Density waves in the natal disks of emerging planets

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Lin-Shu Celebration, Tsinghua

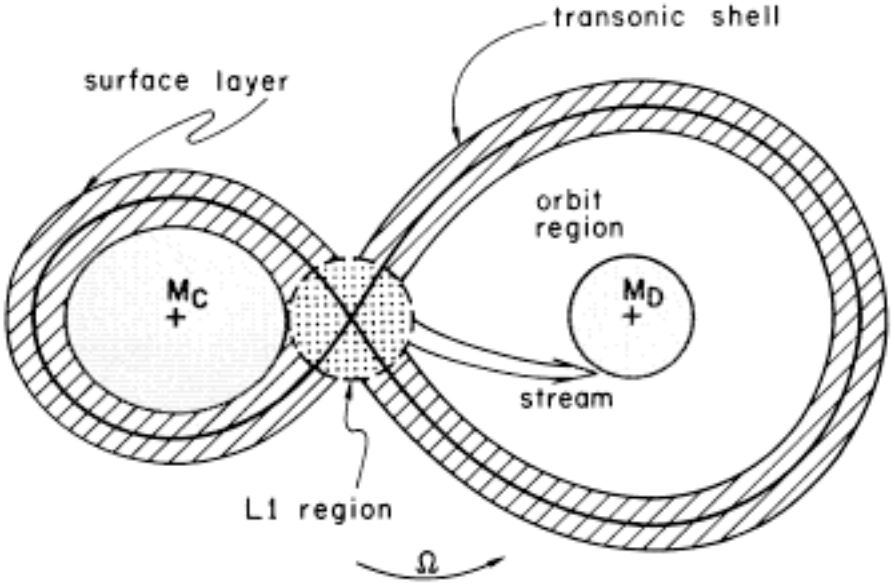
Beijing, 6.27.2013

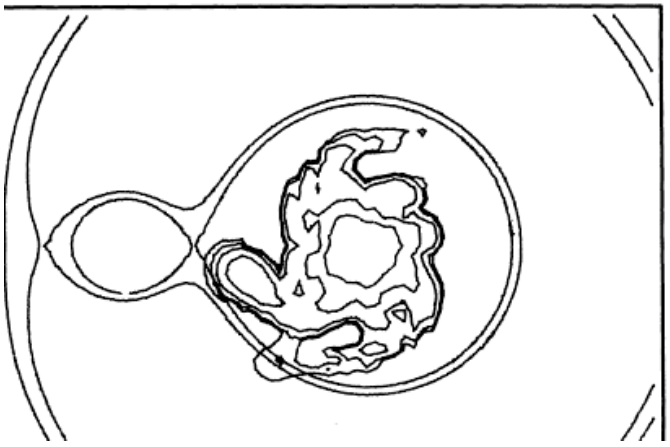
51 slides

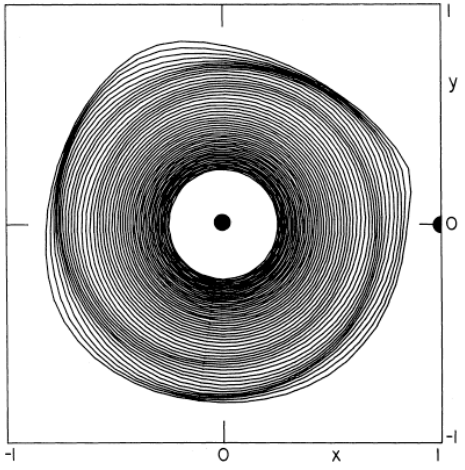

CCP 2

Some reflections

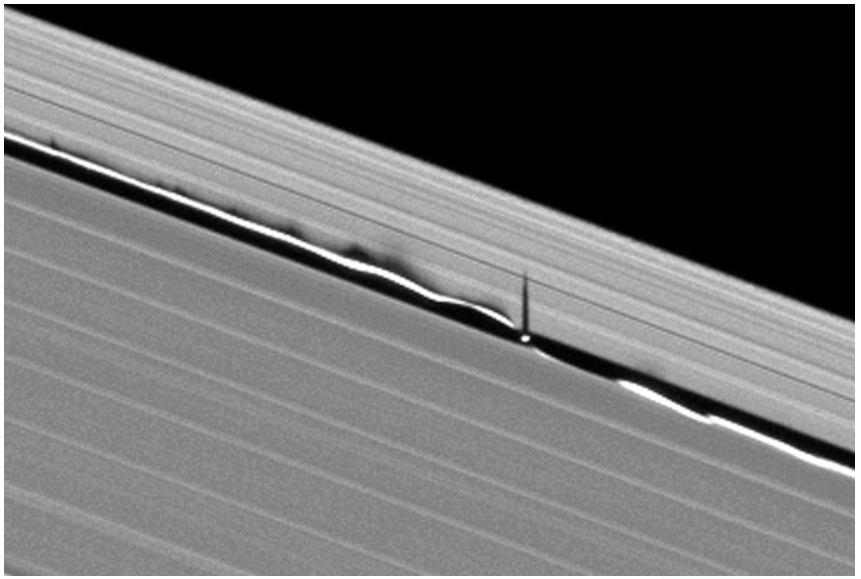
Some anecdotes







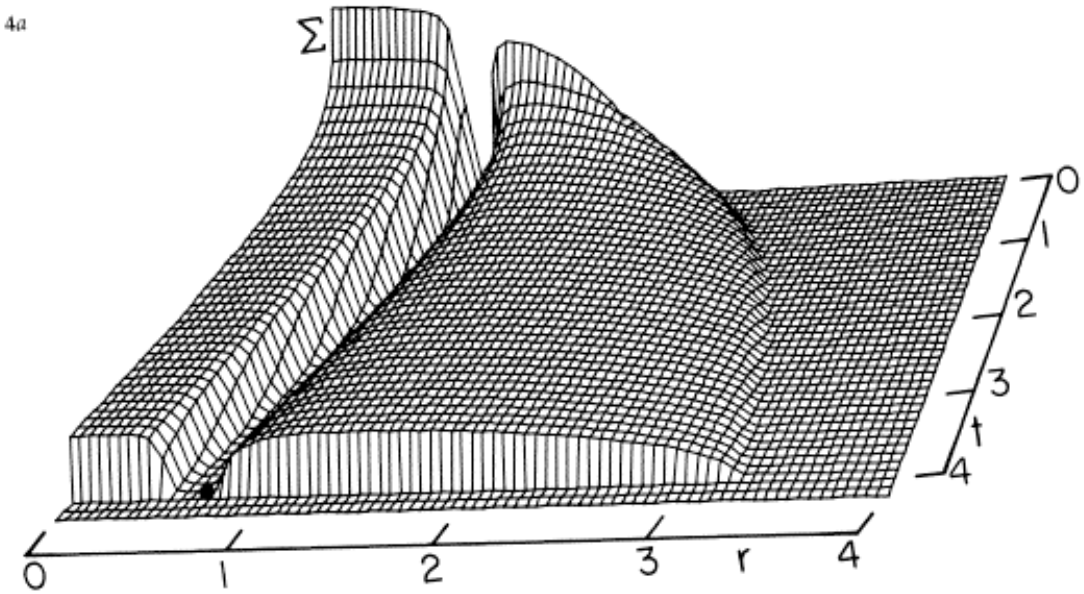
Density waves in rings



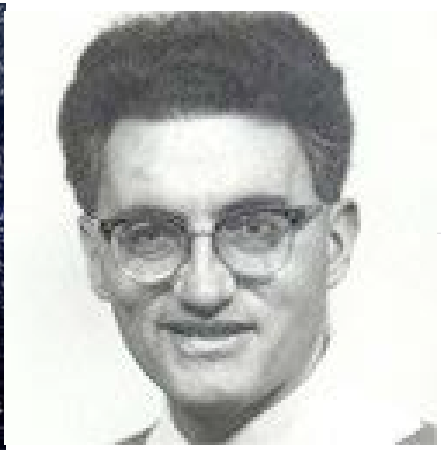
Protoplanetary migration

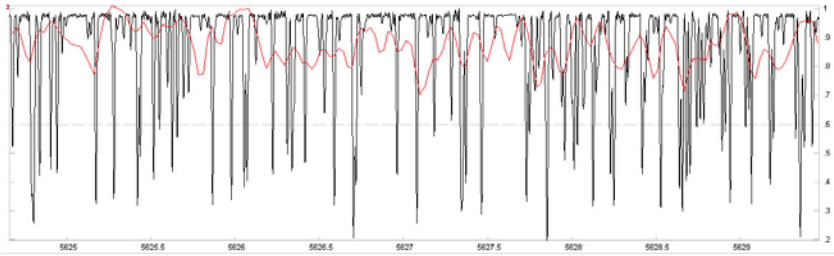
The results obtained here can be used to study the dynamics of both planetary rings and solar system formation. It may be of interest to investigate the dynamical evolution of several protoplanets in a disk. It may also be of interest to examine the possibility that there may have been, at some stage of solar system formation, a protogiant planet interior to the orbit of Jupiter that has evolved into the protosun. Finally, the results presented here may be relevant to the evolution of fragments according to the fission hypothesis. We shall consider these issues elsewhere.

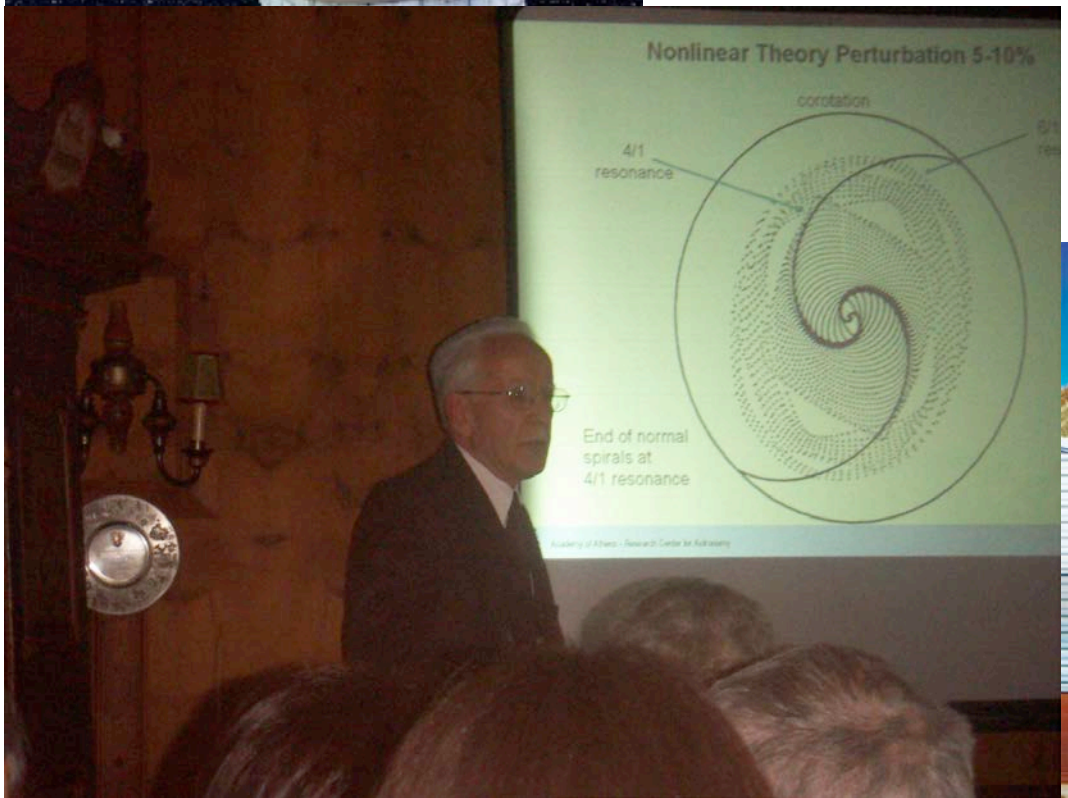
FIG. 4a

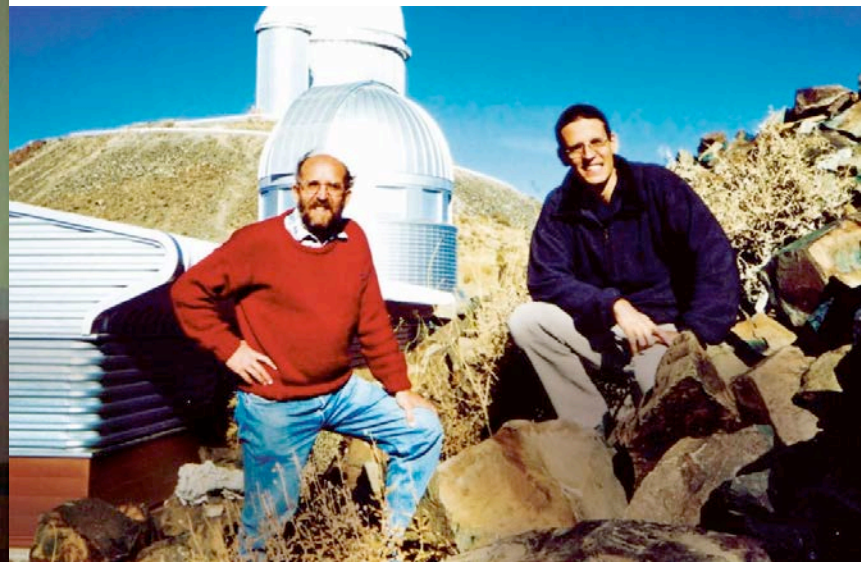


Observational front

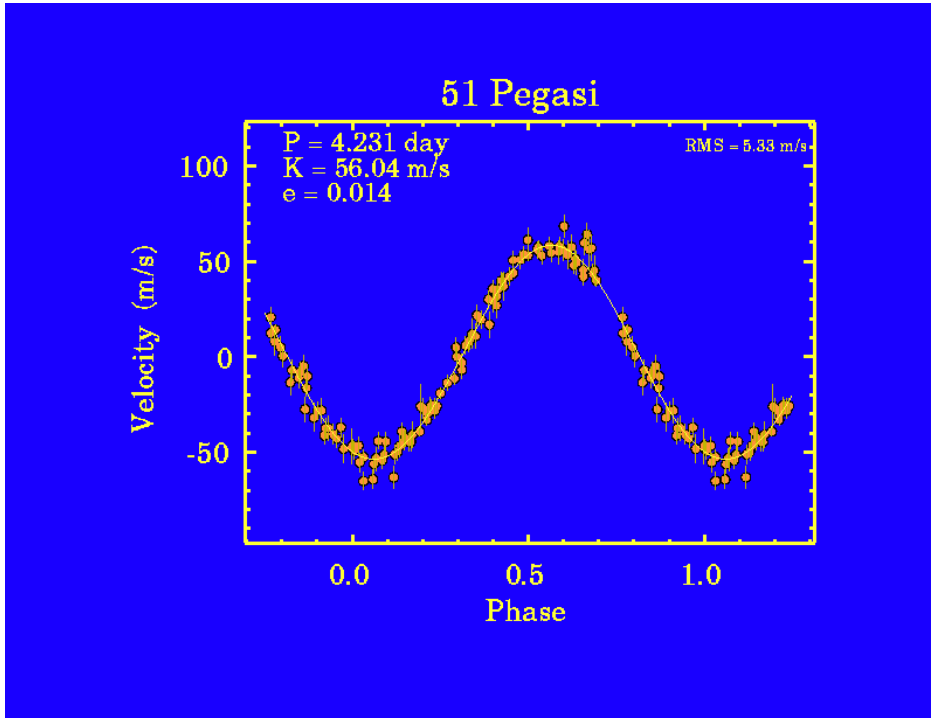


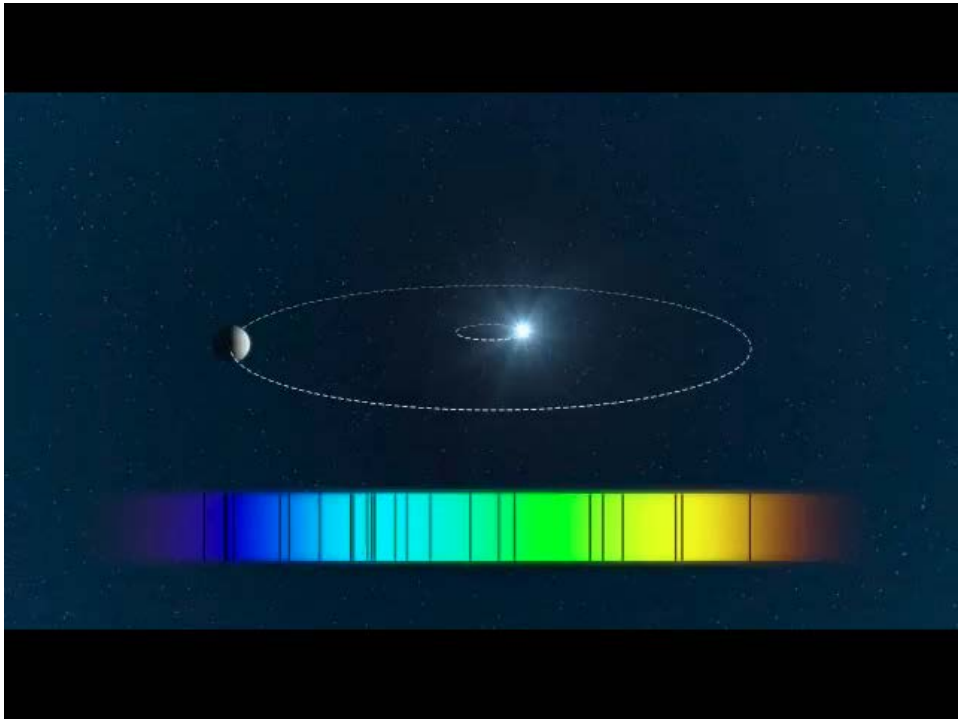




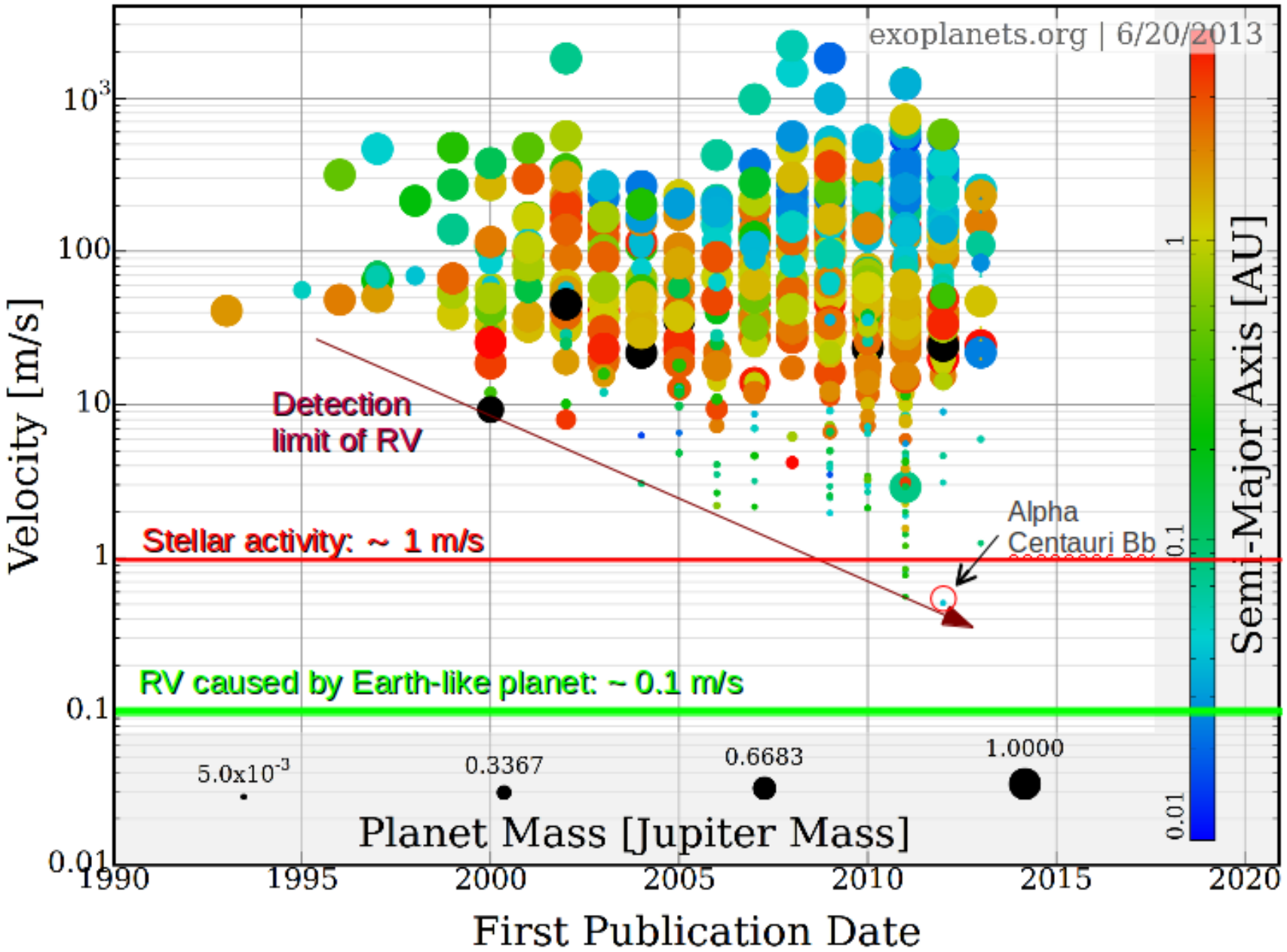


Hot Jupiter !!!

