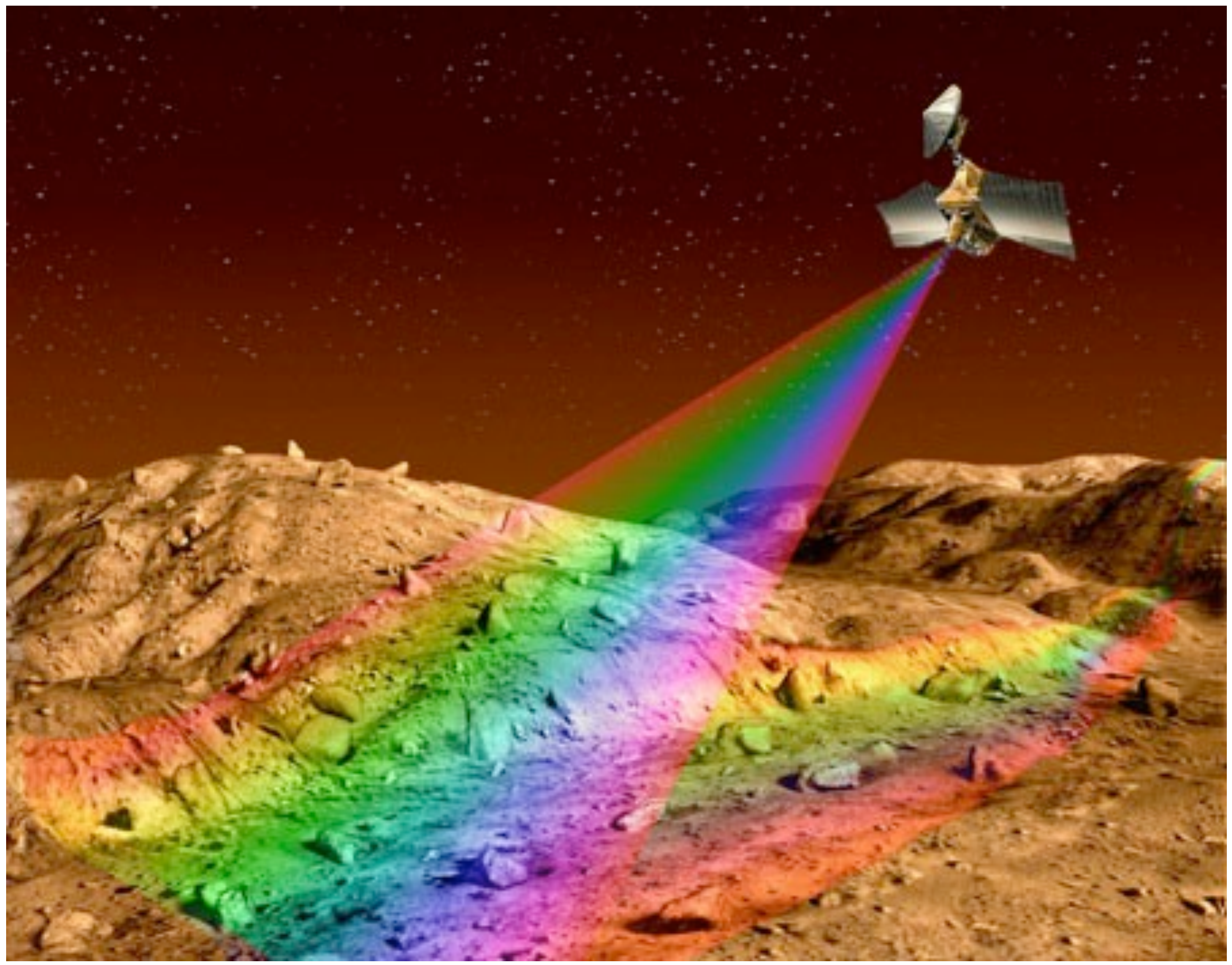
Surface photometric properties from CRISM/MRO hyperspectral multi-angle observations



Jennifer Fernando[1], Frédéric Schmidt[1], Xavier Ceamanos[3], Sylvain Douté[3], Patrick Pinet[2], et Yves Daydou[2]
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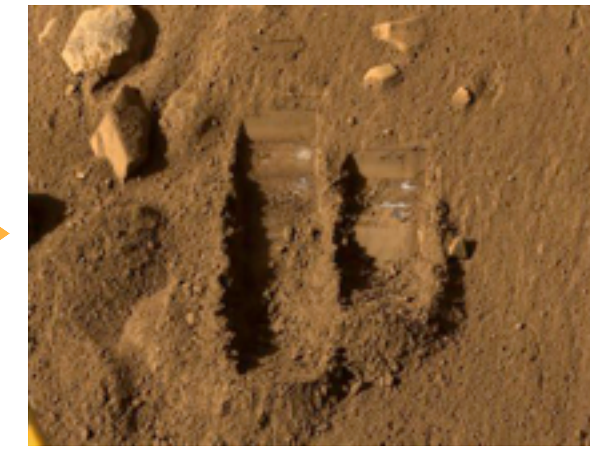
Context: motivation for Mars exploration

Why Mars?

climate → chemical and physical alterations →



granular Martian surface

Characteristics
- seasons
- atmosphere

Geological process
- aelian (past, present)
- aqueous (past)

Recorded in
- composition
- **physical state of surface**

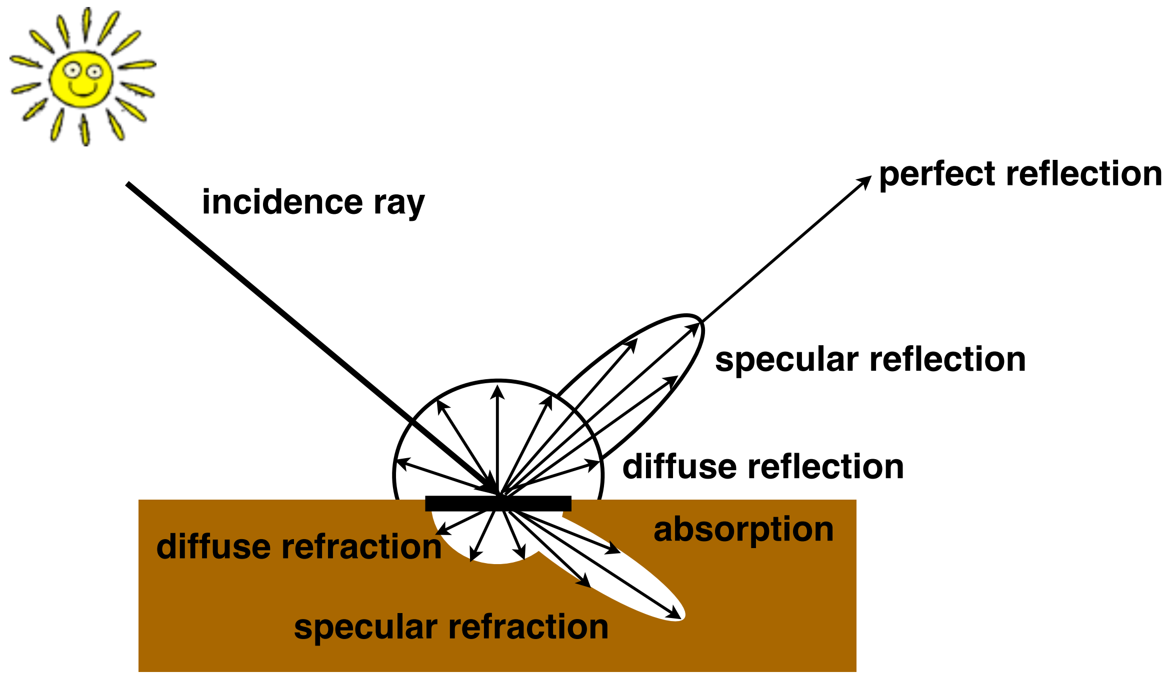
Physical properties?

- brightness of surface
- texture (round/rough) and size of grains
- with or without internal scatterers
- ...

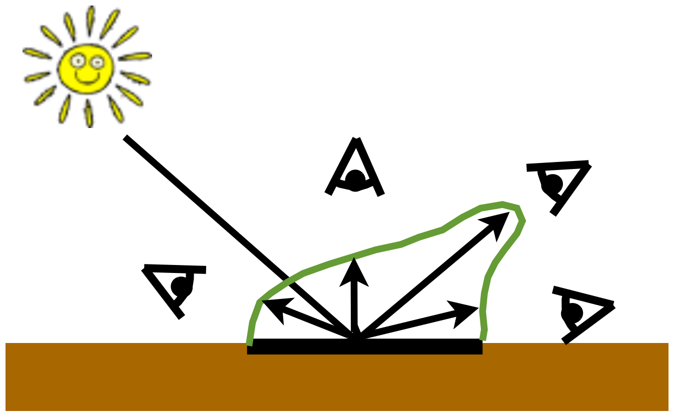
Objective: surface physical properties

How?

- planetary surface: **granular** media (such as regoliths)



- Scattering proprieties depending on:
  - **wavelength**
  - **surface properties** (composition, texture, size grains, roughness, etc...)



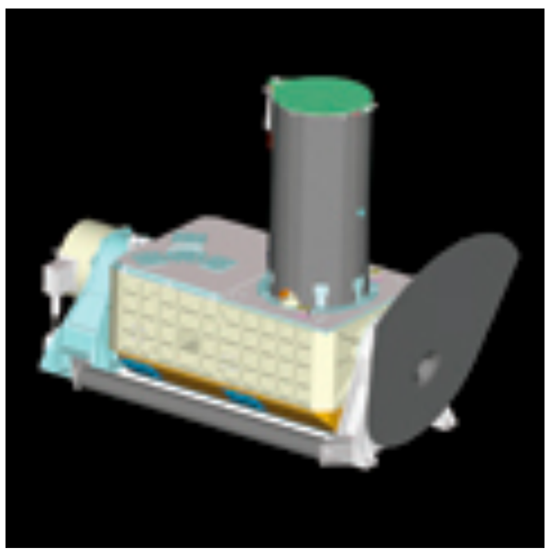
anisotropic scattering

- **varied geometric observations are needed !!!**

Remote sensing: CRISM instrument onboard MRO

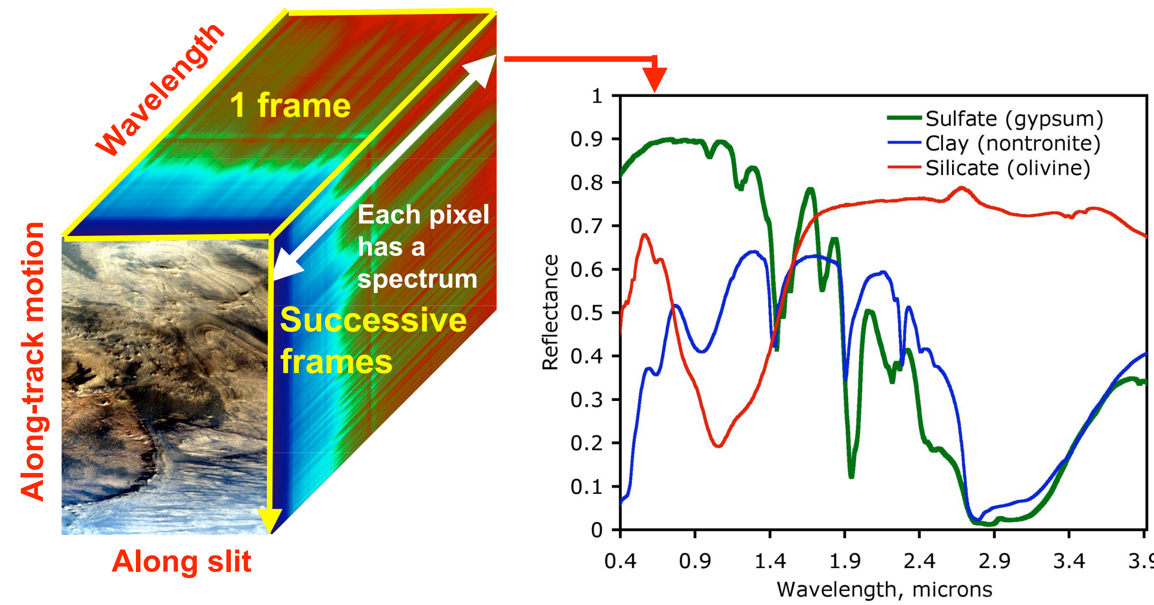
*Compact Reconnaissance Imaging Spectrometer for Mars in Mars Reconnaissance Orbiter spacecraft

CRISM*



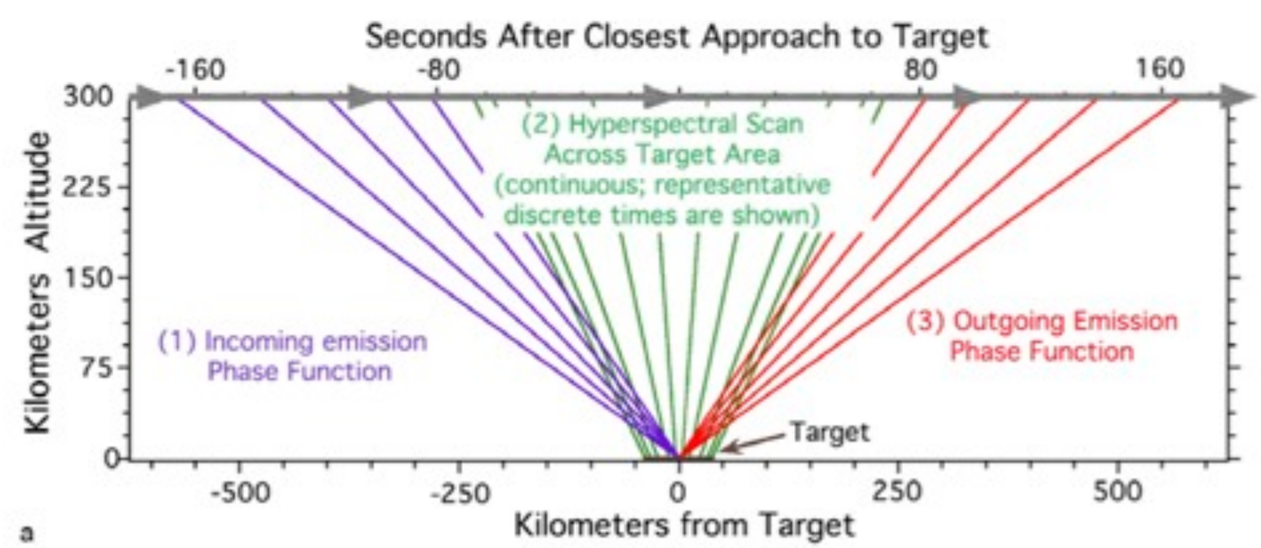
Spectro-imagery

[Murchie et al., 2007]



Hyperspectral data

(0,36 to 3,92 µm)



