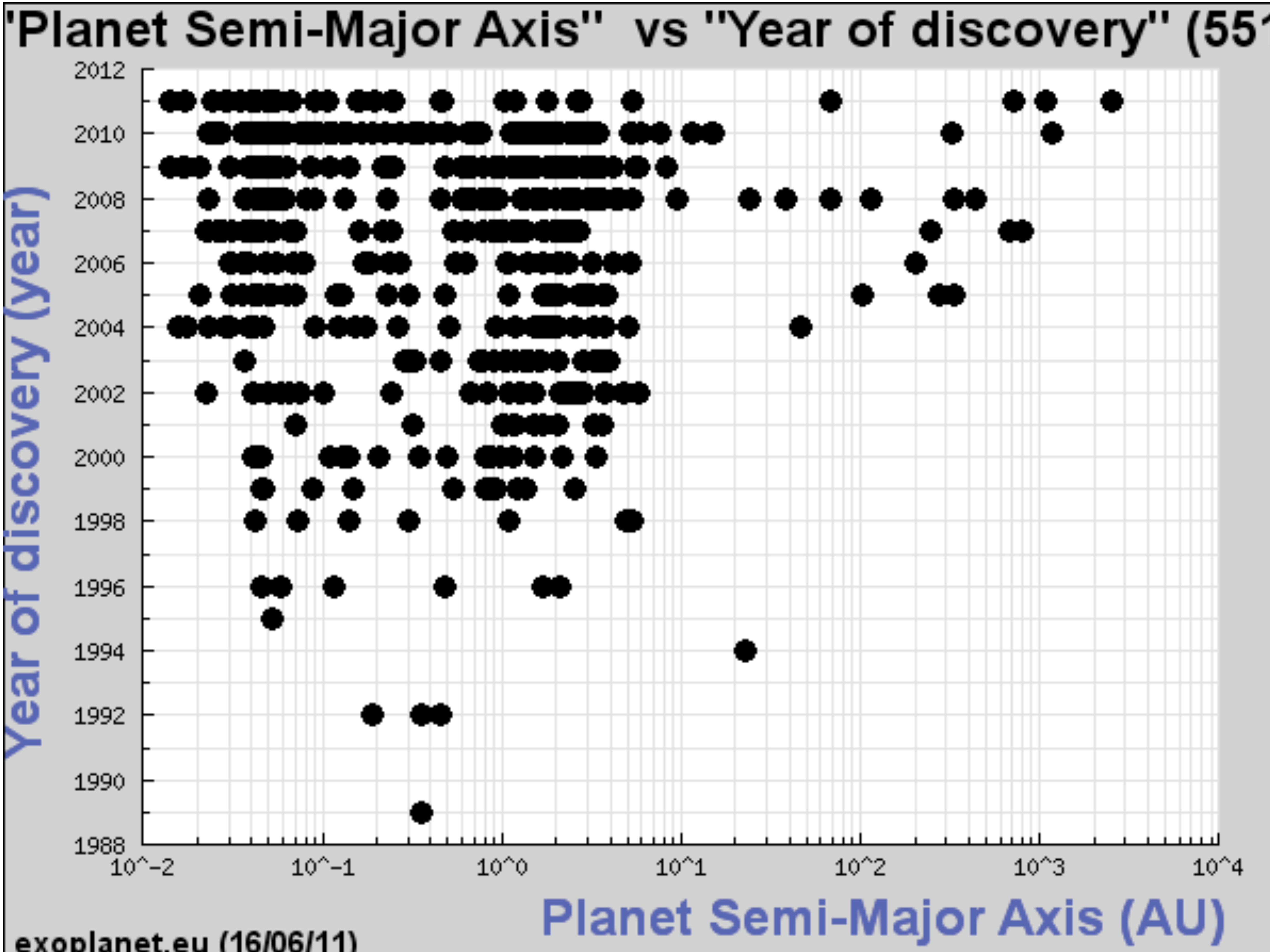
- Transits:
  - ~10% of stars,
  - Limit is ~few M_{Earth} (Kepler)
  - high rate of false alarms,
  - i, R, a



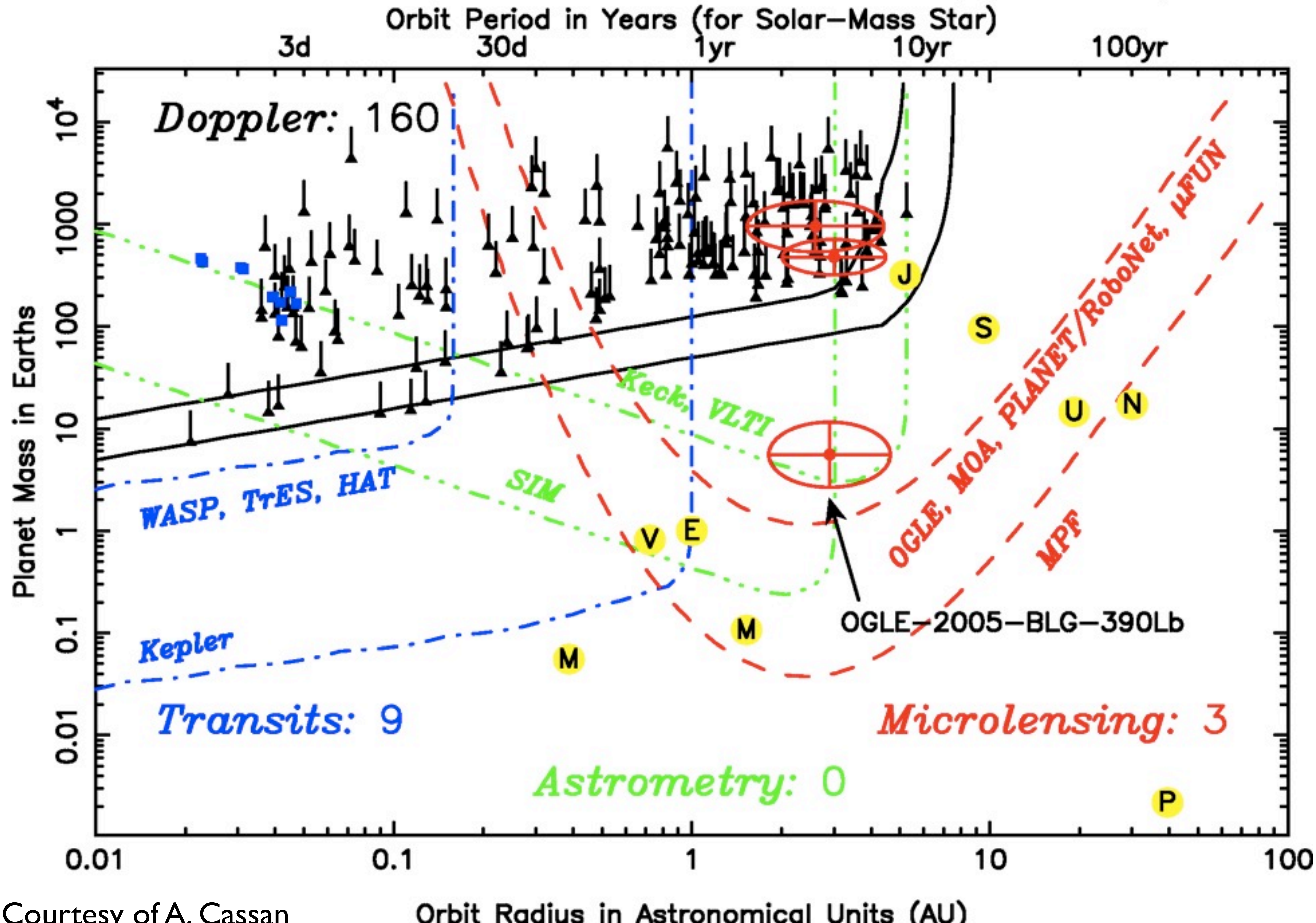
- Direct imaging:
  - R, separation
  - farthermost planets



- Gravitational microlensing:
  - M, separation
  - not restricted by distance
  - single event

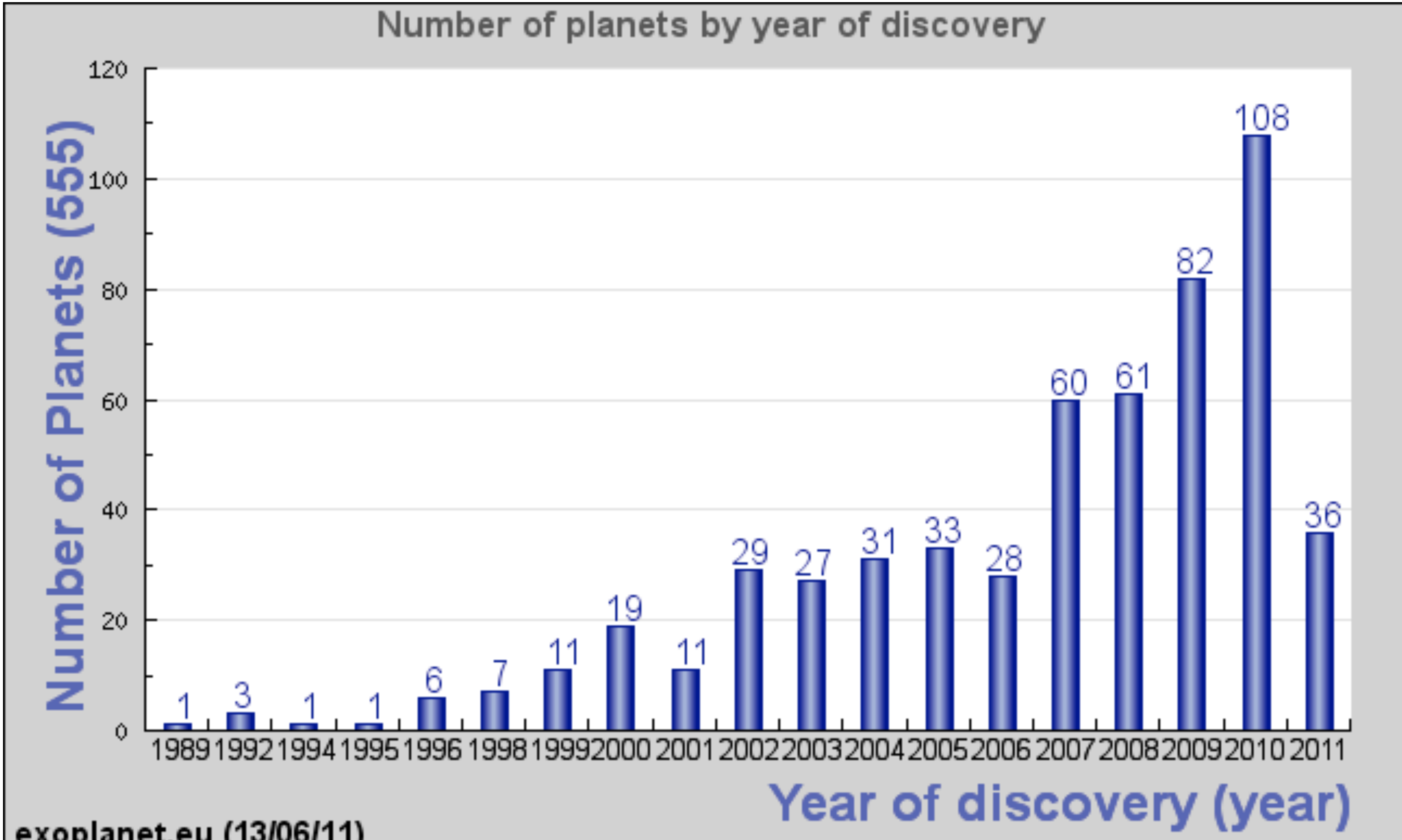

'Planet Semi-Major Axis" vs "Year of discovery" (551
Year of discovery (year)
2012
2010
2008
2006
2004
2002
2000
1998
1996
1994
1992
1990
1988
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
Planet Semi-Major Axis (AU)
exoplanet.eu (16/06/11)

