Mapping Titan's atmospheric and surface properties through massive inversion of Cassini/VIMS data

Luca **Maltagliati**

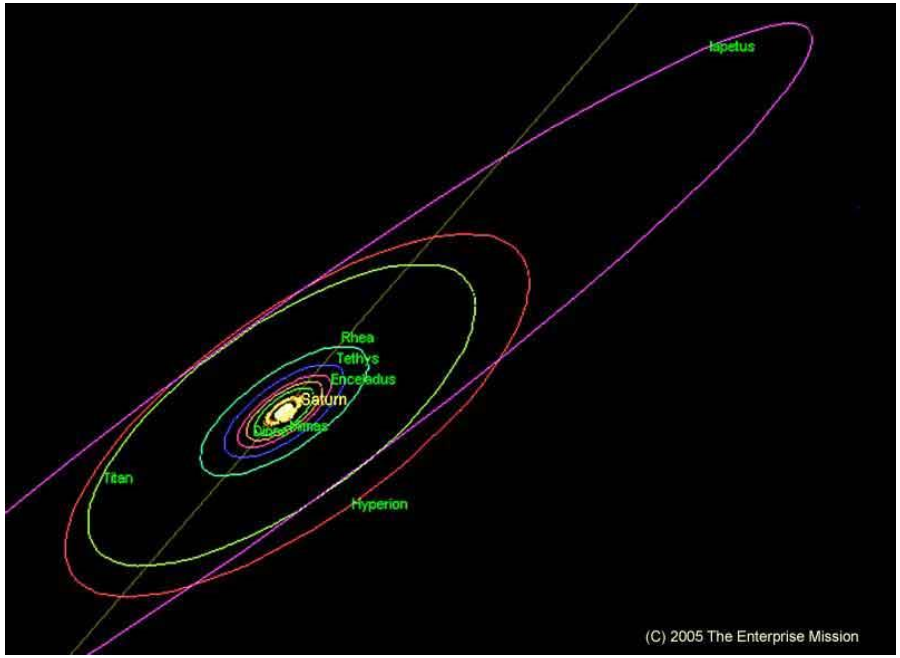
Supervisor: S. Rodriguez

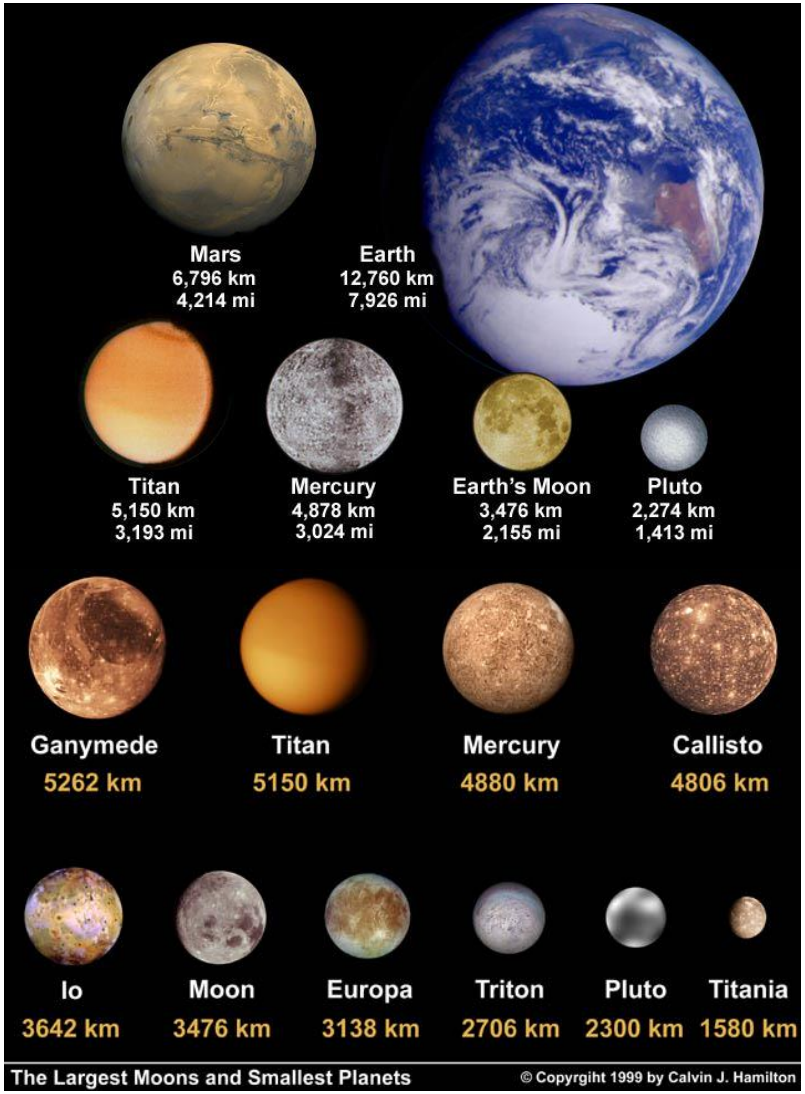
Outline

- Basic facts about Titan
- The Cassini spacecraft and the VIMS spectrometer
- Overview of the atmosphere and the surface of Titan
- Motivation of my work
- Method and first results
- Conclusions and perspectives

Basic facts about Titan

Largest moon of Saturn, second largest in the Solar System





Basic facts about Titan

Largest moon of Saturn, second largest in the Solar System

BUT: g = 0.14g like other icy moons (Moon = 0.17g, Mercury=0.37g)

→ $\rho = 1.88\ g\ cm^{-3}$ → equal *mixture of rocks & ices*

Revolution around Saturn in 15h22'

Tidally locked

The main regulator of seasons is the orbit around the **Sun** (~30 y)

Axial tilt of Saturn (&Titan) = 26.73° → important **seasonal effects**

Saturn eccentricity = 5.5° → yearly solar flux variations ~20%

Basic facts about Titan

Largest moon of Saturn, second largest in the Solar System

Low density, interior of rocks and ices

Significant ***seasonal effects***, cycle of 30 years

Significant ***perihelion-aphelion asymmetry***

Presence of a thick atmosphere

One of the 4 bodies in the Solar System

The only satellite

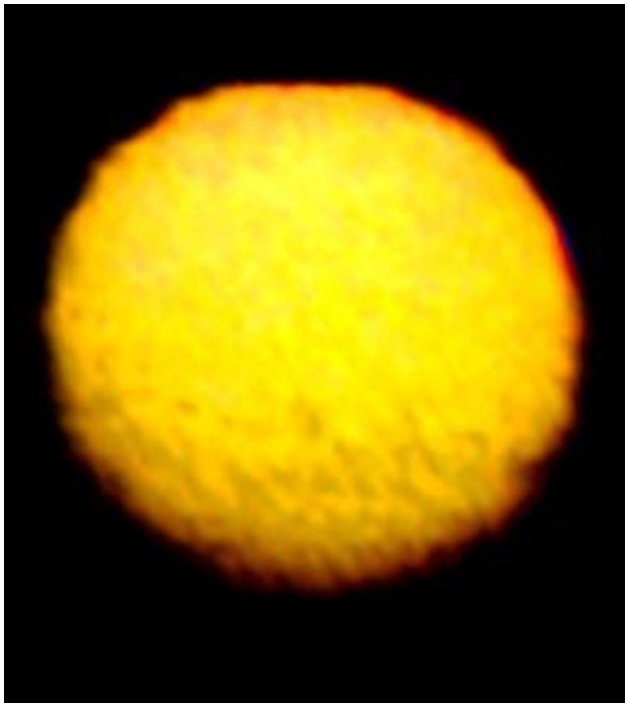
Brief history of observations

1655: discovery (Huygens)

1908: first tentative detection of the atmosphere (Comas Solà)

1944: confirmation of the atmosphere, detection of CH_4 (Kuiper)

1979: Pioneer 11 flyby, first images



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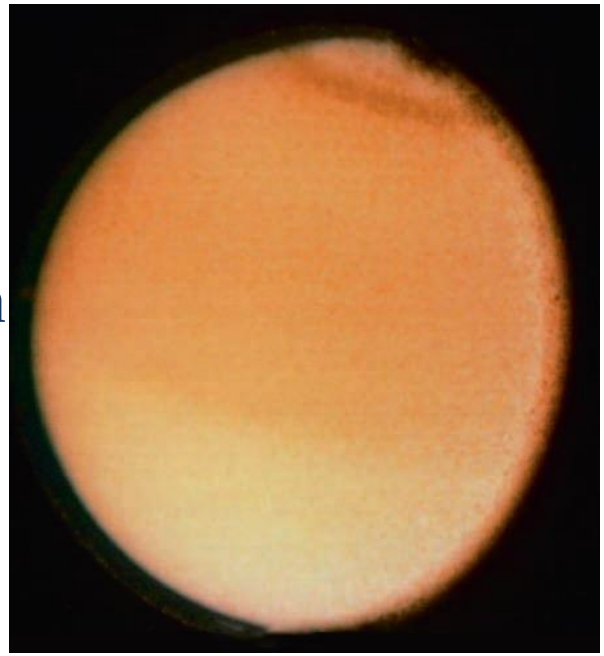

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1980: Voyager 1 (&2) flyby: breakthrough

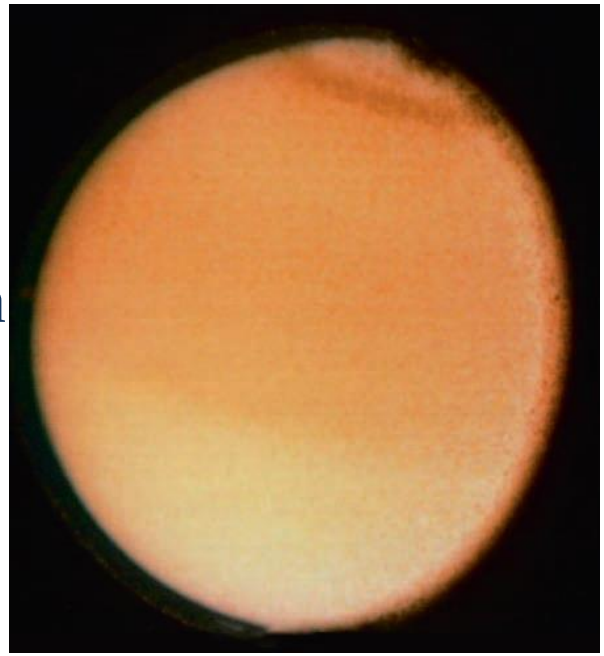
Atmospheric thermal structure

Bulk and trace composition, latitudinal distribution of gases

Observations and optical depth of the haze

Structures attributed to global circulation → climatically active body

Brief history of observations



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- Observations and optical depth of the haze
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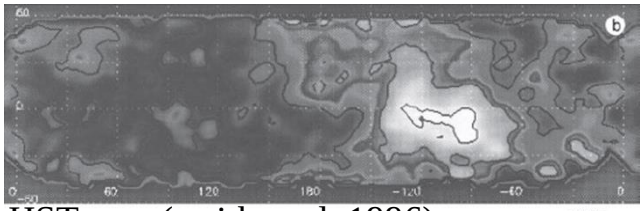
Post-Voyager: from Earth and Earth's orbit (ISO, HST, TEXES…)

- Continuous observations of the atmosphere – clouds, winds
- First observations of the surface (not images)
- Vertical profiles from stellar occultations

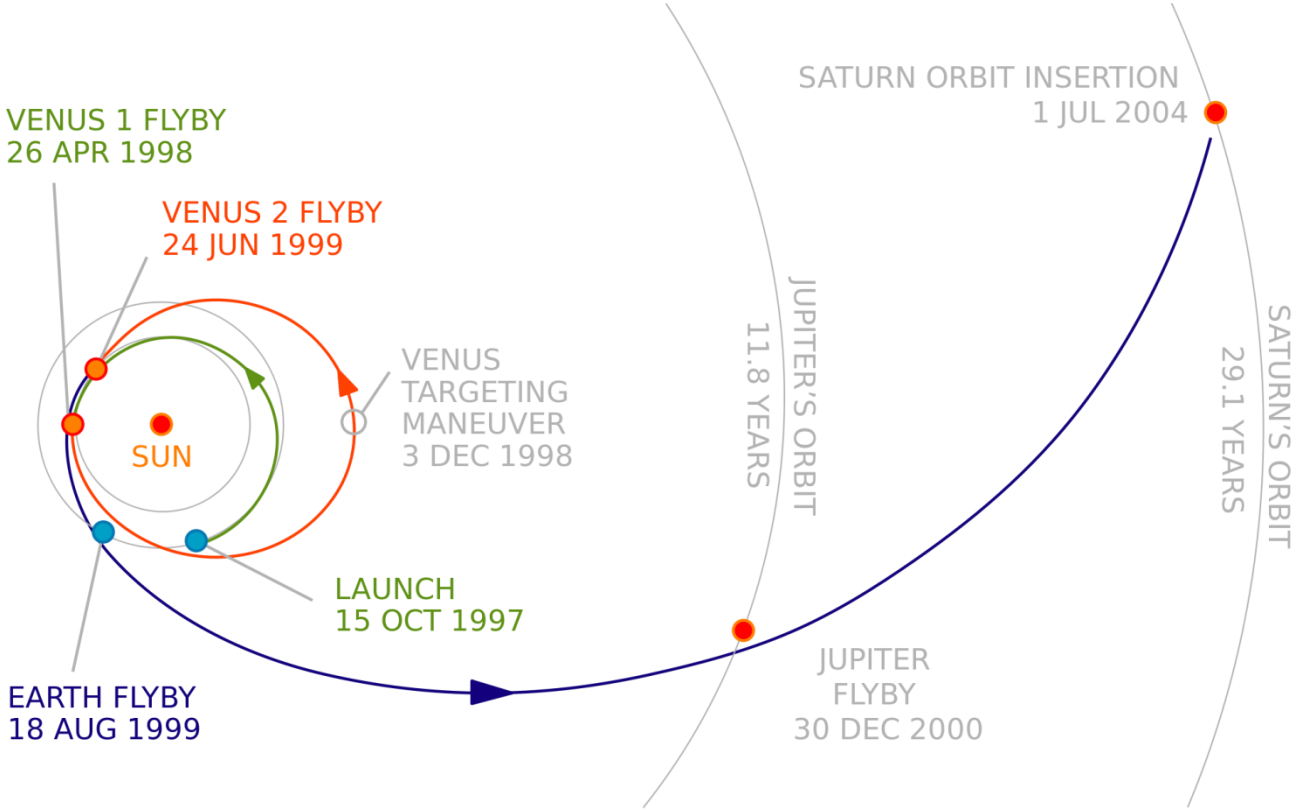


HST map (smith et al. 1996)

The Cassini-Huygens mission

NASA-ESA-ASI flagship mission

Origins in 1982 (!), launch in 1997, arrival in 2004



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Strong ***focus on Titan*** – more than 100 flybys up to now

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Deployment of the Huygens lander, 15 Jan 2005

- 2h30’ atmospheric descent
- ~30’ on ground (then end of communication window)

- Images of the surface
- Measurements of atmospheric temperature and composition (during descent)
- Information on surface characteristics

The Cassini-Huygens mission

Comprehensive payload of **12** instruments

Optical Remote Sensing

4 complementary spectrometers, from UV to mid-IR (+ camera)

Fields, Particles and Waves

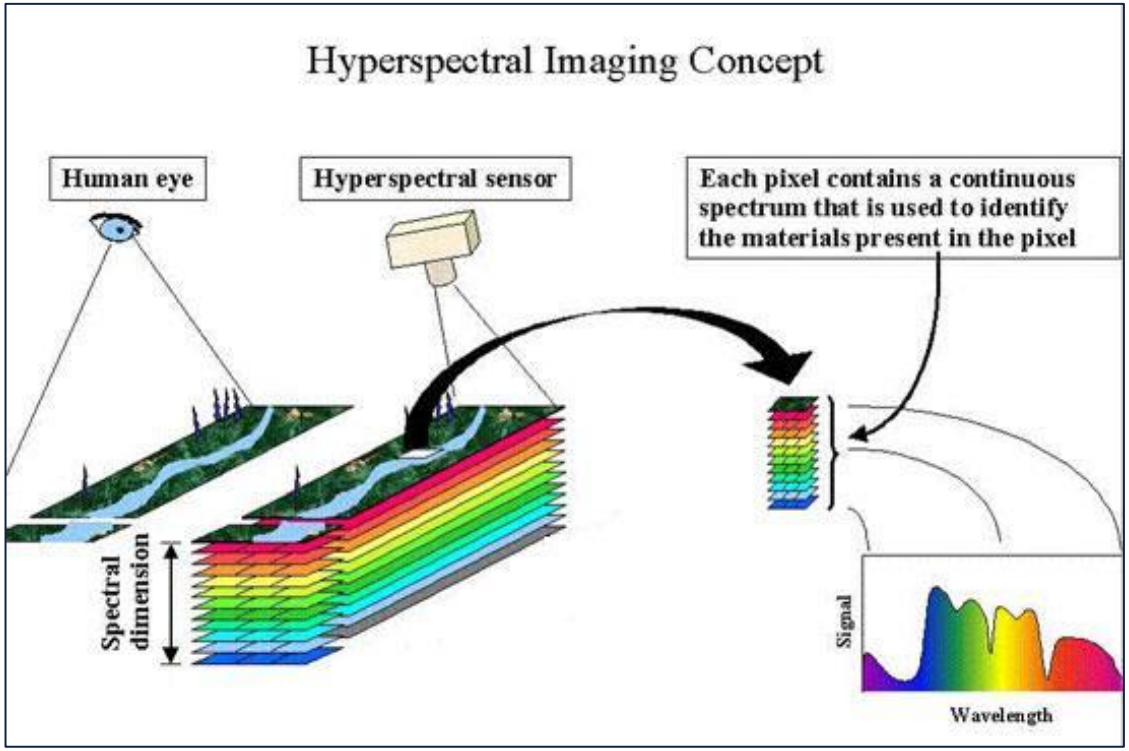
6 instrument for the Kronian environment

(magnetosphere & plasma, cosmic dust, mass spectrometer)

Microwave Remote Sensing

Radar and radio science

VIMS
Visible and Infrared Imaging Spectrometer



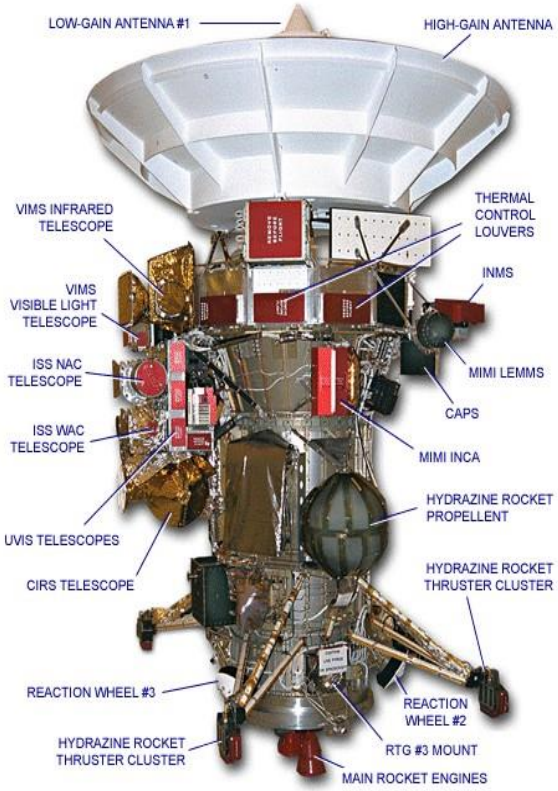
VIMS
Visible and Infrared Imaging Spectrometer

