The origin of the Martian moons revisited

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Session 5 – Observational constraints

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Motivation

- Origin of the Martian moons:

An open issue !

- Previous studies did not pay attention to the interior.

- What can the bulk density of Phobos and Deimos tell us about that issue?

Outline

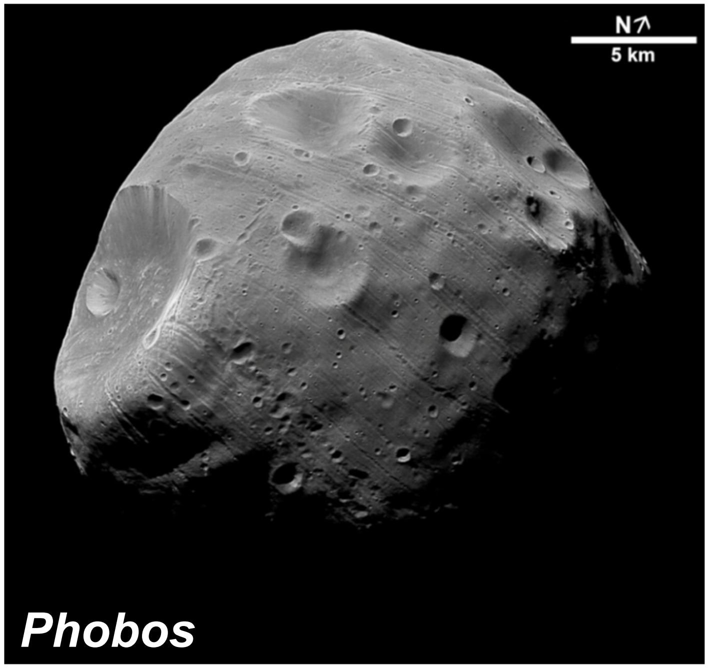
- The scenarios of origin: The pros and the cons
- Recent Mars Express observations of Phobos (surface and interior)
- The internal structure and the origin of the Martian moons

‘Puzzling’ Phobos (and Deimos)

Contradictory clues about the origin !

Asteroid formed away from Mars and then captured by Mars

<u>Main argument:</u>
made of material formed well beyond Mars’ orbit (Carbonaceous chondrite composition)

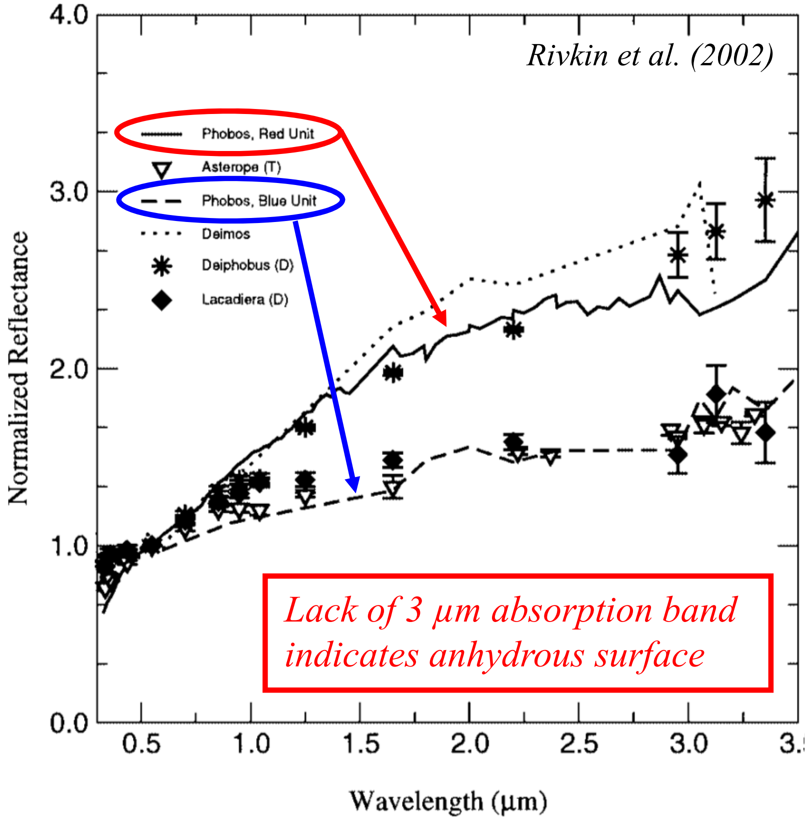


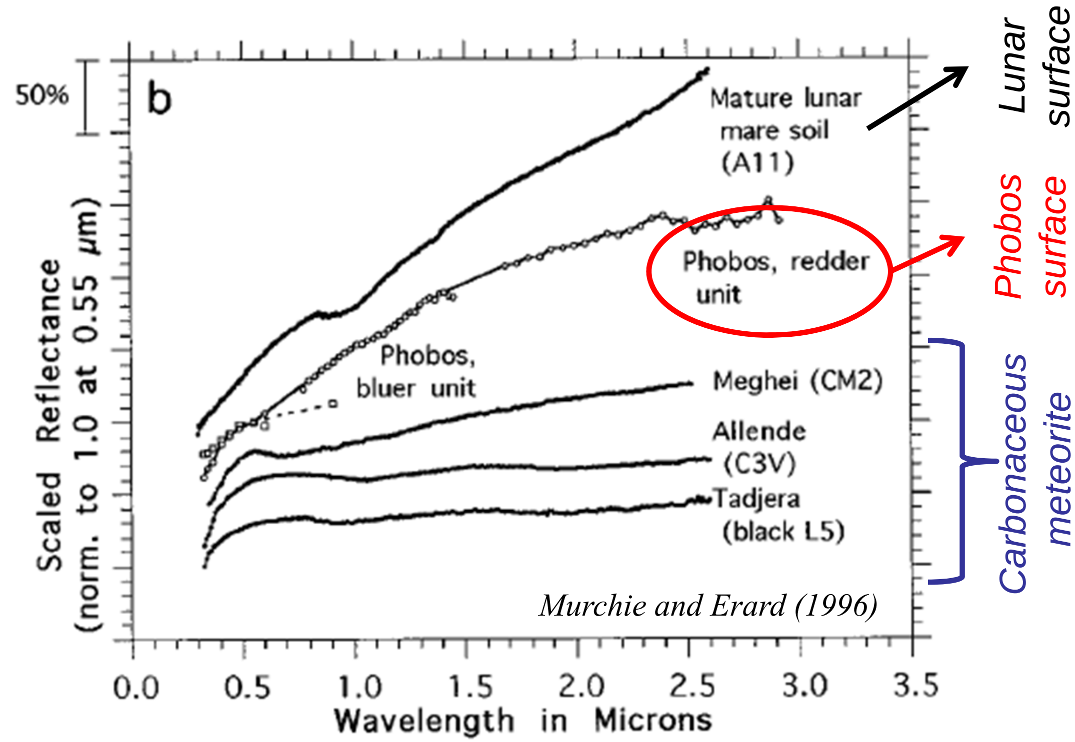
MEX/HRSC image

Alternative scenario
In Situ formation

<u>Main argument:</u>
Current moon orbits cannot be accounted by capture.

Martian moon surface composition from ViS/NIR reflectance spectra (~ 0.5–5 μm)



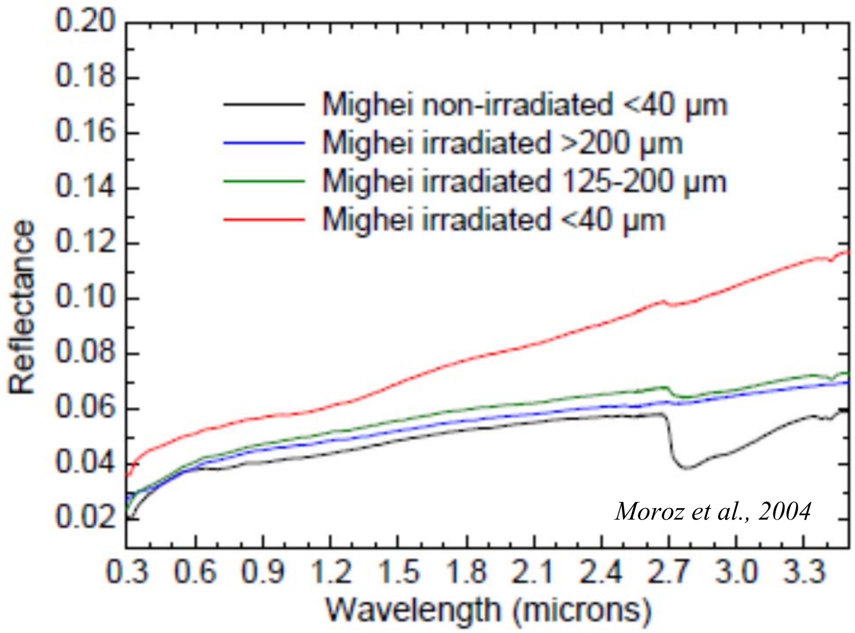


✓ The capture scenario is weakened by ambiguities on compositional interpretation of spectra:

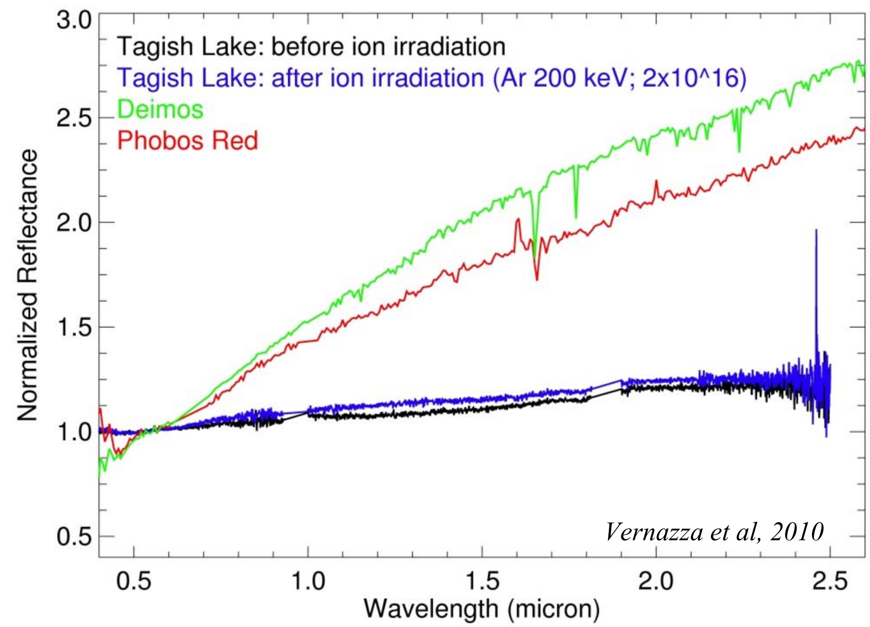
Misfit with meteorite spectra: Inconsistent with carbonaceous composition or space weathering effect?

