The Cassini Grand Finale Mission: Planning for a New Mission Environment

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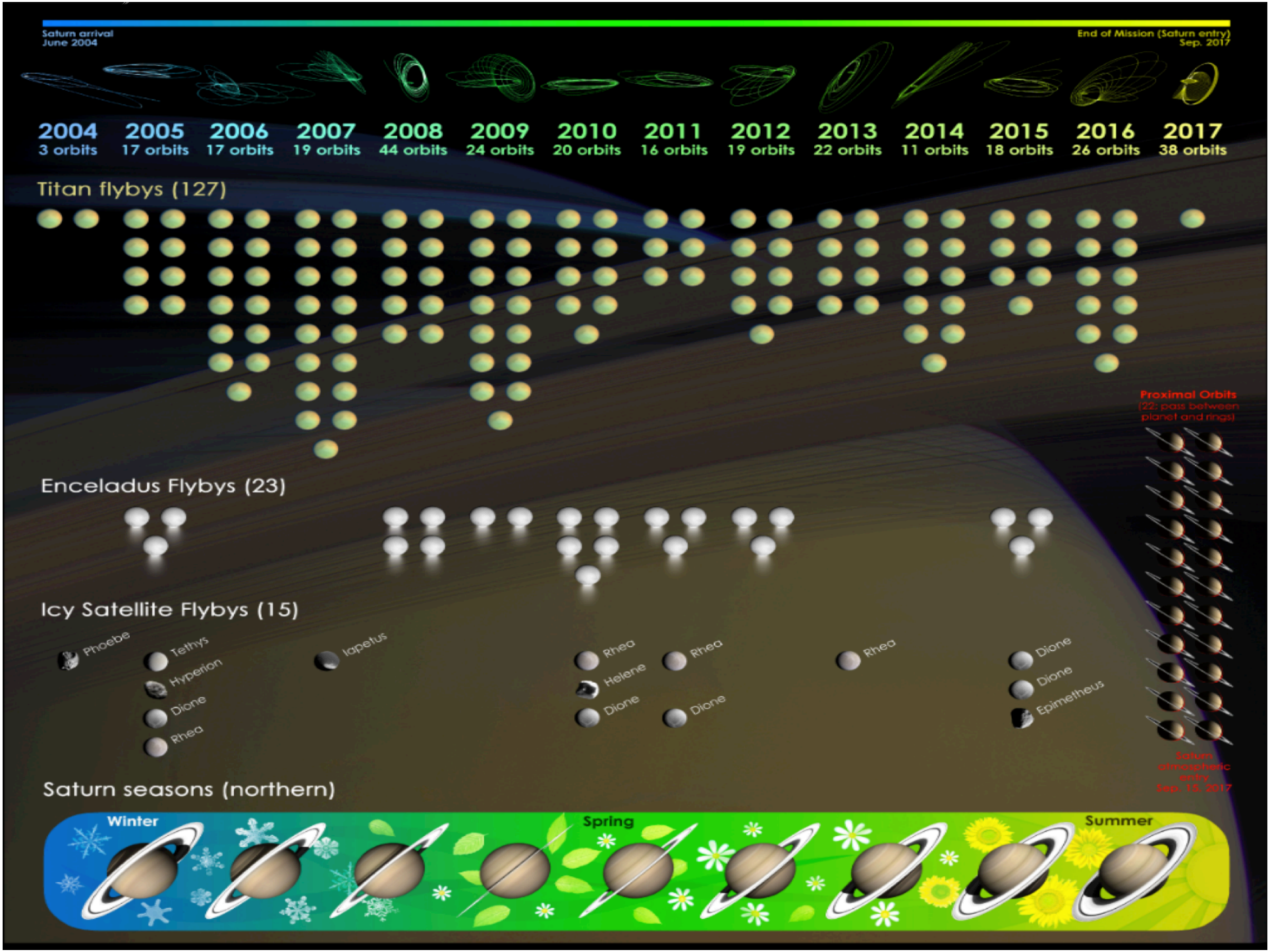
Cassini-Huygens: Mission to Saturn
Jet Propulsion Laboratory/
California Institute of Technology
March 6, 2017


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

Unique Mission Trajectory and Science

November 30, 2016
F-ring (Ring Grazing) Orbits Begin
20 orbits
3 maneuvers

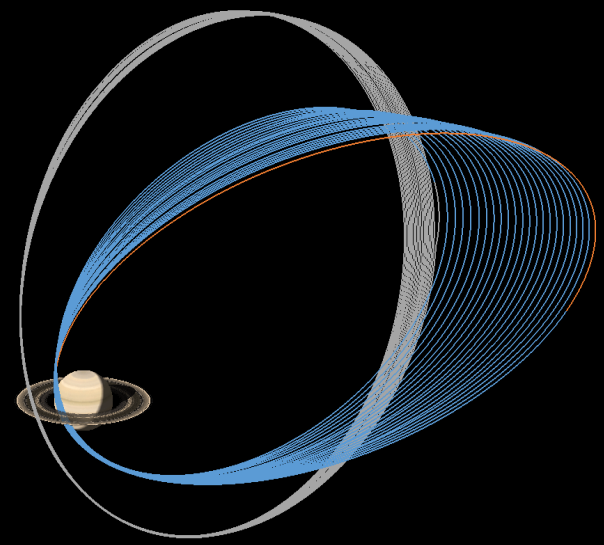
April 22, 2017
Last Targeted Titan Flyby
Produces Grand Finale ballistic trajectory

April 23, 2017
Proximal (Grand Finale) Orbits Begin
22½ orbits
9 non-targeted Titan flybys

April 26, 2017
First dive through gap

September 11, 2017
Last Non-targeted Titan Flyby
Puts Cassini on impact trajectory

