USING SATURN'S RINGS AS A COSMIC LABORATORY

SAURON

Alpbach Summer School 2025

Team Blue

Overview

Science

- Mission Statement
- Science Case
- How do planetesimals form?
- Science Objectives and Requirements
- Instrumentation
- Key Requirements
- Opportunistic science

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- Concept of Operation
- Mission Design Drivers
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- Mass and power budgets
- Subsystems
- Ground segment

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- Cost
- Risk Assessment
- Preparing for Saturn's environment
- Development
- Descoping options
- Public outreach

Science

Science → Mission Design → System Design → Program Execution

- Mission Statement
- Science Case
- How do planetesimals form?
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- Instrumentation
- Key Requirements
- Opportunistic science

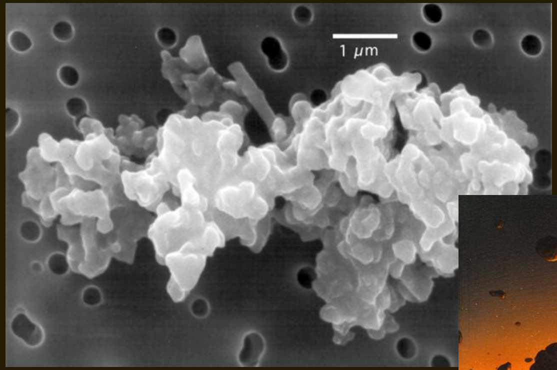
Mission Statement

Saturn’s rings as a window into planet formation:

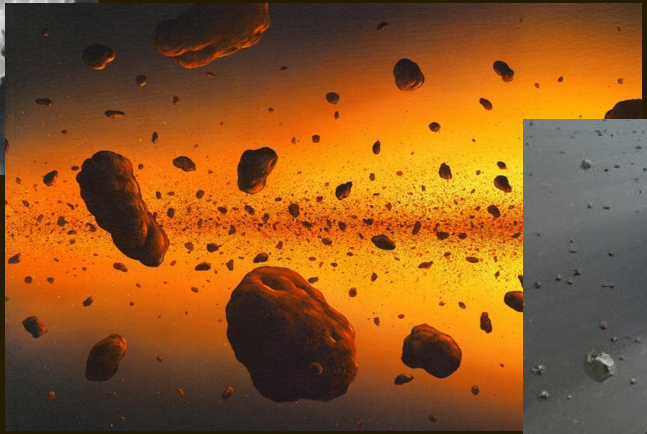
Investigate the fundamental physical mechanisms of particle aggregation, fragmentation, and dynamical evolution in Saturn’s rings as a natural laboratory for planet formation physics.

Science Case

Small bodies

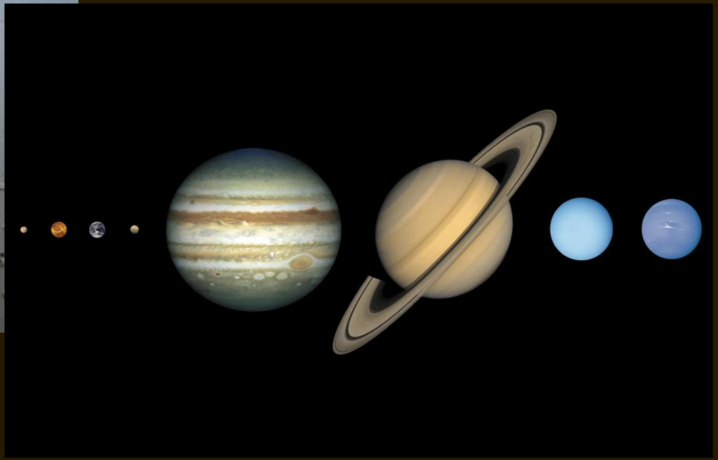


1μm



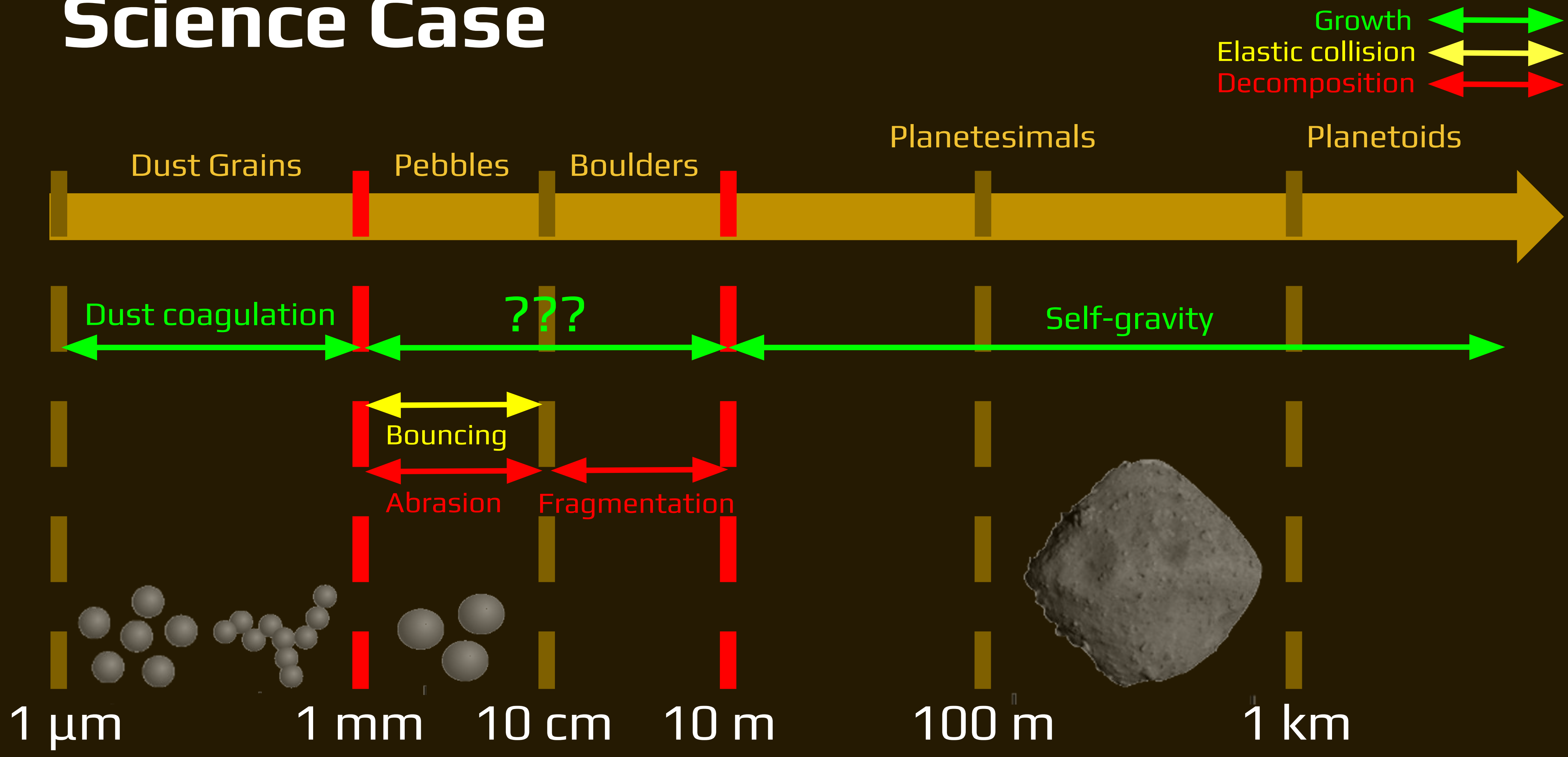
1m

1 km



70 000 km

Science Case

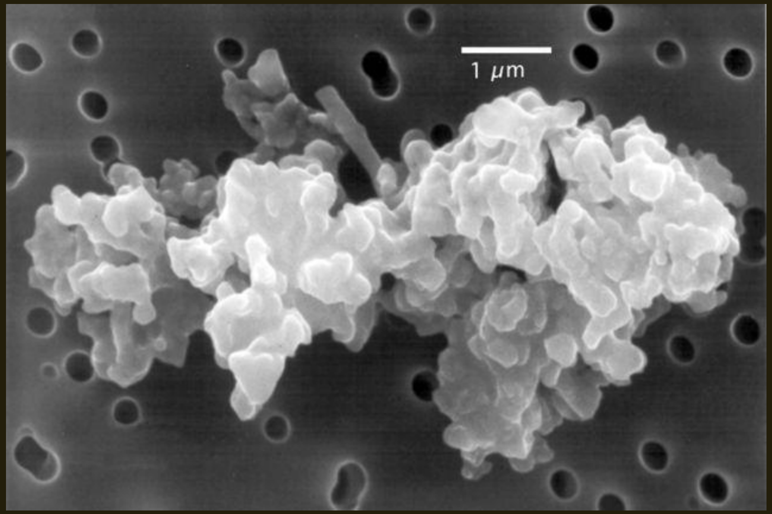


Science Case

Lab / ISS

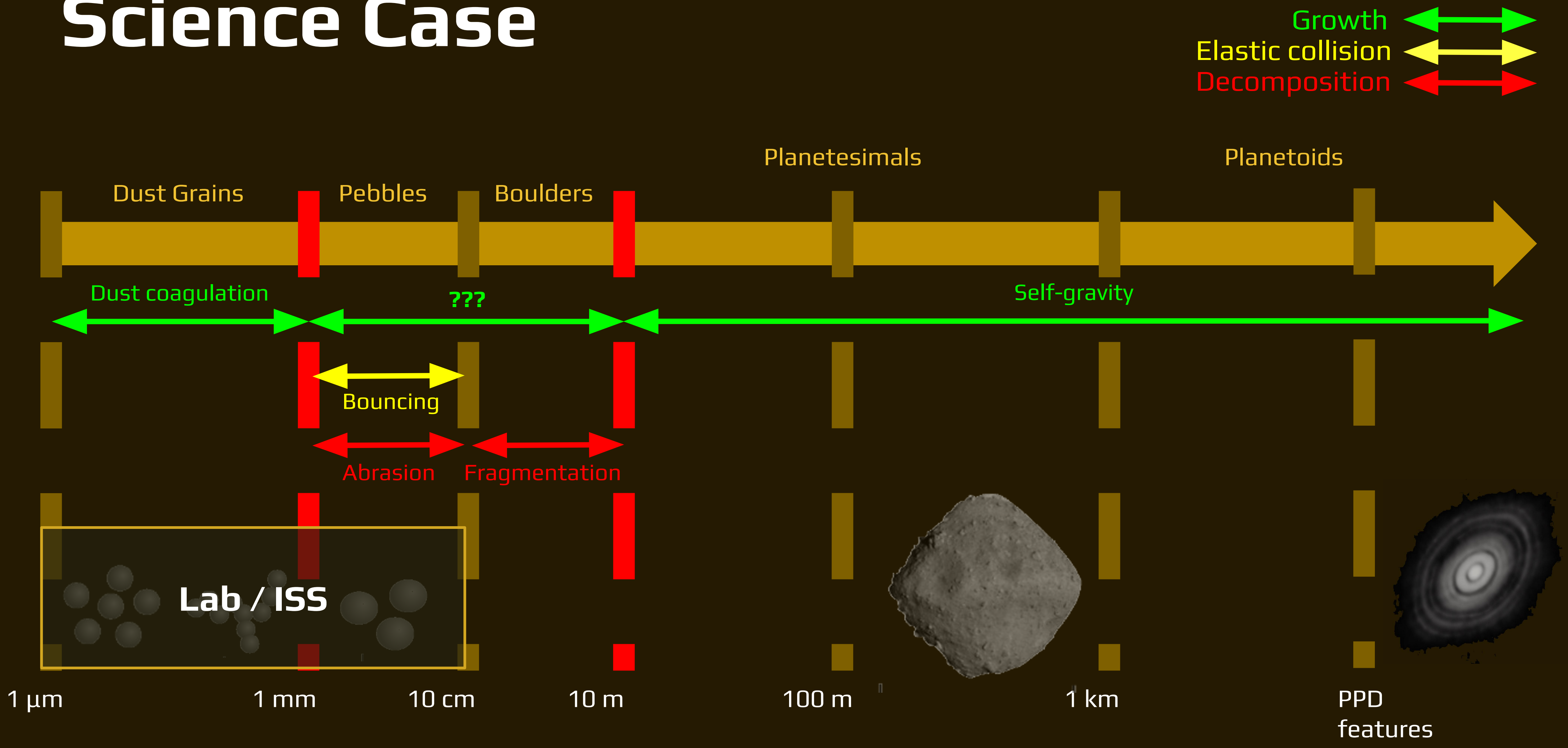
- Collision experiments
- Microgravity dust experiments

