Satellite Formation from Circumplanetary Particle Disks

Ryuki Hyodo, Keiji Ohtsuki, Takaaki Takeda

Introduction

● <u>Single Satellite System：</u>

-Earth-Moon (M_s/M_c~0.012)
-Mass ratio to the host planet M_s/M_c is relatively high
(M_s: satellite mass, M_c: mass of the central planet)

image courtesy of NASA

Introduction

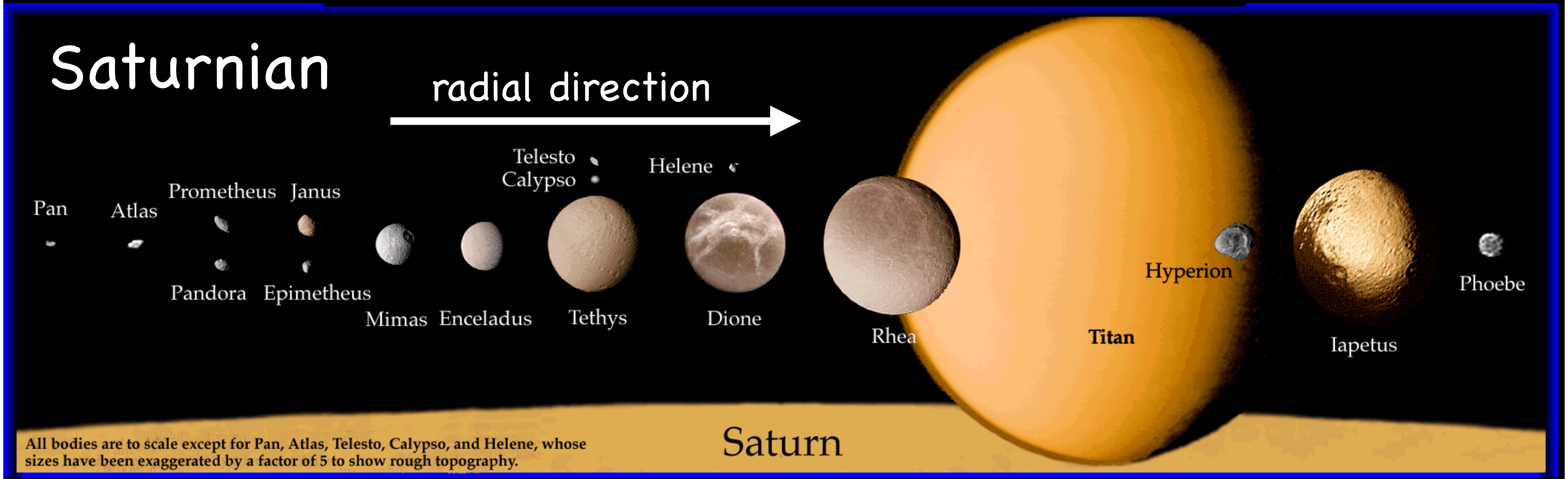


image courtesy of NASA

● Multiple Satellite System :

- inner major satellites: nearly circular, coplanar orbits
  - located just outside Roche limit
  - small mass ratio to the host planet ($M_s/M_c \sim 10^{-4}$)
  - increasing mass with increasing radial distance
  - the existence of co-orbital satellites

- Origin of single satellite system (Lunar formation):

Ida et al. (1997), Kokubo et al. (2000):

- N-body simulations of relatively massive disks ($M_{disk}/M_c \sim 0.05$)

- Origin of multiple satellite system:

Crida & Charnoz (2012):

- 1D analytical model ($M_{disk}/M_c \sim 10^{-4}$)
  - explain orbital architecture of Saturn, Uranus and Neptune
  - No gravitational interaction btw satellites and on disk
  - Mass flux through Roche limit is constant

- This work:

N-body simulations

- Disk evolutions on initial disk mass (and AM of the disk)
- Continuous accretion processes of multiple satellites

Numerical Method

- Gas-free global N-body simulation
  -equations of motion

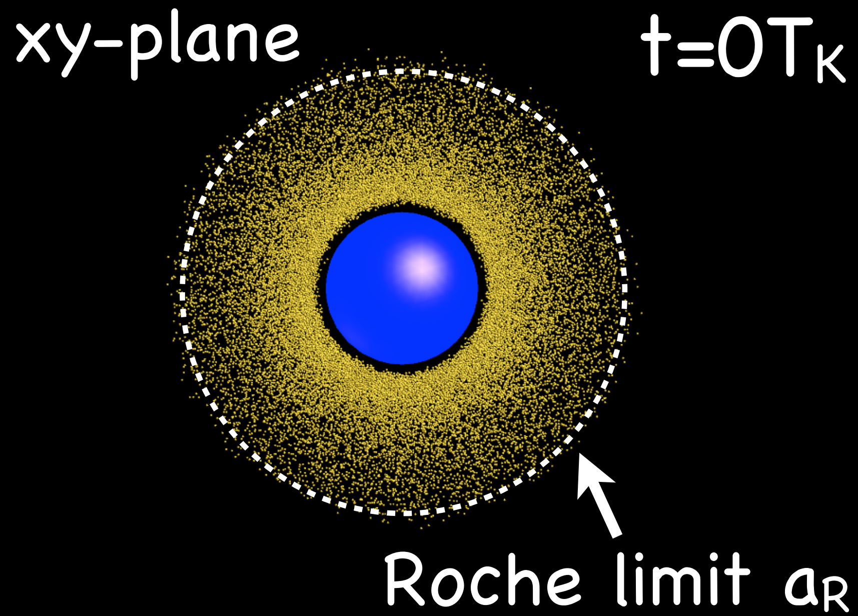
$$\frac{d\boldsymbol{v}_i}{dt} = -GM_c \frac{\boldsymbol{x}_i}{|\boldsymbol{x}_i|^3} - \sum_{j\neq i}^{N} Gm_j \frac{\boldsymbol{x}_i - \boldsymbol{x}_j}{|\boldsymbol{x}_i - \boldsymbol{x}_j|^3}$$