Sensitivity of detection techniques

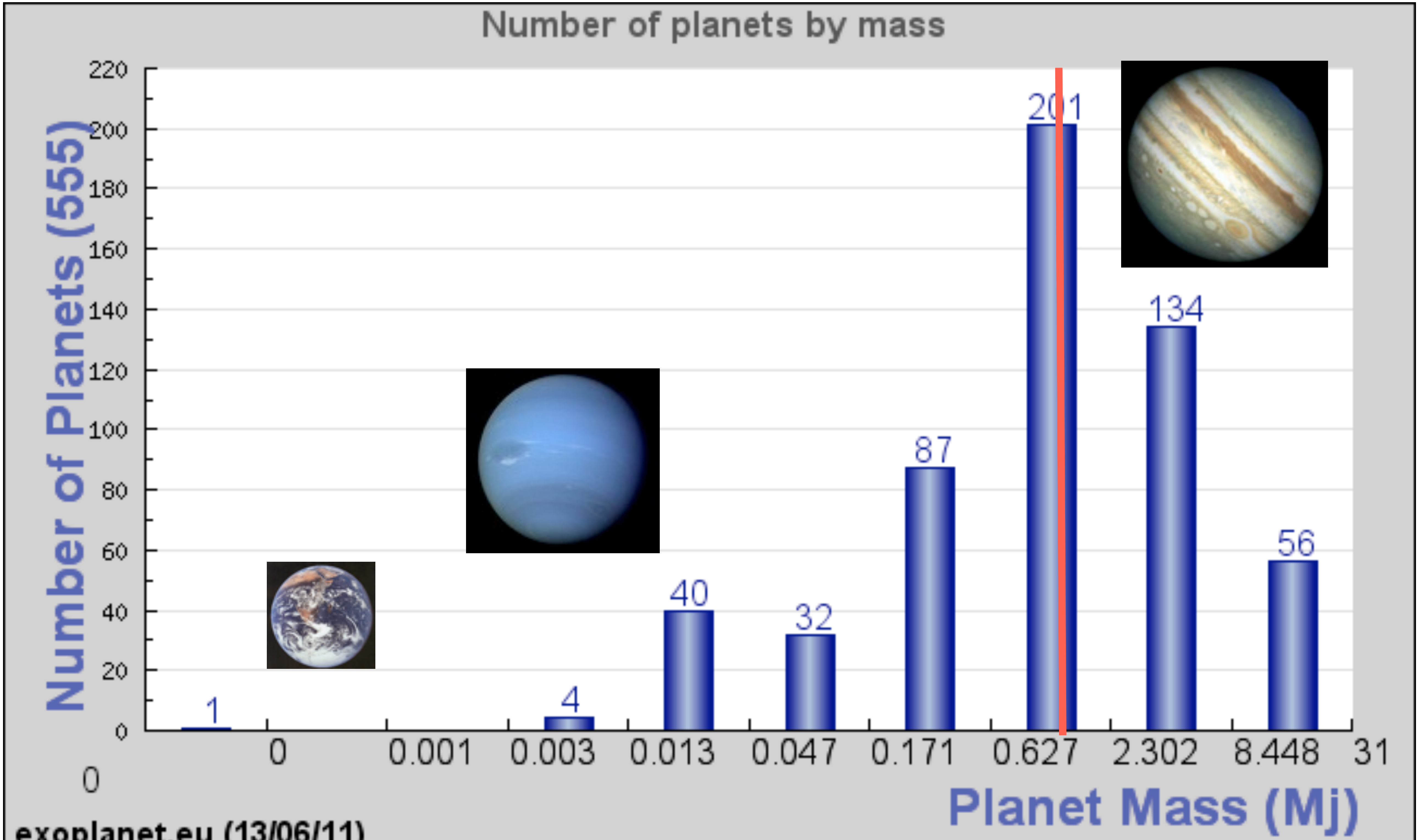


Courtesy of A. Cassan

Years of discovery

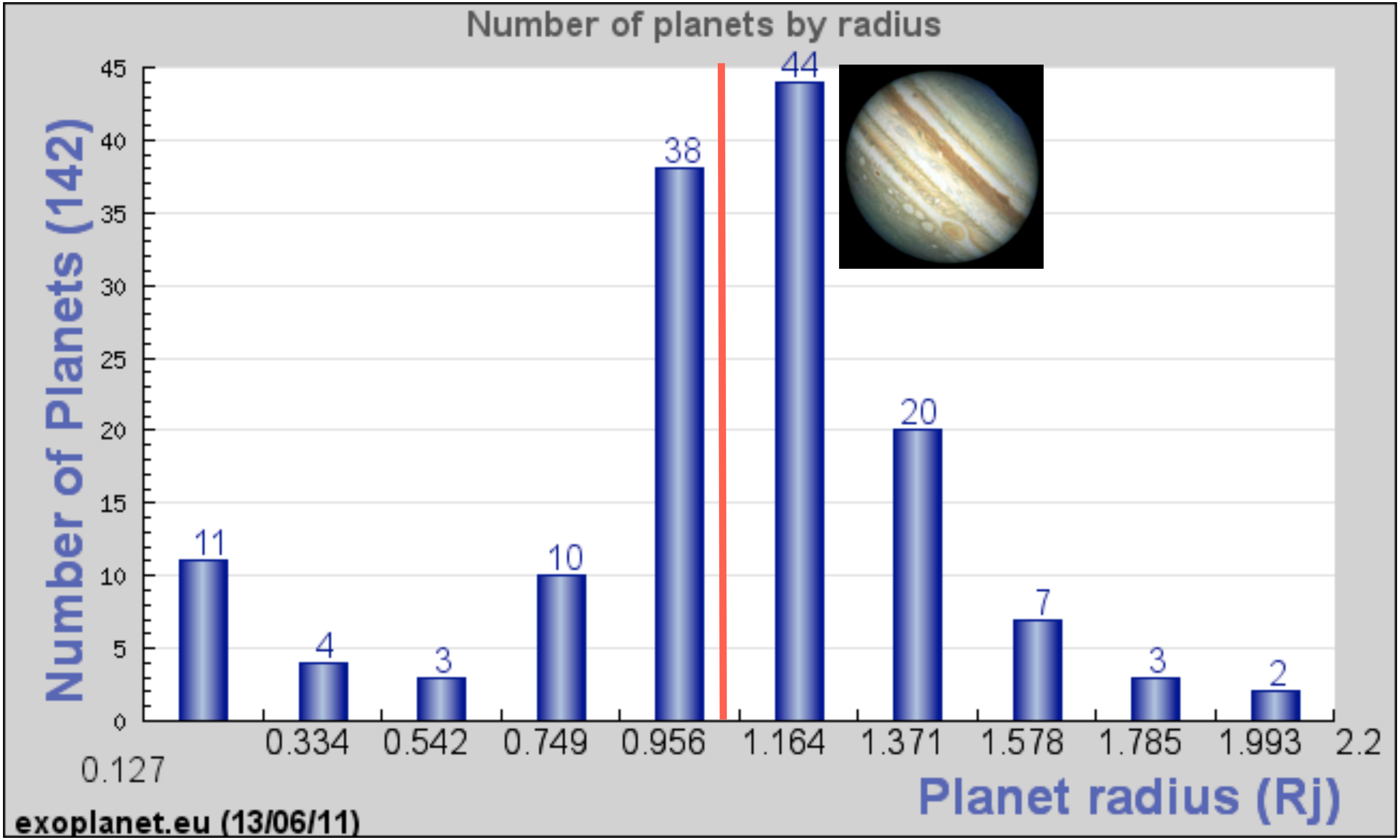


Masses



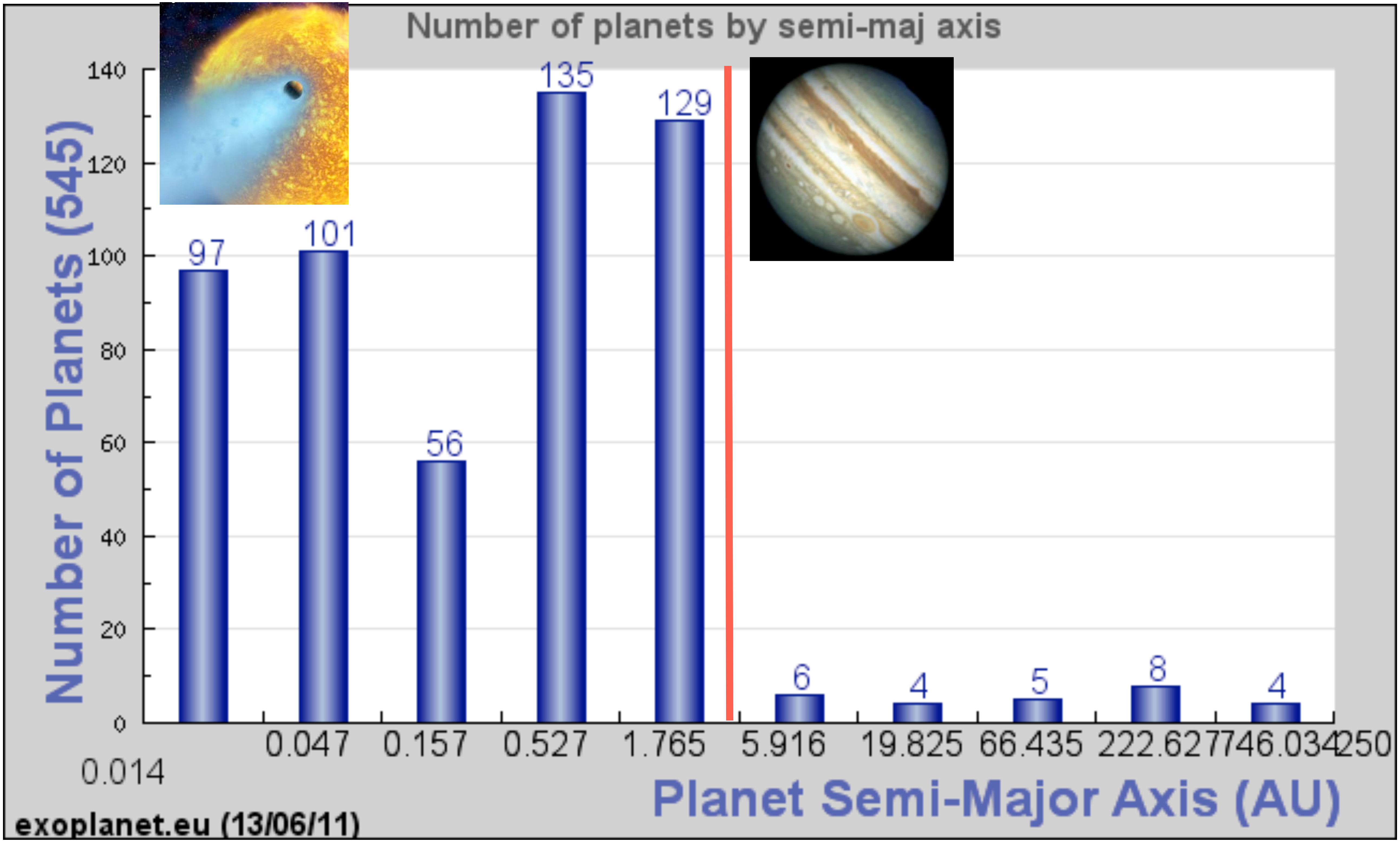
Number of planets by mass
Number of Planets (555)
220
200
180
160
140
120
100
80
60
40
20
0
1
4
40
32
87
201
134
56
0
0
0.001
0.003
0.013
0.047
0.171
0.627
2.302
8.448
31
Planet Mass (Mj)
exoplanet.eu (13/06/11)

Radii

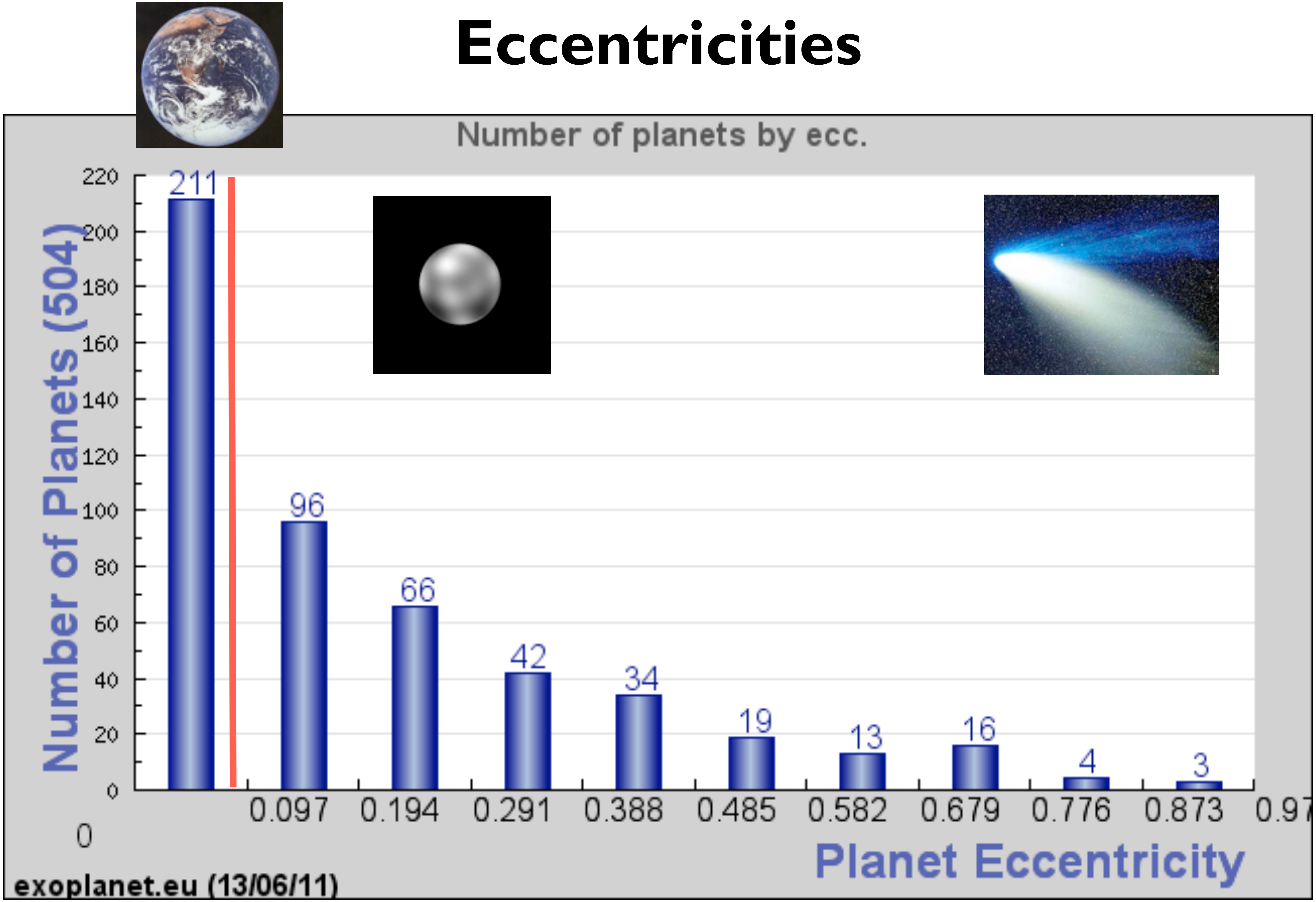


Number of planets by radius
Number of Planets (142)
45
40
35
30
25
20
15
10
5
0
11
4
3
10
38
44
20
7
3
2
0.127
0.334
0.542
0.749
0.956
1.164
1.371
1.578
1.785
1.993
2.2
Planet radius (Rj)
exoplanet.eu (13/06/11)

