



ONE RING
TO RULE THEM ALL

THE TRILLOGY BEGINS DECEMBER 2001

Lord of the Rings

The
**Cassini/Huygens
Mission**
to
SATURN

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MPI Nuclear Physics, Heidelberg, Germany
University Stuttgart

Kobe, March 2010

GALILEO TO KEPLER 1610

ALTISSIMUM PLANETAM TERGEMINUM OBSERVAVI

„The most distant planet has a three-fold shape !“

„Der entfernteste Planet hat eine dreifache Form“

(discovery of Saturn's ring)

CHRISTIAAN HUYGENS

- mathematician and physicist of the netherlands
- (*1629, †1695)
- interpretation of Saturn's ring
- discovery of the large moon titan (1655)

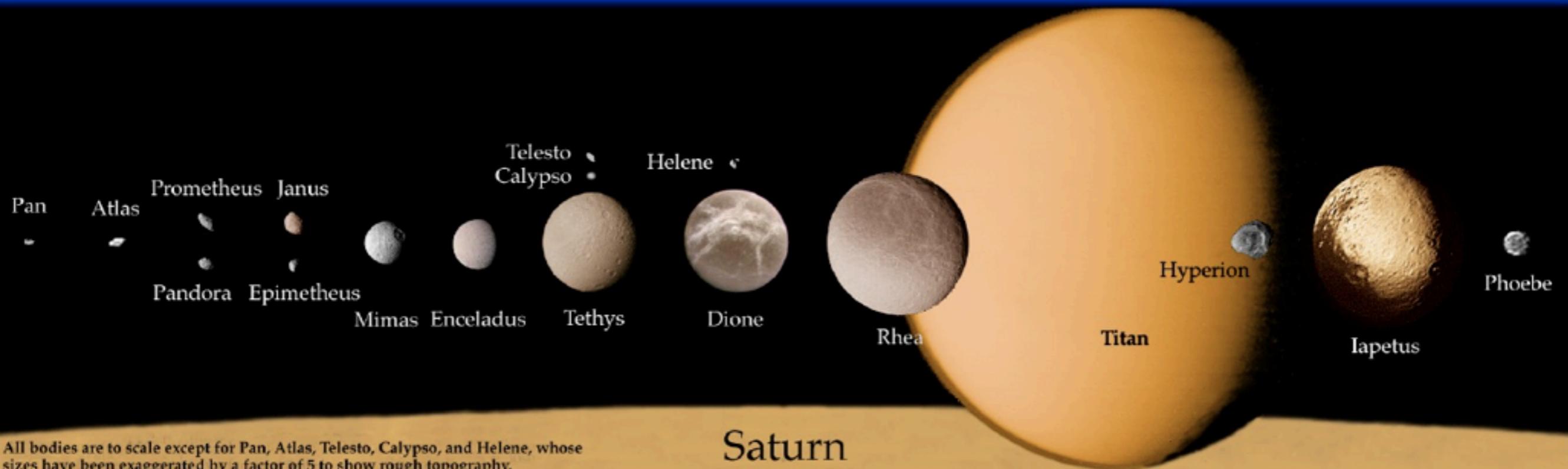


GIOVANNI CASSINI

- french astronomer and mathematician
- (*1625, †1712)
- discovery of 4 Saturn moons and the ring division



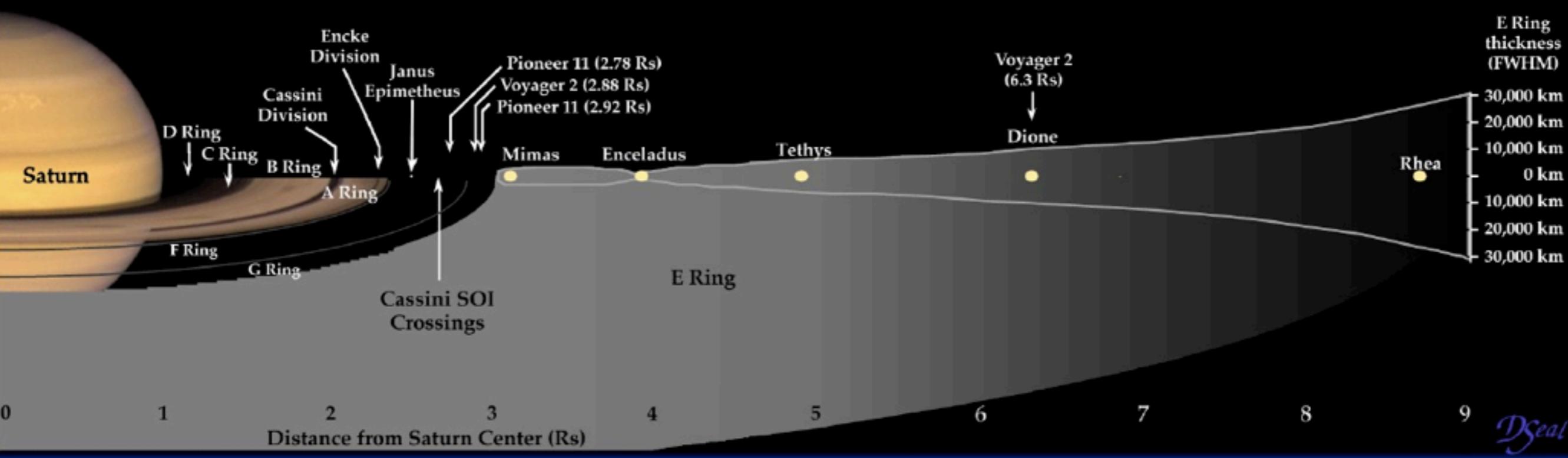
Saturn's Satellites and Ring Structure



All bodies are to scale except for Pan, Atlas, Telesto, Calypso, and Helene, whose sizes have been exaggerated by a factor of 5 to show rough topography.

Not shown:

Pan	2.22 Rs	Titan	20.3 Rs
Atlas	2.28 Rs	Hyperion	24.6 Rs
Prometheus	2.31 Rs	Iapetus	59.1 Rs
Pandora	2.35 Rs	Phoebe	214.9 Rs



This graphic is available in color if required.

SATURN !

1 Saturn year :	29.5 y
Rotation :	10 h, 40 min
Distance to Sun :	1400 Mkm
Diameter at equator :	120.000 km
Mass :	95 x Earth
Volume :	760 x Earth
Density :	0.7 g/cm ³ (Earth 5.5)
Strong pole oblateness	
Magnetic field :	4x10 ⁻⁵ T at pole (Earth : 5x10 ⁻⁵ T)
Dipole field axis = rotation axis !	
ring plane :	27° tilted towards orbit plane



SATURN'S INTERIOR

Atmosphere : 94 % H, 6% He

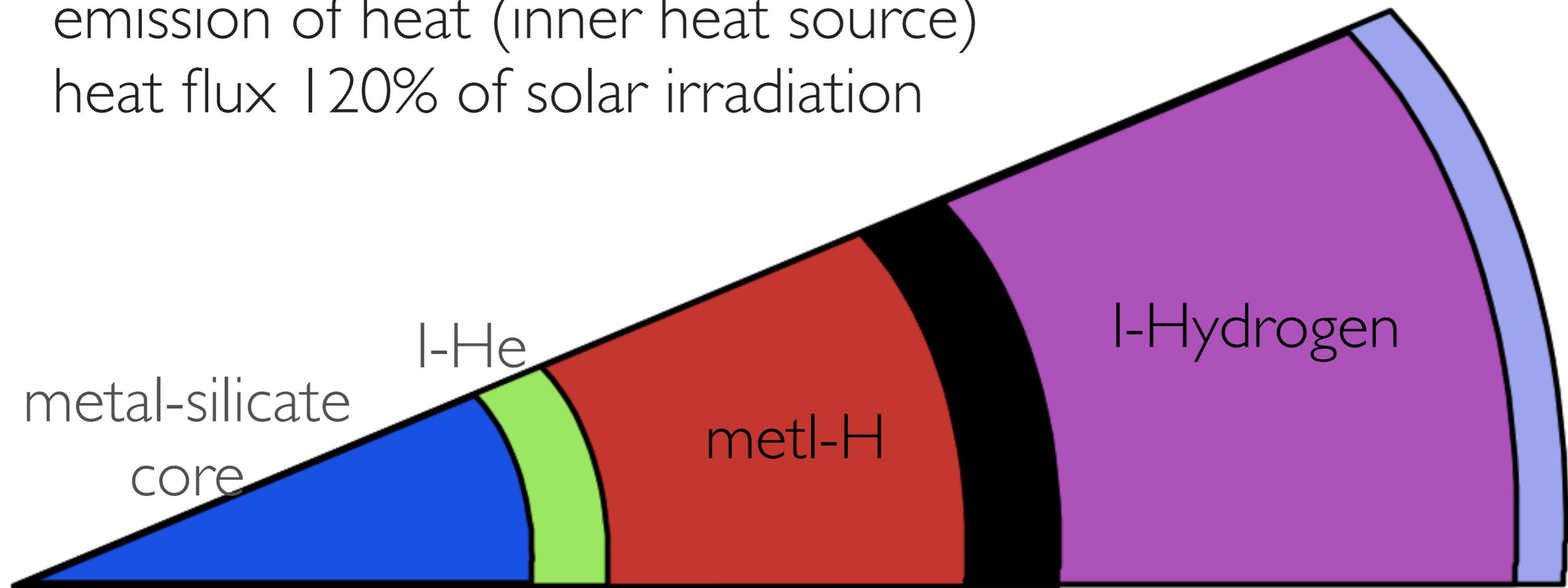
T at upper cloud boundary : 150 K

T at cloud lower boundary : 80 K

T in center : 20.000 K, 5×10^{12} P (Earth: 3800 K)

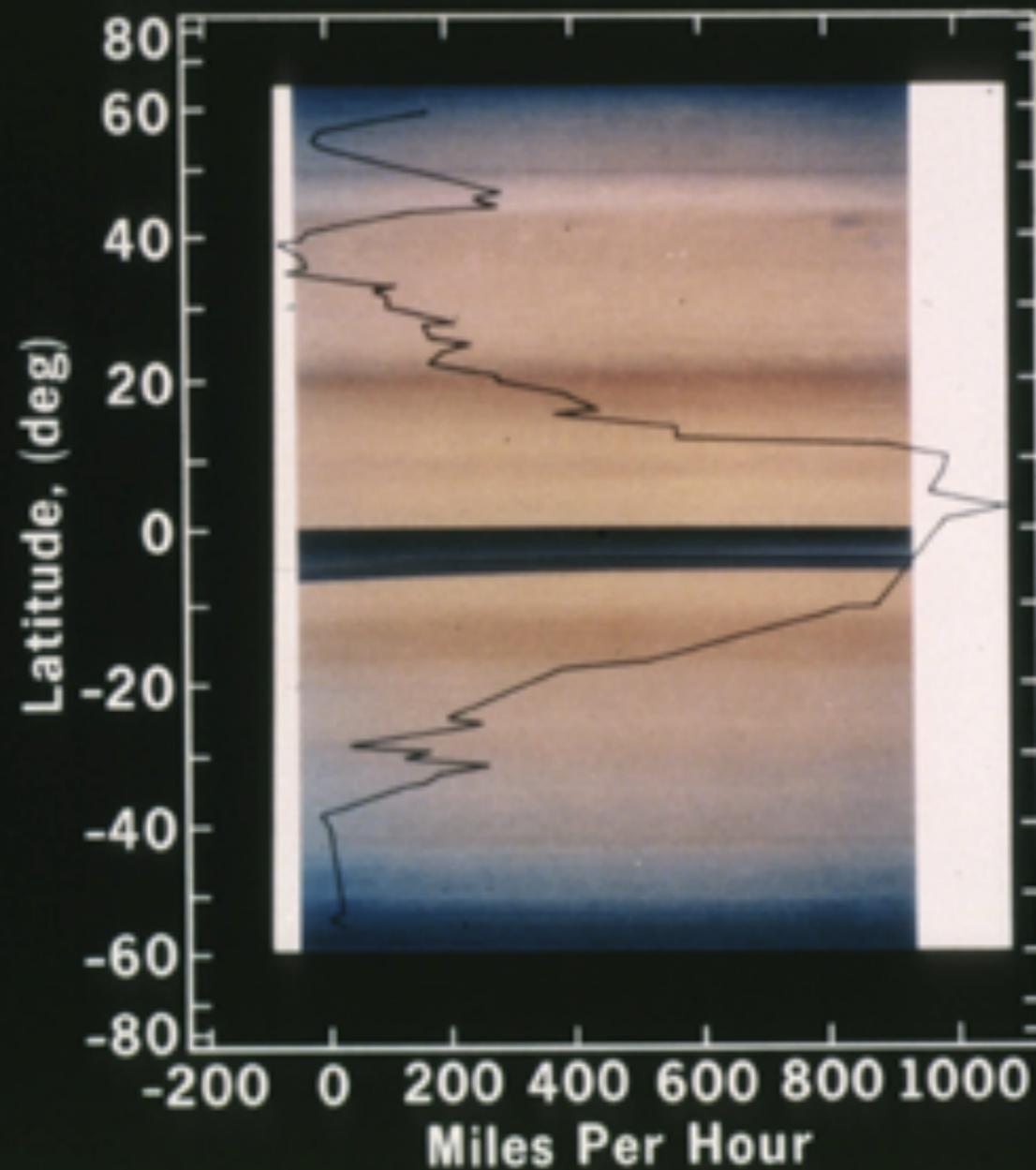
emission of heat (inner heat source)

heat flux 120% of solar irradiation



WINDS OF SATURN

(UP TO 500 M/S)



MOON MYSTERIES

- Pandora and Prometheus are shephard moons for ring
- Dione and Tethys have own moons
- Janus and Epimetheus exchange their orbit
- Iapetus has a dark and bright side
- Mimas has a huge impact crater (1/4 of surface)
- Enceladus is active (ice geysers), highest albedo
- Phoebe has a retrograde orbit, KB object caught by Saturn (?)

CASSINI/HUYGENS

High Gain Antenna

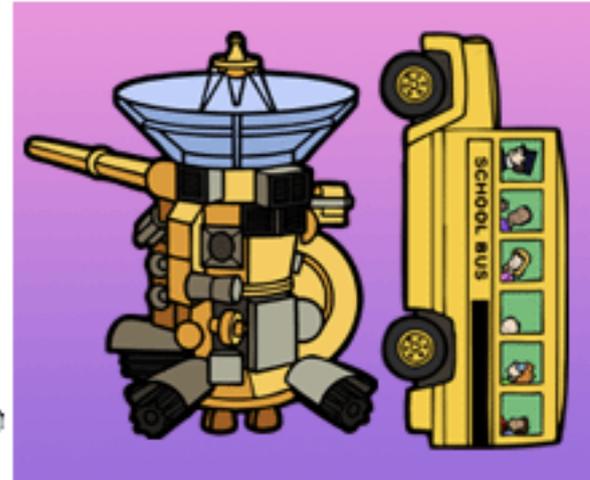
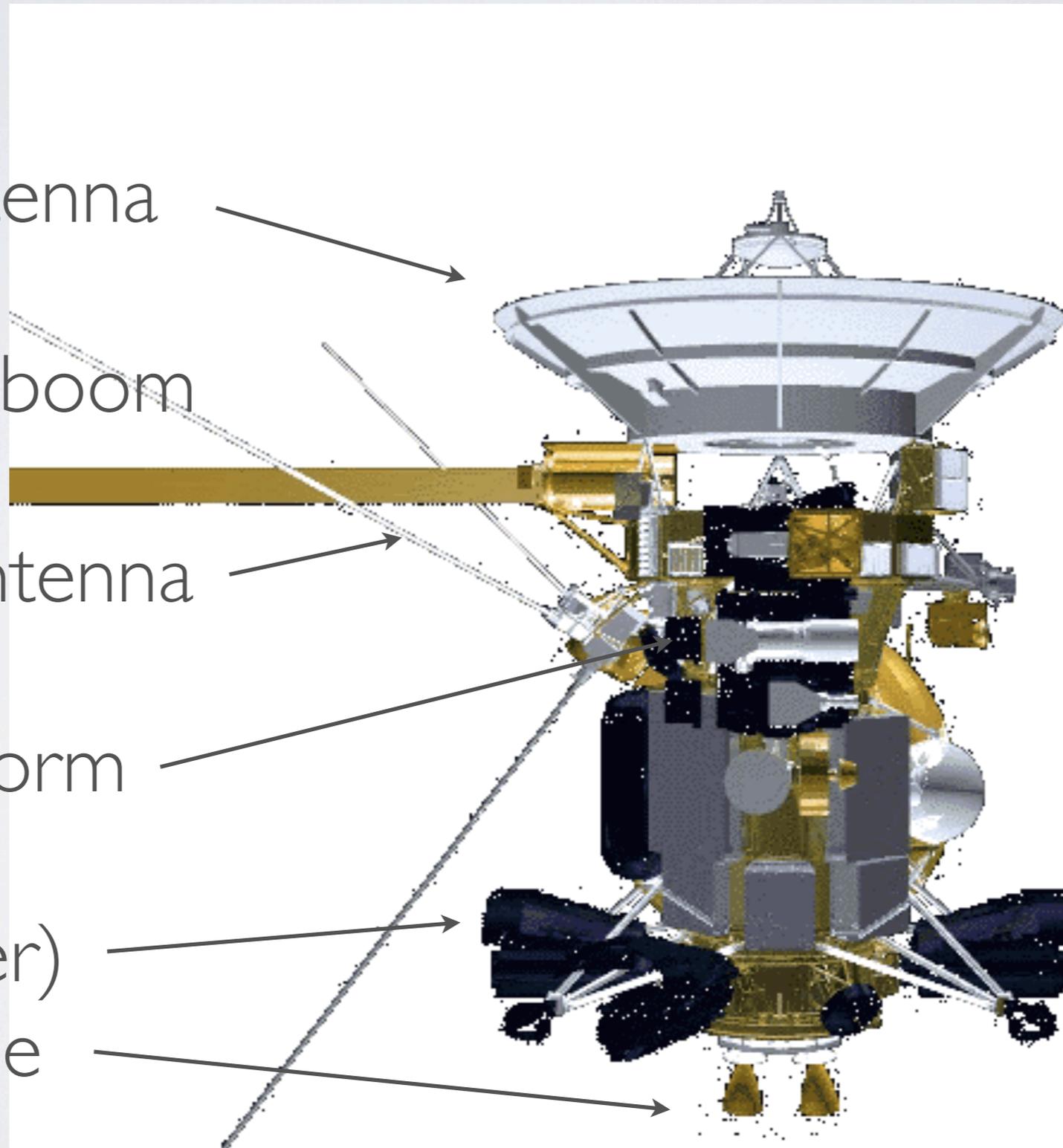
Magnetometer-boom

Plasma wave antenna

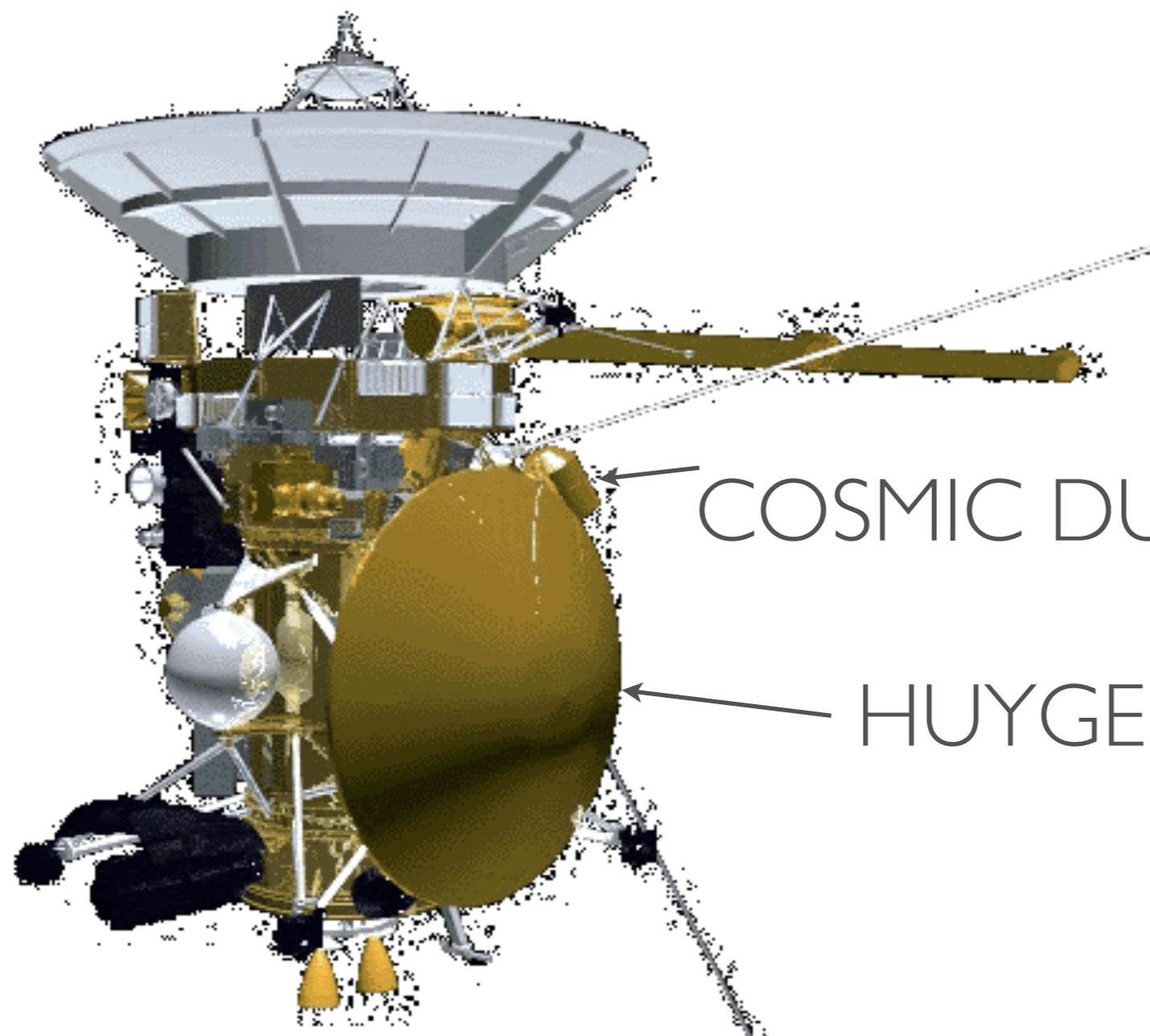
Camera platform

RTG (Power)

Main engine



CASSINI SPACECRAFT



COSMIC DUST ANALYSER

HUYGENS PROBE

CASSINI FACTS

Program partners : NASA, ESA, ASI

17 countries

international engineers and scientists: 5000

costs : 1.4 billion (pre-launch development)

\$ 710 M mission operations

\$ 54 M tracking

\$ 422 M launch vehicle

\$ 500 M ESA (Huygens)

\$ 160 M ASI

\$ 3.27 billion, U.S. \$2.6, Europe \$ 660 M

CASSINI BUS

dry mass 2.1 t + 320 kg Huygens probe + 3.1 t propellant = 5.7 t

height : 6.8 m, 4m antenna, boom 11 m

22.000 wire connections, 12 km cabling

largest interplanetary S/C ever launched

3 RTGs, 750 W + small radio-isotope heaters everywhere

Main Engine : Mono-methyl-hydrazin, N-tetraoxid oxidator

16 small thrusters (Hydrazin)

Inertial Reference Unit - perform turns/firings while retain knowledge of own position

X Band, 20 W, Ka, S, Ku

ADA software, 2x2 Gbit Solid State Recorder,

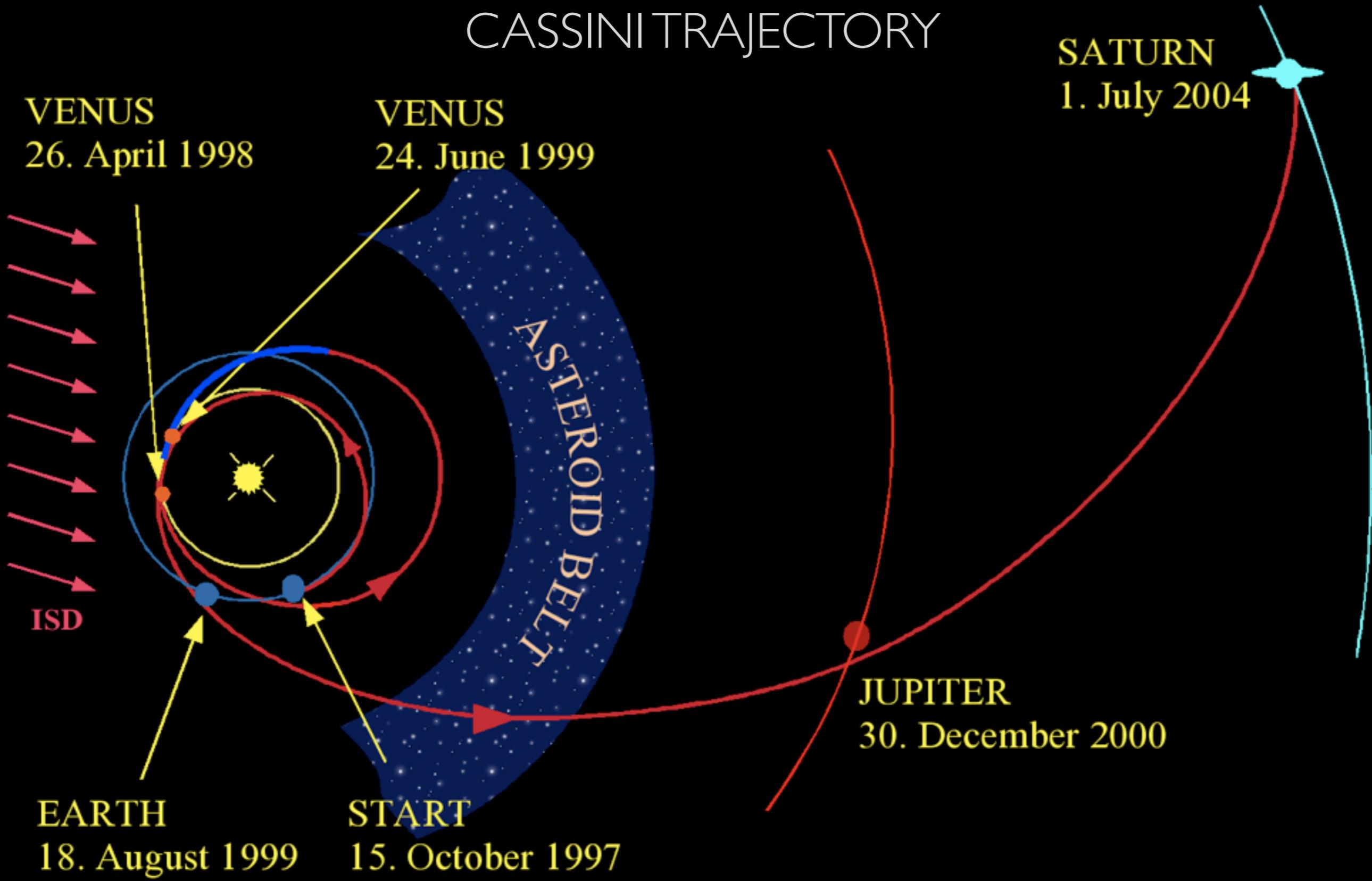
1 MB memory for command subsystem, 16 kB PROM

redundant computers

4 Gyros, cover for main engine

Main engine : 445 Newton, gimbaleed to maintain vector if CoM changes

CASSINI TRAJECTORY



CRUISE SCIENCE: NOT ONLY SATURN ...

Cassini searches for gravity waves with radio science subsystem

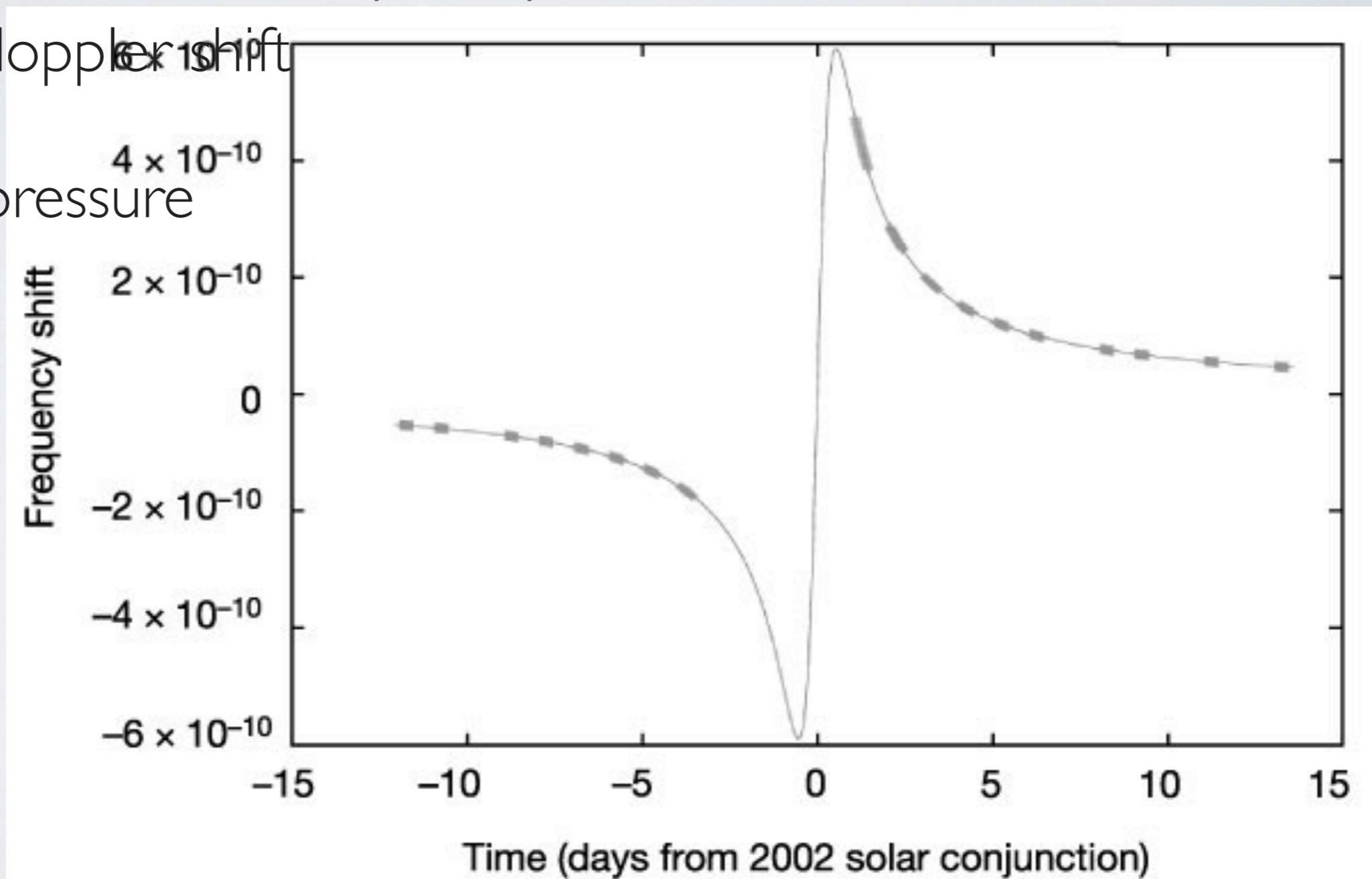
Cassini confirms general relativity theory during conjunction (Cassini - Sun - Earth) in June 2002 ,
Nature 2003



EINSTEIN WAS RIGHT

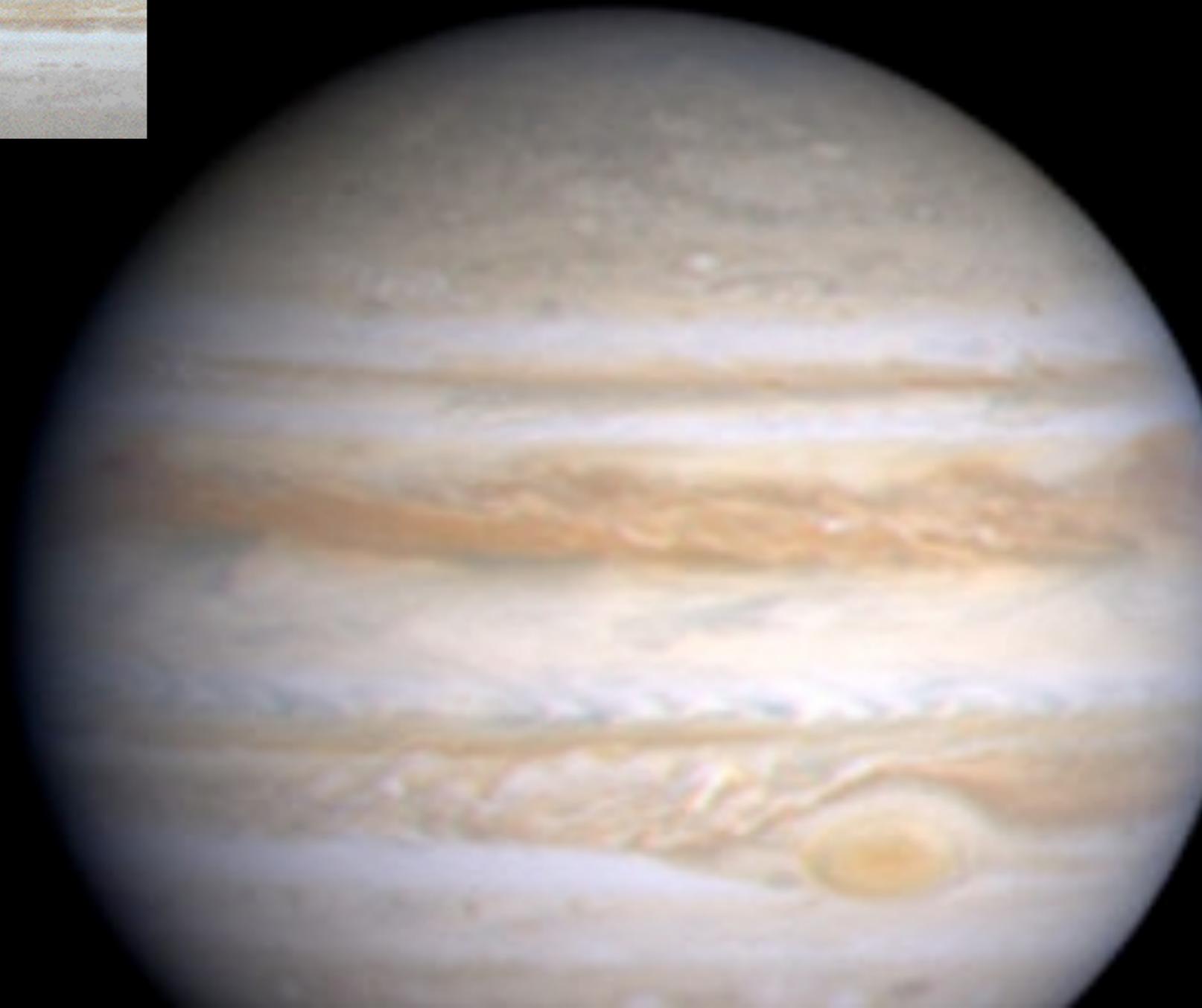
frequency shift after corrections

correction for doppler shift
due to
solar radiation pressure
non-isotrope
heat emission
of RTGs, ...



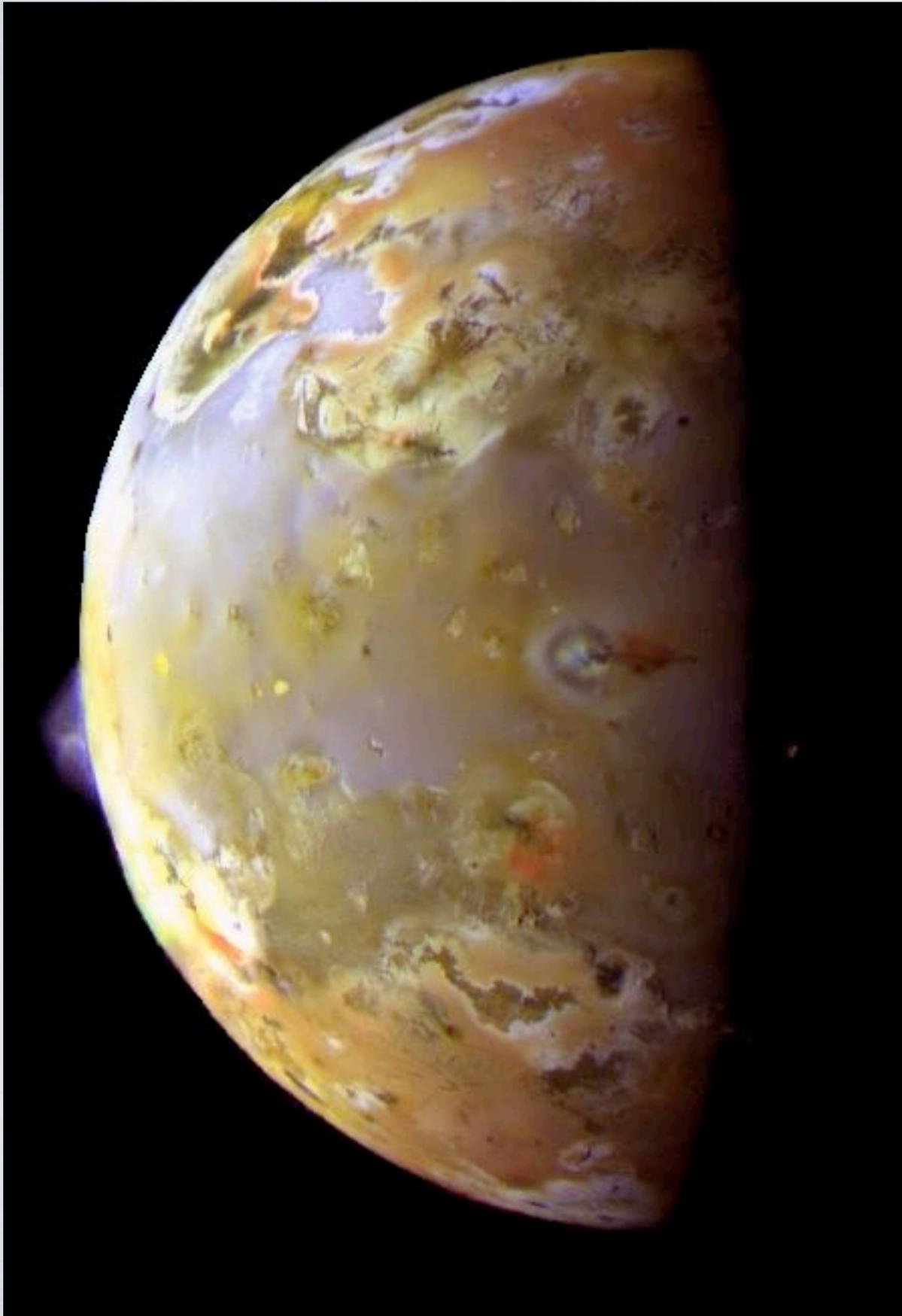
JUPITER SCIENCE

2000



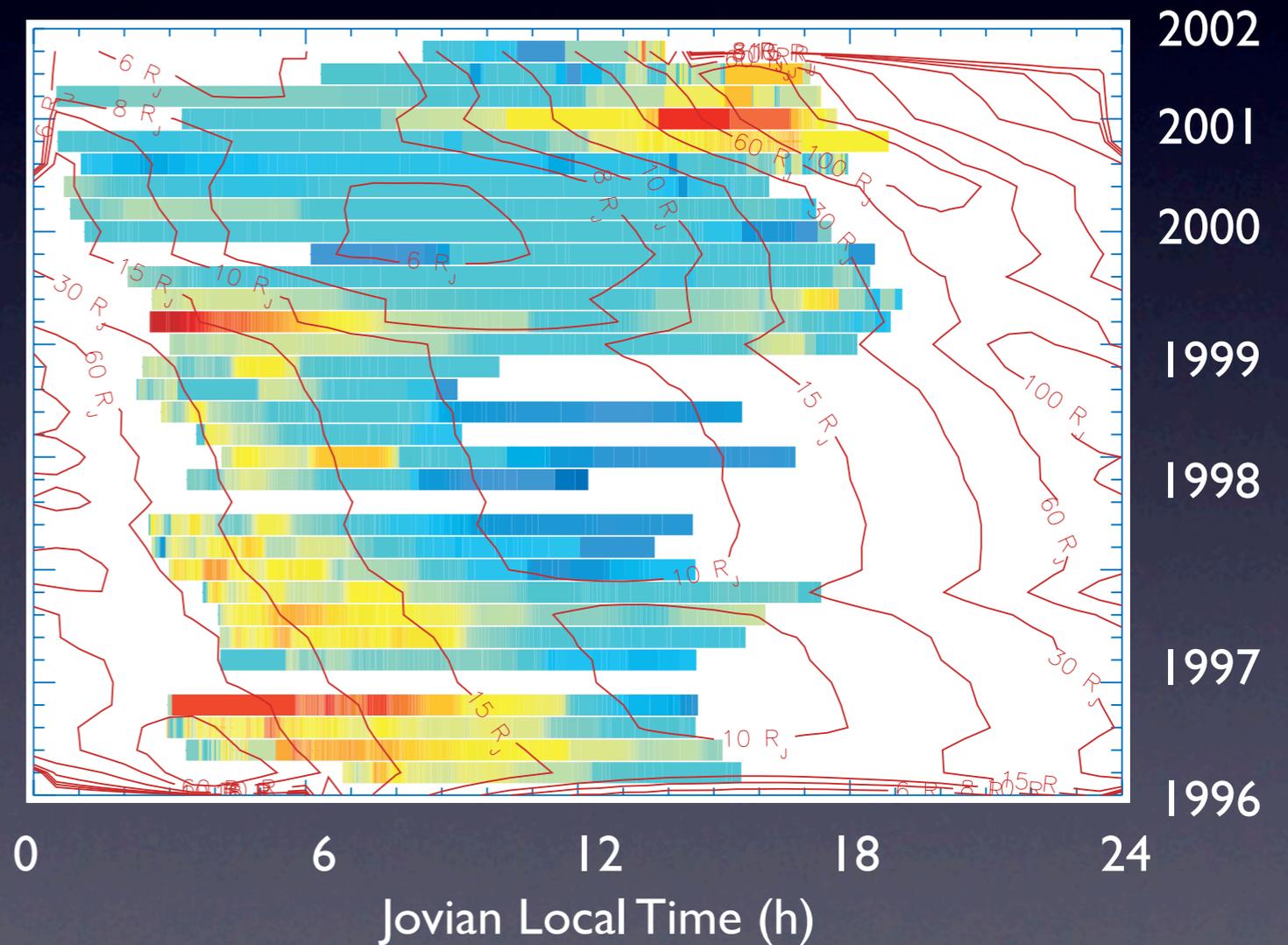
DUST FROM JUPITER

„Io Ashes“



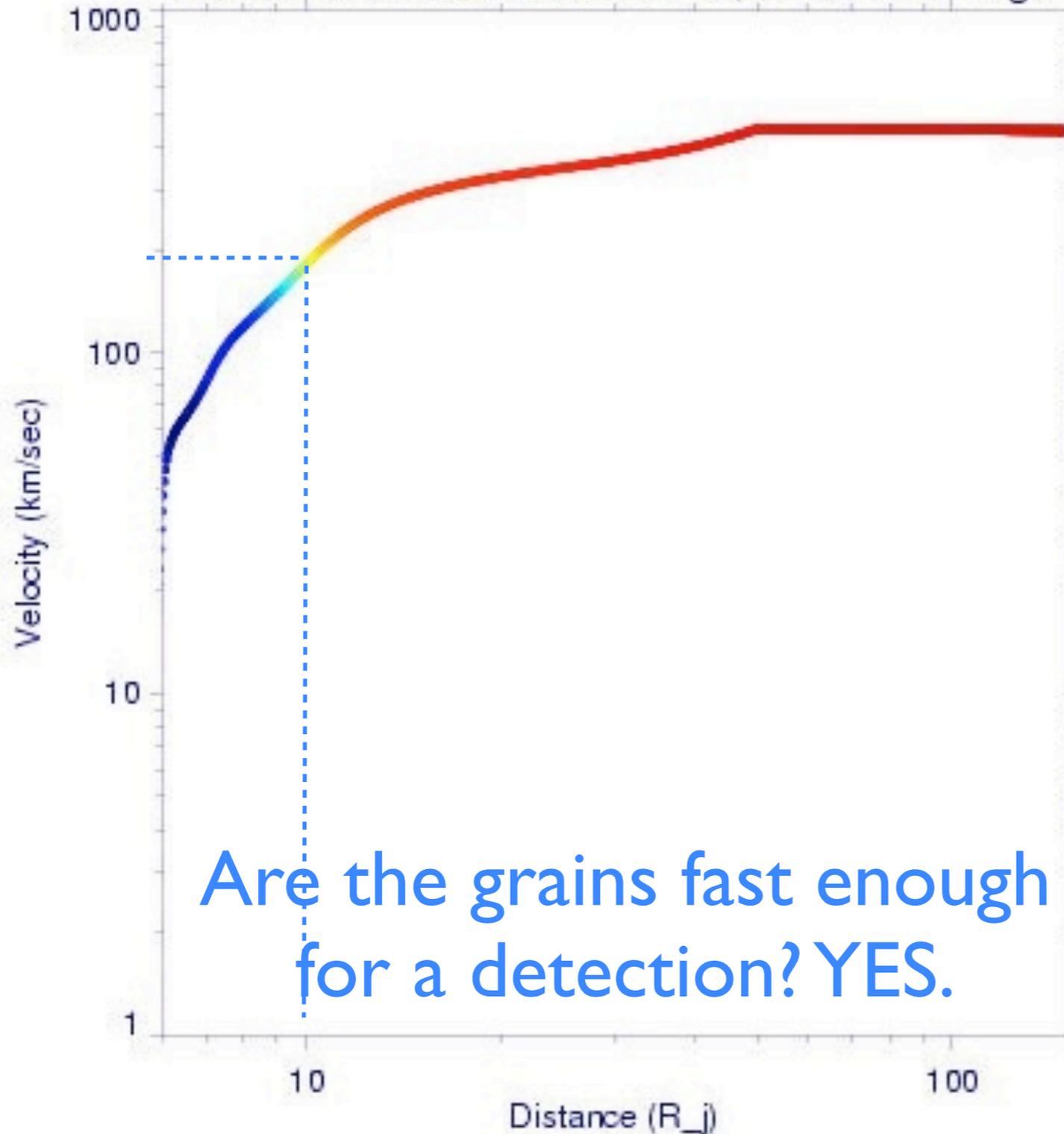
„Io Ashes“ - Stream Particles

- Origin: Io Volcanoes
- Size: 5 ... 40 nm
- Dynamics Dominated by EM Forces
- Fast Enough to Escape From Jovian System
- Allow to Monitor Io Activity