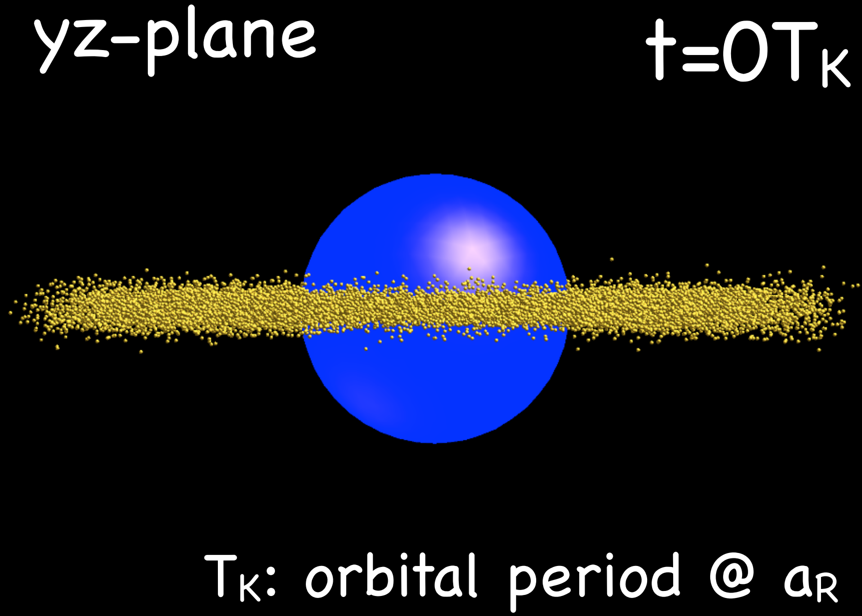
  -4th-order Hermite Method
  -Gravity calculation by GRAPE-DR system
  -Hard-sphere model (smooth particles with normal coefficient of restitution ϵ_n=0.1)

- Isolated aggregate sufficiently far from the Roche limit is replaced by a single body

Initial Disk Conditions

- Equal sized particles (N=30,000-50,000)
- Radial distribution : 0.4-1.0a_R (a_R : Roche limit)
- Specific Angular Momentum : 0.775sqrt{GM_cR_c}
- Initial disk mass : $M_{disk,init}$: 0.01-0.05M_c
  - "massive disk" : $M_{disk,init}$=0.045M_c
  - "less massive disk" : $M_{disk,init}$=0.0235M_c



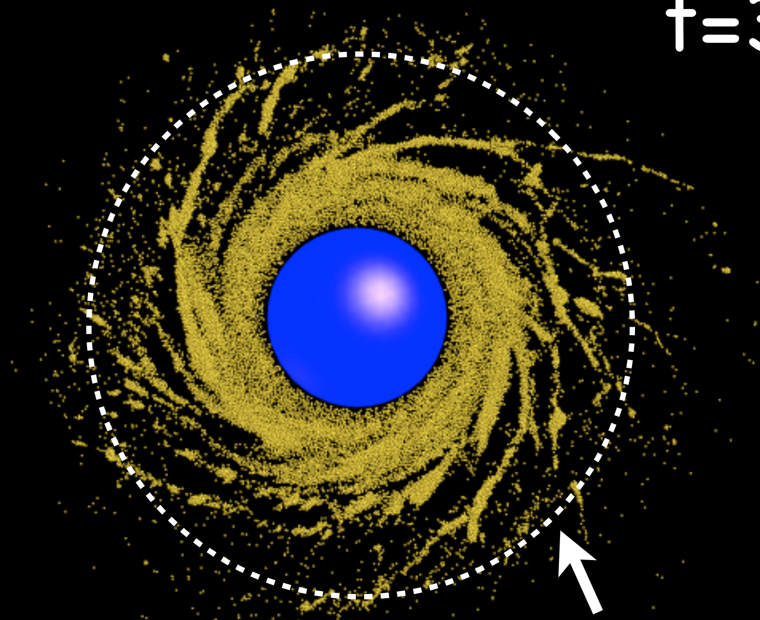


Case of Massive Disk

Case of Massive Disk

($M_{disk,init}$=0.045M_c)

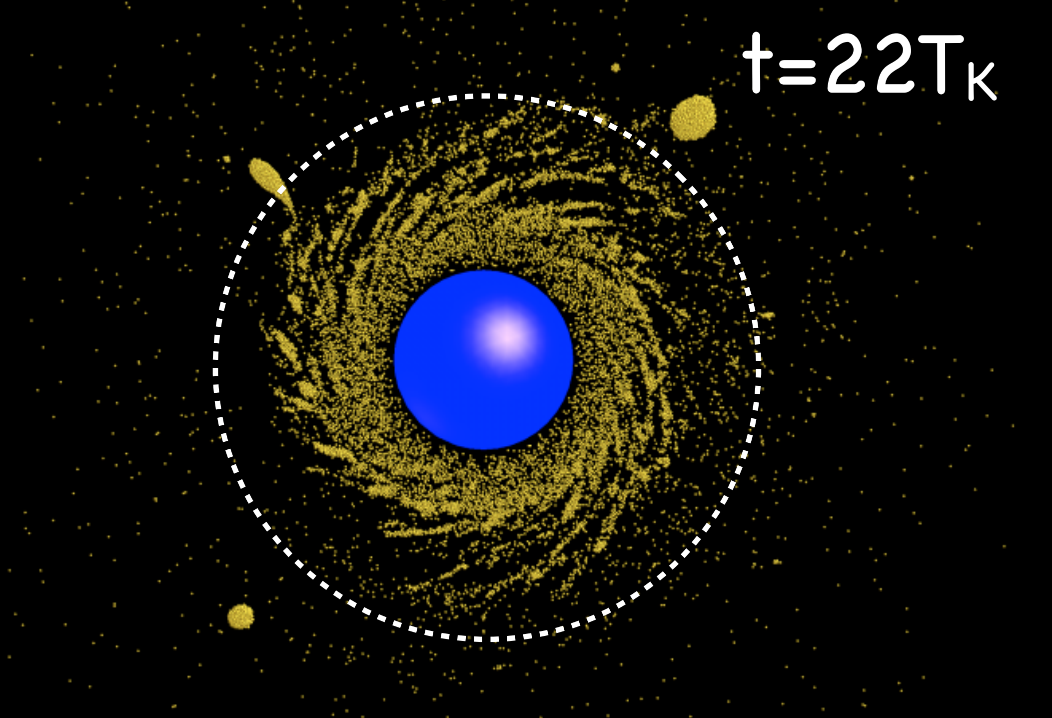
t=3T_K



Roche limit a_R

- Disk material is transferred outside the Roche limit.
- Outside the Roche limit, particles start to form gravitationally bound aggregates.