1cm



1μm

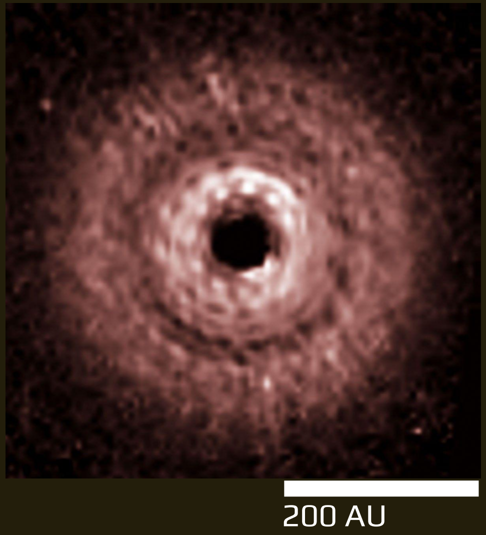
Science Case



Science Case

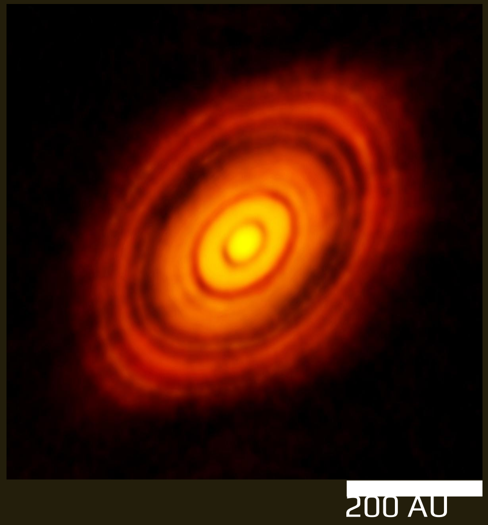
Telescopes

- Hubble: VIS and UV imaging and spectroscopy
- JWST: IR imaging and spectroscopy
- ALMA: Interferometric Radio Astronomy



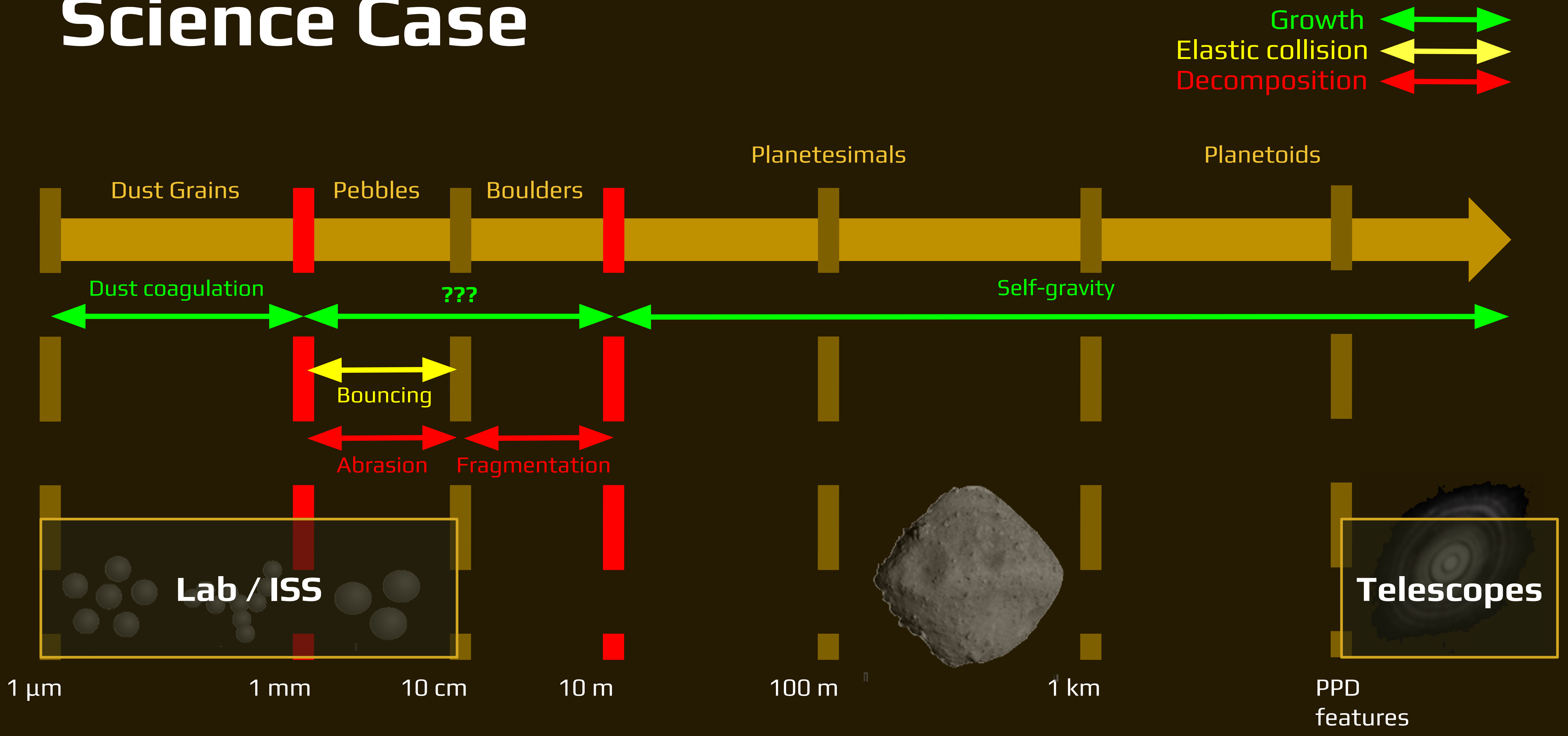
Credit: Hubble, TW Hydrae

Credit: Webb, HH-30



Credit: ALMA, HL Tauri

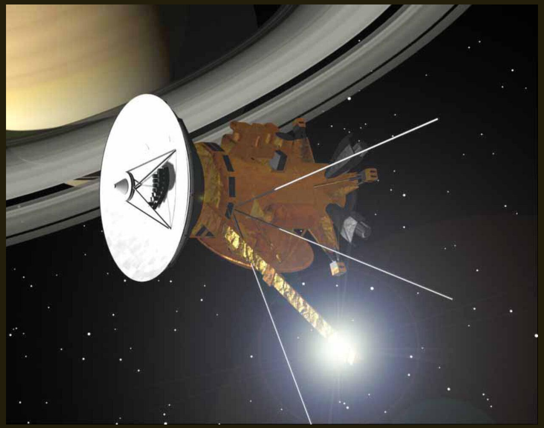
Science Case



Science Case

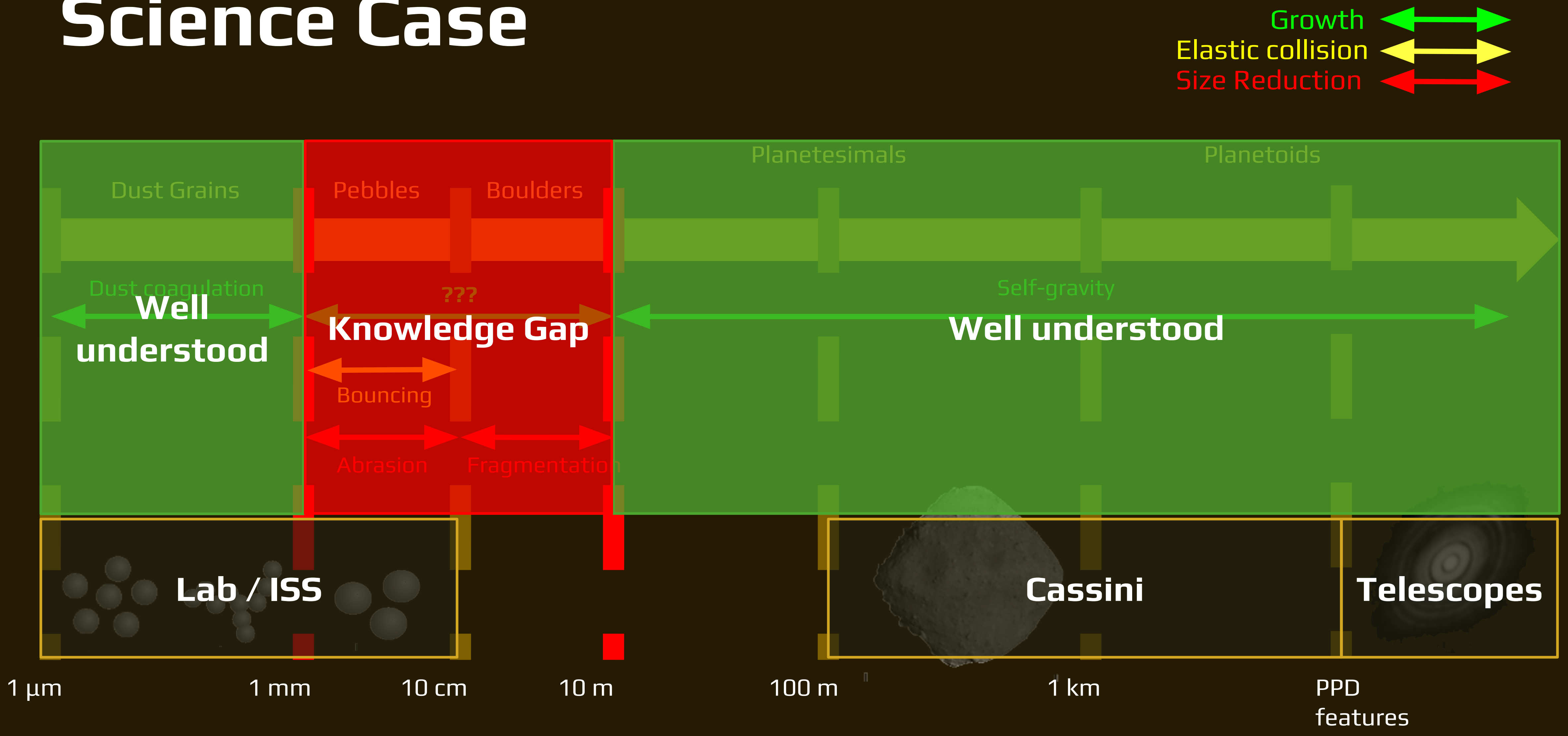
Cassini

- Remote sensing
  - Visual and Infrared Mapping Spectrometer (VIMS)
  - Imaging Science Subsystem (ISS)
- In-situ
  - Cosmic Dust Analyzer (CDA)
  - Radio Science Subsystem (RSS)



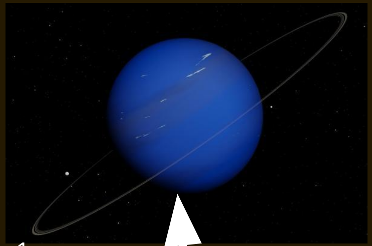
Credit: ESA

Science Case



How do planetesimals form?

- Microcosm for Protoplanetary Disk Processes



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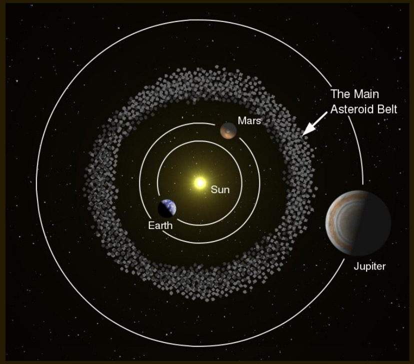