Multi-angular data

Remote sensing: CRISM instrument onboard MRO

better characterization of the **aerosol optical properties**

+

better characterization of the **surface photometric properties**

combination of **hyperspectral** and **multi-angle** data

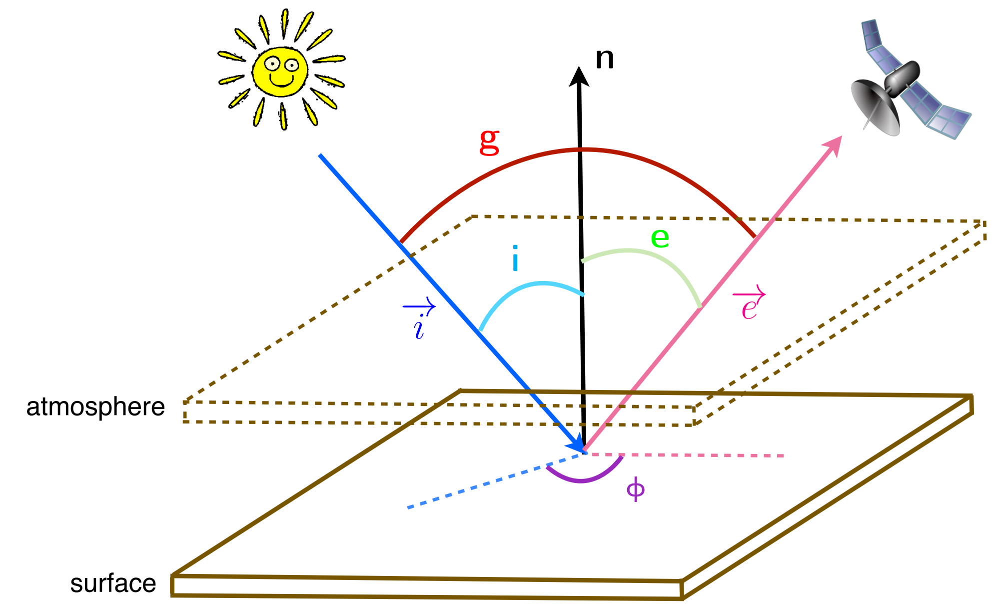
↓

better estimation of the **abundance composition**

Remote sensing: CRISM instrument onboard MRO

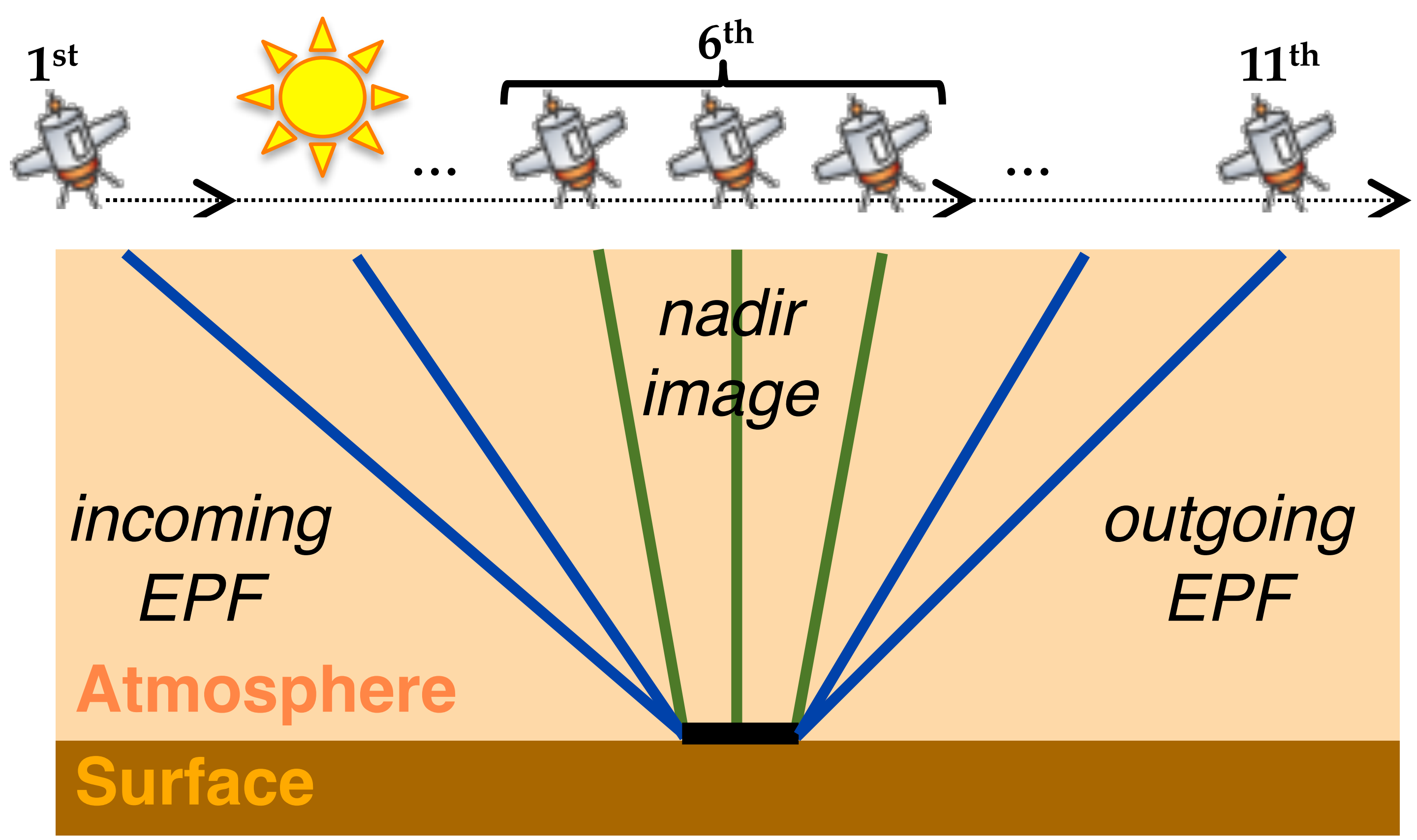
Full resolution targeted observations (FRT) - Multi-angle images

- 1x quasi-nadir scan at 18m/pixel
- 10x off-nadir scans at 180m/pixel
- **atmosphere/surface coupling !!!!**



i: incidence angle, e: emergence angle, g: phase angle, ϕ: azimuth angle

constant i, different e (±60°)



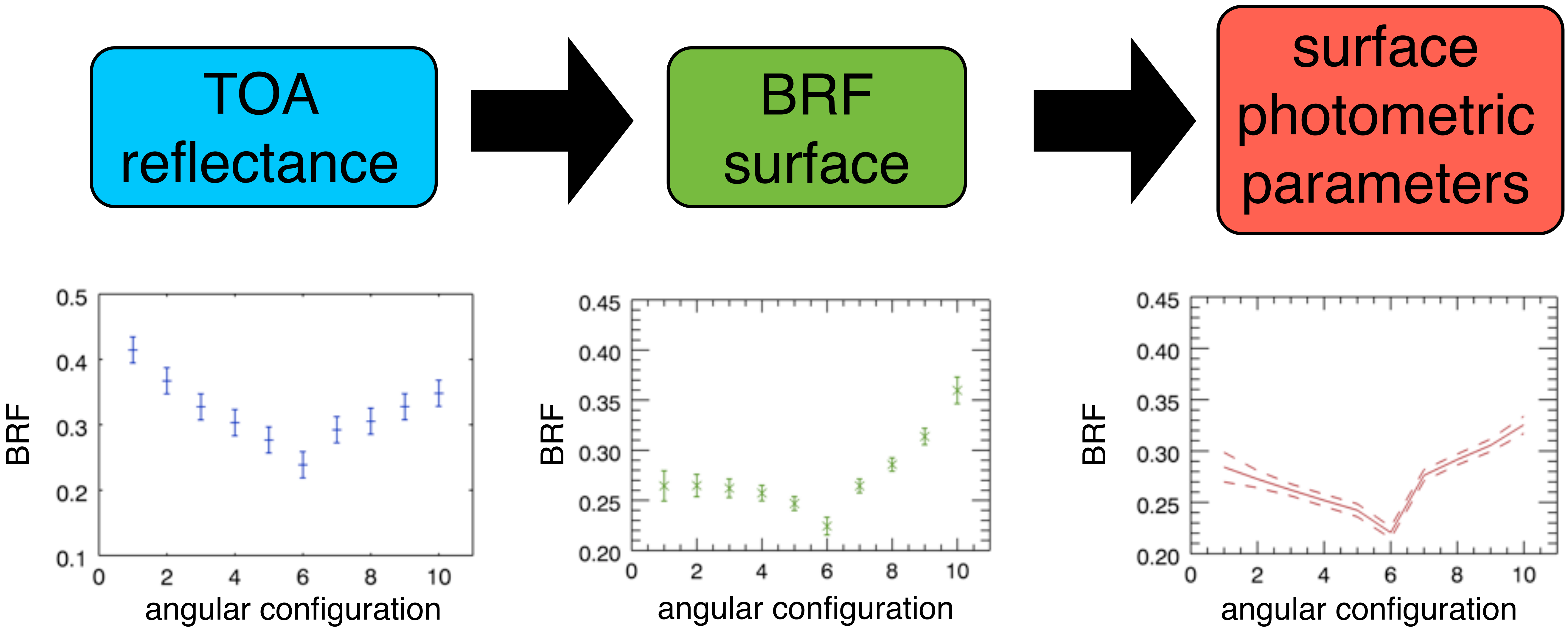
Radiometric unit:

bidirectional reflectance

$$\rho(i,e,\phi)=I/\pi F$$

I: intensity, F: solar flux received at surface

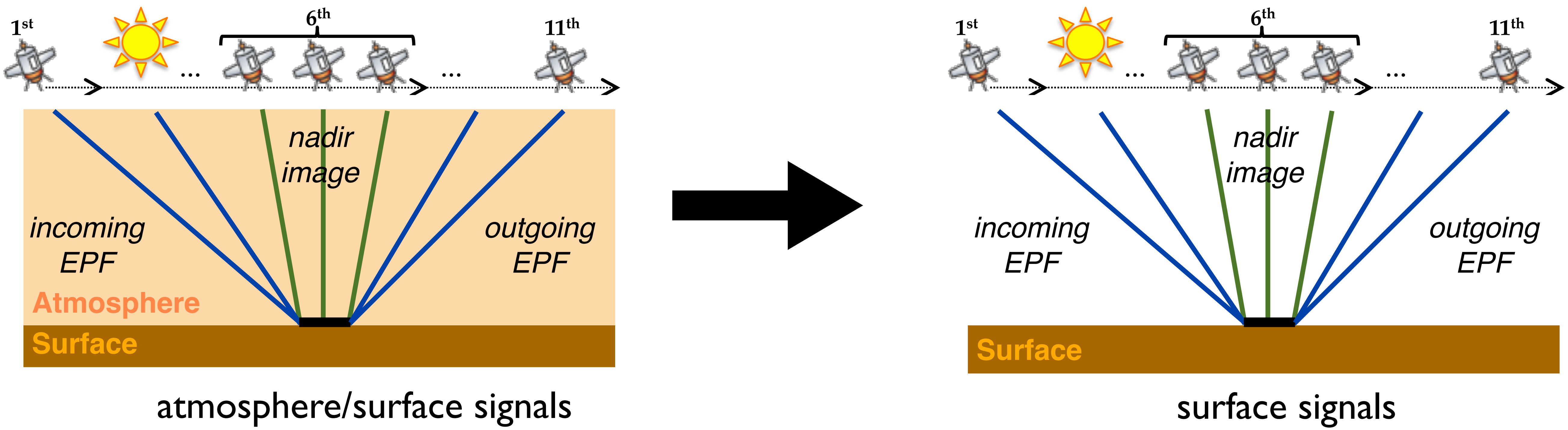
Methodology scheme

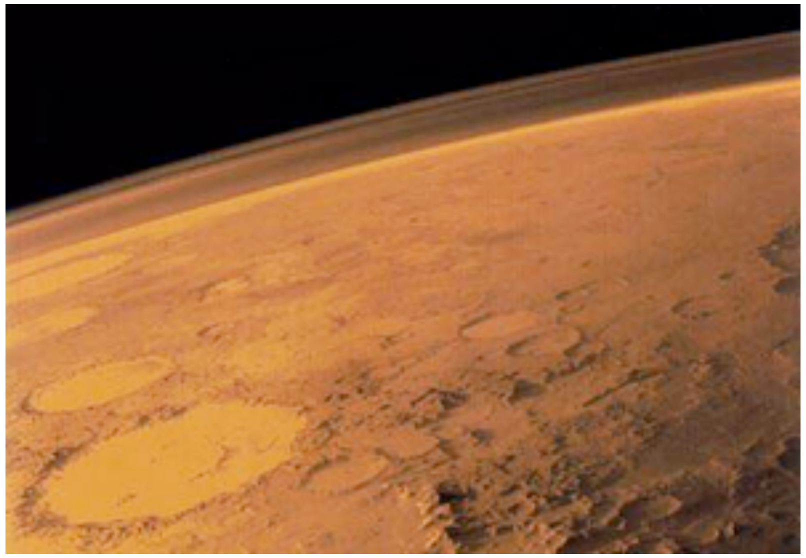


Methodology: 1. atmospheric correction

- for surface photometric study:

1. atmospheric correction of CRISM multi-angle observations to retrieve surface signals





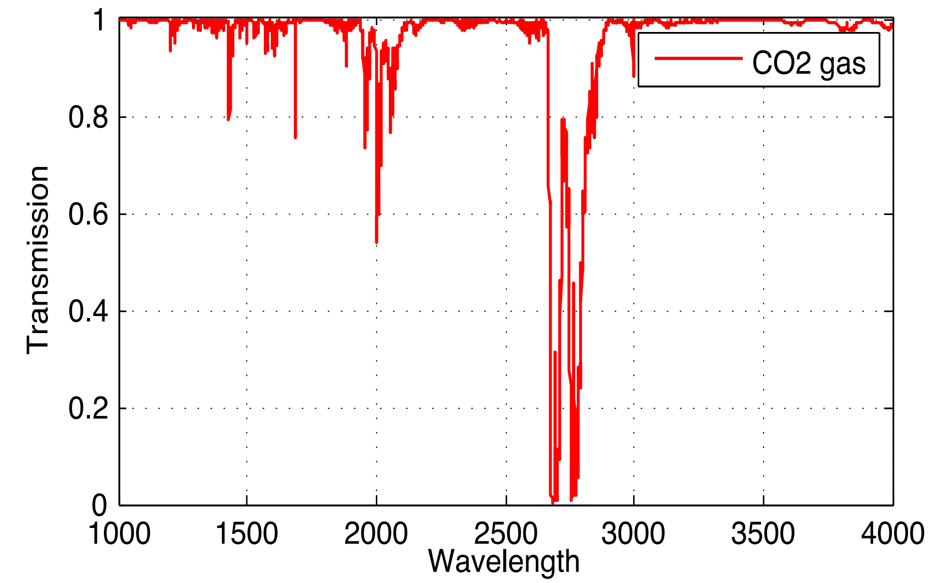
- faint but with significant opacity
- obstacle in sensing the surface
- composed of gases and aerosols