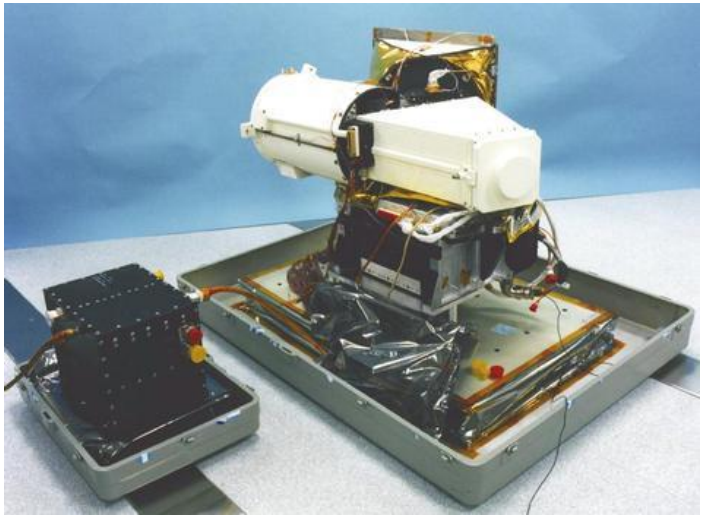
2 channels: ***visible*** (0.35-1.07 µm), ***near-IR*** (0.88-5.1 µm)

Near-IR channel: 256 spectels, FWHM from 13 to 20 nm

S/N > 100 over the whole spectral range

observations in nadir, limb, occultation geometry





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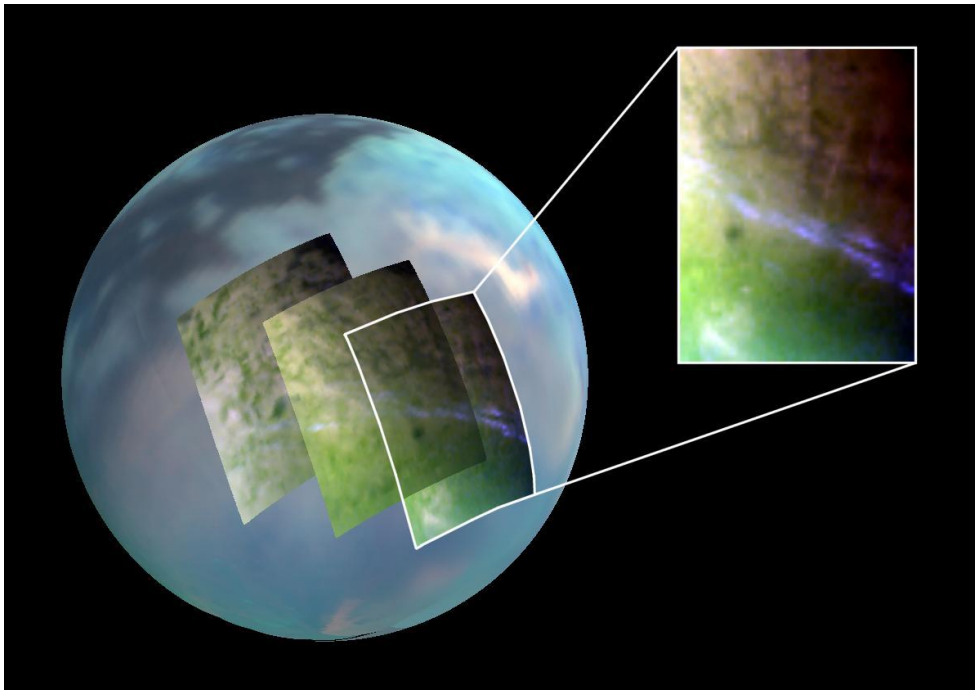
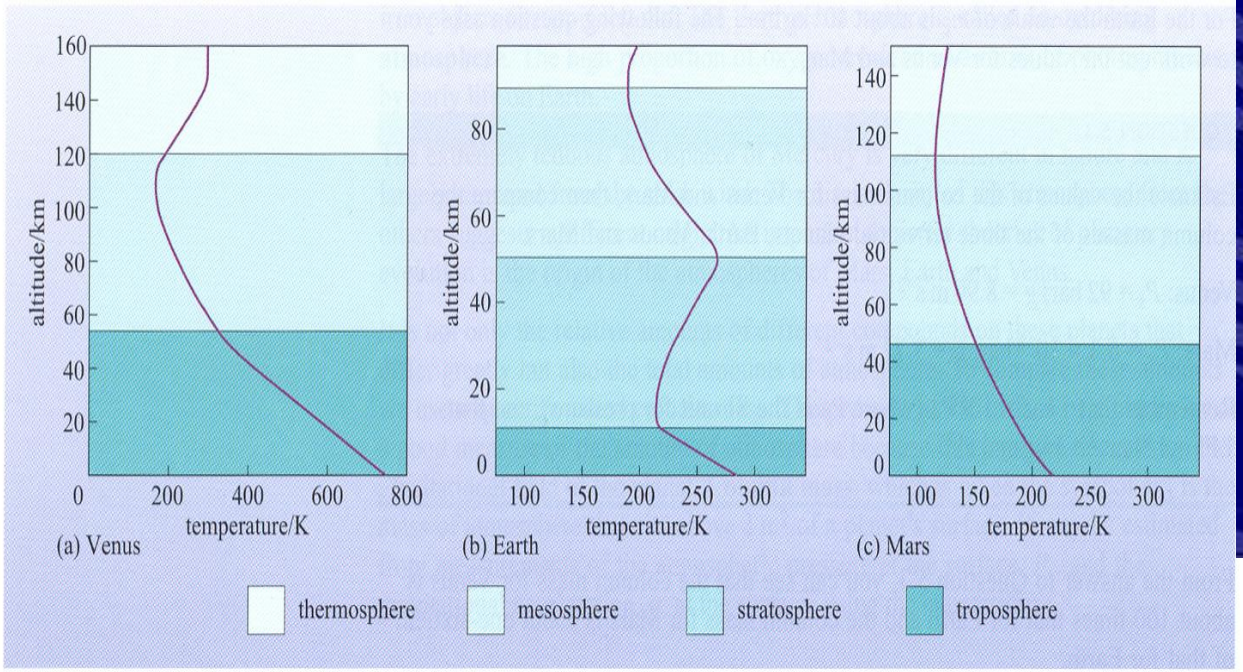
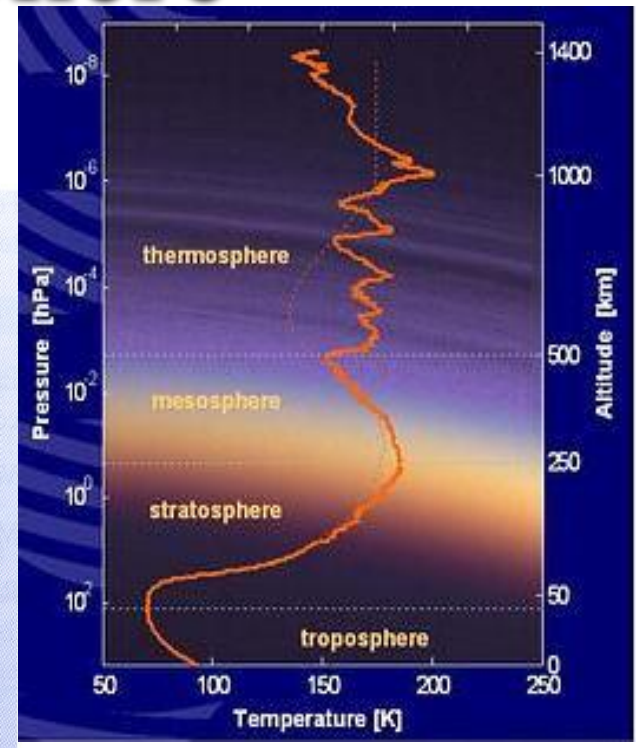
Hyperspectral images

(up to) 64×64×256 pixels
FOV 32×32 mrad
best spatial resolution ~500 m/pix



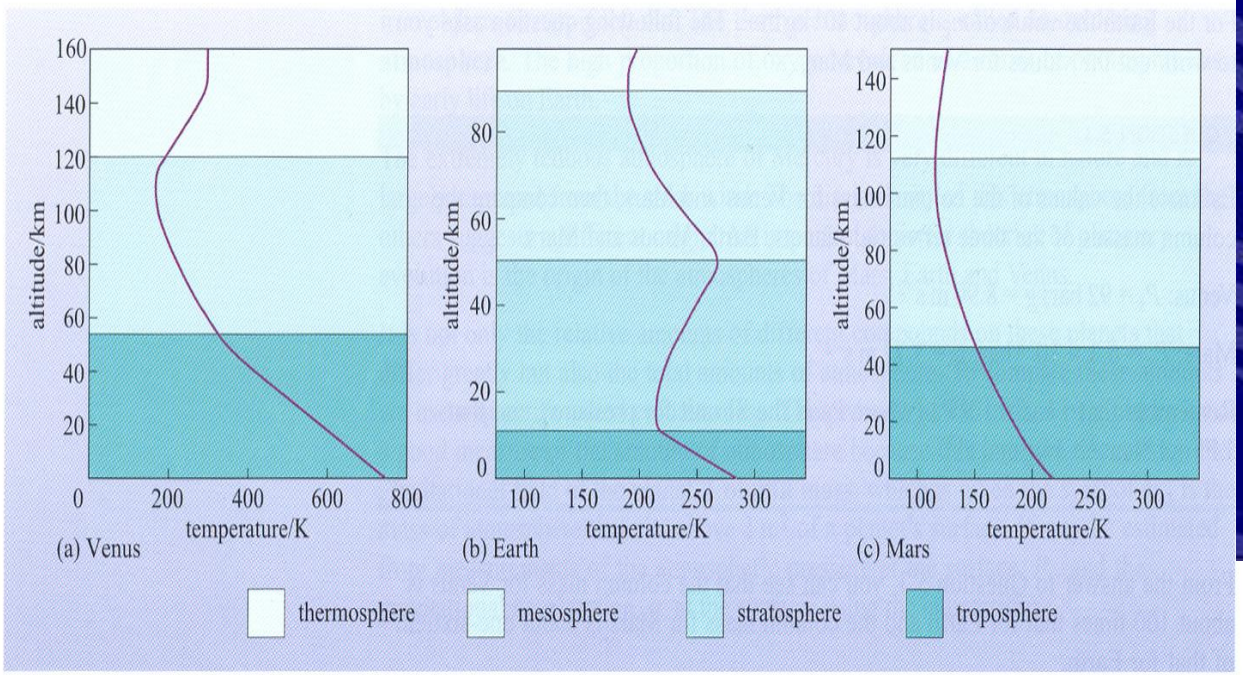
Titan's atmosphere

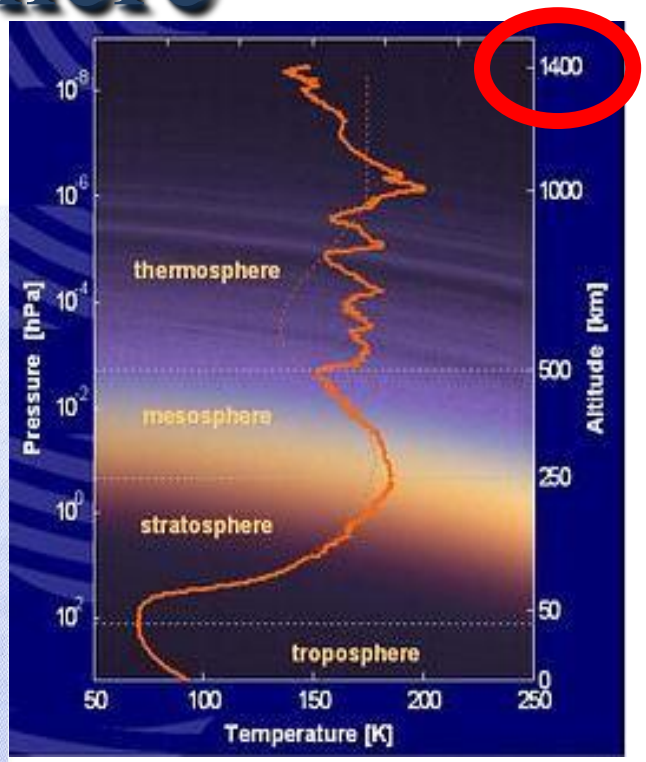




Huygens data (Fulchignoni et al. 2005)

Titan's atmosphere





Huygens data (Fulchignoni et al. 2005)

Much more extended

Much colder troposphere (93.65±0.25 K at the surface)

Thicker than Earth: Surface pressure = 1.467 atm

The most similar to Earth → Similar processes at work?

Atmospheric composition

Vast majority of $\mathbf{N_2}$ (98.4% in the stratosphere)

Second contribution **methane** – 1.4% in the stratosphere

Atmospheric composition

Minor gases in Titan's atmosphere	Abundance (stratosphere)	
Methane - CH_4	1.4%	hydrocarbons
Ethane - C_2H_6	10 ppm	
Acetylene - C_2H_2	4 ppm	
Propane - C_3H_8	1 ppm	
Ethylene - C_2H_4	0.1 ppm	
Methylacetylene - CH_3C_2H	10 ppb	
Diacetylene - C_4H_2	2 ppb	
Benzene - C_6H_6	0.5 ppb	
Hydrogen cyanide - HCN	0.5 ppm	nitriles
Acetonitrile - CH_3CN	2 ppb	
Cyanoacetylene - HC_3N	1 ppb	
Cyanogen - C_2N_2	1 ppb	
Carbon monoxyde - CO	50 ppm	oxygen compounds
Carbon dioxyde - CO_2	20 ppb	
Water – H_2O	0.1 ppb	

Atmospheric composition

Vast majority of $\mathbf{N_2}$ (98.4% in the stratosphere)

Second contribution **methane** – 1.4% in the stratosphere

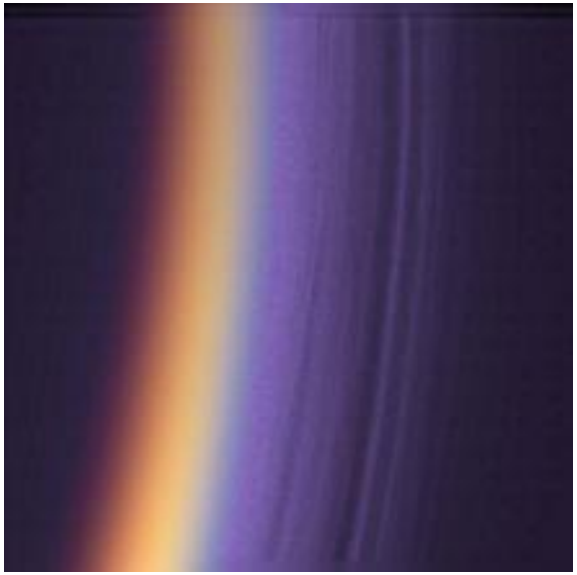
A wealth of trace gases – tracers of **atmospheric dynamics**

but also indicators of **chemical processes**

Strong presence of **aerosols** in addition to gases

Tholins

nitrogen-rich organics with some % of methane



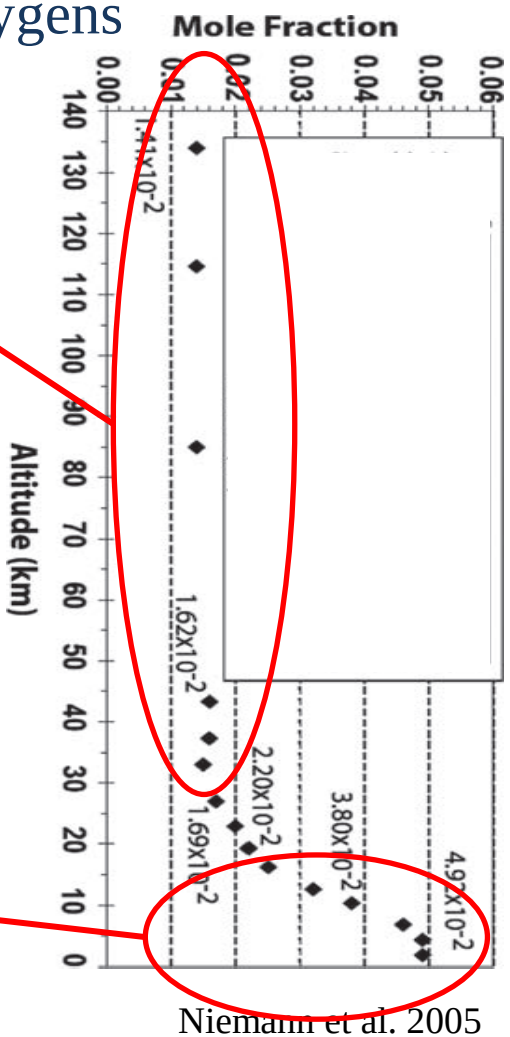
ISS image

The behavior of methane

Lower atmosphere

Mole fraction of methane measured by Huygens

Uniformly mixed by atmospheric circulation
(up to 700-800 km)



Enrichment towards the surface –
Reservoir of methane, production

Niemann et al. 2005

The behavior of methane

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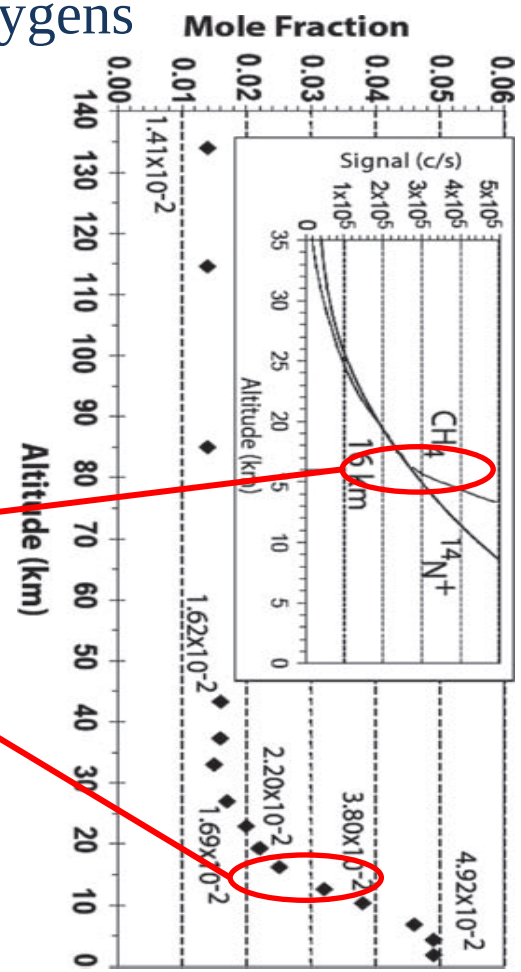


Sudden increase of methane at 16 km

Huygens passed through a methane **cloud** that evaporated from the heat within the instrument

Condensation level of CH_4

Niemann et al. 2005

The behavior of methane

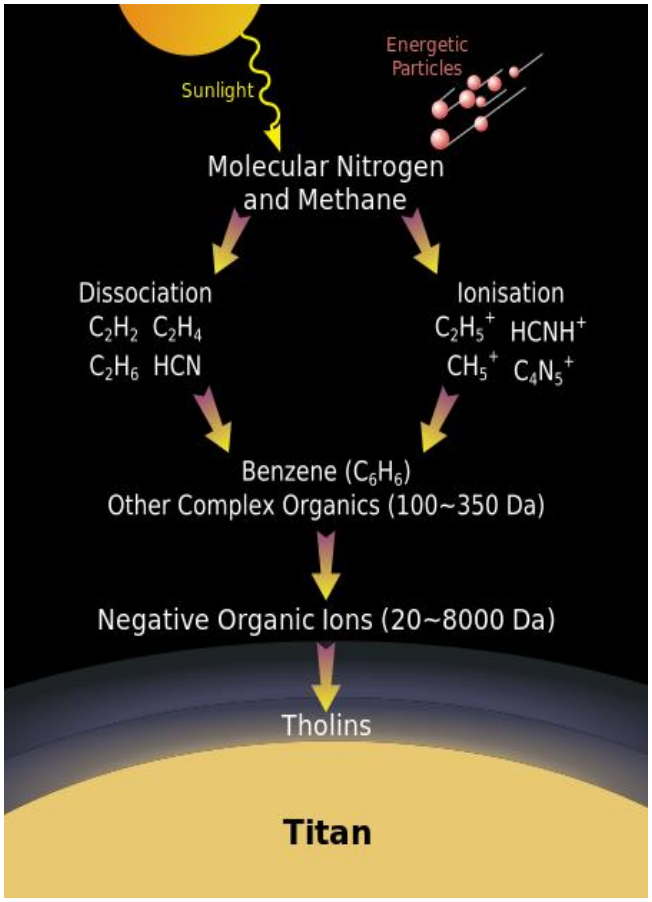
Upper atmosphere

Mass spectrometer measurements high at the thermo- and mesosphere

Methane photolysis drives Titan's atmospheric chemistry (with N_2)