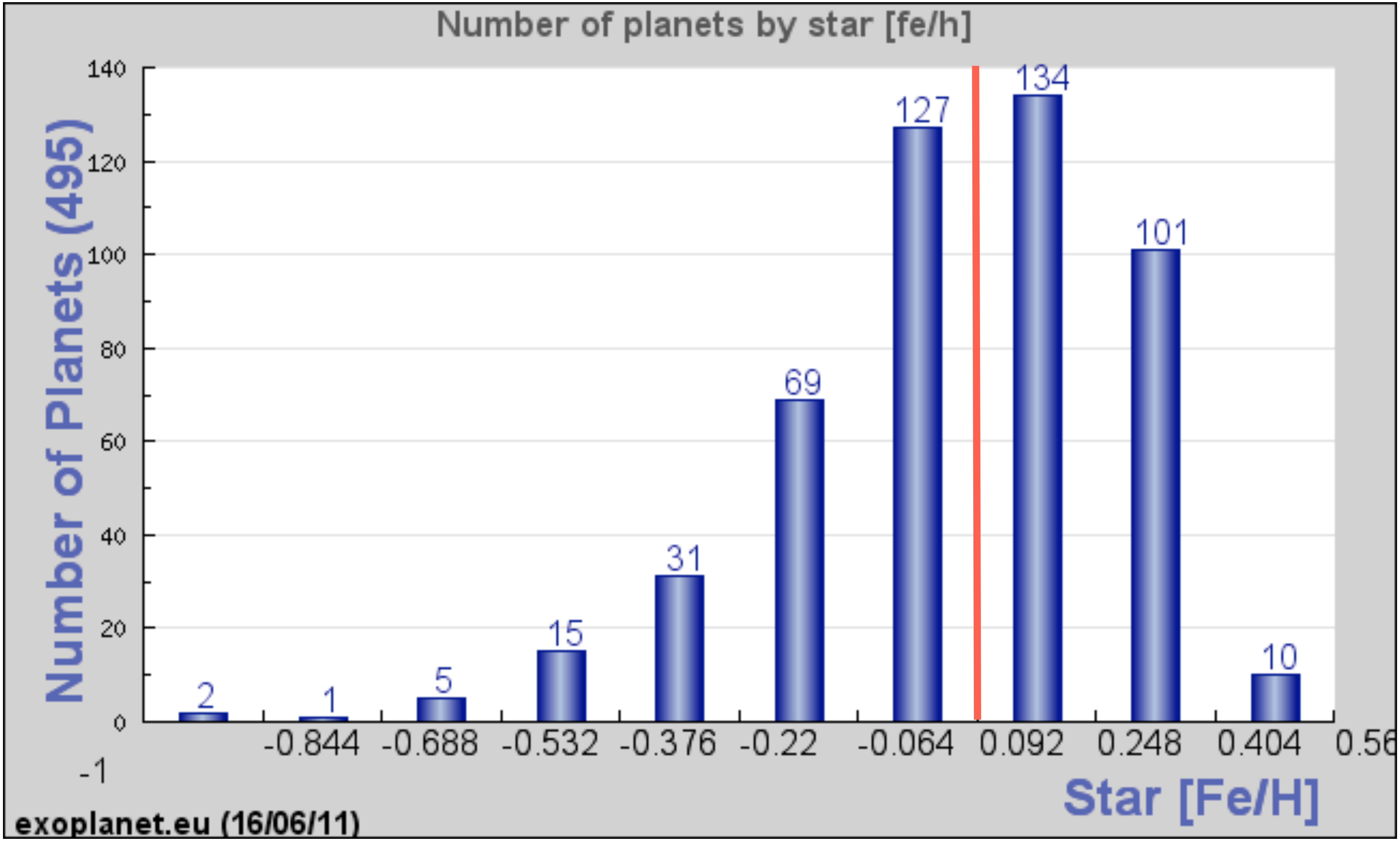
Semi-major axes

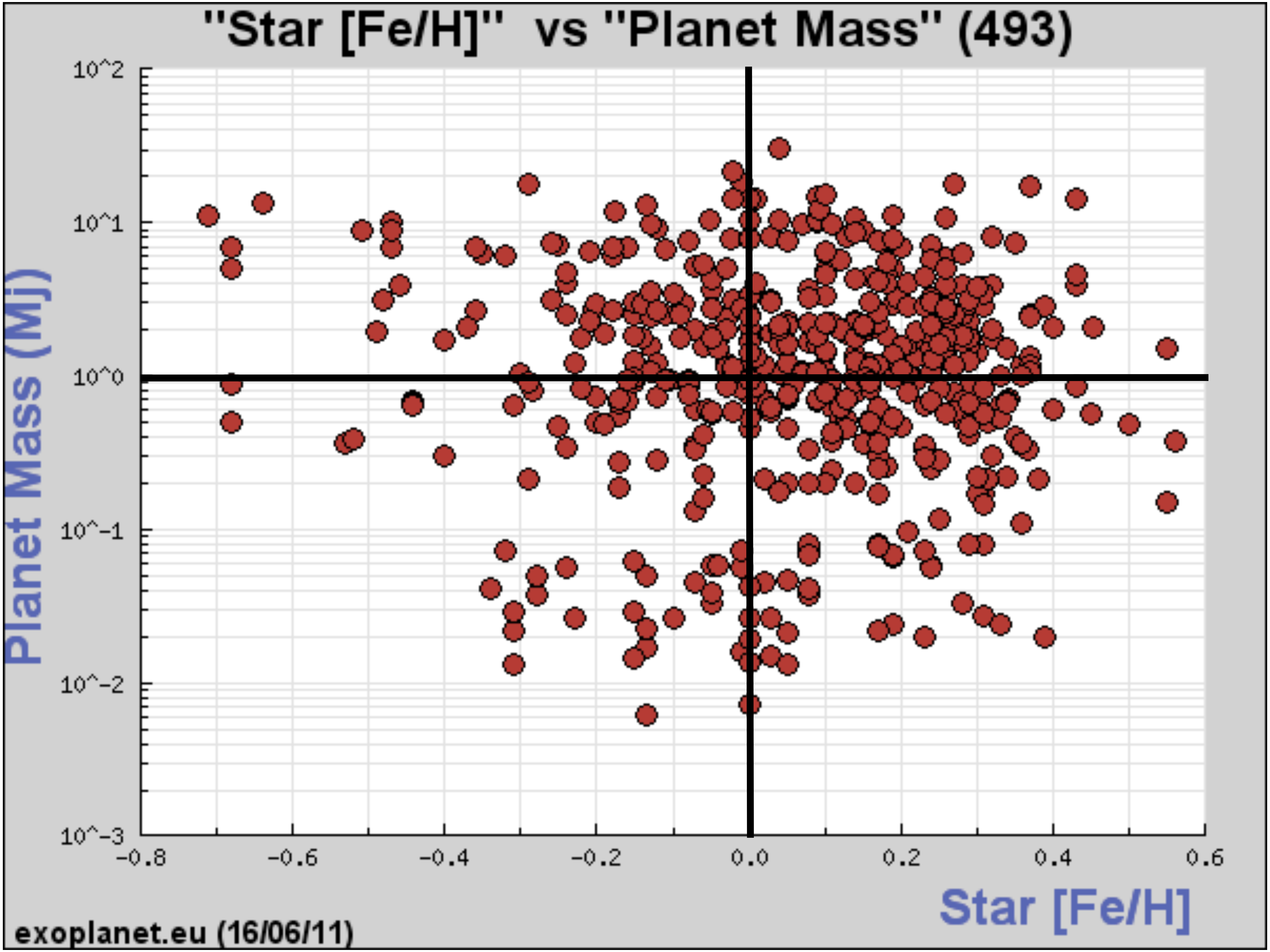


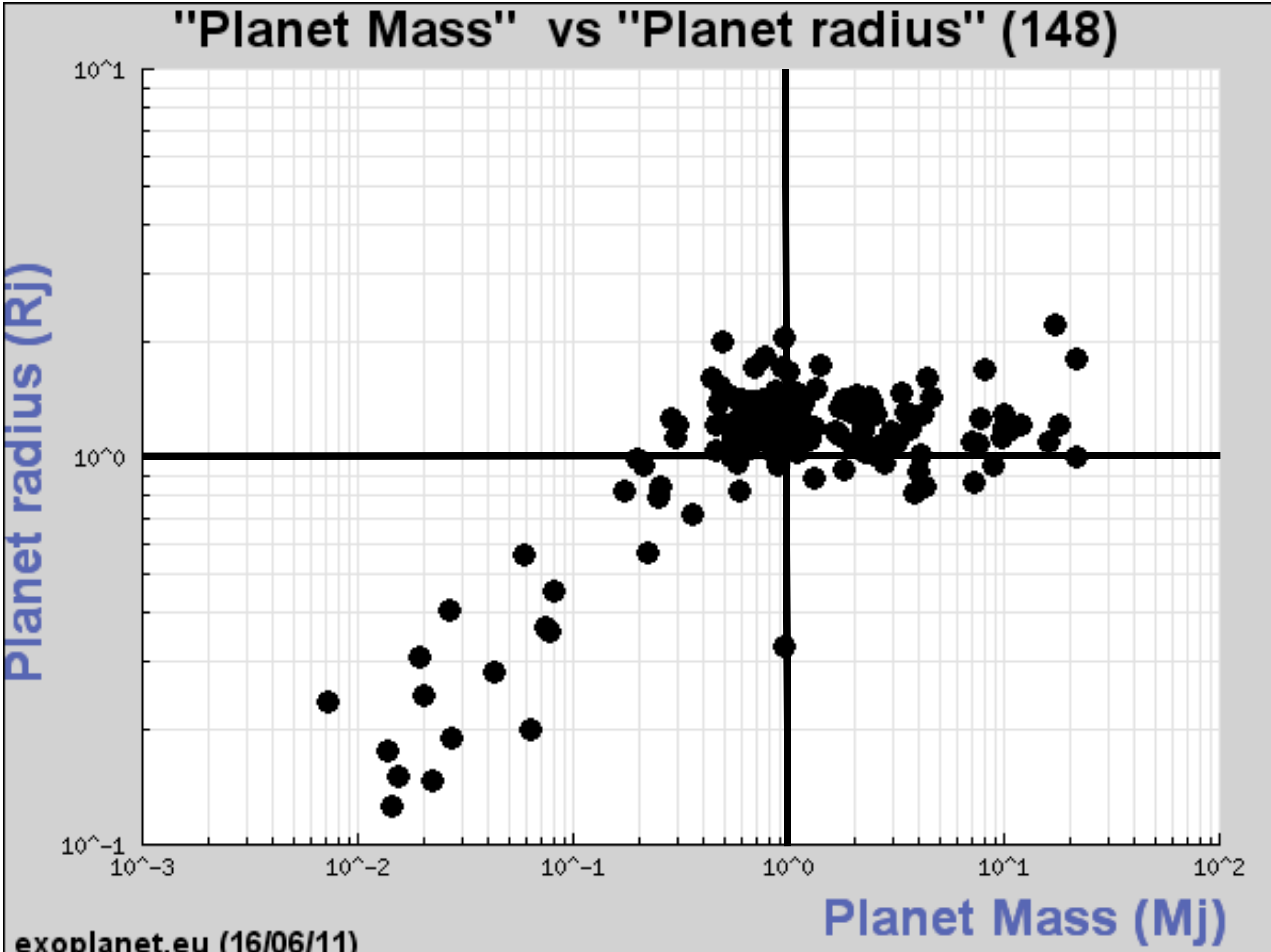
Eccentricities



Stellar metallicities



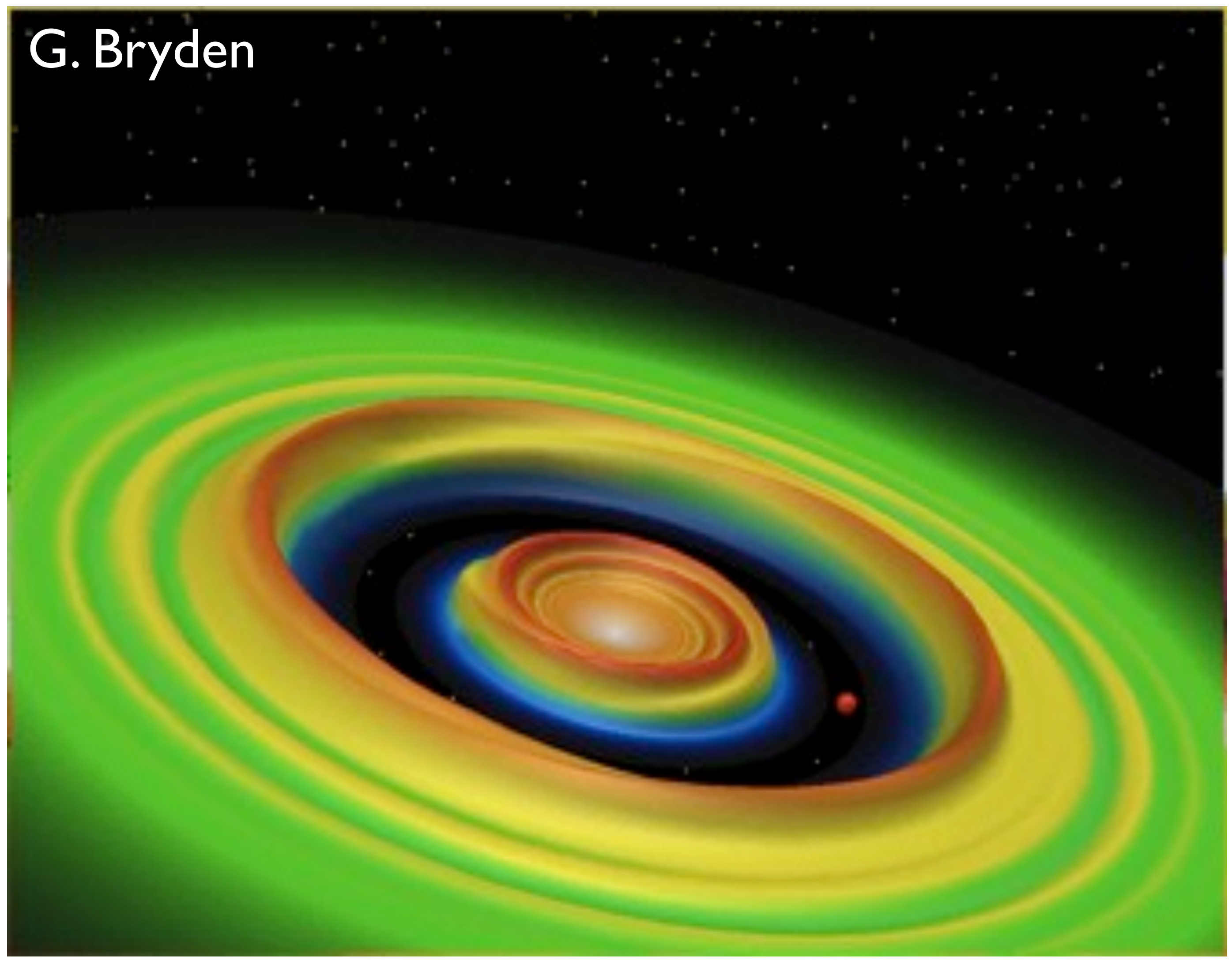

"Star [Fe/H]" vs "Planet Mass" (493)
10^2
10^1
10^0
10^-1
10^-2
10^-3
Planet Mass (Mj)
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
Star [Fe/H]
exoplanet.eu (16/06/11)


"Planet Mass" vs "Planet radius" (148)
10^1
10^0
10^-1
Planet radius (Rj)
10^-3
10^-2
10^-1
10^0
10^1
10^2
Planet Mass (Mj)
exoplanet.eu (16/06/11)

I. Detection & characteristics of exoplanets: Summary

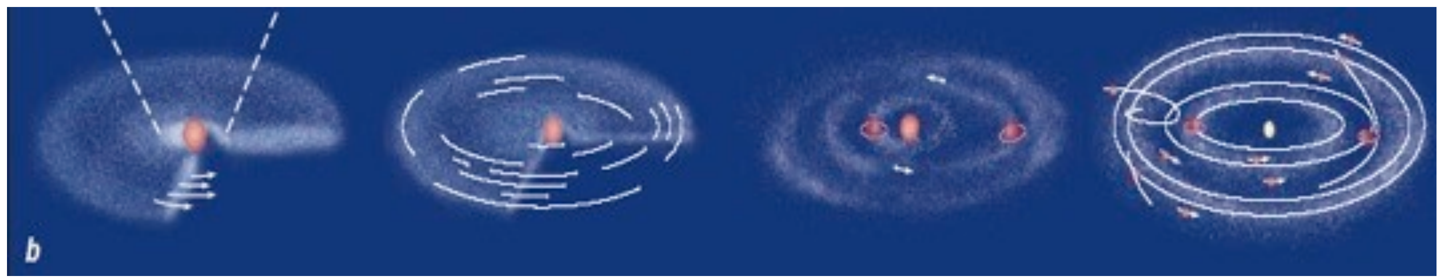
