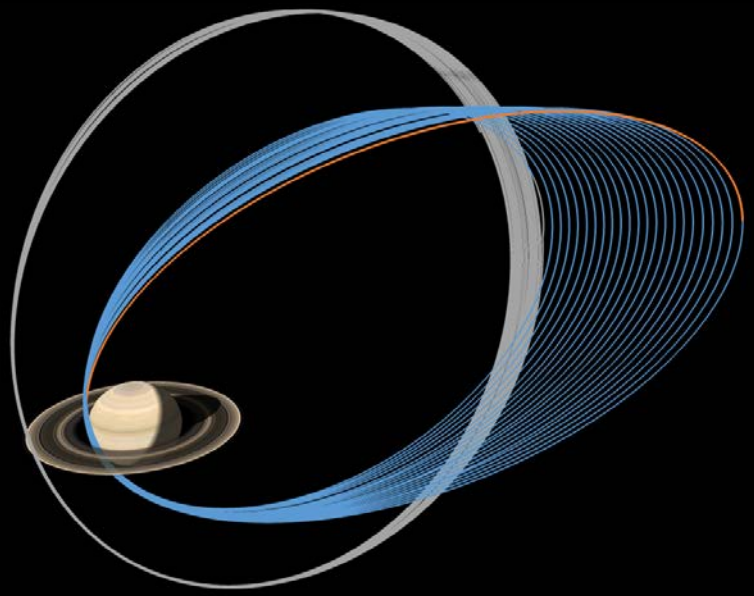

# Cassini-Huygens Science Highlights and Cassini's Grand Finale

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Asia Oceania Geosciences Society

1 August 2016

*Jet Propulsion Laboratory, California Institute of Technology

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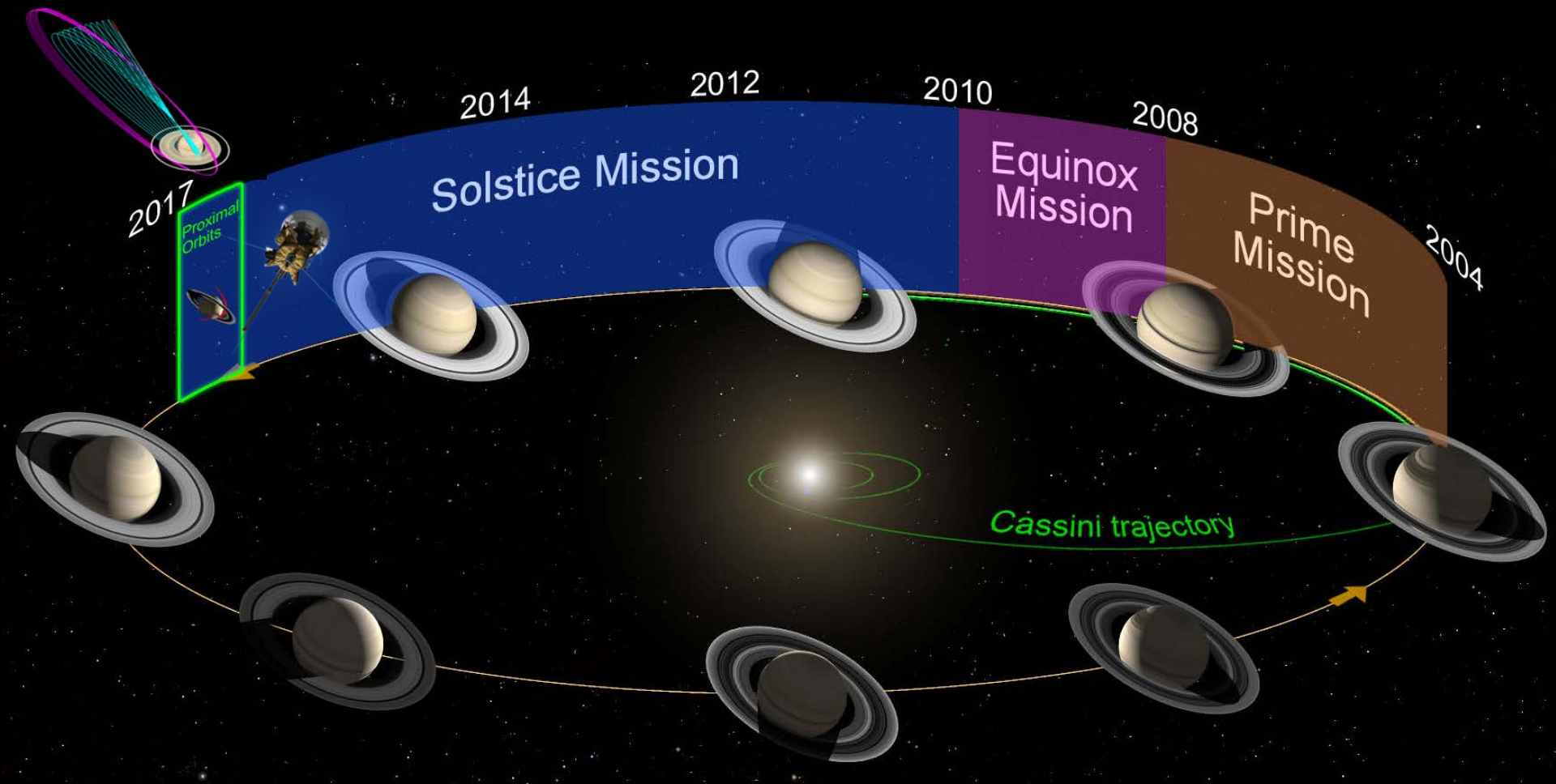
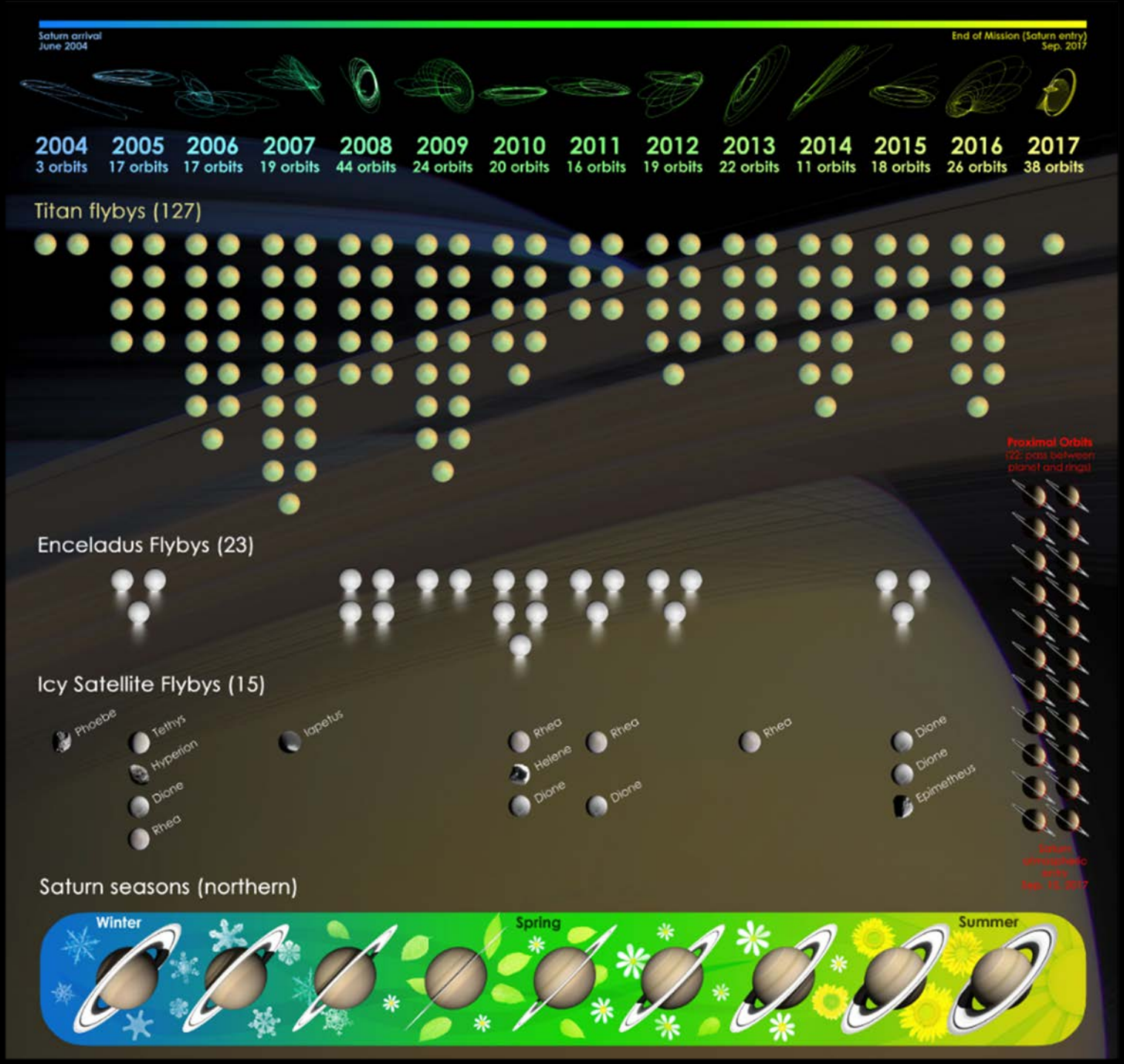
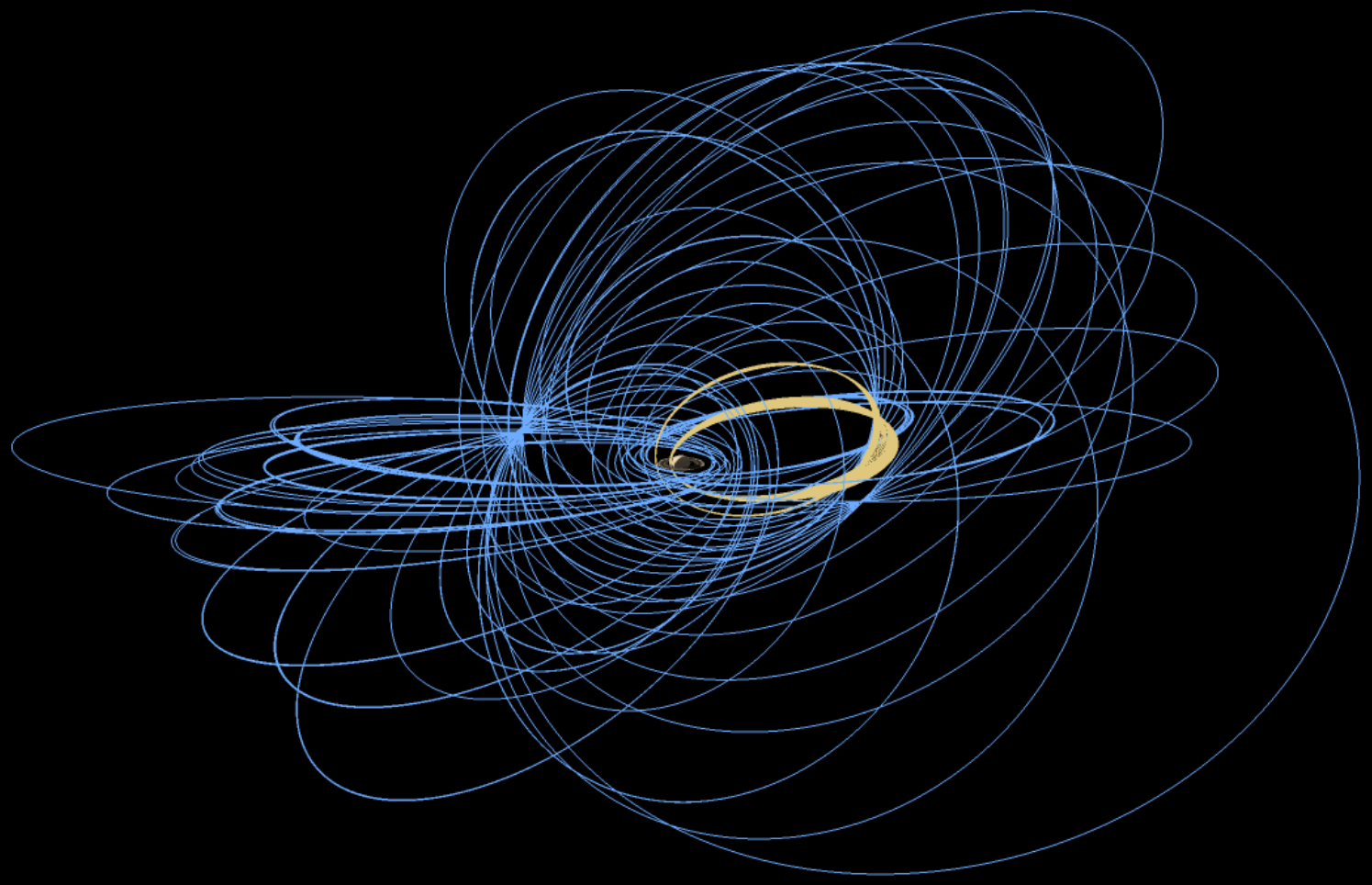
# Cassini-Huygens Mission Overview

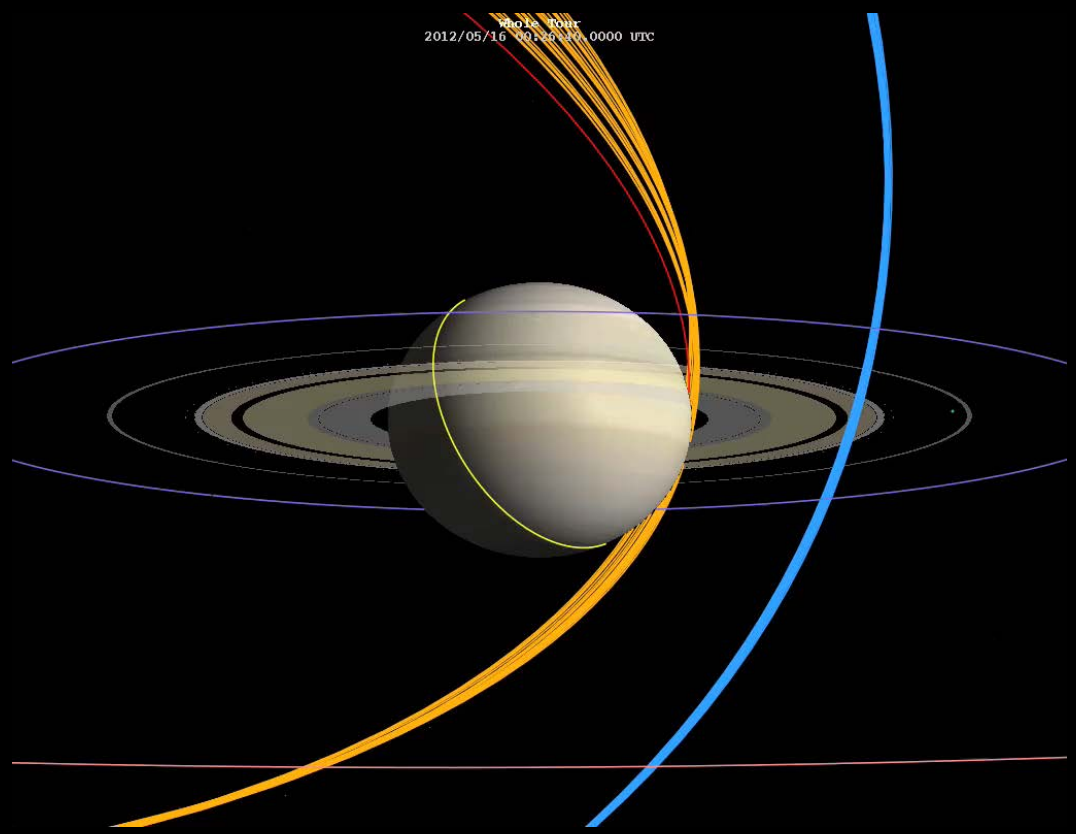



Saturn arrival
June 2004
End of Mission (Saturn entry)
Sep. 2017
2004 3 orbits
2005 17 orbits
2006 17 orbits
2007 19 orbits
2008 44 orbits
2009 24 orbits
2010 20 orbits
2011 16 orbits
2012 19 orbits
2013 22 orbits
2014 11 orbits
2015 18 orbits
2016 26 orbits
2017 38 orbits
Titan flybys (127)
Proximal 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

