Core Accretion Scenario of Exoplanet Formation

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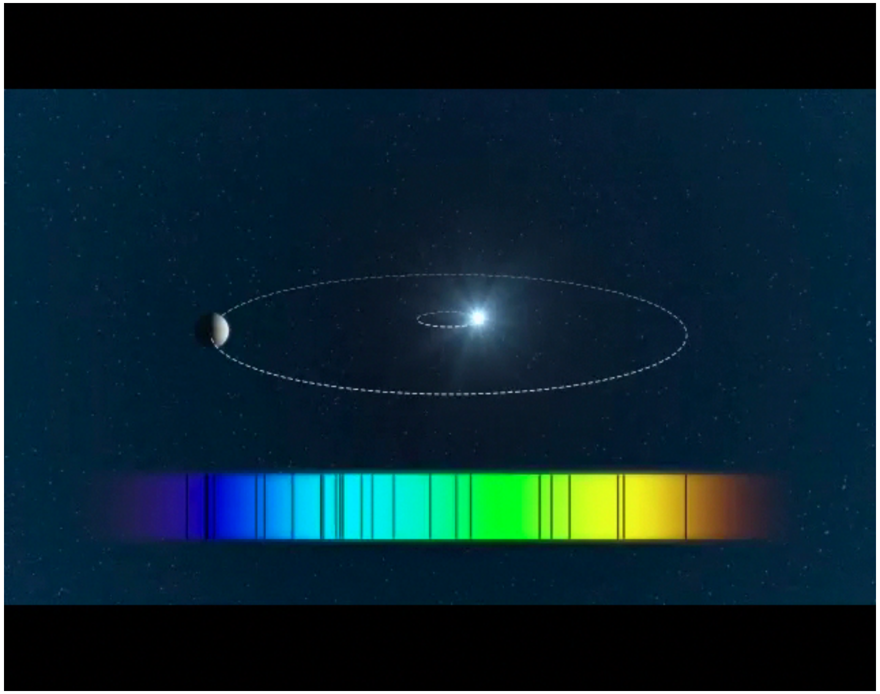
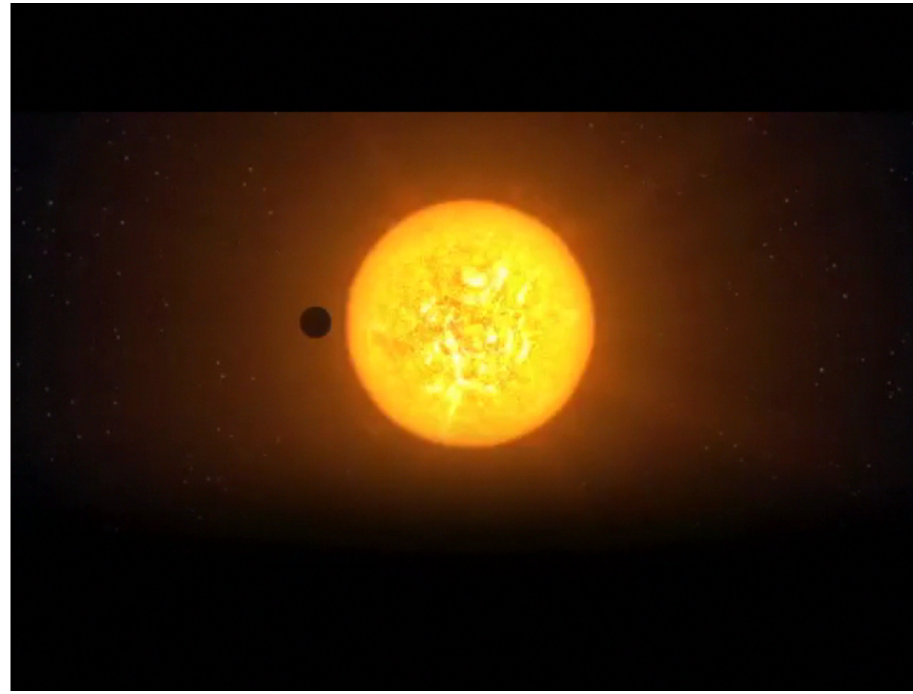
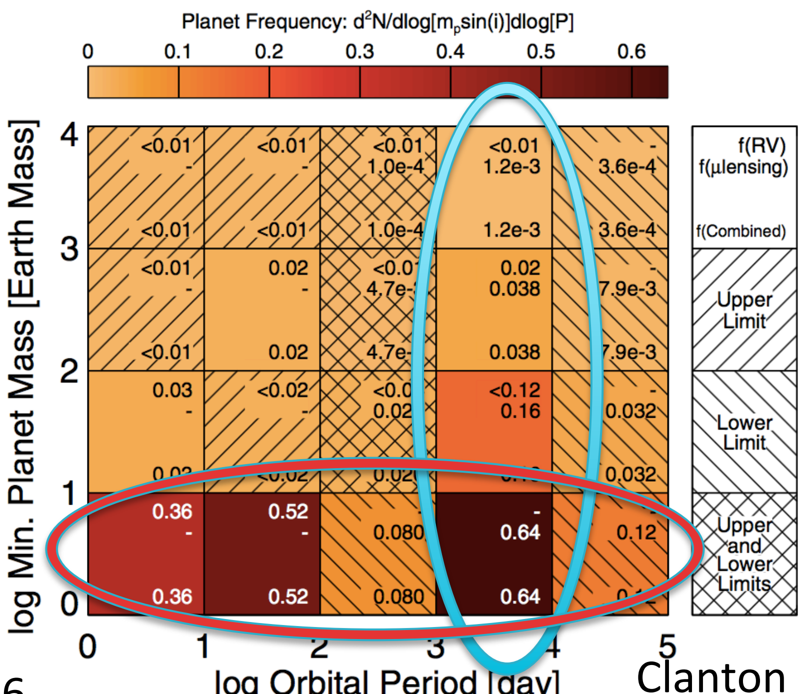
Rui Xu, Rixin Li, Yuan Zhang, Bili Dong, Wenhua Ju, Randy Laine, Yas Hori

Exoplanetary System Demographics: Theory and Observations
Beckman Institute, Caltech, July 27-31, 2015

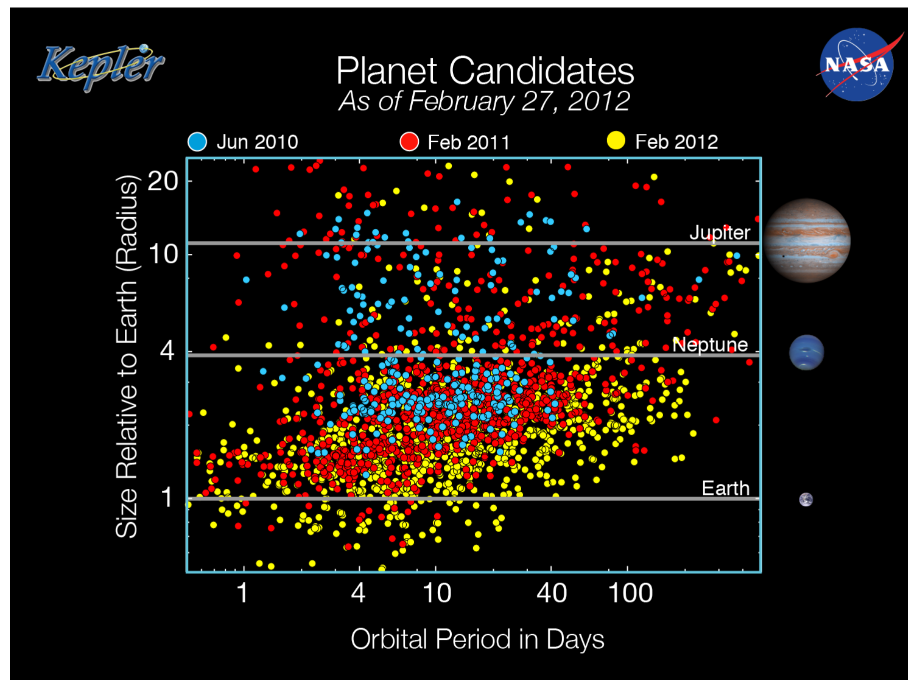
66 slides





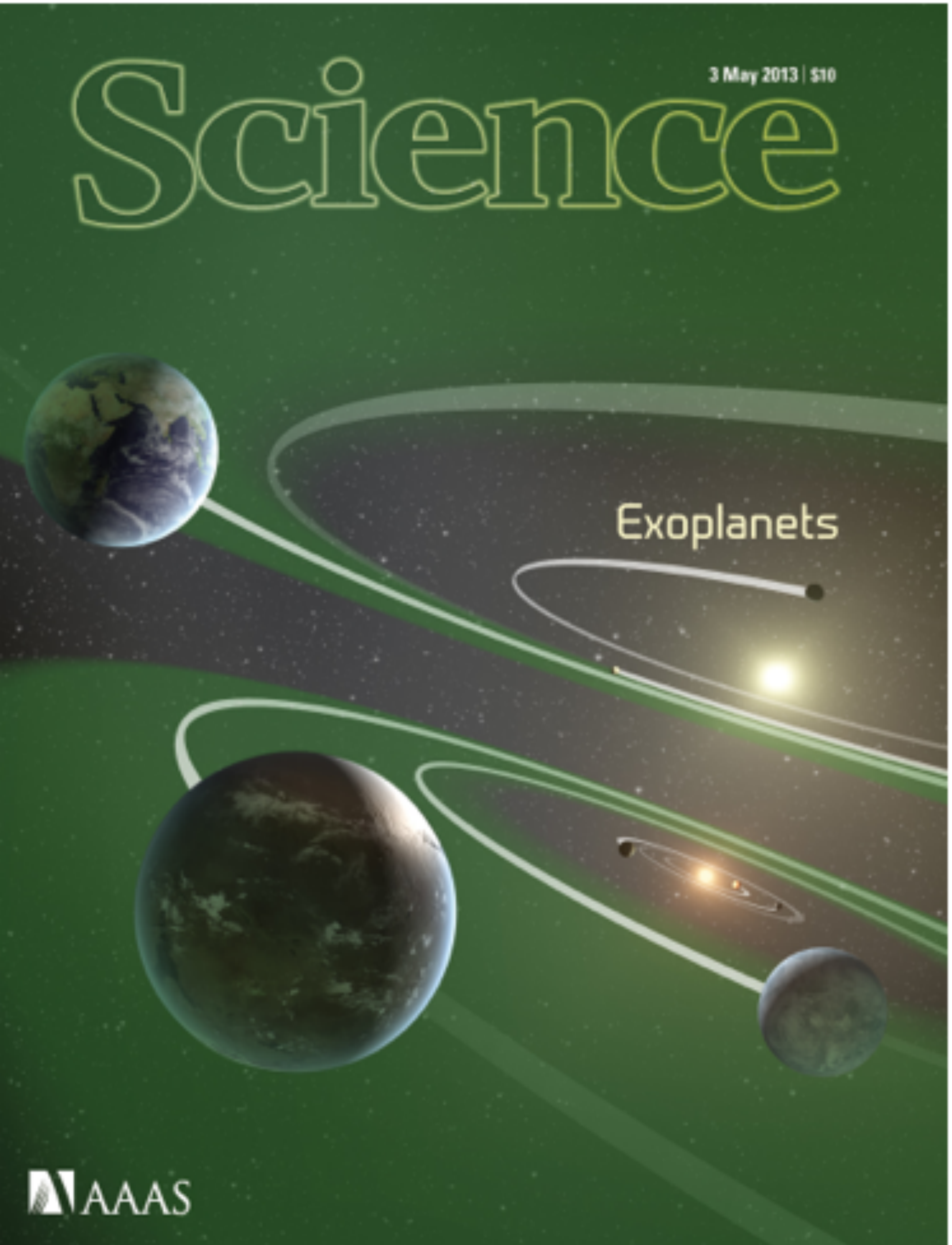


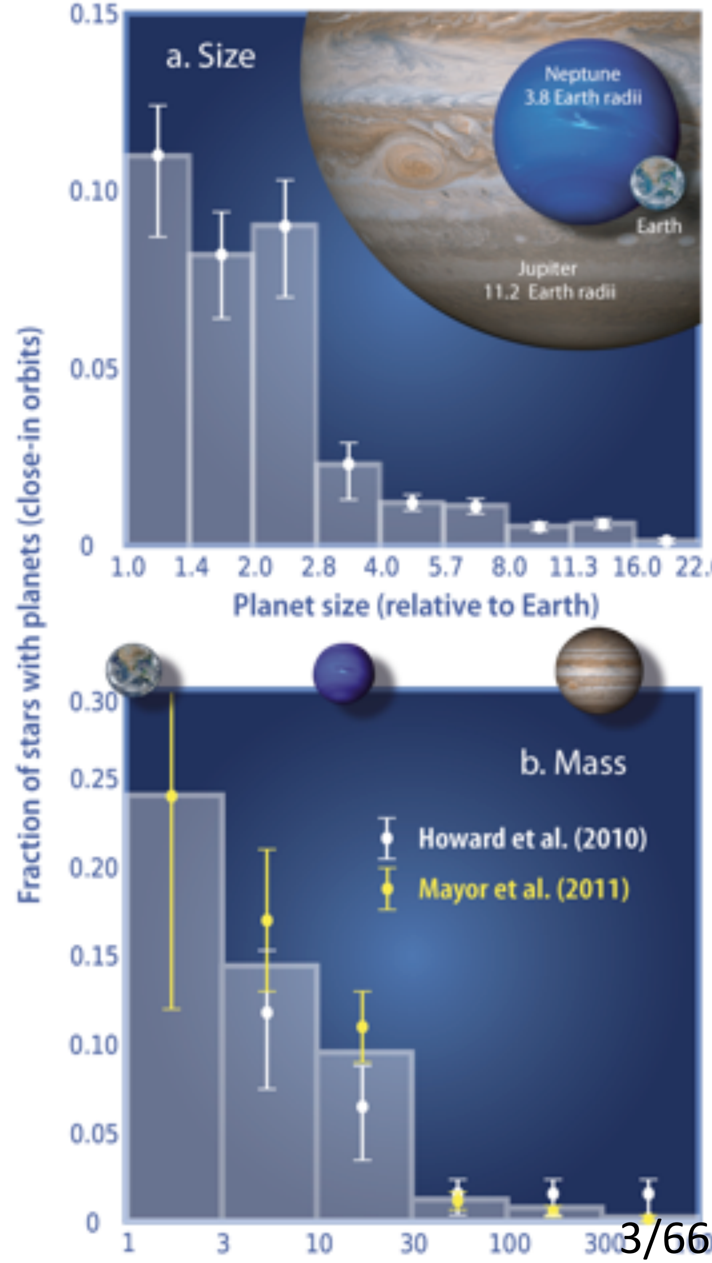
Planet Frequency: d²N/dlog[m_psin(i)]dlog[P]
0
0.1
0.2
0.3
0.4
0.5
0.6
<0.01
<0.01
<0.01
1.0e-4
<0.01
1.2e-3
3.6e-4
<0.01
<0.01
1.0e-4
1.2e-3
3.6e-4
<0.01
0.02
0.02
0.038
7.9e-3
<0.01
0.02
4.7e-
0.038
7.9e-3
0.03
<0.02
<0.12
0.16
0.032
0.032
0.36
0.52
0.080
0.64
0.12
0.36
0.52
0.080
0.64
f(RV)
f(μlensing)
f(Combined)
Upper Limit
Lower Limit
Upper and Lower Limits
log Min. Planet Mass [Earth Mass]
0
1
2
3
4
log Orbital Period [day]
0
1
2
3
4
5
Clanton



Kepler
Planet Candidates
As of February 27, 2012
NASA
Jun 2010
Feb 2011
Feb 2012
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
40
100
Orbital Period in Days

Observed Properties of Extrasolar Planets
Howard (2013)

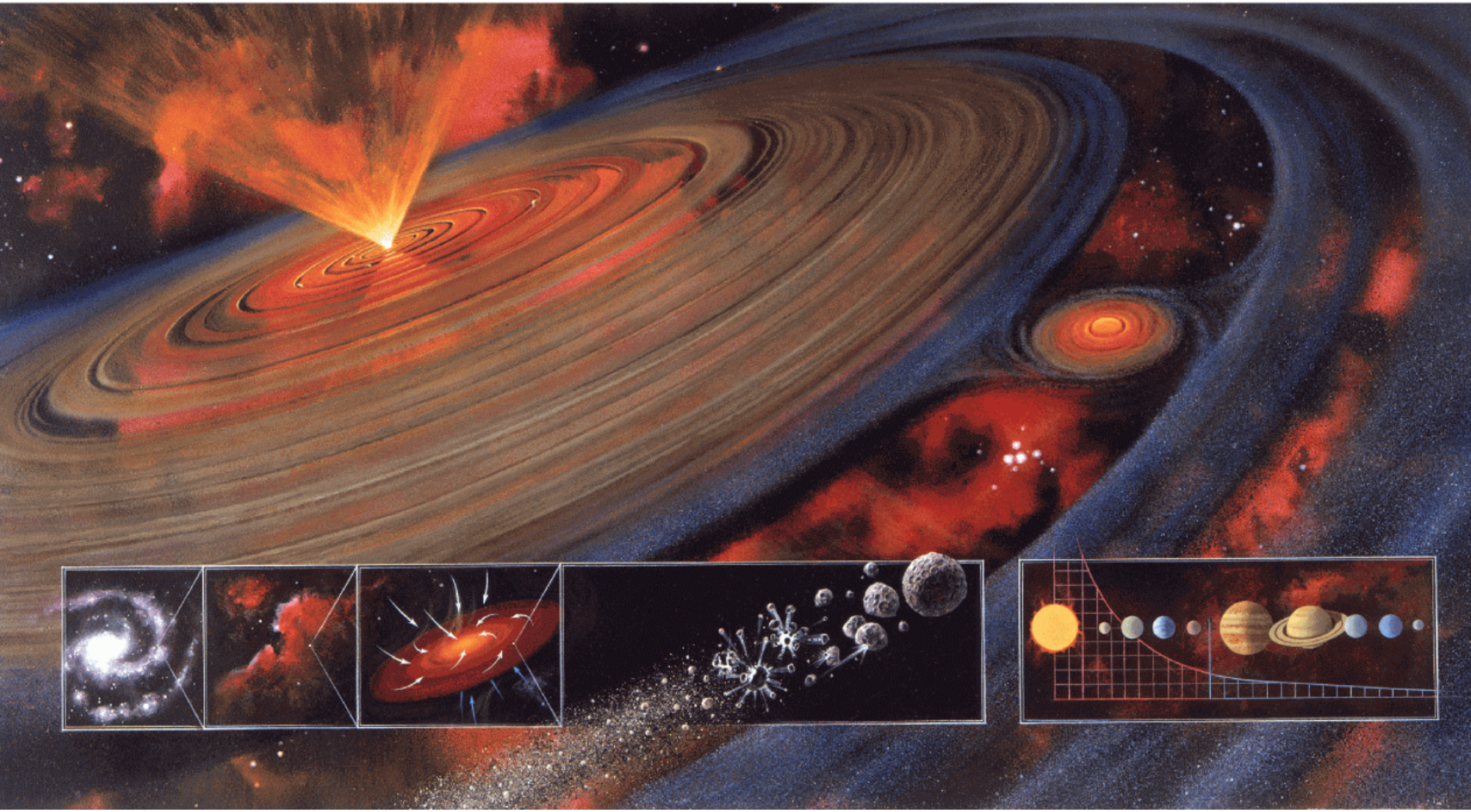




Big picture questions

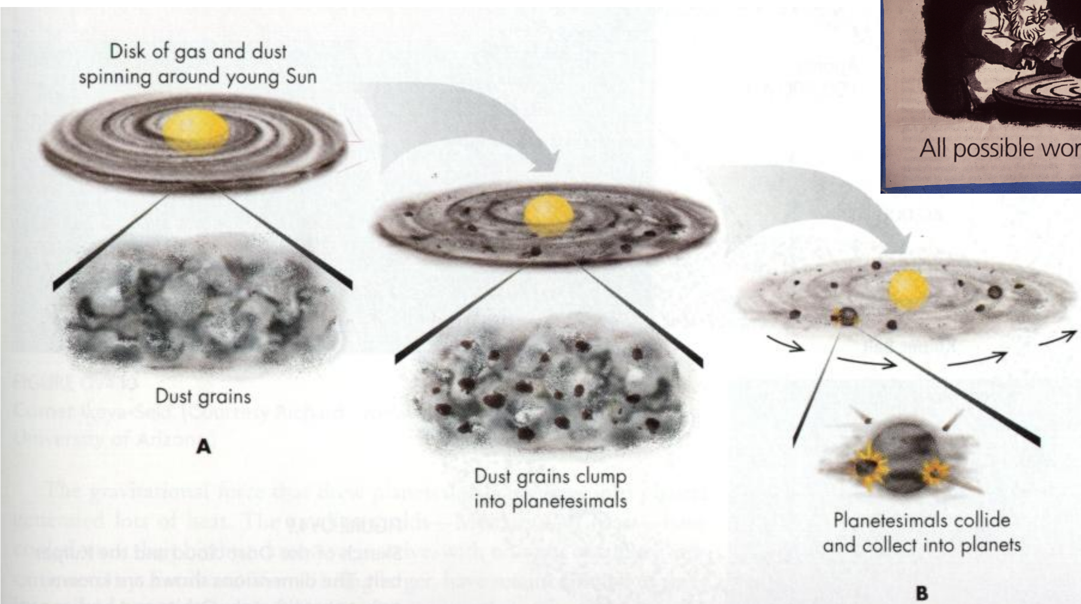
- How did super Earth form so prolifically
- Why is the emergence of gas giant marginal?
- How did planets establish their structural diversity?
- How did planetary systems acquired the observed kinematic distribution?
- How did multiple systems attain meta-stability?

Conventional core accretion scenario



Minimum-mass nebula hypothesis

in situ formation scenario



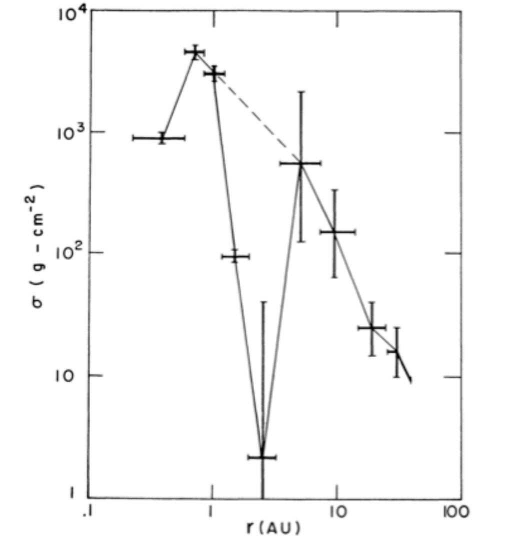
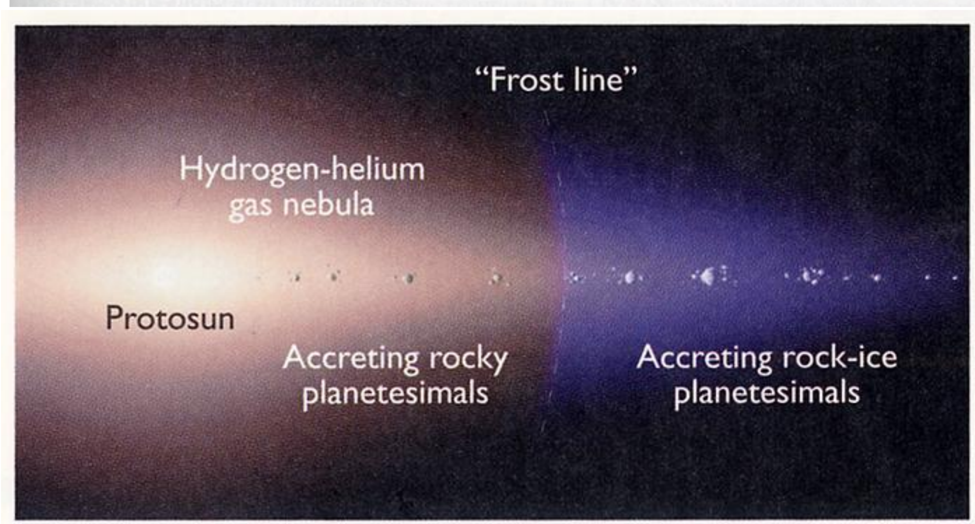
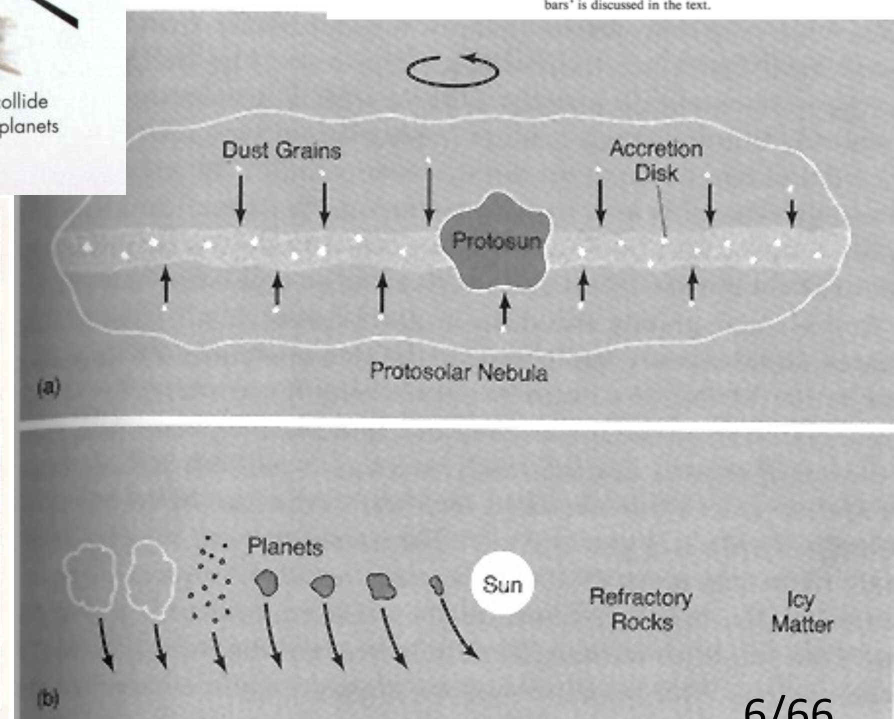


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and sprea[d] the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'e[rror] bars' is discussed in the text.





Some major Challenges:

- Retention of grains: m-size barrier (Whipple)
- Fragmentation: km-size barrier (Benz)
- Planetesimal-growth barrier: Isolation mass barrier (Safronov, Wetherill), Oligarchics (Kokubo, Ida)
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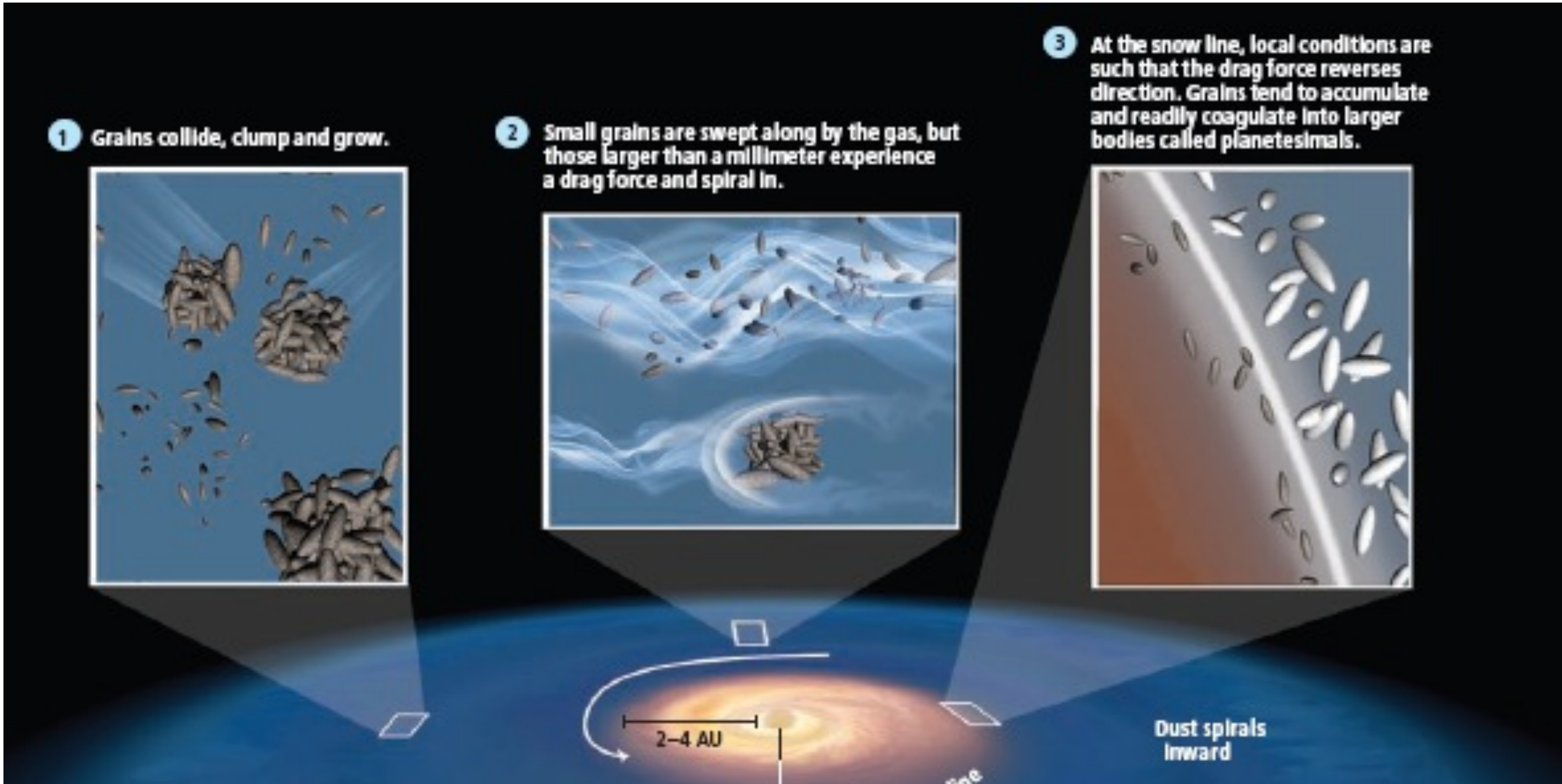
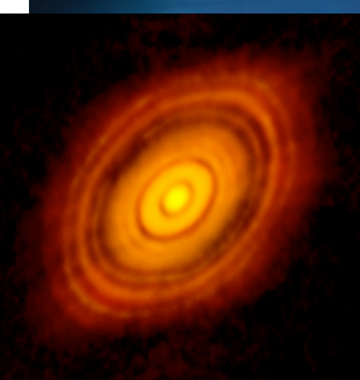
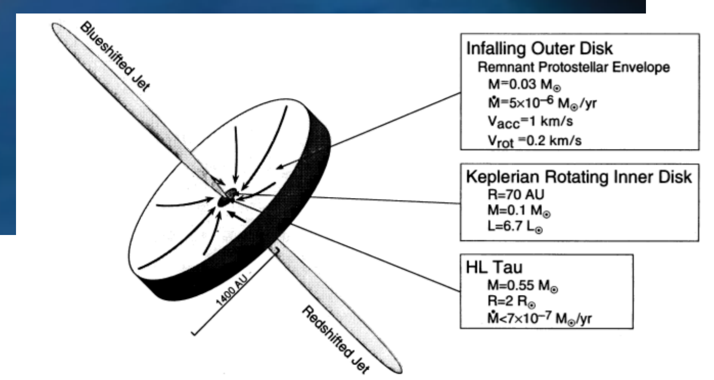
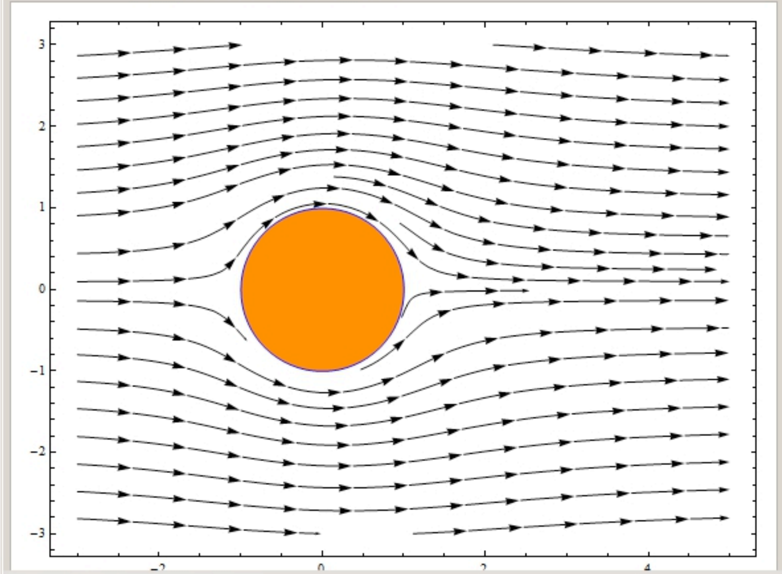
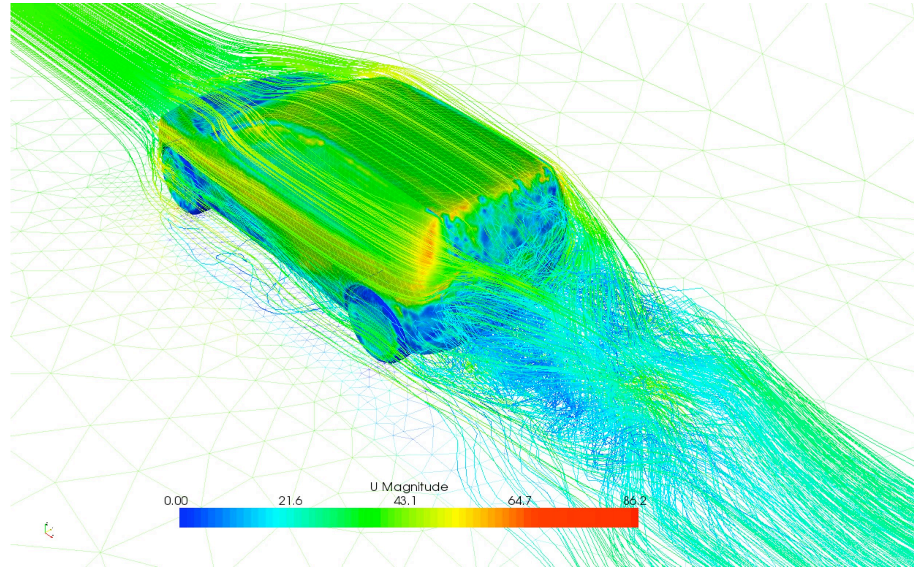
Meter-barrier: Hydrodynamic drag on dusts

