13 années d'exploration de Titan avec la mission Cassini-Huygens

La fin d'une épopée extraordinaire

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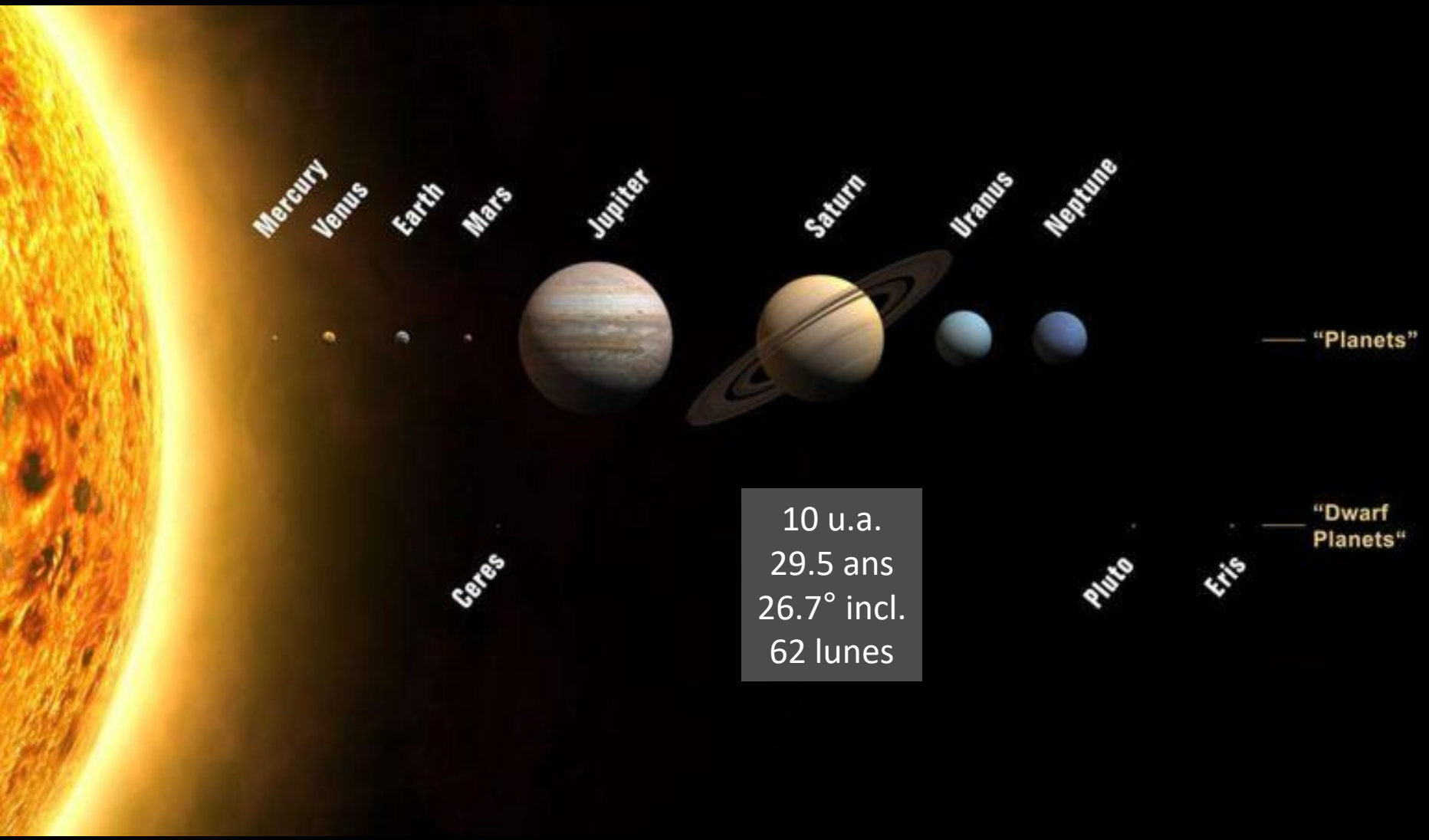
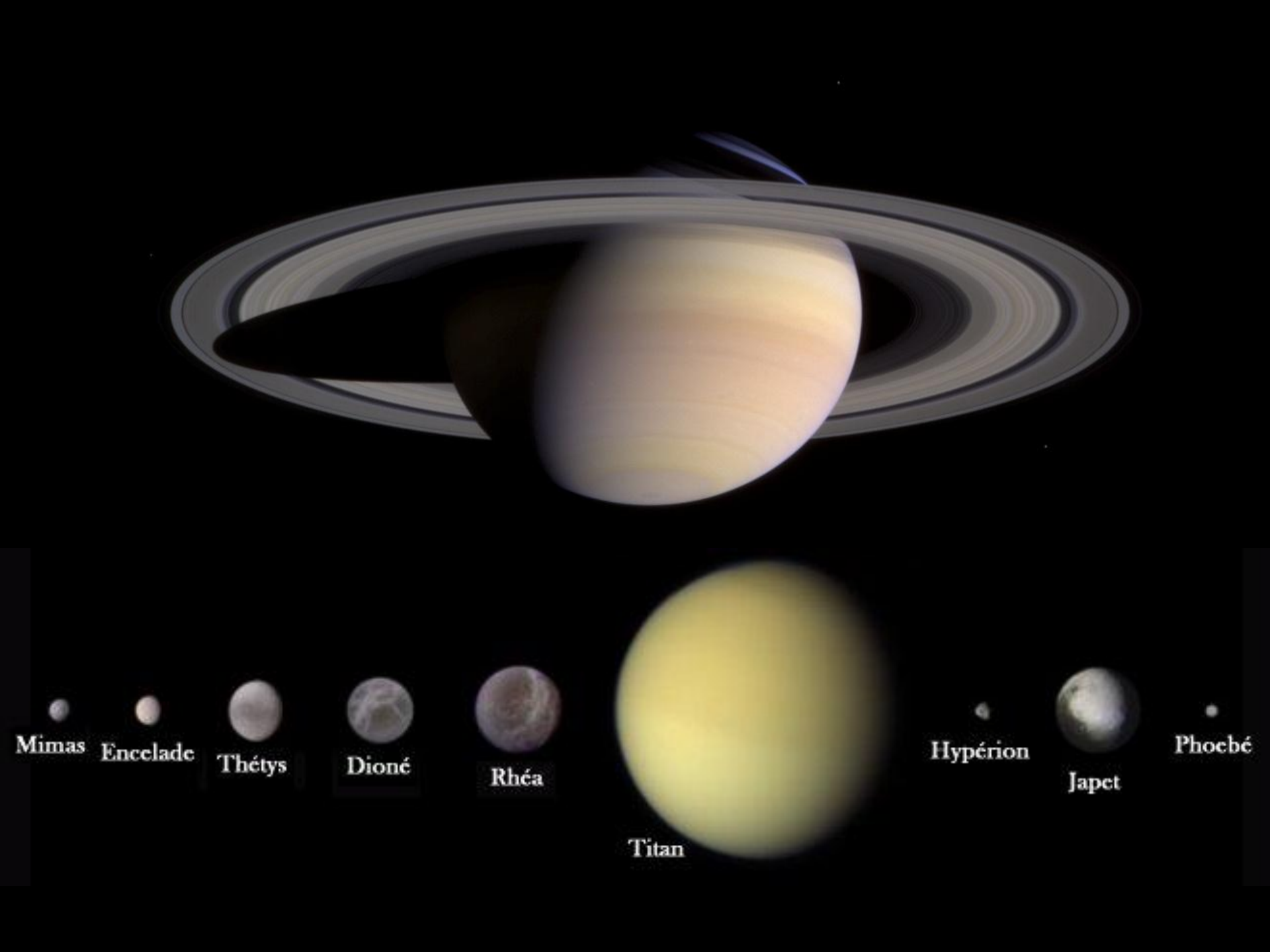
Université Paris Diderot – Paris 7 / USPC

Festival de Fleurance - 06/08/2018


Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
Ceres
Pluto
Eris
"Dwarf Planets"
10 u.a.
29.5 ans
26.7° incl.
62 lunes


Mimas
Encelade
Thétys
Dioné
Rhéa
Titan
Hypérion
Japet
Phoebé

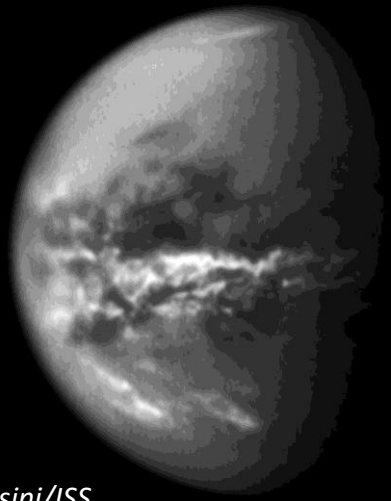
TITAN

UN CORPS PLANETAIRE TRES RESSEMBLANT A LA TERRE, MAIS DANS UN ENVIRONNEMENT EXOTIQUE

R_E = 6371 km

Le seul satellite avec une atmosphère

R_T = 2575 km



Cassini/ISS

Titan

P_{surf}= 1.45 atm
T_{surf}= 94 K
Composition: **N_2**, **CH_4**, C_2H_6, Ar

Terre

P_{surf}= 1 atm
T_{surf}= 288 K
Composition: **N_2**, O_2, **H_2O**, Ar

67P Tchouri [Philae Rosetta]
ESA/Rosetta/Philae/CIVA

Planetary Surfaces

Image Credits:
Venus [Venera 14]: IKI / Don Mitchell / Ted Stryk / Mike Malaska
Earth: Mike Malaska
Moon [Apollo 17]: NASA
Mars [Mars Exploration Rover Spirit]: NASA / JPL / Cornell / Mike Malaska
Asteroid Itokawa [Hayabusa]: ISAS / JAXA / Gordan Ugarkovic
Titan [Cassini Huygens]: ESA / NASA / JPL / University of Arizona

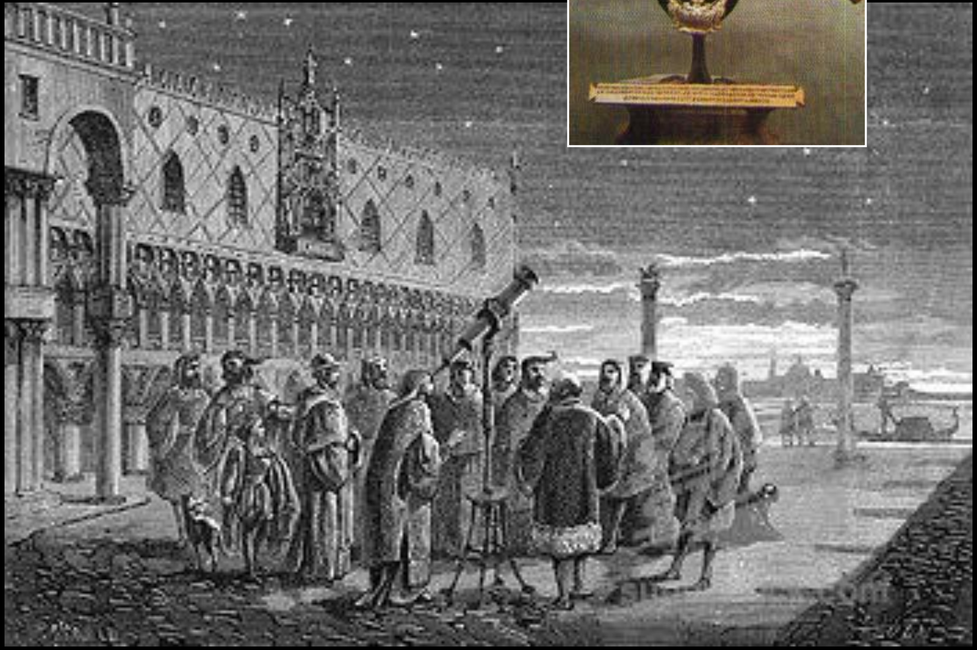
Composition by Mike Malaska

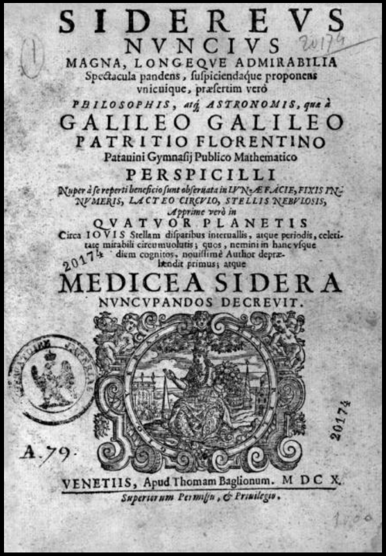
Un peu d’histoire

Galilée (1564-1642)
Dès 1609

- Lune
- Tâches solaires
- Voie lactée
- Amas
- Jupiter & satellites
- Saturne & anneaux (?)

…

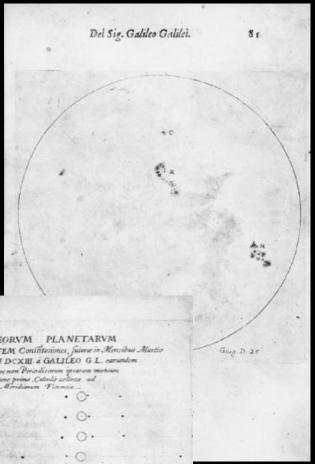


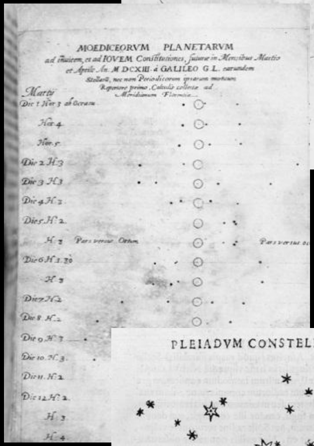


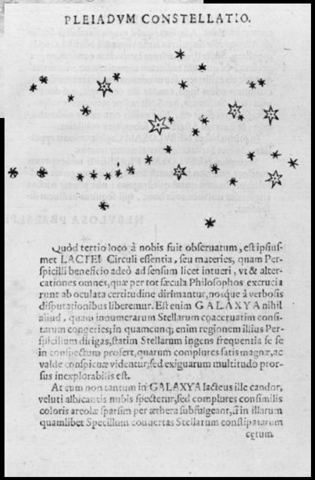
SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author deprælendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

Siderius Nuncius, Le Messager céleste, mars 1610





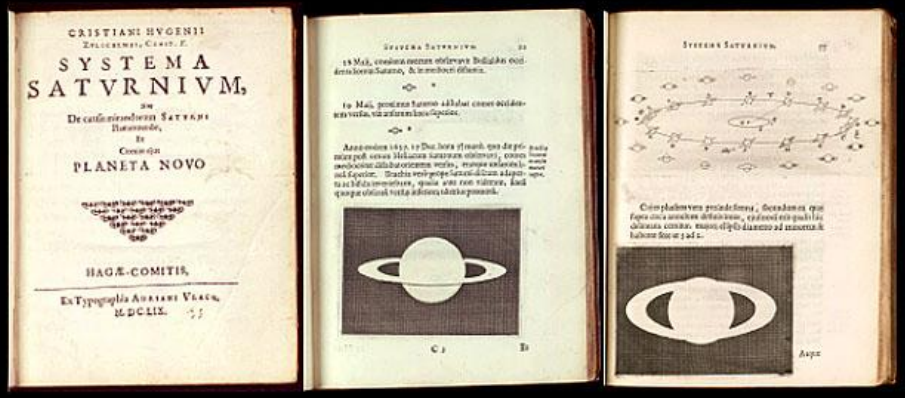


PLEIADVM CONSTELLATIO.

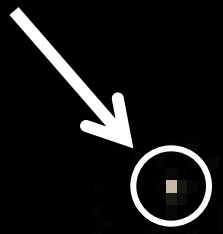
Quòd tertio loco à nobis fuit obseruatum, est ipsiusmet LACTEI Circuli essentia, seu materies, quam Perspicilli beneficio adeò ad sensum licet intueri, vt & altercationes omnes, quæ per tot sæcula Philosophos excruciarunt ab oculata certitudine dirimantur, nosque à verbosis disputationibus liberemur. Est enim GALAXYA nihil aliud, quam innumerarum Stellarum coaceruatim consitarum congeries; in quamcunq; enim regionem illius Perspicillum dirigas, statim Stellarum ingens frequentia se se in conspectum profert, quarum complures satis magnæ, ac valde conspicuæ videntur; sed exiguarum multitudo prorsus inexplorabilis est.

At cum non tantum in GALAXYA lacteus ille candor, veluti albicantis nubis spectetur, sed complures consimilis coloris areolæ sparsim per æthera subfulgeant, si in illarum quamlibet Specillum conuertas Stellarum constipatarum cœtum

Christiaan Huygens (1629-1695)
1655



Systema Saturnium, 1659



J.D. Cassini :
Japet, Rhéa, Thétys, Dioné

W. Herschel :
Mimas, Encelade

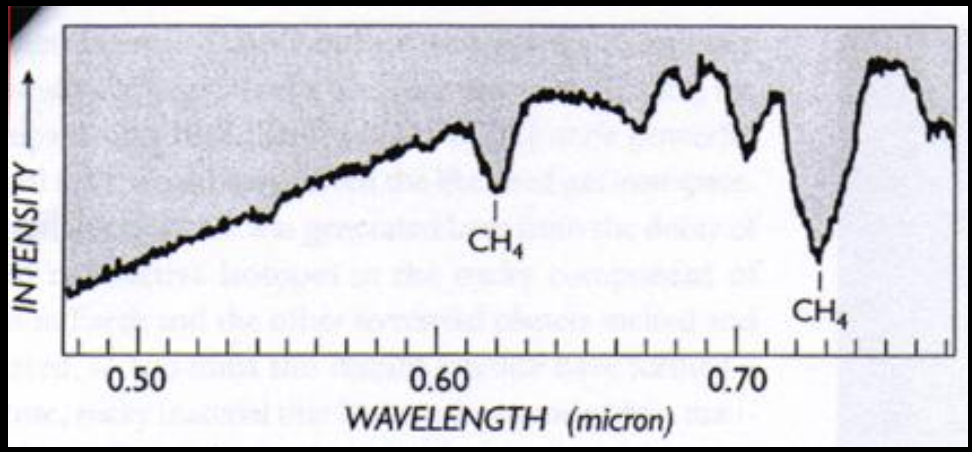
Josep Comas i Solà (1868-1937)
1907

13 août 1907 12h

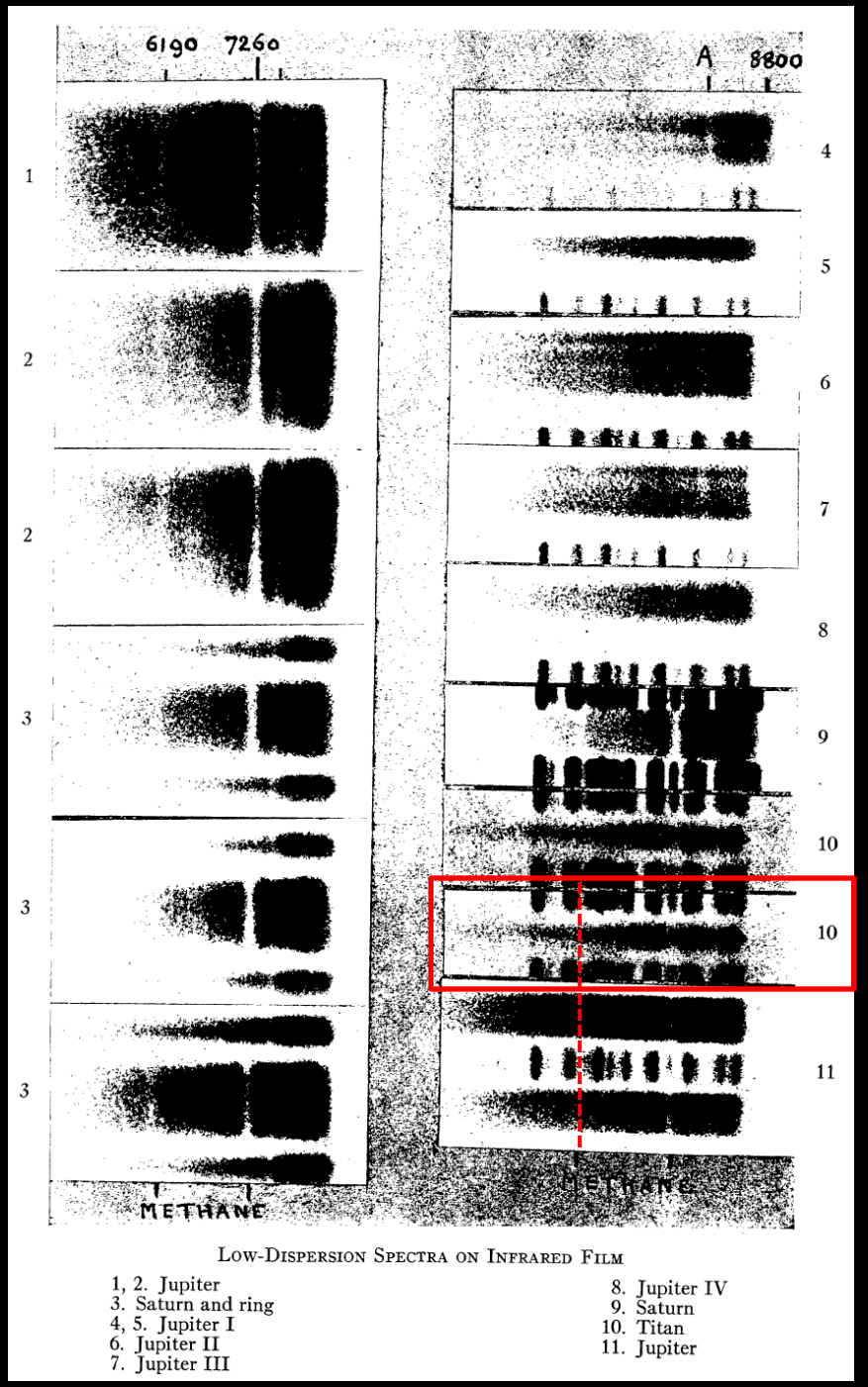
Titan

"...I have observed that Titan's disc becomes darker at its edge. We may reasonably suppose that this demonstrates the existence of a strongly absorbent atmosphere around Titan." Josep Comas i Solà (1907)

Gerard Kuiper (1905-1973)
1944



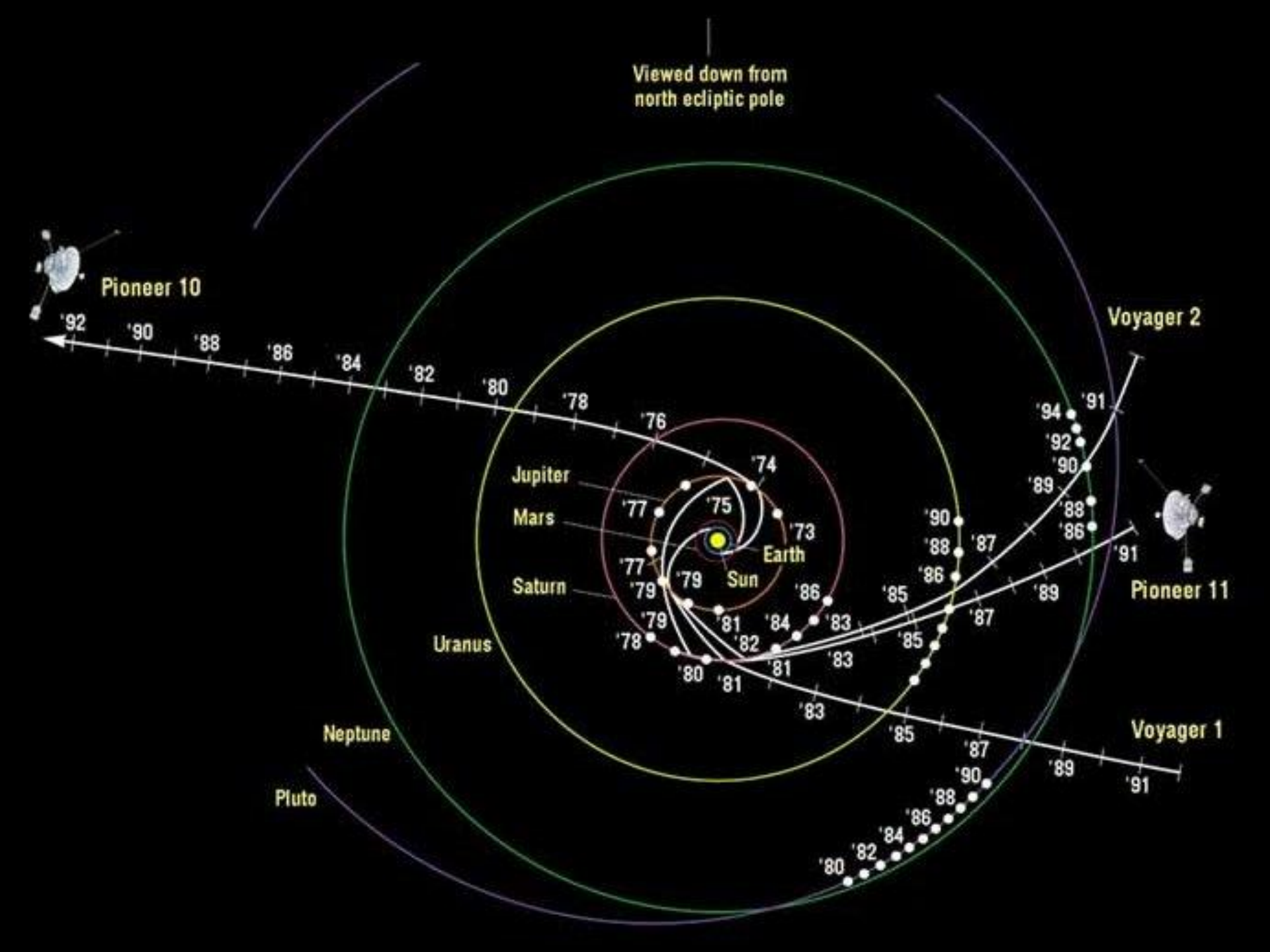
Après cela, les découvertes s'accélèrent :
N_2, C_2H_6, CH_3D, C_2H_4, C_2H_2



Low-Dispersion Spectra on Infrared Film

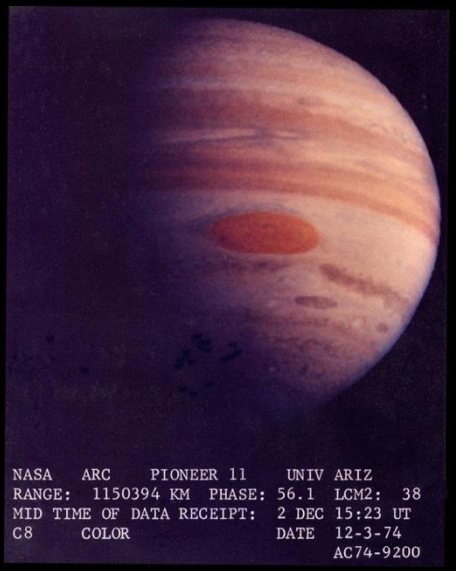
1, 2. Jupiter
3. Saturn and ring
4, 5. Jupiter I
6. Jupiter II
7. Jupiter III
8. Jupiter IV
9. Saturn
10. Titan
11. Jupiter

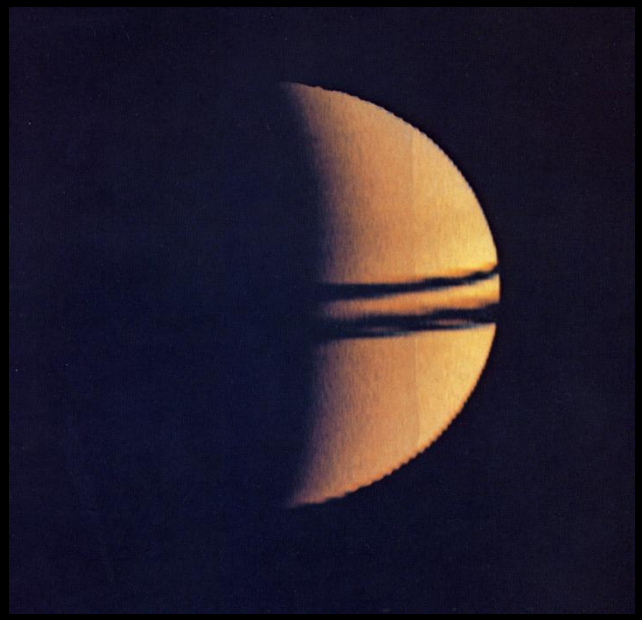
L’ère spatiale : 1979-1981

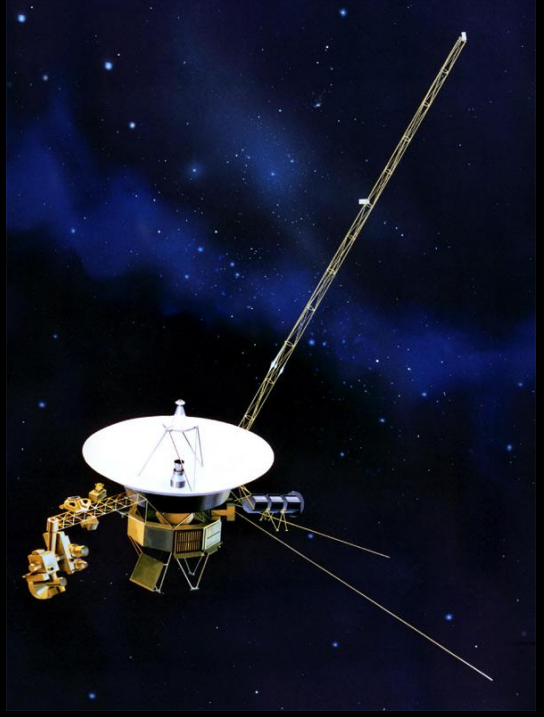

Viewed down from
north ecliptic pole
Pioneer 10
Voyager 2
Pioneer 11
Voyager 1
Jupiter
Mars
Saturn
Uranus
Neptune
Pluto
Earth
Sun
'92
'90
'88
'86
'84
'82
'80
'78
'76
'74
'77
'75
'73
'79
'81
'83
'85
'87
'89
'91
'94

Pioneer 11 (1973)

Survol de Saturne : 1er septembre 1979 (21 000 km)





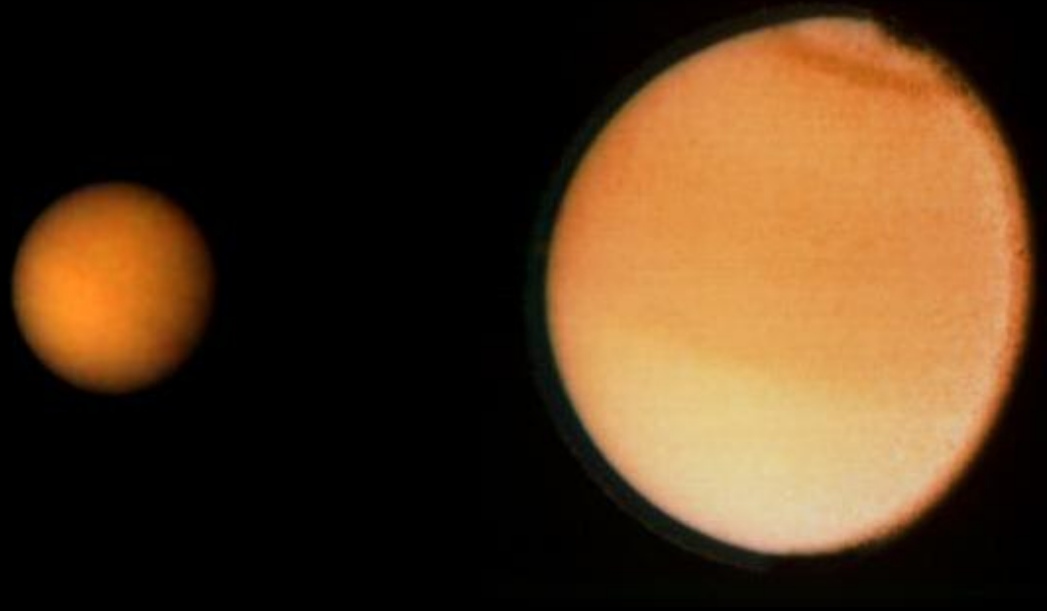


	Voyager 1	Voyager 2
Launch Date	Mon, 05 Sept 1977 12:56:00 UTC	Sat, 20 Aug 1977 14:29:00 UTC
Mission Elapsed Time	40:06:13:21:09:21 (YRS MOS DAYS HRS MINS SECS)	40:06:26:19:36:21 (YRS MOS DAYS HRS MINS SECS)
Distance from Earth	21,151,752,132 km	17,551,261,276 km
	141.39072992 AU	117.32293511 AU
Distance from Sun	21,176,614,475 km	17,505,323,420 km
	141.55692442 AU	117.01585950 AU
Velocity with respect to the Sun (estimated)	16.9995 kps	15.3741 kps
One-Way Light Time	19:35:54 (hh:mm:ss)	16:15:44 (hh:mm:ss)
Cosmic Ray Data	0 5 10 15 20 / 0 1 2 3 4	0 10 20 30 40 / 0 1 2 3 4

IMP MET

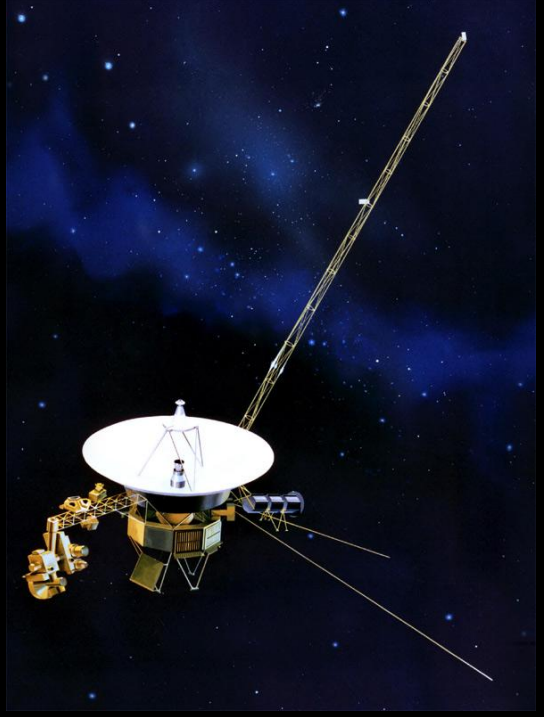
Voyager 1 & 2 (1977)

Survols de Saturne – Titan :
12 nov. 1980 (124 000 km – 6 490 km)
25 août 1981 (101 000 km – 665 960 km)



4 nov. 1980 (12 millions km) [V1]

23 août 1981 (2.3 millions km) [V2]



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Mission Elapsed Time	40:06:13:21:09:21 (YRS MOS DAYS HRS MINS SECS)	40:06:26:19:36:21 (YRS MOS DAYS HRS MINS SECS)
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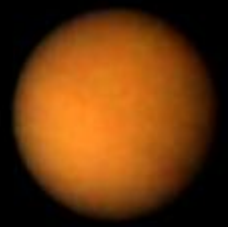
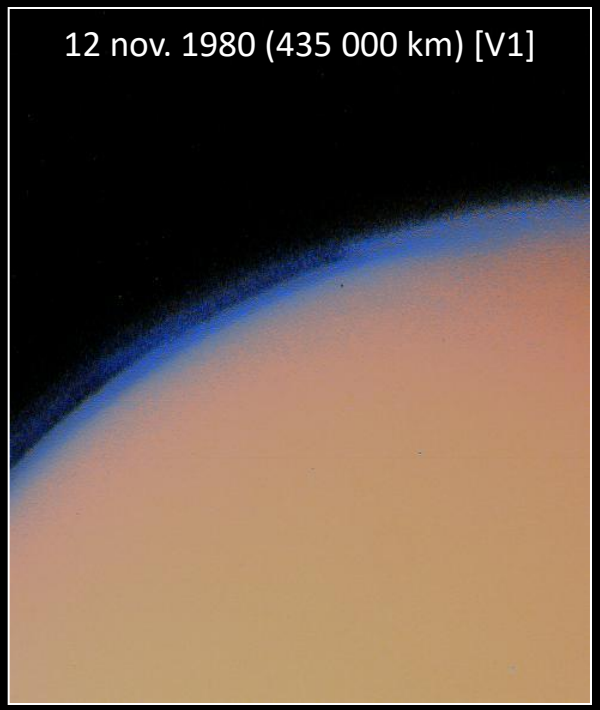
IMP MET

Voyager 1 (1977)

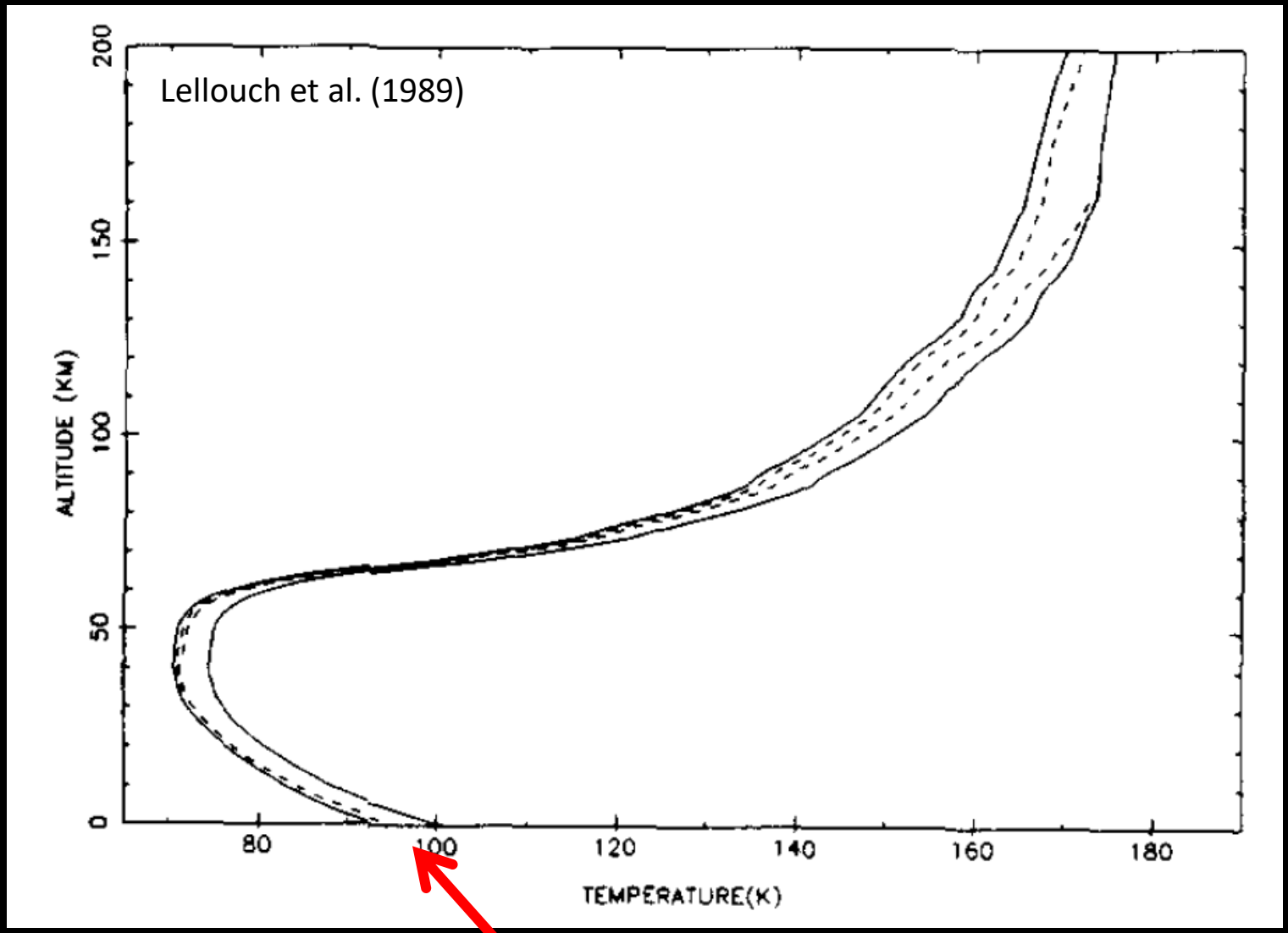
Survols de Saturne – Titan :
12 nov. 1980 (124 000 km – 6 490 km)



4 nov. 1980 (12 millions km) [V1]

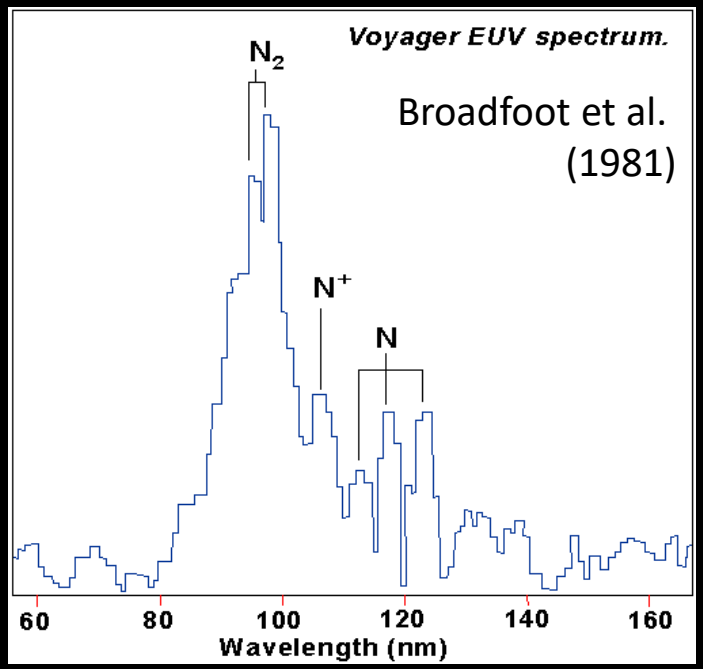


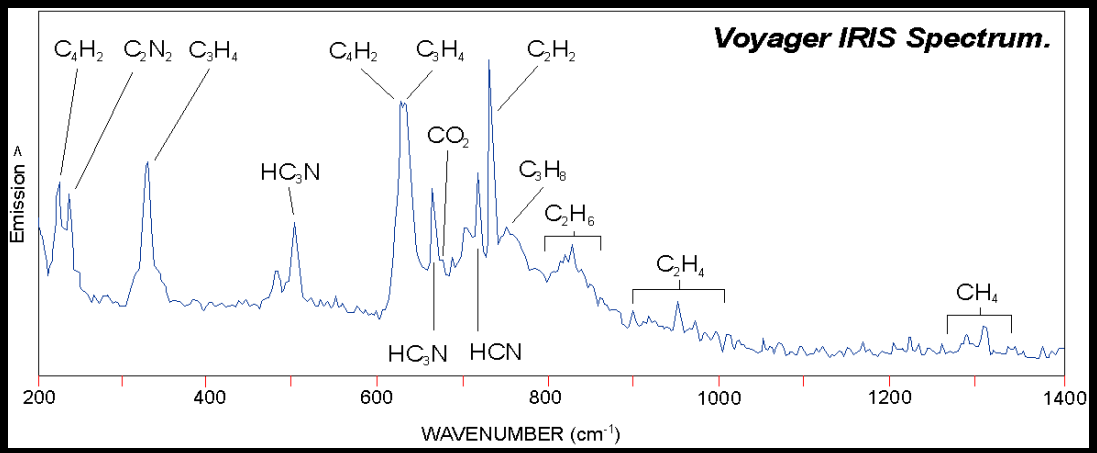
Une atmosphère très proche de celle de la Terre, mais en plus froid !



94 K (-179°C) et 1,44 bar

Une chimie organique en phase gazeuse très active !