Speed of nano-dust : > 100 km/s

Velocities vs. Distance from Io, Variable Charge

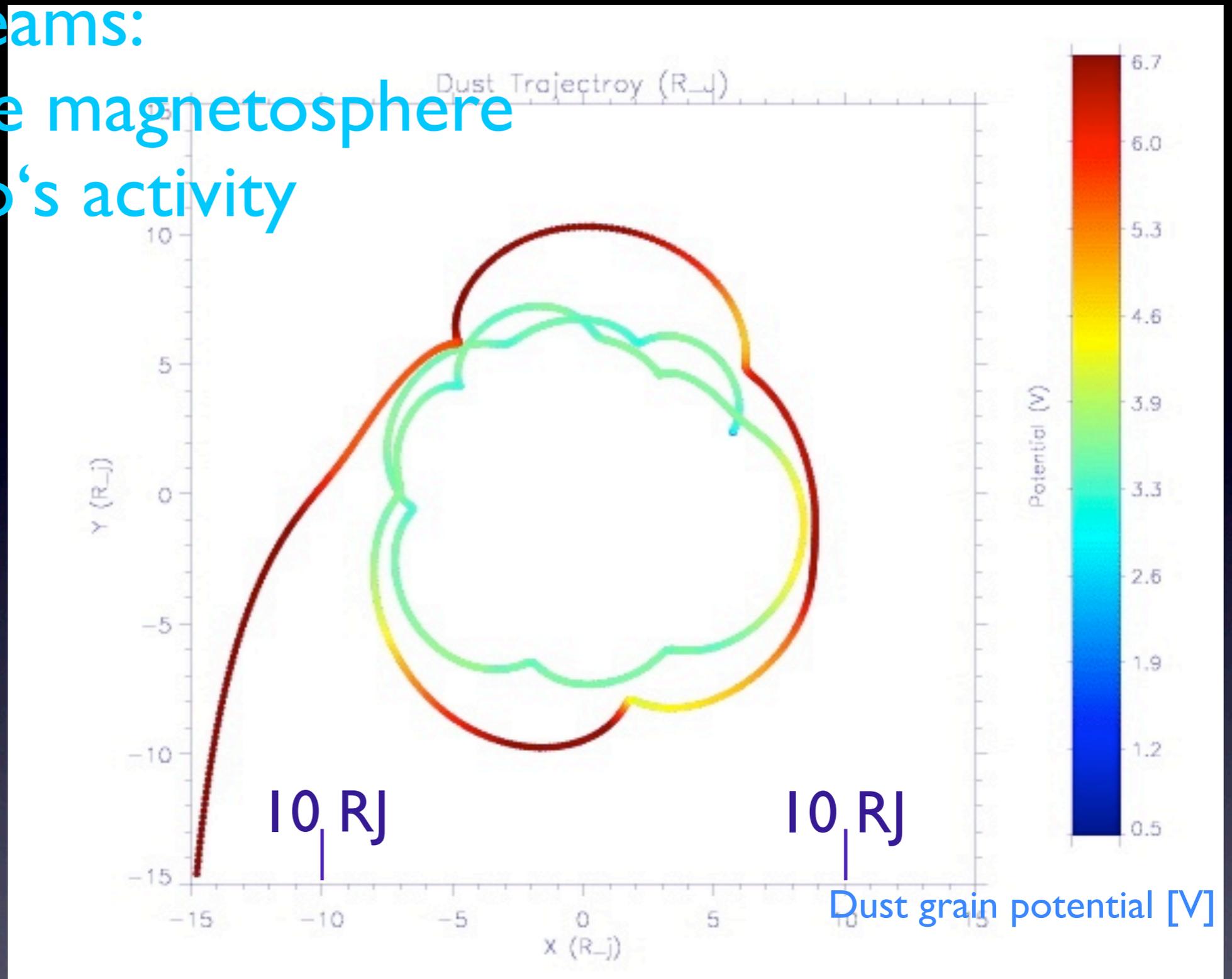


Are the grains fast enough for a detection? YES.

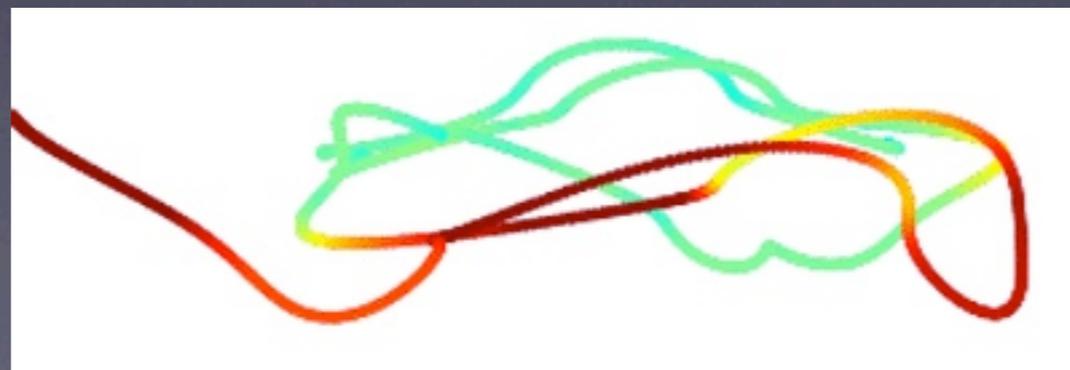
6 nm grains

A. Graps

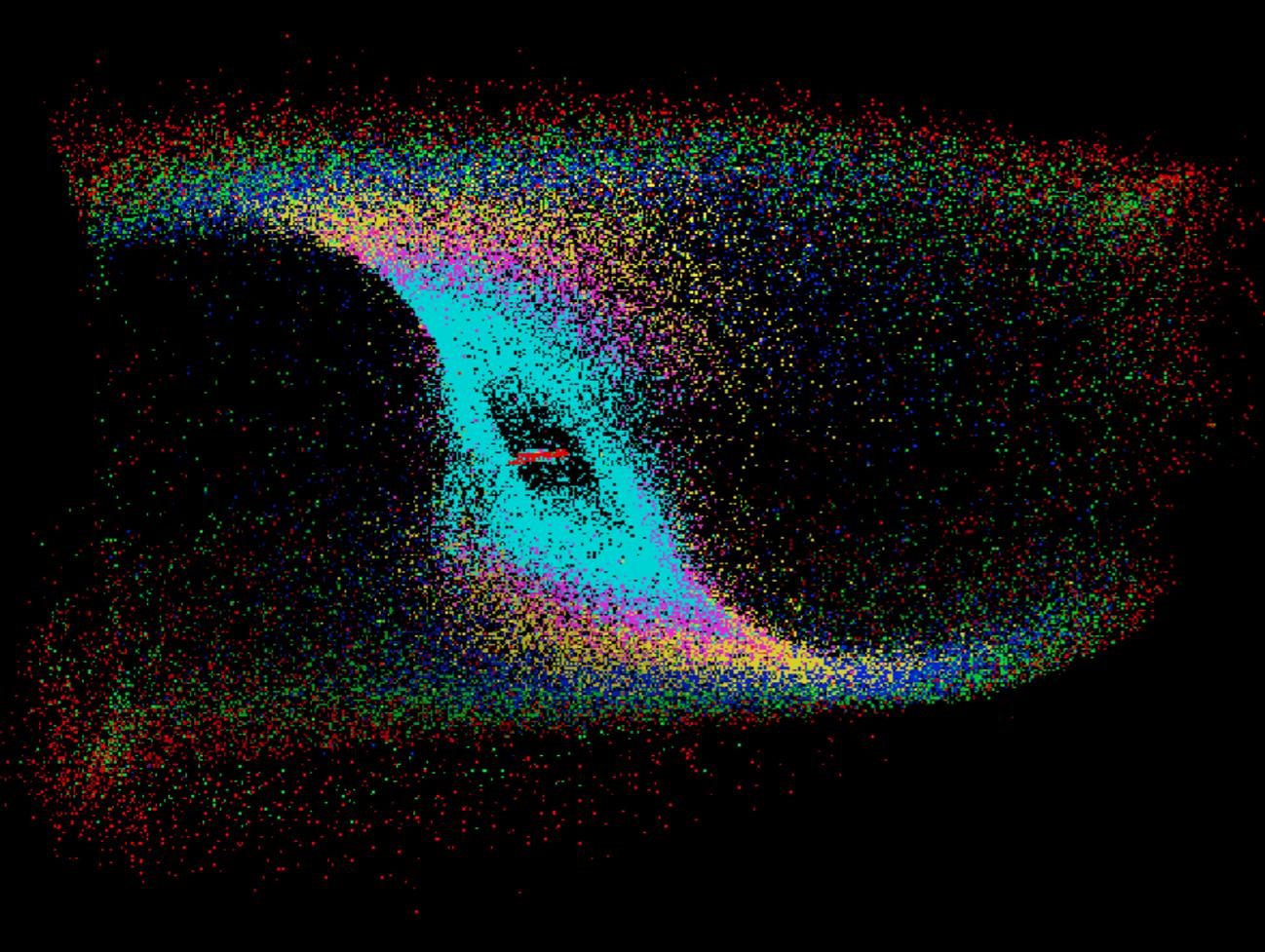
Io's dust streams:
Probes of the magnetosphere
Probes for Io's activity



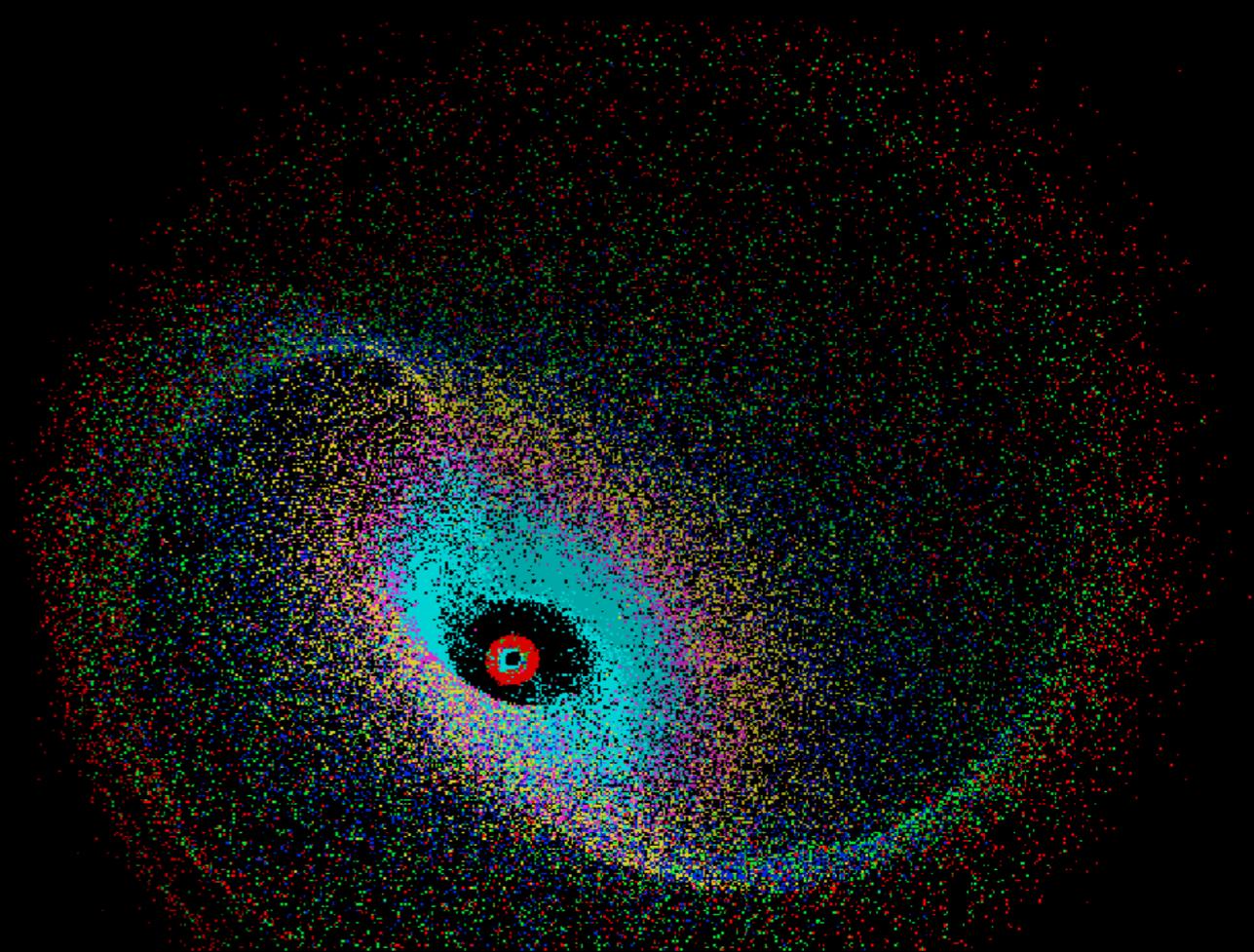
5 nm grain (silicate)



Io as a Dust Source: Nano-Dust Coupling to Magnetosphere

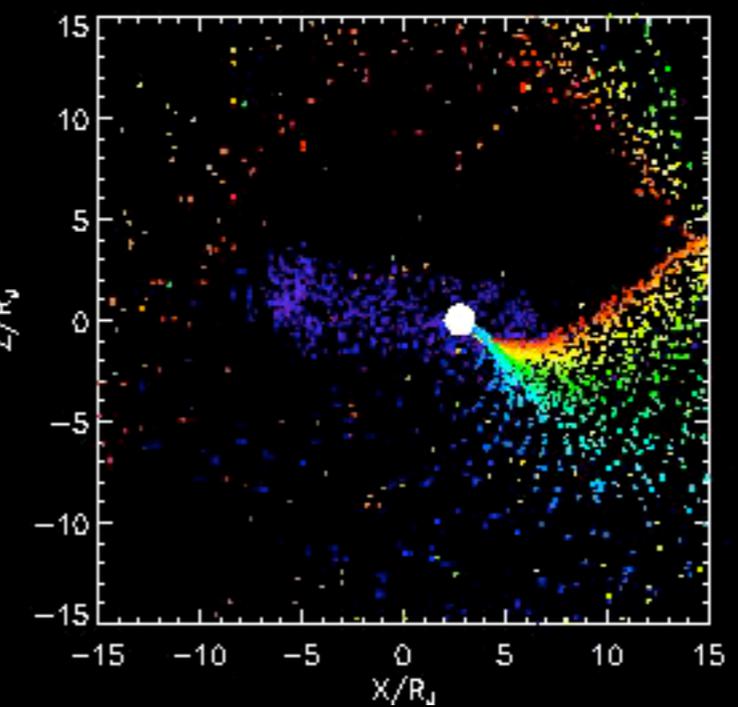
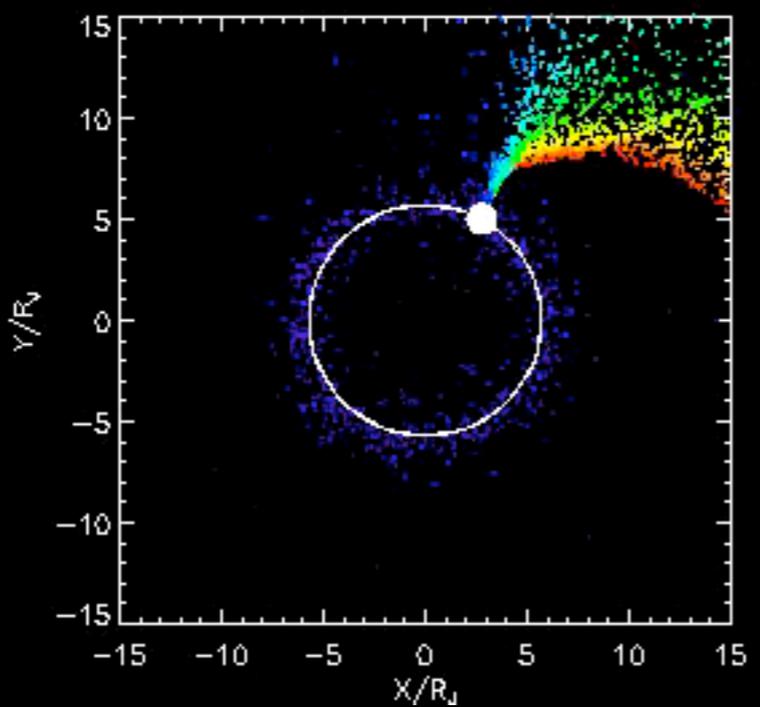
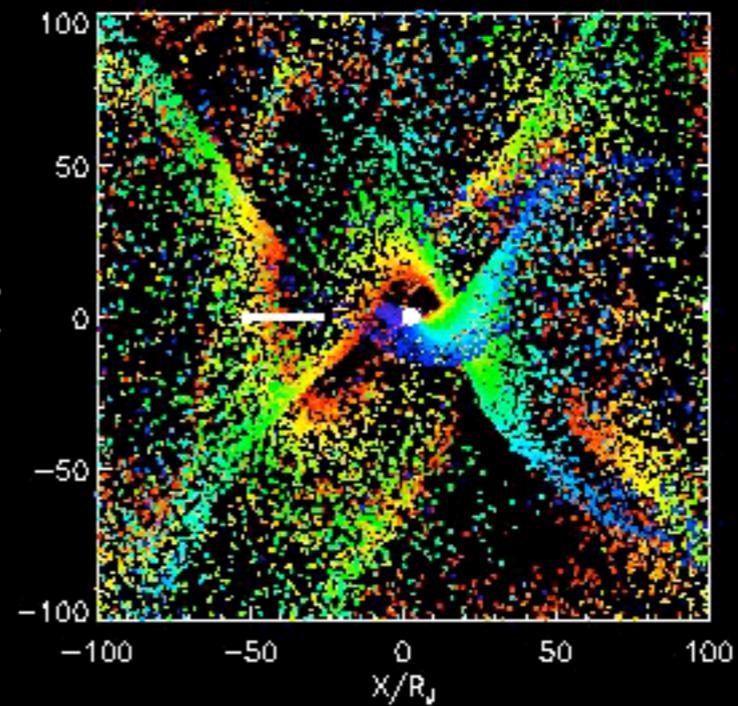
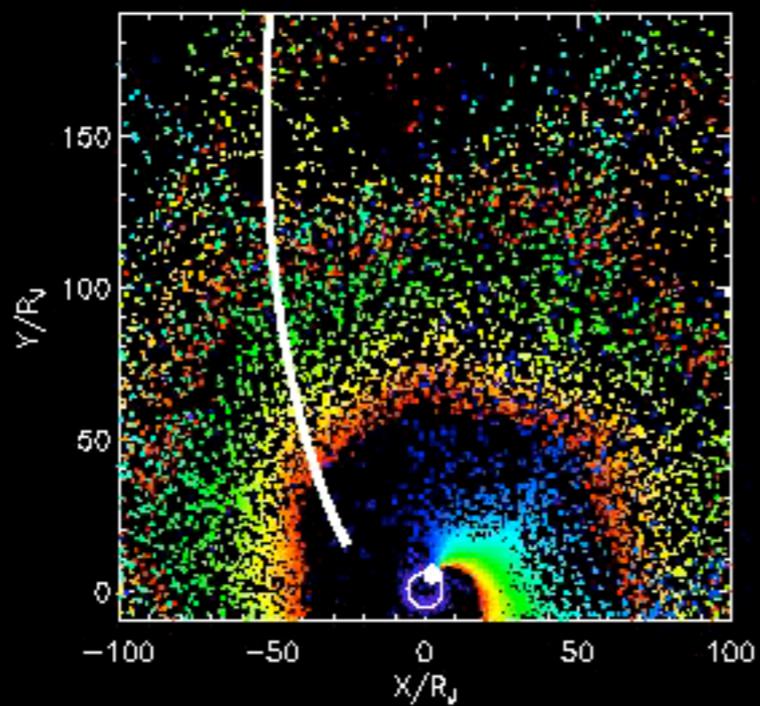
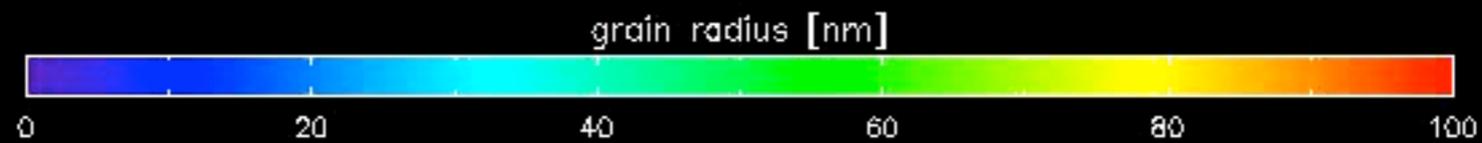


Side View



Top View

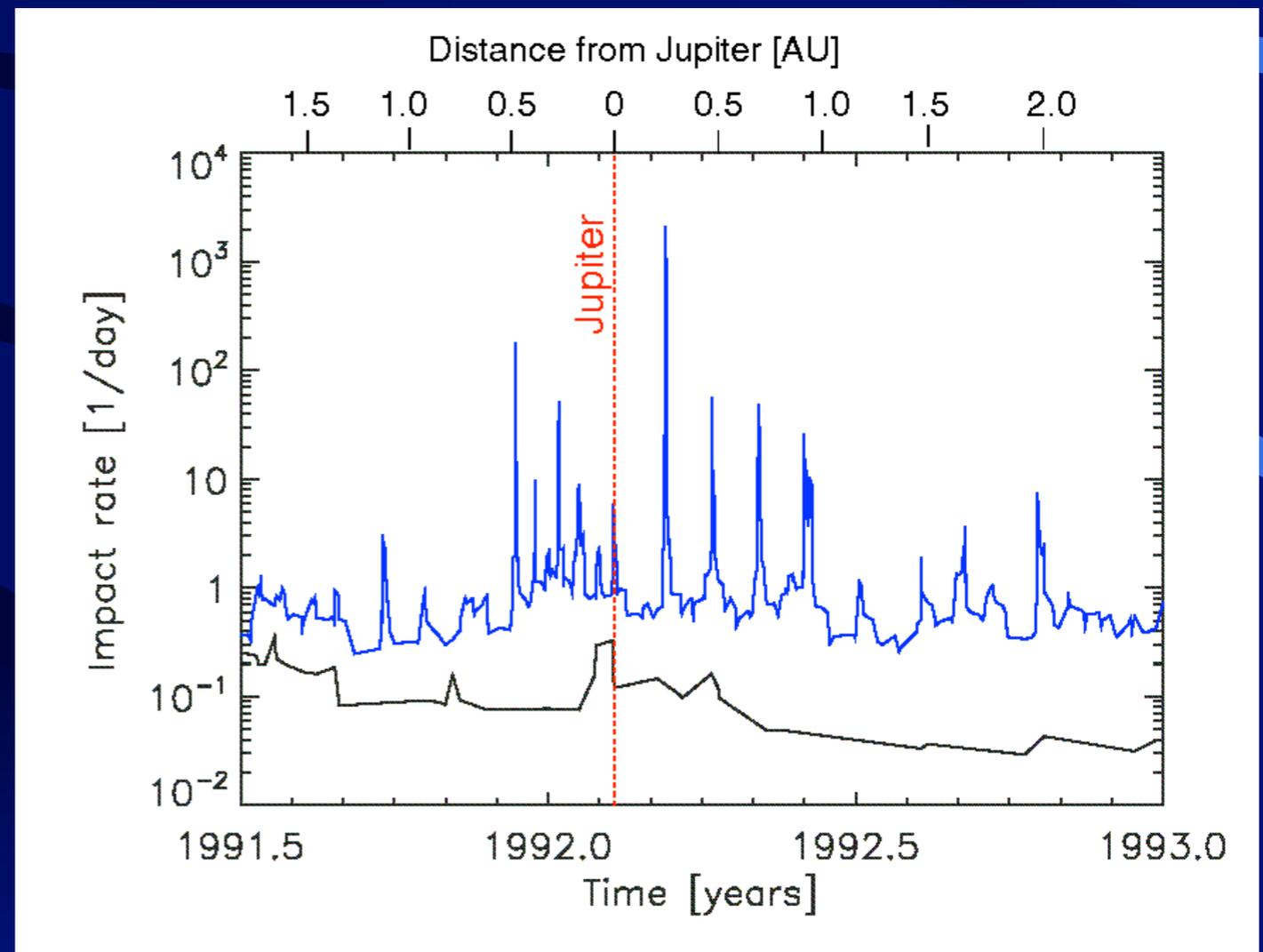
A. Graps



M. Horanyi

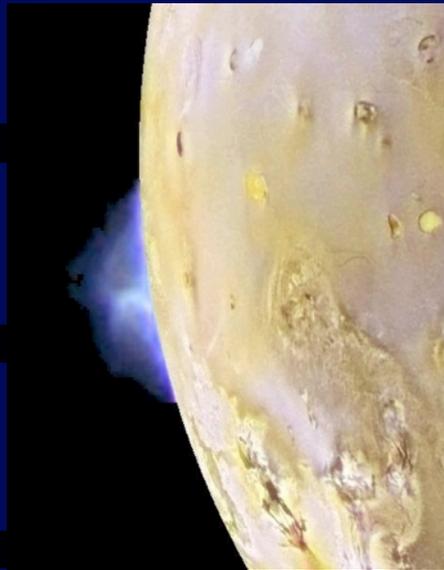
Io as a Dust Source in the Jovian System

- Streams of electrically charged dust grains emanating from the jovian system (Grün et al., 1993)
- 26 day periodicity (Krüger et al., 2006)
- Interaction with interplanetary magnetic field
- Grain radii: ~ 10 nm, speeds > 300 km/sec (Zook et al., 1996)
- Jupiter's magnetosphere: giant dust accelerator
- Source: Io (Graps et al., 2000)
- Confirmed during 2nd Jupiter flyby in 2004 (Krüger et al. 2006)
- Stream formation due to CIR and CME interaction (Flandes & Krüger, 2007)

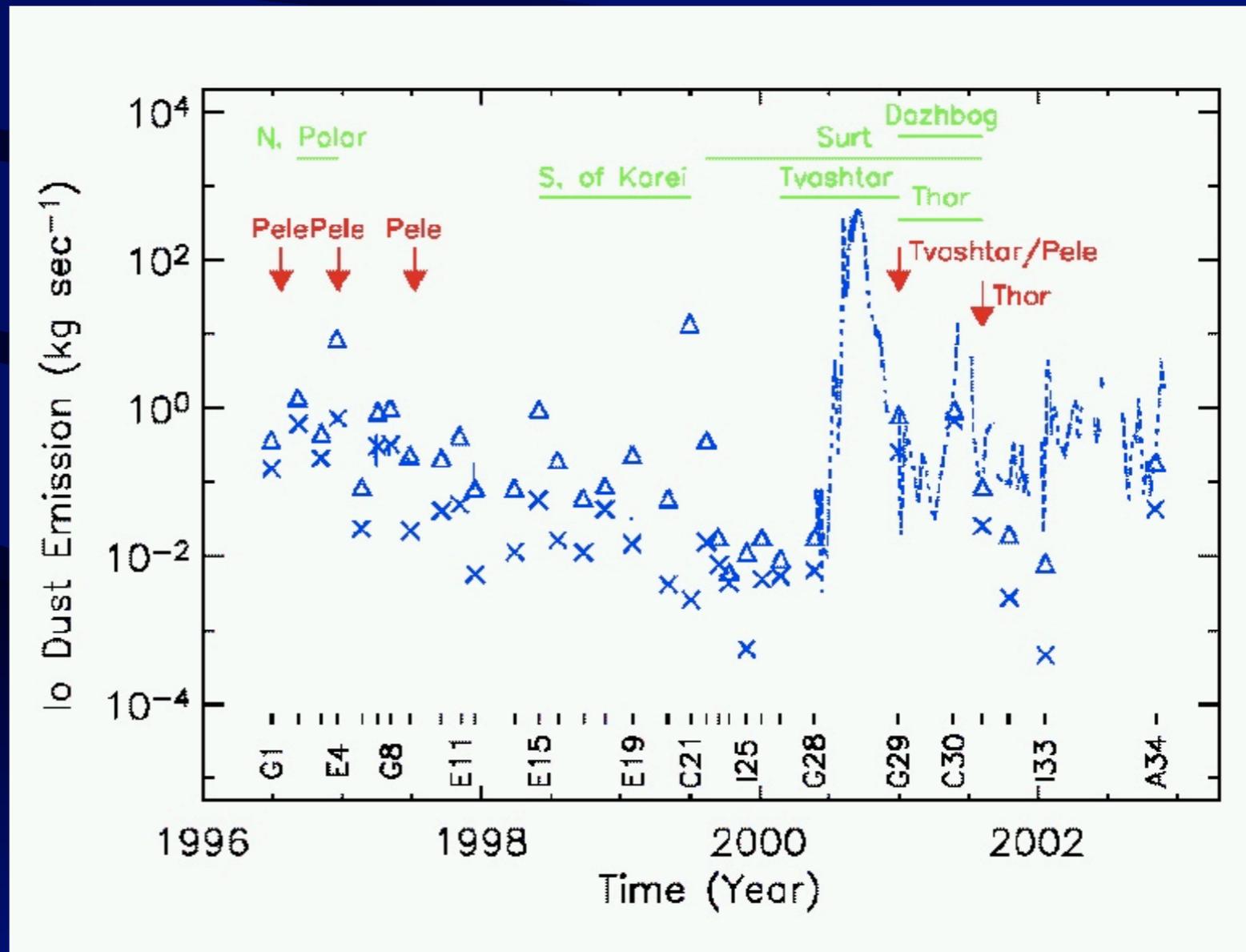
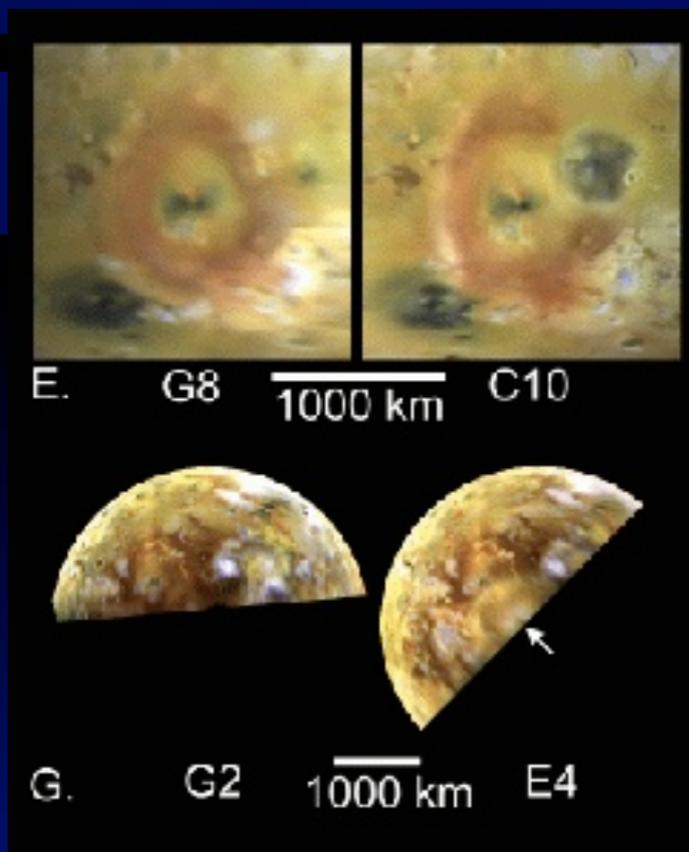


Dust Streams: A Monitor of Io's Volcanism

- Average Io dust emission: $\sim 0.1 - 1 \text{ kg s}^{-1}$
- Small compared to $\sim 1 \text{ ton s}^{-1}$ of plasma ejected
- Peaks in dust emission coincide with largest surface changes
- Dust condensation in plumes

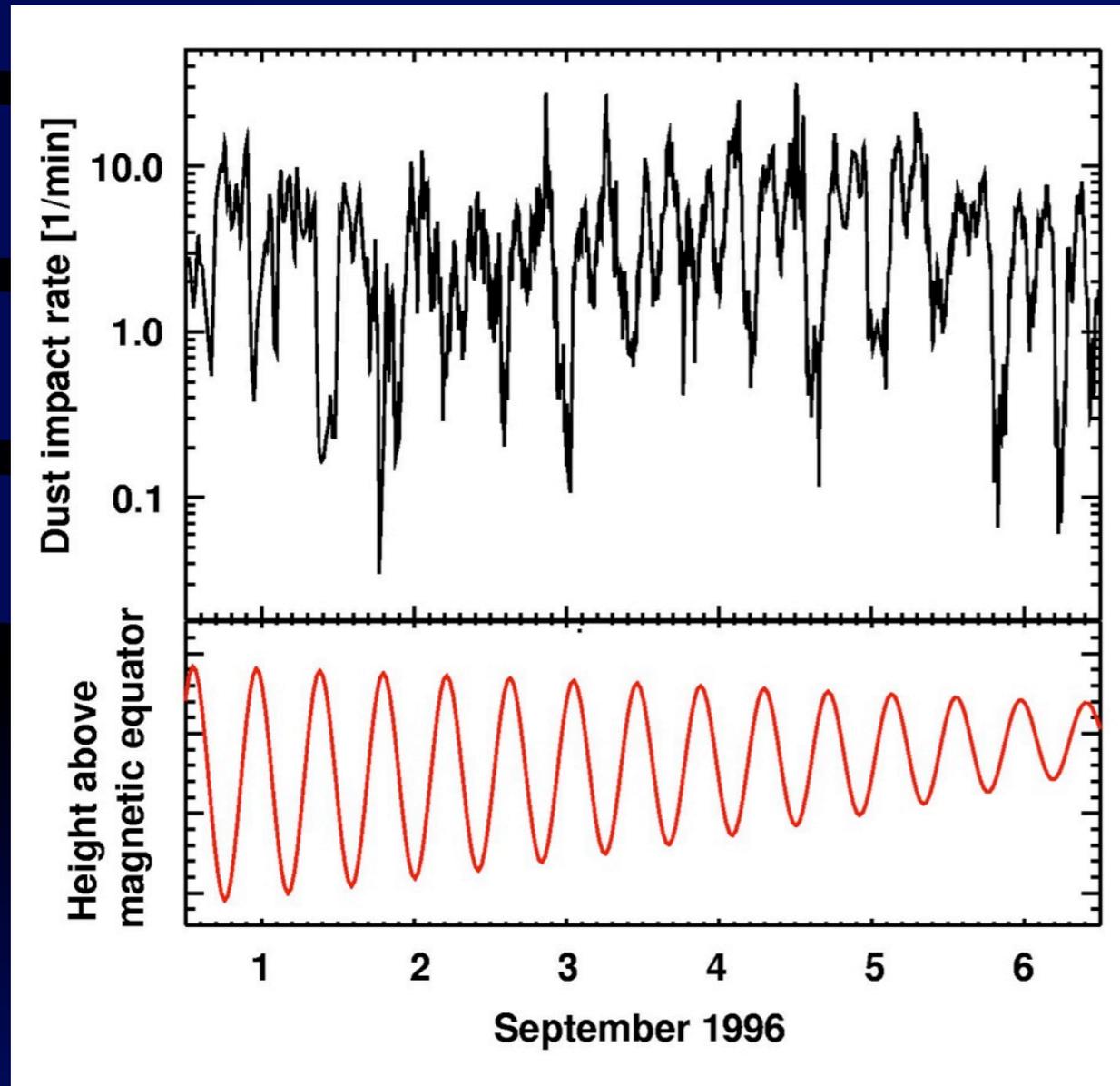
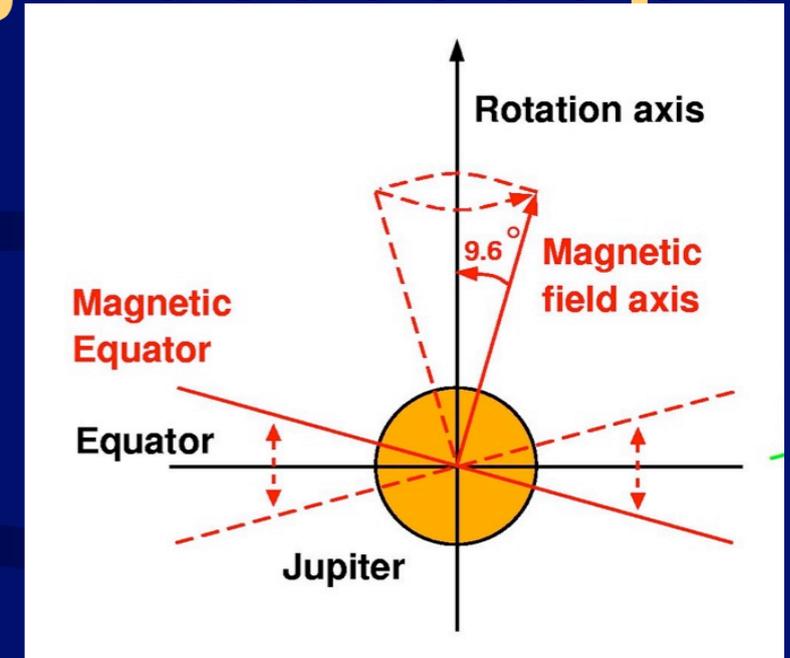


