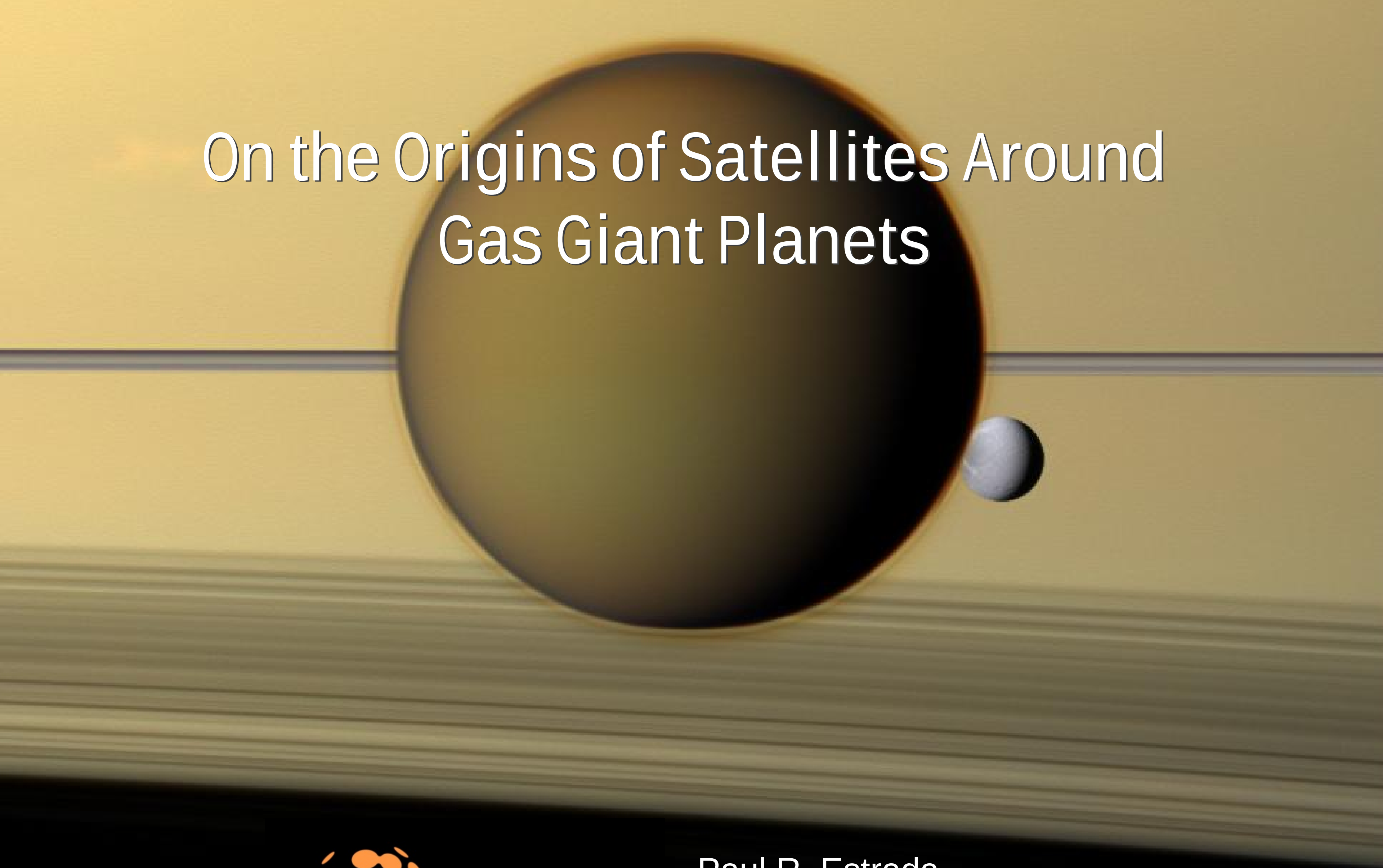
On the Origins of Satellites Around Gas Giant Planets



Carl Sagan Center

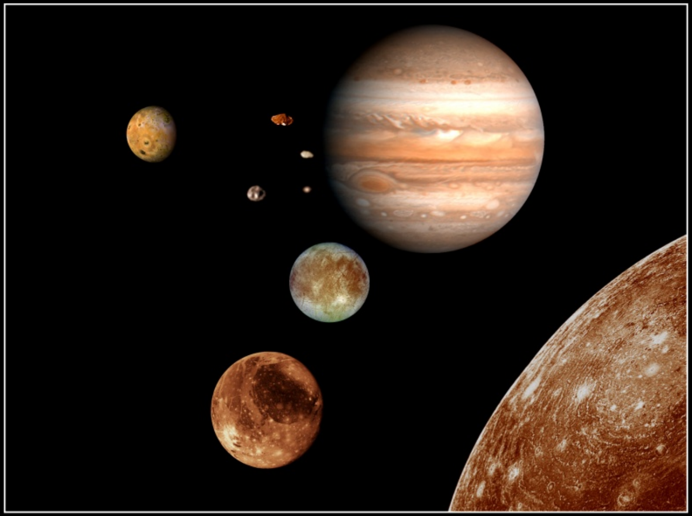
Paul R. Estrada

SETI Institute

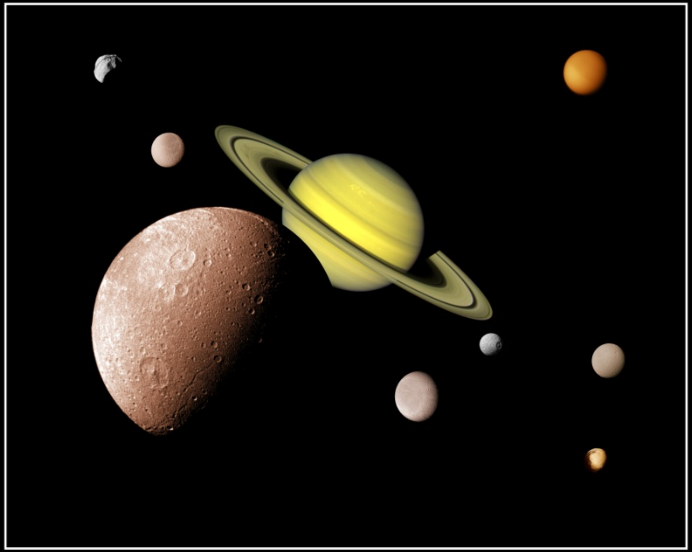
Motivation

- Centuries old fascination. Lots of data amassed.
- Common!
  - 4 data points in 1 solar system
  - by-product of planet formation
  - extra solar giant planet satellite systems – a matter of time!
- Window into understanding the early solar system environment.
  - Composition
  - Chemistry nebula/subnebula
  - Initial conditions
- How do we get these mini-solar systems?
  - as diverse as planetary systems
  - differences
  - similarities

Is there a common framework that applies to all the satellite systems?

