Ubiquity of Planets & Diversity of Planetary Systems

Spring School on Protostellar Disks & Planet Formation

Tsinghua Universitym Beijing

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Astronomy (UCSC), KIAA (PKU), IAS (THU)

59 slides

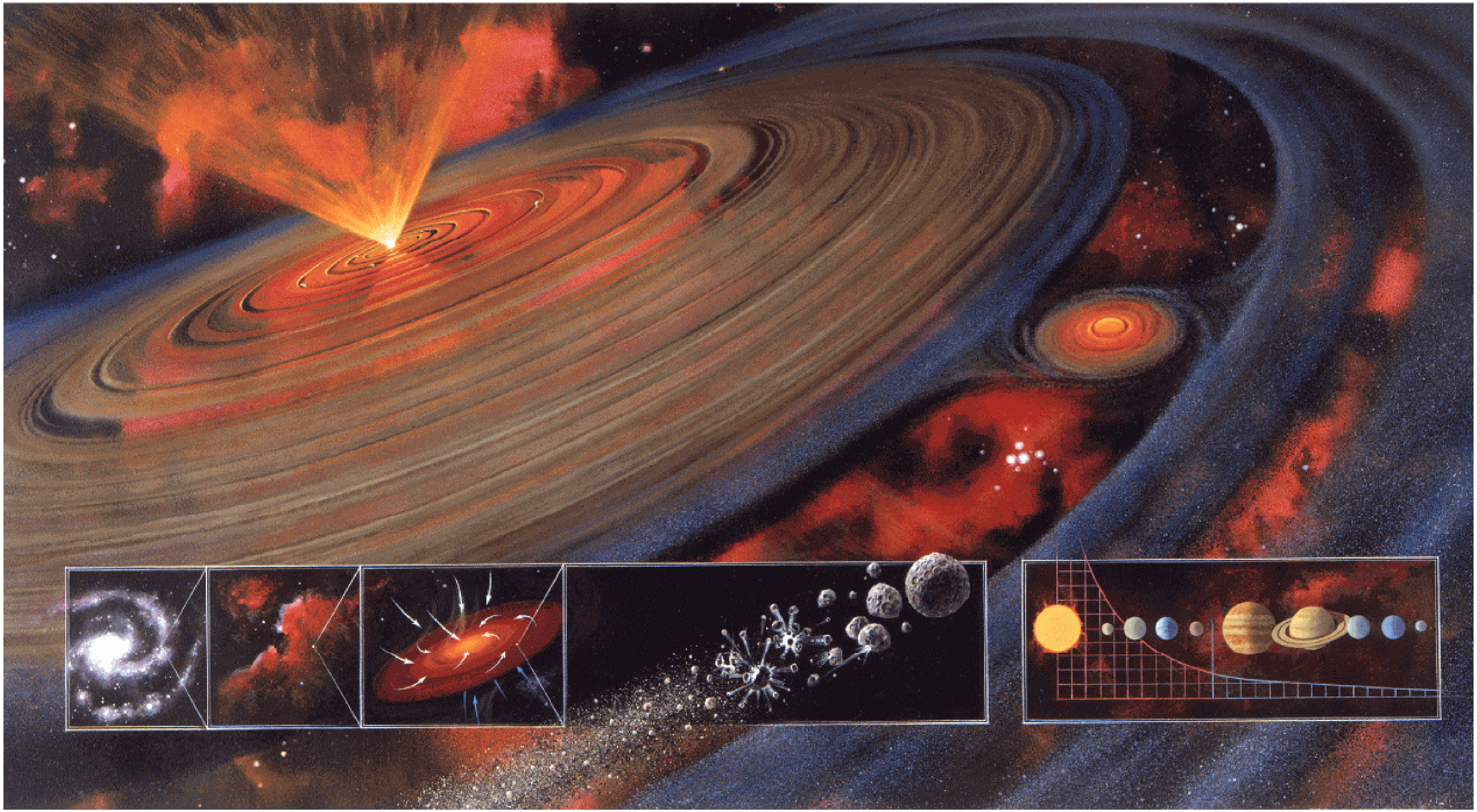
A short summary of the results (RV, Pepe)

- 1% of stars have a hot Jupiter, more frequently around metal-rich stars
- 14% of stars host a giant planets at any period, more frequently around metal-rich stars
- 50 – 80% of stars orbit at least one planet of any kind
- 30% of stars have a planet within < 30 M_{Earth} and within 100 days period …
- More than 70 % of planetary systems with one planet of $m_P \sin i$ < 30 M_{Earth} include more than one planet

Challenge to Theory of Planet Formation

- Why are super Earths so ubiquitous?
- What criteria determine the fraction of stars which bear gas giants?
- What processes led to planets’ mass and size distribution?
- How did planets acquire their period distribution?

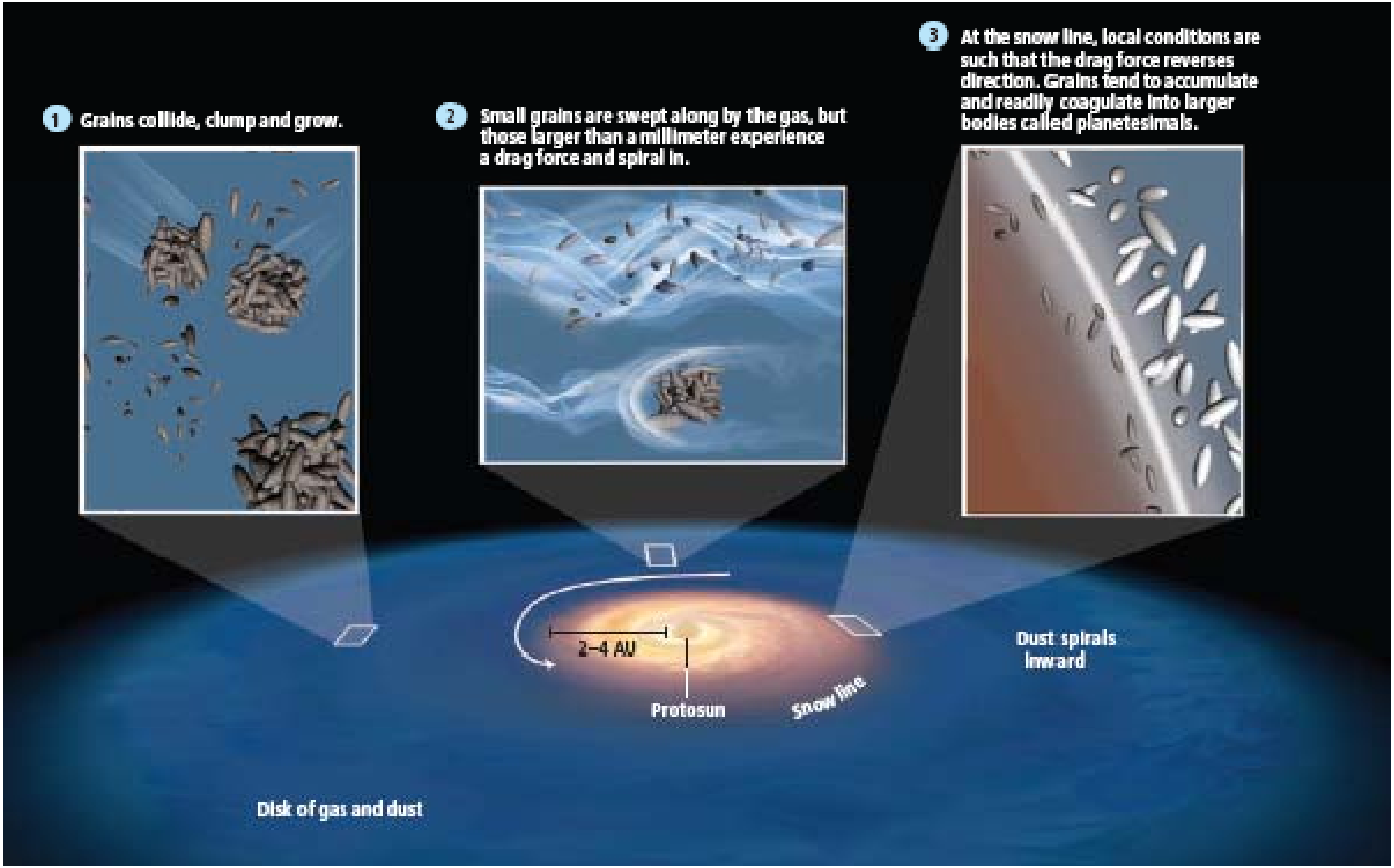
Conventional core accretion scenario



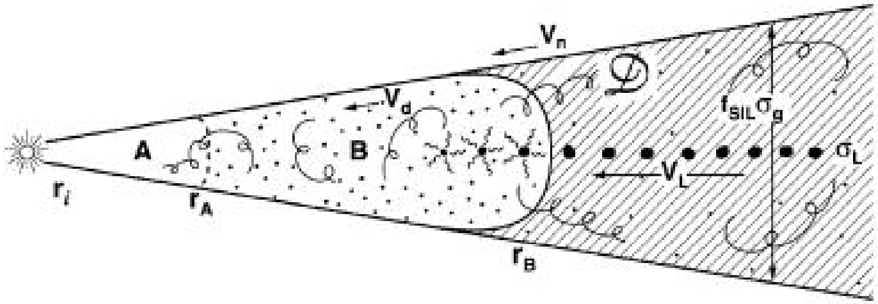
Major Challenges:

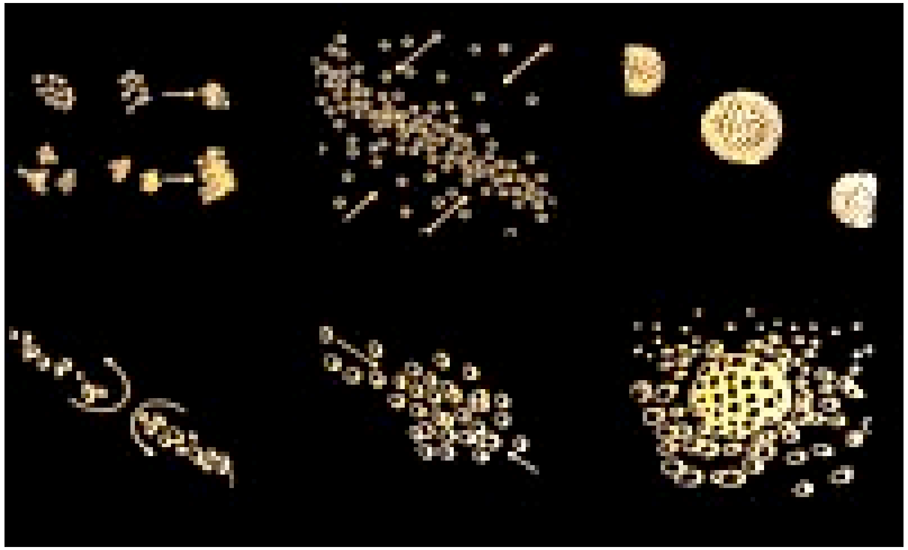
- Retention of grains: m-size barrier (Whipple)
- Fragmentation: km-size barrier (Benz)
- Planetesimal-growth barrier: Isolation mass barrier (Wetherill)
- Gas accretion barrier: critical-mass cores (Cameron)
- Retention of cores: type I migration (Goldreich & Tremaine, Ward)
- Retention of gas giants: type II migration (Lin & Papaloizou)
- Multiple gas giants: rapid depletion of disk gas
- Competing physics on multiple length & time scales

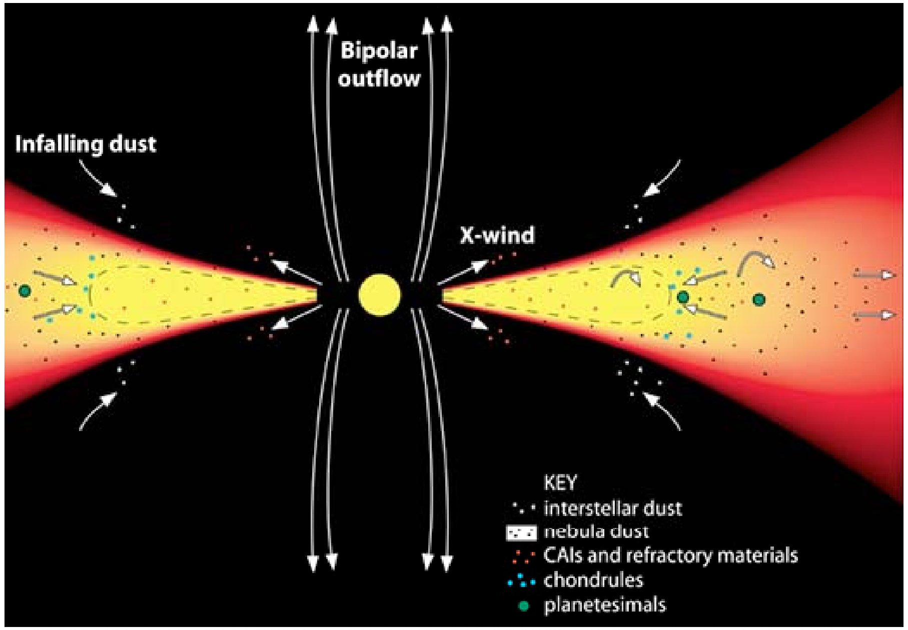
Step I: Meter-barrier
Hydrodynamic drag on dusts



Trapping locations: transition fronts and wall of magnetospheric cavity

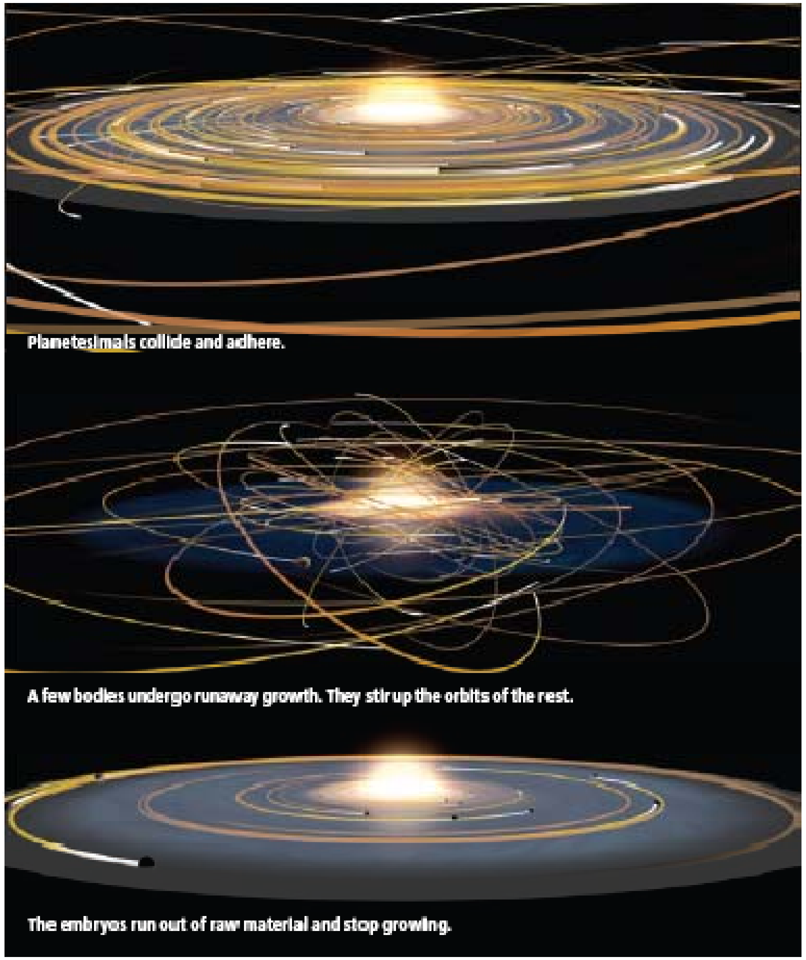


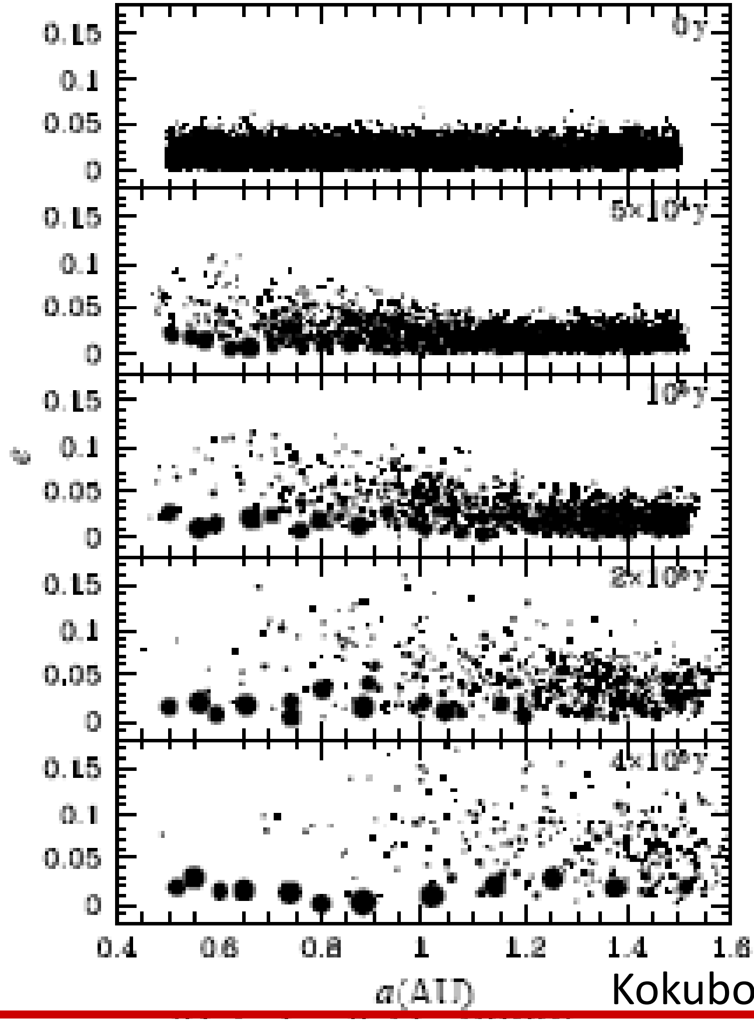




(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

Step III, oligarchic barrier: Isolation mass



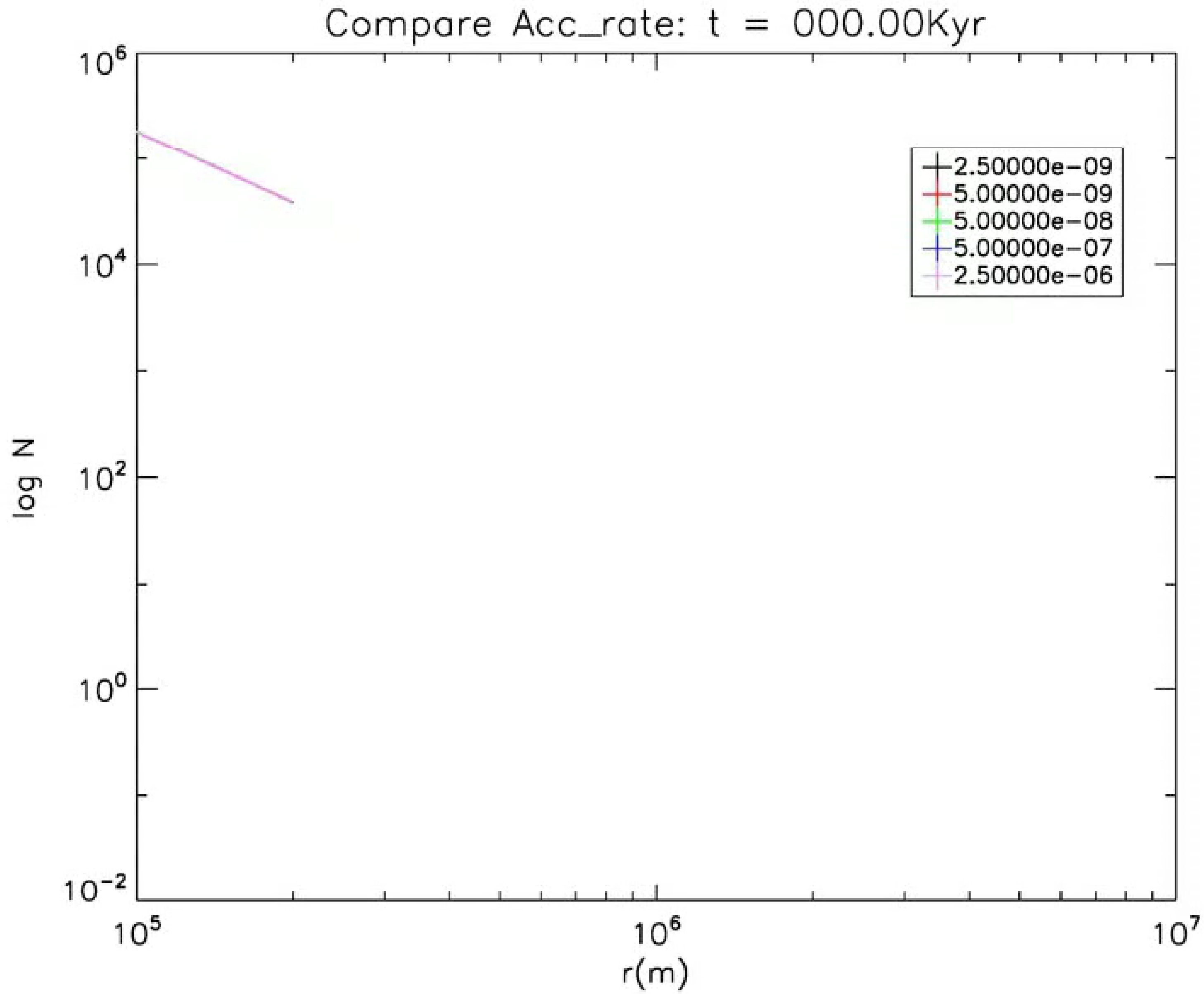


Kokubo & Ida

Feeding zones: $\Delta \sim 10\ r_{Hill}$

Isolation mass: $\mathbf{M_{isolation} \sim \Sigma^{1.5}\, a^3 M_*^{-1/2}}$

Rapid emergence of super Earths



Rixin Li

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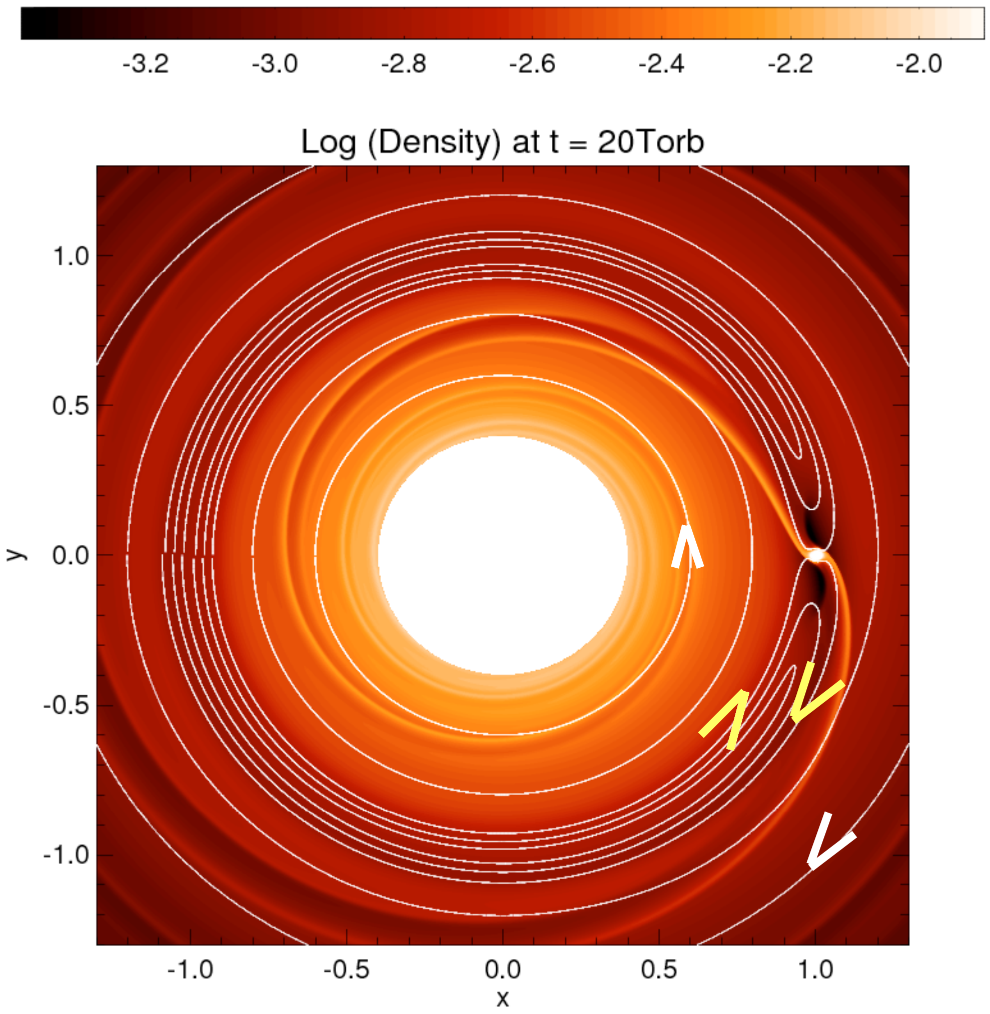
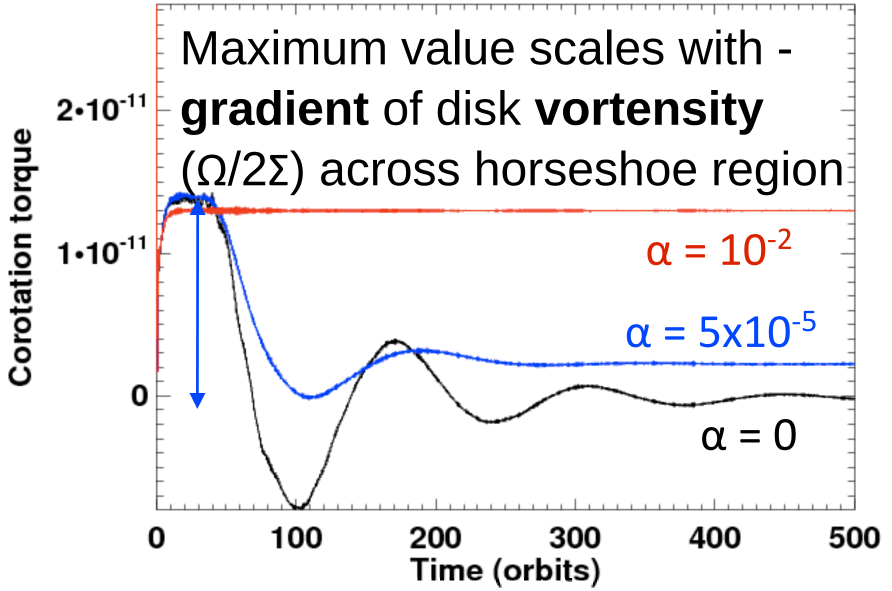
Step IV, Embryos barrier: planetary migration
Type I migration of super-Earth in isothermal disks



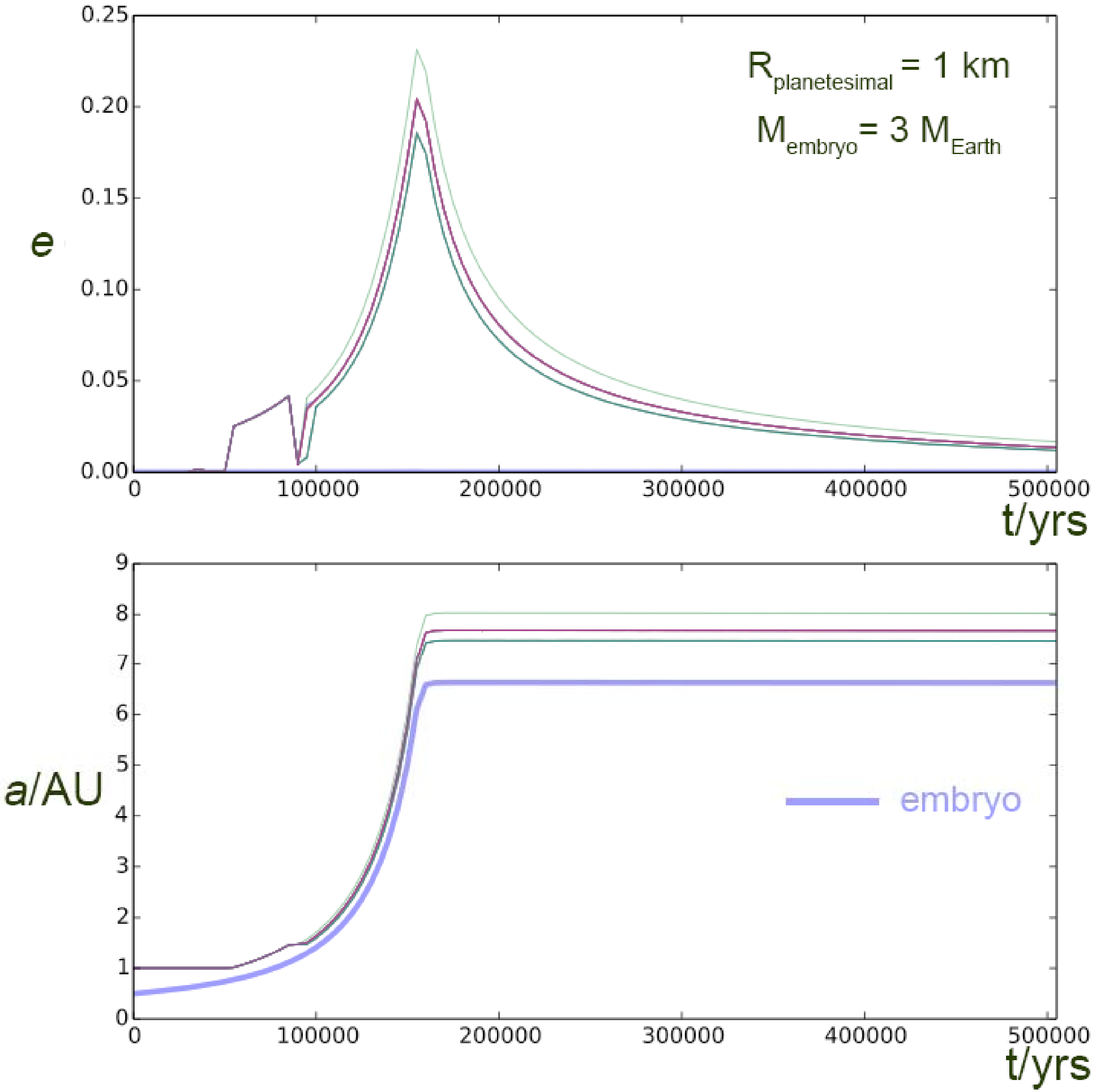
The planet exchanges angular momentum with:

- **circulating** fluid elements:
  → **differential Lindblad torque**
- **librating** fluid elements:
  → **corotation torque**

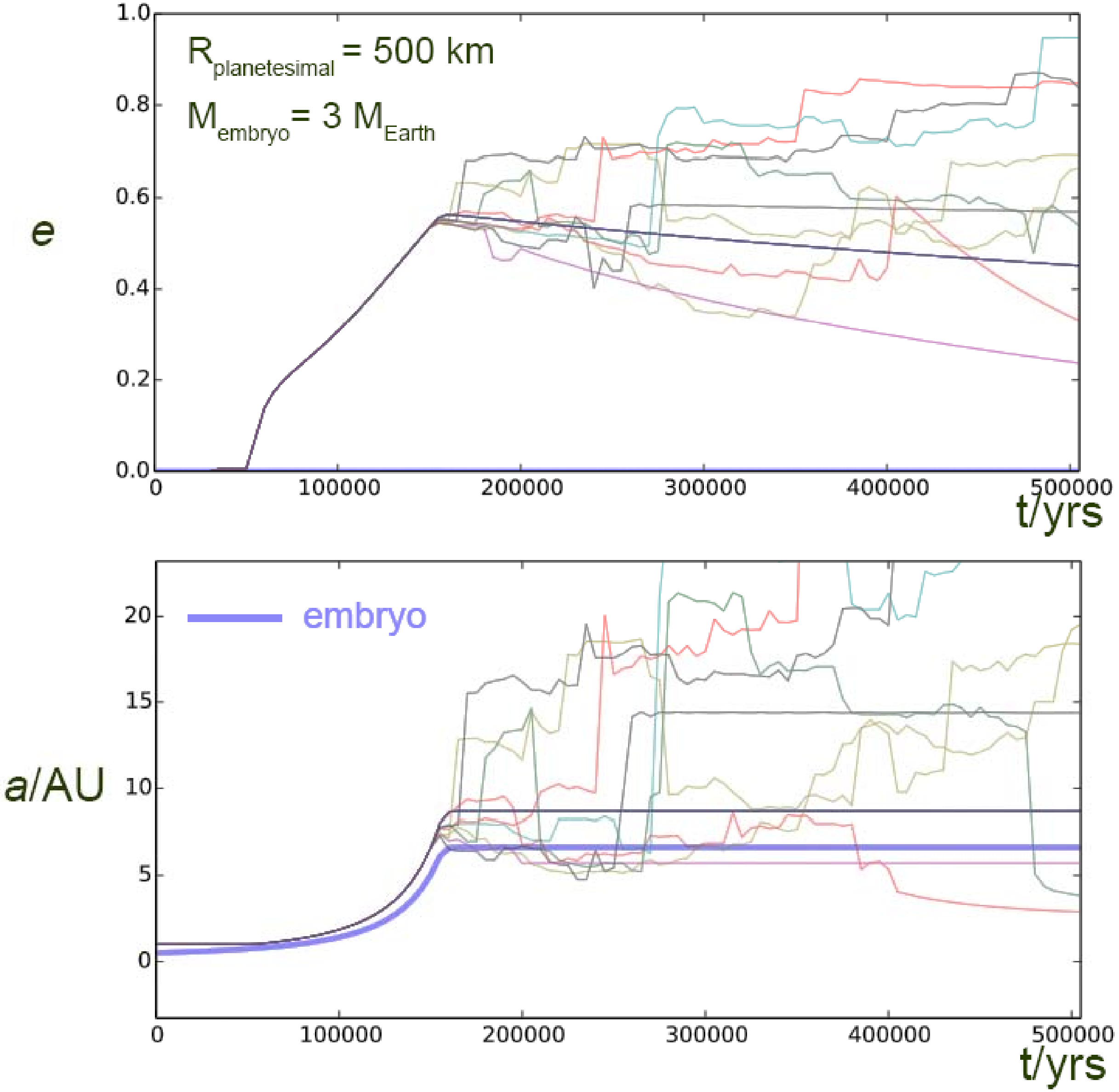


Long-term evolution of the corotation torque is related to the disk viscosity
Paardekooper, **Baruteau**,

e.g. Goldreich & Tremaine (1980), Ward (1992)
Masset (2001), Paadekooper, Baruteau, Kley



0.25
0.20
0.15
0.10
0.05
0.00
e
R_planetesimal = 1 km
M_embryo = 3 M_Earth
0
100000
200000
300000
400000
500000
t/yrs
9
8
7
6
5
4
3
2
1
0
a/AU
embryo
0
100000
200000
300000
400000
500000
t/yrs



1.0
0.8
0.6
0.4
0.2
0.0
e
$R_{planetesimal}$ = 500 km
M_{embryo} = 3 M_{Earth}
0
100000
200000
300000
400000
500000
t/yrs
embryo
20
15
10
5
0
a/AU
0
100000
200000
300000
400000
500000
t/yrs

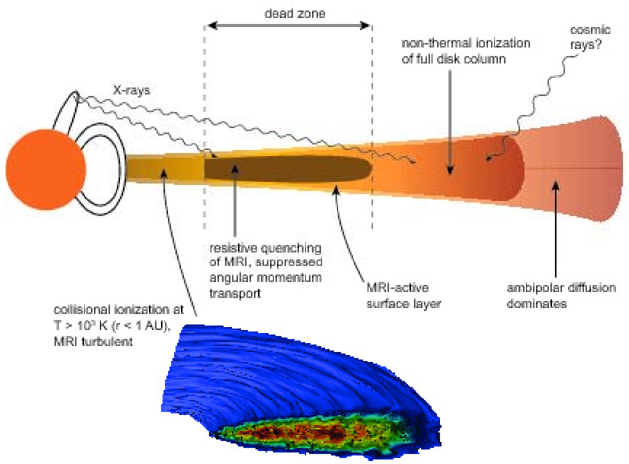
Planet-disk tidal interaction

Total tidal torque:

$$\Gamma = \Gamma_L + \Gamma_c \quad = f(p,q,p_\nu,q_\nu,p_\kappa,q_\kappa)\Gamma_0$$

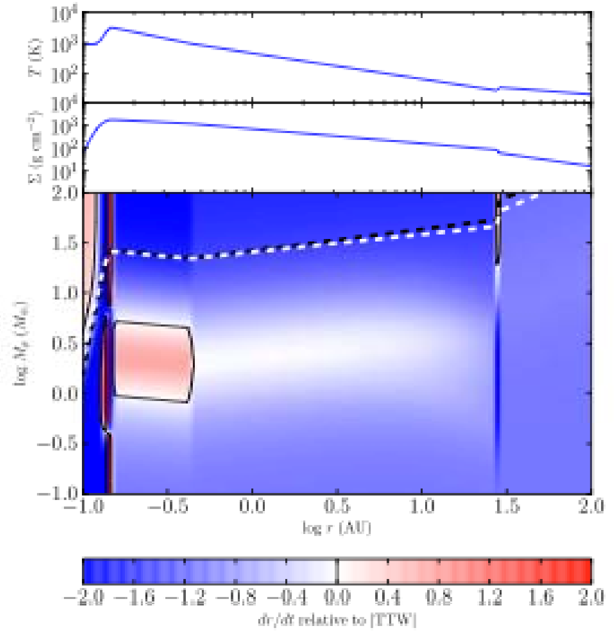
$$\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2,$$