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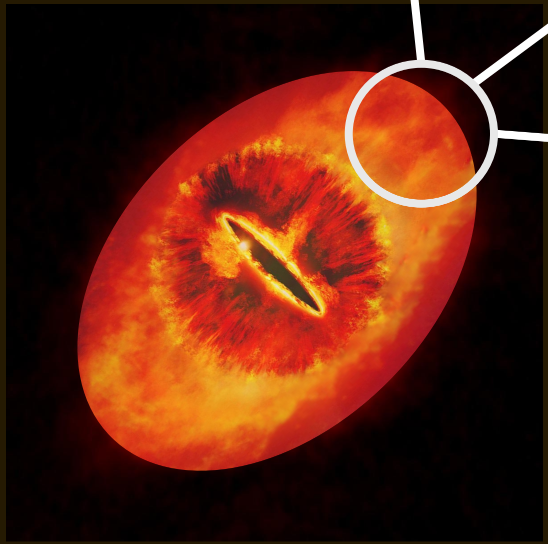
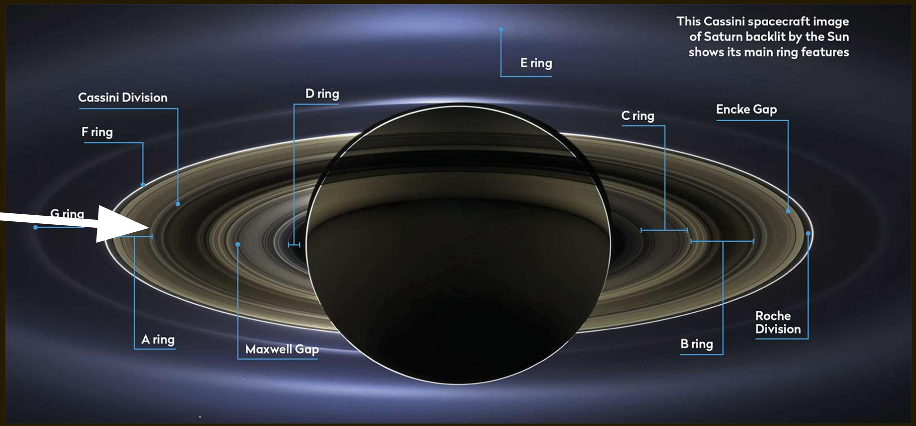
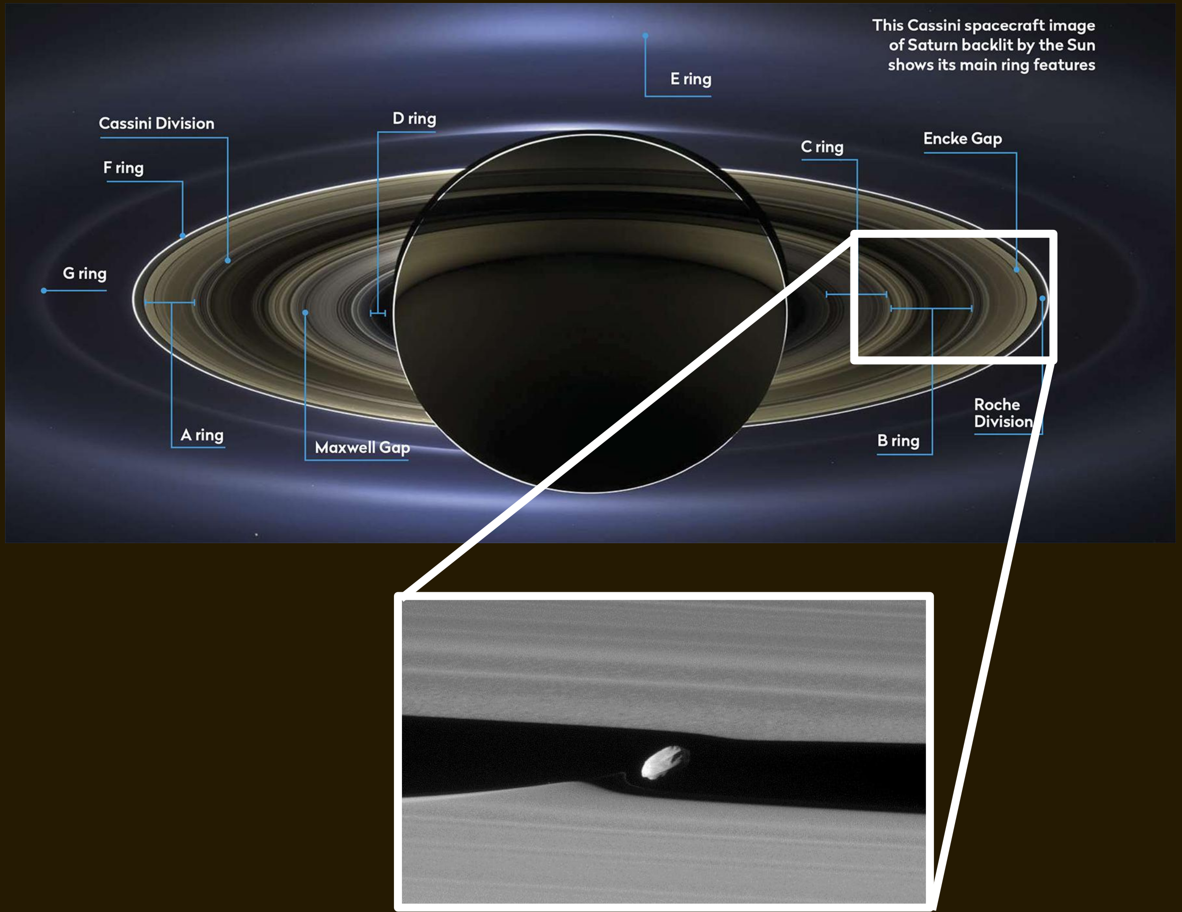




Credit: Cassini 2013

1 https://amazingphysicsforall.com/planet-neptune/
2 https://www.fcipshop.com/?ggcid=3739517

How do planetesimals form?



Credit: Cassini 2013

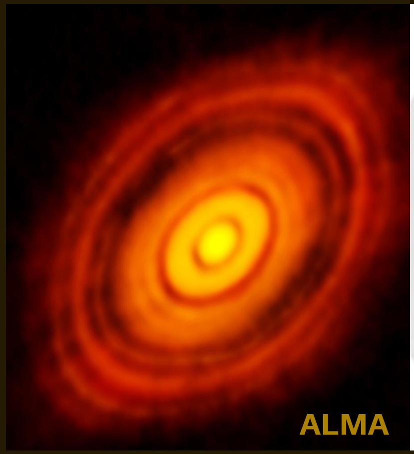
- Different properties
  - Temperature: Saturn’s rings are much colder than PPDs (Miller et al. 2024)
  - Composition: Predominantly water ice vs. mixed ices, silicates, organics (Esposito, 2010)

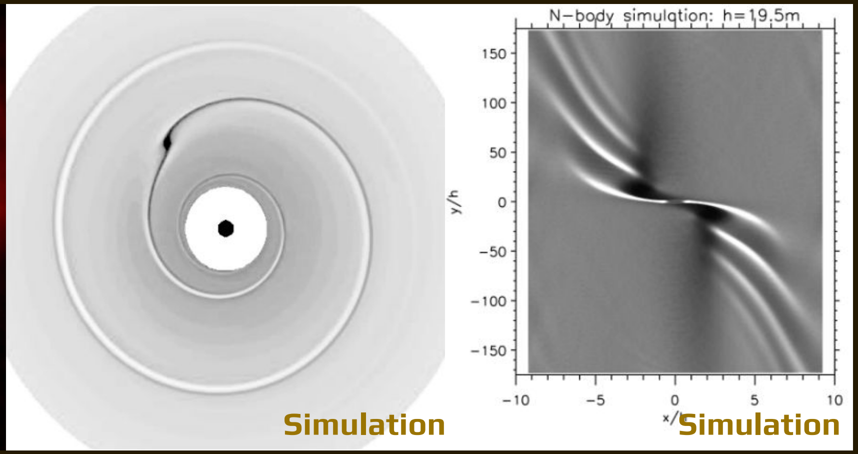
- Shared Physical Processes
  - Sticking, bouncing, fragmentation (Brisset et al. 2013)
  - Overlap in particle size distributions and collision velocities

    (Booth et al. 2016, Ohtsuki et al 2022)

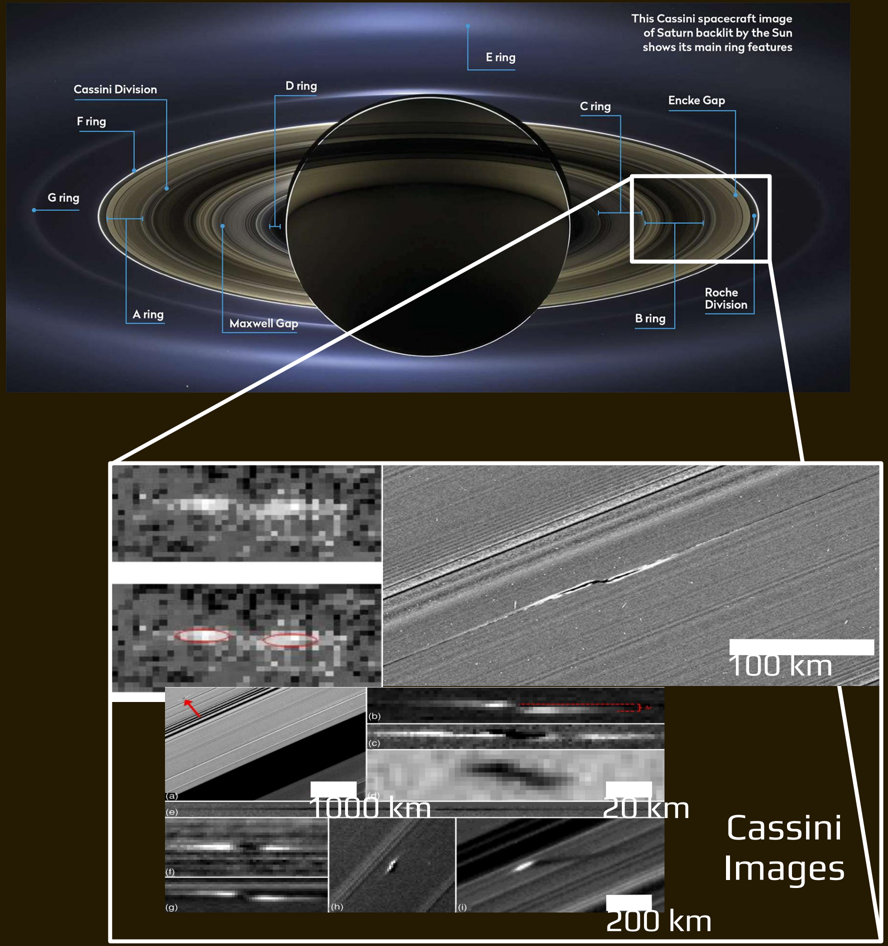
How do planetesimals form?

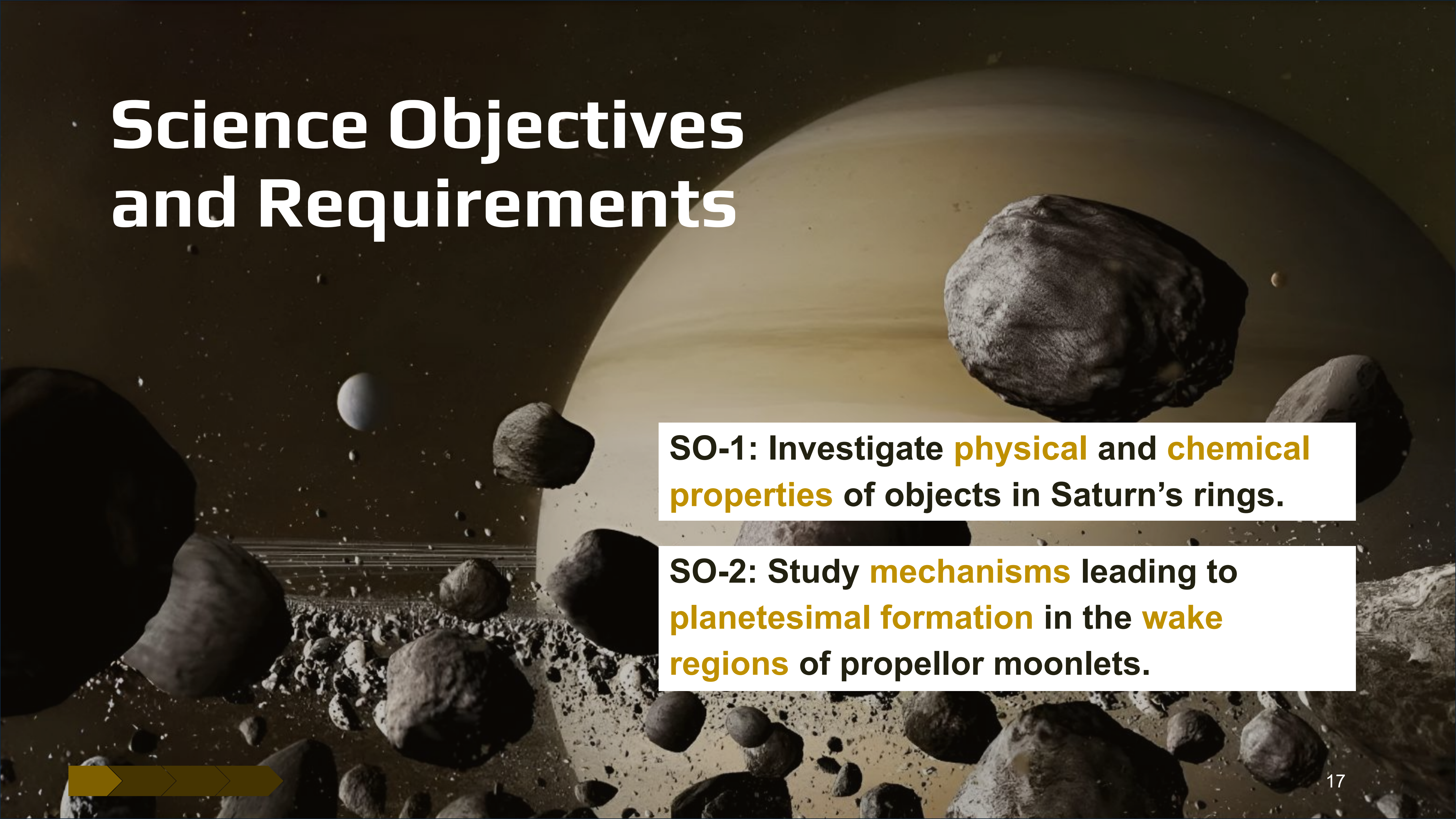
Role of Propeller Moons





Credit: Latter et al., 2017 Credit: Seiβ et al., 2017



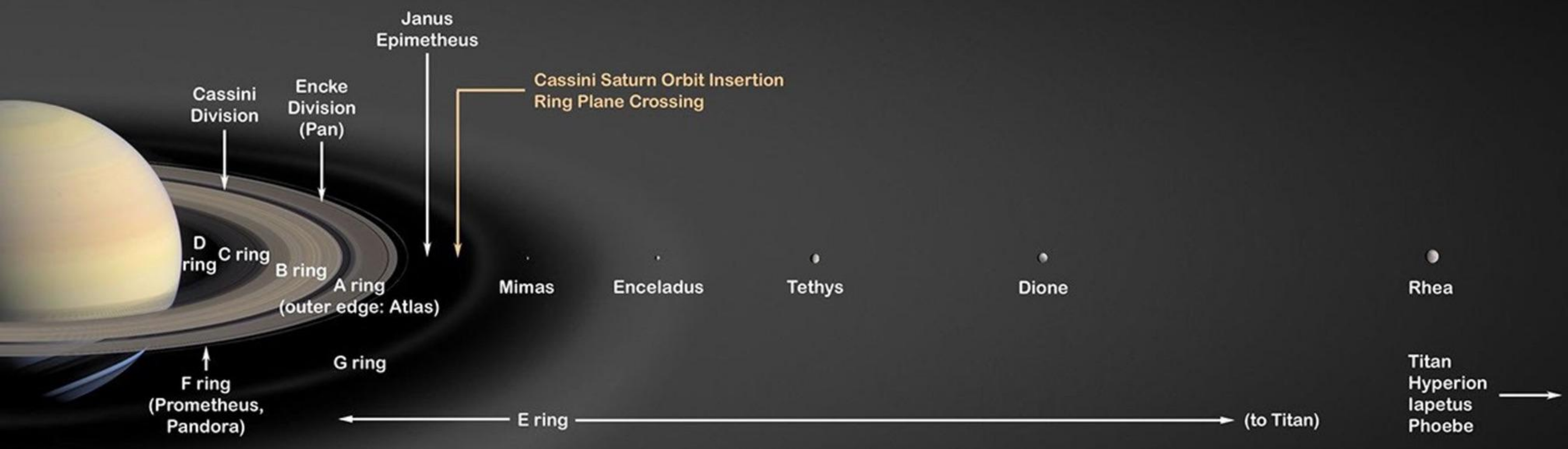


Science Objectives and Requirements

SO-1: Investigate physical and chemical properties of objects in Saturn’s rings.