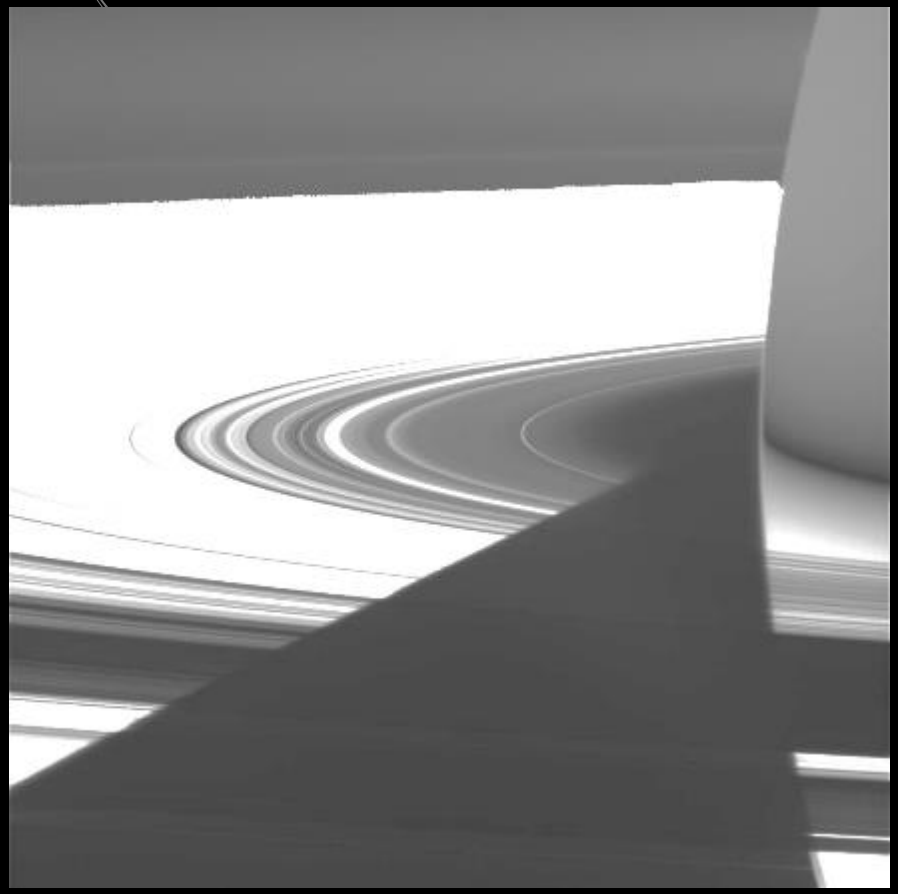
September 15, 2017
Saturn Impact

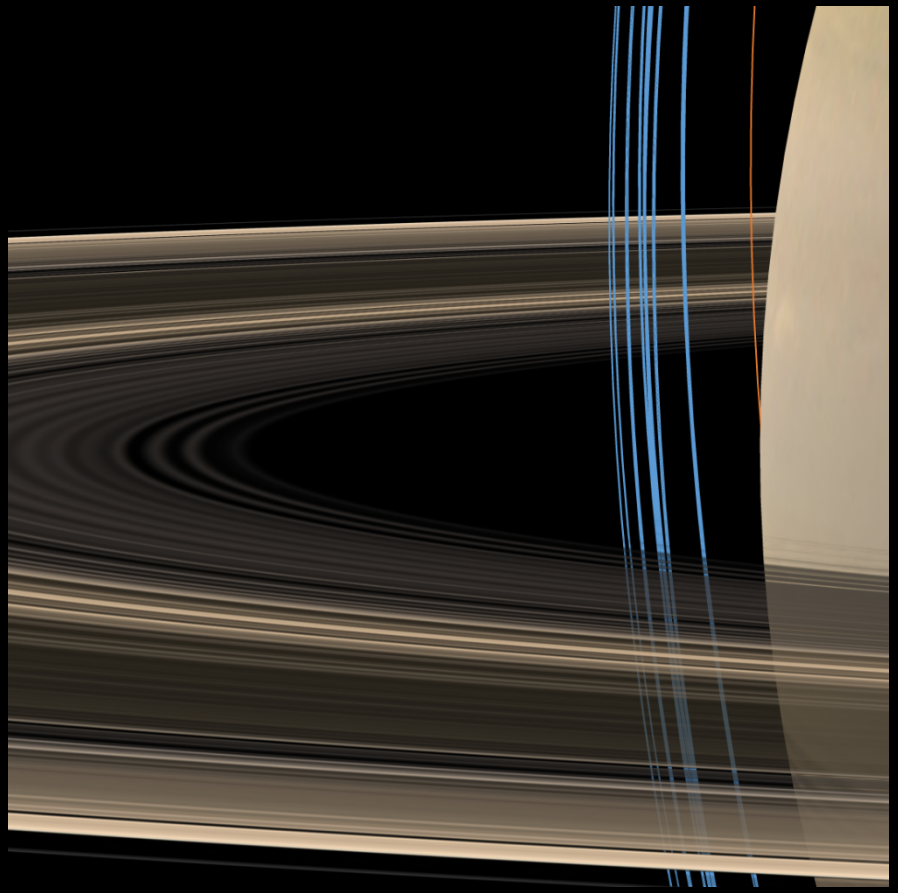


Ring-Grazing orbits
Grand Finale orbits
Impact orbit

- 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

Environment challenges: D-ring dust, Atmospheric density

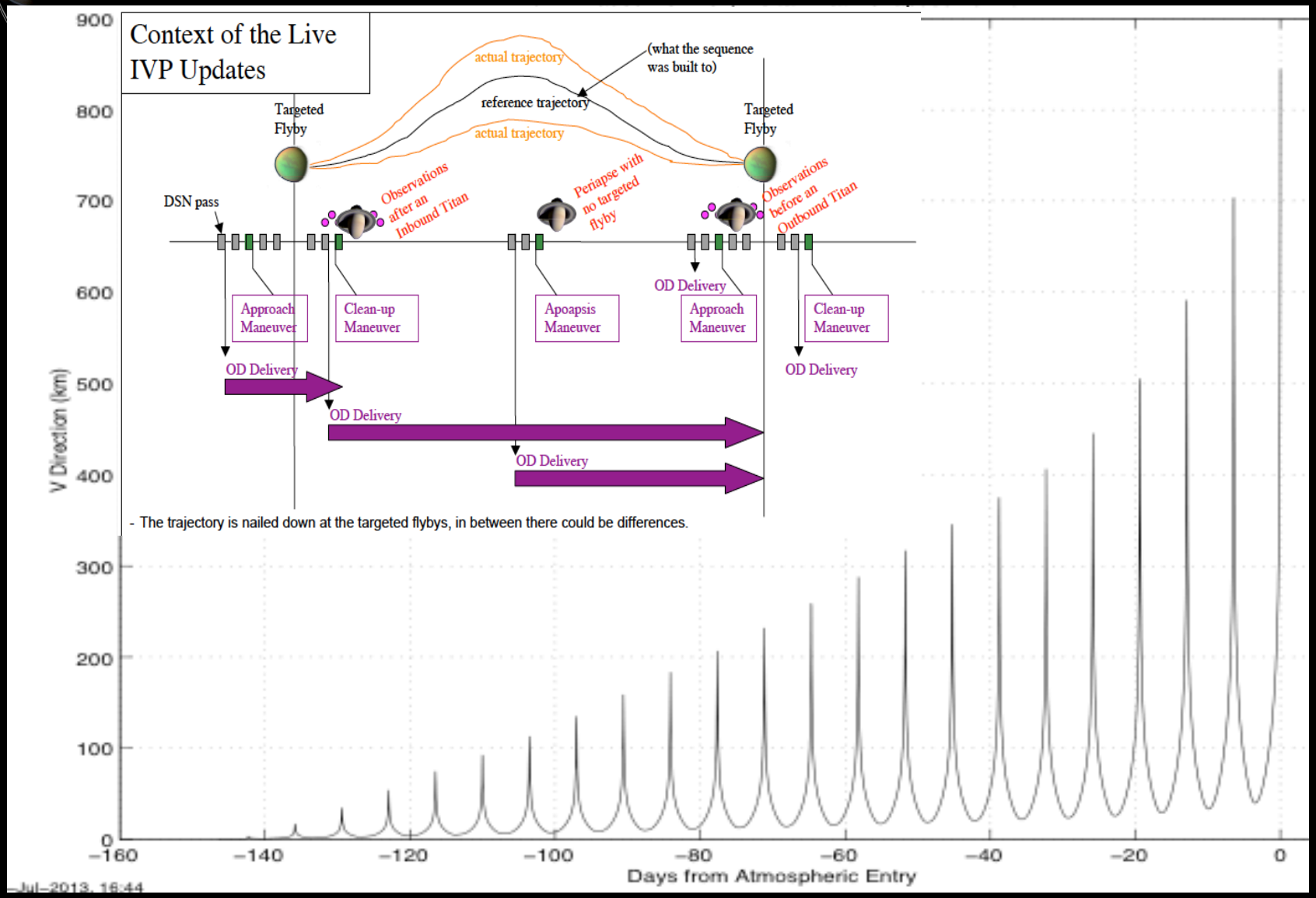




Dust
Close cover on main engine assembly
Turn to high gain antenna shield attitude

Atmosphere
Switch to thrusters
Reduced aerodynamic torque attitude

Pointing uncertainties (Ballistic trajectory)



Grand Finale Objectives – 36 passes needed, we have 22

RSS – 6 flybys
Antenna to Earth

MIMI & RPWS – all (but no pointing constraint)

MAG – 4 flybys
Rolling about 2 axes

CIRS – 3 to 4
(at +1hour)

VIMS – 5
(cold at +1 hour)

INMS - 8

CDA - 8

ISS – 4
3 Cameras to Saturn
1 Cameras to Ring

RADAR 3
1 Z to Saturn
3 Z to Ring

UVIS – 2
1 Cameras to Saturn (slewing)
1 Cameras to Rings (slewing)

Unique Science