Io, Galileo

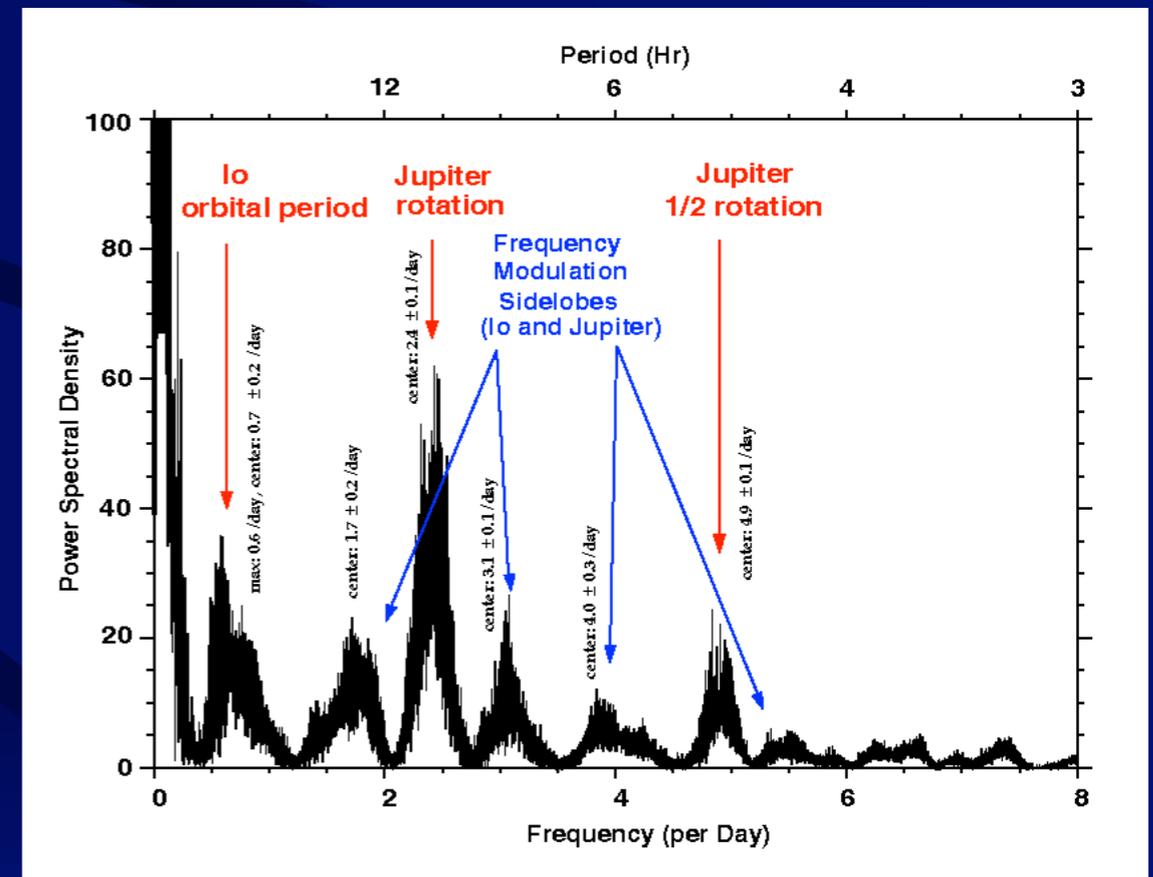


Electromagnetically Interacting Dust at Jupiter

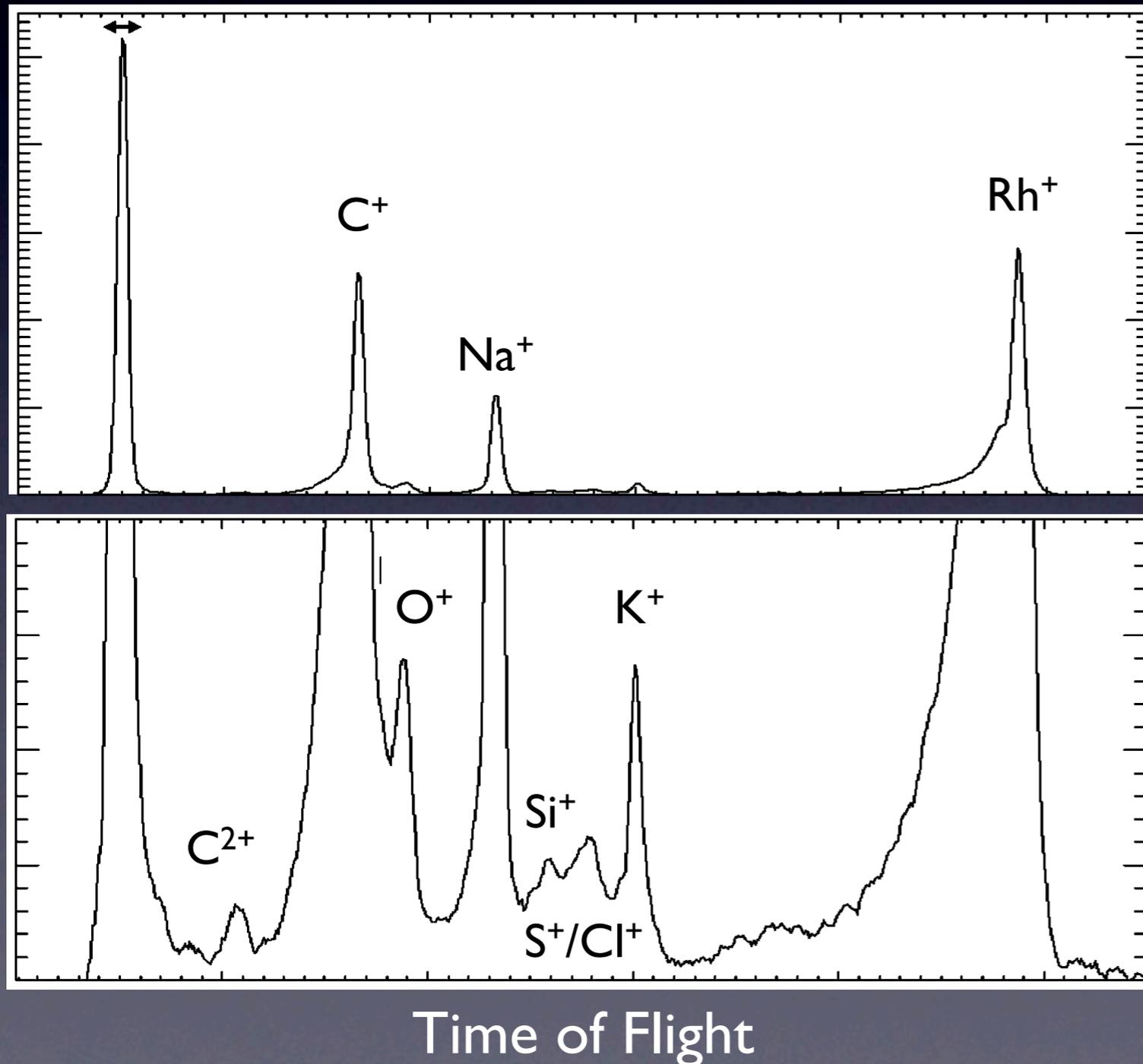
Dust impact rate correlated with Jupiter's 10h rotation period



Periodogram of Galileo data



Composition Of Io's Volcanic Matter



Io Ashes Mostly
NaCl Crystals

Postberg et al., Icarus, 2006

Cosmic Dust Analyser (CDA)

Dust detector on Cassini spacecraft:



- **dust mass/velocity:** impact ionisation detector
- **chemical composition:** time of flight mass spectrometer
- **dust charge/velocity/impact angle:** charge sensitive entrance grids
- **high rate detector (HRD)**

CDA measurement range

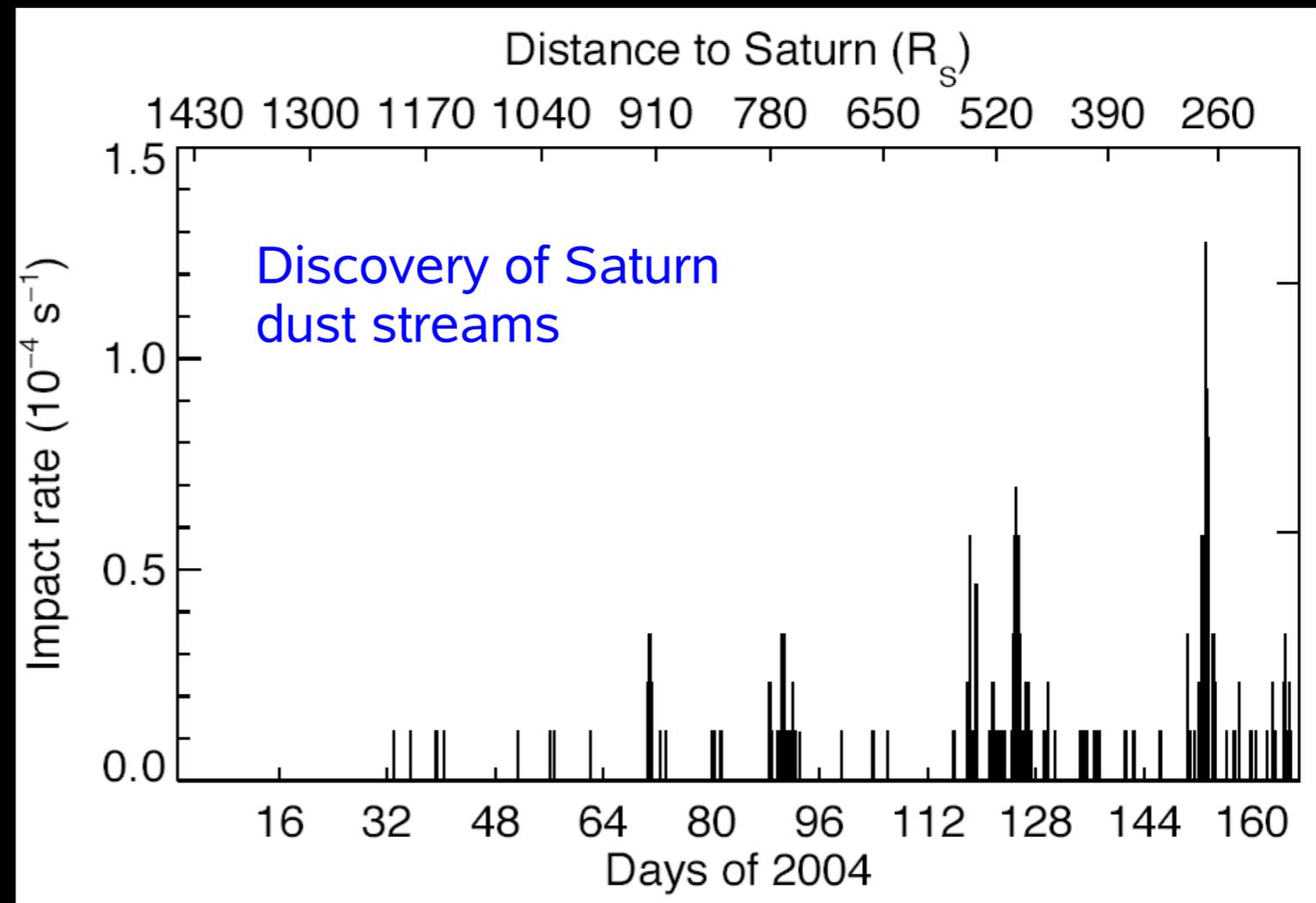
- Sensitive area: 0.1 m^2
- Dust speed: $1\text{-}100 \text{ km s}^{-1}$
- Dust mass: $10^{-15}\text{-}10^{-9} \text{ g (@}20 \text{ km s}^{-1}\text{)}$
- Dust charge: $10^{-15} - 10^{-13} \text{ C}$
- Dust composition: 20-50 mass resolution
- Impact counting rate: $1/\text{week}\text{-}10000/\text{s}$
1000 times more sensitive than optical measurements

CDA finds one particle within one km^3

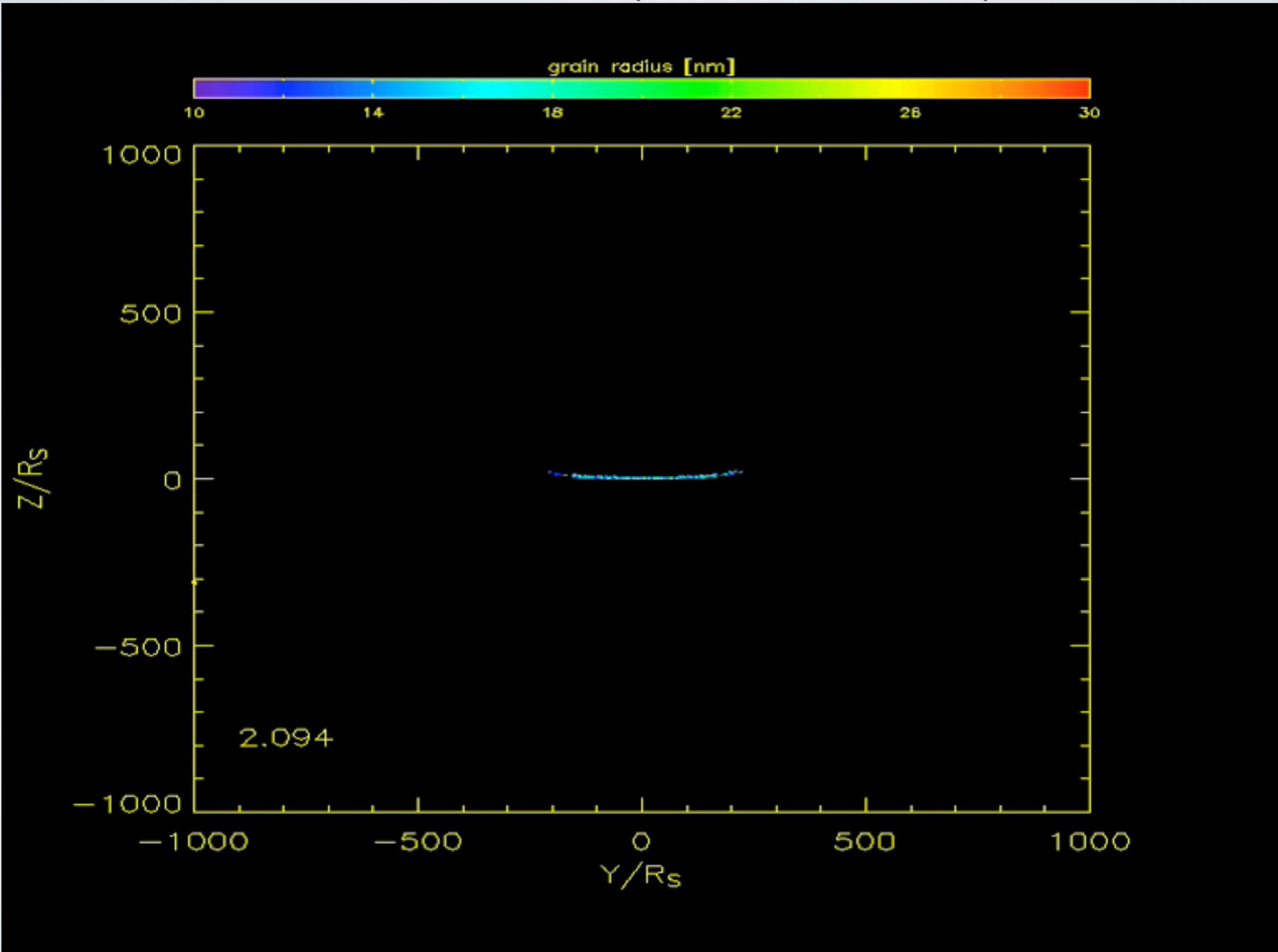


CDA Science Highlights I (Cruise)

- Streams of nano-dust from Saturn :
Discovery, composition and dynamics,
coupling between CIRs/CMEs and dust stream
dynamics (S. Kempf, Nature)
- Origin of particles
detected during the
approach to Saturn
is the A ring
- Composition of
these particles:
silicates

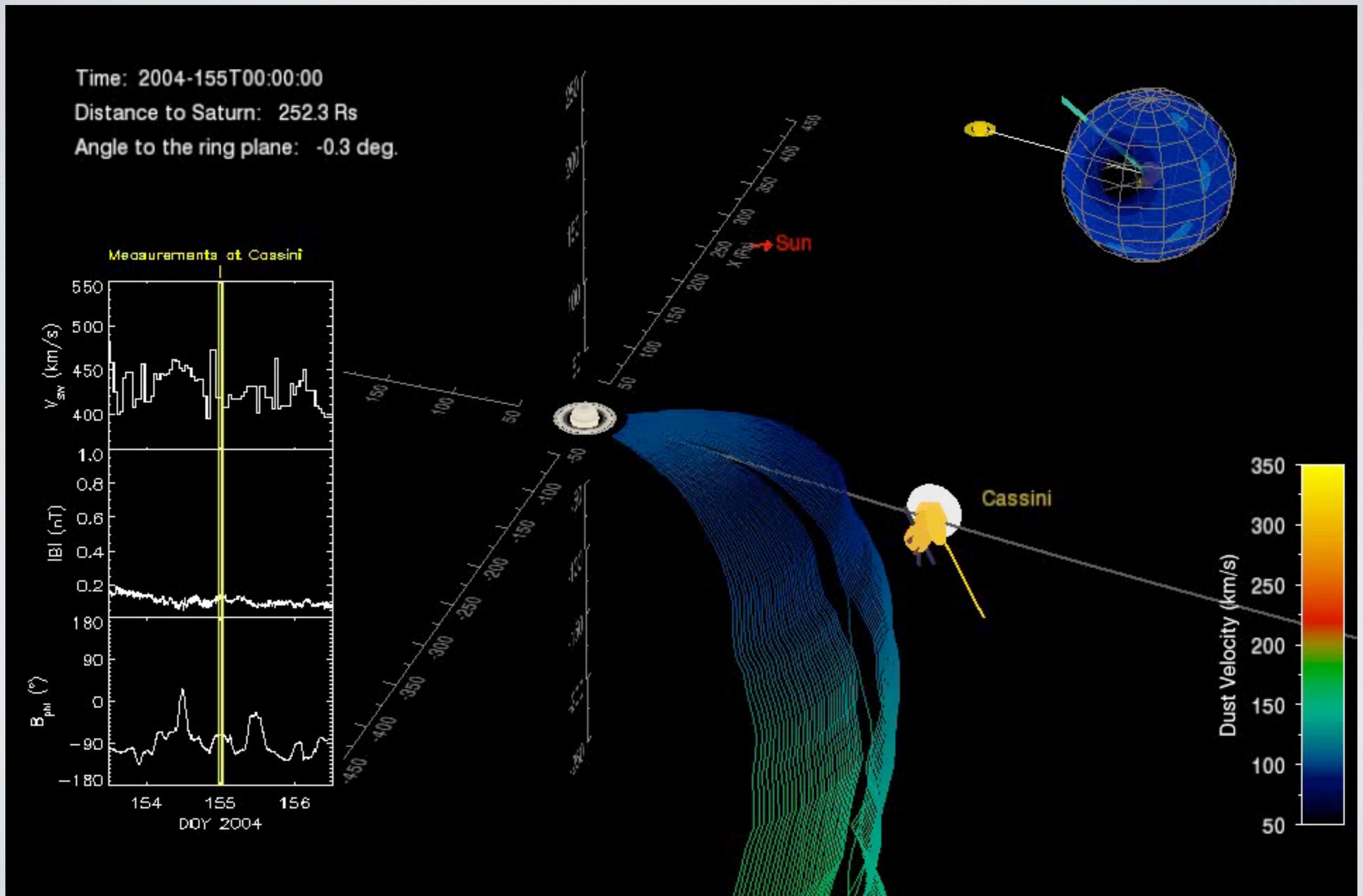


SIMULATION OF ESCAPING DUST STREAMS FROM SATURN (M. HORANYI)



DUST STREAM MODELING

S. Hsu



SATURN APPROACH

Enceladus

Mimas

Tethys



PHOEBE

Flyby : 2004, June 11
ice-rich moon covered
with dark material
bright crater edges

190 m/pixel



PHOEBE CRATER

80 M/PIXEL



A COMET LIKE OBJECT



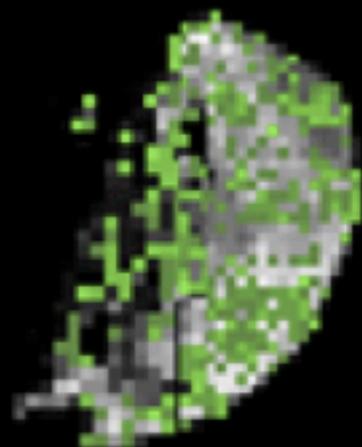
Phoebe
Imaging
Mosaic



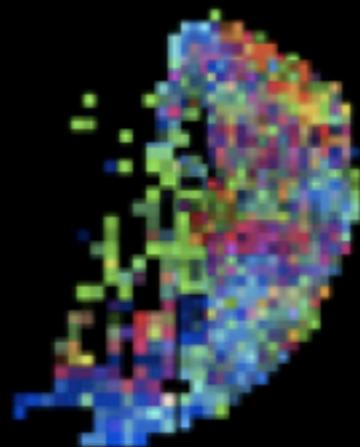
Infrared
Reflectance



Carbon Dioxide
Locations



Unidentified
Material



Ferrous Iron



Unidentified
Material



Water Ice



CO₂ indicator
for Kuiper Belt
origin

retrograde
orbit

ORBIT INSERTION



Saturn orbit insertion 2004-183

SOI Burn
01:12 - 02:49-54

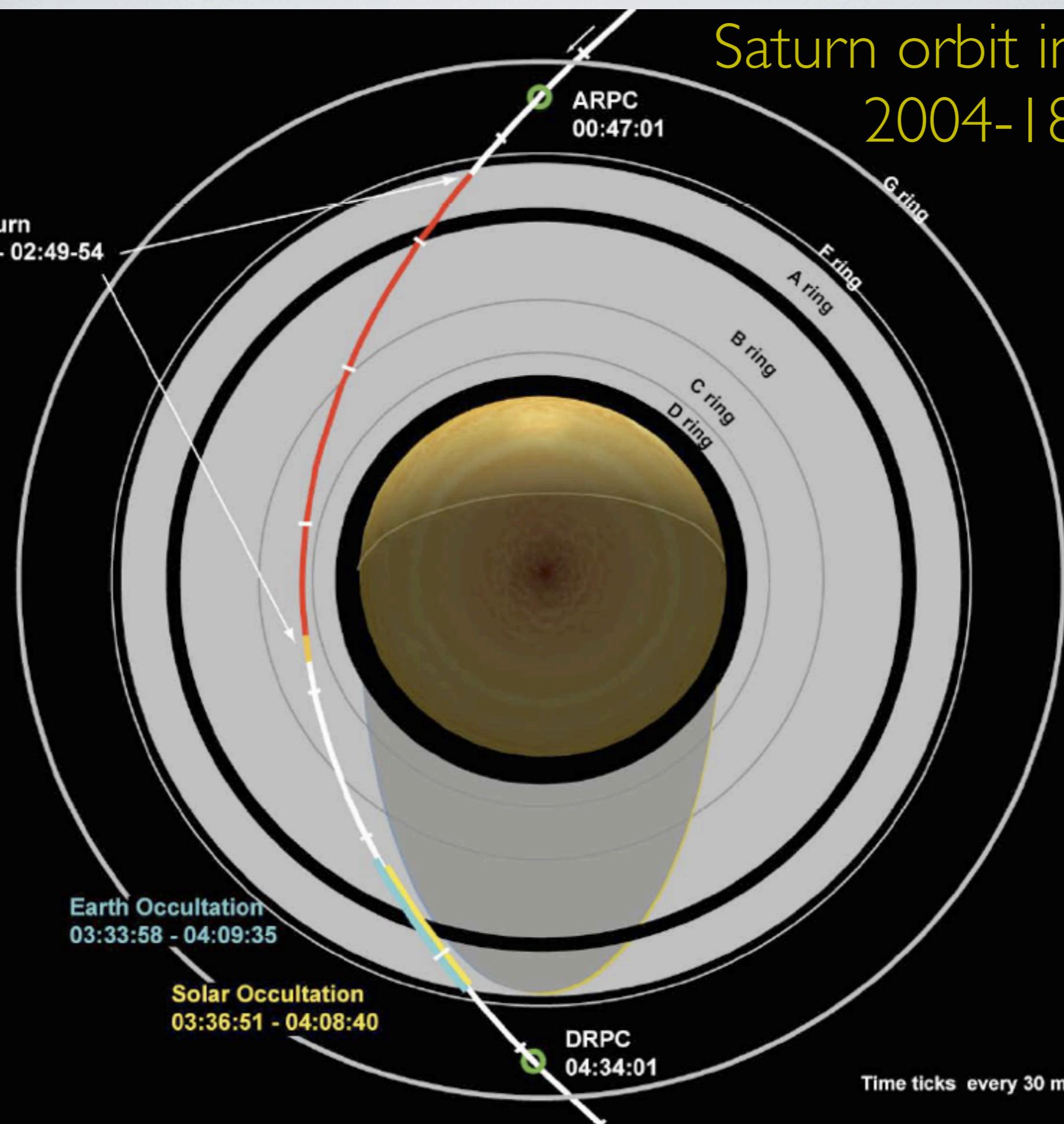
ARPC
00:47:01

Earth Occultation
03:33:58 - 04:09:35

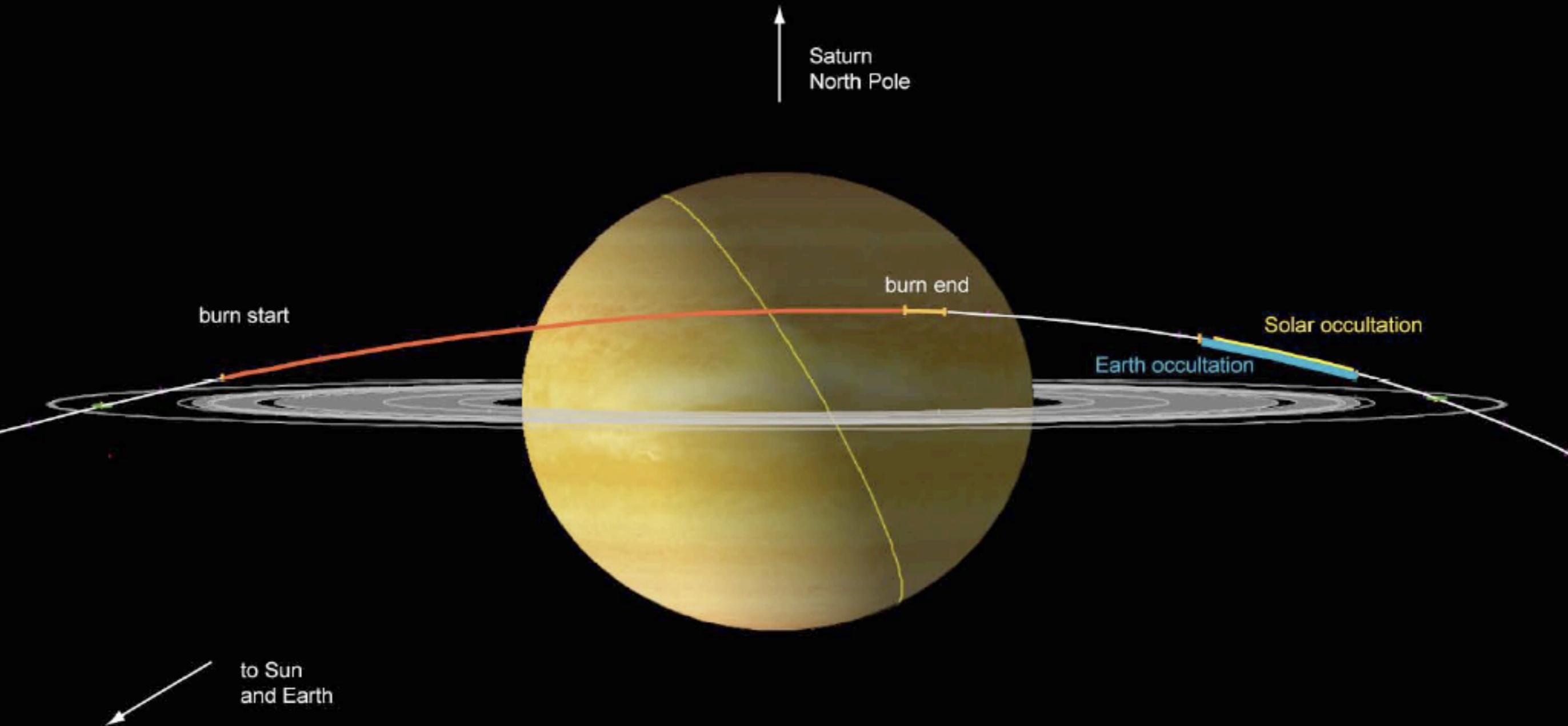
Solar Occultation
03:36:51 - 04:08:40

DRPC
04:34:01

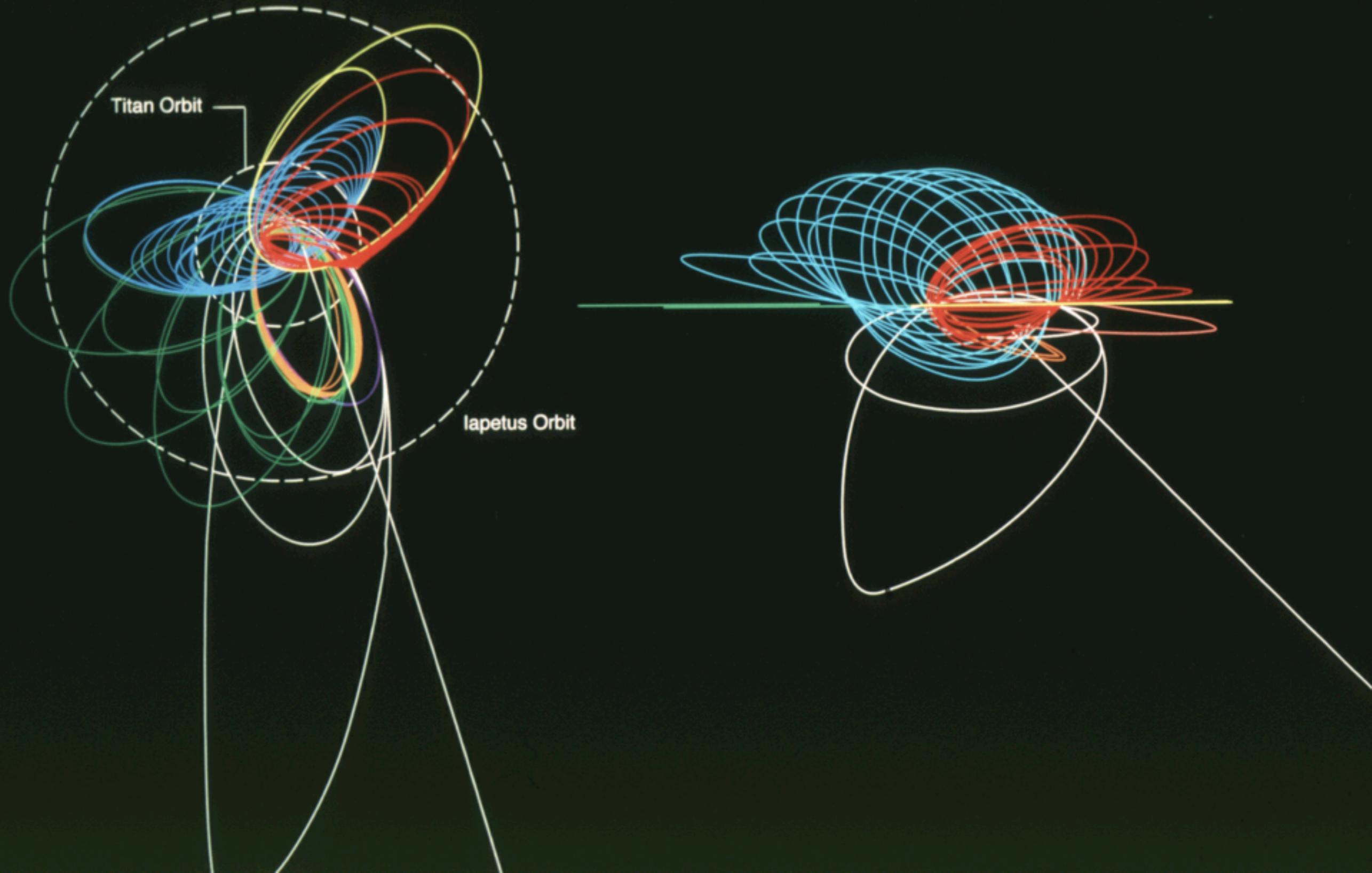
Time ticks every 30 minutes



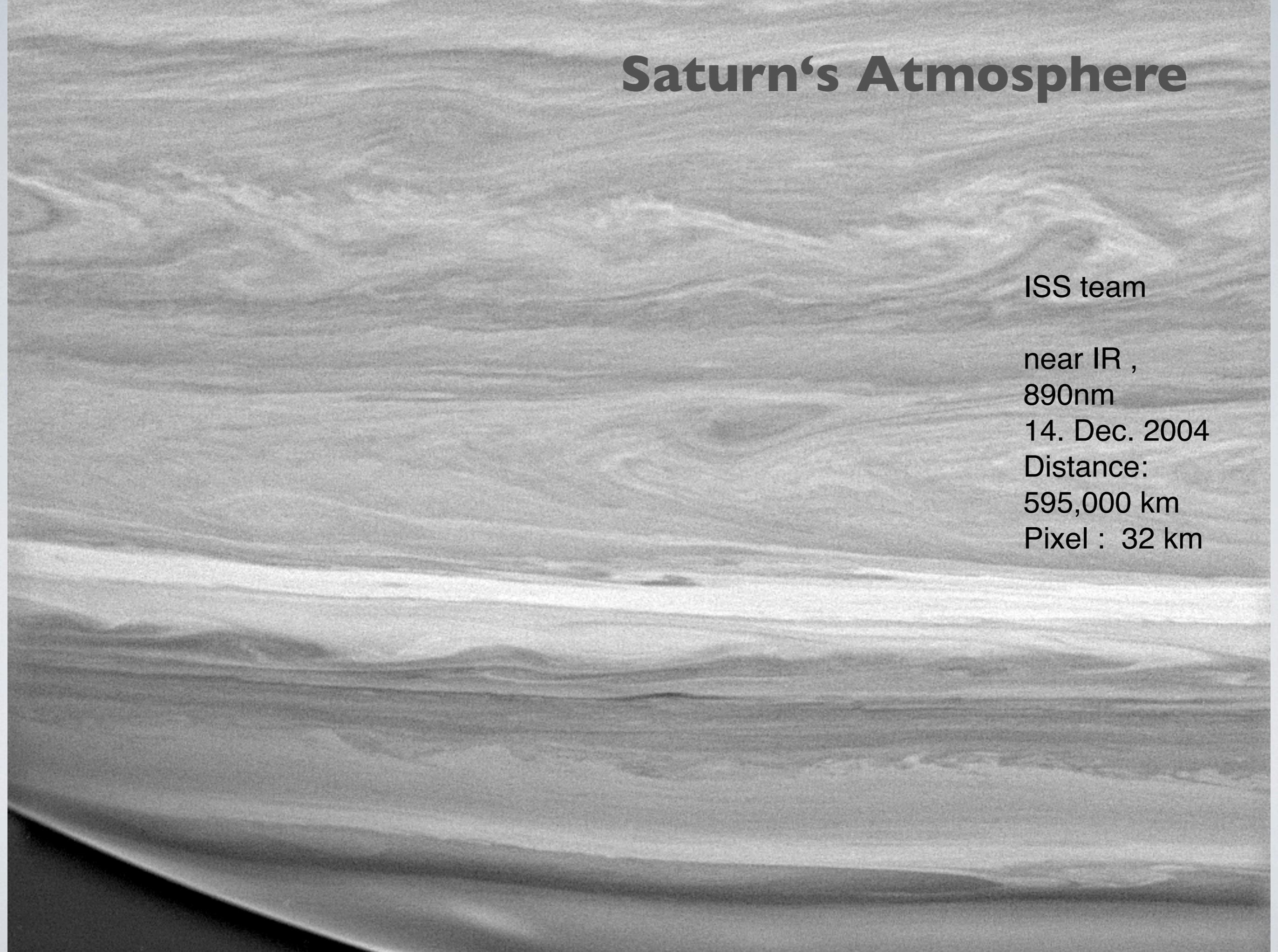
SATURN ORBIT INSERTION



Saturn System Tour Trajectory



Saturn's Atmosphere

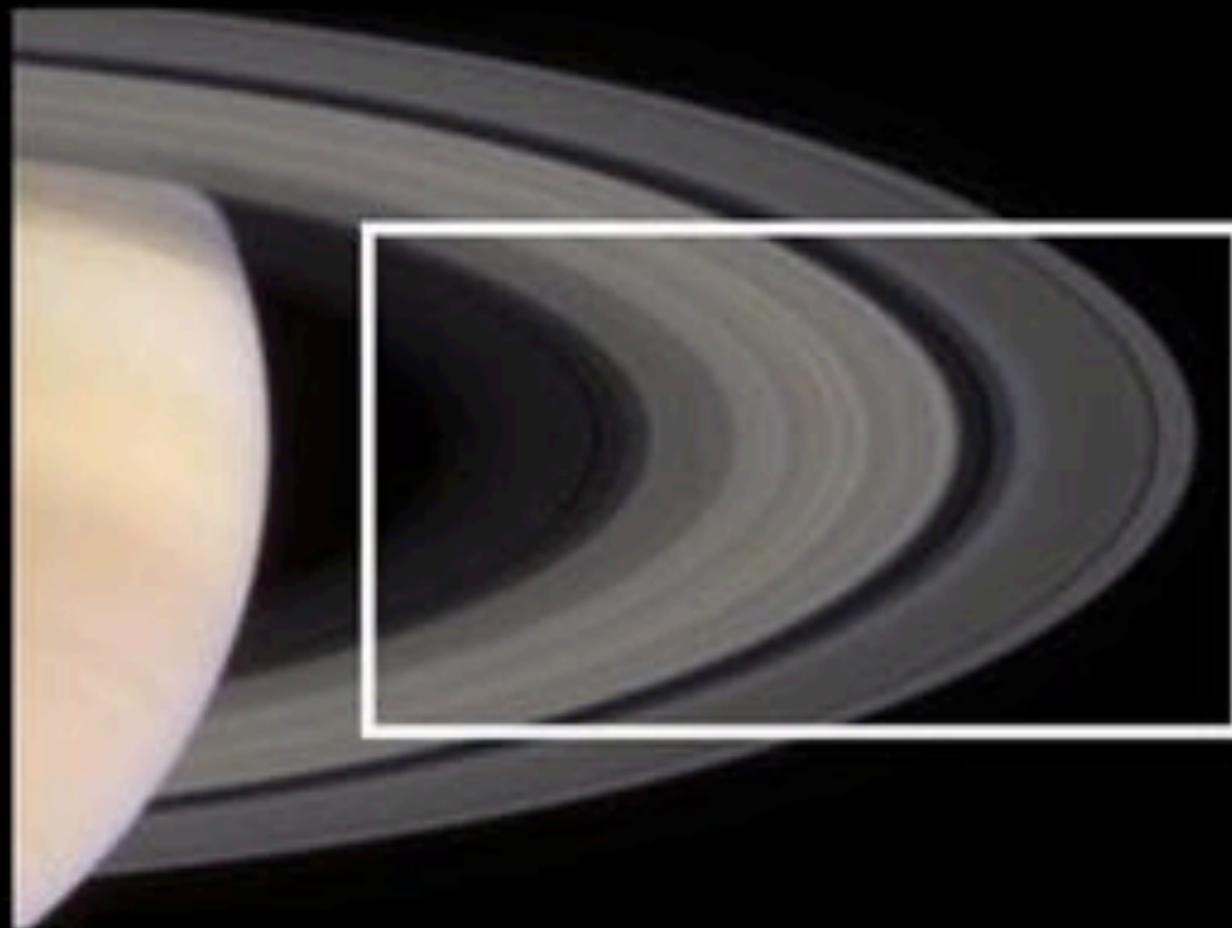
A grayscale image of Saturn's atmosphere, showing distinct horizontal cloud bands and a bright equatorial region. The image is oriented vertically, with the top of the planet at the top of the frame. The atmosphere is characterized by alternating light and dark bands, indicating different cloud layers and chemical compositions. A prominent bright band is visible near the equator, likely composed of ammonia ice clouds. The overall appearance is that of a complex, multi-layered atmosphere.

