LOW THERMAL INERTIAS OF ICY SURFACES

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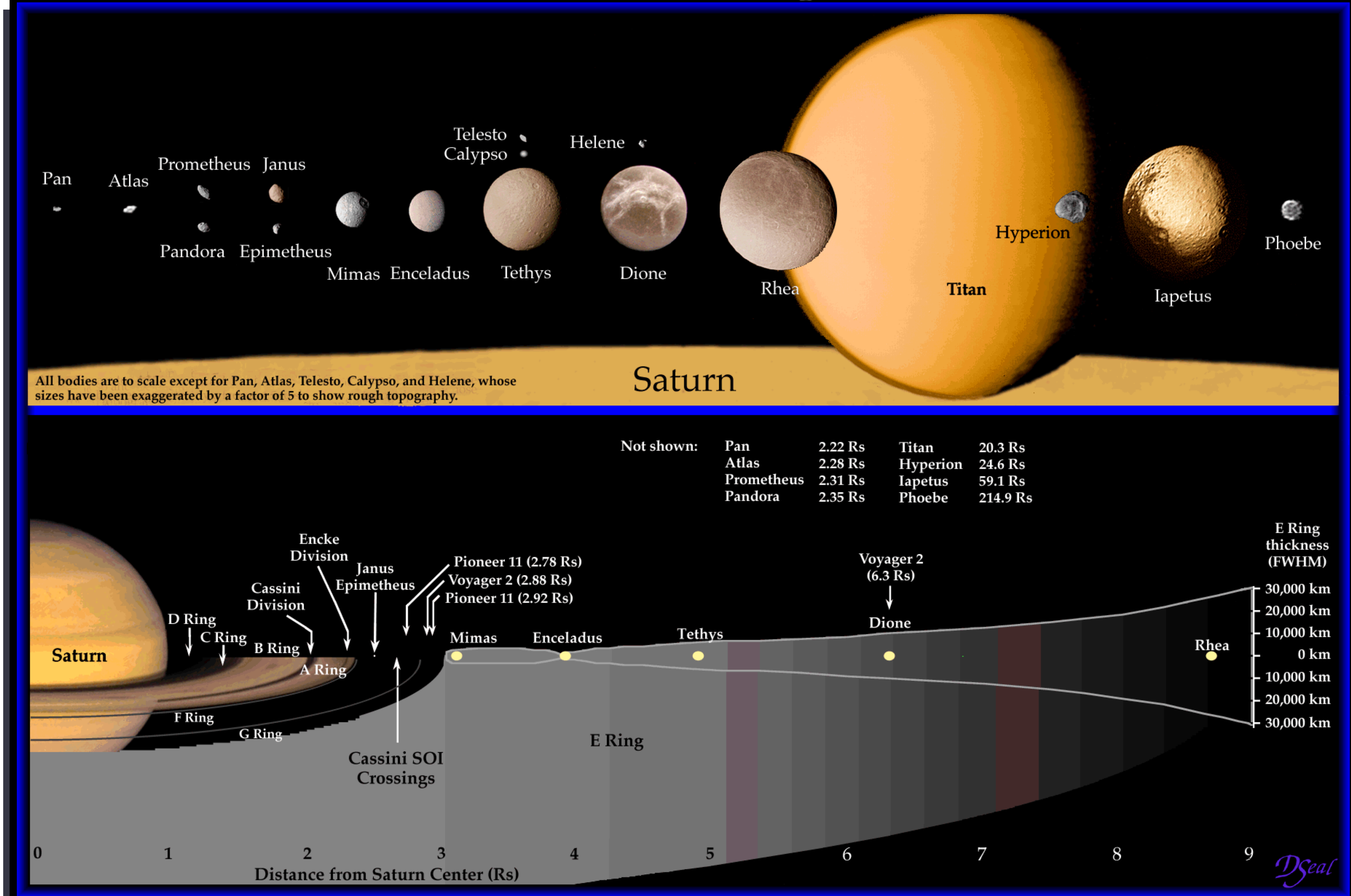
Ferrari and Lucas (2016) A&A, 588, A133

THE QUESTIONS

Why such low thermal inertias ? Mimas case

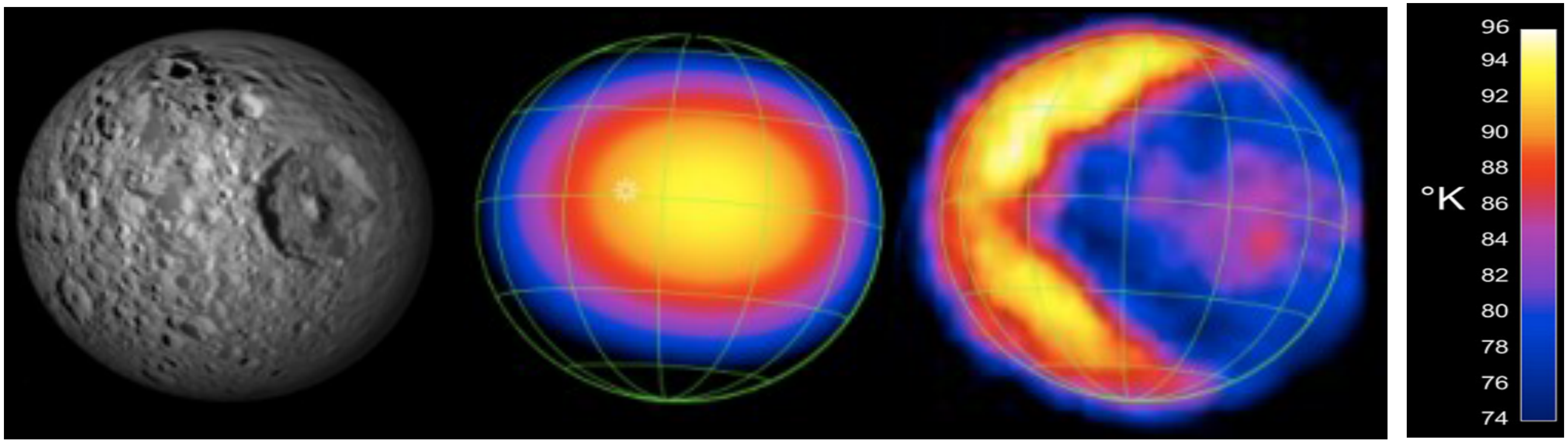
Why dependent on heliocentric distance ? TNOs case

Saturn's Satellites and Ring Structure



This graphic is available in color if required.

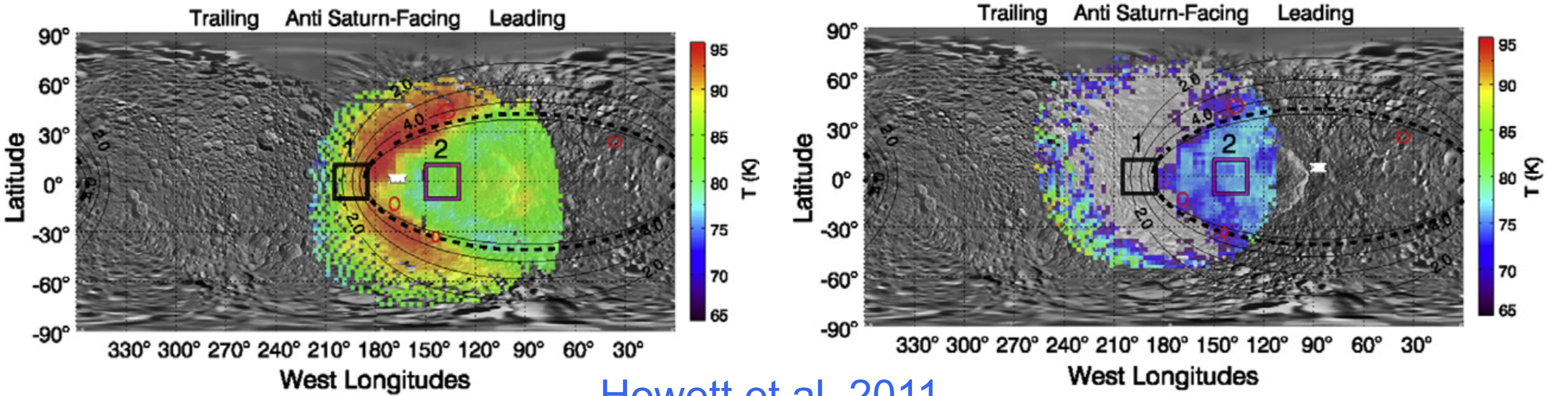
The Mimas case: Pacman revealed



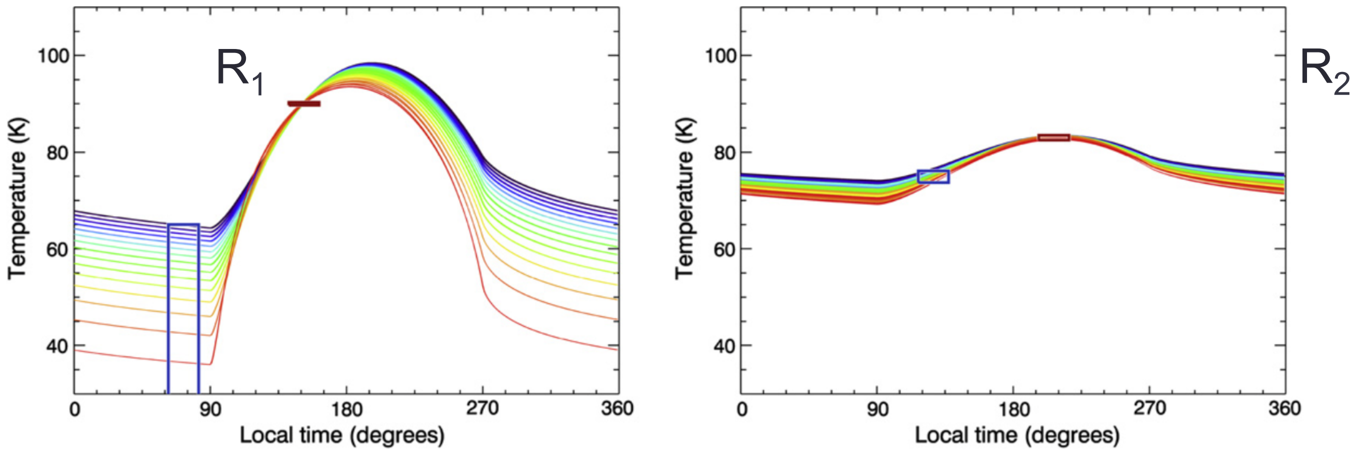
Howett et al. 2011

- Small icy moon ⌀=400 km
- Thermal dichotomy between leading and trailing hemispheres
- CIRS – CASSINI 7-9 μm to get high spatial resolution
- Diurnal cycle , thermal skin depth about a few cm

The thermal anomaly



Howett et al. 2011



Γ(trailing, R_1) < 16 $J/m^2/K/s^{1/2}$

Γ(leading, R_2) = 66±23$J/m^2/K/s^{1/2}$

Regolith thermal inertia

$$\Gamma = \sqrt{(1-p)\rho C K_E(p,R,\varepsilon,K_S)}$$

- C(T): specific heat capacity (J/kg/K)
- ρ volume density (kg/m^3)
- p = porosity, K_E= regolith thermal conductivity (W/m/K)
- Bulk water ice: Γ=2000 (SI) crystalline, Γ~300 (SI) amorphous

$\Gamma < 66$ (SI)

$\Rightarrow$ very high porosity (p > 95-99 %)

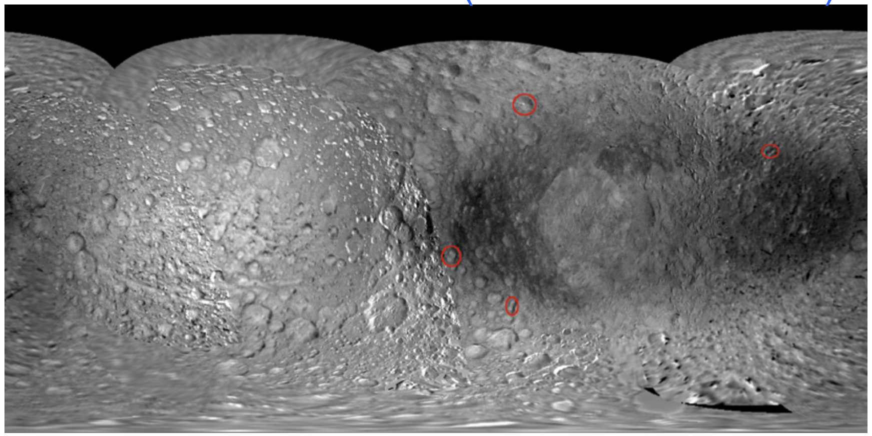
or

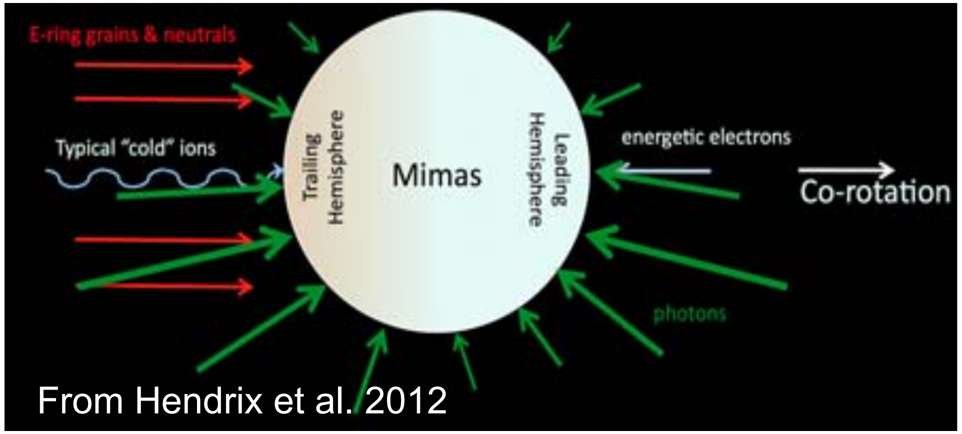
$\Rightarrow$ low thermal conductivity $K_E < 10^{-2}$ W/m/K

~ bulk/1000 !!!

