What's missing: theory and observation

Douglas N.C. Lin
Astronomy (UCSC), KIAA (PKU), IAS (THU)

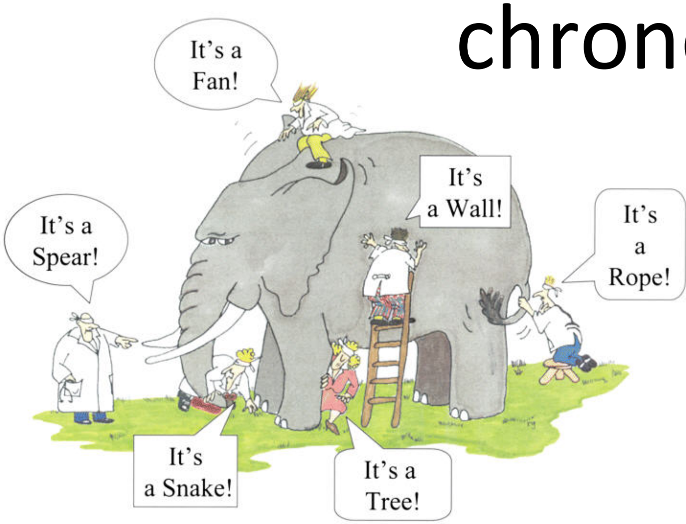
Exoplanetary System Demographics: Theory and Observations

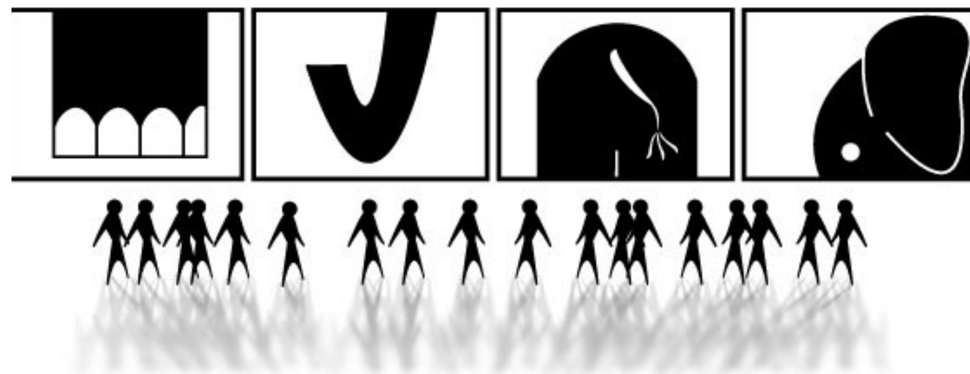
Beckman Institute, Caltech, July 27-31, 2015

SANTA CRUZ

36 slides

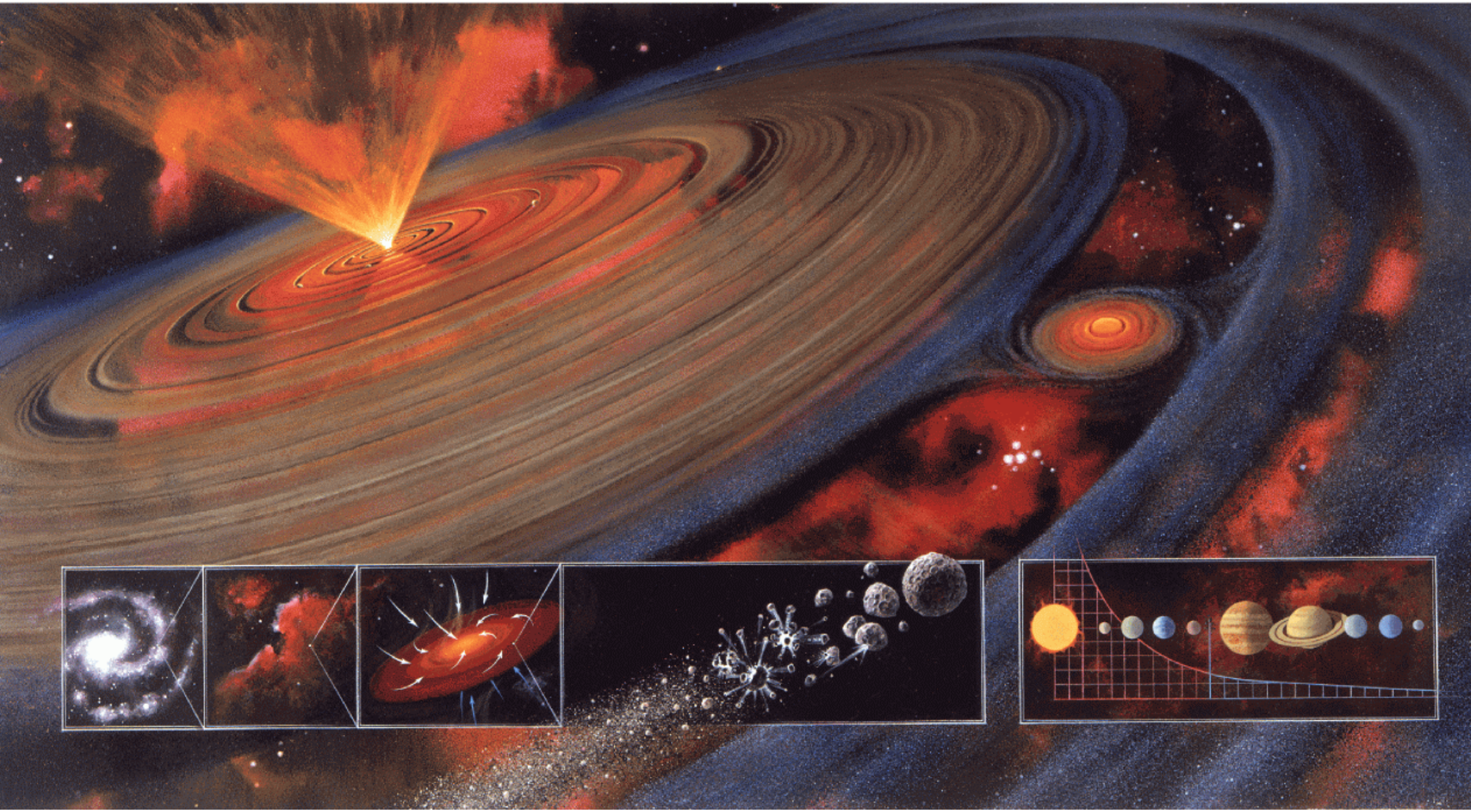
Reconstruct of planet-formation chronology: methodology





- Observational **inputs**
- Piecing together **incomplete information**
- Conceptual paradigm (geocentric) **occam's razor**
- Analytic dissection: **boundary, initial conditions**
- Theoretical **predictions** and observational **tests**

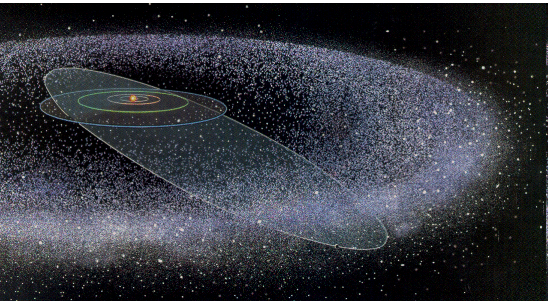
Laplace nebula hypothesis



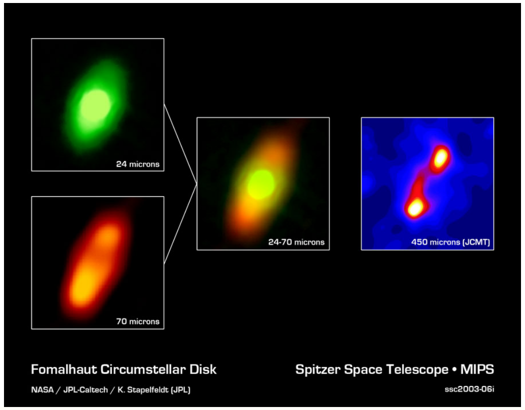
Role of theory

- To identify some fundamental big picture issues
- To understand diverse physical processes
- To analyze the interplay between competing effects
- To extrapolate the observable signatures
- To interpret data and construct testable scenario
- To think out of the box and innovate alternatives
- To infer the next step for search & characterization
- **Always question assumptions and ``folklores''**

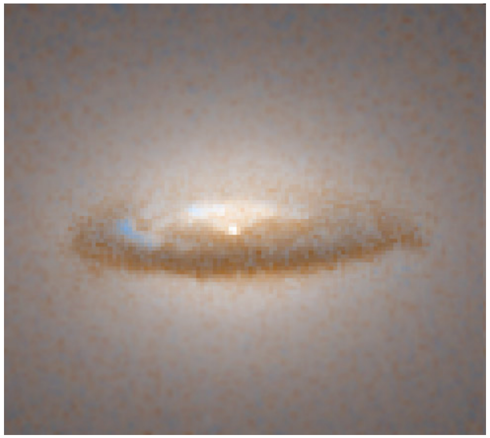
Age of discovery: three fronts



Dwarf planets

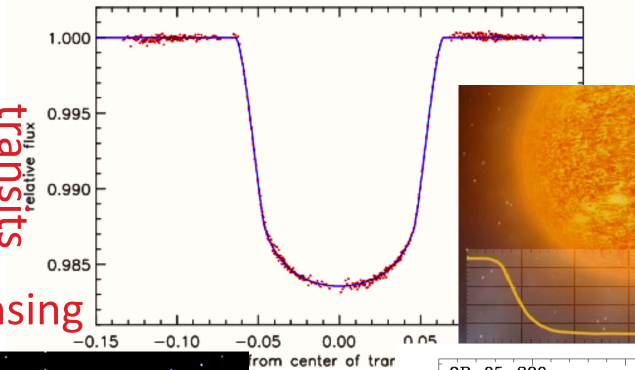


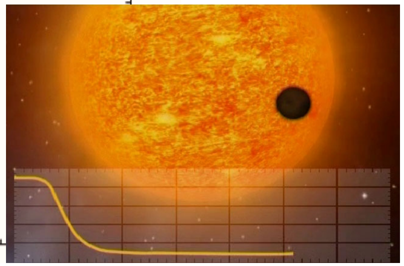
Protostellar disks



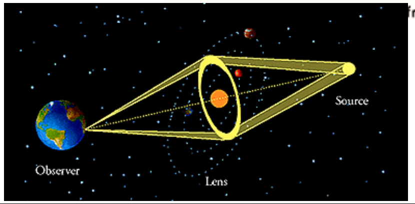
Extra solar planets

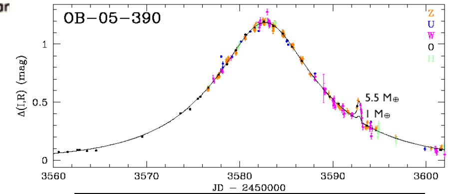
transits

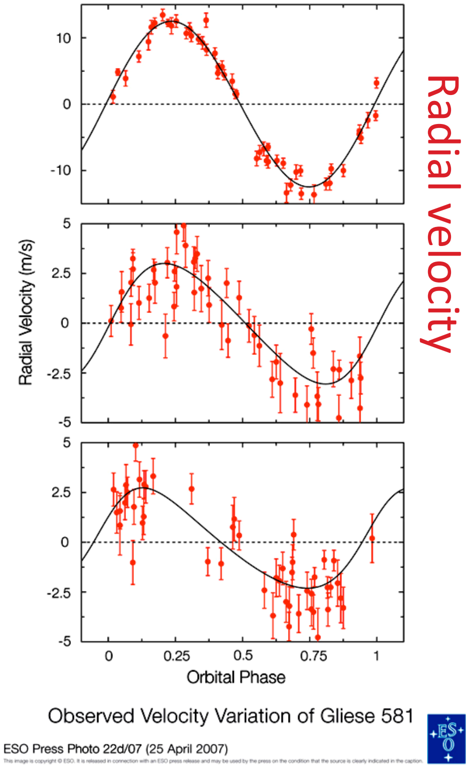




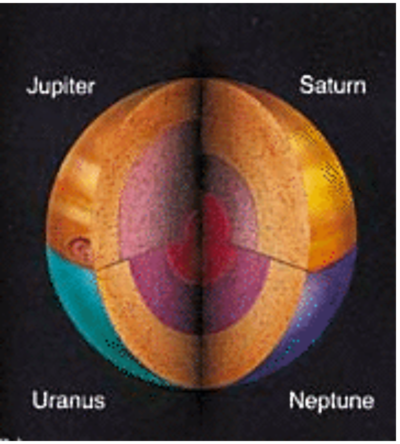
microlensing







Radial velocity

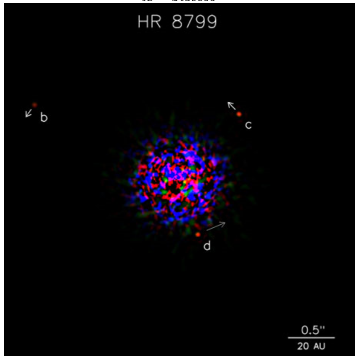


Solar system exploration

meteoritic

<first> <prev> [Dr. Andrew Youdin, Princeton 08] [NEXT> [last>

Direct imaging



Role of observation

- To establish existence and non existence
- To identify common features versus exceptions
- To clearly state precision limits & selection bias
- To think out of box & explore unchartered waters
- To provide complementary or contradictory data
- To establish controlled samples
- To establish dialogues with theorists
- **Be open minded and avoid over interpretation**

Precision COSMOGONY

- Ubiquity of planets:

case study vs **Science**

- Diversity of systems:

realm of possibilities

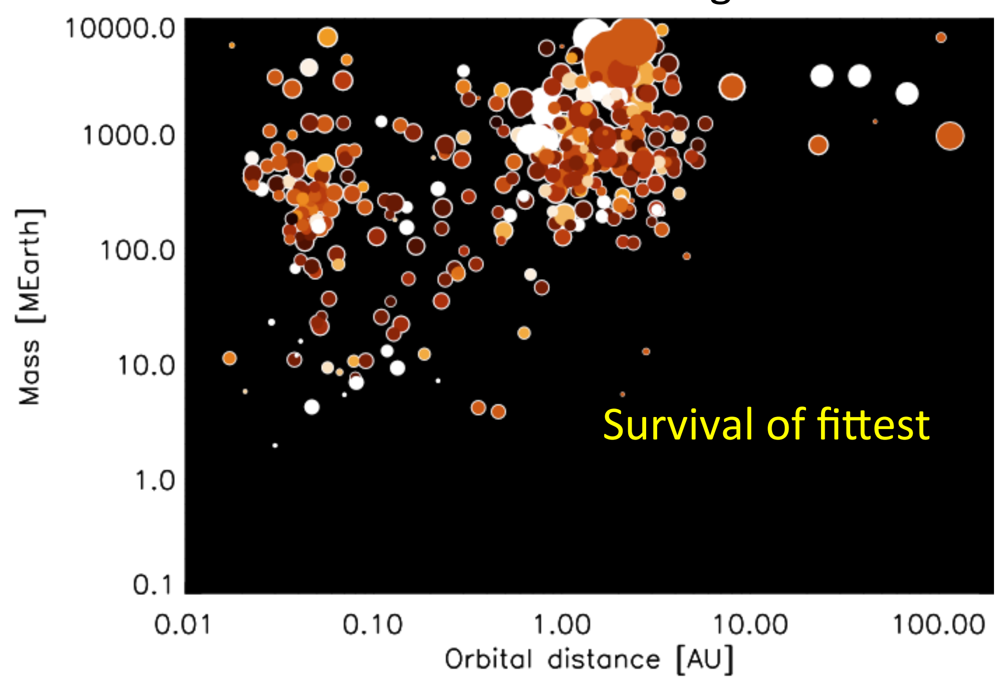
- Population census

missing info & big picture

- Solar system connection

Anthropic principle

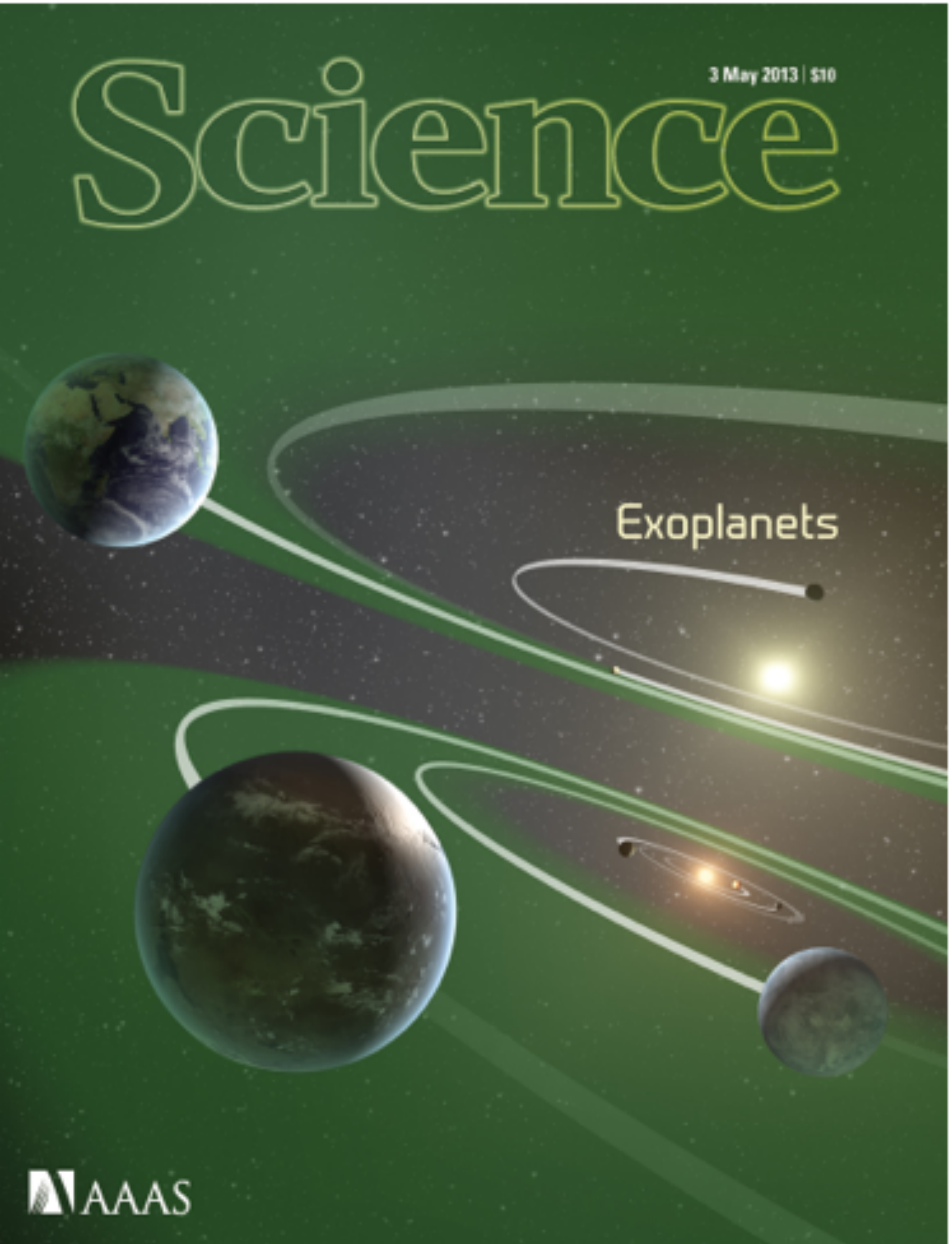
Integral of details



Challenges for linking theory and observations

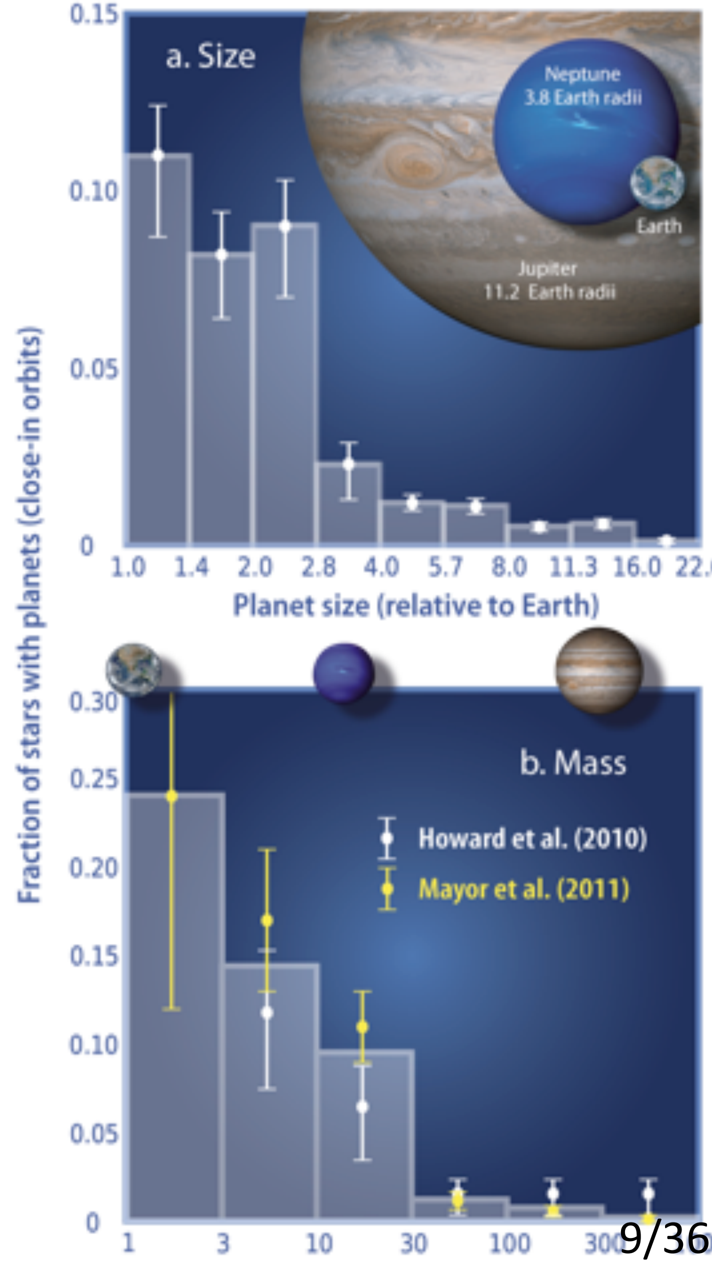
- Main observational clues
- Exoplanet searches: census and characterization
- Protostellar disks: Initial and boundary conditions
- Solar system: relic forensic