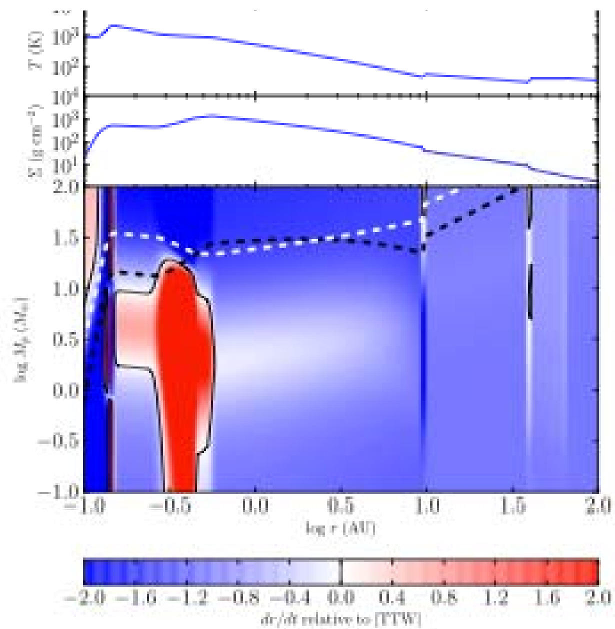
p and q depend on disk structure & p_ν,q_ν,p_κ, and q_κ also depend on m_p



$$\frac{dr}{dt} = f(p,q,p_\nu,p_\chi)\frac{M_p}{M_*}\frac{\Sigma r^2}{M_*}\left(\frac{r\Omega_K}{c_s}\right)^2 r\Omega_K$$

$$(1/e)de/dt = (a/H)^4 (M_p \Sigma a^2/M_*^2)\ \Omega$$

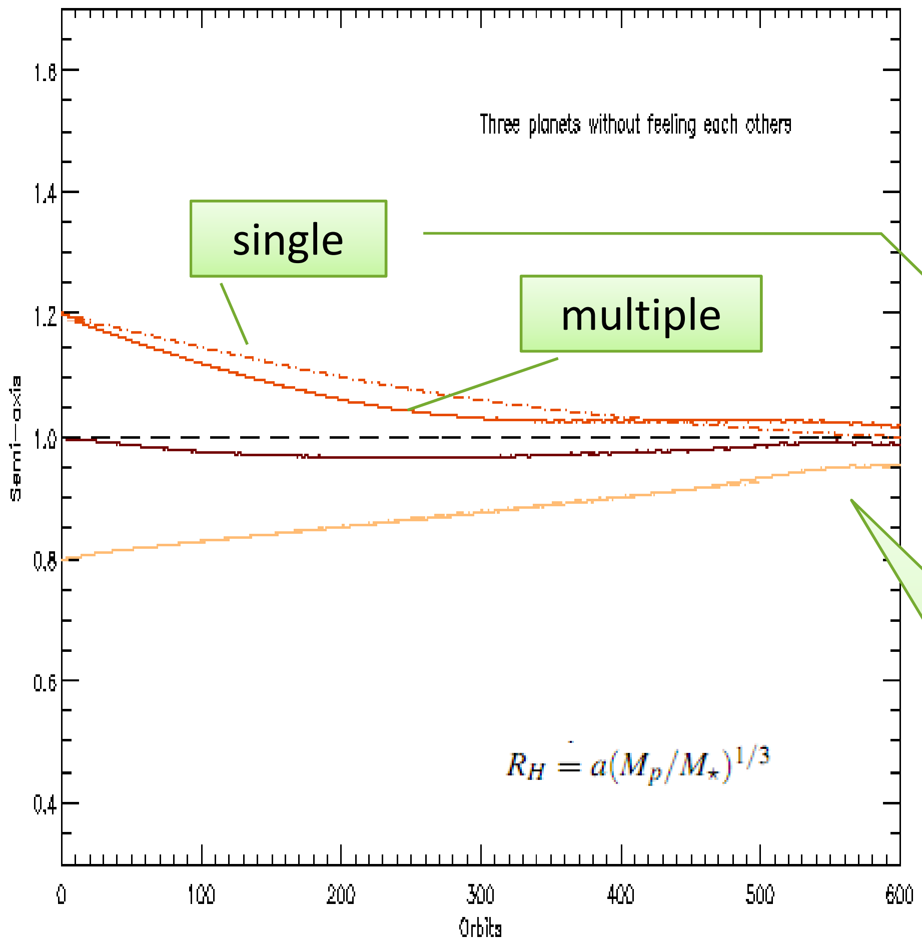




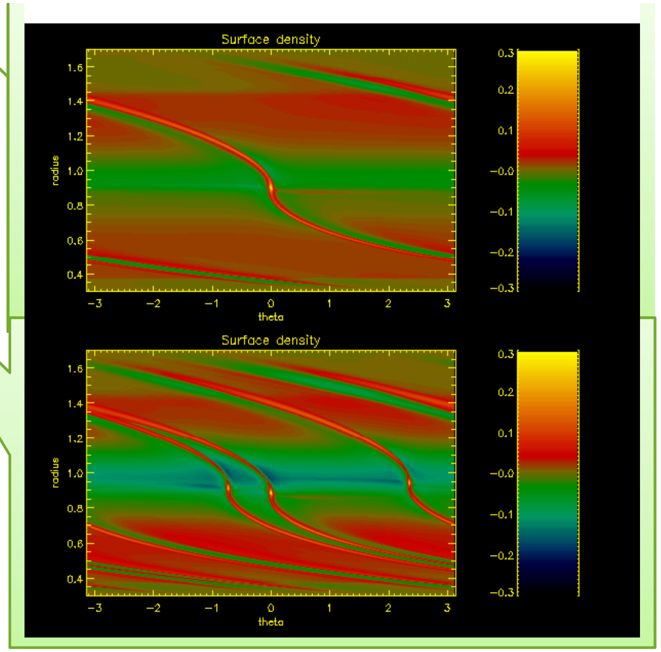
Lecar et al, Garaud, Kretke

Multiple embryo's type I migration: necessary condition for core formation

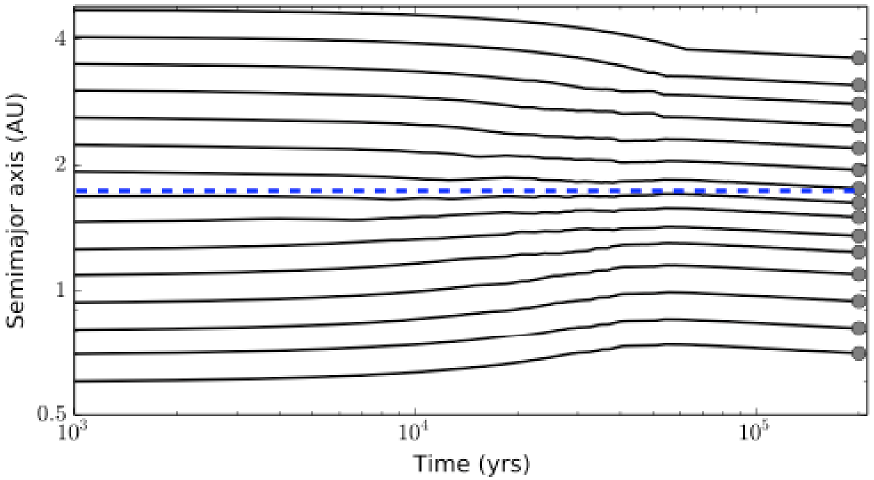
SEMI-AXIS EVOLUTION

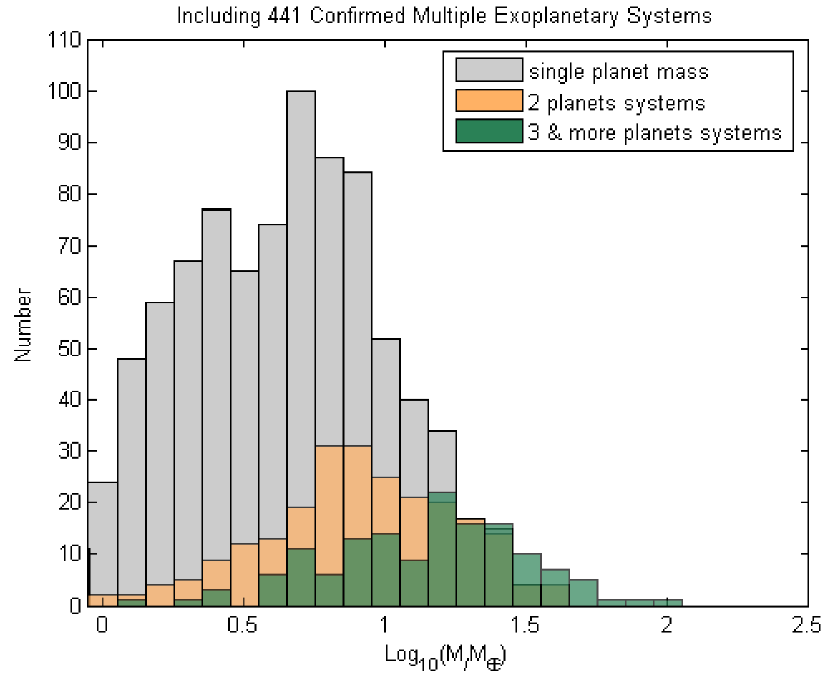


① Only indirect interaction between embryos during disk perturbation



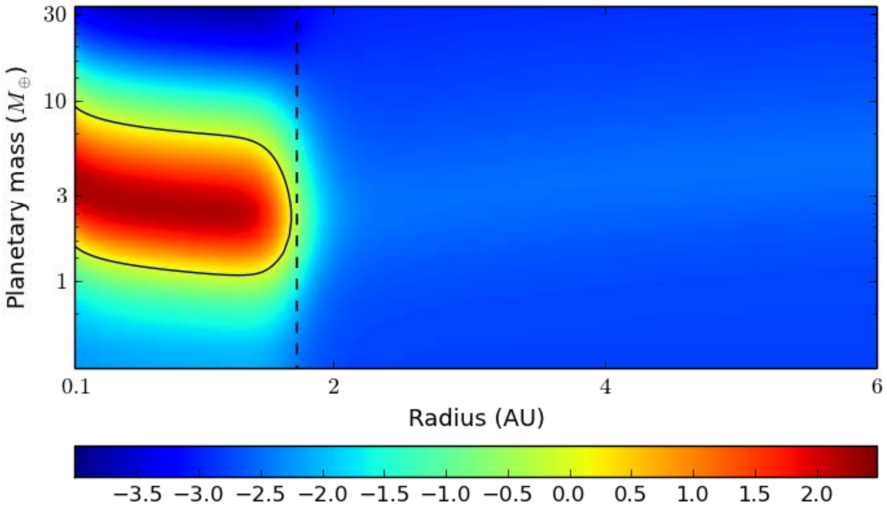
Core barrier: embryos' resonant trapping

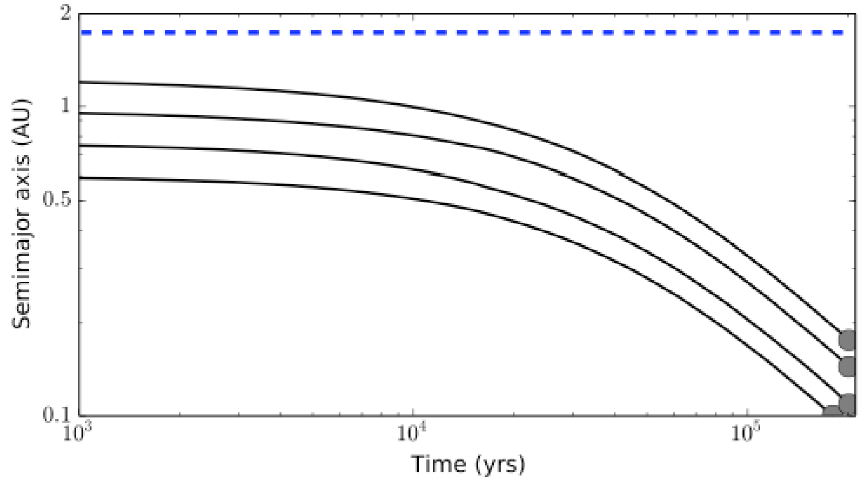




Beibei Liu M=1Msun, Mdot = 10^{-8}M_sun/yr, α=1

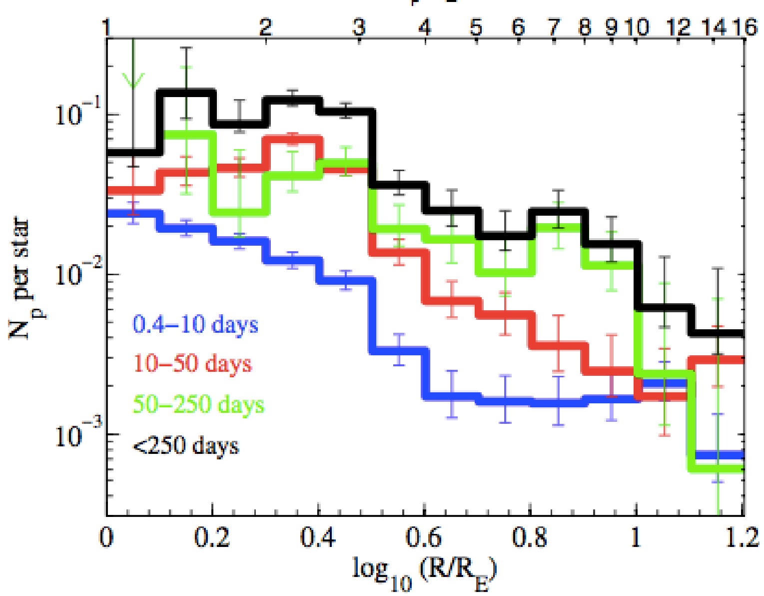
No shortage of building block materials





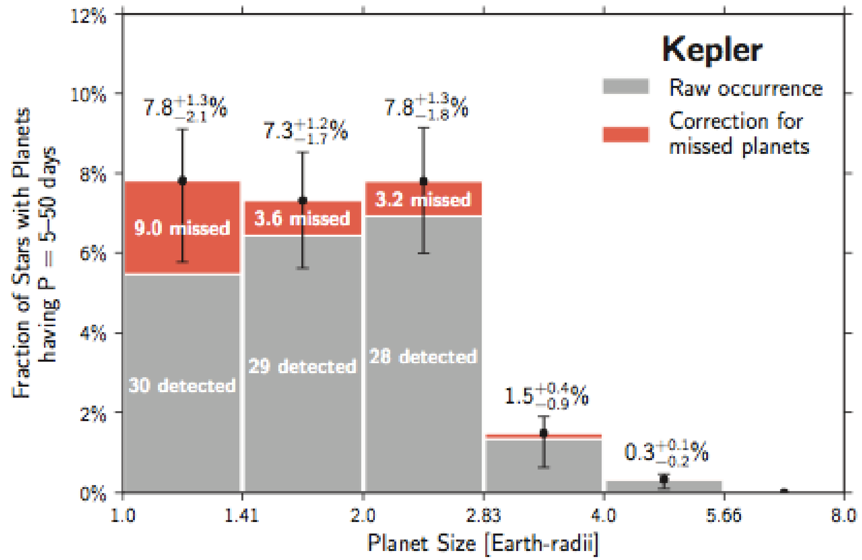
Loss of massive super-Earth embryos?

Log Scale!

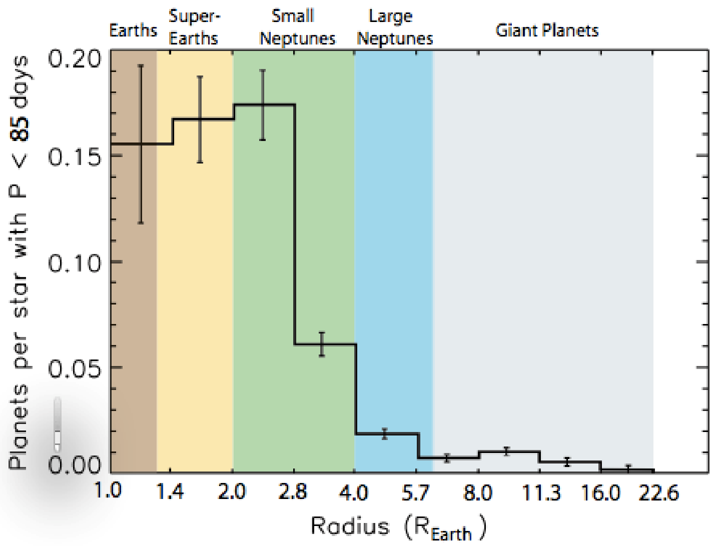


Dong & Zhu (2013)

Comparing Radius Distribution Among three works (Dong)



Petigura et al. 2013a



Fressin et al. (2013)

Core accretion model?

See also Gould et al. (2011); Youdin et al., (2011)

Challenge to Theory of Planet Formation

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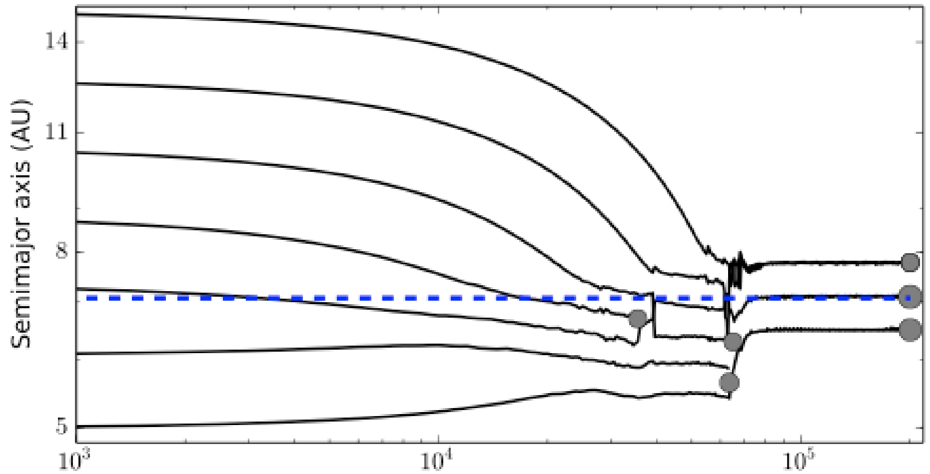
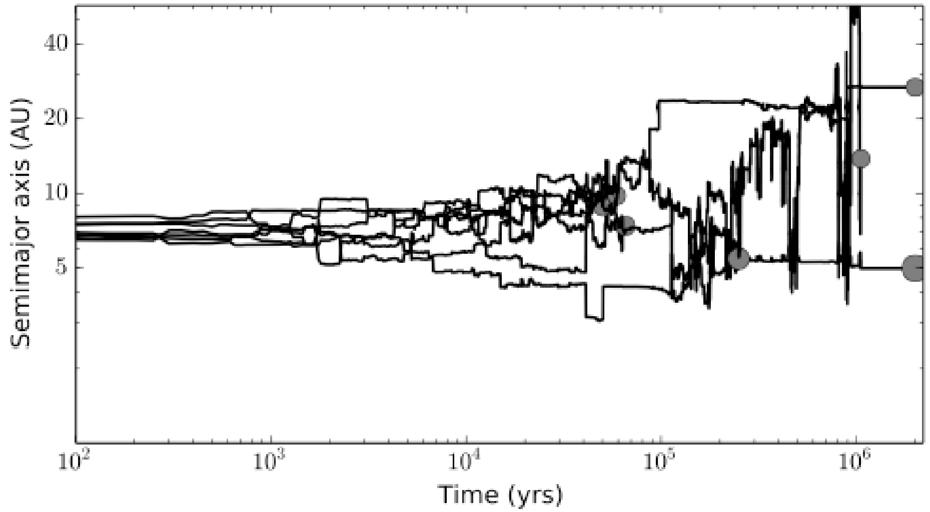
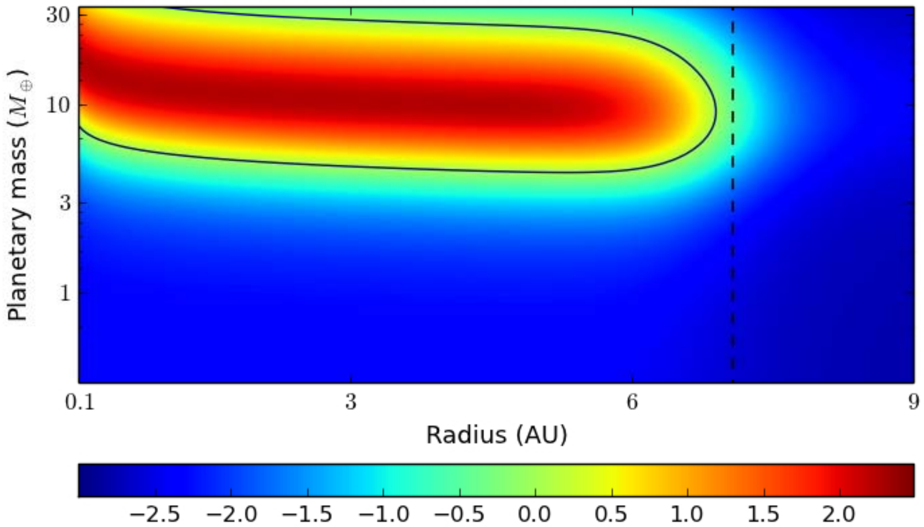
Bypass the resonant barrier







Orbit crossing, close encounters,
Home coming, & collisions

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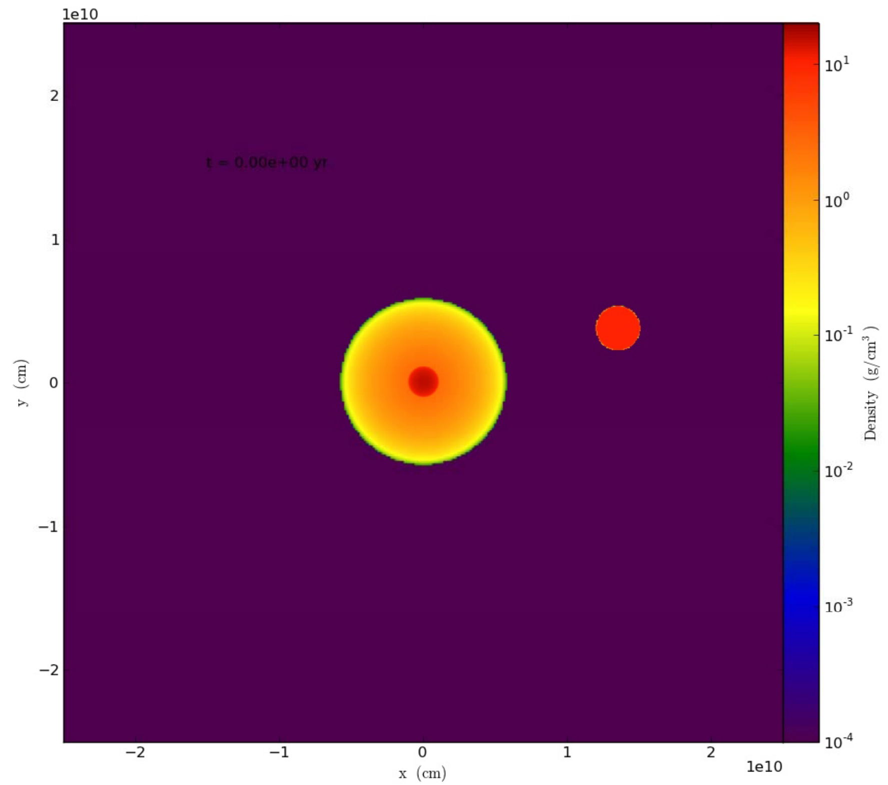
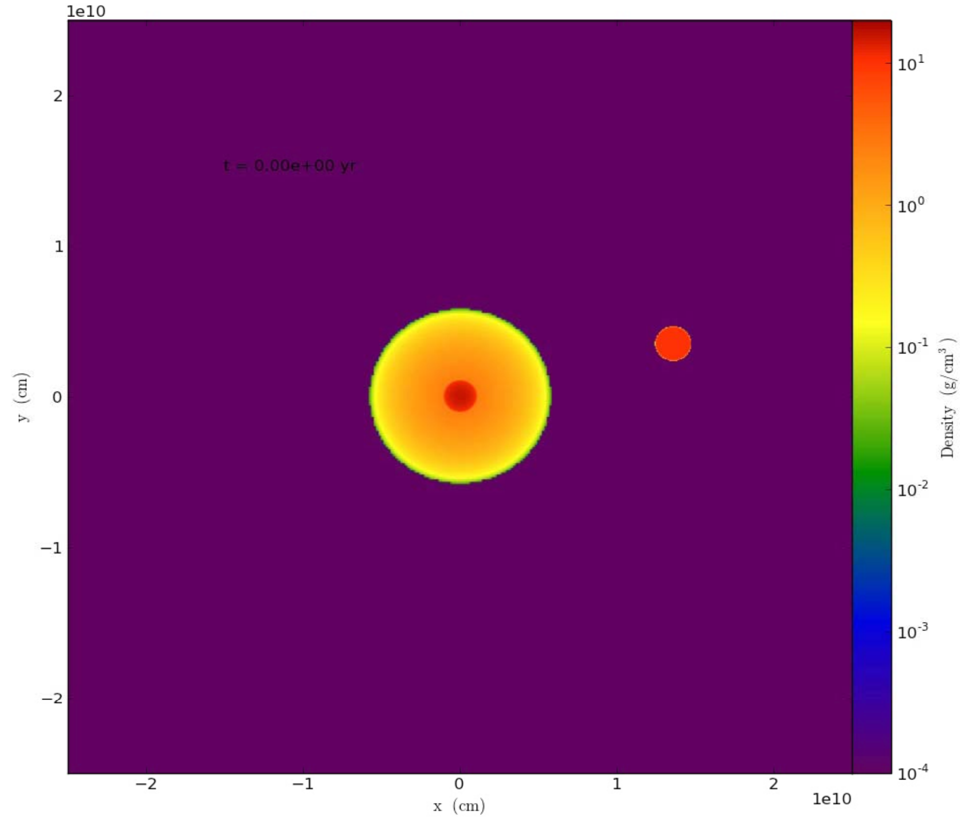
Giant impacts of super Earths

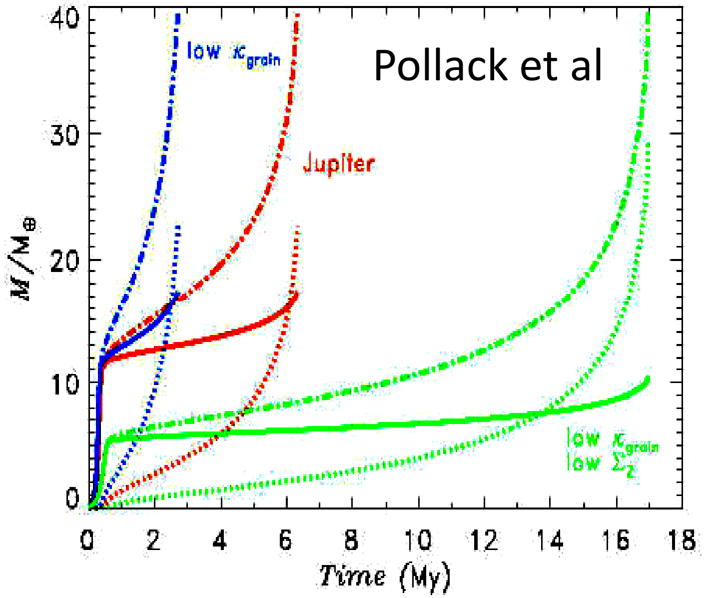


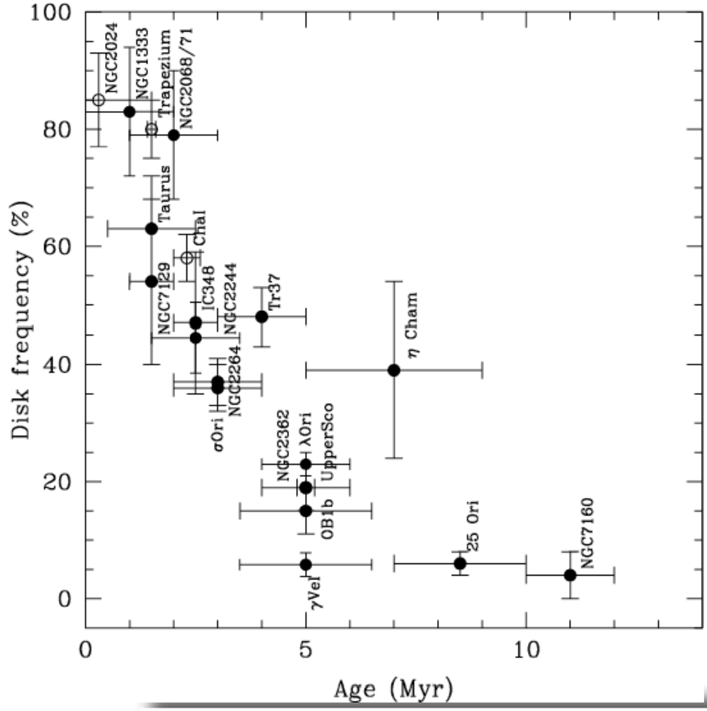


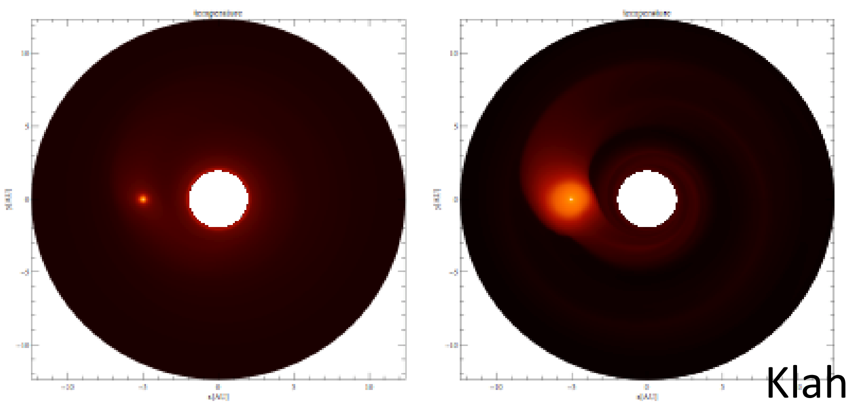
Liu Shangfei

Gas accretion barrier:

- Is there a threshold mass for gas accretion?

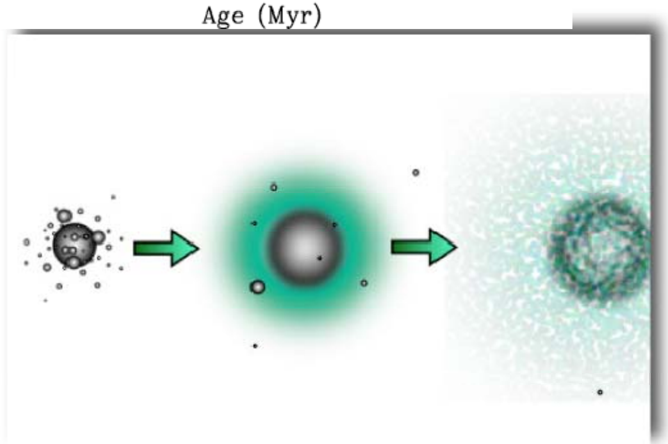






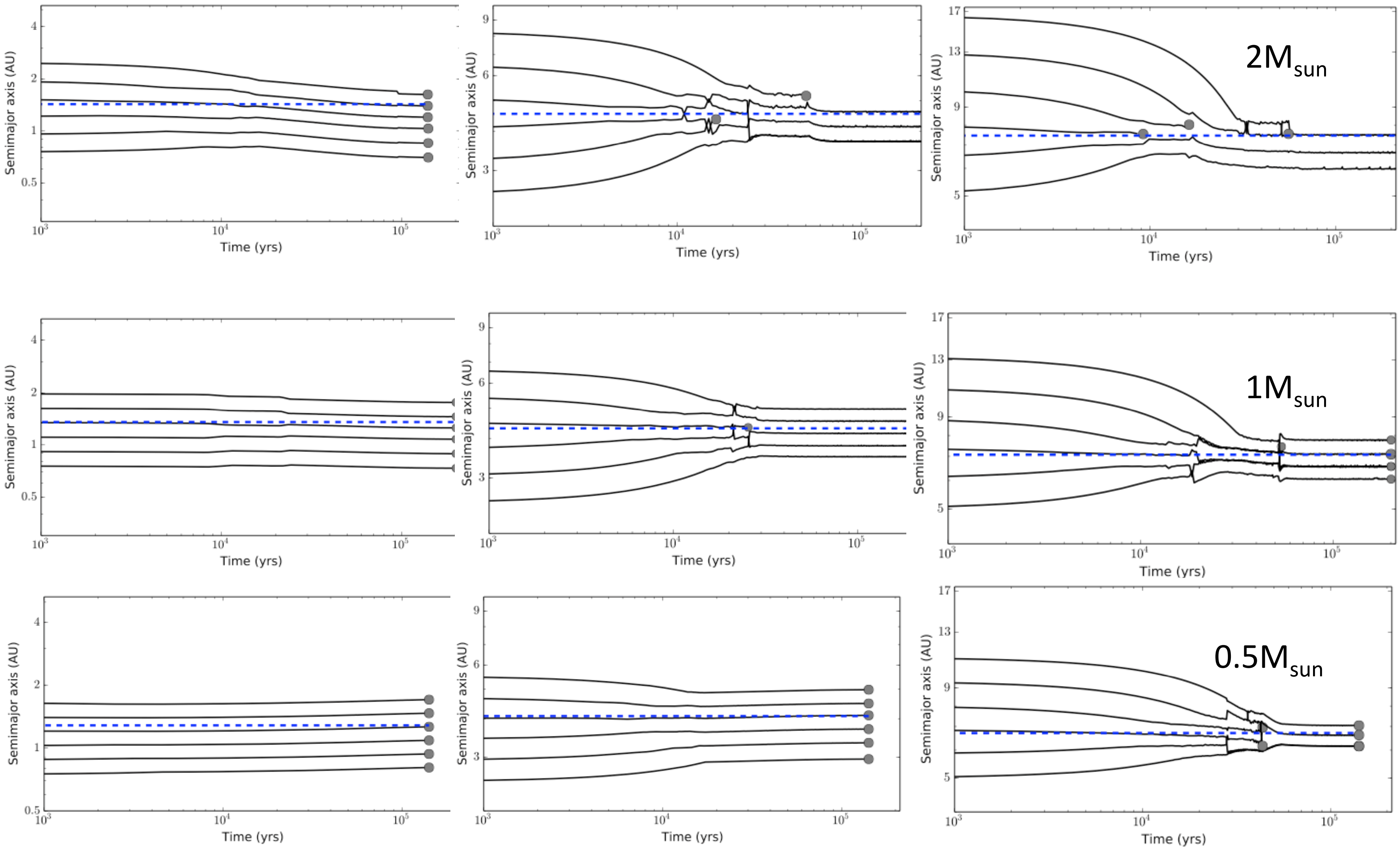
Klahr

Fig. 4.— Tempertature distribution - left: $30M_\oplus$ and $\kappa = 0.01\kappa_0$; right: $30M_\oplus$ and $\kappa = 1\kappa_0$



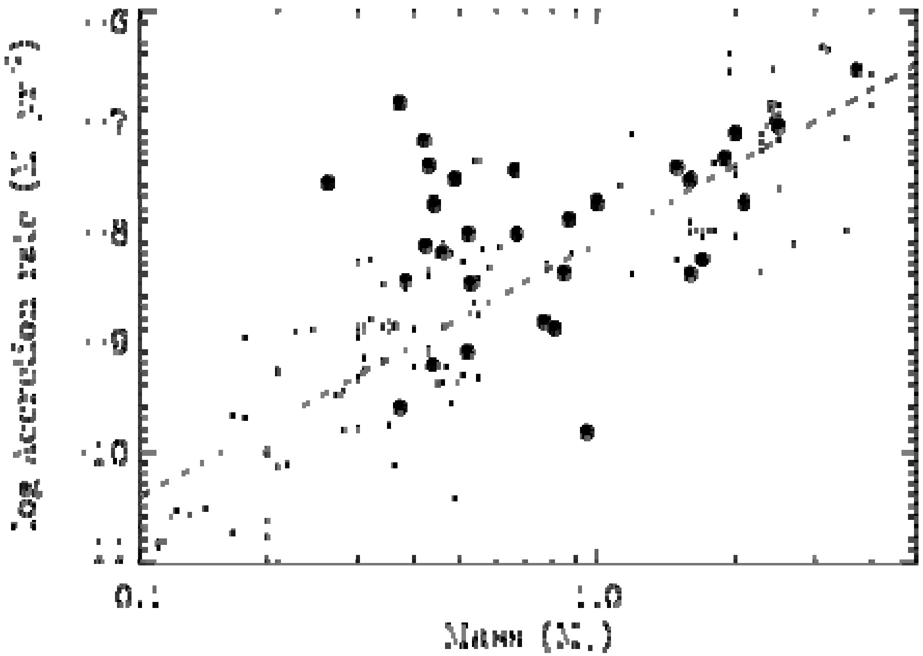
Radiation transfer & gas accretion

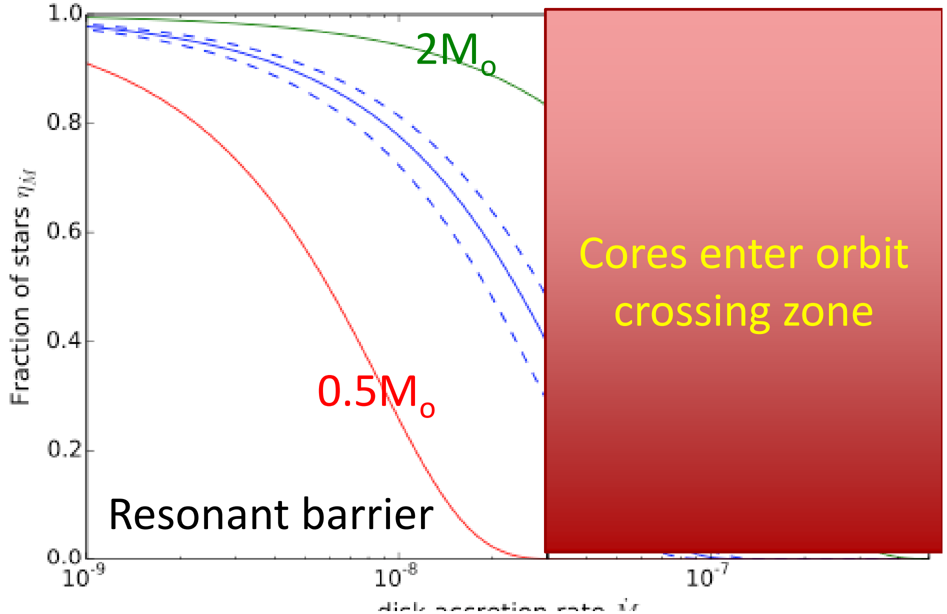
Dependence on the disks' accretion rate

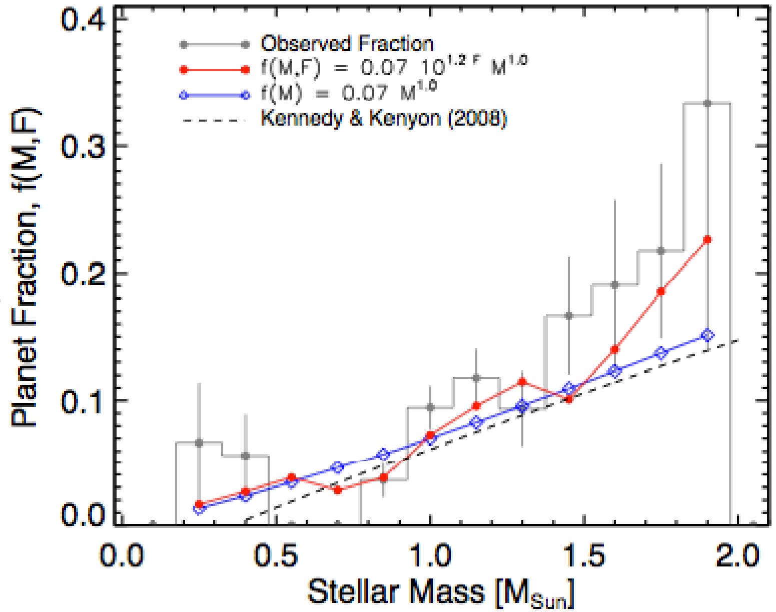


Mdot = 10^{-8} 5 x10^{-8} 10^{-7}

Dependence on the disks' accretion rate

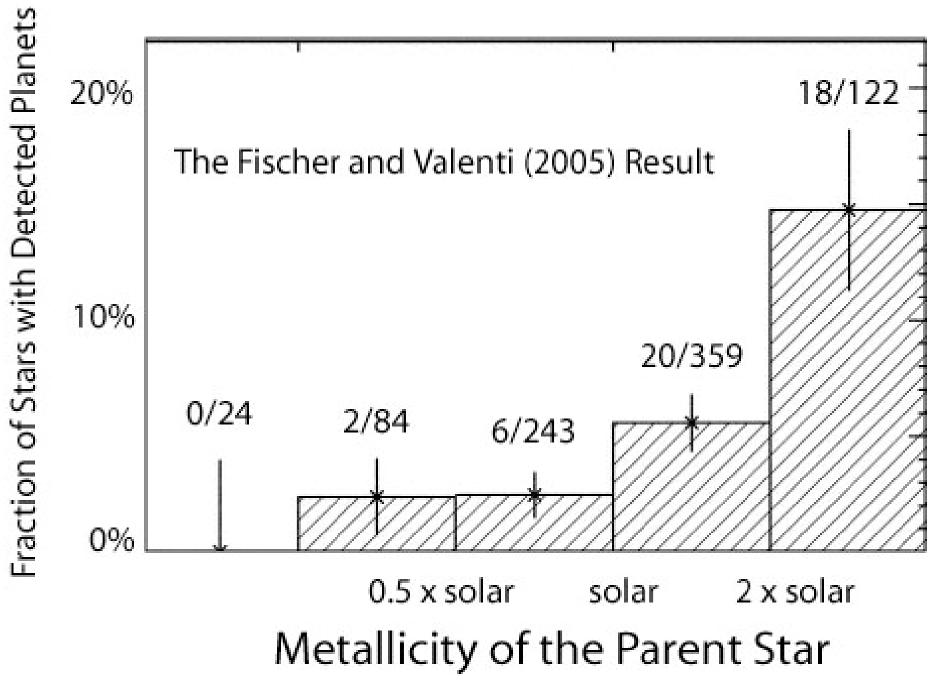


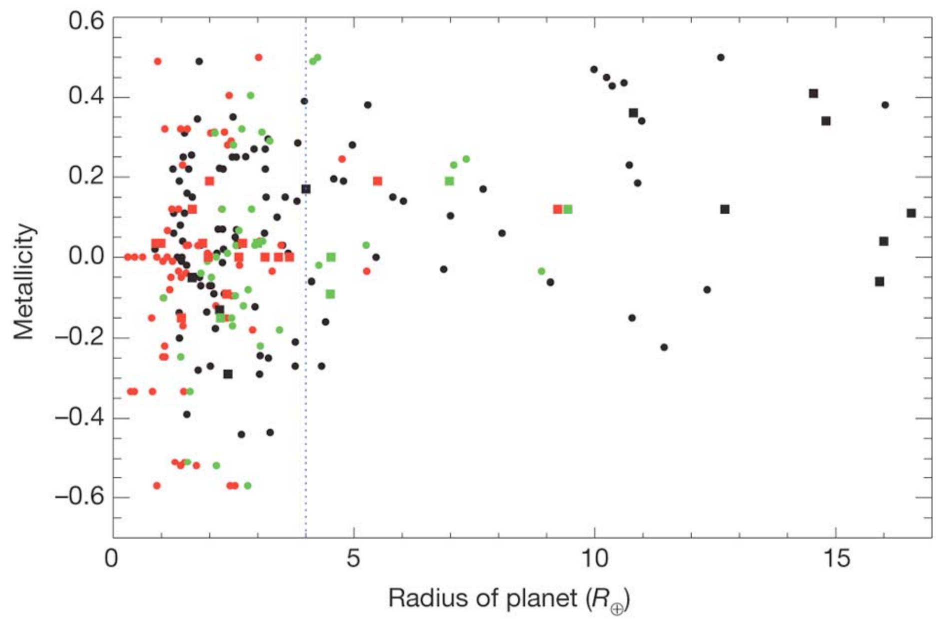




1) Cores' migration speed is determined by the surface density of the disk gas.
2) Surface density of the disk gas is proportional to the gas accretion rate
3) Gas accretion is observed to increase with the host stars' mass.
4) Gas giants' frequency correlation with the host stars' mass is through mdot.