The oval shape…

IR/UV albedo ratio (Schenck et al. 2011)





Trailing Leading

Shape ≡ bombardement on leading by e^- >0,5 MeV

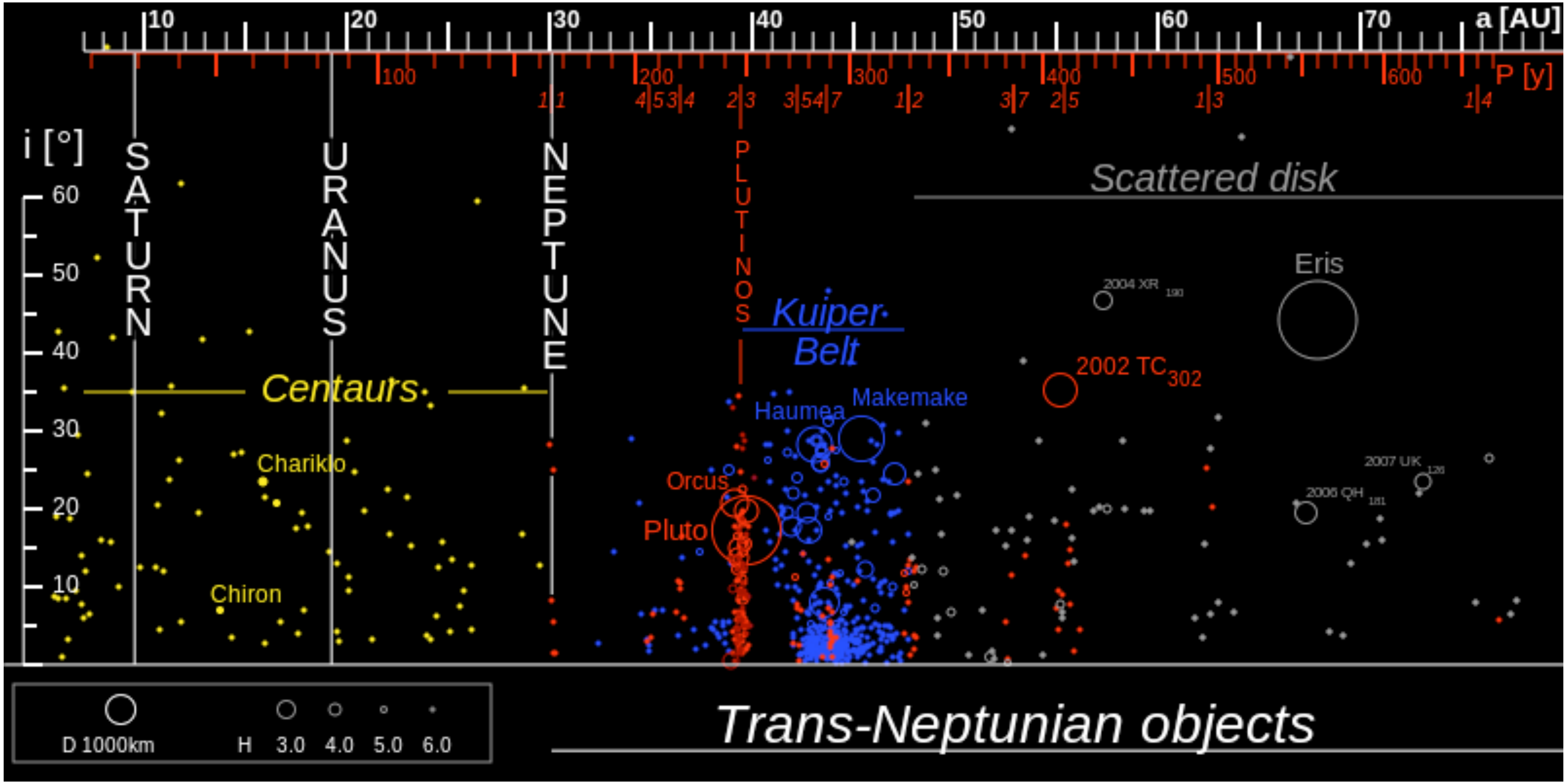
(Paranicas et al. 2012, Schenk et al. 2011)

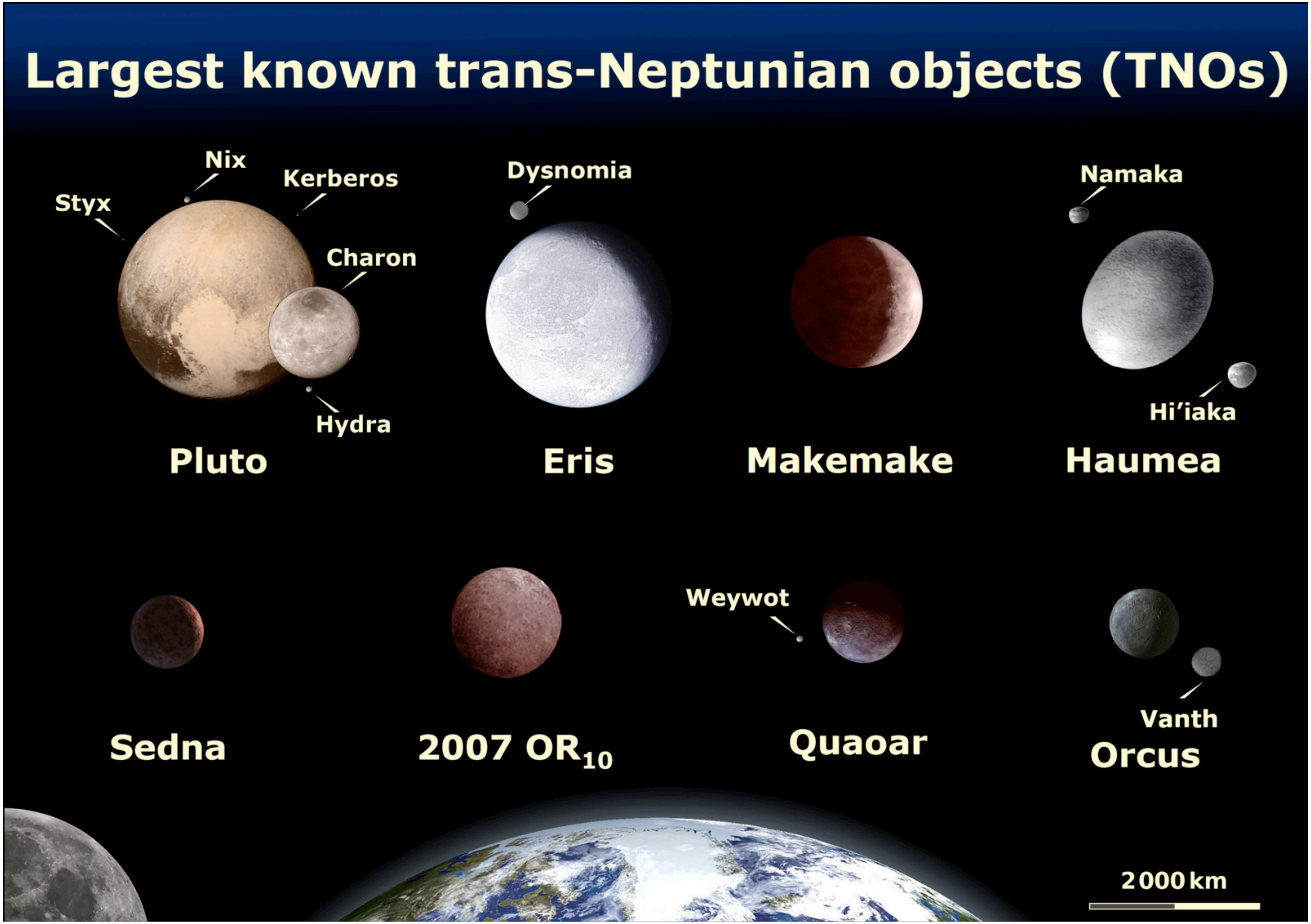
Excitation/ionization (Johnson et al 1990) ⟹ Radiolysis, amorphization, sputtering, desorption ⟹ Creating more defects

Any chance to sinter grains and increase thermal conductivity ?

How does the energy deposit modify the thermal properties?

Beyond Saturn, it's even lower !

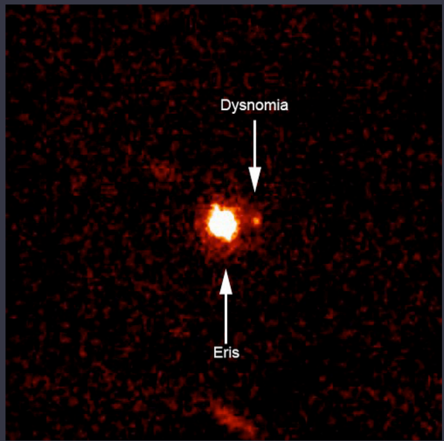


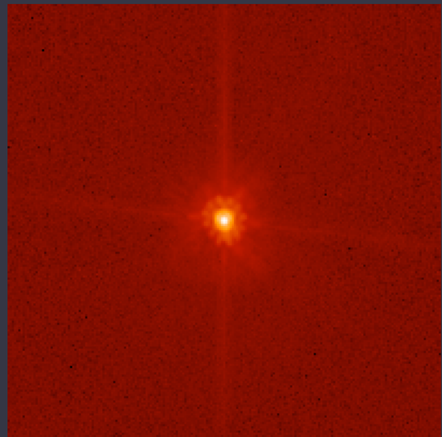


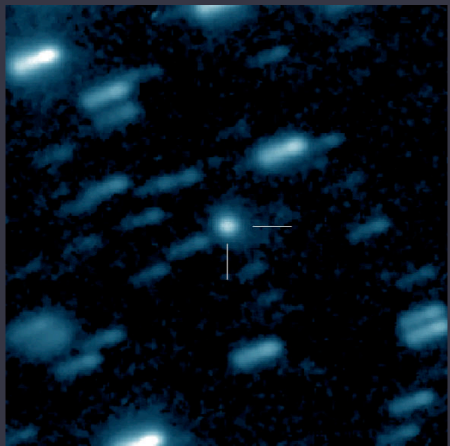
Largest known trans-Neptunian objects (TNOs)
Nix
Kerberos
Styx
Charon
Hydra
Pluto
Dysnomia
Eris
Makemake
Namaka
Hi'iaka
Haumea
Weywot
Sedna
2007 OR10
Quaoar
Vanth
Orcus
2000 km

In real…

TNOs (∅ > 2000 km)

