周惑星粒子円盤の進化と衛星形成

Hyodo, Ohtsuki & Takeda (2014), ApJ in prep

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Introduction

● Single Satellite System :

-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

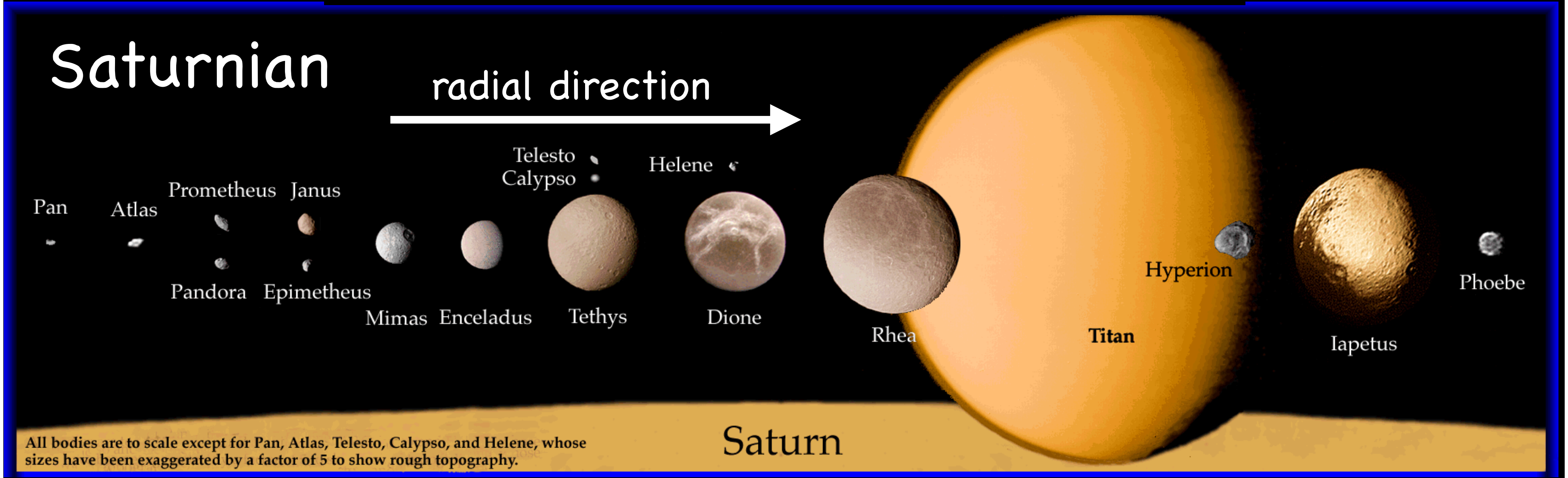


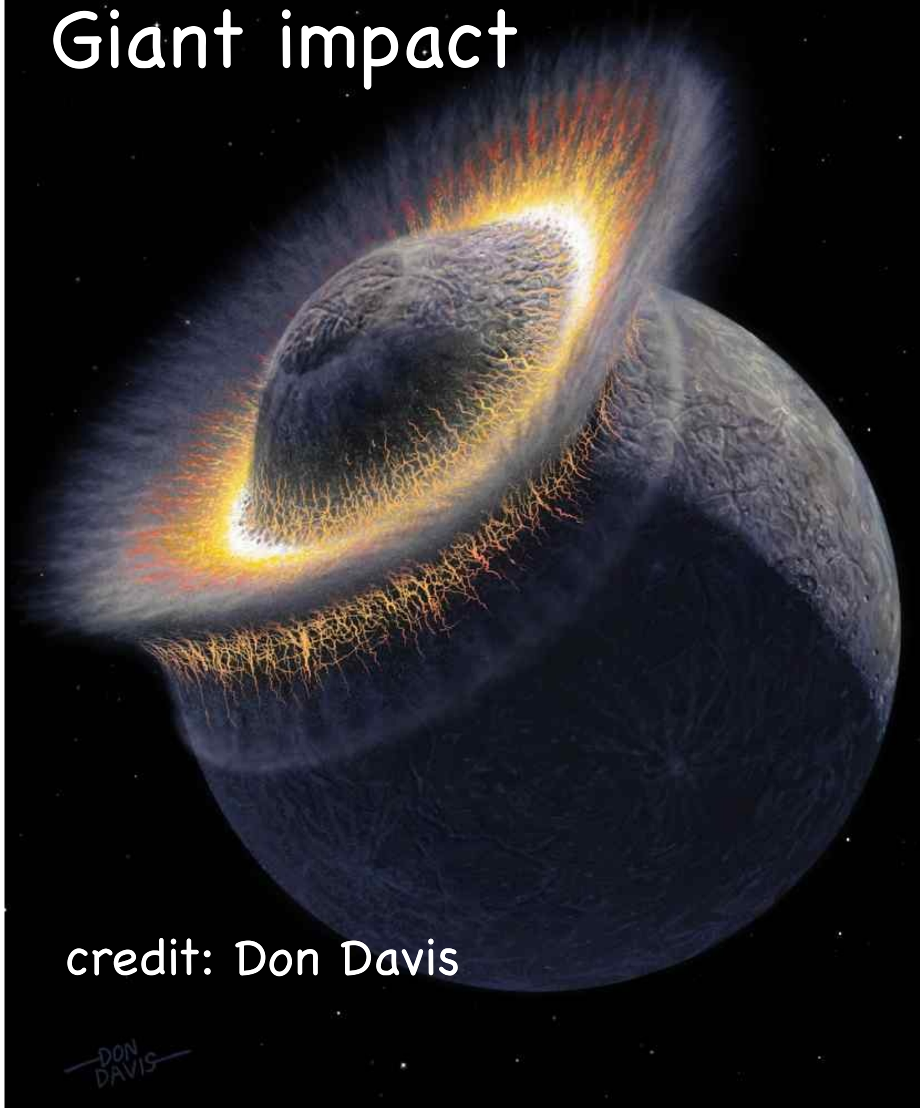
image courtesy of NASA

