
A short course on Titan
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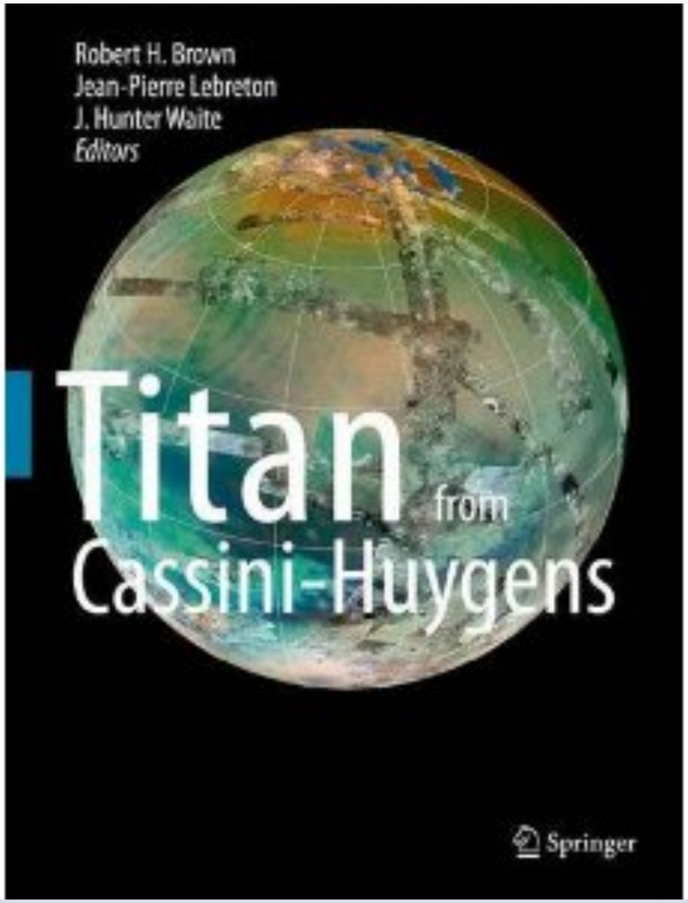
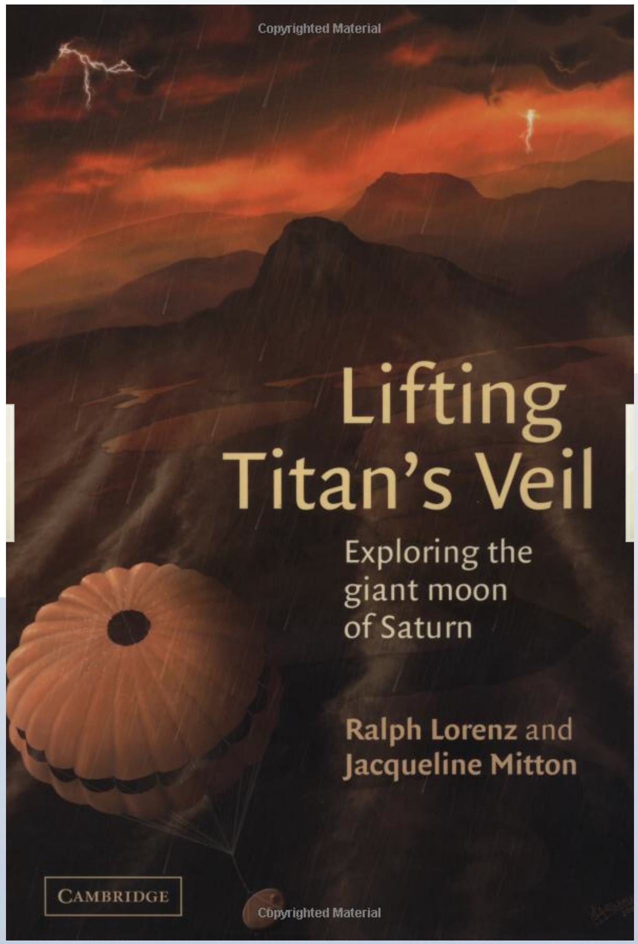
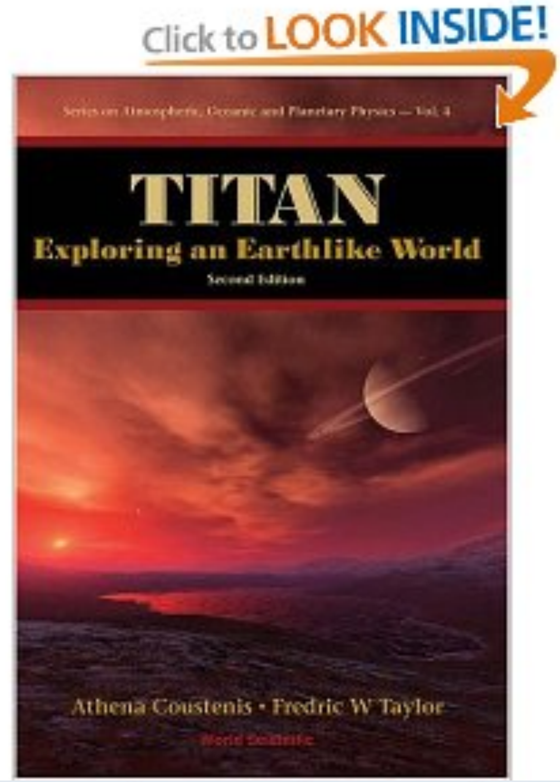
Outline

1. Basics of Titan
2. The hydrologic cycle on Titan
3. Seasonal polar changes
4. Croll-Milankovich polar changes
5. Changes over geologic time
6. Titan's geophysics/internal evolution
7. Wild and crazy ideas:
   a) Hydrocarbon-based life on Titan
   b) Titan as a model for future Earth runaway

Good Reading







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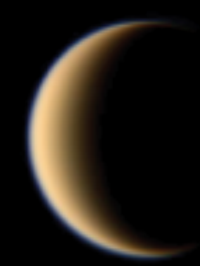
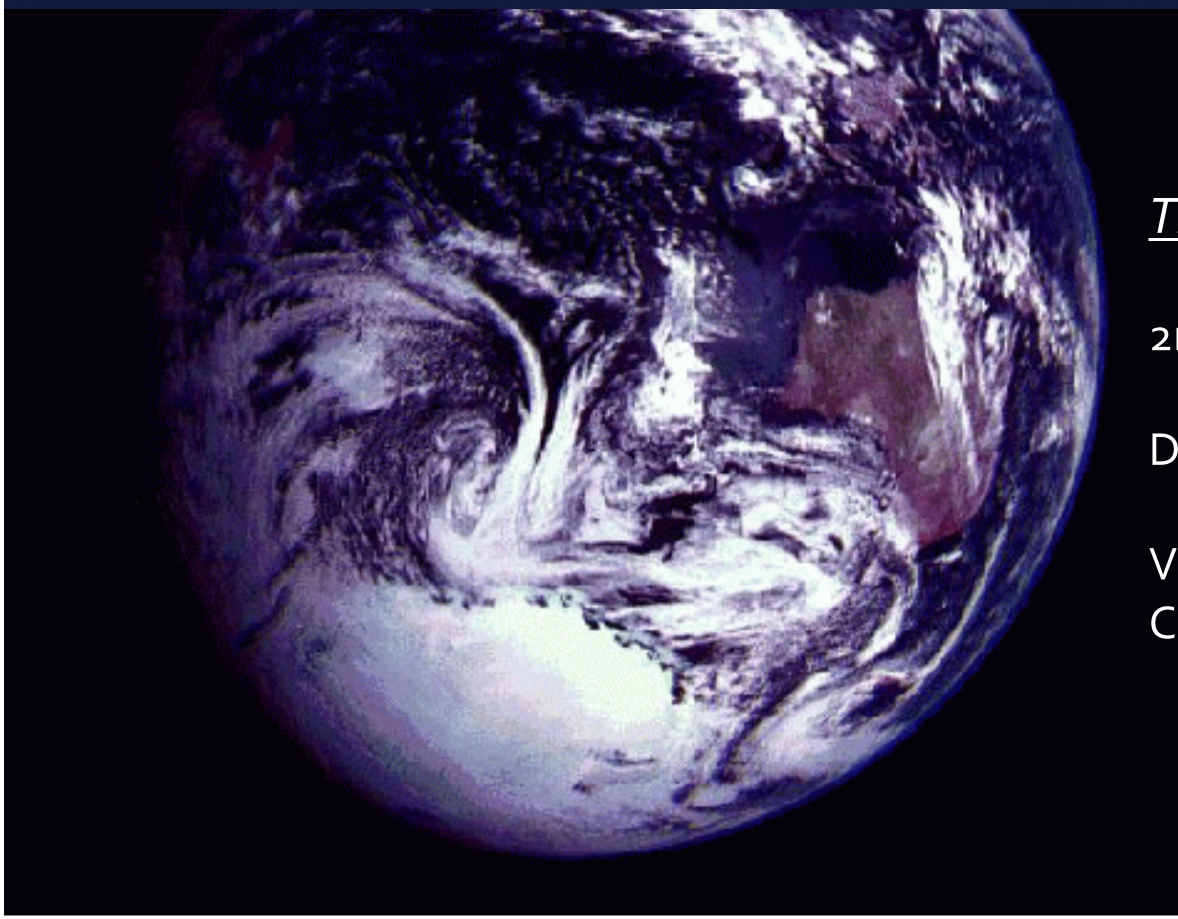
One of four worlds with atmospher and active volatile cycles on solid surfaces

Only Titan and Earth have open bodies of liquid on their surfaces: connects to theme of global change

Titan may be the solar system's example of an extremely common type of planet in the cosmos—its environment may be similar to that of planets at 1 AU from M dwarfs: connects to exoplanet theme





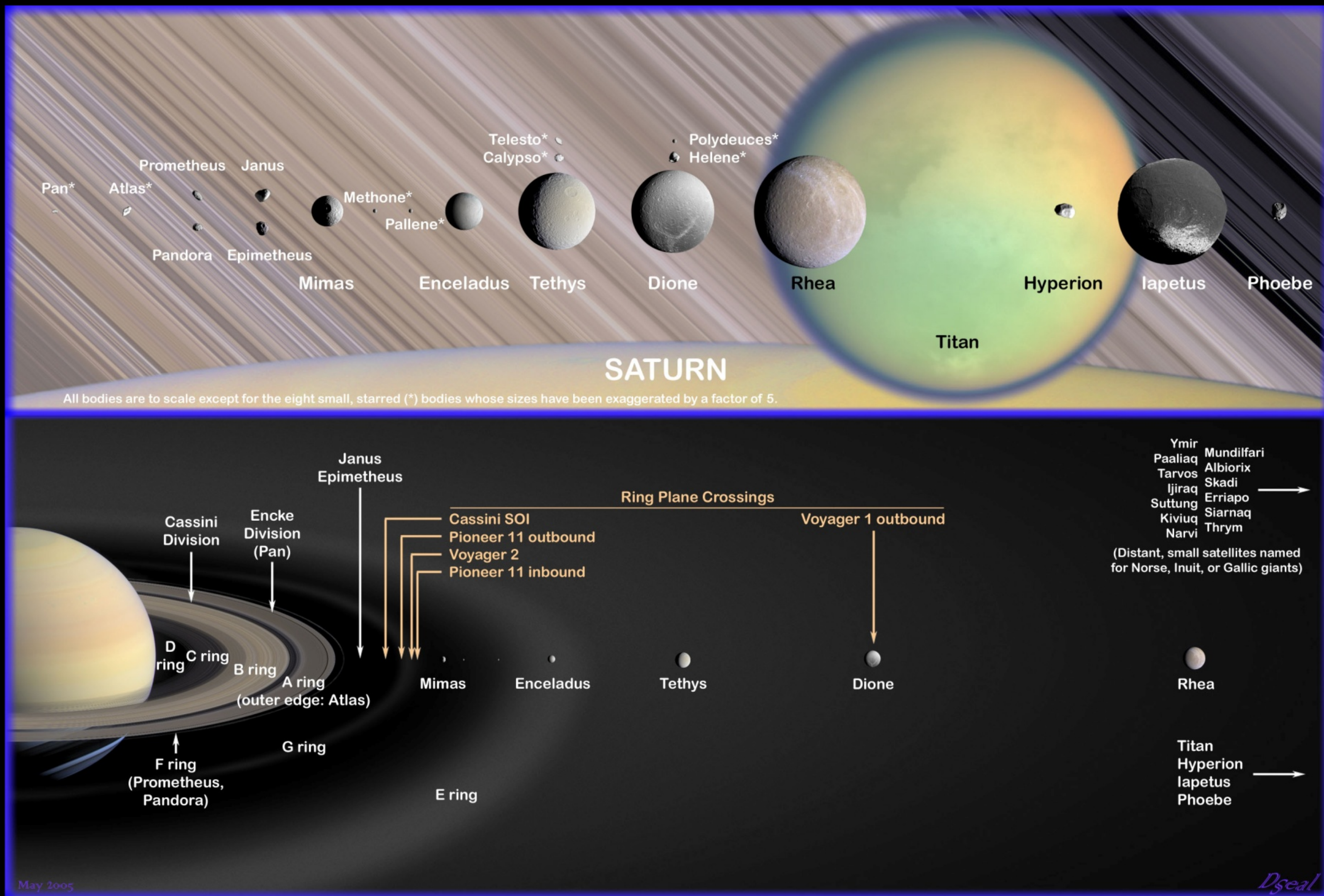
Titan in the solar system

2nd largest moon in the sol sys

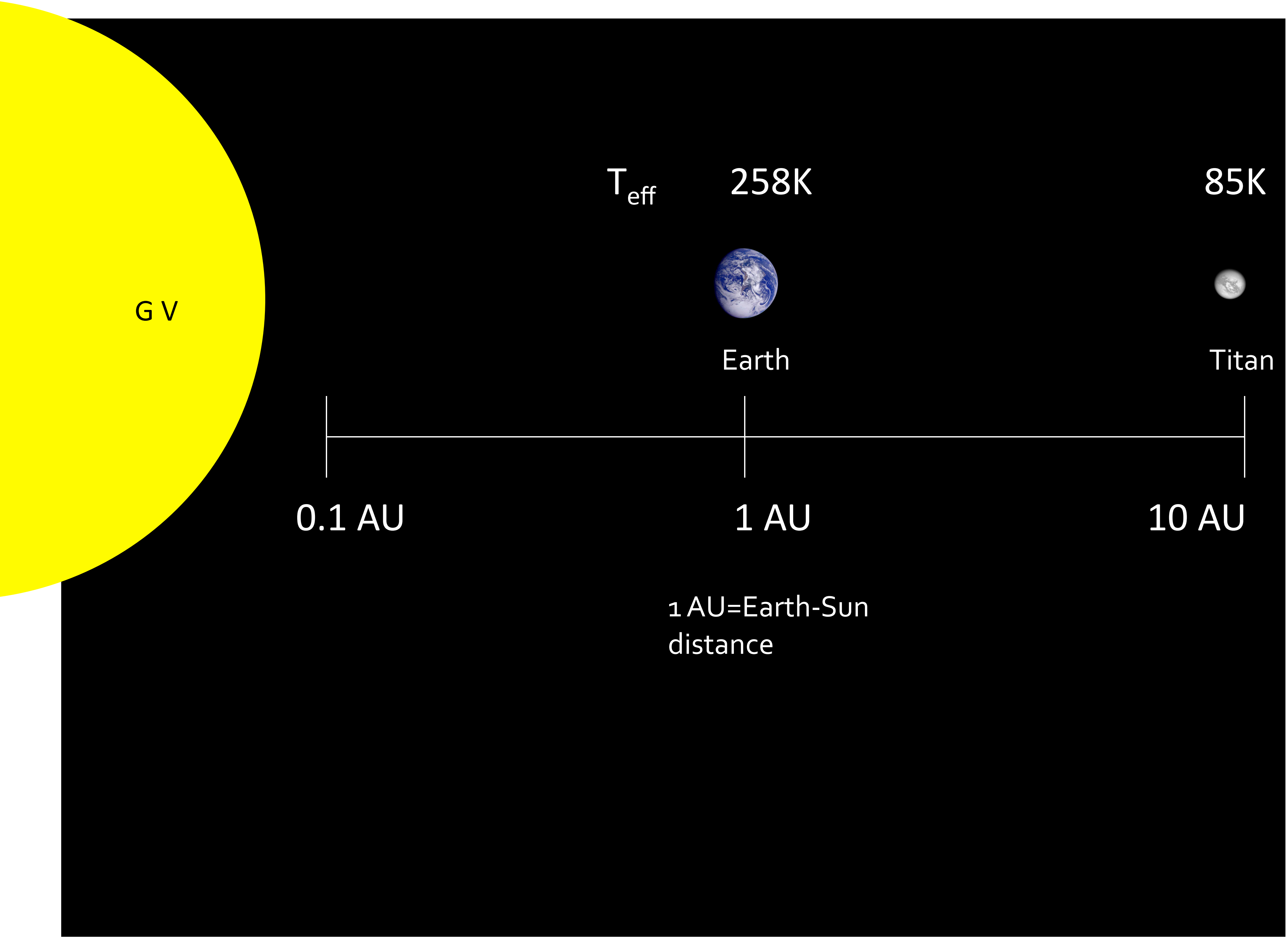
Density 1.88 g/cm^3 --> 60% rock

Voyager flybys in 1980, 1981;
Cassini-Huygens 2004-

The Saturnian System



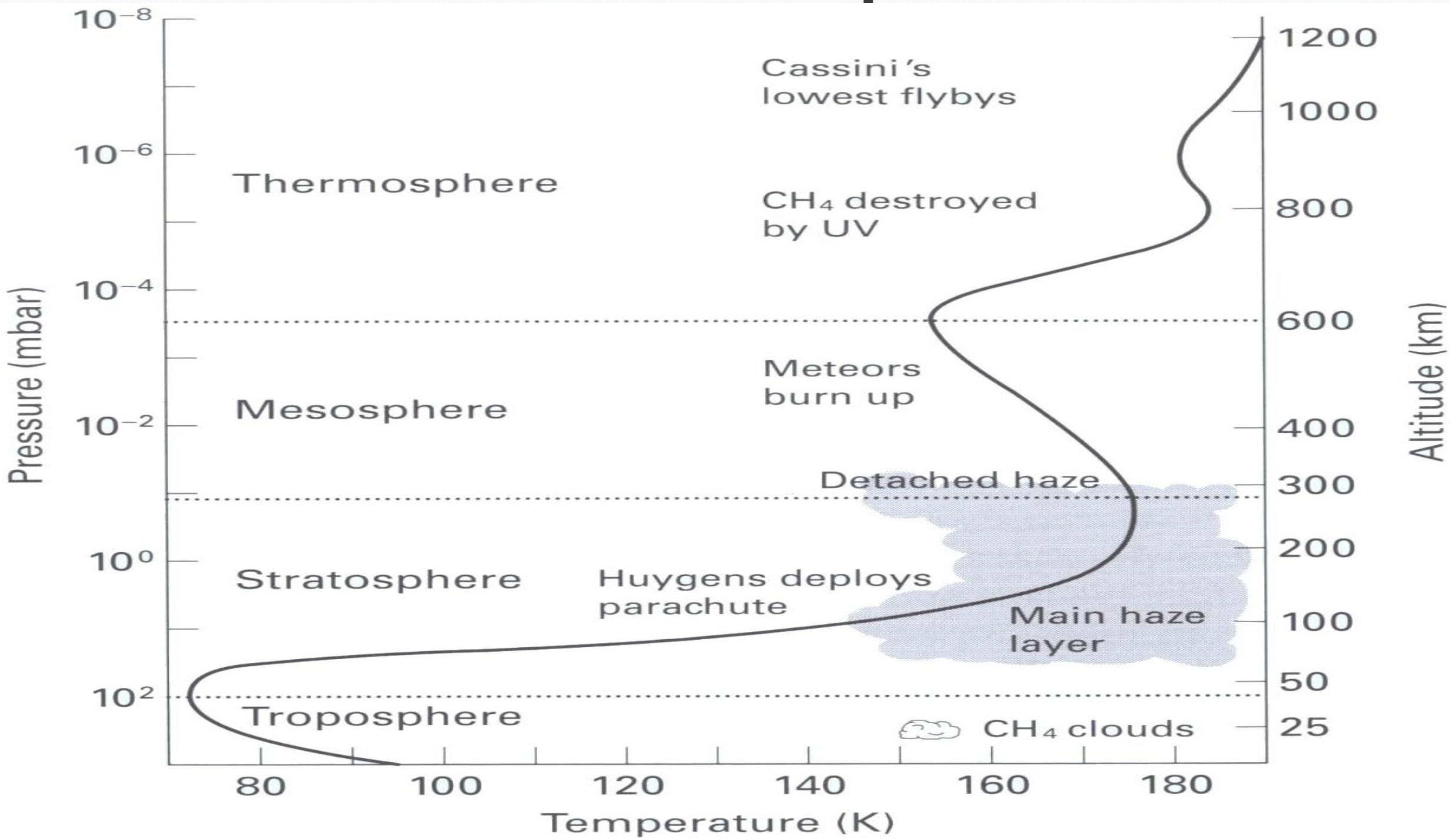
Lunine, Pappalardo, Matson


G V
T_{eff}
258K
85K
Earth
Titan
0.1 AU
1 AU
10 AU
1 AU=Earth-Sun distance

Historic highlights of exploration

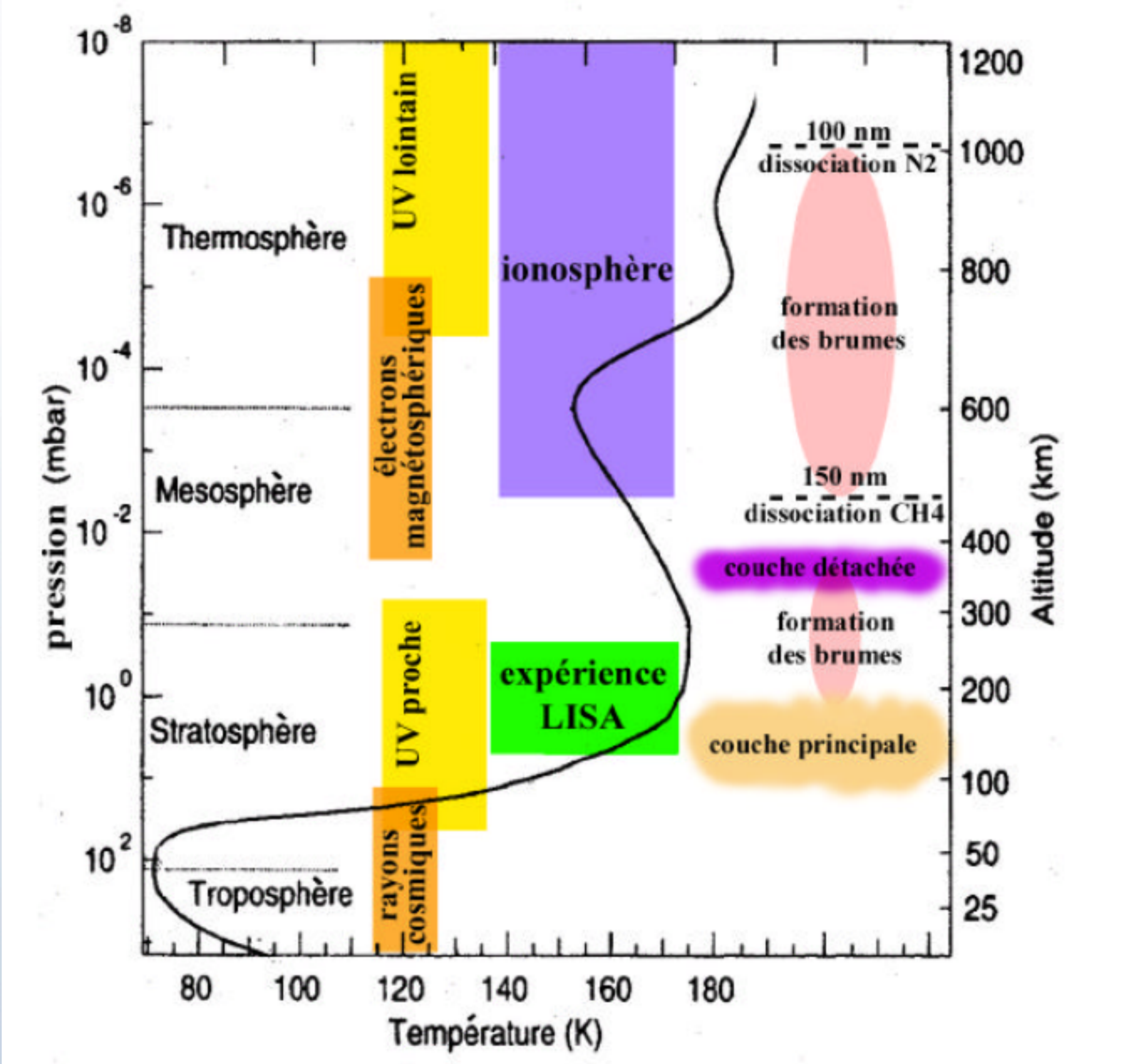
1655	C. Huygens Discovers “Luna Saturni”
1847	John Herschel names it Titan
1908	Comas Solà infers an atmosphere
1943	G. Kuiper discovers methane on Titan
1980	Voyager 1 probes atmosphere/determines size
2005	Huygens probe lands on surface/finds methane
2004-2017	Cassini Orbiter maps Titan surface/atmosphere

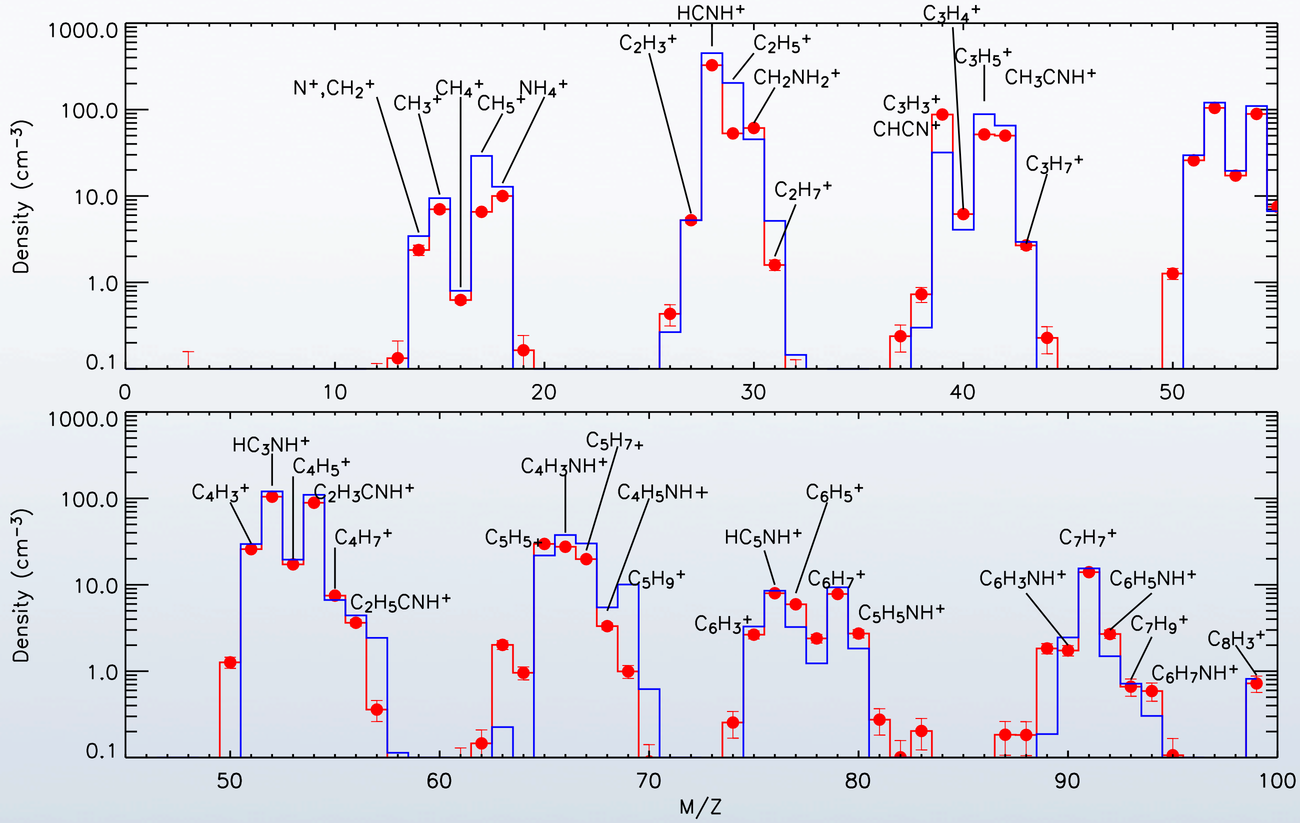
Titan's atmosphere



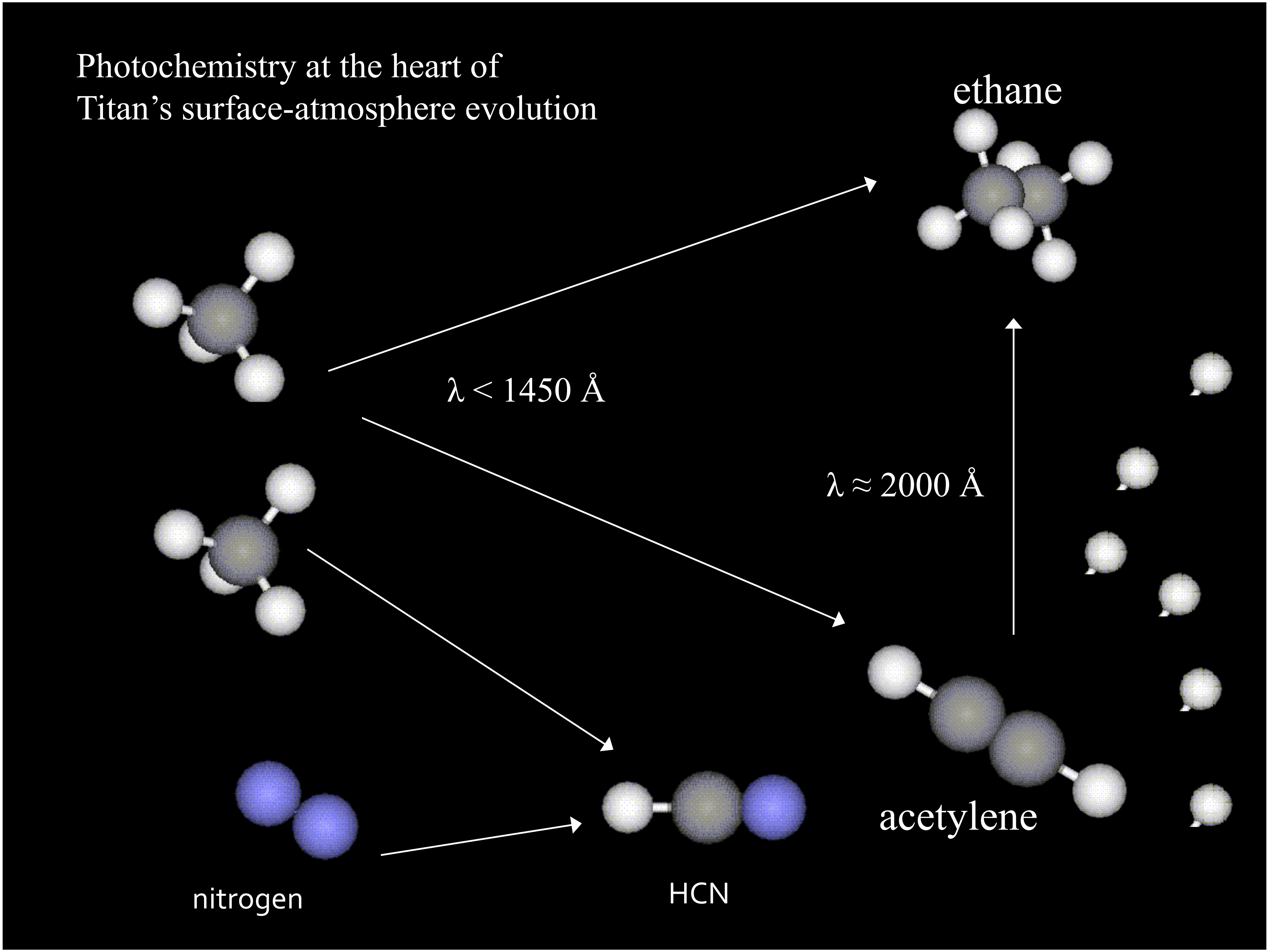
NB – 1D radiative transfer codes are able to produce matching temperature profiles by including what we know about Titan's composition

Energy Sources





INMS shows complex chemistry in the region above 900 km (probably below, too).