- Many theoretical repertoires
- Holistic approach (population synthesis for clues)
- Open mind and testable predictions



Observed Properties of Extrasolar Planets

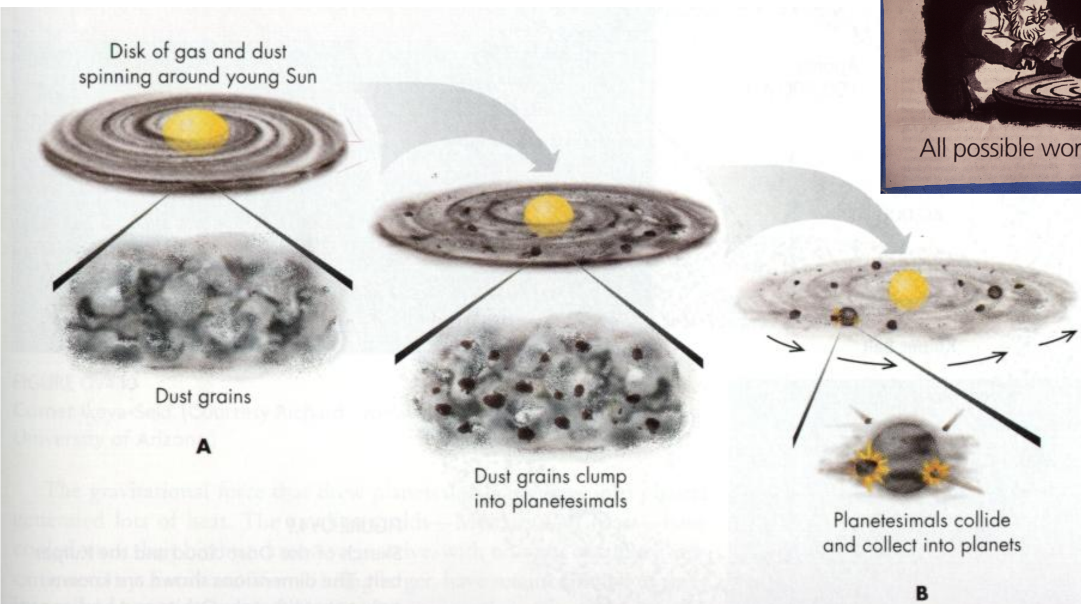
Howard (2013)



Big picture questions

- How did super Earth form so prolifically
- Why is the emergence of gas giant marginal?
- How did planets establish their structural diversity?
- How did planetary systems acquired the observed kinematic distribution?
- How did multiple systems attain meta-stability?

Minimum-mass nebula hypothesis
in situ formation scenario



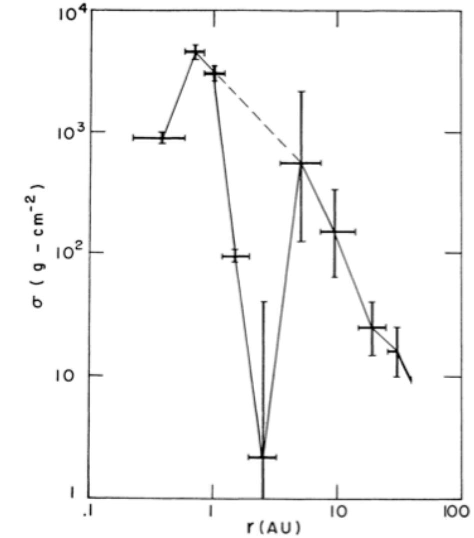
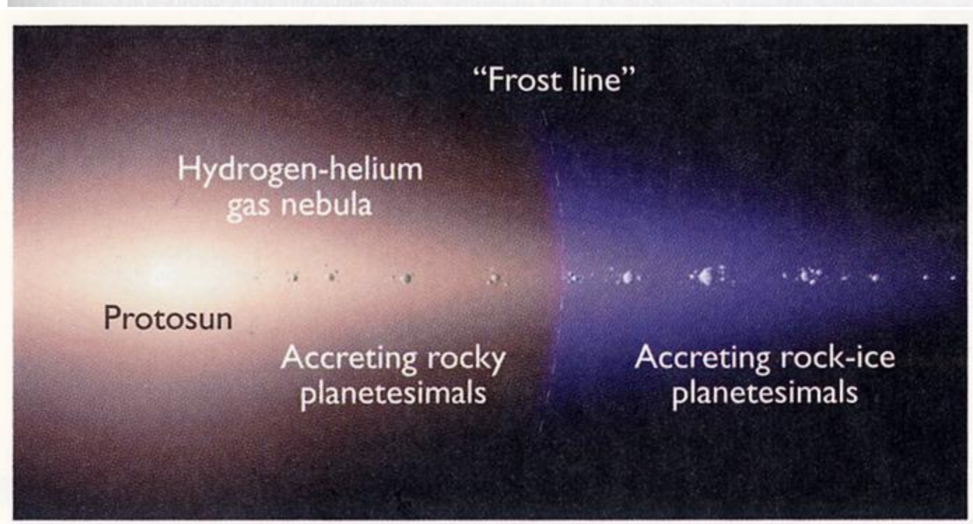
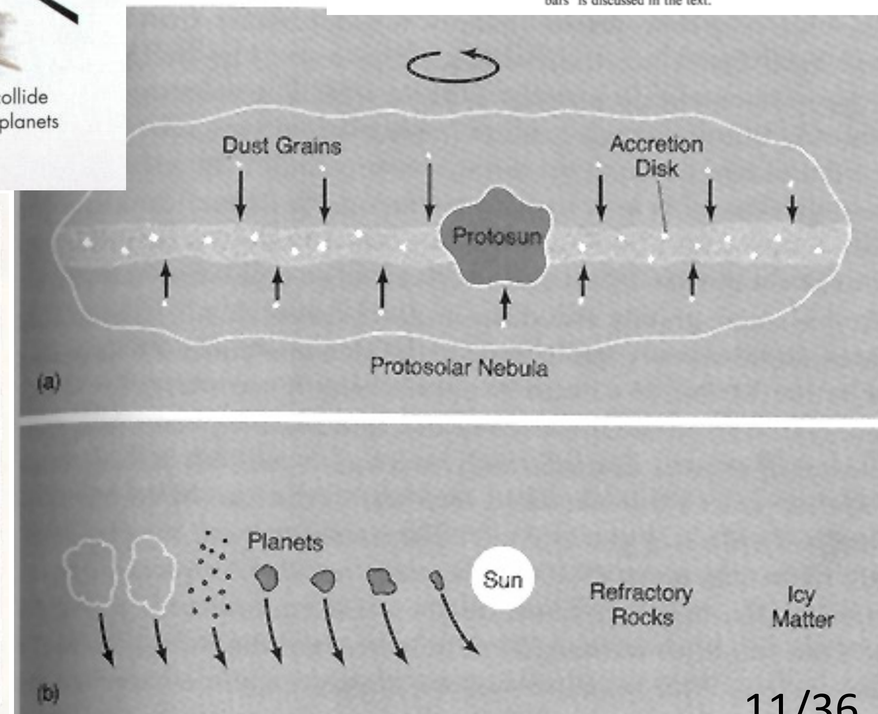
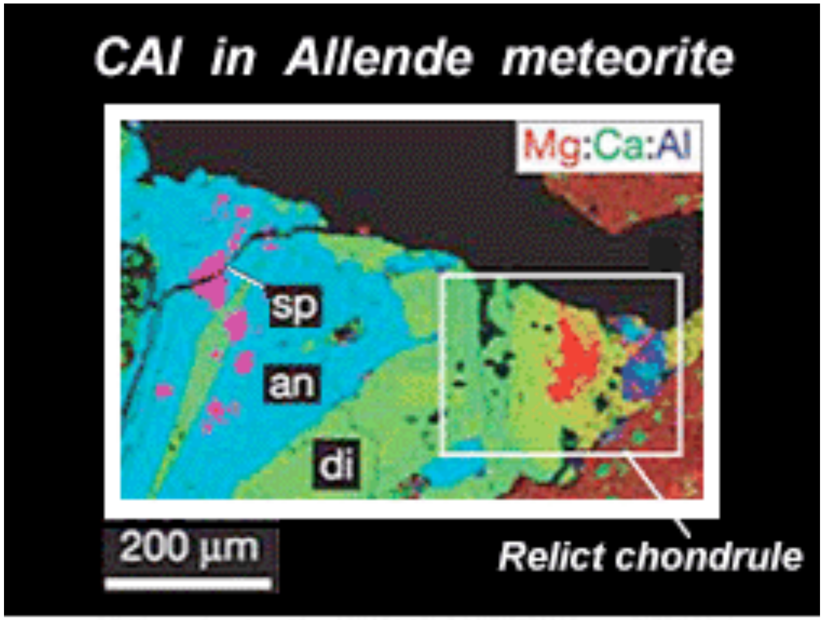


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spread the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'e bars' is discussed in the text.

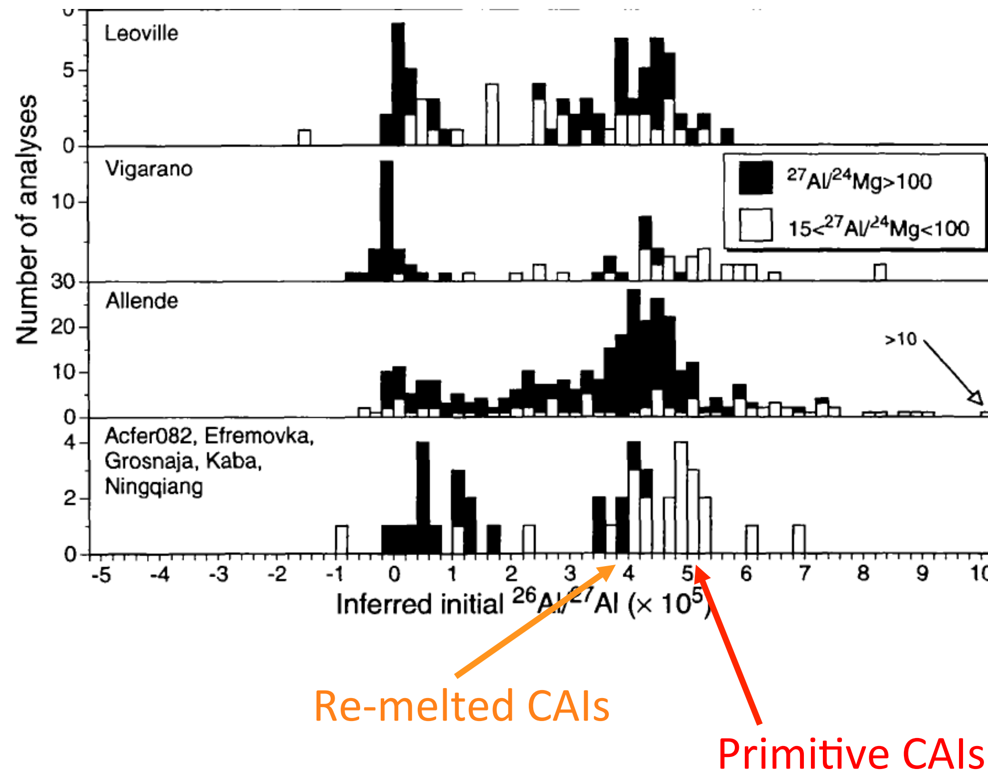




The Formation Time of CAIs



(From Krot, *et al.*, (2005) *Nature*, v. 434, p. 999.)



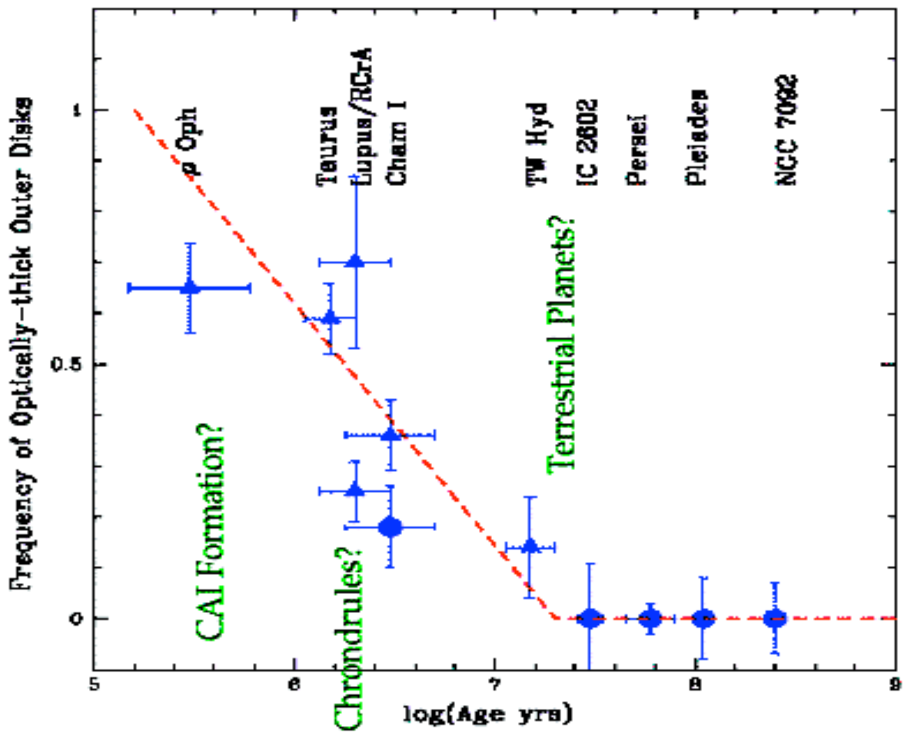
From the spread among CAIs one can derive a relative condensation timescale of t≈20kyr
From Pb-Pb measurements one can derive an absolute formation timescale of t≈4.6Gyr

⇒The first generation of CAIs condensed 4.6 billion years ± 20 thousand years ago
(e.g. Jacobsen et al, 2008, Earth and Planetary Science Letters 272, 353)

Optically-thick Outer Disks (1-10 AU) vs. Age

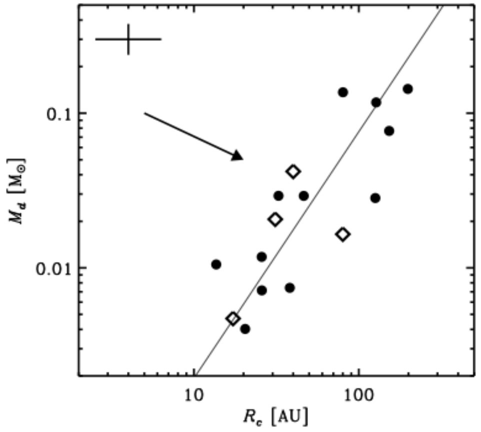
IRAS data (▲).
ISO data (●).

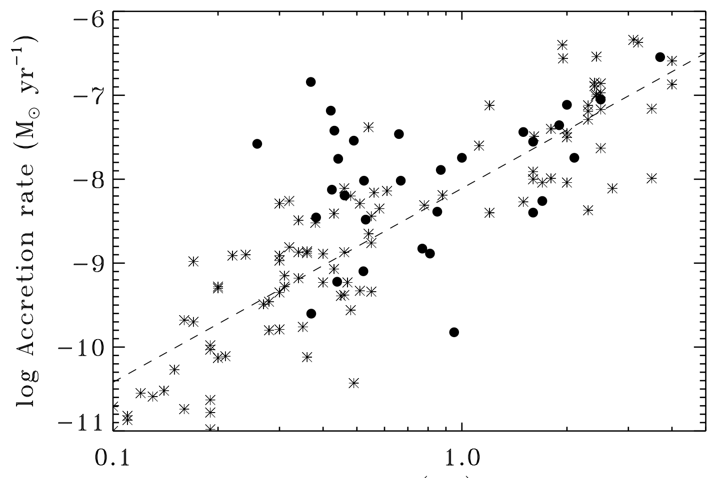
Meyer & Beckwith (2000)



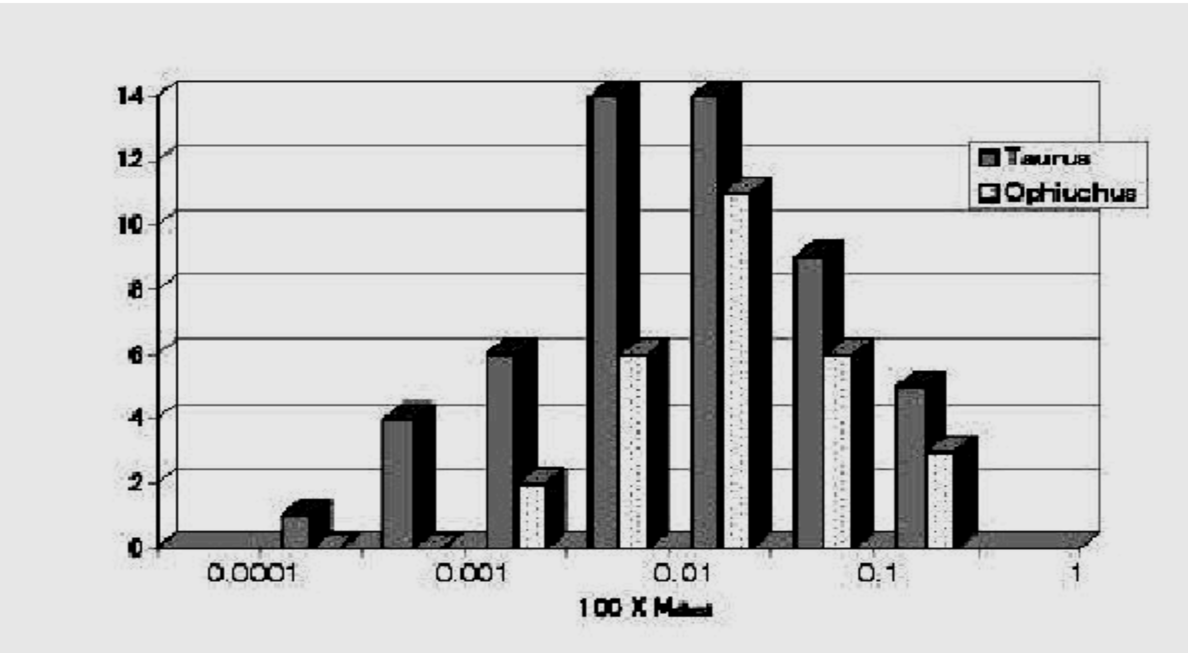
Minimum mass solar nebula

Protostellar disks with gas & dust





Weak mass constraint: Available planet building material

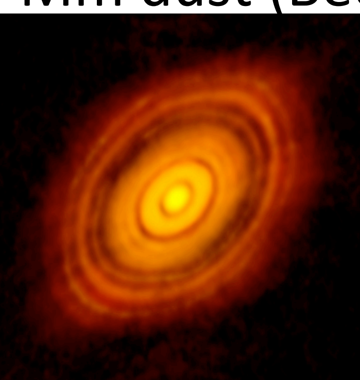


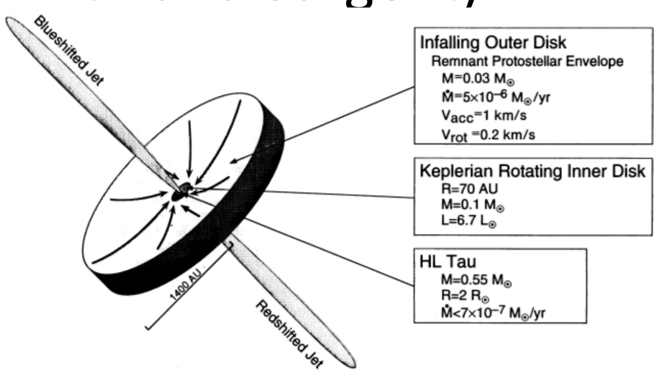
Mm dust (Beckwith and Sargent)