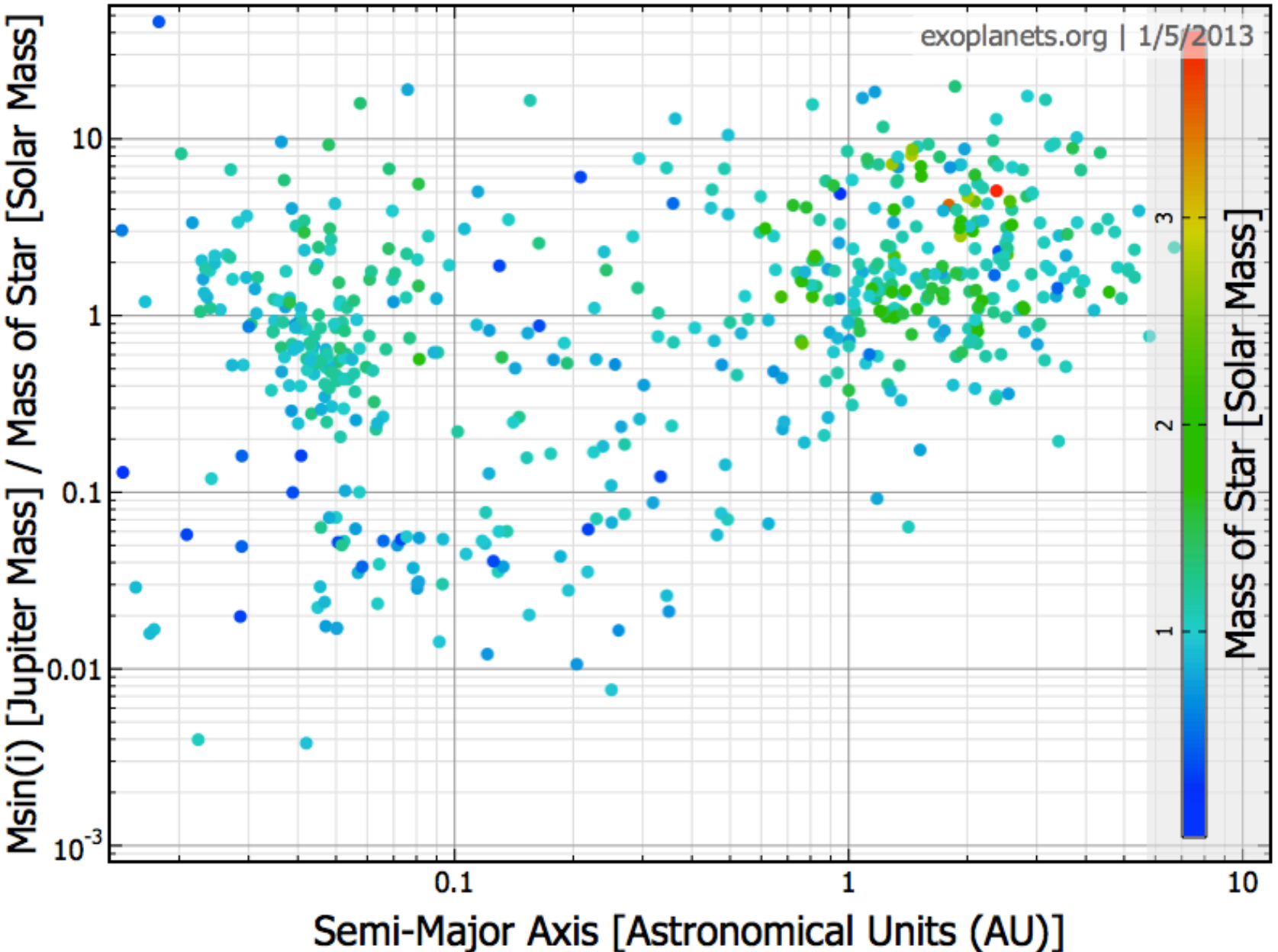

51 Pegasi
P = 4.231 day
K = 56.04 m/s
e = 0.014
RMS = 5.33 m/s
100
50
0
-50
Velocity (m/s)
0.0
0.5
1.0
Phase



Progress on the observational front

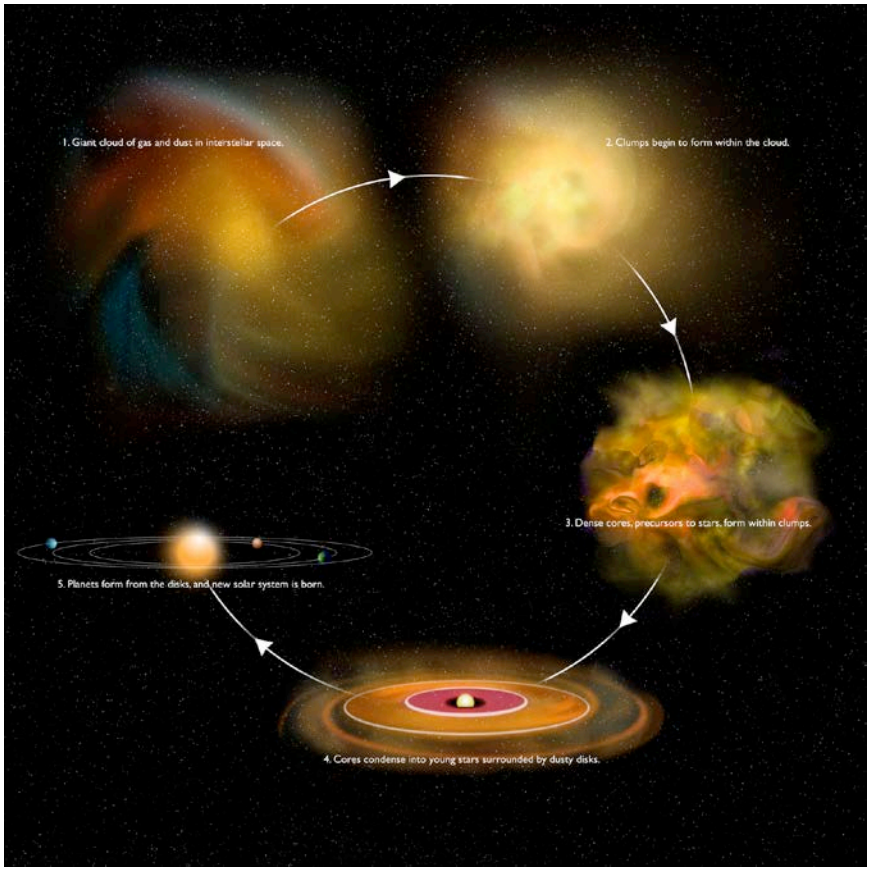


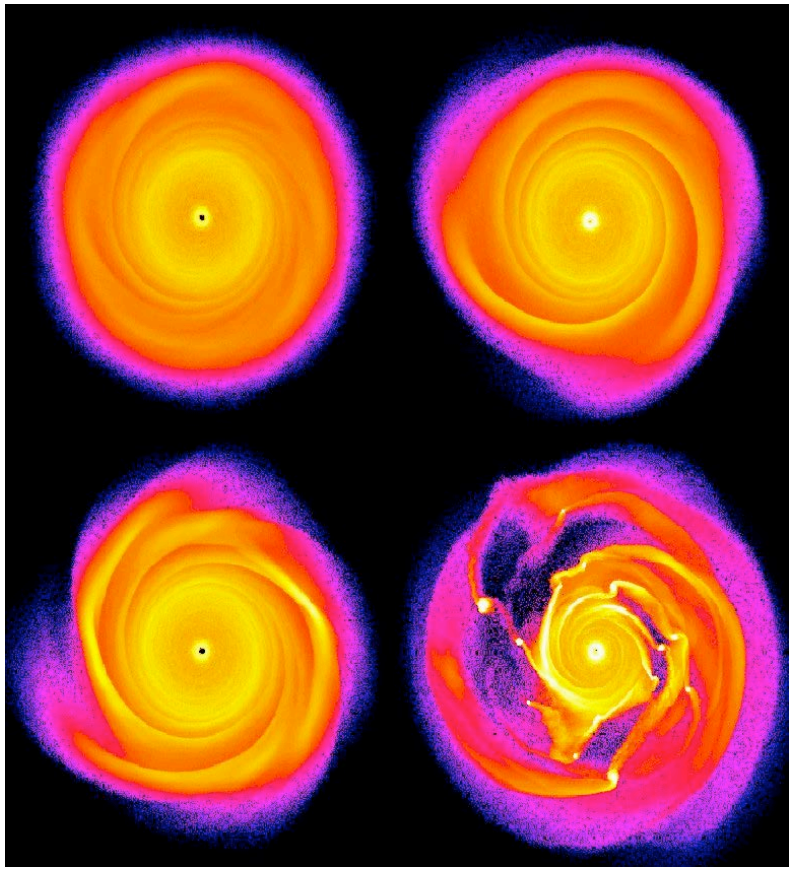
Statistical properties



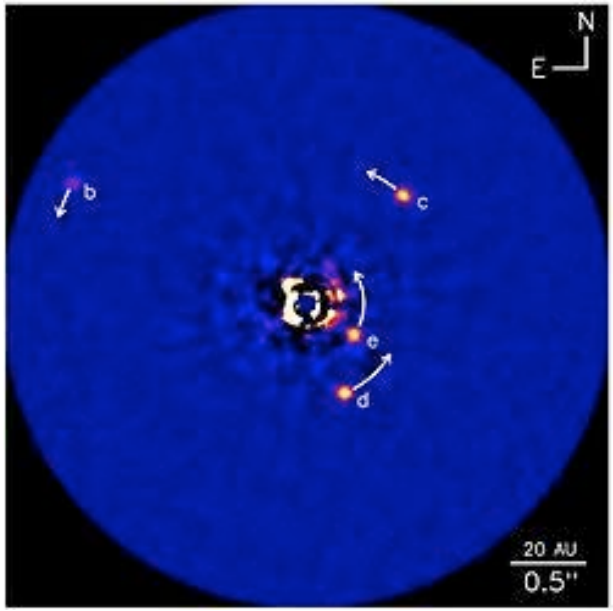
Gas giants: some key issues

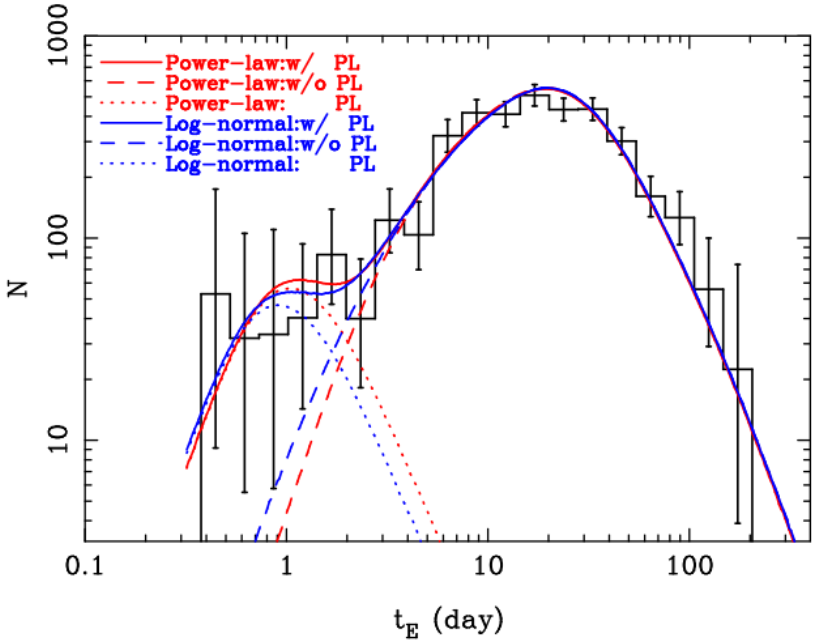
- Did most gas giant form through core accretion or gravitational instability?

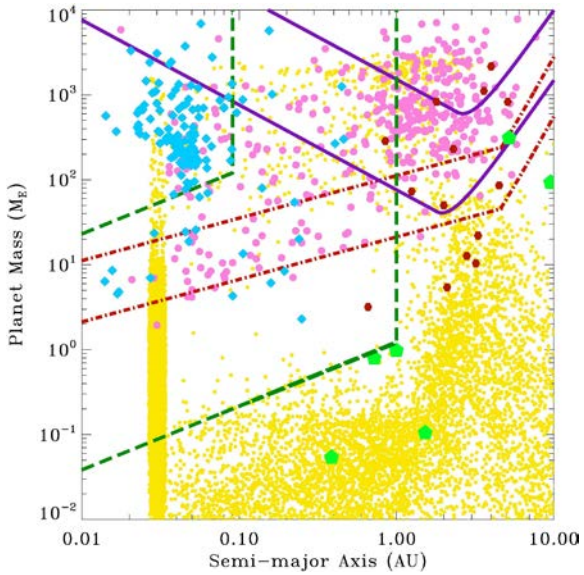


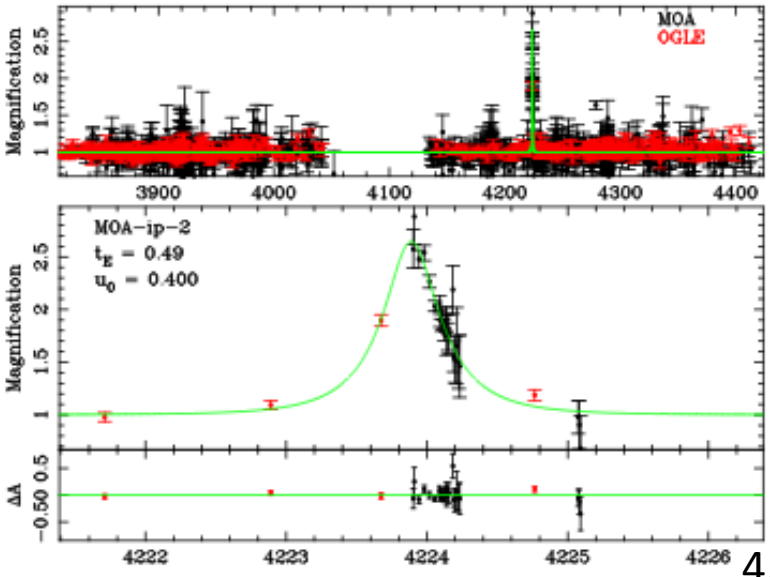


Long-period massive planets

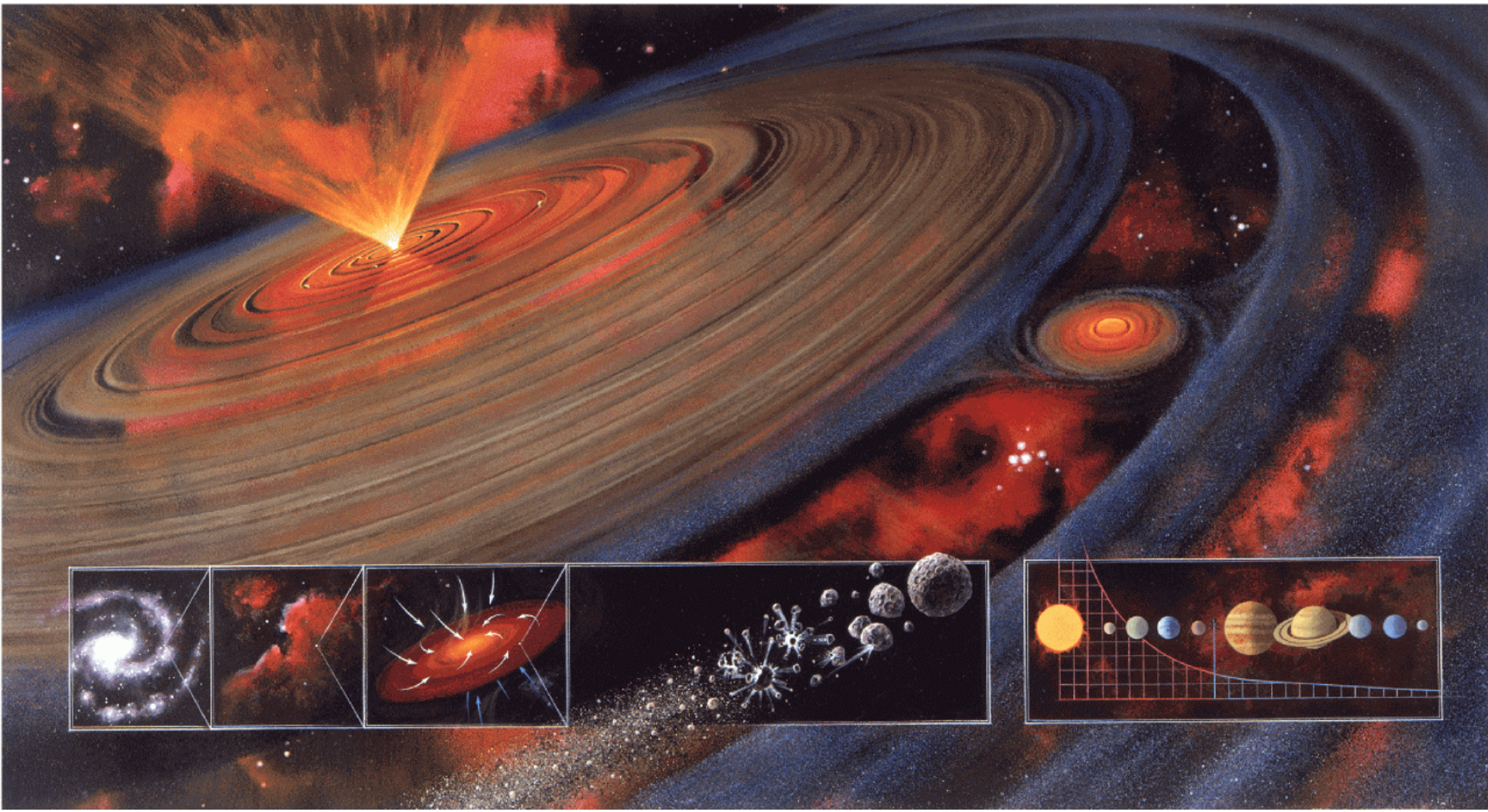




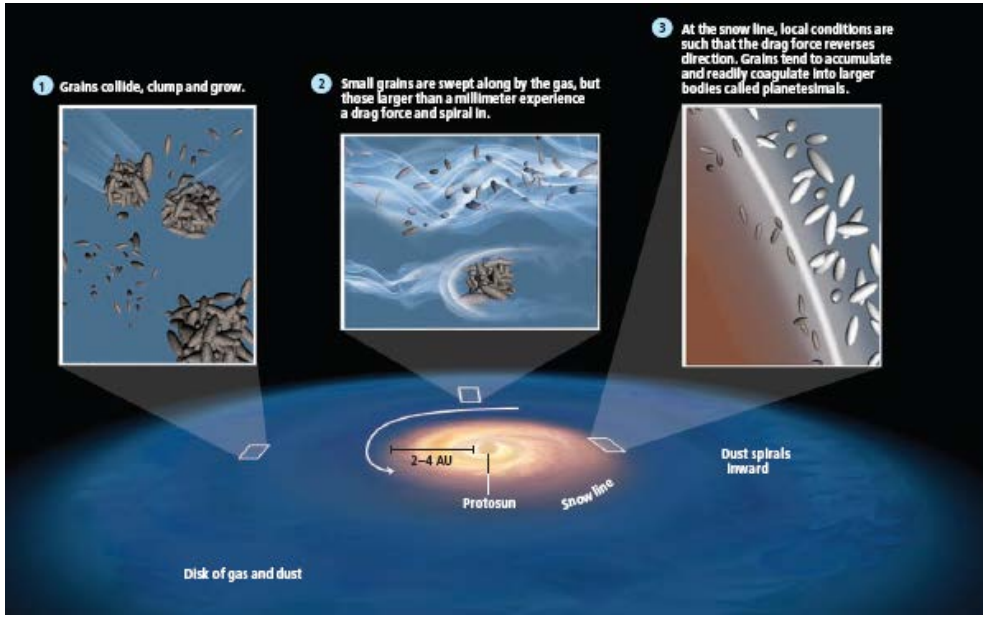


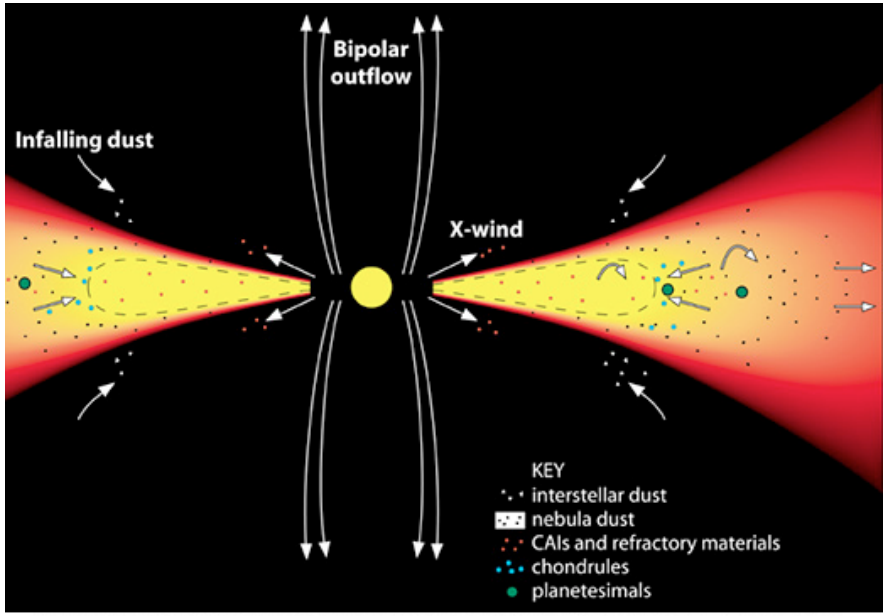


Core accretion paradigm

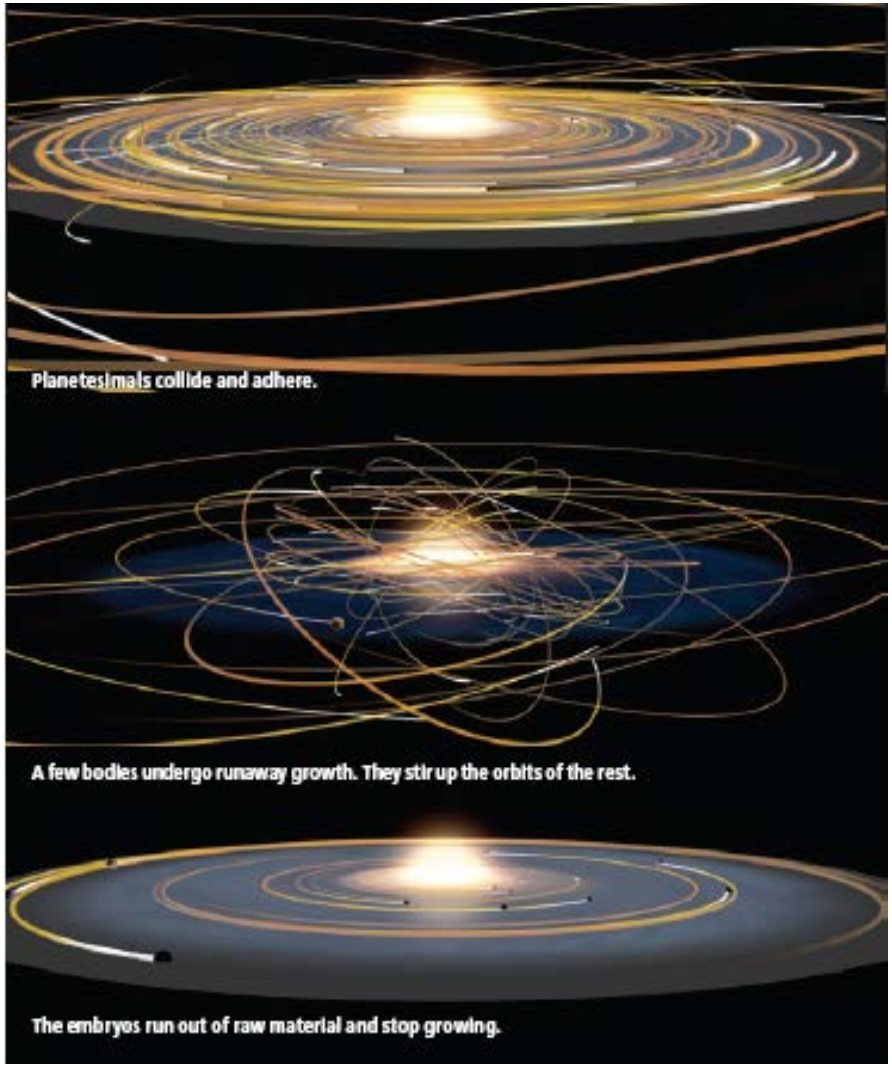


From dust to protoplanetary embryos



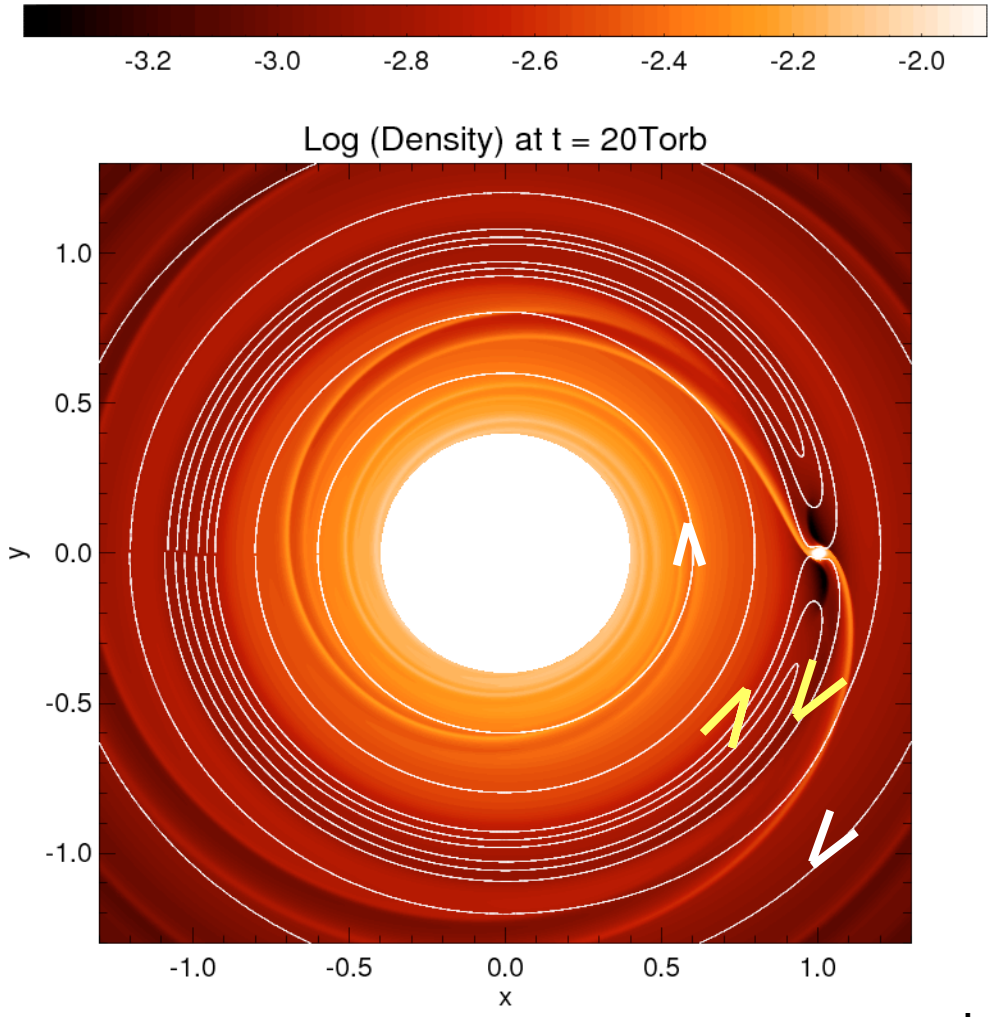


(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)



Zhang Yuan

Theoretical Paradigm: planetary migration
Type I migration of super-Earth in isothermal disks



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

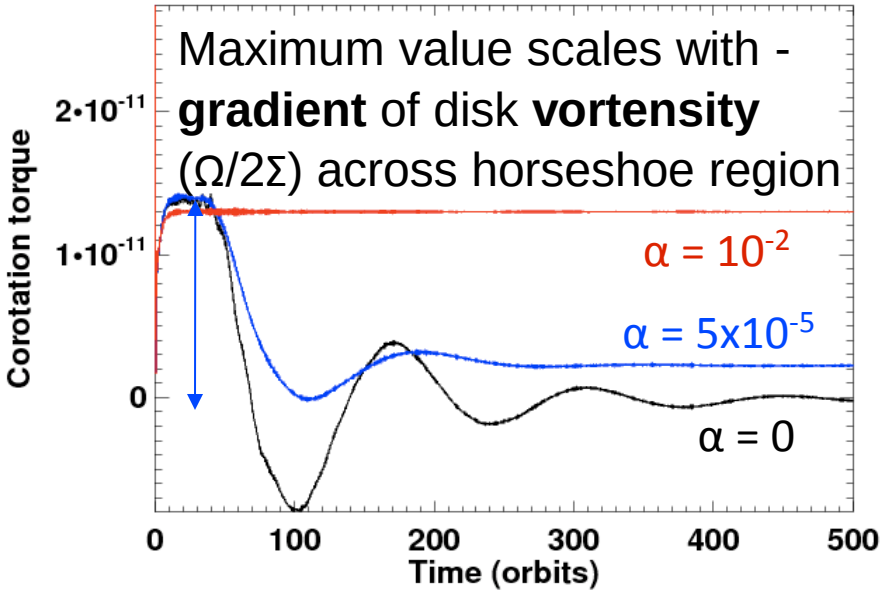
The planet exchanges angular momentum with:

- **circulating** fluid elements:

  → **differential Lindblad torque**

- **librating** fluid elements:

  → **corotation torque**

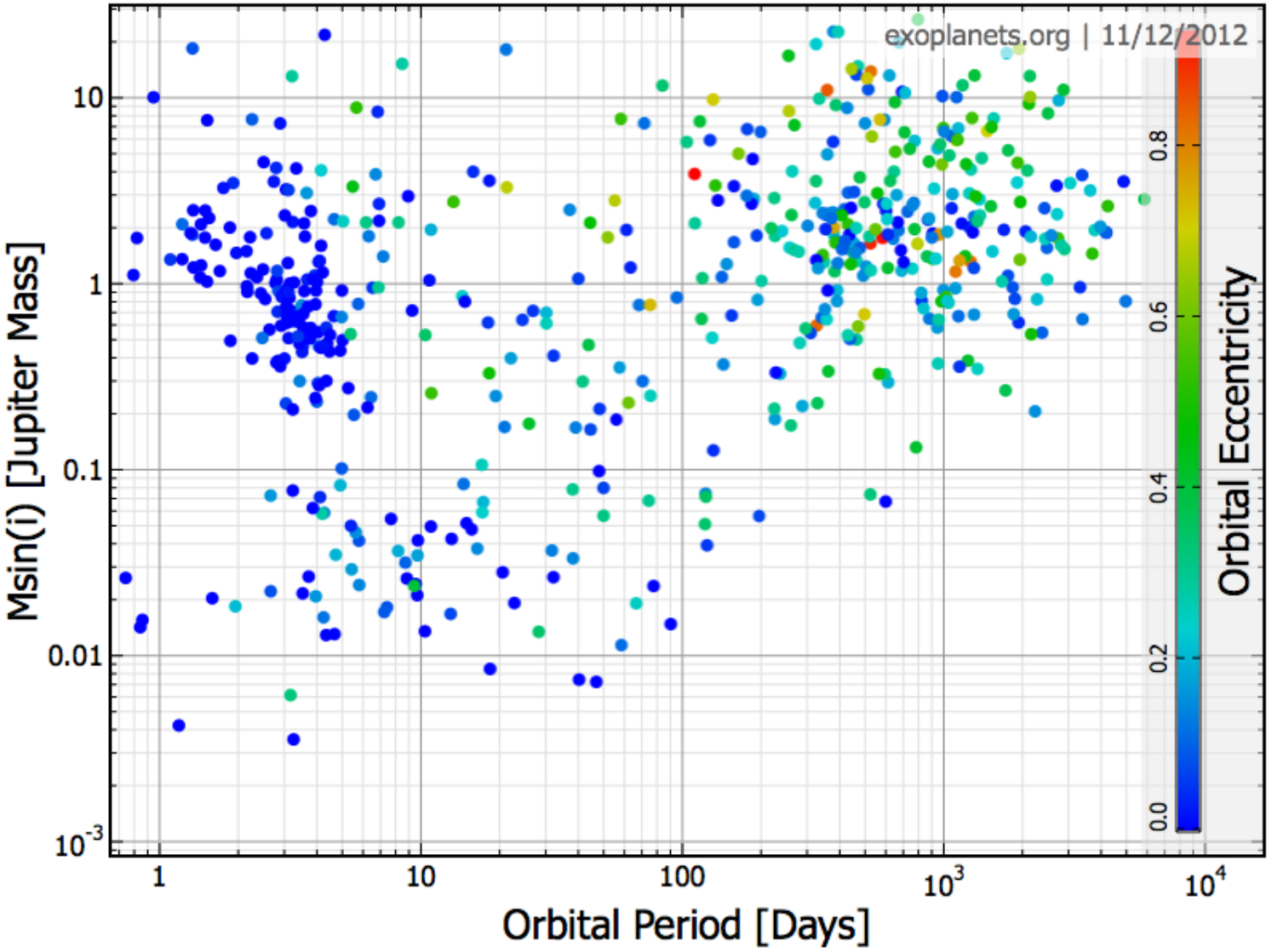


Long-term evolution of the corotation torque is related to the disk viscosity

Paardekooper, Baruteau,

Gas giants: some key issues

- Is there a prefer location for gas giant formation?