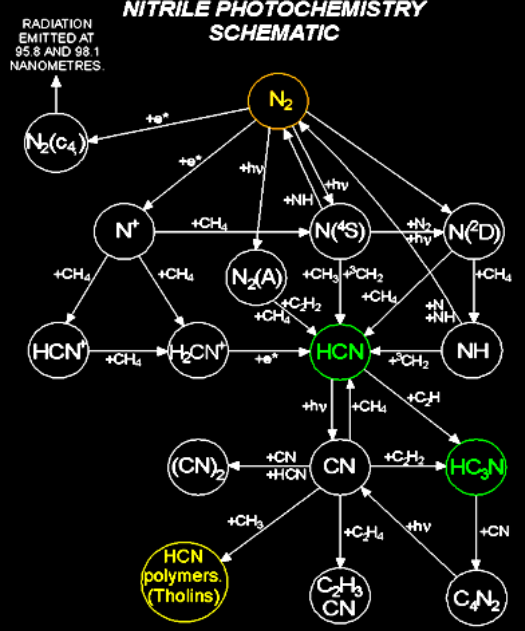


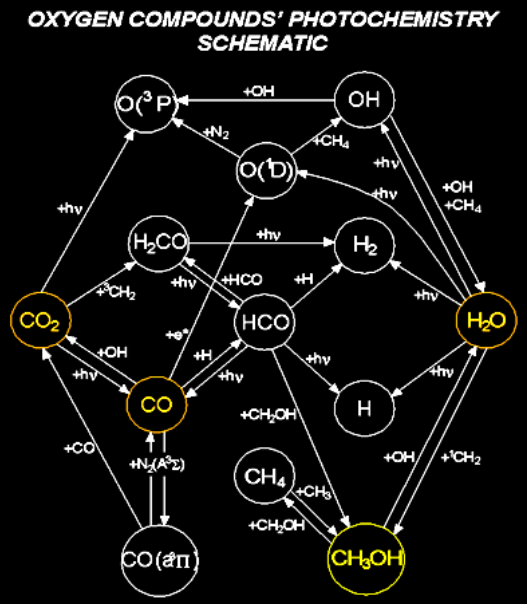


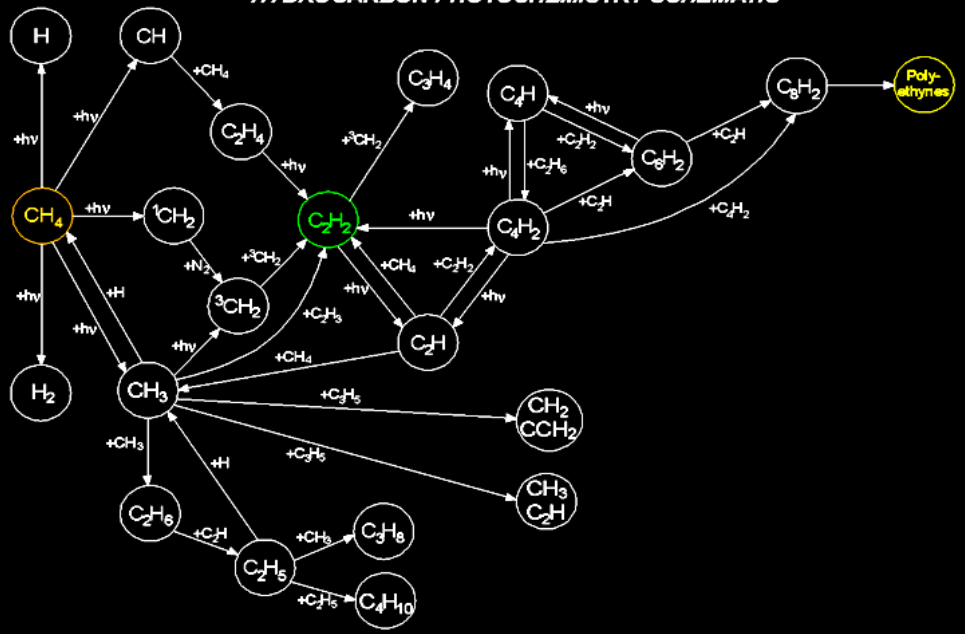
Courtin (1982)

N_2	Nitrogen	77-85%
^{36}Ar	Argon	≈ 12-17%
CH_4	Methane	≈ 3-6%
H_2	Hydrogen	0.1-0.4%
C_2H_6	Ethane	20ppm
C_3H_8	Propane	5-20ppm
C_2H_2	Ethyne	2ppm
C_2H_4	Ethene	0.4ppm
HCN	Methanenitrile (Hydrogen Cyanide)	0.2ppm
C_4H_2	Butadiyne (Diacetylene)	0.03ppm
C_3H_4	Propyne (Methylacetylene)	0.03ppm
HC_3N	Propynenitrile (Cyanoacetylene)	0.01-0.1ppm
C_2N_2	Ethanedinitrile (Cyanogen)	0.01-0.1ppm
CO_2	Carbon Dioxide	0.01ppm
CO	Carbon Monoxide	10ppm*

D'après Thompson et Sagan (1984)





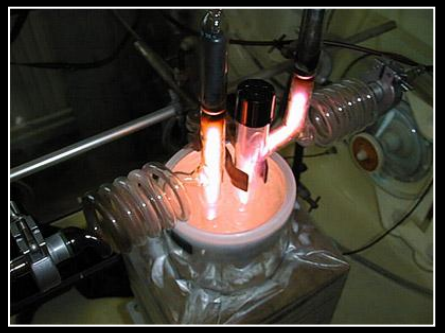


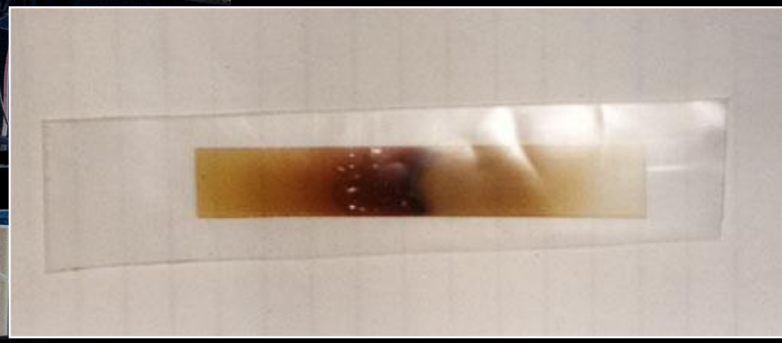
Composition atmosphérique :
N_2 (>80%), CH_4 (6-10%), Ar
+ CO, CO_2, H_2O

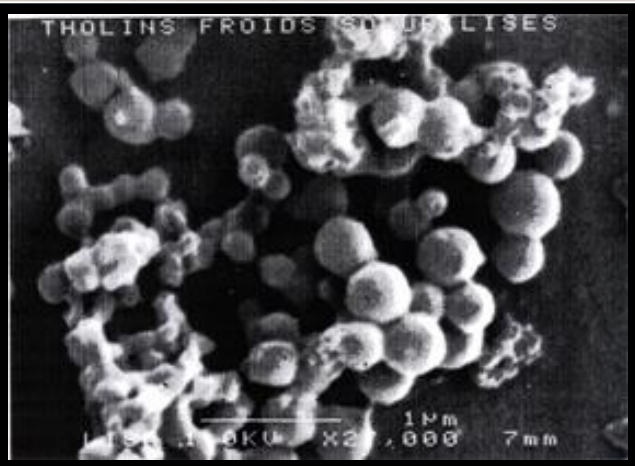
Photochimie du méthane + Chimie de N_2

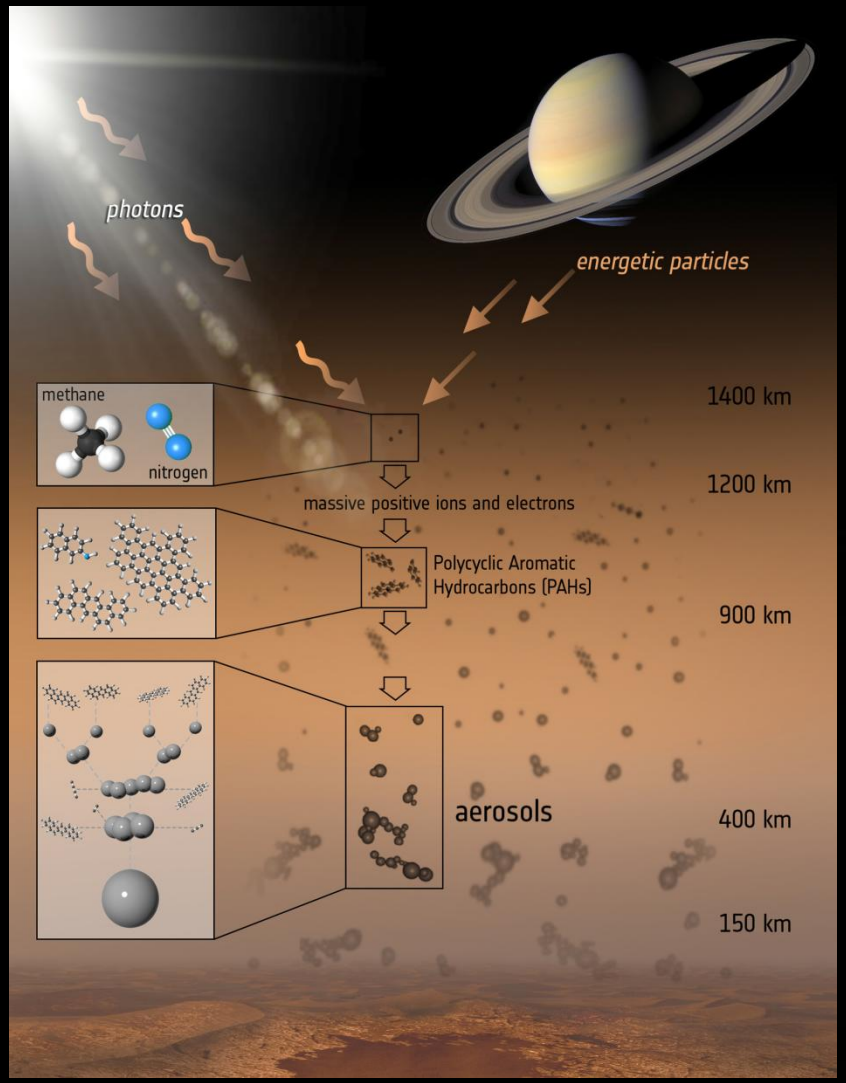
- production d'hydrocarbures et de nitriles, principalement C_2H_6, C_2H_2 (acétylène), C_3H_8, HCN (acide cyanhydrique), HC_3N (cyanoacétylène), CH_3CN …
- La photochimie couplée des hydrocarbures et des nitriles produit des molécules organiques complexes → chimie prébiotique
- Un brouillard d'aérosols se forme à haute altitude par condensation d'oligomères C-H-N-O (« tholins »)


Réacteur
Boîte à gants

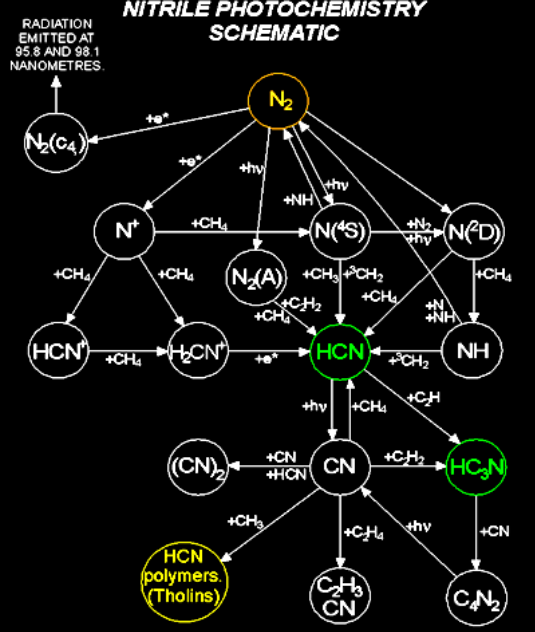


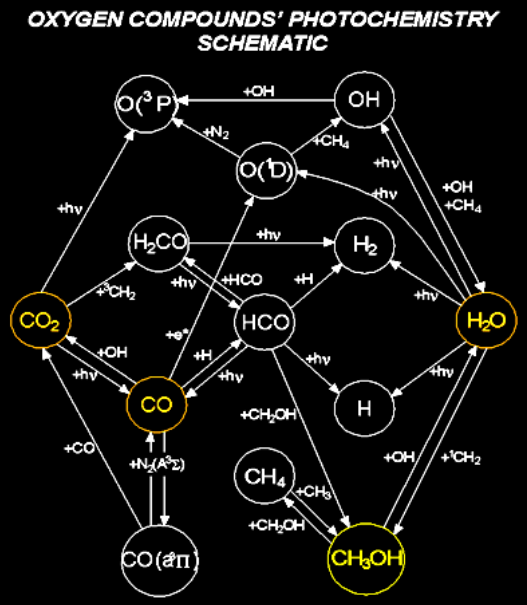


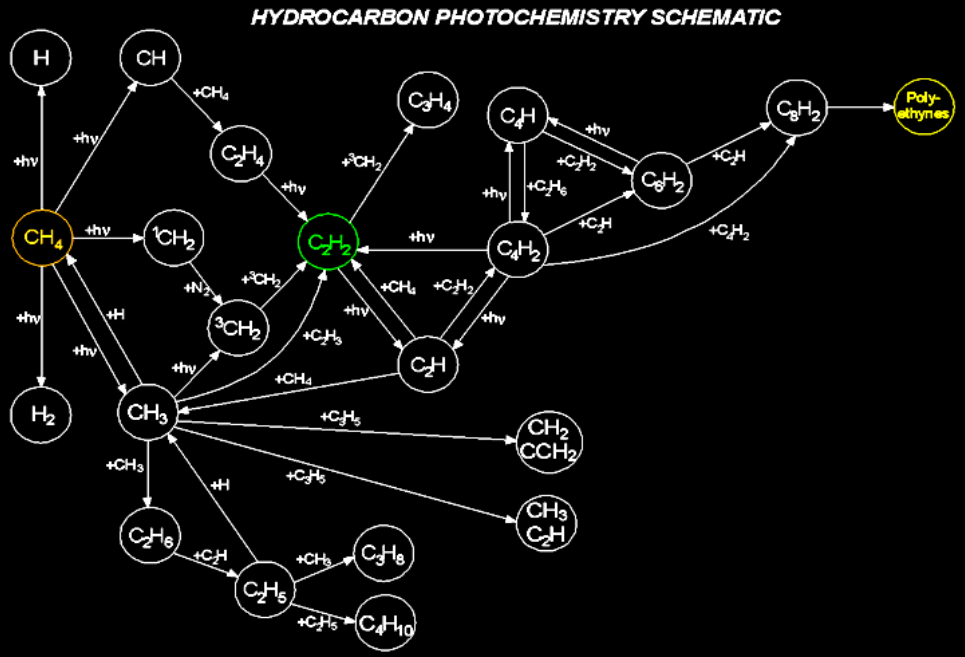

THOLINS FROIDS
1µm
7mm



23 août 1981 (2.3 millions km) [V2]







Composition atmosphérique :
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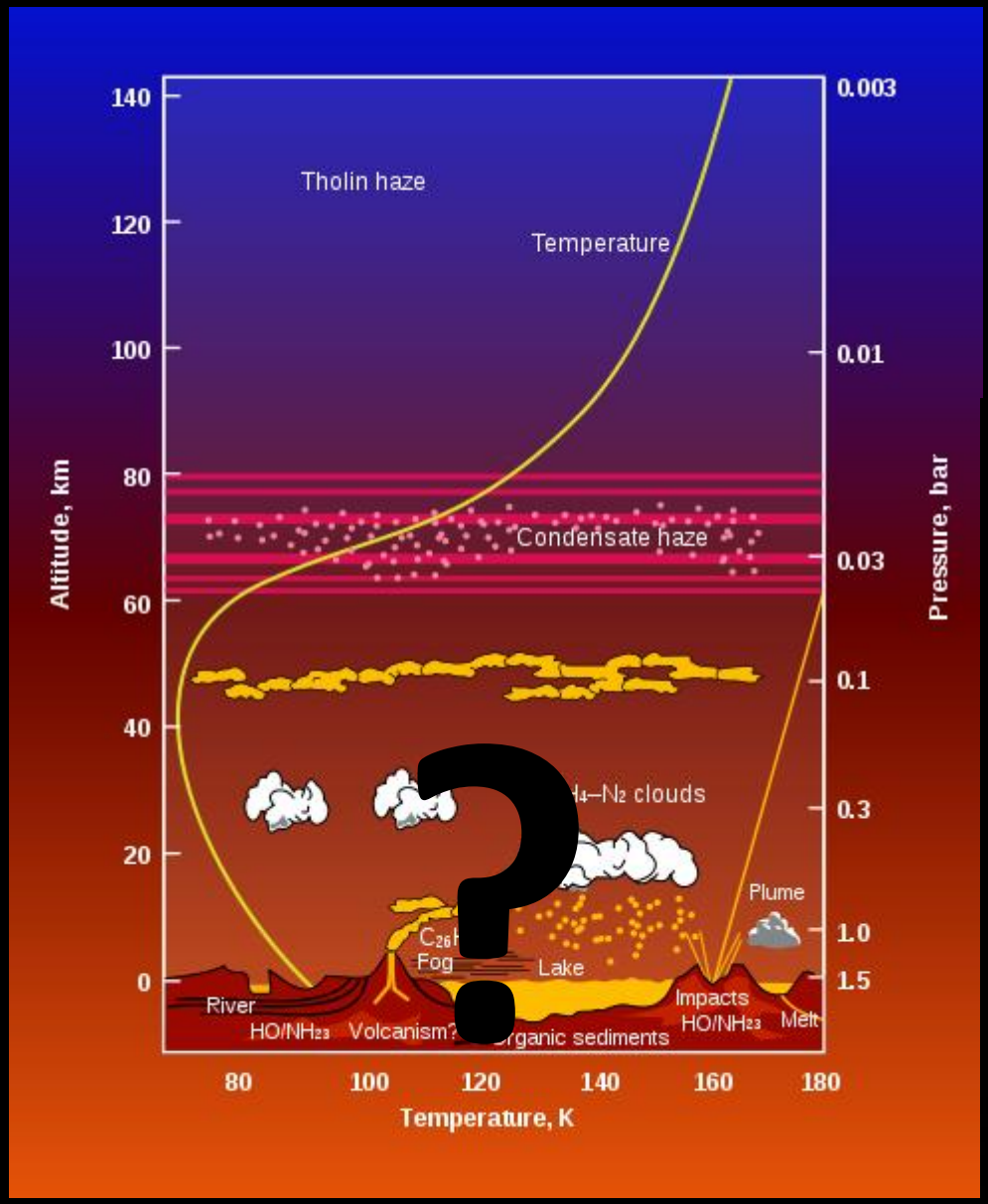
+ CO, CO_2, H_2O

Photochimie du méthane
+
Chimie de N_2

- *production d'hydrocarbures et de nitriles, principalement C_2H_6, C_2H_2, C_3H_8, HCN, HC_3N, CH_3CN …*
- *La photochimie couplée des hydrocarbures et des nitriles produit des molécules organiques complexes → chimie prébiotique*
- *Un brouillard d'aérosols se forme à haute altitude par condensation d'oligomères C-H-N-O (« tholins »)*

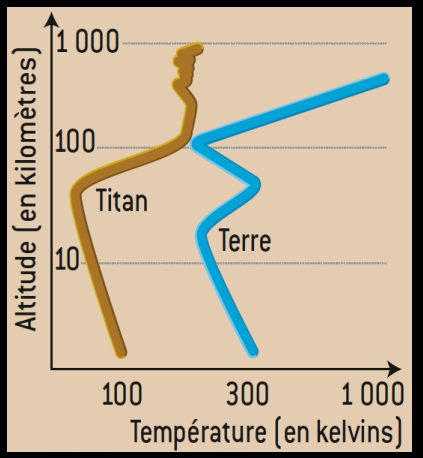
- Formation saisonnière de nuages dans la basse atmosphère par la condensation d'hydrocarbures ?

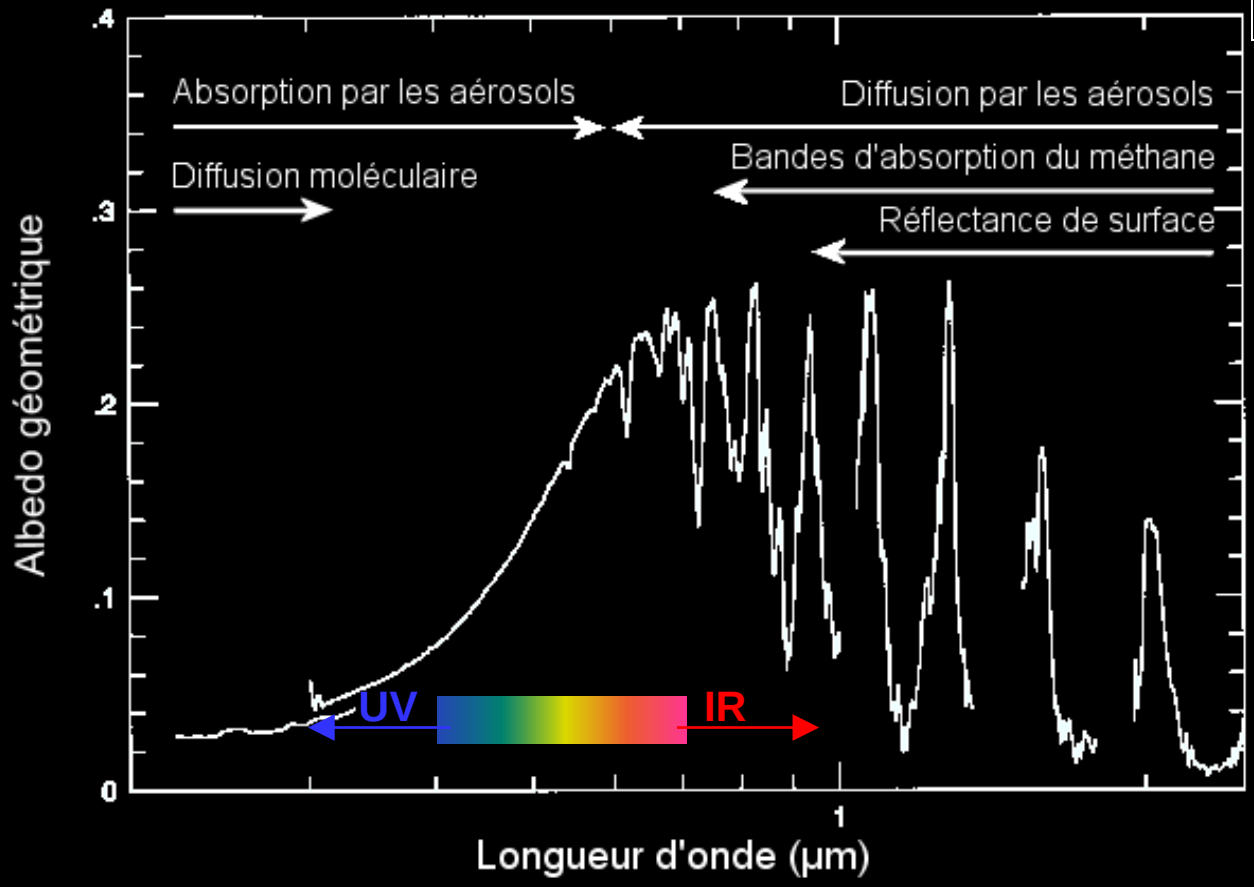
Une atmosphère très proche de celle de la Terre, mais en plus froid !



≈ 90 % de N_2

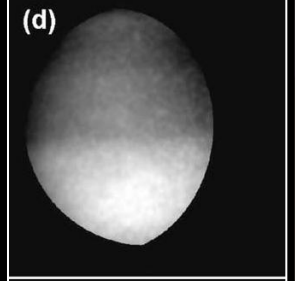
≈ 10 % de CH_4

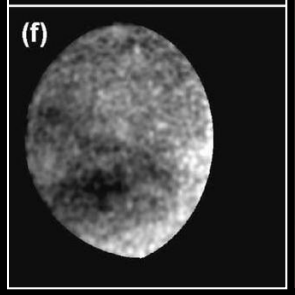




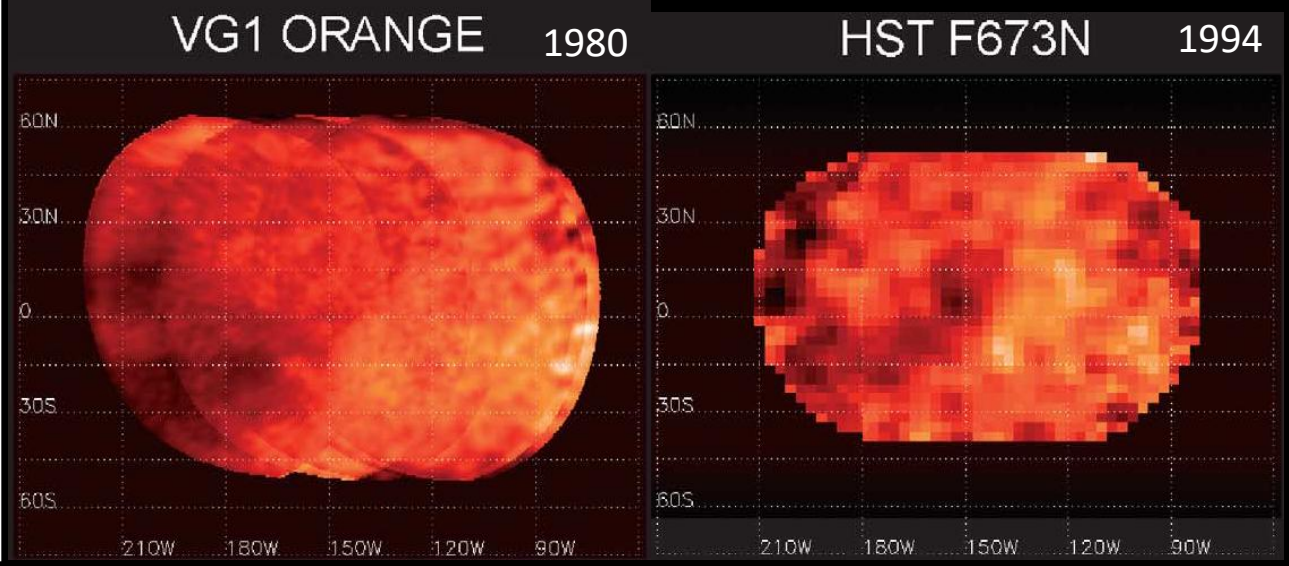
(Karkoschka et al. 1990 ; Coustenis et al. 1998 ; McGrath et al., 1998)

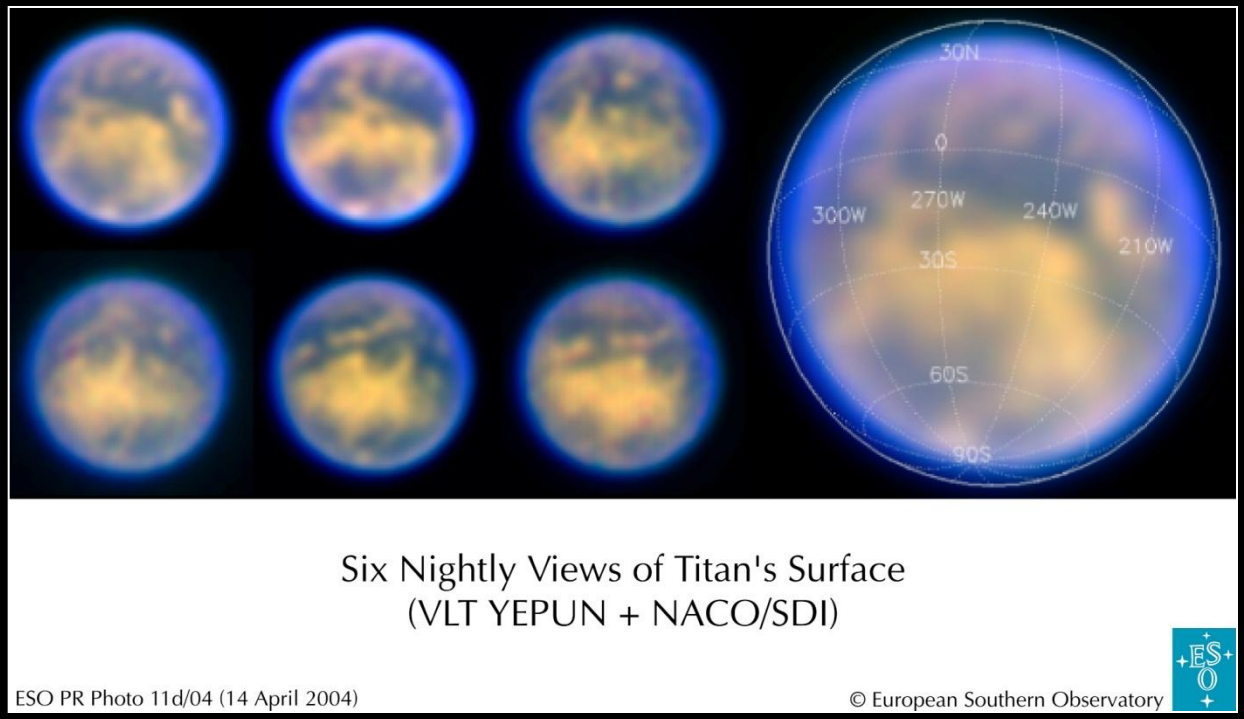
Surface …





Richardson et al. (2004)





… et intérieur ? ⇨ mesure de la masse volumique : 1880 kg/m^3

Questions post-Voyager, jusqu'à l'orée des années 2000 ?

- Quelle est l'origine du méthane et qu'est-ce qui est responsable de son abondance et de sa stabilité ?
- Le méthane est-il impliqué dans des cycles climatiques, semblables au cycle hydrologique sur Terre ?
- Quelle molécule complexe sa chimie atmosphérique est-elle capable de produire ? Intérêt pour l'exobiologie ?
- Quelle est la nature de la surface et de la géologie de Titan ?
- Structure interne et échanges intérieur ⇔ surface ⇔ atmosphère ?

Cassini-Huygens : 2004-2017

Cassini-Huygens

Mission d'exploration planétaire robotisée la plus ambitieuse, la plus lourde, la plus sophistiquée jamais entreprise & un très bel exemple de coopération internationale

- Date de début du projet : milieu des années 80
- Agences spatiales impliquées : NASA, ESA, ASI
- Nombre de pays impliqués : 16 pays et 33 états des US (sciences et ingénierie)
- Nombre de responsables scientifiques : 250, dont 50 français
- Construction : 10 ans impliquant plus de 5000 personnes
- Coût : 3 milliards € (sur près de 30 ans)

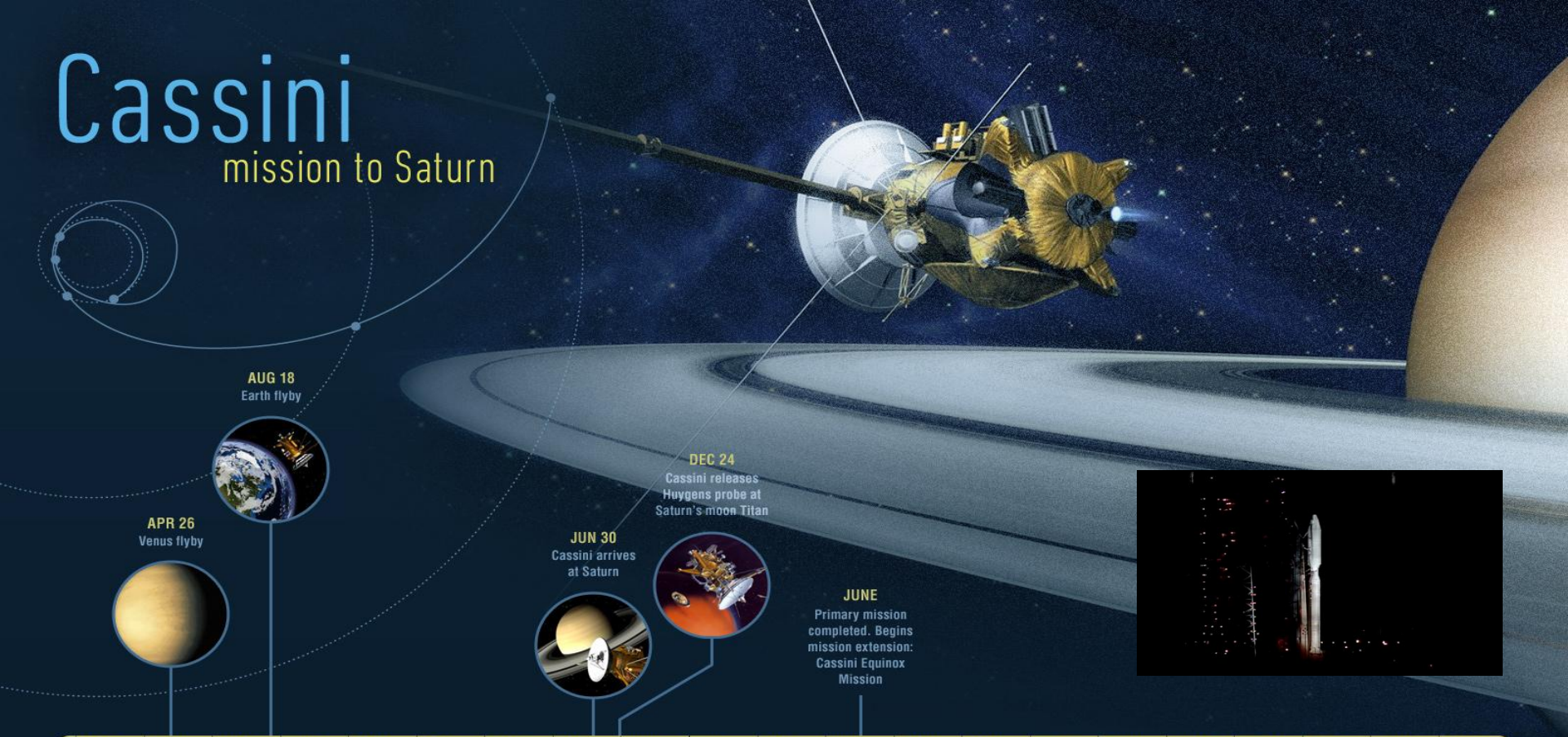
- Durée du voyage Terre-Saturne : 7 ans
- Durée de la mission nominale : 4 ans de 2004 à 2008
- Distance parcourue : 3 milliards de km
- Distance Terre-Cassini : 1,5 milliard de km
- Temps de communication entre Cassini et la Terre : 68 à 84'

CASSINI - HUYGENS

Exploring Saturn & Titan, a fascinating world

http://saturn.esa.int

Cassini
mission to Saturn



AUG 18
Earth flyby

APR 26
Venus flyby

DEC 24
Cassini releases Huygens probe at Saturn's moon Titan

JUN 30
Cassini arrives at Saturn

JUNE
Primary mission completed. Begins mission extension: Cassini Equinox Mission

1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

OCT 15
Launch from Cape Canaveral Air Force Station, Florida

DEC 30
Begins 6-month swing by Jupiter. Collaborates with Galileo to study Jovian system

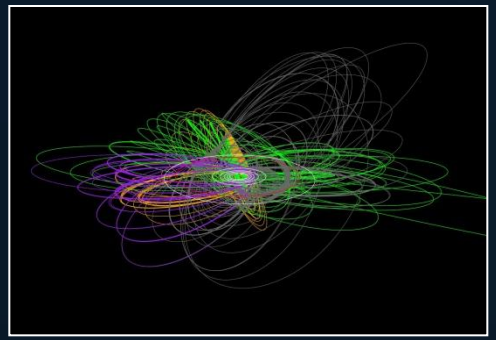
JUN 24
Second flyby of Venus

OCT 26
First flyby of Saturnian moons: Titan and Dione

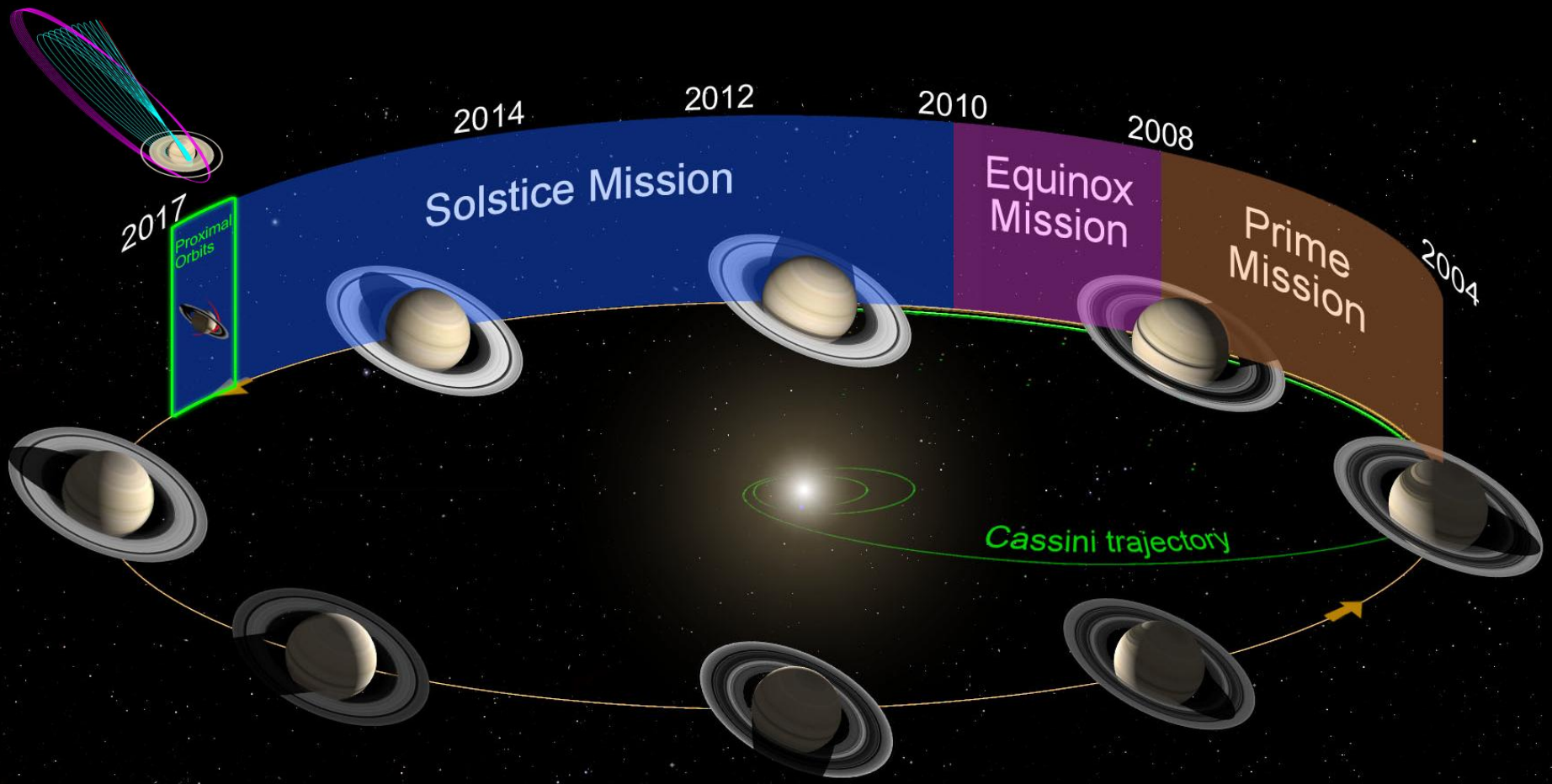
JAN 14
Huygens probe makes descent through Titan's atmosphere

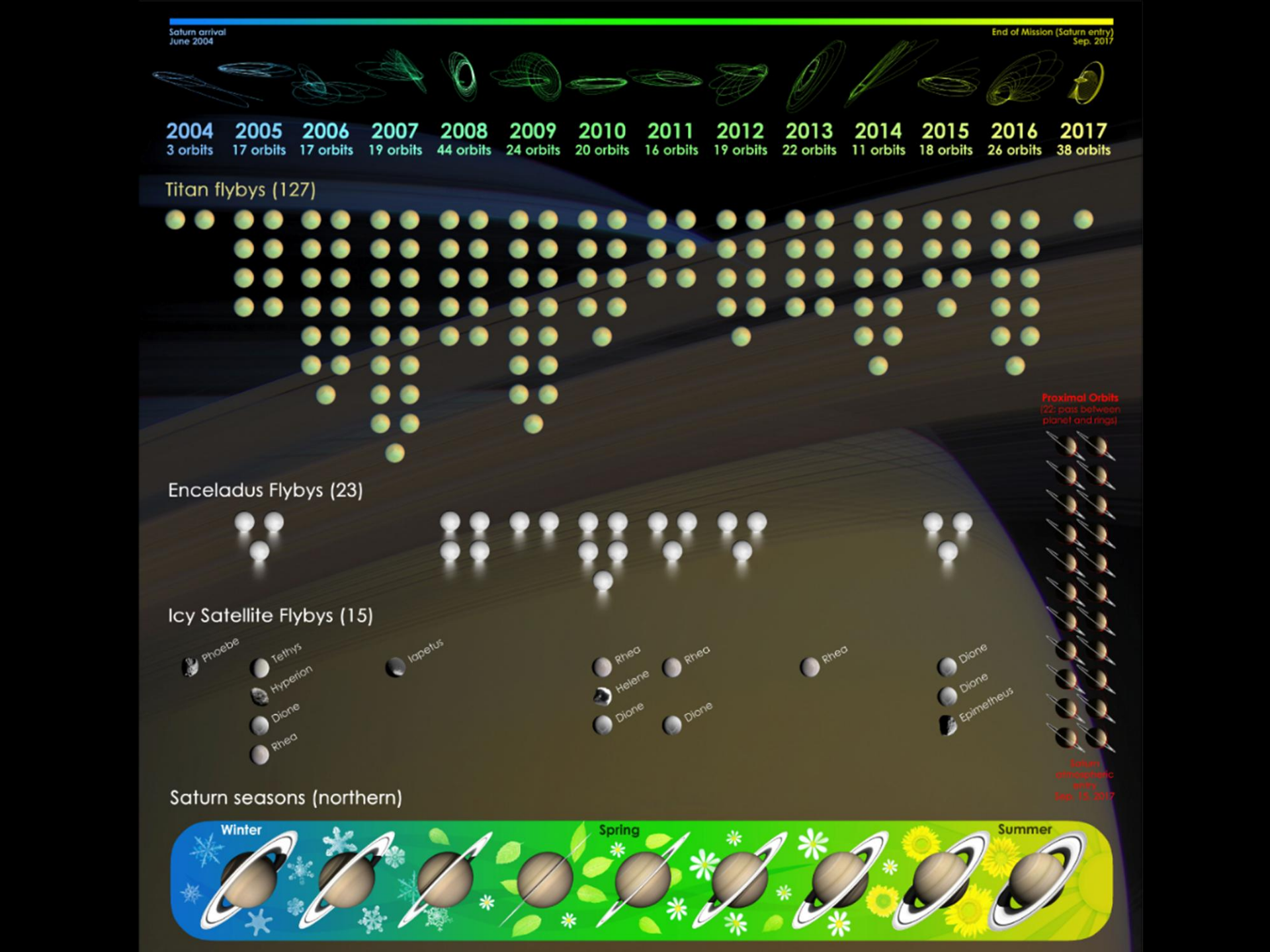
SEPTEMBER
Cassini Equinox Mission completed. Begins second mission extension: Cassini Solstice Mission

SEPTEMBER
Planned completion of the Cassini Solstice Mission



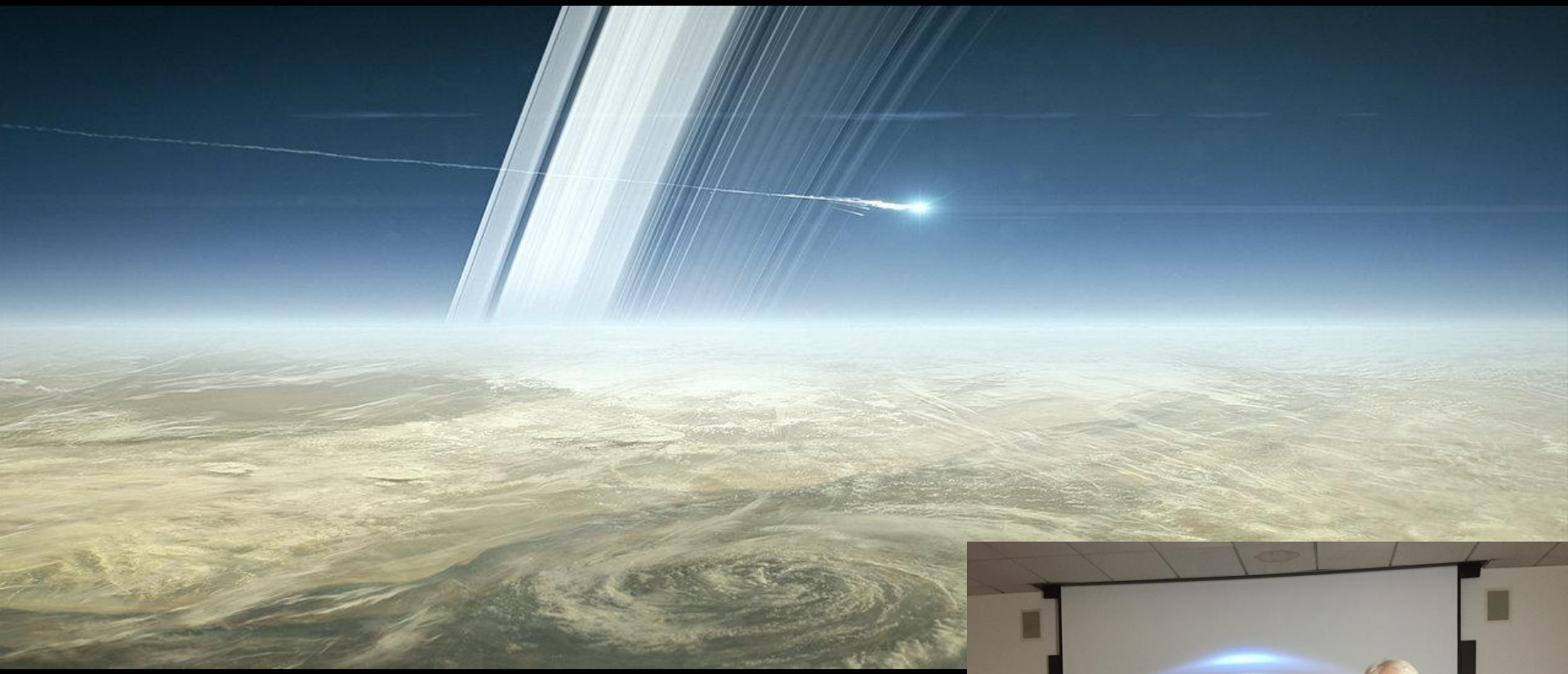
La mission Cassini-Huygens



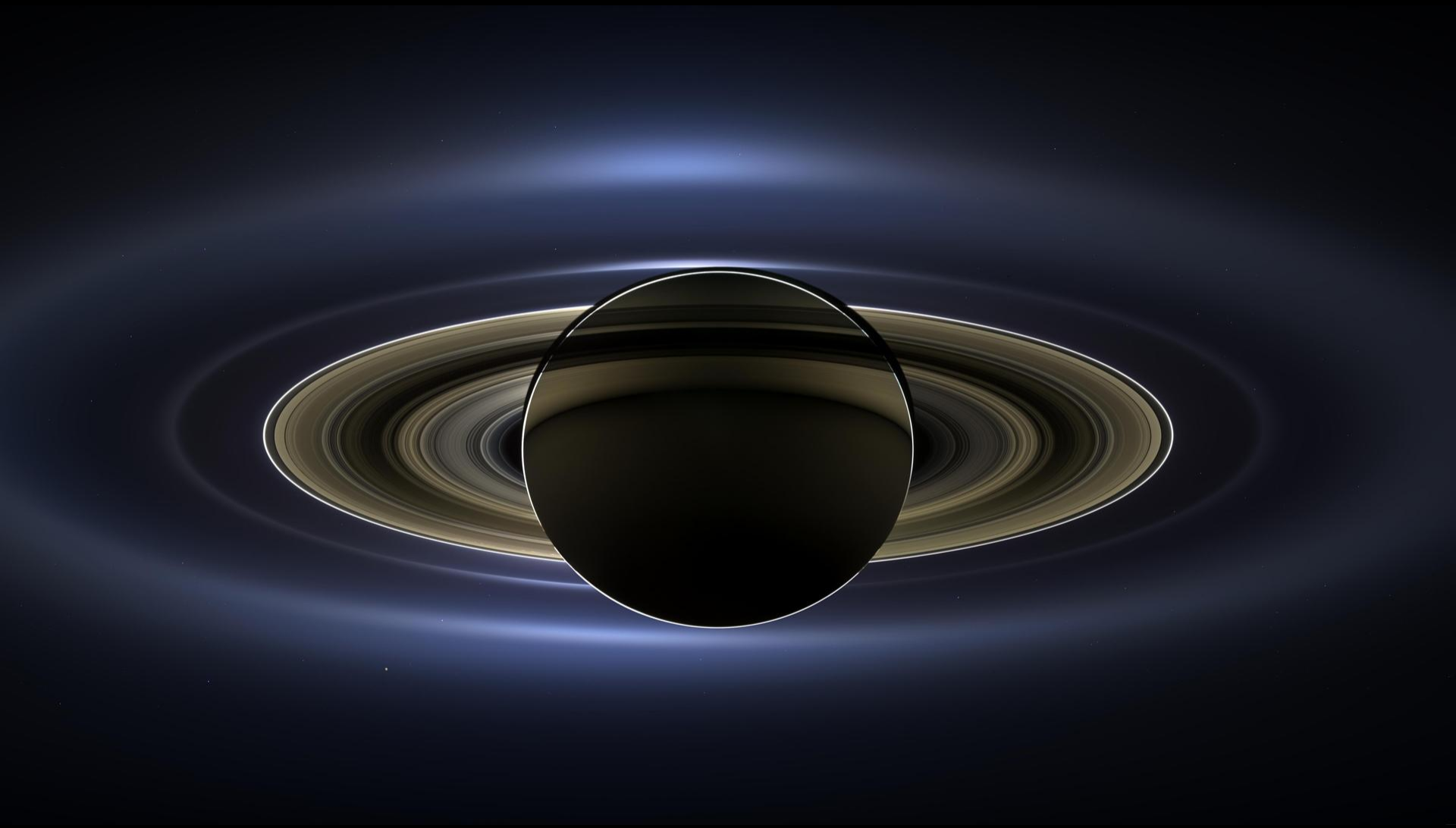

Saturn arrival
June 2004
End of Mission (Saturn entry)
Sep. 2017
2004
3 orbits
2005
17 orbits
2006
17 orbits
2007
19 orbits
2008
44 orbits
2009
24 orbits
2010
20 orbits
2011
16 orbits
2012
19 orbits
2013
22 orbits
2014
11 orbits
2015
18 orbits
2016
26 orbits
2017
38 orbits
Titan flybys (127)
Proximal Orbits
(22: pass between planet and rings)
Enceladus Flybys (23)
Icy Satellite Flybys (15)
Phoebe
Tethys
Hyperion
Dione
Rhea
Iapetus
Rhea
Helene
Dione
Rhea
Dione
Rhea
Dione
Dione
Epimetheus
Saturn atmospheric entry
Sep. 15, 2017
Saturn seasons (northern)
Winter
Spring
Summer

Cassini “Grand Finale” : 22 orbites

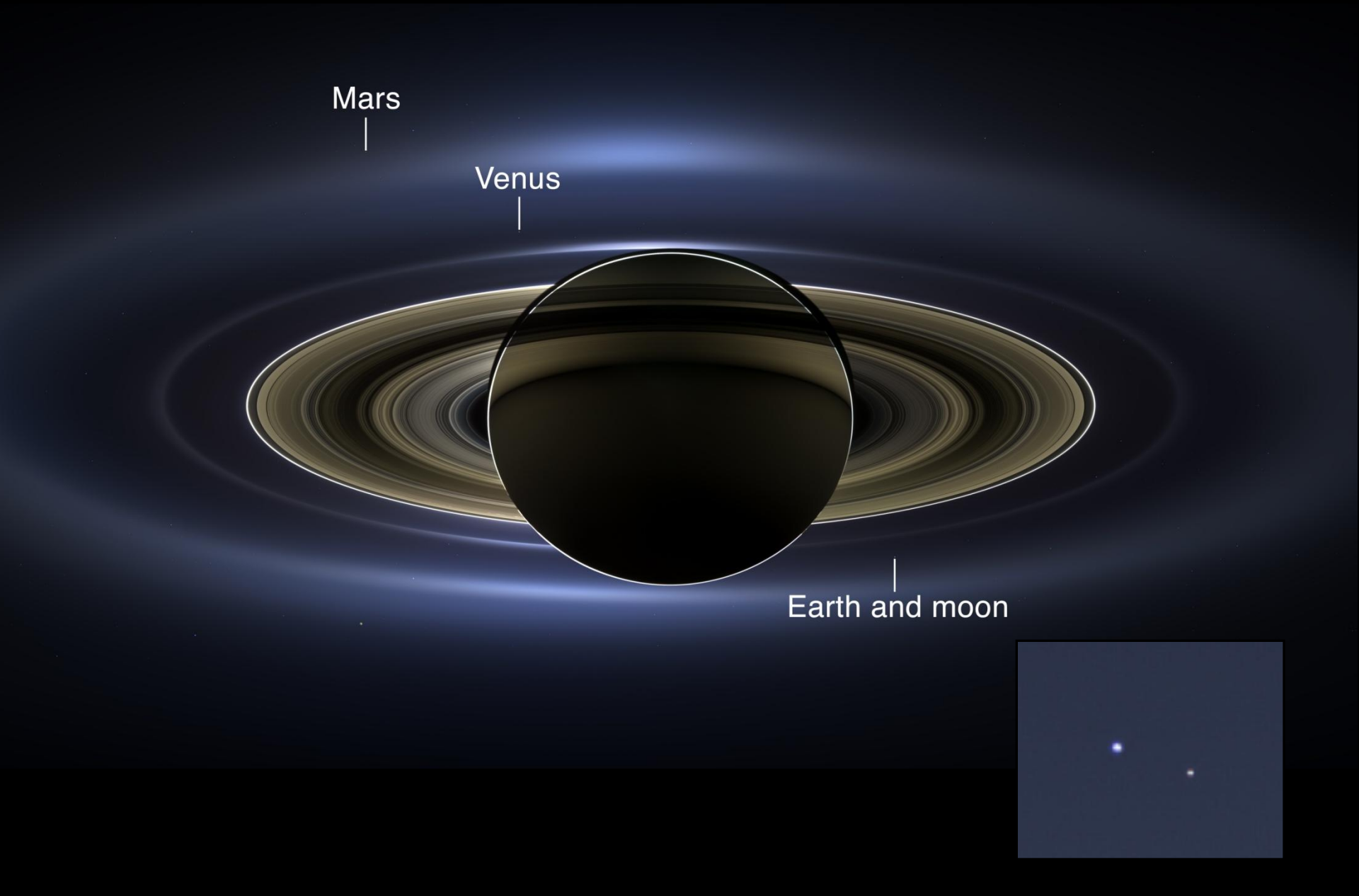
Le grand plongeon de Cassini
15 septembre (≈13h GMT+2)



