Geophysical Study of Iapetus Constrained by *Cassini* Observations

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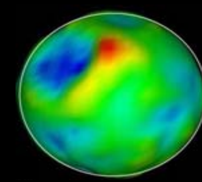
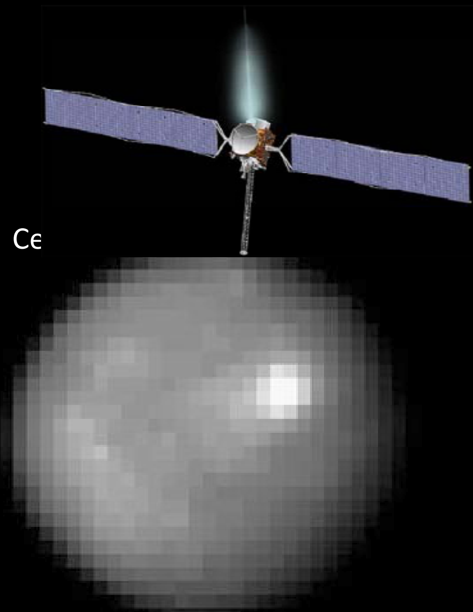
RESEARCH FOCUS AND SIGNIFICANCE

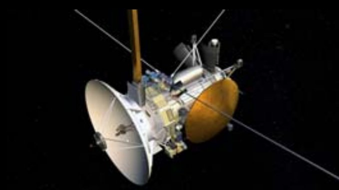
Enceladus

Phoebe





Outer planet moons



Kuiper-belt objects

Asteroid and comets

Icy objects contain information about the early Solar system and the development of potentially habitable environments.

IAPETUS - TWO PUZZLES

SHAPE:

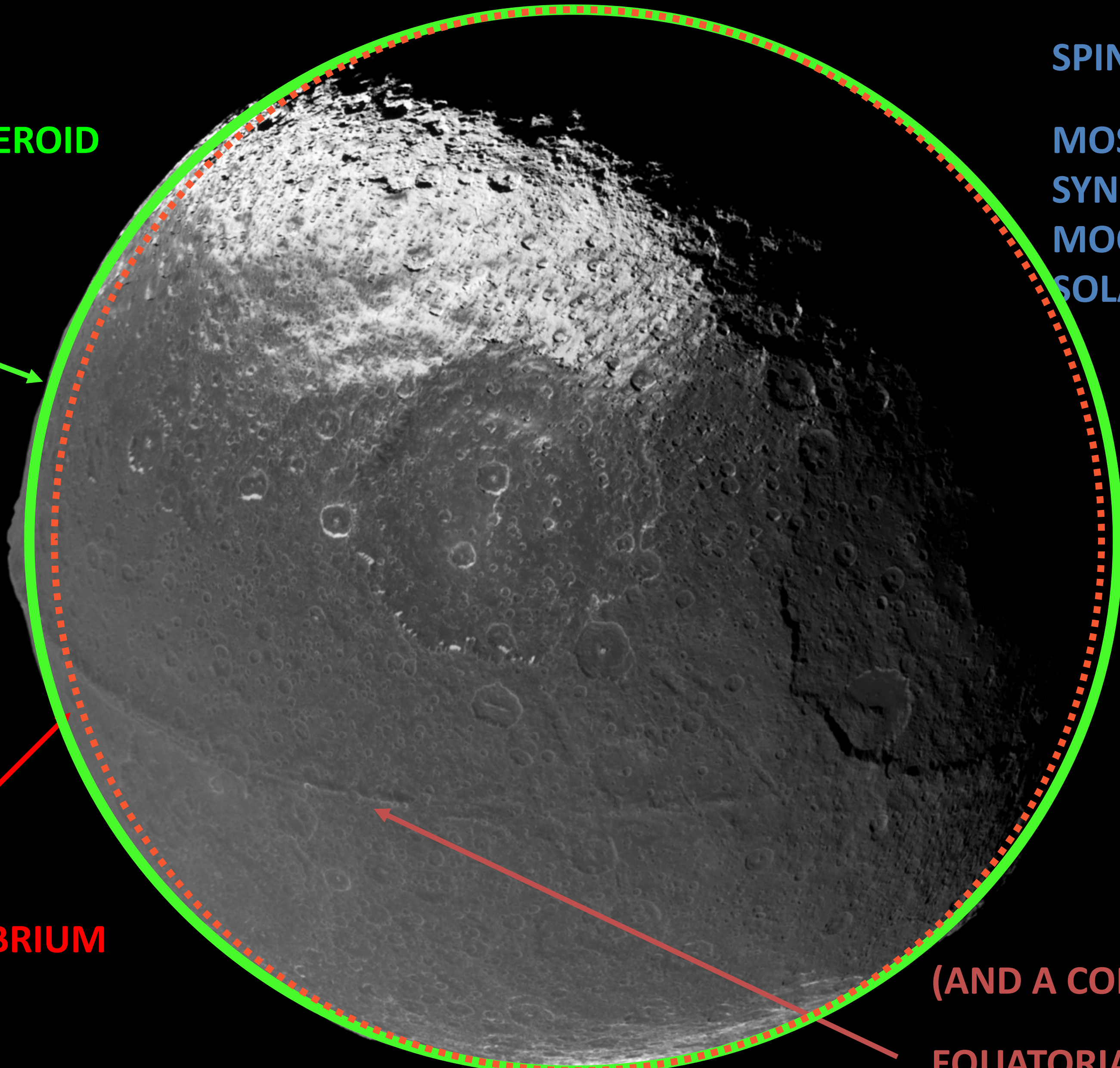
OBLATE SPHEROID

(A-C) = 33 KM

PERIOD:

15 to 17 HRS

79 DAY EQUILIBRIUM
(A-C) = 10 M



SPIN STATE:

MOST DISTANT SYNCHRONOUS MOON IN THE SOLAR SYSTEM

D = 60 RS

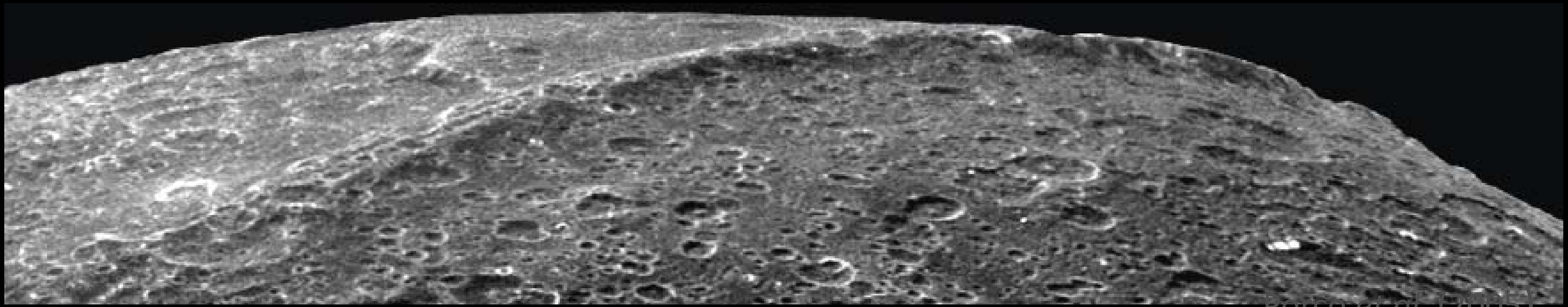
PERIOD:

79.33 DAYS

(AND A CONUNDRUM:

EQUATORIAL RIDGE)

A VERY ANCIENT FEATURES:
IAPETUS’ EQUATORIAL RIDGE



Porco *et al.* (2005)