# Solstice Mission Trajectory



# Key Orbital Characteristics of Final Orbits

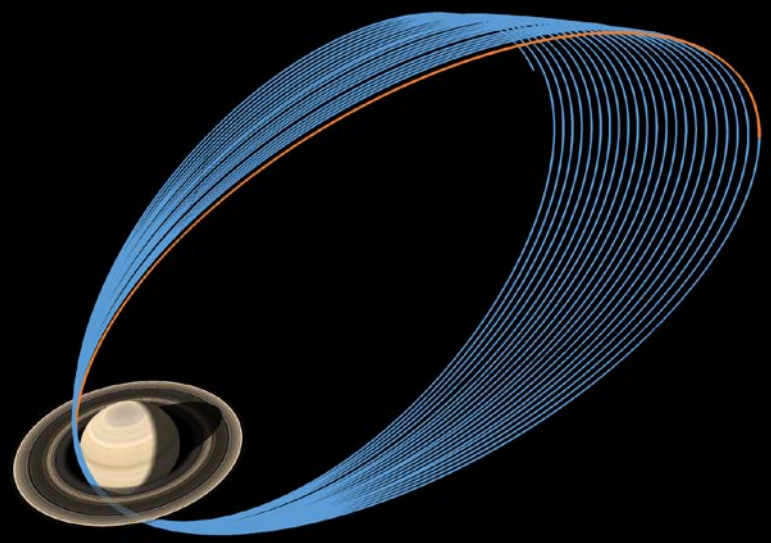



- 42 short-period orbits
  - Nov. 2016 to Sept. 2017

20 F-ring orbits

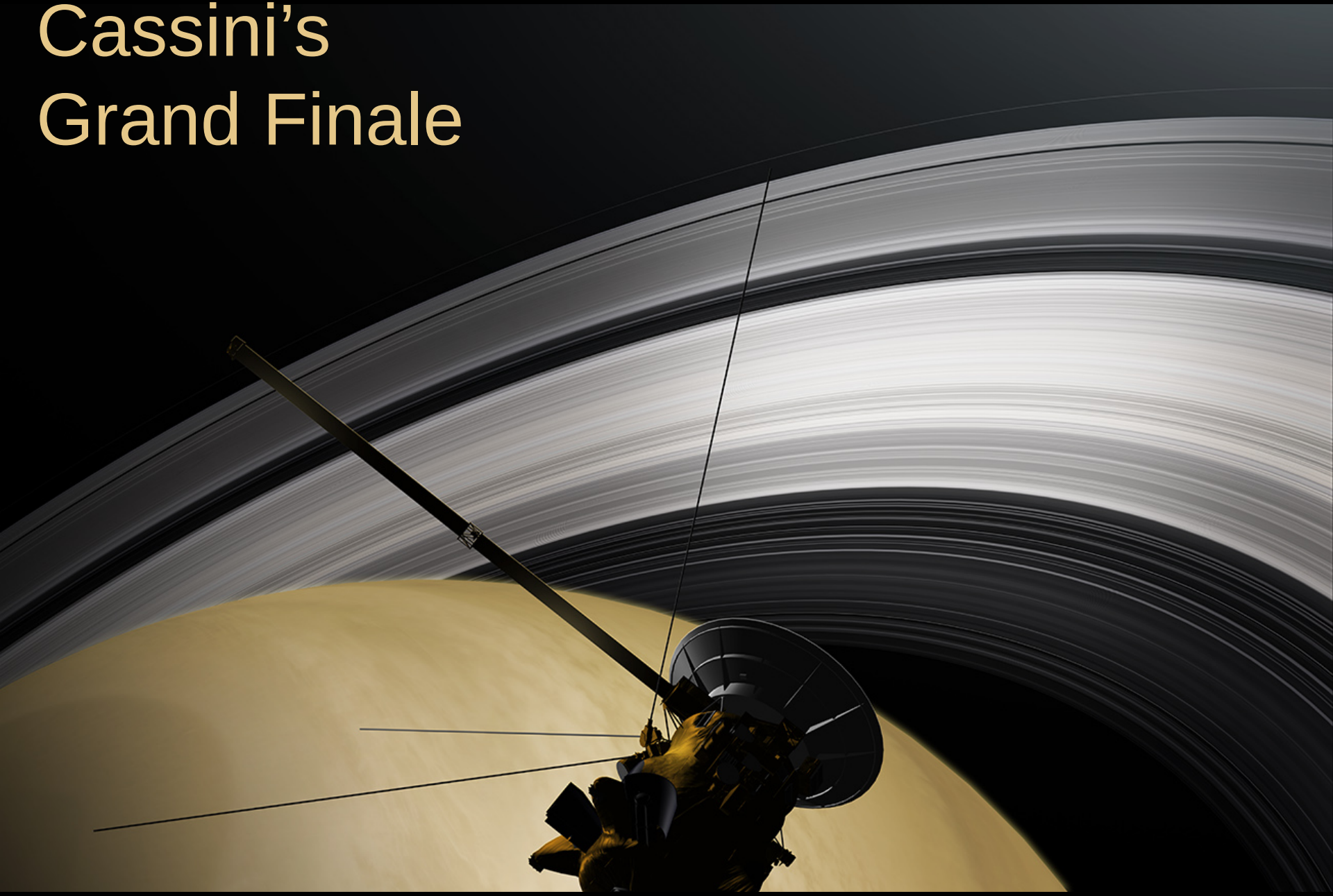
- Periapses just outside Saturn's F ring
- Sets up Cassini for final jump to orbits inside D ring
- Scientifically rich
  - High resolution F and A ring observations
  - Ring occultations (Earth and Solar)
  - Auroral field line crossings at r = 3.4 - 4 $R_S$

# Grand Finale (Proximal) Orbits

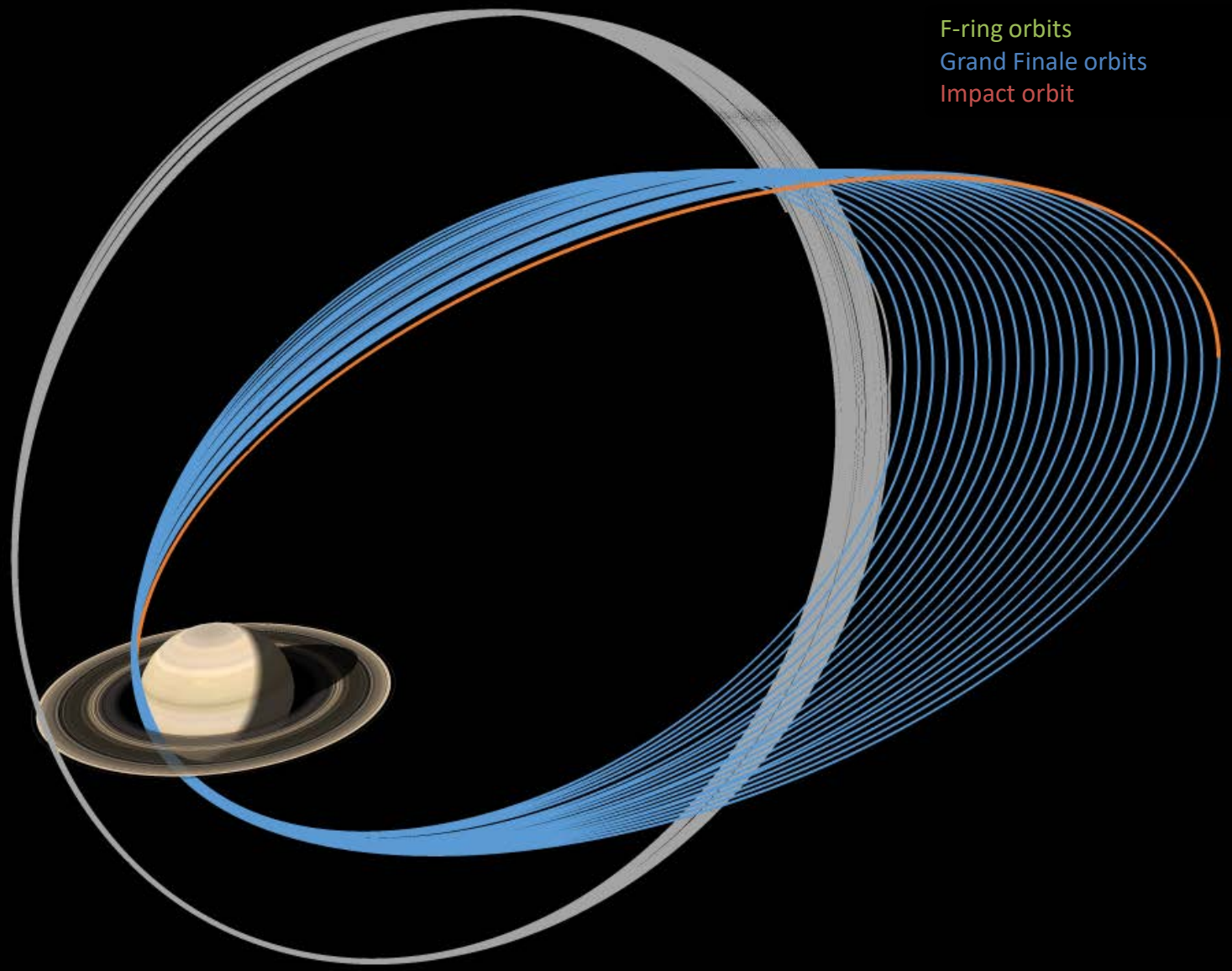


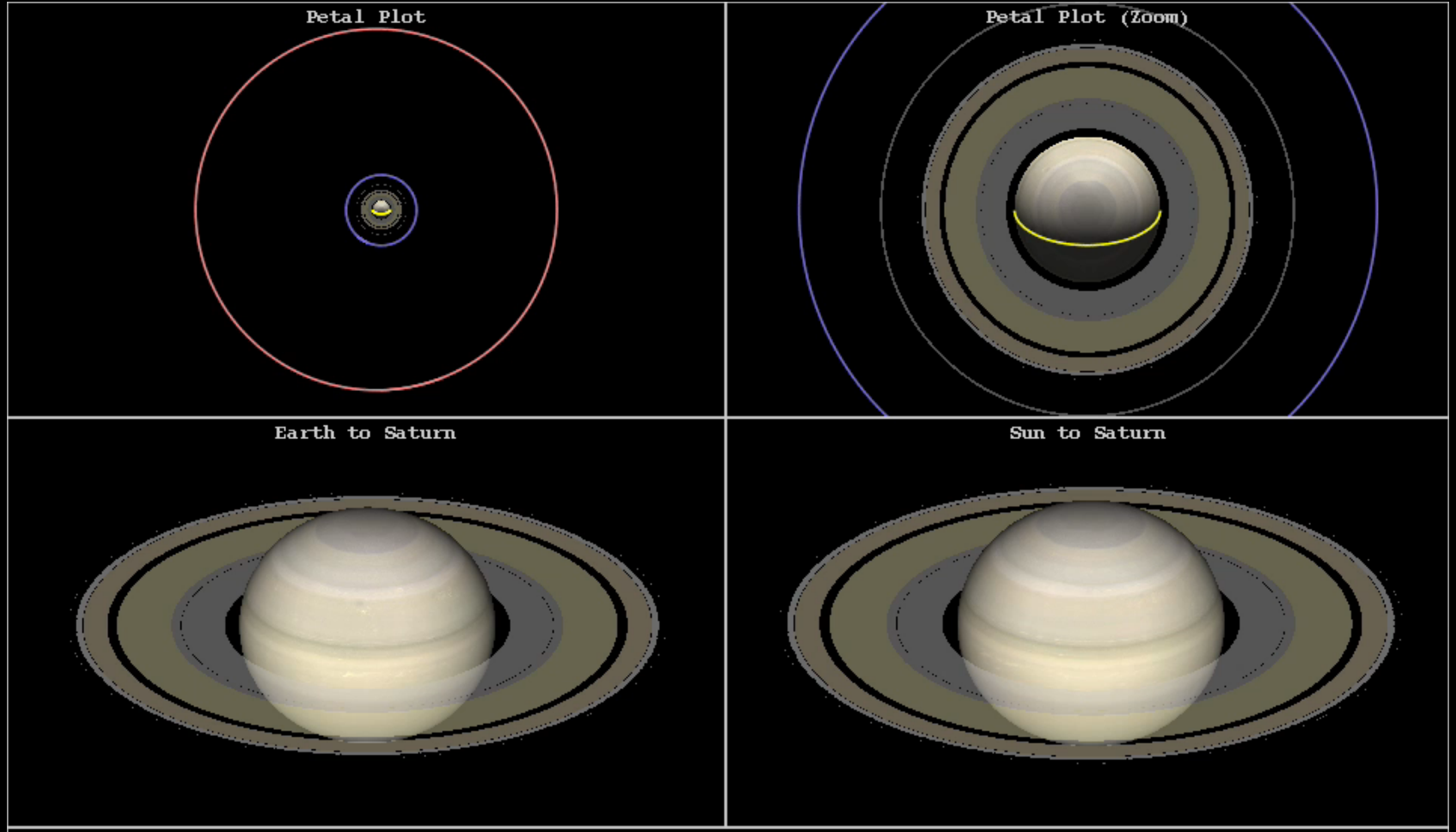
- 22 Grand Finale orbits
  - Periapses in 2,200 km “clear” region
  - First orbit April 2017 (next year during EGU!)
  - Critical inclination: 63.4°
- If delta v is available, go lower if Saturn upper atmosphere continues to shrink
- Current impact date: 15 September 2017
- Juno-like mission with Cassini instruments