Photochemistry at the heart of
Titan's surface-atmosphere evolution
ethane
λ < 1450 Å
λ ≈ 2000 Å
acetylene
nitrogen
HCN

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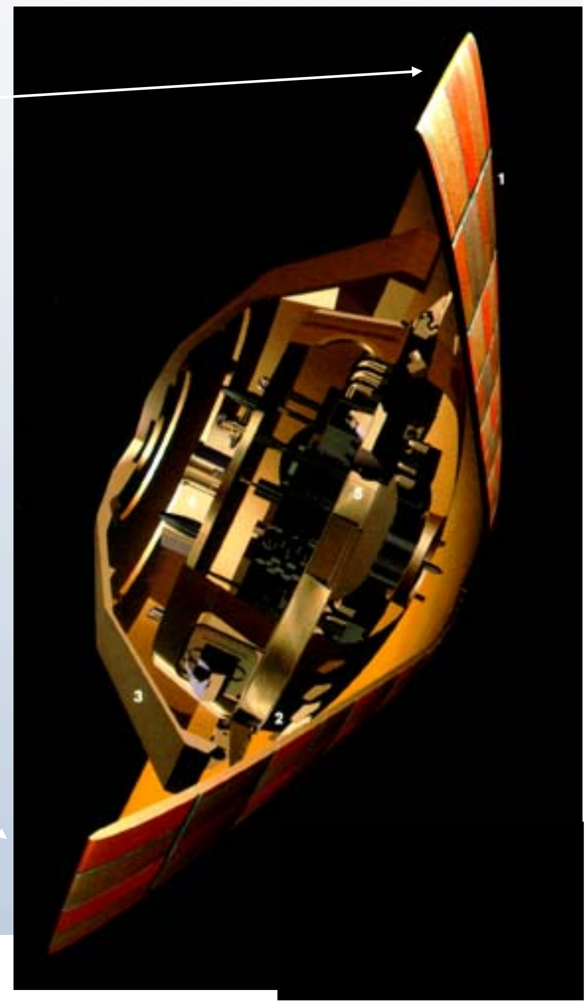
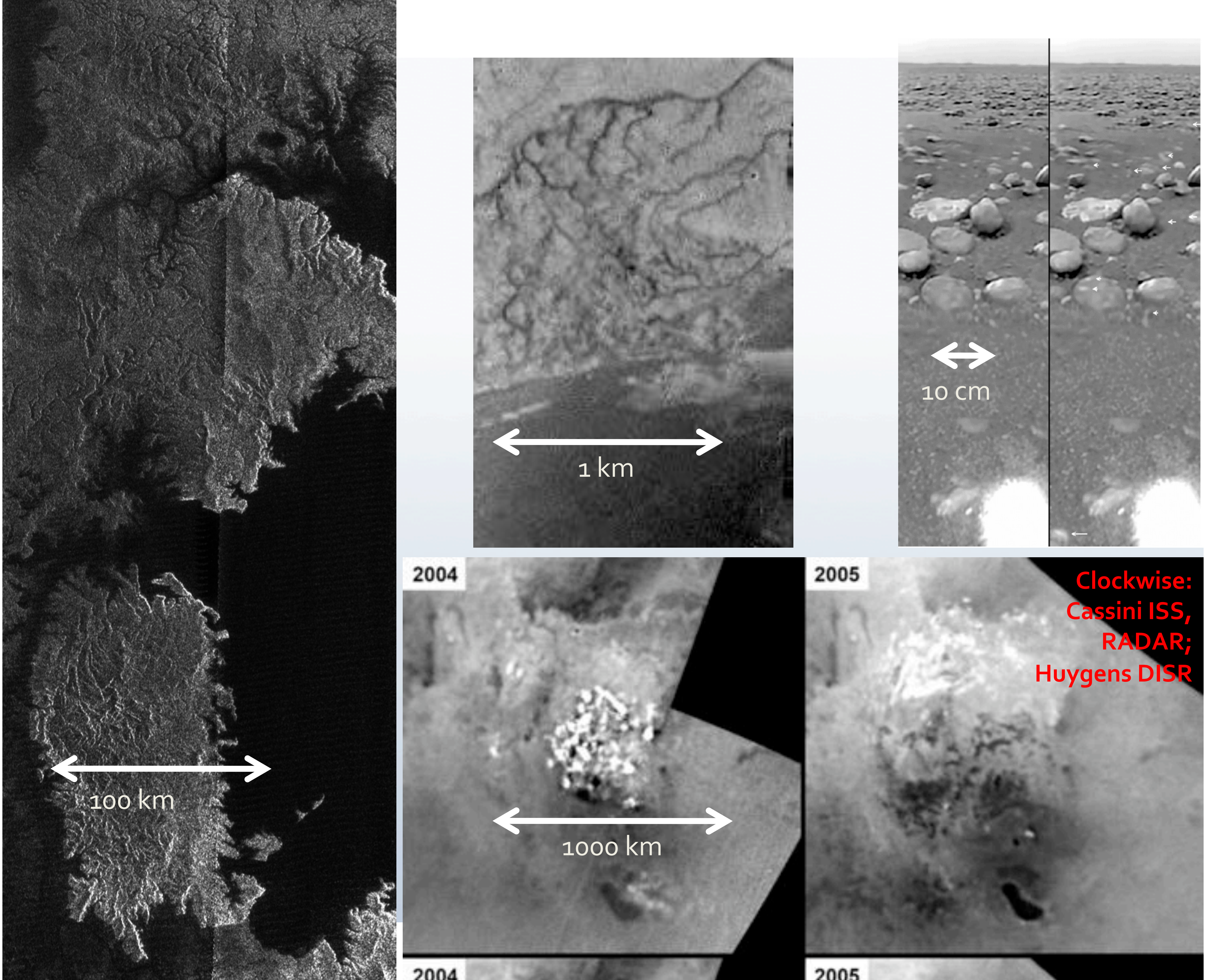
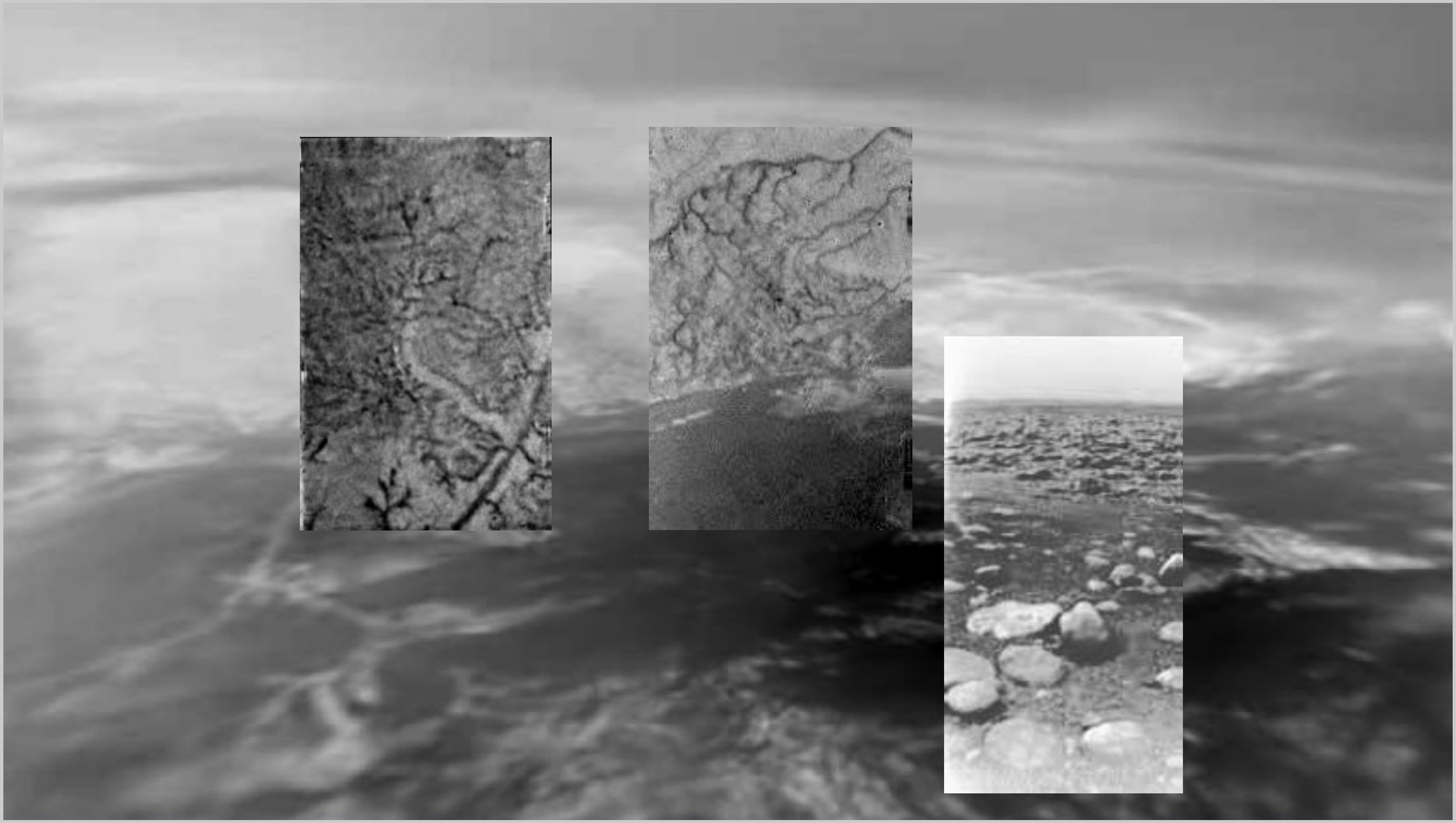
Cassini-Huygens:

A US-European collaboration with three official partners: NASA/ESA/ASI



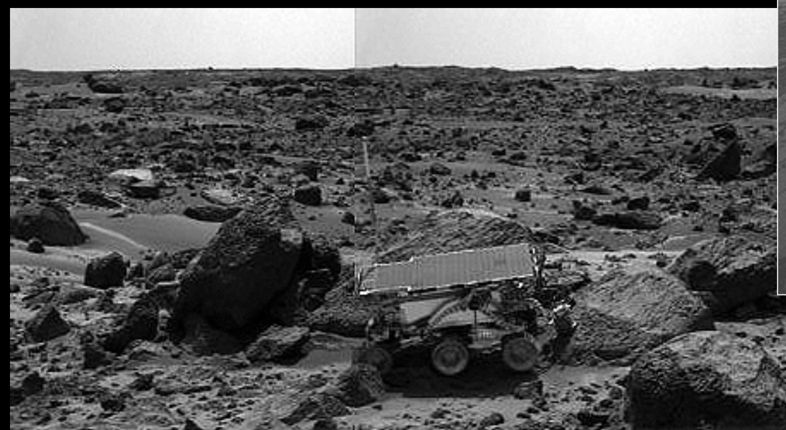

100 km
1 km
10 cm
2004
2005
1000 km
2004
2005
Clockwise:
Cassini ISS,
RADAR;
Huygens DISR

Titan’s surface: jetliner view



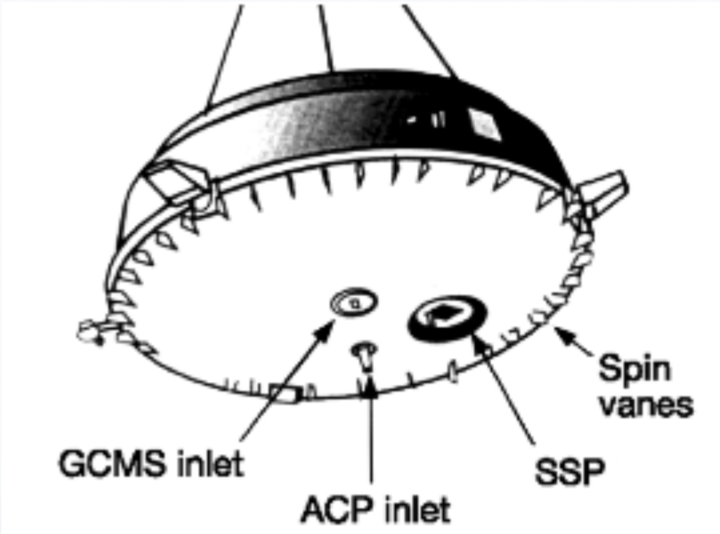
Landing site most resembles a desert bajada on Earth

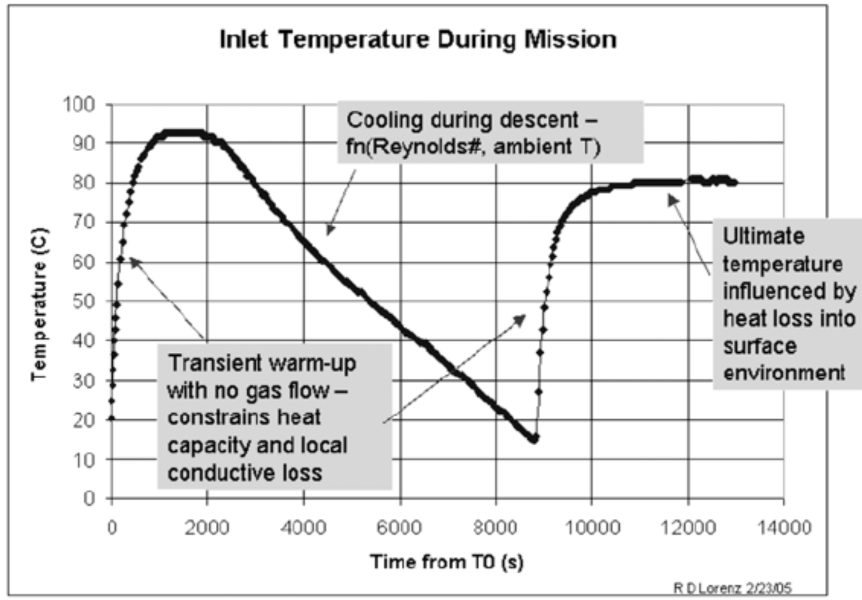
Venus



Mars

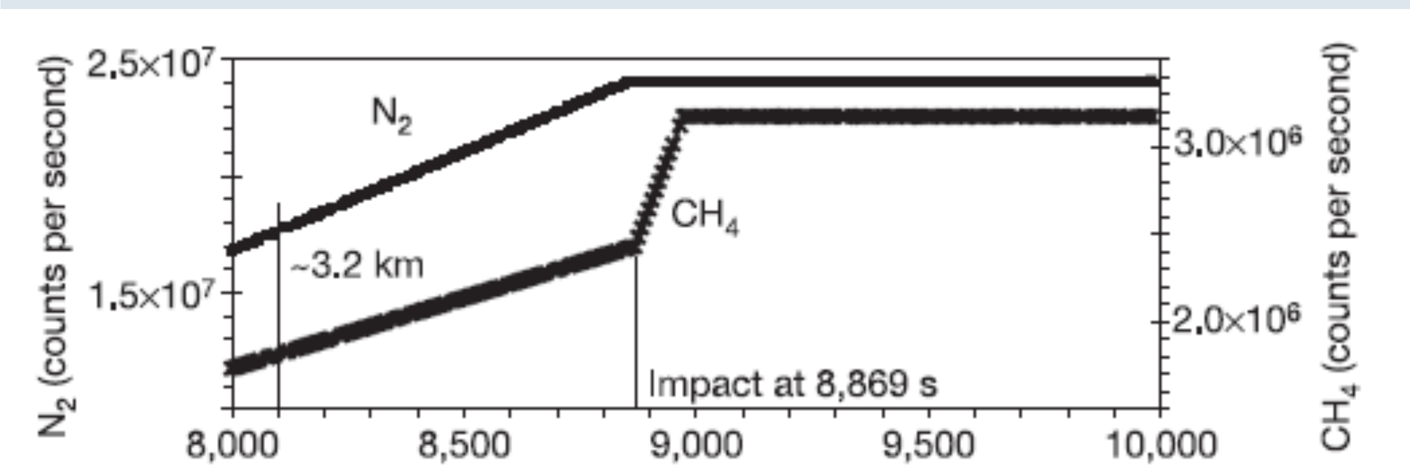
Titan Earth (Desert bajada, Tucson)





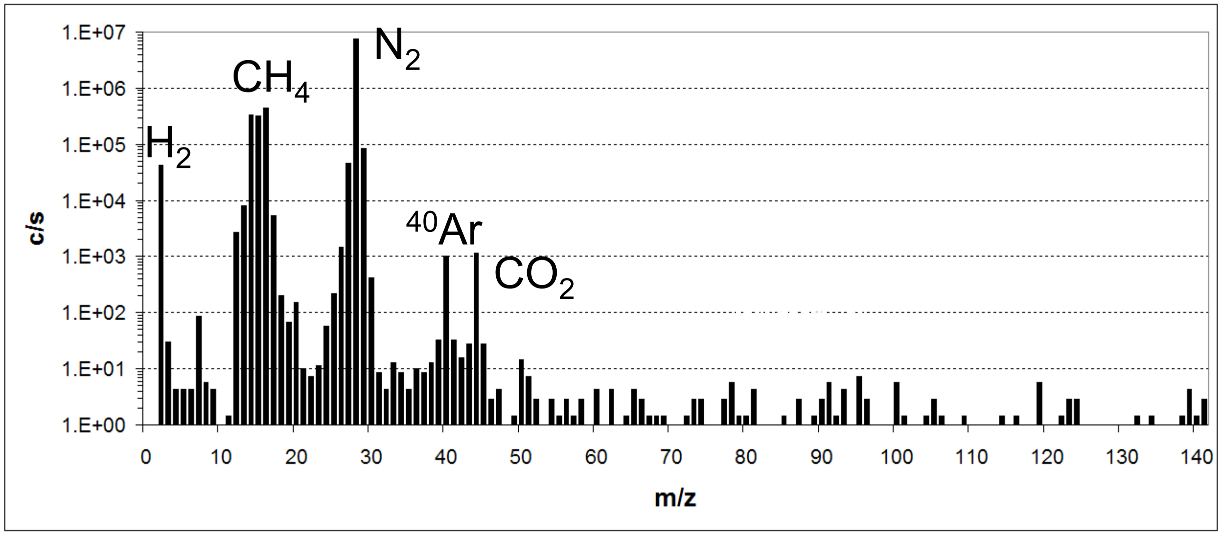
Lorenz et al 2006

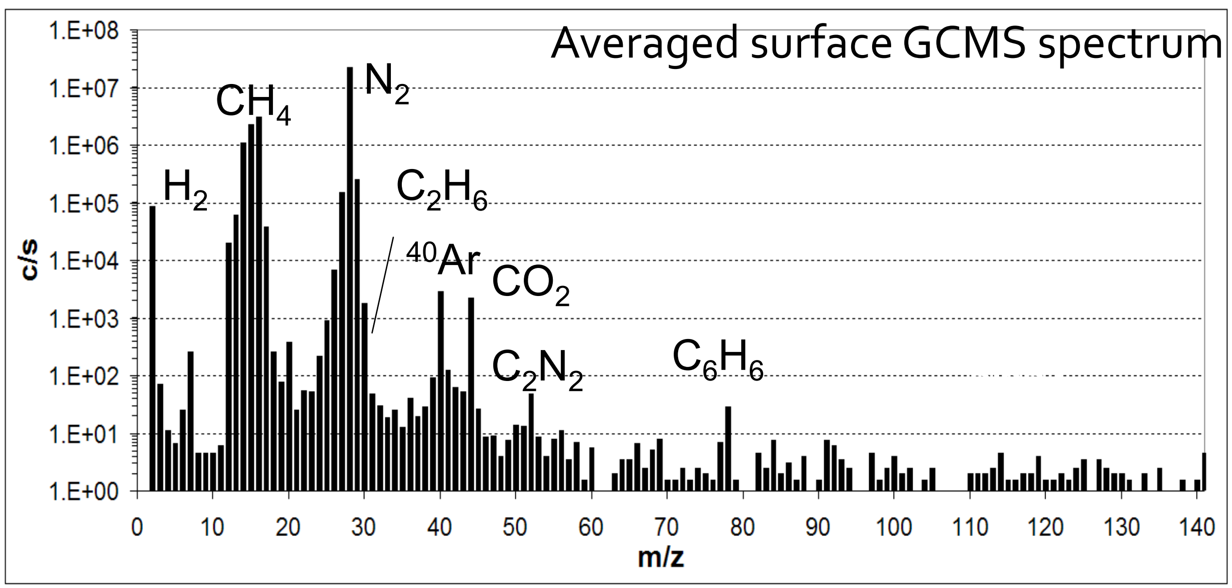
Niemann et al 2005

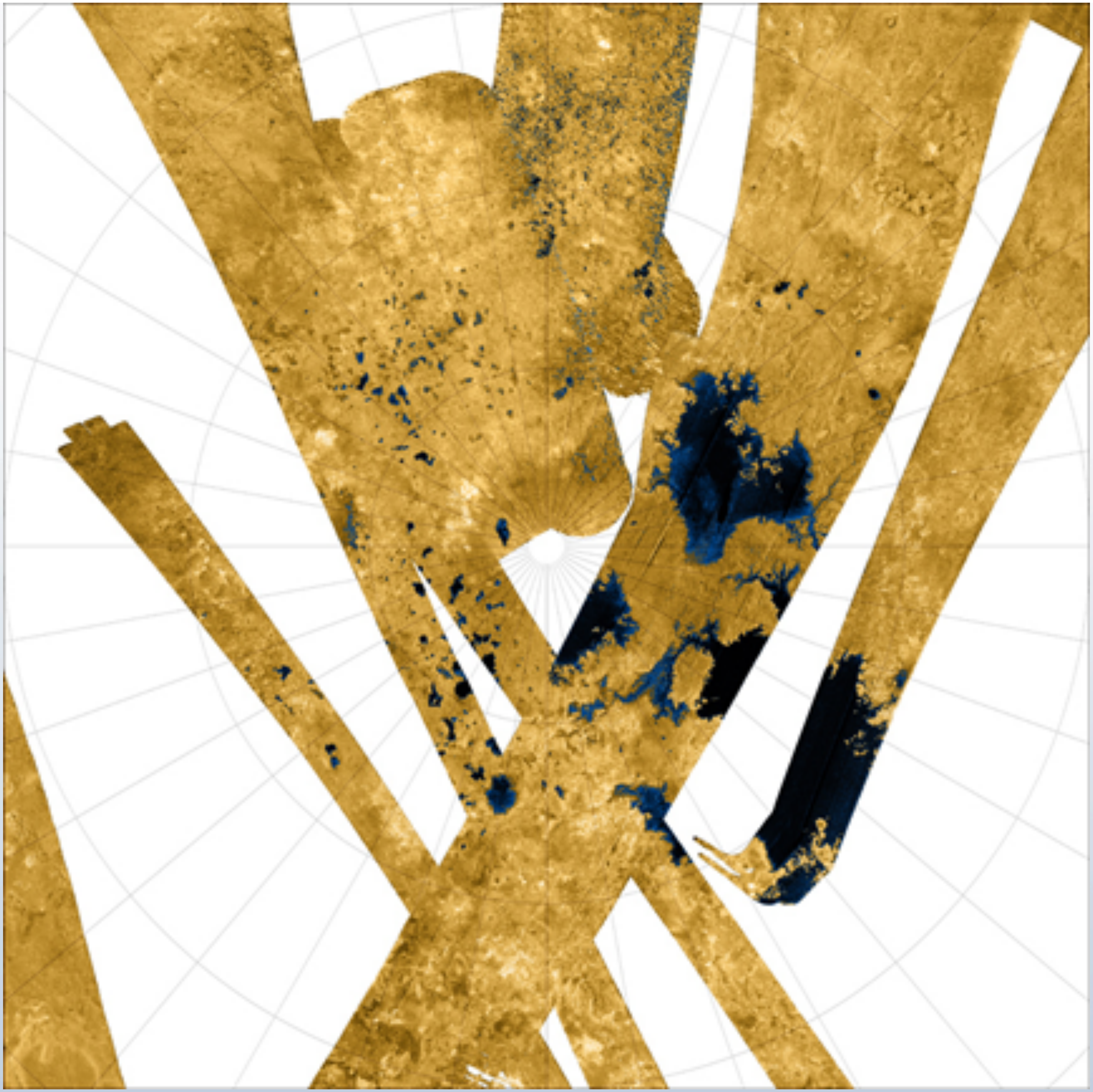


Methane and ethane are evaporating from the surface, based on GCMS measurements from Huygens