Methodology: Correction for gases

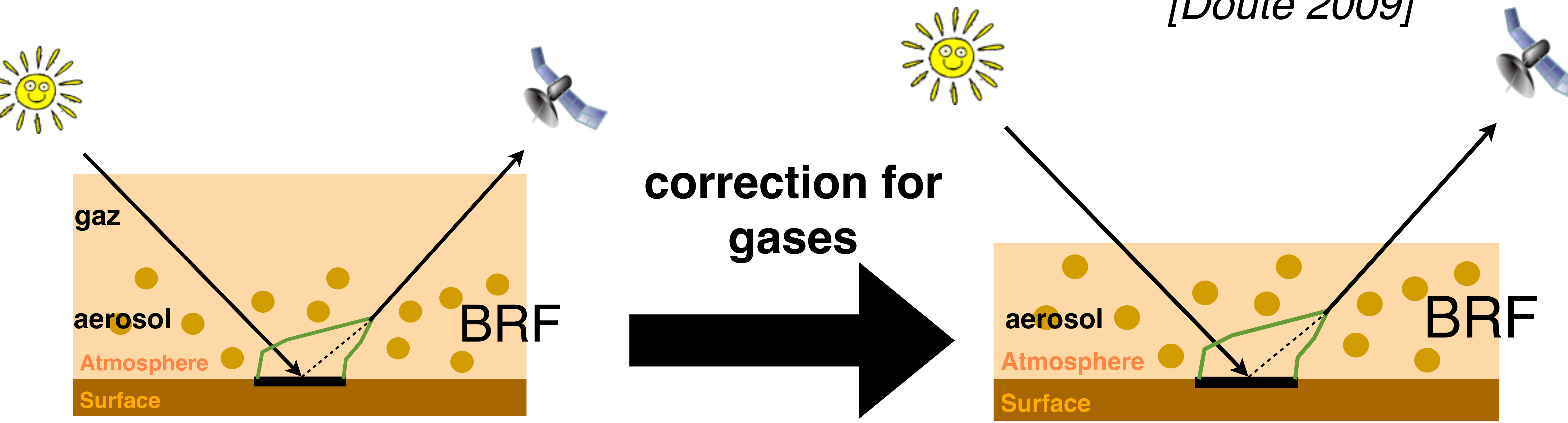
Martian atmosphere: gases

- **composition**: 95% CO_2
- **assumptions**: vertical profil (GCM), altitude

Vertical transmission spectrum of CO_2 gas in the SWIR



[Douté 2009]



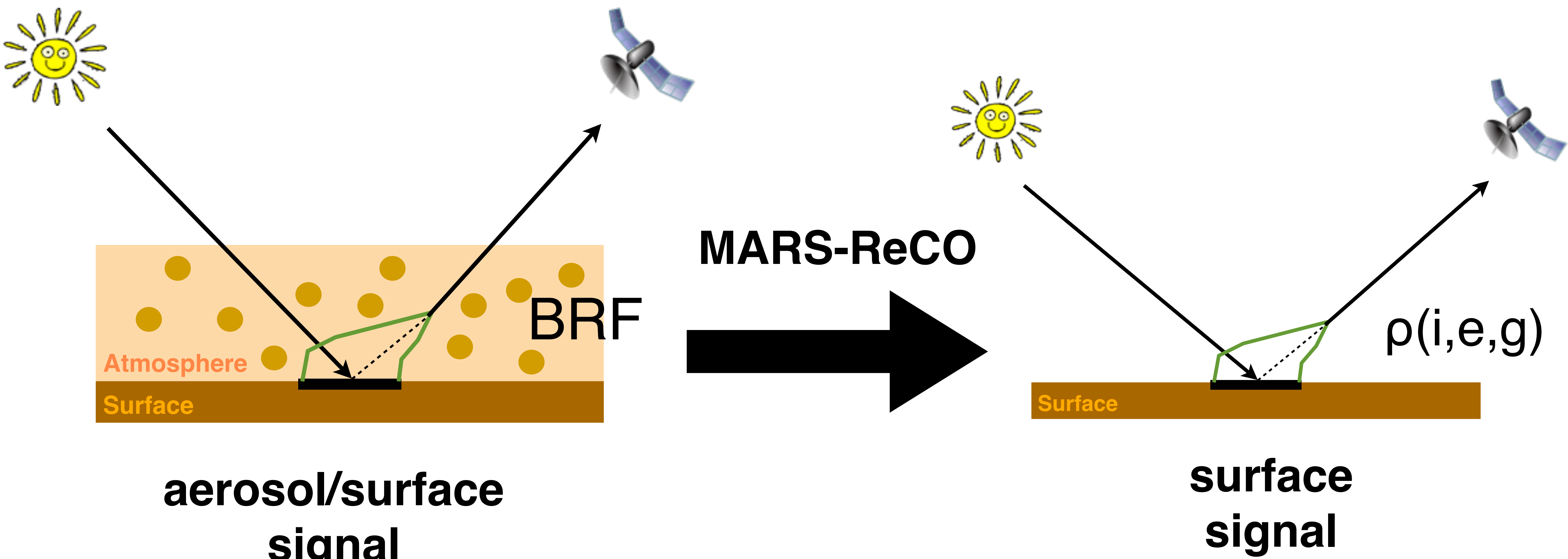
gases/aerosol and surface signal

aerosol and surface signal

Methodology: Correction for aerosols (MARS-ReCO)

Martian atmosphere: aerosols

- **composition**: mineral and water ice particulates
- **assumptions*:*** surface AND aerosols anisotropic properties ***[Ceamanos et al. 2012 in preparation]***

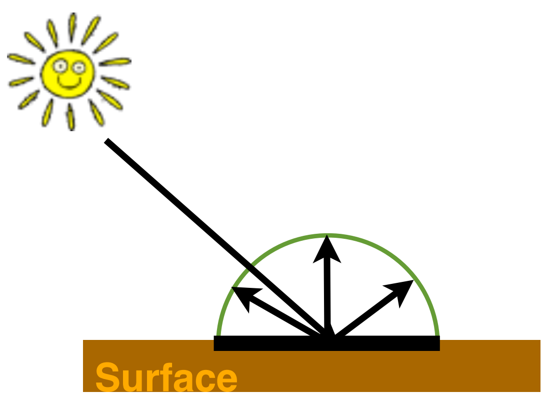


Methodologie: Correction for aerosols (MARS-ReCO)

BFR surface - Ross-Thick Li-Sparse model (RTLS) *[Lucht 2000]*:

$$BRF_{surf}=\rho(\mu_0,\mu,\phi)=\mathbf{k_L}1+\mathbf{k_G}f_G(\mu_0,\mu,\phi)+\mathbf{k_V}f_V(\mu_0,\mu,\phi)$$

Lambertian function — Geometrical optical function — Volumetric function



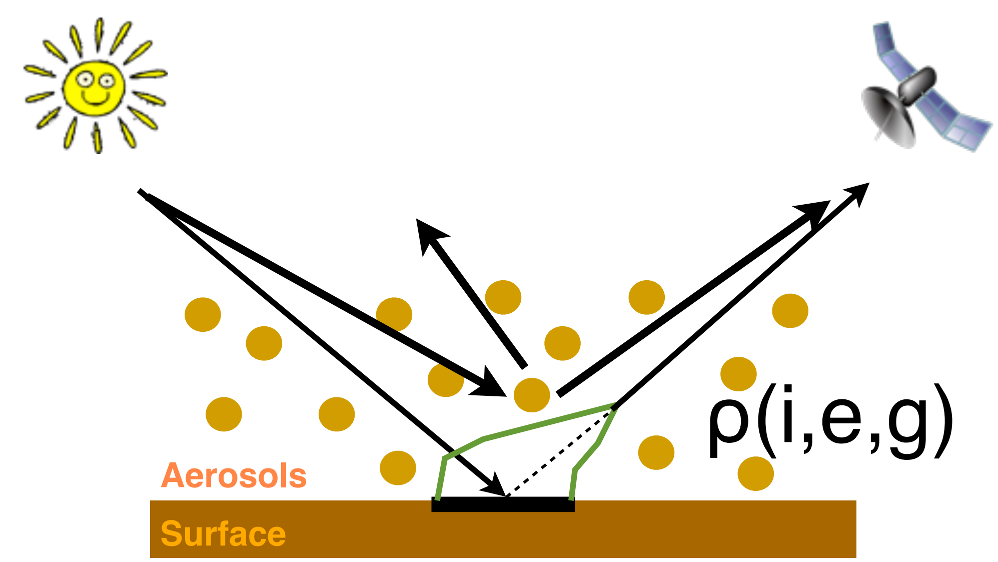
Top-of-atmosphere - Green's function-based formulation *[Lyapustin 2011]* **:**

$$TOA=R(\mu_0,\mu,\phi)=\mathbf{R_D(\mu_0,\mu,\phi)}+\mathbf{k_L}\mathbf{F_L(\mu_0,\mu)}+\mathbf{k_G}\mathbf{F_G(\mu_0,\mu,\phi)}+\mathbf{k_V}\mathbf{F_V(\mu_0,\mu,\phi)}+\mathbf{R_nl(\mu_0,\mu)}$$

atmospheric path reflectance

RTLS multiplicative factor

non-linear term



Methodologie: Correction for aerosols (MARS-ReCO)

Top-of-atmosphere - Green's function-based formulation *[Lyapustin 2011]* **:**

$$R(\mu_0,\mu,\phi)=R_D(\mu_0,\mu,\phi)+k_L F_L(\mu_0,\mu)+k_G F_G(\mu_0,\mu,\phi)+k_V F_V(\mu_0,\mu,\phi)$$
$$+R_{nl}(\mu_0,\mu)$$

Fonctions R_D, F_L, F_G, F_V, R_{nl} :

- optical properties of mineral aerosols: ω, P(g)
- τ_{aer}= {0, 0.05, 0.1, 0.2, 0.33, 0.5, 0.75, 1, 1.4, 2.0, 2.8, 4}
- geometry condition

θ_0={14°, ..., 81°}; θ={0°, ..., 70°} with Δ=0.02°

ϕ={0°, ..., 180°} with Δ=3°

➙ simulated using DISORT *[Stamnes et al. 1988]* = look-up table (LUT)

➙ estimation nearest neighbough geometry with linear interpolation according to τ

Methodology: Bayesian inversion procedure

- **State of information** defined by a **probability density function (PDF)** over the parameter and data spaces *[Tarantola and Valette, 1982]*

  - prior information/PDF:
    - an **uniform PDF for each model parameters** {k_L,k_G,k_V} in the physical range
    - a **gaussian PDF** for CRISM data

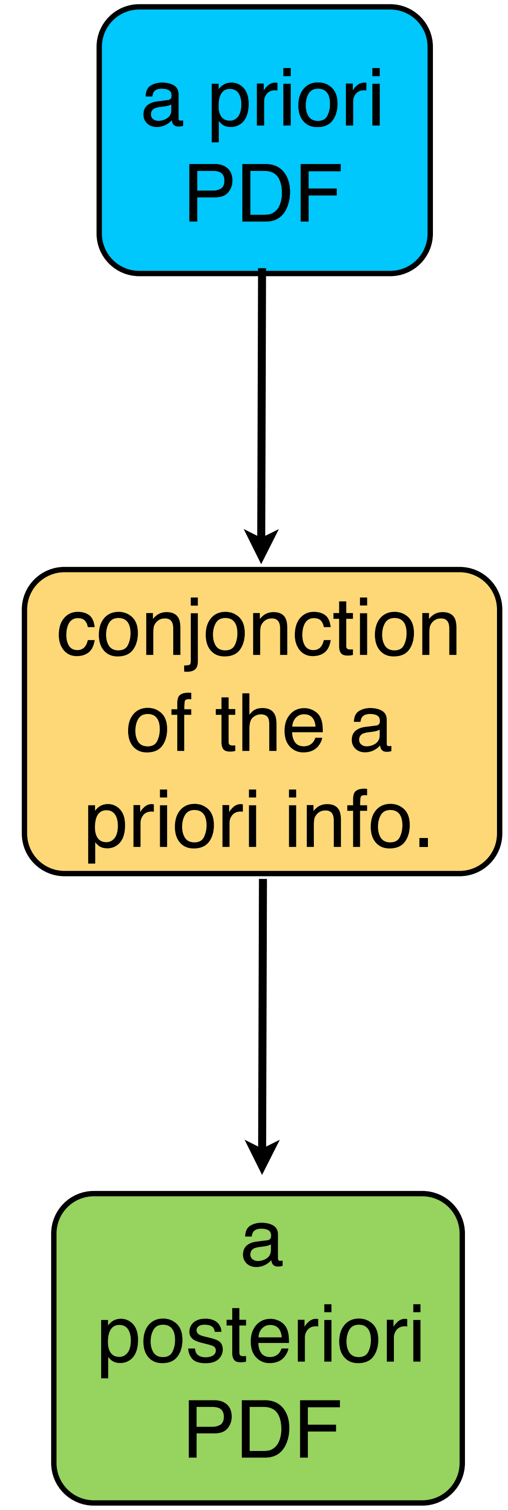
  - **baye's theorem** applied to infer solutions