Wilden

TABLE 5
SME MEAN ABUNDANCES FOR PLEIADES STARS

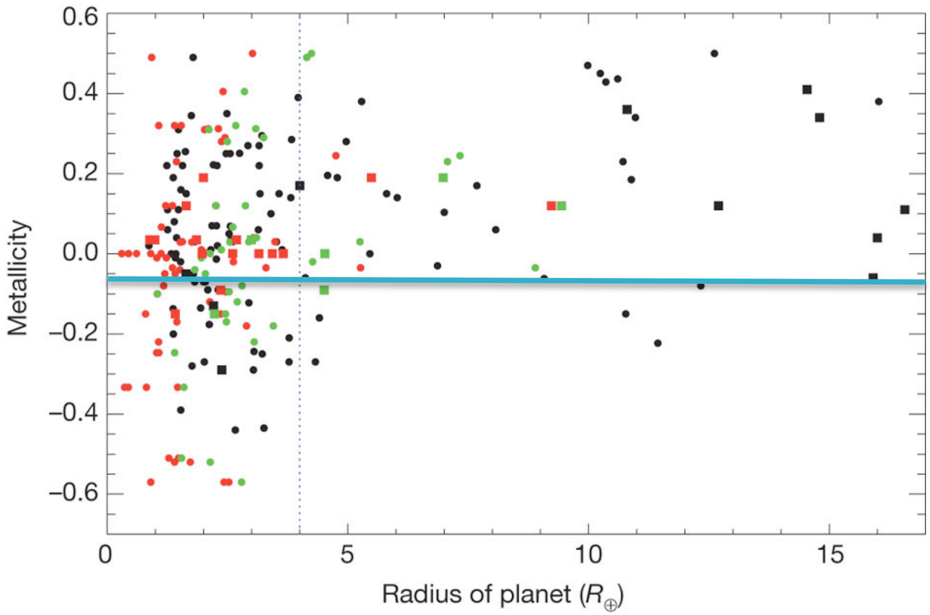
ELEMENT	MEAN log N^a (SME)	log N^b	
		Solar	Meteoritic
Li...	2.51 ± 0.513	1.16	3.31
Na...	6.23 ± 0.042	6.33	6.31
Si...	7.54 ± 0.054	7.55	7.55
Ca...	6.33 ± 0.025	6.36	6.34
Sc...	3.00 ± 0.094	3.10	3.09
Ti...	4.93 ± 0.044	4.99	4.93
V...	4.02 ± 0.038	4.00	4.02
Cr...	5.61 ± 0.037	5.67	5.68
Fe...	7.44 ± 0.021	7.54	7.51
Co...	4.81 ± 0.051	4.92	4.91
Ni...	6.13 ± 0.031	6.25	6.25





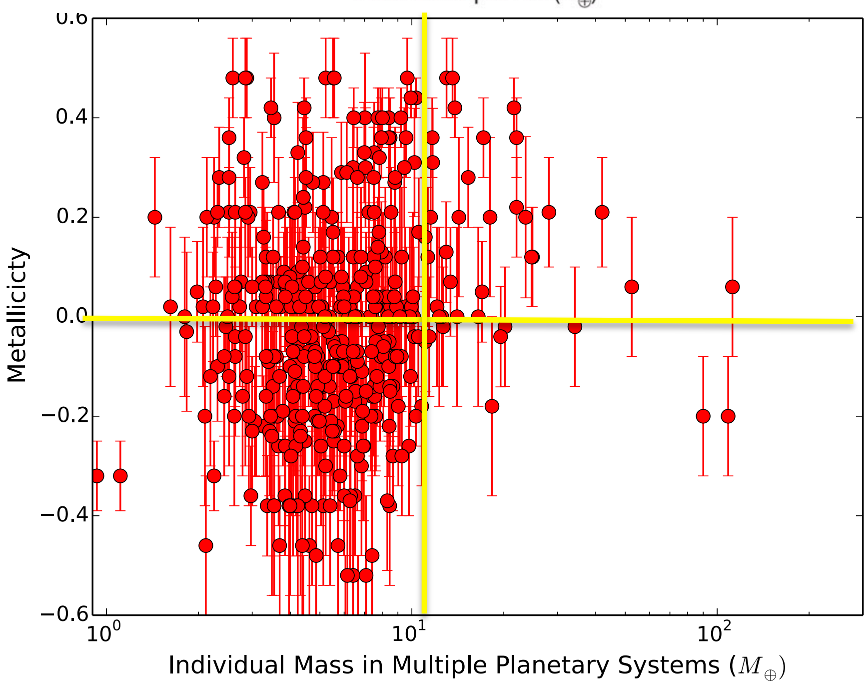
Homogenety $\Delta F_e < 5\%$
G dwarfs in Pleiaides stars (100 Myr old)

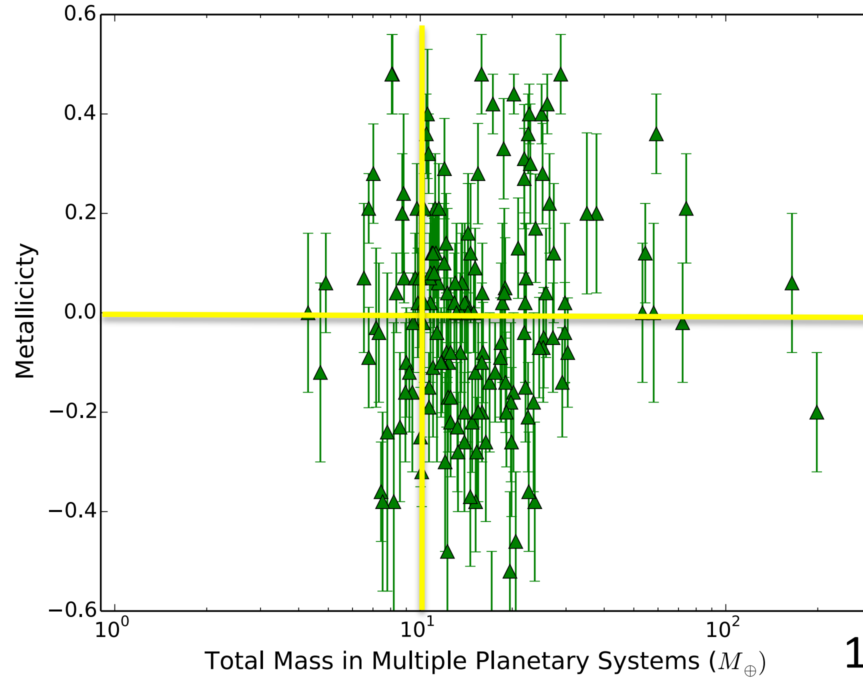
Abundance of super Earths



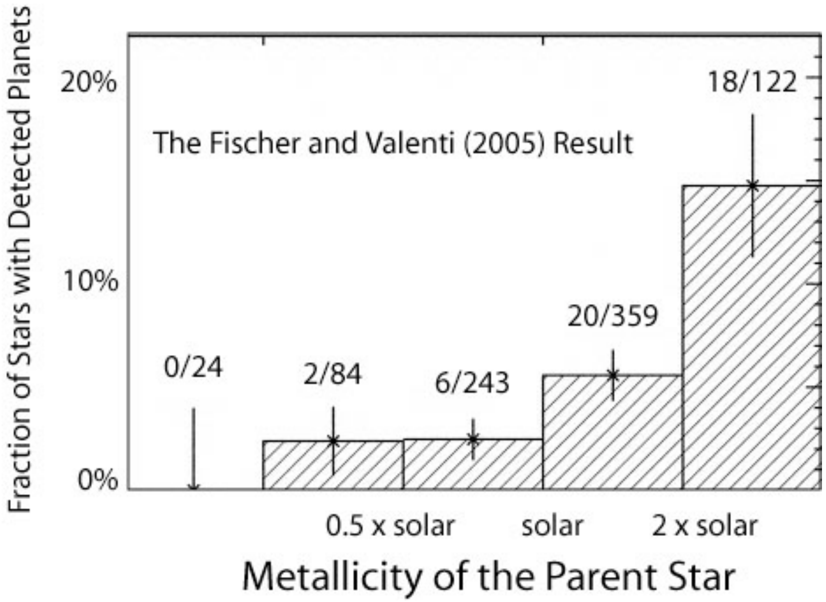
There is **no** shortage of super Earths around metal-poor stars

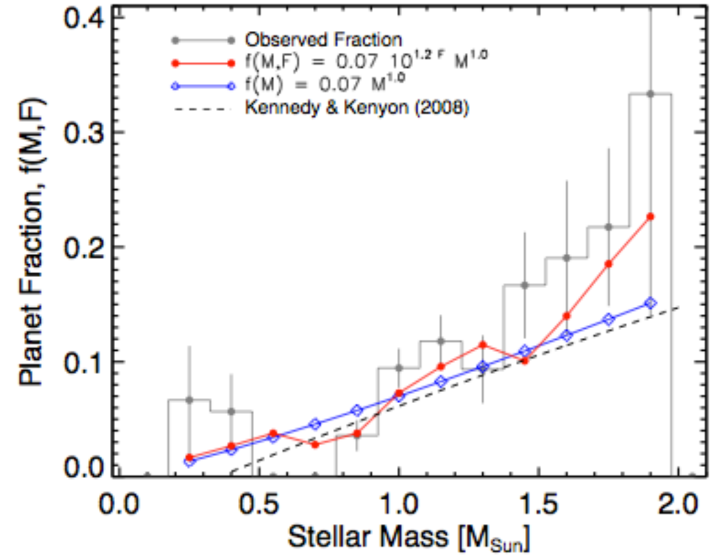
Formation of super Earths Does **not** depend on Z_* or M_*





Planetary mass & size vs stellar metallicity





$$\frac{d^2N}{d\dot{M}_g\, dZ_d} = A_0 \exp-\left[(\log(M_g/M_a)/\Delta_{\dot{M}}\right]^2 \exp-\left[(Z_d - Z_*)/\Delta_Z\right]^2$$

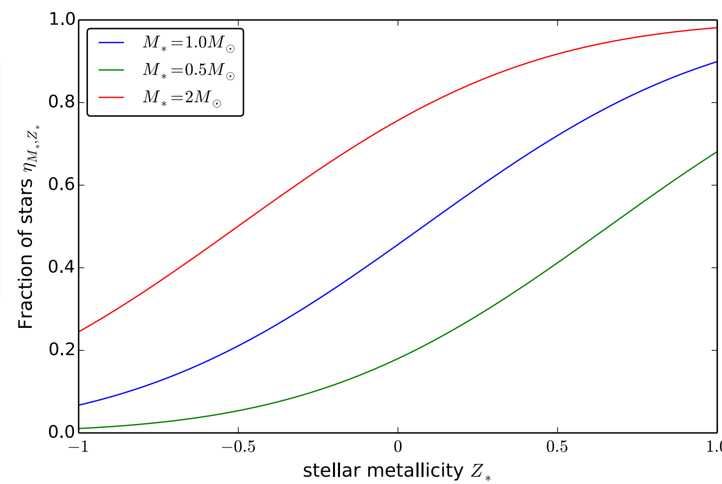
$$\eta_Z(\dot{M}_f, M_*, Z_*) = \frac{1}{2}\int \mathrm{erfc}\left(\frac{\log[\dot{M}_f(M_*, Z_d)/\dot{M}_a(M_*)]}{\Delta_{\dot{M}}}\right) \exp-\left[(Z_d - Z_*)/\Delta_Z\right]^2 dZ_d.$$

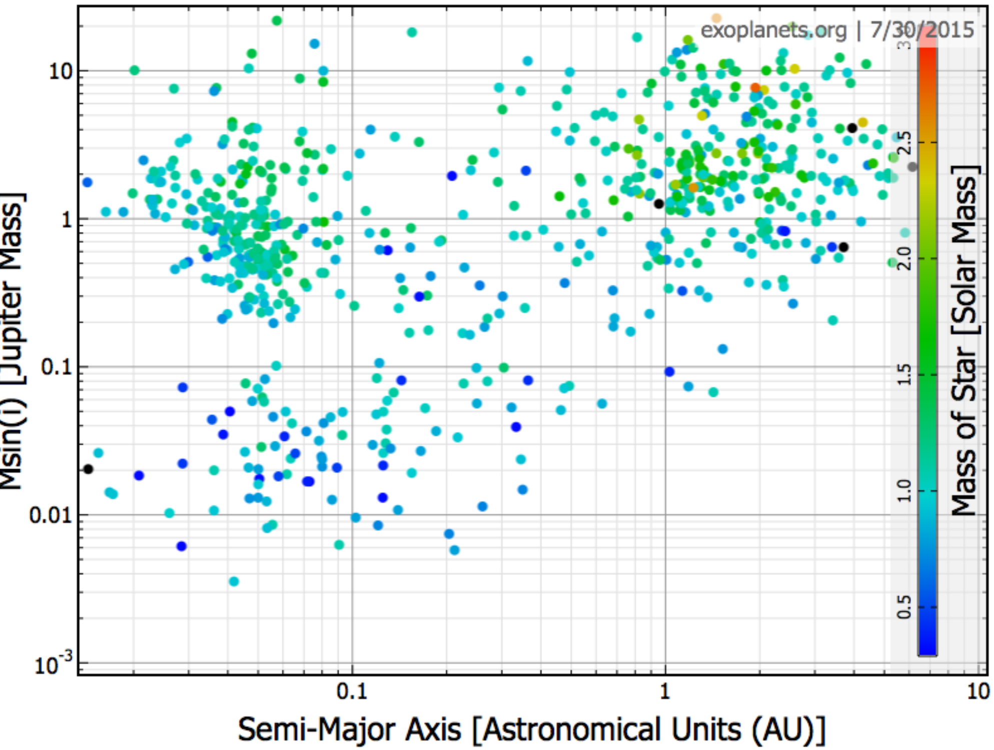
$$r_{\rm trans} \simeq 1.36 \dot{m}_{a8}^{0.72} m_*^{-0.08} \alpha^{-0.36} \kappa_0^{0.36} \mathrm{AU}$$

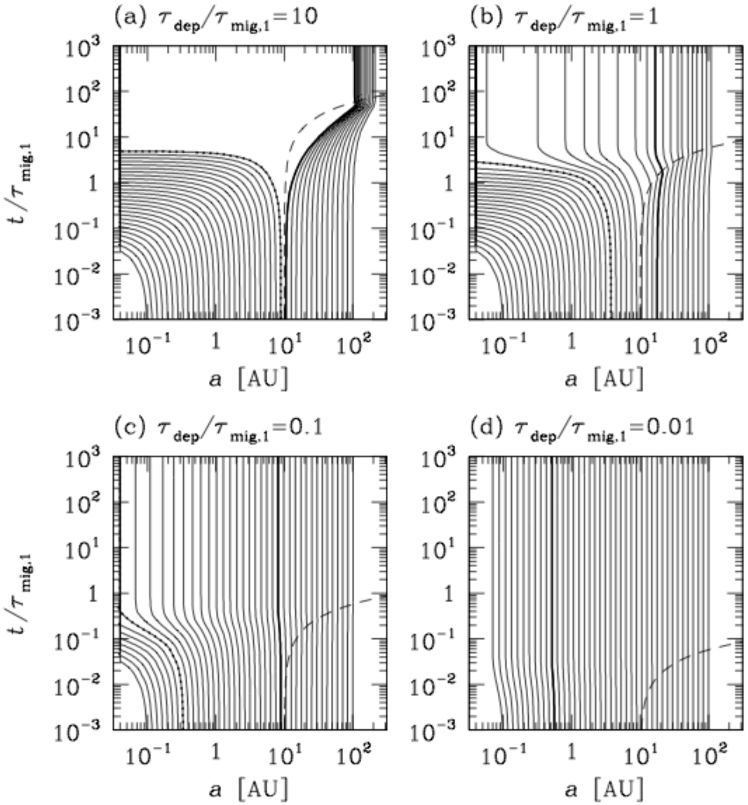
$$M_{\rm opt}(r_{\rm trans}) \simeq 3.6 \dot{m}_{a8}^{0.48} m_*^{1.24} \alpha_3^{0.43} \kappa_0^{0.24} M_\oplus.$$

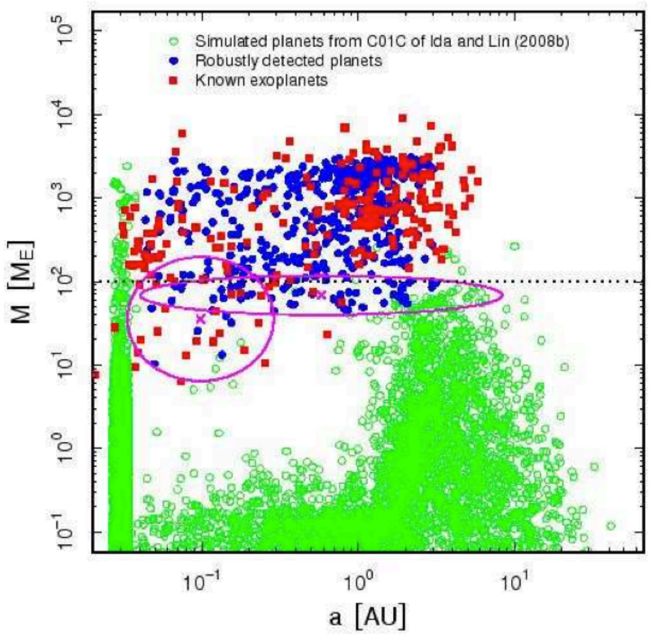
$$\dot{m}_{9\ \rm res} \simeq 6 f_{\rm res}^{0.95} m_*^{0.07} \alpha_3^{0.97} \kappa_0^{-0.026}$$