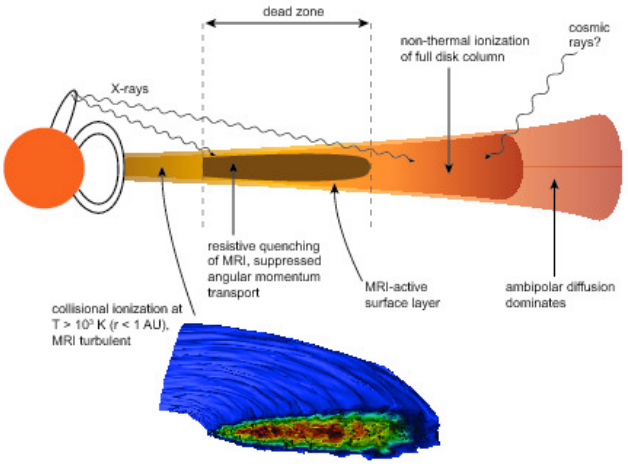
Planet-disk tidal interaction

Total tidal torque:

$\Gamma = \Gamma_L + \Gamma_c$ = f(p,q,p_ν,q_ν,p_κ ,q_κ)Γ_0

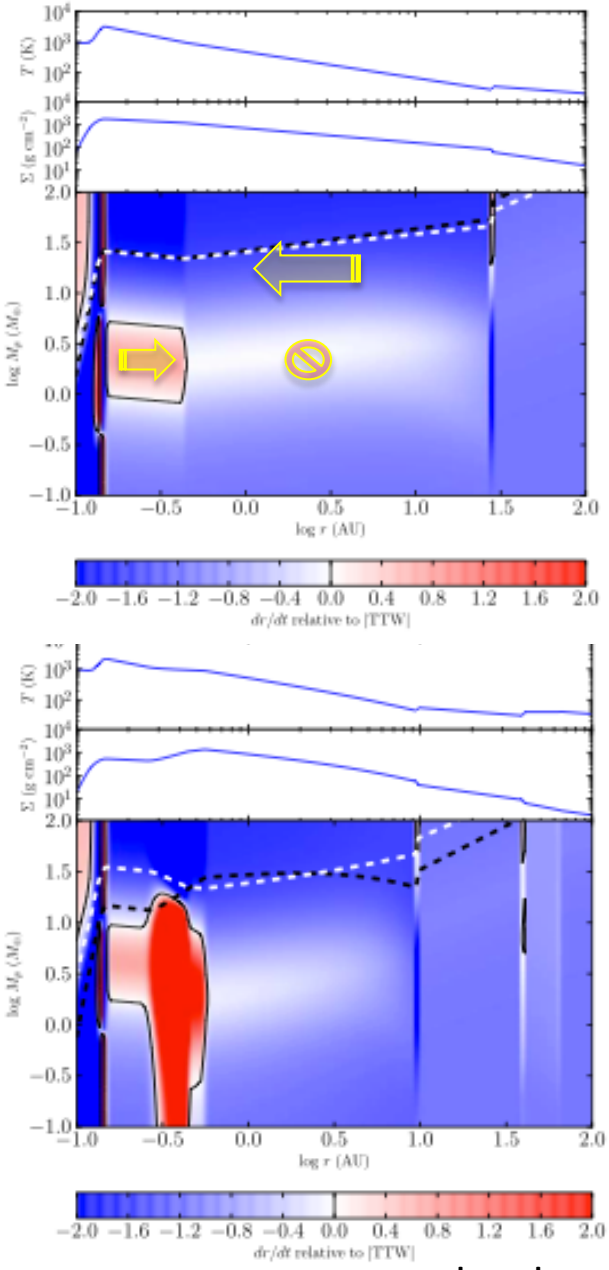
$\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2,$

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



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

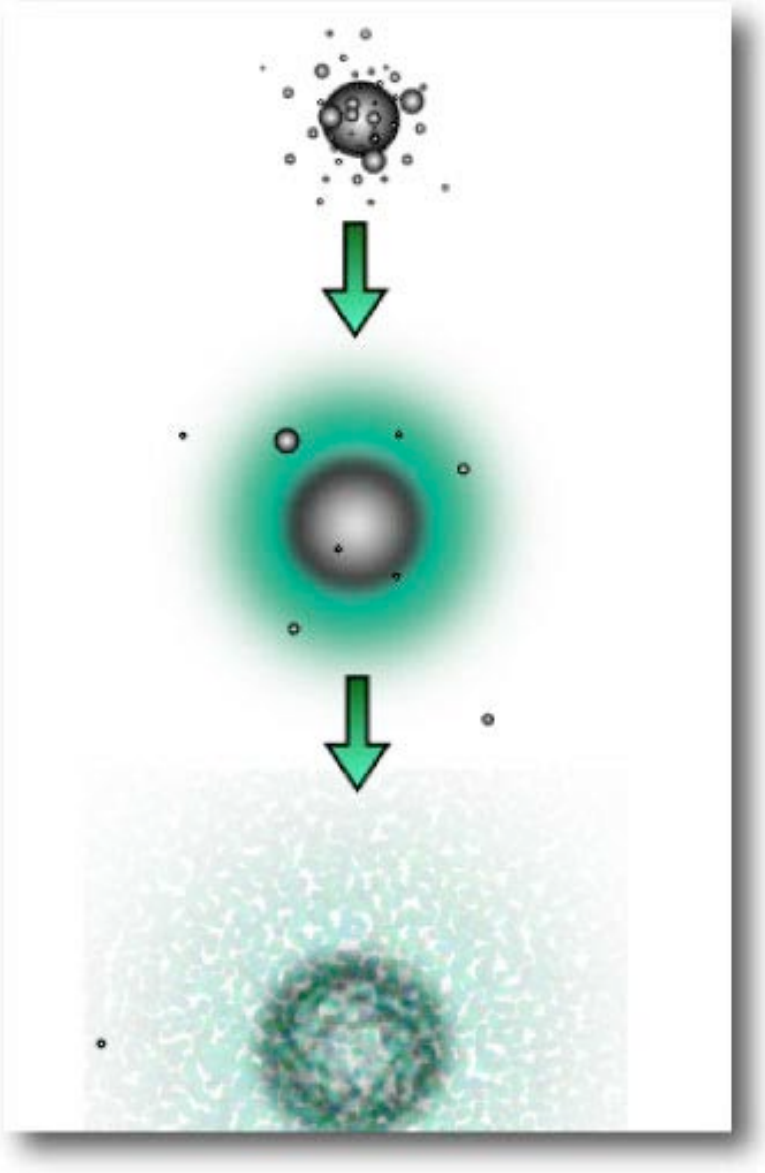
(1/e)de/dt = (a/H)^4 ($M_p\Sigma a^2/M_*^2$) Ω

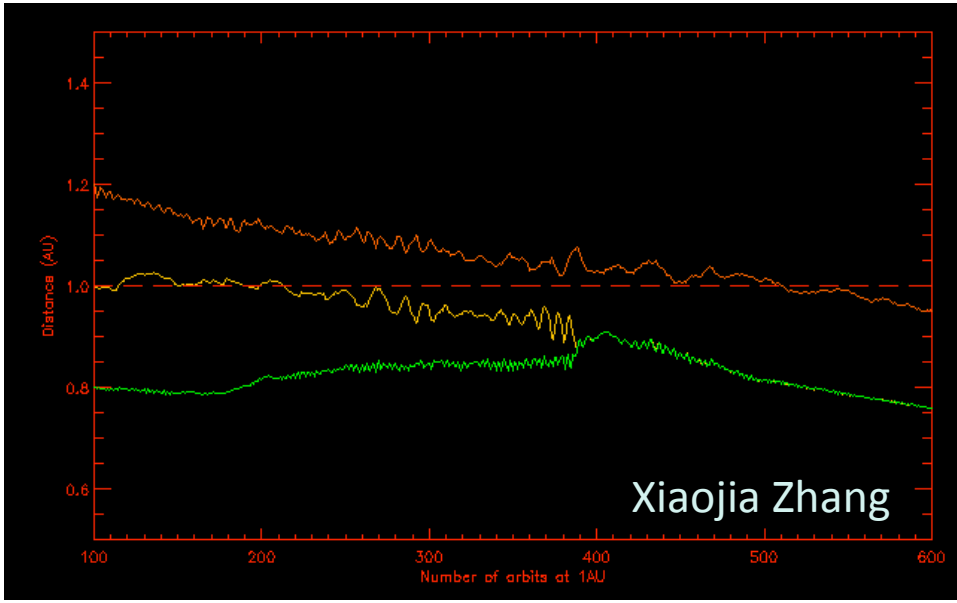


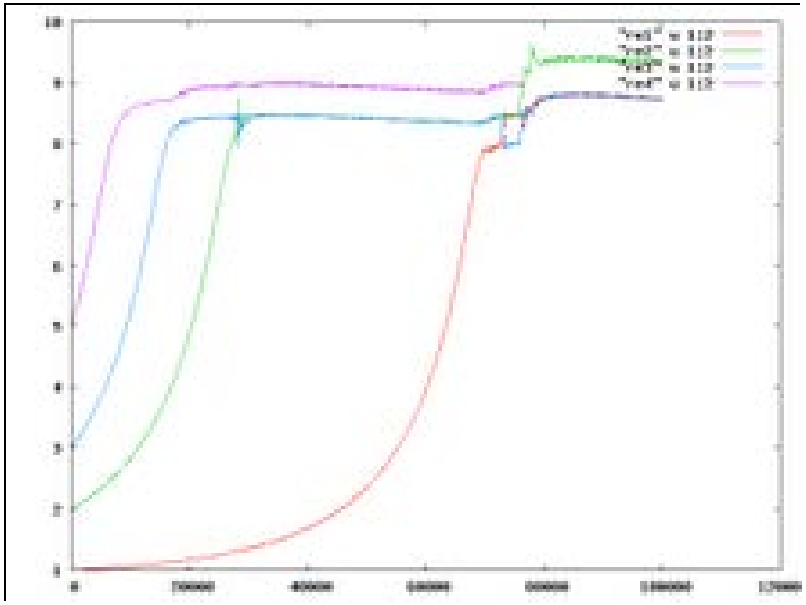
kretke

Gas giants: some key issues

- Can cores form prolifically?

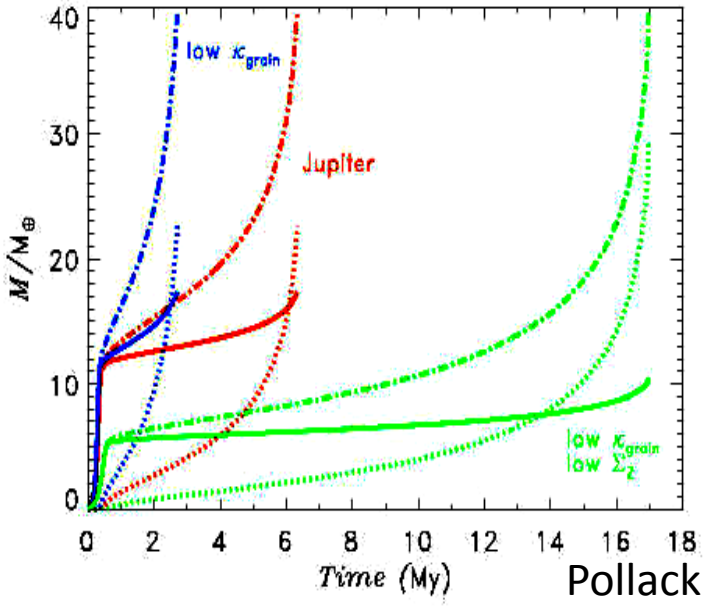




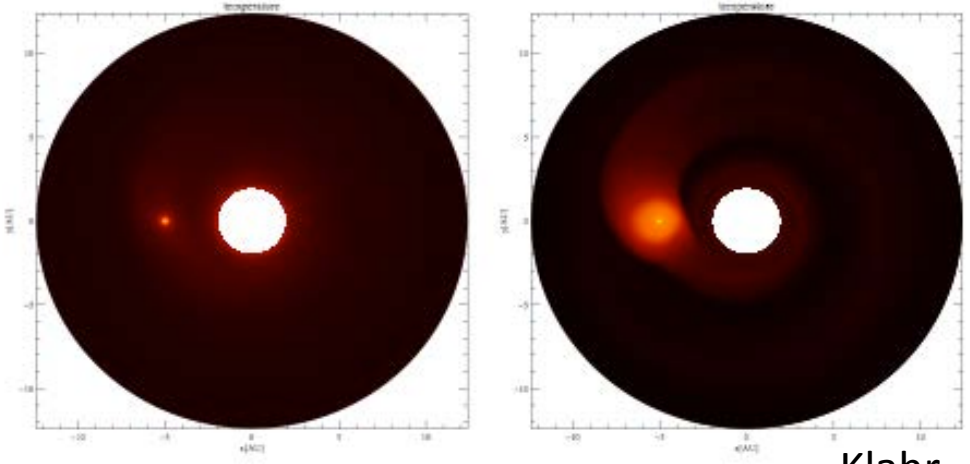


Gas giants: some key issues

- Is there a threshold mass for gas accretion?

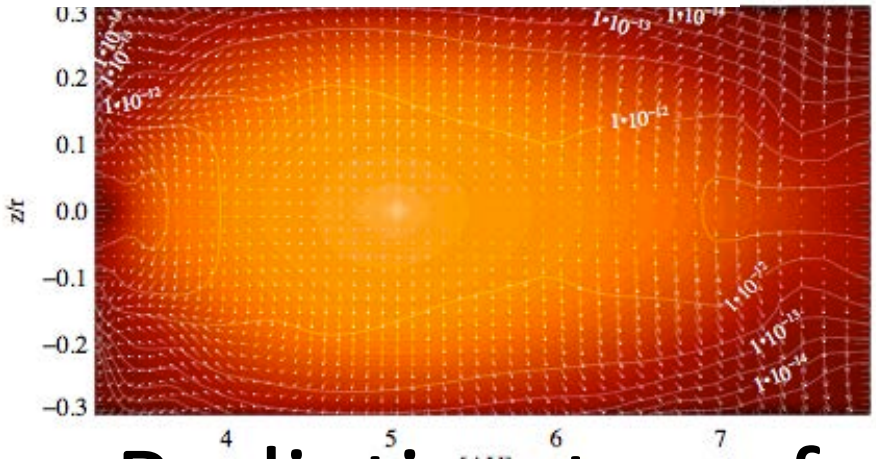


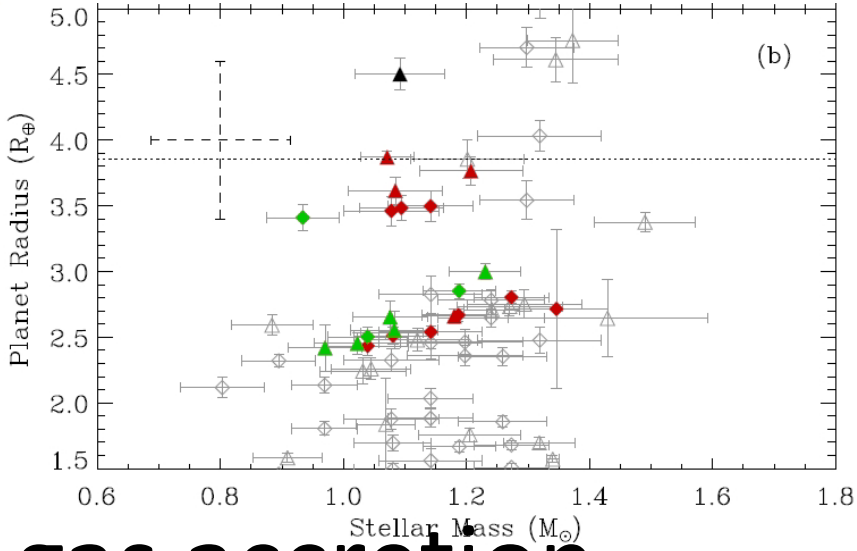
Pollack et al



Klahr

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

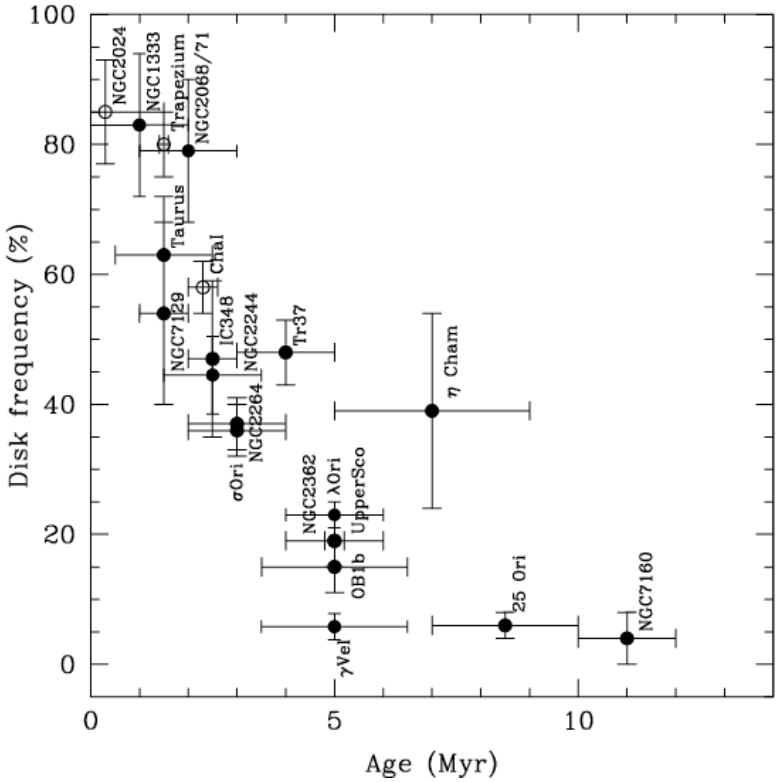


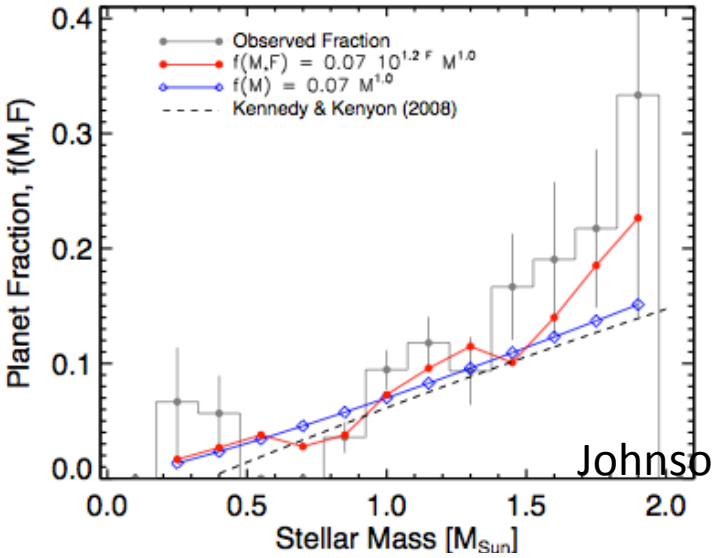


Radiation transfer & gas accretion

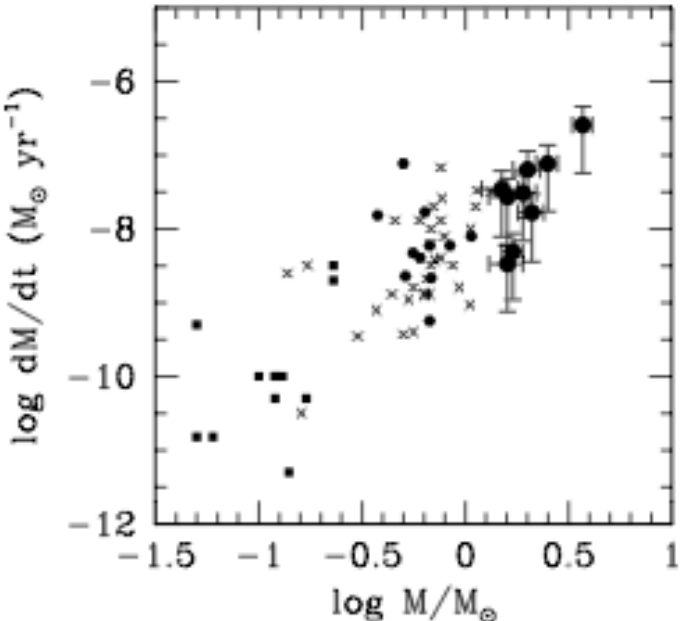
Gas giants: some key issues

- Is there enough time for gas giant to form?