$$\sigma_M(m) = k\,\rho_M(m)\,L(m)$$

$$L(m) = \int_D \partial d \frac{\rho_D(d)\,\theta(d \mid m)}{\mu_D(d)}$$

θ theoritical relation between d and m
μ nul information PDF for d
k constant

  - posterior information/PDF: PDF surface kernel weights K= {k_L,k_G,k_V}



MARS-ReCO: quasi linear expression ➛ iterative analytical inversion

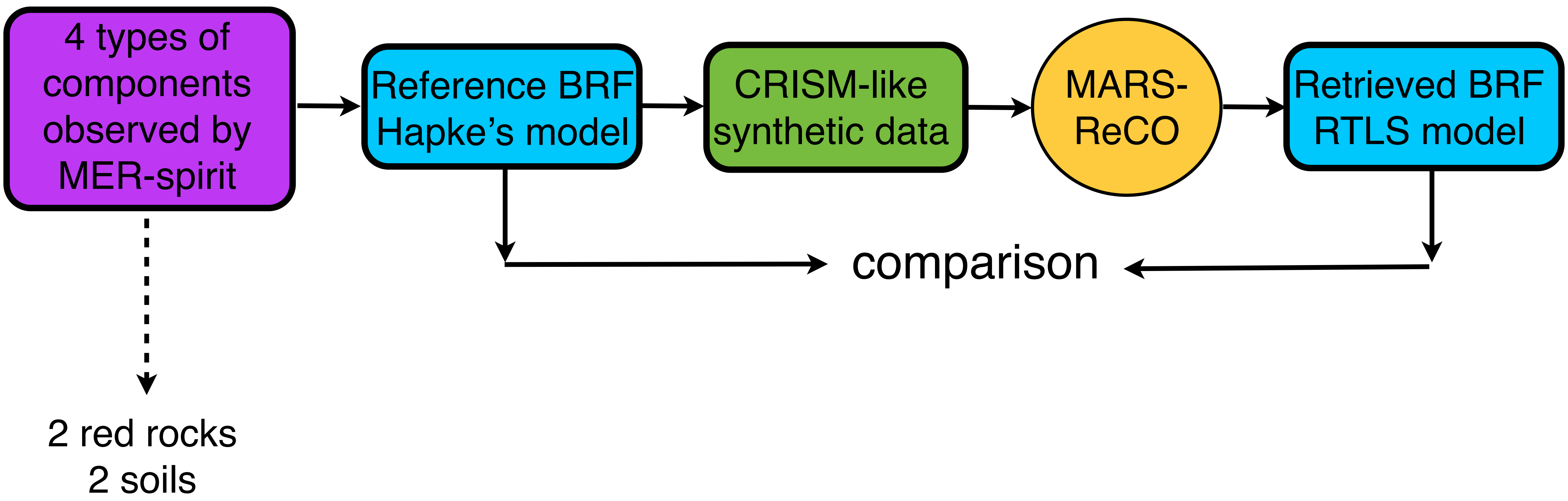
Sensitivity study: validation

Synthetic data mimicking the CRISM observations

Validation of BRF provided by MARS-ReCO

comparison between reference and retrieved BRF models

example: soil unit, AOT=0.5, θ_0=30°,ϕ={30°,150°} as for MRO flyby



Sensitivity study: validation

Synthetic data mimicking the CRISM observations

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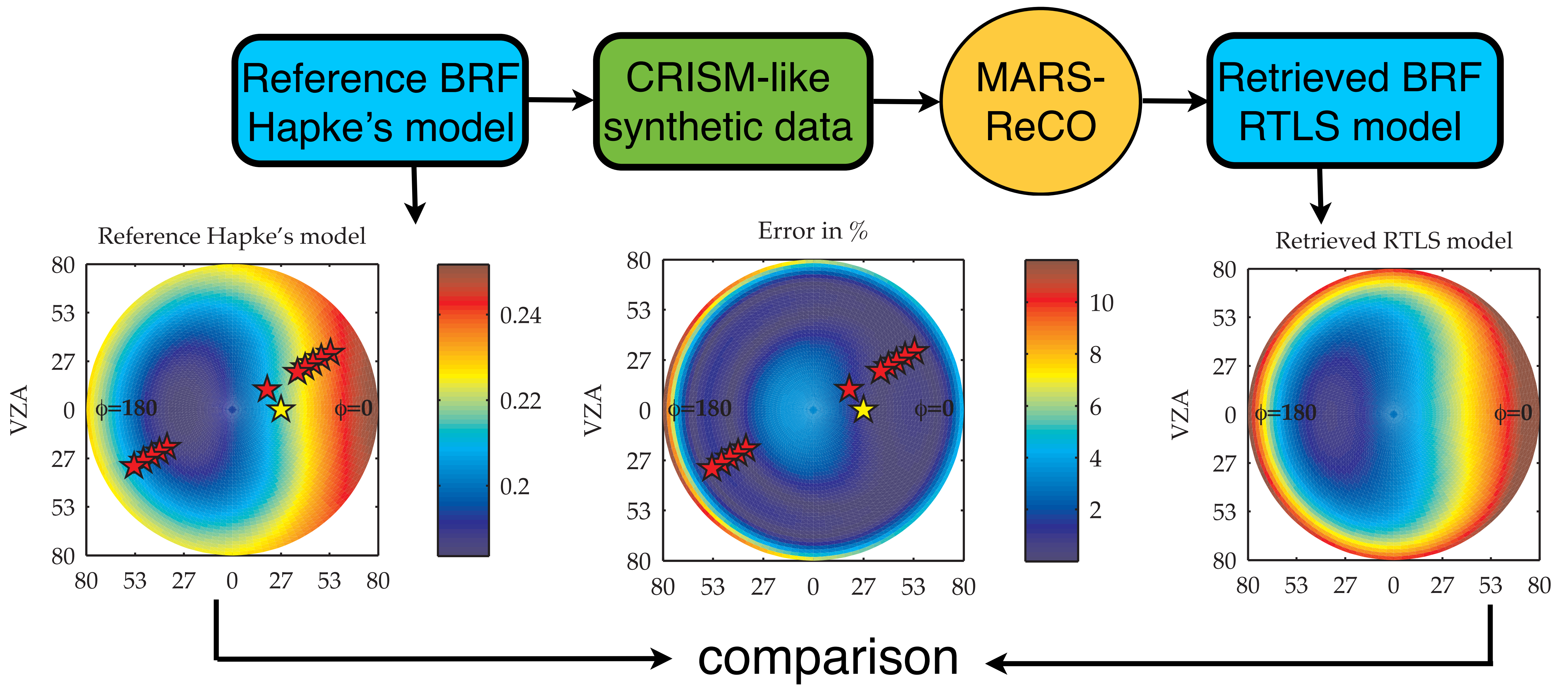
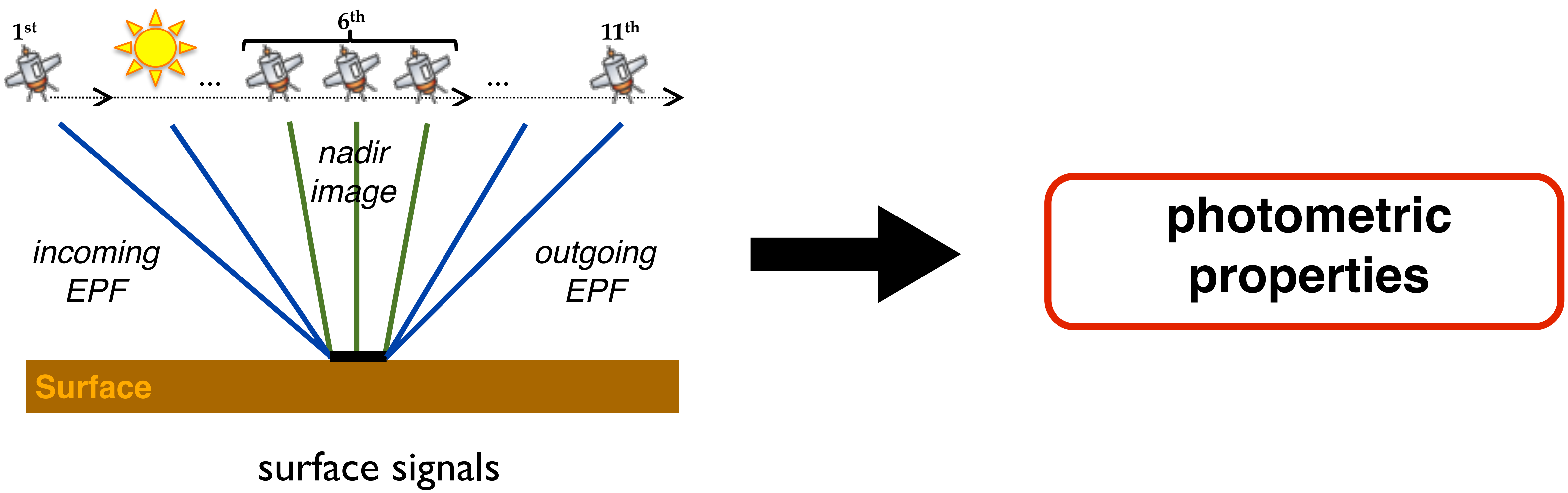


validation

Methodology

- for surface photometric study:

2. retrieval of the surface photometric properties from retrieved surface signals



Methodology: Hapke's photometric model

- semi-empirical photometric model: Hapke's model *[Hapke, 1993]*

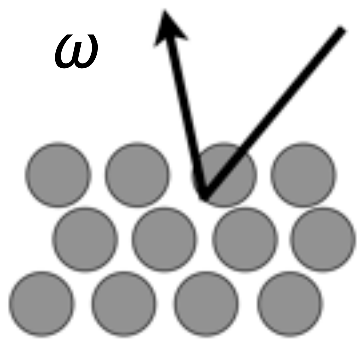
  - common photometric parameters *[e.g., Johnson et al., 2006a, 2006b, Jehl et al., 2008, Souchon et al., 2011]*

$$r\left(i,e,g,\omega,b,c,\theta,B0,h\right)=\frac{\omega}{4\pi}\,\frac{\mu_0}{(\mu_0+\mu)}\,\left\{\left[1+B(g,B0,h)\right]P(g,b,c)+H(\mu_0,\omega)H(\mu,\omega)-1\right\}S(i,e,g,\bar{\theta})$$

↑

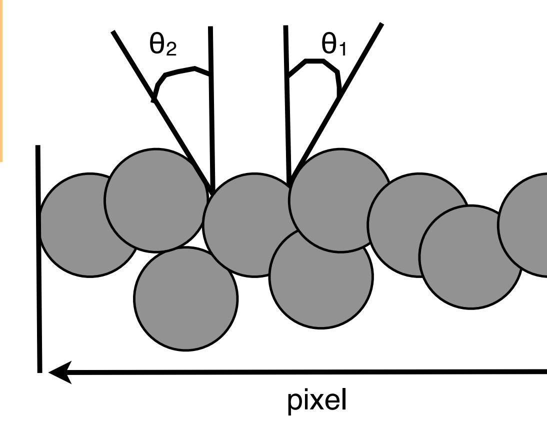
Measured surface bidirectional reflectance → **in function of 6 photometric parameters**

Methodology: Hapke's parameters



Single scattering albedo (0<*ω*<1)

Opposition effects (0<*B0*<1, 0<*h*<1) constrained only with phase angle < 20°

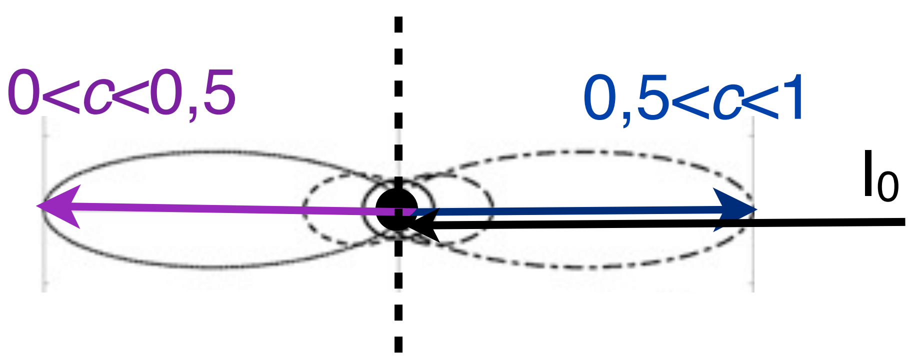


Macroscopic roughness (0<*θ*<45°)

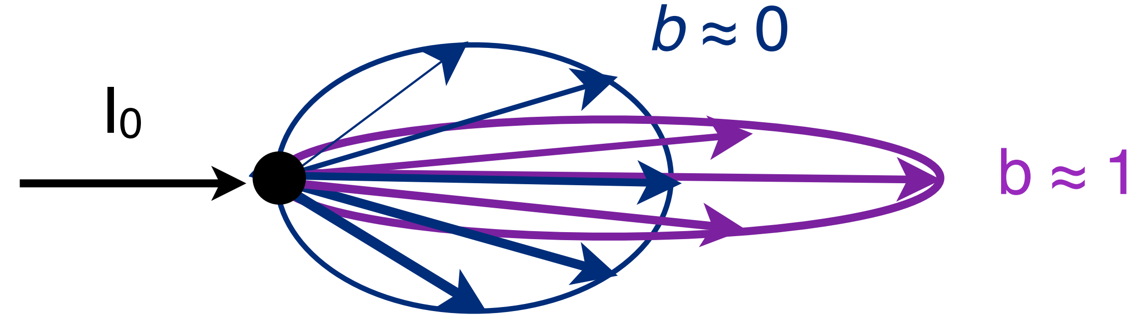
$$r\,(i,e,g,\omega,b,c,\theta,B0,h) = \frac{\omega}{4\pi}\,\frac{\mu_0}{(\mu_0+\mu)}\,\{[1+B(g,B0,h)]\,P(g,b,c)+H(\mu_0,\omega)H(\mu,\omega)-1\}\,S(i,e,g,\bar{\theta})$$

Phase function, 2 term of Henyey-Greenstein function

Backscattering fraction (0<*c*<1)



Asymmetric parameter (0<*b*<1)



Methodology: Bayesian inversion procedure

- **State of information** defined by a **probability density function (PDF)** over the parameter and data spaces *[Tarantola and Valette, 1982]*

  - prior information/PDF:
    - an **uniform PDF for each model parameters** in the physical range
    - a **gaussian PDF** for BRF from MARS-ReCO

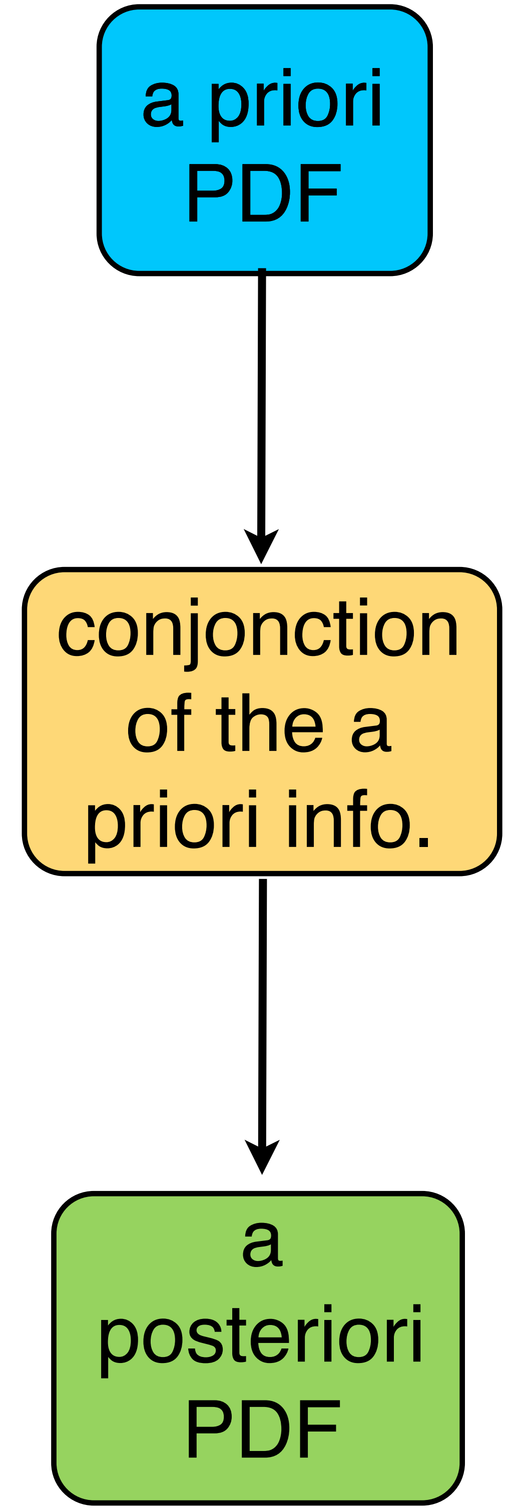
  - **baye's theorem** applied to infer solutions