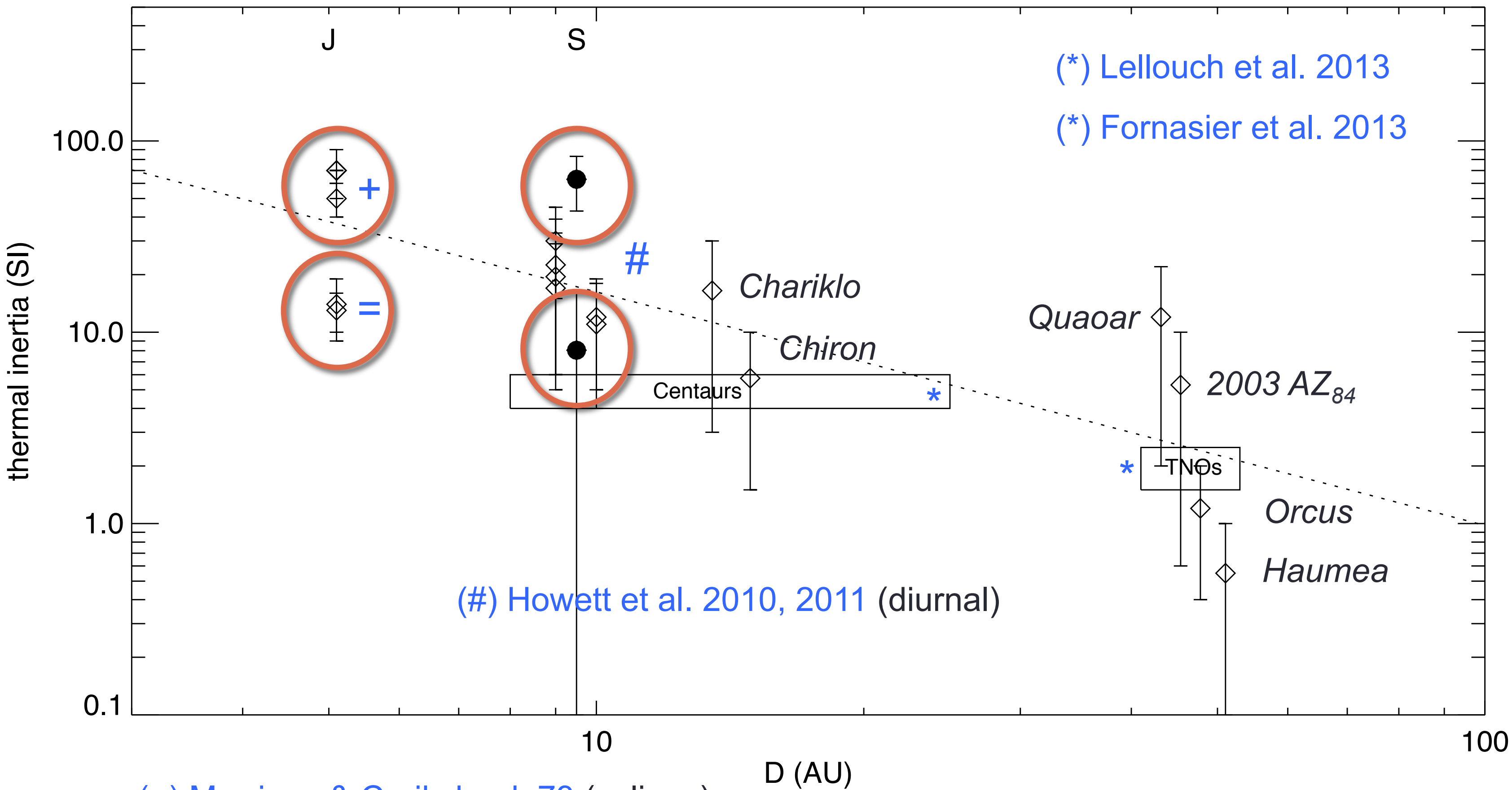


Chiron ringed-comet-asteroid
∅=206 km

Why does Γ depend on heliocentric distance D_{UA}?

(+) Spencer et al. 87, 99 (diurnal)



(=) Morrison & Cruikshank 73 (eclipse)

… and is so low !!

THE MODEL

Link thermal inertia to surface properties

Regolith thermal inertia

$$\Gamma = \sqrt{(1-p)\rho C K_E(p, R, \varepsilon, K_S)}$$

- C(T): specific heat capacity (J/kg/K)
- ρ volume density (kg/m^3)
- p = porosity, K_E= regolith thermal conductivity (W/m/K)
- Bulk water ice: Γ=2000 (SI) crystalline, Γ~300 (SI) amorphous

Heat capacity of water ice

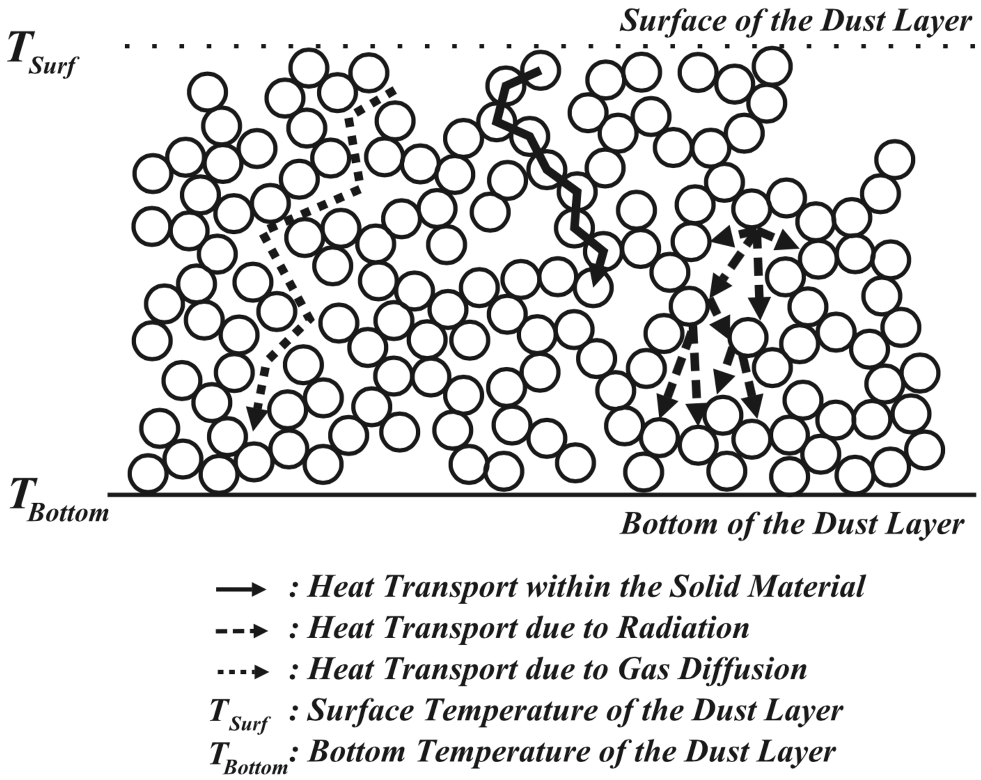
Klinger (1981) for T > 100K: $C(T) = 7.49\ 10^{-3}T + 0.09$

Shulman (2004) includes data from:
Giauque and Stout (1936) @ T > 16K
Flubacher et al. (1960) @ 2 < T < 27K
For crystalline ice to provide :

$$C_{\mathrm{p}} = 7.73 \times 10^{-3} T \left(1 - \mathrm{e}^{-1.263\times10^{-3}T^2}\right) \times \left(1 + \mathrm{e}^{-3\sqrt{T}} \times 8.47 \times 10^{-3} T^6 + 2.0825 \times 10^{-7} T^4 \mathrm{e}^{-4.97\times10^{-2}T}\right).$$

Thermal conductivity K_E

- Scaling of thermal inertia
- Porous medium **p**
- Solid conductivity of grain $\mathbf{K_S}$
- Conduction & radiation on parallel routes
- Atmosphereless
- Emissivity ε
- Grain size **R**

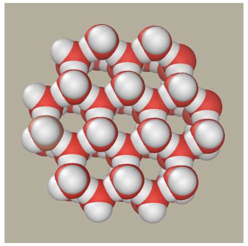


$$K_E(p, R, \varepsilon, K_S) = K_C + K_R$$

Effective thermal conductivity

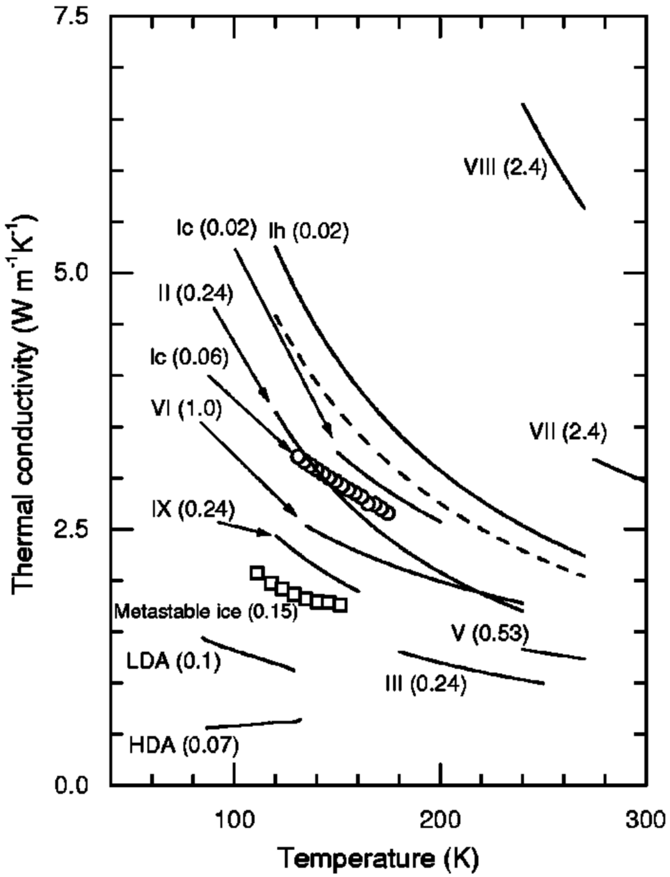
K_S(ice phase)

Crystalline



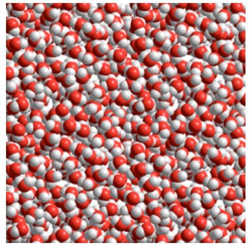
- Hexagonal Ih
- K_S=567/T W/m/K

(Klinger 1980)



(Andersson et al. 2004)

Amorphous



- HDA-LDA

~ $K_S=C(T)\nu\lambda\rho$

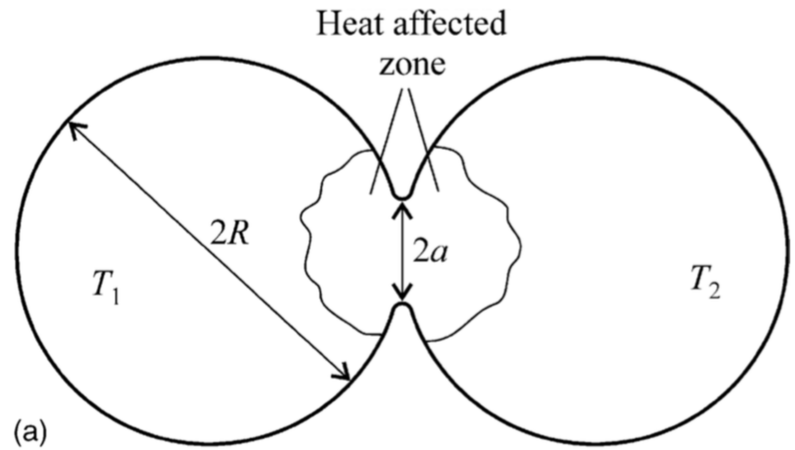
- ν=2500m/s
- λ =mean free path

K_C: Conduction through contacts

Tight contacts

JKR Theory (1971)

- Elastic spheres
- Load F
- adhesion forces at contact



From Gusarov et al. 2003

$$a^3_{\mathrm{H,JKR}} = \frac{3R^*}{4E^*}\left(F + 3\pi\gamma R^* + \sqrt{6\pi\gamma R^* F + (3\pi\gamma R^*)^2}\right).$$