Simulation of space weathering effect on carbonaceous meteorite

C-class 'Mighei' hydrated chondrite:
parent-body -> C-type asteroid



D-class 'Tagish Lake' meteorite:
parent-body -> D-type asteroid

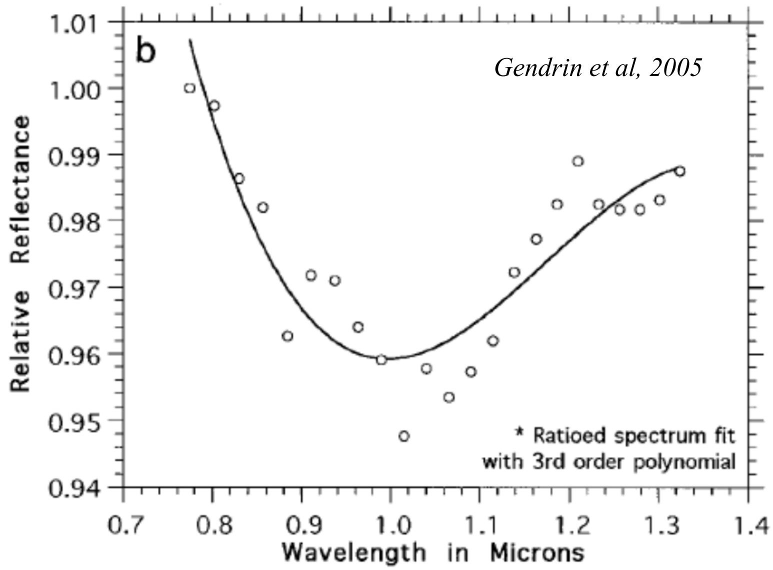


- Space weathering effect studied from Lunar samples ('Fe Nano-phase' process): It can remove the hydrated mineral signature at 3 µm, not seen on Phobos and Deimos spectra, but it cannot reproduce the reddened slope of these spectra.

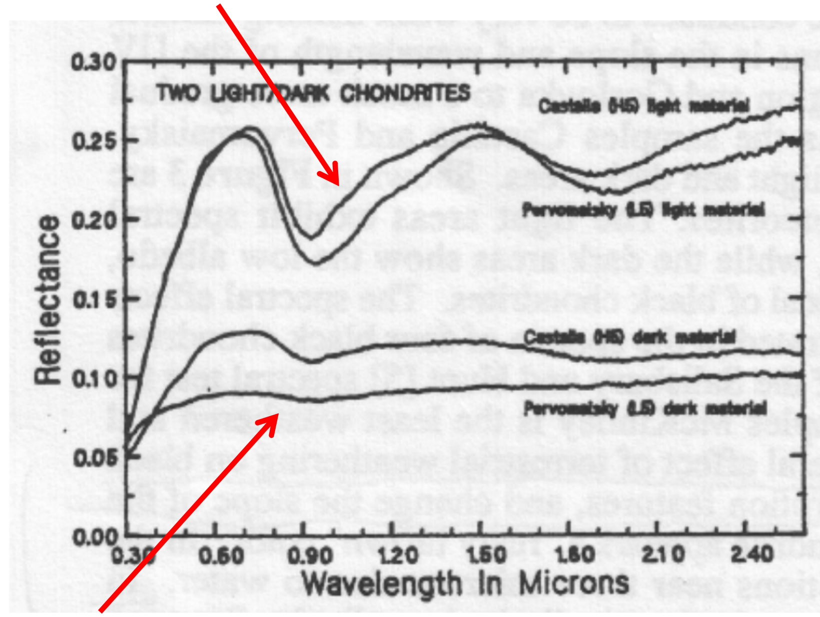
- Carbonaceous material not be representative of Martian moon material
  or
  Simulations might not reproduce the space weathering in Mars' environment

Which material could compose Phobos and Deimos?

Very tiny absorption band ~1 µm



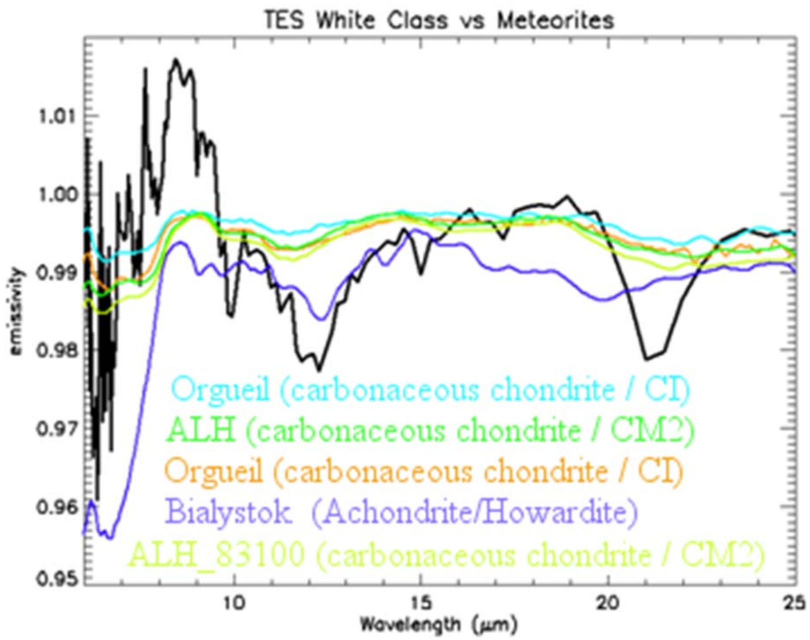
Ordinary chondrite



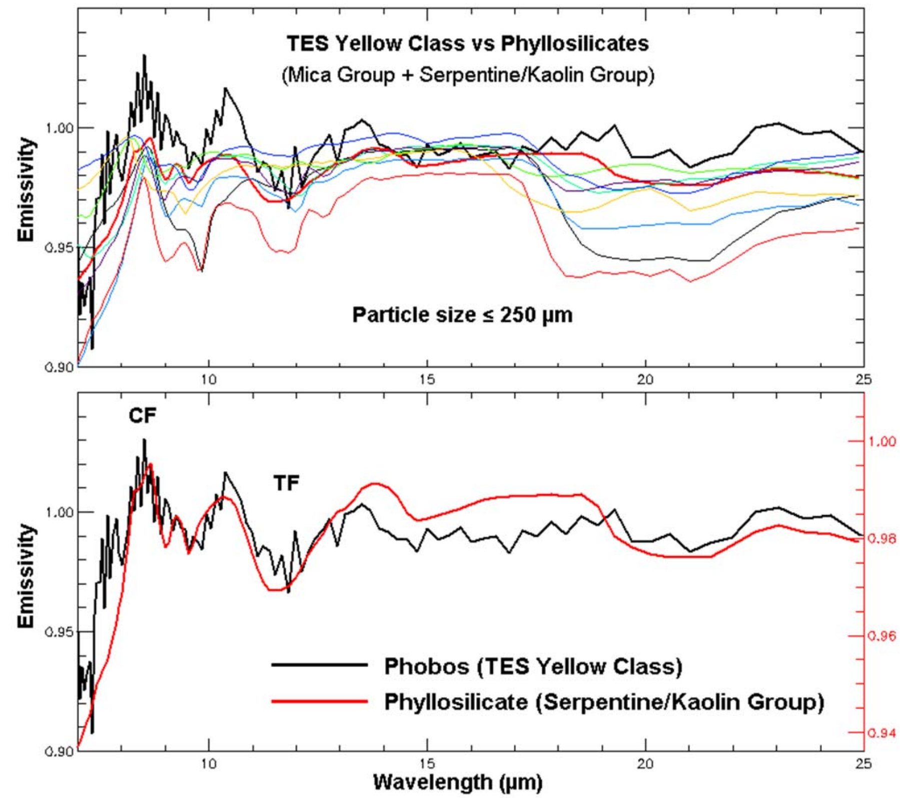
Black chondrite

- Very tiny absorption bands of silicate minerals may have been identified on Phobos' spectra.
- Can Phobos' surface be composed of highly space weathered silicate material (Black chondrite material) ?

Which material analog for Phobos? (1)

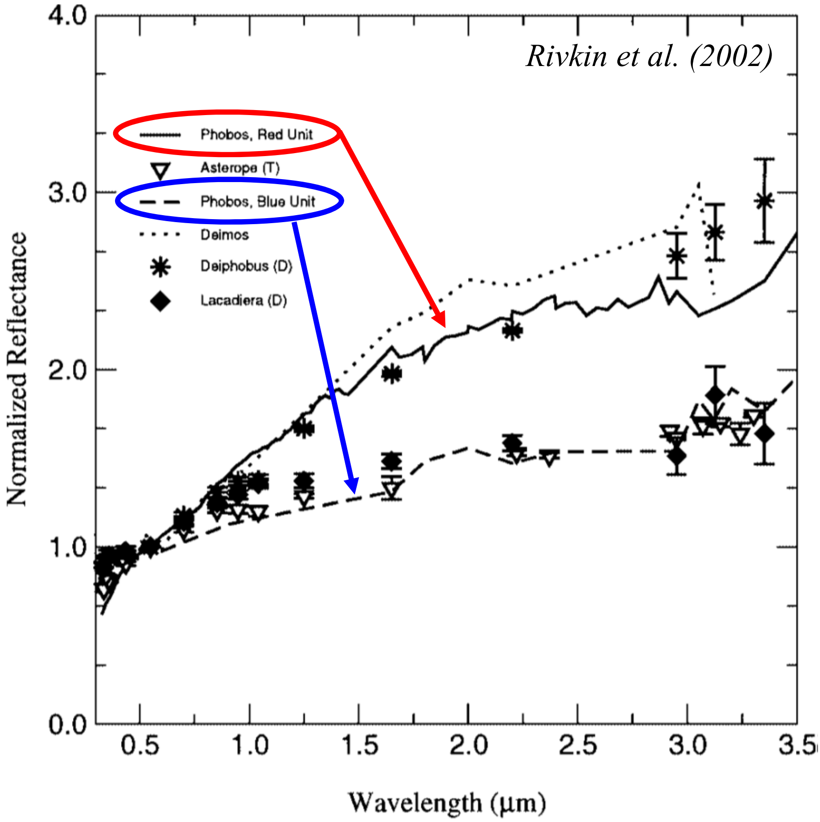


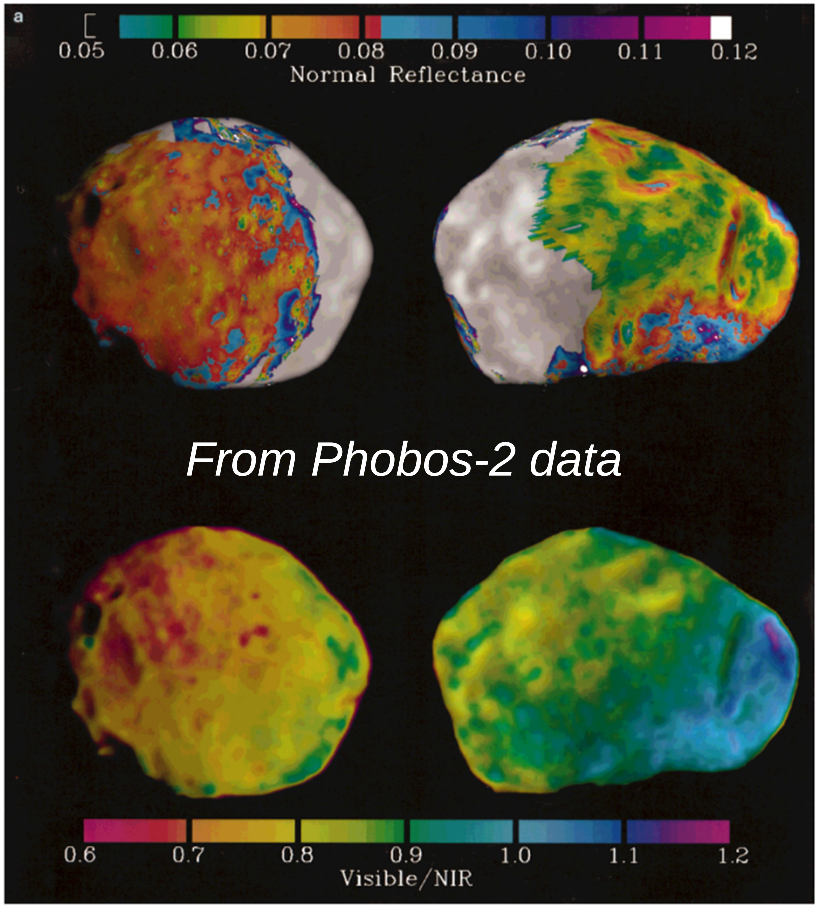
Thermal Infra-Red (TIR) spectra of Phobos' surface (Giuranna et al., 2010)



- Poor match of TIR spectra of Phobos with those of carbonaceous material.
- Good match of TIR spectra of Phobos with those of silicate material
- This emphasizes on the fact that it may not be needed to bring material condensed beyond Jupiter 's orbit at Mars' orbit to account for the Martian moons origin.