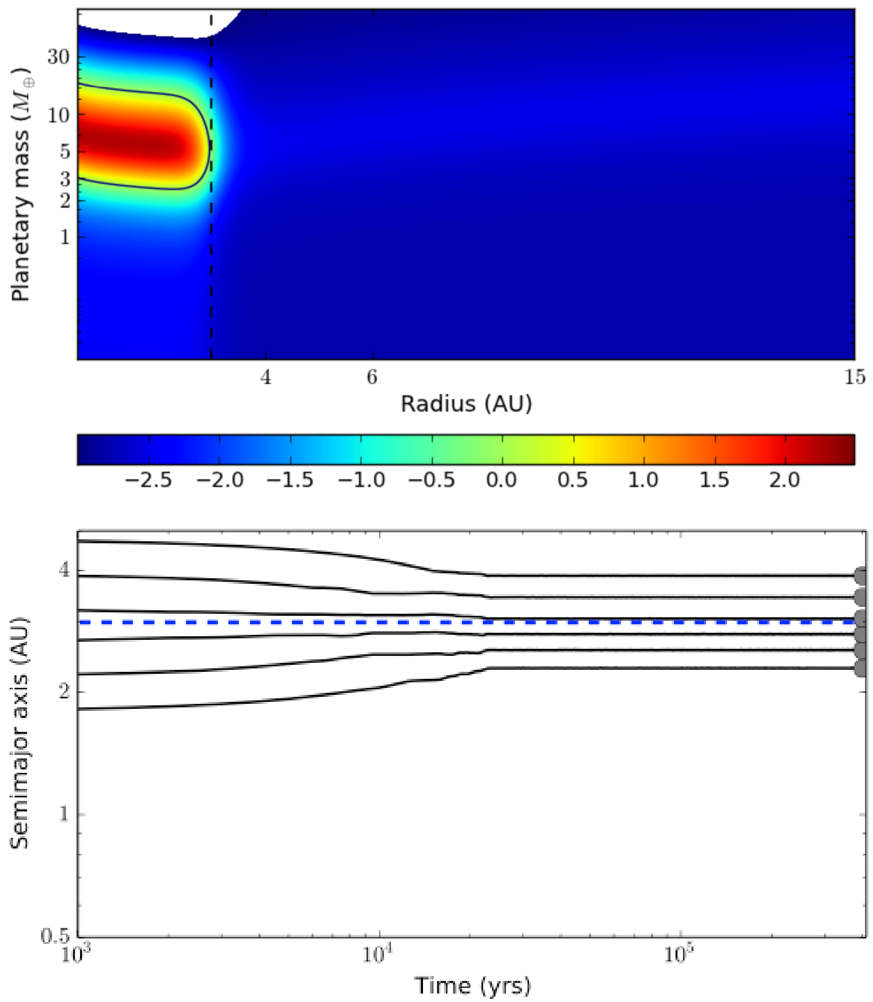
Planetary mass & size vs stellar metallicity



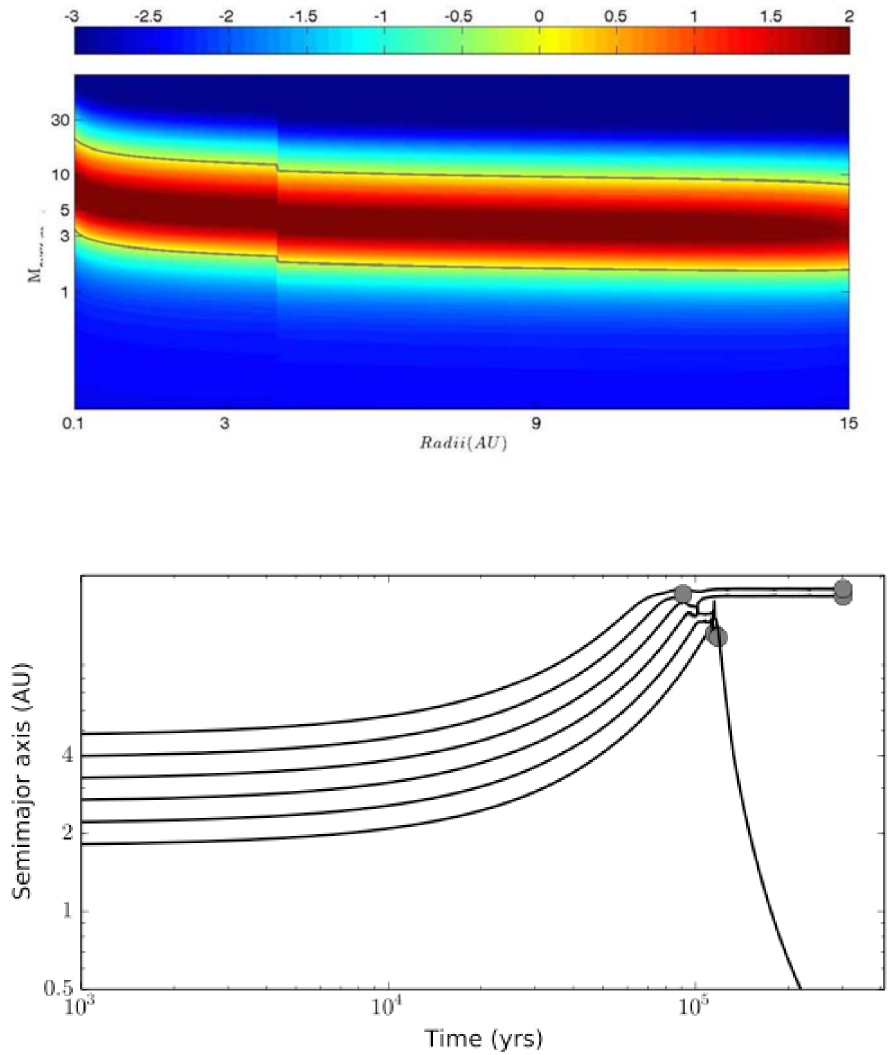


1) There is a strong correlation between η_{HJ} vs stellar metallicity.
2) There is no shortage of super Earths around metal-poor stars

Dependence on metallicity

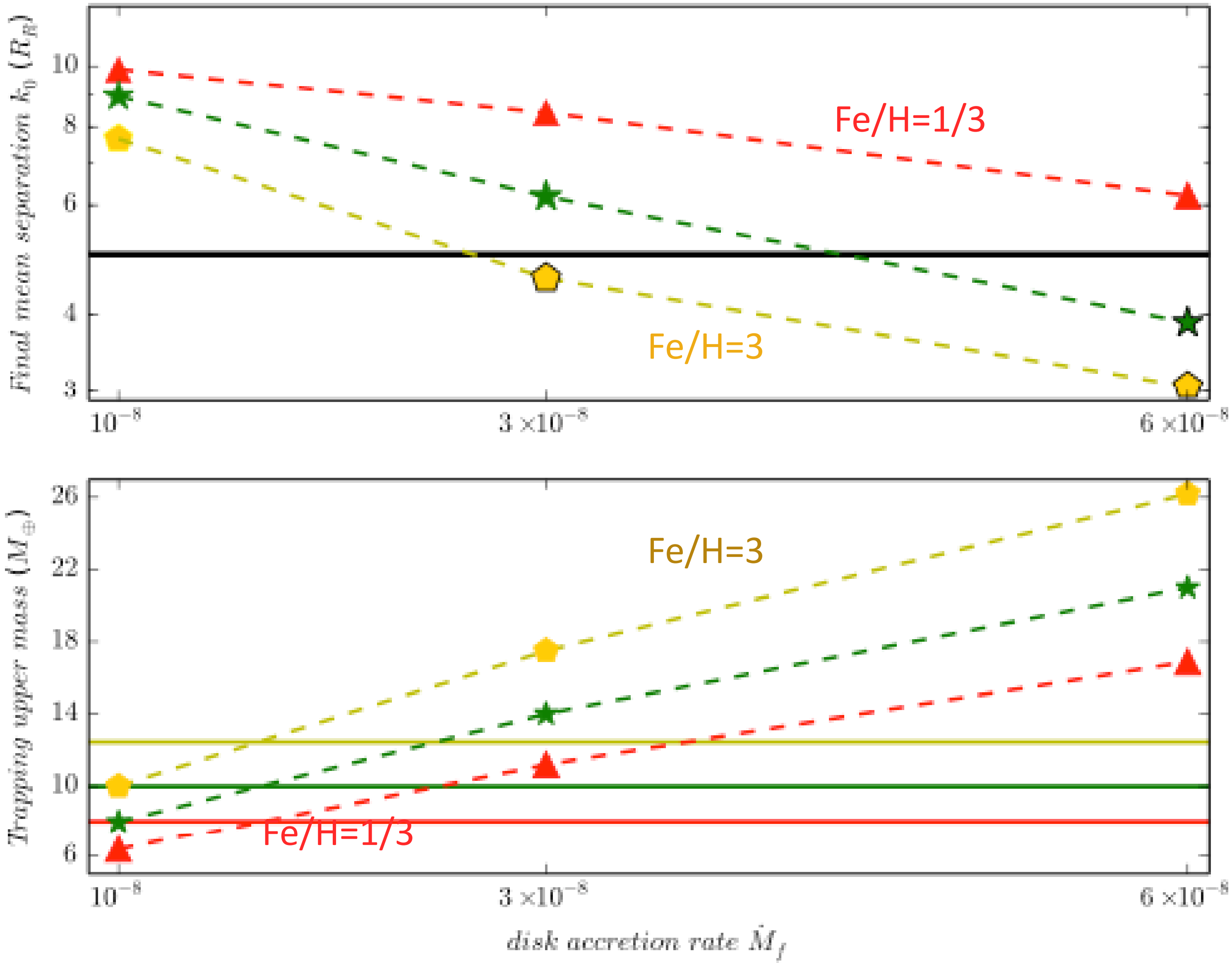


Fe/H=1

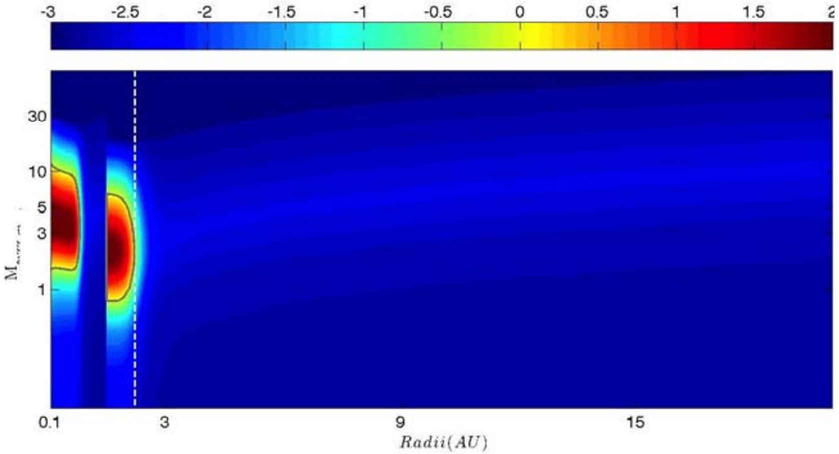


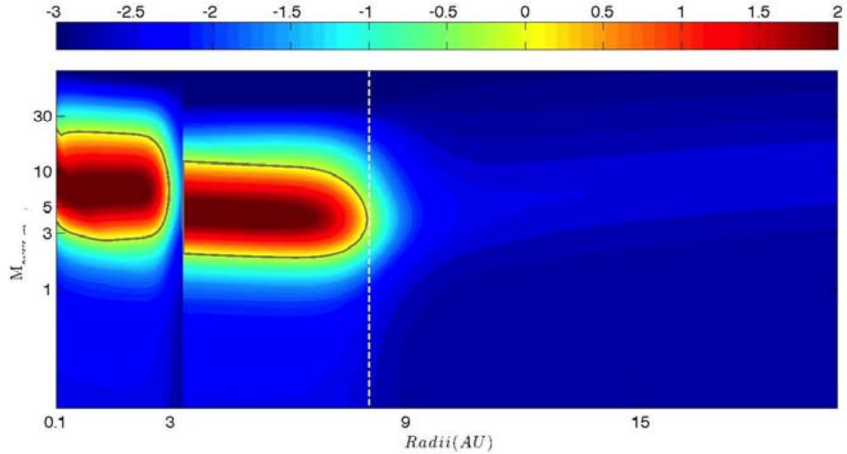
Fe/H=3

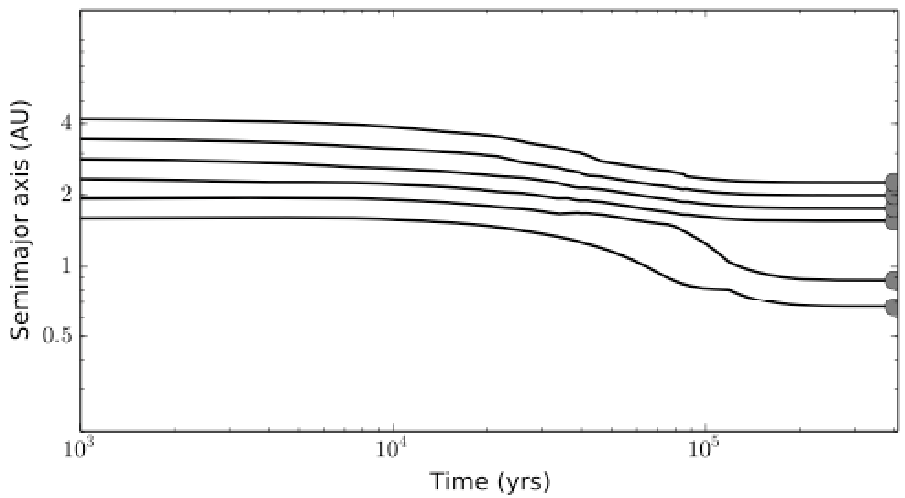
Migration in metal-rich disks

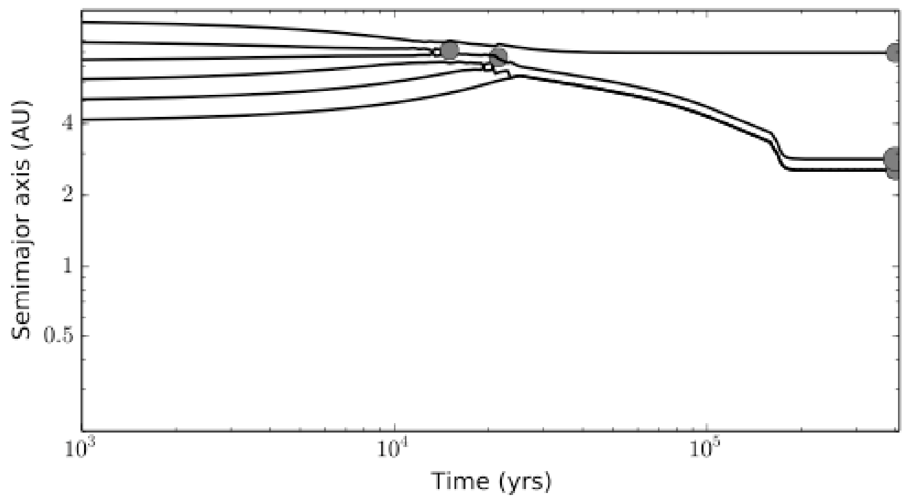


Importance of snow line







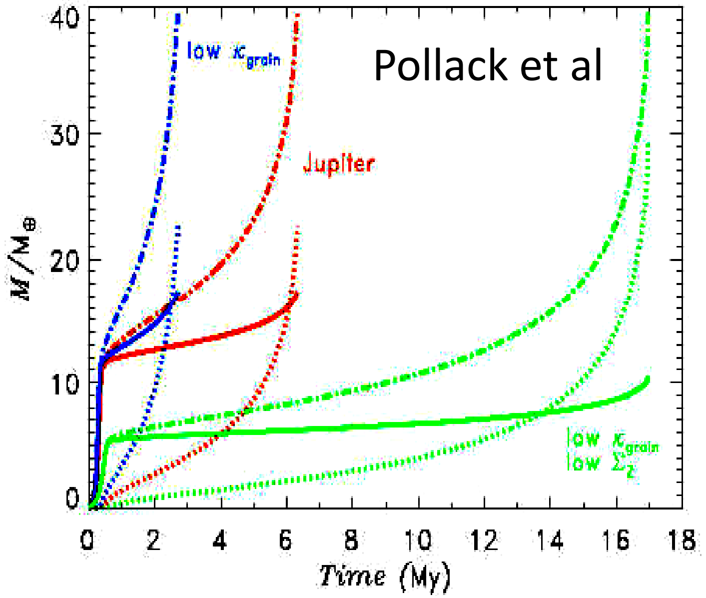


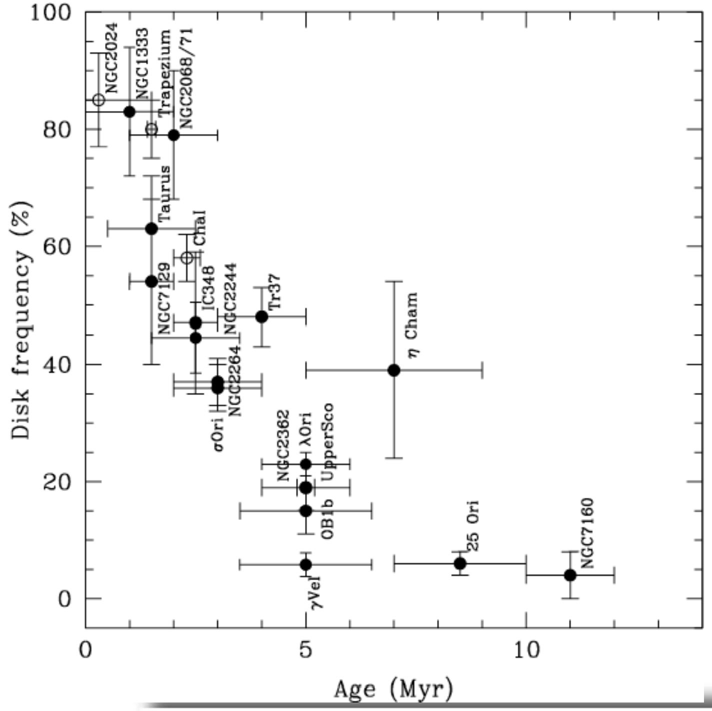
$10^{-8} M_o \; yr^{-1}$

$6 \times 10^{-8} M_o \; yr^{-1}$

Gas accretion barrier:

- Is there a threshold mass for gas accretion?





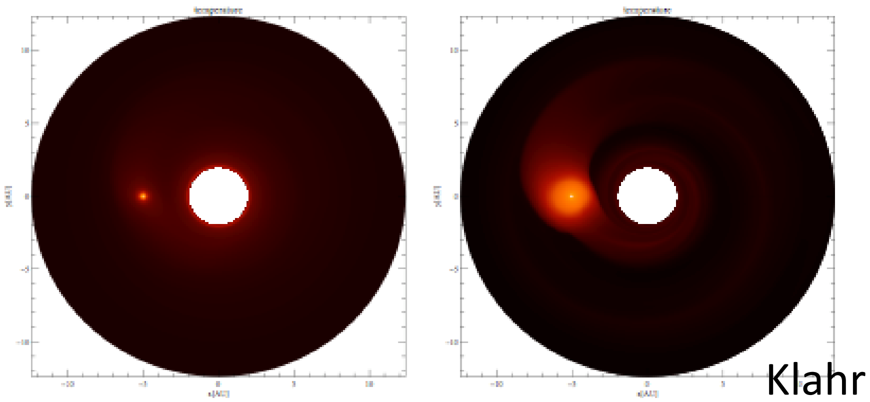
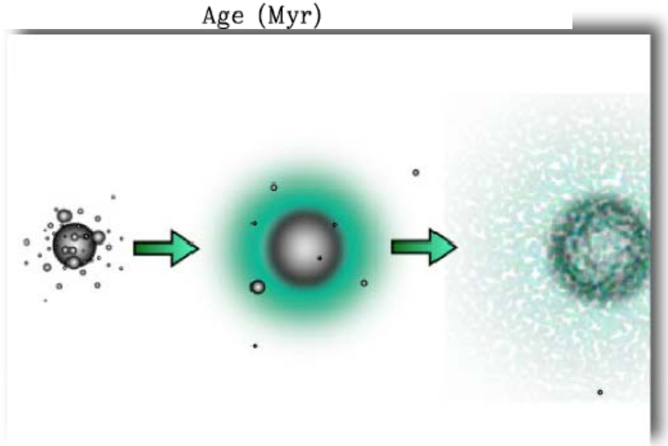
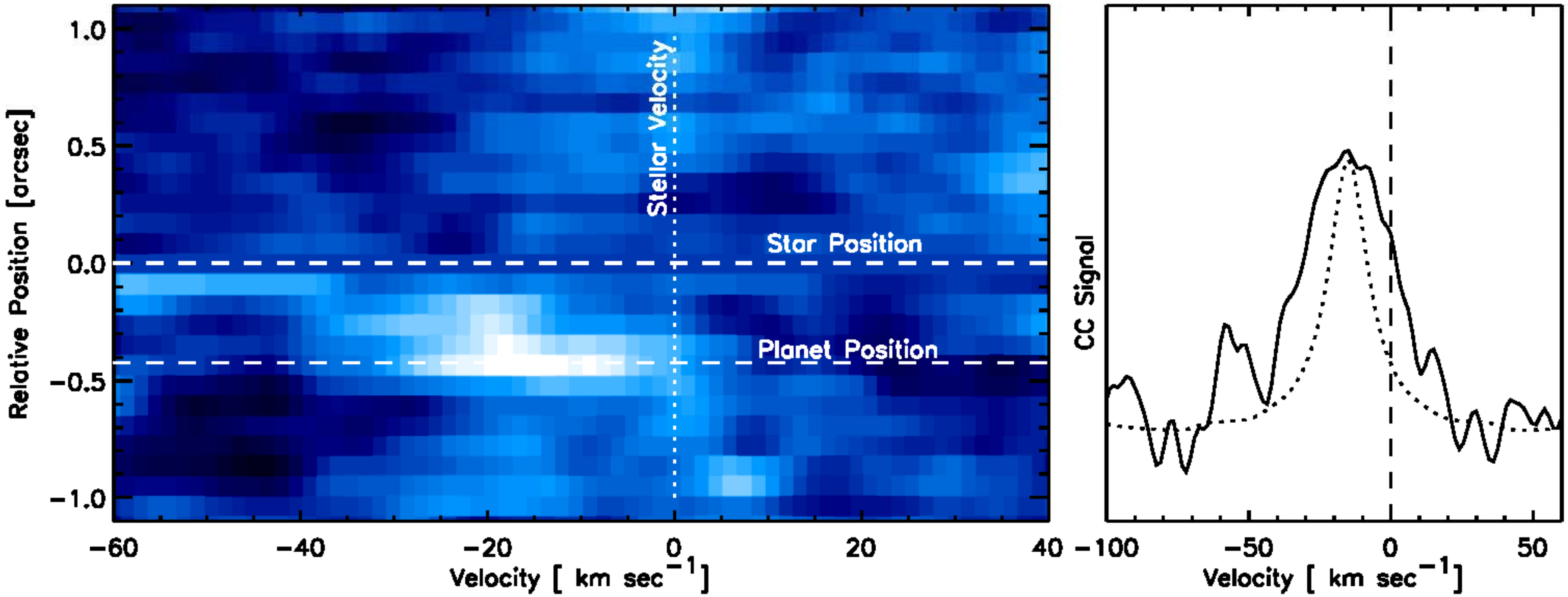


Fig. 4.— Tempertature distribution - left: $30M_\oplus$ and $\kappa = 0.01\kappa_0$; right: $30M_\oplus$ and $\kappa = 1\kappa_0$

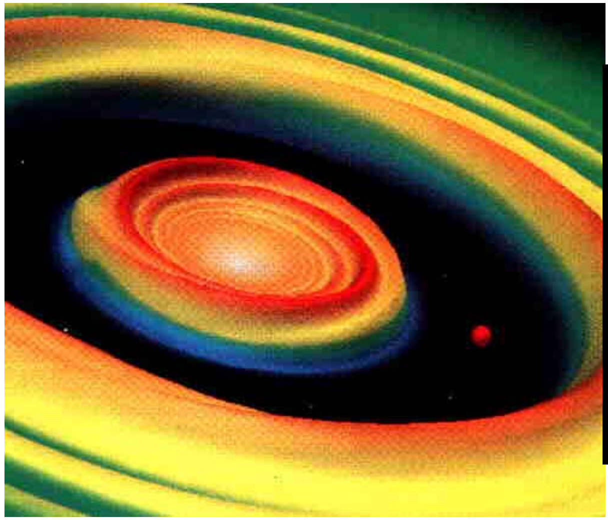


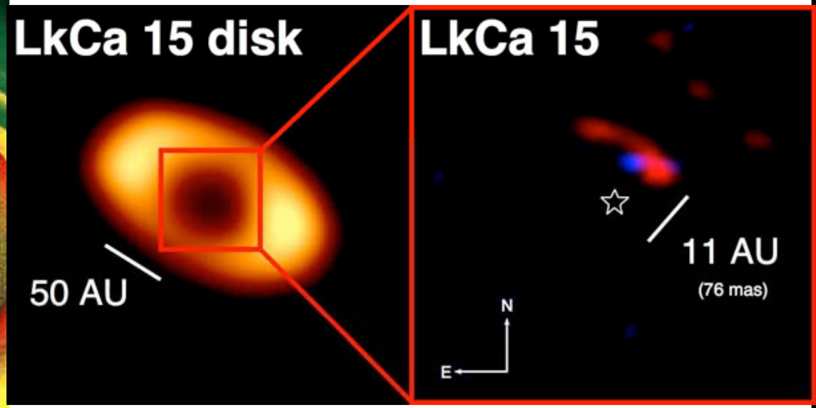
Radiation transfer & gas accretion

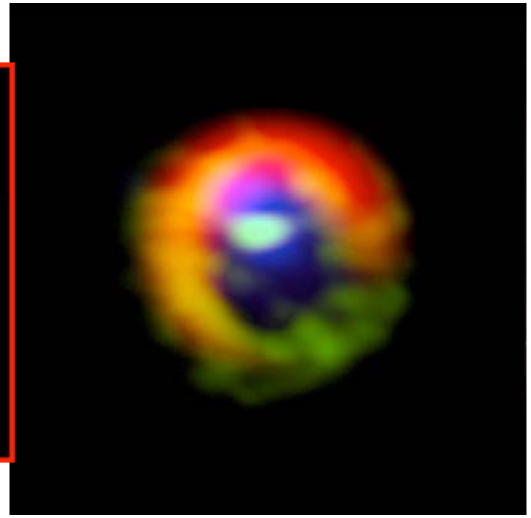
Fast spin of a young extrasolar planet *Snellen et al. - embargoed*

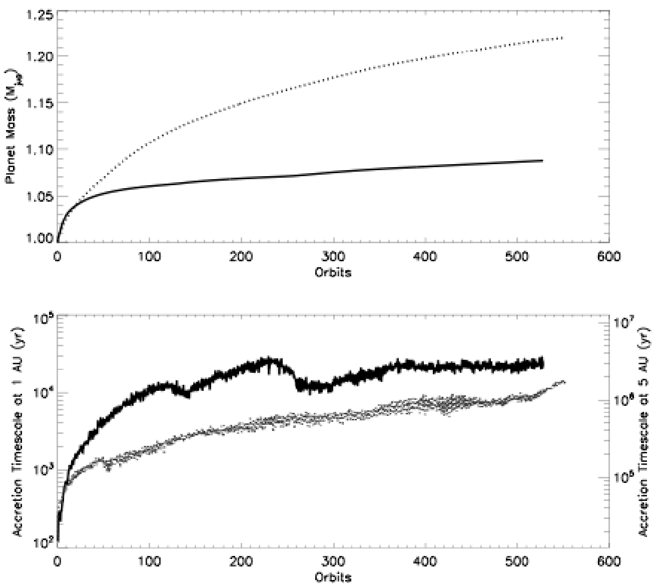


Gas giants' asymptotic mass

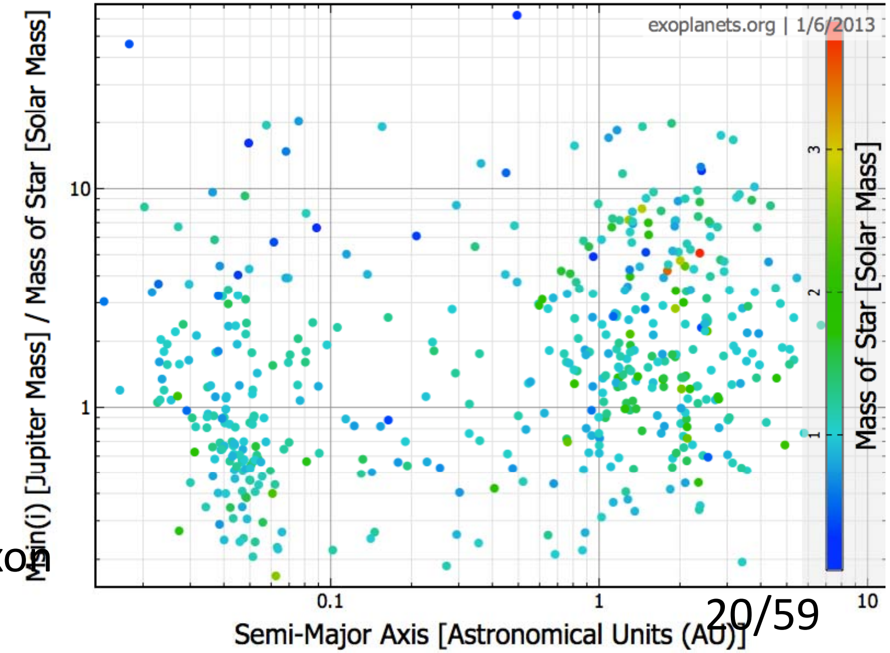




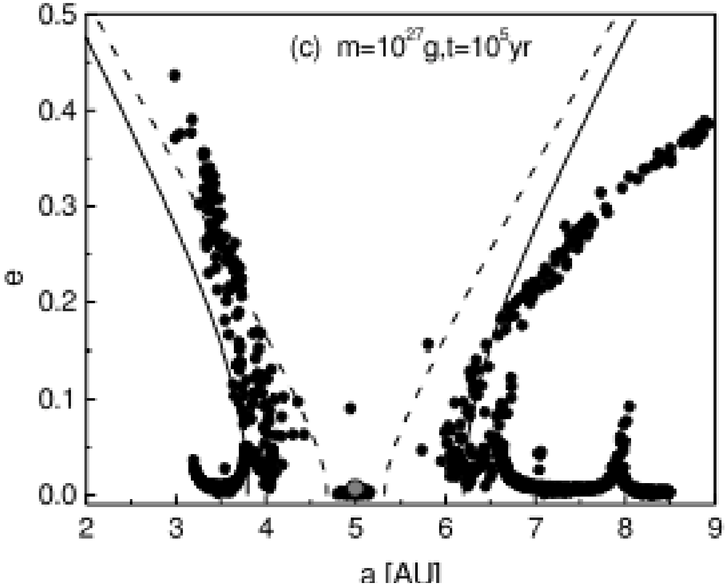


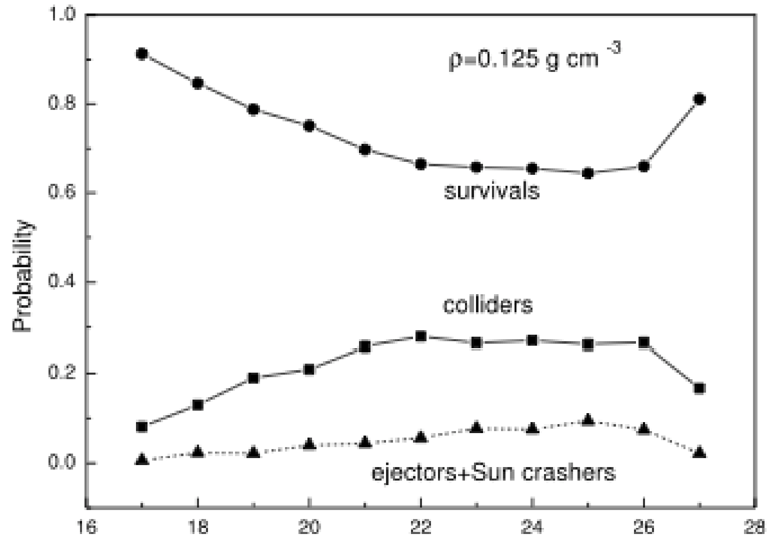


Dobbs-Dixon
Shulin Li

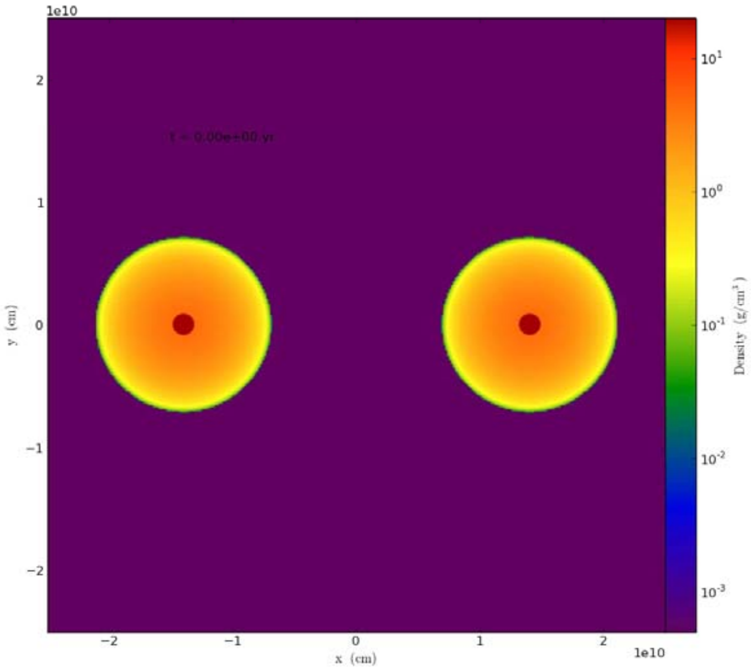


Giant impacts and mergers

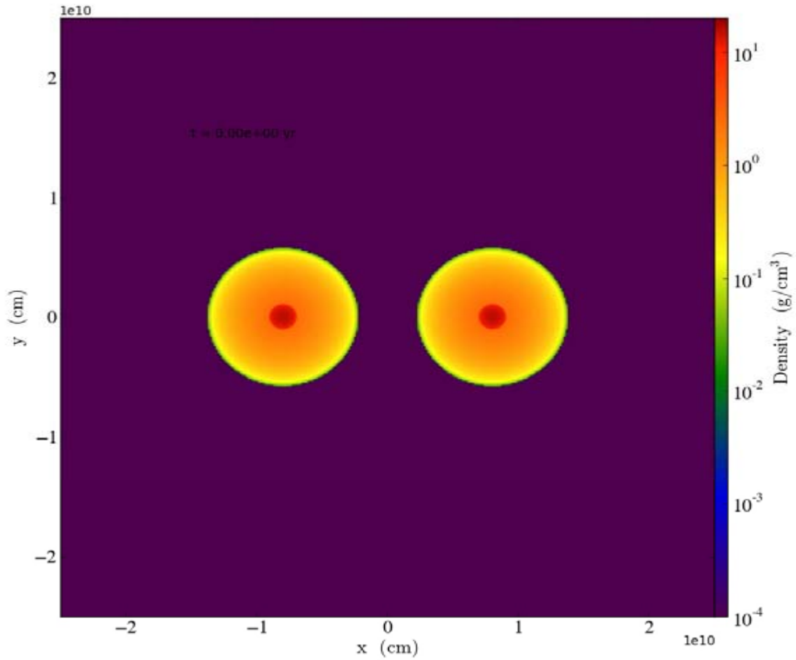




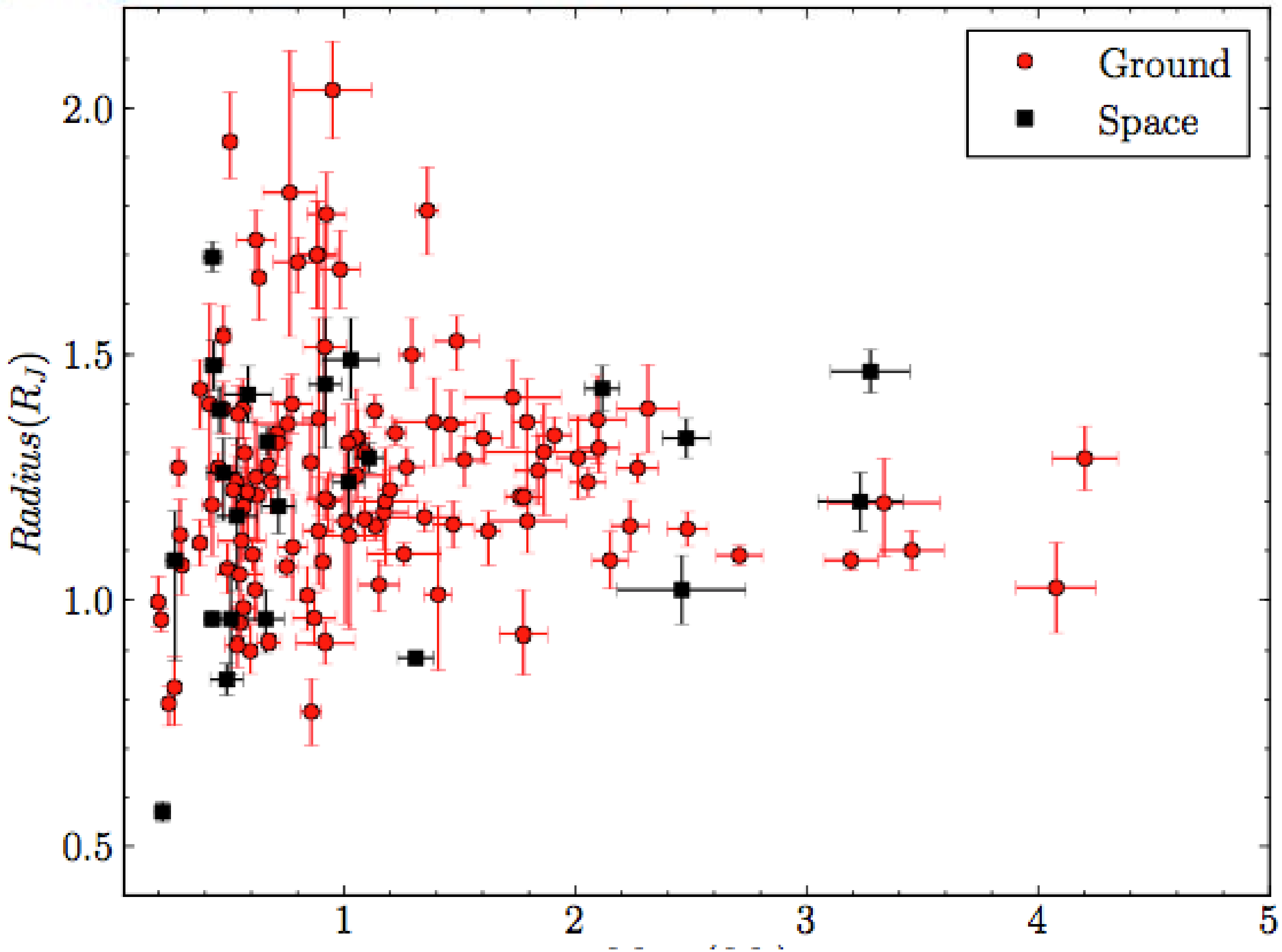
Zhou Jilin



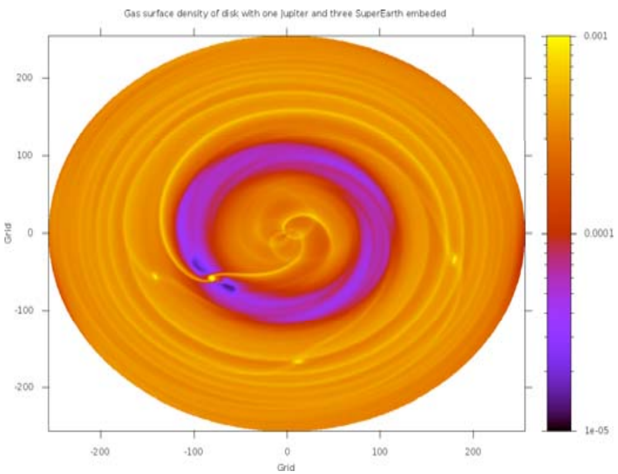
Liu Shangfei

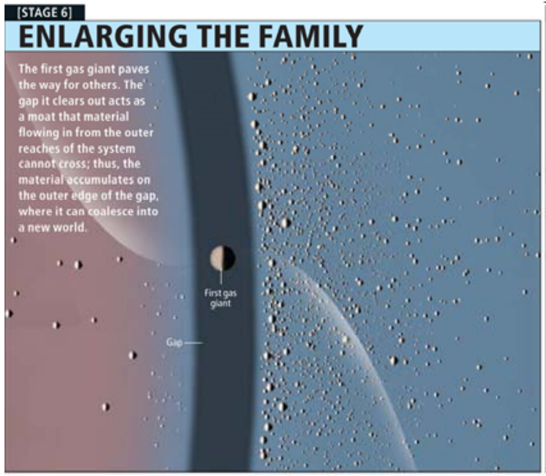


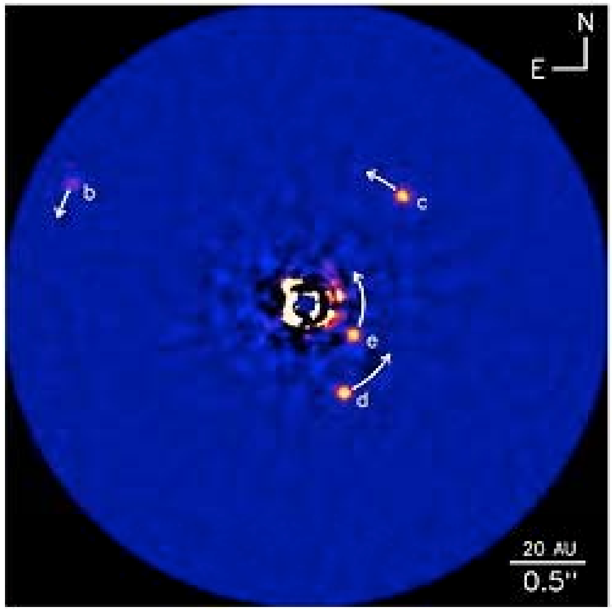
Highlight 1 - Densities (Bayliss)