ISS team

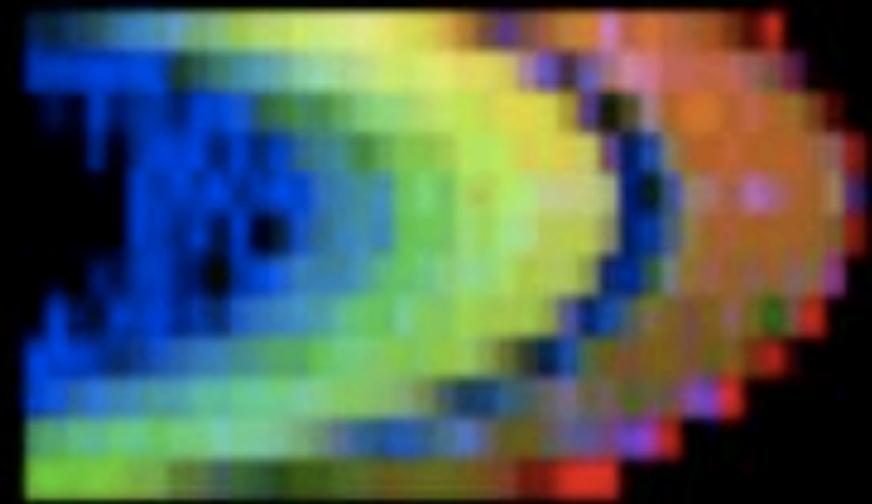
near IR ,
890nm
14. Dec. 2004
Distance:
595,000 km
Pixel : 32 km

SIZE DISTRIBUTION OF RING PARTICLES

Cassini Visual and Infrared Mapping Spectrometer



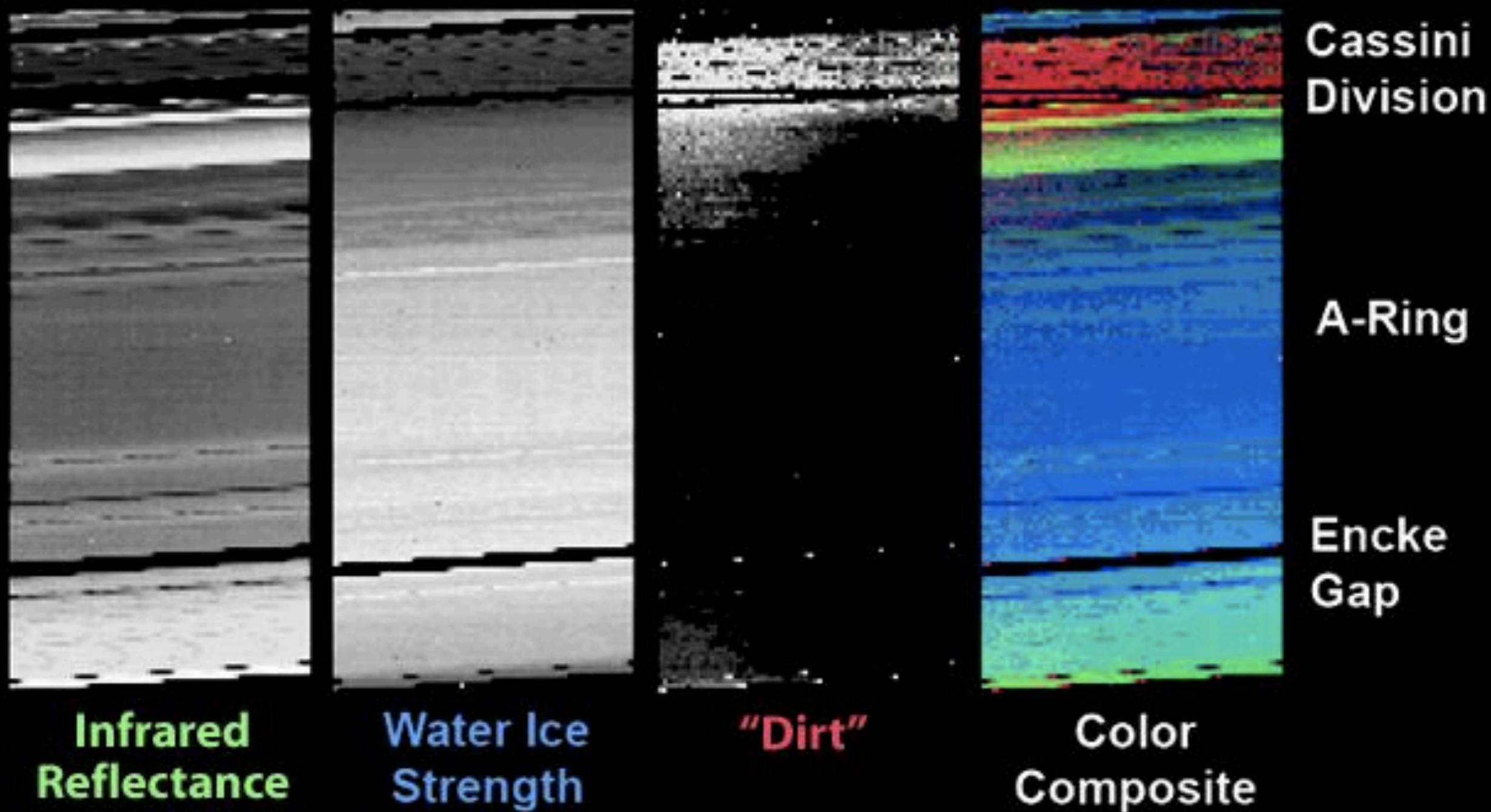
grain-size composite

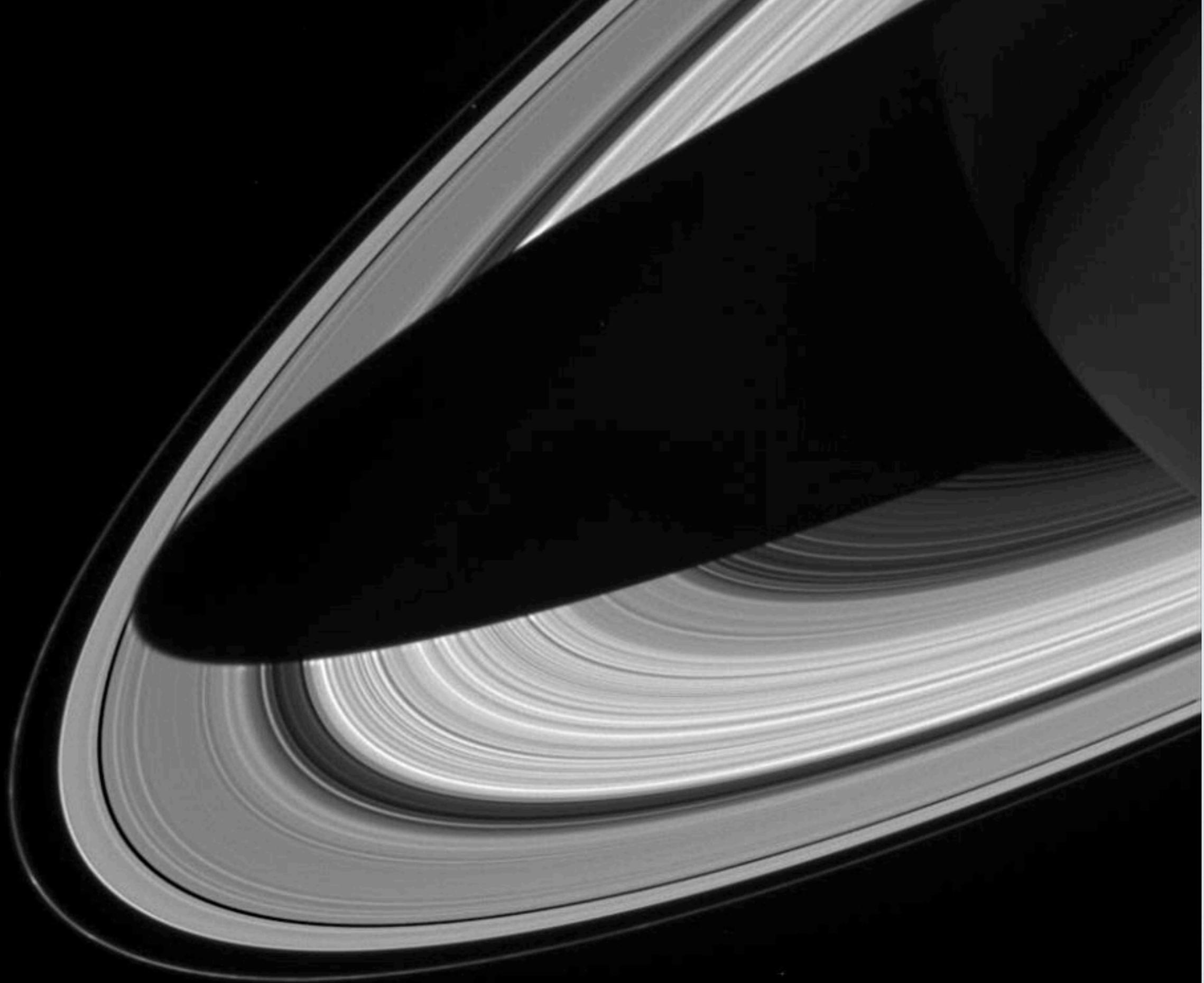


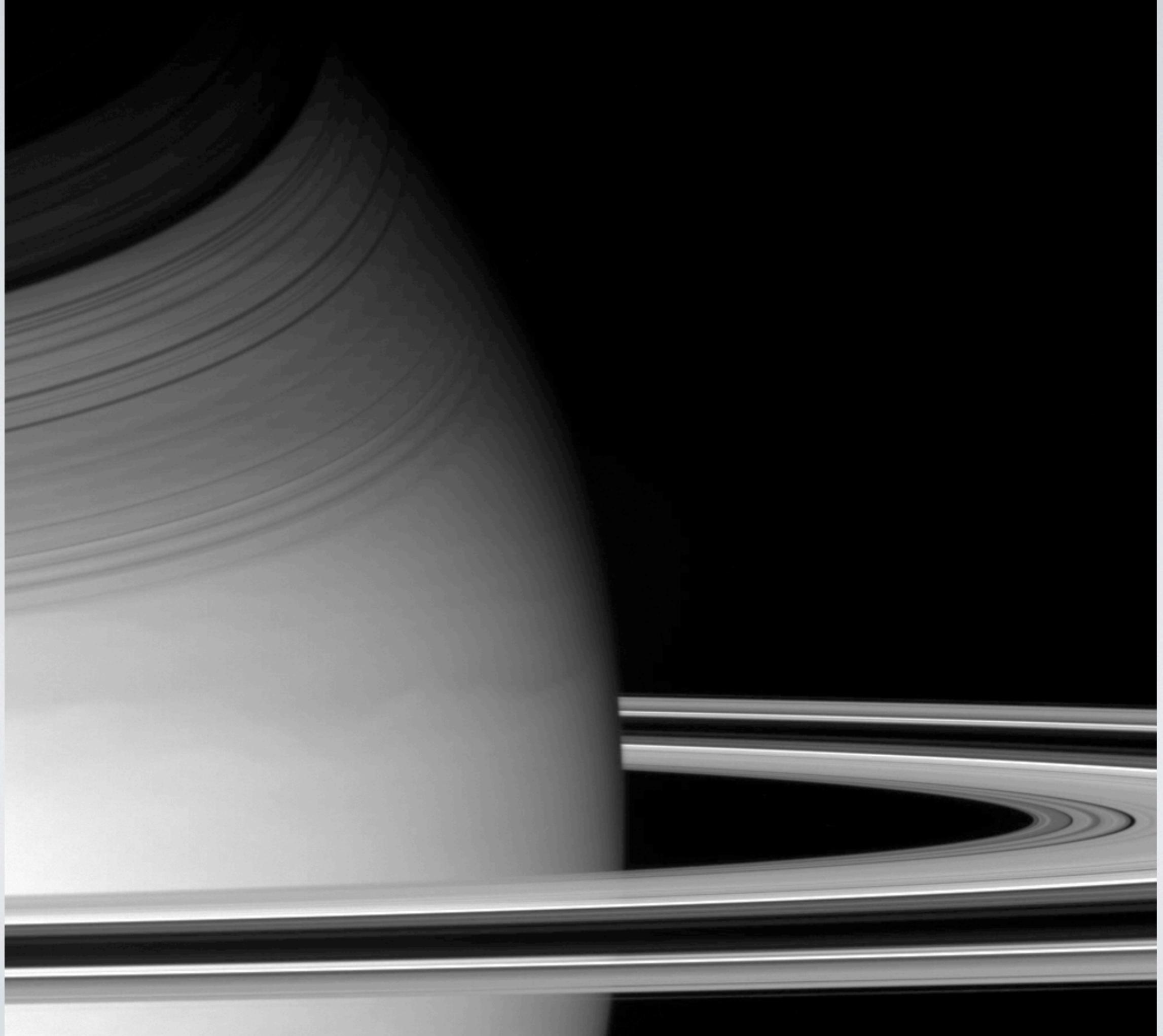
small  large

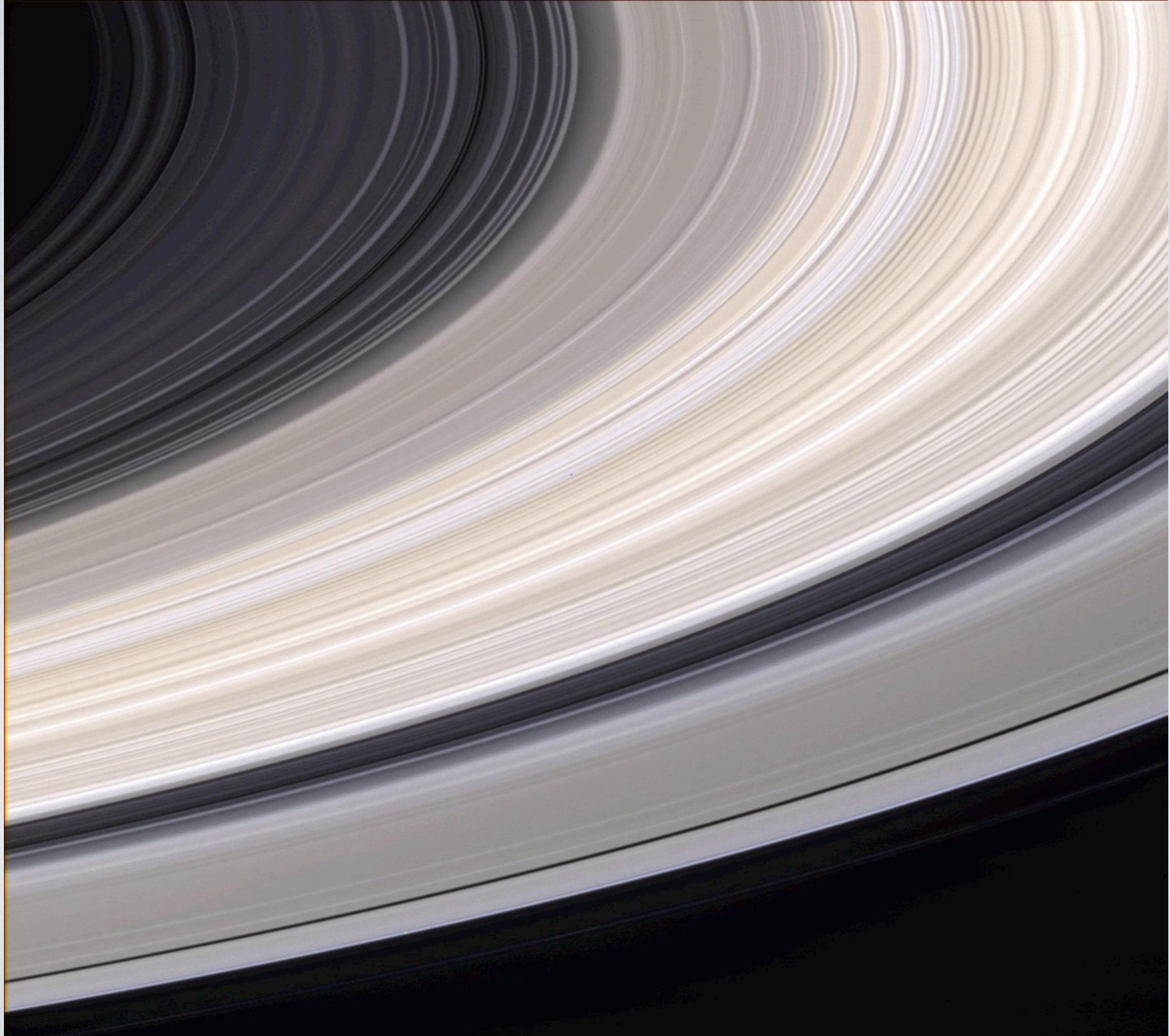
DIRTY RINGS

inside

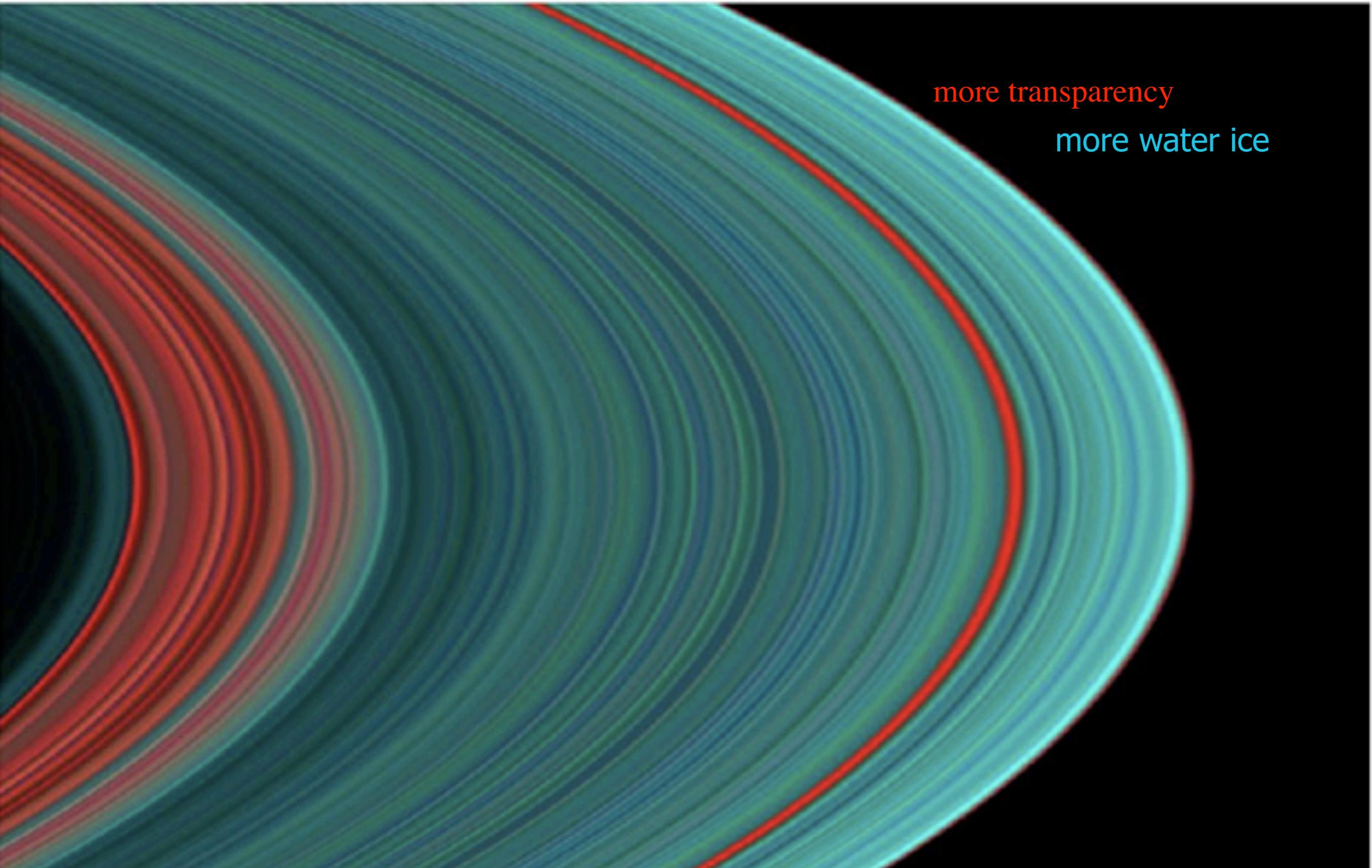


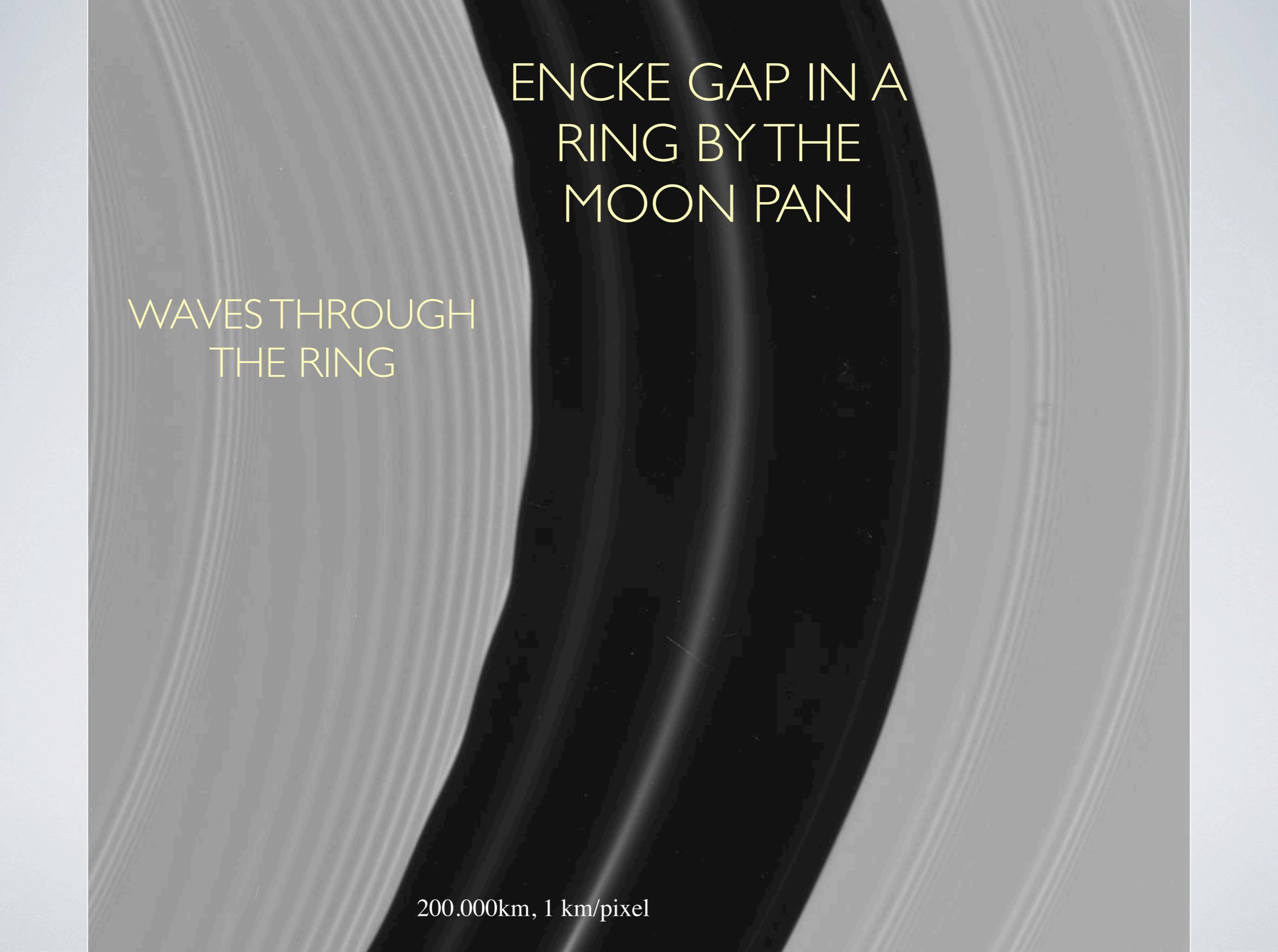






RINGS IN THE UV





ENCKE GAP IN A
RING BY THE
MOON PAN

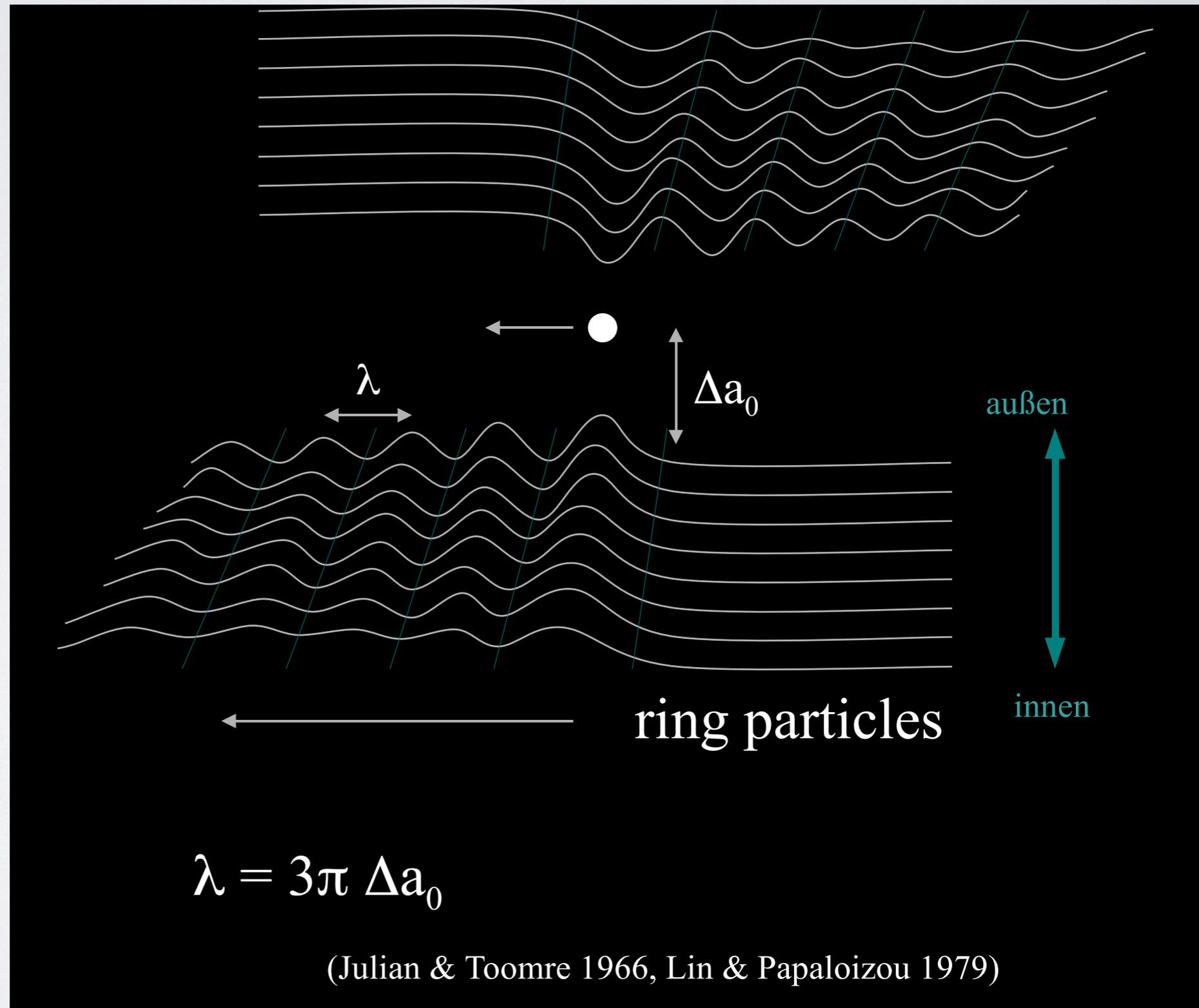
WAVES THROUGH
THE RING

200.000km, 1 km/pixel

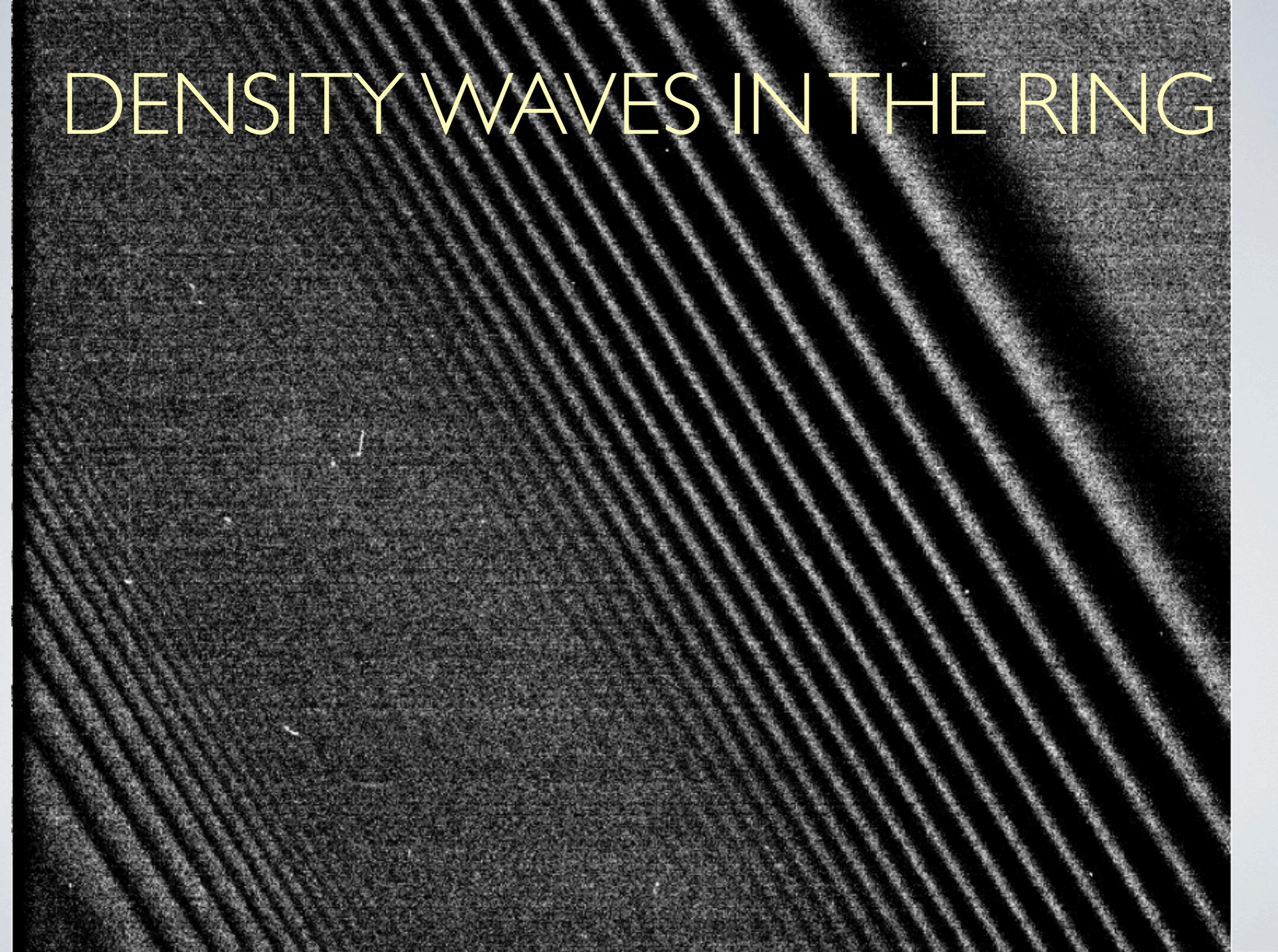
MOON - RING INTERACTION

moon causes
gap and changes
eccentricity
of ring particles

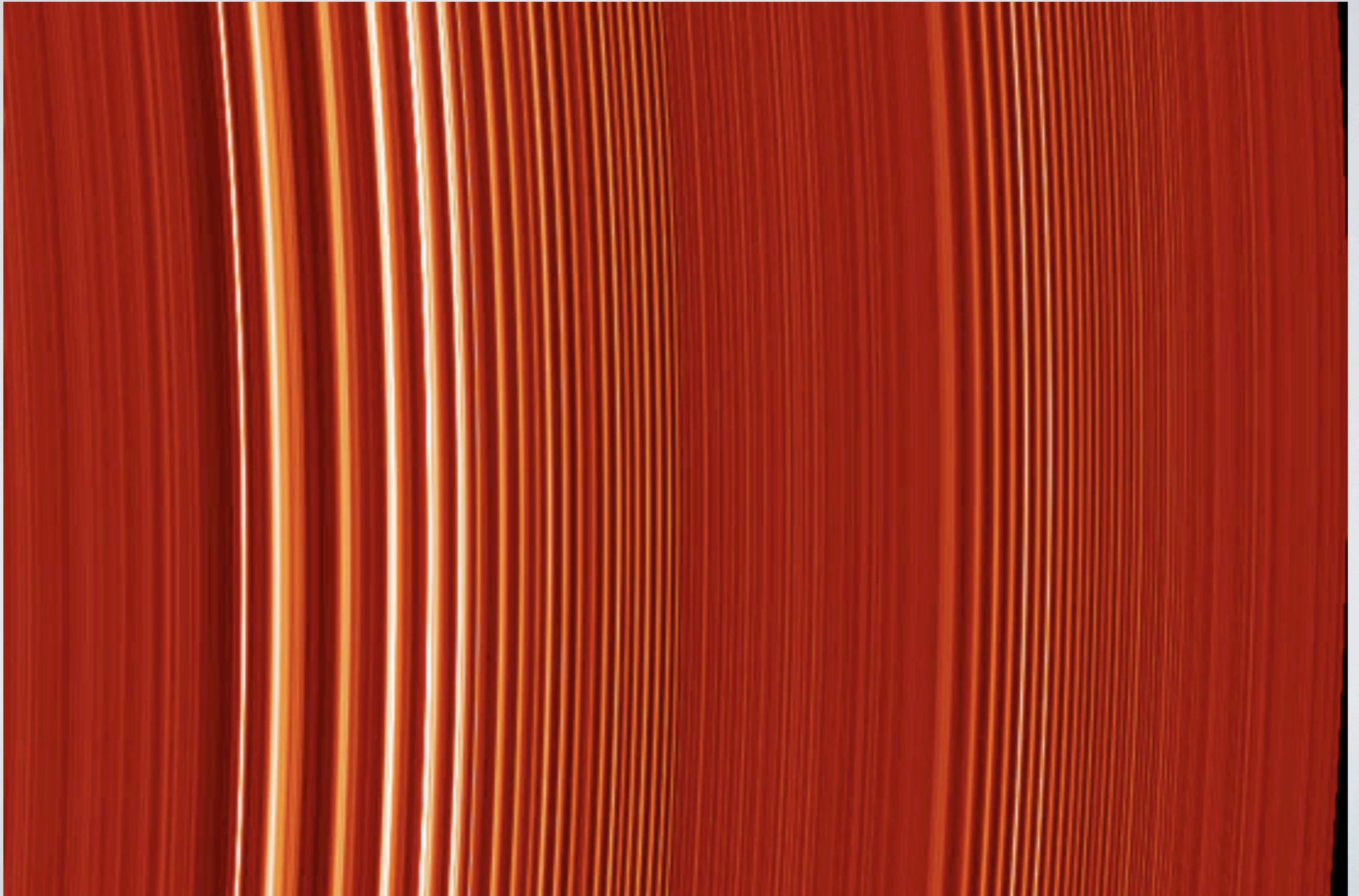
calculation/
discovery of
small embedded
moons by
analysing
ring waves



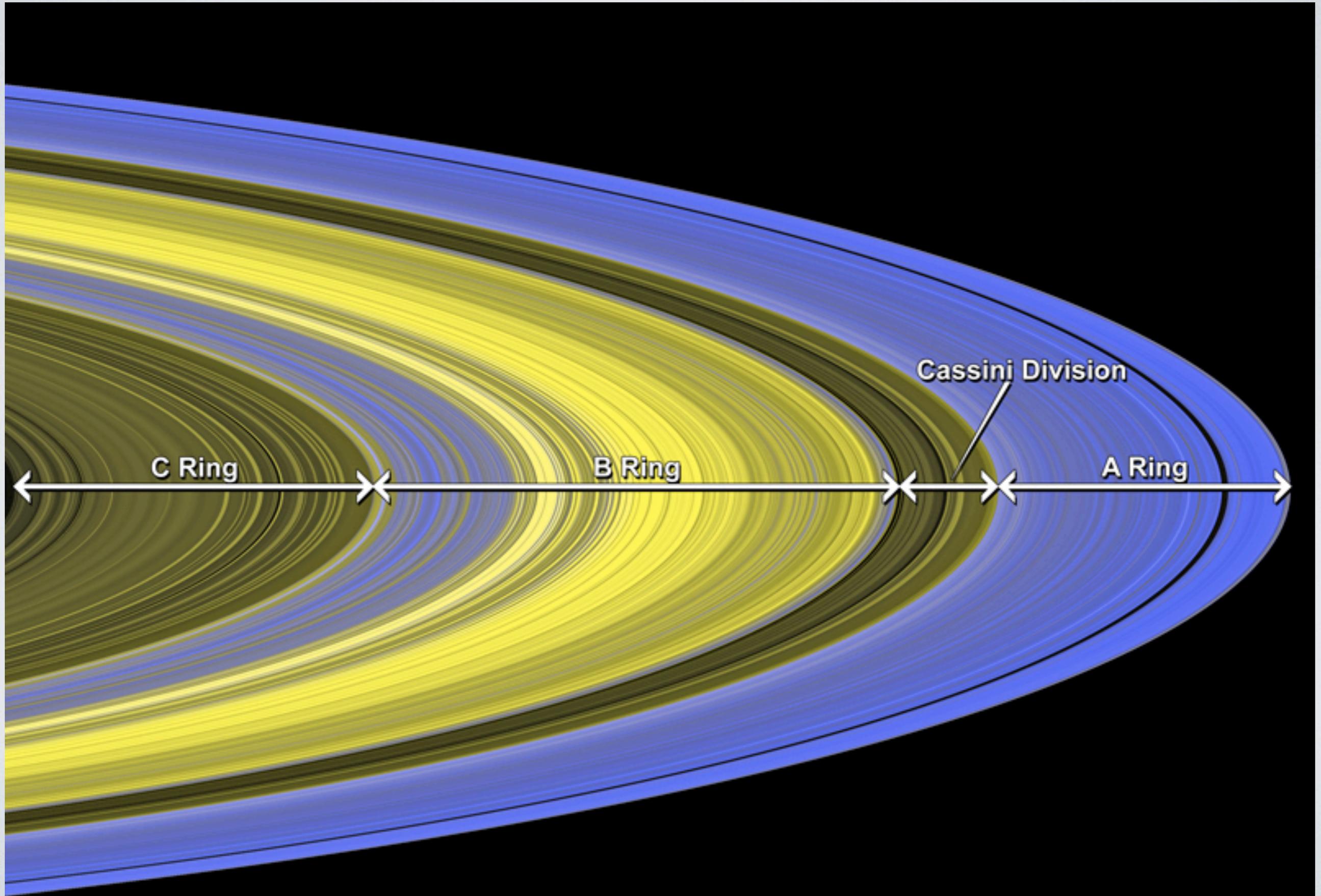
DENSITY WAVES IN THE RING



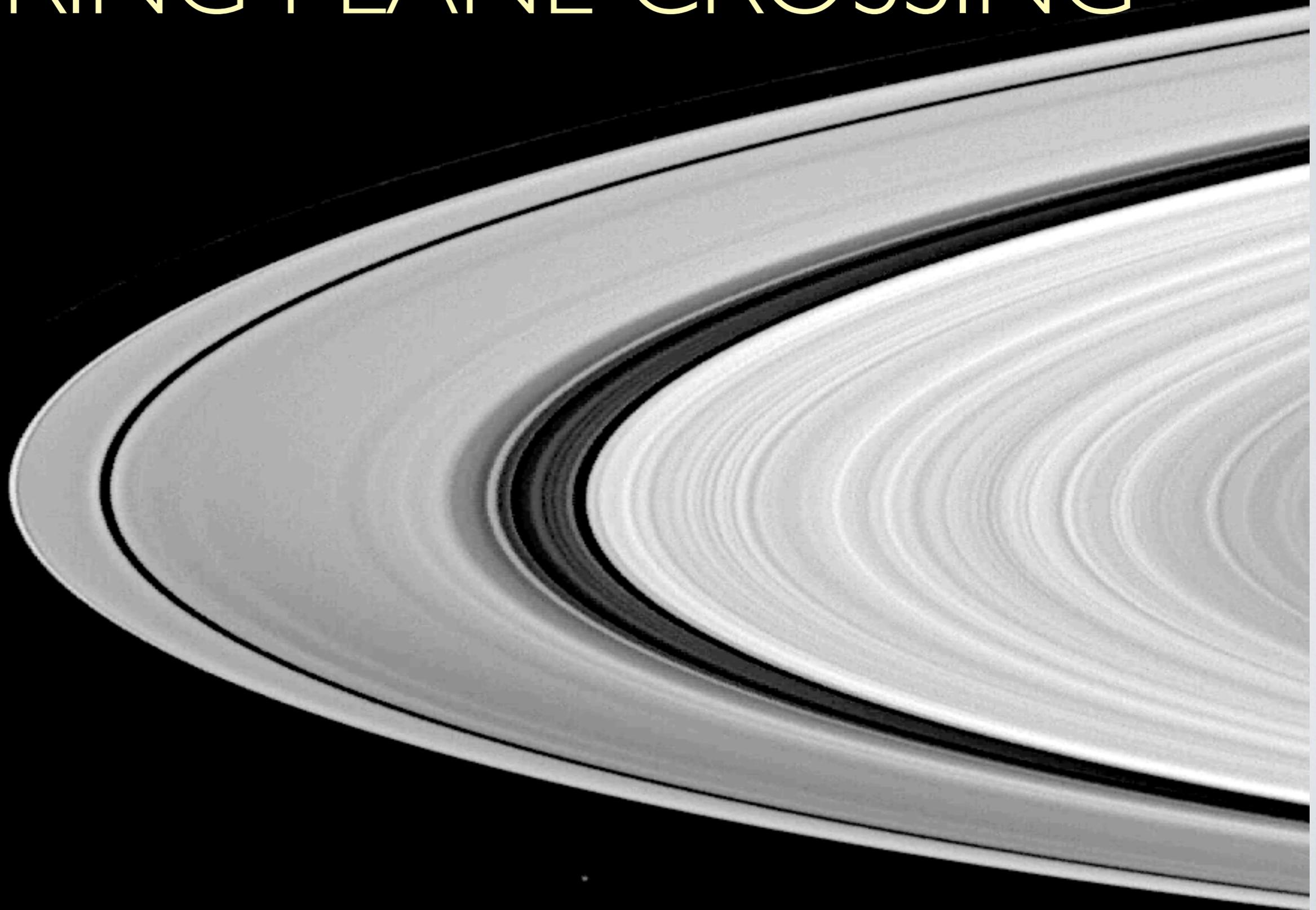
WAVES IN THE UV

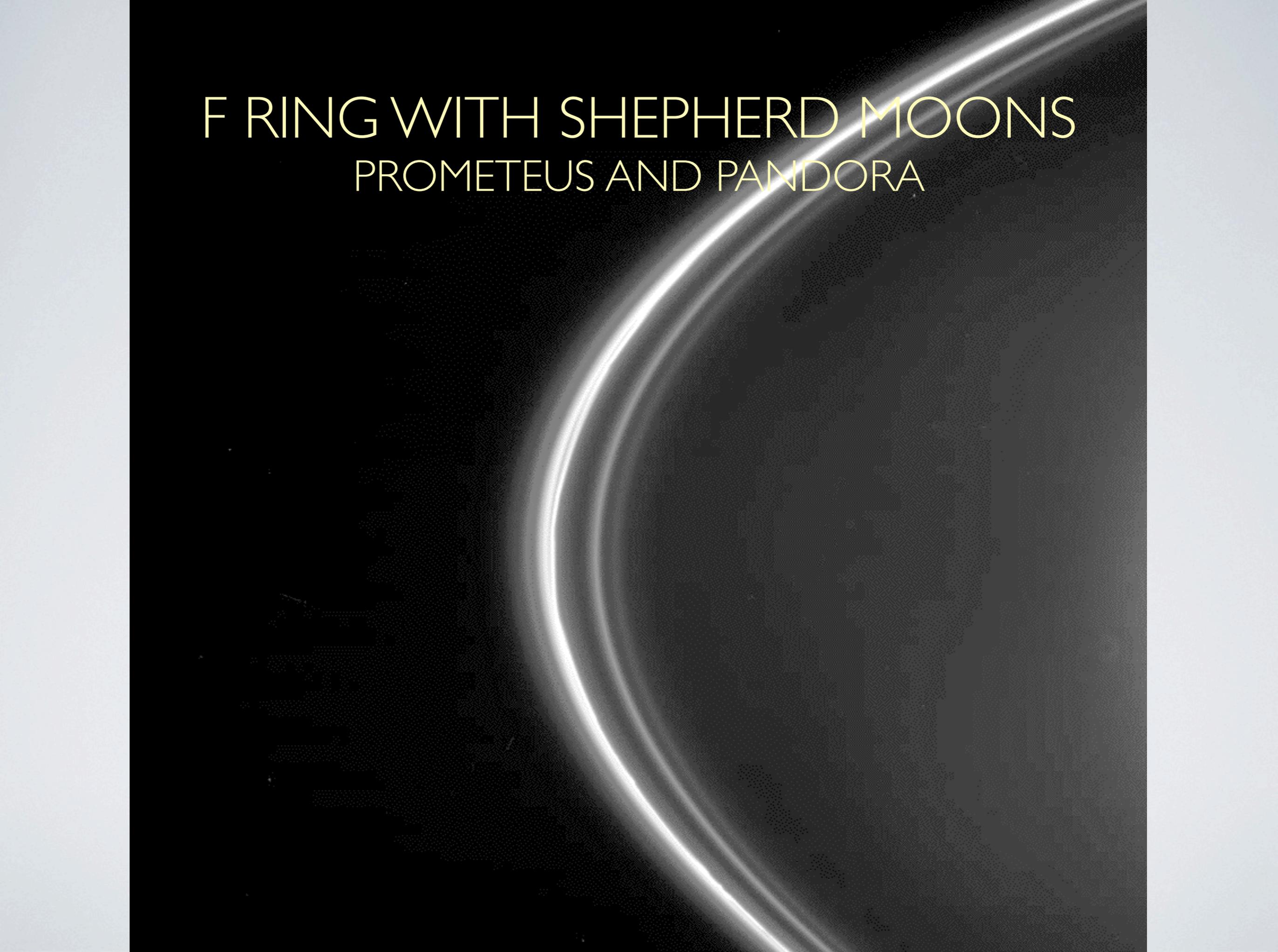


UV STAR OCCULTATION



RING PLANE CROSSING

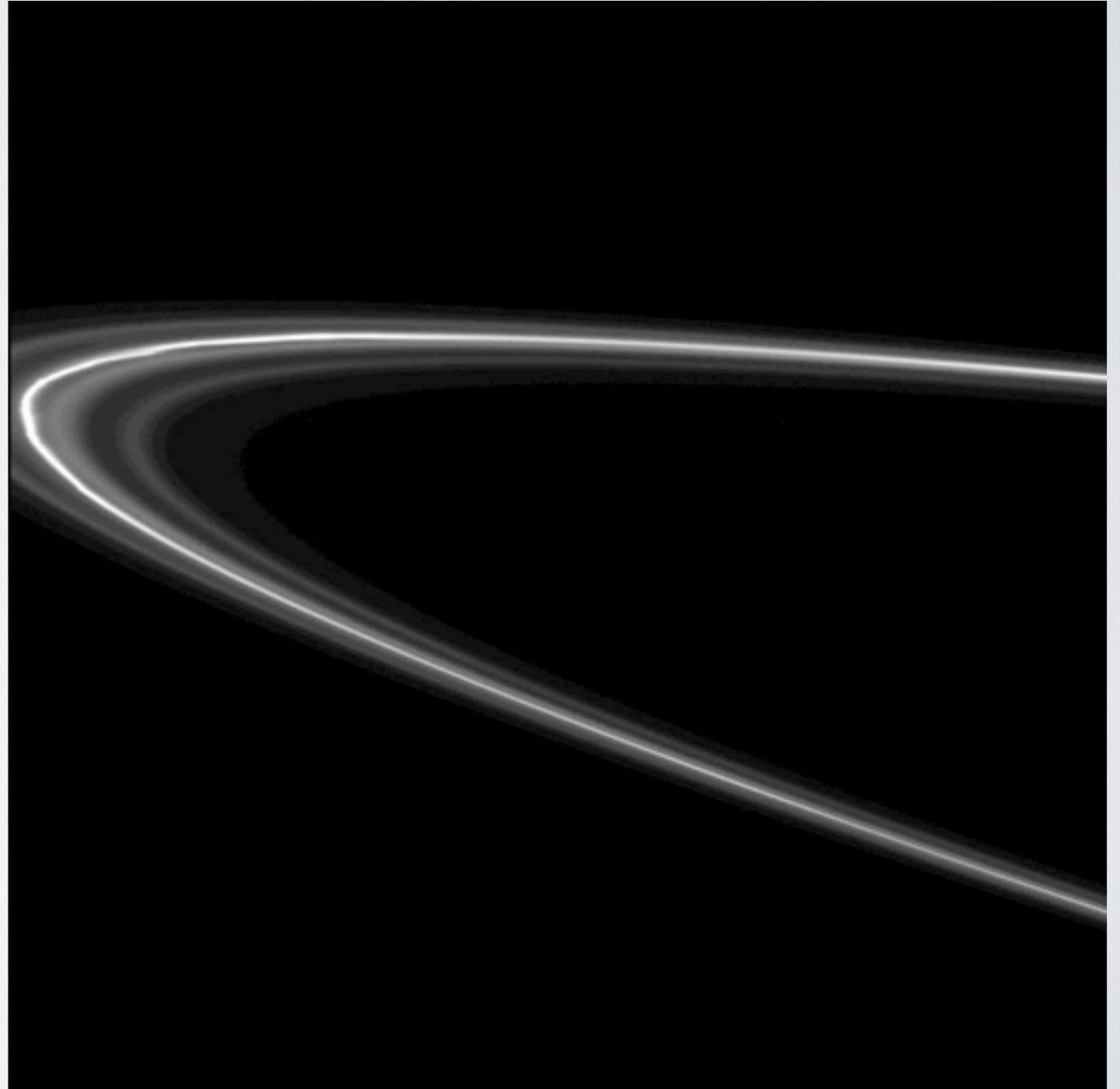
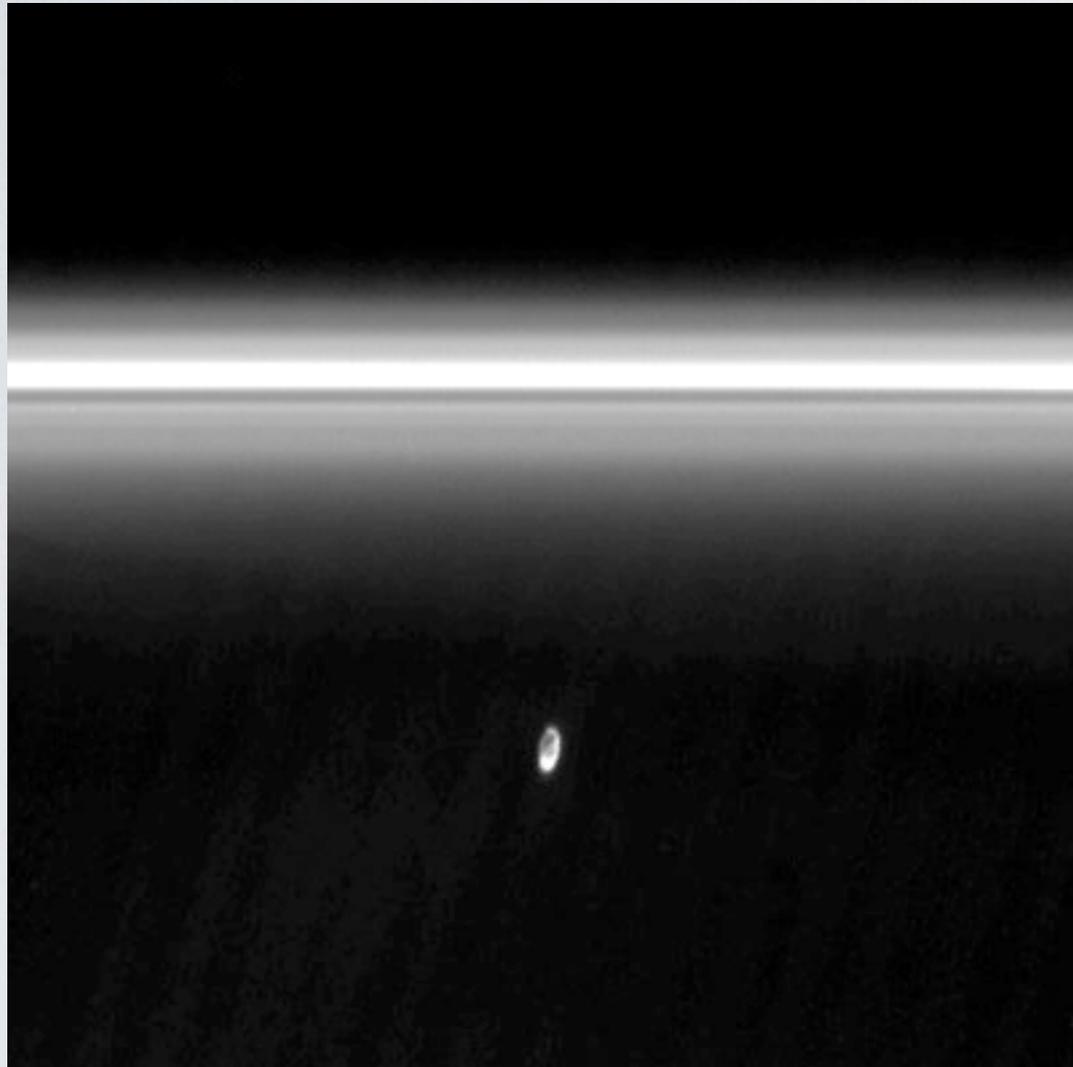


A black and white photograph of Saturn's rings, showing the bright F ring and the shepherd moons Prometheus and Pandora. The rings are curved, and the moons are visible as small dark spots near the ring edges.