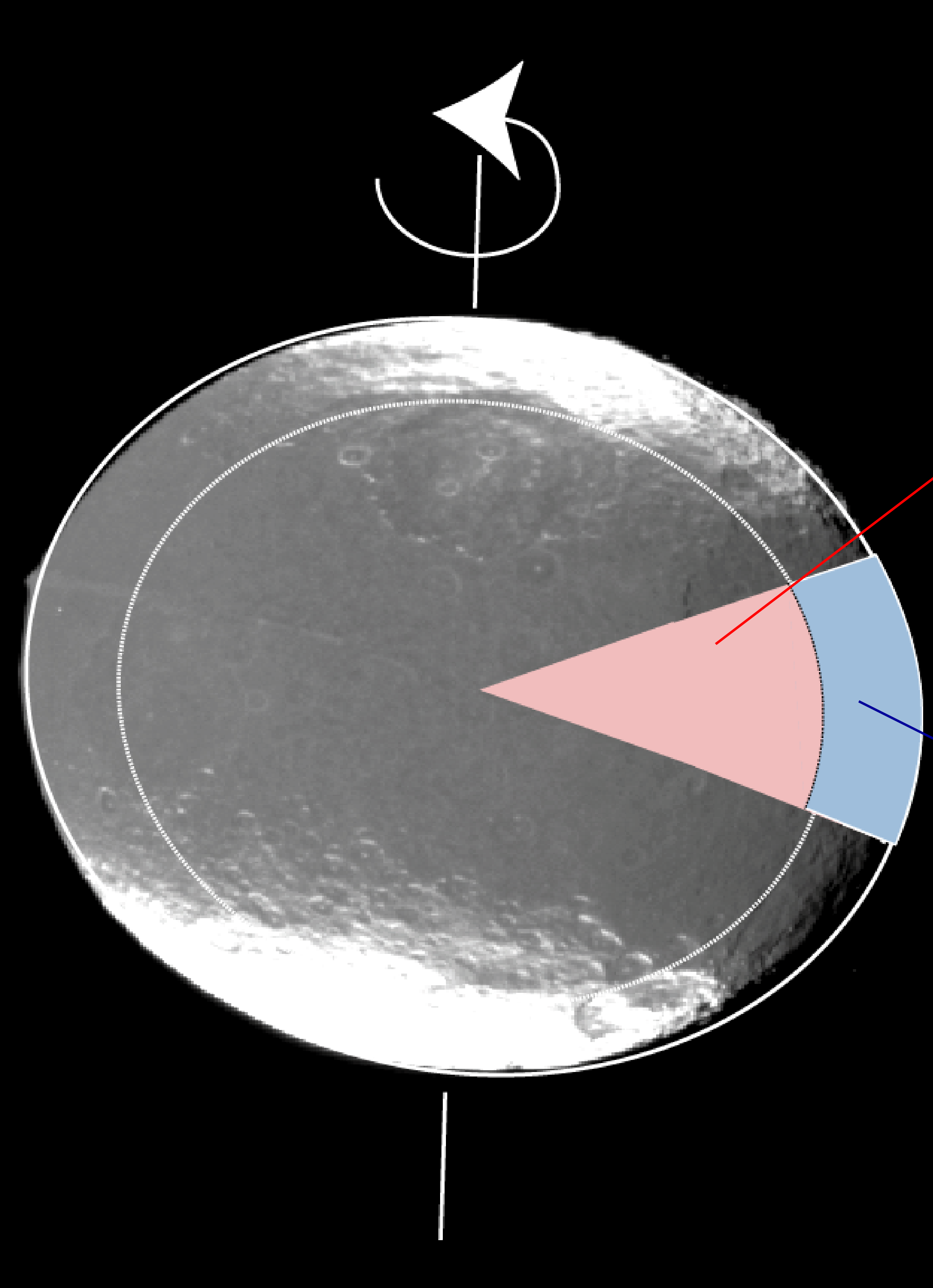
Length ~ 4680 km

Width ~ 100 km

Height up to 20 km

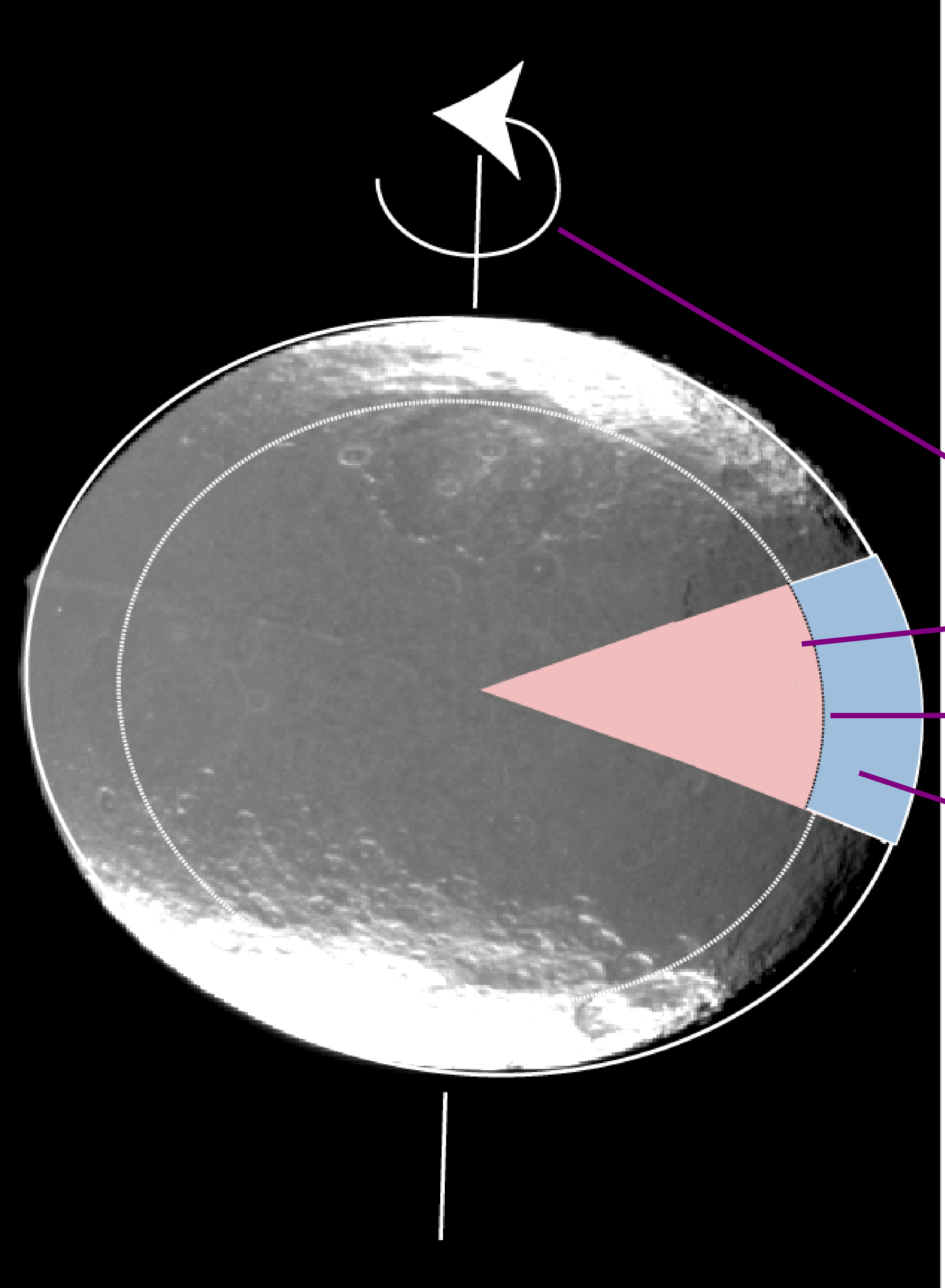
Very steep flanks, slope angle partly >30° !

Age ~ same as surroundings (4.4 - 4.5 By)



Model Requirements

- **Dissipative Interior** sufficient for Iapetus' models to despin in less than the age of the Solar System
- **Stiff lithosphere** to retain the 17-h geoid and other topography