Color variations at Phobos' surface: What does it mean?

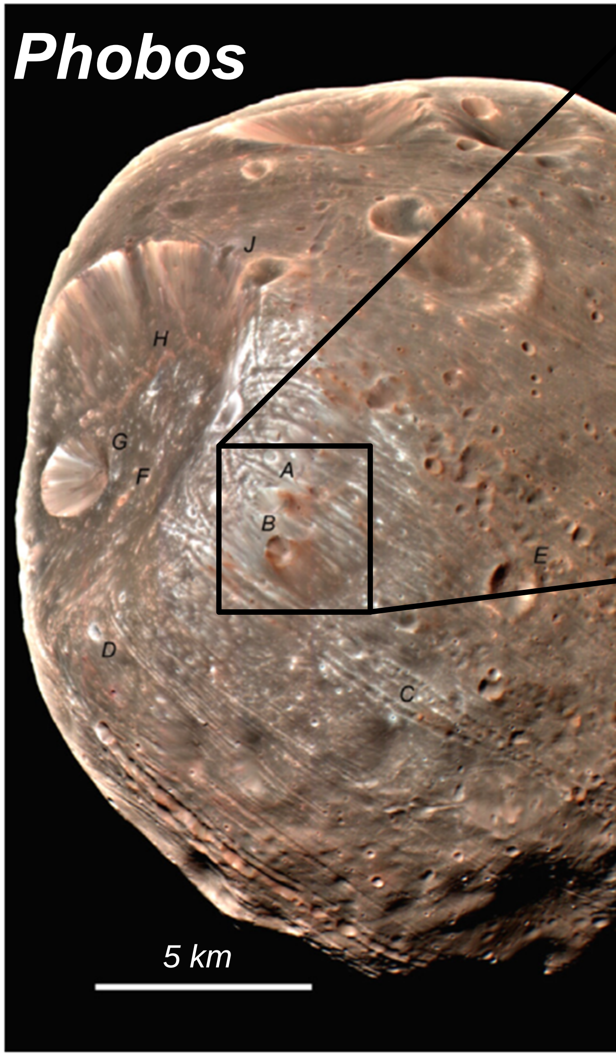


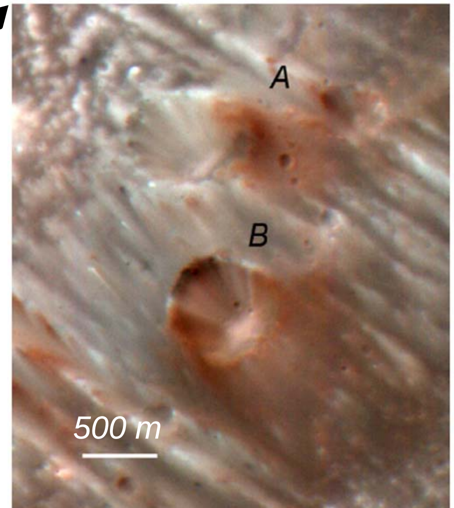


- Phobos' surface shows two spatio-spectral units: **Red** & **Blue** units.

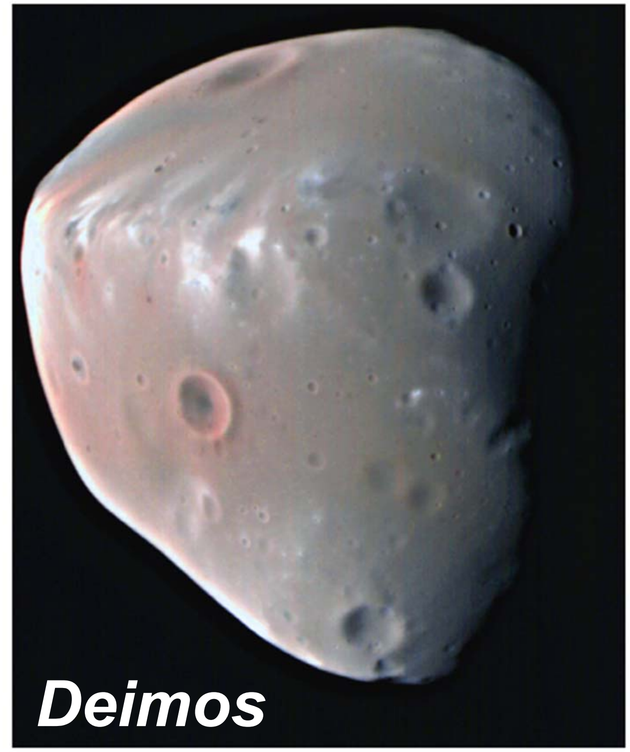
  Blue unit encompasses Stickney crater → deep material exposed at the surface?
  Different degree of space weathering?

Color variations at the moon surfaces (MRO)





Thomas et al. (2010)



✓ *More complex than previously thought !*

➤ **Ambiguity on composition:**

Carbonaceous material altered by yet unidentified process?
Highly space weathered silicate material? Material not in the meteoritic collection?
Thin layer of alien material from Mars or from interplanetary medium?

Is capture possible ?

- Asteroid capture requires tight constraint given Mars' mass and possible initial velocity of the captured asteroid (*Burns, 1992*)

- Asteroid capture has also to explain how changing the orbit after capture (ecliptic & elliptical orbit) into the current near-circular & near-equatorial orbits of both moons.

- Tidal dissipation in Mars and in the moons may provide orbital changes (*Lambeck, 1979; Mignard, 1981*).

  <u>Eccentricity changes:</u>

  For Deimos → Impossible over the age of the solar system
  For Phobos → Possible, given high dissipation rate in its interior (tidal quality factor Q ~ 10), not compatible with rocky composition (Q > 100, for rocky material).

  <u>Inclination changes</u> → for Phobos but even lower Q value (~2) more relevant to icy material !

Is capture possible ?

- Inclination changes problem may be avoided, assuming

  → either Mars' equatorial plane was in the ecliptic plane at time of capture
  → or capture asteroid orbital plane was in Mars' equator, which is not impossible (although unlikely)

  For both assumptions, a rapid decrease of the semi-major axis of the asteroid orbit is required in order to maintain its orbital plane in Mars' equator plane (i.e. semi-major axis < ~13 Mars' radii).

- Orbital changes by drag effect in the primitive Martian planetary nebula (*Sasaki, 1989*).

  But the planetary nebula survival time has to be relatively short to avoid the crash of the capture asteroid onto Mars and to be compatible with the following tidal orbital evolution.

- Alternative scenario: *In-situ* formation

In situ formation

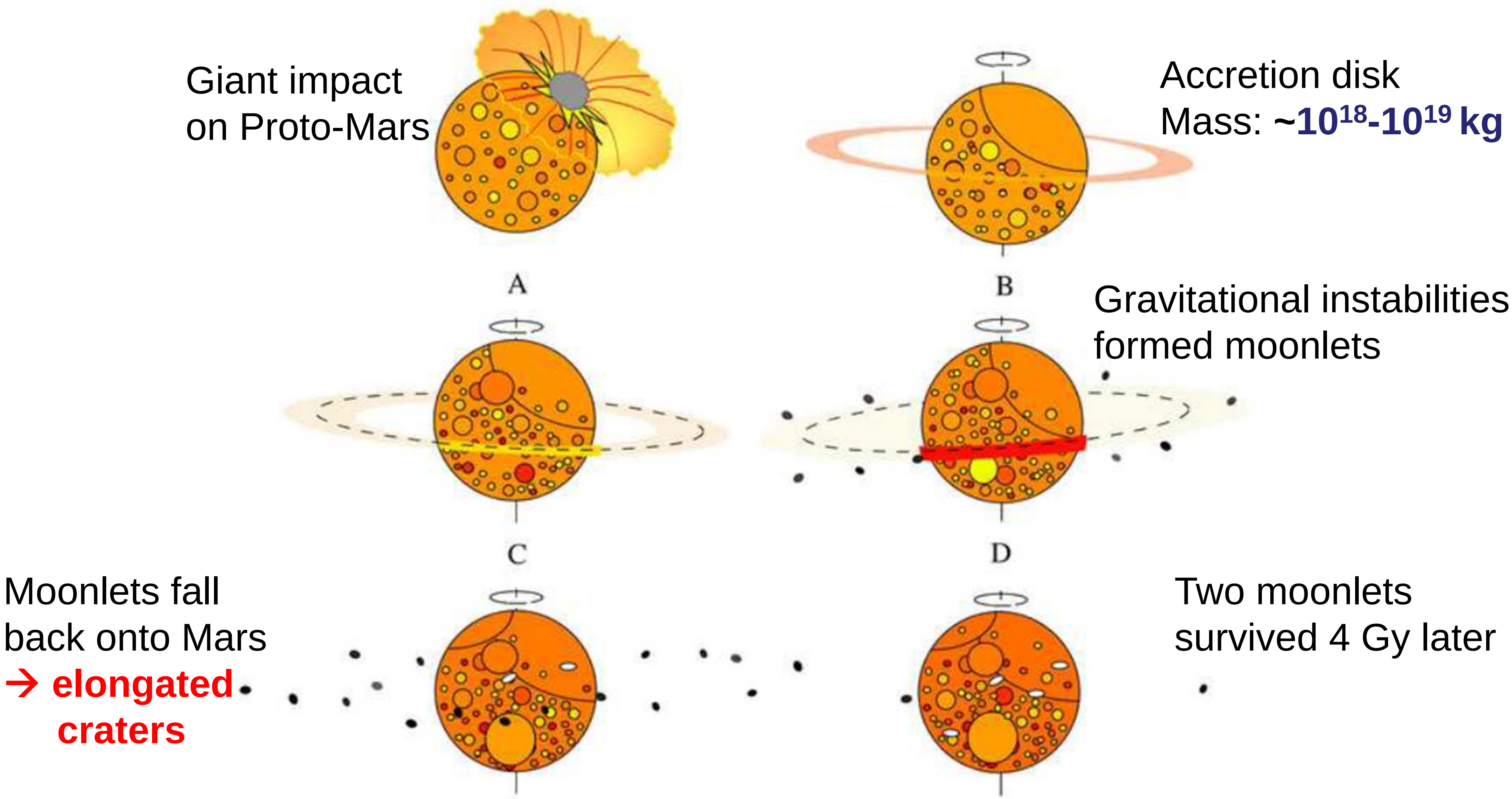
- Co-accretion with Mars (Sofranov et al., 1984)
  It may explain the current orbits.
  How to explain a carbonaceous composition for the two moons ?

- Remnants of a larger early moon captured by Mars, then destroyed by Mars' tidal forces (Singer, 2007):
  It may explain the current orbits.
  It can be 'reconciliated' with carbonaceous composition if the early moon had also a carbonaceous composition.