$$\sigma_M(m) = k\,\rho_M(m)\,L(m)$$

$$L(m) = \int_D \partial d\, \frac{\rho_D(d)\,\theta(d \mid m)}{\mu_D(d)}$$

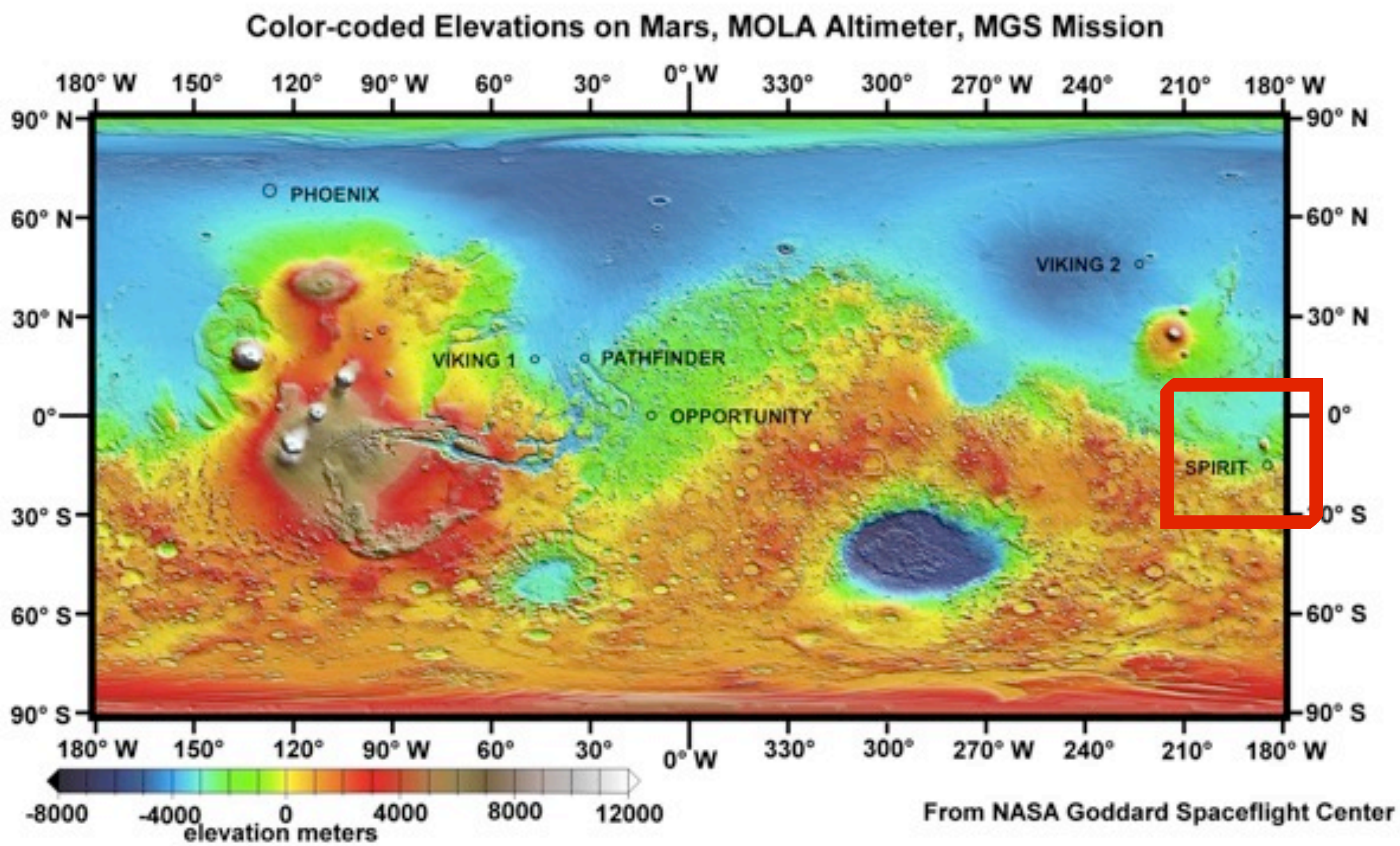
θ theoritical relation between d and m
μ nul information PDF for d
k constant

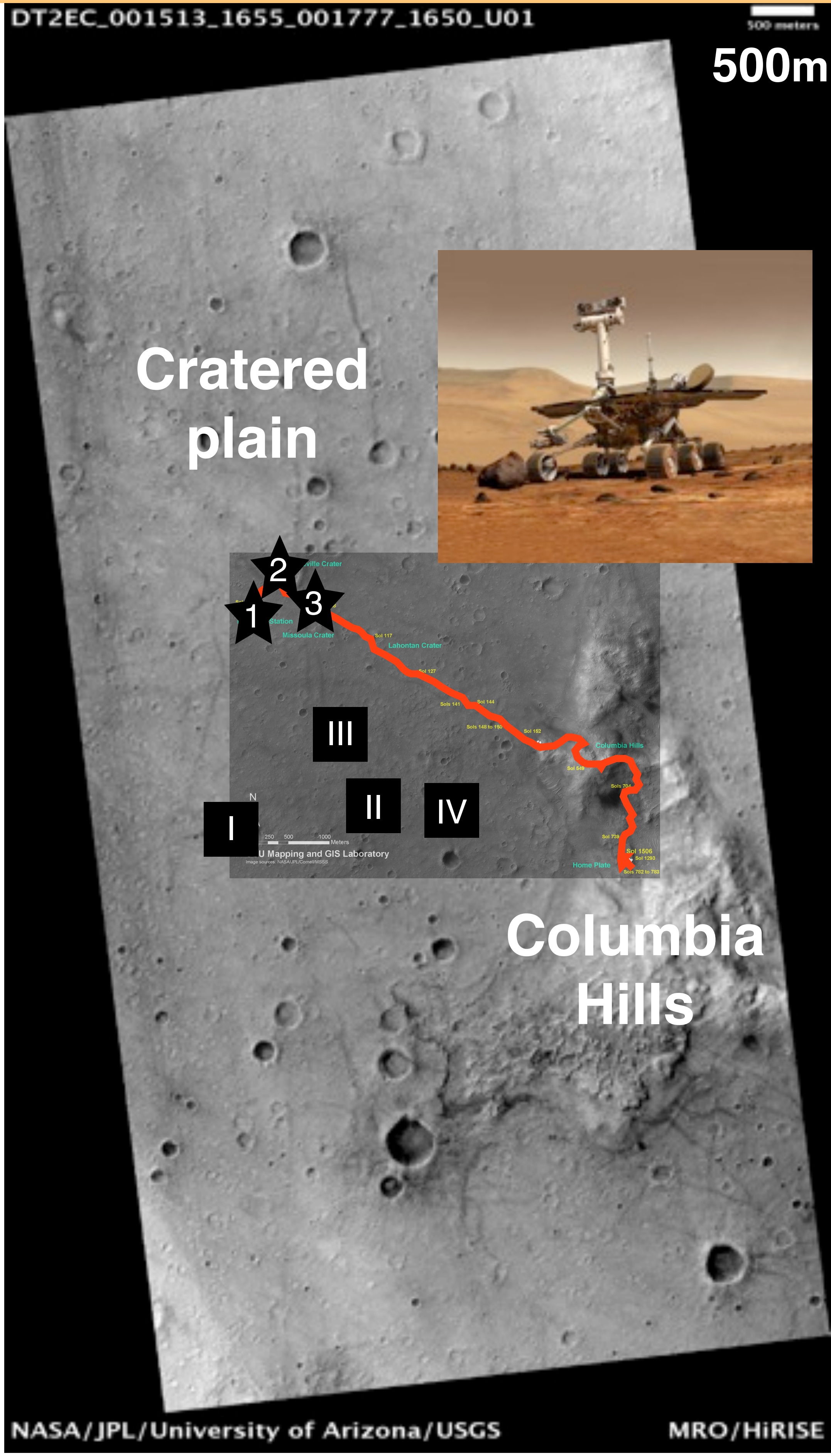
  - posterior information/PDF: PDF surface photometric parameters



Hapke's model: non linear expression ➙ Monte Carlo approach implying Markov chain

Application to CRISM data set: Gusev Crater





- **in situ photometric measurements** from Pancam instrument on Spirit *[Johnson et al., 2006]*

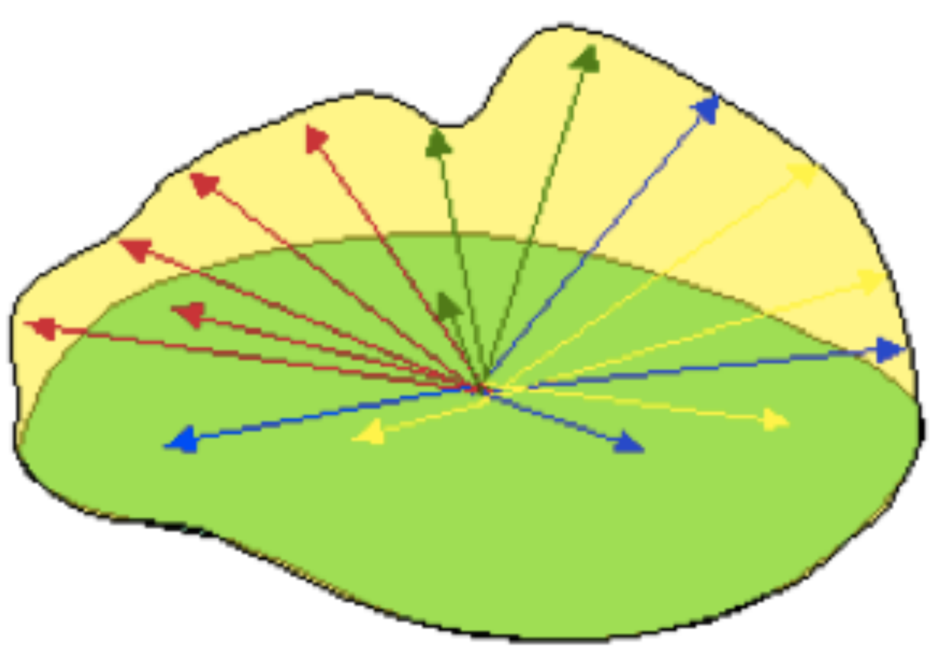
VALIDATION WITH REAL DATA

estimated photometric parameters at λ=750 nm

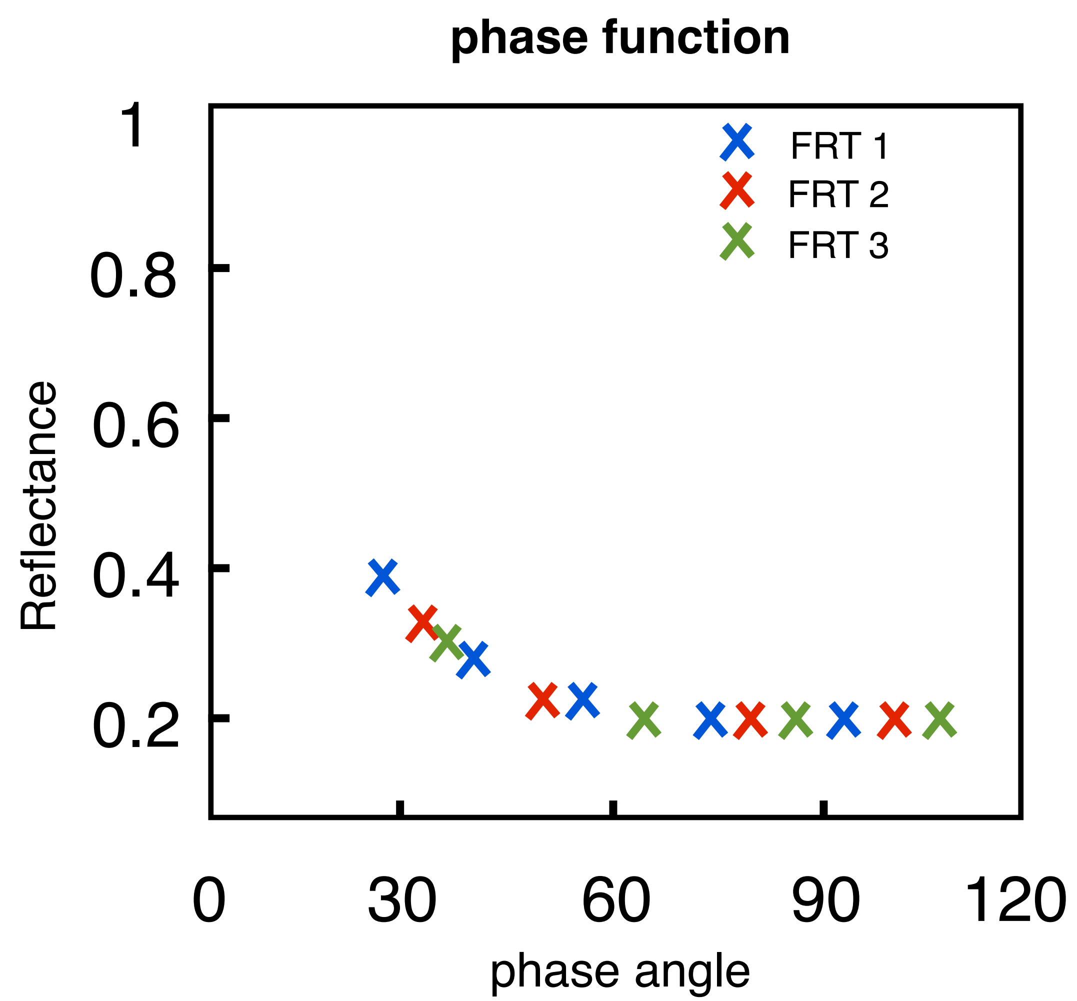
Application to CRISM data set: Gusev Crater

Full resolution targeted observations (FRT) - Multi-angle images

- 1 sequence only = 11 emergences
- combination with varied incidence angles: a better BRF sampling
- heliosynchroneous orbit of MRO: different illuminations = different seasons ! (observations with less surface changes !!!)