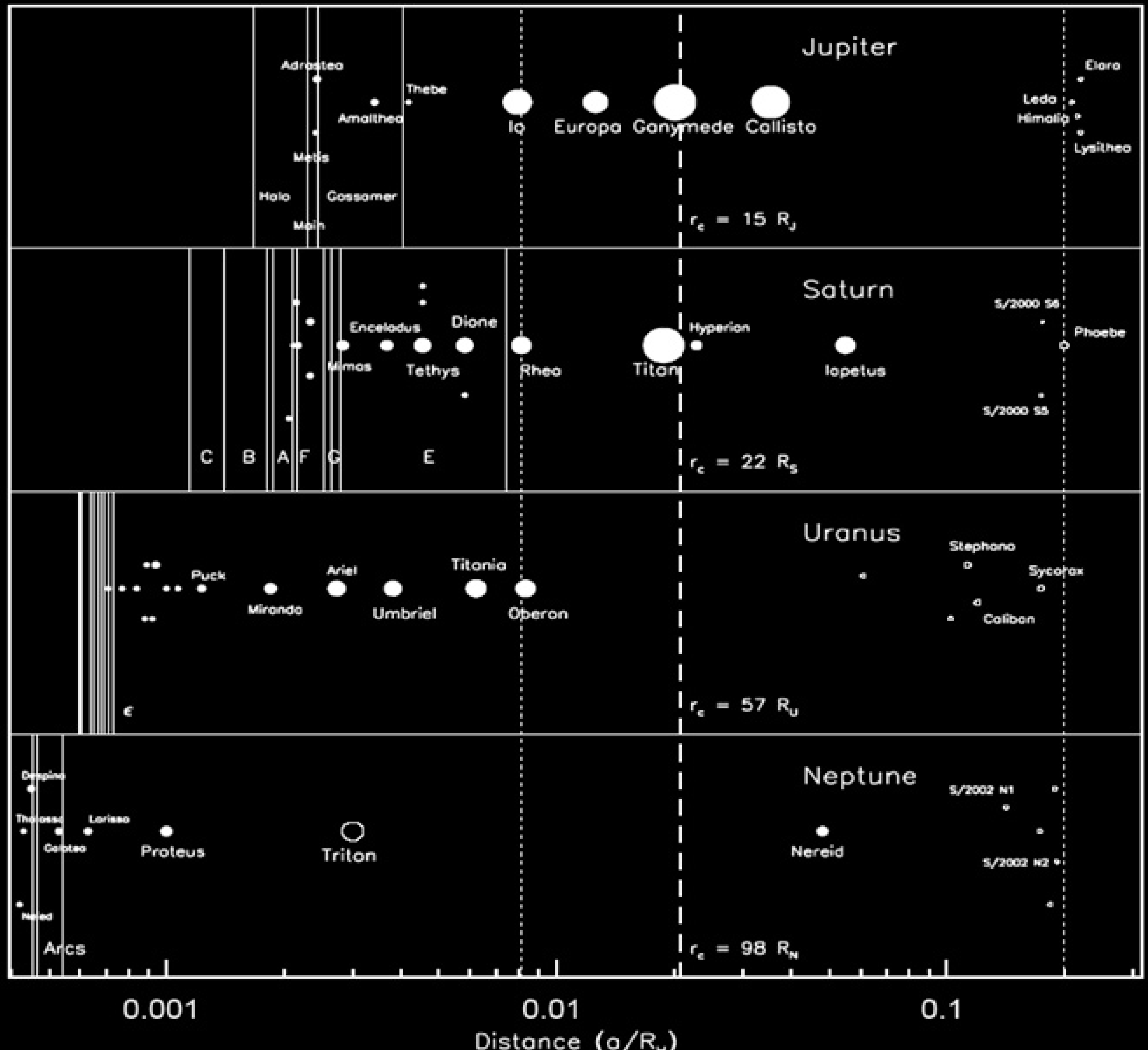


The Jupiter System



The Saturn System

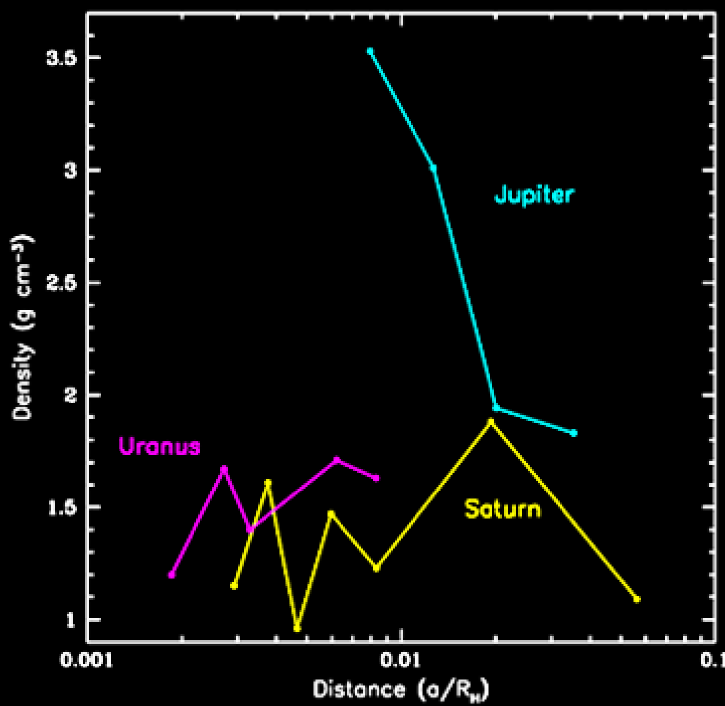
The Giant Planet Satellite Systems



(Mosqueira and Estrada 2003a)

Summary of Constraints

- Strong indirect evidence for a two component (subnebula) disk
  - satellite systems are mostly compact
  - Iapetus forces a long tail
  - Irregulars?
- Most of the satellite systems are *empty*
- Primordial Ar in Jupiter's atmosphere but not Titan's



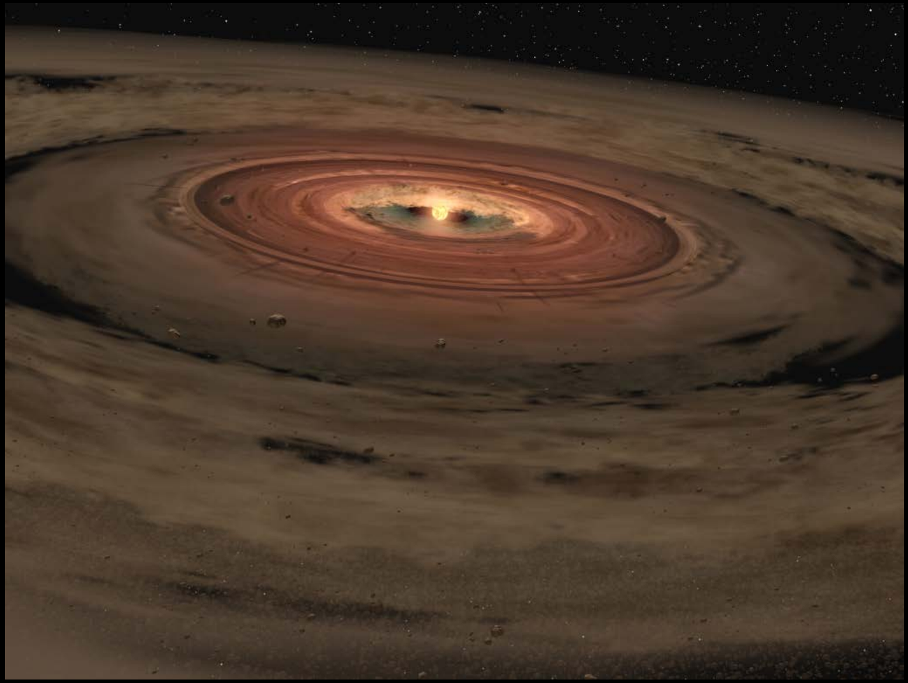
Bulk Compositional Properties →

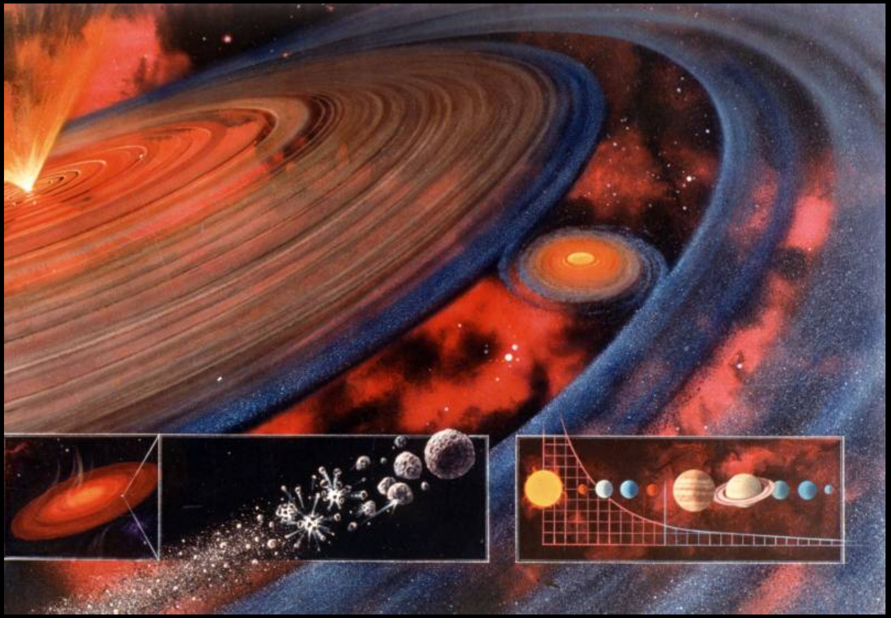
- Non-stochastic compositions of Ganymede, Callisto, Titan and Iapetus
- The Ganymede/Titan/Callisto moment of inertia *trend*