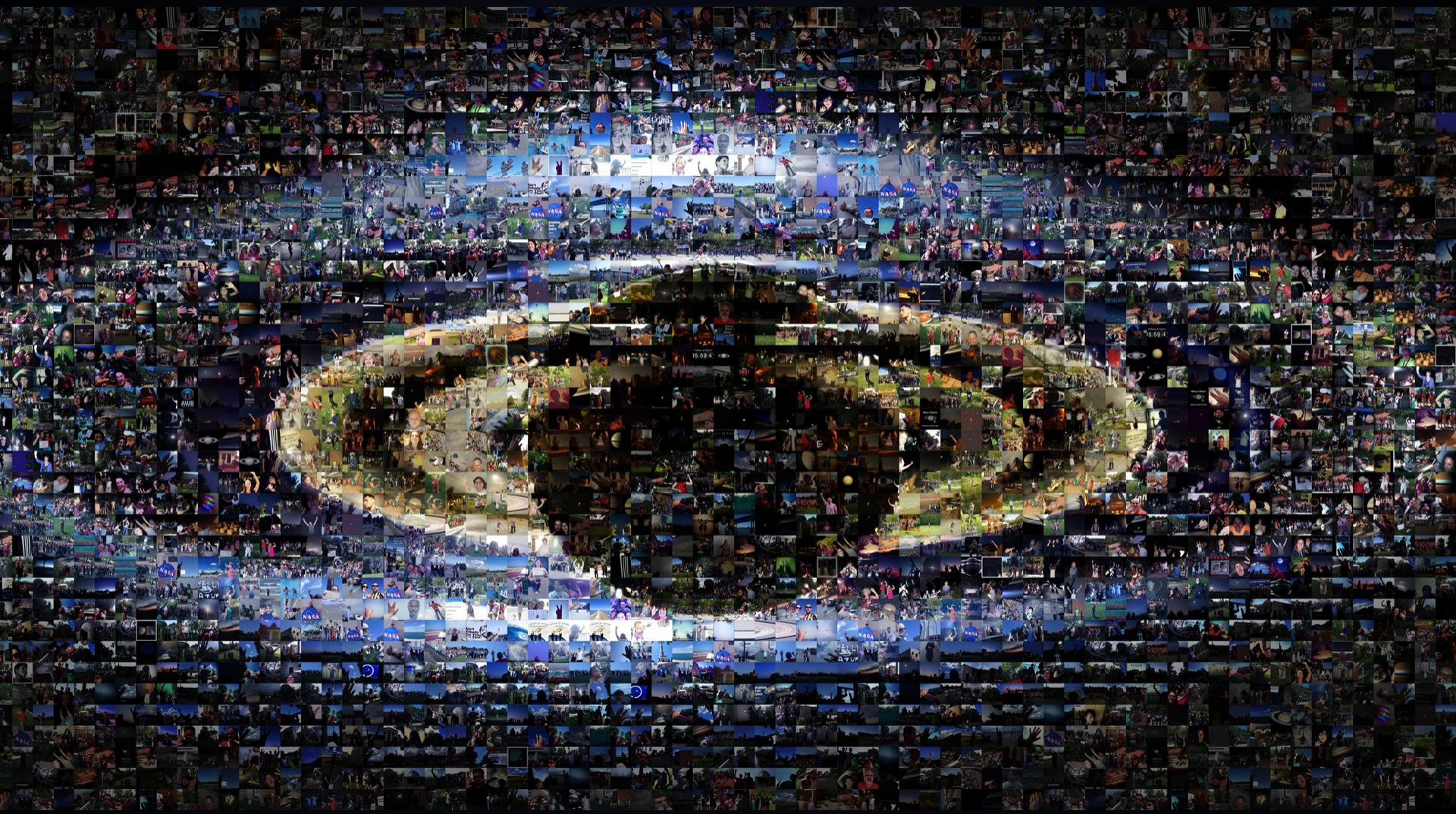
19 juillet 2013



19 juillet 2013

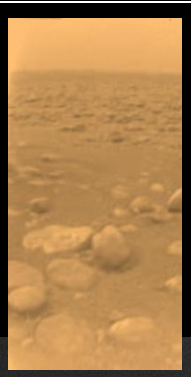


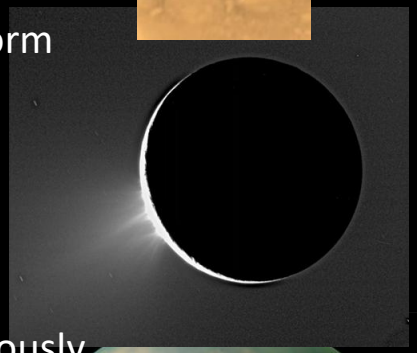
19 juillet 2013

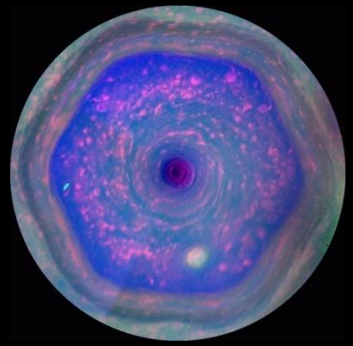


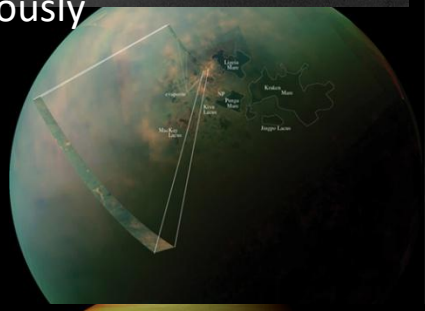
Top 10 des découvertes et avancées majeures de Cassini-Huygens

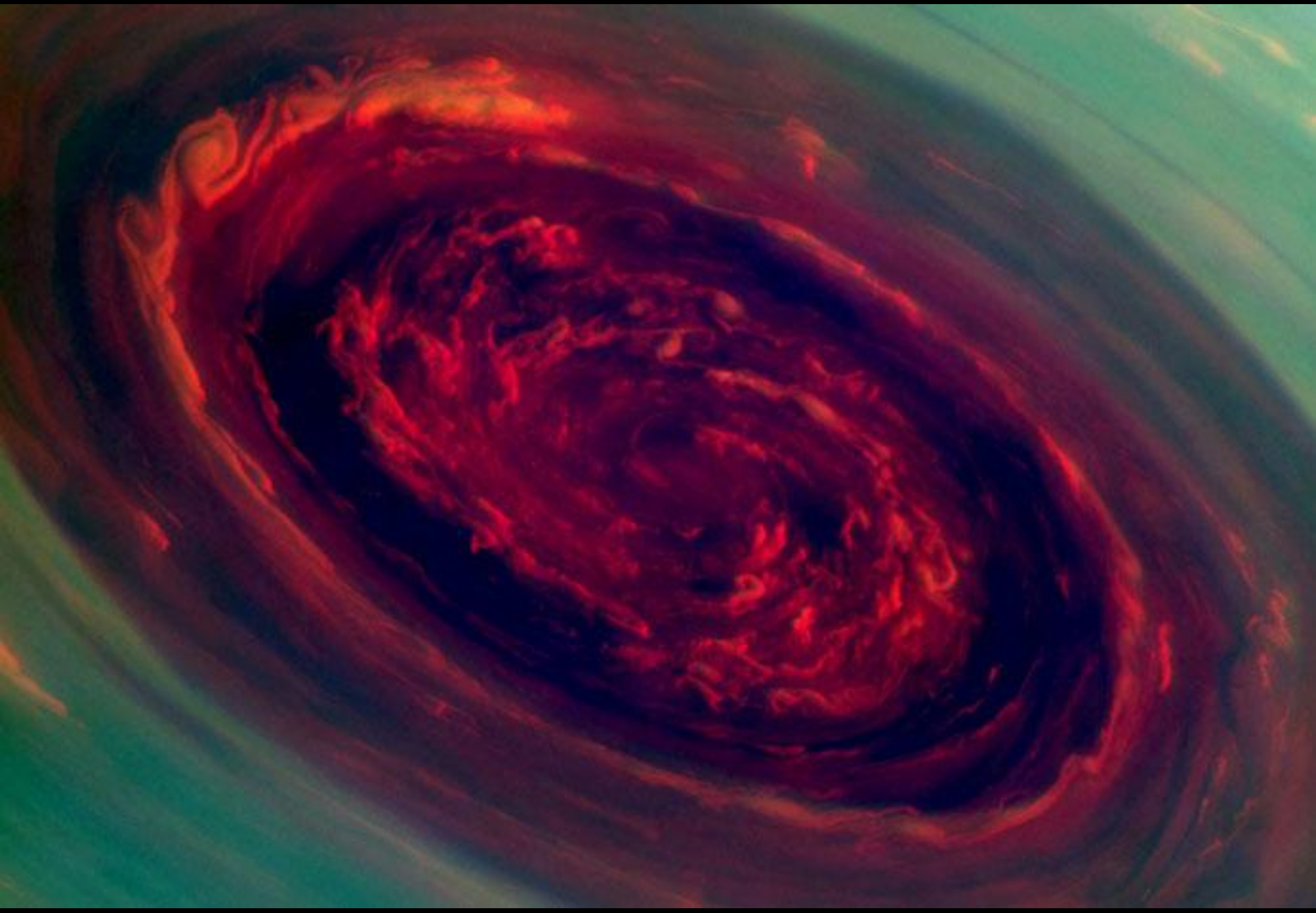
1. The Huygens probe makes first landing on a moon in the outer solar system (Titan)
2. Discovery of active, icy plumes on the Saturnian moon Enceladus
3. Saturn's rings revealed as active and dynamic -- a laboratory for how planets form
4. Titan revealed as Earth-like world with rain, rivers, lakes and seas
5. Studies of Saturn's great northern storm of 2010-2011
6. Radio-wave patterns shown not to be tied to Saturn's interior rotation as previously thought
7. Vertical structures in the rings imaged for the first time
8. Study of prebiotic chemistry on Titan
9. Mystery of the dual bright-dark surface of Iapetus solved
10. First complete view of the north polar hexagon and discovery of giant hurricanes at both of Saturn's poles











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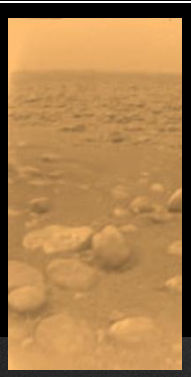
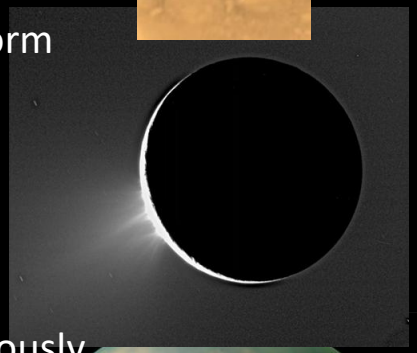
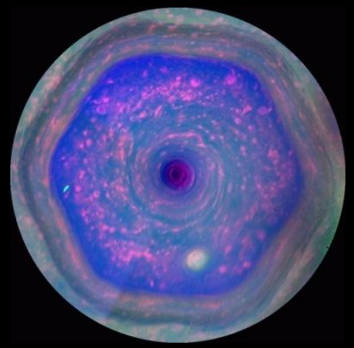
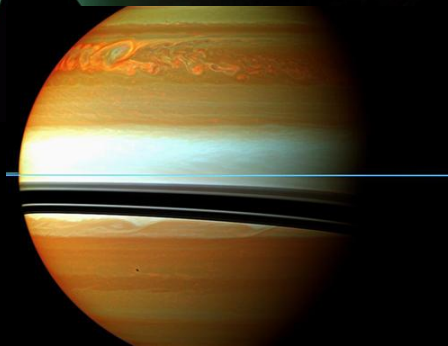
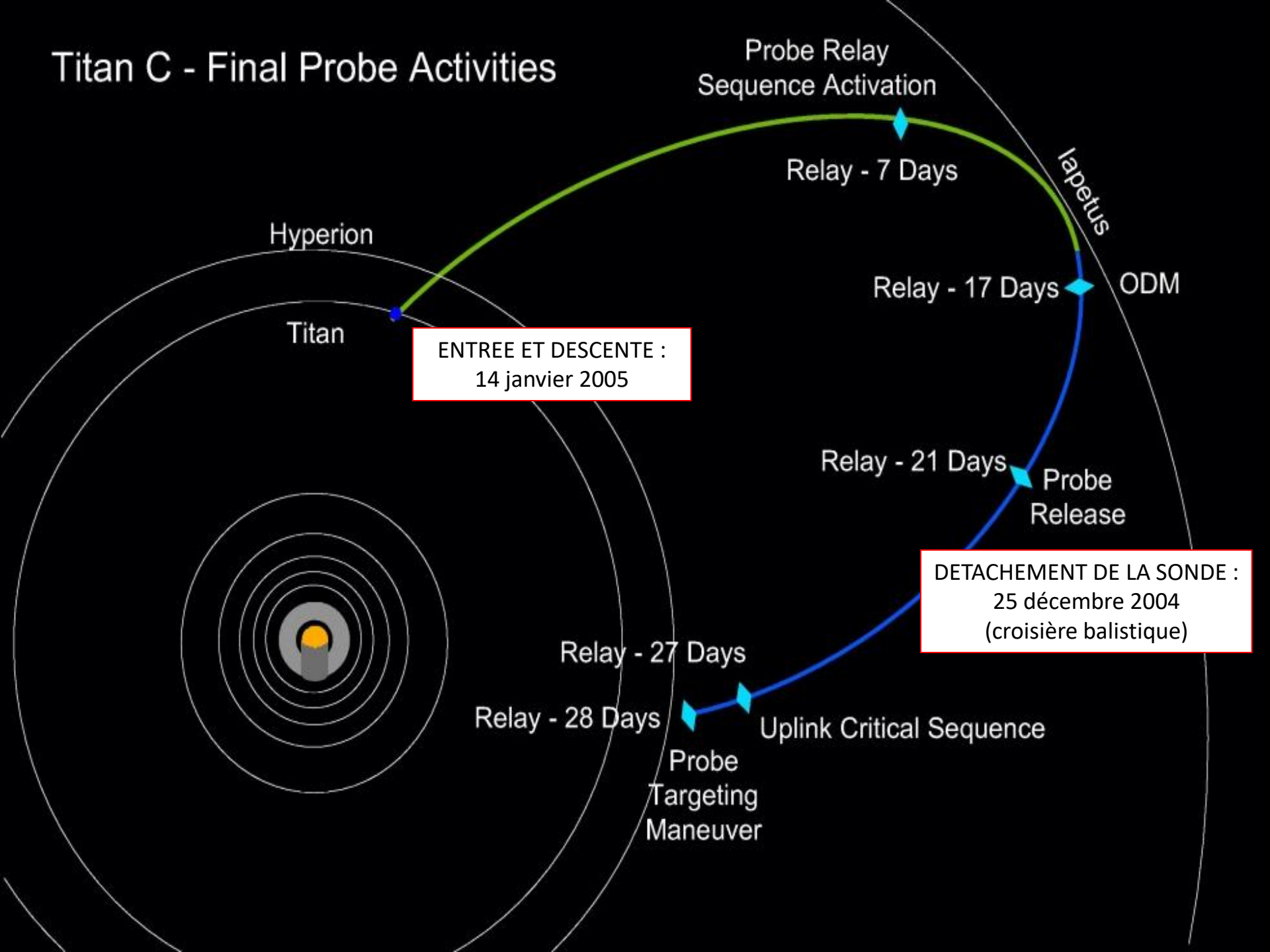








14 janvier 2005 : la descente de Huygens dans l'atmosphère de Titan, un moment historique

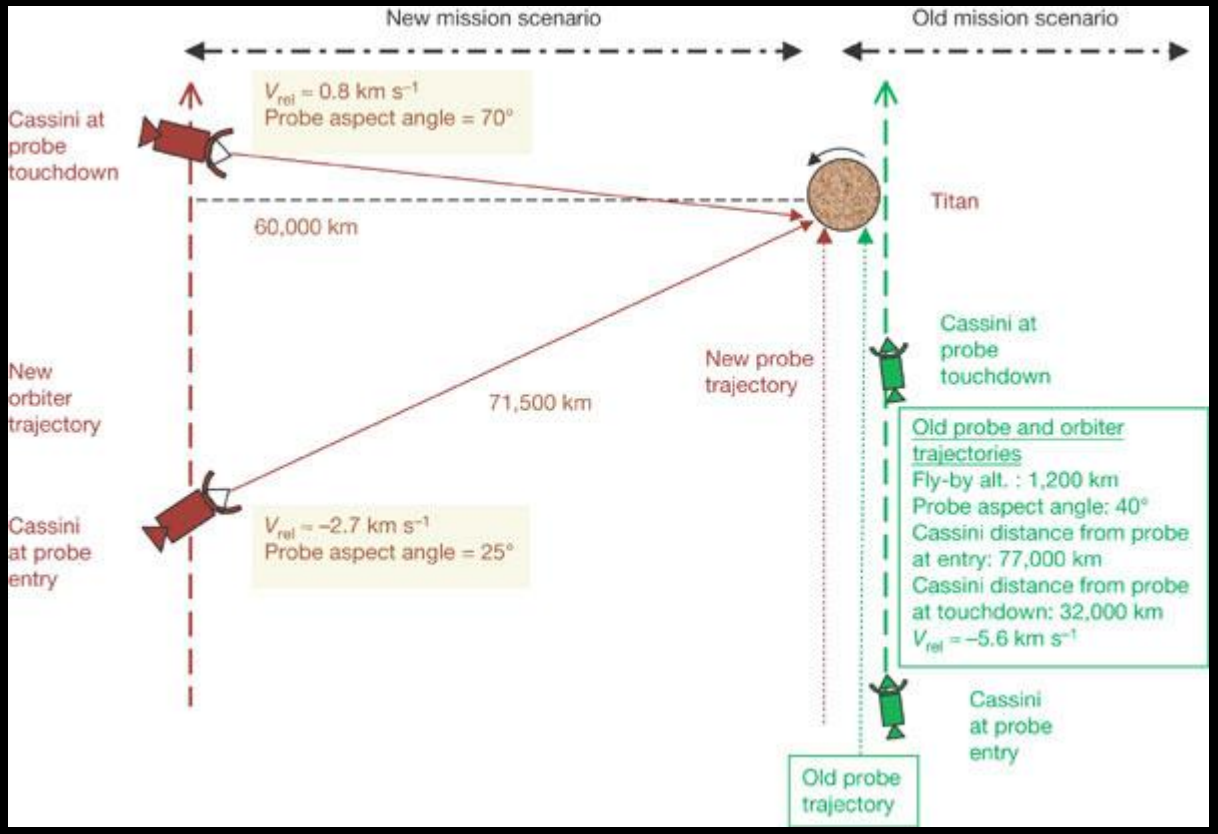

Titan C - Final Probe Activities
Probe Relay Sequence Activation
Relay - 7 Days
Iapetus
Hyperion
Relay - 17 Days
ODM
Titan
ENTREE ET DESCENTE : 14 janvier 2005
Relay - 21 Days
Probe Release
DETACHEMENT DE LA SONDE : 25 décembre 2004 (croisière balistique)
Relay - 27 Days
Relay - 28 Days
Uplink Critical Sequence
Probe Targeting Maneuver

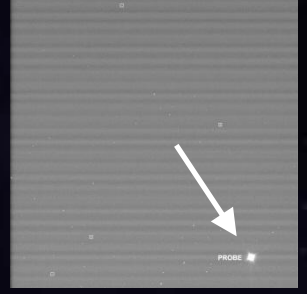
Huygens

La mission est pourtant passée tout près de l'échec :

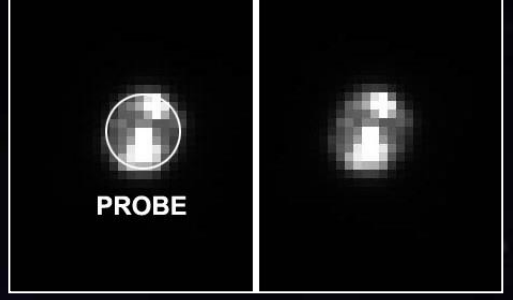
problèmes de communication sonde/orbiteur (sept. 2000) : décalage Doppler Cassini/Huygens non pris en compte

problème réglé par une modification de la géométrie de vol de Cassini par rapport à Huygens et Titan (détachement de Huygens retardée de 1 mois ½ et distance de survol supérieure à celle initialement prévue)

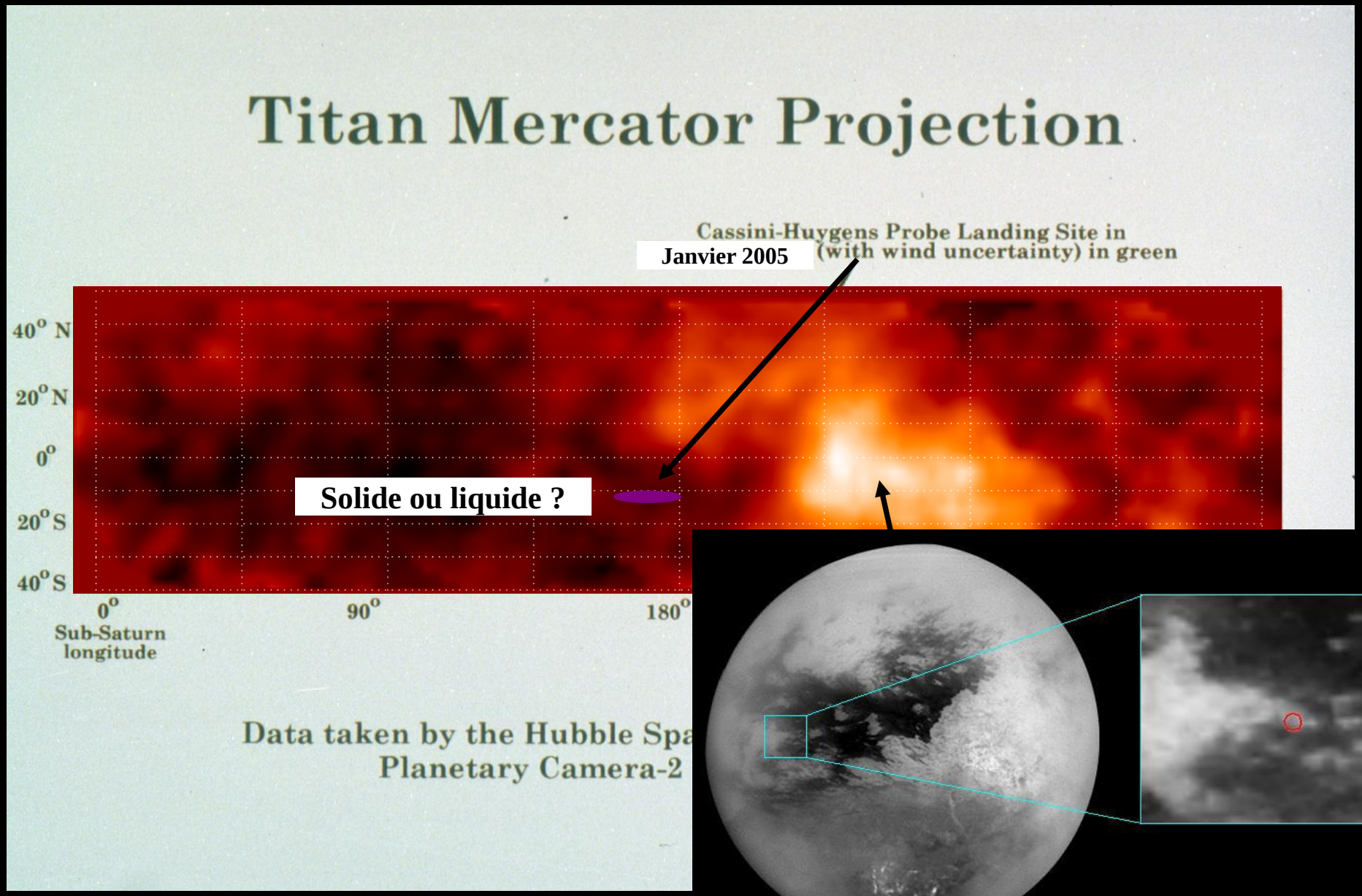




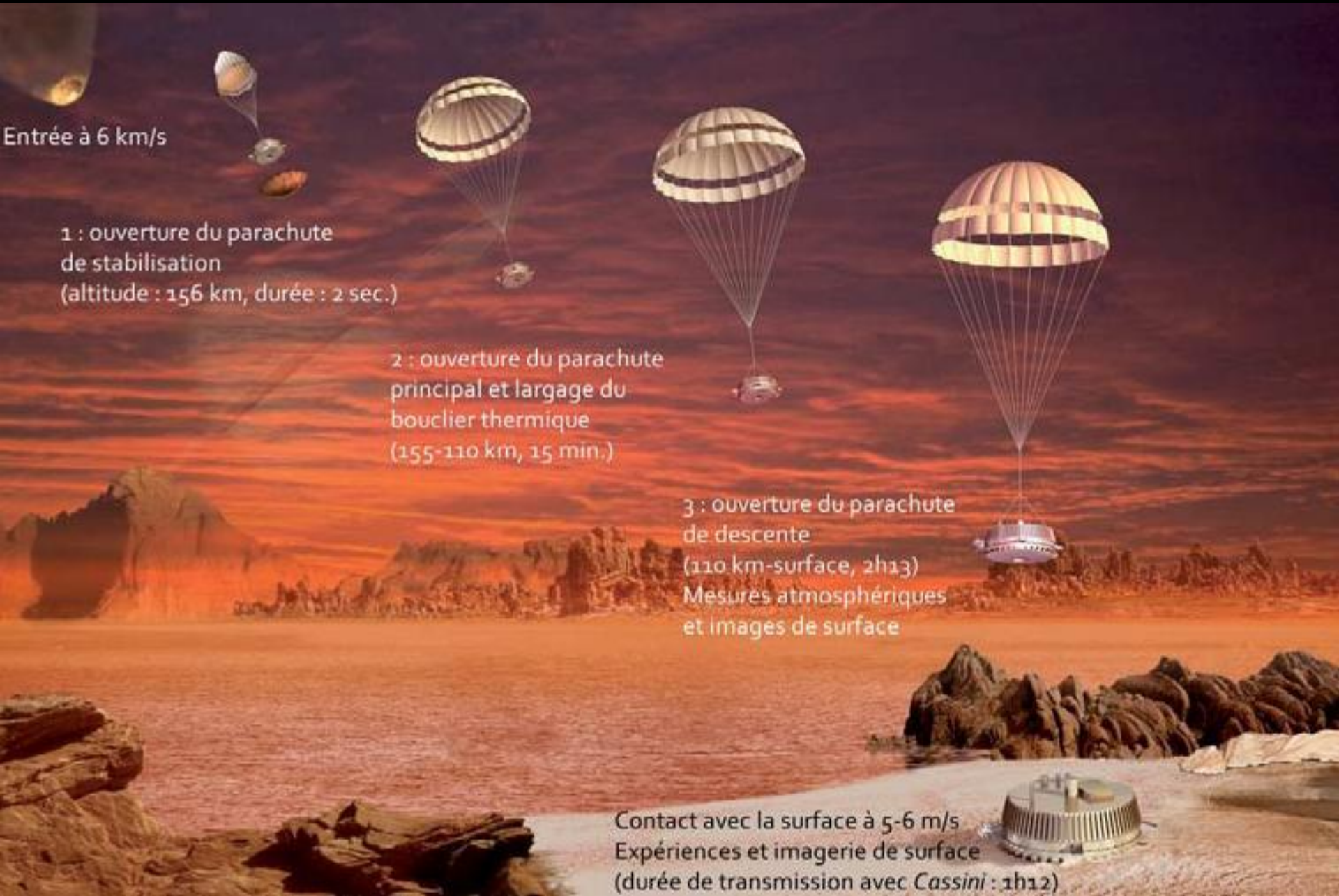
Après 2 jours

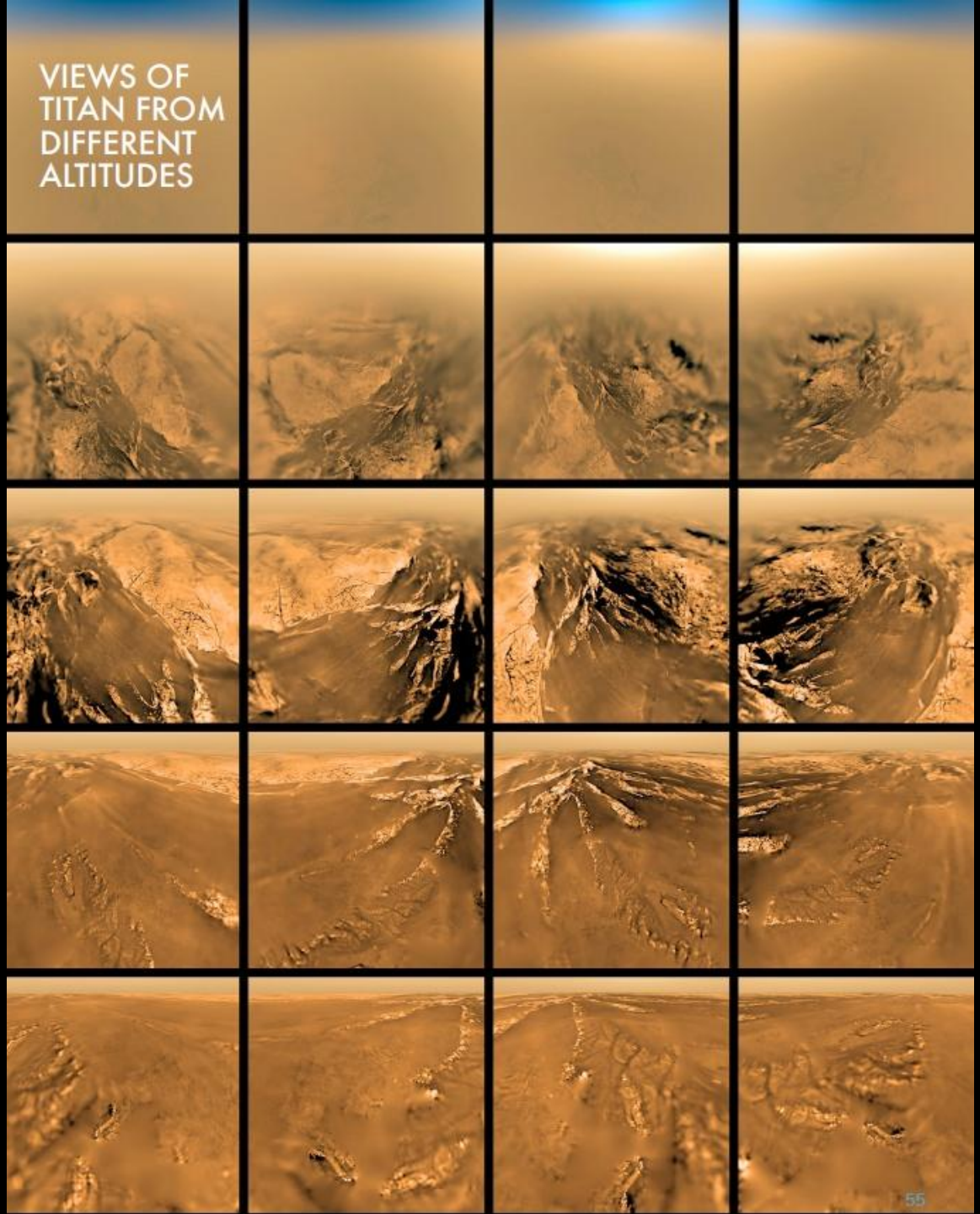


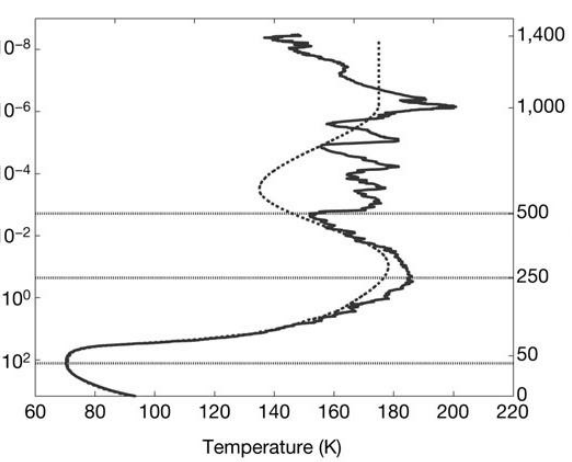
Huygens : phase d'entrée et « atterrissage »

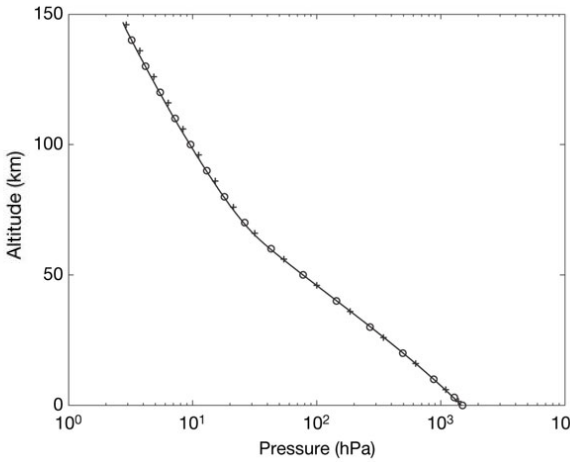


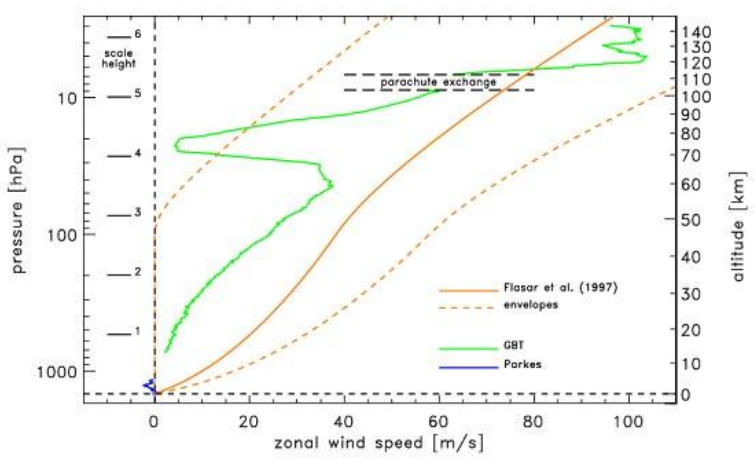
Huygens : phase d'entrée et « atterrissage »




VIEWS OF
TITAN FROM
DIFFERENT
ALTITUDES

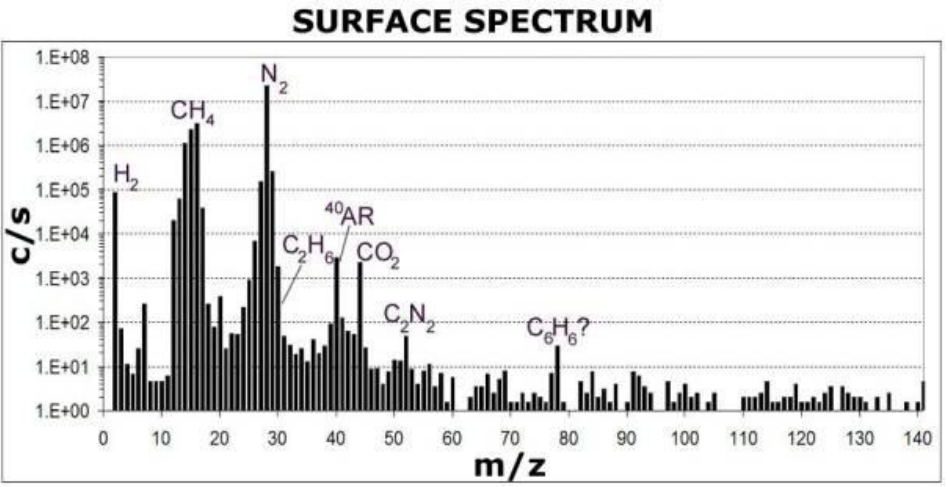


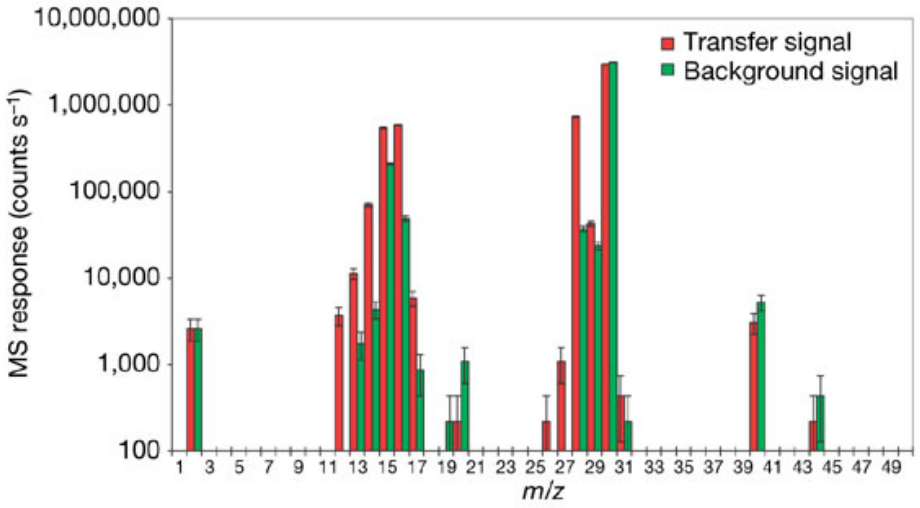




T_{surf} = 93.65 ± 0.25 K et P_{surf} = 1,467 ± 0.001 bar

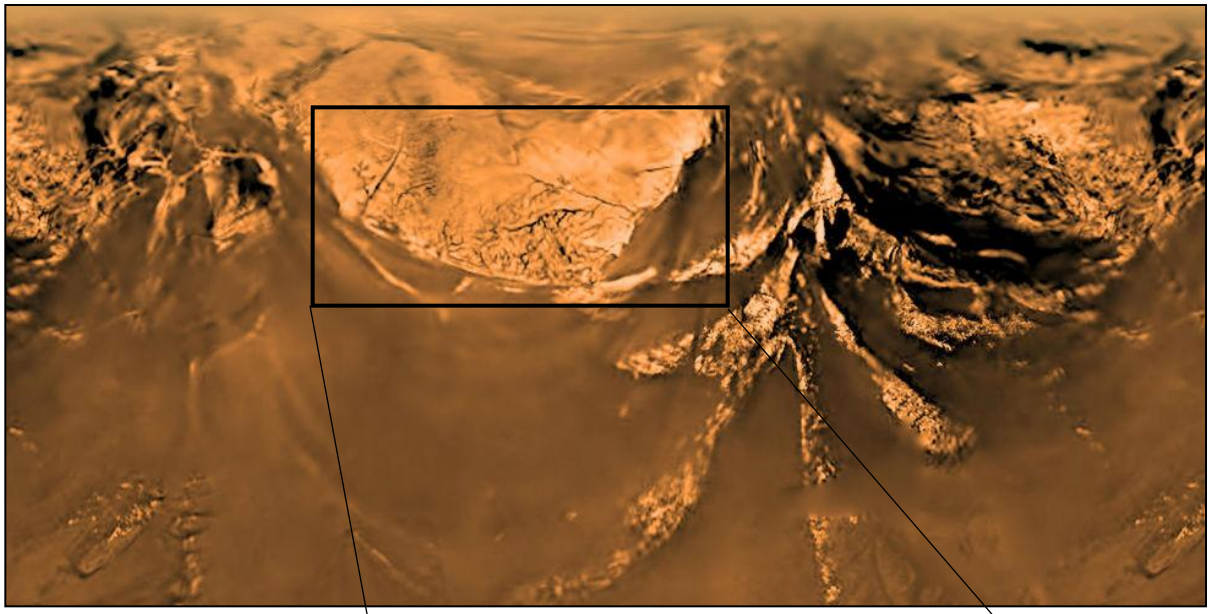
98 % de N_2 et 1,6 % CH_4 (5% en surface)



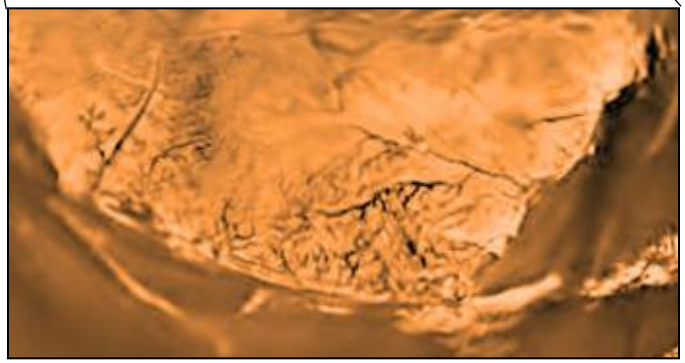


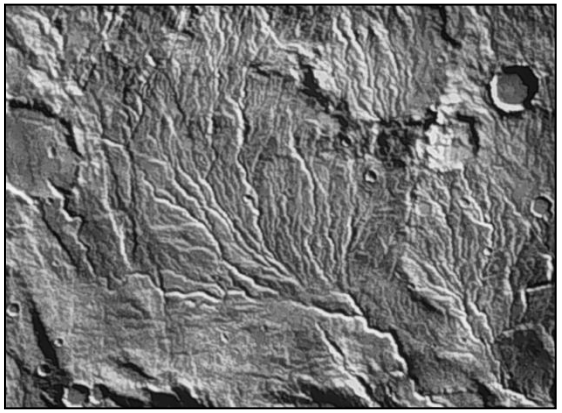
pyrolyse des aérosols

Altitude : 15 km

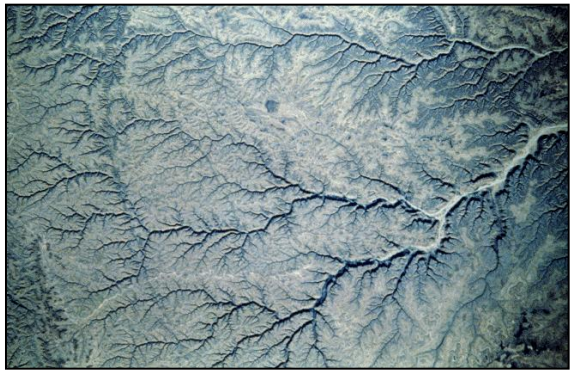


Crédits : ESA/NASA/JPL/University of Arizona



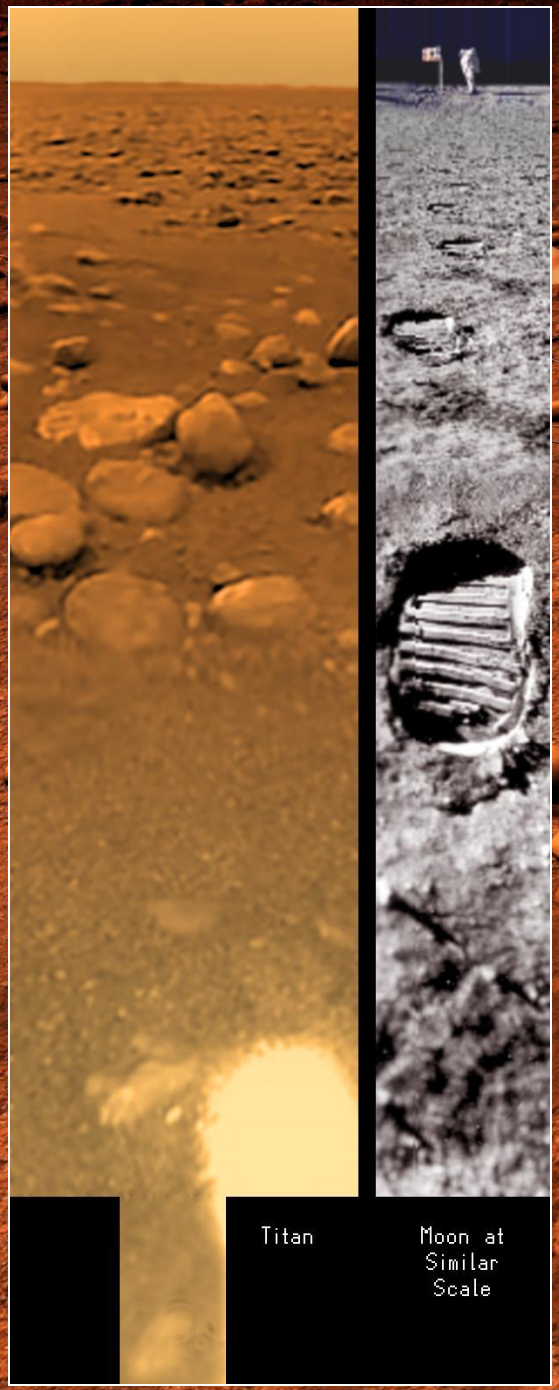


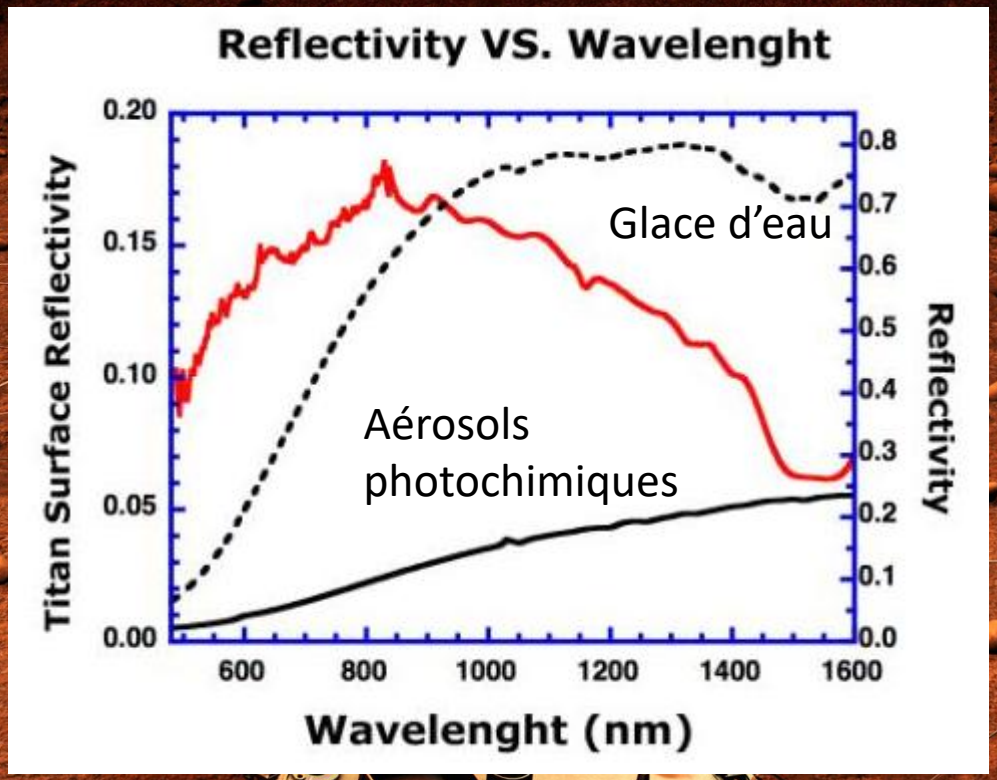
Réseau dendritique de rivières asséchées sur Mars



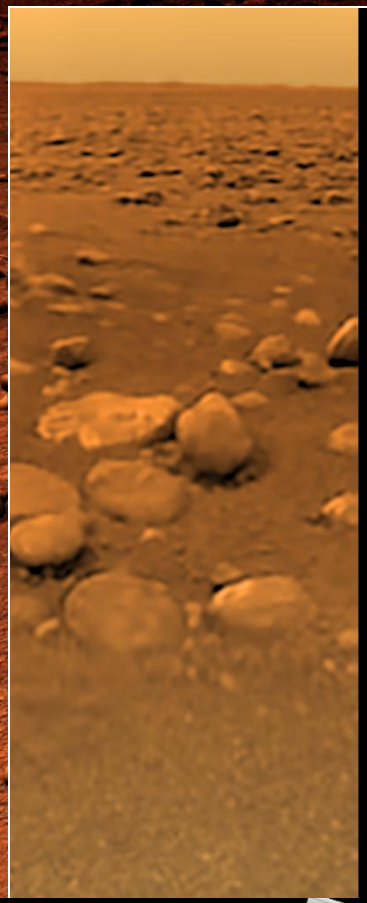
Réseau dendritique de rivières au Yémen, Terre

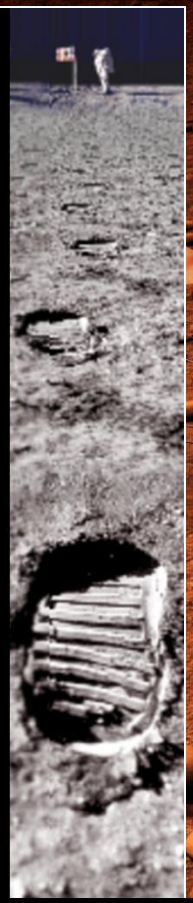
Alice LE GALL (comm. perso.)

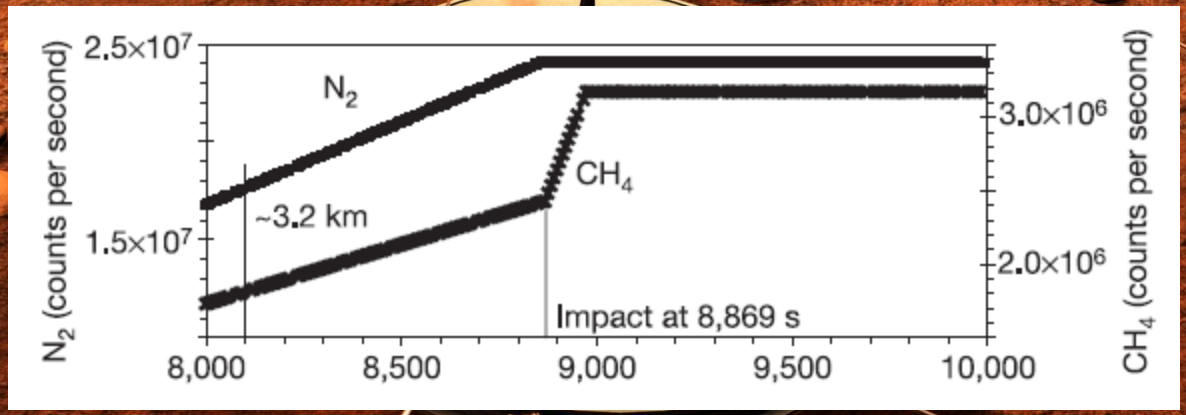

Titan
Moon at Similar Scale

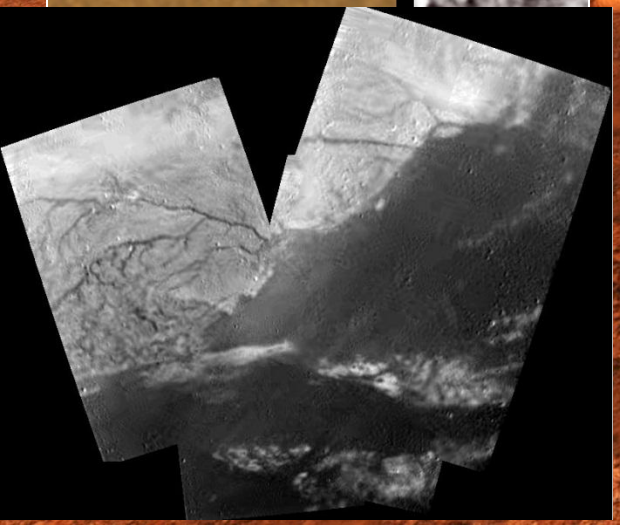

Reflectivity VS. Wavelenght
Titan Surface Reflectivity
Reflectivity
Wavelenght (nm)
0.20
0.15
0.10
0.05
0.00
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
600
800
1000
1200
1400
1600
Glace d'eau
Aérosols photochimiques

Surface ?