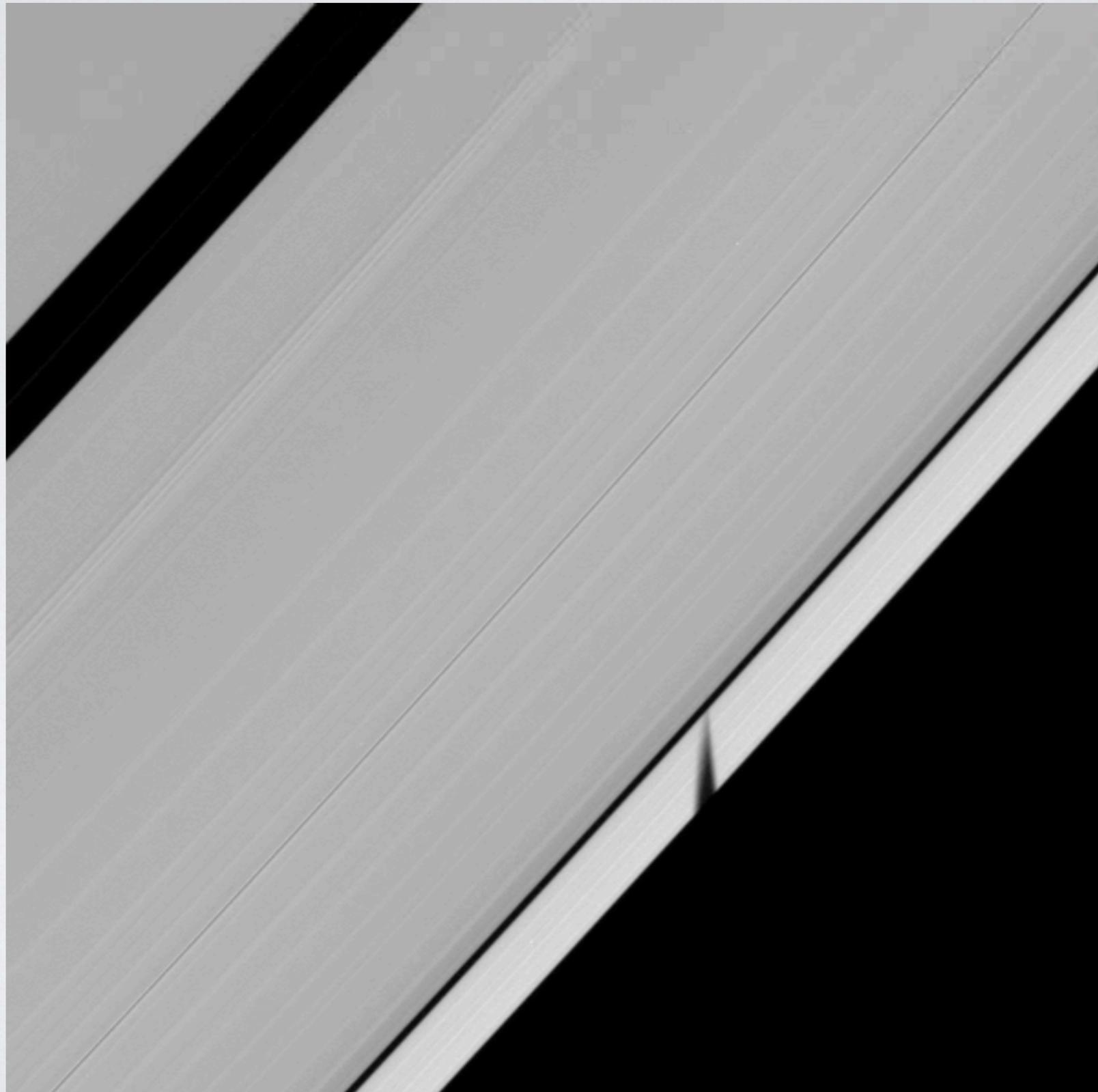
F RING WITH SHEPHERD MOONS PROMETEUS AND PANDORA

F RING

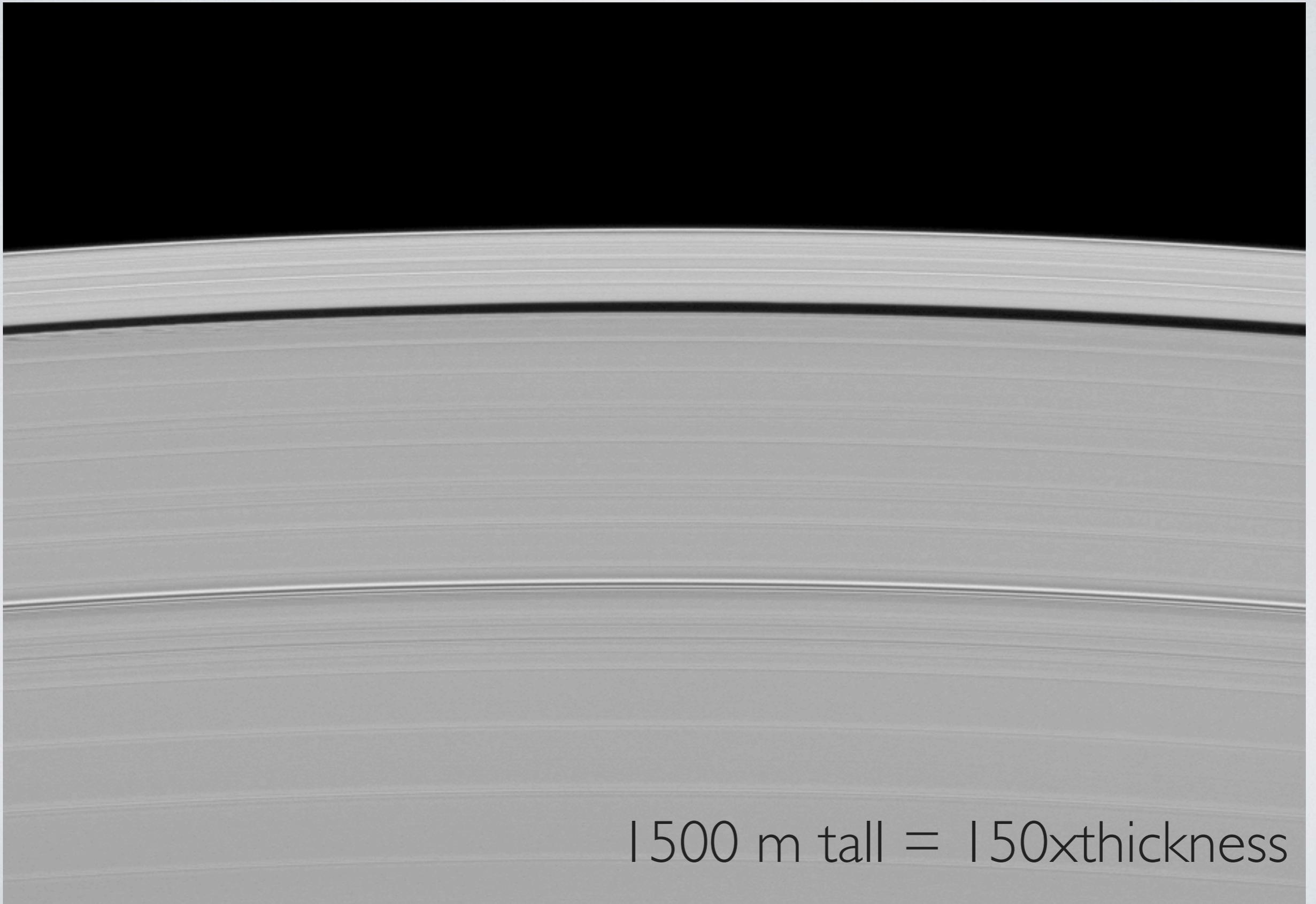
SHEPHERD MOON PROMETHEUS (102 KM)



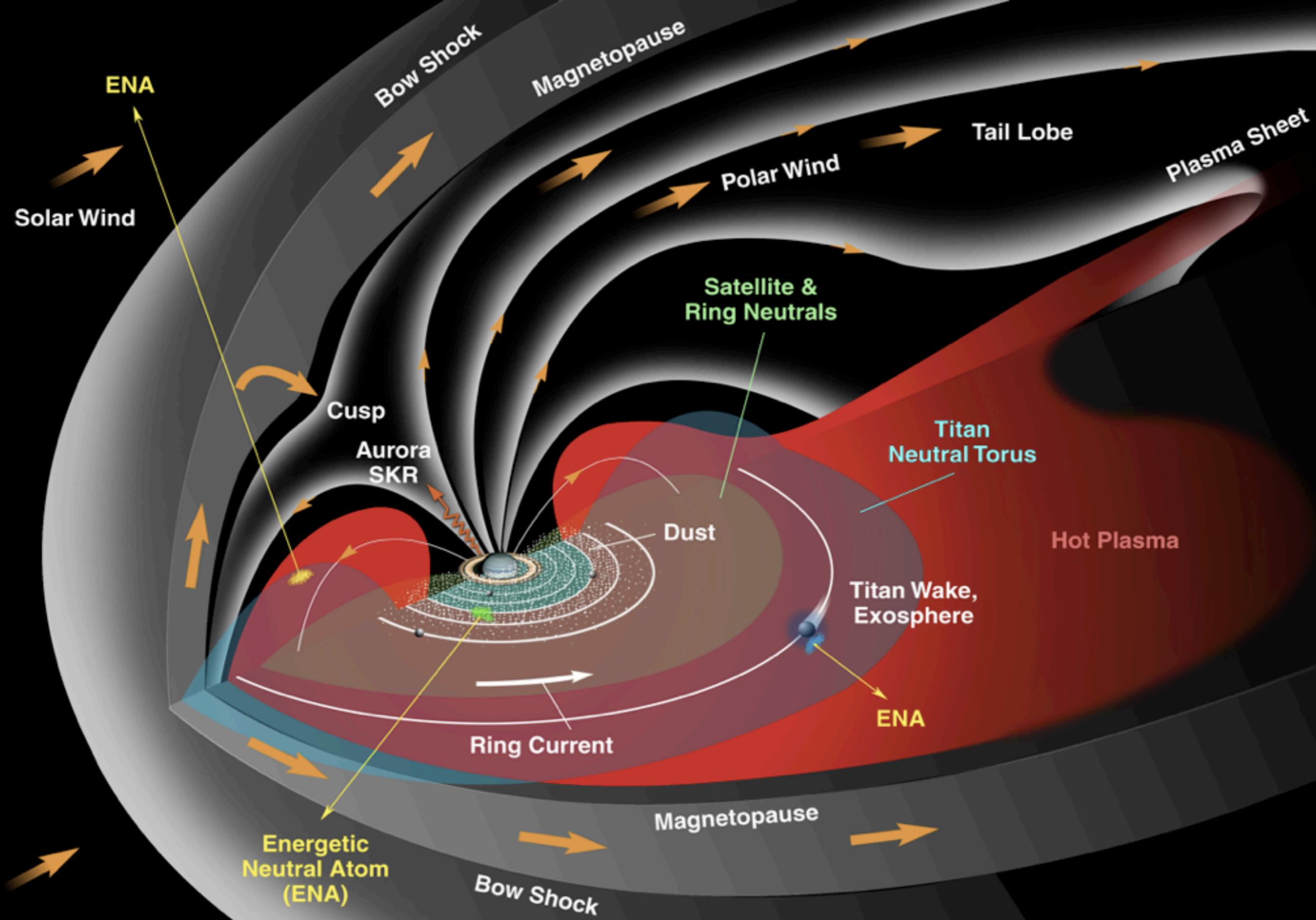
SHADOW OF EPIMETHEUS



MOON DAPHNIS (8 KM) ON INCLINED ORBIT WITHIN
THE 42-KILOMETER WIDE KEELER GAP (A RING)



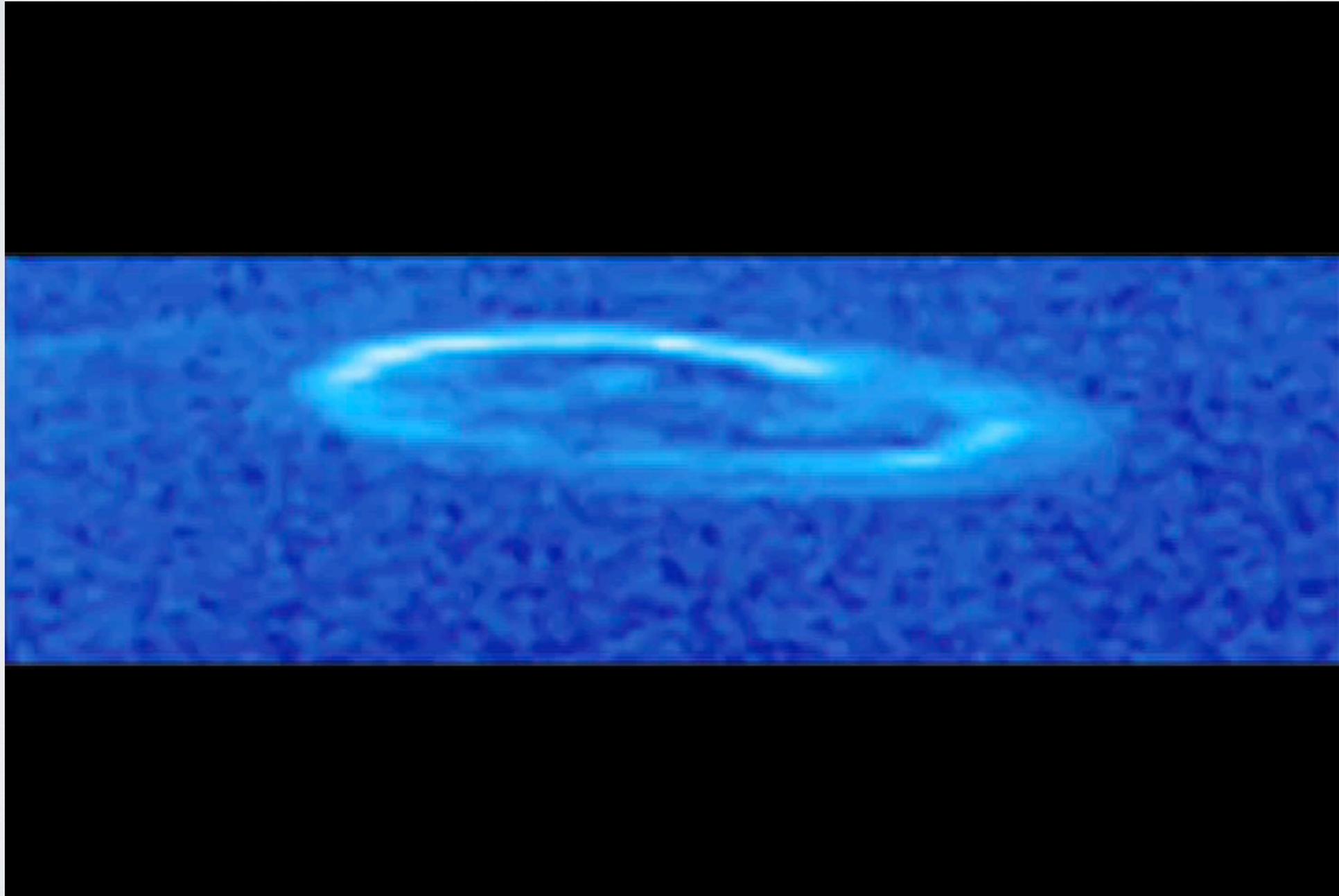
1500 m tall = 150xthickness



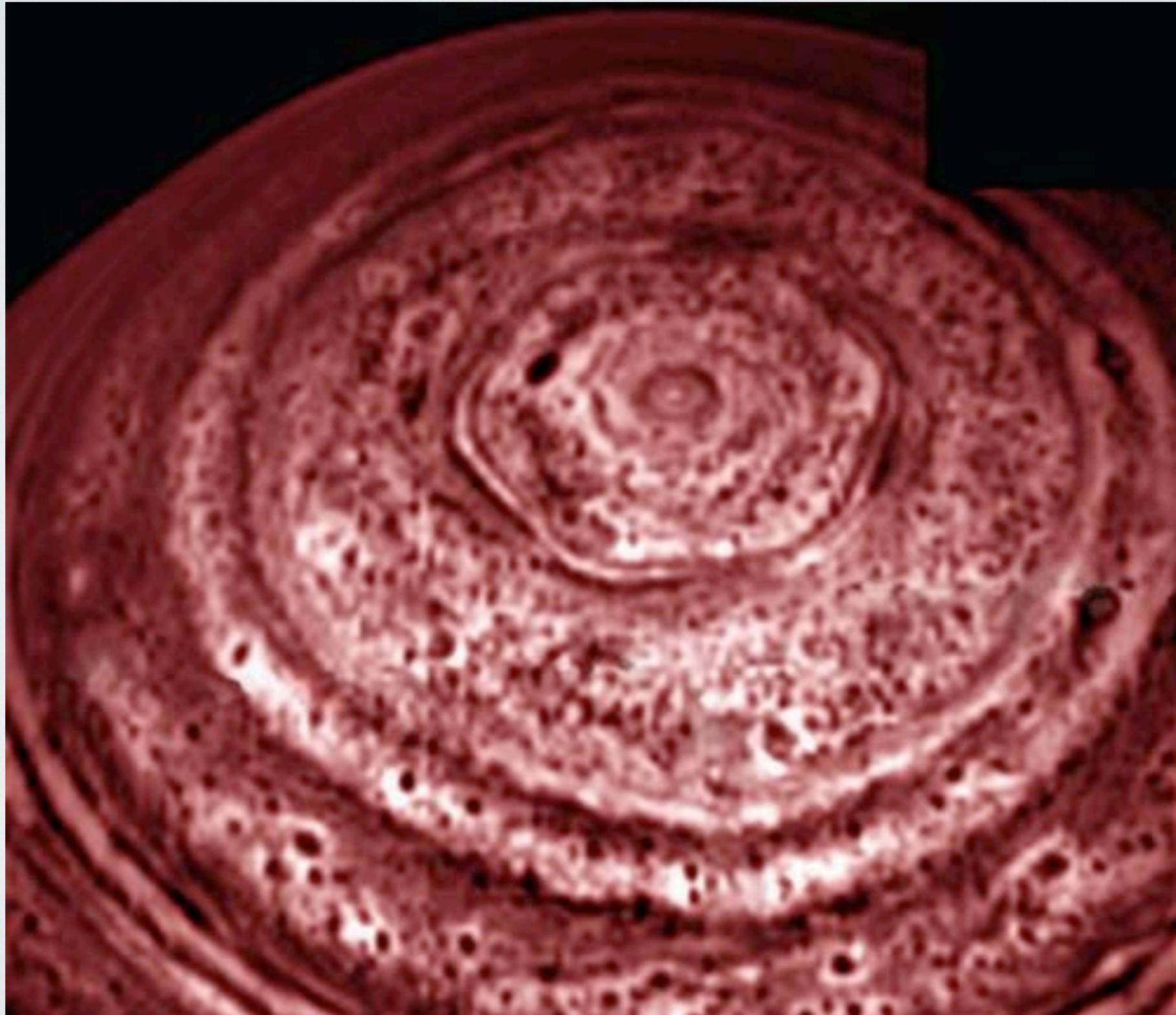
Saturn's Magnetosphere

NEON LASSO

CHARGED PARTICLES STRIKE THE HYDROGEN ATMOSPHERE

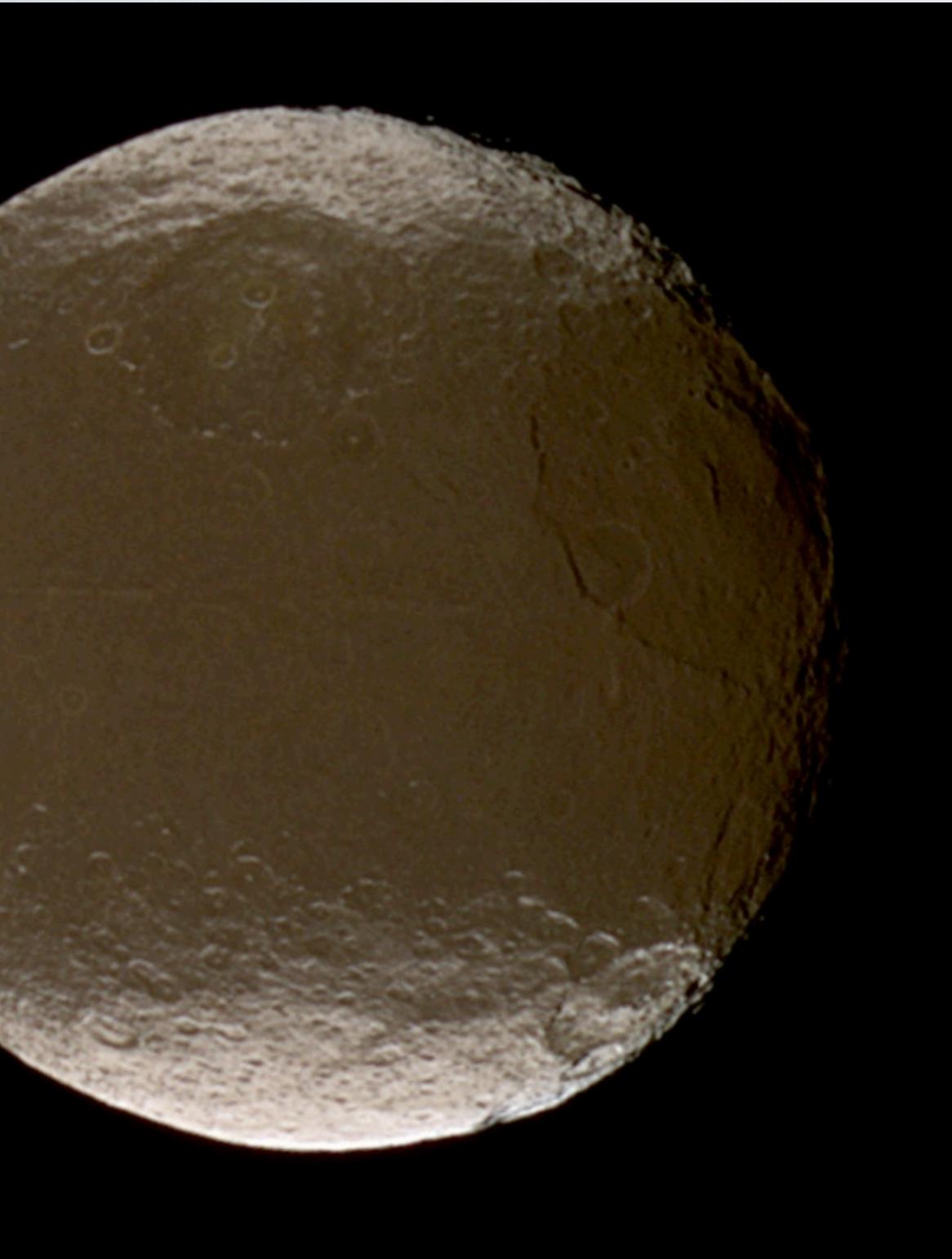


HEXAGON AT THE POLE



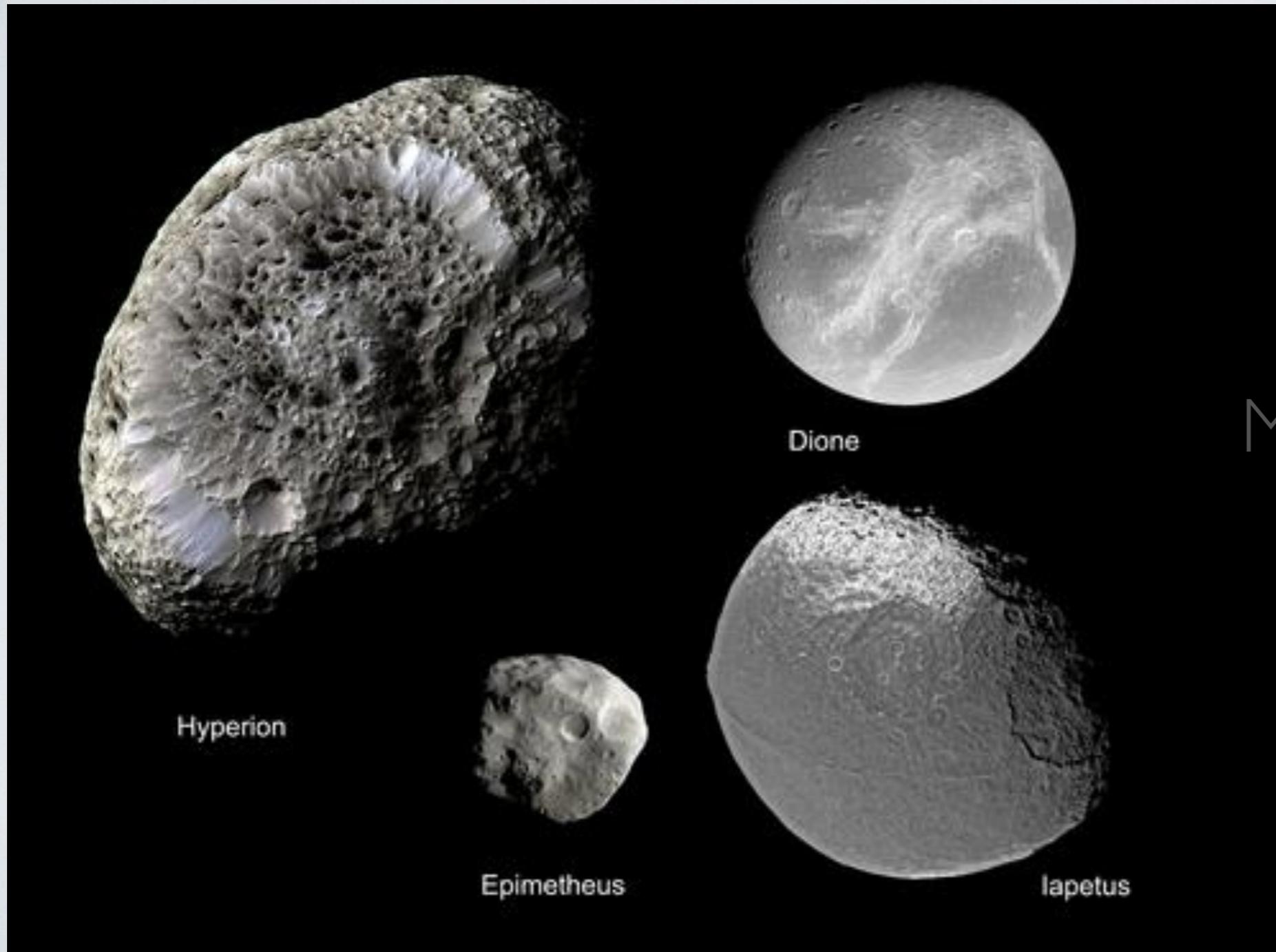
IAPETUS - DICHOTOMY

EVAPORATION OF WATER ICE ON LEADING SIDE (MICROMETEOROID IMPACTS)



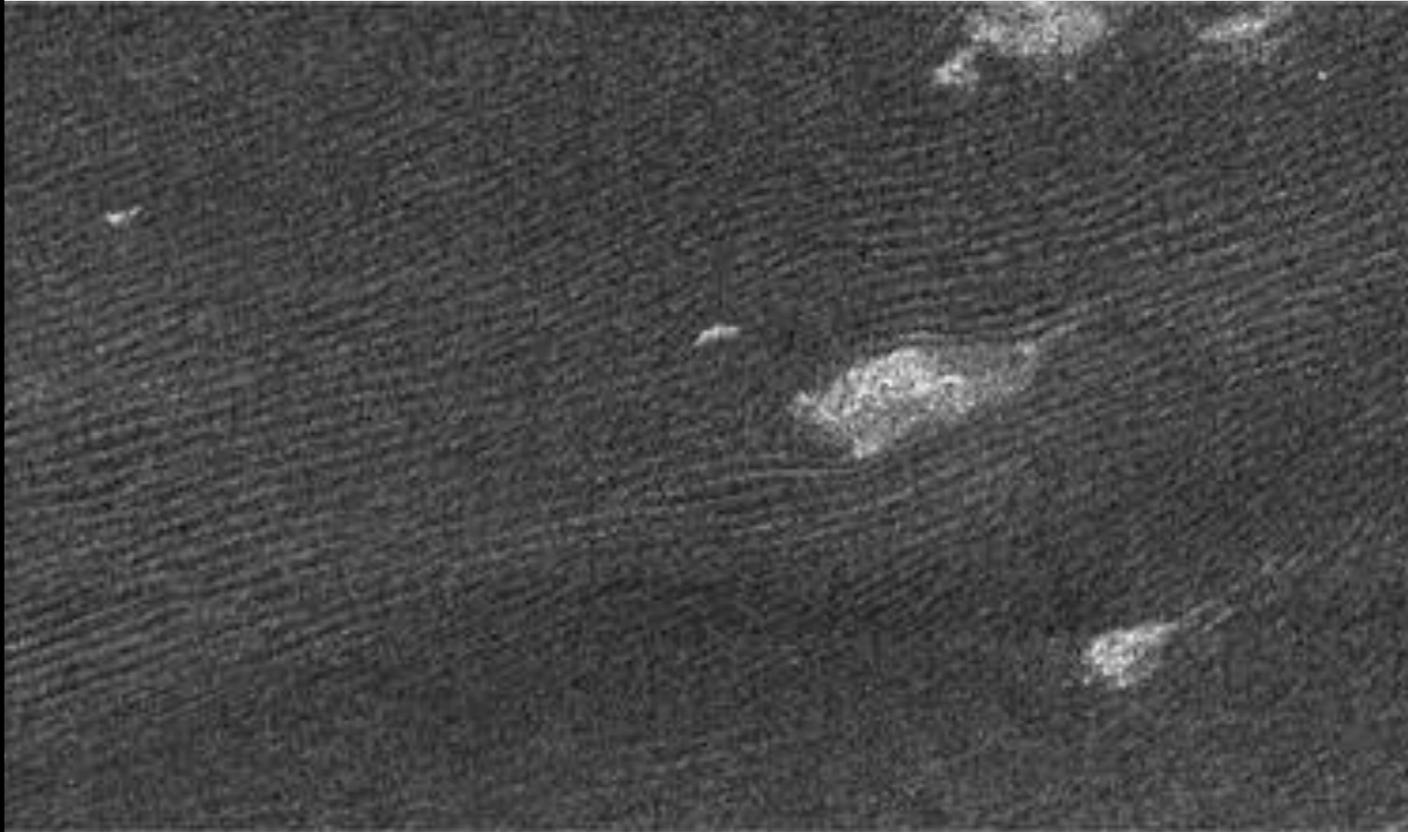
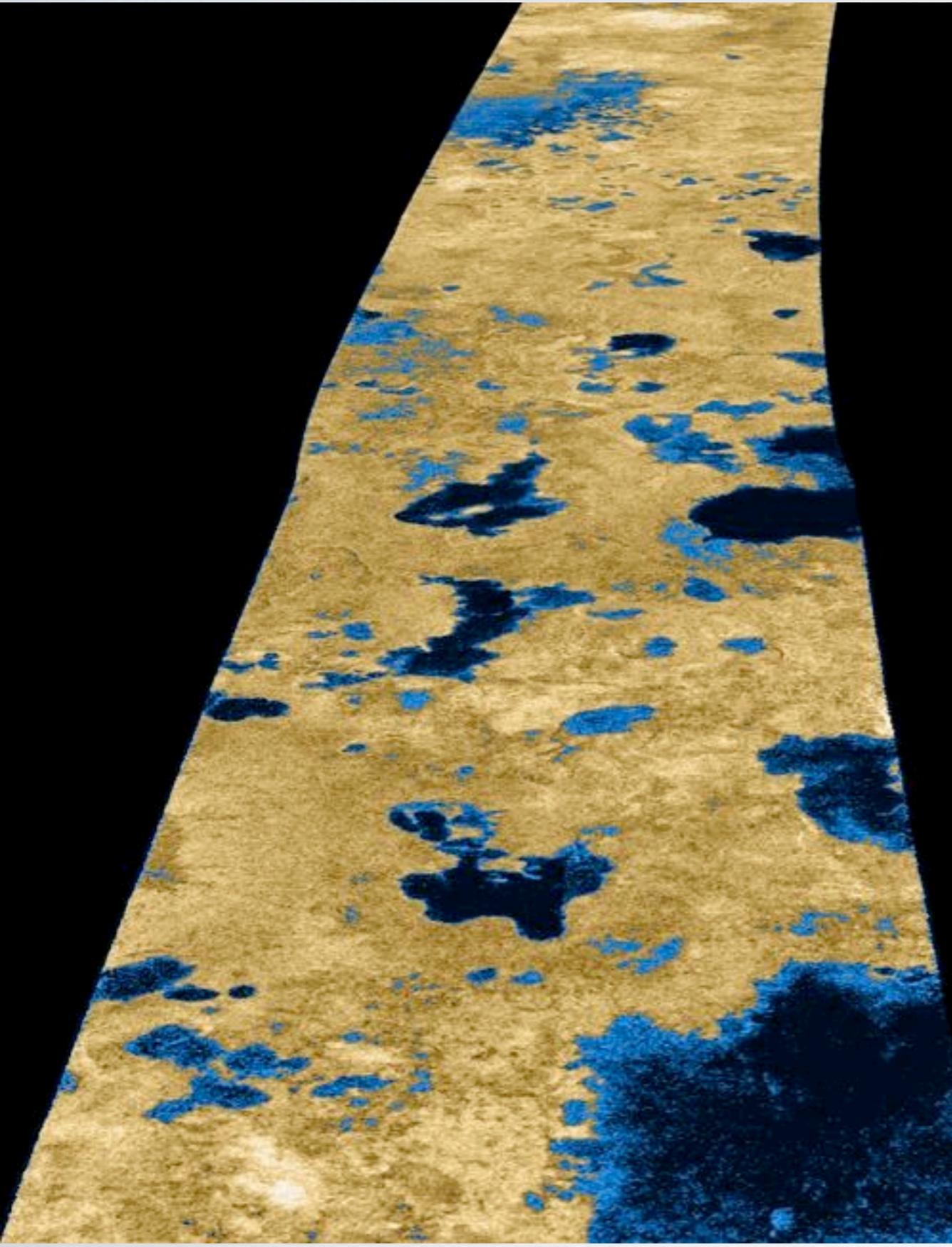


MANY MANY MORE ...