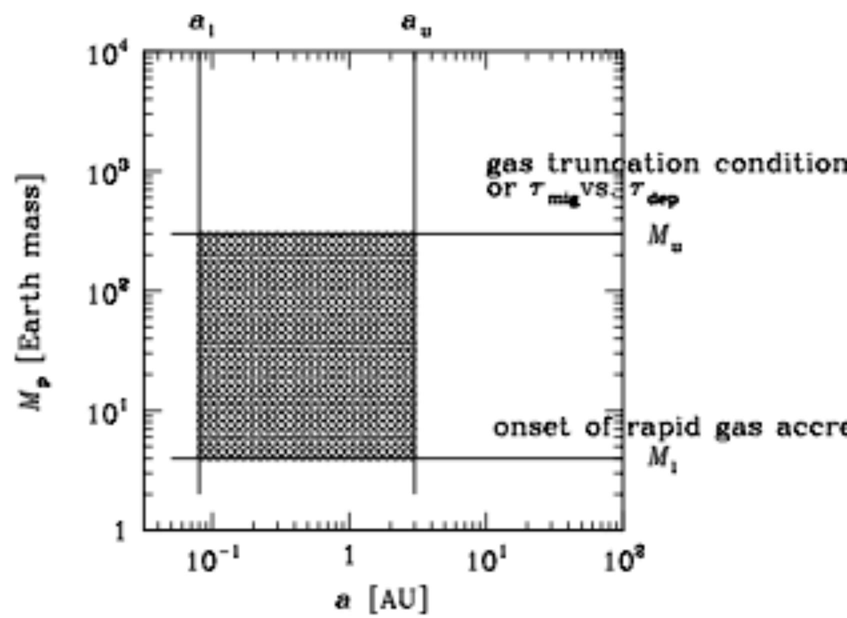
BUT, Z_d is not Z_*



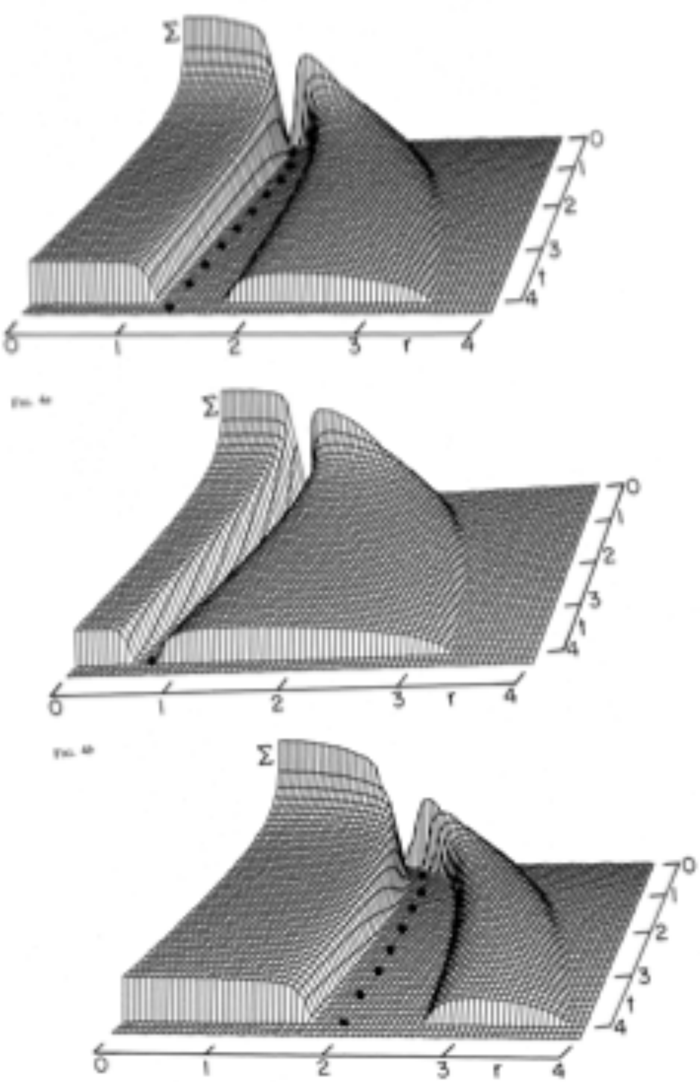

exoplanets.org | 7/30/2015
Msin(i) [Jupiter Mass]
Semi-Major Axis [Astronomical Units (AU)]
Mass of Star [Solar Mass]

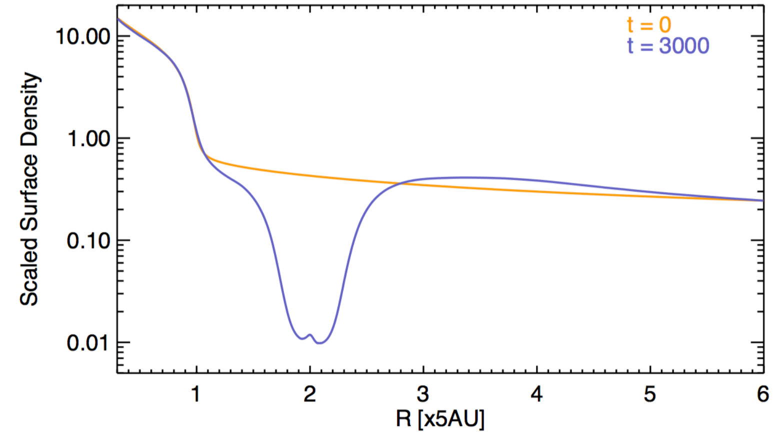

(a) $\tau_{dep}/\tau_{mig,1}=10$
(b) $\tau_{dep}/\tau_{mig,1}=1$
(c) $\tau_{dep}/\tau_{mig,1}=0.1$
(d) $\tau_{dep}/\tau_{mig,1}=0.01$
$t/\tau_{mig,1}$
a [AU]


Simulated planets from C01C of Ida and Lin (2008b)
Robustly detected planets
Known exoplanets
M [M_E]
a [AU]


a_l
a_u
gas truncation condition
or τ_{mig} vs. τ_{dep}
M_u
onset of rapid gas accre
M_l
M_p [Earth mass]
a [AU]

Gas giants' type II migration

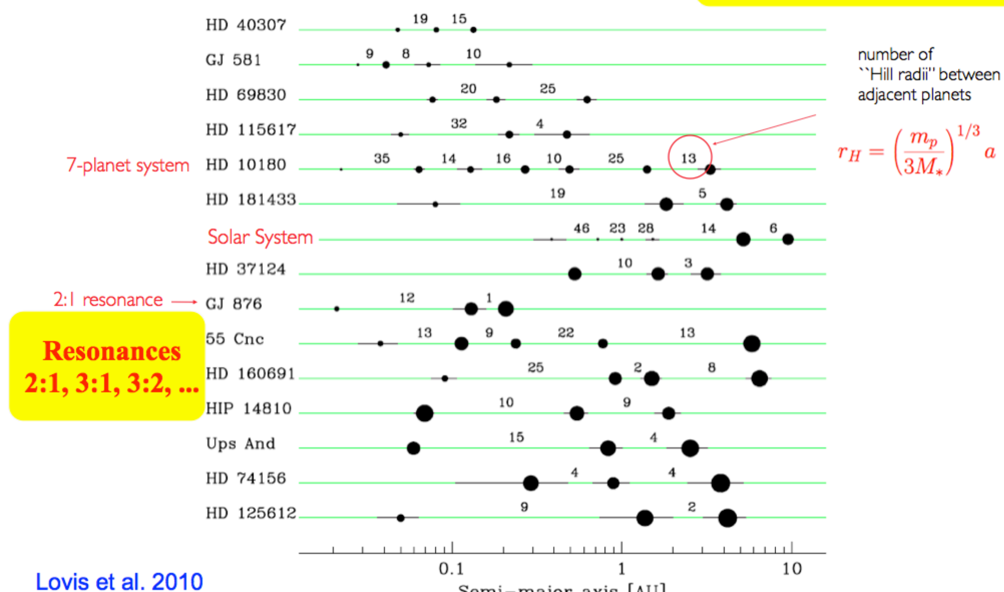




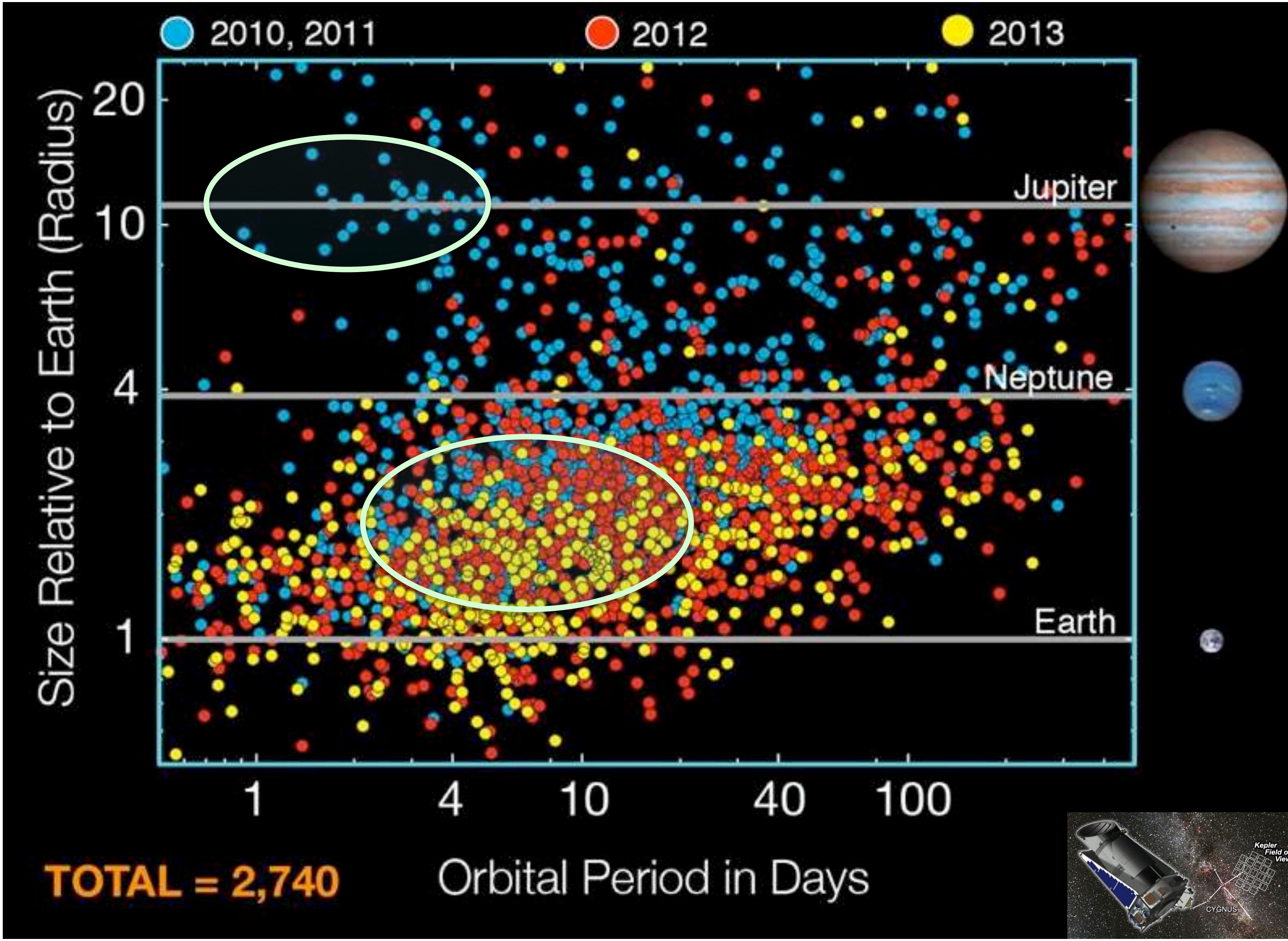
Systems with n>2 planets

multi-planet systems: many are almost optimally ``packed''

Also a constraint for planet formation models!

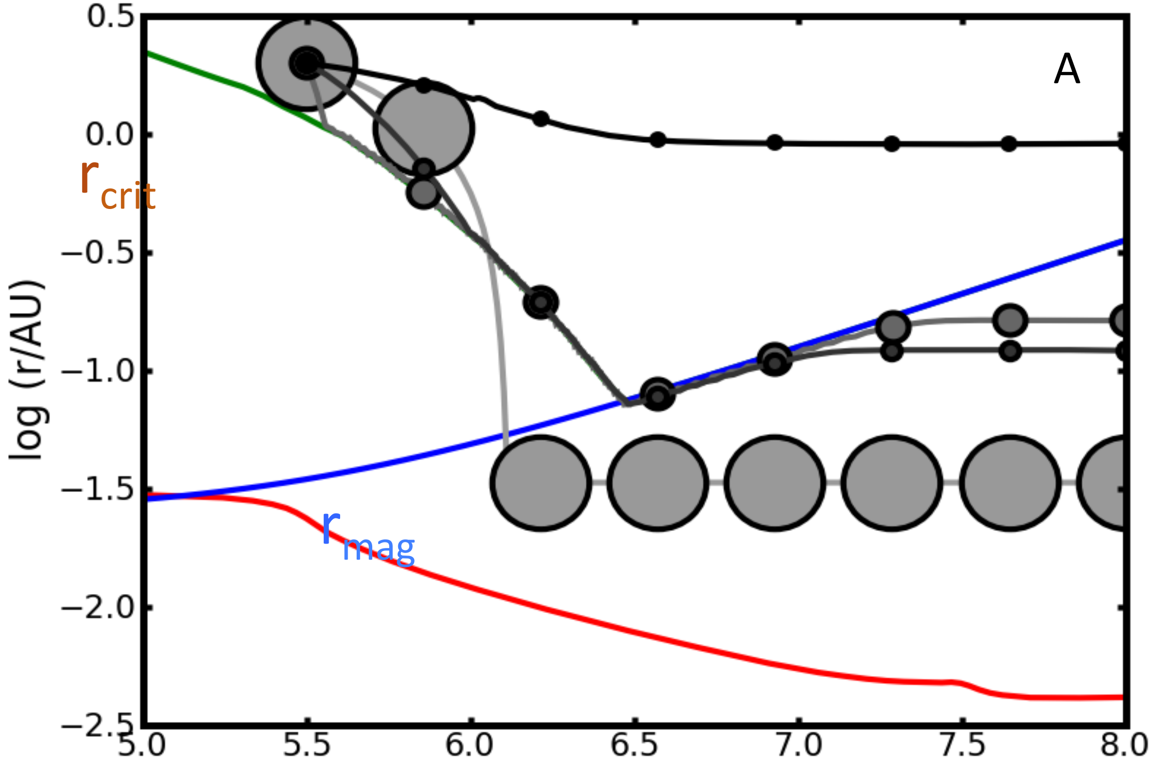


Lovis et al. 2010



2010, 2011
2012
2013
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
40
100
TOTAL = 2,740
Orbital Period in Days
Kepler Field of View
CYGNUS

- How to differentiate type I and II migration?



Sub/warm Earths

½ Earth

Neptunes

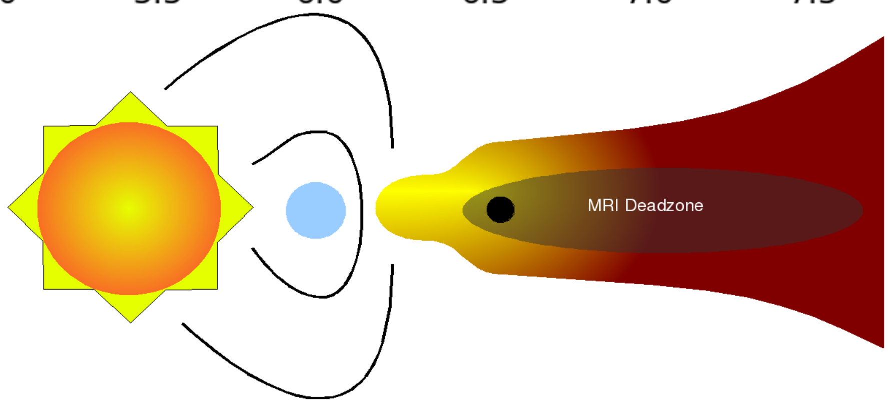
SuperEarths

5 Earth

Gas giants

2 Earth

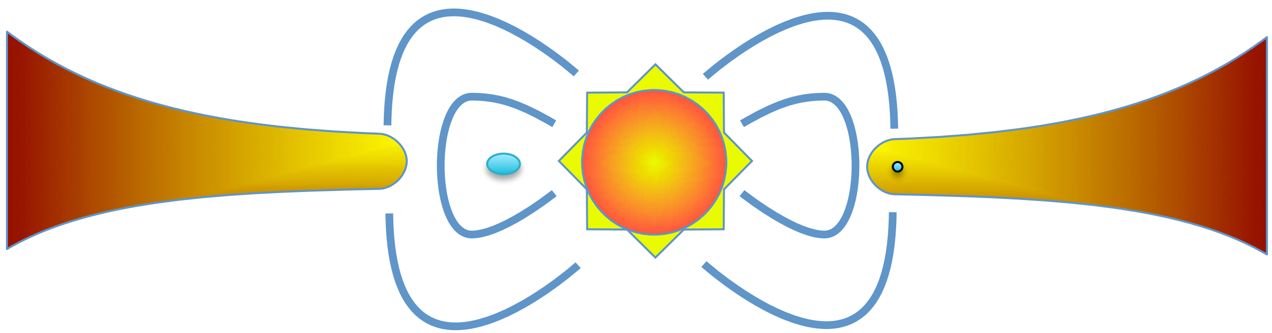
Jupiter



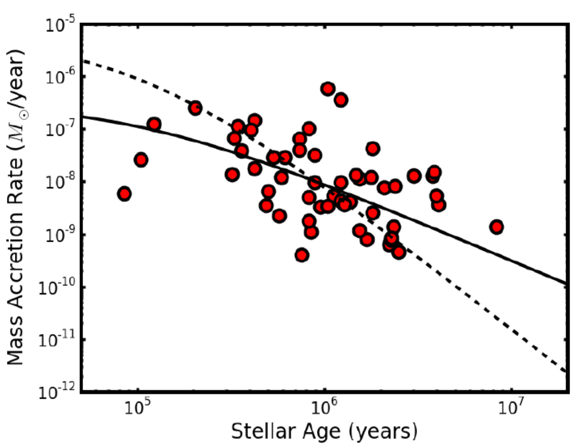
Hot Jupiters park Closer than Super Earths

Kretke

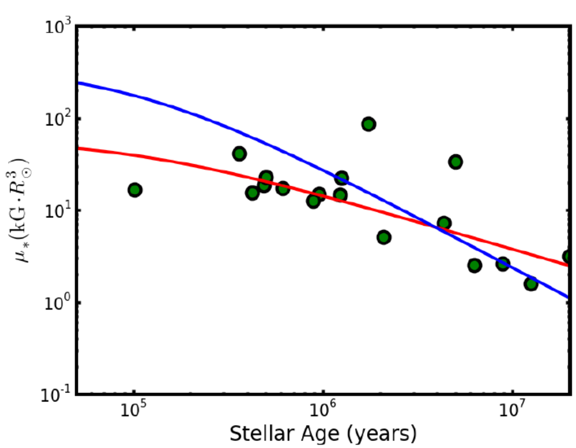
Stalling of planets inside & at the magnetospheric truncation radius



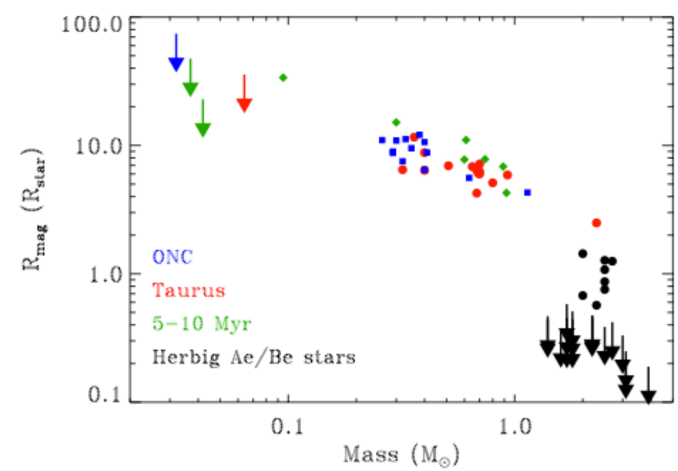
$$r_{\mathrm{mag}} \propto \mu_*^{4/7} \dot{M}^{-2/7}$$