- Saturn internal structure
  - Magnetic & gravity high-order moment measurements
- Ring mass
  - Address age of main rings
- In-situ measurements
  - Ionosphere, inner radiation belts, auroral region, and D ring particles
- High resolution observations
  - Rings, poles/aurora, atmosphere

Advance Planning: 2011-2017

Objectives, Uncertainty Analysis of initial trajectory

Ops Concepts: working groups to address issues

Science desires: how much periapse time is needed, desired trajectory tweaks

Science Observation Design: verify feasibility

Sharing Working Group: Detailed analysis of joint pointing

Validation and Verification Exercise

POST: Proximal Orbit Science Team

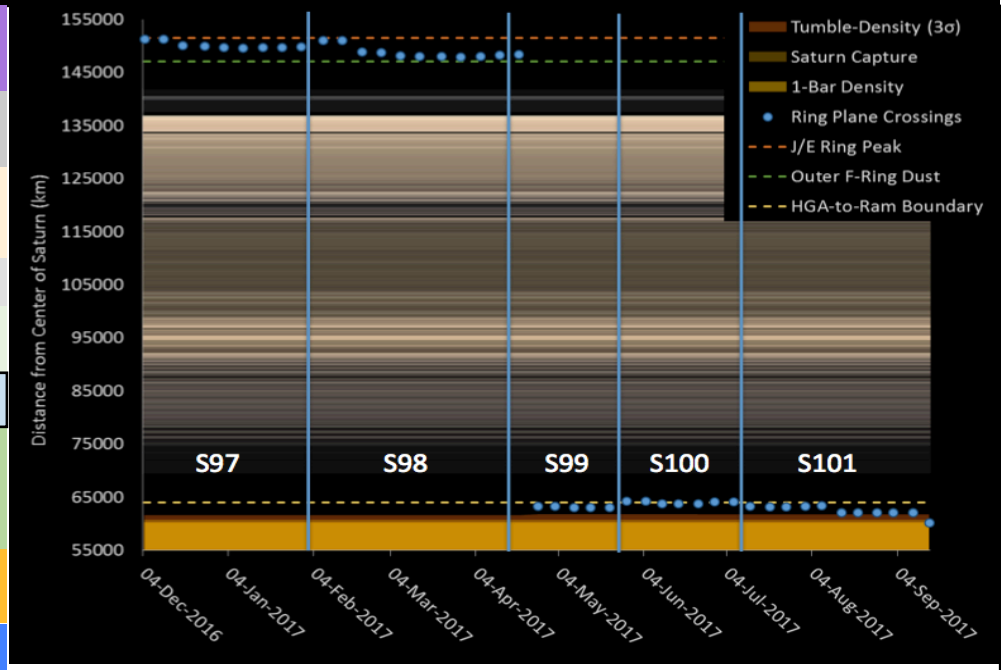
- **Pre-negotiate the 22 proximal periapses**

PIE: Pre-integrated Events (by discipline)

Integration (segment): Negotiate all shared resources

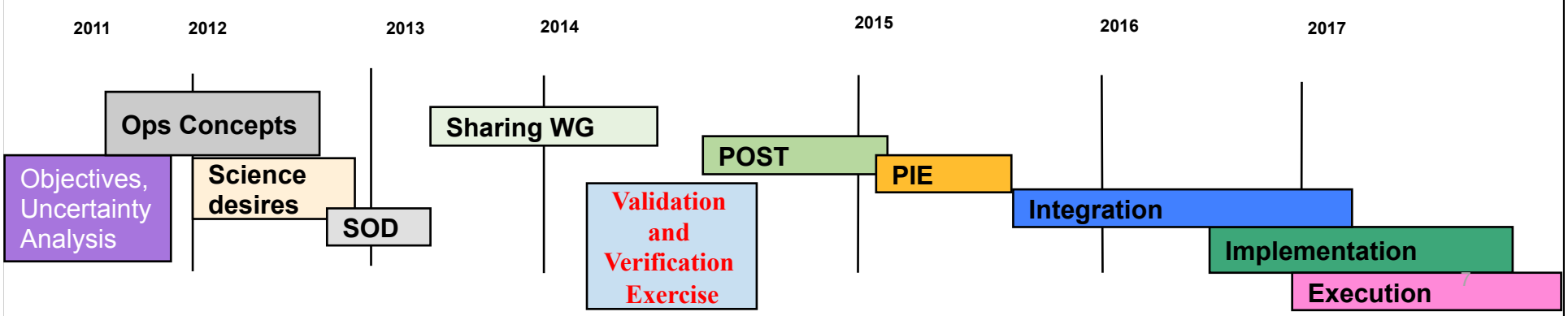
Implementation (sequence) Create and validate commands