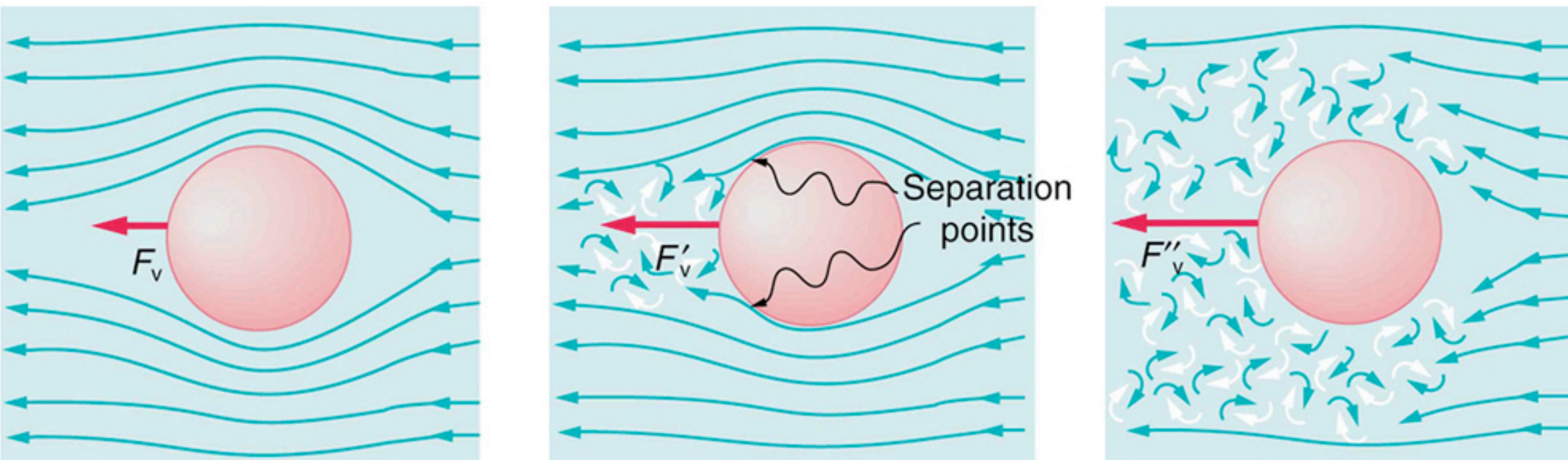












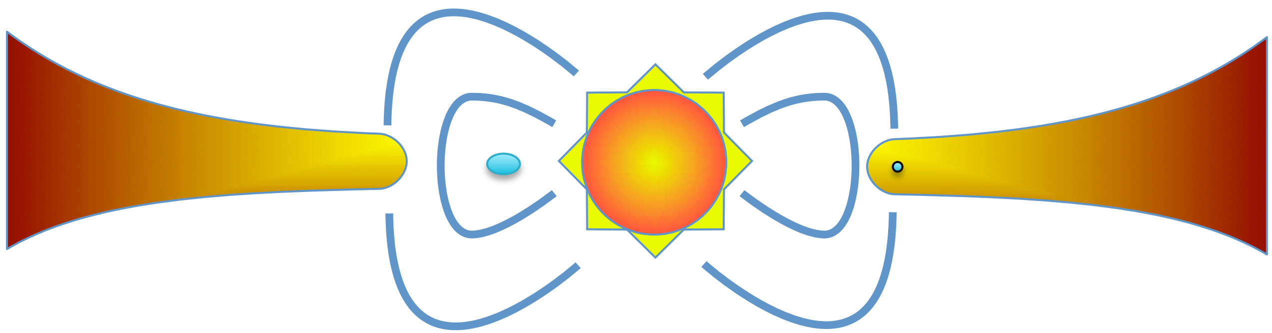
(a) (b) (c)

$$\boldsymbol{F}_d = m_p \frac{\;}{\rho_s}\frac{\;}{s}(\dot{\boldsymbol{r}} - \boldsymbol{v}_g) \quad \text{when } s \ll \lambda,$$

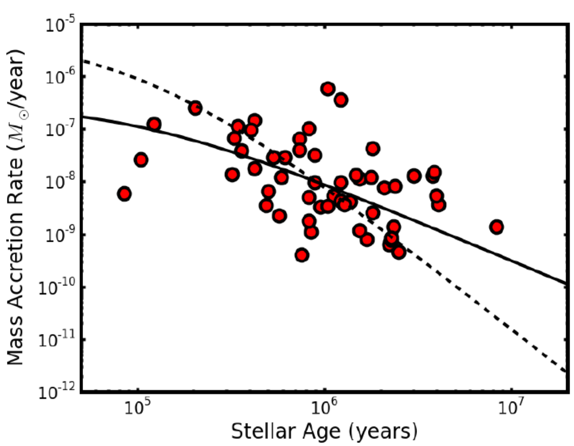
$$\boldsymbol{F}_d = m_p \frac{\rho}{\rho_s}\frac{C(\mathrm{Re})}{s}|\Delta\boldsymbol{v}|(\dot{\boldsymbol{r}} - \boldsymbol{v}_g) \quad \text{when } s \gg \lambda$$

$$C = \begin{cases} 9\mathrm{Re}^{-1} & \text{for } \mathrm{Re} \le 1, \\ 9\mathrm{Re}^{-0.6} & \text{for } 1 \le \mathrm{Re} \le 800, \\ 0.165 & \text{for } 800 \le \mathrm{Re}. \end{cases}$$

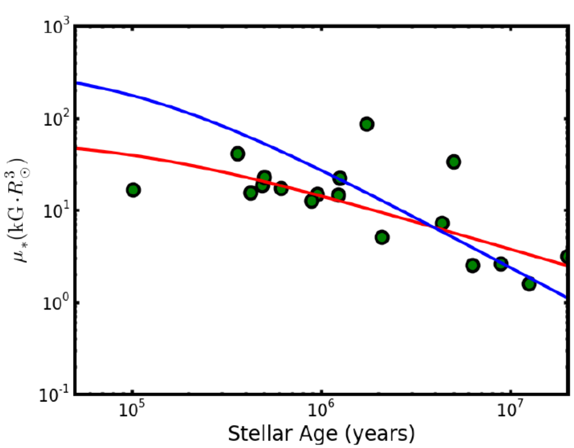
Stalling of planets inside & at the magnetospheric truncation radius



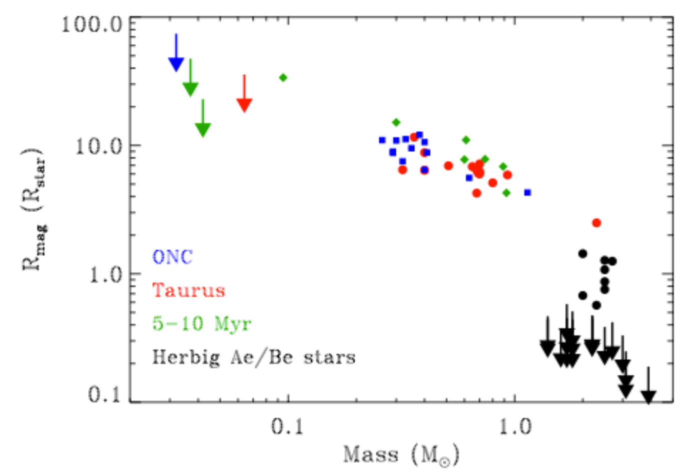
$$r_{\rm mag} \propto \mu_*^{4/7} \dot{M}^{-2/7}$$



Mass Accretion Rate

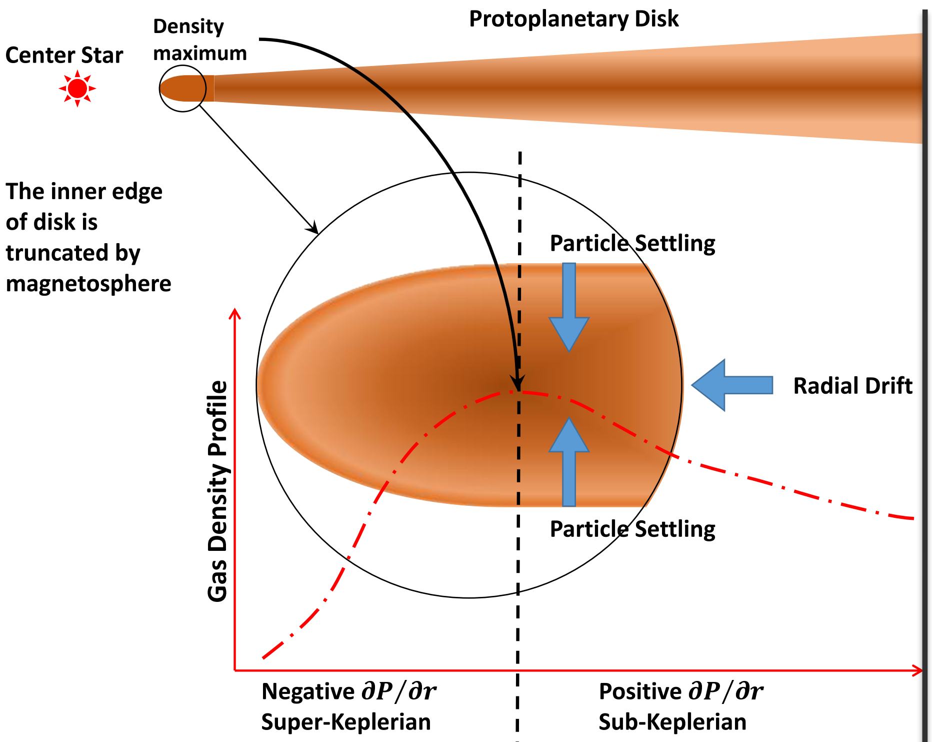


Stellar Dipole Moment

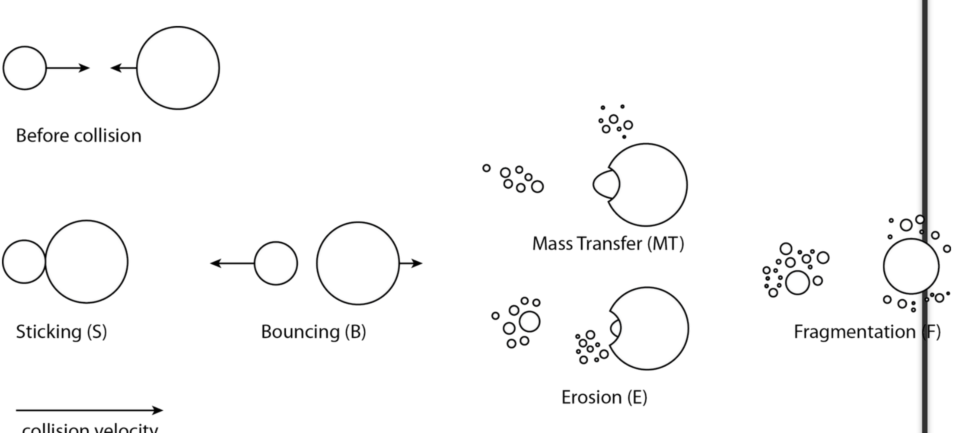


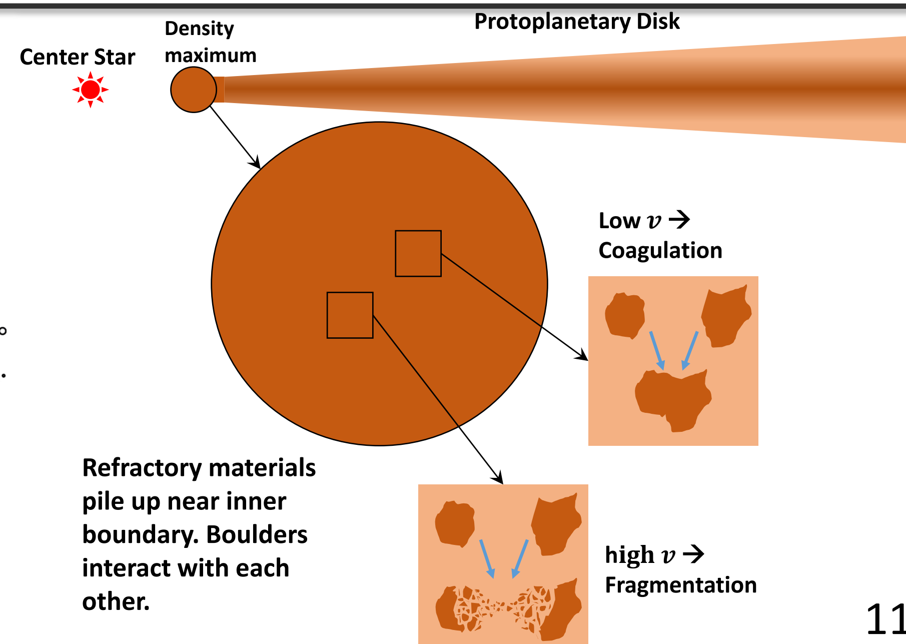
Magnetosphere radius

Herczeg


Protoplanetary Disk
Center Star
Density maximum
The inner edge of disk is truncated by magnetosphere
Particle Settling
Radial Drift
Particle Settling
Gas Density Profile
Negative $\partial P/\partial r$
Super-Keplerian
Positive $\partial P/\partial r$
Sub-Keplerian


NASA


Before collision
Sticking (S)
Bouncing (B)
Mass Transfer (MT)
Erosion (E)
Fragmentation (F)
collision velocity


Center Star
Density maximum
Protoplanetary Disk
Low v → Coagulation
high v → Fragmentation
Refractory materials pile up near inner boundary. Boulders interact with each other.

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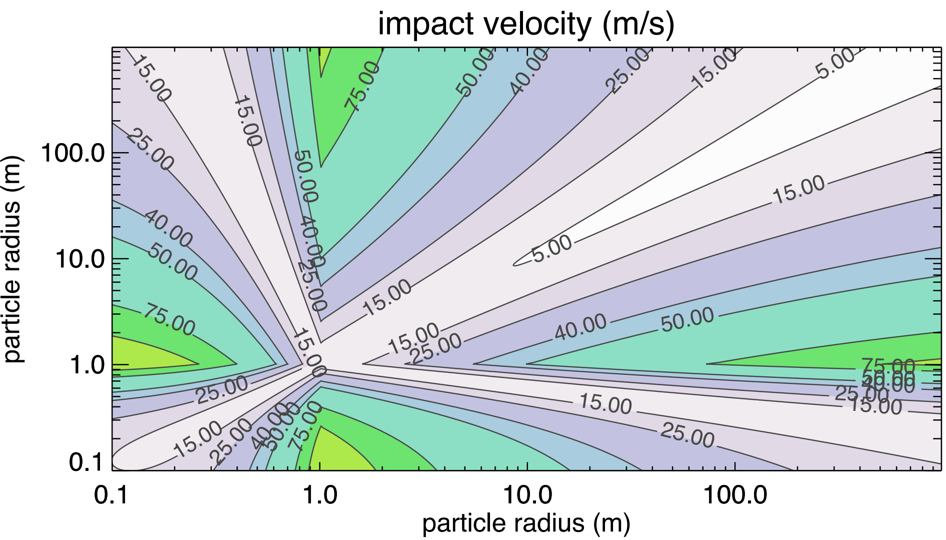
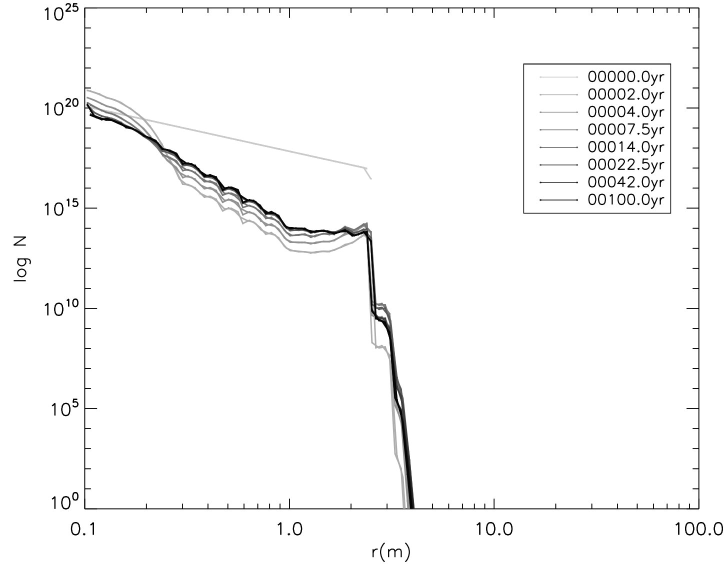
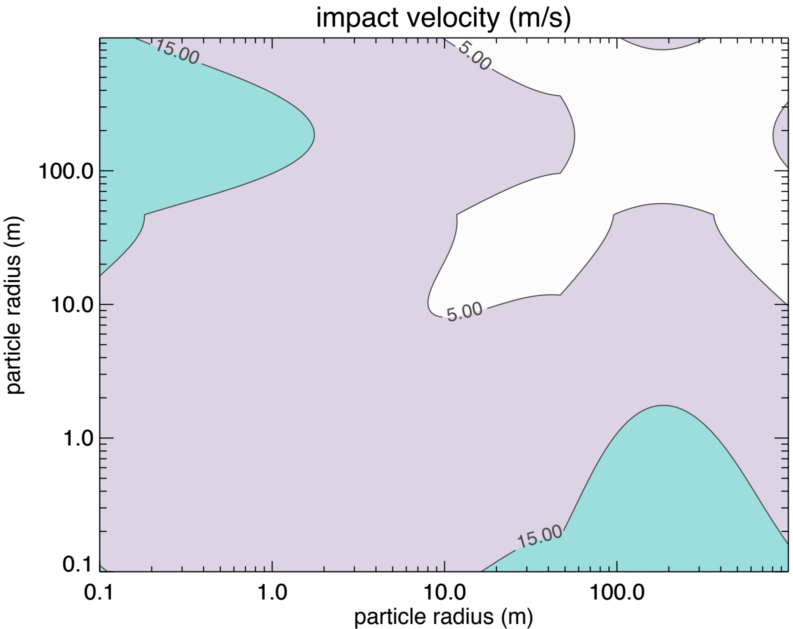
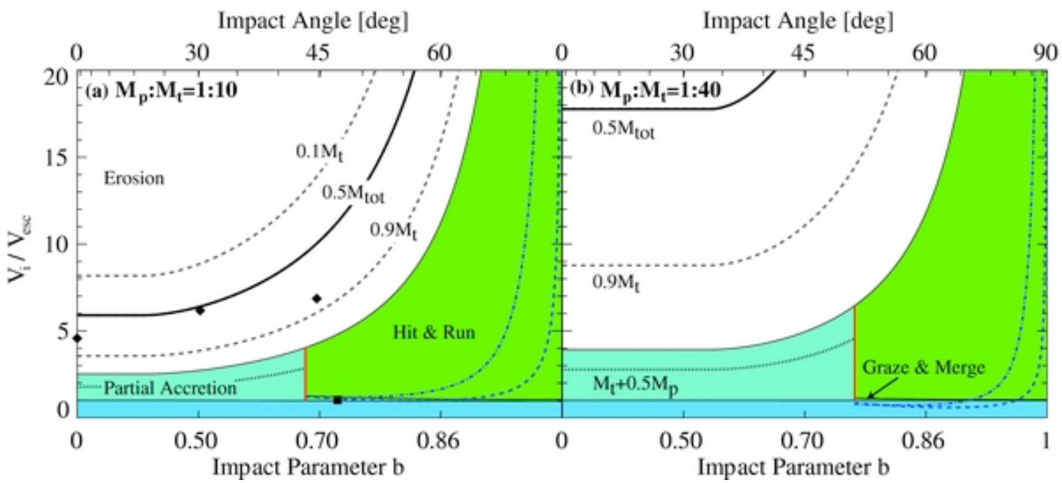
Collisional energy & spectrum

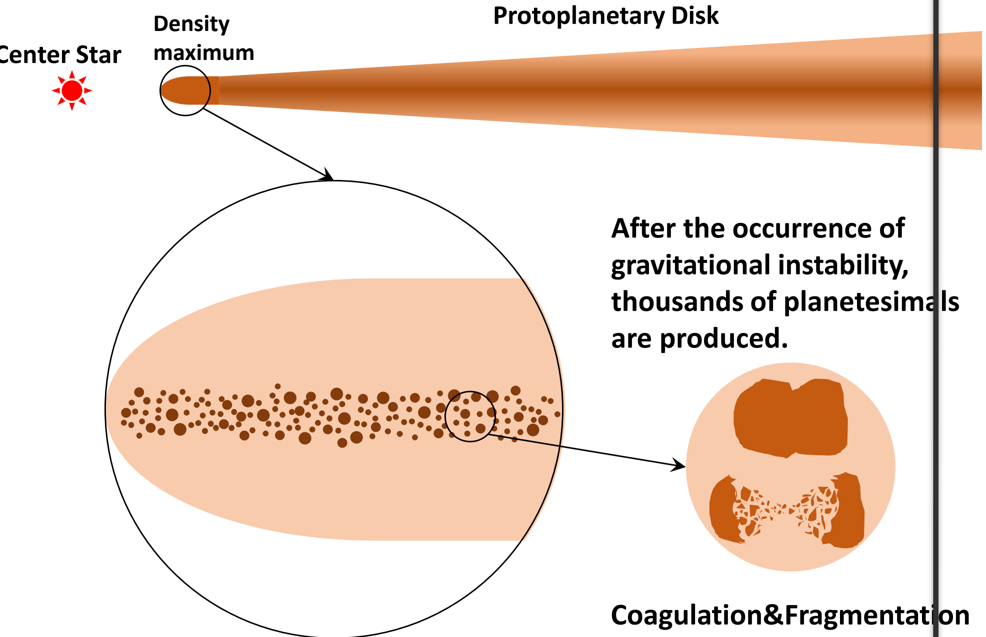






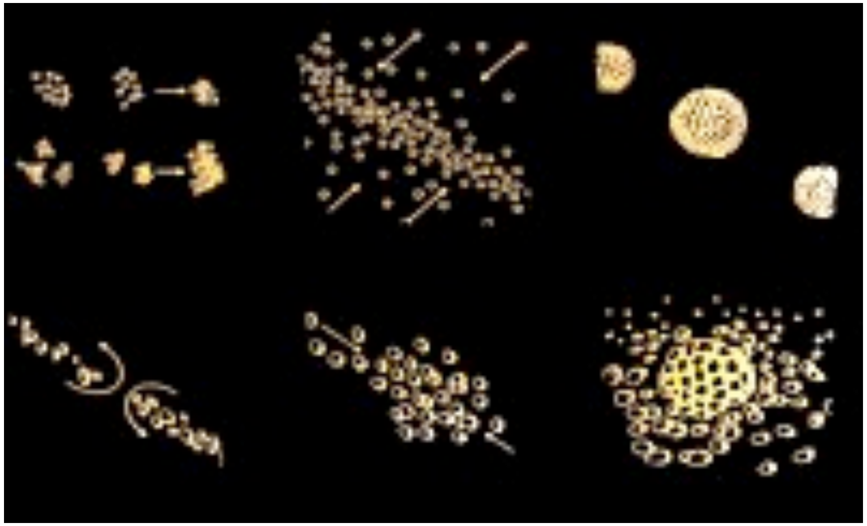


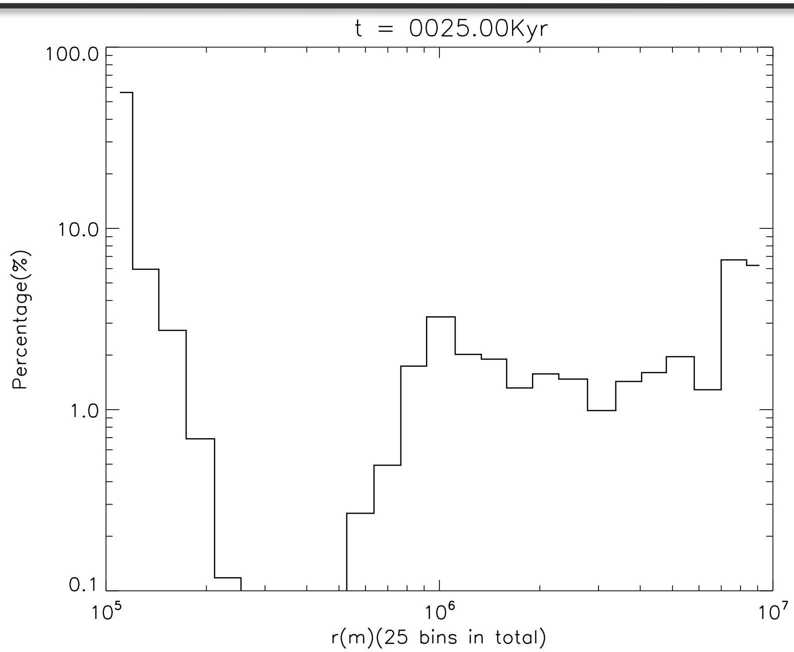
fragmentation vs gravitational instabilities

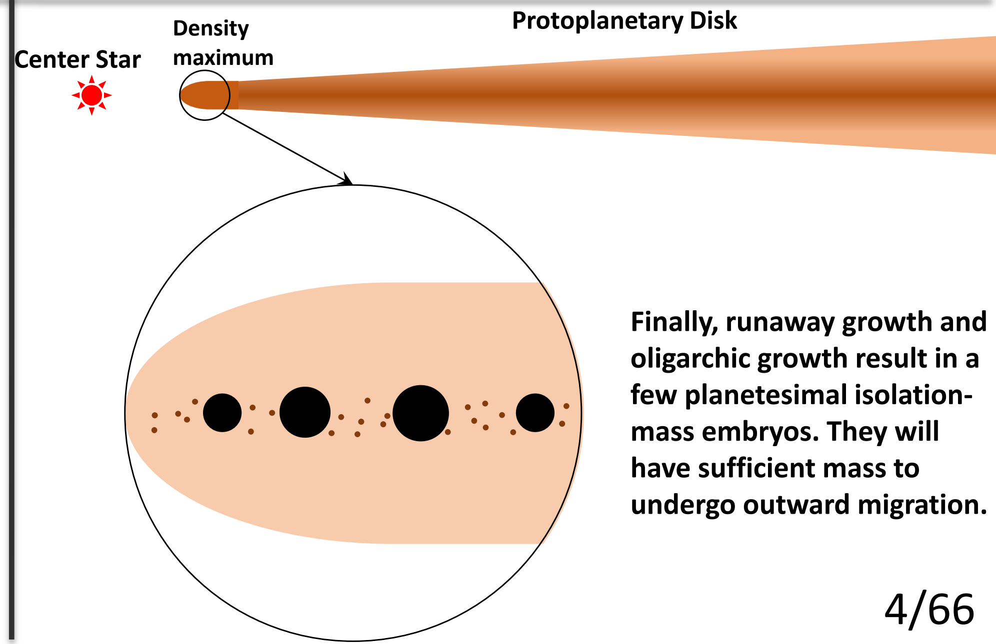


After the occurrence of gravitational instability, thousands of planetesimals are produced.

Coagulation&Fragmentation also happens between planetesimals.







Finally, runaway growth and oligarchic growth result in a few planetesimal isolation-mass embryos. They will have sufficient mass to undergo outward migration.

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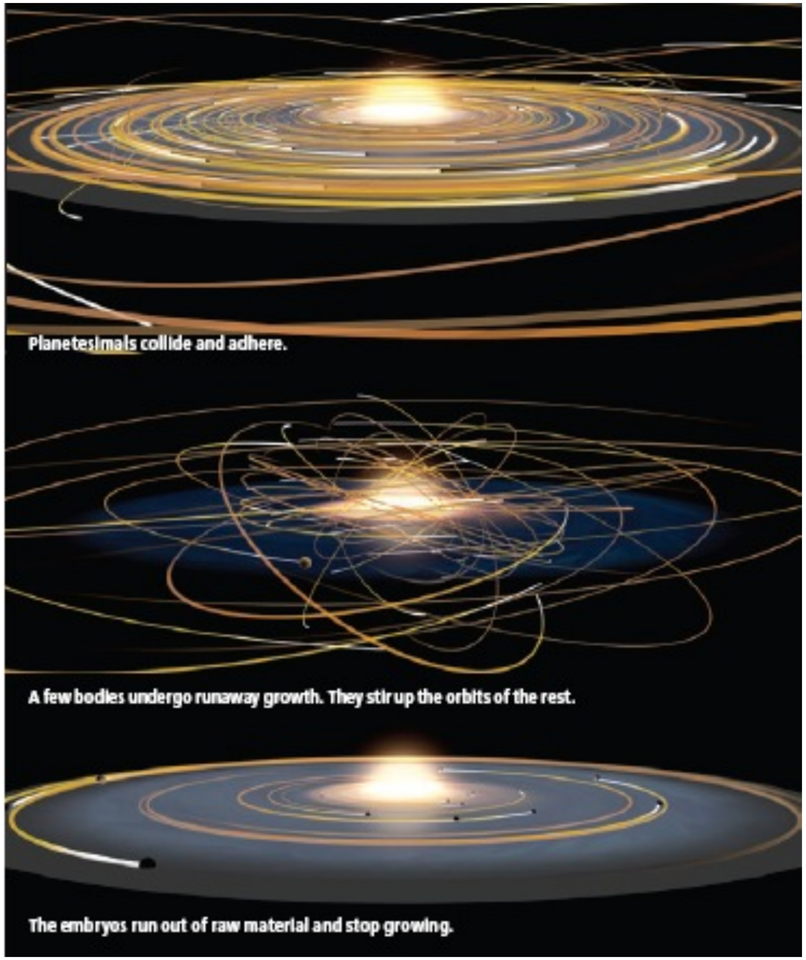
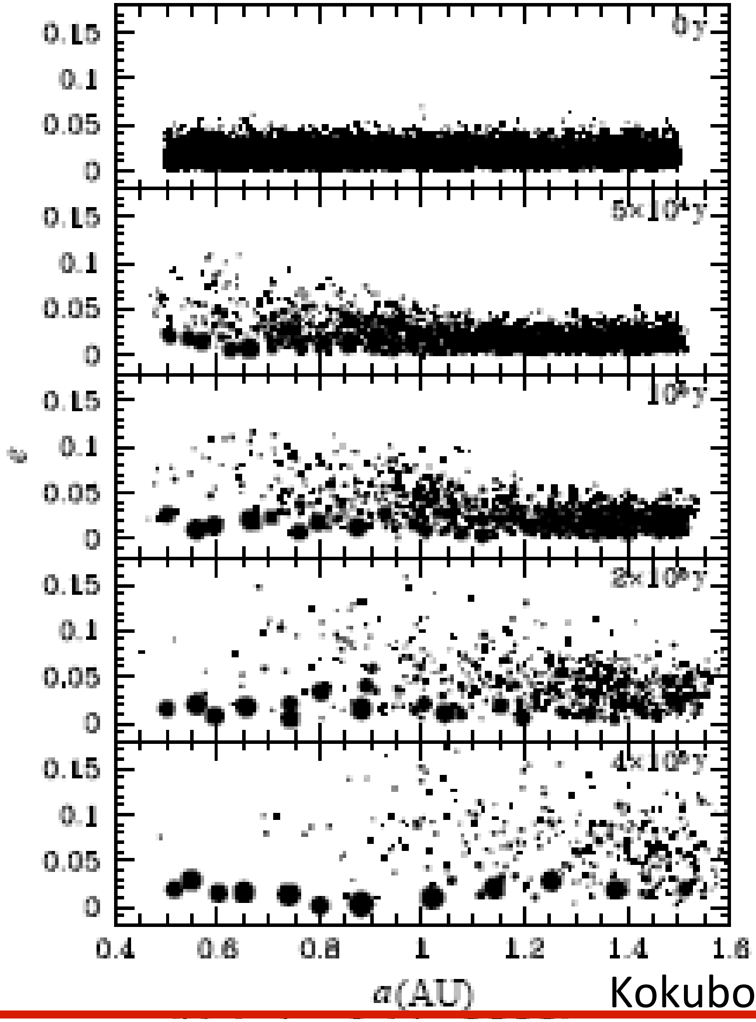
Step III, oligarchic barrier: Isolation mass





Kokubo & Ida

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

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

Equi-potential surface and Roche lope

Energy & angular momentum are not conserved.