$h = a_{H,JKR}/R$ & $K_C = h\,K_S$

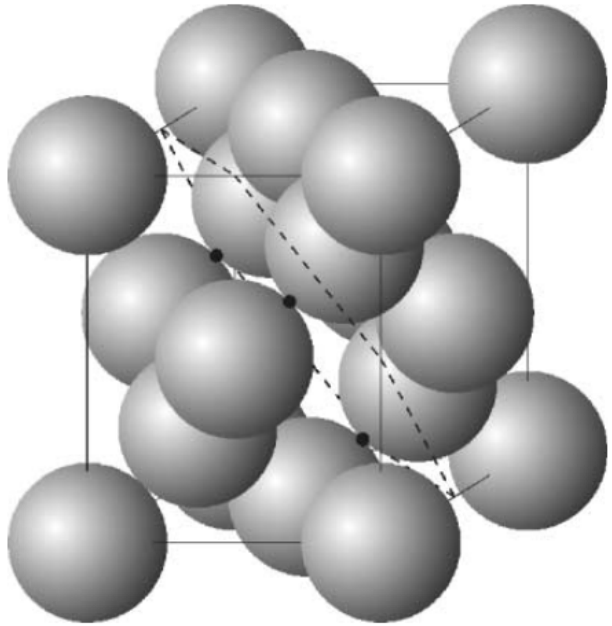
Effect of regolith arrangement

$$K_C = h\, K_S\, \Phi(p)$$

$$\Phi(p) = (1-p)\, n_c(p)/\pi$$

Gusarov et al. 2003

- Modelling sintering of powders
- $n_c(p)$=number of contacts/ grain=f(arrangement)
- Argento and Bouvard 1996, Jagota and Hui 1990, Carlsaw and Jaeger 1959

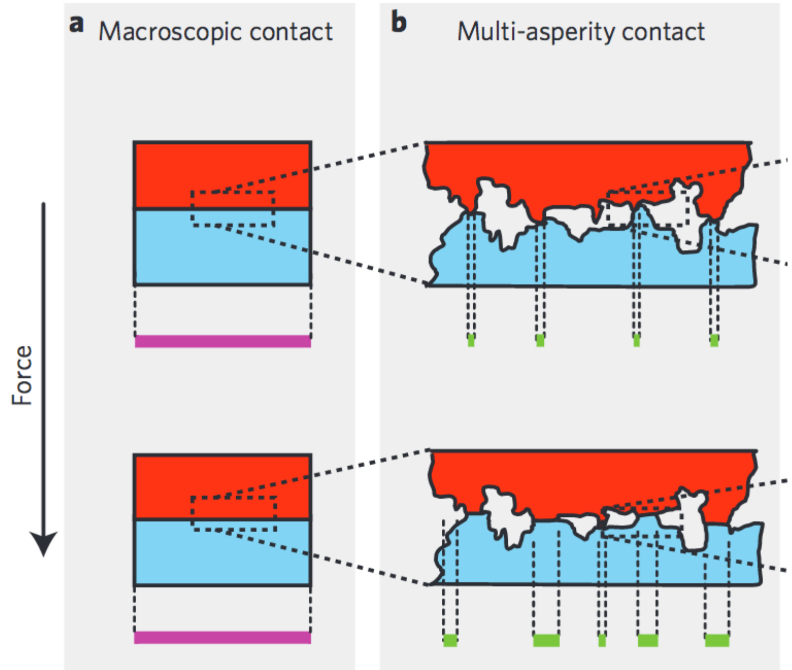


Tight contacts = G+JKR model

Loose contacts: Watson theory (1963)

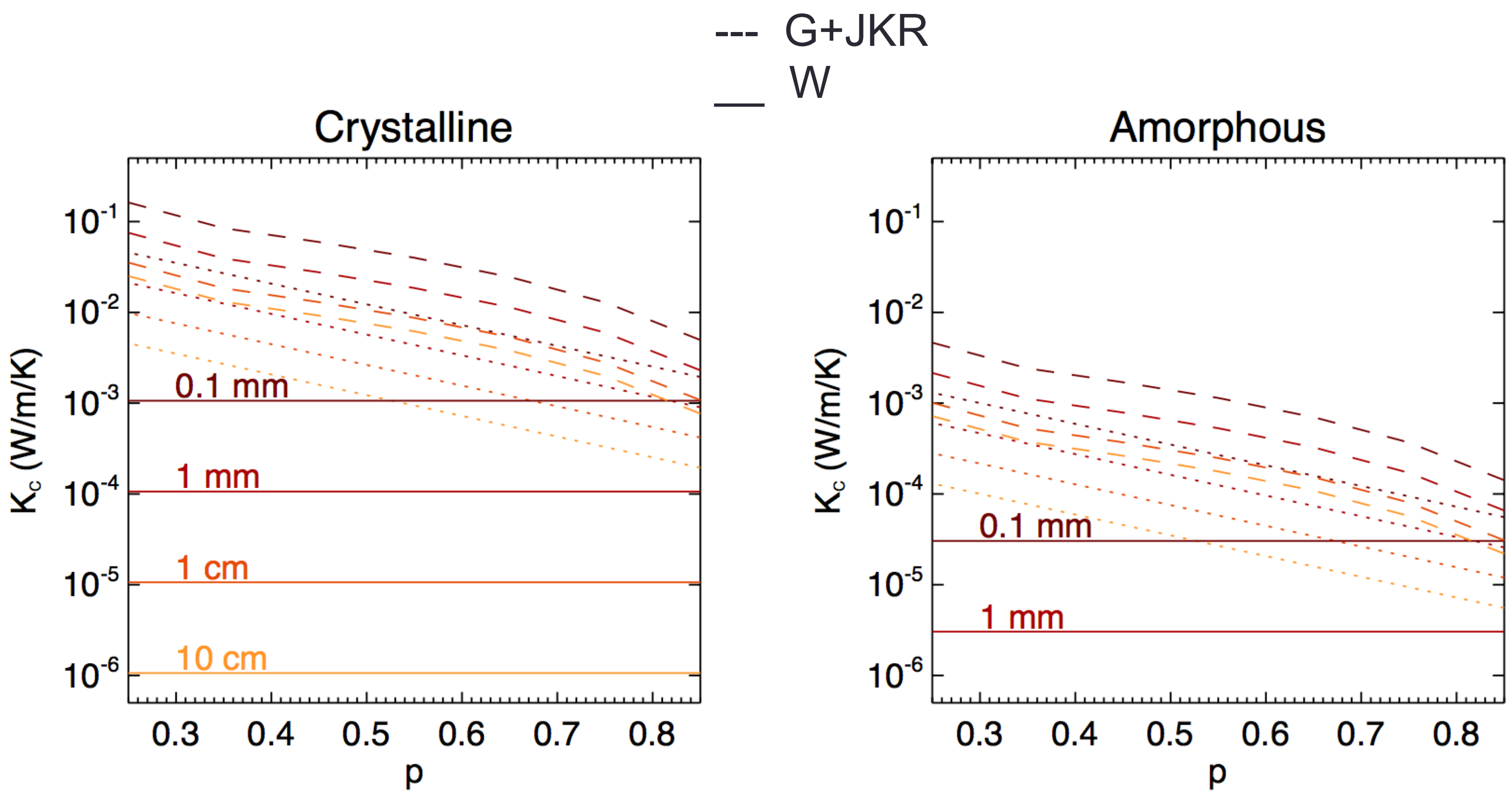
- Microscopic roughness yields highly resistive contacts
- Experimental, silicate powders
- Independent of porosity

$$K_C=1.5\ 10^{-8}\ K_S/R$$



from Gotsman et al. 2013

K_C(p,R,phase)



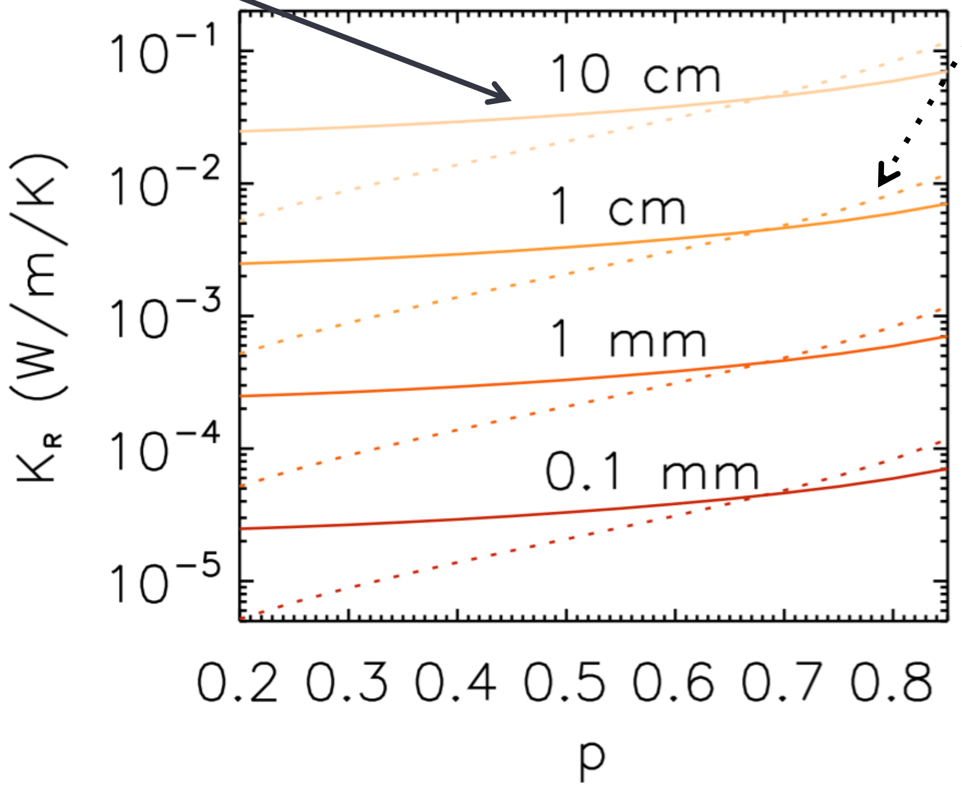
Grain size R (color)
@80 K, thermo-mechanical properties

Radiative conductivity

$$K_R = 8RF_E\sigma T^3$$

$F_E(\varepsilon, p)$
(Gundlach and Blum, 2013 from Dullien 1991, Dusty regoliths)

$F_E(\varepsilon, p, K_S)$
(Breitbach and Barthels,1980, High T packed beds)



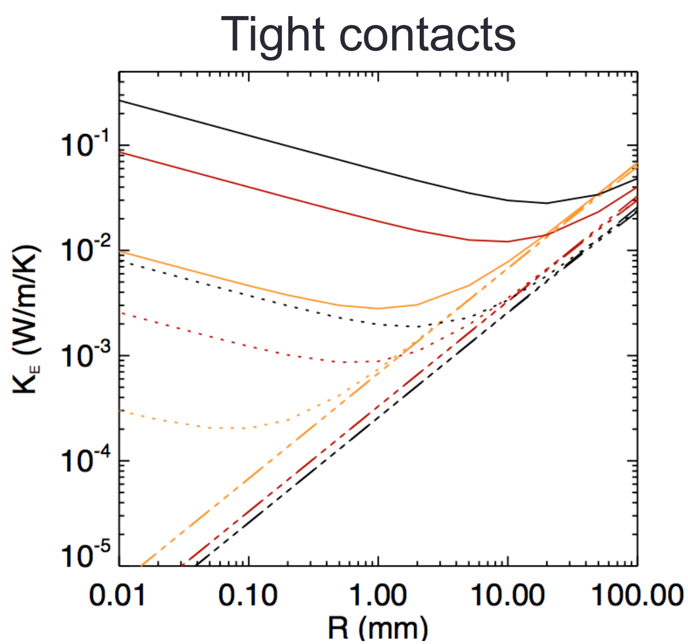
@ 80 K, ε=1

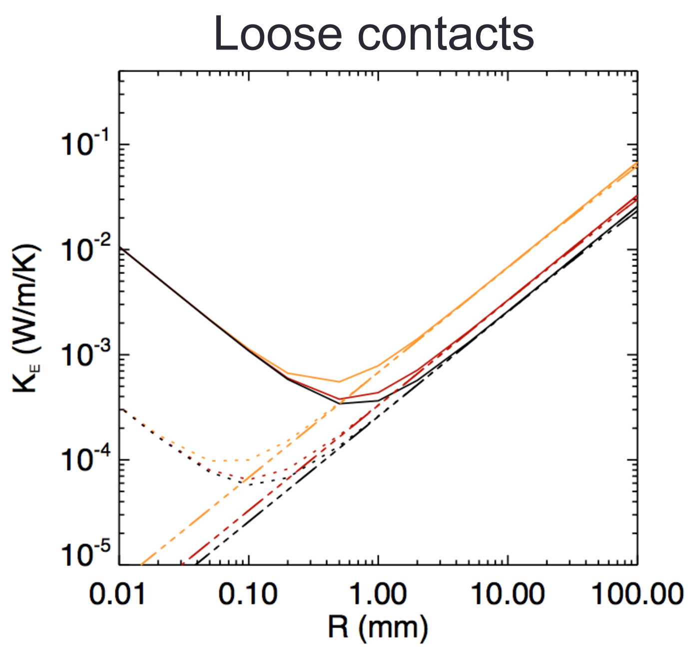
Two regimes vs size

- About mm-cm sizes
- Contact conduction for small grains
- Radiative conduction for larger ones
- Transition size smaller with amorphous