3D scattering lobe

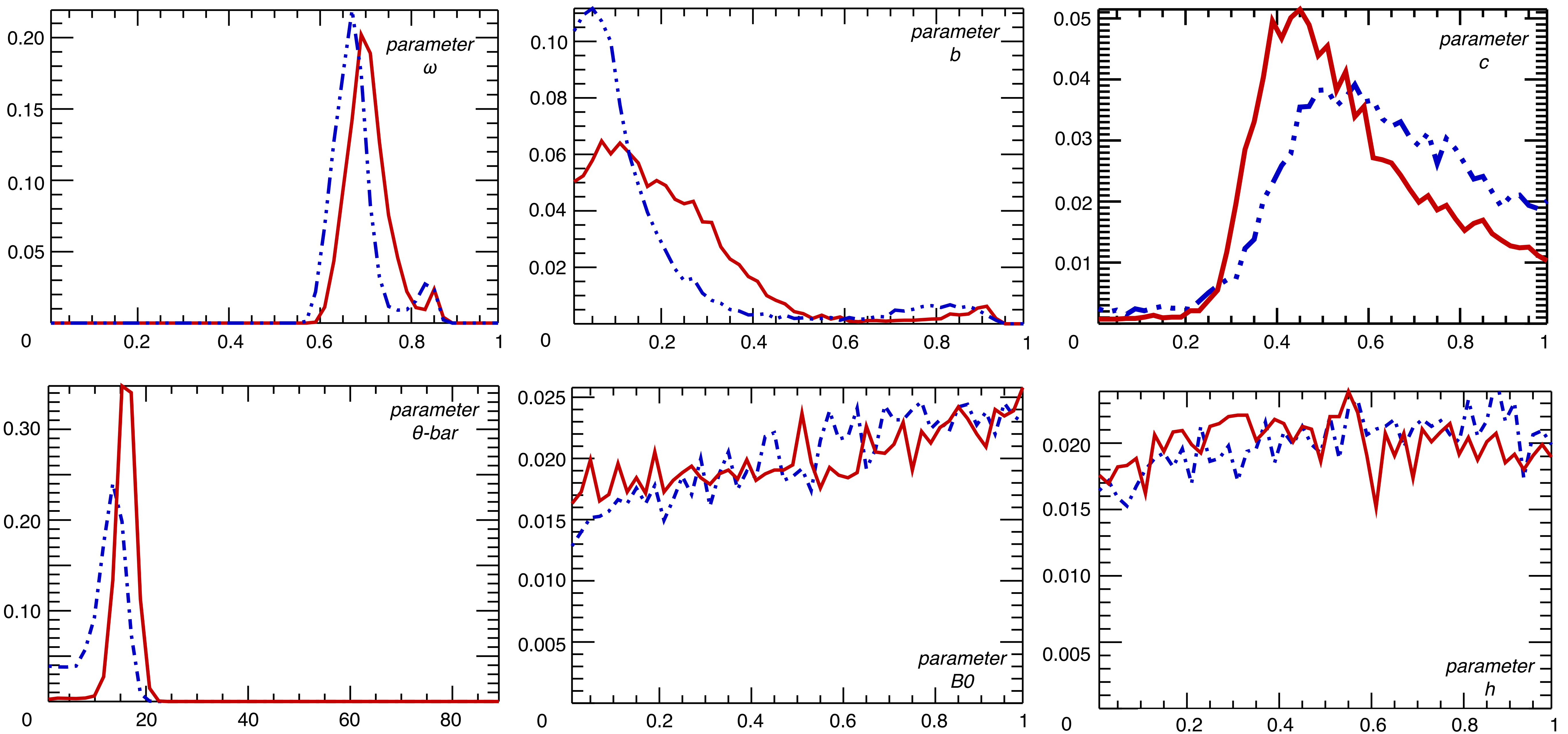


Methodology: inversion procedure

a priori hypothesis: uniform PDF for the parameter / a gaussian PDF for data

using only one FRT

using 3 combined FRTs

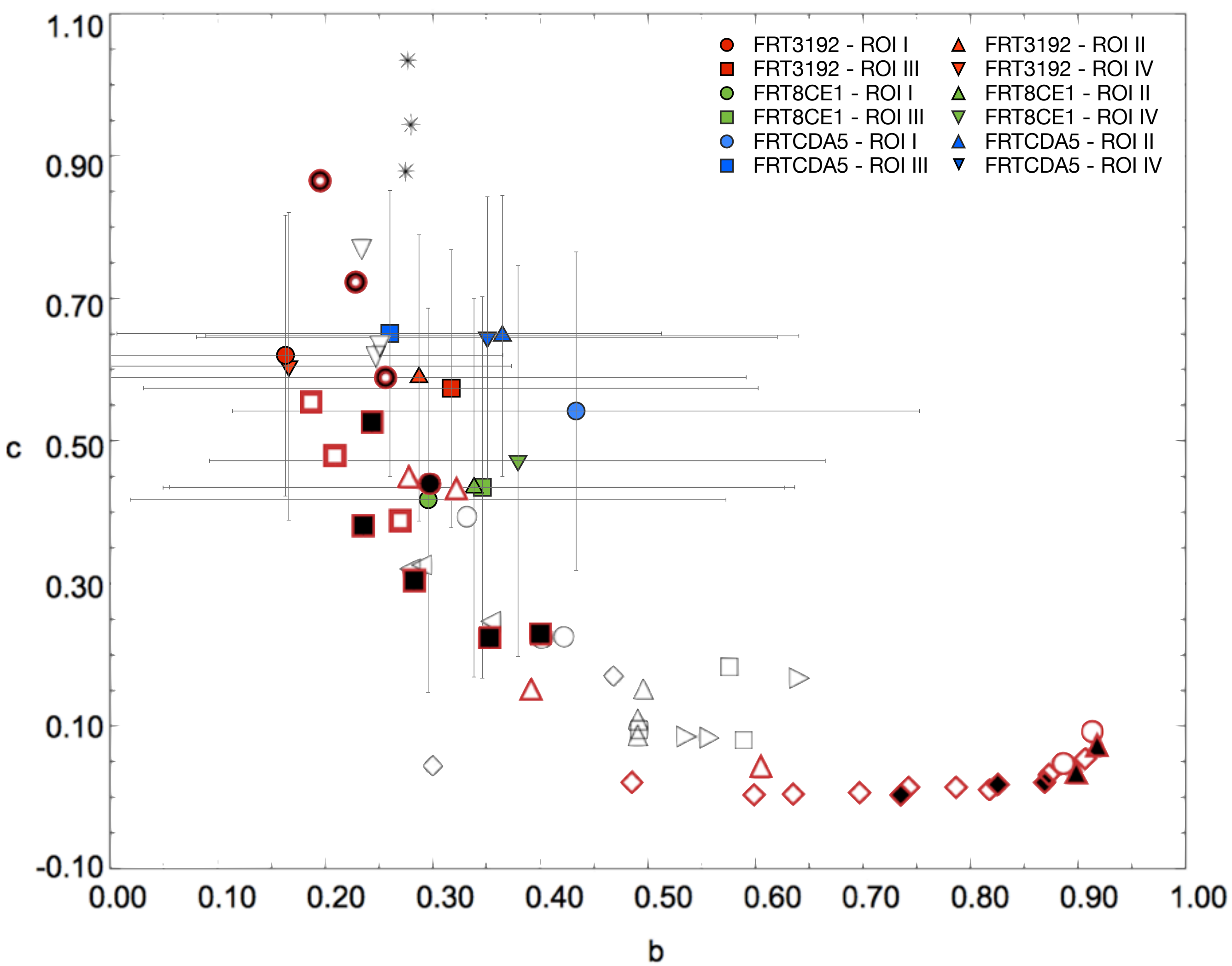


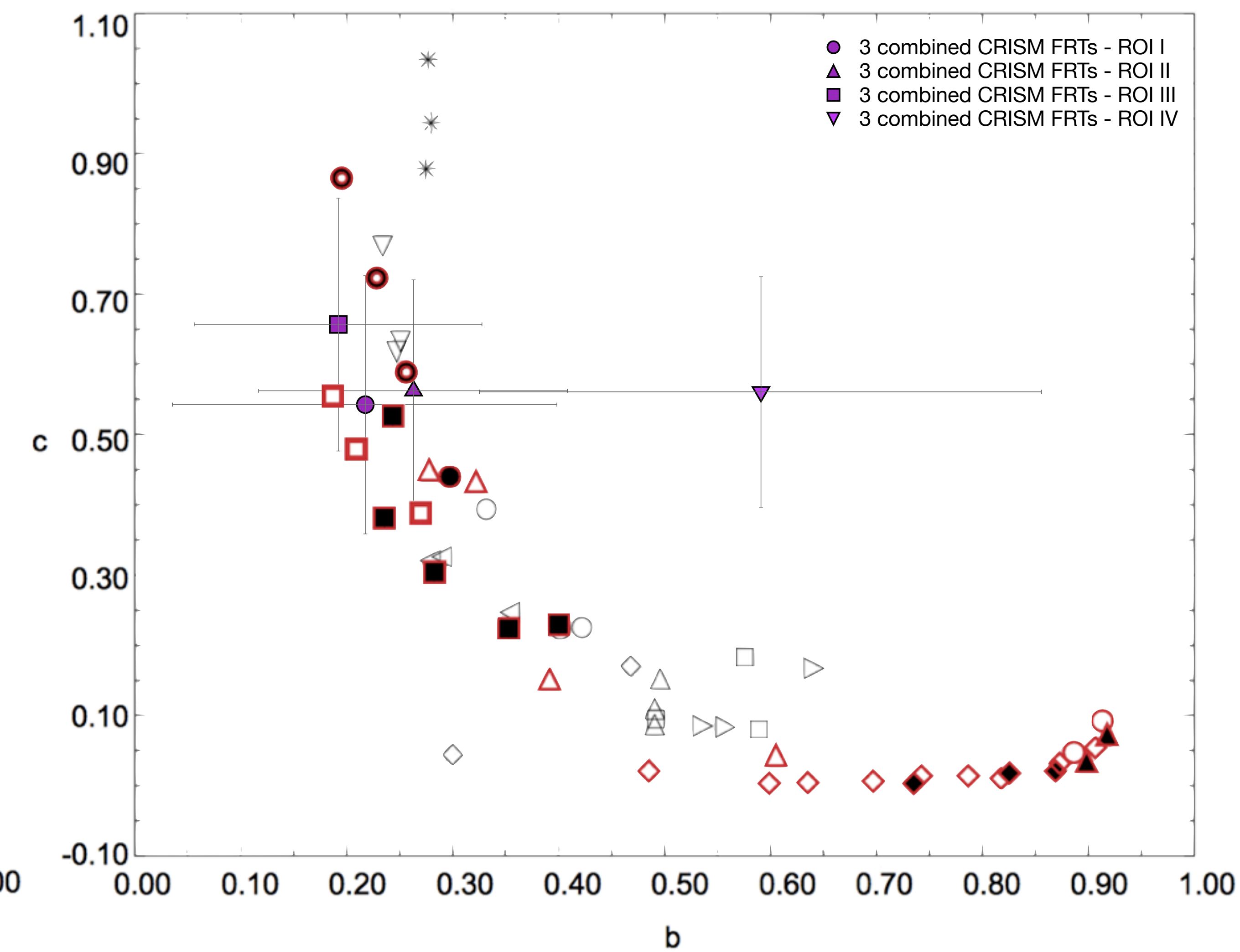
for parameters *ω*, *b*, *c*, *θ*, a solution exists

for parameters *B0*, *h*, not constrained by the CRISM data set (g>20°)

Application to CRISM data set: Gusev Crater

Confrontation with experimental measurements (McGuire and Hapke, 1995, Souchon et al., 2011)

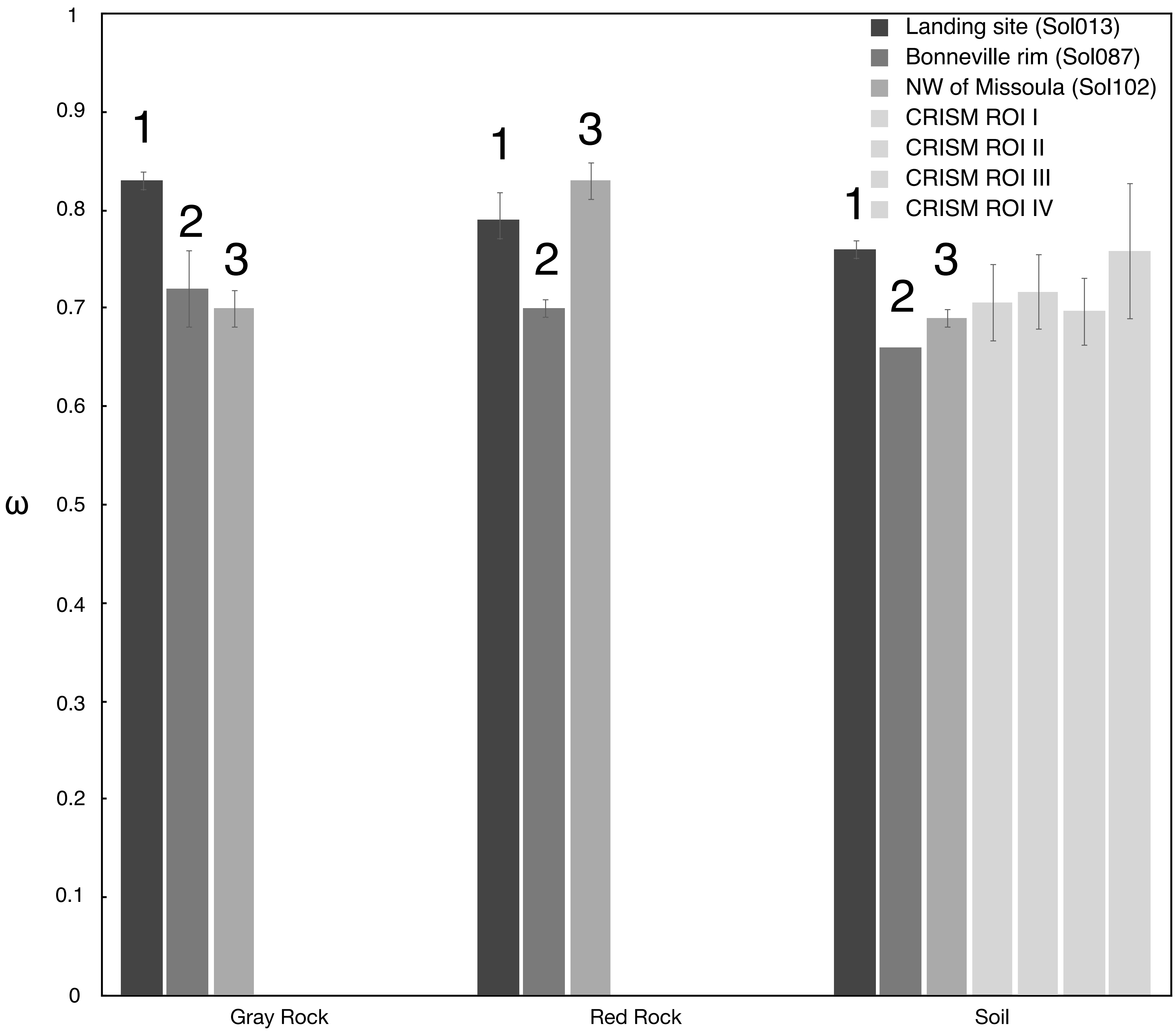


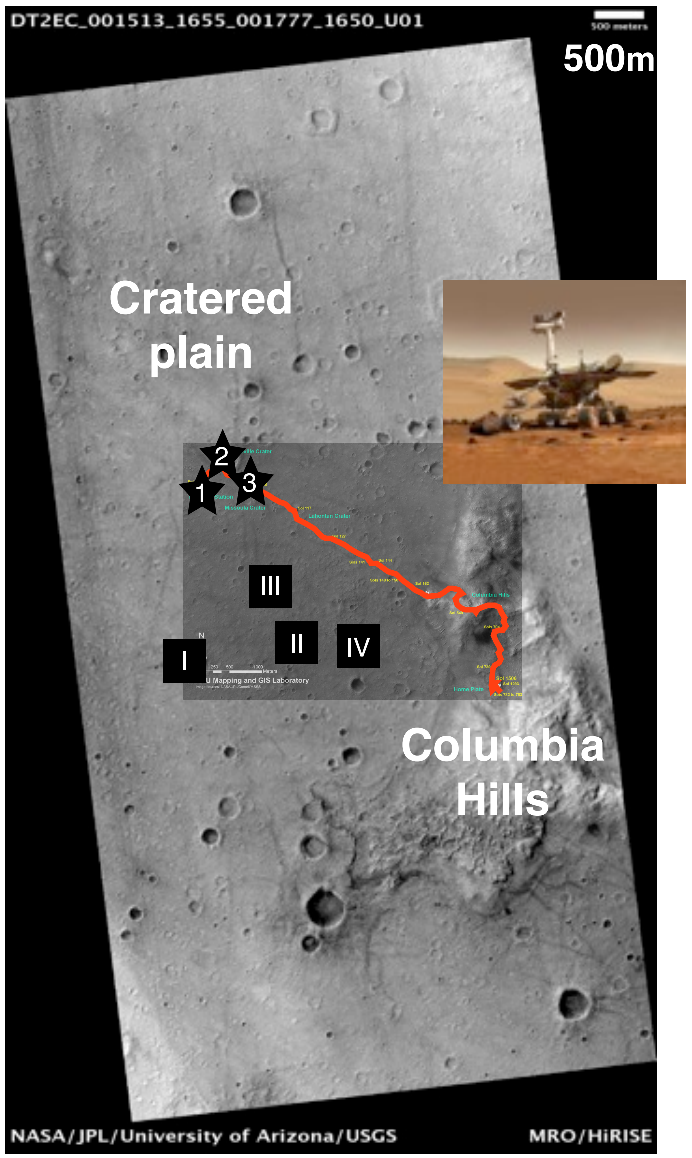


1. **consistent with L-shape** defined by artificial and natural samples
2. broad backscattering properties
3. **3FRTs are necessary to be close to experimental results**