● 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

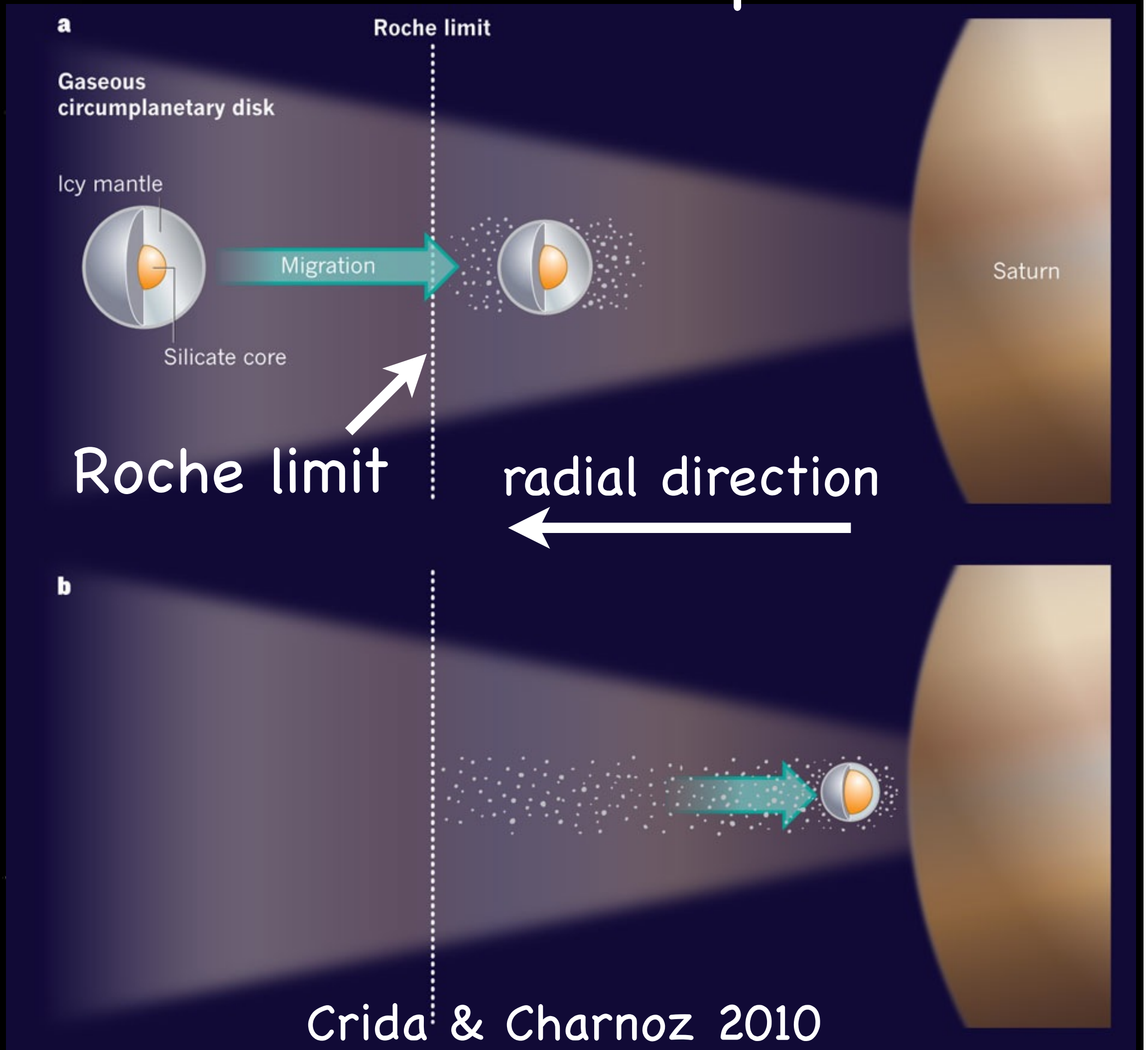
Origin of Disks

Giant impact



credit: Don Davis

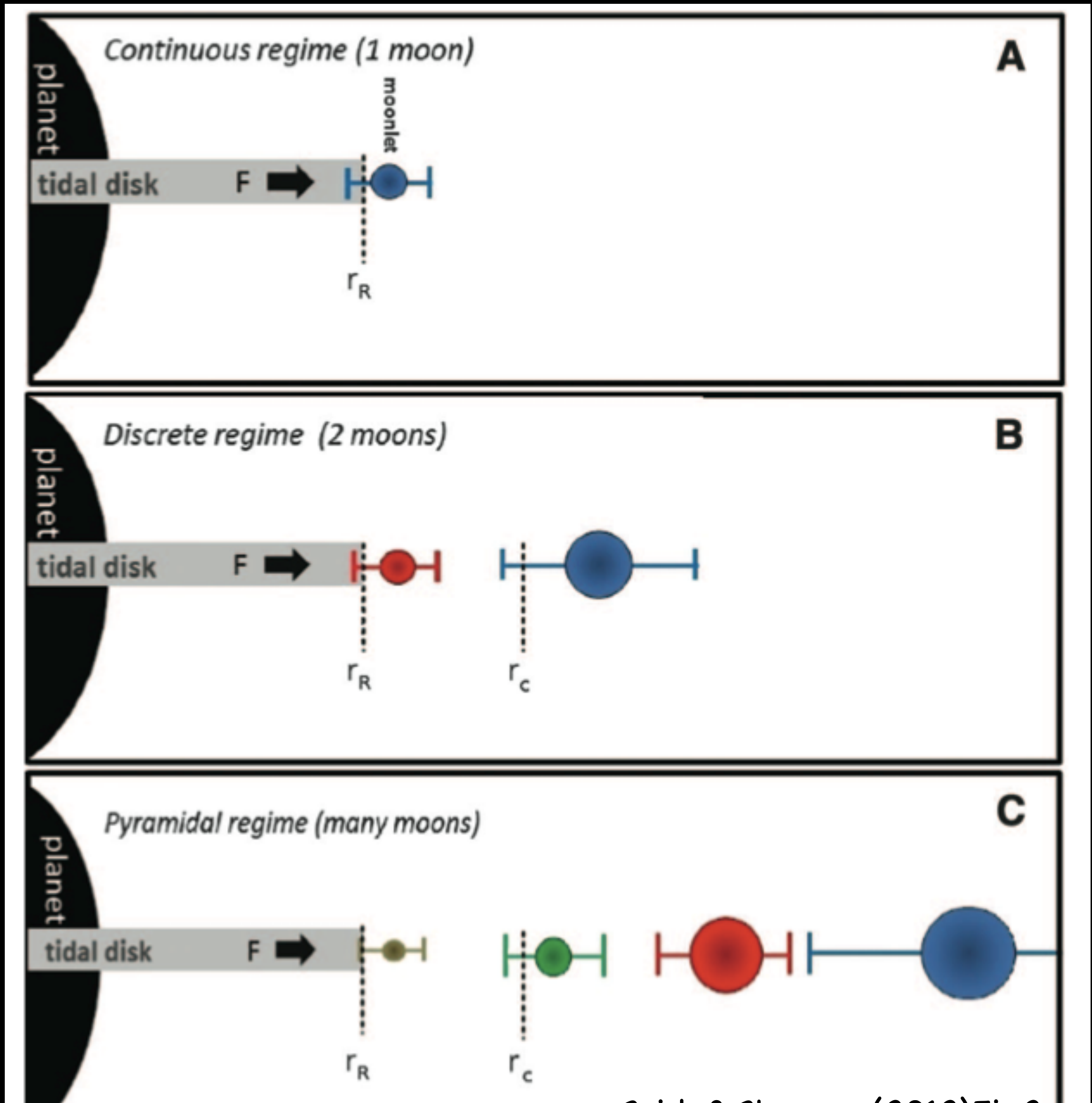
Tidal distruption



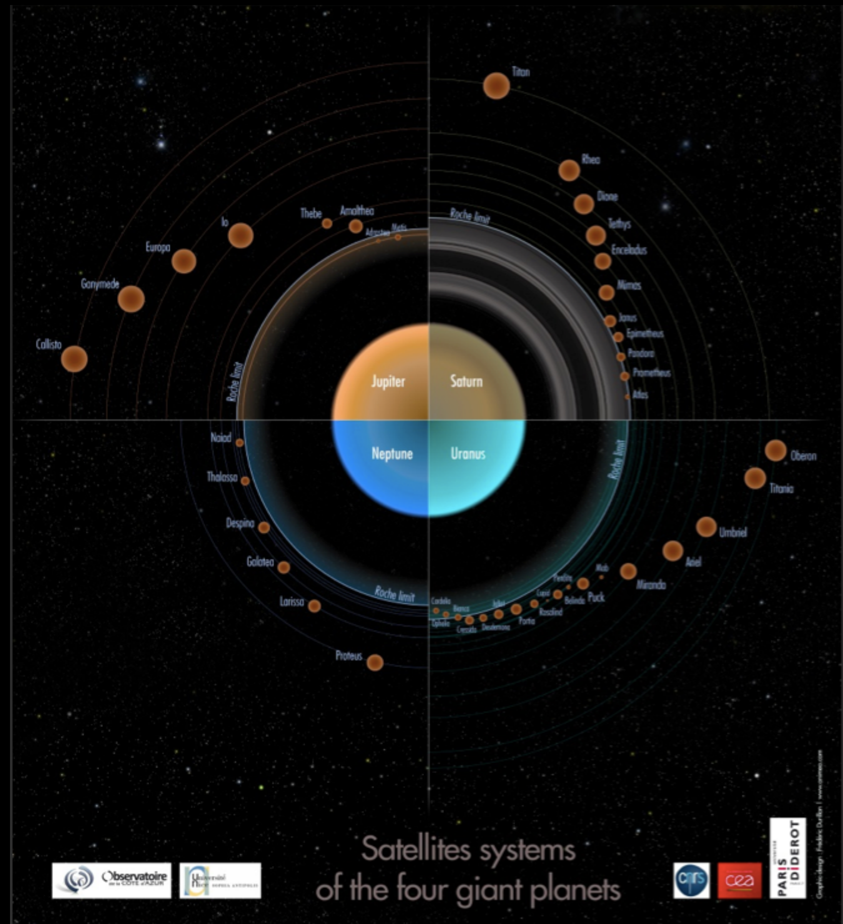
Crida & Charnoz 2010

Origin of multiple satellite system:

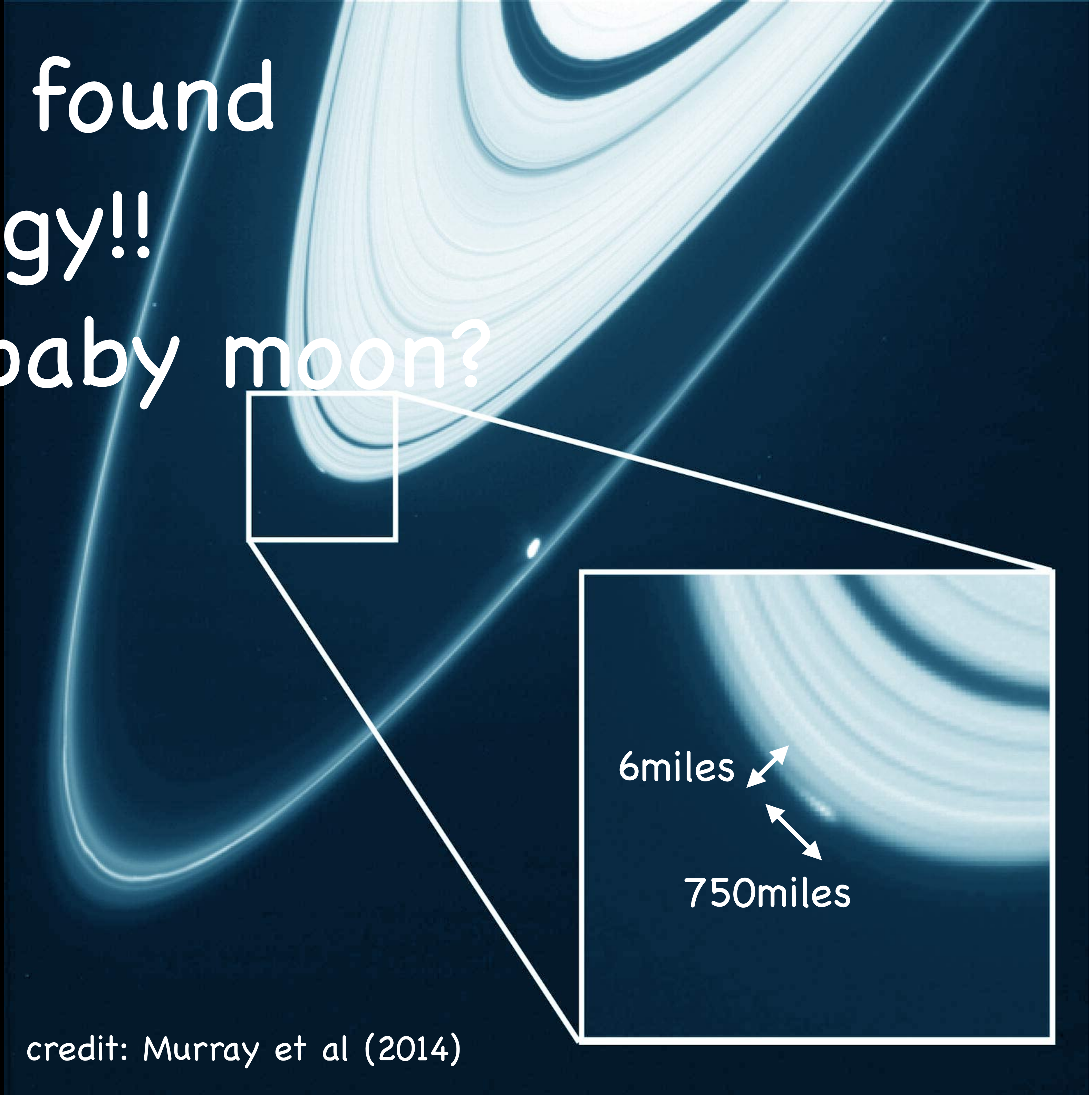
Crida & Charnoz (2012): 1D analytical model ($M_{disk}/M_c \sim 10^{-4}$)



Crida&Charnoz(2012)Fig2



Cassini found Peggy!!
A new baby moon?



credit: Murray et al (2014)

- Issues with (or limitations to) previous works:

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

-aimed only for the formation of the Moon

Crida & Charnoz (2012):

-Ignore satellite torques

-> mass flux weakened & resonance capture?

-Mass flux through Roche limit is constant

-> should decrease with time

-Accretion efficiency is 100%

-> NOT 100% in the tidal field (Hyodo & Ohtsuki 2014)

- This work:

N-body simulations

-Continuous accretion processes of multiple satellites

Numerical Method

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

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

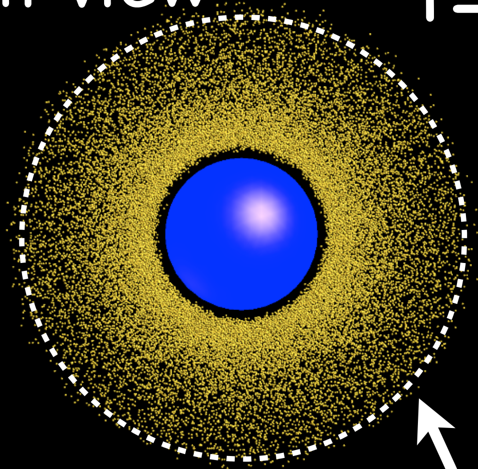
  -4th-order Hermite Method
  -Gravity calculation by GRAPE-DR system
  -Hard-sphere model (smooth particles with normal coefficient of restitution ϵ_n=0.1)

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

Initial Disk Conditions

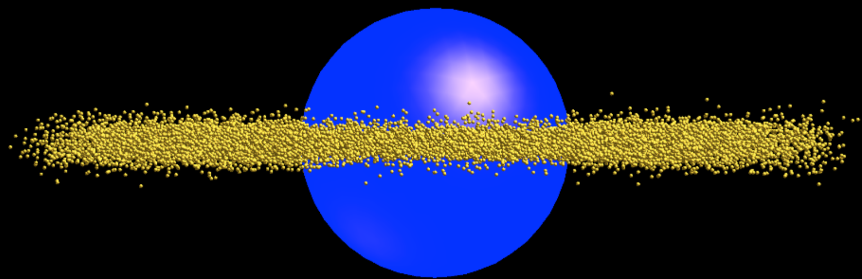
- Equal sized particles (N=30,000-50,000)
- Radial distribution : 0.4-1.0a_R (a_R : Roche limit)
- Specific Angular Momentum : 0.775sqrt{GM_cR_c}
- Initial disk mass : $M_{disk,init}$: 0.01-0.05M_c
  - "massive disk" : $M_{disk,init}$=0.045M_c
  - "less massive disk" : $M_{disk,init}$=0.0235M_c