Creation of complex organics and aerosols

Methane as a key of atmospheric processes

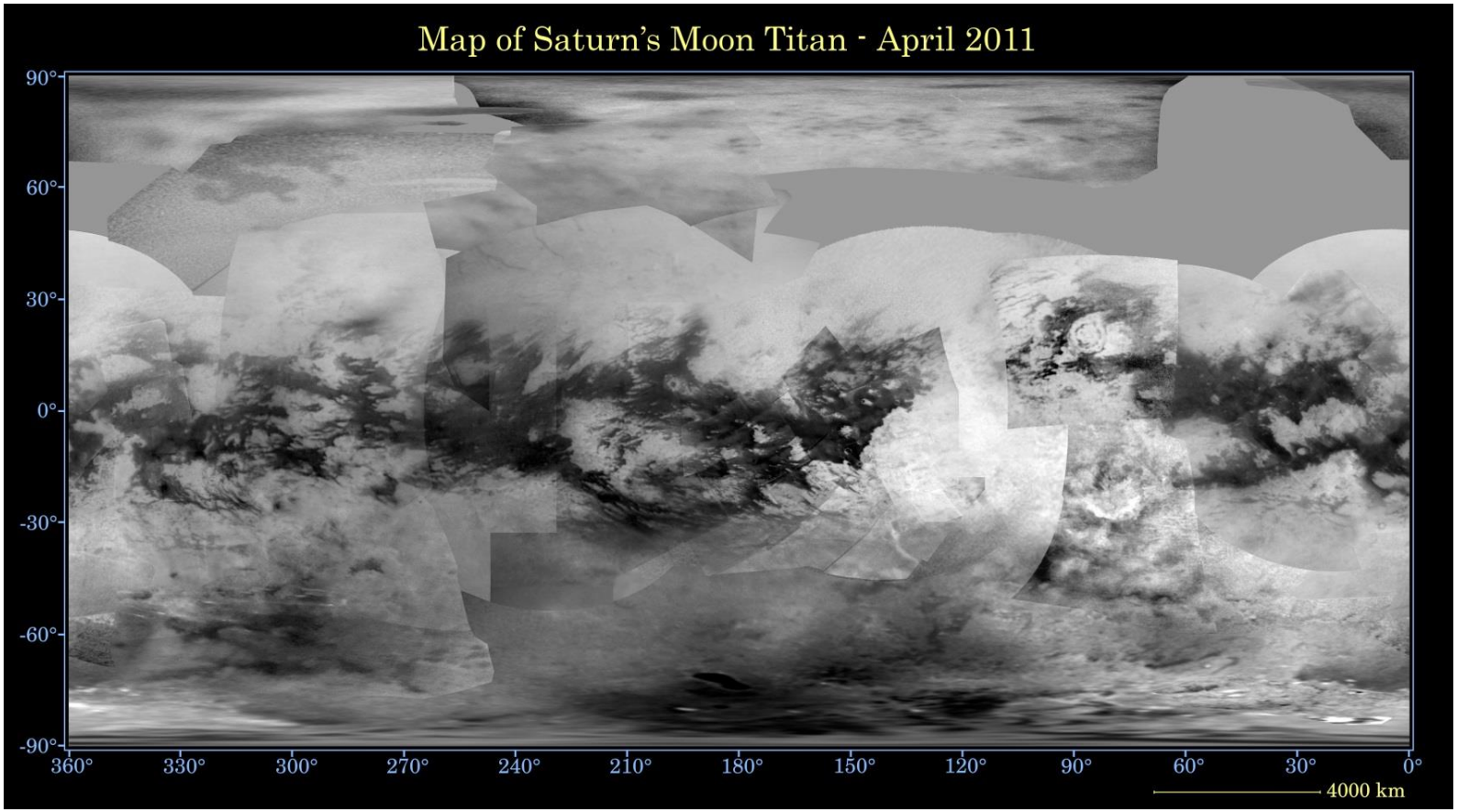


Waite et al. 2007

Surface features

VIMS and the radar covered a good part of Titan's surface

Features appear



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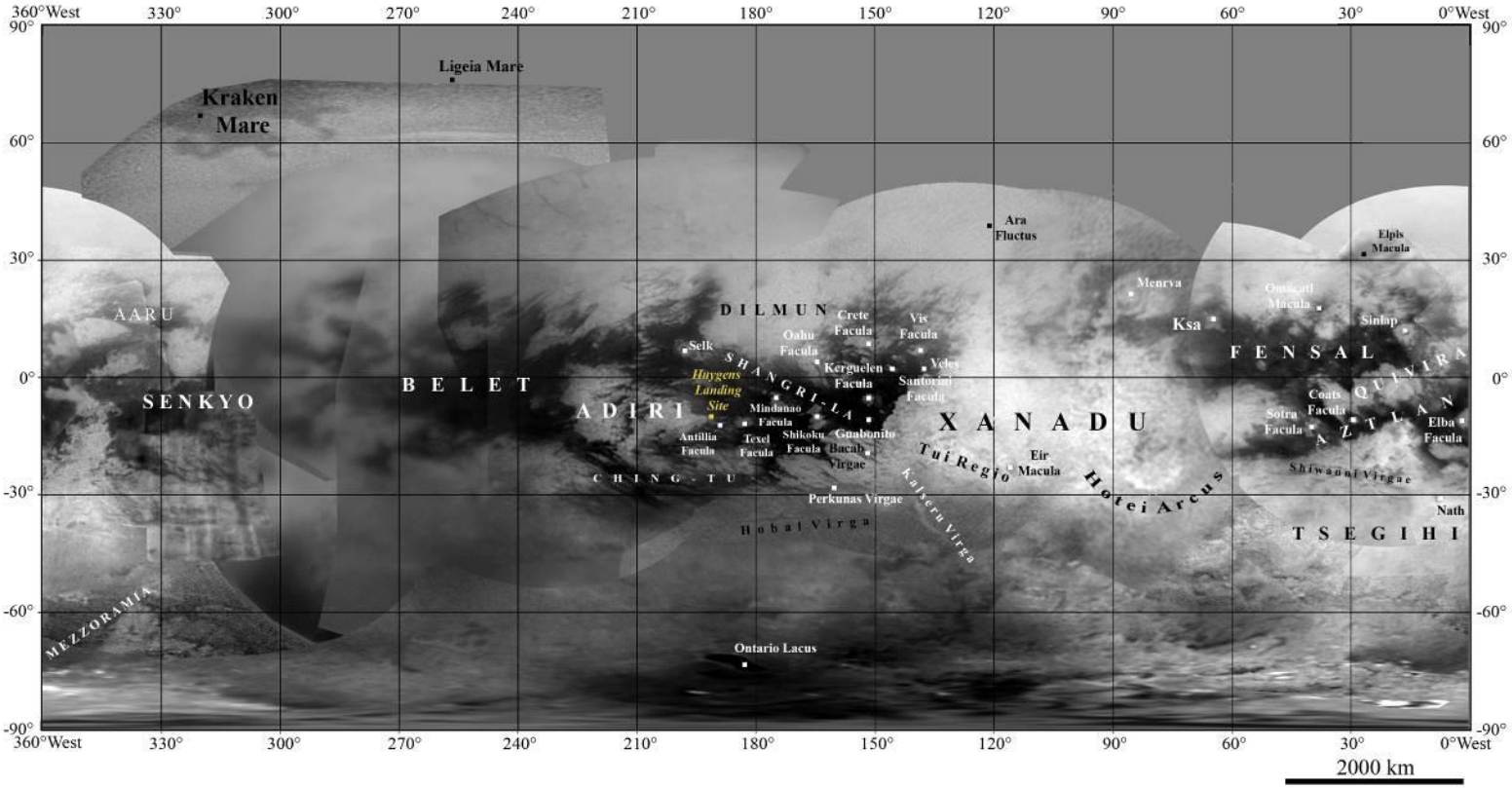
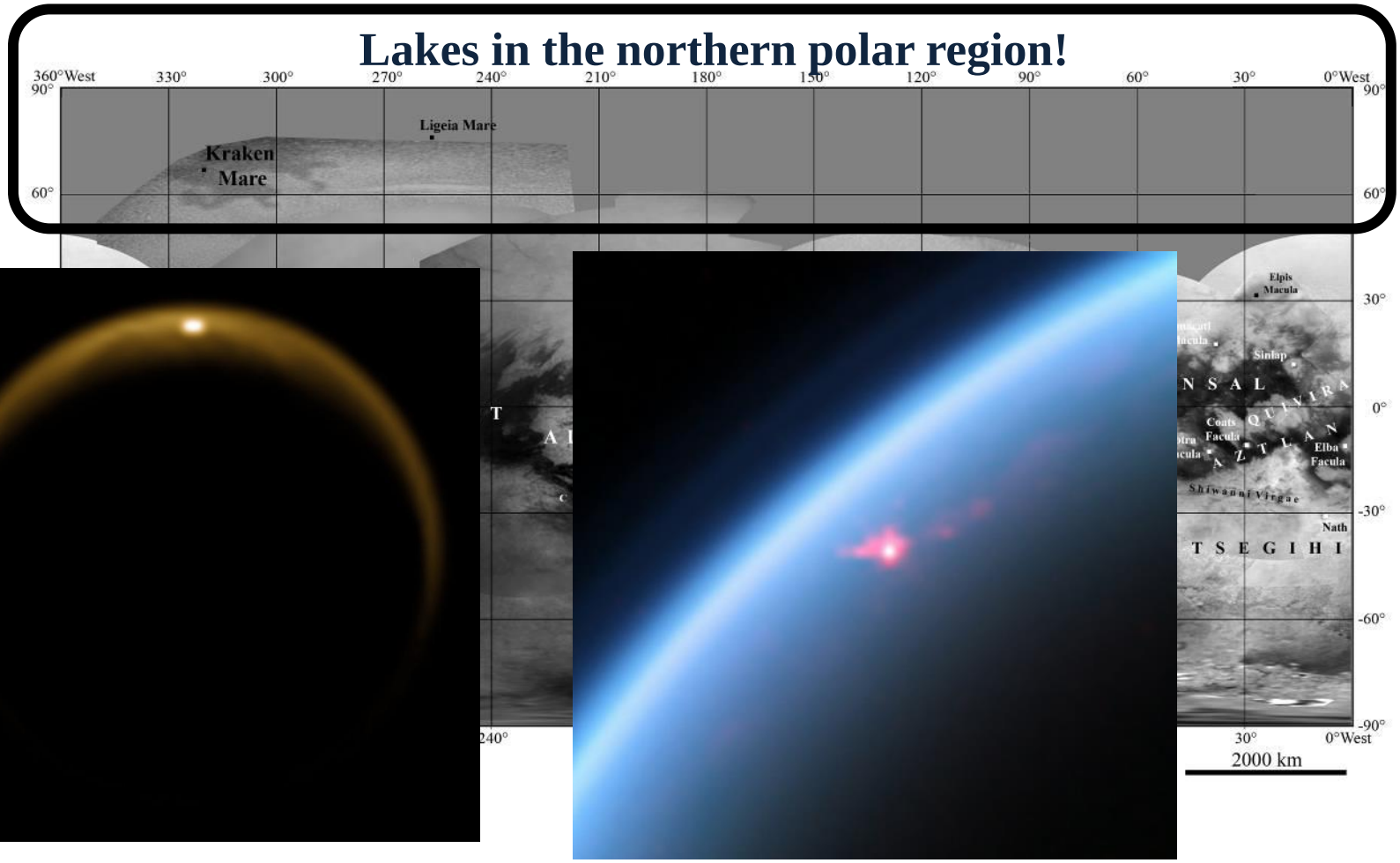


Surface features

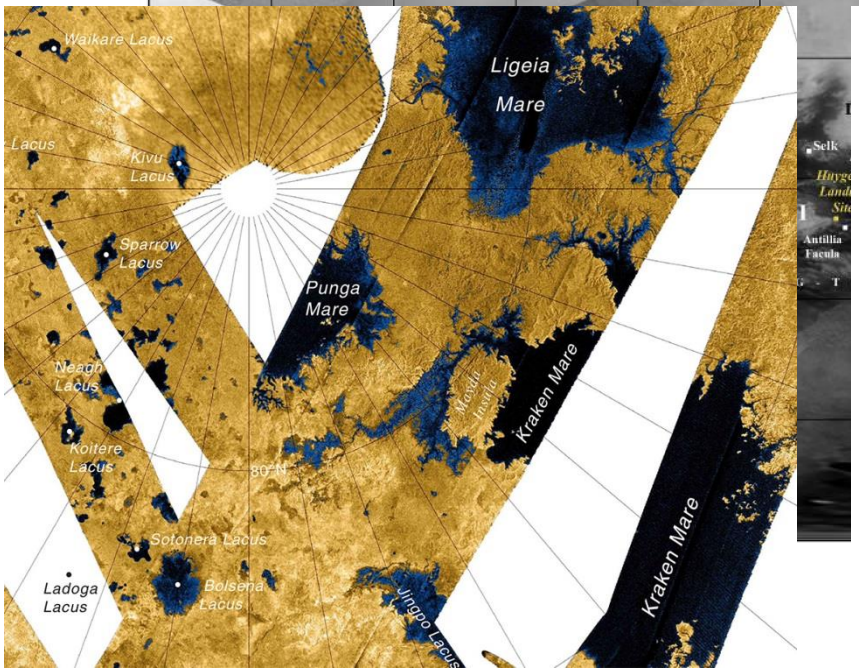
Strong connection to methane (and products) again



Specular reflection observed by VIMS

Surface features

Strong connection to methane (and products) again



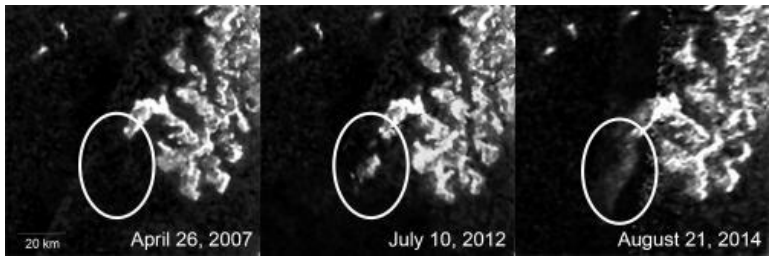
Detailed structures with RADAR

Composition: C_2H_6 + CH_4 + other organics

(not precisely measured)