Execution

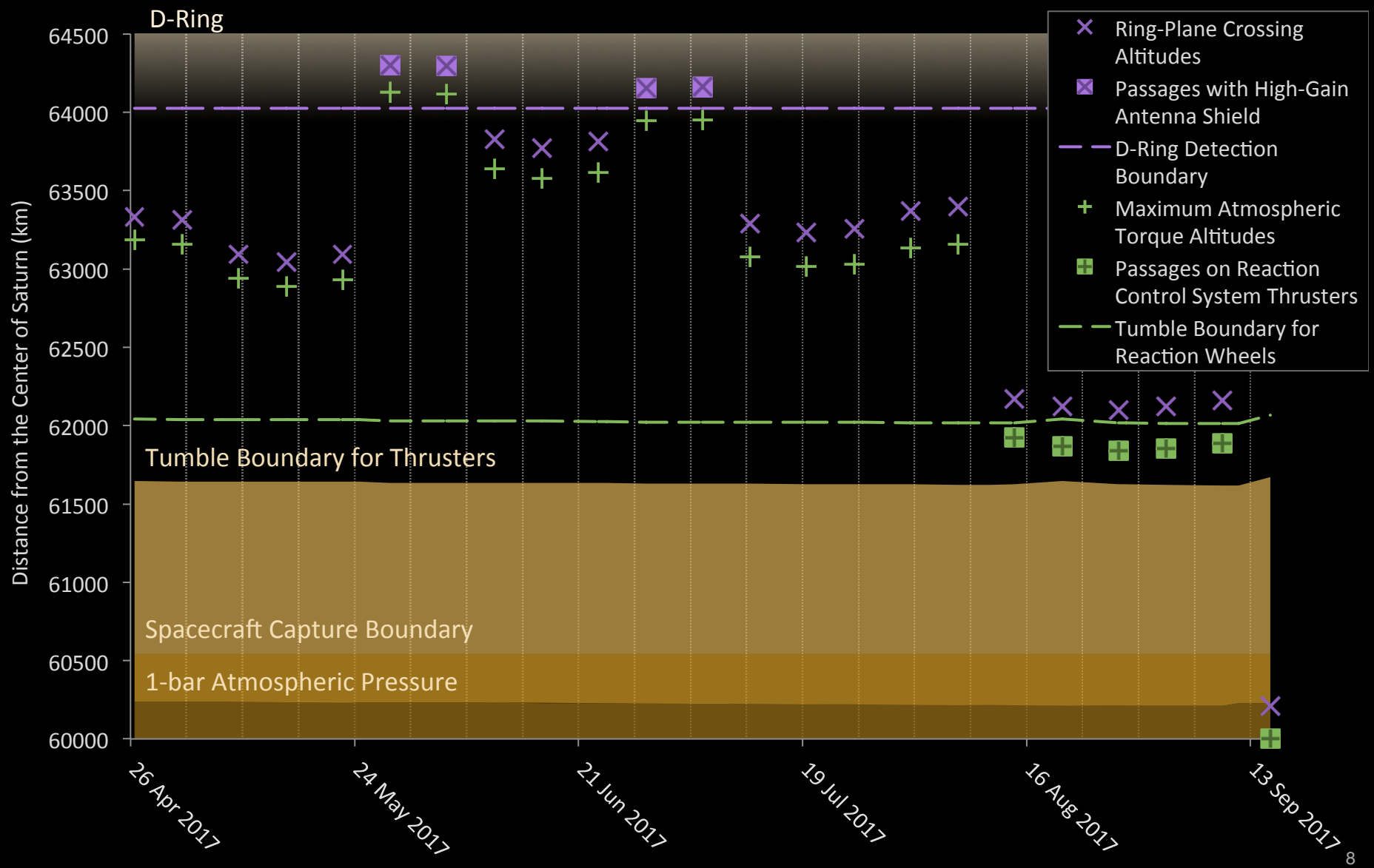


5 Sequences, 65 Segments by discipline

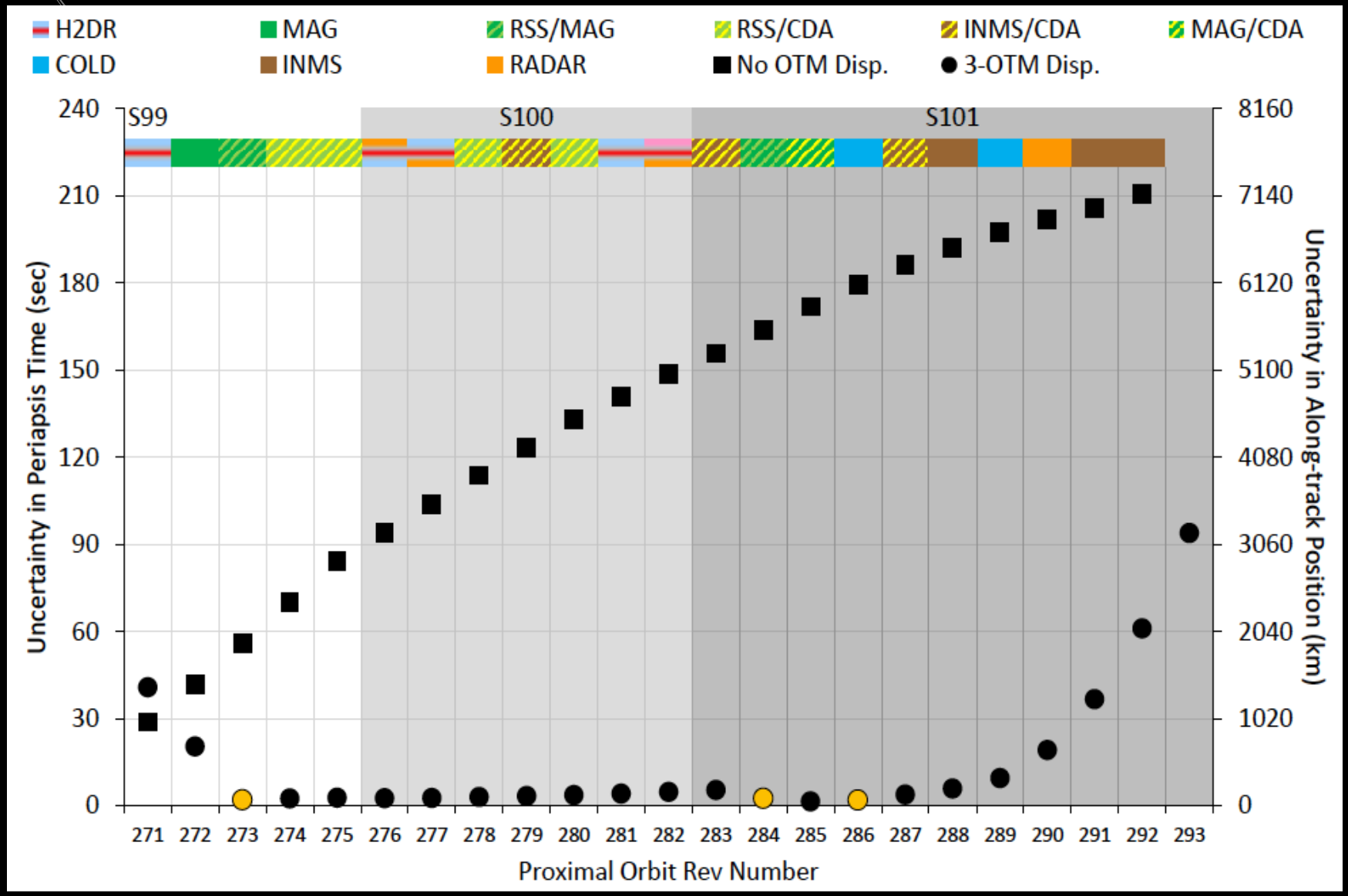
(Rings, Saturn, Icy Satellites, Titan, Magnetosphere, and Cross-Discipline)