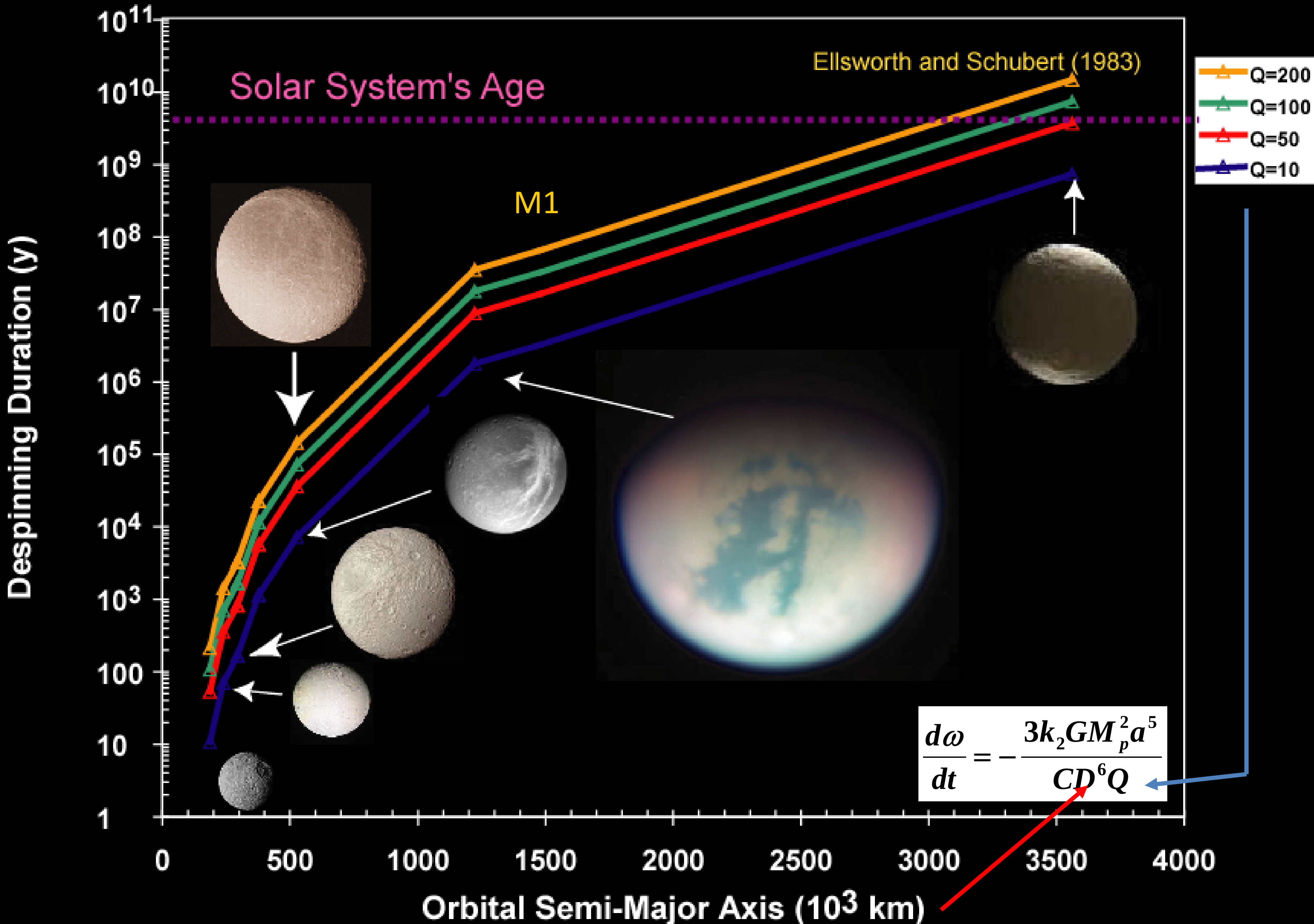
Approach

Simultaneous Solution of a System of Models

- Dynamical
- Thermal
- Rheological
- Lithospheric and Geological

AS A FUNCTION OF TIME

STATUS IN THE EARLY 80'S



Link between viscoelastic structure and dynamics

RAW EGG

COOKED EGG

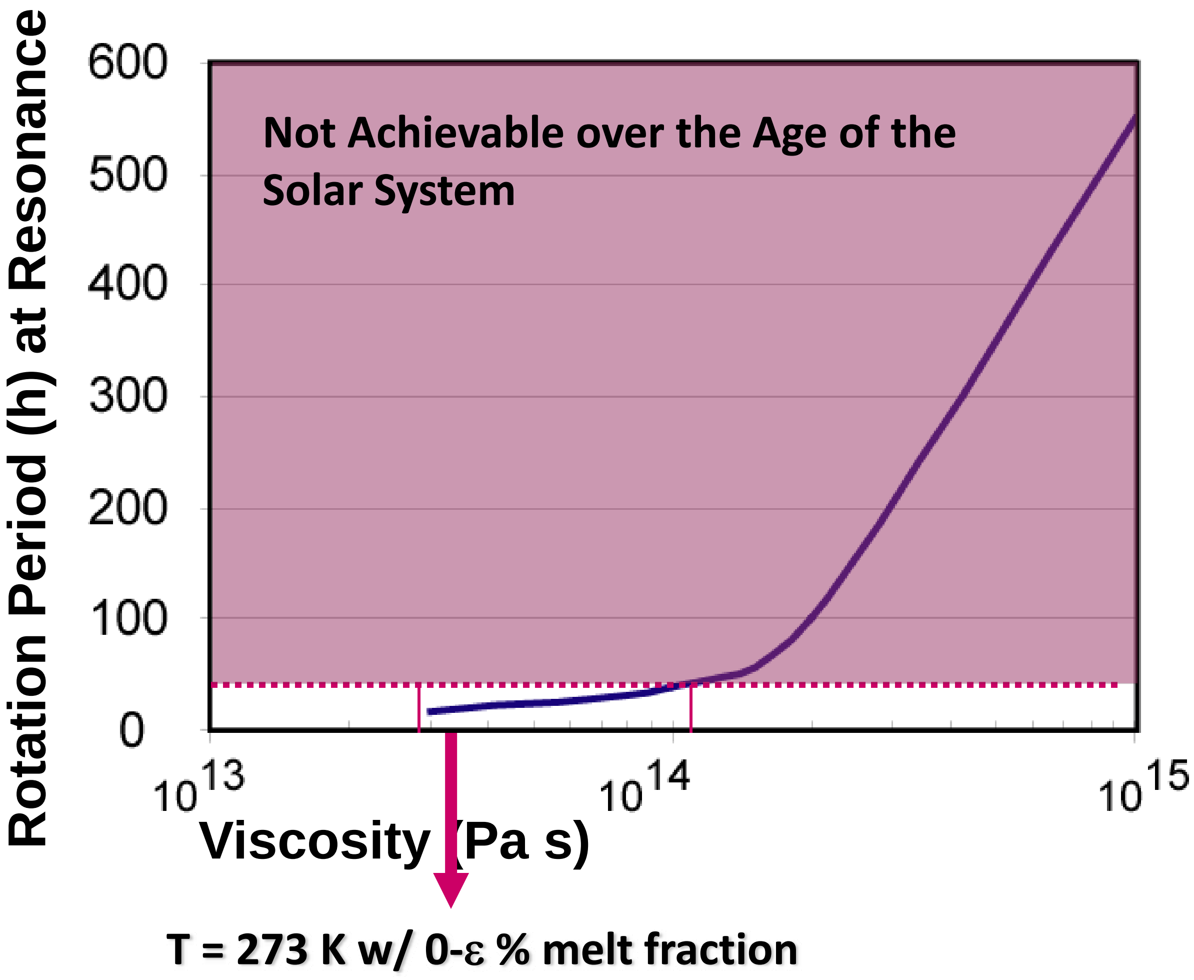
Initial impulse is of similar magnitude

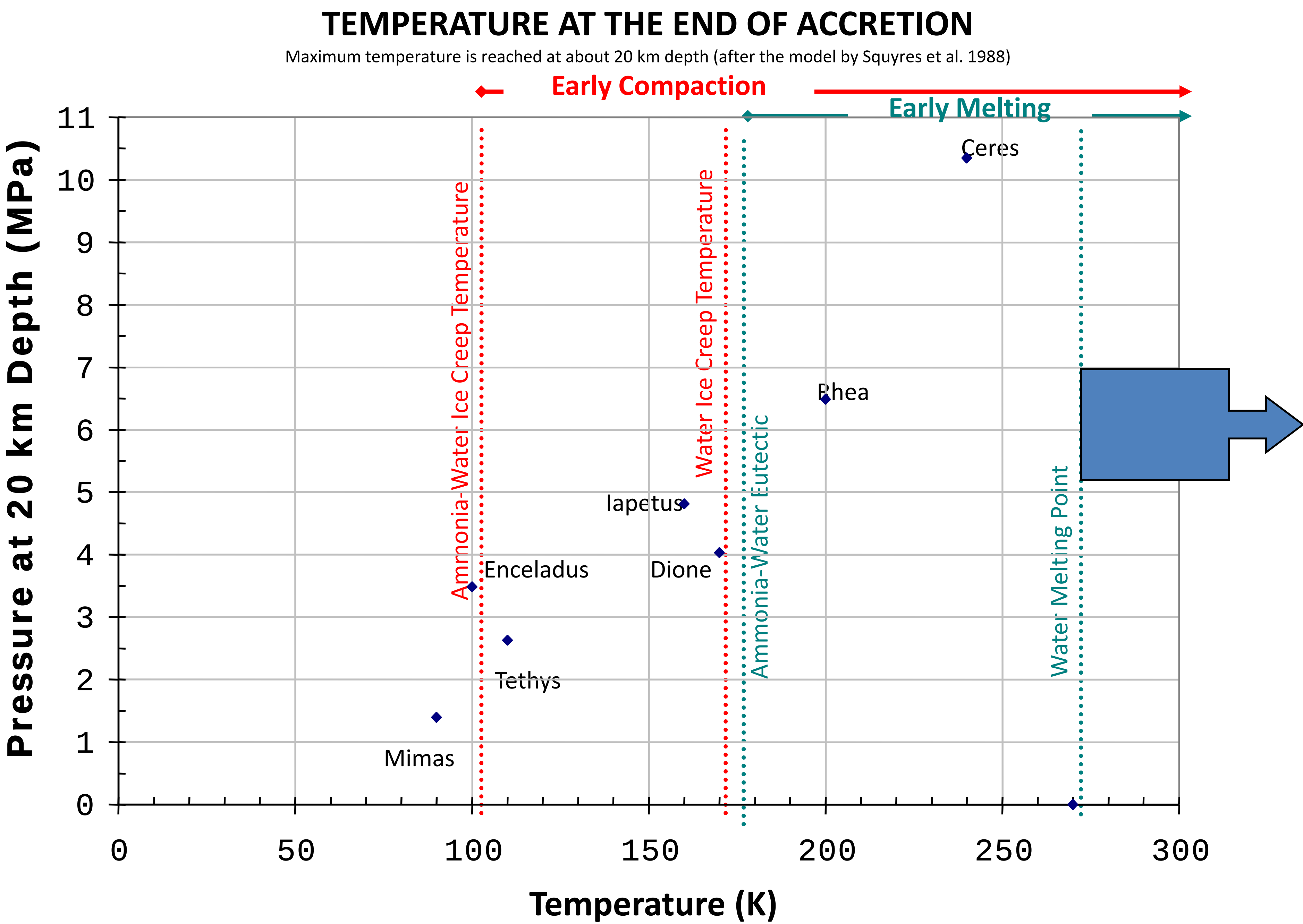
The raw egg slows down faster than the cooked one!

Both eggs are disrupted from spinning in a similar way

The cooked egg stops immediately while the raw one resumes spinning!

ROTATION PERIOD FOR RESONANCE




TEMPERATURE AT THE END OF ACCRETION
Maximum temperature is reached at about 20 km depth (after the model by Squyres et al. 1988)
Early Compaction
Early Melting
Ammonia-Water Ice Creep Temperature
Water Ice Creep Temperature
Ammonia-Water Eutectic
Water Melting Point
Ceres
Rhea
Iapetus
Dione
Enceladus
Tethys
Mimas
Pressure at 20 km Depth (MPa)
Temperature (K)
0
1
2
3
4
5
6
7
8
9
10
11
0
50
100
150
200
250
300

MODELING MEDIUM-SIZED ICY SATELLITES

- Medium-sized satellites accrete cold and porous
- Water ice at 80 K is one of the most conductive planetary minerals
- The time scale to warm the interior from long-lived radionuclides decay is longer than the cooling time scale
- The conditions for tidal heating to become a significant heat source in cold objects are not understood

There is an obvious discrepancy between models and observations

APPROACH

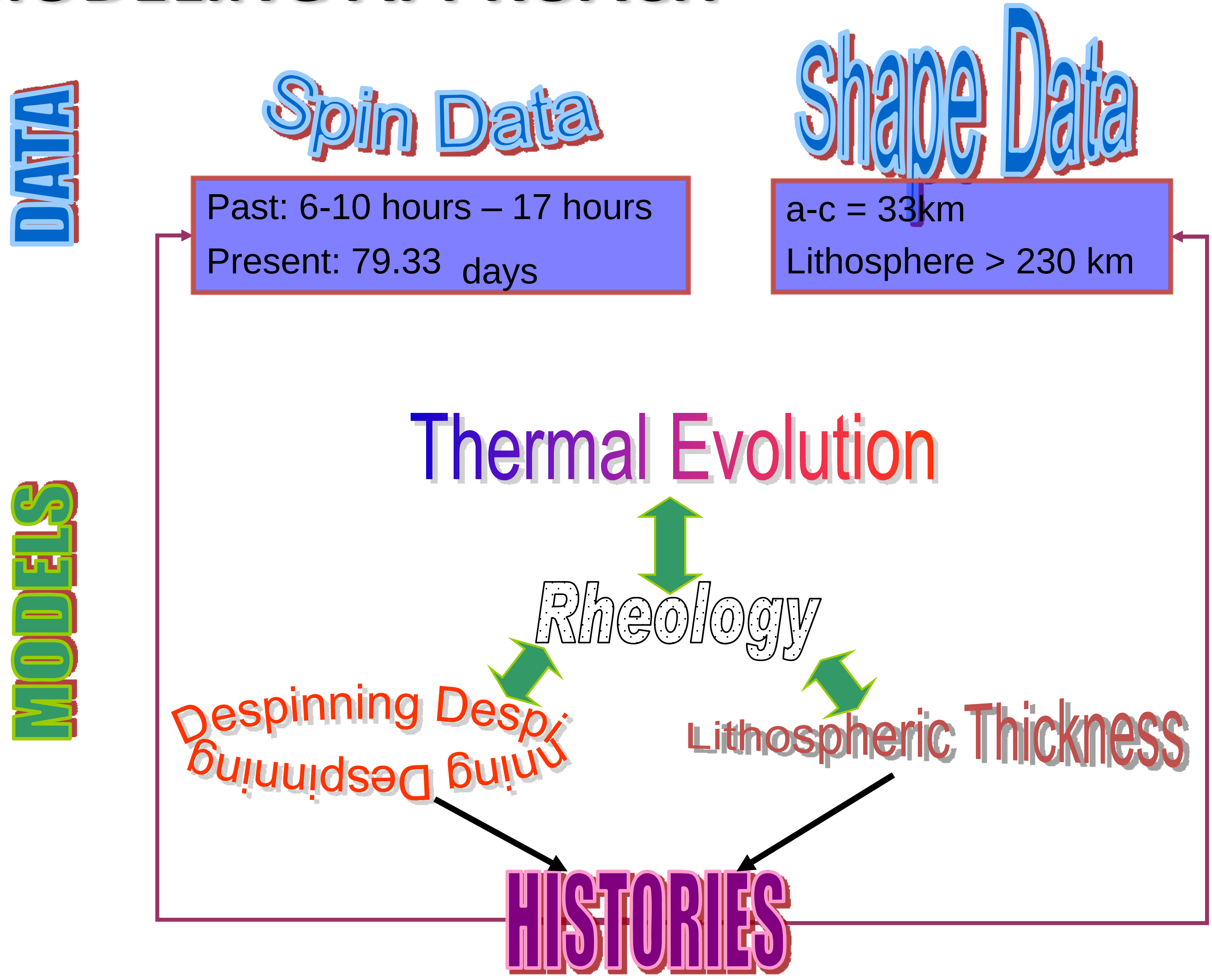
Initial Conditions

- Presence of SLRS
- Formation time: 1.5 to 10 My after CAIs
- Presence of ammonia
- Planetesimals temperature
- Insulating regolith layer

Other sources

- Evolution of the surface temperature
- Silicate hydration heat
- Long-lived radionuclides
- Gravitational energy
- Tidal dissipation (if enabled)