t=22T_K

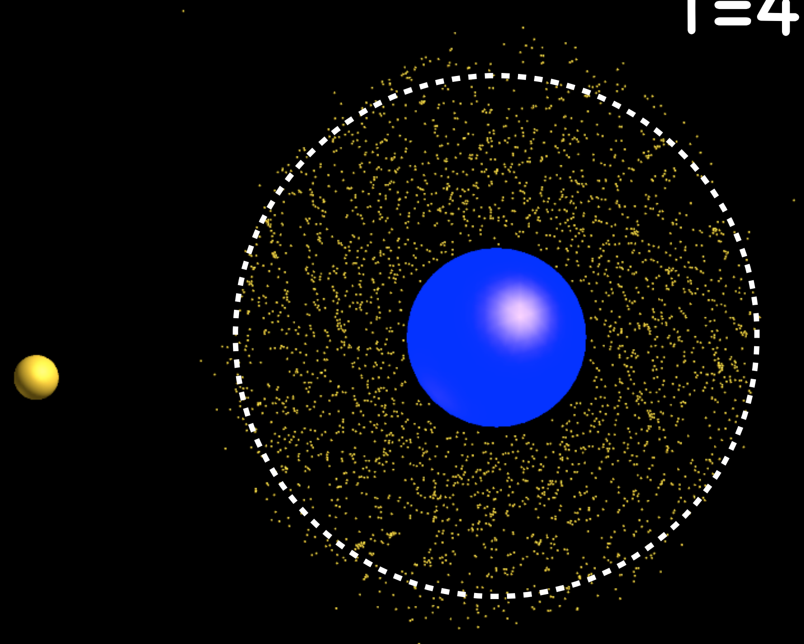


- Some aggregates re-enter the Roche limit and are disrupted.
- Aggregates grow through collisions with other aggregates or disk particles.

Case of Massive Disk

($M_{disk,init}$=0.045M_c)

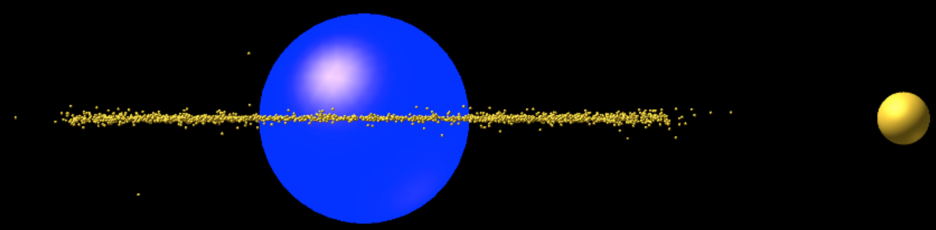
t=434T_K



- The satellite and the disk repelled each other due to gravitational interaction
- A large amount of disk material has fall into the central plant

- A single relatively large satellite is formed and only a very small fraction of the disk material remain (e.g. Ida et al. 1997)
- The formed satellite is on nearly circular orbit with low inclination

t=434T_K

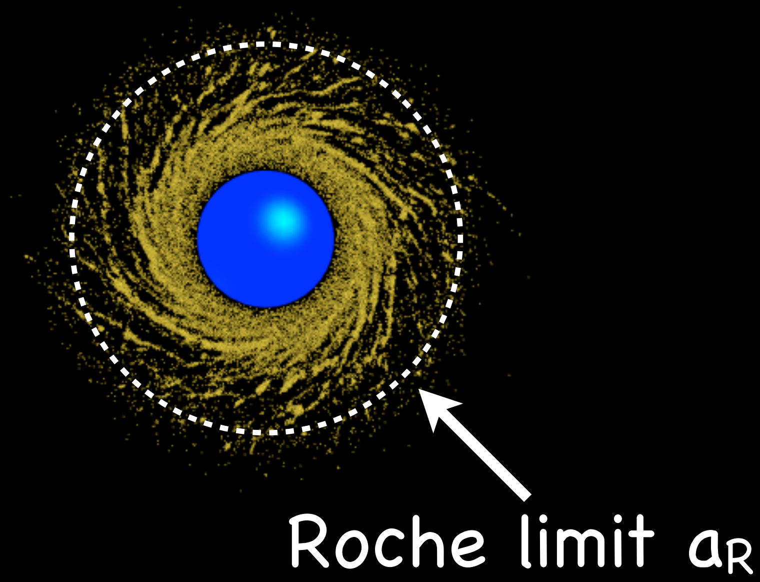


Case of Less Massive Disk

Case of Less Massive Disk

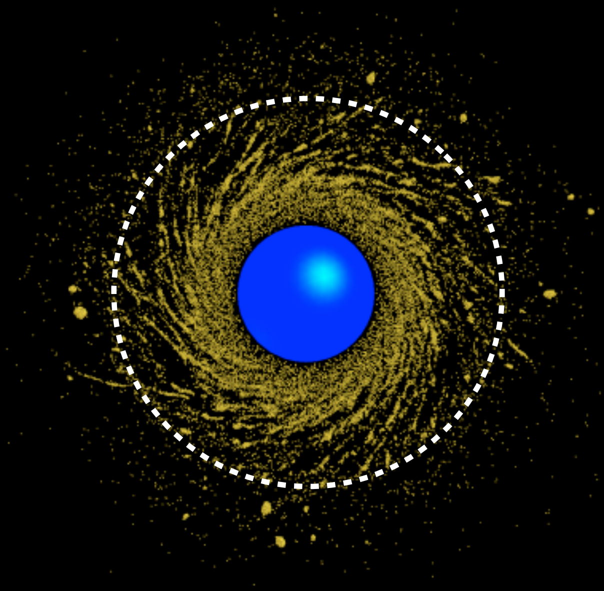
($M_{disk,init}$=0.0235M_c)

$t=5T_K$



- Spirals extend radially outward and disk material is transferred outside the Roche limit.