Quite stable shorelines

BUT presence of evolving features



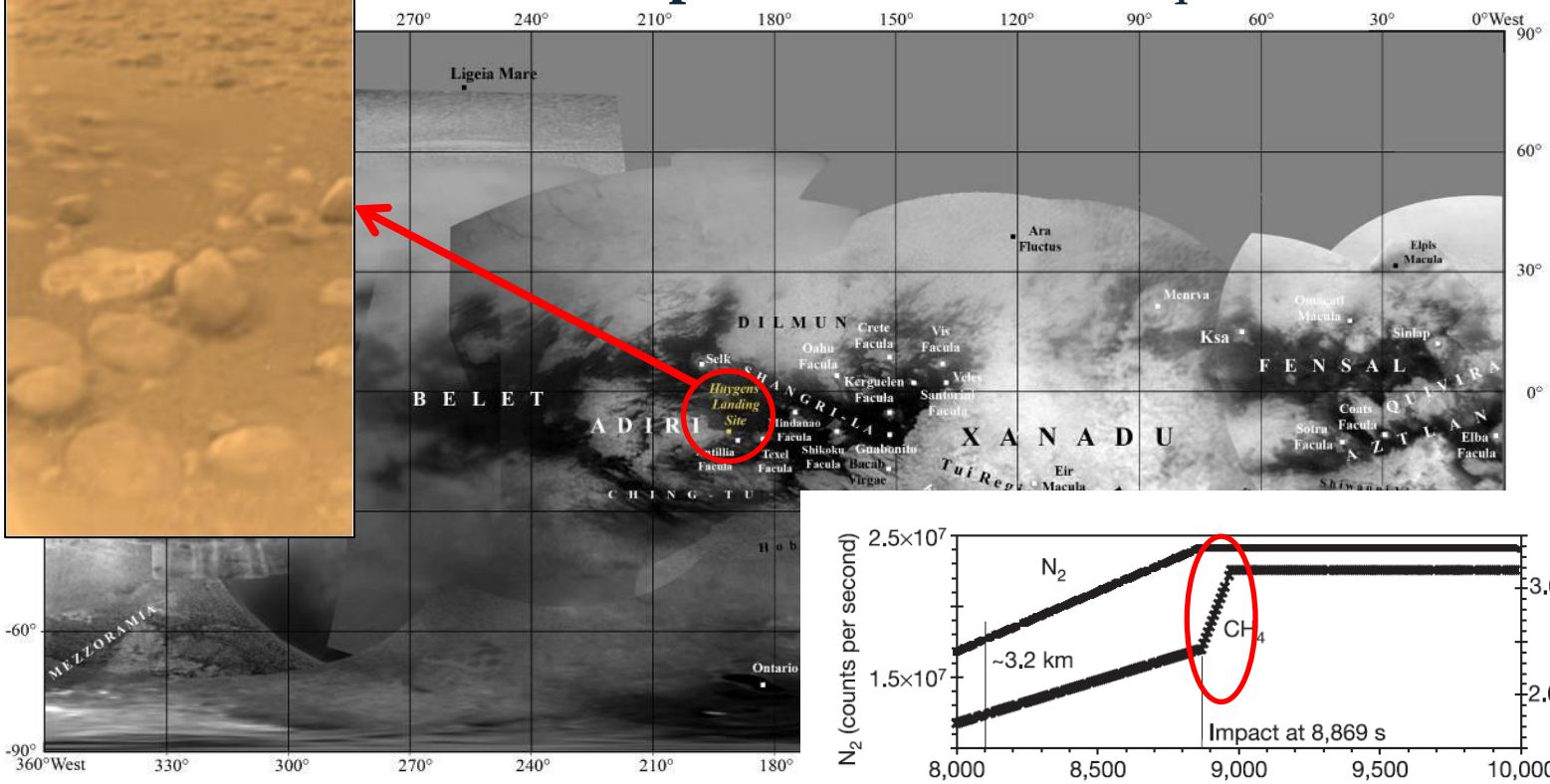
SAR (radar) images

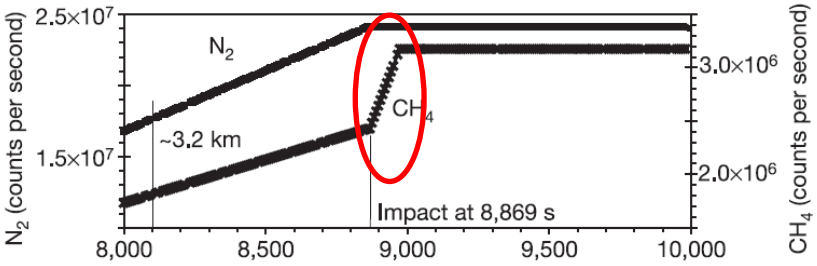
Surface features

Strong connection to methane (and products) again

"Titanian mud" at the Huygens landing site

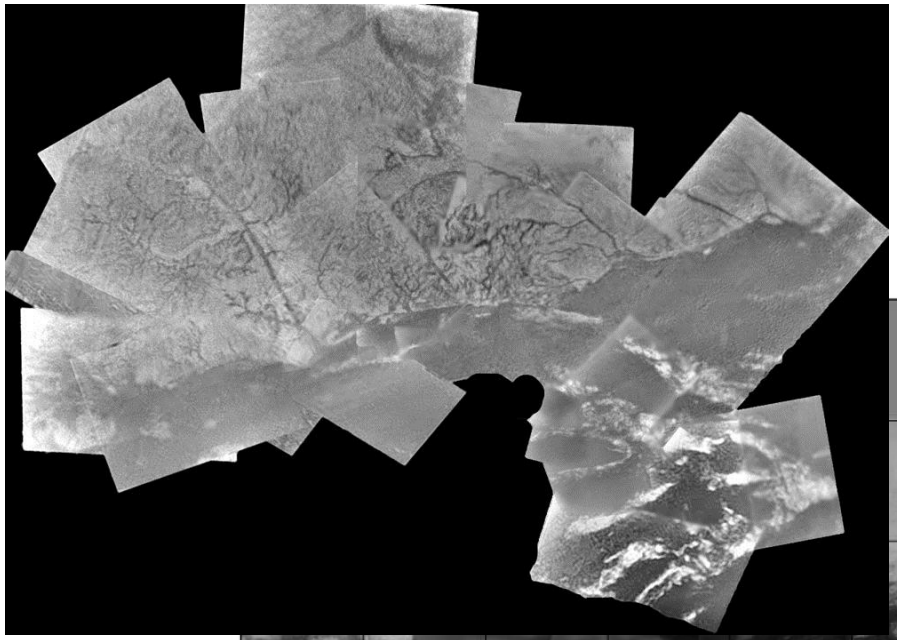
Damp lakebeds at the equator



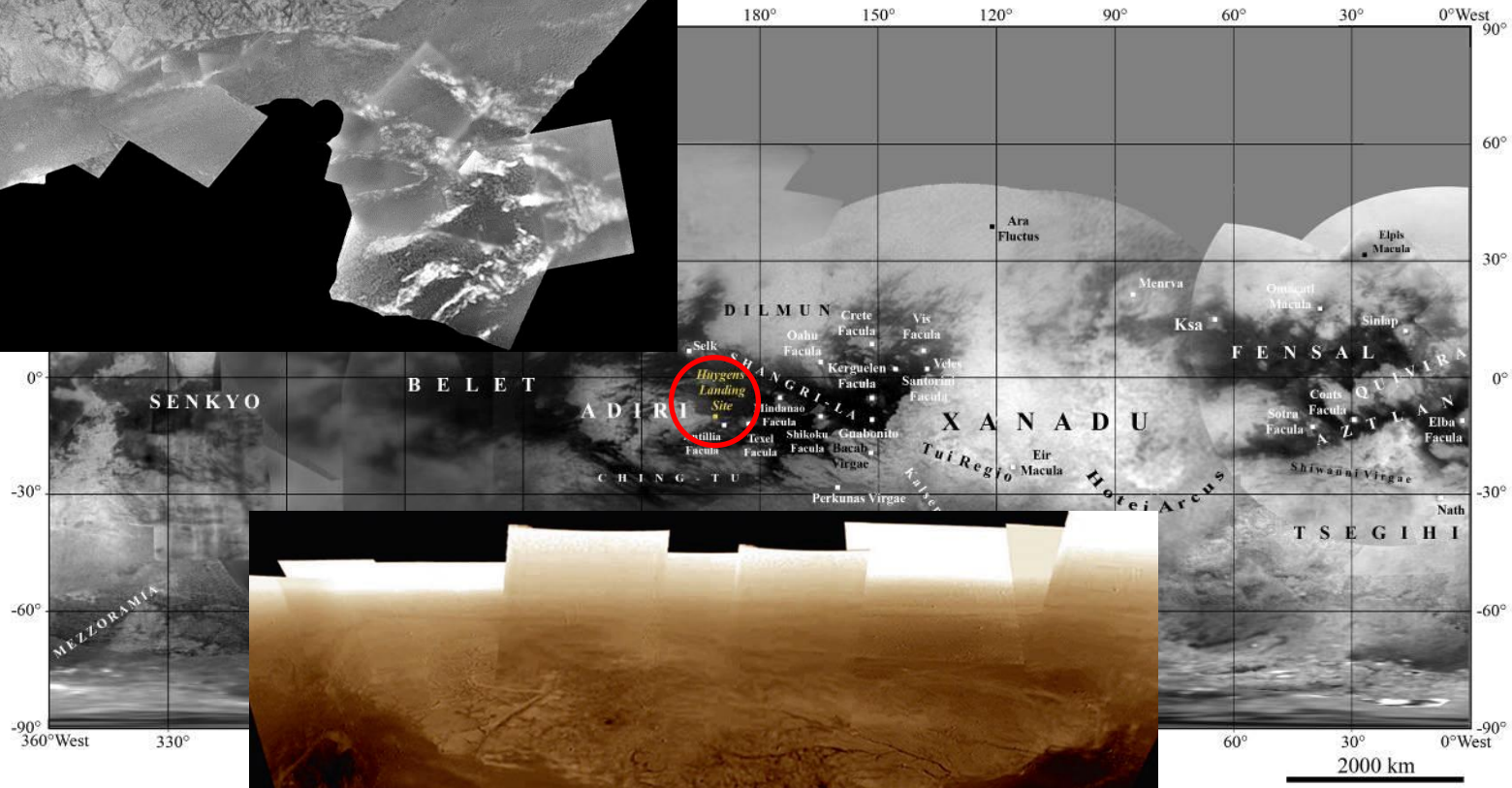


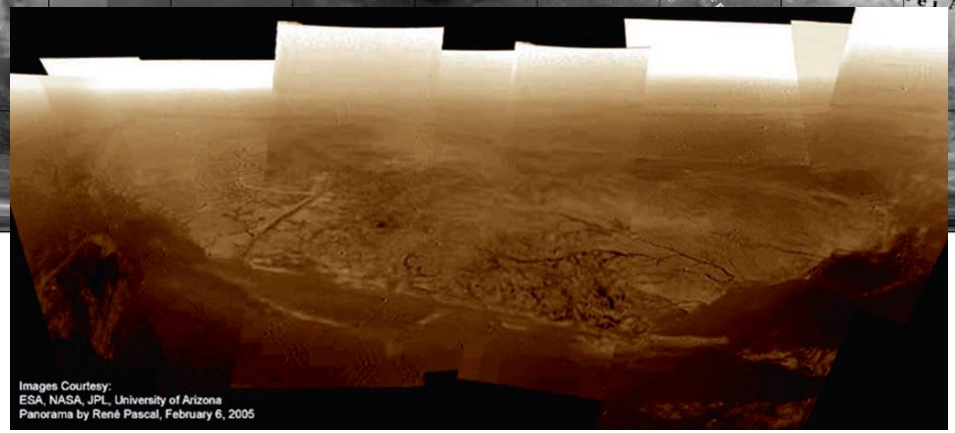
Liquid methane mixed with surface material evaporated by the heat of the Huygens probe

Surface features



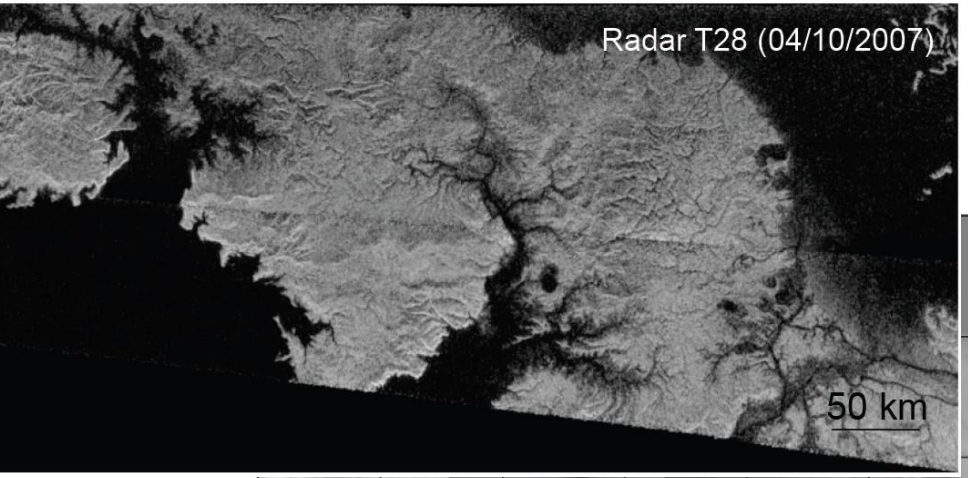
Shorelines and fluvial channels – recent fluvial activity



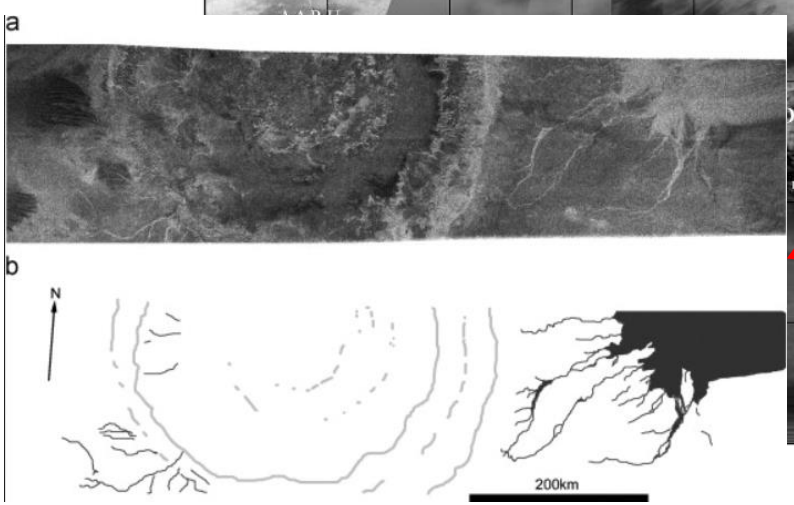


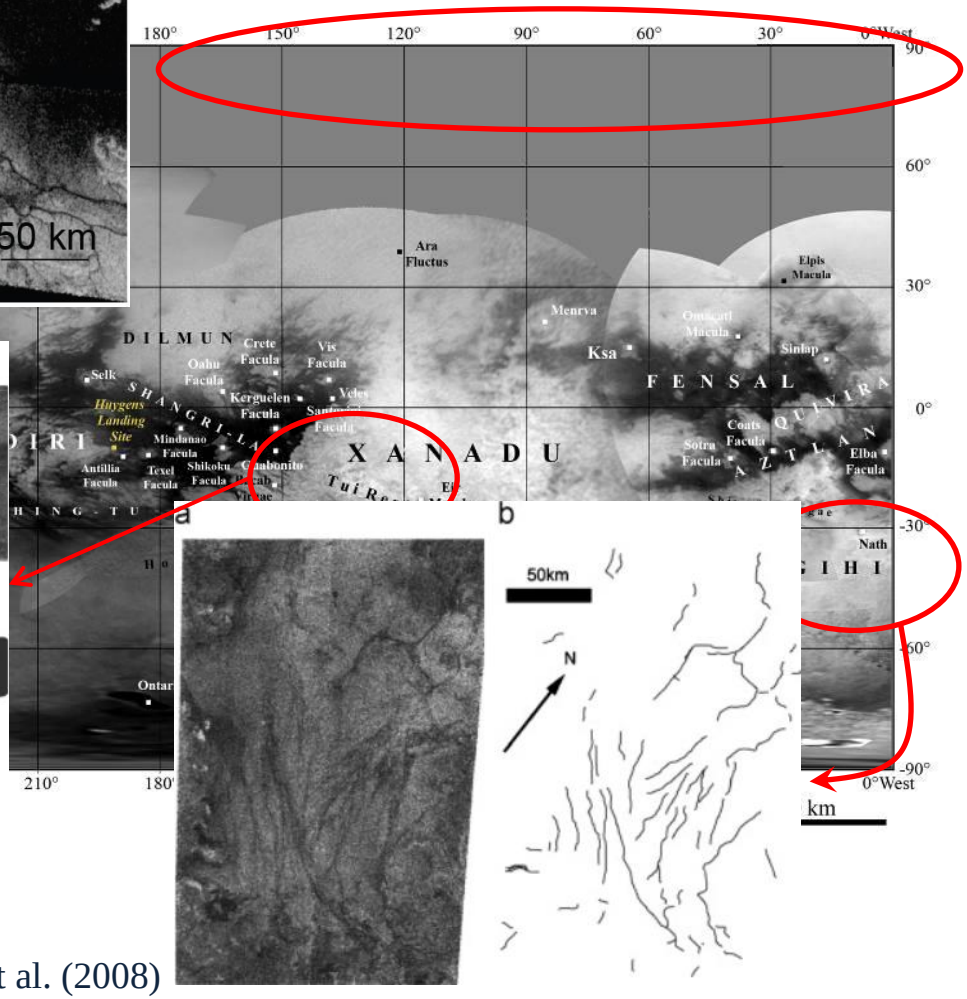
Surface features

Strong connection to methane (and products) again



Fluvial channels everywhere !





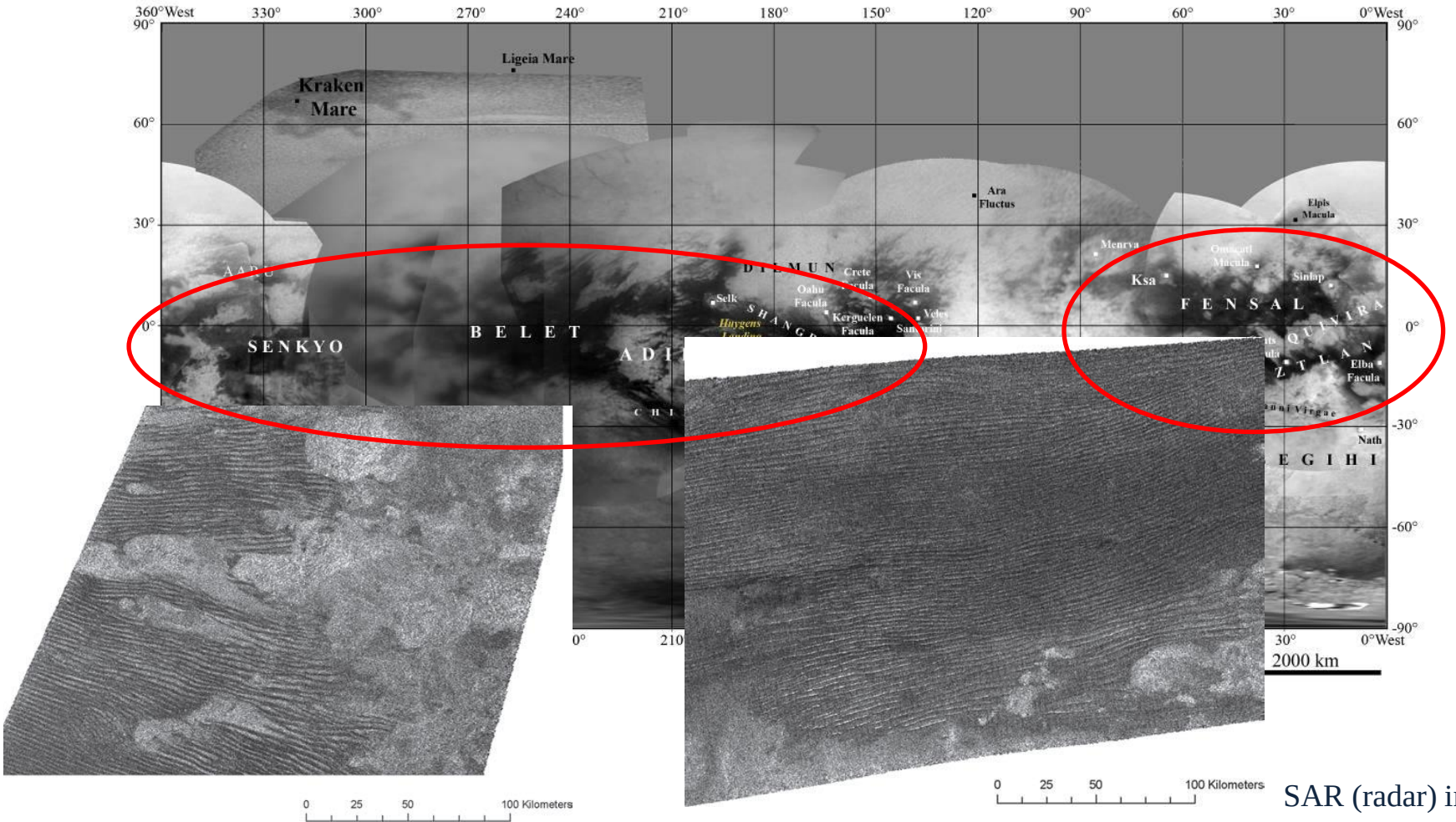
Lorenz et al. (2008)

Surface features

Vast **dune fields** especially in the dark areas at the equator

Solid organics settled from the atmosphere + wind interactions

Strong focus on dunes' studies at AIM (Rodriguez et al. 2014, Lucas et al. 2014)



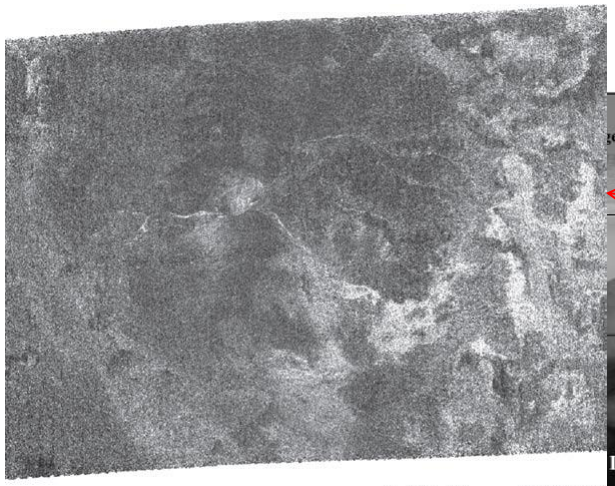
SAR (radar) images

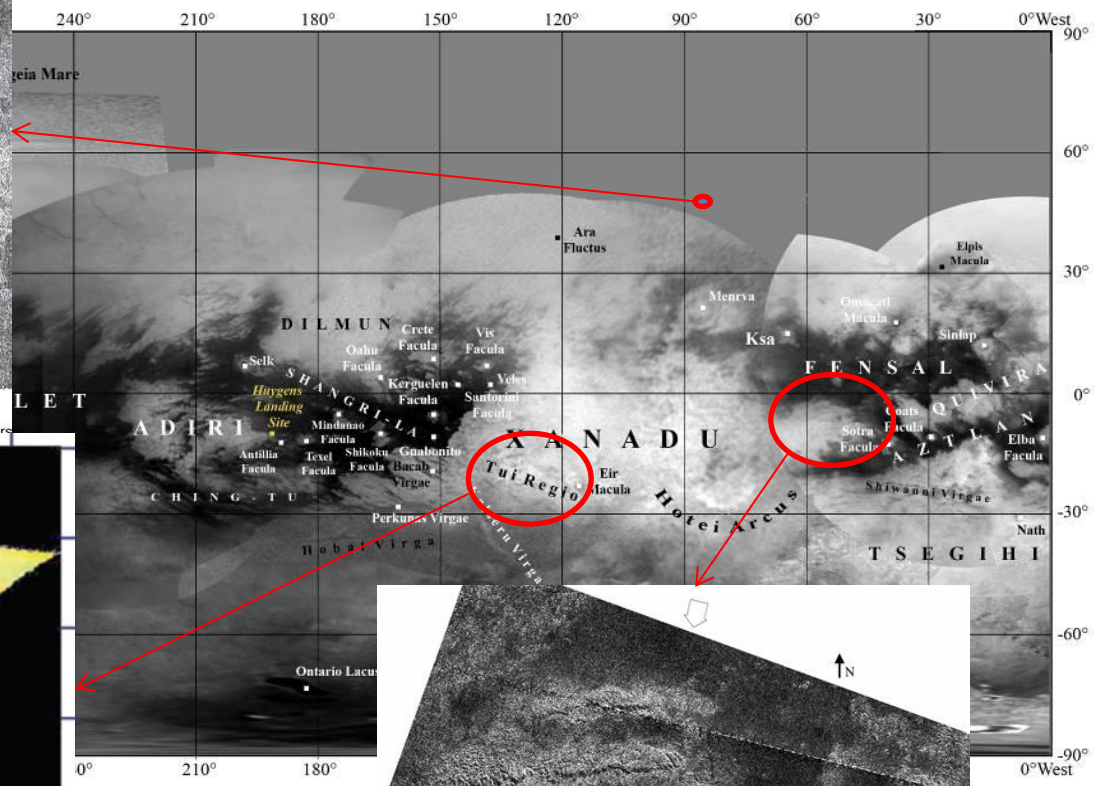
Surface features

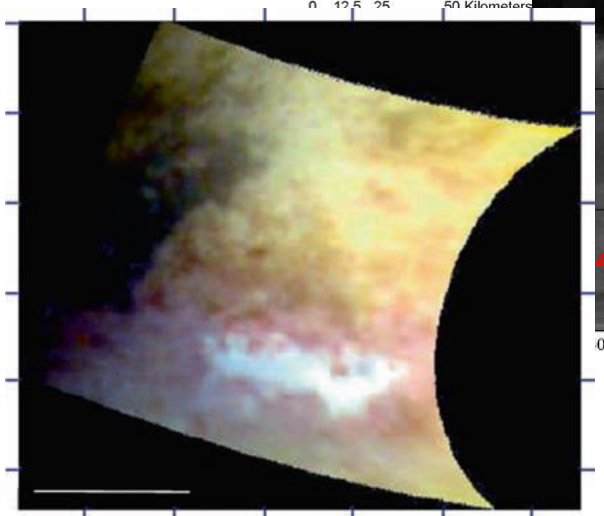
Cryovolcanism and tectonic features, few craters