- >10% of all stars have planets
- Formation probability related to stellar Fe/H
- a: 0.01–500 AU
- M: 4–4000 M_{Earth}
- e: 0–0.9
- 30% in multi-star systems
- Multiple systems: 6 planets in 55 Cnc
- A planet around exogalactic star: HIP 13044
- Planets around pulsars

II. Formation & migration of planets

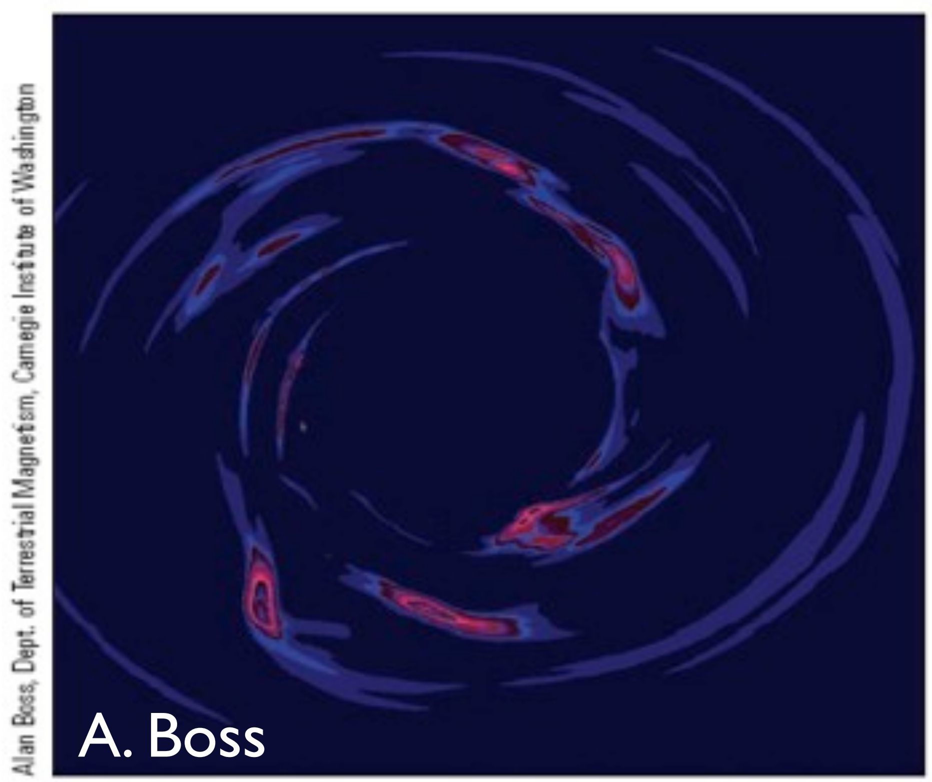


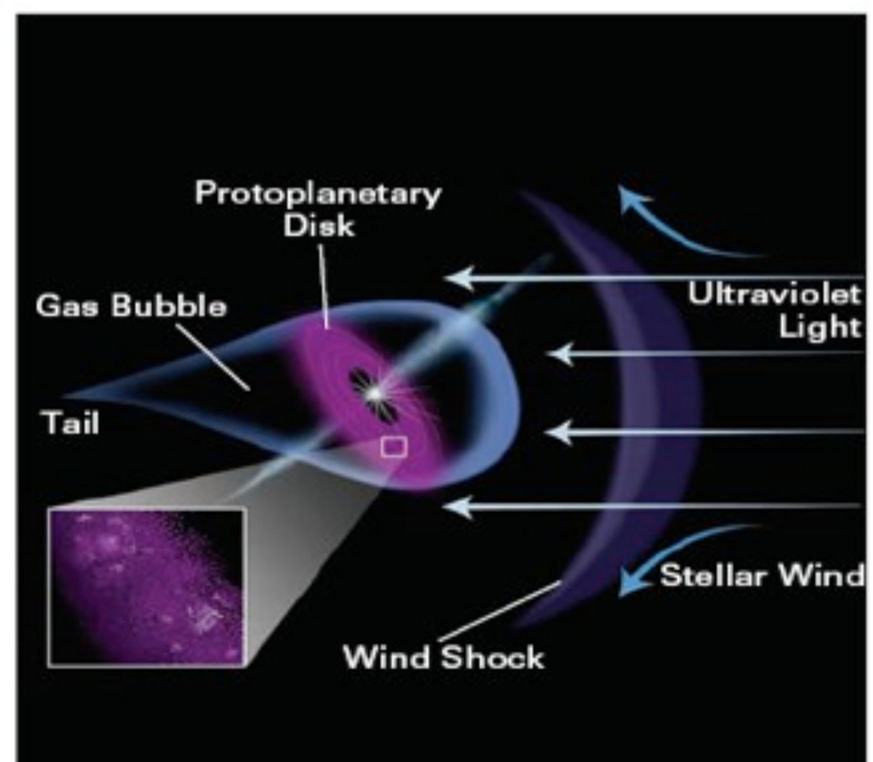
Planet formation scenarios:

• Core accretion from planetesimals & embryos in "old" disk: ~10^6–10^8 years, favors terrestrial planets

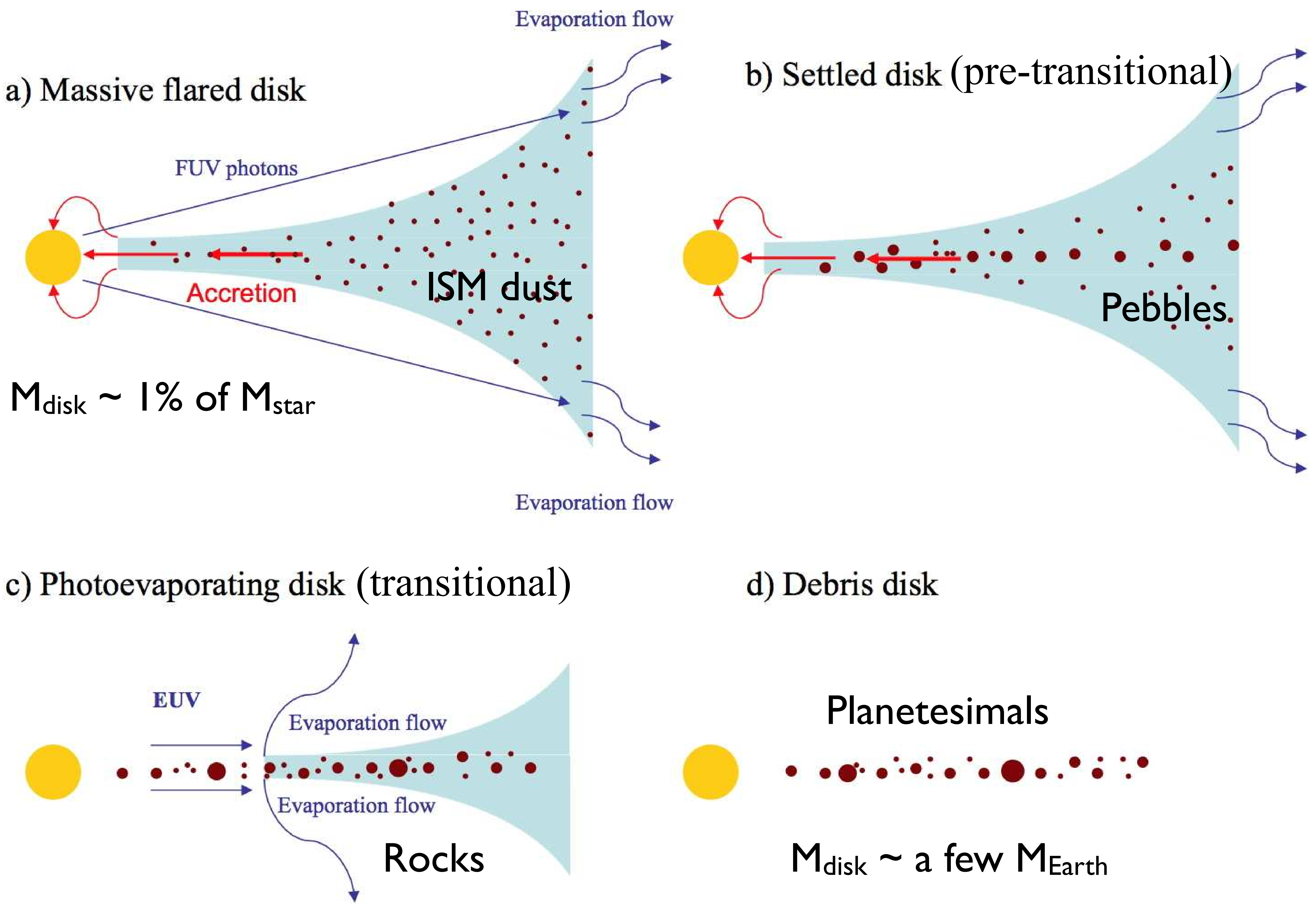


• Gravitational instabilities in "young" massive disk: ~100 years, favors outer Jupiters