$t=20T_K$

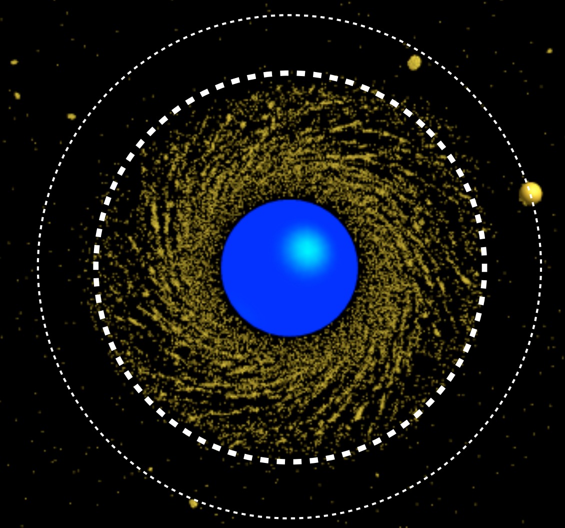


- The timescale of the disk evolution is longer and mass transfer rate is smaller compared to relatively massive disk.

Case of Less Massive Disk

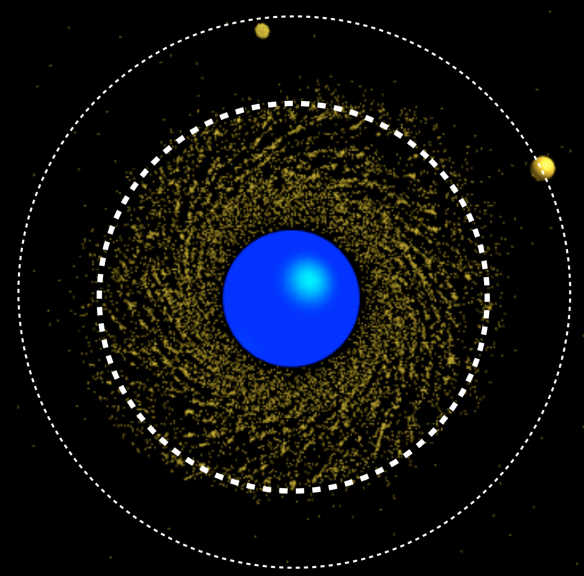
($M_{disk,init}$=0.0235M_c)

t=50T_K



- 1st satellite is smaller compared to the "massive disk" case
- There still remain a large amount of disk material
- A small companion is formed with the 1st satellite

t=100T_K

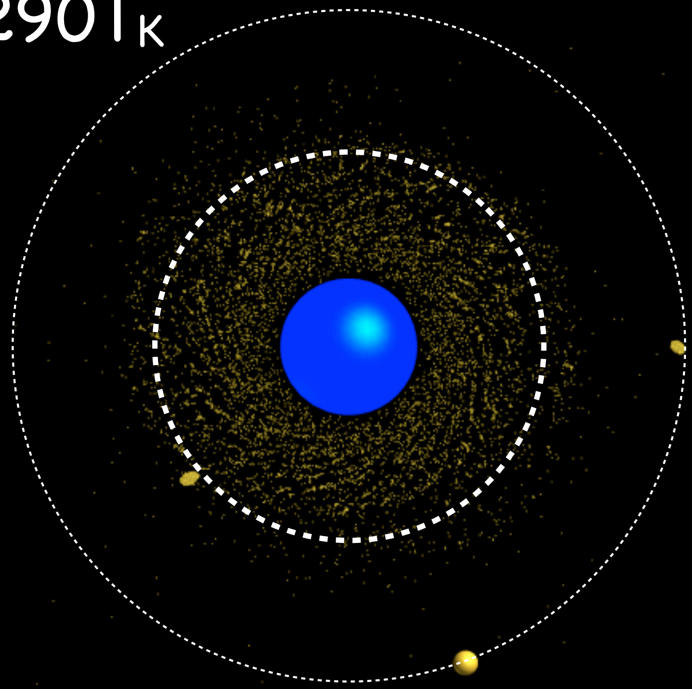


- Even thought the satellite migrates outward and the disk move inward due to gravitational interaction, not huge amount of disk particles fall into the central planet
- The 1st satellite migrates further outward

Case of Less Massive Disk

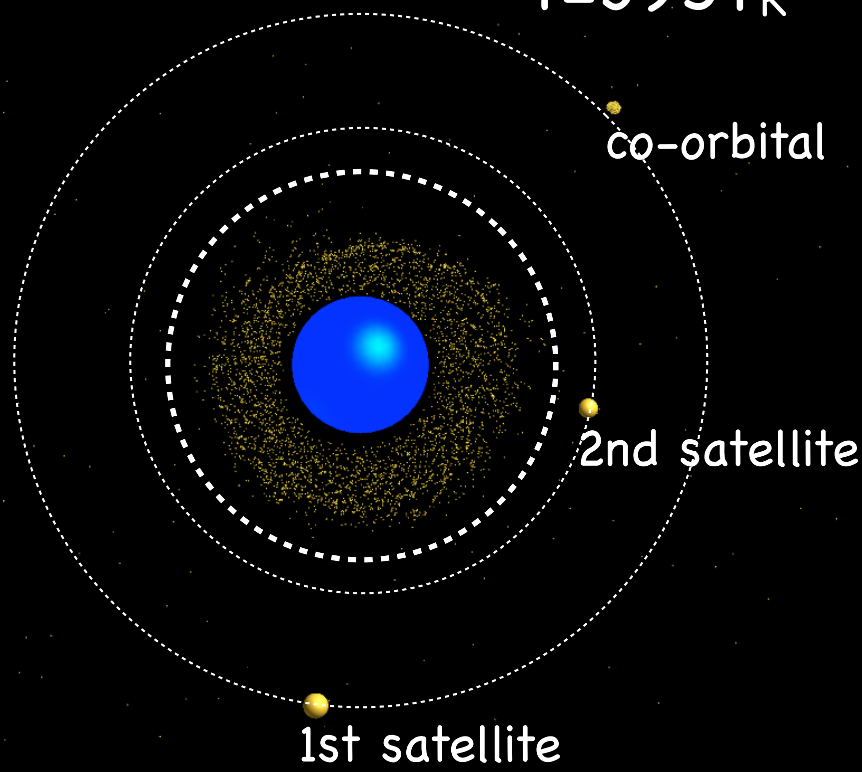
($M_{disk,init}$=0.0235M_c)

t=290T_K



- 1st satellite migrates sufficiently outward and the location of its 2:1 mean motion resonance (MMR) moves just outside the Roche limit, where disk particles are piled up.

t=395T_K



- 2nd satellite is formed from particles piled up at the 2:1 MMR and is locked around the resonance.