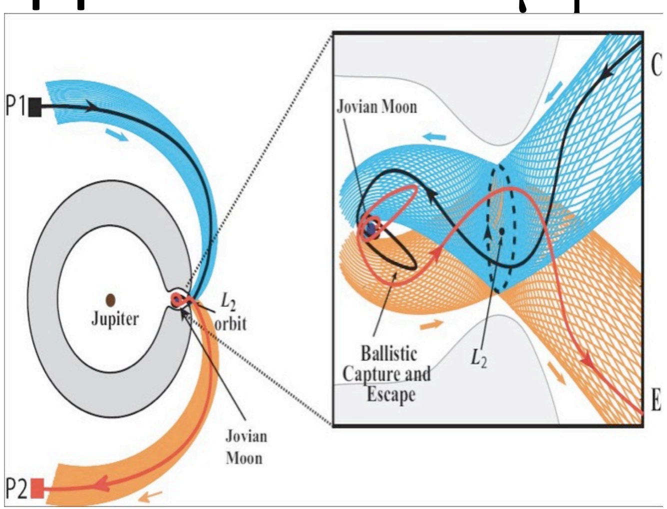
Conserved quantity: Jacobi ``energy'' Integral

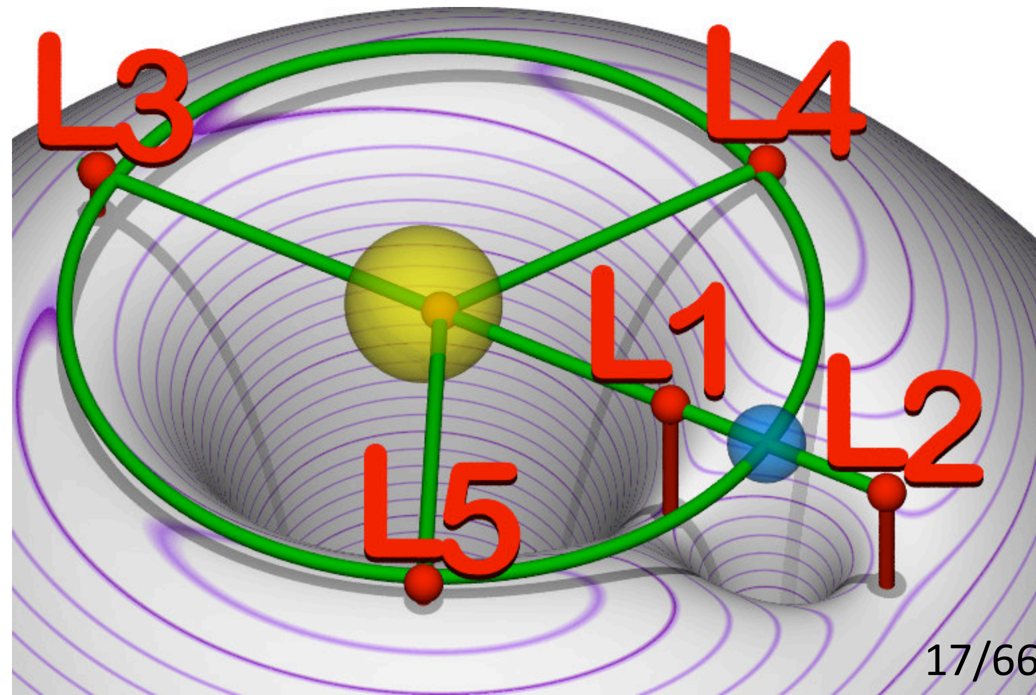
$$C_J = n^2(x^2 + y^2) + 2(\mu_1/r_1+\mu_2/r_2)-(\dot{x}^2+\dot{y}^2+\dot{z}^2)$$

Roche radius: distance between the planet and L_1

$r_R = (\mu_2/3\mu_1)^{1/3}\, a_{12}$ (to first order in μ_2/μ_1)

Hill's equation is an approximation $\mu_1 = 1$





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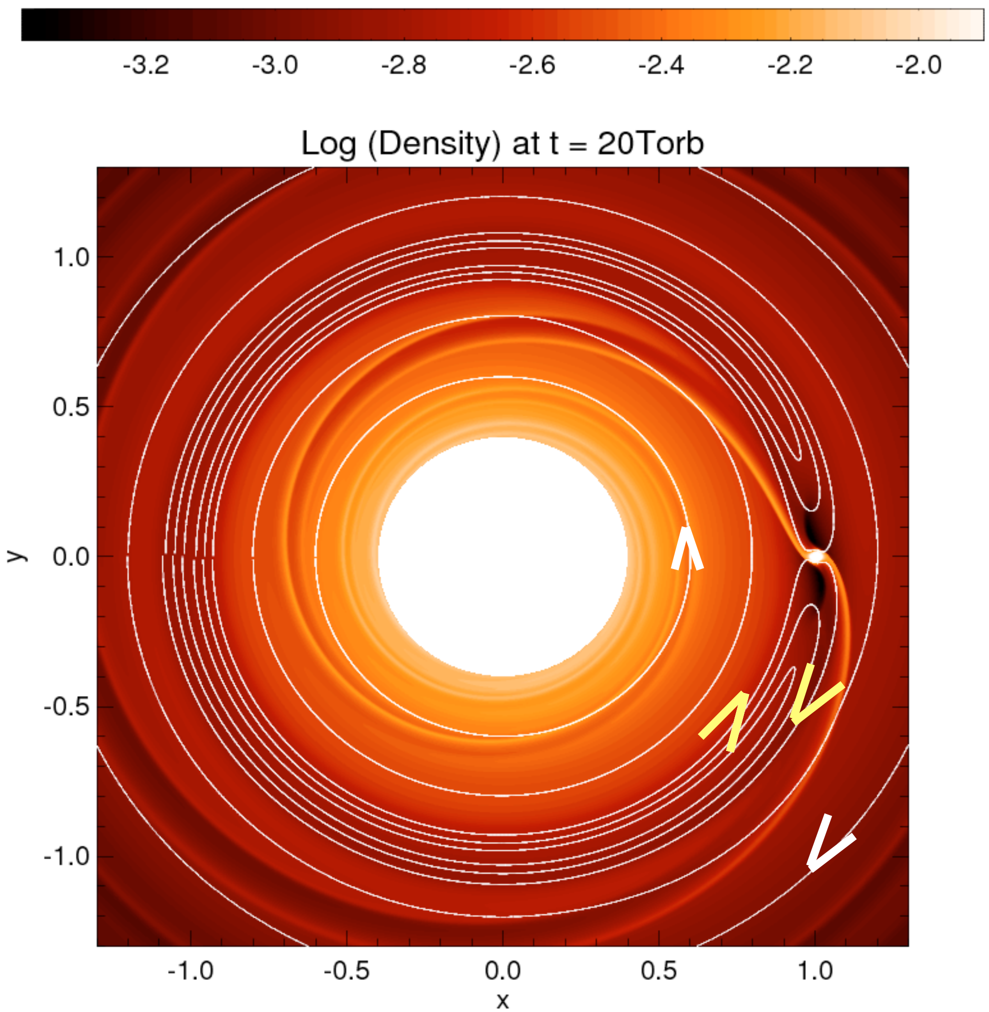
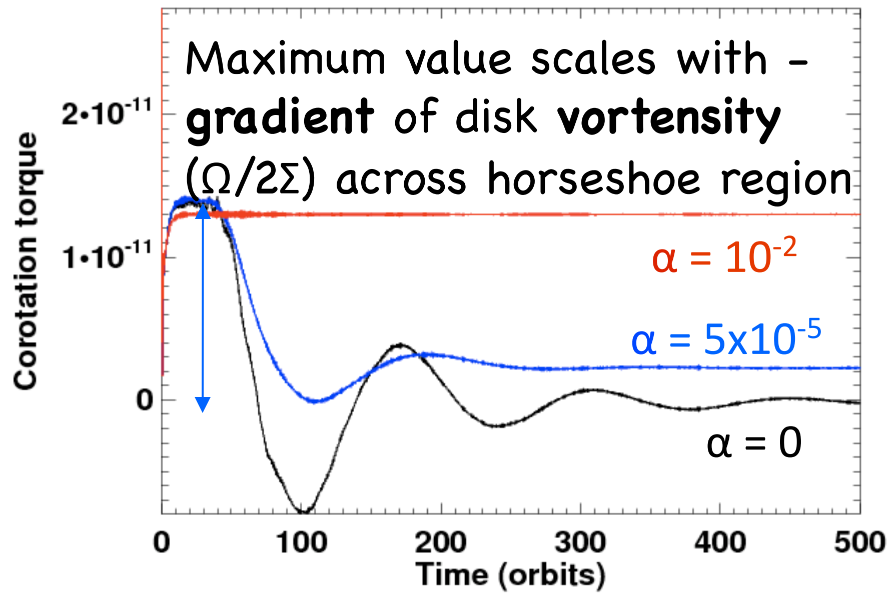
Embryos barrier: planetary migration
Type I migration of super-Earth in isothermal disks



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**,

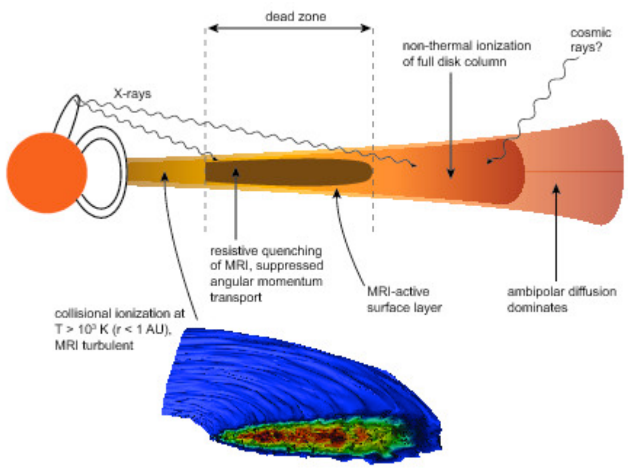
Planet-disk tidal interaction

Total tidal torque:

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

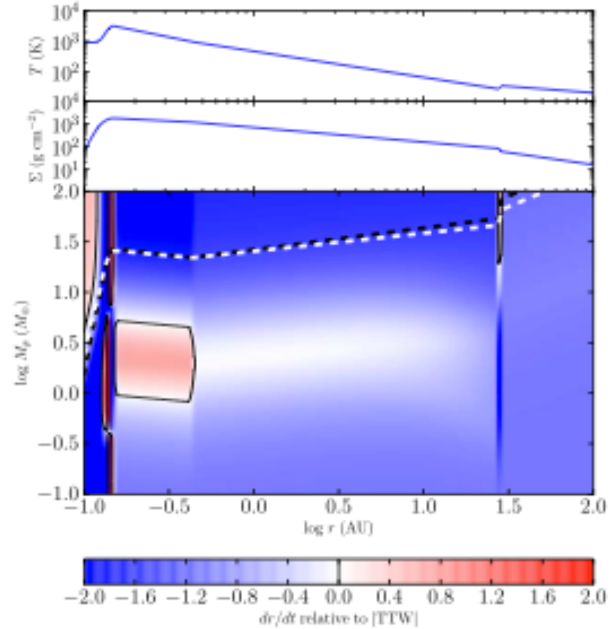
$$\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2,$$

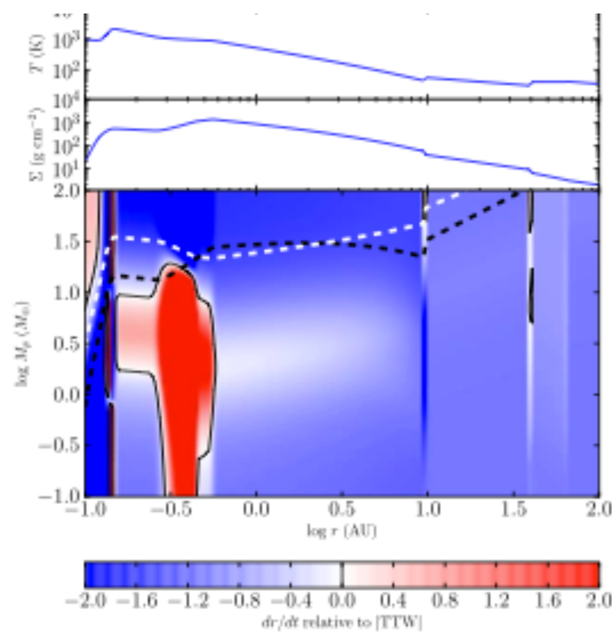
p and q depend on disk structure & p_ν, q_ν, p_κ, and q_κ also depend on m_p



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

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





Garaud, Kretke

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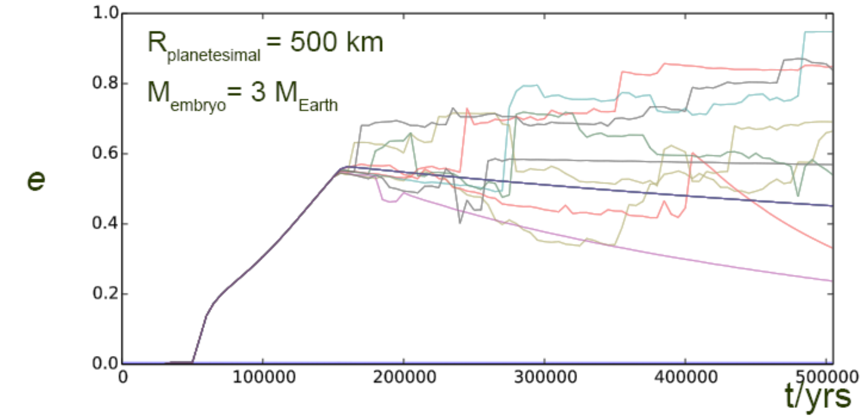
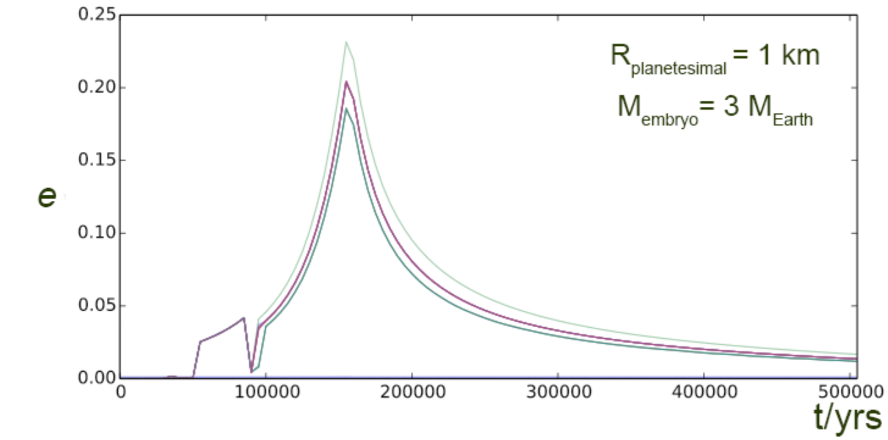
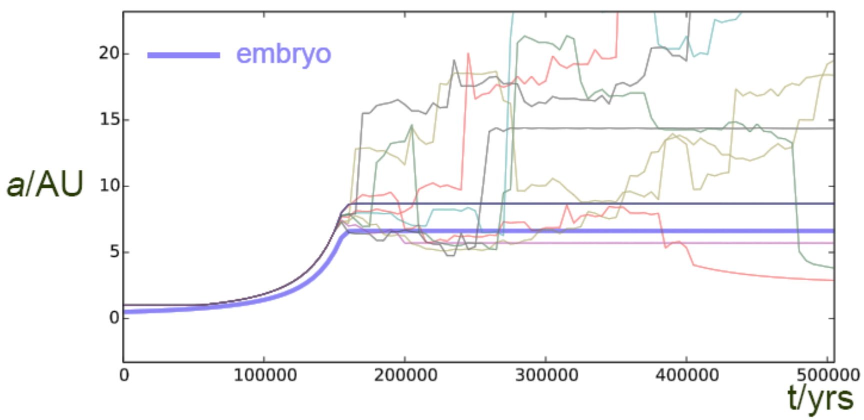
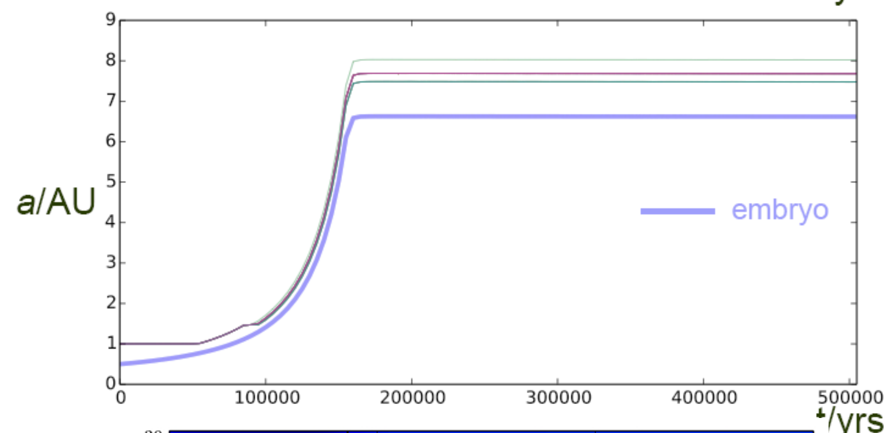
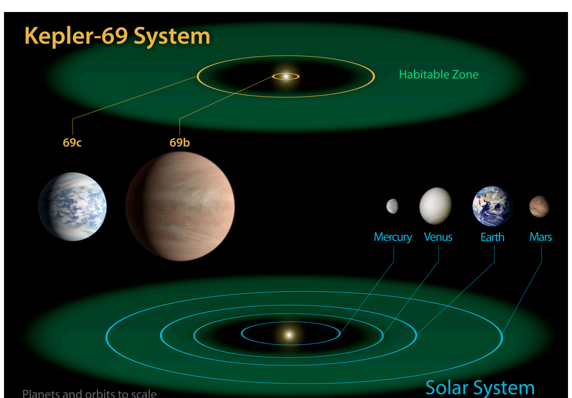
Resonant sweeping of planetesimals

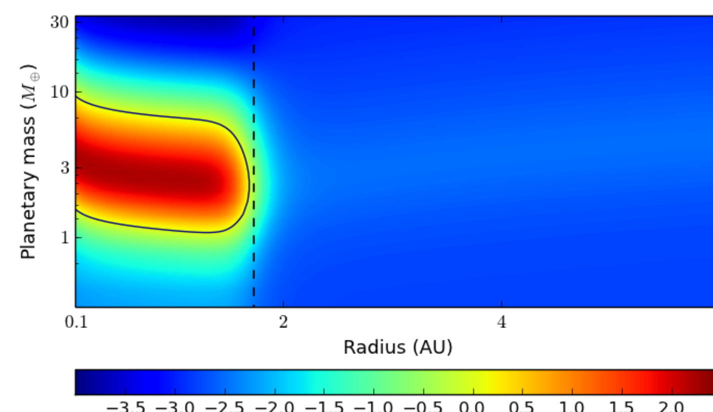












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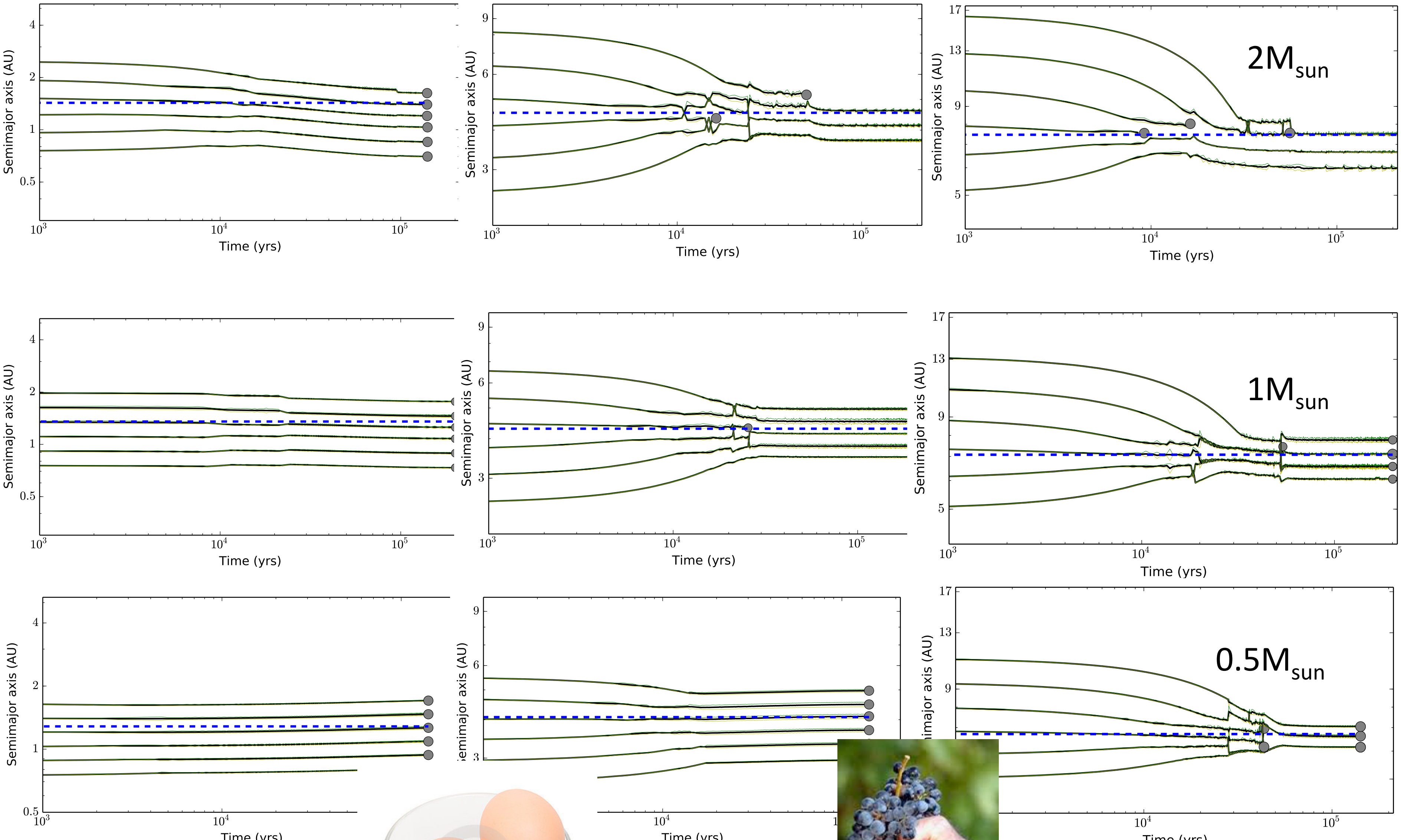
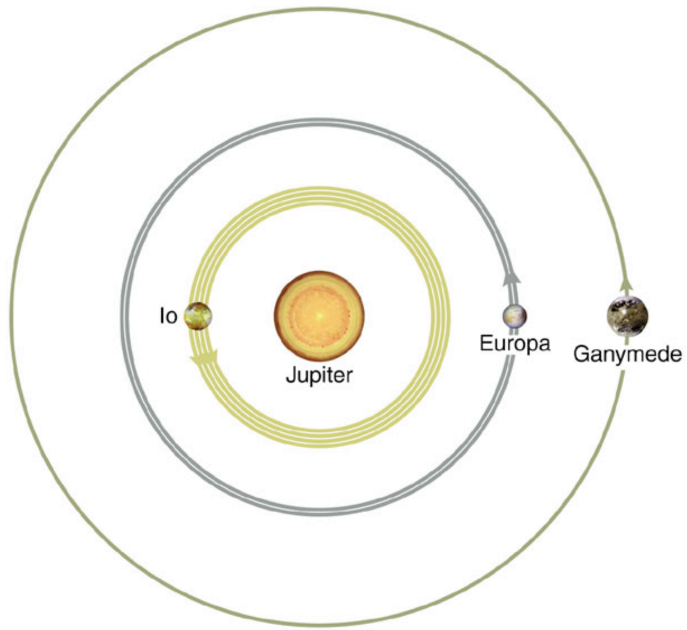
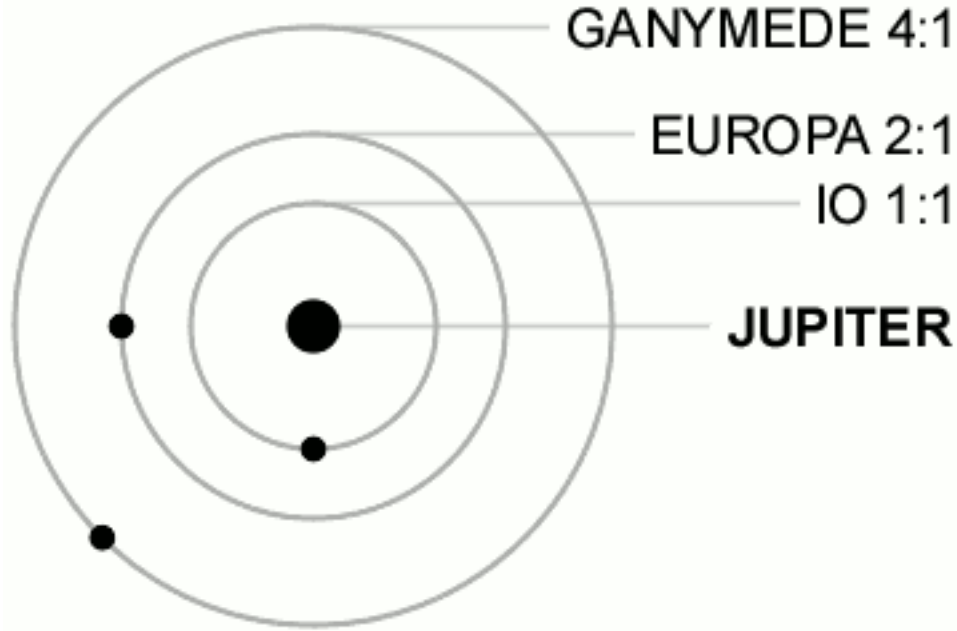
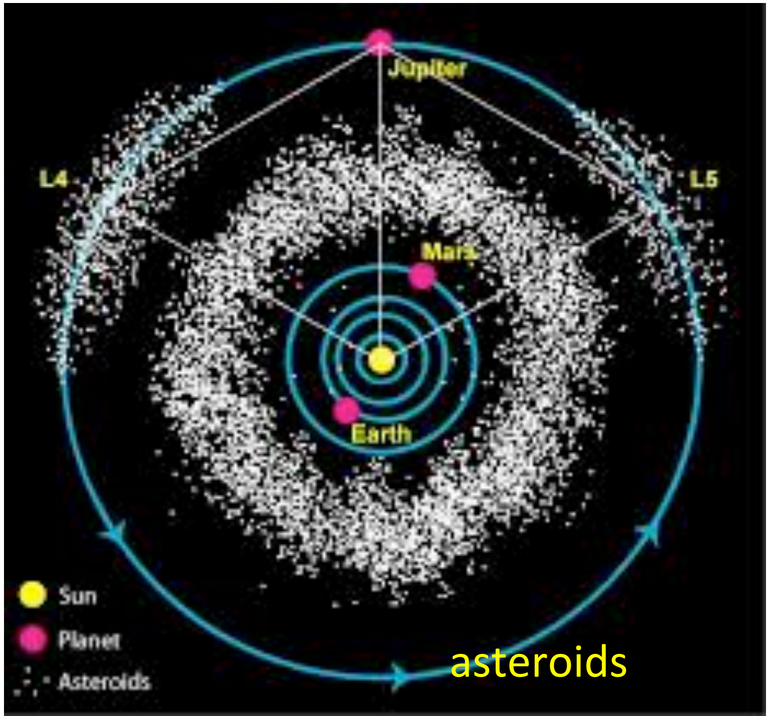
Dependence on the disks' accretion rate