Titan lakes
Titan dunes
Rhea ring
Radiation belts
MAPS in-situ results

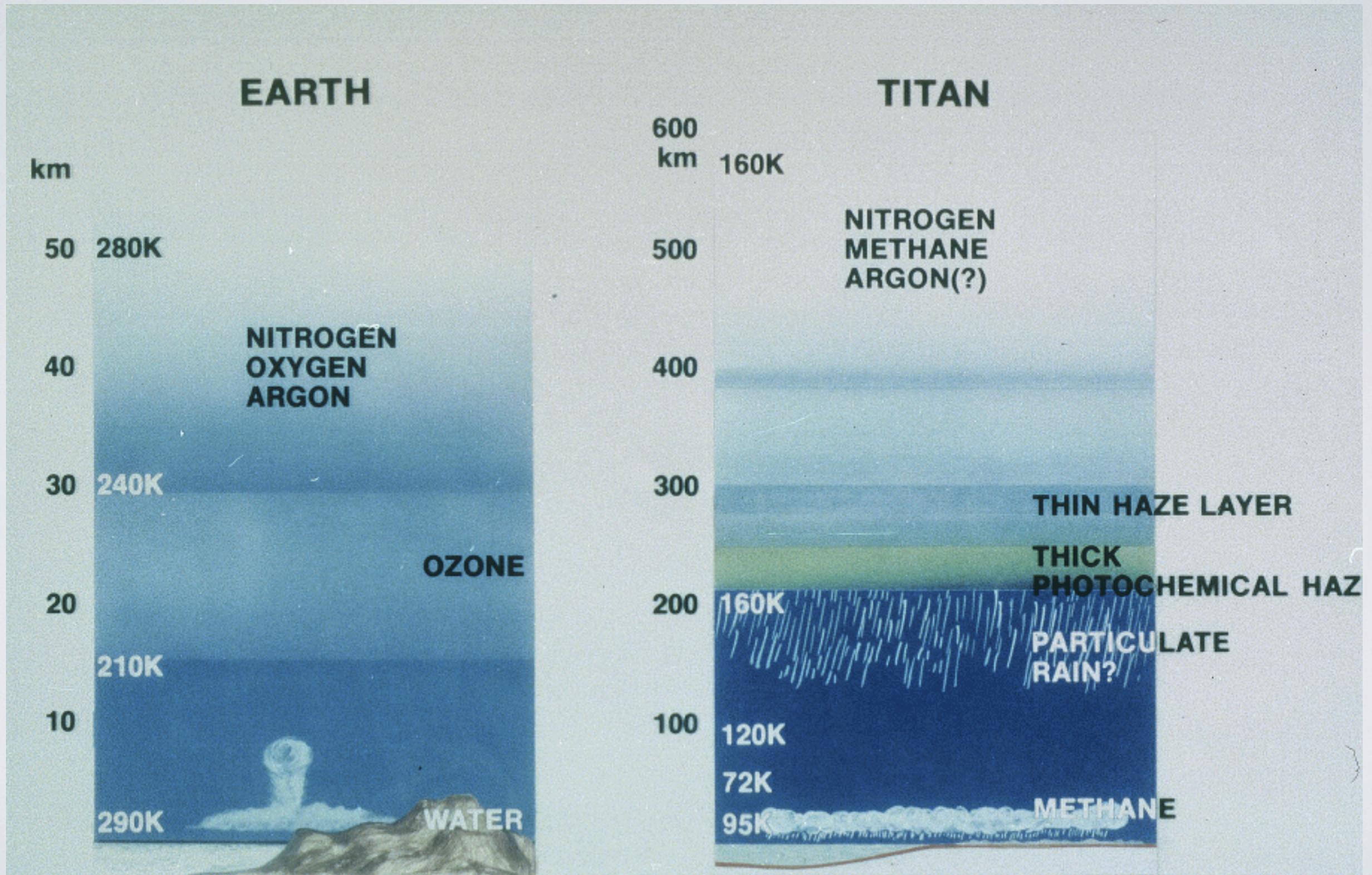
LAKES AND DUNES - TITAN



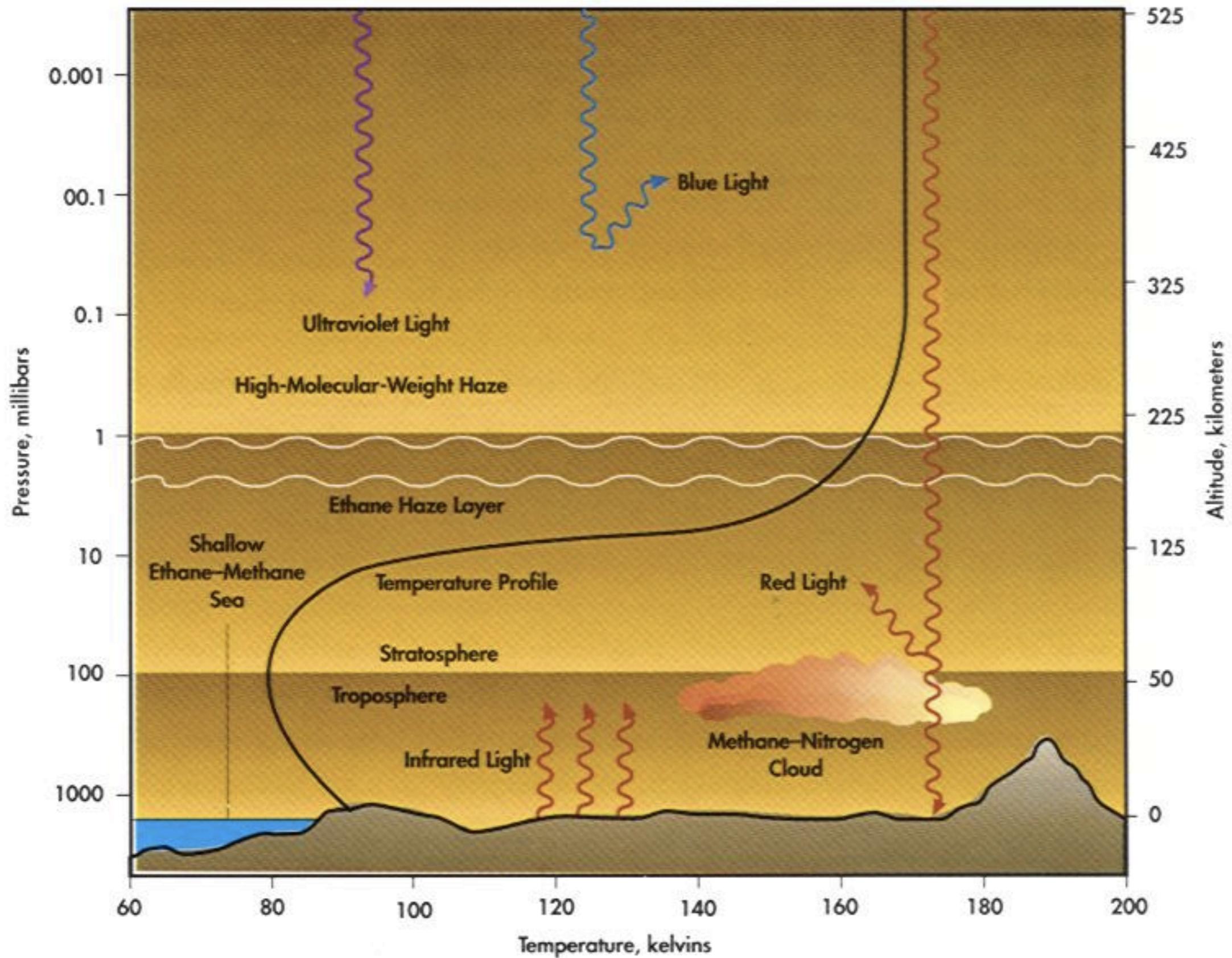
HUYGENS



COMPARE EARTH - TITAN



MODEL OF TITAN'S ATMOSPHERE



HUYGENS PROBE (ESA)

Titan atmosphere,
winds, composition,
temp., pressures,...

Separation - 25. dec 2004

Titan atms entry: 14. Jan 2005

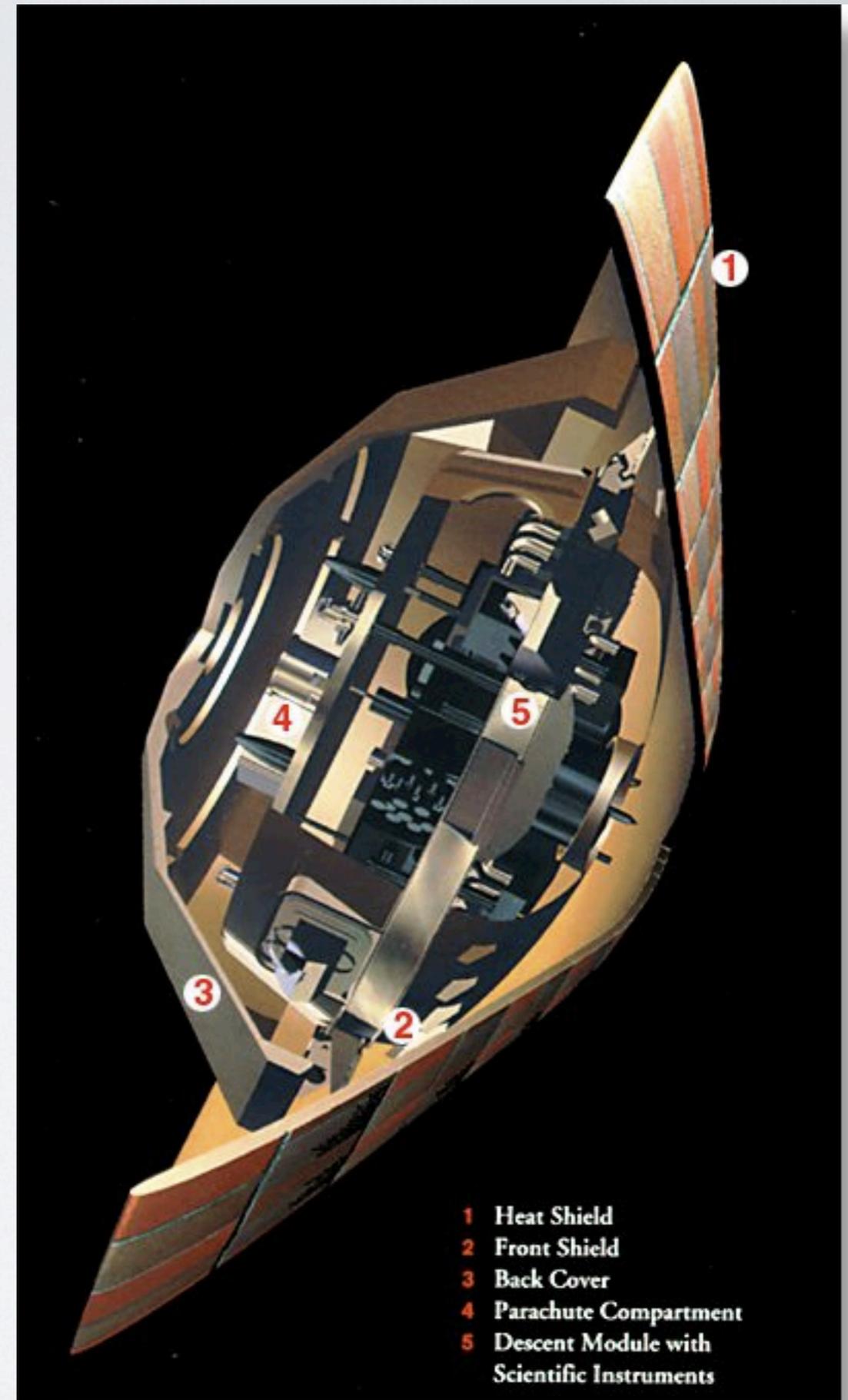
entry angle : 65° (+/- 3°)

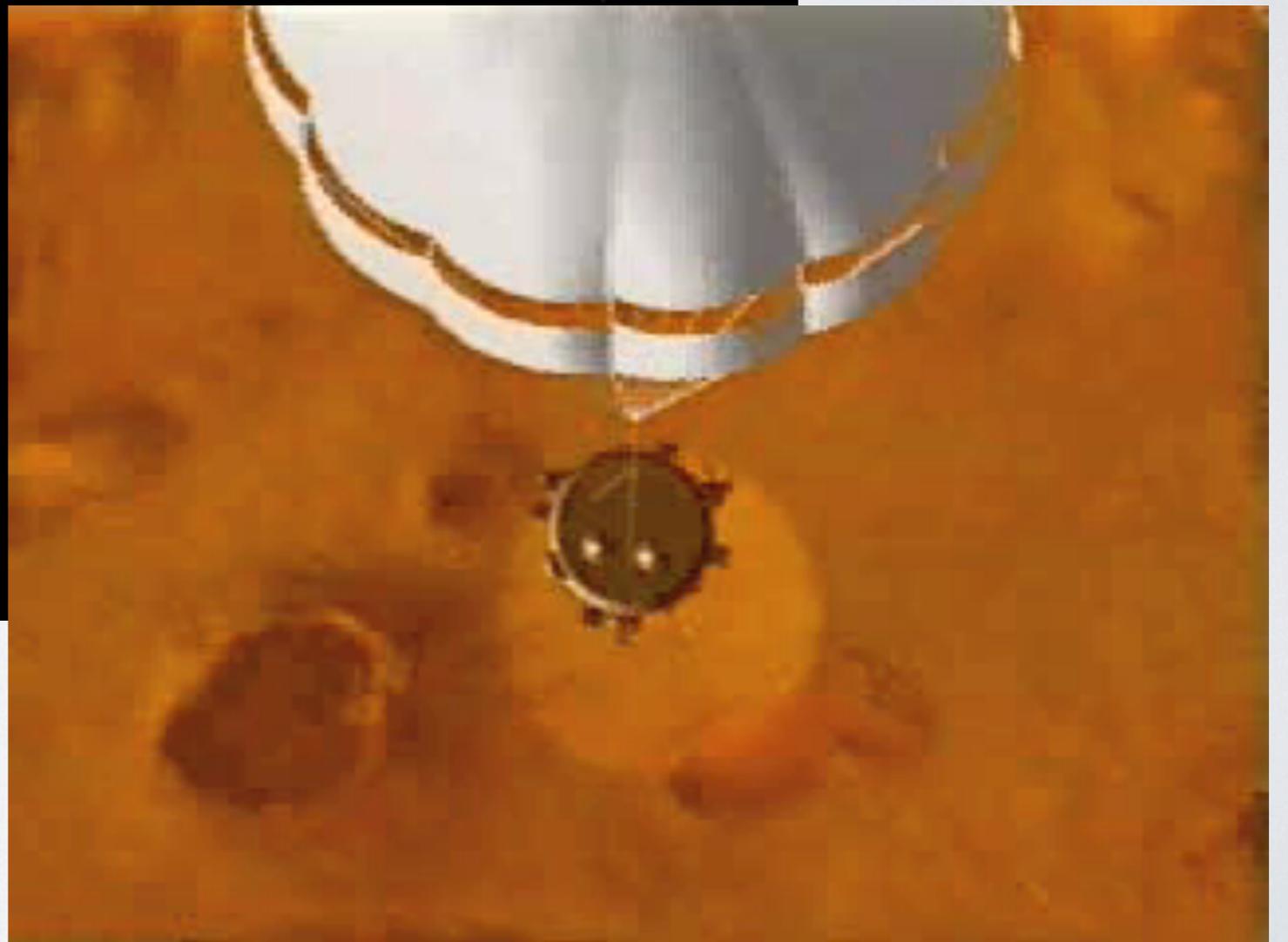
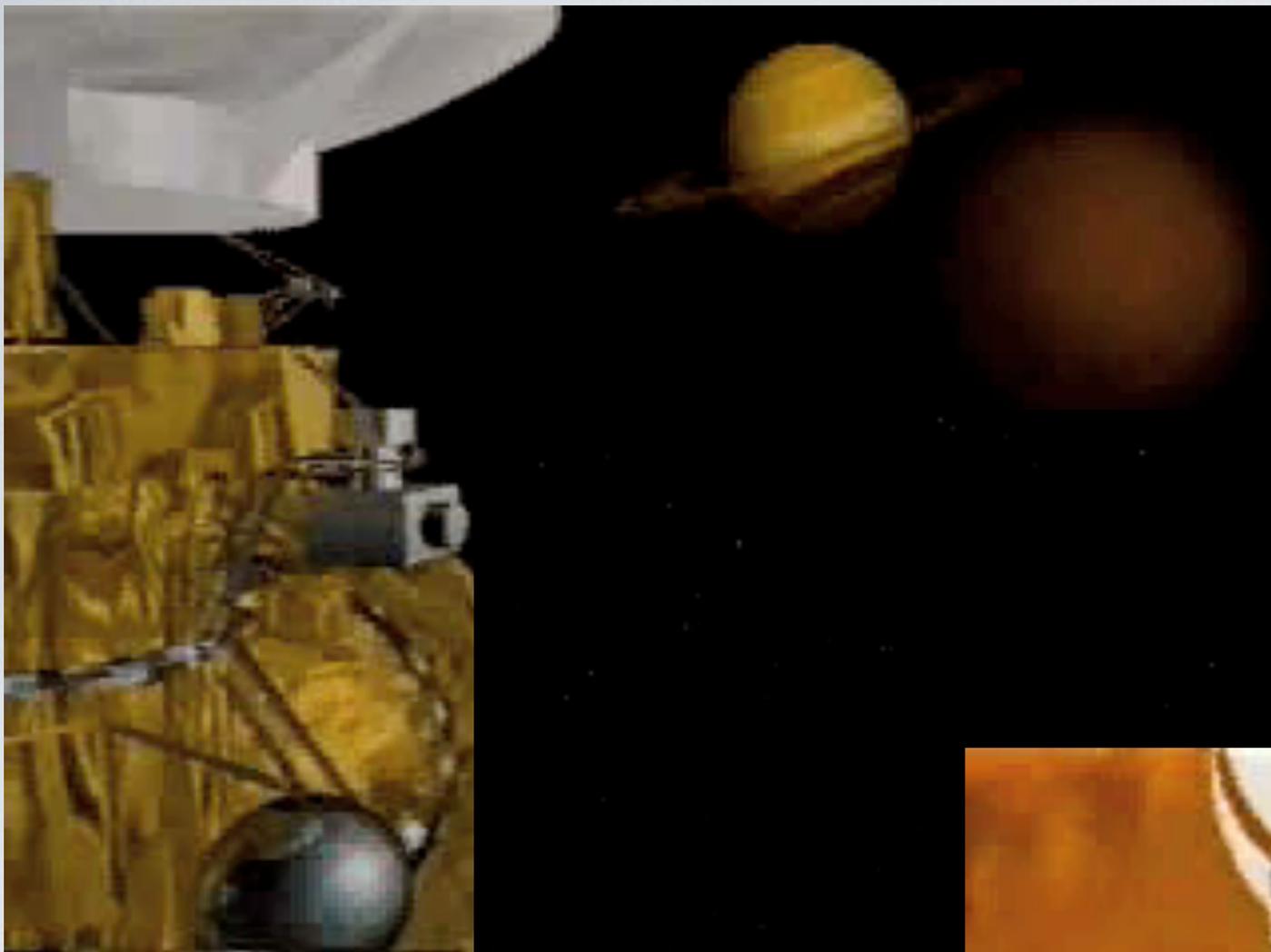
entry speed : 6.1 km/s

peak deceleration : 10-19 g

peak heating : 500-1500 kW/m²

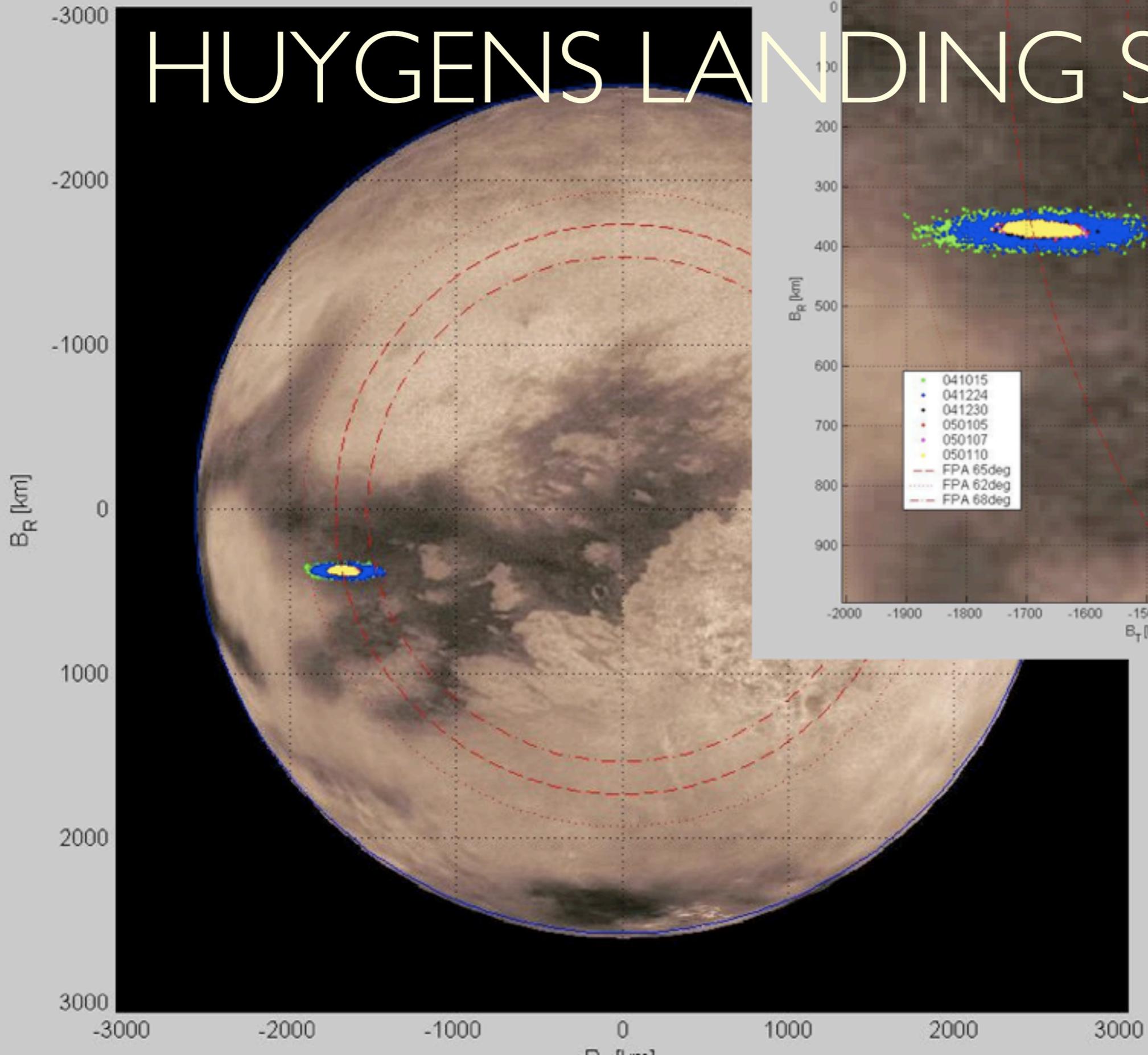
descent time : 2:30 h



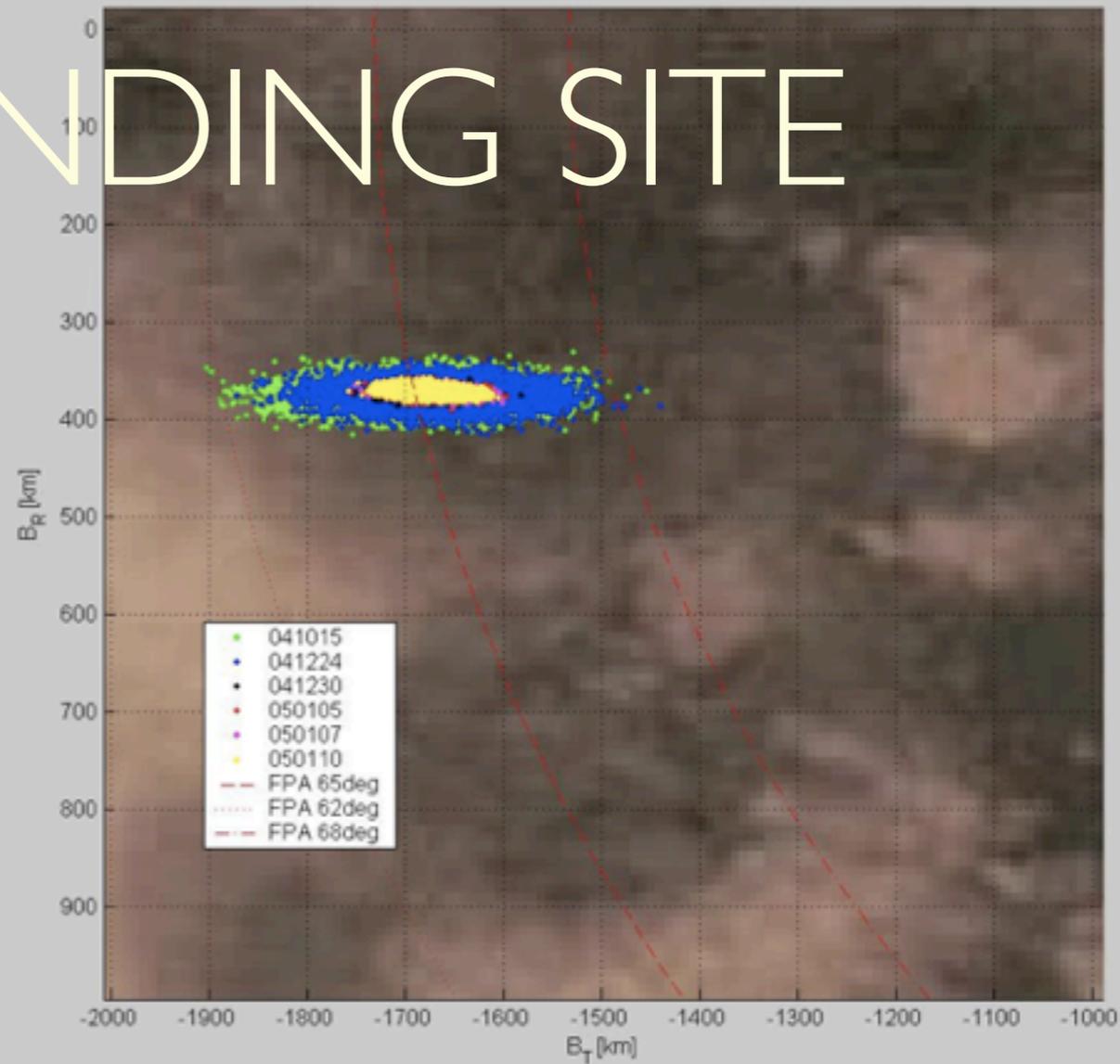


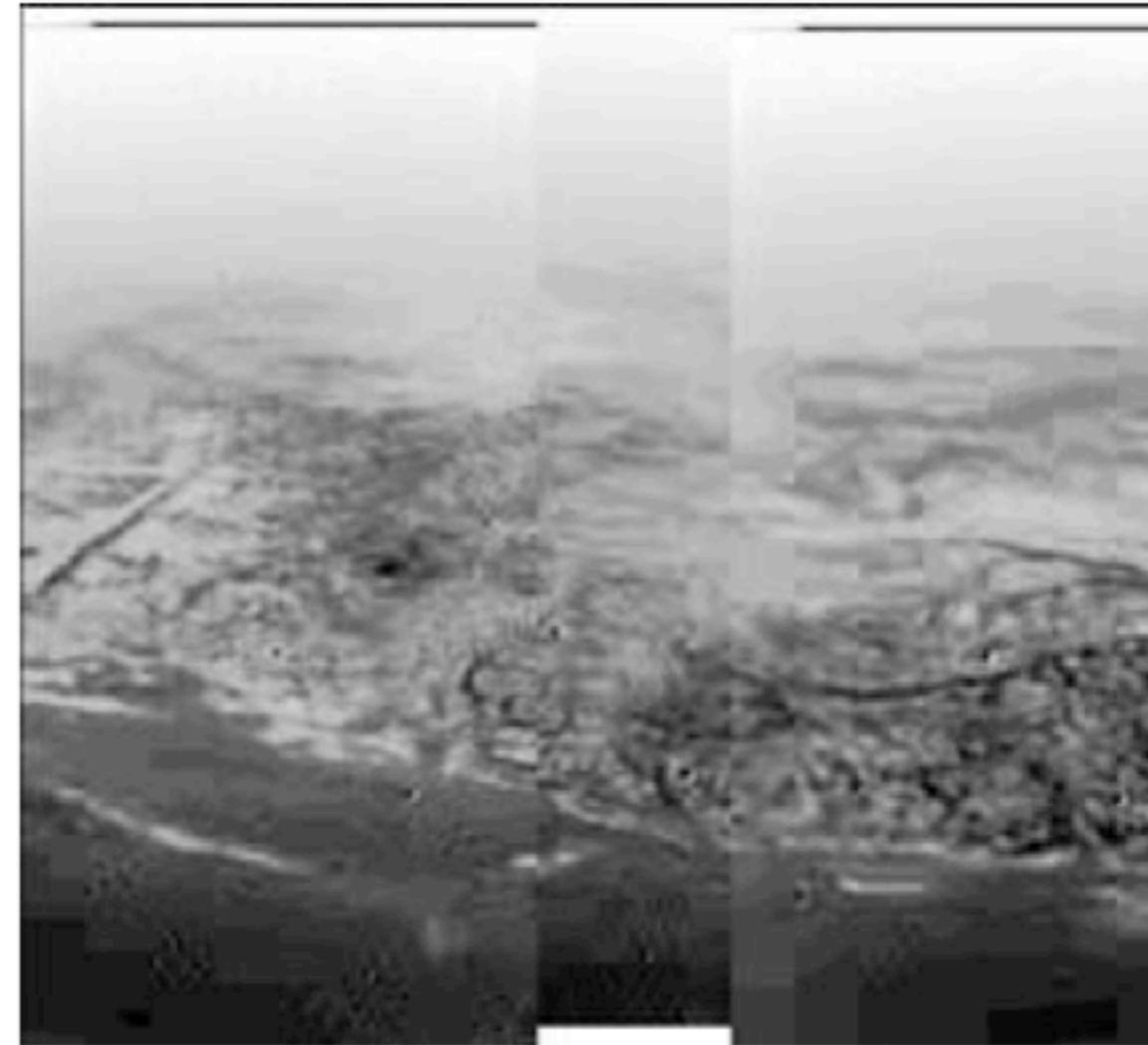
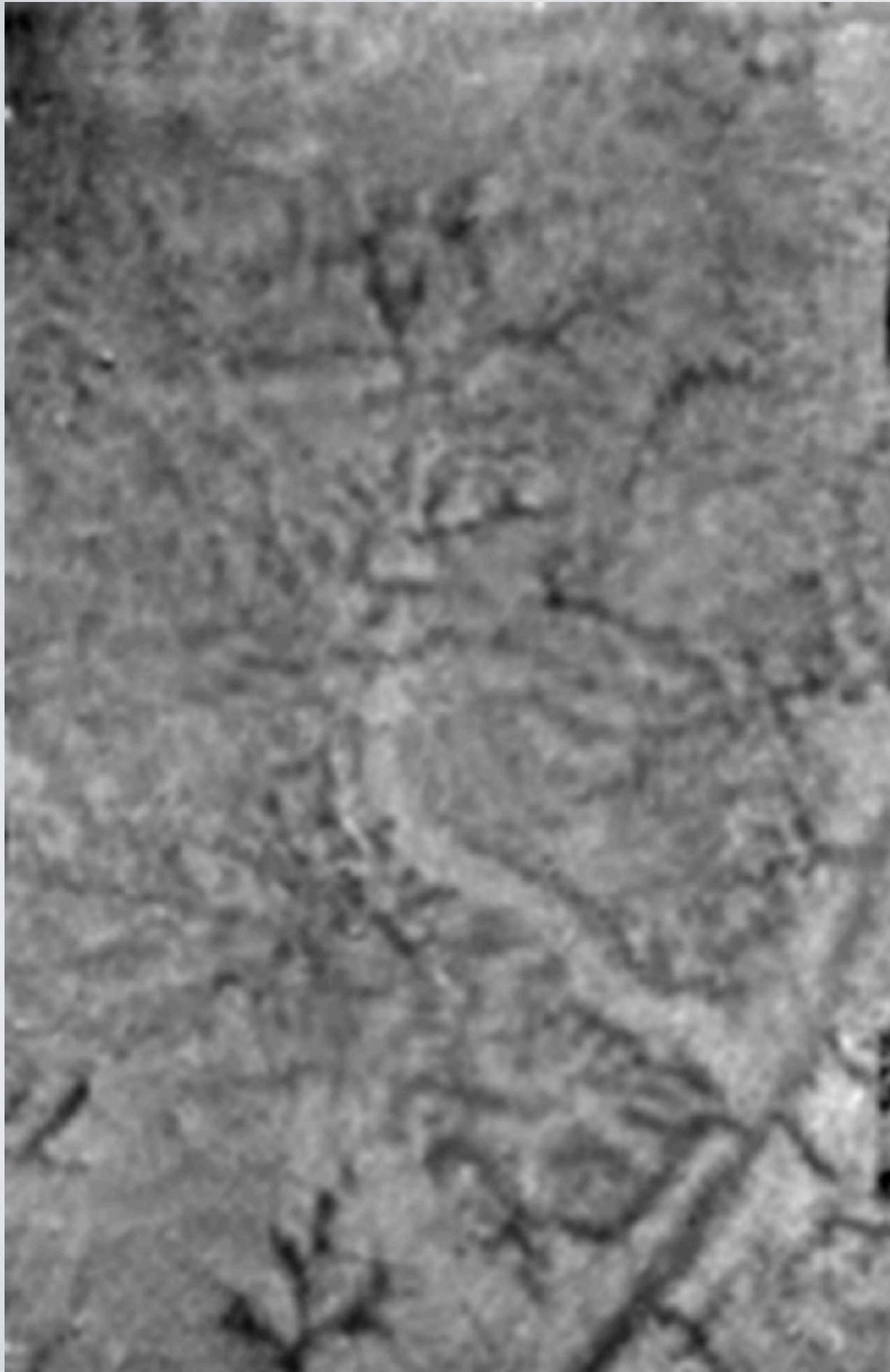
HUYGENS LANDING SITE

MONTECARLO ANALYSIS : Probe B-p



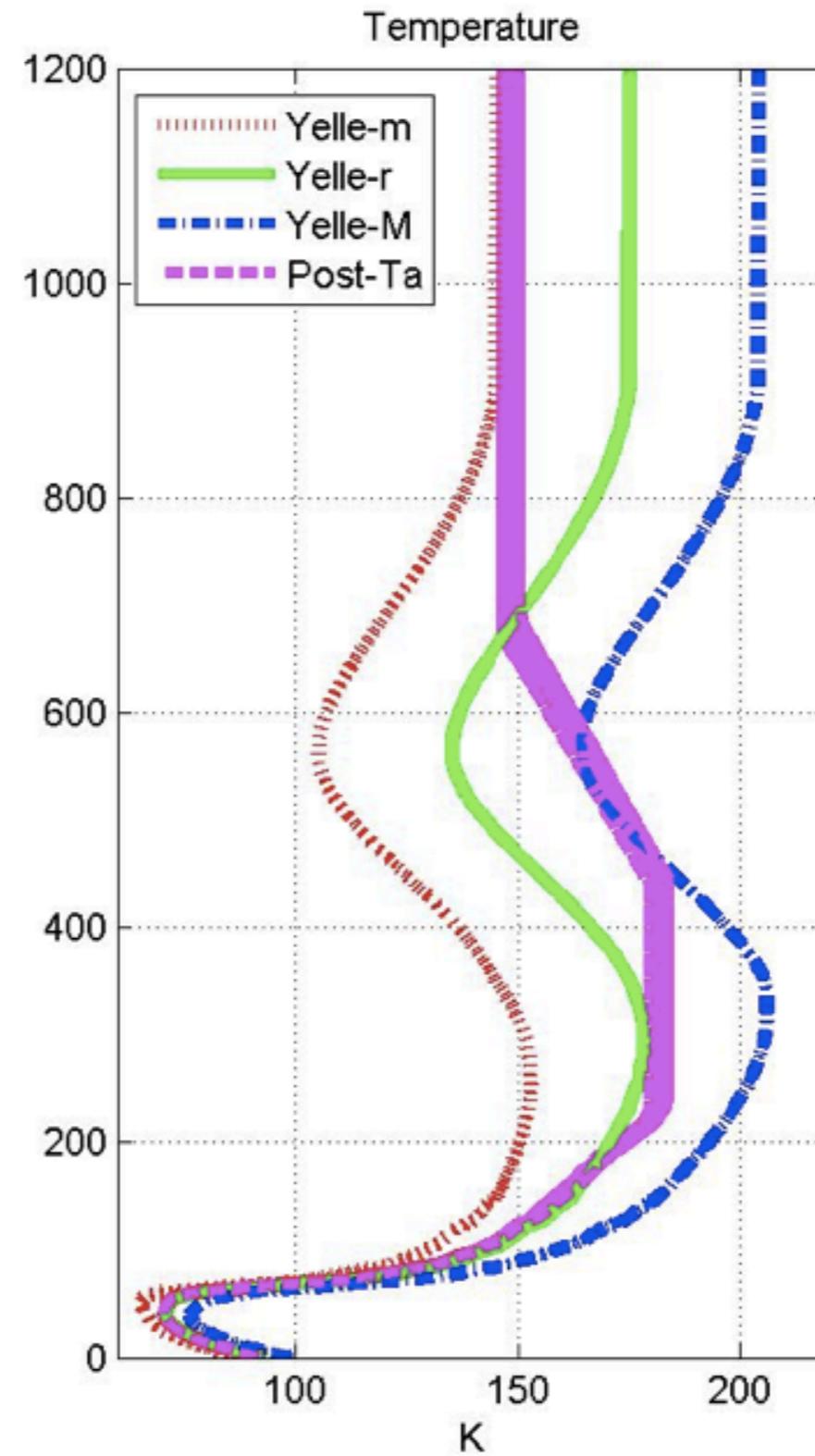
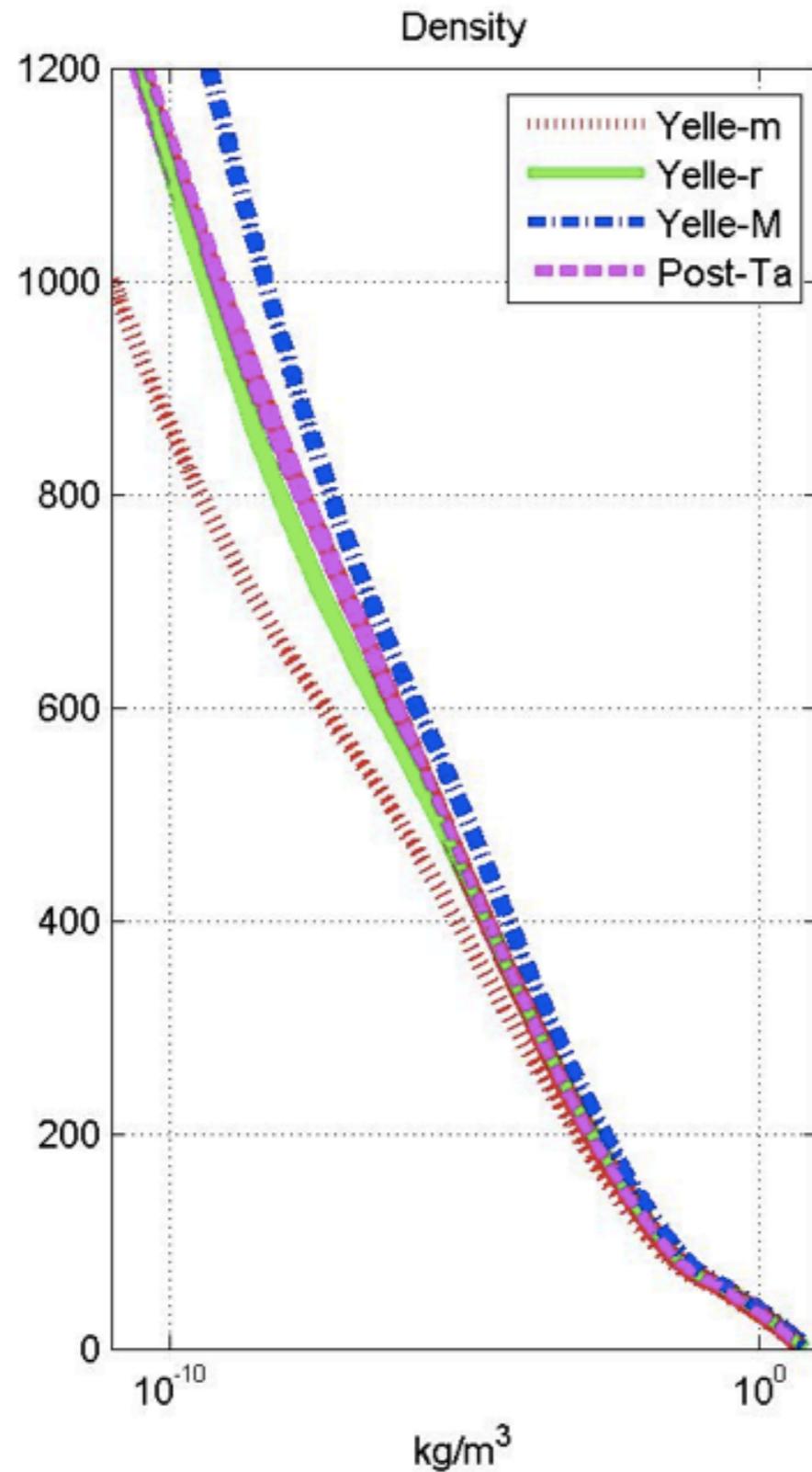
MONTECARLO ANALYSIS : Probe B-plane ellipse

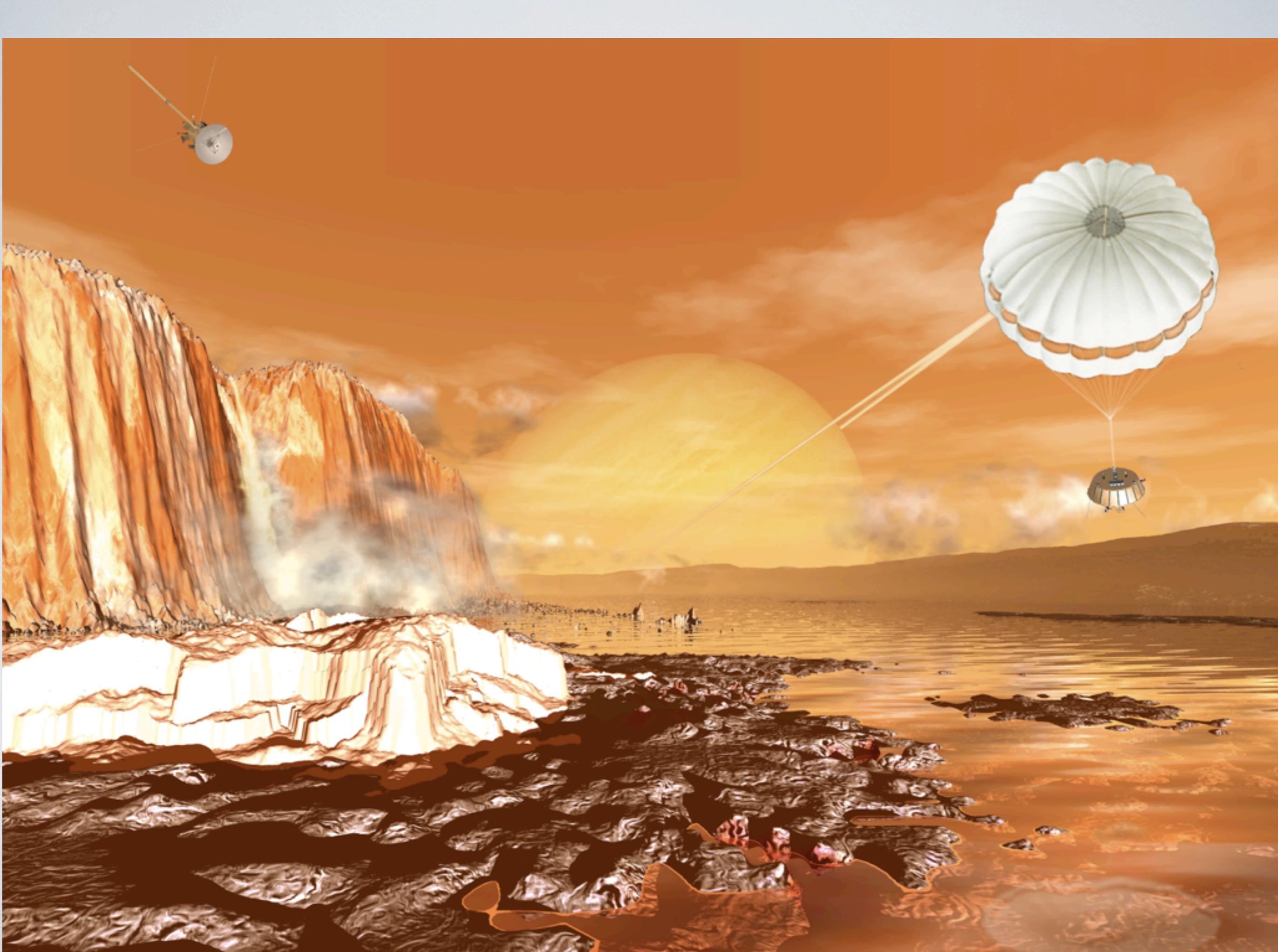




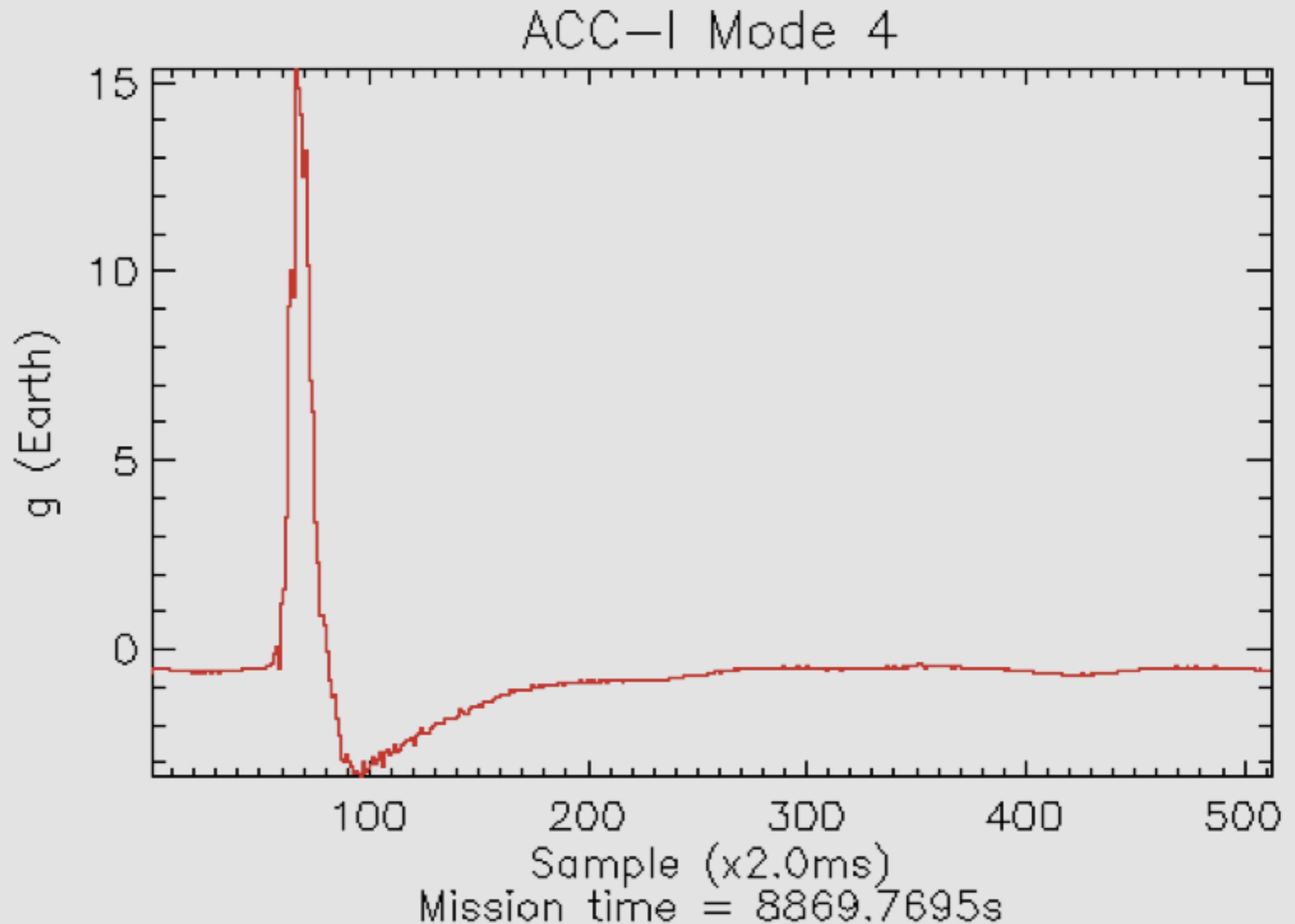
METHANE
SOURCES?

