Insights into Titan's surface and subsurface methane reservoirs at the end of the Cassini Mission

Zibi Turtle

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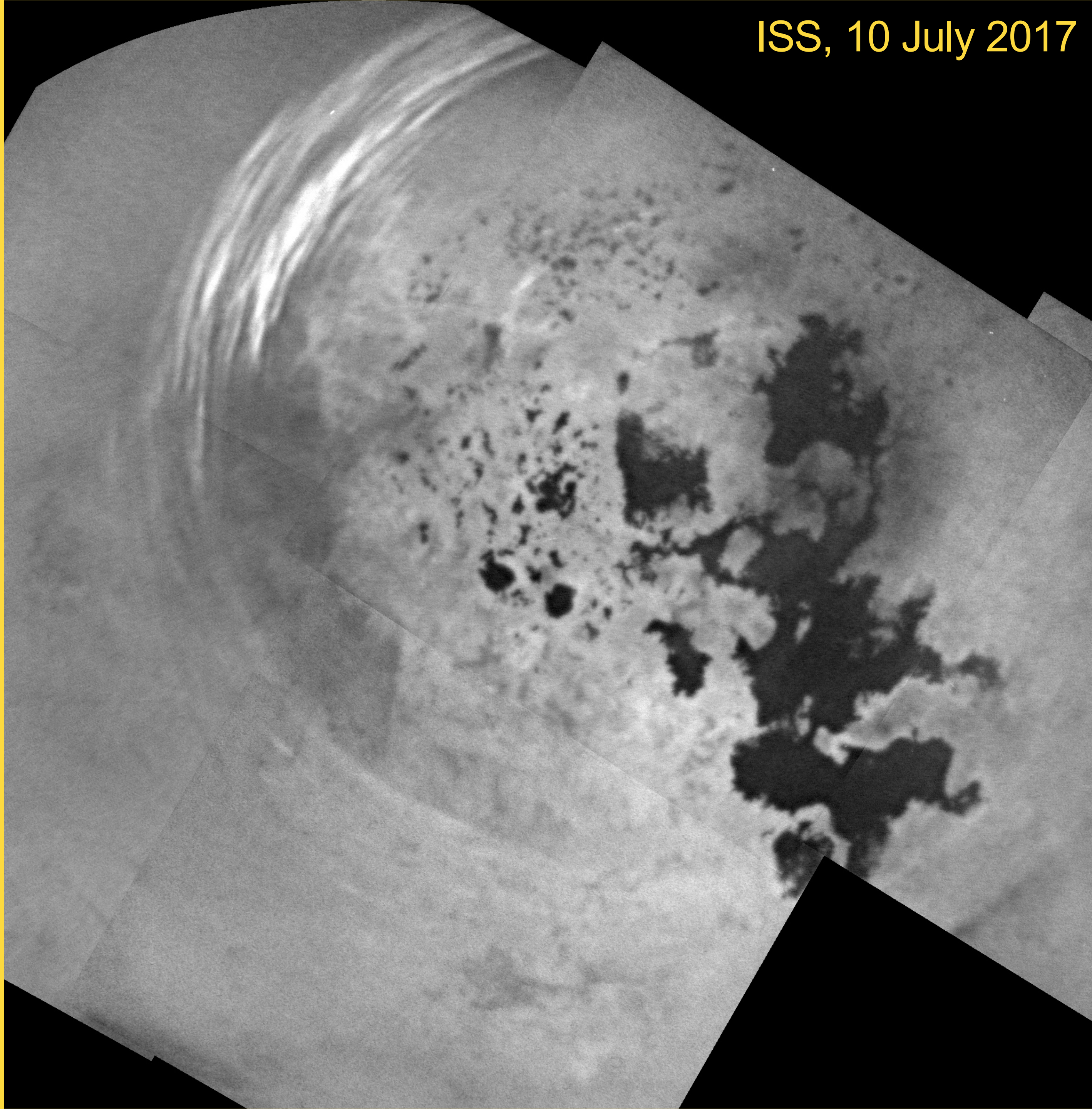
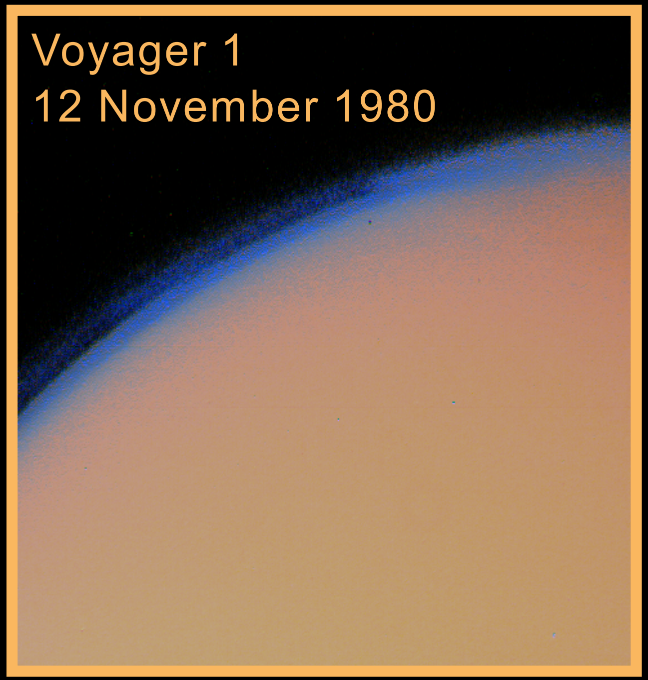
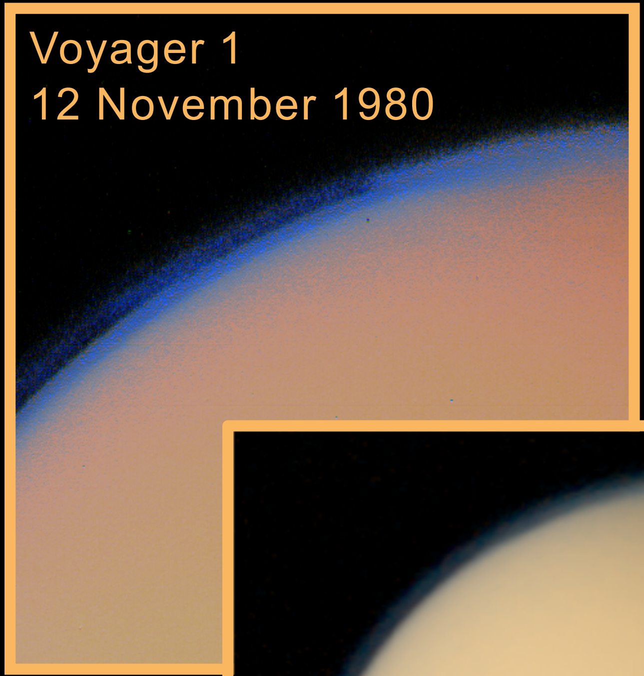
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY



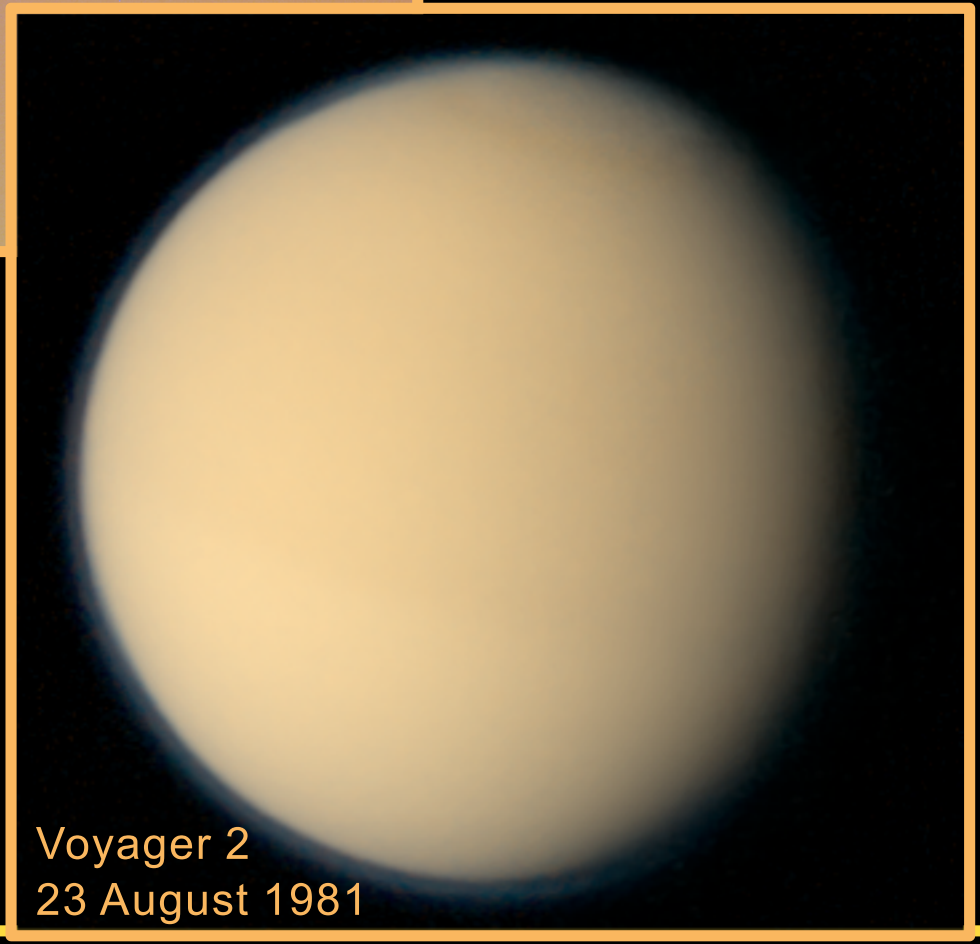


Titan before Cassini

Titan before Cassini

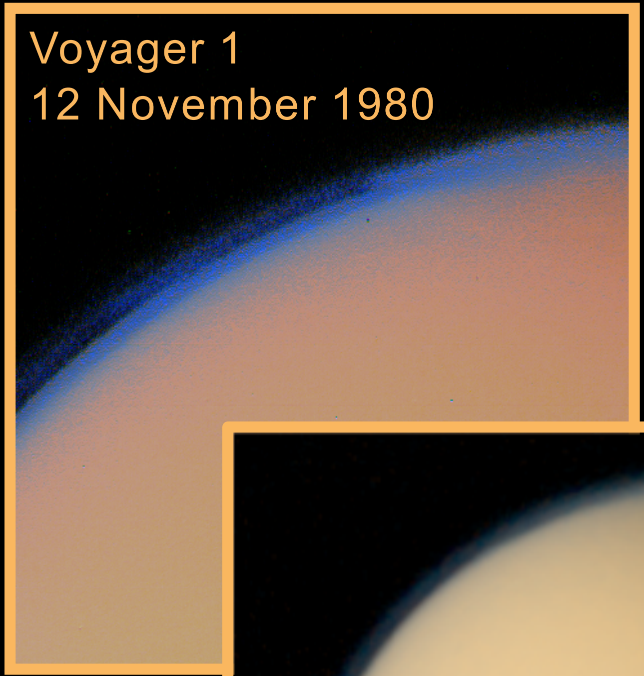


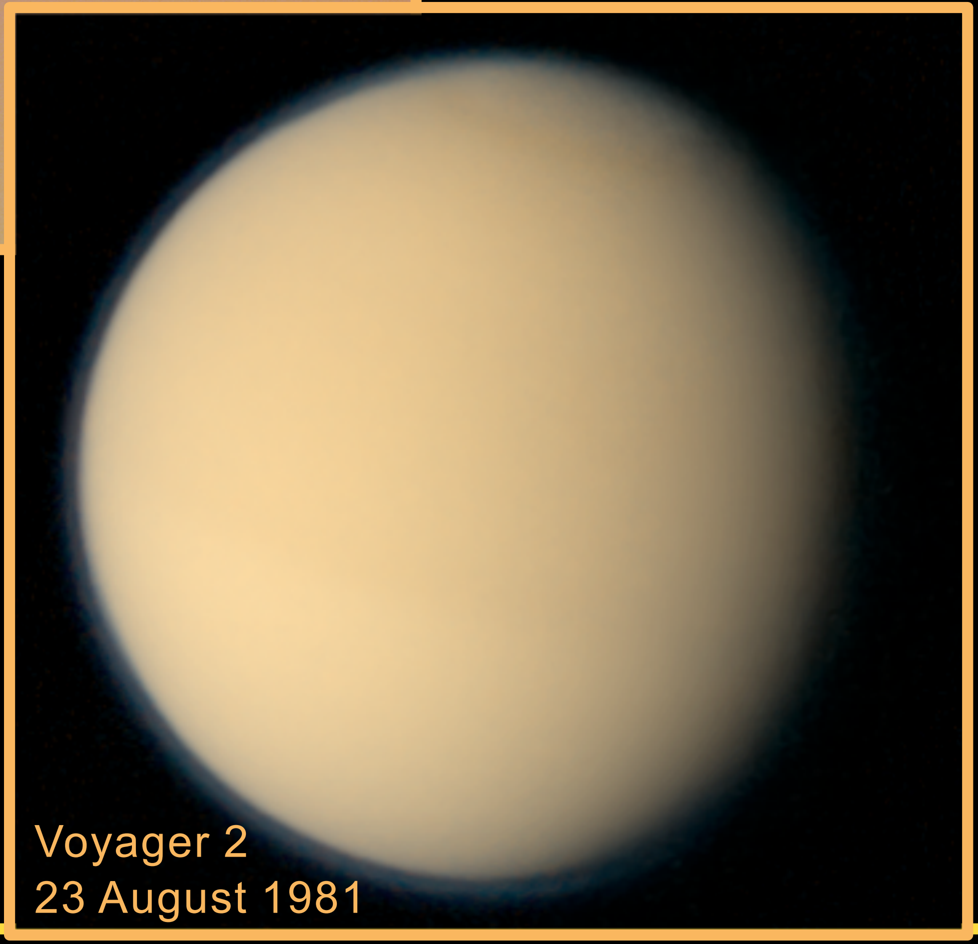
Voyager 1
12 November 1980

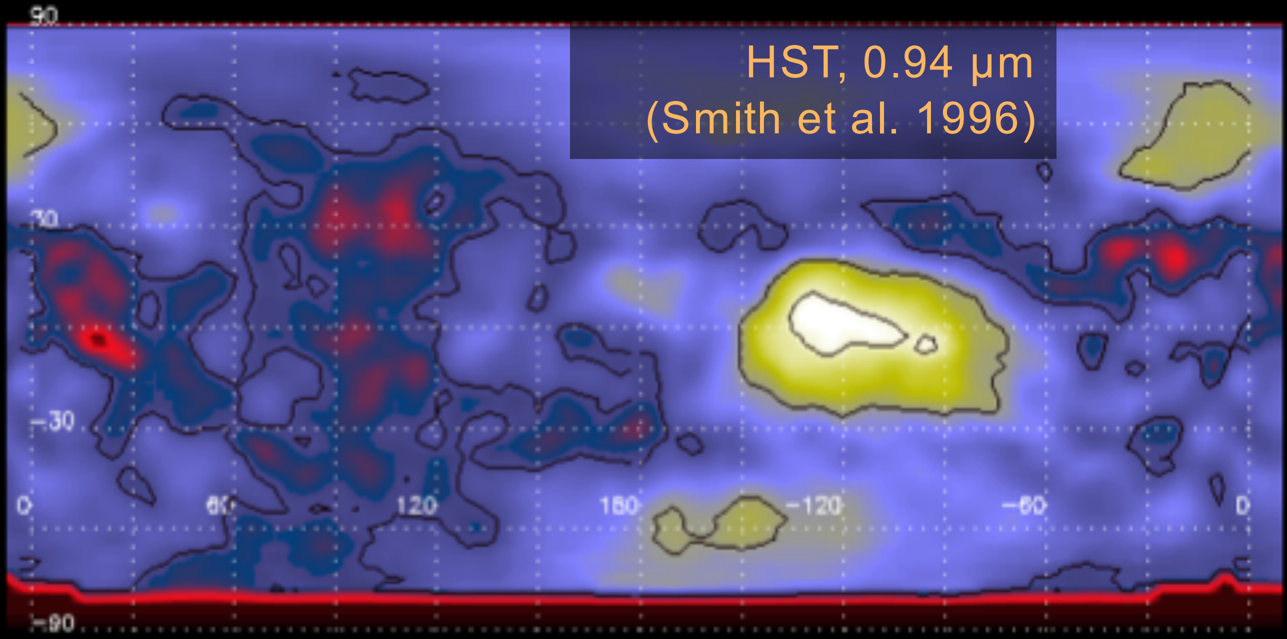


Voyager 2
23 August 1981

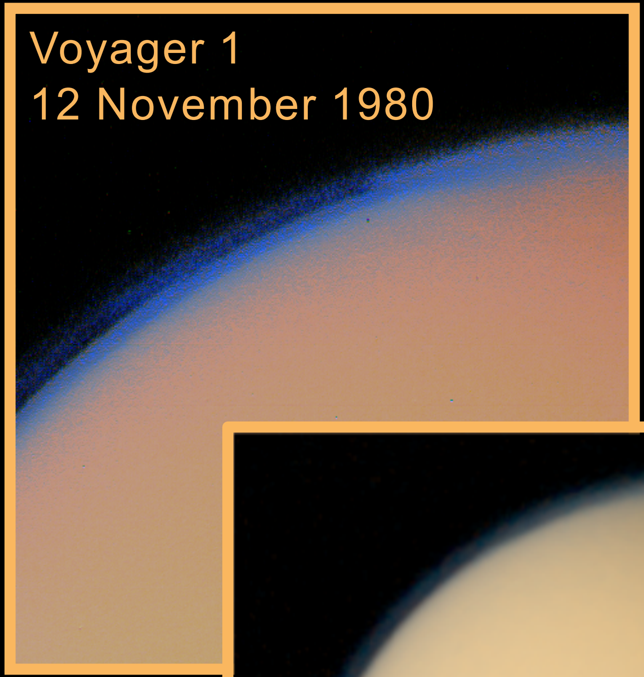
Titan before Cassini

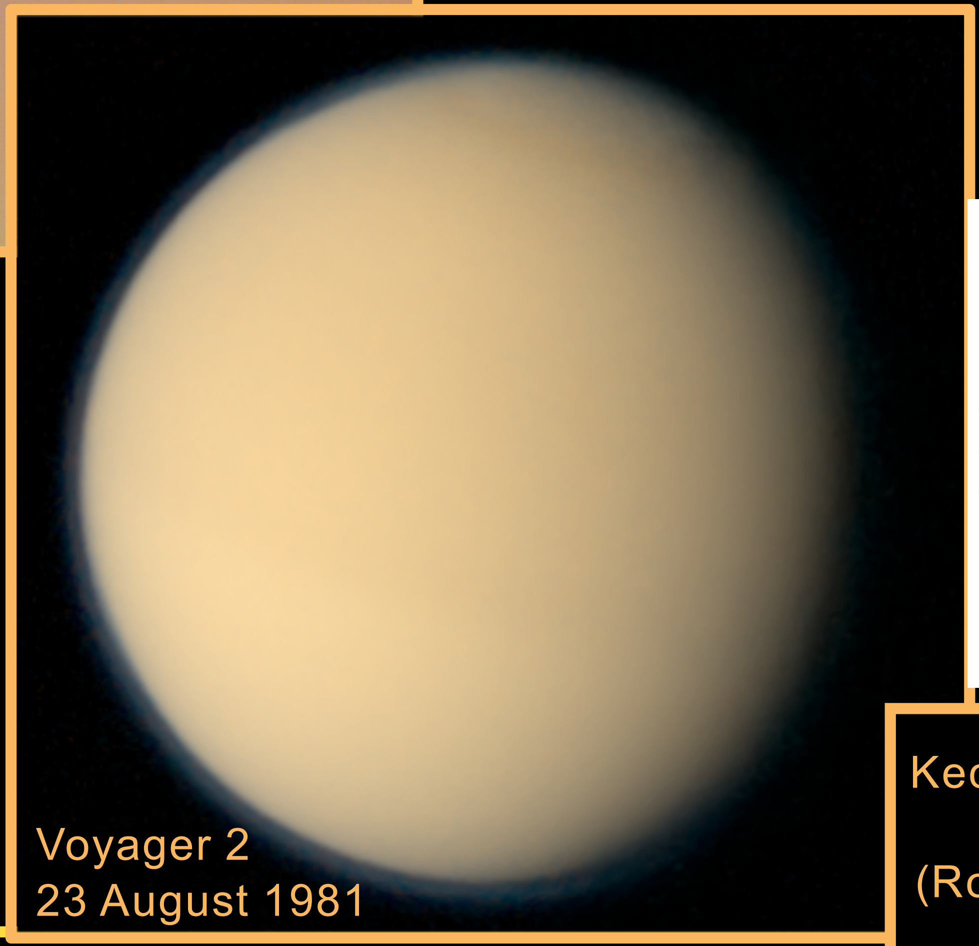


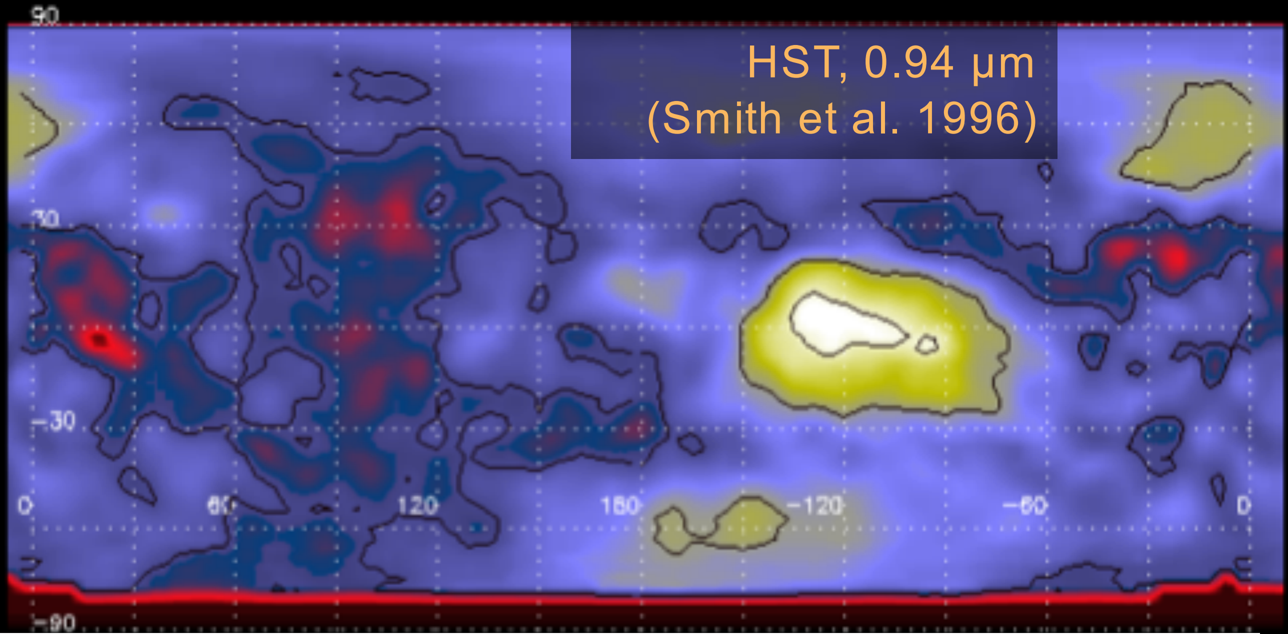


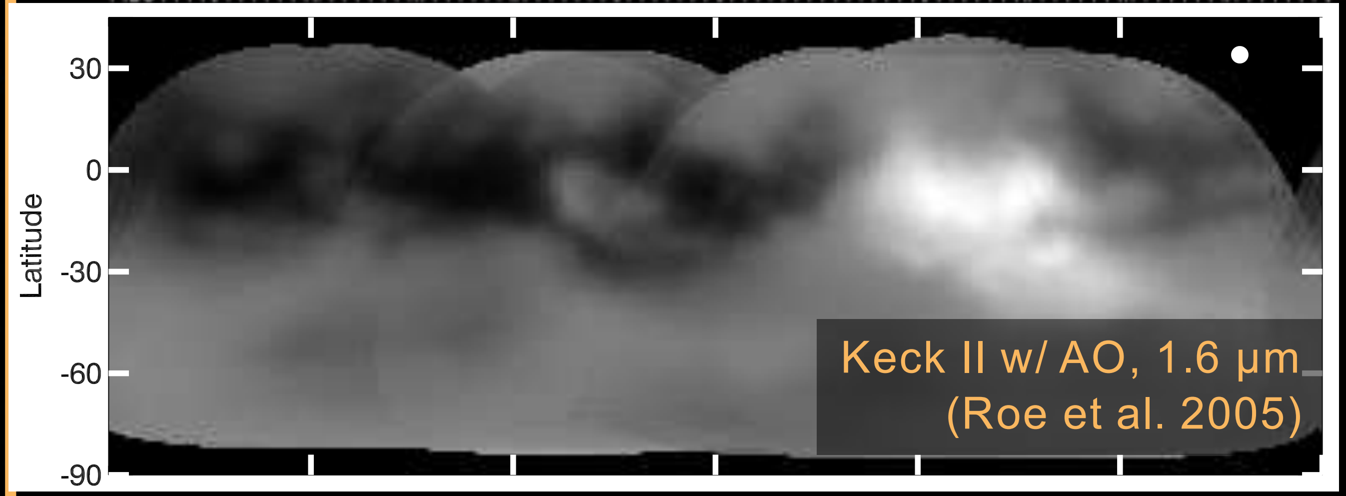


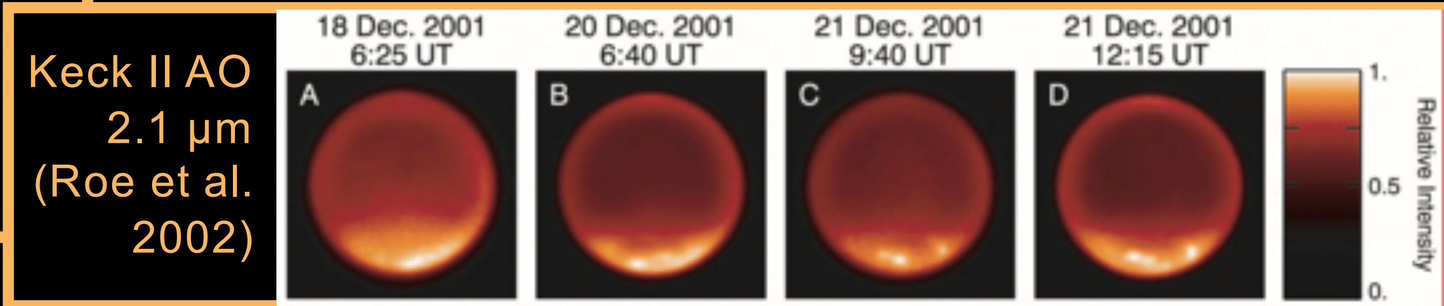
Titan before Cassini



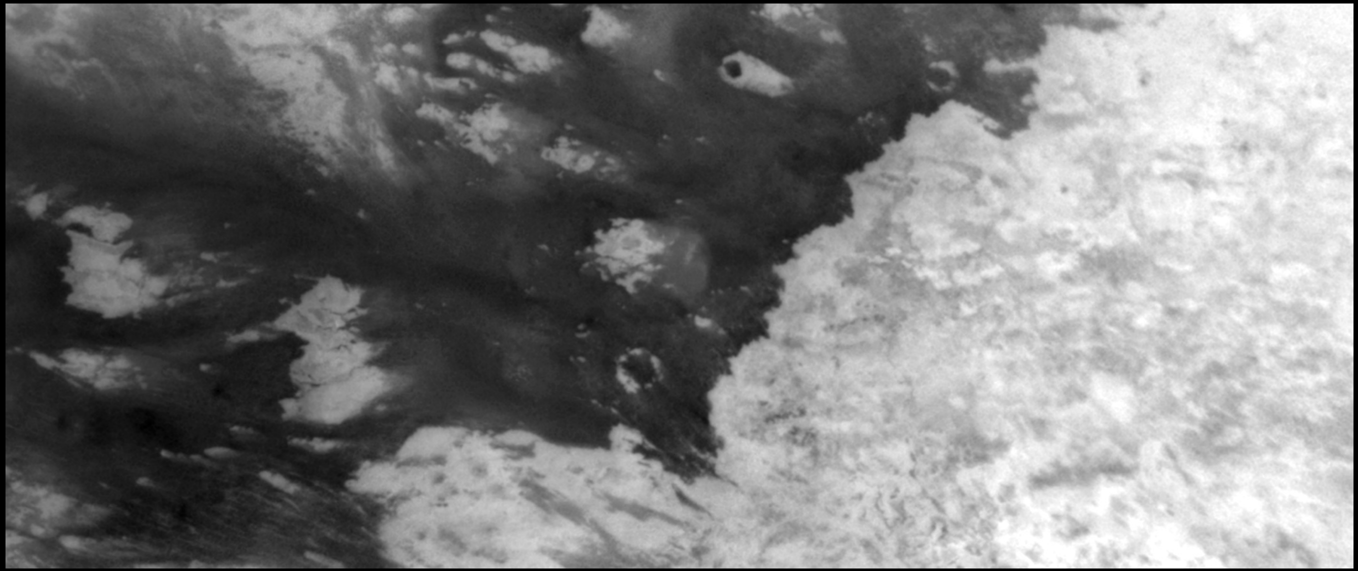


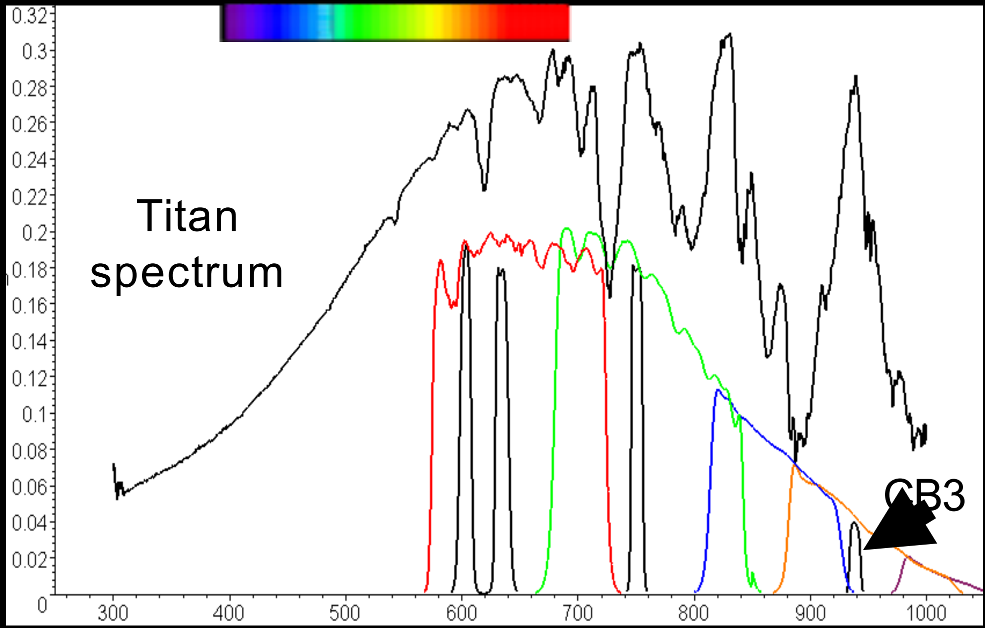




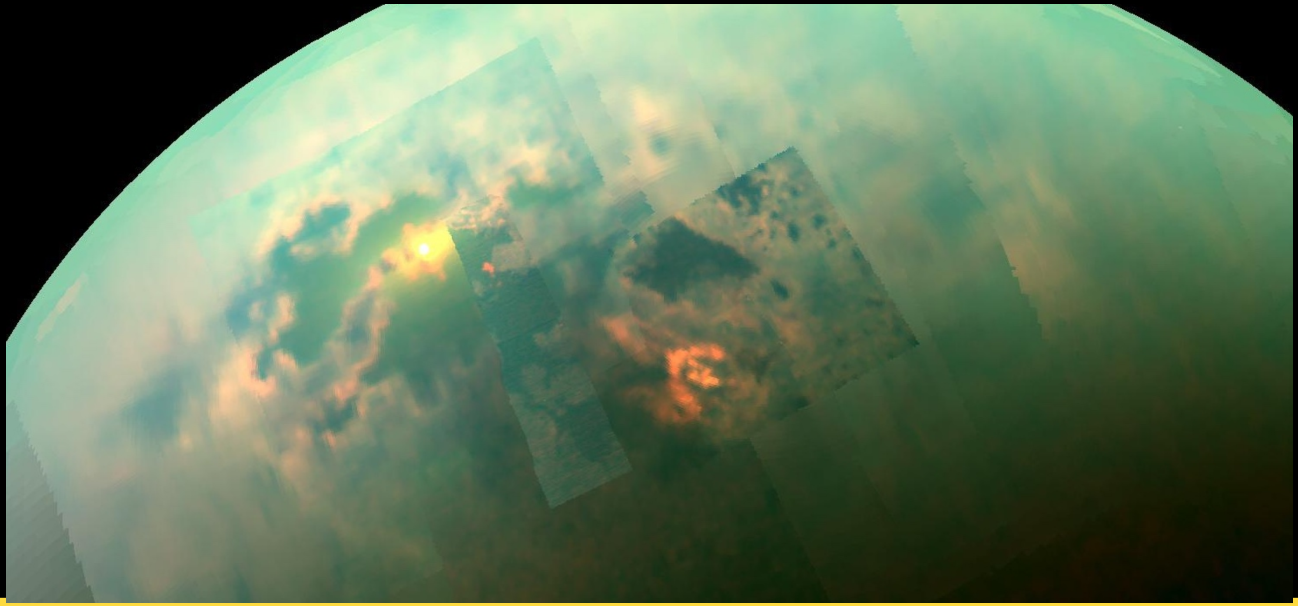


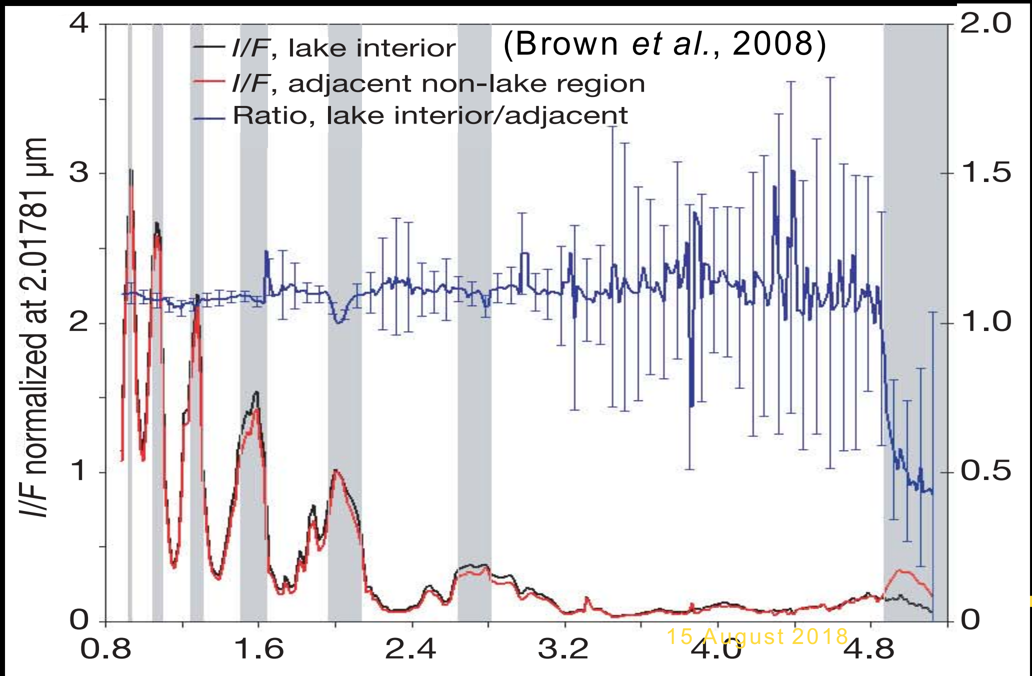
- Imaging Science Subsystem (ISS), primarily 938 nm