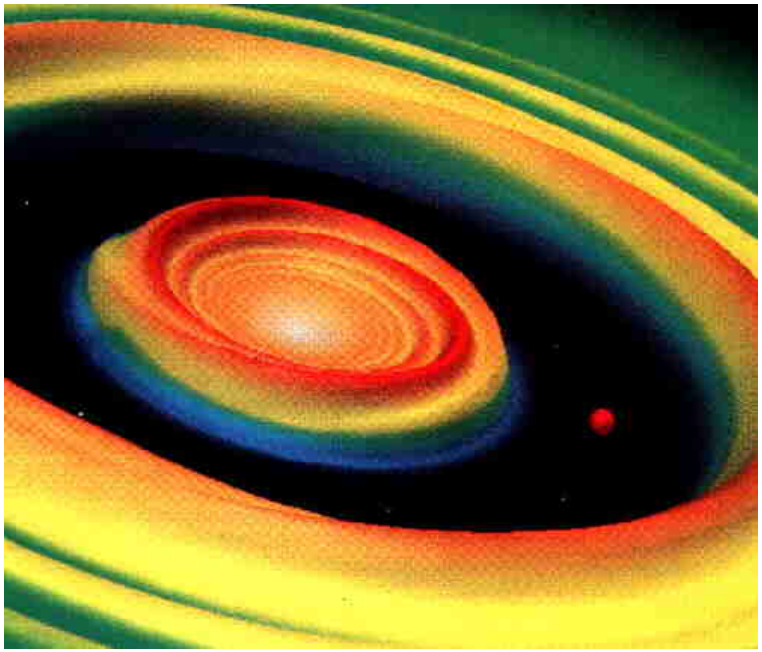


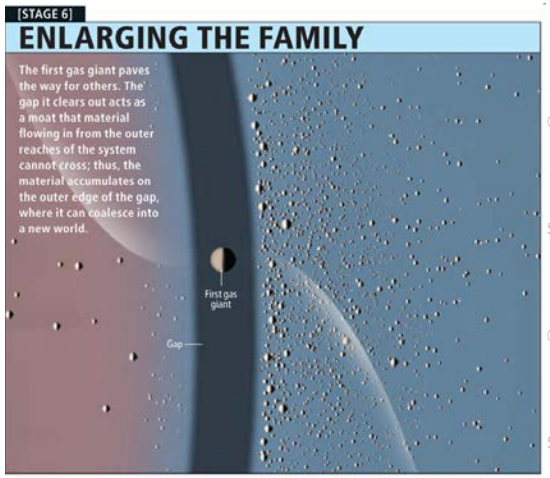


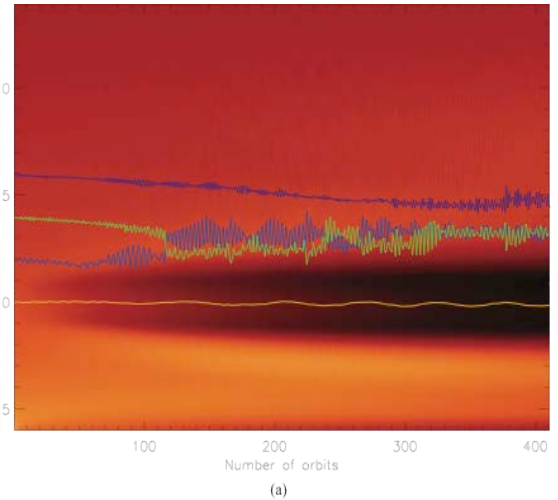
Johnson et al

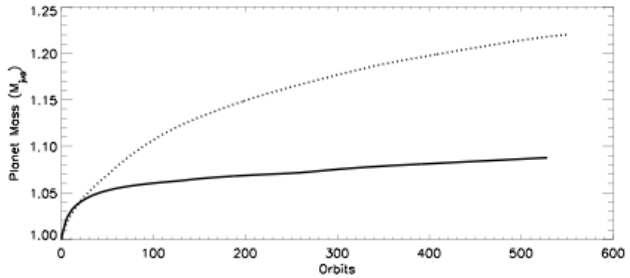


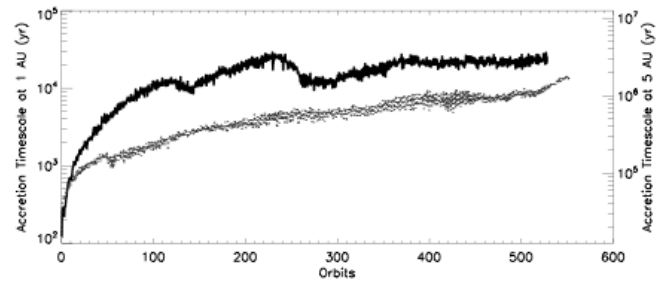
Gas giants' asymptotic mass



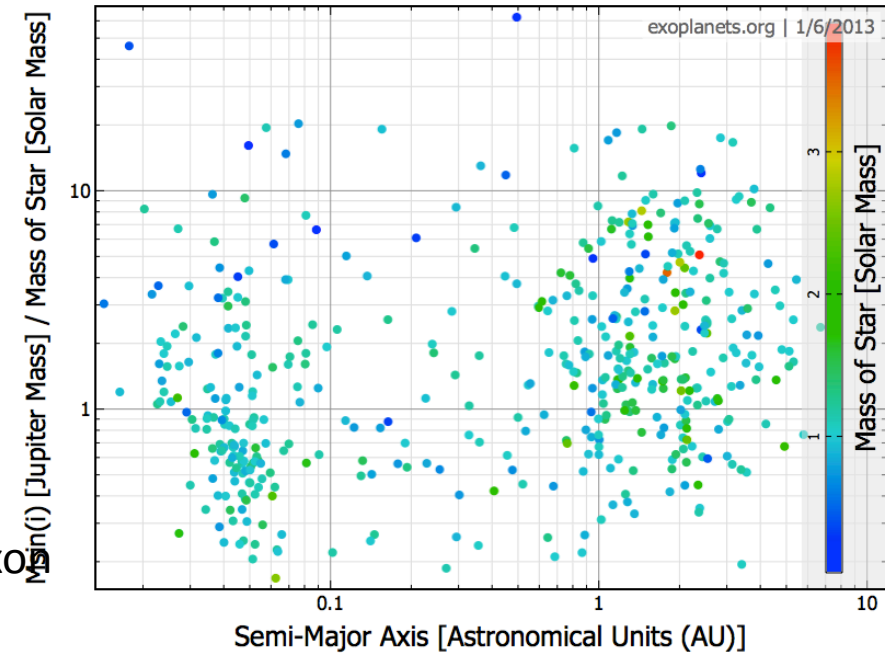






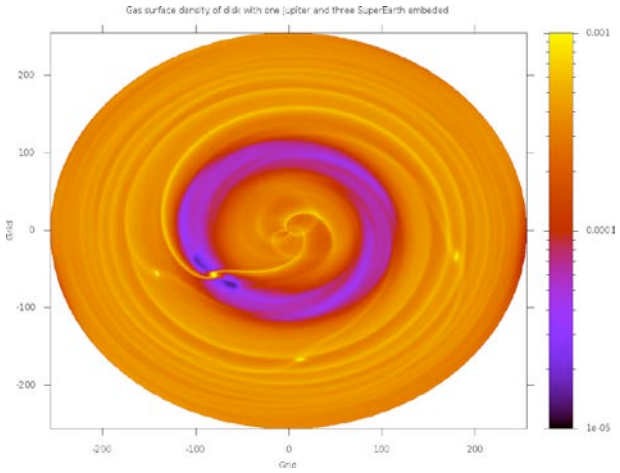


Dobbs-Dixon
Shulin Li

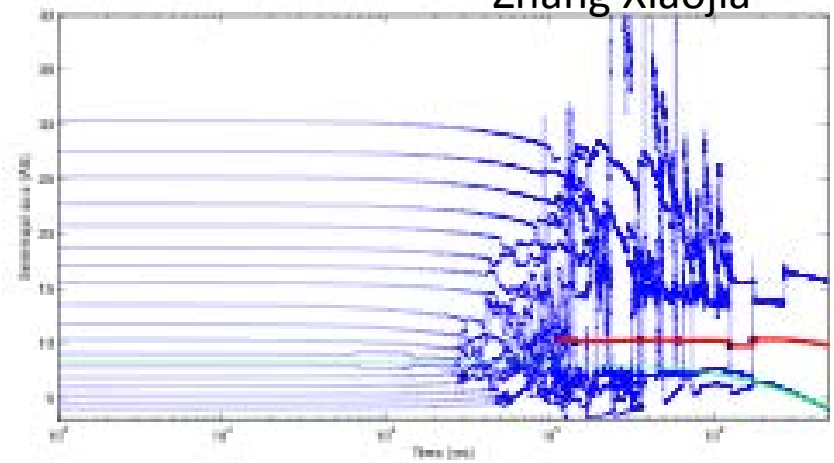


Gas giants: some key issues

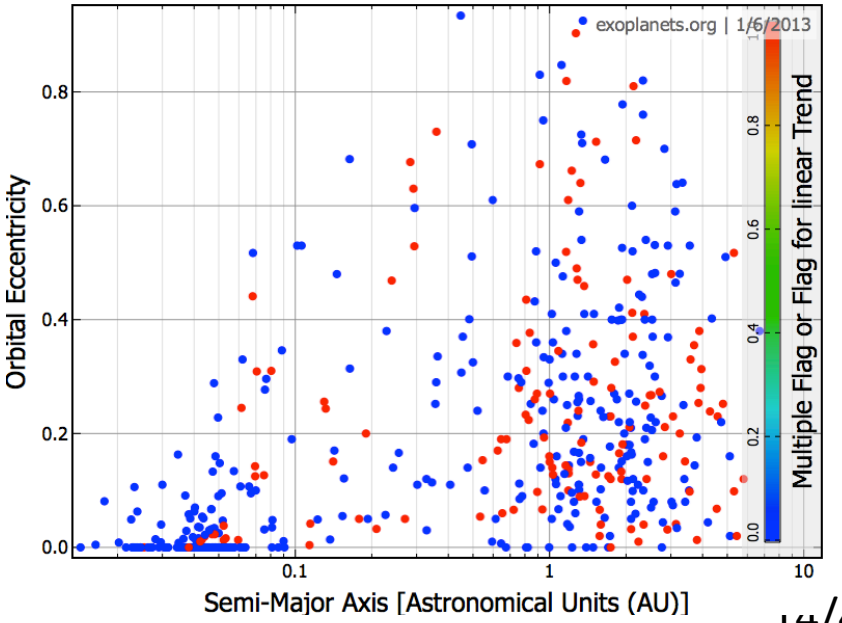
- How did multiple gas giant system form?



Zhang Xiaojia



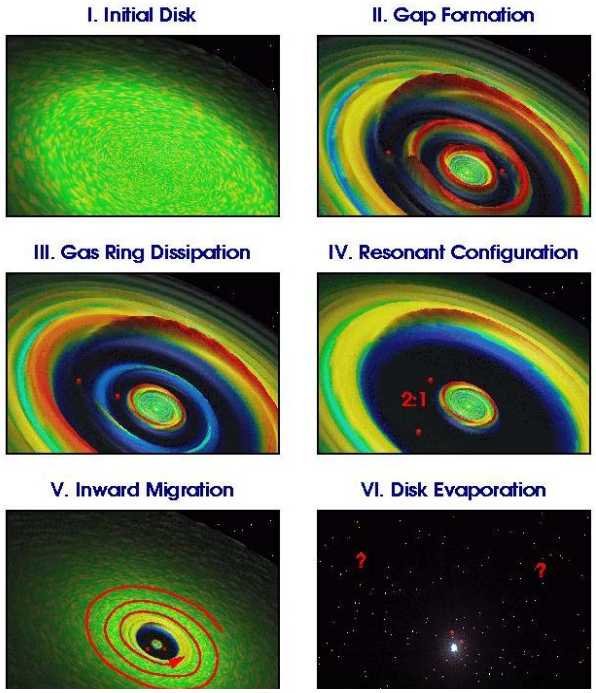
Liu BeiBei



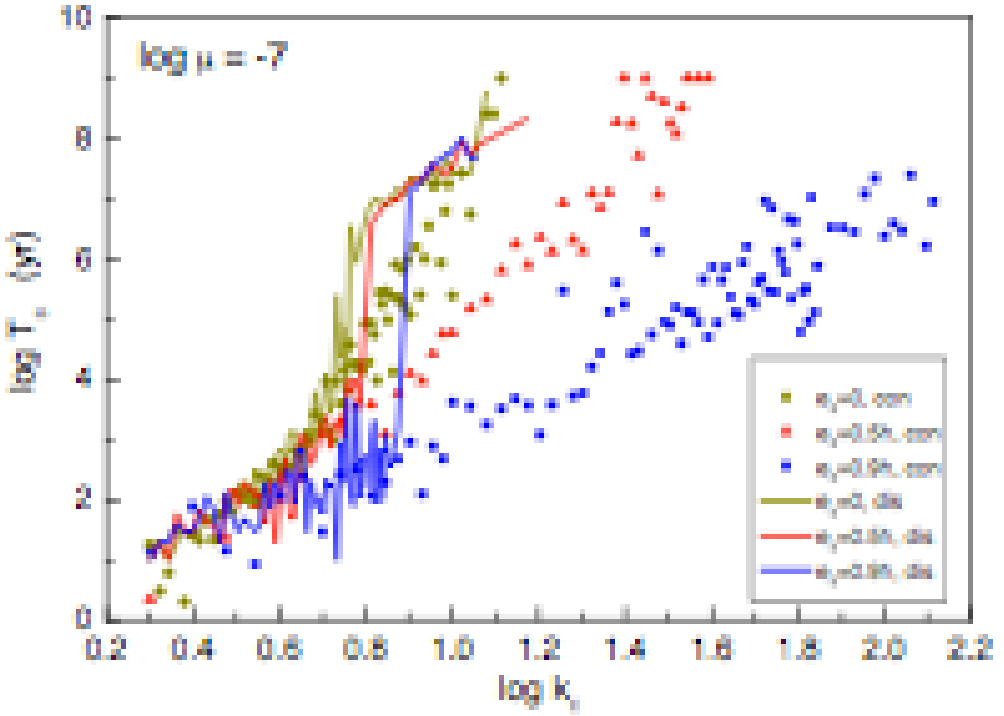
Astrometry, microlensing, direct imaging

Gas giants: some key issues

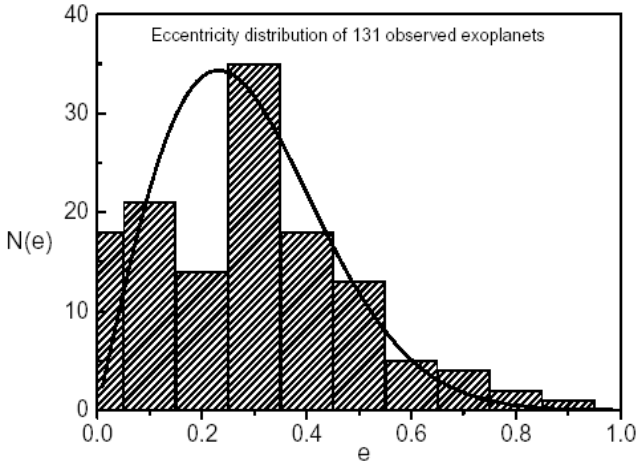
- How did gas giants acquire their eccentricity?



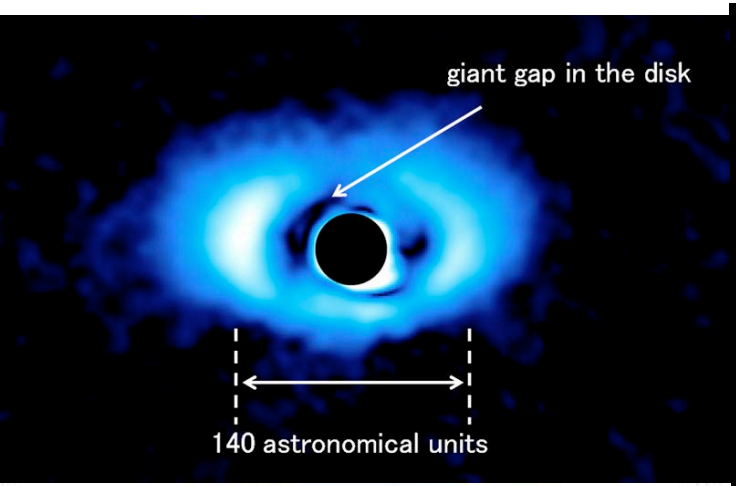
Bryden

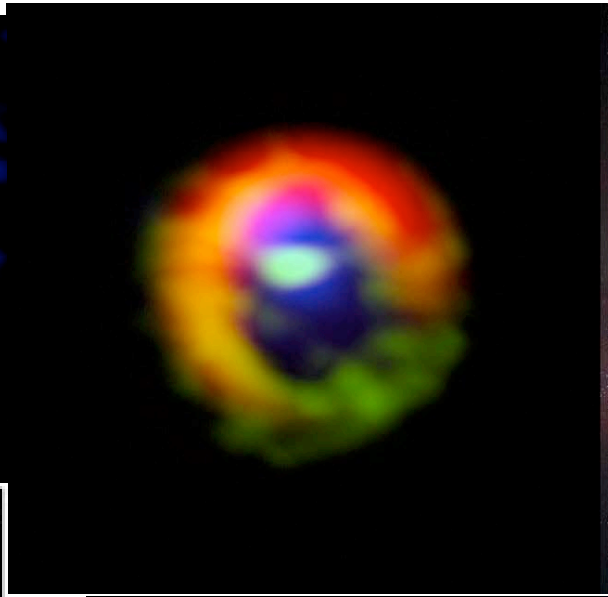


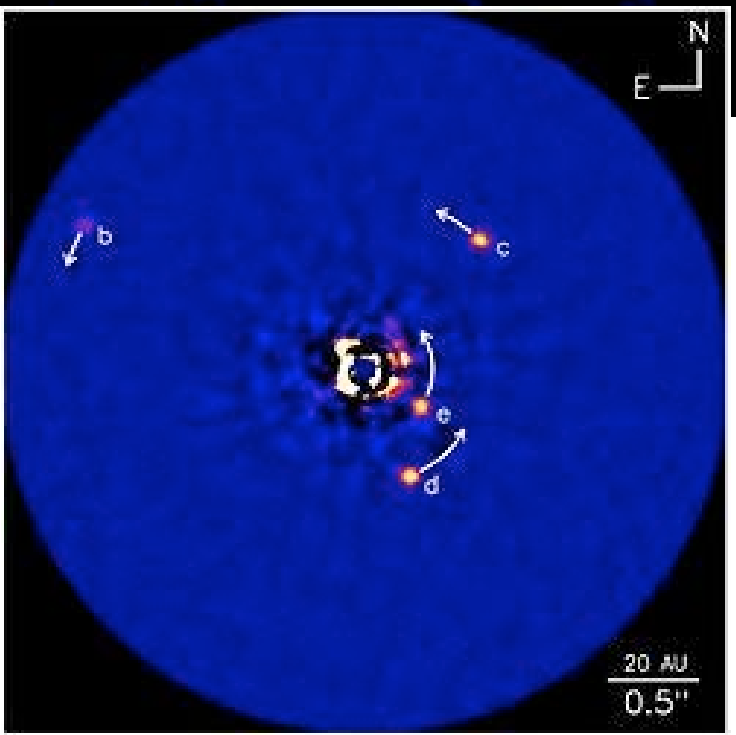
Jilin Zhou

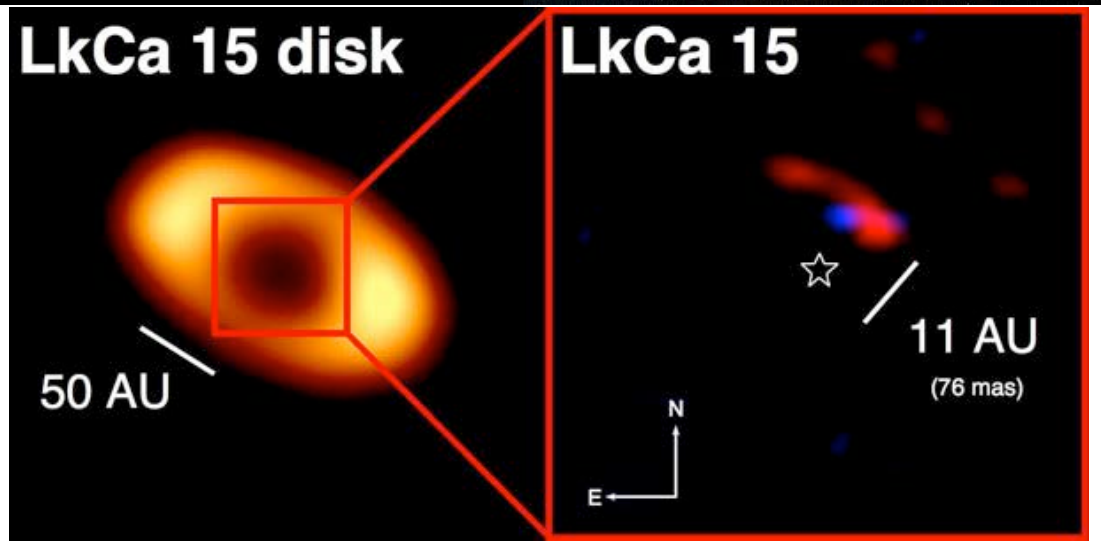


Spirals and gaps in protostellar disks





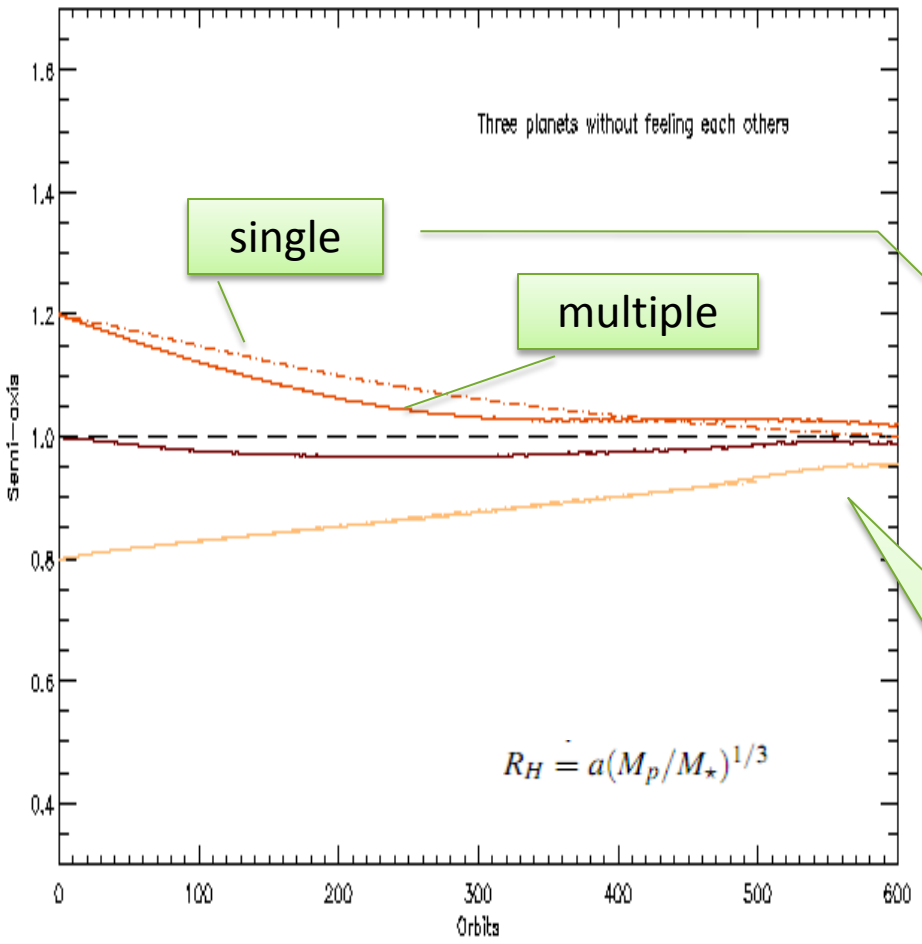




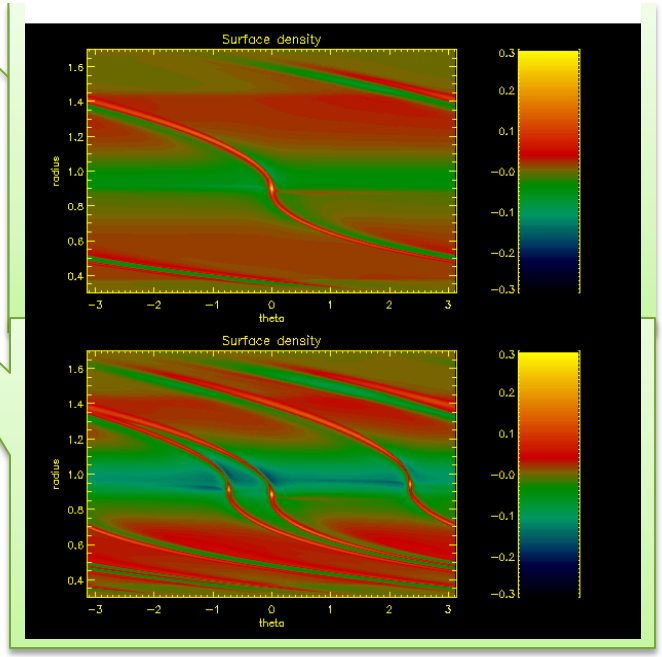
Multiple embryo's type I migration

FARGO

SEMI-AXIS EVOLUTION

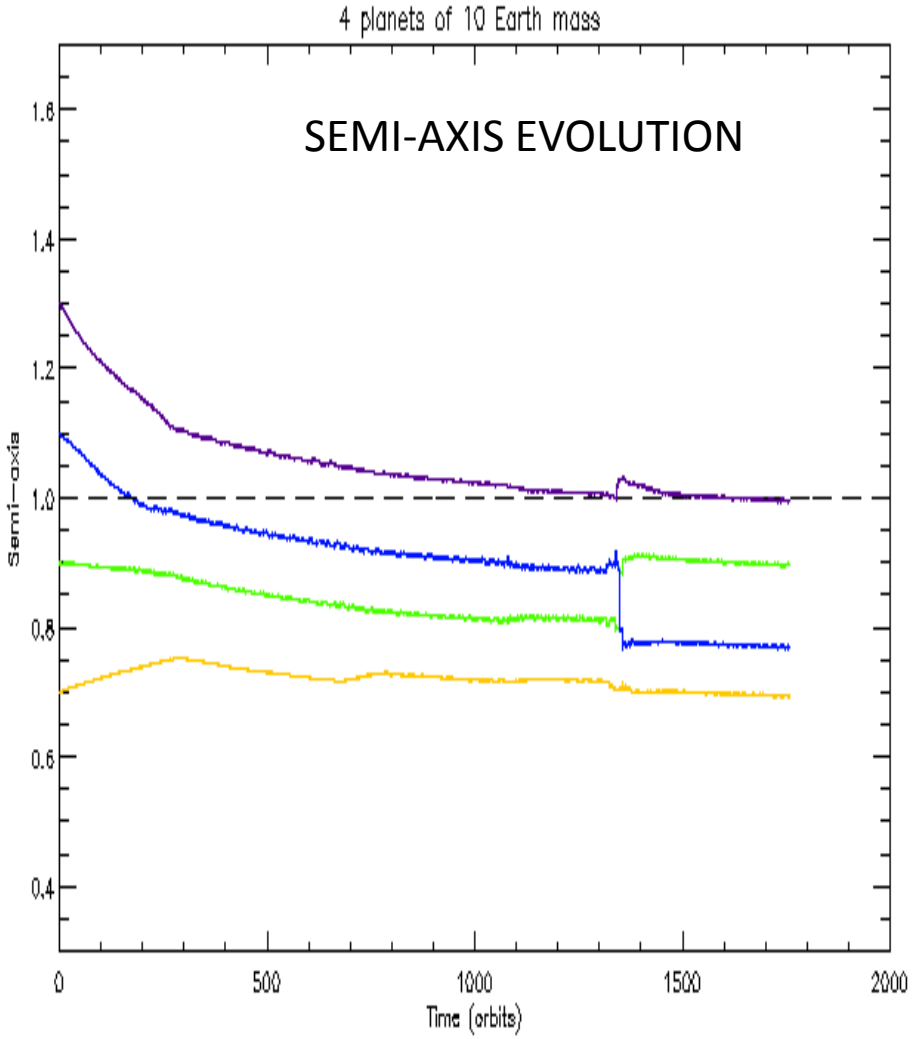


① Only indirect interaction between embryos during disk perturbation

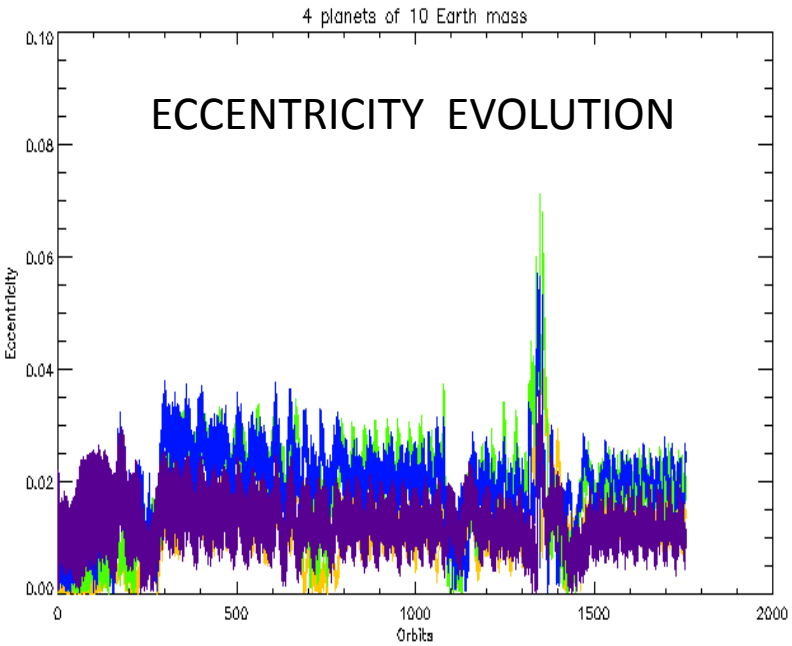


Multiple embryo's type I migration

FARGO

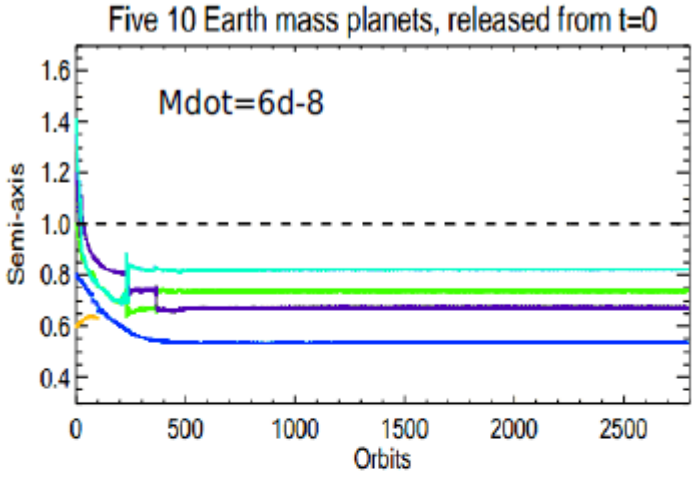


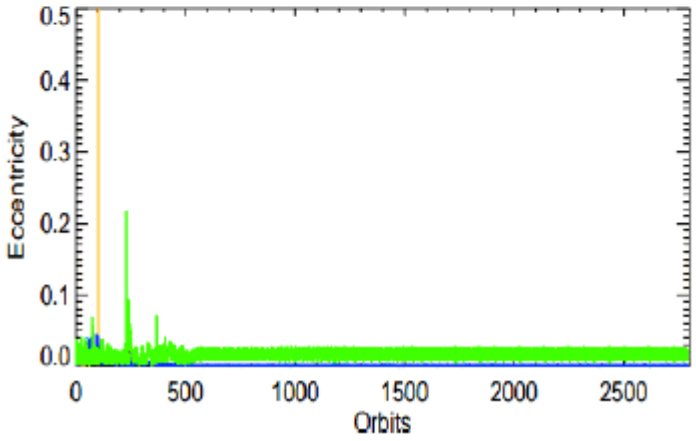
② Direct and indirect interaction between embryos