***** Tie to planet and disk formation *****

Giant Planet and Disk Formation

- Main issues
  - Angular momentum
  - Turbulence
  - Distribution of solids in the solar nebula





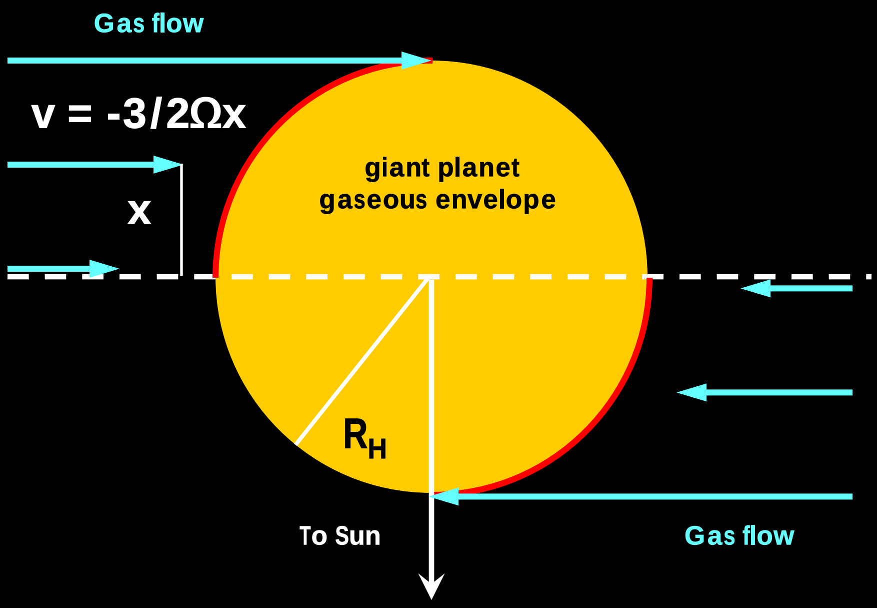
Ultimate Goal

A combined model for Jupiter and Saturn

(See Estrada et al. 2009)

Angular Momentum: Disk Sizes

(Lissauer et al. 1995)



- Prior to opening a clean gap, planet accretes low specific ang. mom. gas from within R_H

- Estimate of disk size

  - **compact** disk forms consistent with numerical estimates (Machida et al. 2008; Lissauer et al. 2009)

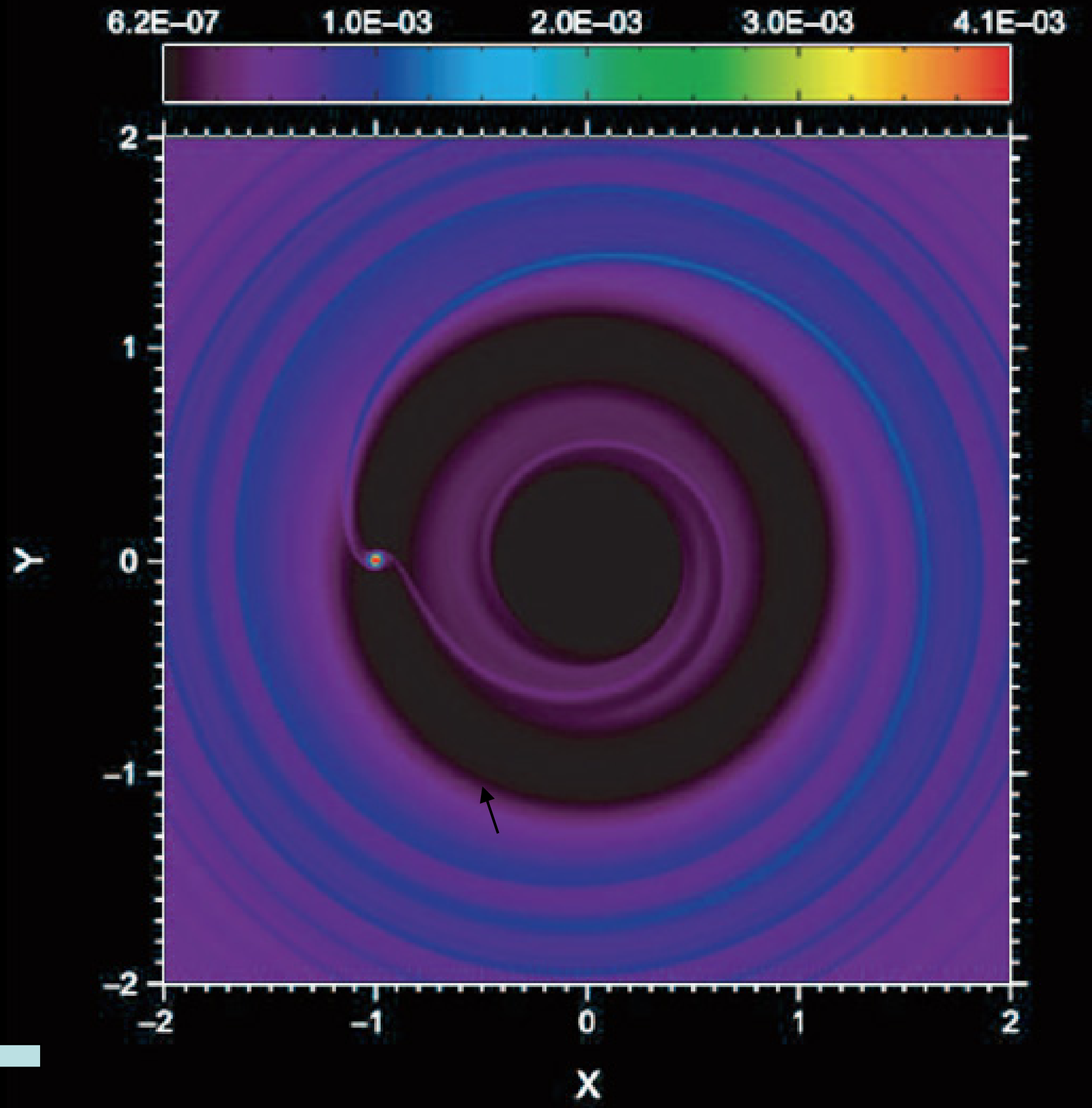
$$\ell \approx -\Omega \frac{\int_0^{R_H} \frac{3}{2} x^3 dx}{\int_0^{R_H} x dx} + \Omega R_H^2 \approx \frac{1}{4} \Omega R_H^2,$$

$$r_c \approx R_H/48$$

→ **Potentially massive disk**

Specific Angular Momentum of Gas Inflow Through Giant Planet Gap

- Both 2D and 3D simulations of gas accretion through a clean gap form an **extended** circumplanetary disk compared with the locations of the regular satellites (D'Angelo et al. 2003; D'Angelo 2007; Ayliffe and Bate 2009; Tanigawa et al. 2012).



Extended low density tail

Turbulence in a Keplerian Disk

- The α-prescription (where $\alpha = \nu / cH$) in the nebula

  - Traditionally is used to remove the gas disk.
  - Unbounded Keplerian disk is linearly stable (Ryu and Goodman 1992, Balbus et al. 1996).
  - Disks may be insufficiently ionized to sustain MRI. Presence of "dead zones" a robust result.
  - There is no evidence that α (typical value is $\sim 10^{-3}$) can be transplanted from the nebula around a star to the subnebula around the planet.
  - α is a **free parameter**. This can lead to fine-tuning.

Once the inflow, which drives disk evolution, wanes as the planet opens a deep, clean gas gap one would expect turbulence to decay in the absence of another driving mechanism.