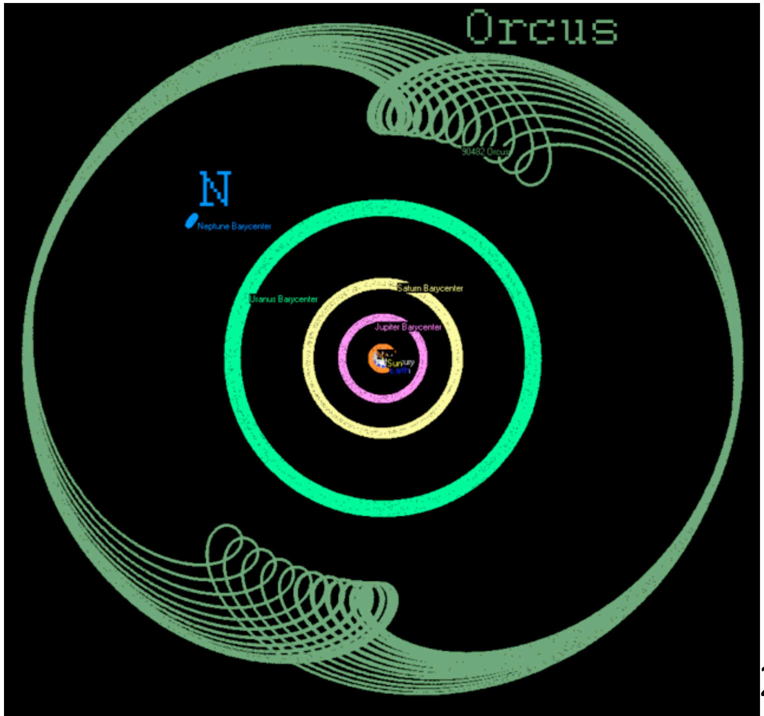


Mdot = 10^{-8} 5 x10^{-8} 10^{-7}


Io
Jupiter
Europa
Ganymede

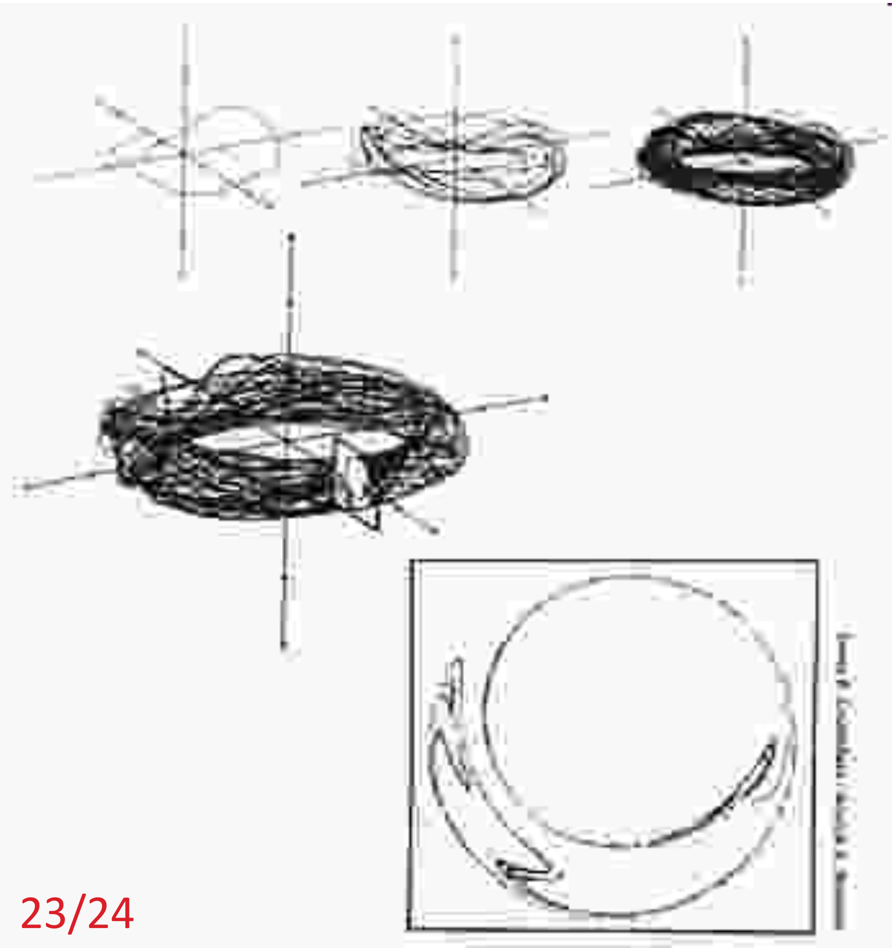

GANYMEDE 4:1
EUROPA 2:1
IO 1:1
JUPITER

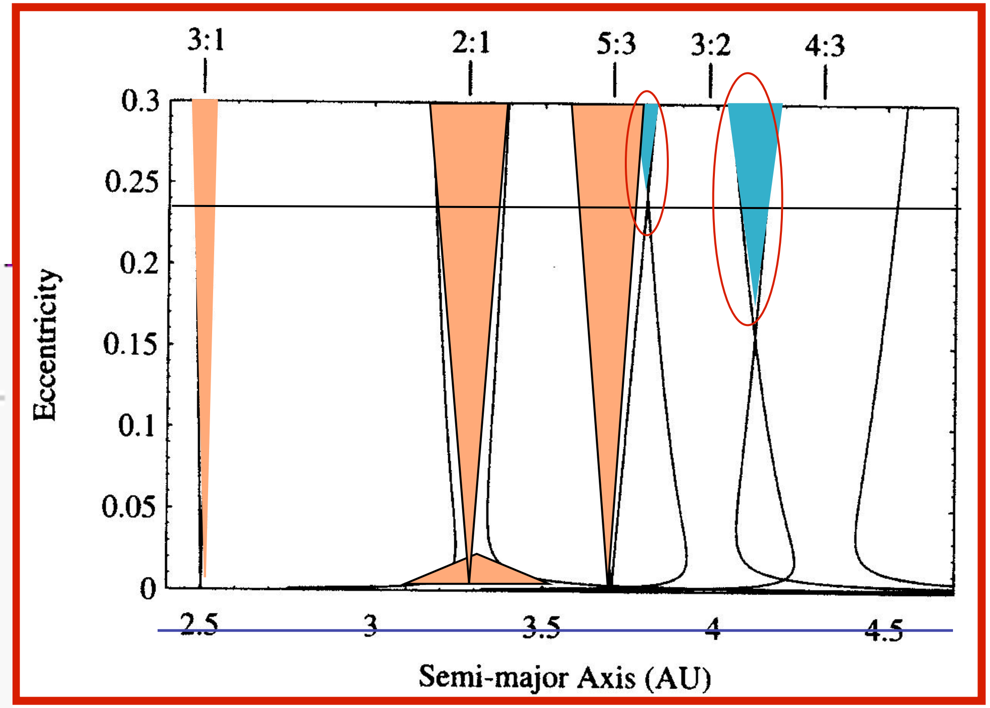

Jupiter
L4
L5
Mars
Earth
Sun
Planet
Asteroids
asteroids


Orcus
N

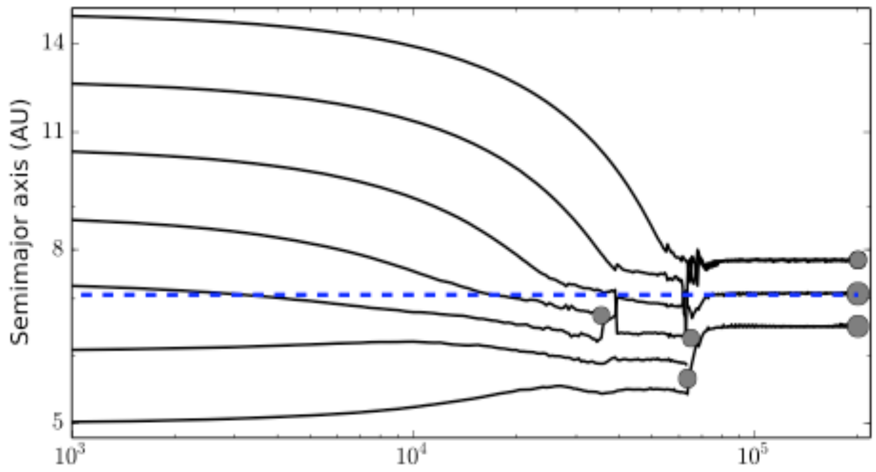
Overlapping resonances & dynamical instability

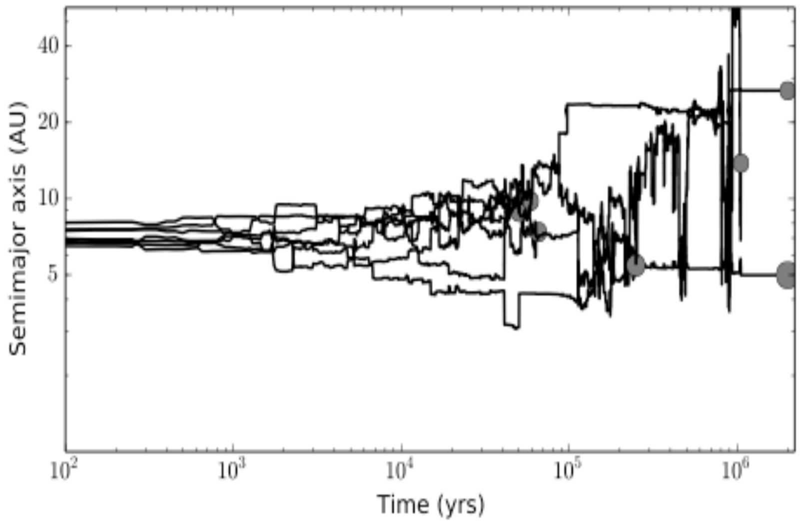
Dynamical filling factor & gas damping

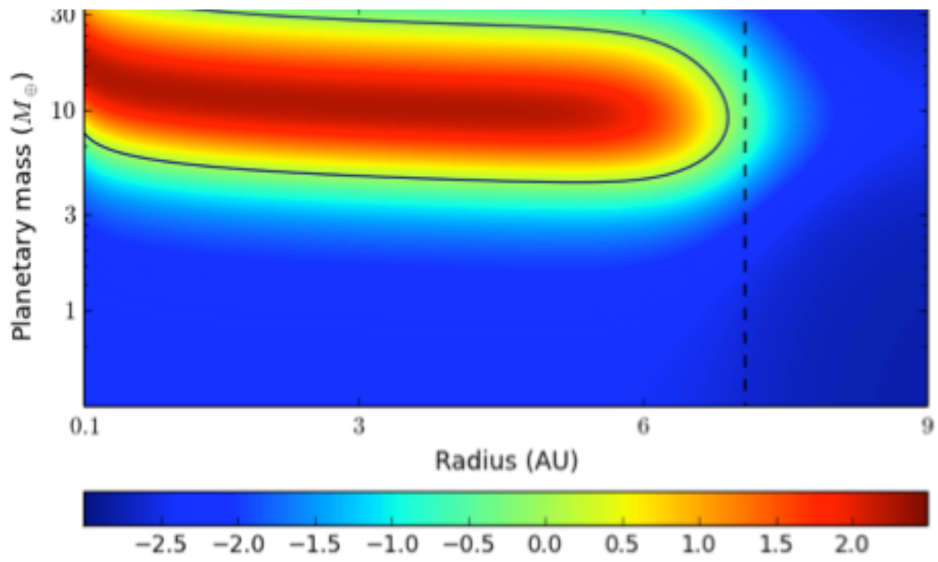




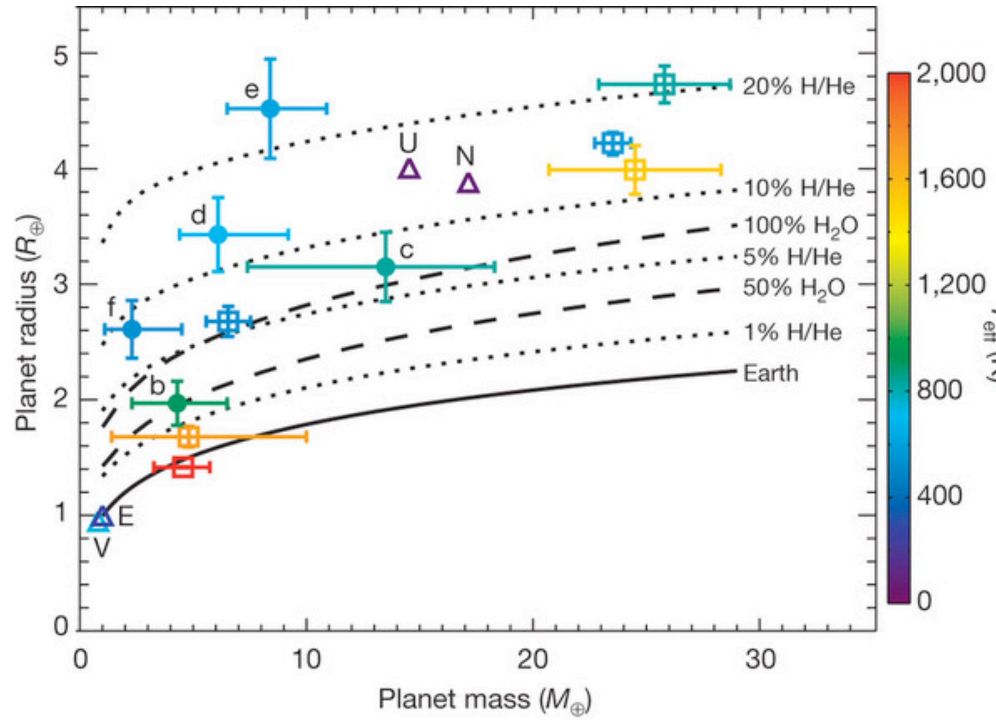
Bypass the resonance barrier



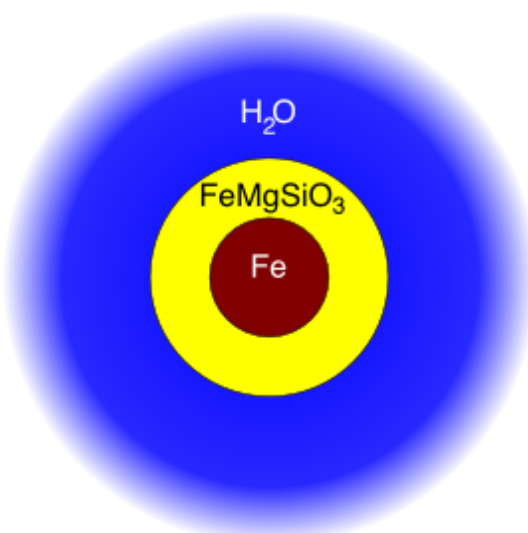


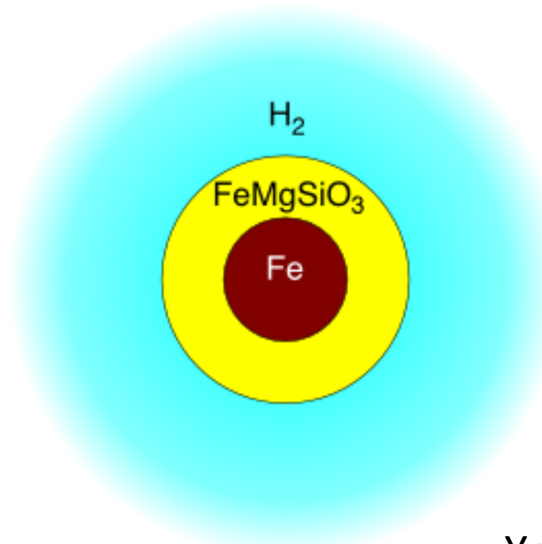


Orbit crossing, close encounters, home coming & collisions

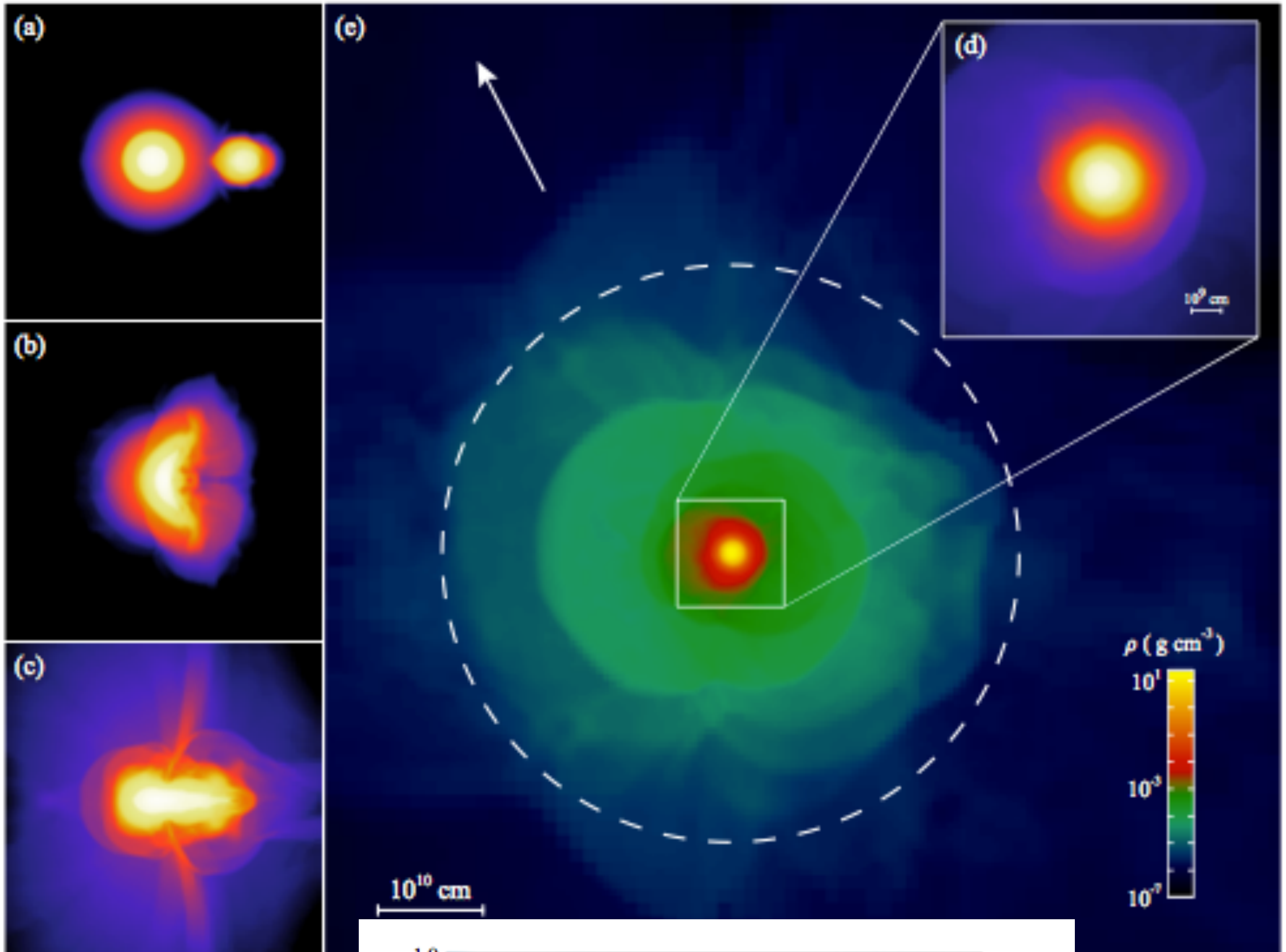


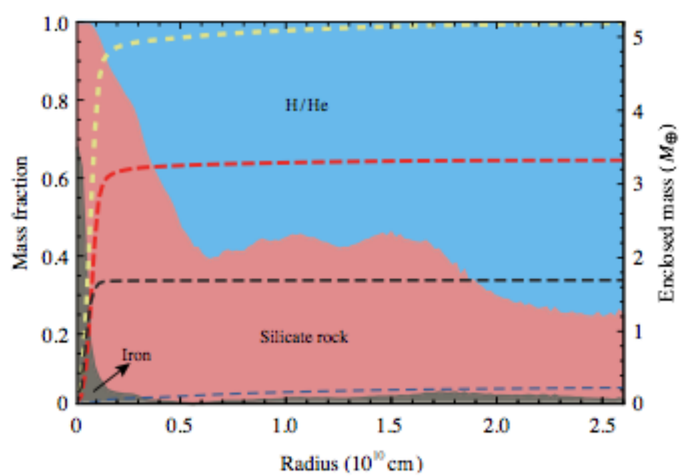
Eric Lopez, Angie Wolfgang





Yas Hori, Shangfei Liu


(a)
(b)
(c)
(c)
(d)
10^9 cm
10^{10} cm
ρ (g cm^{-3})
10^1
10^{-3}
10^{-7}


H/He
Silicate rock
Iron
Mass fraction
Enclosed mass ($M_\oplus$)
Radius (10^{10} cm)
1.0
0.8
0.6
0.4
0.2
0
0.5
1.0
1.5
2.0
2.5
5
4
3
2
1
0

Some major Challenges:

- Retention of grains: m-size barrier (Whipple)
- Fragmentation: km-size barrier (Benz)
- Planetesimal-growth barrier: Isolation mass barrier (Safronov, Wetherill), Oligarchics (Kokubo, Ida)
- Retention of embryos: type I migration (Goldreich, Tremaine, Ward)
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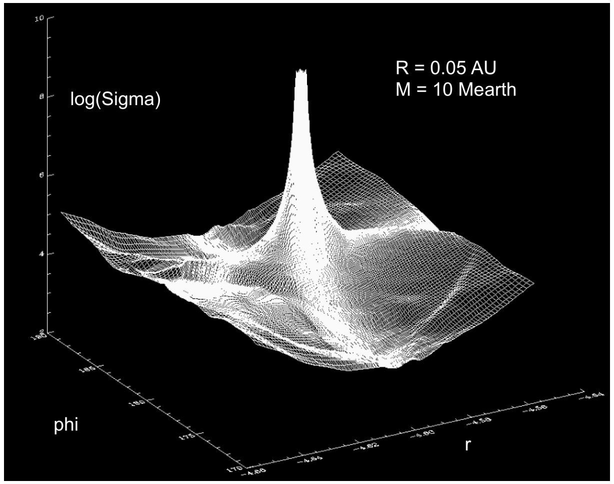
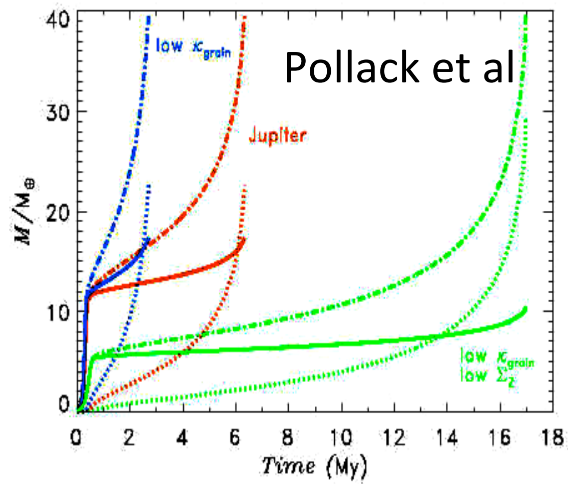
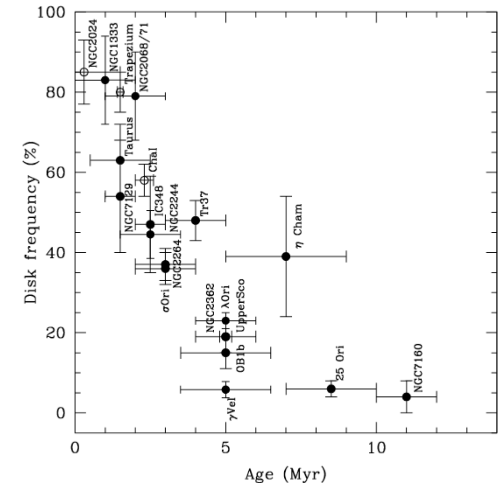
- Diversity of planetary architecture
- Onset of efficient gas accretion (Pollack, Bodenheimer)
- Retention of gas giants: type II migration (Lin & Papaloizou)
- Multiple gas giants: rapid depletion of disk gas
- Competing physics on multiple length & time scales

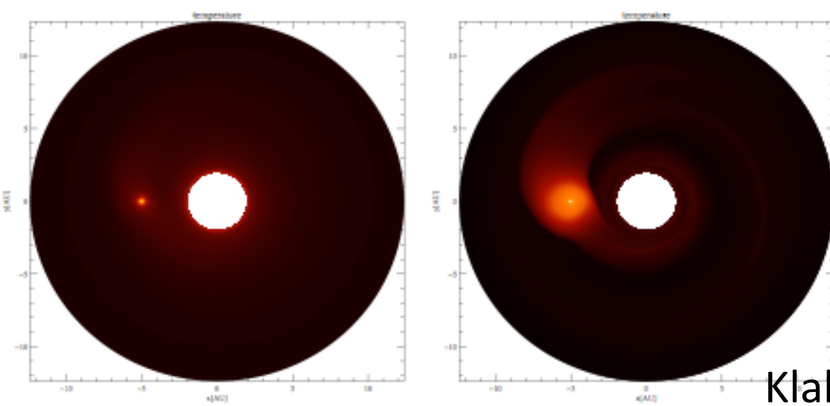
Gas accretion barrier:

- Is there a threshold mass for gas accretion?



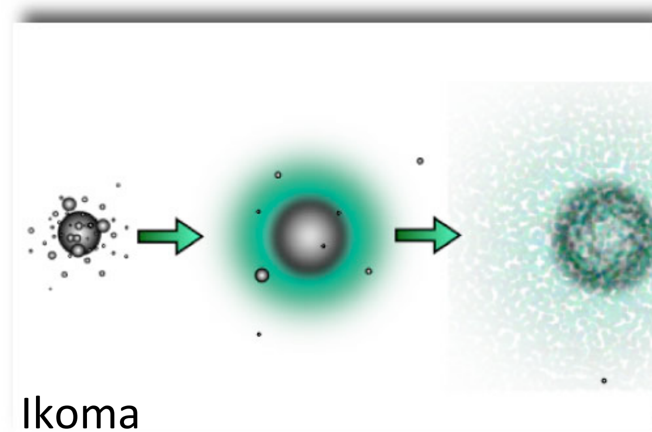






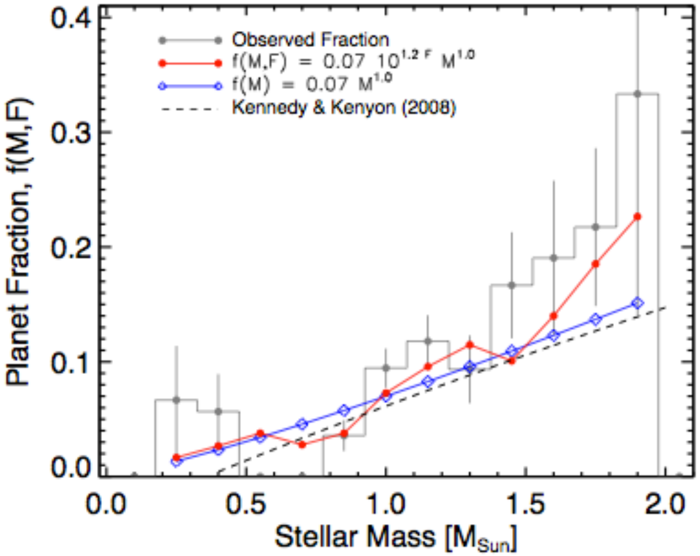
Klahr

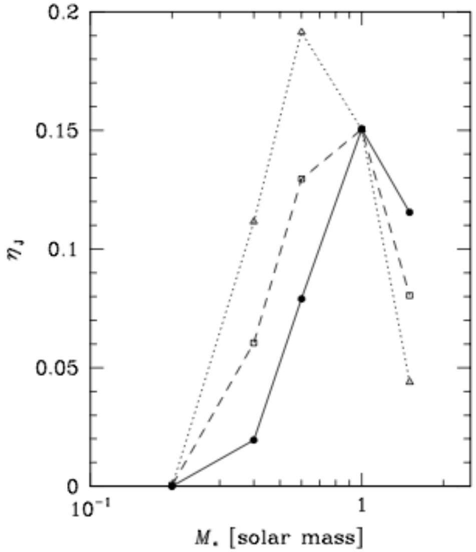
Fig. 4.— Tempertature distribution - left: $30M_\oplus$ and $\kappa = 0.01\kappa_0$; right: $30M_\oplus$ and $\kappa = 1\kappa_0$

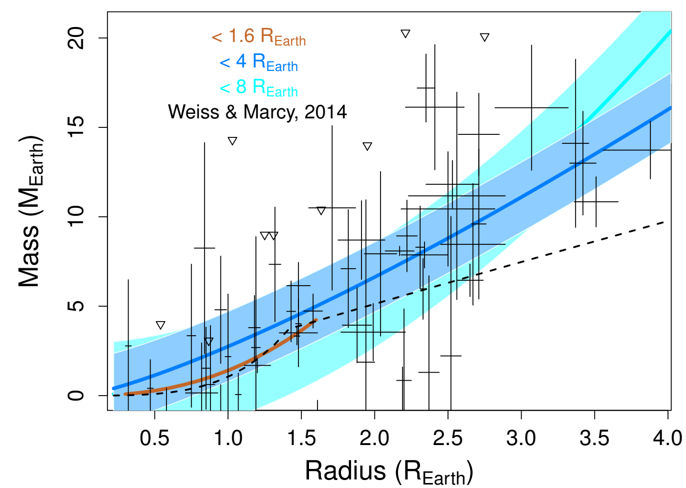


Radiation transfer & gas accretion

Dependence on stellar mass

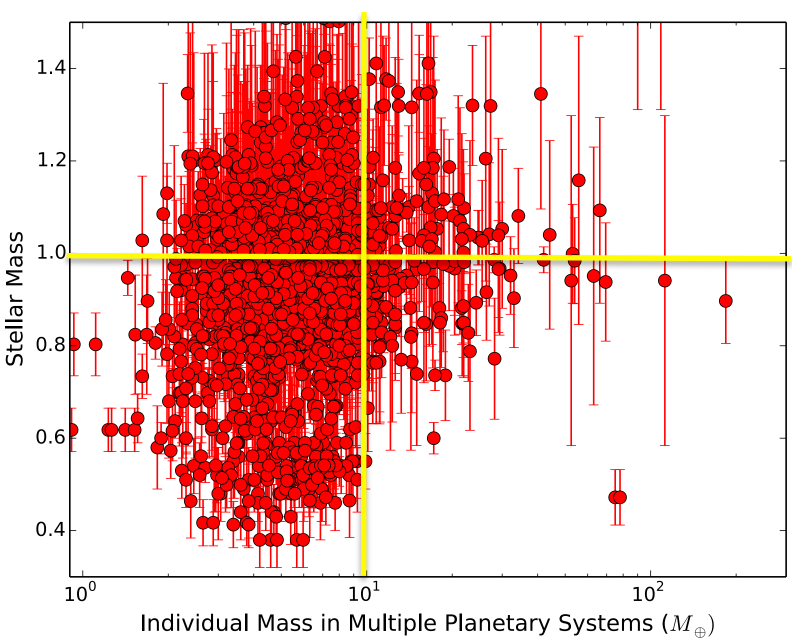




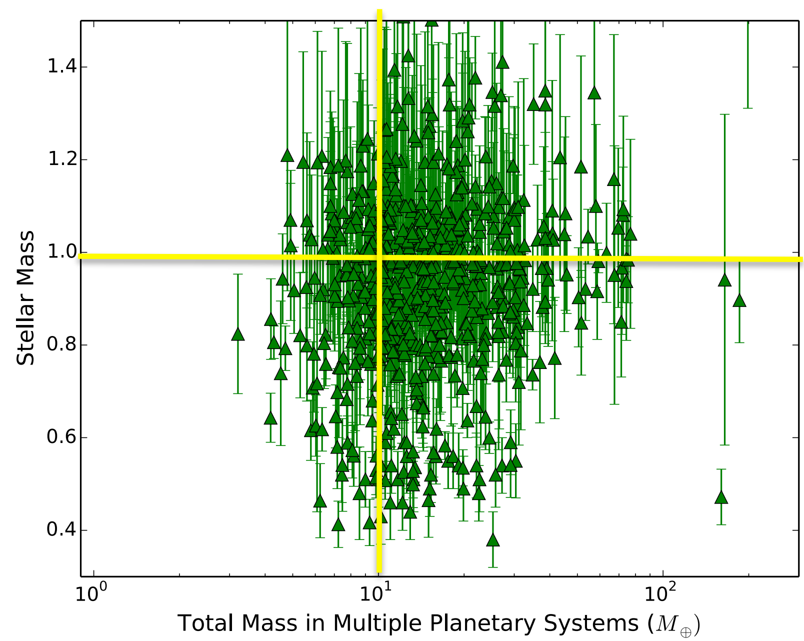


Ida

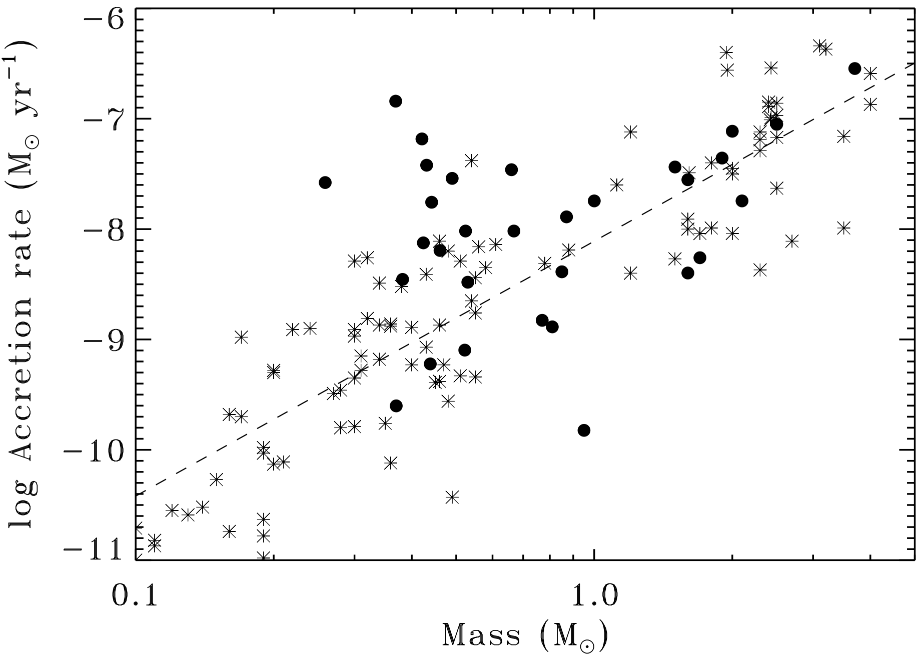
Wolfgang

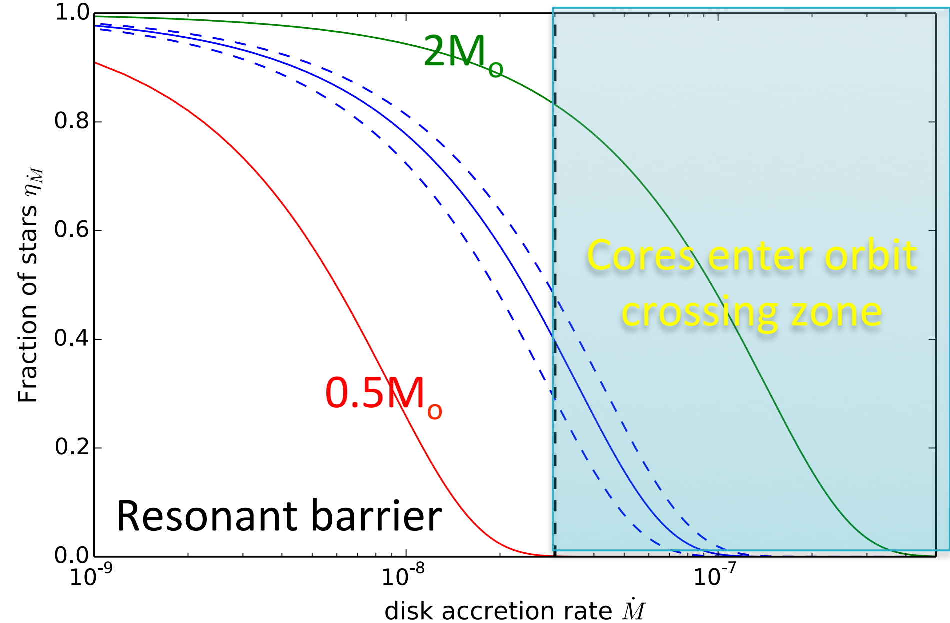


Beibei Liu

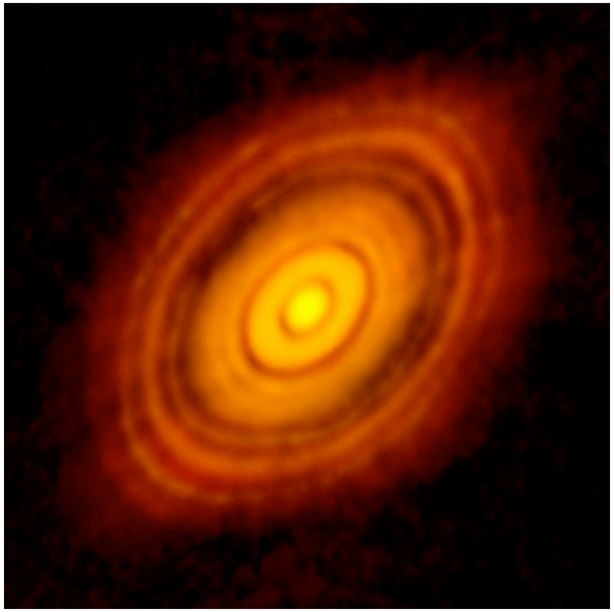


Dependence on the disks' accretion rate

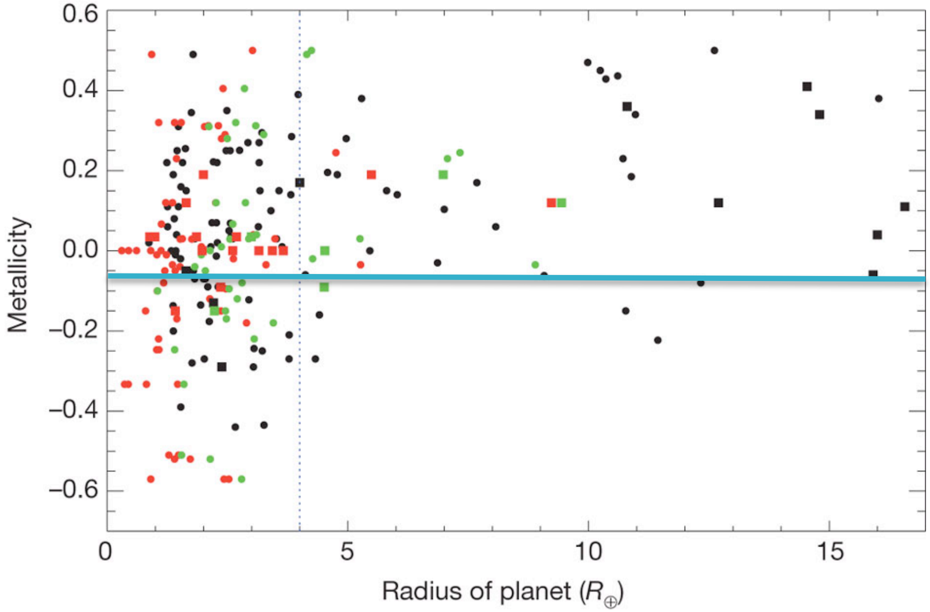




1) Cores' migration speed is determined by the surface density of the disk gas.
2) Surface density of the disk gas is proportional to the gas accretion rate
3) Gas accretion is observed to increase with the host stars' mass.
4) Gas giants' frequency correlation with the host stars' mass is through mdot.