PREDICTION AND MEASUREMENTS OF TITAN'S ATMOSPHERE : GOOD AGREEMENT





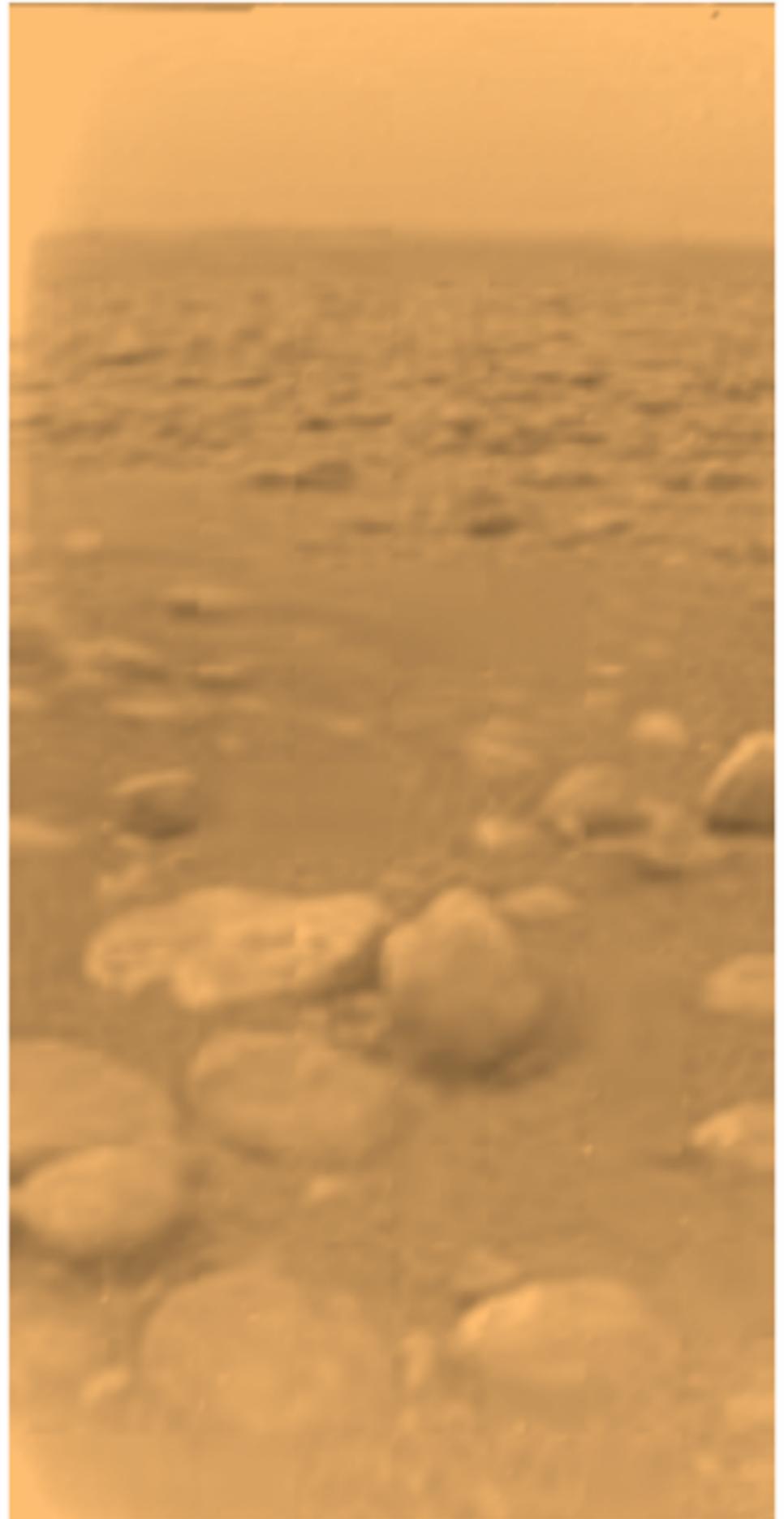
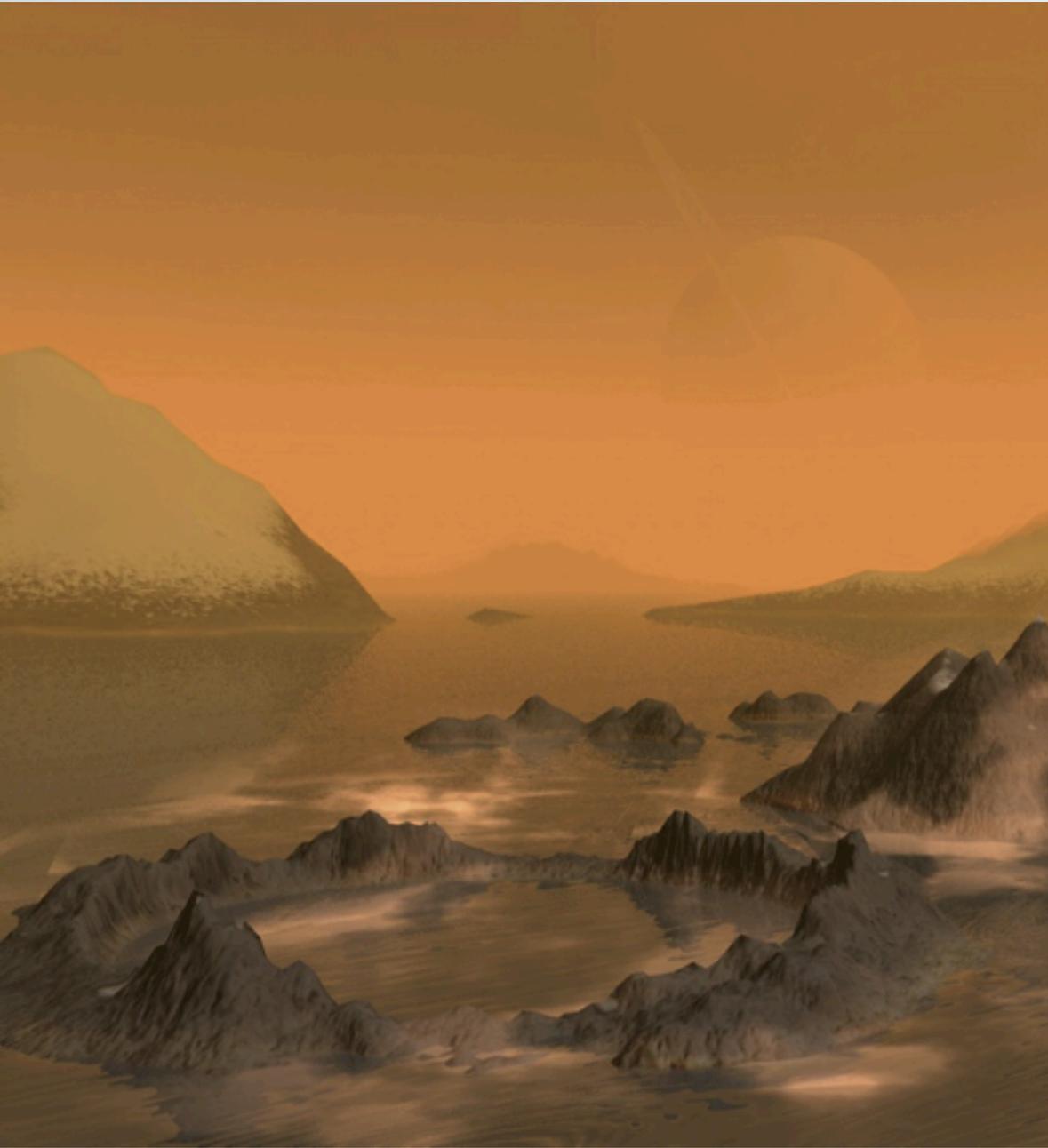
ACCELEROMETER AT LANDING



HUYGENS LANDING SCENARIOS



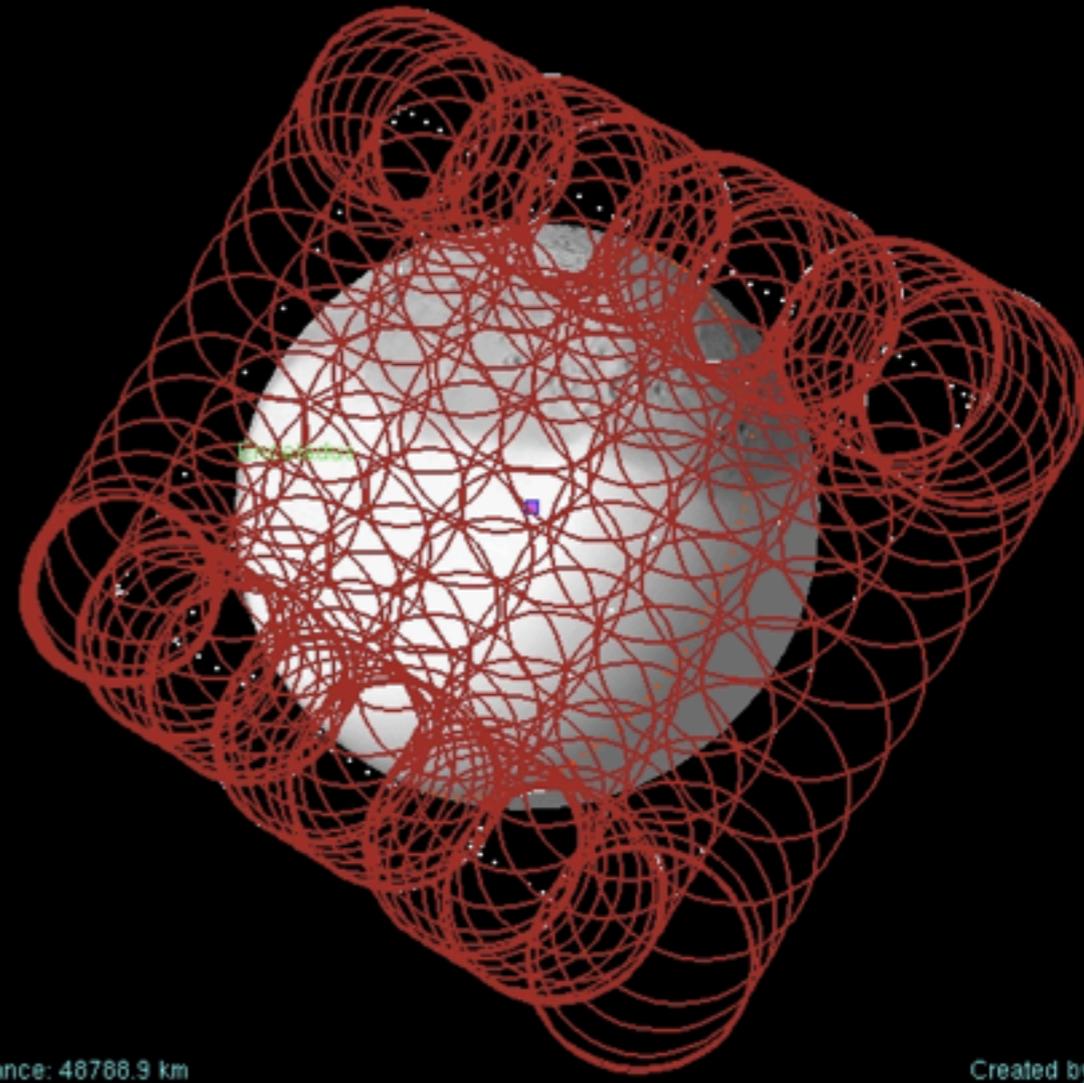
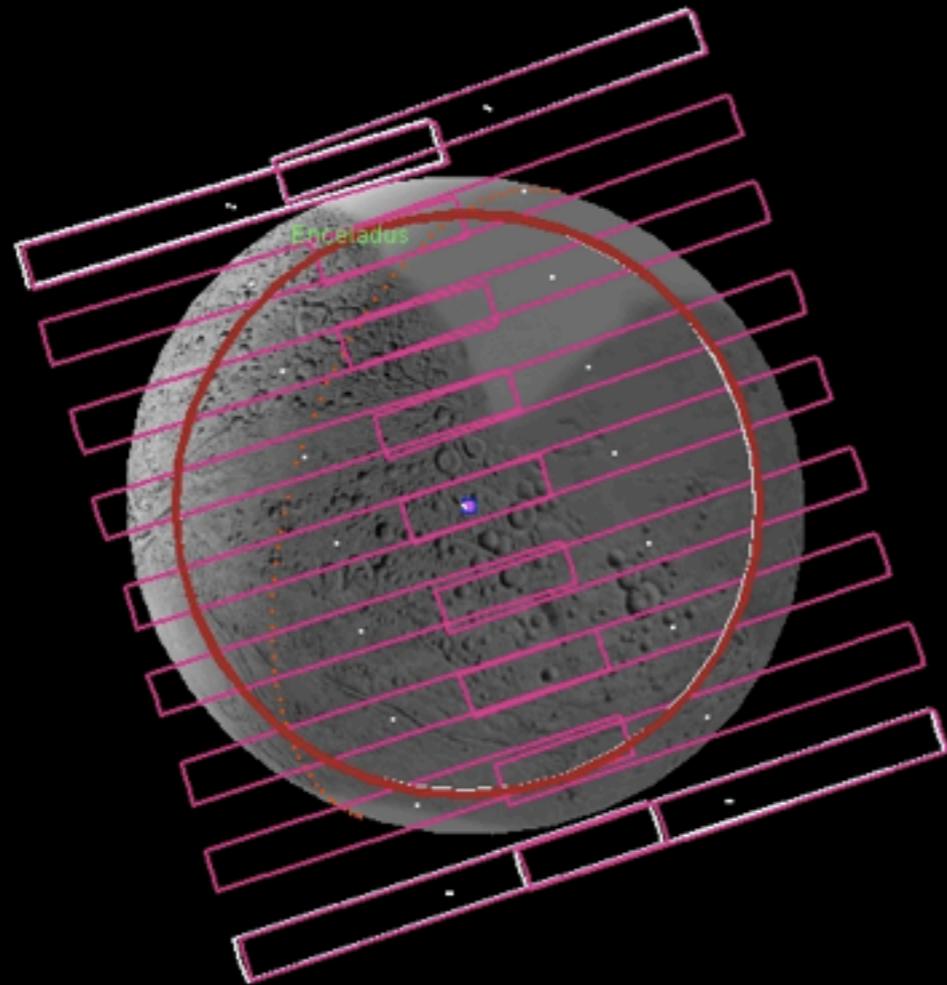
TITAN SURFACE PREDICTION AND REALITY



SCIENCE PLANNING !

EXAMPLE : CIRS

Request: CIRS_008EN_HTSPT31KM161_PRIME Target: Enceladus Observation/Footprint Time:(2005 MAY 21) 2005-
1. Request: CIRS_011EN_FP1GLOBAL020_PRIME Target: Enceladus Observation/Footprint Time:(2005 JUL 14) 2005-

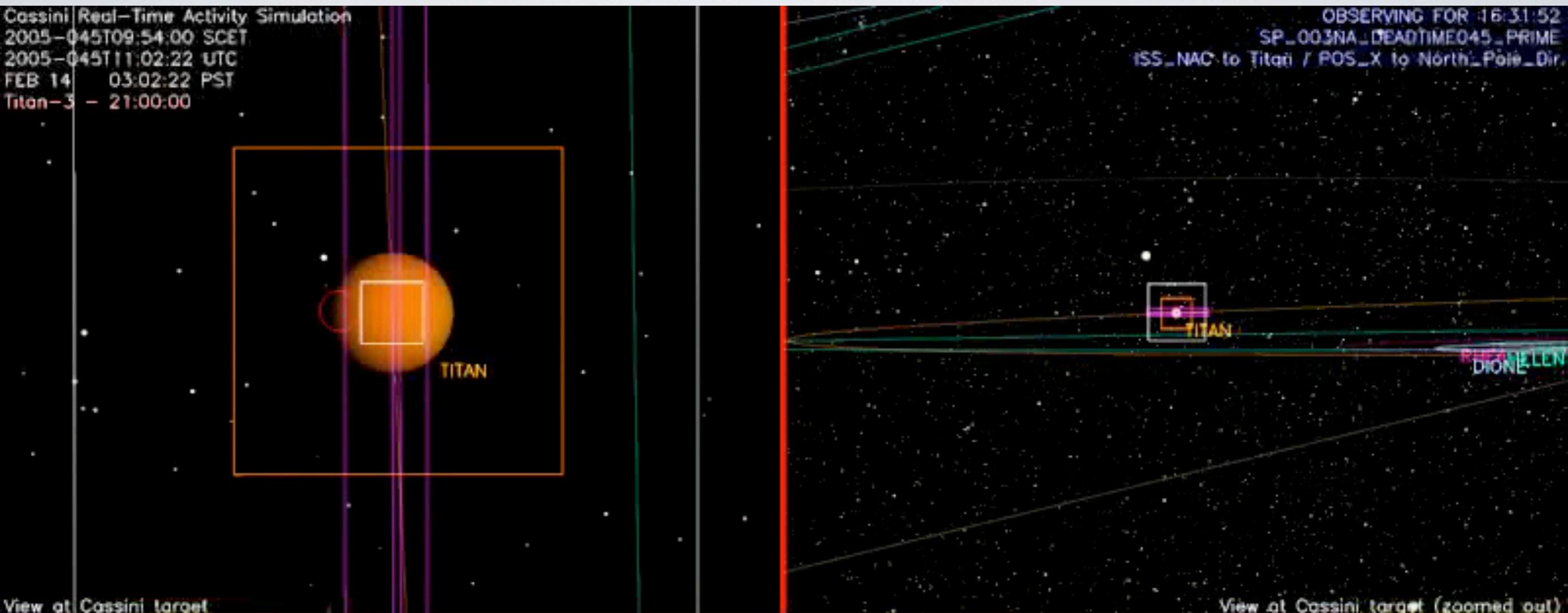


Spacecraft-Target Distance: 106058 km
Spacecraft Velocity(relative to Target): 8.35946 km/s

Spacecraft-Target Distance: 48768.9 km
Spacecraft Velocity(relative to Target): 8.25699 km/s
Created by ODD (MSS D9.0.2d)
on: Thu Jul 24 15:58:44 2003

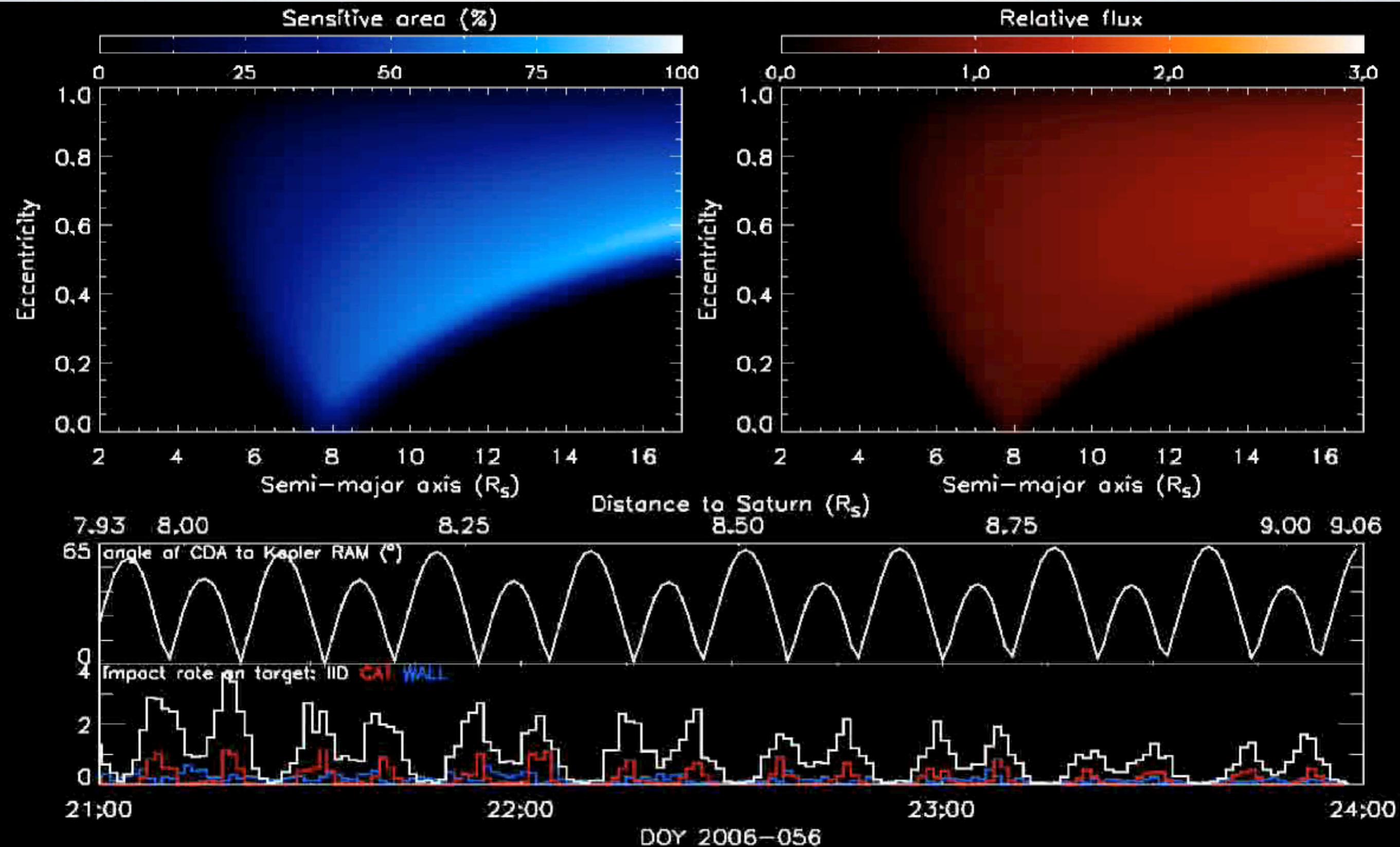
Created by ODD
on: Thu Jul 24 15:58:44 2003

OBSERVATION PLANNING

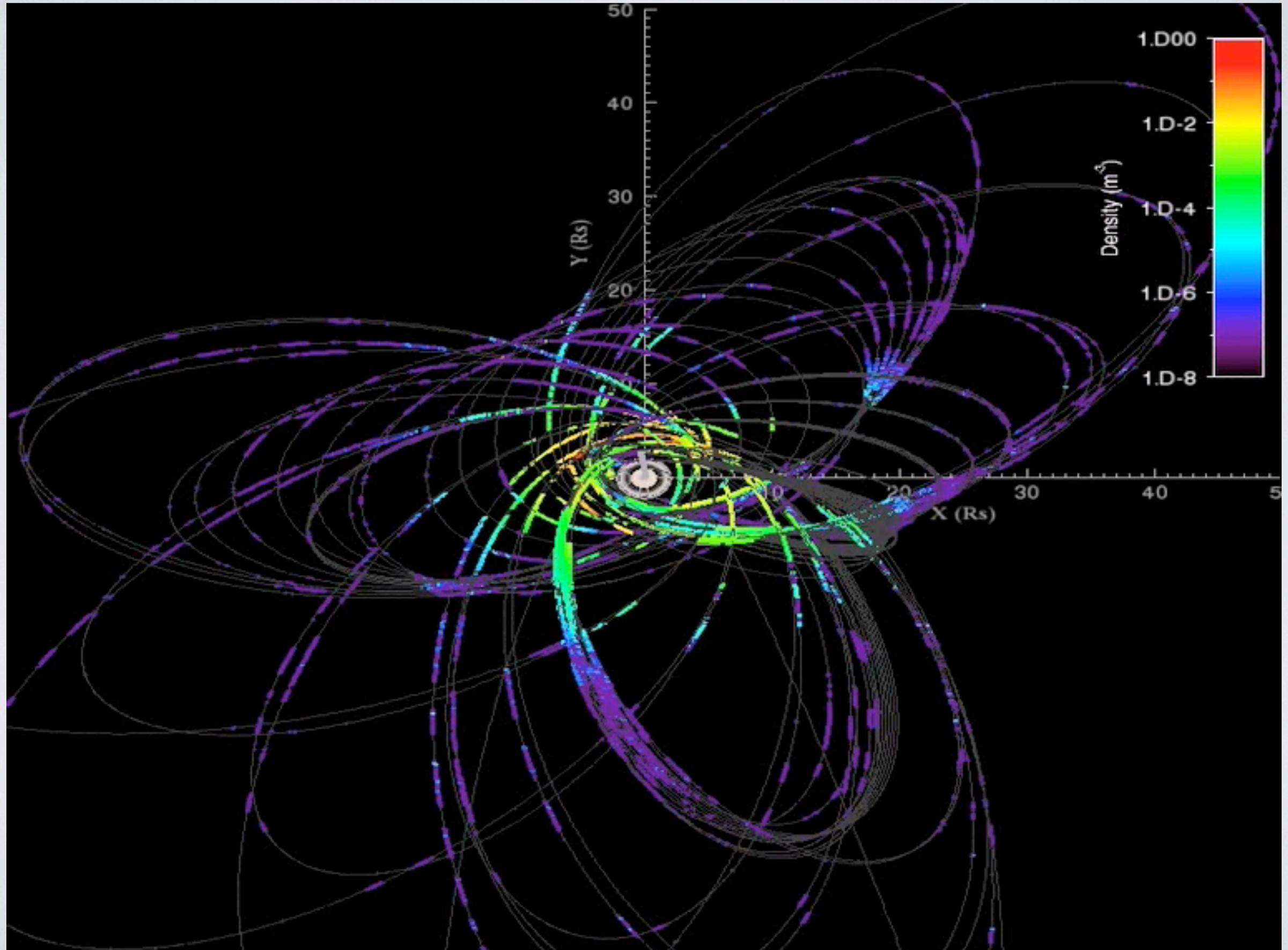


10:54:08 TRIGGER DISTRIBUTED RADIO & PLASMA WAVE SCIENCE SEQUENCE TYPE = ID
11:06:10 BEGIN TARGETING SCART
11:06:10 SET SPACECRAFT OFFSET TURN RATE AND ACCELERATION PARAMETERS: TURN RATE X
11:06:11 SPECIFY BASE SPACECRAFT ATTITUDE PRIMARY
11:06:16 BEGIN ISS_SUPPORT_IMAGING BLOCK

ROCKING CASSINI: DUST DYNAMICS

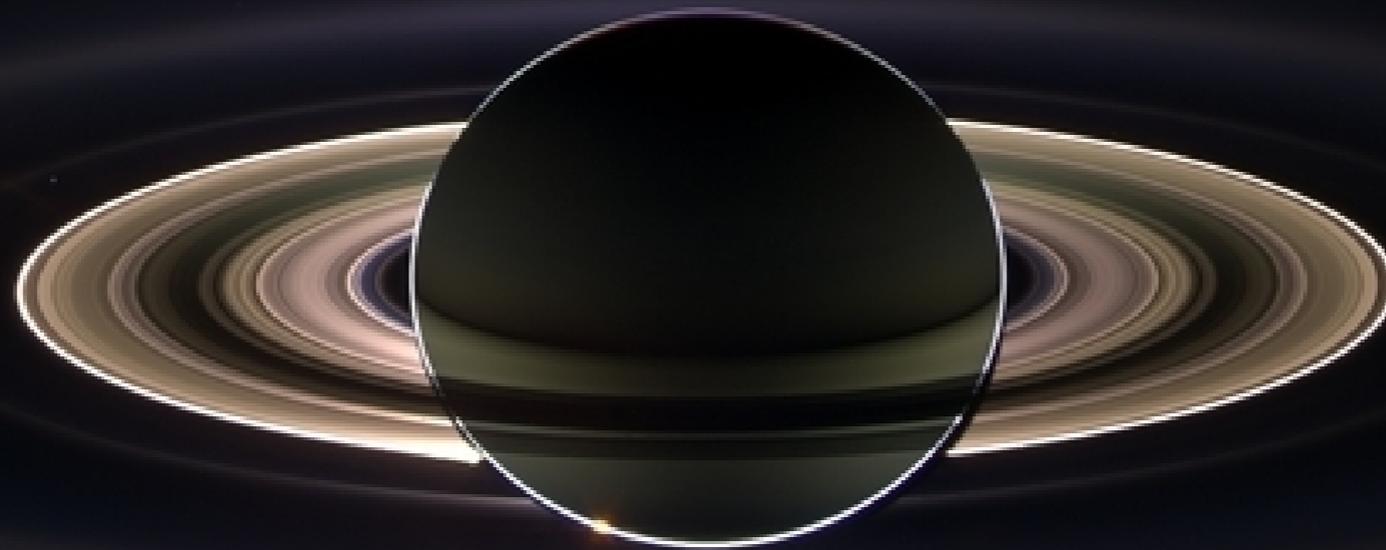


DUST DENSITY



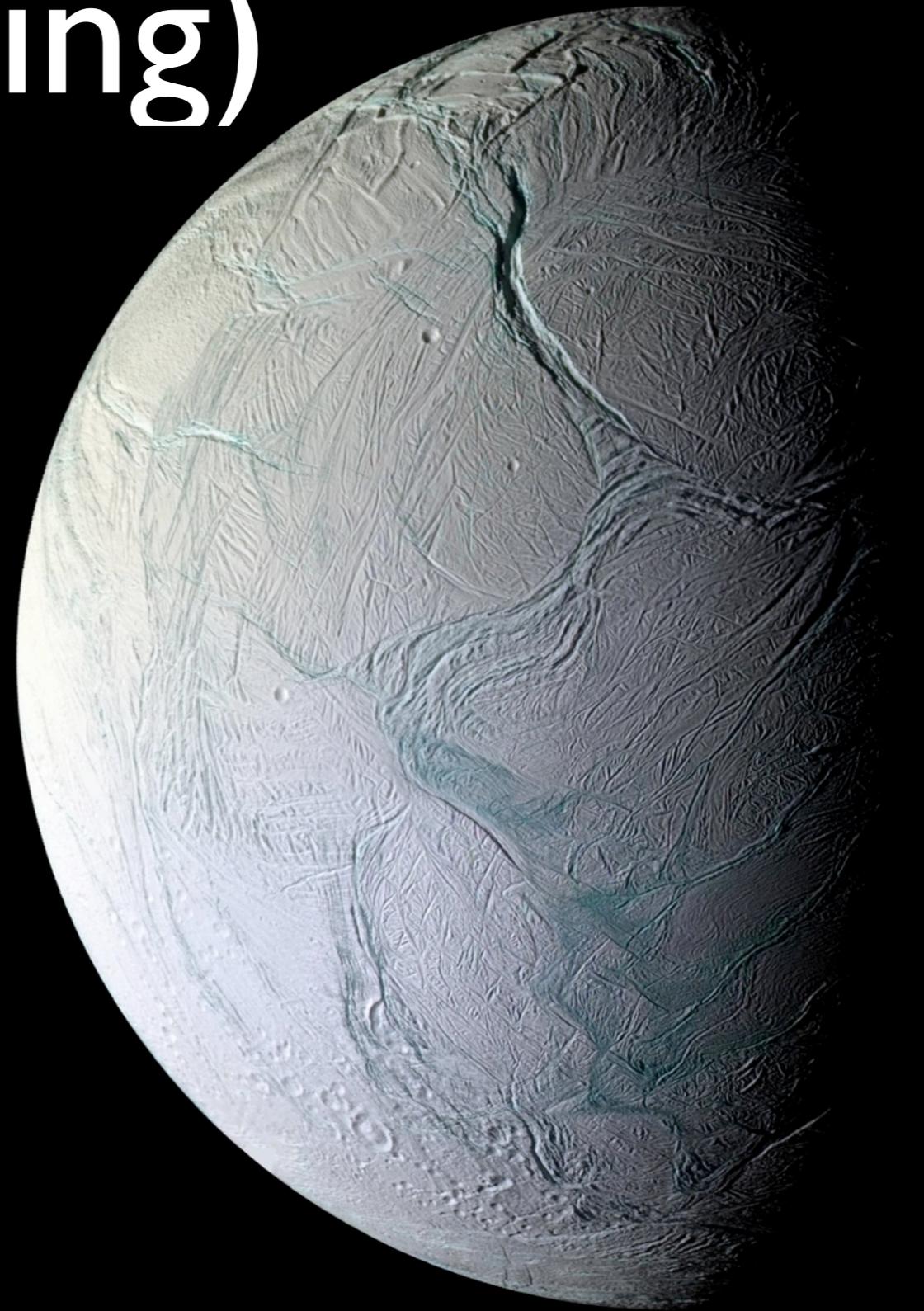
Comparison : Optical measurements

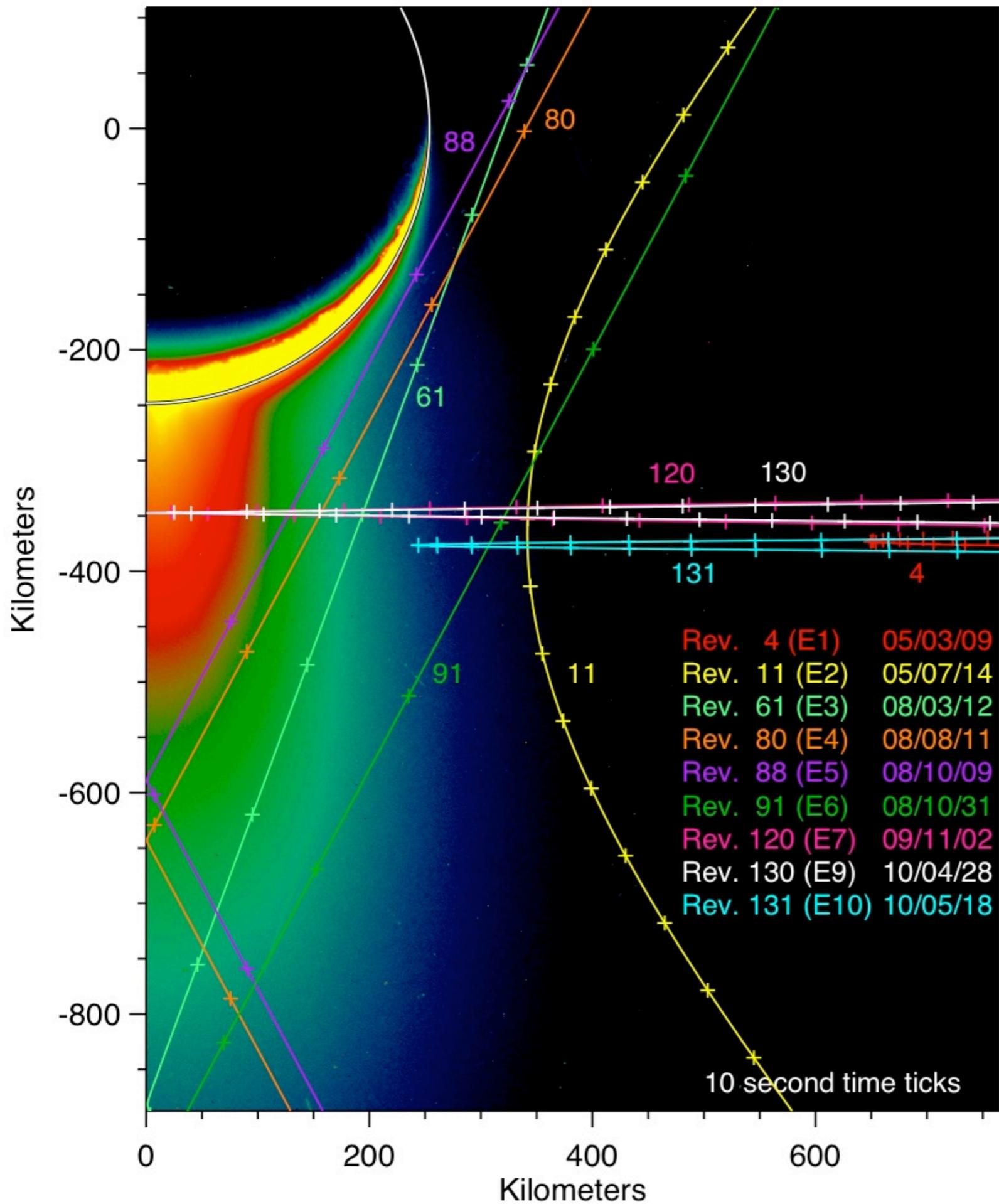
The E-Ring



Enceladus : Source of ice grains (E ring)

- Size: 499 km
- Density: 1600 kg/m^3
- 70 km Ice Crust on Rocky Core

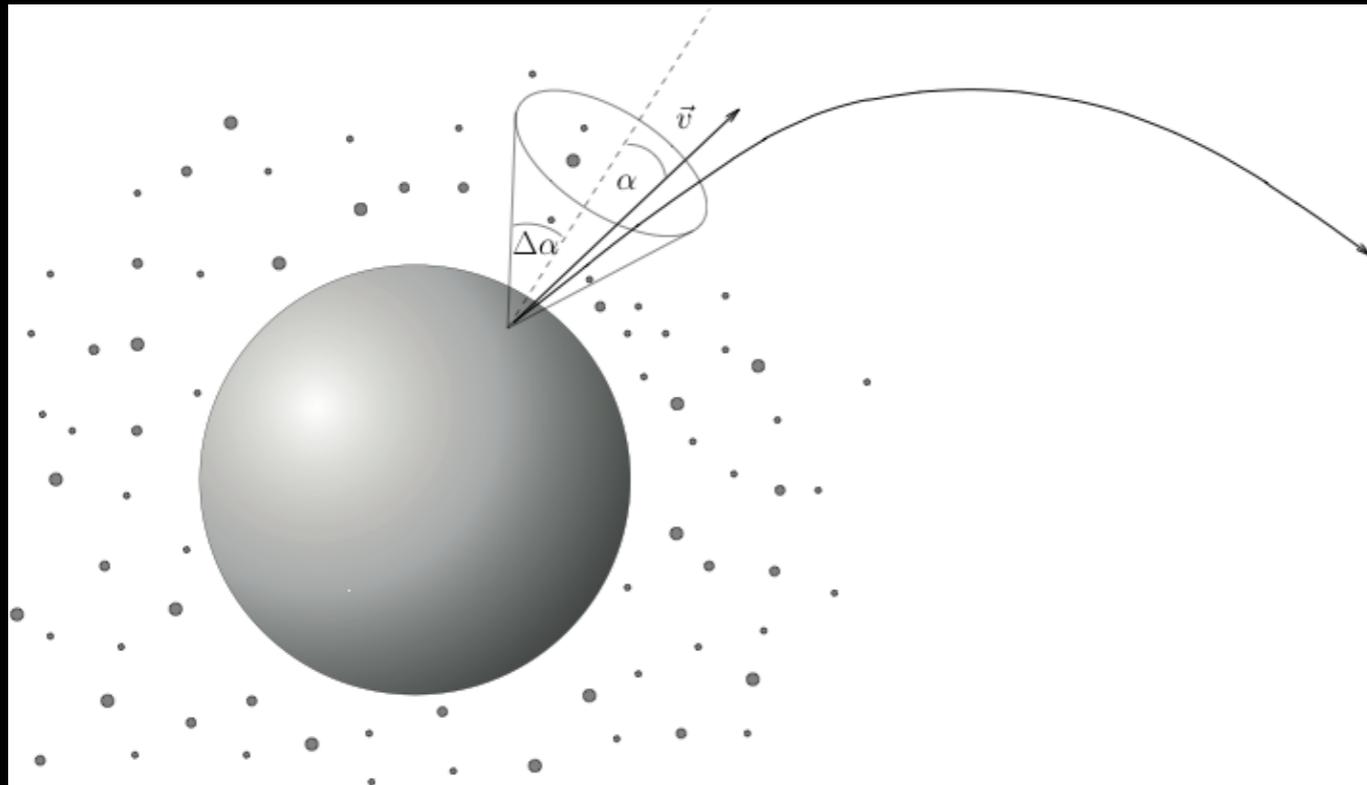




ENCELADUS FLYBY PLANNING

Ejecta Production

Meteoroid Impacts Splash up Ejecta



Sremcevic et al., Icarus, 2005

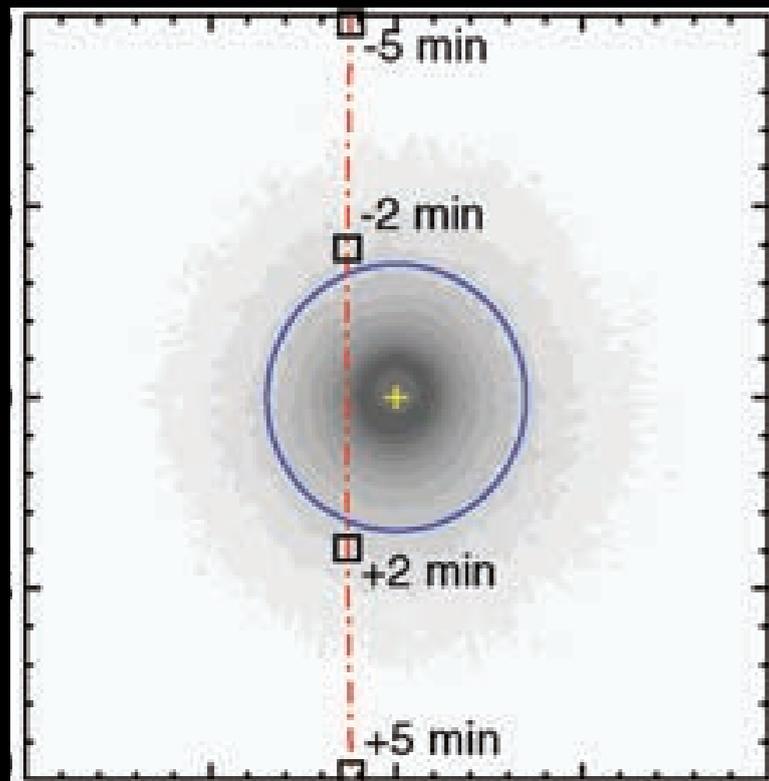
Mass Yield ~ 4000

Koschny & Grün, Icarus, 2001; Krivov et al., Icarus, 2003

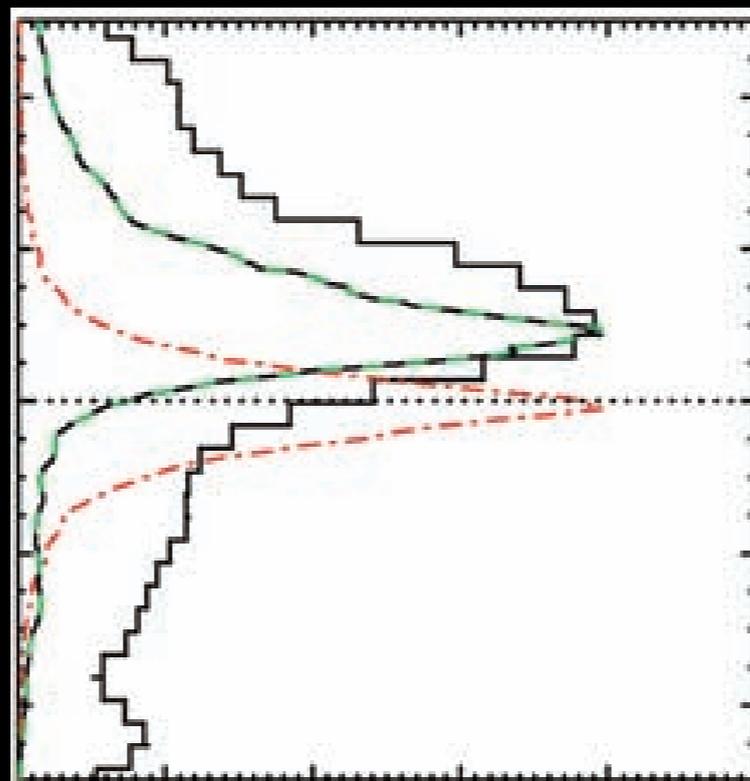
- Gravitationally Bound Ejecta Populate Cloud
- Some Ejecta Escape:
 - Feed Rings
 - Mass Loss Mechanism