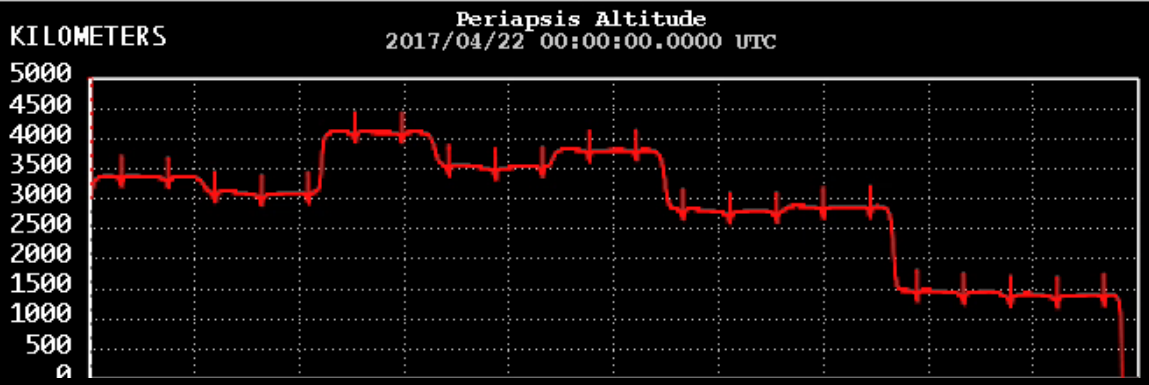
# Cassini's Grand Finale



# Final 42½ Orbits

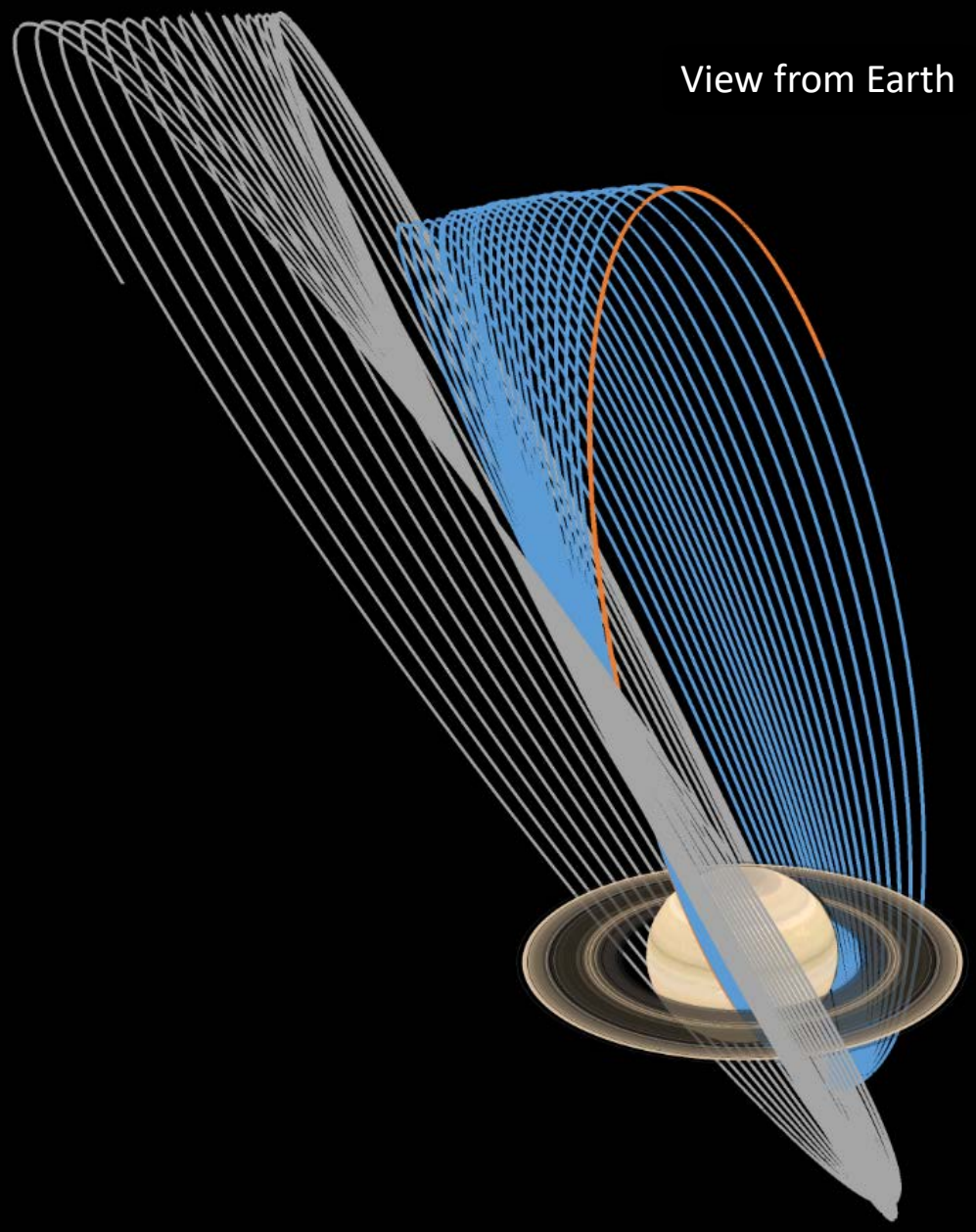





Apr. 22, 2017 July 1, 2017 Sept. 15, 2017

View from Earth

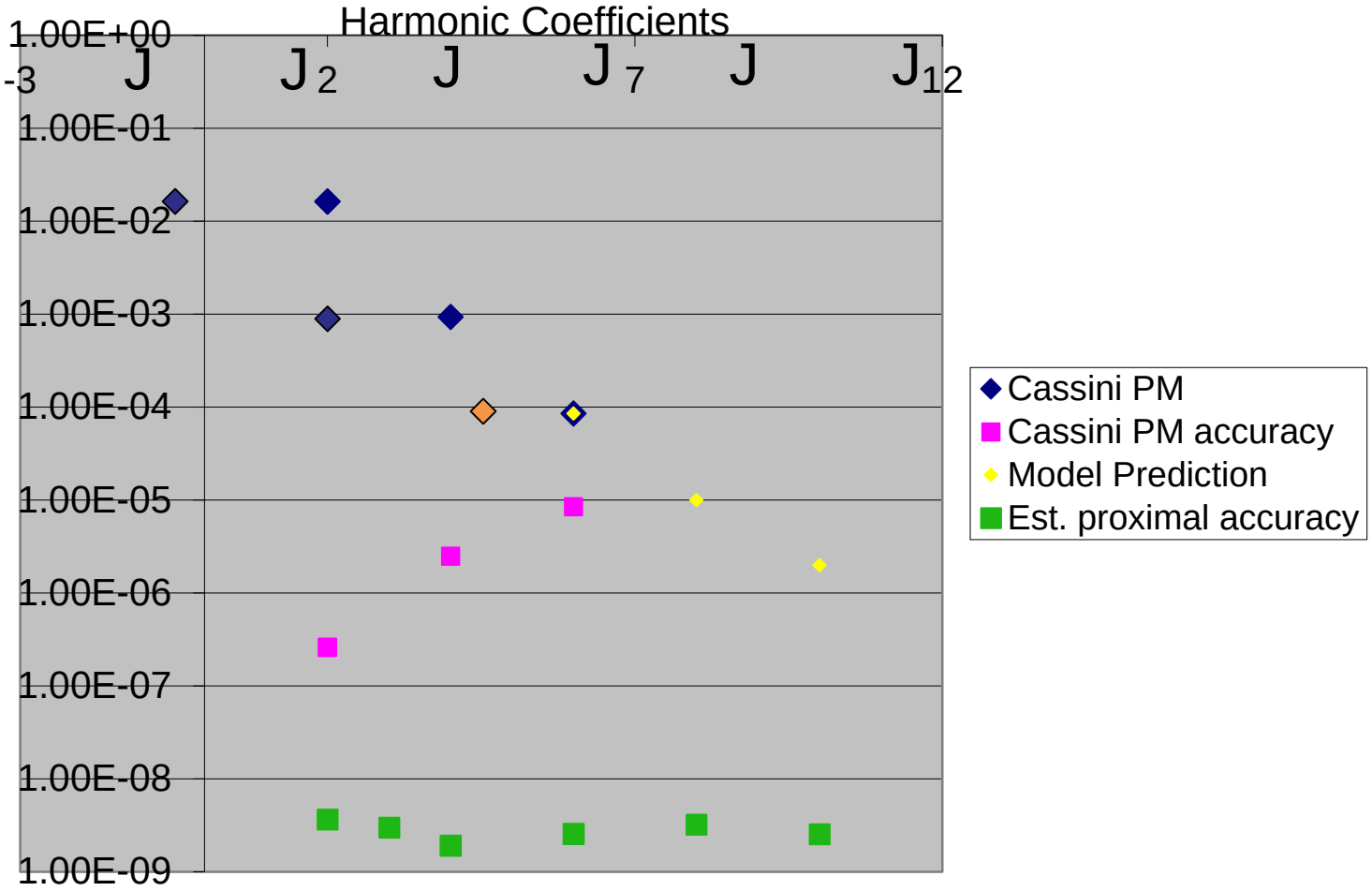


# F Ring and Grand Finale Earth Occultations

# Unique End-of-Mission Science

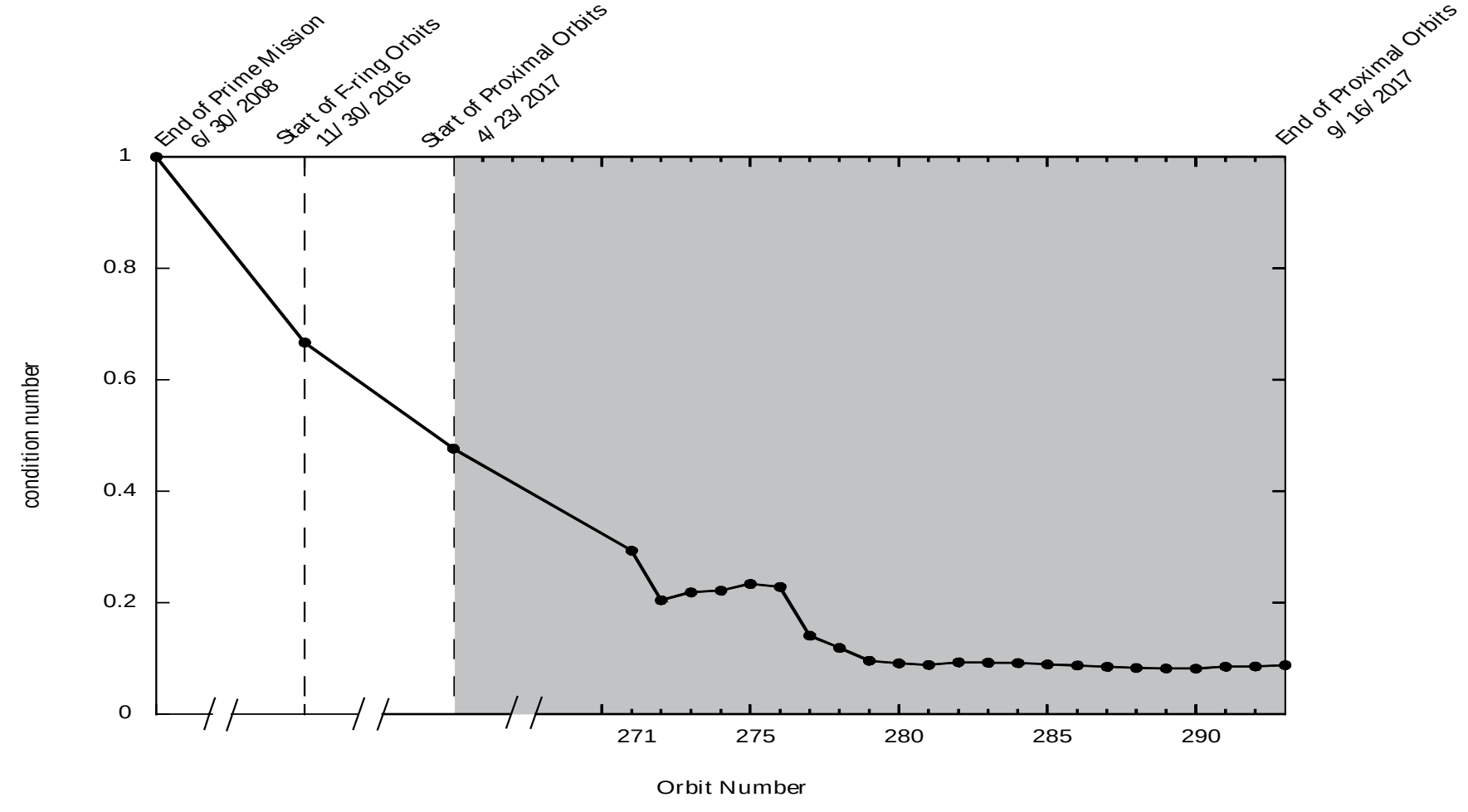
- Saturn internal structure
  - Gravitational & Magnetic Fields measurements
  - Determine Saturn's gravity field to order $J_{10}$
  - Determine Saturn's higher order magnetic field components
  - Measure Saturn's internal rotation rate

# Saturn Internal Structure: Gravity Harmonics



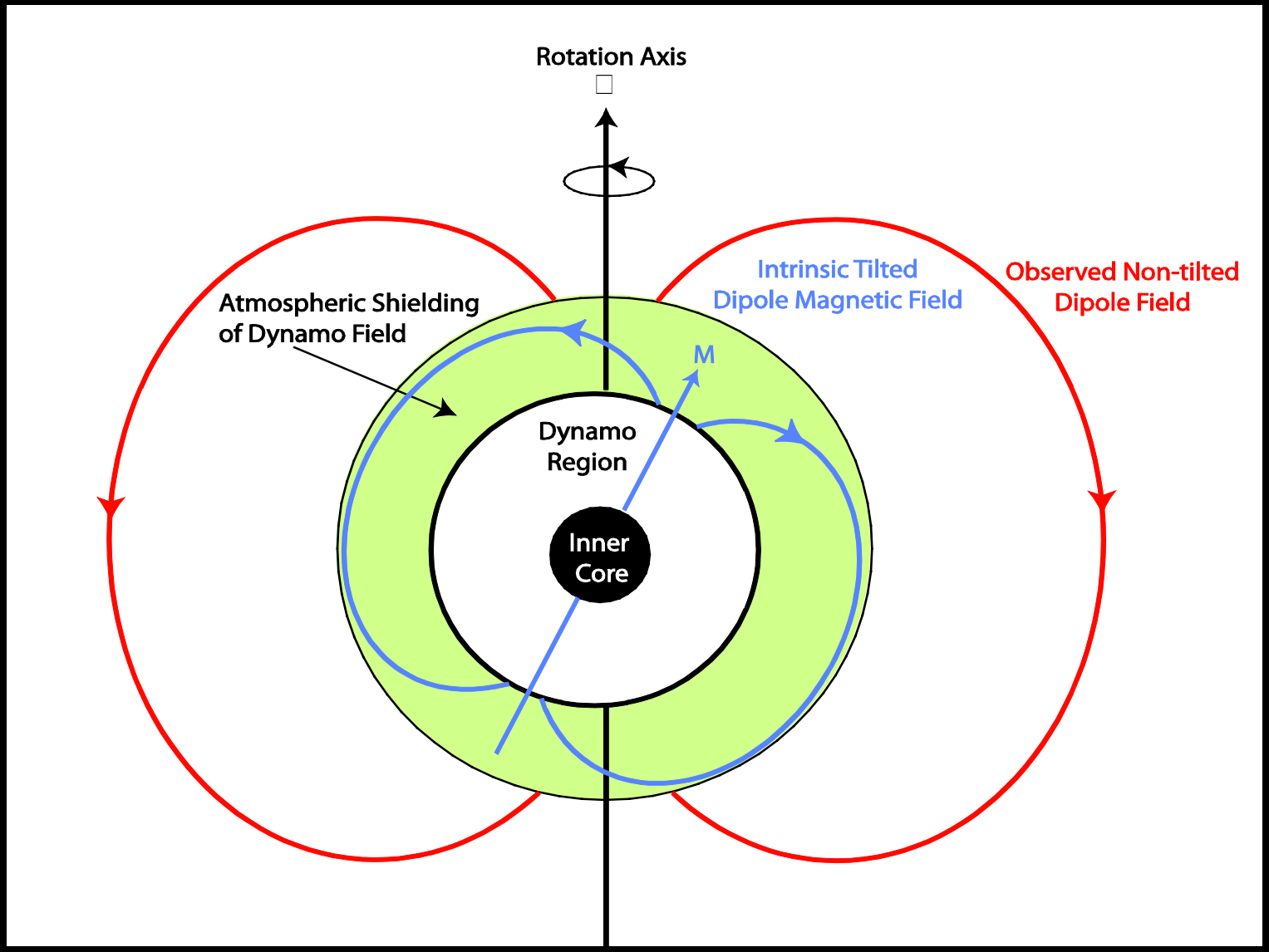

- Saturn gravity harmonics (zonal) up to degree 10 can be estimated with an accuracy < $10^{-8}$ (with multiarc solution using 6 proximal orbits for gravity passes)

# Saturn Internal Structure: Magnetic field



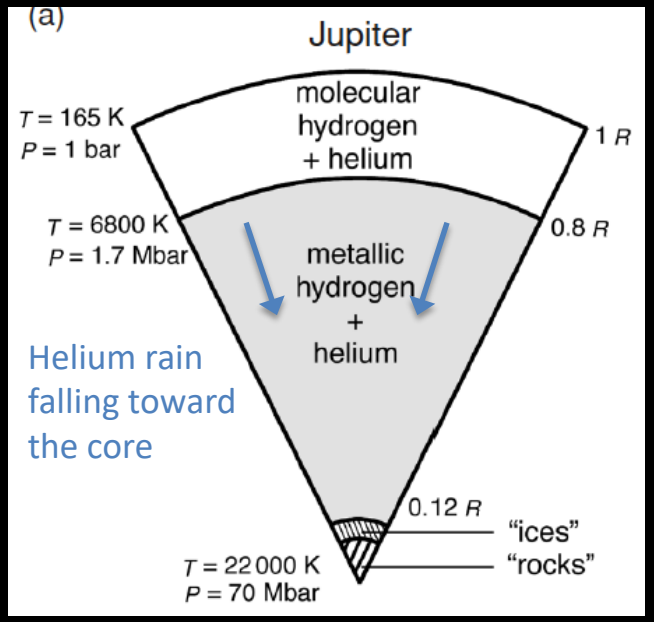

- Condition number is a measure of the accuracy with which a magnetic field model can be determined based on spacecraft trajectory.
- Significant improvement possible with periapse inside D ring.
- May be possible to determine depth of Saturn's conducting, metallic core.

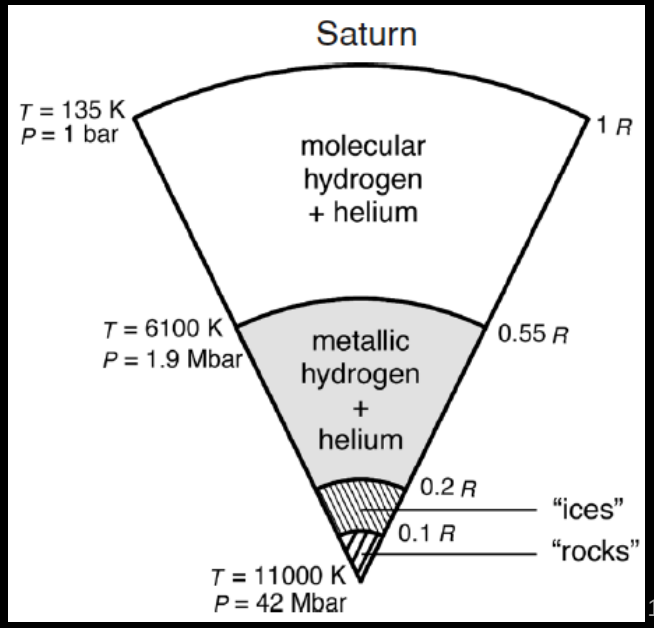
# Saturn Internal Magnetic field: Tilted Dipole?