MODELING APPROACH



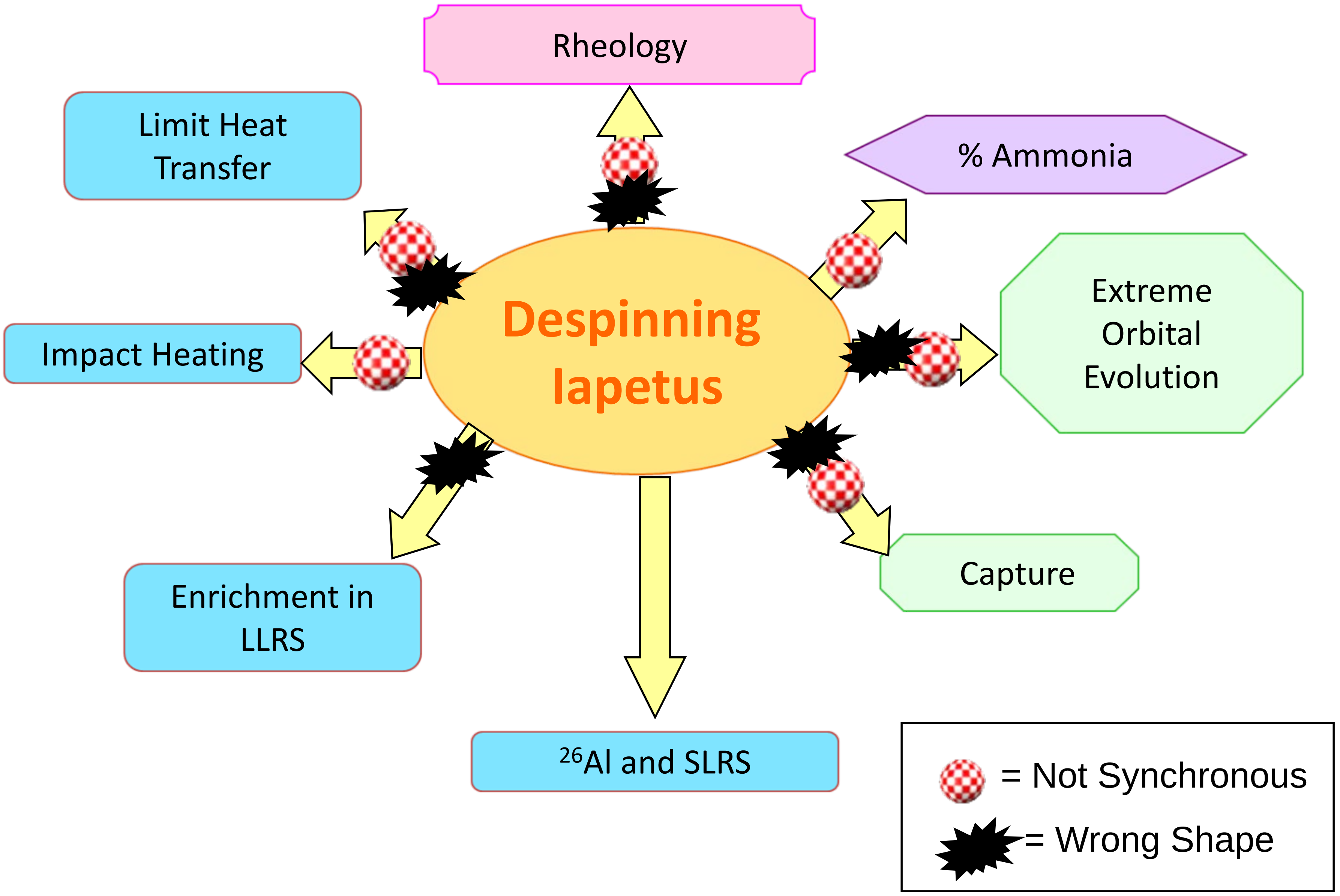
HEATING

- Short- and long-lived radiogenic isotopes
- Insulating, porous layer
- Saturn's luminosity
- Impeded Convection (too cold)
- Tidal dissipation (coupled thermal-orbital evolution)

- Runaway effect of temperature-dependent thermal conductivity
- Ammonia and other ice melting-point depressant (depends on their amount)
- Surface temperature

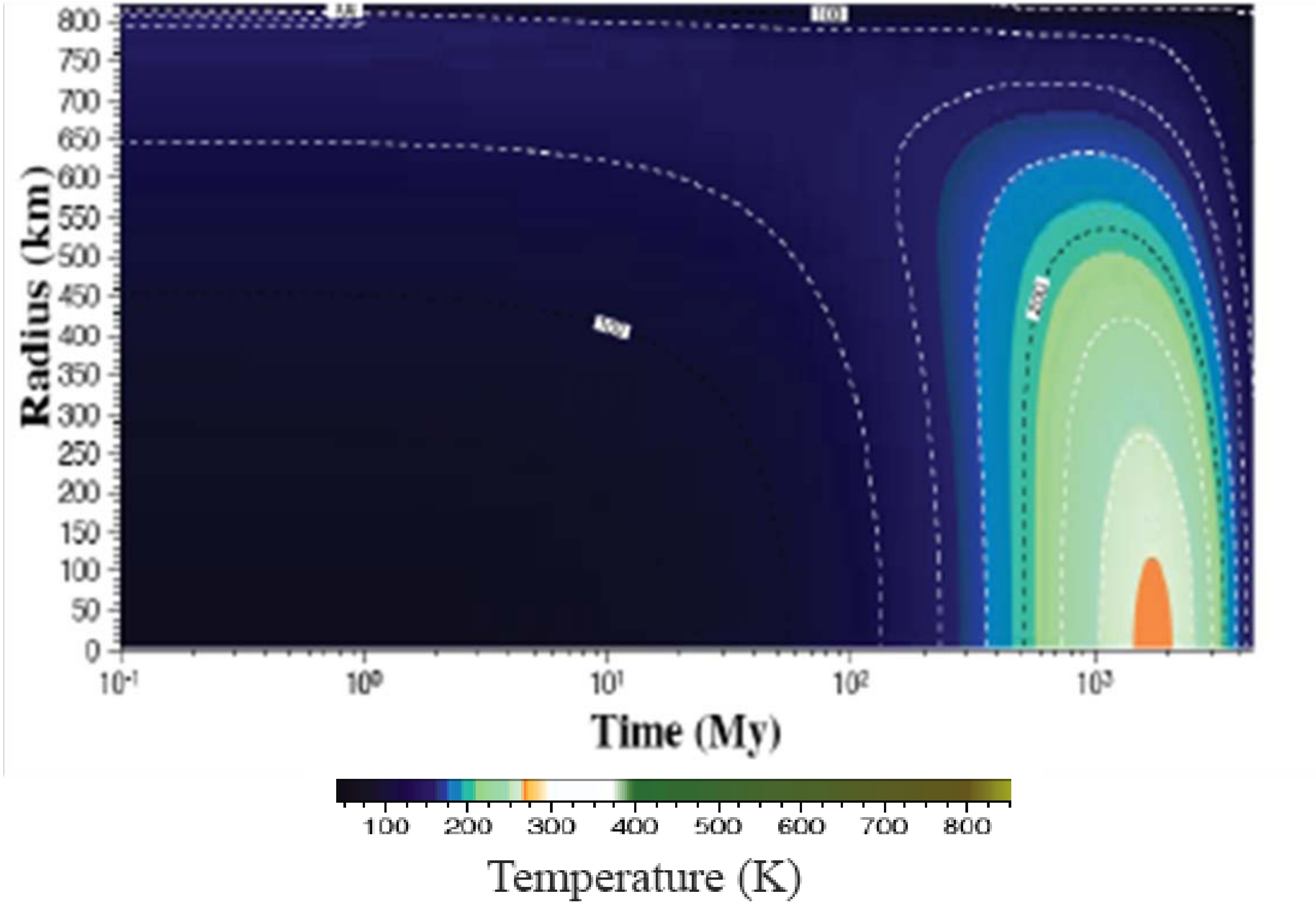
COOLING

A REAL MYSTERY

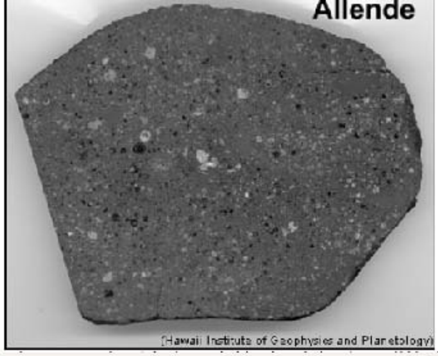


IAPETUS

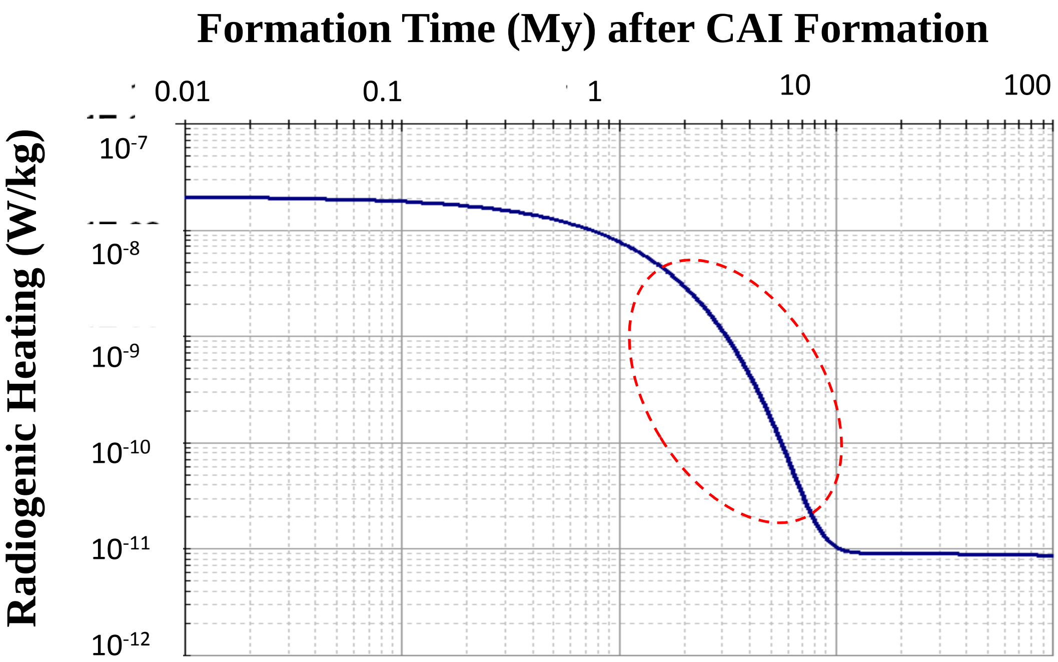
Classical Model, after Ellsworth and Schubert (1983)