Geologically young surface, resurfacing processes

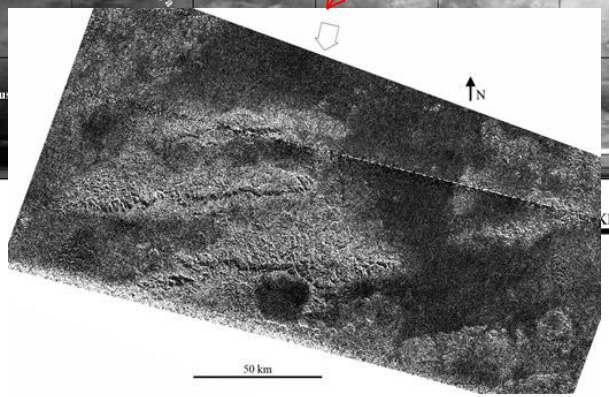
Strong connections with methane, surface-atmosphere coupling







VIMS image at 5µm of Tui Regio



The importance of methane

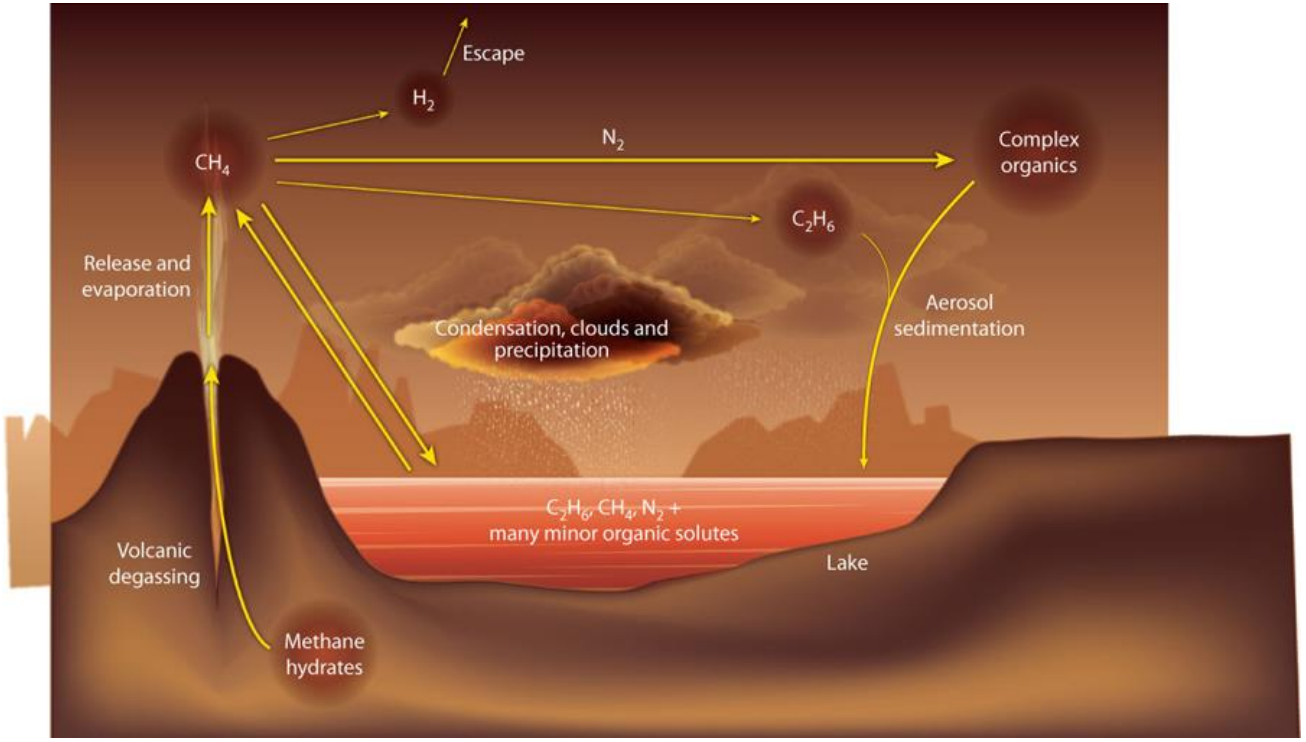
Key factor for the whole Titan's environment

Its greenhouse effect is needed for the stability of the atmosphere

Lorenz et al. 1997

Present in all three states of the matter (only known case after H_2O on Earth)

Structured in a "**methanologic cycle**" equivalent to the Earth water cycle



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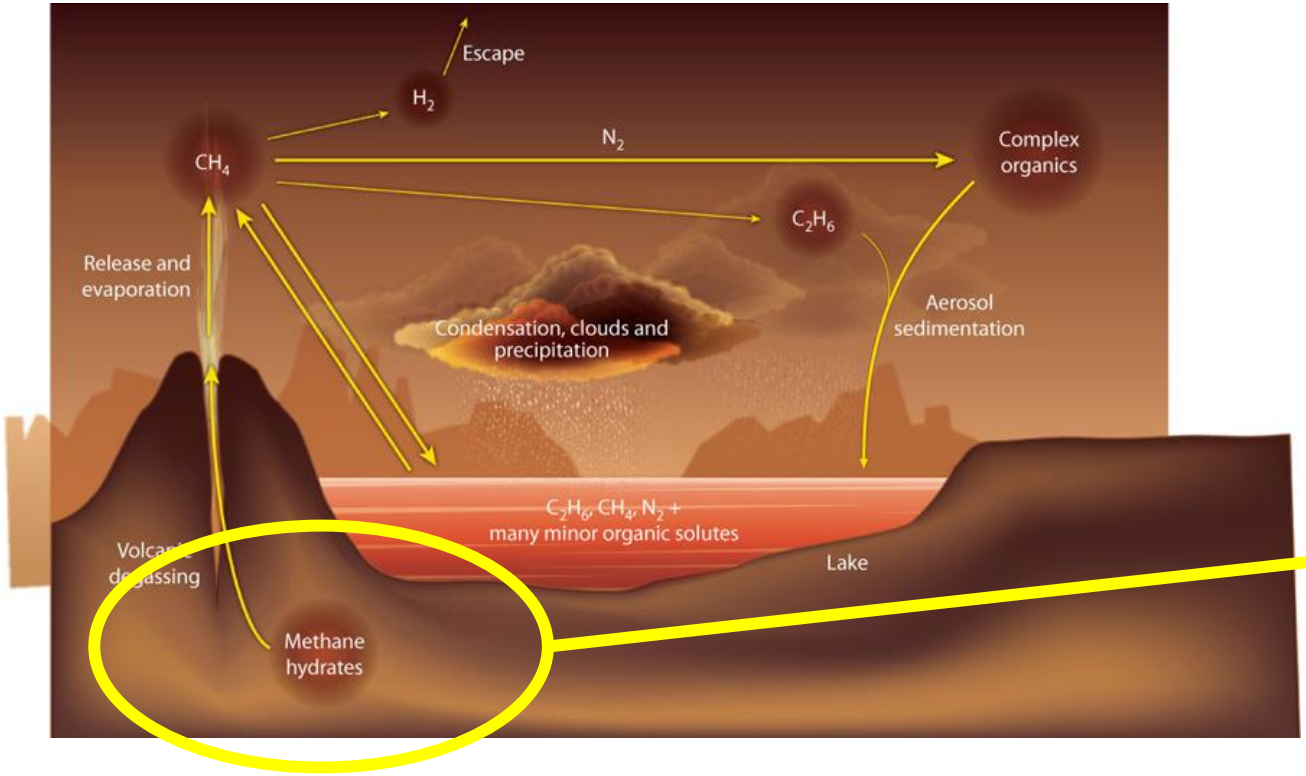

Subsurface reservoir

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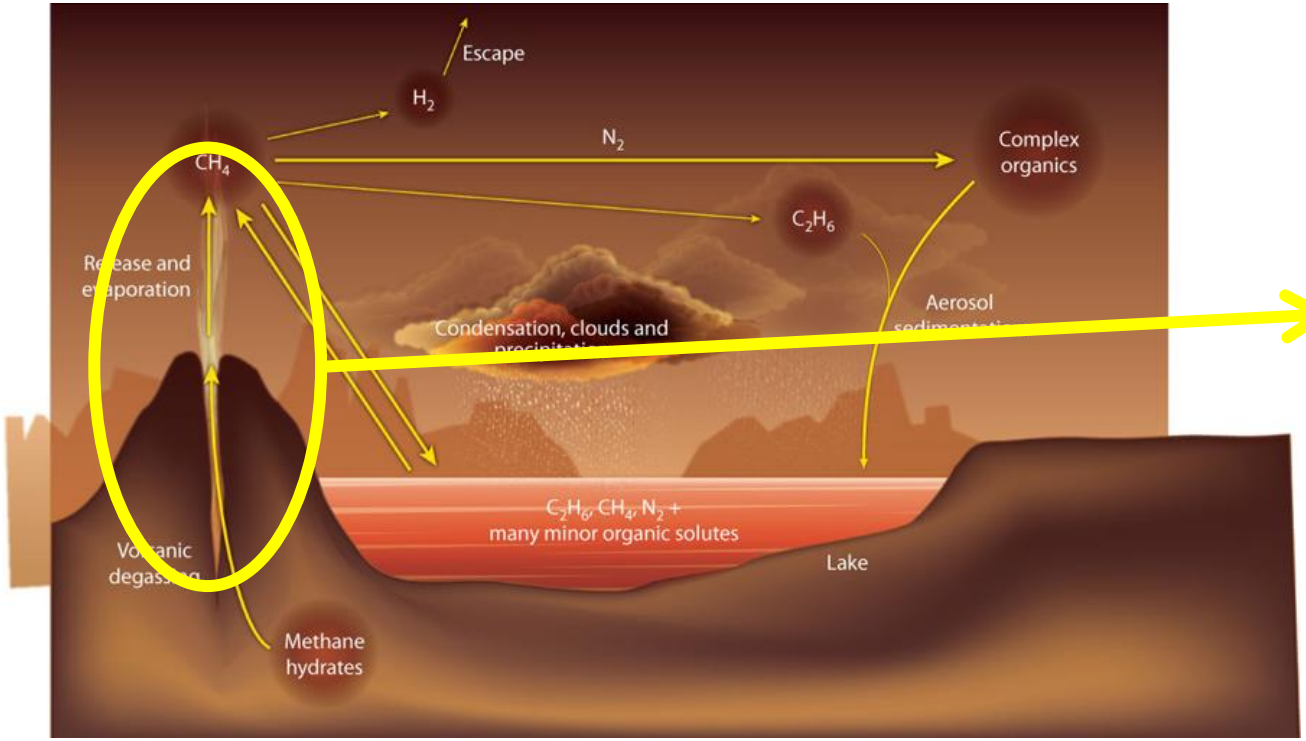

Release mechanism

(not necessarily volcanic)

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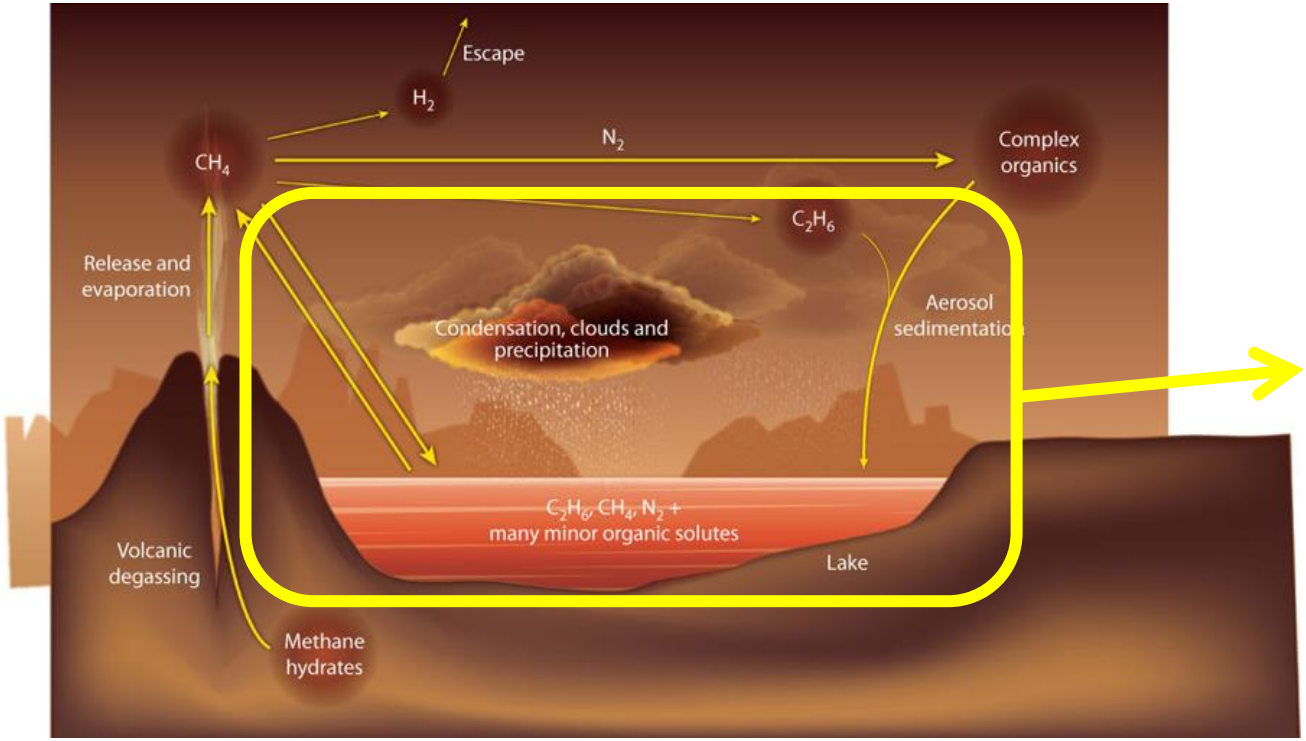

Surface-atmosphere Interactions & tropospheric cycle

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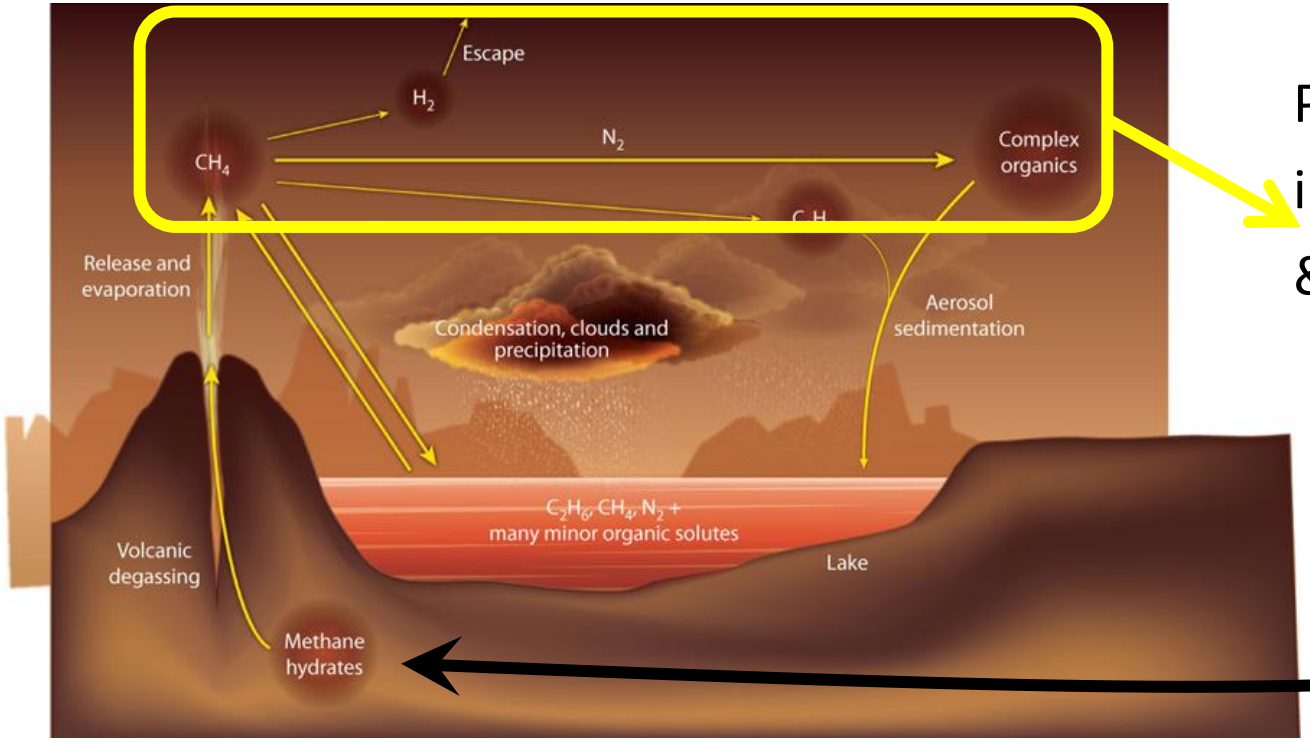


Photochemical processes in the higher atmosphere & CH_4 destruction

(need of continuous or episodic resupply)

Motivation of my work

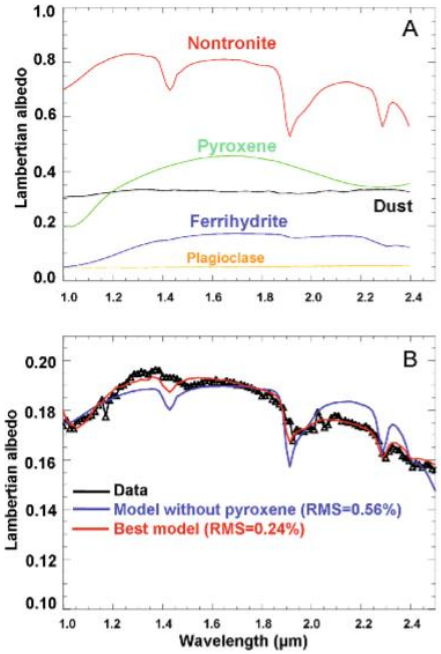
Atmospheric and surface observations unveil a complex world
shaped by a wealth of physical and chemical processes
involving *strong atmosphere-surface-subsurface coupling*

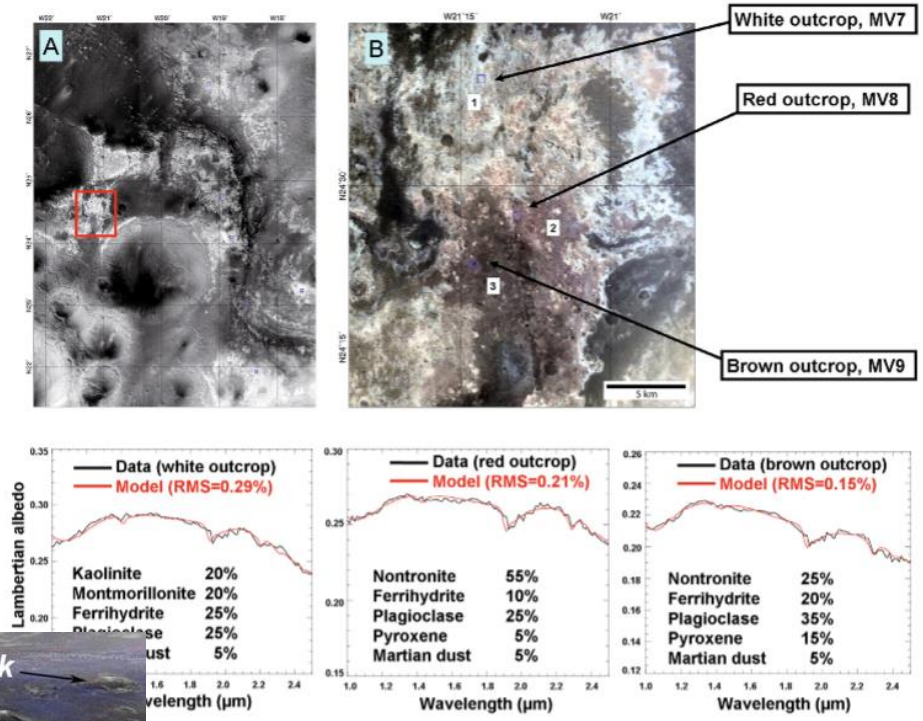
The study of *surface composition and mineralogy*
together with simultaneous information on atmospheric behavior
will give essential insight on these processes.