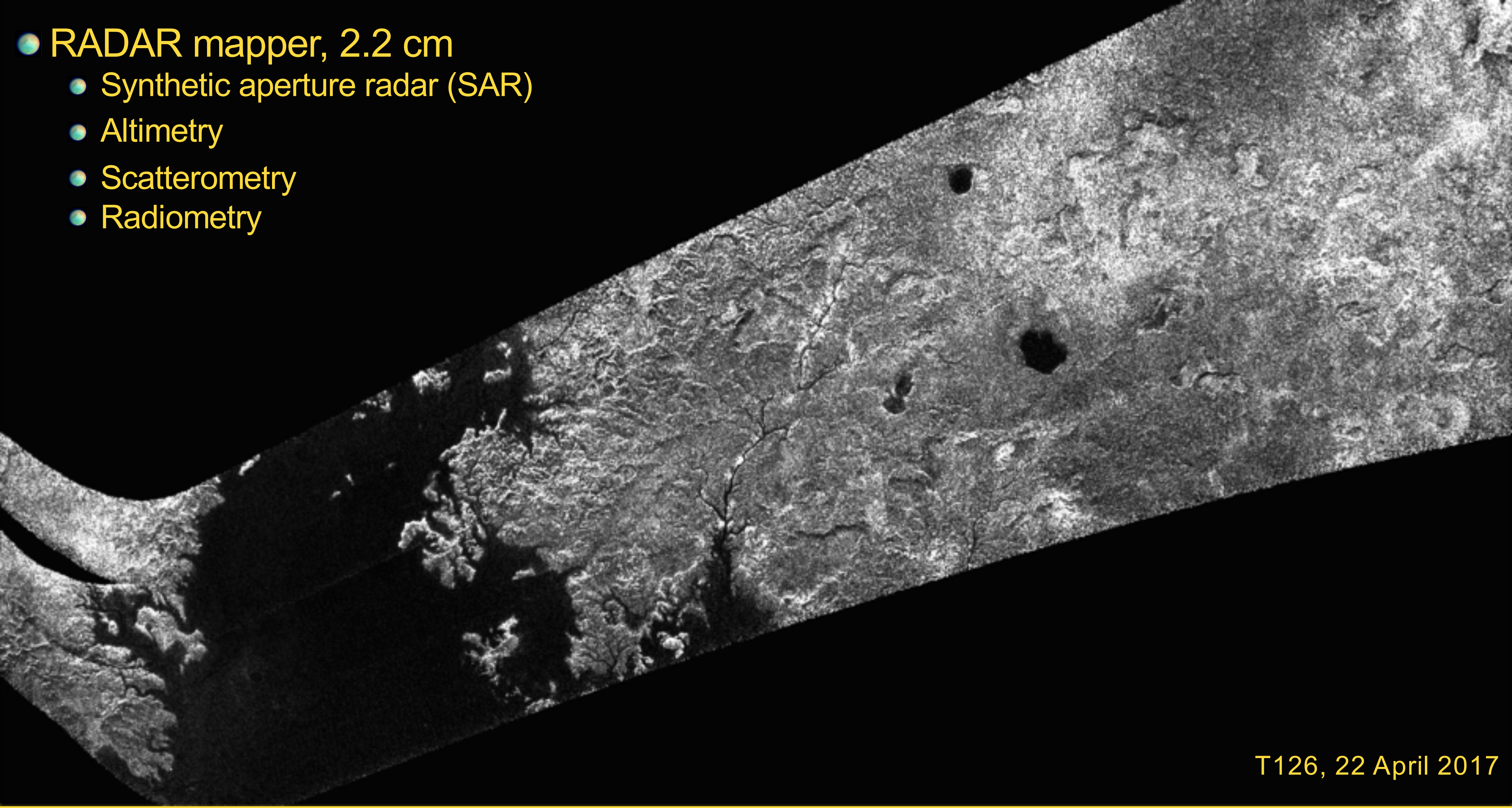
- Visual & Infrared Mapping Spectrometer (VIMS), 0.3 – 5.1 μm





RADAR mapper, 2.2 cm

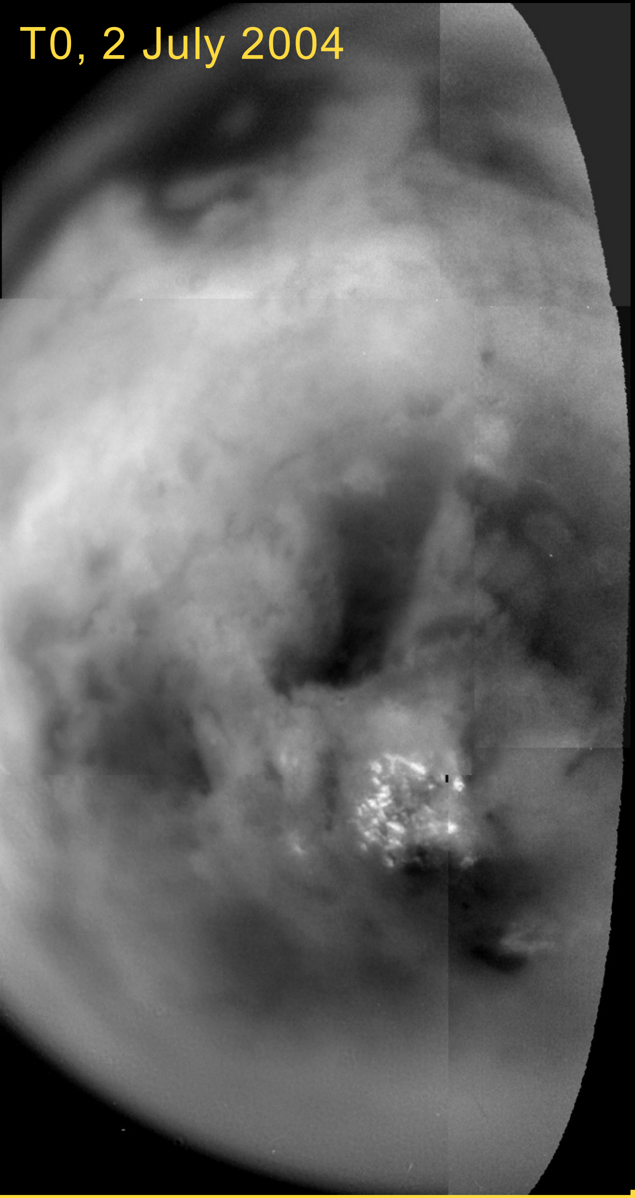
- Synthetic aperture radar (SAR)
- Altimetry
- Scatterometry
- Radiometry