^{26}Al



- First identified in Calcium-Aluminum Inclusions
- Initial $^{26}Al/^{27}Al$ ~ 5-6.5 x 10^{-5} (Pappanastassiou, Wasserburg, Lee)
- Half-life ~ 0.717 My



ROLE OF SLRS IN THERMAL EVOLUTION

- Play a role only in early evolution of the satellite

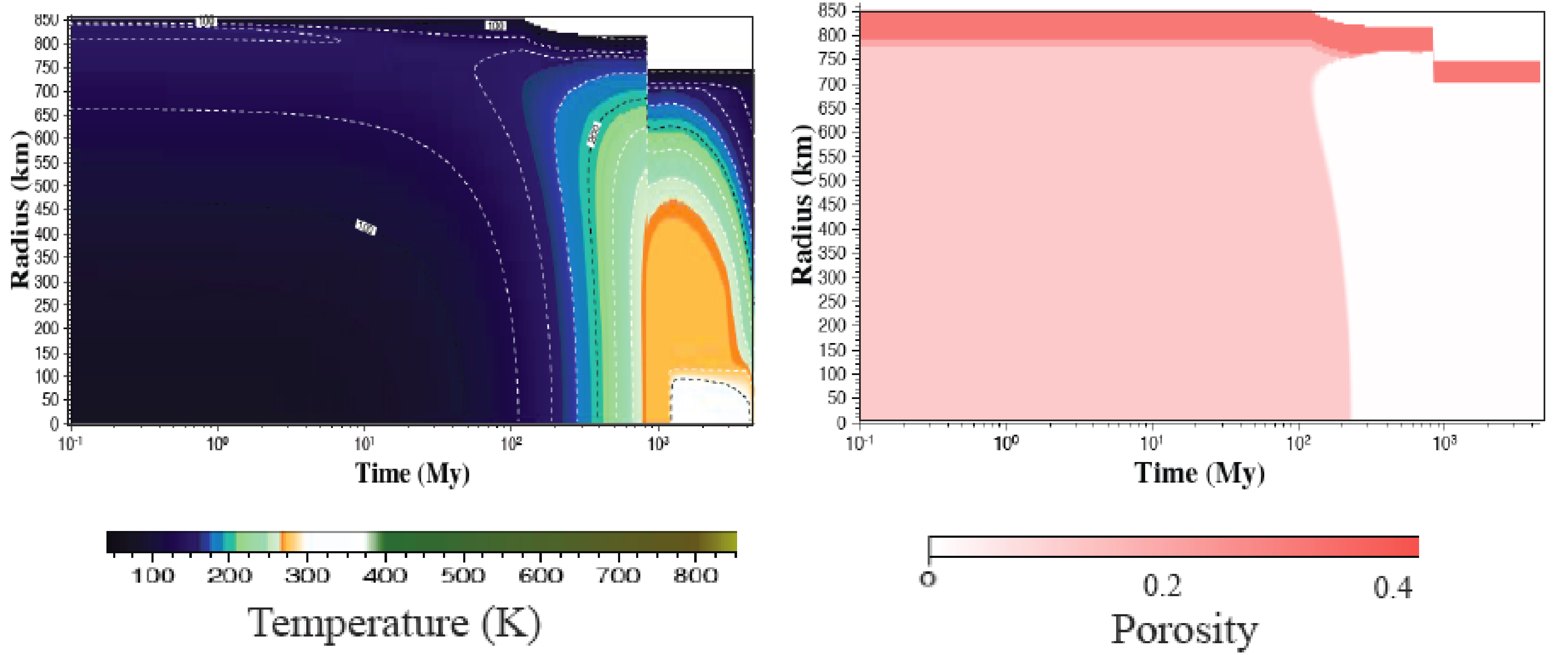
  early differentiation and geological activity)

  e internal temperatures high enough for hydration (and consequent volume change)

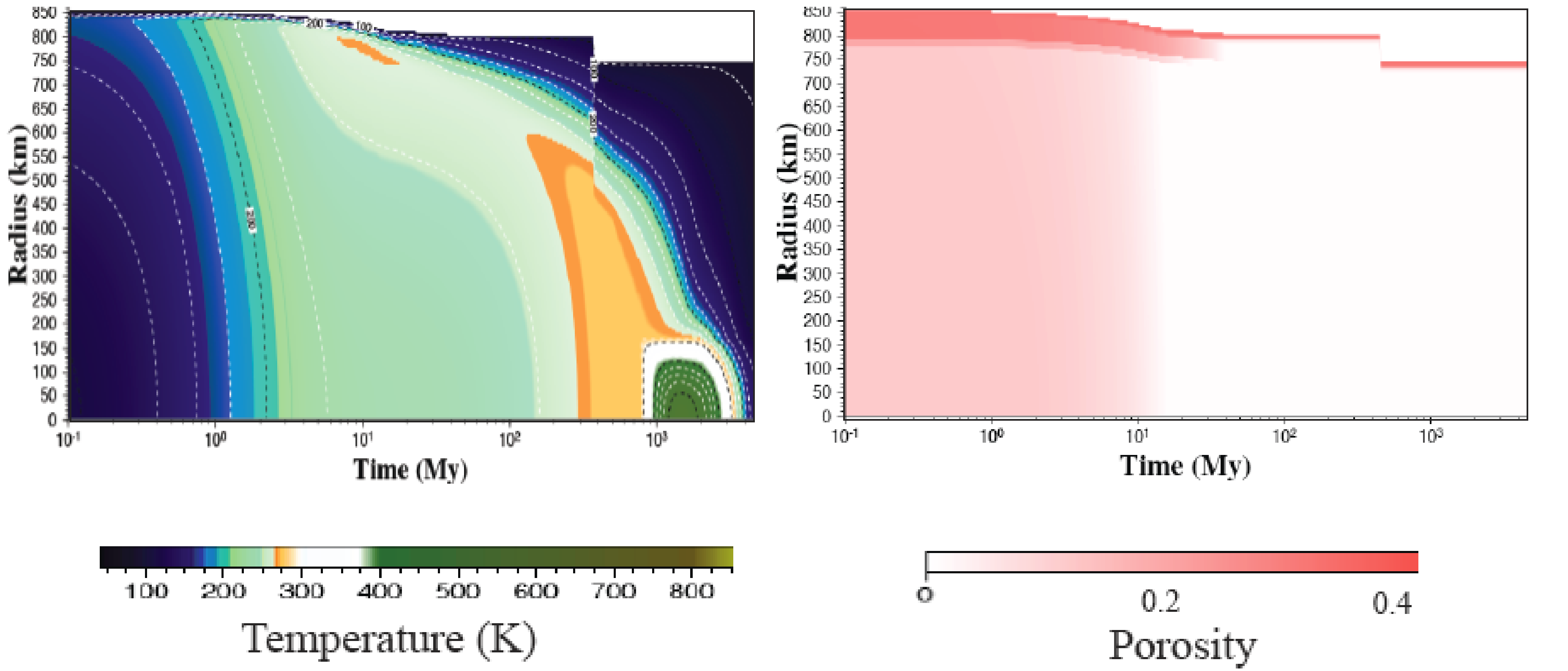
  e internal temperatures high enough for tidal tion to start