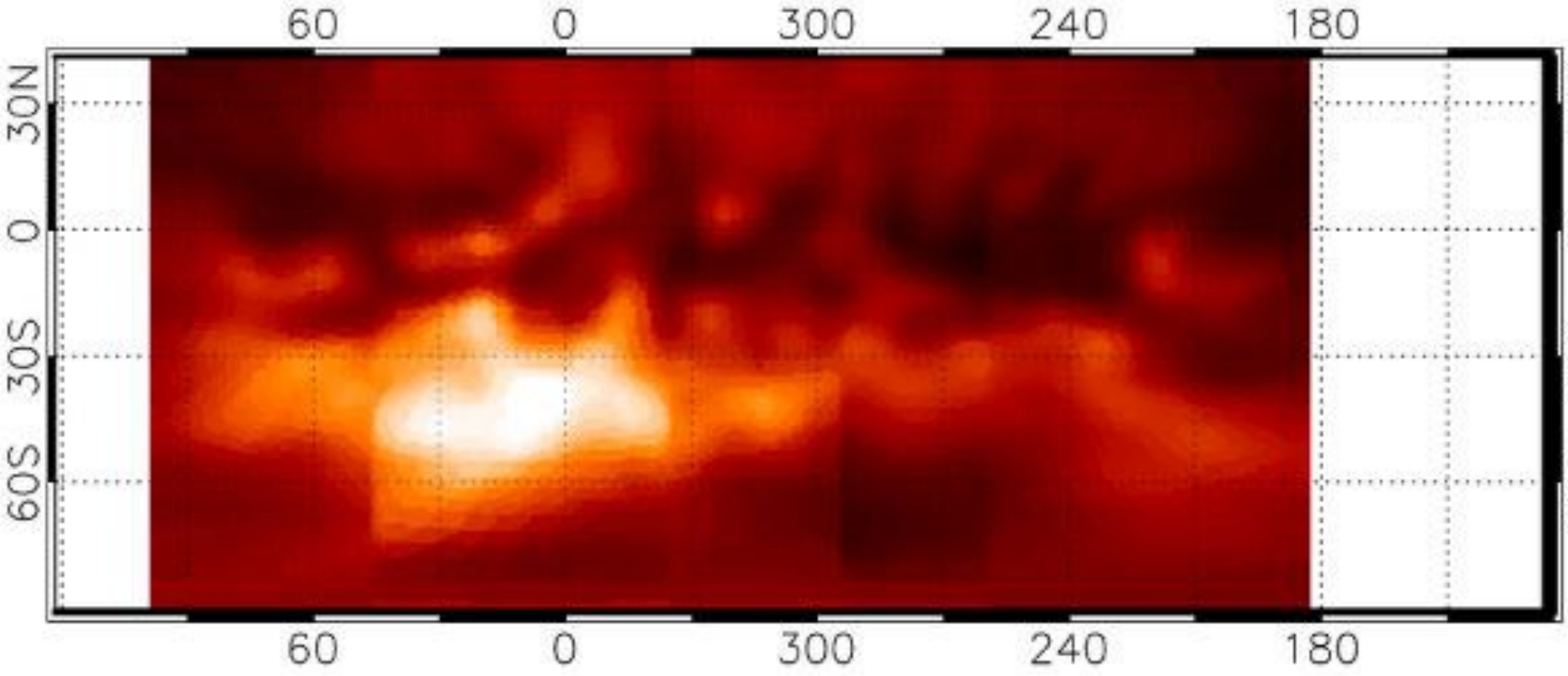
Liquides ?

Grande diversité de paysages et de phénomènes atmosphériques et climatiques

Mais à 1 date et 1 lieu !!!

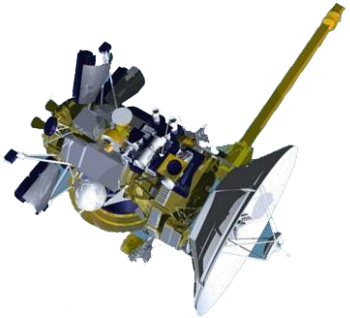
Cassini : une cartographie globale de la surface et l’atmosphère de Titan

En 2004, depuis la Terre …



Map of Titan's Surface Features at 1.575µm
(VLT YEPUN + NACO/SDI)

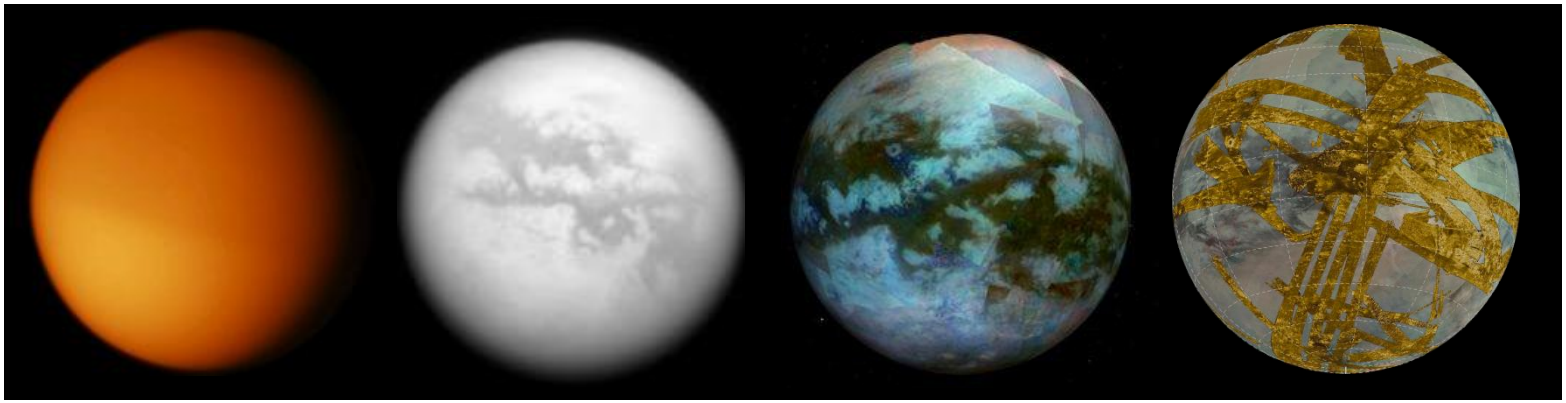
Voir sous les brumes avec Cassini



A bord de la sonde Cassini, 3 instruments permettent d'observer la surface de Titan:

- **ISS** et **VIMS**, à travers 7 « fenêtres atmosphériques » dans le proche infrarouge
- **RADAR** dans le domaine micro-onde

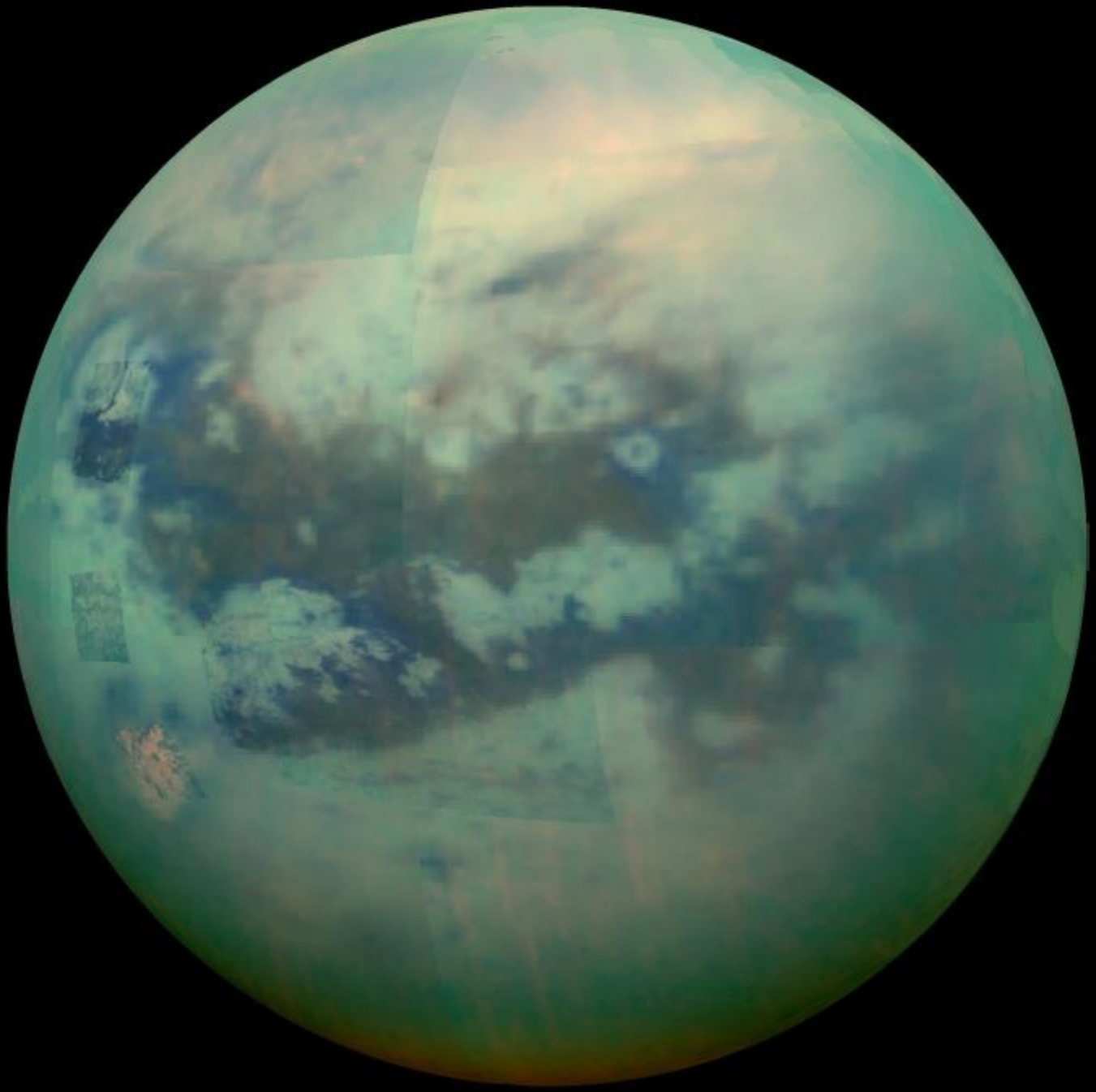
VOYAGER 1 | **CASSINI**



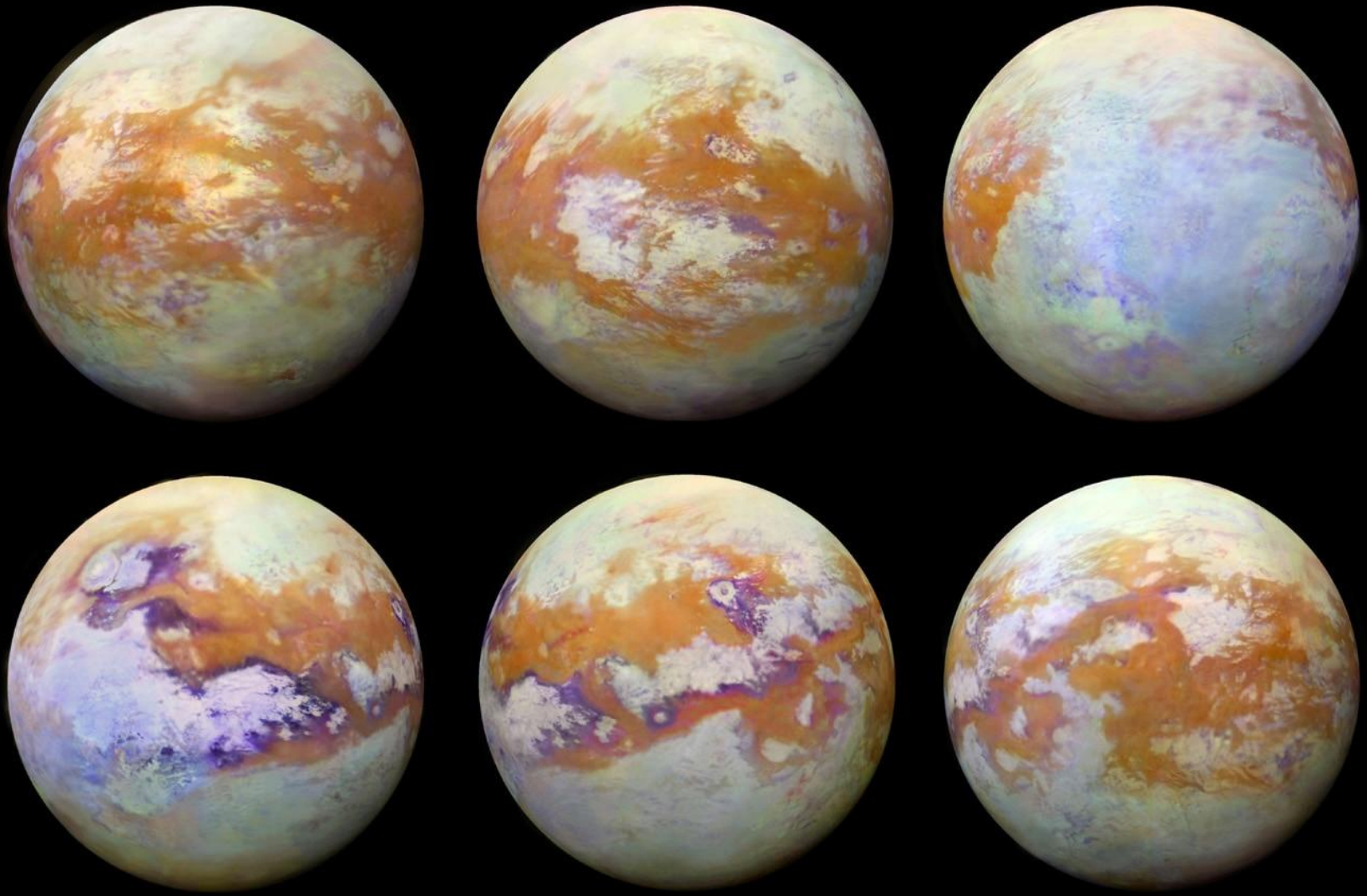
Domaine optique | **ISS** Proche IR (0.939 µm) | **VIMS** Proche IR (0.939,1.08,1.59,2.03,2.7-2.8,5.0 µm) | **RADAR** Micro-onde (2 cm)

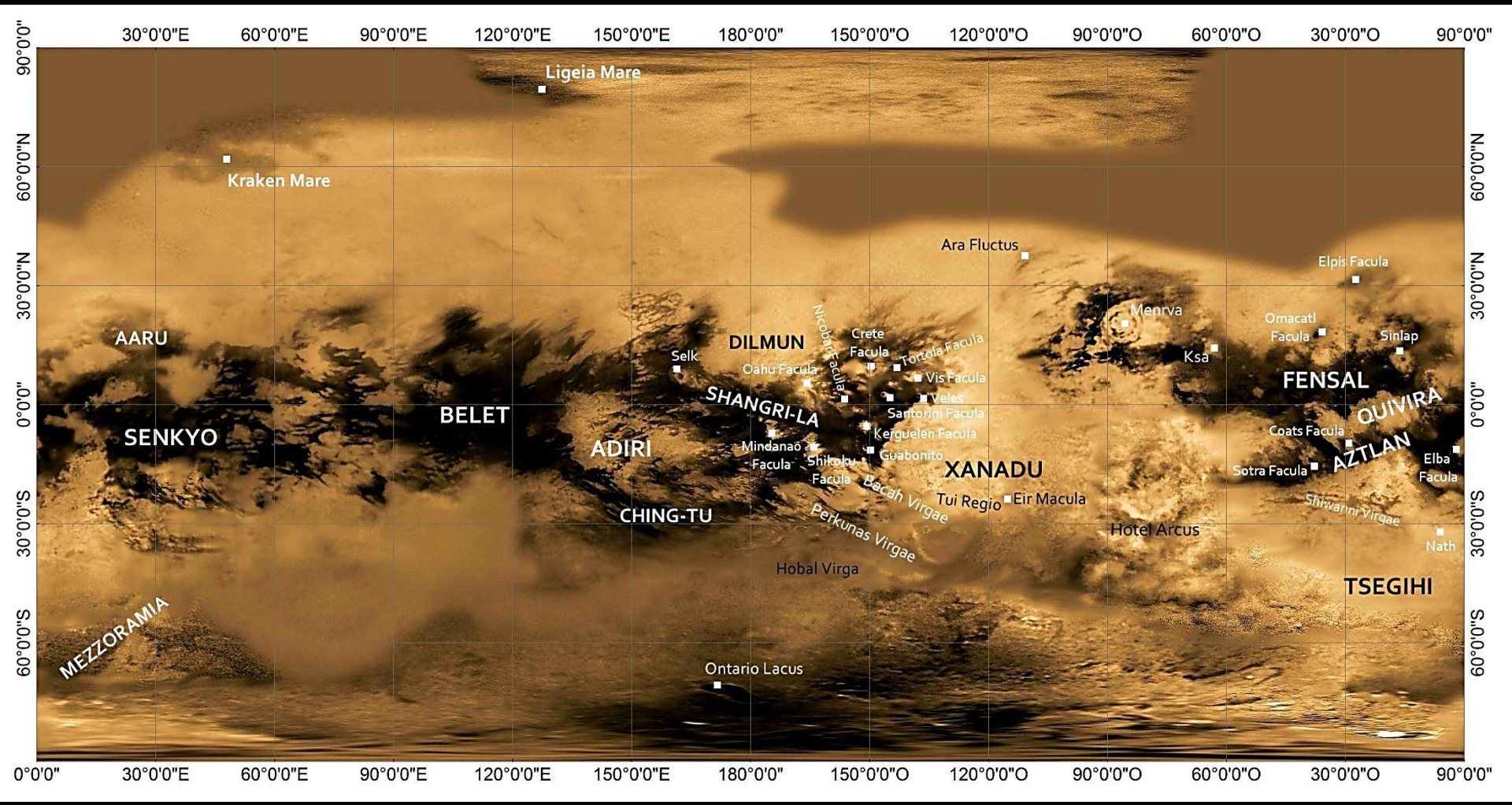
Longueur d'onde croissante

Alice LE GALL (comm. perso.)

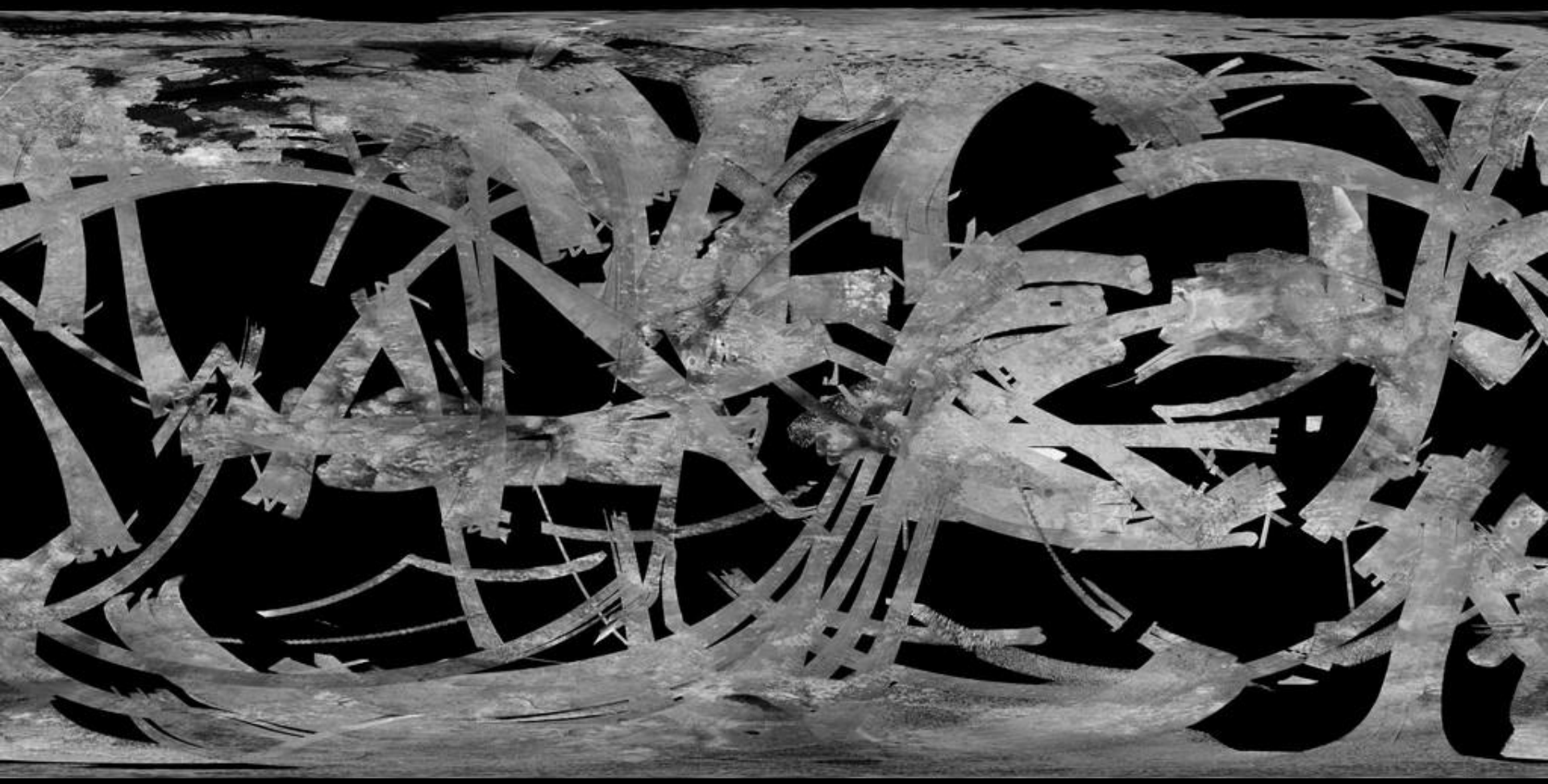


Spectro-imageur VIMS : Cartographie globale à ≈10 km de résolution





Caméras ISS : Cartographie globale à 4-5 km de résolution



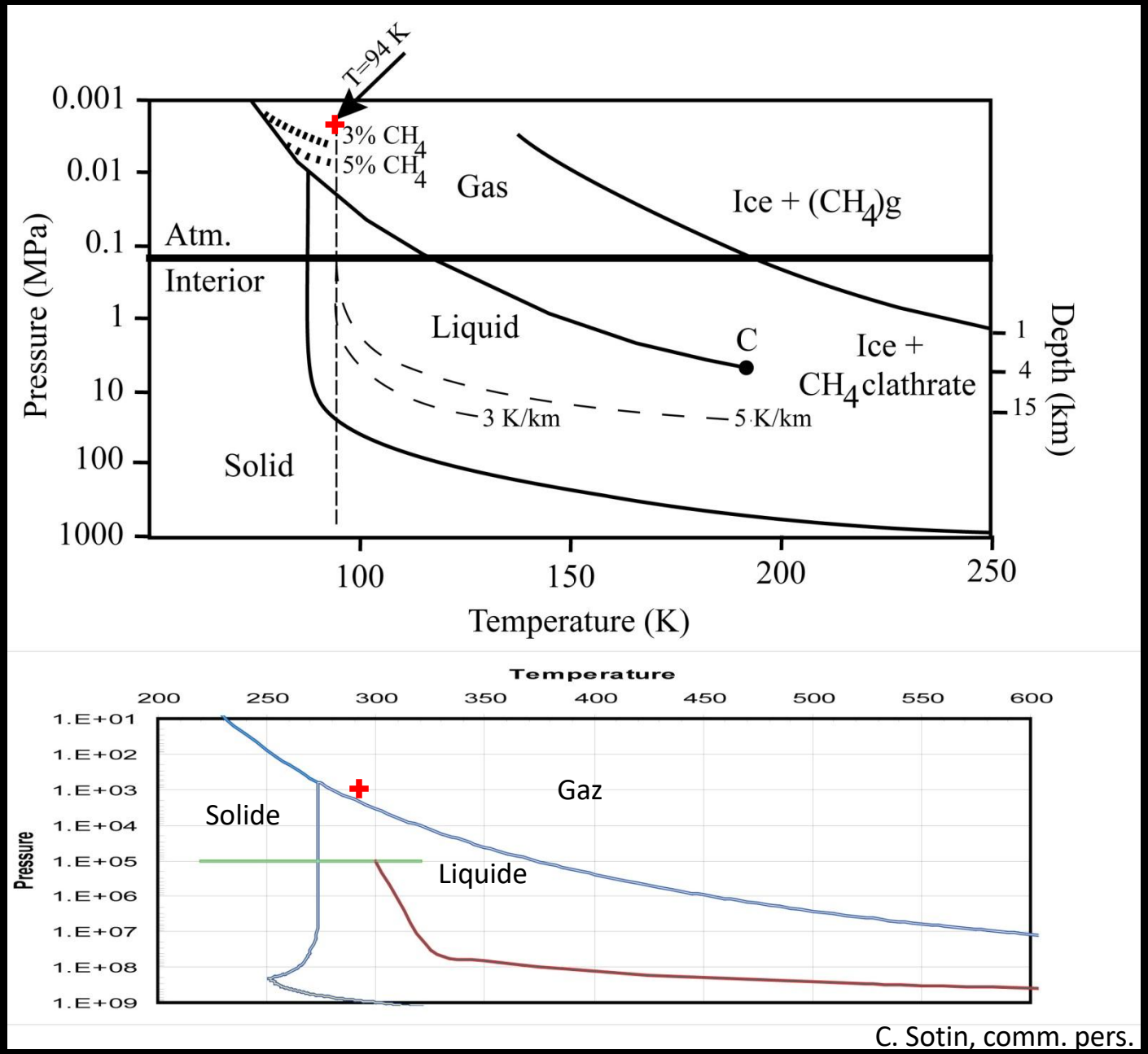
RADAR imageur : Cartographie à 65% à ≈300 m de résolution

Cassini : le climat de Titan

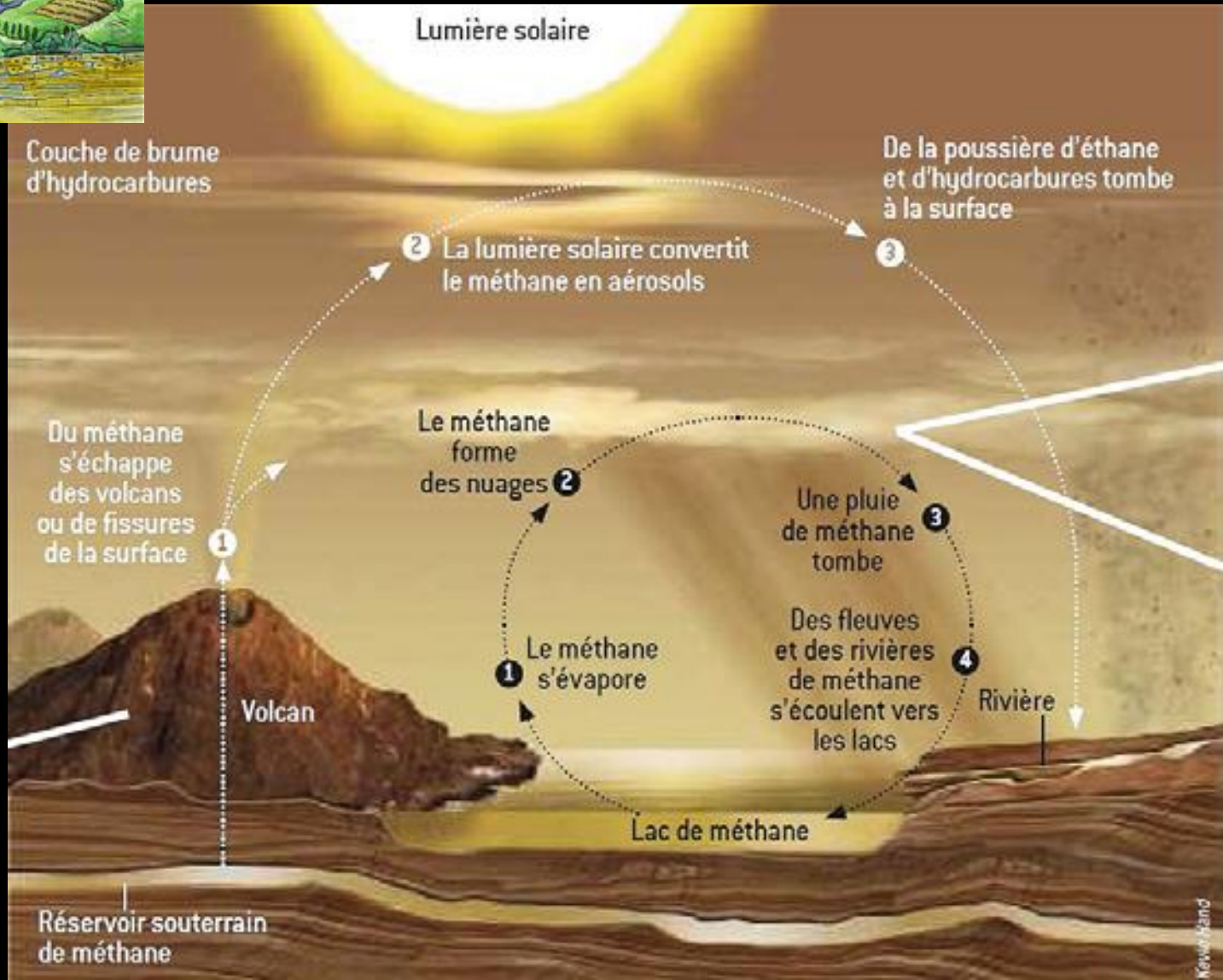
L'équilibre du méthane dans l'atmosphère de Titan :

CH_4 sur Titan

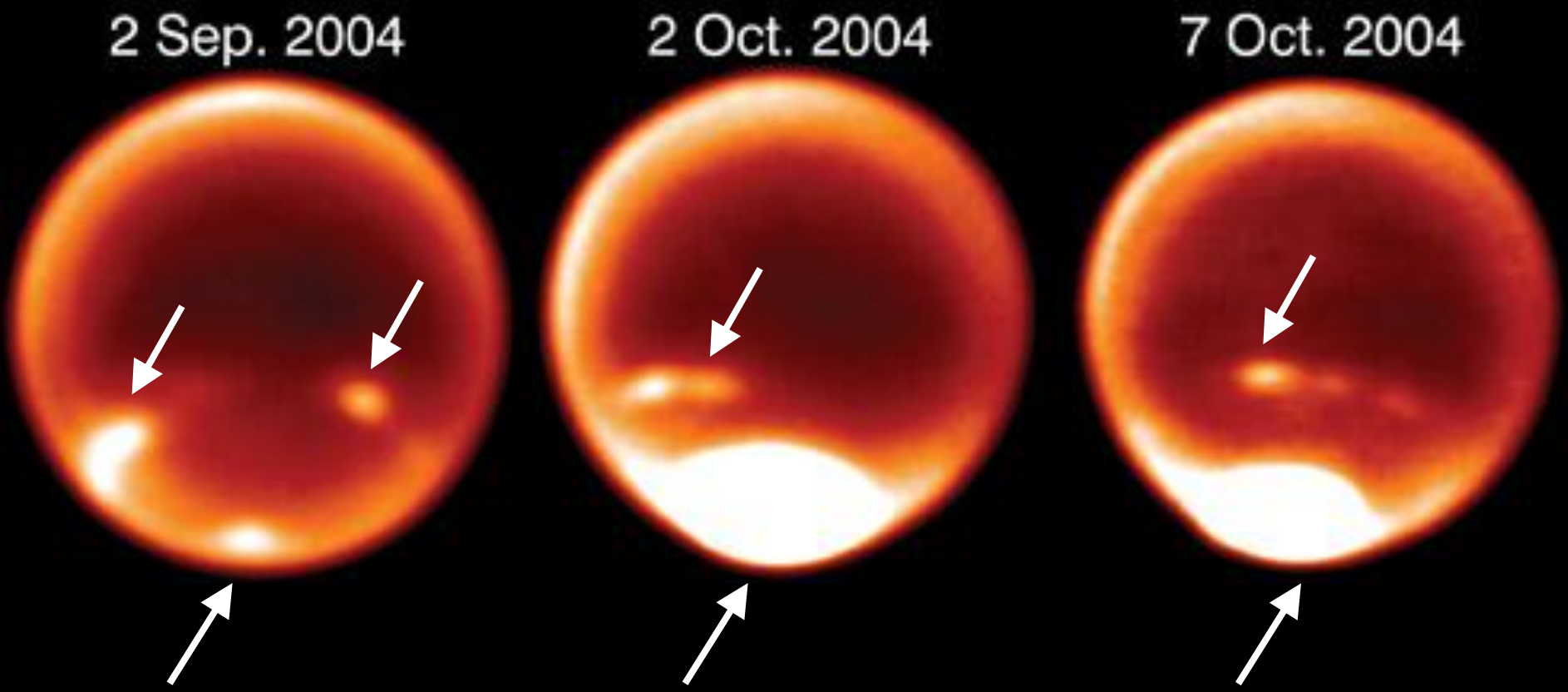
H_2O sur Terre



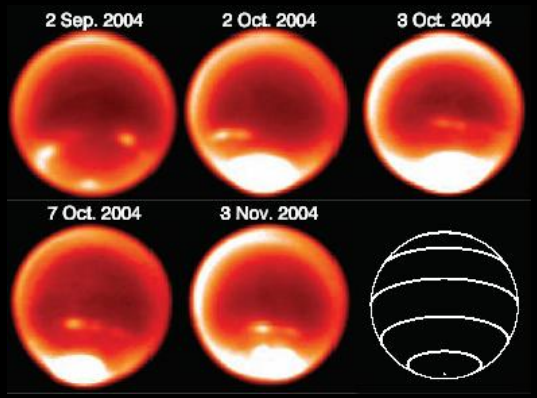
C. Sotin, comm. pers.


Lumière solaire
Couche de brume d'hydrocarbures
De la poussière d'éthane et d'hydrocarbures tombe à la surface
2 La lumière solaire convertit le méthane en aérosols
3
Du méthane s'échappe des volcans ou de fissures de la surface
1
Le méthane forme des nuages 2
Une pluie de méthane tombe 3
Des fleuves et des rivières de méthane s'écoulent vers les lacs 4
Rivière
1 Le méthane s'évapore
Volcan
Lac de méthane
Réservoir souterrain de méthane

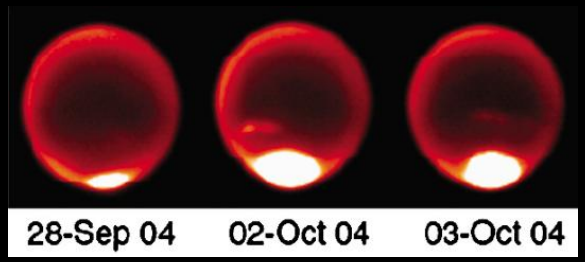
Observations de nuages avec les plus grands télescopes (Keck)



Les nuages observés sur Titan

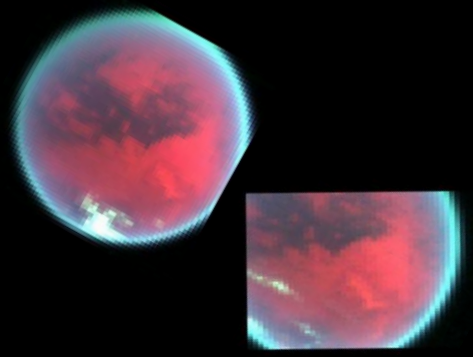


(Roe *et al.*, Science, 2005)

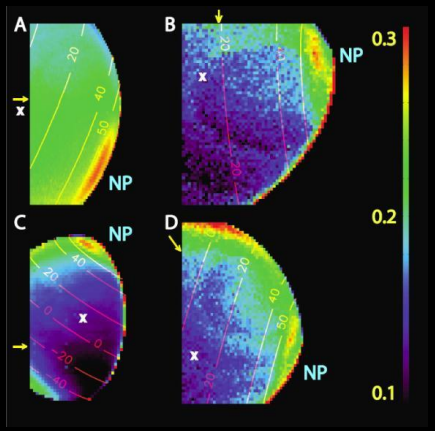


(Shaller *et al.*, Icarus, 2006)

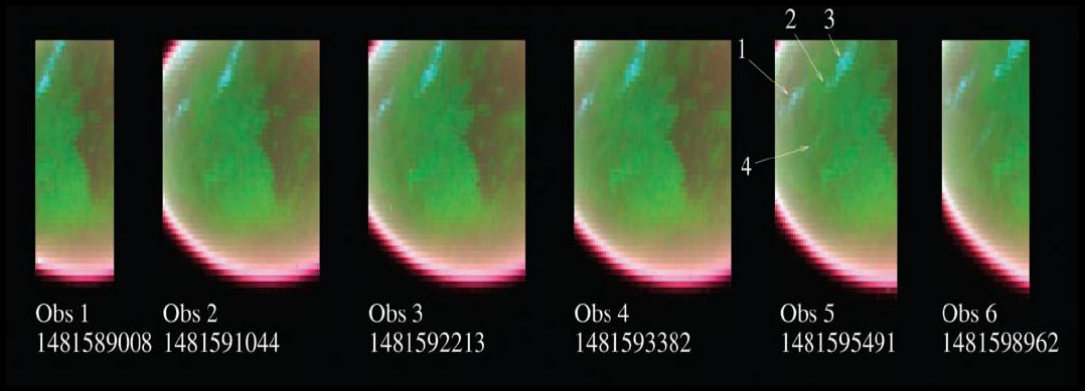
Observations : depuis 1995, au pole sud, aux latitudes tempérées (40°S) de manière transitoire, et récemment au pole nord de façon plus persistente



(Baines *et al.*, EM&P, 2005)

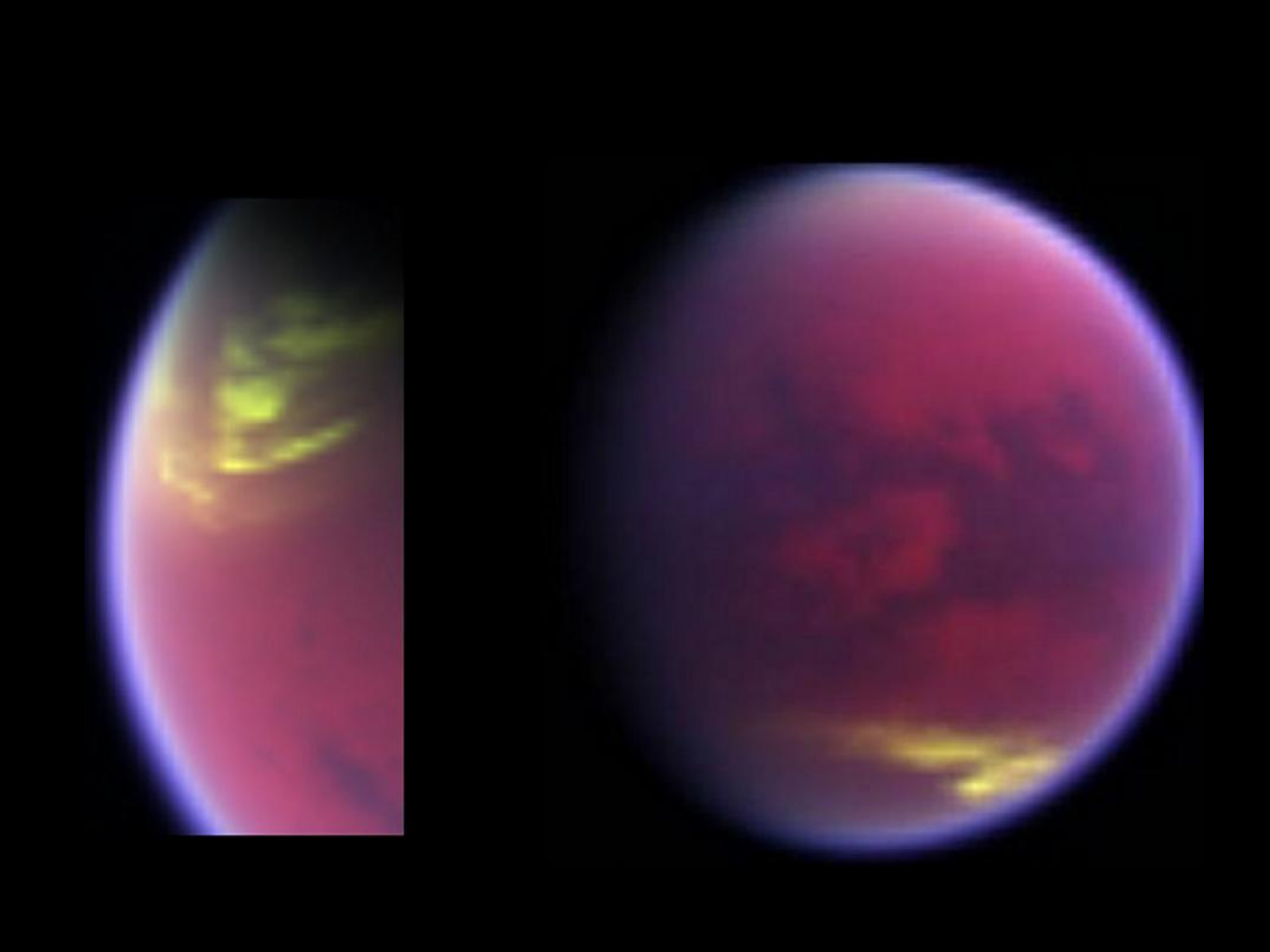


(Griffith *et al.*, Science, 2006)

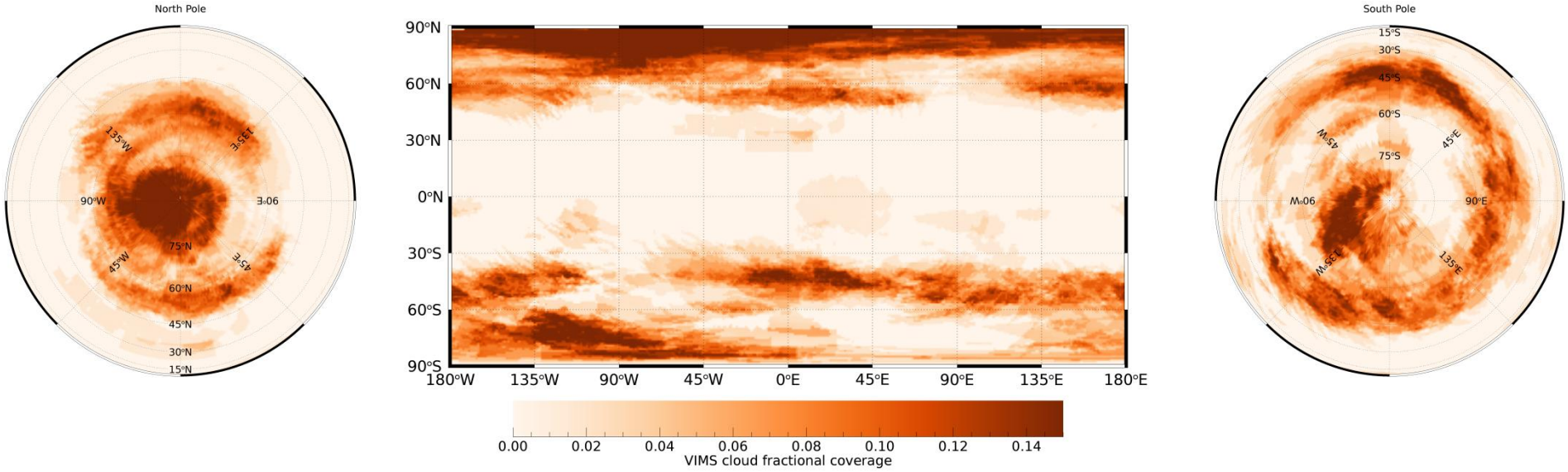


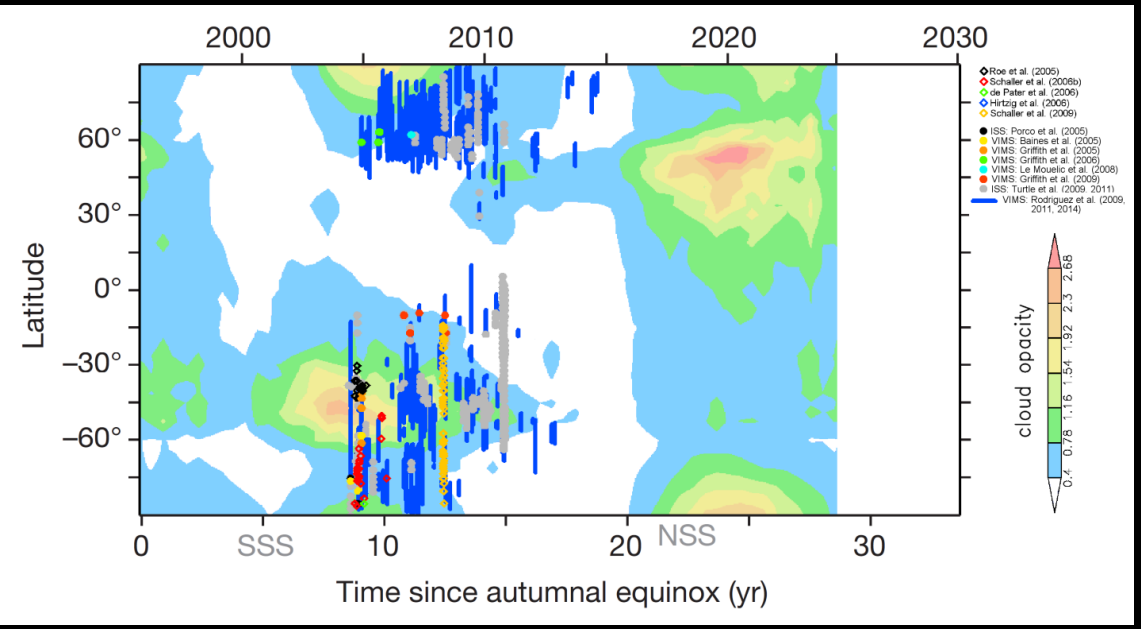
(Griffith *et al.*, Science, 2005)

(Le Mouélic *et al.*, 2012)

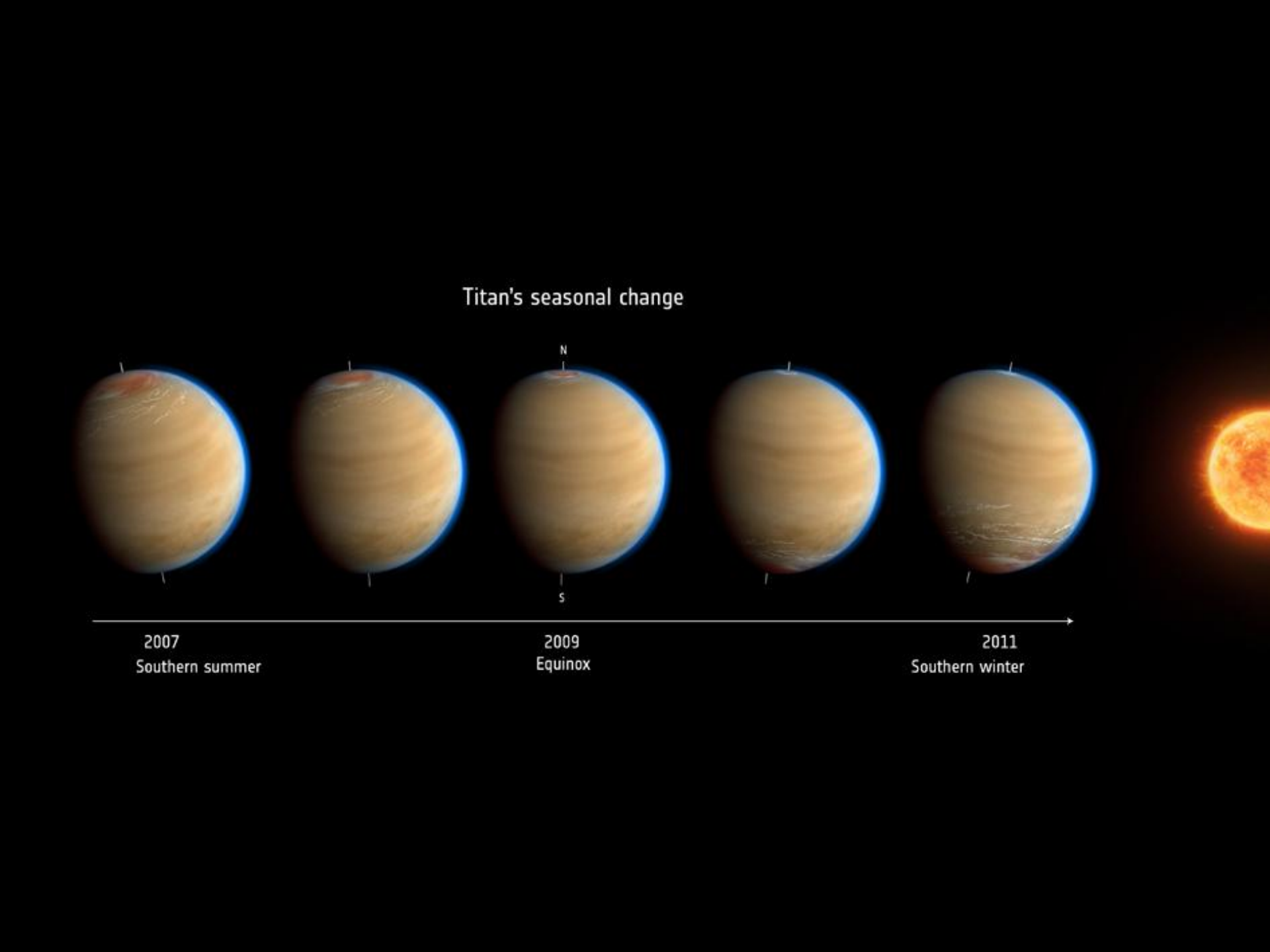


Compilation des 13 années d'observations
Suivi saisonnier : de l'hiver à l'été

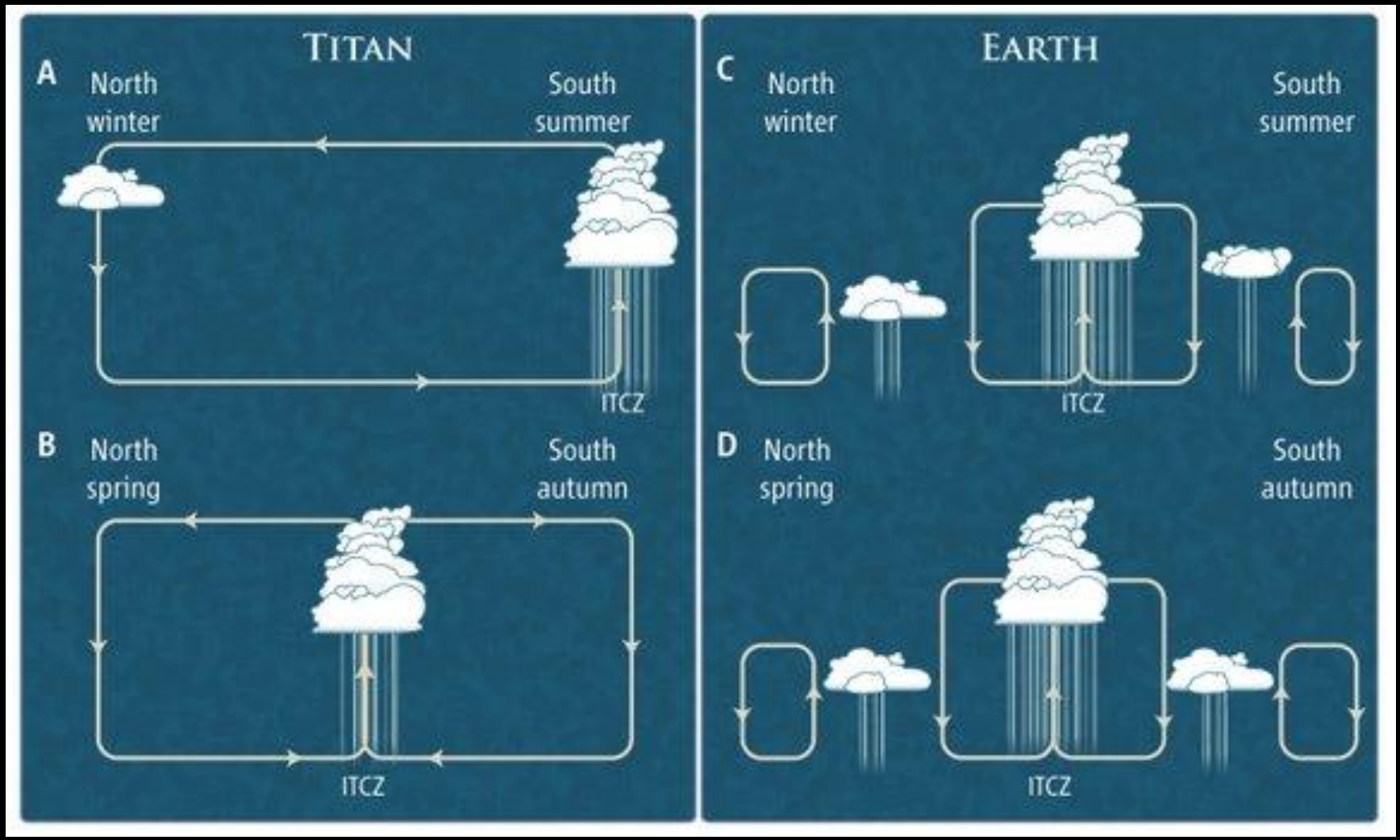




- Activité nuageuse plutôt modérée (>10 % de couverture instantanée)
- Climat plutôt aride à semi-aride
- Distribution en latitudes des nuages contrôlée par la circulation atm.