Satellite Mass

<u>When Σ(surface density)=const.</u>

F(mass flux) $\propto \Sigma^3$

Thus, $M_{sate} \propto \Sigma^3 \propto M_{disk,init}{}^3$

<u>When decrease of Σ is NOT negligible</u>

-single satellite system

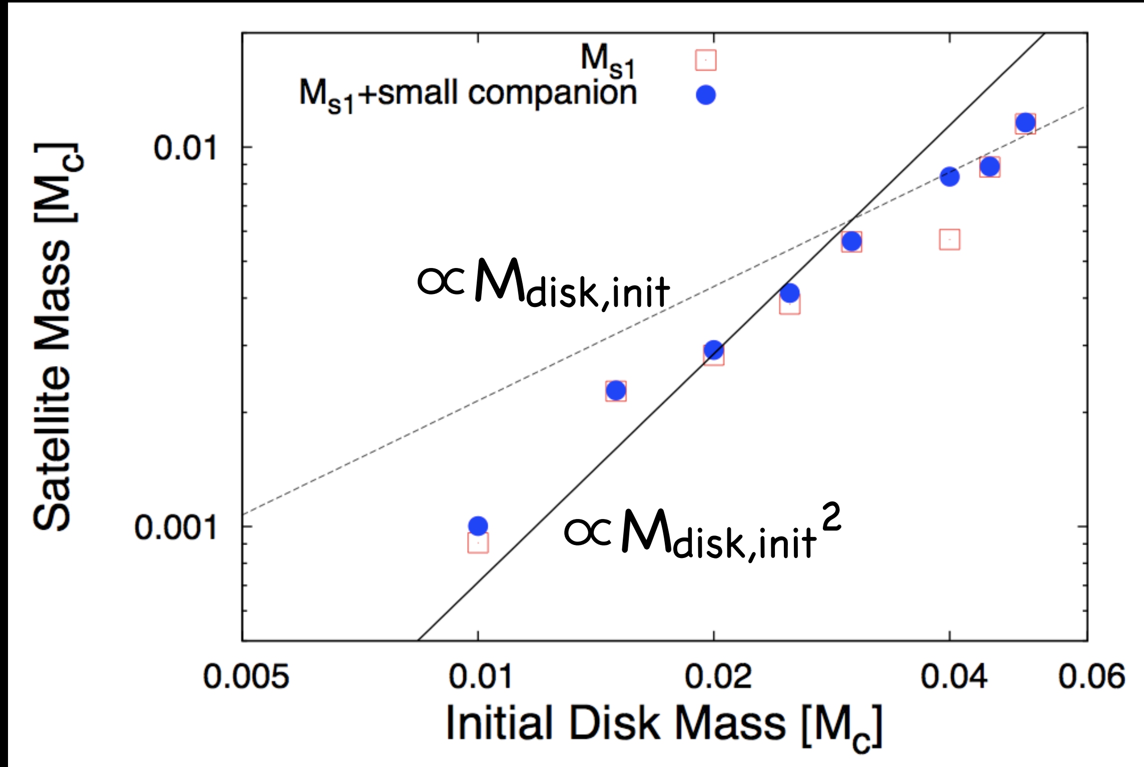
($M_{disk,init}$>0.03M_c)

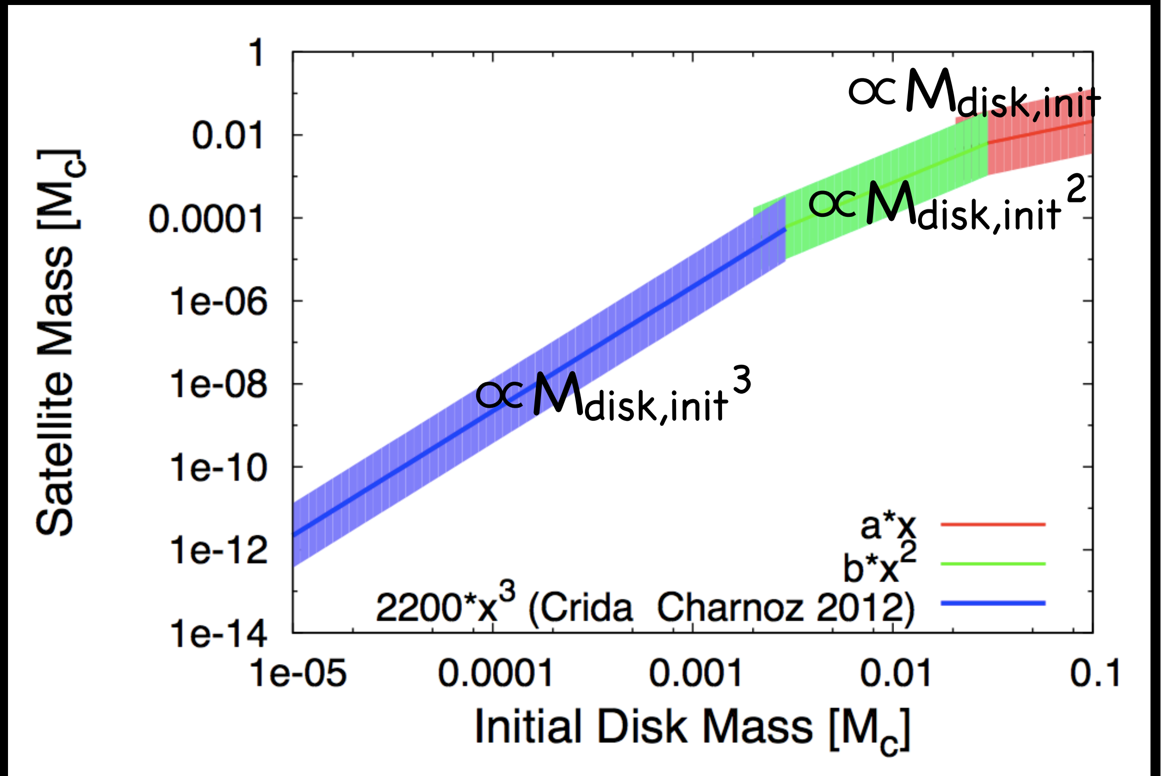
Considering AM and Mass conservation and set Σ(t=∞)=0 then $M_{sate} \propto M_{disk,init}$

-second satellite form

(0.01M_c<$M_{disk,init}$<0.03M_c)