Safe Corridor between Planet and Rings



Pointing uncertainties addressed



Sharing Working Group

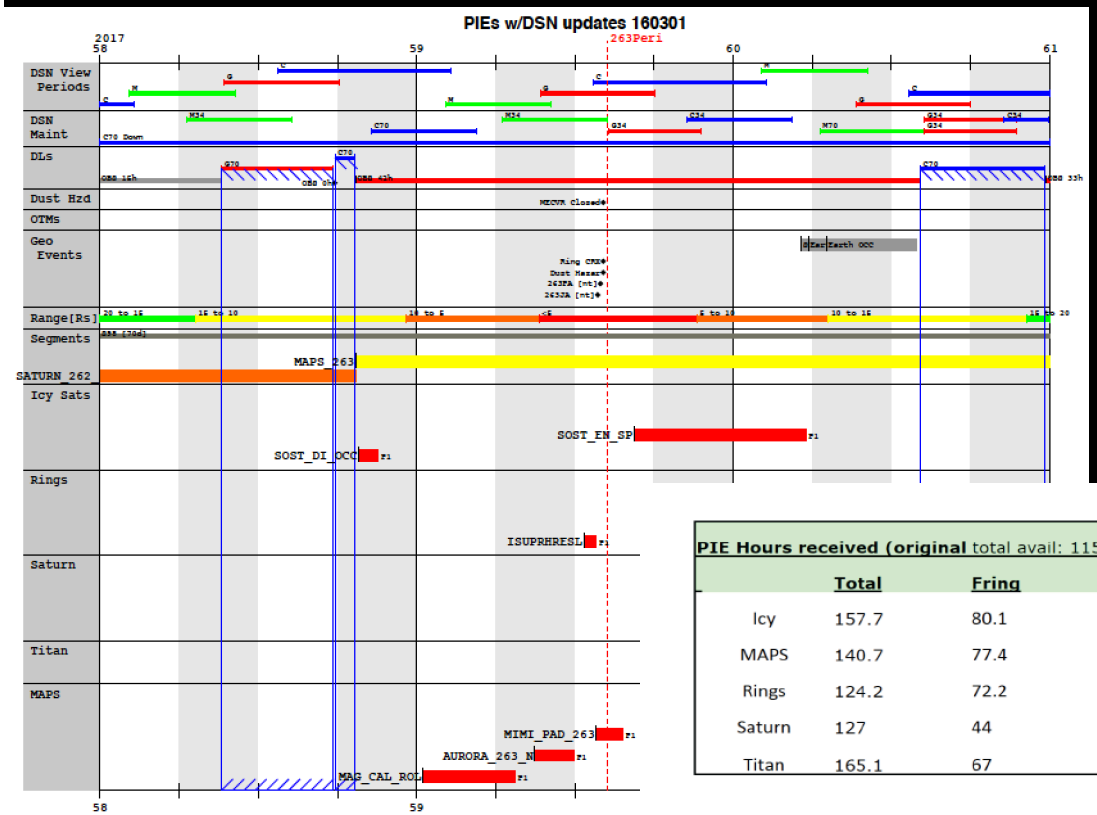
Observation	Pointing	PDT design	Science evaluation	Thermal (CIRS ΔT)	Viable?	Cold?
HGA/CDA	NEG_Z to Ram, POS_Y to Sun (0,0,5)	Yes	Yes, pending verification	8-9 K	Yes	NO
HGA/Cold	NEG_Z to Dust Ram, NEG_X to NSP	Yes (all 2nd tried , ±15 min. only	NA but potentially "cold"	3.1 K	YES	YES
RSS/CDA	XBAND to Earth, POS_X to NSP offset (0,0,0°)	Yes (2nd iteration to improve)	Yes, but could be improved	8.5 K	YES	NO
RSS/INMS	XBAND to Earth, any 2nd axis	Yes	NO		NO	
RSS/MAG	XBAND to Earth, Rolling	Yes	Yes	8-9 K	YES	NO
INMS (Dust)/ MAG	NEG_X to Dust Ram, Rolling	Yes	Yes	> 16 K	NO	NO
INMS (Cor.)/ MAG	NEG_X to COROT Ram, Rolling	Yes	Yes on later orbits	12 K	YES	NO
INMS/CDA	POS_X to COROT, NEG_Z to Sun	Yes (2nd iteration in progress)	Yes on rev 272, No on rev 291	24 K for ± 1 hour on Rev 272	No	NO

POST: Proximal Orbit Science Team

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	S99	S99	S99	S99	S99	S100	S100	S100	S100	S100	S100
Segment owner	Saturn	XD	Maps	Rings	Saturn	Rings	Rings	Saturn	Maps	XD	Saturn
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	

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
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								

PIE: Pre-Integrated Events



- Highest priority science per discipline
- Balance segment workload

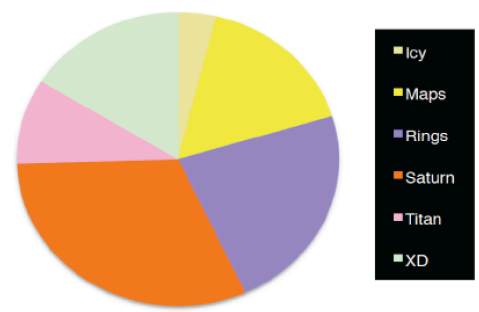
PIE Hours received (original total avail: 115):

	Total	Fring	Proximal
Icy	157.7	80.1	77.6
MAPS	140.7	77.4	63.3
Rings	124.2	72.2	52
Saturn	127	44	83
Titan	165.1	67	98.1

	Total Integration Days		Segments	Periapses
Icy	11.5	4%	3	2
Maps	49	17%	11	11
Rings	68.25	24%	13	13
Saturn	83.5	29%	15	12
Titan	26.25	9%	13	0
XD	50.25	17%	9	4
	289.75		65	42

