Ubiquity of planets and diversity of planetary systems: Origin and Destiny of multiple super Earths and gas giants.

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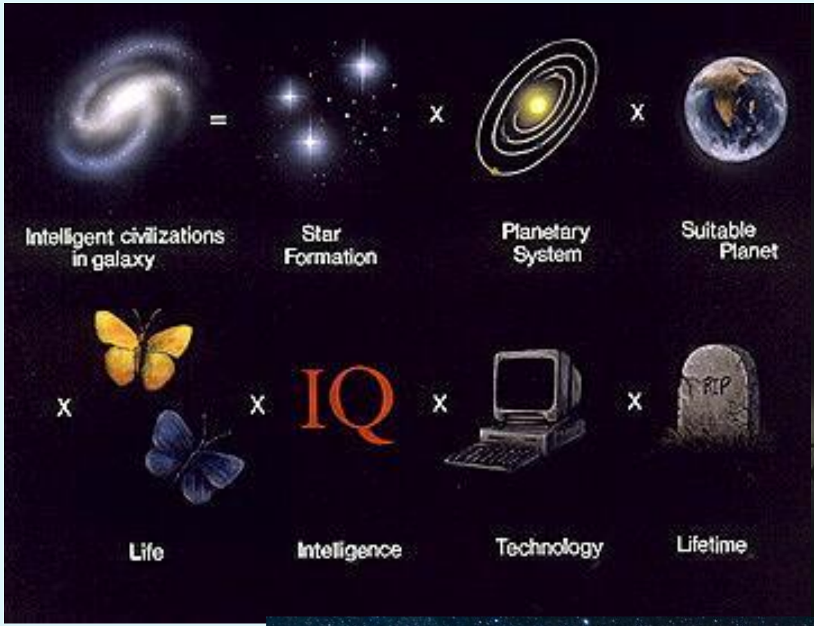
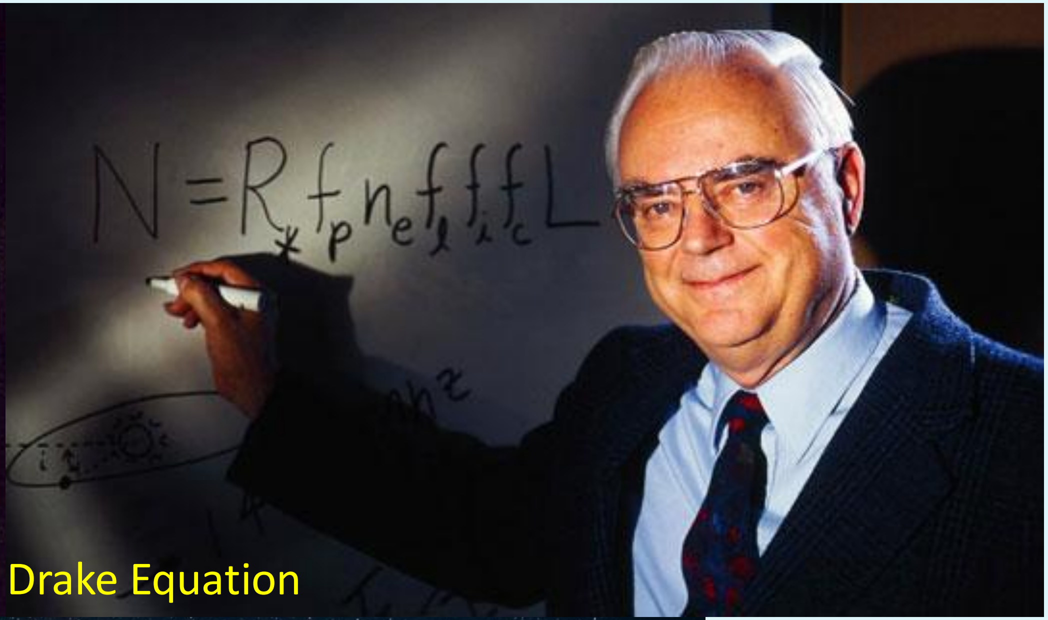
Dec 2, 2014

69 slides

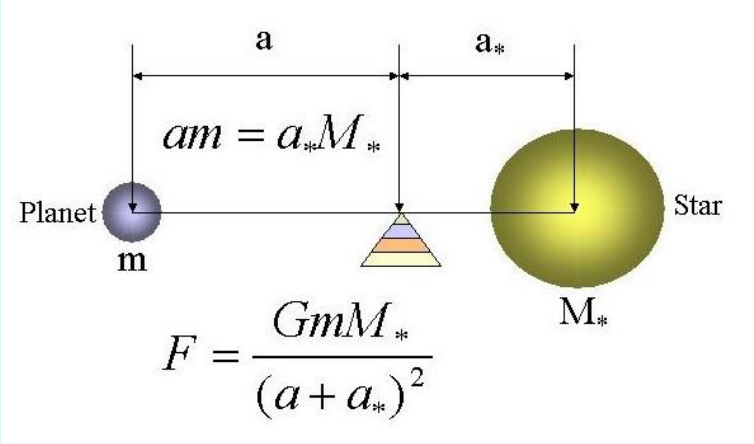

Are We Alone
In The Universe?

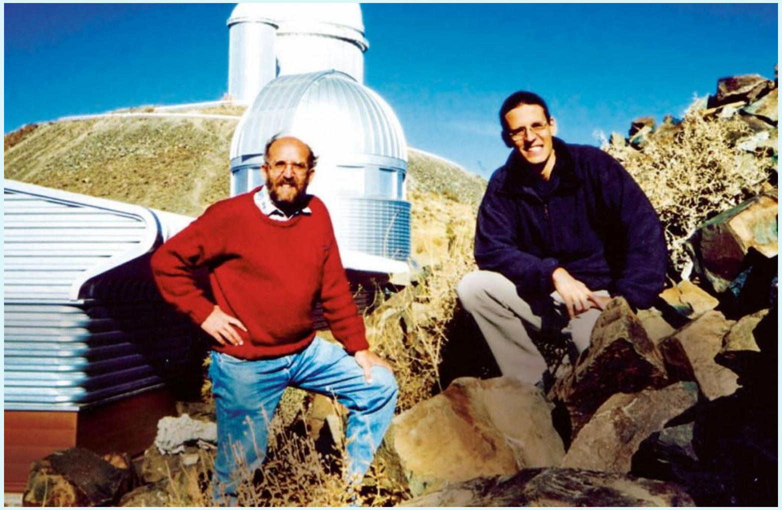
The unknown unknowns



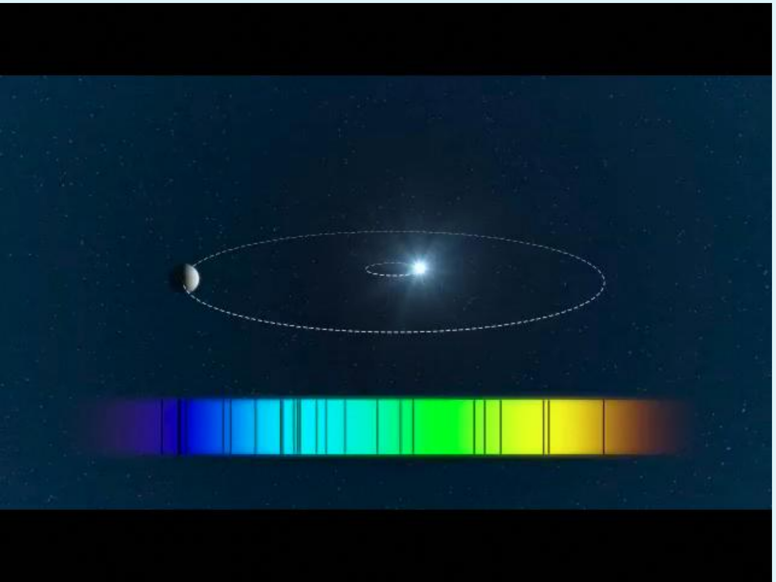


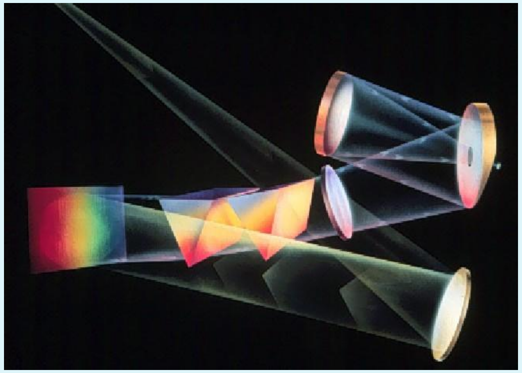
Radial velocity

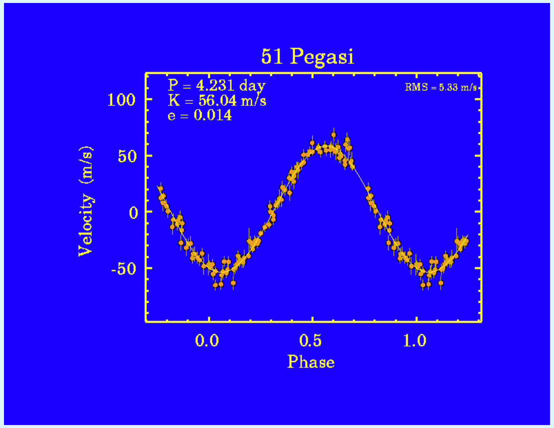


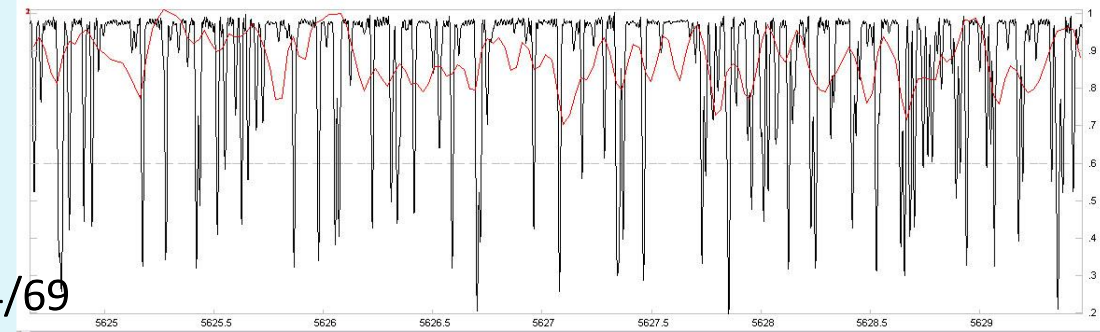


Femtometer Doppler shift
In individual lines









Precision COSMOGONY

- Ubiquity of planets:

case study vs **Science**

- Diversity of systems:

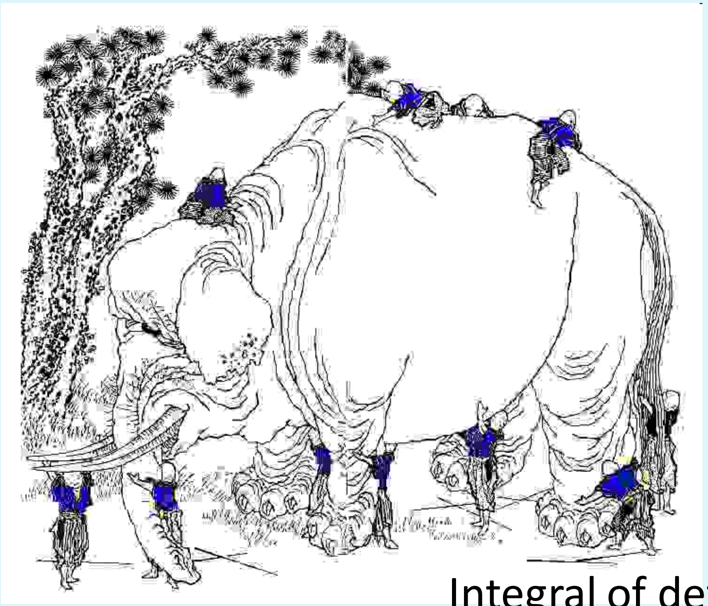
realm of possibilities

- Population census

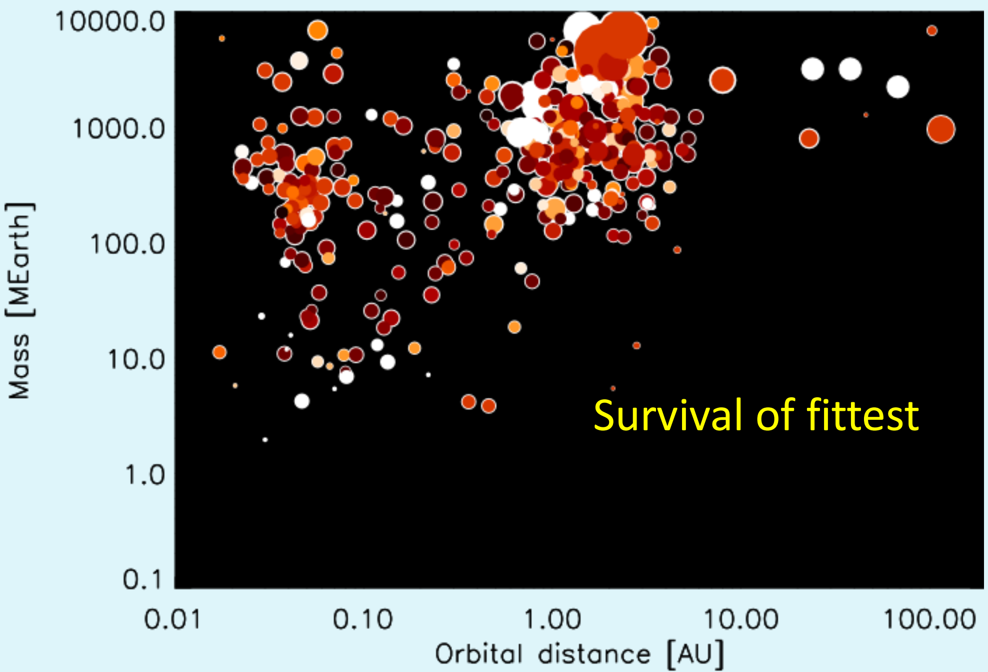
missing info & big picture

- Solar system connection

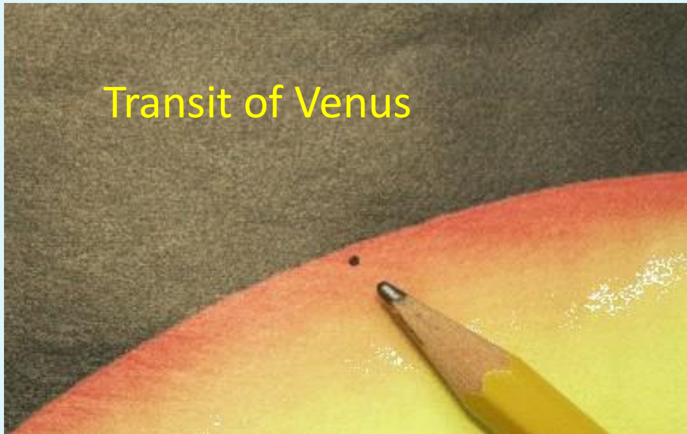
Anthropic principle

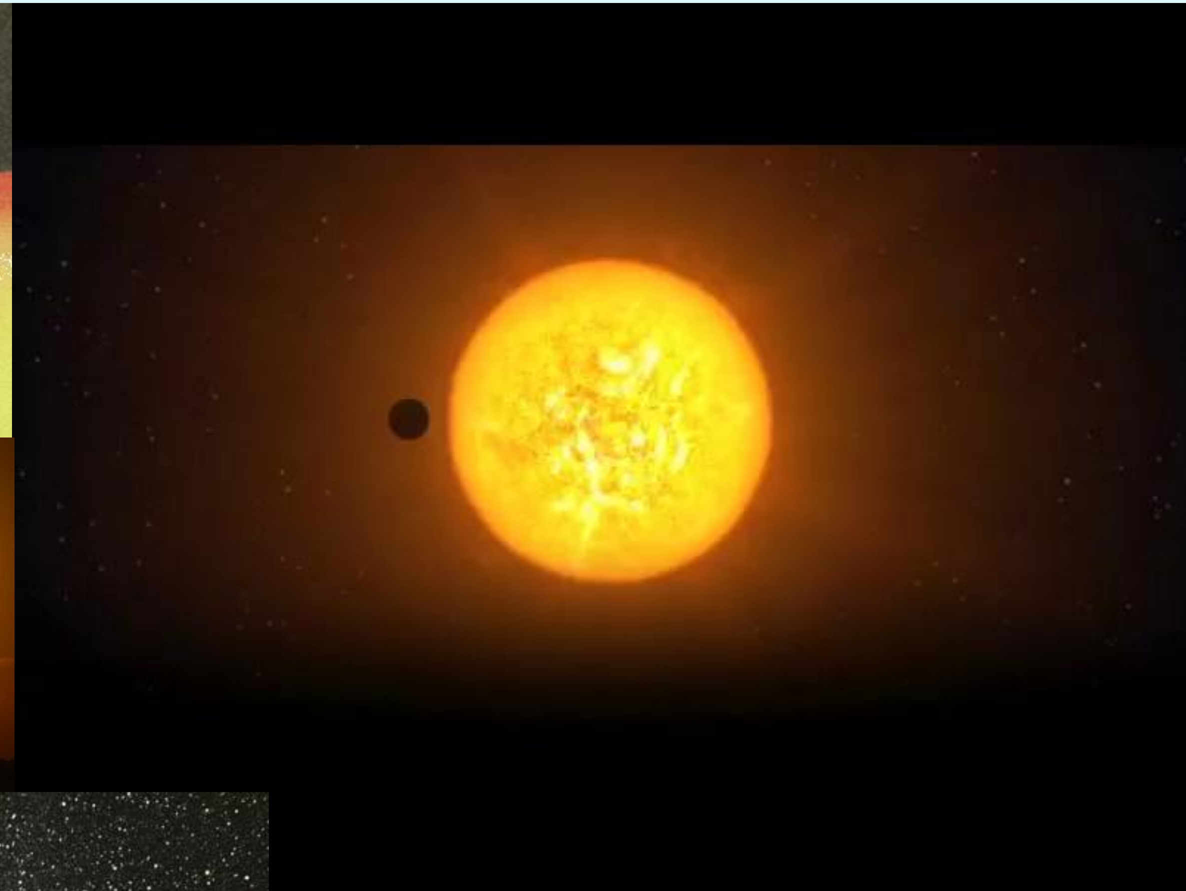


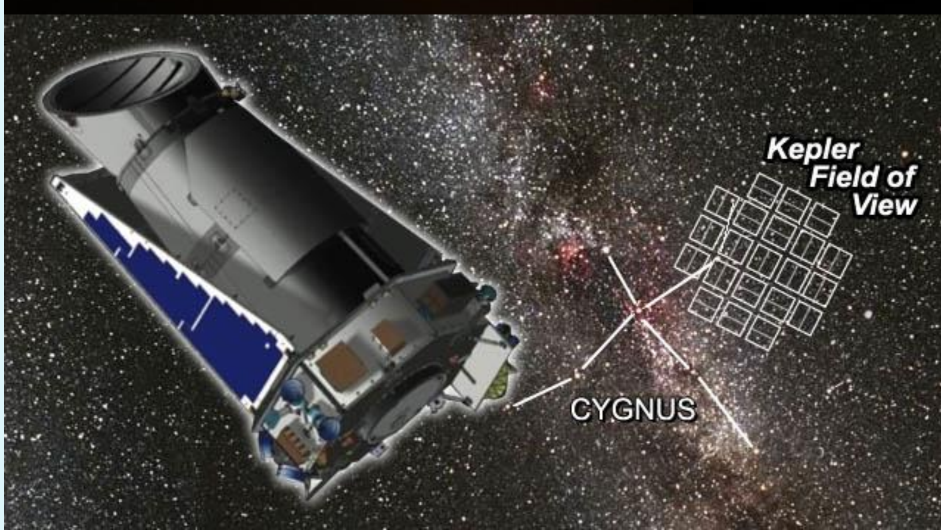
Integral of details

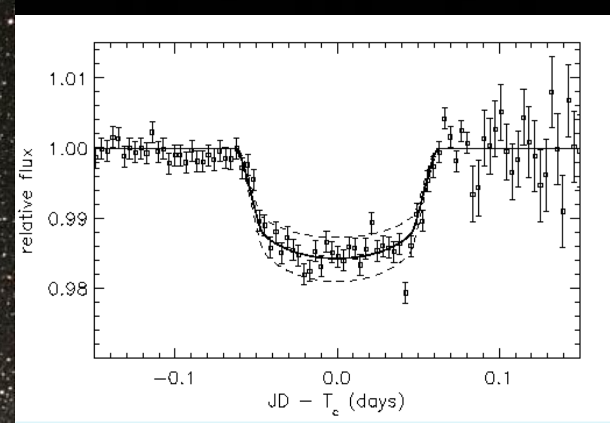


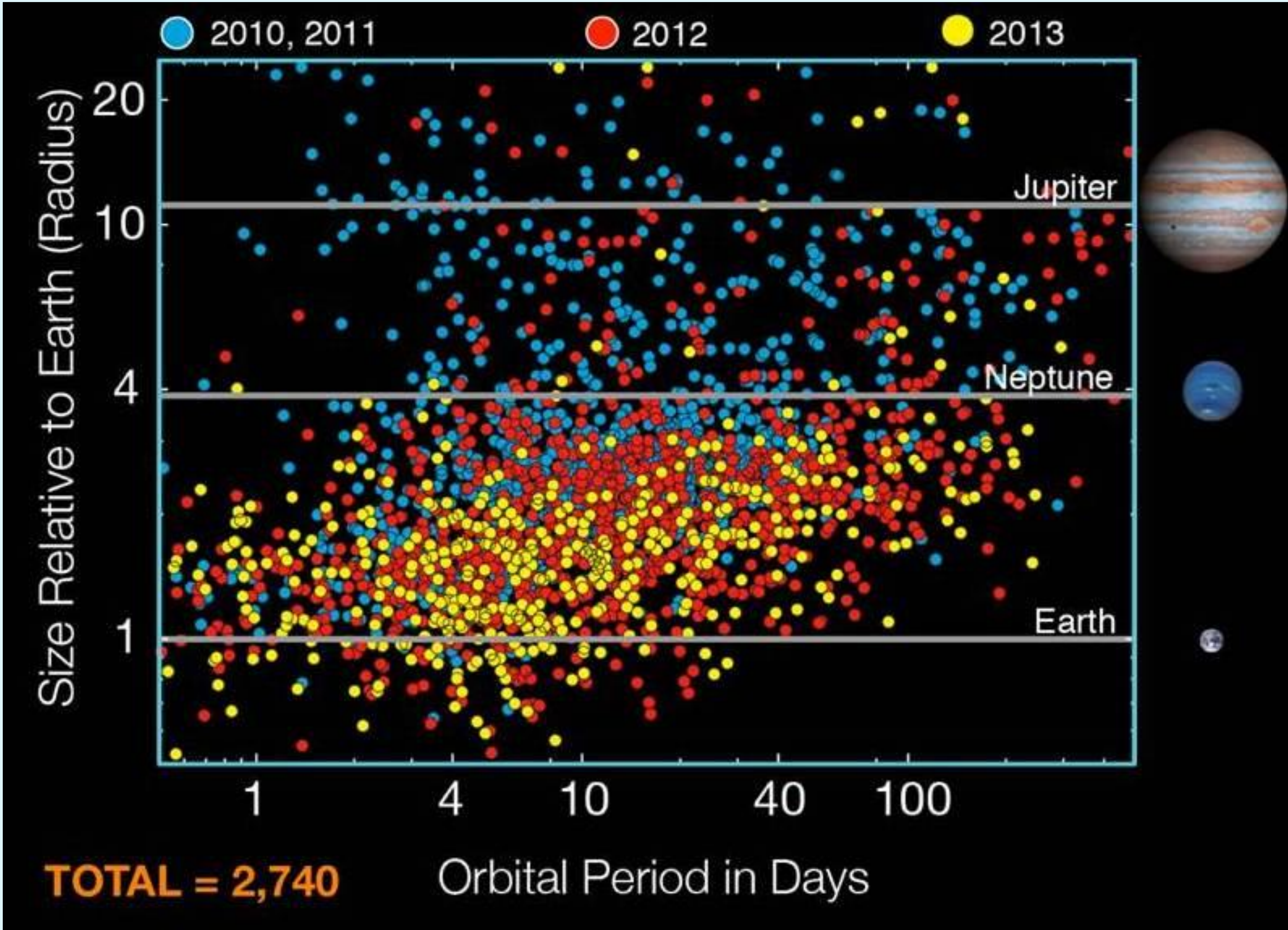
Transit (eclipse) searches



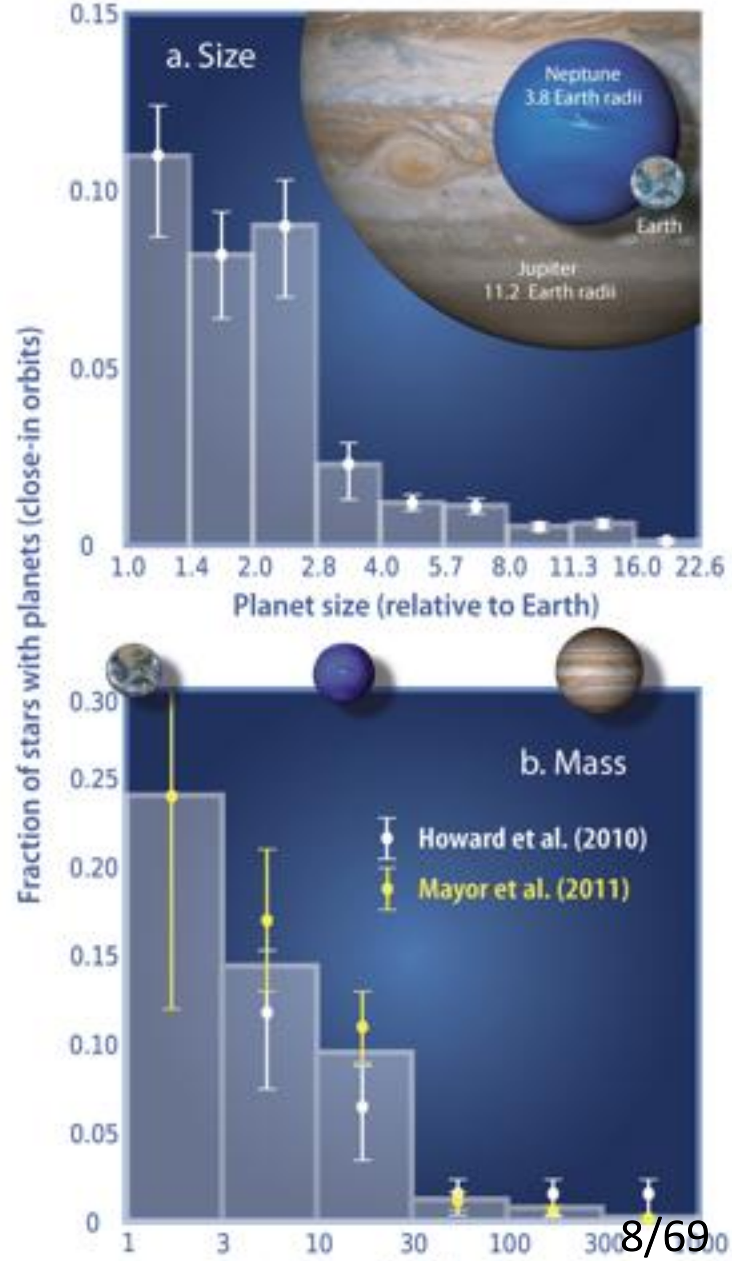




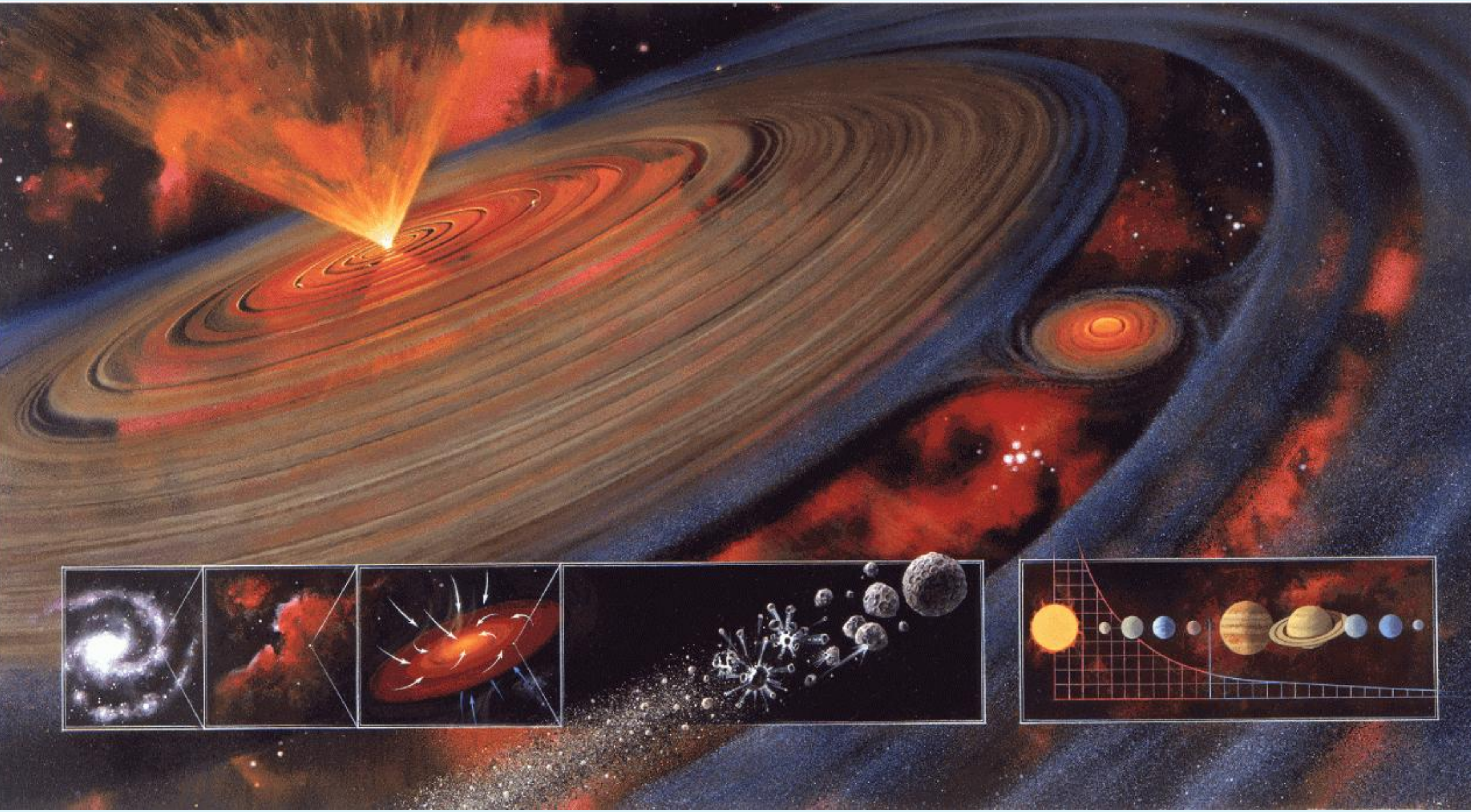



2010, 2011
2012
2013
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
40
100
TOTAL = 2,740
Orbital Period in Days

Observed Properties of Extrasolar Planets
Howard (2013)



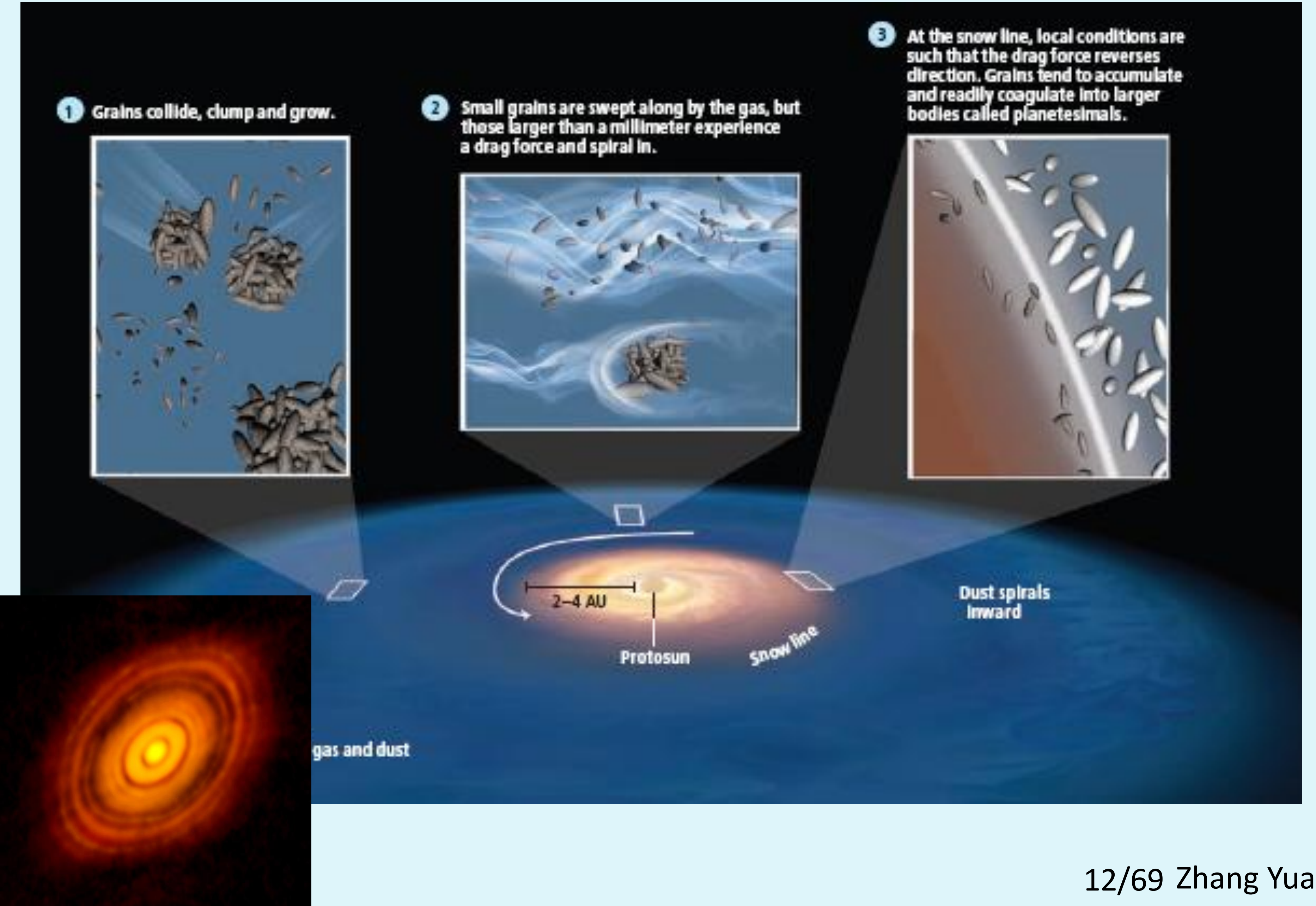
Conventional core accretion scenario



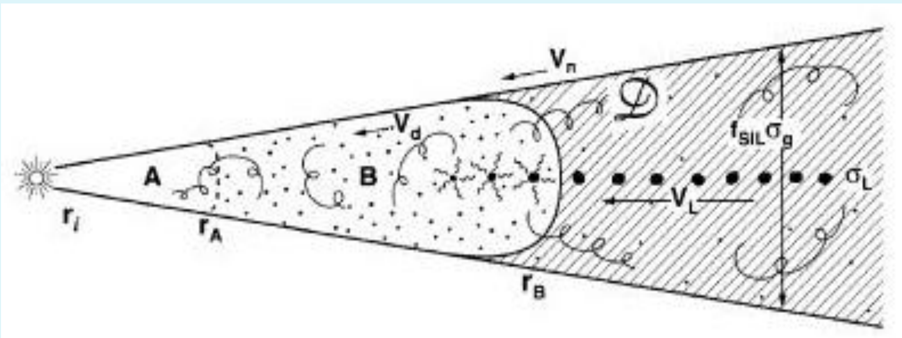
Major Challenges:

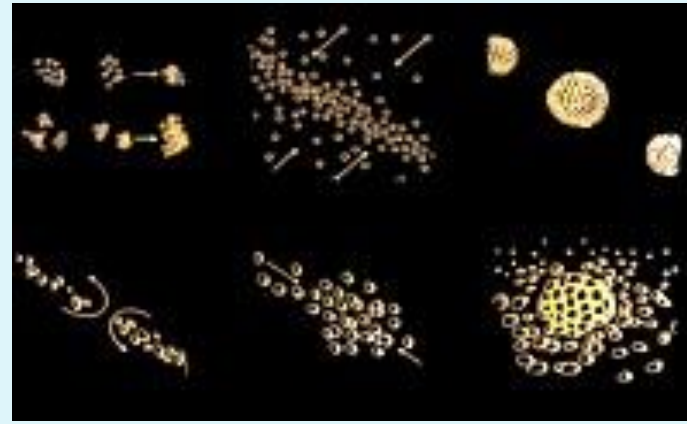
- Retention of grains: m-size barrier (Whipple)
- Fragmentation: km-size barrier (Benz)
- Planetesimal-growth barrier: Isolation mass barrier (Wetherill)
- Gas accretion barrier: critical-mass cores (Cameron)
- Retention of cores: type I migration (Goldreich & Tremaine, Ward)
- Retention of gas giants: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

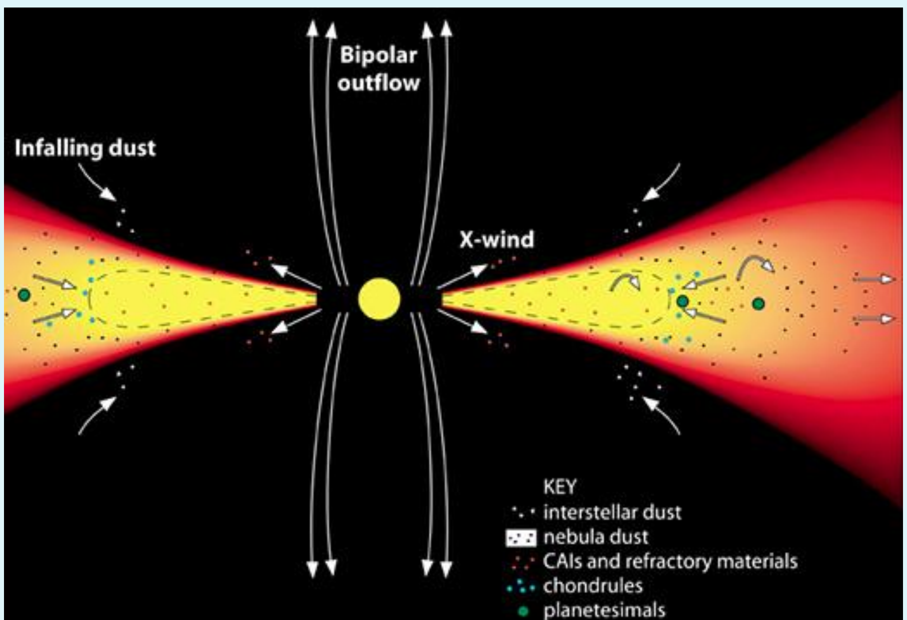
Step I: Meter-barrier   Hydrodynamic drag on dusts



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.)