Mass Accretion Rate



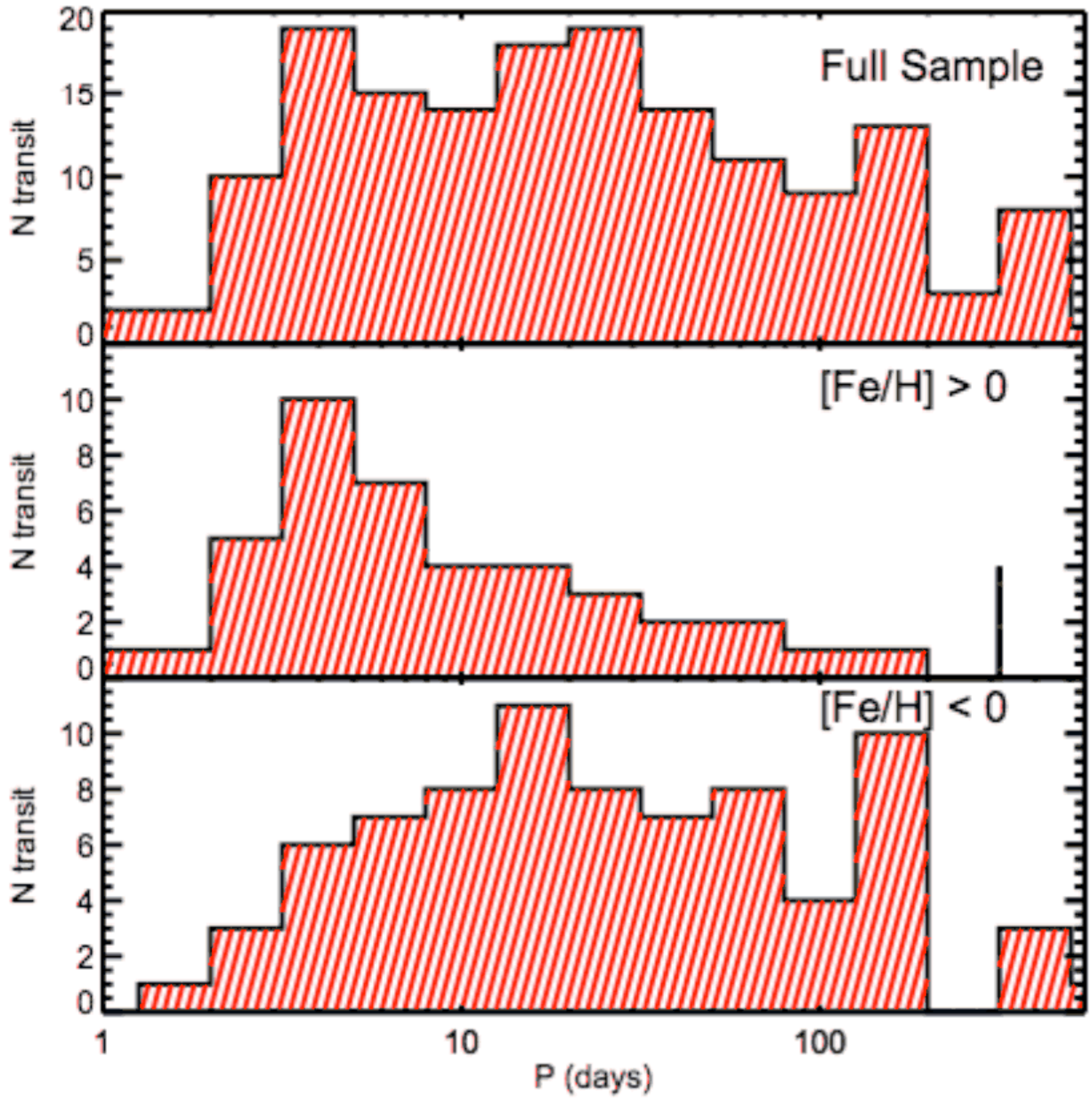
Stellar Dipole Moment

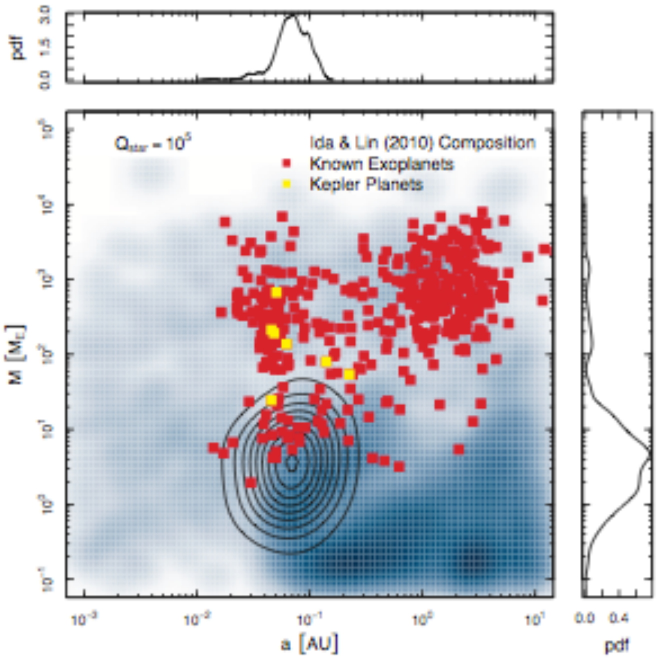


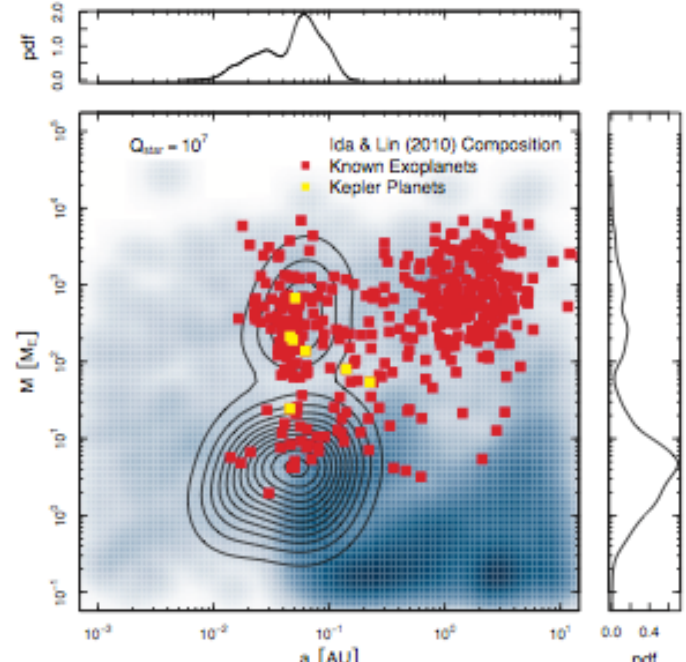
Magnetosphere radius

Herczeg

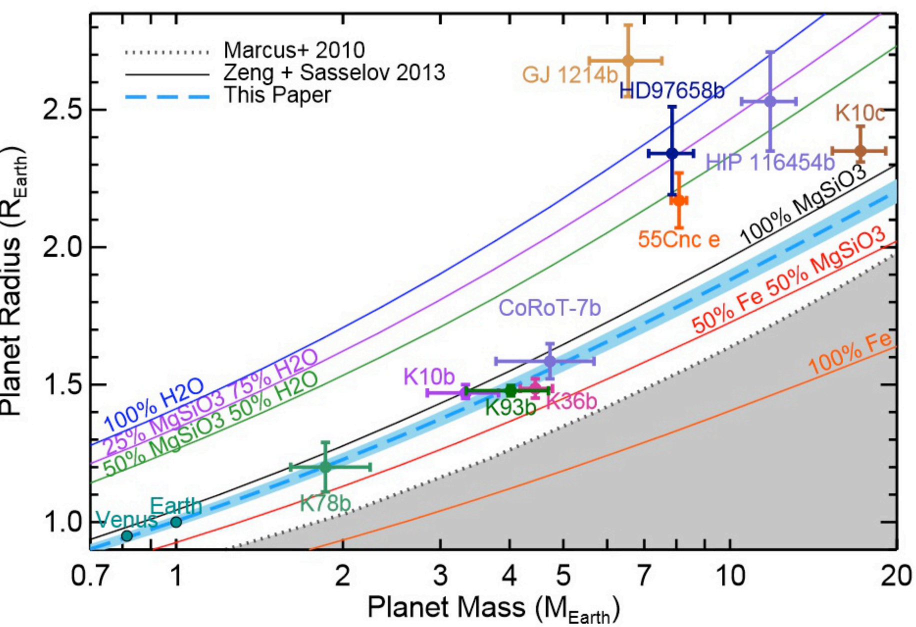
Period distribution of hot Jupiters: Dependence on stellar metallicity

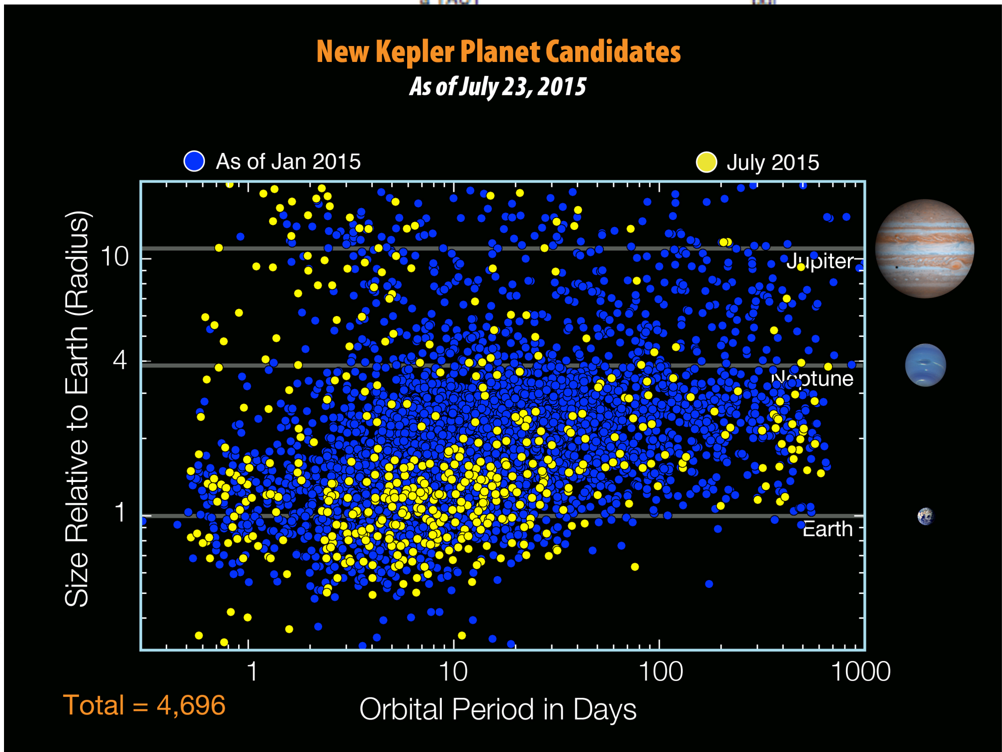



Ida & Lin (2010) Composition
Known Exoplanets
Kepler Planets
pdf
M [M_E]
a [AU]


Ida & Lin (2010) Composition
Known Exoplanets
Kepler Planets
pdf
M [M_E]
a [AU]

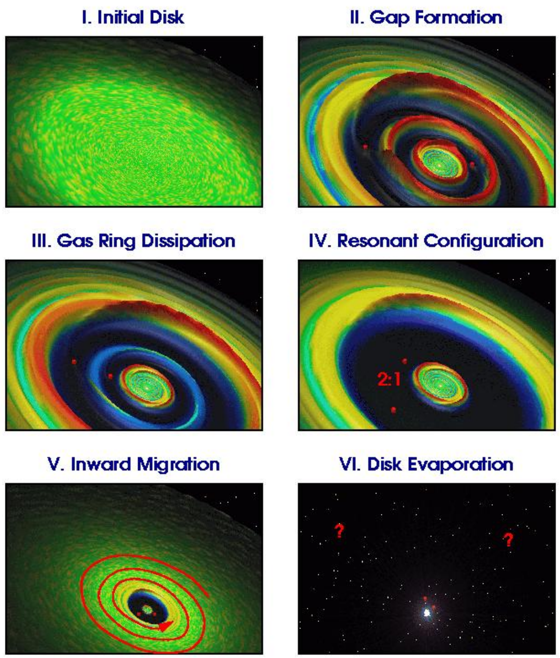
Schlaufman


Marcus+ 2010
Zeng + Sasselov 2013
This Paper
GJ 1214b
HD97658b
K10c
HIP 116454b
55Cnc e
100% MgSiO3
50% Fe 50% MgSiO3
100% Fe
CoRoT-7b
K10b
K93b
K36b
100% H2O
25% MgSiO3 75% H2O
50% MgSiO3 50% H2O
K78b
Venus
Earth
Planet Radius (R_Earth)
Planet Mass (M_Earth)

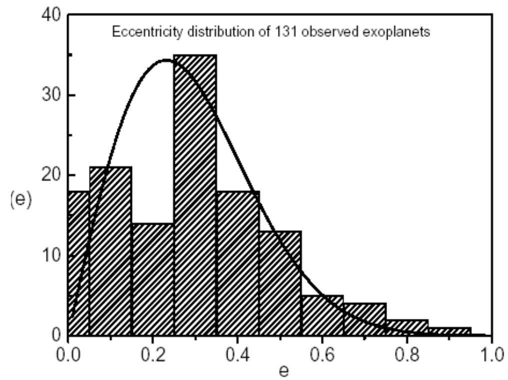

New Kepler Planet Candidates
As of July 23, 2015
As of Jan 2015
July 2015
Jupiter
Neptune
Earth
Size Relative to Earth (Radius)
Orbital Period in Days
Total = 4,696

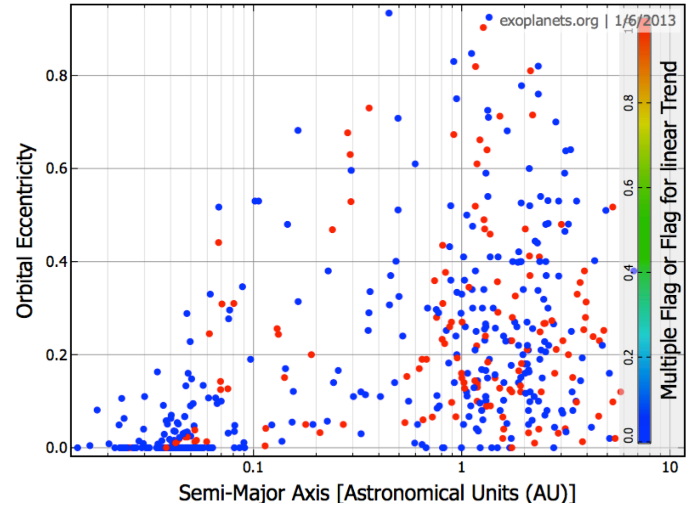
Grand design barrier: dynamical instability

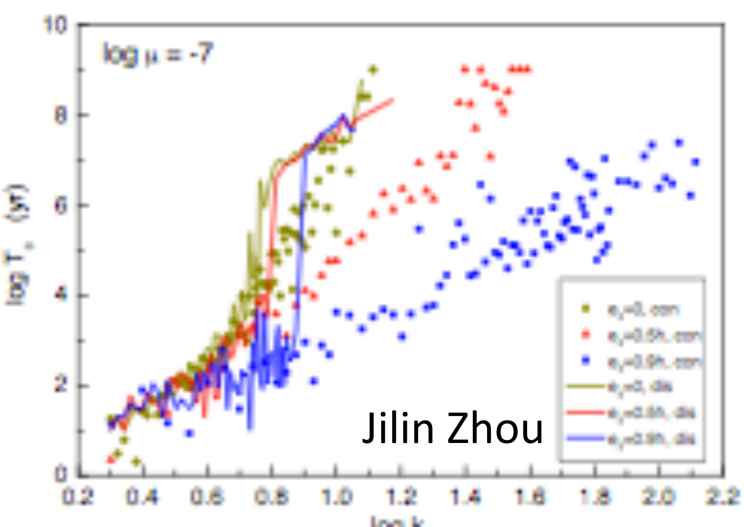
- How did gas giants acquire their eccentricity?

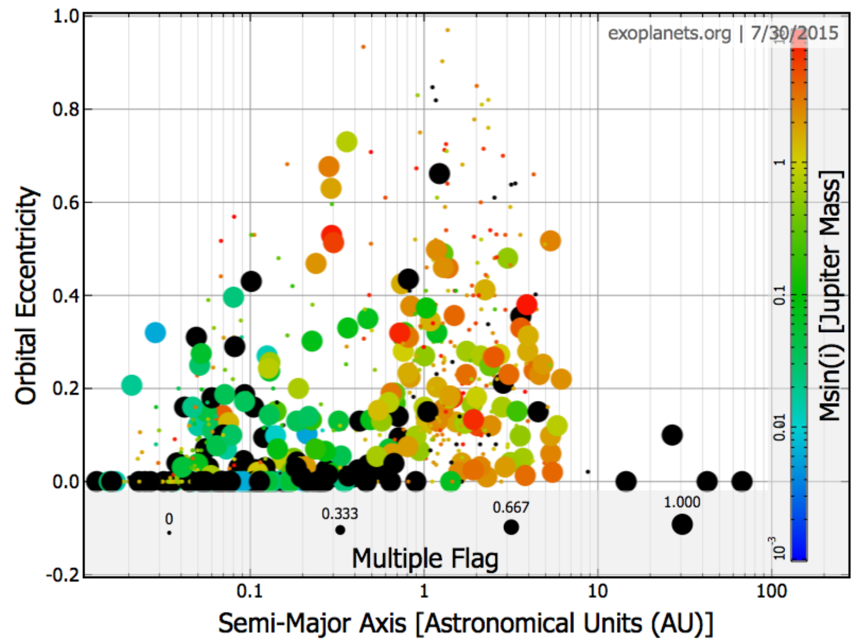


Bryden

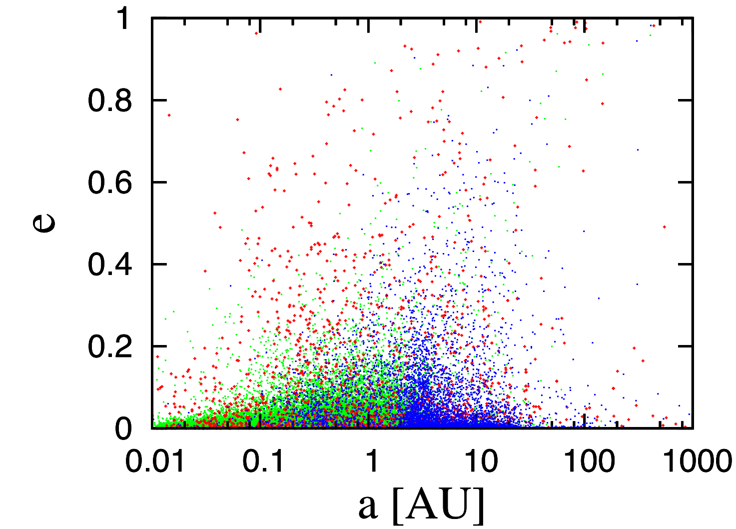


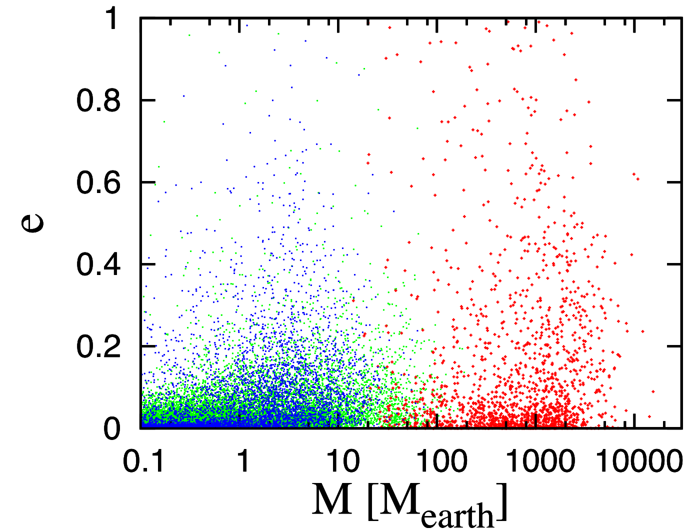


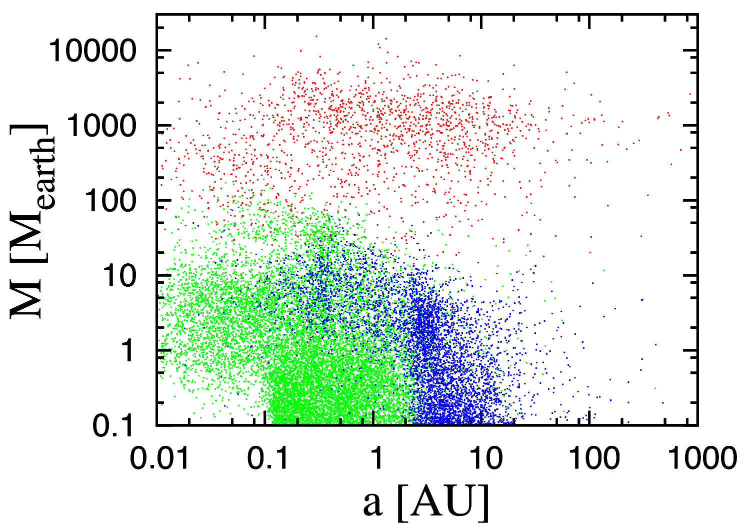




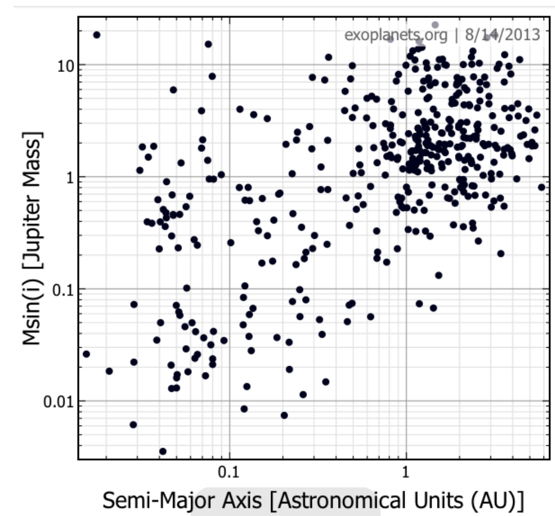
Updated version of population synthesis models