⇒Very easy to reproduce thermal conductivities as low as 10^{-2}-10^{-3} W/m/K

⇒ easier with amorphous ice

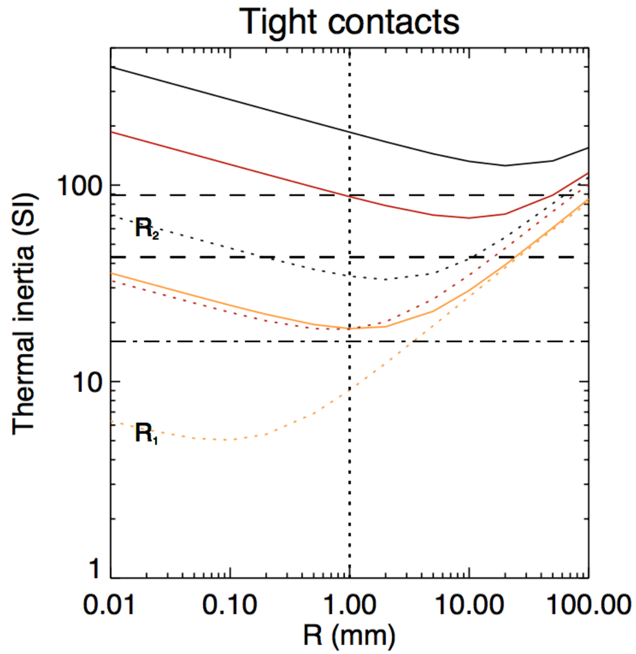


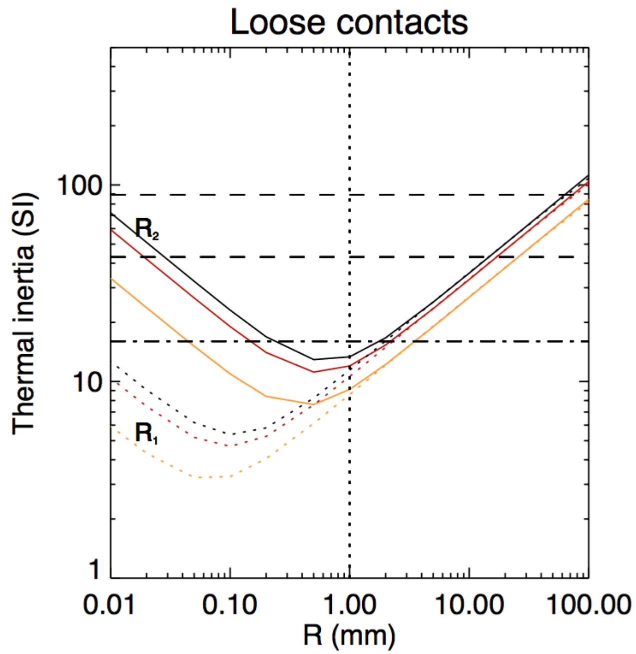


Two regimes vs size

Same for thermal Inertia
More dependent on porosity

$$\Gamma = \sqrt{(1-p)\rho C K_E(p, R, \varepsilon, K_S)}$$

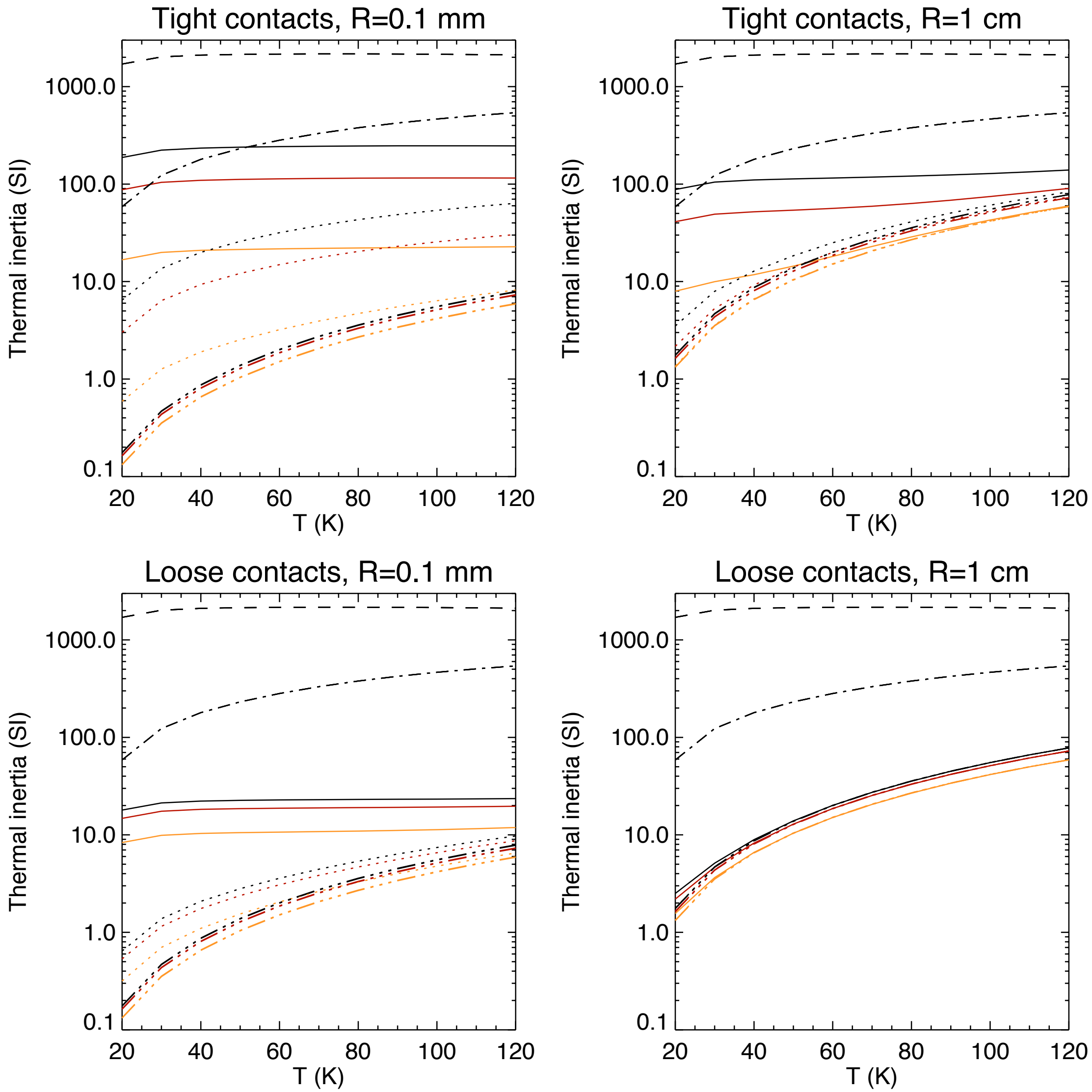




Temperature dependence

- Reduced for crystalline ice but for large grains & loose contacts

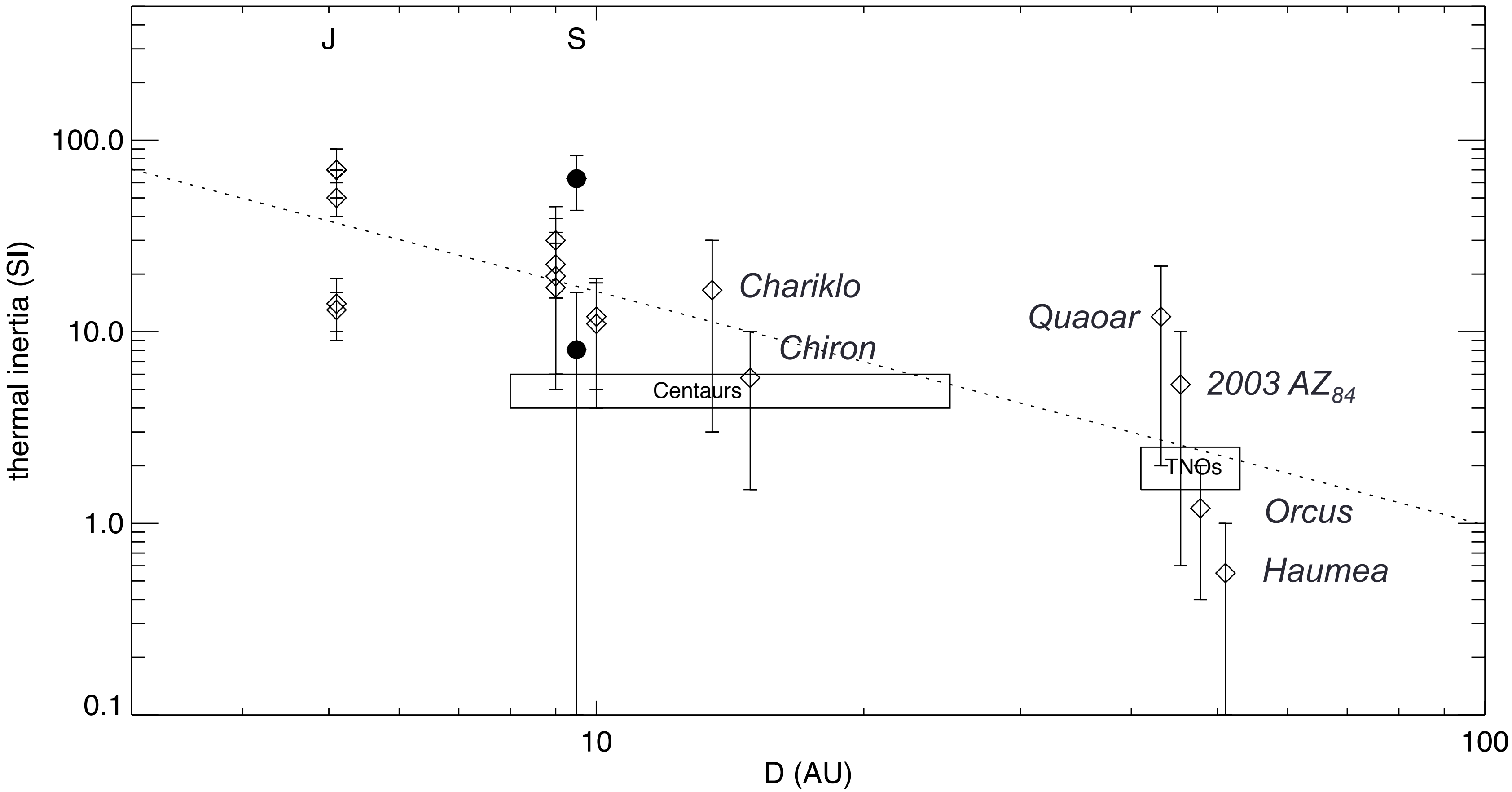
- Systematic for amorphous ice which
  - $K_S \propto C(T)$
  - low K_S limits conduction by contact