Lecar asteroid 4417

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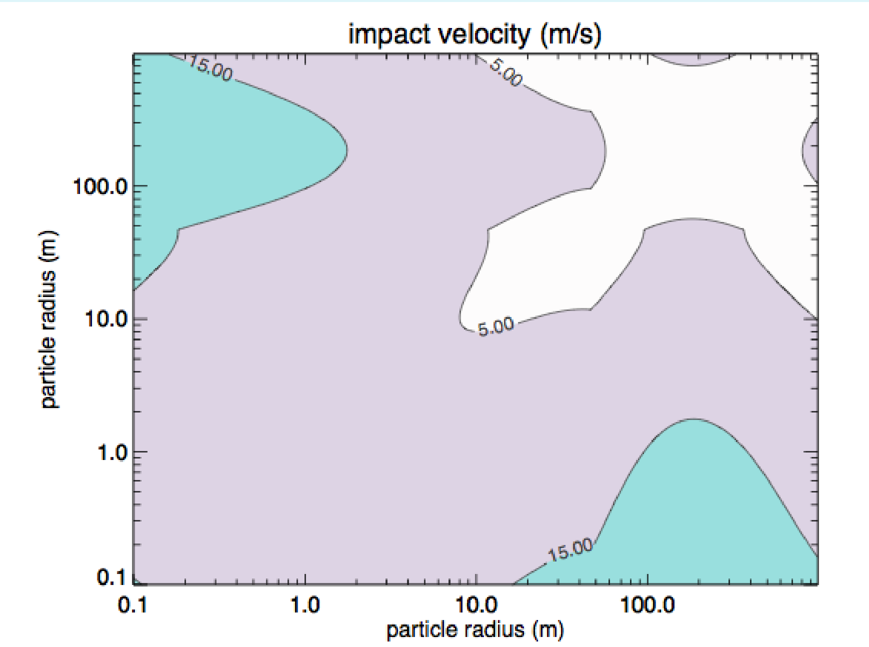
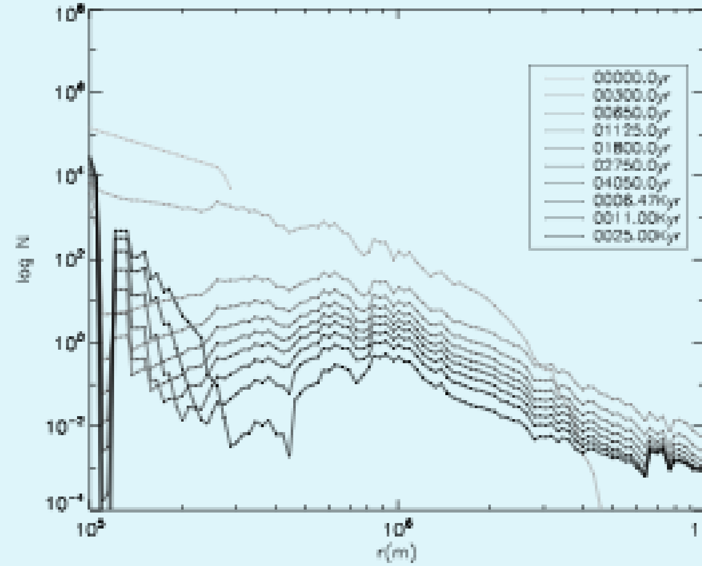
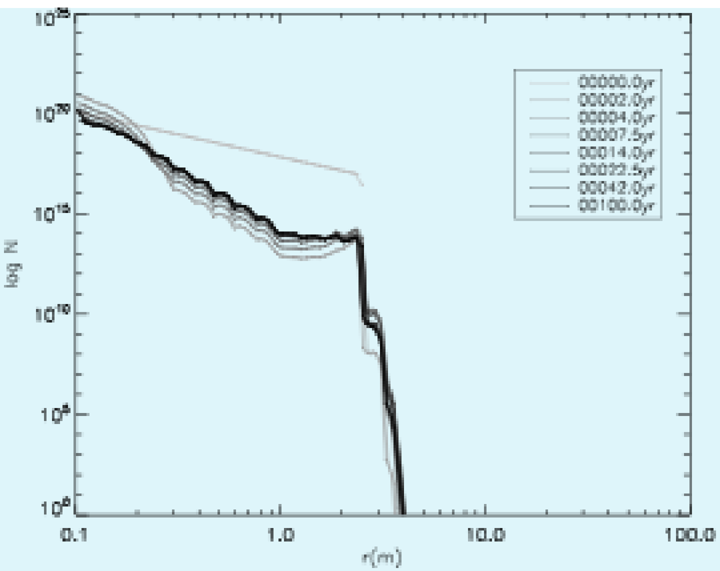
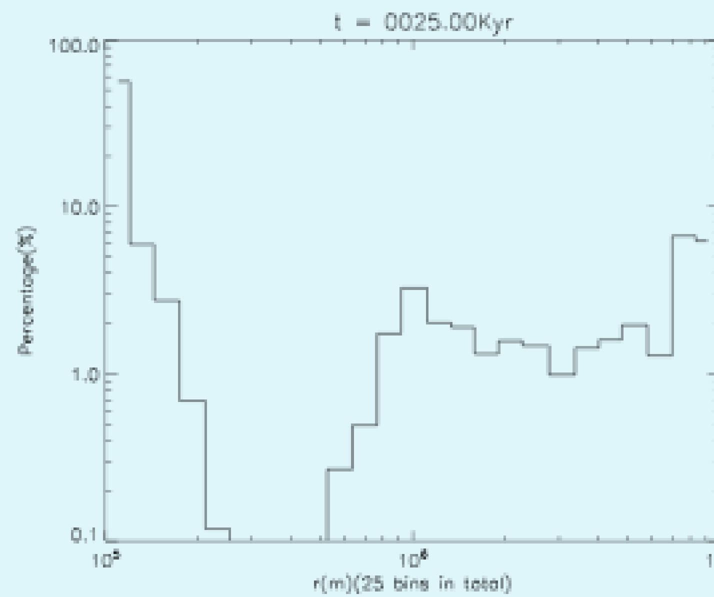
Planetesimal growth in a trap



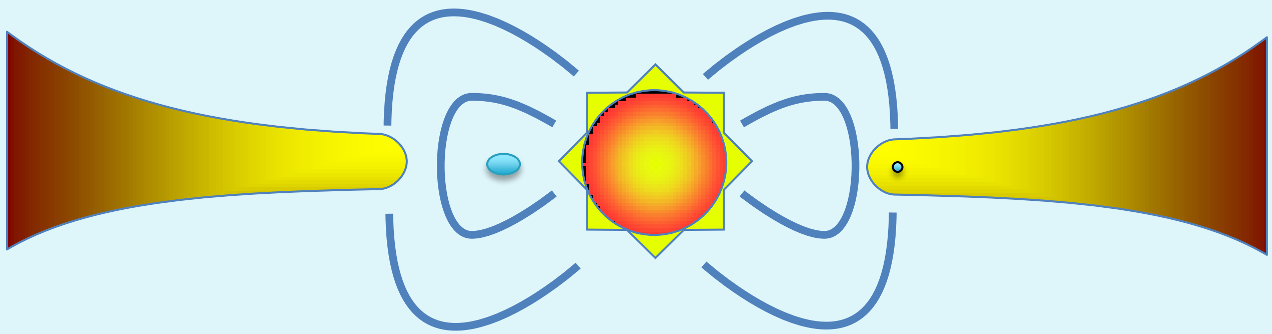




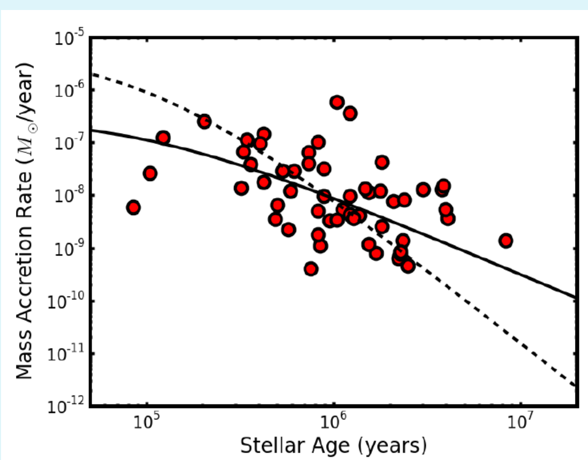


Rixin Li, Yuan Zhang, Bili Dong

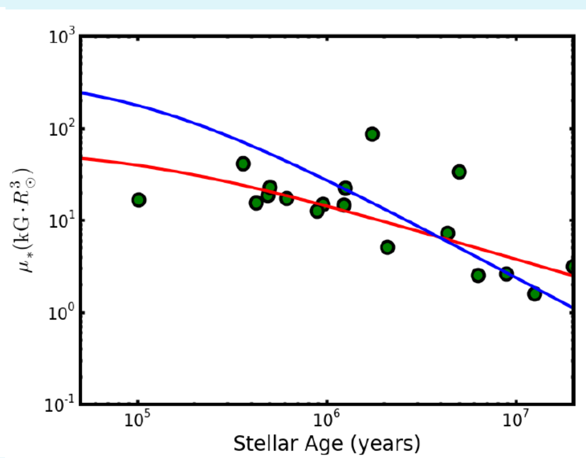
Stalling of planets inside & at the magnetospheric truncation radius



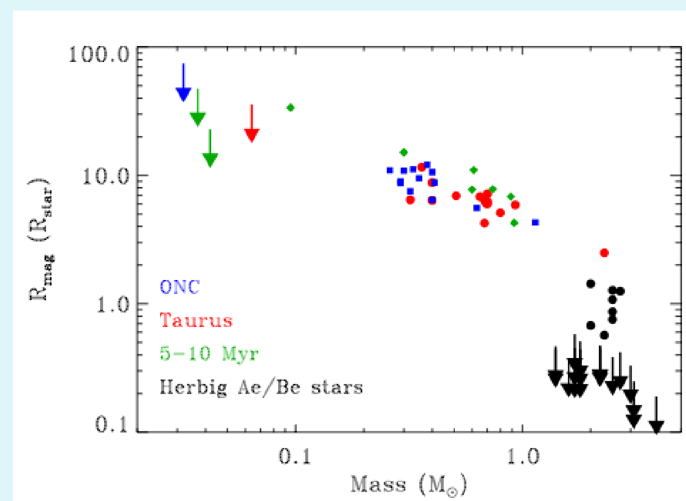
$$r_{\rm mag} \propto \mu_*^{4/7} \dot{M}^{-2/7}$$



Mass Accretion Rate



Stellar Dipole Moment



Magnetosphere radius

Herczeg

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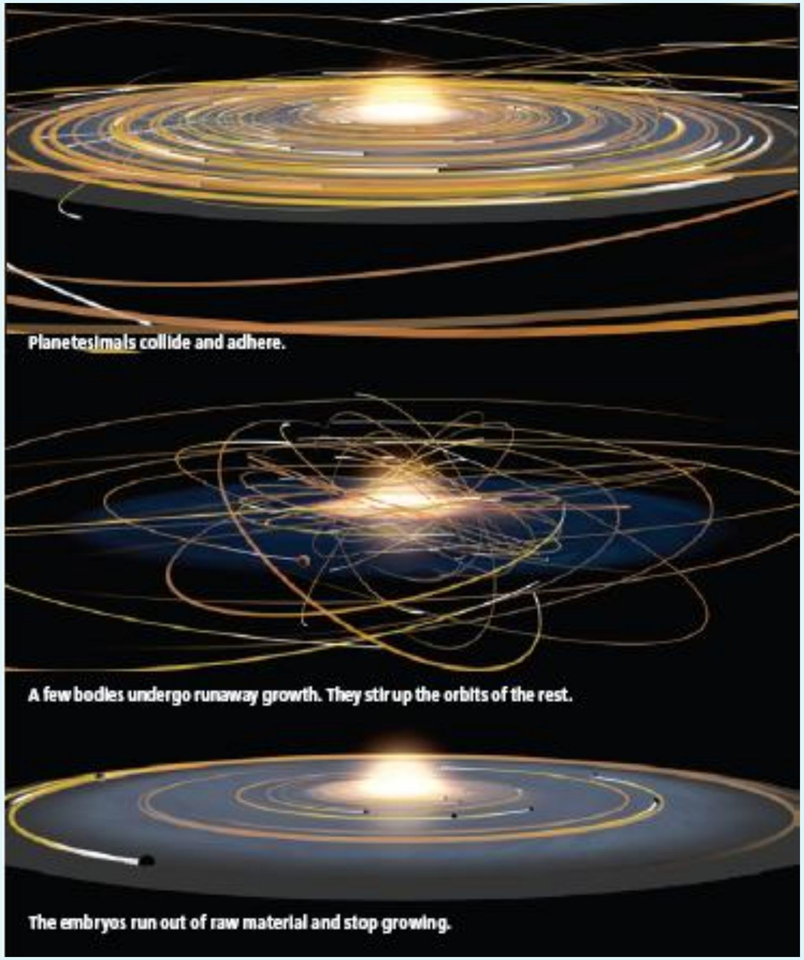
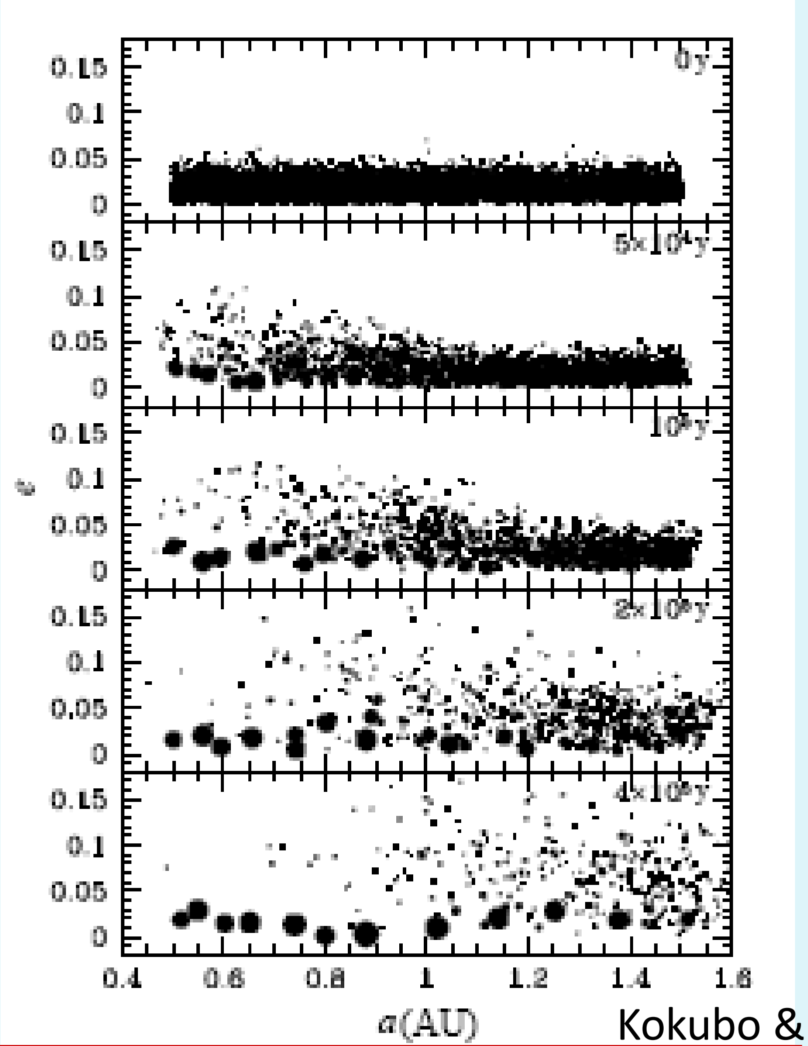
- Planetesimal-growth barrier: Isolation mass barrier (Wetherill)
- Gas accretion barrier: critical-mass cores (Cameron)
- Retention of embryos: type I migration (Goldreich & Tremaine, Ward)
- Retention of gas giants: type II migration (Lin & Papaloizou)
- Multiple gas giants: rapid depletion of disk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

Step III, oligarchic barrier: Isolation mass





Kokubo & Ida

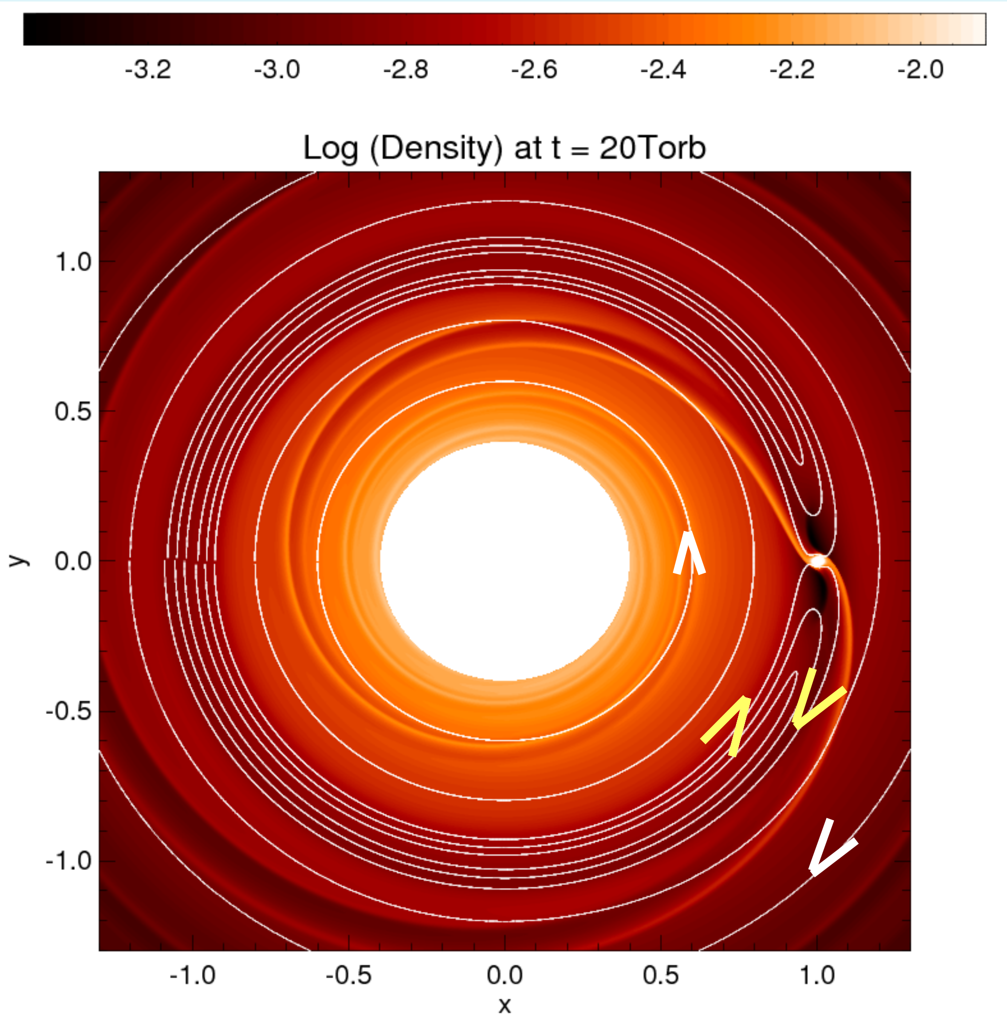
Feeding zones: $\Delta \sim 10\ r_{Hill}$

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

Major Challenges:

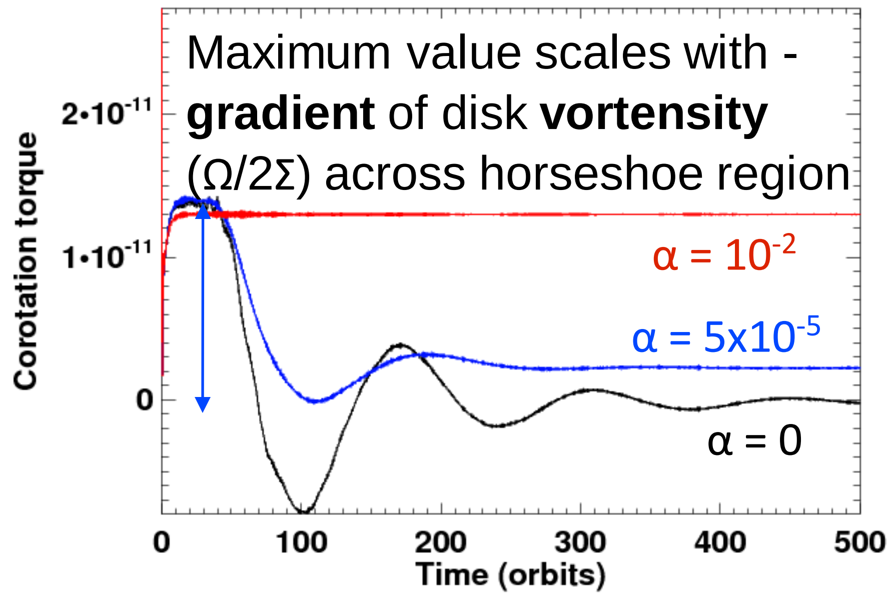
- Retention of grains: m-size barrier (Whipple)
- Fragmentation: km-size barrier (Benz)
- Planetesimal-growth barrier: Isolation mass barrier (Wetherill)
- Proliferation of multiple, wide spread embryos
- Diversity of planetary architecture
- Retention of gas giants: type II migration (Lin & Papaloizou)
- Multiple gas giants: rapid depletion of disk gas
- Competing physics on multiple length & time scales

Step 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**



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

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

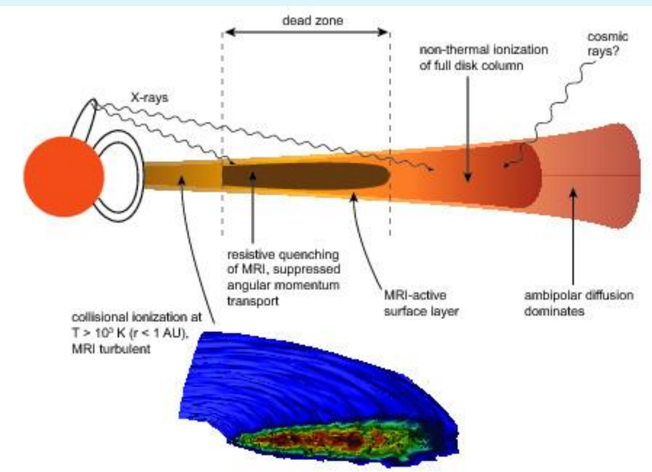
Planet-disk tidal interaction

Total tidal torque:

$$\Gamma = \Gamma_{\rm L} + \Gamma_{\rm c} = f(p,q,p_\nu,q_\nu,p_\kappa,q_\kappa)\Gamma_0$$

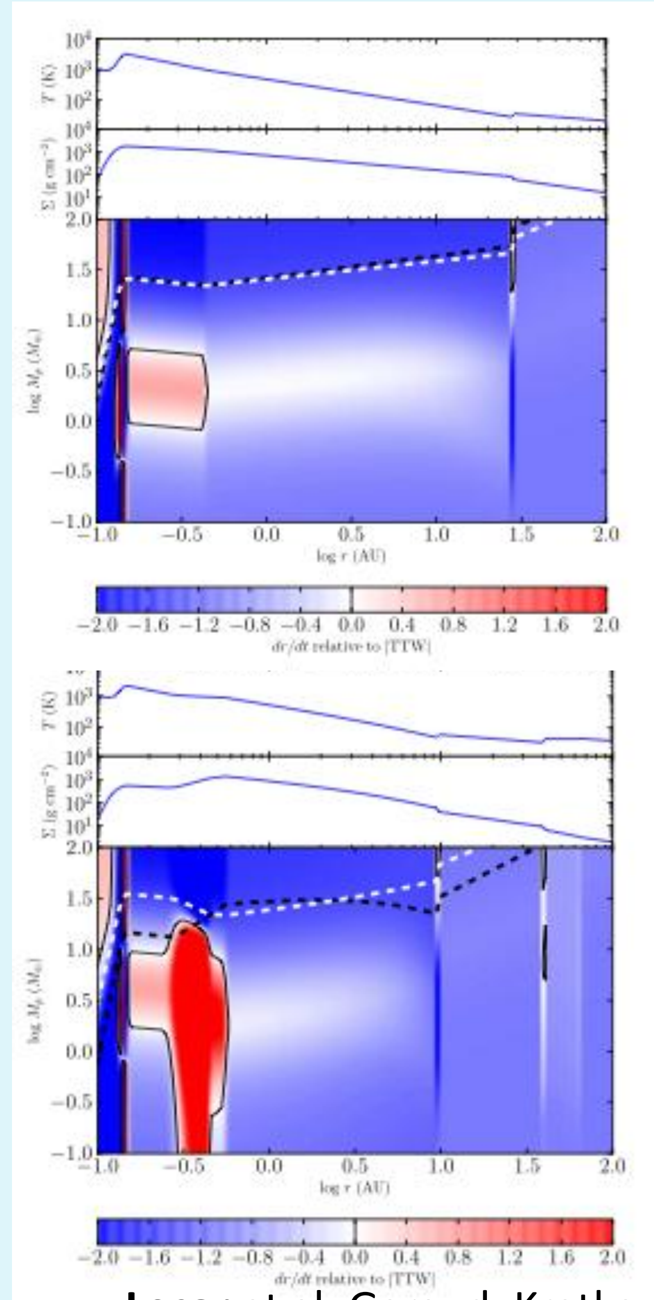
$$\Gamma_0 = (q/h)^2 \Sigma_{\rm p} r_{\rm p}^4 \Omega_{\rm p}^2,$$

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



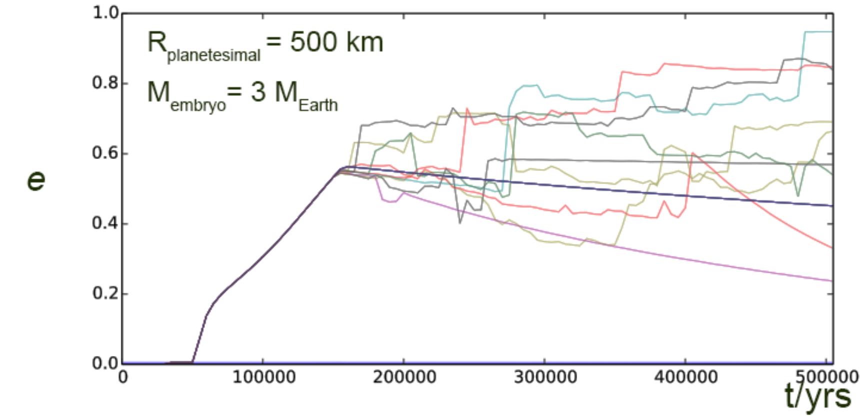
$$\frac{dr}{dt} = f(p,q,p_\nu,p_\chi)\frac{M_p}{M_*}\frac{\Sigma r^2}{M_*}\left(\frac{r\Omega_K}{c_s}\right)^2 r\Omega_K$$

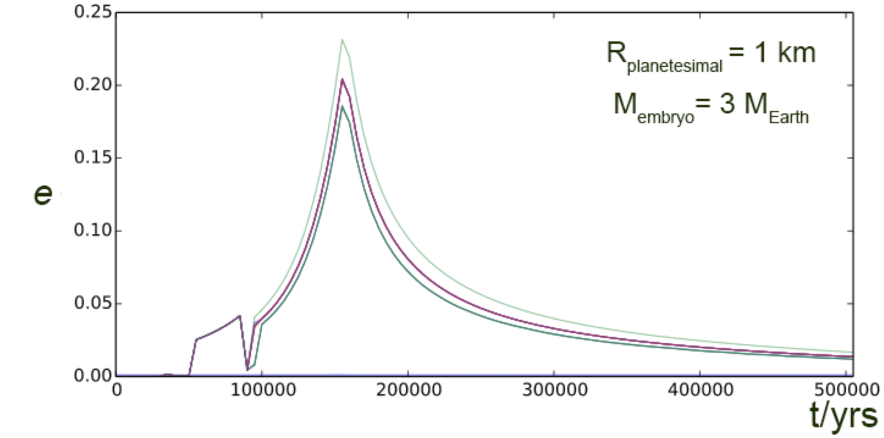
$(1/e)de/dt = (a/H)^4\ (M_p\Sigma a^2/M_*^2)\ \Omega$