10-20 km averaged GCMS spectrum







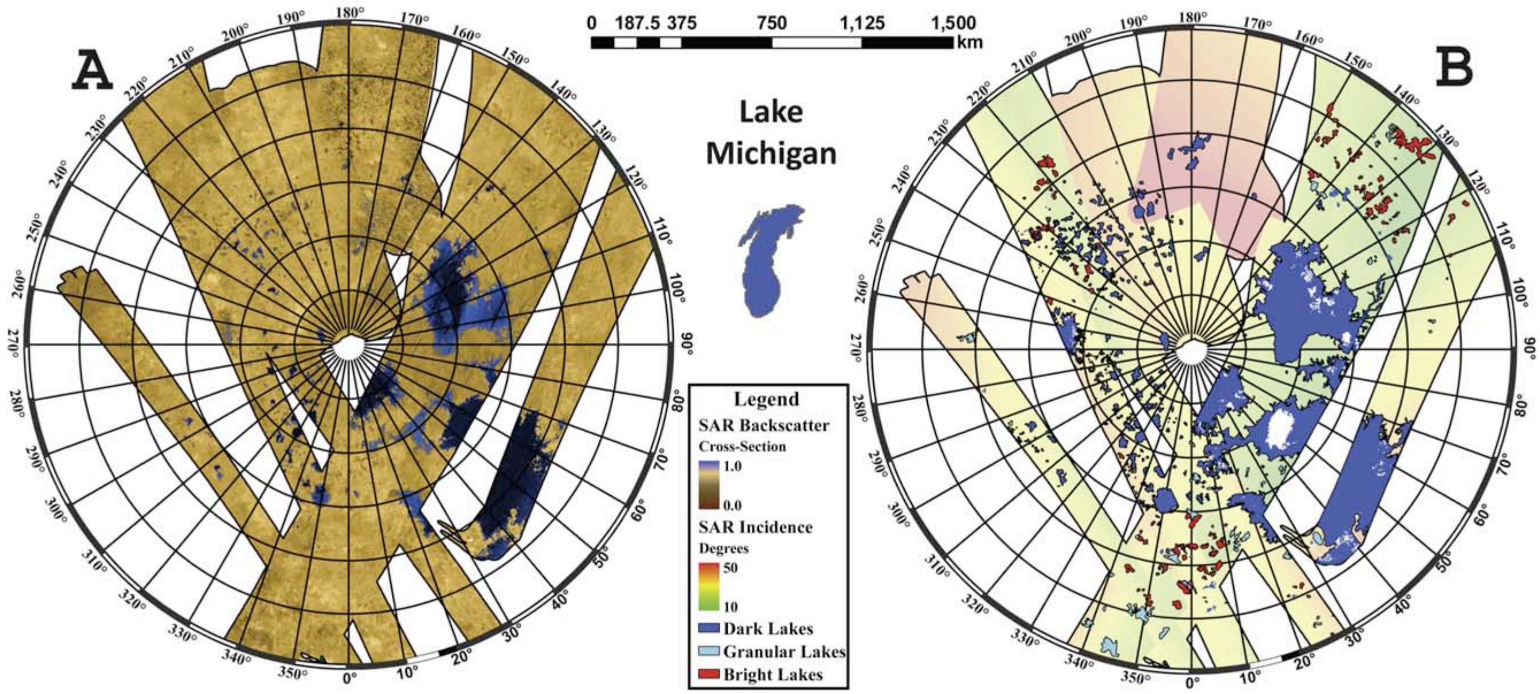
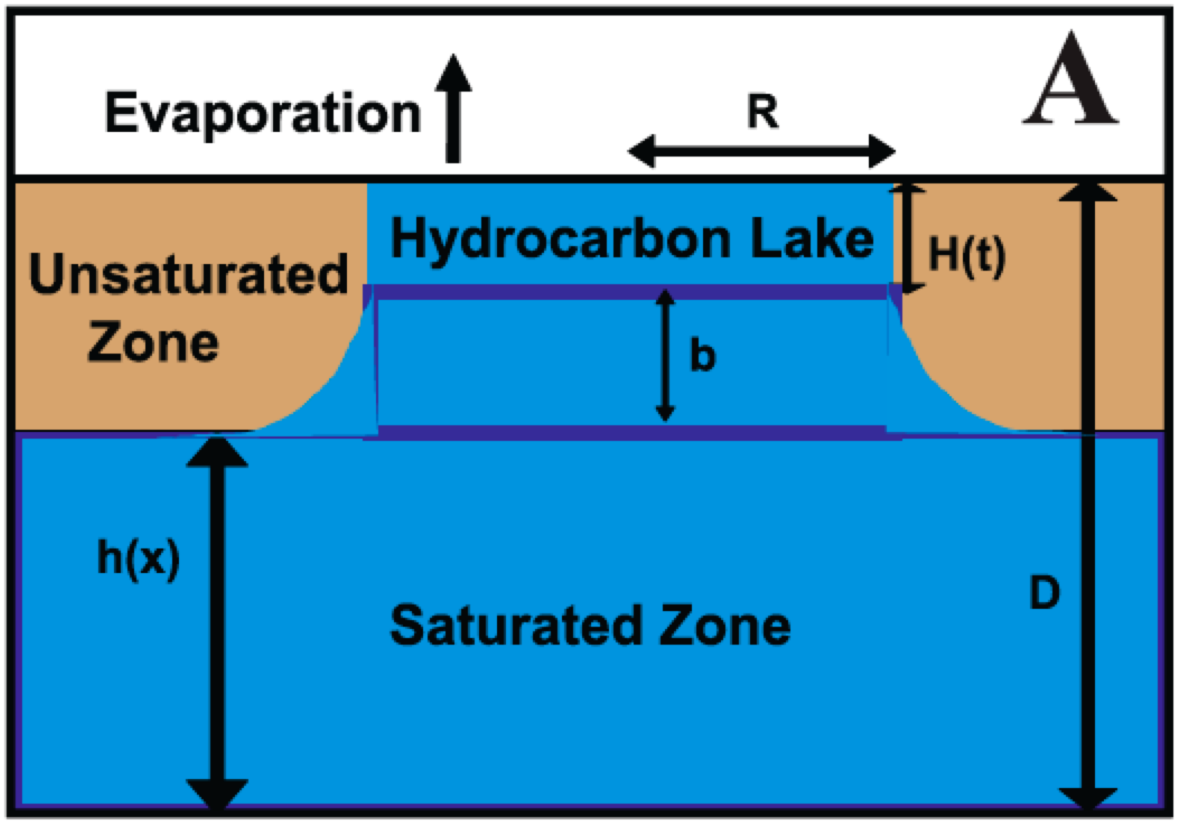


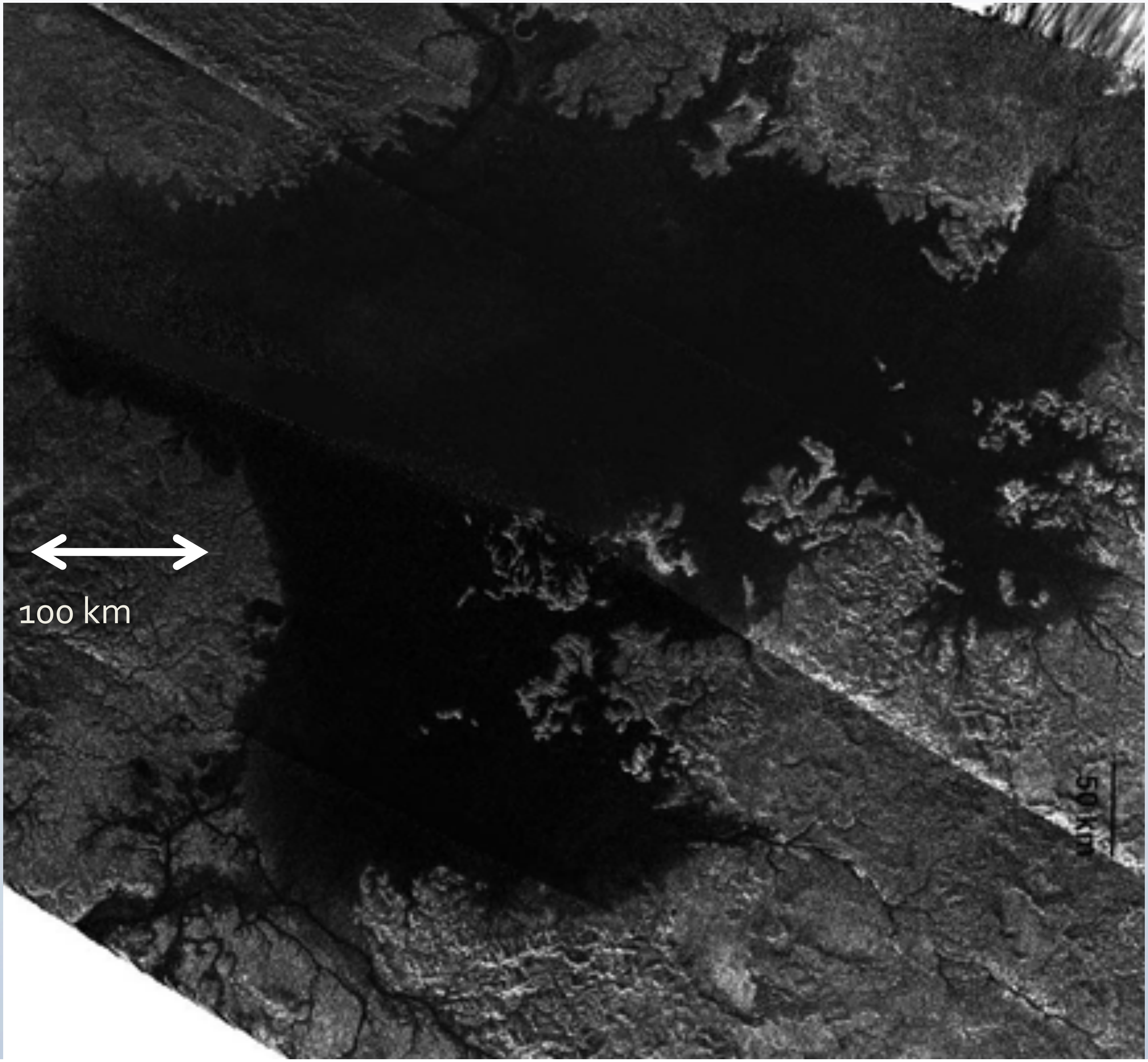
Figure 2. Distribution of lake features above 60°N: (a) Mosaic of Cassini SAR swaths through May 2007. (b) Distribution of mapping units. Dark lakes are blue, granular lakes are cyan, and bright lakes are red. Background color represents incidence angle during acquisition. Note outline of Lake Michigan for relative scale.

Northern lakes the surface expression of a larger "alkanofer"?

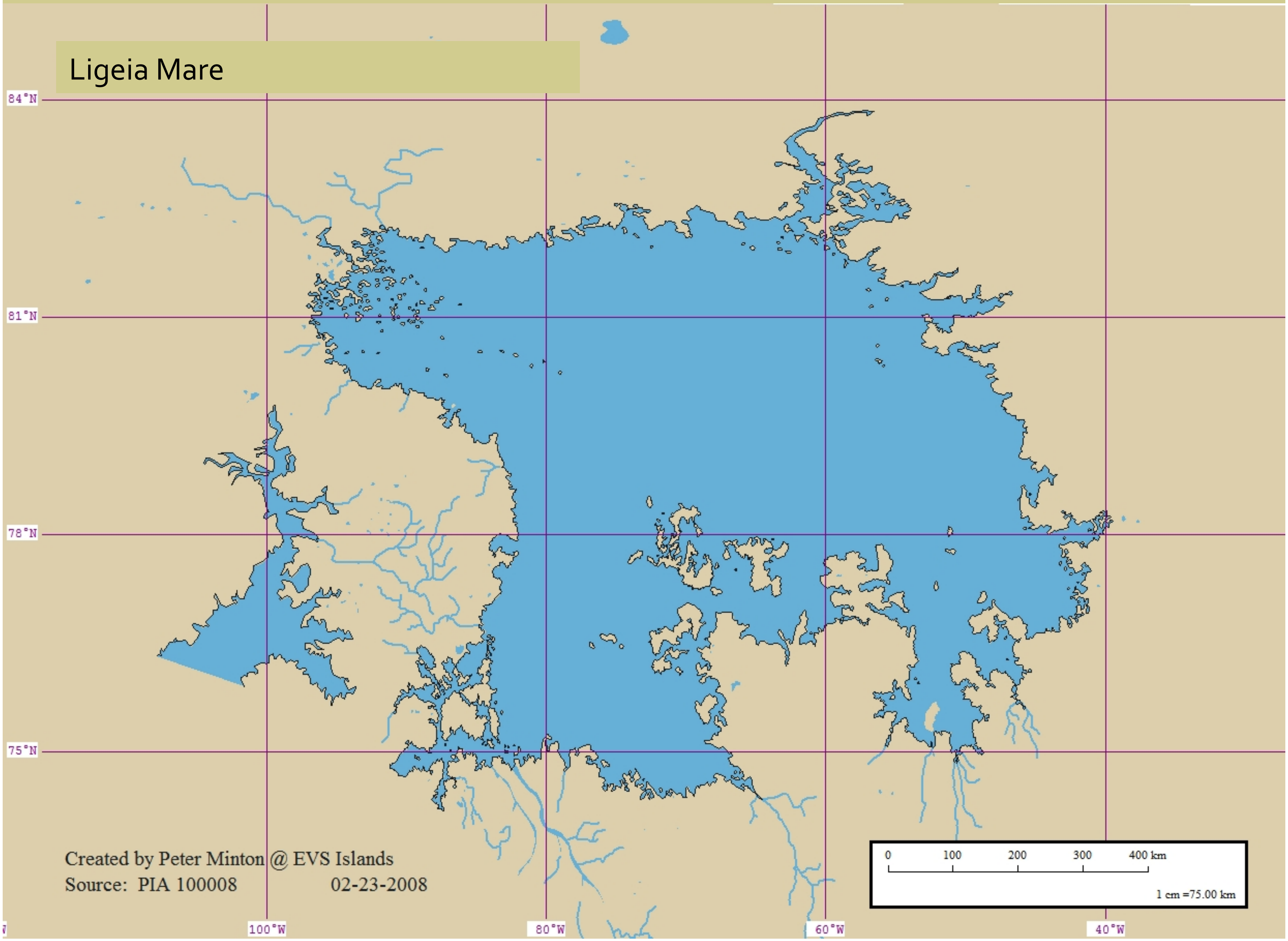


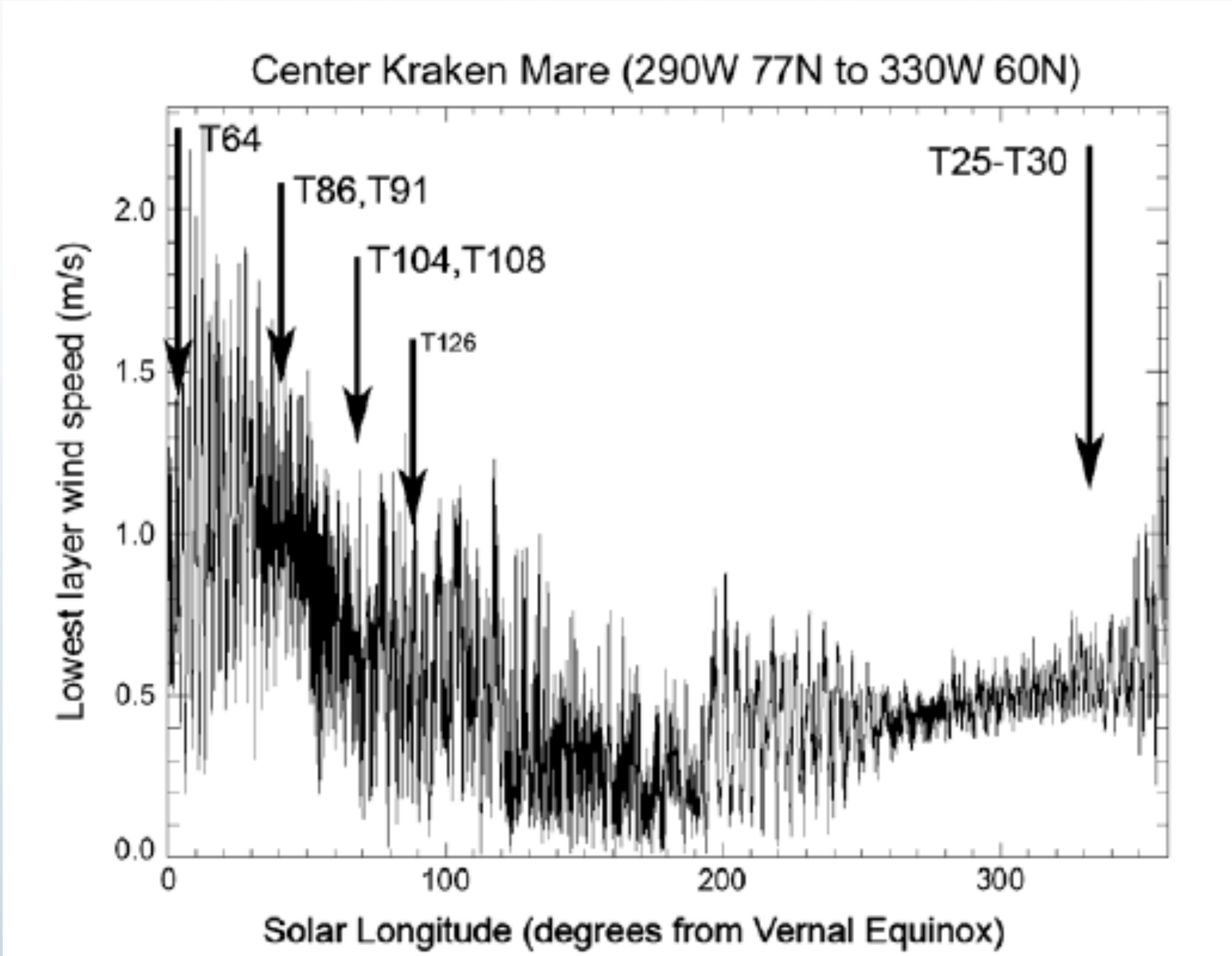
Hayes et al., 2007

Ligeia Mare

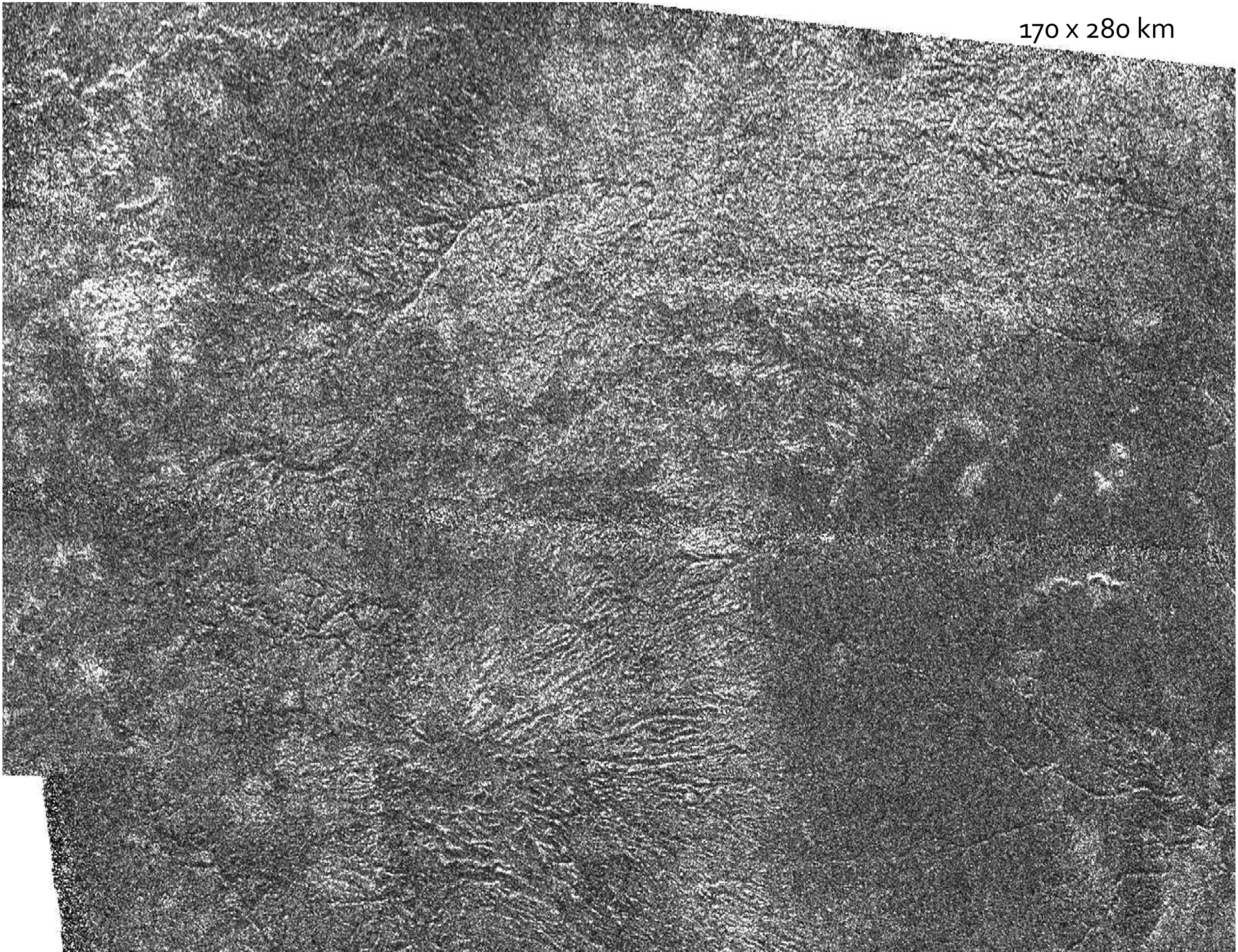


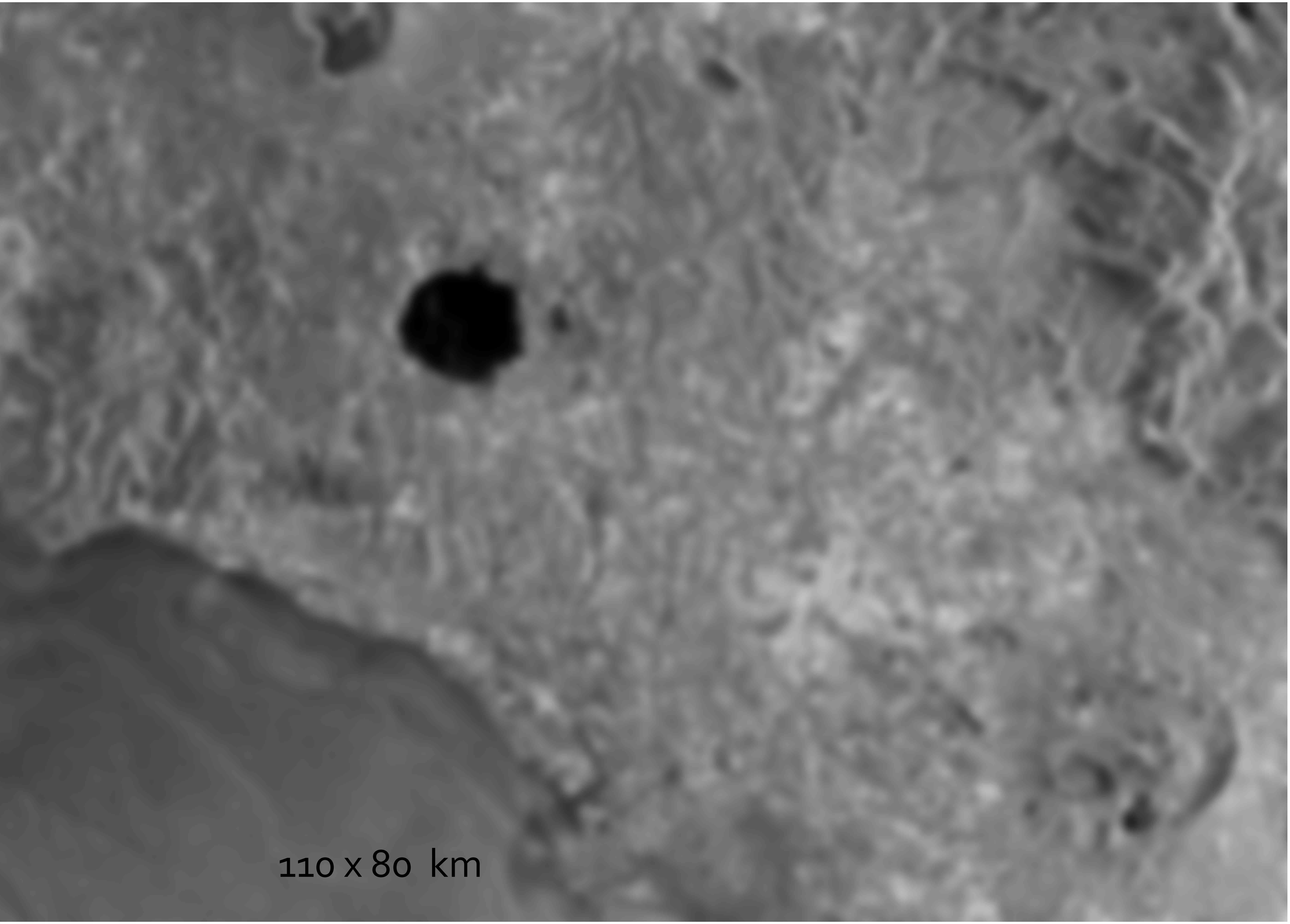
Ligeia Mare

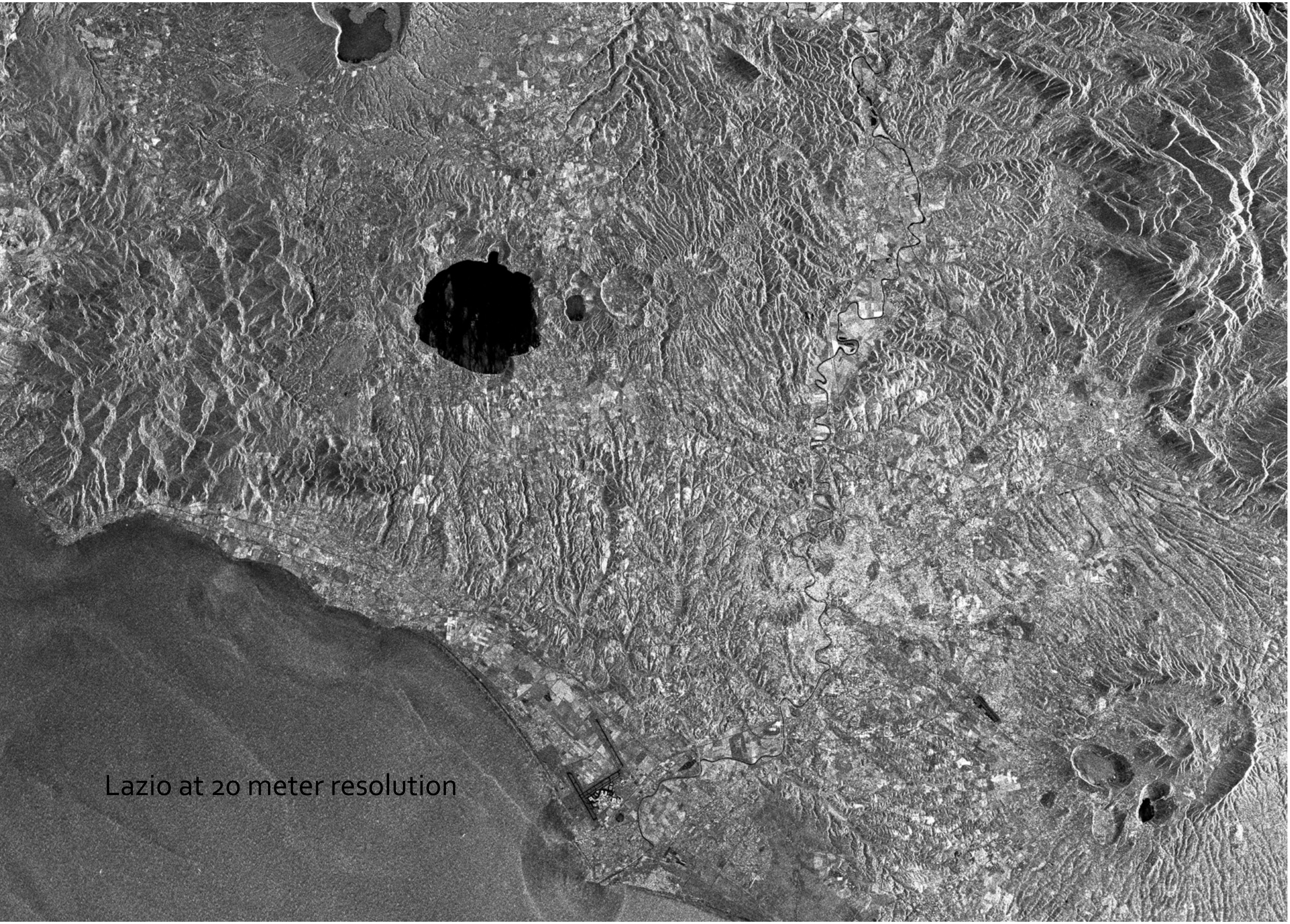

84°N
81°N
78°N
75°N
100°W
80°W
60°W
40°W
Created by Peter Minton @ EVS Islands
Source: PIA 100008 02-23-2008
0 100 200 300 400 km
1 cm =75.00 km