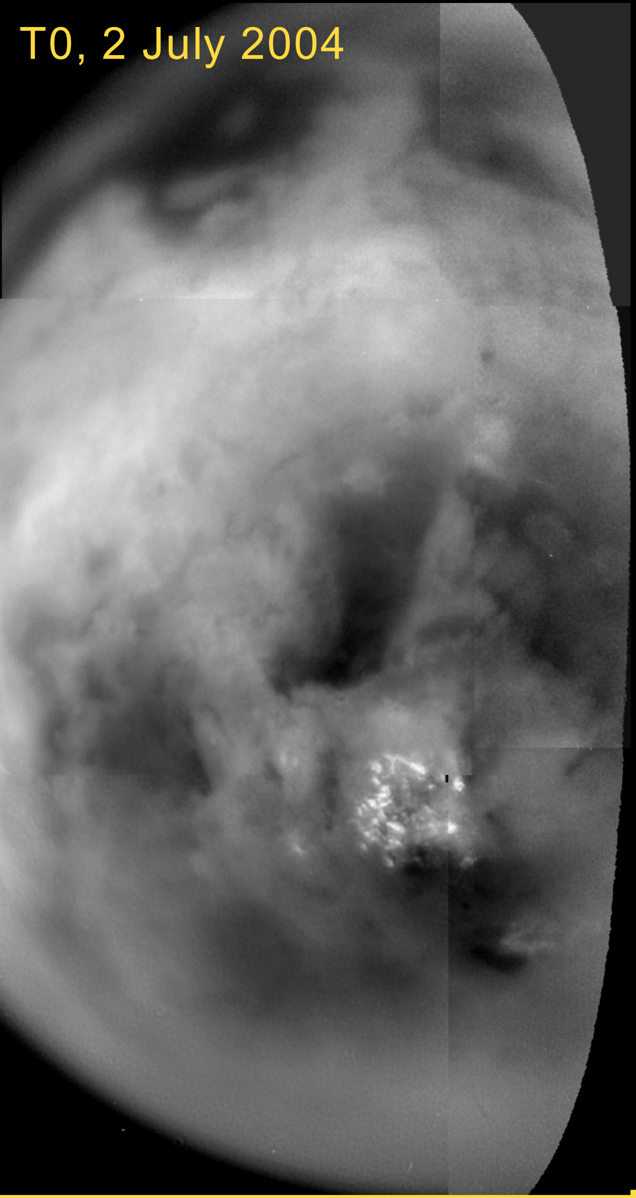
T126, 22 April 2017

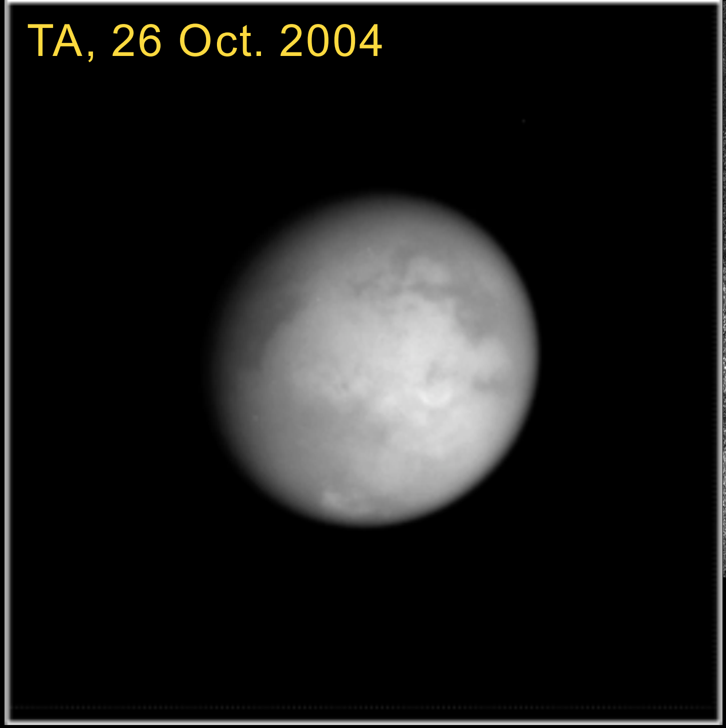
Early flybys

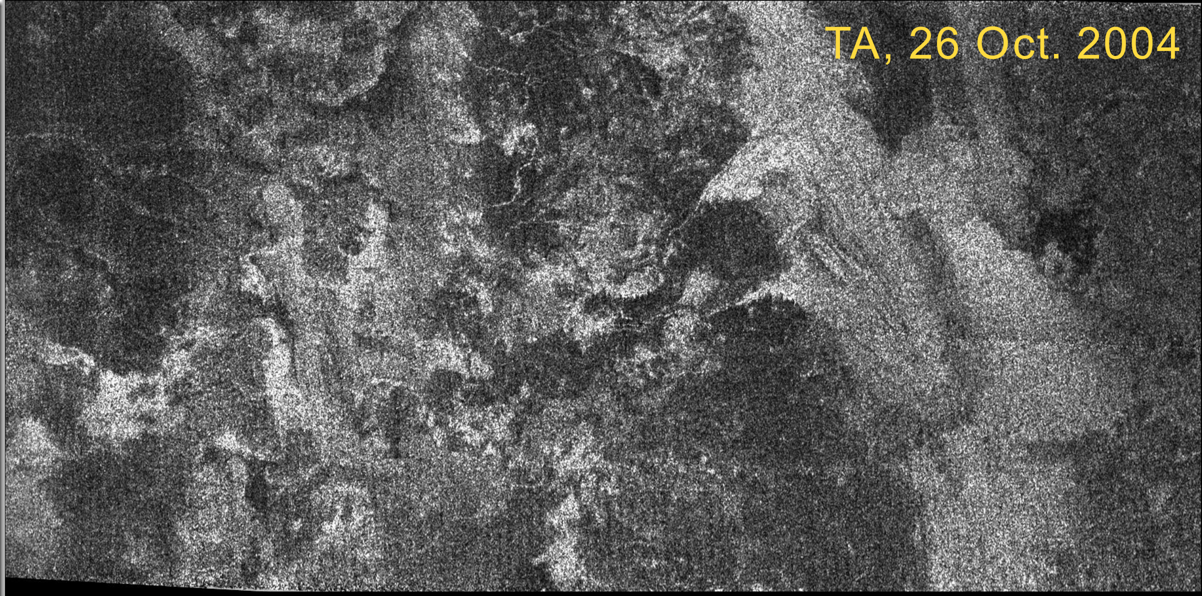
T0, 2 July 2004

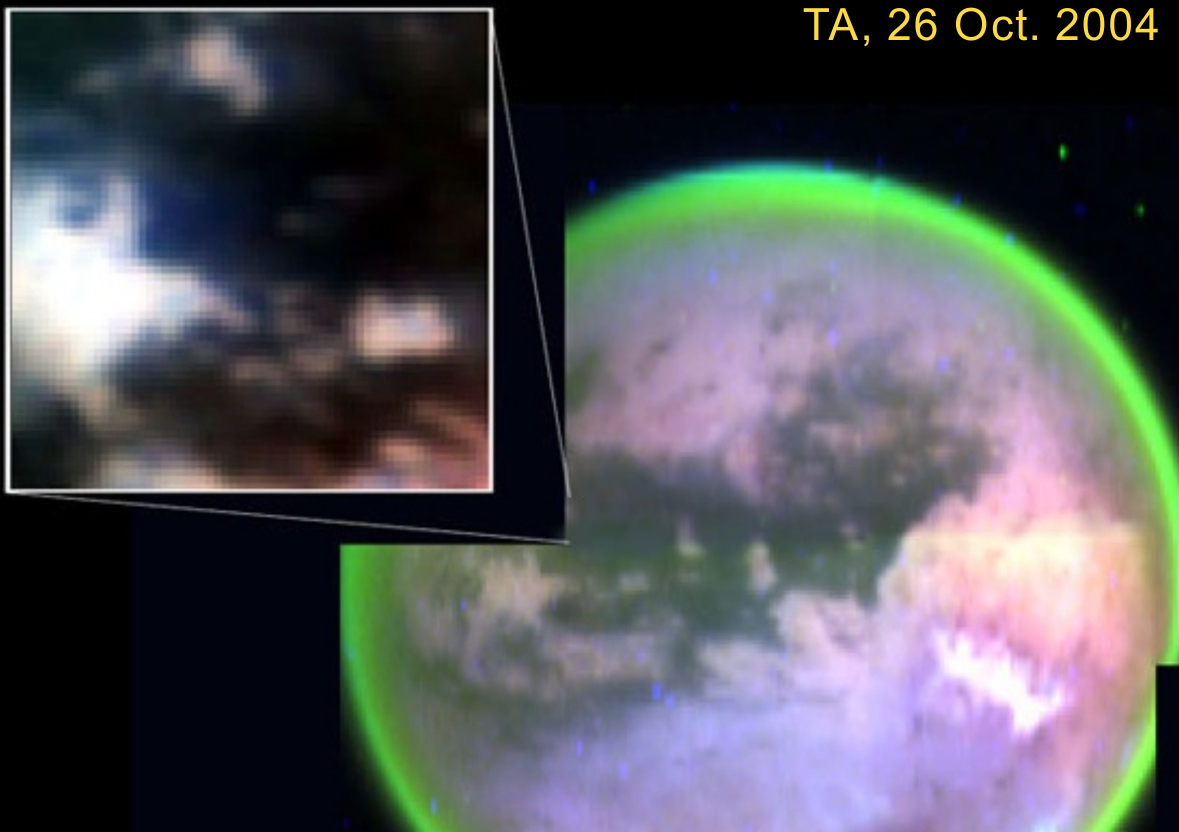


Early flybys

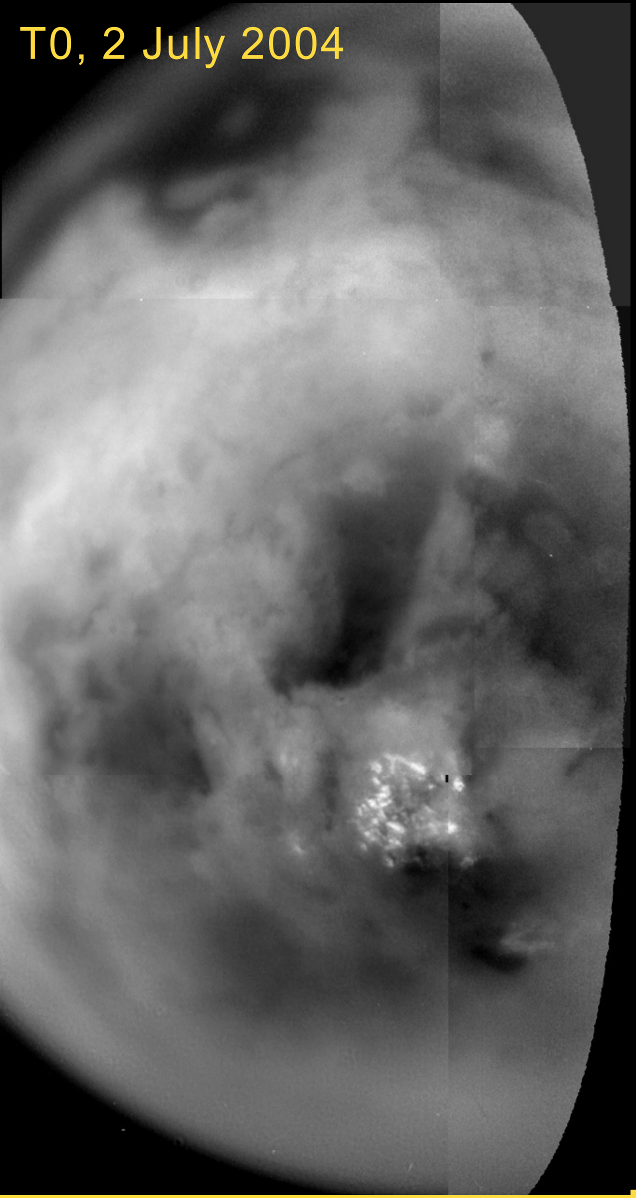


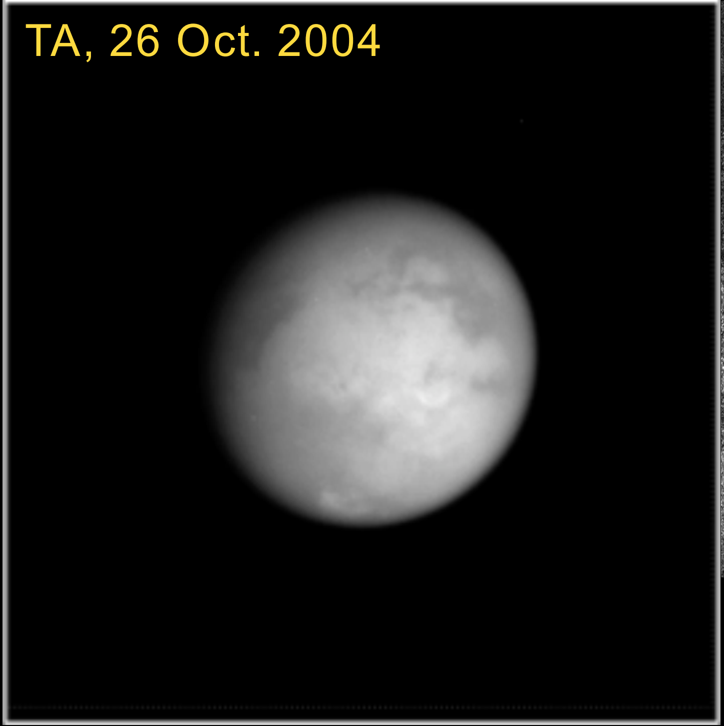


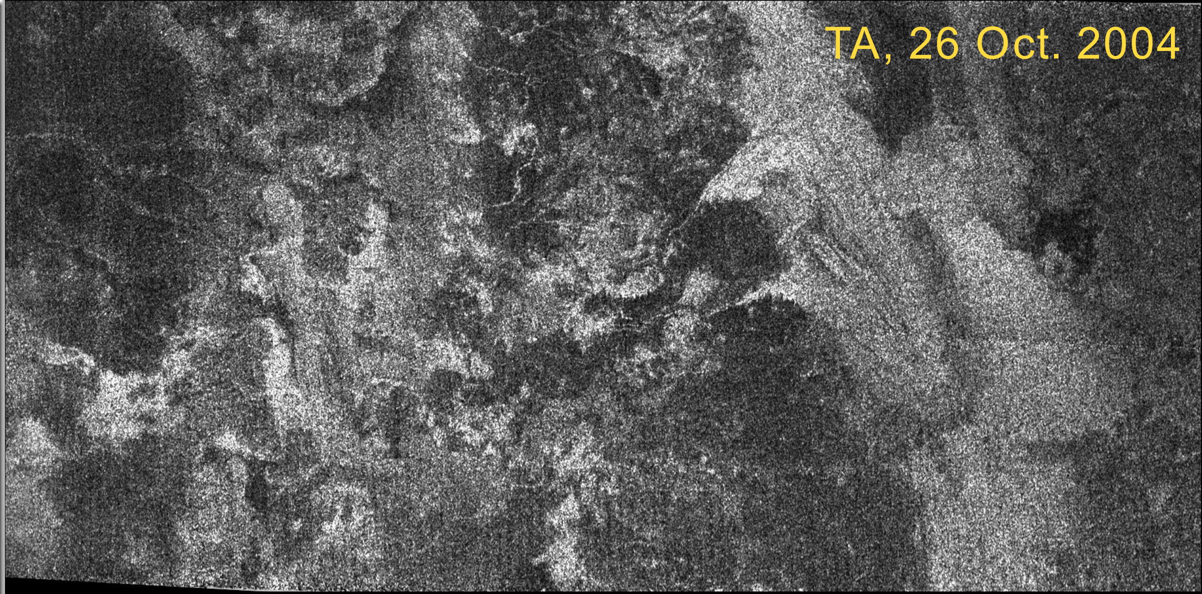


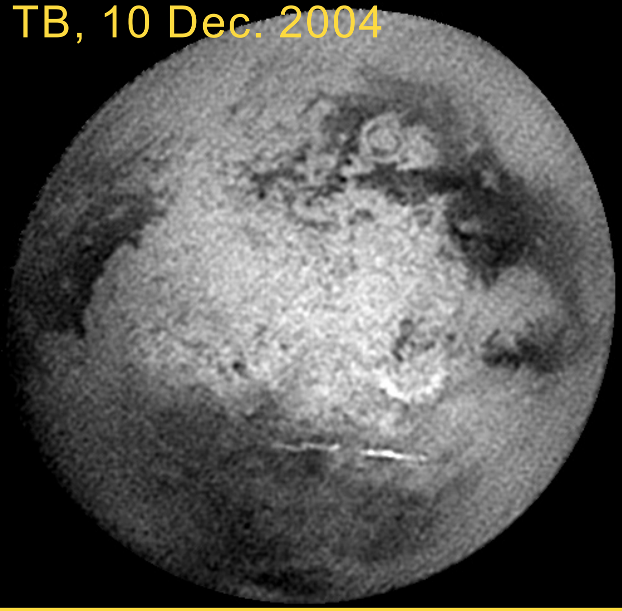


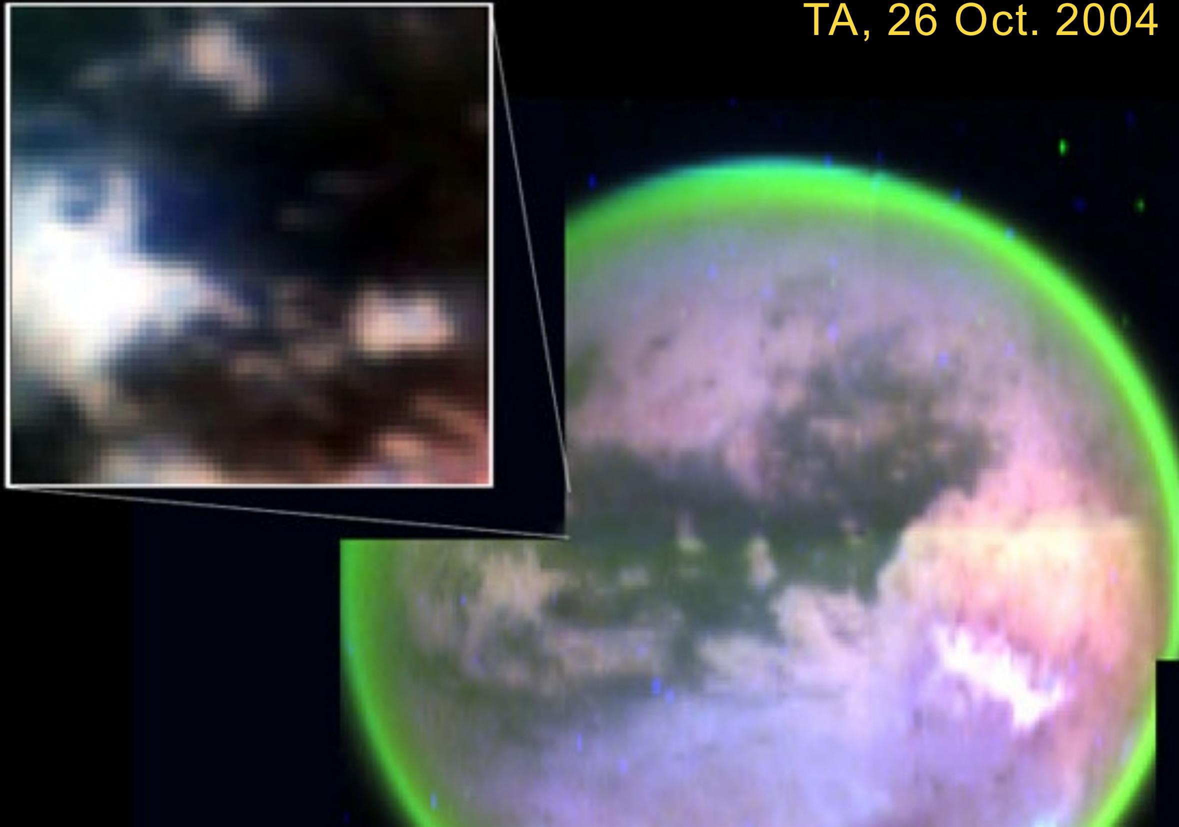
Early flybys



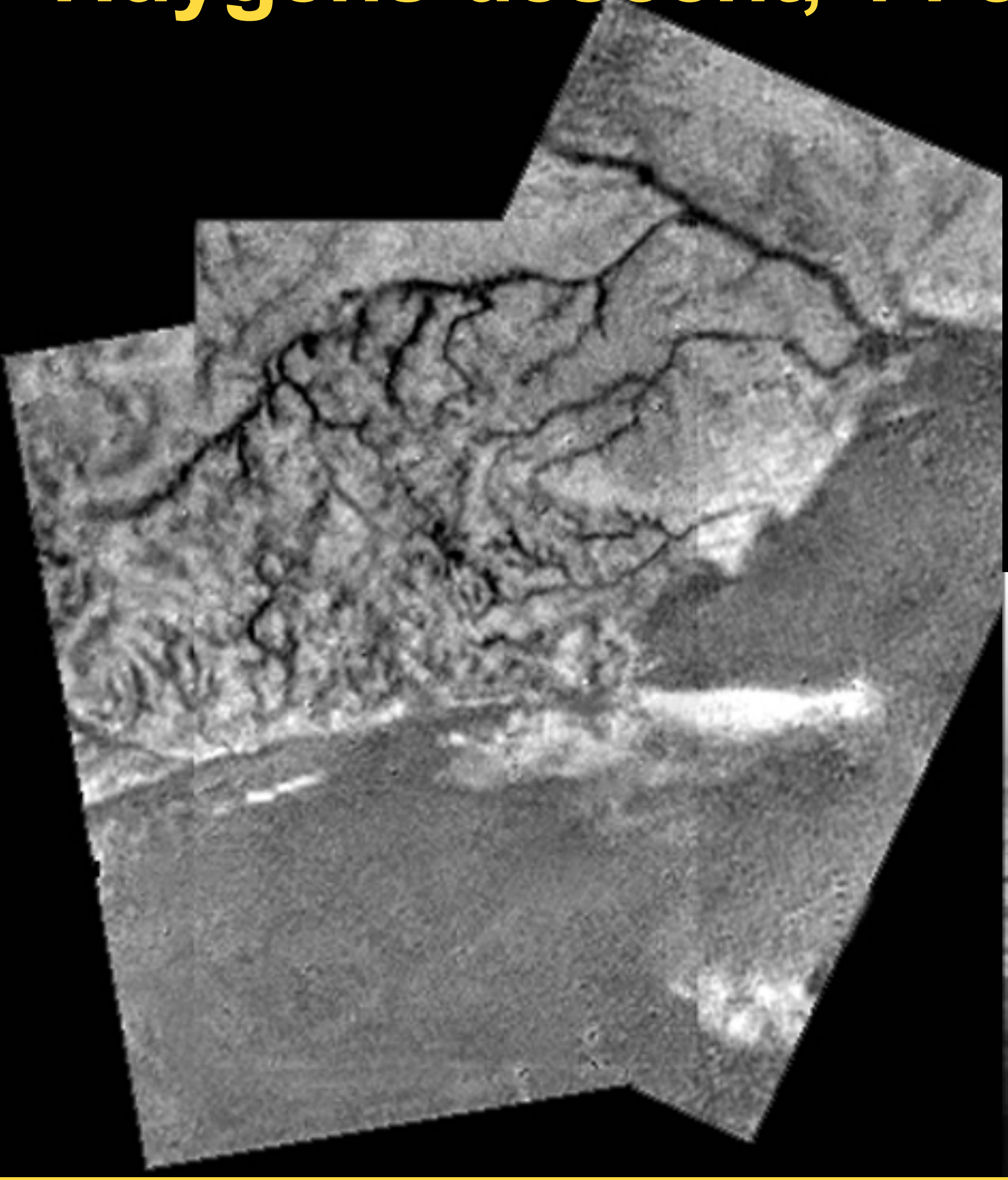


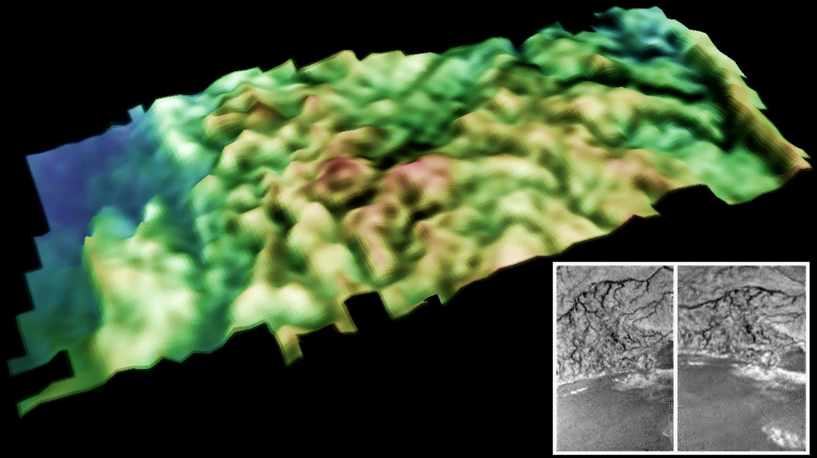


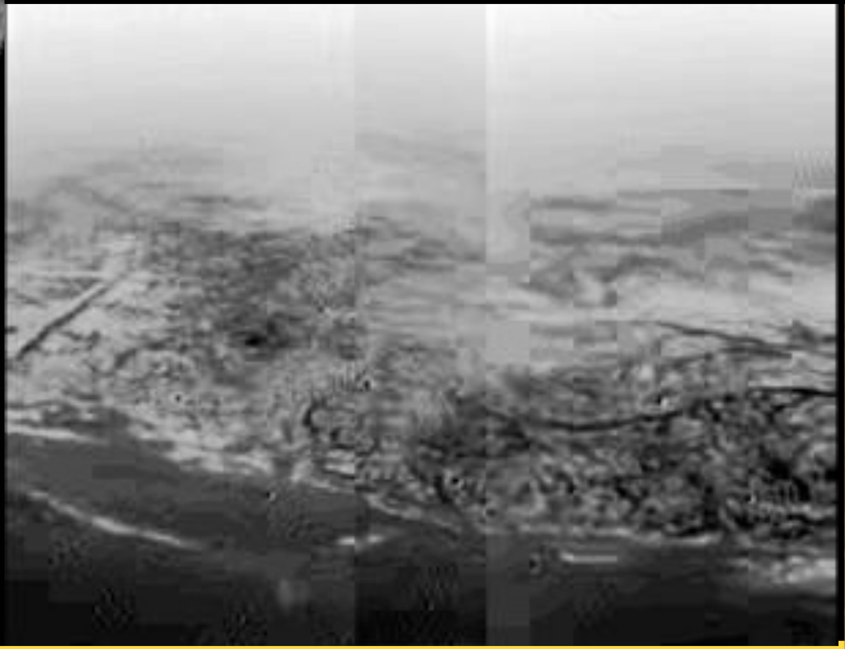


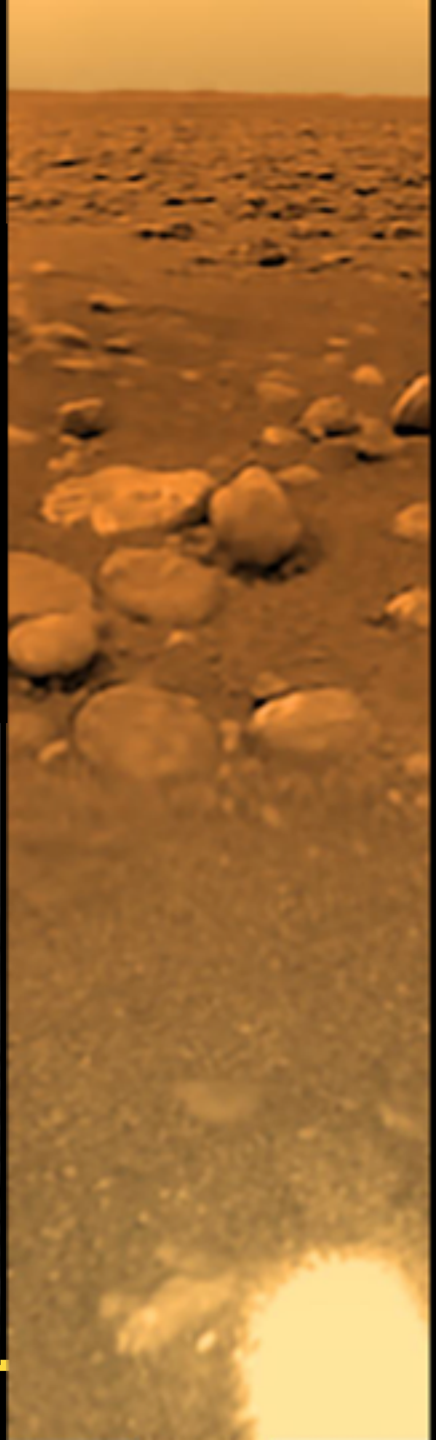


Huygens descent, 14 January 2005

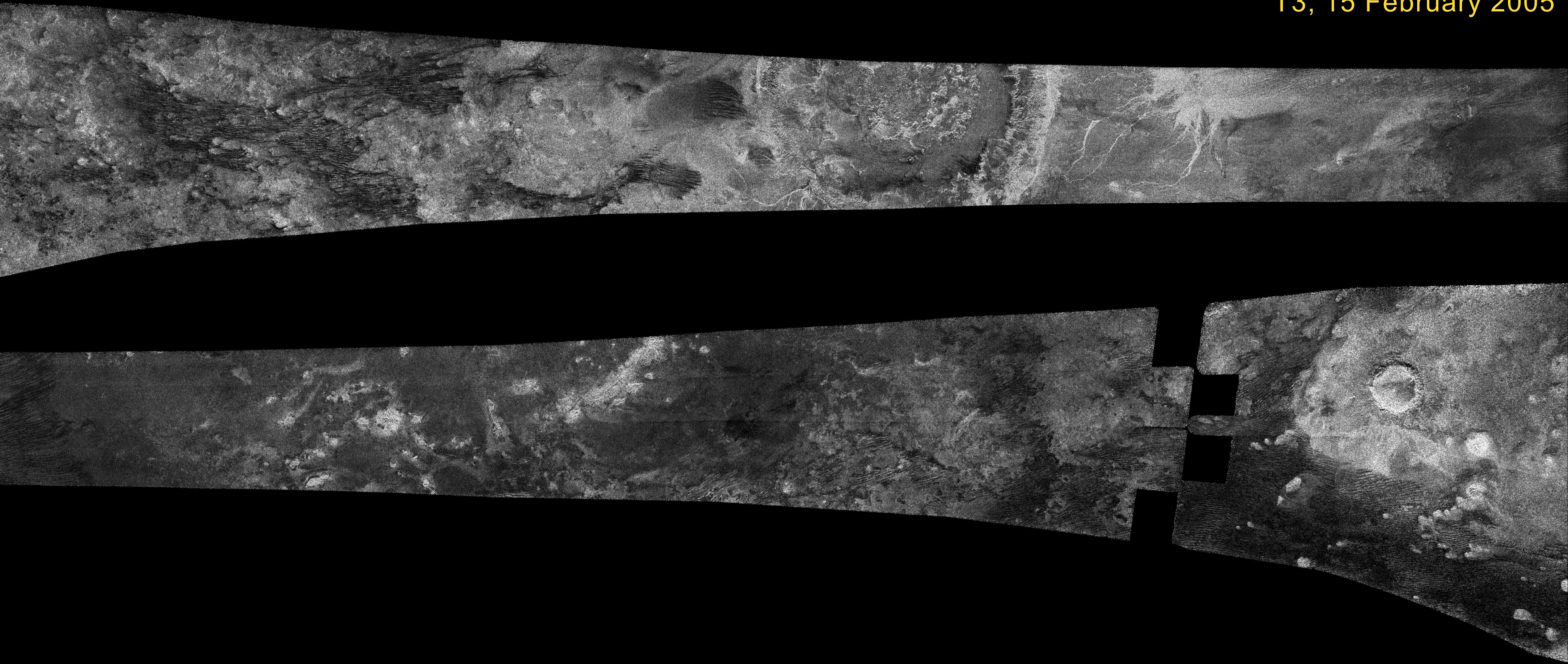




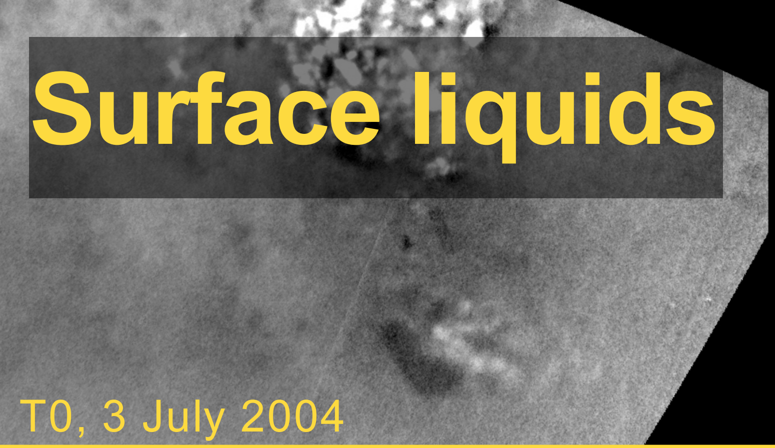




T3, 15 February 2005

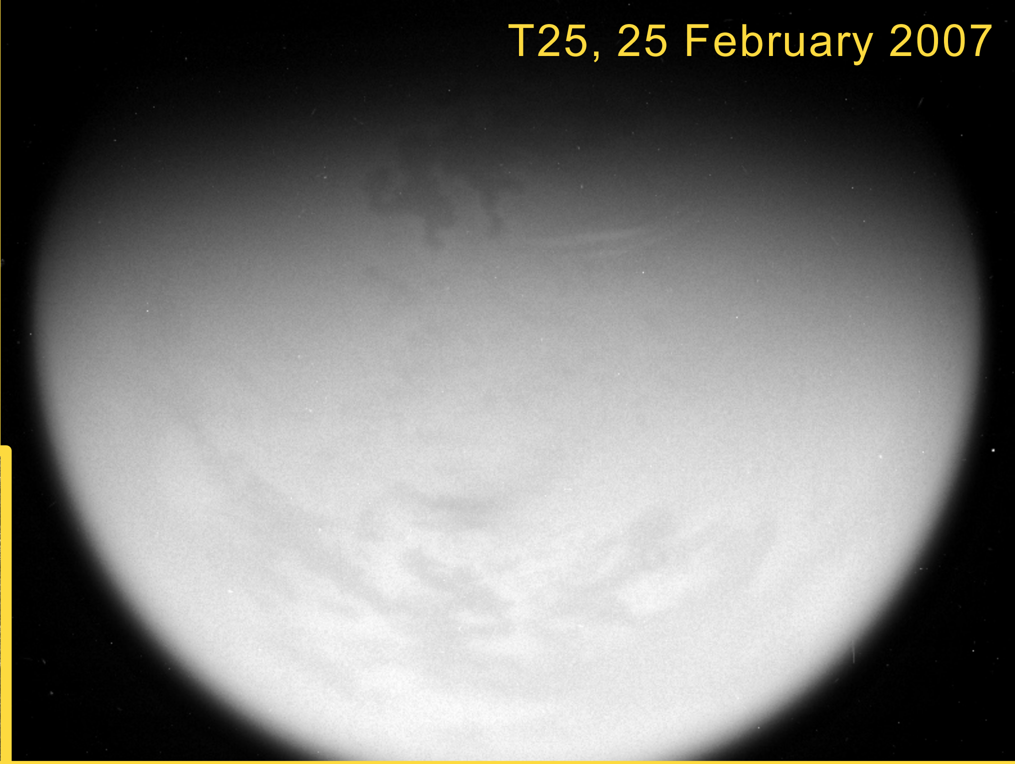


Surface liquids

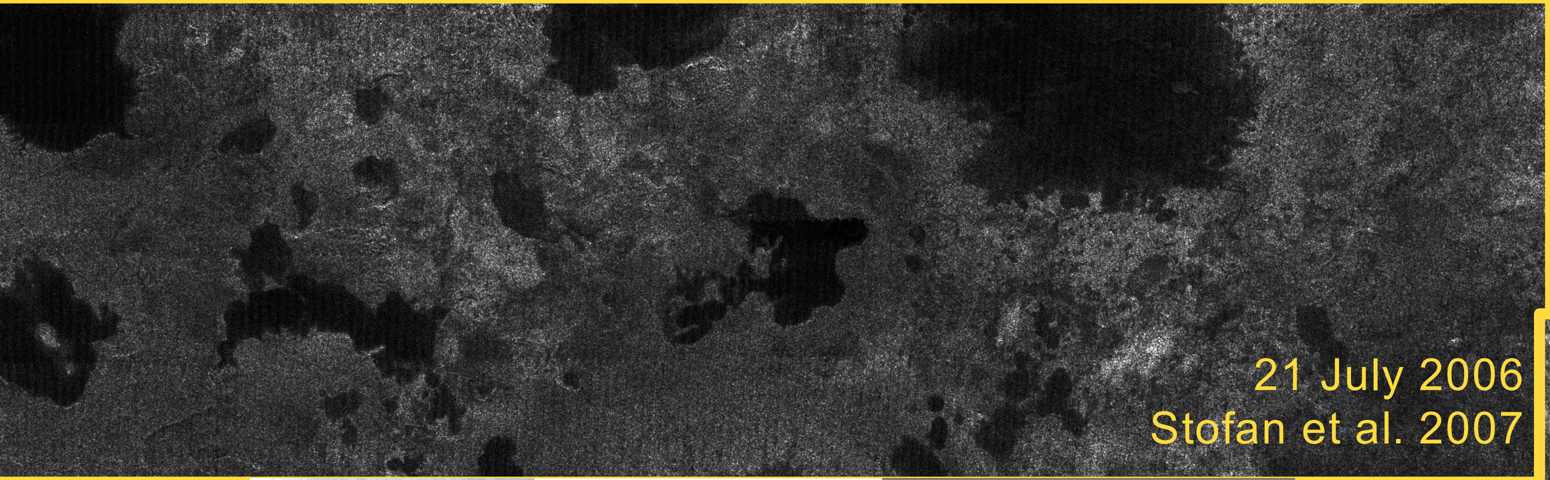


T0, 3 July 2004

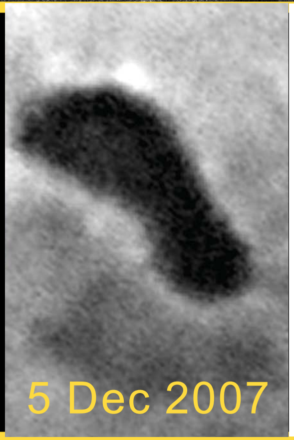
6 June 2005



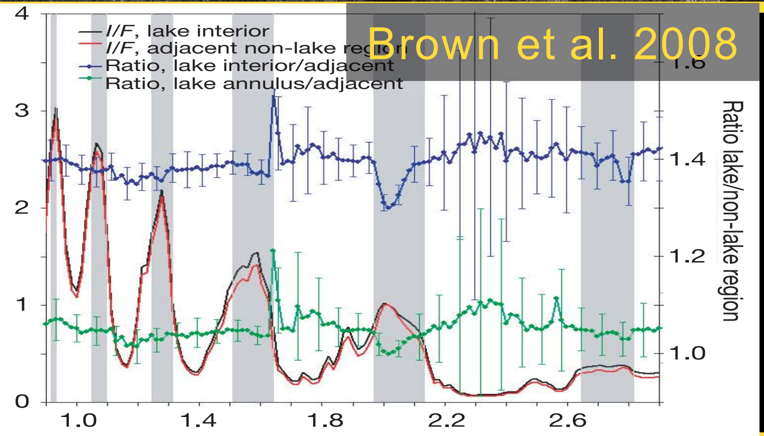
T25, 25 February 2007



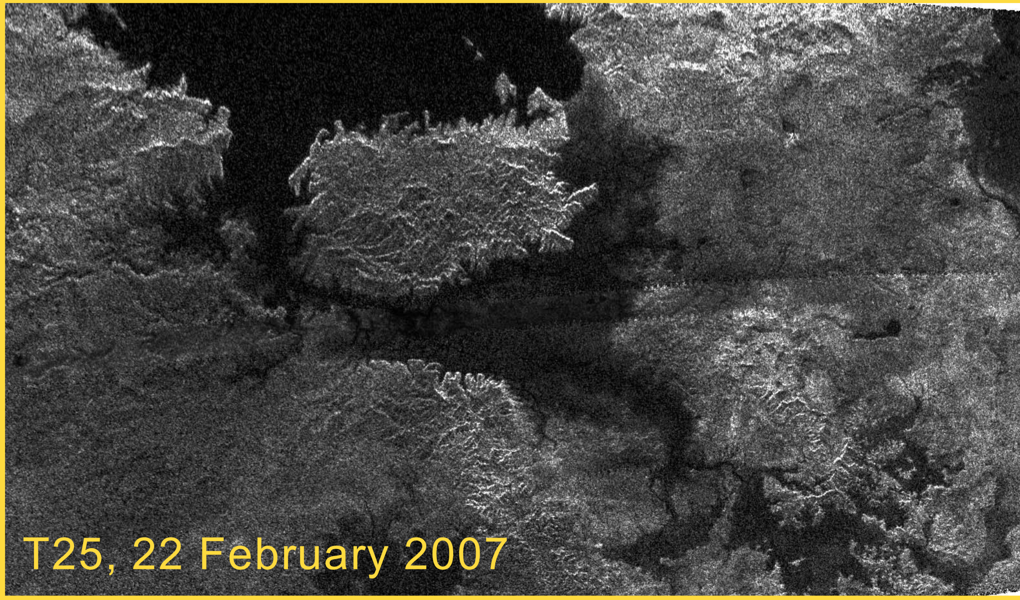
21 July 2006
Stofan et al. 2007



5 Dec 2007

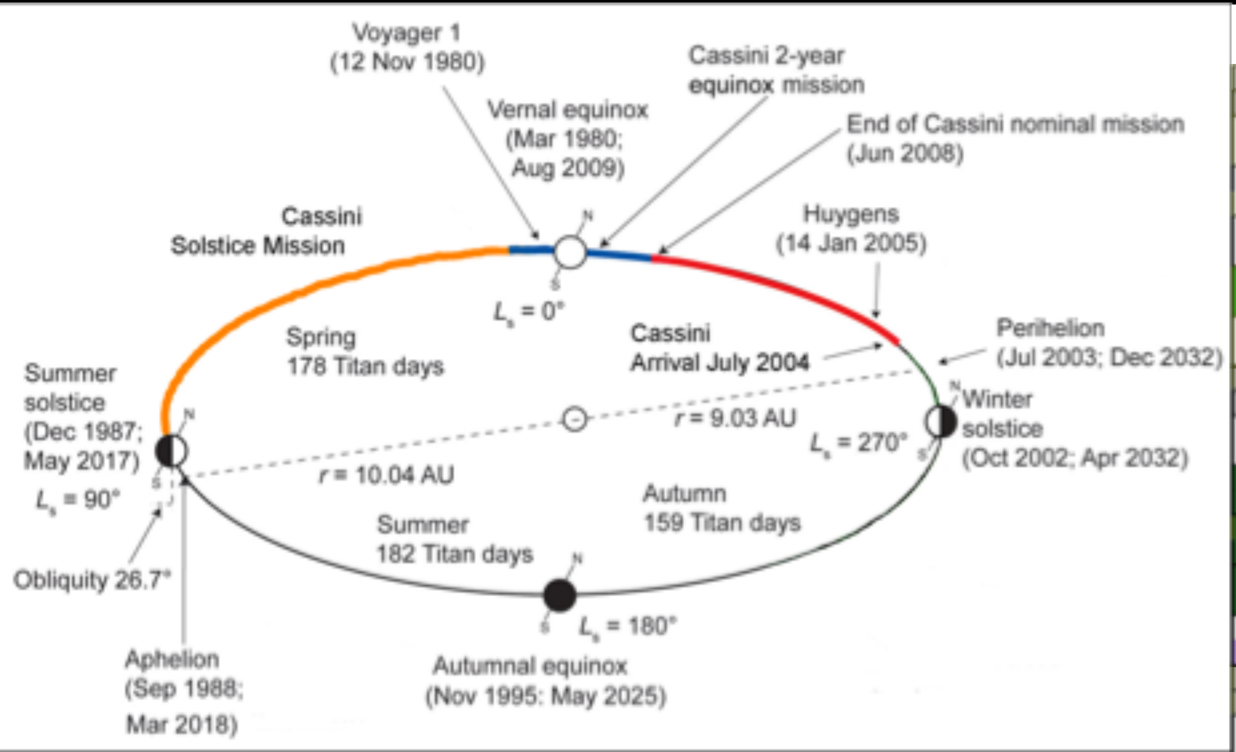


Brown et al. 2008



T25, 22 February 2007

Cassini Titan observations document seasonal changes over almost half a year (Saturn's axial tilt 26.7°)



A year on Saturn. 1 Saturnian calendar day = 29.47 Earth days. *Note: rotation-based Saturnia day is 10 Earth hours*

Prime Mission Titan Activity | Extended Mission Titan Activity | Voyager Birthdays | XXM

January

M	T	W	T	F	S	S
				1	2	3
4	5	6	7	8	9	10
11	12 SOI	13	14	15	16	17 TA
18 TB	19 TC	20 T3	21	22 T4&T5	23	24
25	26	27	28 T6&T7	29	30 T8	31

February

M	T	W	T	F	S	S
1 T9	2 T10	3 T11	4 T12	5	6 T13	7 T14
8 T15	9 T16	10	11 T17&T18	12 T19	13 T20	14 T21
15 T22&T23	16 T24	17 T25&T26	18 T27&T28	19	20 T29&T30	21 T31&T32
22 T33	23 T34	24 T35	25 T36	26	27 T37&T38	28 T39&T40

March

M	T	W	T	F	S	S
1	2 T41	3 T42	4	5	6 T43&T44	7 EOM
8 T45	9	10	11 T46	12 T47	13 T48&T49	14
15 T50	16 T51	17 T52	18 T53	19 T54&T55	20 T56&T57	21 Equinox T58&T59
22 T60&T61	23	24 T62	25	26 T63	27 T64&T65	28 T66
29 V1	30 T67	31 T68&T69				

April

M	T	W	T	F	S	S
			1 T70 & 71	2	3	4 T72
5	6 T73	7	8 V2	9 T74	10	11 T75 & 76
12 T77	13	14	15 T78	16	17	18 T79
19 T80	20 T81&T82	21	22	23 T83	24 T84	25
26 T85	27	28 T86	29 T87	30 T88		

May

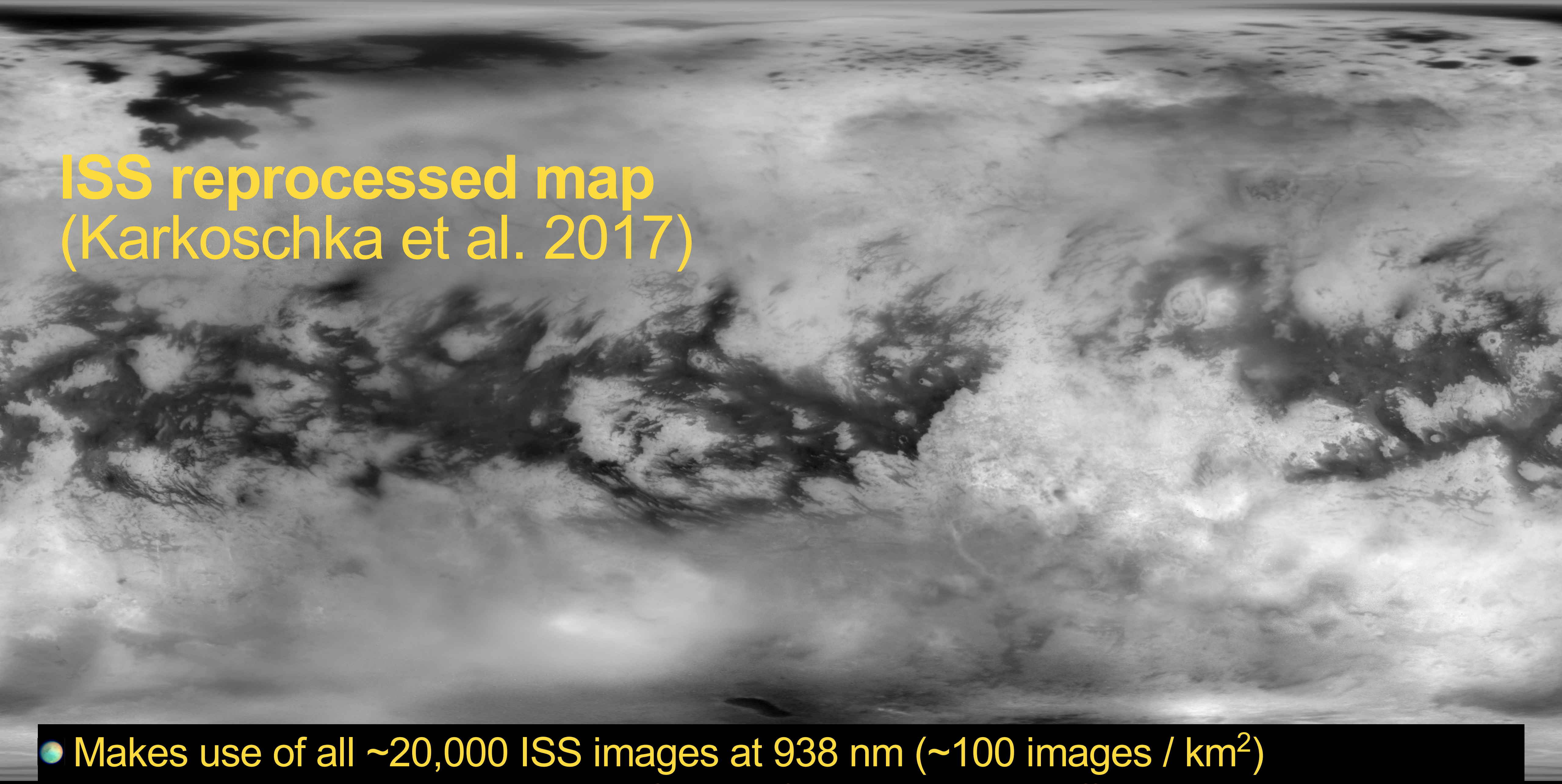
M	T	W	T	F	S	S
					1	2
3 T89 & 90	4	5 T91	6	7 T92&T93	8	9 T94
10 T95	11 T96	12 T97	13	14 T98	15 T99	16 T100
17 T101	18 T102	19 T103	20 T104	21 T105 & 106	22	23 T107
24 T108	25 T109	26 T110	27	28 T111	29	30 T112
31						

June

M	T	W	T	F	S	S
	1	2 T113	3	4 T114	5	6 T115&116
7 T117 &118	8	9 T119	10 T120	11 T121	12 T122	13 T123
14	15 T124	16 T125, nT253	17 nT255	18 nT259,261	19 nT264	20 T126
21 Solstice nT273,275	22 nT278	23 nT283,285	24 nT288	25 EOM nT292	26	27
28	29	30				

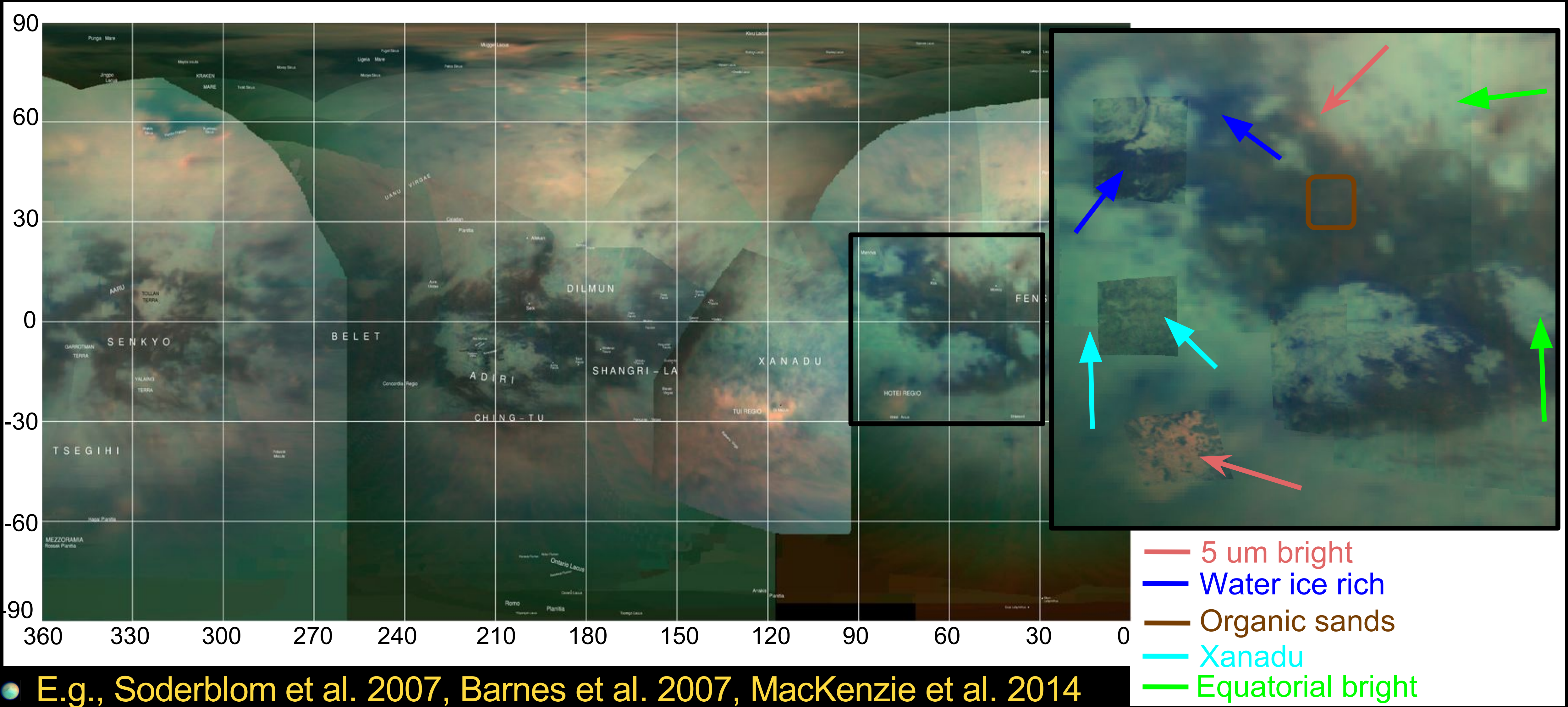
- Prime mission: 2004-2008
- Equinox mission: 2008-2010
- Solstice mission: 2010-2017

ISS reprocessed map
(Karkoschka et al. 2017)



- Makes use of all ~20,000 ISS images at 938 nm (~100 images / km^2)
- Improves signal-to-noise ratio by factor of 4-5 along with effective resolution
- Albedos calibrated to *Huygens* DISR range from 0.25 (dunes) to 0.9 (Hotei Arcus)

VIMS compositional mapping

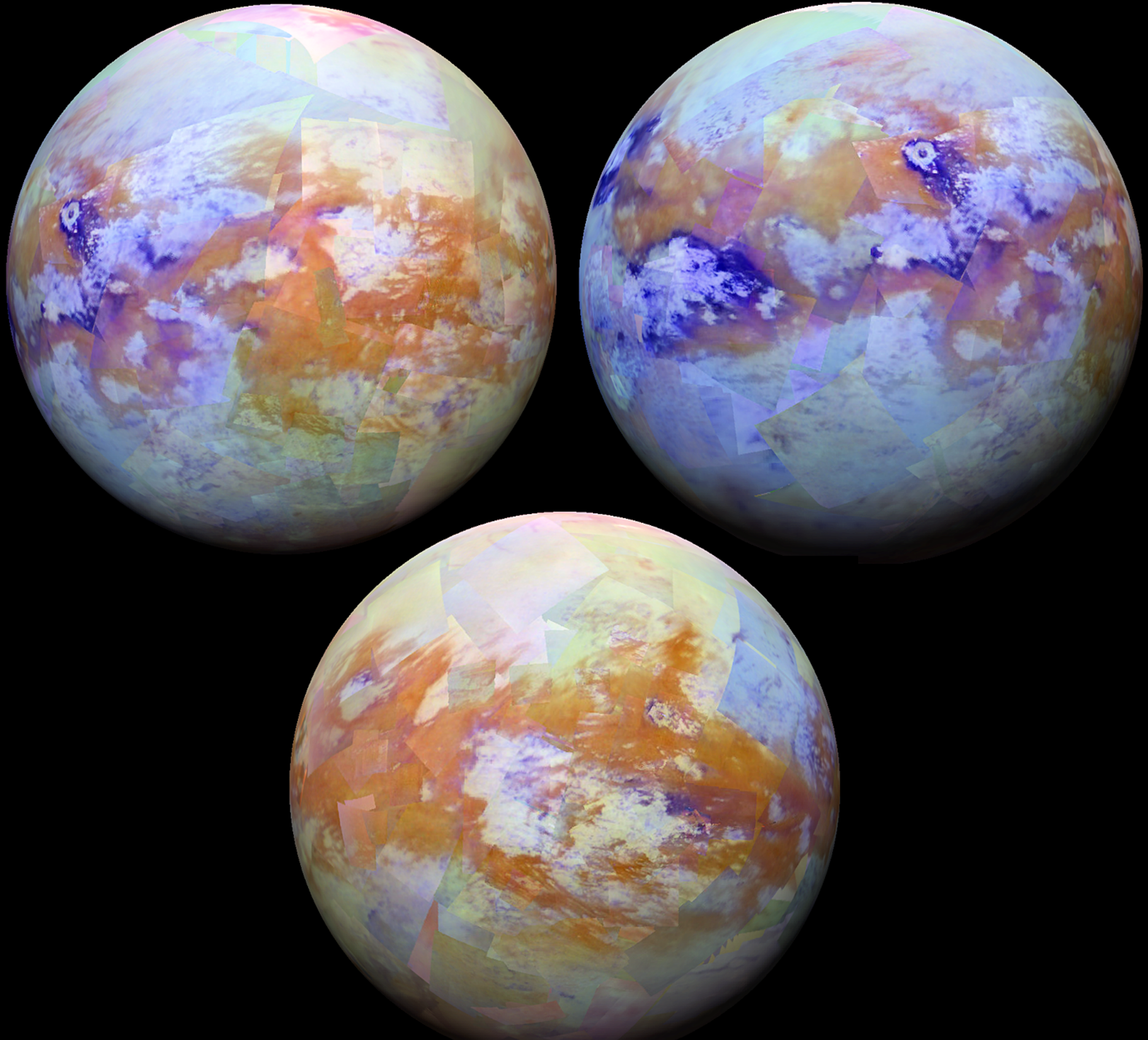


- E.g., Soderblom et al. 2007, Barnes et al. 2007, MacKenzie et al. 2014

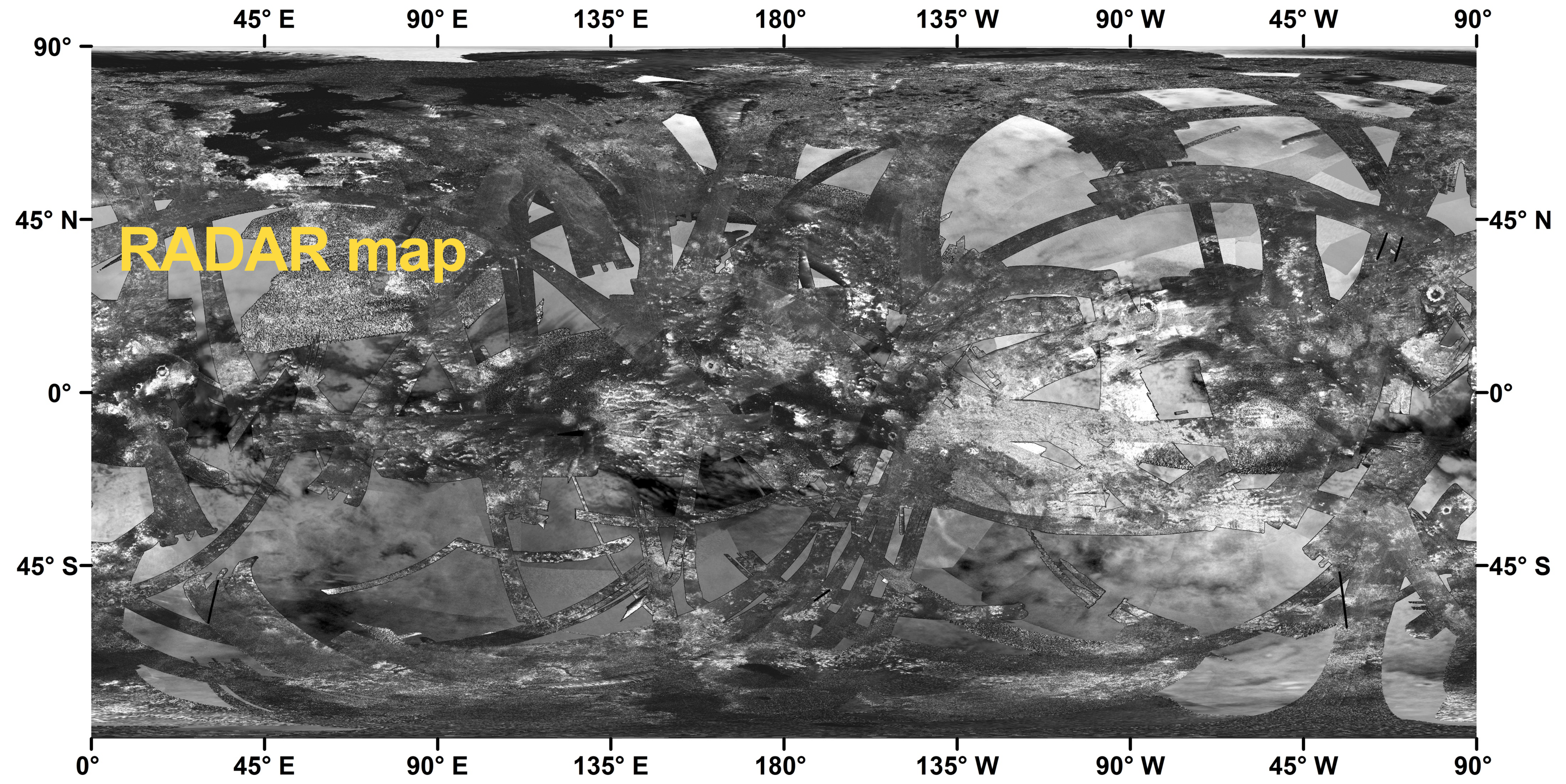
VIMS global-scale hyperspectral map

Le Mouélic *et al.* Cassini Science Symposium and manuscript in review

- Representative colors highlighting dunes

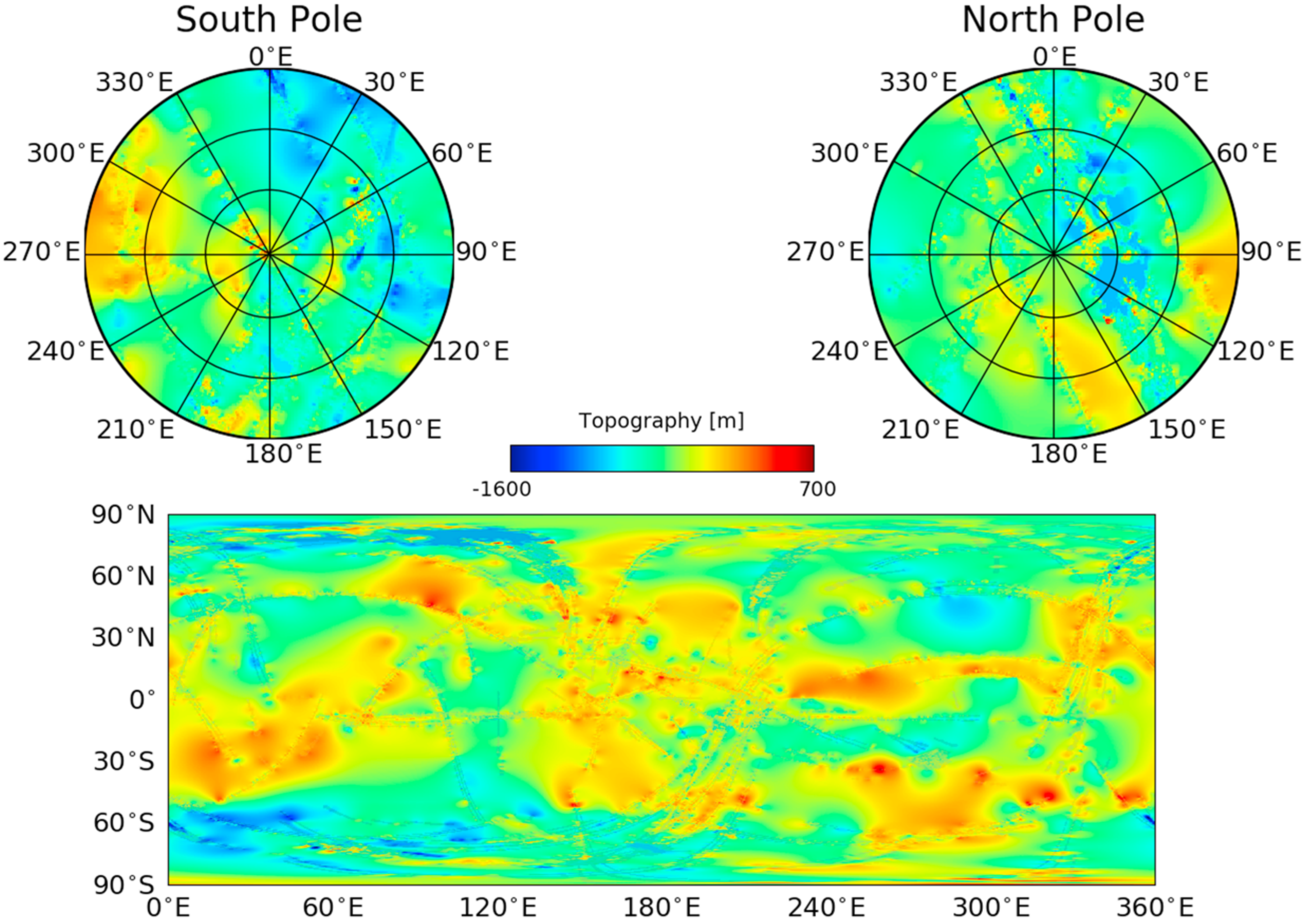


VIMS color composite (LPGNantes)