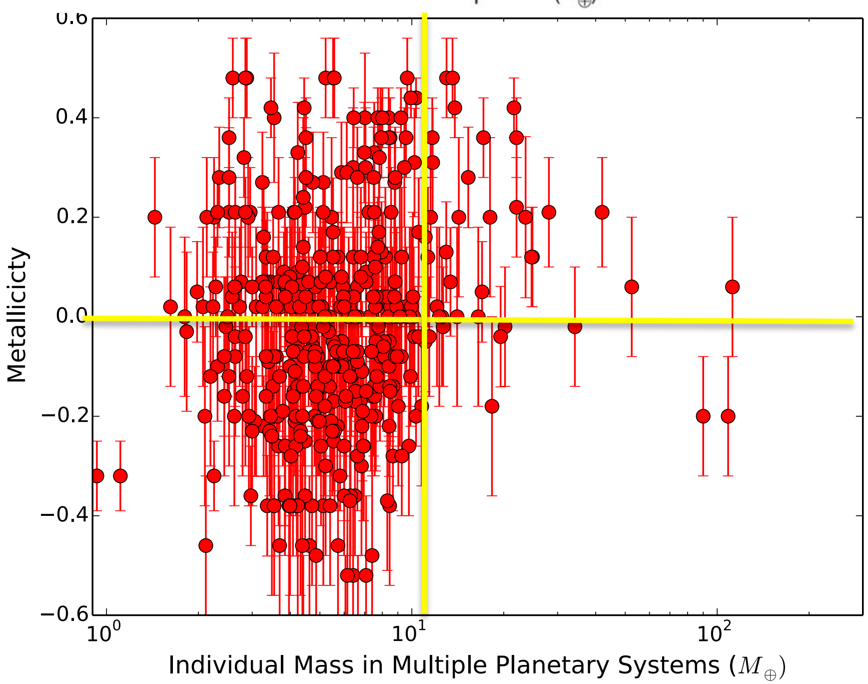


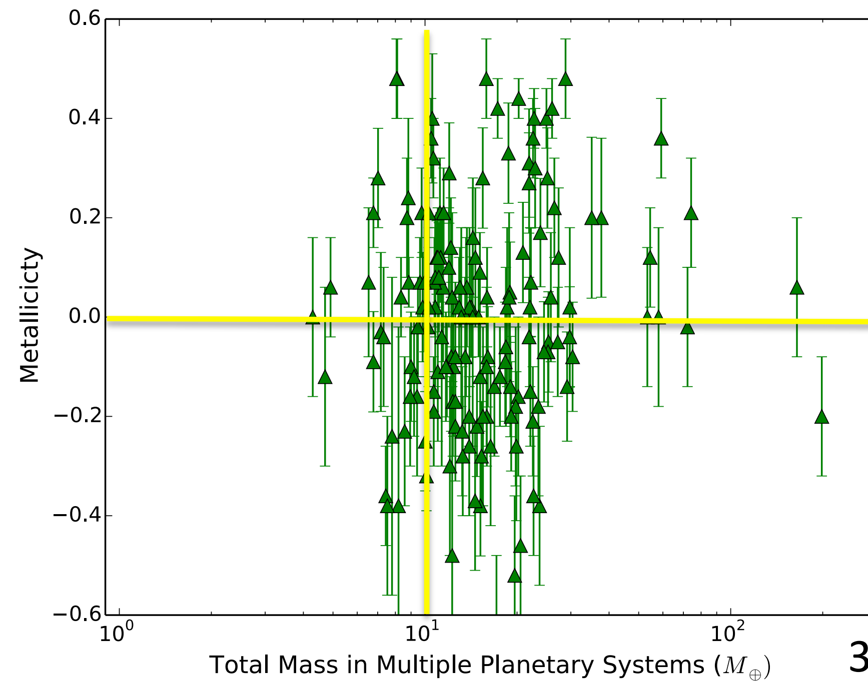
Abundance of super Earths



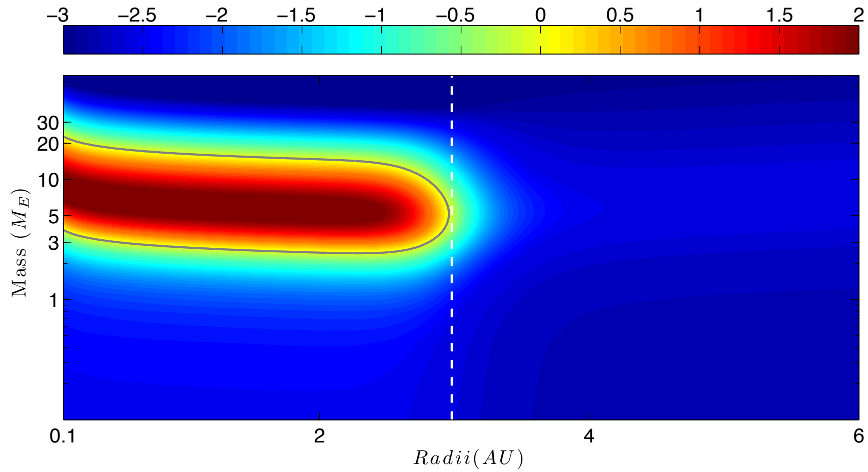
There is **no** shortage of super Earths around metal-poor stars

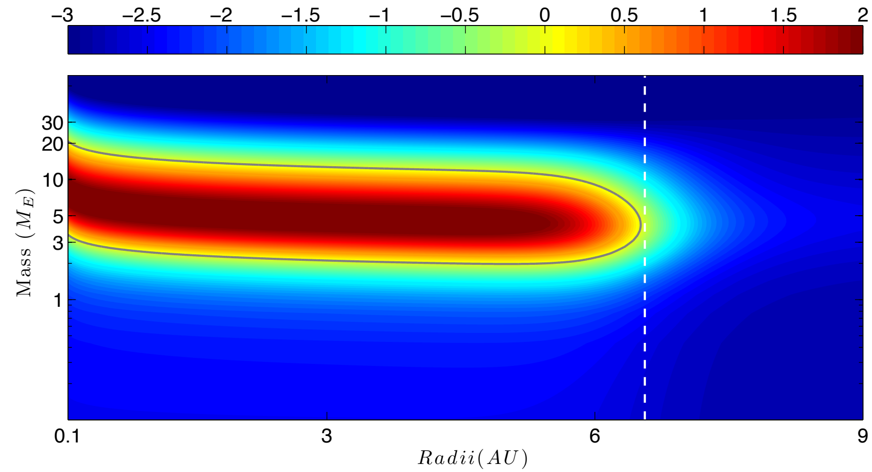
Formation of super Earths Does **not** depend on Z_* or M_*

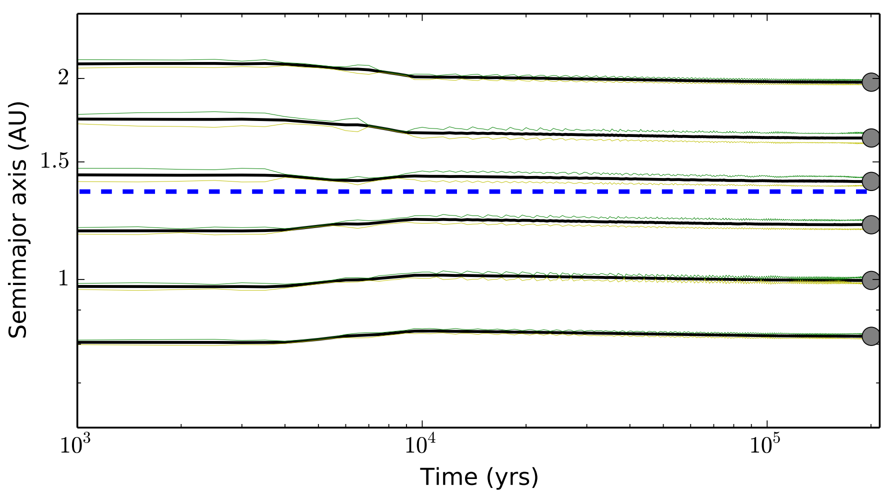


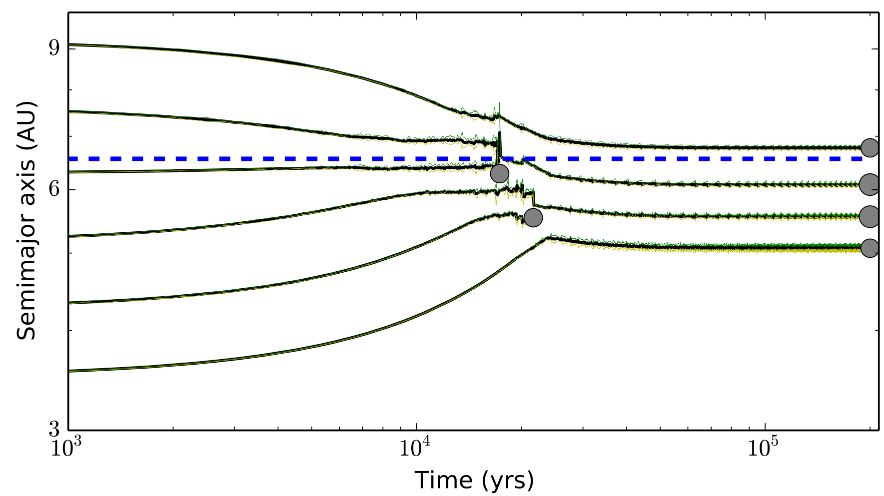


Dependence on metallicity

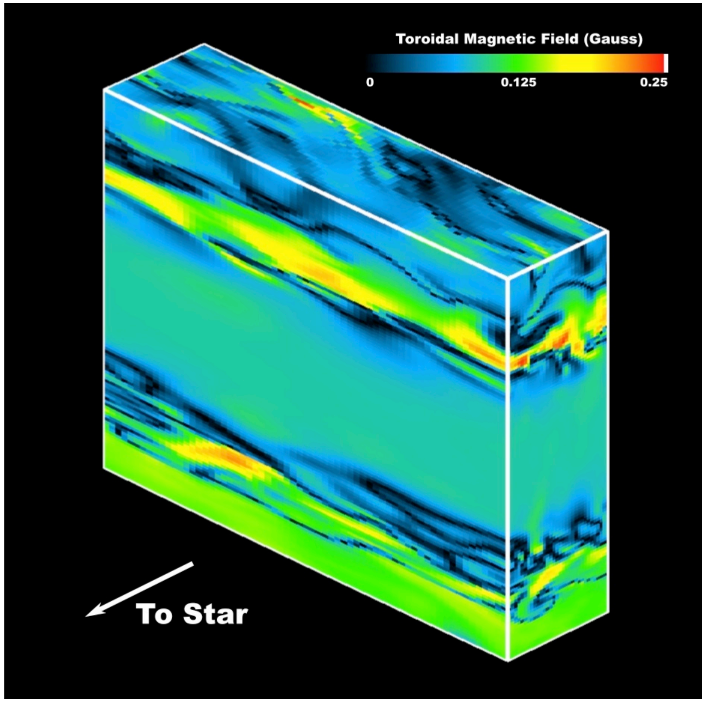


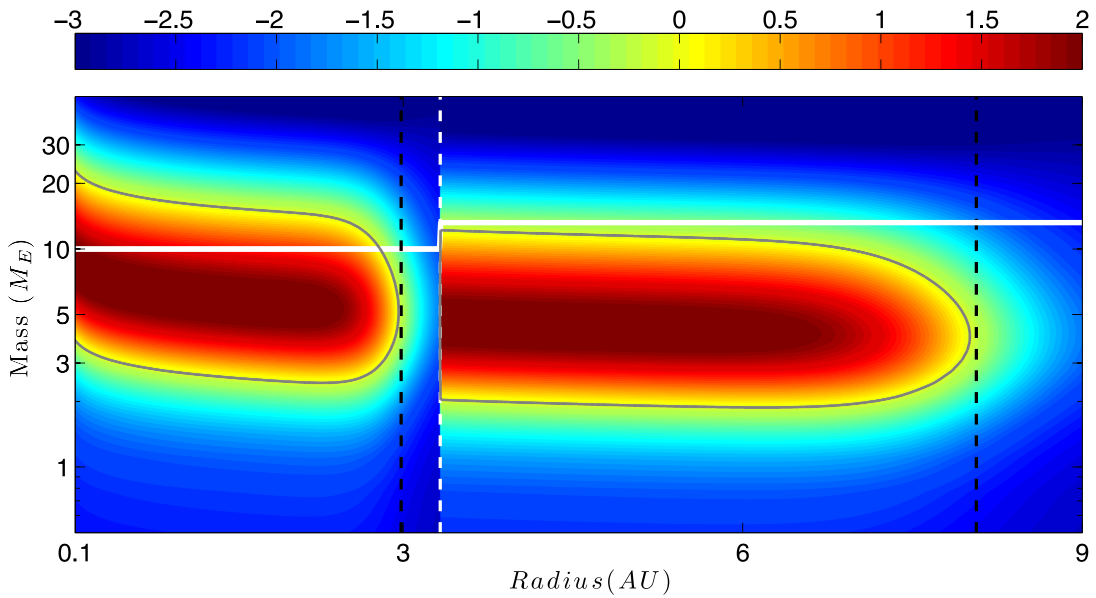


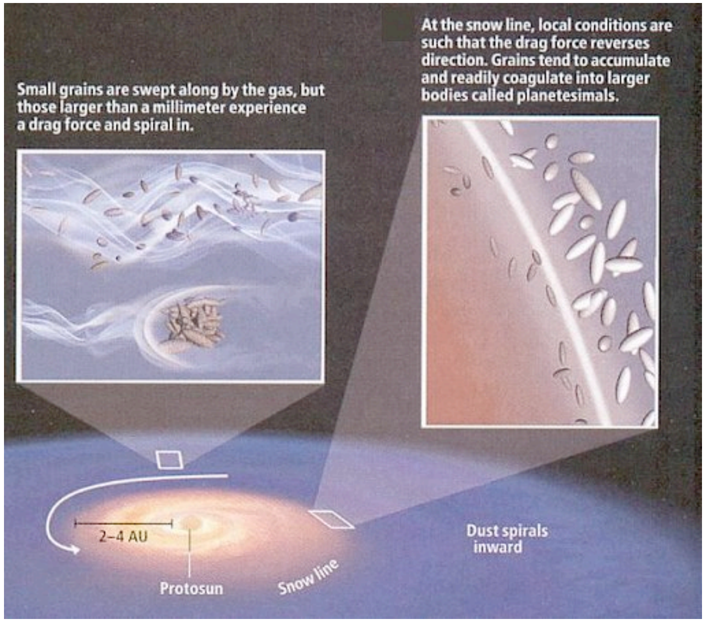


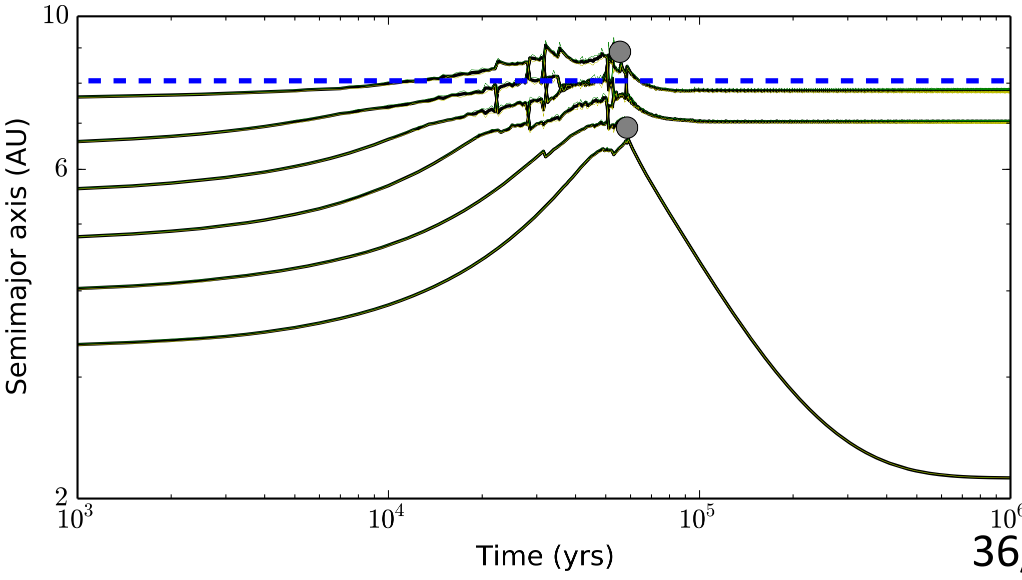


Fe/H=1 3×10^{-8} M_{sun}/yr Fe/H=3

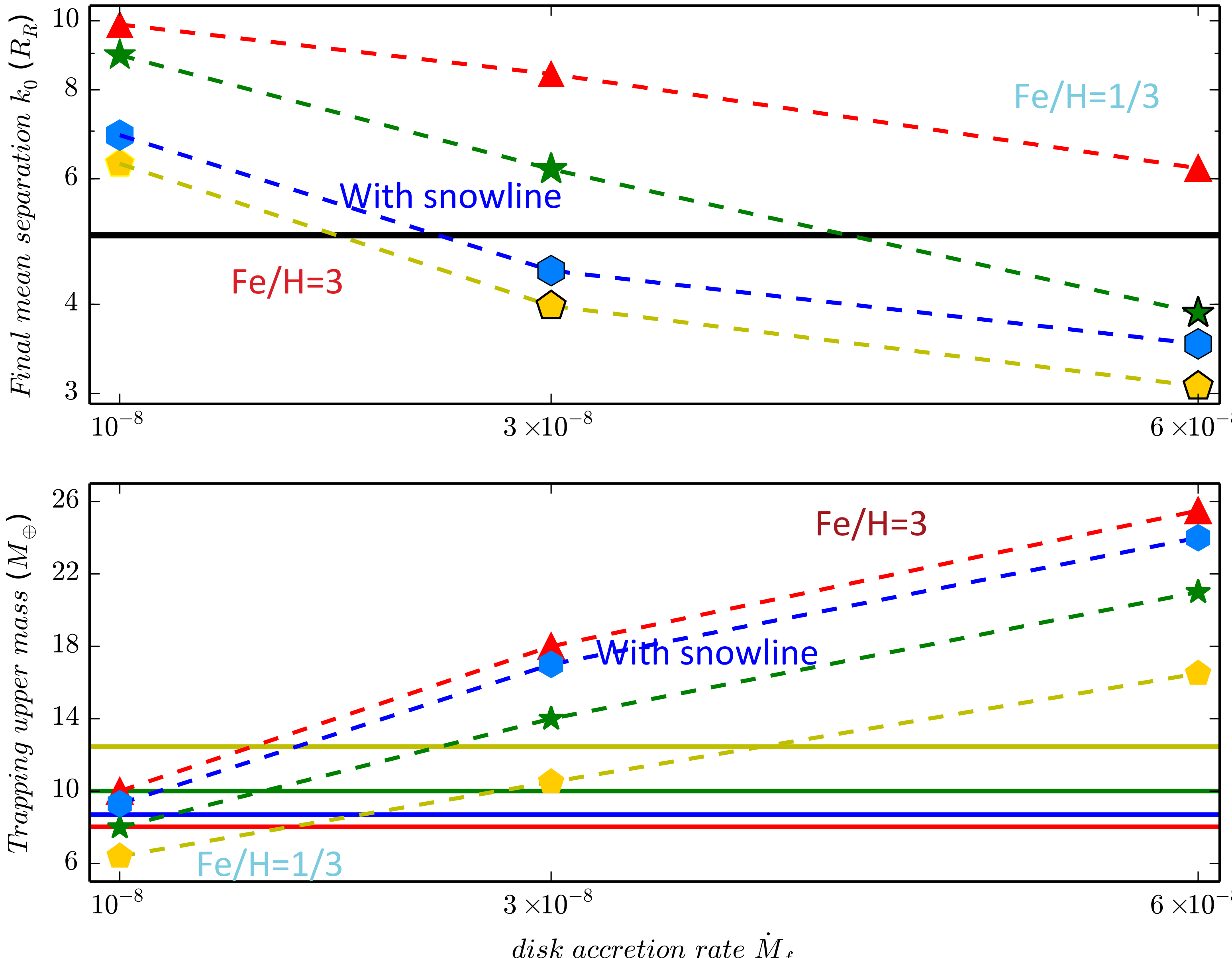

Toroidal Magnetic Field (Gauss)
0
0.125
0.25
To Star


−3
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
Mass (M_E)
30
20
10
5
3
1
0.1
3
6
9
Radius(AU)

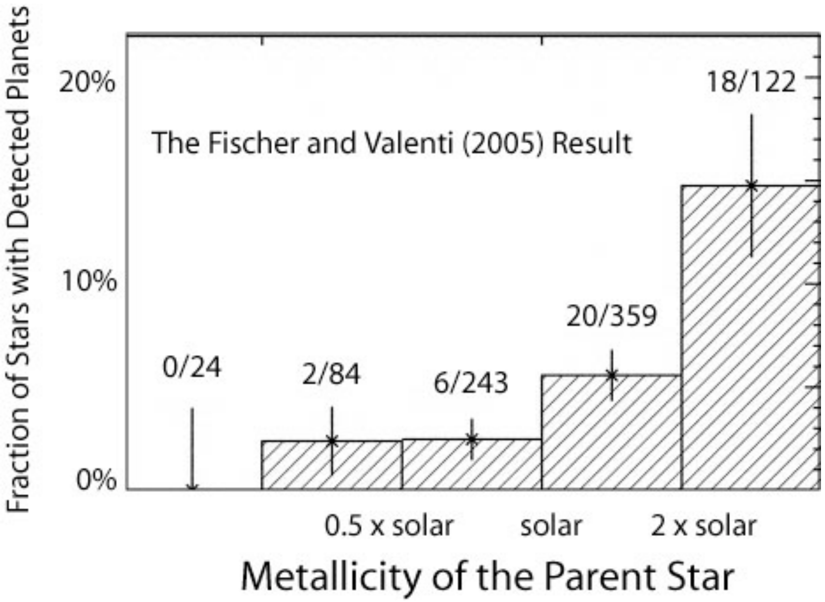

At the snow line, local conditions are such that the drag force reverses direction. Grains tend to accumulate and readily coagulate into larger bodies called planetesimals.
Small grains are swept along by the gas, but those larger than a millimeter experience a drag force and spiral in.
2–4 AU
Protosun
Snow line
Dust spirals inward

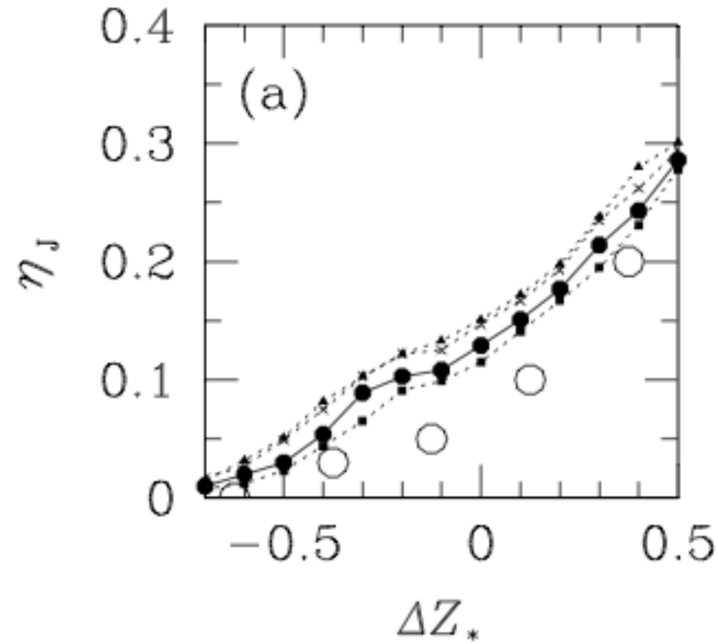

10
6
2
Semimajor axis (AU)
10^3
10^4
10^5
10^6
Time (yrs)

Migration in metal-rich disks



Planetary mass & size vs stellar metallicity





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

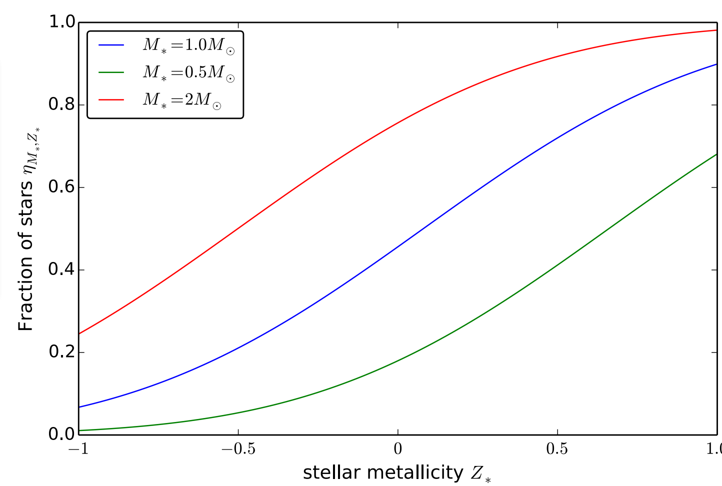
$$\eta_Z(\dot{M}_f, M_*, Z_*)$$
$$= \frac{1}{2}\int \mathrm{erfc}\left(\frac{\log[\dot{M}_f(M_*, Z_d)/\dot{M}_a(M_*)]}{\Delta_{\dot{M}}}\right) \exp - \left[(Z_d - Z_*)/\Delta_Z\right]^2 dZ_d.$$

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

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

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

BUT, Z_d is not Z_*



Some major Challenges:

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- Multiple gas giants and eccentricity excitation
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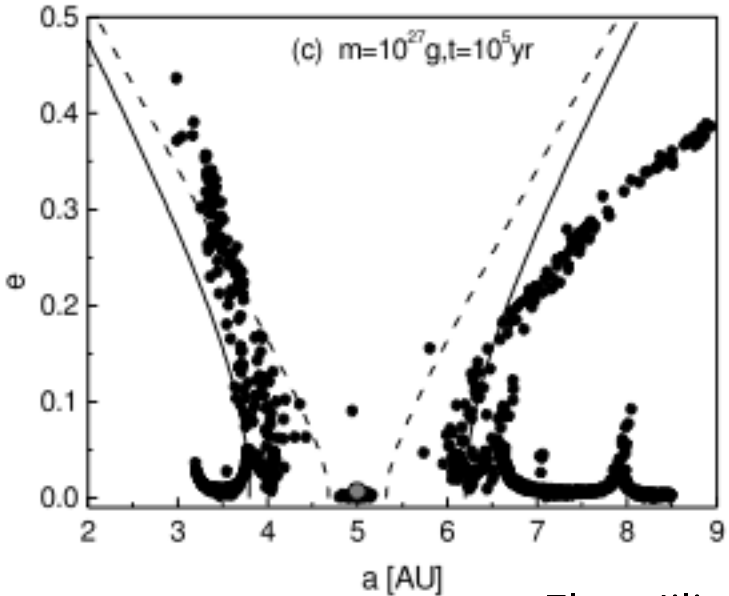
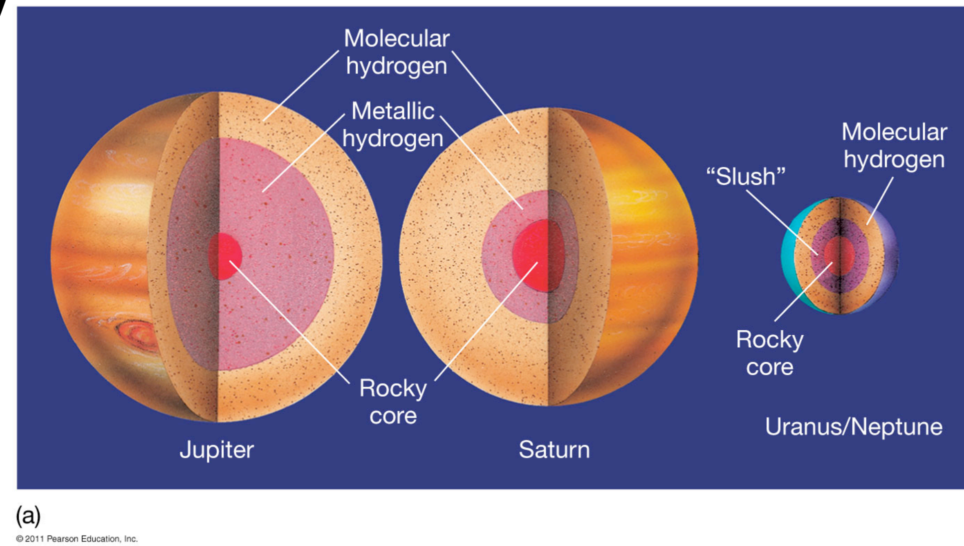
- Multiple planets: rapid & slow depletion of disk gas
- Competing physics on multiple length & time scales

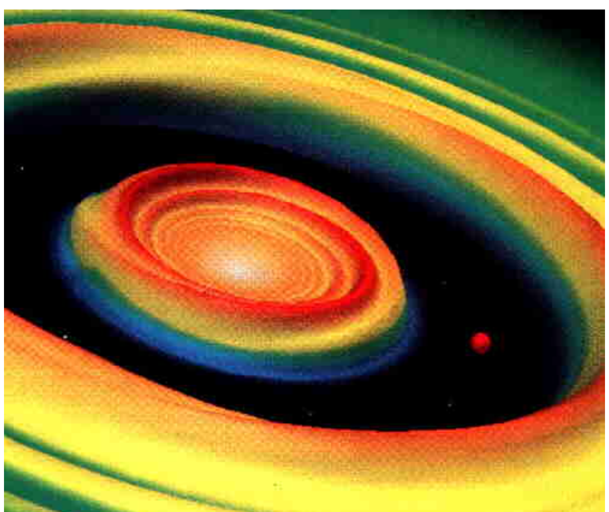
Rapid growth of proto gas giant planets:
Dynamical instability, impacts & mergers