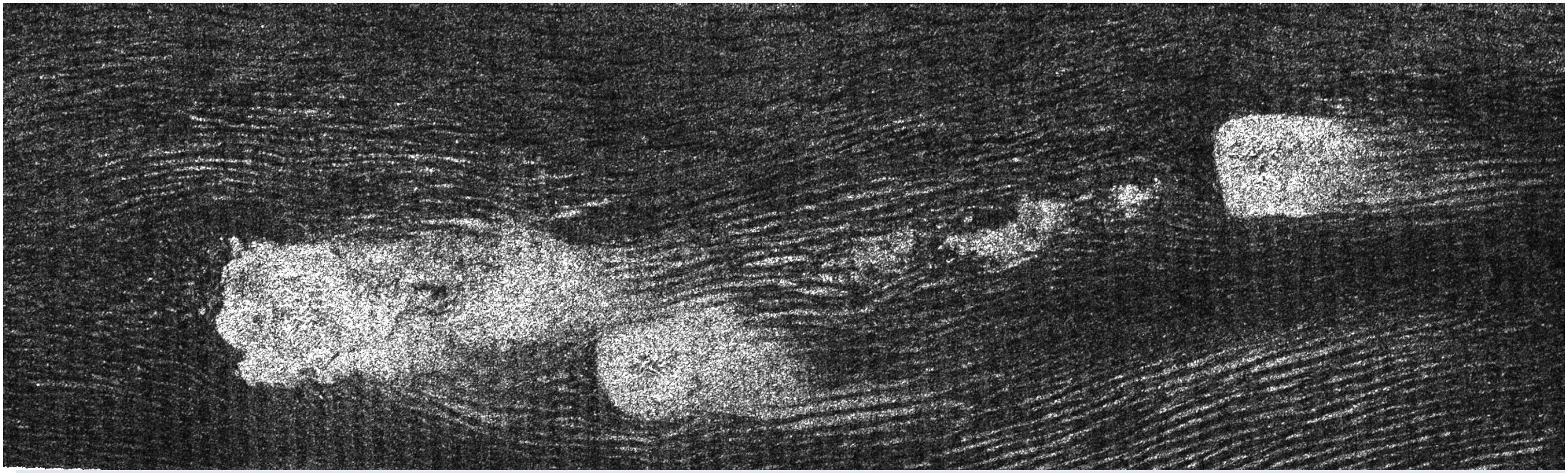
Lorenz et al. 2010

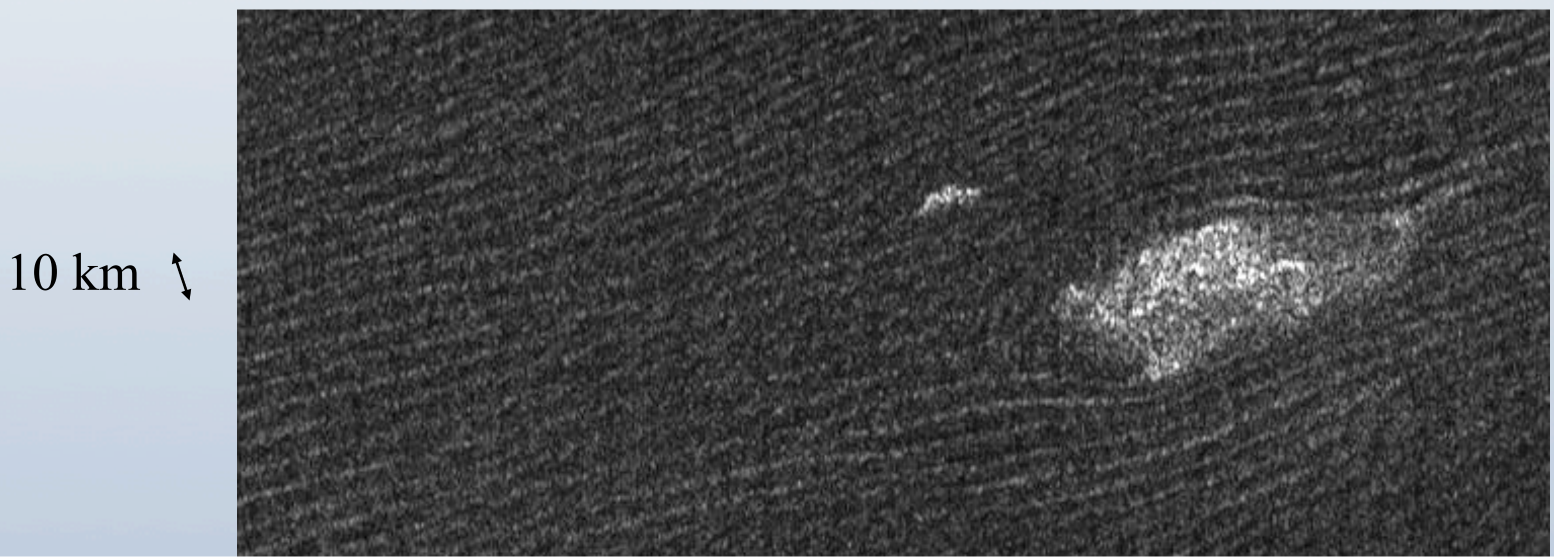

170 x 280 km


110 x 80 km

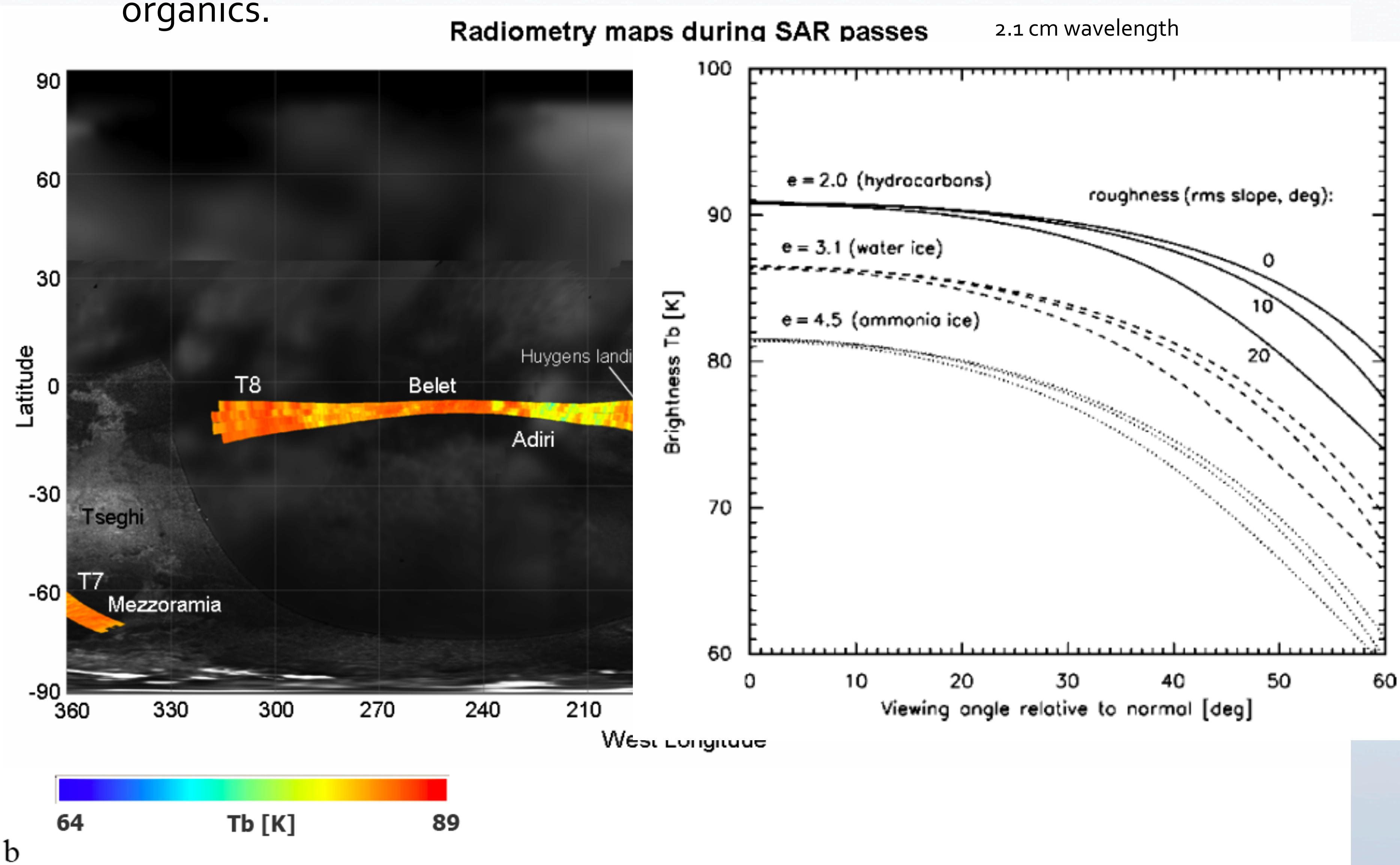

Lazio at 20 meter resolution

Dunes cover 20% of Titan's surface.



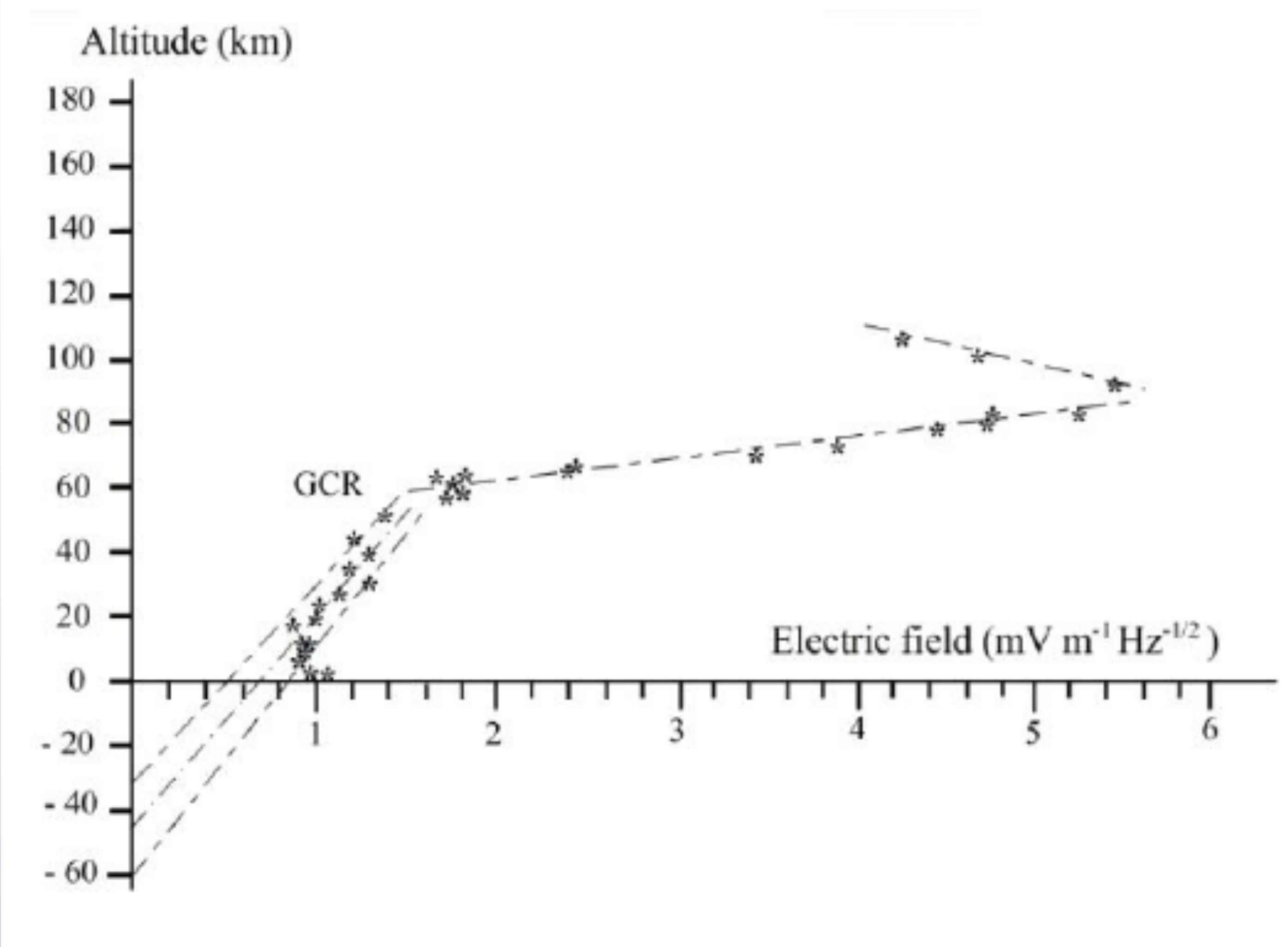


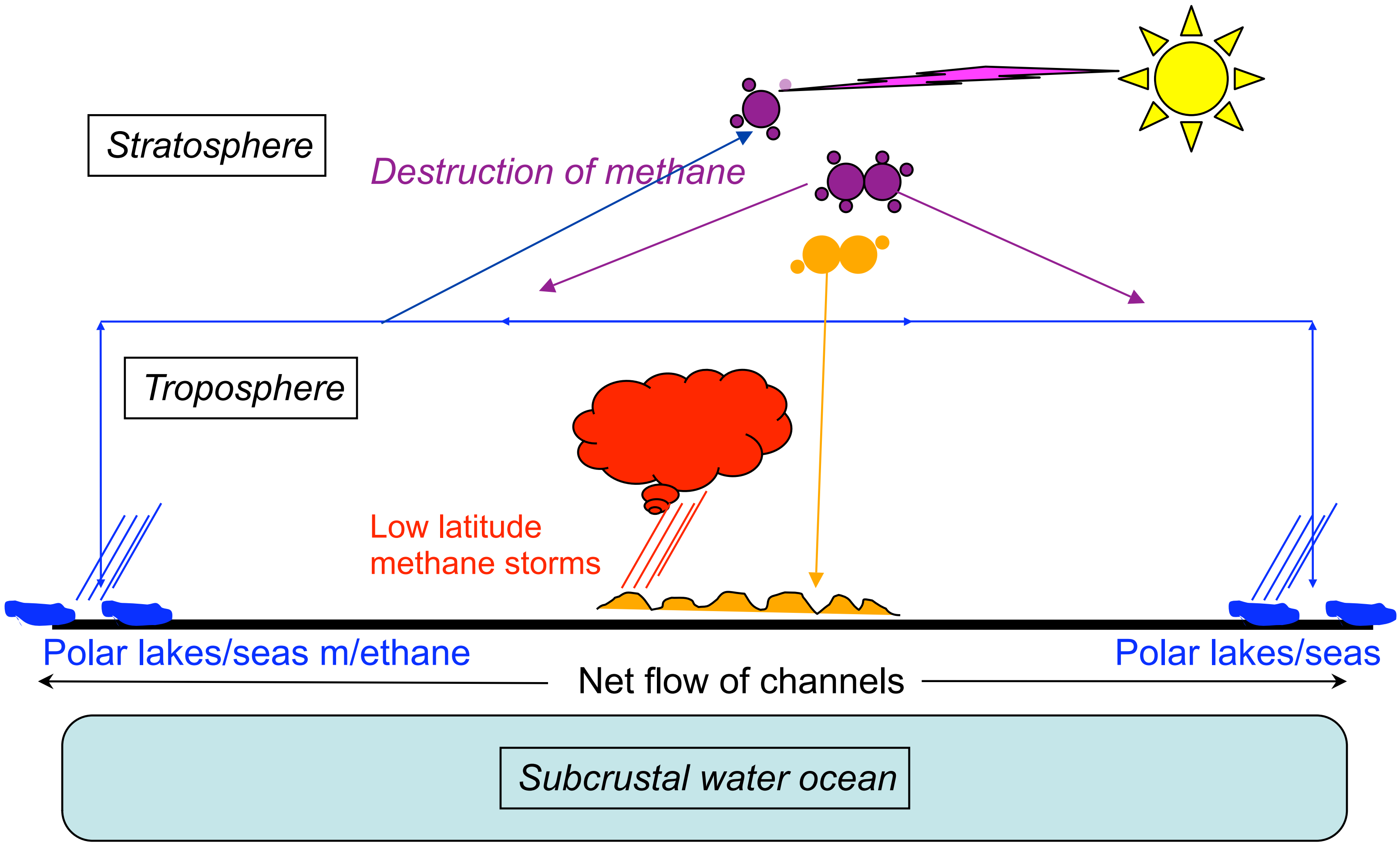
Microwave radiometry --> dunes are not silica sand or clean ice; best fit organics.



Paganelli et al, 2006

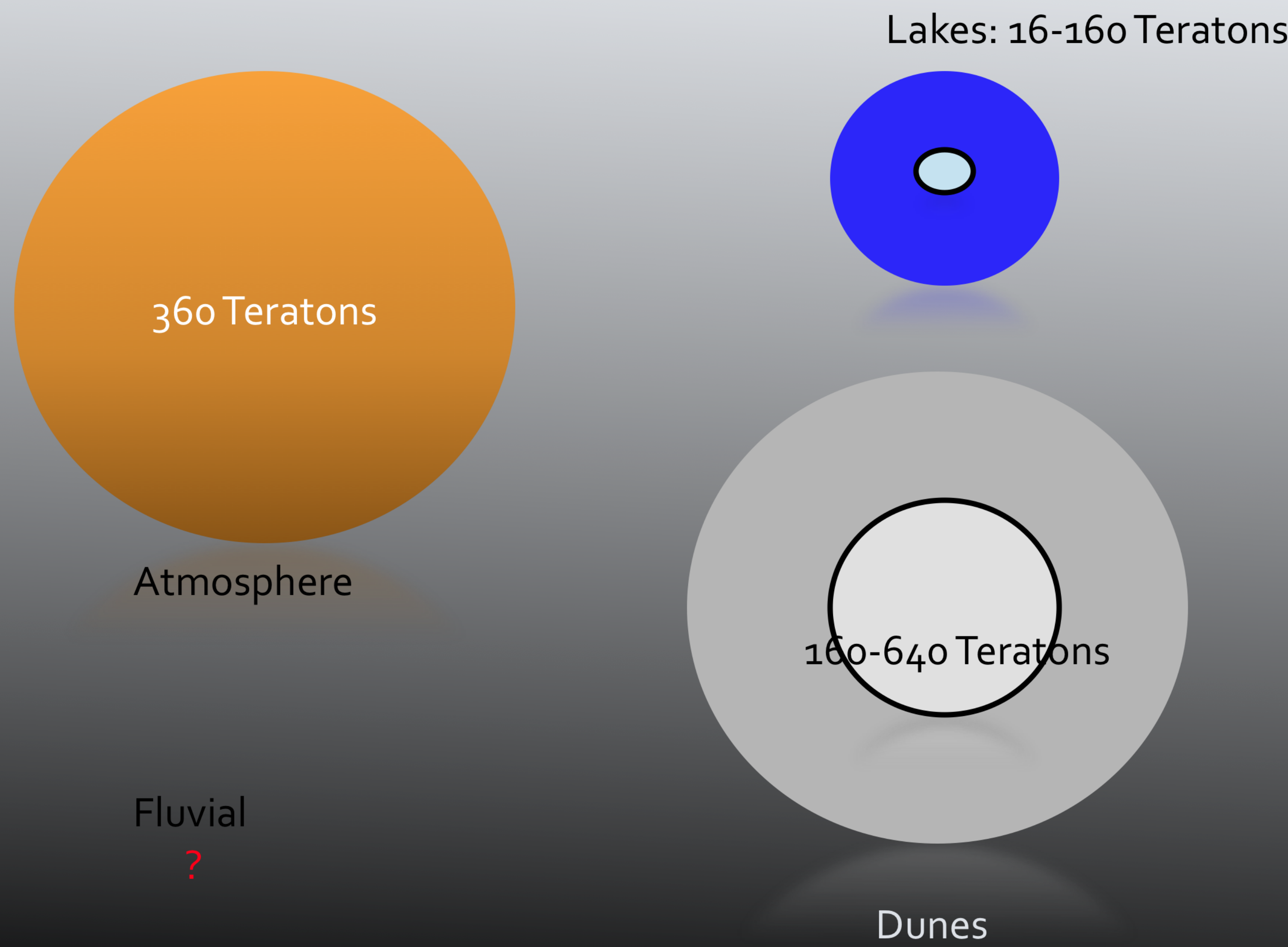
Beghin et al: Electric field data from Huygens → subsurface water ocean





The methane cycle on Titan

Carbon budget. (Area of slide is ~ CH_4 consumed over Titan's history: ~10,000 Teratons)



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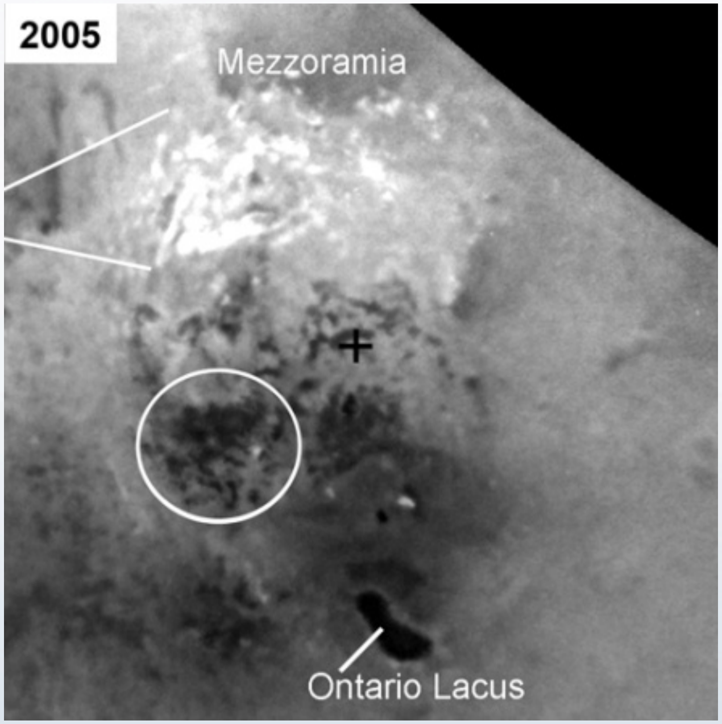
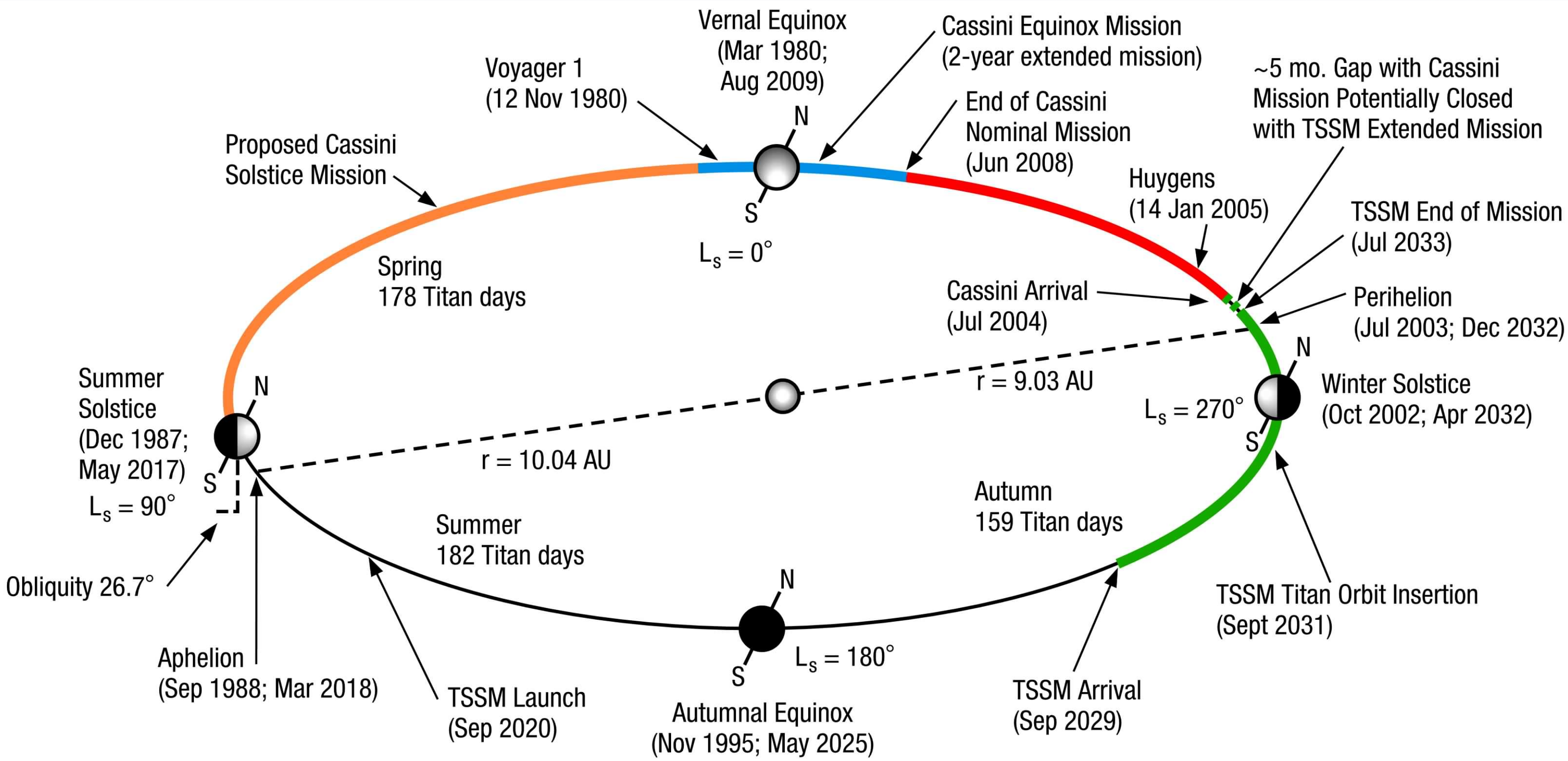


Cassini ISS image of the South Polar region of Titan

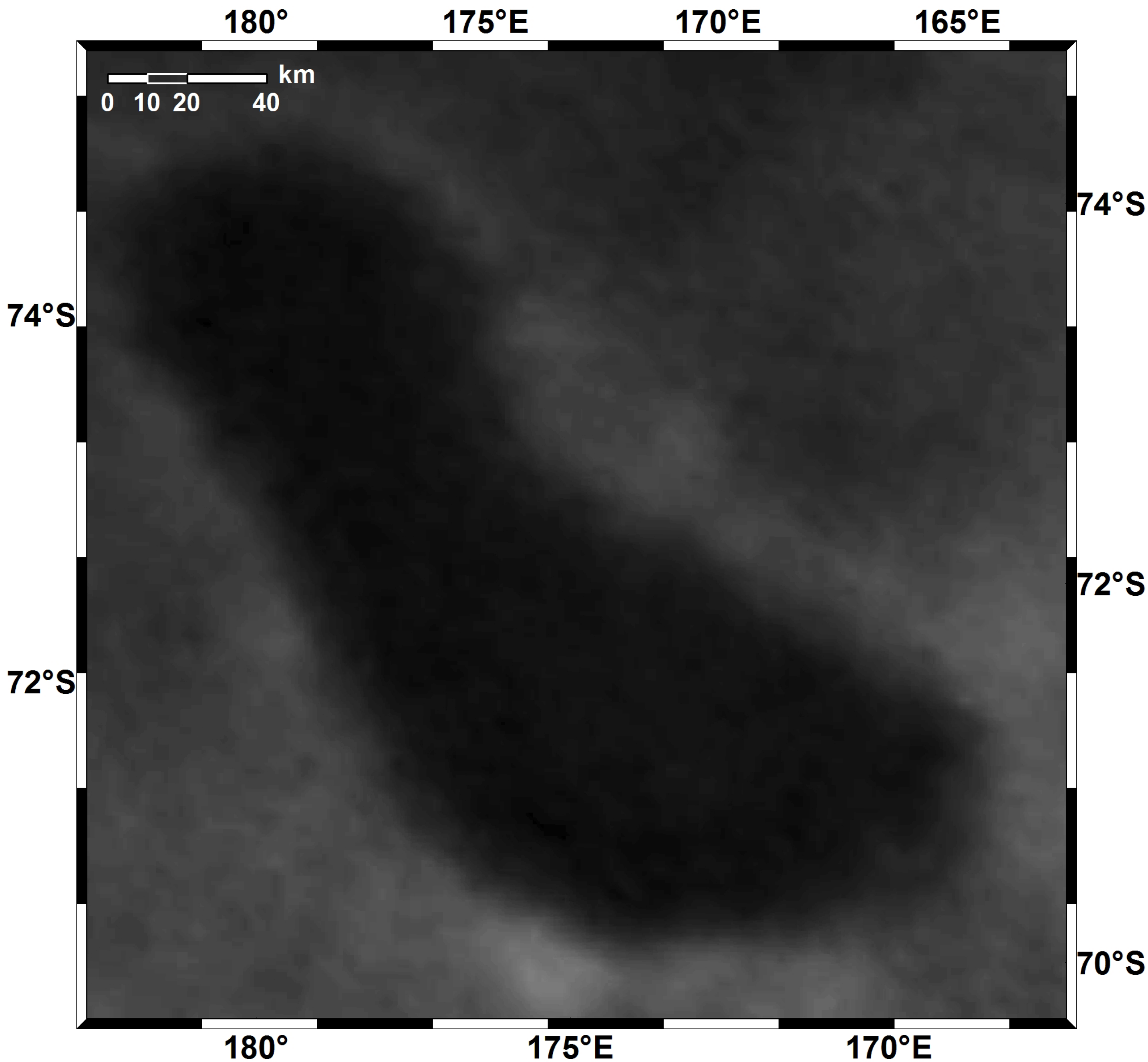
Cassini arrived at Saturn during southern hemisphere summer



Orbital motion of Titan and Saturn around the Sun during one Saturn year. L_s denotes the Kronocentric (Saturnicentric) orbital longitude of the Sun that characterizes the season.