SO-2: Study mechanisms leading to planetesimal formation in the wake regions of propellor moonlets.

Saturn’s Rings



Credit: NASA

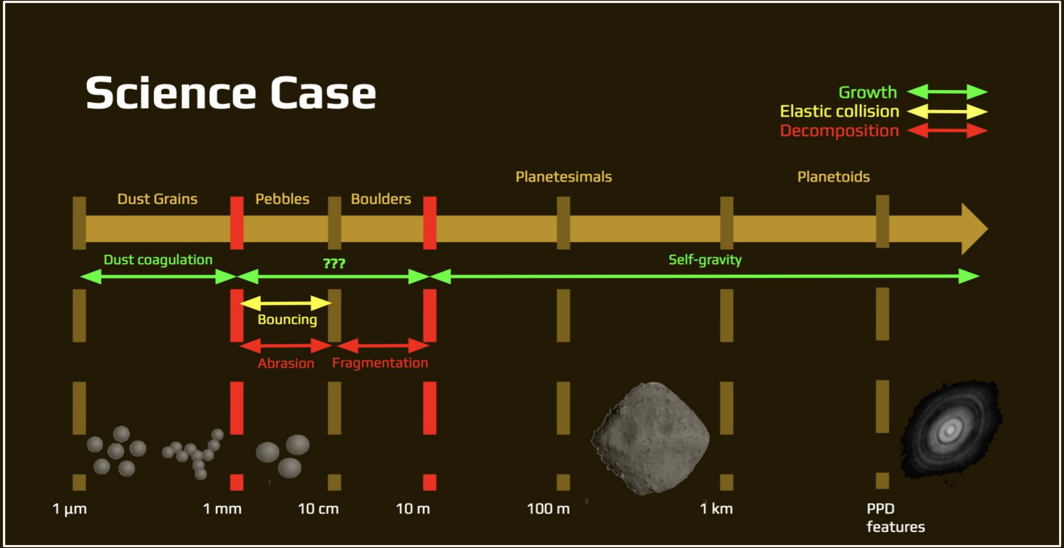
Science Objectives and Requirements

Science Objective	Sub Objectives
SO-1: Investigate physical and chemical properties of objects in Saturn's rings.	SO-1.1: Characterise the size distribution of **agglomerates**.
	SO-1.2: Study physical and chemical properties of **particles** in the outer rings.
	SO-1.3: Investigate the location, abundance, lifespan, and formation/destruction processes of **moonlets**.

SO-1: Investigate physical and chemical properties of objects in Saturn’s rings.

SO-1.1: Characterise the **size distribution** of agglomerates in Saturn’s rings.

Radius	Instrument
0.01 - 10 μm	Dust Analyser
0.1 - 10 μm	Spectro-polarimeter
1 - 50 mm	Radio Occultation
0.4 - 10 m	NAC Stereo Camera
1 - 100 m	WAC Stereo Camera



SO-1: Investigate physical and chemical properties of objects in Saturn’s rings.

SO-1.2: Study physical and chemical properties of **particles** in the outer rings.

Observable	Instrument
Velocity	Dust Analyser
Charge	
Isotopic ratios (H/D, O16/18, N14/15)	
Composition (Si, H, ..)	Dust Analyser / Spectro-polarimeter

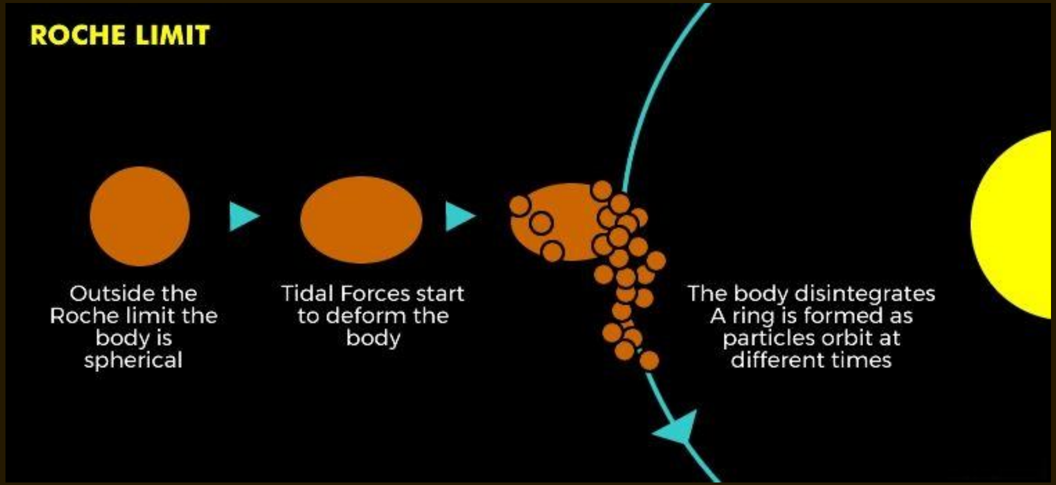
SO-1: Investigate physical and chemical properties of objects in Saturn's rings.

SO-1.3: Investigate the location, abundance, lifespan, and formation/destruction (roche limit) processes of moonlets in Saturn's rings.

Measure moonlet size, number, and distribution (WAC)

- In Ring A
- In the other Rings

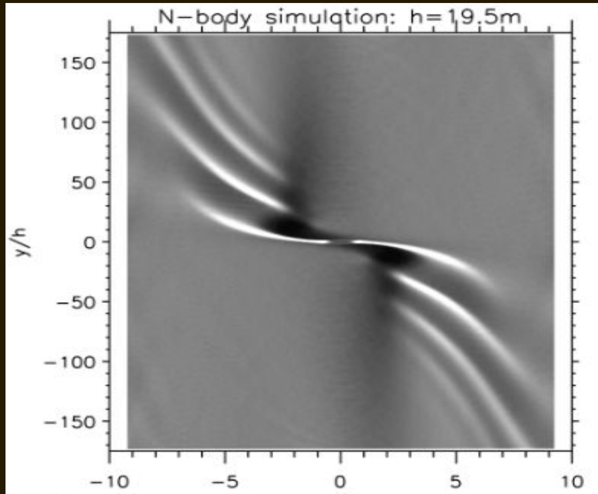
[Cassini Images]



Science Objectives and Requirements

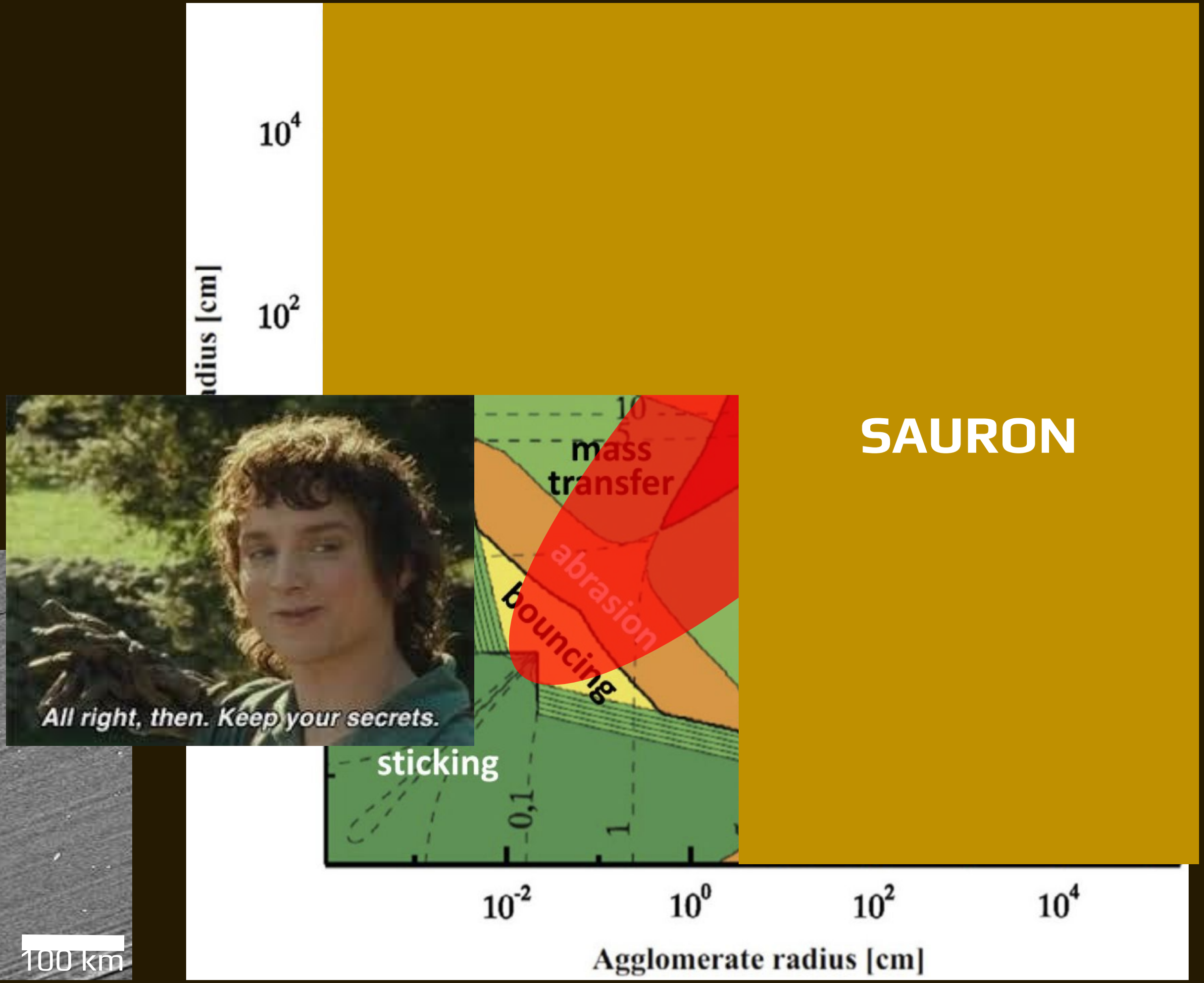
Science Objective	Sub Objectives
SO-2: **Study mechanisms leading to planetesimal formation in the wake regions of propellor moonlets.**	SO-2.1: Examine different types (coagulation, bouncing, abrasion, fragmentation) of **agglomerate collisions** and their frequency.
	SO-2.2: Investigate agglomerate **growth barriers** and the influence of charge and volatile content.

Propeller moonlet wake regions



Seiss + 2017

Cassini Image



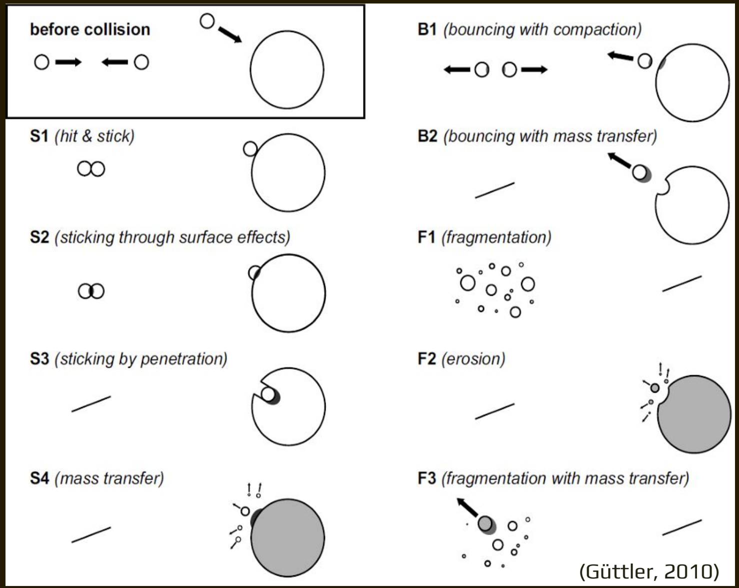
Blum (2018)

SO-2: Study mechanisms leading to planetesimal formation in the wake regions of propellor moonlets.