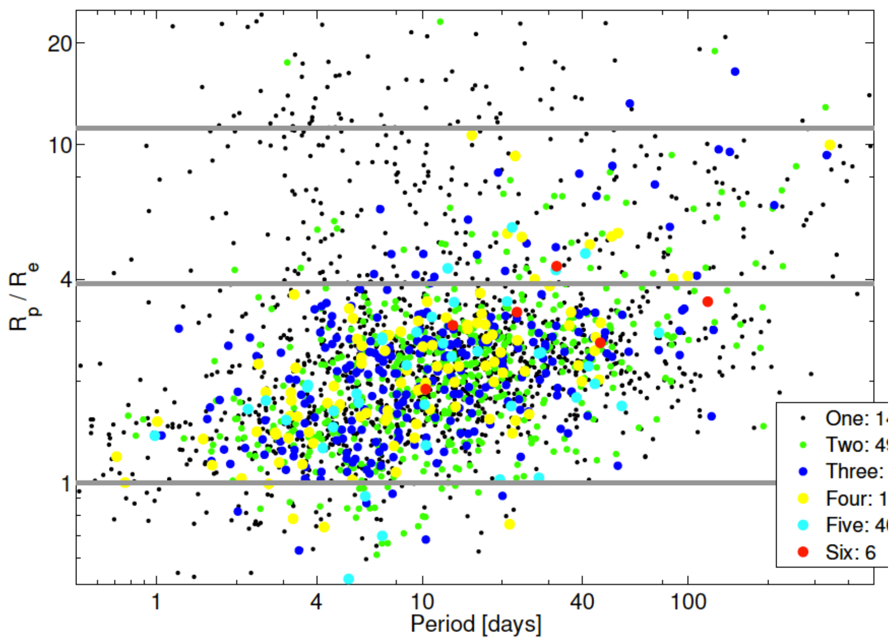


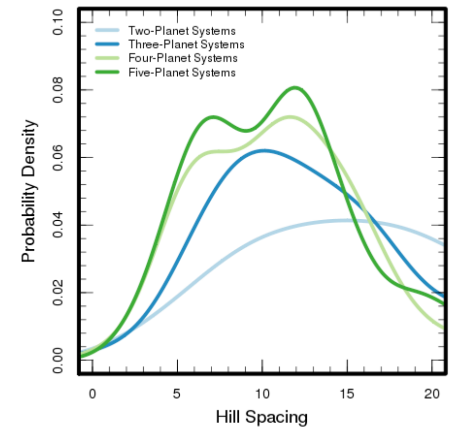
Ida

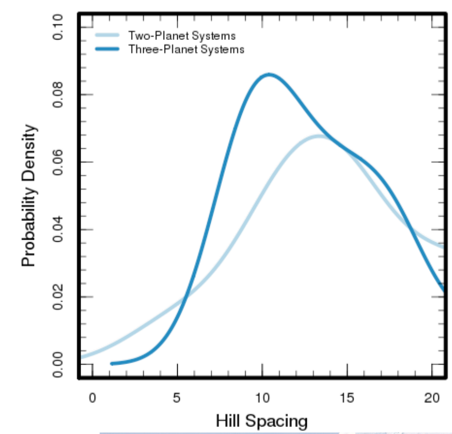


New Candidate Catalog (Batalha et al. 2012)

What can we learn from Multiple systems !!!



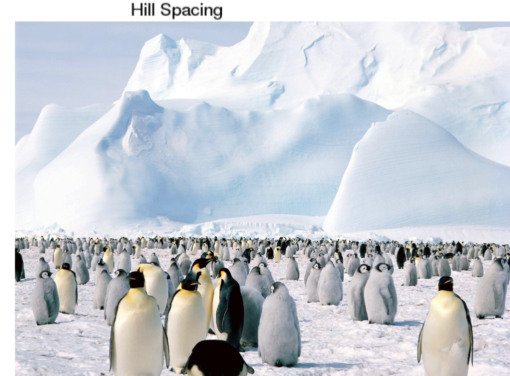




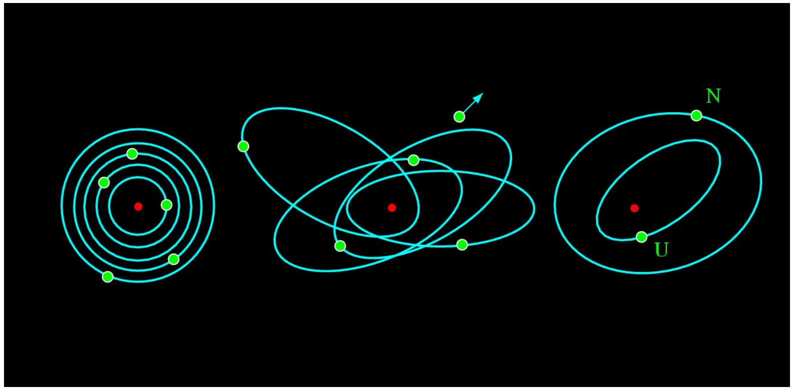
How compact can multiple systems be?