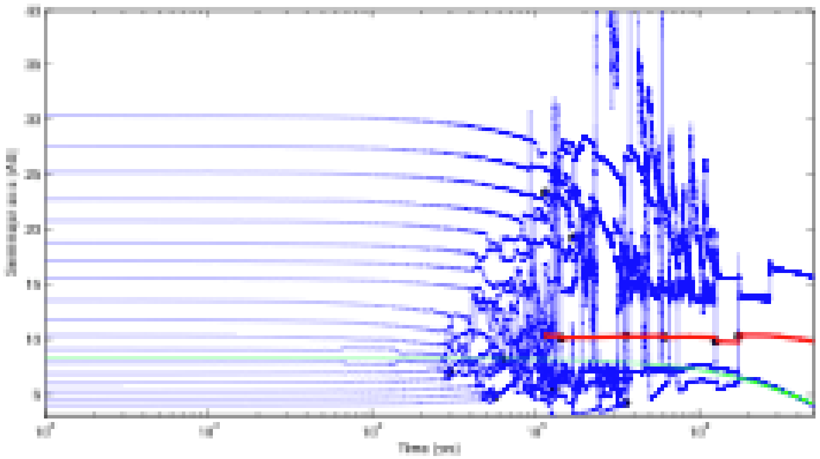
Enhanced formation of multiple planets

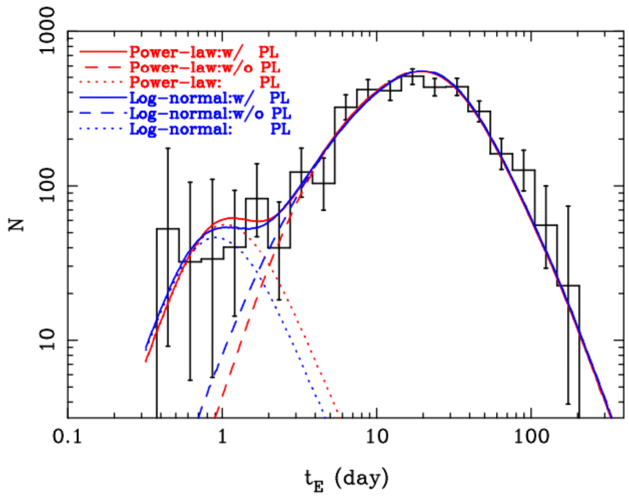






XJ Zhang

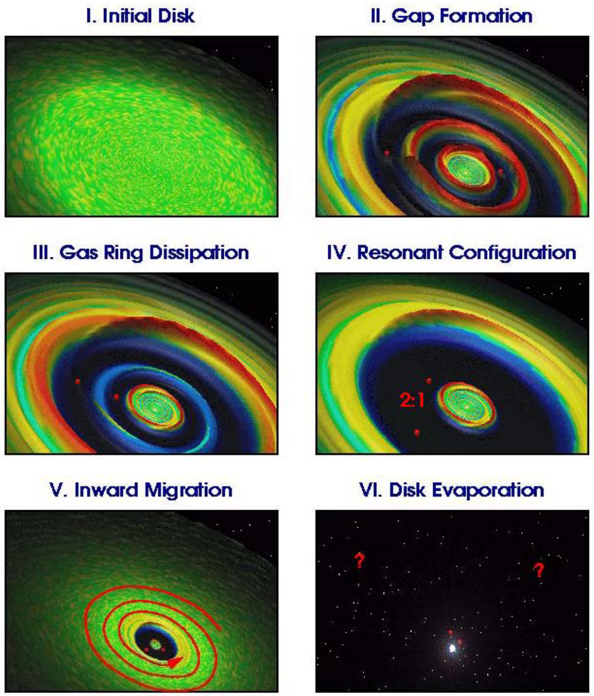




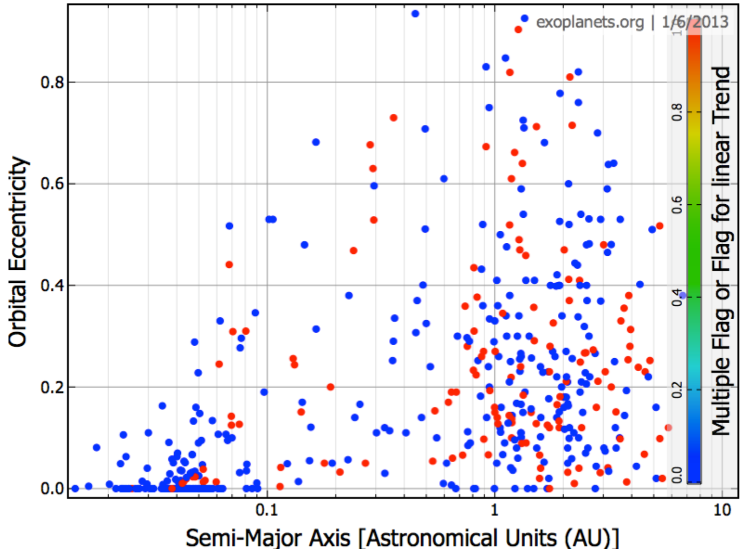
BB Liu

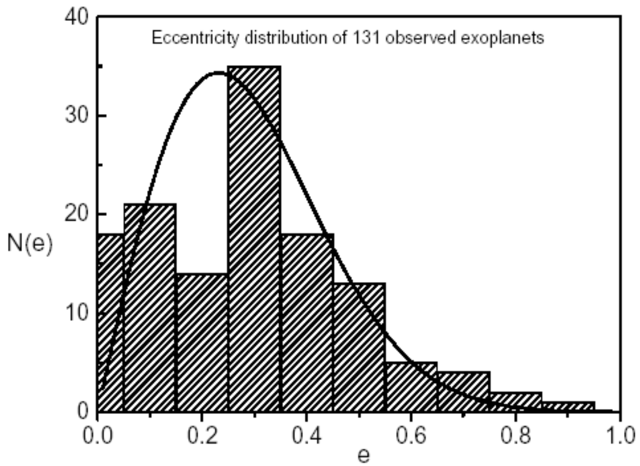
Grand design barrier: dynamical instability

- How did gas giants acquire their eccentricity?

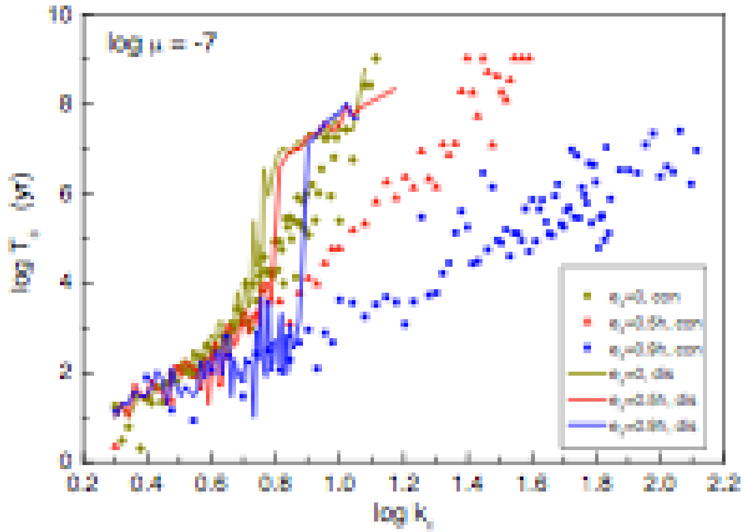


Bryden



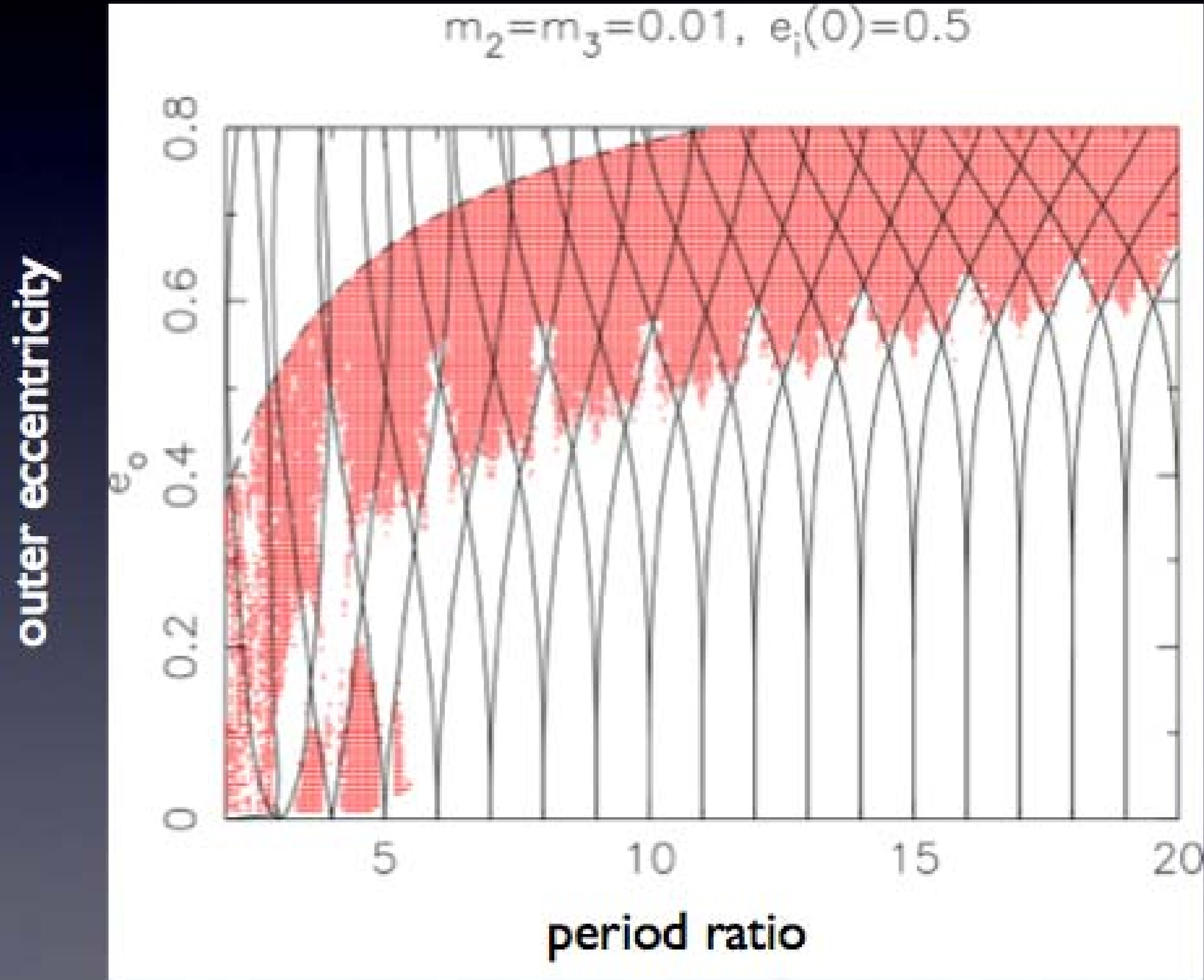


Jilin Zhou

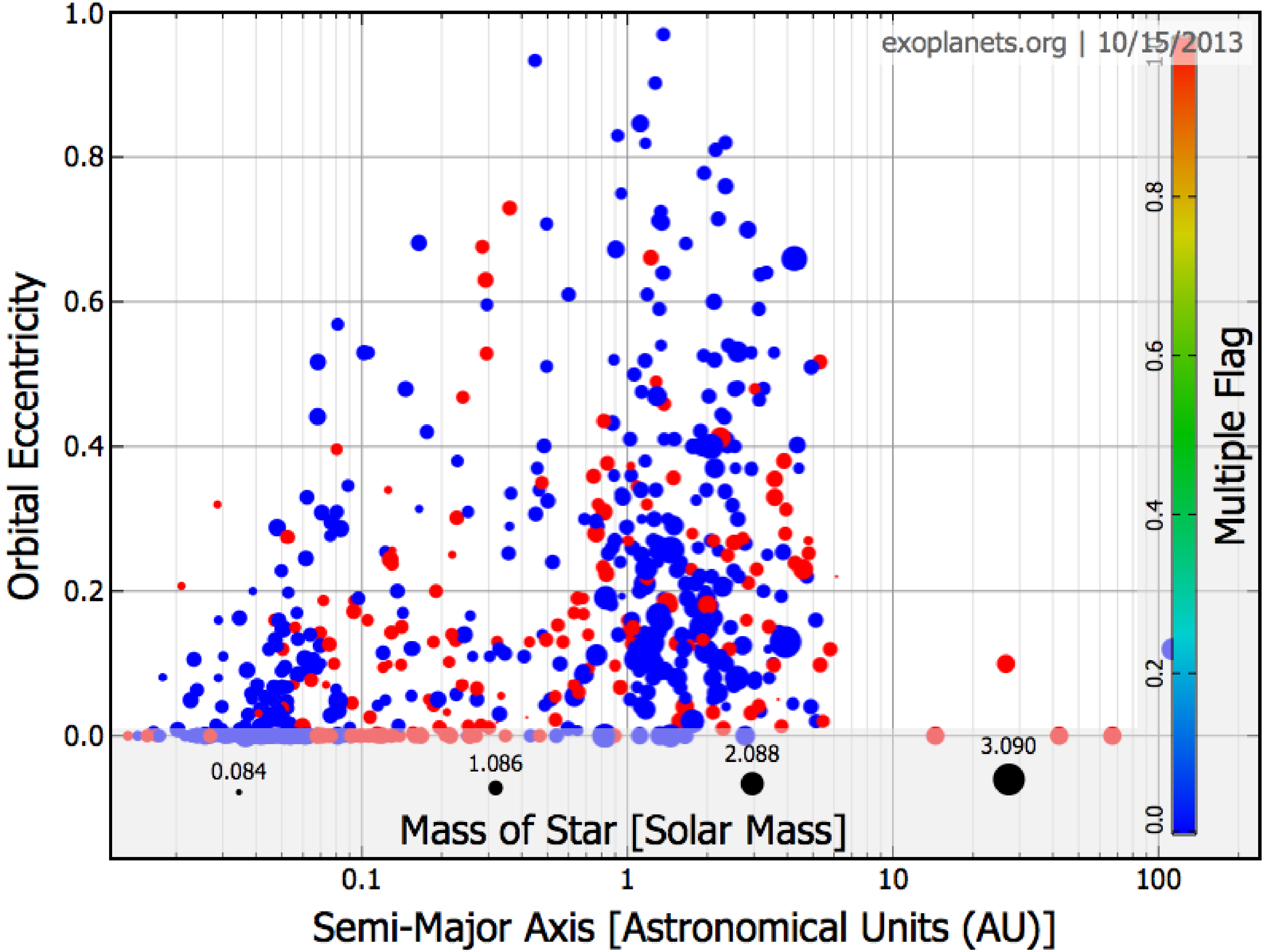


The stability boundary

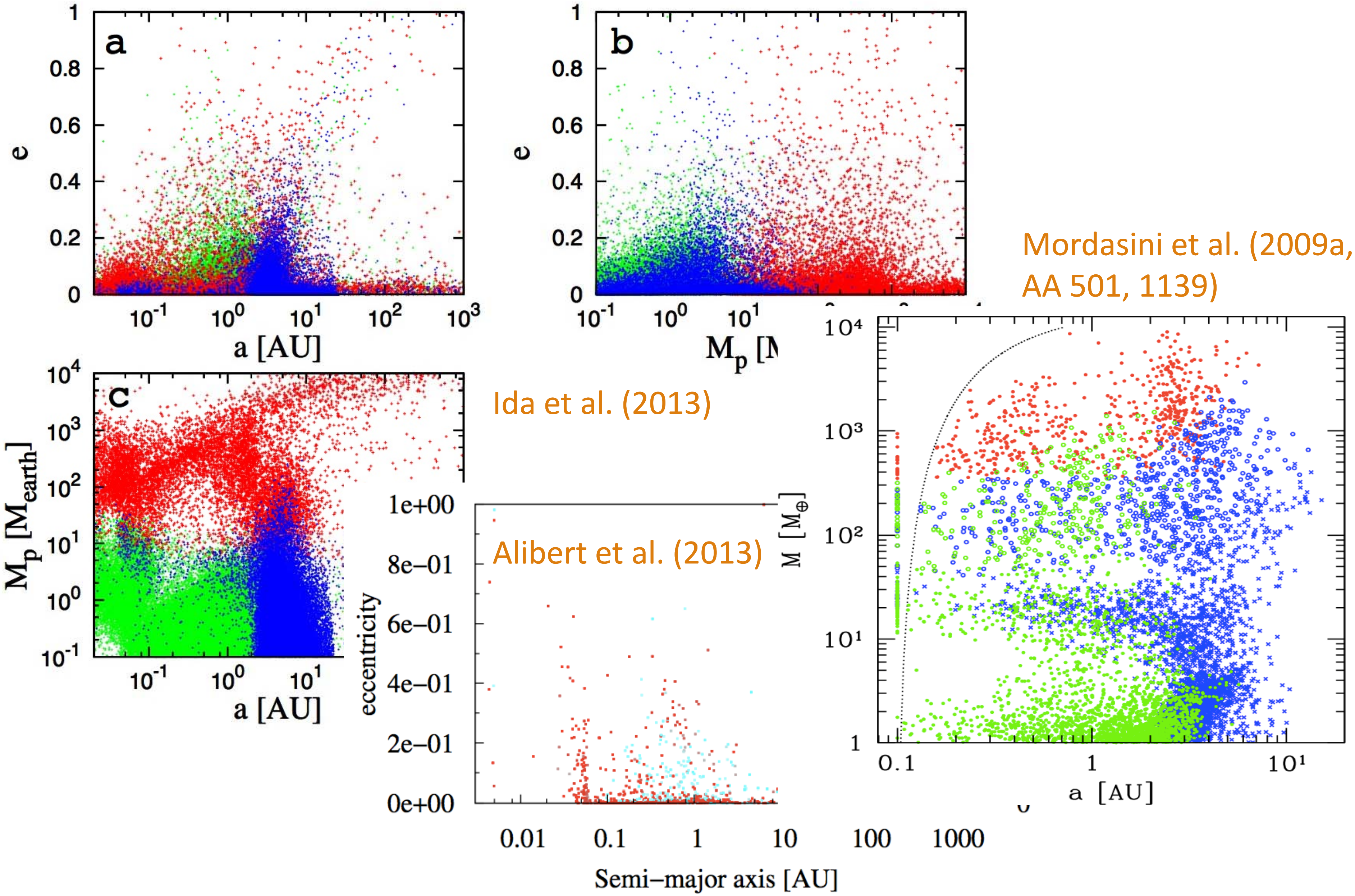
Mardling 2008, 2013



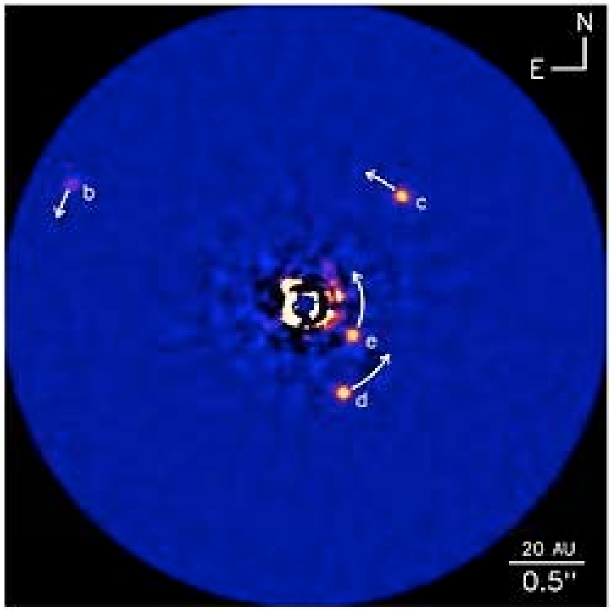
Dynamical diversity

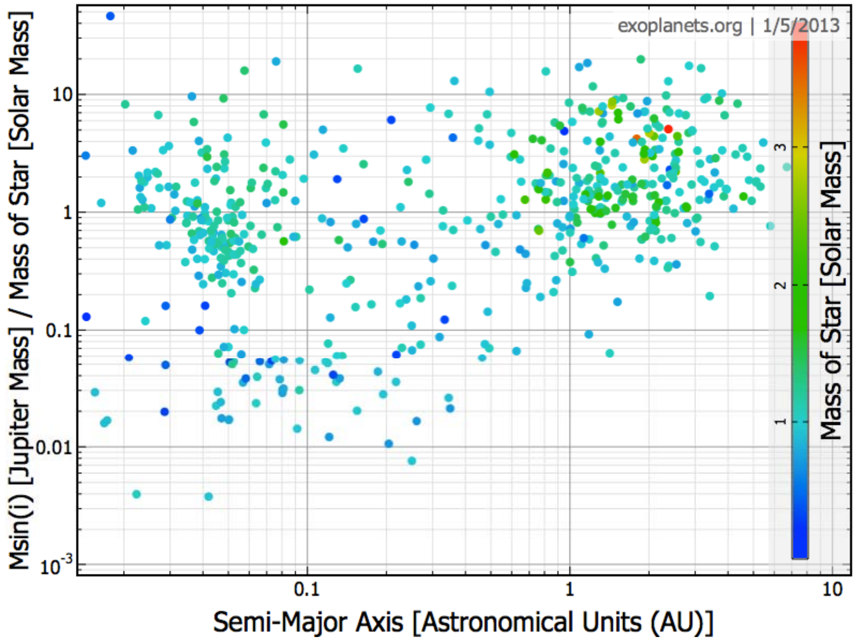


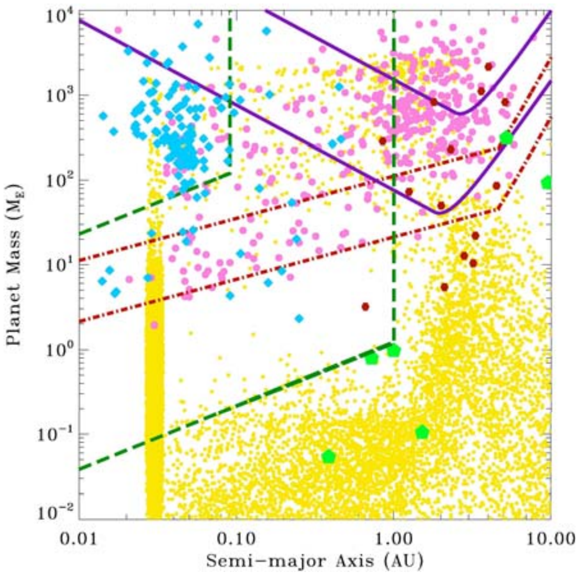
Superpose the final results of many different systems
→ predict distribution of planets (Ida)

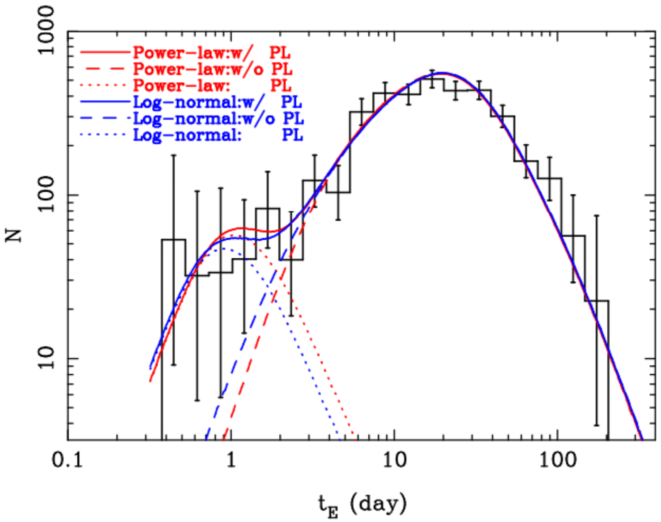


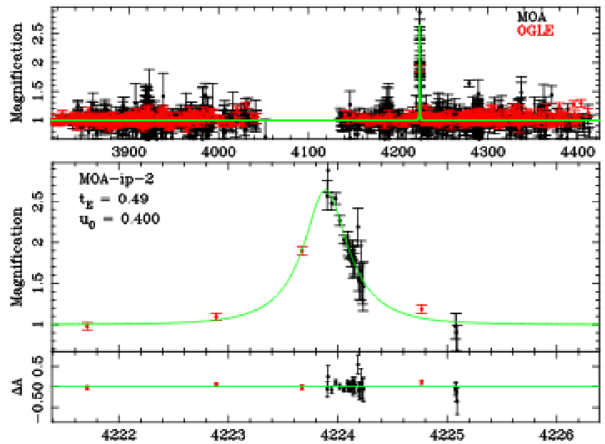
Long-period massive planets









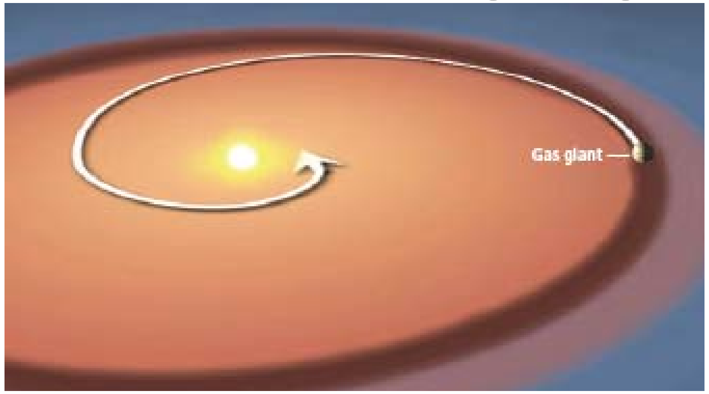


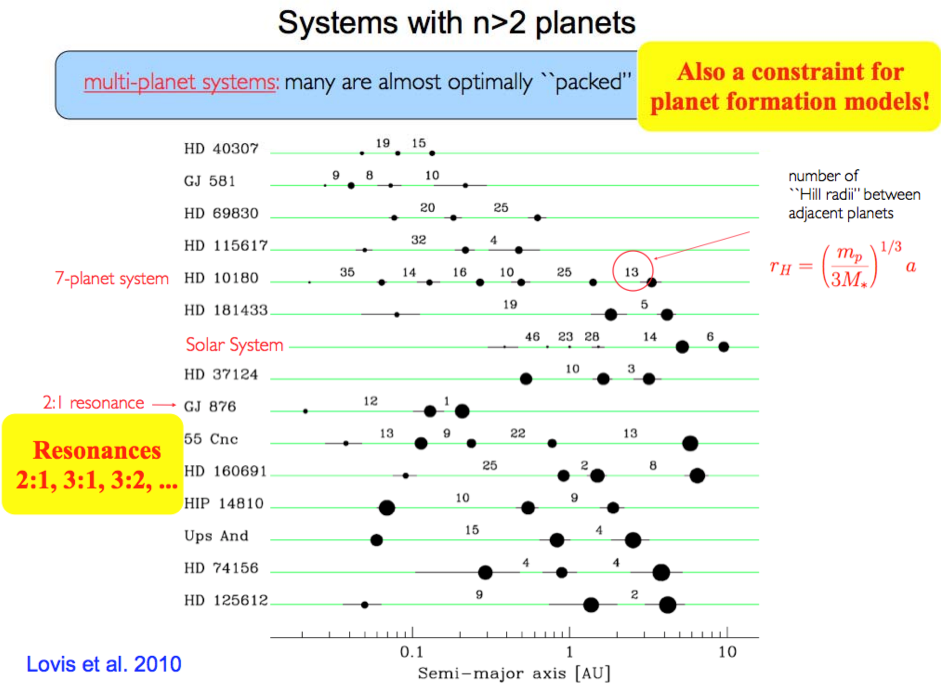
Major Challenges:

- Retention of grains: m-size barrier (Whipple)
- Fragmentation: km-size barrier (Benz)
- Planetesimal-growth barrier: Isolation mass barrier (Wetherill)
- Gas accretion barrier: critical-mass cores (Cameron)
- Retention of cores: type I migration (Goldreich & Tremaine, Ward)
- Retention of gas giants: type II migration (Lin & Papaloizou)
- Multiple gas giants: rapid depletion of disk gas
- Competing physics on multiple length & time scales

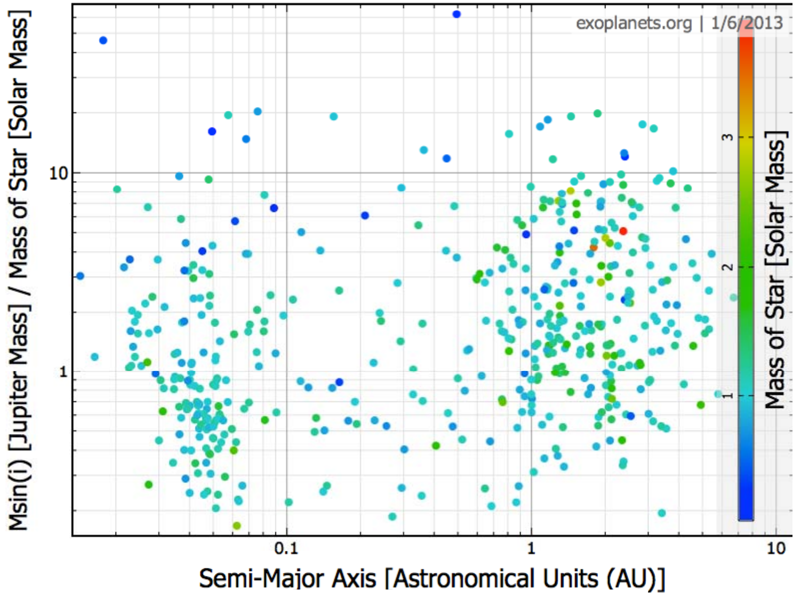
Giants’ retention barrier: type II migration

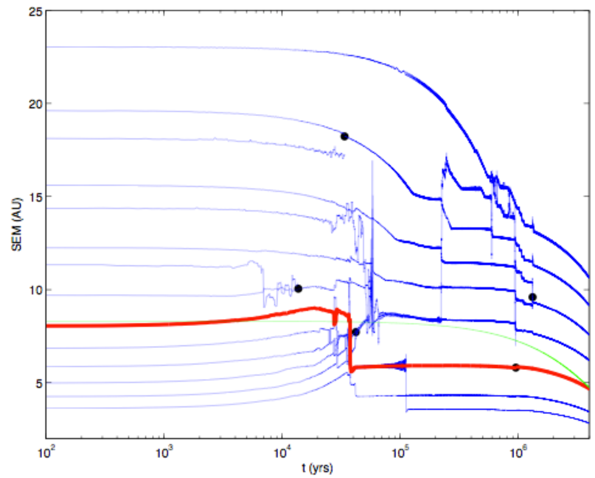
- How prevalent is gas giants’ migration?
- How do lone gas giants migrate?