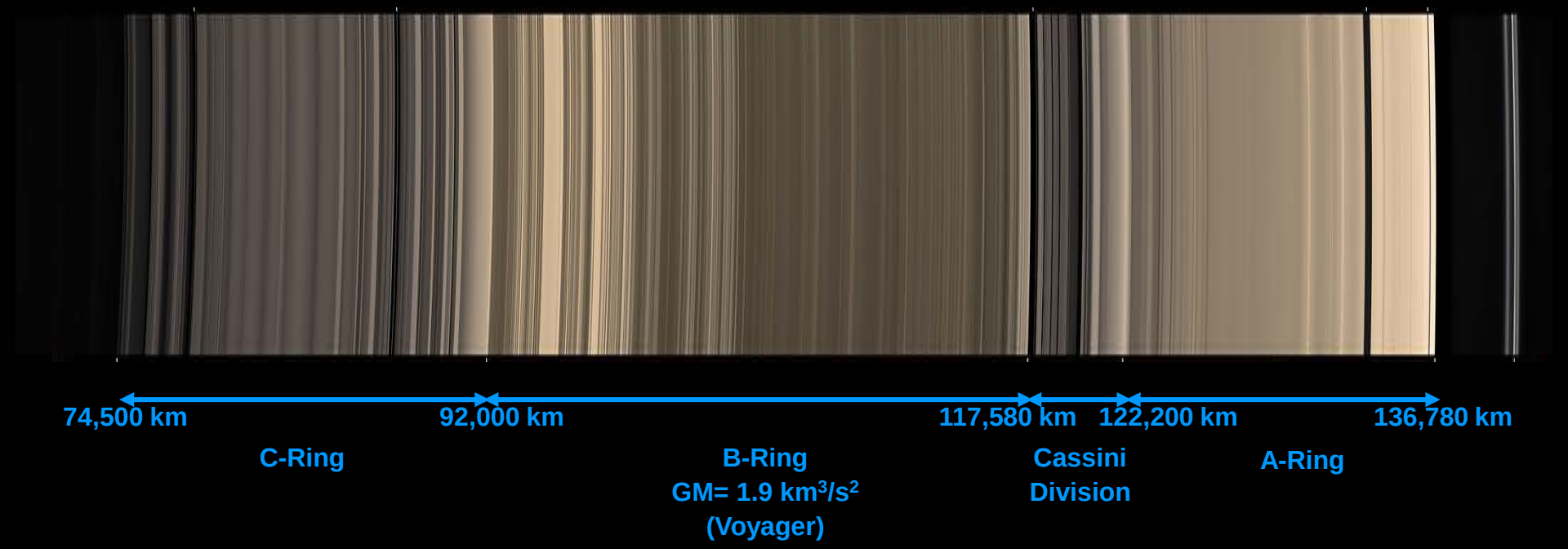
# Probe Saturn's Interior

$He/H_2$ in the atmosphere is a clue to cooling history and phase separation in the interior



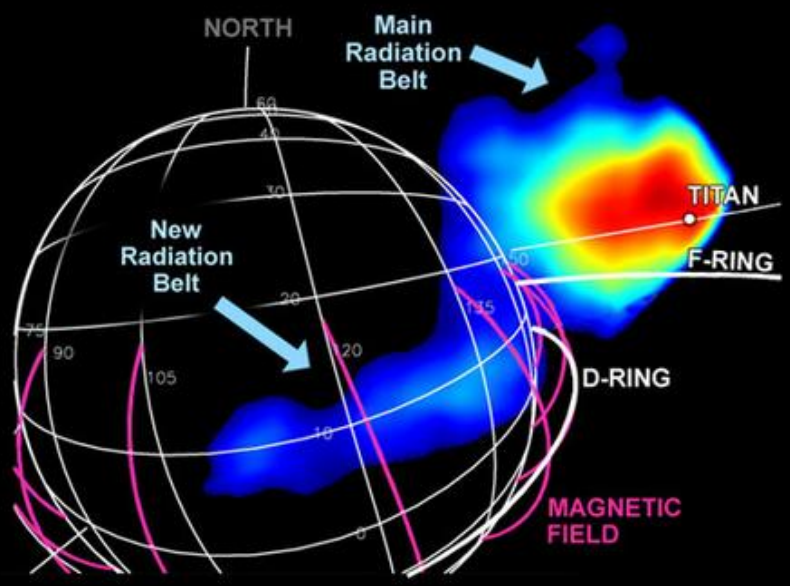



# Ring Mass: Constrain age of rings



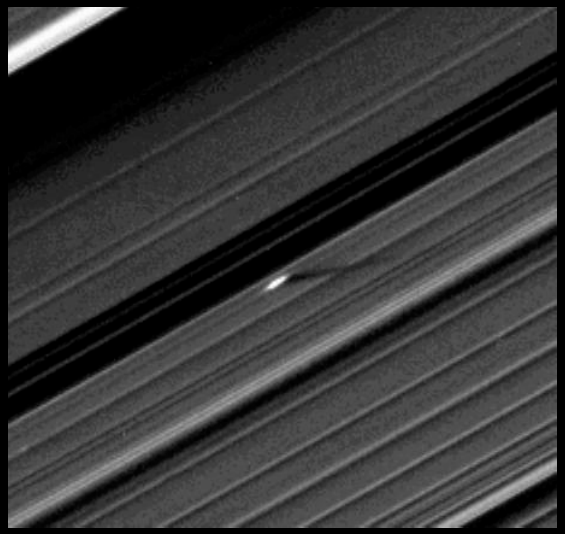

- Without proximal orbits, a-priori ring mass uncertainty is 100% of nominal values
- 6 orbital arcs for ring mass (and Saturn gravity) provide estimation accuracy for total ring $\delta GM \sim 0.34\ km^3/s^2$ (~5%)

# Ionosphere, innermost radiation belts & inner D ring particles

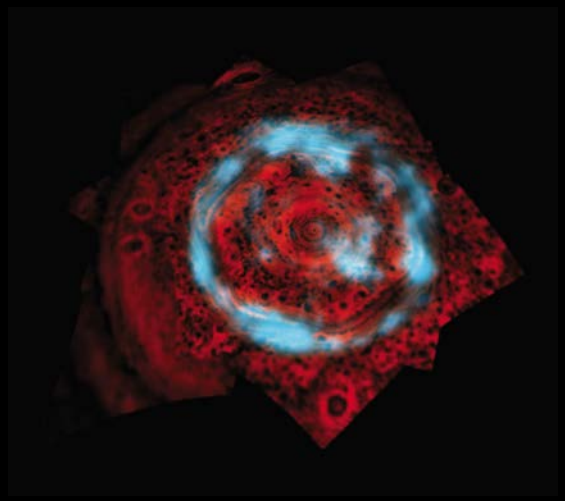



- Measure *in situ* plasma of Saturn's ionosphere, innermost radiation belts and D ring for the first time
- *In situ* observations of Saturn's auroral magnetosphere at solstice

# Unique End-of-Mission Science

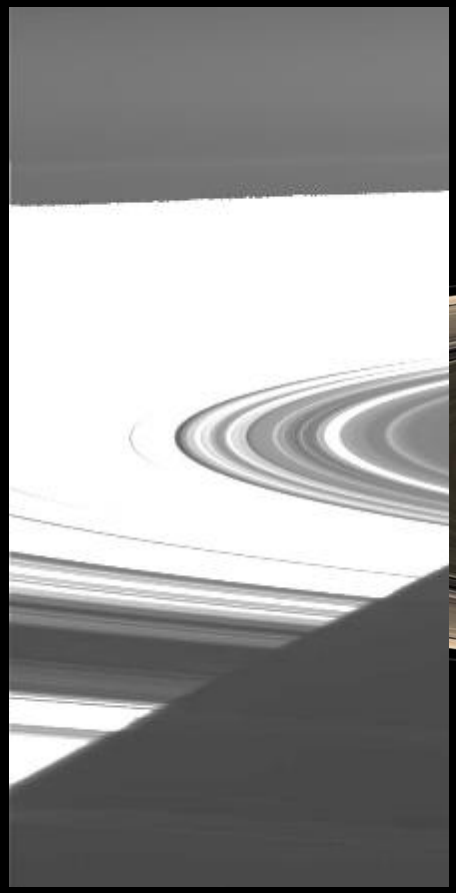


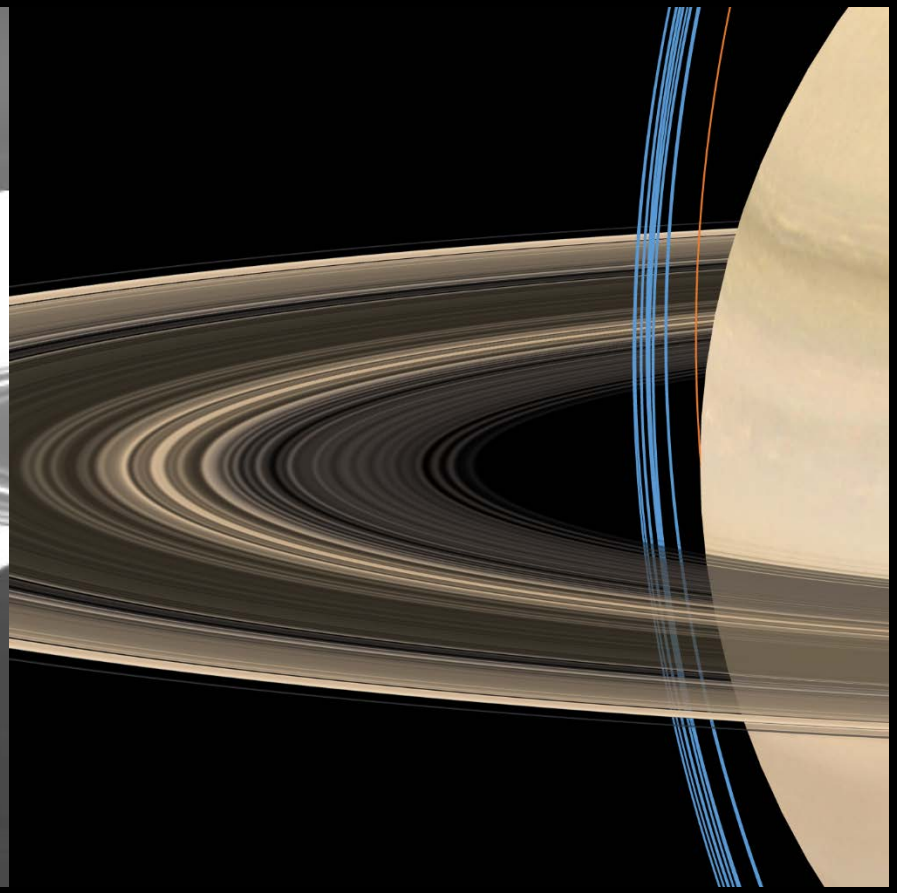
- Highest resolution main ring observations
  - First Active Radar of the Rings



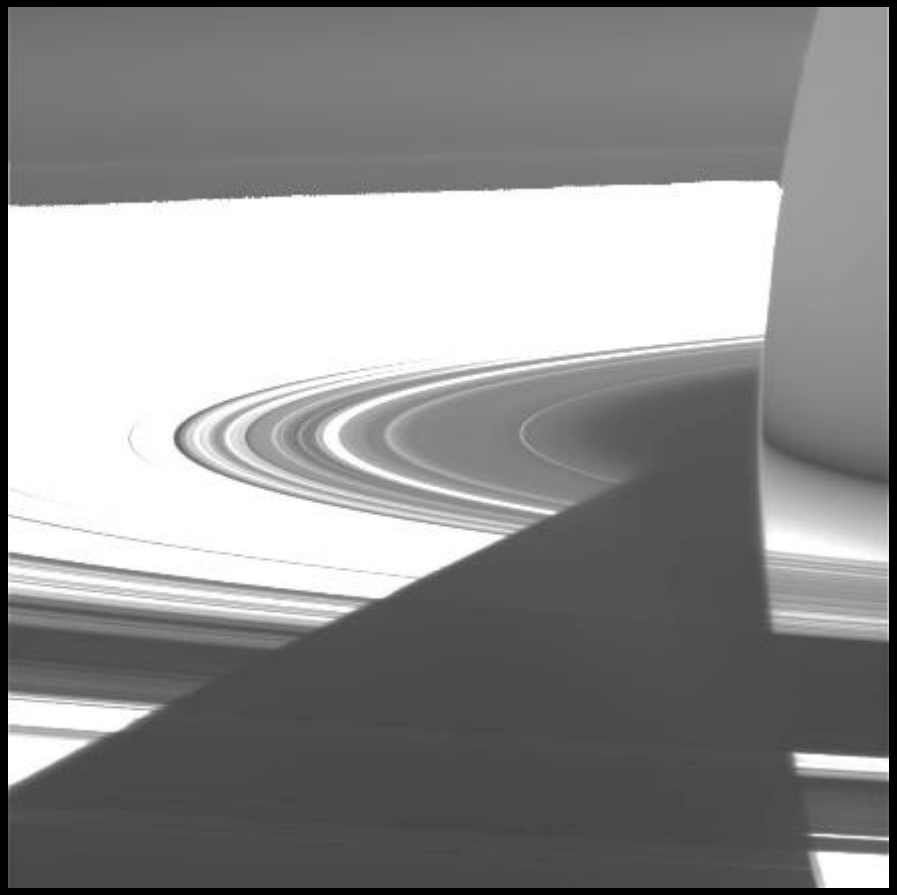
- Highest resolution Saturn atmospheric studies including polar observations and aurora