- Re-accretion of impact or collision ejecta/debris blasted into Mars' orbit (Craddock, 2011)
  It may explain the current orbits.
  It can be reconciliated with carbonaceous composition if the impactor body had a carbonaceous composition.

A scenario of in-situ formation of Phobos and Deimos from a Mars-circum accretion disk

Adapted from Craddock R.A., Icarus (2011)



➢ Not so easy ! → *Rosenblatt & Charnoz, this meeting*

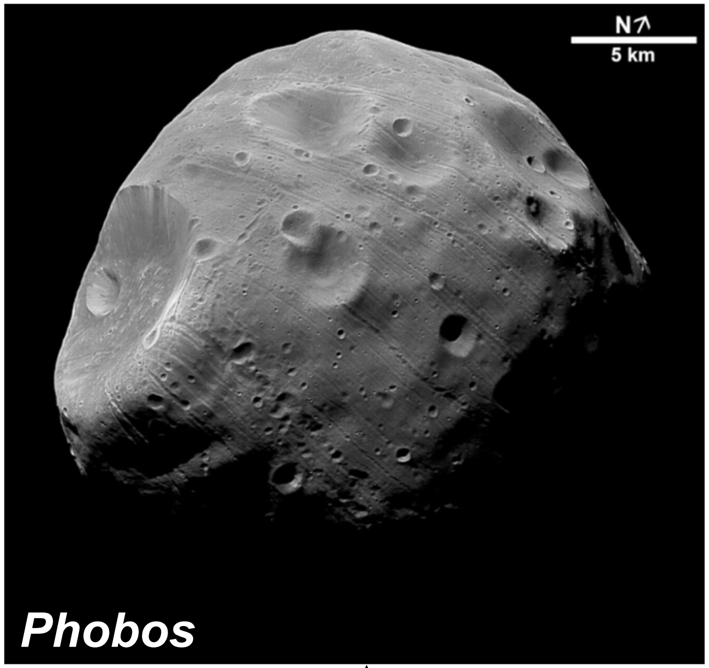
‘Puzzling’ Phobos (and Deimos)

Contradictory clues about the origin !

Capture scenario:

Main argument:
ViS/NIR spectra
→ Carbonaceous

But:
•No carbonaceous meteorite spectral analog yet found.



MEX/HRSC image

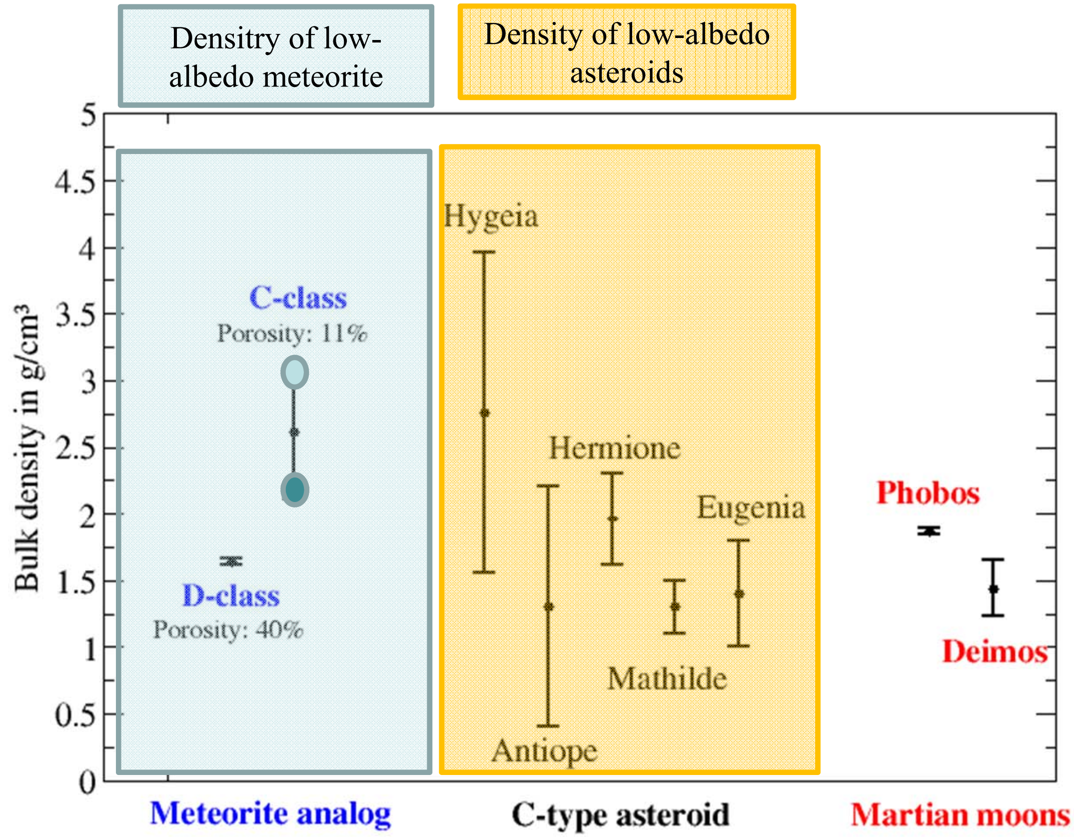
Alternative scenario
In Situ formation

•Main argument:
Current moon orbits
→ Unlikely capture

Additional argument:
A silicate composition cannot be excluded.

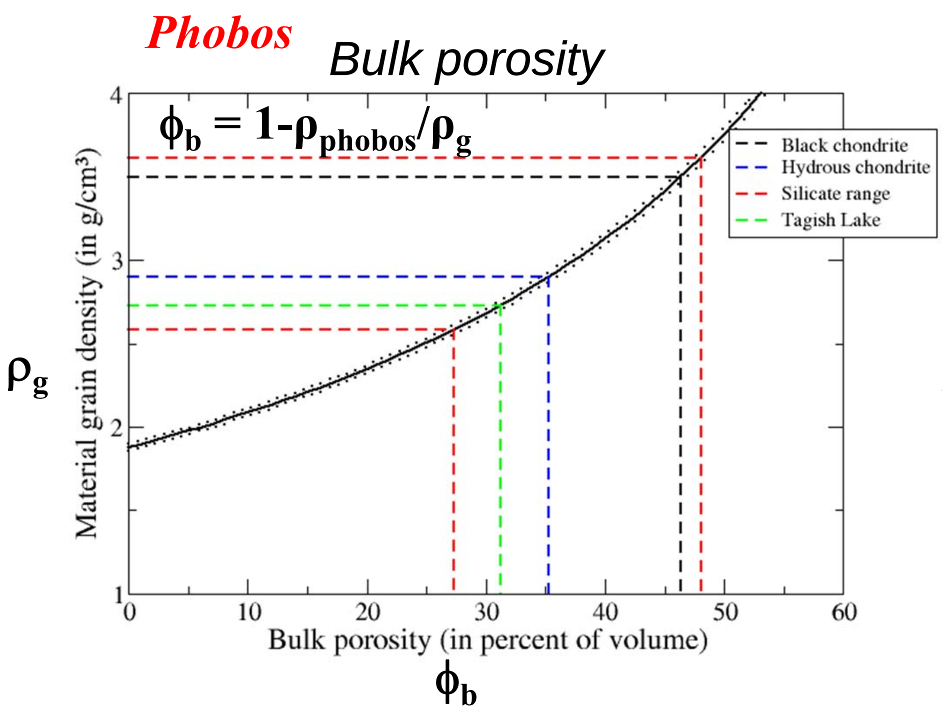
Can bulk density provide a key constraint to origin?

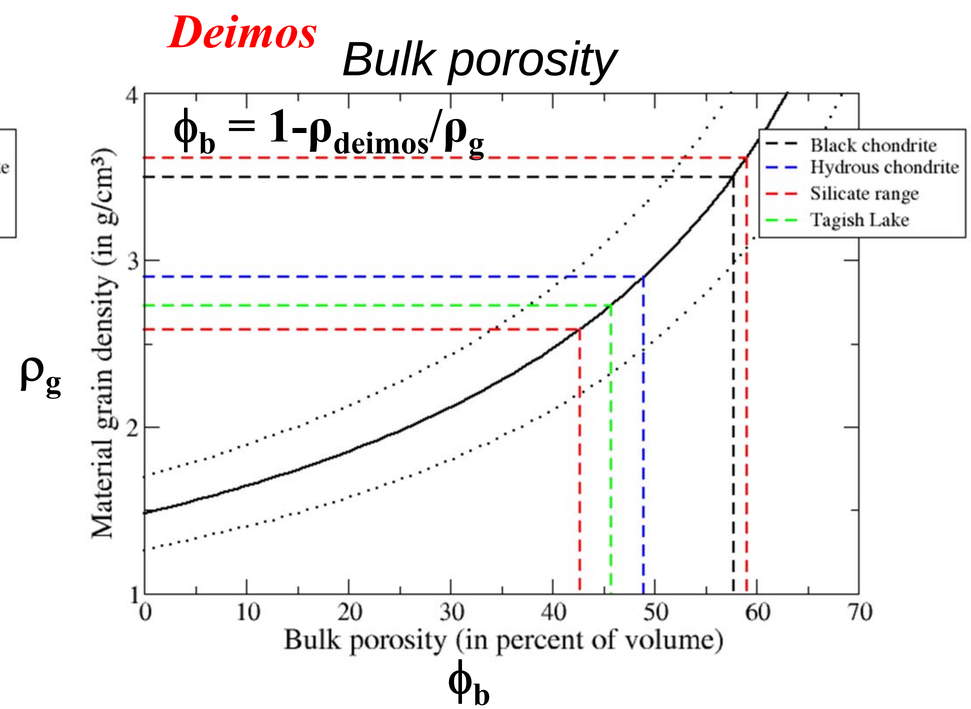
Bulk density of Phobos & Deimos



- Low density: **Phobos 1.87 +/- 0.03 g/cm^3** *(Andert et al., 2010; Rosenblatt, 2011)*
  Deimos 1.48 +/- 0.22 g/cm^3 *(Rosenblatt, 2011)*
- Light elements in the interior of the moons is required: *porosity and/or water-ice?*
- Low-albedo asteroid have also a low density compared to their chondritic material analog, interpreted as large space of voids (*macro-porosity*) in their interior.