Distribution of Solids at the time of Satellite Formation

- Most of the solids mass in the nebula contained within ~ 10 km planetesimals

- Reasons to treat planetesimals

  - Observations of comets (e.g., Charnoz and Morbidelli 2007)

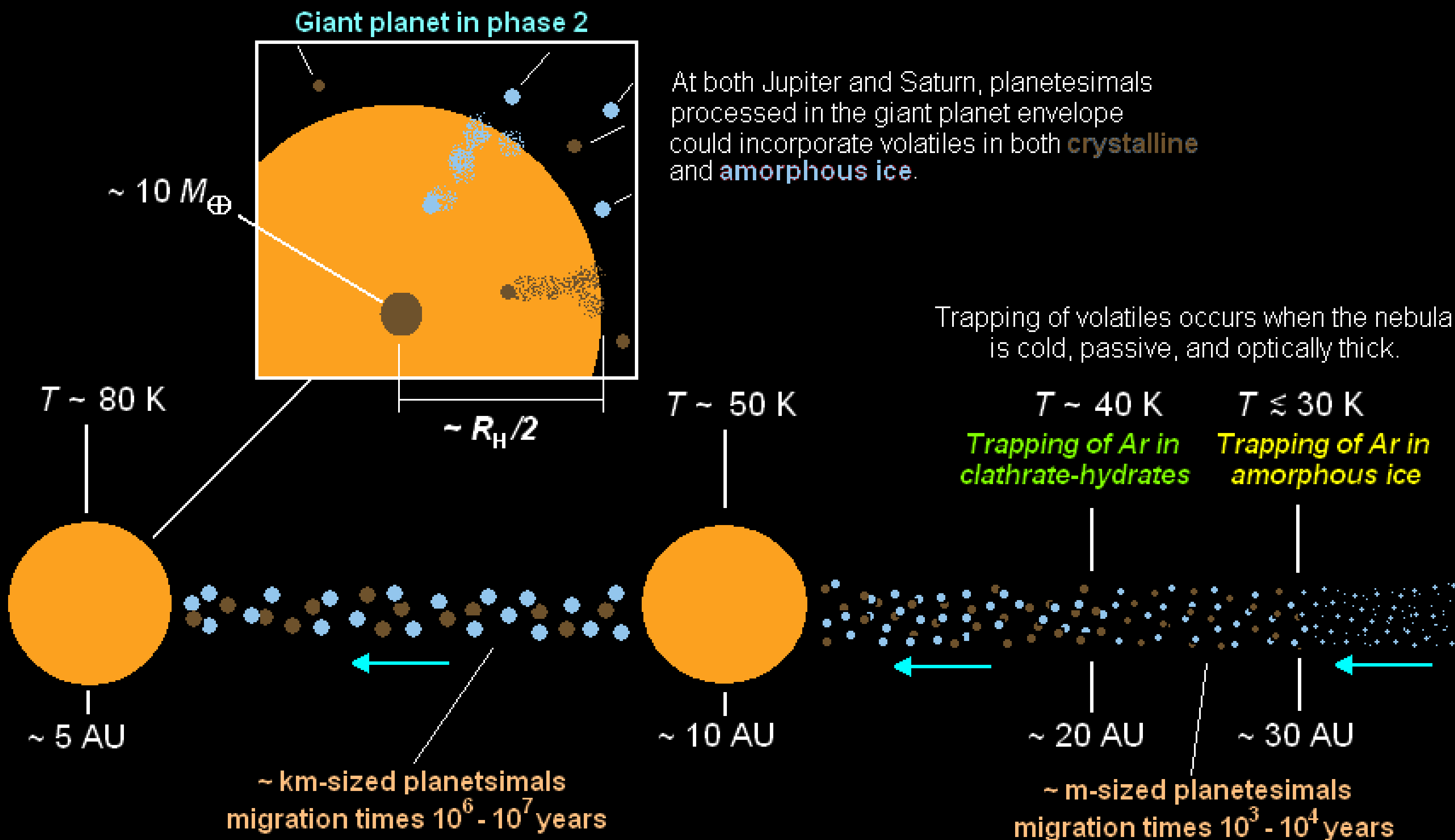
  - Nice model needs many Pluto-sized planetesimals to power planet migration (LHB)

  - Asteroid belt mass problem (top-heavy size distribution)

  - Formation of cores of giant planets

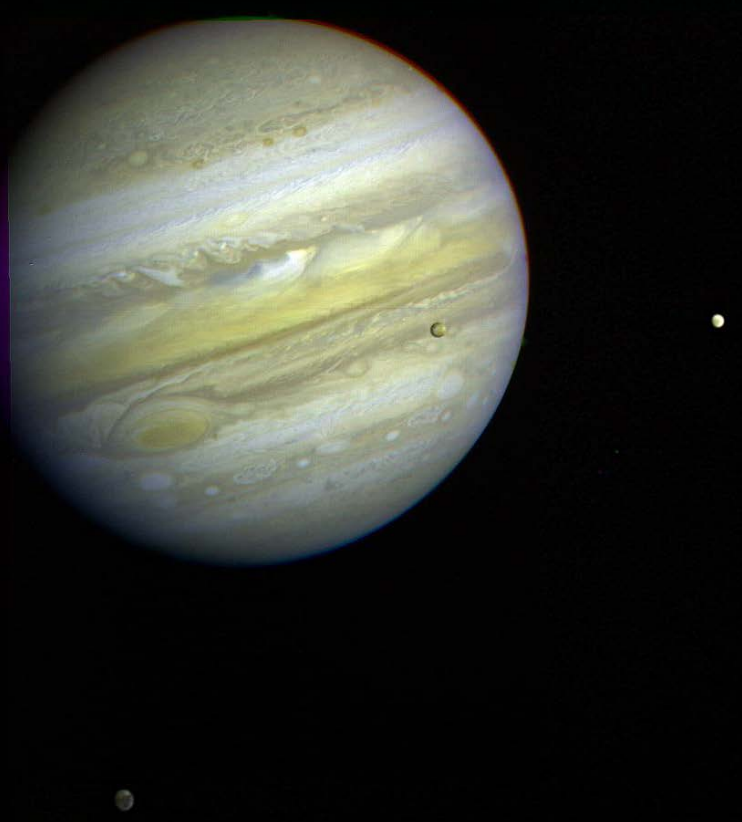
  - Volatile enhancement in giant planet atmospheres

Planetesimal Processing and Delivery of Volatiles



(Estrada et al. 2009)

Regular Satellite Formation



- Key Issues
  - Turbulence
  - Delivery of solids to the disk
  - Satellite survival
- Bulk constraints
  - Mass
  - Angular momentum
  - Satellite compositions
    - Solar nebula to subnebula
    - Subnebula gradients
- Galileo & Cassini constraints
  - Phoebe, Iapetus, Hyperion, Titan, Ganymede/Titan/Callisto MOI trend, inner icy moons and rings...

→ **Combined model for Jupiter and Saturn**

The SEMM and GPPC Models

- Gaseous Solids-Enhanced Minimum Mass model (Mosqueira and Estrada 2003a,b)
  - Not a "minimum mass" or local accretion model
- Gas-Poor (not gas-free) Planetesimal Capture model (Estrada and Mosqueira 2006).
- Both models are attractive because:
  - Self-consistent
  - Neither model relies on fine-tuning of the turbulence α
  - Properly account for the angular momentum
  - Link subnebulae to outer solar nebula
  - Both treat planetesimal dynamics explicitly

Model Comparison

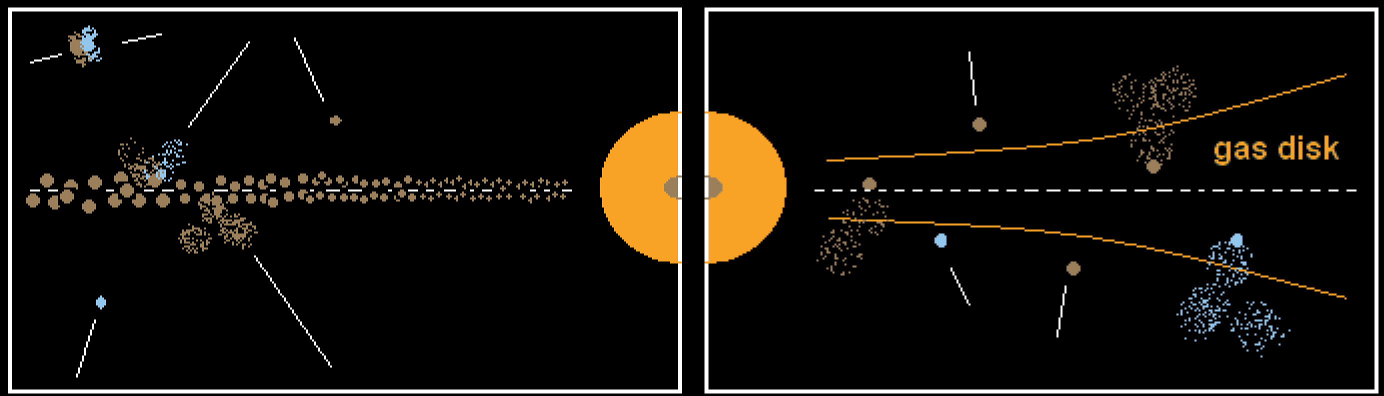
- **Solids-Enhanced Minimum Mass Model** (Mosqueira and Estrada 2001; Estrada 2002; Mosqueira and Estrada 2003a,b)

  - Turbulence decays as gas inflow wanes during tail end of planet formation.
  - Survival of satellites by gap-opening (determines Σ_{gas}).
  - Formation time for Callisto (around Jupiter) and Iapetus (around Saturn) determined by time it takes gas drag to clear the extended subnebula disk from as far as ~ $\boldsymbol{R_H/5}$.
  - Compositional gradient of Galilean satellites is due to planet's luminosity.