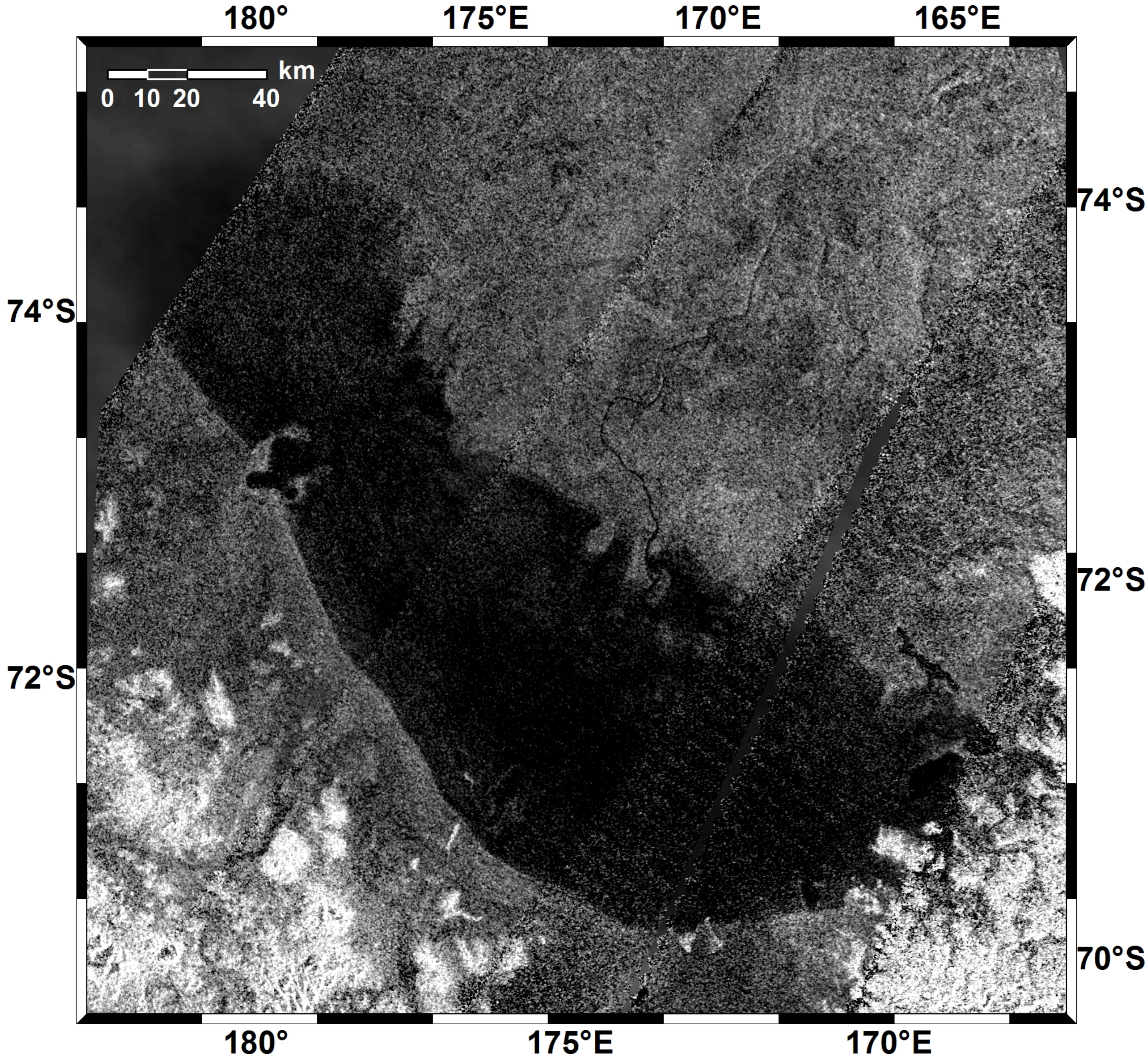
2005

Ontario Lacus

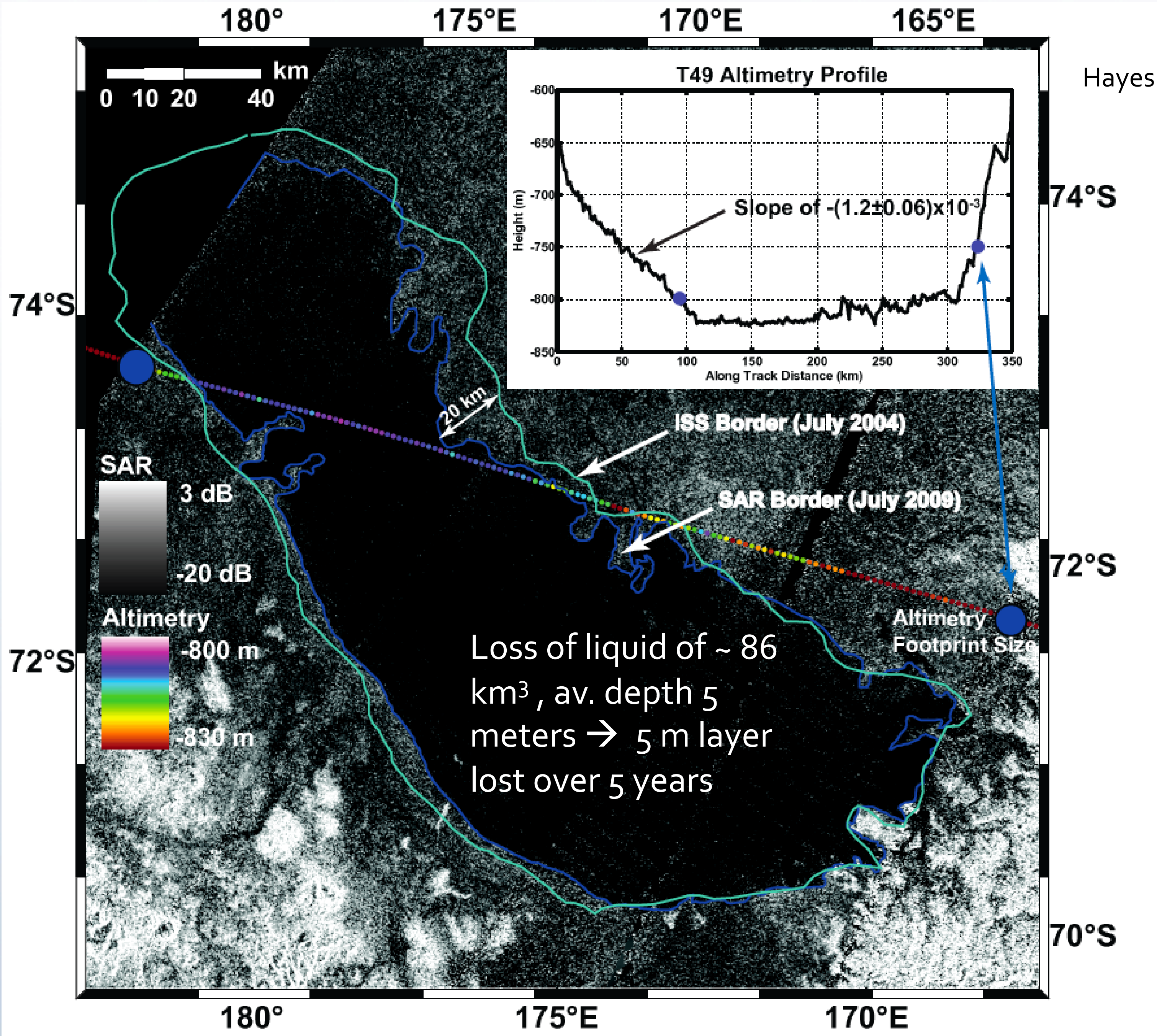


2009

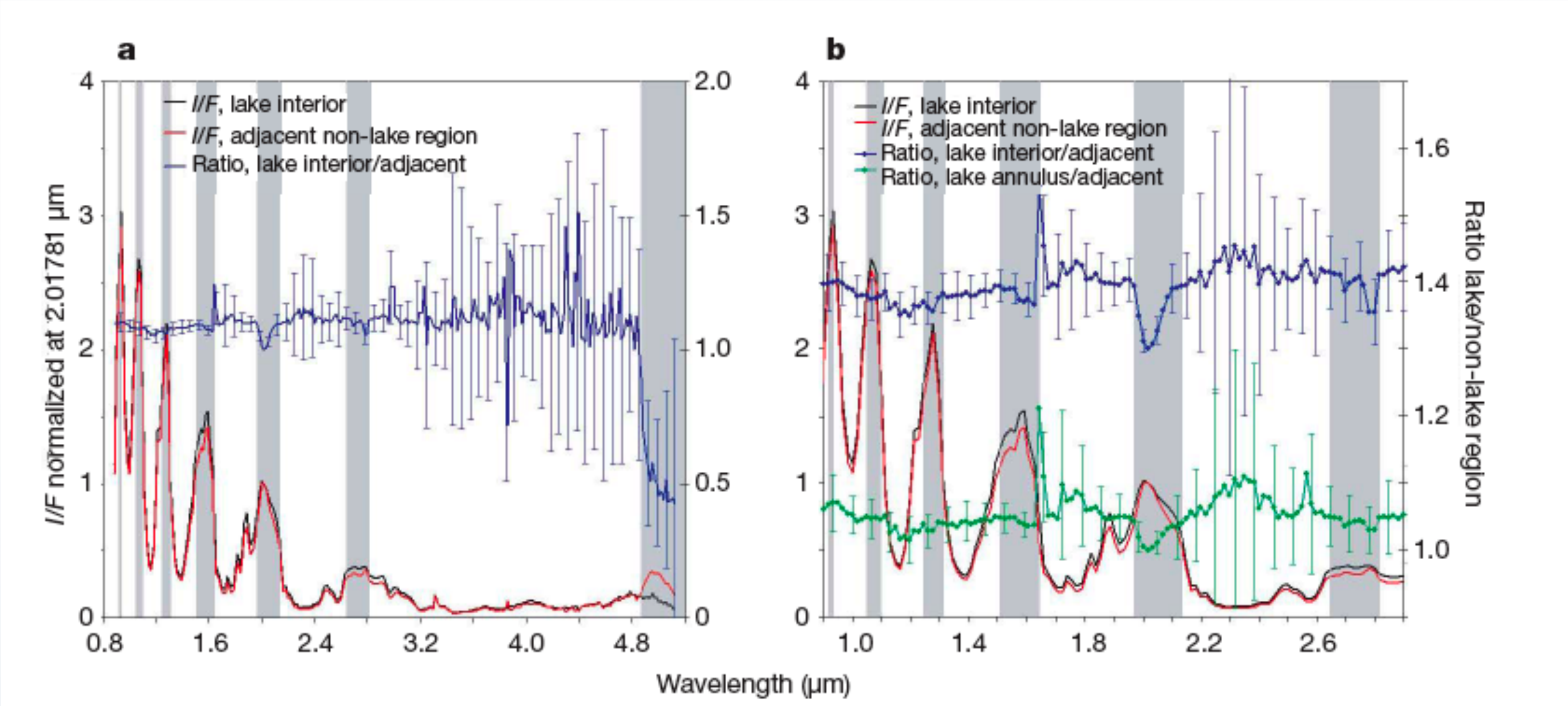
Ontario
Lacus



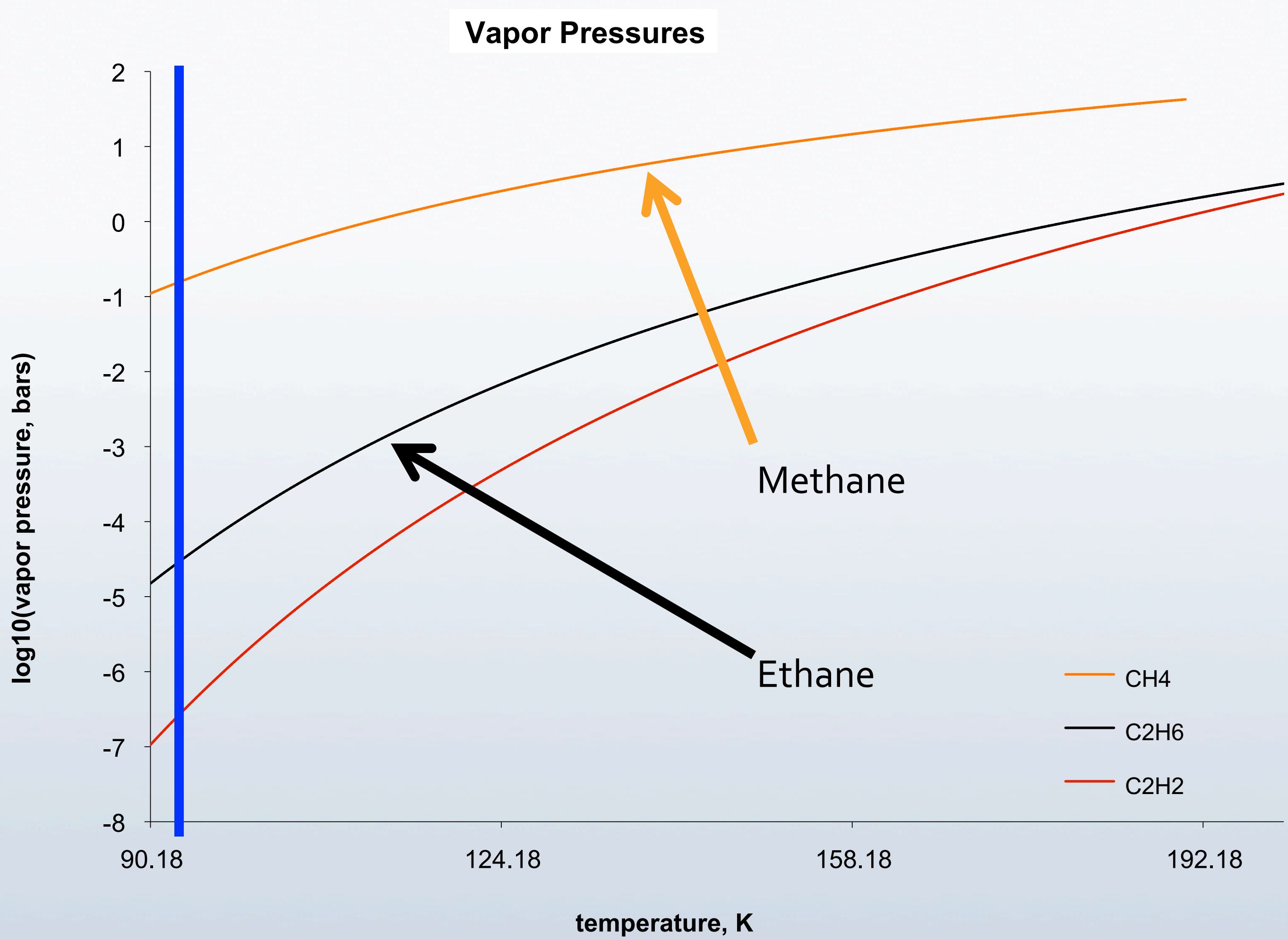
Hayes et al, 2009



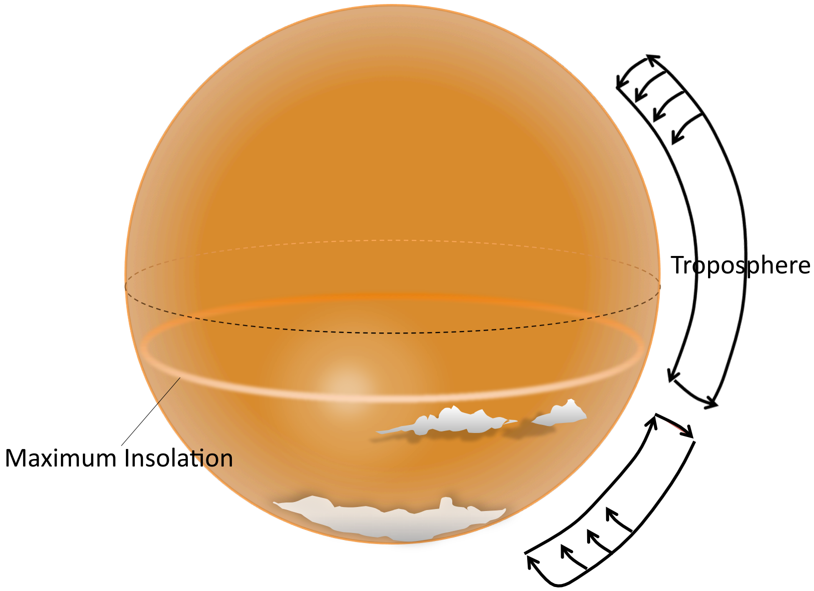
Loss of liquid of ~ 86 km^3 , av. depth 5 meters → 5 m layer lost over 5 years



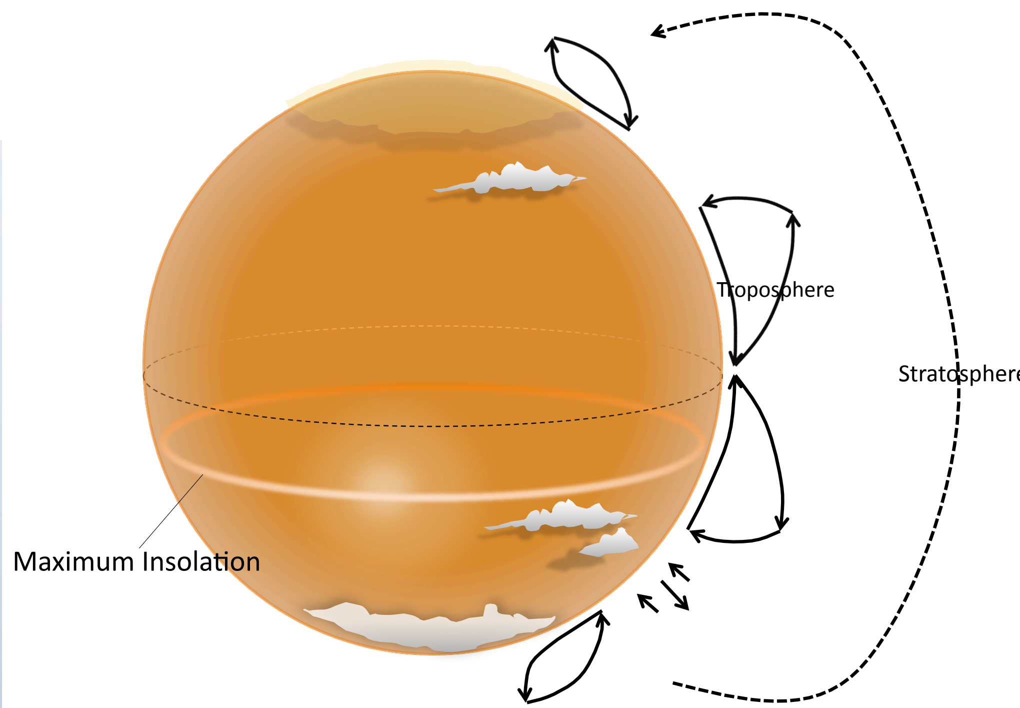
Cassini VIMS (Brown et al. 2008): Spectral evidence for ethane



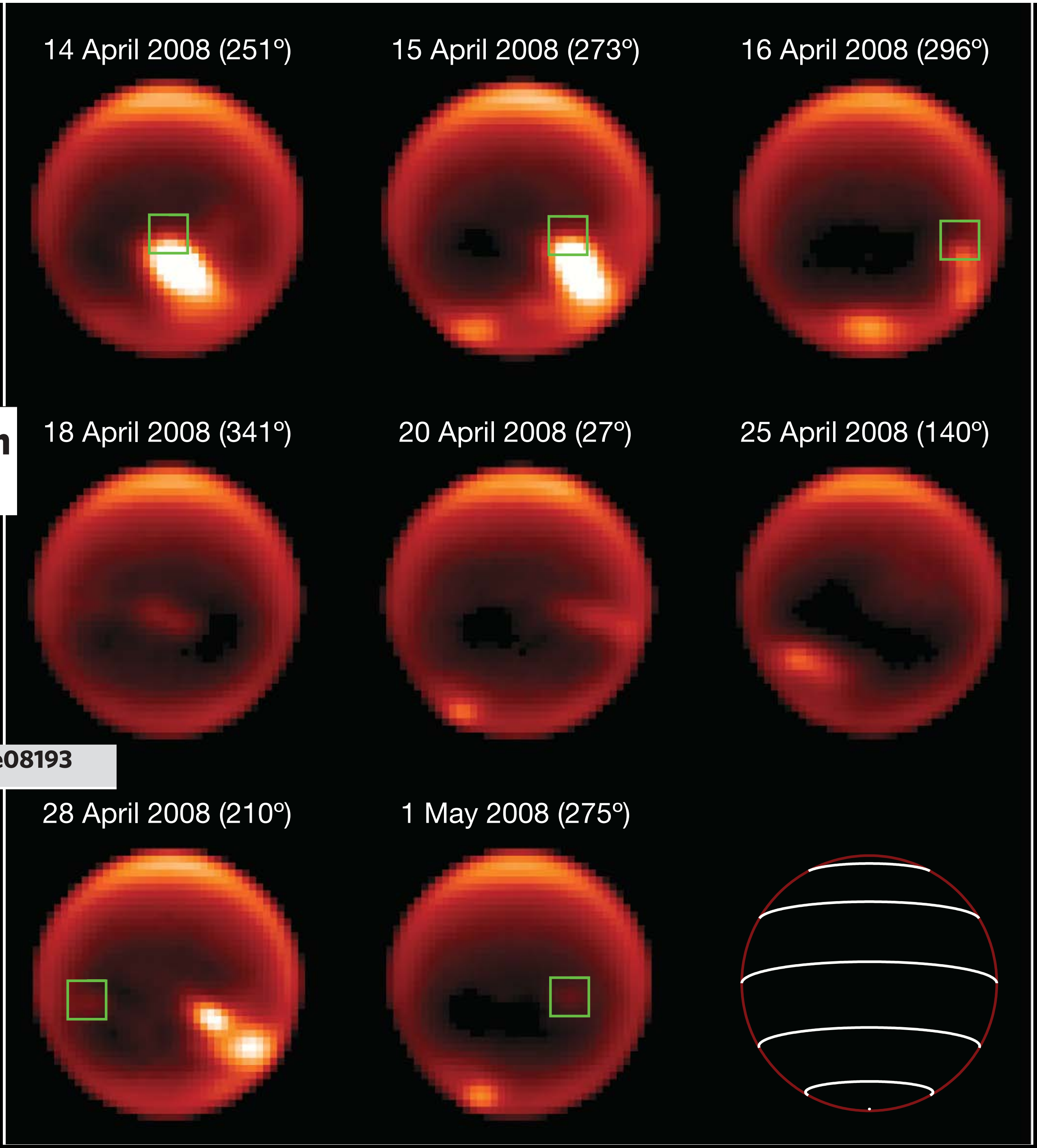
Vapor Pressures
log10(vapor pressure, bars)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
90.18
124.18
158.18
192.18
temperature, K
Methane
Ethane
CH4
C2H6
C2H2



Mitchell et al. (2006)



Rannou et al. (2006)



Storms in the tropics of Titan

E. L. Schaller[1], H. G. Roe[2], T. Schneider[3,4] & M. E. Brown[3]

Vol 460 | 13 August 2009 | **doi:10.1038/nature08193**

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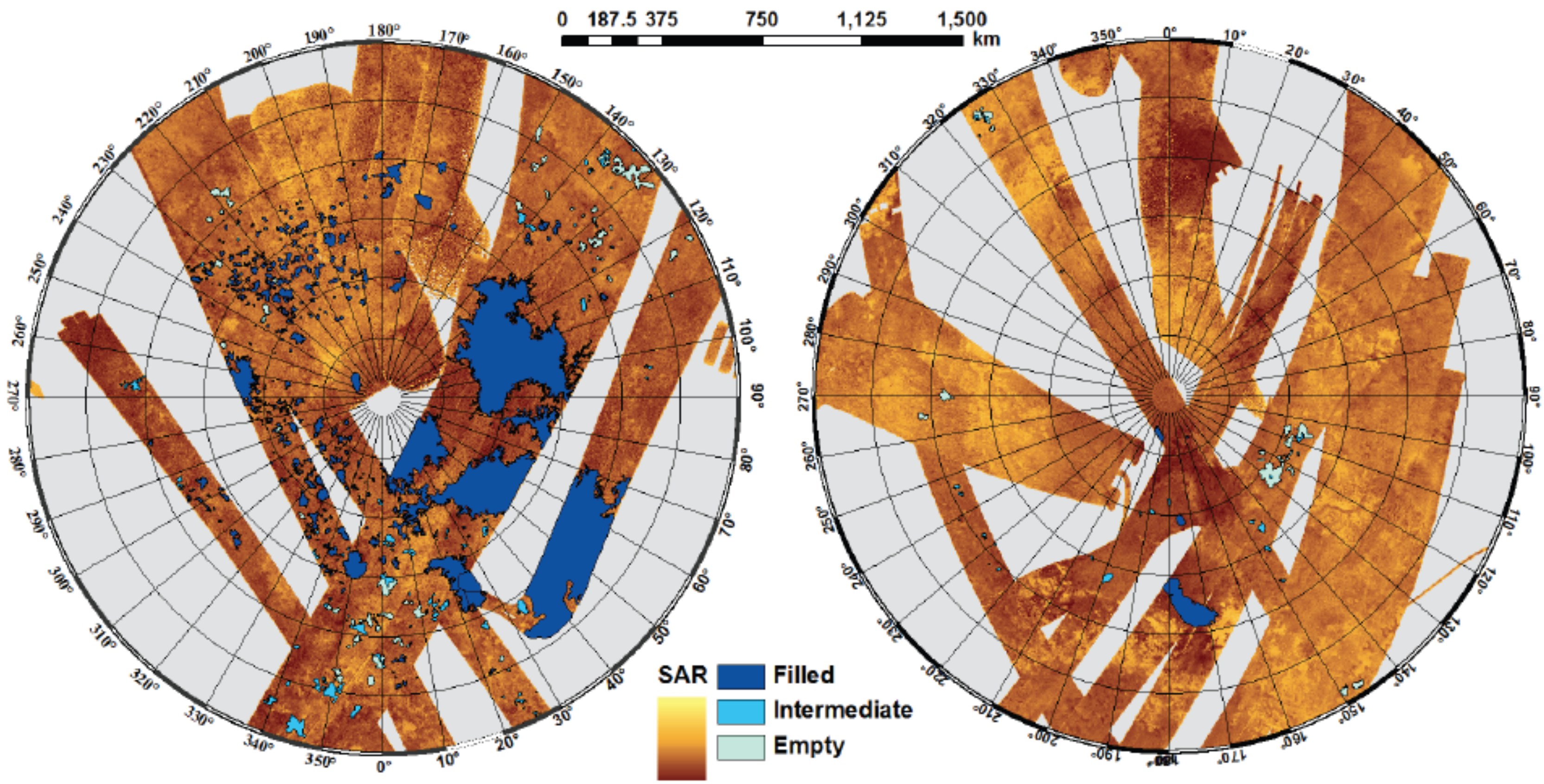

nature geoscience

LETTERS

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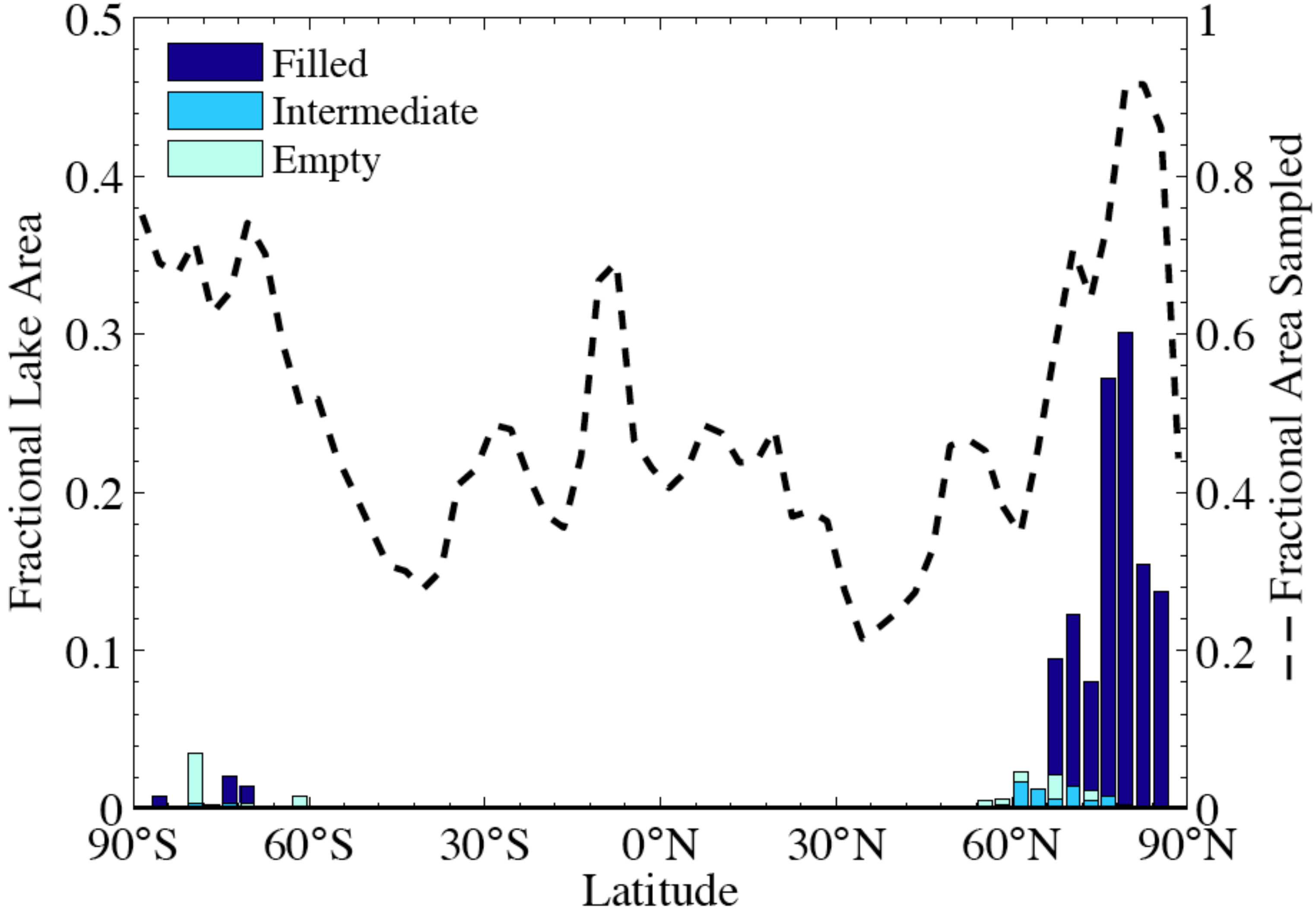
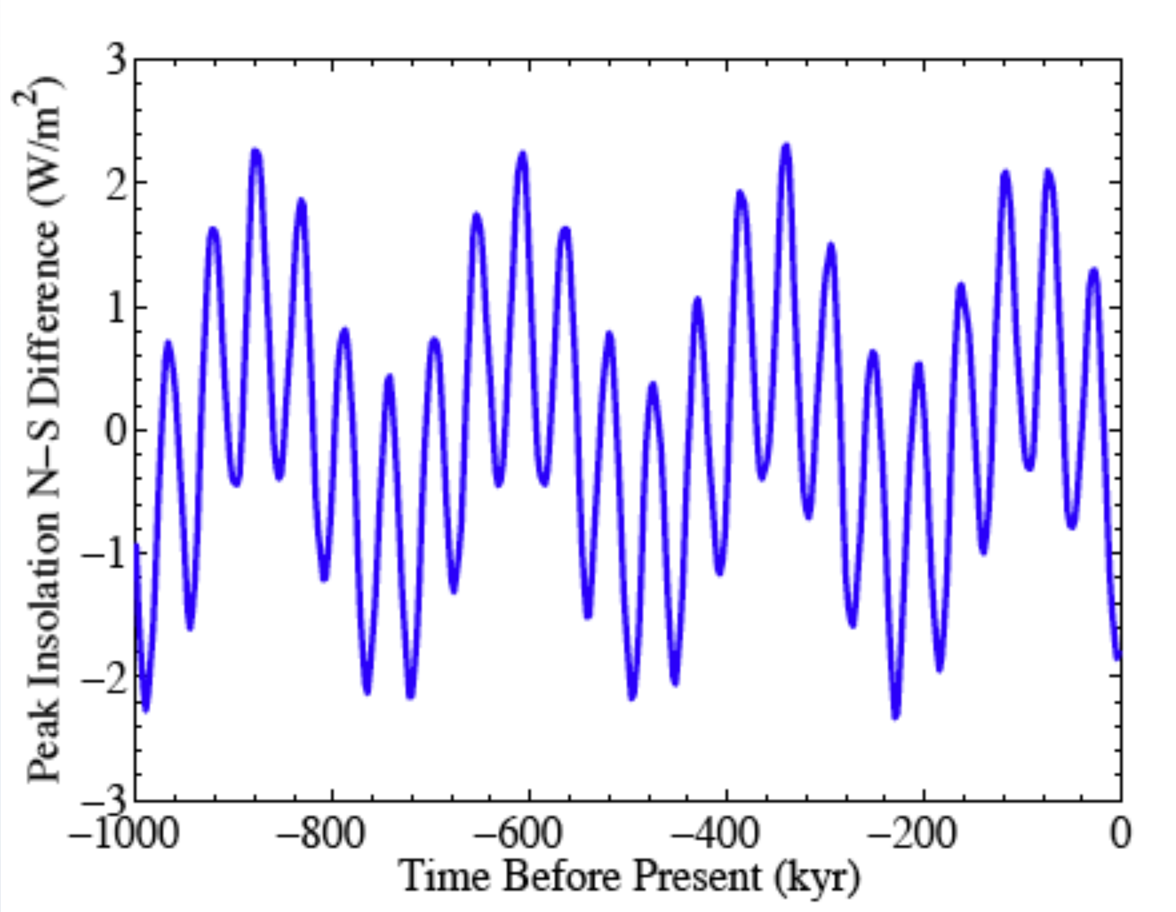
An asymmetric distribution of lakes on Titan as a possible consequence of orbital forcing