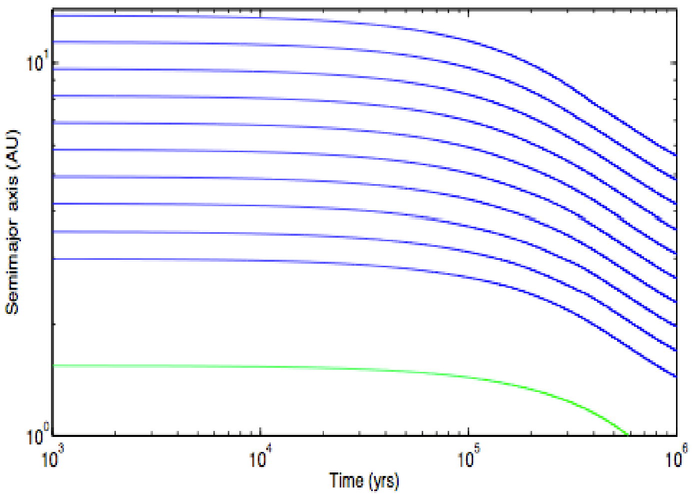
Lovis et al. 2010

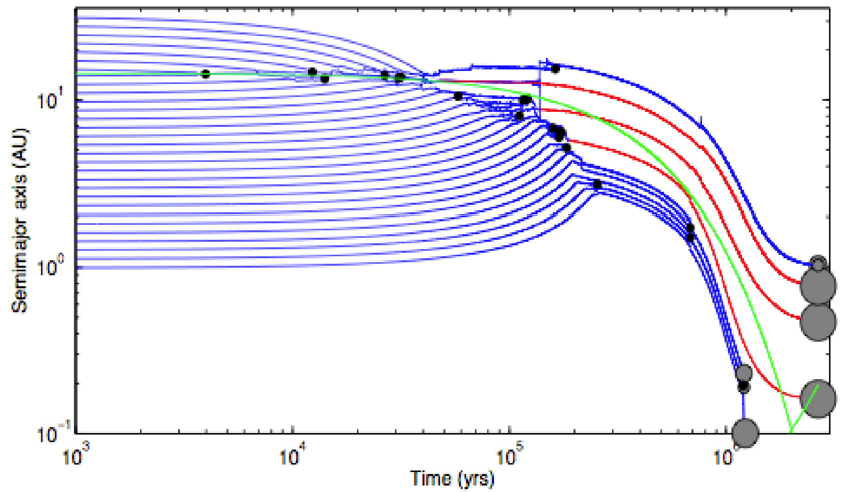




Core barrier: embryos' resonant trapping

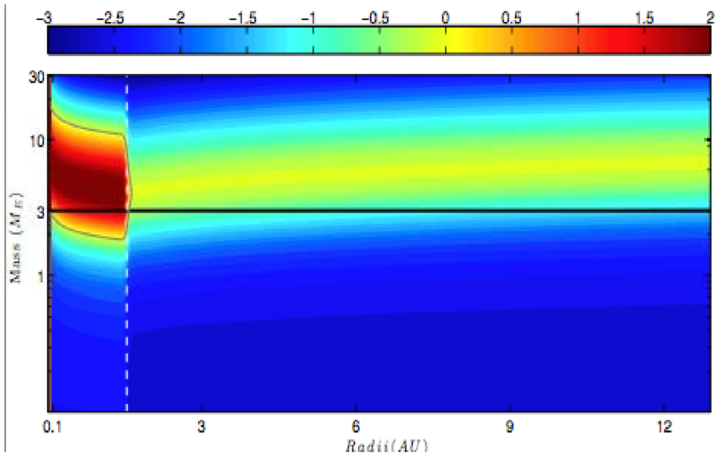
- Long term evolution: largest cores formed early

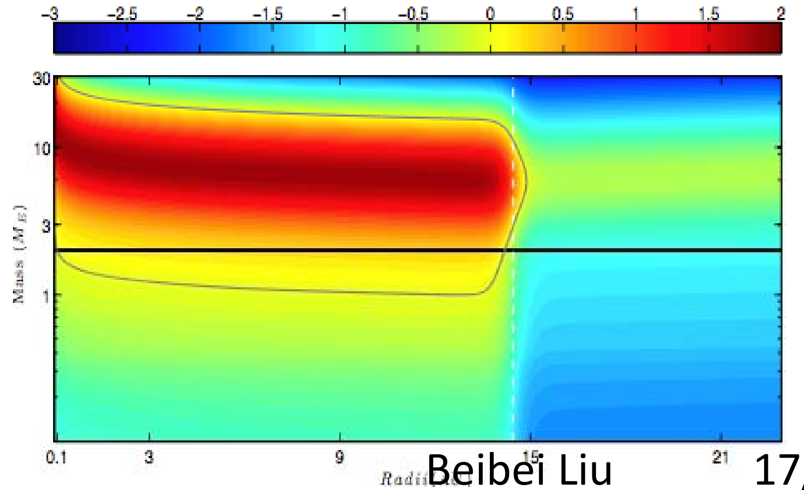




$\dot{\mathrm{M}} = 1 \times 10^{-8}\ \mathrm{M}_{\odot}/\mathrm{yr}\ \alpha = 10^{-2}\ \tau = 1 \times 10^{6}\mathrm{yrs}$

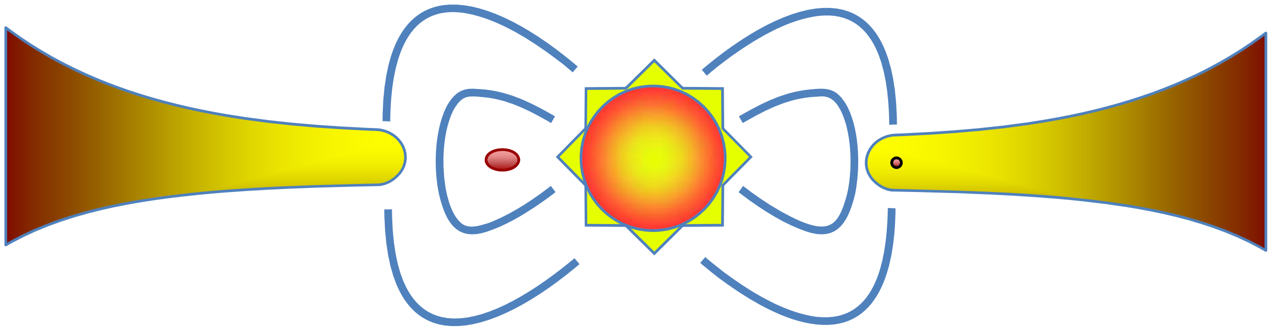
$\dot{\mathrm{M}} = 3 \times 10^{-7}\ \mathrm{M}_{\odot}/\mathrm{yr}\ \alpha = 10^{-3}\ \tau = 3 \times 10^{5}\mathrm{yrs}$





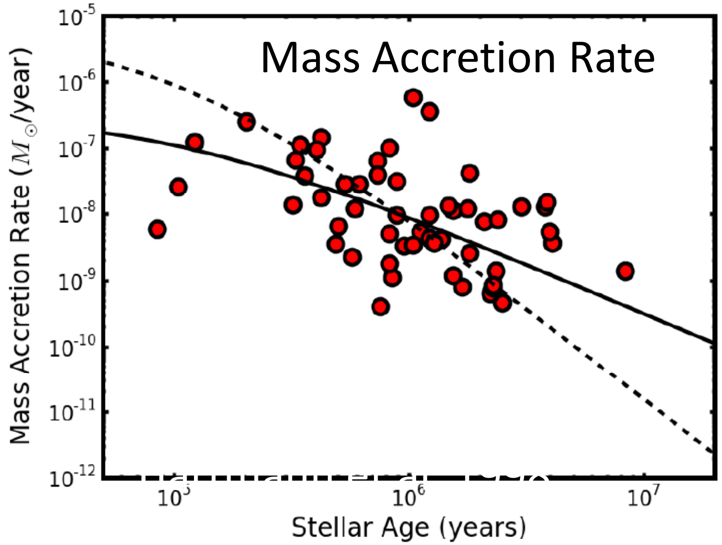
Hot jupiter retention barrier: stellar consumption

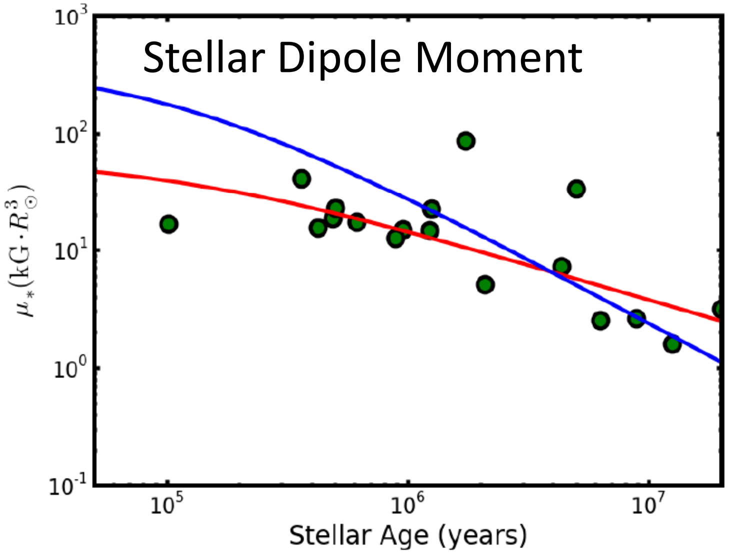
Stalling of planets inside & at the magnetospheric truncation radius



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

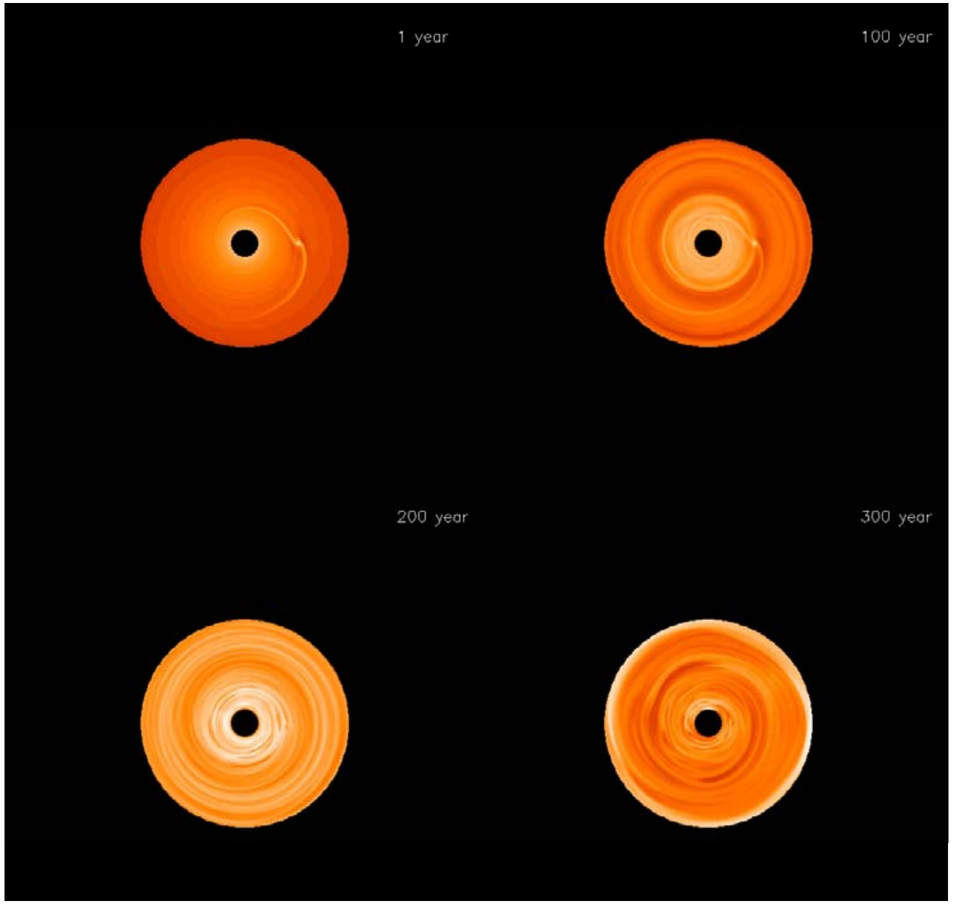
Konigl

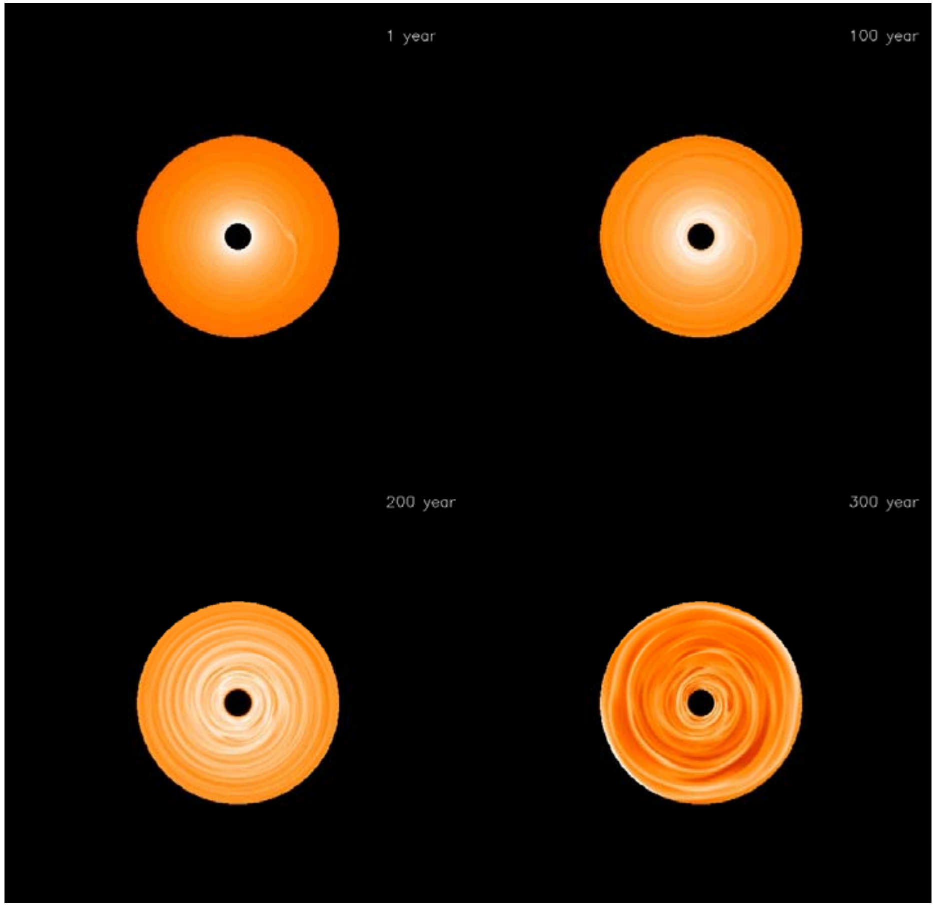




Herczeg

Stalling near the magnetosphere

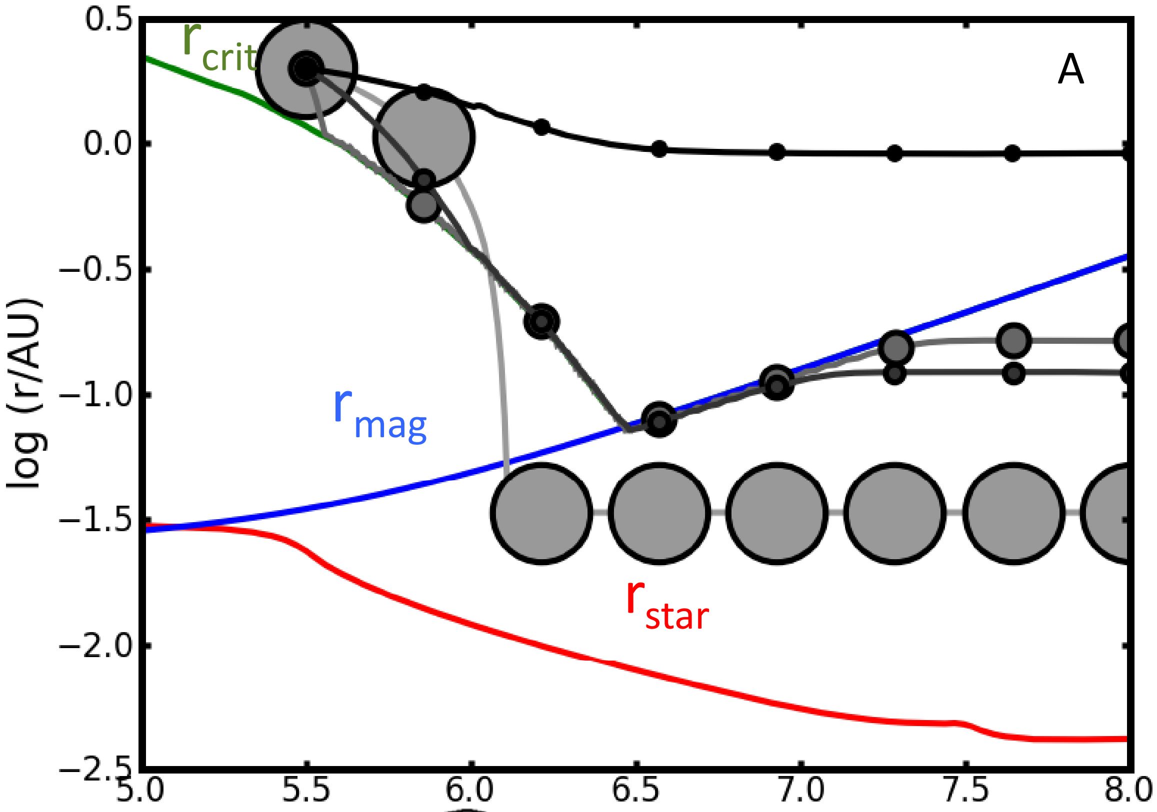




Hot Jupiters versus close-in super Earths
Zhuoxiao Wang

Super Earths: some key issues

- How to differentiate type I and II migration?

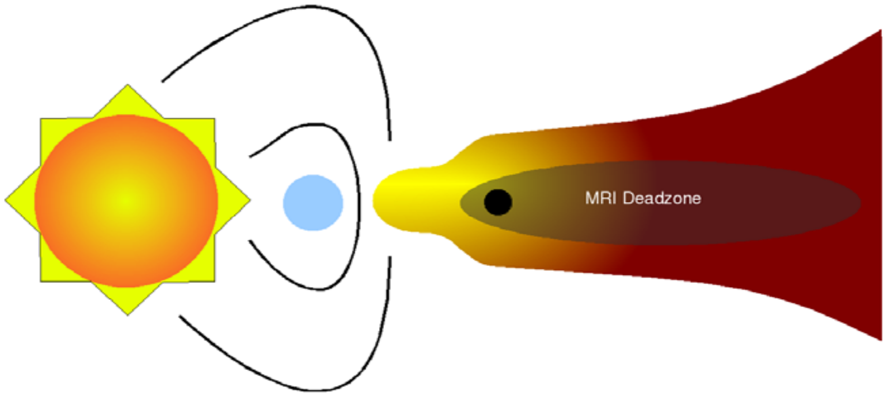


Sub/warm Earths

Neptunes

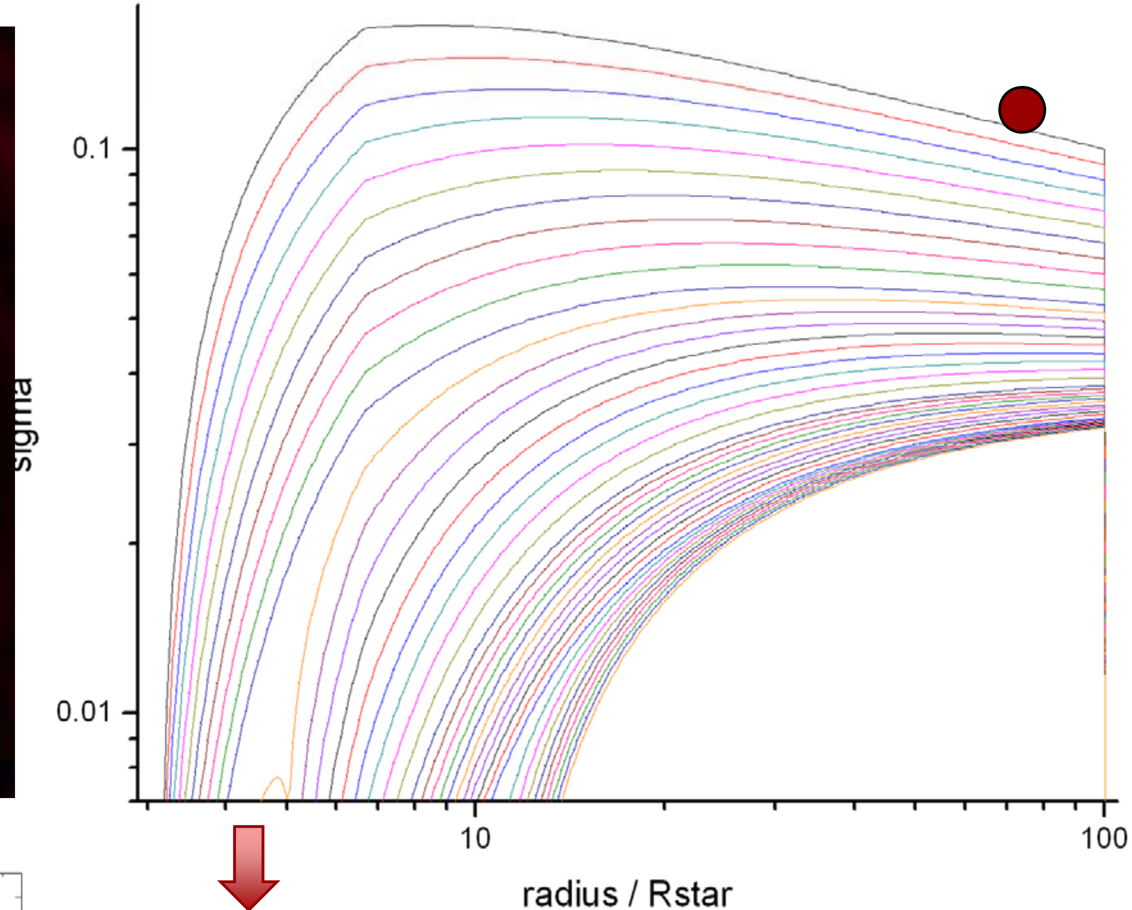
SuperEarths

Gas giants

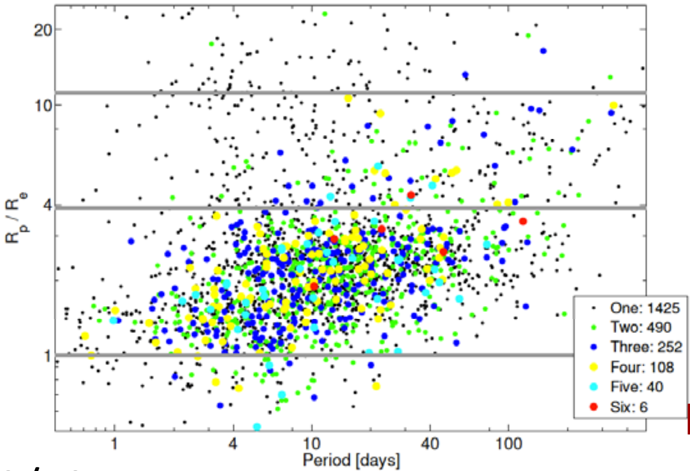


Hot Jupiters park Closer than Super Earths

Kretke



Migration of a Super Earth in protostellar disk around a magnetized T Tauri star. The Super Earth: (a) grows & migrate inward to inner-edge; (b) migrates slightly outwards with the expanding disk inner edge; (c) halts migrating after gas is mostly depleted. (Ju et al 2013 in preparation)



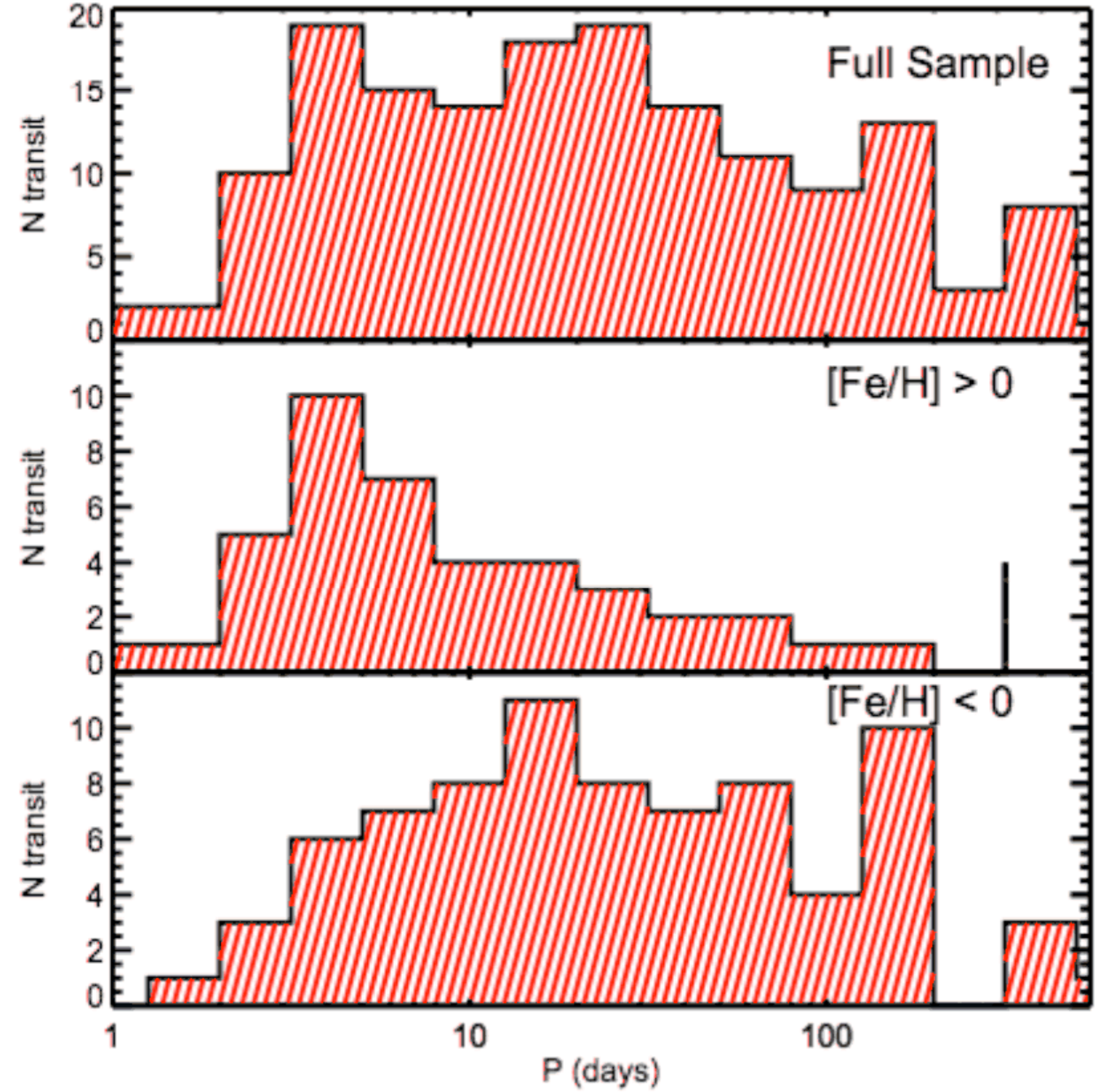
To model P distribution of Kepler's new-found planetary candidates.

KIAA undergraduate student Ju Wenhua now at Princeton U

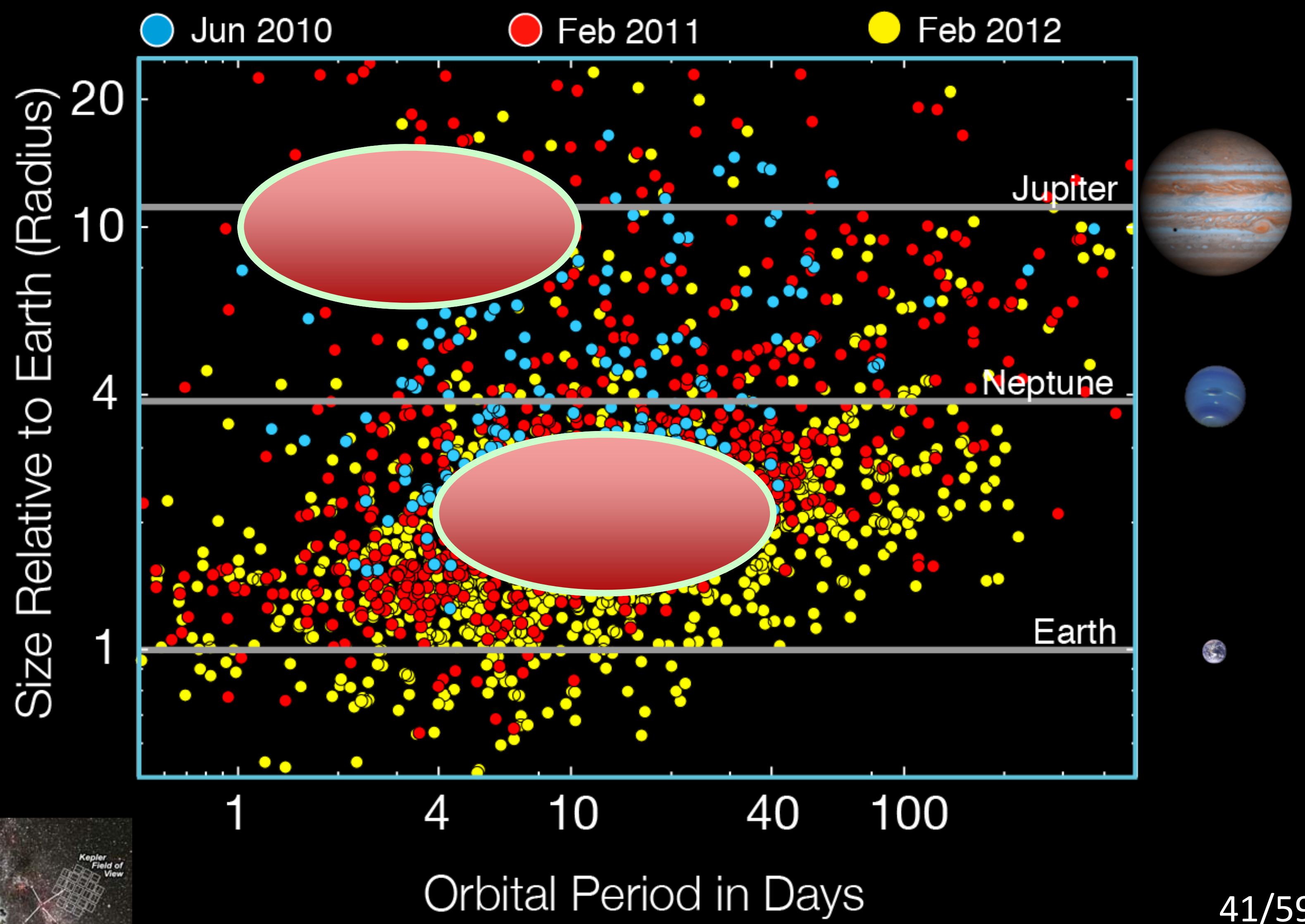
Challenge to Theory of Planet Formation

- Why are super Earths so ubiquitous?
- What criteria determine the fraction of stars which bear gas giants?
- What processes led to planets' mass and size distribution?
- How did planets acquire their period distribution?

Period distribution of hot Jupiters: Dependence on stellar metallicity

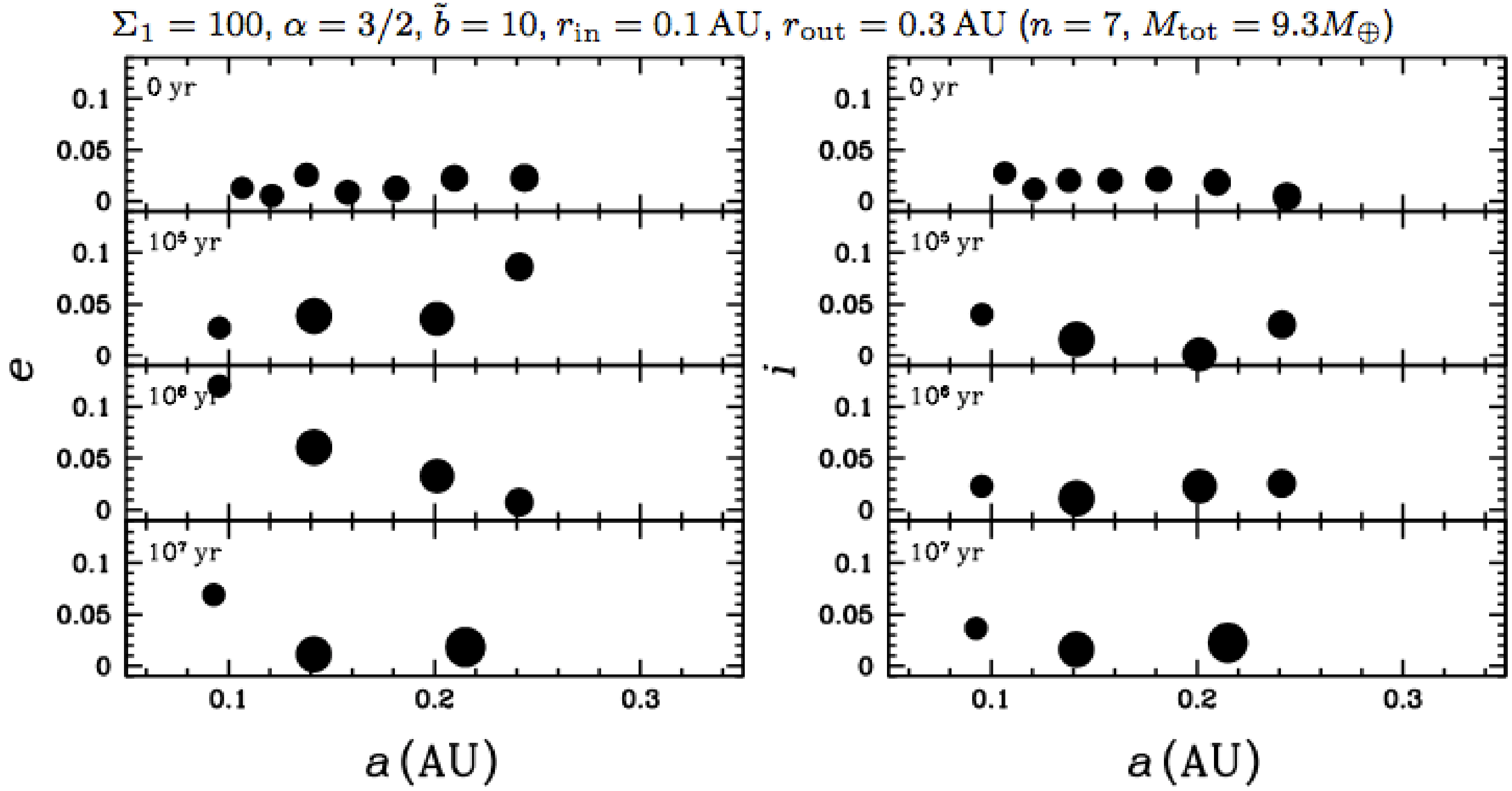


Planets' size-period distribution from the Kepler surveys



In Situ Formation of Super Earth (Kokubo)

$\Sigma_1 = 100$ Disk – An Example Run



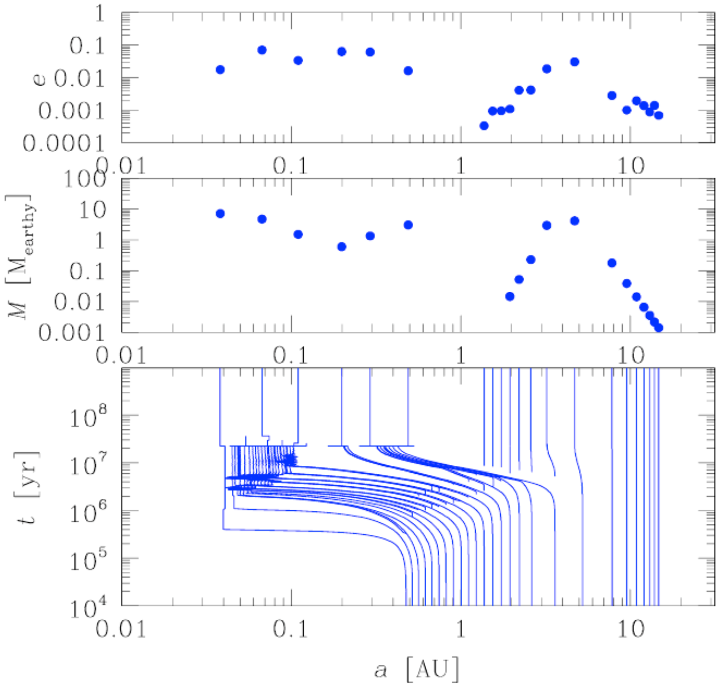
$n = 3$

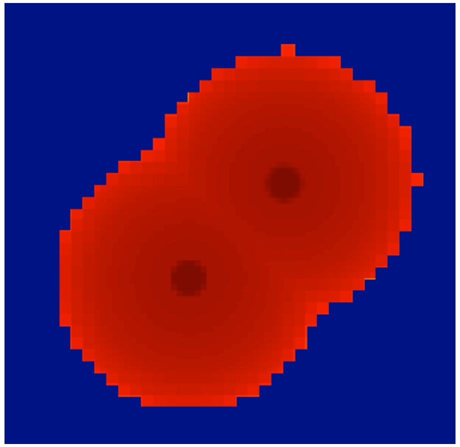
$M_1 = 4.8 M_\oplus$ ($a_1 = 0.21$ AU, $e_1 = 0.02$, $i_1 = 0.02$)

$M_2 = 3.5 M_\oplus$ ($a_2 = 0.14$ AU, $e_2 = 0.01$, $i_2 = 0.02$)

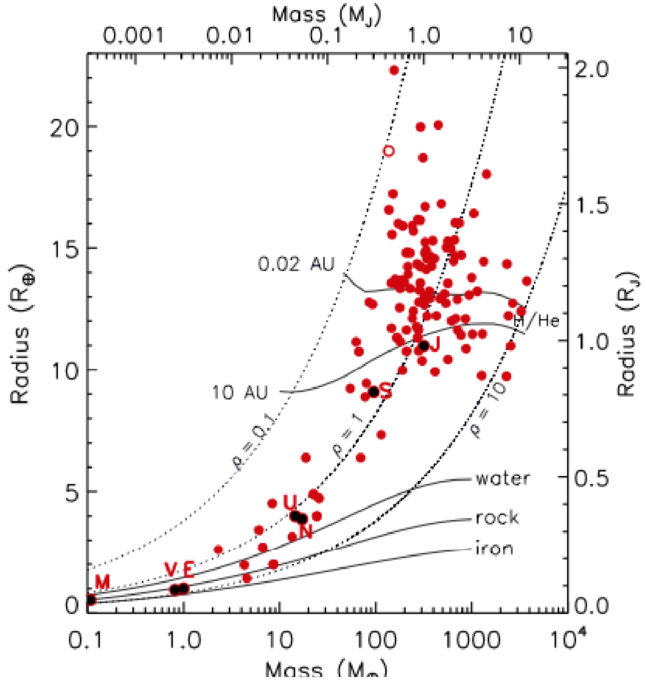
Super Earths: some key issues

- How to identify *in situ* assembly?