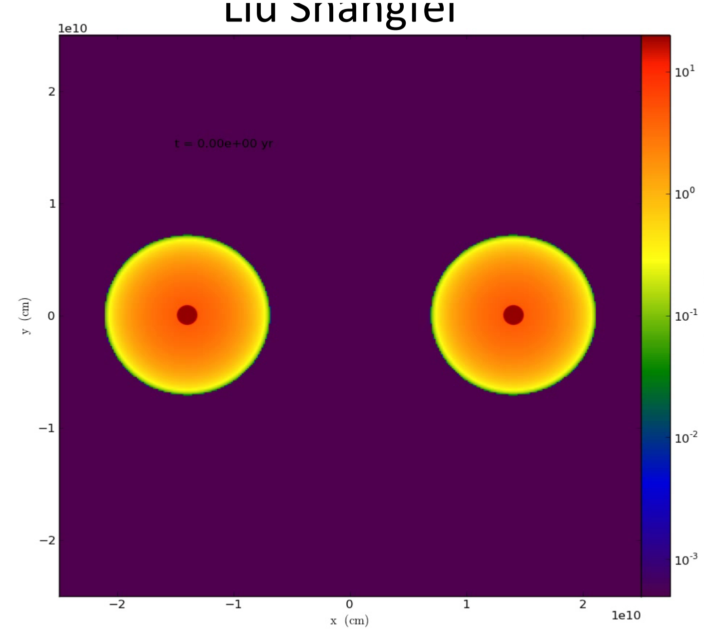
Zhou Jilin



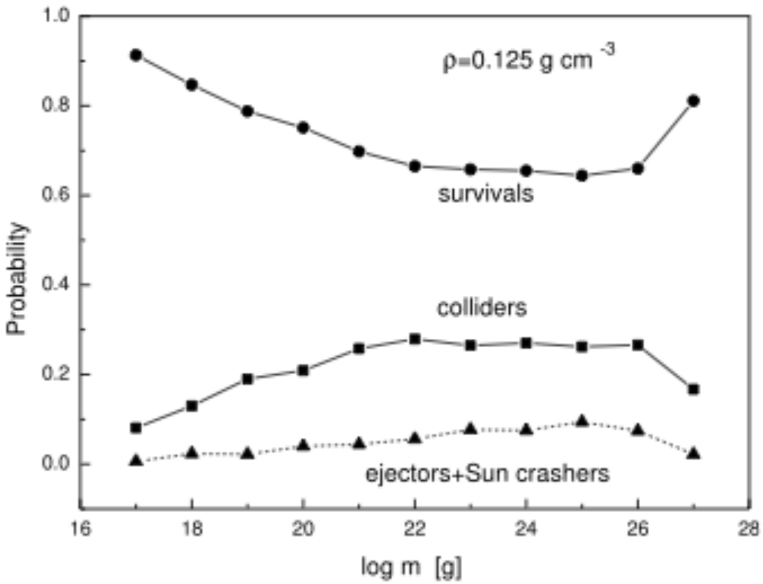
Liu Shangfei

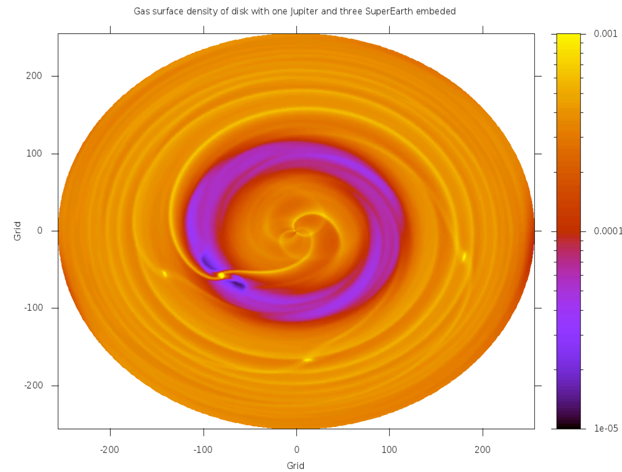


Bryden

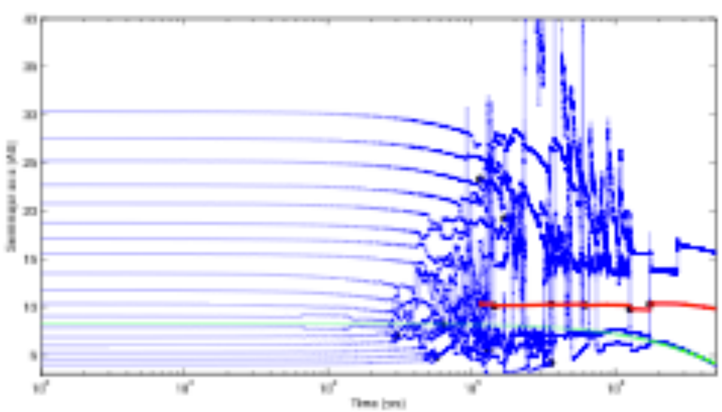


Enhanced formation of multiple planets

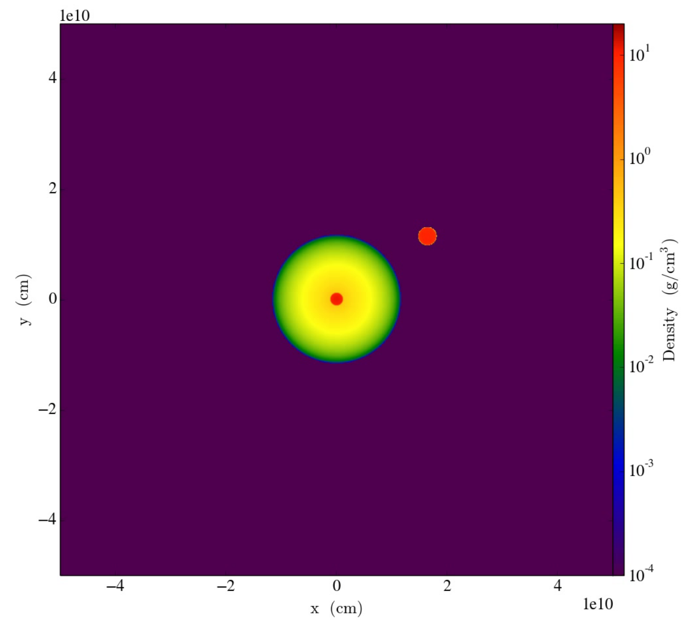




XiaoJia Zhang

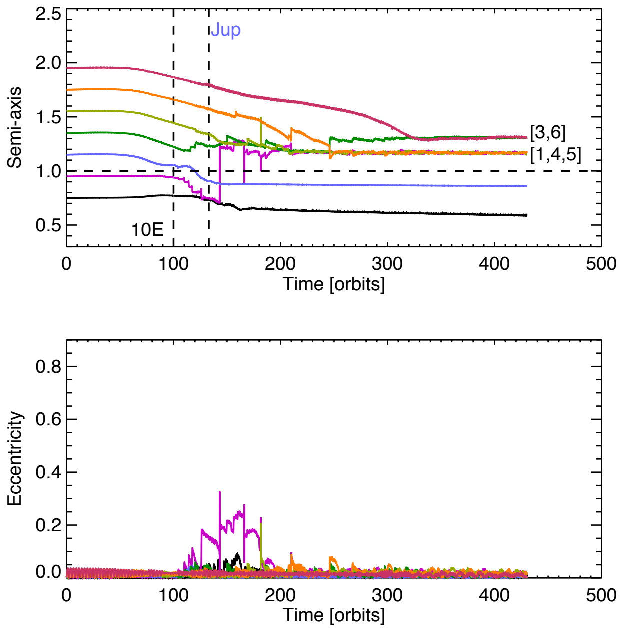


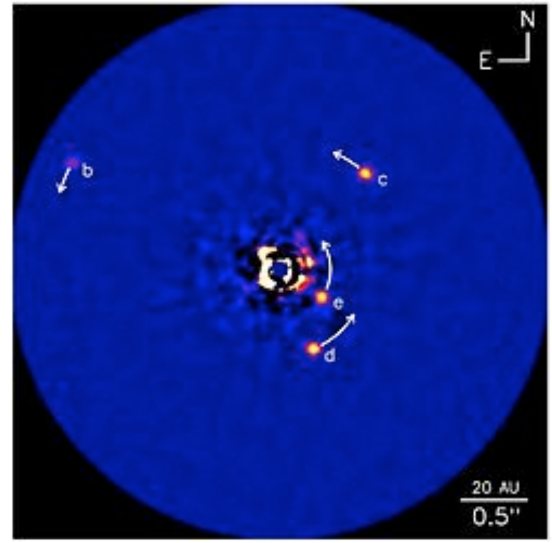
BeiBei Liu



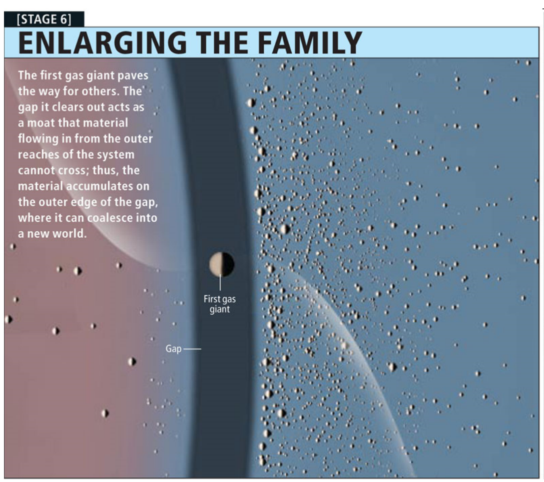
Shangfei Liu

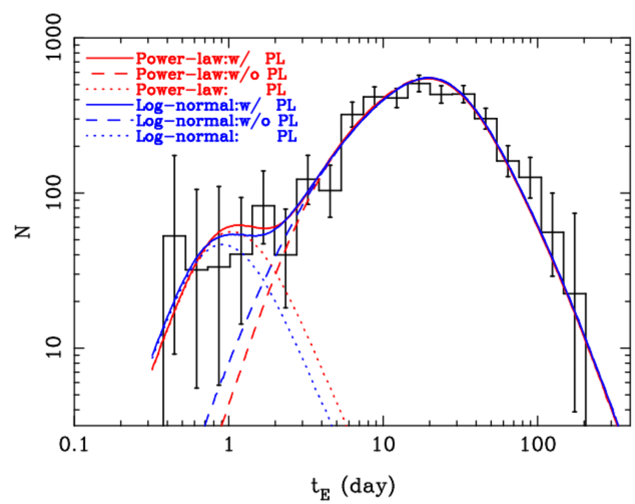
Enhanced formation of multiple planets





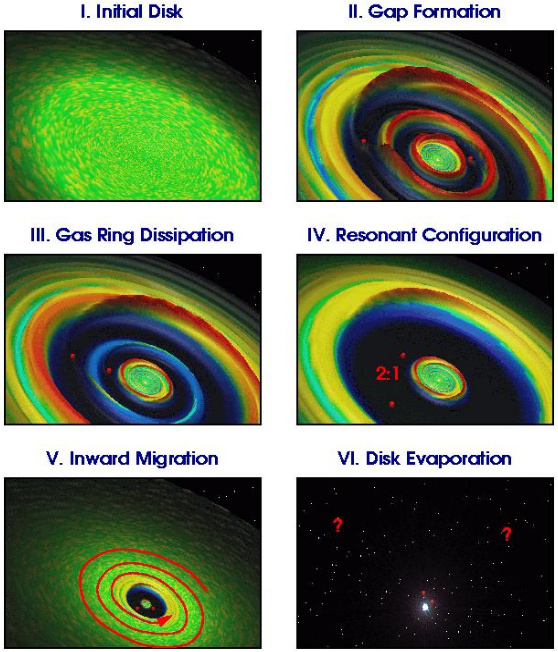
XiaoJia Zhang

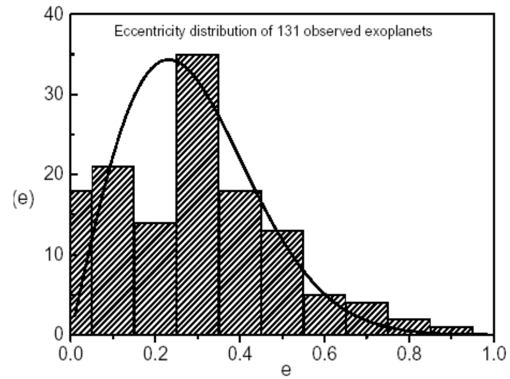




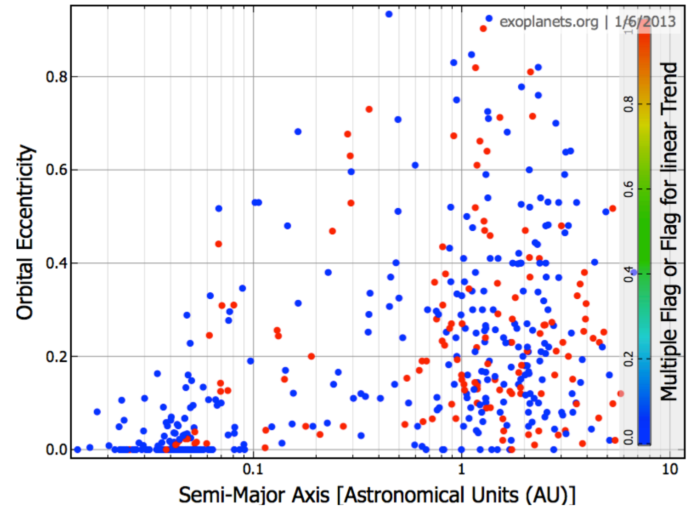
Grand design barrier: dynamical instability

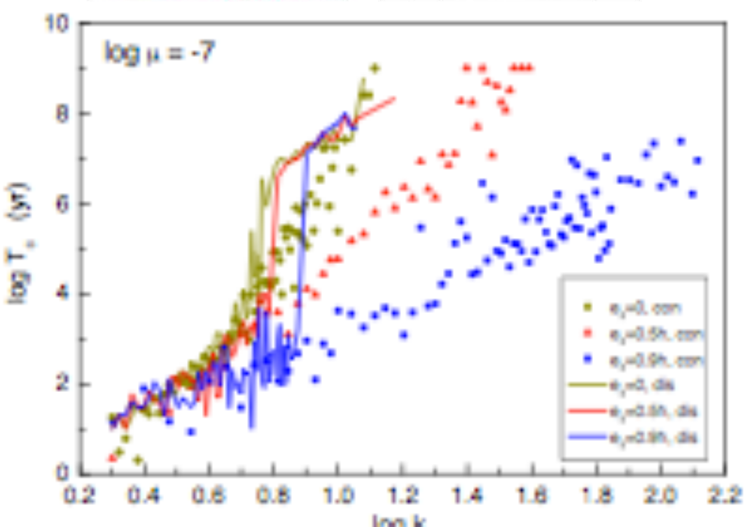
- How did gas giants acquire their eccentricity?

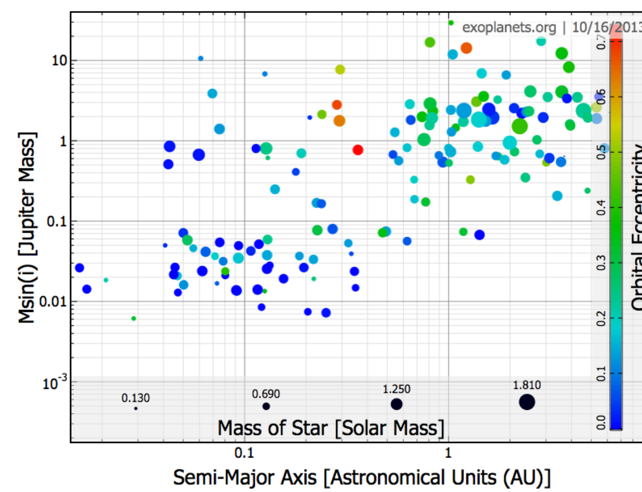




Bryden

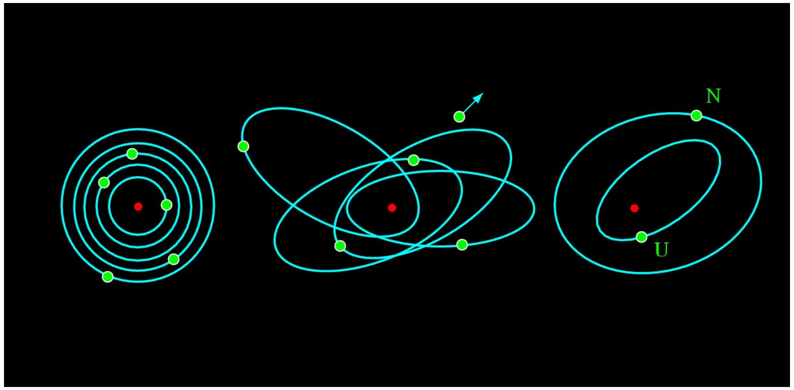


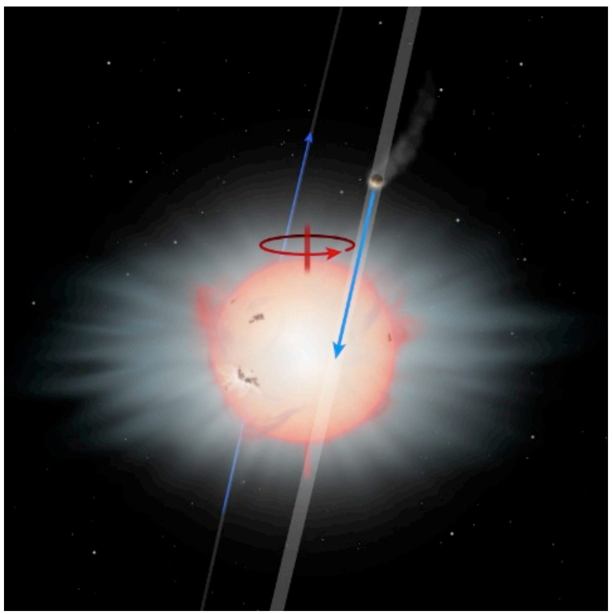


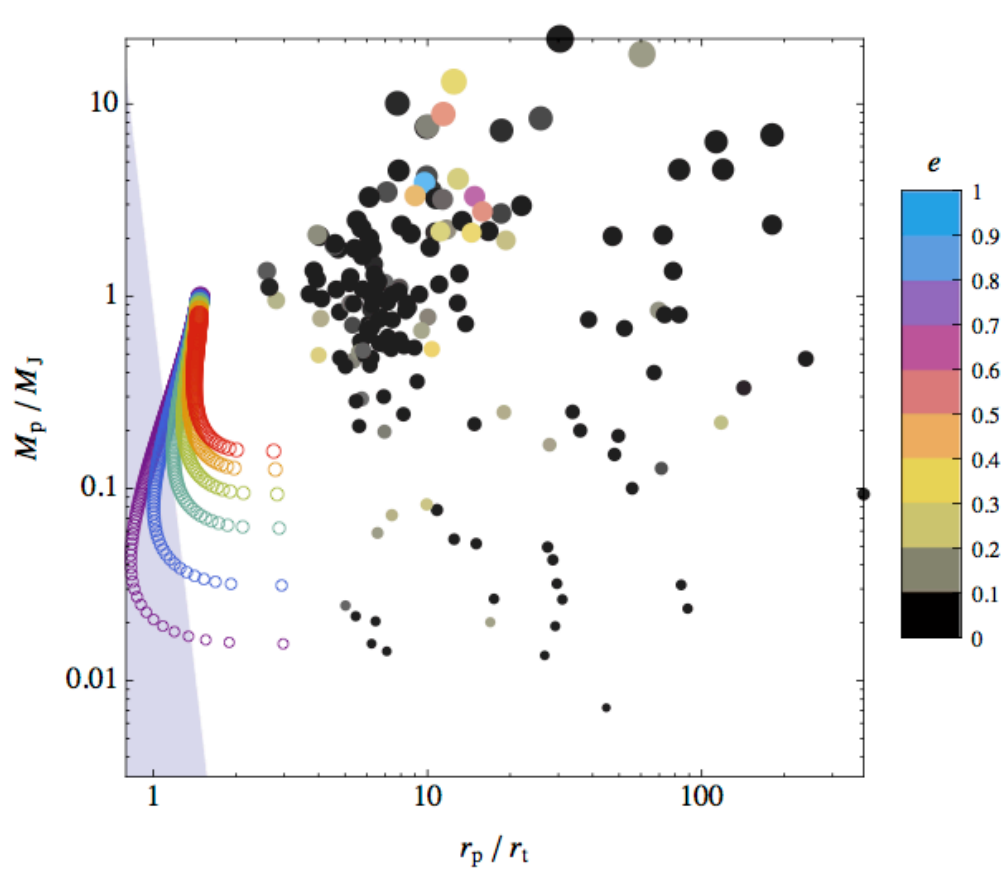


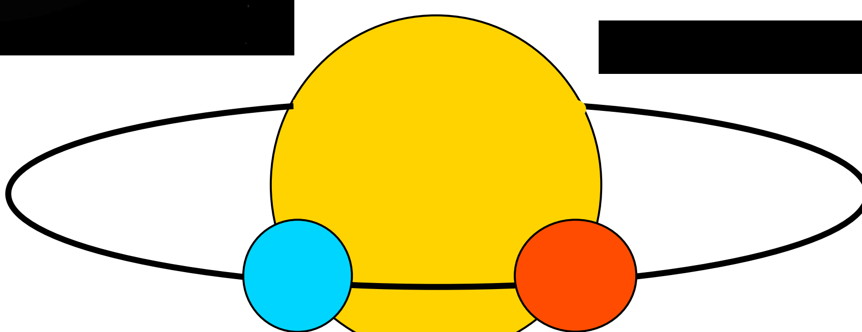
Jilin Zhou

RM effect and challenge to migration









Liu, Guillichon

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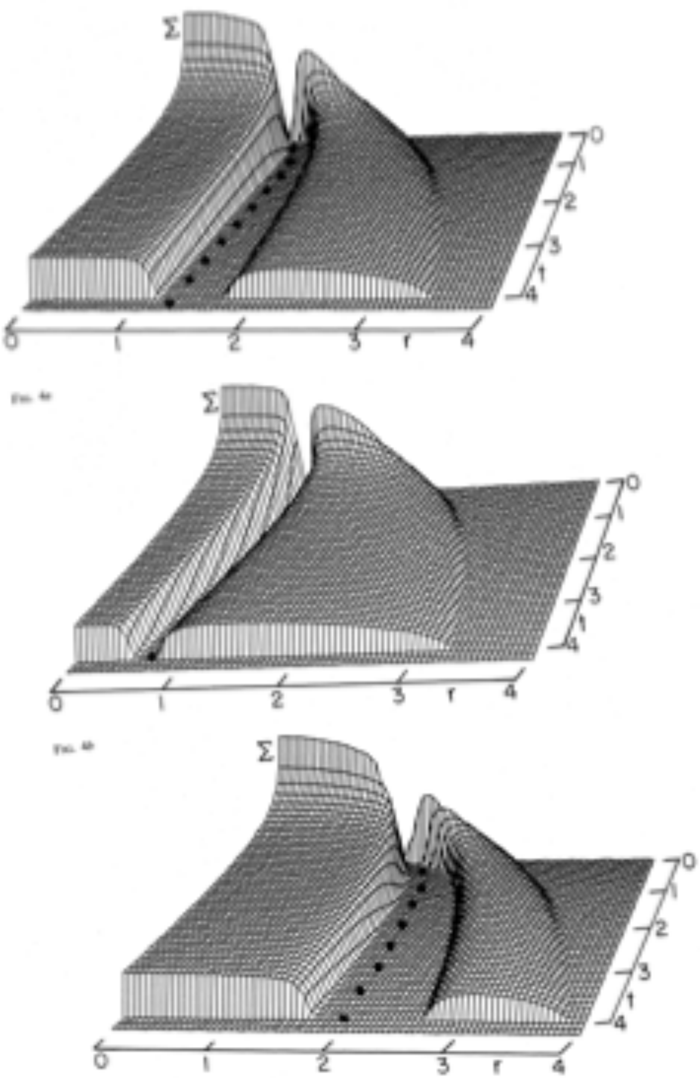
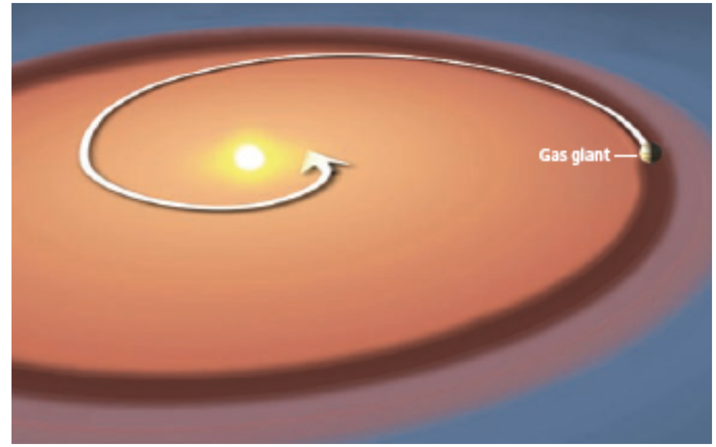
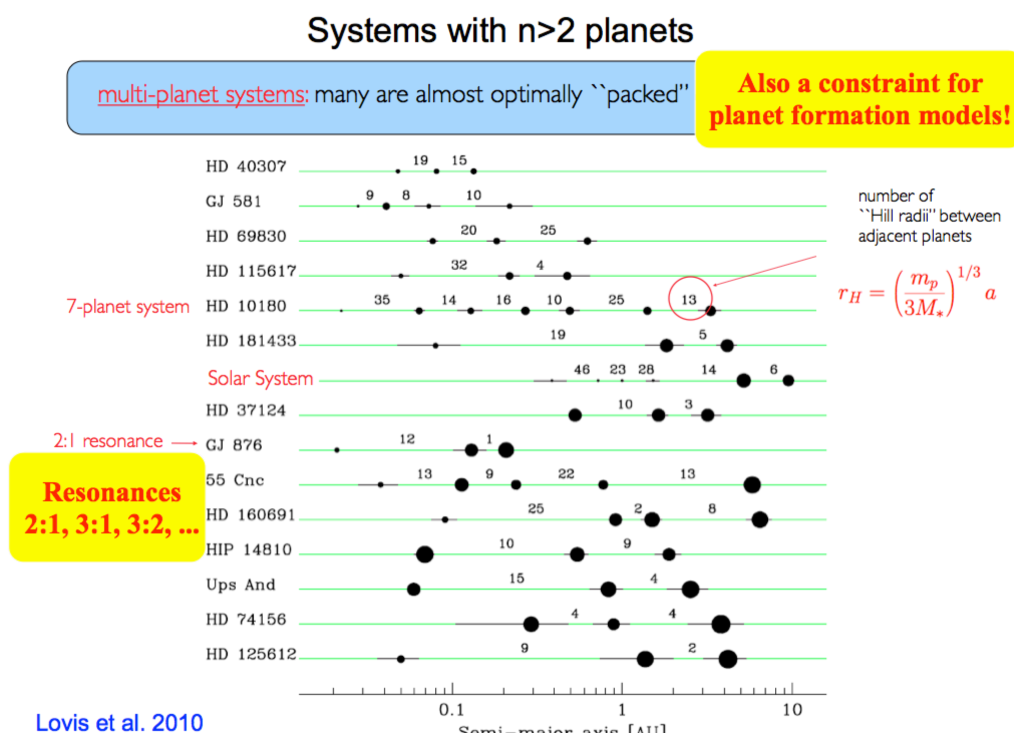
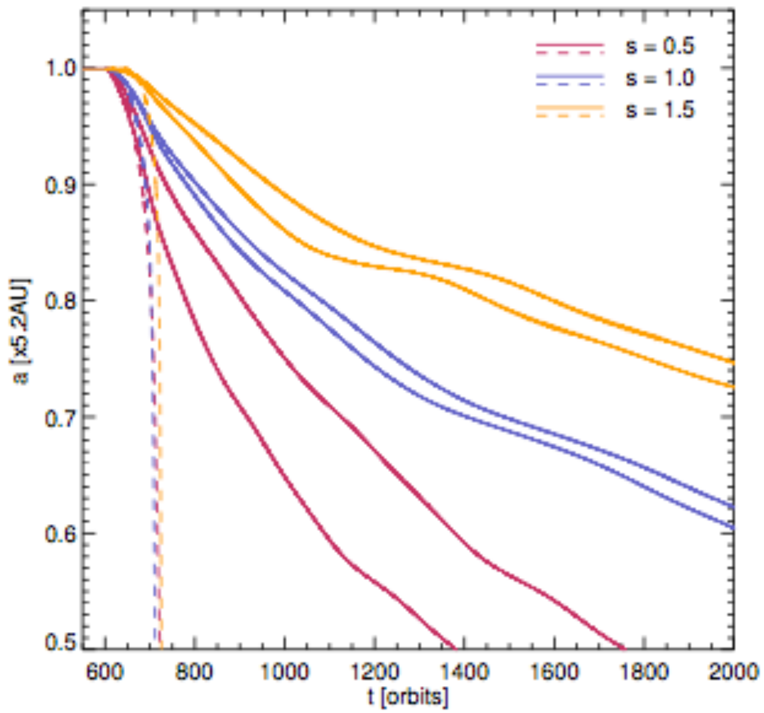
- Multiple gas giants: rapid depletion of disk gas
- Competing physics on multiple length & time scales

Gas giants' type II migration

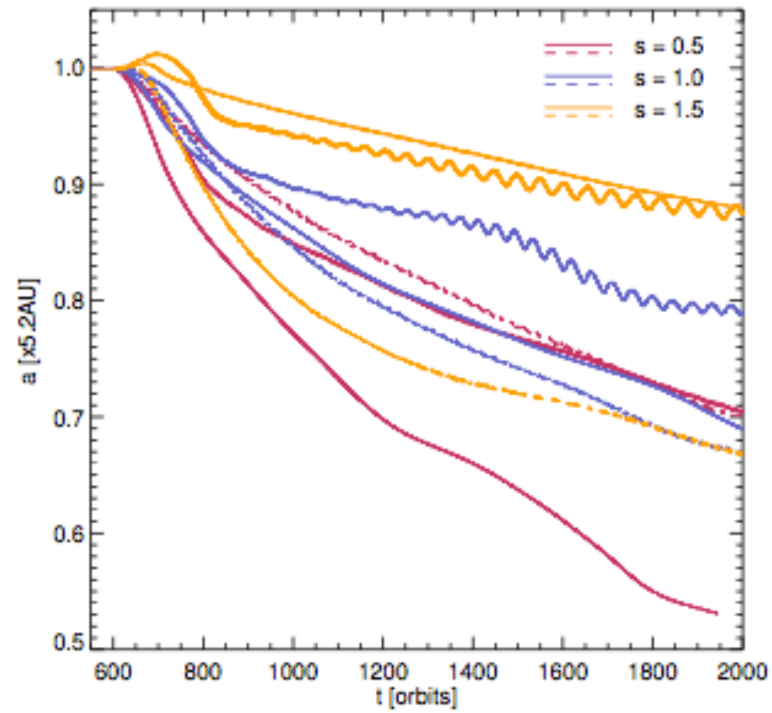




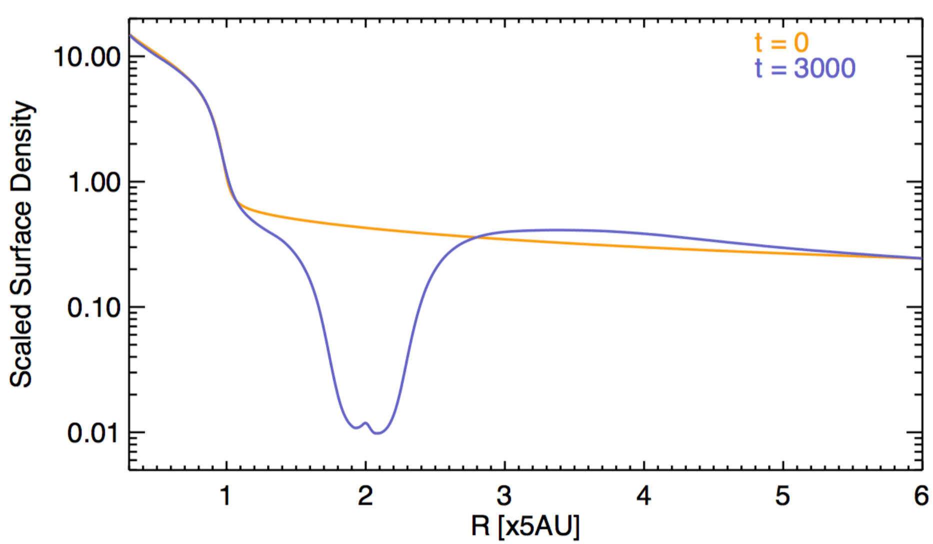




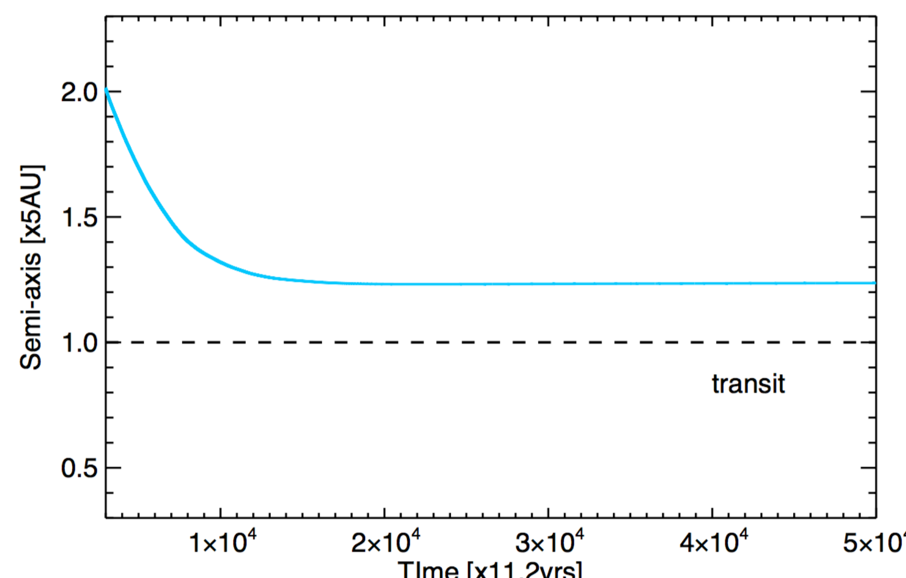
s = 0.5
s = 1.0
s = 1.5
a [x5.2AU]
t [orbits]



s = 0.5
s = 1.0
s = 1.5
a [x5.2AU]
t [orbits]