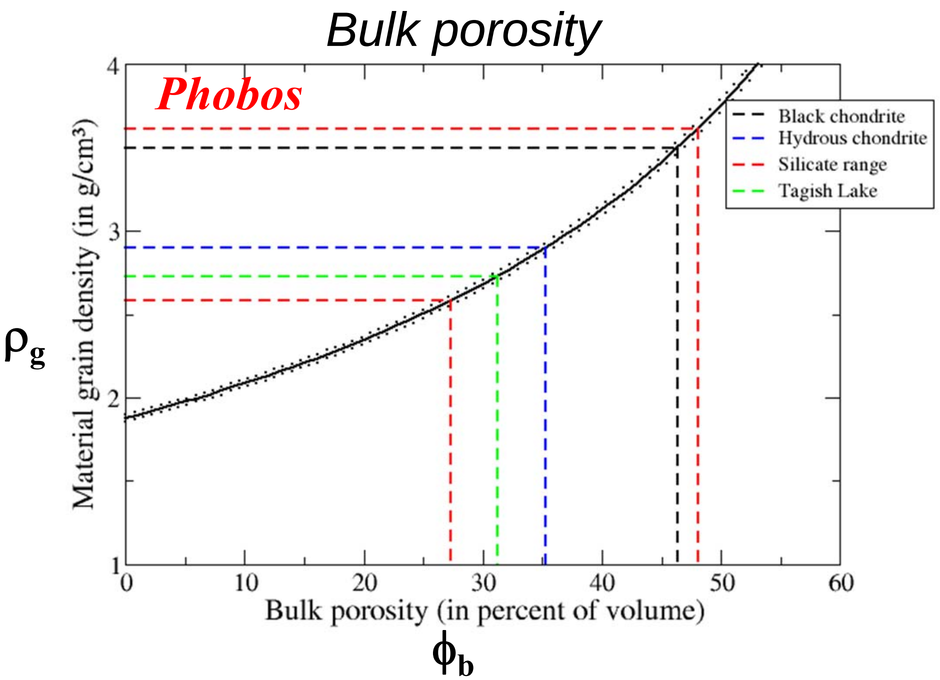
Bulk porosity estimates inside Phobos & Deimos from their bulk densities

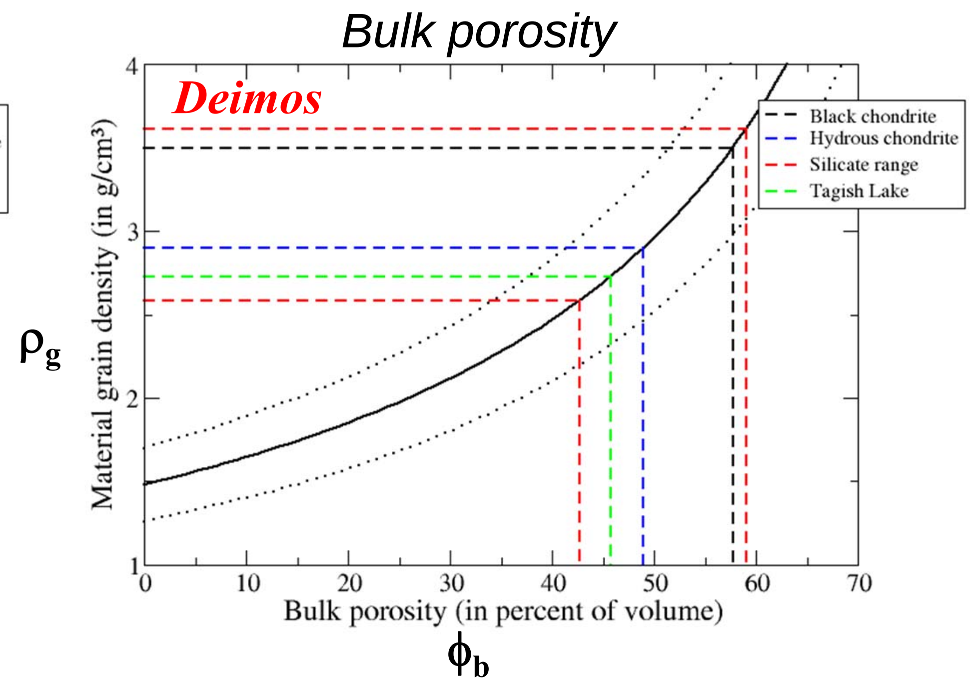




- ✓ Considering grain density of material analog, $\boldsymbol{\rho_g}$, provide bulk porosity $\boldsymbol{\phi_b}$, which fit measured density
- ✓ All material yield high bulk porosity inside the Martian moons: Phobos: 25-45% of the volume and Deimos: 40-60% of the volume.
- ✓ *Gravitational-aggregate* structure for the interior of the Martian moons.

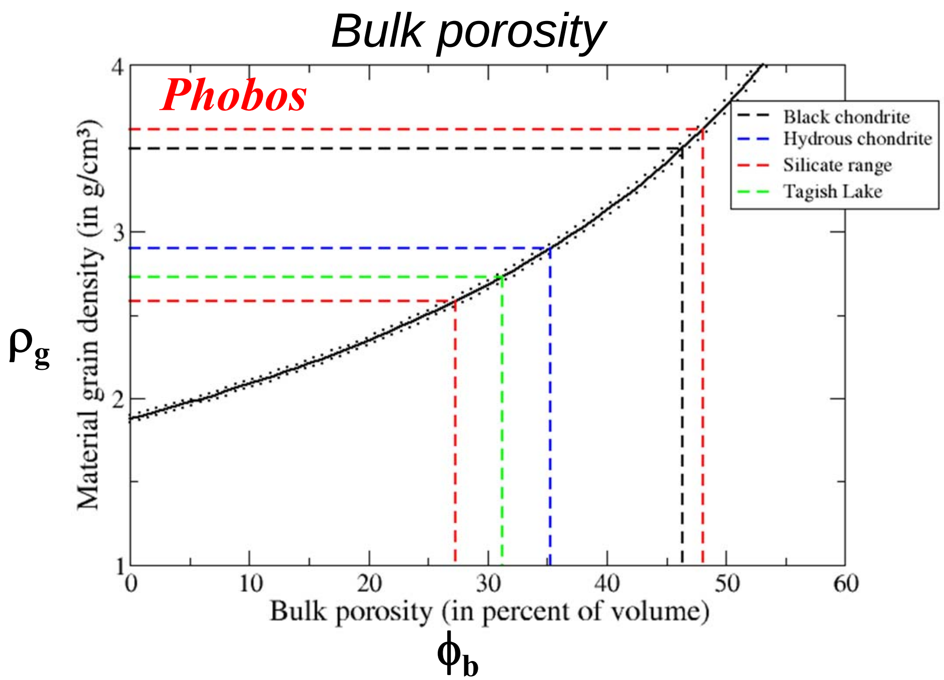
High porosity and capture scenario

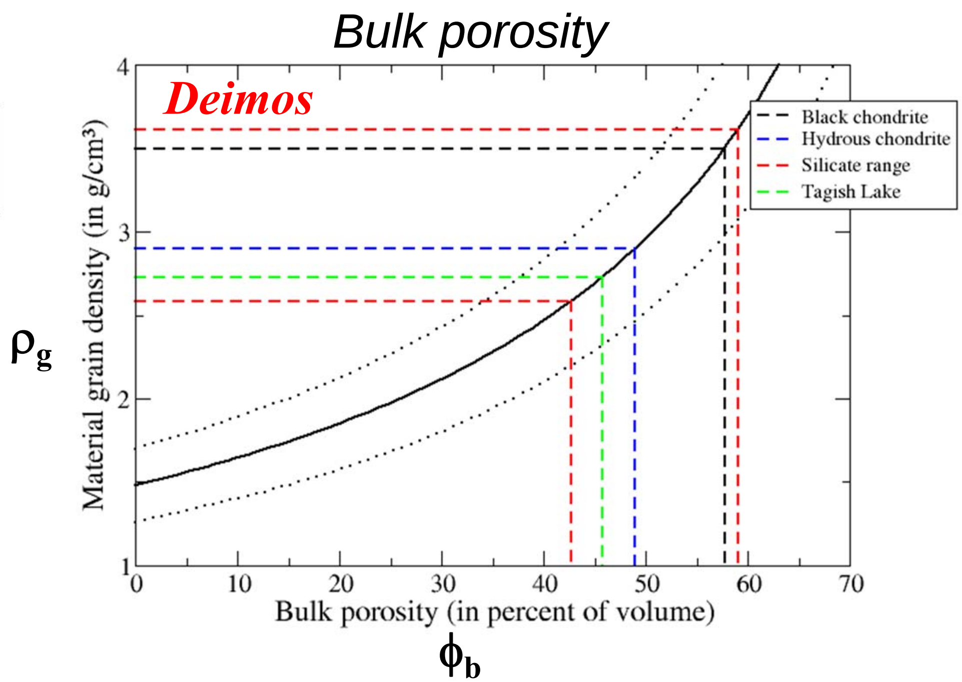




- High porosity from catastrophic collisional event(s) in asteroid history.
- High porosity can increase the tidal dissipation rate by a factor of less than 10, (Castillo-Rogez et al., 2011), not so much as needed to reach the current moon orbit around Mars
- High porosity cannot permit to preclude a capture scenario but ***it may not solve for the problem of orbital evolution after capture.***

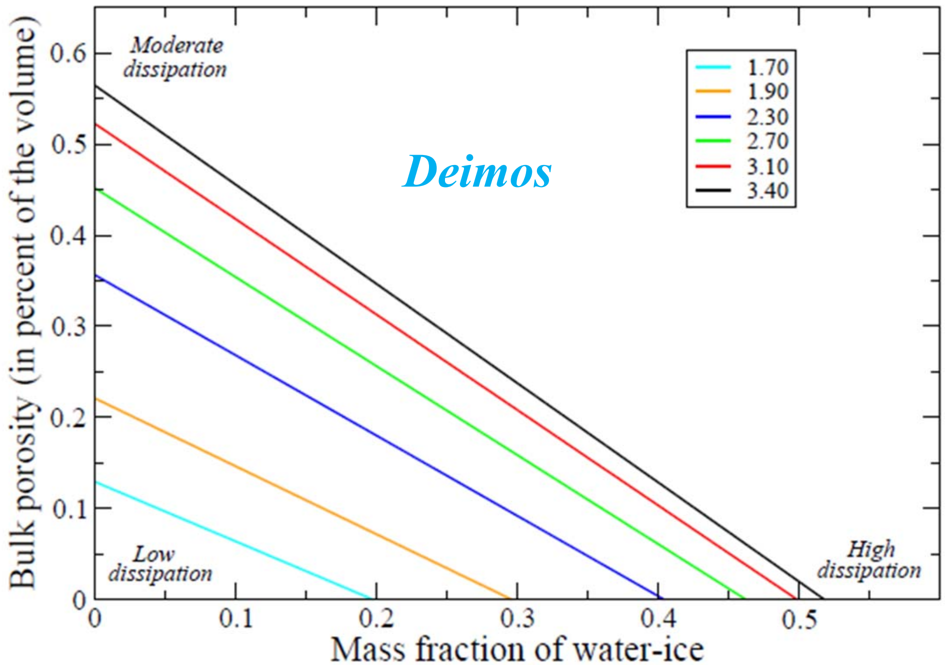
High porosity and *in-situ* formation





- High porosity supports formation from re-accretion of debris in Martian orbit.
- It does not support the origin as remnants of a former larger moon (Singer, 2007), unlike these remnants re-accreted later.
- ***Additional support to the scenario of re-accretion of large Martian impact debris in Mars' orbit (Craddock, 2011).***

Water ice inside Phobos and Deimos.



$$\Phi_b = 1 - \frac{\rho_{ph}}{\rho_{rock}} - f_{ice}\rho_{ph}\frac{(\rho_{rock} - \rho_{ice})}{\rho_{rock}\rho_{ice}}$$

With:

ρ_{rock} = *density of rocky material*
ρ_{ice} = *density of water ice*
ρ_{ph} = *density of Phobos*
f_{ice} = *mass fraction of water ice*
ϕ_b = *Phobos bulk porosity*

Unknows ρ_{rock} & f_{ice} while one observable ρ_{ph}

- **Phobos: up to 35%,** depending on the actual porosity and rock density
  Deimos: up to 50%, depending on the actual porosity and rock density
- Water-ice rich interior requires formation beyond Mars' orbit, and may significantly increase tidal dissipation rate (by a factor of 10-100), thus favoring capture scenario.
- The bulk density alone cannot permit to precisely constrain the water-ice content.
- Needs additional observables such as the gravity field and the forced libration amplitude of the moons (→ ***Models of mass repartition inside Phobos***).