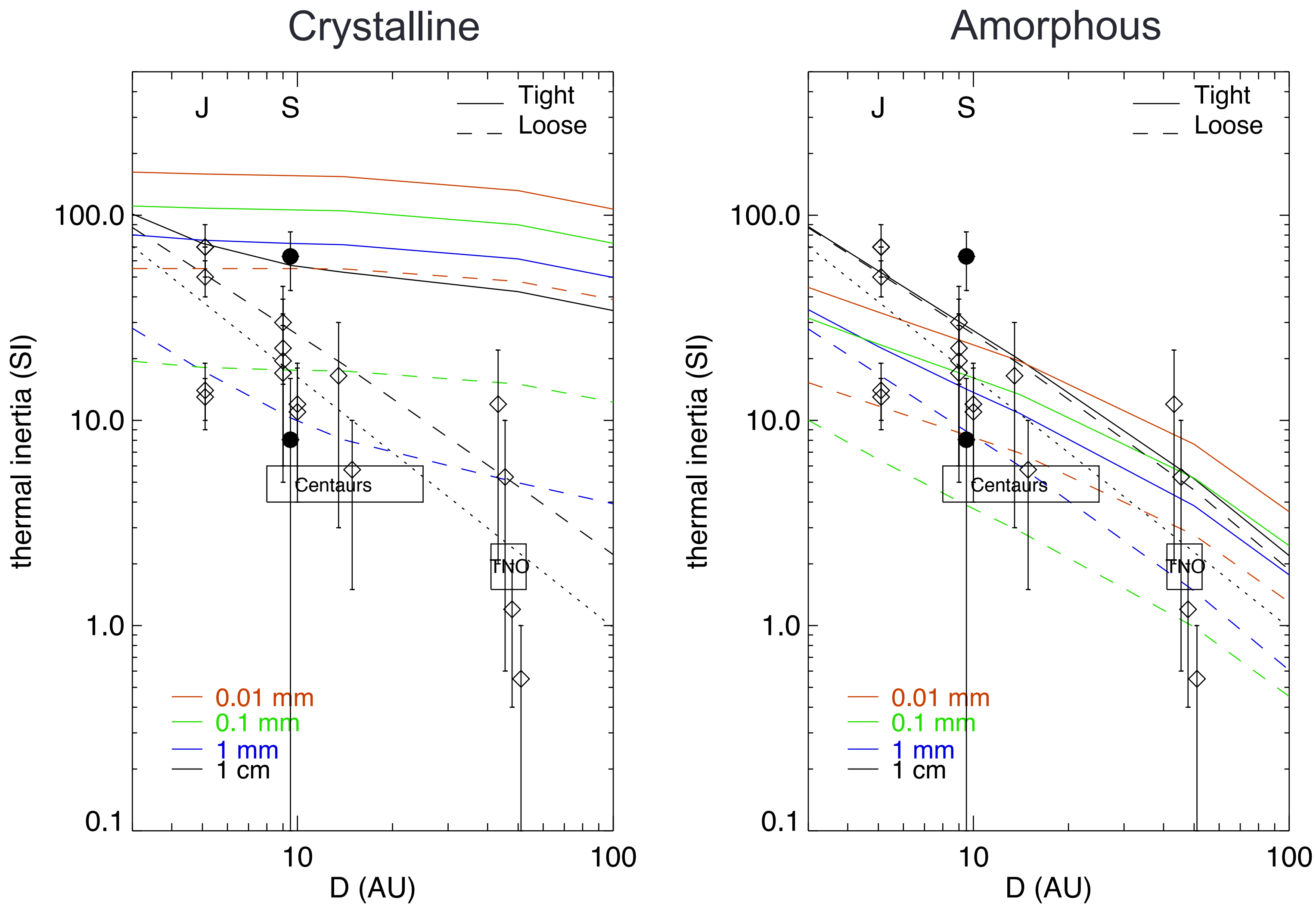


THE RESULTS

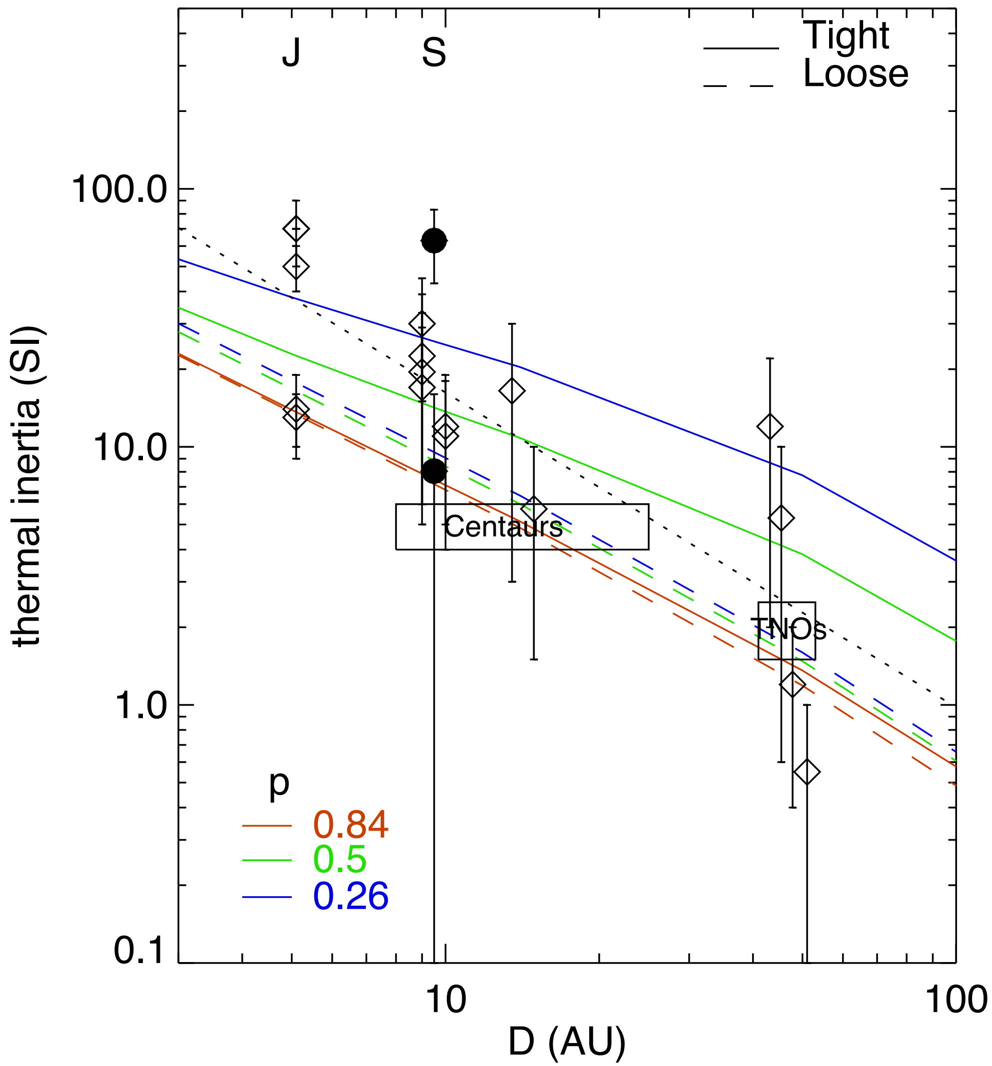
The model and the observations

Origin of heliocentric dependence

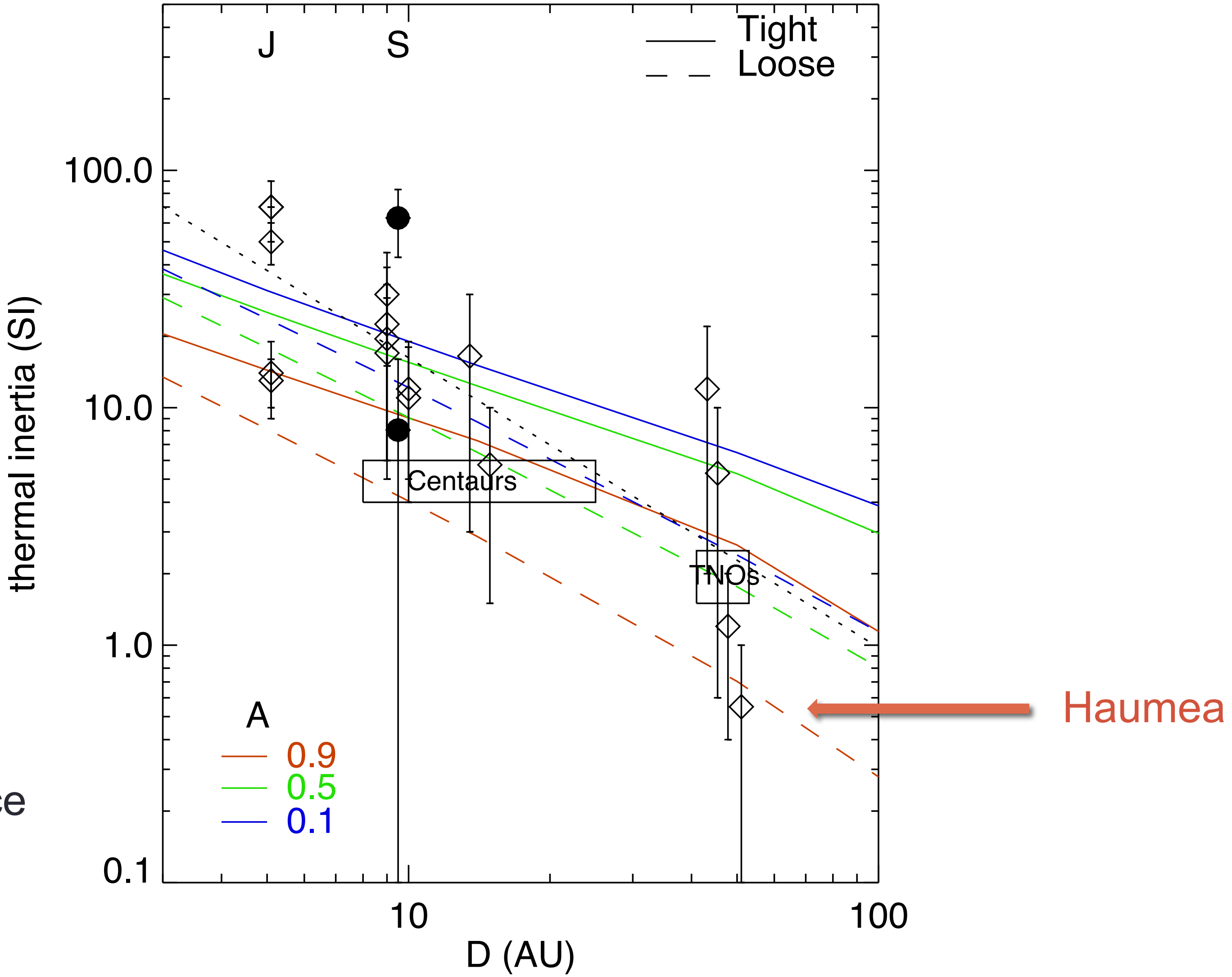



Crystalline
Amorphous
J
S
Tight
Loose
100.0
10.0
1.0
0.1
thermal inertia (SI)
Centaurs
TNO
0.01 mm
0.1 mm
1 mm
1 cm
10
100
D (AU)

Effect of porosity

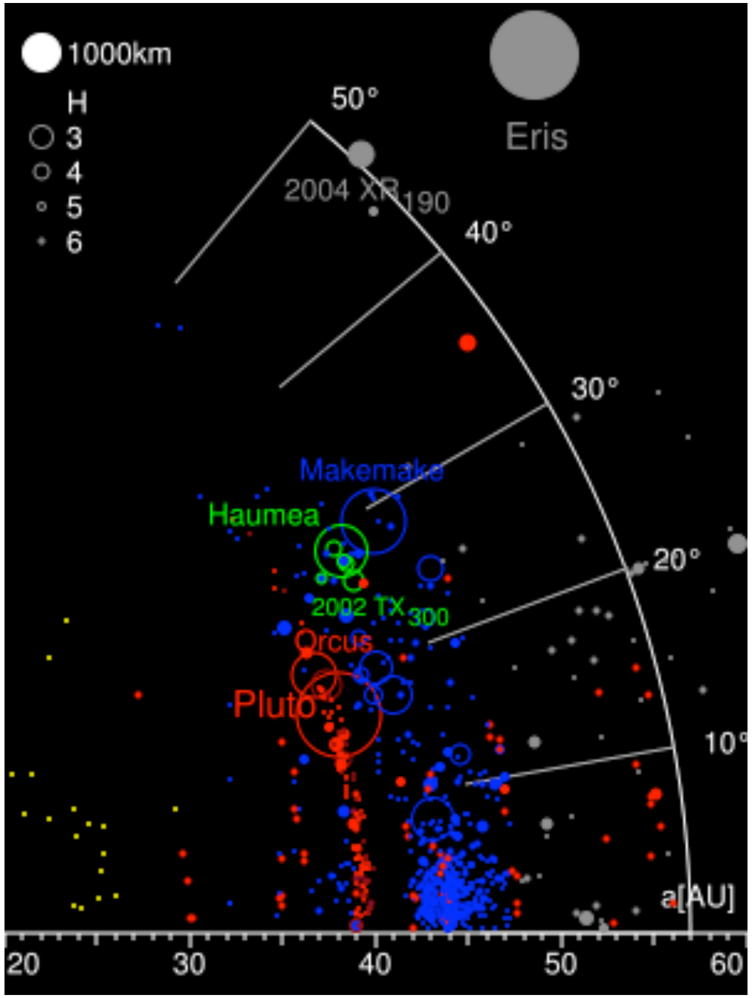


Effect of albedo



Amorphous ice
p=0.5, ε=1

Haumea & al



- 1250 ±100 km
- 41.6 - 43.6 AU – group with same compositional and orbital characteristics.
- Water ice