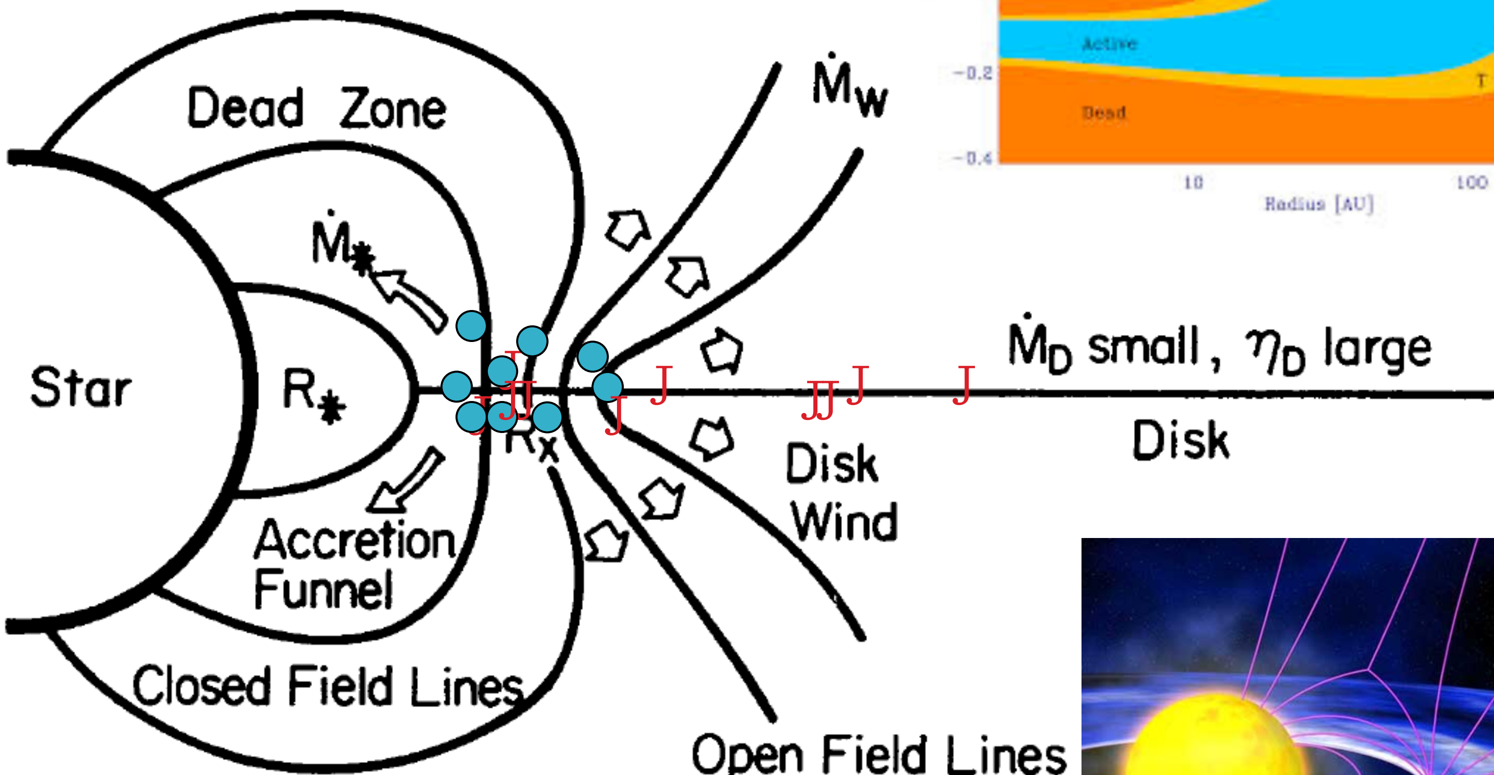


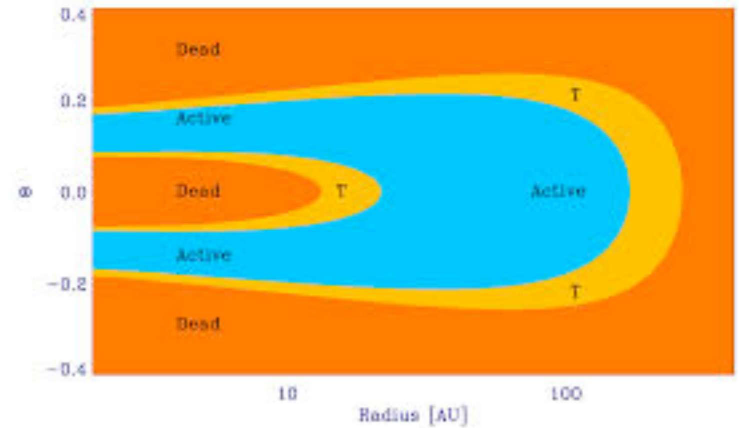
t = 0
t = 3000
Scaled Surface Density
R [x5AU]

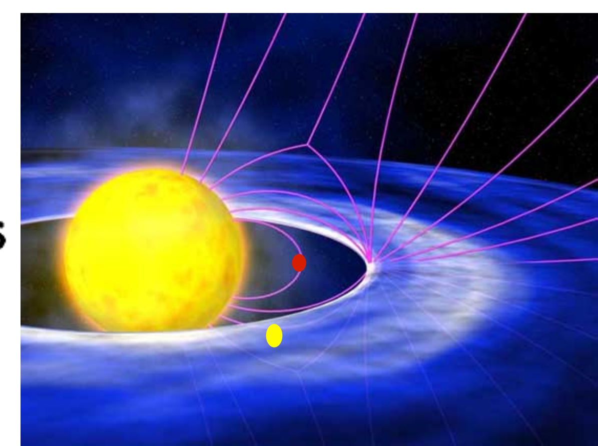


transit
Semi-axis [x5AU]
TIme [x11.2yrs]

Stalling type II migration







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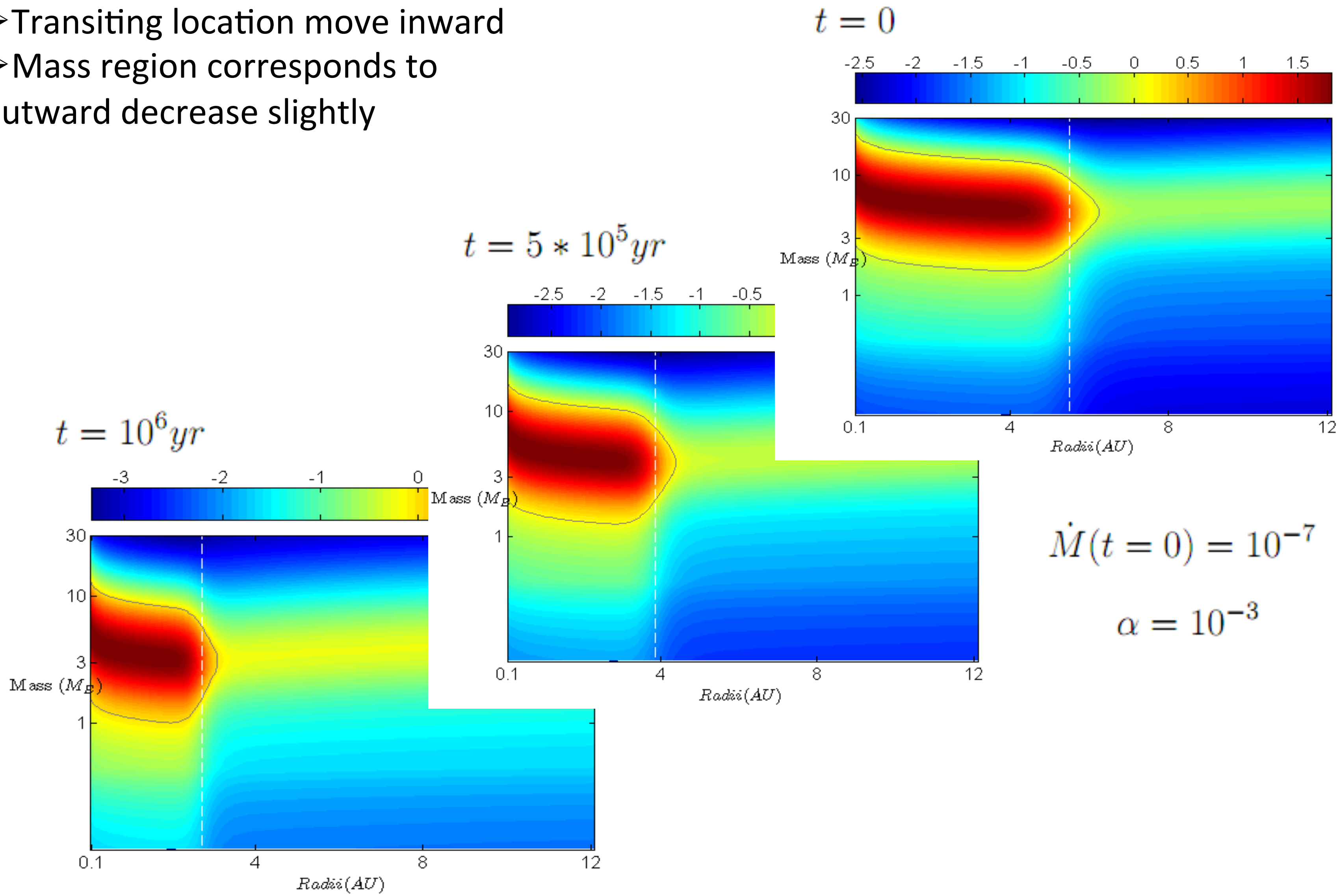
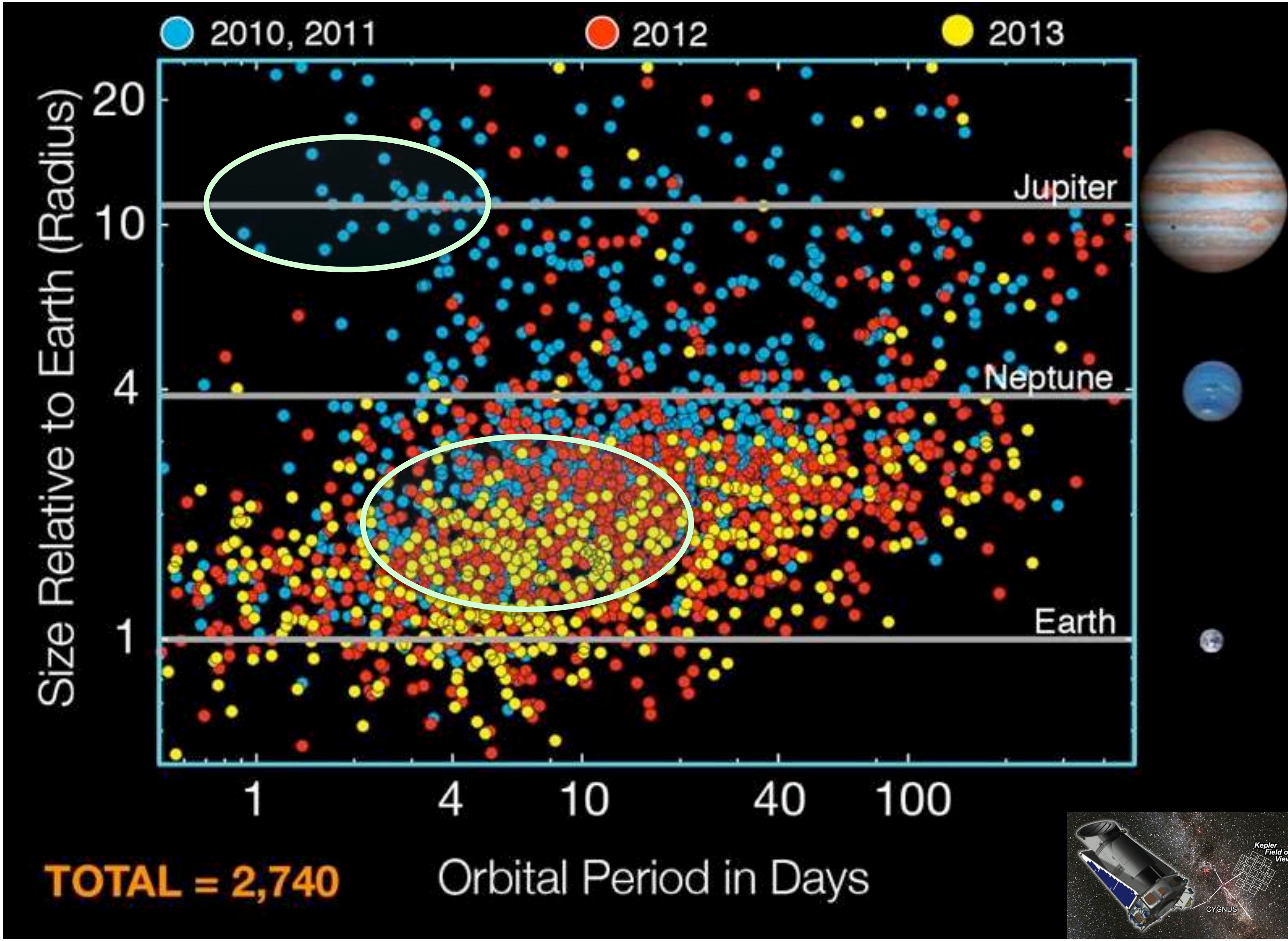
Type I migration with evolving disk

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



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

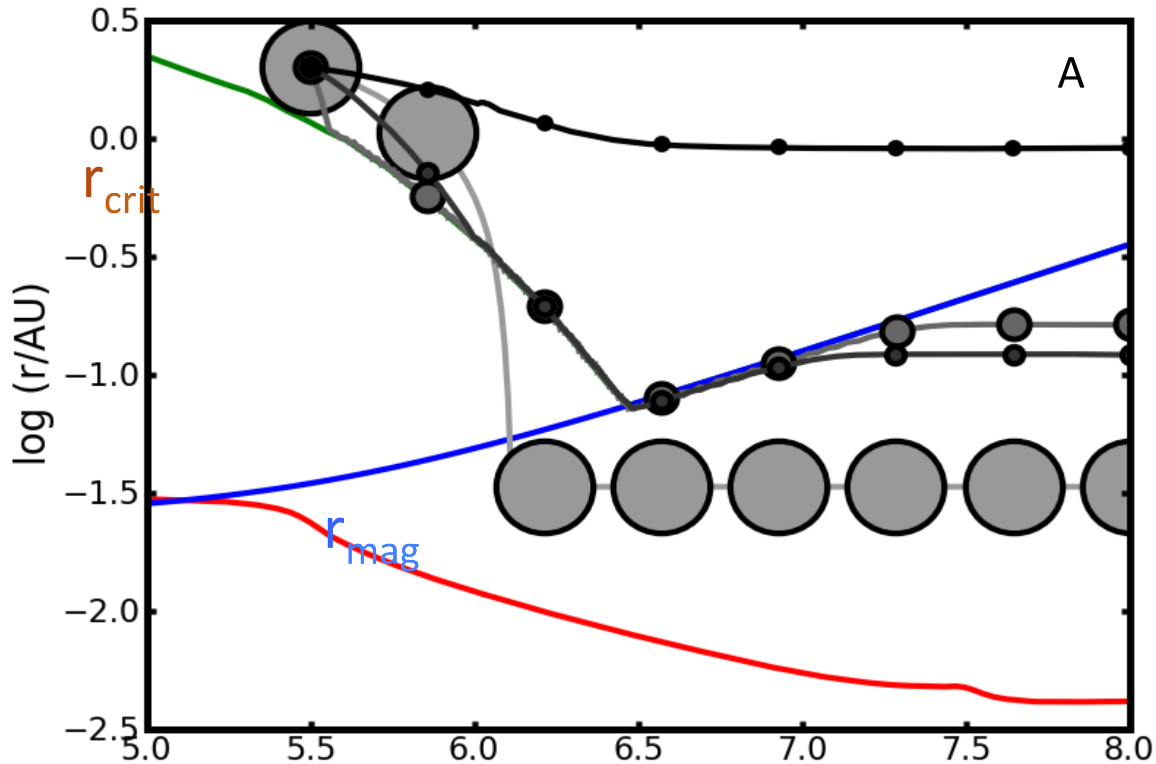
$$\alpha = 10^{-3}$$



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

Super Earths: some key issues

- How to differentiate type I and II migration?



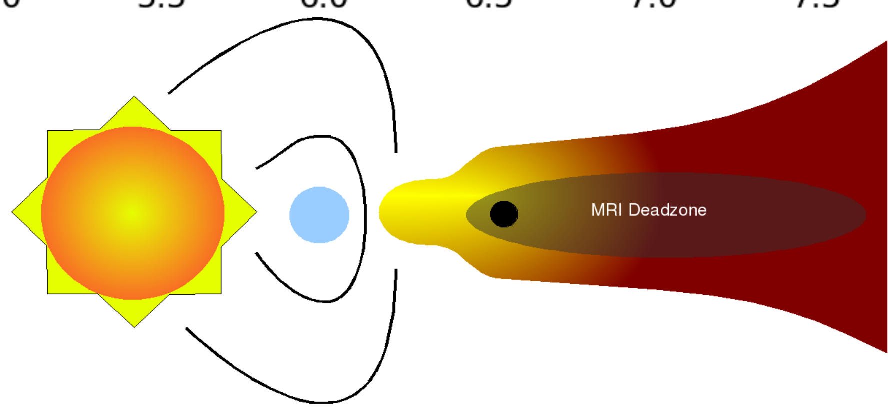
Sub/warm Earths

½ Earth
Neptunes
SuperEarths

5 Earth

Gas giants
2 Earth

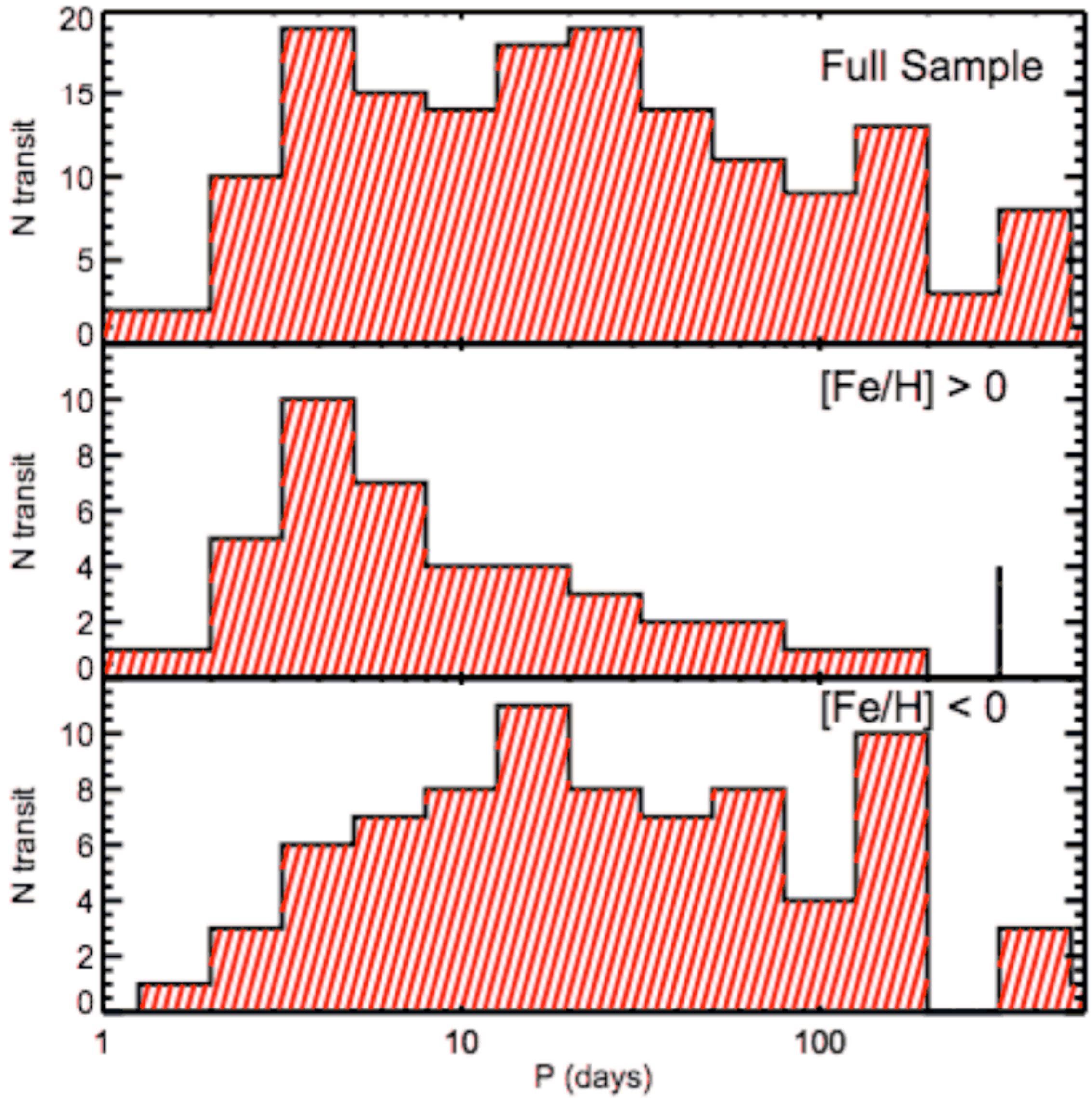
Jupiter

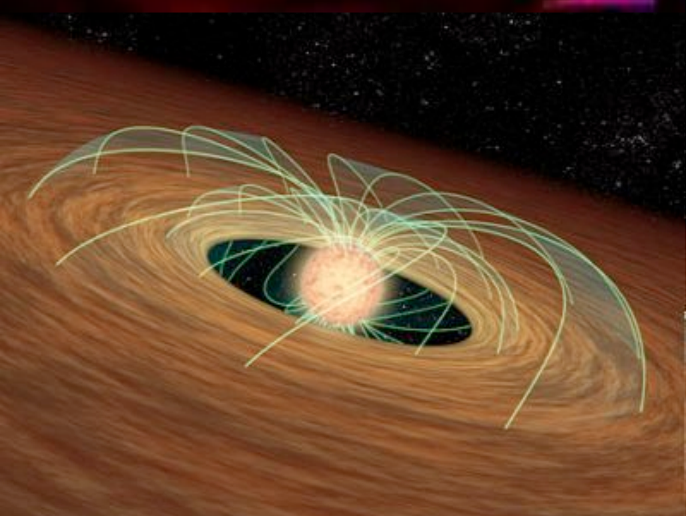


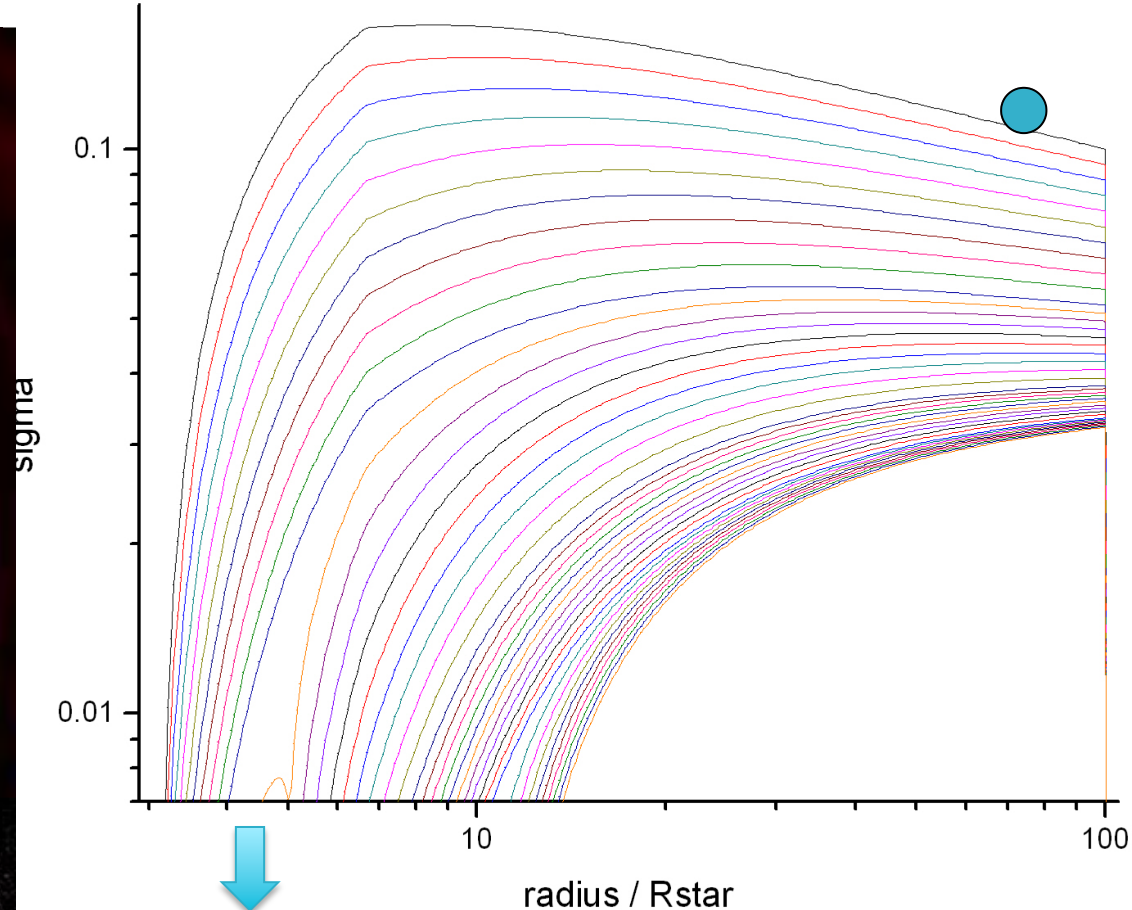
Hot Jupiters park Closer than Super Earths

Kretke

Period distribution of hot Jupiters: Dependence on stellar metallicity



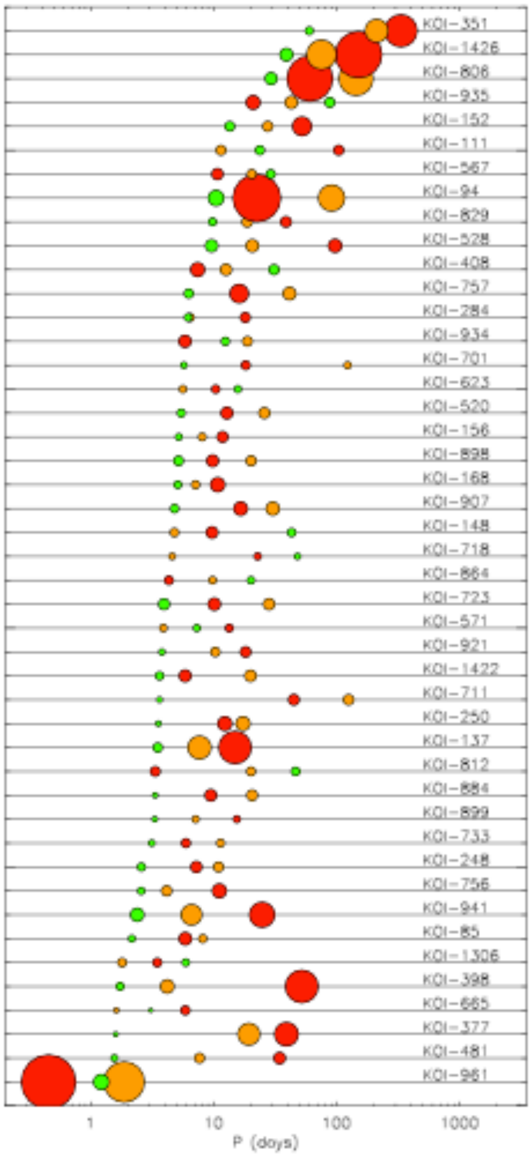


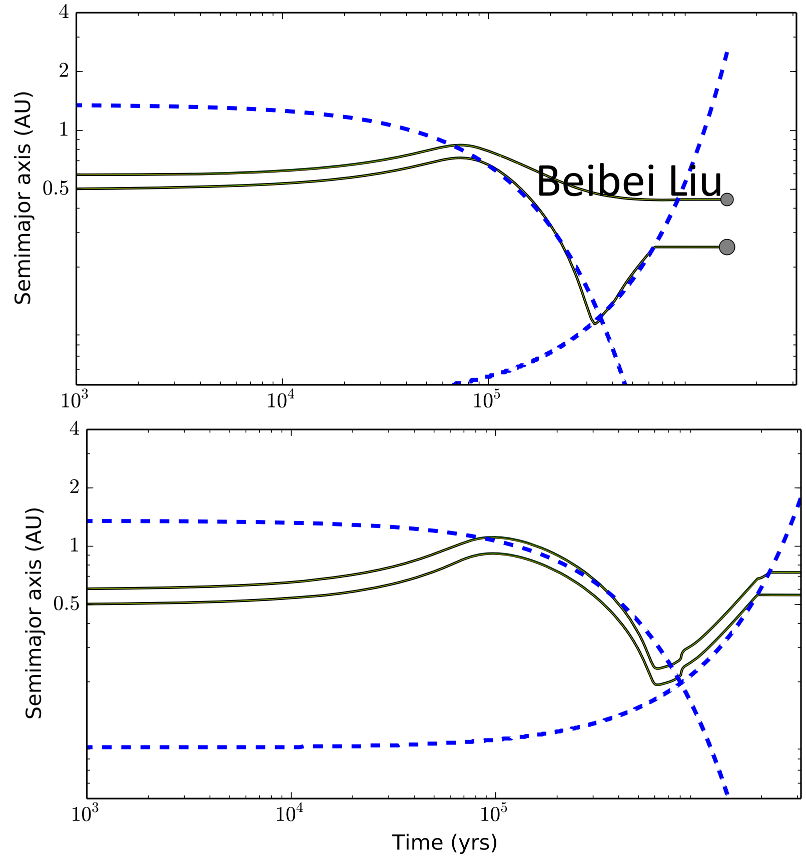


Migration of a Super Earth in protostellar disk around a magnetized T Tauri star. The Super Earth: (a) grows & migrate inward to inner-edge; (b) migrates slightly outwards with the expanding disk inner edge; (c) halts migrating after gas is mostly depleted. (Ju et al 2014 in preparation)

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

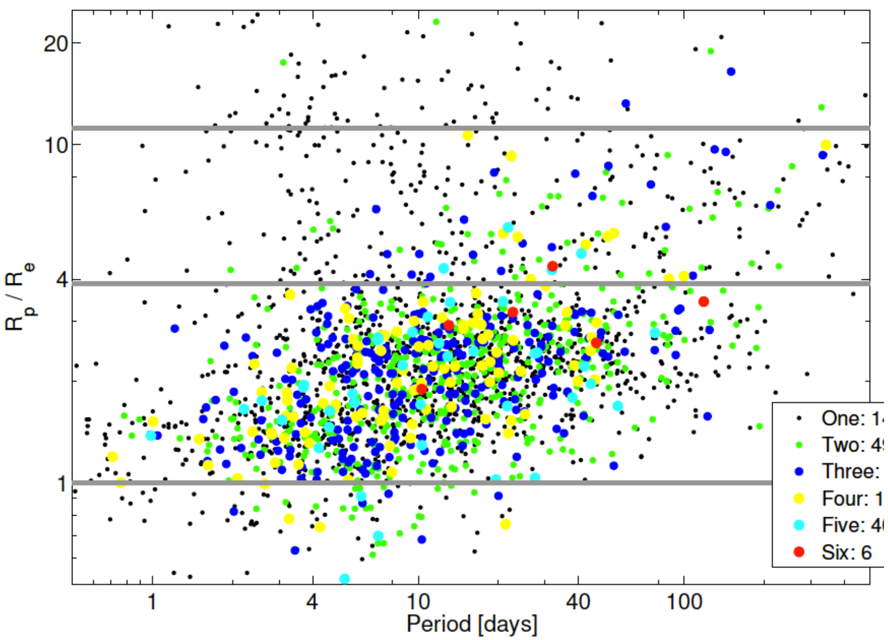
KIAA undergraduate student Ju Wenhua (Princeton) and Xu Rui (CfA, Harvard)