$M_{sate} \propto M_{disk,init}{}^2$

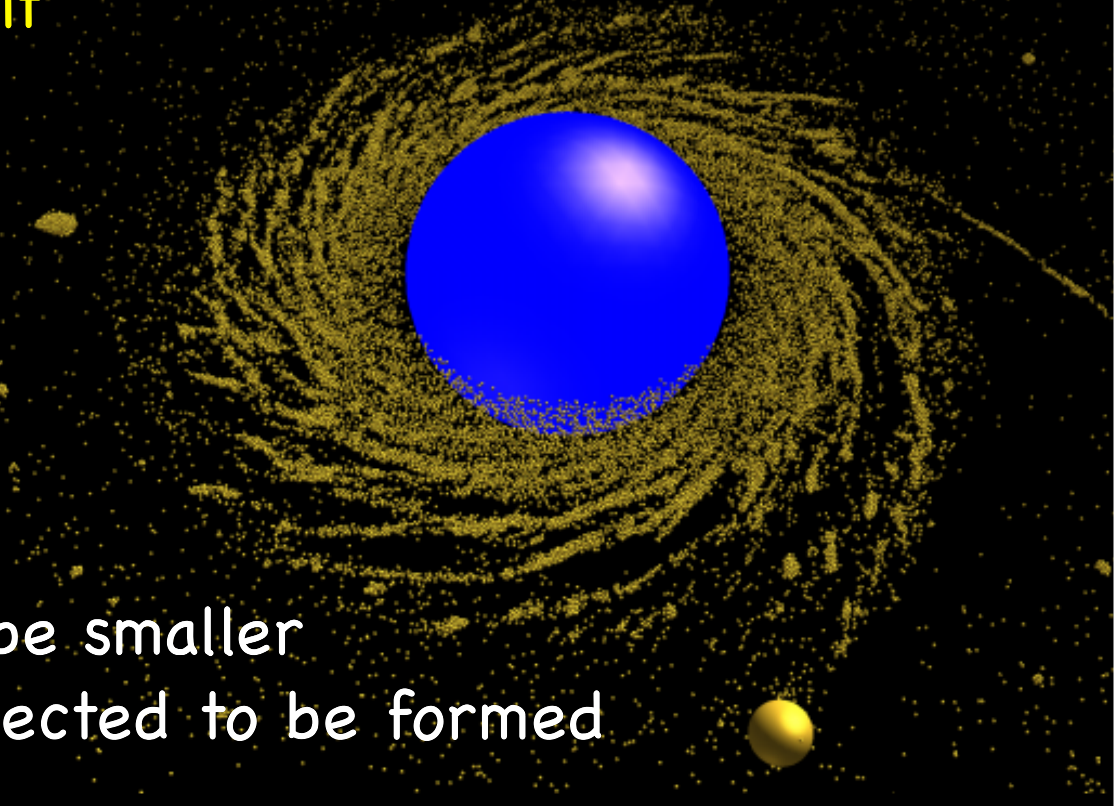




Conclusions

● Multiple Satellite Formation ($0.01 < M_{disk,init}/M_c < 0.03$)

- M_s more strongly depends on initial disk mass ($\propto M_{disk,init}^2$)
- 2nd satellite is in the 2:1 MMR with the 1st satellite
- increasing mass with increasing radial distance
- nearly circular, coplanar orbit
- co-orbital satellite can form

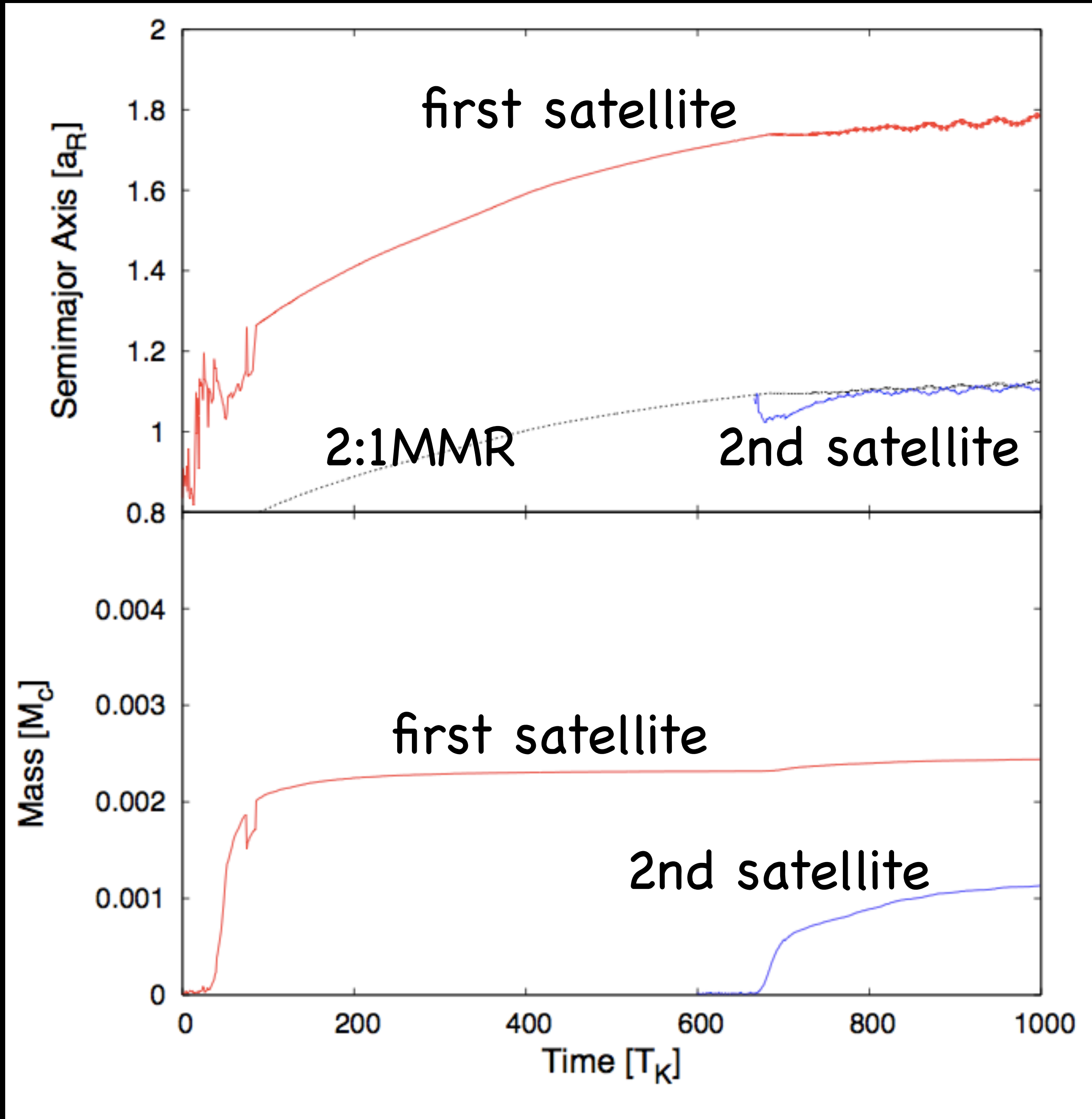


● Further less massive disk:

- Satellite mass expected to be smaller
- 3rd, 4th... satellites are expected to be formed

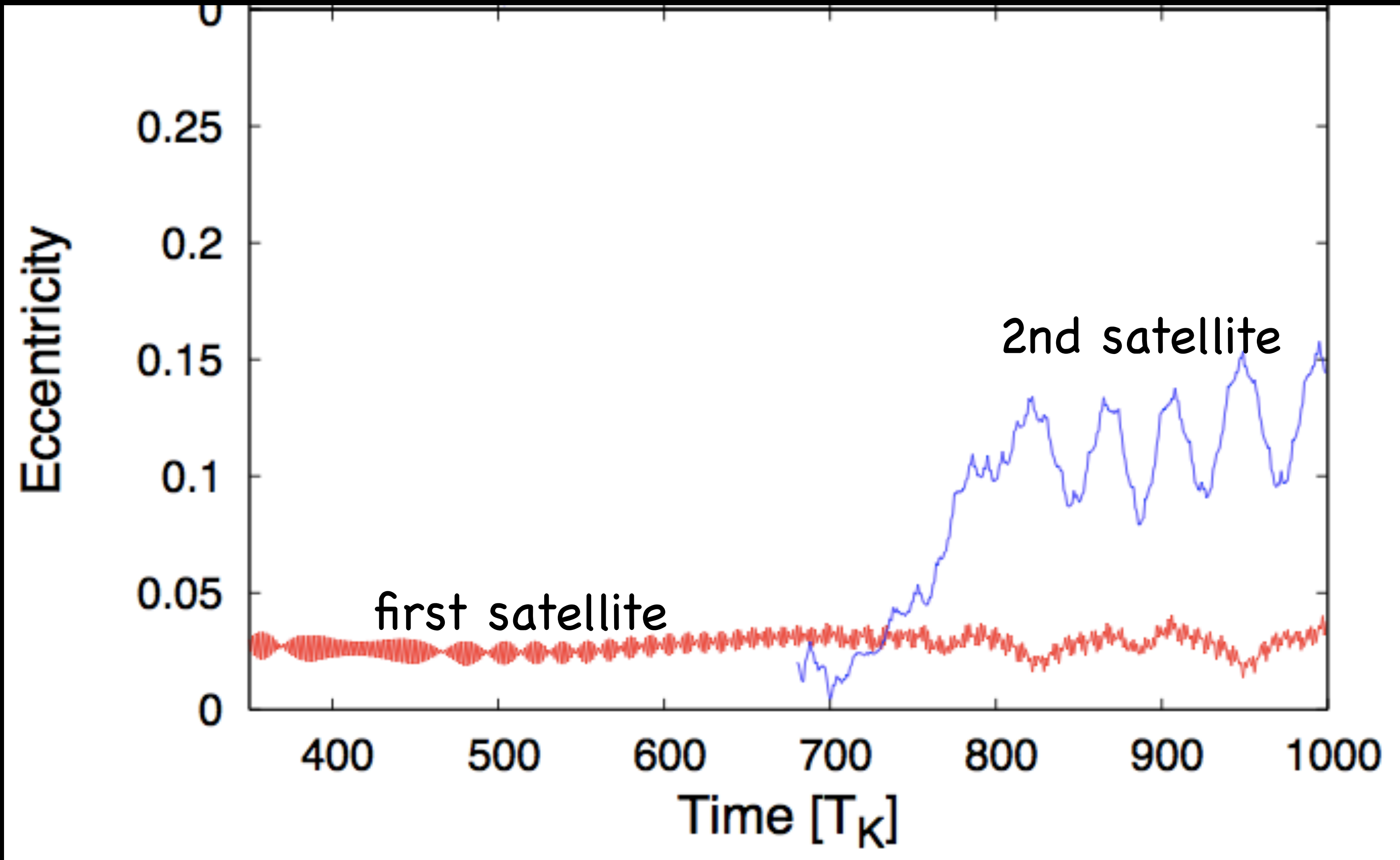
Orbital Evolution

($M_{disk,init}$=0.015M_c)