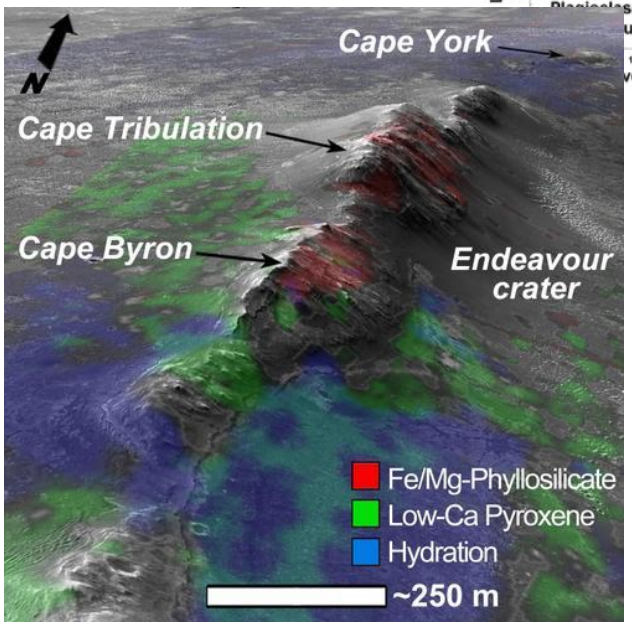
VIMS, thanks to its hyperspectral imaging capability,
is the *best-suited instrument* to perform this kind of study

Motivation of my work

Like OMEGA or CRISM on Mars…



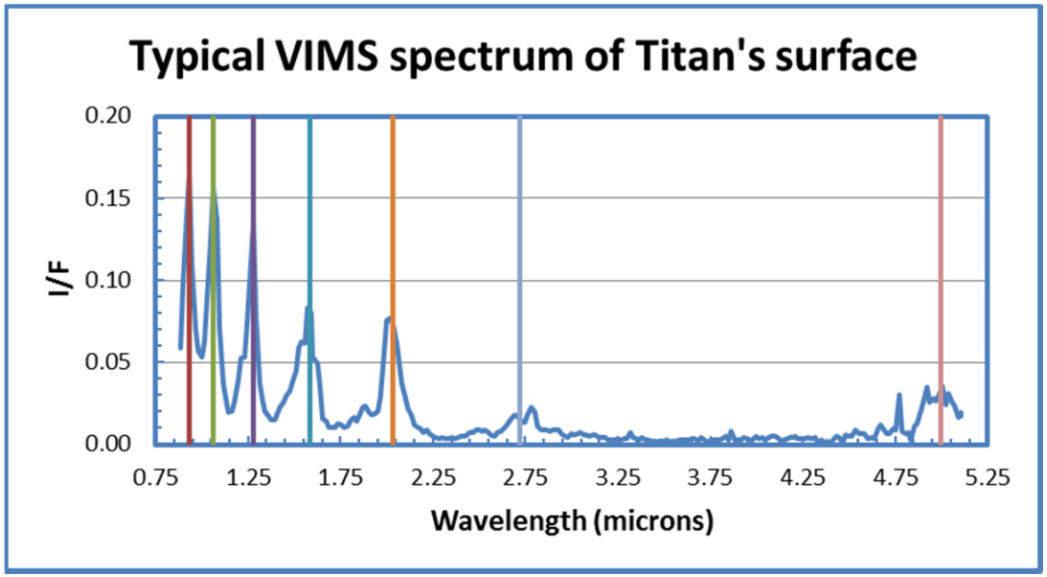




Motivation of my work

BUT: after 10 years of Cassini no such maps exist on Titan!

And that's why



1: Atmospheric gases and haze opacity affect the whole spectrum

(surface windows included)

Motivation of my work

BUT: after 10 years of Cassini no such maps exist on Titan!

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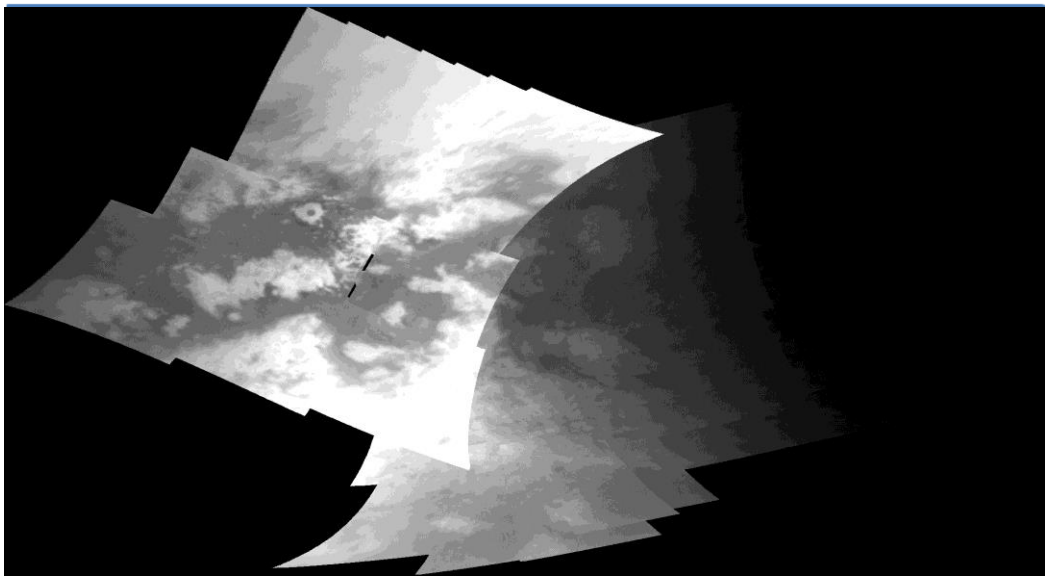


1: Atmospheric gases and haze opacity affect the whole spectrum

(surface windows included)

2: Atmospheric gases and haze opacity make the observations very sensitive to the geometry

difficulty to retrieve the geometric **albedo**
needed to apply compositional models

Motivation of my work

Need of a comprehensive **radiative transfer model**

Several applications have shown the potential of a RT model for VIMS data

(Adriani et al. 2005, Rannou et al. 2010, Griffith et al 2012, Hirtzig et al. 2013, Solomonidou et al. 2013, …)

Problem: computational time

1 spectrum inverted in ~10 minutes

1 full VIMS datacube of 4096 spectra in ~10 days

the whole VIMS dataset of ~40000 cubes in… !!!

Inadequacy to treat the whole set of VIMS datacubes

Our strategy

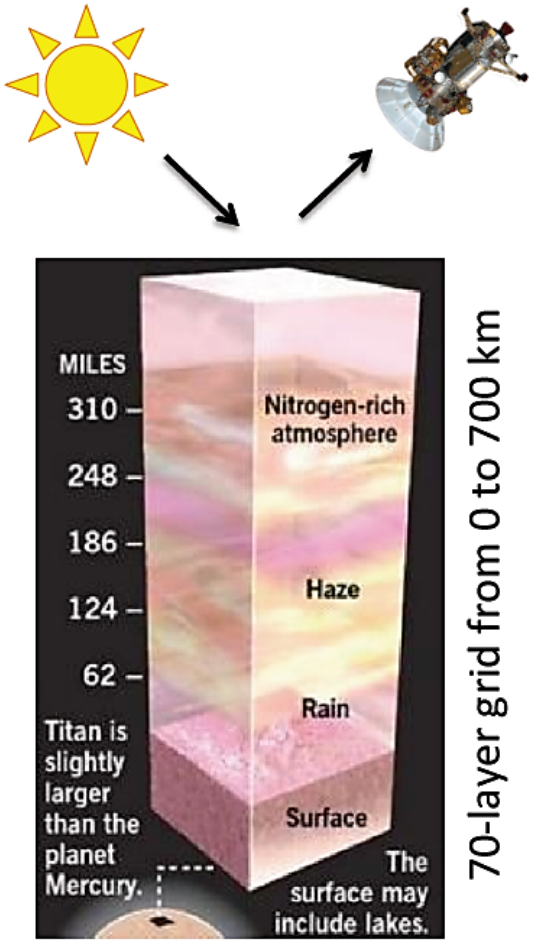
1) "Distillation" of the outputs of a full RT model into ***look-up tables***
   grid of model's parameters – a spectrum for each node

2) Development of a *minimization procedure* to find the best-fit of
   the look-up tables spectra to any VIMS observation

3) Interpolation on the output parameters (haze factor, surface albedo) to refine the final result

Our radiative transfer model

(Hirtzig et al. 2013)



70-layer grid from 0 to 700 km

Inputs

Gas

- (T, P) vertical profile from HASI/Huygens
- (χ_{CH4}, M_{CH4}) vertical profile from GCMS/Huygens
- CO mole fraction=3.2×10^{-5} from CIRS/Cassini
- Molecular lines opacities of $^{12}CH_4$, $^{13}CH_4$, $^{12}CH_3D$ and CO
- Rayleigh scattering from N_2 and CH_4
- N_2-N_2 and N_2-H_2 collision-inducted absorptions

Aerosols

- Number density, extinction, phase function and single scattering albedo vs altitude from DISR/Huygens

Cloud

- Mean radius of particles
- Refractive index
- Opacity at 2µm
- Top altitude of the cloud

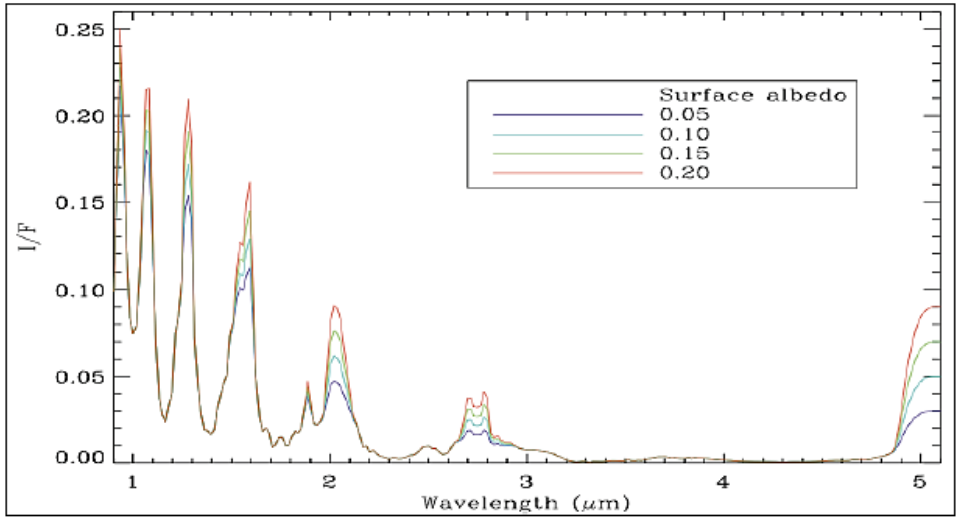
Surface

- Lambertian albedo of the surface

Our radiative transfer model

Inputs

1D multi-stream RT solver for a plane-parallel atmosphere:
SHDOMPP [Evans, 2007]



Simultaneous inversion of aerosol opacity and surface albedo

(Hirtzig et al. 2013)

The look-up tables

Fixed the inputs, the Hirtzig et al. (2013) model depends on **five** parameters

geometric input
given by navigation

- incidence angle
- emergence angle
- azimuth angle

physical output

- haze opacity scale factor wrt HASI/Huygens
- surface albedo

The look-up tables

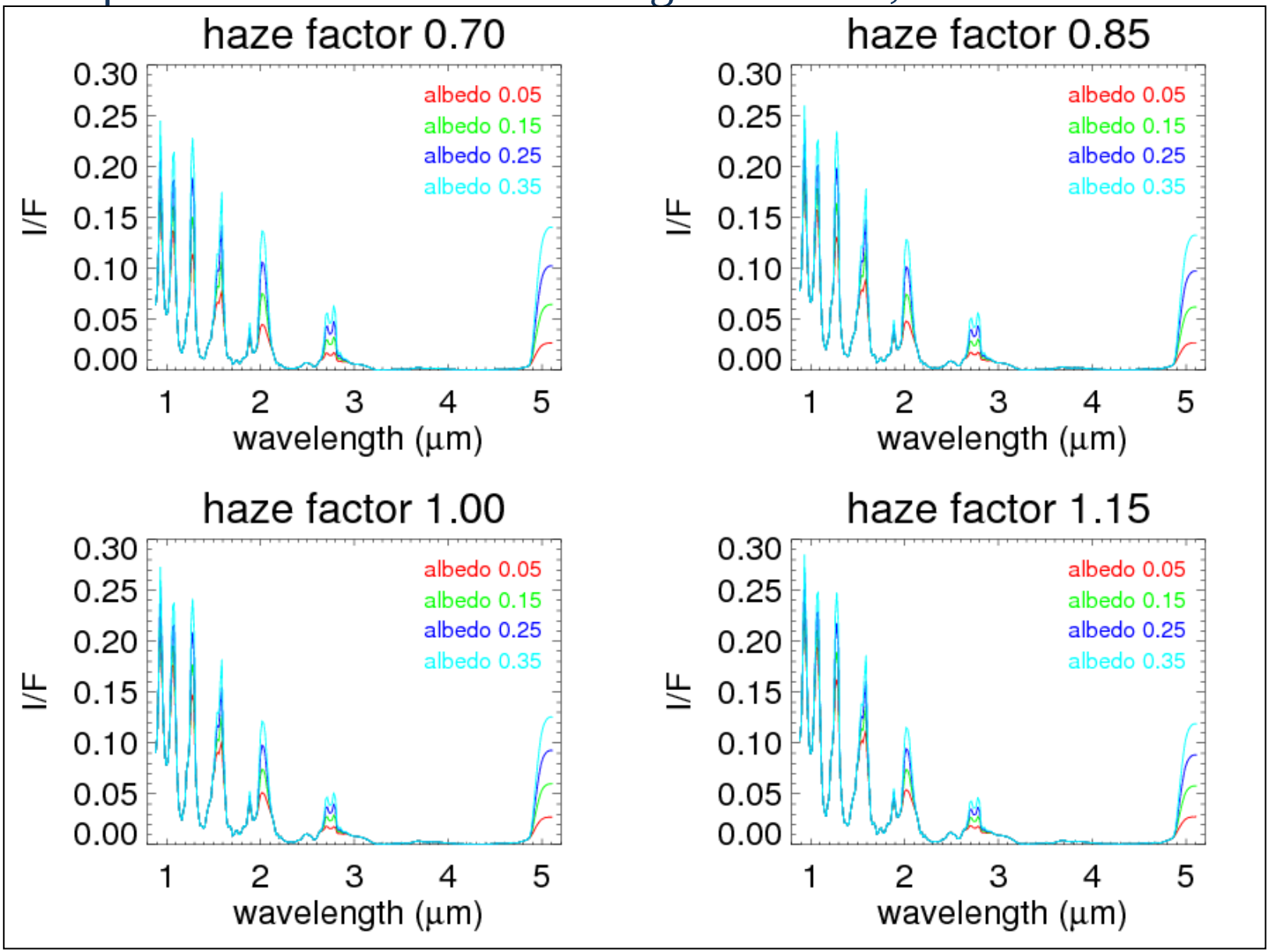
We present results from a test coarse look-up table

geometric input given by navigation	incidence angle	[0°,20°,40°,60°]
	emergence angle	[0°,20°,40°,60°]
	azimuth angle	[0°,60°,120°,180°]
physical output	haze opacity scale factor wrt HASI/Huygens	[0.7,0.85,1.0,1,15]
	surface albedo	[0.05,0.15,0.25,0.35]

1024 spectra in total

The test look-up table

spectra for incidence = emergence = 40°, azimuth = 60°



Inversion method

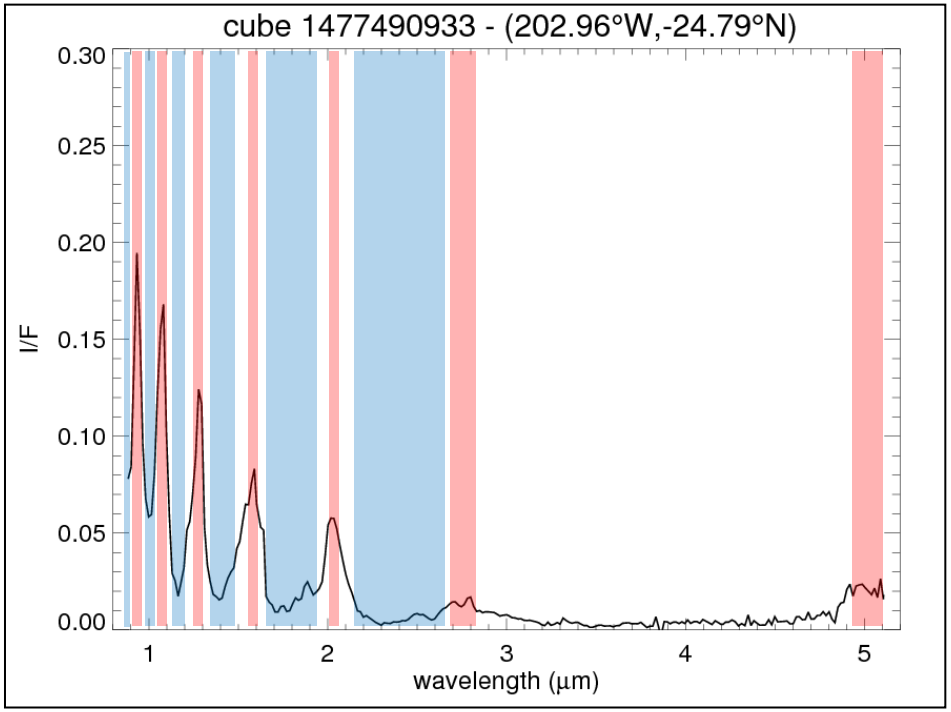
- Interpolating spectra within the grid of the geometry parameters
- Actual minimization

Surface windows: affected by surface + haze
Bands' core: affected by haze only (sensitive at ~100 km)