- **Gas-poor Model** (Ruskol 1975; Safronov et al. 1986; Estrada and Mosqueira 2006)

  - Relies on sustained turbulence OR some other dissipation mechanism.
  - Satellite survival due to gas disk removal (undetermined Σ_{gas}).
  - **All** the satellites form in a timescale set by external planetesimal feeding.
  - Impacts and Laplace resonances may explain compositional gradient of Galilean satellites.

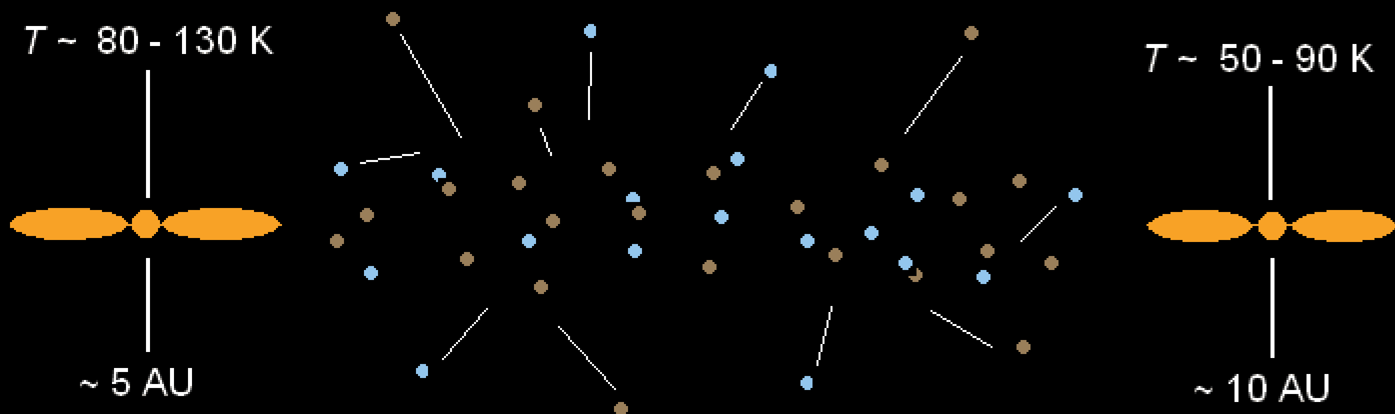
Planetesimal Re-Processing and Delivery of Volatiles to Satellites



Processing of planetesimals due to collisions.

or

Processing of planetesimals in the gas disk through ablation.



Planetesimals are scattered in a timescale of ~ 10^5 years.

Possibly too hot for re-condensation of CH_4 and NH_3.

Too hot for re-trapping of Ar.

(Estrada et al. 2009)

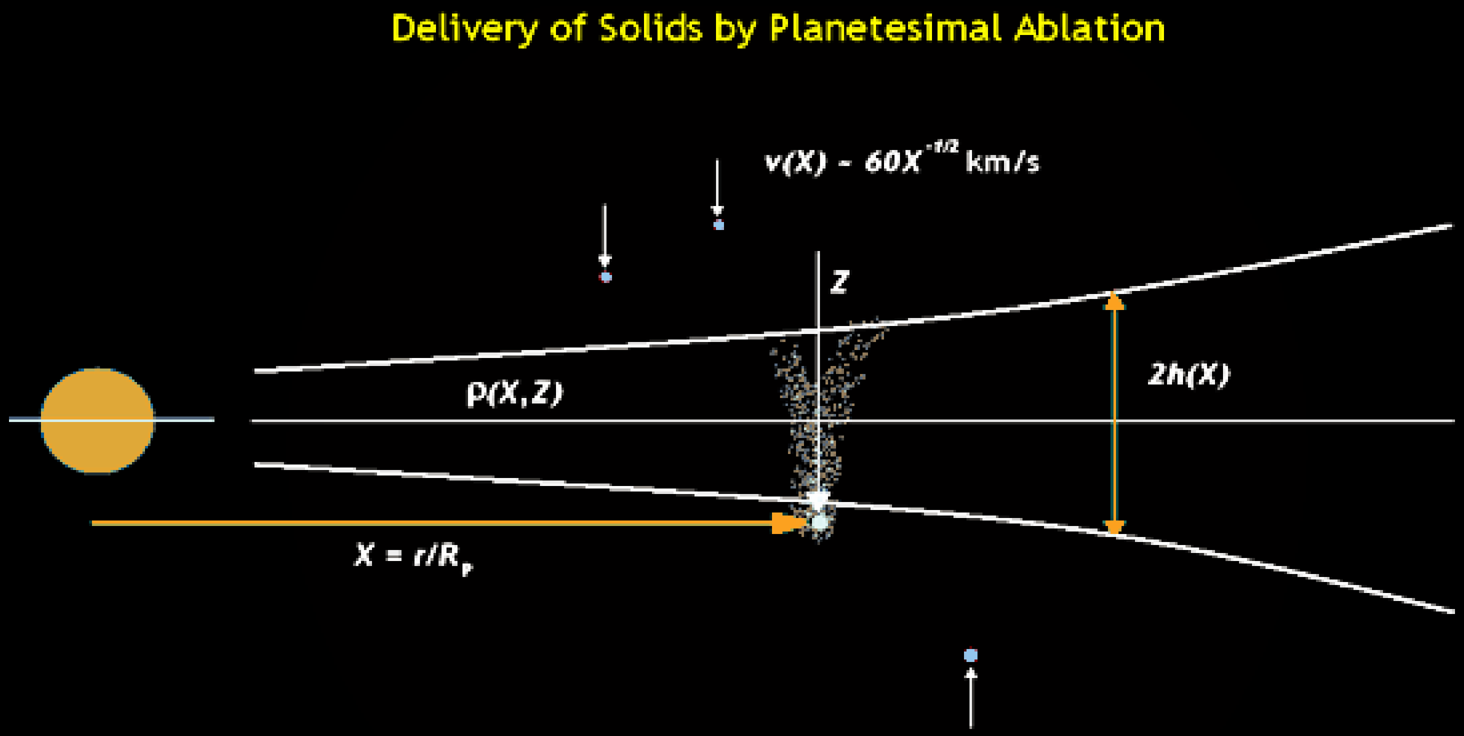
SUMMARY OF SEMM INITIAL CONDITIONS

- Massive disk compared to the mass of the satellites (~ 10 times in gas)
- Dense inner portion containing most of the mass of gas and solids.
- Extended, low density tail out the location of the irregular satellites.
- Non-local accretion, gas-drag clearing/resonance trapping.
- Delivery of solids by ablation through the circumplanetary disk of planetesimal fragments.

(e.g., see Mosquiera and Estrada 2003a,b; Estrada et al. 2009; Johnson and Estrada 2009; Mosqueira, Charnoz and Estrada 2010)

Ablation and Capture of Disk Crossers

(e.g. Podolak et al. 1988)



- At <u>Titan</u> and <u>Callisto</u>, one can ablate meter-to-kilometer-sized planetesimals (or capture).

- At <u>Iapetus</u>, one can ablate meter-sized icy planetesimals (e.g., Iapetus' composition.

Planetesimal size distribution following giant planet formation?