From dust till planetesimals



Williams & Cieza (2011)

Steady growth along with disk evolution

- A miracle occurs: planetesimals ~1 km (~10^4 years), ~10^{12} at 1 AU
- Runaway/"oligarchic" growth: Mars-size embryos ~10^3 km (10^4–10^5 years)
- Late-stage accretion via impacts: Earth-like planets ~10^4 km (10^8 years)
- Inner, hot disk: only refractory solids, H & He lost
- Outer, icy disk: gas giants ~10^5 km, core accretion of ~10 M_{Earth} (10^6 years) + accretion of massive gas envelope (10^7–10^8 years)
- Less massive "ice" planets lost some gas
- Growth in mass by 45 orders of magnitude
- Restricted by lifetime of a disk: 1–10 Myr

Runaway growth

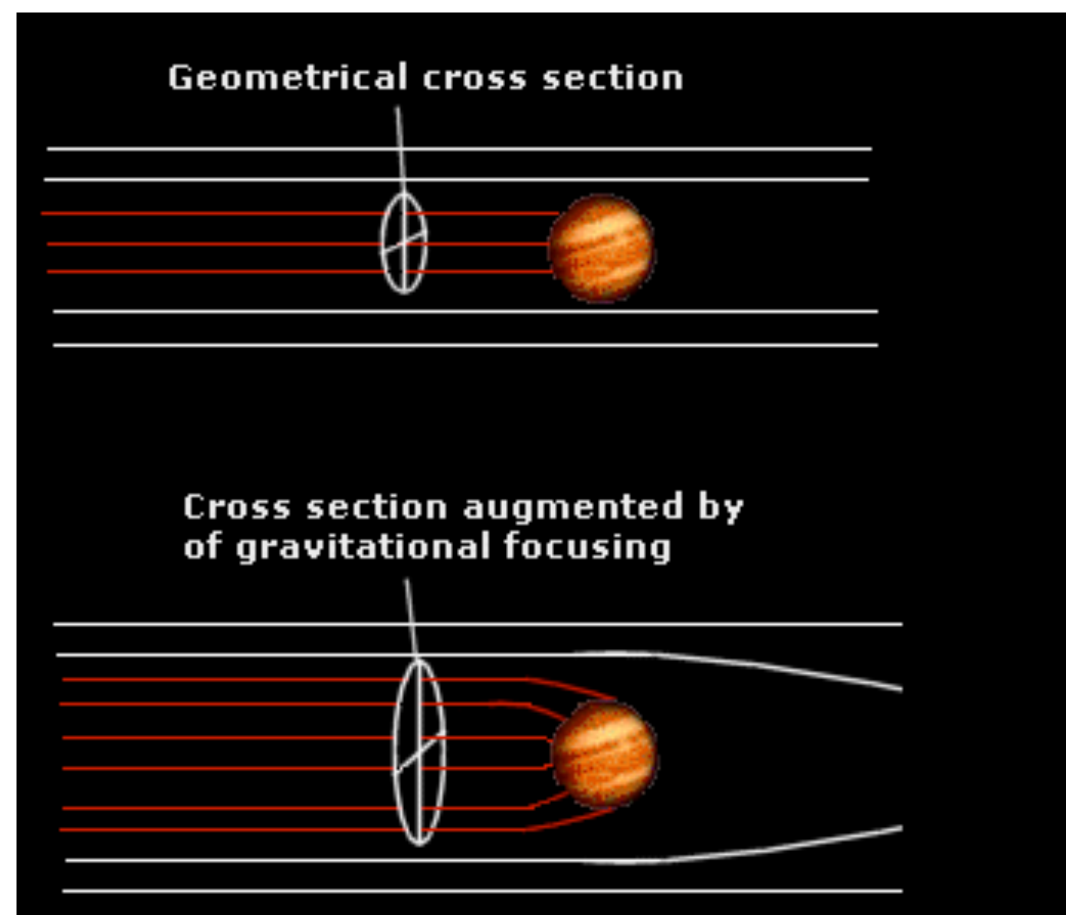
- Planetesimals evolution is collision-dominated
- Collisional cross-section with a body of mass M and a radius R:

$$dr/dt = \Sigma\Omega/\rho$$

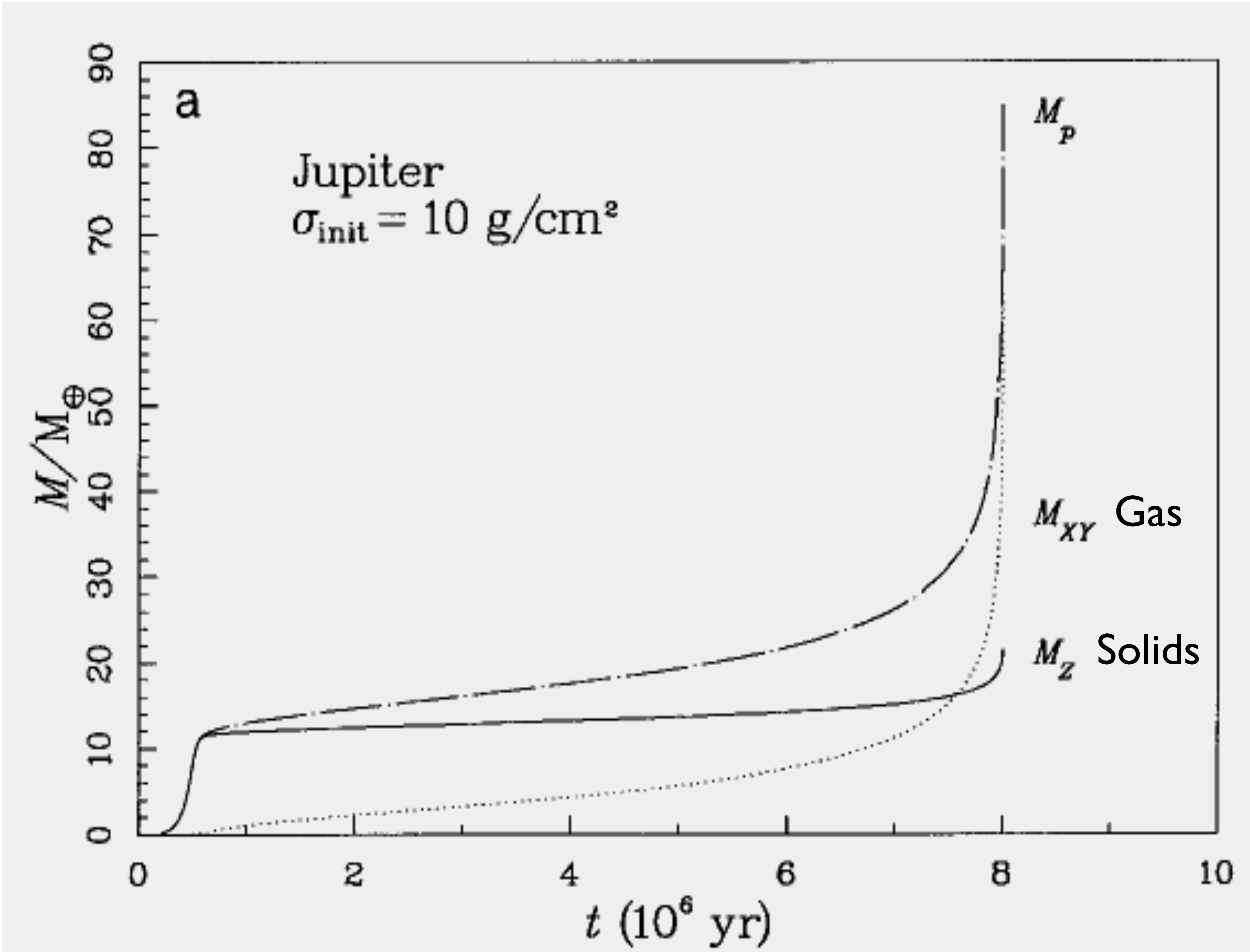
- Earth would grow in 20 Myr, outer planets >100 Myr
- Gravity increases cross-section (focussing):

$$dr/dt = \Sigma\Omega/\rho(1+\Theta),$$
$$\Theta = V_{\mathrm{escape}}^2/V^2$$

- Earth forms within 10^5–10^6 years



Core accretion: Jupiter



Pollack et al. (1996)

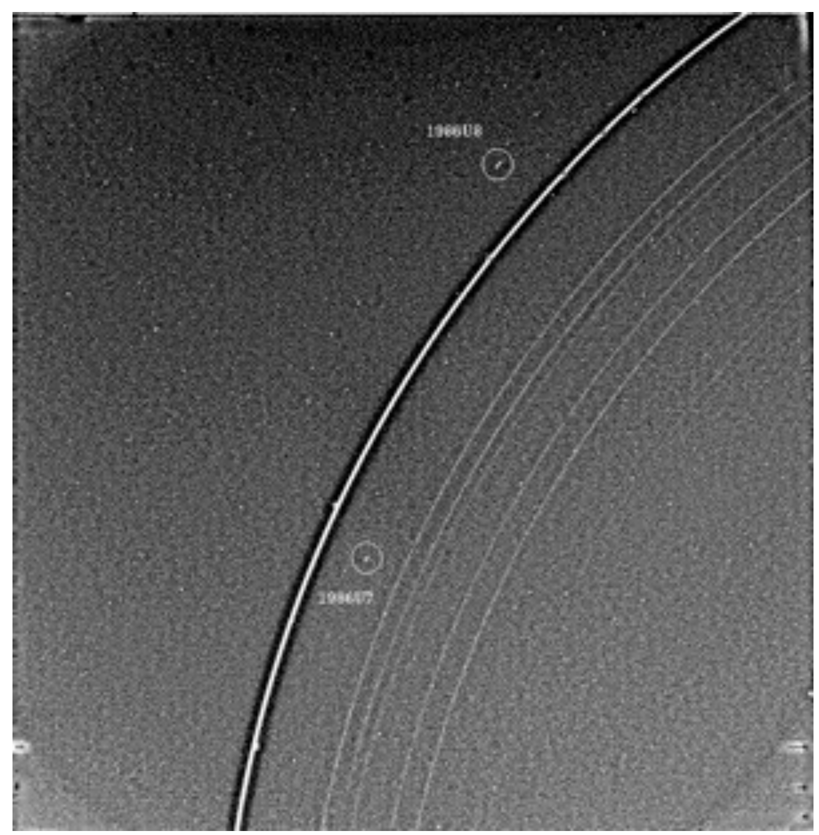
Hints for migrations

• At 0.1 AU no minerals can condense, yet hot Jupiters exist

• Planet(s) within a gas disk: density waves, repulsive gravitational torques between inner & outer disk

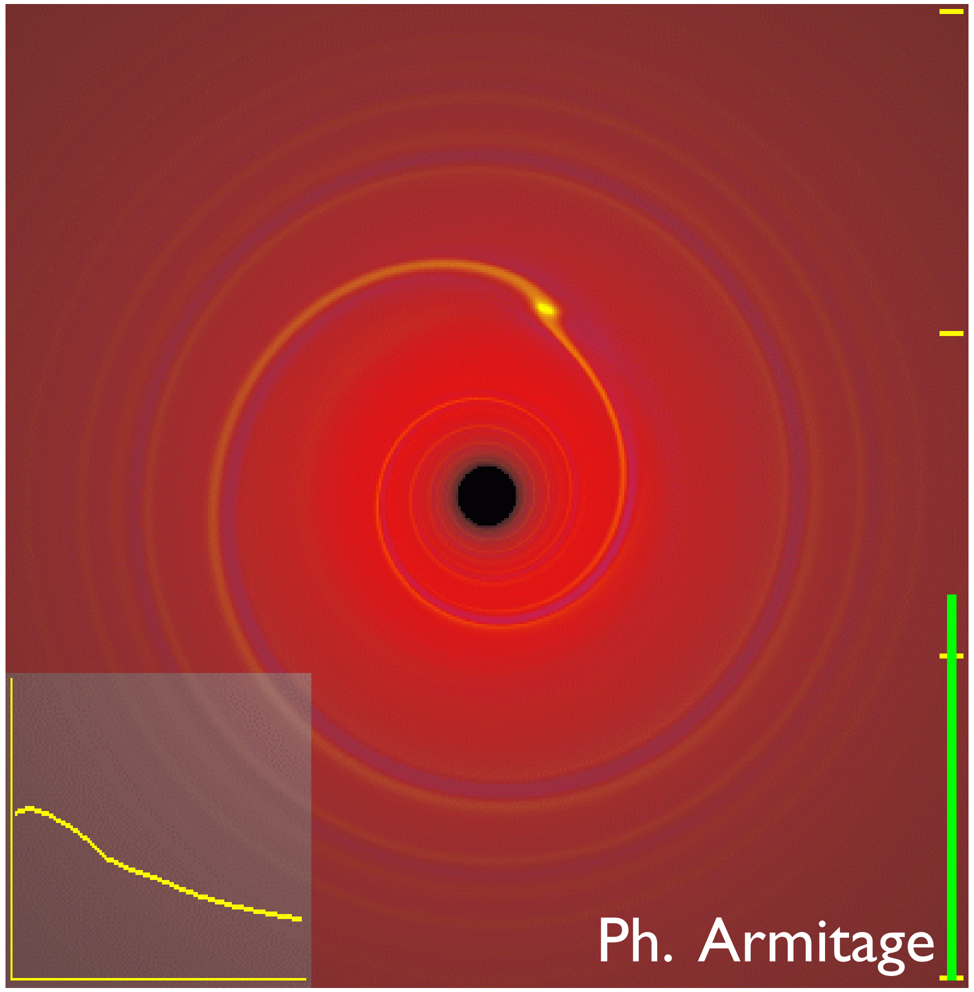
• Example: satellites guarding icy rings around Saturn