2-step minimization

1. The haze is given by the bands

2. Fixed the haze, the albedo is computed for each window



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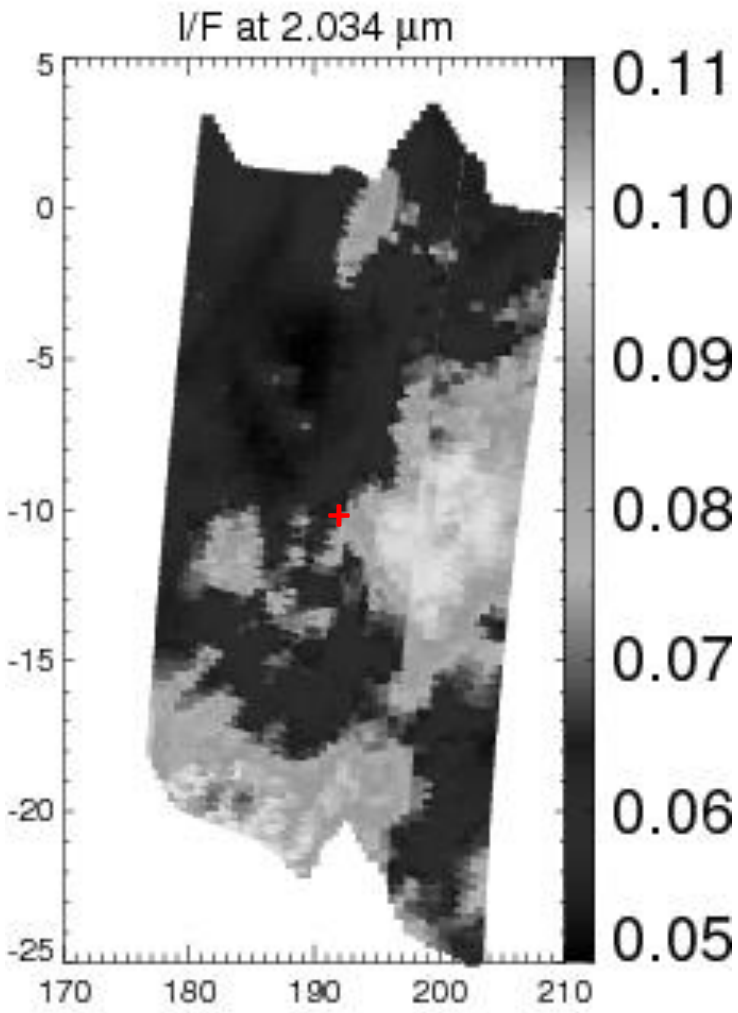
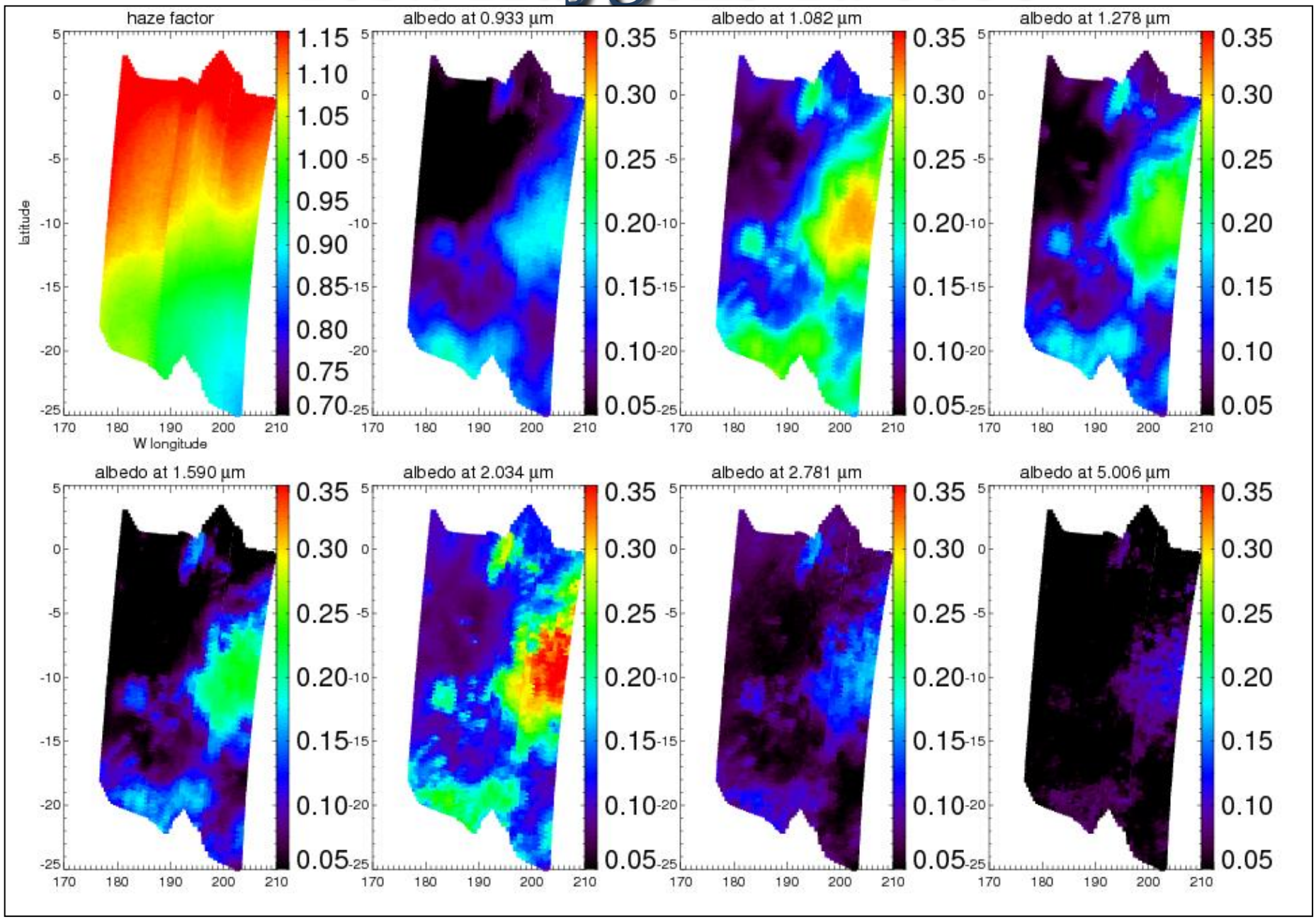
Computational time:
1 cube of 4094 spectra, ~20 s

Test: Huygens Ta cube

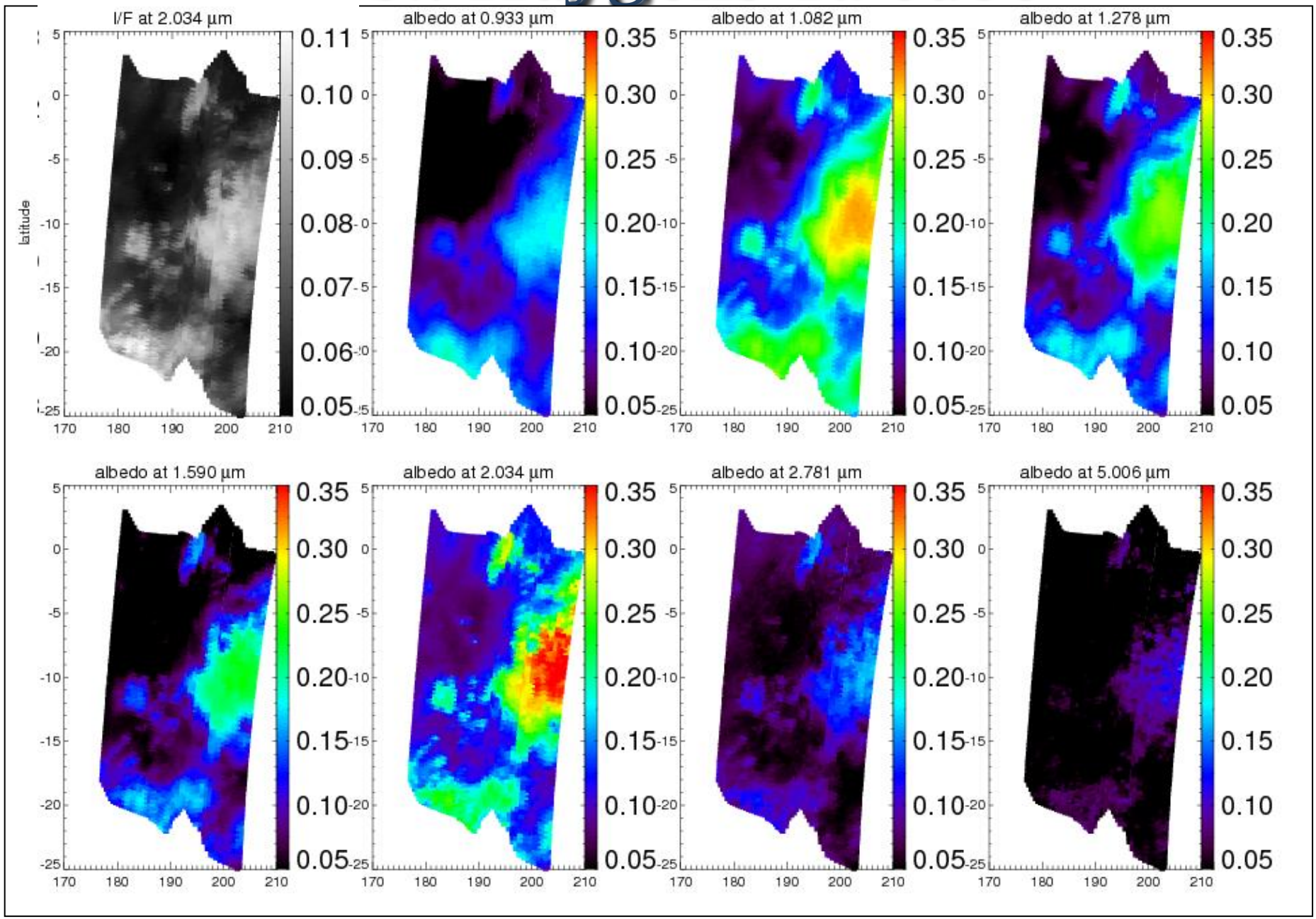


(we actually tested two cubes of the same region taken 15 minutes apart with similar observational conditions – the results are the same)