  e internal temperatures high enough for ant porosity decrease

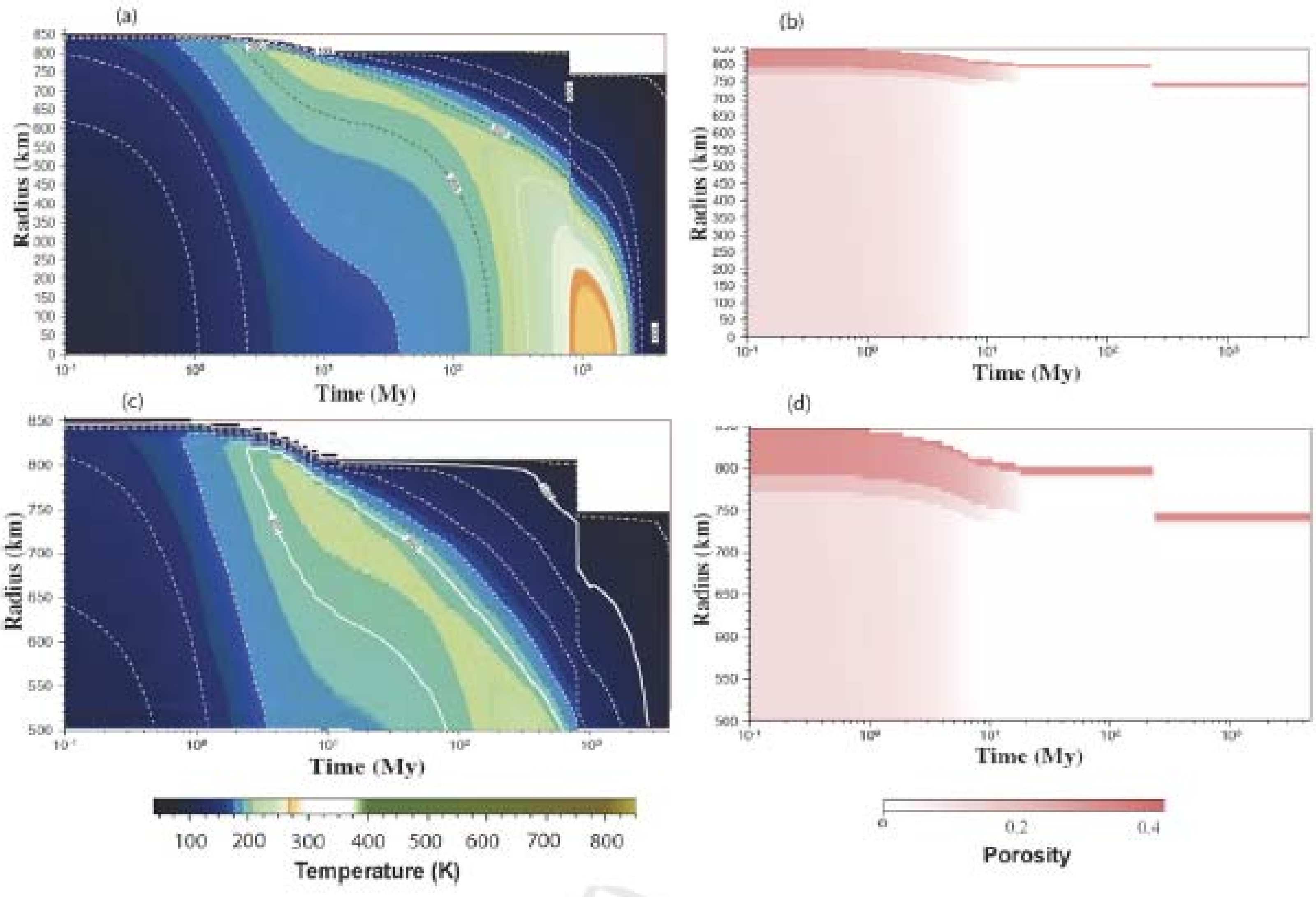
Porous Model, t_0 > 6 My after CAIs



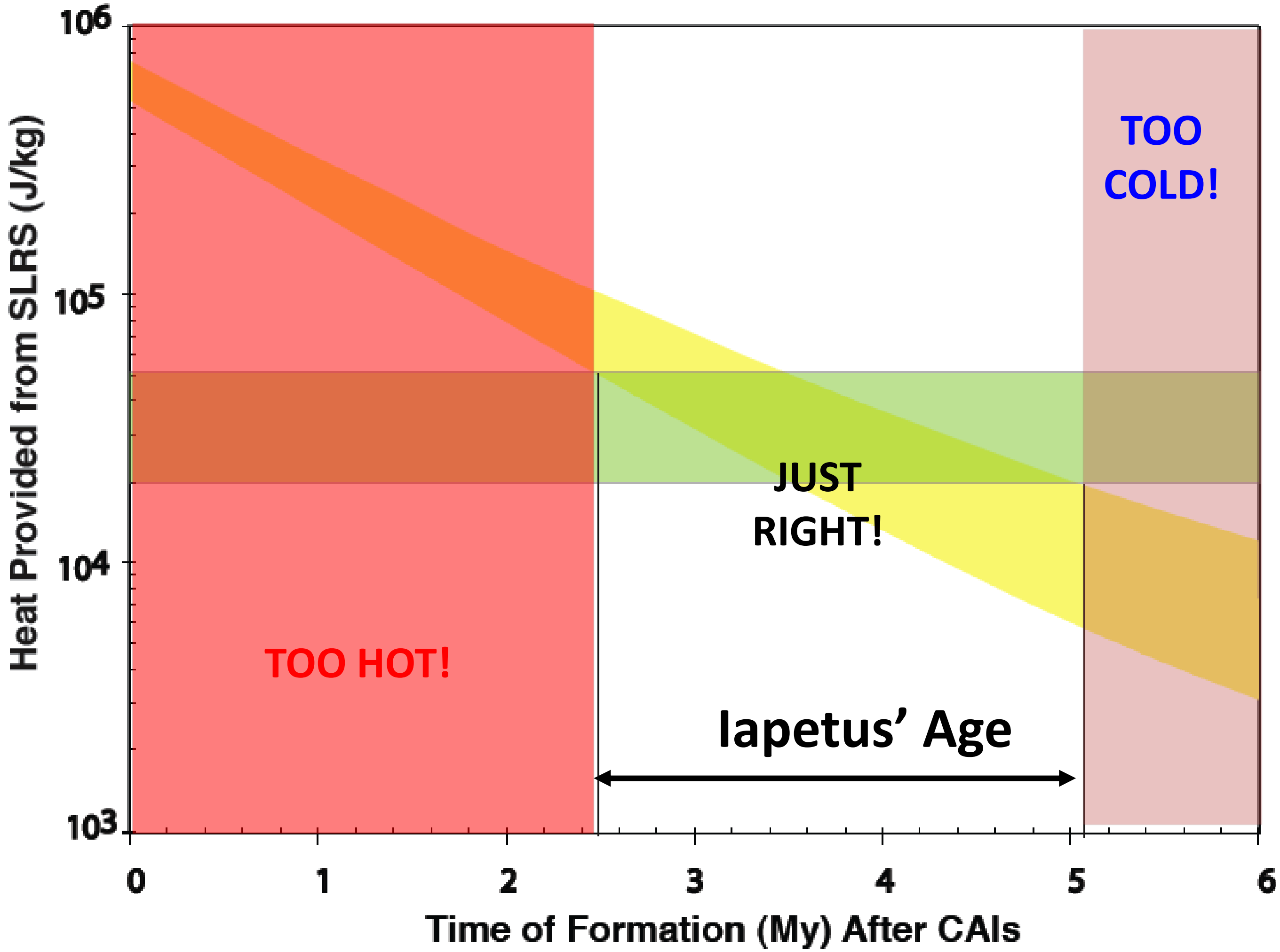
Porous Model, t_0 = 2.5 My after CAIs



GEOLOGICAL CONSEQUENCES



^{26}AL IS NOT A FREE PARAMETER



Castillo-Rogez *et al.* (2007)

Planet Formation Timescales

Giant planets Models

- Gravitational instability – e.g. Boss
- Core nucleated accretion – currently favored
  - Time scale problem – analogy to terrestrial accretion yields O(10^8 yrs) – too long compared with stellar evidence
  - “runaway growth” and Oligarchic growth models can result in <10^7 yr times scales (e.g. Lissauer, 1987)

Planet Formation Timescales

Evidence from stellar protoplanetary disks

- Gas loss <10^7 yr (Meyer et al., 2007)
- Spitzer studies for ~ solar mass stars show that stars with 3-5 x 10^6 yr ages lack indications of primordial planet-forming disks (e.g. Carpenter et al., 2006; Dahm and Hillenbrand 2007: Currie and Kenyon, 2008)

Evidence for Early Planet Formation

1 Million Year Old Planets?!

"A stellar prodigy has been spotted about 450 light-years away in a system called UX Tau A by NASA's Spitzer Space Telescope. Astronomers suspect this system's central Sun-like star, which is just *one million years old*, may already be surrounded by young planets. "

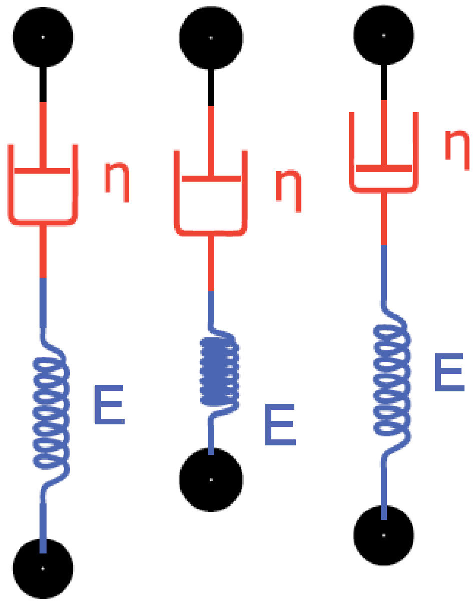
Spitzer Science Center release 11/28/2007

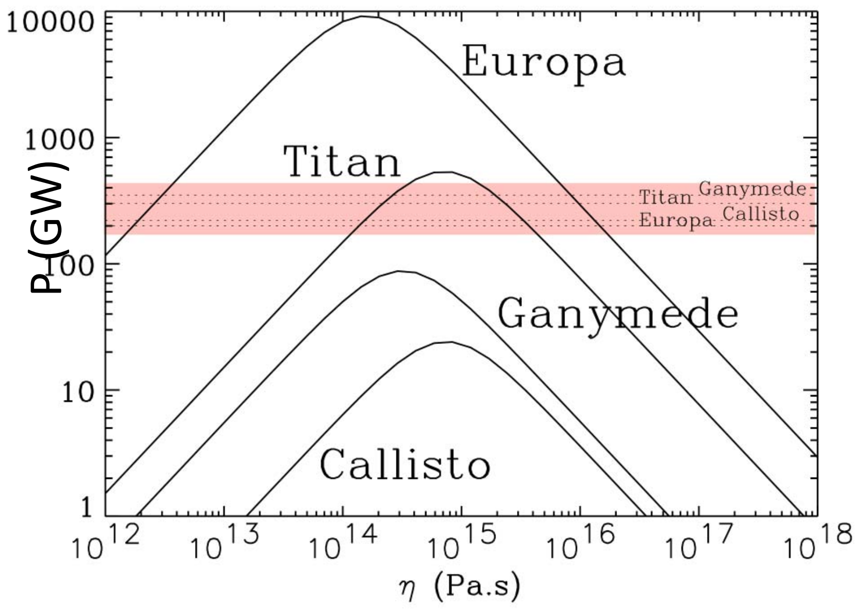
THE FUTURE: LABORATORY-BASED MODELS

- Current models are not supported by laboratory measurements
- Viscoelastic response models rely on the Maxwell model, known to be applicable for a very limited range of conditions in satellites

Mechanical Measurements in Cryogenic Conditions at Low Frequencies and Stresses are Challenging