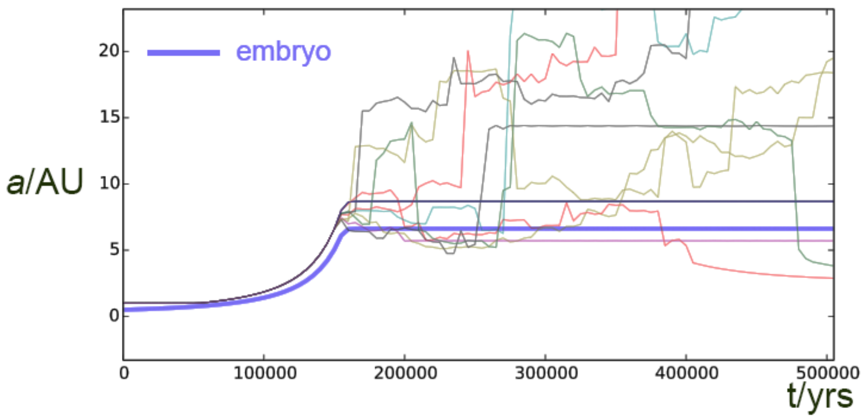


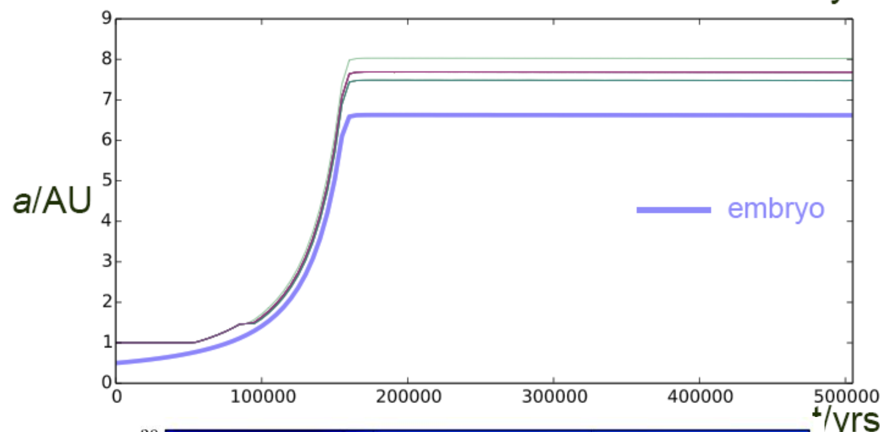
Lecar et al, Garaud, Kretke

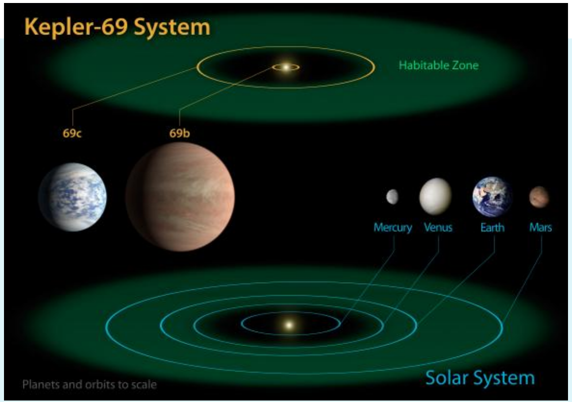
Resonant sweeping of planetesimals

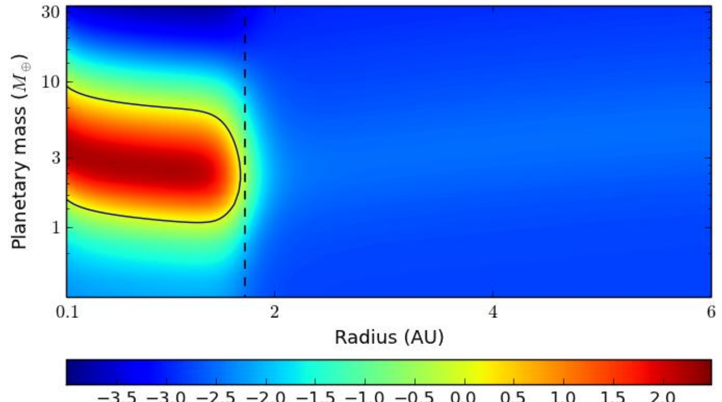












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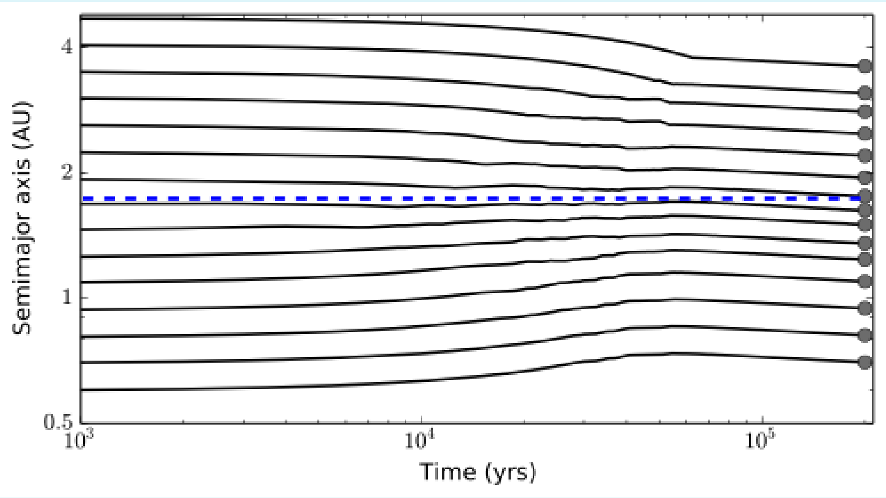
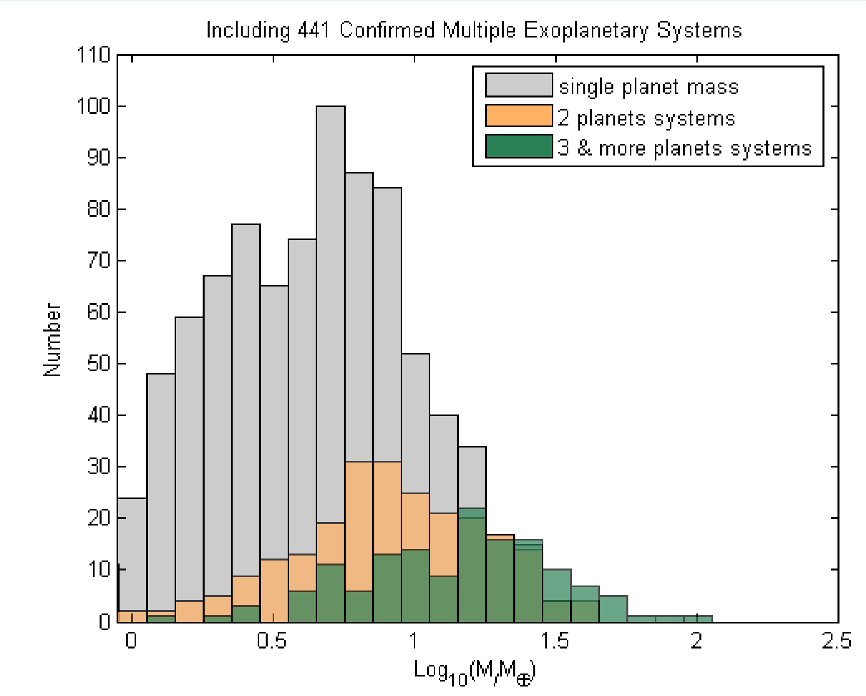
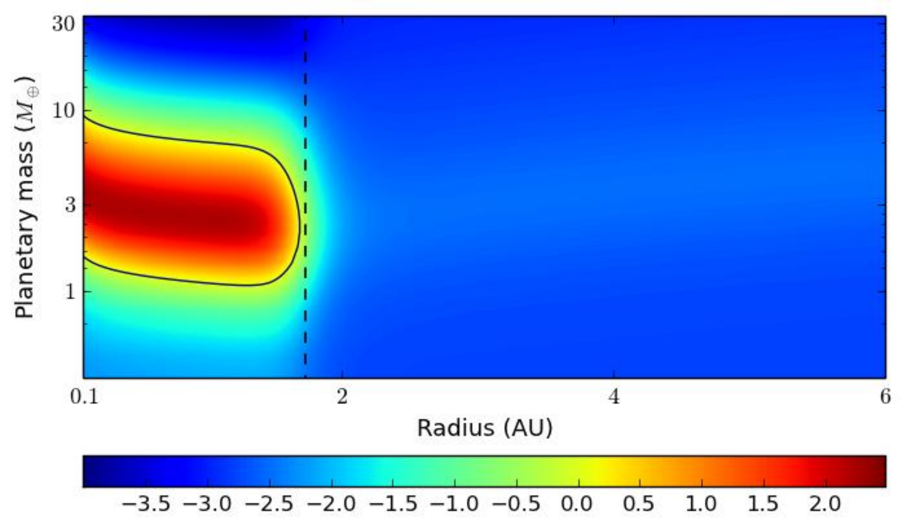
Core barrier: embryos' resonant trapping

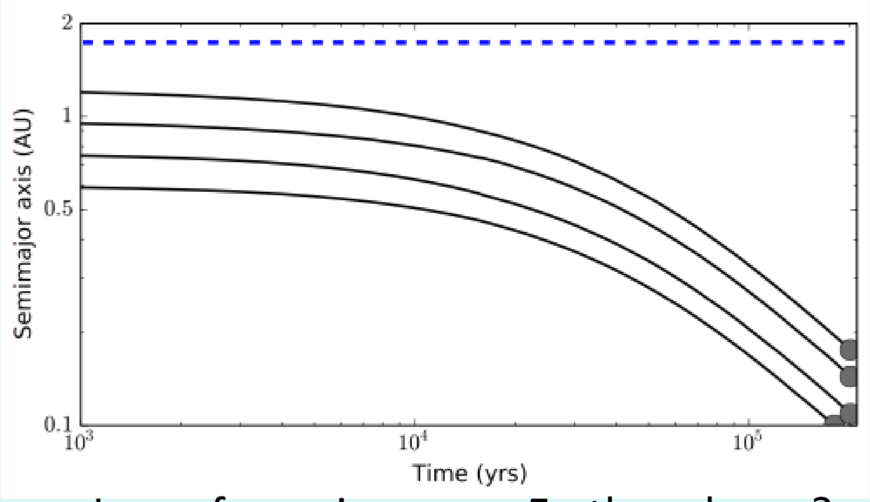




Beibei Liu   M=1Msun, Mdot = 10^{-8}M_sun/yr, α=1

No shortage of building block materials





Loss of massive super-Earth embryos?

Major Challenges:

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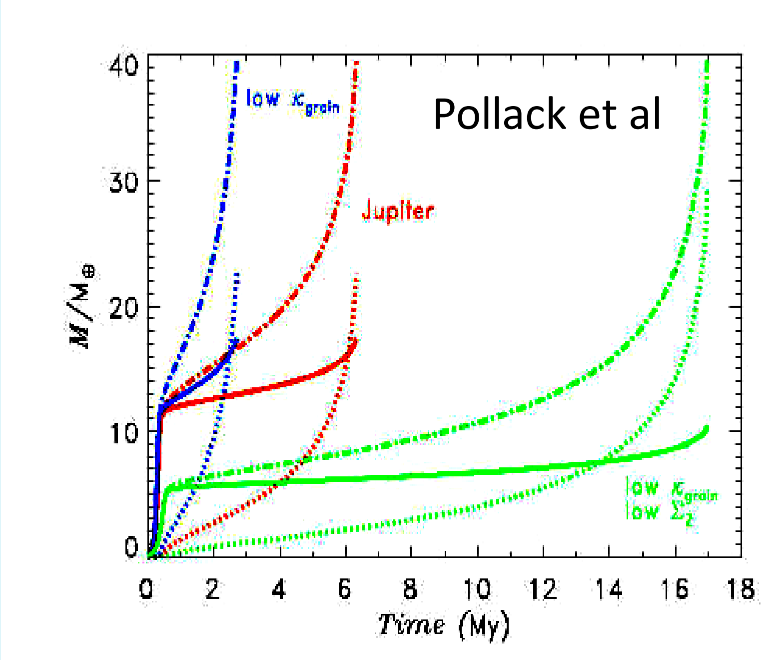
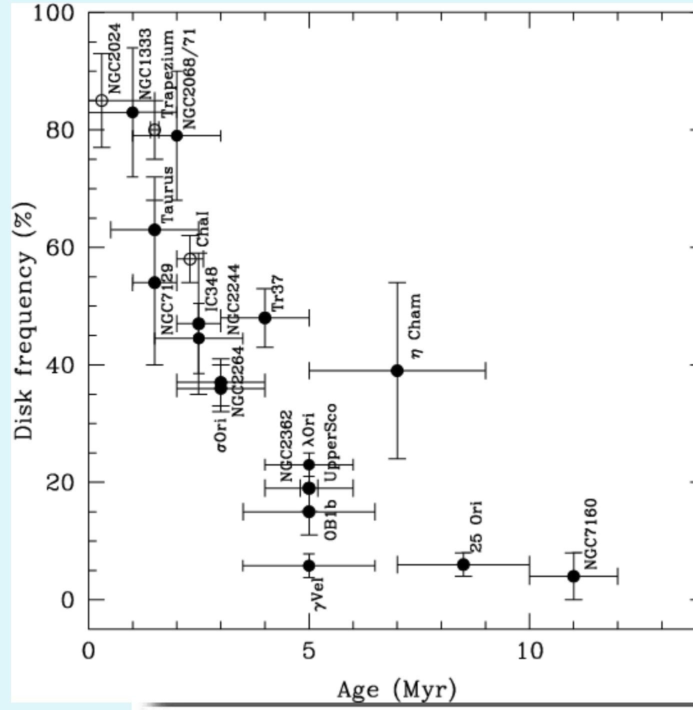
Gas accretion barrier:

- Is there a threshold mass for gas accretion?





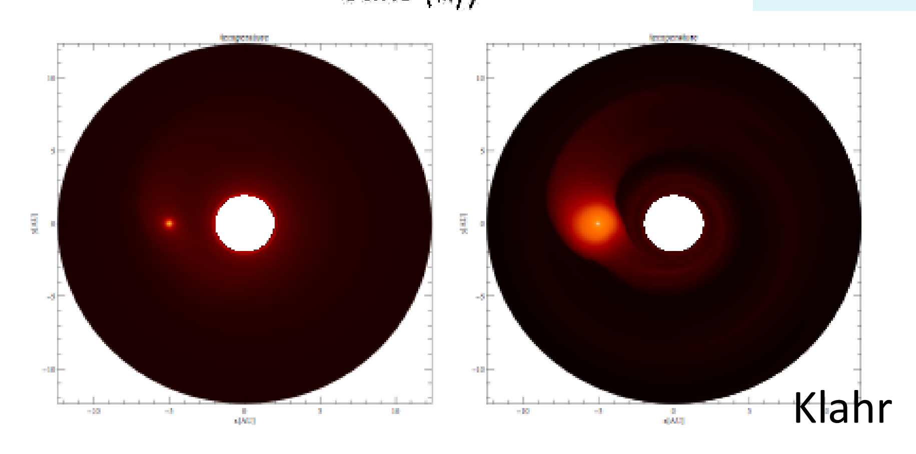
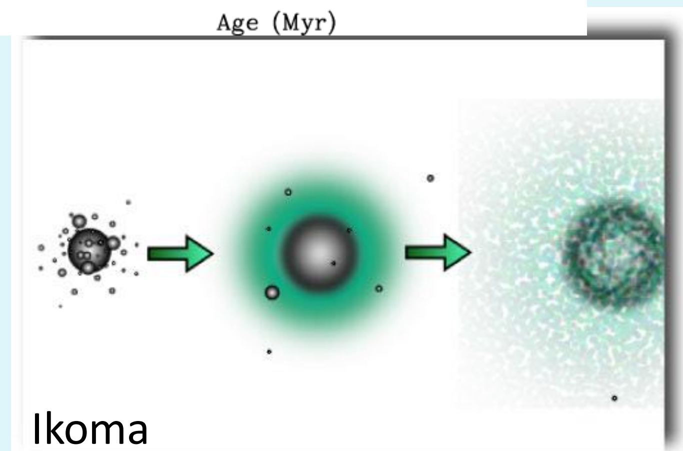
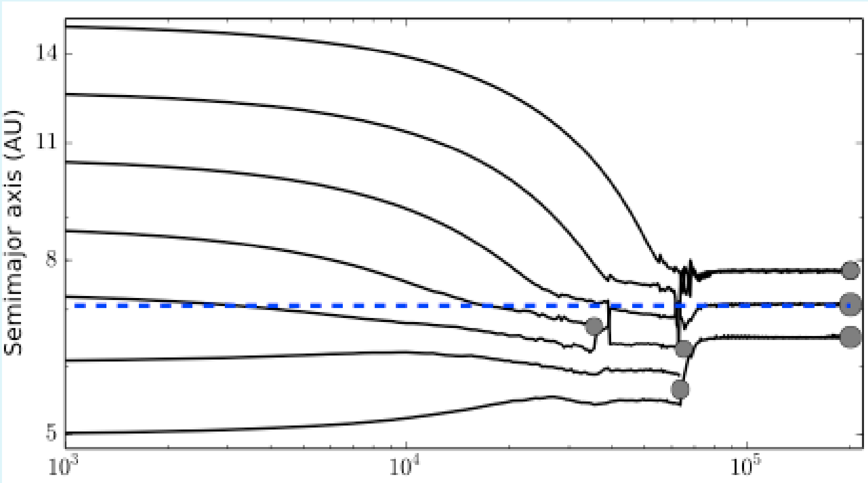


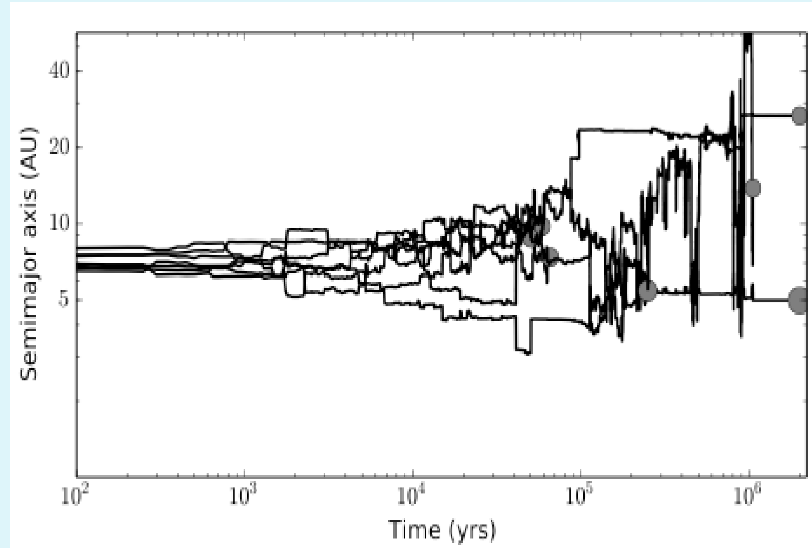
Fig. 4.— Tempertature distribution - left: $30M_\oplus$ and $\kappa = 0.01\kappa_0$; right: $30M_\oplus$ and $\kappa = 1\kappa_0$

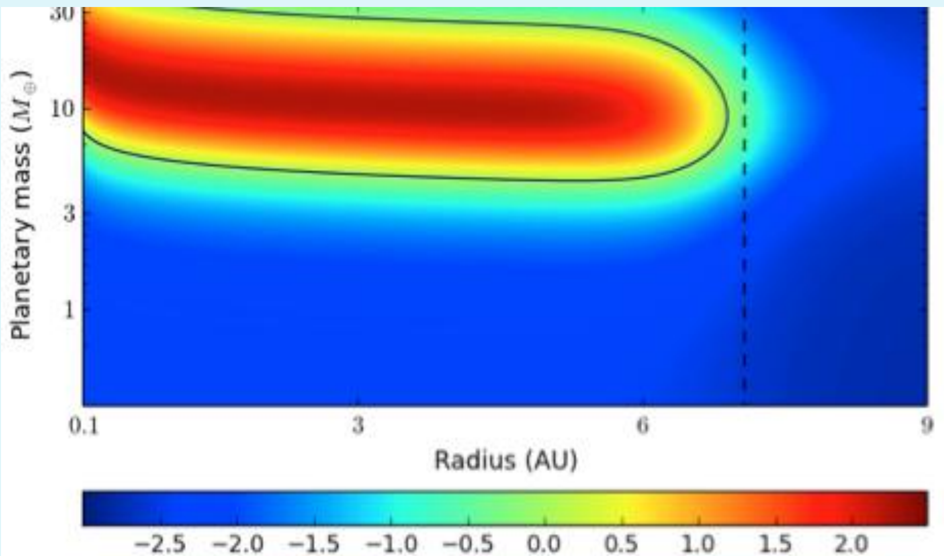


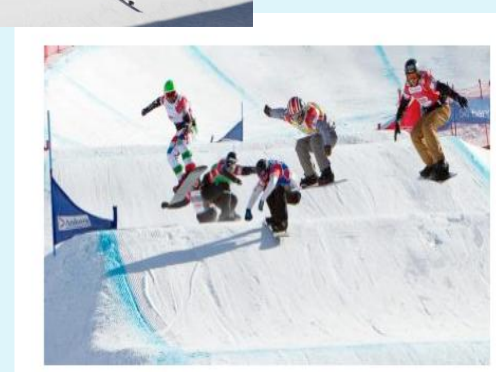
Radiation transfer & gas accretion

Bypass the resonance barrier



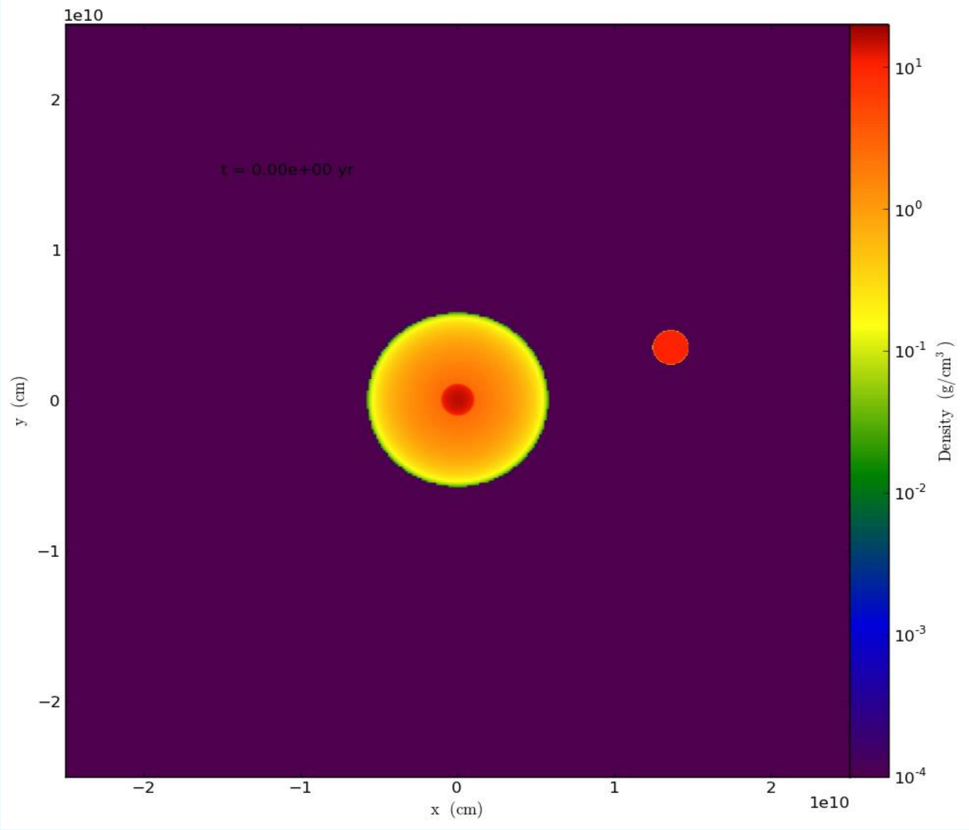


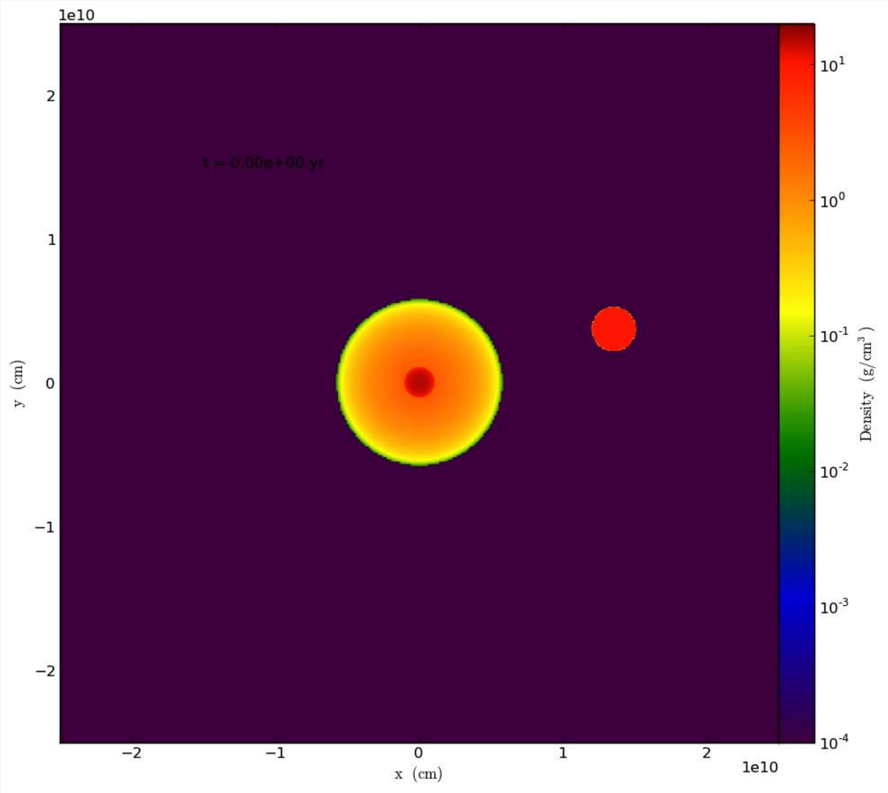




Orbit crossing, close encounters, home coming & collisions

Giant impacts of super Earths



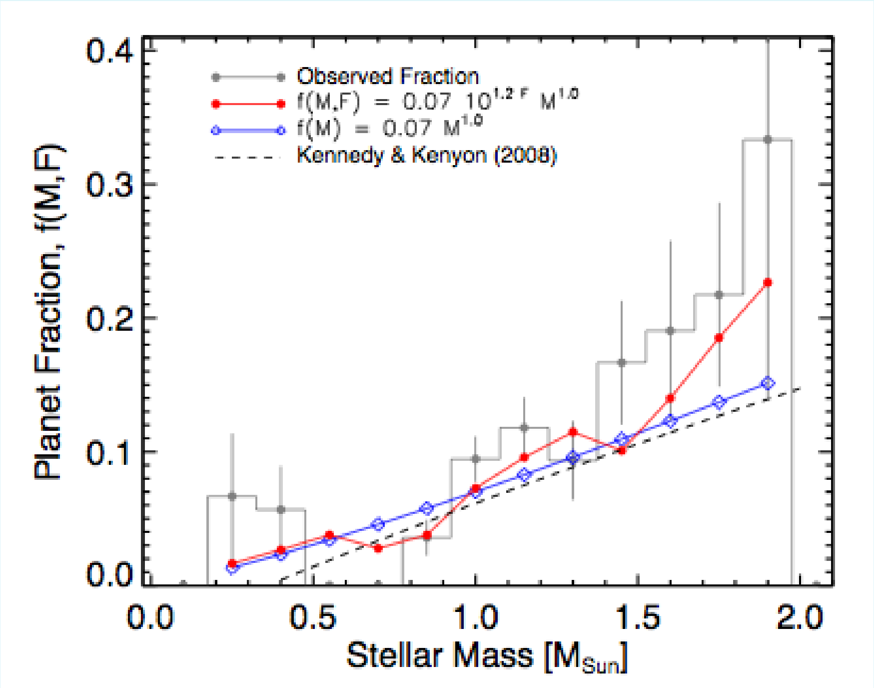


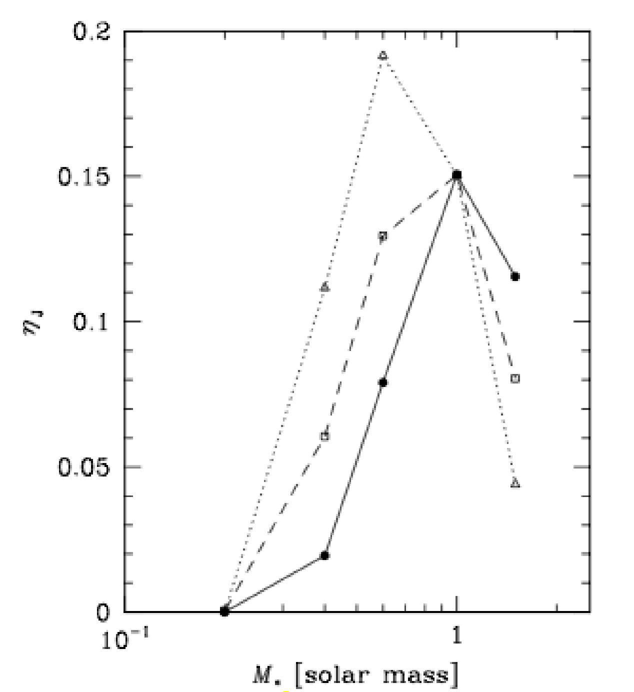
Liu Shangfei

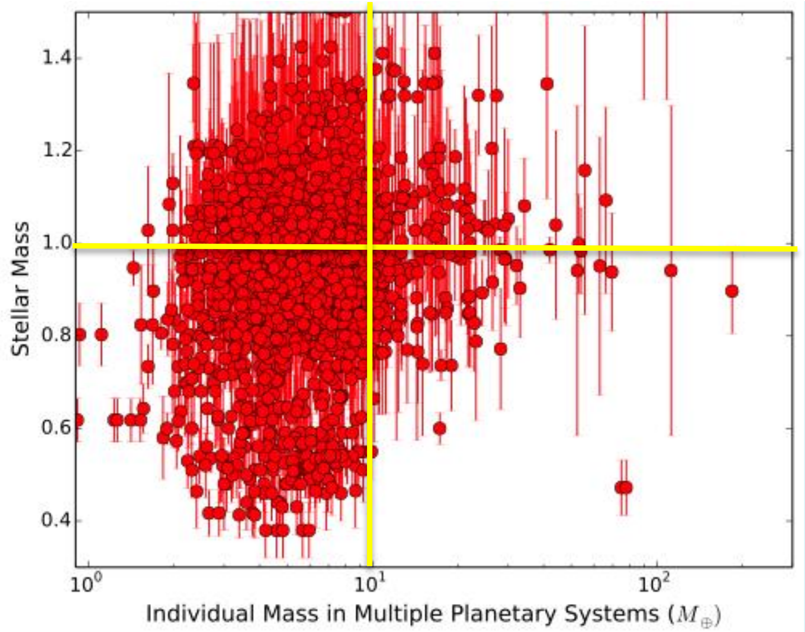
Major Challenges:

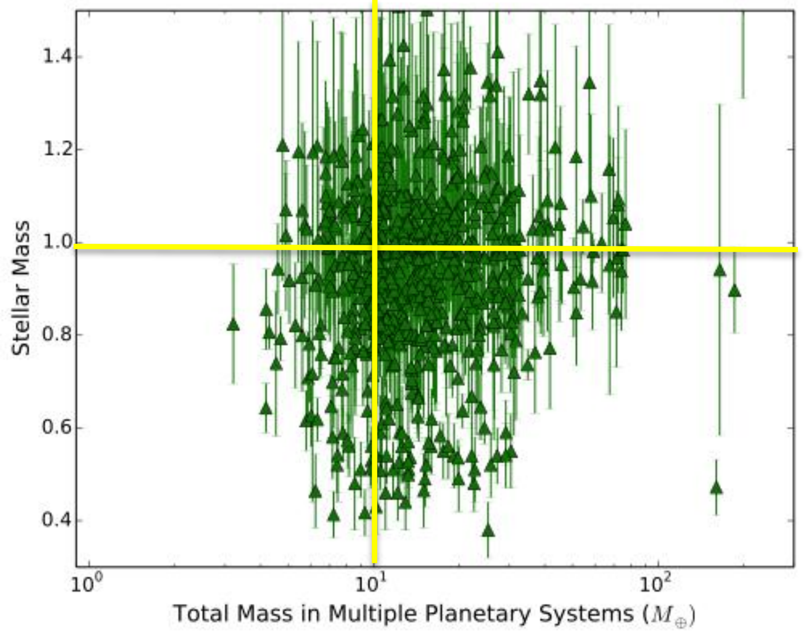
- Retention of grains: m-size barrier (Whipple)
- Fragmentation: km-size barrier (Benz)
- Planetesimal-growth barrier: Isolation mass barrier (Wetherill)
- Availability of building block material
- Frequency of planets around different type stars
- Retention of gas giants: type II migration (Lin & Papaloizou)
- Multiple gas giants: rapid depletion of disk gas
- Competing physics on multiple length & time scales