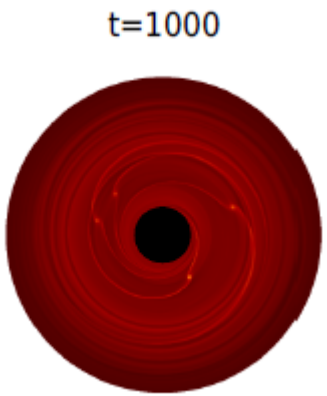


Five planets' convergent migration in un-uniform disk structure

Consider planets merging when separation < 6 Earth radius

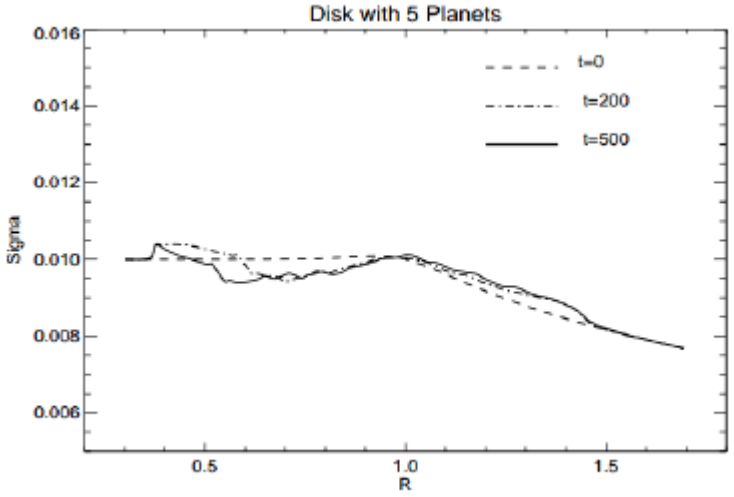


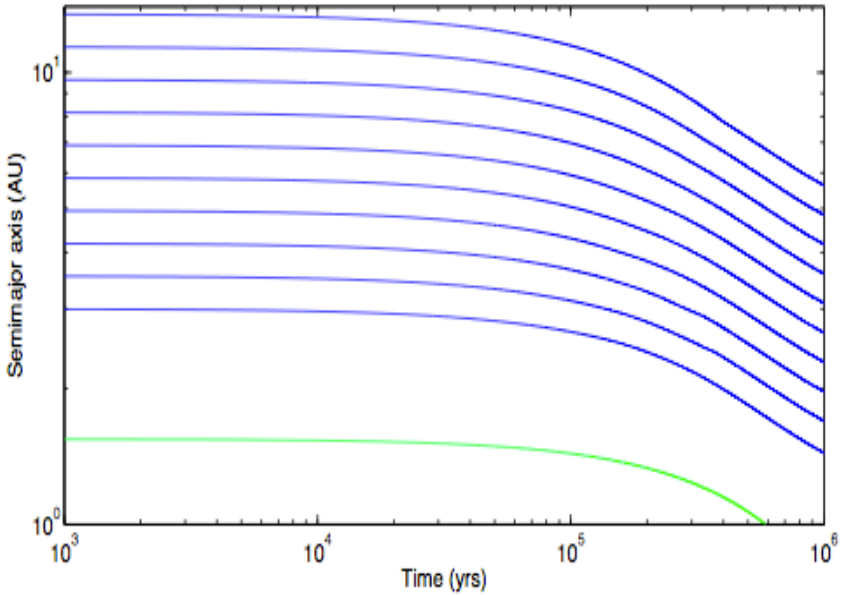


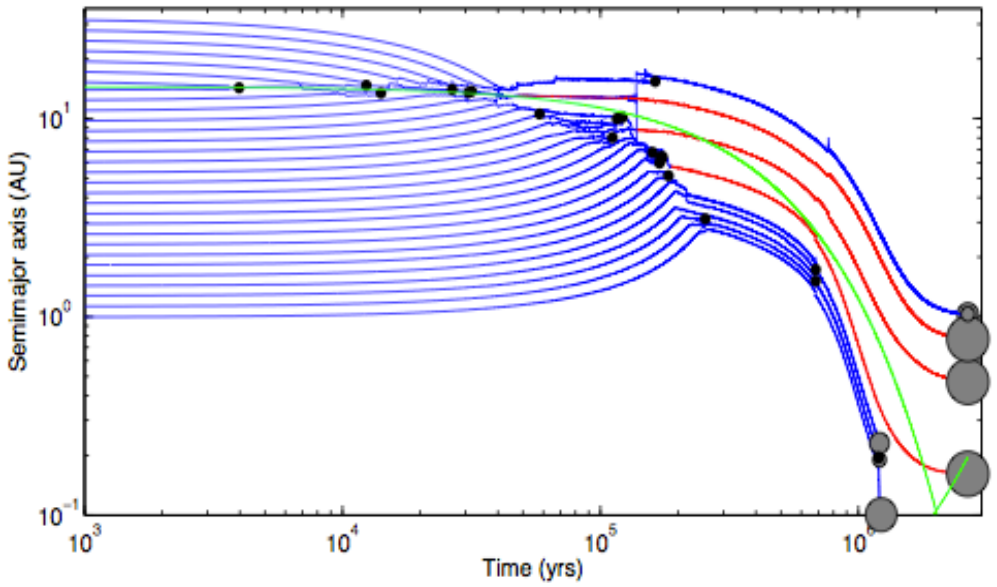


5 planets together o pen a shallow gap

Finally got into resonance

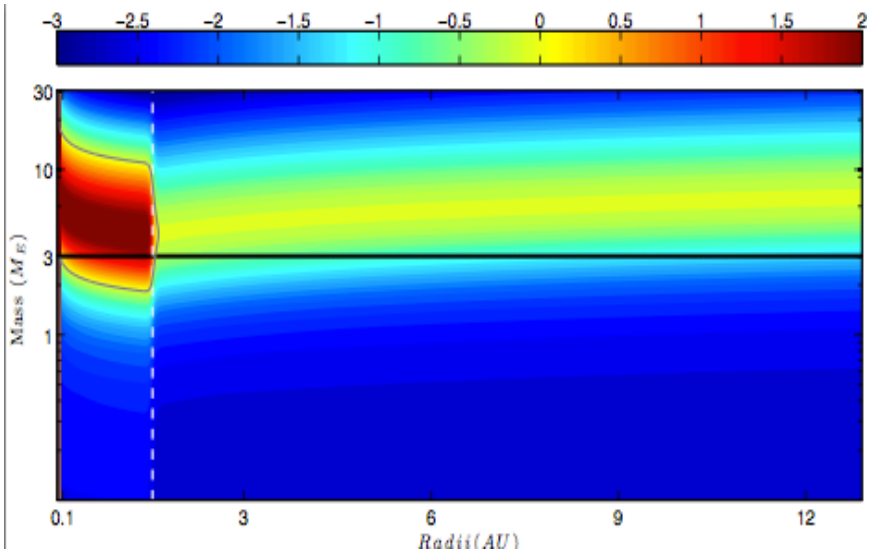


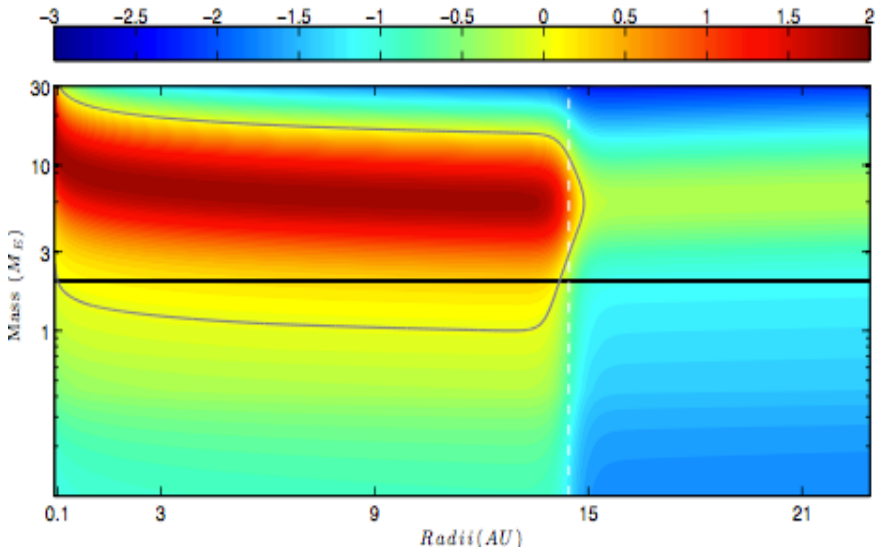




$\dot{M} = 1 \times 10^{-8}\ M_\odot/\mathrm{yr}\ \alpha = 10^{-2}\ \tau = 1 \times 10^{6}\mathrm{yrs}$

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

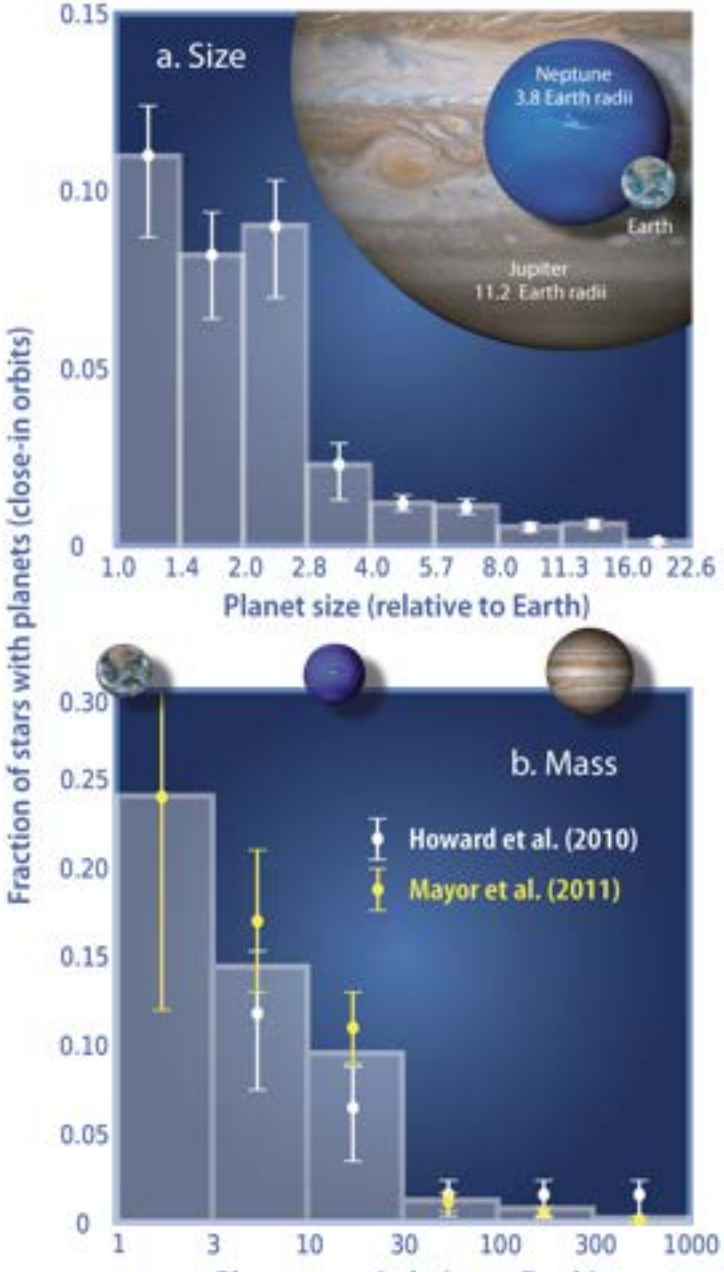




Liu Beibei

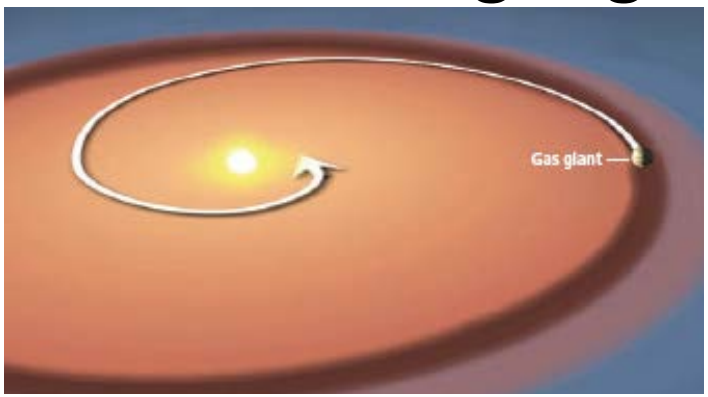
Observed Properties of Extrasolar Planets

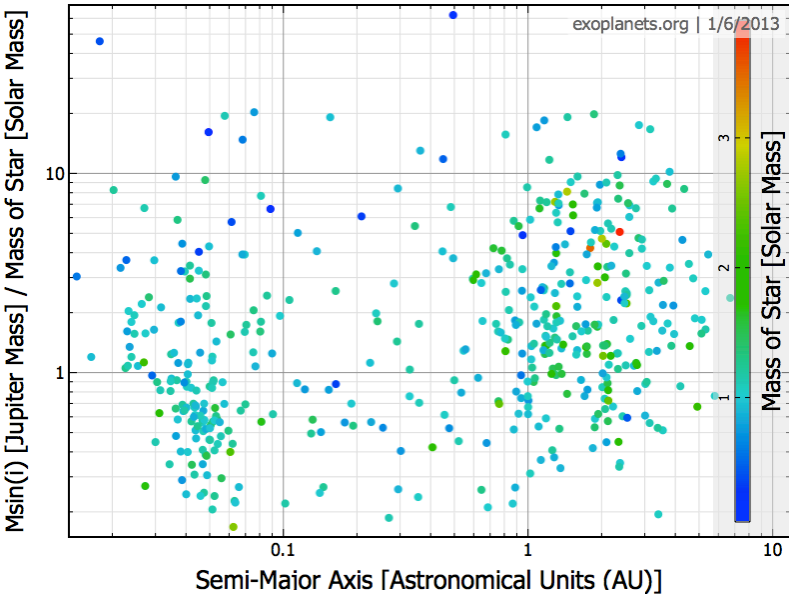
Howard (2013)



Gas giants: some key issues

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

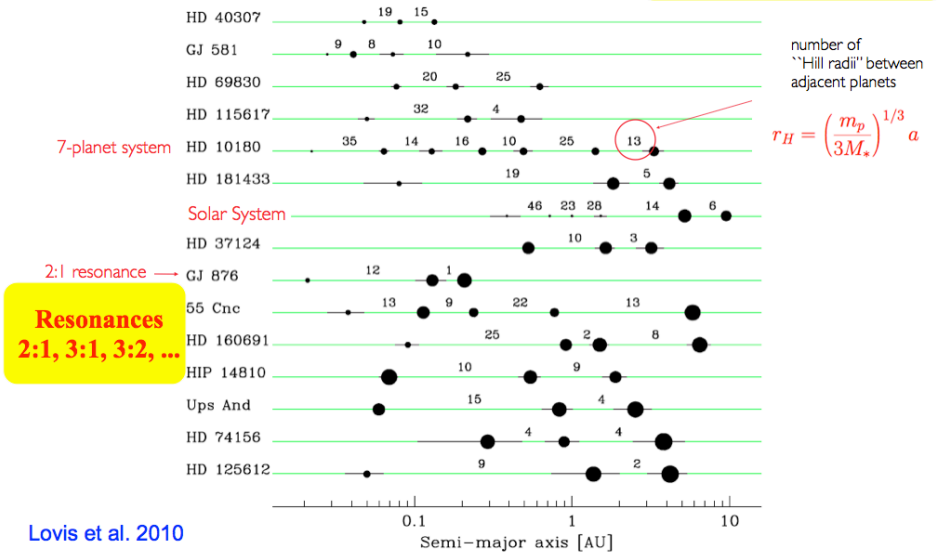




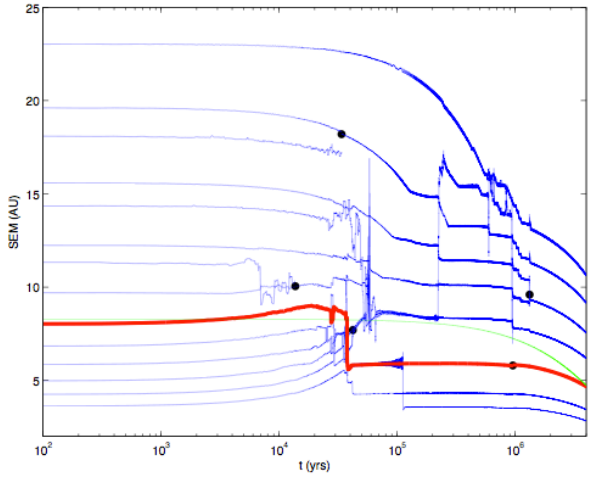
Systems with n>2 planets

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

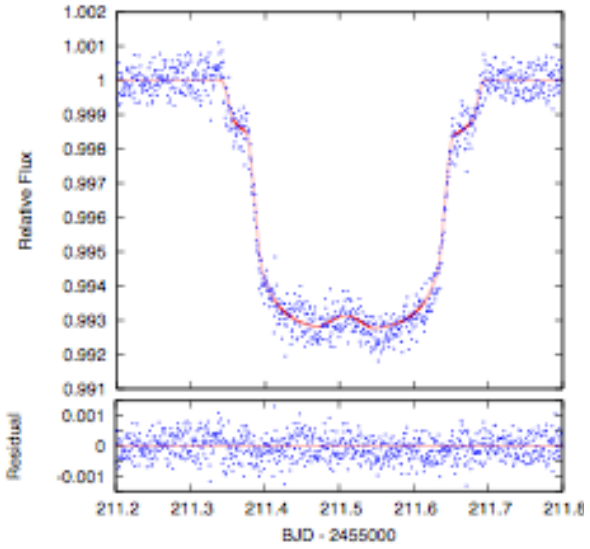
Also a constraint for planet formation models!



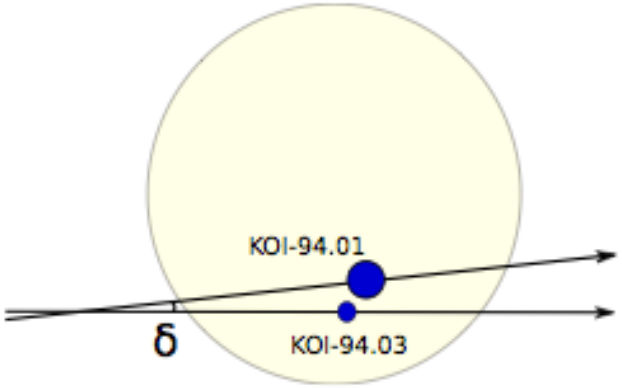
Lovis et al. 2010

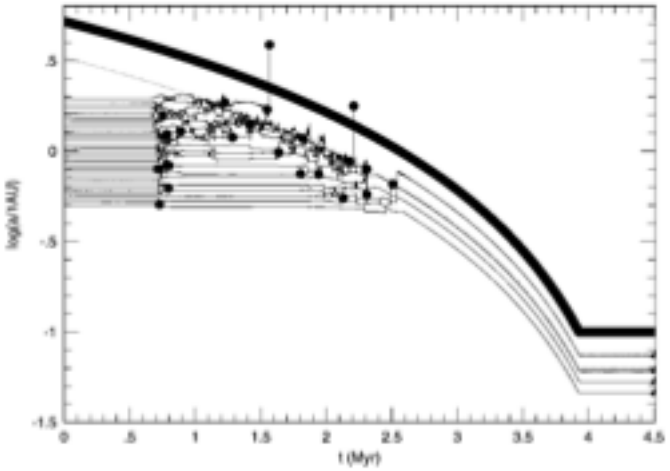


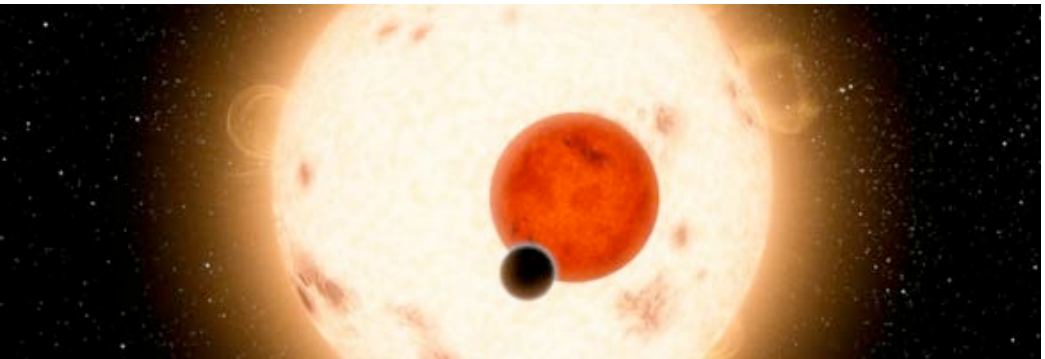
Smoking gun for core accretion (KOI 94)

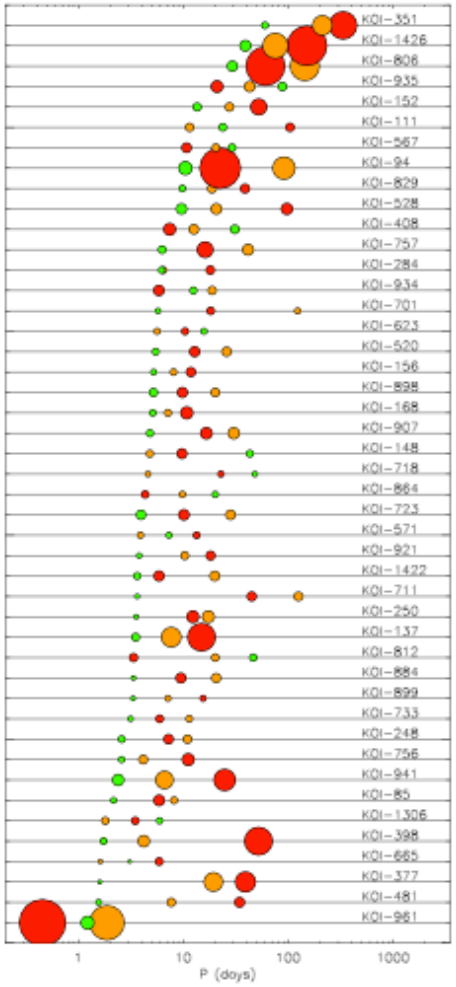


Candidate	Orbital Period (days)	R_p/R_s
KOI-94.01	22.343000 ± 0.000011	0.06856 ± 0.00012
94.02	10.423707 ± 0.000026	0.02544 ± 0.00012
94.03	54.31993 ± 0.00012	0.04058 ± 0.00013
94.04	3.743245 ± 0.000031	0.01045 ± 0.00019

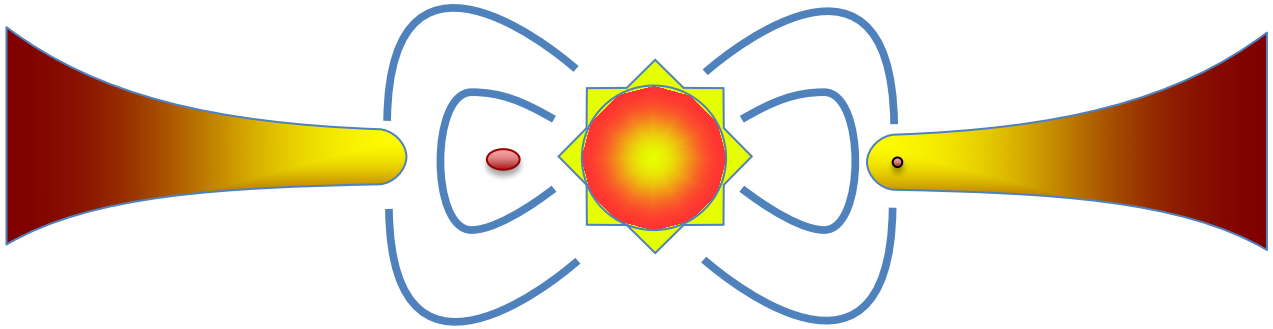




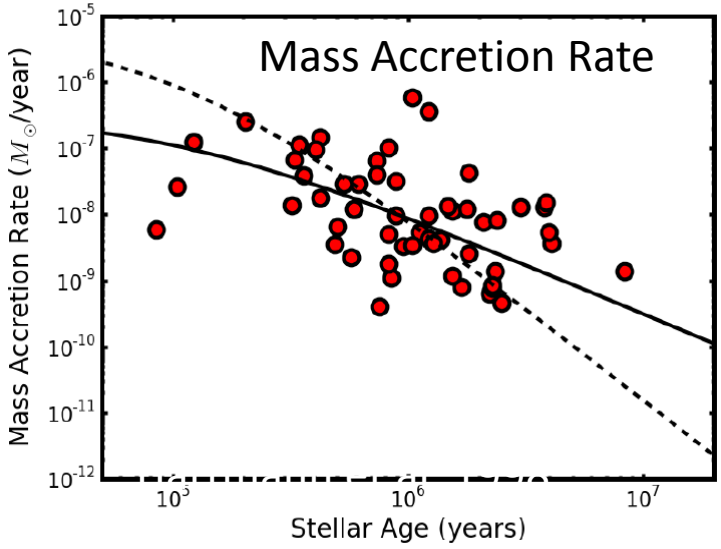


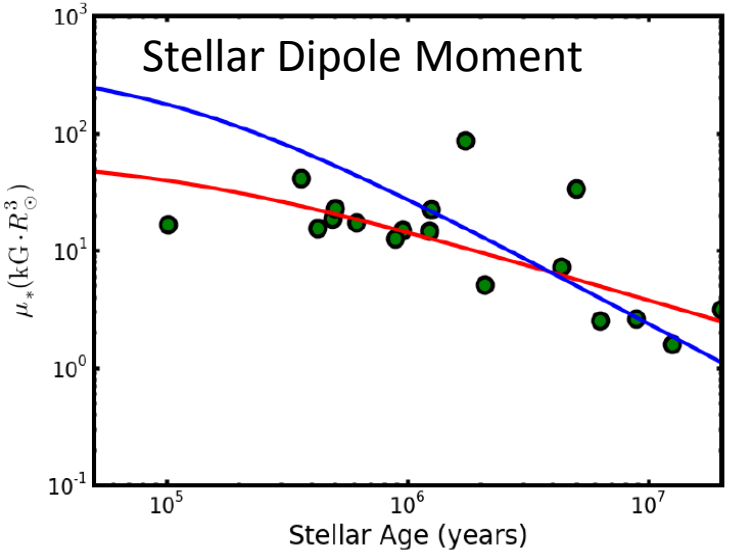


Stalling of planets inside & at the magnetospheric truncation radius



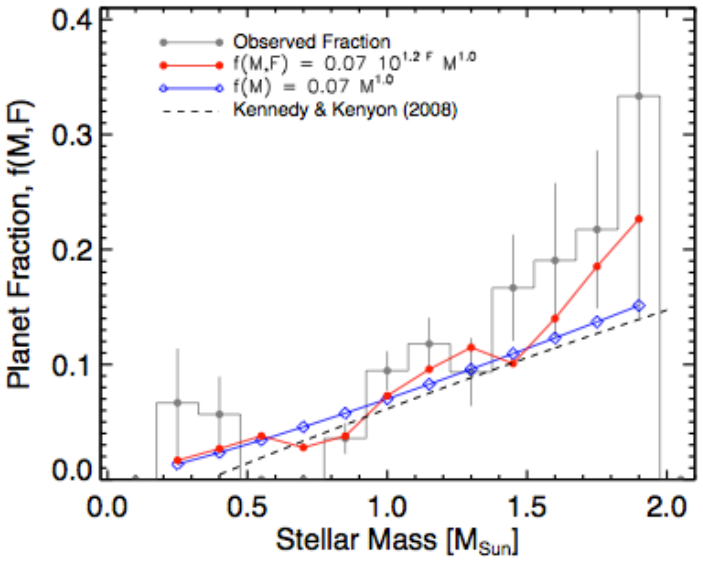
$$r_{\rm mag} \propto \mu_*^{4/7} \dot{M}^{-2/7}$$