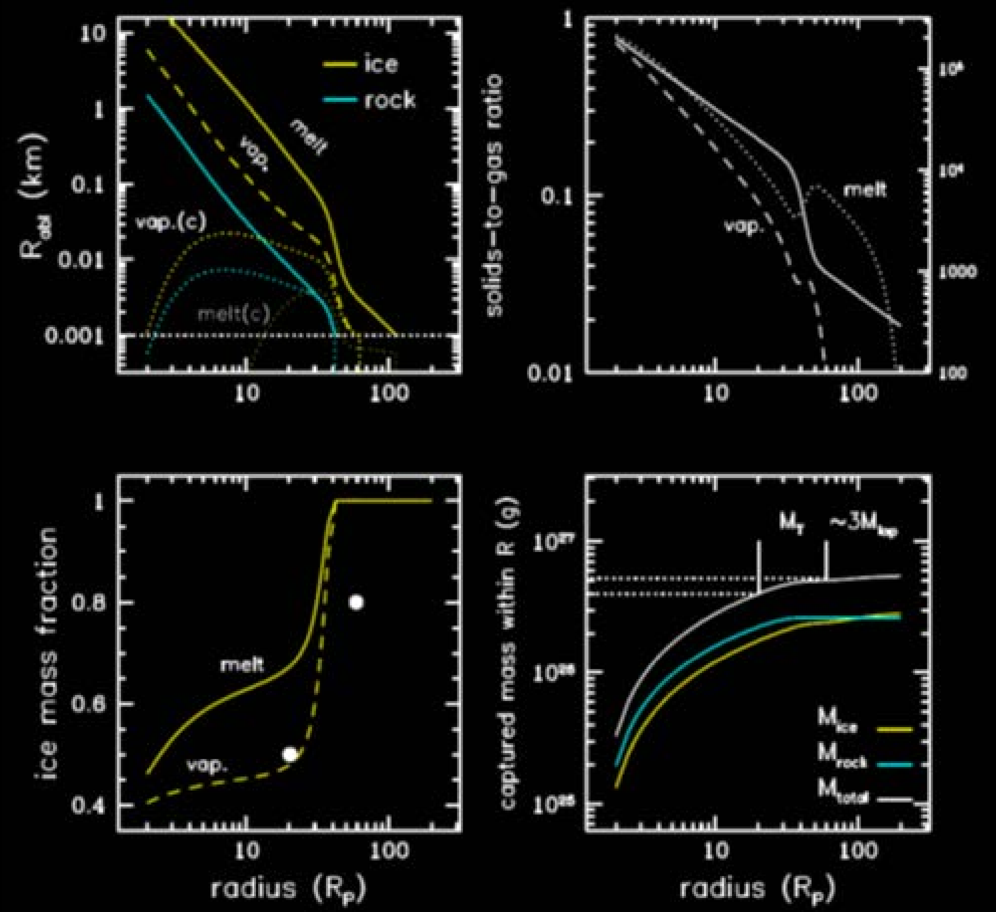
Non-homogeneous ice/rock distribution?

Explaining Iapetus' Composition

- Assume unmixed population of planetesimal fragments
  - 1^{st} generation of planetesimals contain ^{26}Al
  - 70% rock, 30% ice by mass
  - 1 meter to ~10-100 km fragments

- Use *N*-body simulations (e.g. Charnoz and Morbidelli 2003) to calculate how much mass passes within ~ $\boldsymbol{R_H/5}$

- **This process can naturally account for the *compositional* trend we see:**
  - Fractionated ice/rock population due to the collisional cascade
  - Lower density + lower velocities in the outer disk favors ice.



(Mosqueira, Estrada, and Charnoz 2010)

Ganymede/Titan/Callisto MOI Trend

- Relevant observations:

  - Ganymede (MOI = 0.311) \ Callisto (MOI = 0.358) dichotomy.
  - Titan's moment of inertia (MOI = 0.34).
  - Dichotomy has morphed into a (Ganymede \ Titan \ Callisto) ***trend***.
  - <u>Major caveat</u>: Are all three satellites in hydrostatic equilibrium?

- Geophysical issues:

  - Sources of Energy: Accretion, sinking rock, radiogenic heating.
  - Will melting lead to runaway sinking rock resulting in full differentiation (e.g., Friedson and Stevenson 1983)?

    - Observational evidence argues against this for Titan and Callisto.

  - Accretion DOES bury energy BUT how much heat is trapped by (conductive?) ice shell (if present)?

    - Hotspots (we do not model yet).
    - Collisional overturn (we do model; Squyres et al. 1988).
    - Atmosphere (we do not model yet).

Key Satellite Formation Model Parameters

- **Background temperature** (of accreting material plus background radiation):
  - Ganymede ~ 200 K
  - Titan ~ 100 K
  - Callisto ~ 100 K

    - Strong dependence of viscosity of interior with temperature.

- **Accretion timescale:**
  - Ganymede ~ 10^4 years.
  - Titan ~ 10^5 years.
  - Callisto ~ 10^6 years.

    - A million years is long enough to allow heat of accretion to be radiated away.

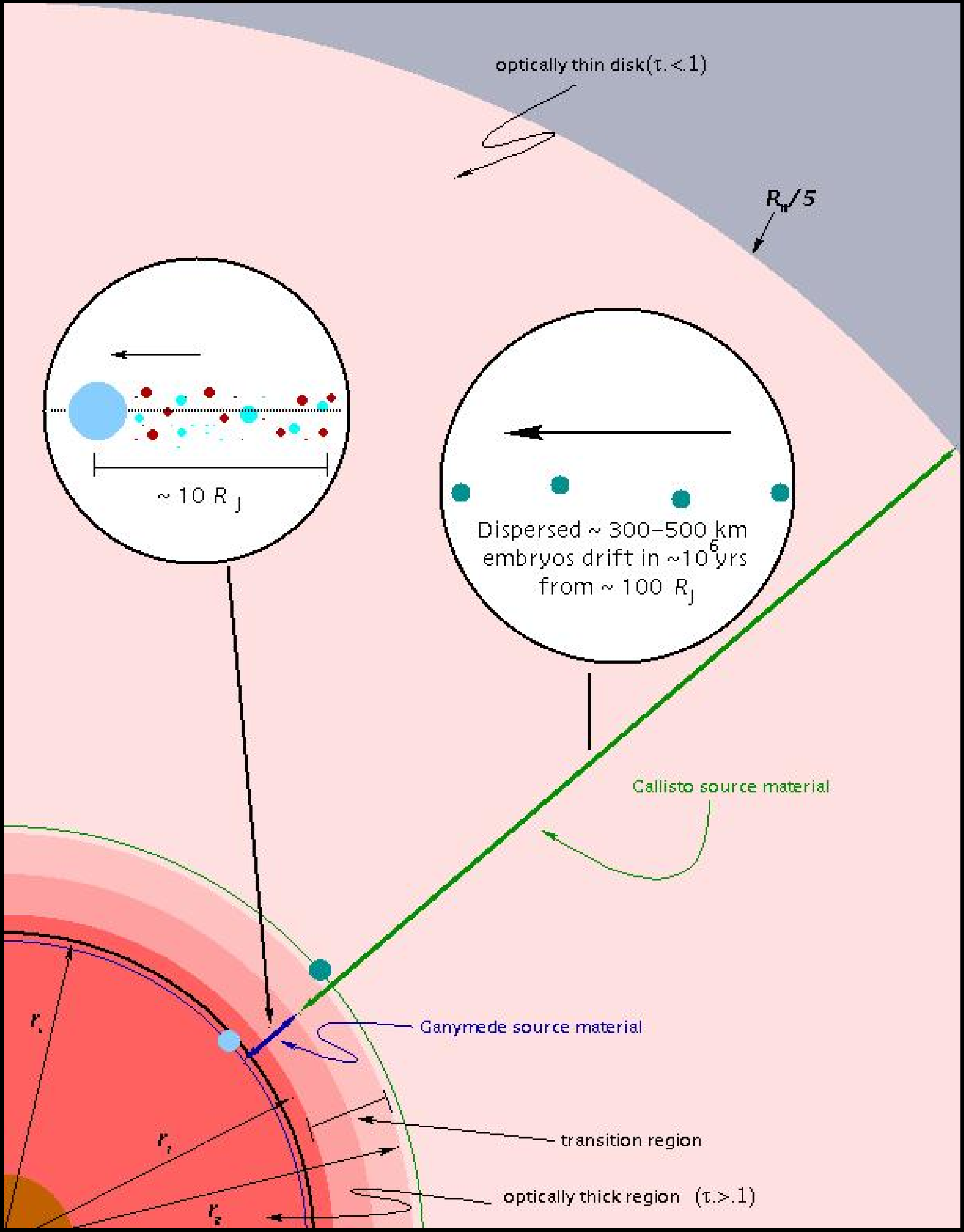
→ **All in the right sense to explain observed MOI trend without resorting to fine-tuning uncertain parameters.**

Accretion in a Two-component Gas Disk

Ganymede: Embryo forms quickly due to sweep up of dust and debris. Timescale for completion controlled by time gas drag clears region of satellitesimals out to Callisto.