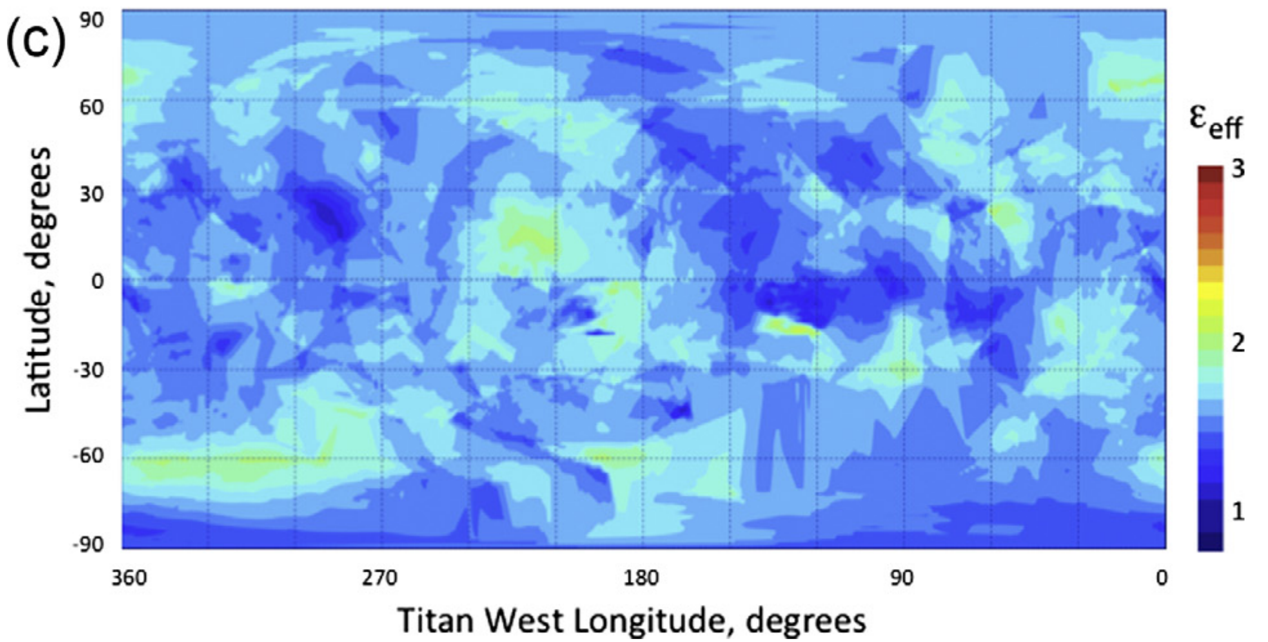
45° E
90° E
135° E
180°
135° W
90° W
45° W
90°
90°
45° N
0°
45° S
RADAR map
0°
45° E
90° E
135° E
180°
135° W
90° W
45° W
90°
45° N
0°
45° S

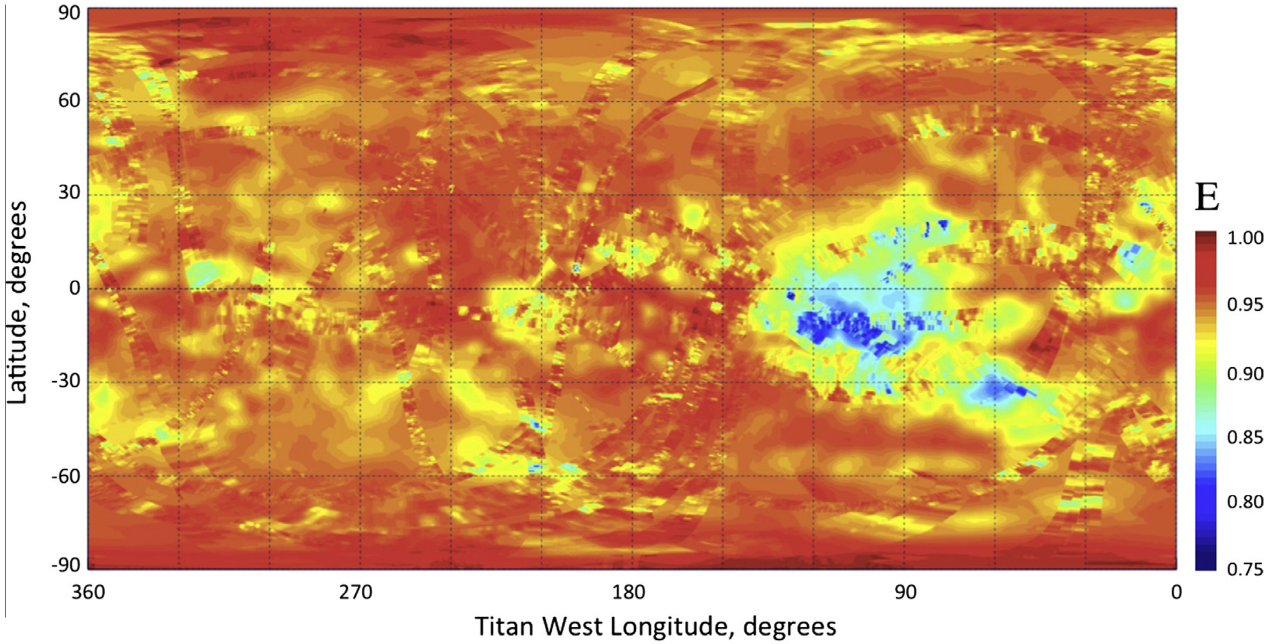
Global topography from RADAR altimetry, SARtopo, and stereo (Corlies et al. 2017)

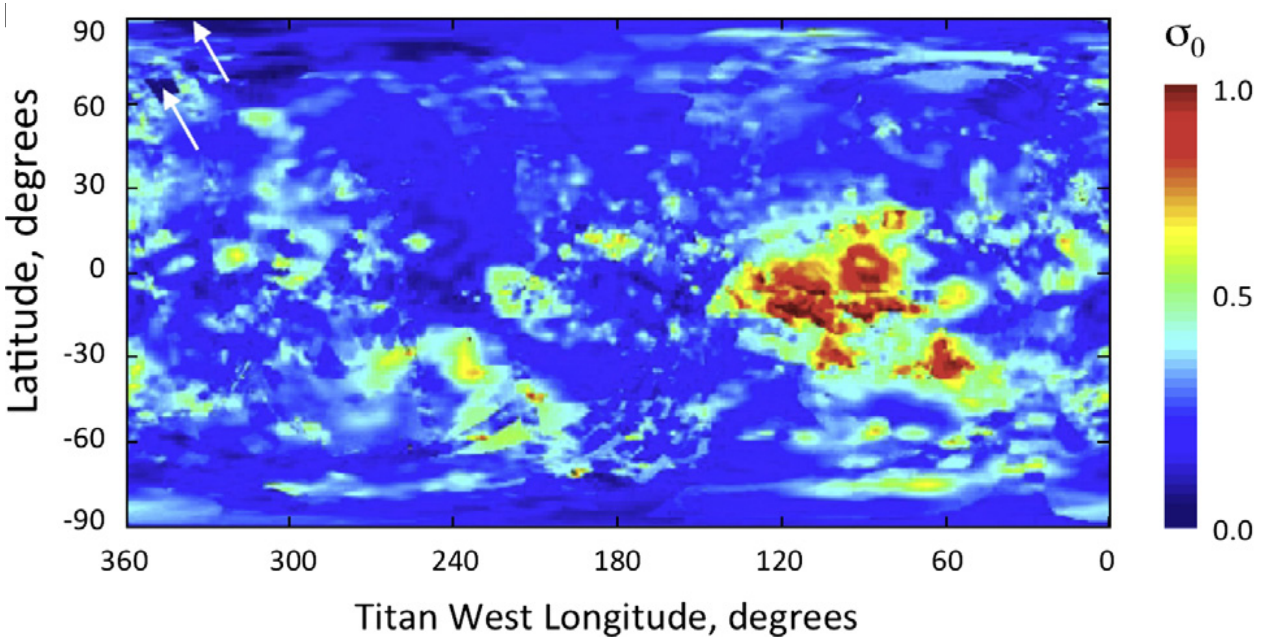


Radar surface properties

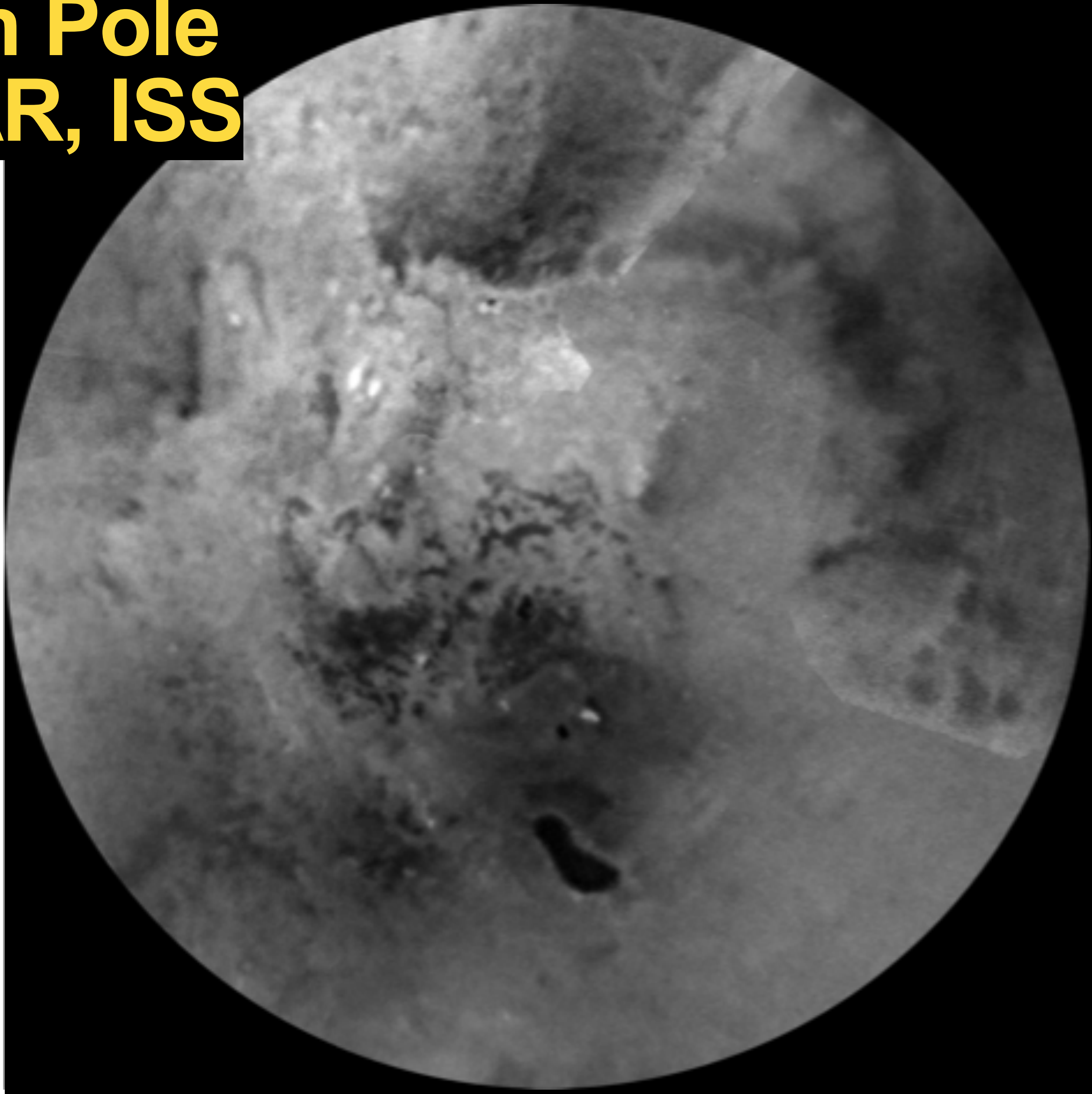
- Janssen et al. 2016
- Effective dielectric constant
- Scattering
- Emissivity