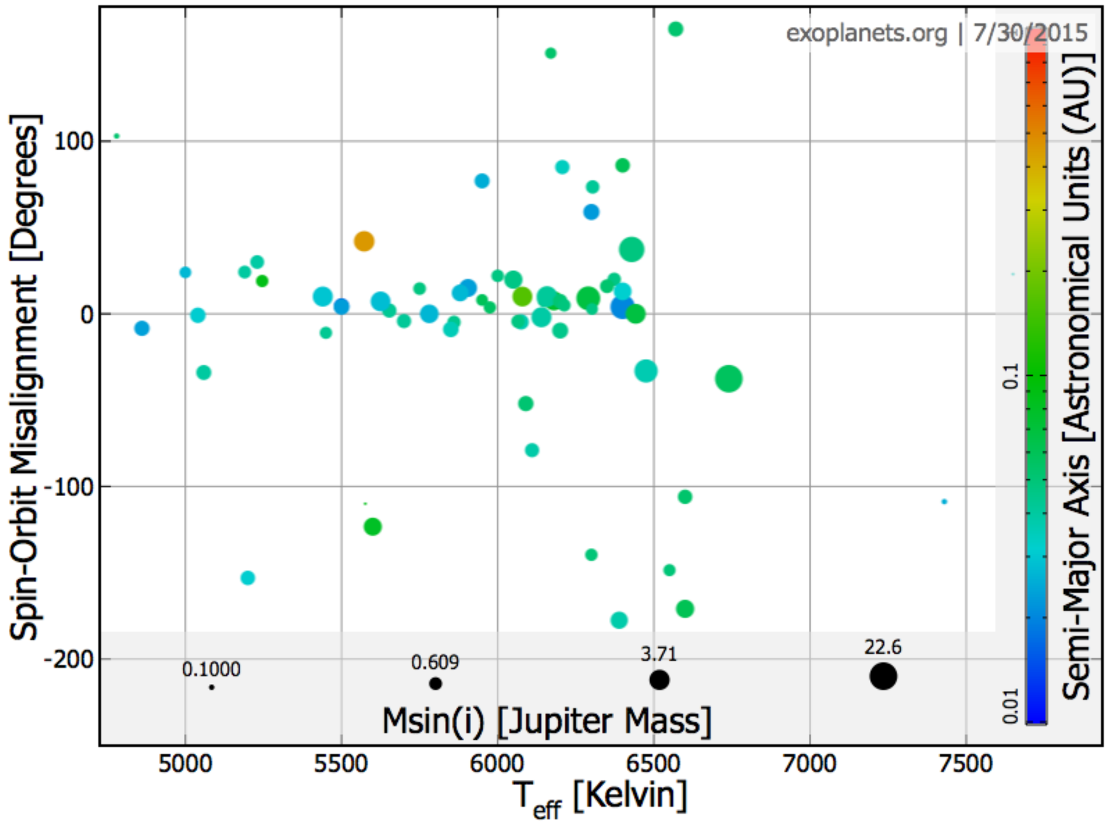
Stability and coplanarity

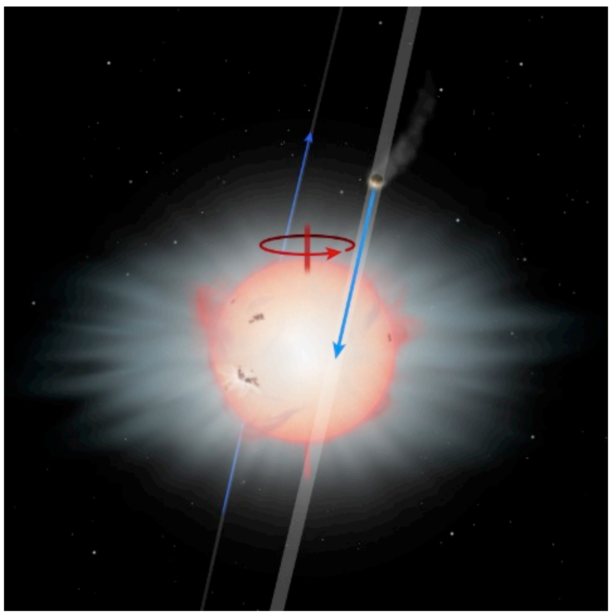
Kevin Schlaufman
Xiaojia Zheng

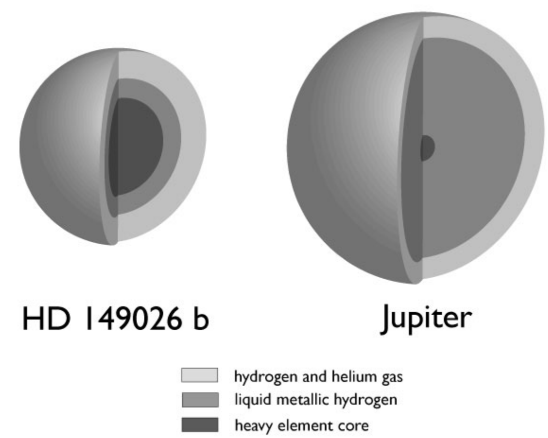


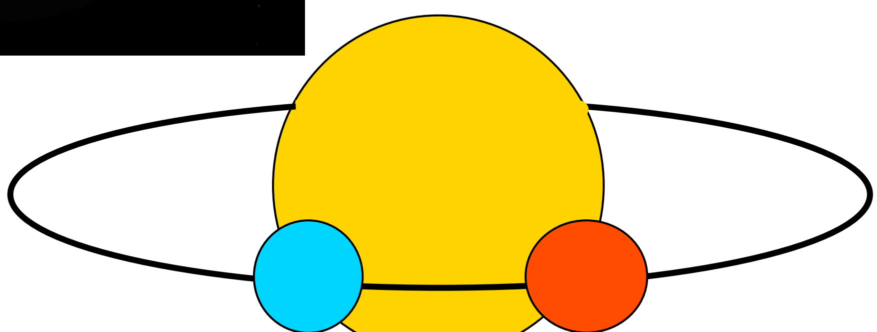
RM effect and challenge to migration

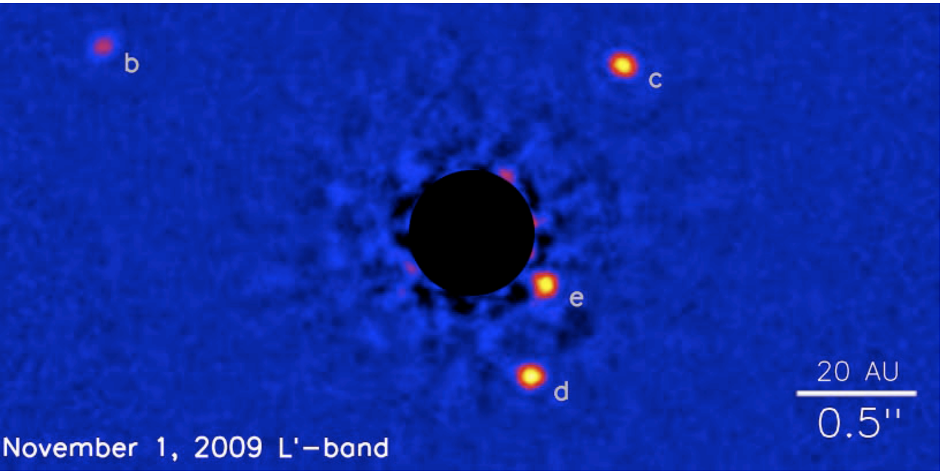


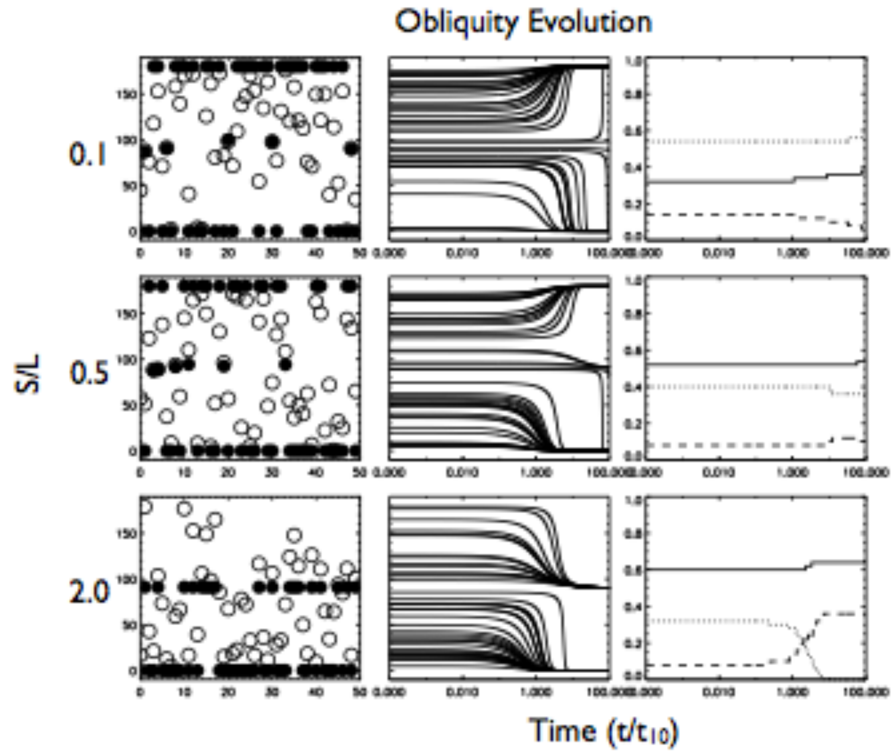


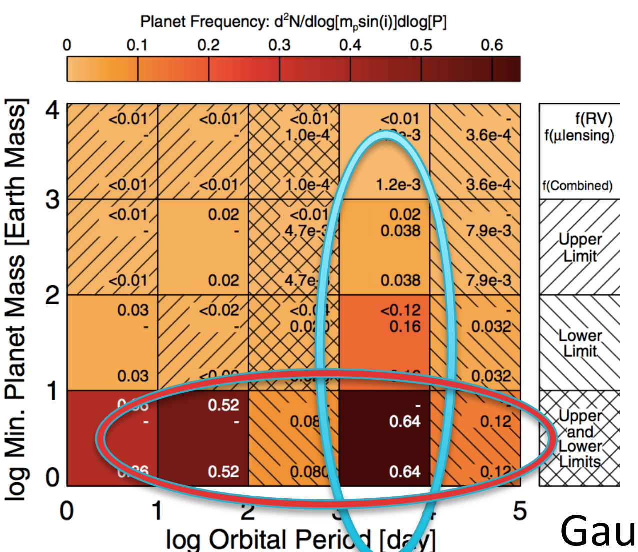




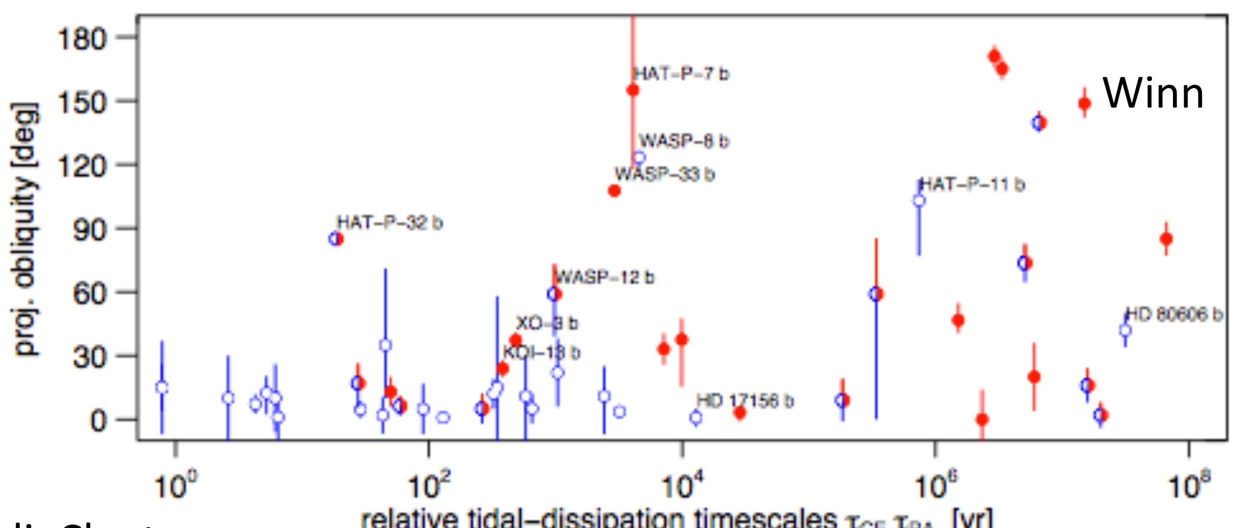




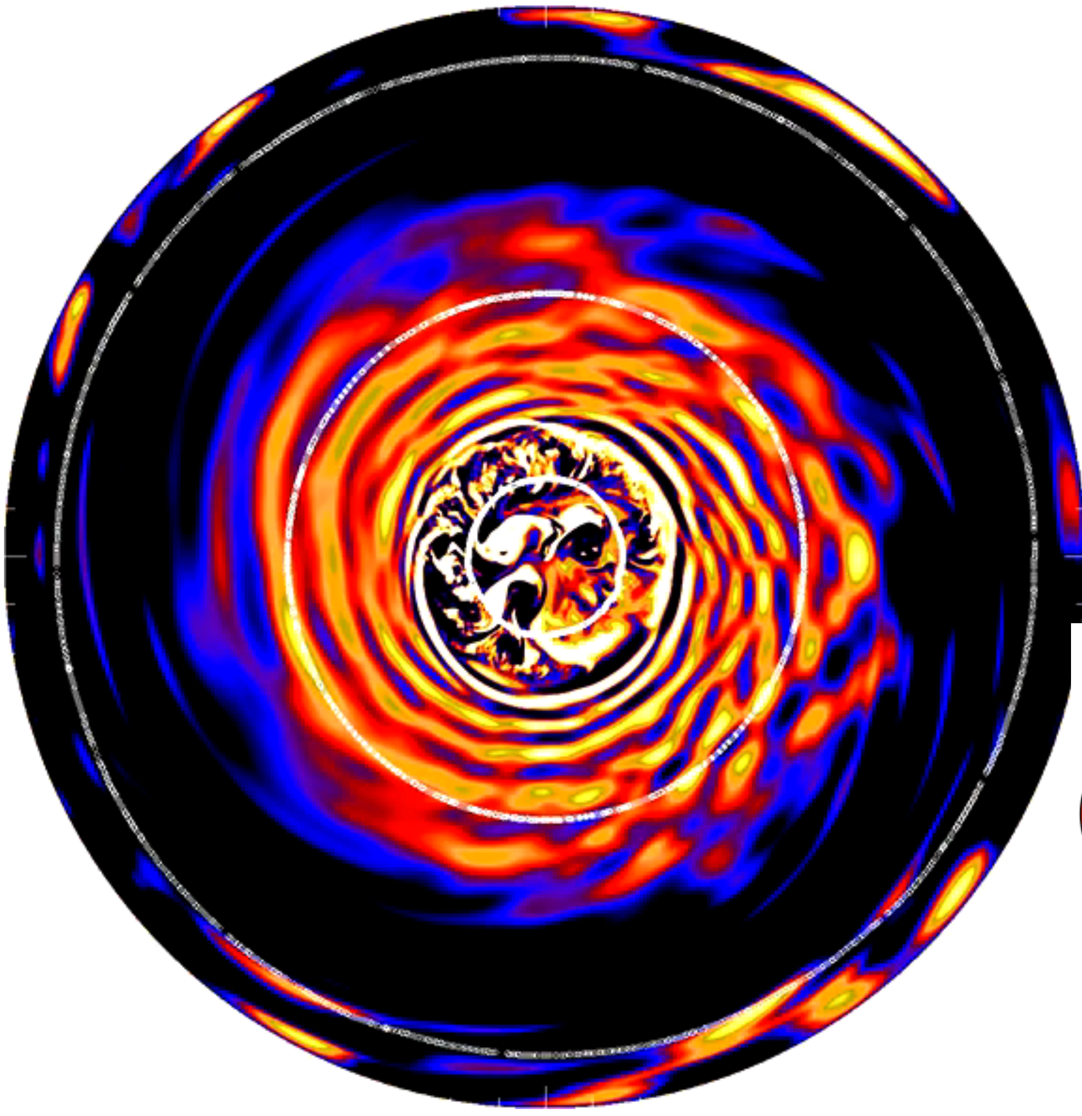


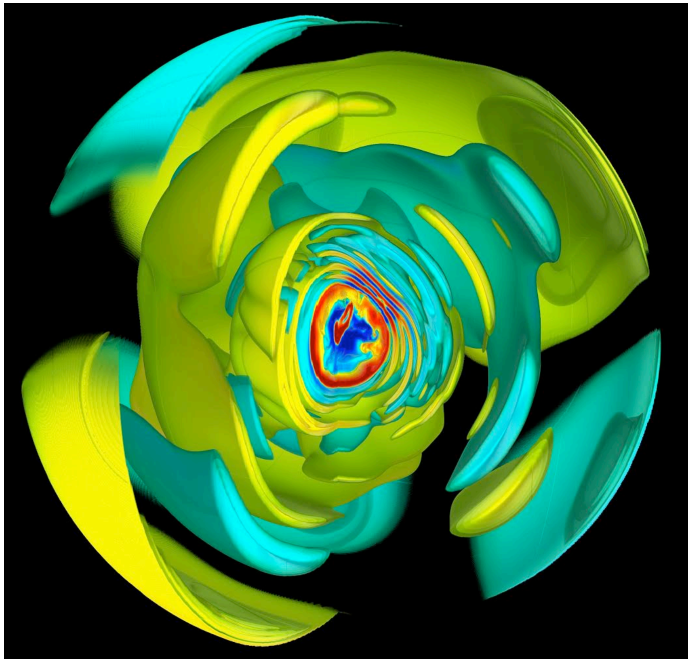


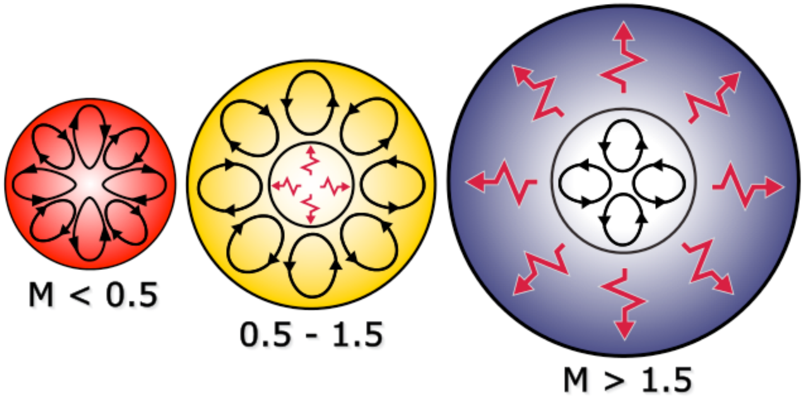
Gaudi, Clanton



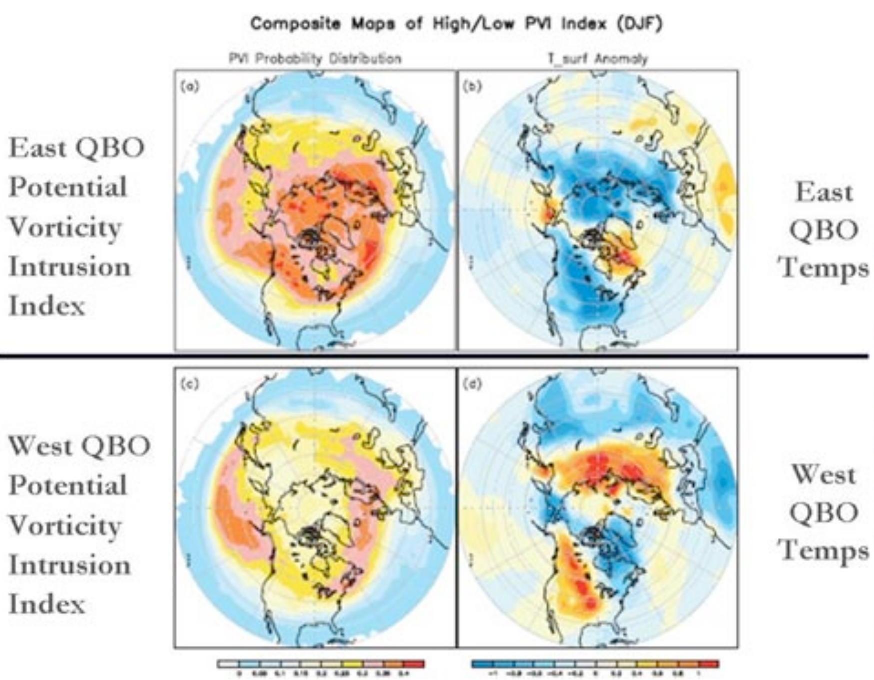
Gravity waves in intermediate-mass stars

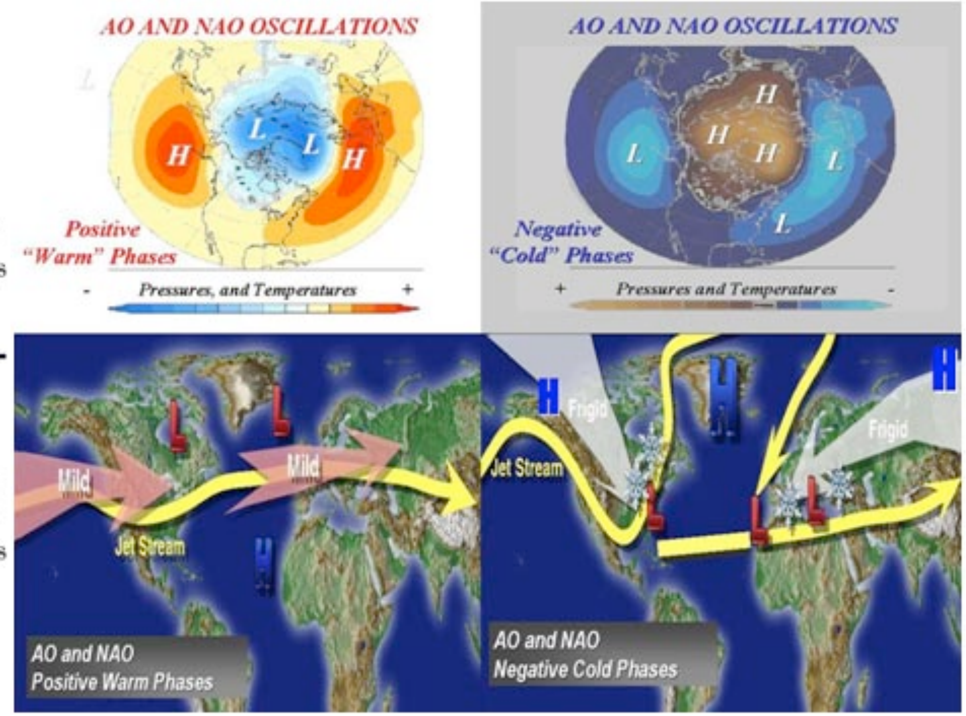


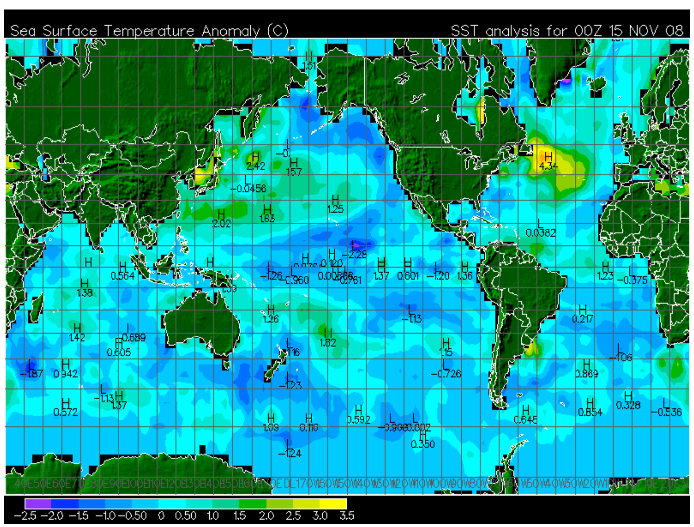


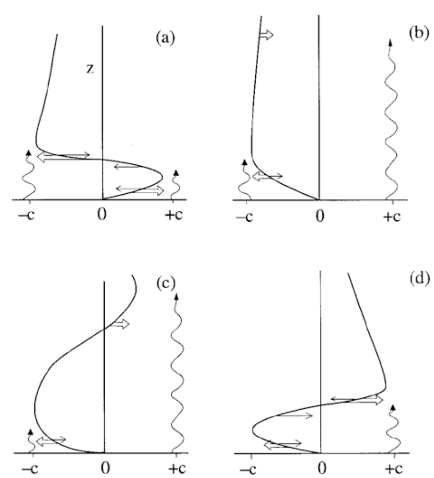


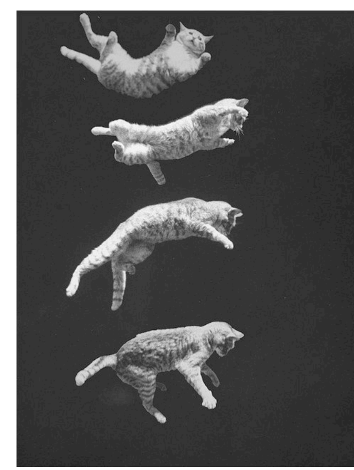
Alternative model: internal gravity wave









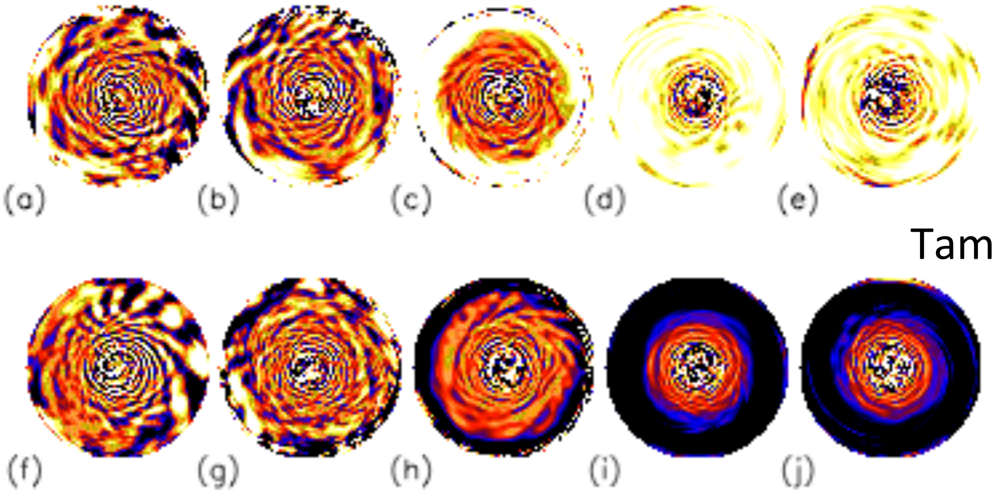


29/36

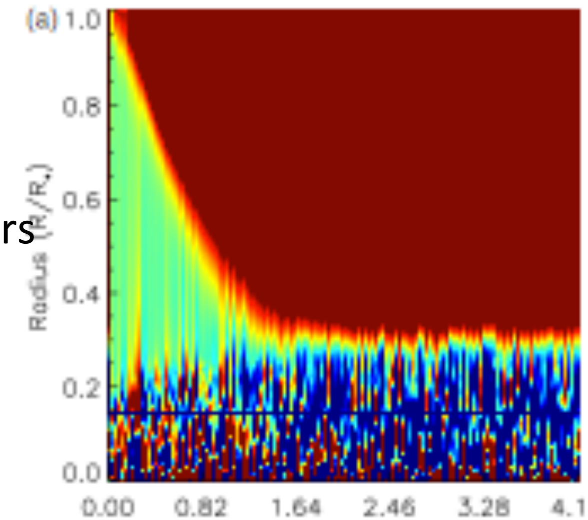
Tami Rogers

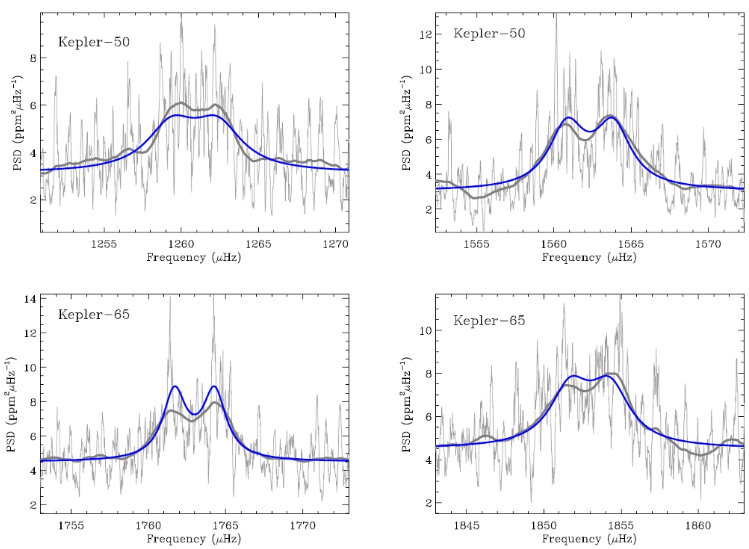
Gas giants: some key issues

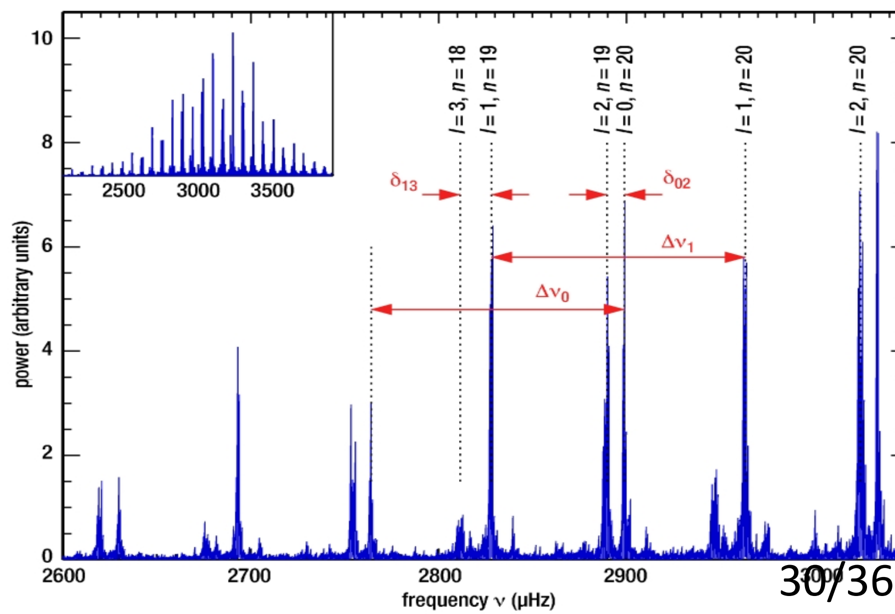
- Is there evidence for internal differential rotation ?



Tami Rogers

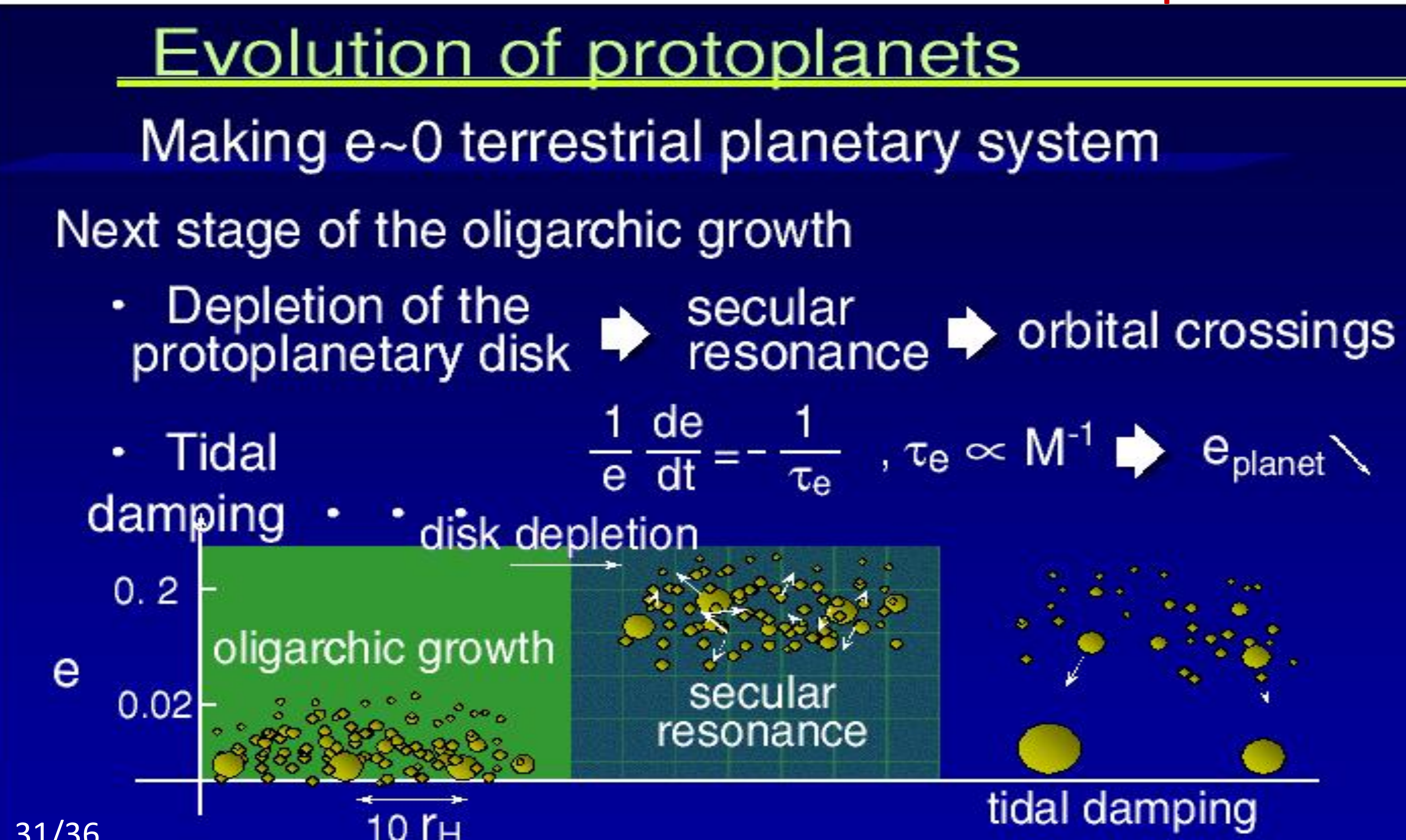




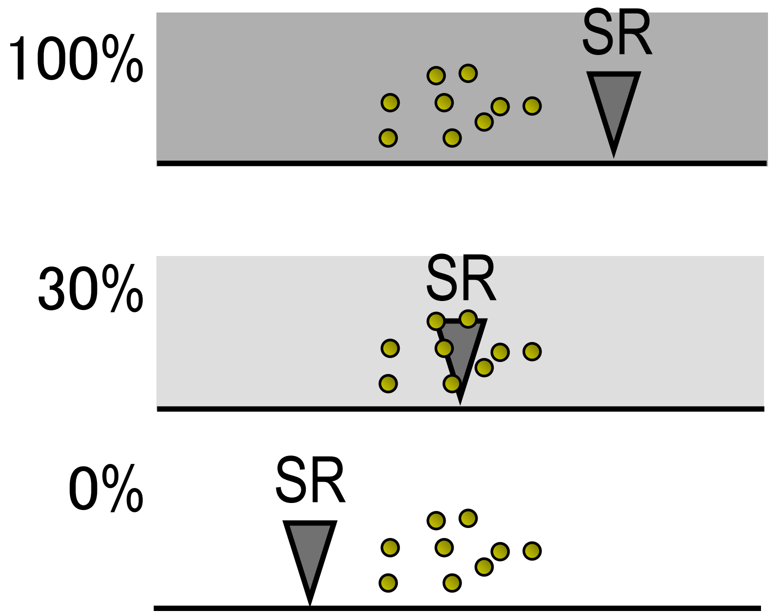


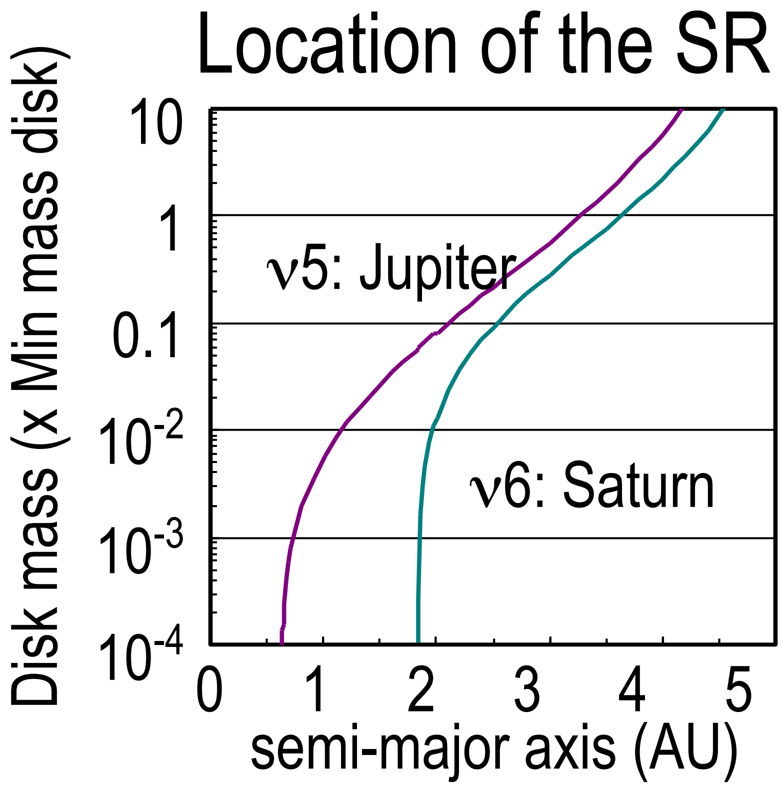
Dynamical shake up (Nagasawa, Thommes)