• Separate regimes for low- and high-mass planets



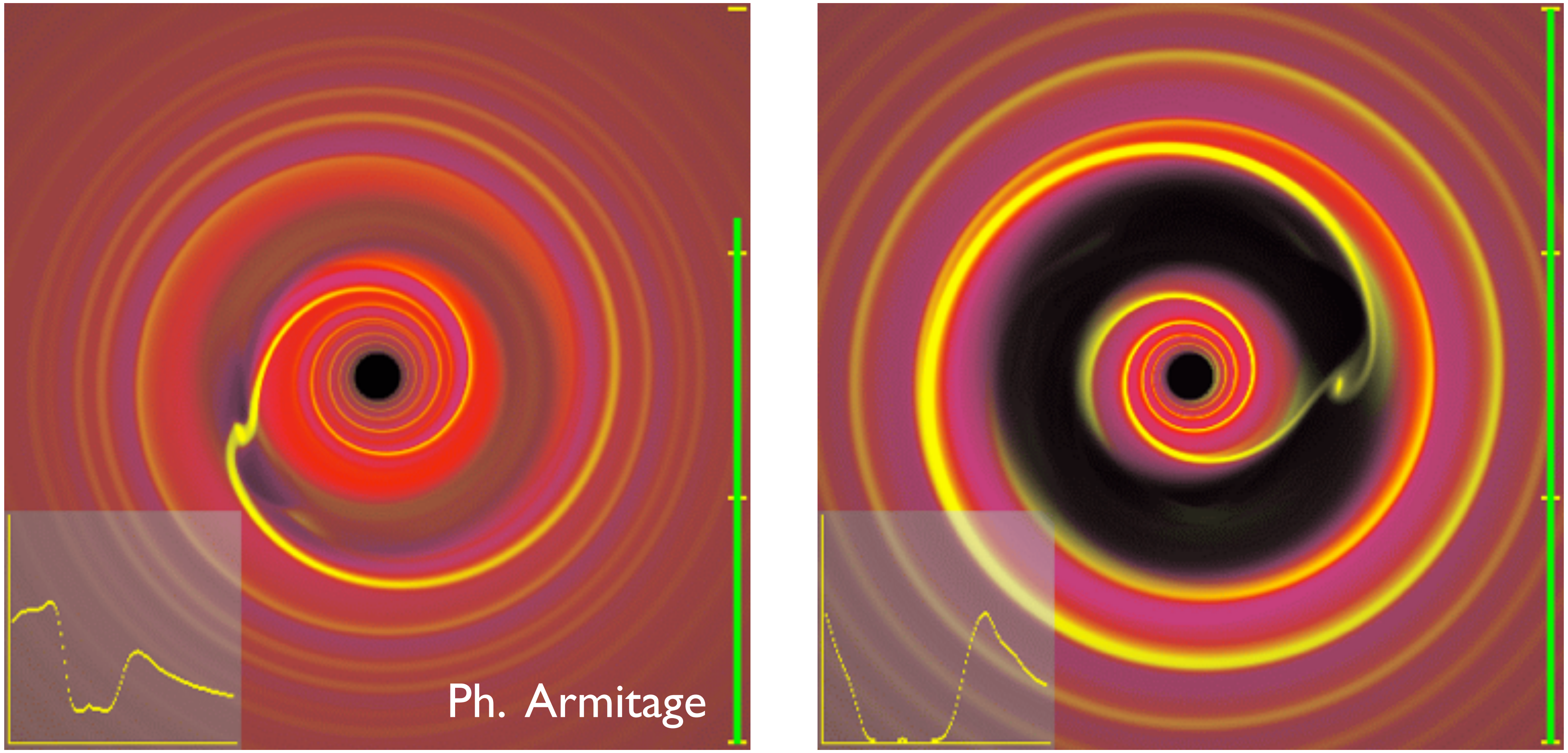
Planet-disk interactions: Type I migration

- Type I migration: back-reaction from tidally generated spiral waves
  - 0.1-10 M_{Earth},
  - no gap,
  - outer disk torques dominate,
  - typically inward (chaotic),
  - planets at resonant orbits: $P_i/P_j=n/k$,
  - timescale: ~10^4 years

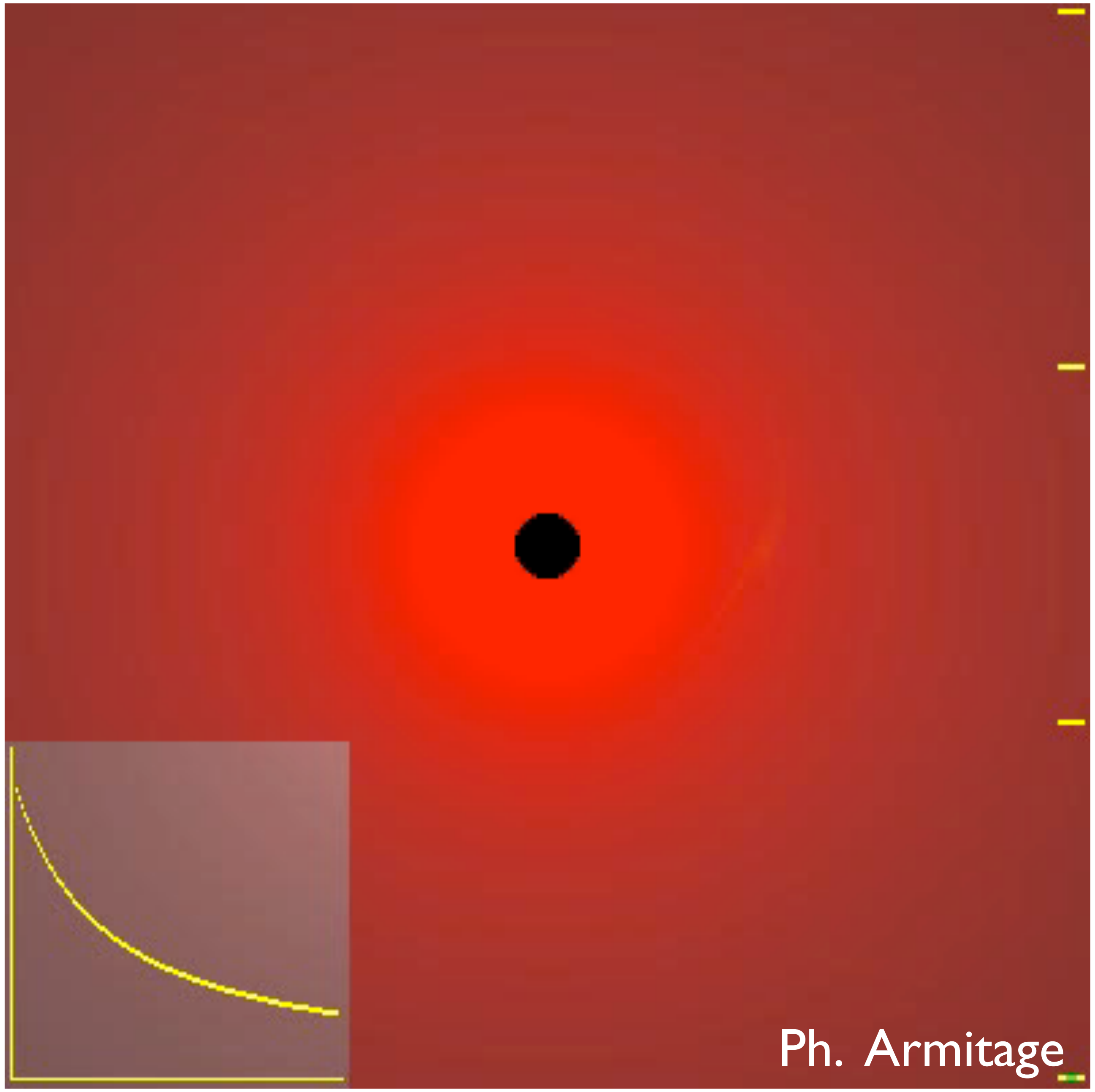


Planet-disk interactions: Type II migration

- Type II migration:
  - >300 M_{Earth},
  - gap opens,
  - residual gas flow over the gap,
  - migration along with viscous disk evolution,
  - inward,
  - timescale: ~10^5 years



Formation of a giant planet: simulations

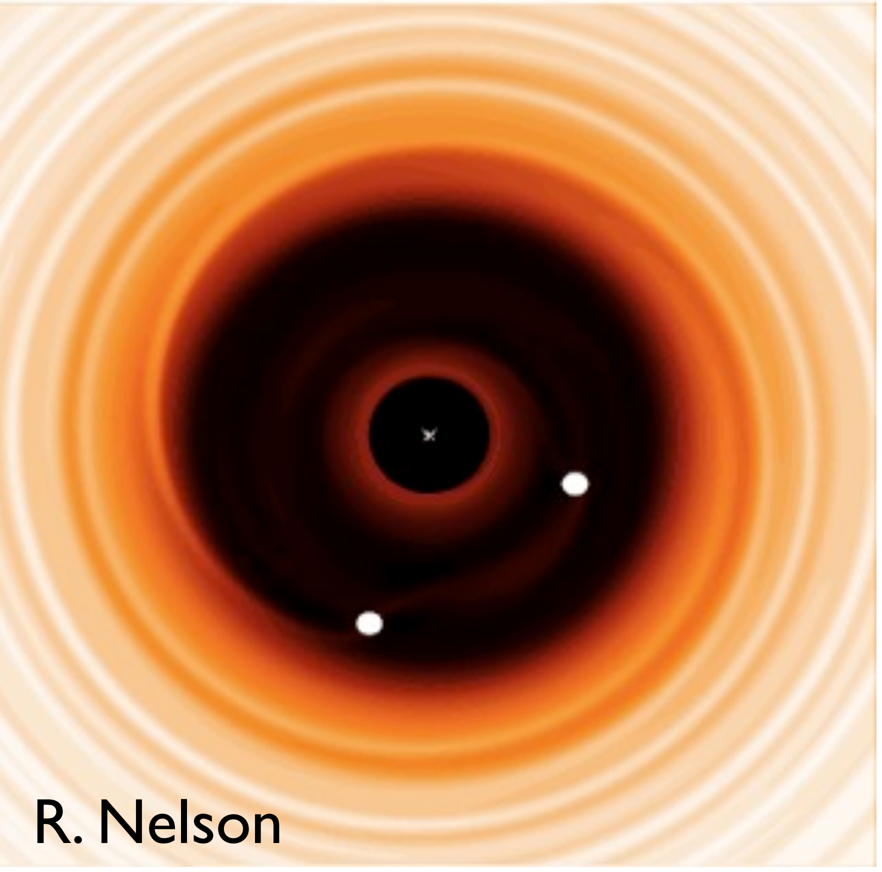


- Fixed orbit, exponential growth: $3M_{Earth}$ till $10M_{Jp}$
- 2D hydrodynamical disk structure
- Gap opening at $\sim 1M_{Jp}$

http://jila.colorado.edu/~pja/planet_migration.html

Halting planetary migration

- Turbulence
- Planet-planet scattering
- Strong magnetic fields
- Strong variations in density & T
- Formation of a massive planet traps less massive ones



Steady growth scenario

- Observational support: planet-metallicity correlation
- Planets in multi-star systems & odd orbits
- Varying ratio of elements in the core & envelope
- Jupiter can be made within ~1–10 Myr
- Timescales: 1 M_{Jp} @ 5 AU, $t_{accr} \sim 10 t_{migr}$ ⇒ protoplanet falls into the star before it accretes 10 M_{Earth}
- Migration has to be 10x slower
- No evidence for migration in Solar System
- Cannot explain presence of planets at r>100 AU

Disk instabilities

$$Q = \frac{\Omega_{\mathrm{K}} c_{\mathrm{s}}}{\pi G \Sigma}$$

- Gravitational instabilities leads to fragmentation of disk (dust) when $Q<1$ and cooling is ~orbital time

- ~1 M_{Jp} fragments of gas and dust start to collapse

- Rapid dust grow & sedimentation leads to solid core

- A gap in disk gas opens

- t_{acc}: ~100 years!