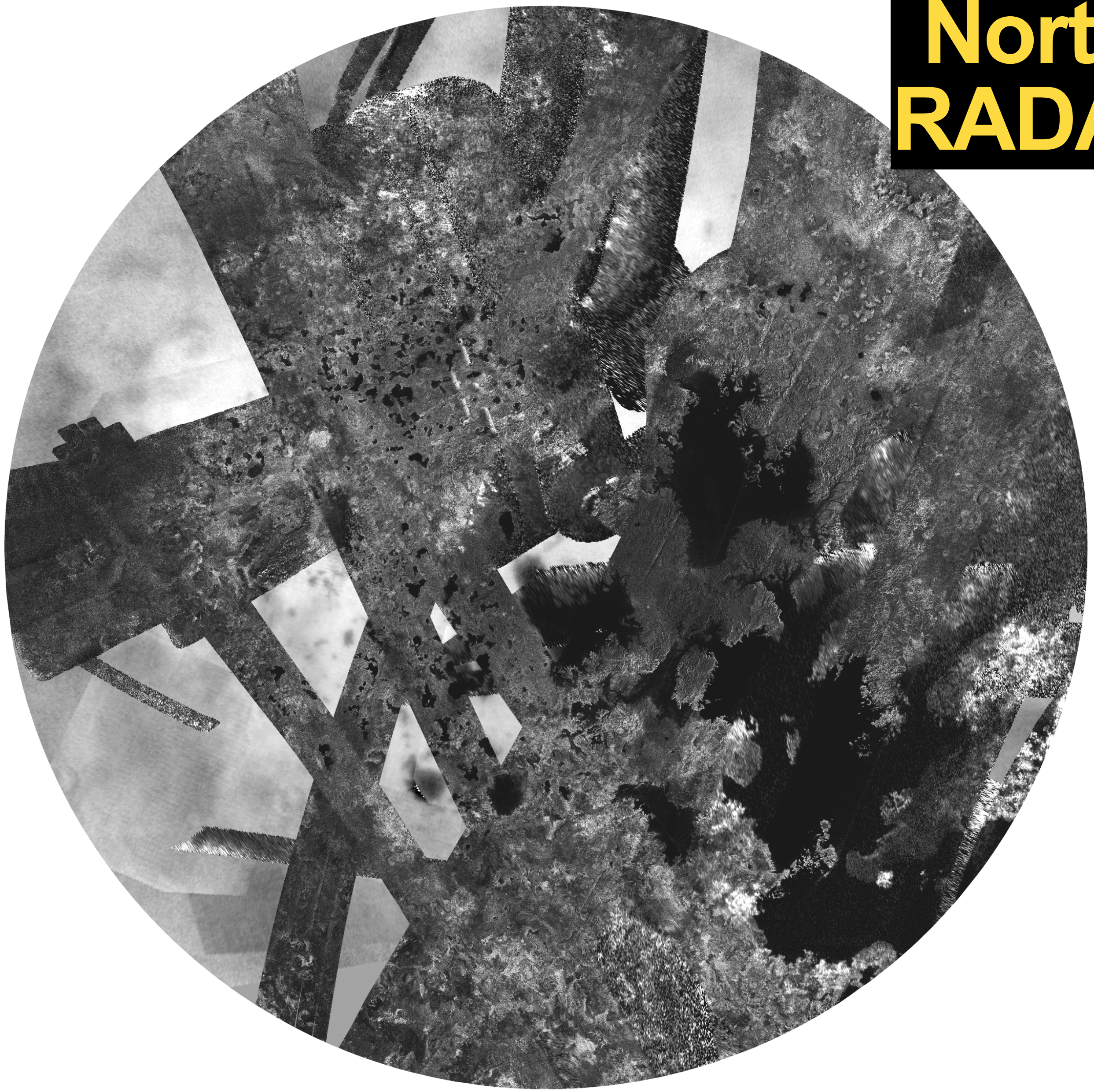


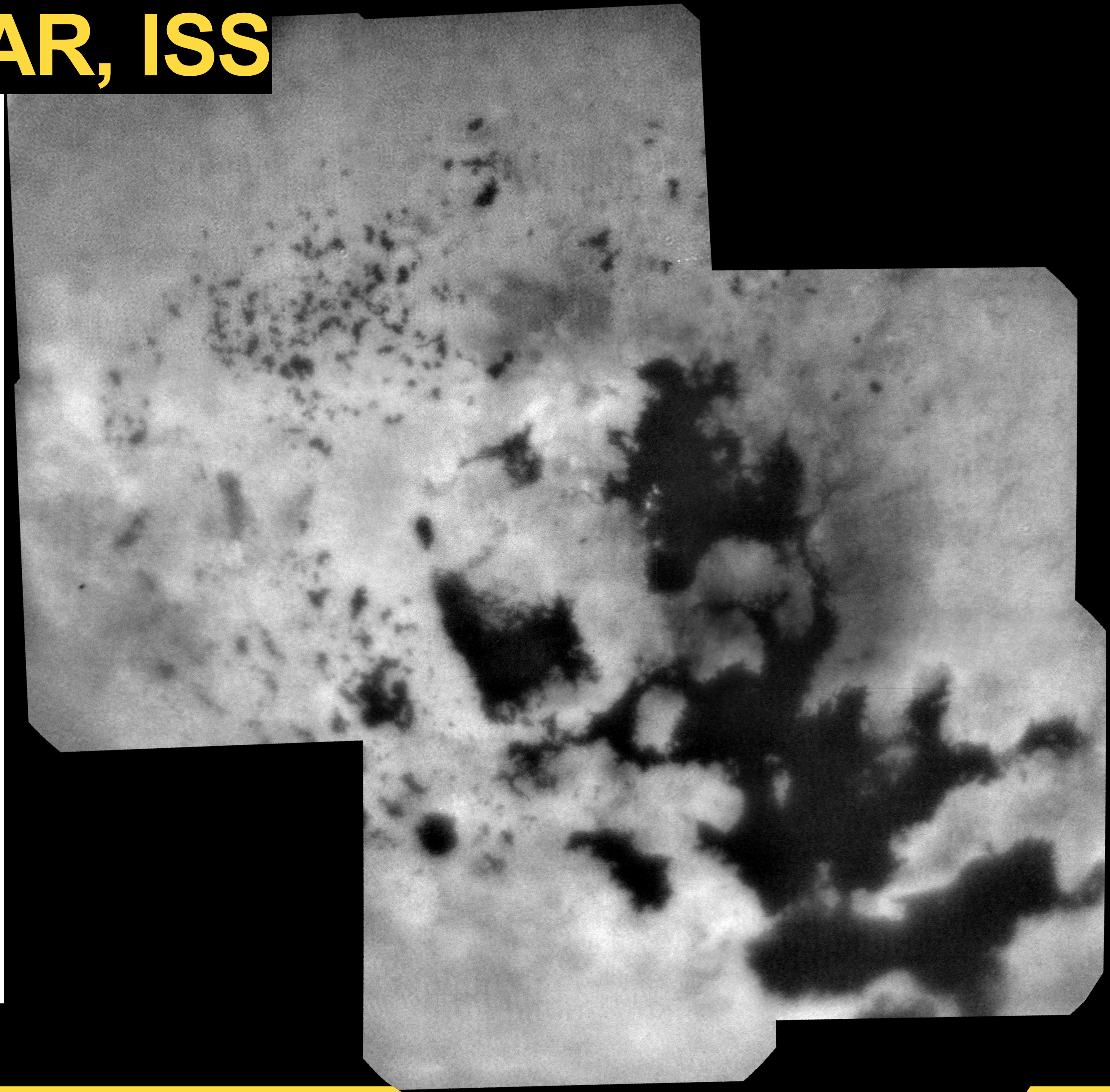
South Pole
RADAR, ISS



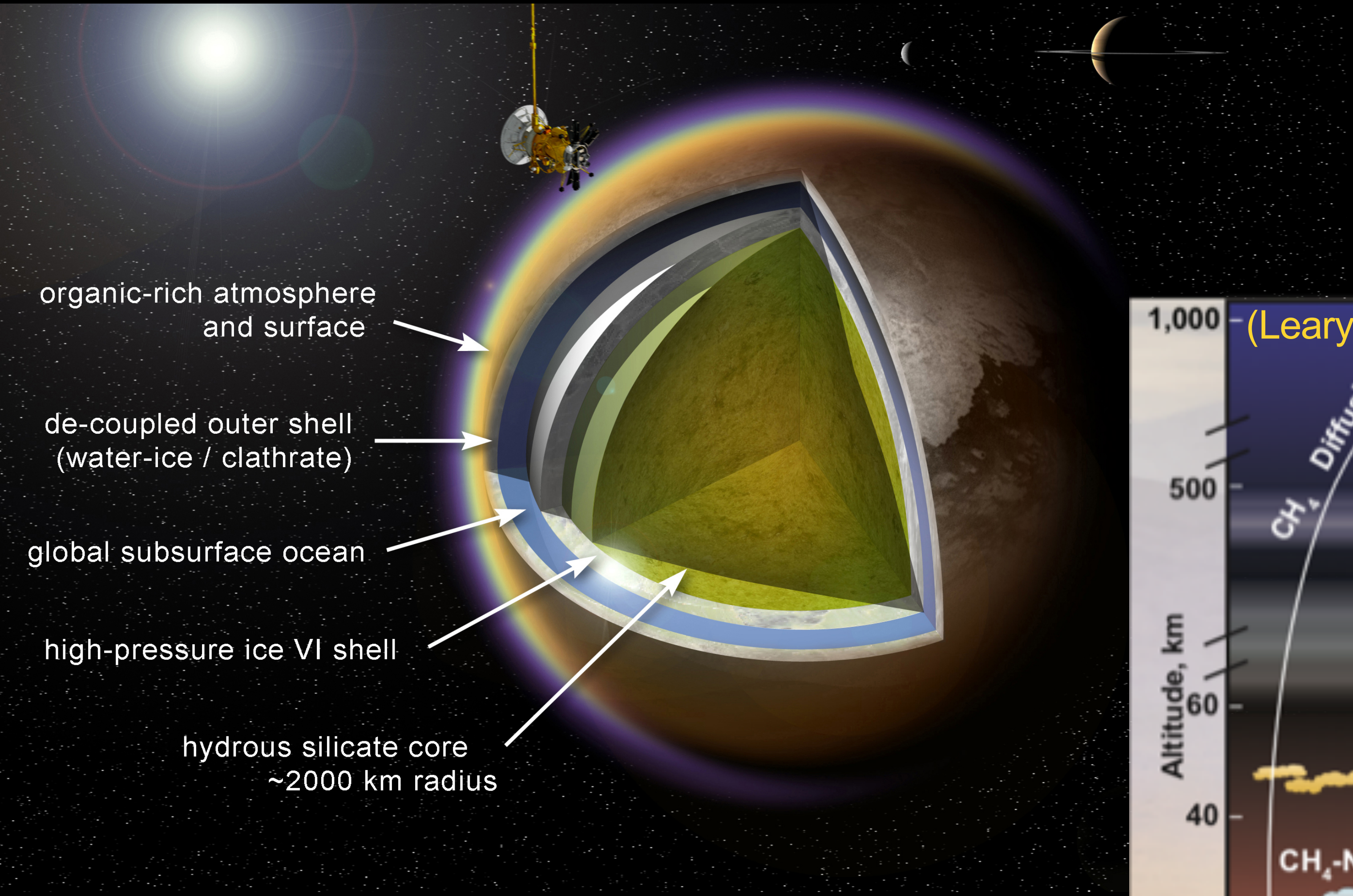
North Pole RADAR, ISS

Rev292, Sept. 2017

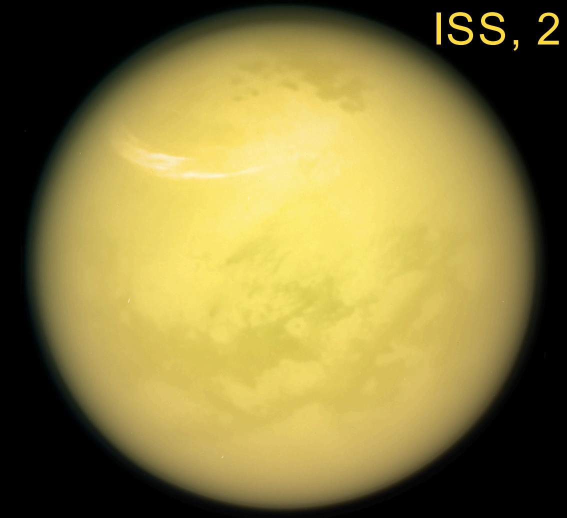


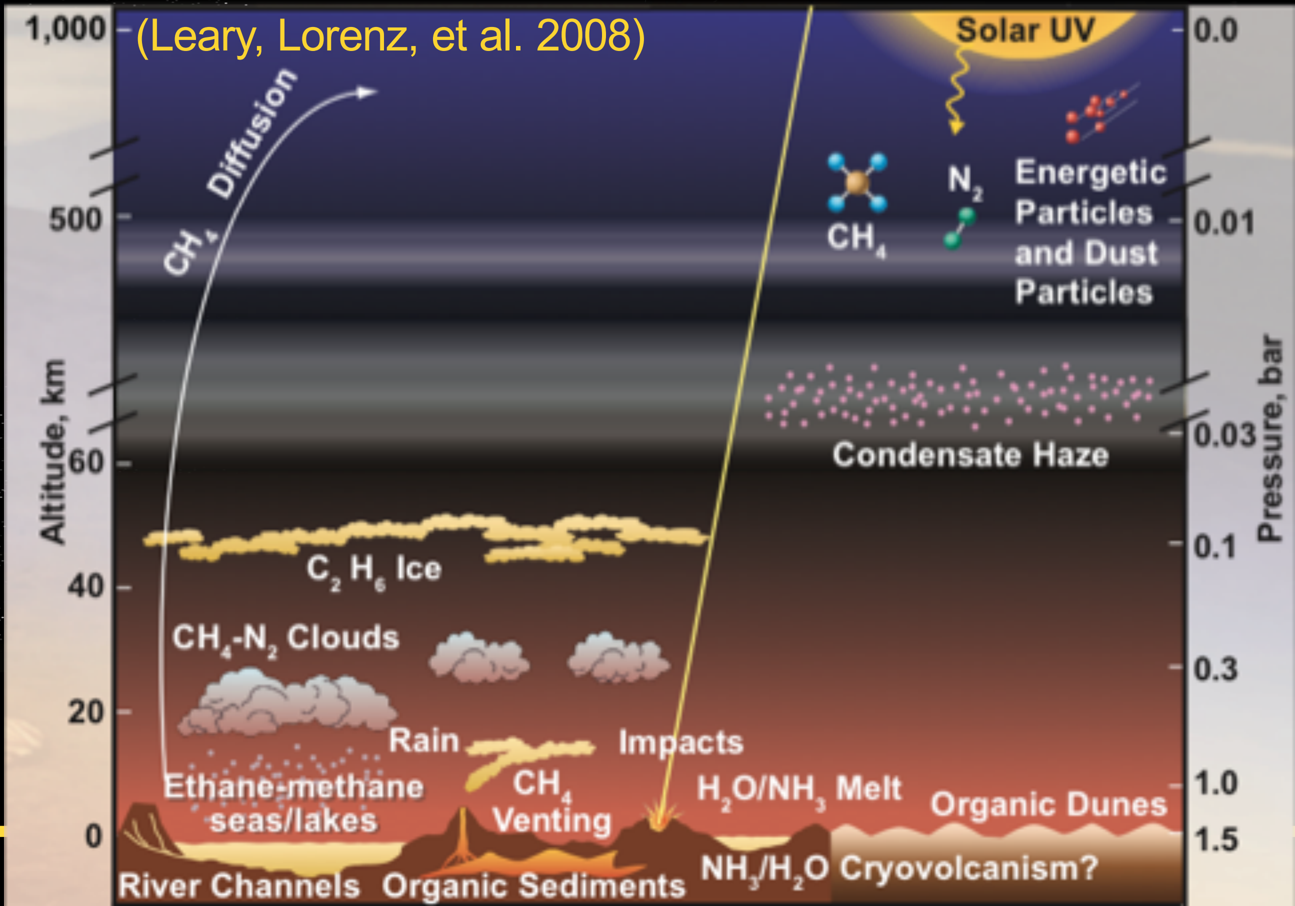


Titan as a system

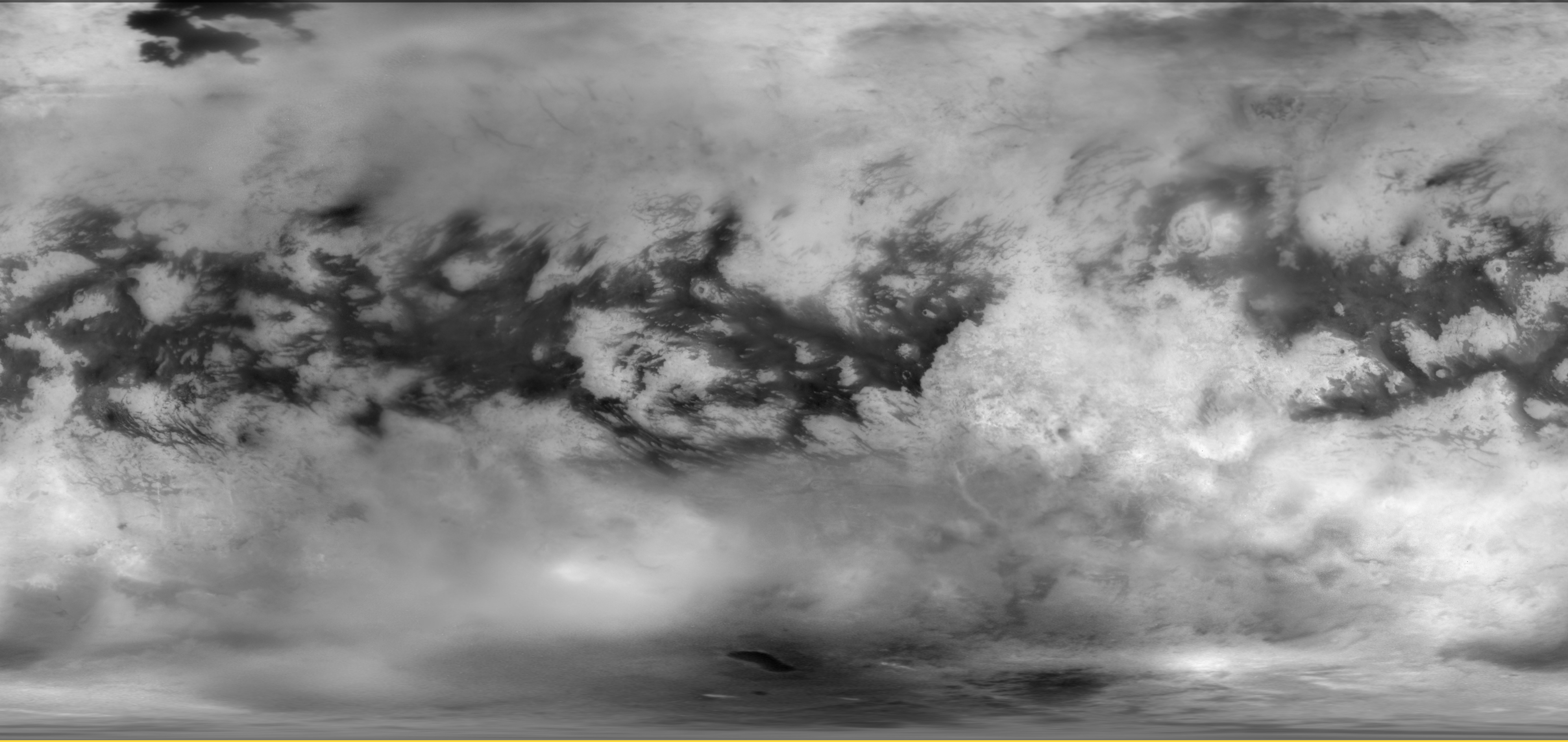


ISS, 21 March 2017

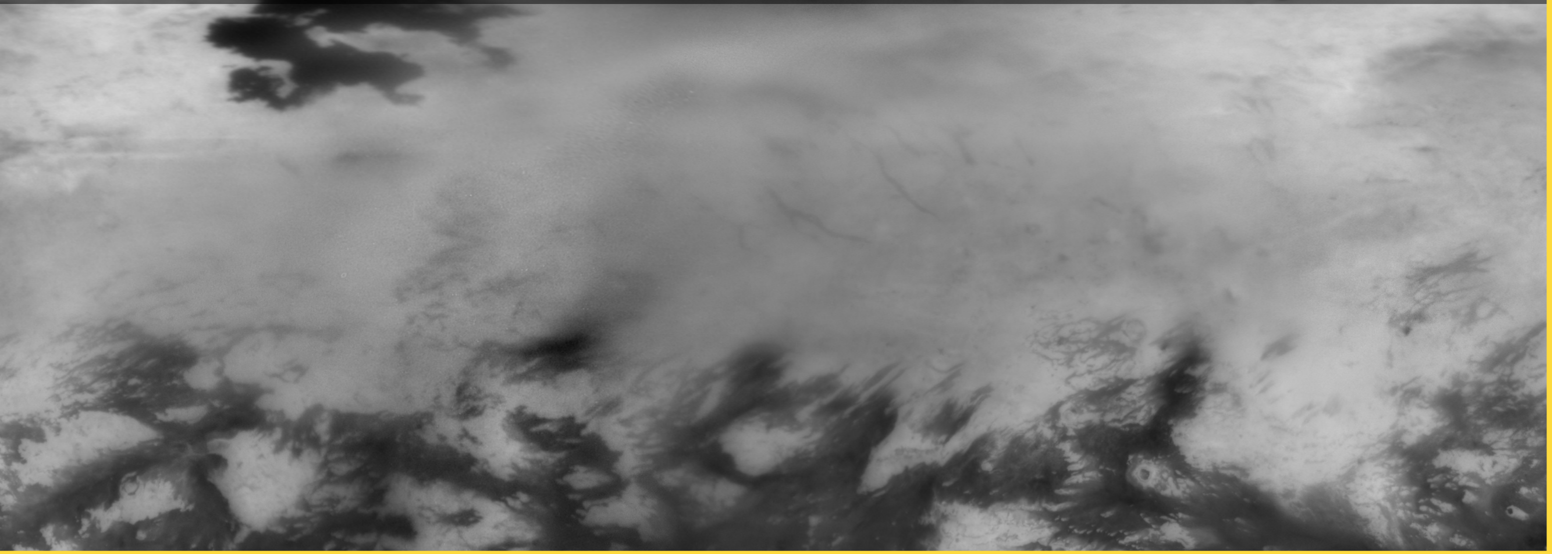


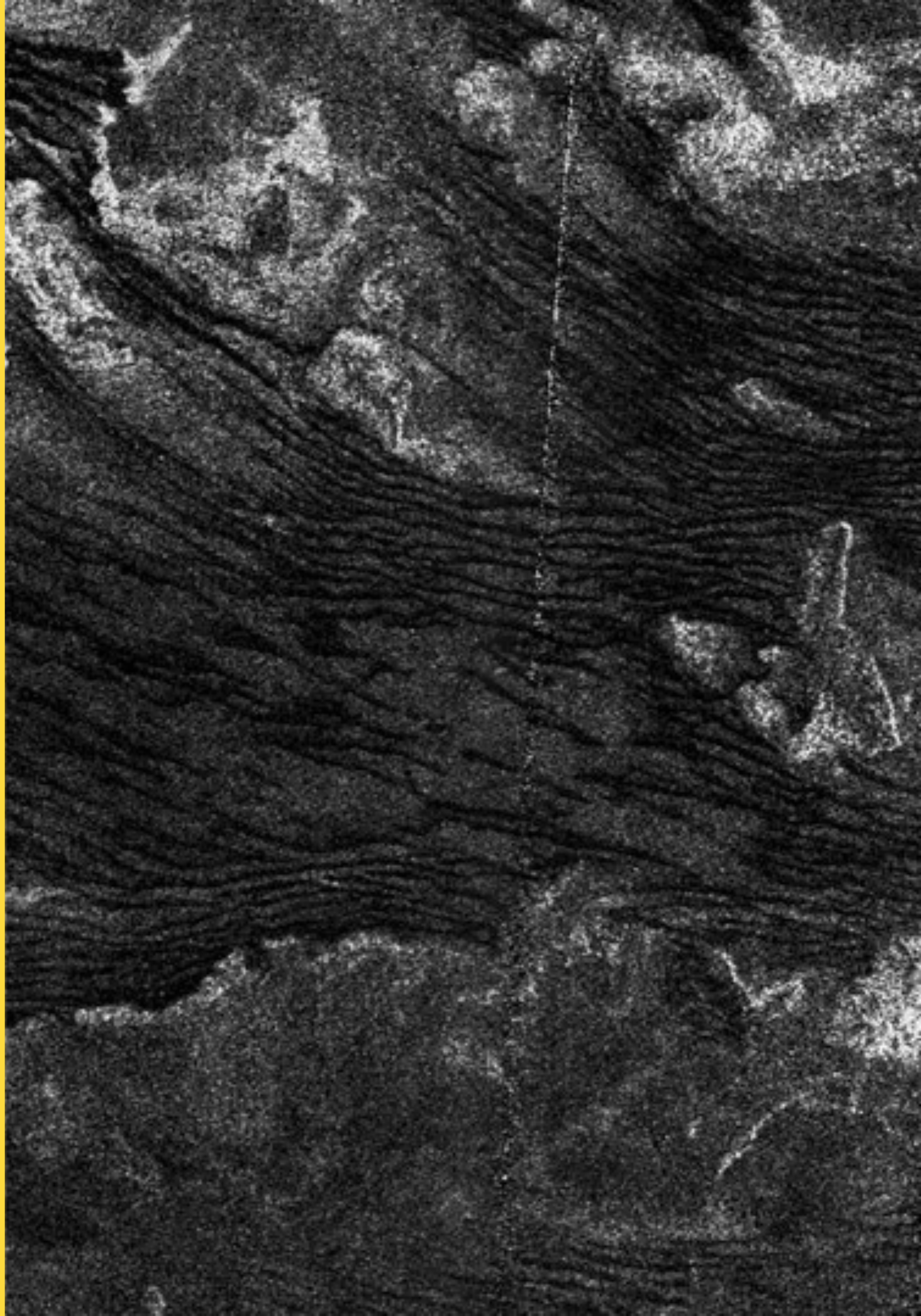


Equatorial organic sand dunes



Equatorial organic sand dunes

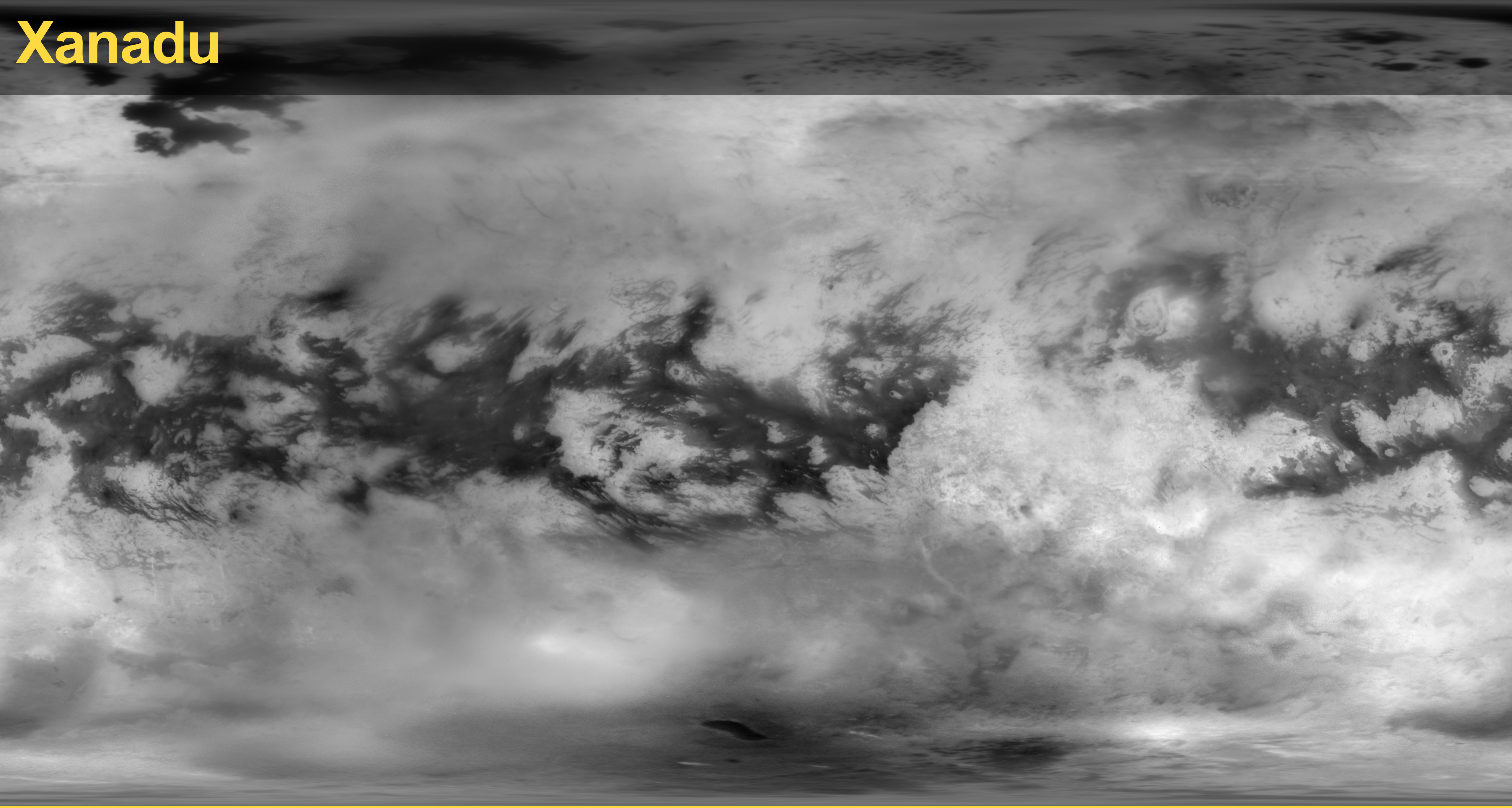




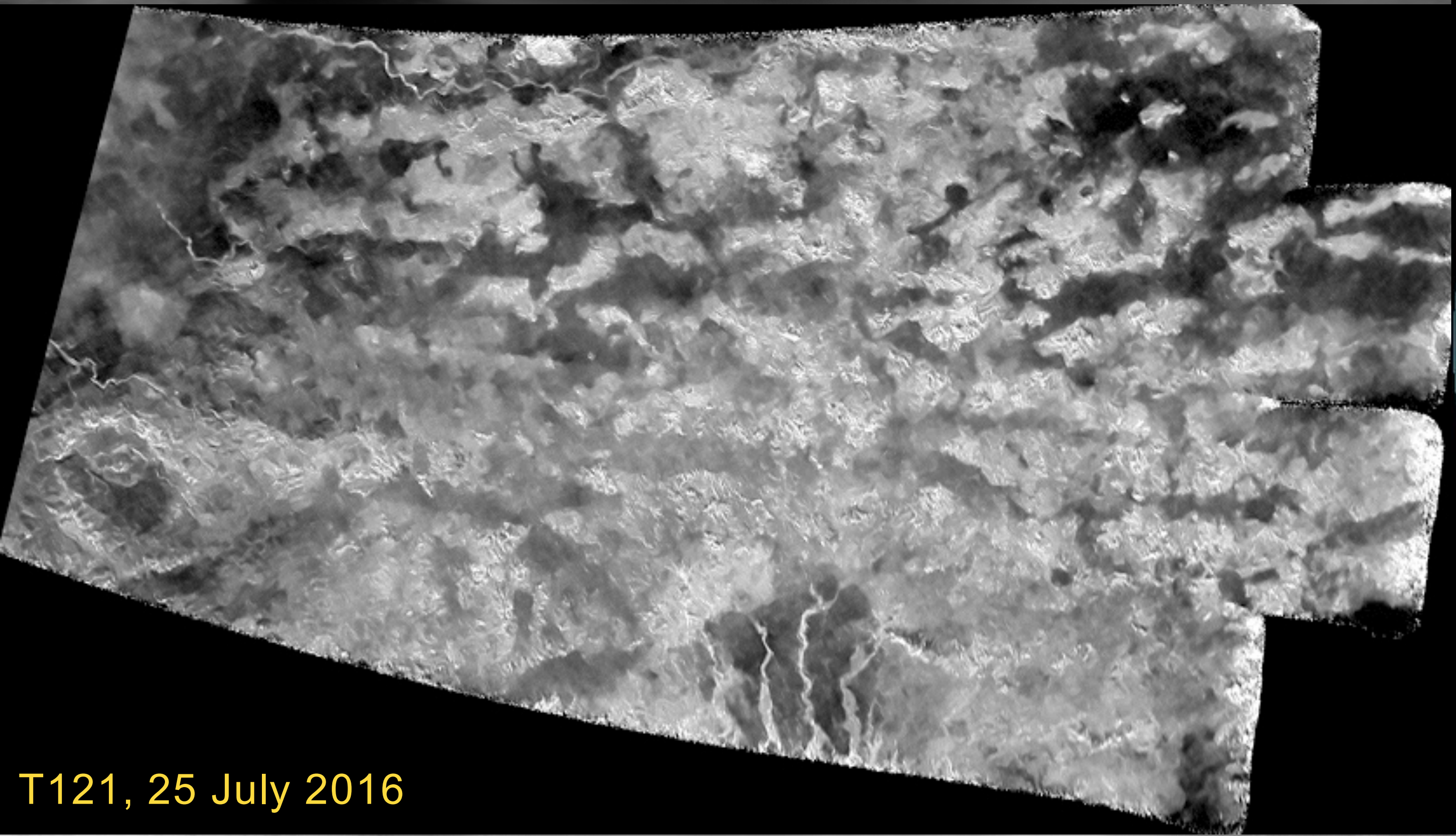
Equatorial organic sand dunes

- Longitudinal dunes 1-2 km wide, >100 km long, 80-130 m high, spaced 1-4 km apart (Lorenz et al. 2006, Radebaugh et al. 2008, Neish et al. 2010)
- Youngest features at the scale of mapping (100s m to few km)
- Implications for wind patterns and material transport (e.g., Tokano 2010)
- Unknowns
  - Composition(s) of and source(s) sand particles
  - What prevents dunes from forming on Xanadu
  - Implications of damp surface detected by Huygens Probe at ~10°S latitude

Xanadu



Xanadu



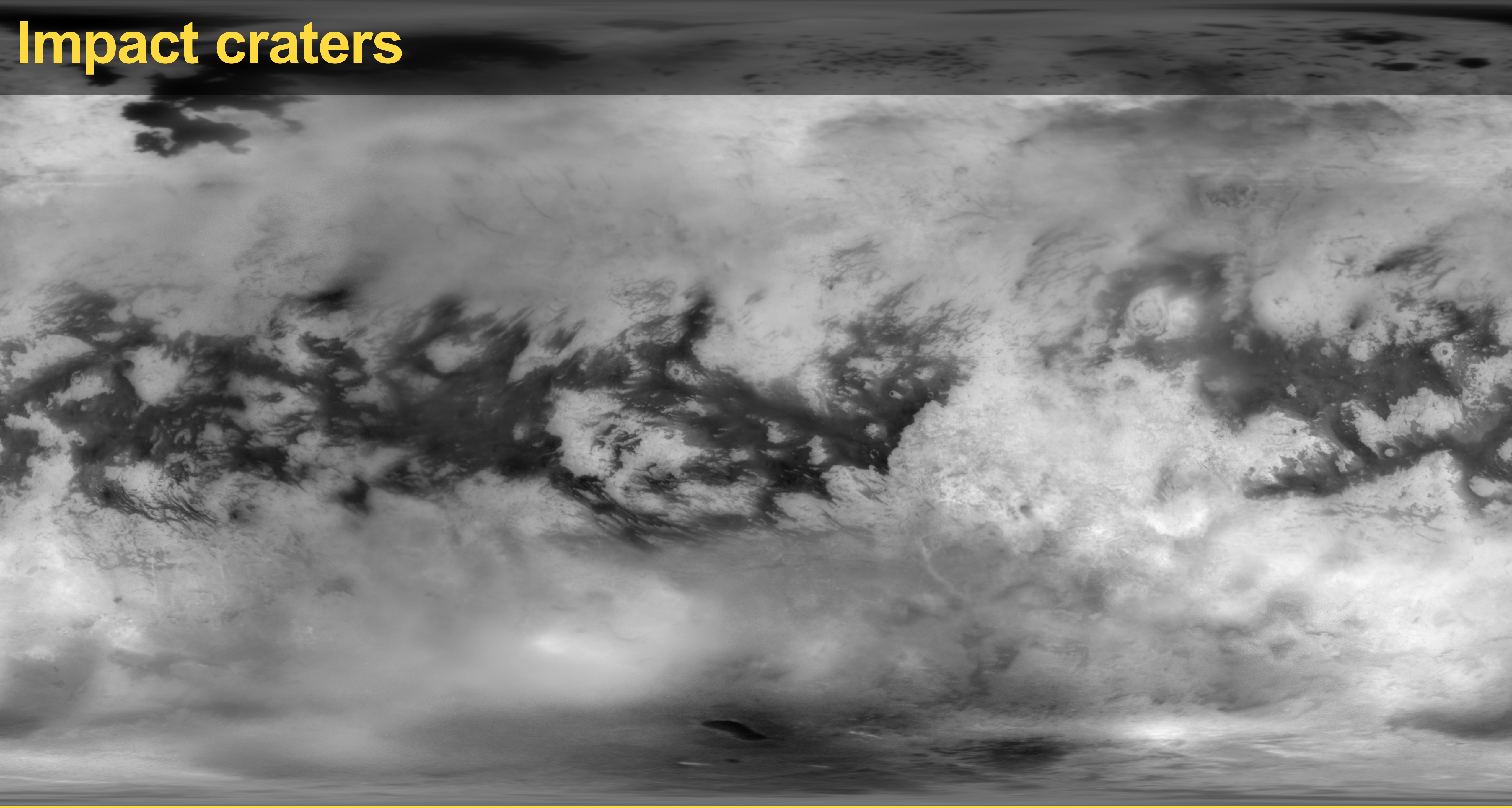
T121, 25 July 2016

T20, 28 Oct. 2005

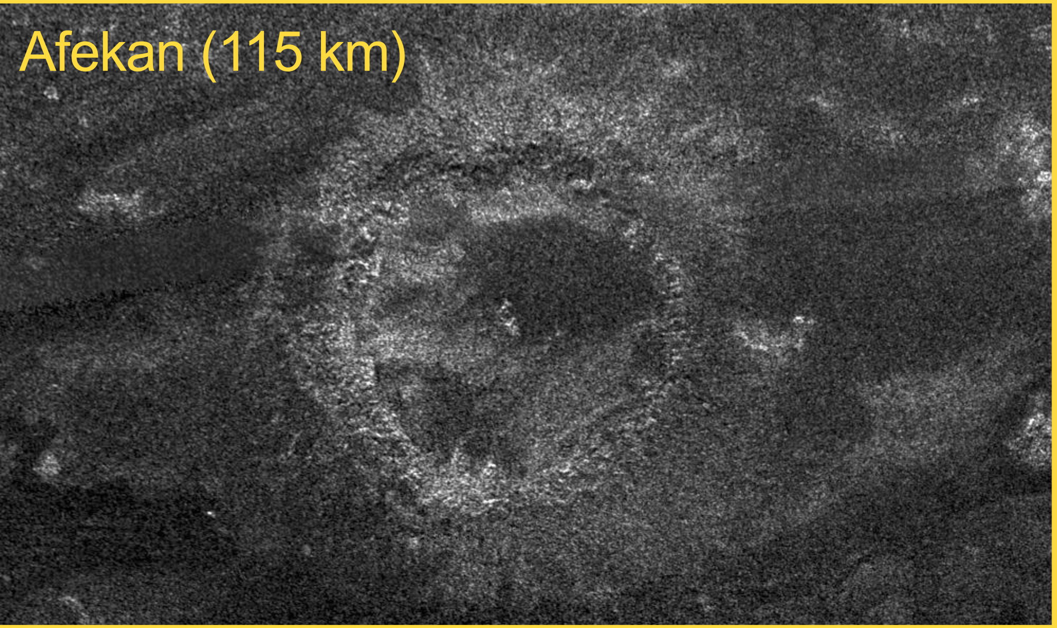
Xanadu

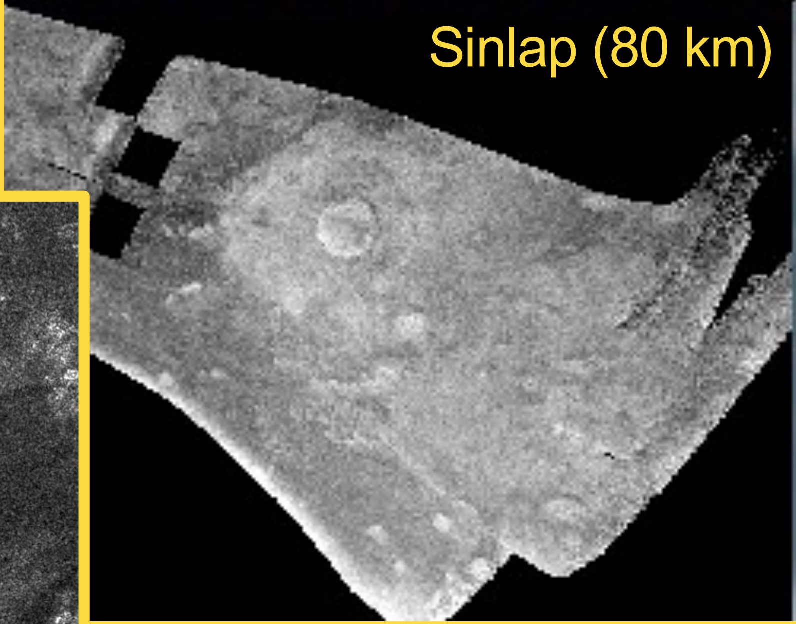
- Bright region identified by HST observations
- Complex terrain cut by river channels with Titan's oldest population of craters
- Varied topography, not a distinct topographic high
- Former lakebeds and possible cryovolcanic features
- Unknowns
  - Formation of Xanadu as a distinct geologic feature
  - Composition(s) of bright organic material
  - What prevents dunes from forming on Xanadu

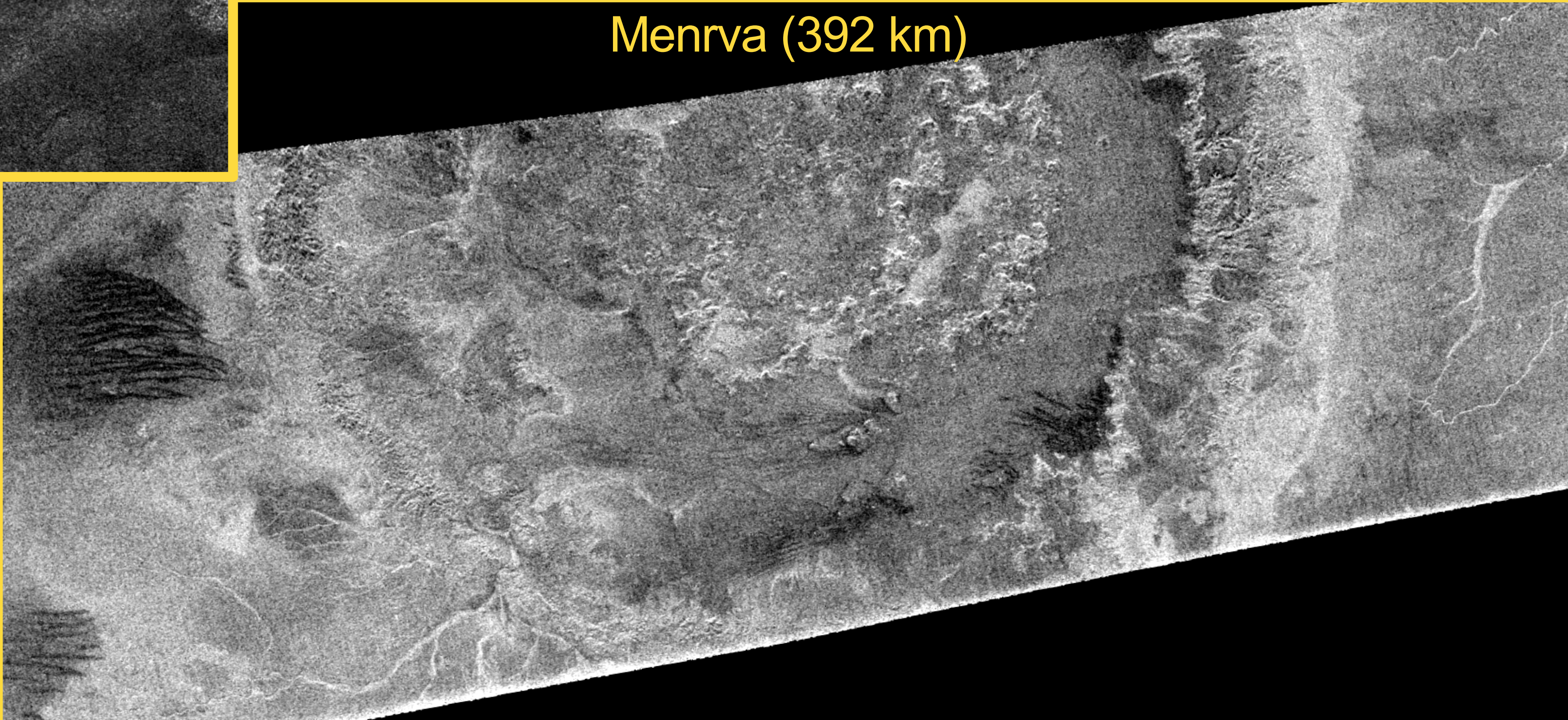
Impact craters



Impact craters



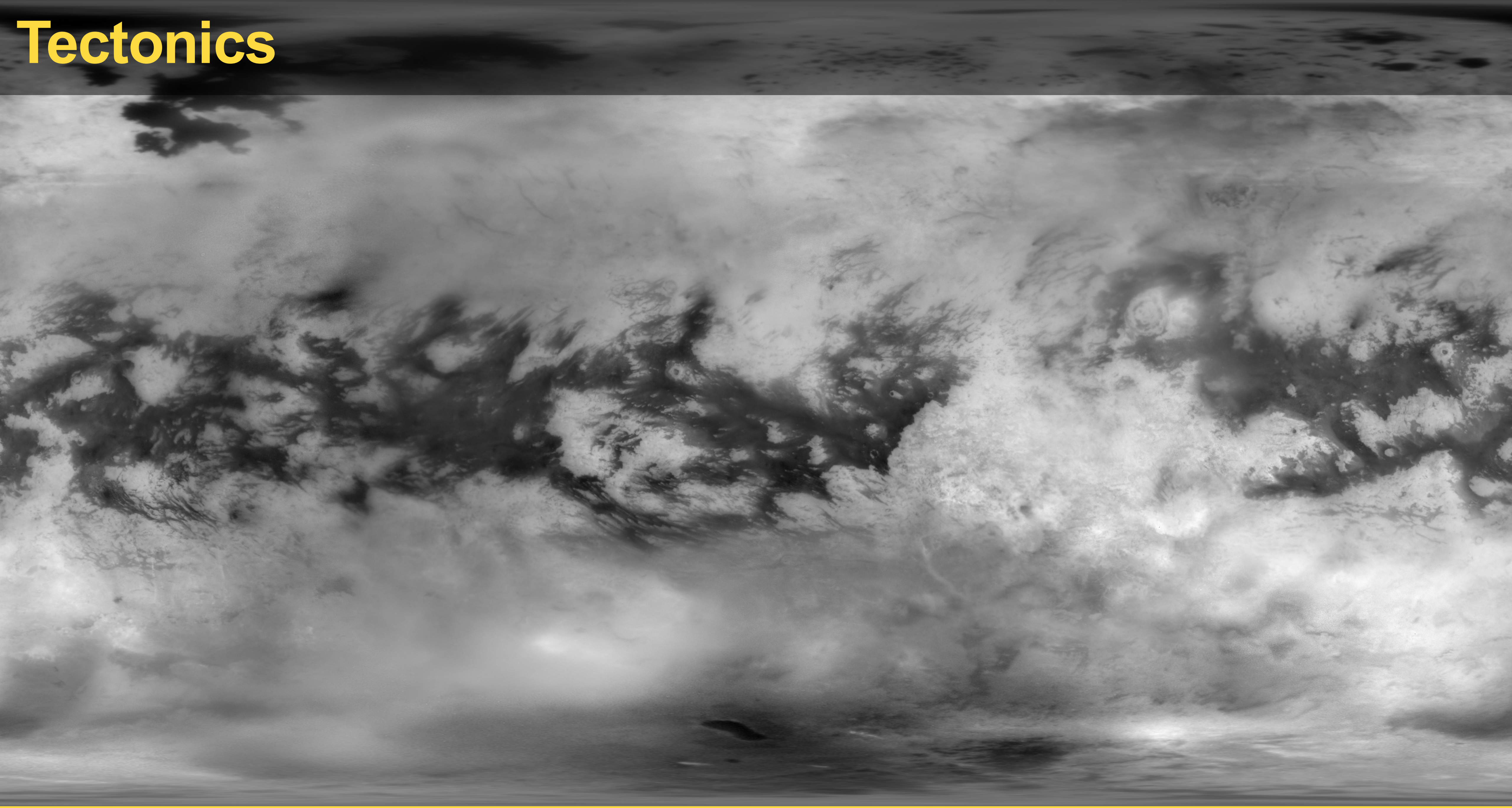




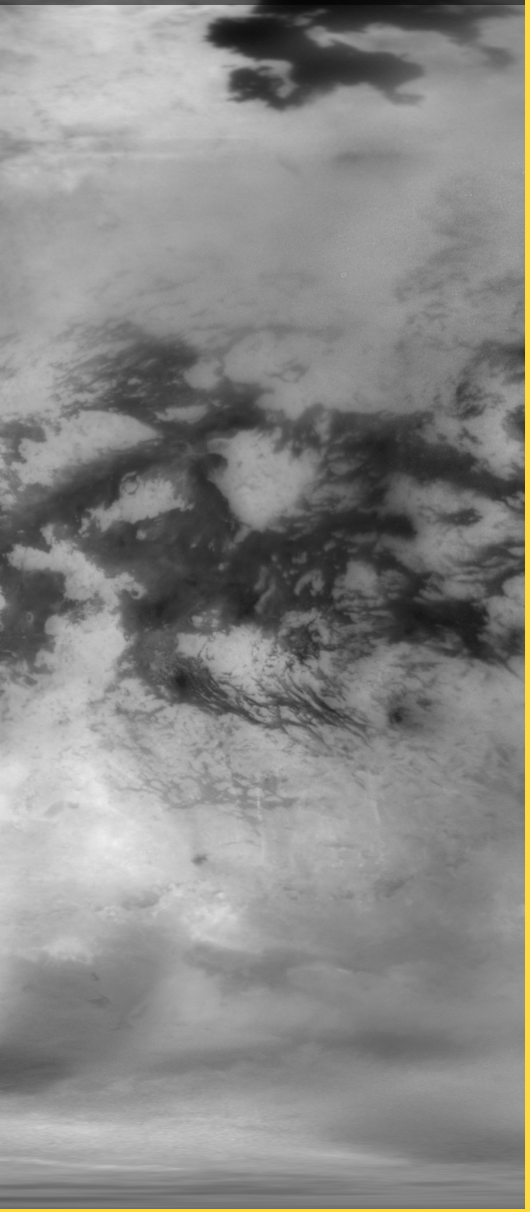
Impact craters

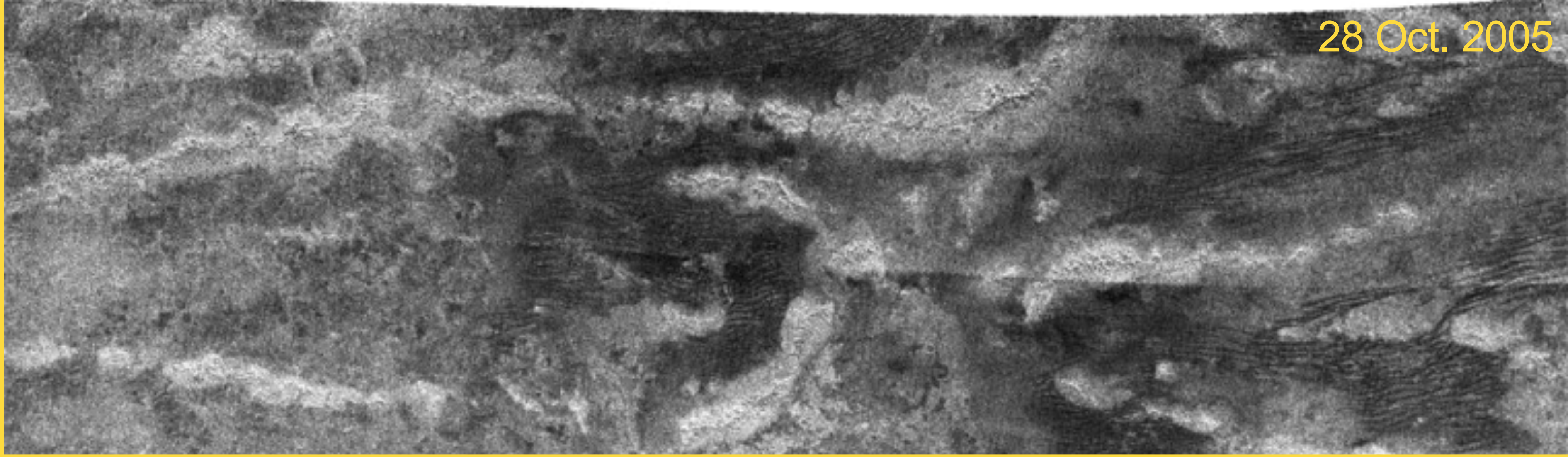
- Modification processes → young crater retention age, ~200 Myr – 1 Gyr (Wood et al. 2010; Neish and Lorenz 2012)
- Shallow compared to craters on similarly sized Ganymede with significant modification, especially by aeolian infill and fluvial erosion (Neish et al. 2013) as well as chemical weathering (Neish et al. 2015) and viscous relaxation (Schurmeier and Dombard 2018)s
- Non-uniform crater population: higher number in Xanadu and very few at high latitudes, suggestive of formation in wetlands or shallow sea where crater topography isn't maintained (Neish and Lorenz 2014)
- Unknowns
  - Degree to which water-ice crust has been excavated at craters
  - History of modification processes

Tectonics



Tectonics



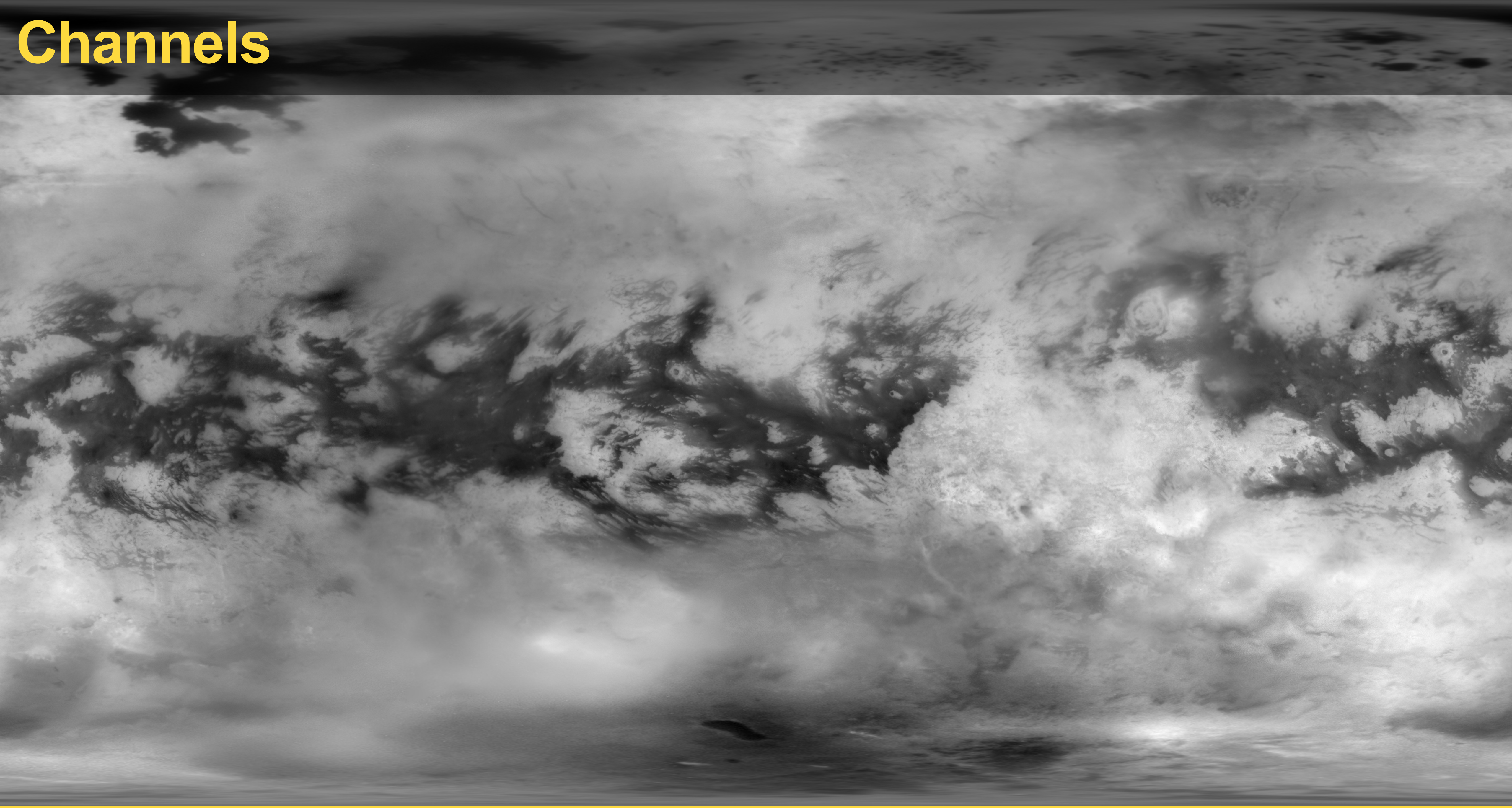


Tectonics

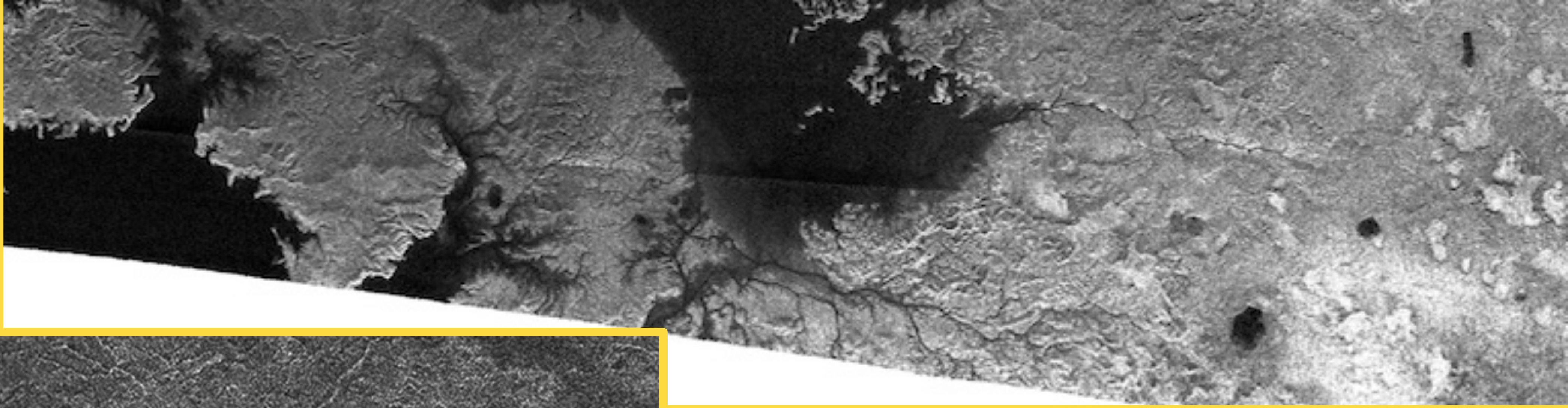
- Rugged mountain ridges modified by erosion
- Topography ~1-2 km
- Local organization and global E-W trend (Liu et al. 2016)
- Observations consistent with formation by contraction (Liu et al. 2016; Mitri et al. 2010)
- Structural control of channel networks (Burr et al. 2013)
- Unknowns
  - Degree of endogenic tectonic activity, relative rates of tectonic and erosional processes
  - Larger-scale organized tectonic activity