Total PIE hours

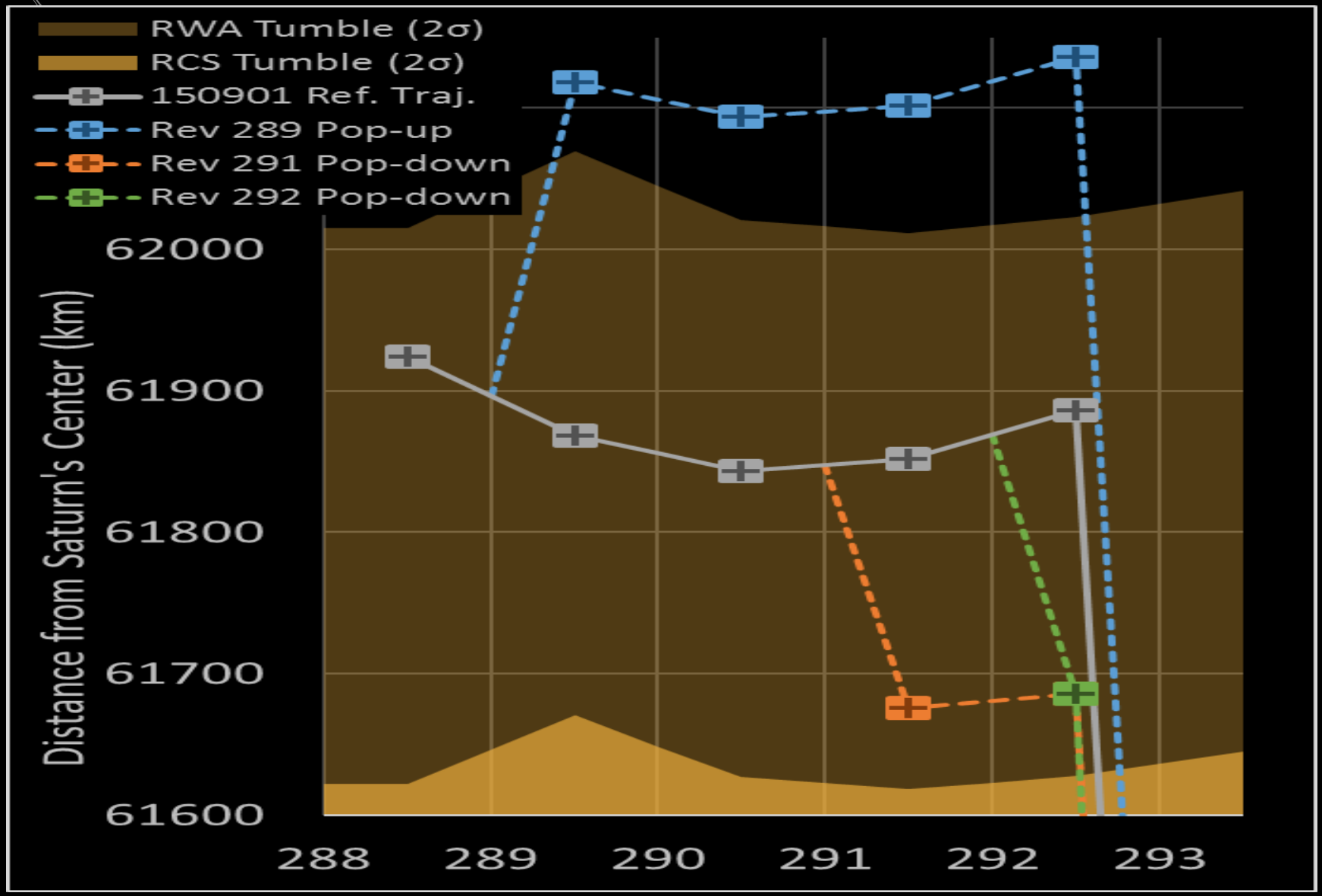
Total Integration Days



Integration process (red is changed)

- Having POST and PIEs pre-integrated into a segment
- Negotiate a conflict free timeline for pointing
  - Geometrically challenging and high density timelines
    - Pointing designs done early (in integration)
      - All custom periods
      - Pre-approval for consumable level heating of instruments
      - Allowed relaxation of reaction wheel protection policies
      - Addressed workload issues
- Negotiate standard shared resources of data volume, power
  - Additional dual playback requests from Project Science
- Prepare supplemental science highlights/products for outreach