Discovery (MAG, INMS, CDA): South Pole Ice Geysers

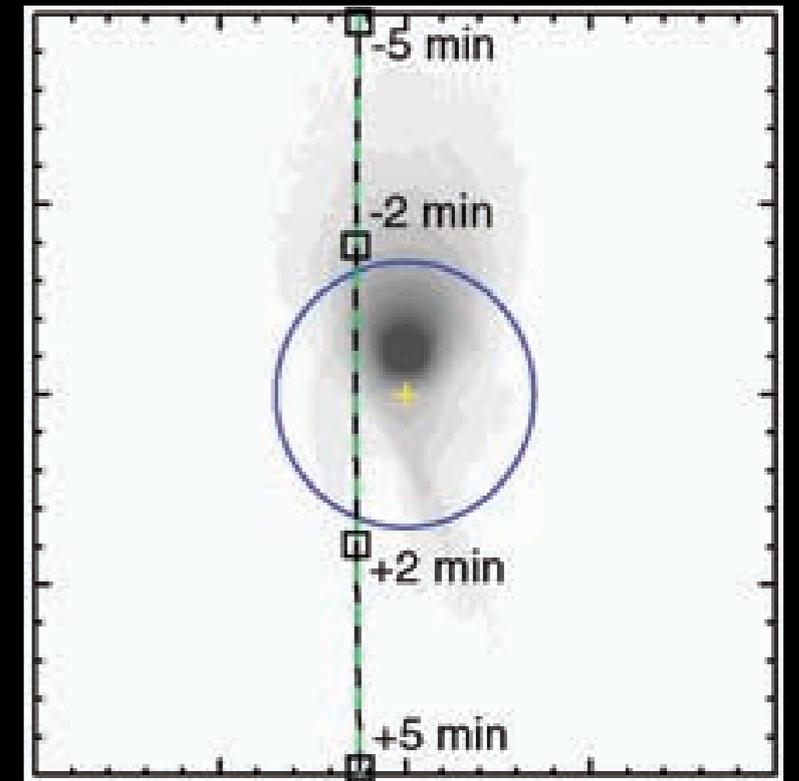
Dust Cloud



Dust Data



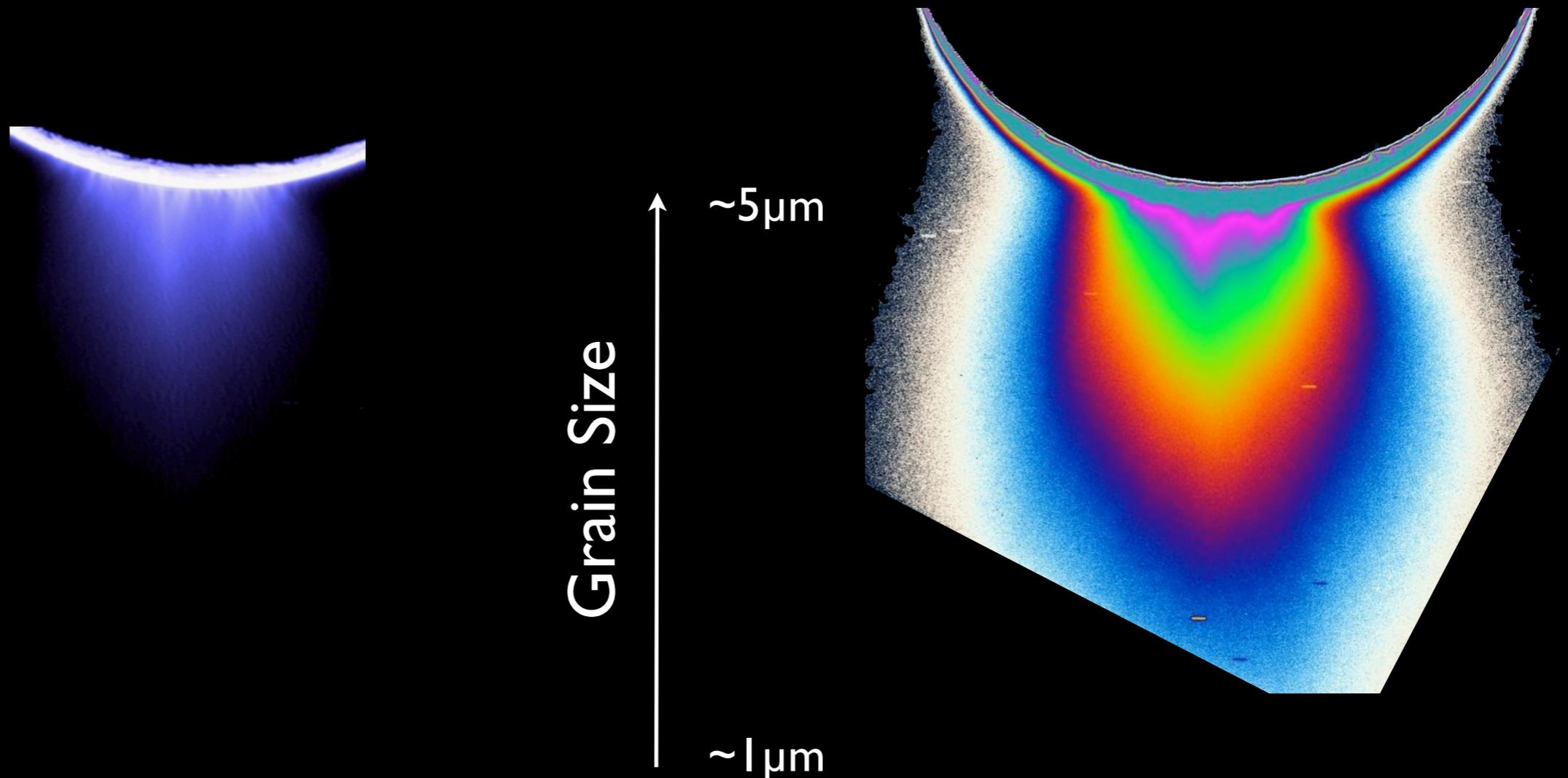
Dust Plume



Spahn et al., Science, 311, 2006

peak rate not at closest
approach

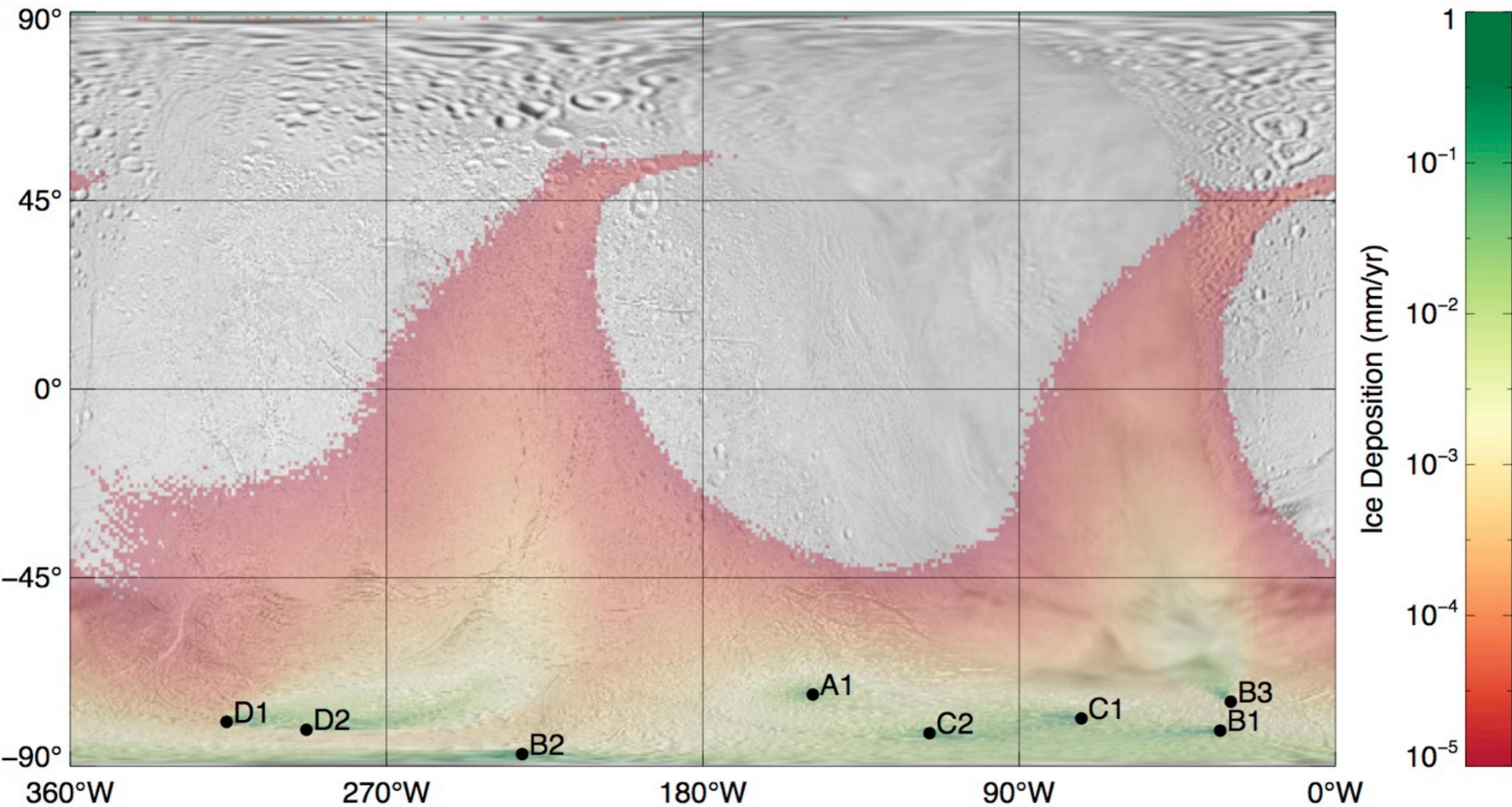
Geyser Grains Slower Than Escape Speed



Hill Radius $\sim 950 \text{ km}$

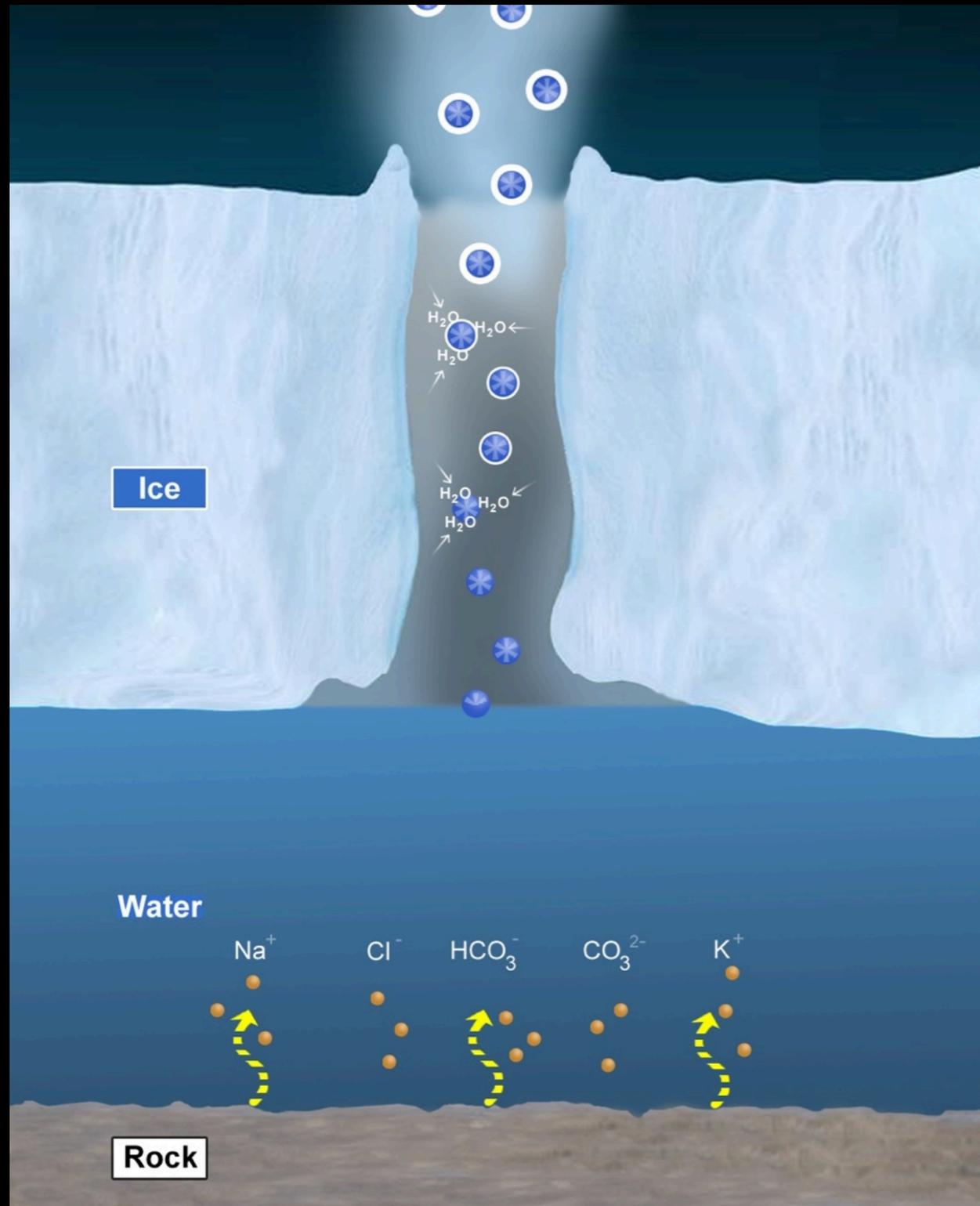
Escape Speed $\sim 207 \text{ m/s}$

Snow on Enceladus !



Salty icy grains : Direct Evidence for Subsurface Liquid Water Reservoir

Water + Rocky Core



Water Dissolves Akali Salts

Zolotov, Geophys. Res. Lett., 34, 2007



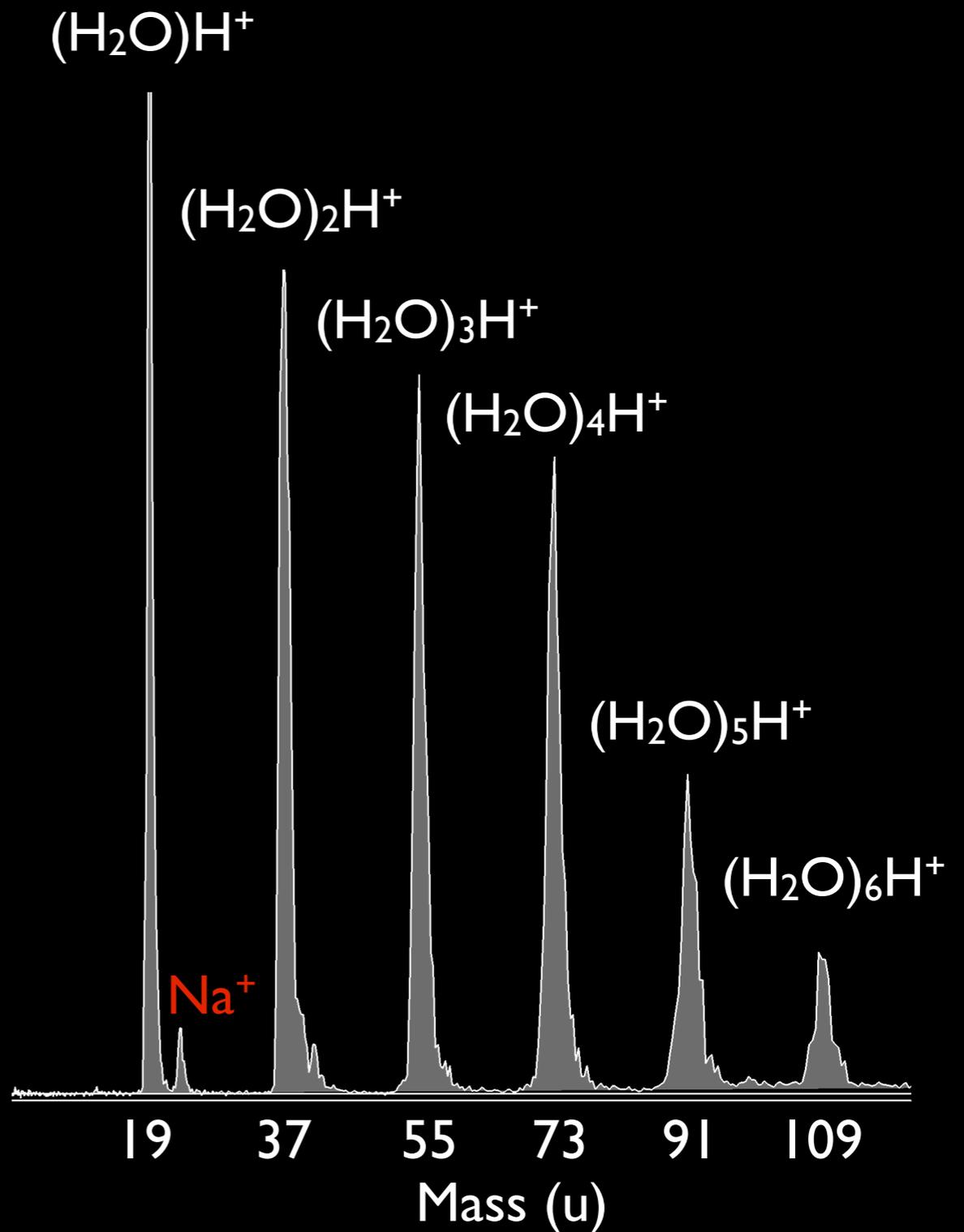
Ice Grains Should be Salty!

Dust Composition

Cassini Dust Detector CDA



Geyser Water Ice Grain



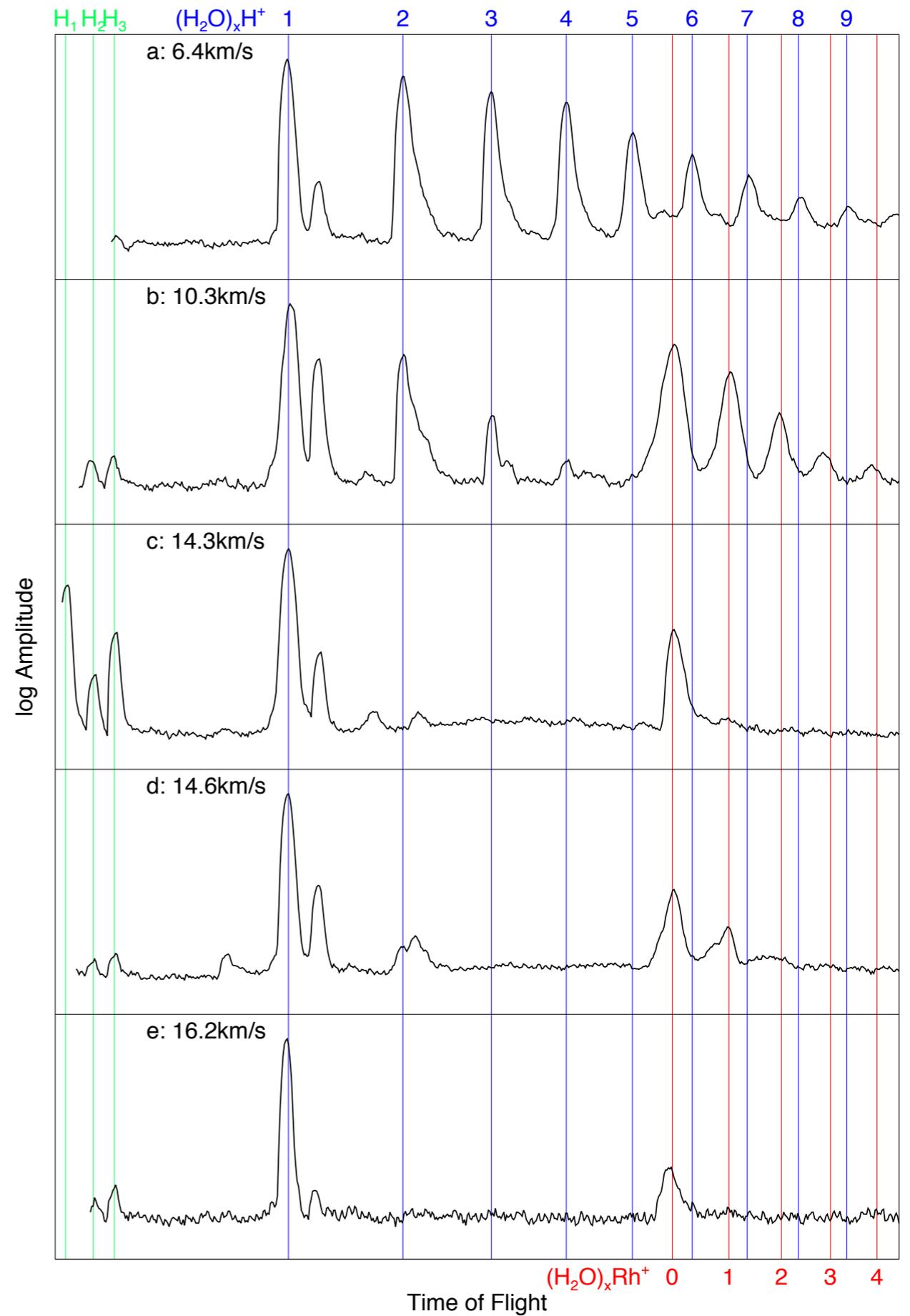
TOF Mass spectra (Cassini-CDA)

< 6 km/s

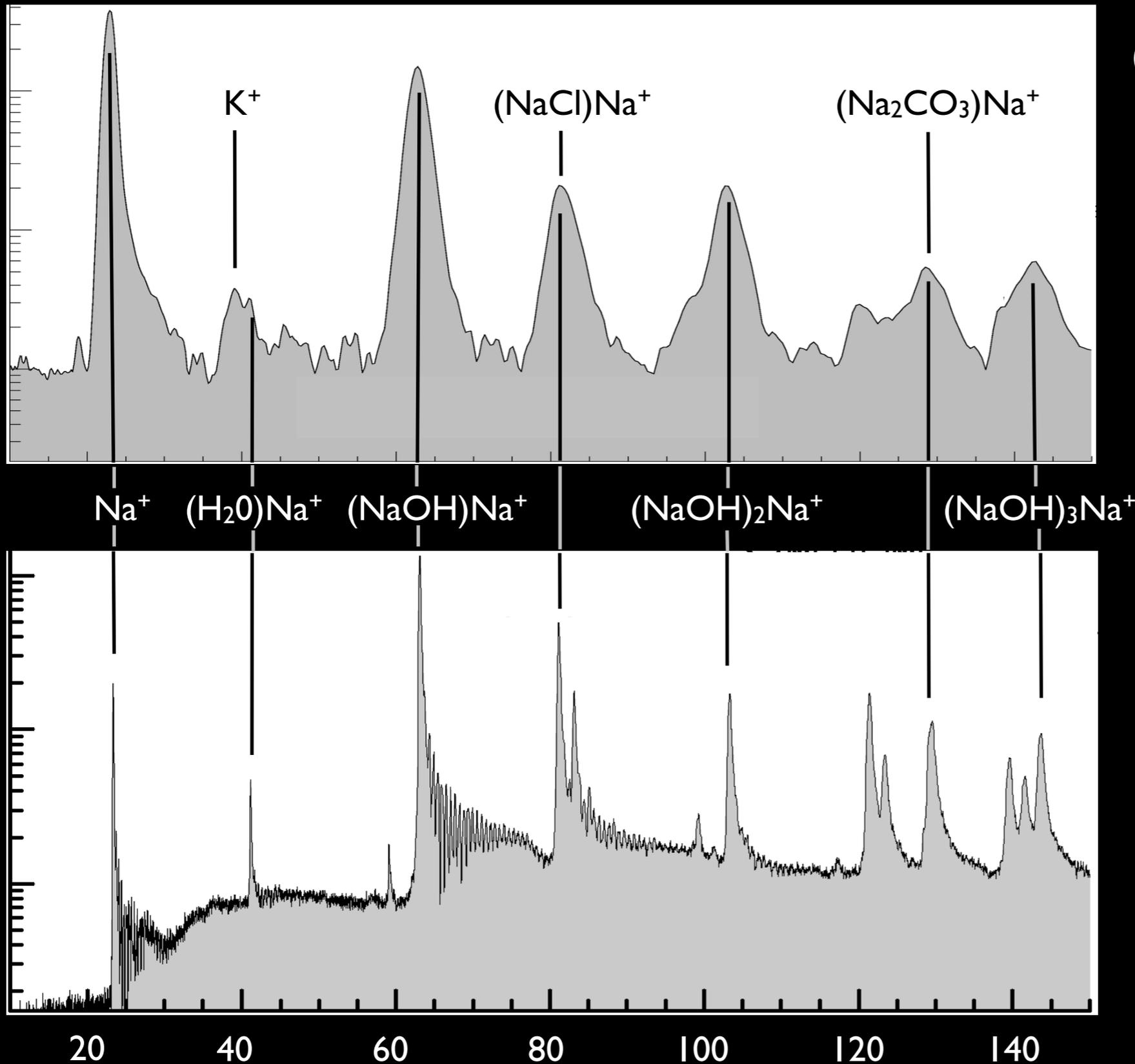
Cluster length



16 km/s



Salty Ice Grains - measured in E ring



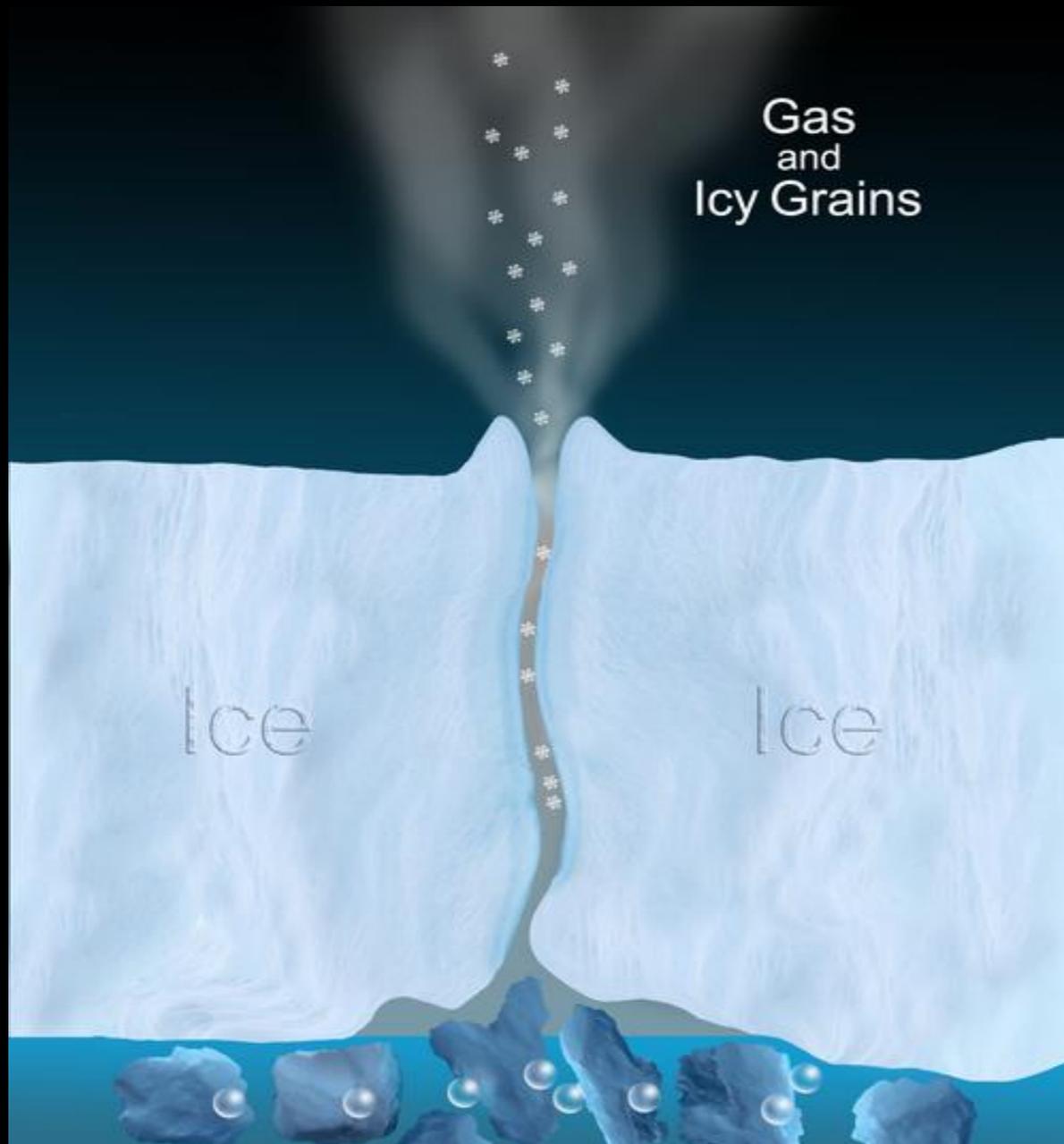
Co-Added CDA
Spectrum:

Salt-rich Geyser
Ice Grains
(6%)

Lab Spectrum:

Laser Dispersion
of Salt Water

Results from Dust Measurements: Enceladus Ocean

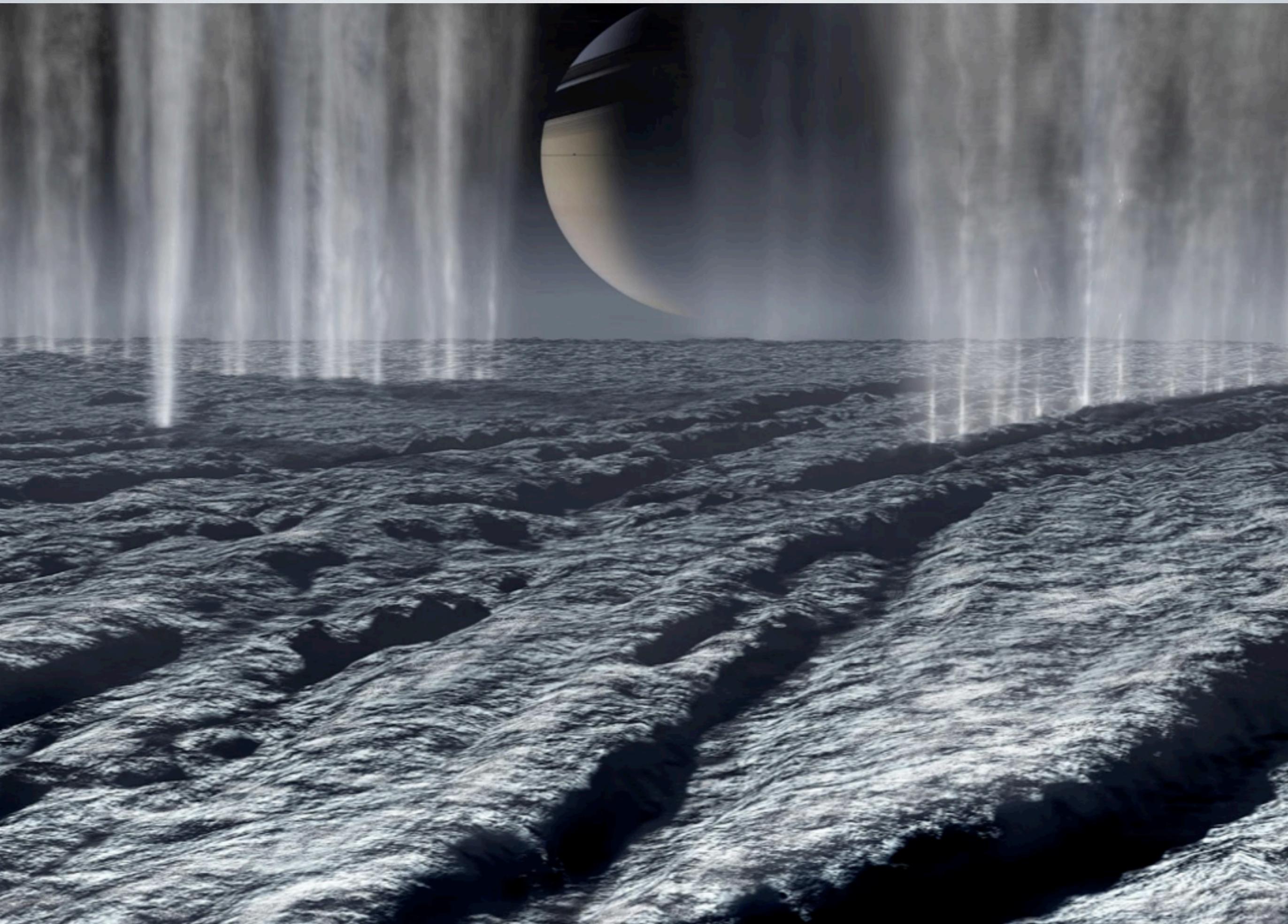


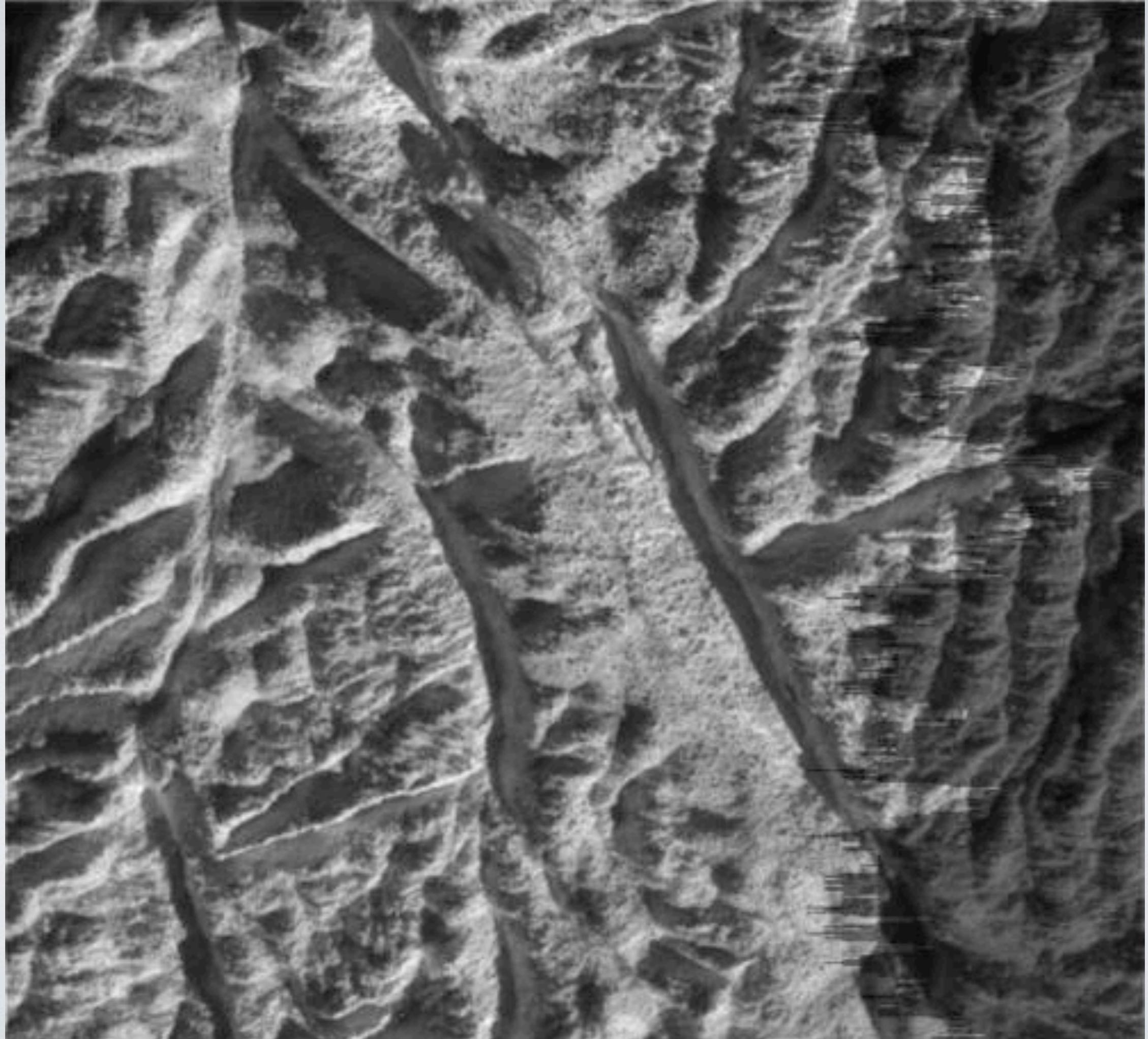
„Soda“ Ocean

Rich in Carbonates

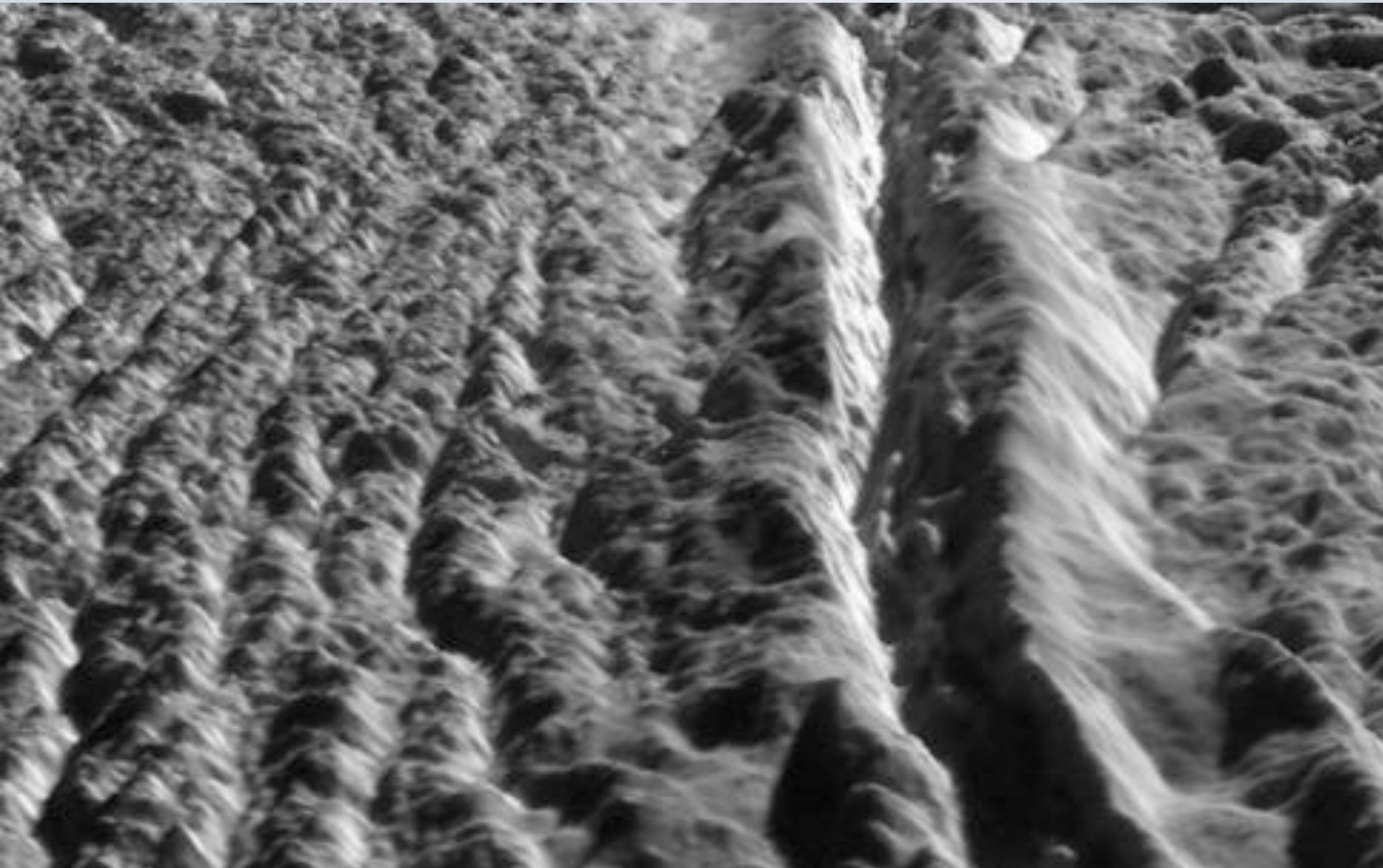
pH ~ 9

Salinity ~ 1% (Earth 1..4%)





ARTISTS WERE ALMOST RIGHT



ENCELADUS REALITY

thanks to: NASA/JPL

S. Kempf, G. Moragas-Klostermeyer

F. Postberg, E. Grün, M. Burton, M. Roy

S. Hsu, H. Krüger, M. Horanyi, U. Beckmann, P. Strub,

N. Altobelli, V. Sterken, J. Schmidt, F. Spahn, ...

Cassini-CDA project grant by DLR