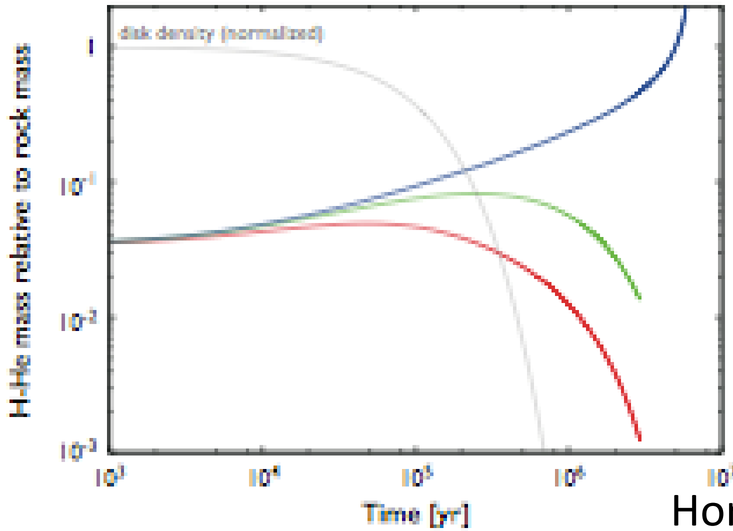




Ida



For a $10M_e$ planet at 0.04AU
R_{roche} ~0.02a ~8R_e
R_p ~ 2-3 R_e ~0.3 R_{roche}
R_m ~R_{roche} if B~10 Gauss
H ~ 0.02 a ~R_{roche}

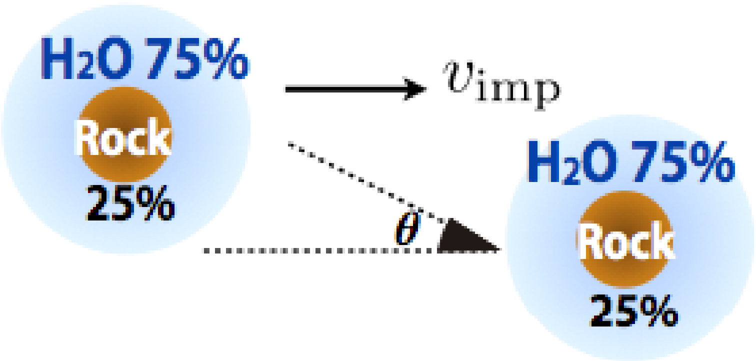


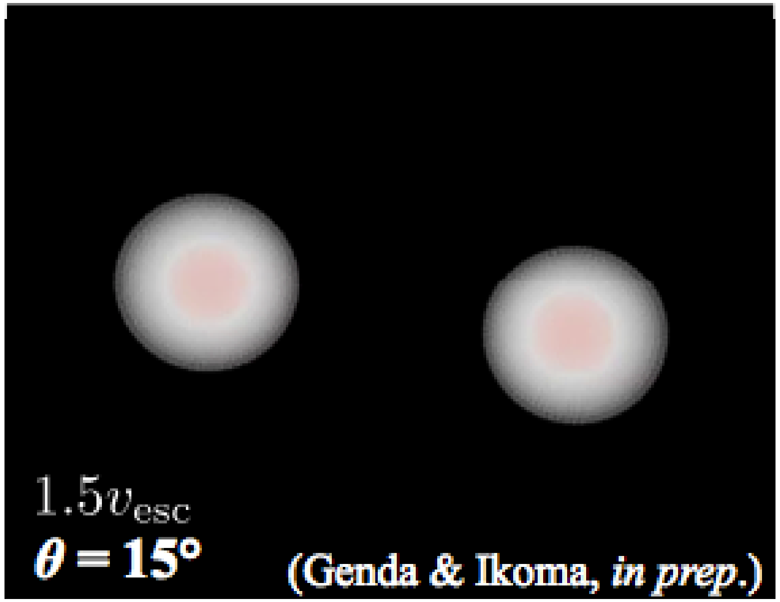
Hori

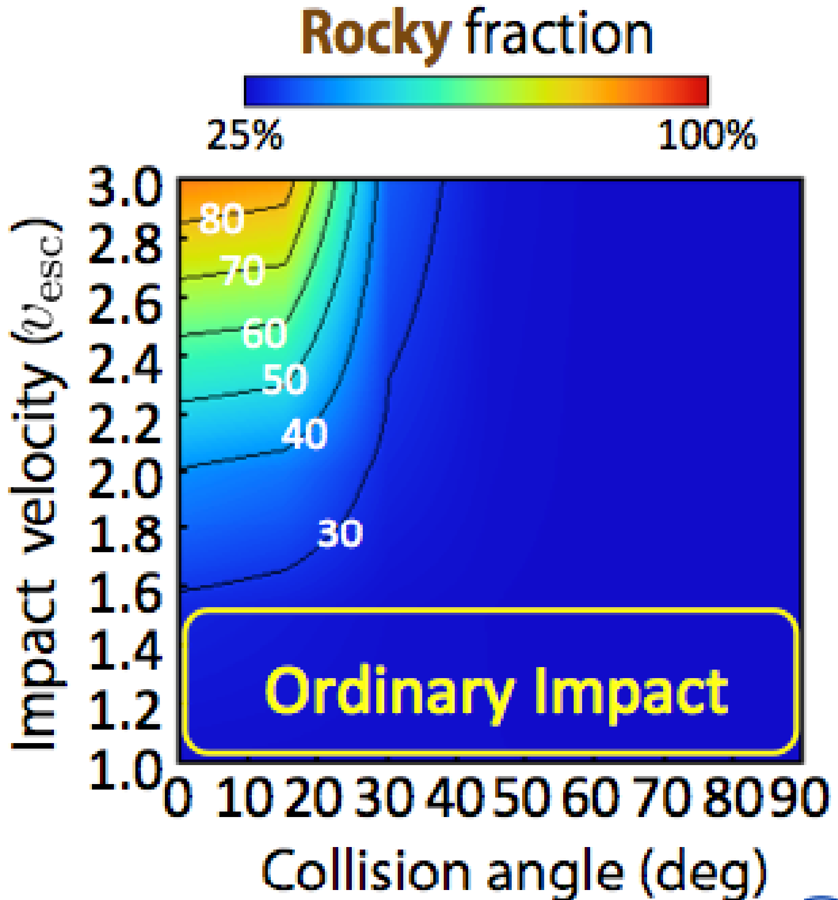
Mantle Stripping of Water-dominated Planets

(Hori)

SPH simulation
(Two $5M_\oplus$ super-Earths)



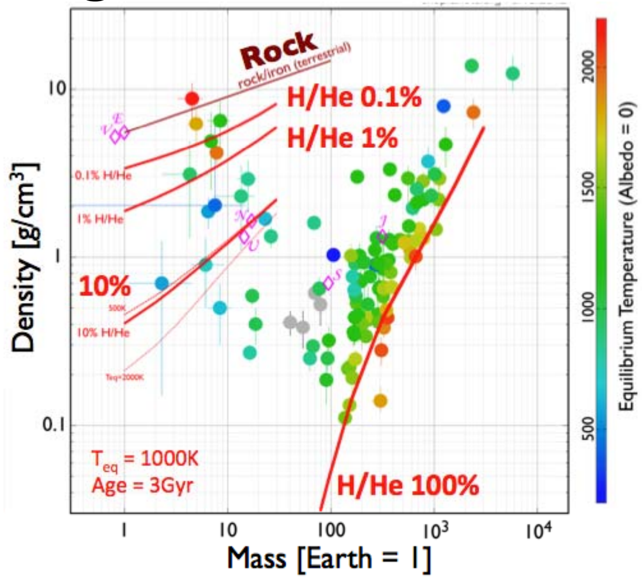


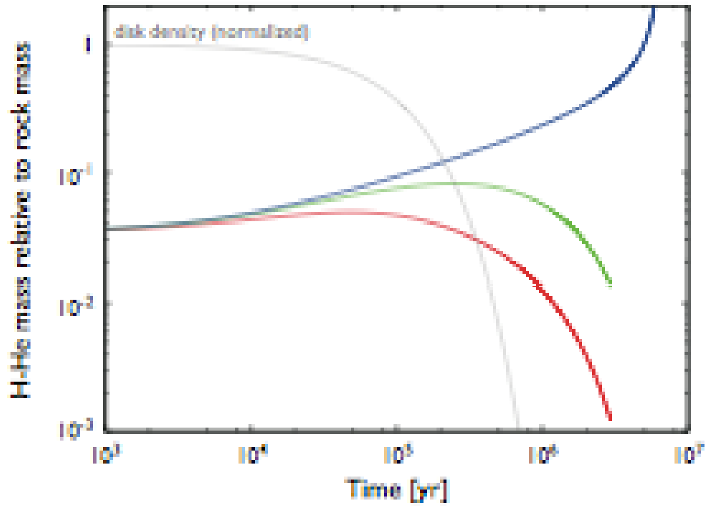


Giant impacts change little the ratio

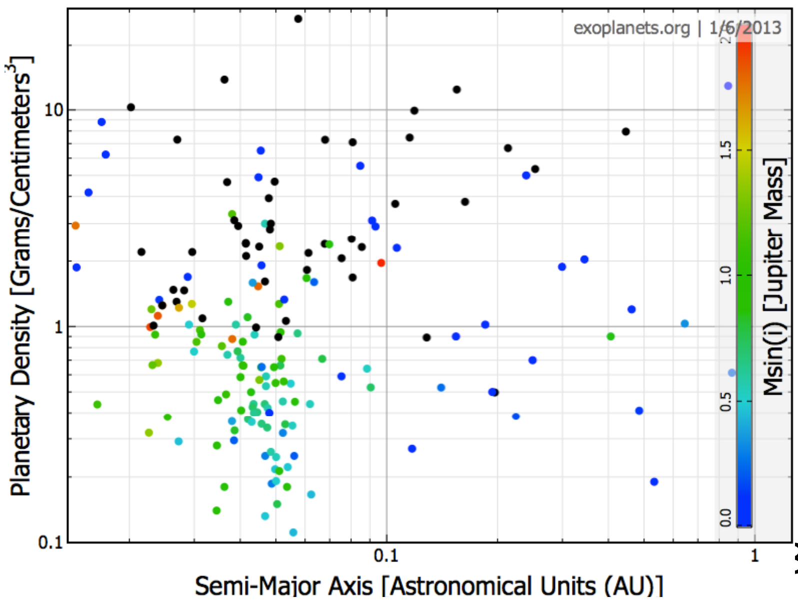
Super Earths: some key issues

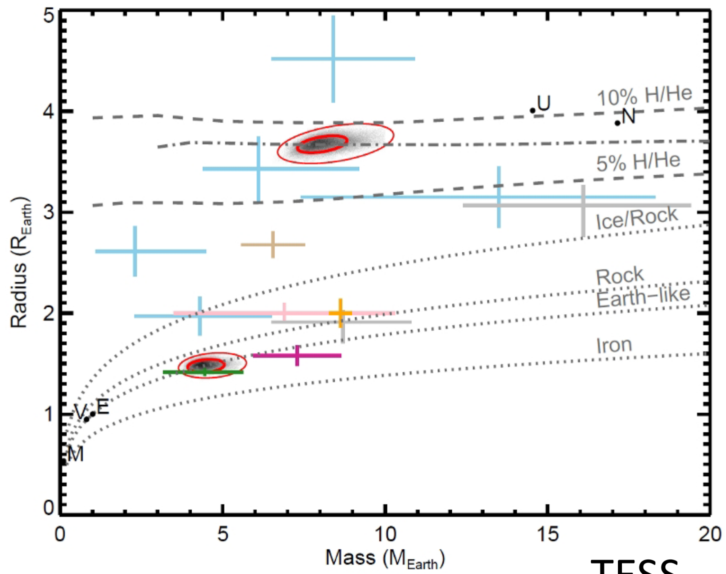
- Can gas be accreted and retained?





- Why is density-period distribution so diverse?

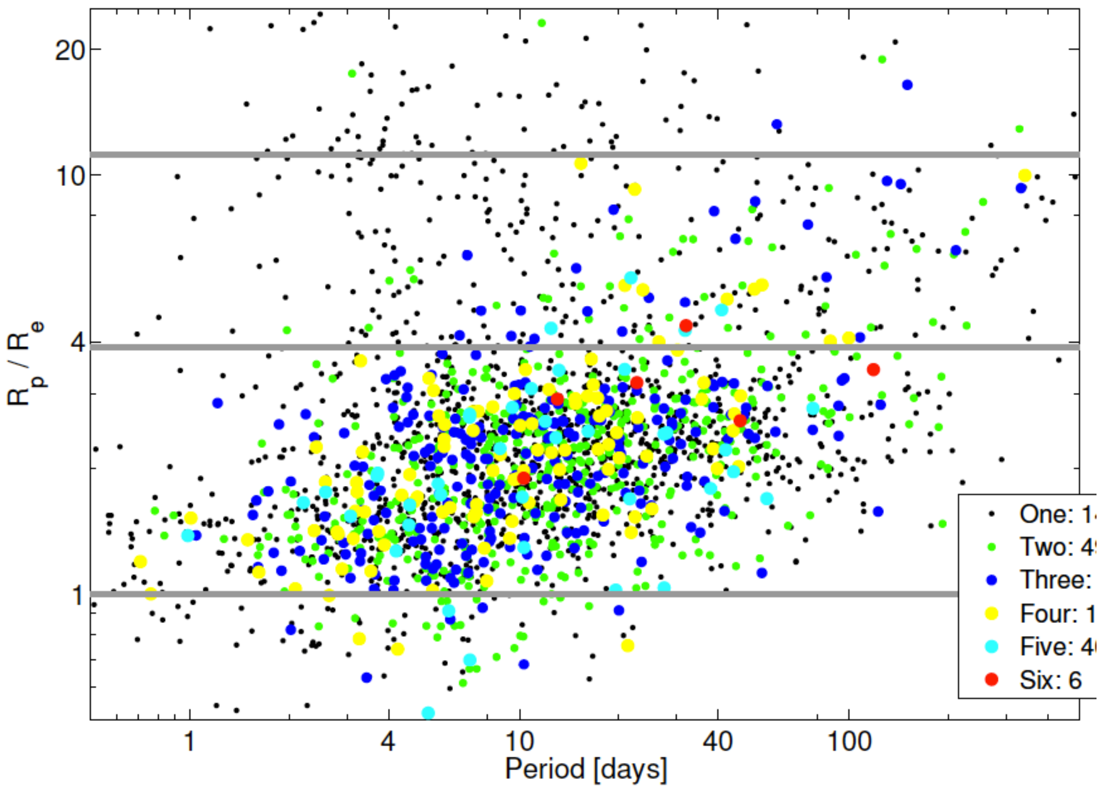




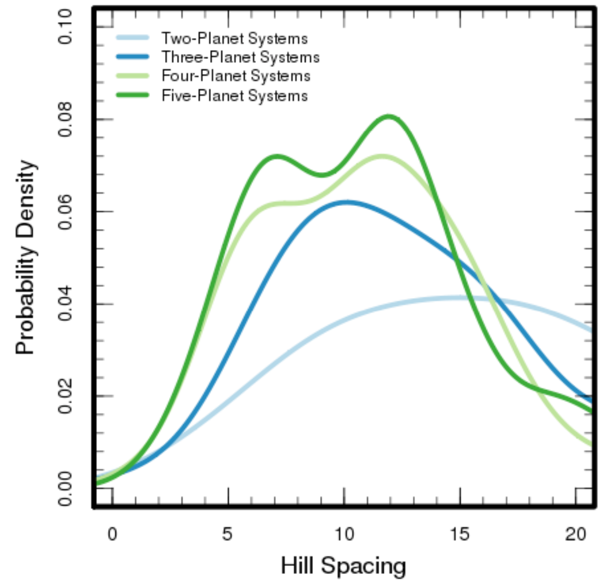
TESS

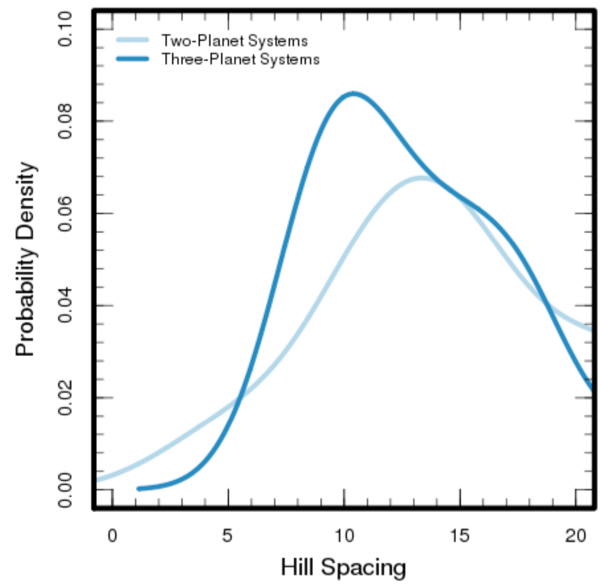
New Candidate Catalog (Batalha et al. 2012)

What can we learn from Multiple systems !!!



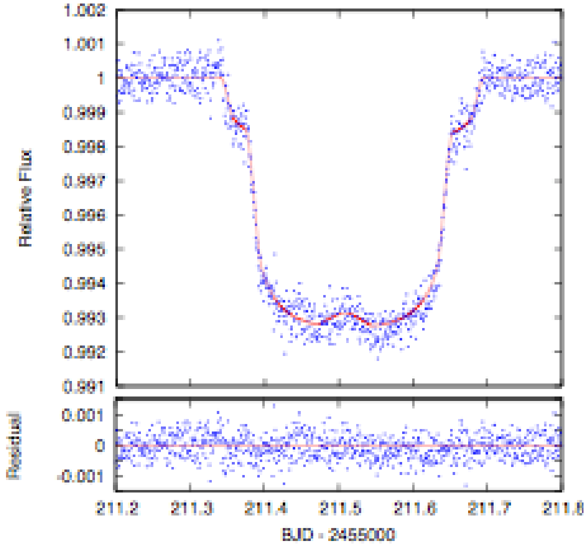
How compact can multiple systems be?



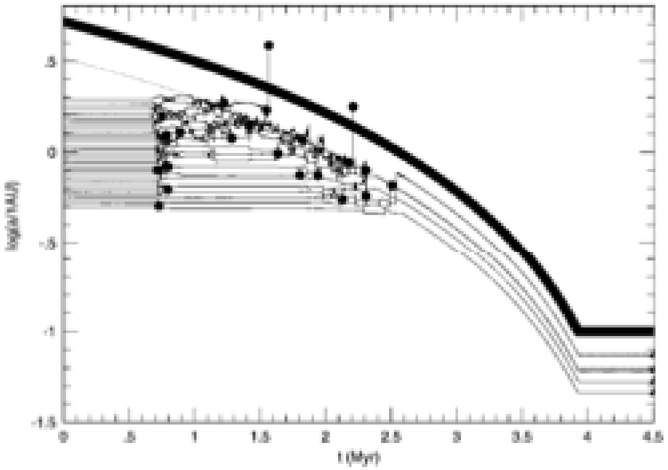


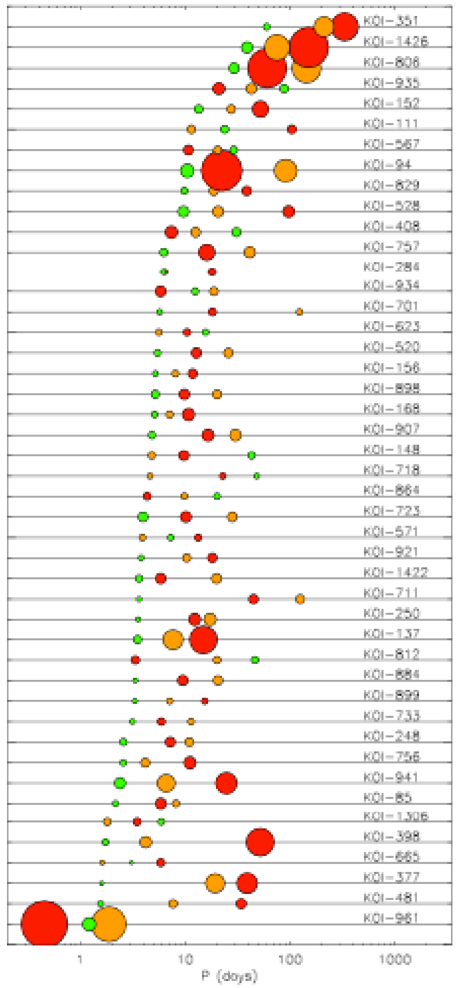
Kevin Schlaufman
Xiaojia Zheng

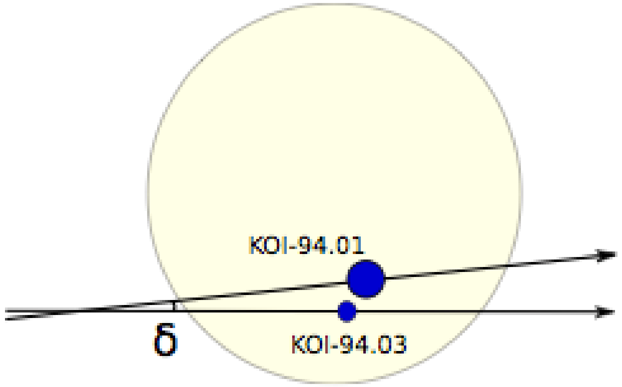
Multiple, resonant planets

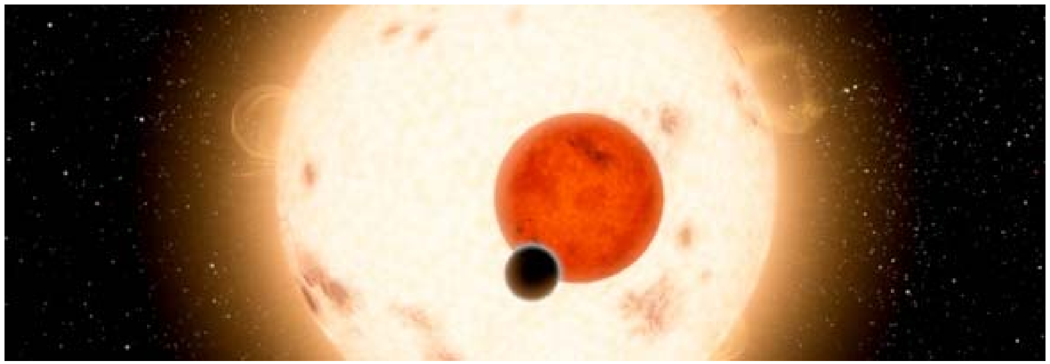


Candidate	Orbital Period (days)	R_p/R_*
KOI-94.01	22.343000 ± 0.000011	0.06856 ± 0.00012
94.02	10.423707 ± 0.000026	0.02544 ± 0.00012
94.03	54.31993 ± 0.00012	0.04058 ± 0.00013
94.04	3.743245 ± 0.000031	0.01045 ± 0.00019



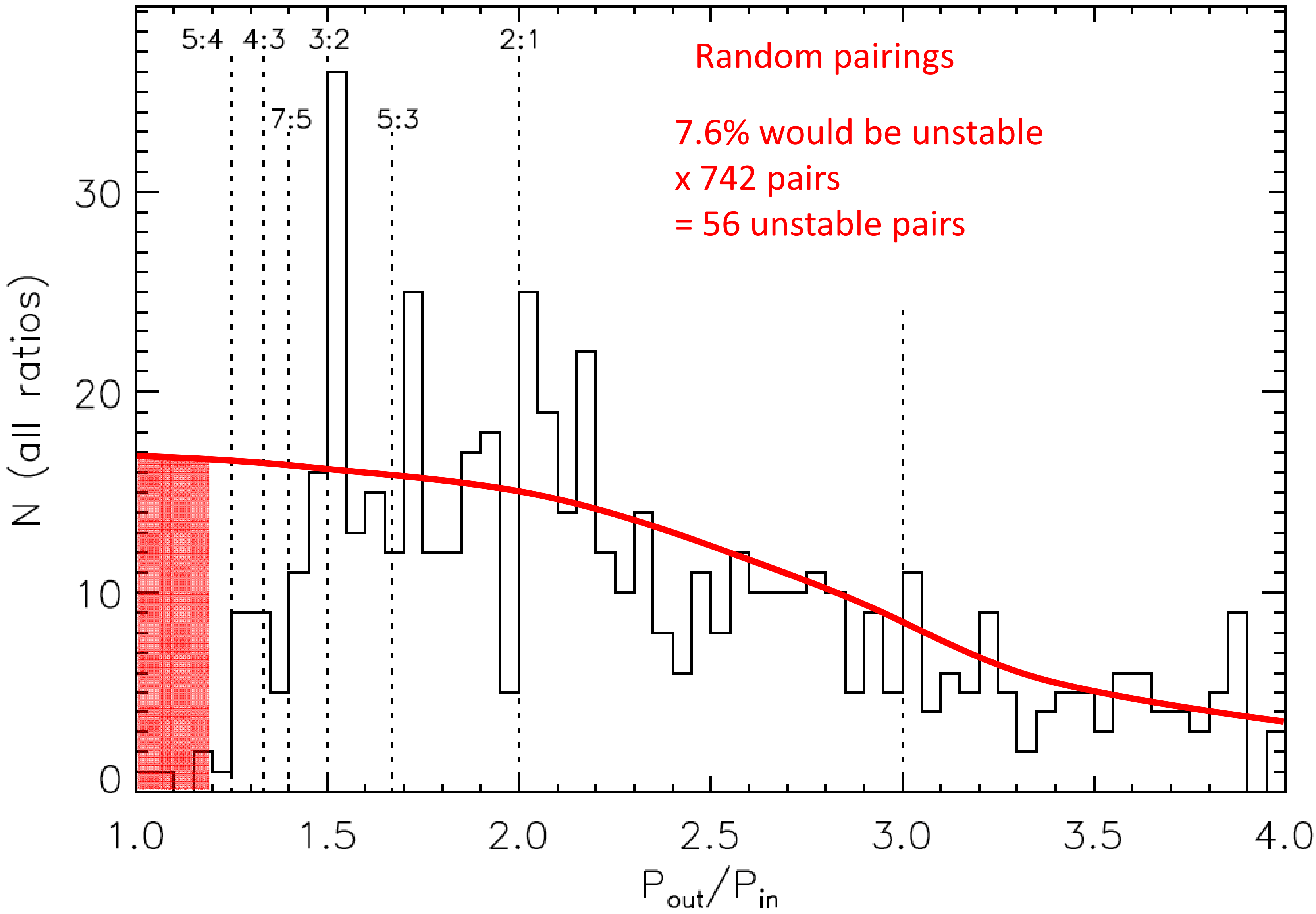




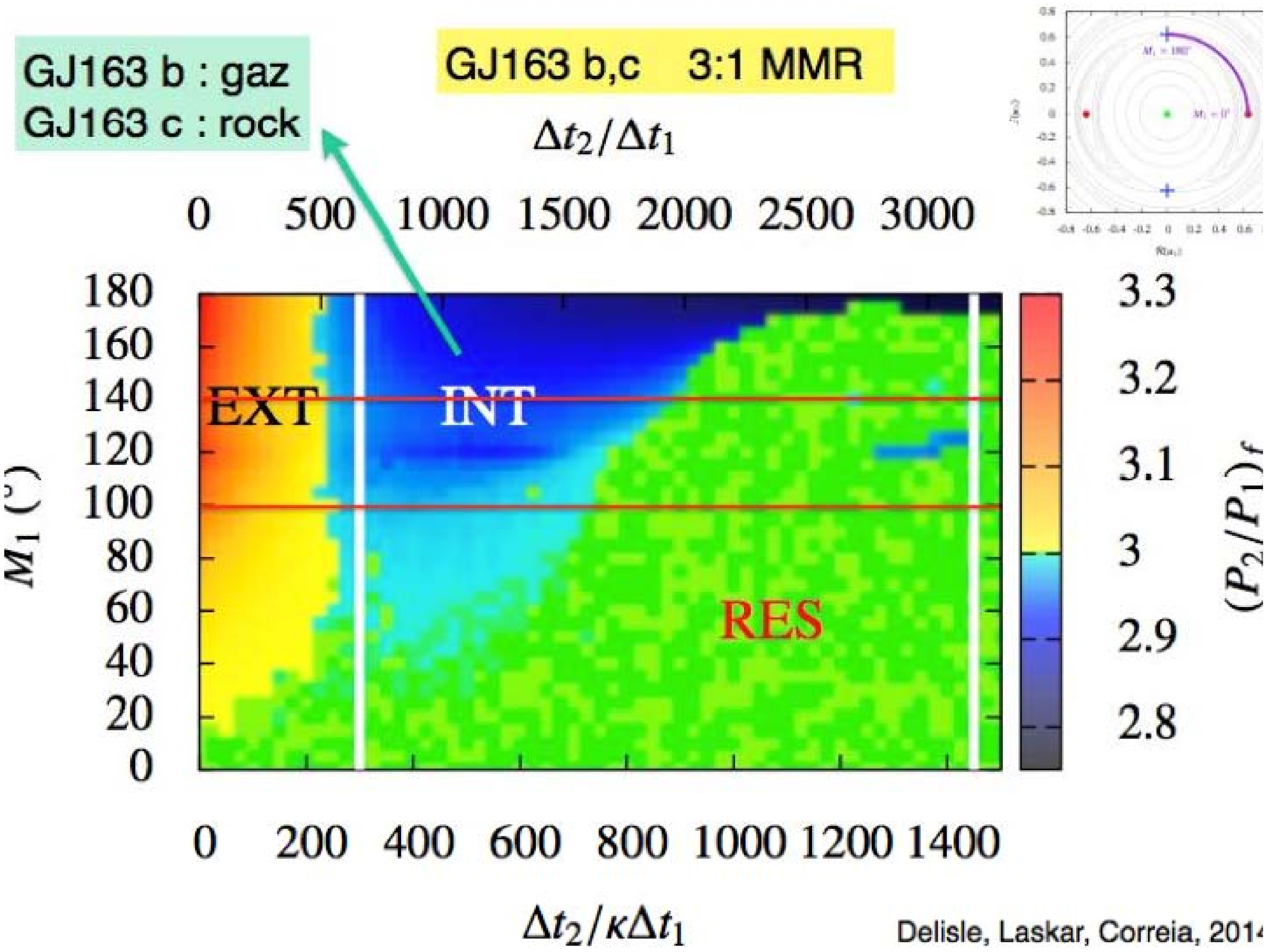


Super Earths: some key issues

- Did planets capture each other and parted their ways?

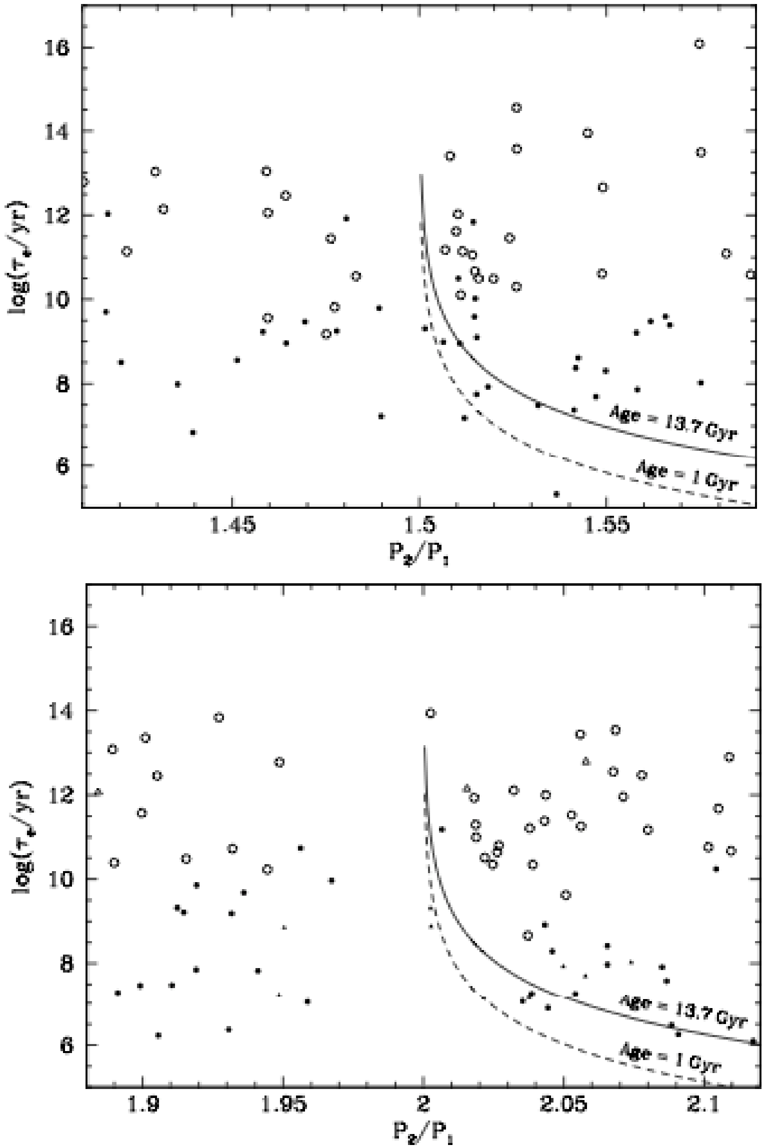


Fabricky



Delisle, Laskar, Correia, 2014

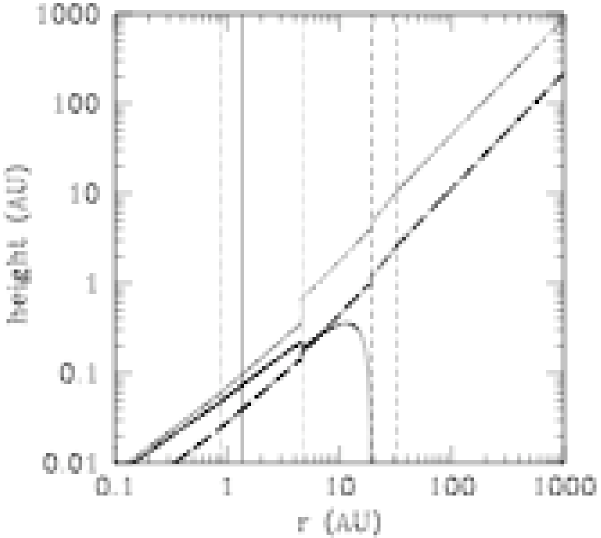
Exiting Resonance through Tides

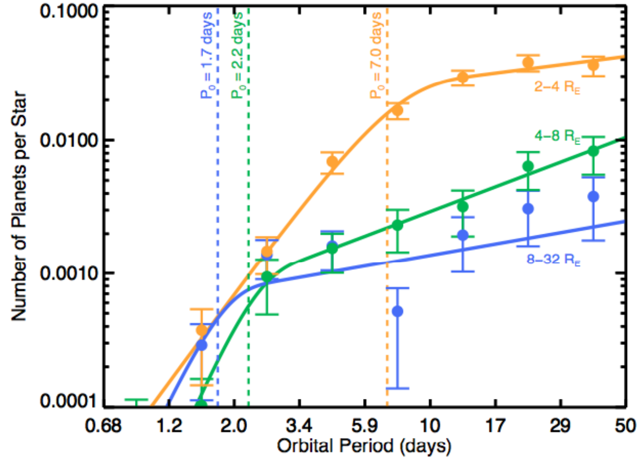


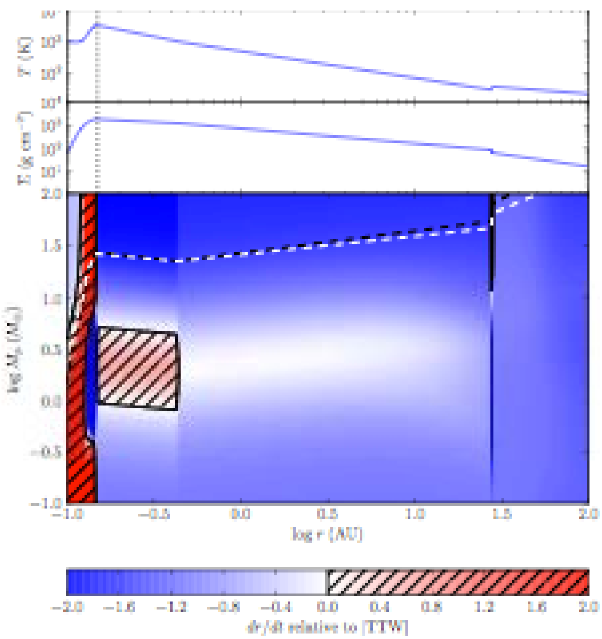
Lee, Fabrycky

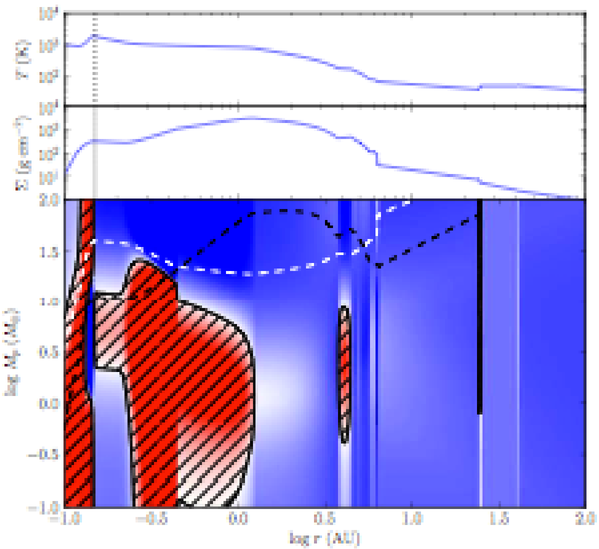
Super Earths: some key issues

- What determines the super-Earths' mass-period domain?





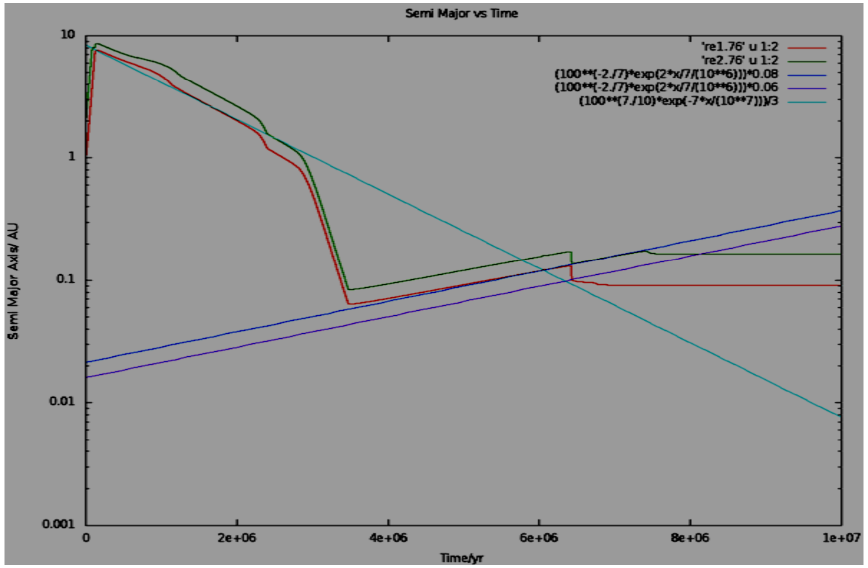


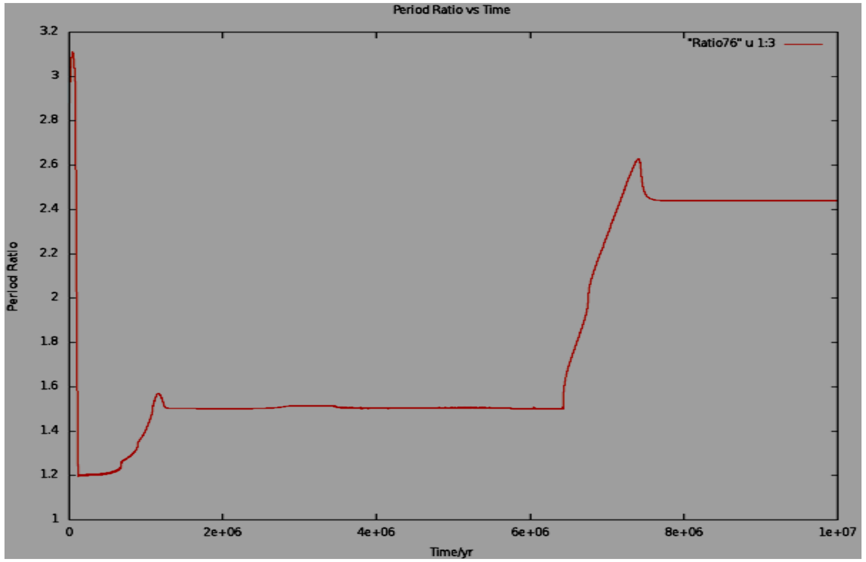


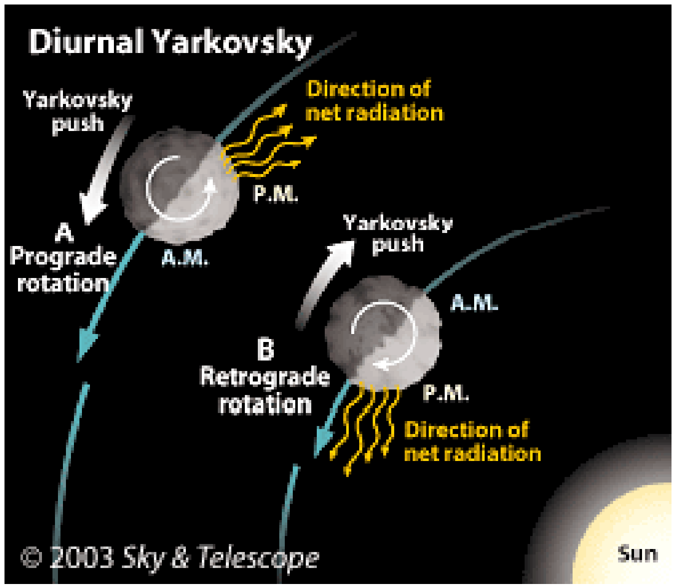
Kretke

Super Earths: some key issues

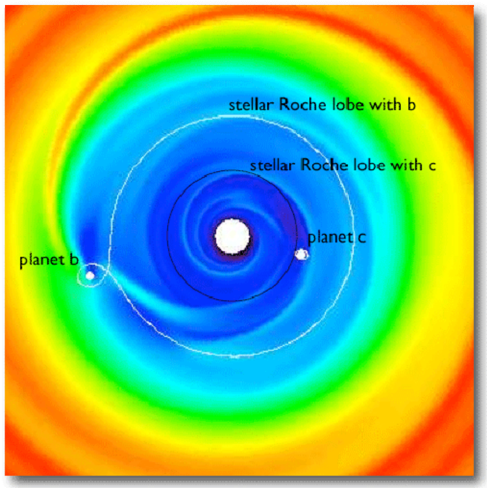
- Can type I migration be resurrected at the late stages?