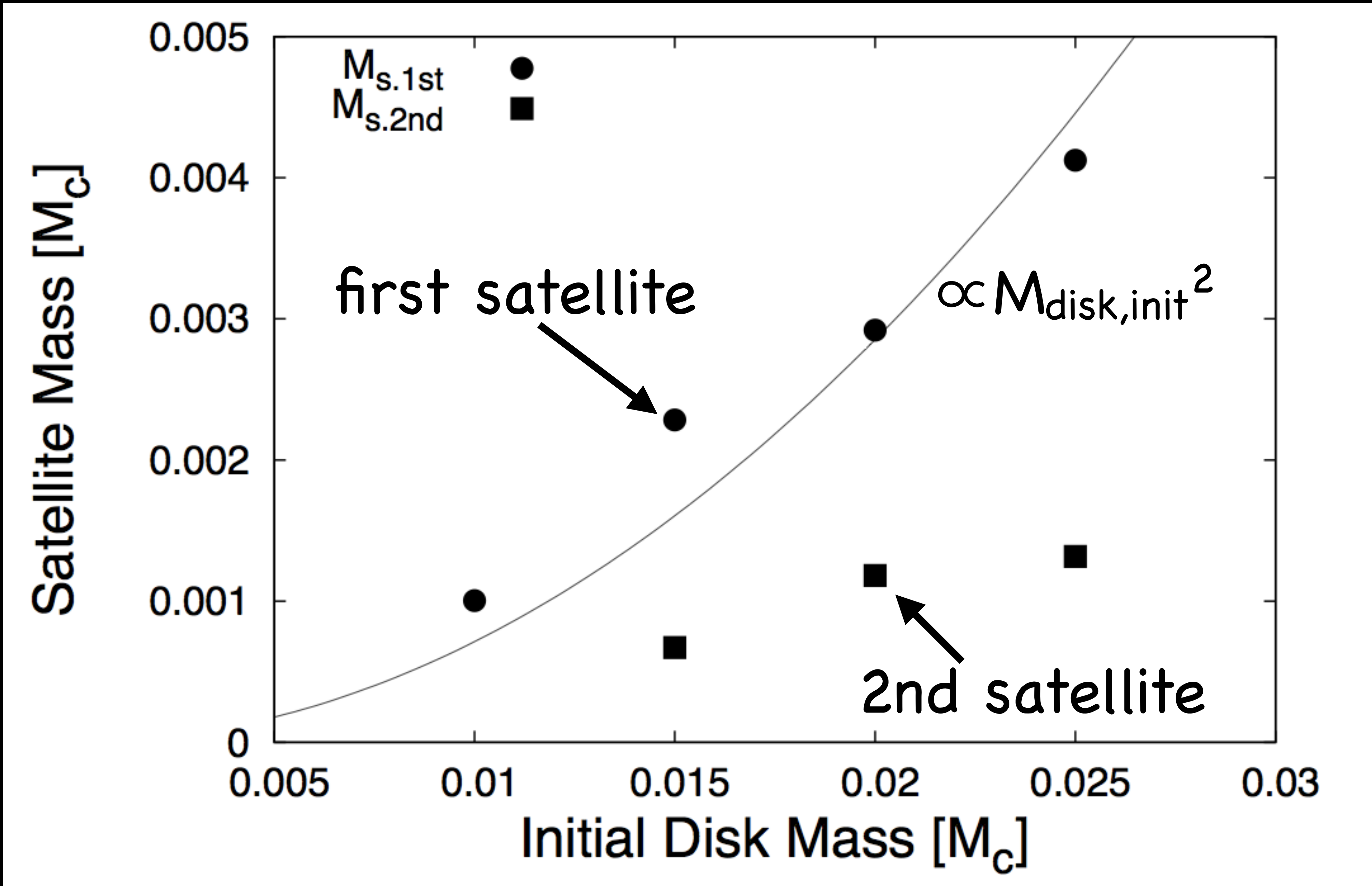


Eccentricity Evolution

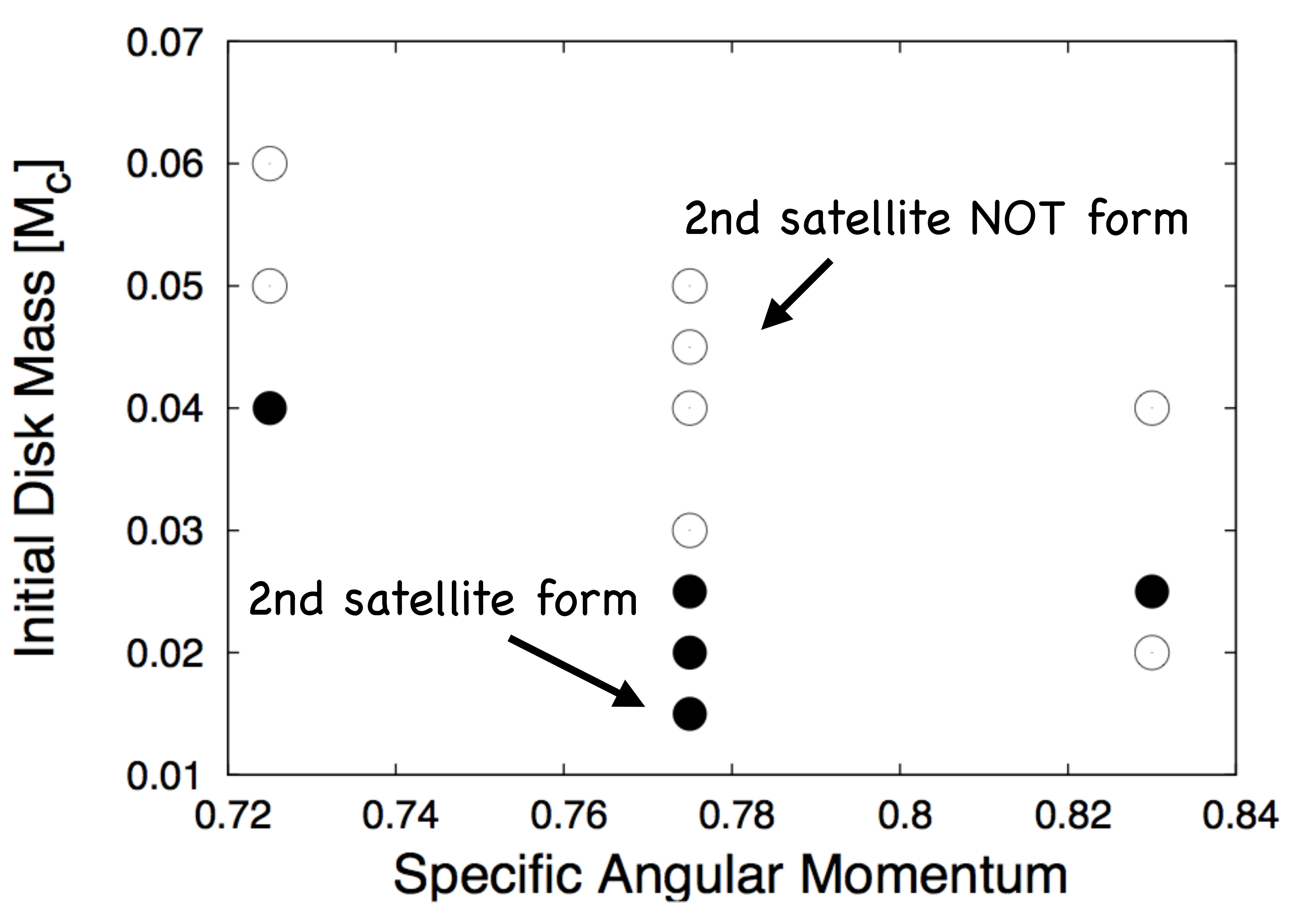
($M_{disk,init}$=0.015M_c)



Satellite Mass on Disk Mass



Dependence on Disk Angular Momentum



Orbital Evolution

(rubble pile model on 2nd satellite, $M_{disk,init}$=0.025M_c)