  Homogeneously covered
- 2000-3000 kg/m^3

A=0.95

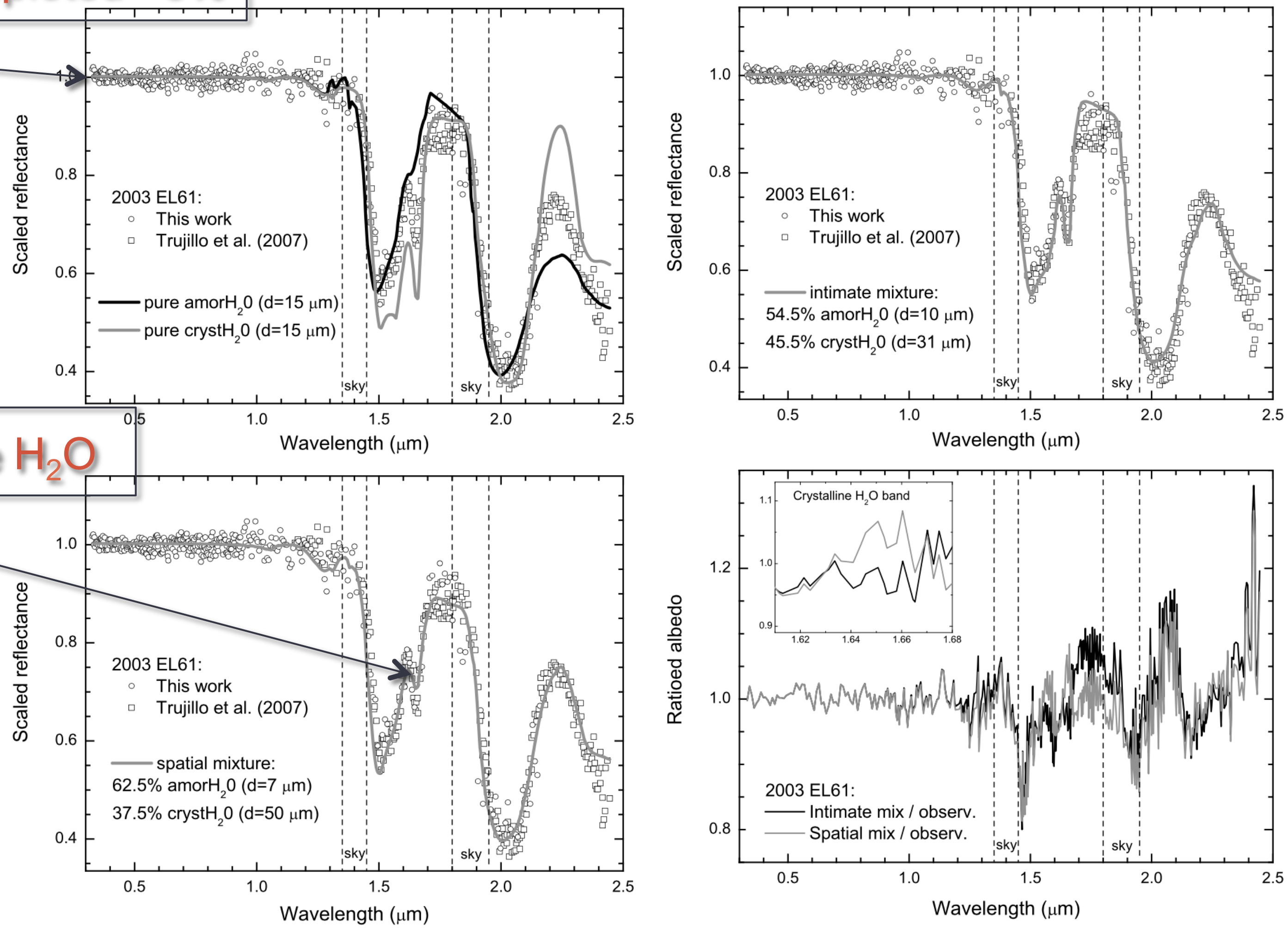
Amorphous ice at cm depths

Haumea, a dwarf planet

Pinilla-Alonso et al. 2009

Carbon-depleted <8%

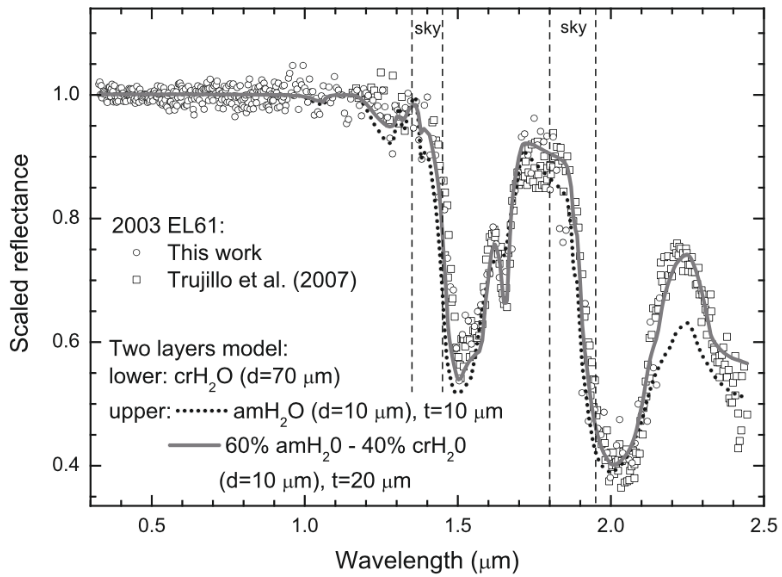
Crystalline H_2O



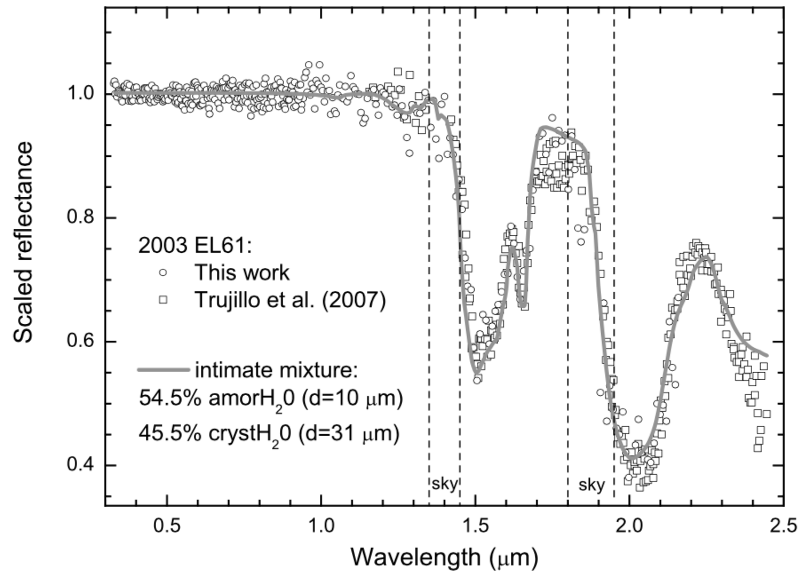
Haumea: ice mixture

Pinilla-Alonso et al. 2009

Layered model



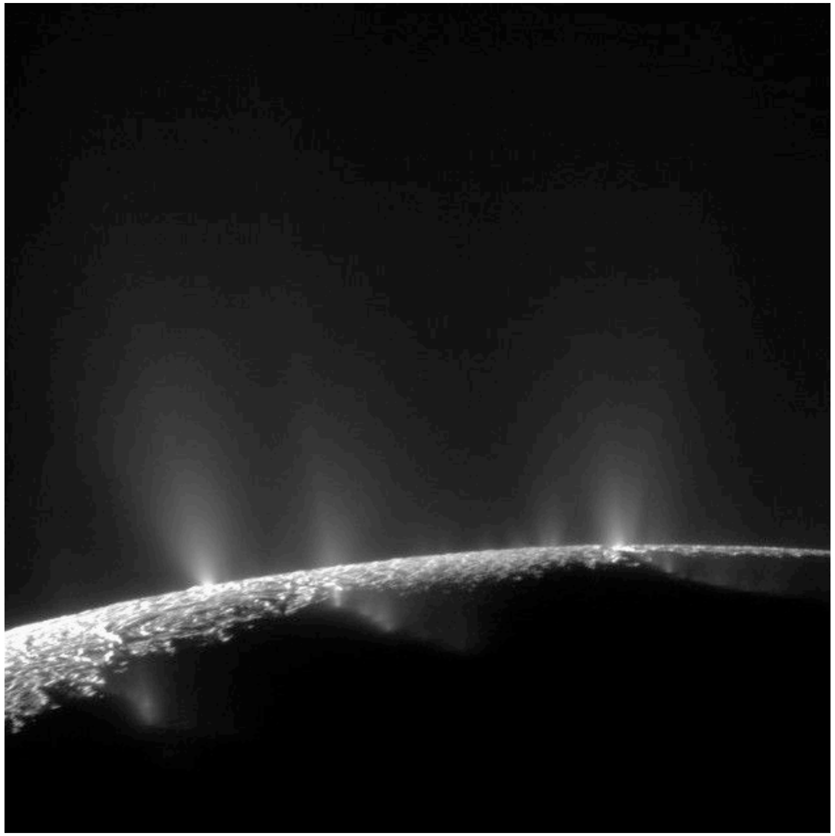
Intimate mixture



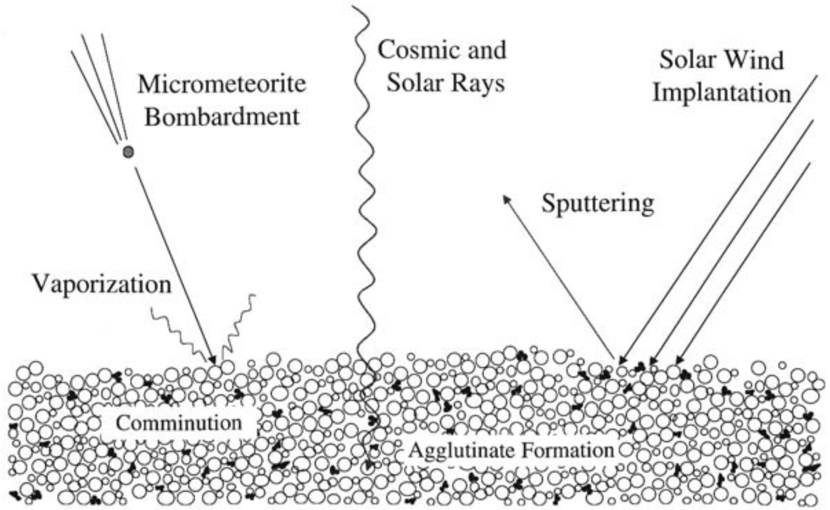
Difficult to make a difference between spatial/intimate/layered

Scenarios…

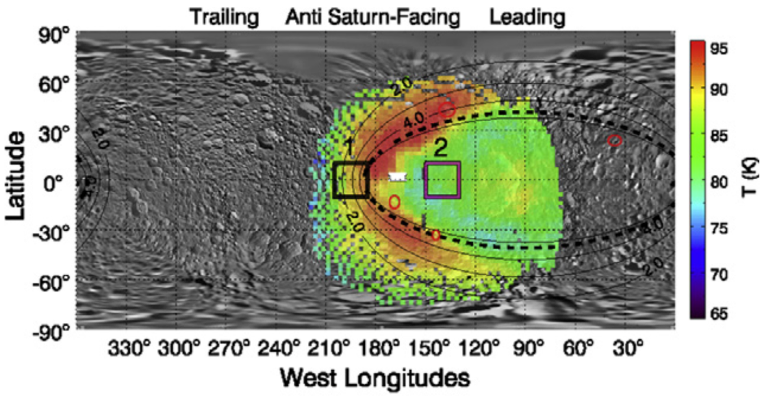
Initial amorphous
+ crystalline resurfacing
+ space weathering