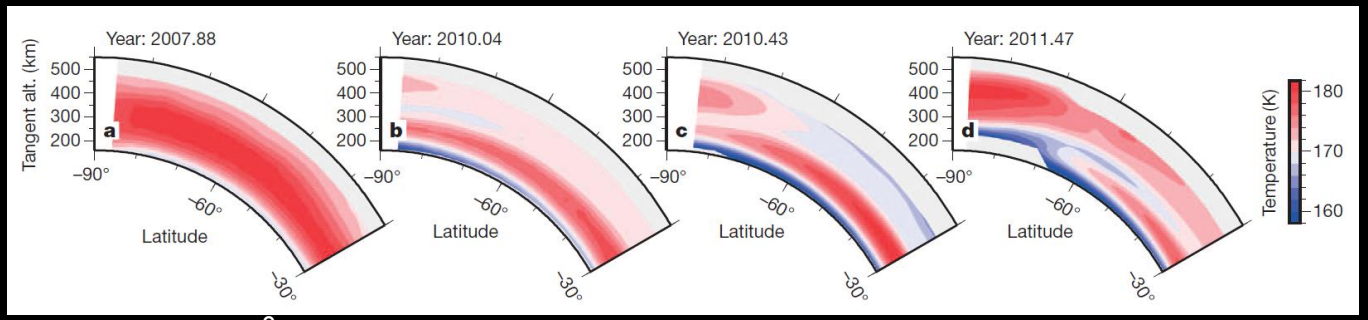

Titan's seasonal change
N
S
2007
Southern summer
2009
Equinox
2011
Southern winter

Global circulation with seasons

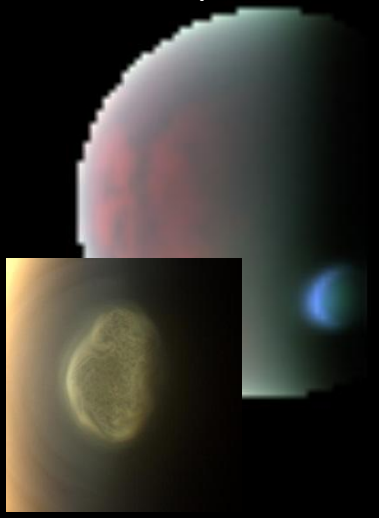


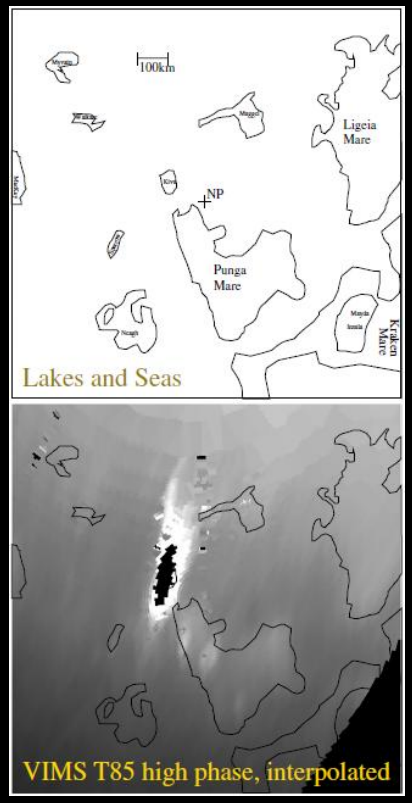
The South/North reversal

Votrex polaire sud
(ISS/VIMS – depuis mai 2012)

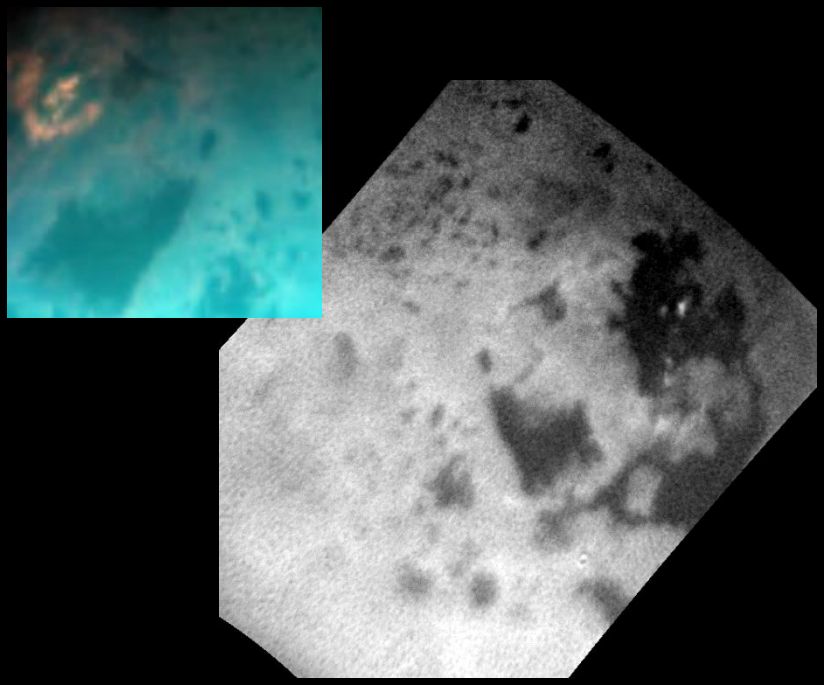


Variation de T° et de la chimie au pôle sud (CIRS – Teanby et al., 2012)

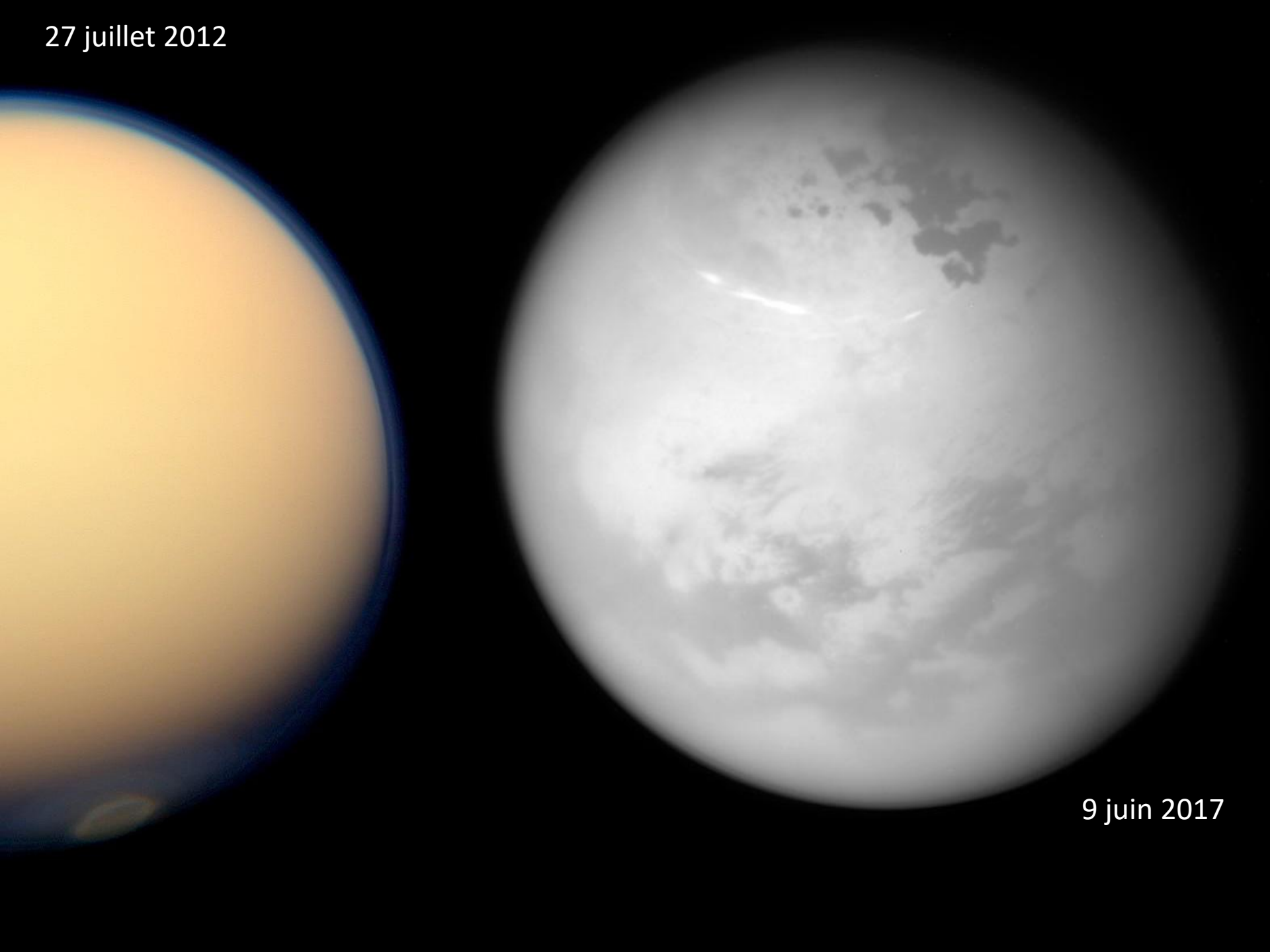




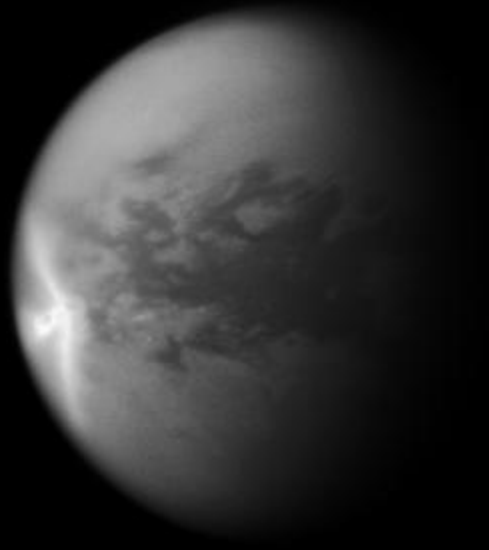
Vagues sur Punga Mare
(VIMS – juillet 2012)



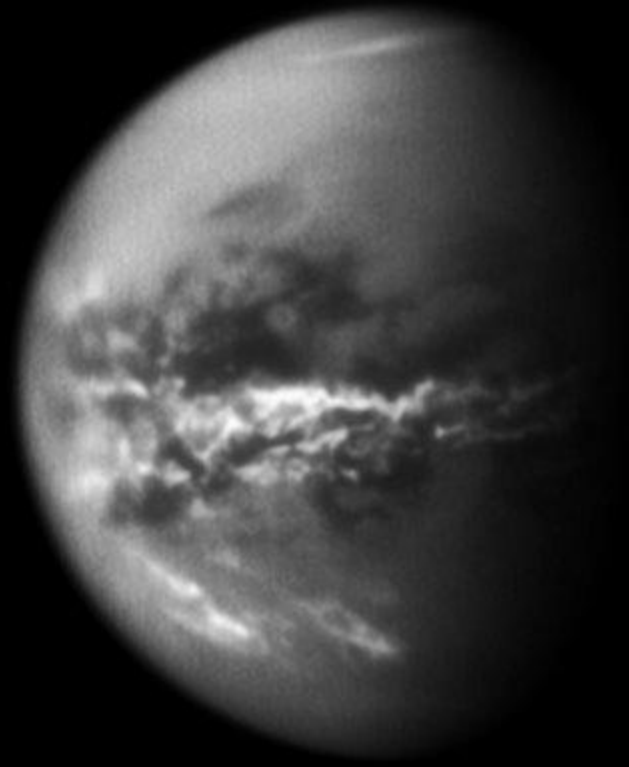
Nuages convectifs au dessus de Ligeia (ISS/VIMS – juillet-août 2014)


27 juillet 2012
9 juin 2017

A l’équinoxe de printemps

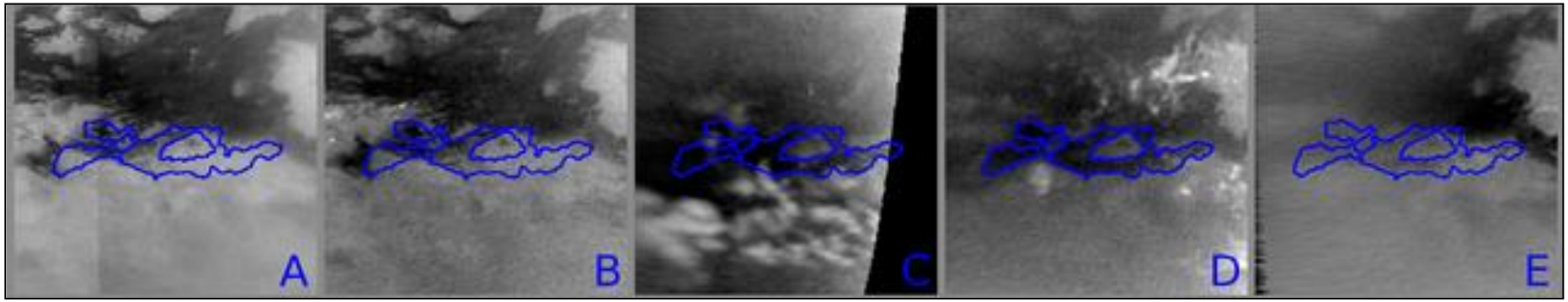


27 septembre 2010



18 octobre 2010

Des pluies rares mais violentes…



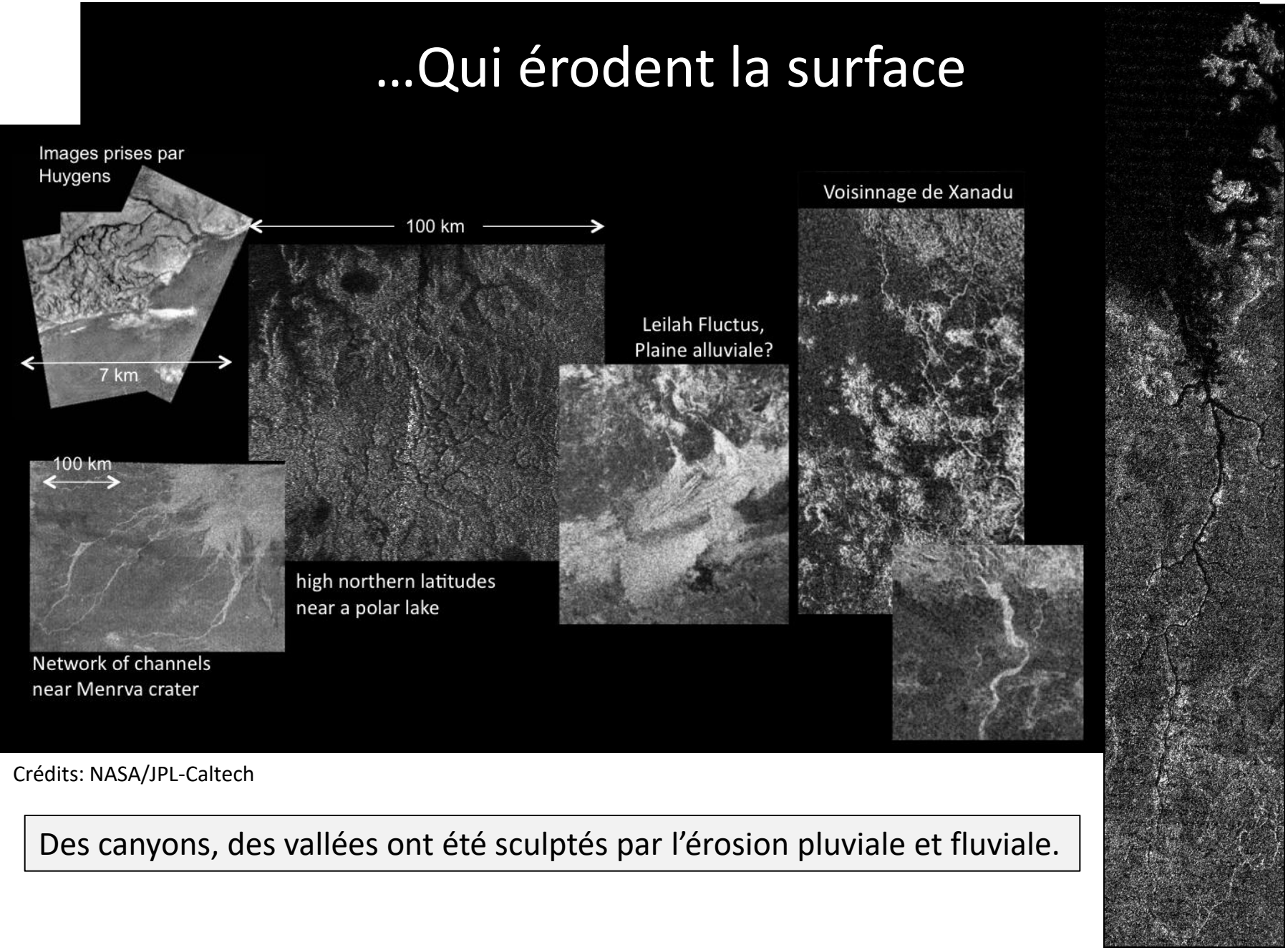
Crédits: NASA/Space Science Institute

Deux épisodes de pluie ont été observés.

Les précipitations sont sans doute moins abondantes sur Titan que sur Terre mais probablement violentes.

Alice LE GALL (comm. perso.)

…Qui érodent la surface

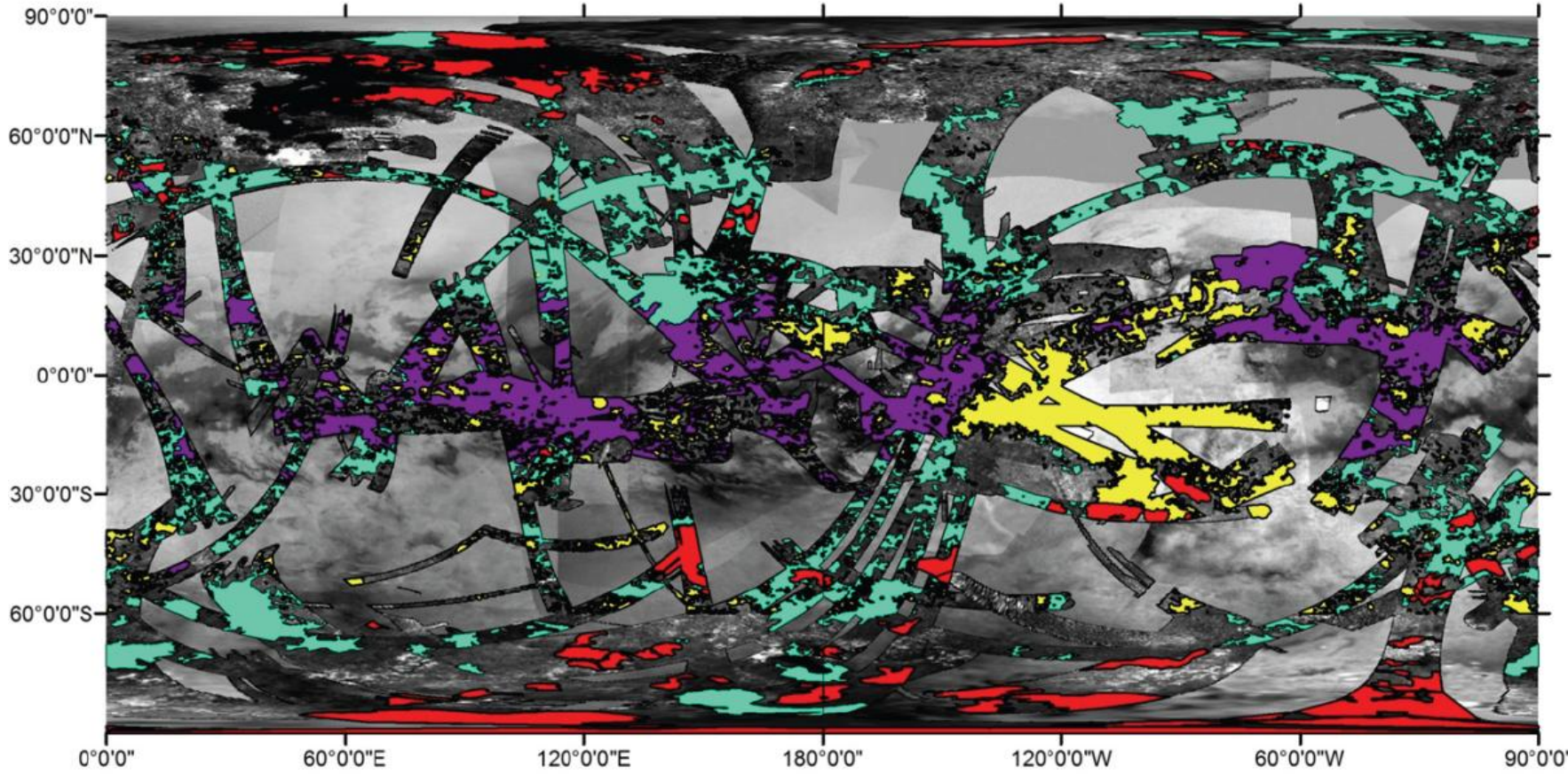


Crédits: NASA/JPL-Caltech

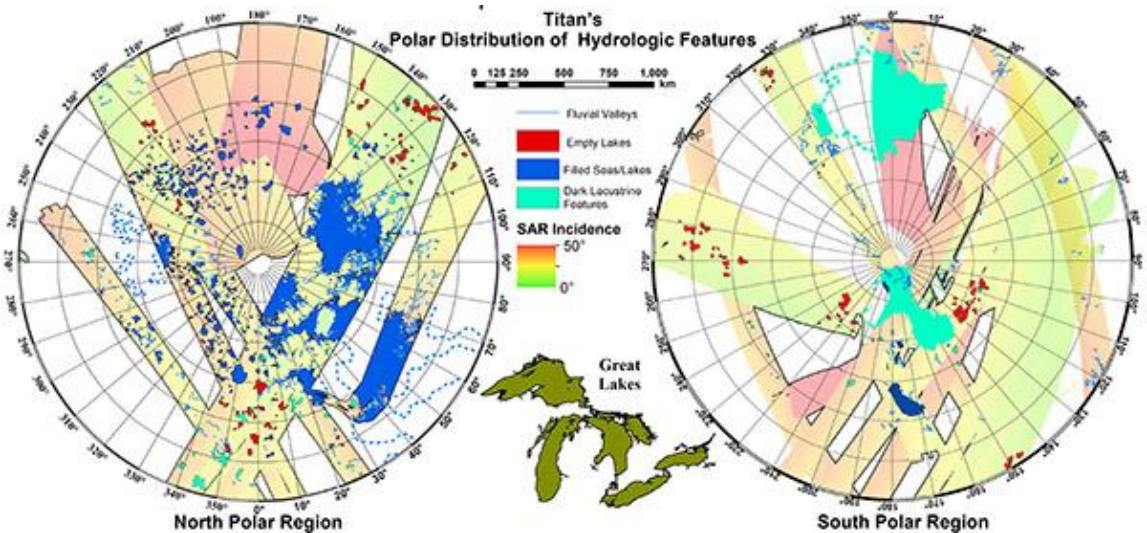
Des canyons, des vallées ont été sculptés par l'érosion pluviale et fluviale.

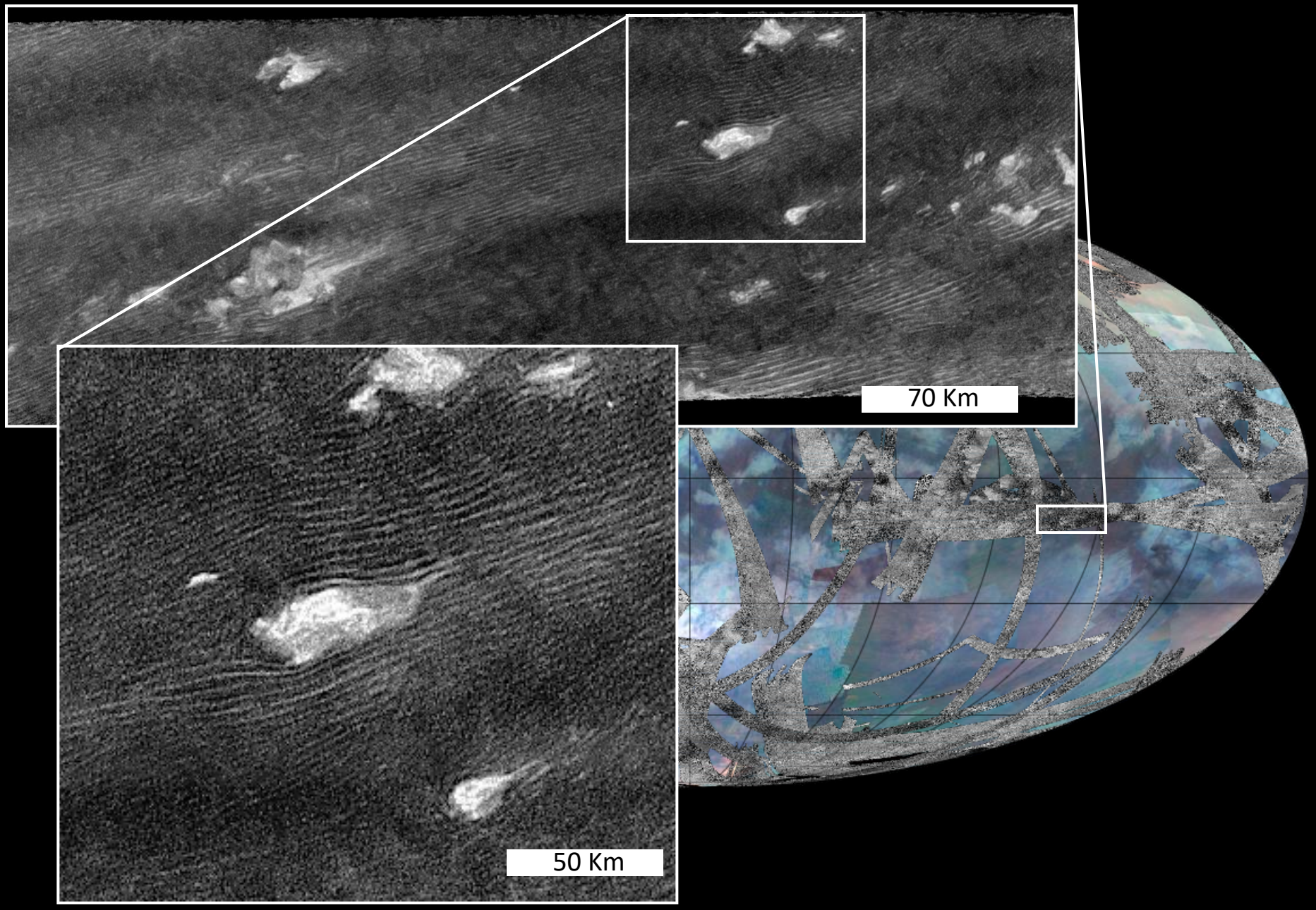
Alice LE GALL (comm. perso.)

Cassini : géologie de Titan et lien avec le climat



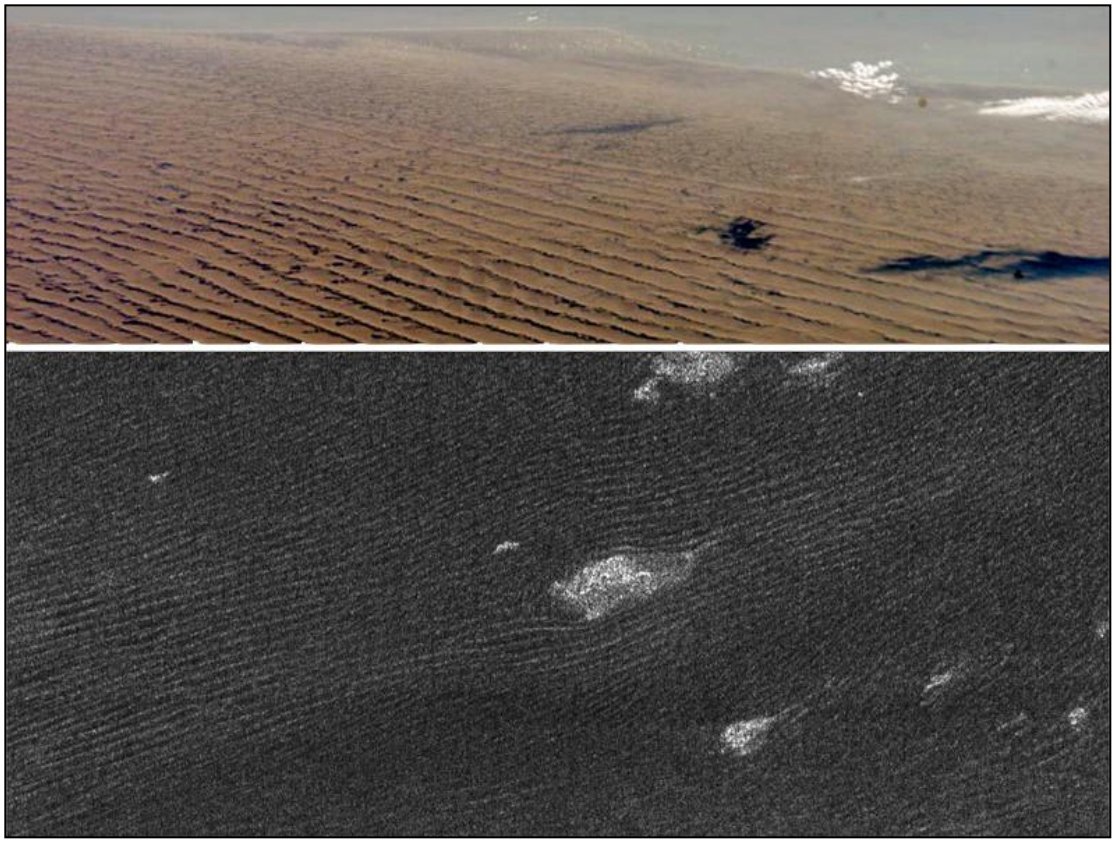
- Labyrinth
- Hummocky/mountainous
- Undifferentiated Plains
- Dunes





Les régions équatoriales

Du vent qui distribue et sculpte la matière



Dunes linéaires de Namibie (Terre) et de Belet (Titan)
Crédits: NASA/JPL-Caltech

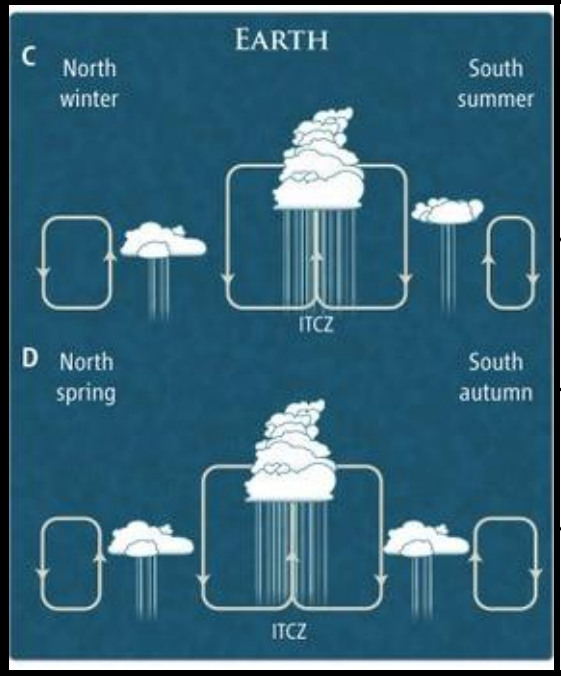
Environ 15% de la surface de Titan est couverte de champs de dunes linéaires.

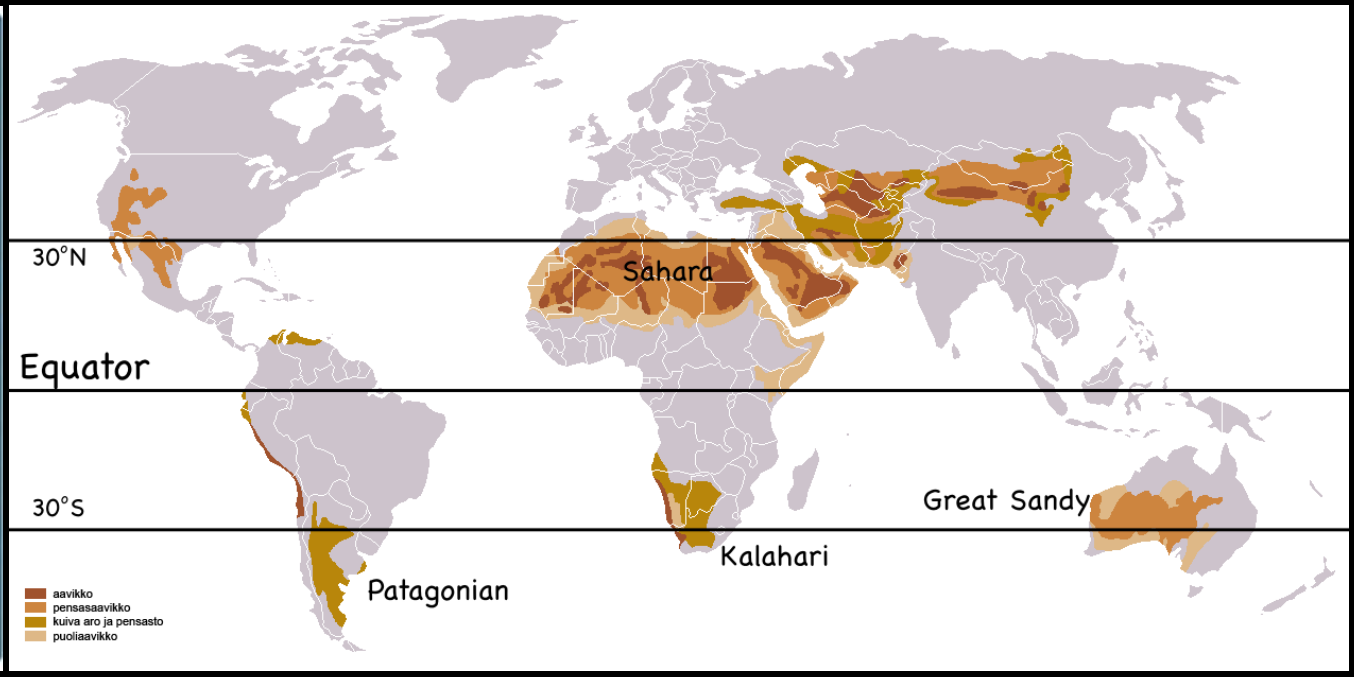
Dunes géantes: hautes de ~50-200 m de haut, larges de ~1-3 km et longues de plusieurs centaines de km.

Grains de « sable » organique (100-200 µm)

Alice LE GALL (comm. perso.)

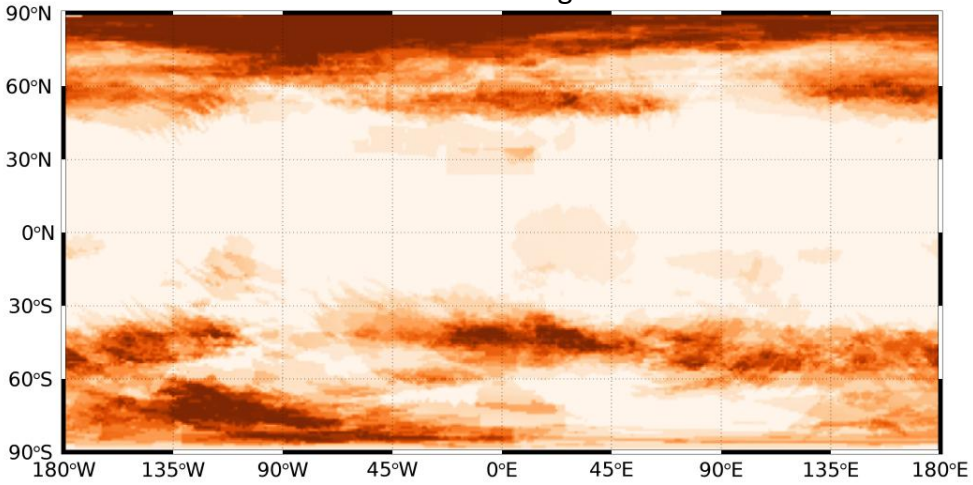
Sur Terre



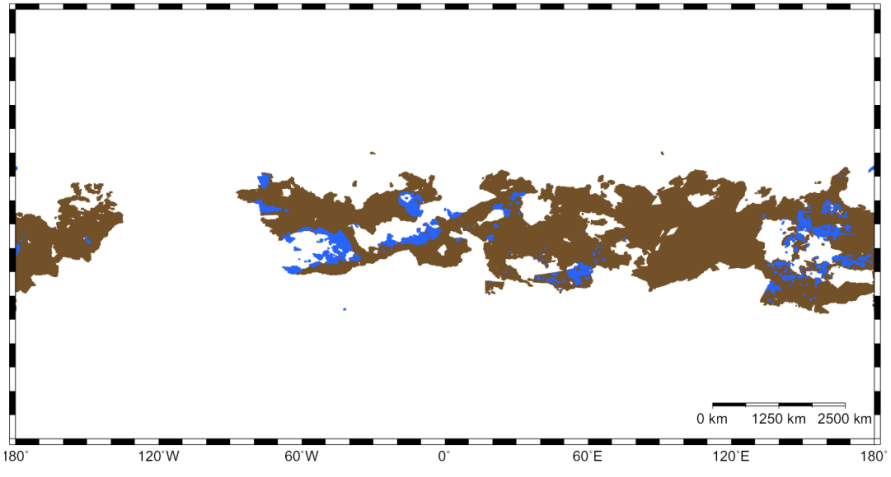


Climat sur Titan ?

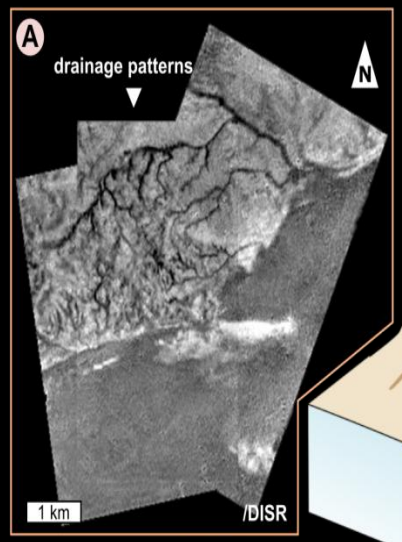
Couverture nuageuse

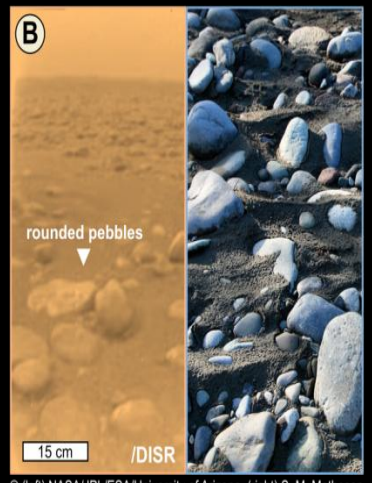


Distribution géographique des champs de dunes



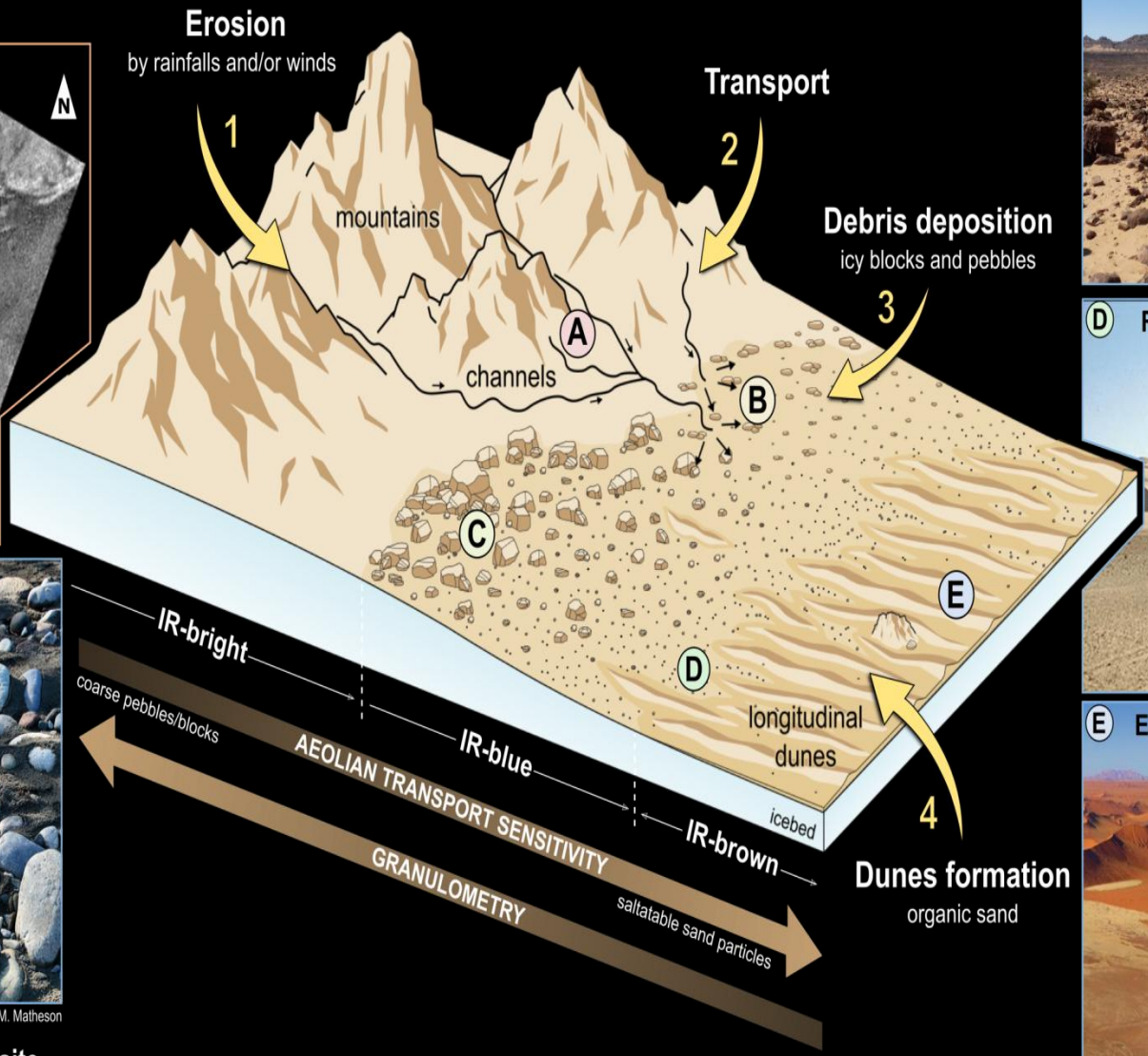
Analogie avec les déserts terrestres ?



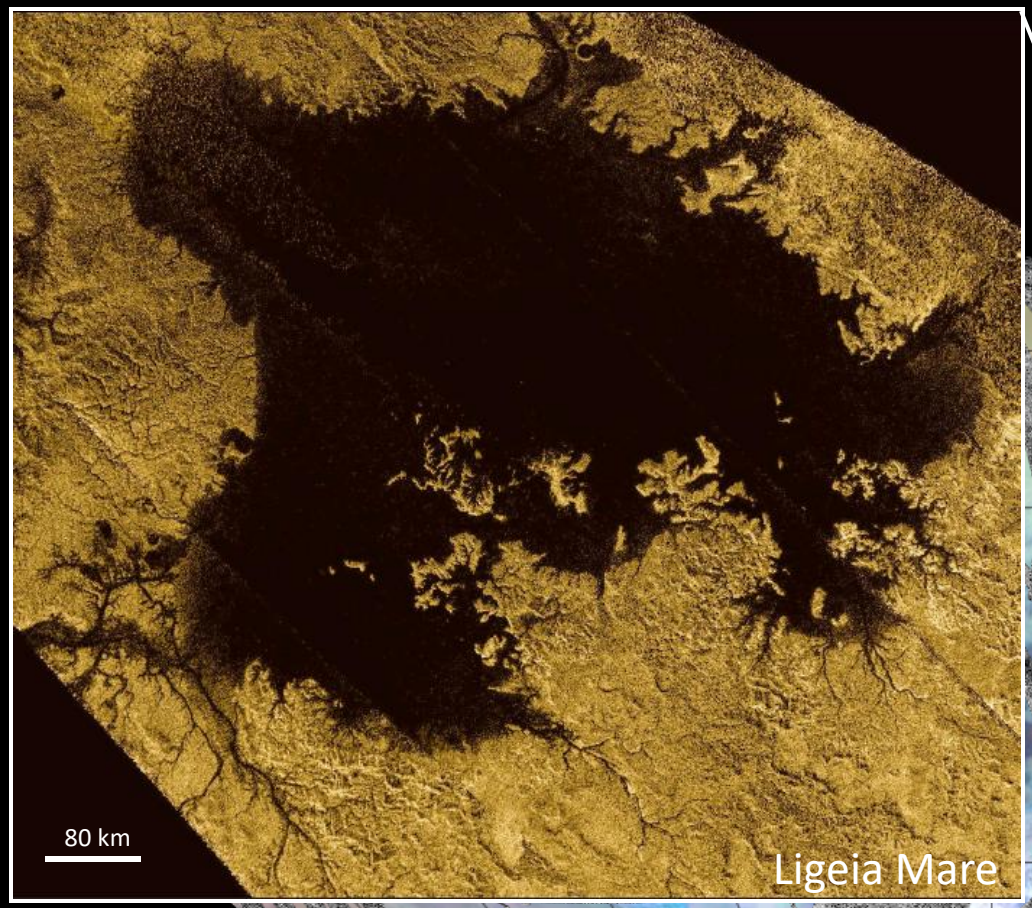


© (left) NASA/JPL/ESA/University of Arizona, (right) S. M. Matheson

▲ Huygens landing site
January 14, 2005



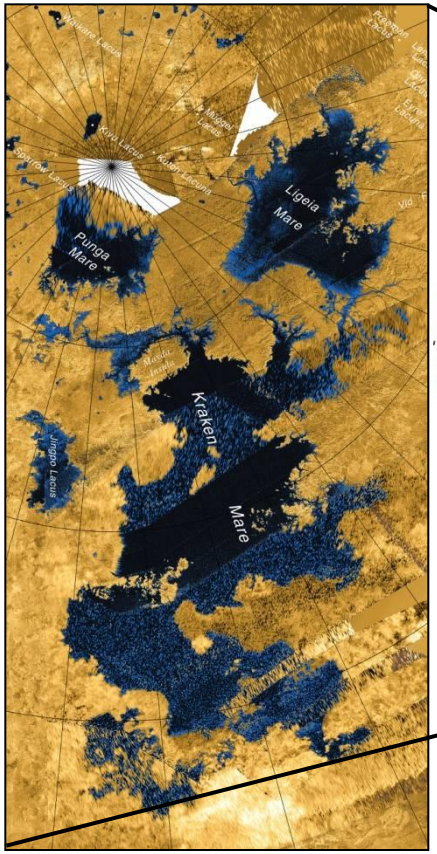
* from Titan and Earth



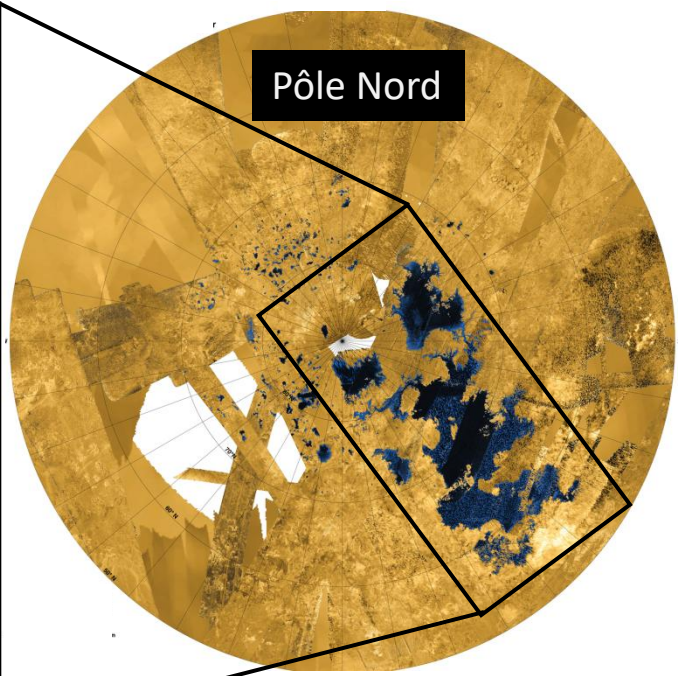
Aux pôles

Des mers et lacs d'hydrocarbures

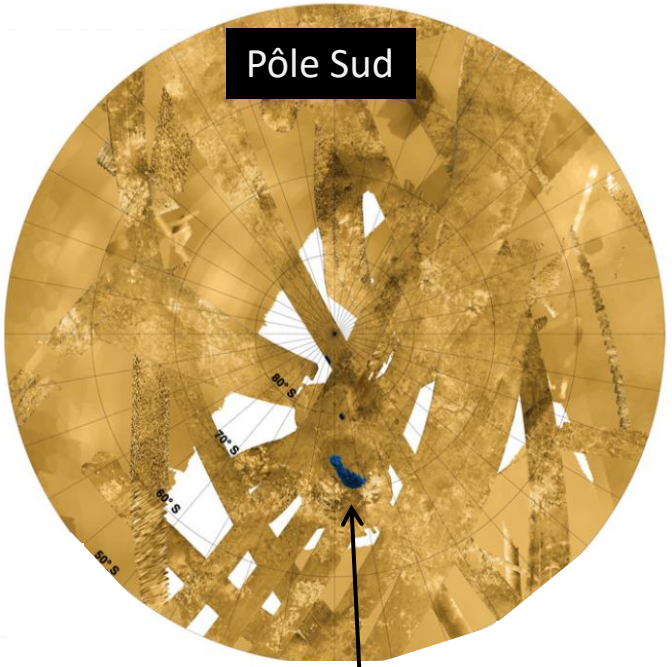
Titan est le seul objet extraterrestre disposant d'étendues liquides.