SO-2.1: Examine different types of **agglomerate collisions** and their frequency.

Observable	Instrument
Velocity cm/s - m/s	NAC Stereo Camera
Radius 0.15 - 250 m	
Radius 0.4 - 1400 m	WAC Stereo Camera

Type of Collision:	Outcome
Hit & Stick	Growth
Bouncing	Neutral
Abrasion	Mass Loss
Fragmentation	Mass Loss

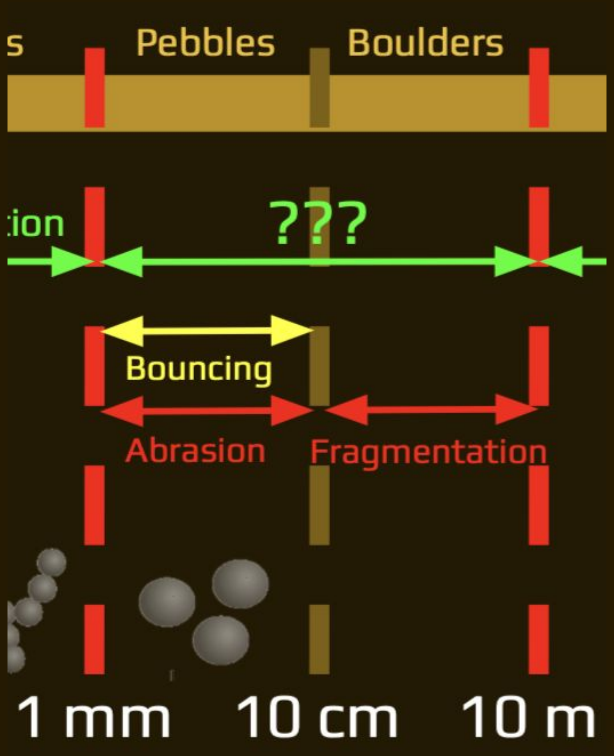


(Güttler, 2010)

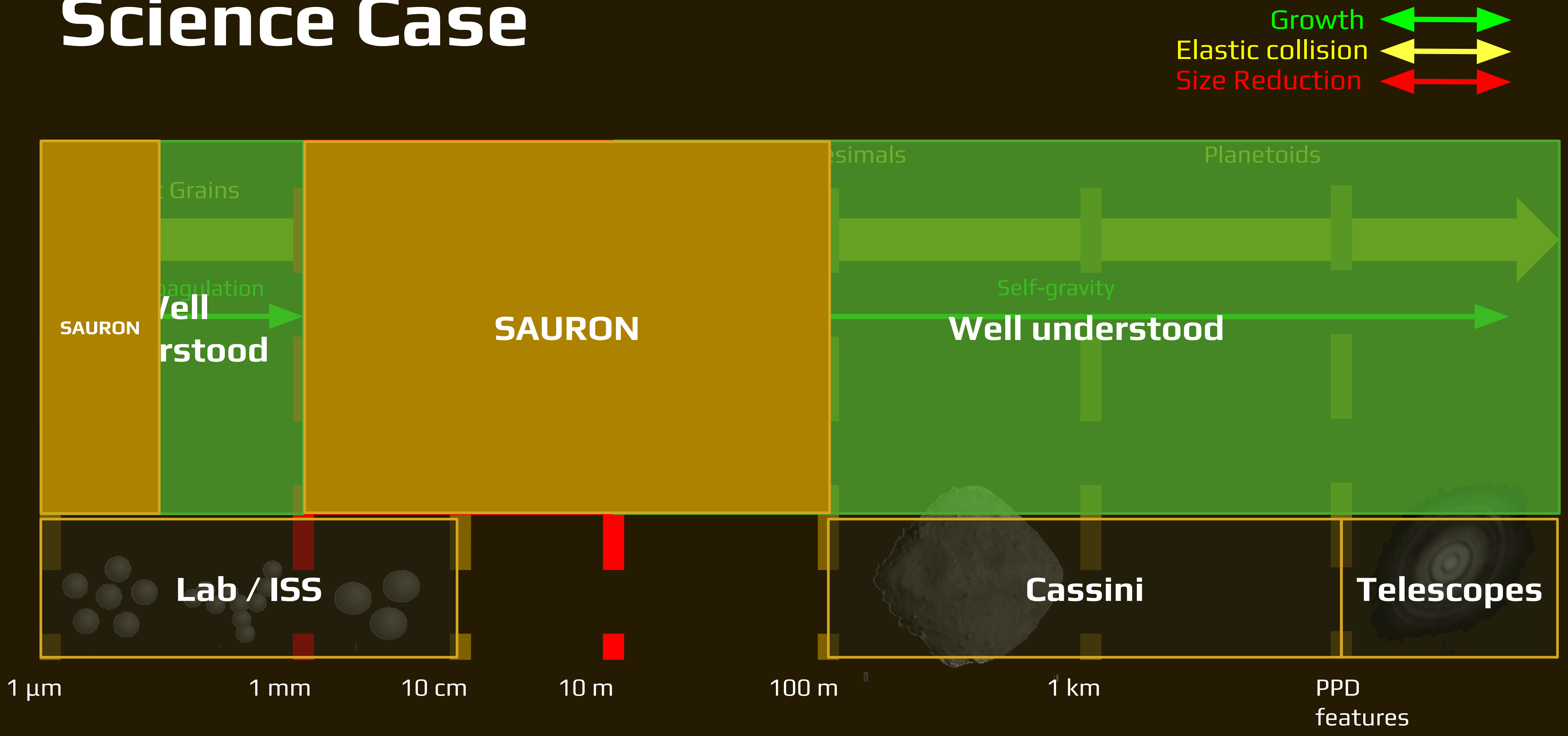
SO-2: Study mechanisms leading to planetesimal formation in the wake regions of propellor moonlets.

SO-2.2: Investigate agglomerate **growth barriers** and the influence of volatile content.

Observable	Instrument
Velocity cm/s - m/s	NACs Stereo System
Radius 0.15 - 250 m	
Radius 0.4 - 1400 m	WACs Stereo System
Composition (Si, H, ..)	Spectropolarimeter



Science Case



Instrumentation

SO-1.1: Size Distribution of particles	
Radius	Instrument
0.01 - 10 μm	Dust Analyser
0.1 - 10 μm	Spectropolarimeter
1 - 50 mm	Radio Science Exp.
0.4 - 10 m	NACs Stereo System
1 - 100 m	WACs Stereo System

SO-1.2: Chemical and Physical Particle Properties	
Observable	Instrument
Velocity	Dust Analyser
Charge	Dust Analyser
Isotopic ratios (H/D, O16/18, N14/15)	Dust Analyser
Composition (Si, H, ..)	Dust Analyser Spectropolarimeter

SO-1.3: Moonlets	
Observable	Instrument
Characteristics	WACs Stereo System

SO-2.1: Collision types	
Observable	Instrument
Velocity cm/s - m/s	NACs Stereo System
Radius 0.15 - 250 m	NACs Stereo System
Radius 0.4 - 1400 m	WACs Stereo System

SO-2.2: Growth barriers	
Observable	Instrument
Velocity cm/s - m/s	NACs Stereo System
Radius 0.15 - 250 m	NACs Stereo System
Radius 0.4 - 1400 m	WACs Stereo System
Composition (Si, H, ..)	Spectropolarimeter

Remote

WACs Stereo System

Radio Science Exp.

NACs Stereo System

Spectropolarimeter

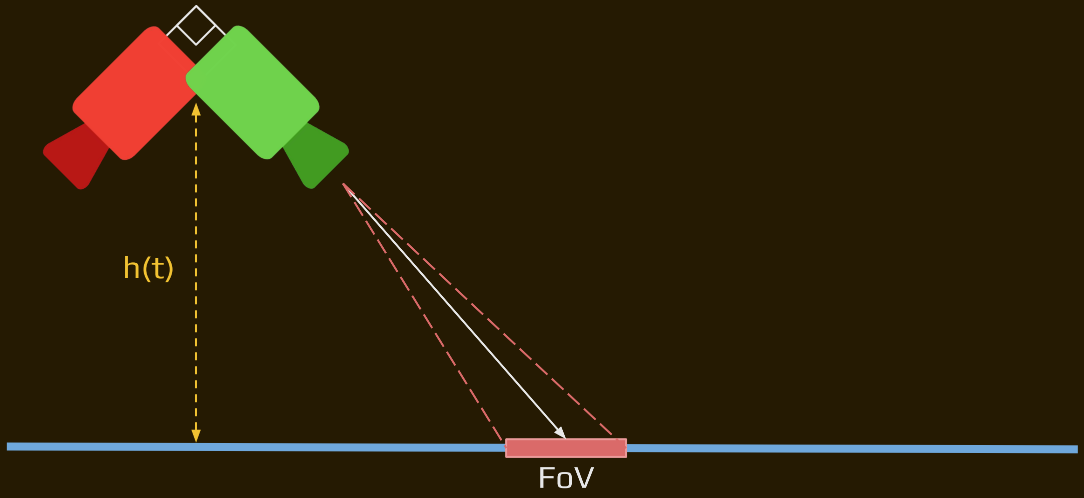
In-situ

Dust Analyser

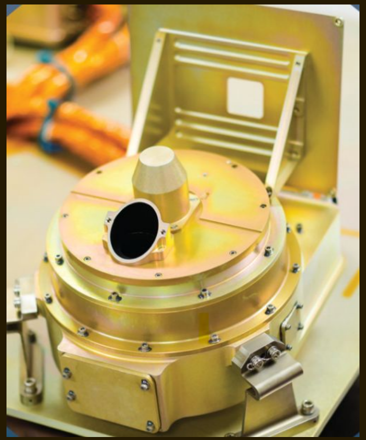
Instrumentation:
Wide Angular Cameras (WACs) Stereo System

Instrument Requirement:

- VIS range (280-900 nm)
- Pixel resolution 42 arcsec



Min. relative speed: 5 km/s @3.8 km
Max. relative speed: 7.65km/s @10 km



[SamCam OSIRIS-REx]

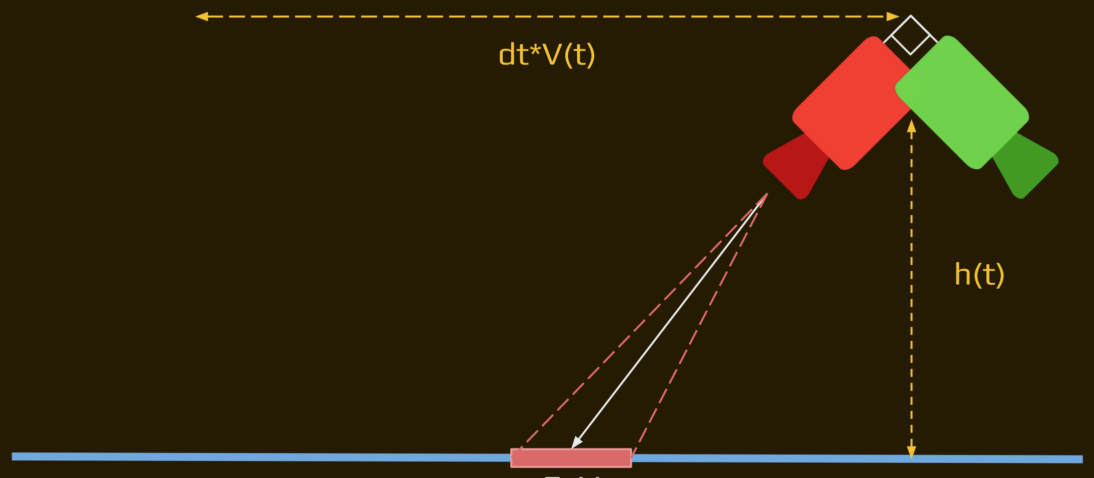
Optic	20 mm F/3.5
FoV	5.6 deg
Pixel res.	41 arcsec
Sensor	CCD 1024x1024 pixels
fps	20
Mass	2.68 kg each
Size	100x100x50 mm
Power	25 W each
TRL	7 (adaptation of SamCam, OSIRIS-REx mission)

Instrumentation:

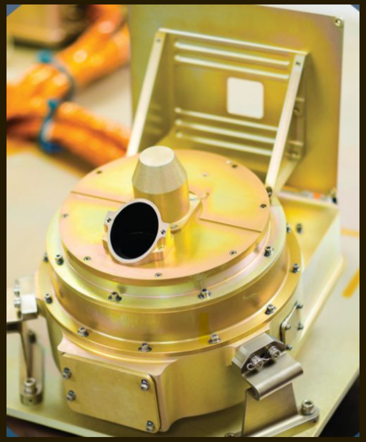
Wide Angular Cameras (WACs) Stereo System

Instrument Requirement:

- VIS range (280-900 nm)
- Pixel resolution 42 arcsec



Min. relative speed: 5 km/s @3.8 km
Max. relative speed: 7.65km/s @10 km

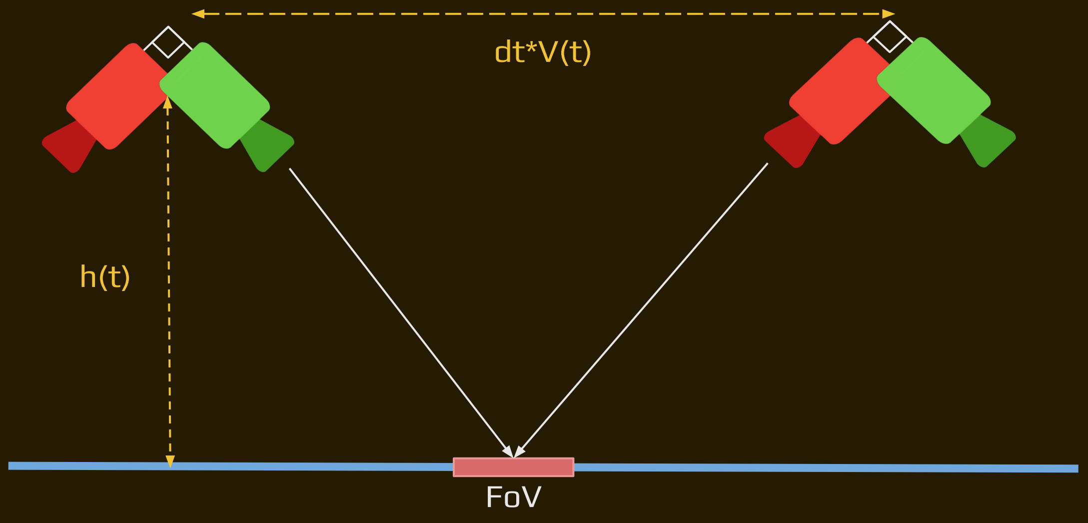


[SamCam OSIRIS-REx]

Offset dt 0.8 - 2 s

Optic	20 mm F/3.5
FoV	5.6 deg
Pixel res.	41 arcsec
Sensor	CCD 1024x1024 pixels
fps	20
Mass	2.68 kg each
Size	100x100x50 mm
Power	25 W each
TRL	7 (adaptation of SamCam, OSIRIS-REx mission)

Instrumentation:
Narrow Angular Cameras (NACs) Stereo System



Instrument Requirement:

- VIS band (280-900 nm)
- Pixel resolution 2.8 arcsec

[PolyCam OSIRIS-REx]

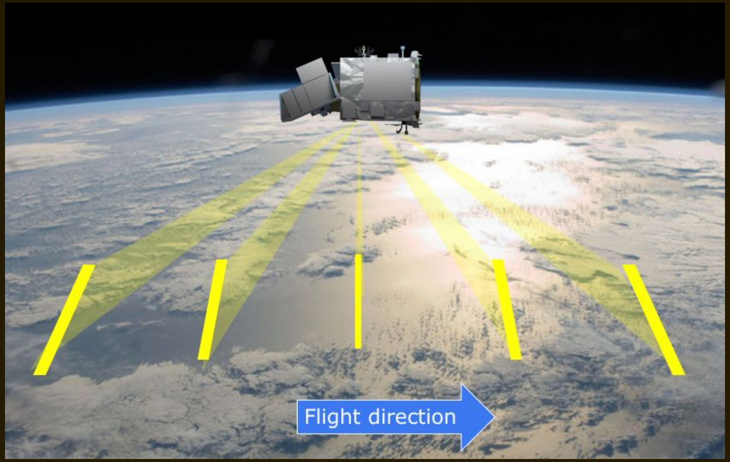
Optic	203 mm F/3
FoV	3.16 deg
Pixel res.	2.78 arcsec
Sensor	CMOS, 4046 x 4096 pixels
fps	30
Mass	9 kg each
Size	330x350x500 mm each
Power	32 W each
TRL	7 (adapted PolyCam, OSIRIS-REx mission)

Instrumentation:
Spectro-polarimeter

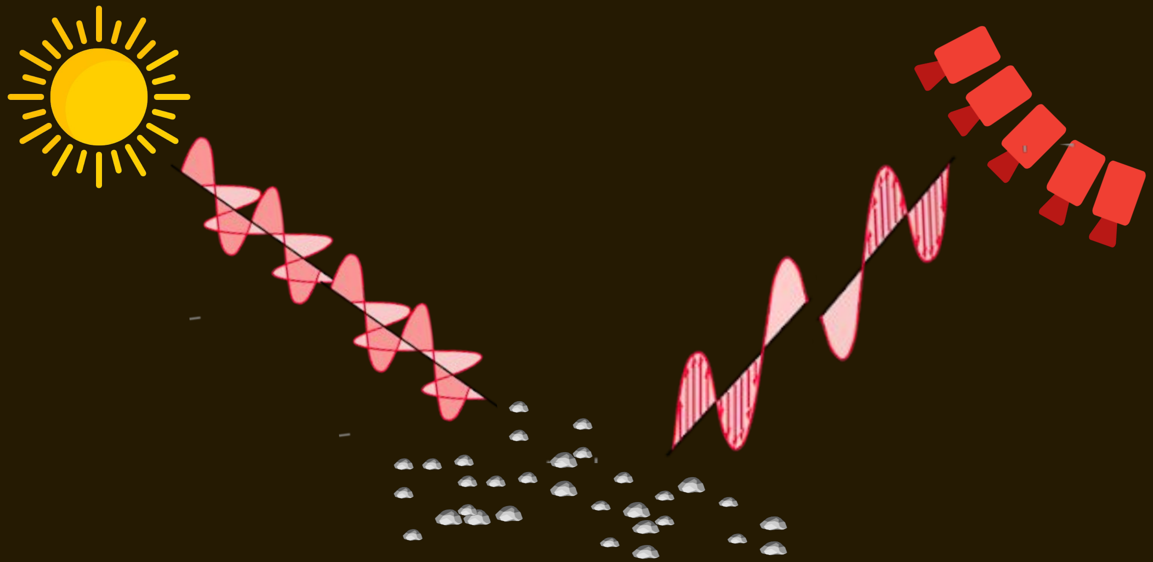
Instrument Requirement:

- Size measurements: VIS band [0.35 - 0.8 µm]
- Composition: near to mid IR [0.8 - 5.1 µm]
- Spectral resolution = 4 nm

Angles	0, ±10, ±25 deg
Mass	15 kg
Size	200x200x400 mm
Power	20 W
TRL	6 (SPEXone ,PACE project)



[SRON]

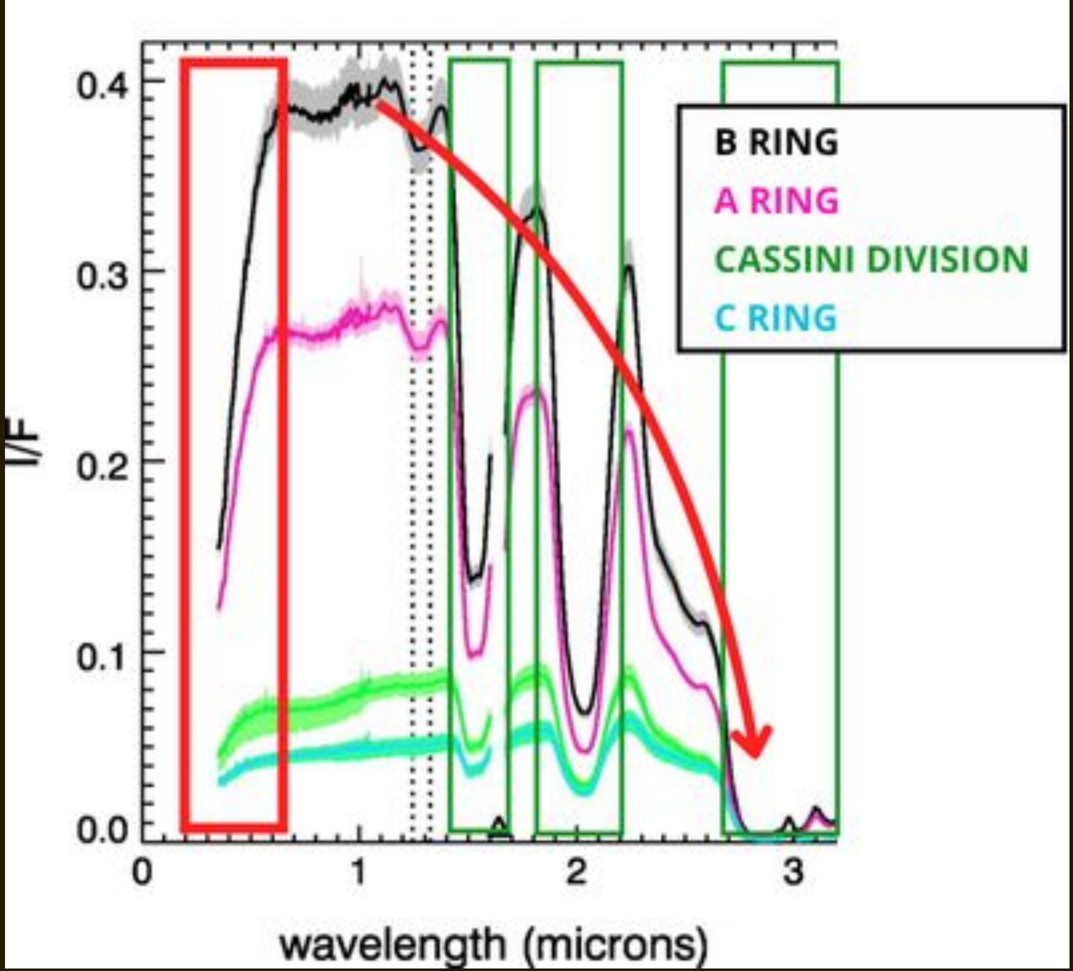


Instrumentation:
Spectro-polarimeter

- Relevant range [0.35 - 5.1] μm
    - Centered around absorption peaks of interest (e.g. ice water peaks)

BUT Cassini's results show 2 unknown absorbers

- Possible exogenous origins (e.g. organic tholins contribution)



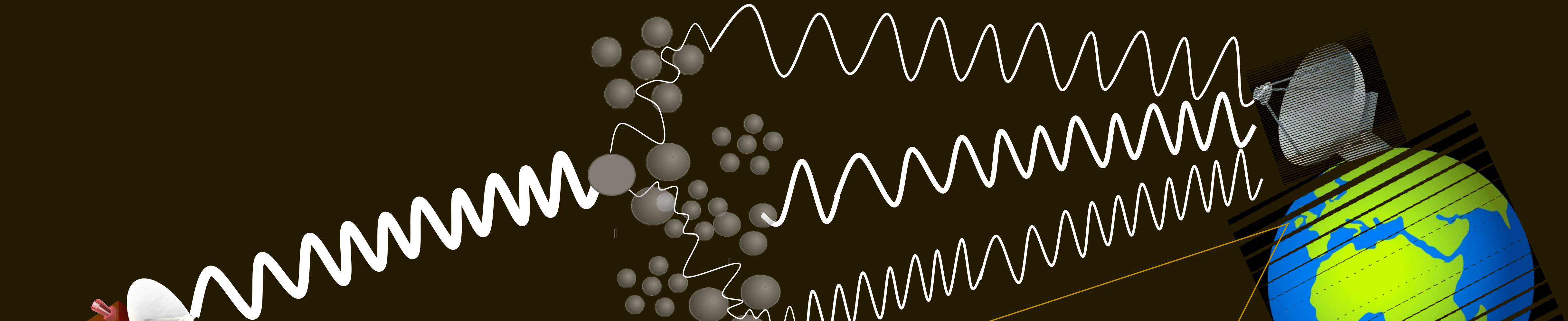
[Icorus, 2013]

Instrumentation:

Radio science experiment

Measurement principle: Rings Radio Occultation

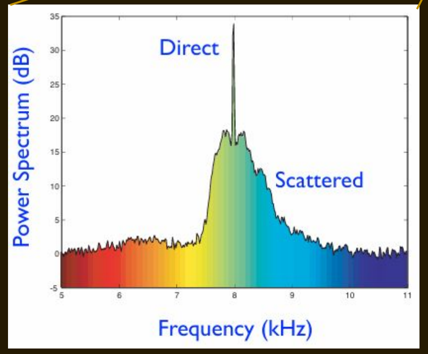
Characteristics	TTC subsystem, X-Ka band
TRL	9 (Cassini, BC, JUICE)



Instrument Requirement:

Earth Pointing accuracy
0.5 mrad

*Not to scale



[Jet Propulsion Laboratory, 2014]

Instrumentation:

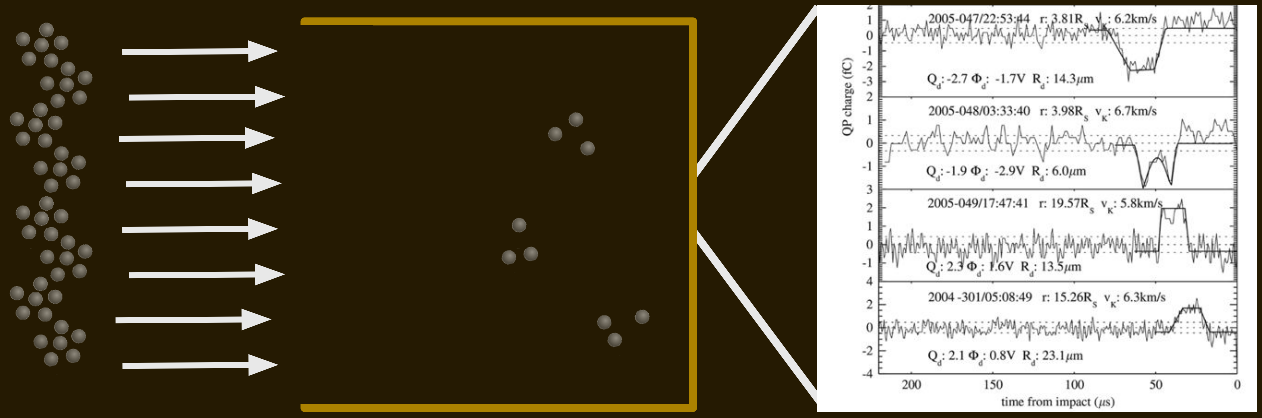
Dust analyzer

[Europa Clipper's Dust Analyzer]

Instrument Requirement:

Rotation Capability to align along velocity vector +- 5°.