Dependence on stellar mass

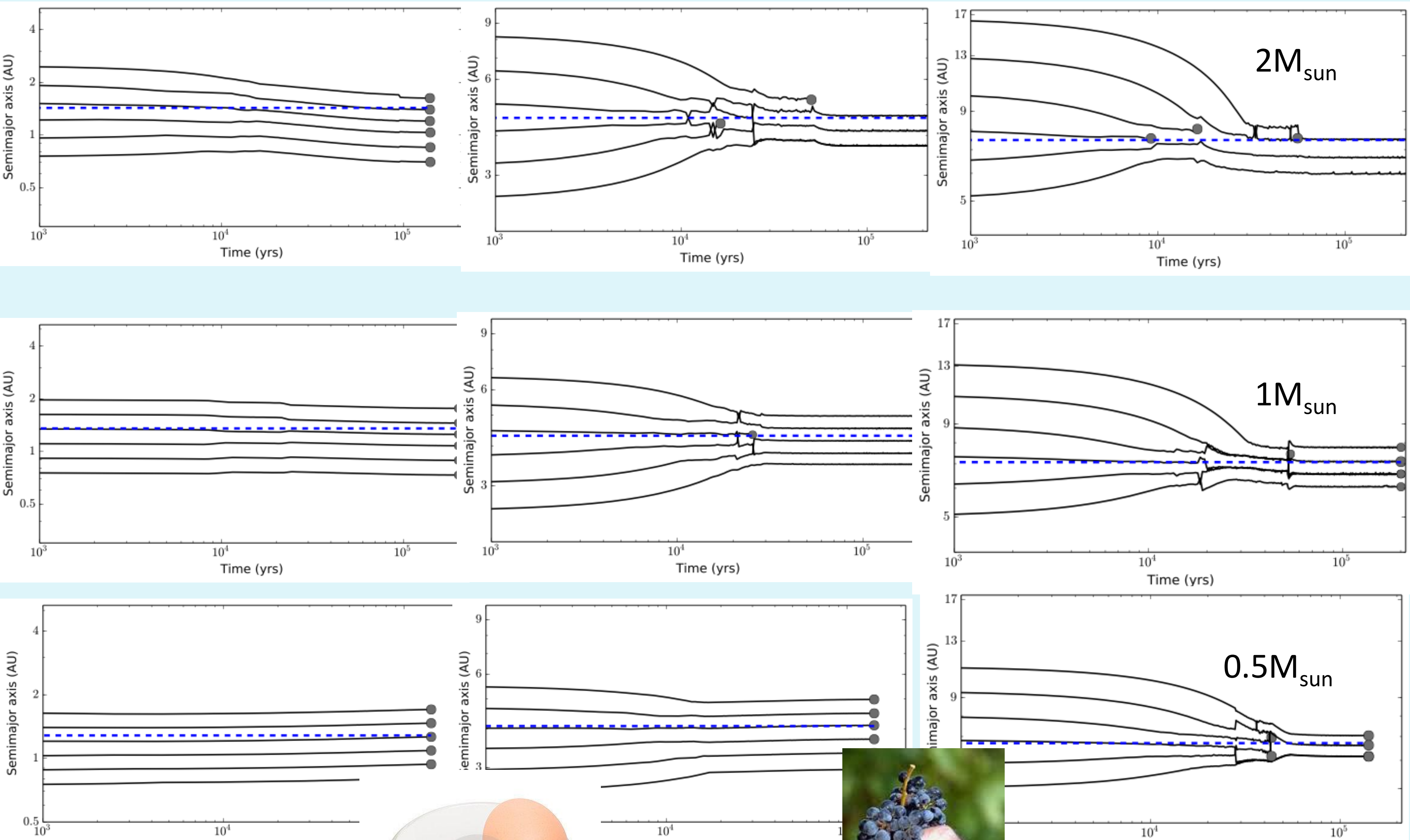






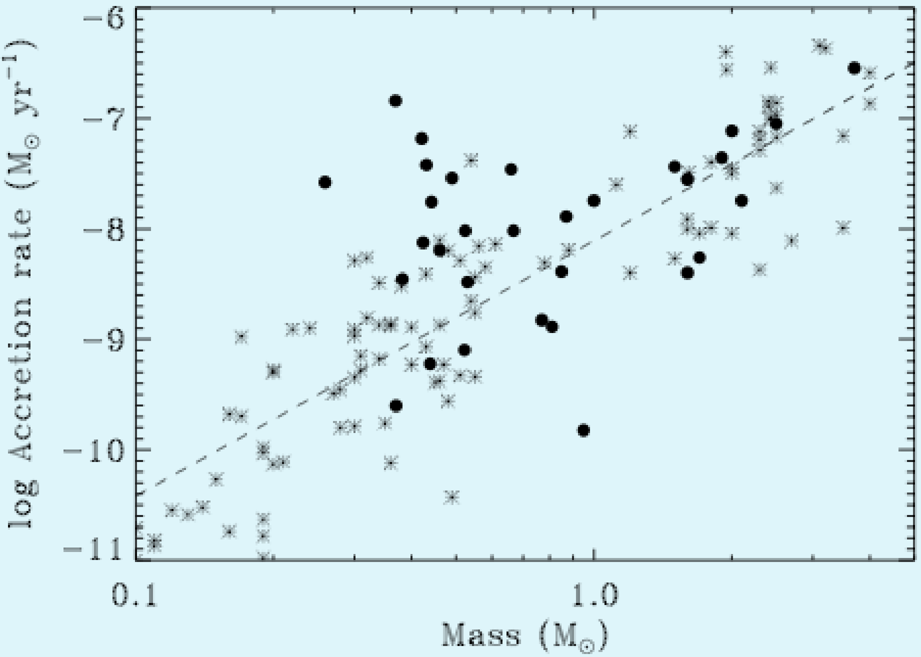


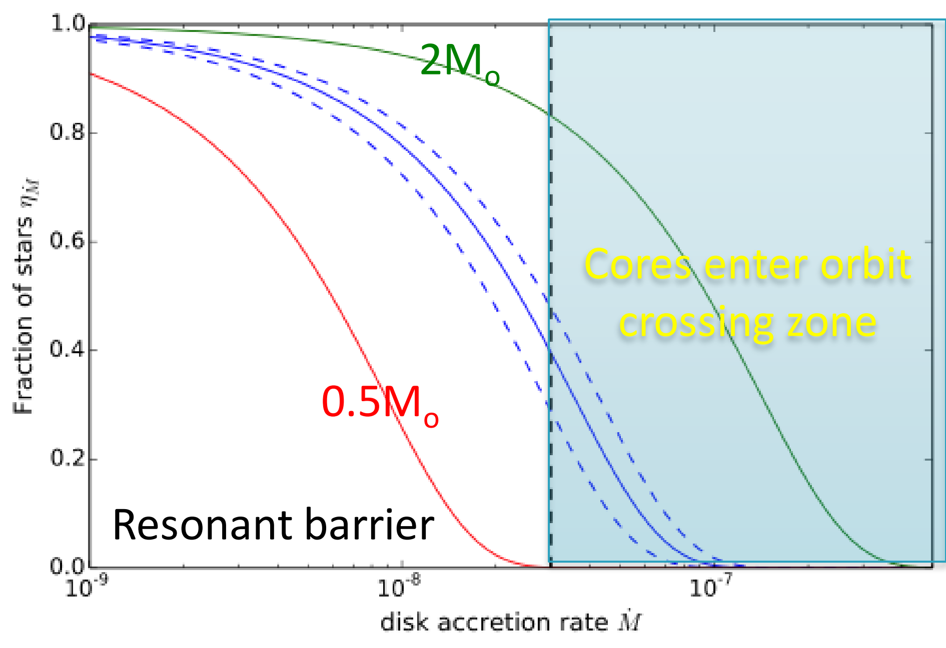
Dependence on the disks’ accretion rate



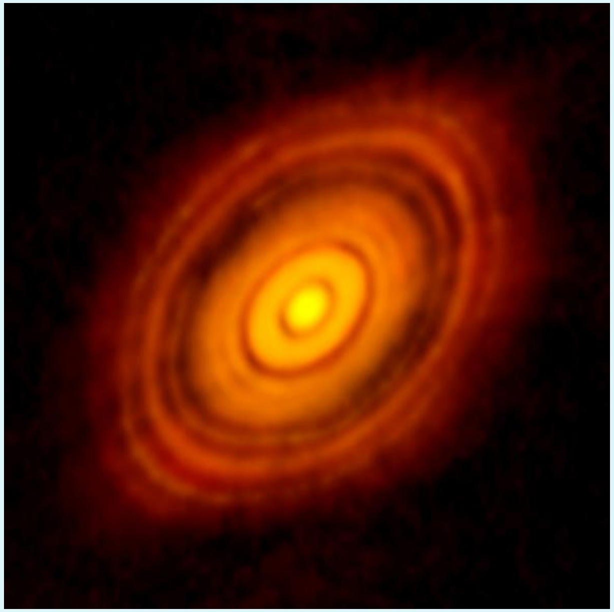
Mdot = 10^{-8} | 5×10^{-8} | 10^{-7}

Dependence on the disks' accretion rate

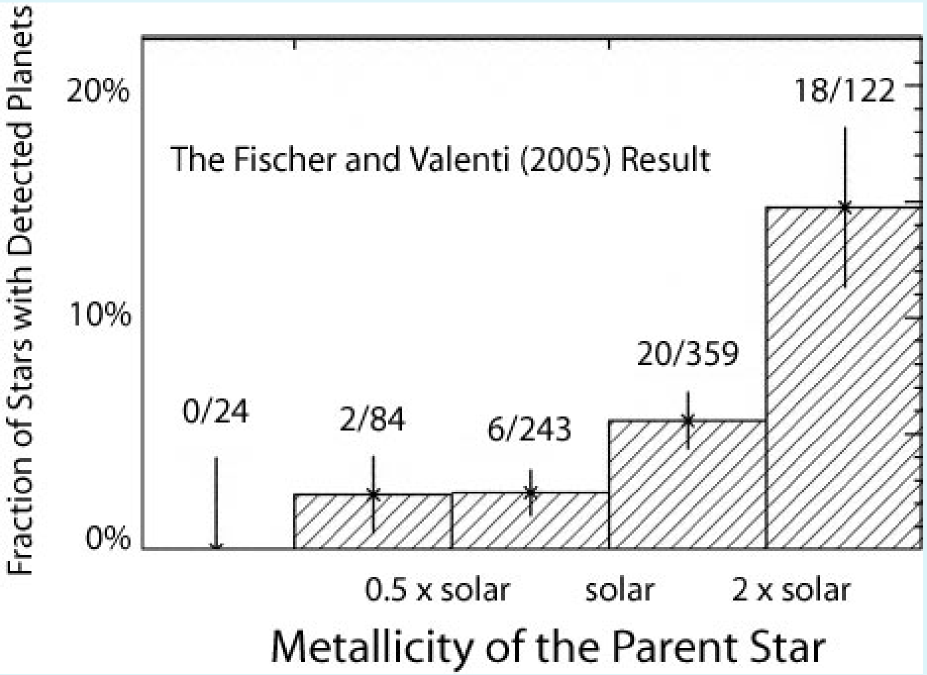


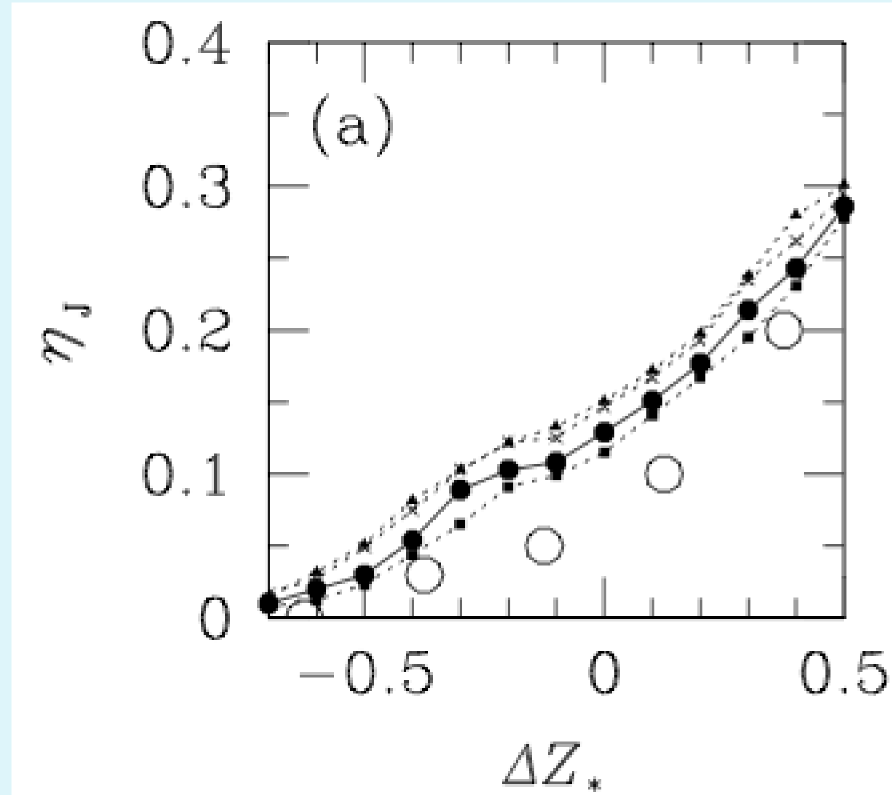


1) Cores' migration speed is determined by the surface density of the disk gas.
2) Surface density of the disk gas is proportional to the gas accretion rate
3) Gas accretion is observed to increase with the host stars' mass.
4) Gas giants' frequency correlation with the host stars' mass is through mdot.



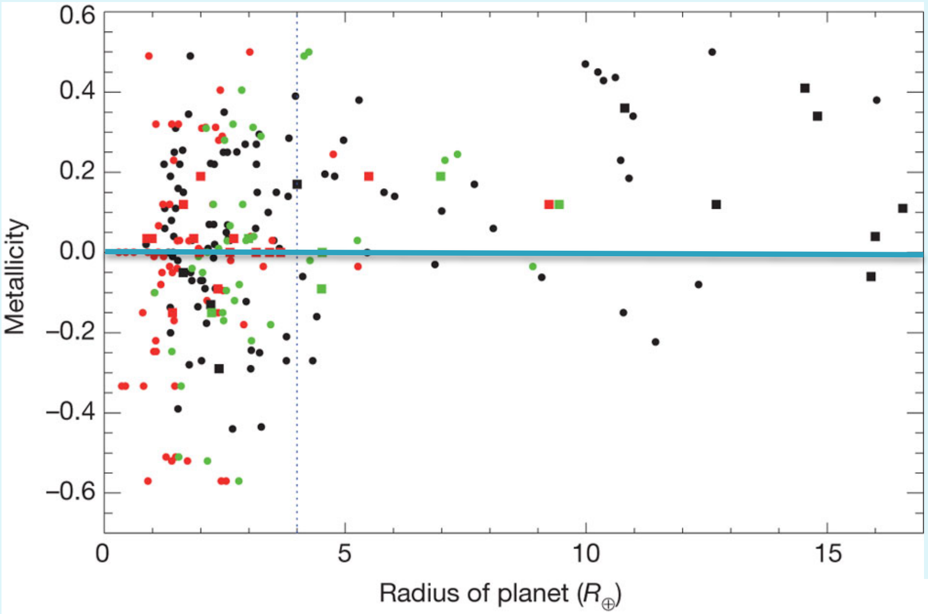
Planetary mass & size vs stellar metallicity





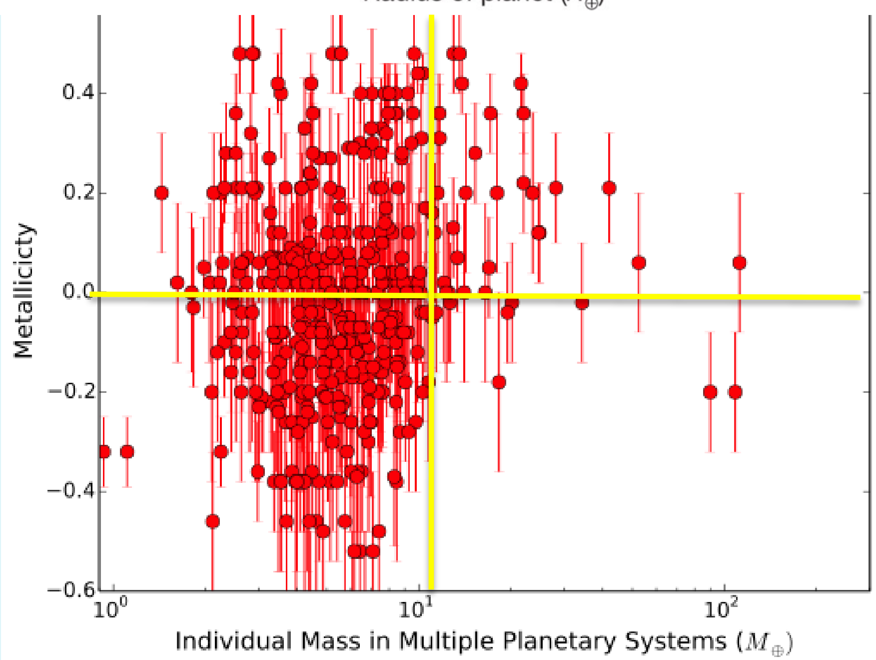
There is a strong correlation between η_{HJ} vs stellar metallicity.

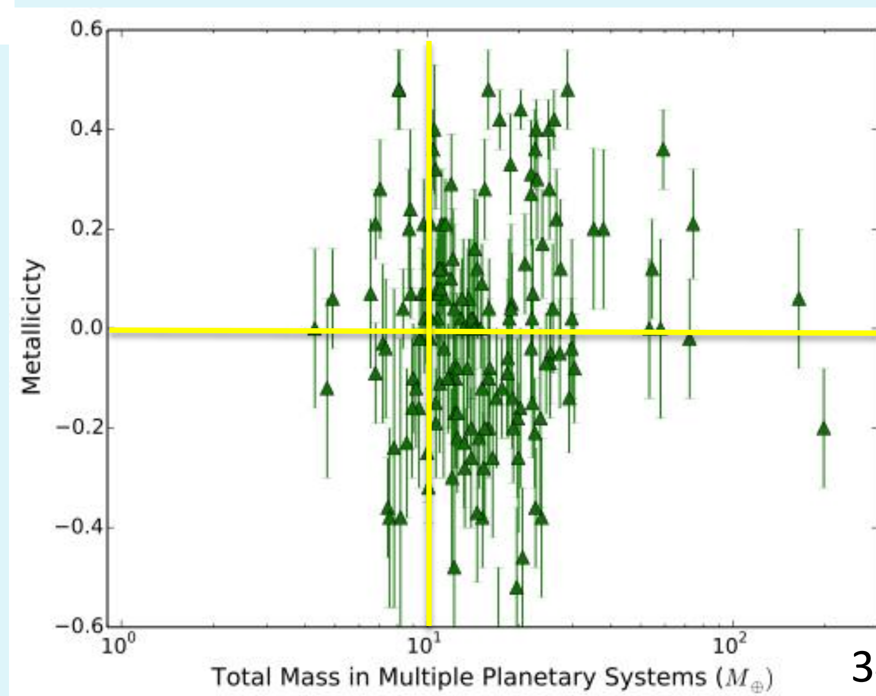
Abundance of super Earths



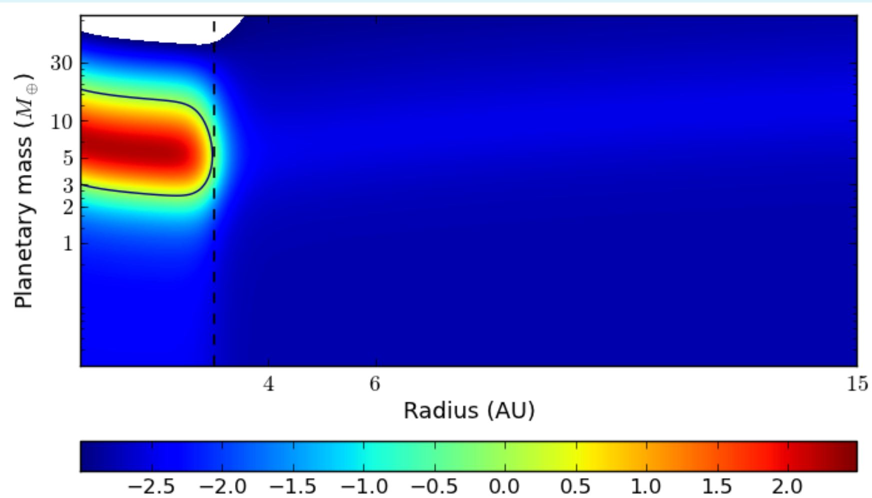
There is no shortage of super Earths around metal-poor stars

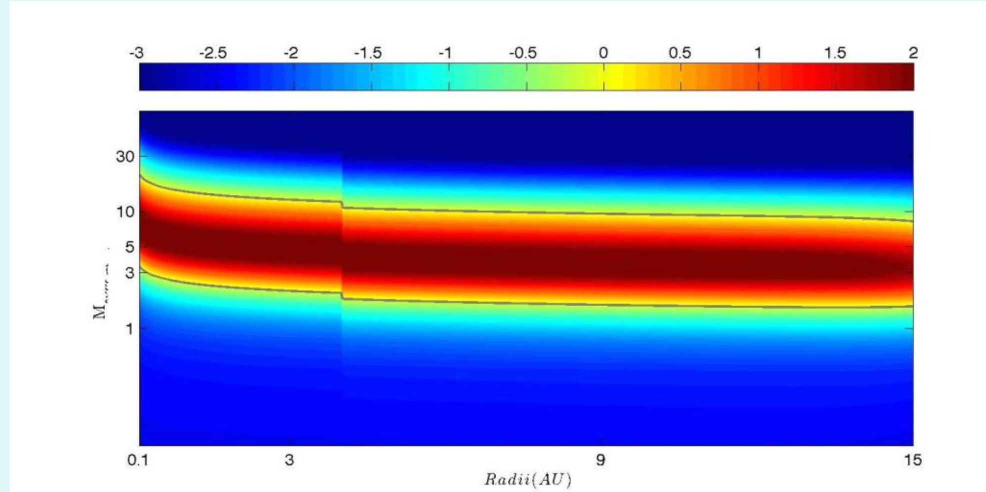
Formation of super Earths Does not depend on Z or M

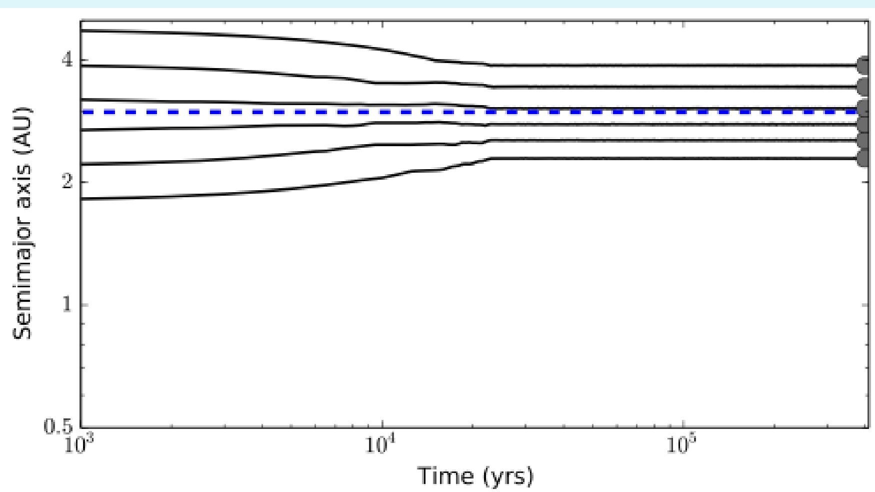


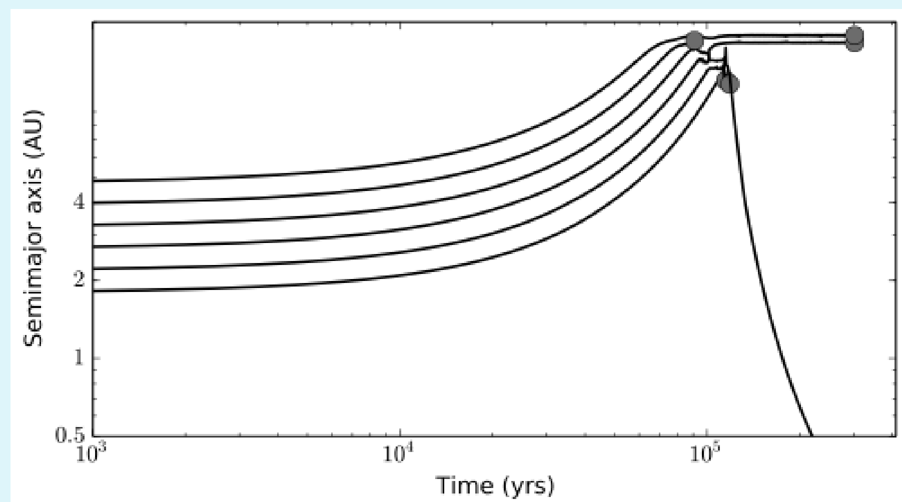


Dependence on metallicity





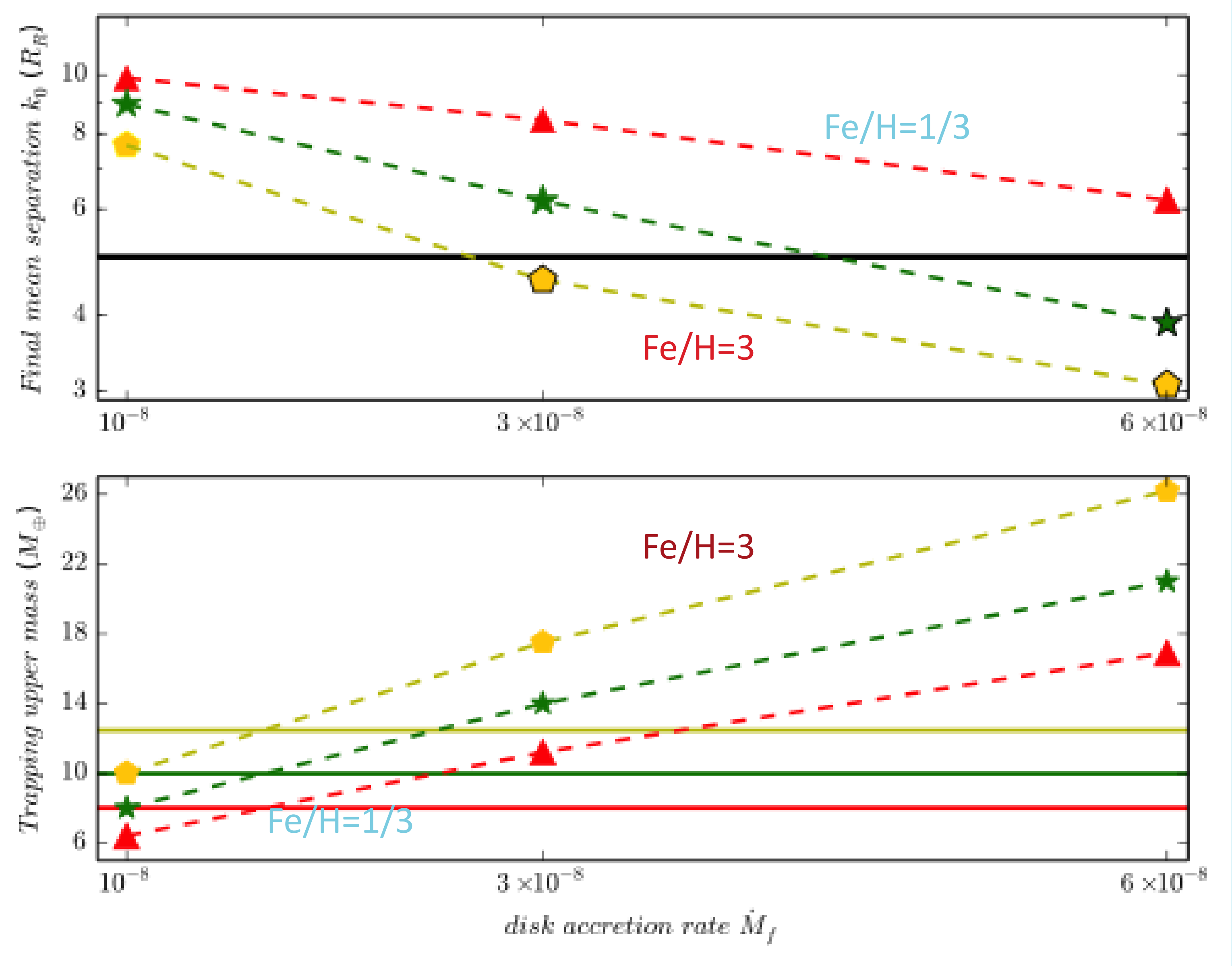




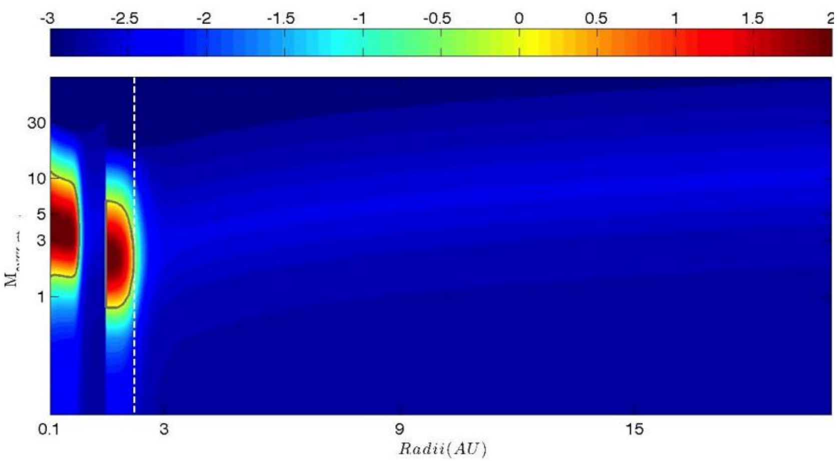
Fe/H=1

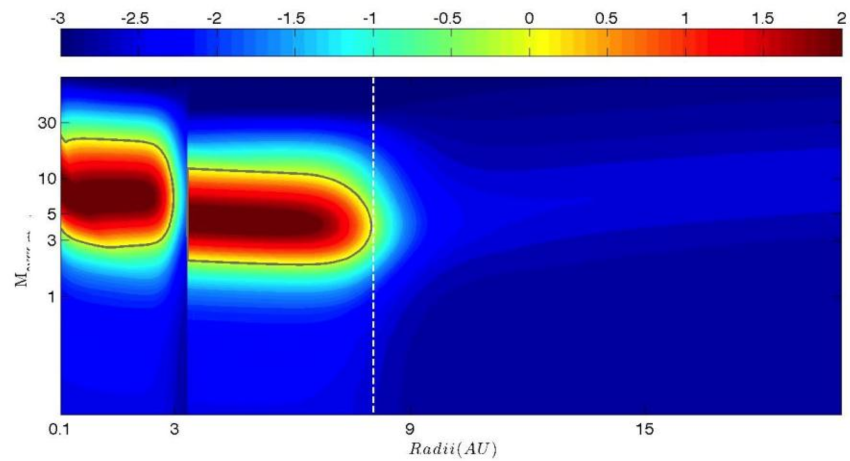
Fe/H=3

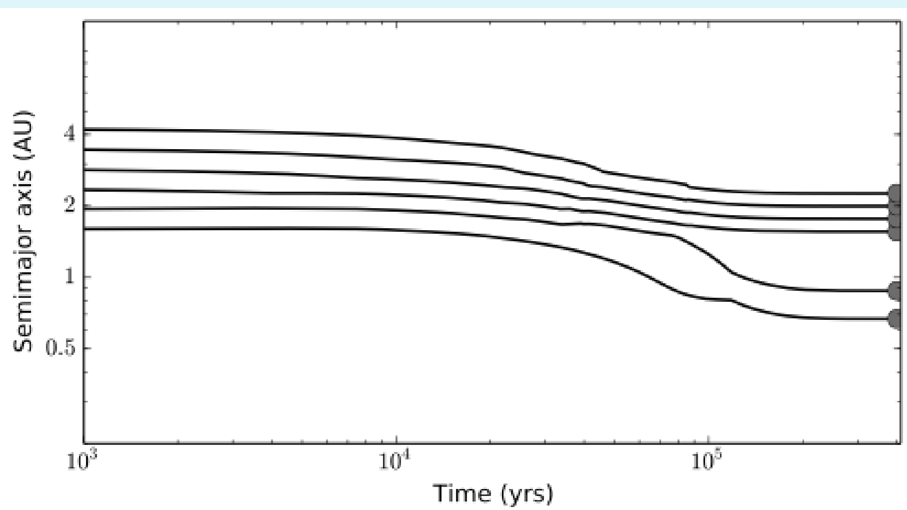
Migration in metal-rich disks

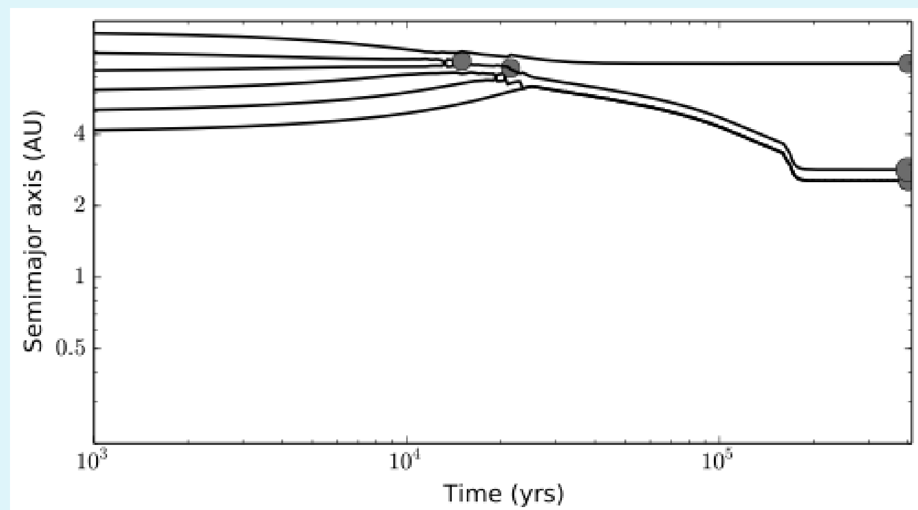


Importance of snow line









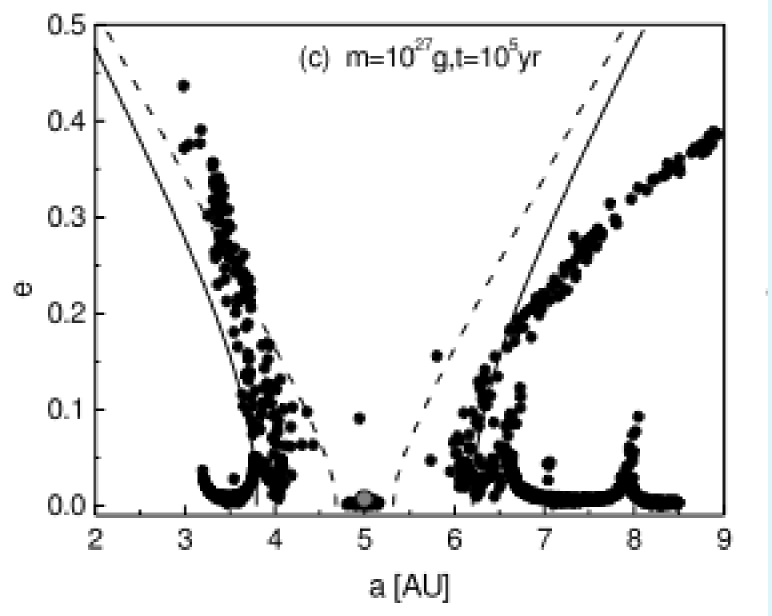
$10^{-8} M_o\ yr^{-1}$

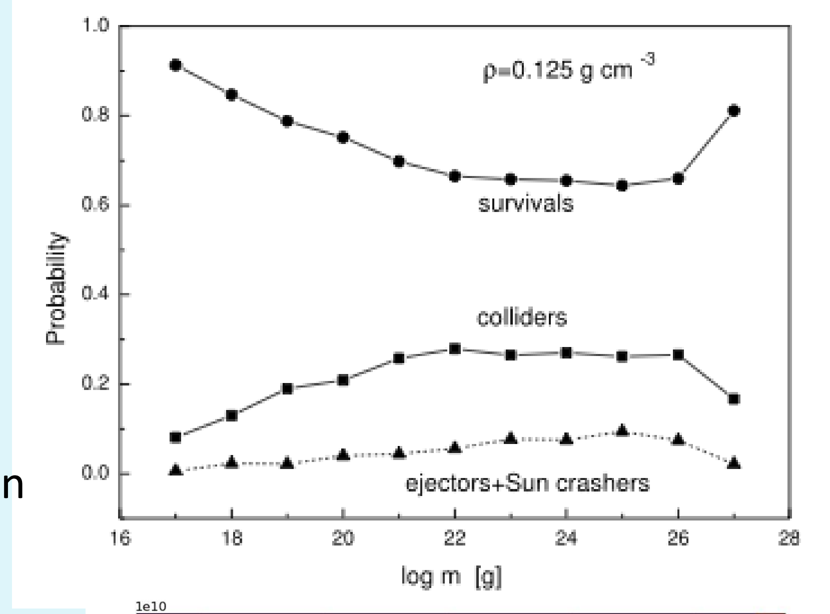
$6 \times 10^{-8} M_o\ yr^{-1}$

Major Challenges:

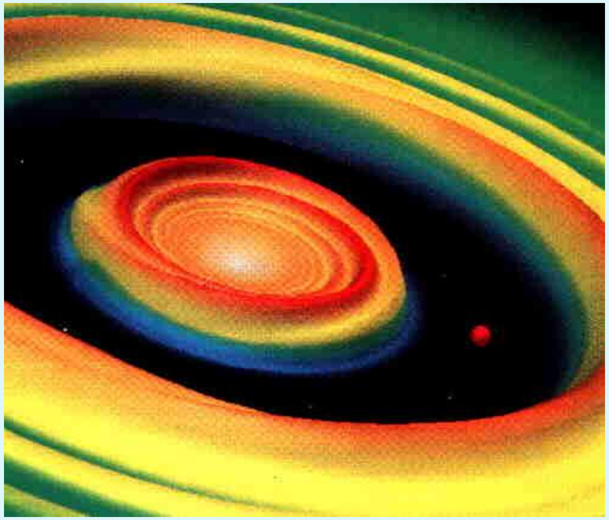
- Retention of grains: m-size barrier (Whipple)
- Fragmentation: km-size barrier (Benz)
- Planetesimal-growth barrier: Isolation mass barrier (Wetherill)
- Gas accretion barrier: critical-mass cores (Cameron)
- Retention of cores: type I migration (Goldreich & Tremaine, Ward)
- Retention of gas giants: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