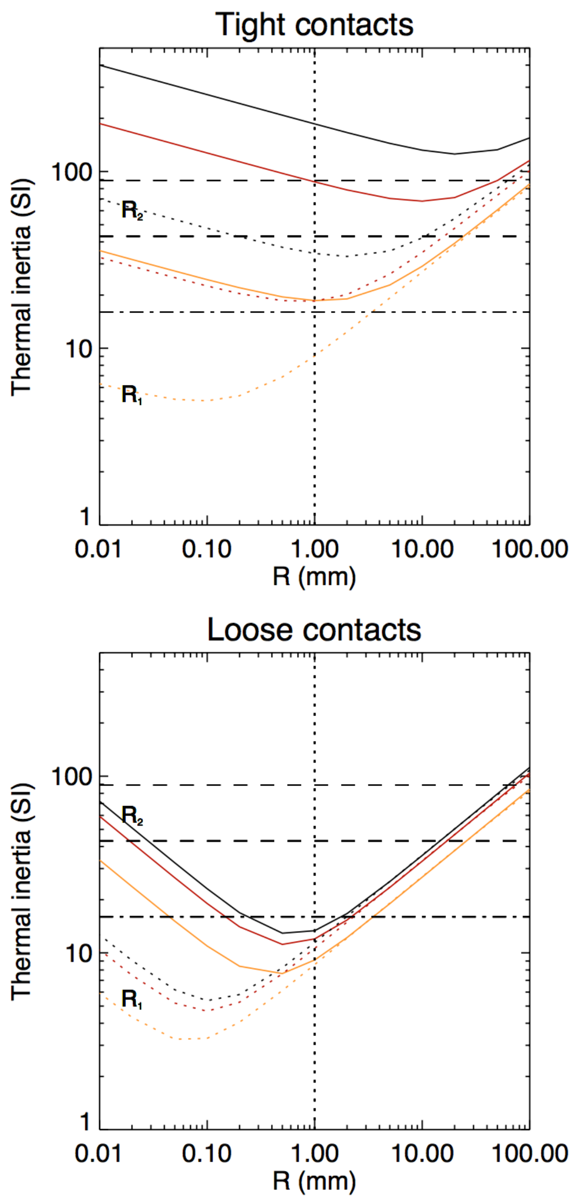
Initial crystalline or collision+ Global covering by crystlline ejecta
+ Amorphization by space weathering



Mimas case



(a) Orbit 126



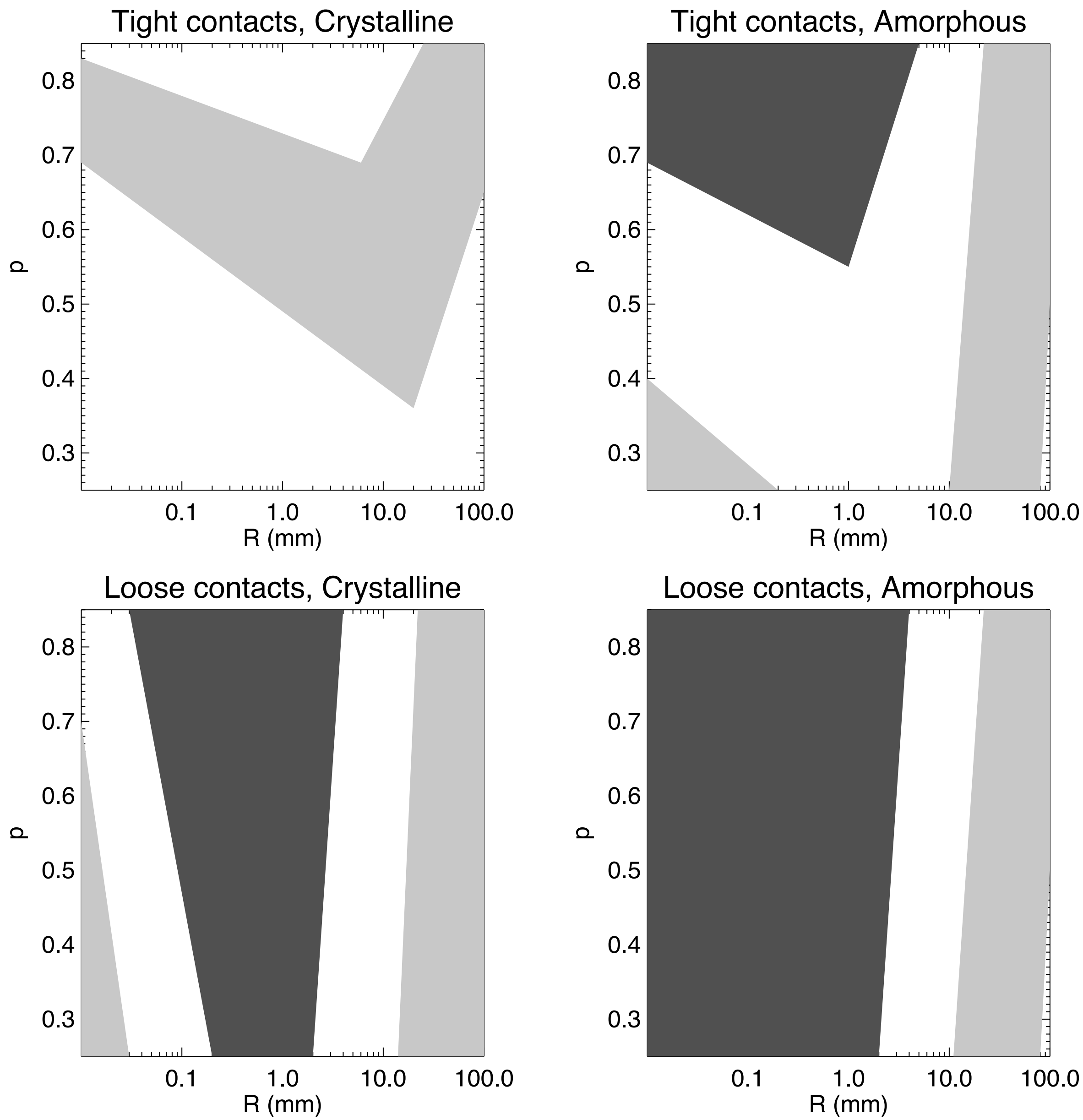
Leading

Trailing

Leading

Trailing

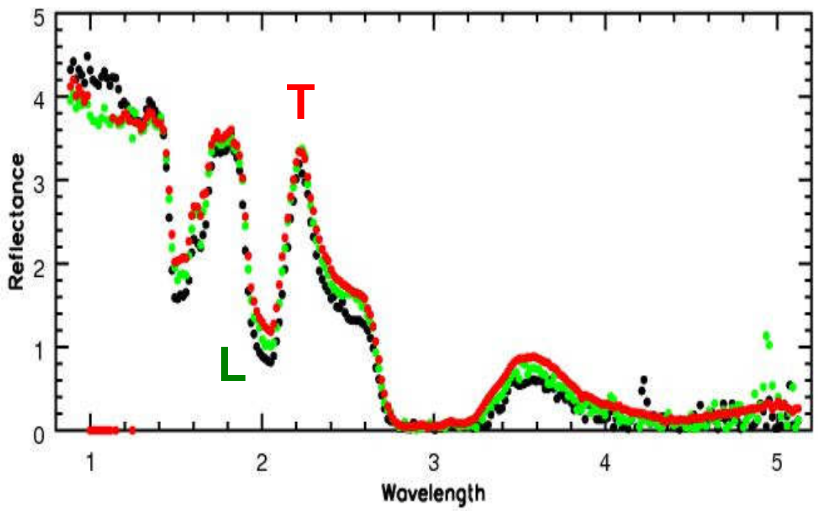
Sintering ?



Leading

Trailing

A multi-wavelength dichotomy



- Herschel

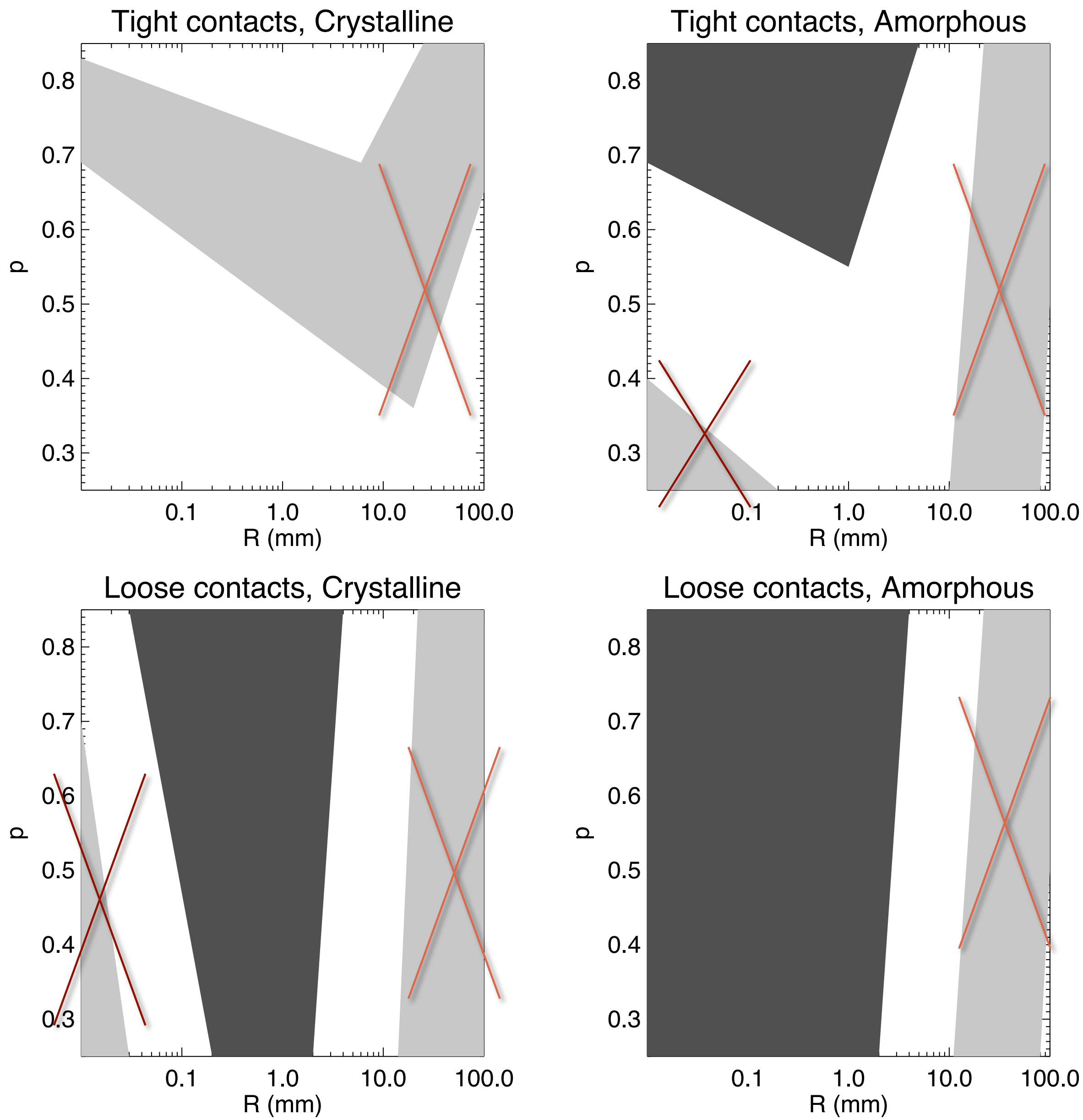
(Buratti et al. 2011)

- Crystalline ice on the very surface,
- NIR H_2O band depths deeper on Leading ⇒ larger grains size (Clark et al. 1984, Emery et al. 2005, Filacchione et al. 2007, 2012)
- [20-100]μm leading / [10-50] μm trailing (Buratti et al. 2011)
- But (L+T) grains size in range [30 μm-0,75cm] (Filacchione et al. 2012)

Sintering ?

Leading

Trailing



CONCLUSIONS

Conclusions & Future Work

- Icy surfaces beyond Jupiter
  - Amorphous ice at mm-cm depths may explain:
    - dependency with heliocentric distance
    - Thermal inertia as low as a few beyond Saturn orbit
- Reconsidering models:
  - Loose contacts may favor radiative conductivity
  - Radiative conductivity may be important despite low temperature
- The Mimas case:
  - Sintering on leading face with crystalline ice
  - Trailing compatible with crystalline E ring grains porous deposit
  - Analyse CIRS data with temperature-dependent model
  - Analyse diurnal cycle at high resolution over large zones
  - Relate to crystallinity on Mimas surface