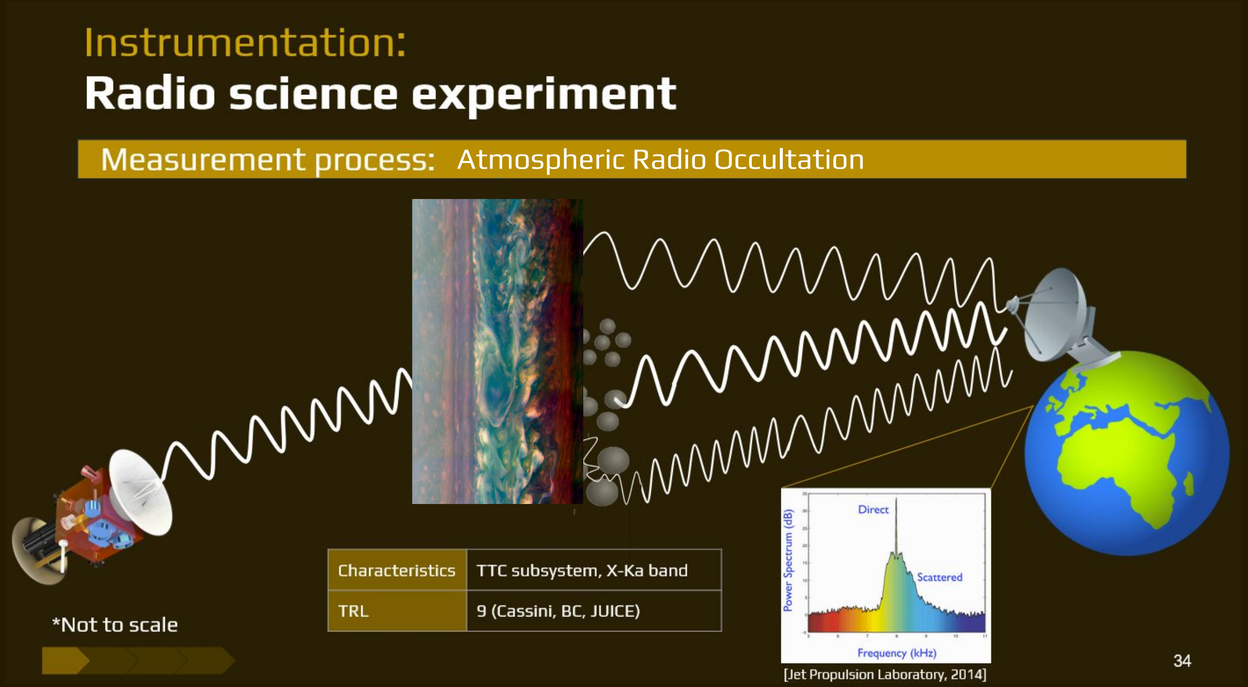
Measure dust: velocity, mass,size, composition & isotopes presence



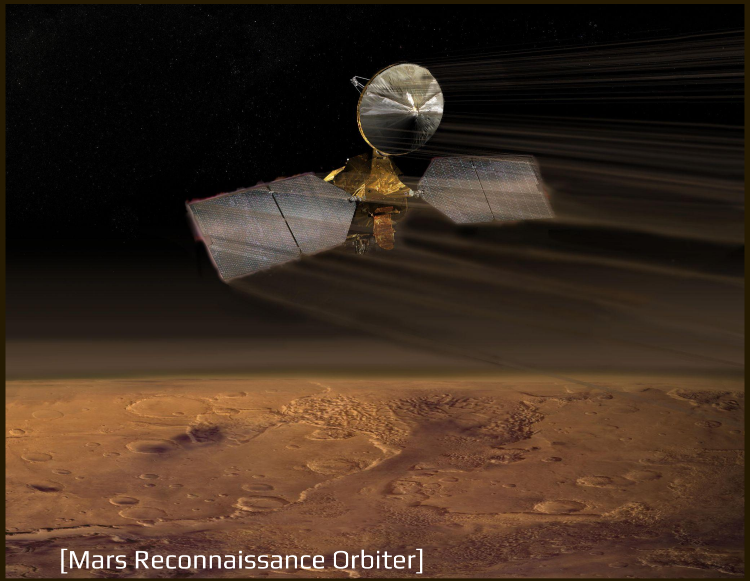
[Cassini CDA, 2006]

Particle size	0.01-100 μm
Mass	5 kg
Size	270x250x170 mm
Power	20 W
TRL	6 (adapted from EUROPA CLIPPER)

Opportunistic Science: **Investigate density variations in Saturn's uppermost atmosphere**



Observable	Instrument
Radio signal	Radio occultation (remote)
Drag force → local density	Accelerometer (in situ)


[Mars Reconnaissance Orbiter]

Key Requirements

- Sun illumination of the rings
- Angular resolution (WAC 41 arcsec & NAC 2.8 arcsec)
- Pointing accuracy to descope particles relative velocities

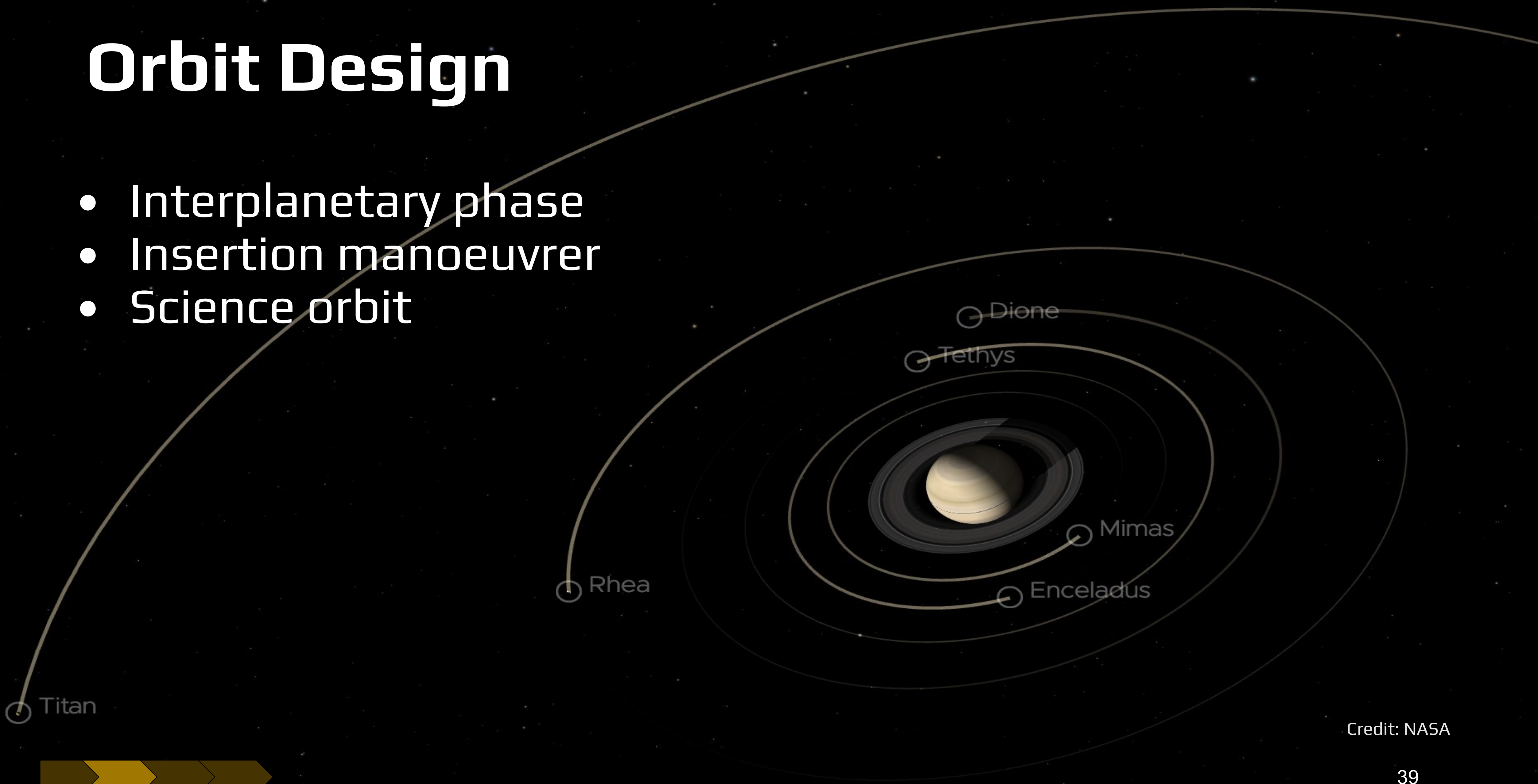
Mission Design

Science → **Mission Design** → System Design → Program Execution

- Orbit Design
- Concept of Operation
- Mission Design Drivers
- Mission constraits

Orbit Design

- Interplanetary phase
- Insertion manoeuvrer
- Science orbit



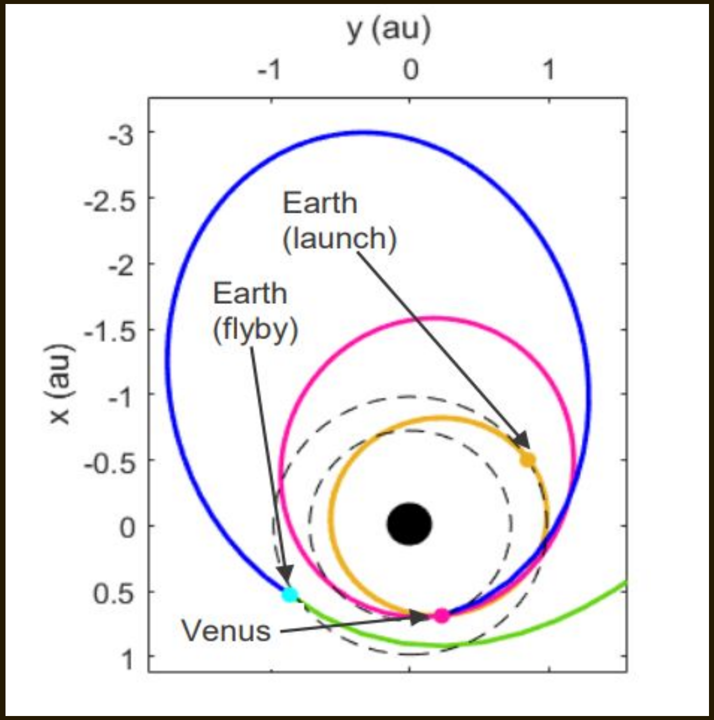
Credit: NASA

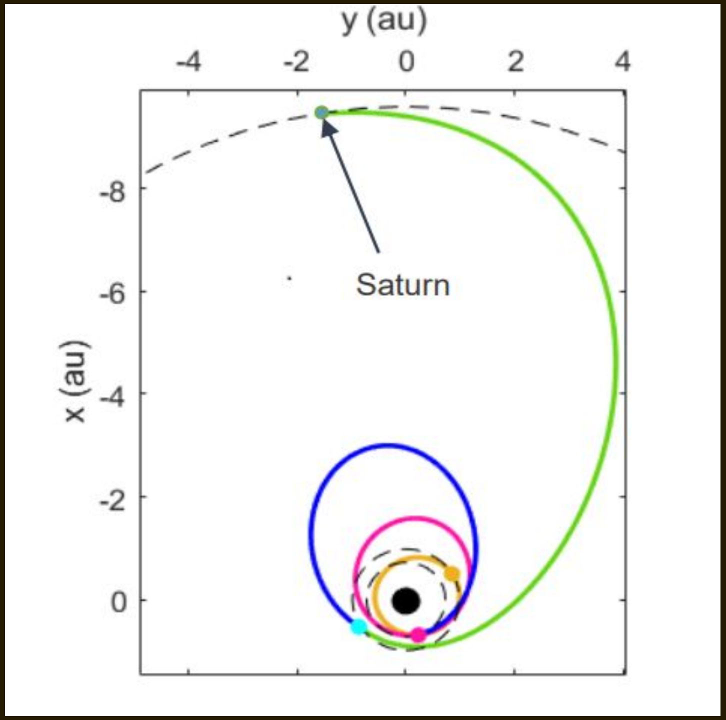
Orbit design: **Interplanetary phase**

Low thrust trajectory to Saturn:

- Earth-Venus-Venus-Earth-Saturn
- Low flight path at Saturn -> V_{inf} = 1 km/s
- Propulsion system - 486 kg of propellant used (at 40 mN thrust, Isp = 1400 s, 640 W)