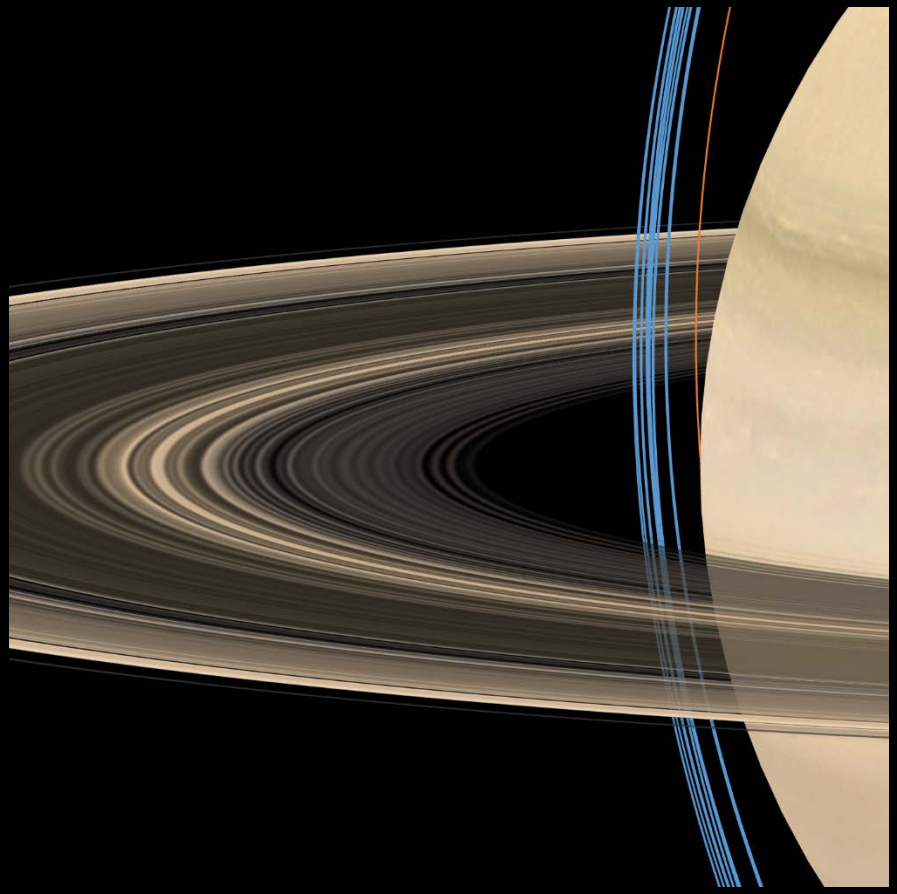
# Grand Finale Environment



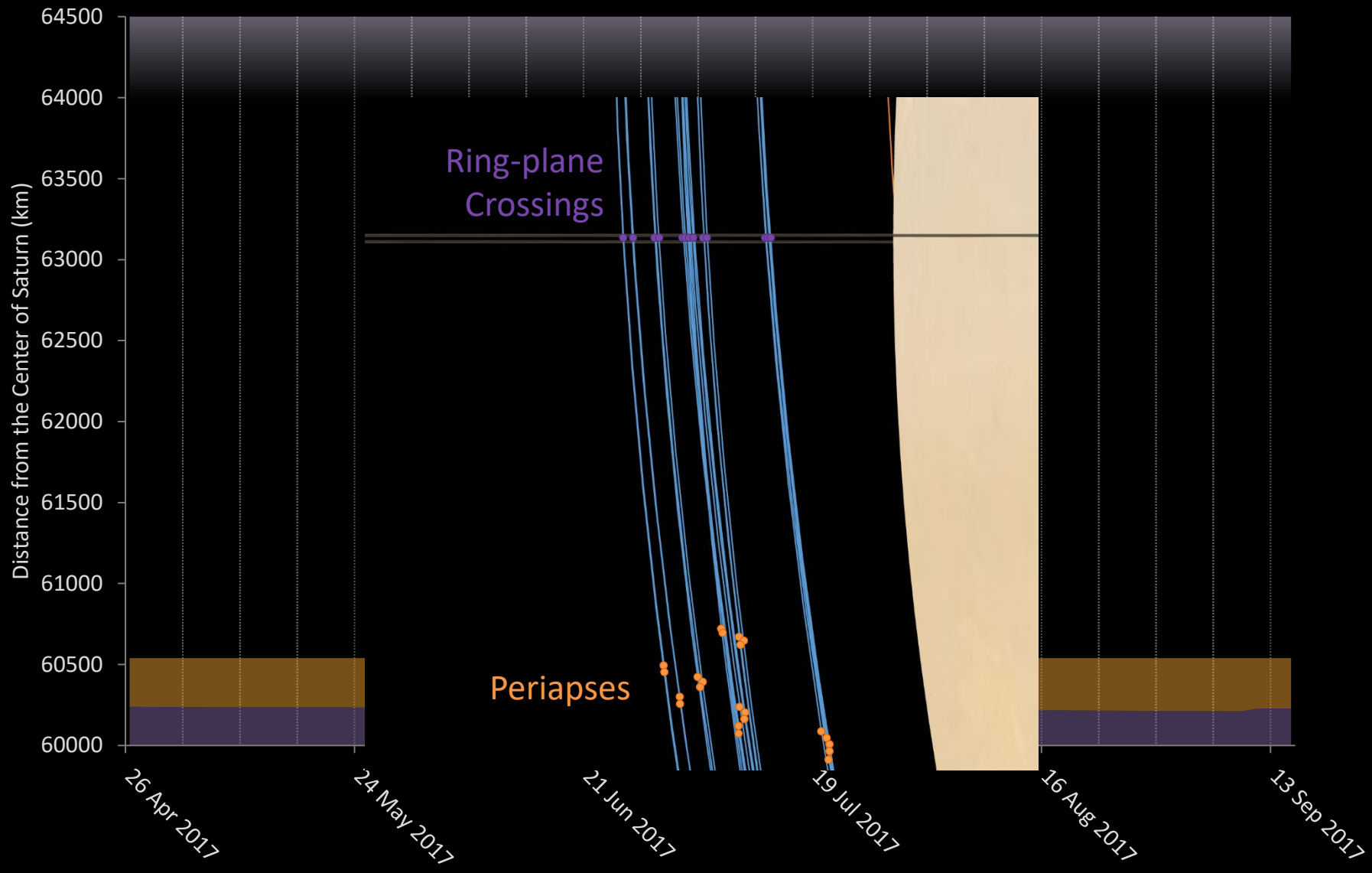


# Grand Finale Environment

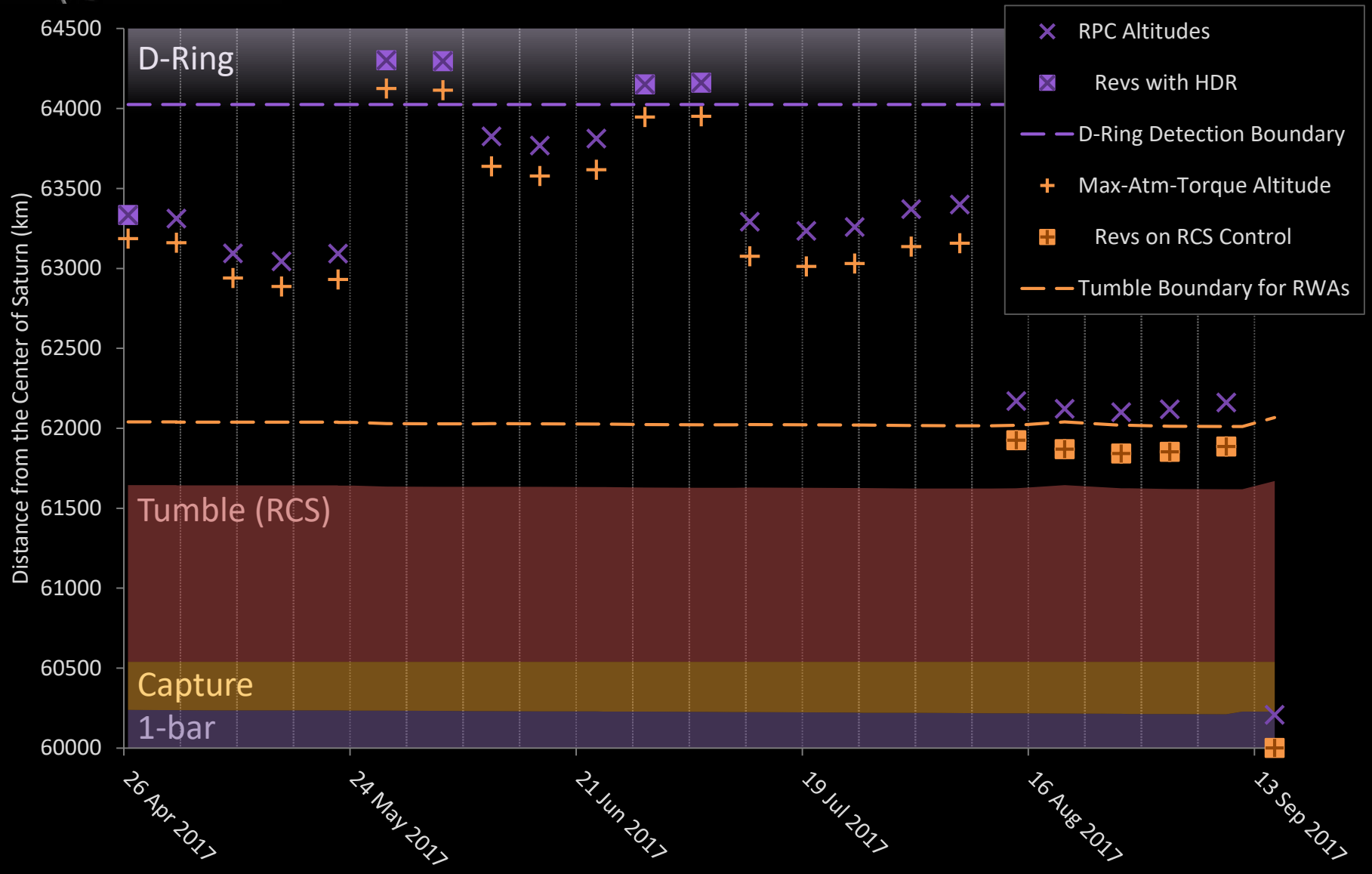




# Grand Finale Environment



# Grand Finale Corridor



# Between Rings & Planet 22 Times

**Option 9 (updated in Sept 2015)**

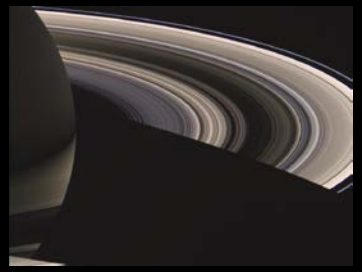
| Rev | 271 | 272 | 273 | 274 | 275 | 276 | 277 | 278 | 279 | 280 | 281 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Intermediate Altitude Periapses (~63,000 km) | | | | | High Altitude Periapses (~64,000 km) | | | | | |
| **RCS control at periapse** | | **RCS 3:08** | | | | | | | | | |
| **Sequence** | S100 | S100 | S100 | S100 | S100 | S100 | S100 | S100 | S100 | S100 | S100 |
| **Segment owner** | Saturn | XD | Maps | Rings | Saturn | Rings | Rings | Saturn | Maps | XD | Saturn |
| **Primary Pointing** | NEG_Y to Saturn | MAG rolling (with SRU pauses) | XBAND to Earth (SP prime) | XBAND to Earth | XBAND to Earth | | | XBAND to Earth | NEG_X to RAM | XBAND to Earth | NEG_Y to Saturn |
| **Secondary axis** | | x-axis roll | z-axis roll | NEG_X to SSP [0,0,20] | NEG_X to SSP [0,0,20] | | | NEG_X to SSP [0,0,-10] | NEG_Z to SATURN | NEG_X to SSP [0,0,-10] | |
| **Comments on Pointing** | *** ORS on Saturn** | | **INMS phasing Unique: RSS3, RWA Full, CDA articulating (VIMS/ISS/UVIS sleep)** | | | | | | | | *** ORS on Saturn** |
| **Op Mode** | | | | | | | | | | | |
| peri-12 to -6 hrs | | | RSS | RSS | RSS | | | RSS | | RSS | |
| peri -6 to -5 hrs | | | RSS | RSS | RSS | | | RSS | | RSS | |
| peri -5 to -4 hrs | | MAG | RSS/MAG | RSS | RSS | | | RSS | | RSS | |
| peri -4 to -3 hrs | | MAG | RSS/MAG | RSS | RSS | | | RSS | | RSS | |
| peri -3 to -2 hrs | | MAG | RSS/MAG | RSS | RSS | | | RSS | | RSS | |
| peri -2 to -1 hrs | CIRS N Pol | MAG | RSS/MAG | RSS | RSS | RADAR Rings | ISS Rings | RSS | | RSS | ISS Saturn |
| peri-60 to-45 min | ISS Saturn | MAG | RSS/MAG | RSS/CDA | RSS/CDA | RADAR Rings | ISS Rings | RSS/CDA | INMS/CDA | RSS/CDA | ISS Saturn |
| peri -45 to-30 min | ISS Saturn | MAG | RSS/MAG | RSS/CDA | RSS/CDA | RADAR Rings | ISS Rings | RSS/CDA | INMS/CDA | RSS/CDA | ISS Saturn |
| peri-30 to-10 min | Slew* | MAG | RSS/MAG | RSS/CDA | RSS/CDA | Slew | Slew | RSS/CDA | INMS/CDA | RSS/CDA | Slew* |
| peri-10 to -0 min | HGA to RAM* | MAG | RSS/MAG | RSS/CDA | RSS/CDA | HGA to RAM | HGA to RAM | RSS/CDA | INMS/CDA | RSS/CDA | HGA to RAM* |
| peri 0 to +10 min | HGA to RAM* | MAG | RSS/MAG | RSS/CDA | RSS/CDA | HGA to RAM | HGA to RAM | RSS/CDA | INMS/CDA | RSS/CDA | HGA to RAM* |
| peri+10 to+30 min | Slew* | MAG | RSS/MAG | RSS/CDA | RSS/CDA | Slew | Slew | RSS/CDA | INMS/CDA | RSS/CDA | Slew* |
| peri+30 to +45min | ISS Saturn | MAG | RSS/MAG | RSS/CDA | RSS/CDA | ISS Rings | RADAR Rings | RSS/CDA | INMS/CDA | RSS/CDA | ISS Saturn |
| peri +45 to +60 min | ISS Saturn | MAG | RSS/MAG | RSS/CDA | RSS/CDA | ISS Rings | RADAR Rings | RSS/CDA | INMS/CDA | RSS/CDA | ISS Saturn |
| peri+1 to +2 hrs | CIRS S Pol | MAG | RSS/MAG | RSS | RSS | ISS Rings | RADAR Rings | RSS | | RSS | CIRS S Pol |
| peri+2 to +3 hrs | | MAG | RSS/MAG | RSS | RSS | | | RSS | | RSS | |
| peri+3 to +4 hrs | | MAG | RSS/MAG | RSS | RSS | | | RSS | | RSS | |
| peri+4 to +5 hrs | | MAG | RSS/MAG | RSS | RSS | | | RSS | | RSS | |
| peri+5 to +7 hrs | | | RSS | RSS | RSS | | | RSS | | RSS | |
| peri+7 to +12 hrs | | | RSS | RSS | RSS | | | RSS | | RSS | |
| **Temperature status** | COOL ORBIT | HOT ORBIT | N/A | N/A | N/A | COOL ORBIT | COOL ORBIT | N/A | HOT ORBIT | N/A | COOL ORBIT |
| **CIRS max delta_T** | 6.5K | 14.5K | 8.5K | 9K | 8.7K | 6K | 5.5K | 10.5K | 15.5K | 10.5K | 6K |
| **CIRS end delta_T** | 5K | 3.5K | 0.5K | 0.5K | 1K | 4K | 3.5K | 1K | 14K | 1K | 5.5K |
| **VIMS max T** | 65.8K | 69.4K | 66.2K | 66.8K | 66.7K | 63.8K | 63.7K | 67.6K | 66.2K | 67.7K | 65K |
| **VIMS max delta_T** | 6.2K | 7K | 6.5K | 7.2K | 7.1K | 4K | 4K | 8K | 6.5K | 8.1K | 5.8K |
| **VIMS end delta_T** | 6K | 2.4K | 2.5K | 3K | 3.2K | 3.7K | 3.7K | 3.5K | 6.3K | 3.8K | 5.2K |
| **SID suspend?** | outside POST | in MAG | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Data Volume estimate** | 1G, 4G avail | 300Mb, 3G avail | n/a | n/a | n/a | 2G; 688 avail | 2G, 1.7G avail | n/a | 200Mb, 2.5G avail | n/a | 1G, 3G avail |

# Between Rings & Planet 22 Times

| Rev | 282 | 283 | 284 | 285 | 286 | 287 | 288 | 289 | 290 | 291 | 292 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Intermediate Altitude Periapses (~63,000 km) | | | | | Low Altitude Periapses (62,000 km) | | | | |
| **RCS control at periapse** | | | | **RCS 3:55** | | | **RCS 2:17** | **RCS 2:10** | **RCS 3:19** | **RCS 2:15** | **RCS 2:15** |
| **Sequence** | S100 | S101 | S101 | S101 | S101 | S101 | S101 | S101 | S101 | S101 | S101 |
| **Segment owner** | Rings | Rings | Saturn | Maps | SOST | Maps | Saturn | Maps | Saturn | Saturn | Saturn |
| **Primary Pointing** | | POS_X to COROT | XBAND to Earth (SP prime) | MAG rolling (with SRU pauses) | | POS_X to COROT | POS_X to COROT | | XBAND to Saturn | POS_X to COROT | POS_X to COROT |
| **Secondary axis** | | POS_Y to SUN [-25,0,0] | z-axis roll | x-axis roll | | POS_Y to SUN [-25,0,0] | POS_Y to Sun | | POS_X to COROT | NEG_Y to Saturn | NEG_Z to Saturn |
| **Comments on Pointing** | | cda did not agree to the tweak so it's back to the January 2015 design | **INMS phasing** | | COLD ORBIT a mix of VIMS auroral and CIRS Enceladus | cda did not agree to the tweak so it's back to the January 2015 design | Secondary for RADAR | COLD ORBIT | Secondary for INMS for +/- 20 min | NEG Y to Saturn secondary for ISS | **Secondary for RADAR** |
| **Op Mode** | | | | | | | | | | | |
| peri-12 to -6 hrs | | | **RSS** | | | | | | | | |
| peri -6 to -5 hrs | | | **RSS** | | | | | | | | |
| peri -5 to -4 hrs | | | **RSS/MAG** | **MAG** | | | | | | | |
| peri -4 to -3 hrs | | | **RSS/MAG** | **MAG** | | | | | | | |
| peri -3 to -2 hrs | | | **RSS/MAG** | **MAG** | | | | | | | |
| peri -2 to -1 hrs | **UVIS Rings** | | **RSS/MAG** | **MAG** | | | | | **RCS xtion** | | |
| peri-60 to-45 min | **UVIS Rings** | **INMS/CDA** | **RSS/MAG** | **MAG** | **COLD AUR** | **INMS/CDA** | **INMS/CDA*** | **AUR INB** | **RADAR Saturn** | **INMS**** | **INMS***** |
| peri -45 to-30 min | **UVIS Rings** | **INMS/CDA** | **RSS/MAG** | **MAG** | **COLD AUR** | **INMS/CDA** | **INMS/CDA*** | **COLD** | **RADAR Saturn** | **INMS**** | **INMS***** |
| peri-30 to-10 min | Slew | **INMS/CDA** | **RSS/MAG** | **MAG** | **COLD AUR** | **INMS/CDA** | **INMS/CDA*** | **COLD** | **RADAR/INMS** | **INMS**** | **INMS***** |
| peri-10 to -0 min | **HGA to RAM** | **INMS/CDA** | **RSS/MAG** | **MAG** | **COLD AUR** | **INMS/CDA** | **INMS/CDA*** | **COLD** | **RADAR/INMS** | **INMS**** | **INMS***** |
| peri 0 to +10 min | **HGA to RAM** | **INMS/CDA** | **RSS/MAG** | **MAG** | **COLD AUR** | **INMS/CDA** | **INMS/CDA*** | **COLD** | **RADAR/INMS** | **INMS**** | **INMS***** |
| peri+10 to+30 min | Slew | **INMS/CDA** | **RSS/MAG** | **MAG** | **COLD AUR** | **INMS/CDA** | **INMS/CDA*** | **CIRS S Pol** | **RADAR/INMS** | **INMS**** | **INMS***** |
| peri+30 to +45min | **RADAR Rings** | **INMS/CDA** | **RSS/MAG** | **MAG** | **COLD AUR** | **INMS/CDA** | **INMS/CDA*** | **CIRS S Pol** | **RADAR Saturn** | **INMS**** | **INMS***** |
| peri +45 to +60 min | **RADAR Rings** | **INMS/CDA** | **RSS/MAG** | **MAG** | **COLD AUR** | **INMS/CDA** | **INMS/CDA*** | **CIRS S Pol** | **RADAR Saturn** | **INMS**** | **INMS***** |
| peri+1 to +2 hrs | **RADAR Rings** | | **RSS/MAG** | **MAG** | **COLD AUR** | | **RCS xtion** | | **RCS xtion** | **RCS xtion** | **RCS xtion** |
| peri+2 to +3 hrs | | | **RSS/MAG** | **MAG** | **COLD AUR/ENC** | | | | | | |
| peri+3 to +4 hrs | | | **RSS/MAG** | **MAG** | **COLD ENC** | | | | | | |
| peri+4 to +5 hrs | | | **RSS/MAG** | **MAG** | **COLD ENC** | | | | | | |
| peri+5 to +7 hrs | | | **RSS** | | **COLD ENC** | | | | | | |
| peri+7 to +12 hrs | | | **RSS** | | | | | | | | |
| **Temperature status** | **COOL ORBIT** | **HOT ORBIT** | **N/A** | **HOT ORBIT** | **COLD ORBIT** | **HOT ORBIT** | **HOT ORBIT** | **COLD ORBIT** | **HOT ORBIT** | **HOT ORBIT** | **HOT ORBIT** |
| **CIRS delta_T** | **5.2K** | **16K** | **8.5K** | **14.5K** | **3.5K** | **16K** | **16.5K** | **5K** | **16.2K** | **16.2K** | **16.5K** |
| **CIRS end delta_T** | **3.5K** | **14.5K** | **0.5K** | **3.5K** | **n/a** | **14.5K** | **15K** | **4.5K** | **14.2K** | **14K** | **15K** |
| **VIMS max T** | **64.2K** | **66.6K** | **66.6K** | **68.3K** | **61.5K** | **66.6K** | **68.2K** | **62.2K** | **68.9K** | **66.9K** | **68.5K** |
| **VIMS max delta_T** | **4.5K** | **7K** | **5.2K** | **7.3K** | **3.5K** | **7K** | **8.5K** | **3K** | **9.2K** | **7.2K** | **9K** |
| **VIMS end delta_T** | **3.9K** | **7K** | **1.3K** | **4.8K** | **2.7K** | **7K** | **8.5K** | **2.5K** | **9.1K** | **7.2K** | **9K** |
| **SID suspend?** | **Yes** | **Yes** | **Yes** | **in MAG** | **No** | **Yes** | **No** | **No** | **No** | **No** | **No** |
| **Data Volume estimate** | 1.5G, 2.5G avail | 200Mb, 3G avail | n/a | .5G, 3G avail | .5G, 2G avail | 300 Mb, 3.5G avail | 300 Mb, 3.5G avail | ? | 300 Mb, 1.5G avail | 300 Mb, 3.5G avail | 300 Mb, 3.5G avail |