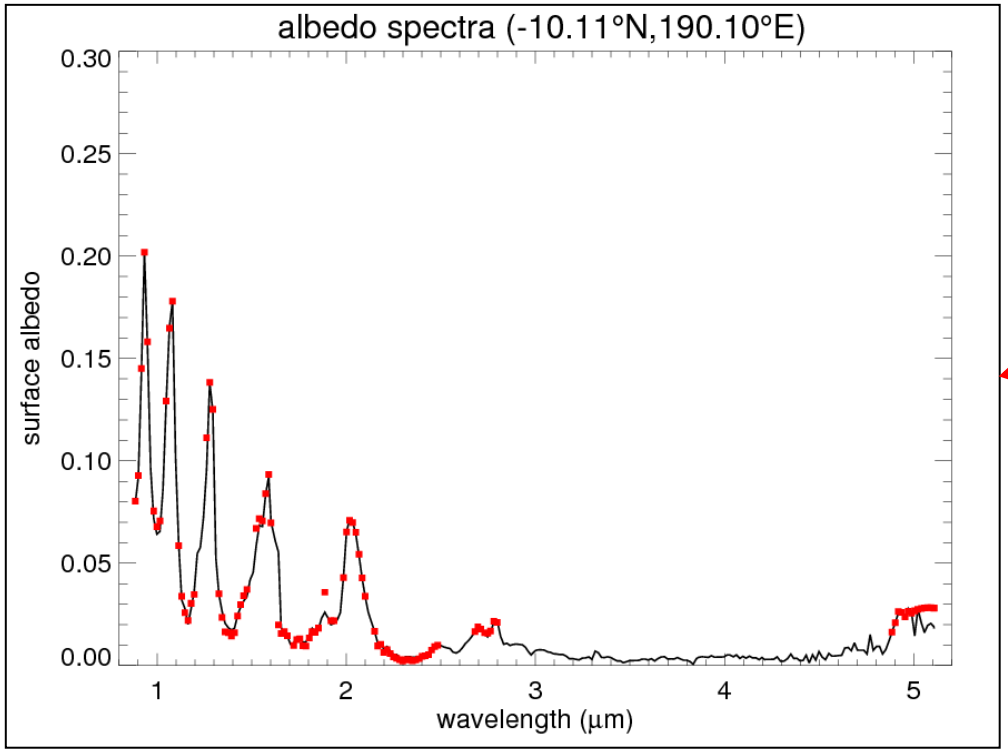
Test: Huygens Ta cube

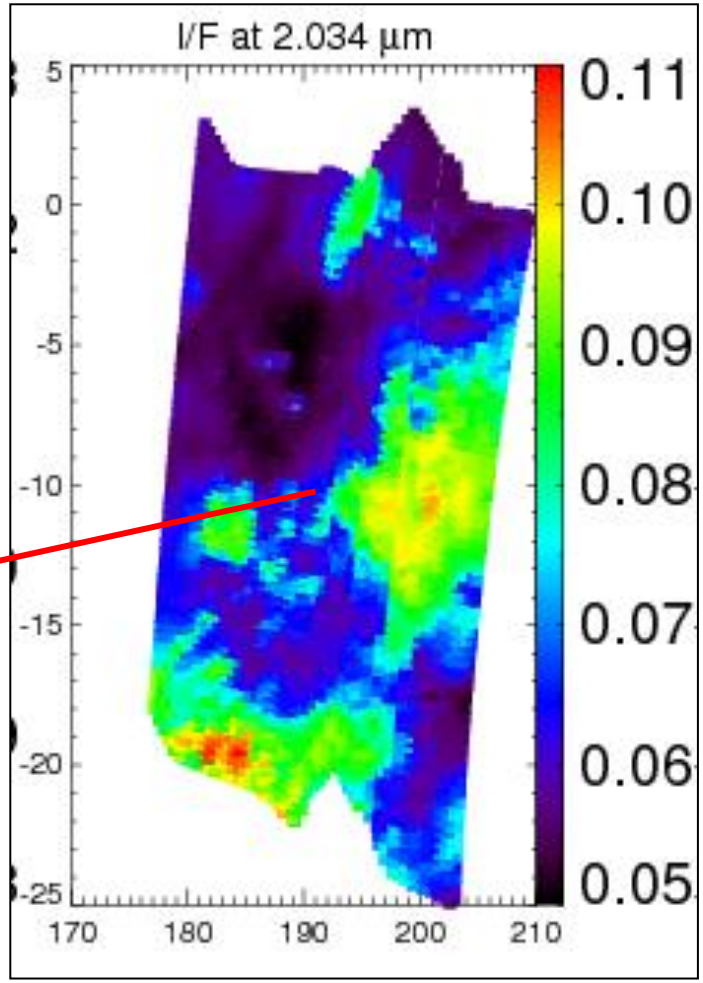


Test: Huygens Ta cube

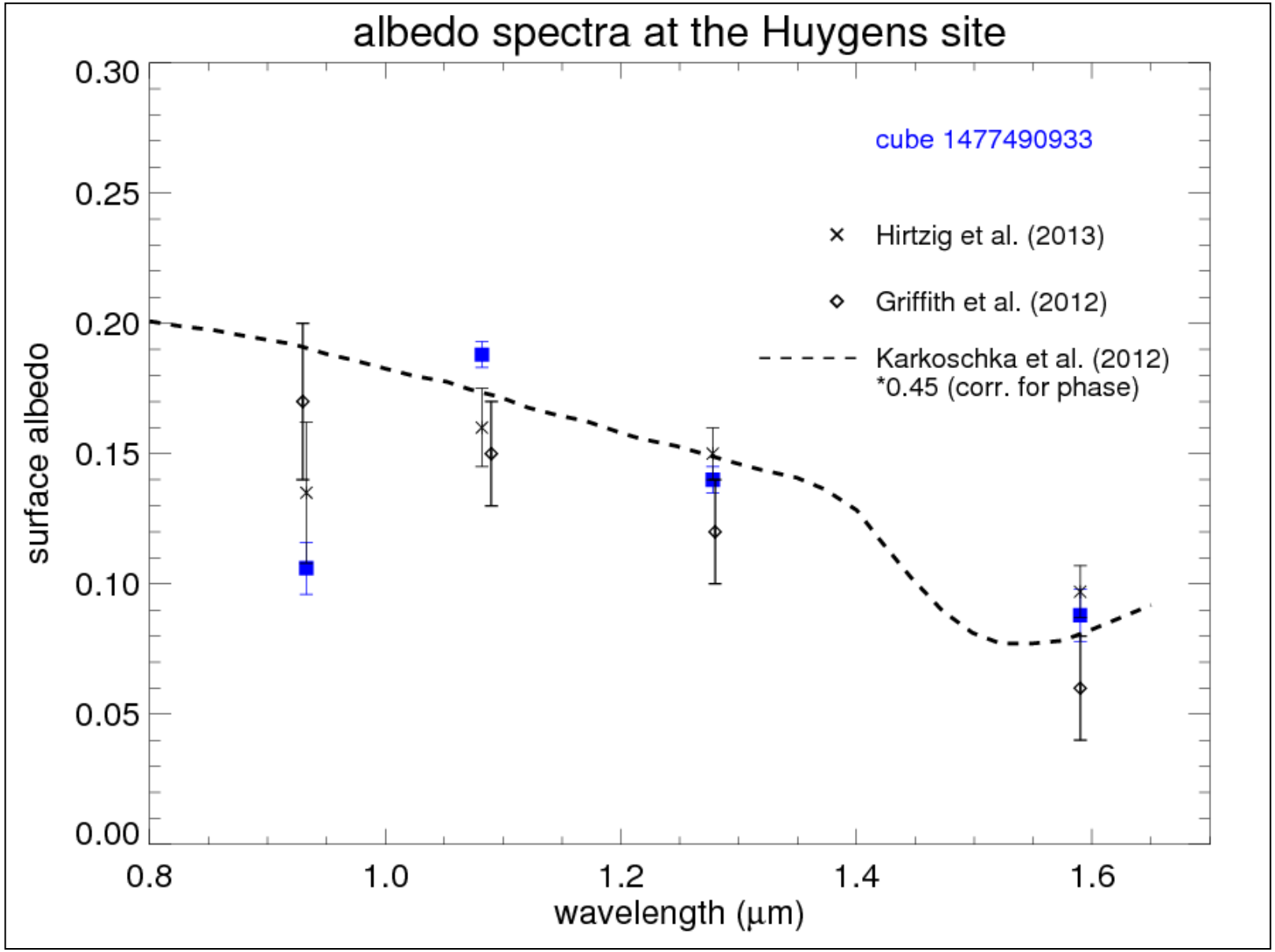


best-fit spectra

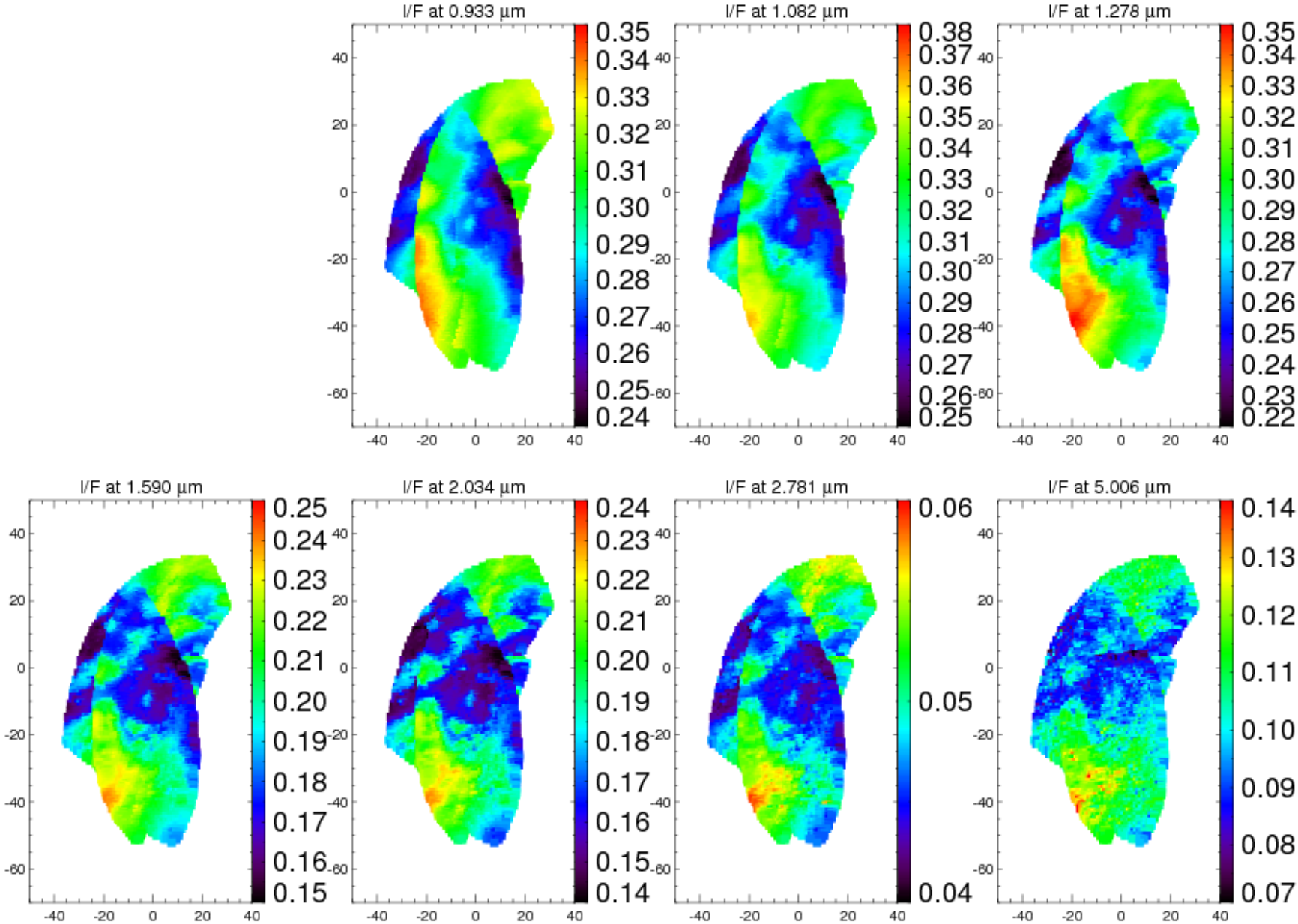




Comparison with DIRS & others



A more difficult task: the T13/T17 mosaic



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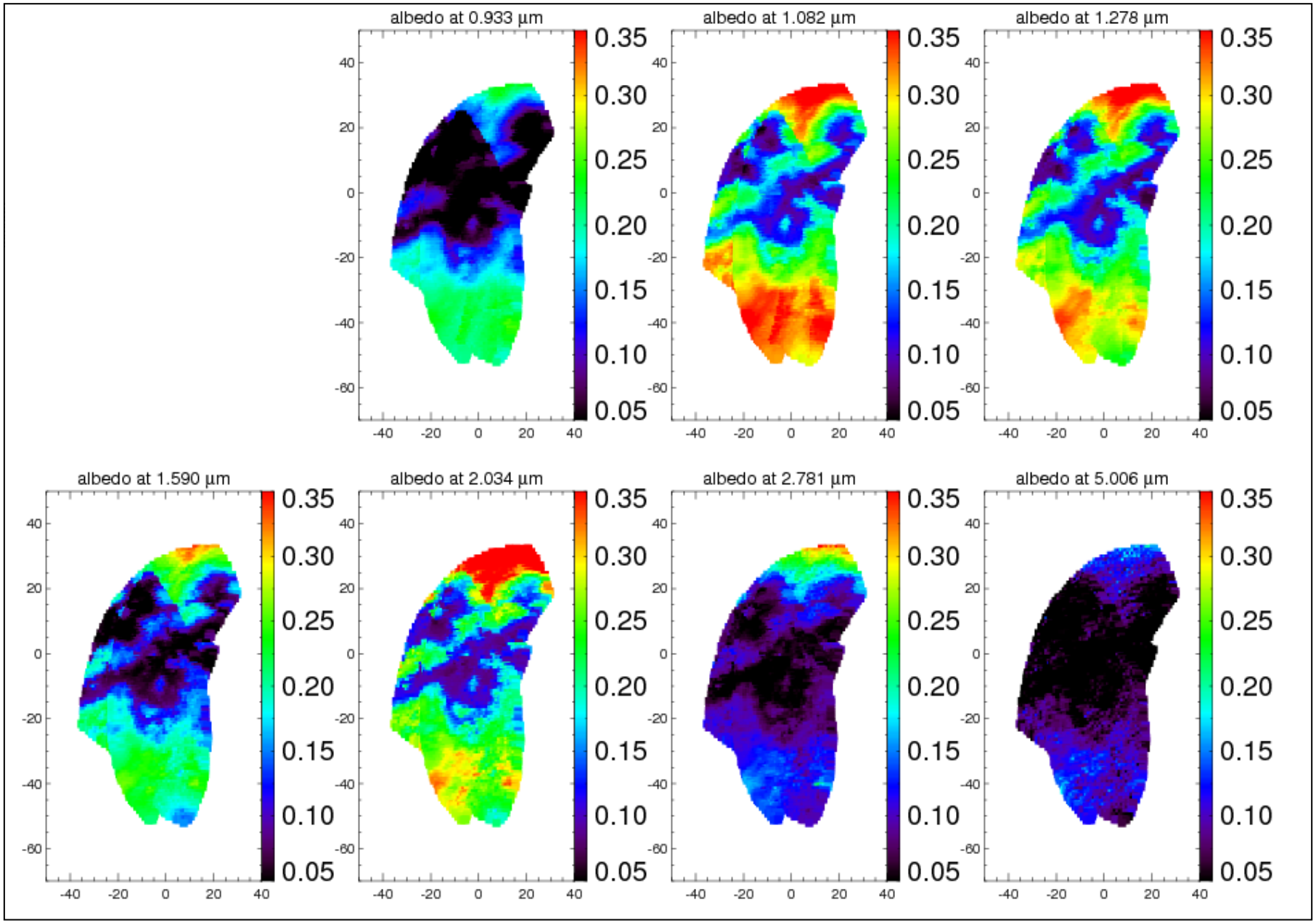

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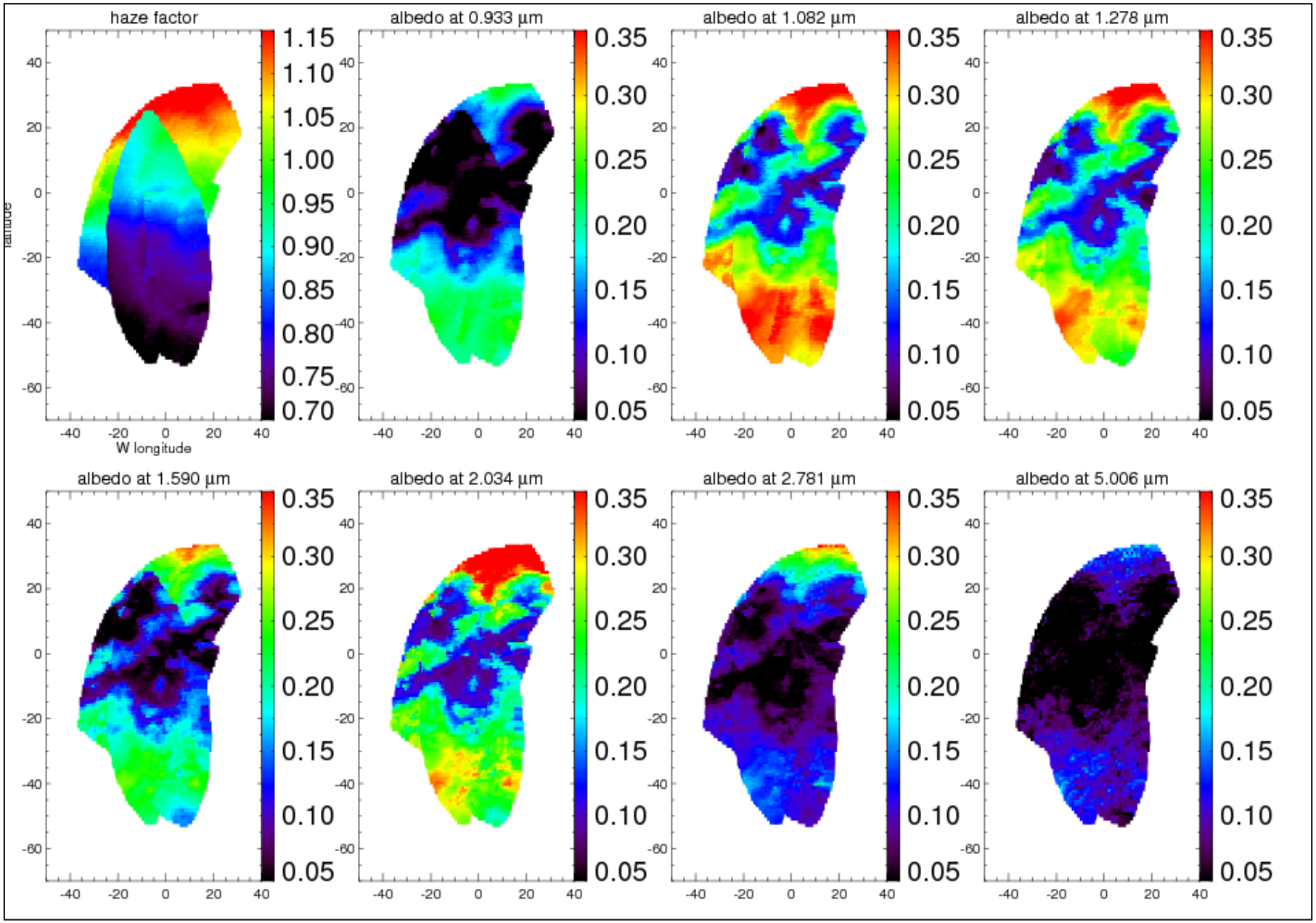


Conclusions

- Developing a method that will allow the massive inversion of maps of surface albedo and haze opacities simultaneously
- …plus corresponding errors
- Application of a full RT treatment without the cumbersome part

First results are promising!

☺ Reliable maps from the Ta Huygens cube in 20s!

☺ Good agreement with other datasets for Huygens site spectrum

☺ Good first results from the T13/T17 mosaic

☹ …but still not excellent especially for the haze

Future work

Improvements

- Optimisation of the parameters' grid, sensitivity study

- Touching the physical model: a better description of the haze
  updating info on methane lines

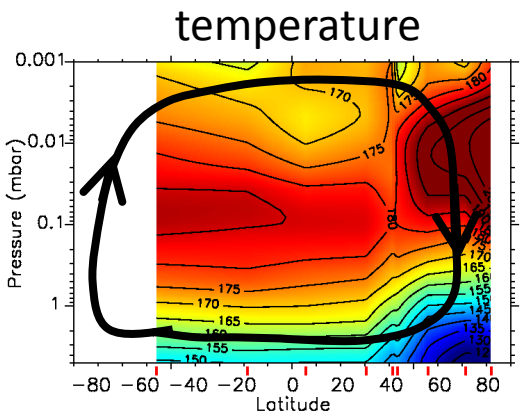
- Extension outside the limit of the plane-parallel approximation
collaboration with M. Vincendon (IAS), Monte-Carlo 3D model

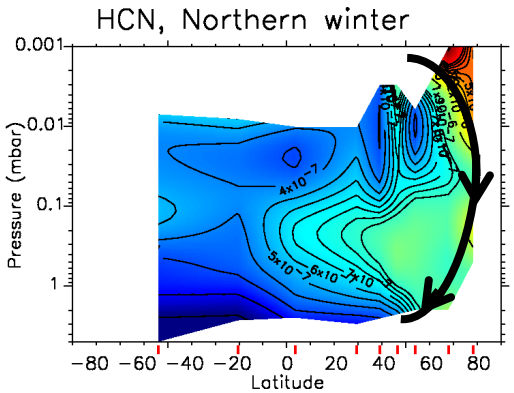
Validation on the T13/T17 mosaic

Computation of final look-up table

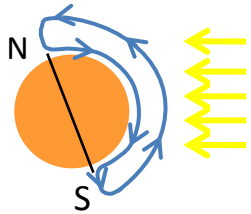
…then the fun starts!

Atmospheric dynamics



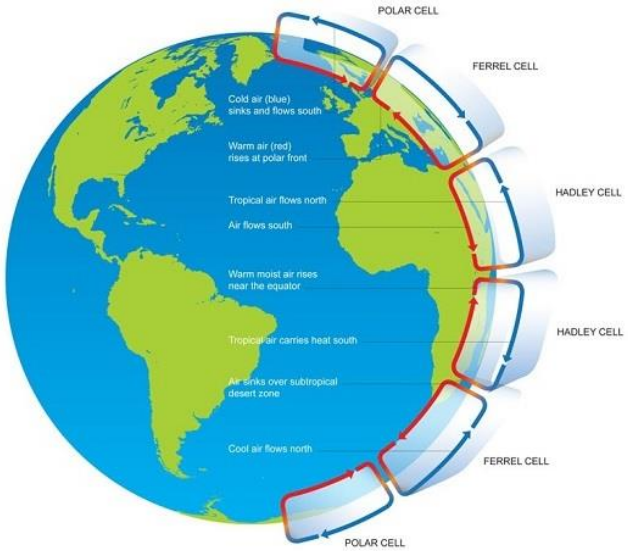


CIRS data, Vinatier et al. 2010

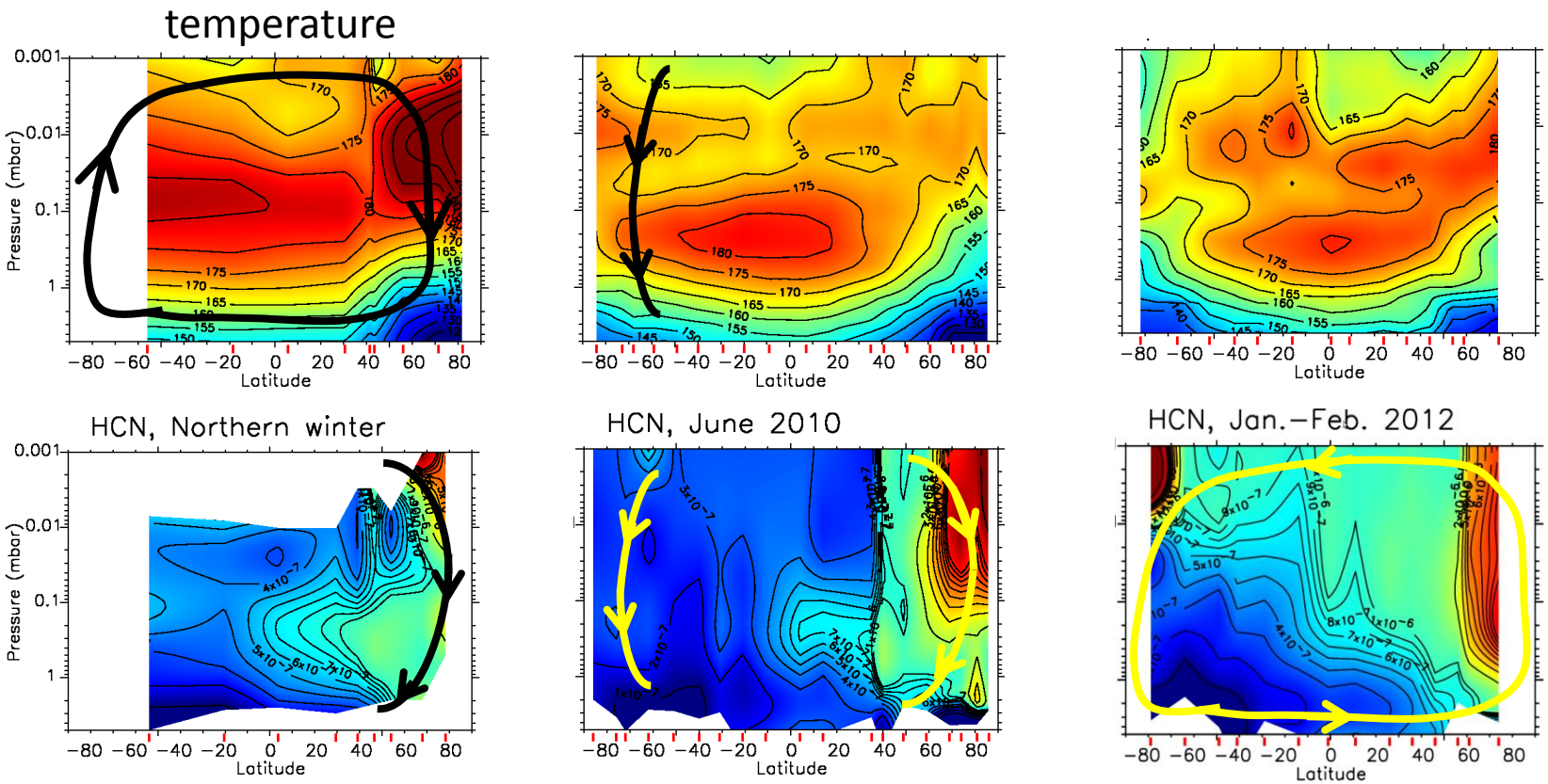


Hadley cell structure

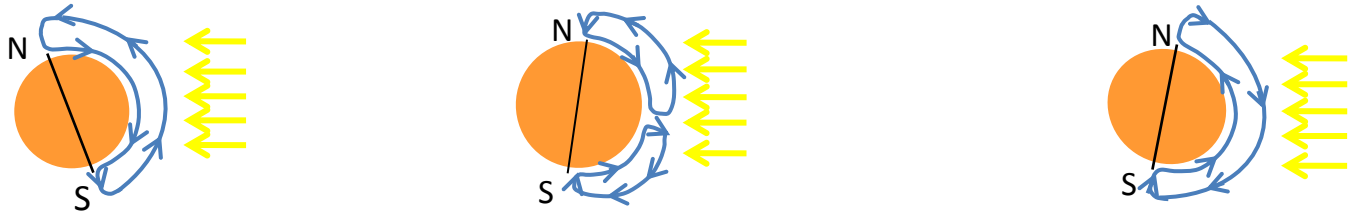
Developed global circulation



Atmospheric seasonal evolution



CIRS data, Vinatier et al. 2010



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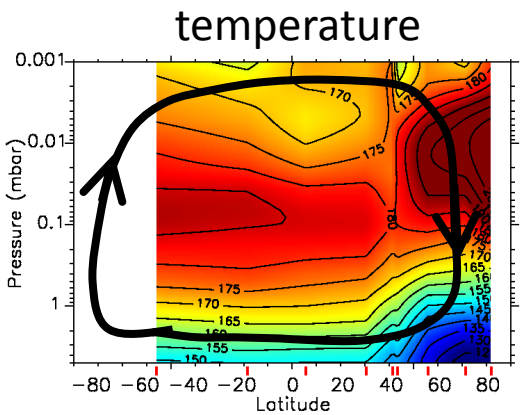
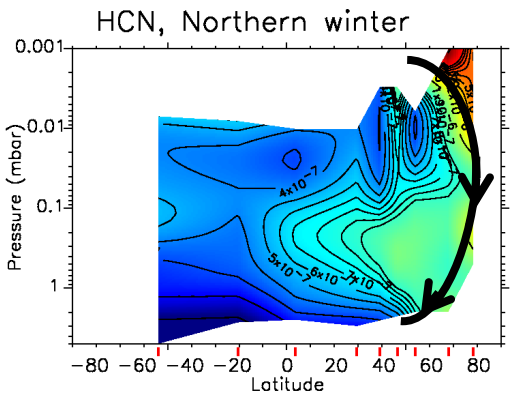
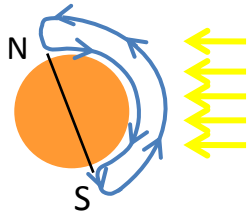




CIRS data, Vinatier et al. 2010



Hadley cell structure

Developed global circulation

Clouds

DOMANDARE FIGURA A SEB.

Determination of uncertainty maps

Effect of detector noise on the output maps

- Dark
- Read noise
- Shot noise

} Quadratic sum → Noise spectrum (I/F)

Adding a random gaussian-distributed fluctuation around the noise to the spectra

↓

100 times

↓

Standard deviation maps

Determination of uncertainty maps