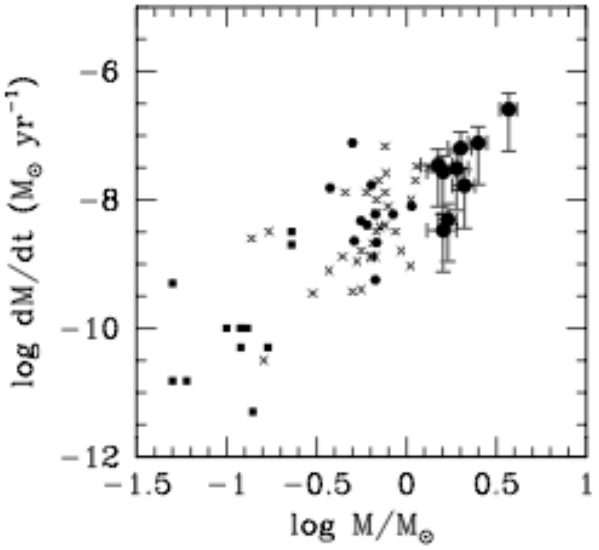


Herczeg

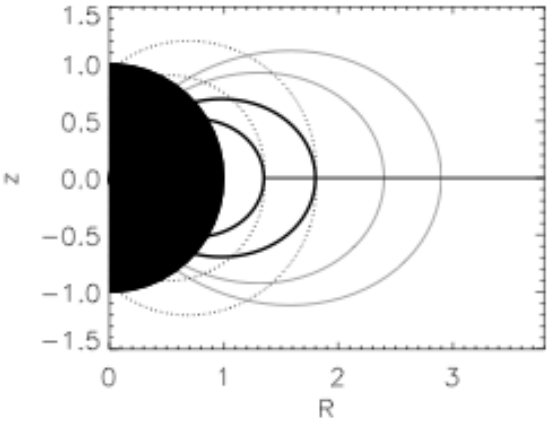
Paucity of hot Jupiters around hot stars



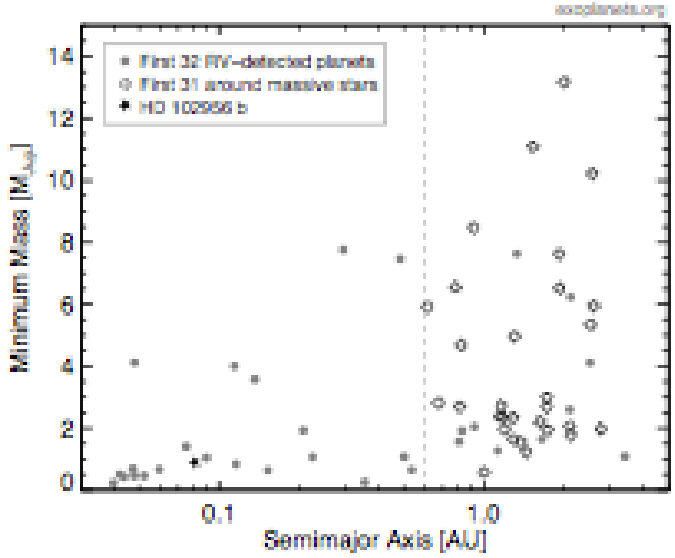
Johnson et al 2010a,b

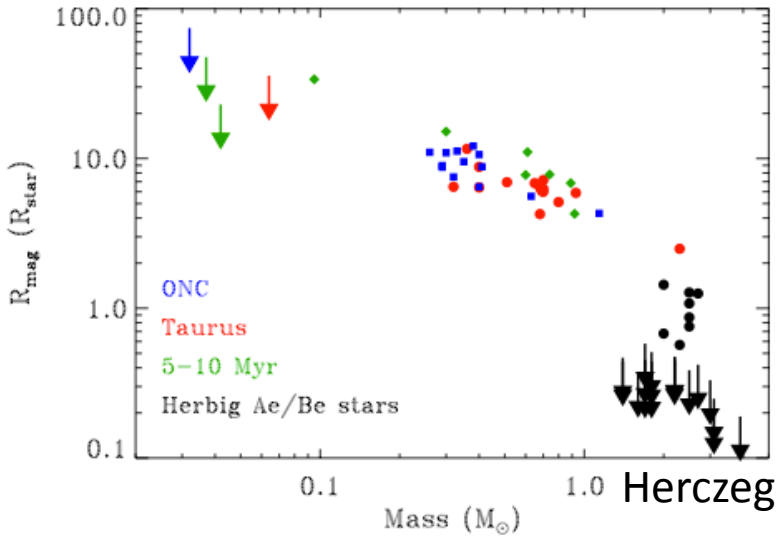


Calvet et al 2005



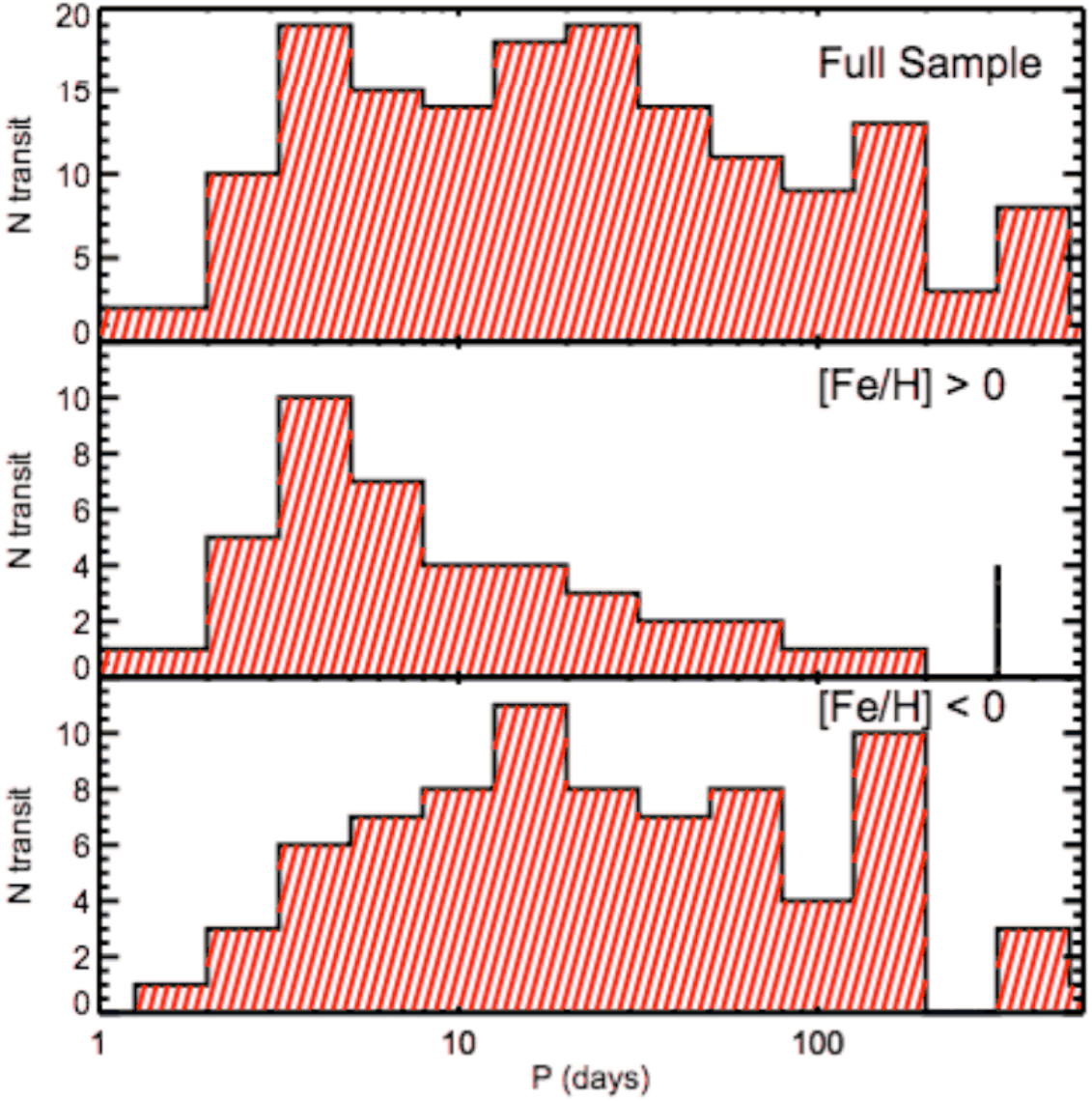
Muzerolle et al 2004



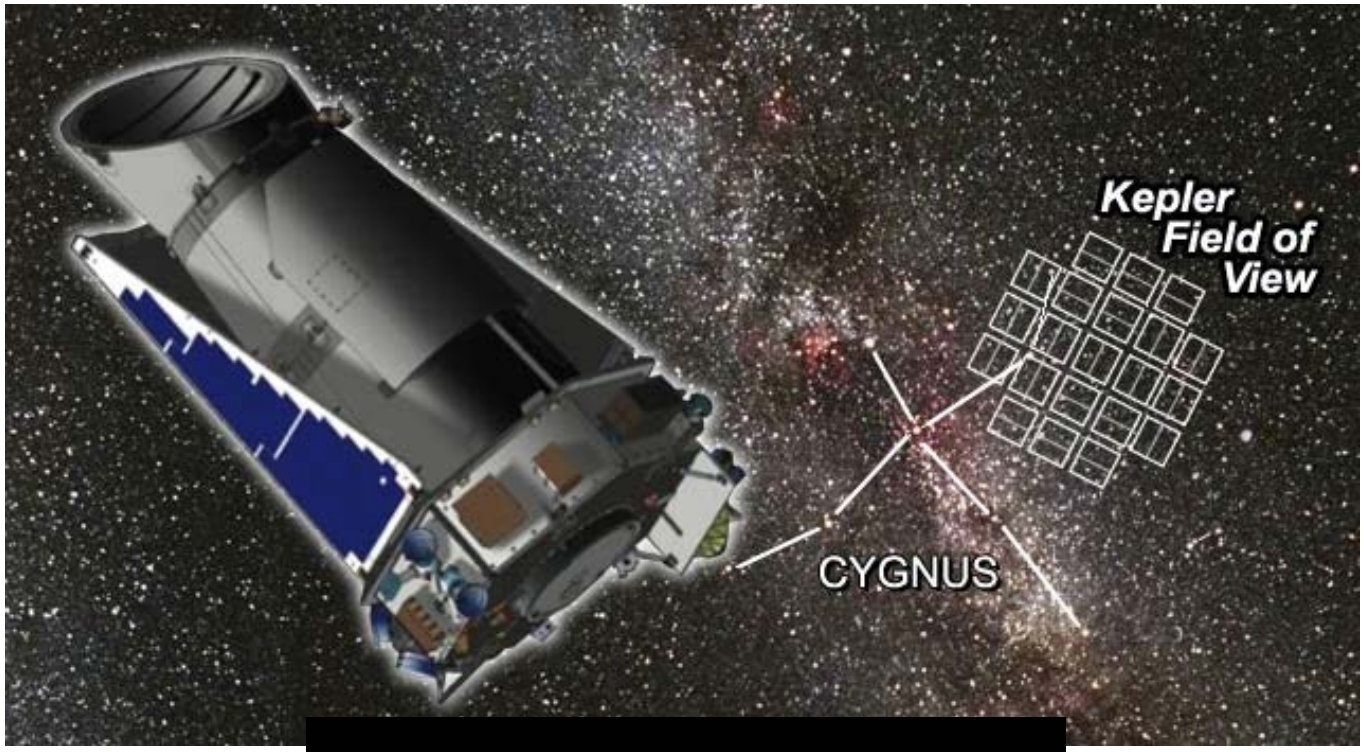


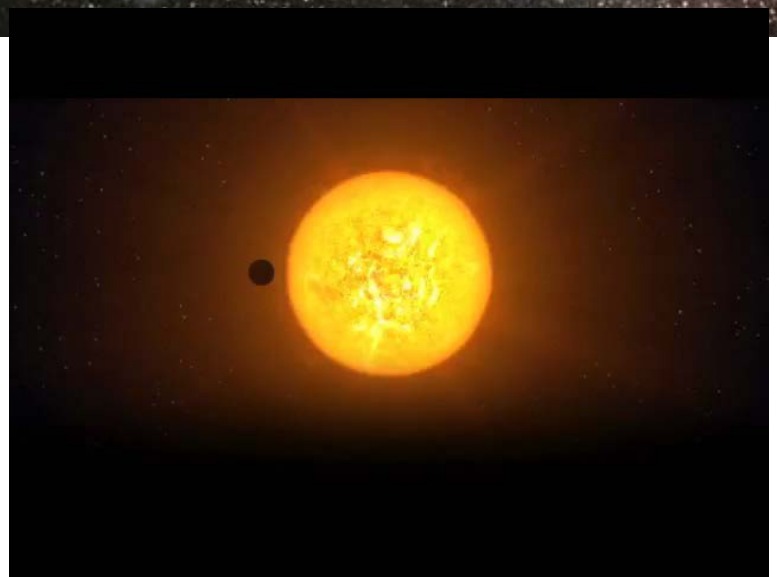
Herczeg

Dependence on stellar metallicity



Transit survey

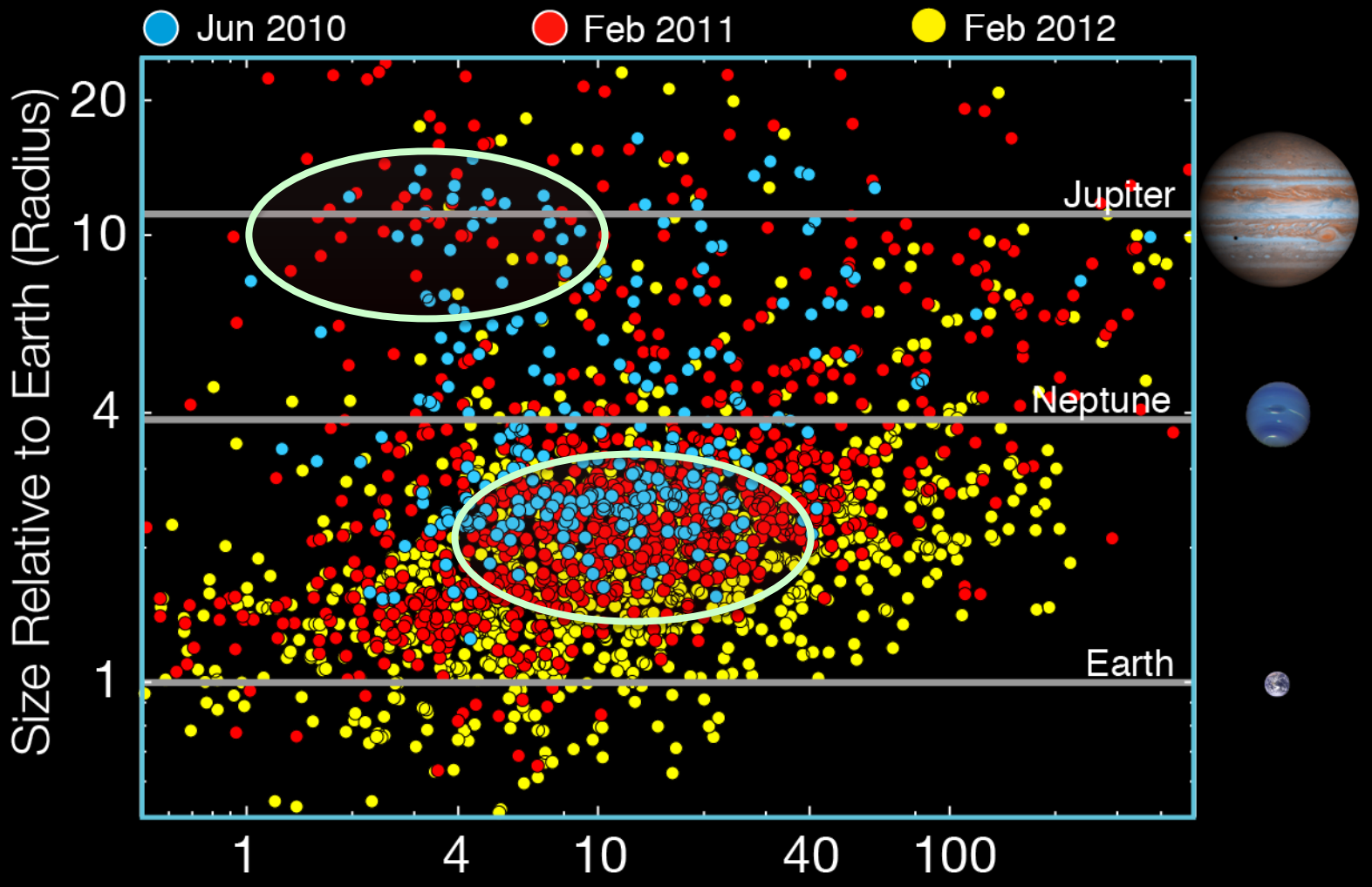




行星半径与周期的分布

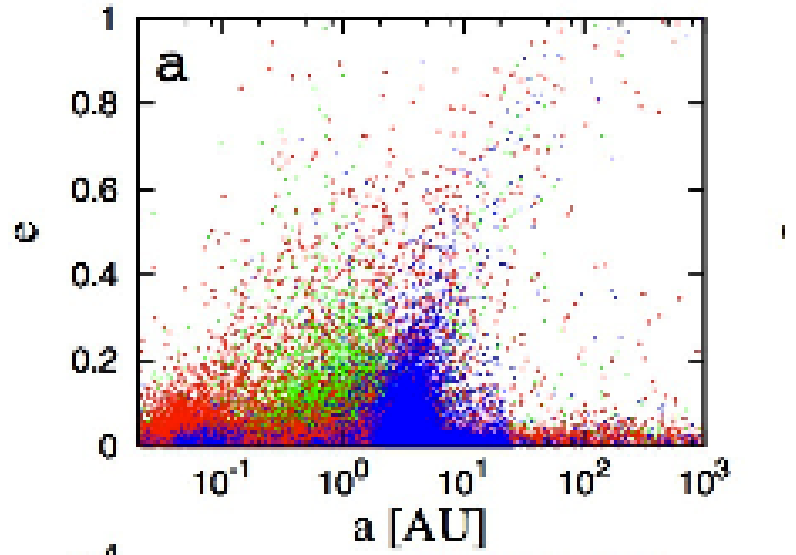
Planet Candidates

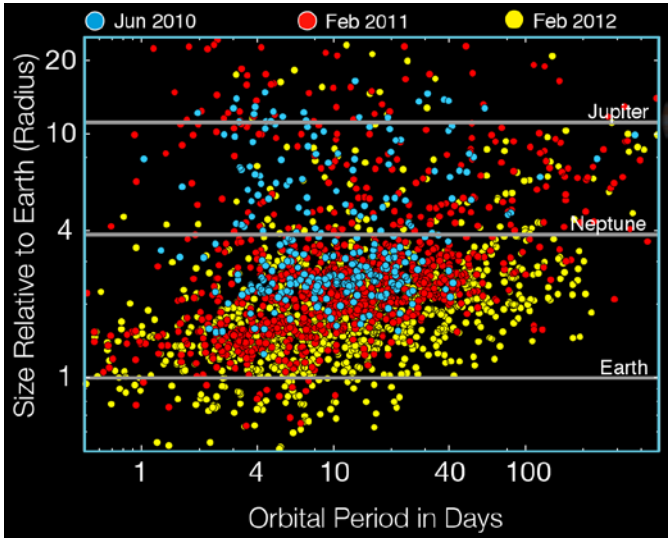
As of February 27, 2012

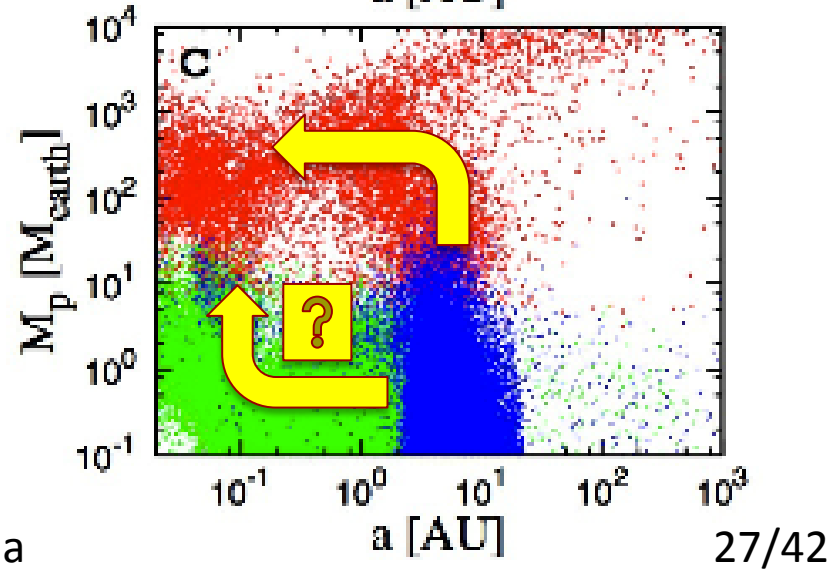


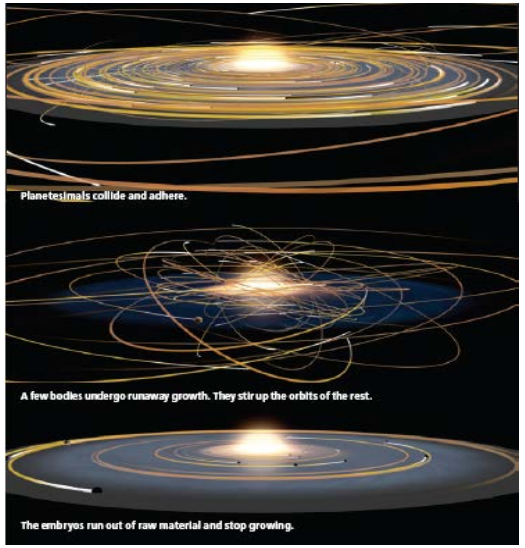
Super Earths: some key issues

- Did super Earths assemble in situ or form at large a and migrate?



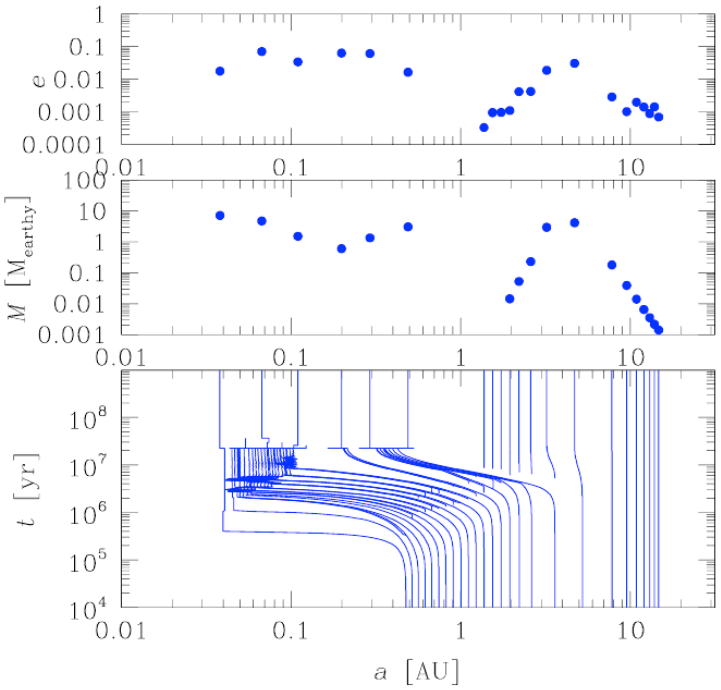


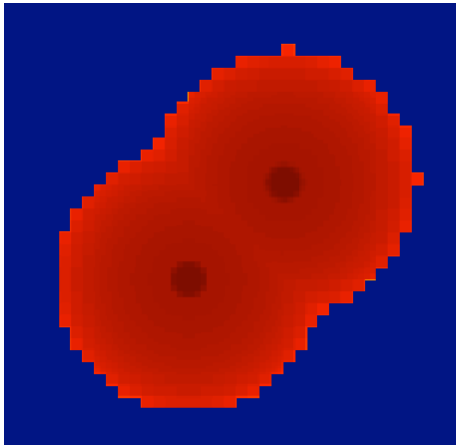




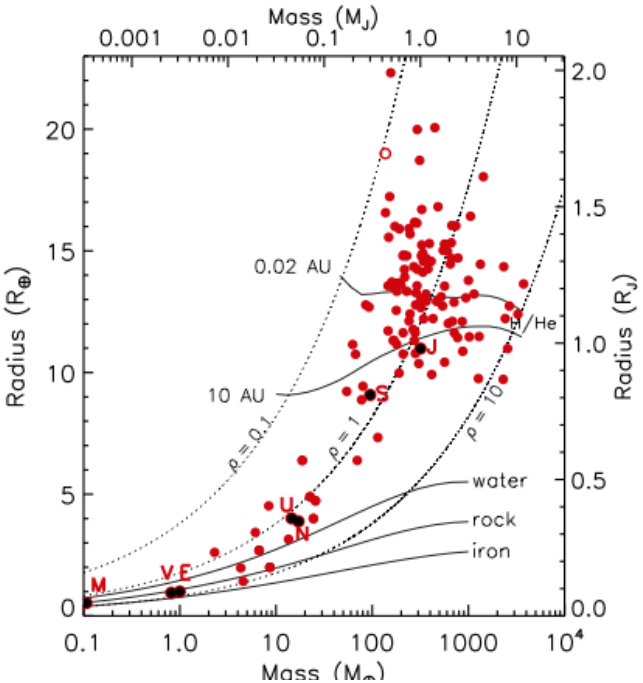
Super Earths: some key issues

- How to identify *in situ* assembly?