Maxwell Model

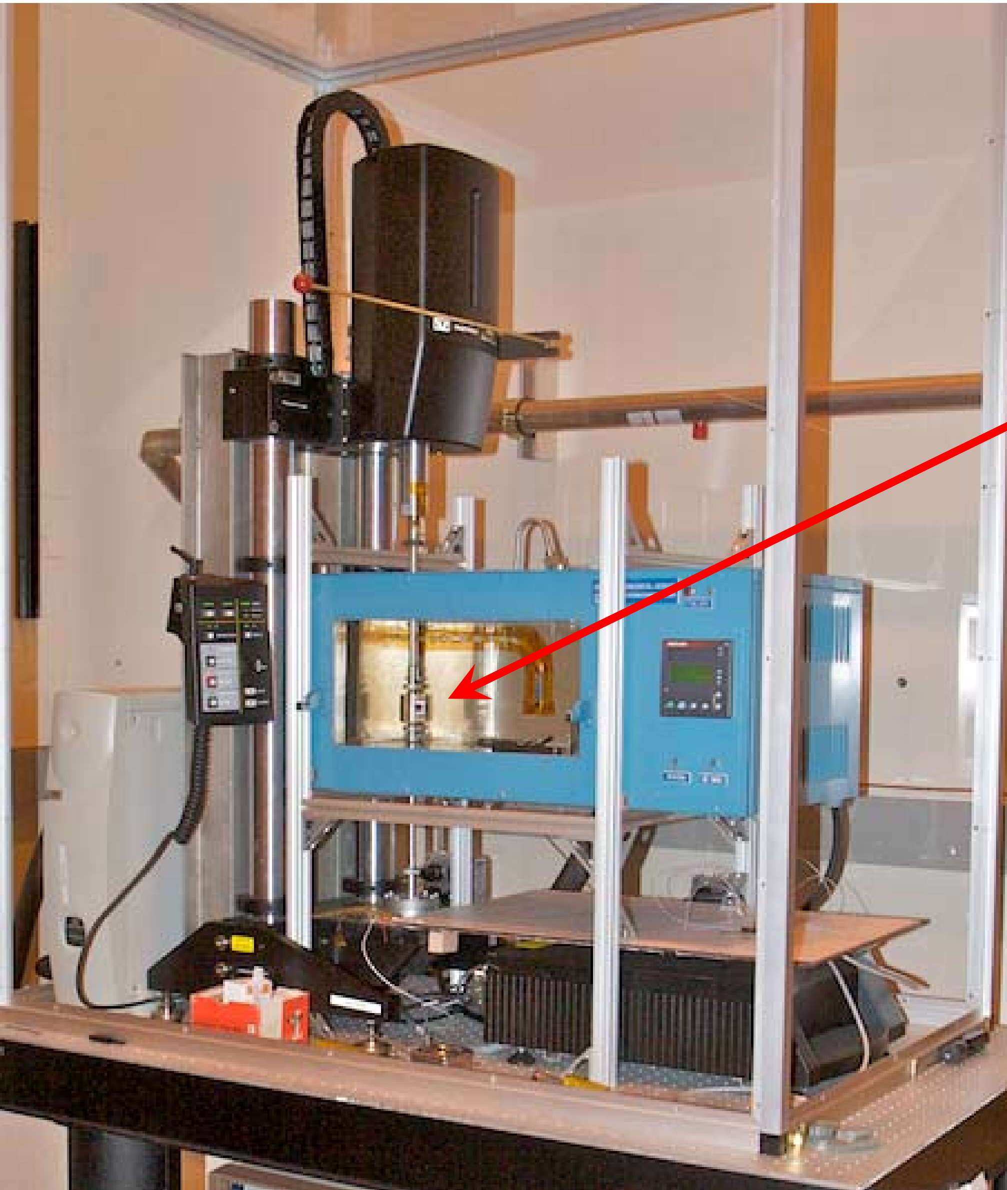


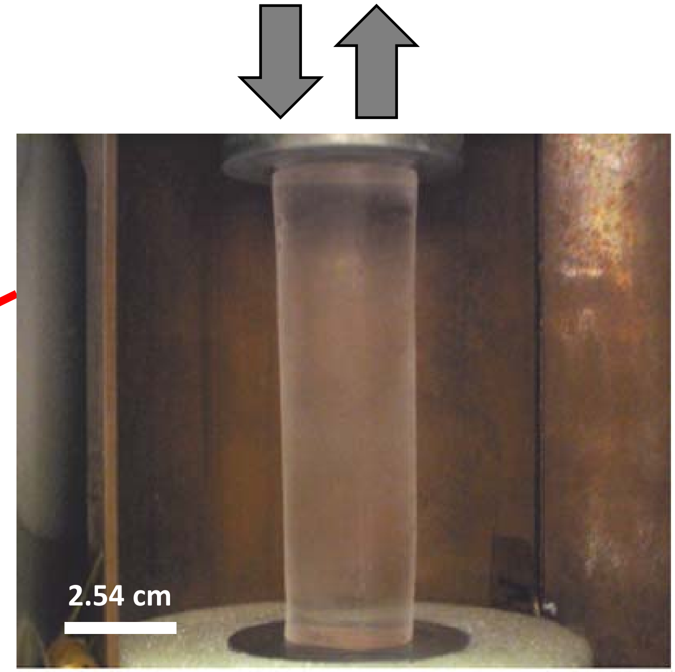


- $Q^{-1} \sim \omega^{-1}$, assumes one relaxation time $\tau=\eta/E$
- Easy to implement: depends only on two parameters
- Various measurements (lab-based, seismic data, glaciers) indicate that this model is not adequate

LABORATORY WORK

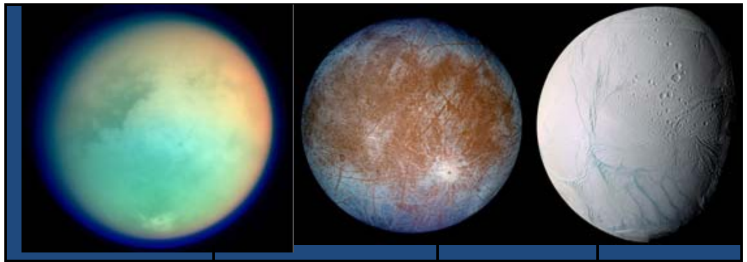
NEW EXPERIMENTAL FACILITIES AT JPL

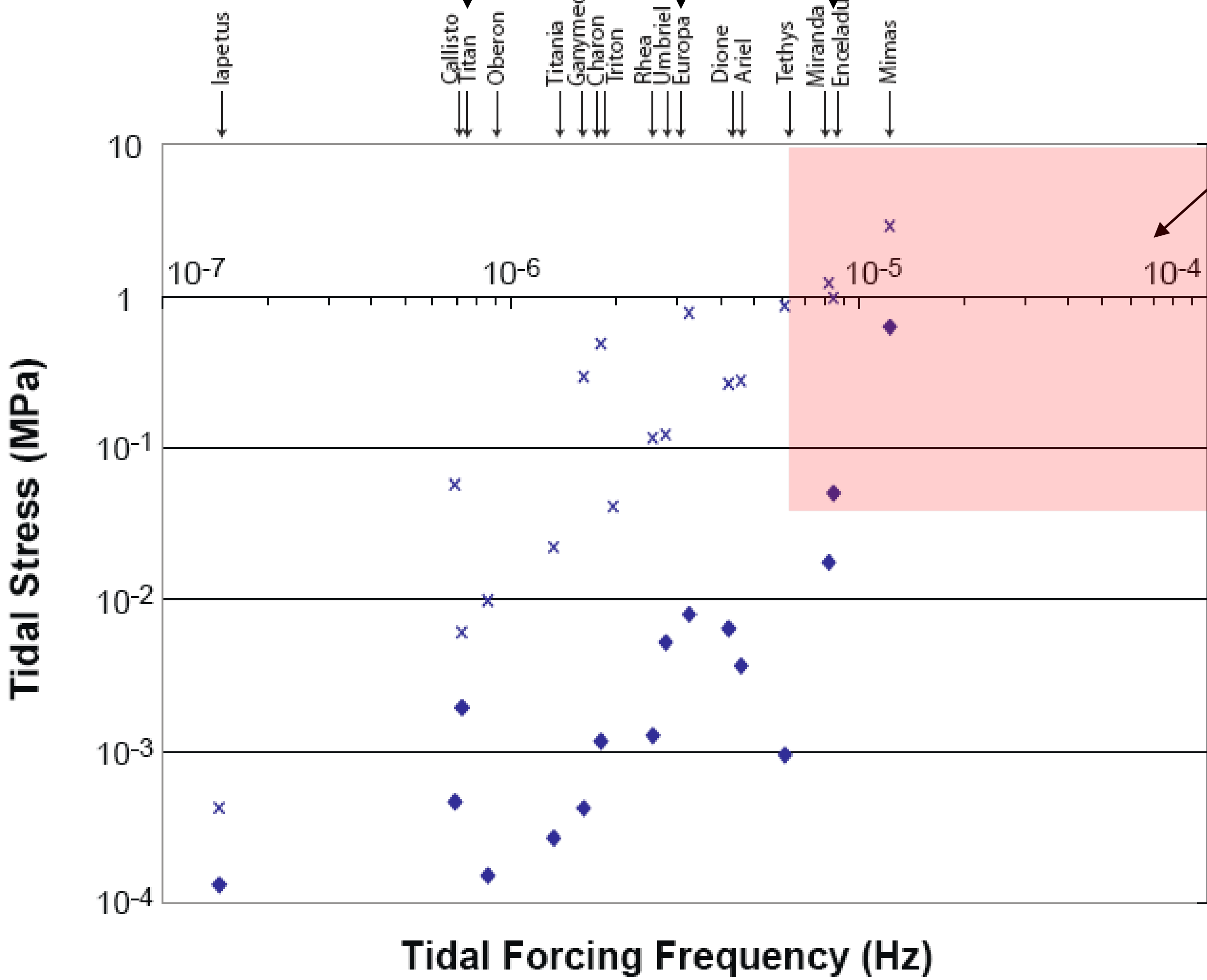




First and only system able to simulate tidal dissipation under realistic satellite conditions

CAPABILITY OF NEW SYSTEM



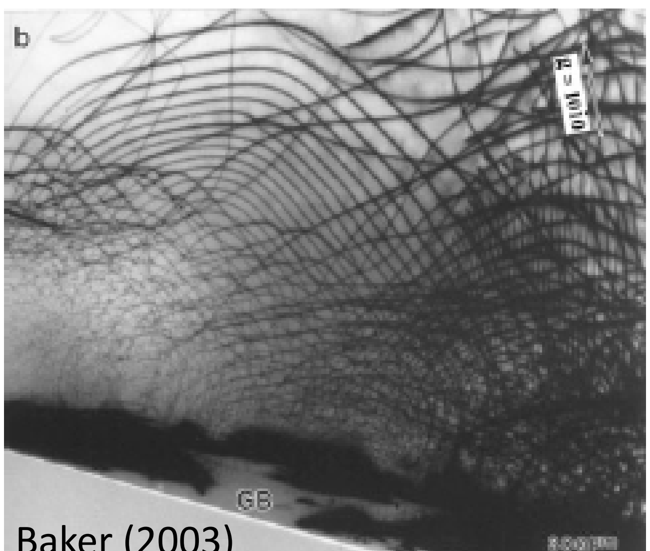


10^{-2} Hz

WHERE DO WE START?