Giant impacts and mergers

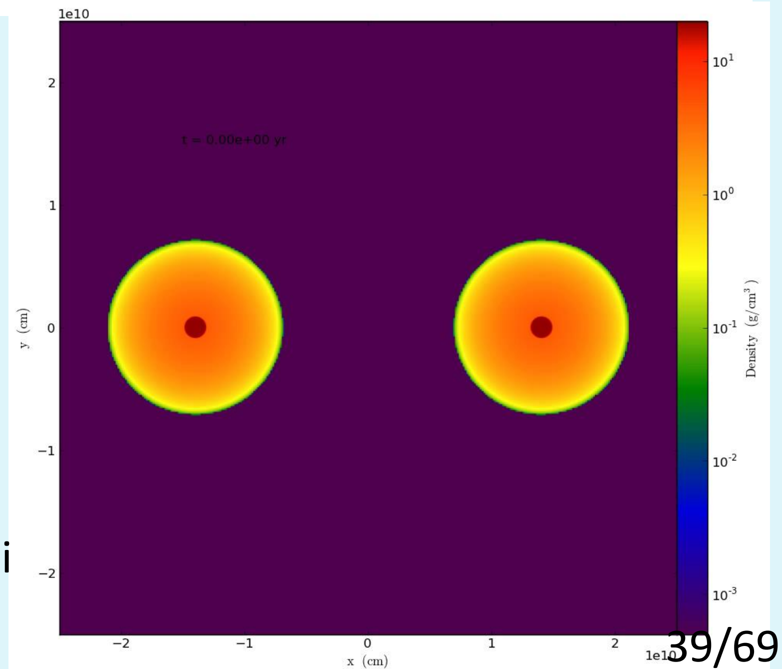




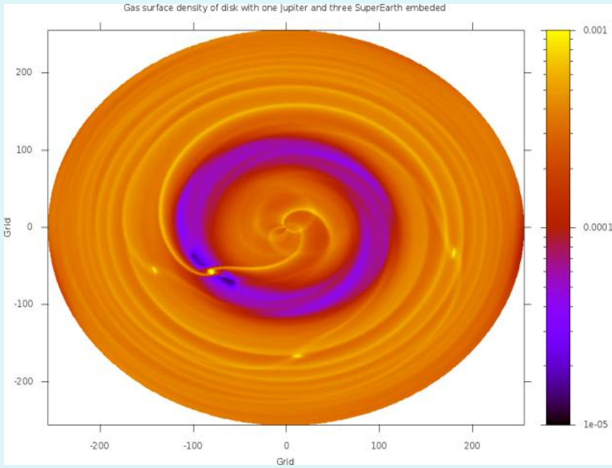
Zhou Jilin

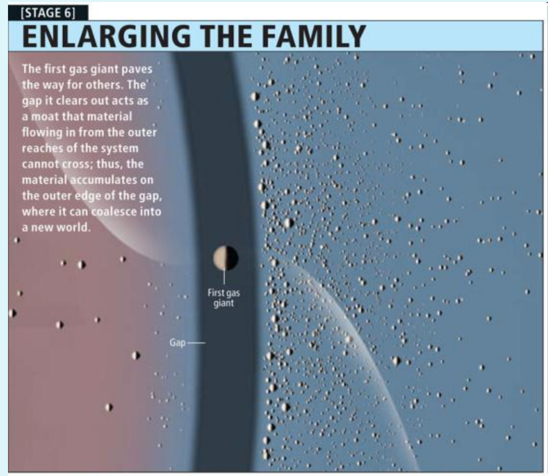


Liu Shangfei

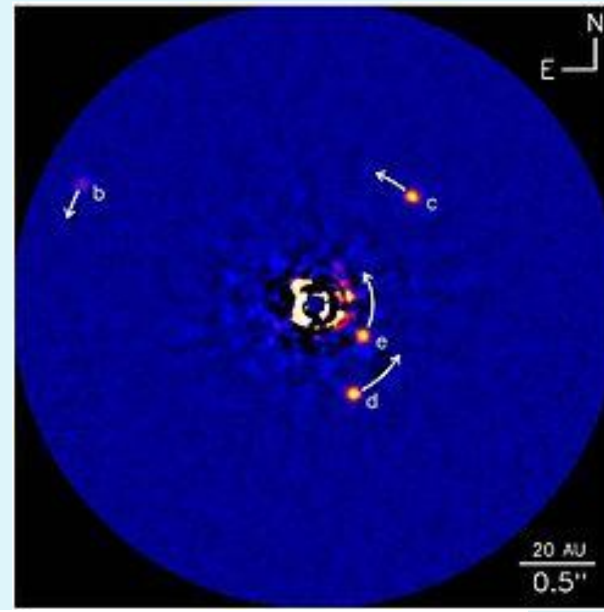


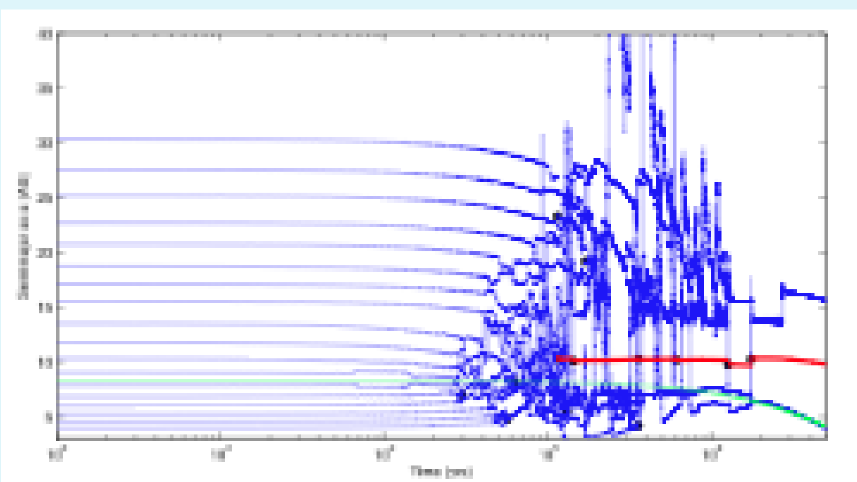
Enhanced formation of multiple planets

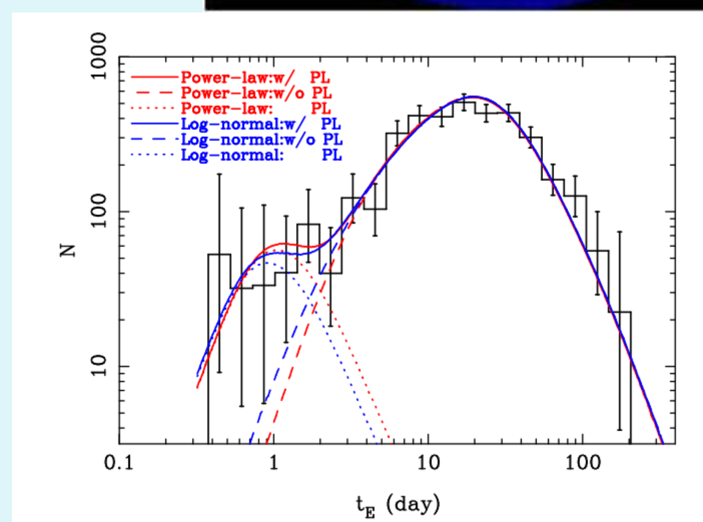




XiaoJia Zhang



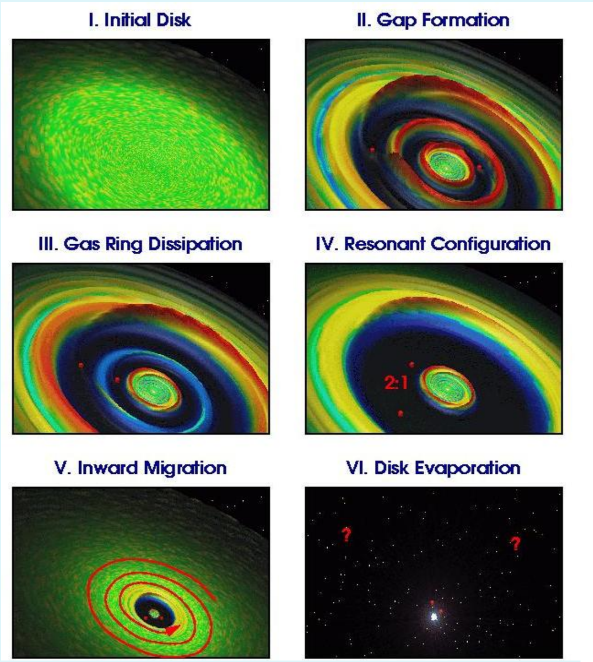




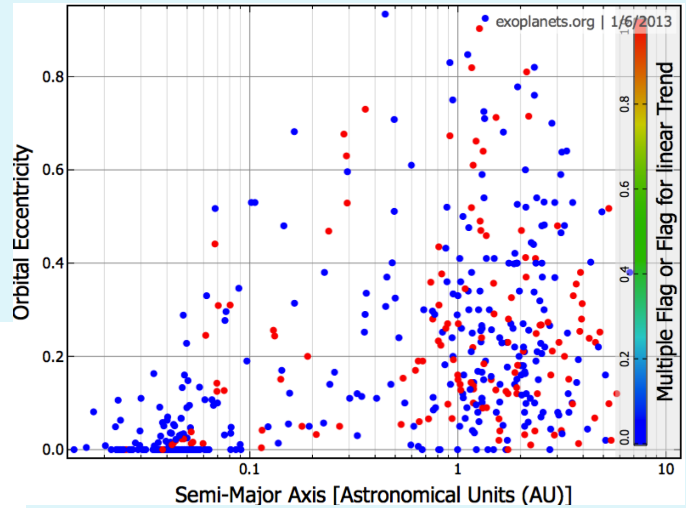
BeiBei Liu

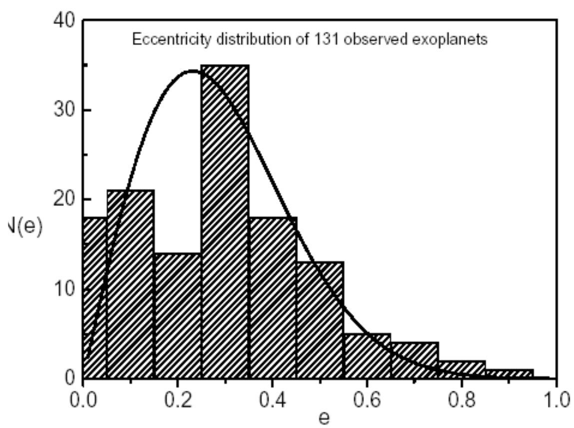
Grand design barrier: dynamical instability

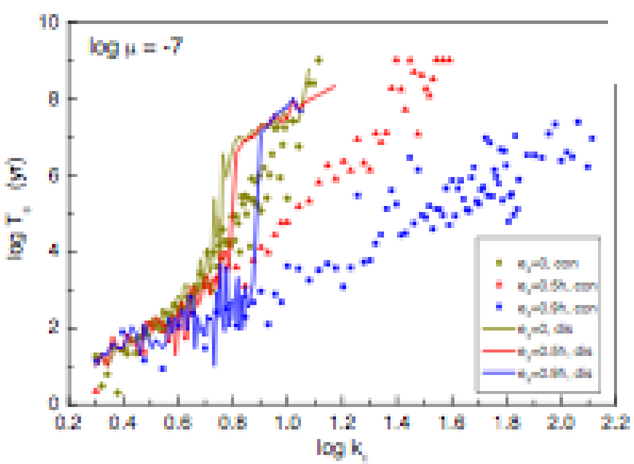
- How did gas giants acquire their eccentricity?

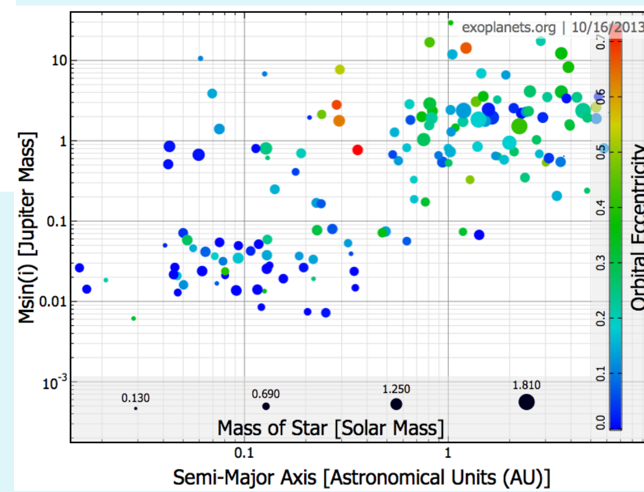


Bryden



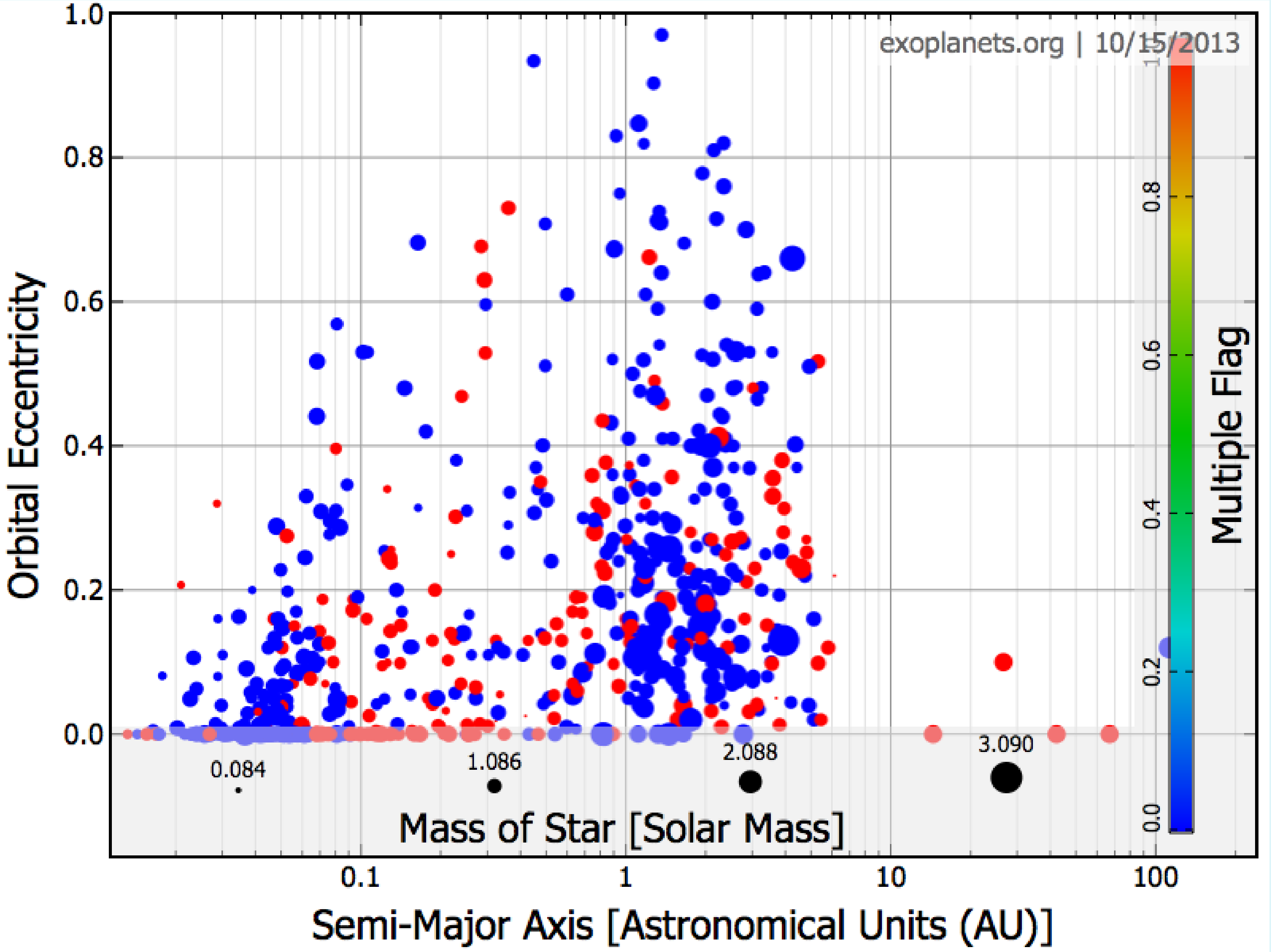




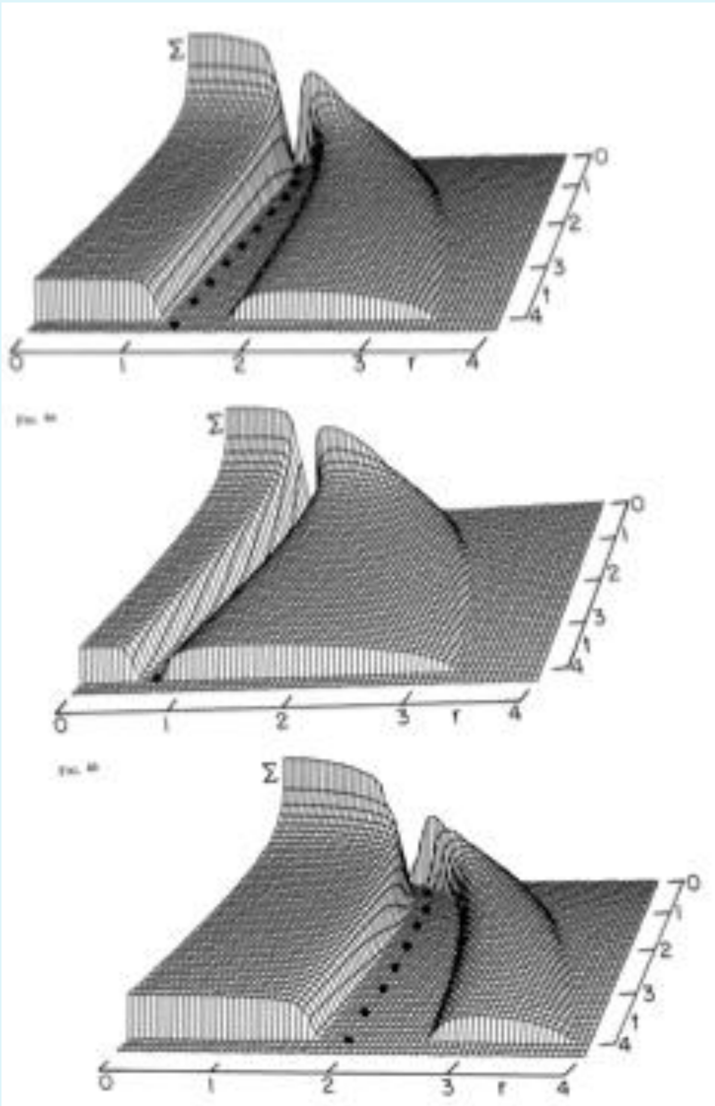


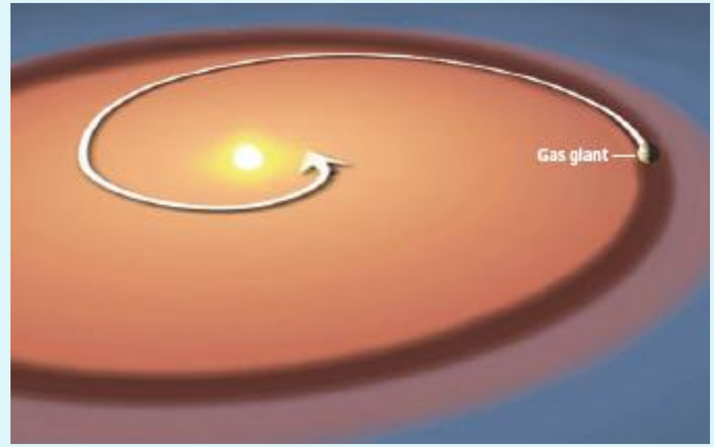
Jilin Zhou

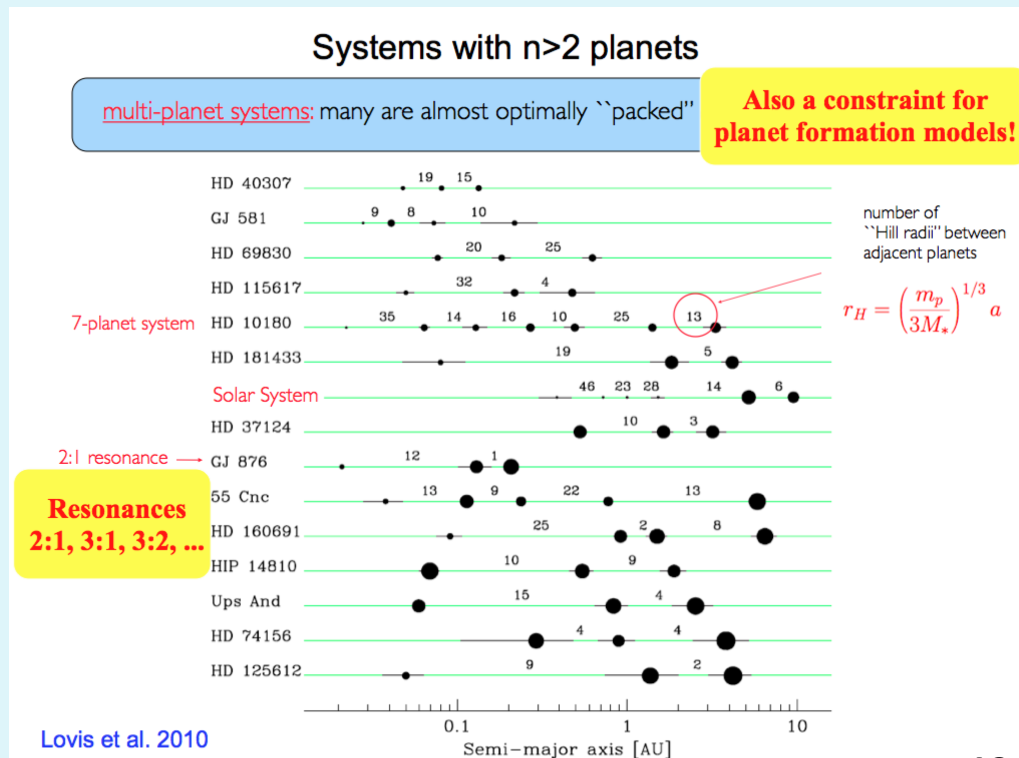
Dynamical diversity



Gas giants' type II migration

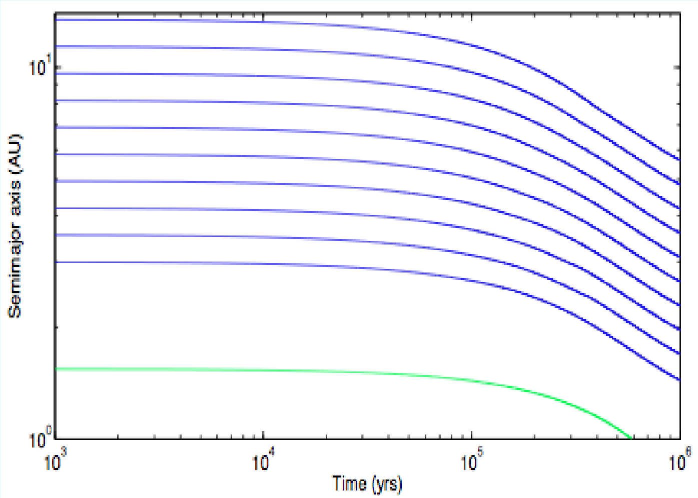


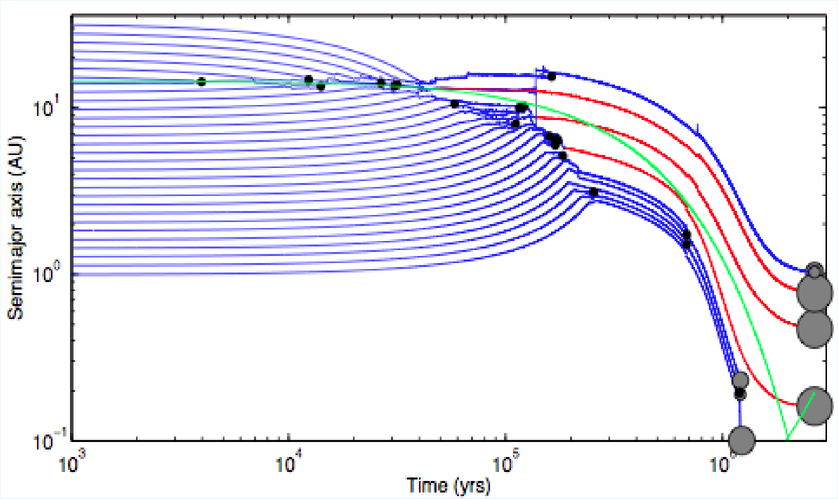




Core barrier: embryos' resonant trapping

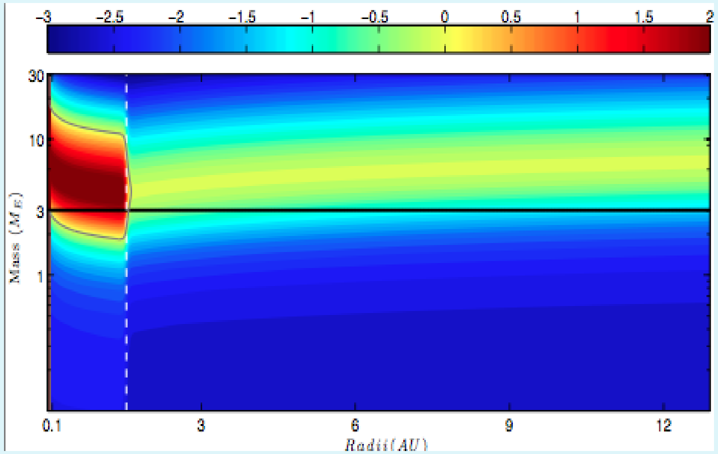
- Long term evolution: largest cores formed early

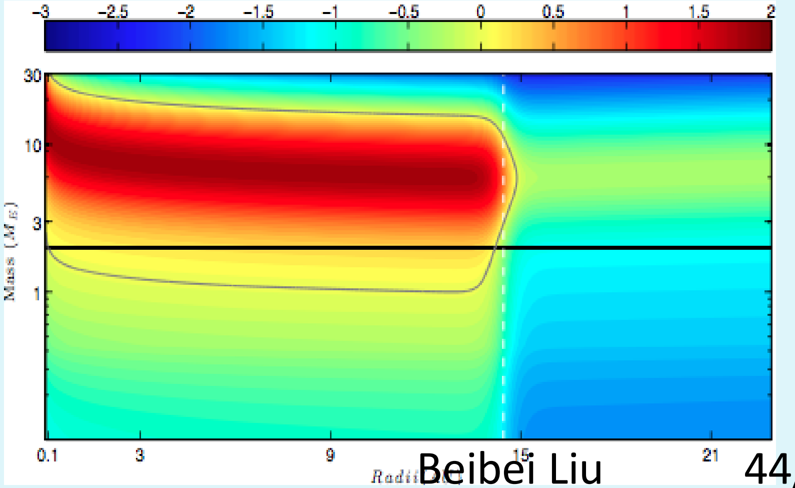




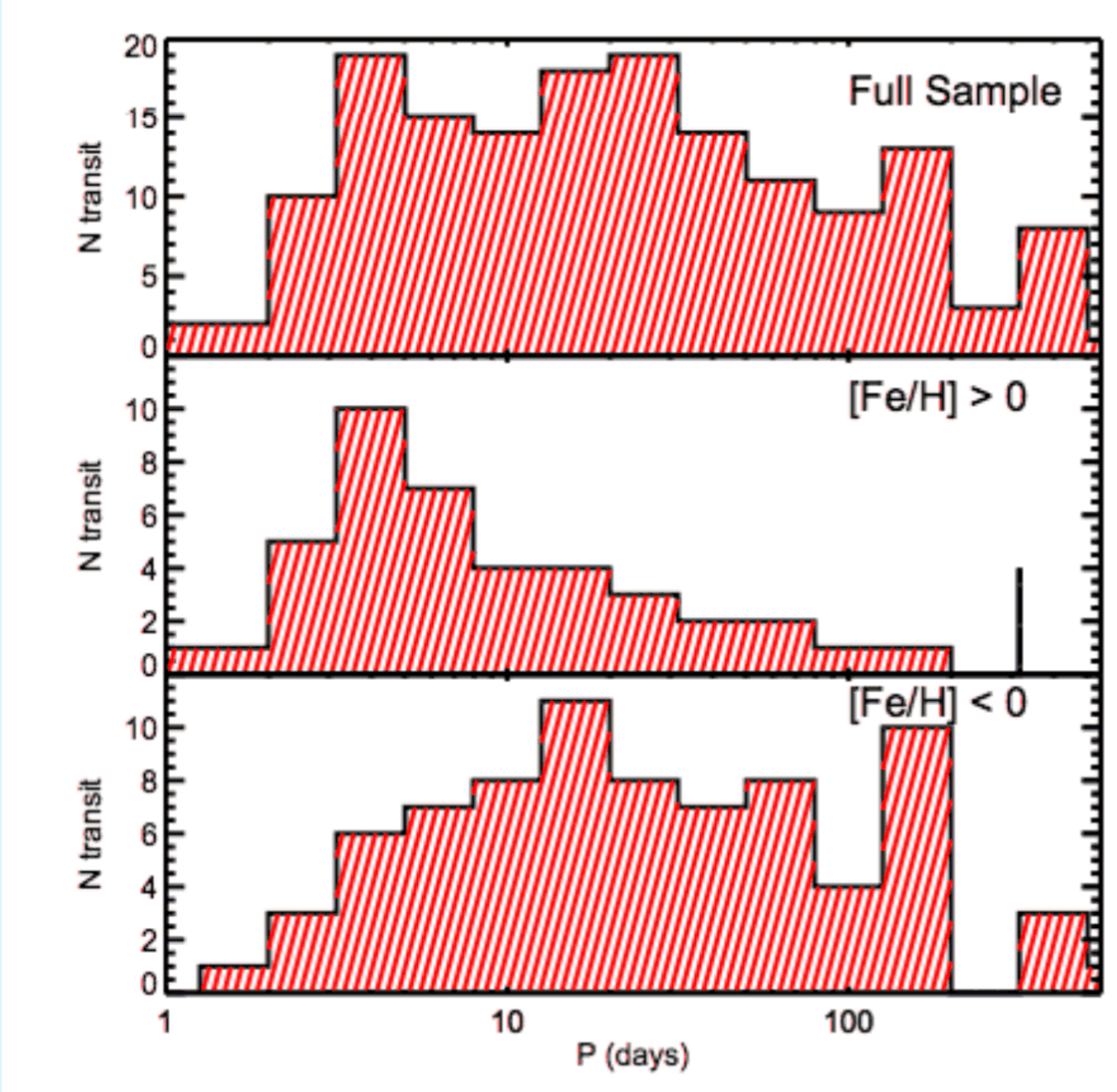
$\dot{\mathrm{M}} = 1 \times 10^{-8}\ \mathrm{M}_{\odot}/\mathrm{yr}\ \alpha = 10^{-2}\ \tau = 1 \times 10^{6}\mathrm{yrs}$

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

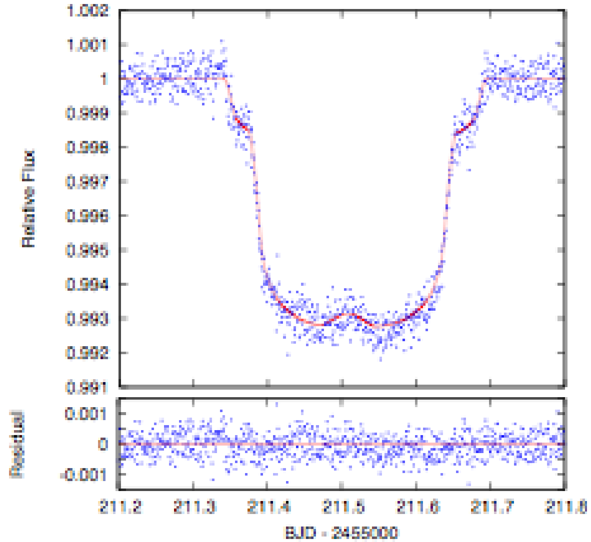




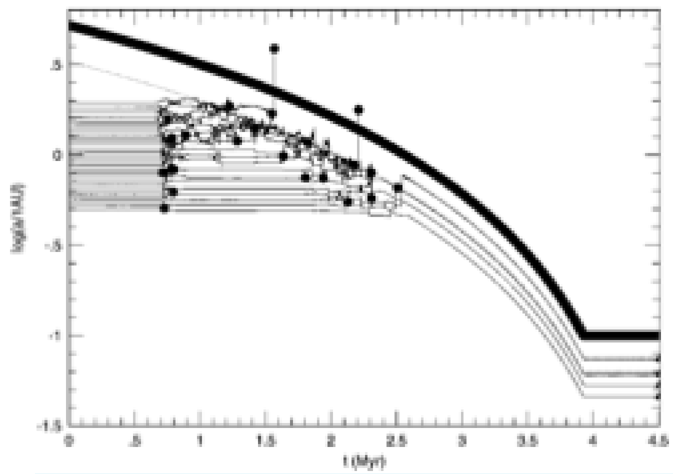
Period distribution of hot Jupiters: Dependence on stellar metallicity

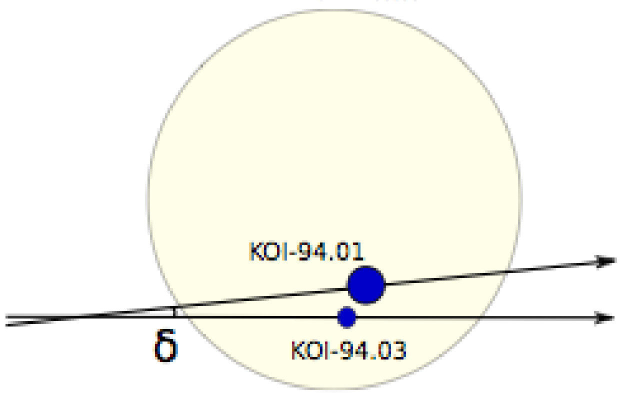


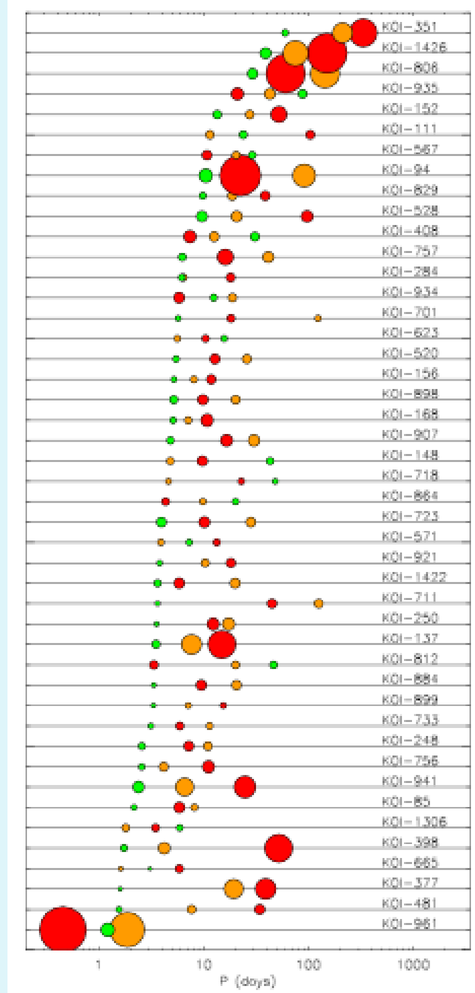
Smoking gun for core accretion (KOI 94)

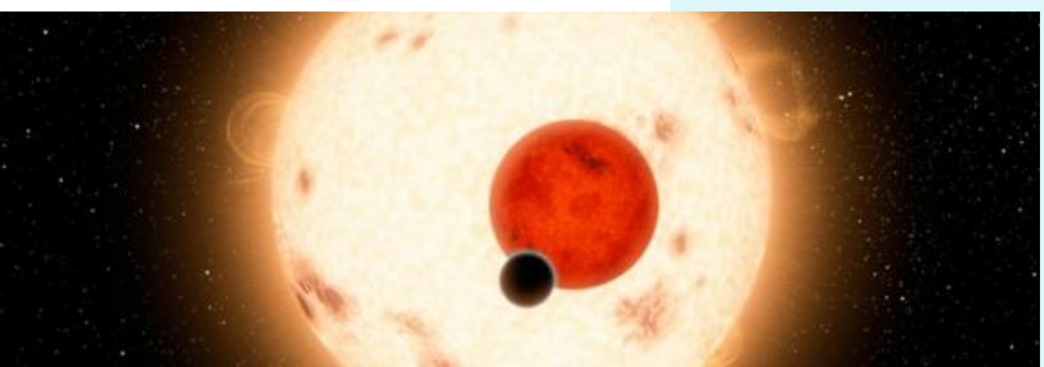


Candidate	Orbital Period (days)	R_p/R_*
KOI-94.01	22.343000 ± 0.000011	0.06856 ± 0.00012
94.02	10.423707 ± 0.000026	0.02544 ± 0.00012
94.03	54.31993 ± 0.00012	0.04058 ± 0.00013
94.04	3.743245 ± 0.000031	0.01045 ± 0.00019