O. Aharonson[1]*, A. G. Hayes[1], J. I. Lunine[2], R. D. Lorenz[3], M. D. Allison[4] and C. Elachi[5]

Asymmetry is not an observational effect

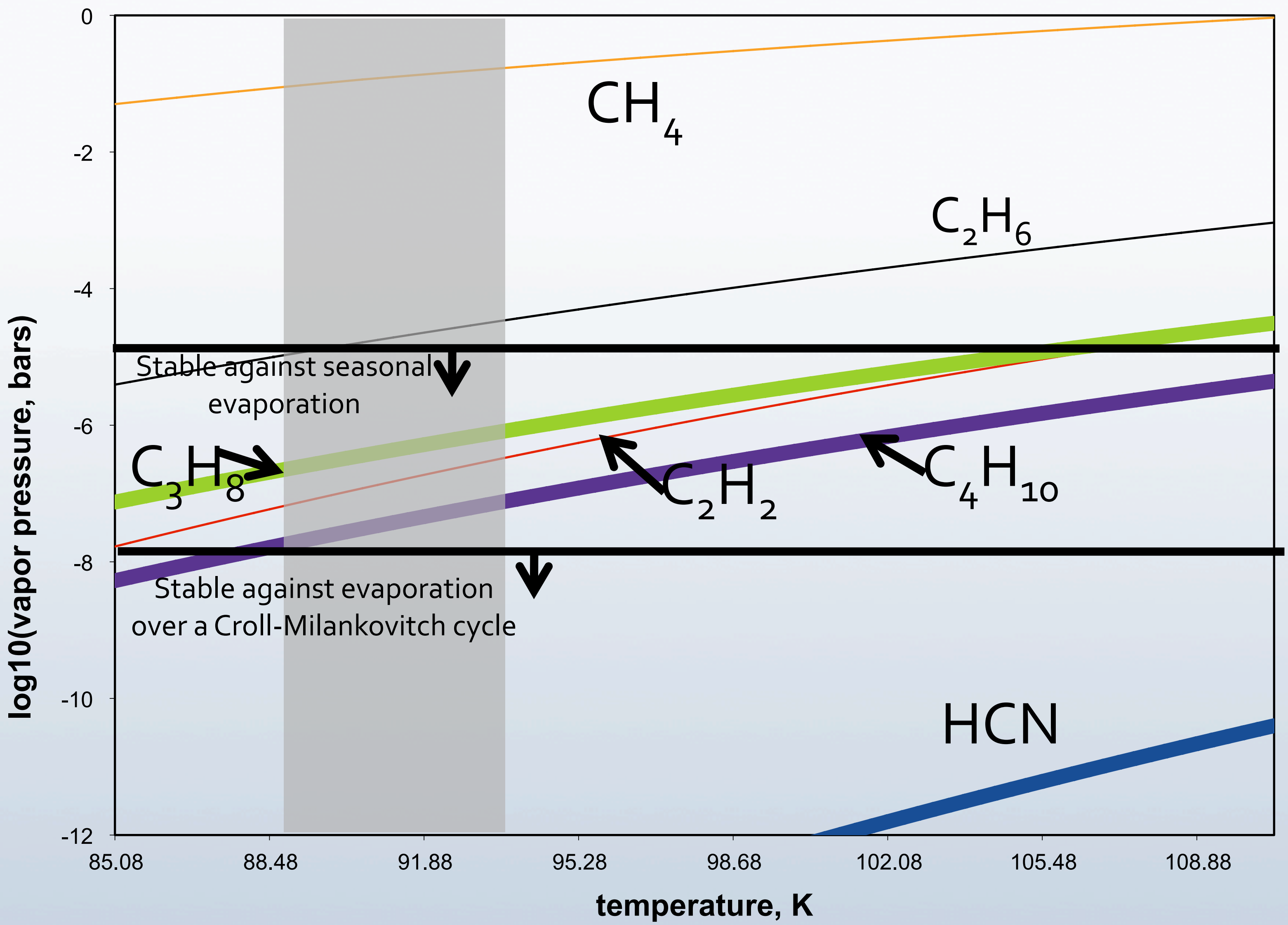


. (Cassini RADAR data)



Titan's Milankovitch cycles: precession of Saturn's eccentric orbit

Evaporation timescales

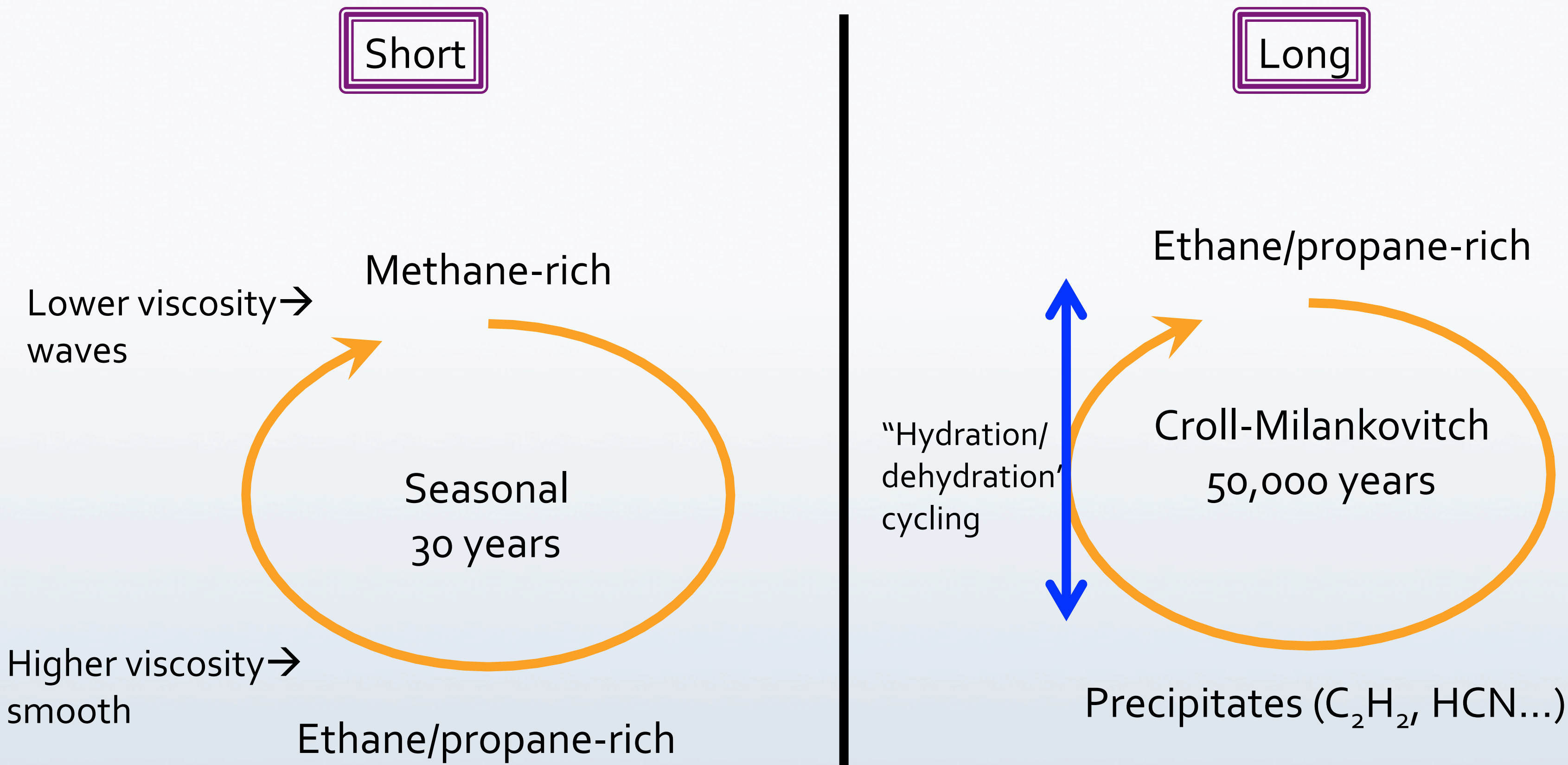


Note that presence of propane increases viscosity, damps waves (Lorenz et al 2010)

What effect might this seasonal asymmetry have on methane/ethane?

- Insolation difference is 1.5 W/sq. meter at top of atmosphere
- Difference in peak evaporative flux N vs S is ~ ½ W/sq. meter based on circulation models (e.g. Mitchell, 2008).
- Net difference, if averaged over a summer would remove *hundreds* of meters worth of ethane
- However, more intense southern summer is shorter: integrated annual insolation is the same. Therefore, indirect effects of more intense sunlight over a briefer period must be considered. This requires detailed modeling.

Compositional Cycling of lakes/seas



viscosity scale (Lorenz et al 2010):
methane < water < ethane/propane

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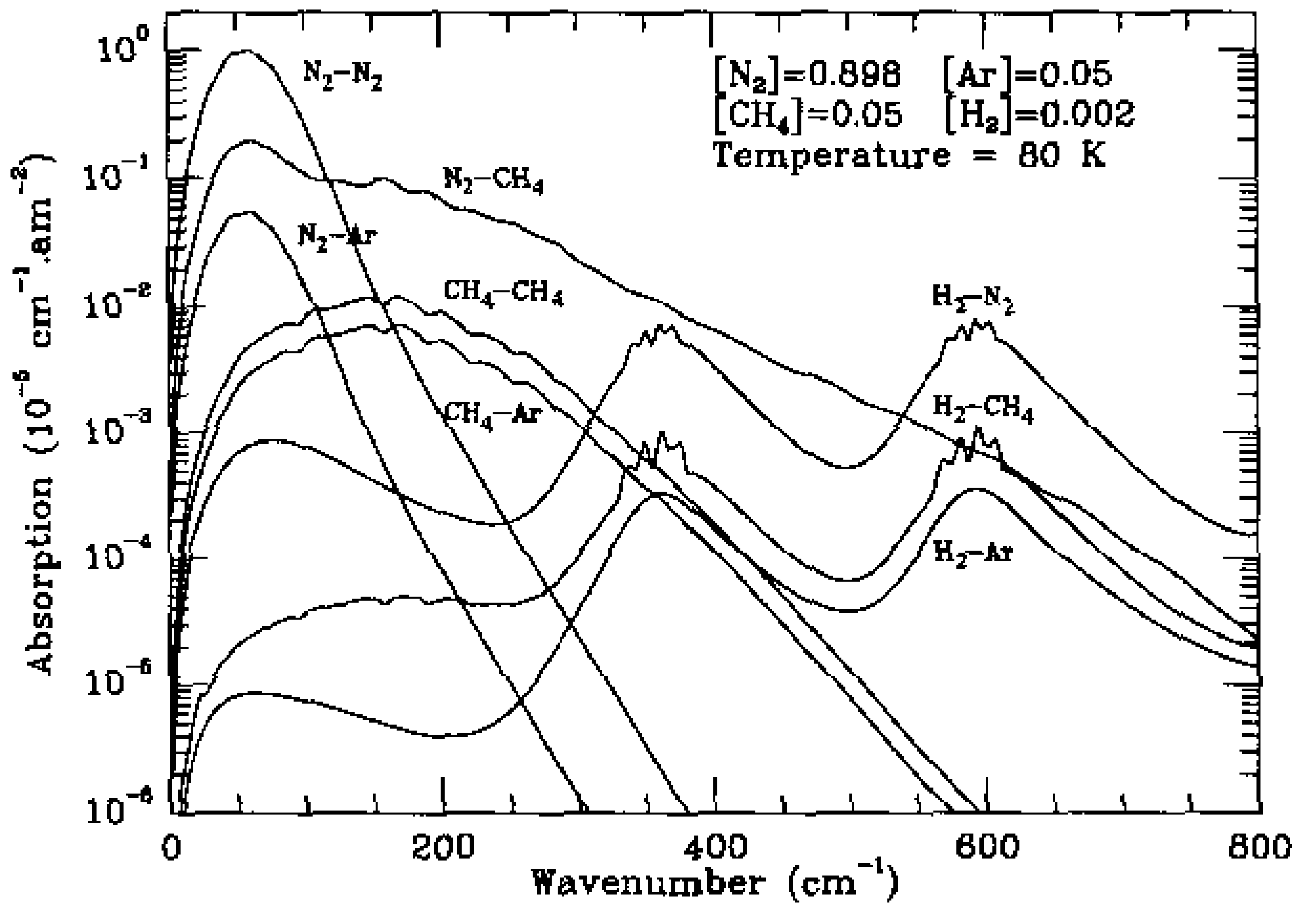
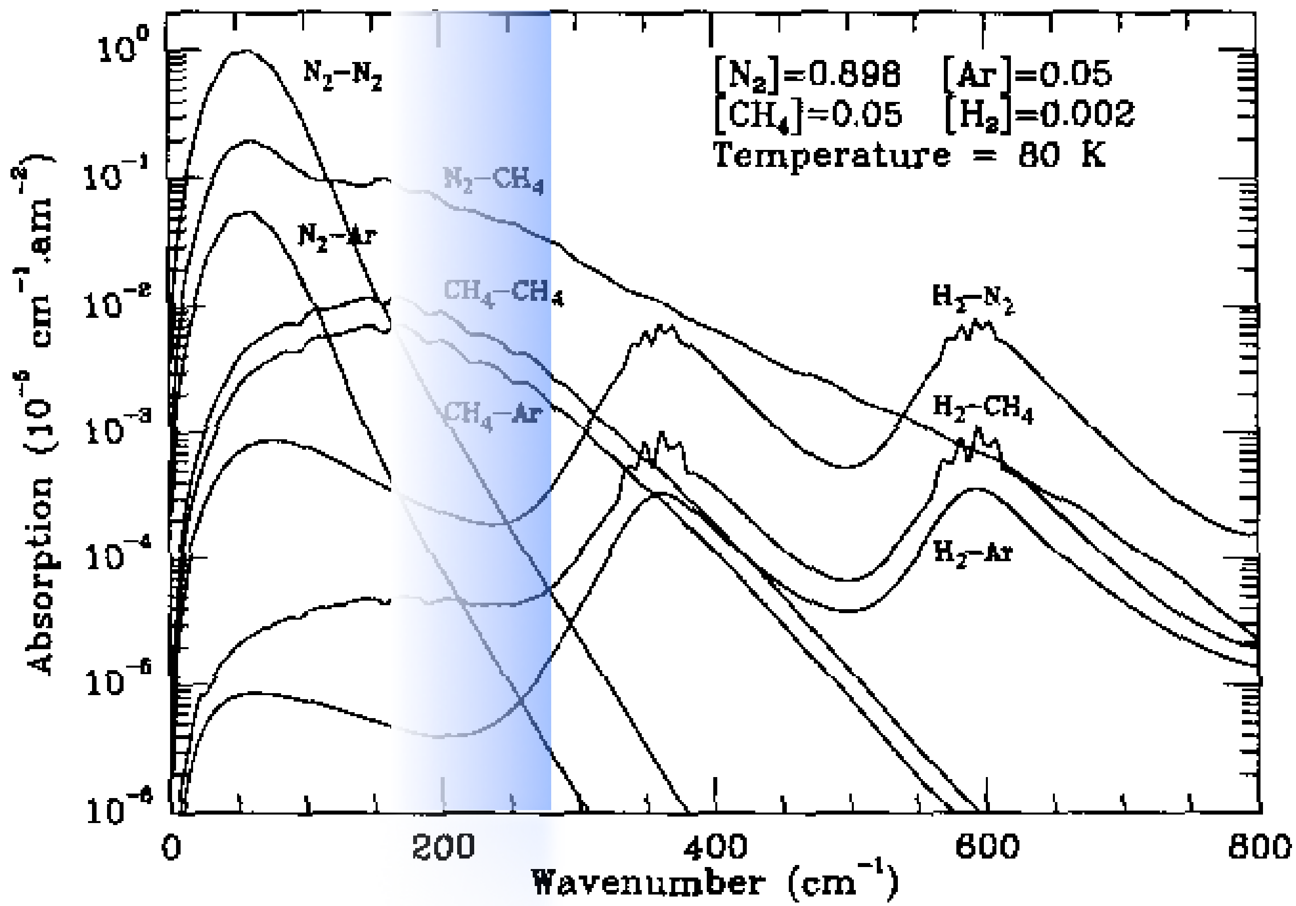
IR opacity sources in Titan's lower atmosphere

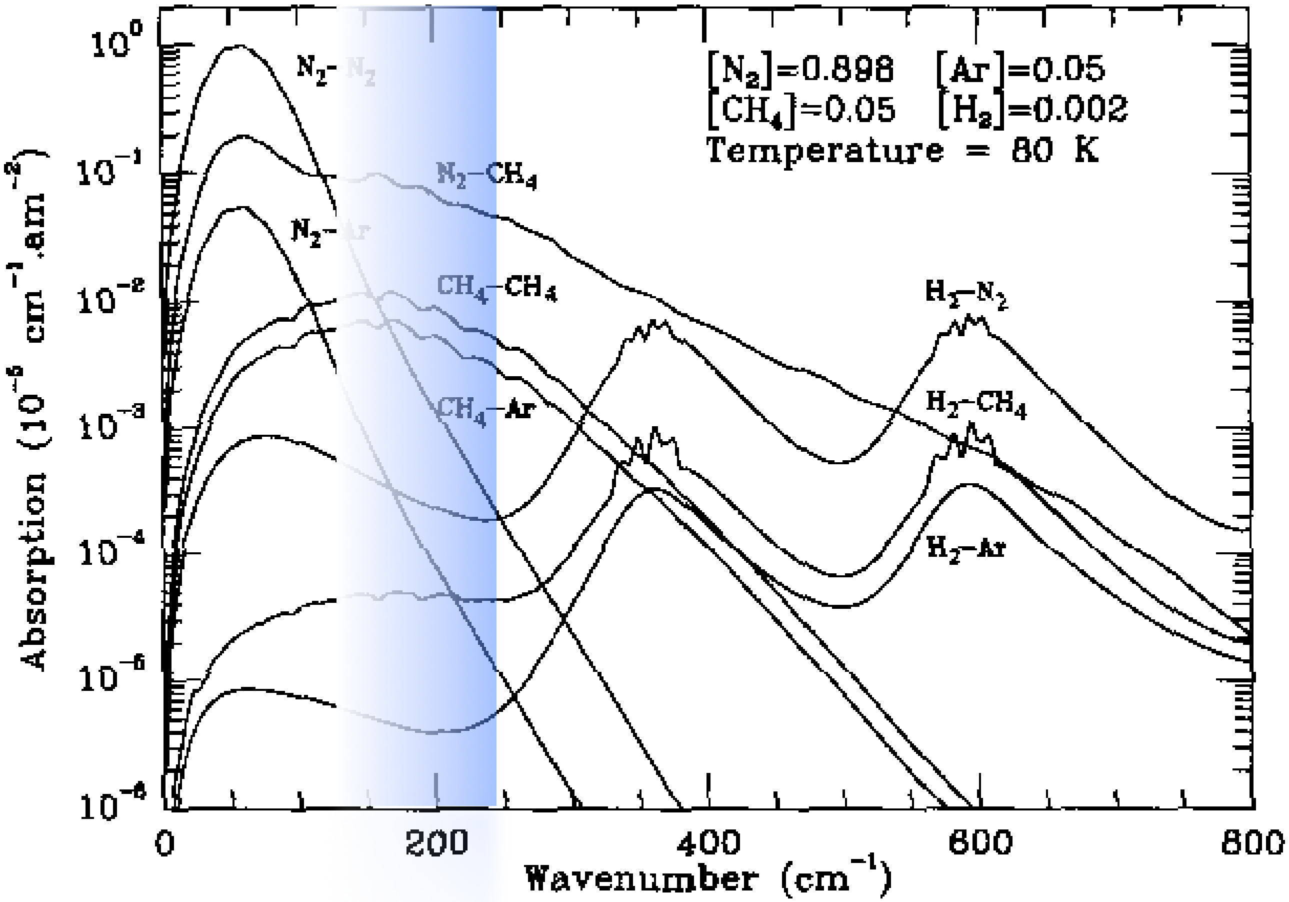


T=94 K.

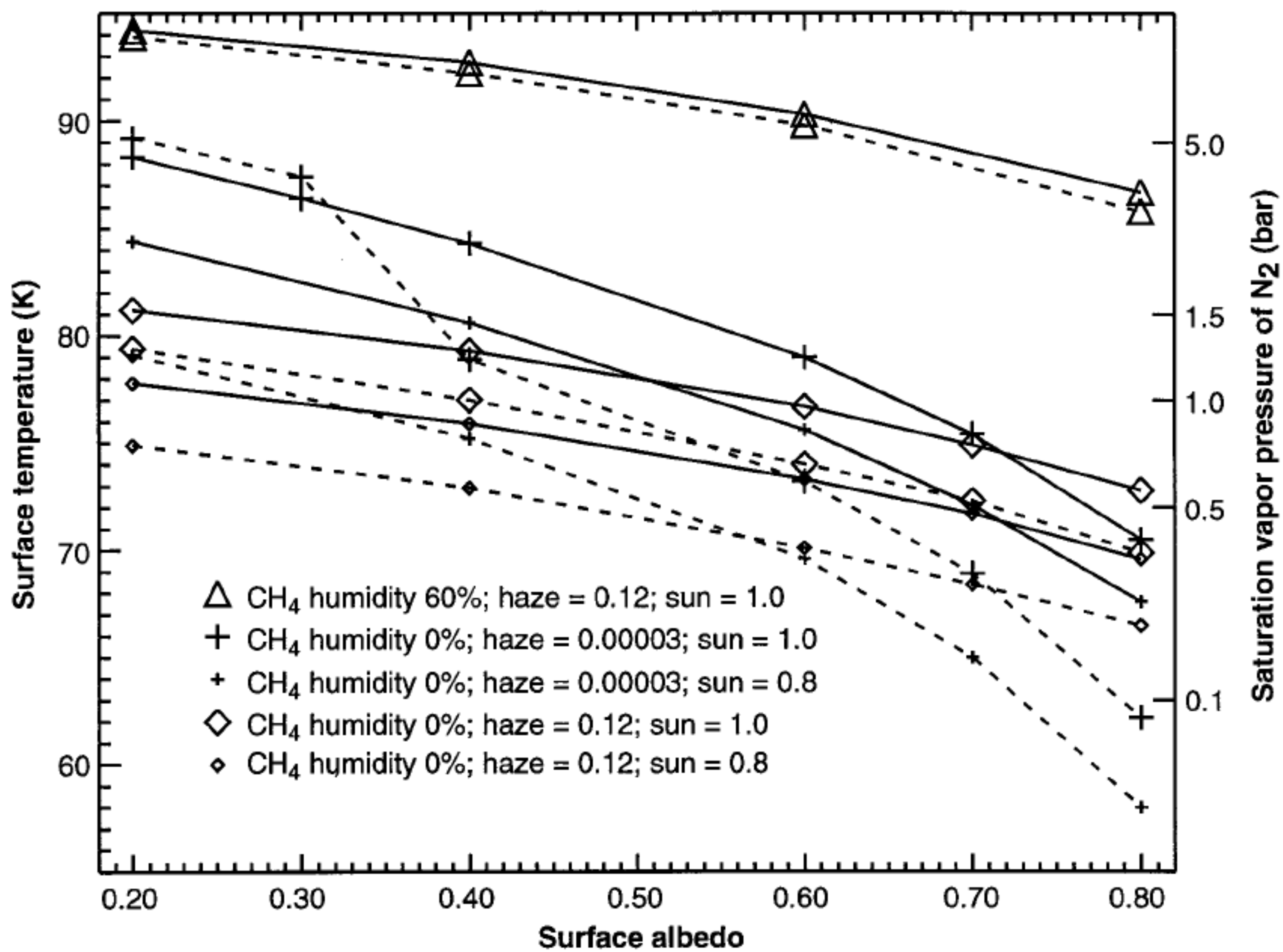


[N2]=0.898 [Ar]=0.05
[CH4]=0.05 [H2]=0.002
Temperature = 80 K
N2–N2
N2–CH4
N2–Ar
CH4–CH4
CH4–Ar
H2–N2
H2–CH4
H2–Ar
Absorption (10^-5 cm^-1 .am^-2)
Wavenumber (cm^-1)

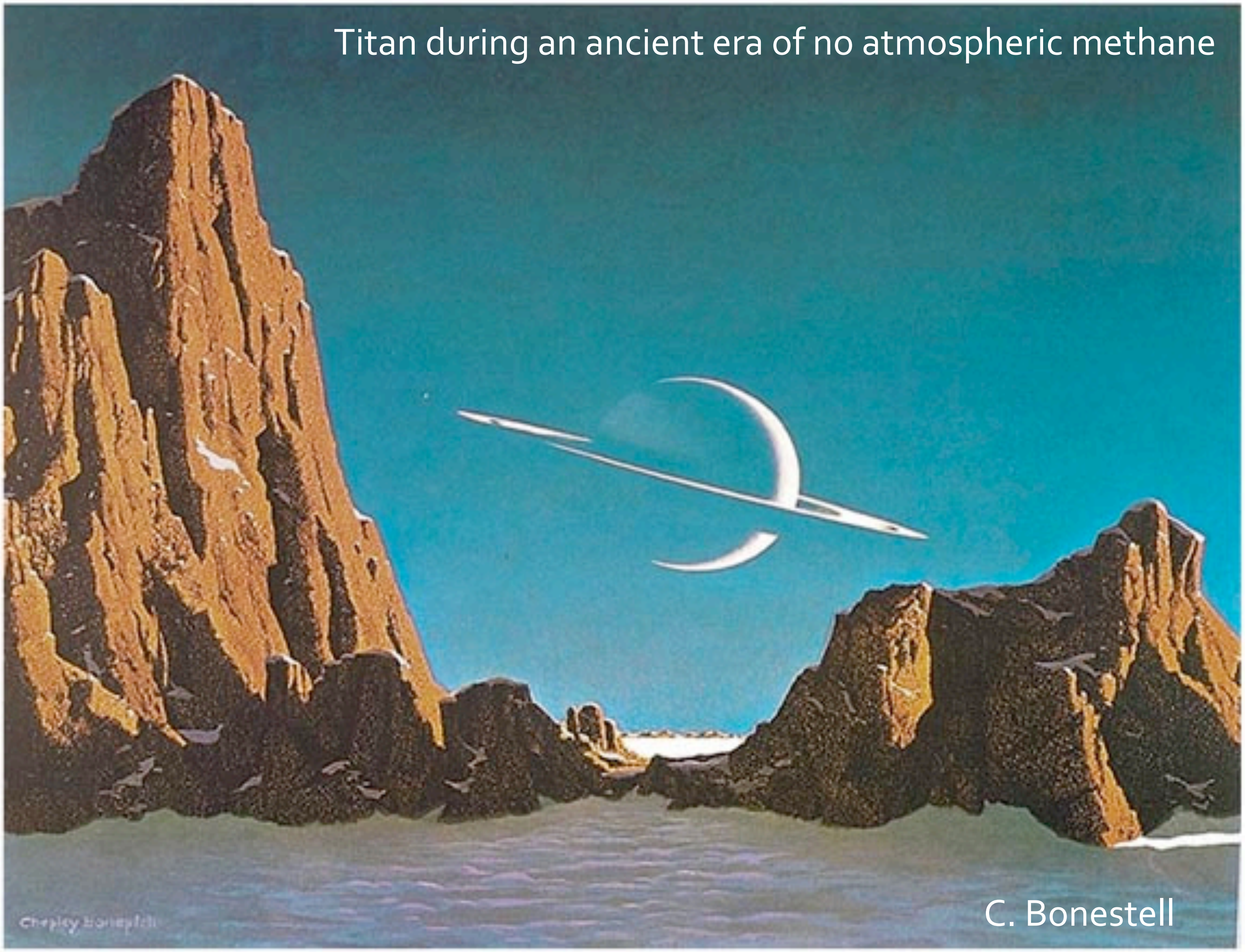
T=84 K.