Internal mass distribution through geodetic parameters

- Internal mass distribution related to principal moments of inertia (A<B<C).
- Principal moments of inertia also related to quadrupole gravity coefficients C_{20} and C_{22} and the libration θ

$$\theta = \frac{2e}{1 - \frac{C}{3(B-A)}}$$

$$C_{20} = \frac{\frac{(A+B)}{2} - C}{Mr_0^2}$$

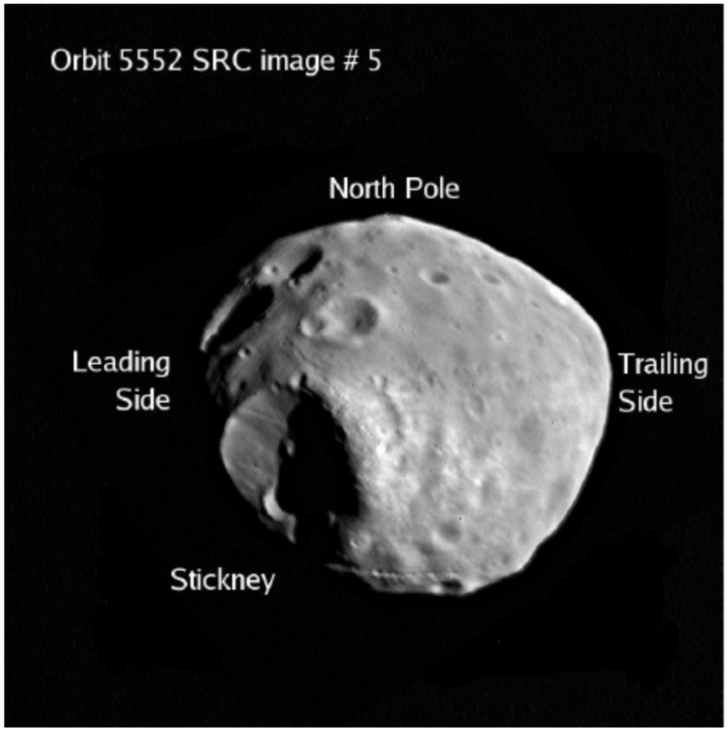
$$C_{22} = \frac{B-A}{4Mr_0^2}$$

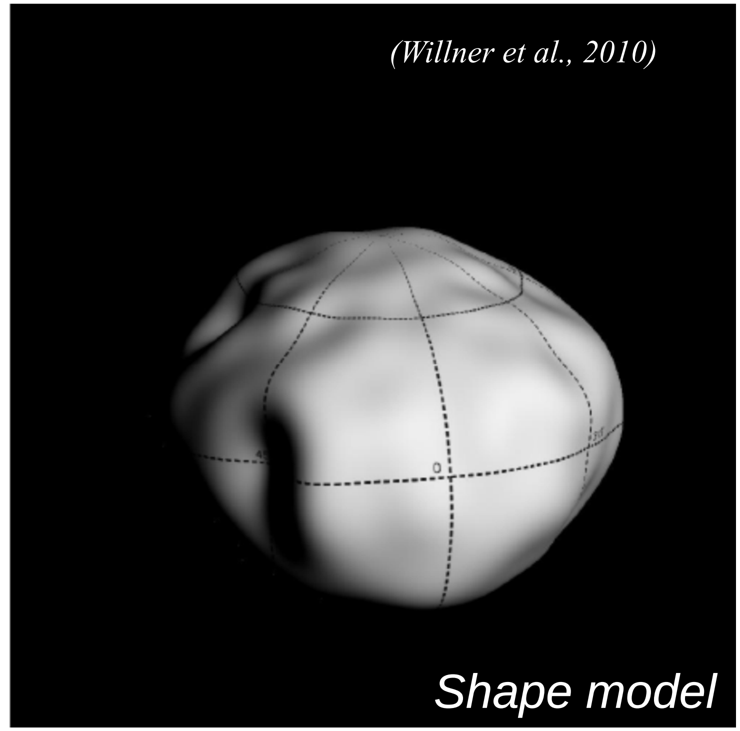
Where M is the mass of Phobos, r_0 is the mean radius of Phobos and *e* is the ellipticity of its orbit around Mars.

- Modeling internal mass distribution
- Constraining those models by measurements:

Geodetic experiment

Mars Express: Libration measurement





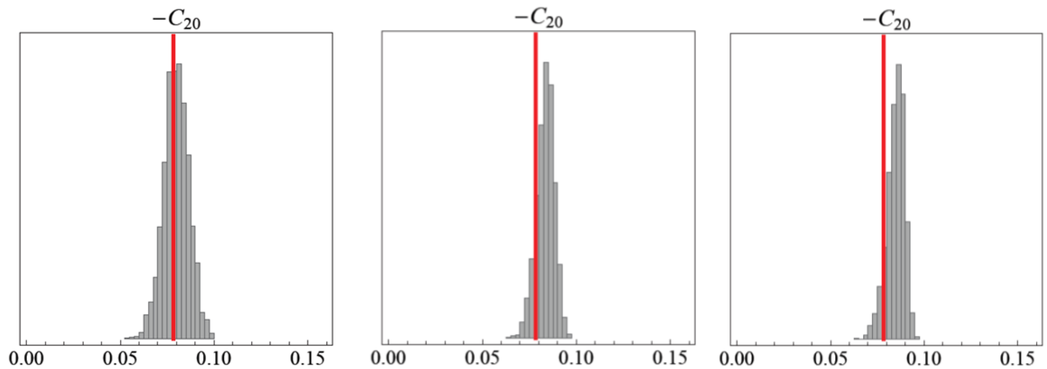
- Monitoring of control points network (*Willner et al., 2010*)

$\theta = 1.2° \pm 0.15°$ (Homogeneous value from the shape = 1.1°)

- Homogeneous/Heterogeneous …

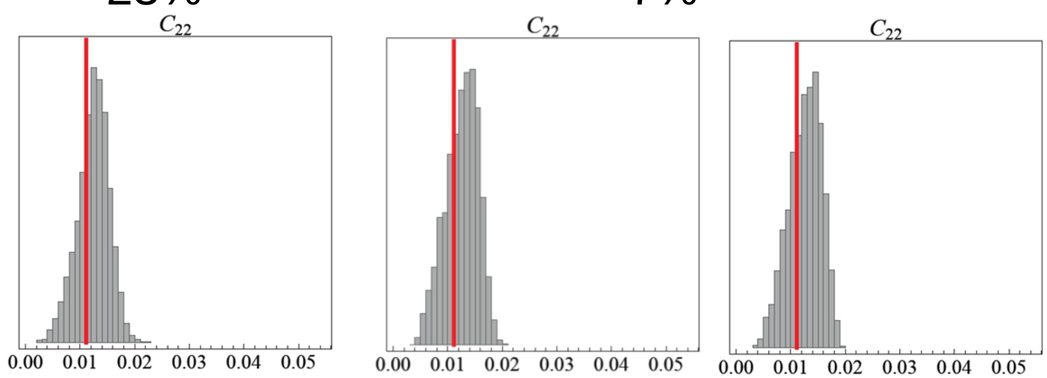
Modeling heterogeneity inside Phobos

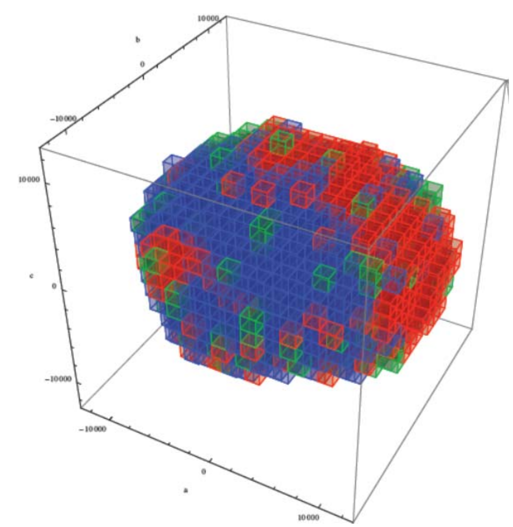
Probability density functions of the quadrupole gravity coefficients C_{20} and C_{22}



Rivoldini et al., Poster session

Porosity:	10%	30%	40%
Water ice:	23%	7%	0%

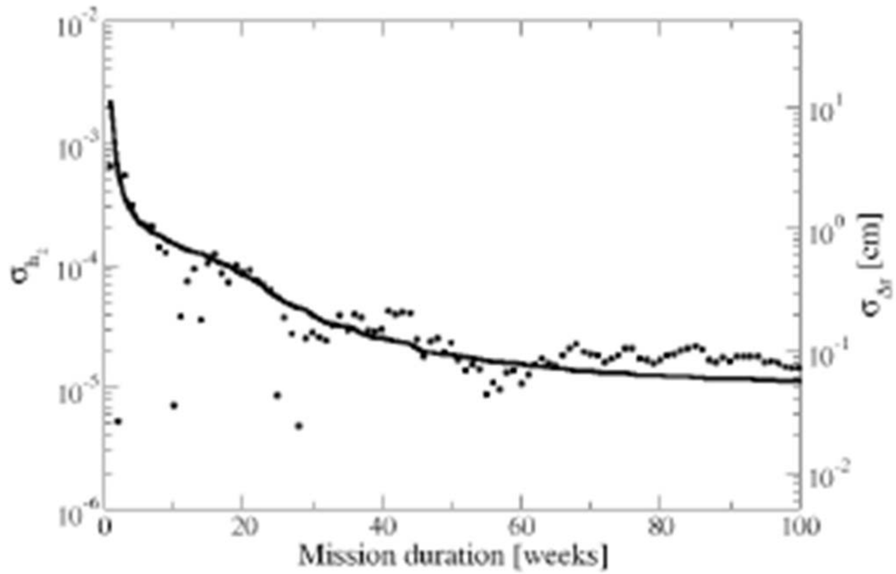




- Geodetic parameters of heterogeneous interior departs by a few percent (<10%) from the homogeneous interior
- Precise measurement is required (geodetic experiment)

Additional measurement: Tides

Le Maistre et al., Poster session



- ➢ Phobos' surface displacement due to Tides raised by Mars inside Phobos (up to 5 cm)
- ➢ Additional constraints on Phobos' internal structure (*rubble-pile vs monolith*)
- ➢ Measurement through lander on Phobos surface (also can improve libration)

Phobos Geodetic Experiment with orbiter/lander

Credit IKI

Approach Phobos and landing

✓ Mars Express extended mission till 2014 → C_{20} but not C_{22} nor θ

✓ Phases of mission encompassed in a Phobos Return Sample mission (*like ill-fated Phobos-Soil spacecraft*)

- Better knowledge of Phobos' interior will significantly improve the scientific return from Phobos' surface sample

- Among the dedicated suite of instruments for the interior, a radio-science experiment can easily be implemented on any mission to Phobos !

Summary

- The low density of the Martian moons can be explained either by a large porosity or water-ice (or both) content in their interior.

- A large porosity suggests a *gravitational-aggregate structure* which is consistent with *in-situ* formation: re-accretion of impact debris in Mars' orbit.

- A water-ice rich interior may favor a capture scenario.

- The density alone does not permit to answer the question about the origin.

- But it emphasizes on the importance of taking into account the interior structure (→ *constraining dissipative properties*) .

- Needs of theoritical studies on material properties and observables about the interior.