Application to CRISM data set: Gusev Crater

Confrontation with in situ photometric measurements (Johnson et al., 2006)





at λ=750 nm

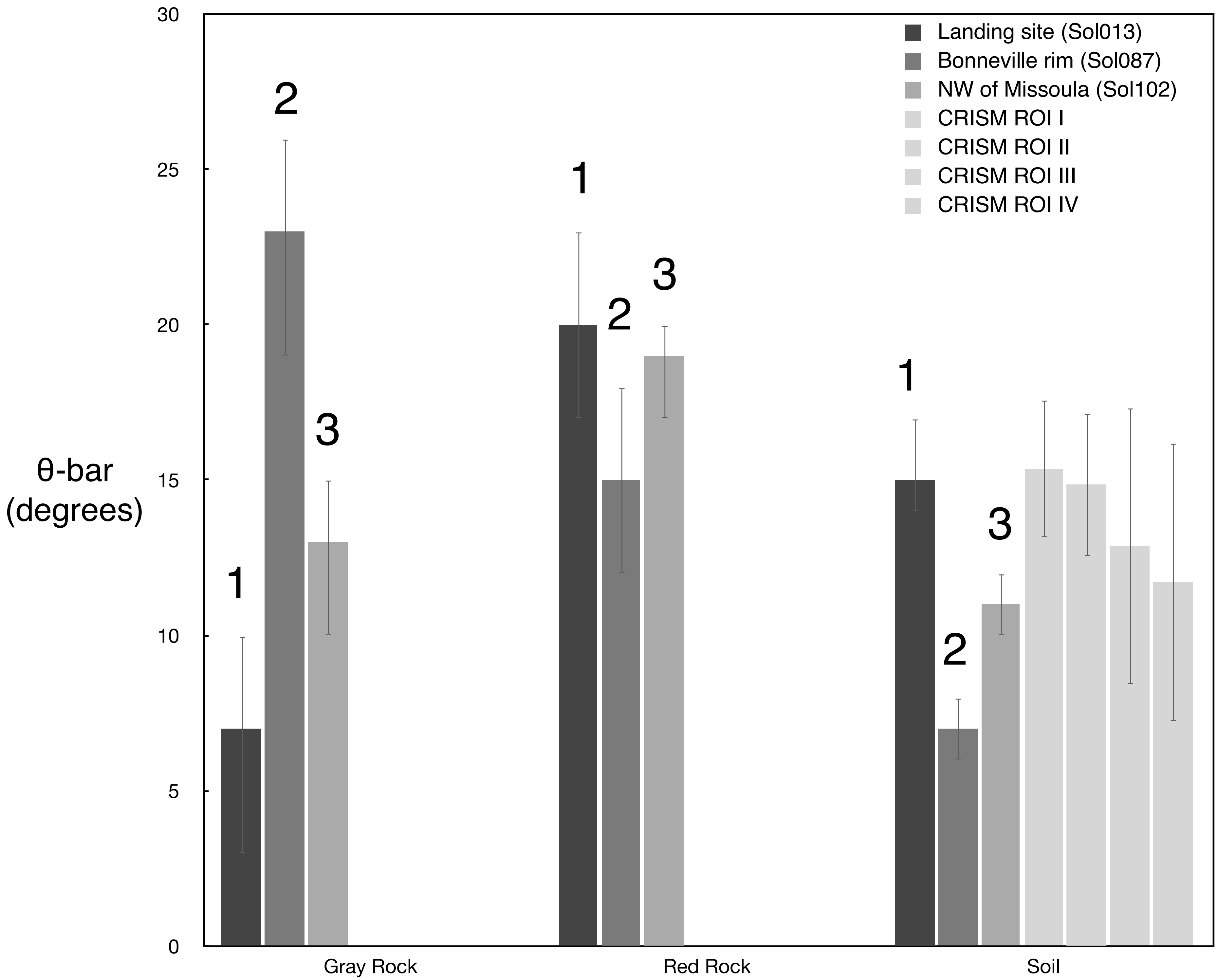
Pancam:
0,65 < w < 0,85

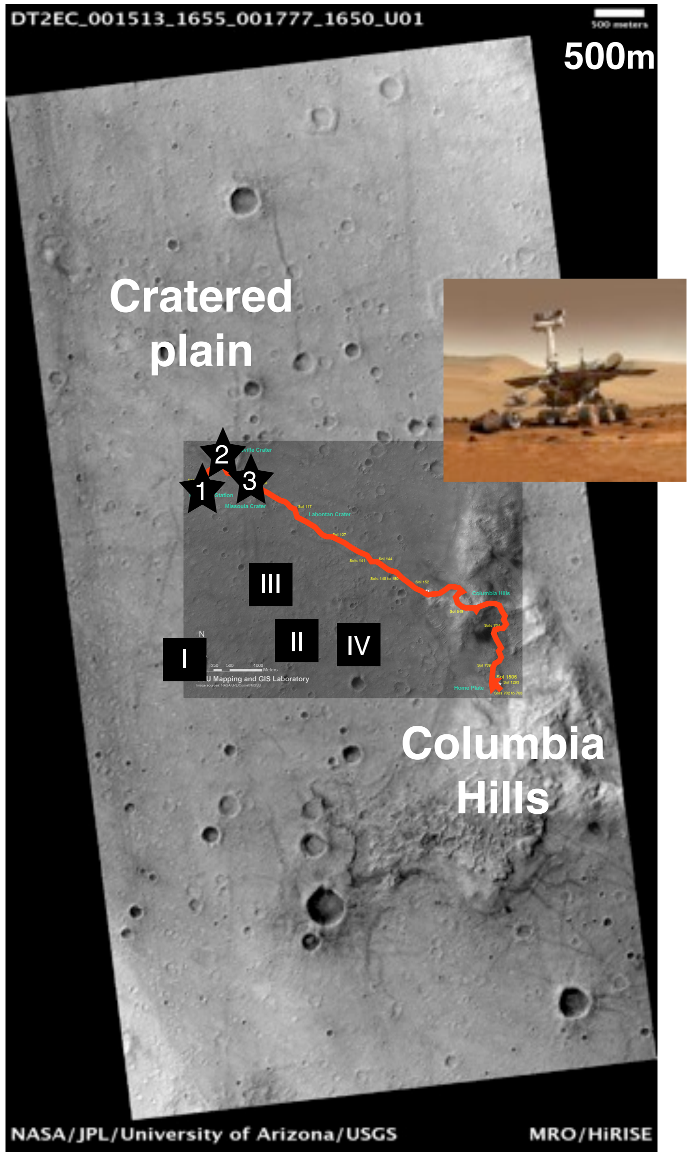
CRISM:
0,69 < w < 0,79

Consistent

Application to CRISM data set: Gusev Crater

Confrontation with in situ photometric measurements (Johnson et al., 2006)



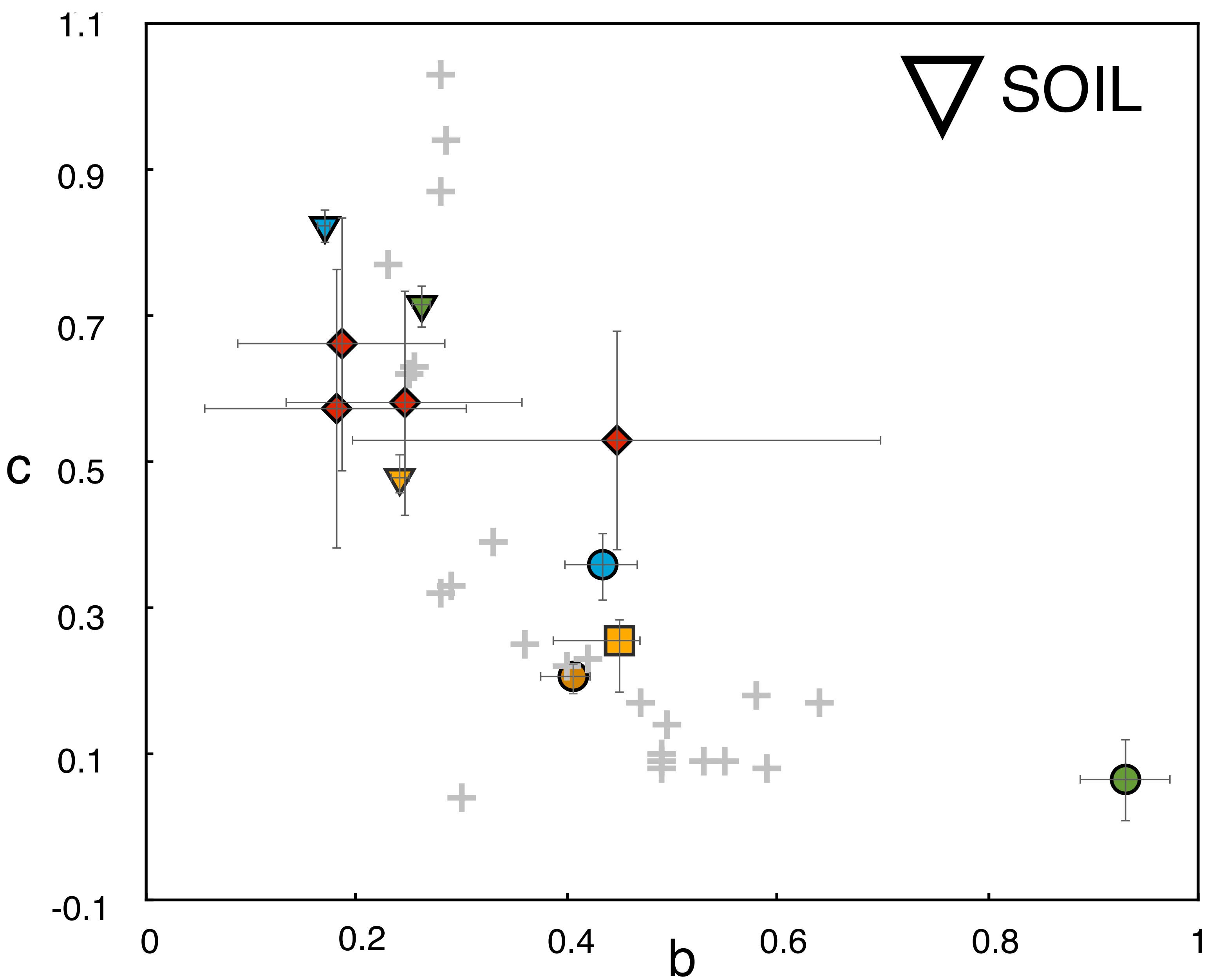


consistent

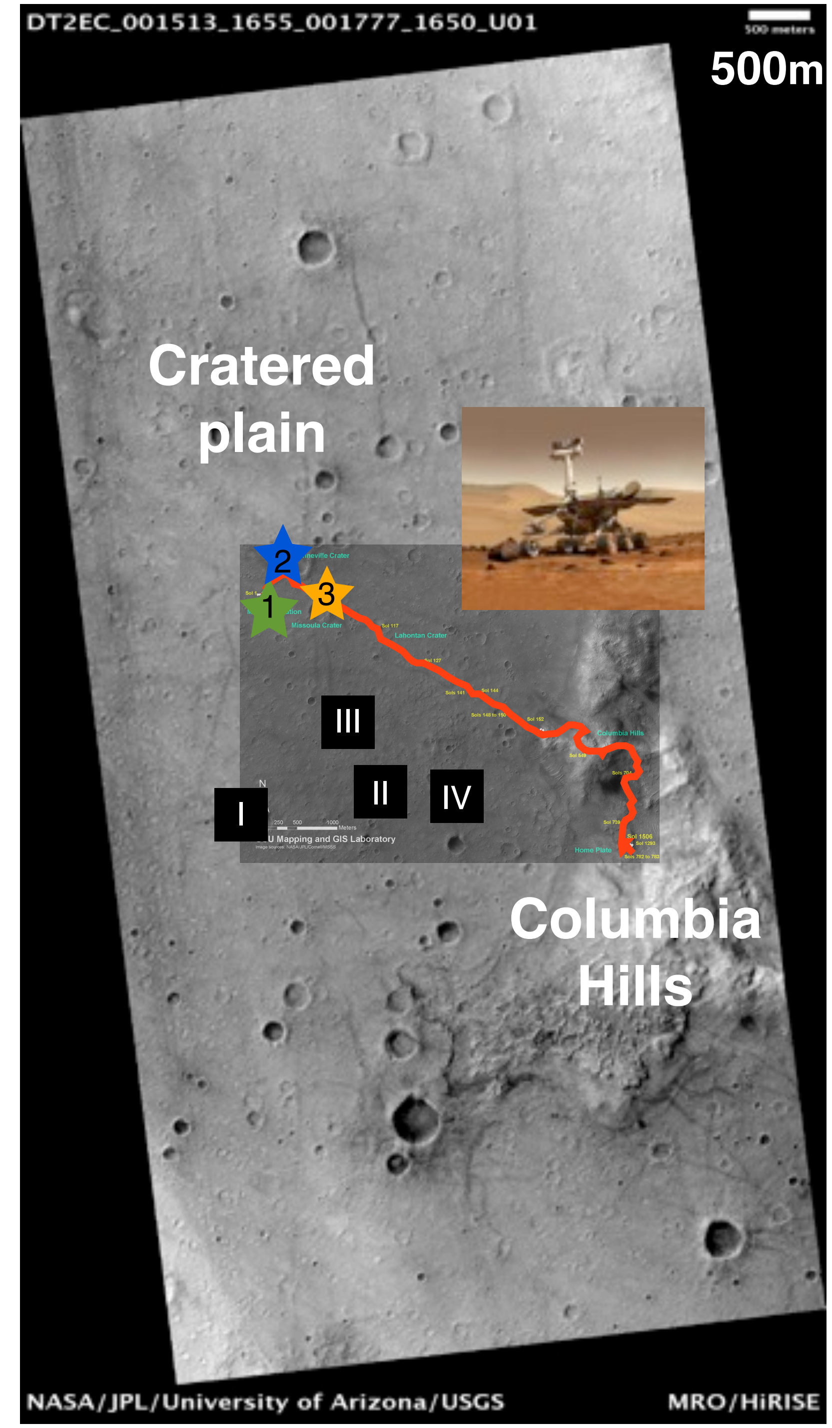
- close to soil unit

Application to CRISM data set: Gusev Crater

Confrontation with in situ photometric measurements (Johnson et al., 2006)