face-on view $t=0T_K$



Roche limit a_R

edge-on view $t=0T_K$



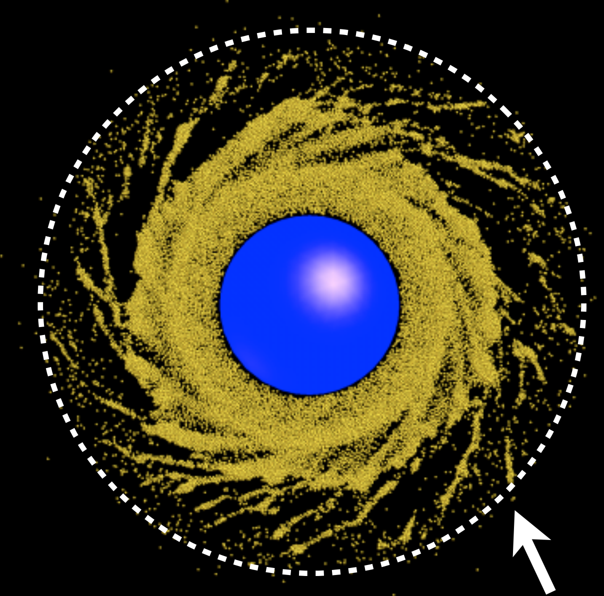
T_K: orbital period @ a_R

Case of Massive Disk

Case of Massive Disk

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

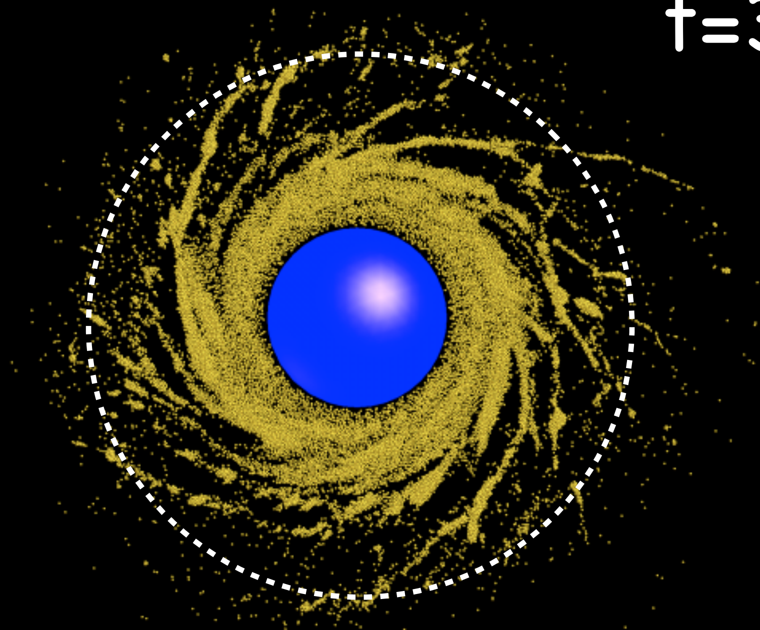
$t=1T_K$



Roche limit a_R

- Inside the Roche limit, tidal force prevents disk particles from gravitational accretion.
- The disk radially shrinks due to inelastic collision damping and temporary "clumps" form.

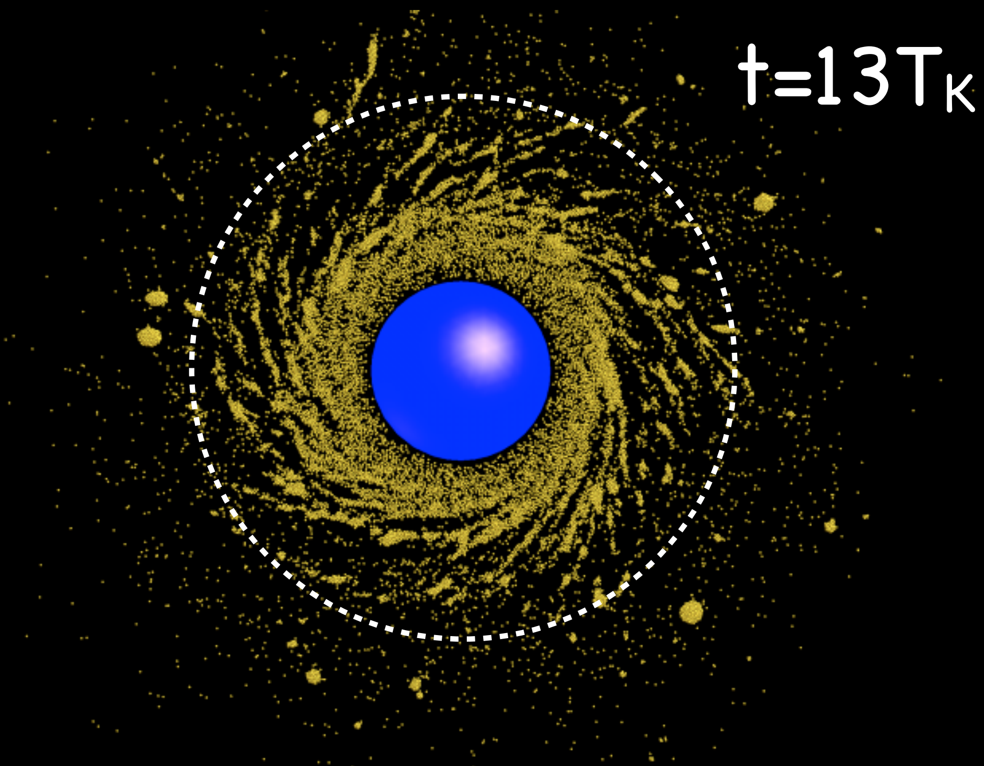
$t=3T_K$



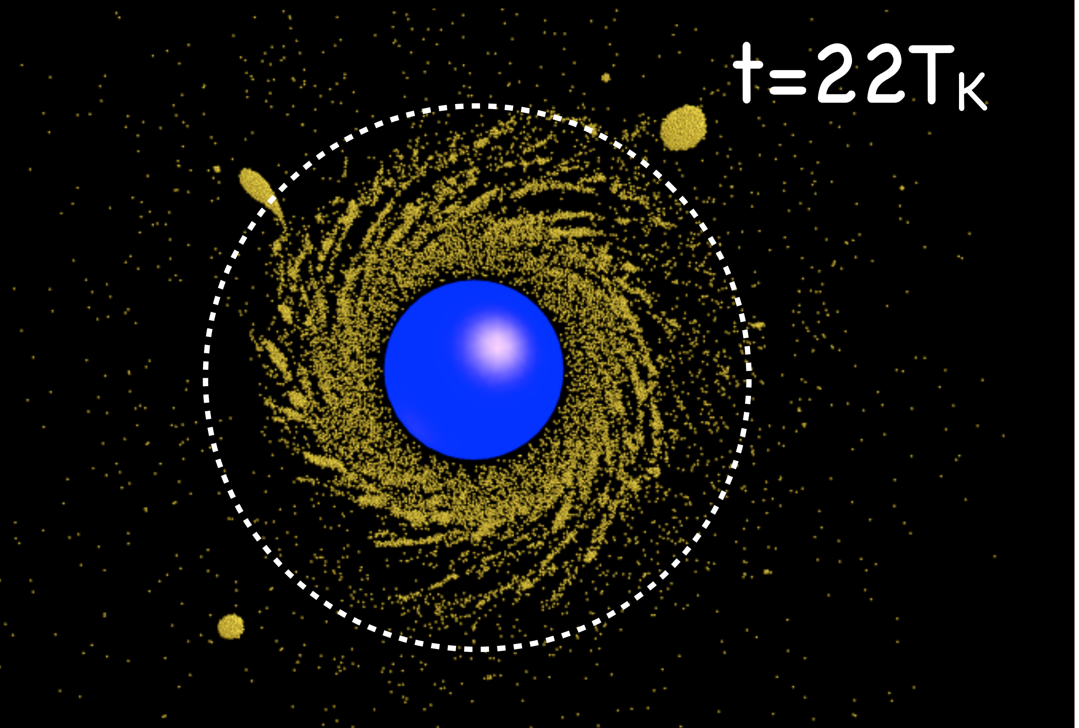
- Tidal force soon disrupt the clumps and spiral patterns form.
- Spirals extend radially outward and disk material is transferred outside the Roche limit.

Case of Massive Disk

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



- Outside the Roche limit, particles start to form gravitationally bound aggregates.

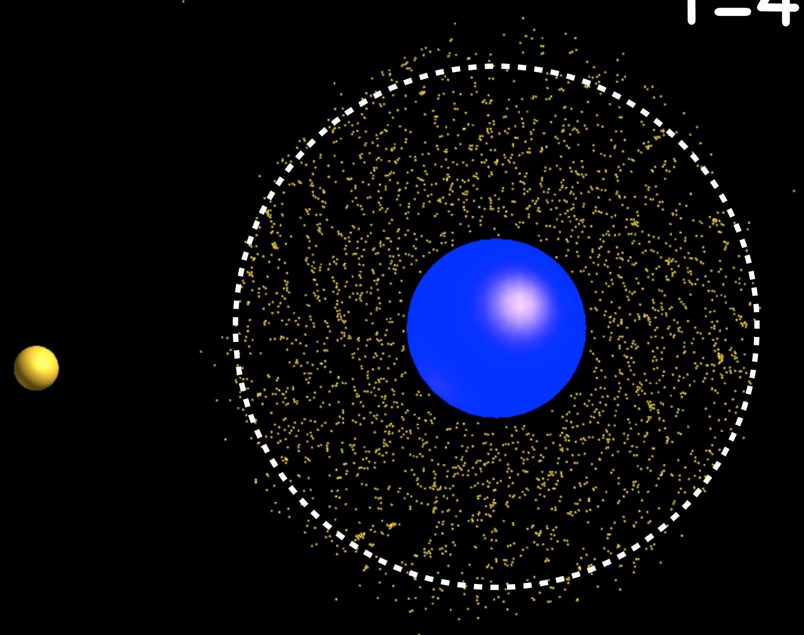


- Some aggregates re-enter the Roche limit and are disrupted.
- Aggregates grow through collisions with other aggregates or disk particles.