Pop-down or Pop-up

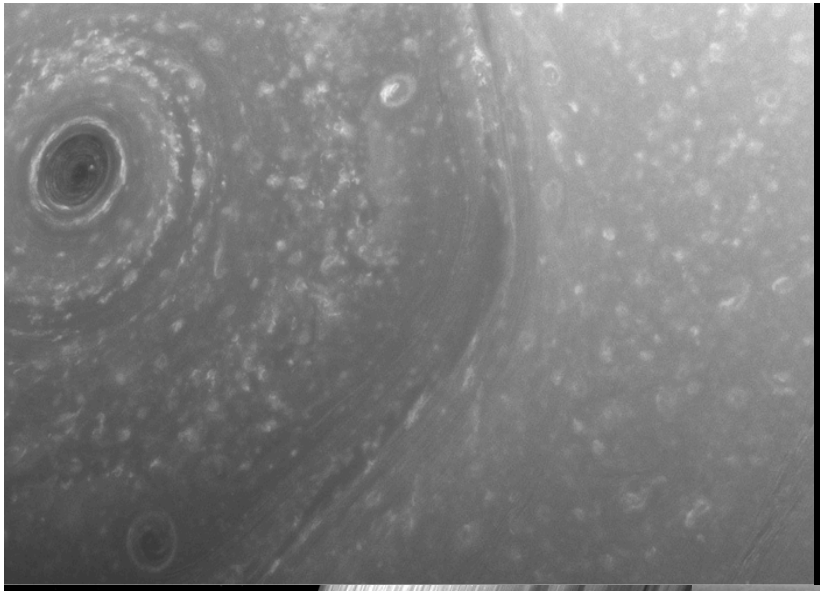


Lessons learned

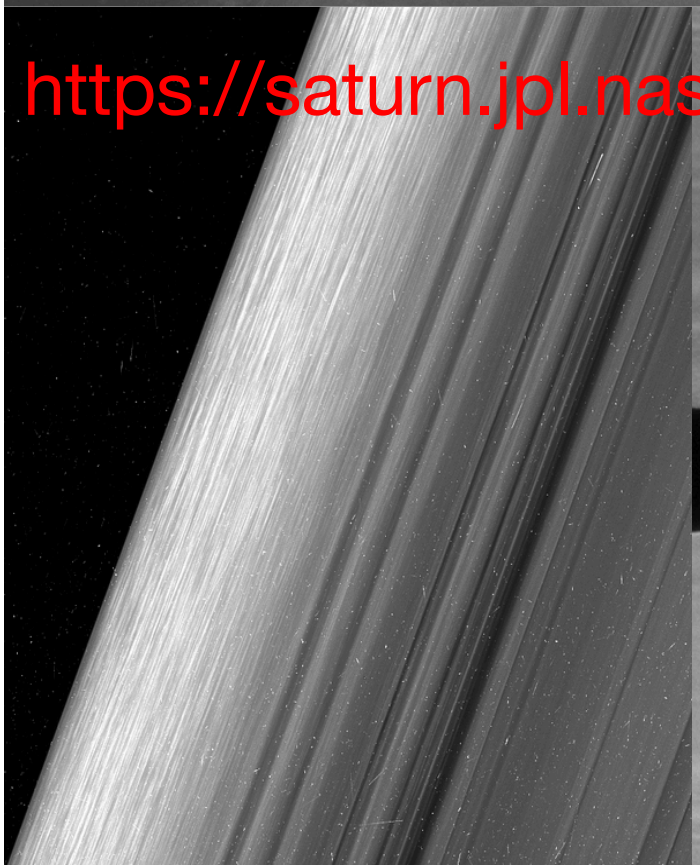
- *Advanced Planning*- Starting more than 6 years early was crucial in allowing the existing teams to fly a complex spacecraft, while simultaneously performing analysis and development work to fly a brand new mission with aging hardware. Working groups tackled the challenges early (heating, reaction wheels, pointing uncertainty tolerances, HGA contingency process, pop-down/pop-up, etc.) The early SOD, sharing working group, and exercise flushed out many of the main challenges. Process changes, like the early PDT designs, allowed teams to meet ambitious delivery schedules.

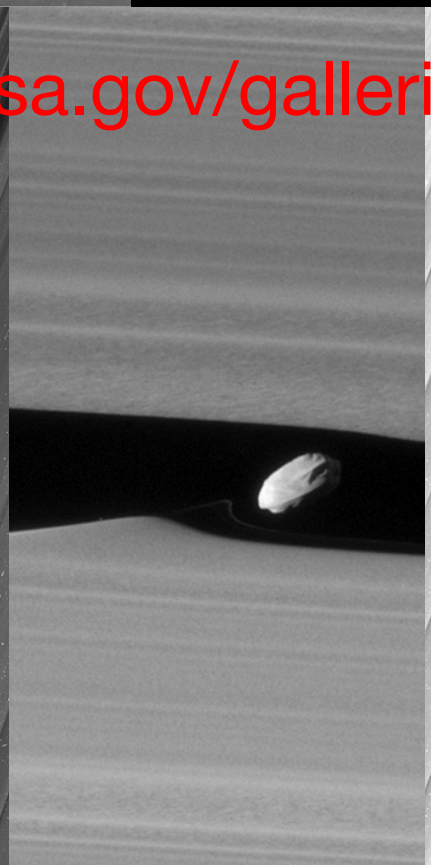
- *Build in flexibility and the ability to react as late as possible to issues* - Identifying model uncertainties (Saturn's atmosphere and D-Ring dust) allowed the project technical teams to create plans that optimized science yet provide contingency options should the need arise, if the environment is deemed too hazardous.

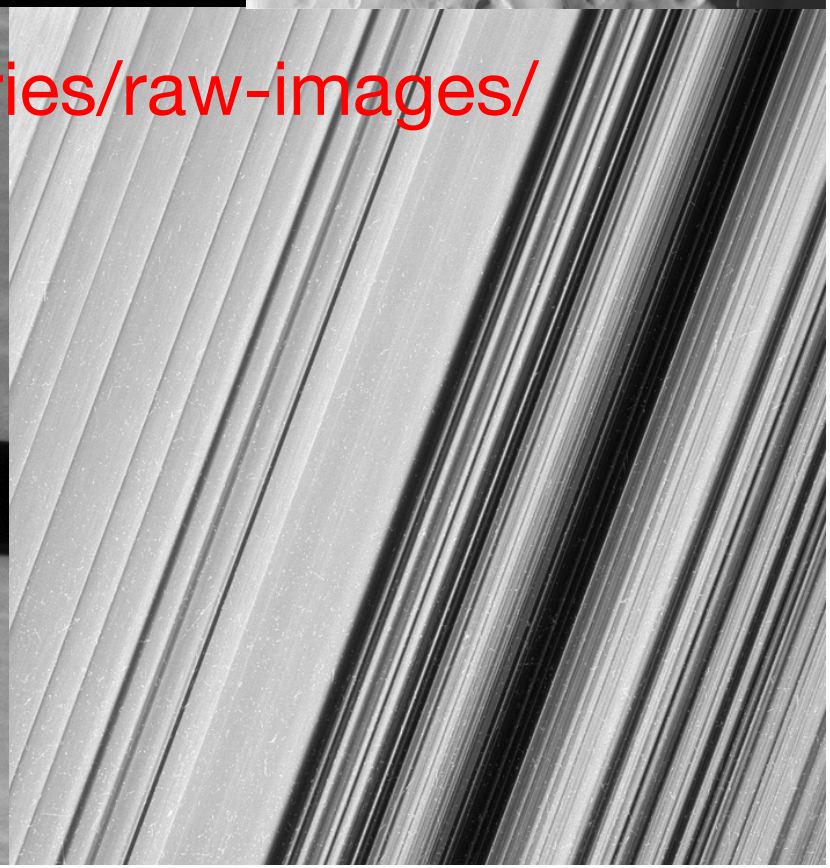
Results (first 7 F-ring orbits)!



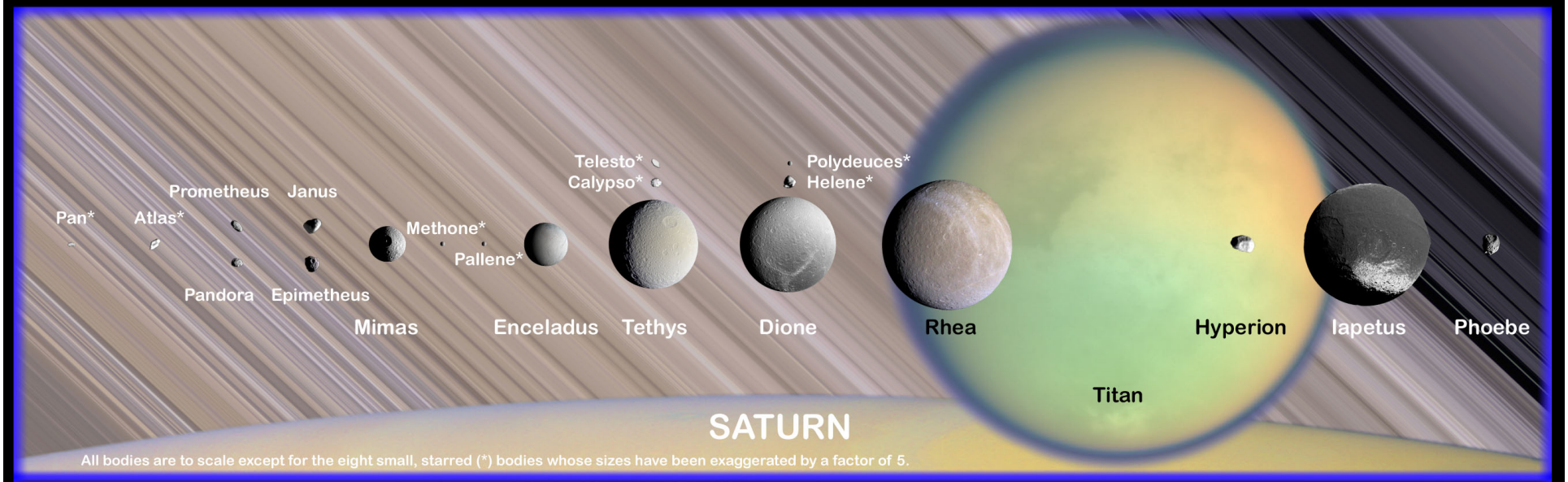
https://saturn.jpl.nasa.gov/galleries/raw-images/