Crédits: NASA/JPL-Caltech/USGS



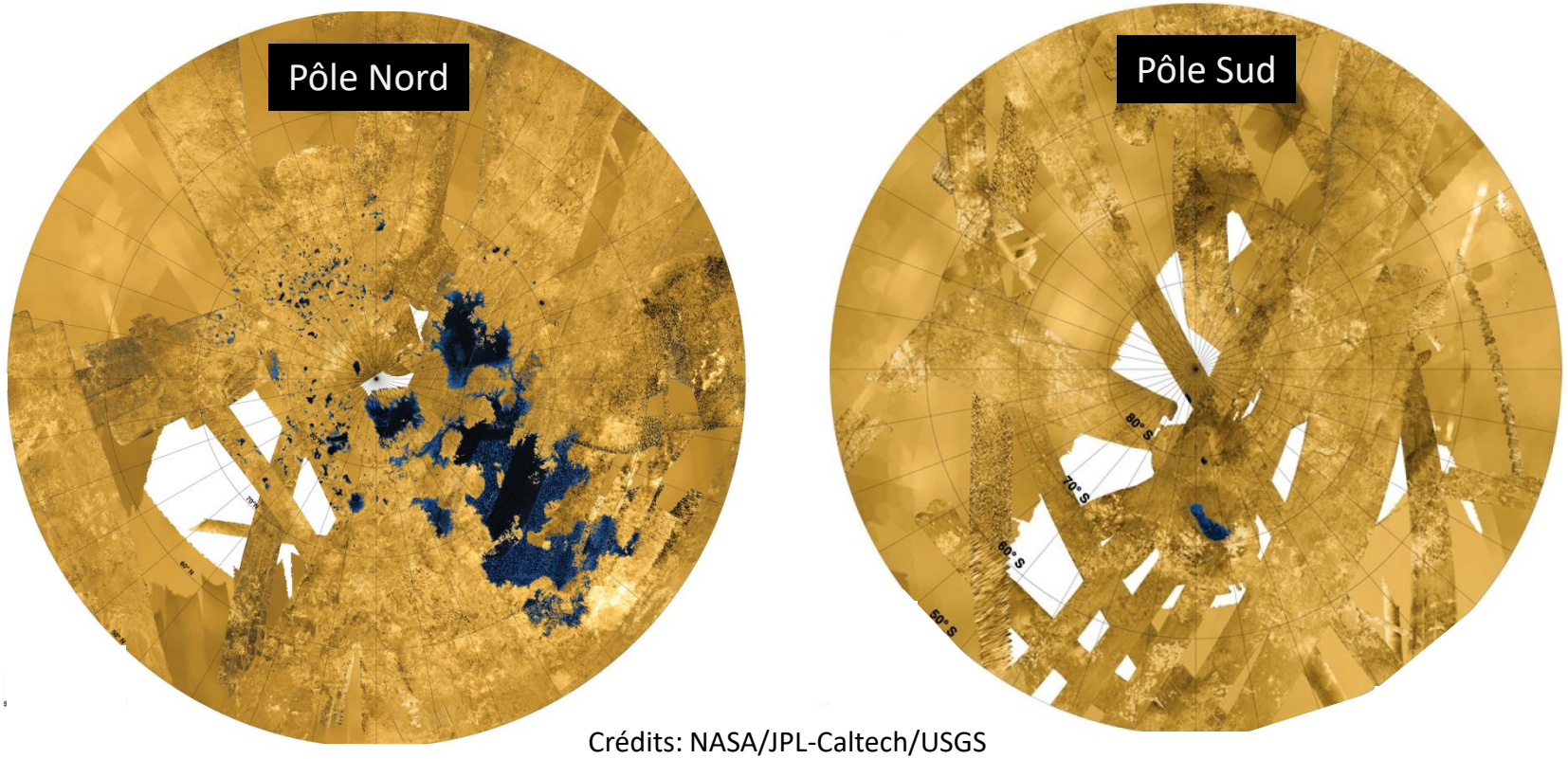
Kraken Mare
Ligeia Mare
Punga Mare



Ontario Lacus

Alice LE GALL (comm. perso.)

Dichotomie Nord/Sud

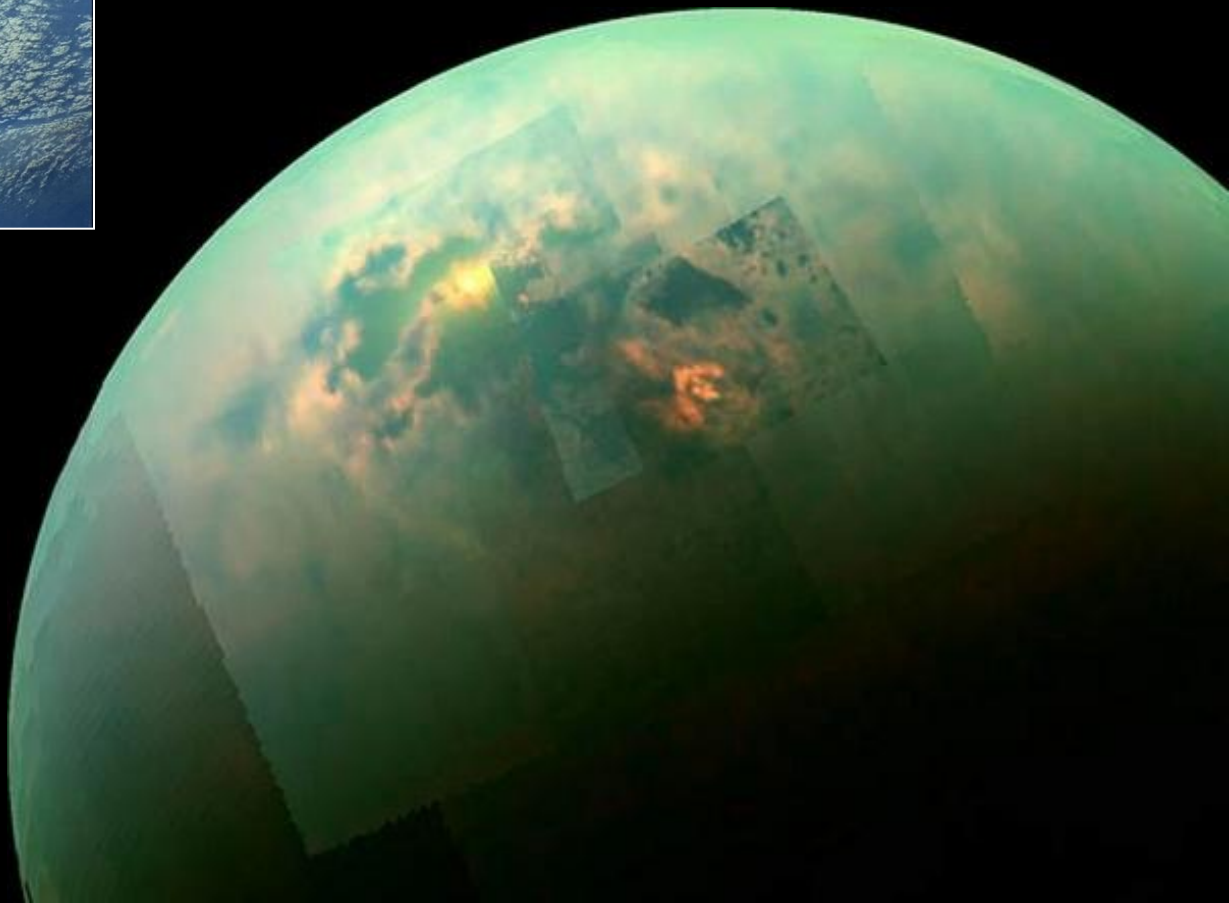


Crédits: NASA/JPL-Caltech/USGS

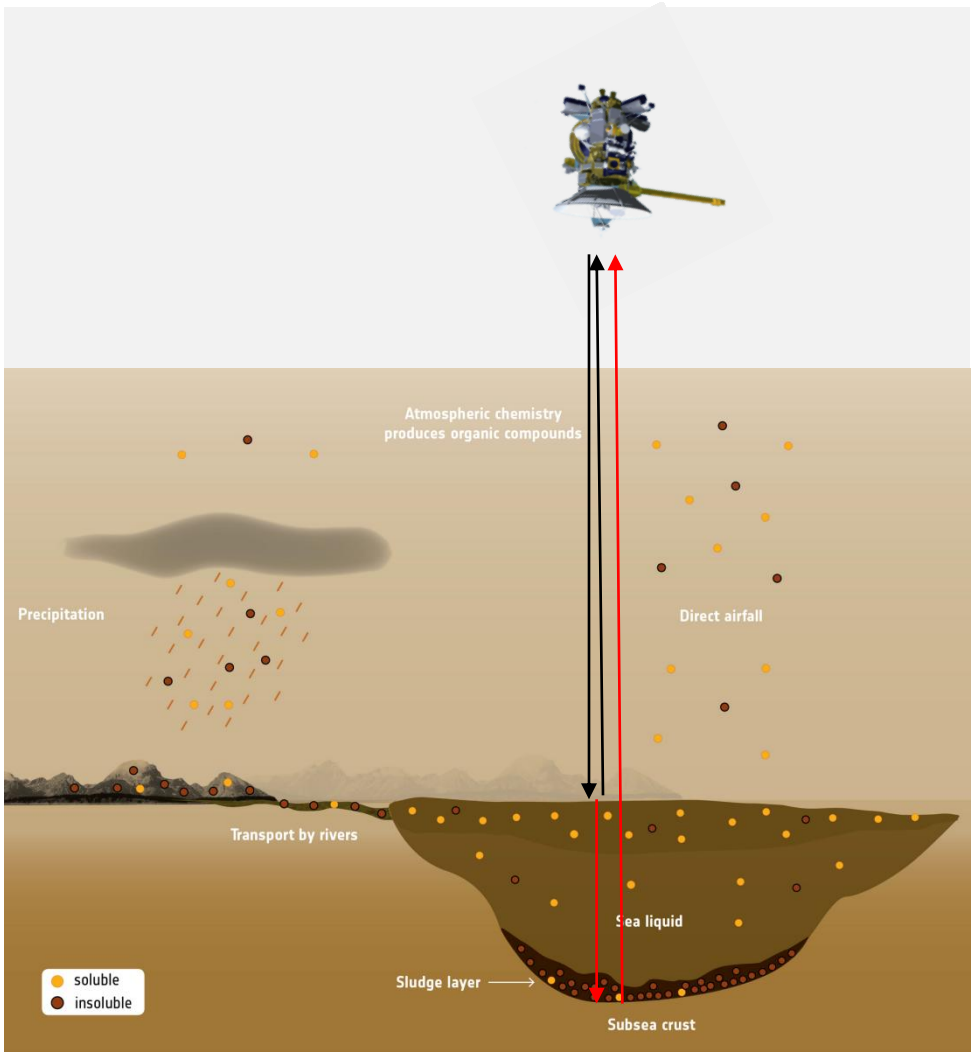
La dichotomie Nord-Sud s'explique par des étés australs plus courts mais plus intenses que les étés boréaux.

Cette situation s'inverse tous les ≈50 000 ans (analogues au cycle de Croll-Milankovitch sur Terre).

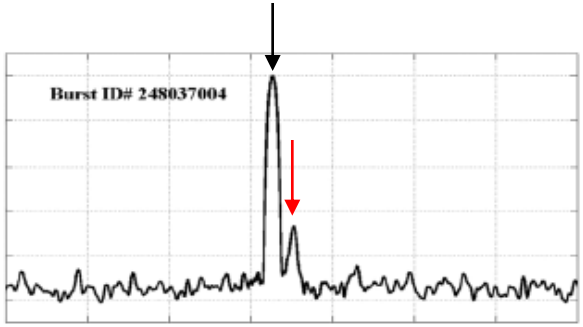
Alice LE GALL (comm. perso.)



Première détection du fond d'un lac extraterrestre!



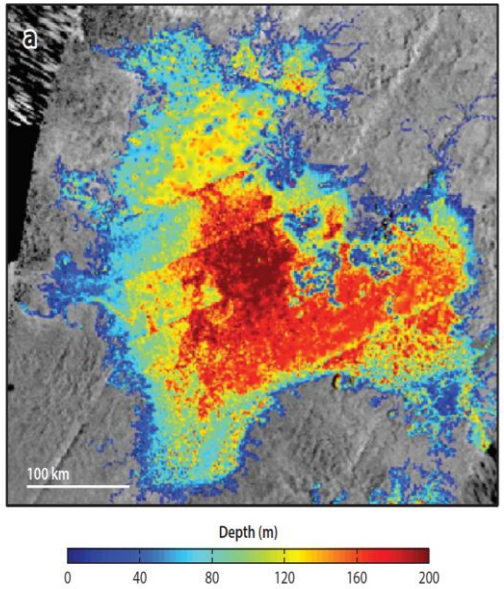
Crédits: ESA



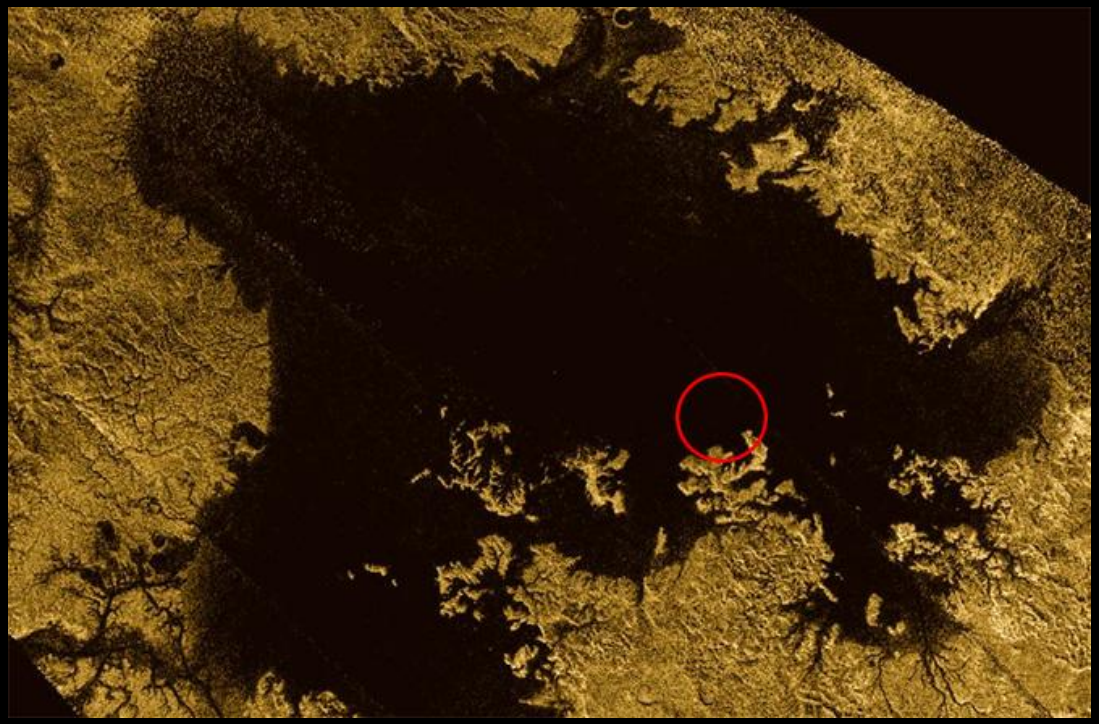
Crédits: M. Mastrogiuseppe

Première carte bathymétrique du plancher d'une mer extraterrestre

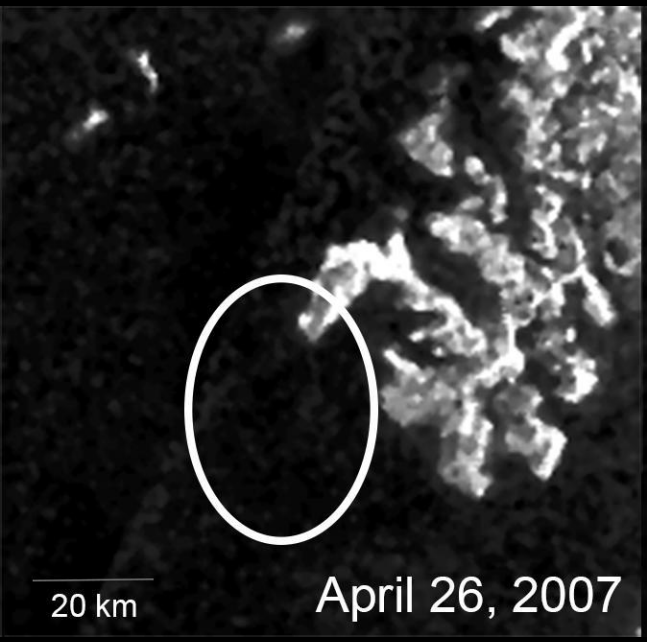
Crédits: A. Hayes

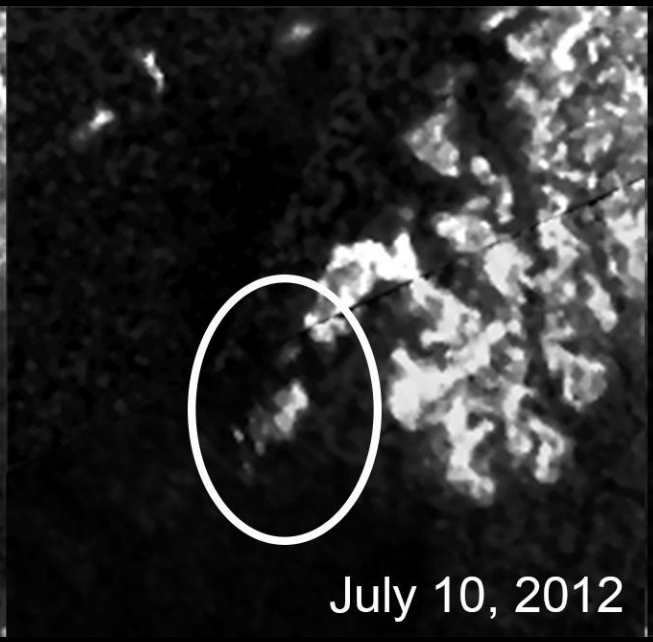


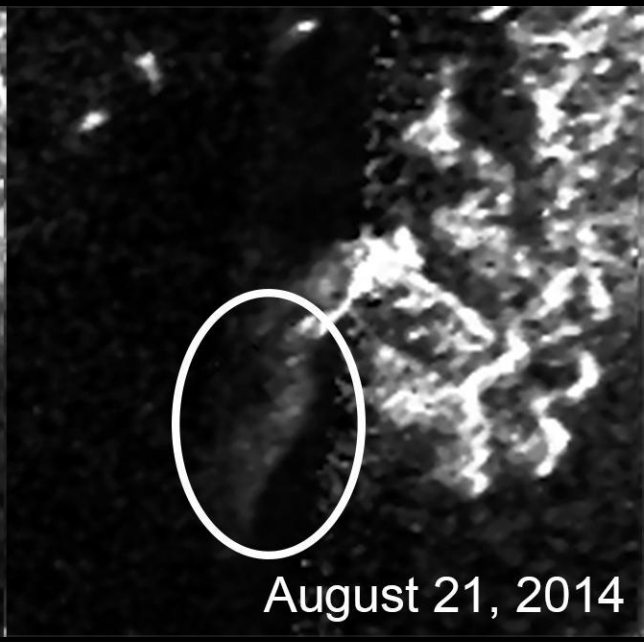
Alice LE GALL (comm. perso.)



L’île magique !





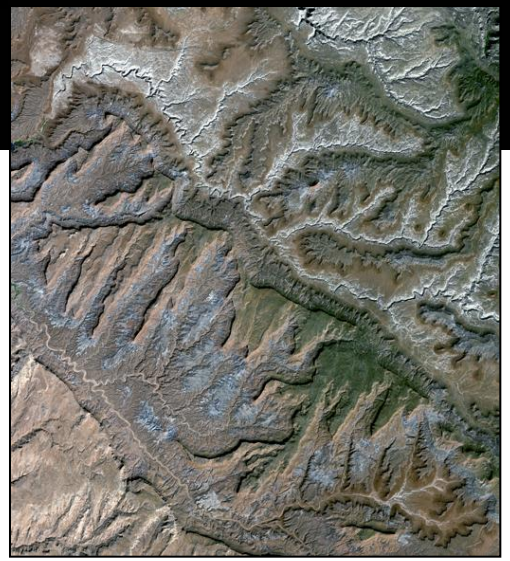



You are here.

Des terrains de type karstique

Crédits: NASA/JPL-Caltech

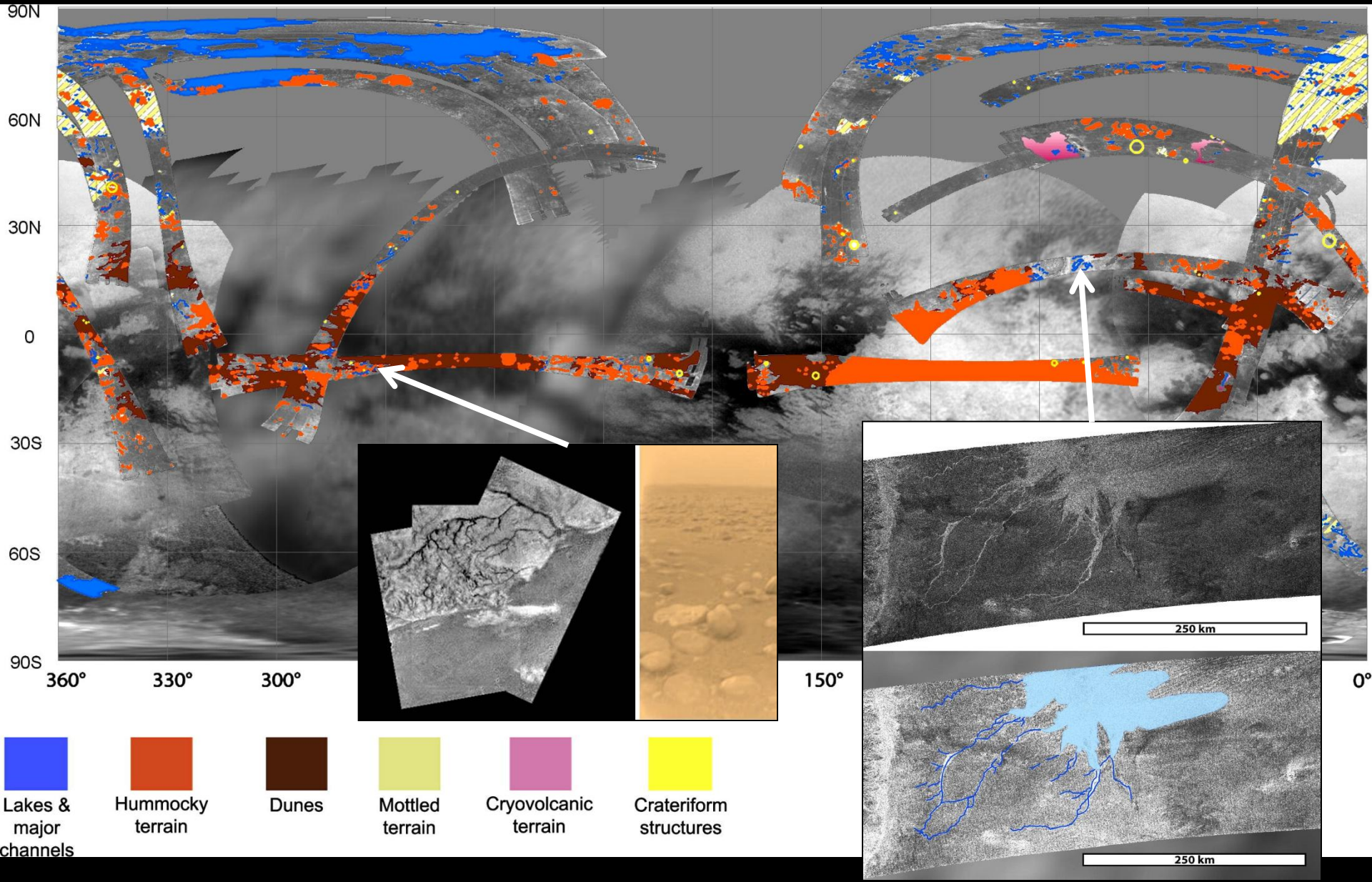
Le méthane liquide peut être un agent d'érosion, aussi bien physique que chimique, d'une croûte de glace riche en ammoniaque ou organique aussi efficace que l'eau avec le silicate sur Terre.



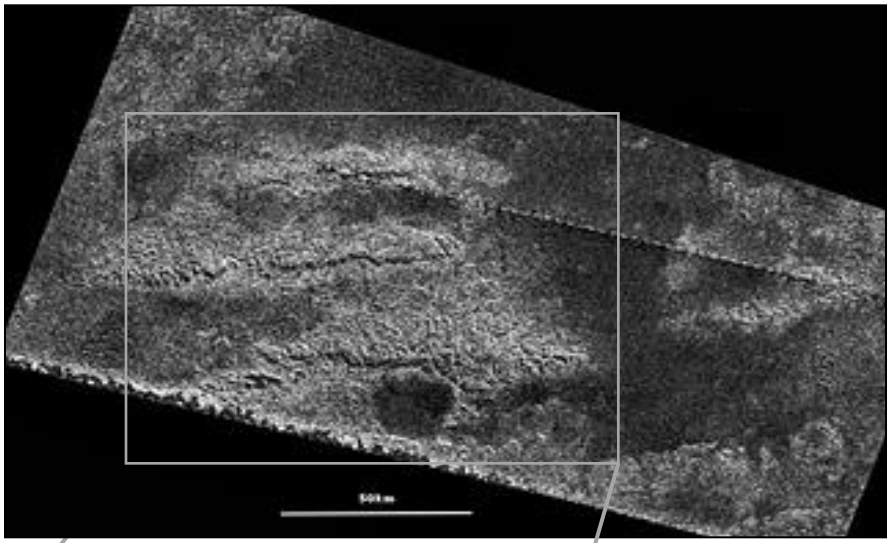
White Canyon, Utah
Crédits: NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team

Alice LE GALL (comm. perso.)

Aux latitudes moyennes :



Des reliefs mais modérés



Crédits: NASA/JPL-Caltech

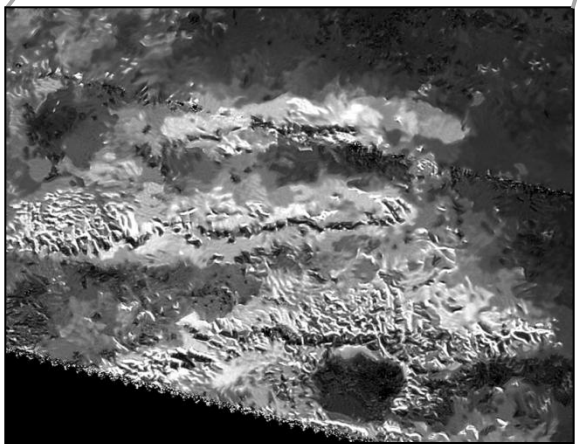
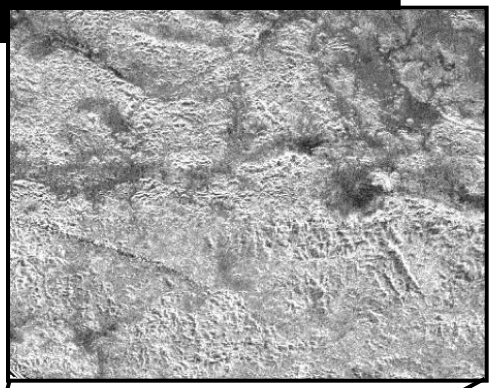
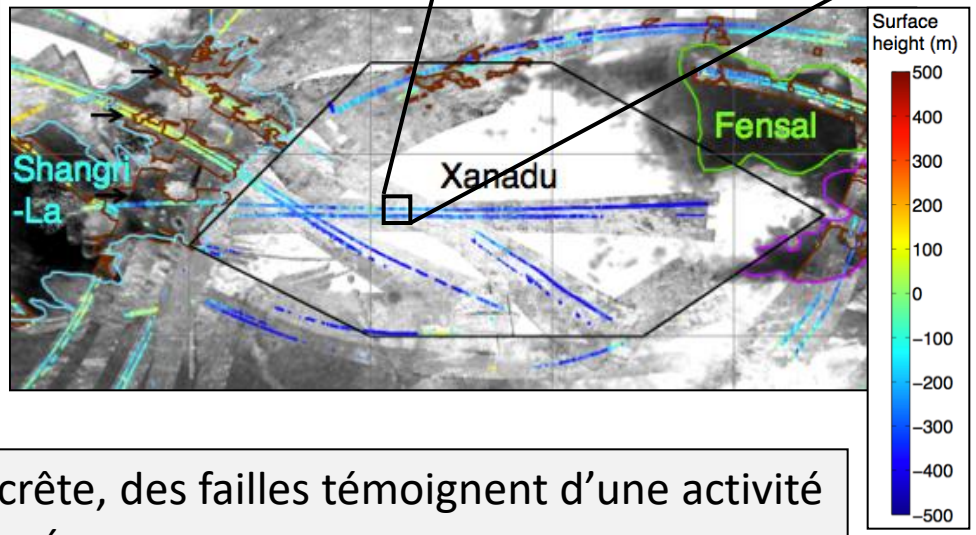


Image radar « débruitée » de Mithrim Montes (max 3300 m)



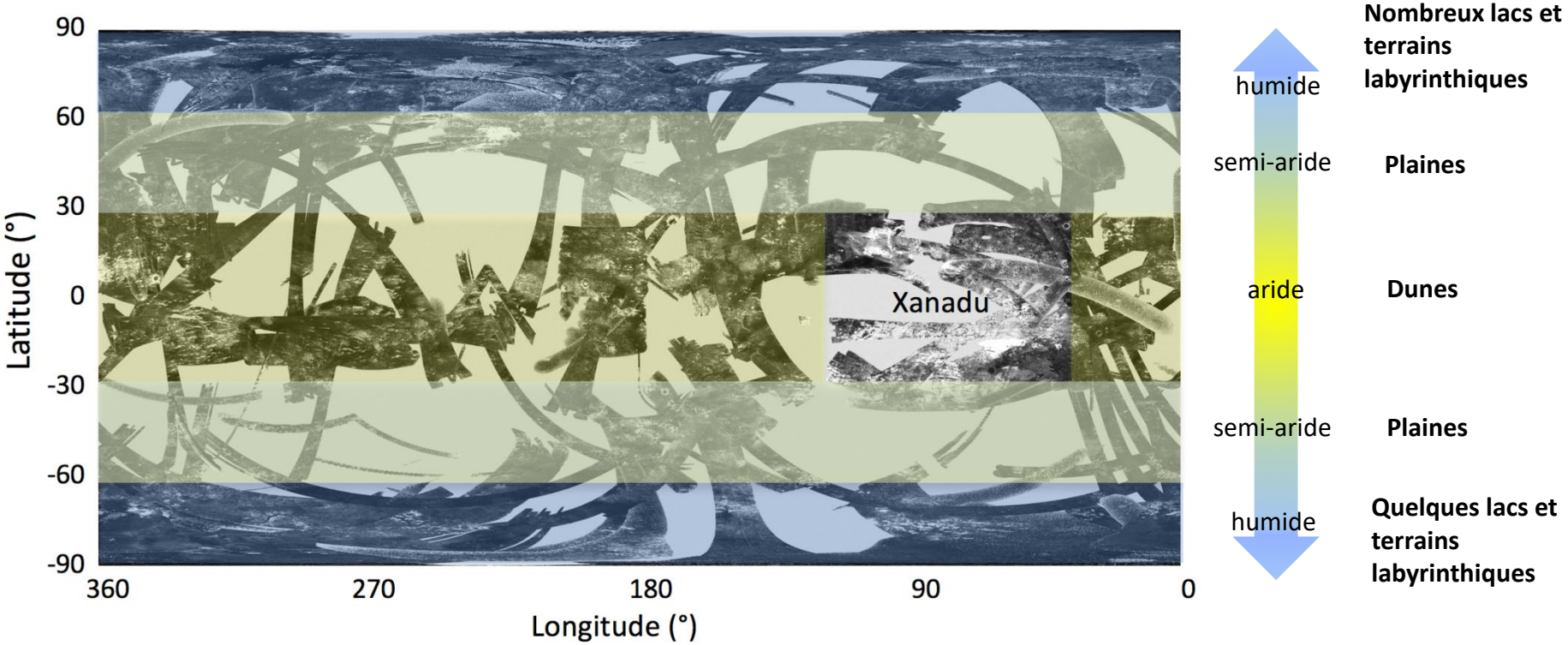


Des lignes de crête, des failles témoignent d'une activité tectonique passée.

Les reliefs sur Titan reste modérés : rarement plus de 2000 m de haut.

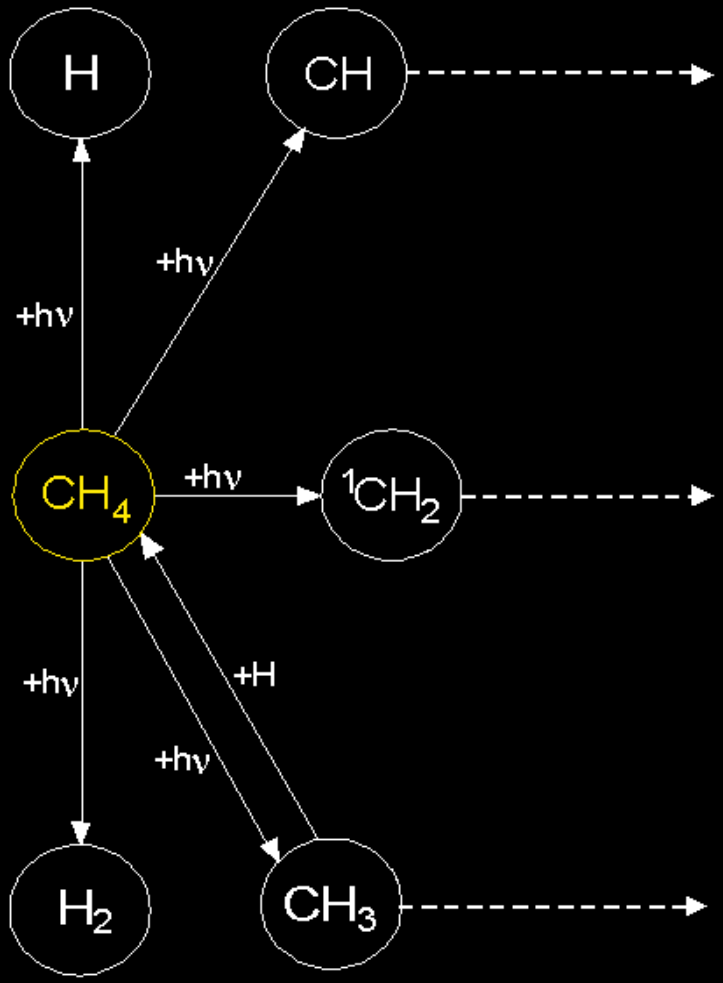
Alice LE GALL (comm. perso.)

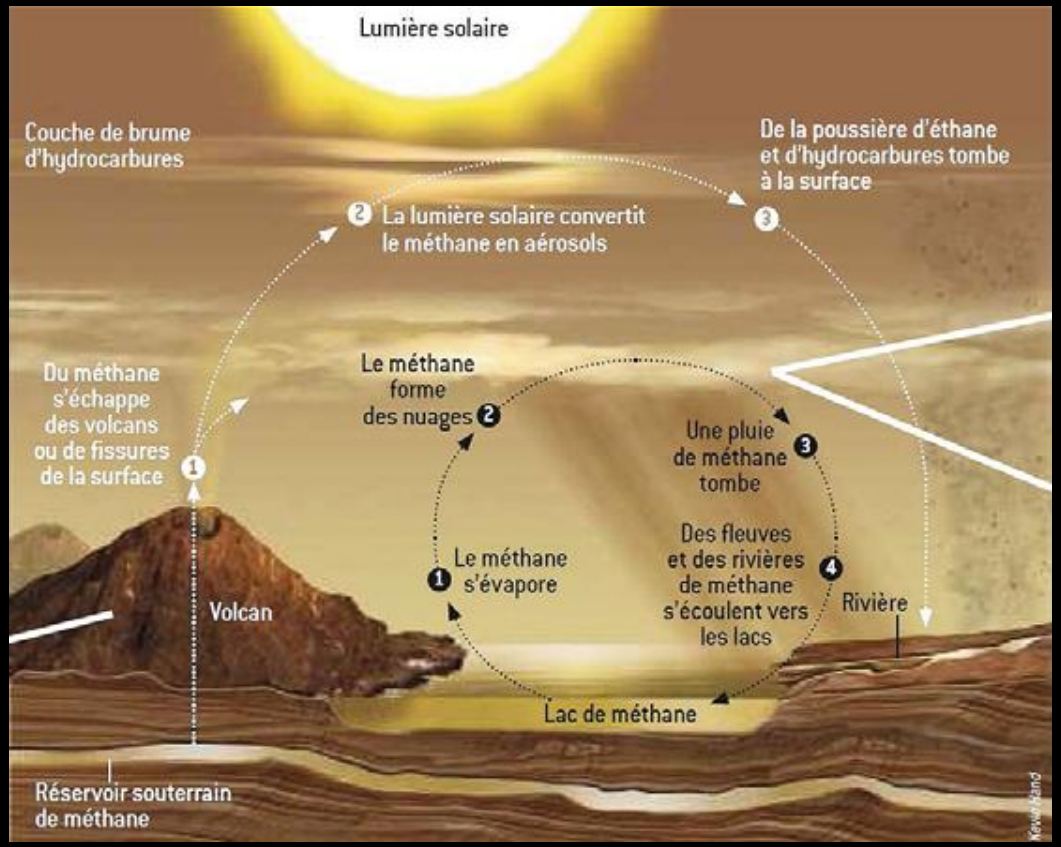
En résumé



La distribution des paysages de Titan est liée à la météo du méthane (passée et présente).
Un monde organique, plus que glacé.
Un monde façonné par l'érosion éolienne et fluviale.
Un monde glacial mais dynamique.

D’où provient le méthane ?

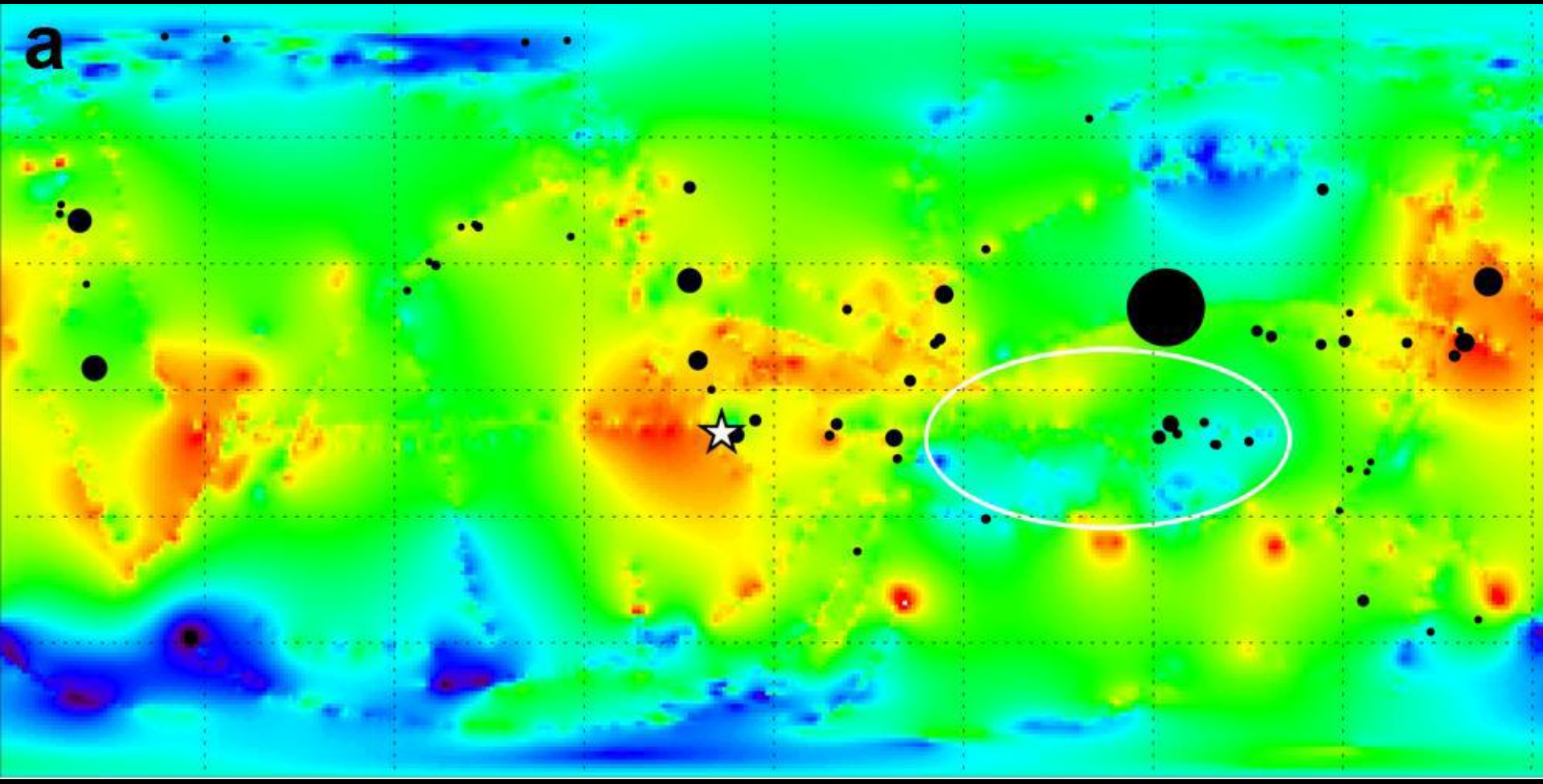




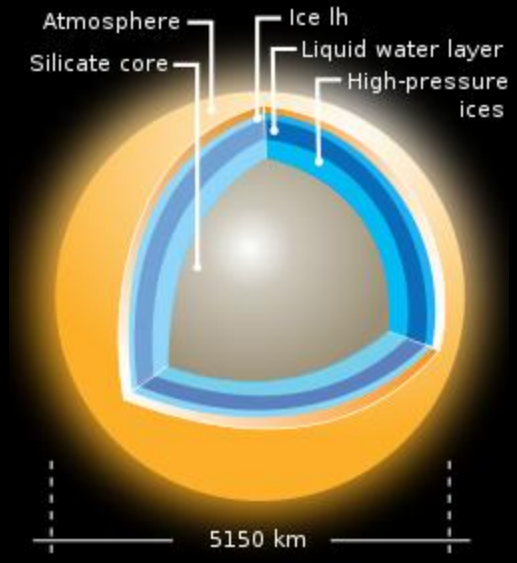
Destruction irréversible du CH_4 (≈10-100 Ma)

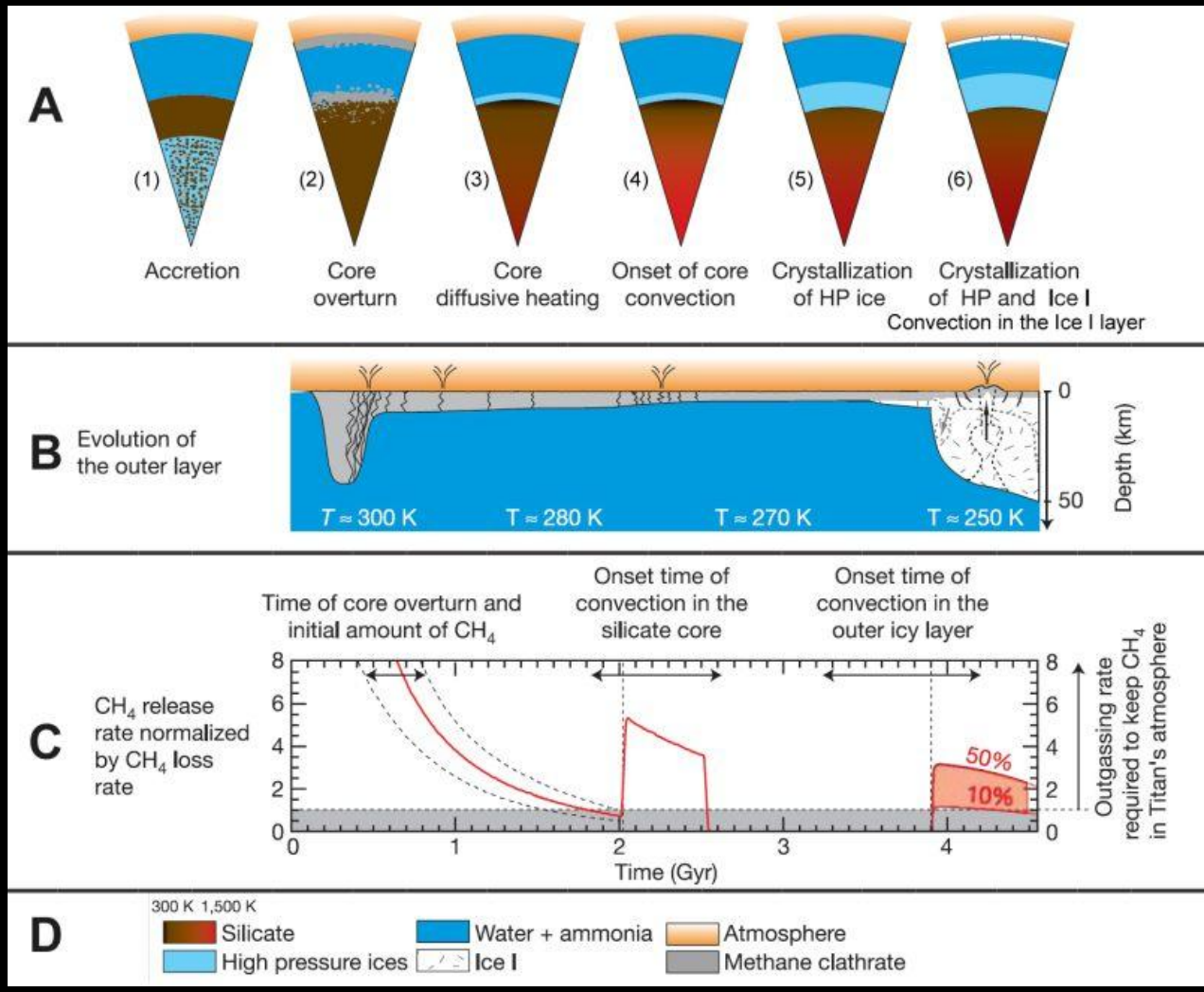
D'où vient le méthane ? Réservoirs ?

Surface très jeune, peu de trace de tectonique, ni point chaud évident …

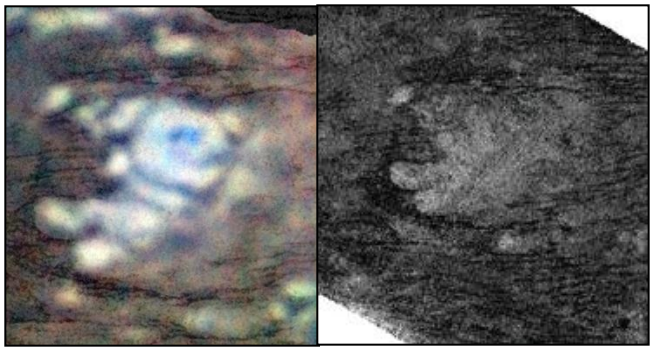


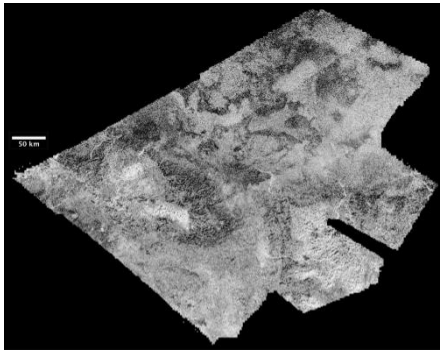
Quelques indices d’activité volcanique …

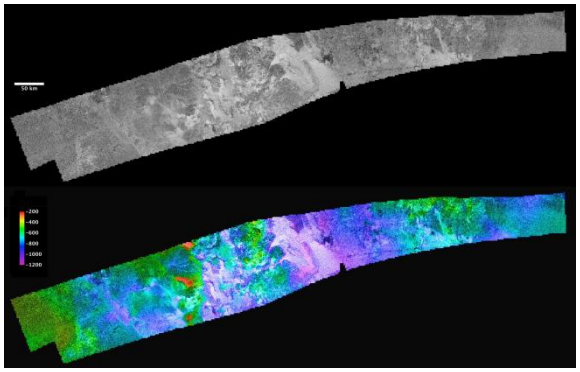

Atmosphere
Ice Ih
Liquid water layer
Silicate core
High-pressure ices
5150 km


A
(1)
(2)
(3)
(4)
(5)
(6)
Accretion
Core overturn
Core diffusive heating
Onset of core convection
Crystallization of HP ice
Crystallization of HP and Ice I
Convection in the Ice I layer
B
Evolution of the outer layer
T ≈ 300 K
T ≈ 280 K
T ≈ 270 K
T ≈ 250 K
0
50
Depth (km)
C
CH4 release rate normalized by CH4 loss rate
Time of core overturn and initial amount of CH4
Onset time of convection in the silicate core
Onset time of convection in the outer icy layer
50%
10%
Outgassing rate required to keep CH4 in Titan's atmosphere
Time (Gyr)
D
300 K 1,500 K
Silicate
Water + ammonia
Atmosphere
High pressure ices
Ice I
Methane clathrate

Des cryo-volcans?