Ida



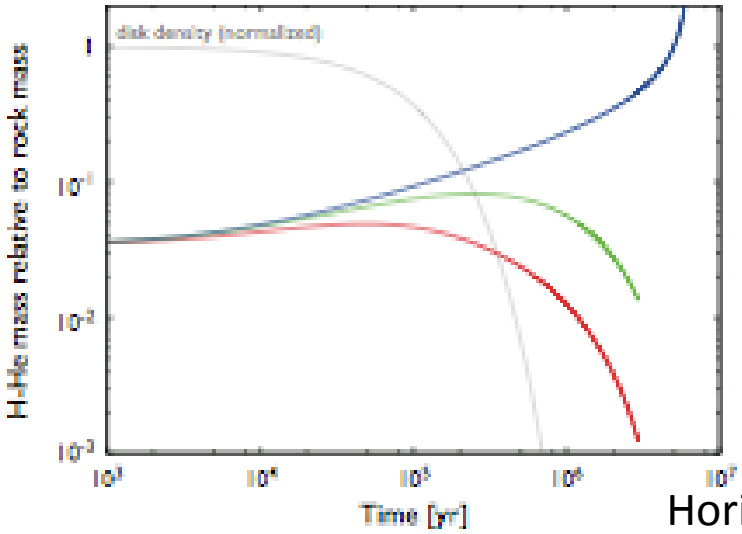
For a $10M_e$ planet at 0.04AU

$R_{roche} \sim 0.02a \sim 8R_e$

$R_p \sim$ 2-3 $R_e \sim 0.3\ R_{roche}$

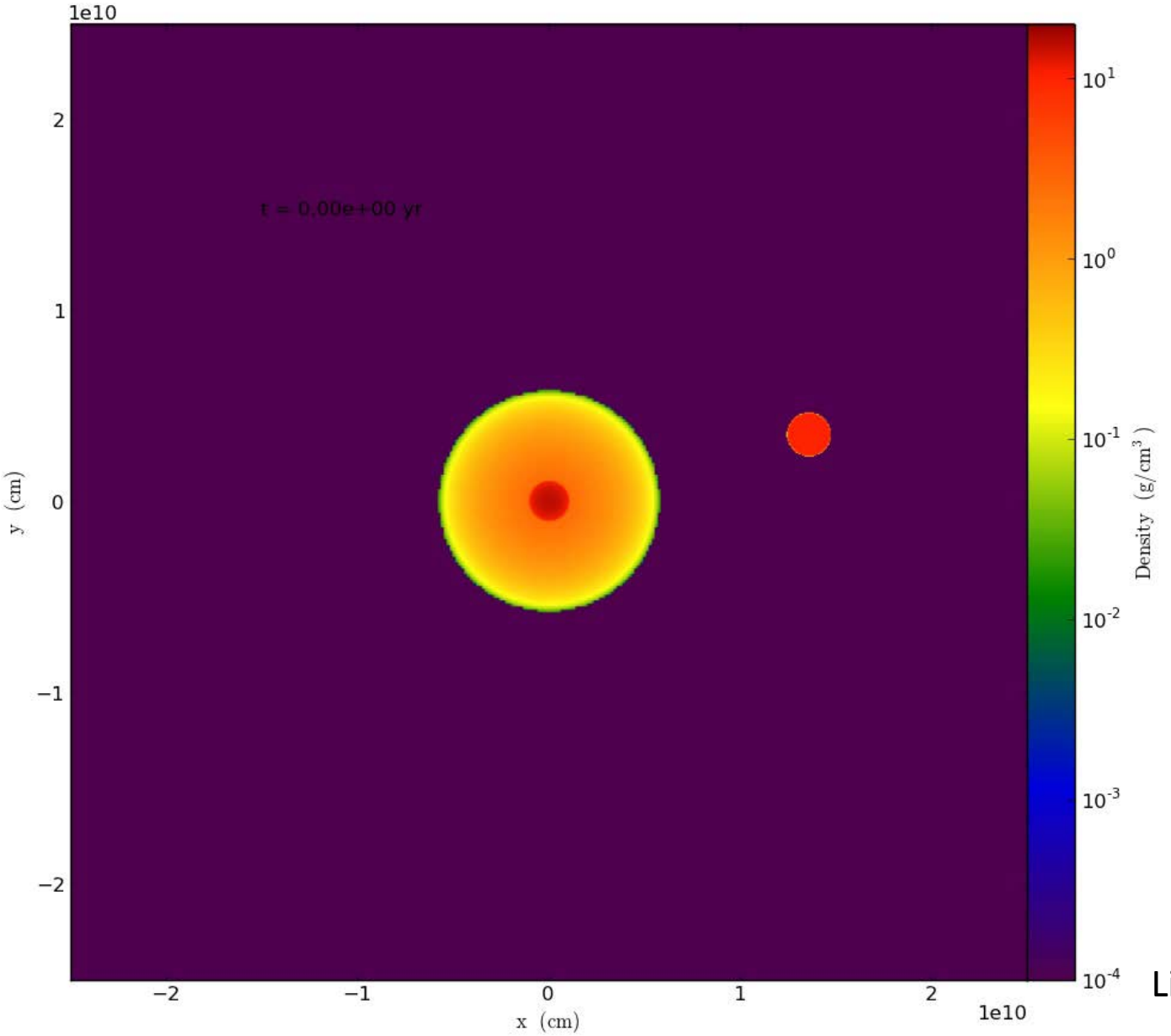
$R_m \sim R_{roche}$ if B~10 Gauss

$H \sim 0.02\ a \sim R_{roche}$



Hori

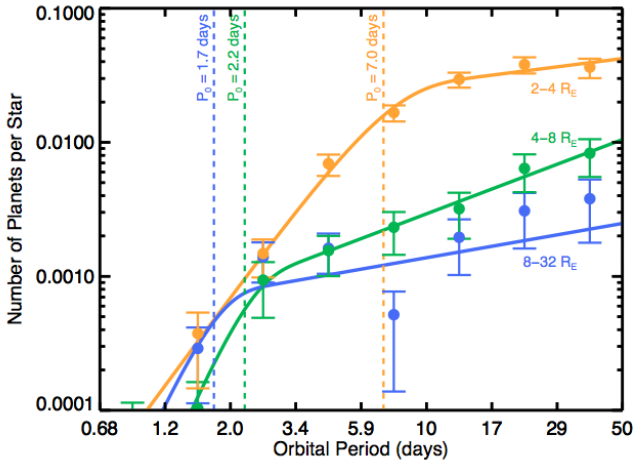
行星的巨大相撞



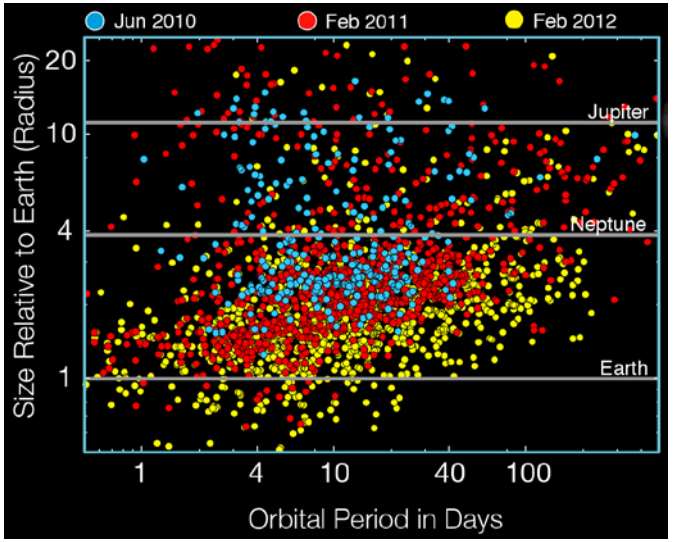
Liu Shangfei

Super Earths: some key issues

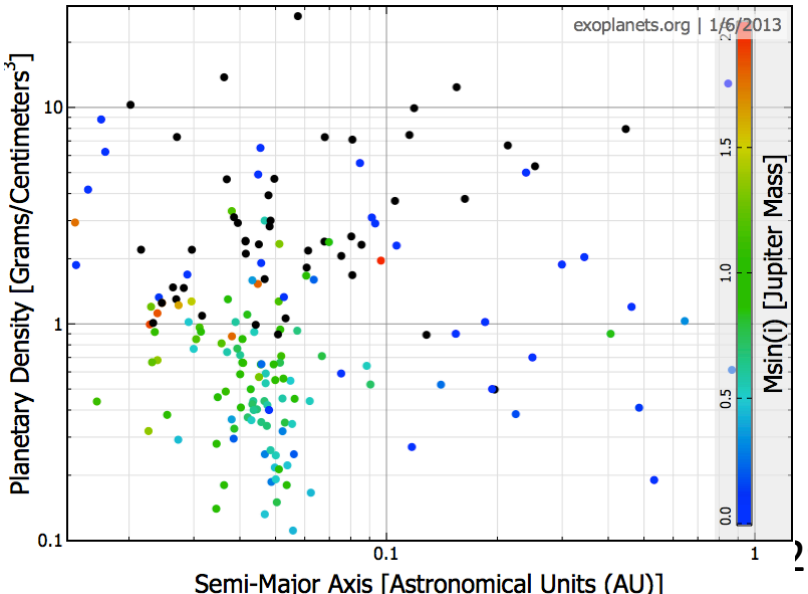
- What determines the period distribution?

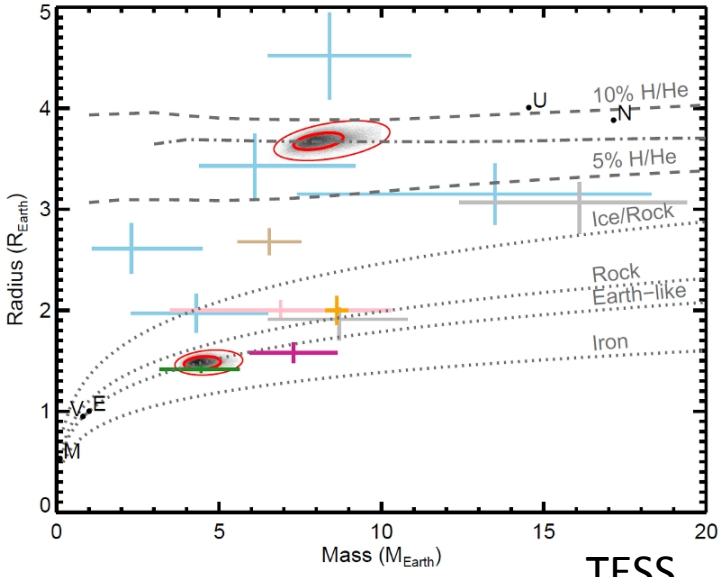


Does the M-P distribution fall off?



- Why is density-period distribution so diverse?



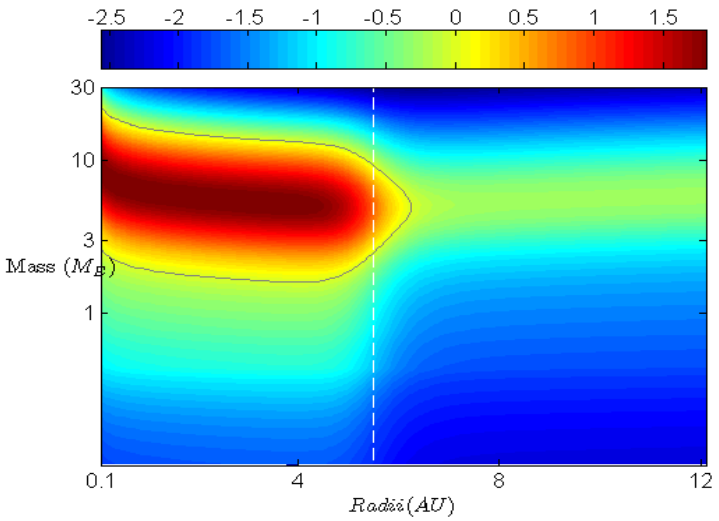


TESS

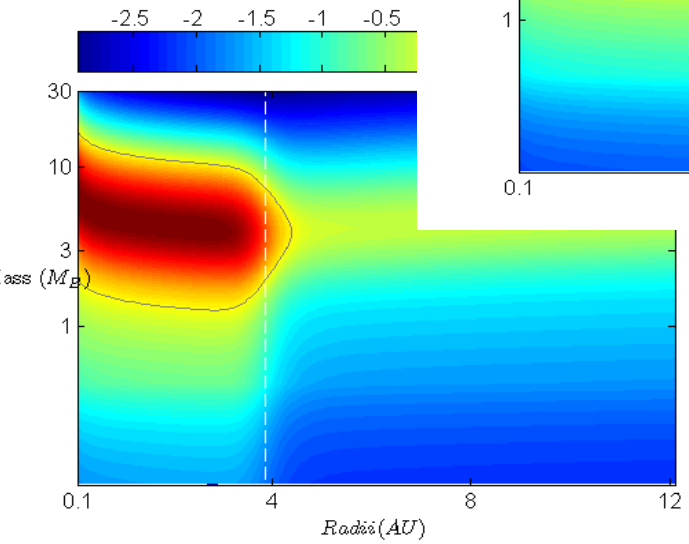
Type I migration with evolving disk

- Transiting location move inward
- Mass region corresponds to outward decrease slightly

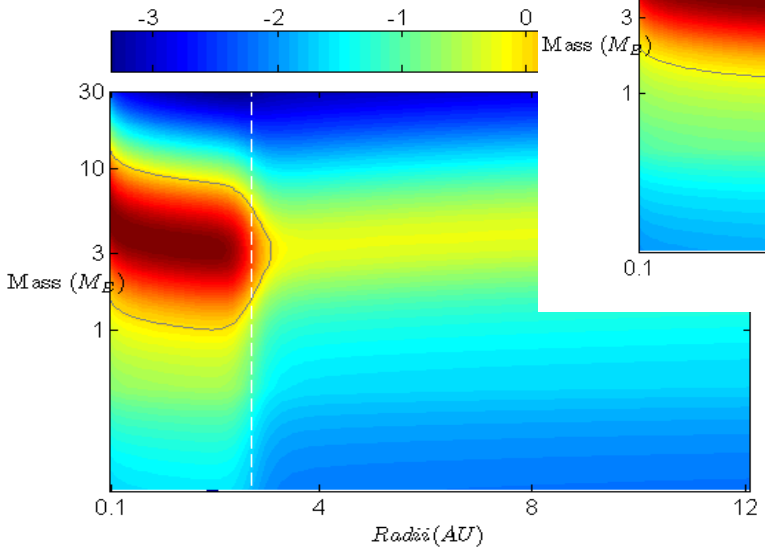
$t = 0$



$t = 5 * 10^5 yr$



$t = 10^6 yr$

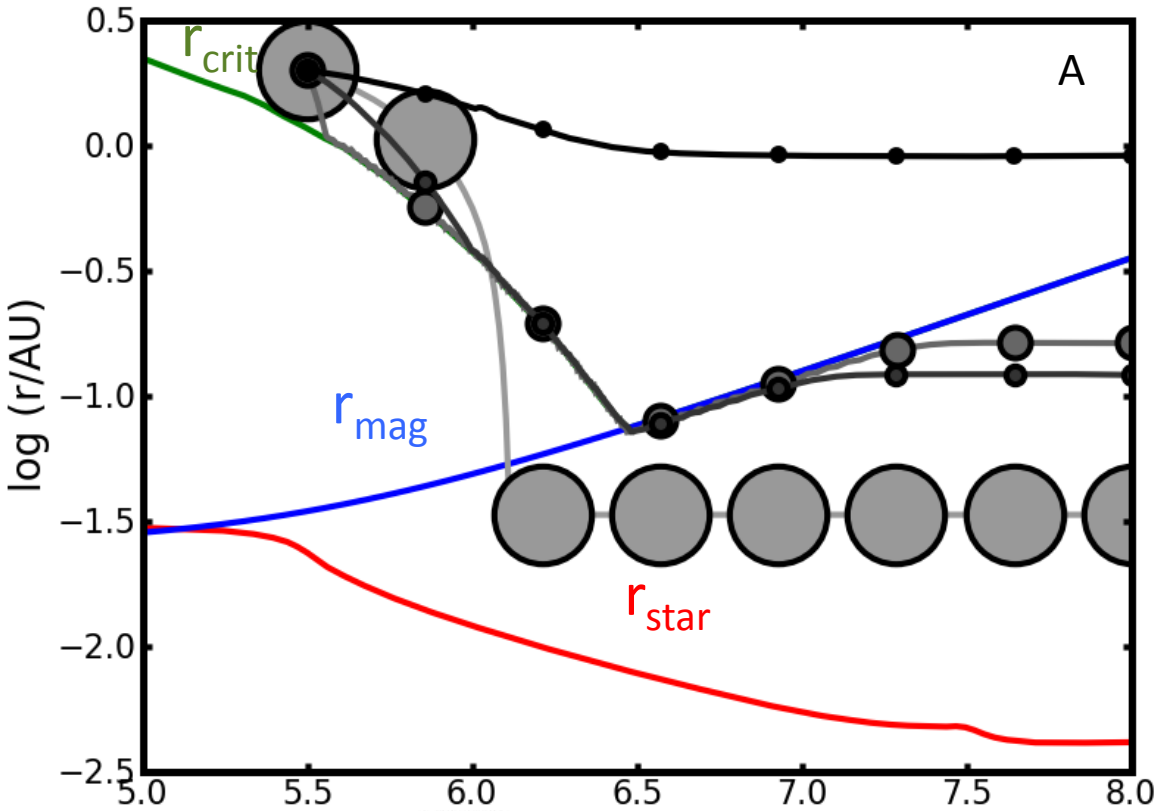


$\dot{M}(t = 0) = 10^{-7}$

$\alpha = 10^{-3}$

Super Earths: some key issues

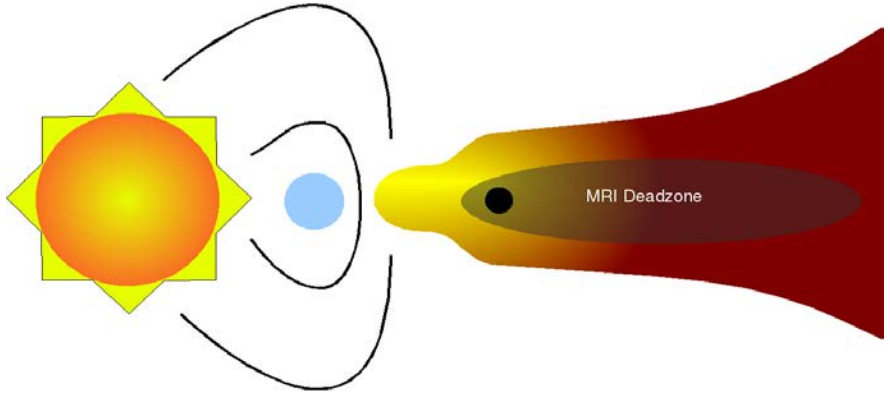
- How to differentiate type I and II migration?



Sub/warm Earths

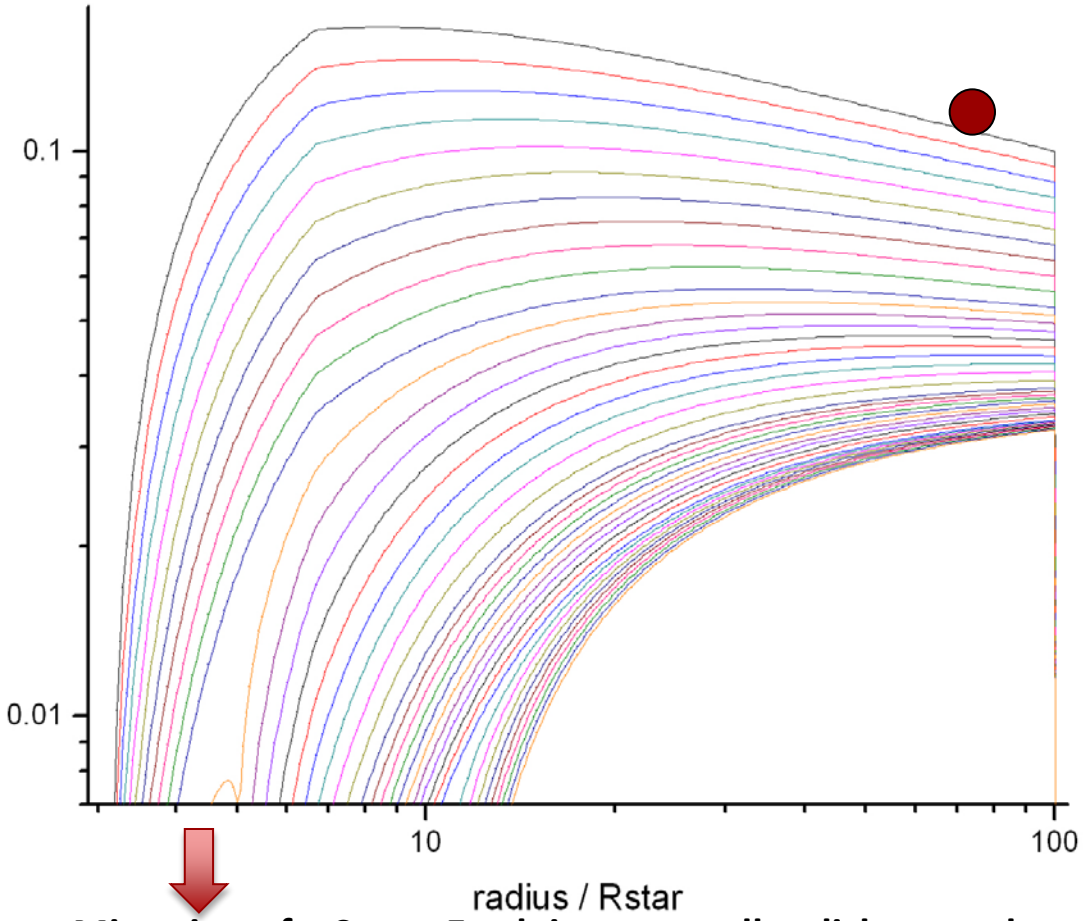
Neptunes
SuperEarths

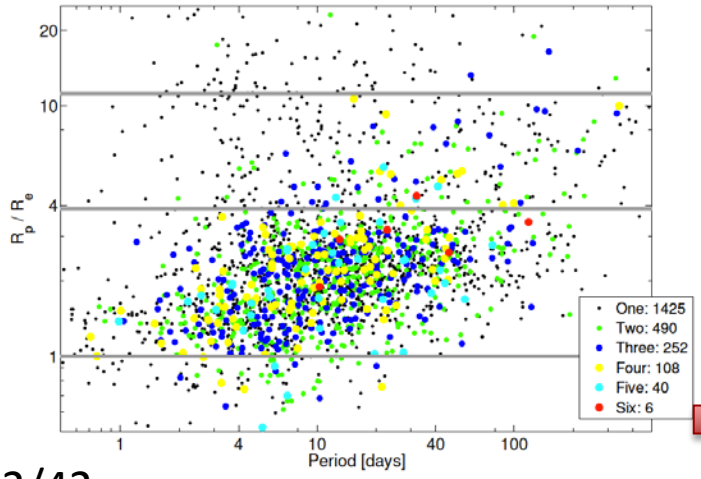
Gas giants



Hot Jupiters park Closer than Super Earths

Kretke





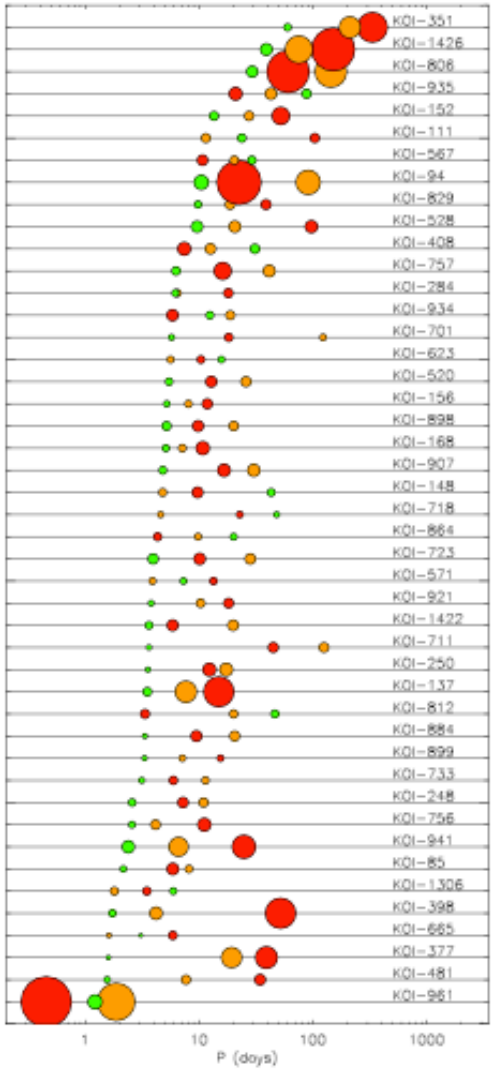
Migration of a Super Earth in protostellar disk around a magnetized T Tauri star. The Super Earth: (a) grows & migrate inward to inner-edge; (b) migrates slightly outwards with the expanding disk inner edge; (c) halts migrating after gas is mostly depleted. (Ju et al 2012 in preparation)

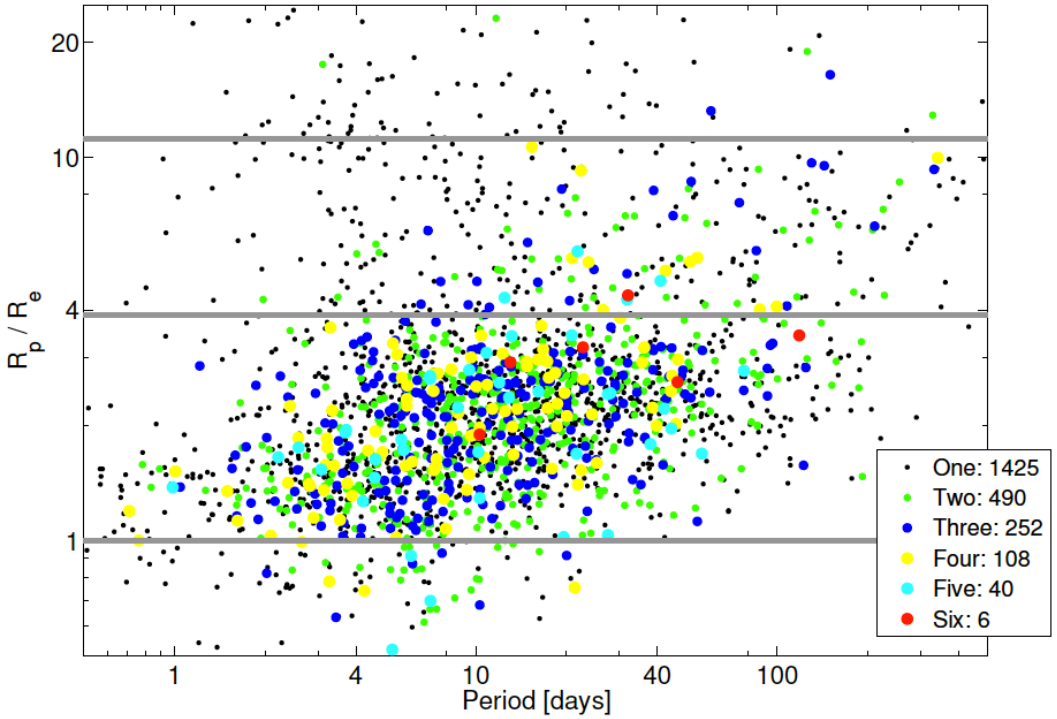
To model P distribution of Kepler's new-found planetary candidates.