Fate of Phobos

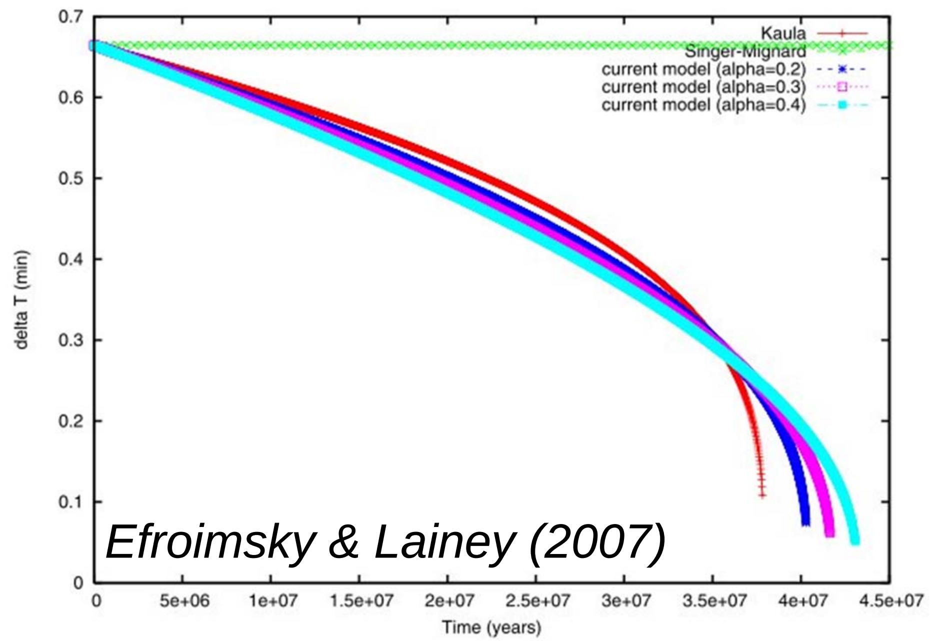
Fate of Phobos: Its orbital evolution

$$\Delta t = \varepsilon \left(2\, \varepsilon \left|\omega_p - n\right|\right)^{-(\alpha+1)}$$

$$\alpha = 0.2 - 0.4$$

$$\alpha = -1\ (Singer - Mignard)$$

$$\alpha = 0\ (Kaula)$$

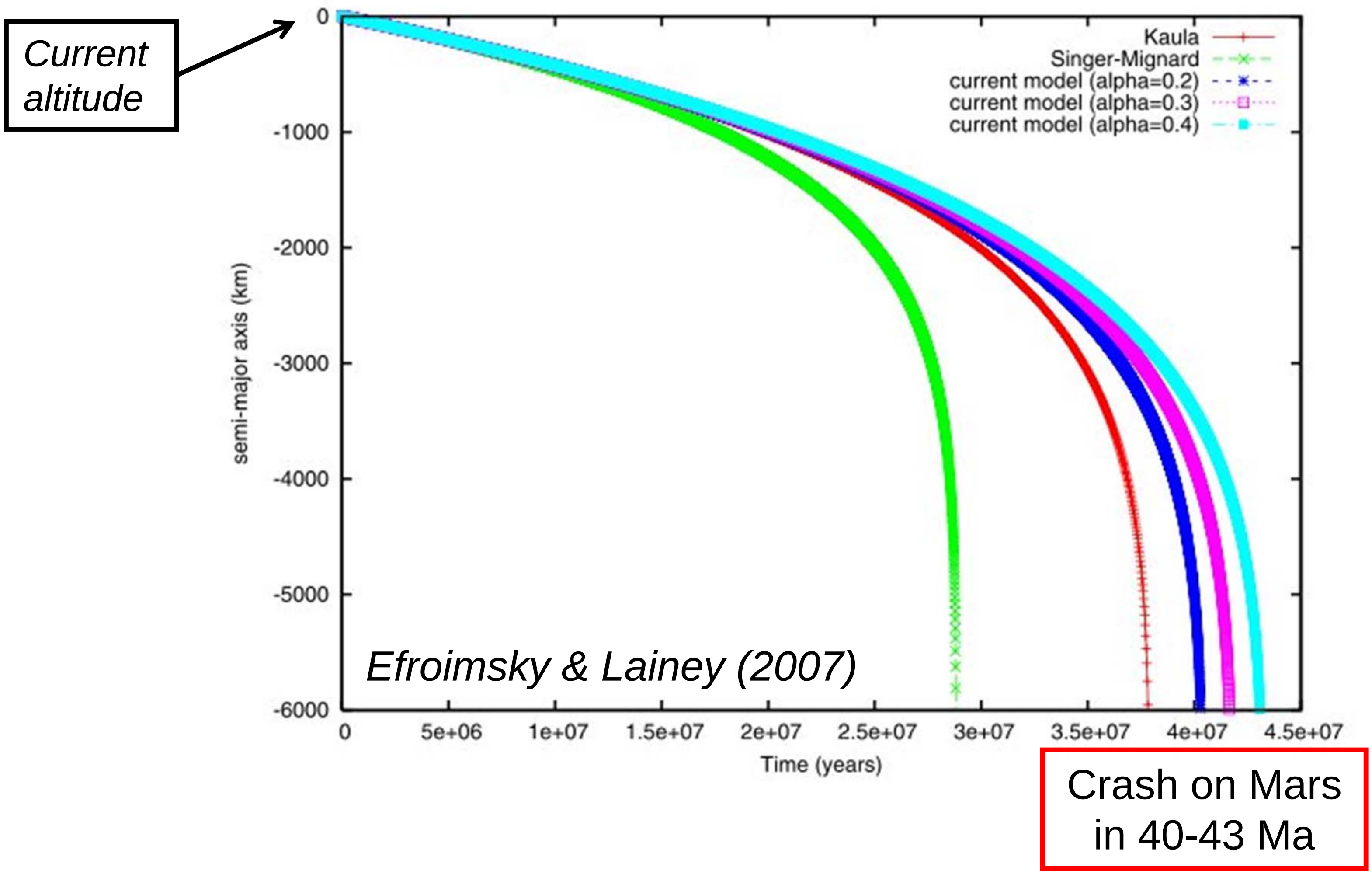


- ✓ 'Δt' is the time lag between the tidal bulge raised by Phobos in Mars and the Mars-Phobos direction.
  The larger 'Δt', the larger the dissipation
- ✓ 'Δt' depends on the tidal frequency, thus on the Phobos-Mars distance.
- ✓ The dissipation makes Phobos' orbit spiralling toward Mars, thus decreasing its semi-major axis.

➢ Time of Phobos' crash on Mars is provided by the numerical integration of the equation:

$$\frac{da}{dt} = -\frac{3k_2 R^5 n\, m_p \Delta t}{M_0 a^4}(n - \omega_p)$$

Fate of Phobos: Its orbital evolution



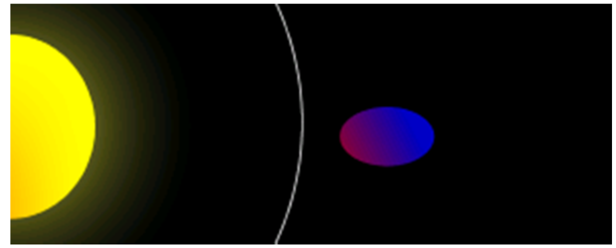
- ✓ More realistic physical laws of dissipation yields less dissipation than previously thought (Singer-Mignard or Kaula)

- ✓ Phobos may survive ~50% longer than previously estimated (Burns, 1992).

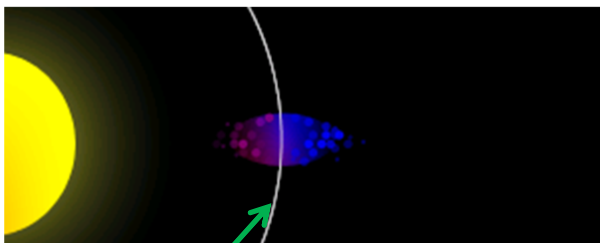
Fate of Phobos: Its disruption

Far away from the planet

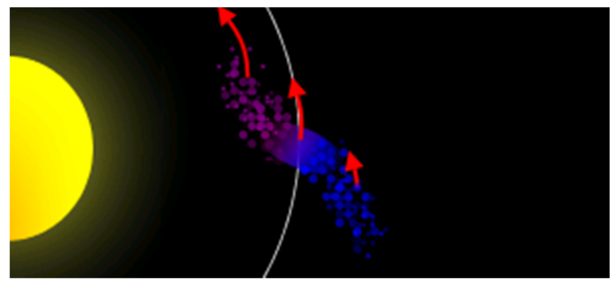
Close to the planet



Crossing the roche limit



Toward total disruption



Roche limit (fluid)

$$d \approx 2.42 \left(\frac{\rho_{planet}}{\rho_{moon}} \right)^{\frac{1}{3}} R_{planet}$$

$$d_{phobos} \approx 3.2\ R_{Mars}$$

Roche limit (Rubble-pile)
(Sharma, 2009)

Current Phobos' orbit:
2.76 *Rmars*

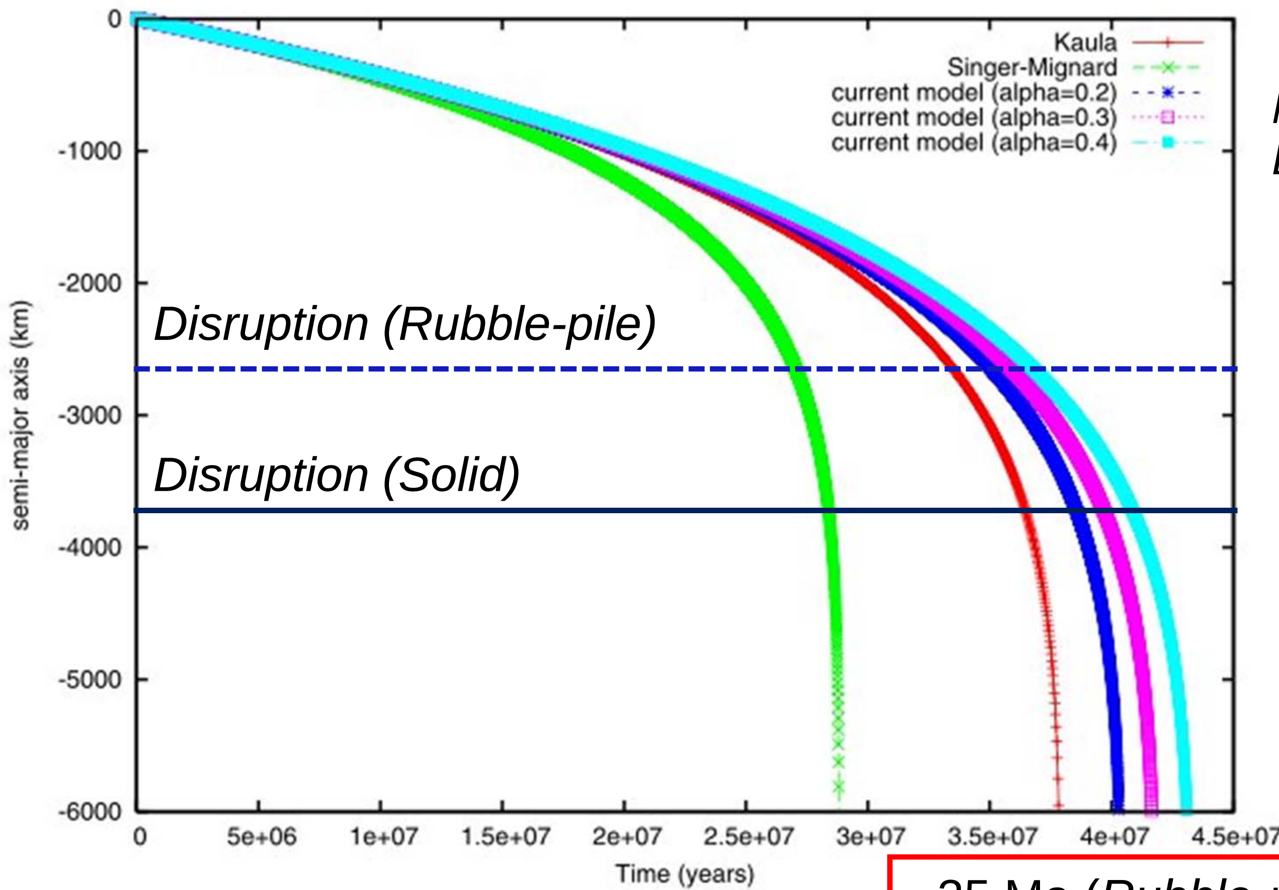
$$d_{phobos} \approx 2.0\ R_{Mars}$$

Roche limit (solid-rock)