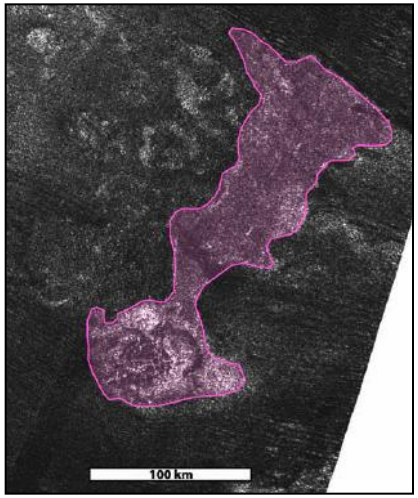




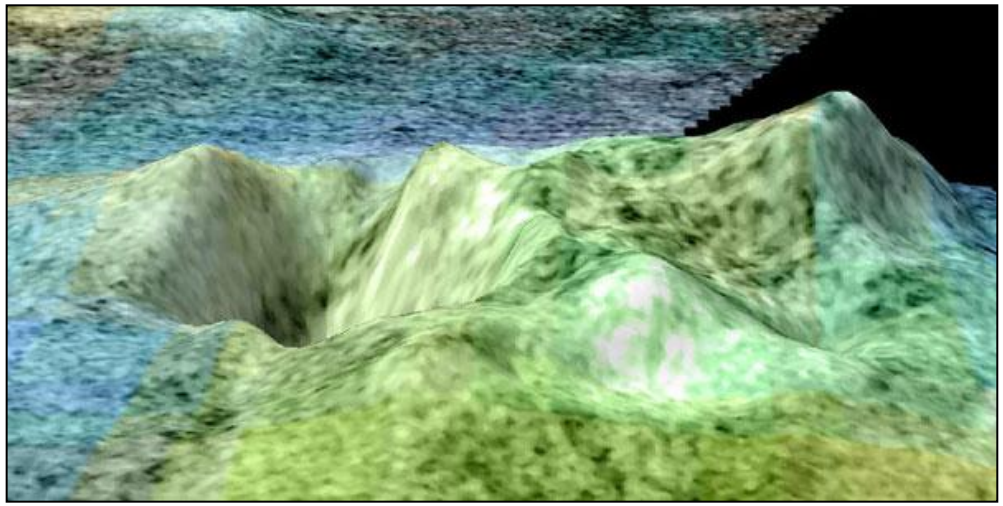


Pas de preuve évidente d'un cryo-volcanisme à l'œuvre.

Seul candidat sérieux: Sotra Facula, un édifice présentant deux pics de 1000-1500 m à côté d'un cratère profond.

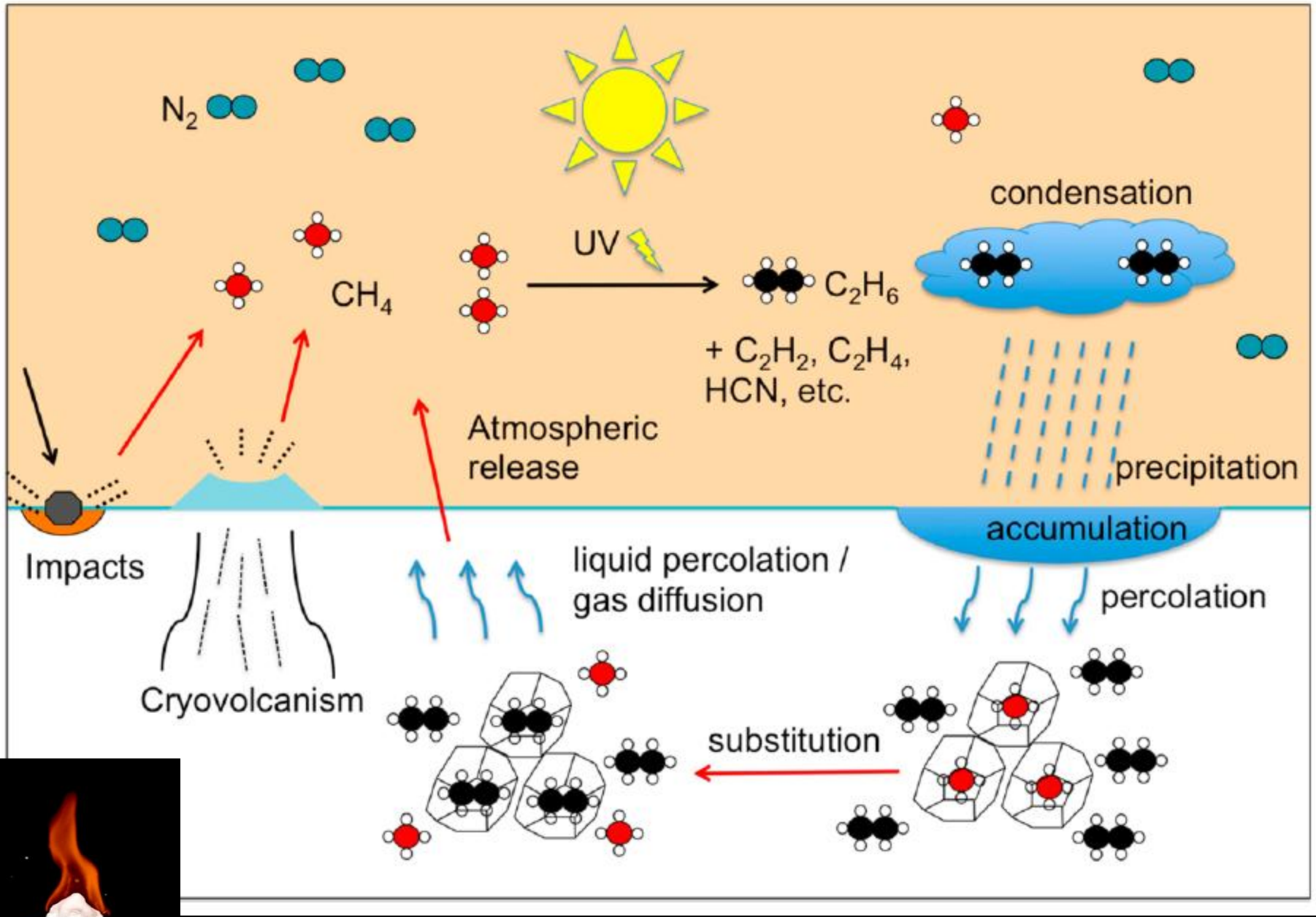


Sotra Facula
Crédits: NASA/JPL-Caltech

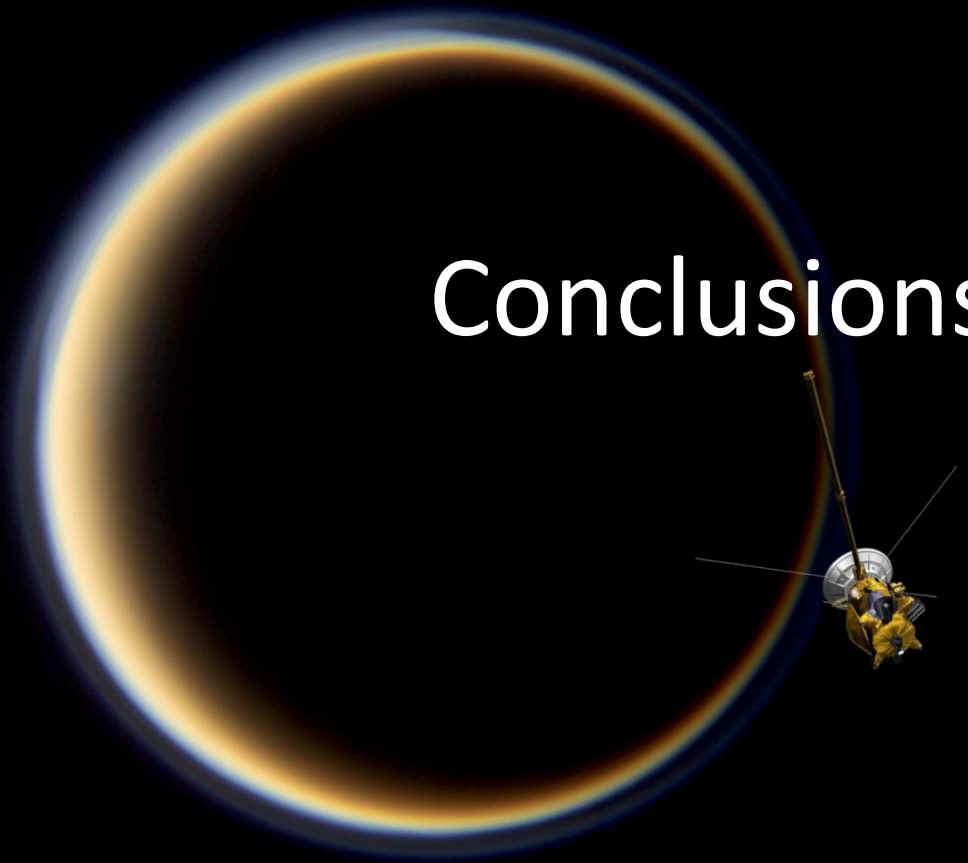


Crédits: NASA/USGS

Alice LE GALL (comm. perso.)



Conclusions…

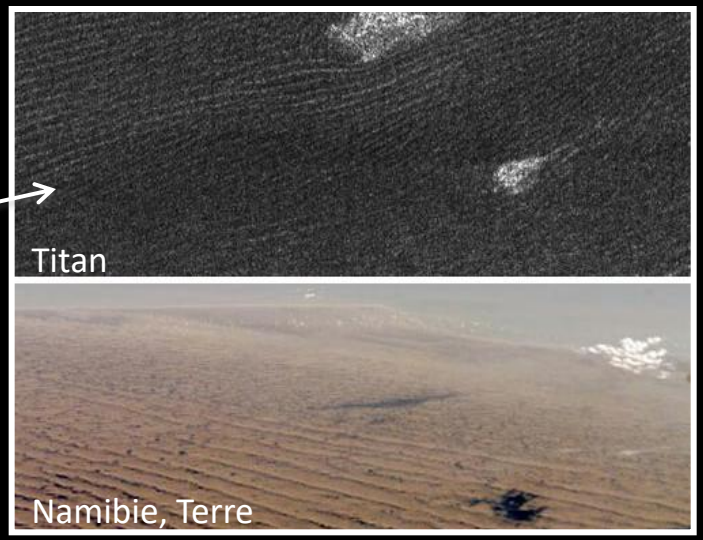


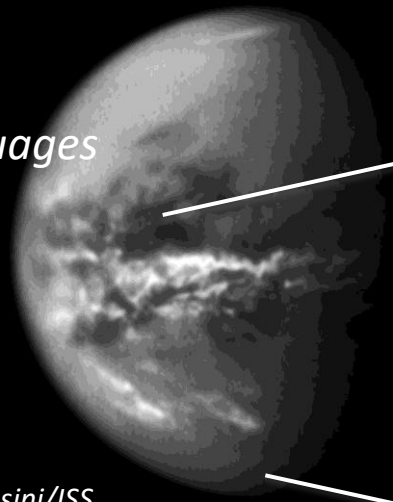
TITAN

UN CYCLE DU METHANE ACTIF ANALOGUE AU CYCLE DE L'EAU SUR TERRE, EVOLUANT AU GRE DE SAISONS DE 7 ANS

PROCSSUS GEOLOGIQUES ANALOGUES A CEUX A L'ŒUVRE SUR TERRE

Champs de dunes

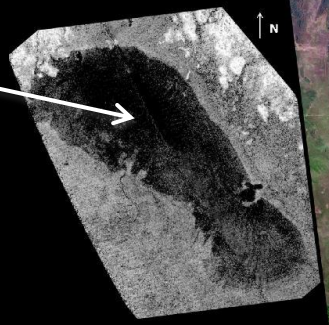




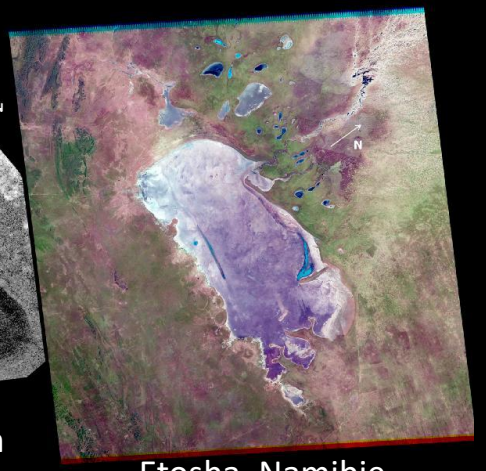
Nuages

Cassini/ISS

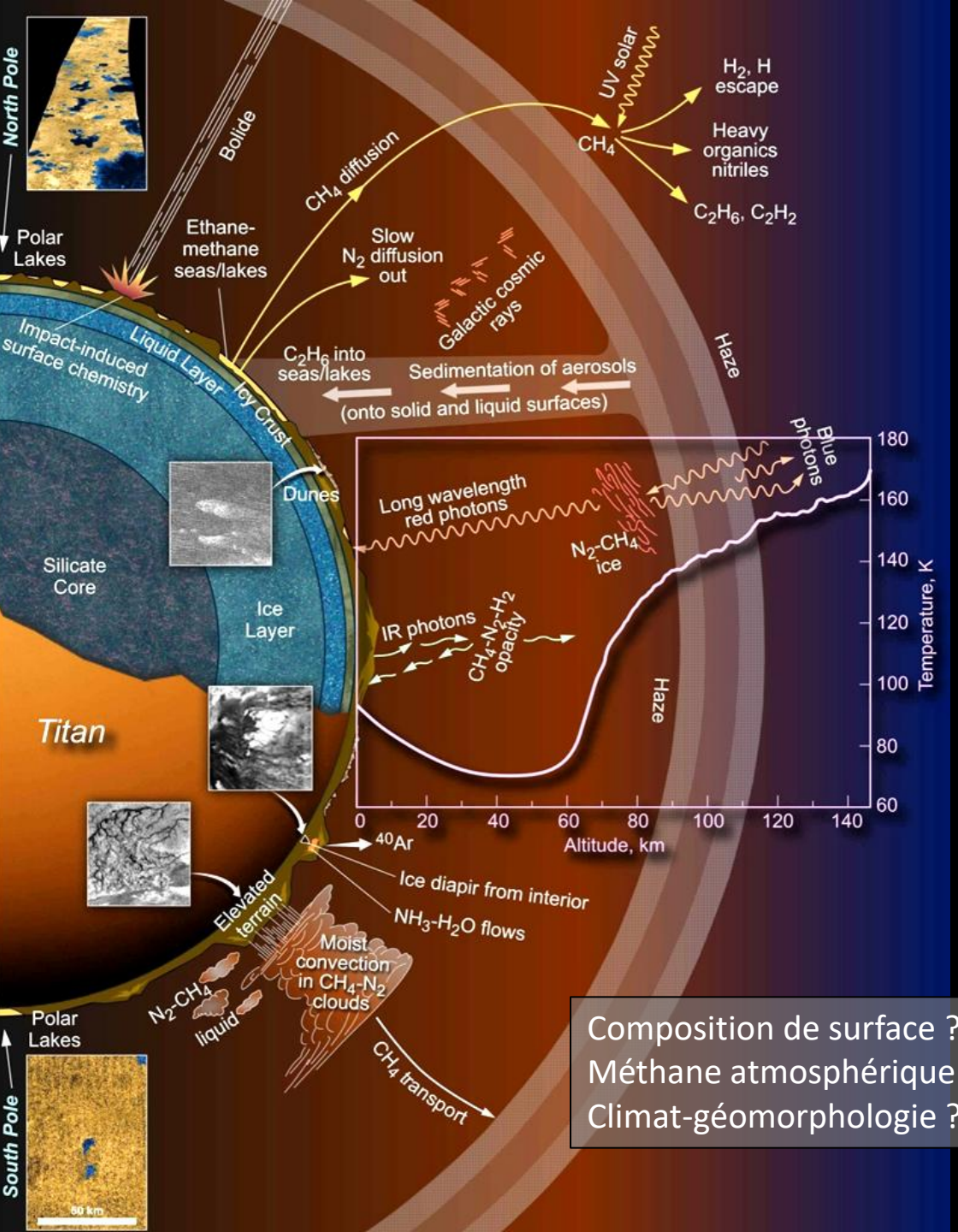
Lacs



Ontario lacus, Titan



Etosha, Namibie



Atmosphère

Surface

Intérieur

Composition de surface ?
Méthane atmosphérique ?
Climat-géomorphologie ?

Cassini-Huygens (2004-2017)

Télédétection

UVIS

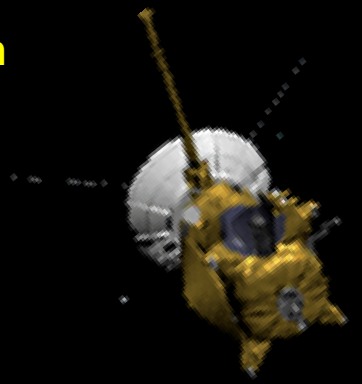
ISS

VIMS

CIRS

RADAR

RSS



Et la vie?

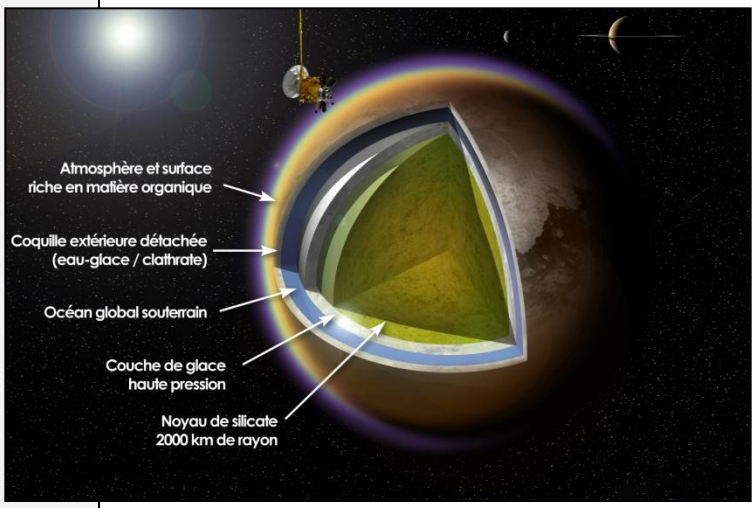
La question de habitabilité de Titan reste en suspens.

A la surface:

- Présence de molécules organiques très complexes: précurseurs de molécules prébiotiques?
- De l'eau liquide temporairement ? (après un impact météoritique ou un épanchement de cryo-lave)
- Mais aussi du méthane liquide: possible berceau d'une forme de vie différente que la nôtre?

Sous la surface:

- Un océan souterrain d'eau liquide
- Communiquant ou ayant communiqué avec la surface et/ou le noyau silicaté de Titan?
- Des températures plus clémentes



Crédits : A. D. Fortes/UCL/STFC/P. Volvert

Alice LE GALL (comm. perso.)

Titan's cold case files - Outstanding questions after Cassini-Huygens

Nixon et al. (2018)

- Was methane captured into Titan's interior, or formed later?
- What is the relative balance of methane resupply/destruction, and is there a net positive or negative flux into the at day?
- Has Titan's atmosphere collapsed in 1997a)?
- Is ethane being entirely sequestered
- V

- What is the reason for the difference in the crater population of Xanadu Regio from other regions on Titan?
- To what extent have internal activity, deposition, erosion and weathering caused

- How thick is the ice shell, and how deep is the global ocean? Is it in contact with a silicate core at the lower boundary, or a high pressure ice layer?
- Have exchanges occurred between the surface and the interior? This would mplex organic material produced in the deep water ocean.
- vater ocean? This would provide an ne of the places where life may have

- Is Titan currently, or has it been in the past, cryovolcanically active?
- Has Titan post-formation experienced large scale plate tectonics or crustal upheaval?
- How has internal activity affected the surface age in various different terrains?
- Has activity allow the atmosphere?

- What simple and complex compounds are covering Titan's surface, and how do these vary from region to region?
- How does the surface change on short and long timescales, e.g. rain storms,

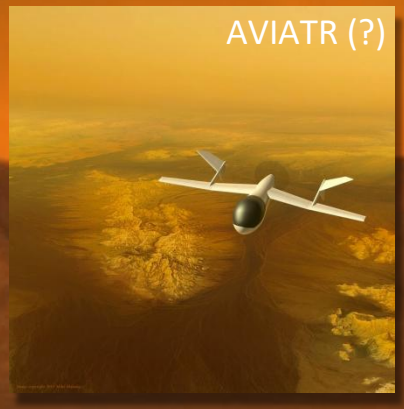
- Were the potential paleobasins that have been identified in the south polar terrain truly once liquid filled?
- How are lacustrine basins, particularly the sharp edged depressions, formed?
- While available topography suggests at least local subsurface communication, the extent that the lakes are globally or reg
- Similarly, the transport pathways for generation and expansion remains a m
- And finally, where there ever lakes and

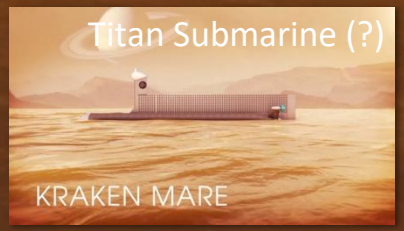
- If the lakes and seas are methane-dominated, where is all of the ethane produced by photochemistry in Titan's atmosphere (see §2.1)?
- What is the variability of composition amongst the lakes and seas?
- Similarly, what are the abundances of higher-order hydrocarbons in Titan's lakes and seas?

- What is the greatest depth of Kraken Mare, Titan's largest sea?
- Why is Onta

- What is the interaction of storms with the north-polar lakes and seas (*e.g.*, Tokano 2009, 2013)?
- What is the nature of the north-polar cloud features observed by VIMS at 2.1 μm but not by VIMS and ISS at other shorter and longer wavelengths (*e.g.*, Turtle *et al.* 2016, Turtle *et al.* 2018)?
- What is the distribution of subsurface methane reservoirs (*e.g.*, Lora *et al.* 2015; Newman *et al.* 2016)?

...



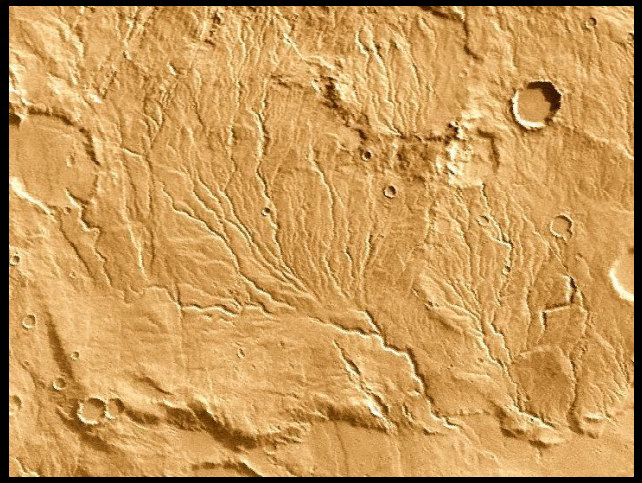


Titan

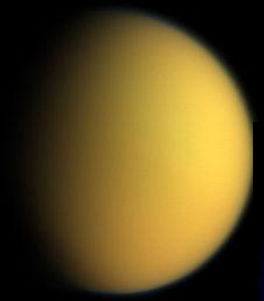
- Cassini (fin sept. 2017)
- Observations depuis la Terre
- JWST (2018), E-ELT (2024)
- AO NASA, ESA (?)

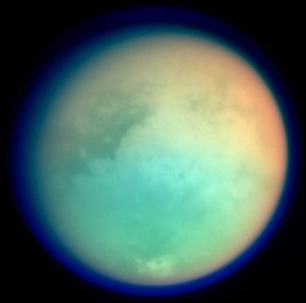
La Terre

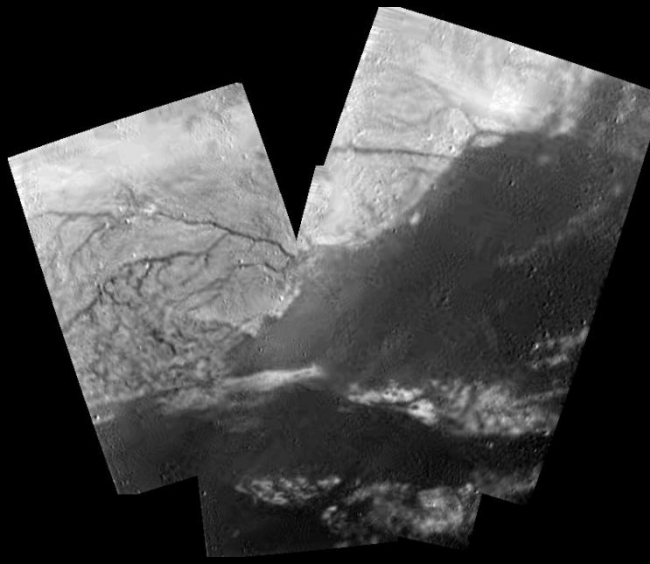
Mars



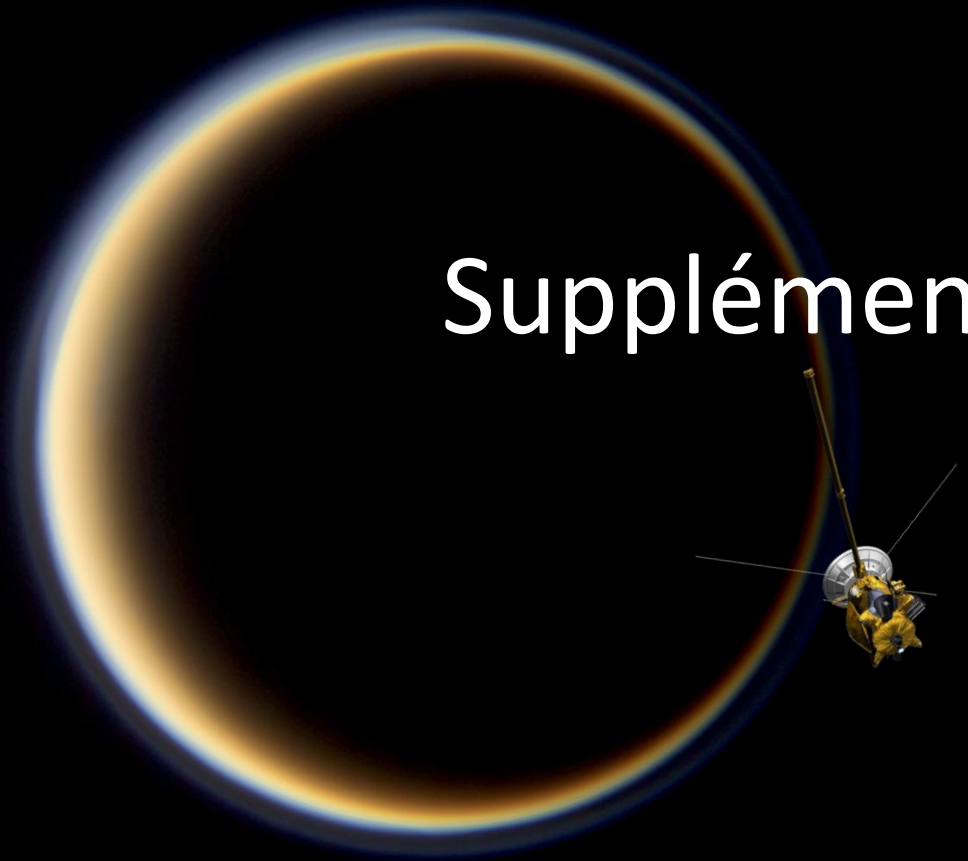
Titan

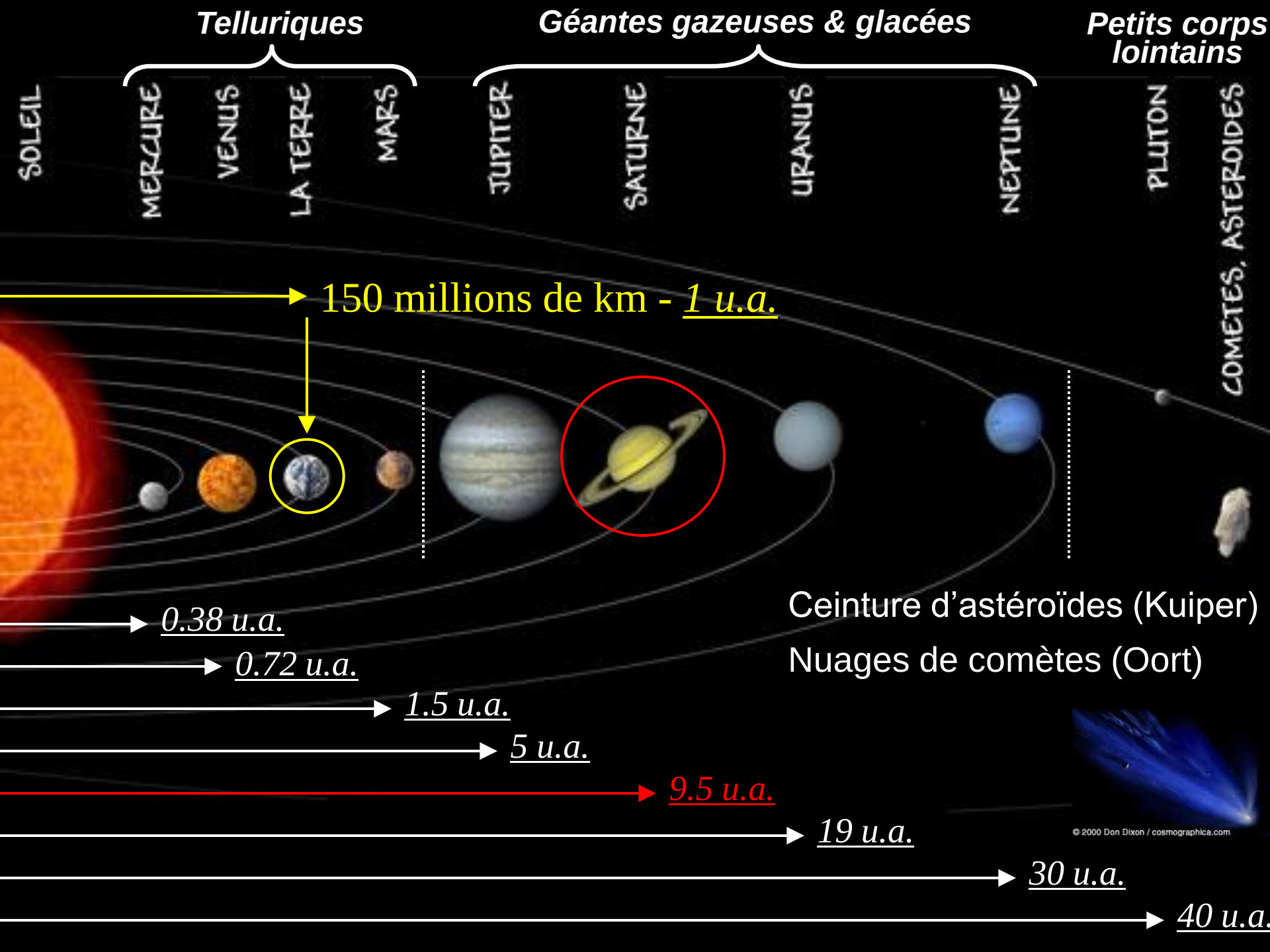


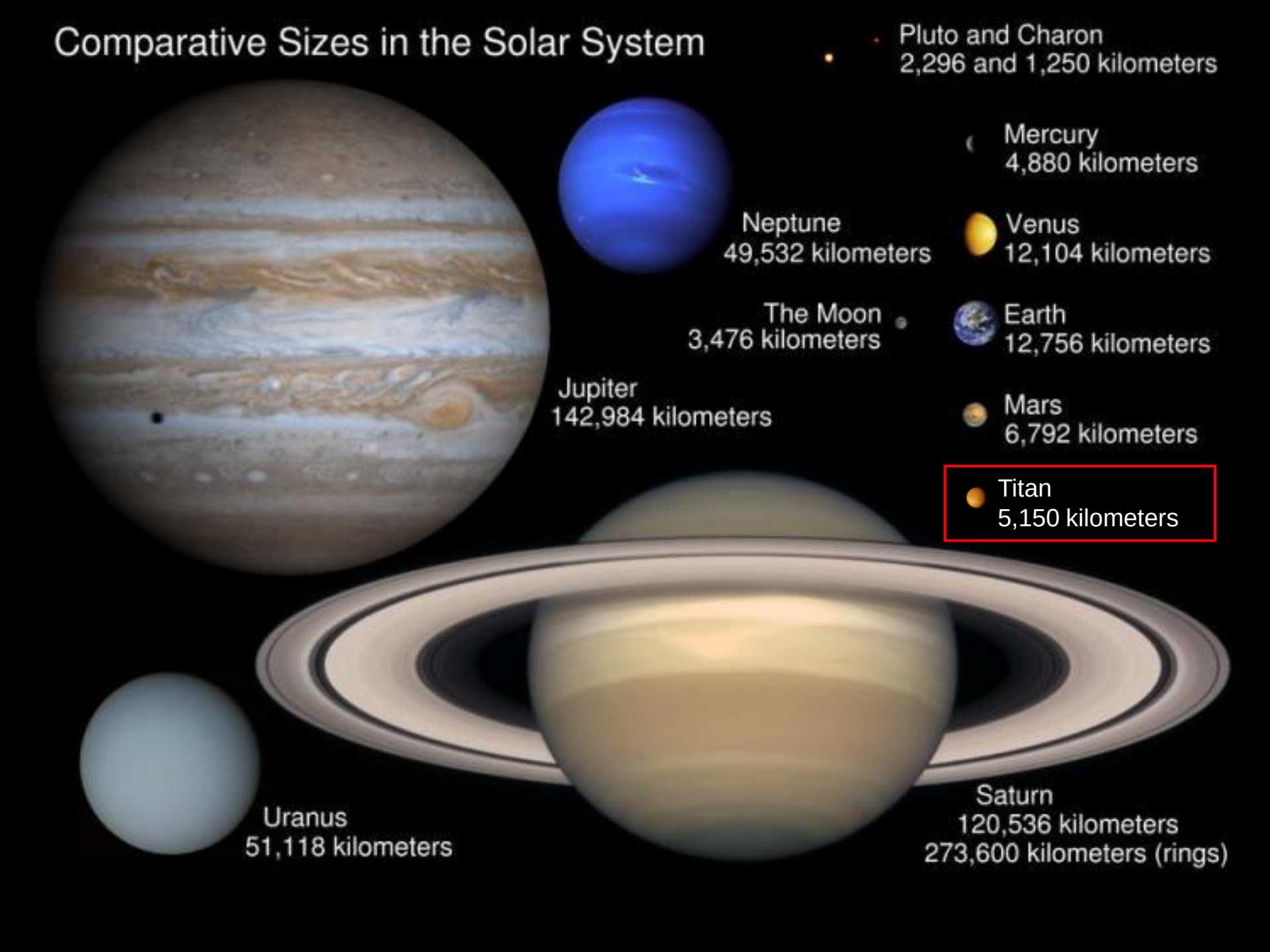




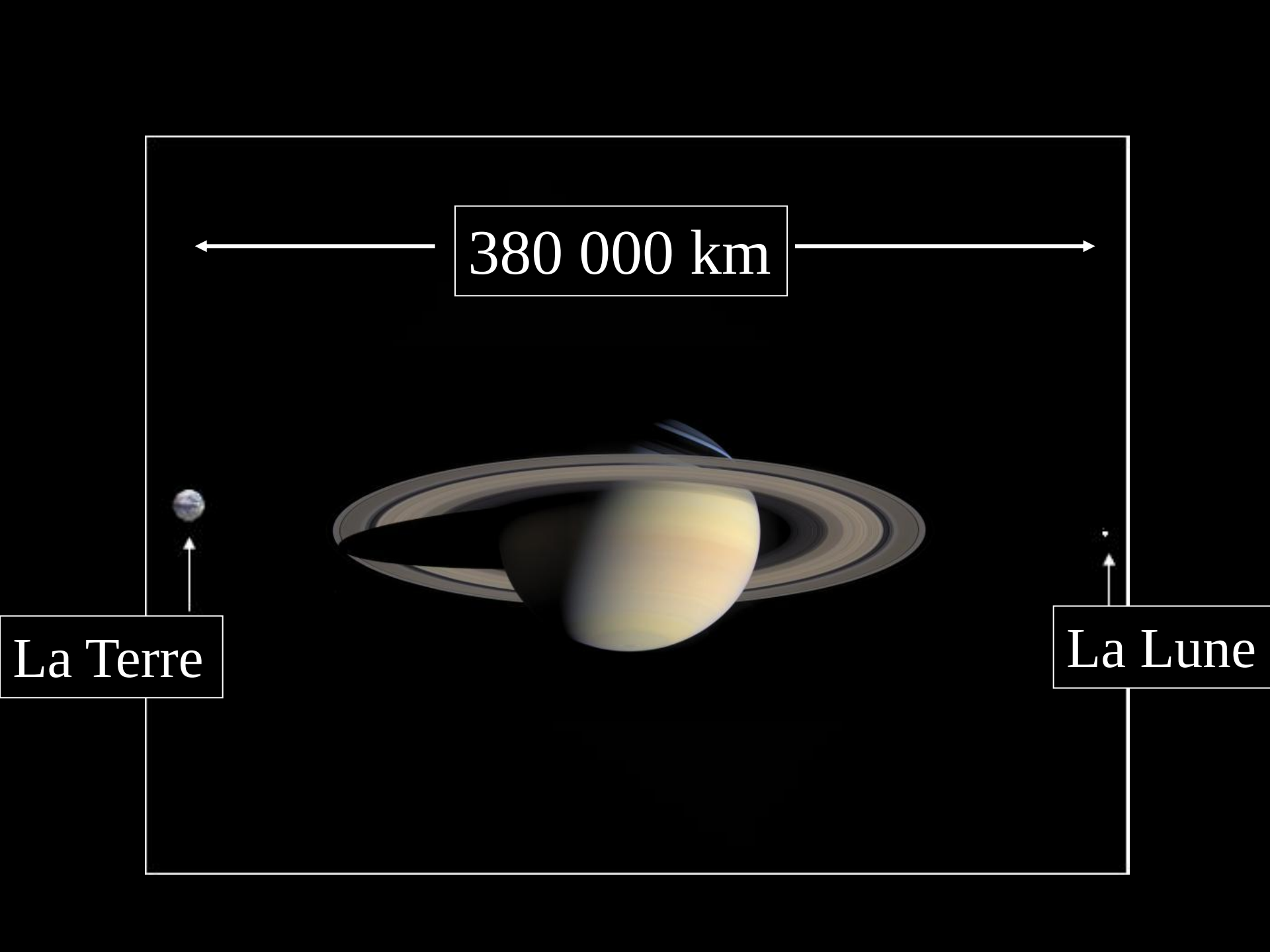
Suppléments

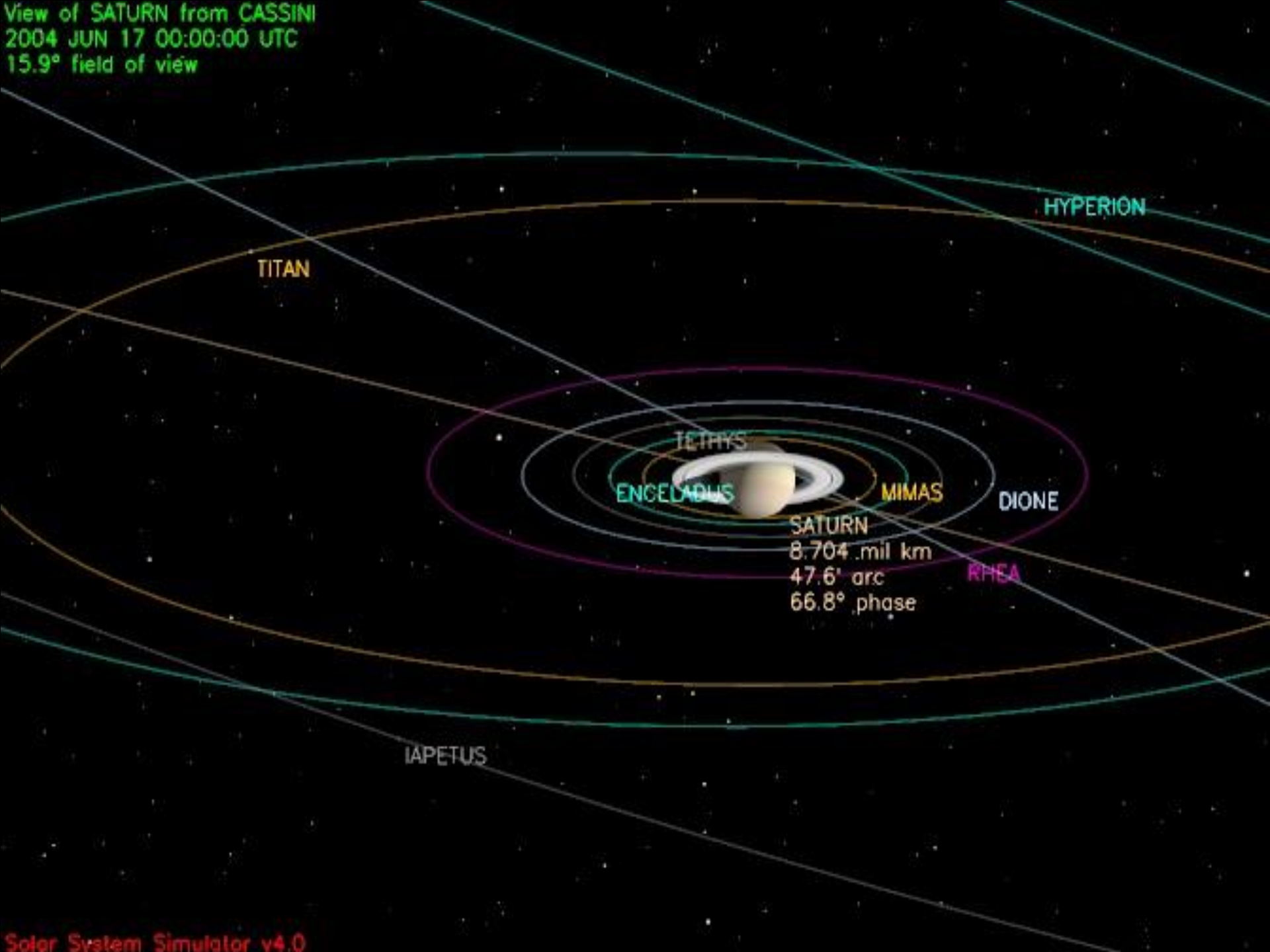


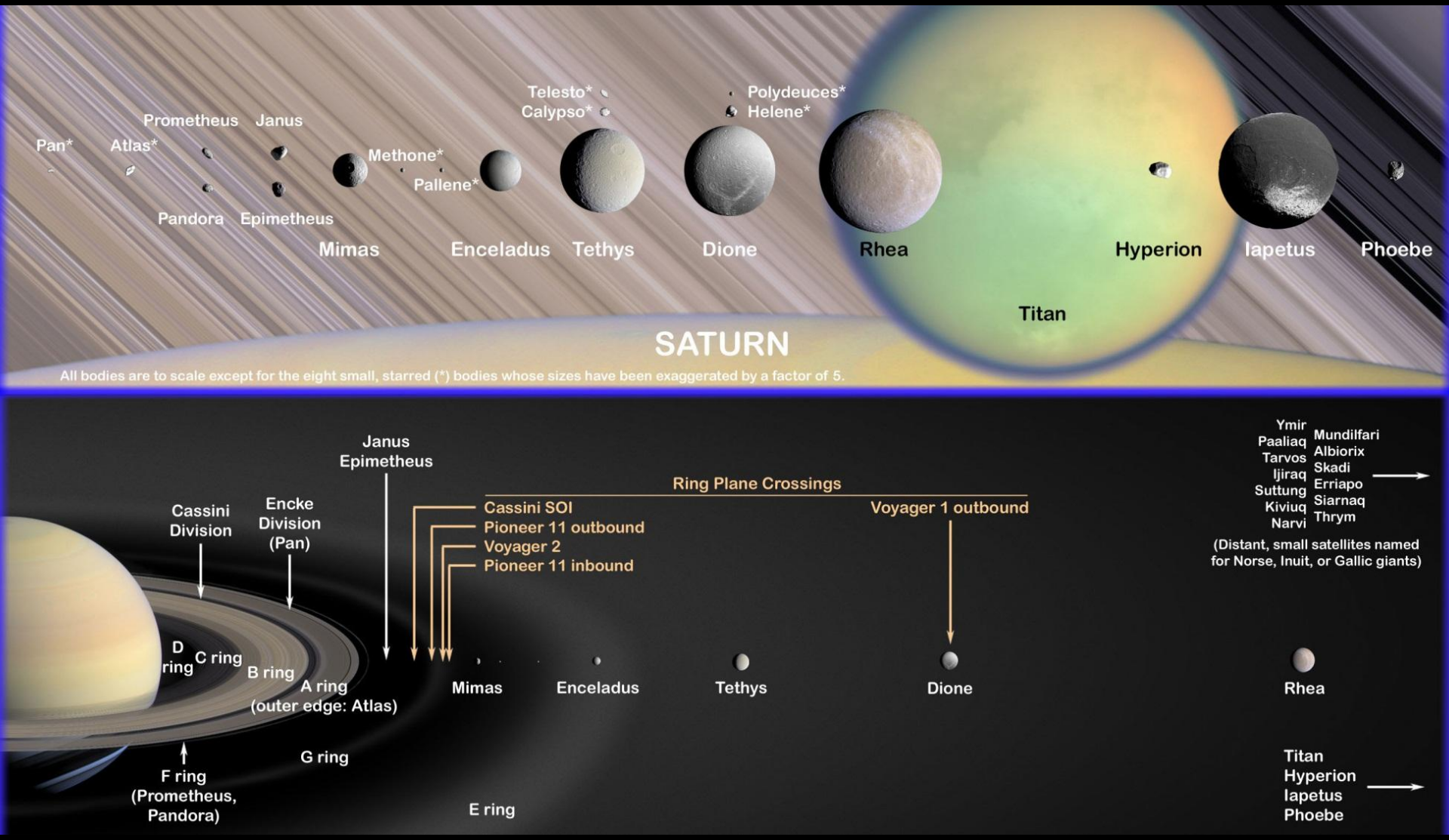

Telluriques
Géantes gazeuses & glacées
Petits corps lointains
SOLEIL
MERCURE
VENUS
LA TERRE
MARS
JUPITER
SATURNE
URANUS
NEPTUNE
PLUTON
COMETES, ASTEROIDES
150 millions de km - 1 u.a.
0.38 u.a.
0.72 u.a.
1.5 u.a.
5 u.a.
9.5 u.a.
19 u.a.
30 u.a.
40 u.a.
Ceinture d'astéroïdes (Kuiper)
Nuages de comètes (Oort)
© 2000 Don Dixon / cosmographica.com

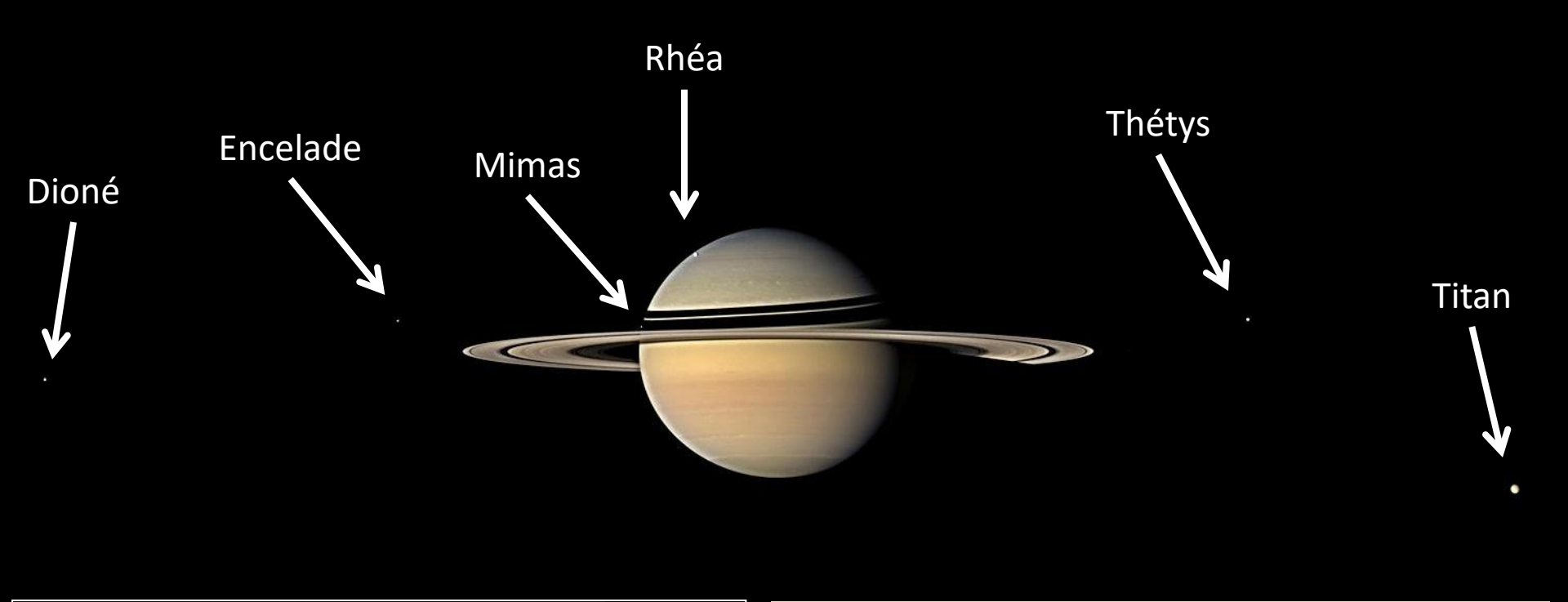

Comparative Sizes in the Solar System
Pluto and Charon
2,296 and 1,250 kilometers
Mercury
4,880 kilometers
Neptune
49,532 kilometers
Venus
12,104 kilometers
The Moon
3,476 kilometers
Earth
12,756 kilometers
Jupiter
142,984 kilometers
Mars
6,792 kilometers
Titan
5,150 kilometers
Uranus
51,118 kilometers
Saturn
120,536 kilometers
273,600 kilometers (rings)

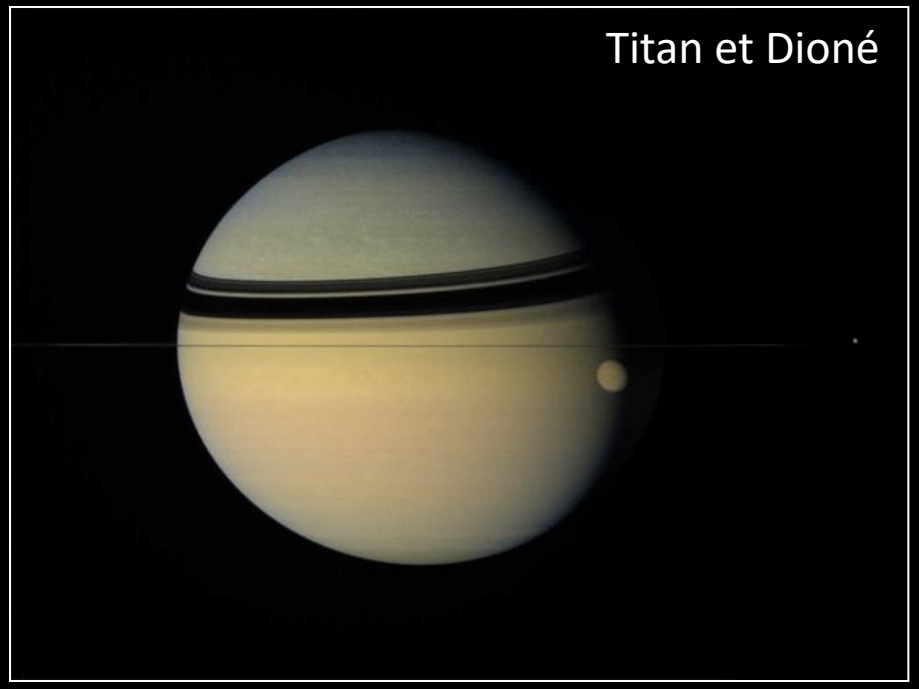

380 000 km
La Terre
La Lune


380 000 km
La Terre
La Lune


View of SATURN from CASSINI
2004 JUN 17 00:00:00 UTC
15.9° field of view
HYPERION
TITAN
TETHYS
ENCELADUS
MIMAS
DIONE
SATURN
8.704 mil km
47.6' arc
66.8° phase
RHEA
IAPETUS
Solar System Simulator v4.0