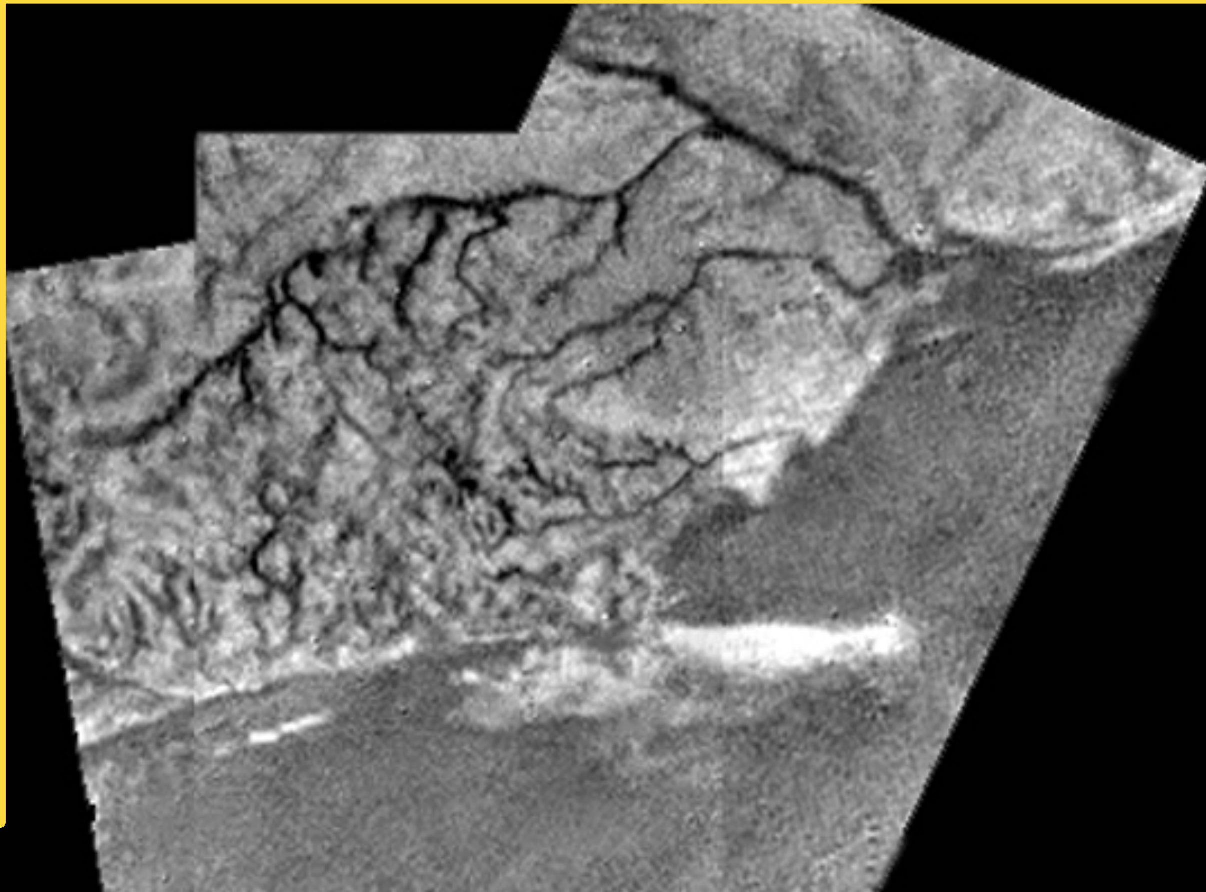
N

Channels



Channels

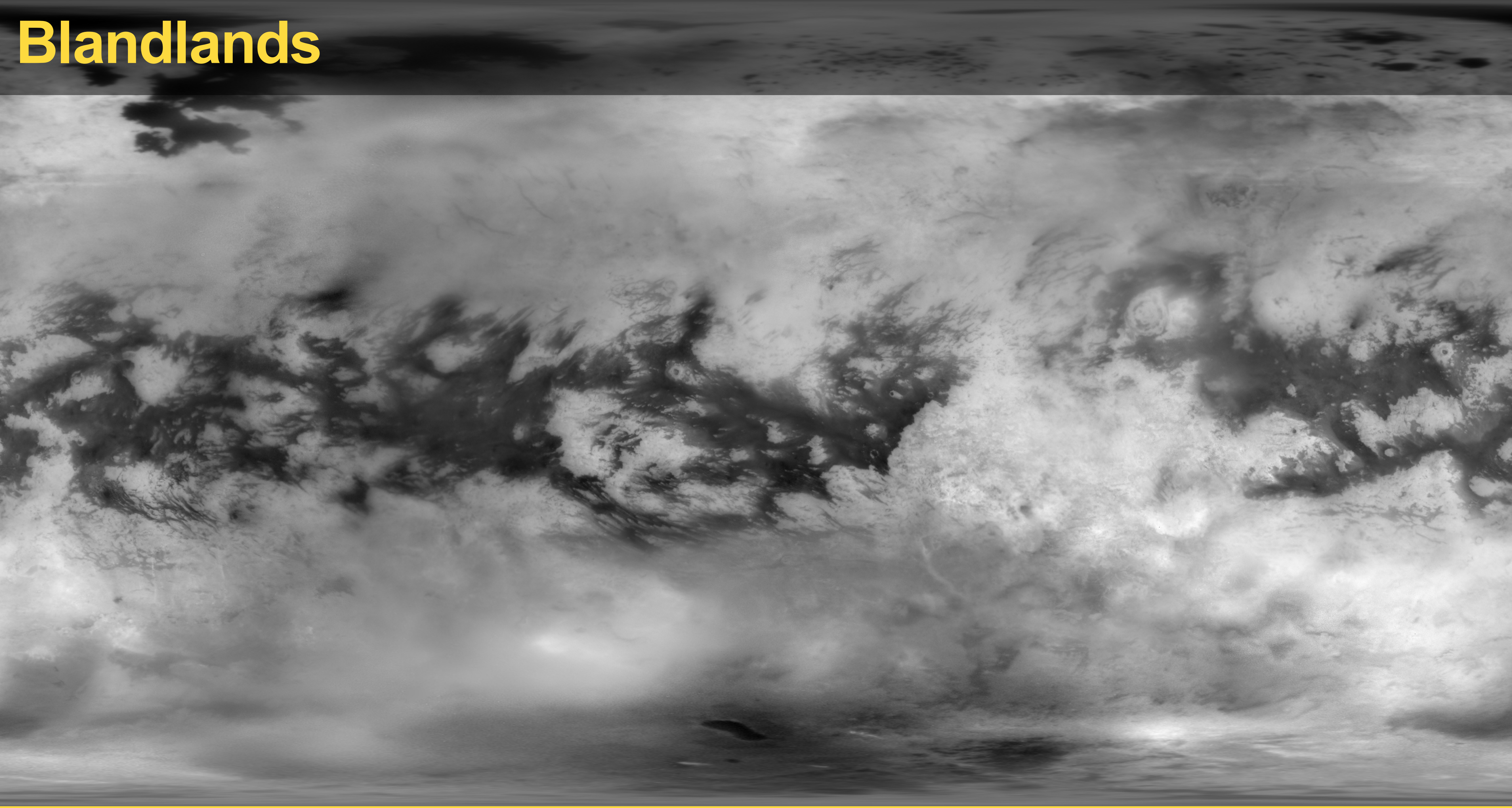




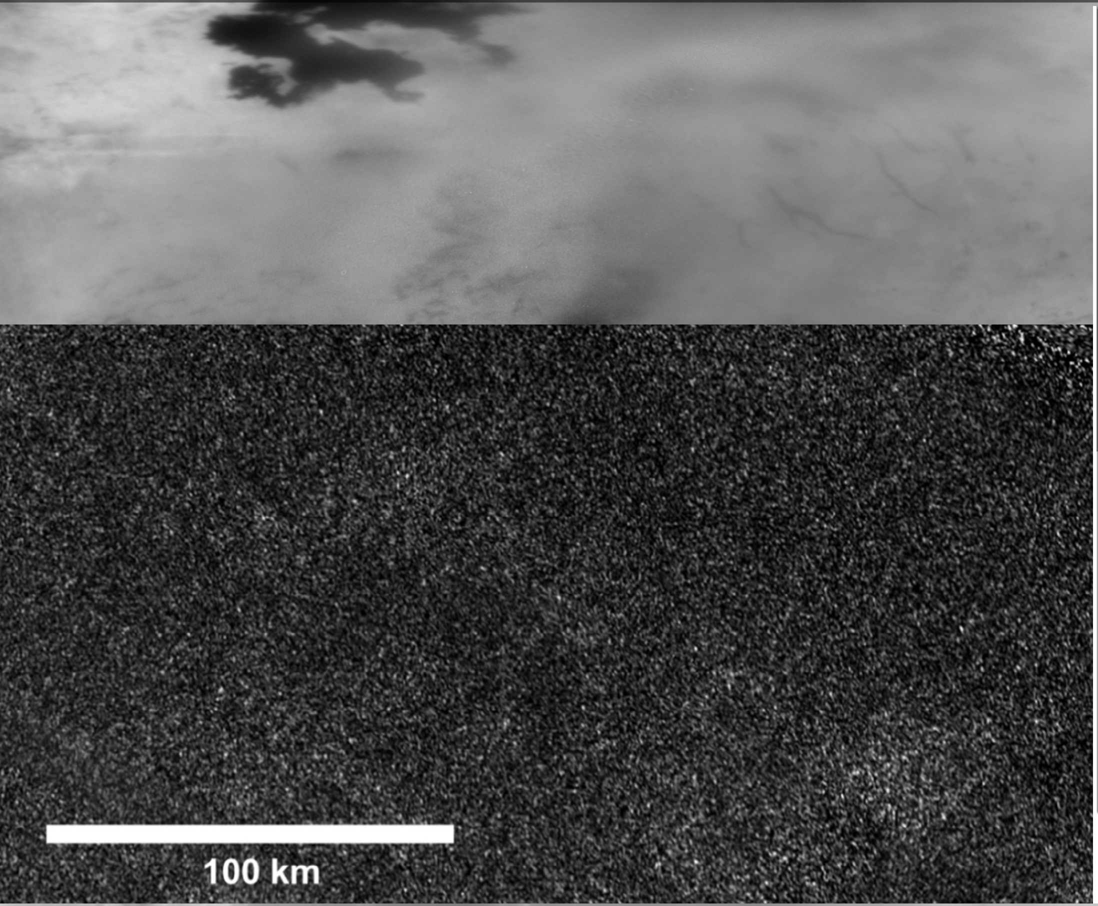
Channels

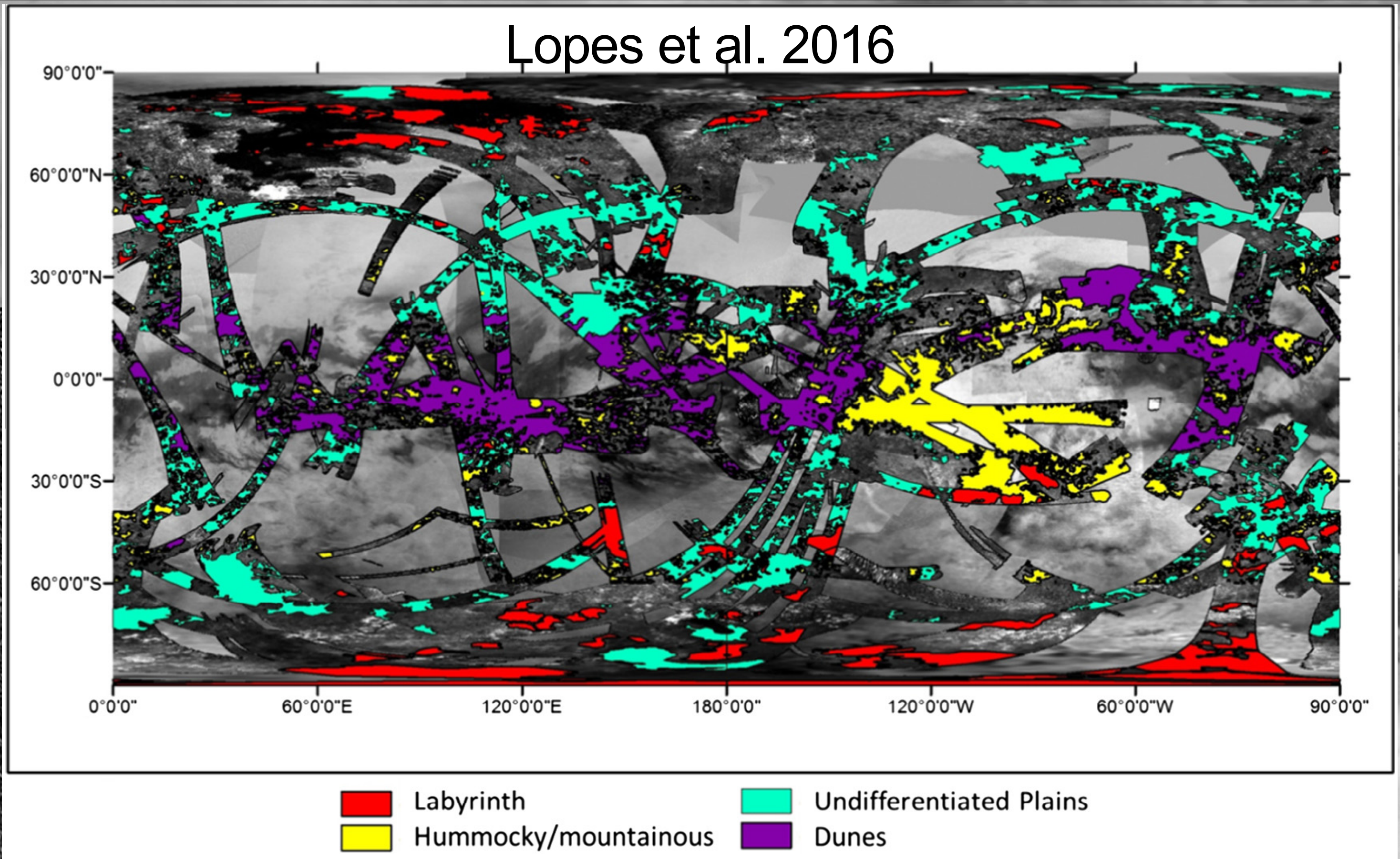
- Found at all latitudes, including arid equatorial region indicating variation in weather on seasonal or longer timescales (Turtle et al. 2011)
- Implications for sediment transport (Burr et al. 2010)
- Variation in floor roughness (Le Gall et al. 2010)
- Evidence of tectonic control in places (Burr et al. 2013)
- Unknowns
  - Resolution of observations limits understanding of modification rates

Blandlands



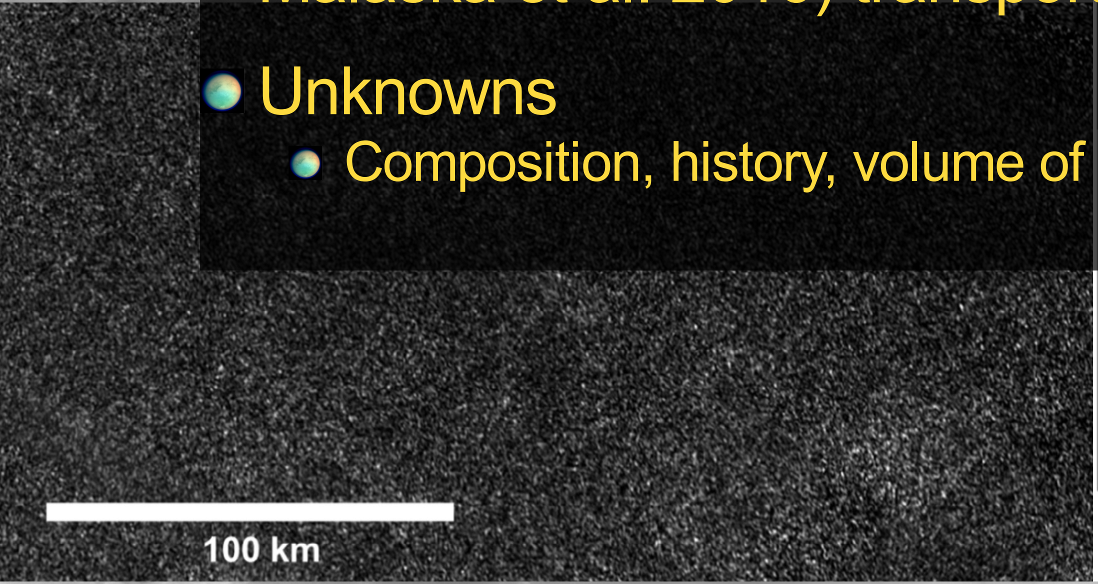
Blandlands

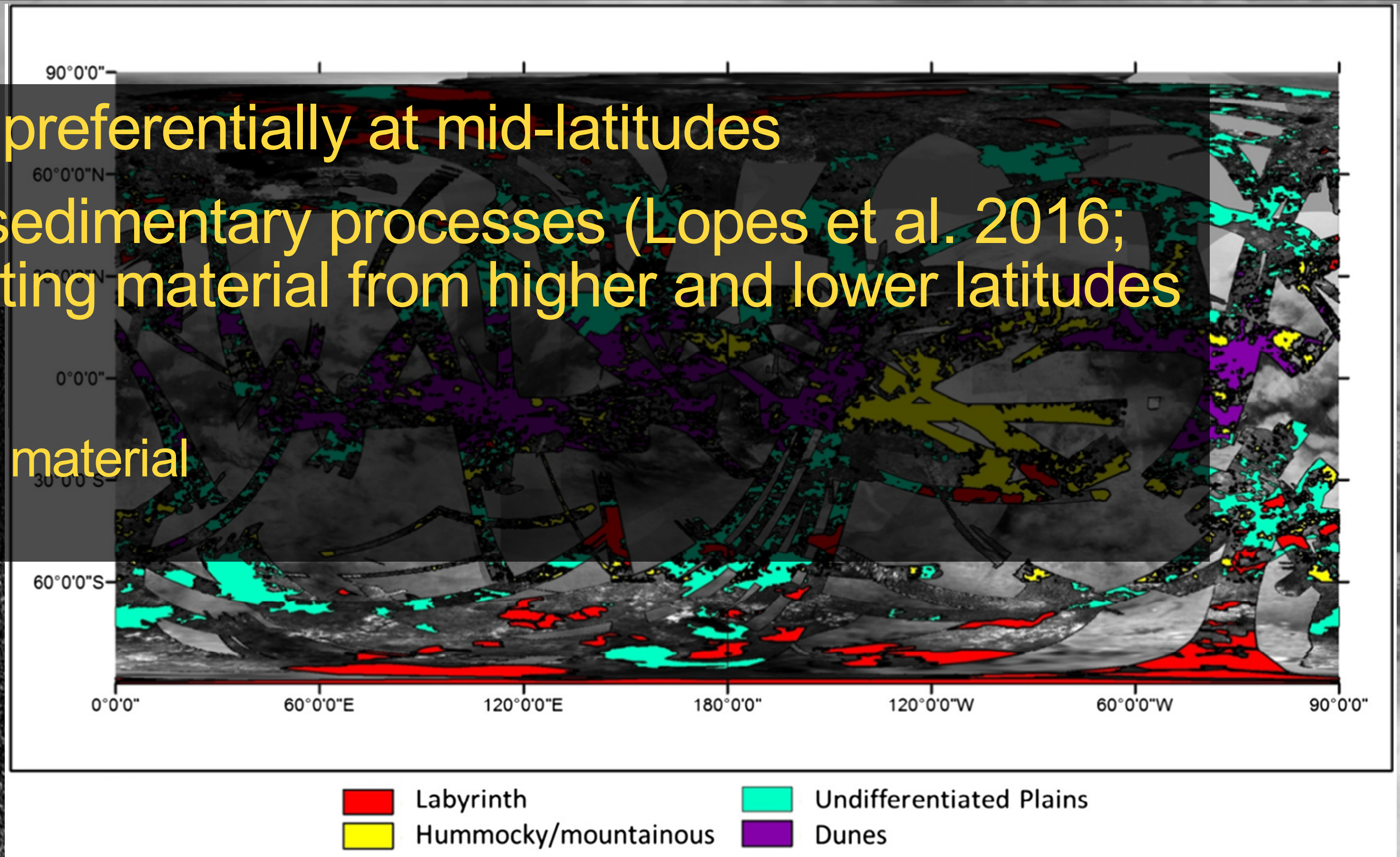

100 km


Lopes et al. 2016
90°0'0"
60°0'0"N
30°0'0"N
0°0'0"
30°0'0"S
60°0'0"S
0°0'0"
60°0'0"E
120°0'0"E
180°0'0"
120°0'0"W
60°0'0"W
90°0'0"
Labyrinth
Hummocky/mountainous
Undifferentiated Plains
Dunes

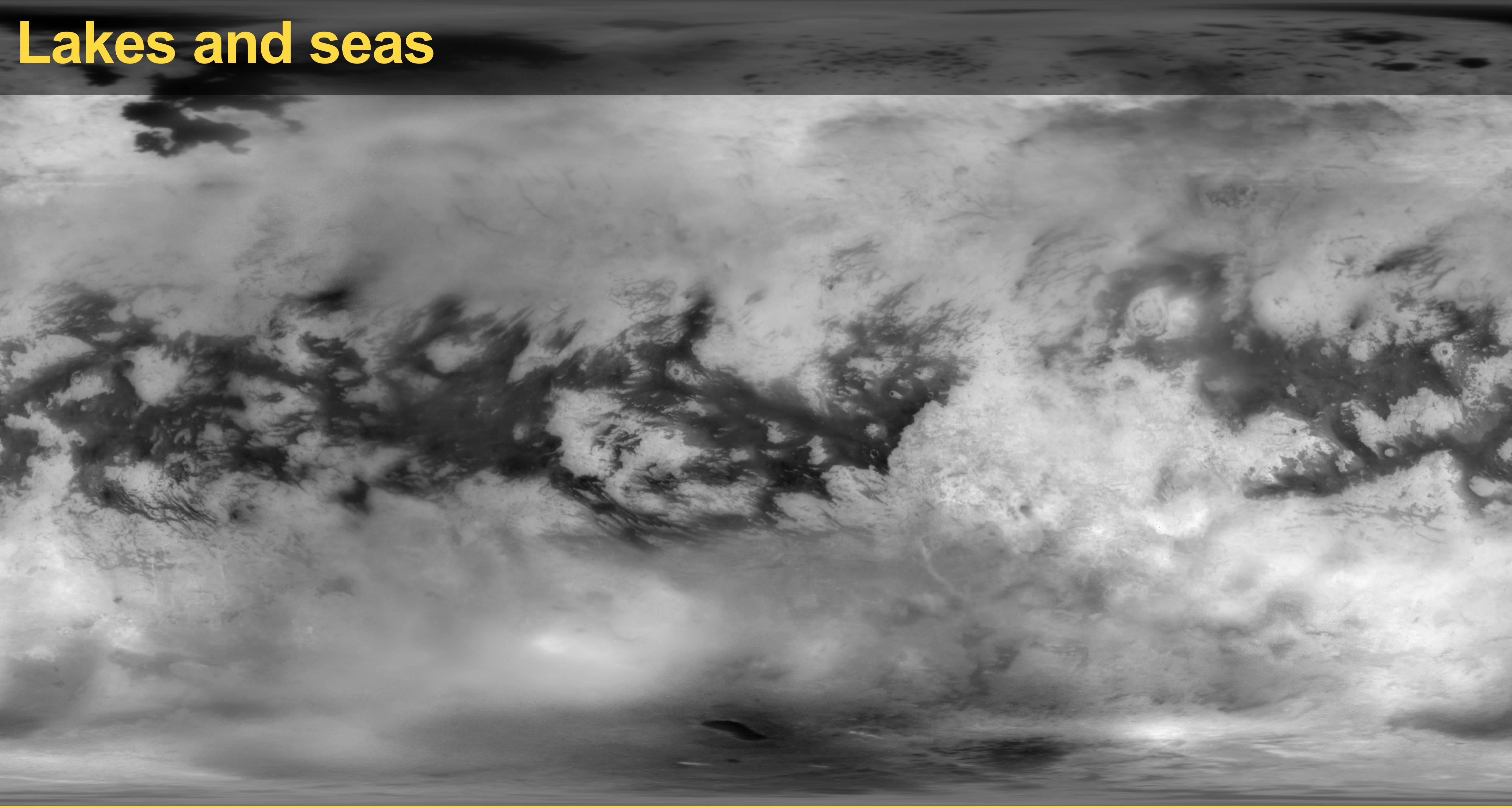
Blandlands

- Undifferentiated plains found preferentially at mid-latitudes
- Formed by depositional and sedimentary processes (Lopes et al. 2016; Malaska et al. 2016) transporting material from higher and lower latitudes
- Unknowns
  - Composition, history, volume of material