[N2]=0.898 [Ar]=0.05
[CH4]=0.05 [H2]=0.002
Temperature = 80 K
N2-N2
N2-CH4
N2-Ar
CH4-CH4
CH4-Ar
H2-N2
H2-CH4
H2-Ar
Absorption (10^-5 cm^-1.am^-2)
Wavenumber (cm^-1)
0
200
400
600
800



Surface temperature (K)
Saturation vapor pressure of N_2 (bar)
Surface albedo
90
80
70
60
5.0
1.5
1.0
0.5
0.1
0.20
0.30
0.40
0.50
0.60
0.70
0.80
CH_4 humidity 60%; haze = 0.12; sun = 1.0
CH_4 humidity 0%; haze = 0.00003; sun = 1.0
CH_4 humidity 0%; haze = 0.00003; sun = 0.8
CH_4 humidity 0%; haze = 0.12; sun = 1.0
CH_4 humidity 0%; haze = 0.12; sun = 0.8


Titan during an ancient era of no atmospheric methane
C. Bonestell

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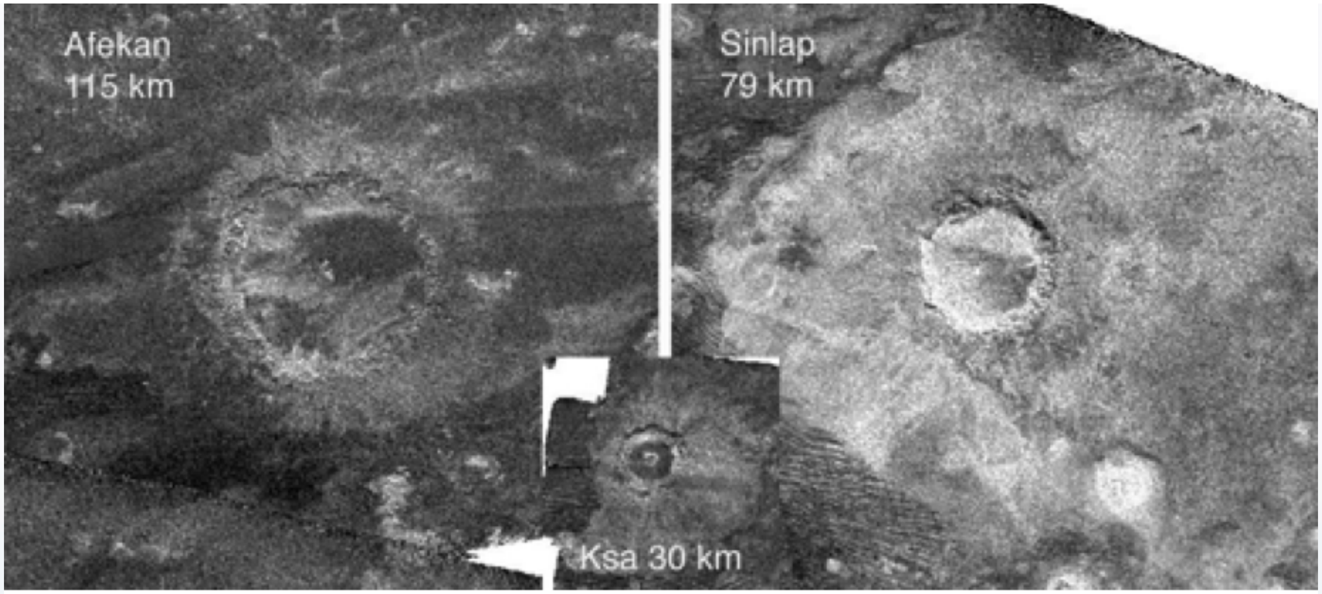
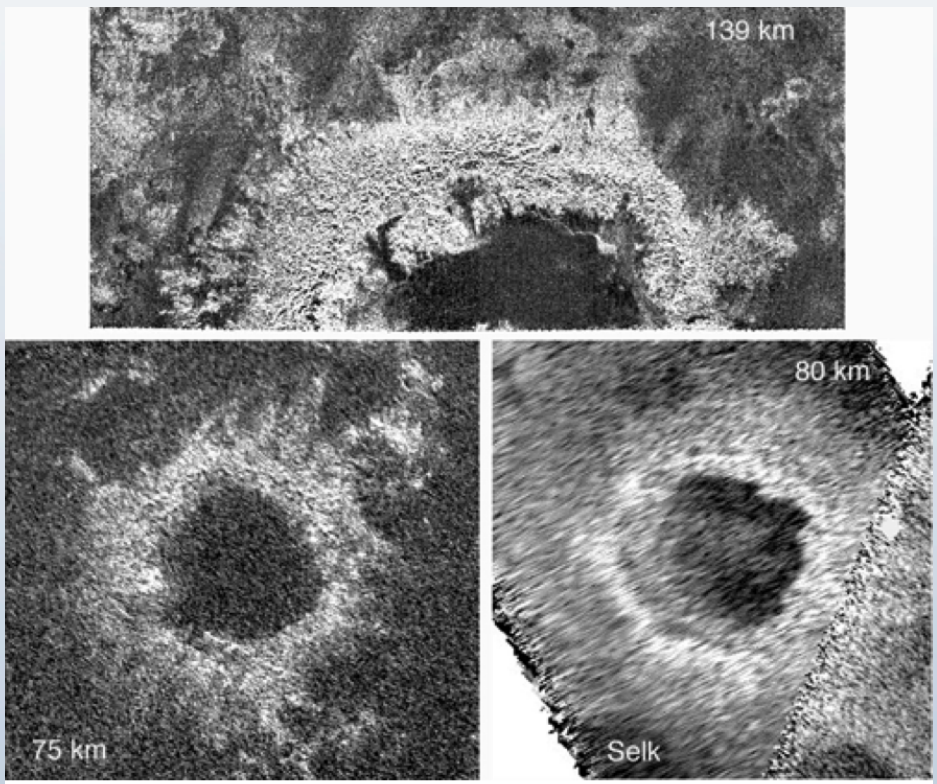
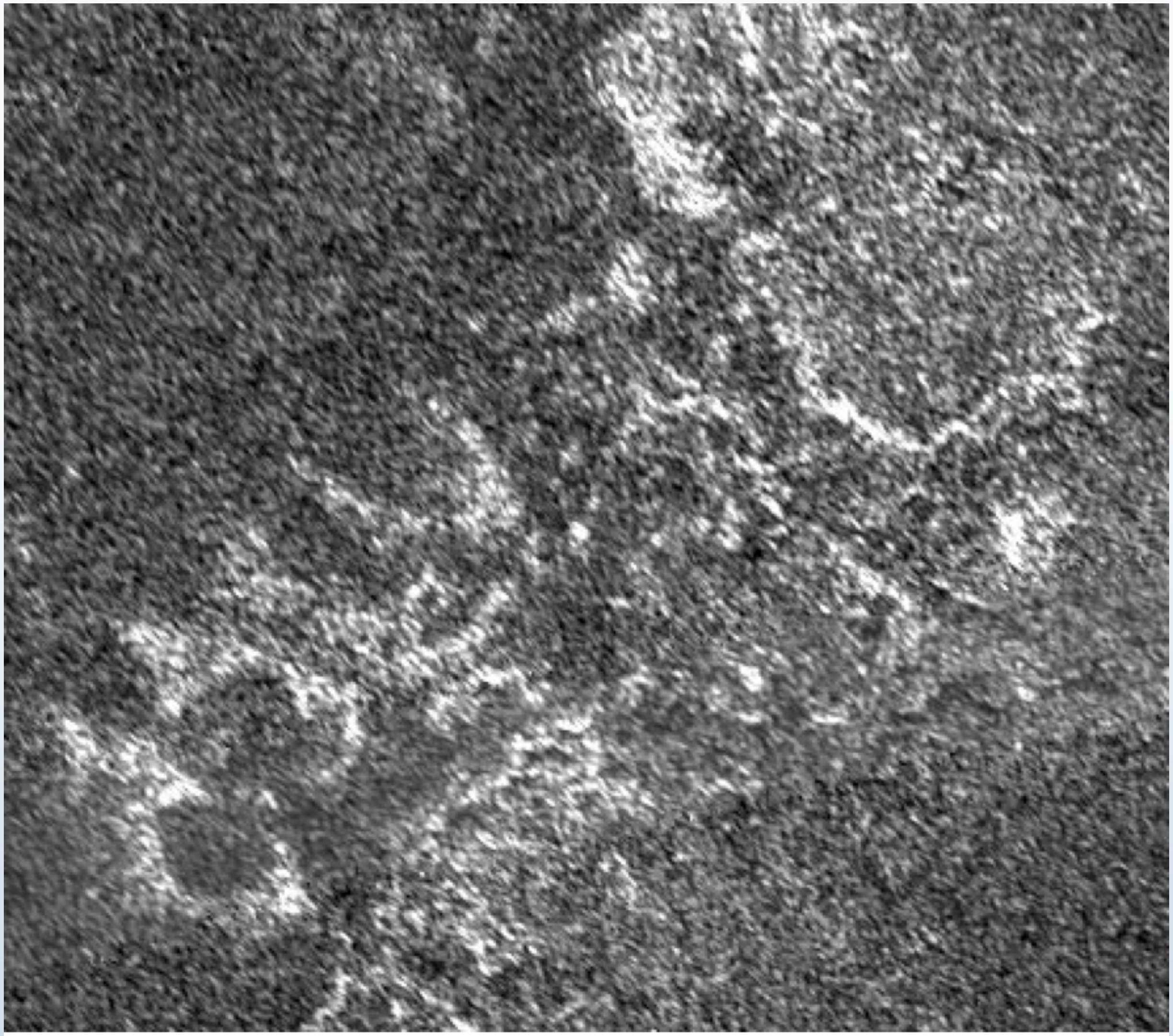


About 70 possible impact craters on Titan....

(Chuck Wood, PSI

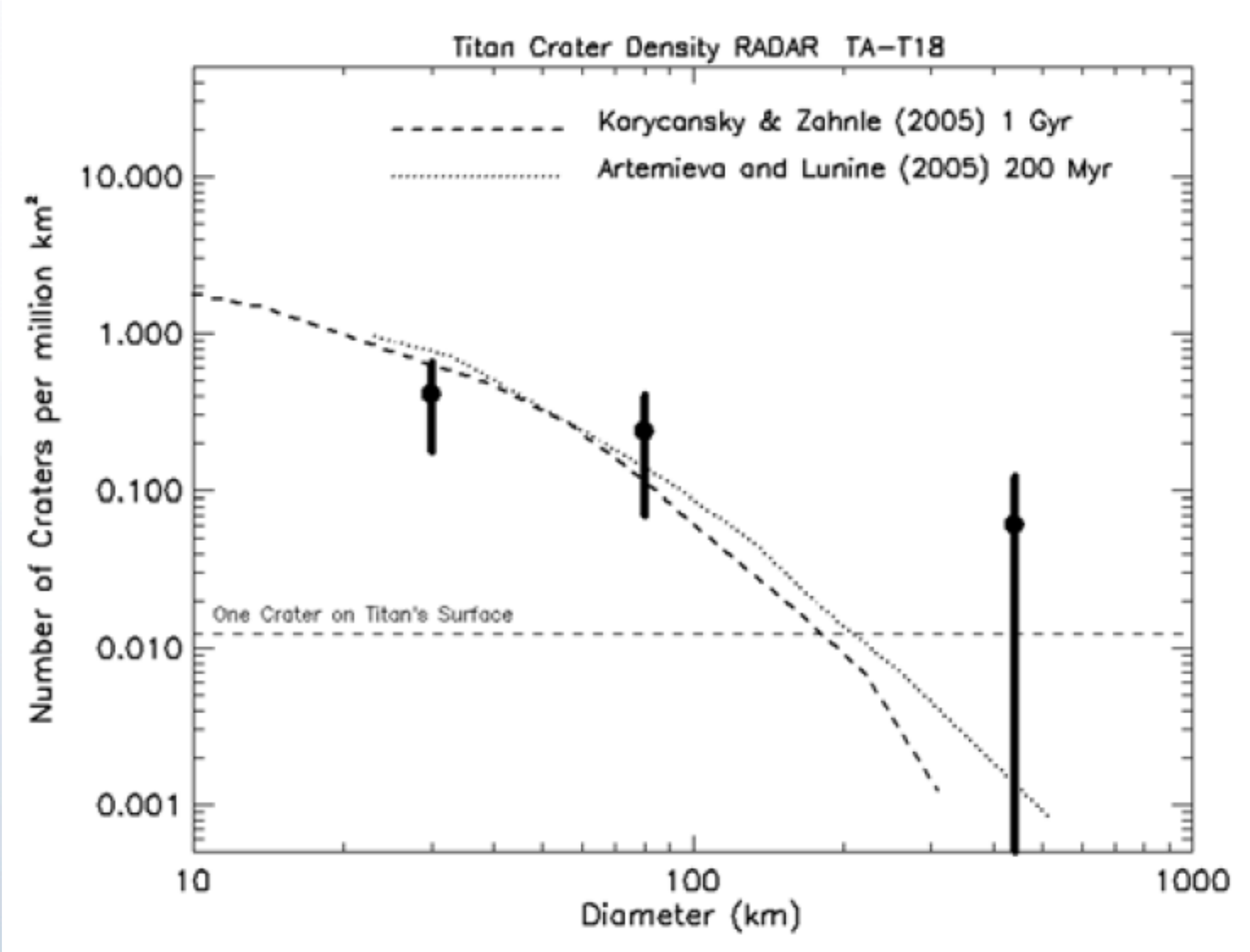




Ghost rings on swath T16; image 175 km wide.

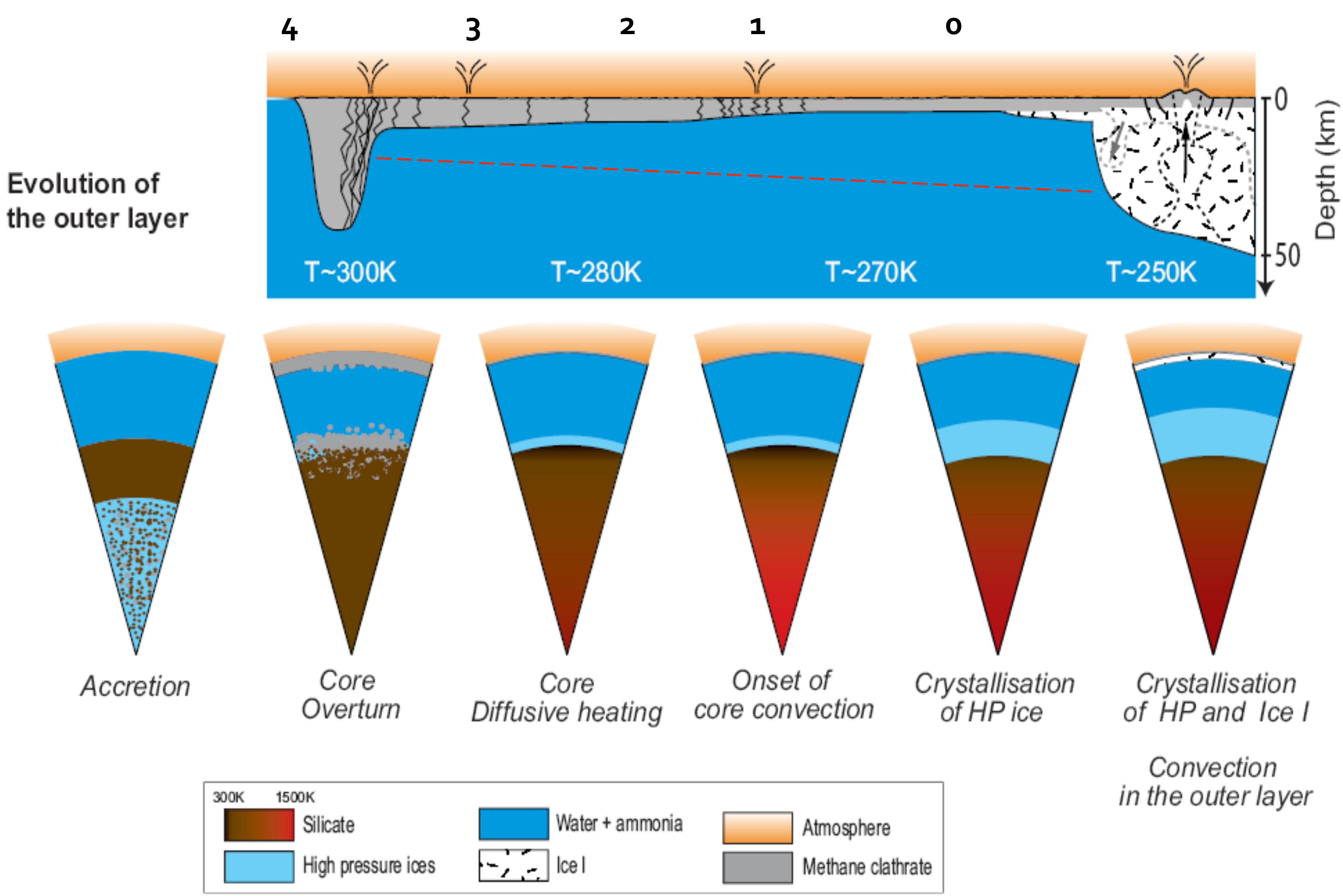
(Chuck Wood, PSI

Many craters may be buried in organic sediments….

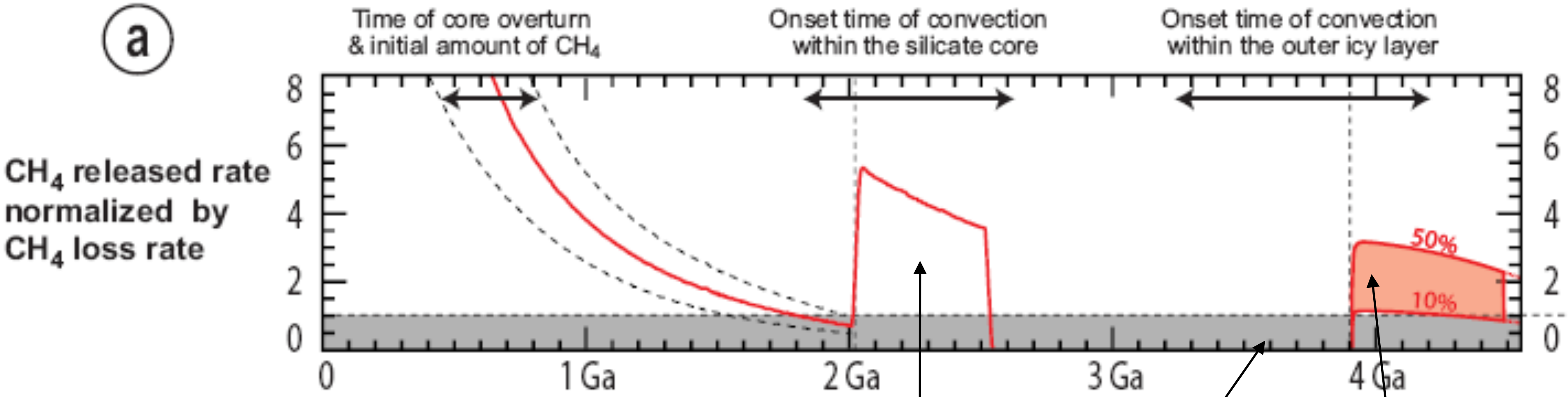


Age of the surface based on impact craters ~ 0.2-1- GYR

Billions of years ago



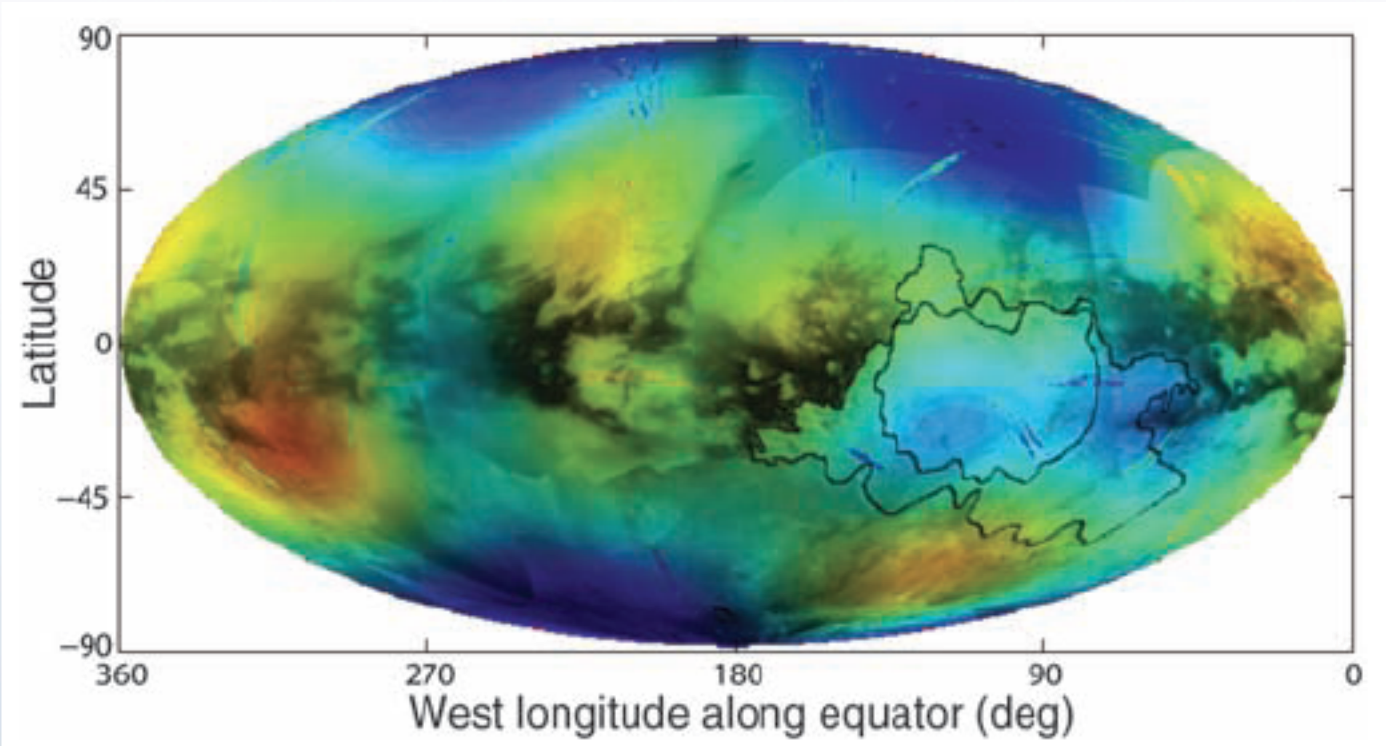
Tobie, Lunine, Sotin. Nature, 2006



Area under this curve is equivalent to enough methane to sustain photolysis for ~ 1 billion years

Surface methane expires here and Titan becomes "dry"

Renewed outgassing of methane begins



Fifth order shape of Titan from radar data (Zebker et al., 2009)

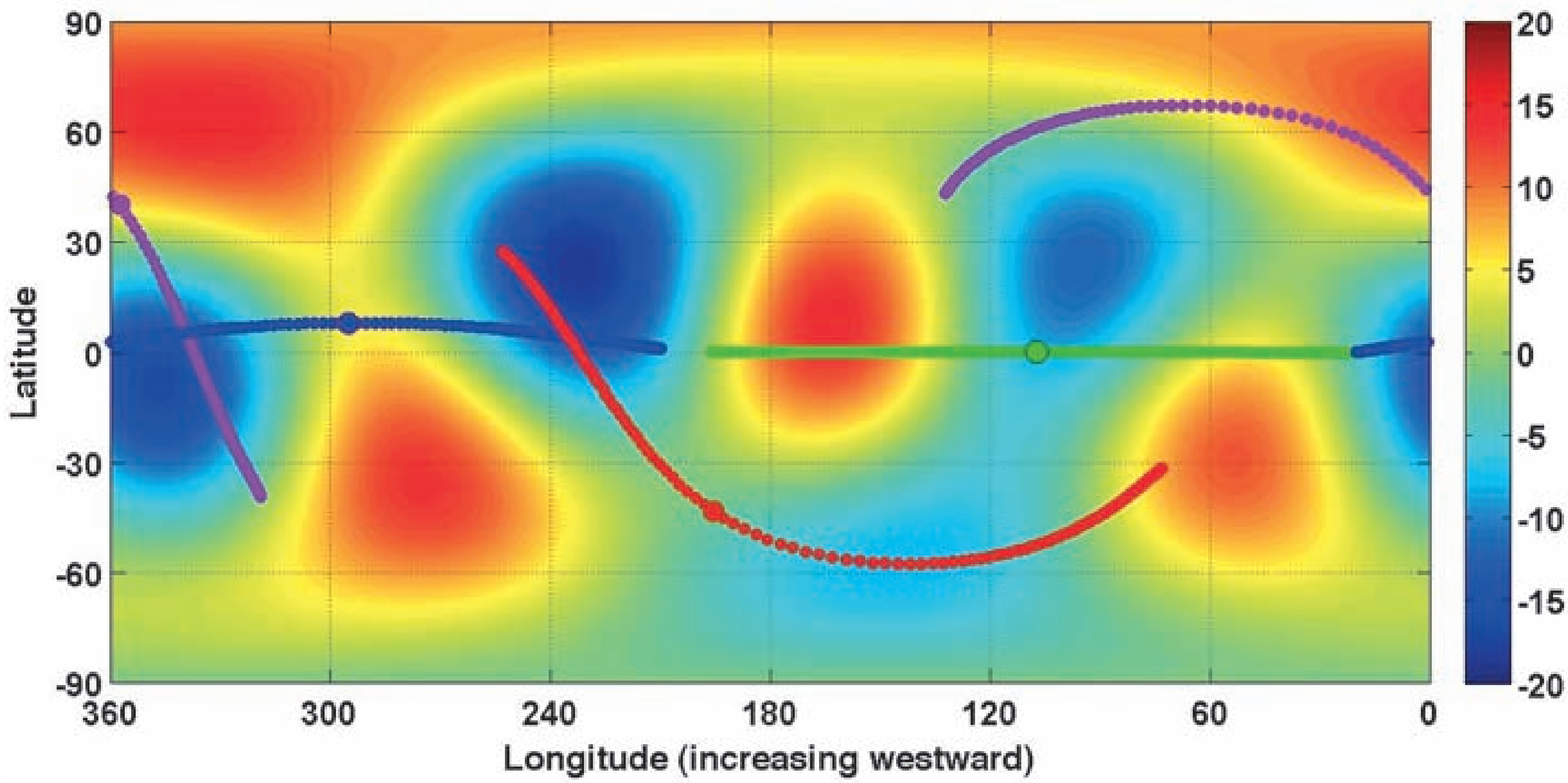


Fig. 1. Titan's geoid with respect to the reference ellipsoid, in meters. The lines represent the subspacecraft trajectory for ±2 hours for Cassini's flybys of Titan (T) T11 (green), T22 (magenta), T33 (blue), and T45 (red). The large solid circles represent the points at closest approach.

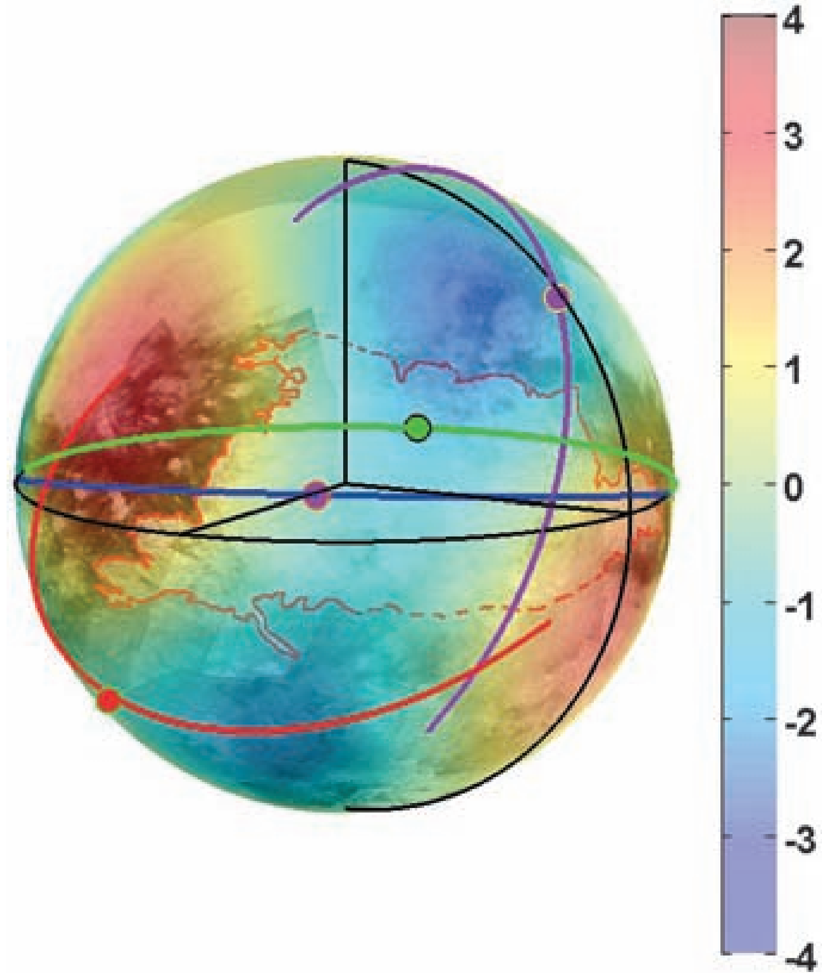


Fig. 2. Titan's gravity disturbances with respect to the reference ellipsoid, in mGal, plotted over Titan's albedo. The region delimited by the red dashed line is Xanadu. South of Xanadu is an area of negative gravity anomaly. The coordinate axes, the equator, and the prime meridian are shown in black.