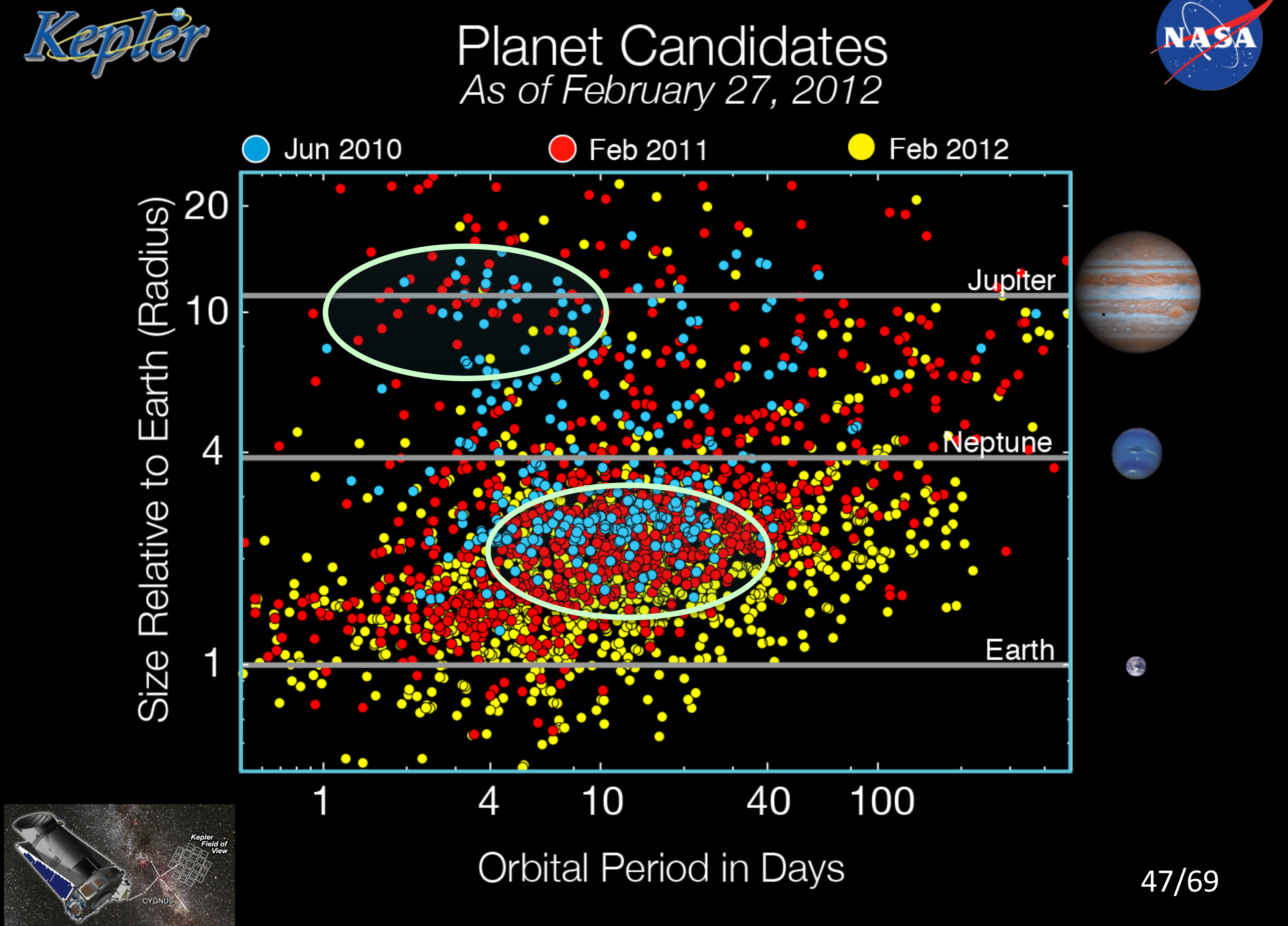






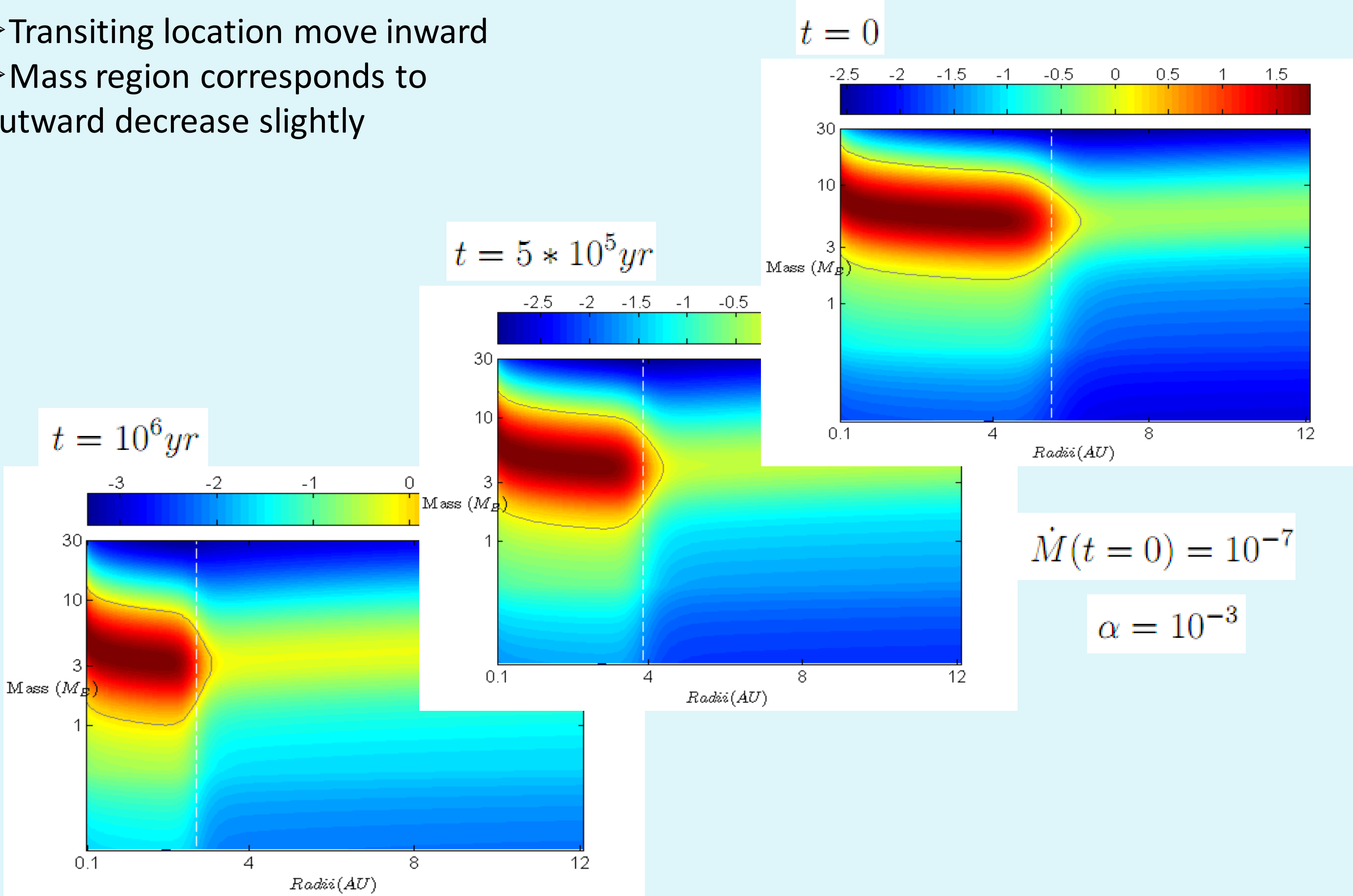


Planets' size-period distribution from the Kepler surveys



Type I migration with evolving disk

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

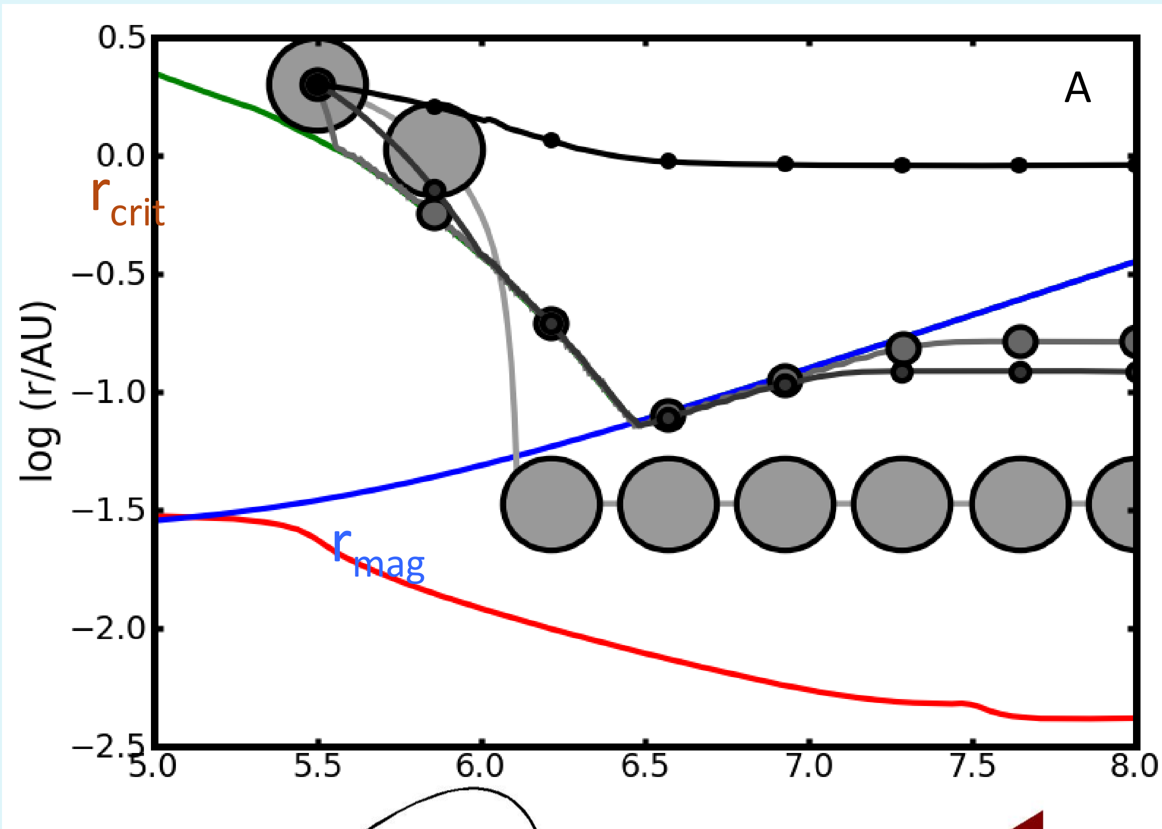


$$\dot{M}(t=0) = 10^{-7}$$

$$\alpha = 10^{-3}$$

Super Earths: some key issues

- How to differentiate type I and II migration?



Sub/warm Earths

½ Earth

Neptunes

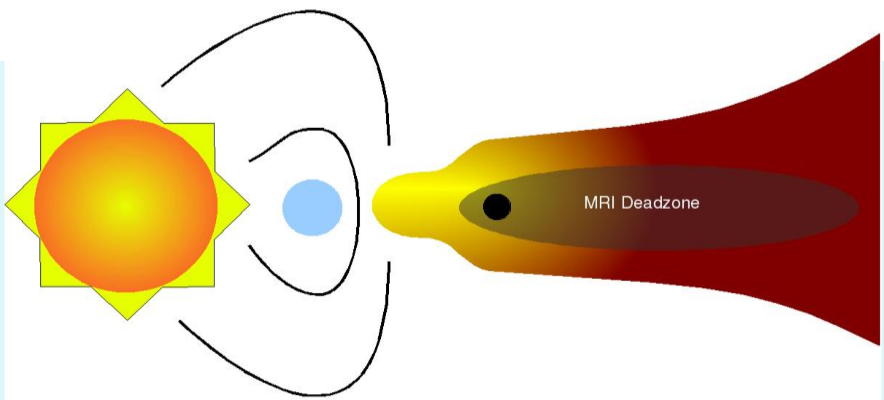
SuperEarths

5 Earth

Gas giants

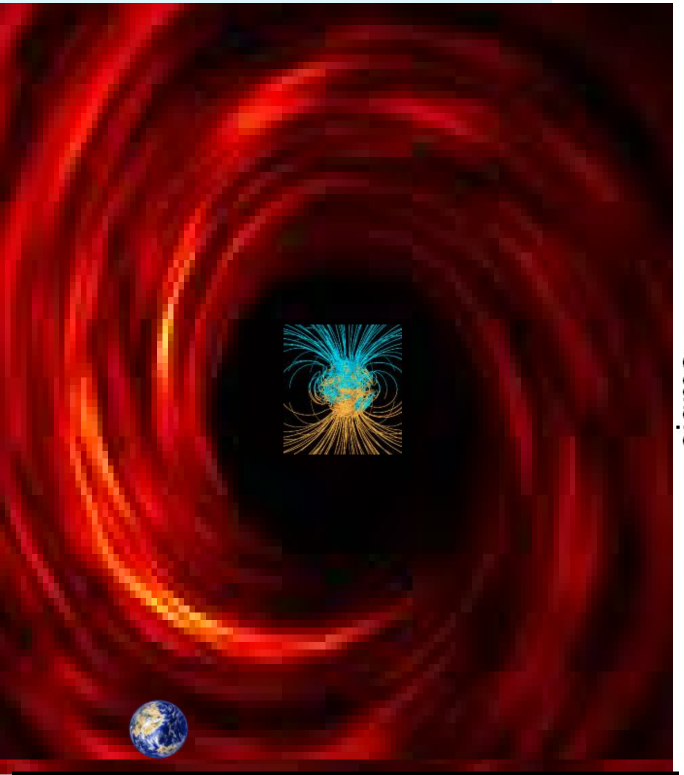
2 Earth

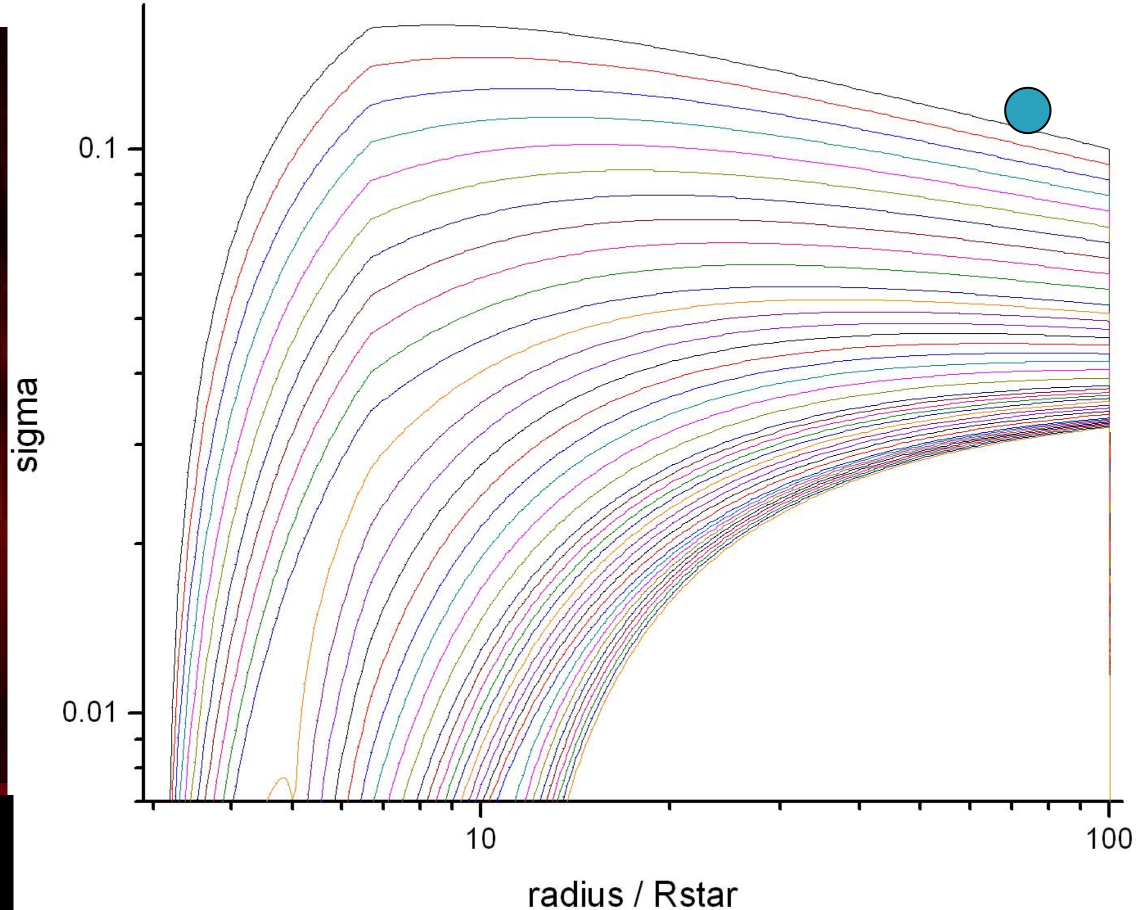
Jupiter



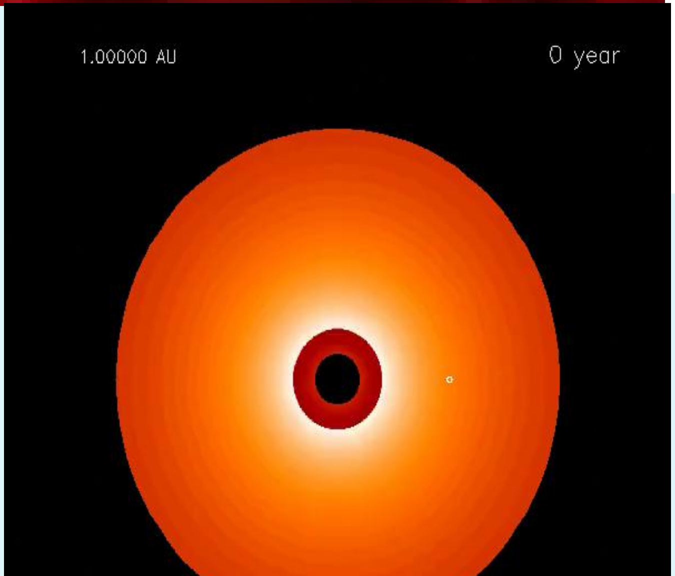
Hot Jupiters park Closer than Super Earths

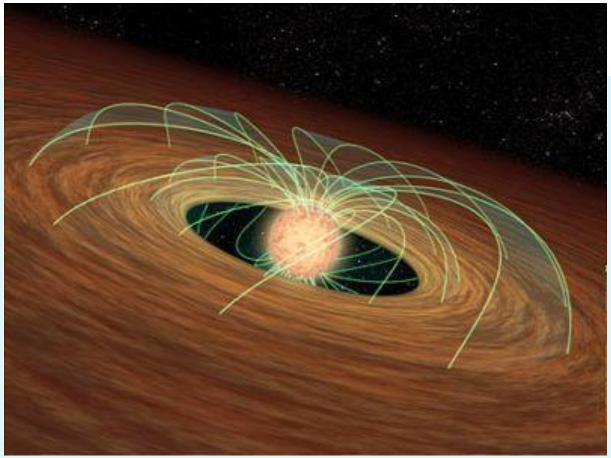
Kretke



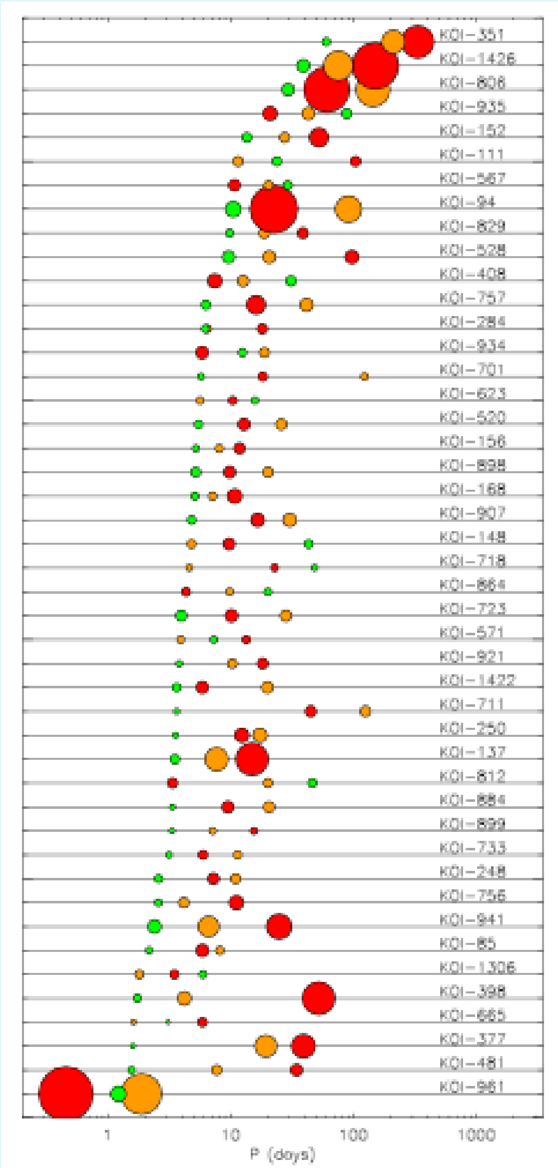


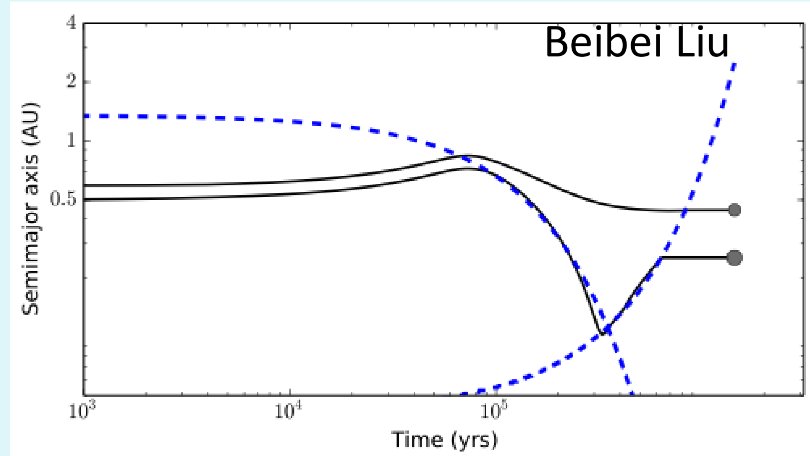
50/69

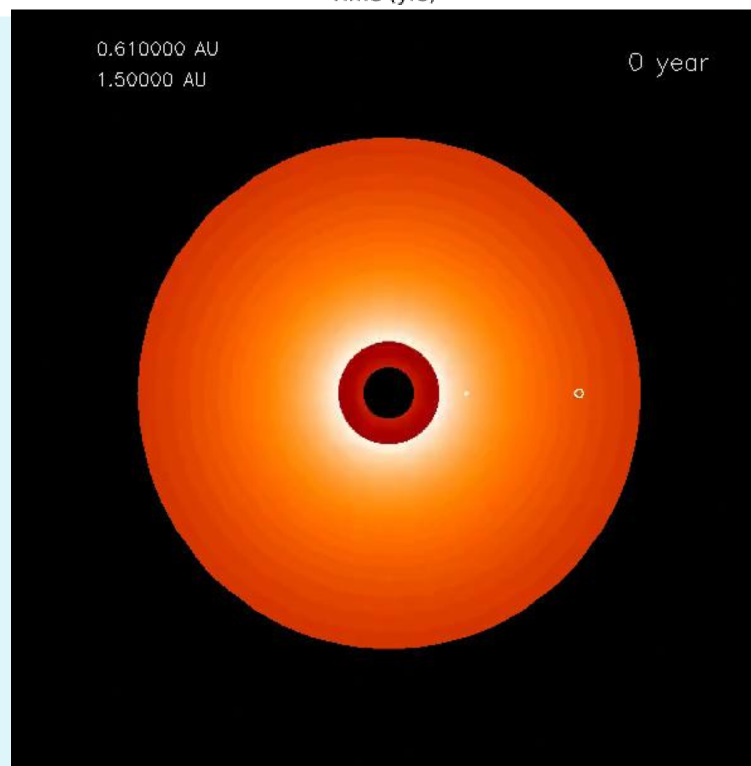




Rai Xu, Wendy Ju

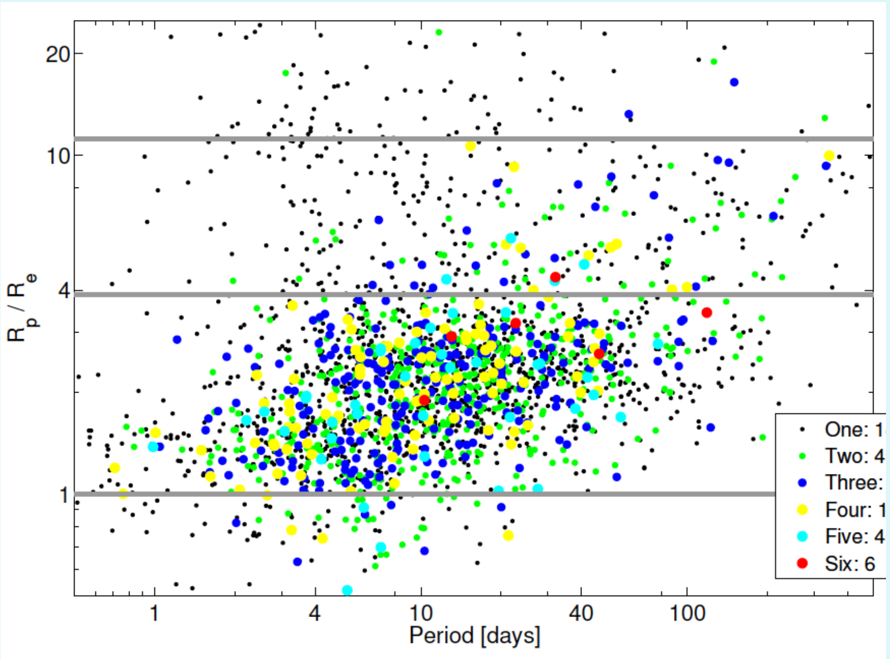

KOI−351
KOI−1426
KOI−806
KOI−935
KOI−152
KOI−111
KOI−567
KOI−94
KOI−829
KOI−528
KOI−408
KOI−757
KOI−284
KOI−934
KOI−701
KOI−623
KOI−520
KOI−156
KOI−898
KOI−168
KOI−907
KOI−148
KOI−718
KOI−864
KOI−723
KOI−571
KOI−921
KOI−1422
KOI−711
KOI−250
KOI−137
KOI−812
KOI−884
KOI−899
KOI−733
KOI−248
KOI−756
KOI−941
KOI−85
KOI−1306
KOI−398
KOI−665
KOI−377
KOI−481
KOI−961
1
10
100
1000
P (days)

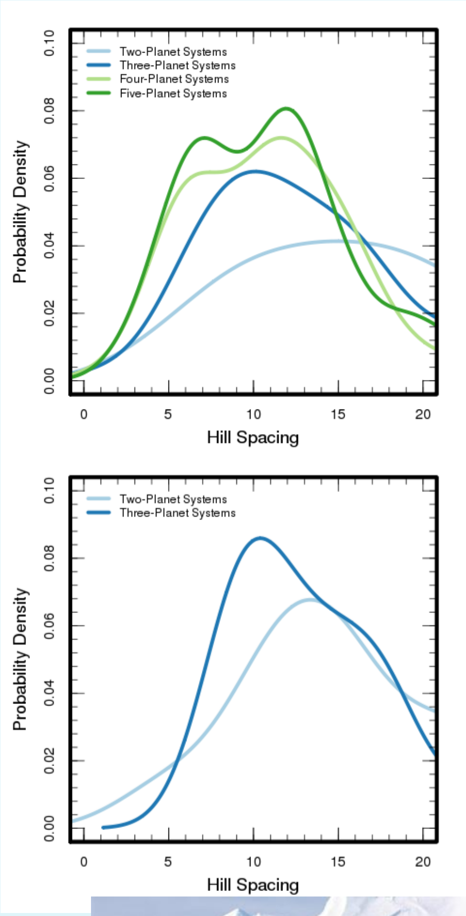

Beibei Liu
4
2
1
0.5
Semimajor axis (AU)
10^3
10^4
10^5
Time (yrs)


0.610000 AU
1.50000 AU
0 year

New Candidate Catalog (Batalha et al. 2012)

What can we learn from Multiple systems !!!





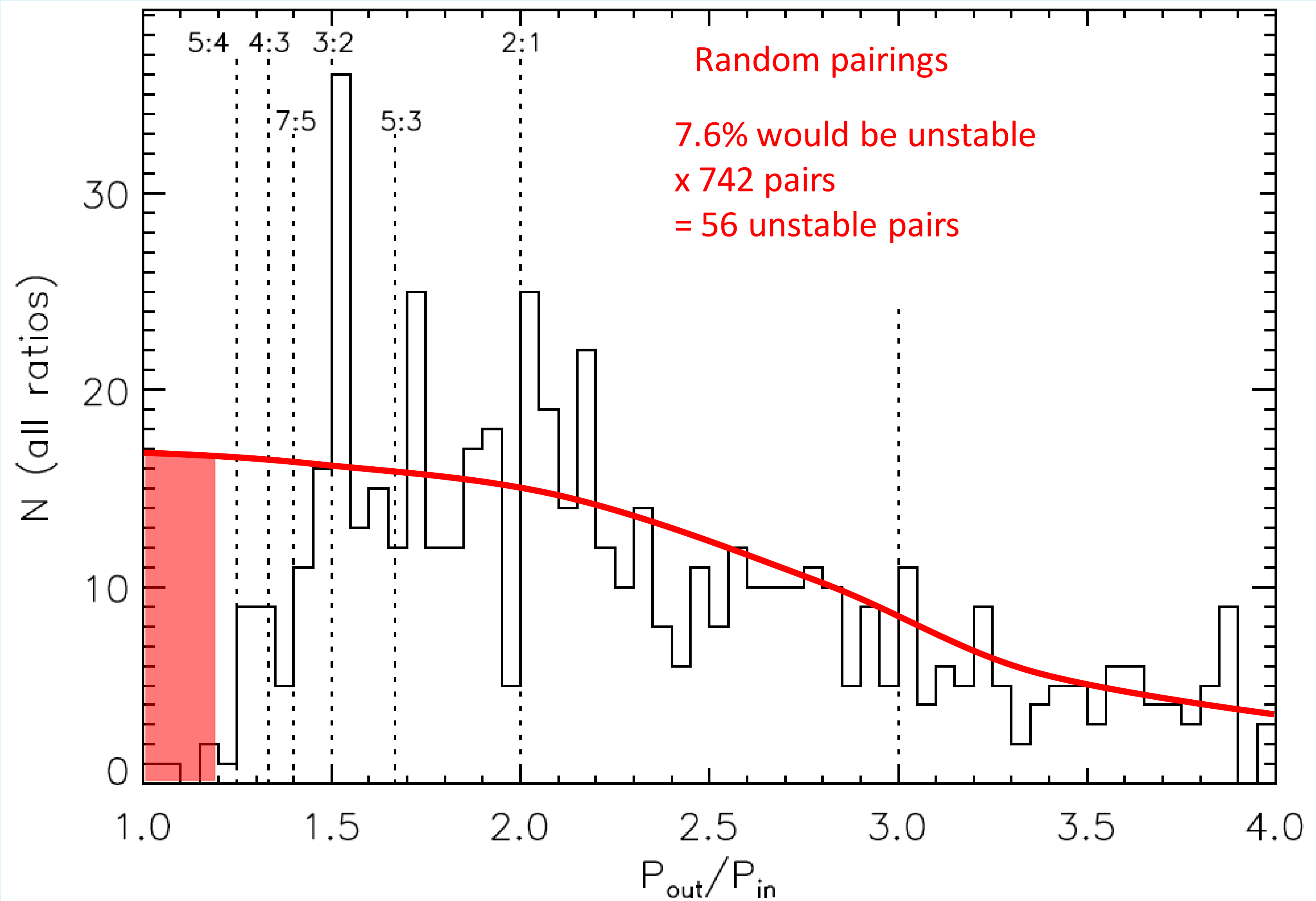
How compact can multiple systems be?

Stability and coplanarity

Kevin Schlaufman
Xiaojia Zheng

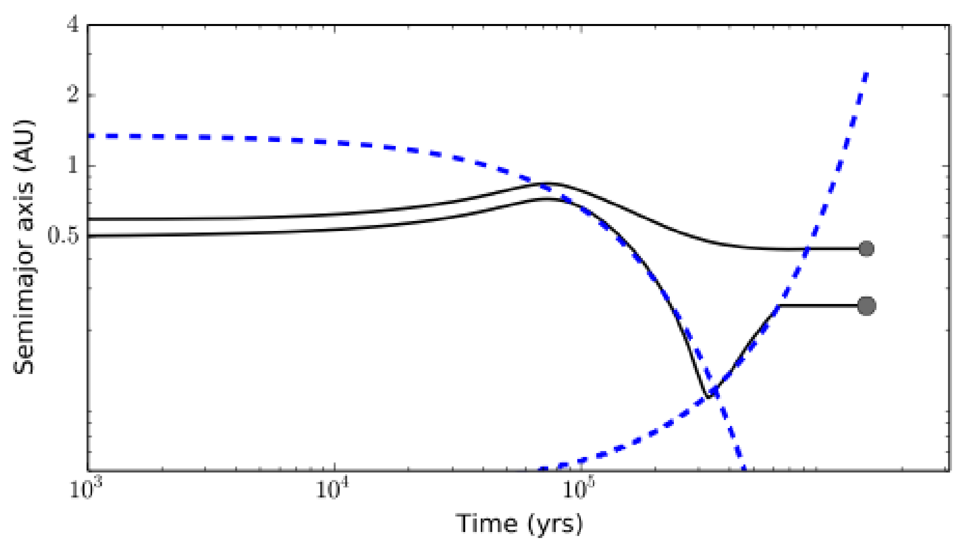
Super Earths: some key issues

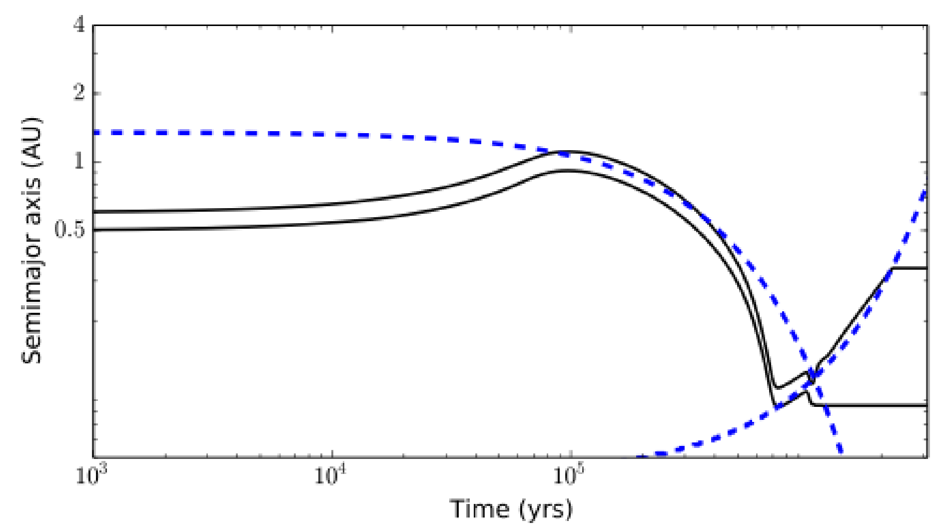
- Did planets capture each other and parted their ways?