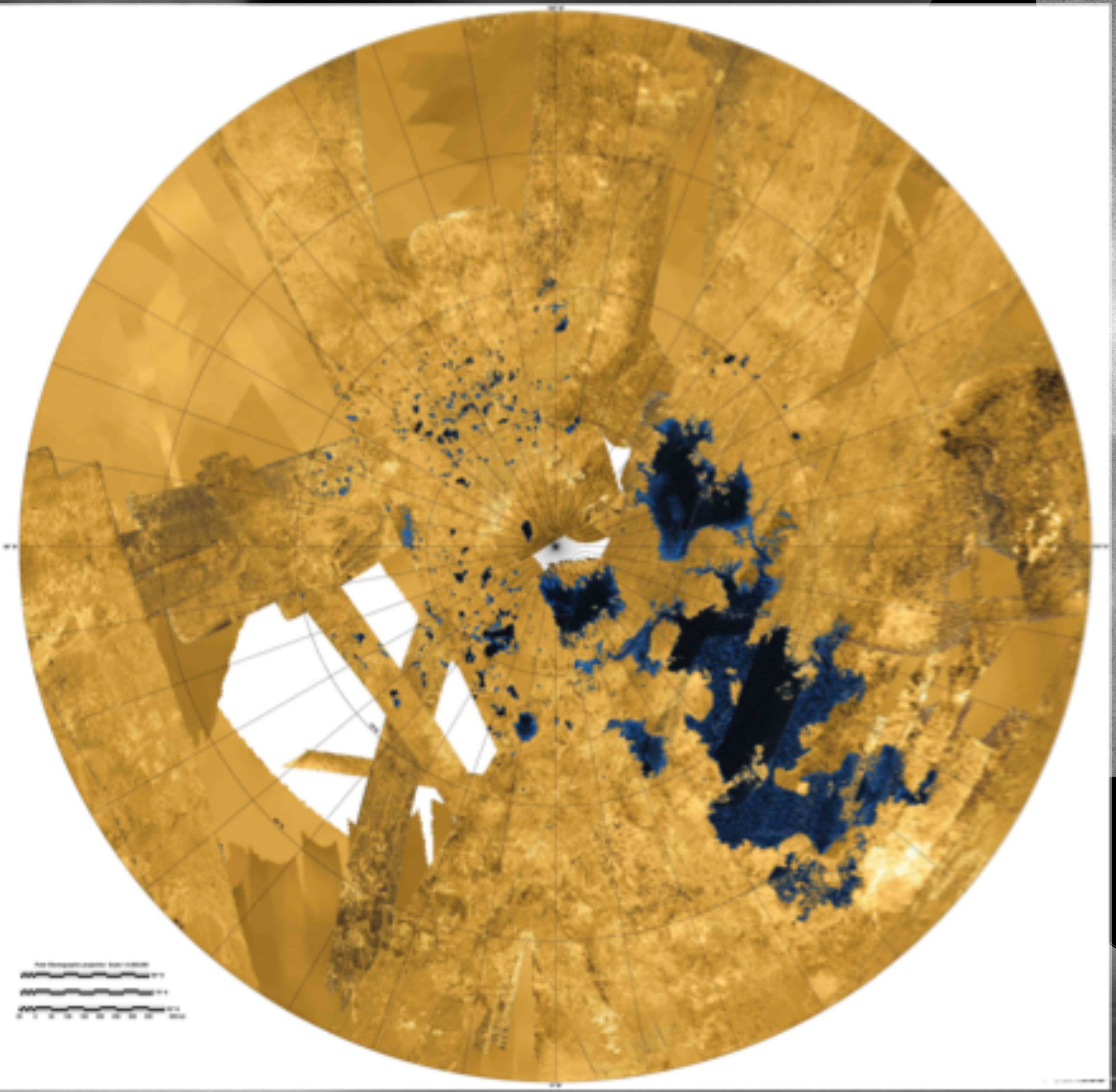




Lakes and seas

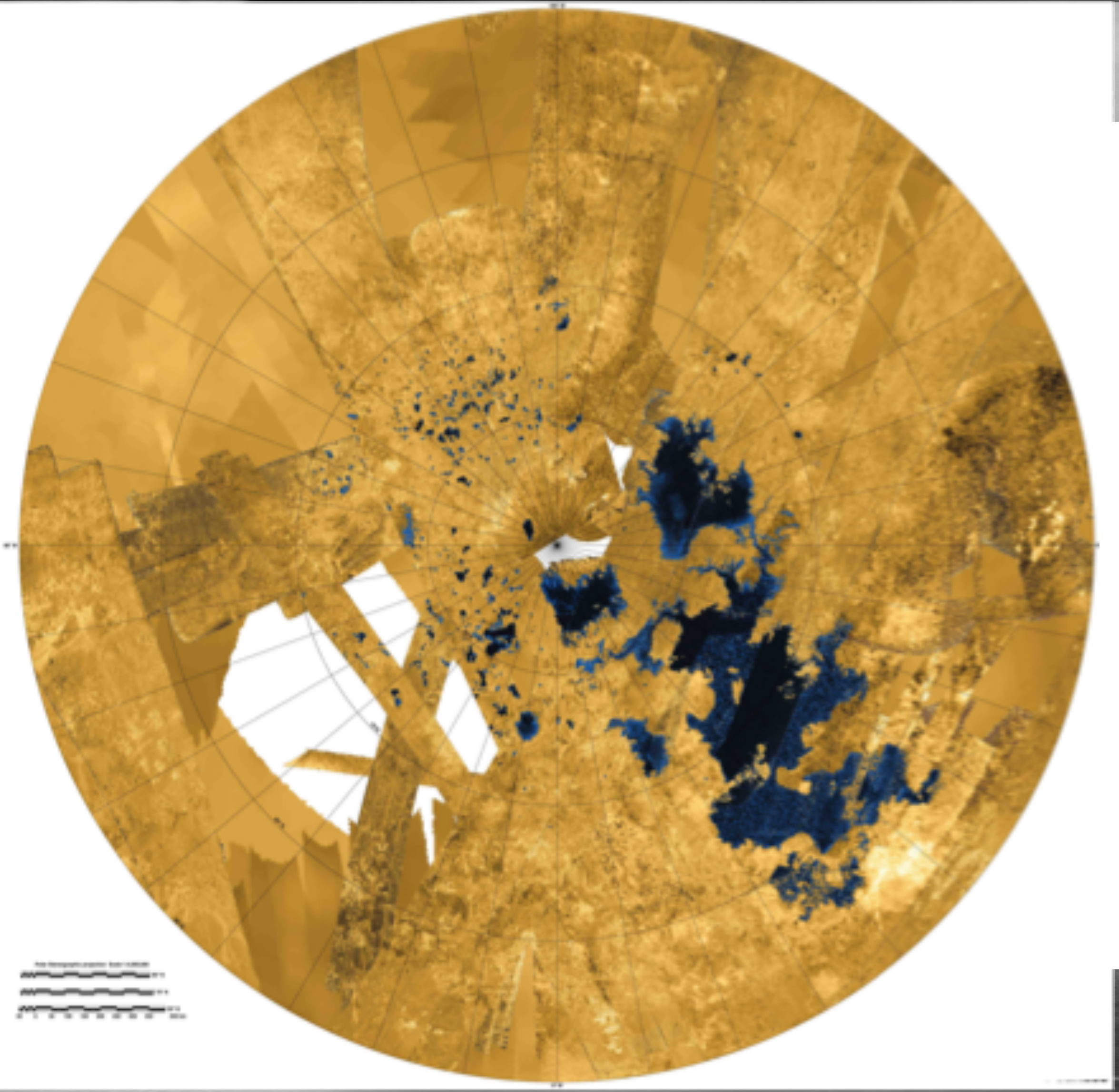


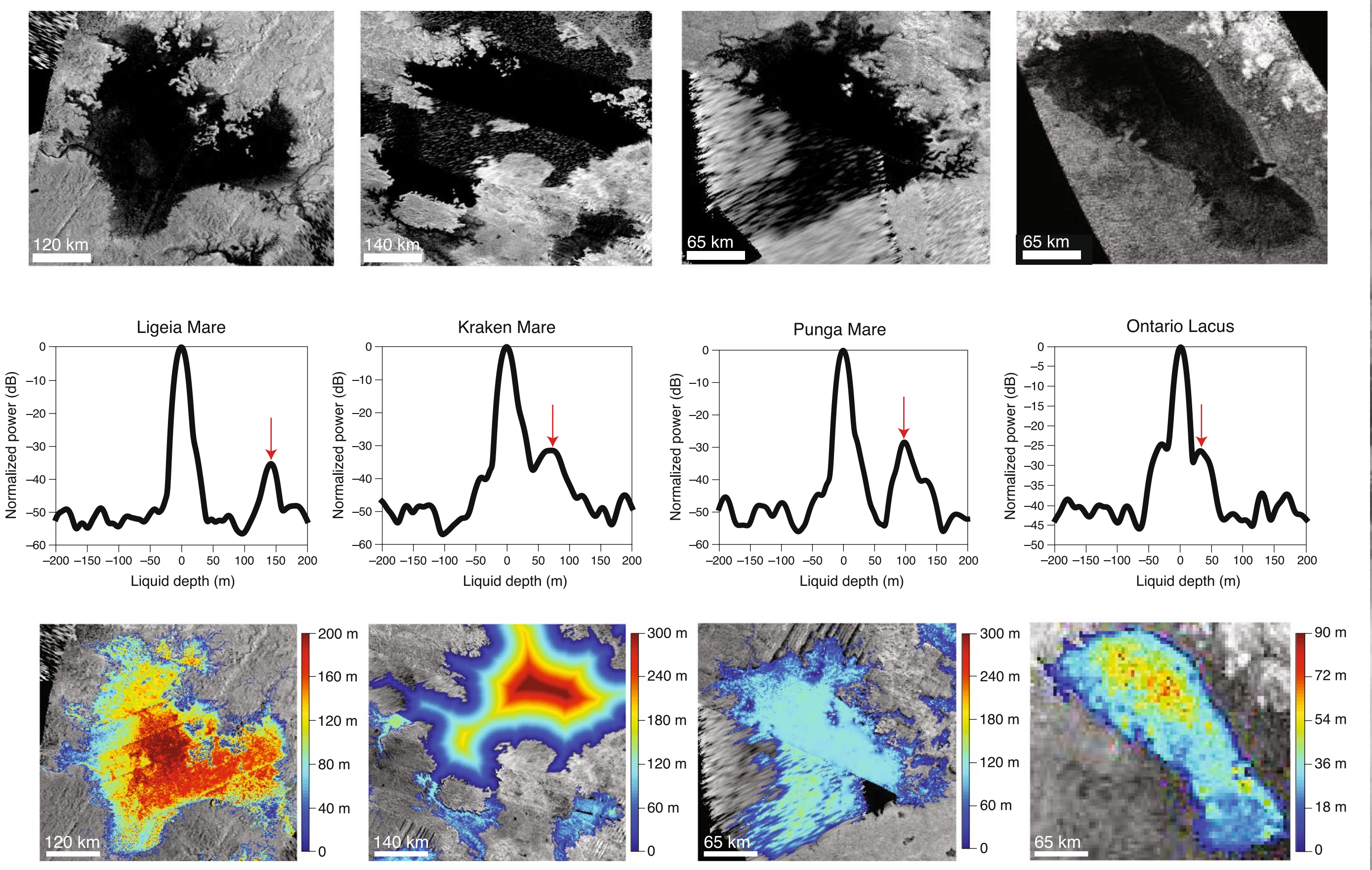
Lakes and seas



Rev292, Sept. 2017

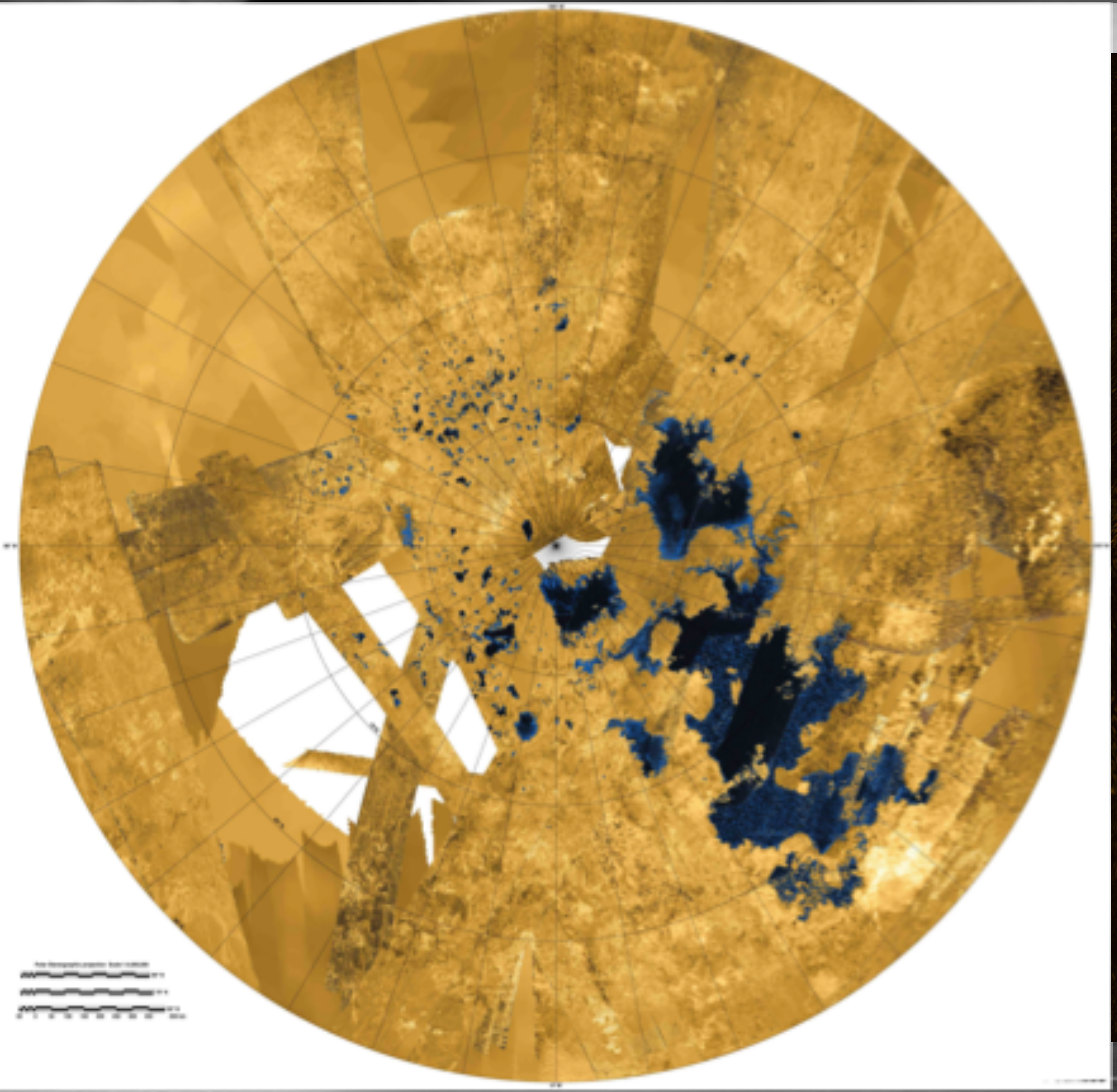
Lakes and seas

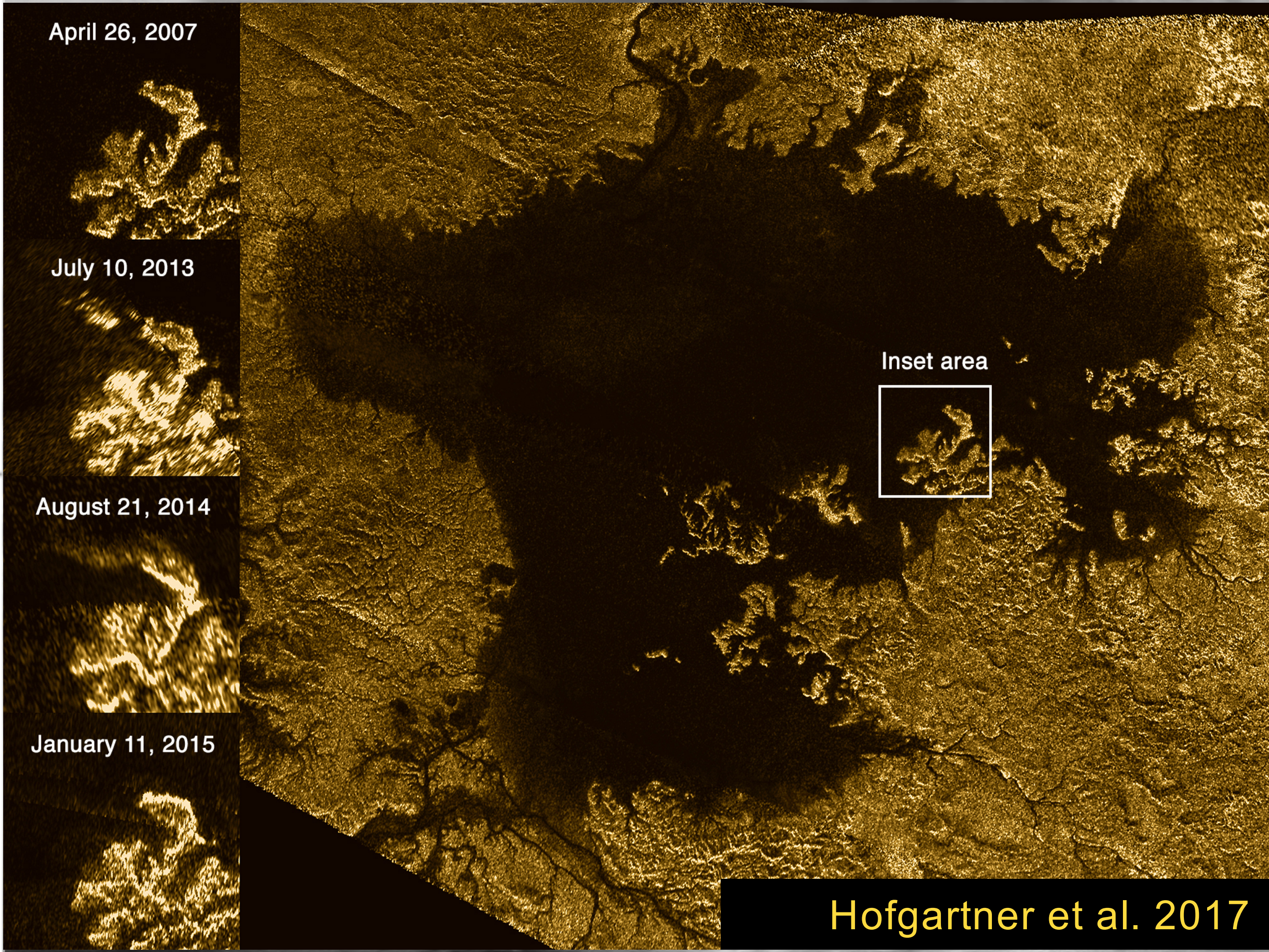




Hayes et al. 2018

Lakes and seas



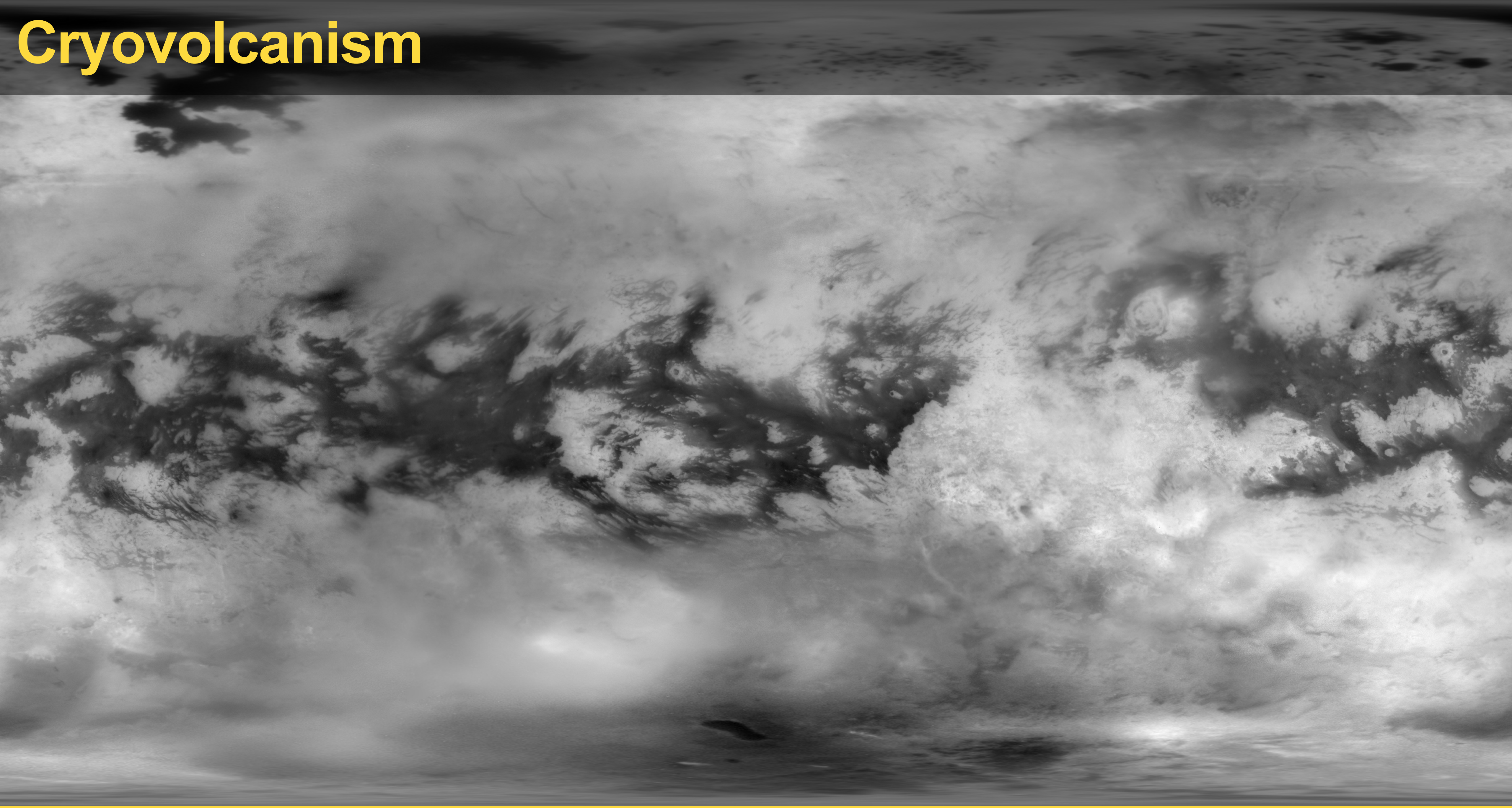


Hofgartner et al. 2017

Lakes and seas

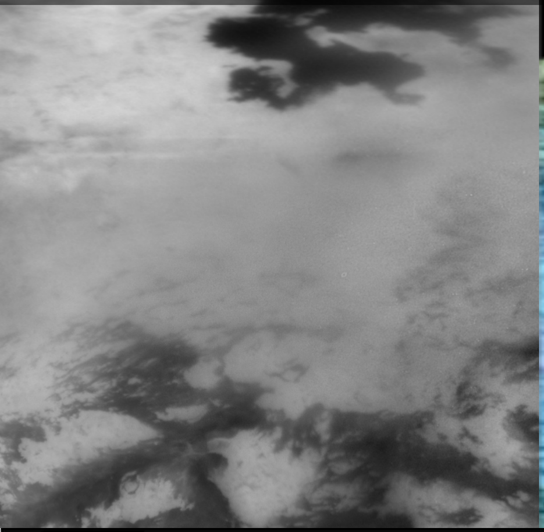
- Found at high latitudes, substantially more at northern latitudes
- Large seas with inundated shorelines at north pole, paleobasins at south pole (Birch et al. 2018)
- Transient features likely caused by waves, bubbles, or floating/suspended solid material (Hofgartner et al. 2014, 2017)
- Smaller lakes with steep, raised, "cookie-cutter" rims (Birch et al. 2018)
- Sub-surface hydrologic connections (Hayes et al. 2017)
- Evaporite deposits (MacKenzie et al. 2014)
- Depths on the order of 100 m (Mastrogiuseppe et al. 2014, 2018)
- Unknowns
  - Migration of liquids from pole to pole (Aharonson et al. 2012) and timescale of structural modification of surface
  - Lake formation process and implications for the solubility of the surface

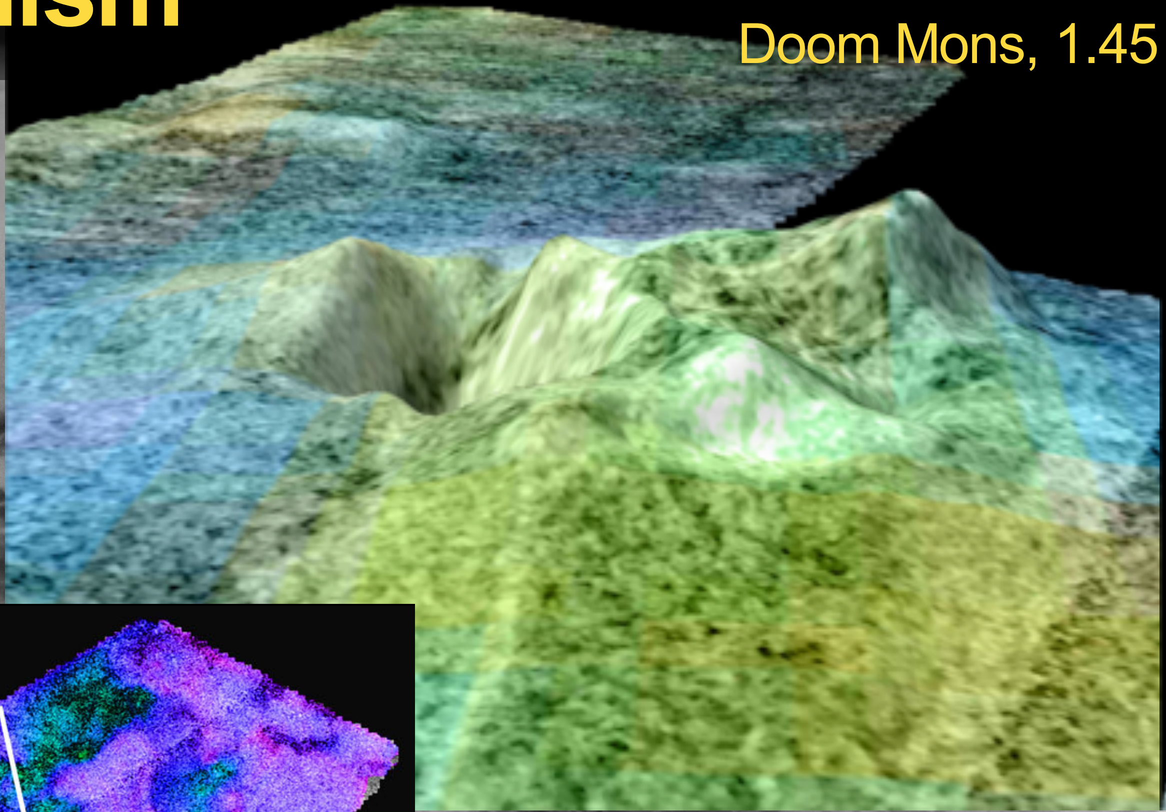
Cryovolcanism

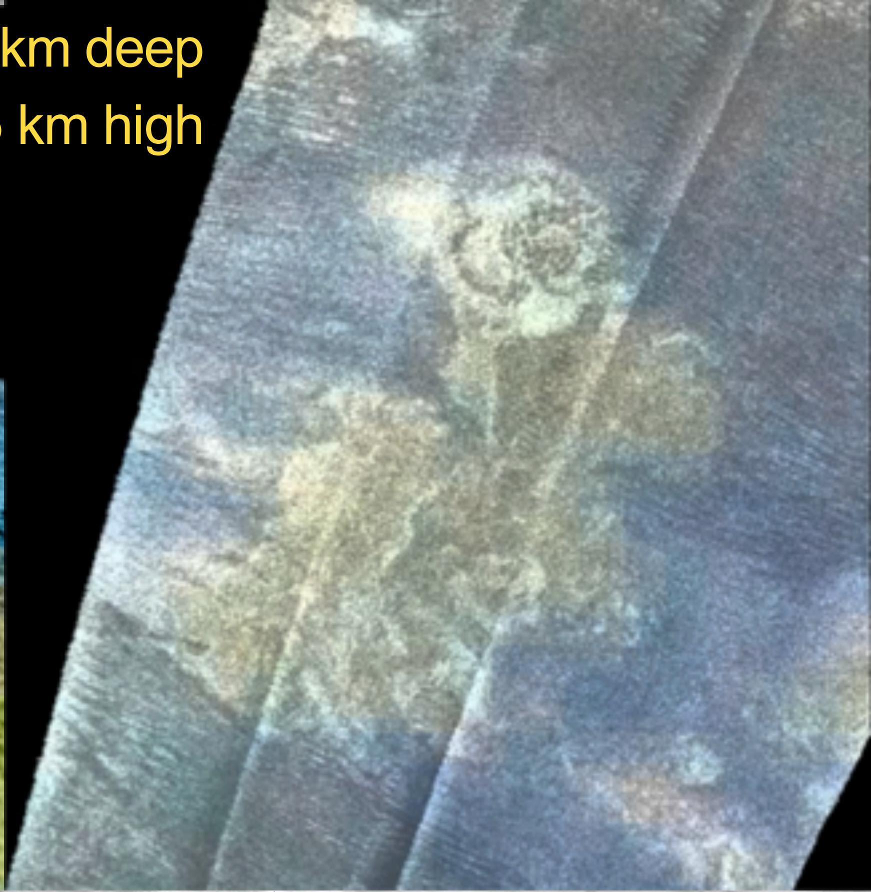


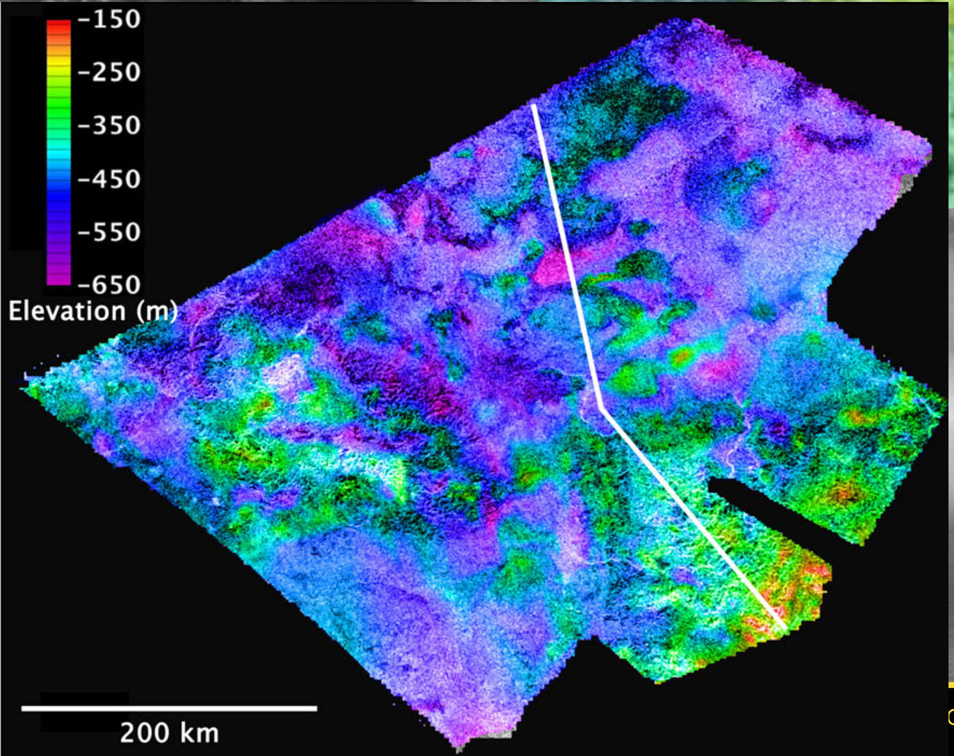
Cryovolcanism

Sotra Patera, 1.7 km deep
Doom Mons, 1.45 km high

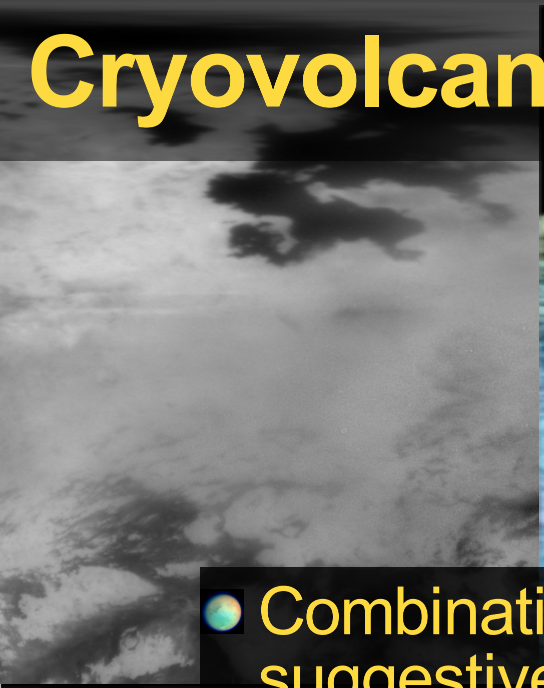


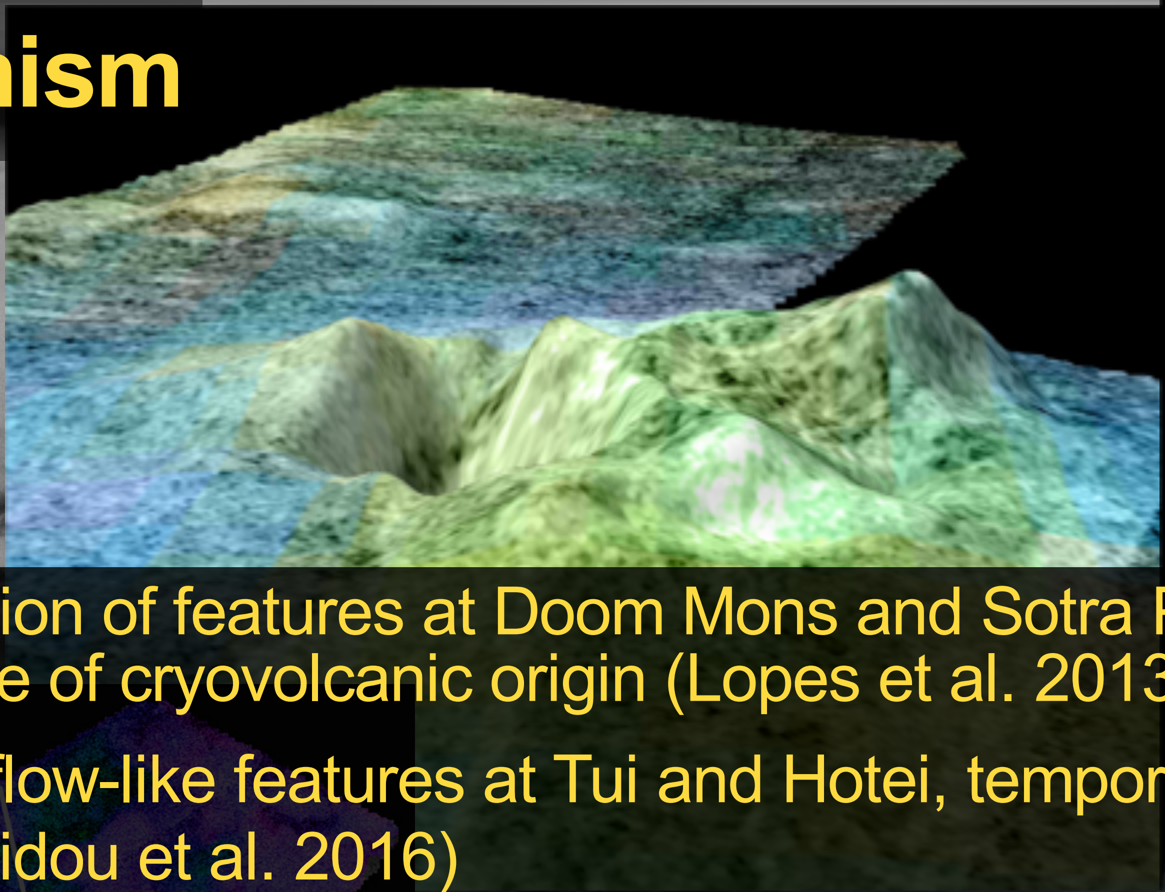


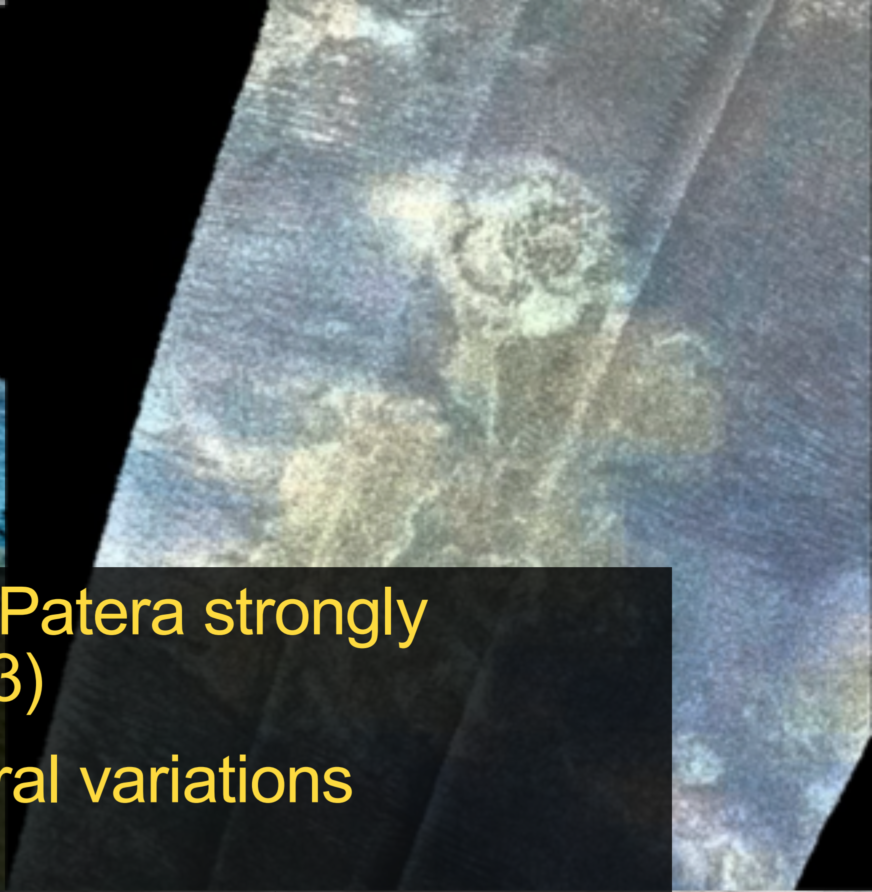


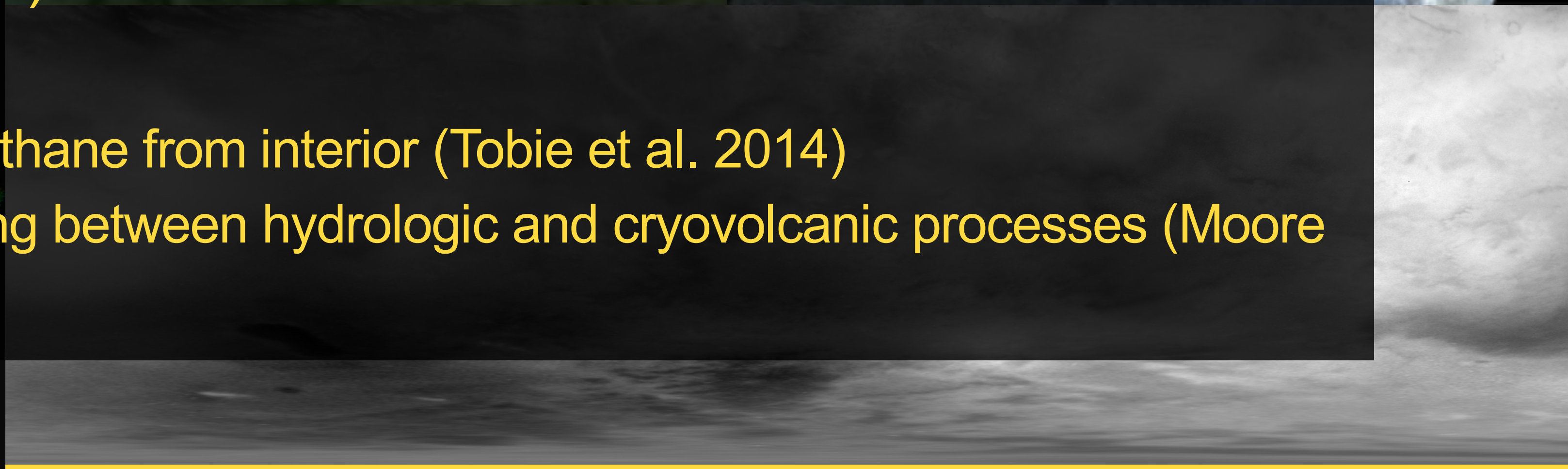


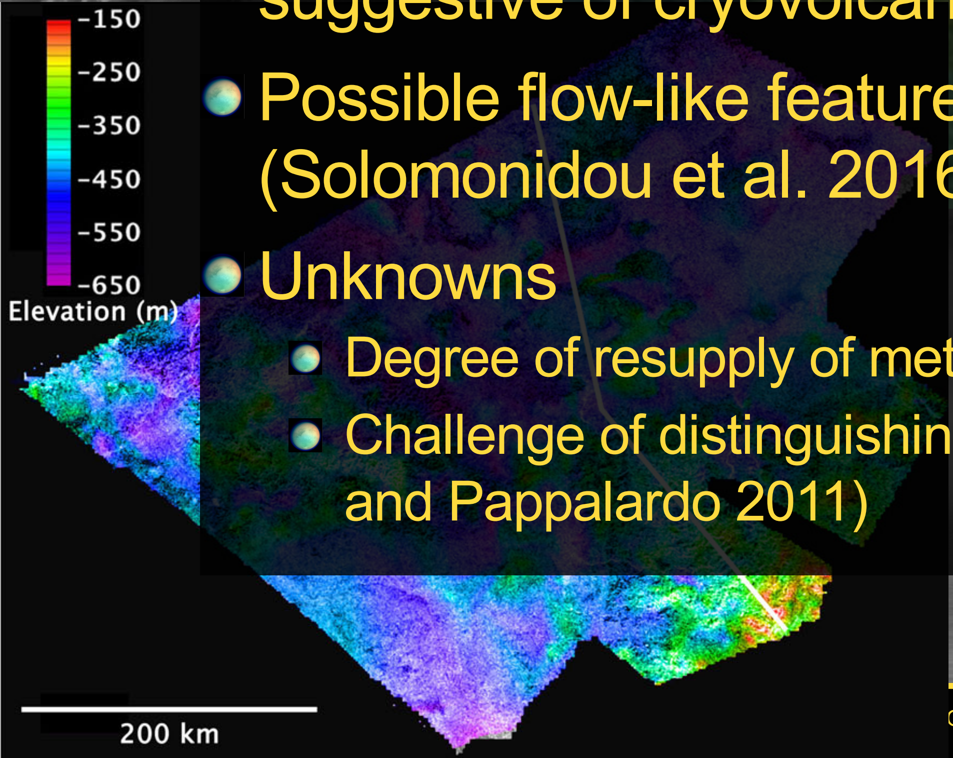
Cryovolcanism





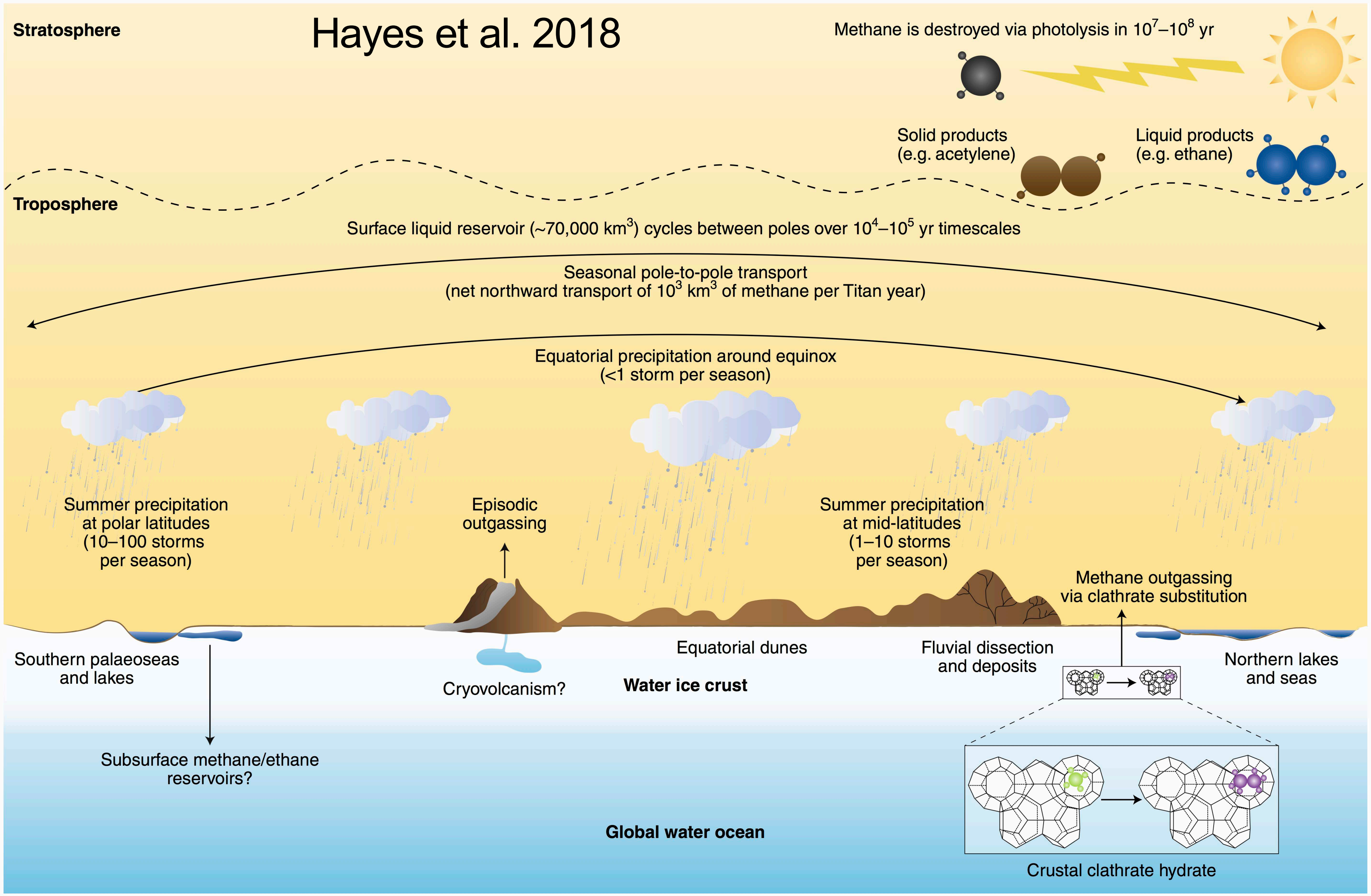




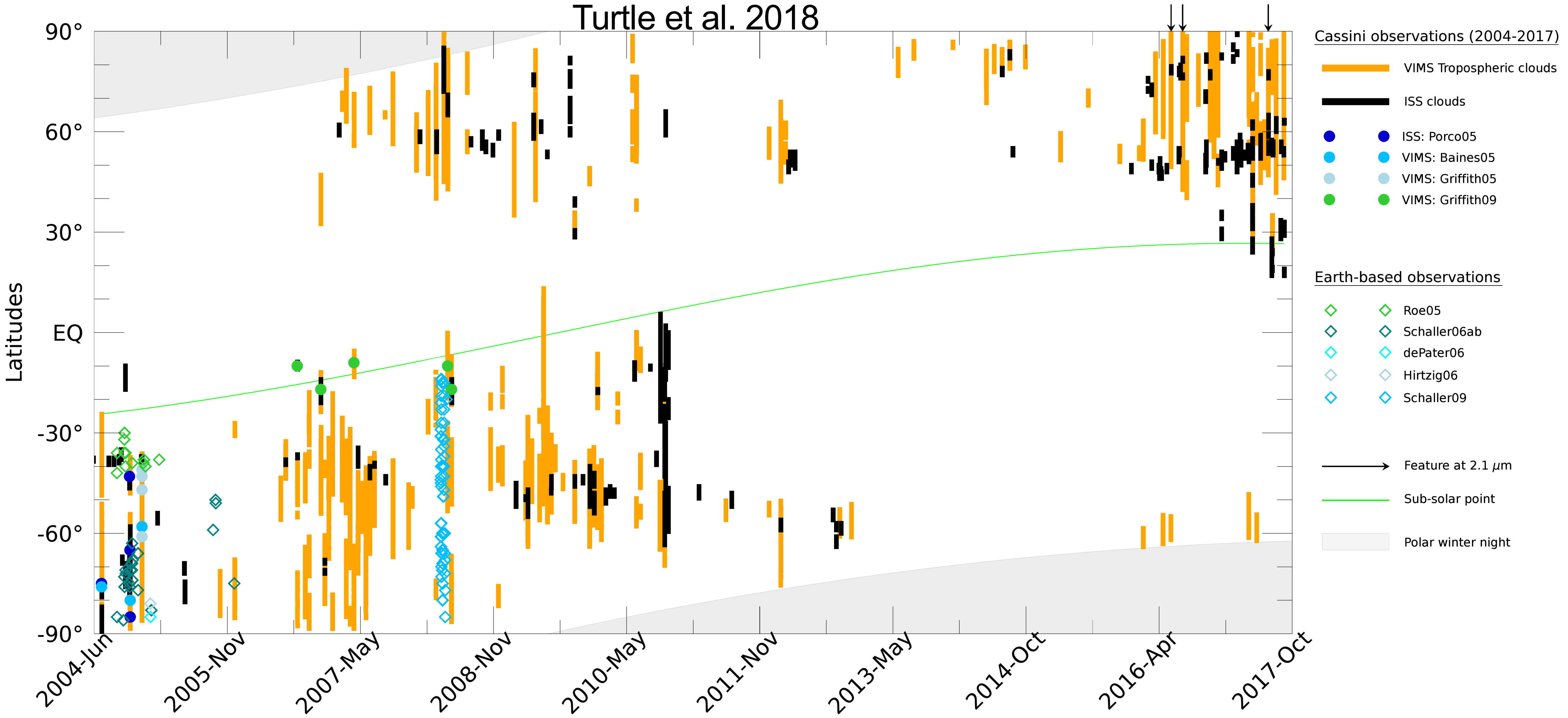


- Combination of features at Doom Mons and Sotra Patera strongly suggestive of cryovolcanic origin (Lopes et al. 2013)
- Possible flow-like features at Tui and Hotei, temporal variations (Solomonidou et al. 2016)
- Unknowns
  - Degree of resupply of methane from interior (Tobie et al. 2014)
  - Challenge of distinguishing between hydrologic and cryovolcanic processes (Moore and Pappalardo 2011)