Pan*
Atlas*
Prometheus
Janus
Pandora
Epimetheus
Methone*
Pallene*
Telesto*
Calypso*
Polydeuces*
Helene*
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
SATURN
All bodies are to scale except for the eight small, starred (*) bodies whose sizes have been exaggerated by a factor of 5.
Janus
Epimetheus
Ring Plane Crossings
Cassini SOI
Pioneer 11 outbound
Voyager 2
Pioneer 11 inbound
Voyager 1 outbound
Cassini Division
Encke Division (Pan)
D ring
C ring
B ring
A ring
(outer edge: Atlas)
F ring
(Prometheus, Pandora)
G ring
E ring
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
Ymir
Paaliaq
Tarvos
Ijiraq
Suttung
Kiviuq
Narvi
Mundilfari
Albiorix
Skadi
Erriapo
Siarnaq
Thrym
(Distant, small satellites named for Norse, Inuit, or Gallic giants)





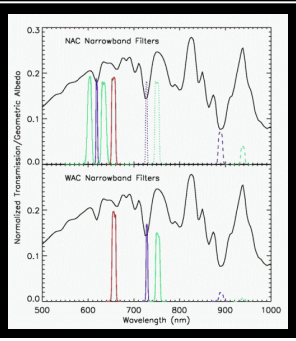
Quelques chiffres

Distance / Saturne	1 221 870 km (20 r_{SAT})
Distance / Soleil	1 427 000 000 km (9.54 AU)
Diamètre (atmosphère)	5550 km
Diamètre (surface)	5150 km (0,4x la Terre)
Masse	1/45 de la Terre
Densité moyenne	1,881 kg/m^3
Température (surface)	94 K (-180 °C)
Pression atm. (surface)	1,5 bar (1,5x la Terre)
Composition atm.	N_2, CH_4, Ar, … + brouillard d'aérosols
Période orbitale	15.95 jours
Période de rotation	15.95 jours

The Cassini orbiter: the optical and microwave remote sensing suite

ISS (2 multispectral cameras)

1 Mpx cameras with broadband filters between 0.2 and 1.1 µm



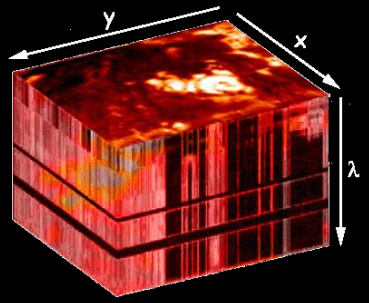
RADAR (Ku-band)

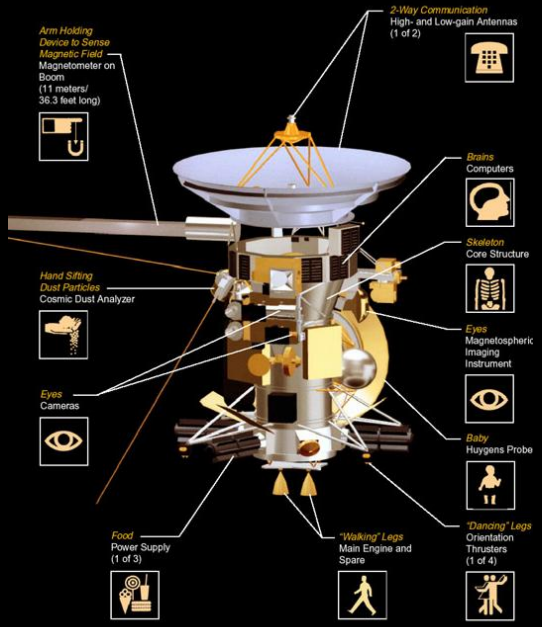
radiometer, scatterometer, altimeter, SAR

2.2 cm

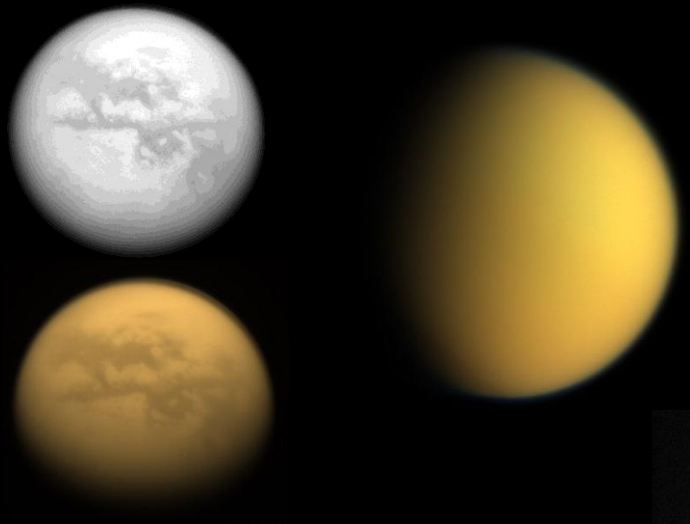
VIMS (Visual and Infrared Mapping Spectrometer)

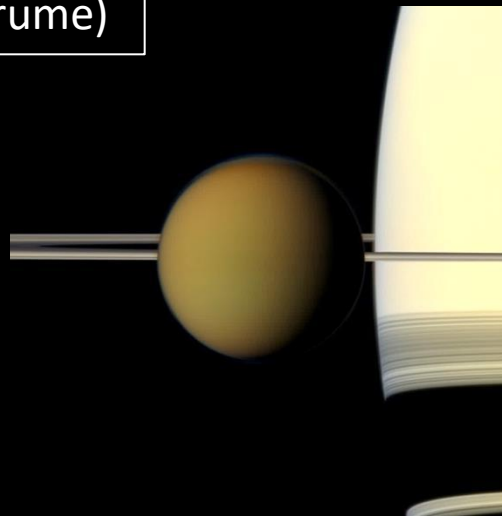
64x64 pixels, 352 spectral channels between 0.3 and 5 µm





Imagerie et cartographie
Spectroscopie large bande (brume)





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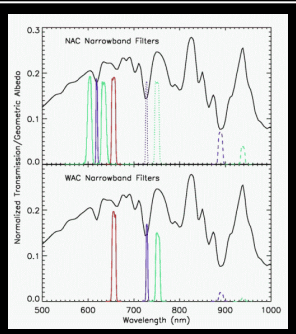

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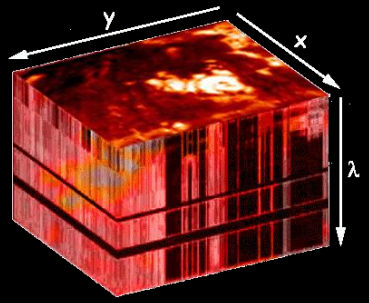
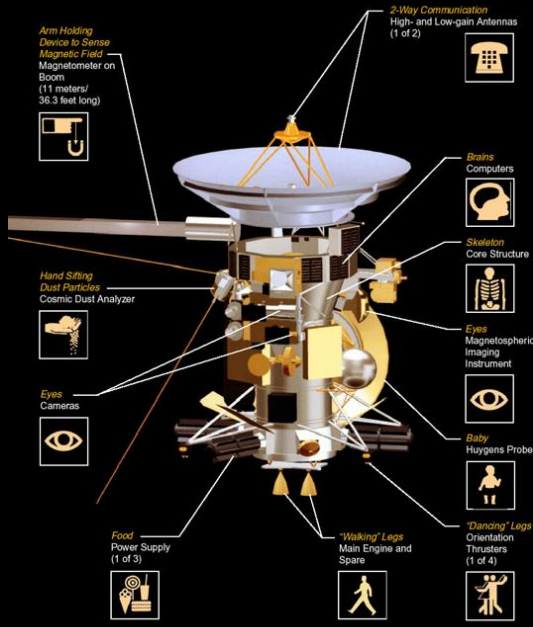
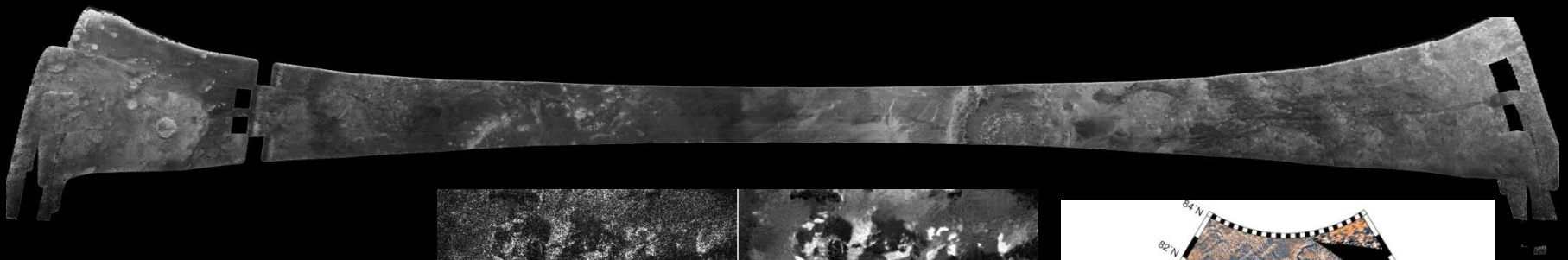
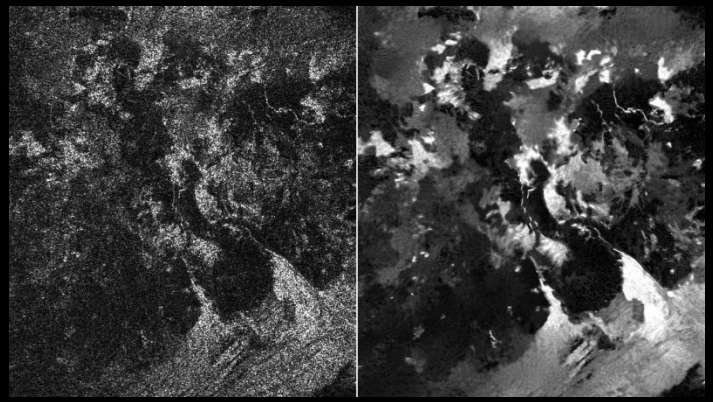
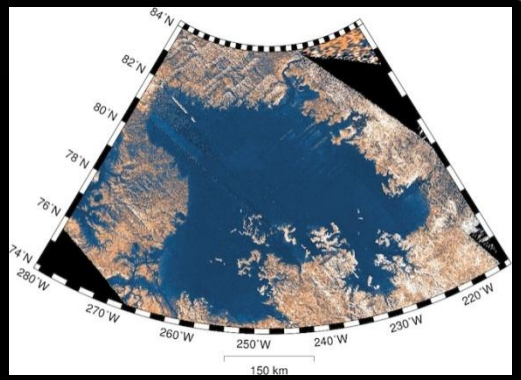






Imagerie et cartographie HR
Topographie
Composition et texture





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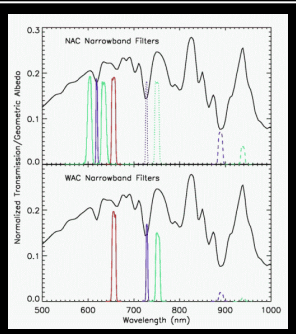

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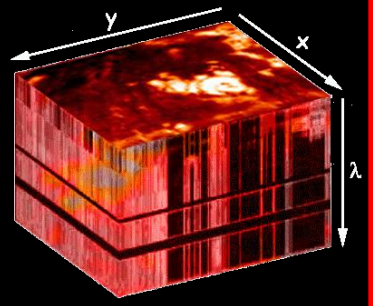
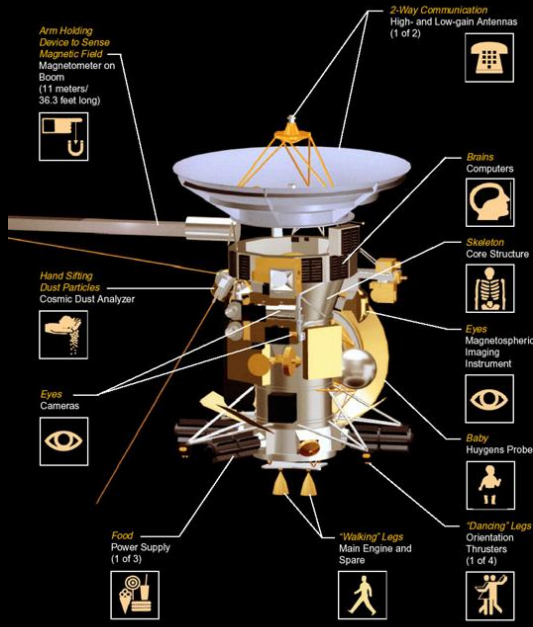
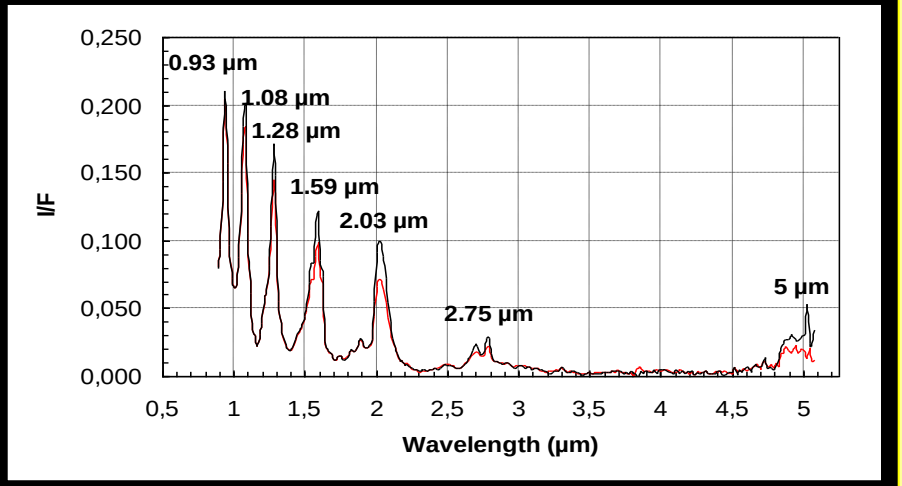


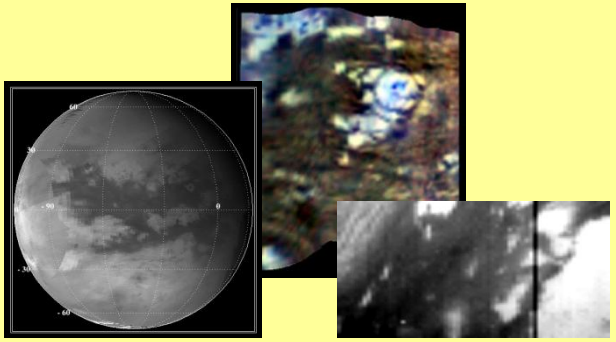




Titan's VIMS typical spectra

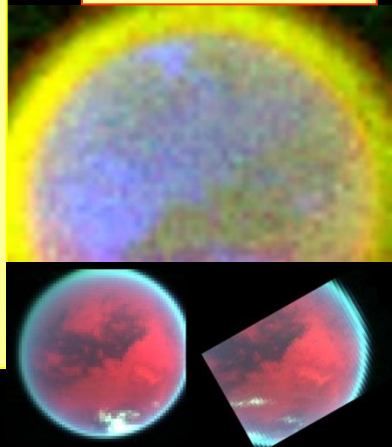
Mapping and surface analysis

- morphology
- composition

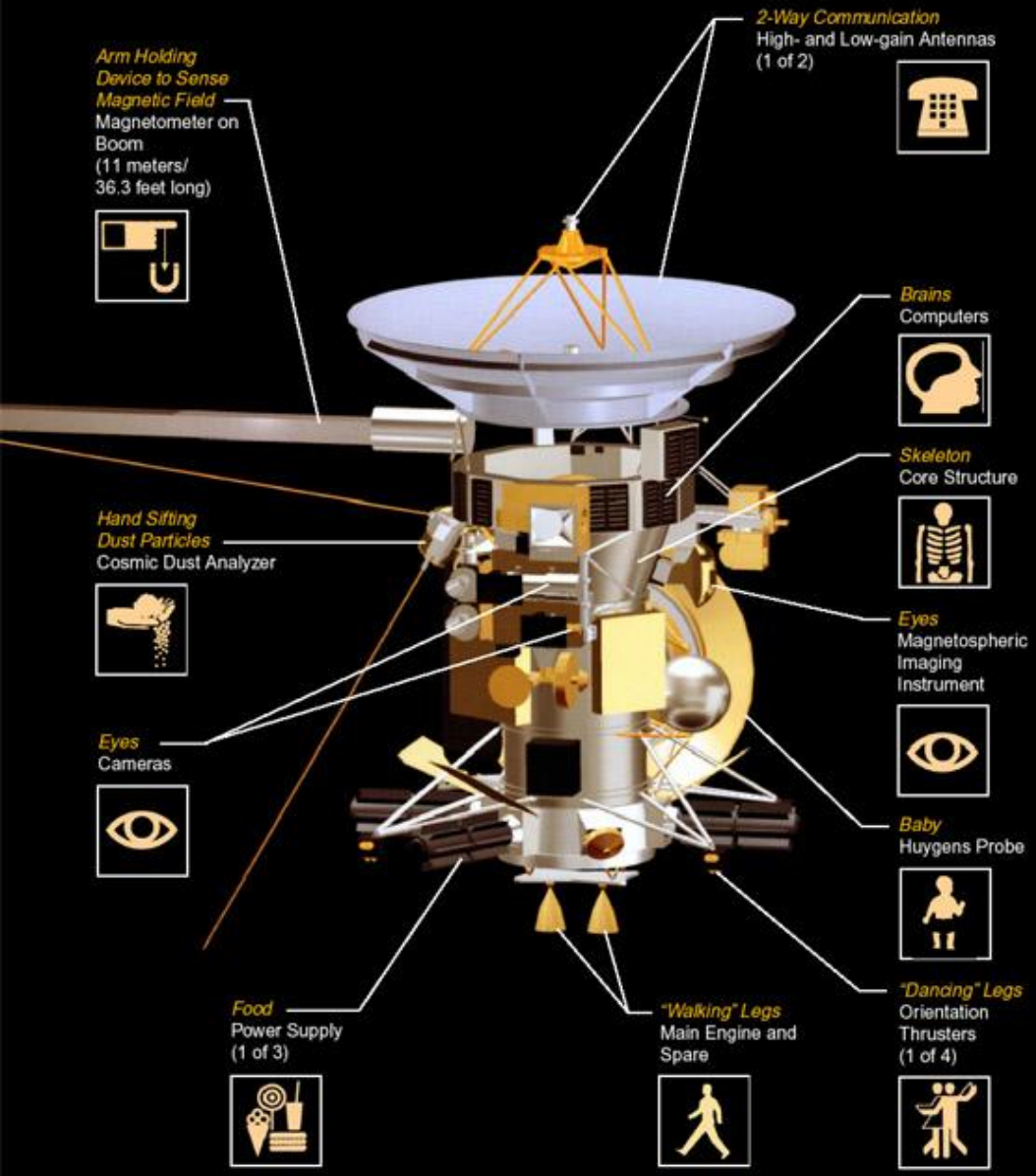


+

Atmospheric survey



Orbiteur Cassini



5,6 t au décollage (dont 3,5 t de carburant – 63 % du poids), dont 270 kg d'instruments

Lanceur Titan-IV : 1040 t au décollage

7x4 m (sinon 11 m avec le magnétomètre)

12 instruments scientifiques + Huygens

14 km de câblages divers

18 ans de travail

Sonde européenne Huygens

Masse totale : 318 kg (dont 44 kg d'instruments)
Diamètre : 270 cm

Énergie

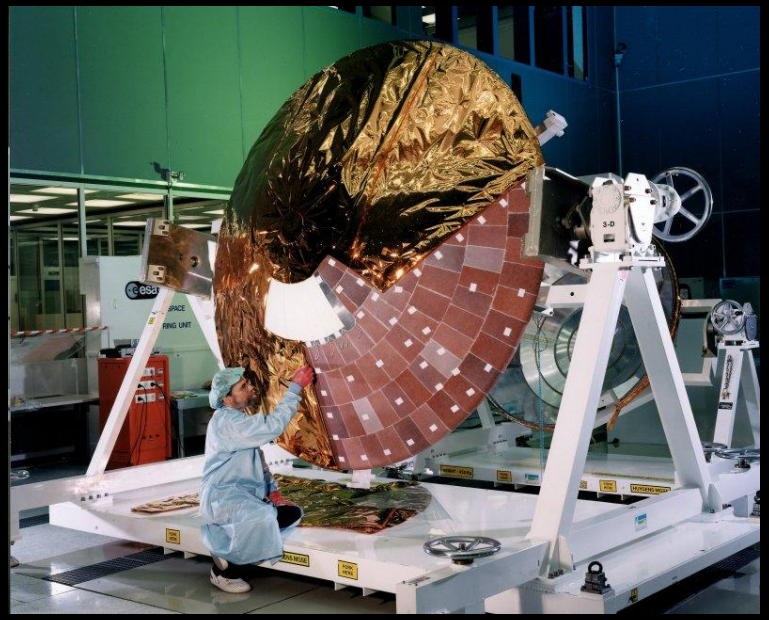
5 batteries chacune composée de 2 modules de 13 cellules de $LiSO_2$ en série : 7.6 Ah (devait fournir Huygens en énergie pendant au moins 30 mn une fois l'atterrissage accompli)

Instrumentation

- imageur de descente et spectro-radiomètre (+ lampe 20W)
- instrument d'étude de la structure atmosphérique
- chromatographe en phase gazeuse et spectromètre de masse
- pyroliseur-collecteur d'aérosols
- banc de mesures dédié à l'étude de la surface
- expérience de mesure de la vitesse du vent par effet Doppler

Durée des opérations

2h30 de descente
2h30 d'acquisition de données (dont ???? à la surface)



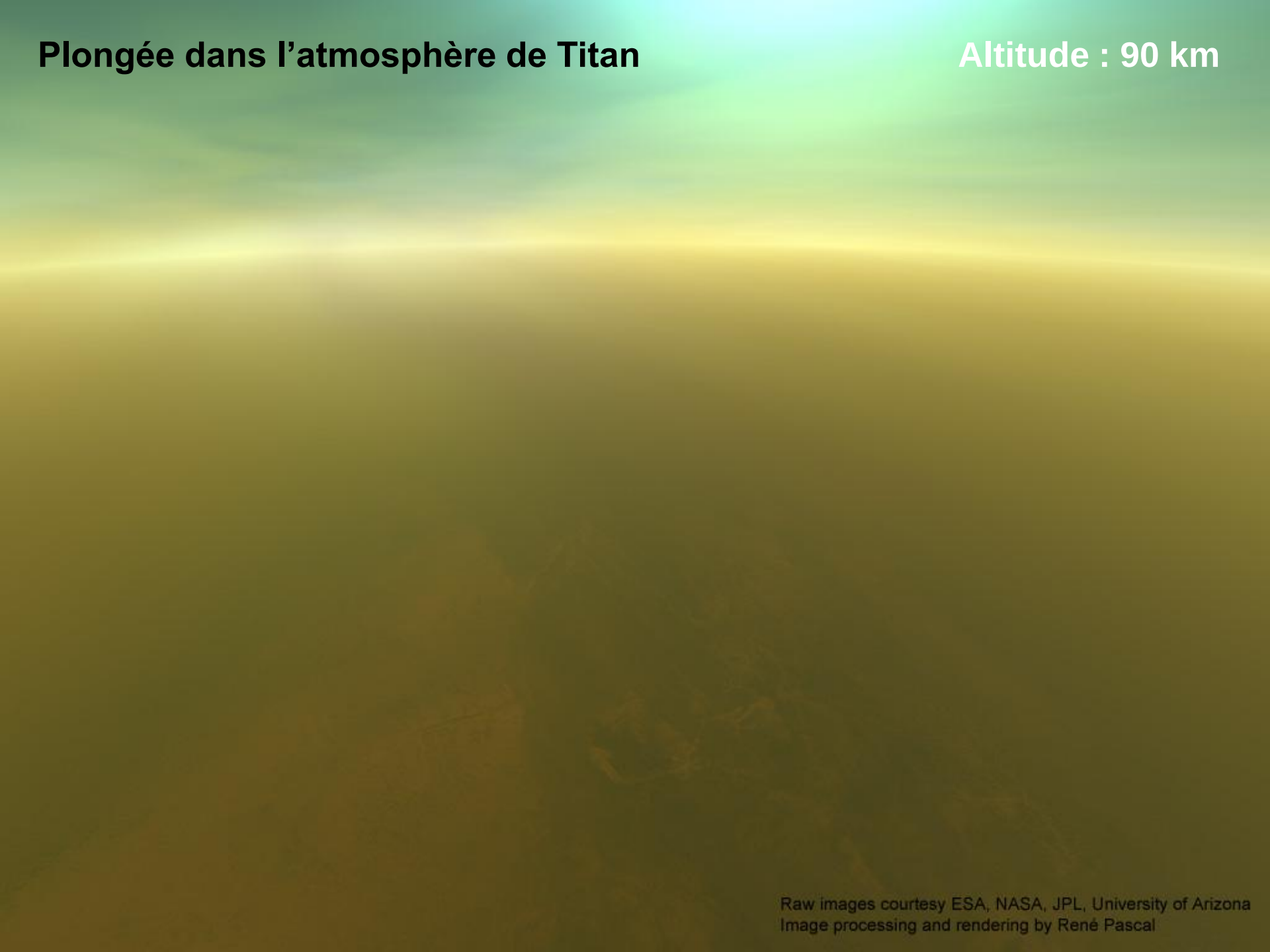
Plongée dans l’atmosphère de Titan

Altitude : 110 km

Raw images courtesy ESA, NASA, JPL, University of Arizona
Image processing and rendering by René Pascal

Plongée dans l’atmosphère de Titan

Altitude : 90 km



Raw images courtesy ESA, NASA, JPL, University of Arizona
Image processing and rendering by René Pascal

Plongée dans l’atmosphère de Titan

Altitude : 70 km

Raw images courtesy ESA, NASA, JPL, University of Arizona
Image processing and rendering by René Pascal

Plongée dans l’atmosphère de Titan

Altitude : 40 km

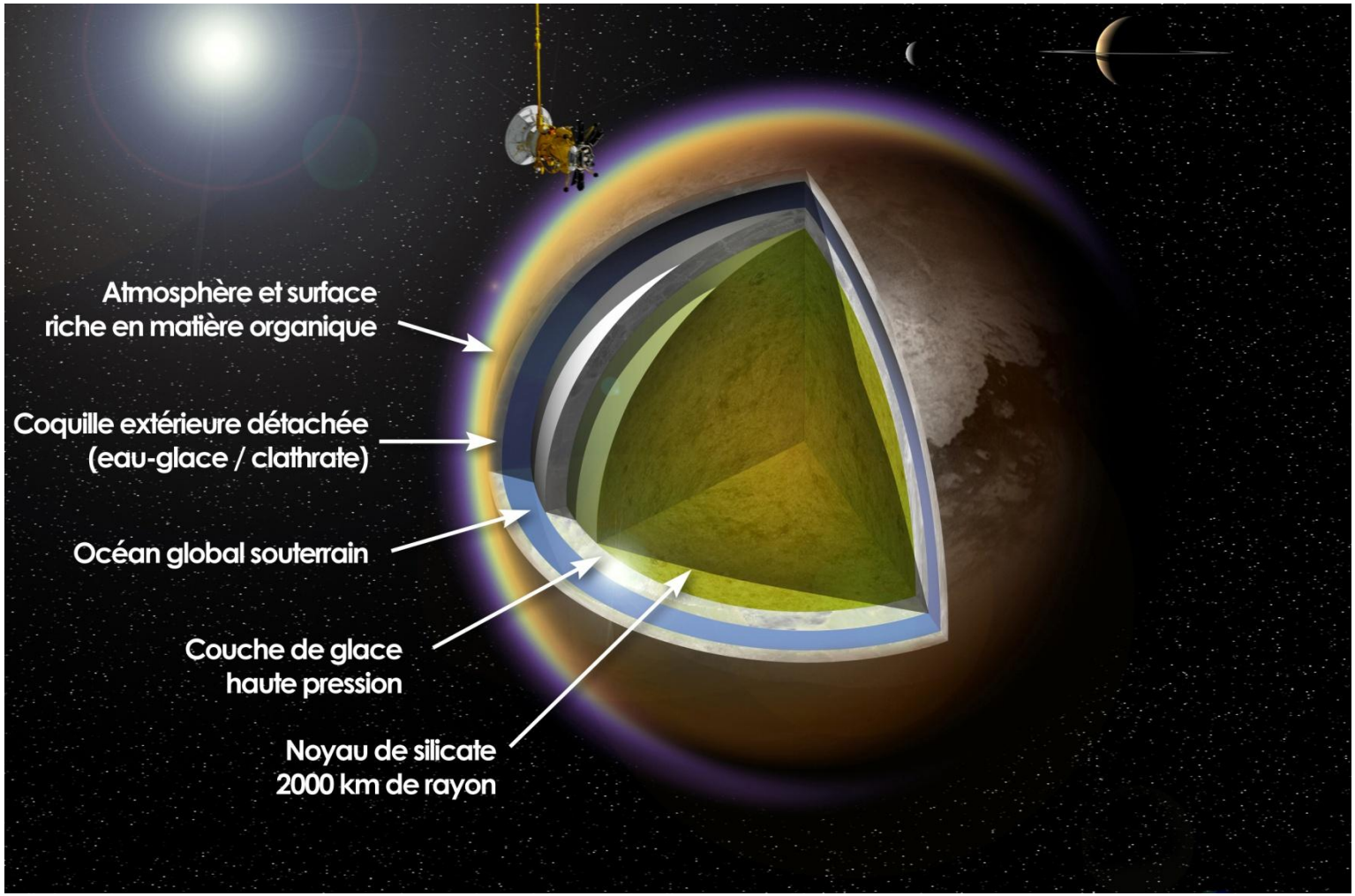
Plongée dans l’atmosphère de Titan

Altitude : 25 km

Raw images courtesy ESA, NASA, JPL, University of Arizona
Image processing and rendering by René Pascal

Los Angeles sous le « fog » de pollution

A 50% constitué de glace



Crédits : A. D. Fortes/UCL/STFC/P. Volvert

Alice LE GALL (comm. perso.)

La Terre

Diamètre	: 1
Masse	: 1
Pression (sur.)	: 1 bar
Temp. (sur.)	: 15°C
Densité	: 5,15
Composition	: roches

Mars

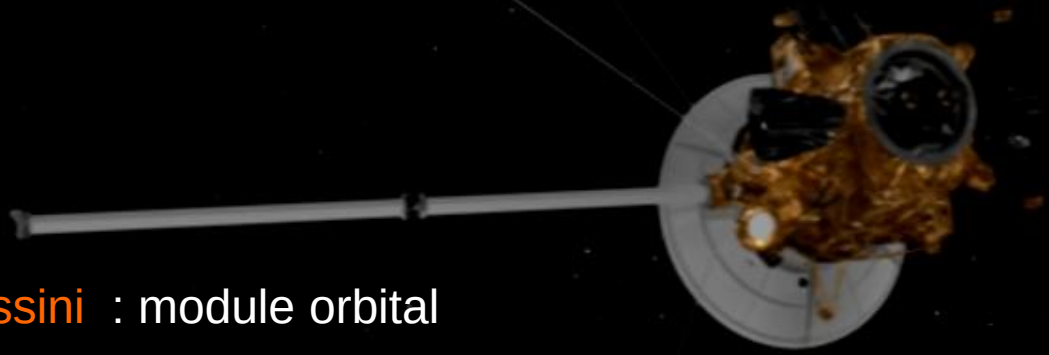
Diamètre	: ~ 0,53
Masse	: ~ 1/10
Pression (sur.)	: 0,007 bar
Temp. (sur.)	: -63°C
Densité	: 3,94
Composition	: roches

Titan

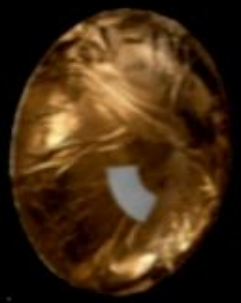
Diamètre	: ~ 0,4
Masse	: ~ 1/45
Pression (sur.)	: 1,5 bar
Temp. (sur.)	: -178°C
Densité	: 1,88
Composition	: glaces , roches

Cassini-Huygens :
Mission d'exploration de Saturne et de Titan

- *Titan, la plus grosse lune de Saturne est une des cibles majeures de la mission.*
- Cassini/Huygens :
  - l'orbiteur « Cassini » qui reste autour de Saturne, construit par la NASA; équipé de 12 instruments scientifiques;
  - la sonde « Huygens » qui doit plonger dans l'atmosphère de Titan, construite par l'ESA; équipée de 6 instruments scientifiques et attachée à Cassini durant toute la durée du voyage.



Cassini : module orbital



Huygens : « atterrisseur »

CASSINI-HUYGENS
Exploring Saturn & Titan, a fascinating world

Cassini-Huygens : Mission d'exploration de Saturne et de Titan

- *Programme international pour lequel ont collaboré l'agence spatiale européenne (ESA), américaine (NASA) et italienne (ASI).*
- *Titan, la plus grosse lune de Saturne est une des cibles majeures de la mission.*
- *Cassini/Huygens :*
  - *l'orbiteur « Cassini » qui reste autour de Saturne, construit par la NASA; équipé de 12 instruments scientifiques;*
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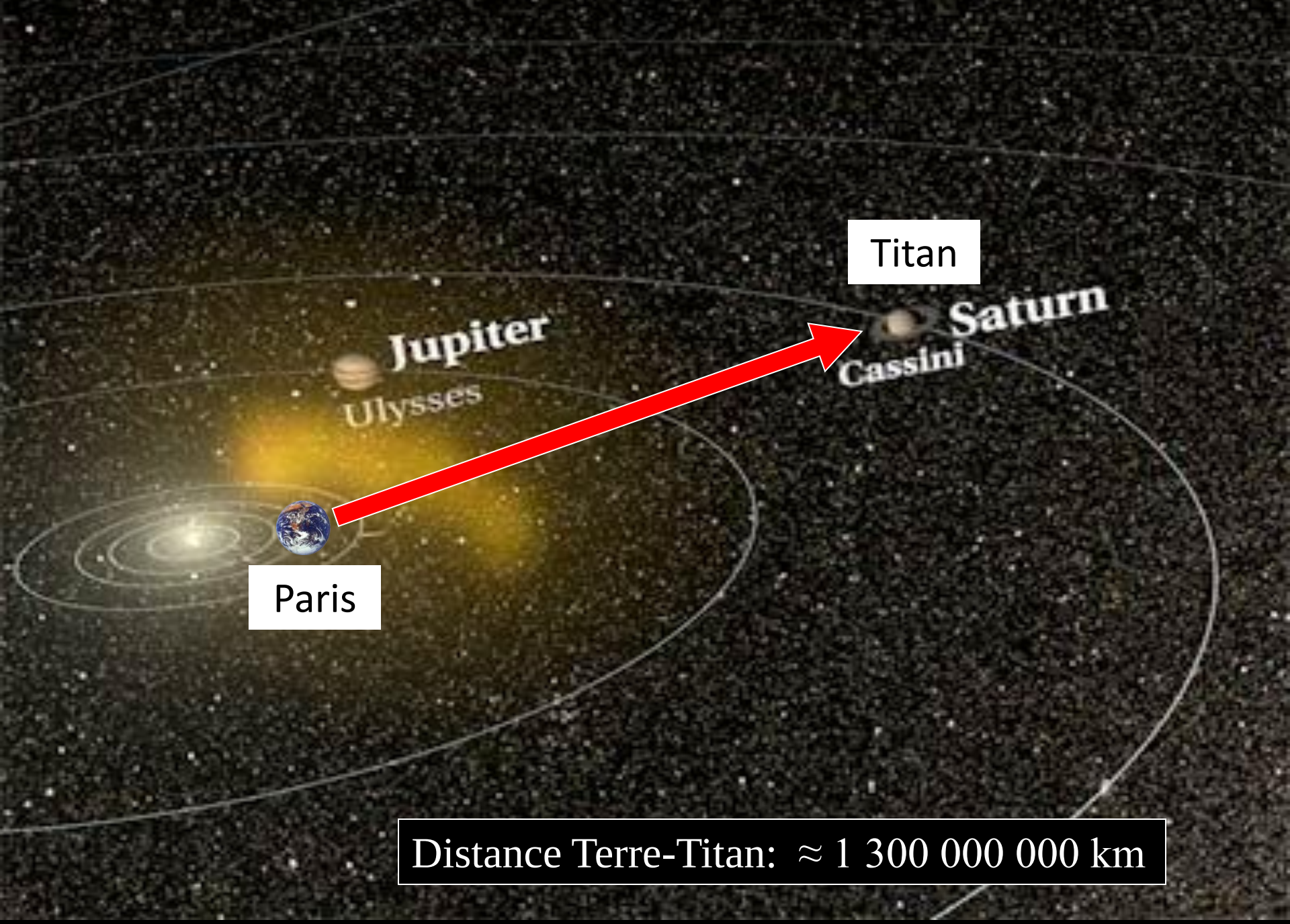
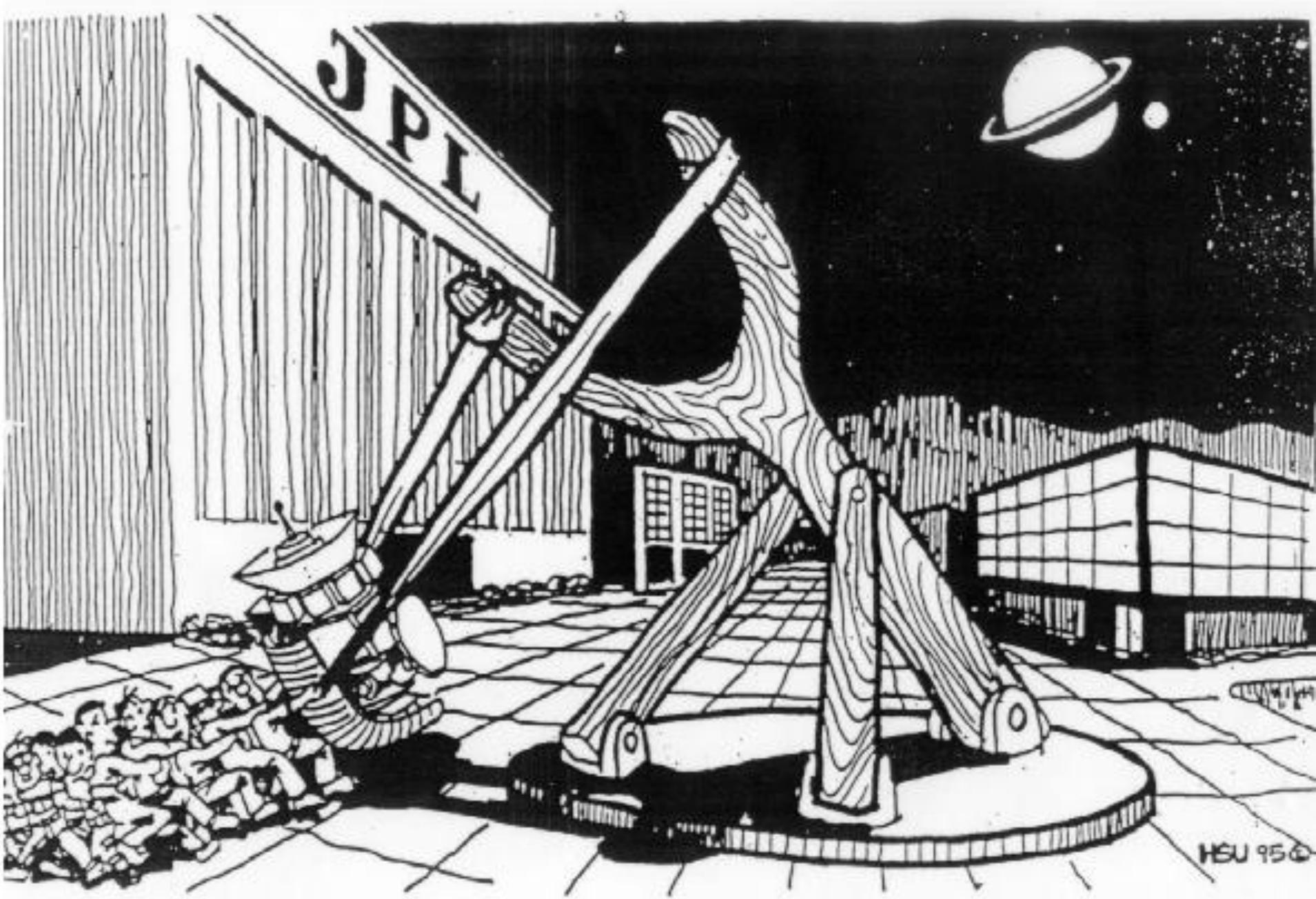
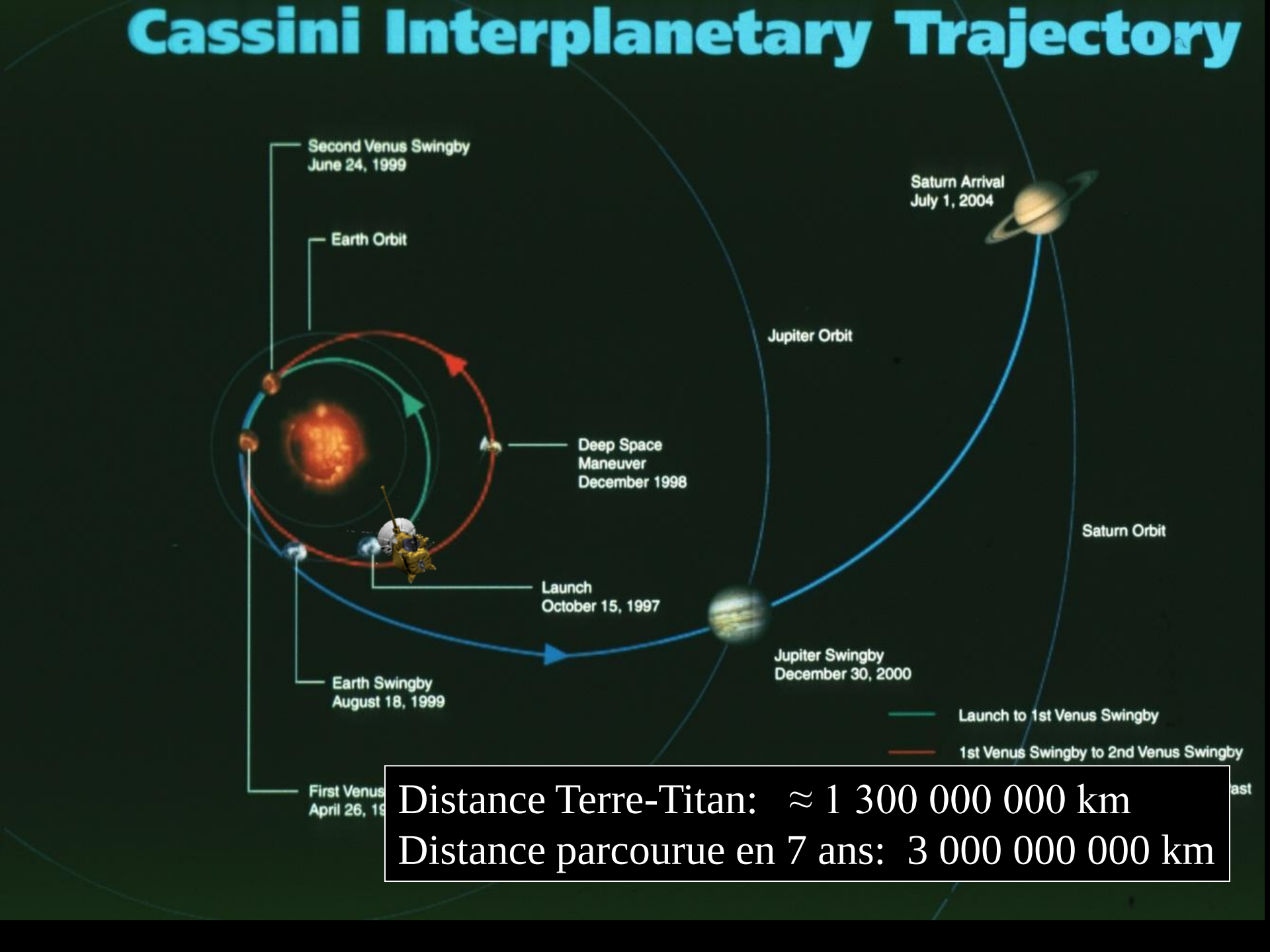
- 7 années de voyage à travers le Système Solaire … vers Saturne


Titan
Saturn
Cassini
Jupiter
Ulysses
Paris
Distance Terre-Titan: ≈ 1 300 000 000 km

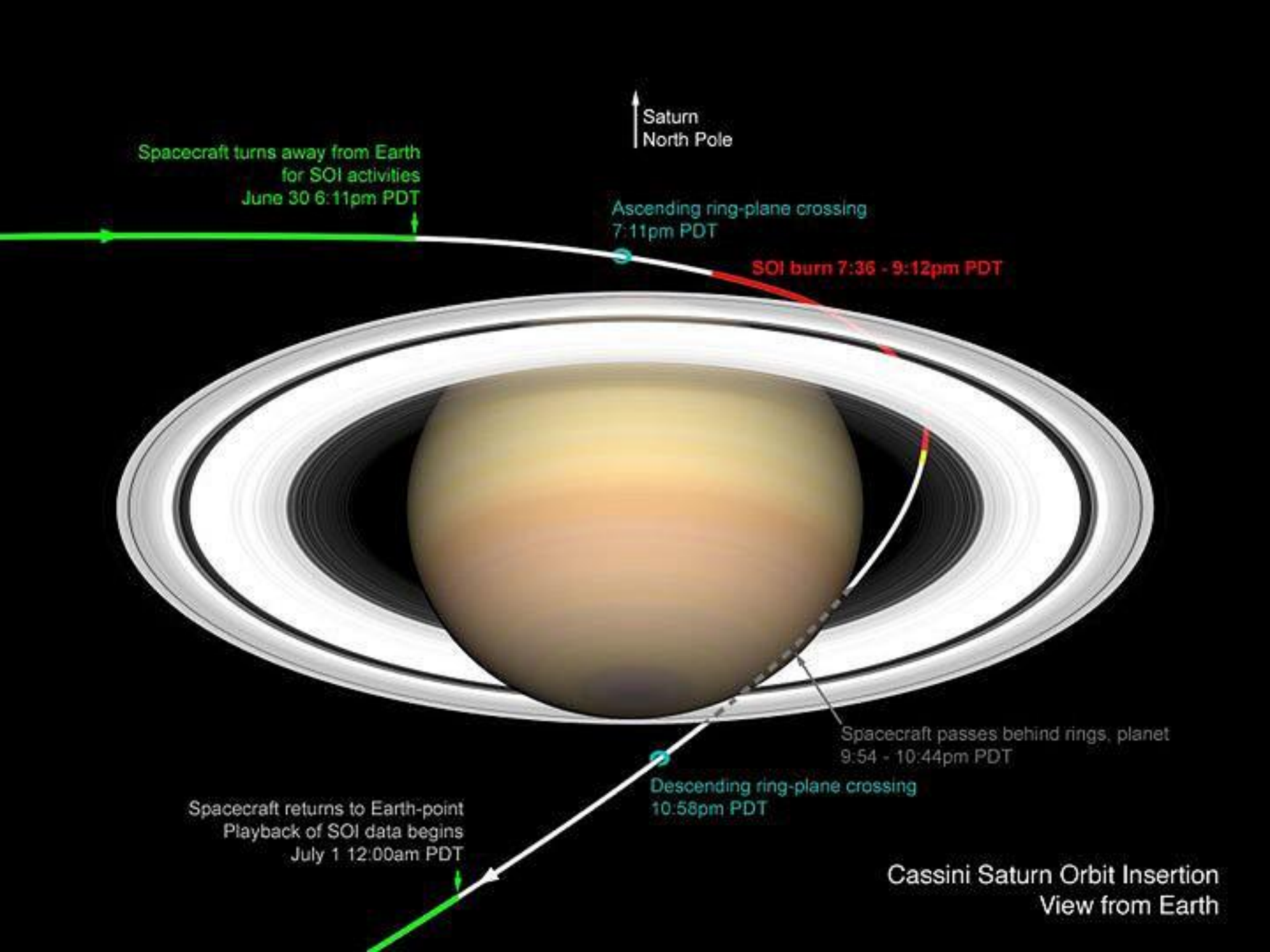

JPL
HSU 95

Cassini Interplanetary Trajectory

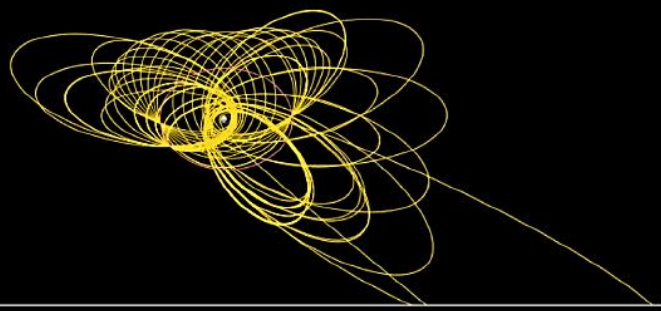


Distance Terre-Titan: ≈ 1 300 000 000 km

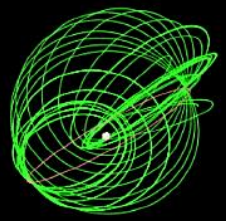
Distance parcourue en 7 ans: 3 000 000 000 km


Saturn
North Pole
Spacecraft turns away from Earth
for SOI activities
June 30 6:11pm PDT
Ascending ring-plane crossing
7:11pm PDT
SOI burn 7:36 - 9:12pm PDT
Spacecraft passes behind rings, planet
9:54 - 10:44pm PDT
Descending ring-plane crossing
10:58pm PDT
Spacecraft returns to Earth-point
Playback of SOI data begins
July 1 12:00am PDT
Cassini Saturn Orbit Insertion
View from Earth

Prime Mission (2004-2008)



Equinox Mission (2008-2010)



Solstice Mission (2010-2017)

Cassini Mission (2004-2017)