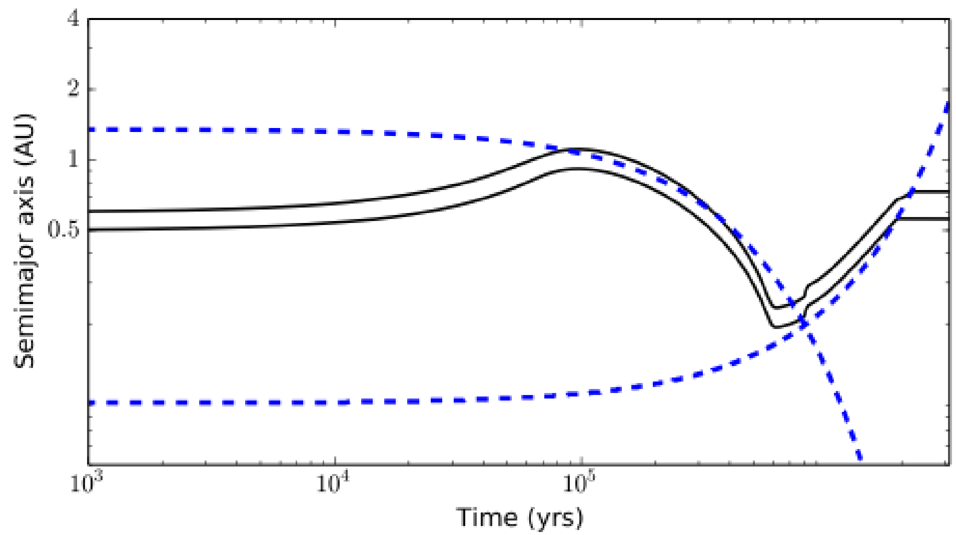


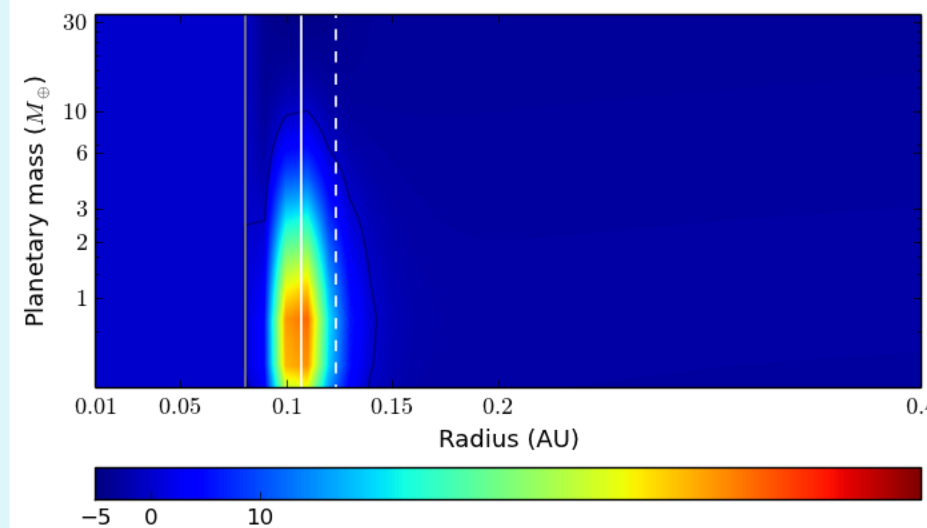
Fabricky

Exit resonances

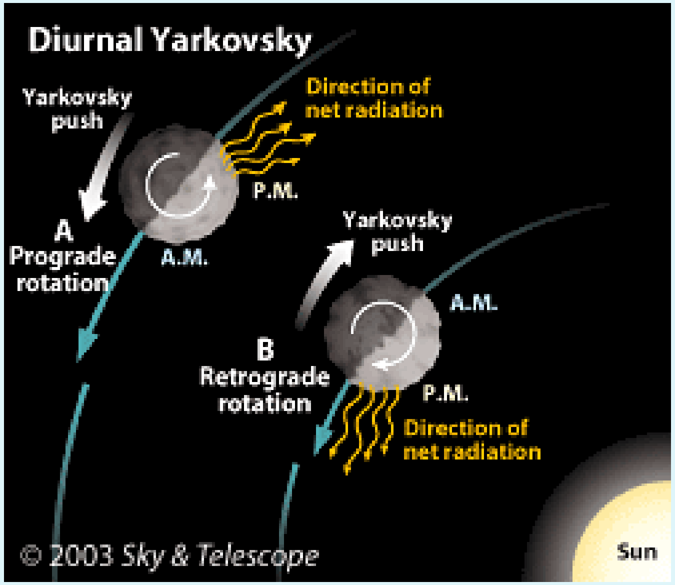


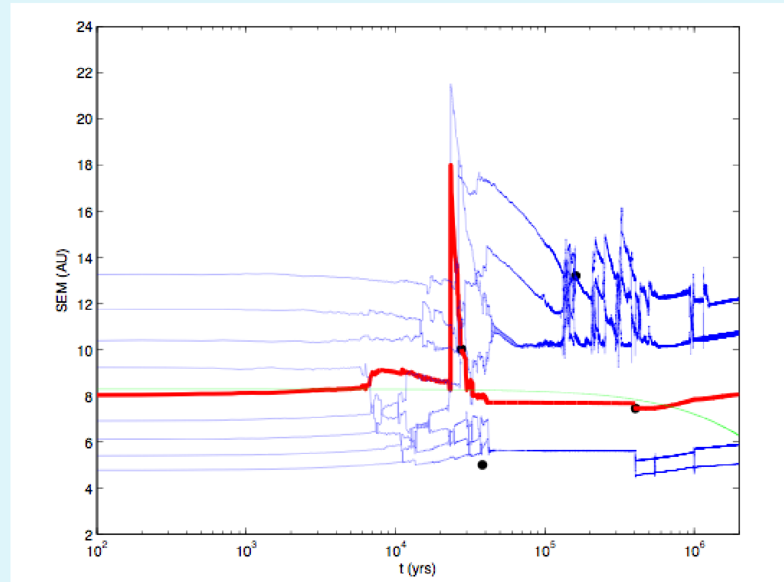




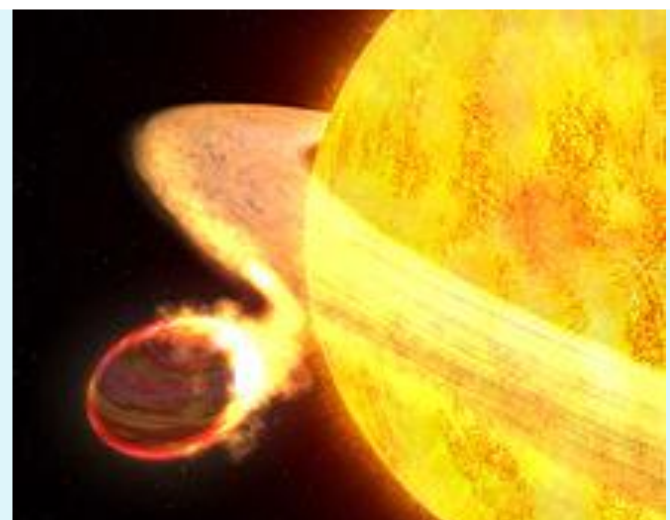


diverse migration mechanisms



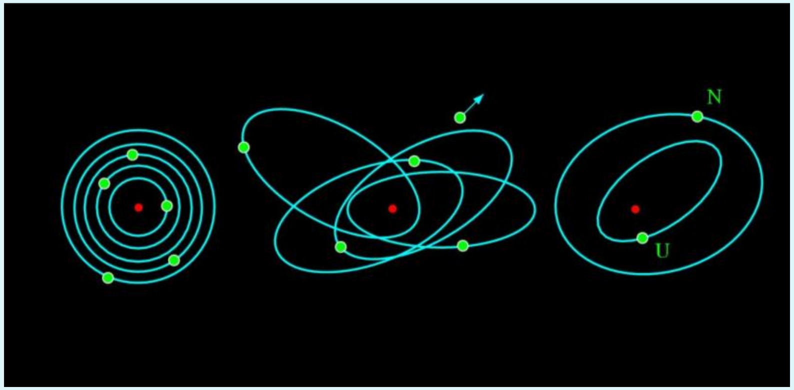


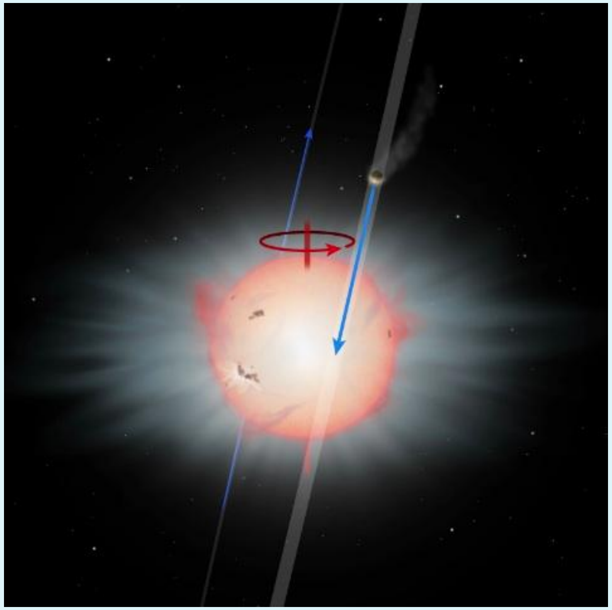
$$\tau_a = 4\times10^8 yr \left(\frac{\rho_p}{1\ g/cm^3}\right)\left(\frac{r_p}{1\ km}\right)\left(\frac{a}{1\ AU}\right)^{3/2}(1-e^2)^{1/2}$$

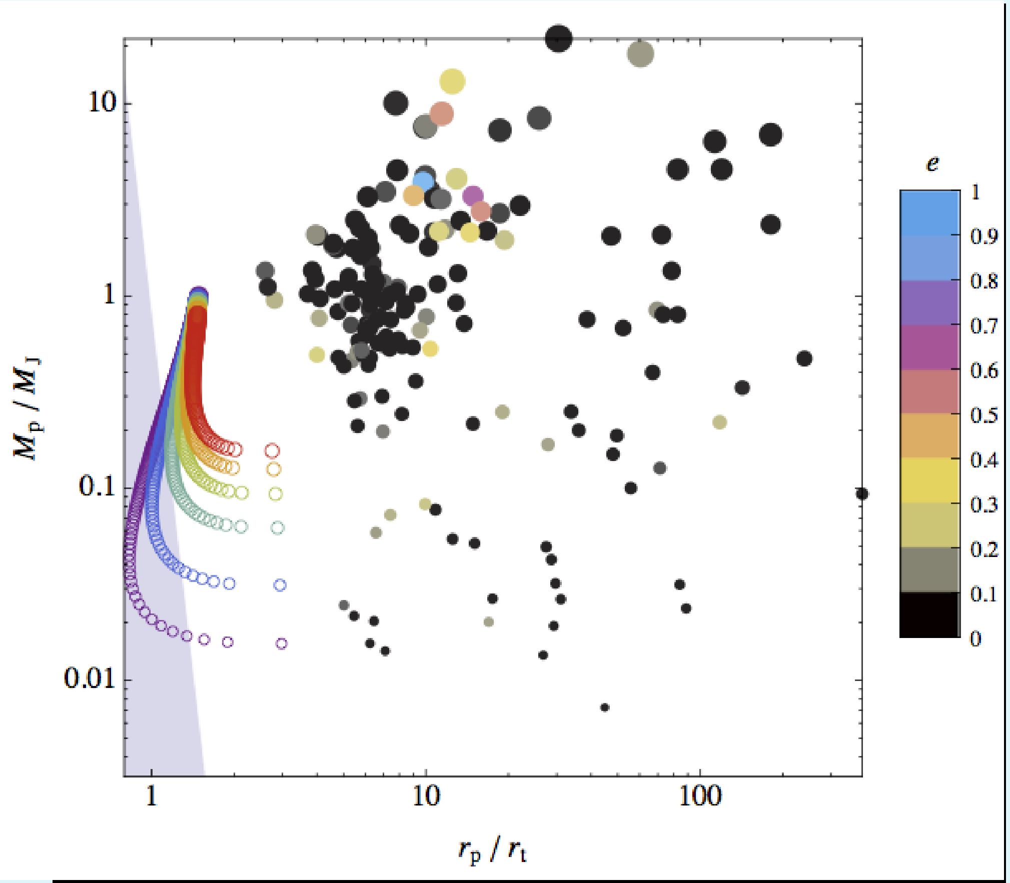


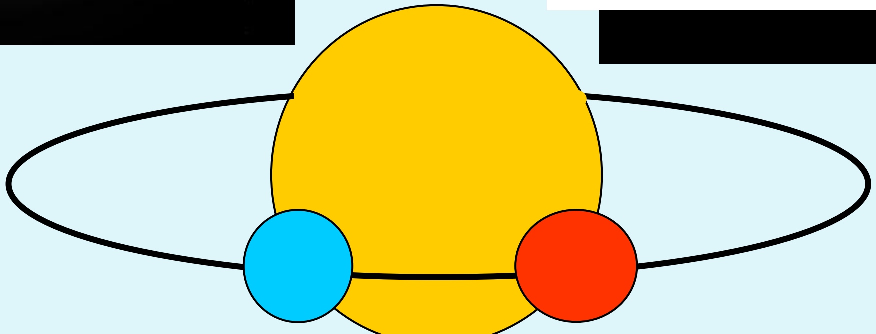
Resonant capture
Collisional damping
Gas drag

RM effect and challenge to migration





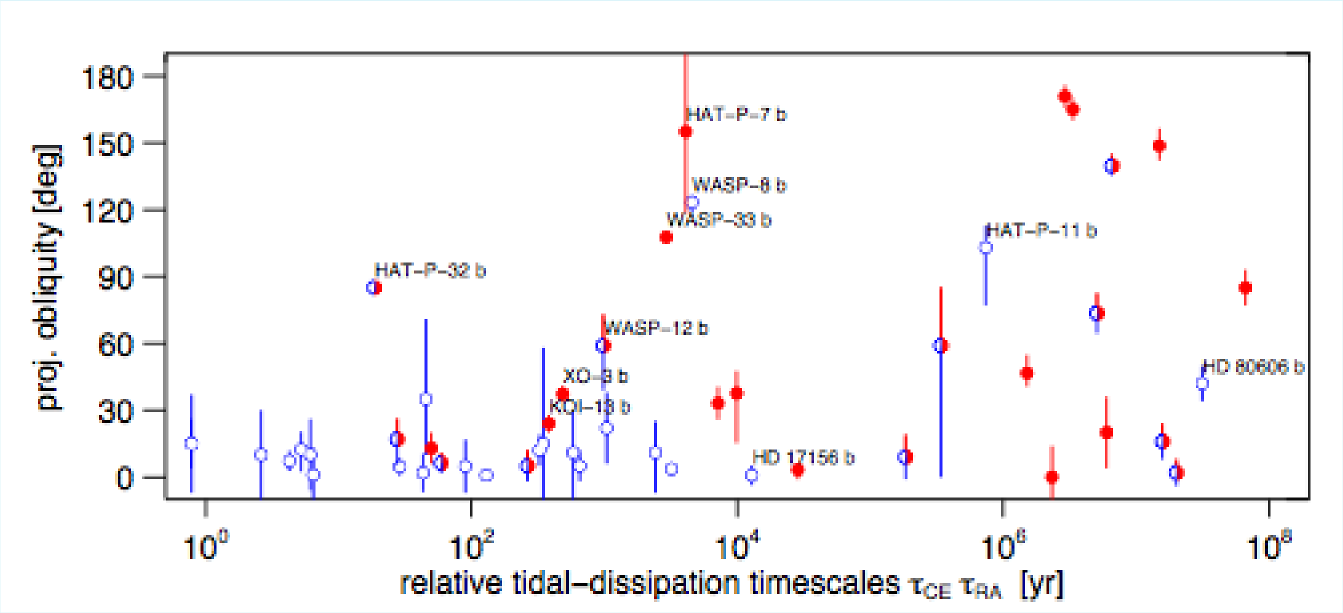




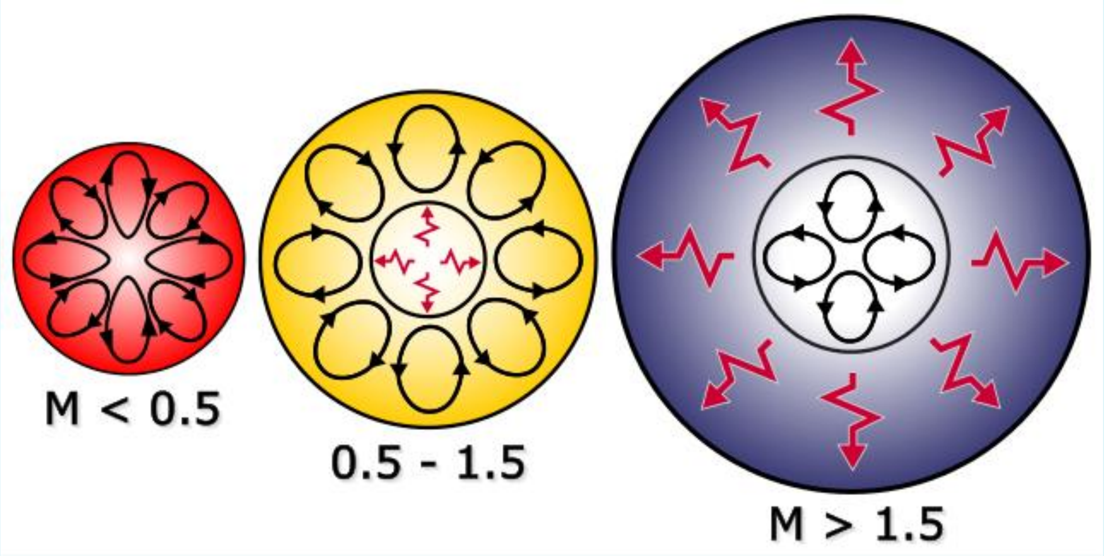
Liu, Guillichon

Gas giants: some key issues

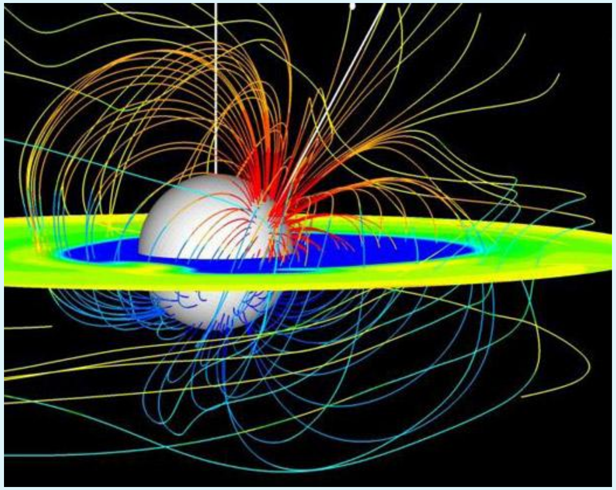
- Is there evidence for M_*-dependent tidal dissipation?

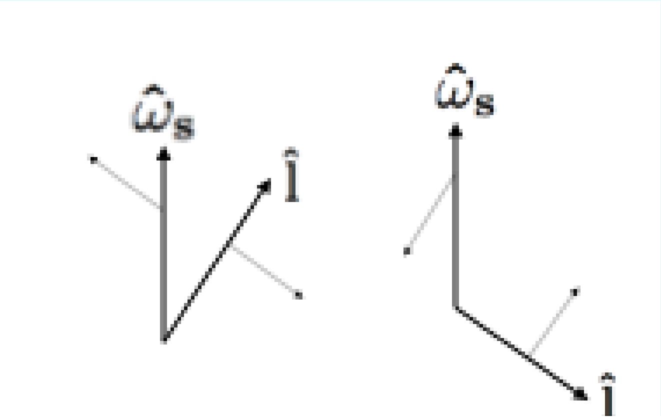


Winn



Misaligned magnetosphere





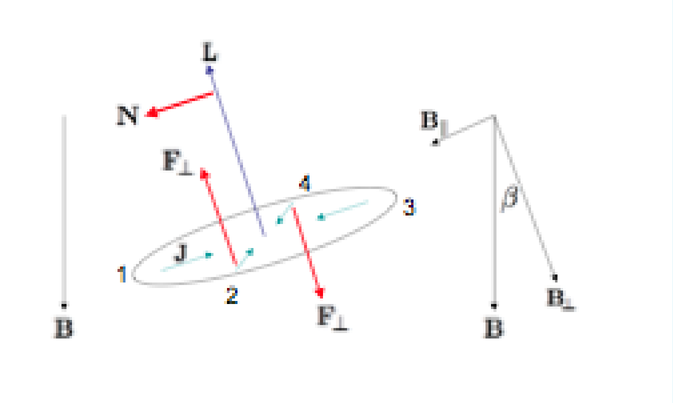
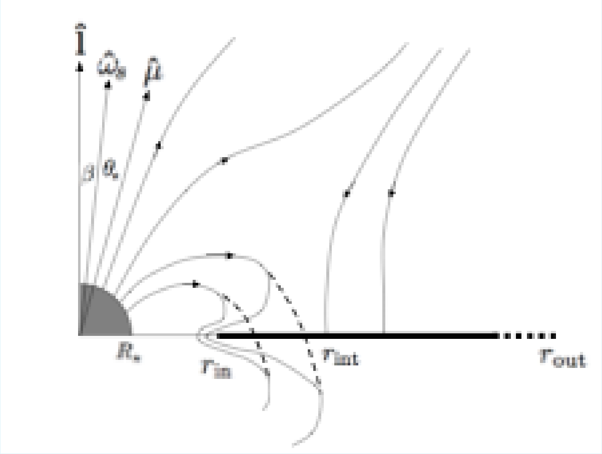


Figure 3. A toy model for understanding the origin of the warping torque. A tilted rotating metal plate (with angular momentum **L**) in an external magnetic field **B** experiences a vertical magnetic force around region 2 and 4 due to the interaction between the induced current **J** and the external $\mathbf{B}_\parallel$, resulting in a torque **N** which further increases the tilt angle β.

Observable tests

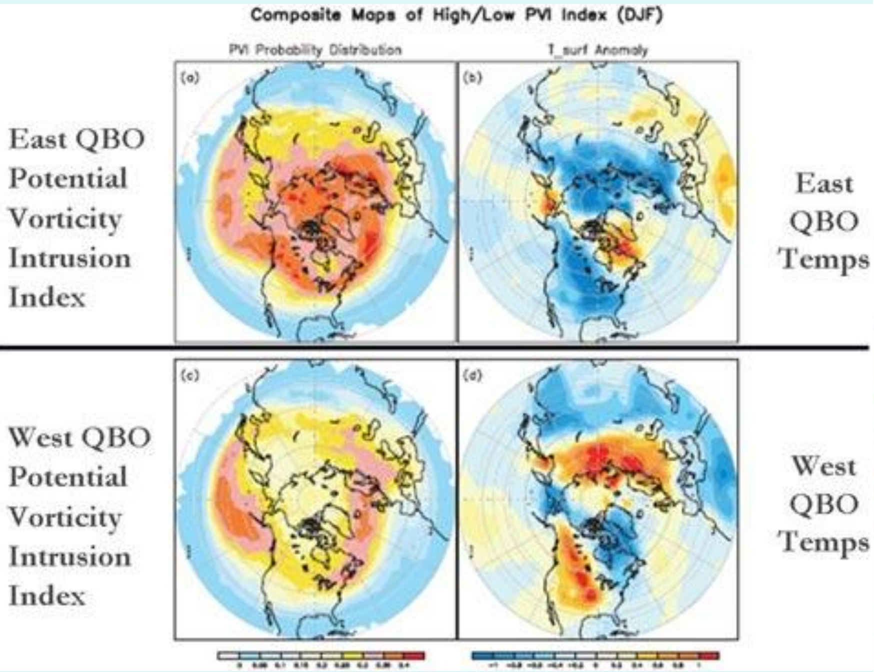


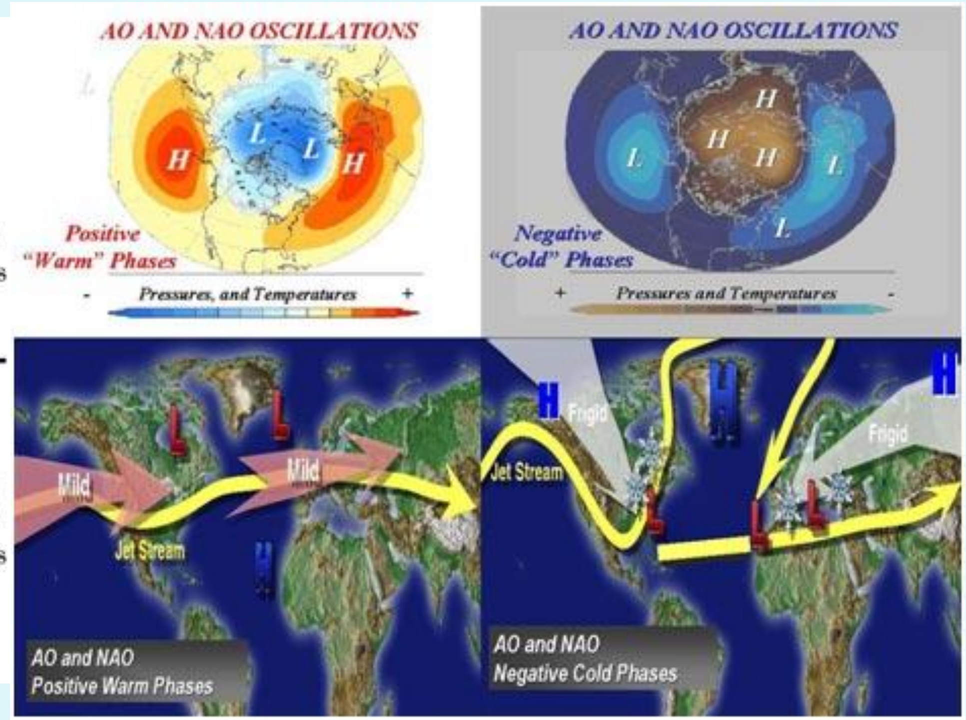
Similar effects in close-in planets: additional Torque and dissipation avenues

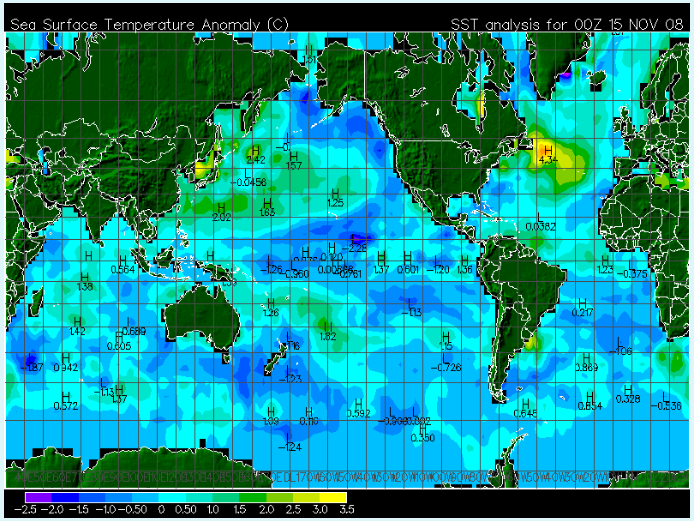
Lai, Foucart, & Lin

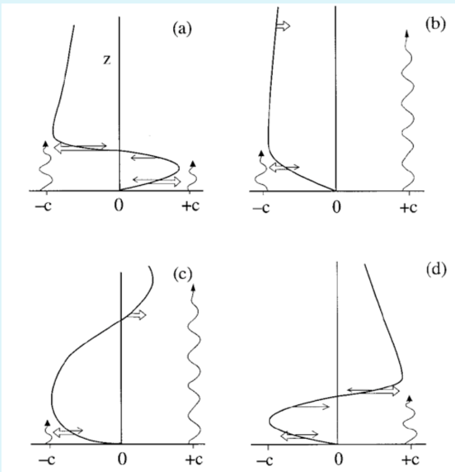
Cumming & Lin

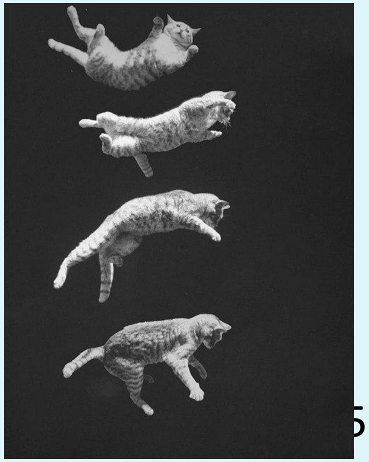
Alternative model: internal gravity wave





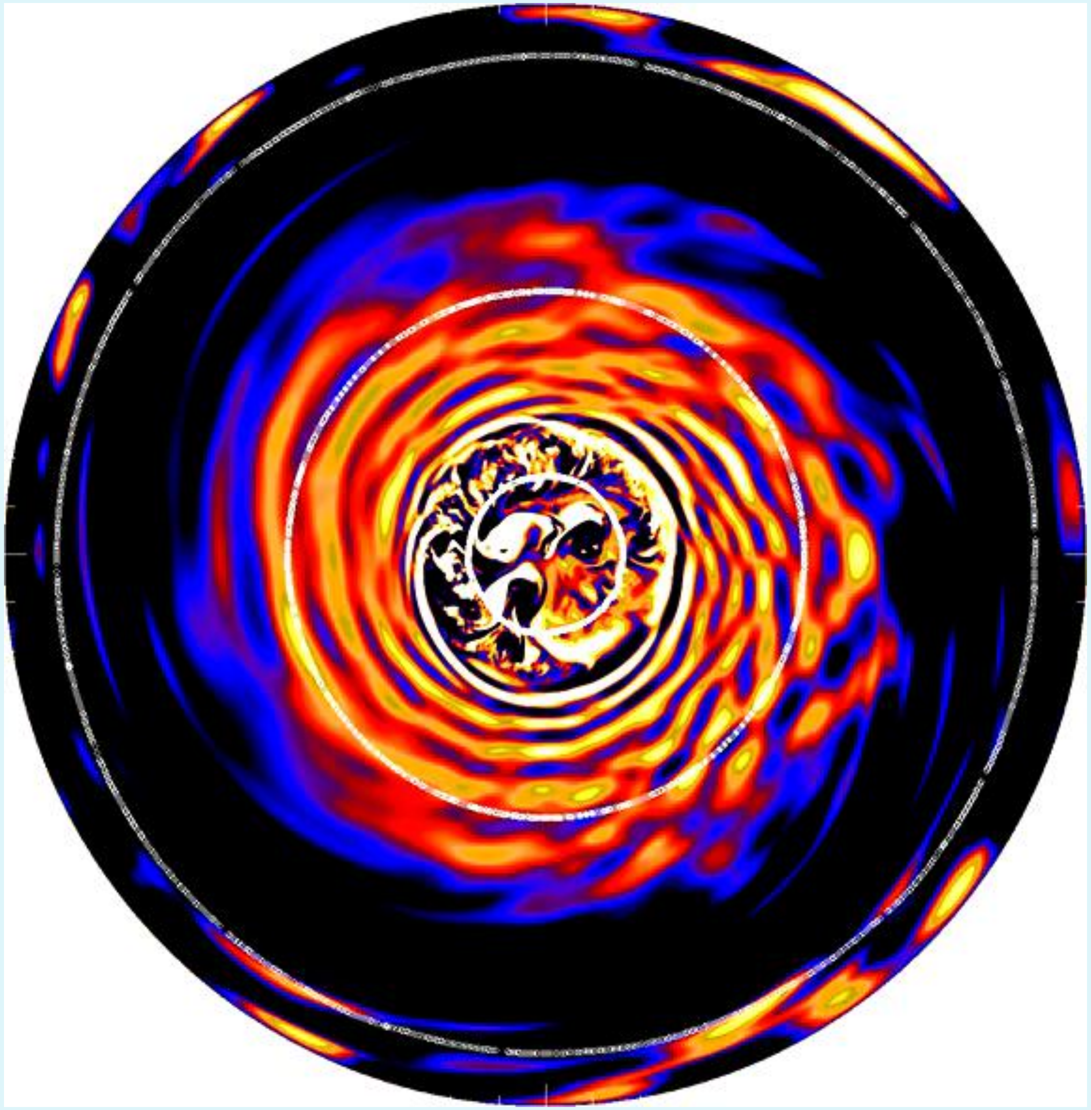


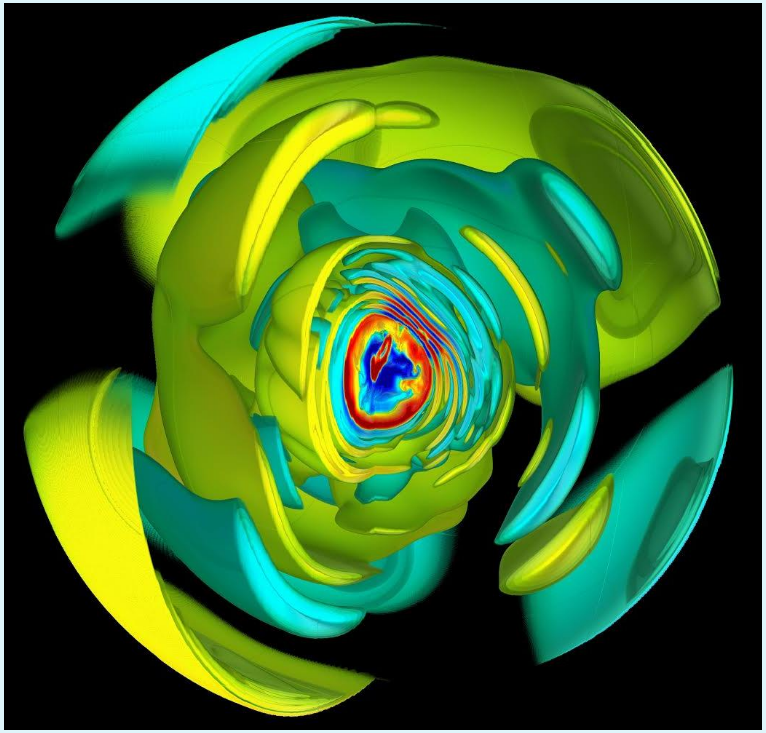




Tami Rogers

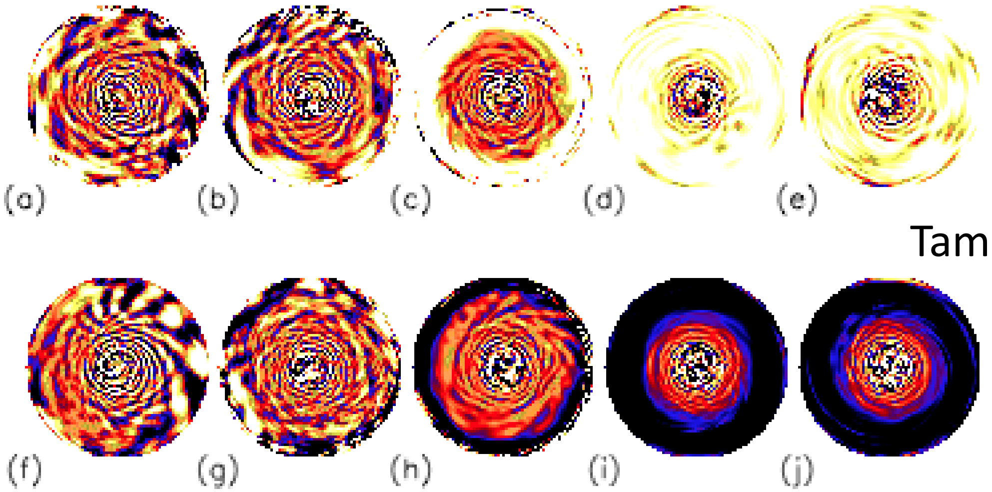
Gravity waves in intermediate-mass stars



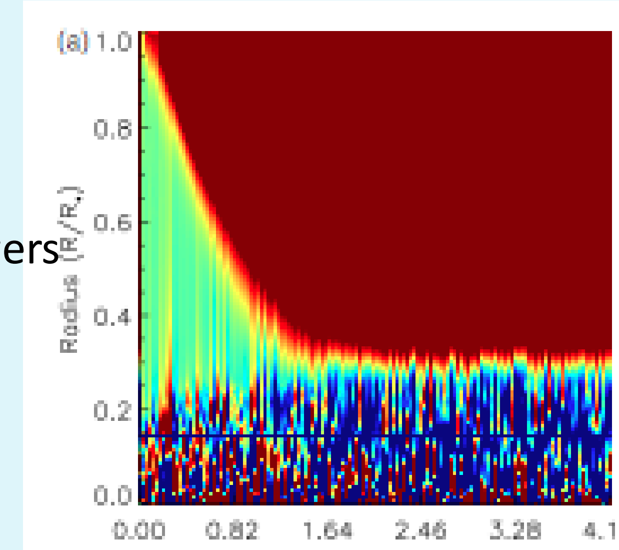


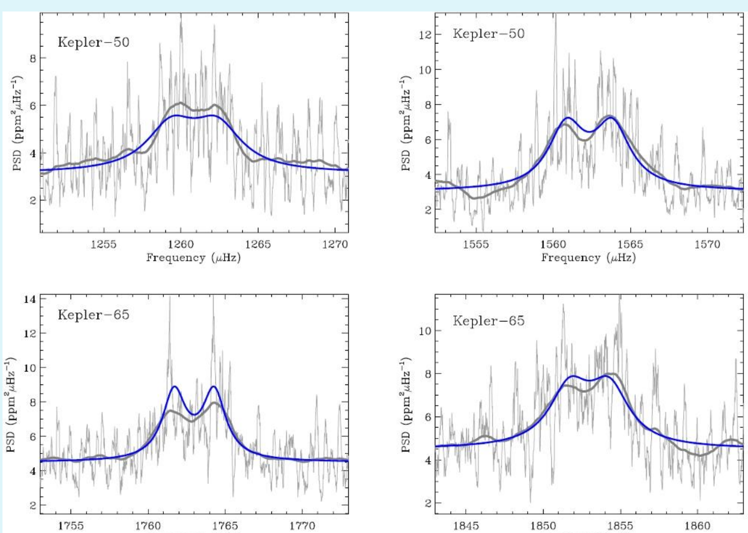
Gas giants: some key issues

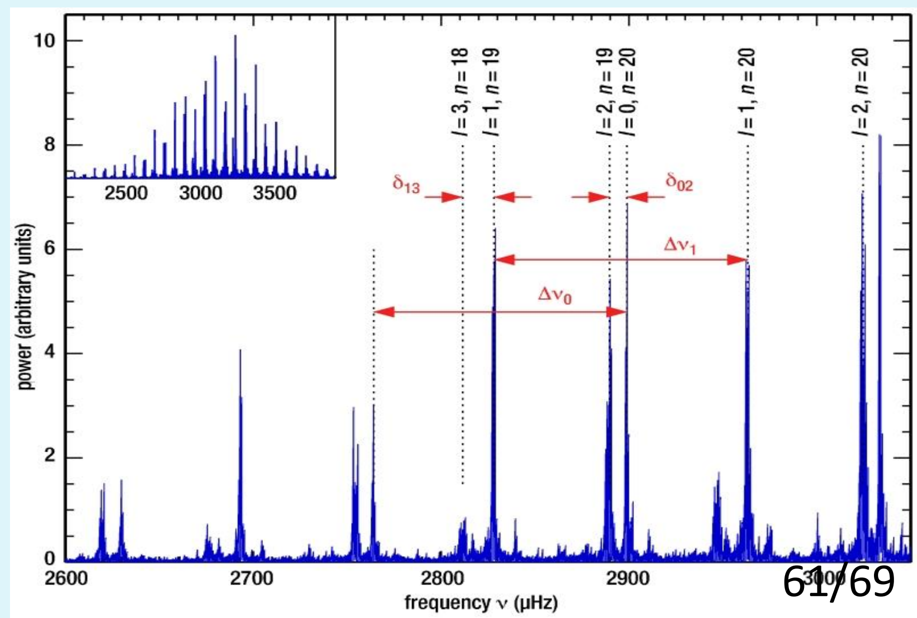
- Is there evidence for internal differential rotation ?