Bode's law: dynamically porous terrestrial planets orbits with low eccentricities with wide separation



Sweeping Secular Resonance





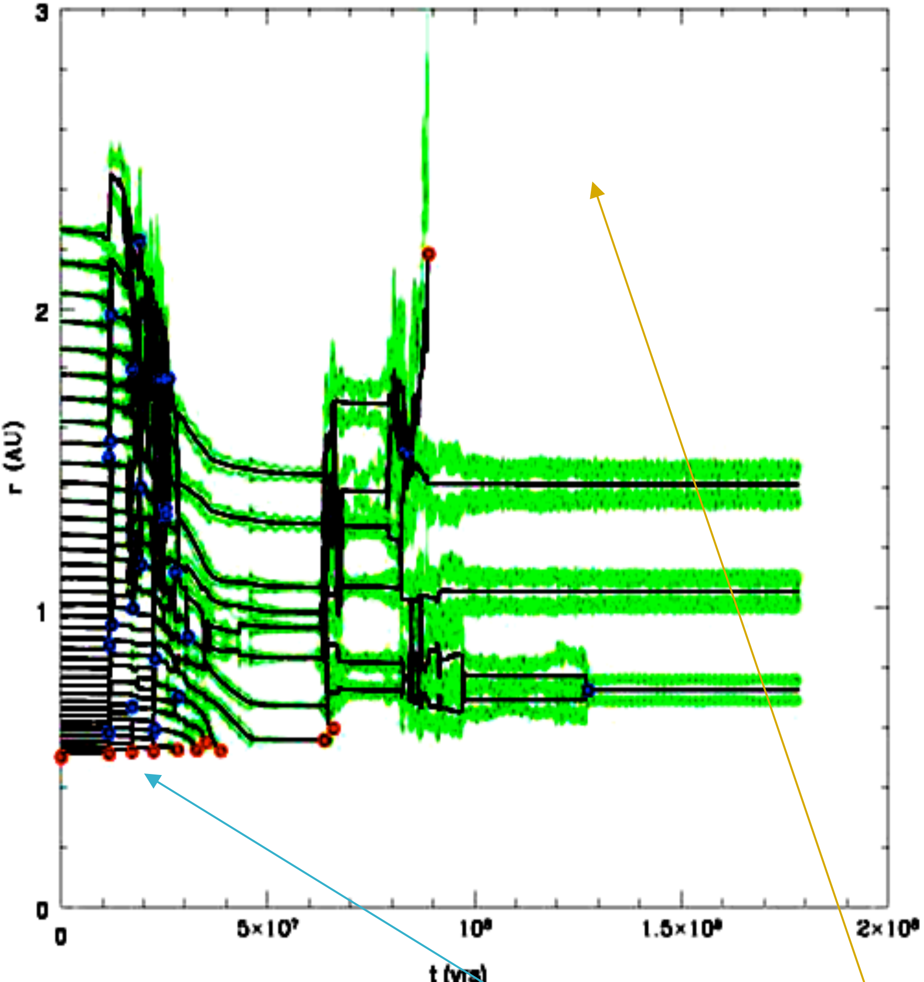
- Protoplanetary disk ~10M_J
  - ➡ Location of SR differs
- Depletion of the disk
  - ➡ Migration of SR

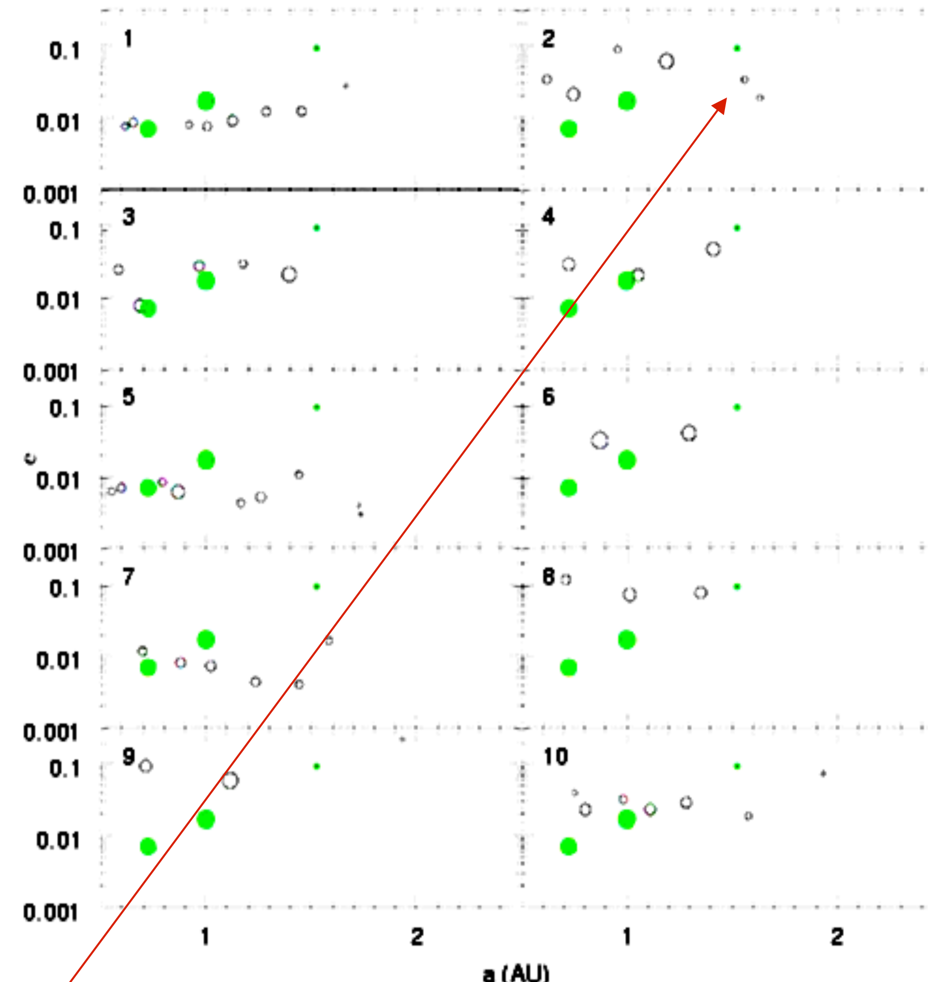
☑ ν5 sweeps from >3AU ➡ 0.5AU

- ~ Independent of disk model
- Only Jupiter is needed

Secular resonance passes though the terrestrial planet region

Migration, Collisions, & damping

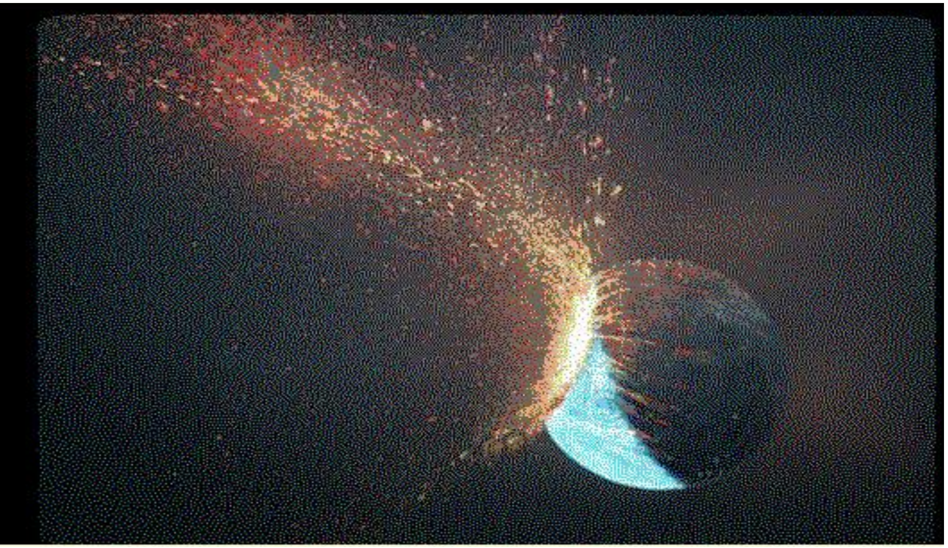




1. Clearing of the asteroid belt
2. Earlier formation of Mars
3. Sun ward planetesimals

A. Late formation (30-60 Myr)
B. Giant-embryo impacts
C. Low eccentricities, stable orbits

Giant impact & lunar formation



1) Lunar material similar to the Earth's crust.
2) Formation after the differentiation (30 Myr)
3) Mars-size impactor
4) Post impact circular orbit

About 20 hours later, a spiral-arm structure forms due to gravitational instability.

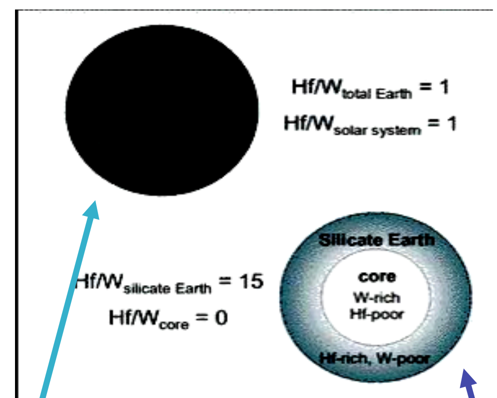
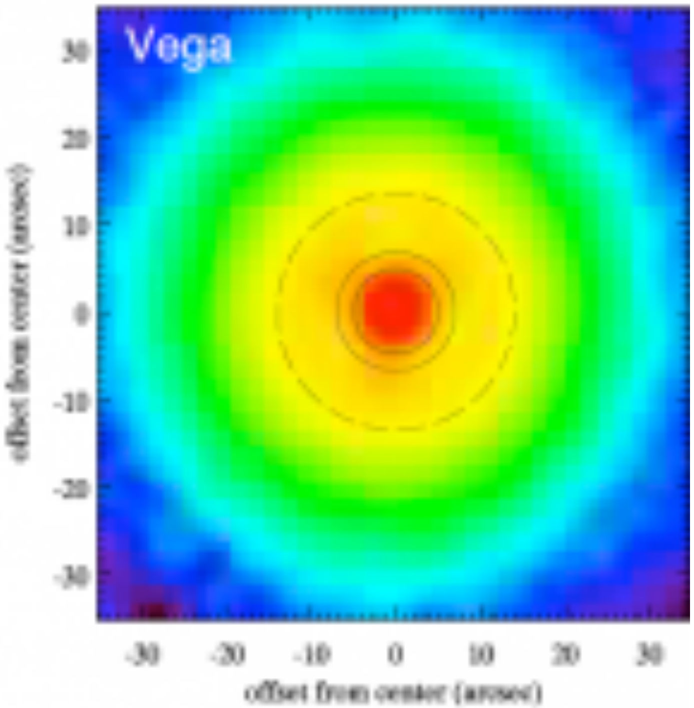


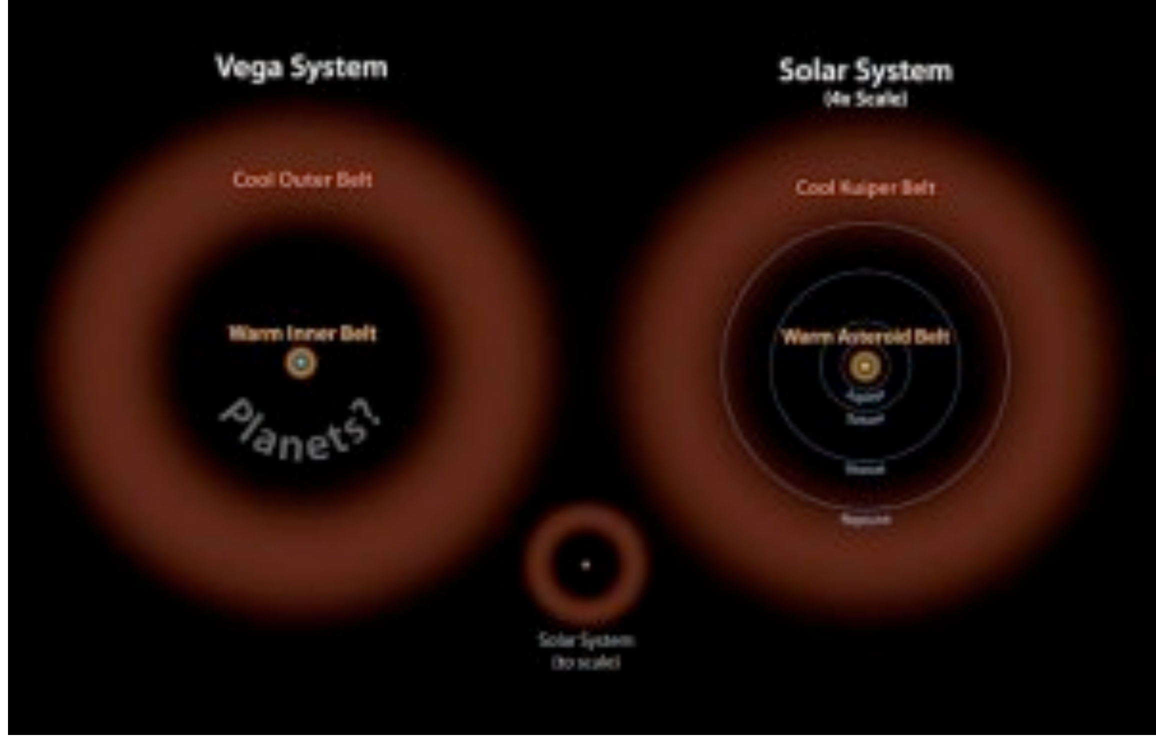
Fig. 2. Schematic showing the fractionation of Hf from W in the early solar system.

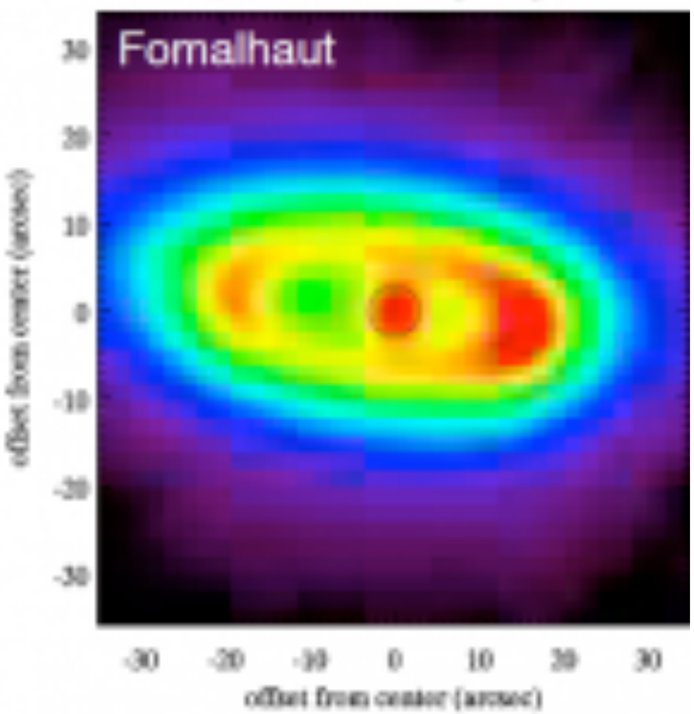
After Halliday et al. (2000)

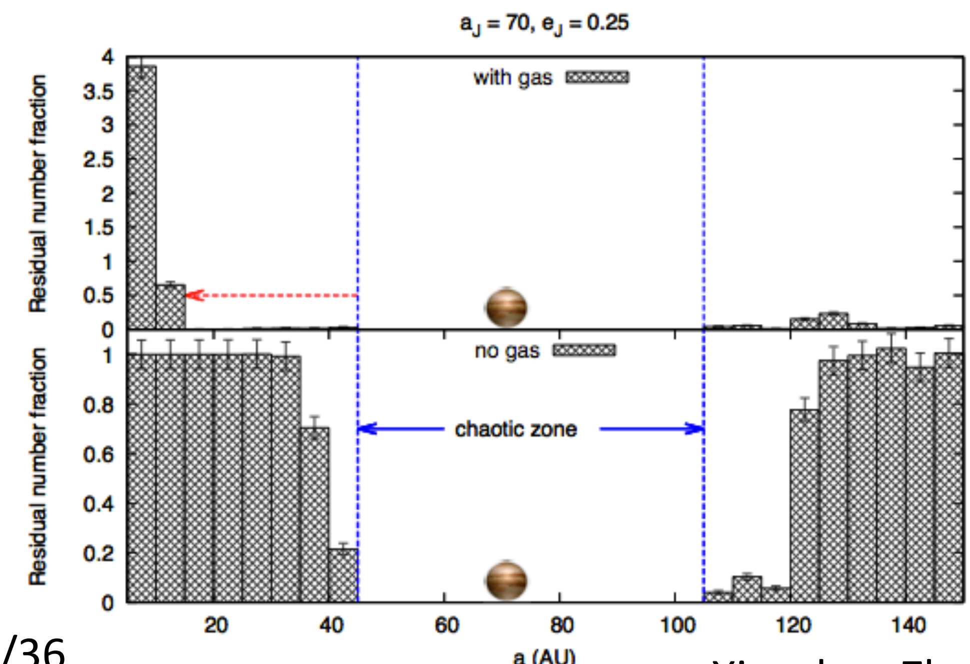
Formation after 60 Myr

Formation on 30-60 Myr









Xiaochen Zheng

Many outstanding issues

Late-stage evolution in debris disks
Post formation dynamical evolution
Non planar planetary systems
Planets around different mass stars
The role of elemental differentiation in natal disks
Planets in binary stars
Planets around stars in clusters
Planets’ magnetic and tidal interaction with their host stars
Planets’ consumption by their host stars
Planets’ survival around evolved stars
Planets’ internal structural evolution
Planets’ atmospheric dynamics
How is habitability affected by dynamical interaction between planets

Population synthesis models should be used as a discovery tool rather than knob-turning fitting gadget