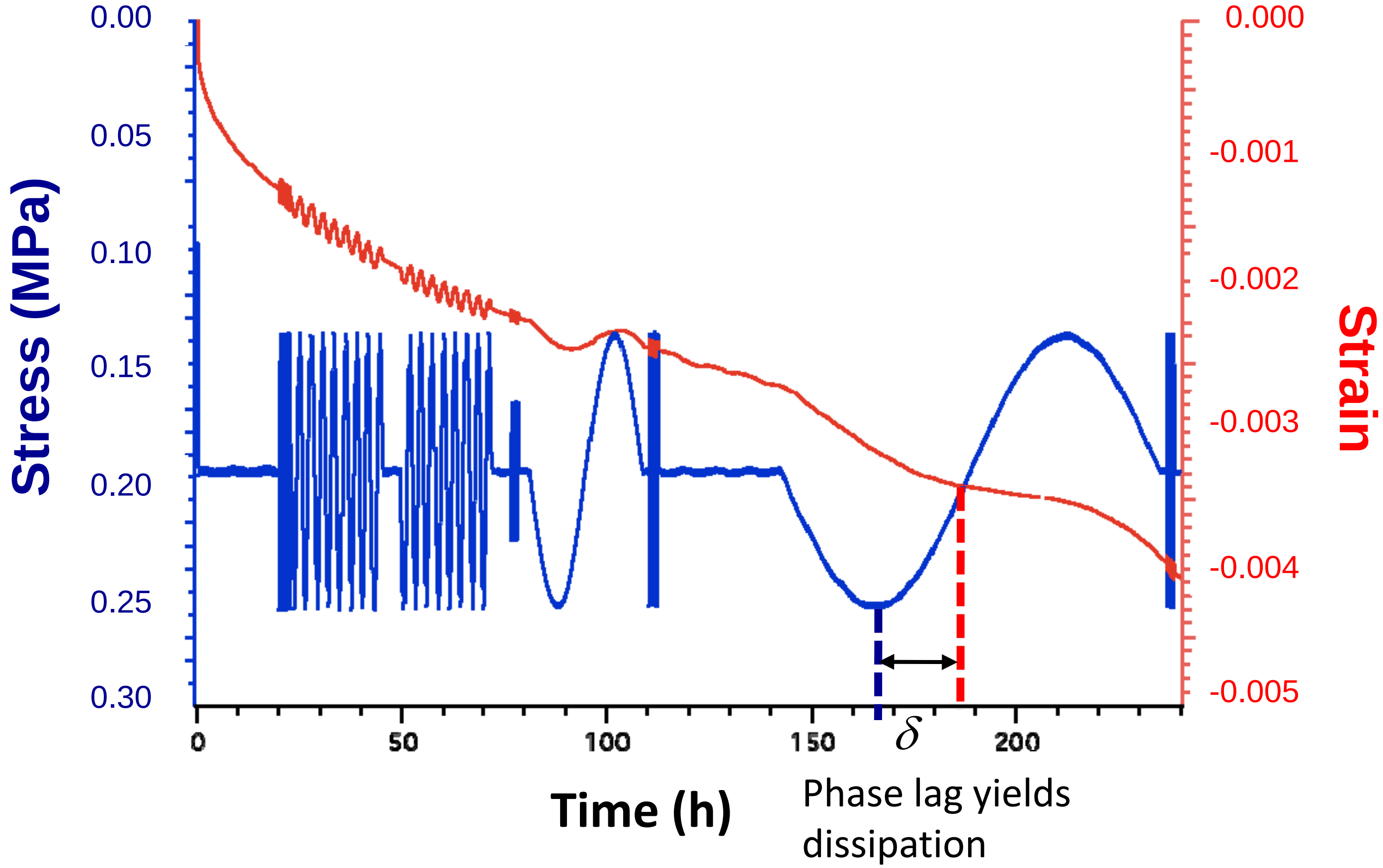
- Monocrystalline ice in order to identify dislocation-driven anelasticity

- Dislocation creep is thought to drive anelasticity in many conditions: warm temperatures, large grain size, high stress (cf. terrestrial rocks)



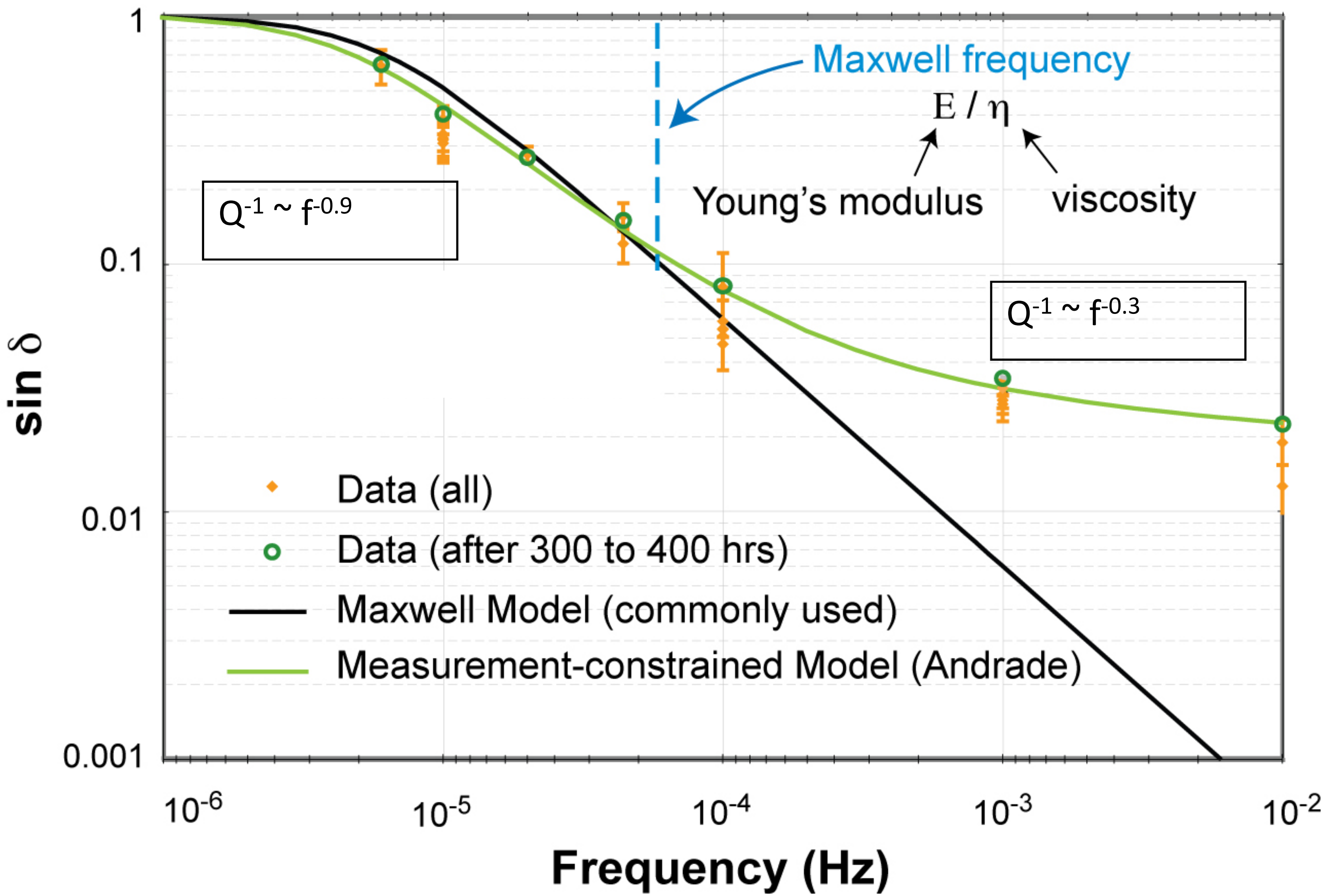
Baker (2003)

LABORATORY MEASUREMENTS

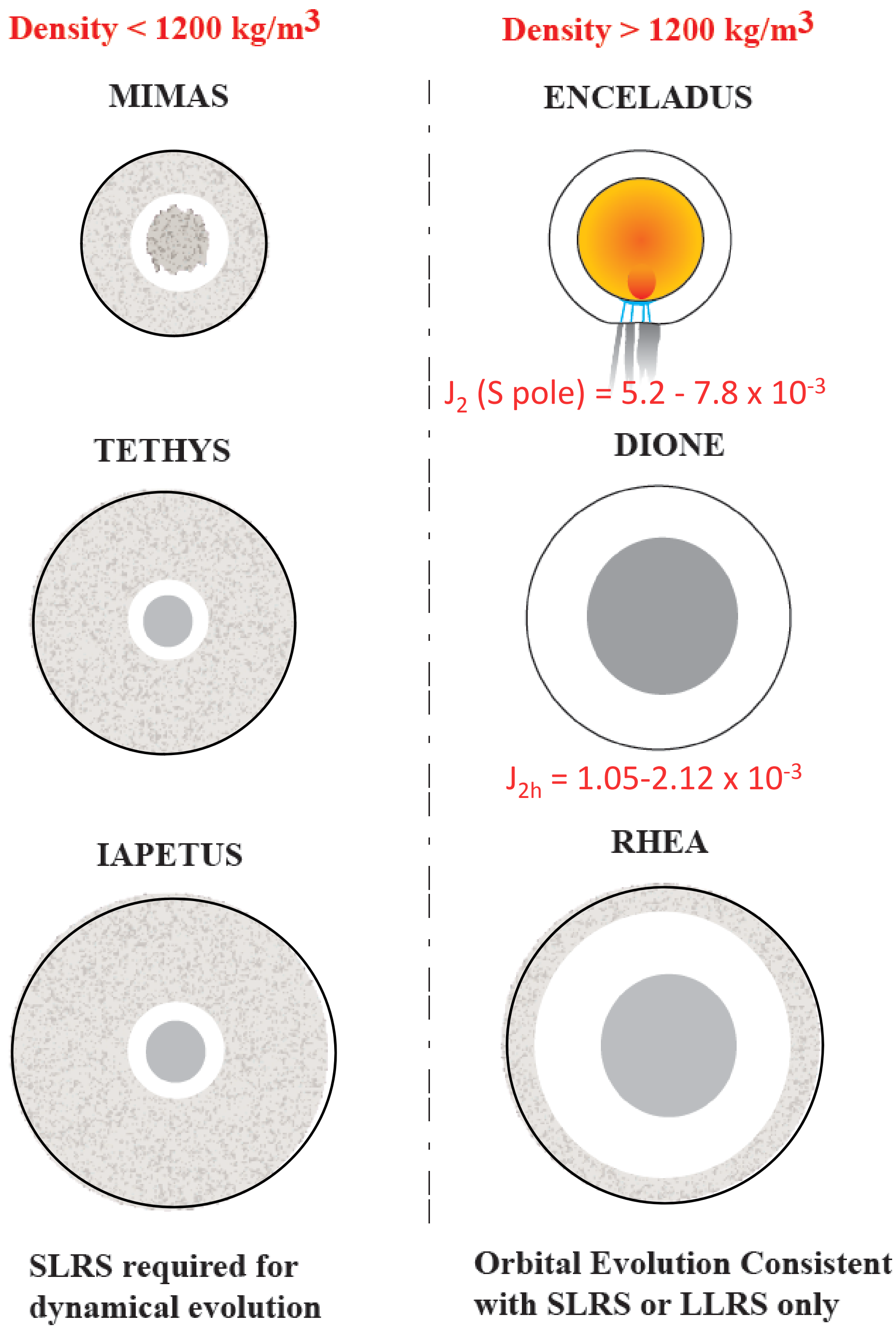


• Results have demonstrated that existing models of dissipation need to be revised using our laboratory data

SPECTRUM AT -30 deg. C



FUTURE *CASSINI* OBSERVATIONS WILL HELP CONSTRAIN THE FORMATION TIMESCALE FOR THE SATURNIAN SYSTEM



Density < 1200 kg/m3
Density > 1200 kg/m3
MIMAS
ENCELADUS
J2 (S pole) = 5.2 - 7.8 x 10-3
TETHYS
DIONE
J2h = 1.05-2.12 x 10-3
IAPETUS
RHEA
SLRS required for dynamical evolution
Orbital Evolution Consistent with SLRS or LLRS only

POTENTIAL OBSERVATIONS

- **Geology**: Ongoing and Past Geologic Activity (*e.g.*, Enceladus)
- **Craters shape** (porosity, thermal gradient)
- **Surface Age**: Crater Counting and resurfacing
- **Equilibrium of the Shape**
- **Internal Structure**: (*e.g.*, for Rhea)
- **Dynamical Evolution** (*e.g.*, Iapetus)
- **Surface composition** (especially in craters, *e.g.*, Enceladus)