Case of Massive Disk

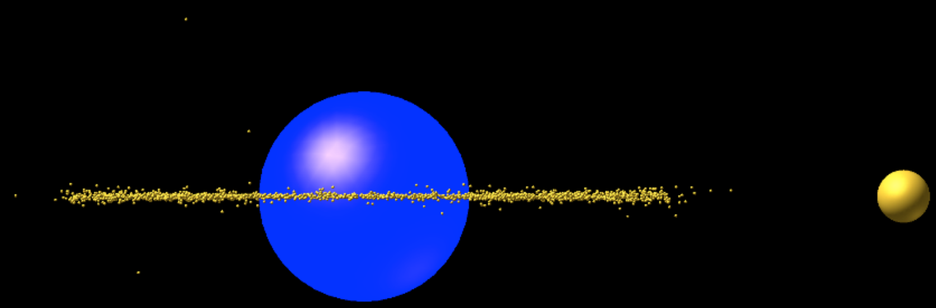
($M_{D,init}$=0.045M_c)

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

t=434T_K



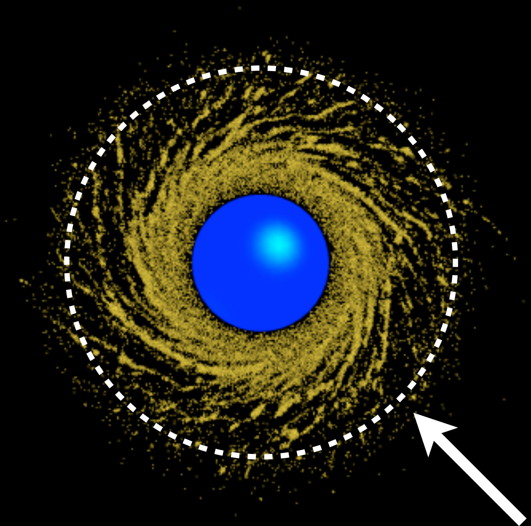
- A single relatively large satellite is formed and only a very small fraction of the disk material remain (e.g. Ida et al. 1997)
- The formed satellite is on nearly circular orbit with low inclination

Case of Less Massive Disk

Case of Less Massive Disk

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

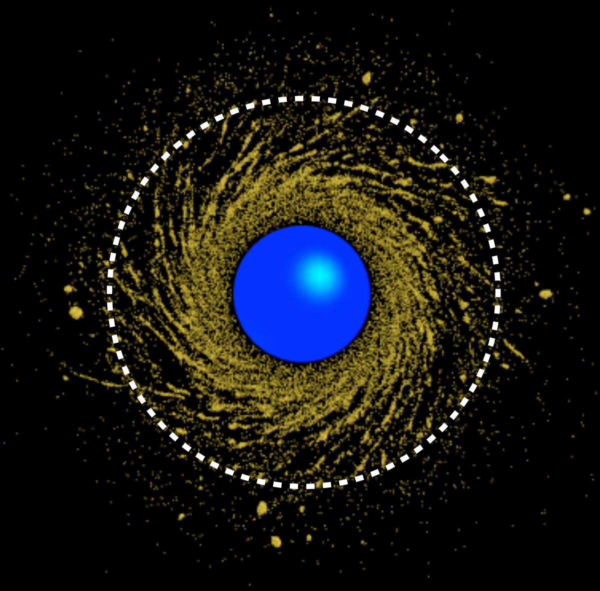
t=5T_K



Roche limit a_R

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

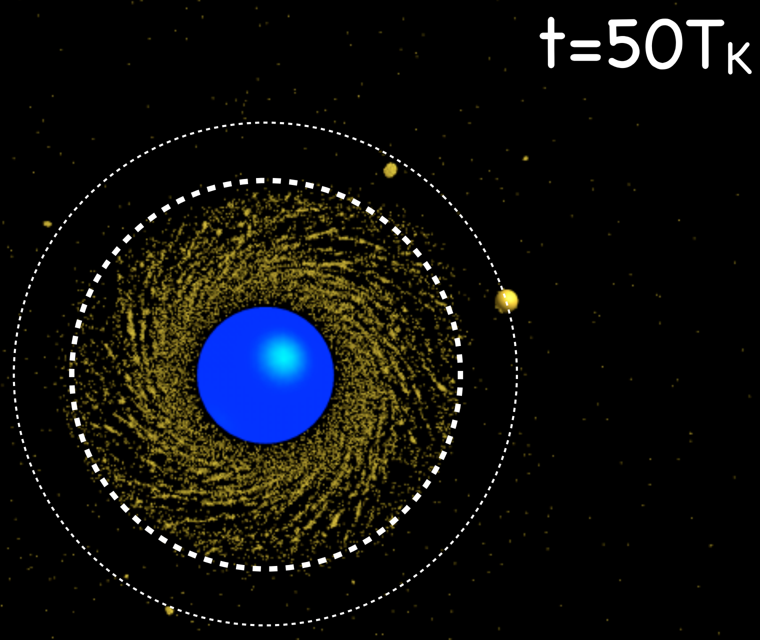
t=20T_K



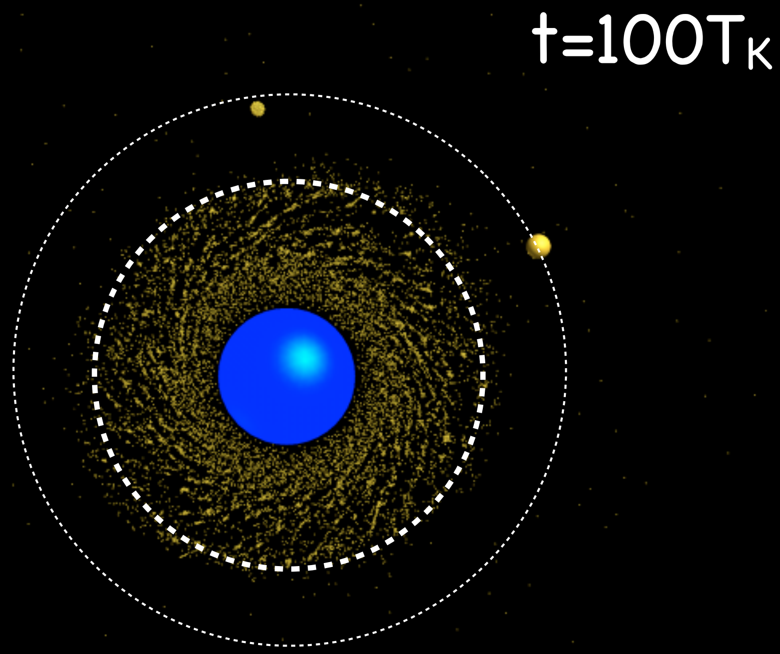
- The timescale of the disk evolution is longer and mass transfer rate is smaller compared to relatively massive disk.