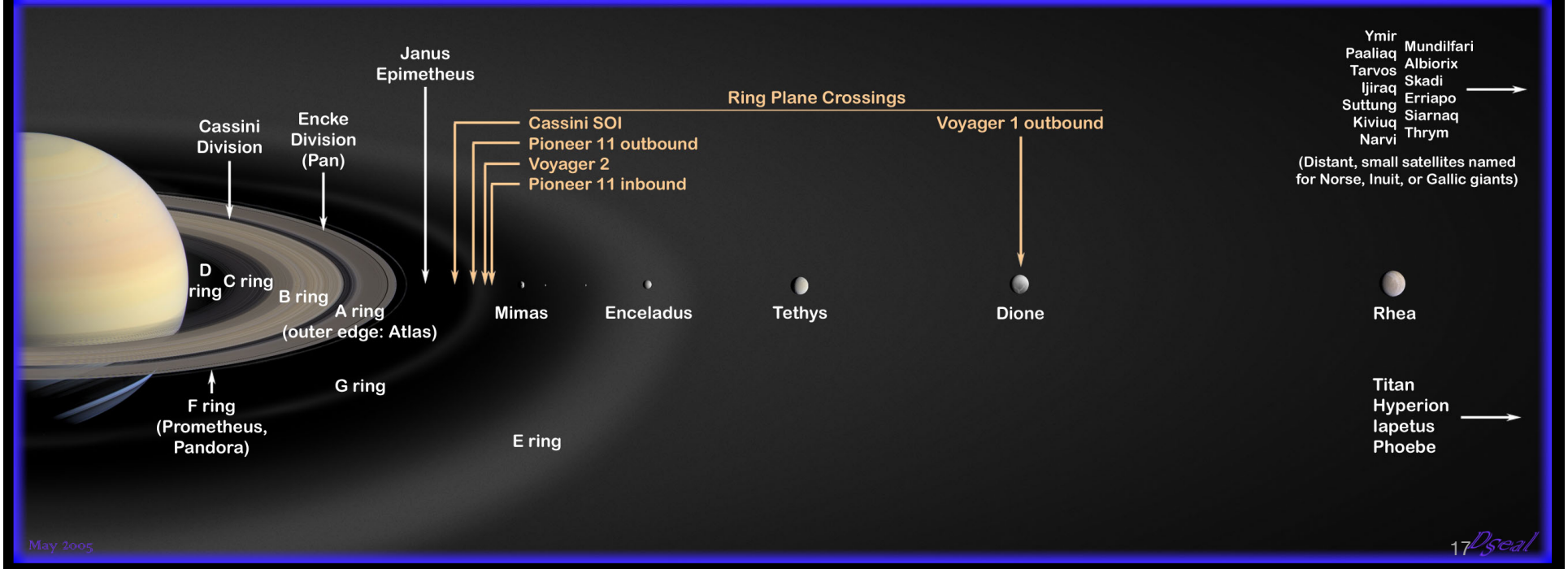




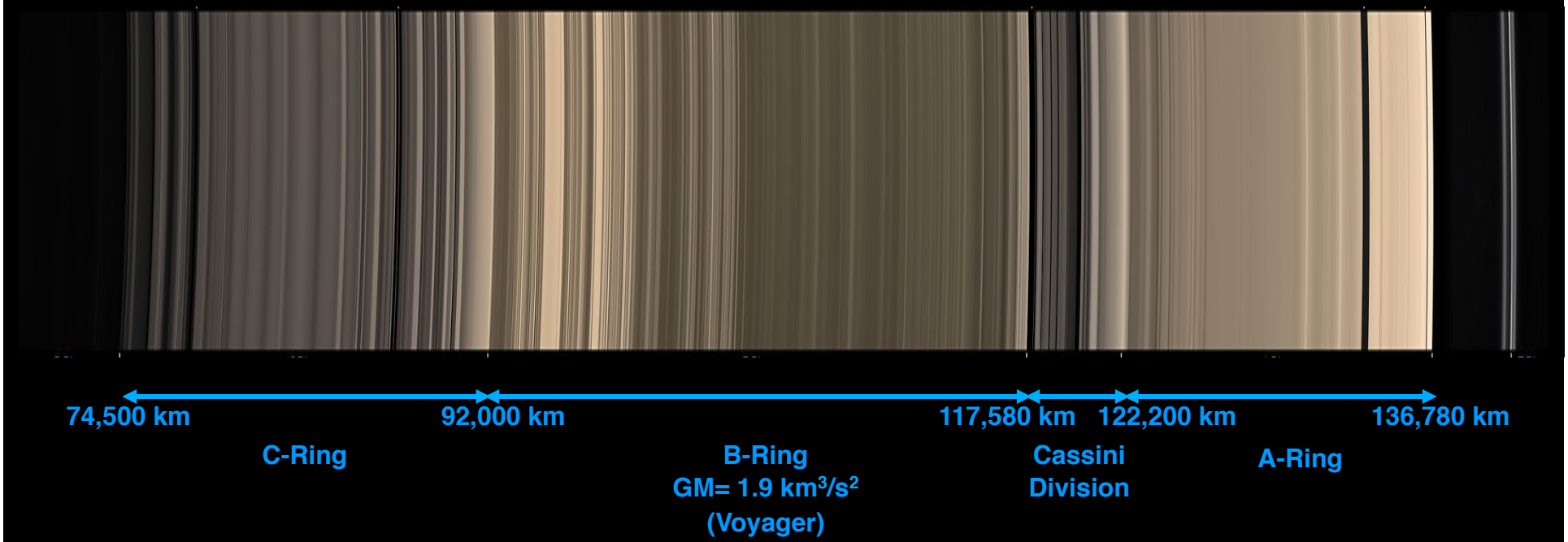


THE SATURNIAN SYSTEM





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%)