# F ring/Grand Finale orbits compared to Juno orbits

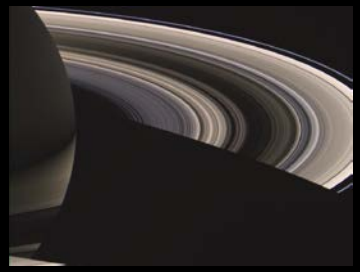
- Cassini's F ring/Grand Finale orbits and Juno orbits are comparable and scientific goals are very similar
- Juno spacecraft will orbit Jupiter, July 2016 to Feb. 2018
  - 37 science orbits over 20 months
- Cassini's F ring/Grand Finale orbits, Nov. 2016 to Sept. 2017
  - 42 science orbits, 22 with Juno-like periapses
- Both have low periapses close to their planets and eccentric orbits (0.9-0.95)
- Main difference is inclination
  - Cassini: 63.4° vs. Juno: 90°
- Cassini F ring orbits cross auroral field lines at r =3.4 - 4 $R_S$, vs. 1.9 $\pm$ 0.7 $R_J$ for Juno



# F ring/Grand Finale Science compared to Juno Science

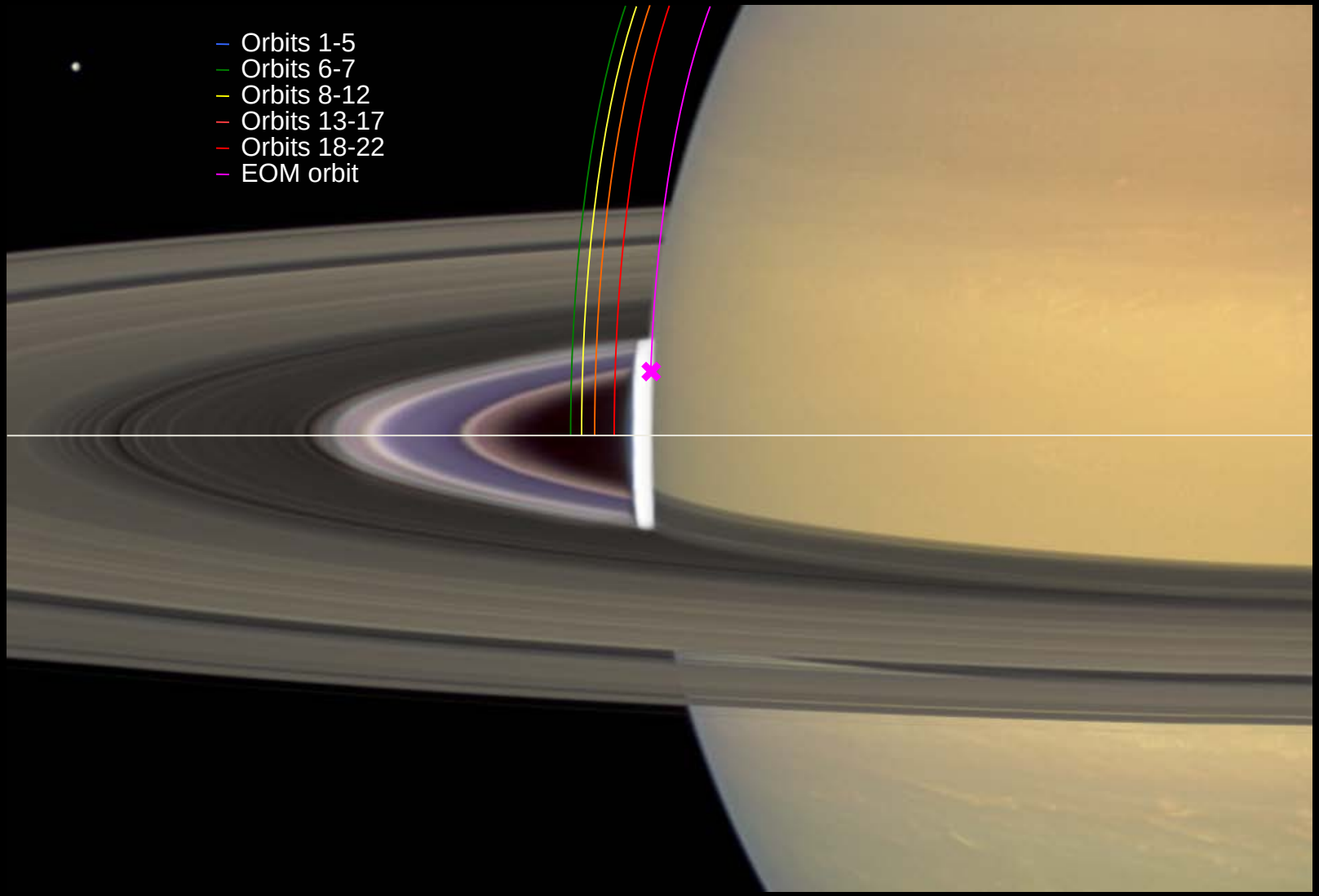
- Common science goals:
  - Interior structure of the giant planets: Gravity and magnetic field mapping
  - Dynamics of the polar ionosphere and auroral magnetosphere
  - Very high resolution measurements of giant planet atmospheres
  - In situ measurements of the giant planet ionospheres

- Differences in science goals:
  - Juno: Deep interior composition/water abundance
  - Cassini: Rotation rate of the planet (well known for Jupiter)
  - Cassini: Saturn's ring mass and detailed ring structure

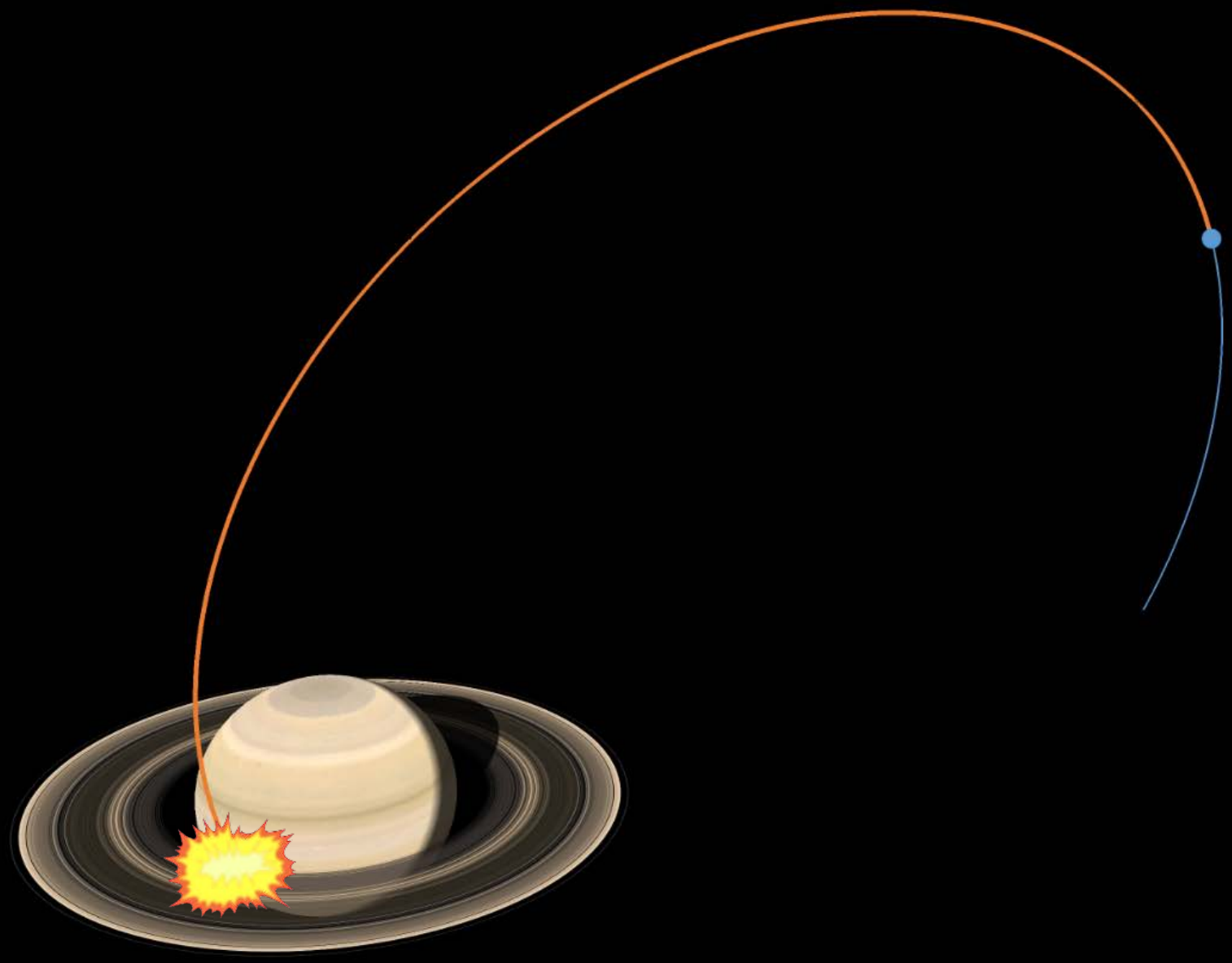


# Cassini’s Final Plunge

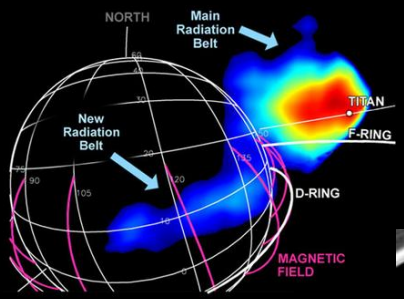
# Impact Orbit Geometry

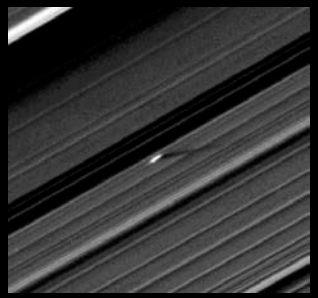


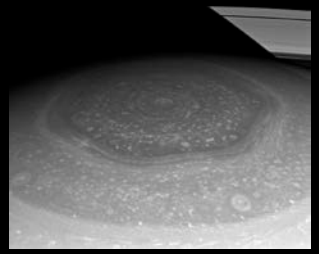
# Cassini's Final Plunge



# Science Summary



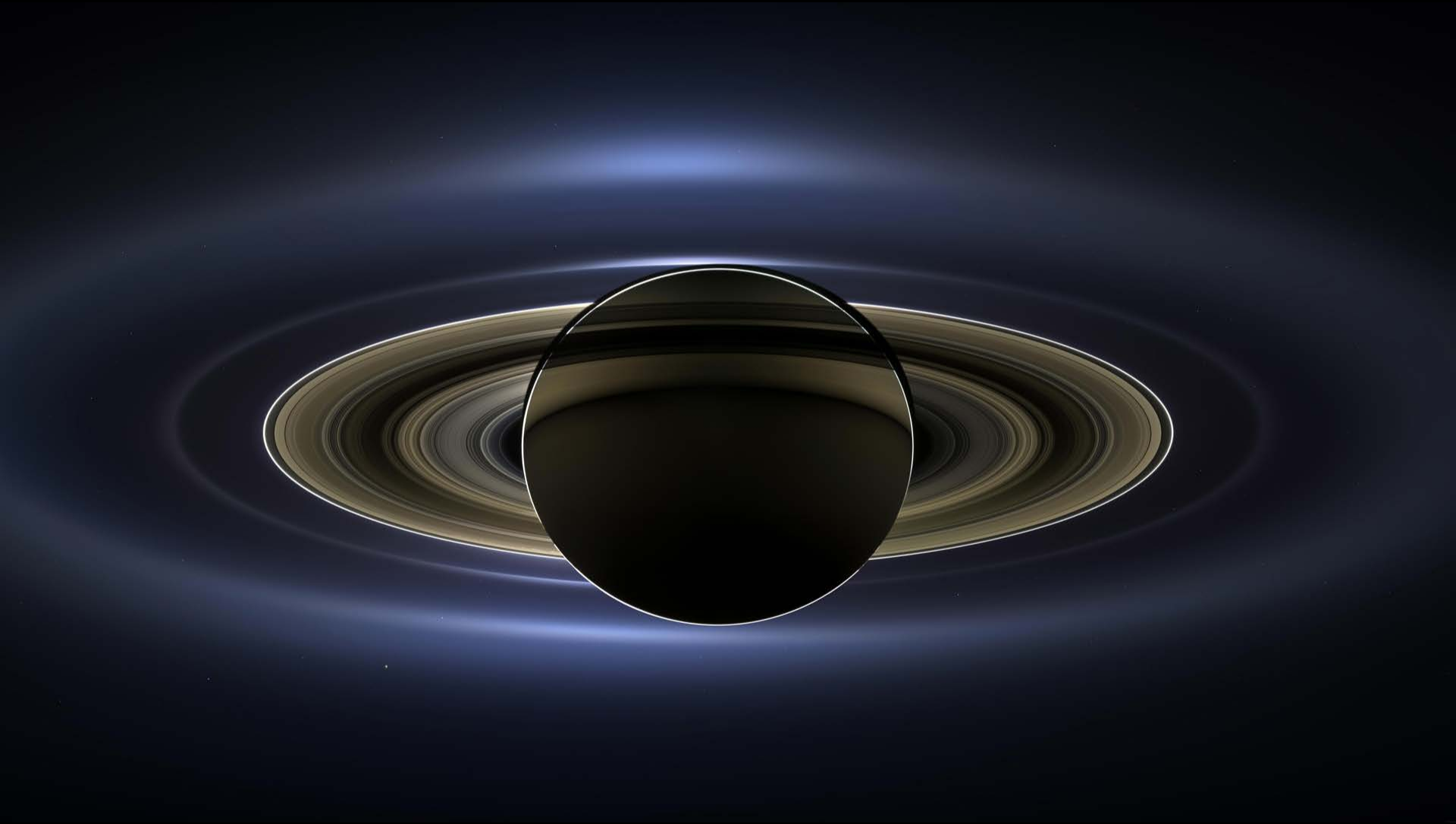





- Saturn internal structure
  - Gravitational & Magnetic Fields
- Ring mass
  - Address age of main rings
- Saturn's ionosphere, innermost radiation belts & inner D ring particles
- Highest resolution main ring observations
  - First Active Radar of the Rings
- Highest resolution Saturn polar observations and aurora