Case of Less Massive Disk

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



- 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

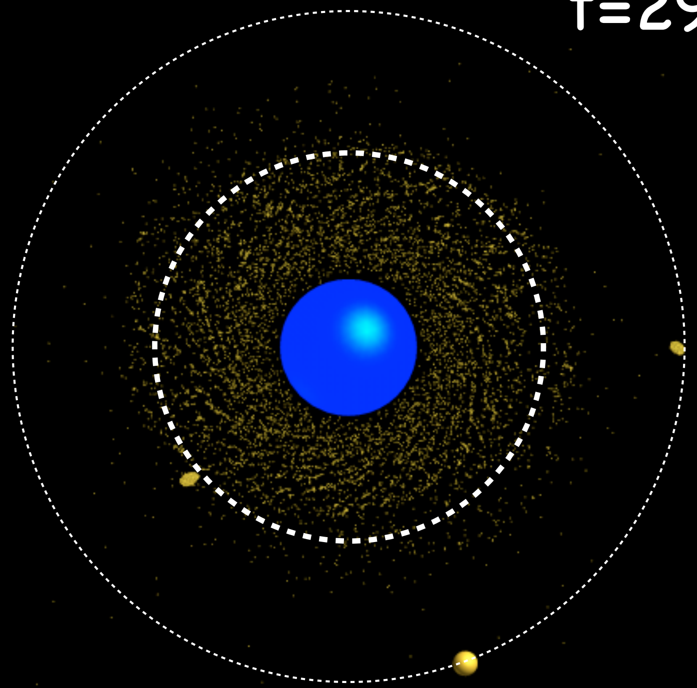


- Even thought the satellite migrates outward and the disk move inward due to gravitational interaction, not huge amount of disk particles fall into the central planet
- The 1st satellite migrates further outward

Case of Less Massive Disk

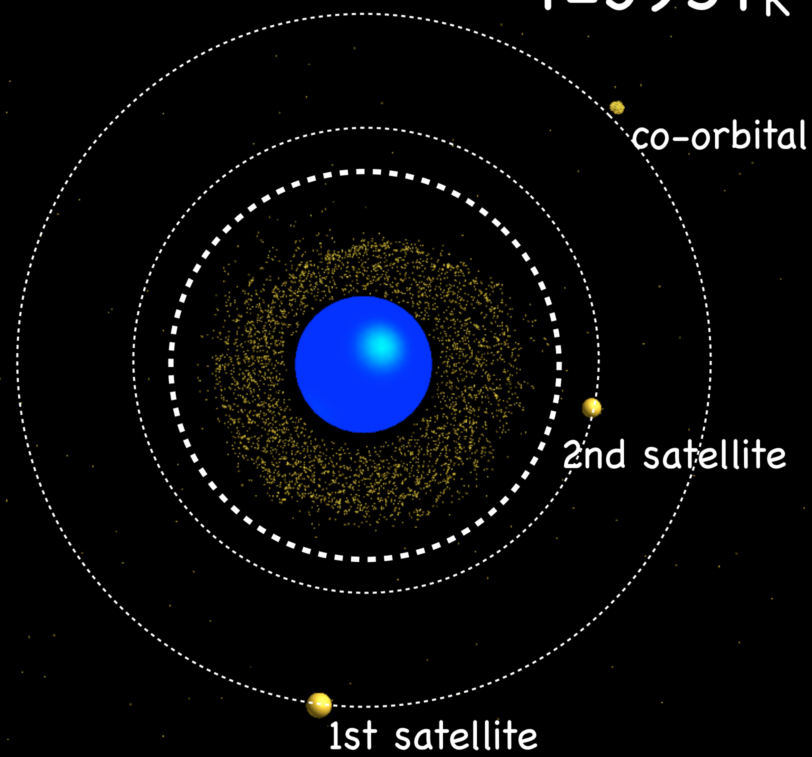
$(M_{D,init}=0.0235M_c)$

$t=290T_K$



- 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.

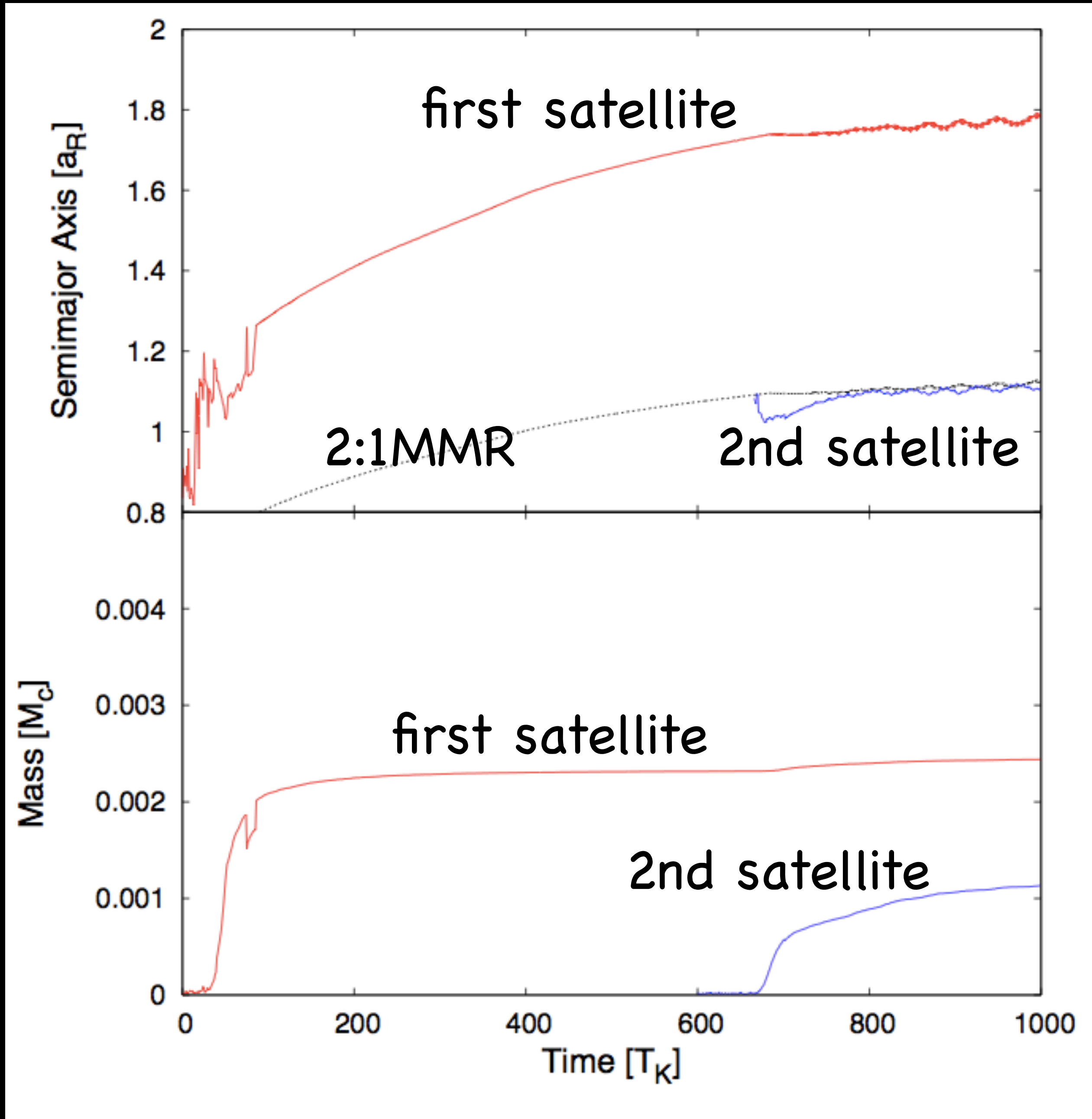
$t=395T_K$



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

Orbital Evolution

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



Overall Results

Satellite Mass

When Σ(surface density)=const.