- UV radiation removes gas from outermost planets

Disk instabilities scenario

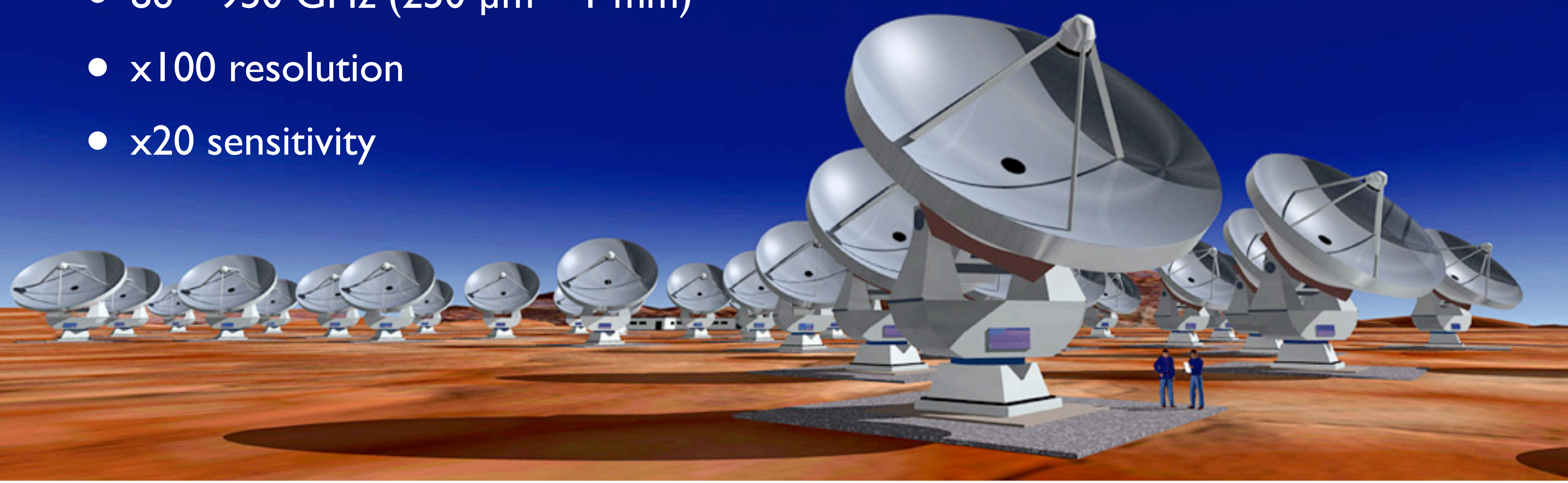
- Minimum-mass solar nebula: $Q \sim 60/r^{1/4}$, very stable!
- More massive younger disk, cold outer regions
- Observational support: presence of planets at $r>100$ AU
- Rapid inward migration is not an issue
- Not restricted by disk lifetime
- Works only for large outer planets
- Cannot explain varying composition of gas/core

II. Formation of planets: Summary

- Two plausible mechanisms: gravitational instabilities & steady growth
- Can explain presence of hot Jupiters & far-away planets
- Can explain Fe/H correlation & exoplanets at odd orbits
- Type I migration: ~Earth-like planets, typically inward
- Type II migration: ~Jupiter-like planets, inward
- Migration is too fast
- Jupiter-like planets open gaps in disk gas

III. The Brave New World: ALMA

- Atacama Large Millimeter Array (2013)
- 50 x 12m + 12x7m + 4x12m
- Spatial resolution: 0.005″
- Spectral resolution: <0.05 km/s
- 8 GHz bandwidth for continuum
- 86 – 950 GHz (250 µm – 1 mm)
- x100 resolution
- x20 sensitivity

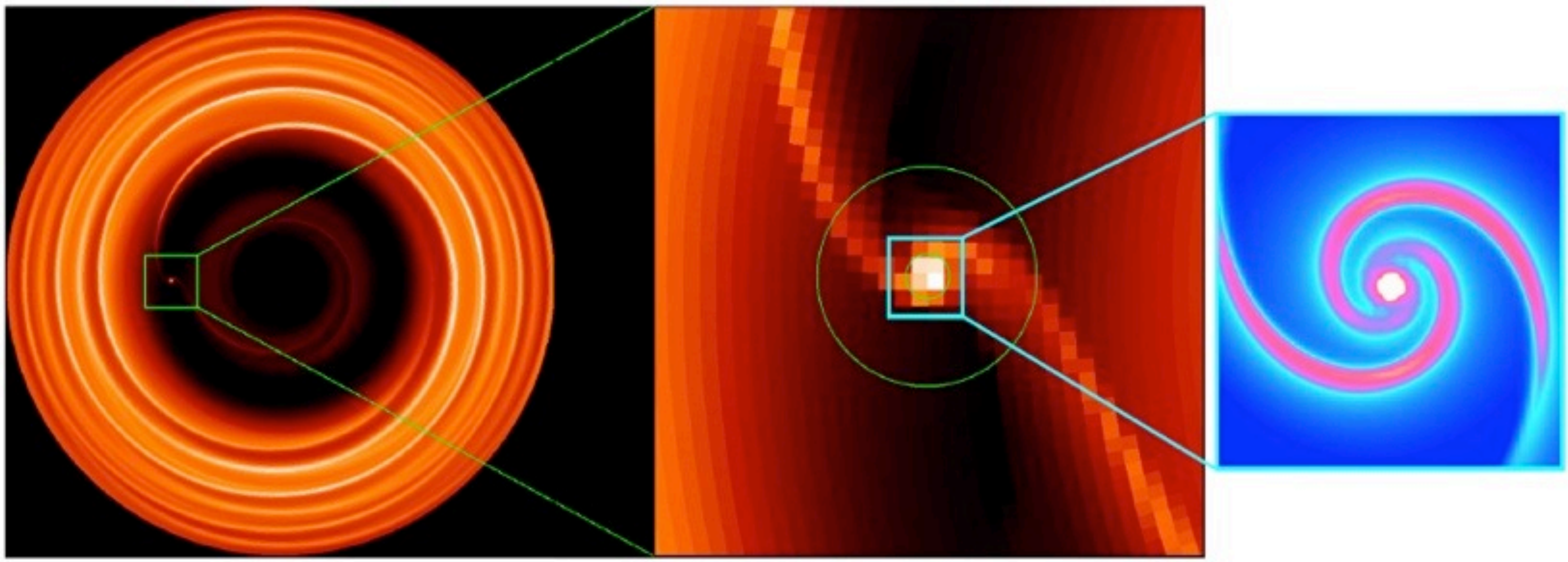


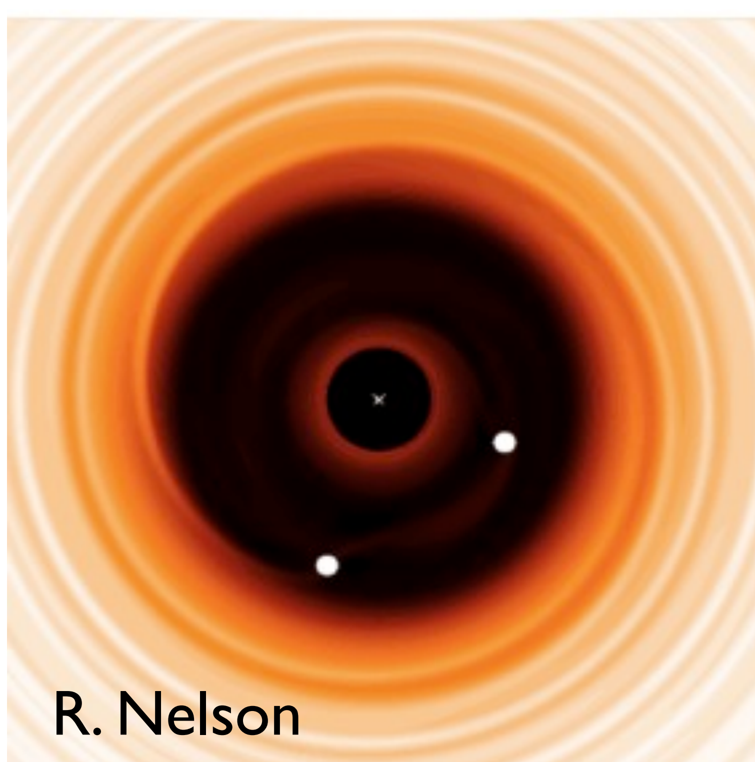
Credit: ALMA (ESO)

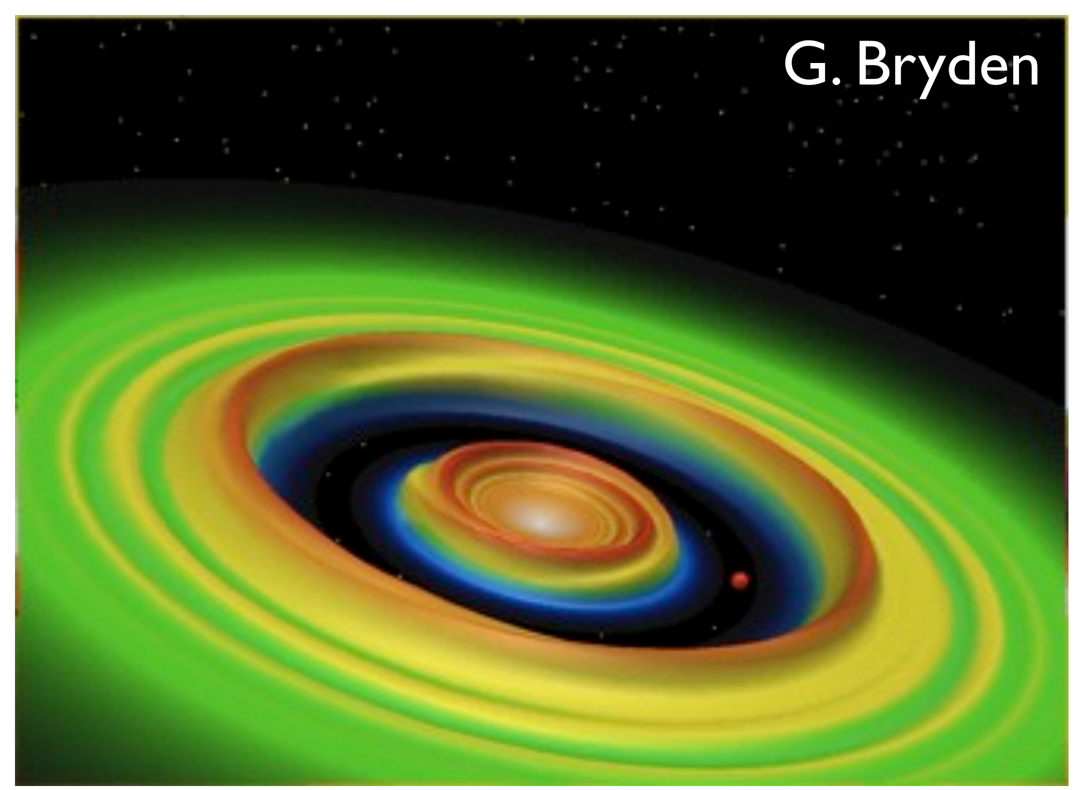
ALMA studies of planet formation:

- Gaps & inner holes opened by (proto-)planets
- Vorticities
- Circumplanetary disks?
- Asymmetries in dust distributions in "debris" disks
- Large sample of transitional & "debris" disks
- Not-so-close star-forming regions

ALMA: Spiral waves (density & kinematics)