$$d \approx 1.26 \left(\frac{\rho_{planet}}{\rho_{moon}} \right)^{\frac{1}{3}} R_{planet}$$

$$d_{phobos} \approx 1.6\ R_{Mars}$$

Fate of Phobos: Its disruption



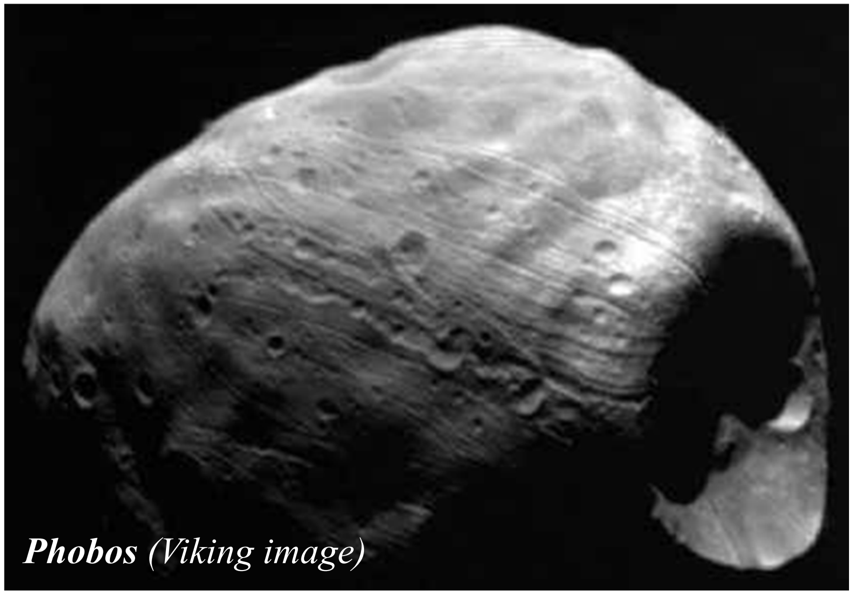
Modified after Efroimsky & Lainey (2007)

~35 Ma (*Rubble-pile*)
~40 Ma (*Solid*)

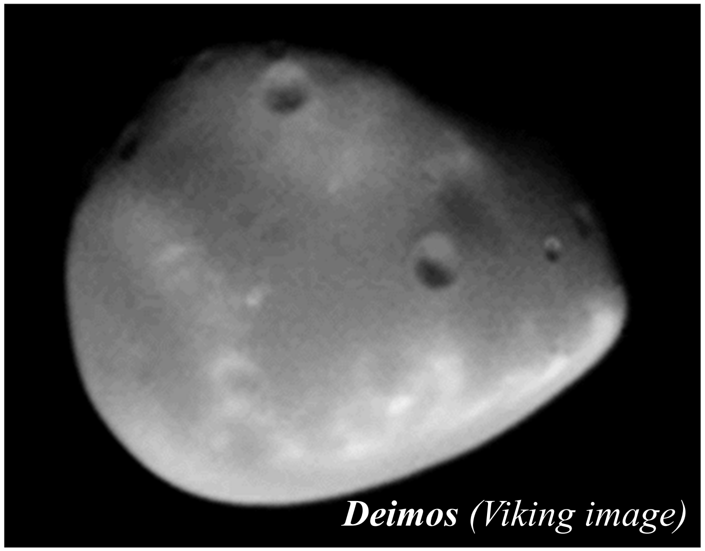
- ✓ Phobos will be disrupted by Mars' tidal forces before *crashing* on Mars
- ✓ Disruption of a *rubble pile* Phobos is expected in the next ~35 Ma (or ~5 Ma sooner than for a solid 'monolithic' Phobos)

BACKUP SLIDES

Planetary geodesy and the origin of the Martian moons



Size: 13.0km x 11.39km x 9.07km



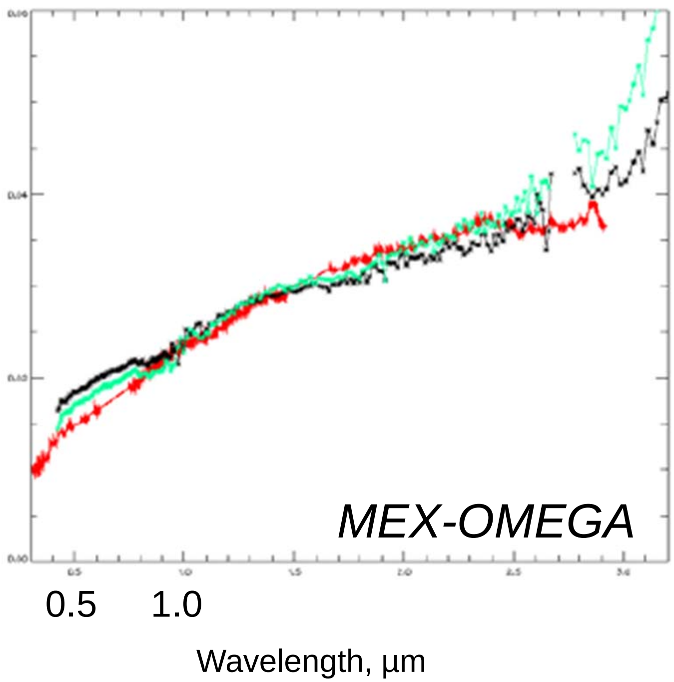
Size: 7.5km x 6.1km x 5.2km

- *Unlike the Moon of the Earth, the origin of Phobos & Deimos is still an open issue.*

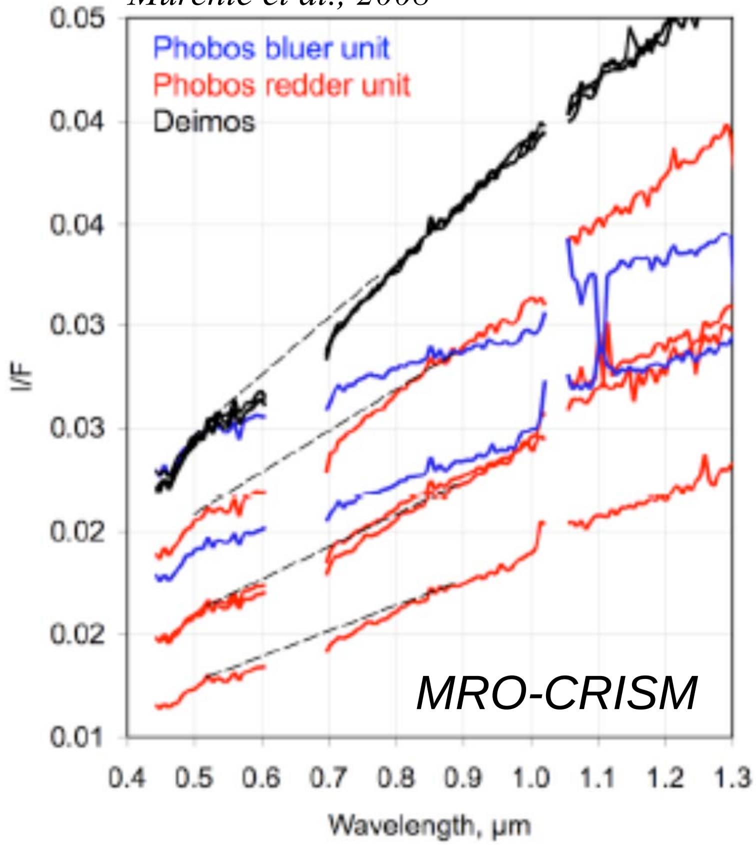
- *What can space geodesy tell us about that?*
  → Bulk density of these small bodies.

New ViS-NiR spectra (MEX & MRO)

Gondet et al., 2008



Murchie et al., 2008



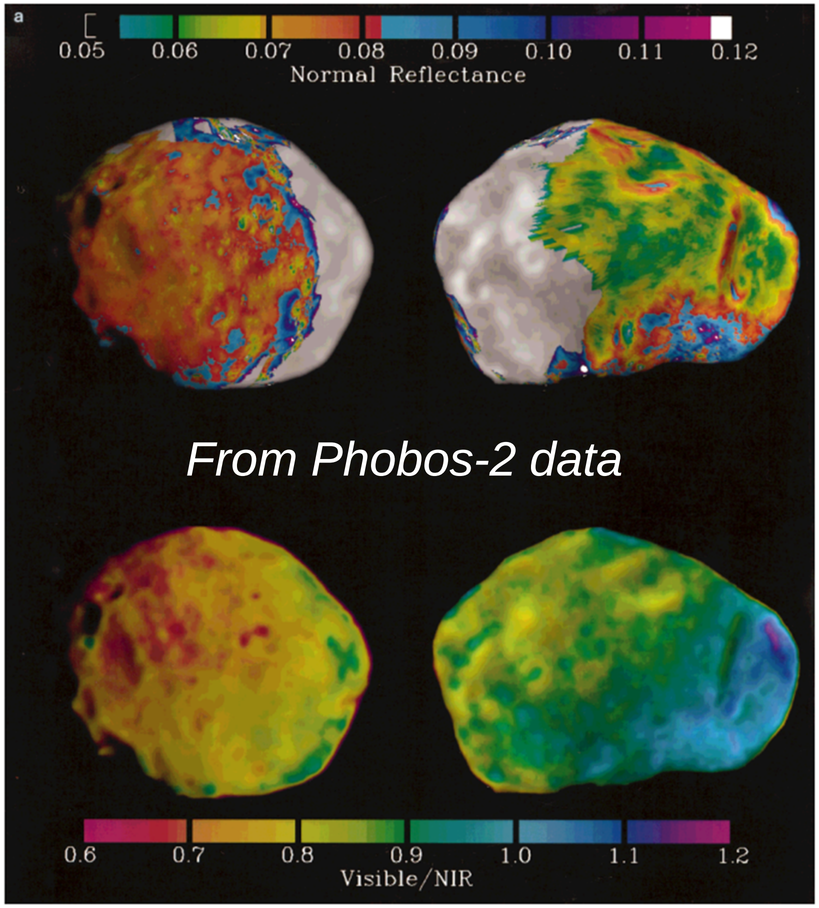
- New ViS-NiR spectra confirm previous spectra (i.e. reddened featureless spectra)
- MRO-spectra may have seen an absorption band ~0.65 µm?
- MEX-OMEGA has not seen this absorption band?

Color variations at Phobos' surface: What does it mean?

- Phobos' surface shows two spatio-spectral units: **Red** & **Blue** units.

  Blue unit encompasses Stickney crater → deep material exposed at the surface?

  Different degree of space weathering?



From Phobos-2 data

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