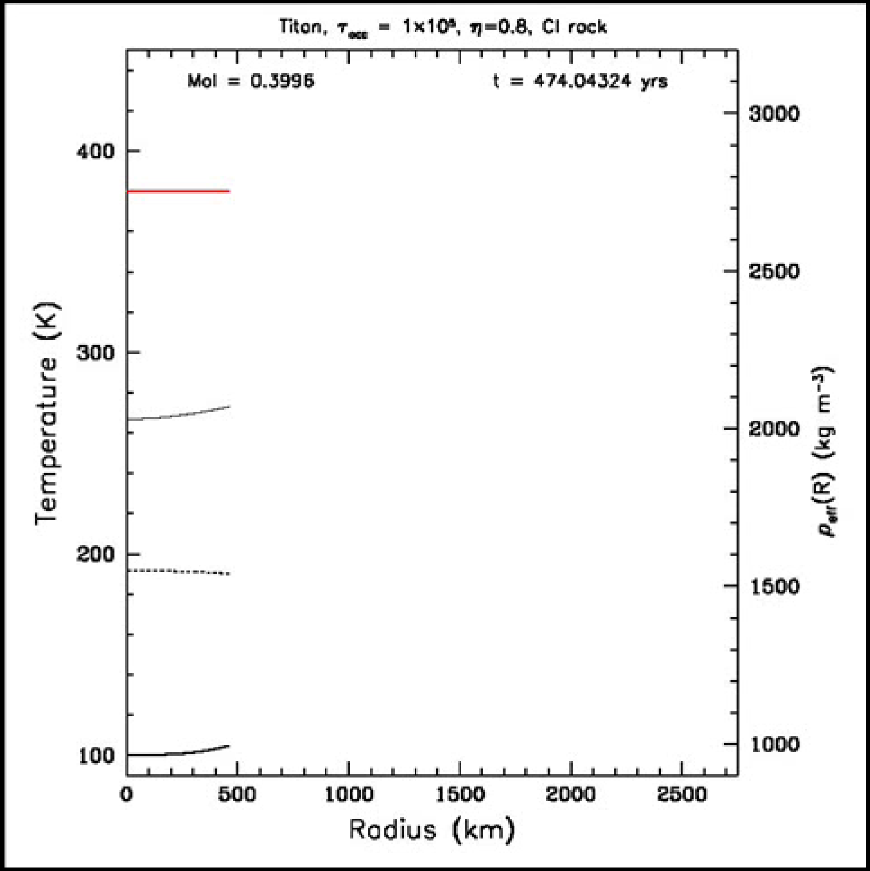
Callisto: Timescale for formation is controlled by the time it takes gas drag to clear the extended outer disk.

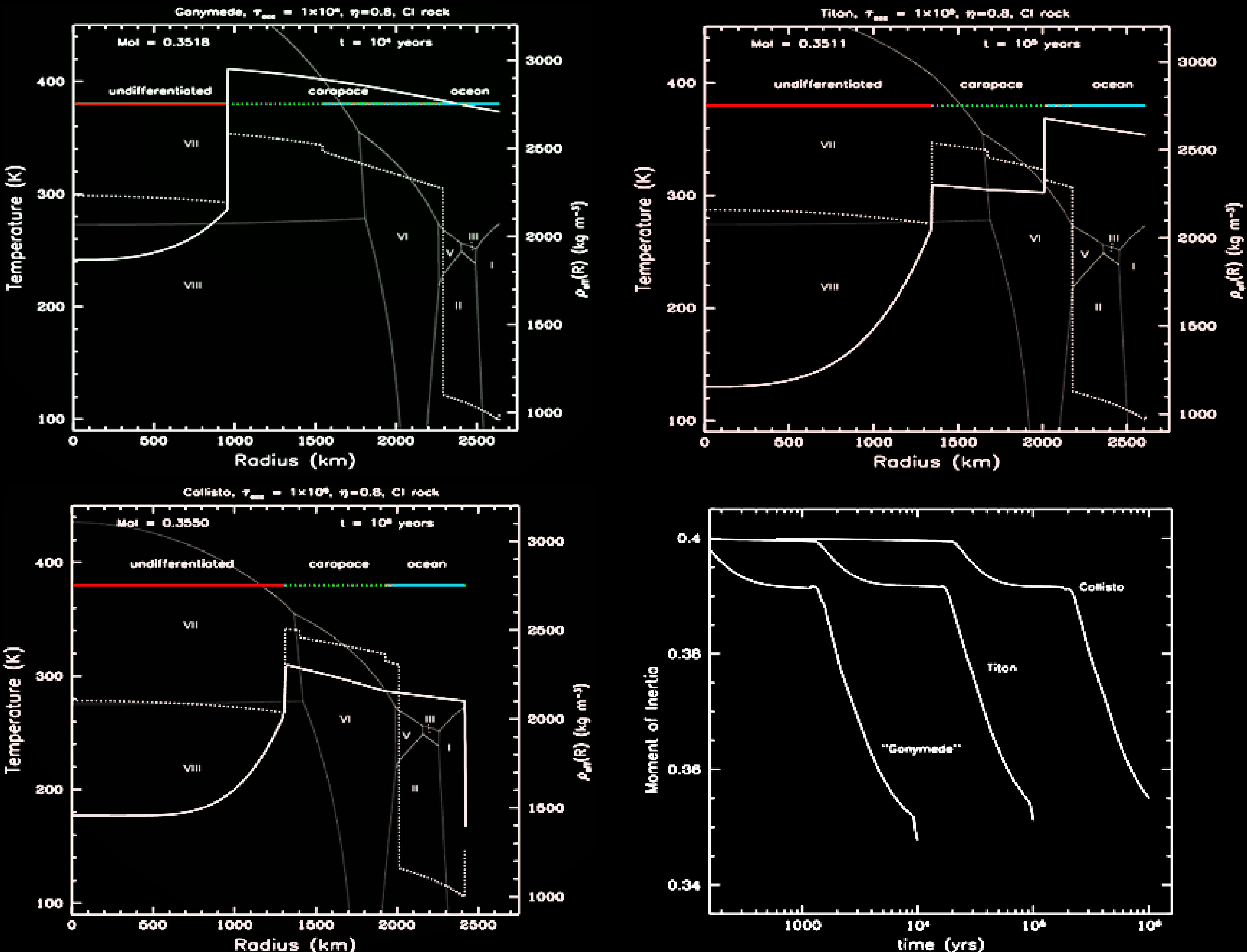
Titan: May accrete material from as far out as Iapetus. Hyperion may be a leftover satellitesimal fragment captured into resonance.