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

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

When decrease of Σ is NOT negligible

-single satellite system

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

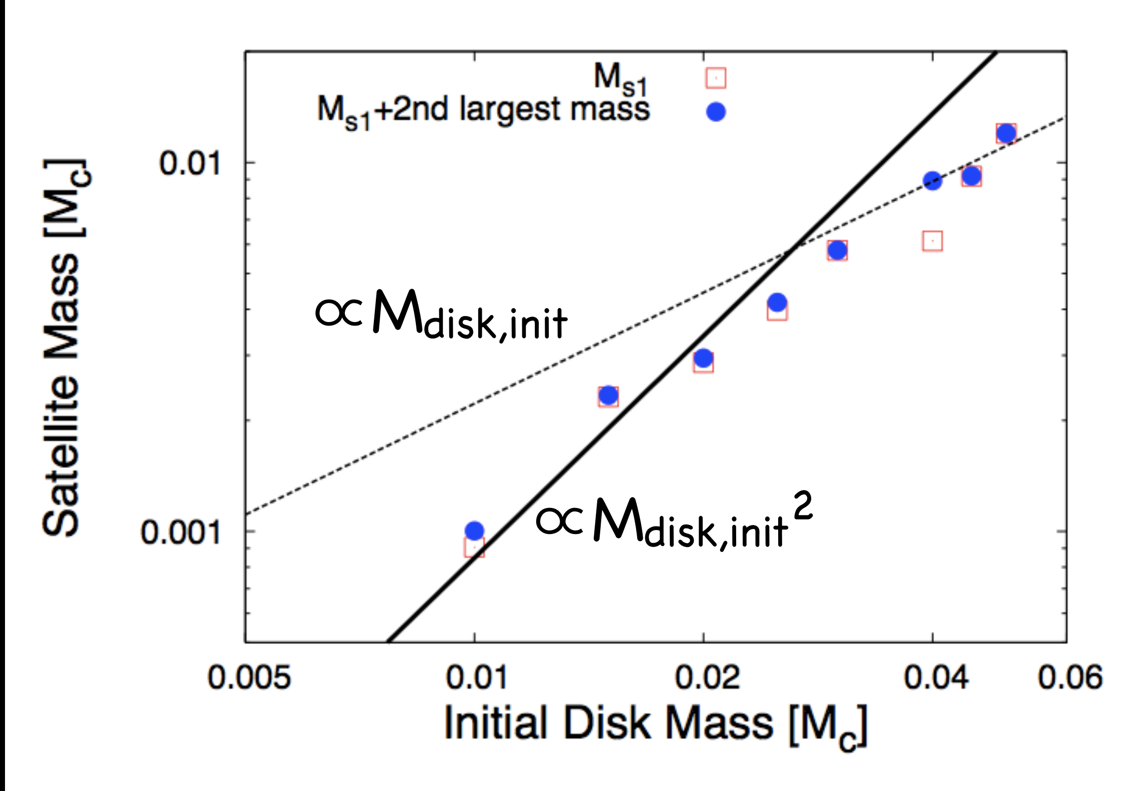
Considering AM and Mass conservation and set $\Sigma(t=\infty)=0$

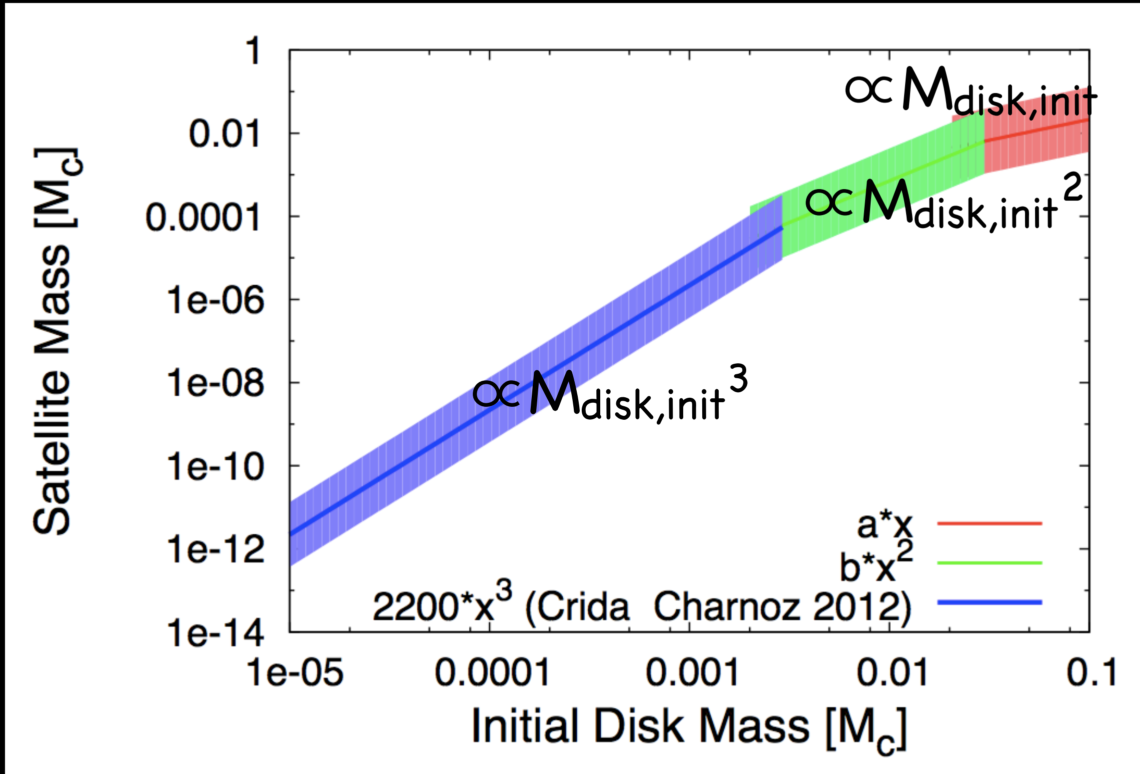
then $M_{sate} \propto M_{disk,init}$

-second satellite form

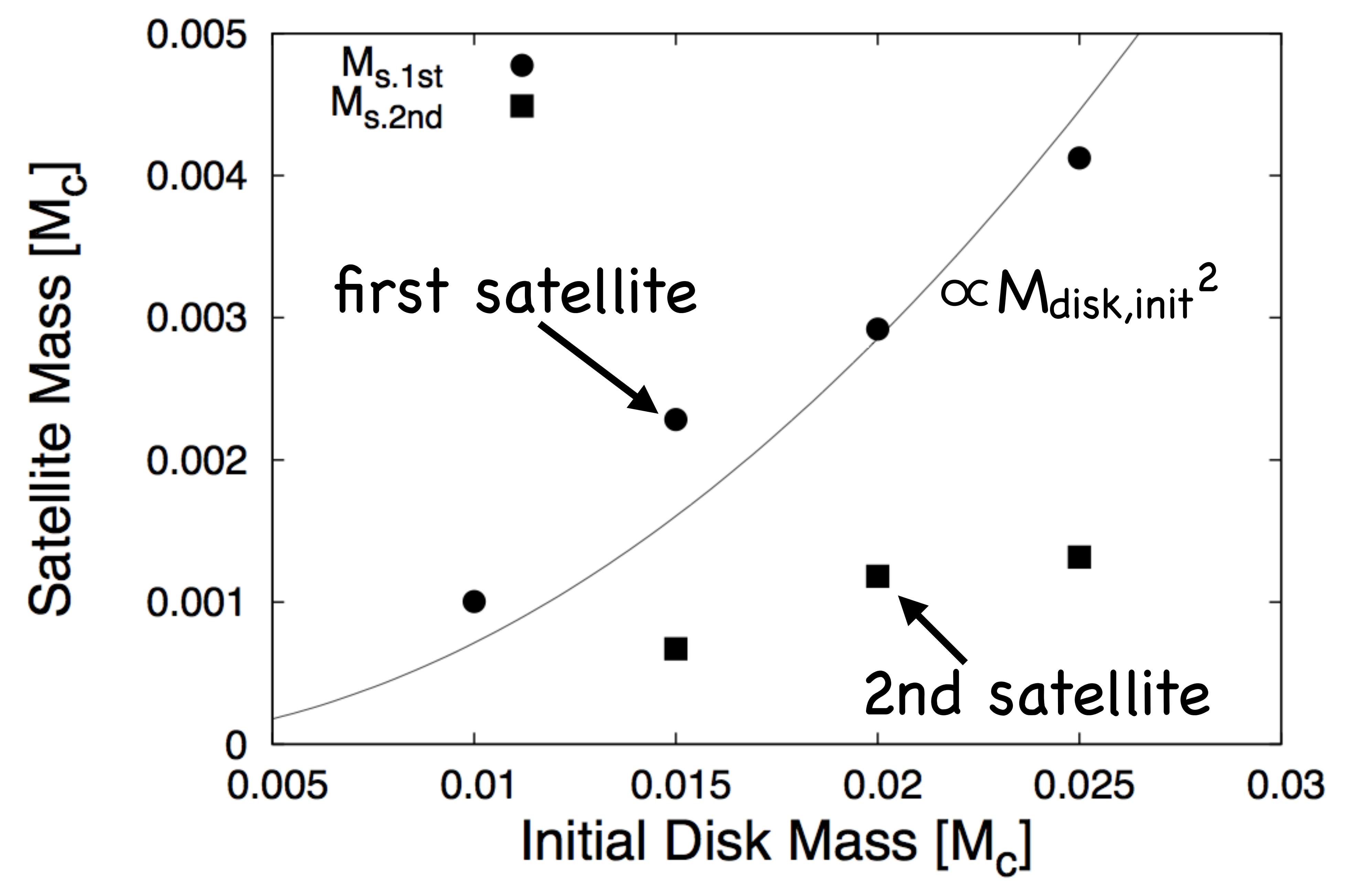
($0.01M_c$<$M_{disk,init}$<$0.03M_c$)