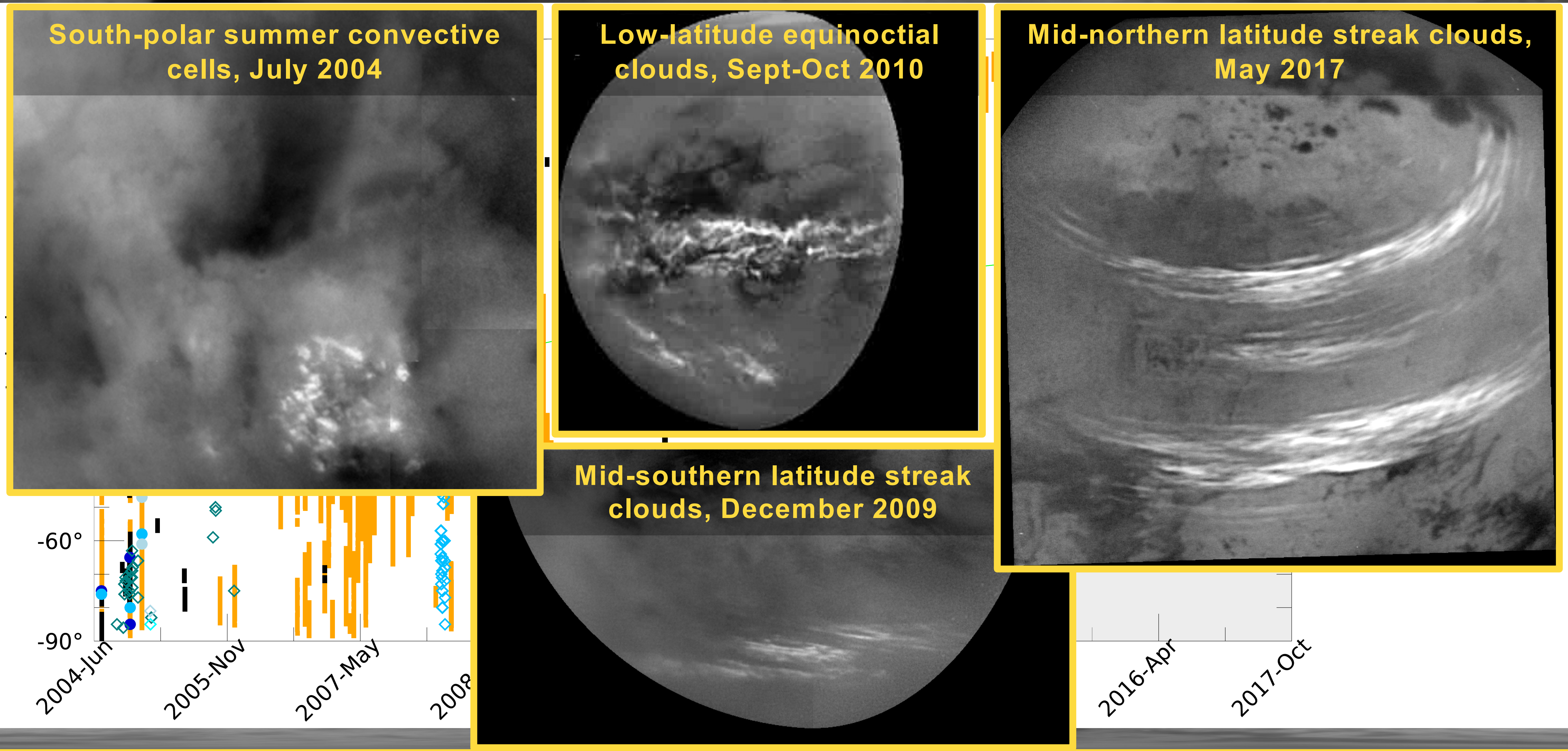
Methane Cycle and subsurface reservoirs



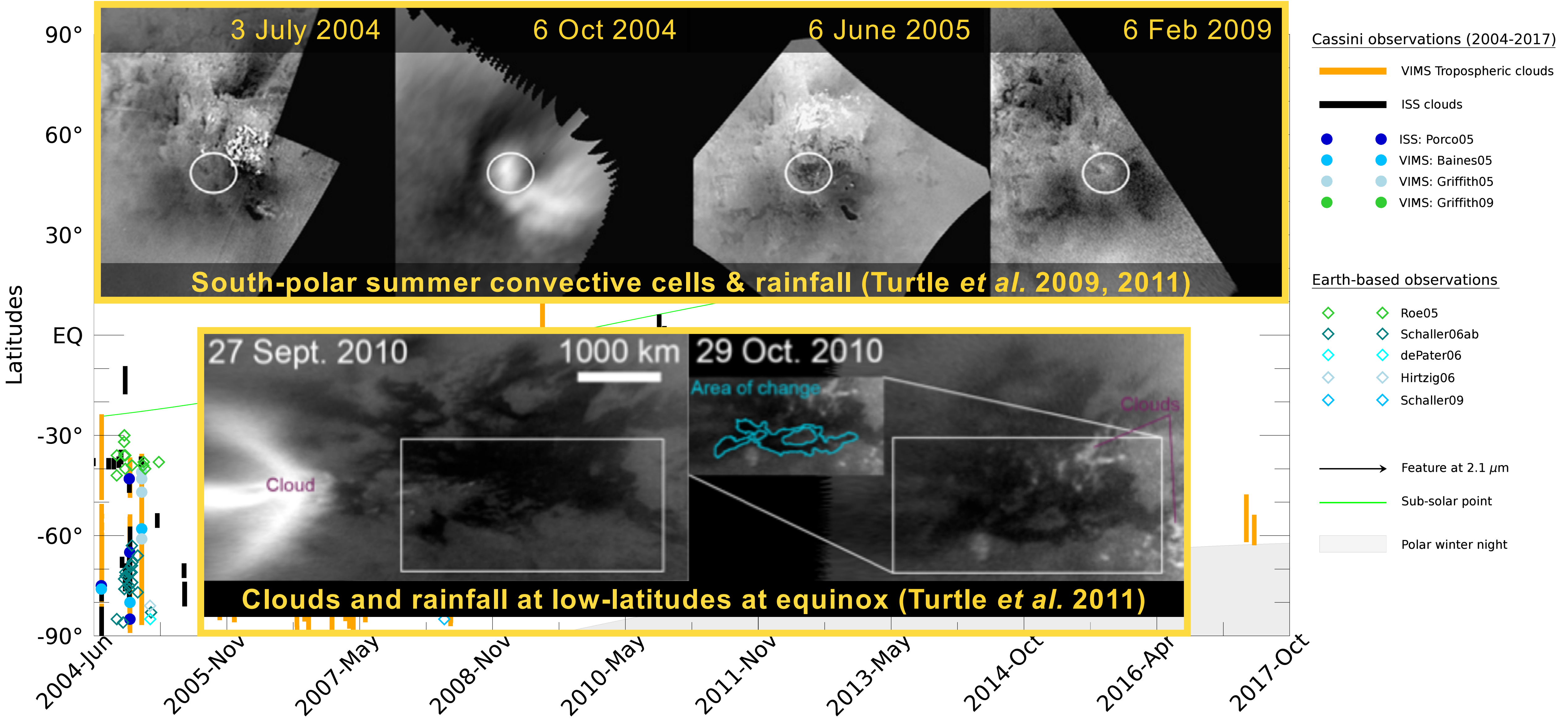
Methane Cycle and subsurface reservoirs



Methane Cycle and subsurface reservoirs



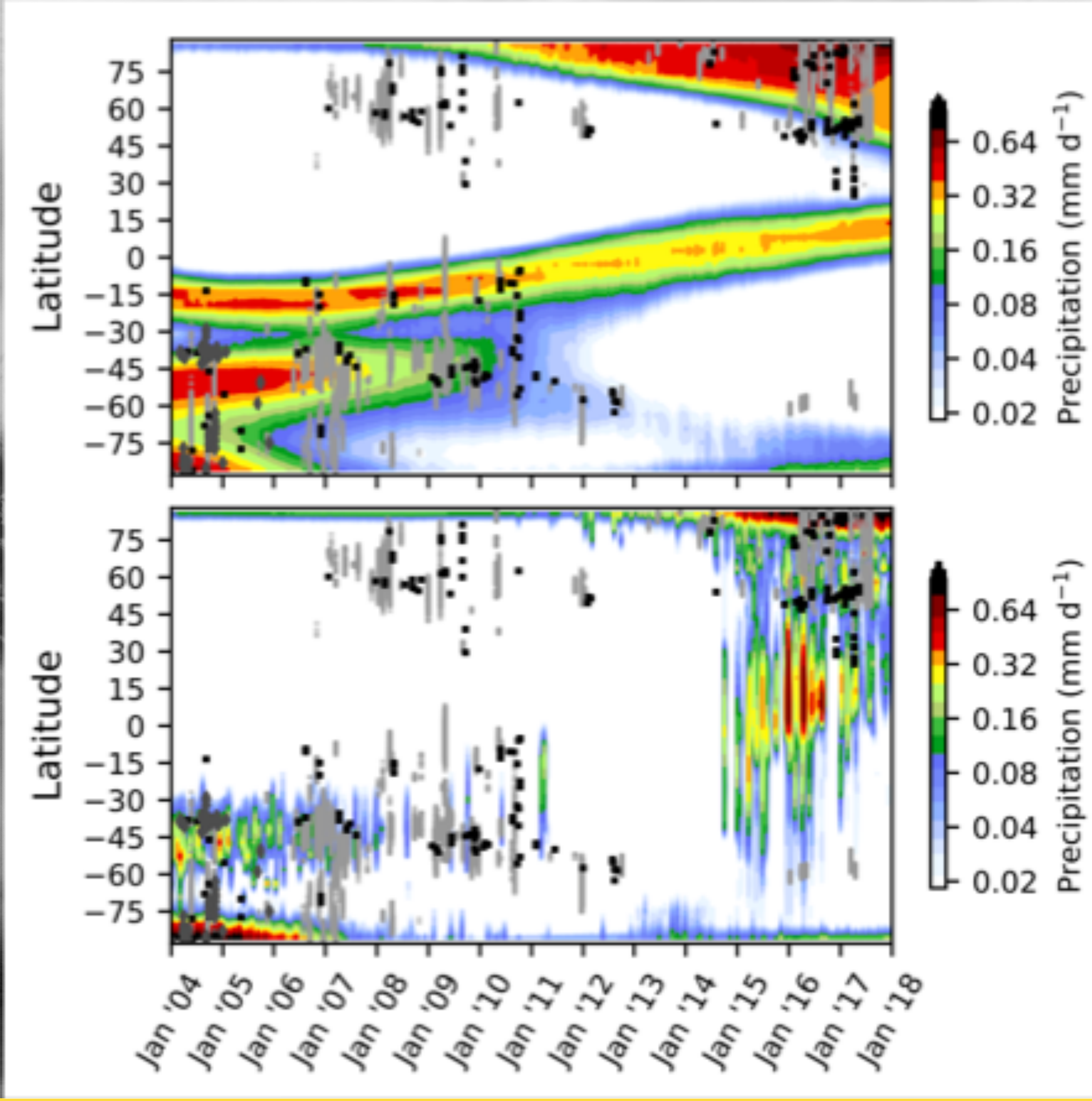
Methane Cycle and subsurface reservoirs



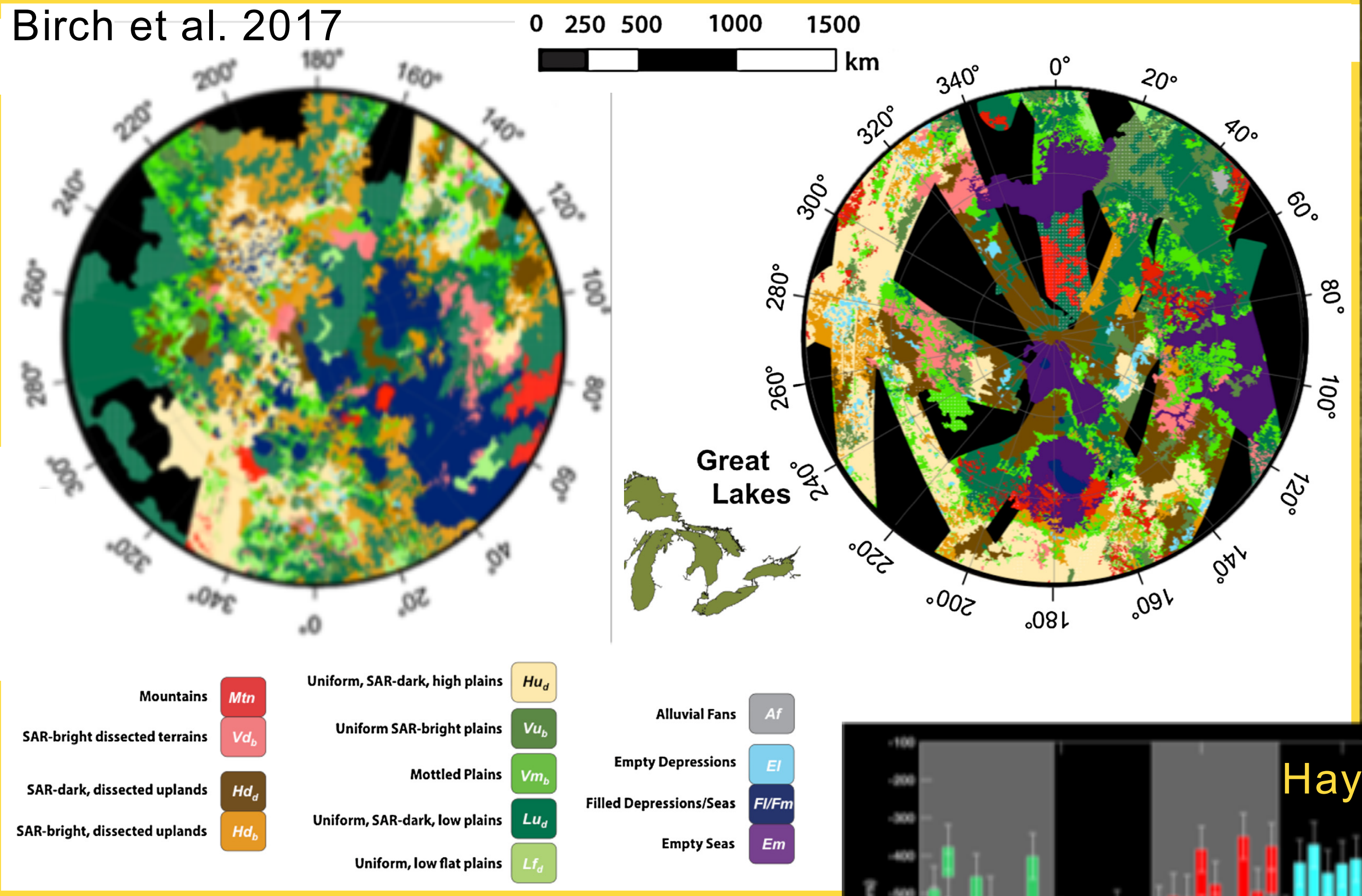
Methane Cycle and subsurface reservoirs

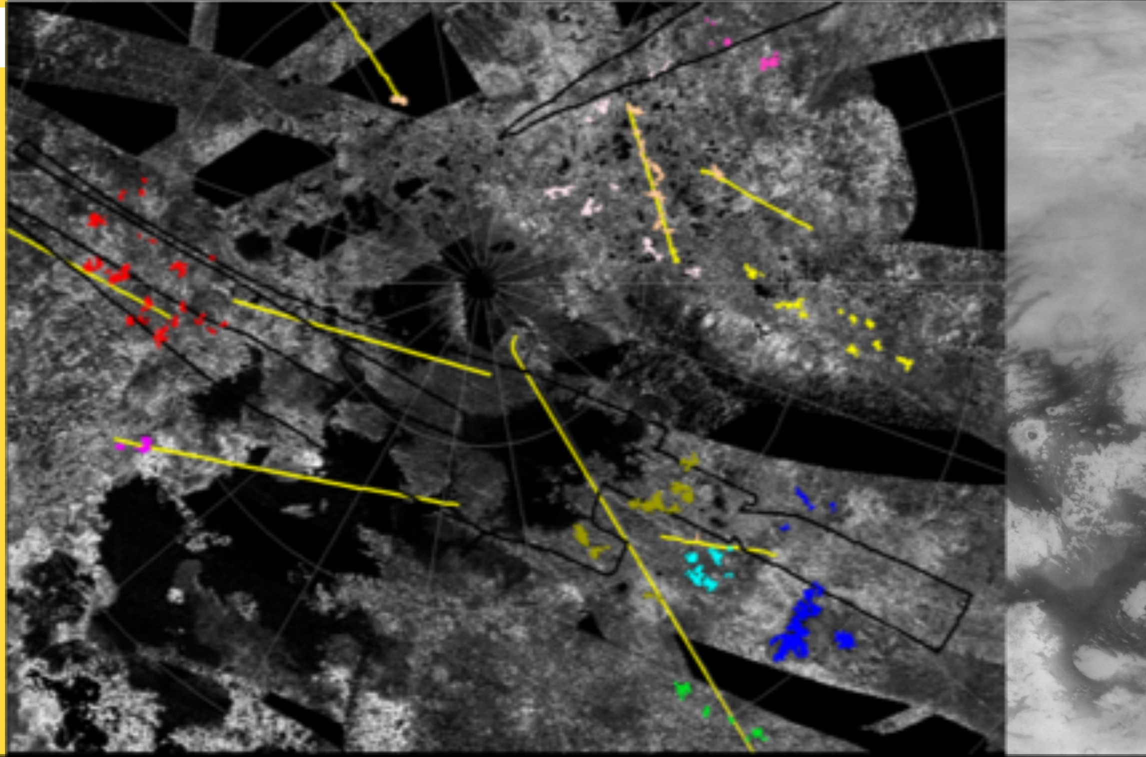
- Atmospheric circulation models with an unlimited global reservoir predict zonal mean precipitation patterns that move from pole to pole, overestimating low-latitude activity particularly around equinox and north-polar clouds and precipitation in northern summer
- Polar wetlands model – dry lower latitudes and subsurface reservoirs at both poles – better matches observed cloud locations and timing as well as sporadic nature or activity

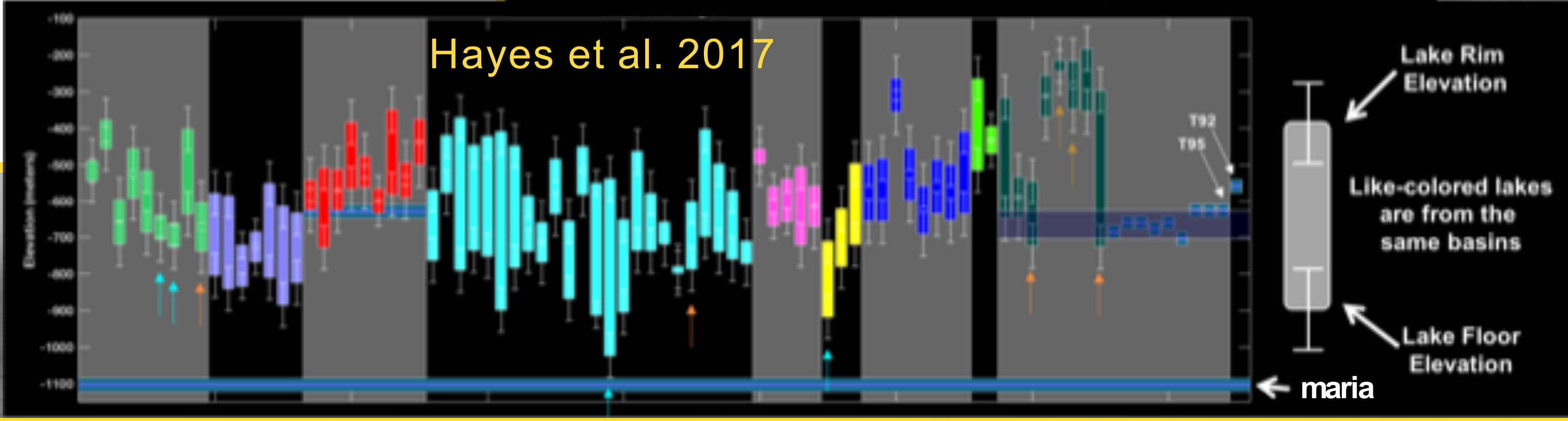
(Faulk *et al.* 2017; Turtle *et al.* 2018)



Methane Cycle and subsurface reservoirs



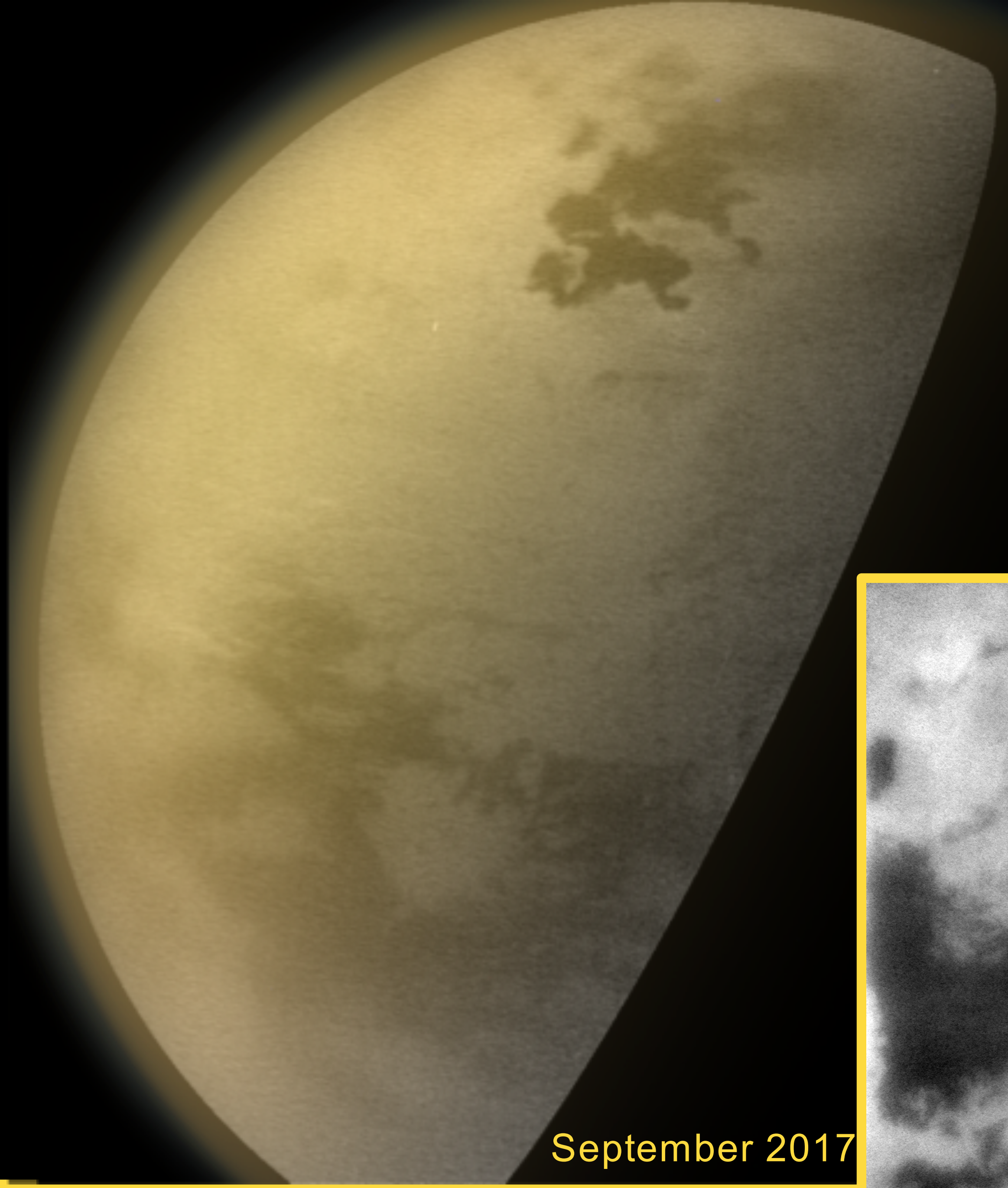




Methane Cycle and subsurface reservoirs

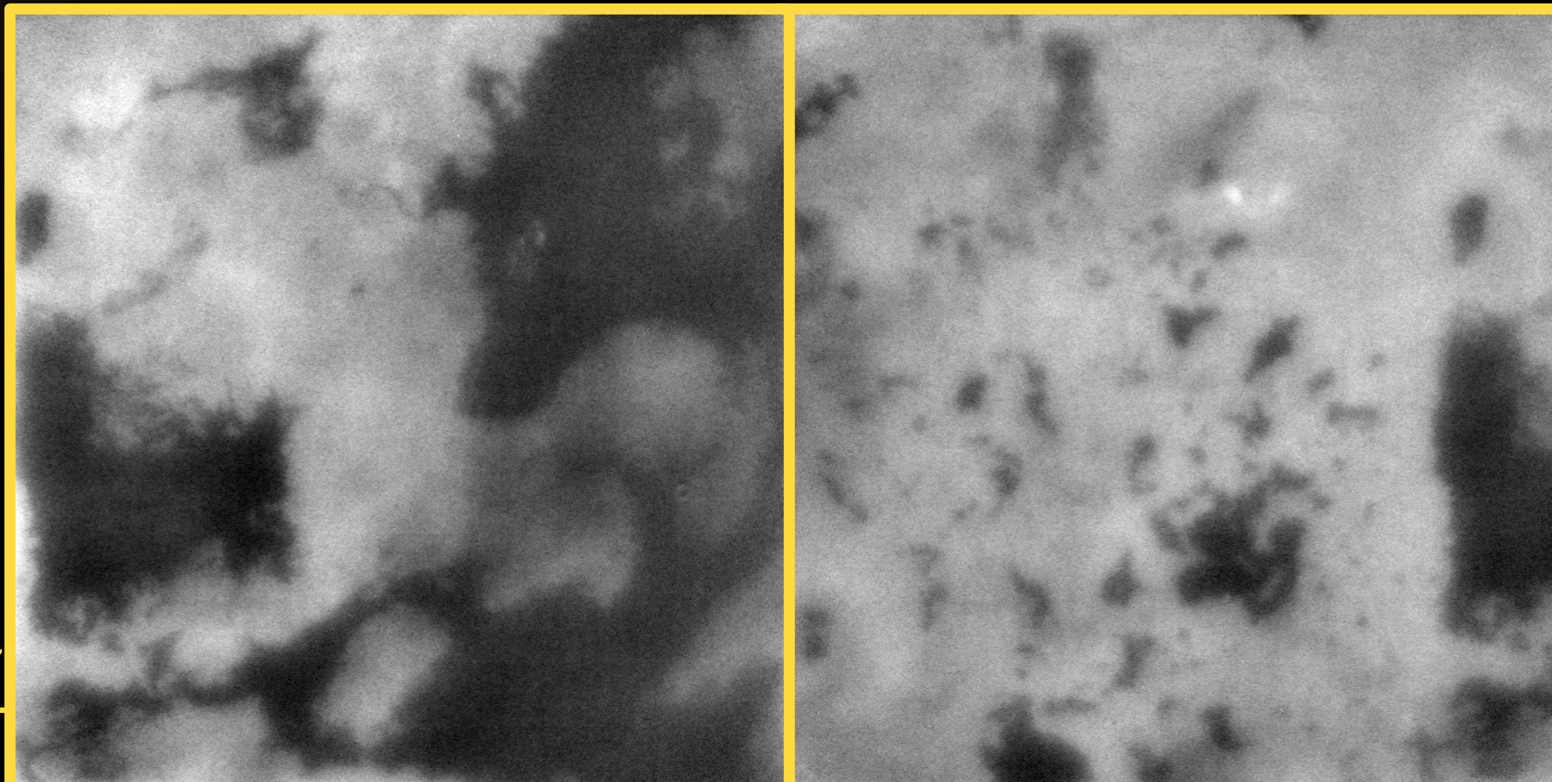
ISS, September 2017

- Observations spanning almost half a Titan year (equivalent of mid-January – late June on Earth) document seasonal weather patterns (Turtle et al. 2018)
- Multiple lines of evidence suggest connected hydrology at Titan's north pole (e.g., Hayes et al. 2008, 2017; Neish and Lorenz 2014; Jennings et al. 2016; Horvath et al. 2016; Birch et al. 2017; Lora & Ádámkovics 2017; MacKenzie et al., in review)
- Unknowns
  - Were observed weather patterns typical for a Titan year?
  - How late does summer cloud activity at the north pole start?
  - What explains differences in ISS and VIMS cloud observations in 2016–2017?
  - Rates of surface change



September 2017

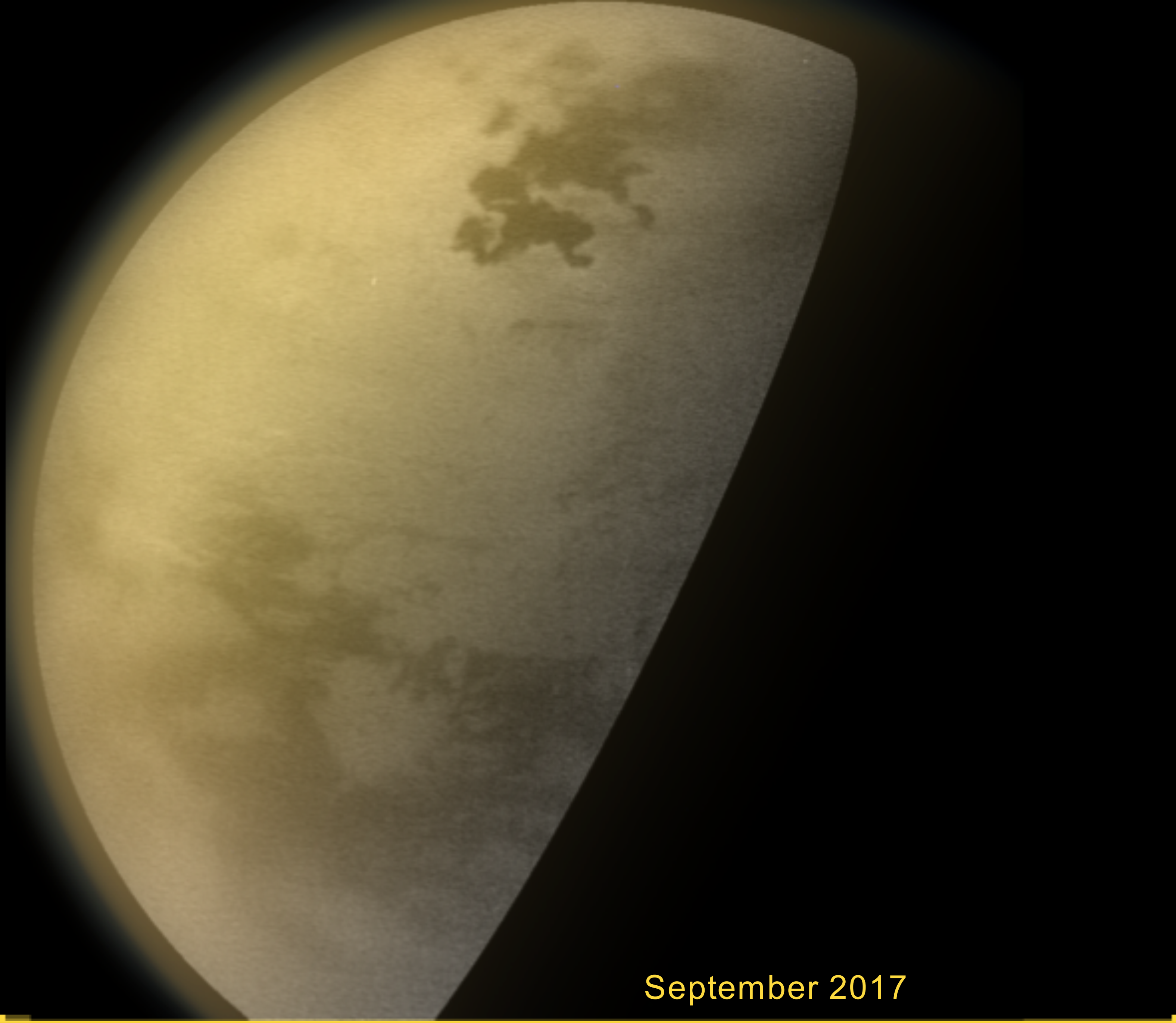
- Nixon et al., *PSS*, 2018, Titan's cold case files – Questions unanswered after Cassini-Huygens
- Titan Through Time, April 2019, Boulder CO
- Titan surface working meeting, June 2019



Next steps: multiple mission concepts for future exploration of Titan, including Dragonfly, a rotorcraft lander currently under study in the New Frontiers program that would perform in situ investigation of prebiotic chemistry and habitability

Aerial mobility provides access to Titan's diverse materials at a wide range of geologic settings *10s to 100s of kilometers* apart in *over 2 years of exploration*

- Rich, multidisciplinary science at each landing site, with ***dozens of potential sites***



September 2017