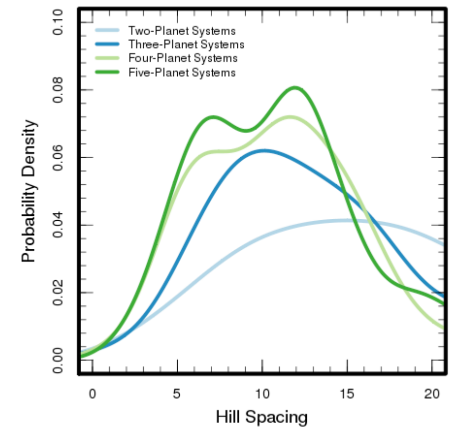

KOI-351
KOI-1426
KOI-806
KOI-935
KOI-152
KOI-111
KOI-567
KOI-94
KOI-829
KOI-528
KOI-408
KOI-757
KOI-284
KOI-934
KOI-701
KOI-623
KOI-520
KOI-156
KOI-898
KOI-168
KOI-907
KOI-148
KOI-718
KOI-864
KOI-723
KOI-571
KOI-921
KOI-1422
KOI-711
KOI-250
KOI-137
KOI-812
KOI-884
KOI-899
KOI-733
KOI-248
KOI-756
KOI-941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

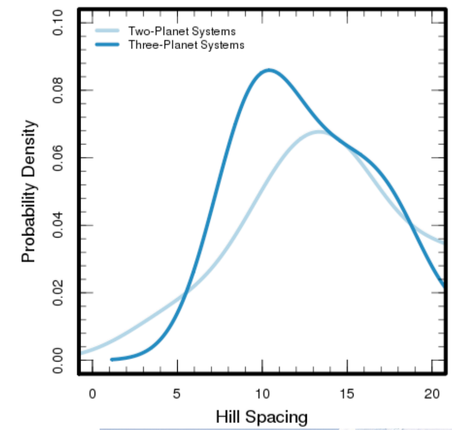

4
2
1
0.5
Semimajor axis (AU)
Beibei Liu
10^3
10^4
10^5
4
2
1
0.5
Semimajor axis (AU)
10^3
10^4
10^5
Time (yrs)

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

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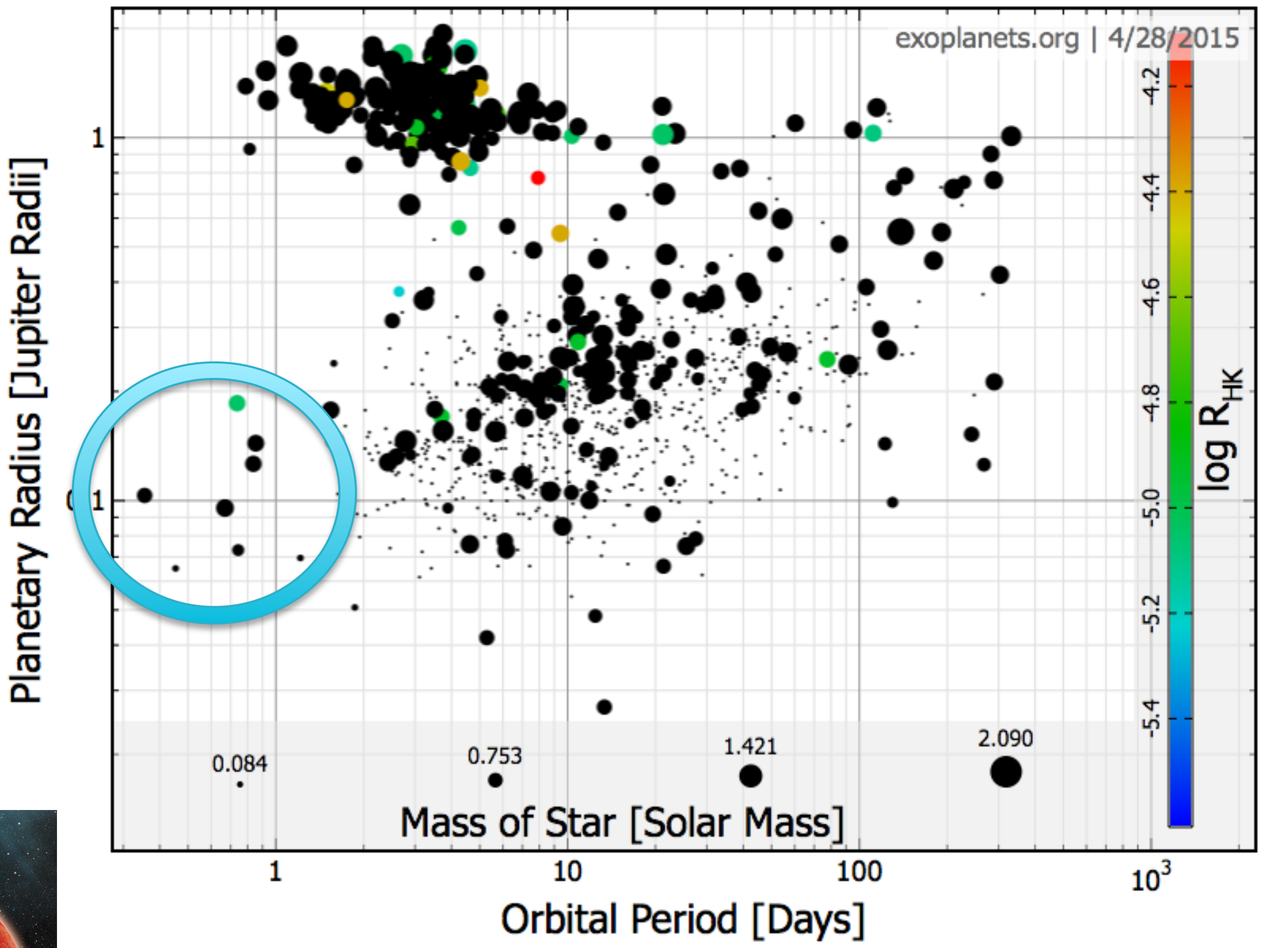
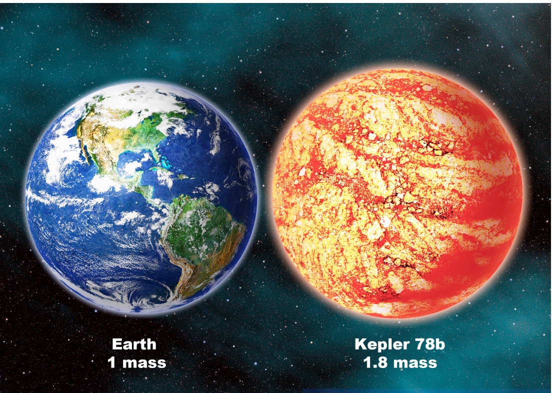
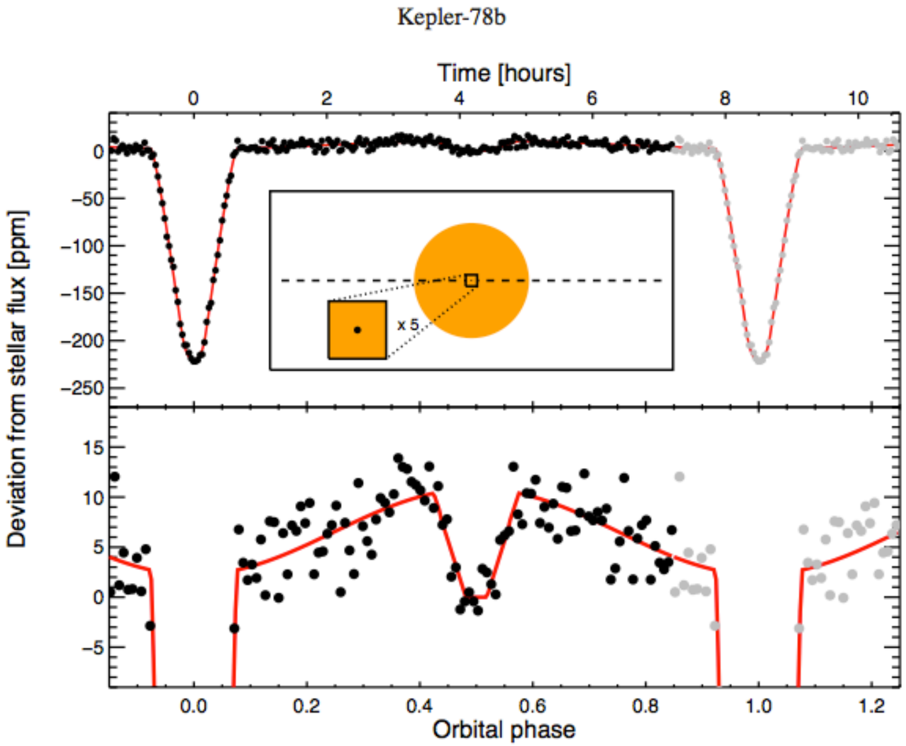
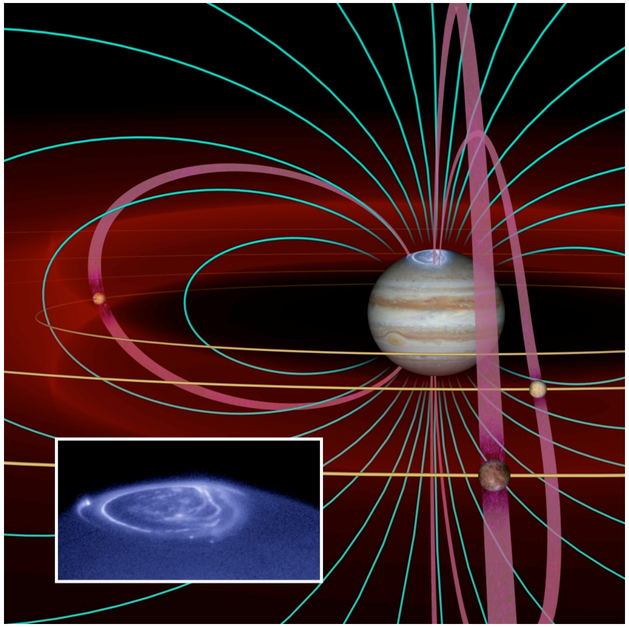
Close-in super Earths

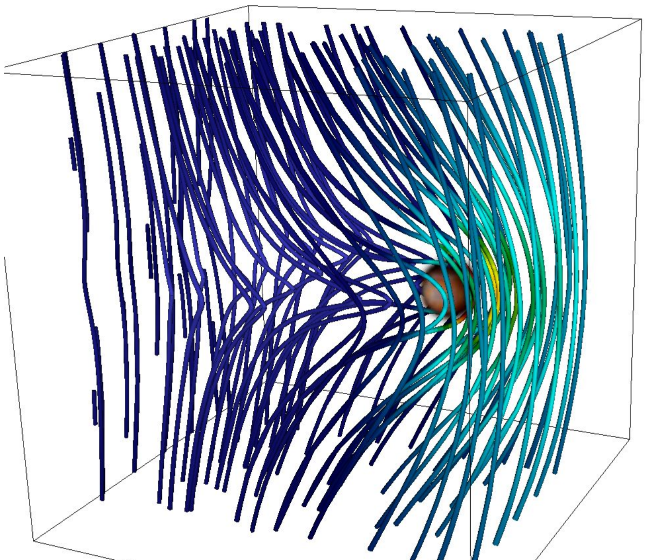


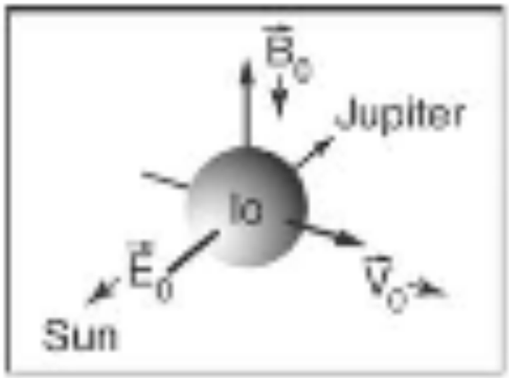


Inside the stellar magnetosphere



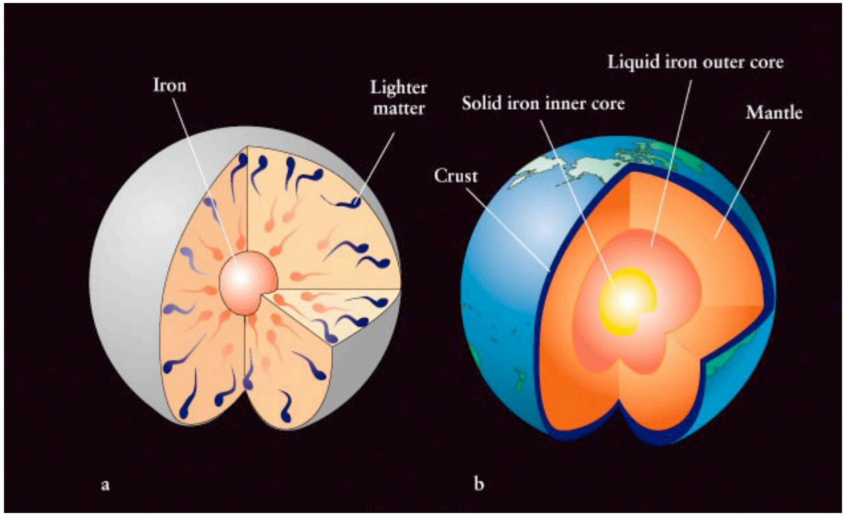






Laine, De Colle

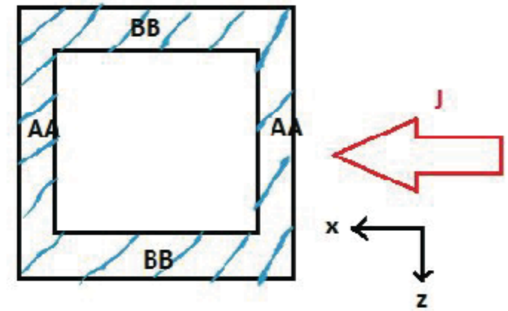
Geology and conductivity



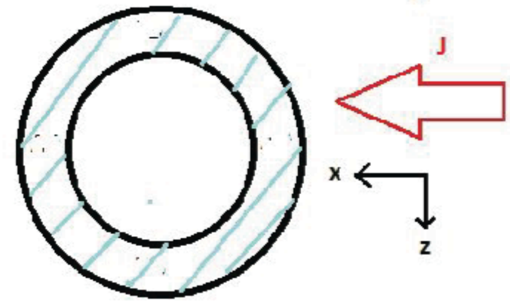
High conductivity region

High resistivity region

Electric conductivity depends only on height, i.e. on x in AA and on z in BB



Electric conductivity depends only on radius



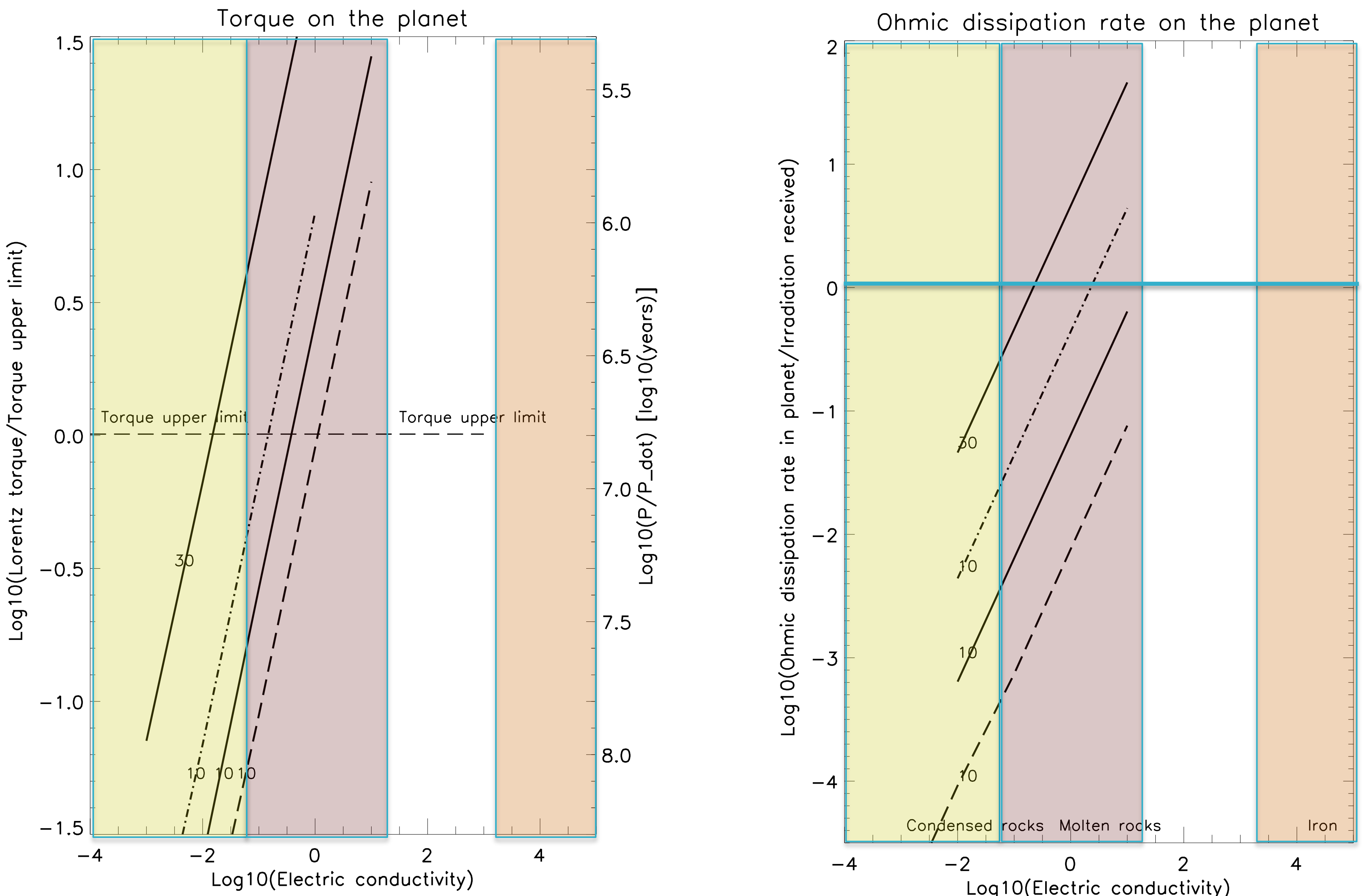
$$\mathcal{R}_p^{-1} = \int_{z=0}^{R_{max}} \int_{y=0}^{\sqrt{R_{max}^2 - z^2}} dydz \left(\int_{x=0}^{\sqrt{R_{max}^2 - z^2 - y^2}} \frac{dx}{\sigma_p(r)} \right)^{-1}$$

$$\mathcal{R}_\perp = \left([2s] \int_z \sigma(z) dz \right)^{-1}$$

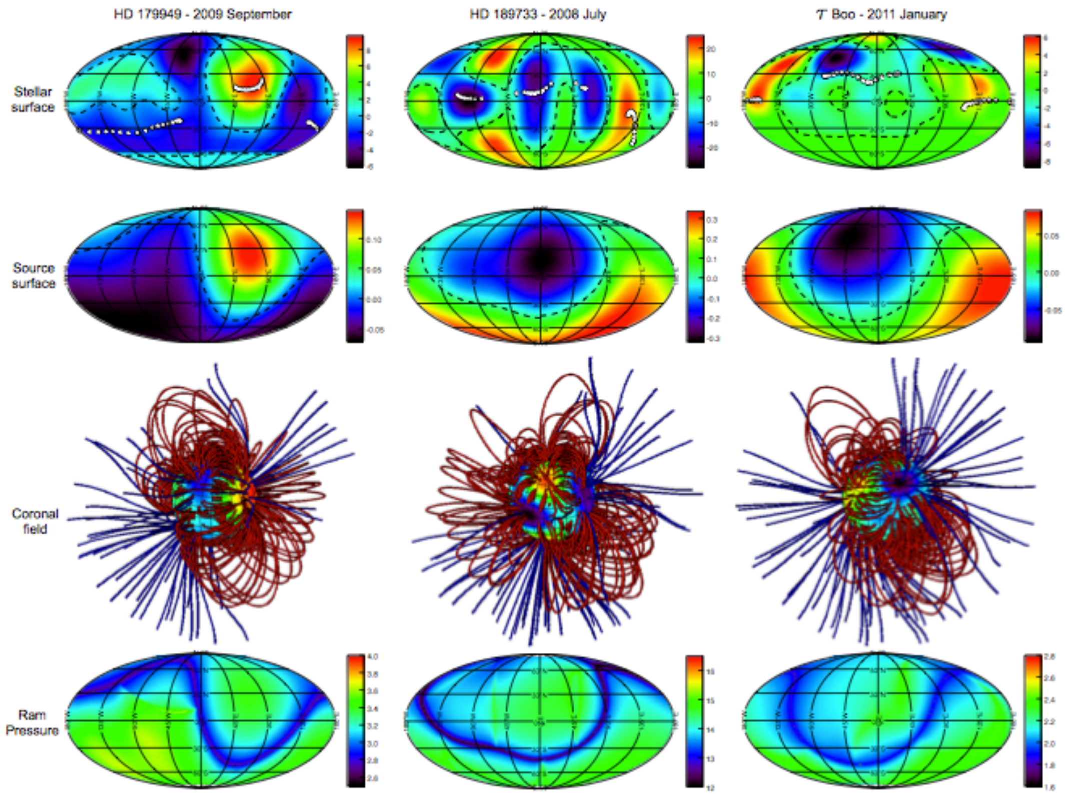
$$\mathcal{R}_\parallel = \frac{1}{R_p^2} \int_z \frac{dz}{\sigma(z)},$$

$$\mathcal{R}_\perp = (2/R_p)\, 1/[\sigma(inner) + \sigma(outer)] \text{ and } \mathcal{R}_\parallel = (1/2R_p)[1/\sigma(inner) + 1/\sigma(outer)].$$

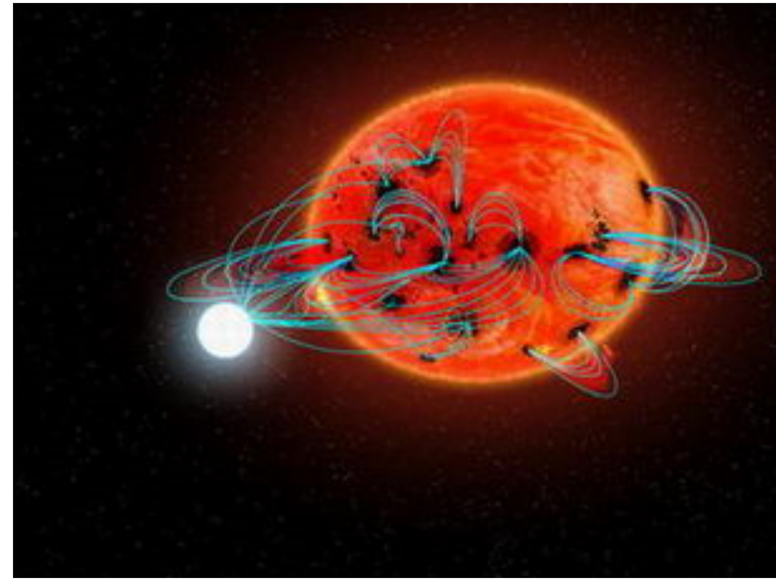
Torque and power

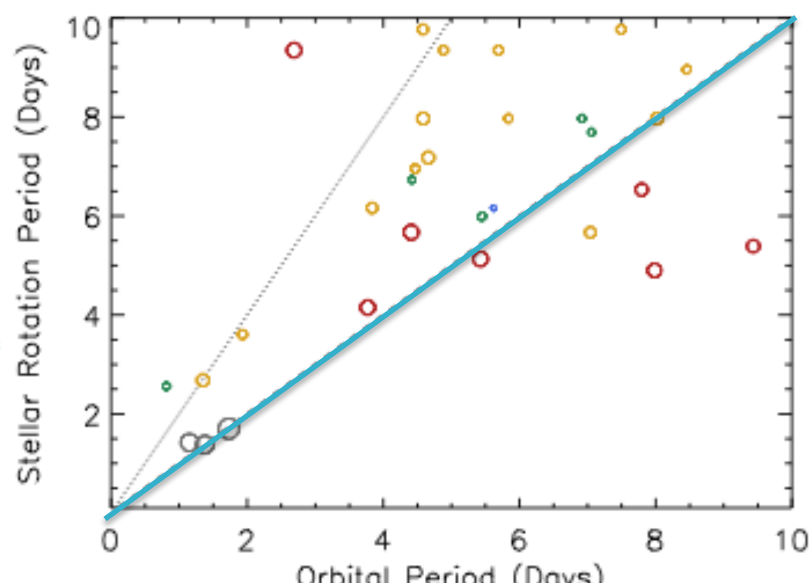


Foot prints and stellar spots



igure 1. Examples of the magnetic field geometries of HD 179949 (2009 September), HD 189733 (2008 July), and τ Boo (2011 January). For each star, maps





See et al 2015

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

Precision COSMOGONY

- Ubiquity of planets:

case study vs **Science**

- Diversity of systems:

realm of possibilities

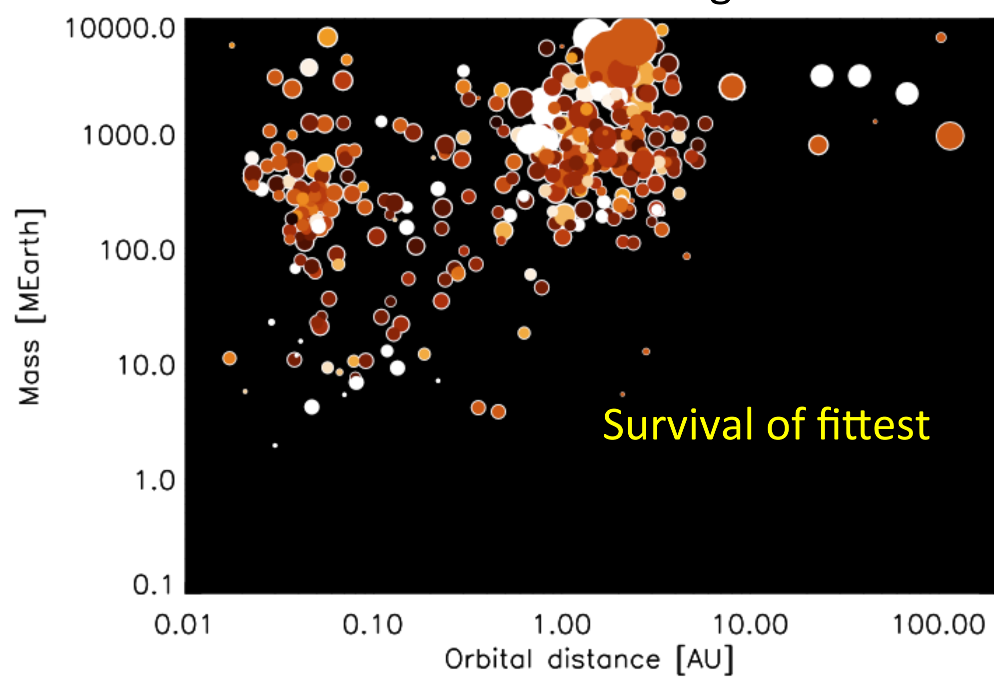
- Population census

missing info & big picture

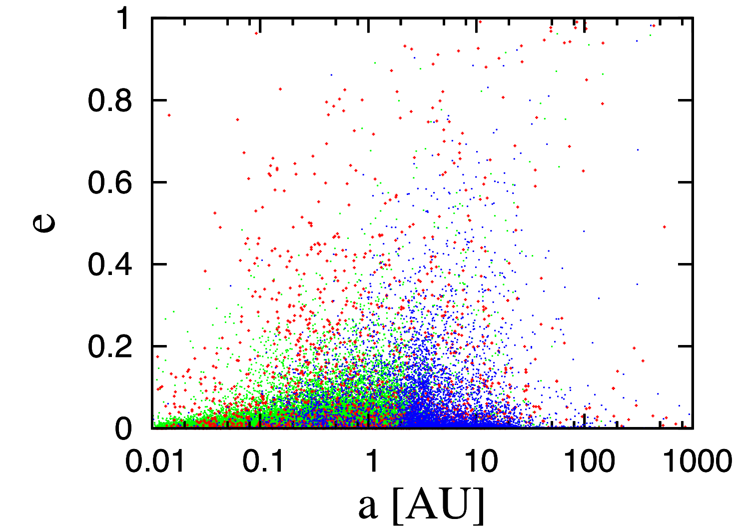
- Solar system connection

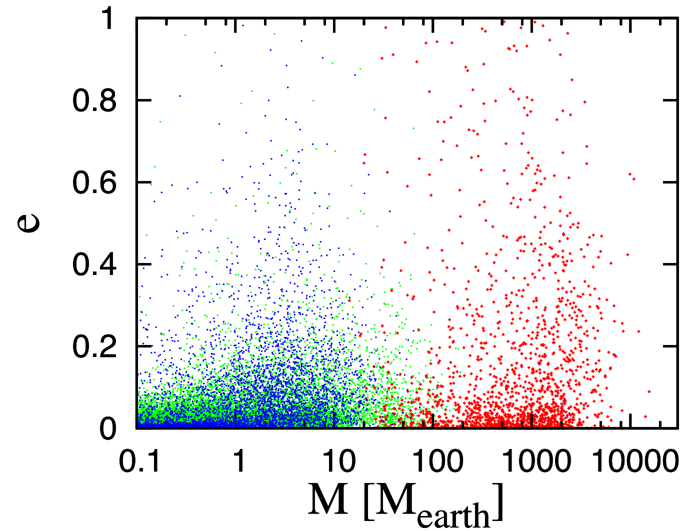
Anthropic principle

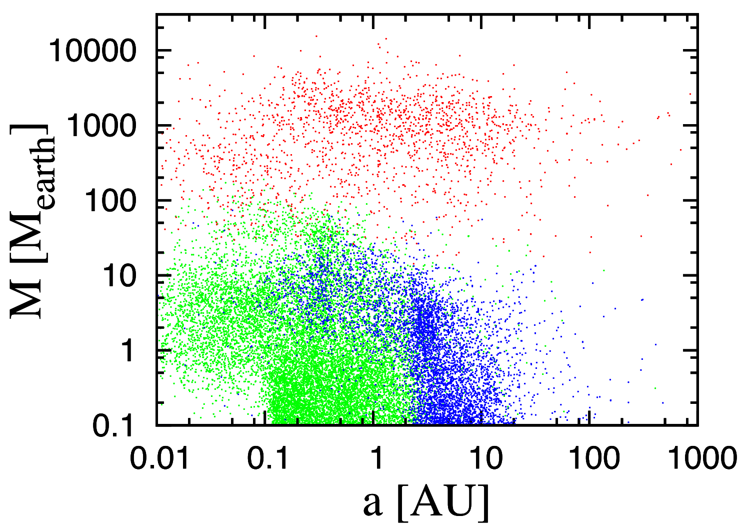
Integral of details

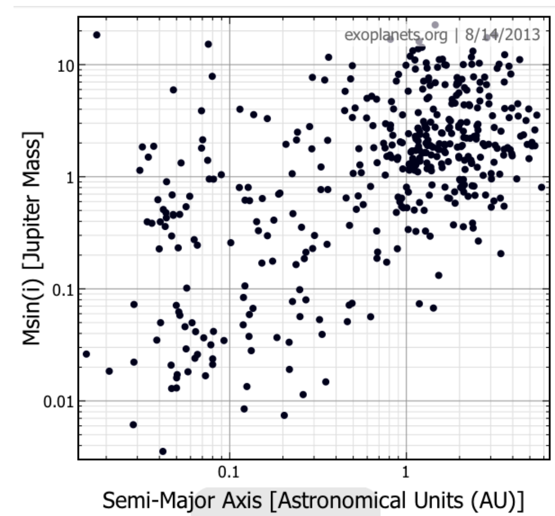


Updated version of population synthesis models









Ida

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.