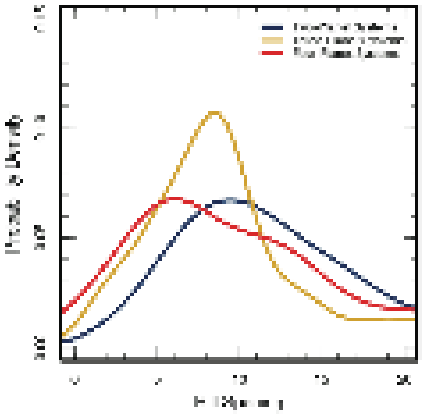
KIAA undergraduate student Ju Wenhua now at Princeton U

New Candidate Catalog (Batalha et al. 2012)

What can we learn from Multiple systems !!!





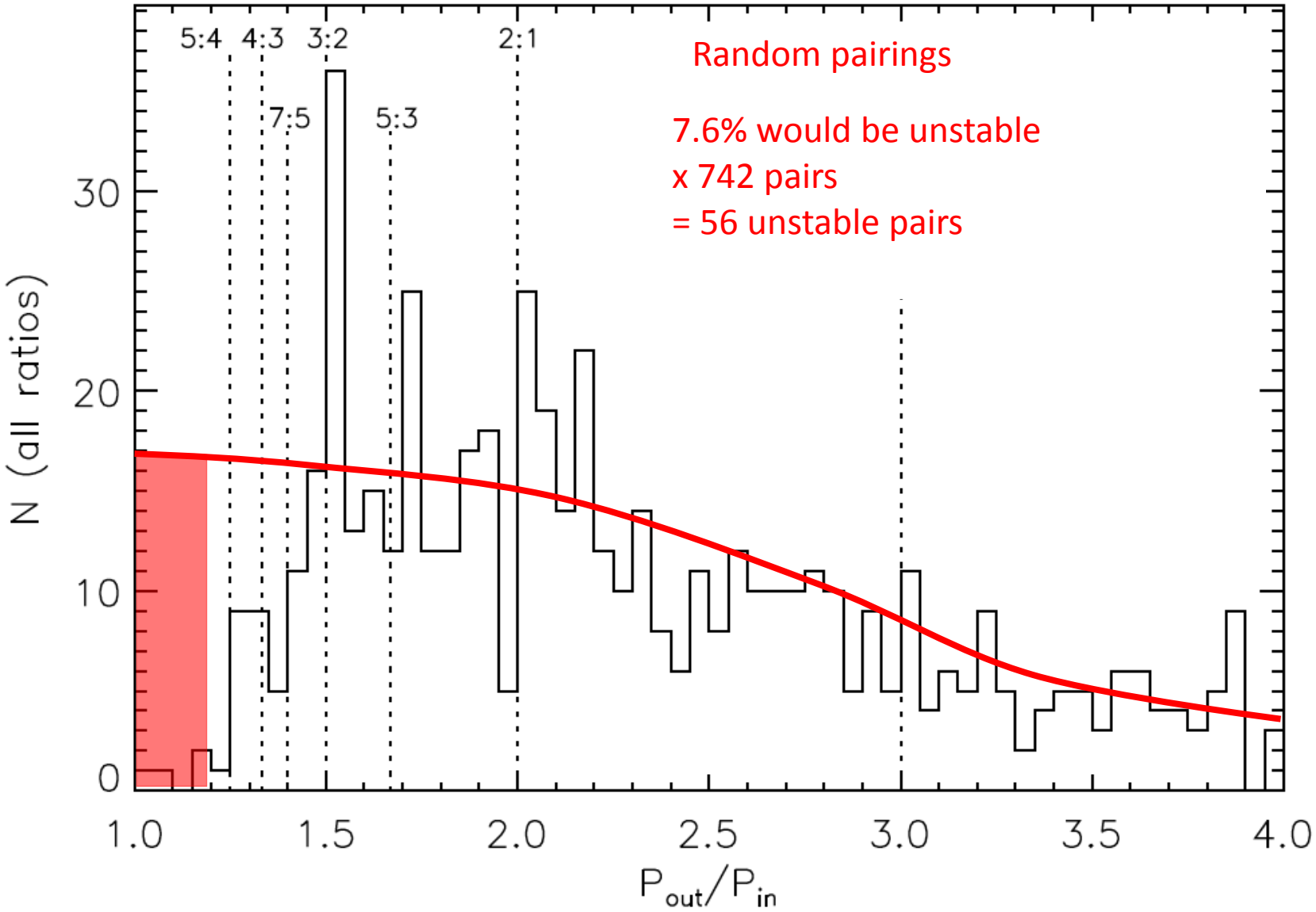


How compact can multiple systems be?

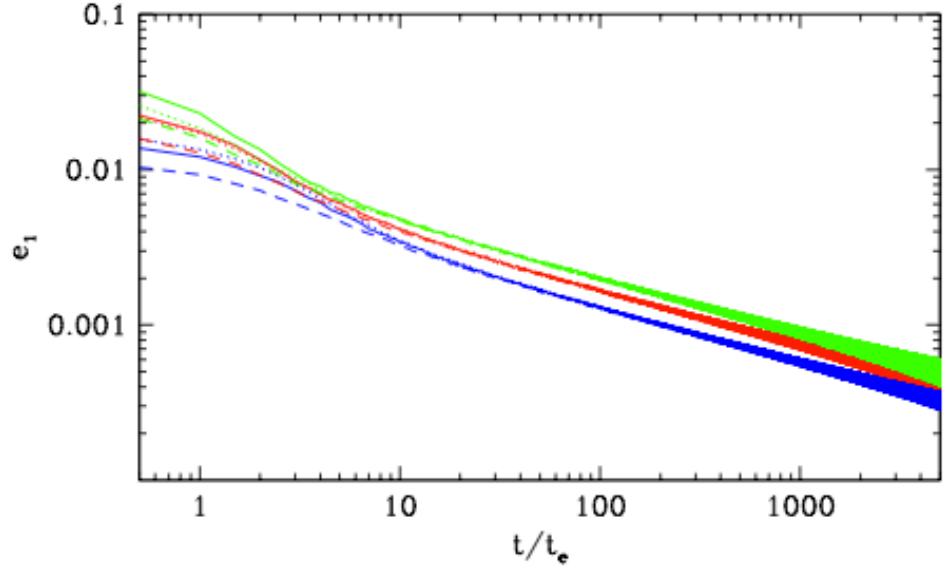
Kevin Schlaufman
Xiaochen Zheng

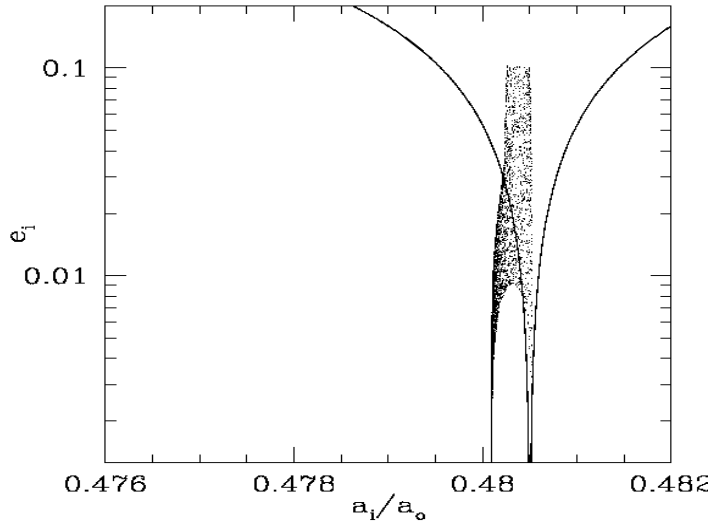
Super Earths: some key issues

- Did planets capture each other and parted their ways?

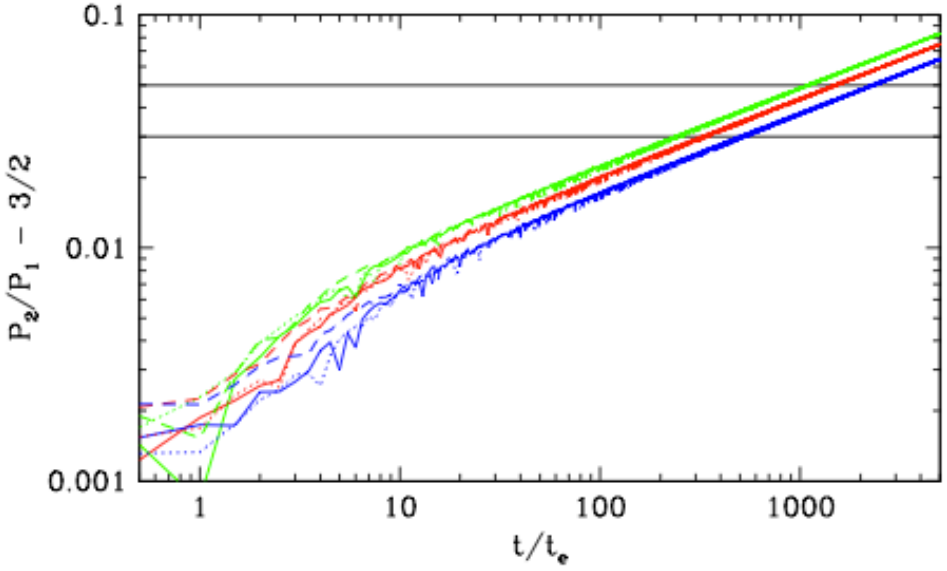


Resonance breaking





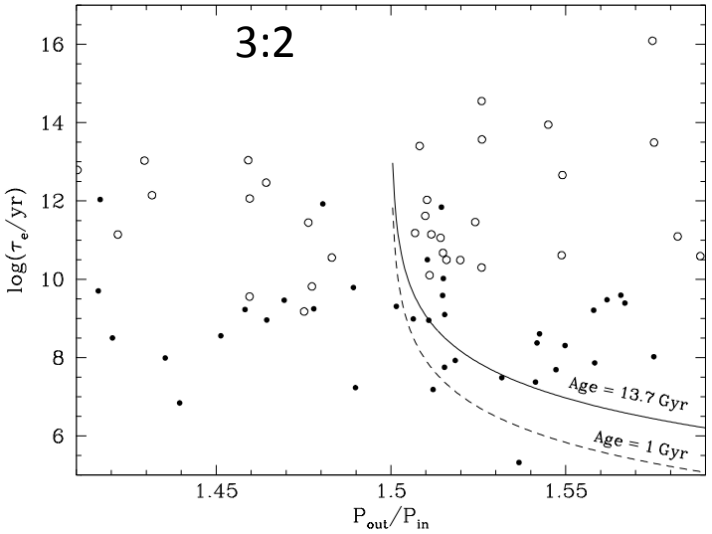
Novak, Lai

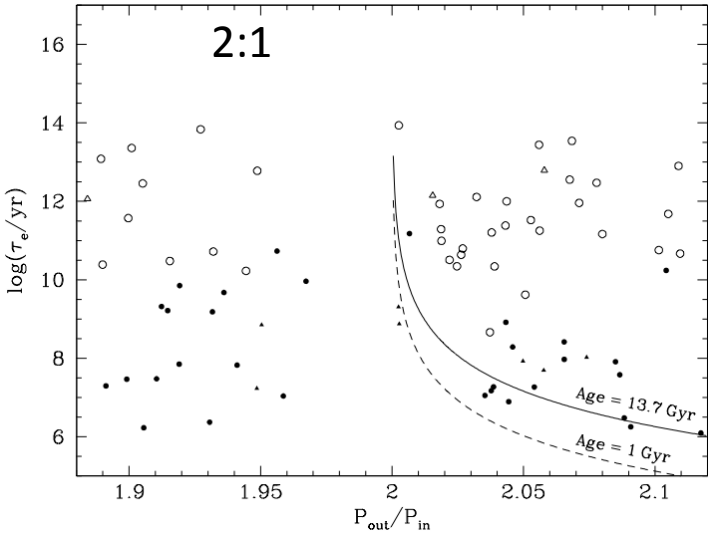


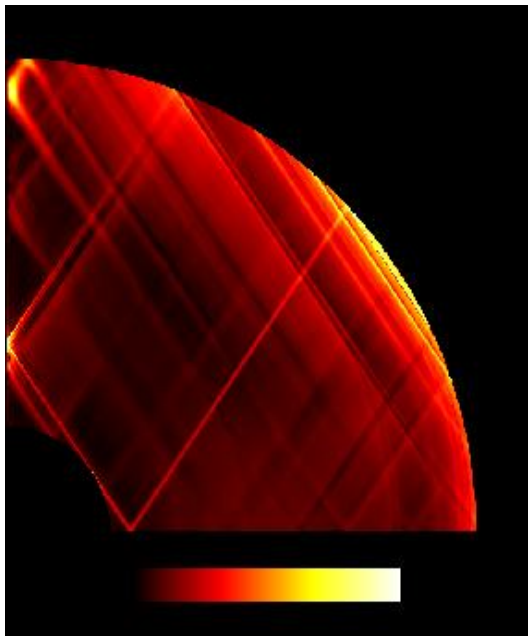
MH Lee, D. Fabrycky

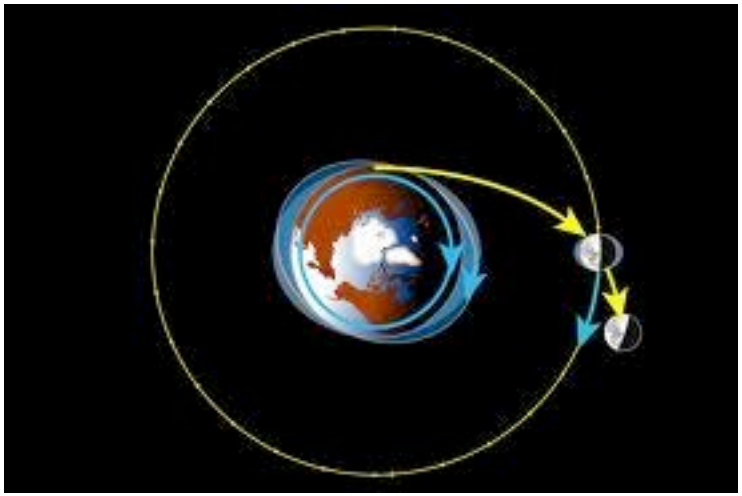
Super Earths: some key issues

- Can tidal dissipation really cause orbital evolution at large a?





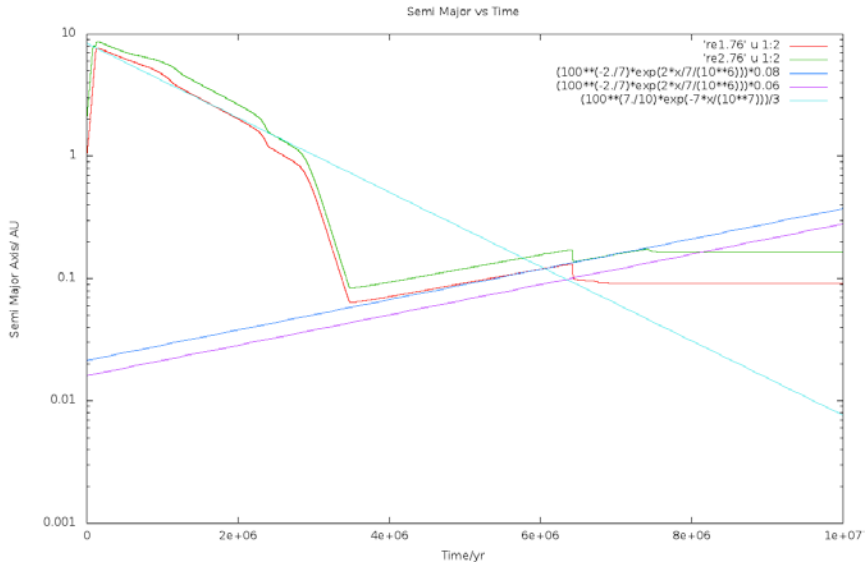


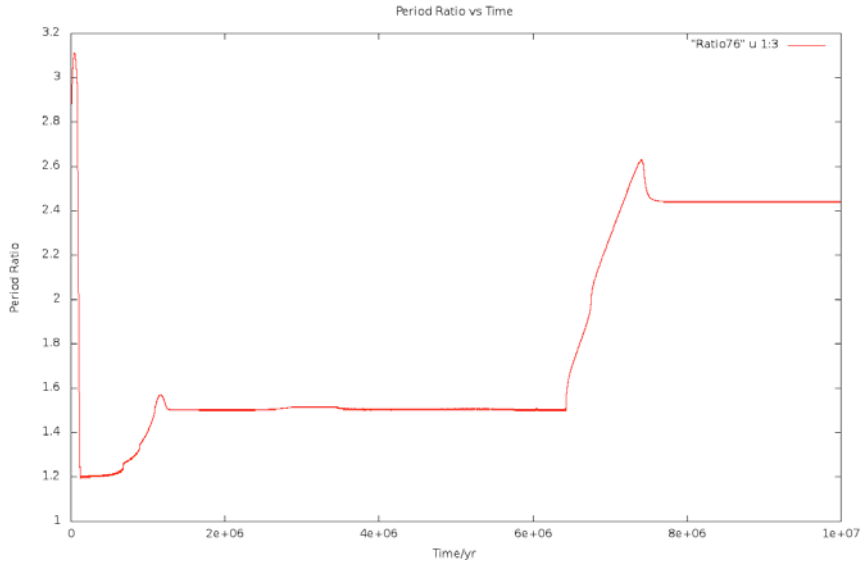


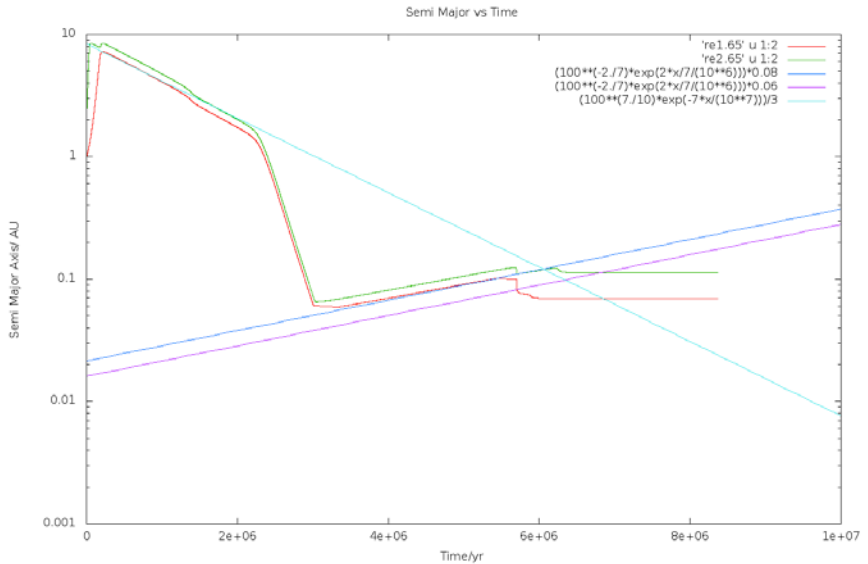
Lee, Fabrycky

Super Earths: some key issues

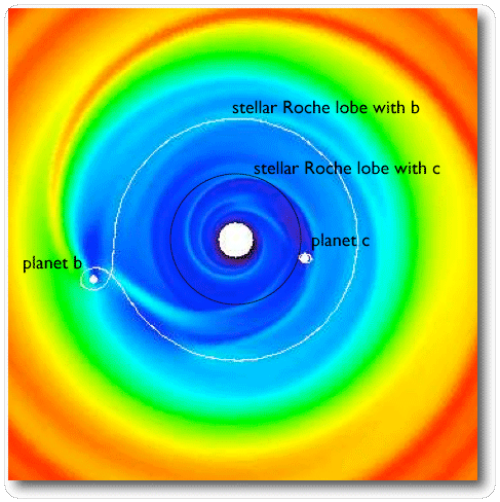
- Can type I migration be resurrected at the late stages?



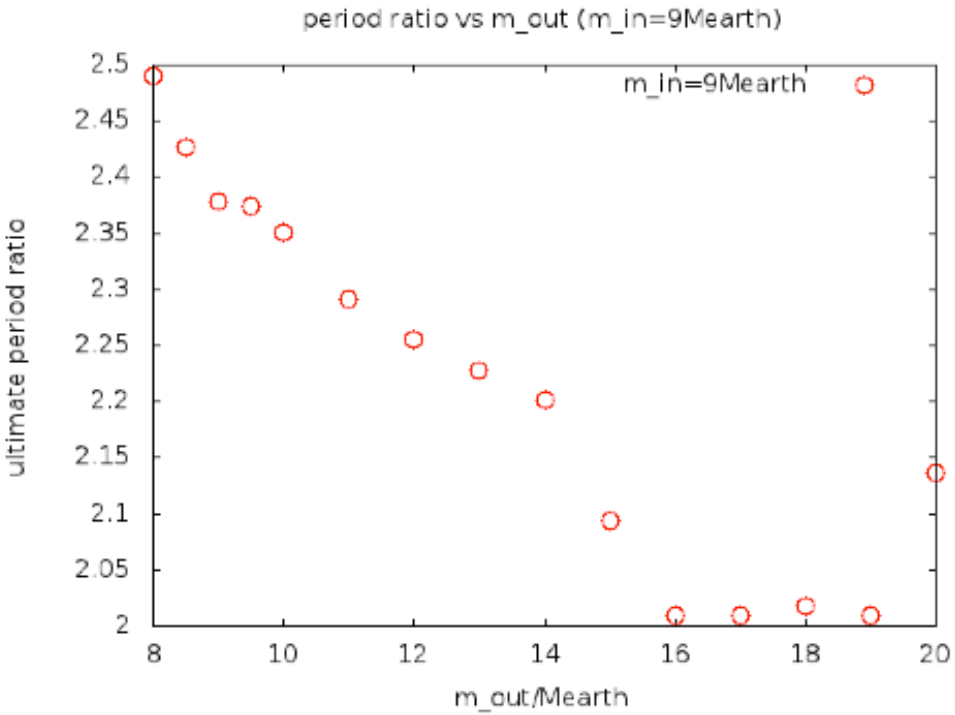




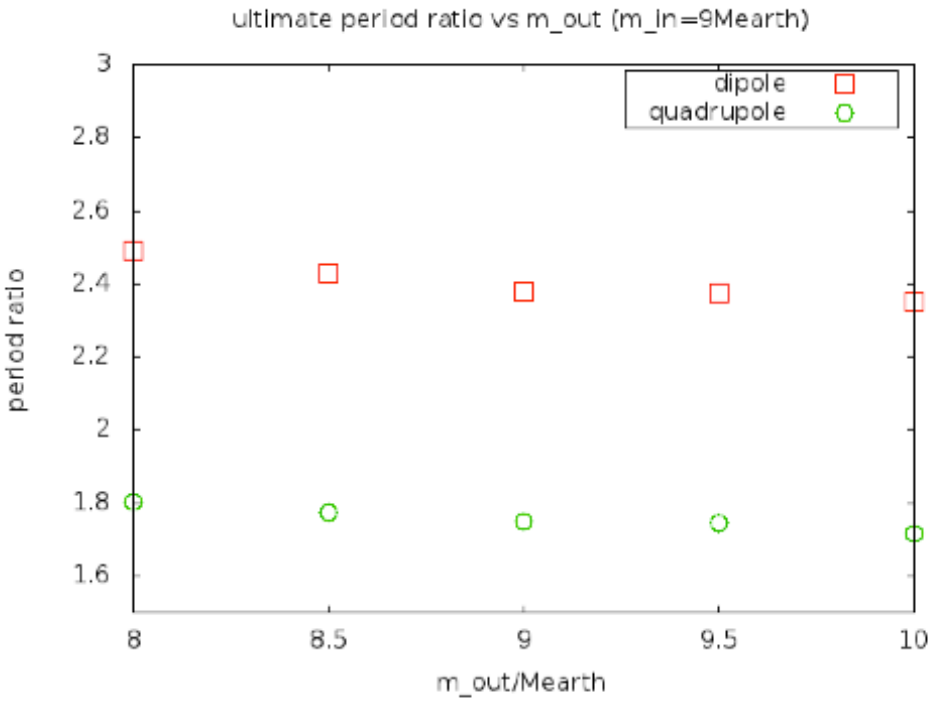
Bin Dai



Asymptotic period ratio



m_in = 9 Mearth



m_in = 9 Mearth

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

Summary

- Theory is an useful exercise for the interpretation of data and planning of exploration strategy.
- Planetary astrophysics is a rich discipline which can be tackle at all levels.
- Planet formation is a robust process and their dynamical architecture is diverse.
- Migration played a big role in their final destiny.
- Theory of planetary astrophysics is relevant to many other astrophysical contexts.