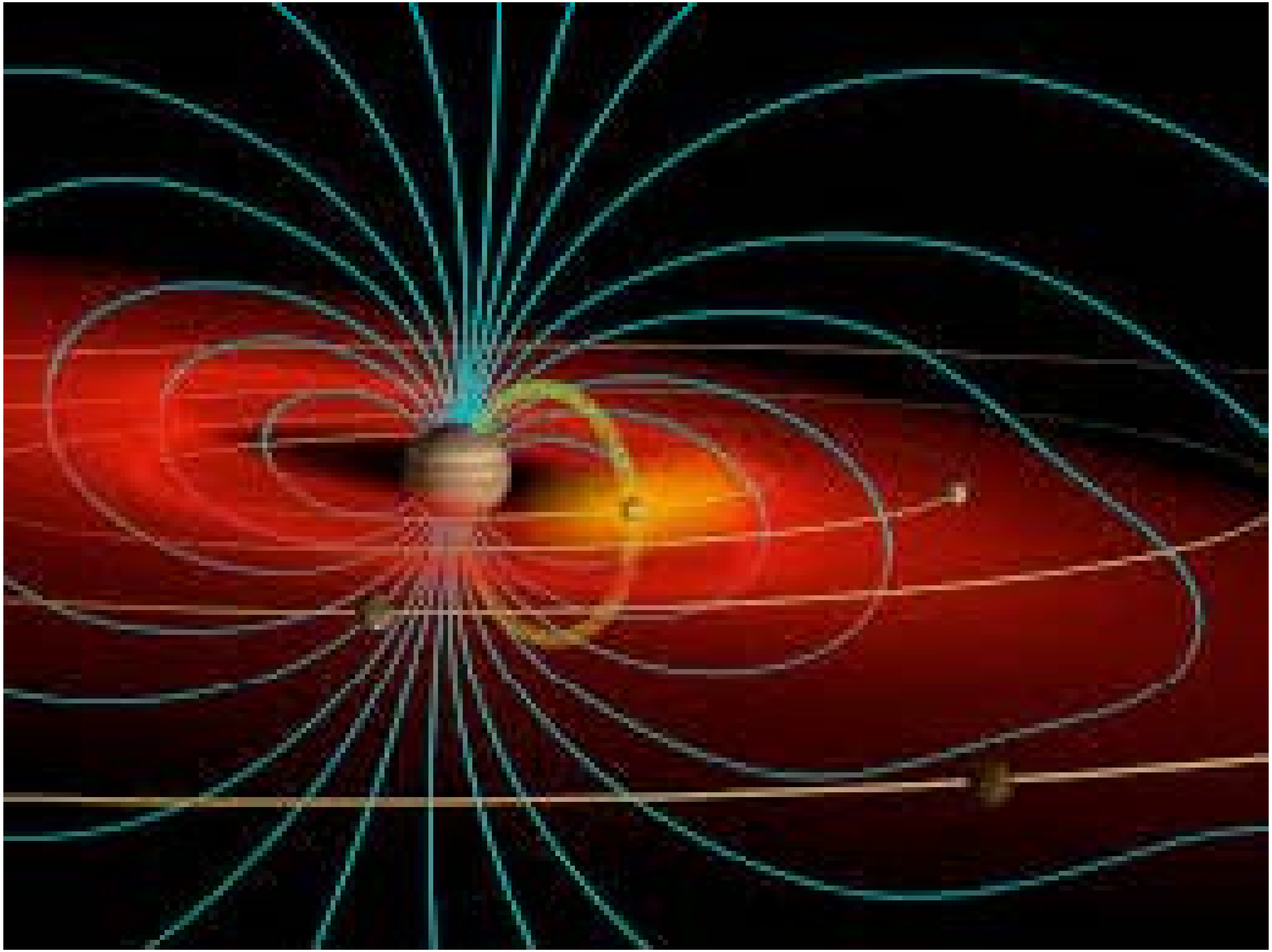


Wei Zhu

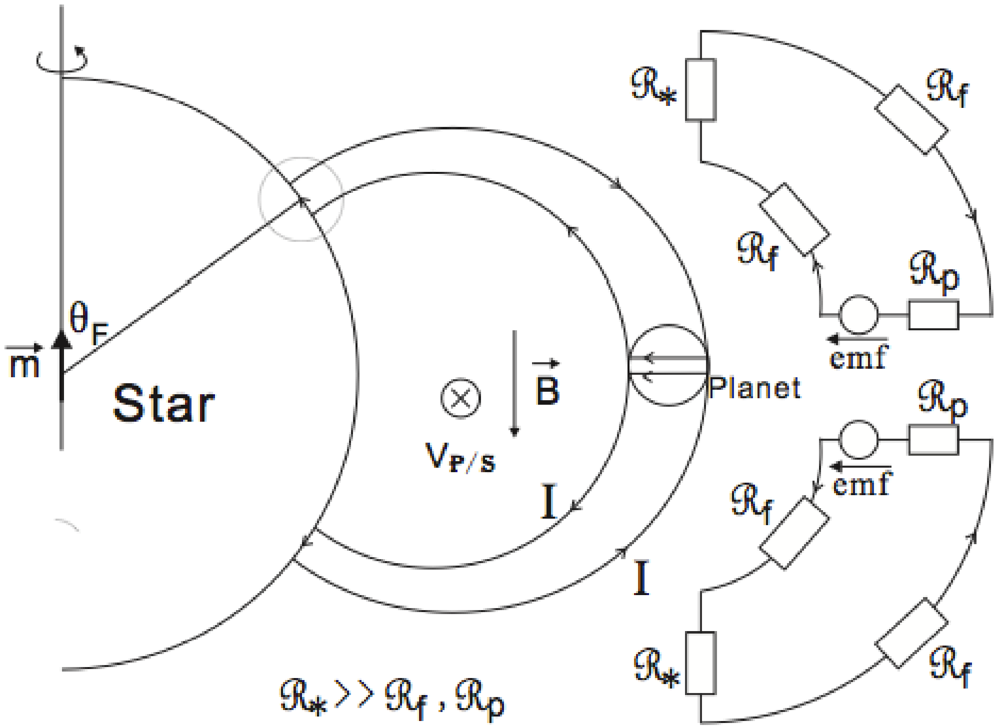


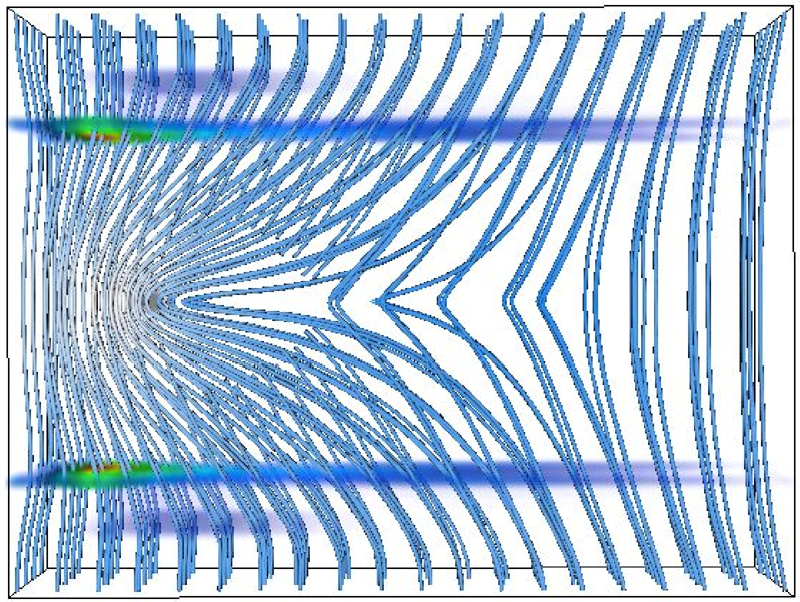
Bin Dai

Planets in the stellar magnetic field



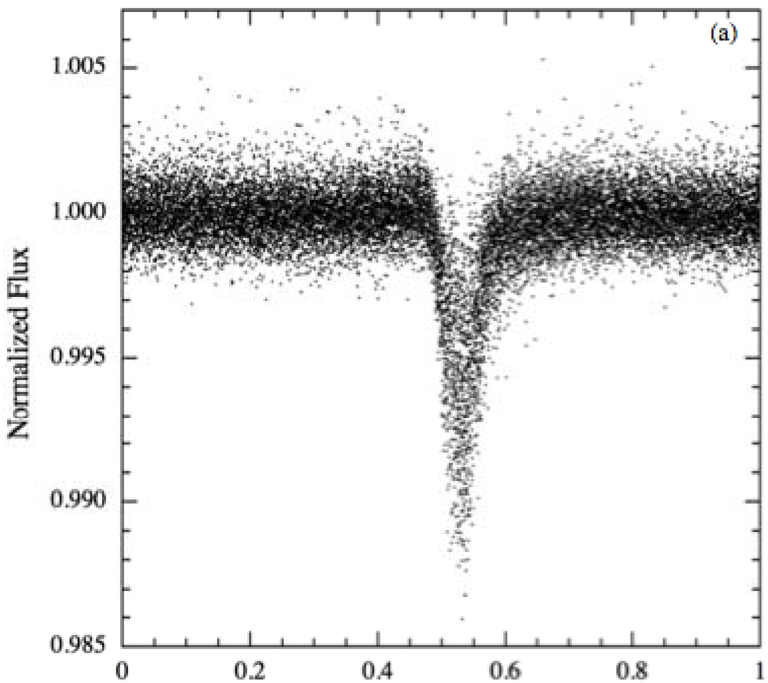
What about magnetic fields? Unipolar induction



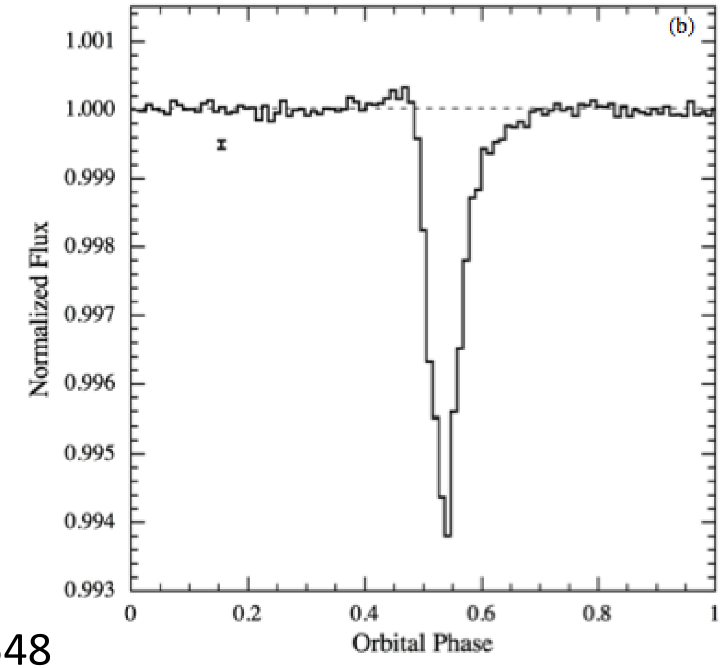


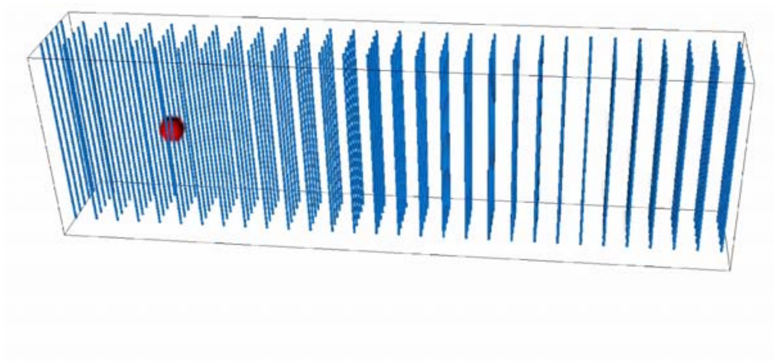
Unipolar Inductor: torque & dissipation.
Jupiter/Io system: Goldreich & Lynden-Bell
Orbital evolution & mass loss. Laine & Lin

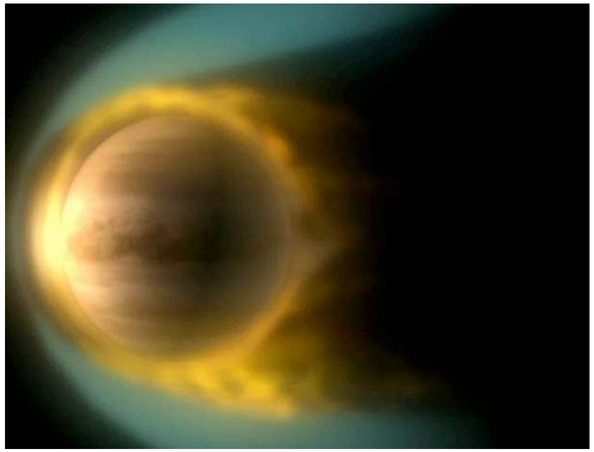
Evaporating planets



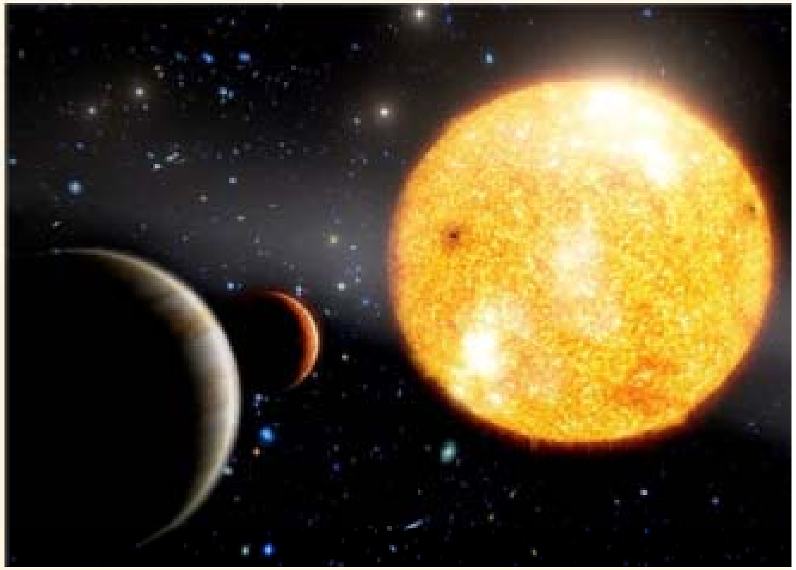
Kic12557548





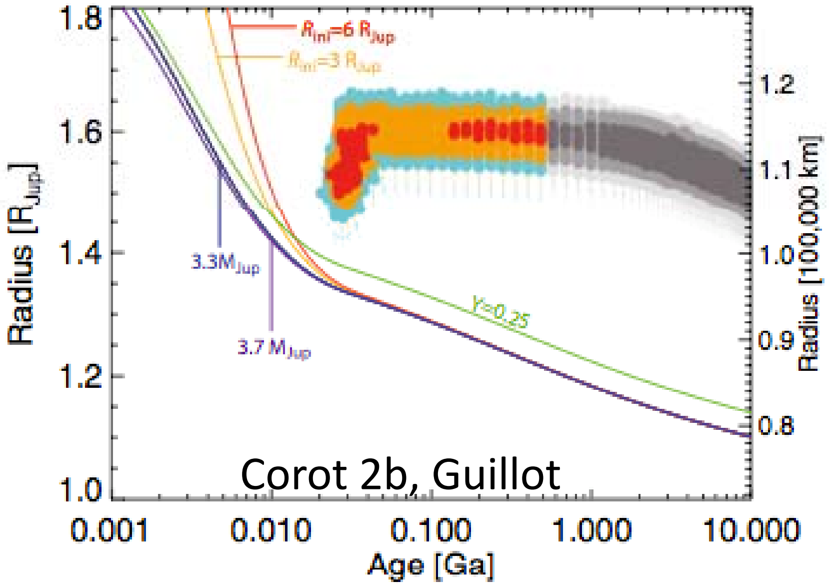


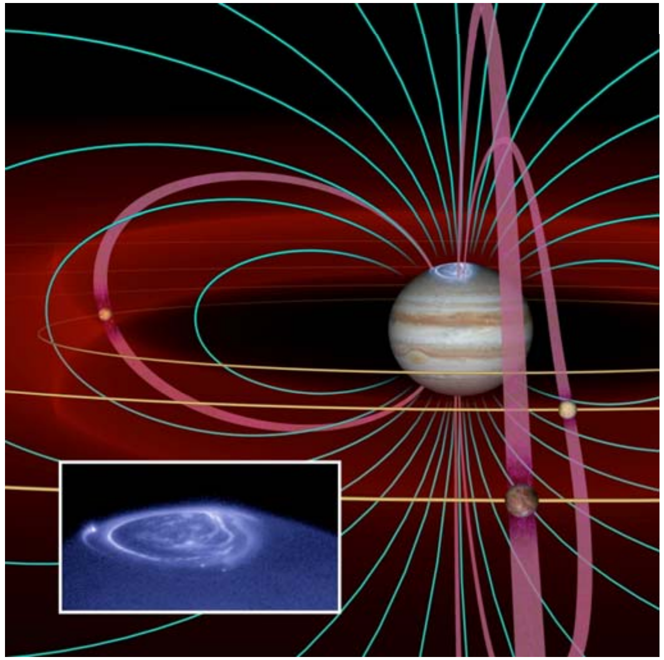
Application to CoRoT-7 (Haywood)

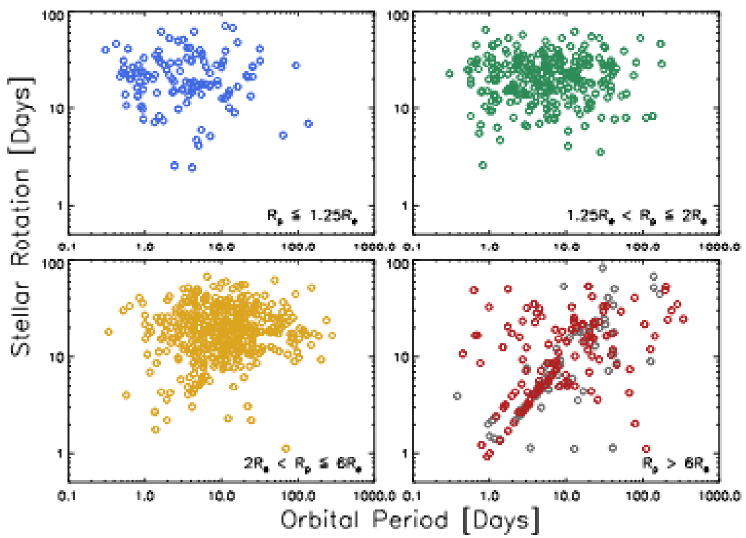


- G9, V=11.7
- CoRoT transit observations in 2009
  ➡ super-Earth CoRoT-7b (Léger et al. 2009)
- HARPS radial-velocity campaign (2009)
  ➡ another super-Earth CoRoT-7c (Queloz et al. 2009)
  ➡ sub-Neptune mass planet CoRoT-7d at 9 days (Hatzes et al. 2010)
- Many analyses, no agreement
  Bruntt et al. 2010, Lanza et al. 2010, Pont et al. 2010, Boisse et al. 2010, Ferraz-Mello et al. 2011, Hatzes et al. 2011
- Jan. 2012: New observations: simultaneous CoRoT photometry & HARPS RV

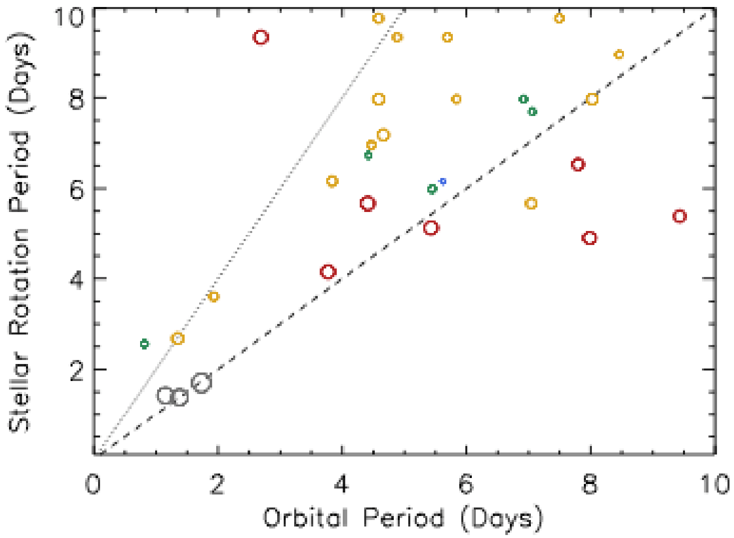
Oversized planets and stellar hot spots



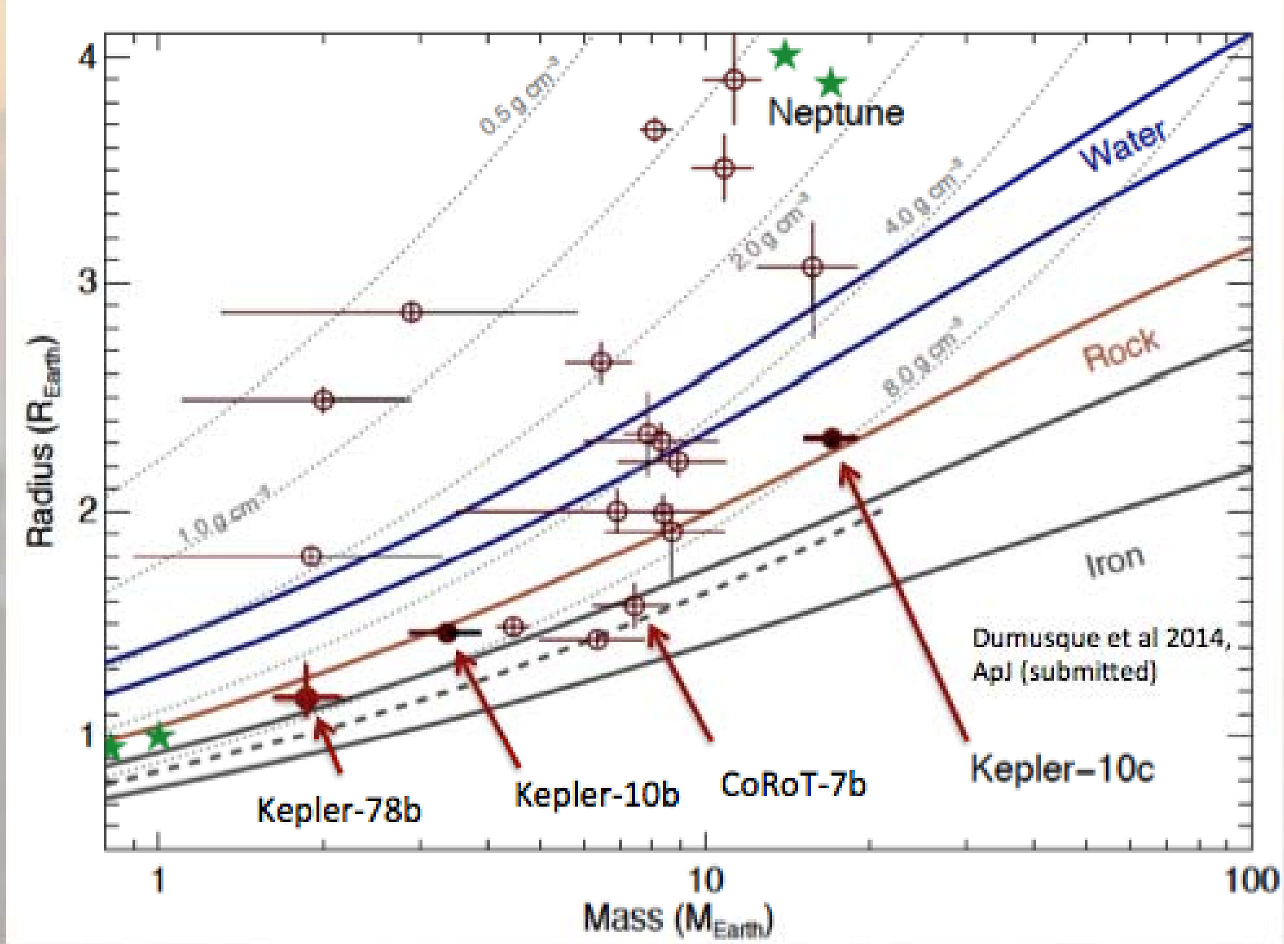




Walkowicz & Basri

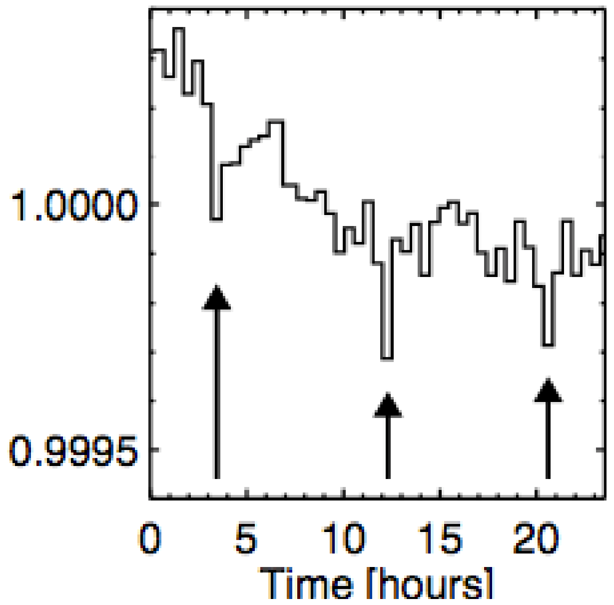


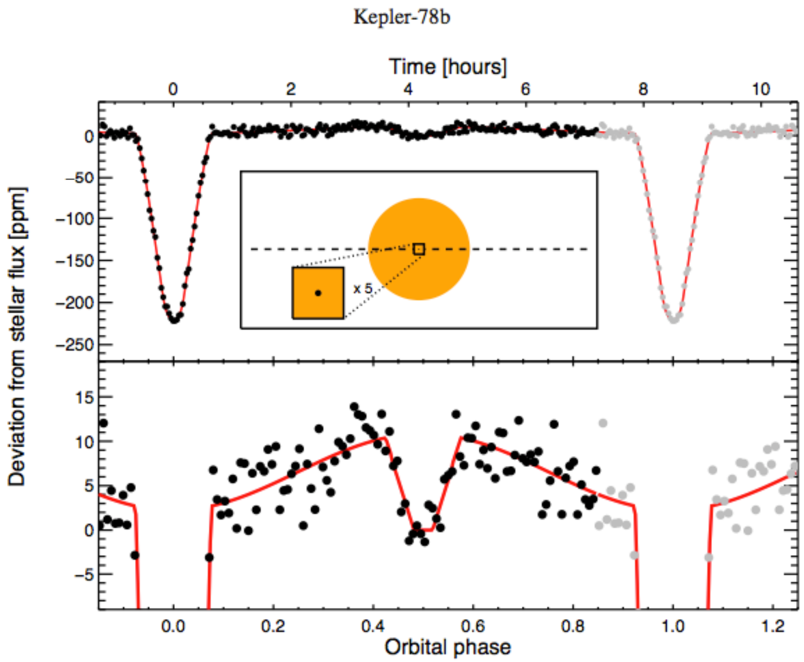
Mass-radius diagram

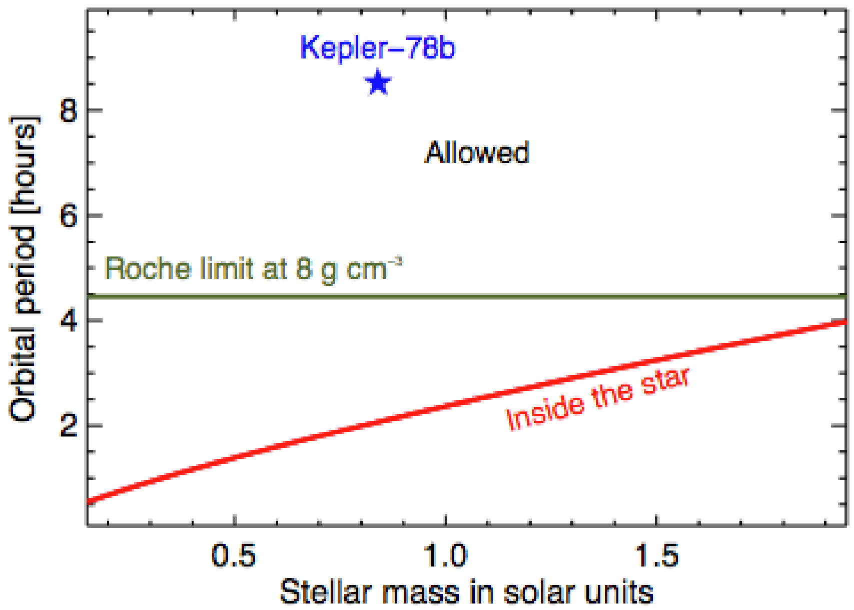


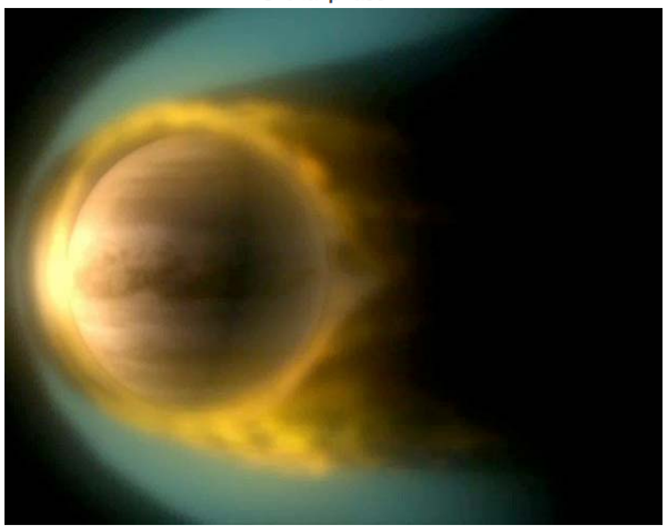
Cameron

How to identify differentiation





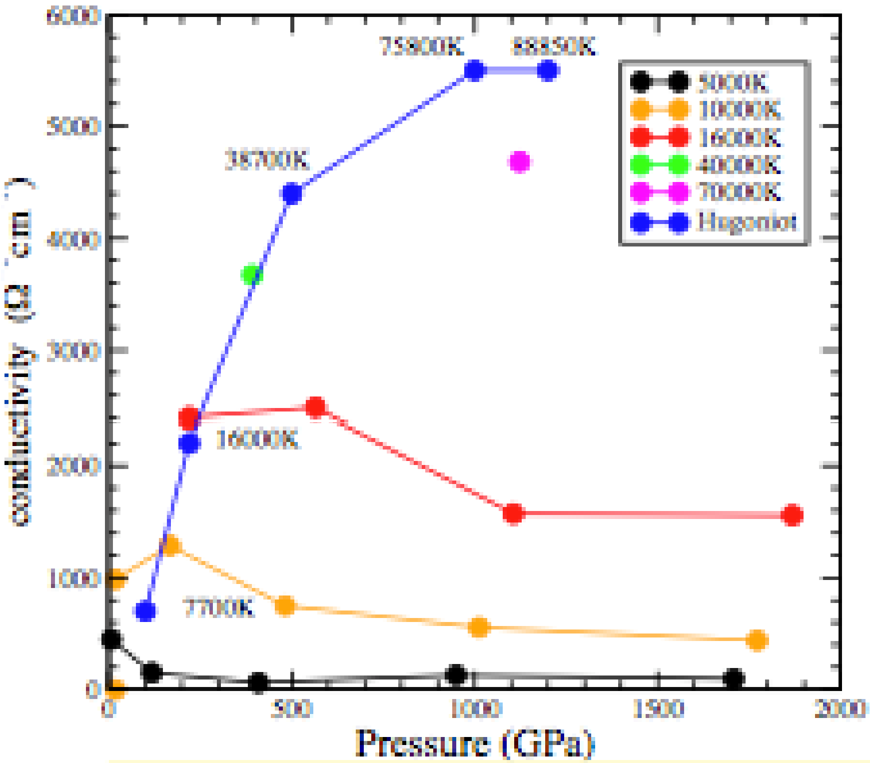




(Mazevet)

SiO_2 conductivity

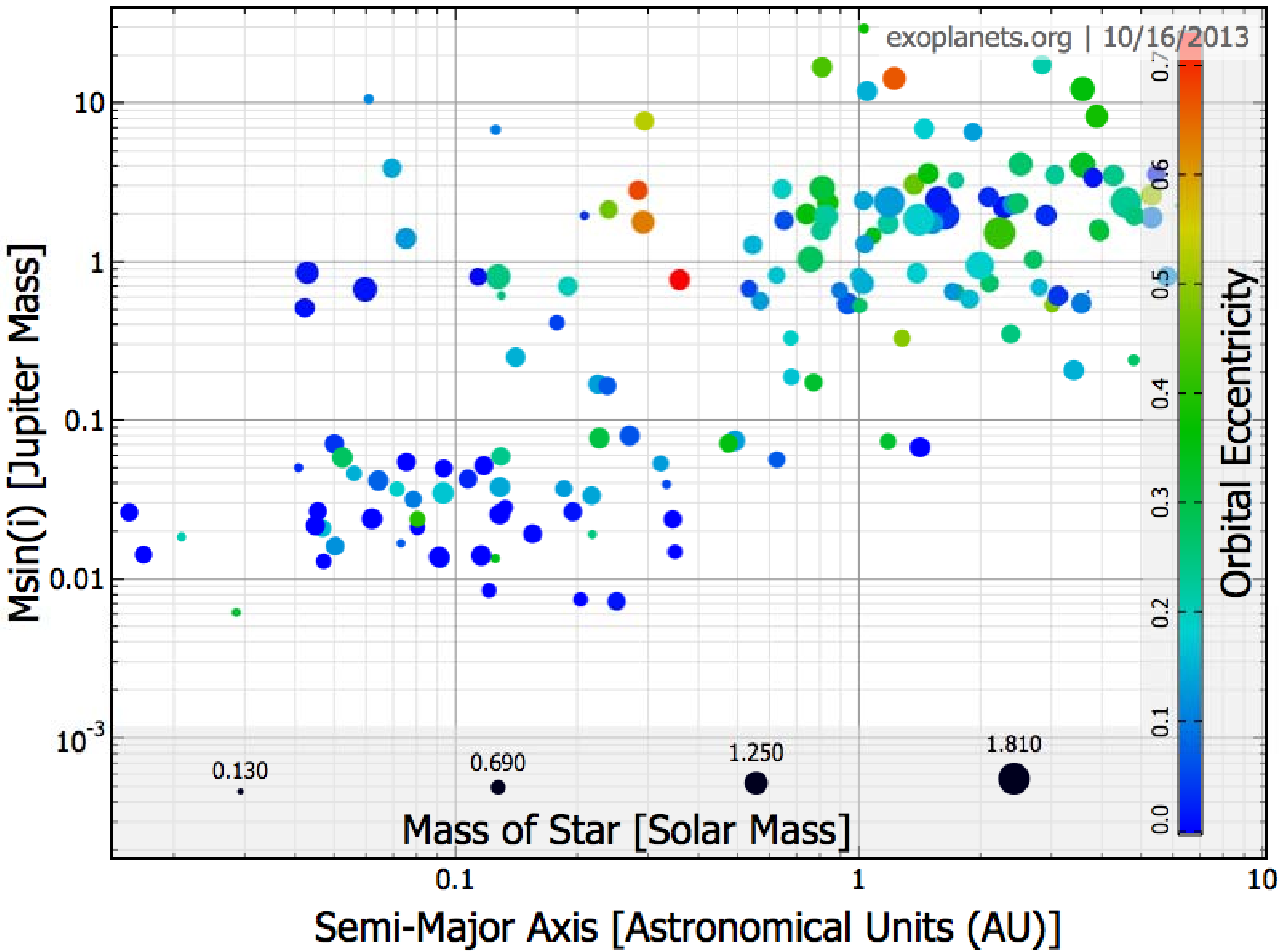
Is silica becoming metallic in super-earths?