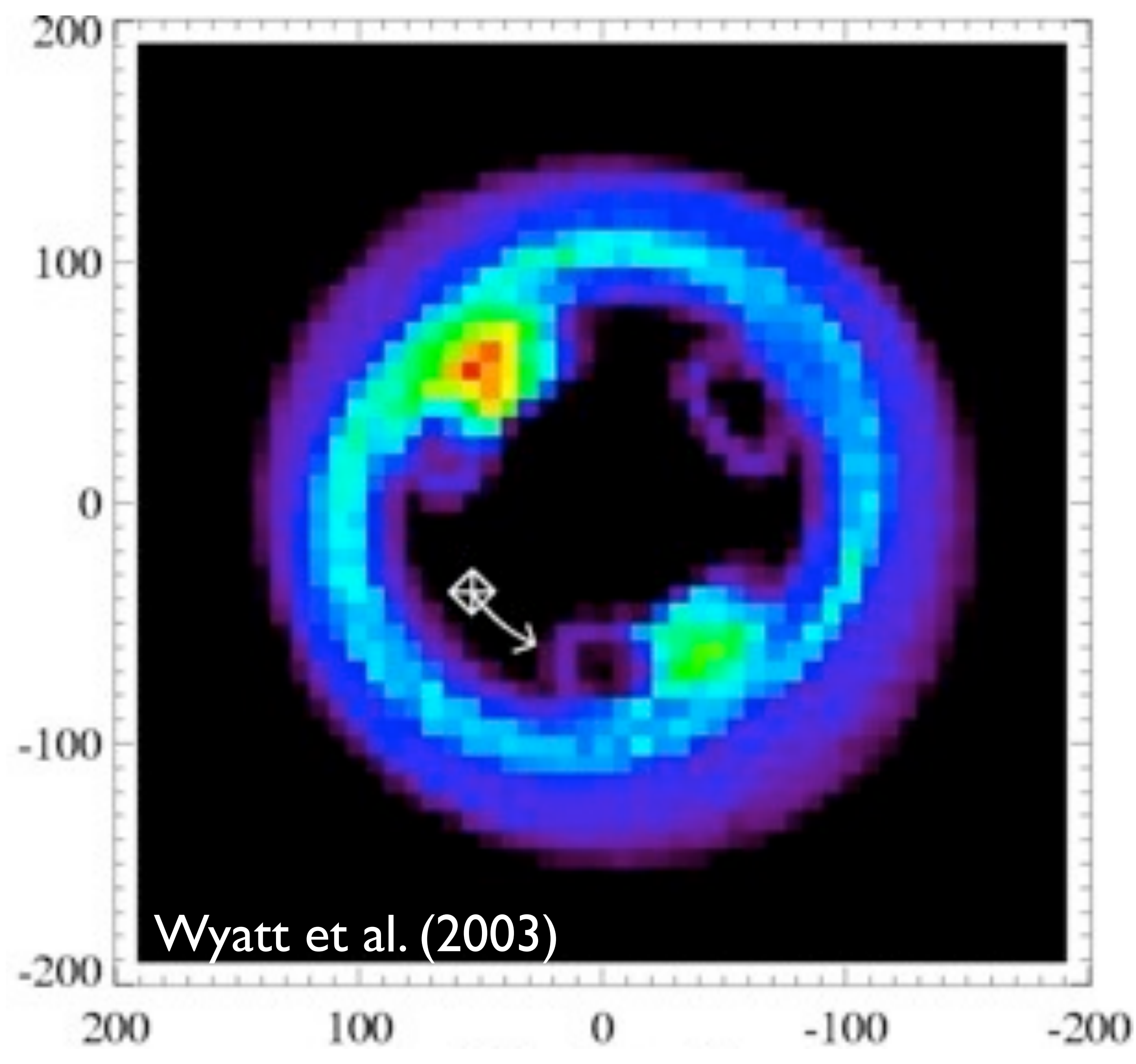






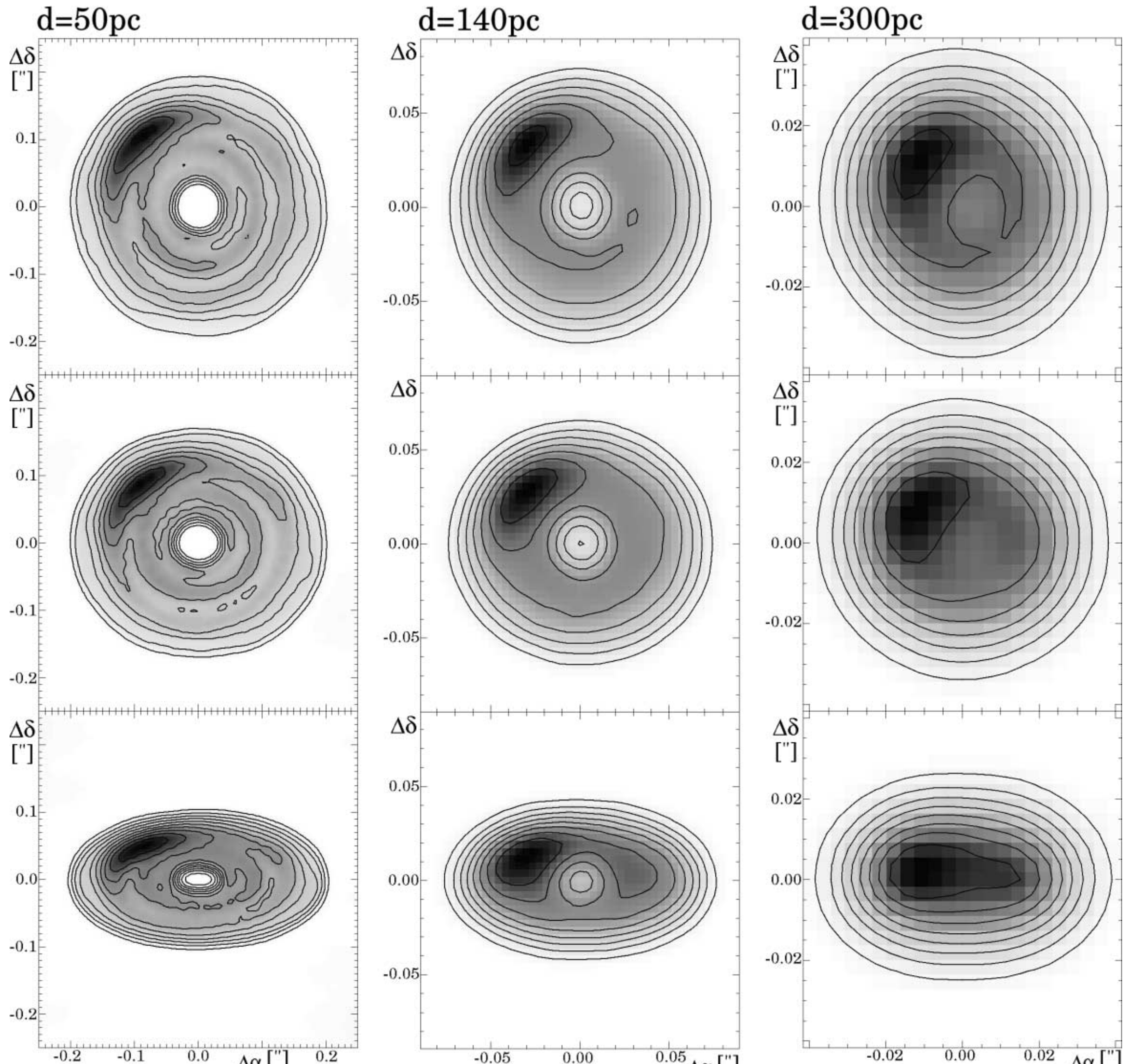
ALMA: dust clumps

- Asymmetries in dust distributions in "debris" disks
- Dust trapped in resonances due to planet-disk interactions



ALMA: large-scale vorticities

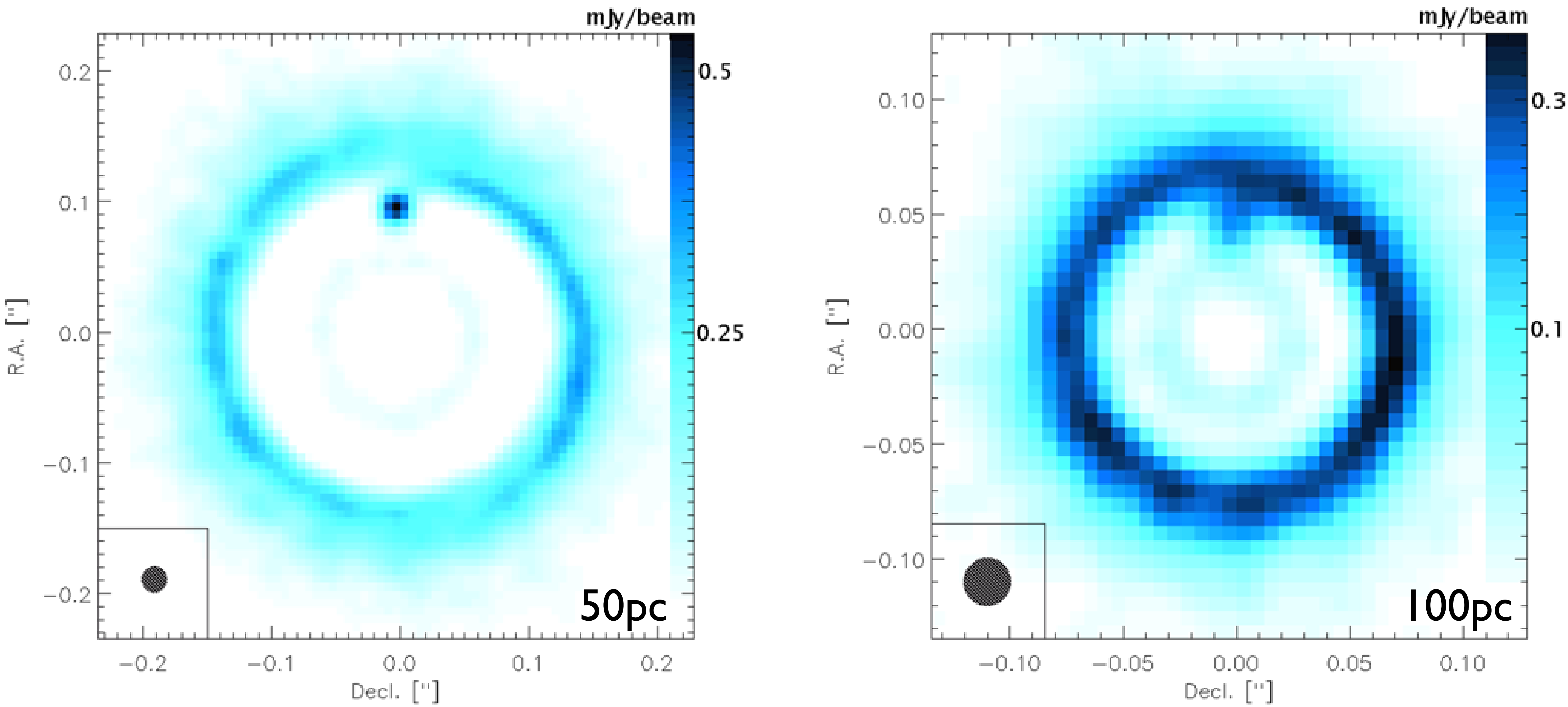
Disk density perturbed by baroclinic instability



Wolf & Klahr (2002)

ALMA: gaps in disks

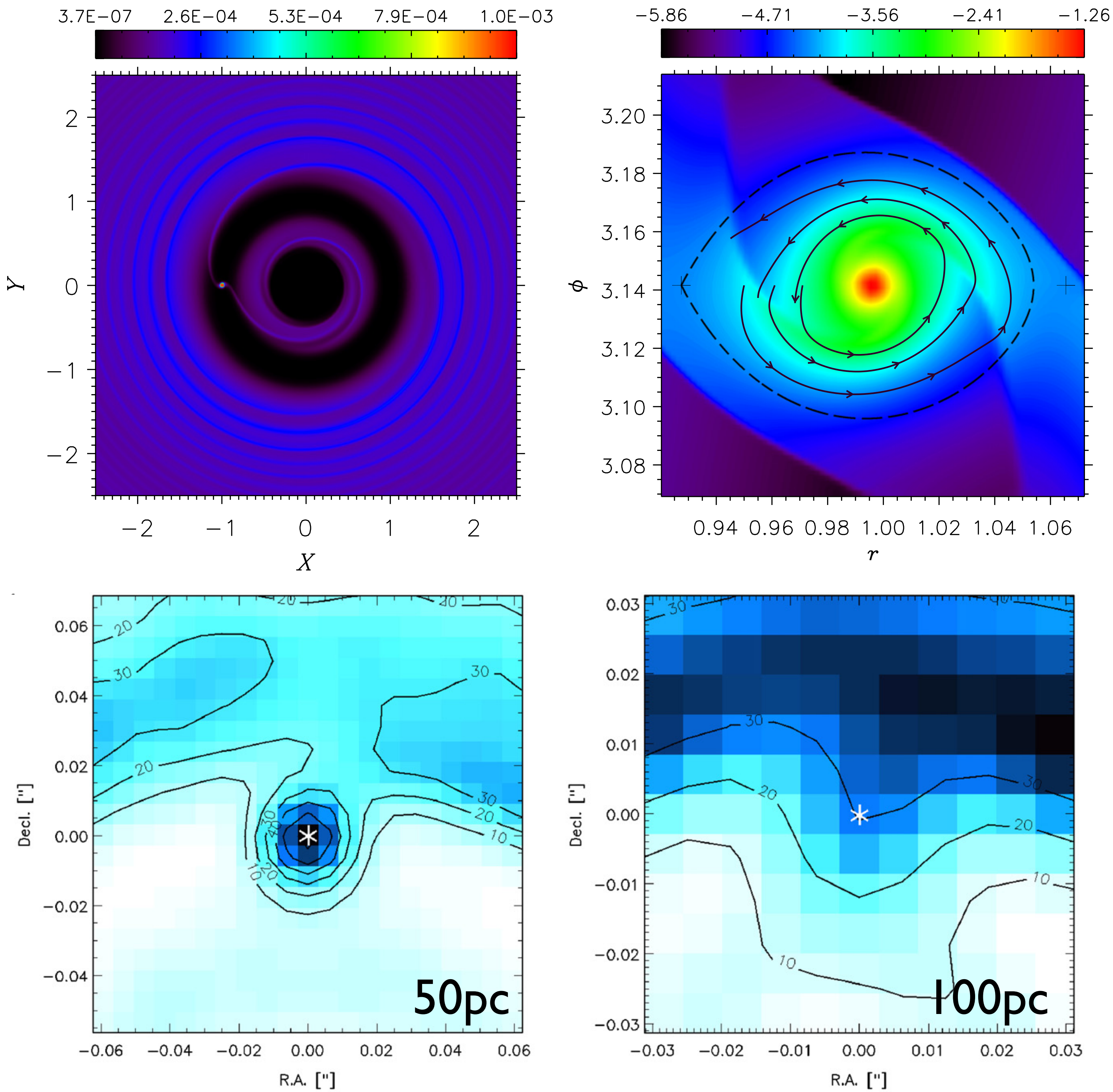
Simulations: 0.5 M_{Sun}, 1 M_{Jp} @ 5 AU, 950 GHz, 2 AU gap



Wolf & D'Angelo (2005)

ALMA: circumplanetary disks?

Simulations: 0.5 M_{Sun}, 1 M_{Jp} @ 5 AU, 950 GHz



Wolf et al. (2007)