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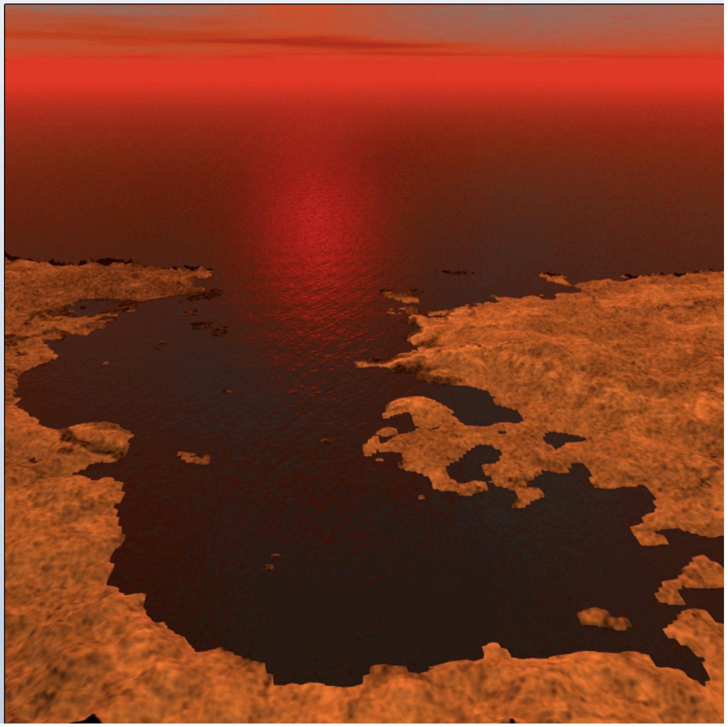
Could methane and ethane act as a liquid medium for life?

- Allows organic molecules to hydrogen-bond
- Suitable for low temperatures
- Polar hydrocarbons might create “insides” and “outsides” in liquid ethane/methane
- “Biological” molecules would be dominated by C-N bonds rather than C-O as on Earth. No DNA, or RNA, or proteins…



Steve Benner and colleagues

LIFE AS WE KNOW IT……

C,H,O,N,P…

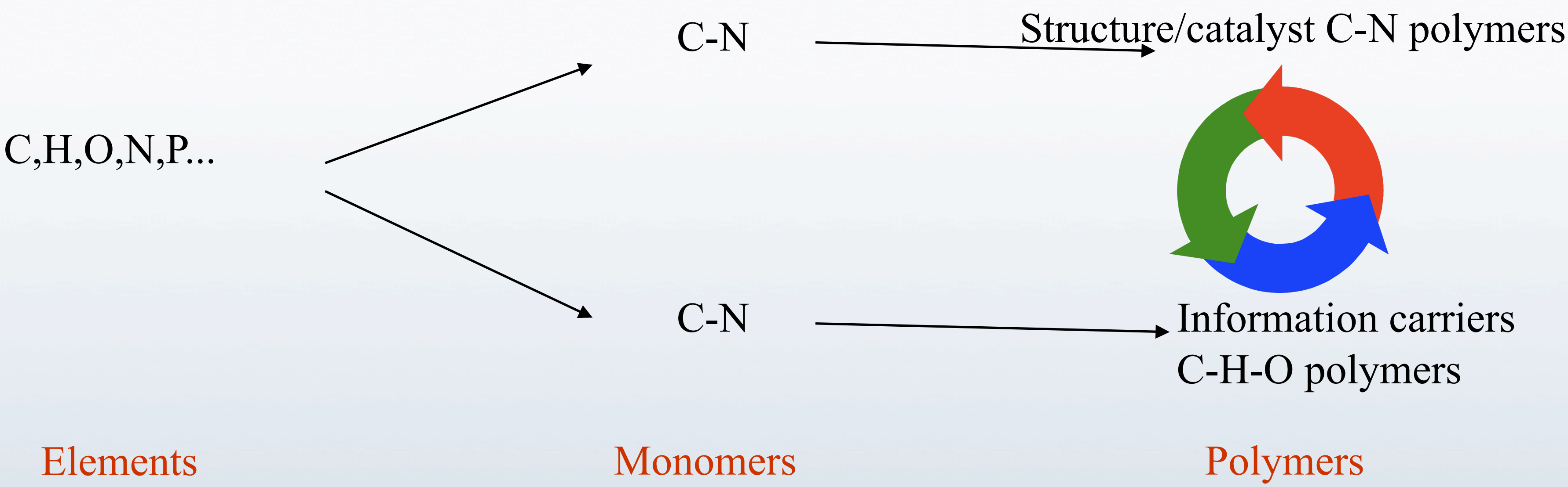
Amino acids → Proteins

Nucleotides → DNA, RNA

Elements   Monomers   Polymers

Carbon is the scaffolding and water is the liquid medium.

LIFE AS WE DON'T KNOW IT……



Carbon is the scaffolding and ethane-methane the liquid medium.

Solubility Calculations Cordier et al. (2009)

$$Y_i P = \Gamma_i X_i P_{\mathrm{vp},i}$$

$$\ln(\Gamma_i X_{i,\mathrm{sat}}) = (\Delta H_m / R T_m)(1 - T_m / T)$$

Chemical Composition of Lakes at the Poles and the Equator

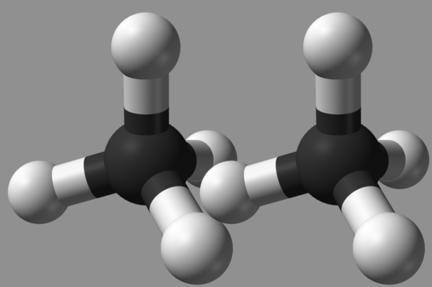
	Equator (93.65 K)	Poles (90 K)
Main composition (lake mole fraction)		
N_2	2.95×10^{-3}	4.90×10^{-3}
CH_4	5.55×10^{-2}	9.69×10^{-2}
Ar	2.88×10^{-6}	5.01×10^{-6}
CO	2.05×10^{-7}	4.21×10^{-7}
C_2H_6	7.95×10^{-1}	7.64×10^{-1}
C_3H_8	7.71×10^{-2}	7.42×10^{-2}
C_4H_8	1.45×10^{-2}	1.39×10^{-2}
H_2	5.09×10^{-11}	3.99×10^{-11}

Chemical Composition of Lakes at the Poles and the Equator

	Equator (93.65 K)	Poles (90 K)
Solutes (lake mole fraction)		
HCN	2.89×10^{-2}(s)	2.09×10^{-2}(s)
C_4H_{10}	1.26×10^{-2} (ns)	1.21×10^{-2}(ns)
C_2H_2	1.19×10^{-2} (ns)	1.15×10^{-2}(ns)
C_6H_6	2.34×10^{-4} **(ns)**	2.25×10^{-4}**(ns)**
CH_3CN	1.03×10^{-3} (ns)	9.89×10^{-4}(ns)
CO_2	3.04×10^{-4} (ns)	2.92×10^{-4}(ns)

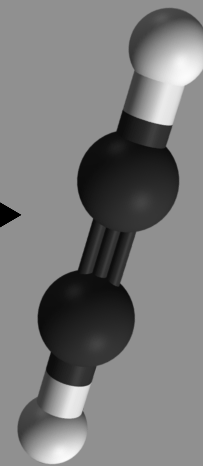
Notes. (s): saturated; (ns) non-saturated.

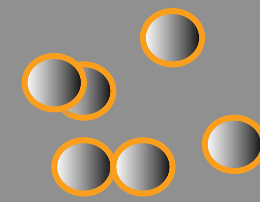
Focus on the chemistry of acetylene, which should be fairly abundant (1%) in the lakes



$$2CH_4 \rightarrow C_2H_2 + 3H_2$$

+2 hν (UV)





Acetylene transports solar UV and magnetospheric energy to the surface

stored chemical energy
(~100's kjoules/mole)

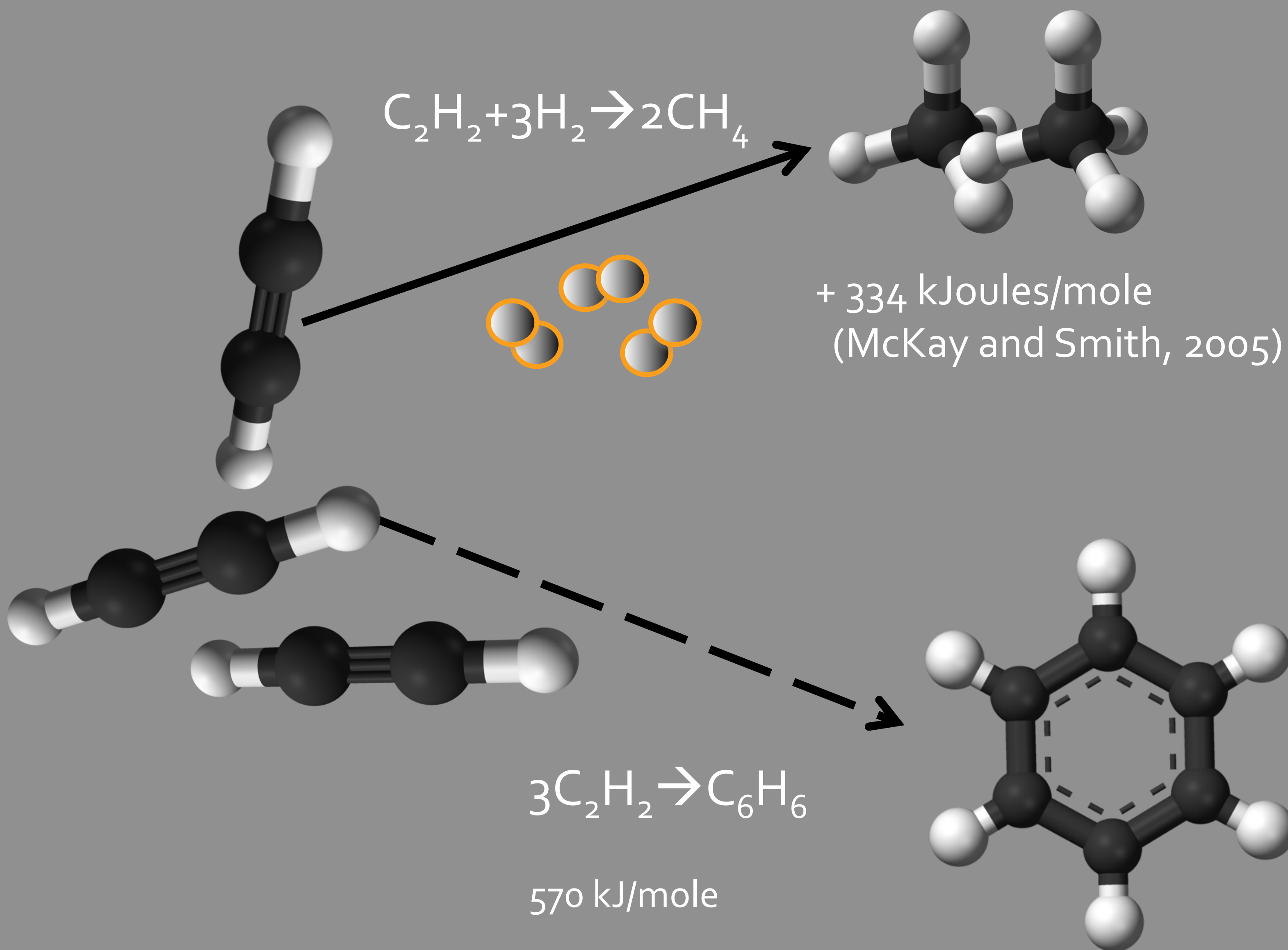
tholins (C/H >> 1)
then aerosols to surface

saturated hydrocarbons (ethane)
then aerosols to surface

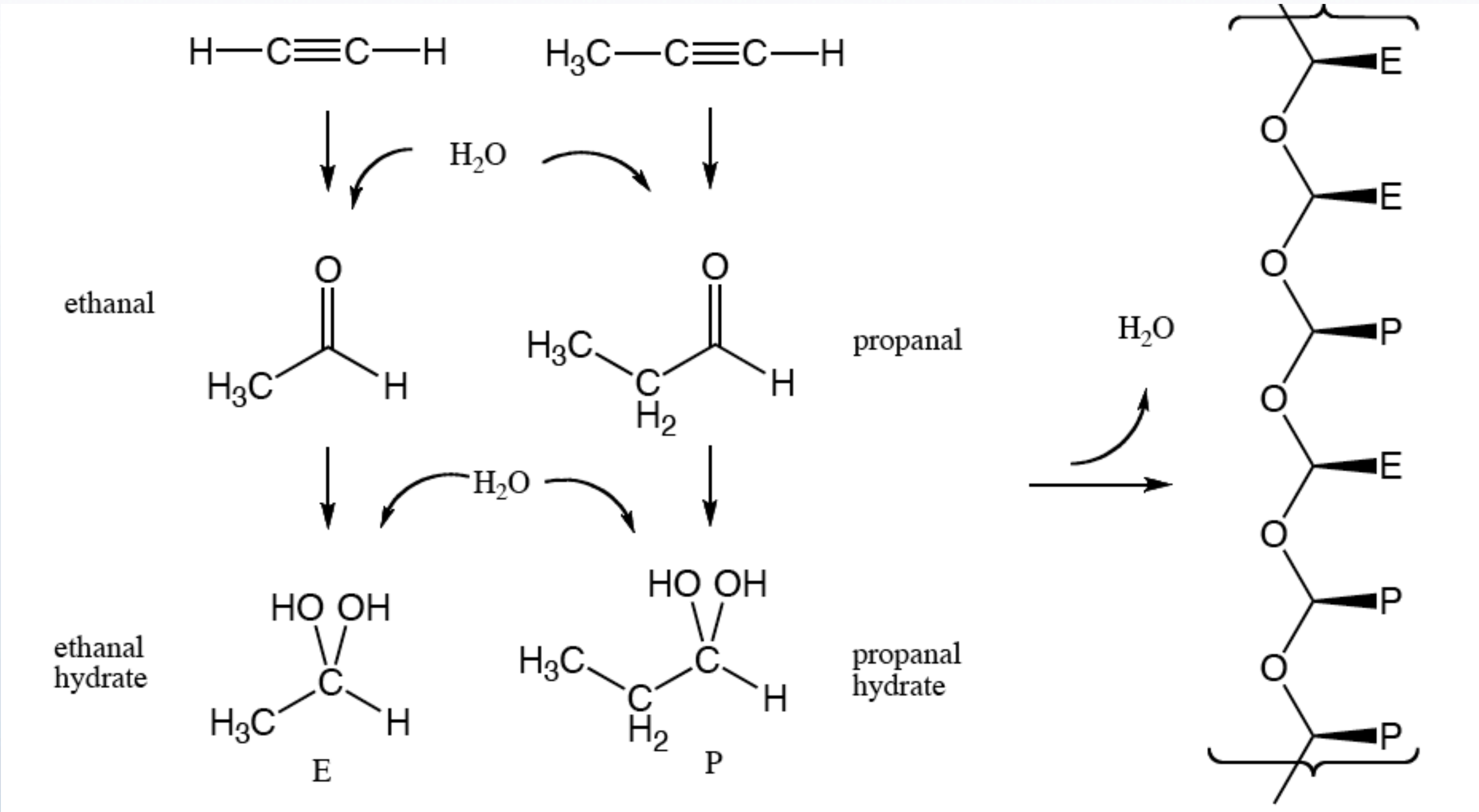
C_2H_2 ice (to surface)

This is a unique situation in the solar system thanks to Titan's dense atmosphere

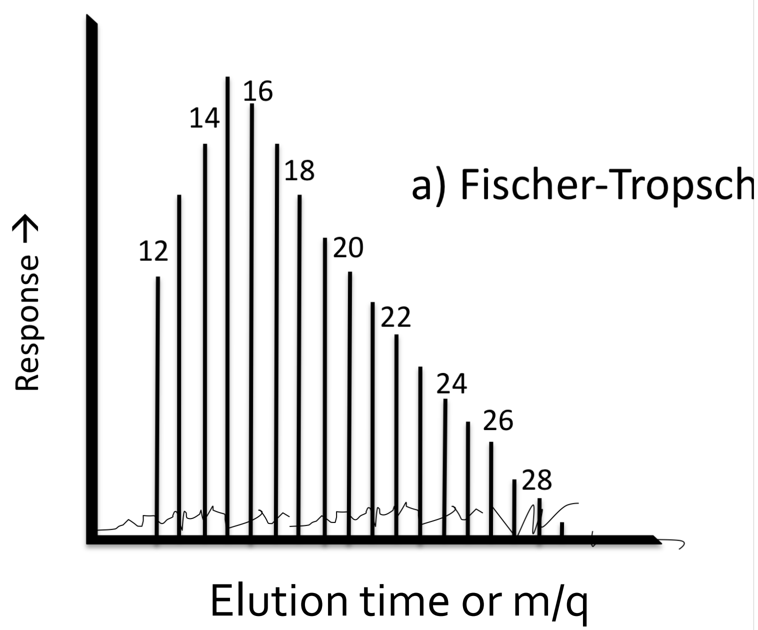
However, a source of hydrogen may change everything…

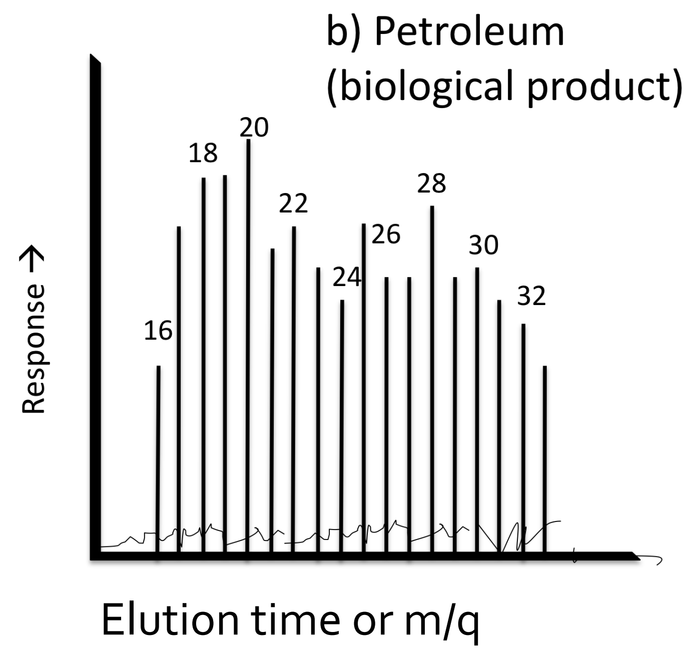


And with a source of oxygen (water)… (Benner and Kim, Abscicon 2010 April, Houston):



Seek deviations from abiotic abundance patterns





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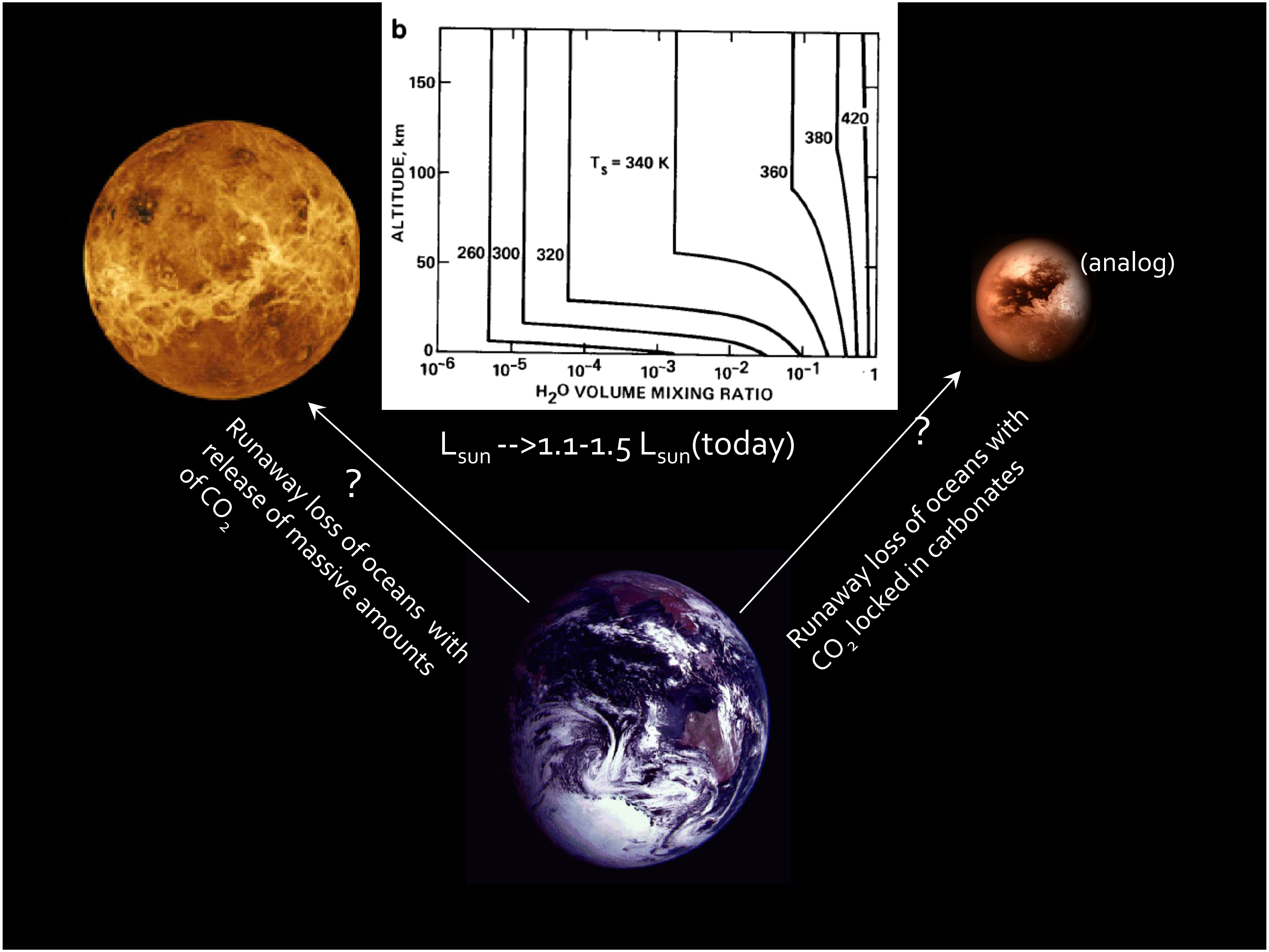
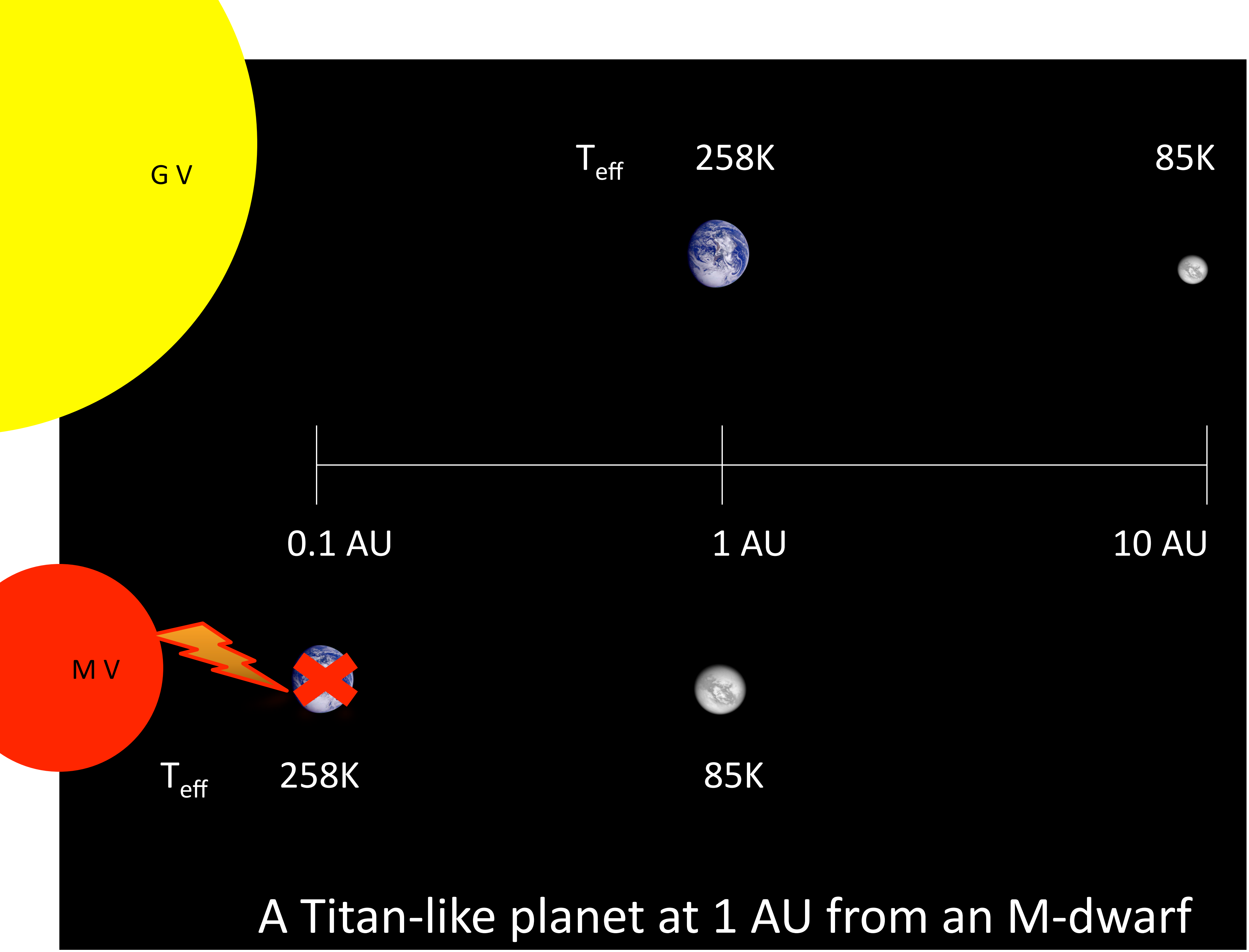

b
ALTITUDE, km
150
100
50
0
T_s = 340 K
260
300
320
360
380
420
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
H_2O VOLUME MIXING RATIO
L_{sun} -->1.1-1.5 L_{sun}(today)
?
Runaway loss of oceans with release of massive amounts of CO_2
?
Runaway loss of oceans with CO_2 locked in carbonates
(analog)

(R5) $H_2O + h\nu \rightarrow H + OH$

The final sterilization of the Earth will occur when the planet loses its water. Today, the timescale for the loss of the oceans through photodissociation and hydrogen escape is much longer than the age of the Earth; as the atmosphere warms beyond 60 to 70 °C, however, the H_2O mixing ratio in the stratosphere increases markedly[20]. As surface temperatures approach ~80 °C, the stratospheric H_2O mixing ratio reaches ~2.5%. Above this mixing ratio, the loss of hydrogen to space is limited by the solar extreme ultraviolet heating rate to $\sim 6 \times 10^{11}$ atoms H cm^{-2} s^{-1} (ref. 21), giving a timescale for ocean loss of ~1 Gyr.

Kasting, 1992


G V
T_eff
258K
85K
0.1 AU
1 AU
10 AU
M V
T_eff
258K
85K
A Titan-like planet at 1 AU from an M-dwarf

Key questions about Titan and classes of measurements

Cassini Extended Mission

- Seasonal changes: Spring equinox begins in the north this year
  - Cassini S. Hemisphere observations → strong polar seasonality
  - North is different from south: large-scale coverage by lakes; weaker summer solstice flux in north vs south.
  - If lakes are not connected to an aquifer smaller ones should shrink.
  - Expect to observe convection/rainfall in north as in south. But more areas covered in liquids → different behavior?
  - Onset of spring in the north→ sunlight→ opportunity to map lake composition.
  - Seasonal asymmetry at high altitude → new chemistry to be explored.

- Future Titan missions
  - Completion of the map of Kraken mare is essential to its potential as a splashdown site for future probes.

- Internal structure
  - Detecting presence of an ocean requires four RSS flybys

Post-Cassini Key Science Questions and Measurements

- What are the lakes and seas made of? What's flowing in the rivers?
  - Direct measurement of lake/sea composition
  - 1-6 micron spectral images with resolving power 1000
  - 10-20 m imaging in selected areas
  - Temperatures to better than 1 K over poles
- Is there active volcanism? Tectonics?
  - Global imaging to 50 m resolution
  - Global topography to 10 m precision over km spot size
  - Mapping of volcanic gases (CO_2) and CH_4 geysers
  - Surface seismometry
- How are the polymers made in the atmosphere? What is the distribution and deposition of the energy source?
  - Mass spec to 1000 amu w/ resolving power of 1 amu
  - Composition and dynamics in 400-900 km region.
- When and how do the heavy rains occur?
  - Deep atmosphere temperature measurements to 1 K
  - Selective imaging to 10 meters resolution

Blue = orbiter or close flyby spacecraft; red = mobile aerial platform; green=surface lander

Post-Cassini Key Science Questions and Measurements

- Is there a rock/metal core? How thin is the crust?
  - Magnetic measurements of possible induced magnetic field to sub-Europa sensitivity
  - Global gravity mapping to degree and order 6
  - Global topography to 10 m precision over km spot size
  - Surface seismometry

- What is the loss rate of the major gases?
  - Detection of energetic particles from solar wind and magnetosphere
  - Detection of Titan material within the Saturn system
  - 1-6 micron spectral images with resolving power 1000
  - Rotational spectra of molecules in Titan's limb
  - Conditions and dynamics in the 400-900 km region

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Post-Cassini Key Science Questions and Measurements

- What is the vertical extent and composition of the subcrustal ocean?
  - Electric field measurements of high sensitivity across various parts of the surface
  - (Possibly required): a better determination of tidal love numbers than Cassini.

- Are ammonia and methanol present on the surface?
  - 1-6 micron spectral images with resolving power 1000
  - Direct sampling of surface materials by GCMS

- What is the state of pre-biotic/biotic evolution of Titan's surface organics? Is there life ?
  - Direct sampling of lakes and seas with MS and/or GCxGC
  - Chiral measurements on organic materials
  - Direct determination of the presence of inorganic catalysts
  - 1-6 micron spectral images with resolving power 1000

Blue = orbiter or close flyby spacecraft; red = mobile aerial platform; green=surface lander

A land that is lonelier than ruin
A sea that is stranger than death
Far fields that a rose never blew in,
Wan waste where the winds lack breath

By the North Sea (A.C. Swinburne)