- Conductivity reaches a maximum
- Corresponds to loss of Si-O coordination: Laudernet *et al.* 2005
- Confirmed experimentally: Hicks *et al.* 2007 (bounded liquid)
- Conductivity decreases with density along an isotherm
- Close connection between conductivity and Si-O ordering

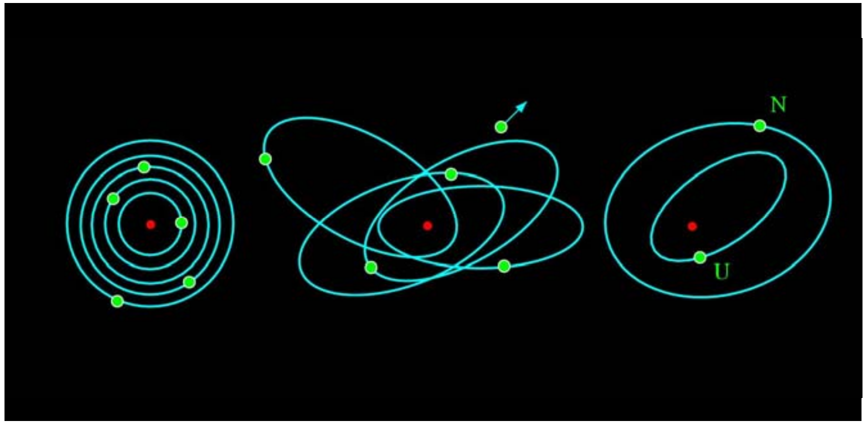
No non-metal metal transition, below $1000\Omega^{-1}\text{cm}^{-1}$, for super-earths

Multiple-gas-giant barrier: perturbation

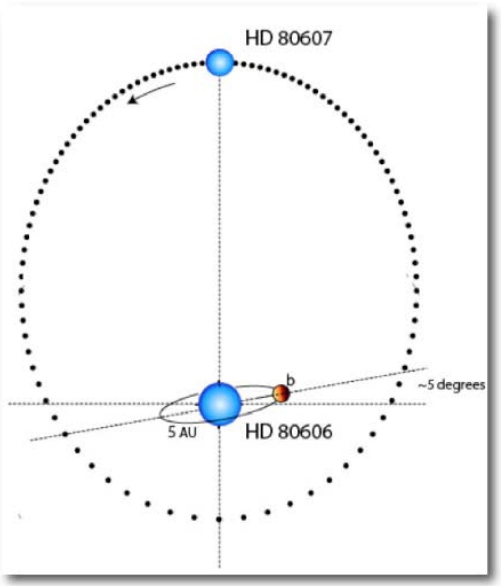


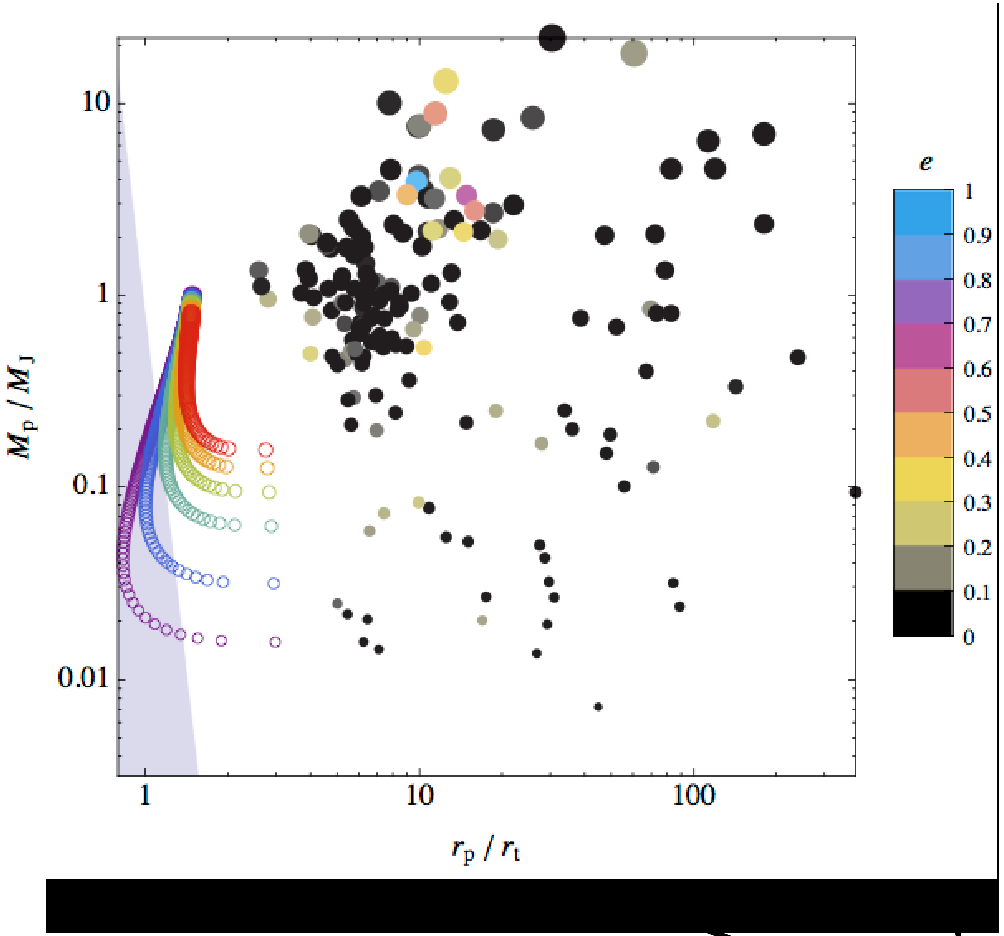
Confirmed members of multiple planet systems

Tidal Disruption of a Jupiter-like Planet



A gas giant planet disrupted by a sun-like star as a result of planet-planet scattering or the Kozai effect.
Nagasawa

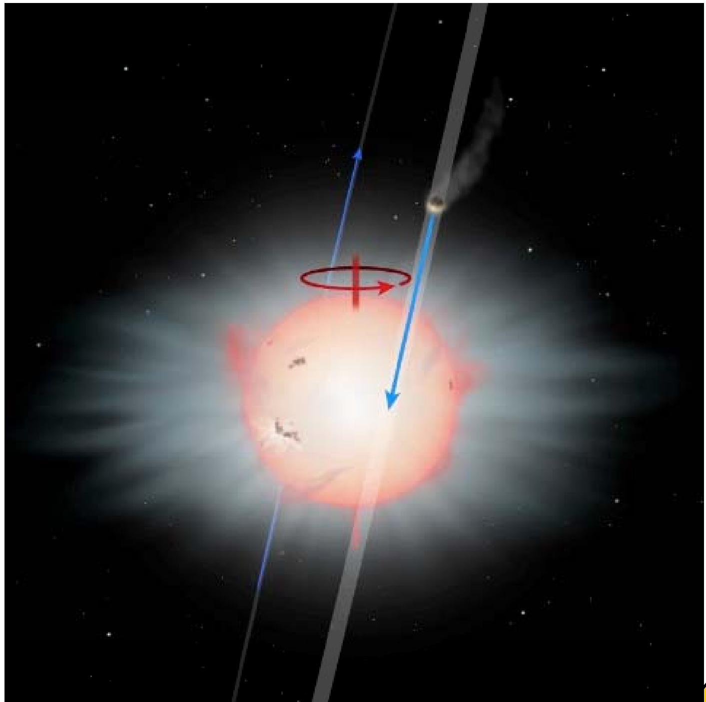


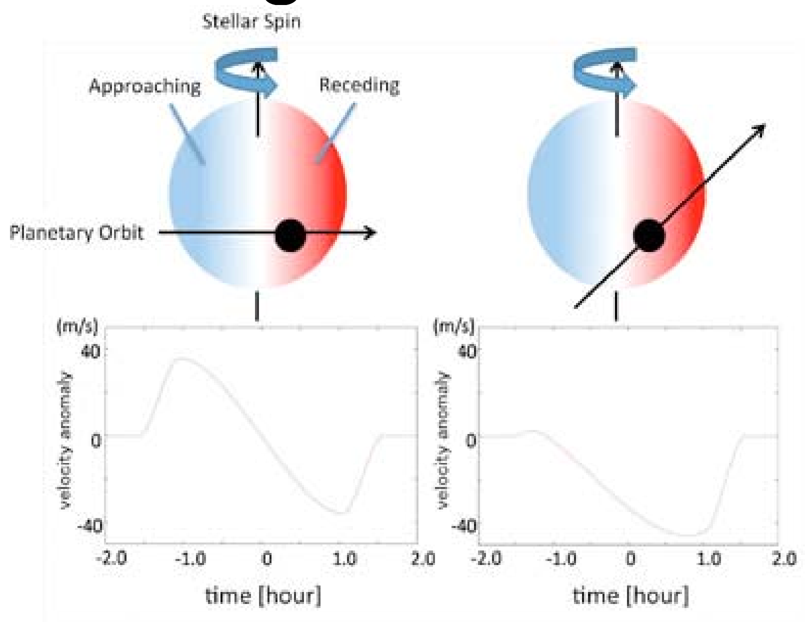


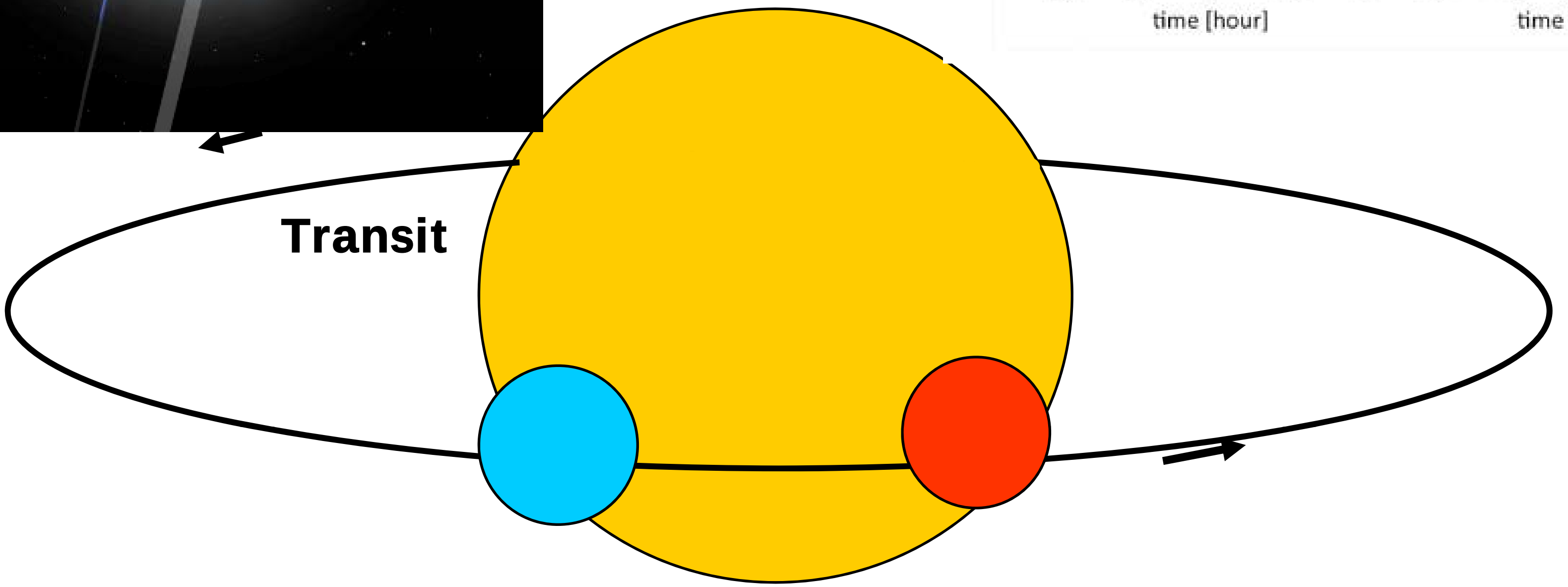
Liu, Guillochon

Disk migration challenge: obliquity

What about spin-orbit misalignment?

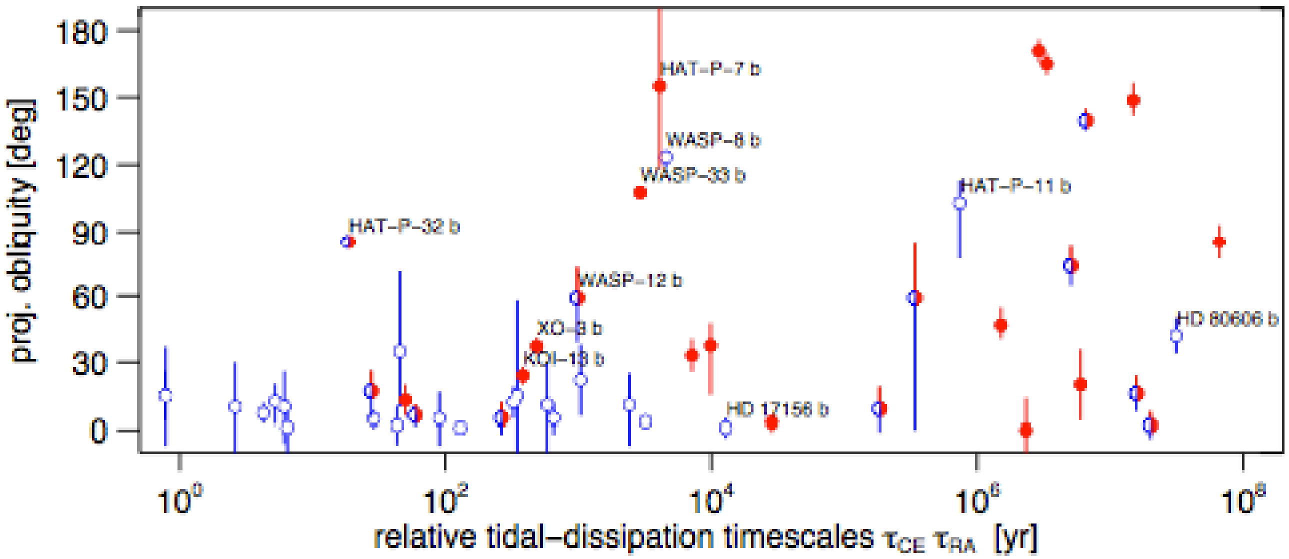




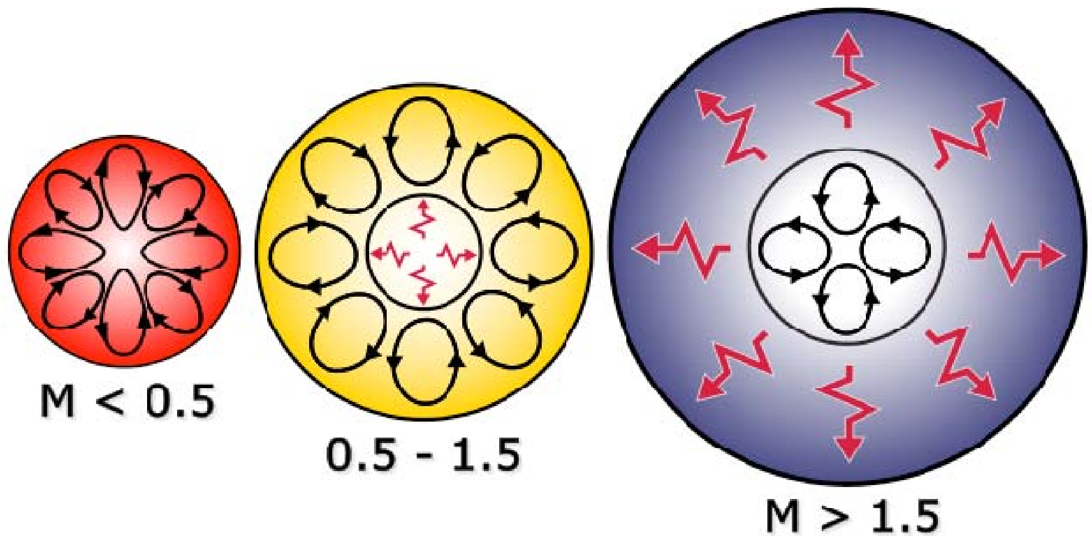


Gas giants: some key issues

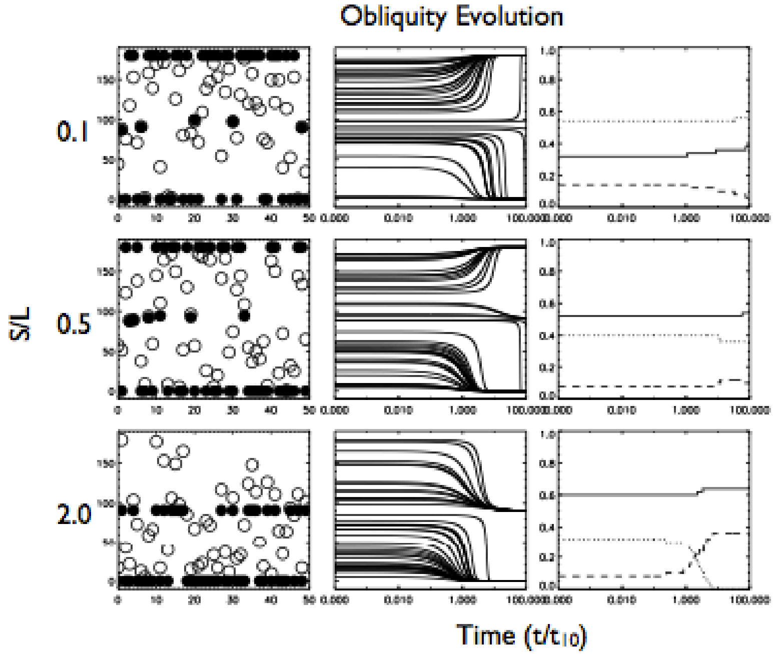
- Is there evidence for M_*-dependent tidal dissipation?



Winn



Tidal alignment of obliquity

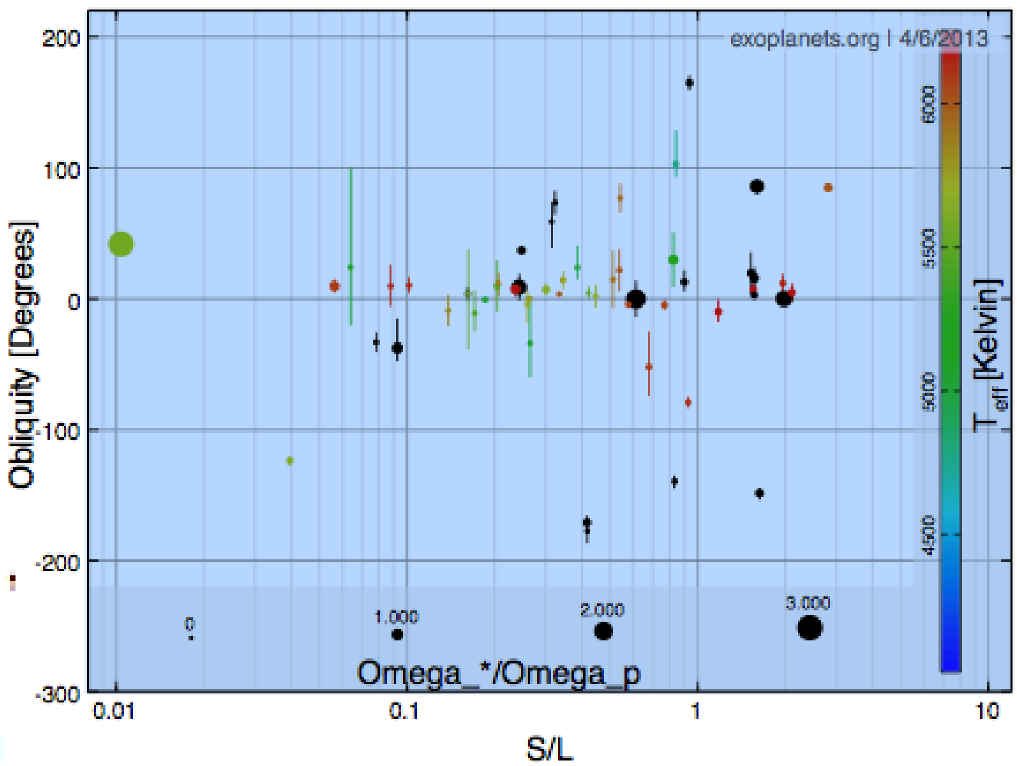


Lai

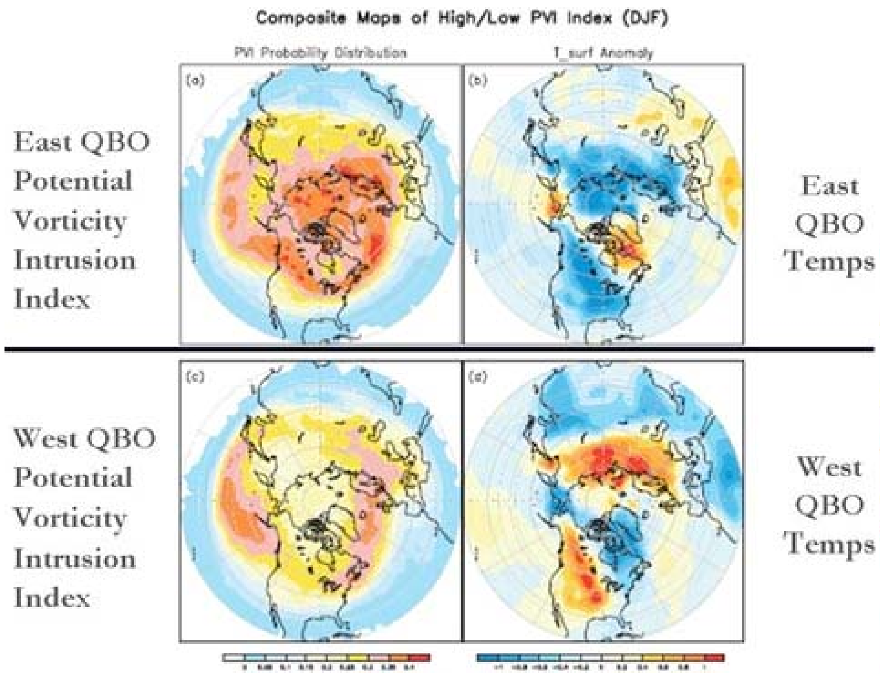
$$\left(\dot{\Theta}\right)_{10} = -\frac{1}{t_{s10}} \sin\Theta \cos^2\Theta \left(\cos\Theta + \frac{S}{L}\right),$$

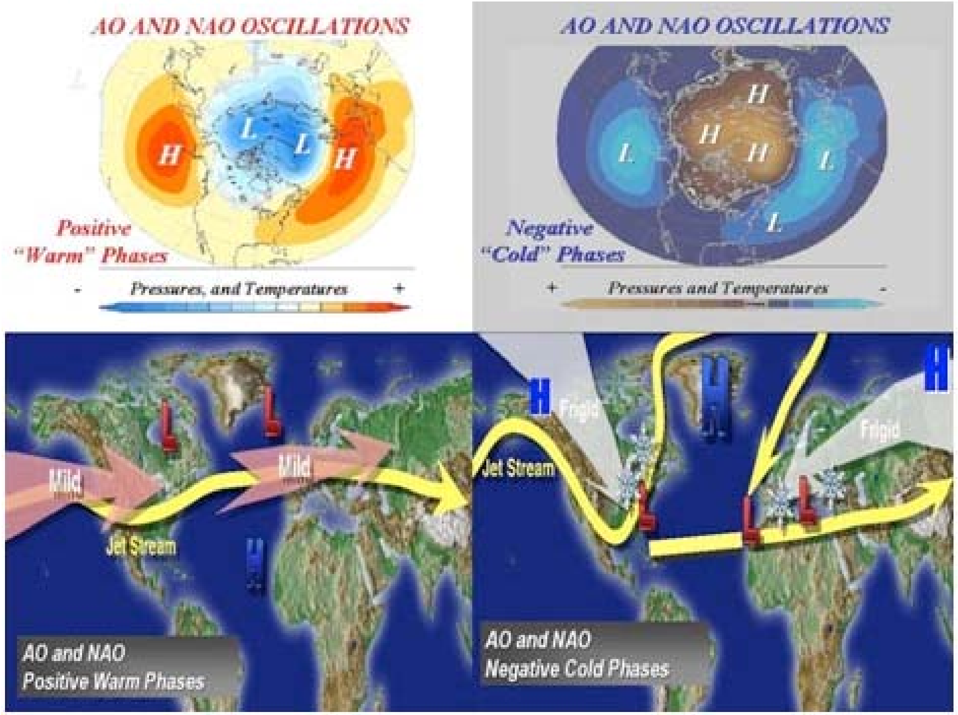
$$t_{s10} = 4.3 \left(\frac{\kappa}{0.1}\right) \left(\frac{Q_{10}/k_{10}}{10^7}\right) \left(\frac{M_*}{10^3 M_p}\right)^2 \left(\frac{\bar{\rho}_*}{\bar{\rho}_\odot}\right) \times \left(\frac{10\,\mathrm{d}}{P_*}\right) \left(\frac{P}{1\,\mathrm{d}}\right)^4 \mathrm{Gyr}$$

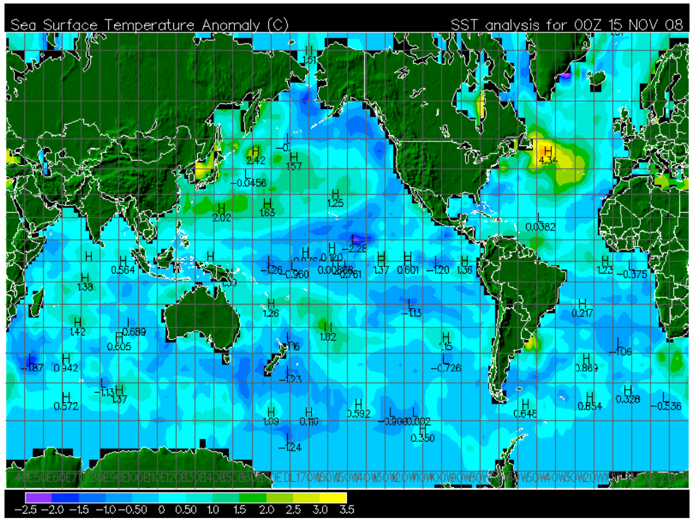
Rogers

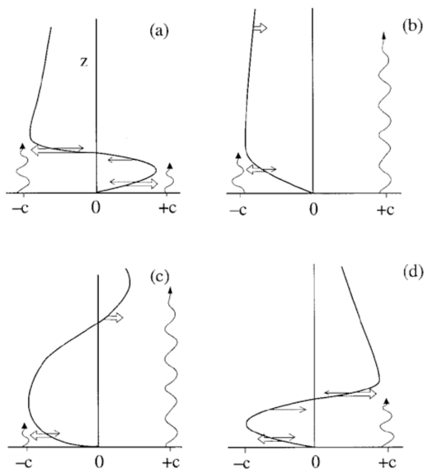


Alternative model: internal gravity wave





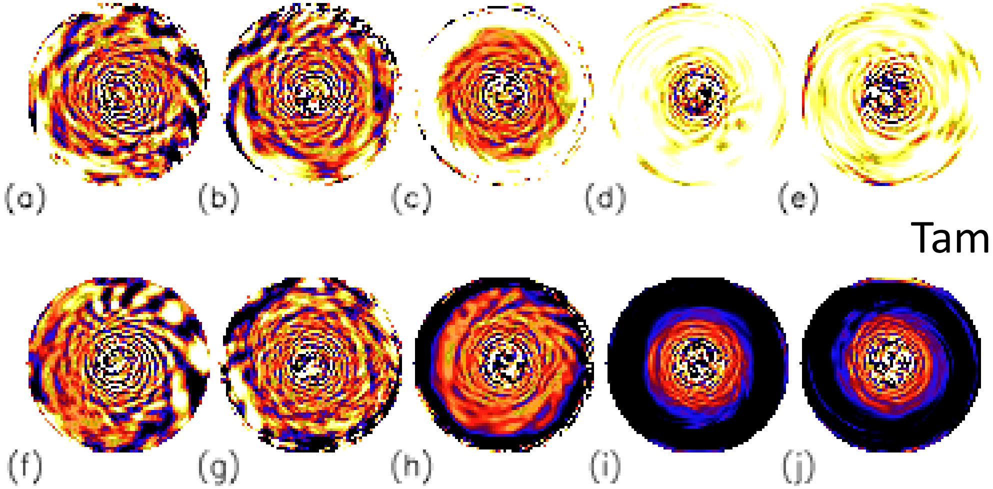




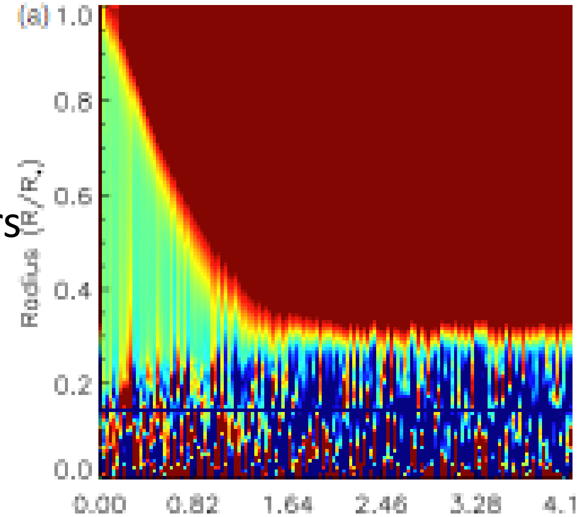
Tami Rogers

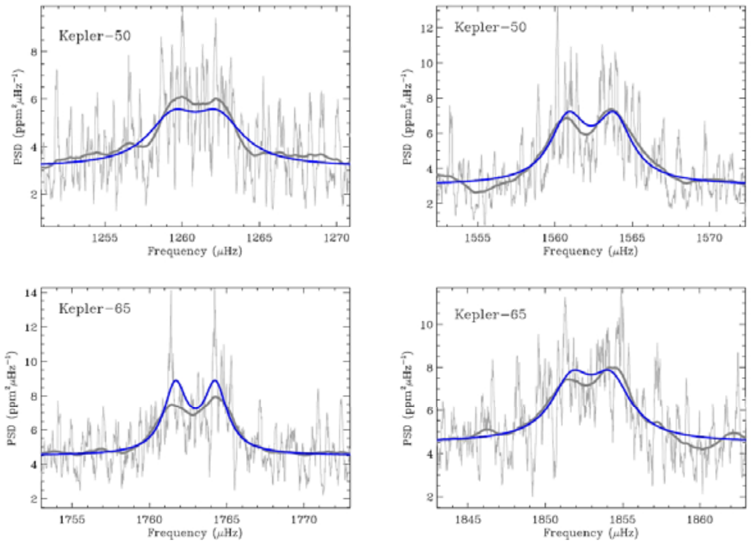
Gas giants: some key issues

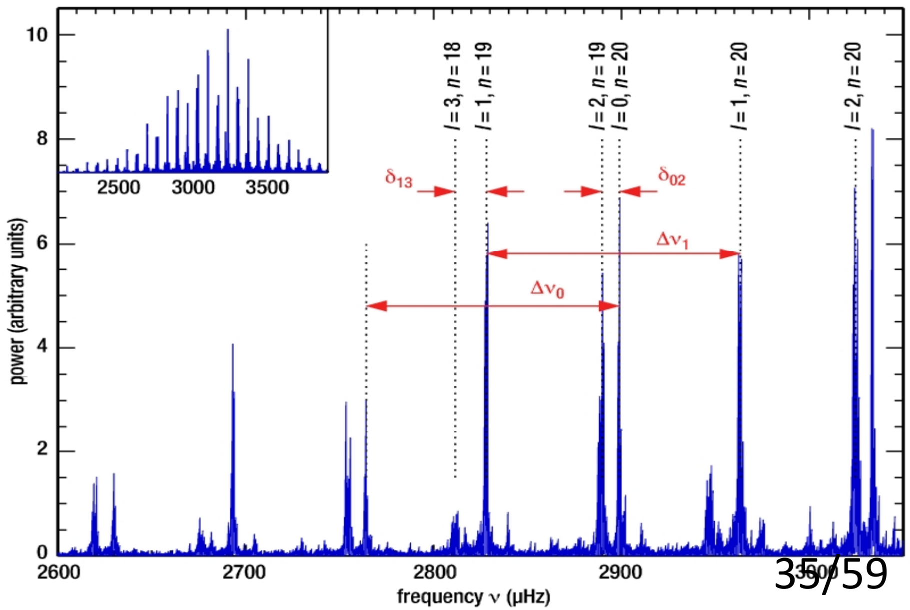
- Is there evidence for internal differential rotation ?



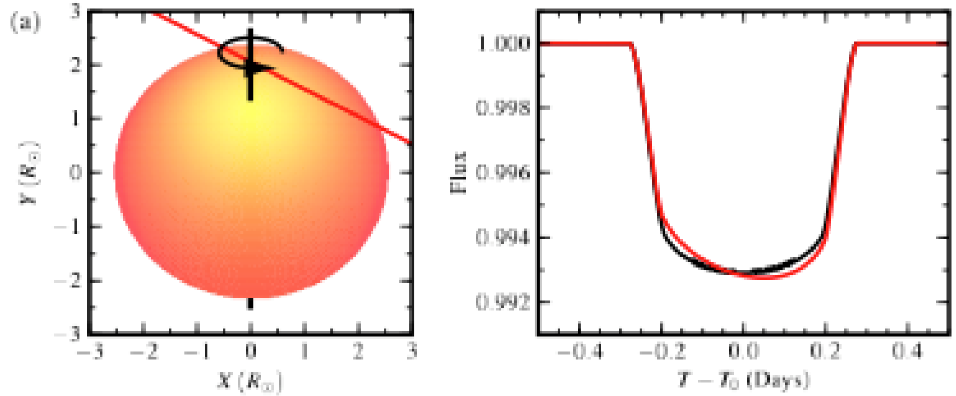
Tami Rogers

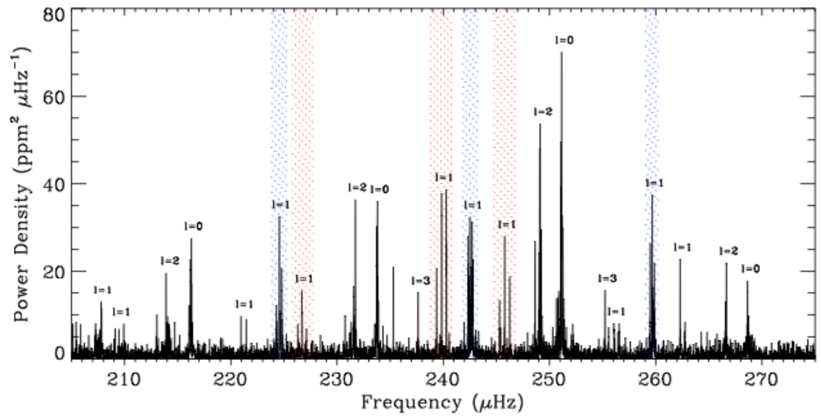






Alternative obliquity determination

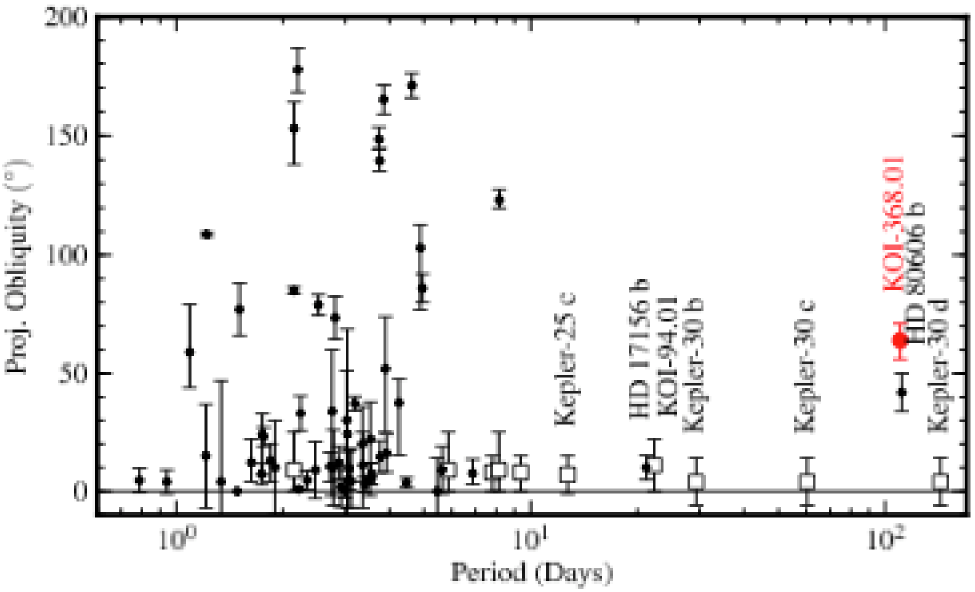




Zhou & Huang

Huber et al

KOI 368-01



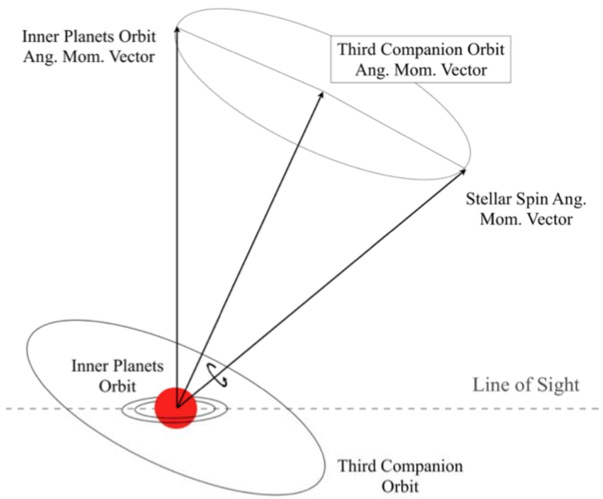
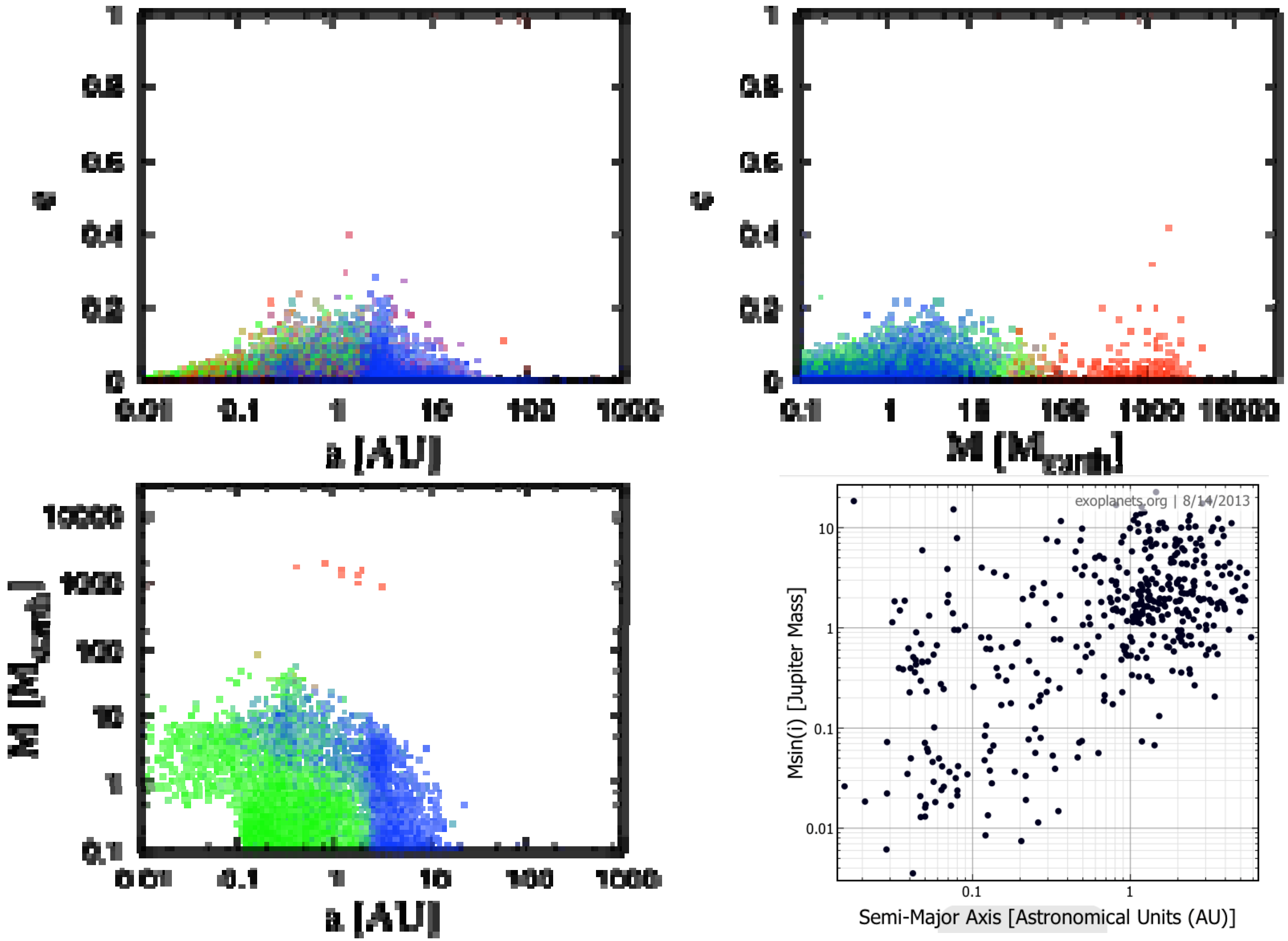
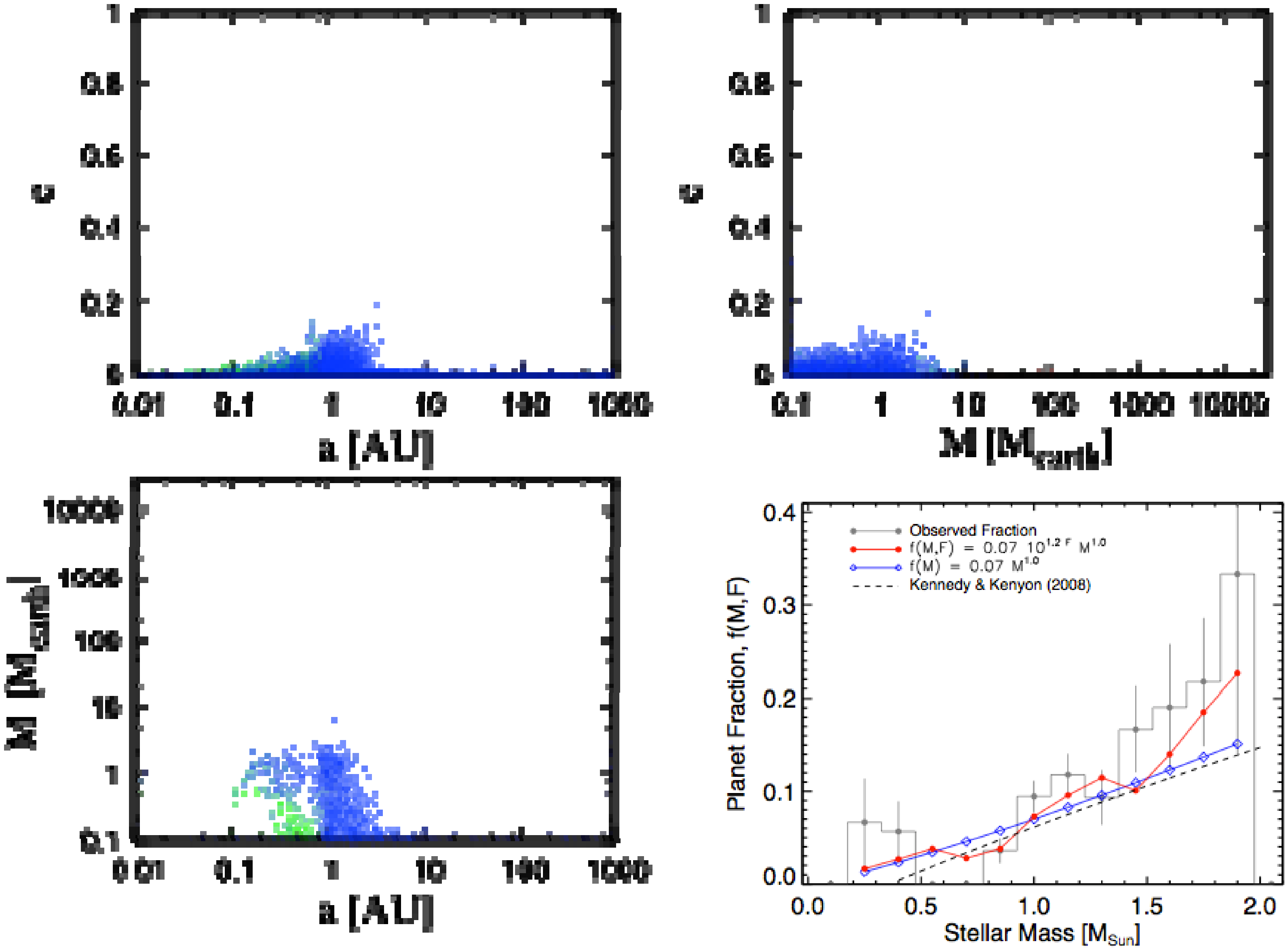


Figure S23: Graphical illustration of the dynamical tilting hypothesis for the Kepler-56 system. Note that the sizes are not to scale.

Updated version of population synthesis models



Low-mass host stars



Other 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

Paradigm shifts

- Planet formation is a robust process
- Planets migrate throughout their lives
- Dynamical and structural properties of planets are subjected to rich variety of physics
- Habitable environment may have evolved throughout the life span of their host stars
- Life may indeed be common.

Thank you