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

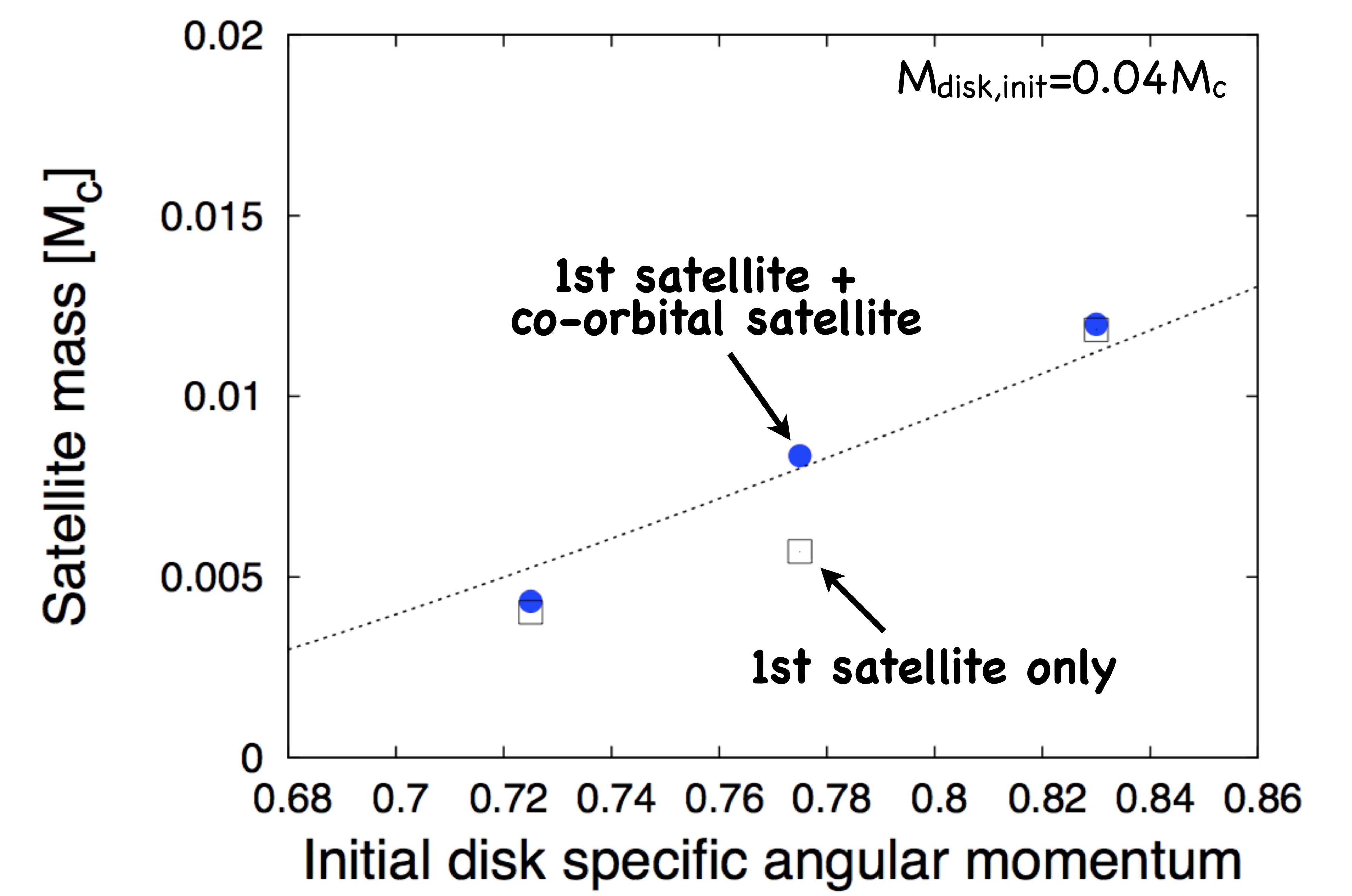




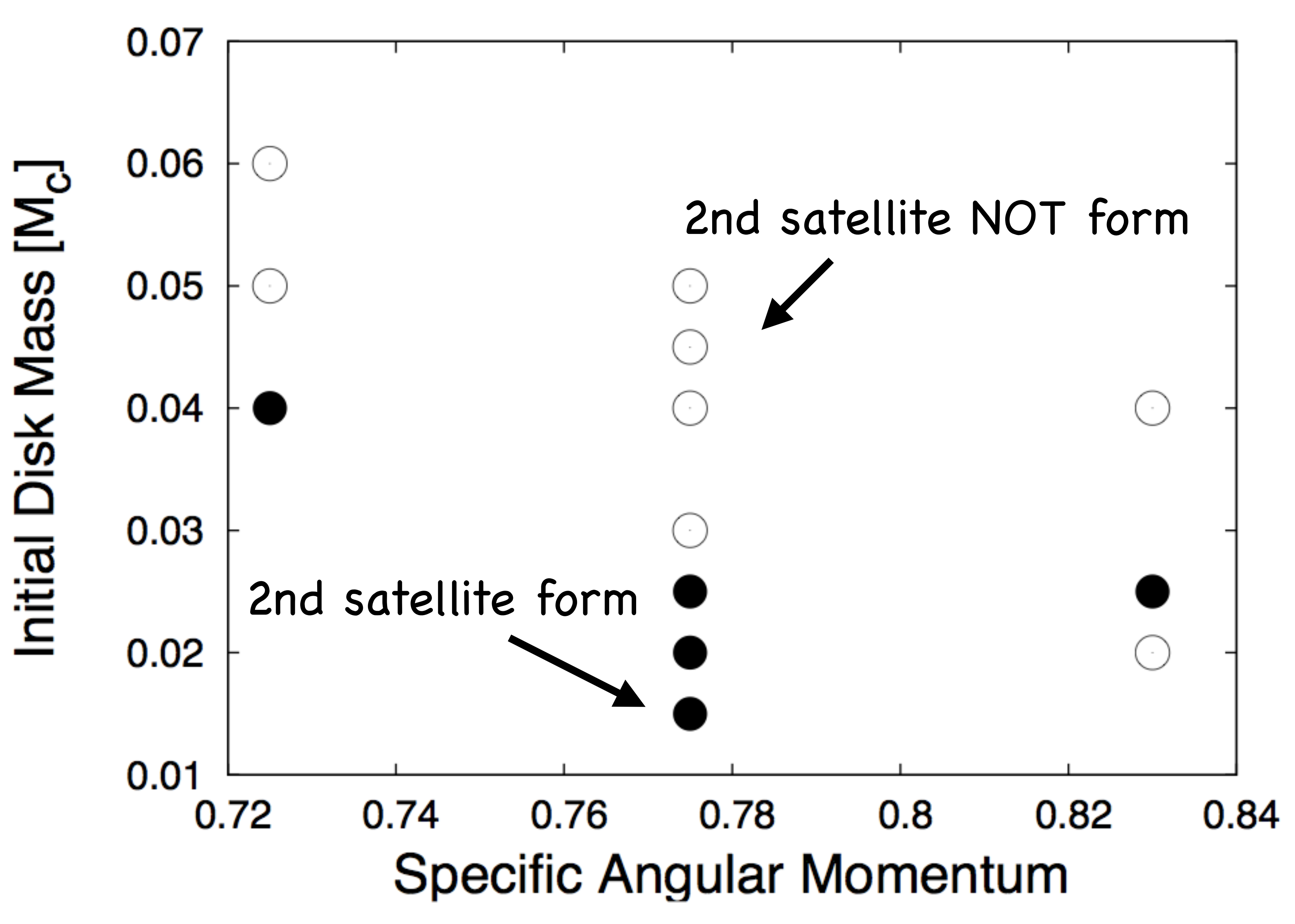
Satellite Mass on Disk Mass



Dependence on Disk Angular Momentum



Dependence on Disk Angular Momentum



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