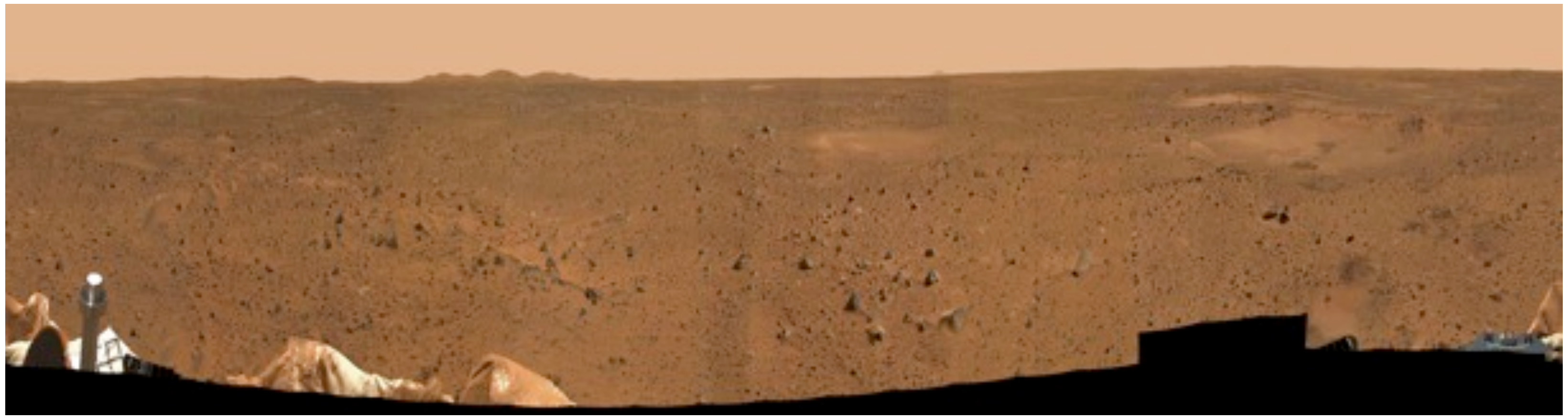
- Artificial particles (L-shape)
- Gray Rock (Landing Site Sol 013)
- Gray Rock (Bonneville Rim Sol 087-088)
- Gray Rock (NW of Missoula Sol 102-103)
- Soil (NW of Missoula Sol 102-103)
- 3 combined CRISM FRT observations (Gusev Crater)
- Soil (Landing Site Sol 013)
- Soil (Bonneville Rim Sol 087-088)
- Red Rock (NW of Missoula Sol 102-103)



photometrically and spatially consistent with soil unit

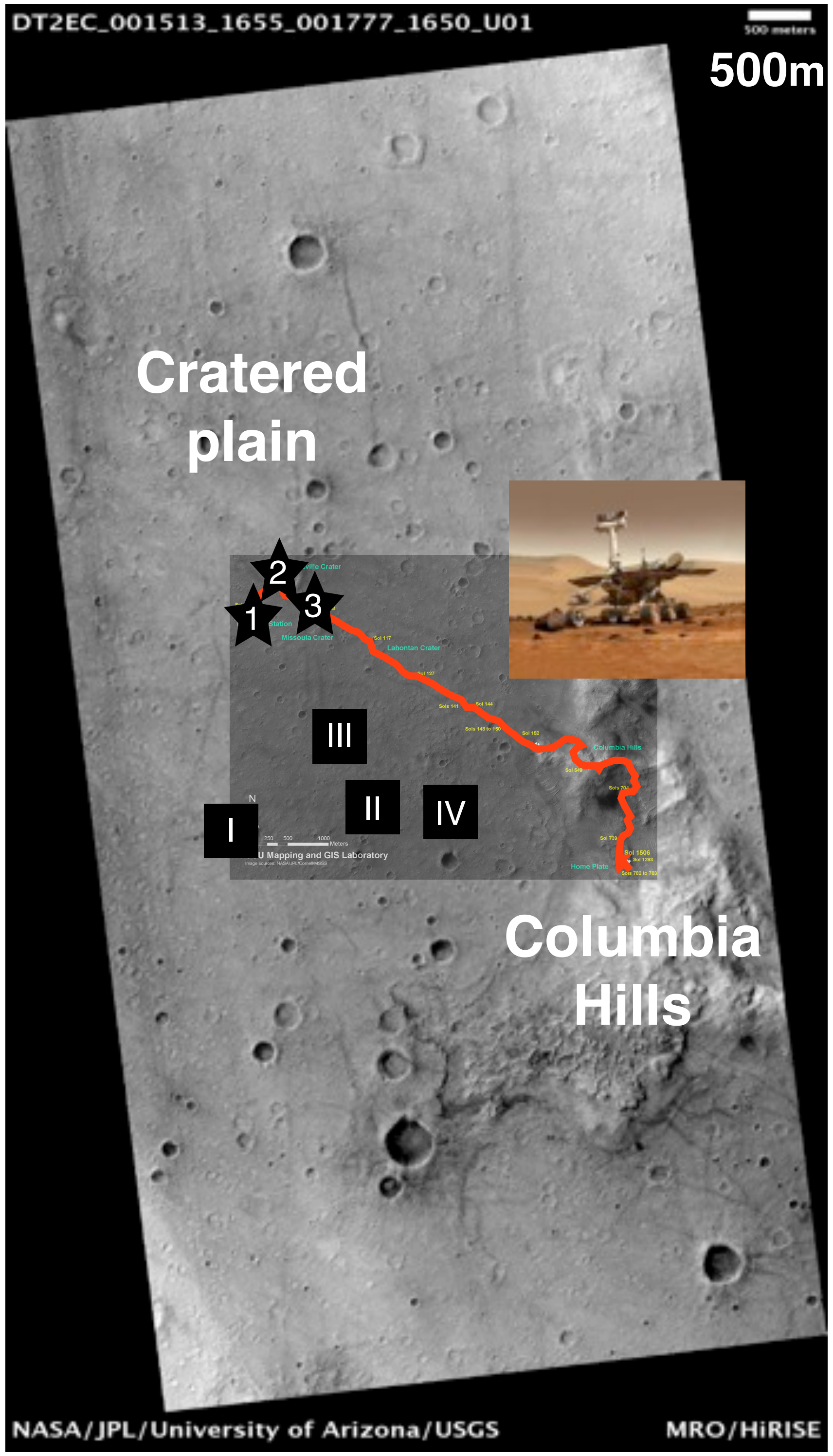
Application to CRISM data set: Gusev Crater

Confrontation with in situ photometric measurements (Johnson et al., 2006)



Landscape, dominated by **soil**
(unconsolidated materials)
Panaroma from Spirit

consistent with soil unit !!!



Conclusion

The novelties:

- **hyperspectral multiangular** data by **CRISM:** better characterize the surface and aerosol scattering properties

- **new aerosol correction (MARS-ReCO)**: determination **more precisely** the surface BRF

b, c, ω, θ **from CRISM consistent with in situ photometric results**
(Johnson et al., 2006)

VALIDATION

Perspectives:

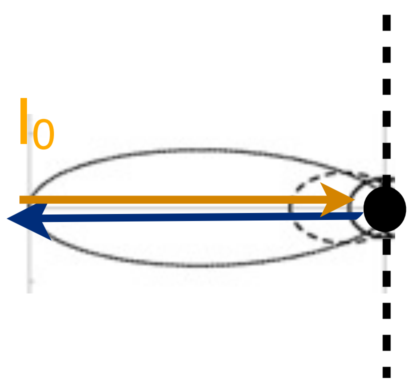
- to **map** the surface physical properties

- to do **laboratory experiments** to improve our knownledge of the meaning of each physical parameters

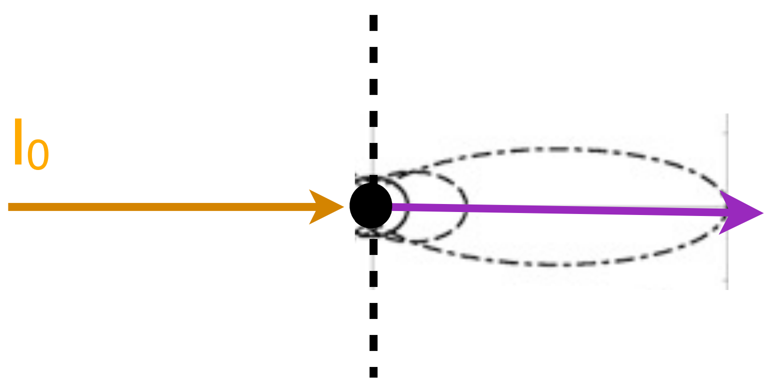
- to study the photometric parameters in function of **wavelength**

Application to CRISM data set: Gusev Crater

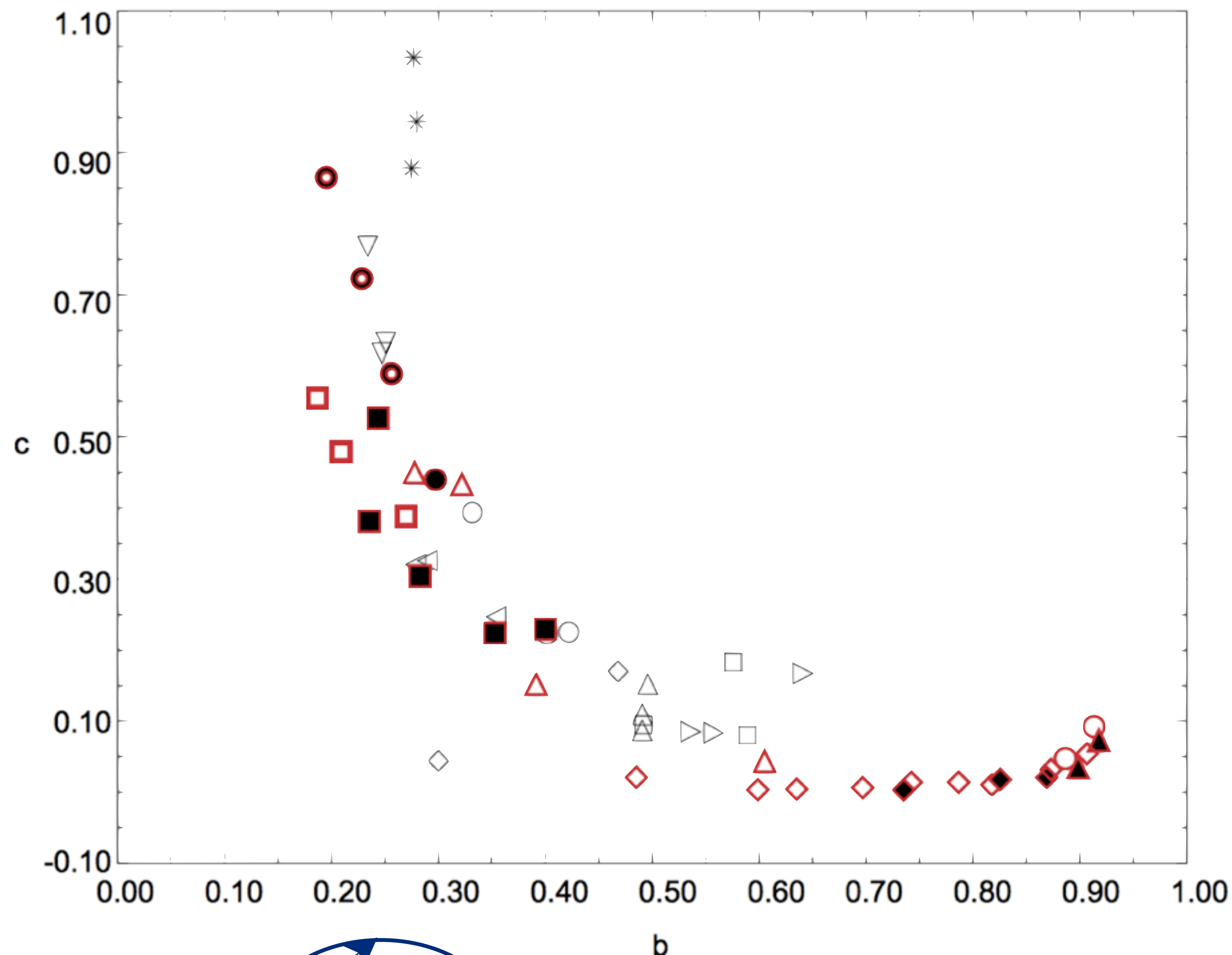
Confrontation with experimental measurements (McGuire and Hapke, 1995, Souchon et al., 2011)

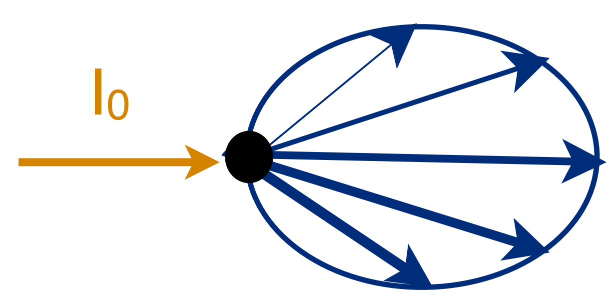


backward scattering



forward scattering

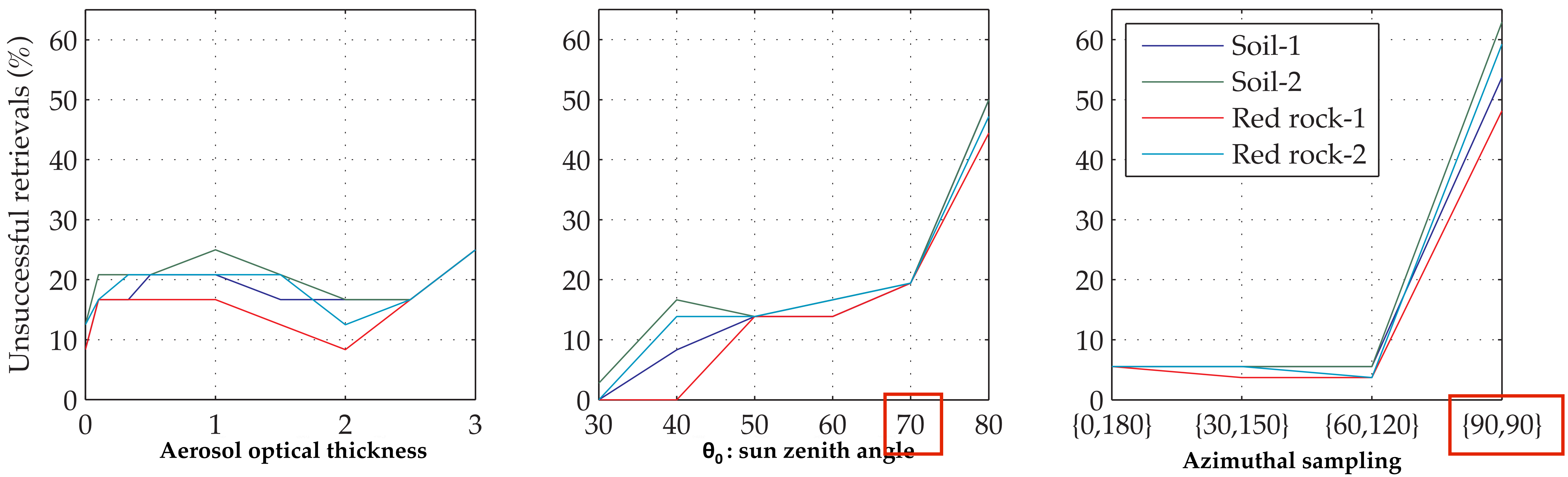




Sensitivity study

Limits of MARS-ReCO

Rate of unsuccessful retrievals



not depends on AOT input (aerosol optical thickness)

model less accurate when:

- extreme illumination
- solar cross-principal plane