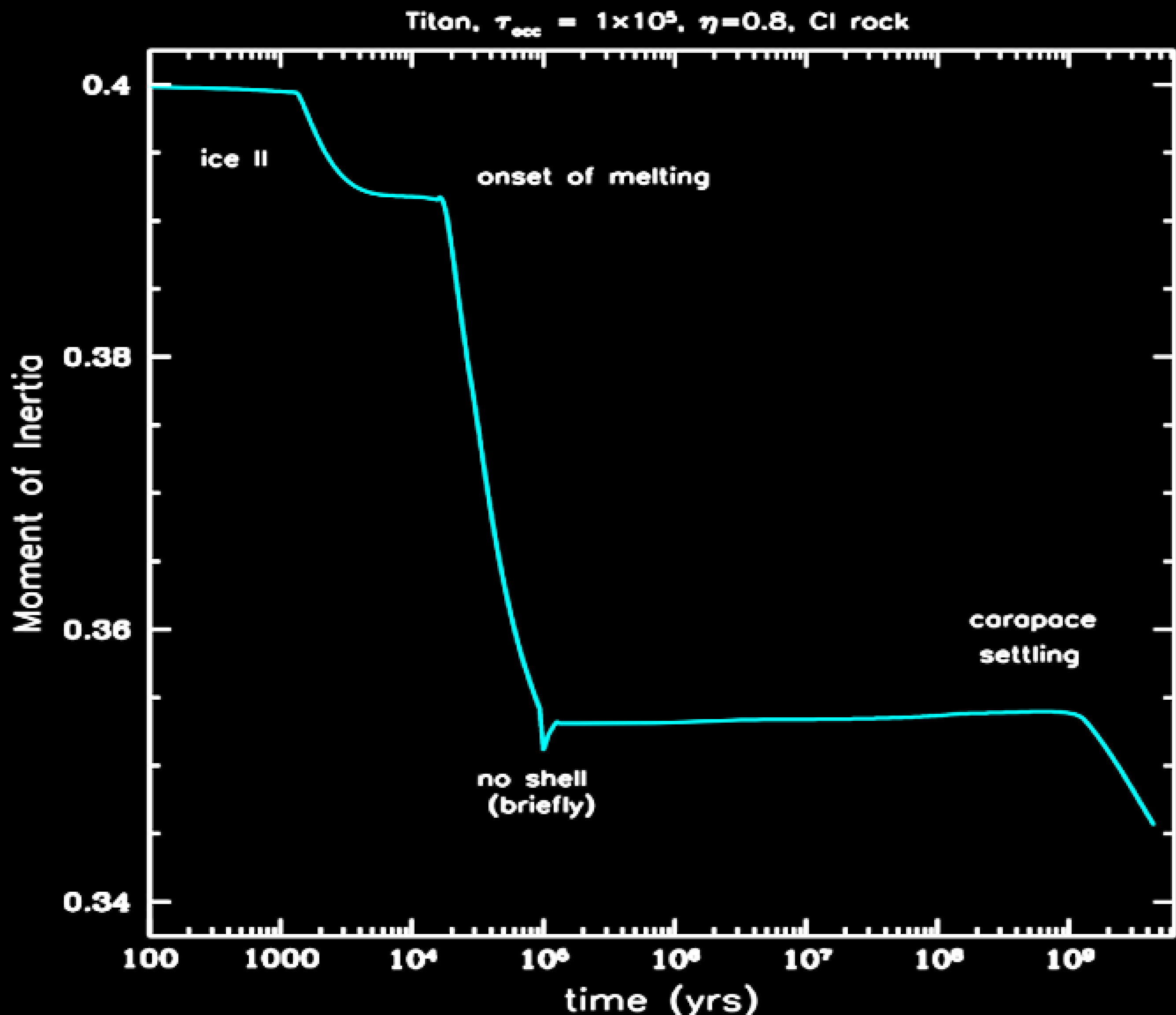
Accretion of Large Regular Satellites

- Combined model of satellite accretion and thermal evolution using ACCTHERM code.
  - Impactor size distribution
  - 80/20 burial/surface heat
  - 3-5 Myrs after CAIs
- Key Points to take away
  - Large satellites **<u>do not</u>** form undifferentiated.
  - Rocky carapace
  - Cold interior + relatively long formation times may prevent full overturn





Ganymede, η=0.8, CI rock
MoI = 0.3518
t = 10⁴ years
undifferentiated
carapace
ocean
VII
VIII
VI
V
III
II
I
Temperature (K)
Radius (km)
ρ_eff(R) (kg m⁻³)
Titan, η=0.8, CI rock
MoI = 0.3511
t = 10⁵ years
undifferentiated
carapace
ocean
VII
VIII
VI
V
III
II
I
Temperature (K)
Radius (km)
ρ_eff(R) (kg m⁻³)
Callisto, η=0.8, CI rock
MoI = 0.3550
t = 10⁶ years
undifferentiated
carapace
ocean
VII
VIII
VI
V
III
II
I
Temperature (K)
Radius (km)
ρ_eff(R) (kg m⁻³)
Moment of Inertia
time (yrs)
Callisto
Titan
"Ganymede"



Titan, τ_{acc} = 1×10^5, η=0.8, CI rock
Moment of Inertia
0.4
0.38
0.36
0.34
time (yrs)
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
ice II
onset of melting
no shell
(briefly)
carapace
settling

Conclusions

- **A Solids-enhanced Minimum Mass (SEMM) model can account for:**

  - The mass and angular momentum budgets of the regular satellites.

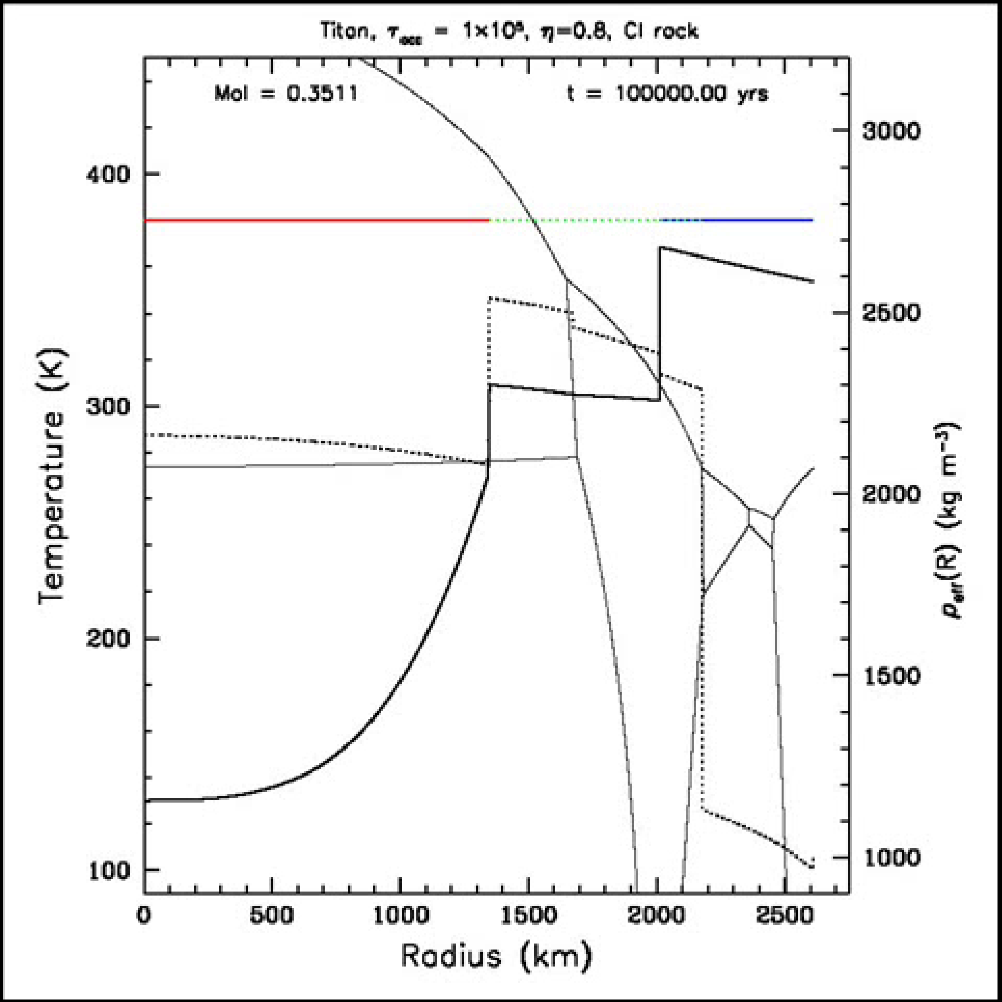
  - Non-stochastic satellite compositions (cf. Ganymede, Callisto, Titan, and Iapetus).

  - It is possible to enhance the I/R at Iapetus by ablating icy m-sized planetesimal fragments crossing the circumplanetary gas disk-as well as those of Ganymede, Titan and Callisto.

  - The Ganymede/Titan/Callisto trend.

  - Satellite survival by gap-opening.

  - Other constraints such as the lack of primordial Ar in Titan's atmosphere may also fit within this framework.



Titan, τ_{acc} = 1×10⁵, η=0.8, CI rock
Mol = 0.3511
t = 100000.00 yrs
Temperature (K)
Radius (km)
ρ_{eff}(R) (kg m⁻³)
100
200
300
400
0
500
1000
1500
2000
2500
1000
1500
2000
2500
3000