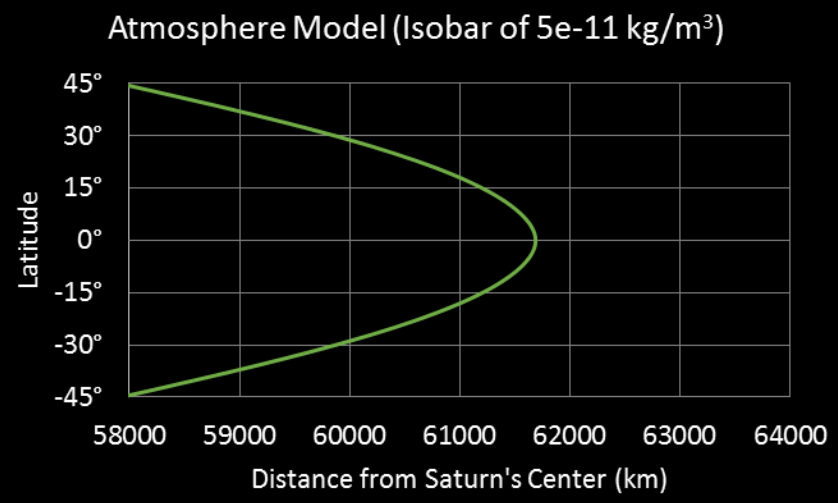
***Cassini Saturn science complements that from Juno mission to Jupiter***

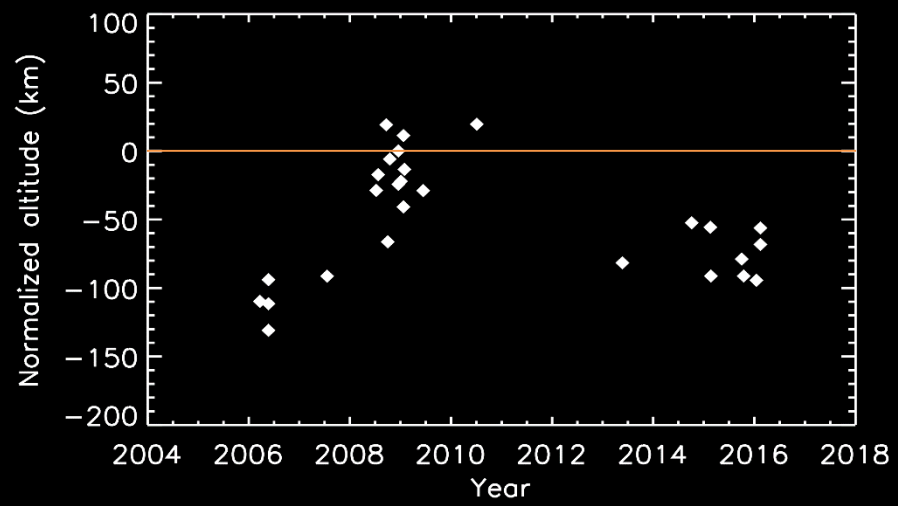
# Questions?



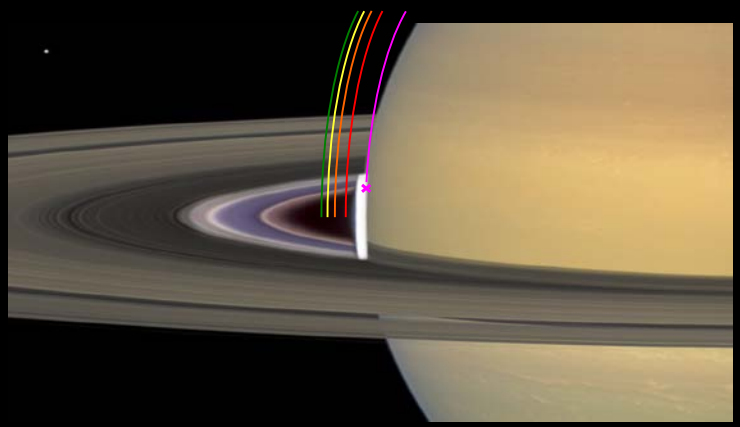
# Backup

# Remote Atmosphere Detection

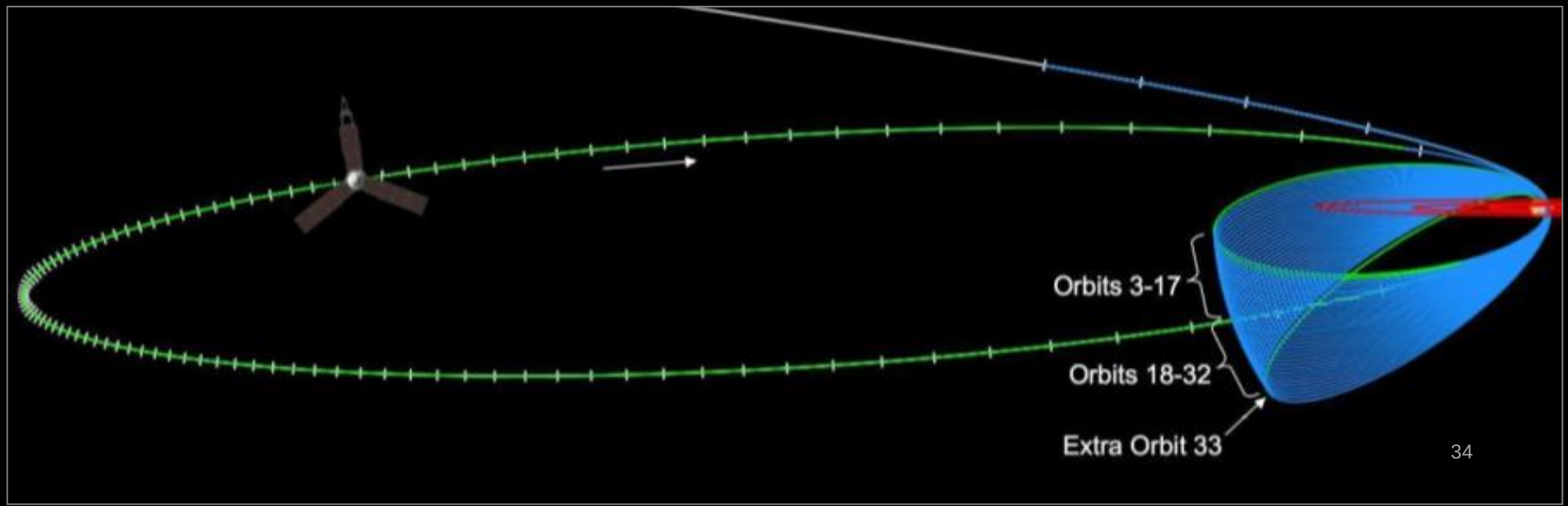


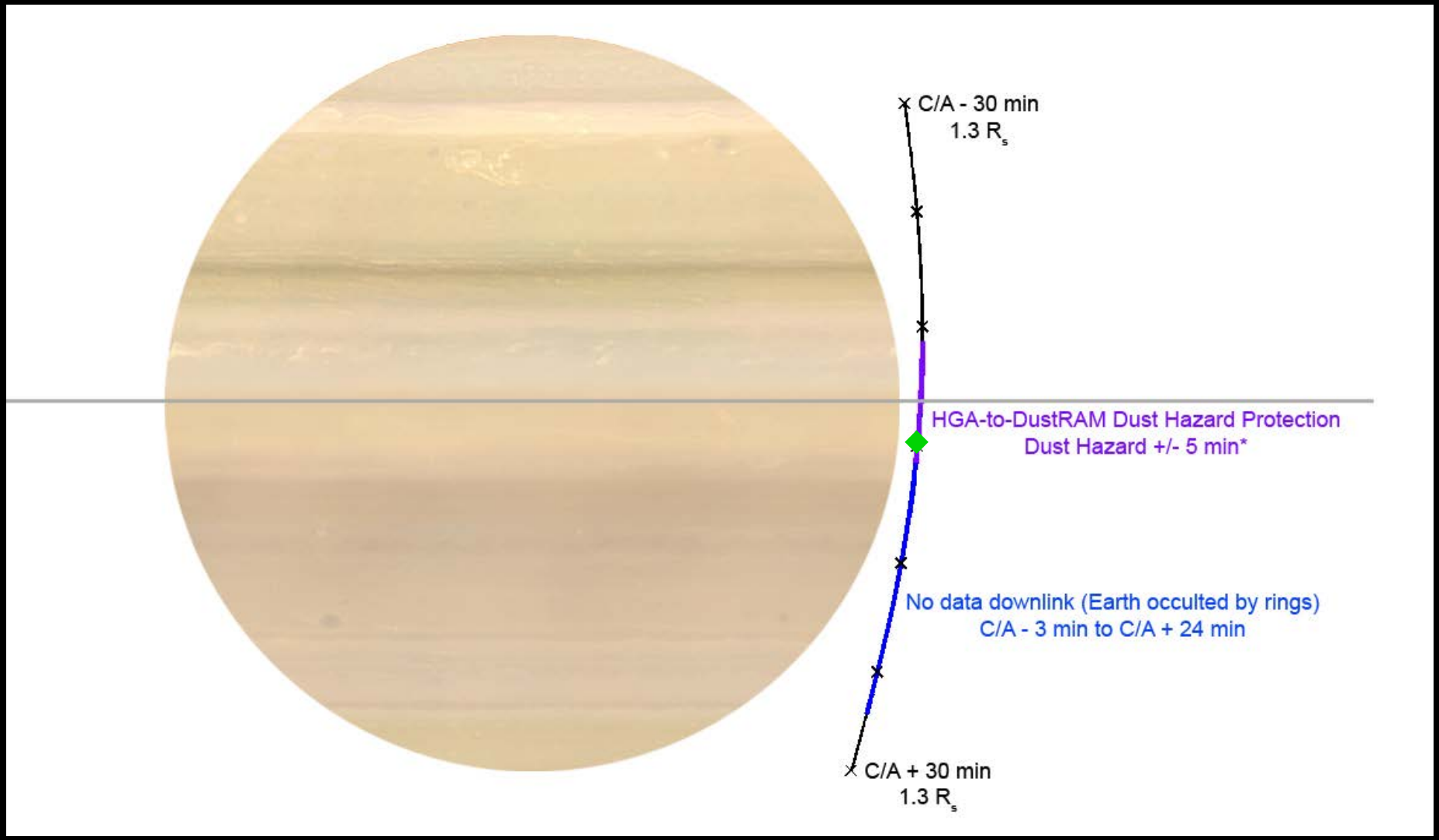
# Final stages of Juno and Cassini missions



- After a long successful mission at Saturn Cassini End-of-Mission is planned for September 2017 when fuel is very low
- Juno End-of-Mission at Jupiter is predicted as October 2017 with expected radiation damage
- In both cases the spacecraft are deliberately plunged into atmosphere for planetary protection



# Between Rings & Planet 22 Times



# Saturn Observations

- Important periapse observations and initial estimate of number of orbits to accomplish them:
  - Gravity field determination: *RSS: 6* orbits
    - Earth-pointed through periapse
  - Magnetic field determination (see MAPS list)
  - In-situ sampling of ionosphere/exosphere/thermosphere - *CAPS/MIMI: 5, CDA: 4, INMS: 3*
    - Specified pointing direction (e.g. dust RAM) through C/A

# Saturn Science and Observations

- Saturn science outside closest approach
  - Saturn atmospheric studies for composition and dynamics
    - High resolution scans and mosaics of Saturn's polar regions, e.g. the North Polar Hexagon and aurora - ISS/VIMS
      - ~180-degree turn to switch between poles
    - Spectra up-close - CIRS/UVIS/VIMS
      - Concern about heating CIRS and VIMS radiators beyond health and safety limits outbound from periapse (need project study of orientations that can be used to minimize heating)
    - RADAR scans (noodles)
      - 90-degree turn from ORS to Radar pointing
      - Potentially large turn from MAPS pointing to Radar pointing
  - Occultations (radio, solar, and stellar) – RSS/UVIS/VIMS
    - Inertial pointing, sensitive to timing shifts
- Apoapse observations (similar to current apoaspse Saturn science)
  - CIRS Mid-IR Maps, UVIS EUV-FUV scans, VIMS/ISS dynamics imaging mosaics, and auroral (ORS & MAPS) observations, occasional distant occ
- For detailed instrument-by-instrument breakdown see 2008 SWG report

# Ring Science and Observations

- Ring science goals include a combination of seasonal factors and time baseline that are only satisfied by the proximal phase orbits

- Study ring vertical, radial, and azimuthal structure
  - RSS occultations covering ring opening range 24-27 degrees, as yet unobserved by Cassini or Voyager
  - Stellar occultations (UVIS, VIMS)
  - Occultations are sensitive to timing shifts of more than a few minutes
  - In this geometry the rings are the widest open and the optically thickest regions (dense core of the B ring) can be optimally studied. Several different specific science goals are addressed by these observations RC1a4b (RSS) (RN1b4c - time variation, RN1c1e, RN2a2e).

- Determine the Ring Mass
  - Requires 6 RSS earth-pointed passes to determine ring mass to a few percent
  - This fundamental measurement - critical to determining the age of the rings - is best, and perhaps only, done by detecting minute gravitational perturbations on the spacecraft trajectory in orbits passing between the ring and the planet, RN1a2a (RSS)

# Ring Science and Observations

- Determine compositional variations at high resolution
  - Only proximal orbits provide the combination of distance and opening angle needed (especially for VIMS)
  - Requires at least two full scans and at least two targeted "patches". In order for VIMS to get the appropriate dwell time for their observations, some might be done tracking a particular target or targets - that is, on RWAs.
  - Another possibility is SOI drift-scan type pointing, RN1c2c (VIMS, ISS)

- Determine the composition of the close-in and/or newly discovered "ringmoons" as targets of opportunity; especially when they fill a VIMS pixel.
  - These opportunities may arise on F-ring orbits in particular, and will require tracking, RN1c3b

# Ring Science and Observations

- Study self-gravity wakes and other ring microstructure in depth
  - Need at least three full multifilter radial scans; drift scans probably OK. RN2a1c, RN2a2d (ISS)
- Obtain very high resolution images of propellers; lit and unlit faces not specified in TM but are desirable.
  - Targeting will be needed and possibly partial azimuthal mosaicing. RN2b1b, RN2b1c
  - Propose to add all the large propellers whose orbits are well known (or will be by then) to the NAV database so late pointing updates will be made automatically
- No high priority ring observations identified outside periapse

# MAPS Science Objectives and Observations

- Measurement of Saturn's internal magnetic field to high order
  - Frequent Mag cals to calibrate magnetometer data
- In-situ measurements at peripse for all MAPS instruments

# Icy Satellite Science

- No targeted icy satellite flybys are present in F-ring and Proximal orbits

- Excellent non-targeted opportunities exist for:
  - Ringmoons Pan, Daphnis, Atlas, Prometheus, Pandora, Epimetheus and Janus
  - Mimas, Enceladus and Tethys
- Some of these flybys provide unique coverage and/or the highest resolution of the mission
- Mosaics and scans are needed to cover targets as have been done throughout the mission
  - Some live updates may be necessary
- Potential icy satellite stellar occultations

# Icy Satellite Flybys (preliminary)

| Object | Time (2017) | C/A (km) | Uniqueness | Comments |
|---|---|---|---|---|
| Daphnis | 16 Jan 13:22 | 17,600 | Closest ever by > order of mag | |
| Pandora | 23 Jan 17:17 | 19,000 | Closest by a factor of 3 | |
| Mimas | 30 Jan 21:06 | 40,385 | Close flyby of N. Pole | Map N. Pole |
| Epimetheus | 30 Jan 21:07 | 5900 | One of closest, but not unique | |
| Prometheus | 30 Jan 21:28 | 50,250 | One of closest, but not unique | |
| Pan | 7 Mar 18:09 | 25,350 | Closest by factor of 2 | |
| Janus | 22 Mar 01:50 | 43,950 | Second best (see below) | |
| Pan | 22 Mar 02:23 | 55,200 | Equal to best yet | |
| Enceladus | 29 Mar 05:46 | 93,046 | Last VGR class flyby | |
| Janus | 12 Apr 13:45 | 9060 | Best by an order of magnitude | |
| Atlas | 12 Apr 13:45 | 13,170 | Best by almost factor of 2 | |
| Enceladus | 3 May 00:45 | 174,730 | | |
| Tethys | 15 May 00:24 | 193,000 | | |
| Enceladus | 17 June | 195,000 | | |
| Enceladus | 13 July | 173,000 | | |
| Enceladus | 27 Aug | 146,000 | | |

# Titan Observations

- Titan observations present no additional mission drivers

- Two targeted Titan flybys T125 (at start of F-Ring orbits), and T126 (at start of Proximal Orbits)
  - T125: ORS at closest approach and T126: RADAR
  - Both closest approach periods focus on surface observations (in particular Hotei and the northern lake regions, longest possible baseline for change detection).
    - Typical Titan flyby observation strategy with typical uncertainties
- ~12 high priority non-targeted Titan viewing periods ranging from 90,000 km to over 1 million km, but typically around 500,000km; i
  - Very good high northern latitude opportunities near summer solstice which are essential for achieving the atmospheric objectives such as understanding Titan's atmospheric circulation and surface-atmosphere interactions as close to solstice as possible, and thus its methane cycle. High northern latitudes are difficult to observe from Earth
  - Typical non-targeted Titan observations, long ORS observations with some mosaicing