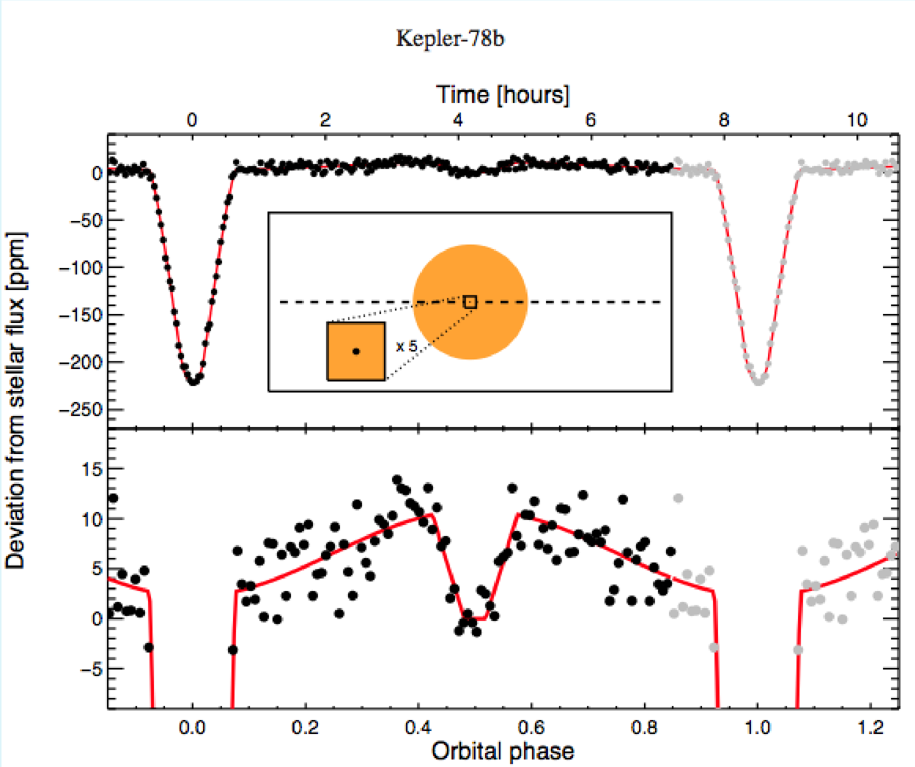
Tami Rogers

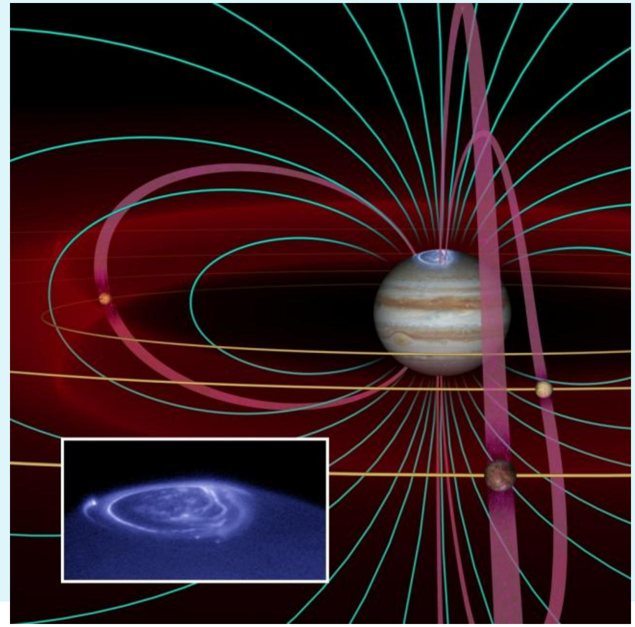


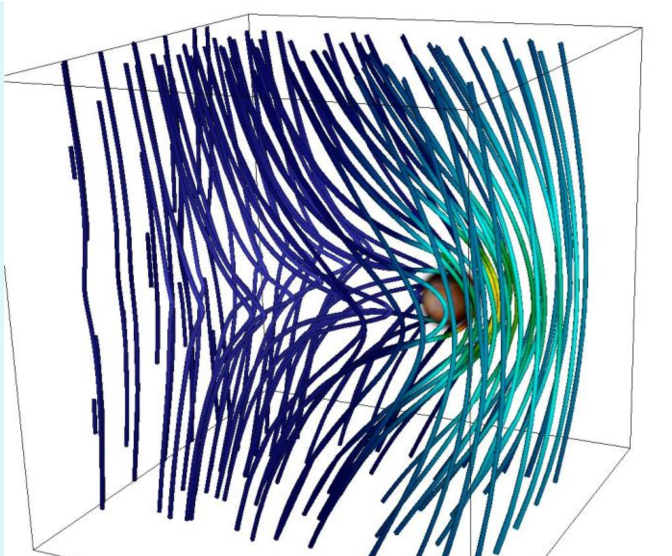


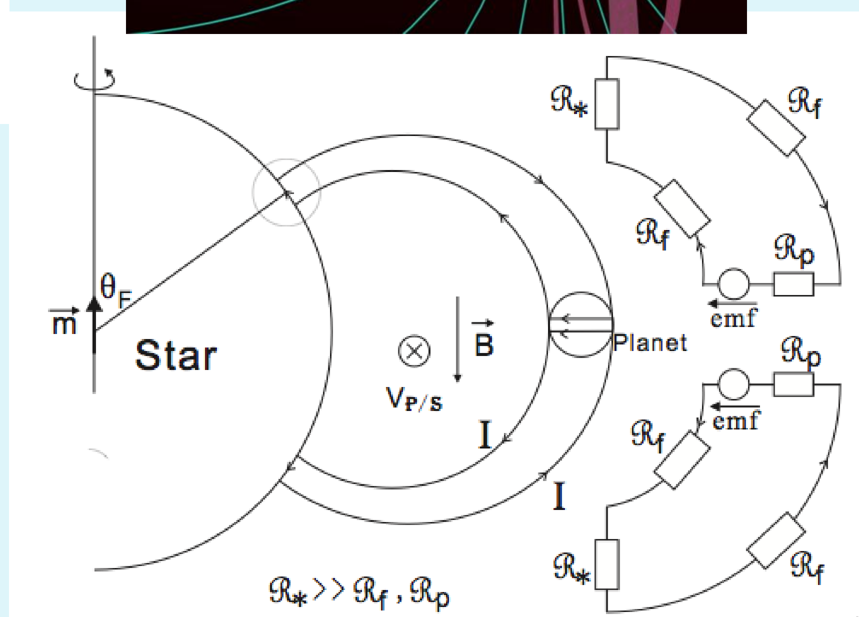


Inside the stellar magnetosphere



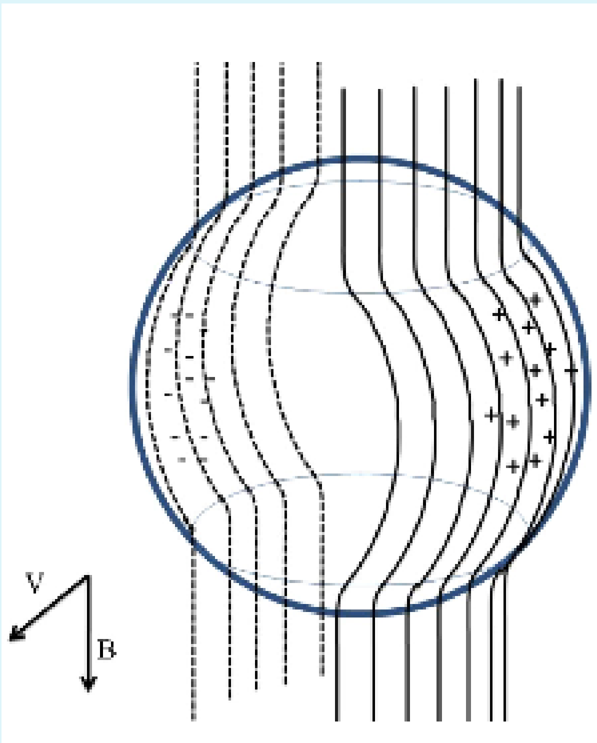


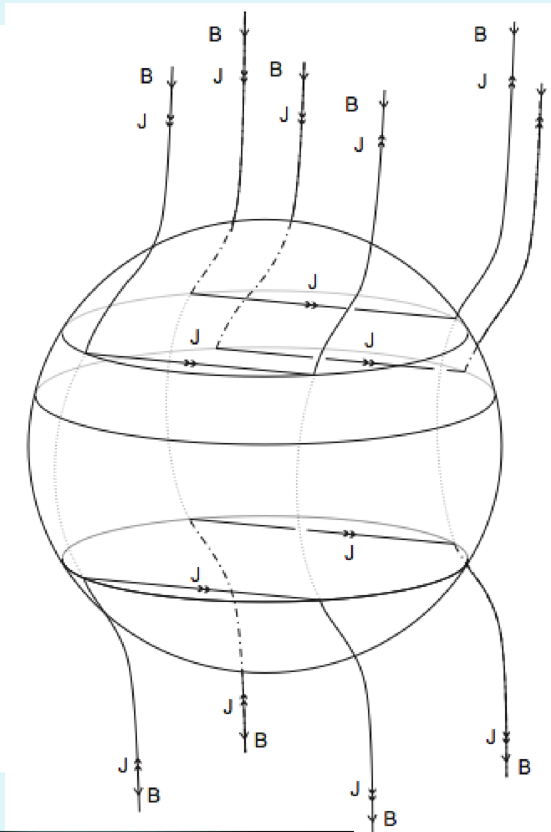


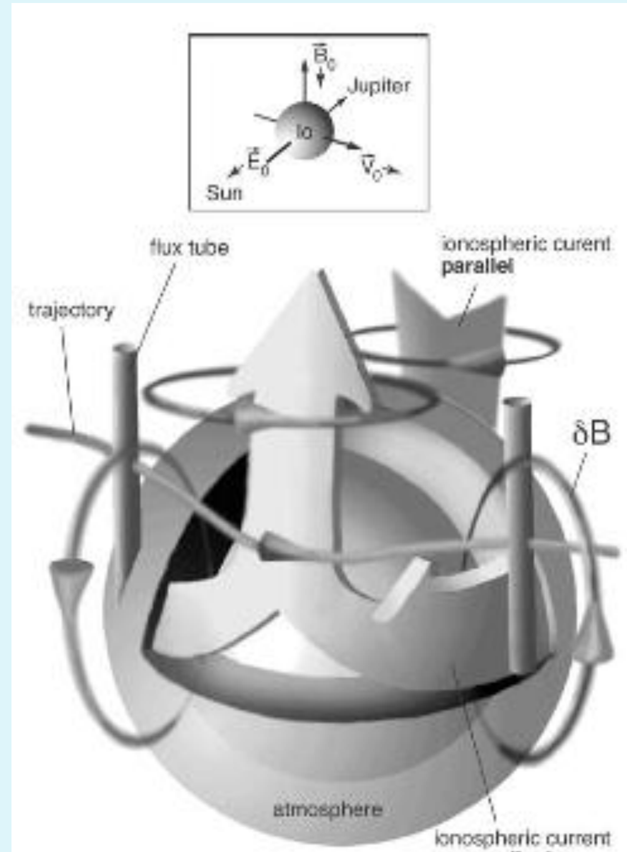


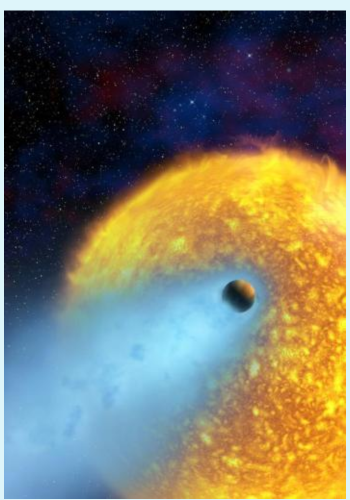
Laine, De Colle

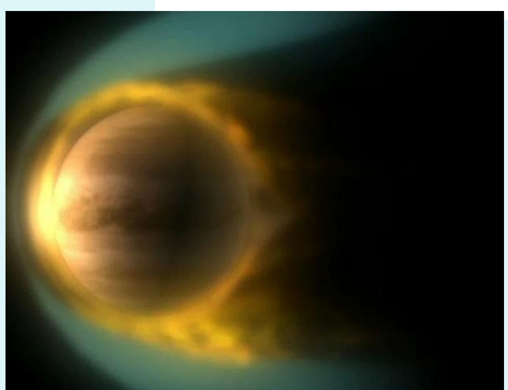
Inside the super Earths



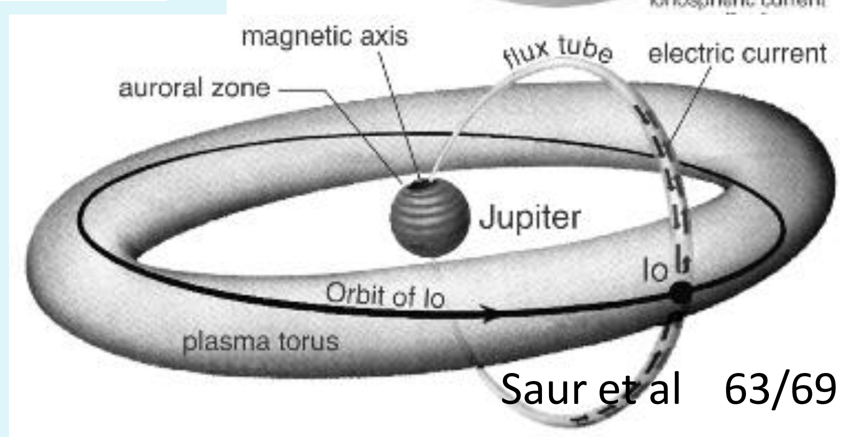






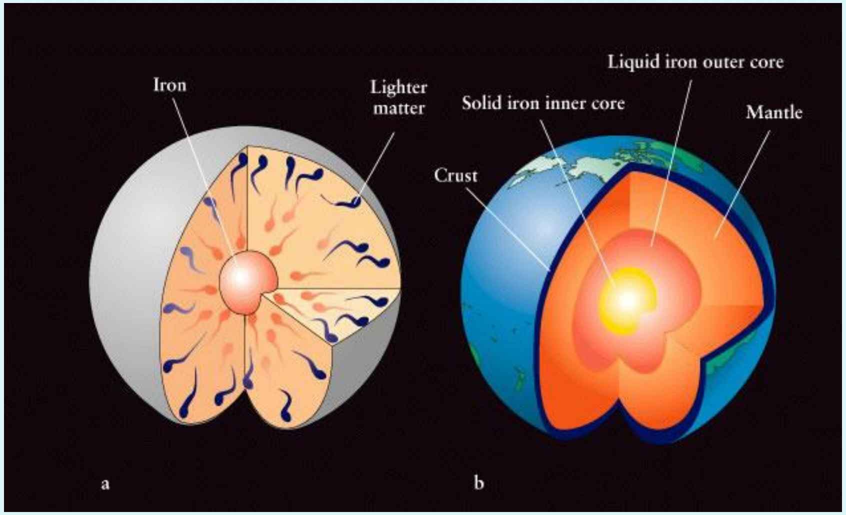


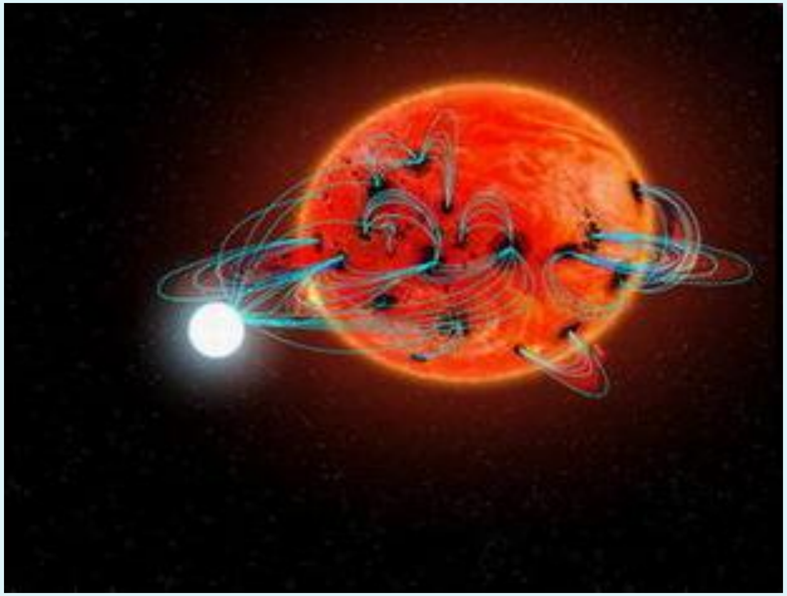
B. Dai, Y.Z. Niu, R. Laine

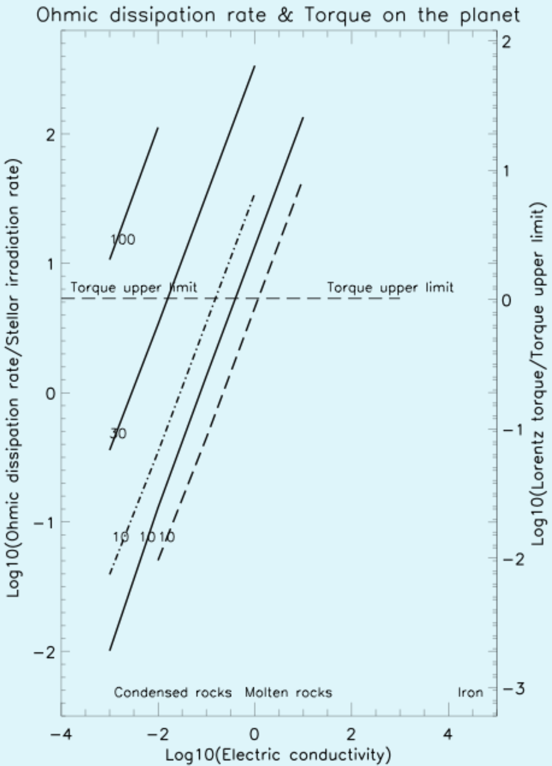


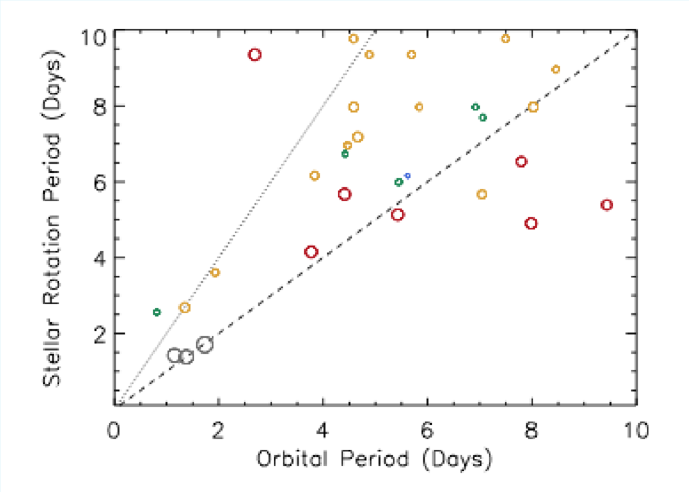
Saur et al

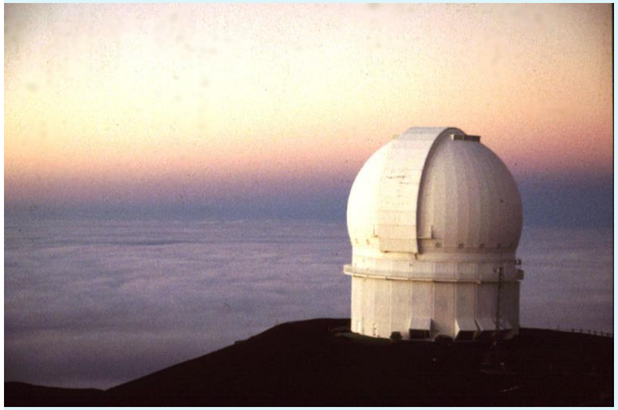
Super Earths' geology & atmosphere







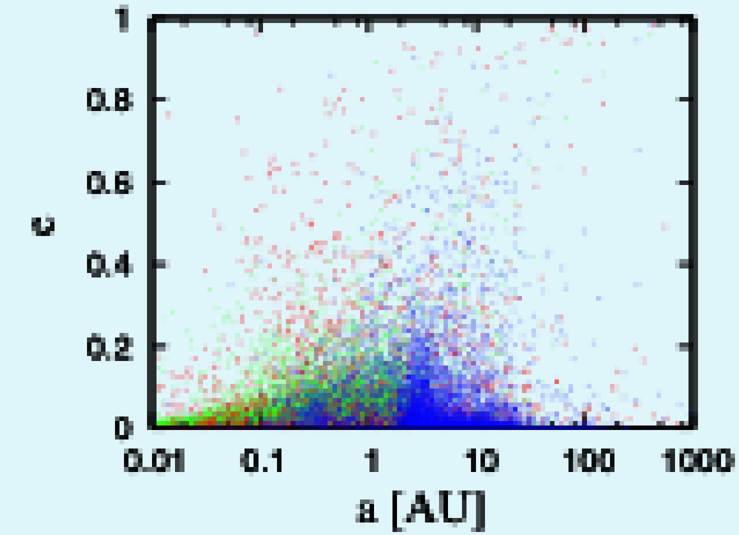


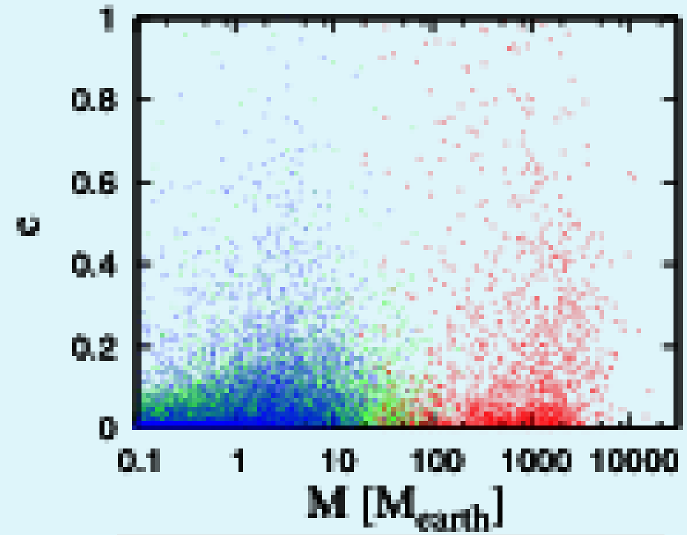


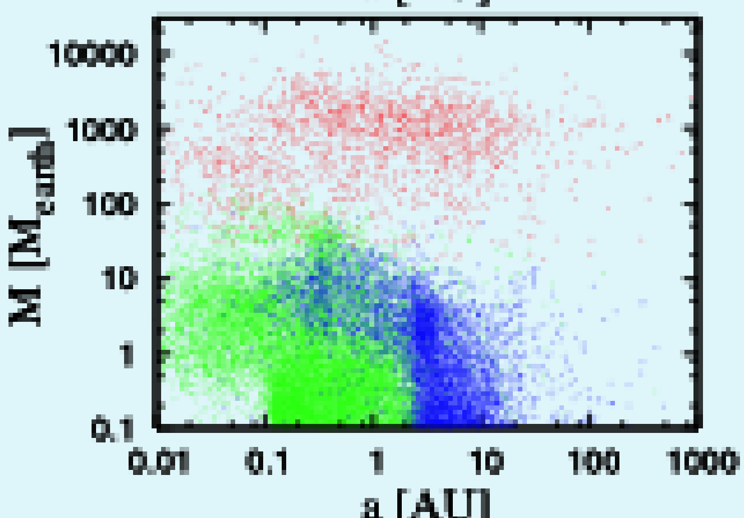
Other issues

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

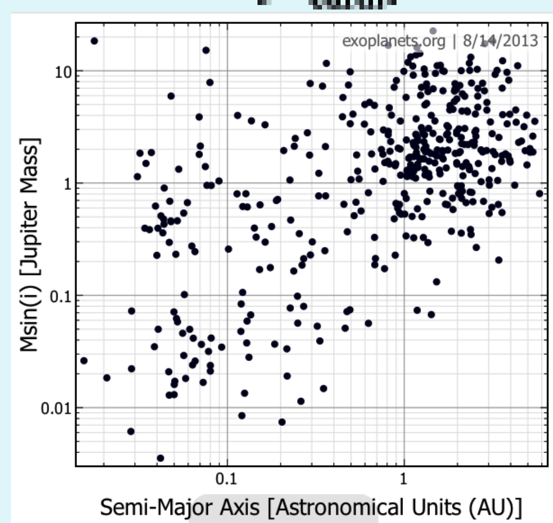
Updated version of population synthesis models

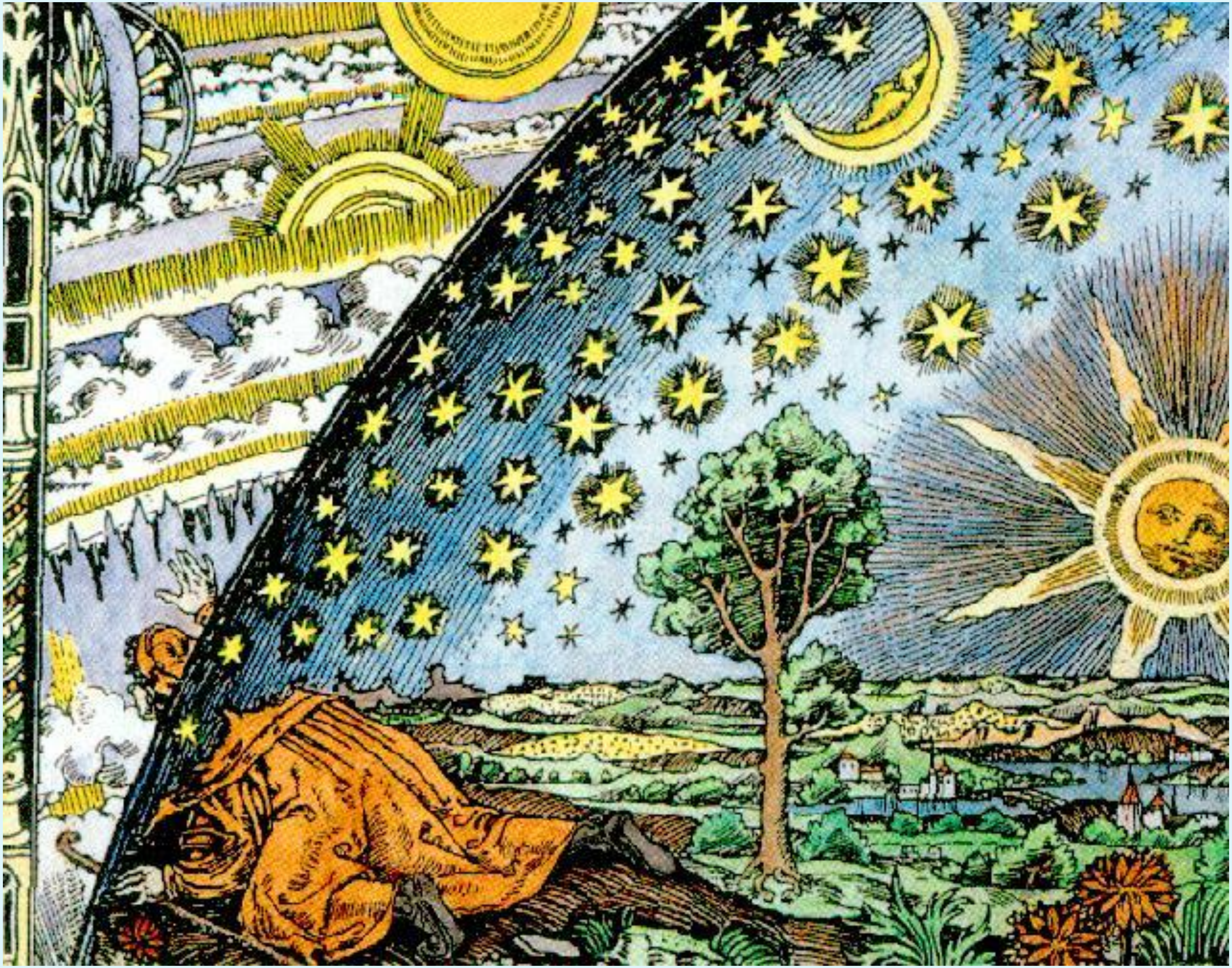






Ida

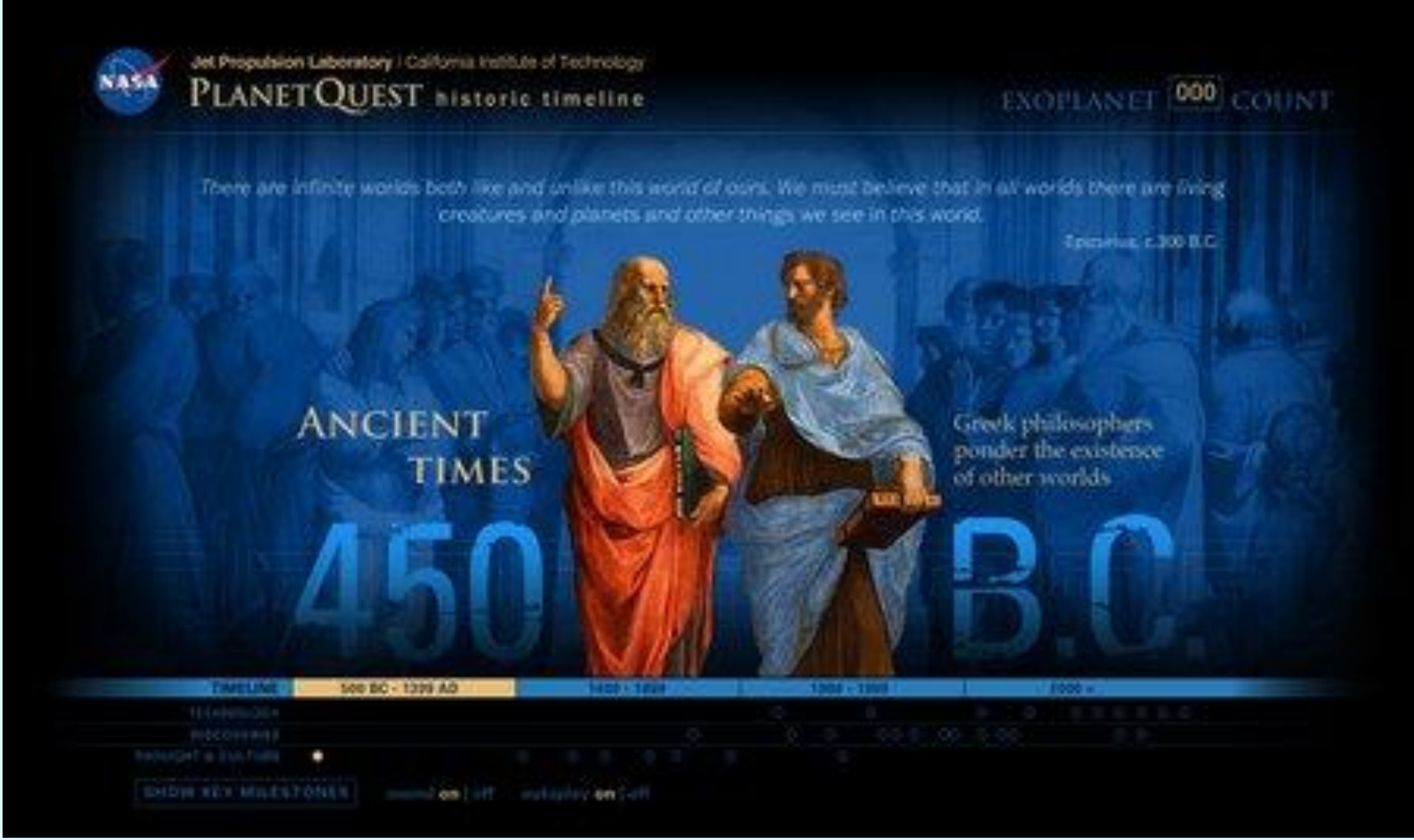




Cosmographia 1544

Summary

- Planet formation is a robust process and their dynamical architecture is diverse.
- Planetary origin and destiny are determined largely by the structure & evolution of the disks.
- Migration due to planet-disk interaction played a big role in the asymptotic properties of the planets.
- Theory of planetary astrophysics is relevant to many other astrophysical contexts.



``there are infinite worlds both like and unlike this world of ours …''

Epicurus