# Titan Non-targeted details

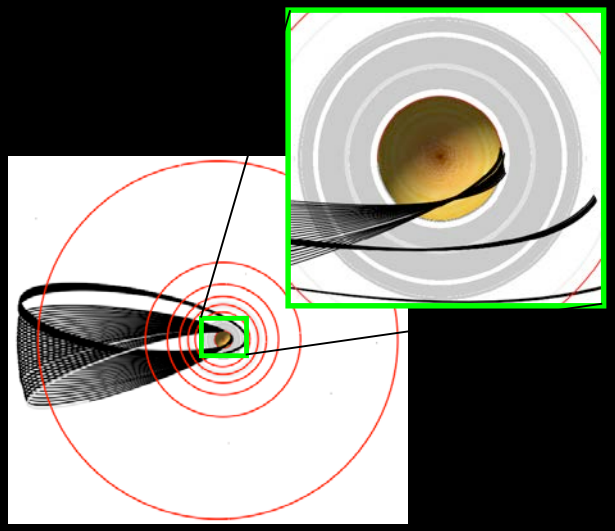
| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Rev(Target) | | | | C/A Range (km) | flyby speed (km/s) | Phase (deg) | Notes | F-Ring or Proximal orbits |
| 2 | 250TI | (t) | T125 | 2016-334T22:23:48 | 3197.2 | 5.7 | 81 | | |
| 3 | 253TI | (nt) | | 2016-350T21:58:30 | 343112.9 | 5.3 | 58 | priority 1: approaches over Menrva, North Pole from Saturn side, recedes over Kraken!! 70°N, 90°W at C/A | FO |
| 4 | 255TI | (nt) | | 2016-366T12:22:12 | 681360.4 | 7.2 | 29 | priority 2: 70°-15° W, 30-45°N | FO |
| 5 | 257TI | (nt) | | 2017-017T18:30:42 | 723657.1 | 9.3 | 96 | | FO |
| 6 | 259TI | (nt) | | 2017-032T20:05:11 | 220293.4 | 6.3 | 91 | priority 1.5: close and C/A over VIMS mountain chains | FO |
| 7 | 261TI | (nt) | | 2017-048T13:20:37 | 186712.6 | 5.1 | 77 | priority 1: approaches south of Menrva, high northern lats from anti-Saturn side, recedes over trailing hemisphere: >60°N 130-260°W!! | FO |
| 8 | 264TI | (nt) | | 2017-064T11:59:01 | 491860.4 | 5.9 | 42 | priority 1: approaches north of Menrva, high northern lats from leading-to-sub-Saturn side, recedes over sub-Saturn side: >60°N 130-260°W!! | FO |
| 9 | 266TI | (nt) | | 2017-079T17:46:04 | 873563.5 | 8.7 | 32 | priority 2: 55-15°W, 30-35°N | FO |
| 10 | 266TI | (nt) | | 2017-082T00:24:43 | 954957.7 | 11.3 | 97 | | FO |
| 11 | 268TI | (nt) | | 2017-096T22:20:11 | 477708 | 7.7 | 89 | priority 2: c/a over terminator ~315°W, -~20°S (backup for 259TI) | FO |
| 12 | 270TI | (t) | T126 | 2017-112T06:21:21 | 990 | 5.8 | 62 | | |
| 13 | 273TI | (nt) | | 2017-127T21:25:06 | 488138 | 7.1 | 30 | priority 1: 75-10°W, 35-45°N | PO |
| 14 | 273TI | (nt) | | 2017-129T22:16:24 | 978644.5 | 12.6 | 90 | | PO |
| 15 | 275TI | (nt) | | 2017-144T01:08:20 | 137250.3 | 6 | 69 | priority 1: recedes over trailing hemisphere, ~20° S to equator | PO |
| 16 | 278TI | (nt) | | 2017-159T19:56:41 | 349959.3 | 6 | 40 | priority 1: approaches over Menrva, high northern lats (~60°) from Saturn side, recedes over sub-Saturn hemisphere: 55°N, 45°W at C/A | PO |
| 17 | 280TI | (nt) | | 2017-176T00:24:07 | 335615.8 | 7.2 | 68 | priority 1: recedes over trailing hemisphere, ~20° S to equator (more distant, therefore lower priority than rev 275) | PO |
| 18 | 283TI | (nt) | | 2017-191T14:24:48 | 249521.6 | 5.3 | 61 | priority 1: approaches over Menrva, North Pole from Saturn side, recedes over Kraken!!~80°N from ~70-330°W | PO |
| 19 | 285TI | (nt) | | 2017-206T03:24:52 | 910554.5 | 10.4 | 56 | | PO |
| 20 | 285TI | (nt) | | 2017-208T02:19:29 | 545648.4 | 8.6 | 68 | priority 2: recedes over trailing hemisphere, ~equator | PO |
| 21 | 288TI | (nt) | | 2017-223T04:57:12 | 177459.6 | 5 | 82 | priority 1: approaches south of Menrva, high northern lats from anti-Saturn side, recedes over trailing hemisphere (which is better illuminated than rev 261) !!>60°N 120-260°W | PO |
| 22 | 290TI | (nt) | | 2017-238T06:17:52 | 739806.1 | 8.8 | 54 | priority 3: 60°-15°W, 20-25°N | PO |
| 23 | 290TI | (nt) | | 2017-240T05:01:14 | 740490.5 | 10.1 | 67 | priority 3: recedes over trailing hemisphere, ~equator | PO |
| 24 | 292TI | (nt) | | 2017-254T19:13:38 | 87425.8 | 5.2 | 80 | priority 1: approaches over eastern leading hemisphere, high northern lats from anti-Saturn side, recedes over trailing hemisphere (which is better illuminated than rev 261)!!>60°N 110-240°W | PO |

# Science within Proximal orbit phase

- Beginning revs: High Gain Antenna to ram
  - Magnetometer and fields and particles *in situ* measurements
- Middle revs: ring occultations (traverse inside B ring) and gravity measurements
- End revs: Periapses near upper extent of Saturn atmosphere for *in-situ* measurements

# Proximal Orbit Science Summary

- F ring/Proximal orbits offer unique scientific opportunities
  - Determine Saturn's gravity field to $J_{10}$
  - Determine Saturn's higher order magnetic field components to degree 6
  - Measure Saturn's internal rotation rate
  - Estimate mass of main rings to 5%
  - Measure *in situ* plasma for the first time
  - Highest resolution main ring studies
  - High resolution Saturn atmospheric studies
- Cassini Saturn science complements science from Juno mission to Jupiter



# Key Mission Drivers and Liens

- Stares, scans and mosaics

- Live updates:
- Large Turns:
  deg (Radar/RSS to ORS or MAPS) turns needed: Any constraints on these turns in the proximal orbits?
- Health and safety radiator concerns for CIRS and VIMS outbound from periapse:
- Add large propeller orbital parameters to NAV database:

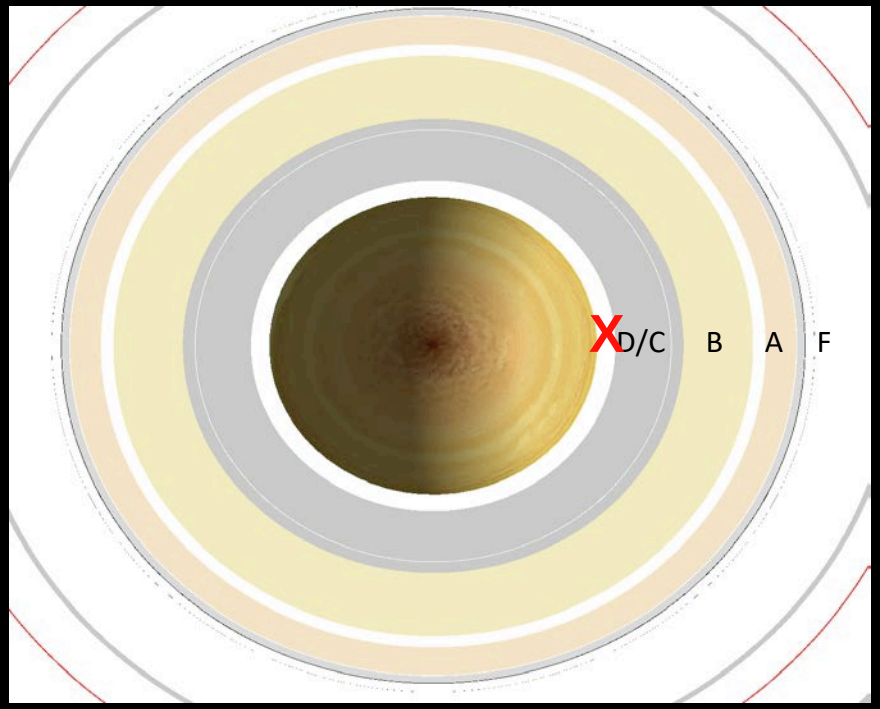
- Newly discovered ringmoons and other potential discoveries

- Opmode and power issues:

# Unique End-of-Mission Science

- Ring mass
  - Estimate mass of main rings to 5%
  - Address age of main rings

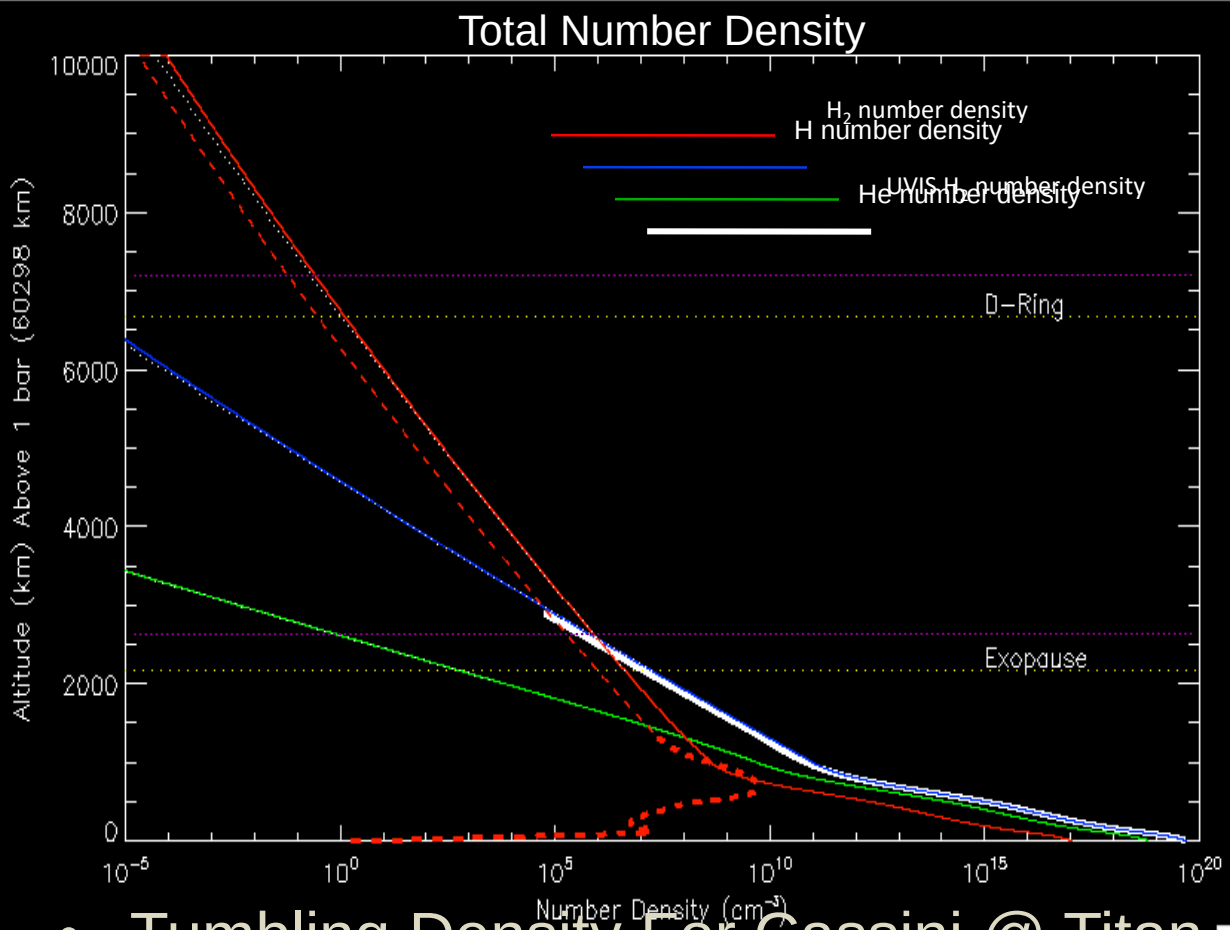
# Grand Finale Orbit Location

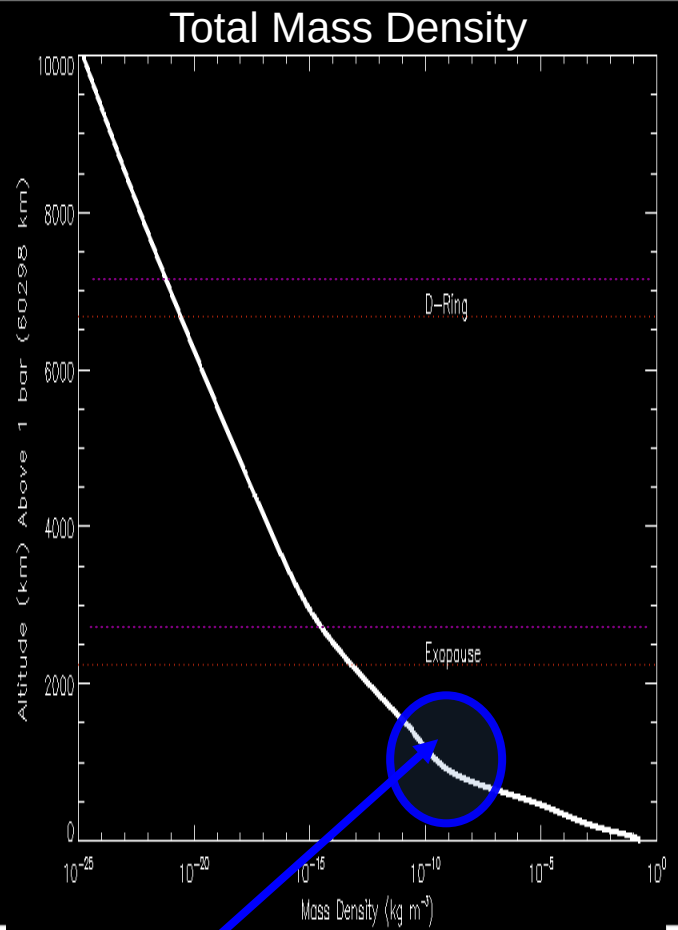



Periapse in 2,000 km gap (X) between inner D ring and Saturn upper atmosphere

- Saturn impact from short period orbits
- EOM geometry reachable from any point in XXM tour
  - 2-10 months set up
  - Delta v: 5 - 30 m/s
- Inner D-ring radius:
  - ~ 65,000 km
- Upper Extent of Saturn atmosphere:
  - ~ 62,000 km (at equator)
- Saturn focus addresses key science and new discoveries
- Gap: ~ 2,000 km

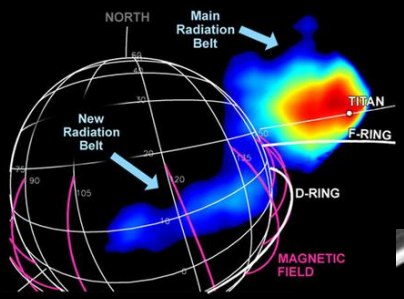
# Saturn's Atmosphere: 40ºS

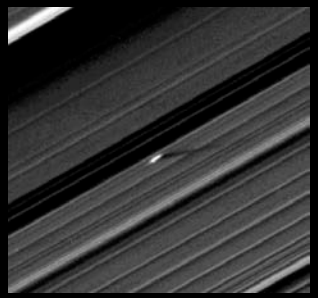


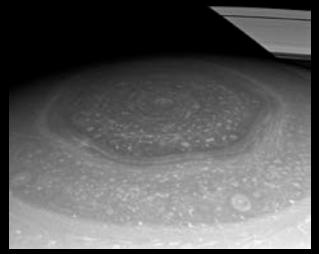




- Tumbling Density For Cassini @ Titan
  - ~ 30x10$^{-10}$ kg m$^{-3}$ (~ 10x10$^{-10}$ kg m$^{-3}$ the Cassini XXM)
  - 70% Thruster Duty Cycle (less for the Cassini XXM)
- *Note that Cassini uses 60330 km (100 mbar) for 1 Rs.

# Summary





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  - Determine Saturn's gravity field to order $J_{10}$
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  - Measure *in situ* plasma of Saturn's ionosphere, innermost radiation belts and D ring for the first time
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  - First Active Radar of the Rings
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*Cassini Saturn science complements that from Juno mission to Jupiter!*