Burhani et. al. “Low-thrust Earth-Saturn trajectory with multiple gravity assists and unpowered orbit insertion”

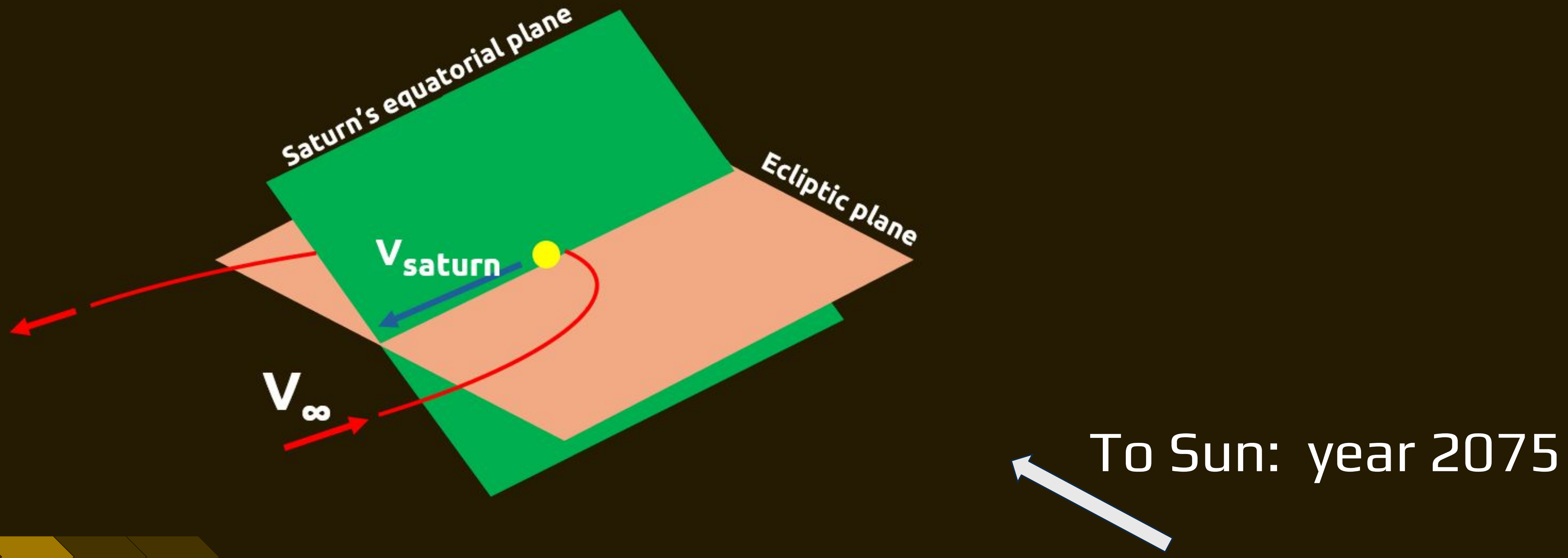




Orbit design: **Insertion**

Low thrust trajectory to Saturn:

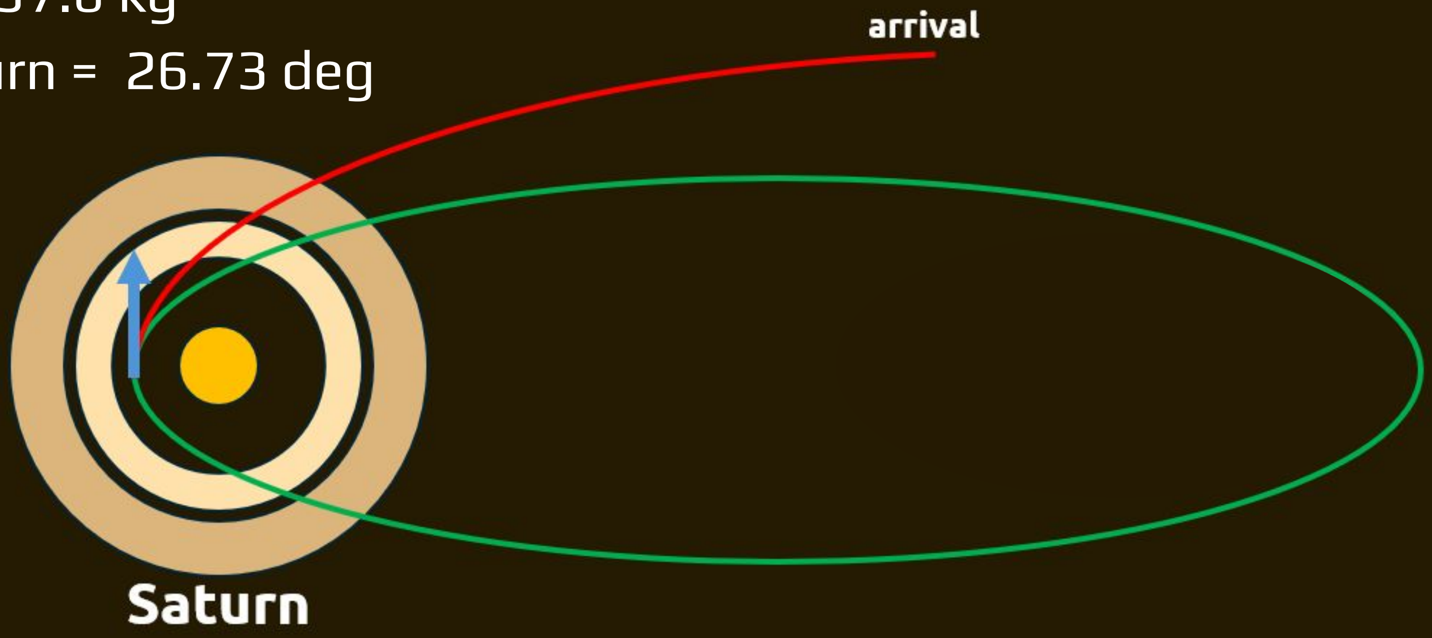
- Initial insertion orbit in the Ecliptic plane
- Inclination with respect to Saturn of 26.73 deg.
- Line of nodes contained in Saturn's equatorial plane -> Intersection with Titan's orbit!



Orbit design: **Insertion**

1. Chemical burn at the closest approach to Saturn -> Insertion into a highly elliptical orbit:

- $e = 0.98$
- $r_p = 65{,}000$ km
- $\Delta V_i = 186$ m/s, $m_{pi} = 57.6$ kg
- Inclination w.r.t Saturn = 26.73 deg

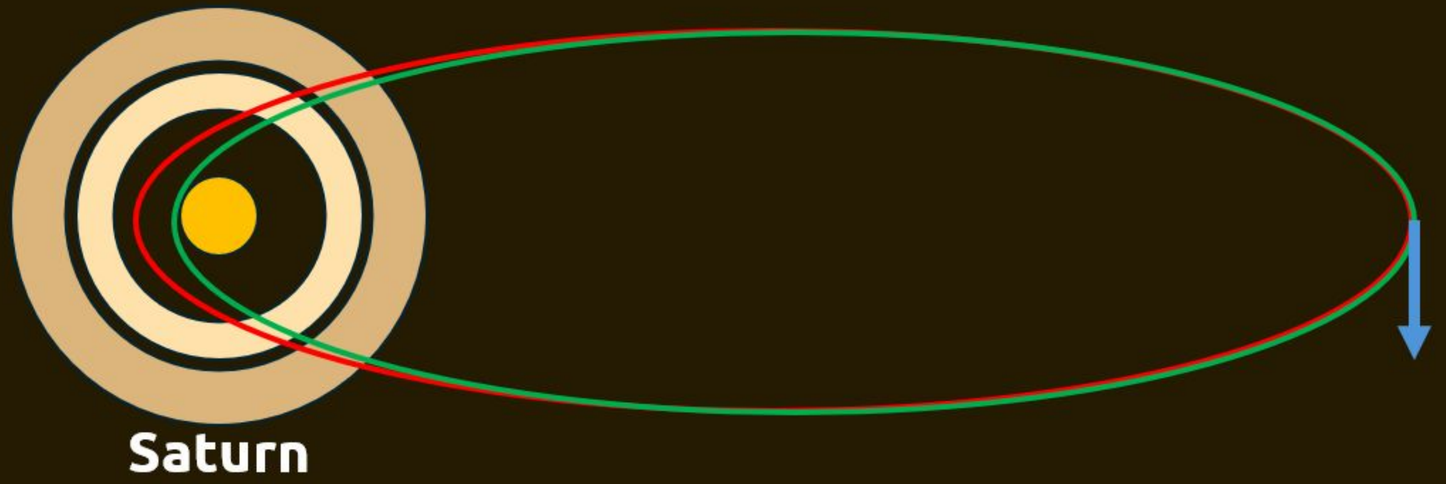


Orbit design: **Insertion**

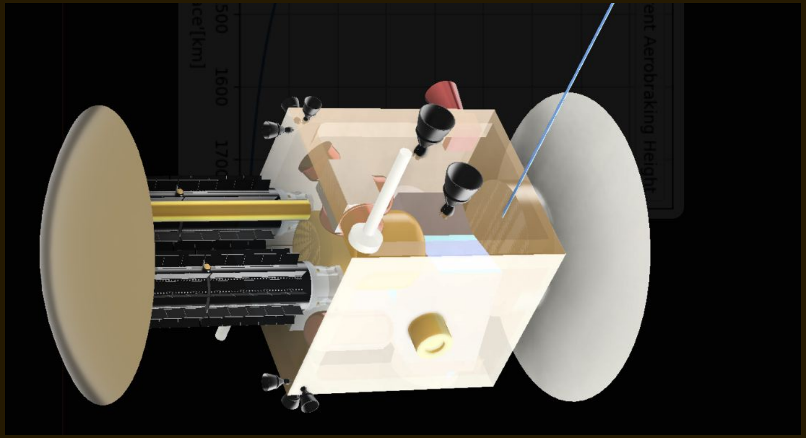
1. Chemical burn at the closest approach to Saturn

2. Lowering of the periapsis into edge of Saturn's atmosphere - beginning of aerobraking maneuver:

- ΔVa = 10 m/s, m_{pa} = 3.3 kg
- r_p reduced to 61168 km

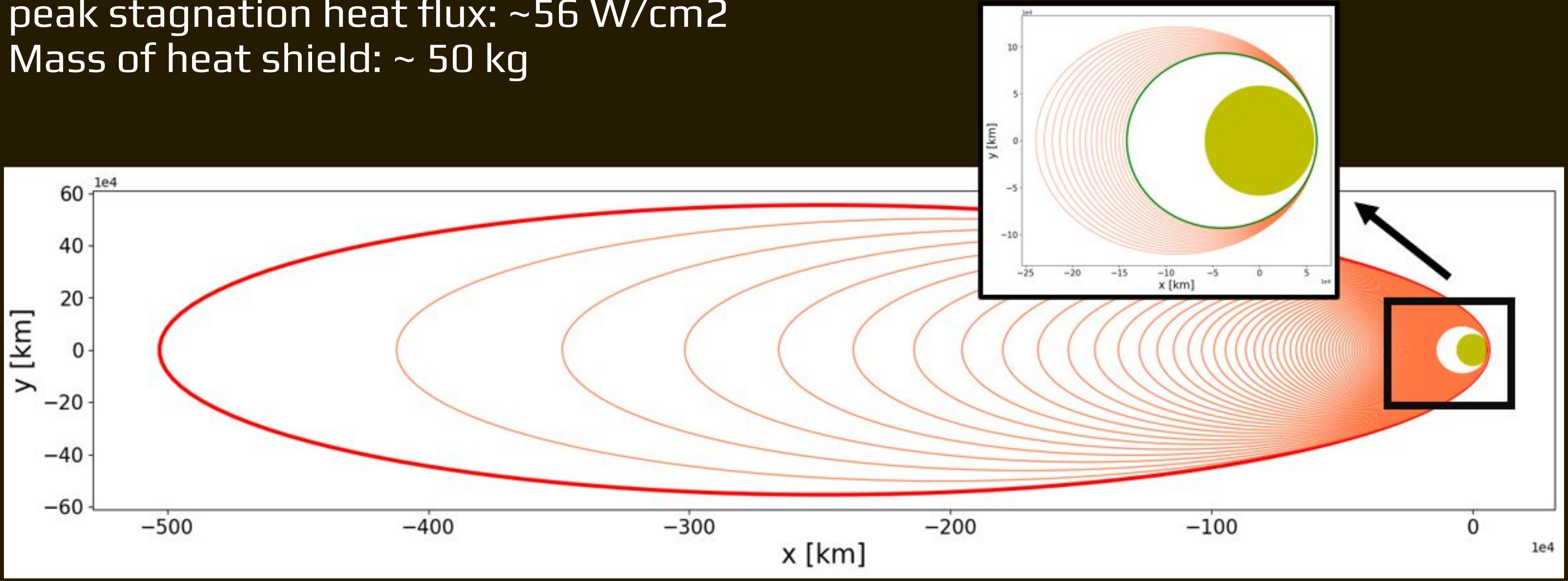


Orbit design: **Insertion**



Aerobraking:

- braking time: ~400 days
- effective ΔV: 5.6 km/s
- peak stagnation heat flux: ~56 W/cm2
- Mass of heat shield: ~ 50 kg



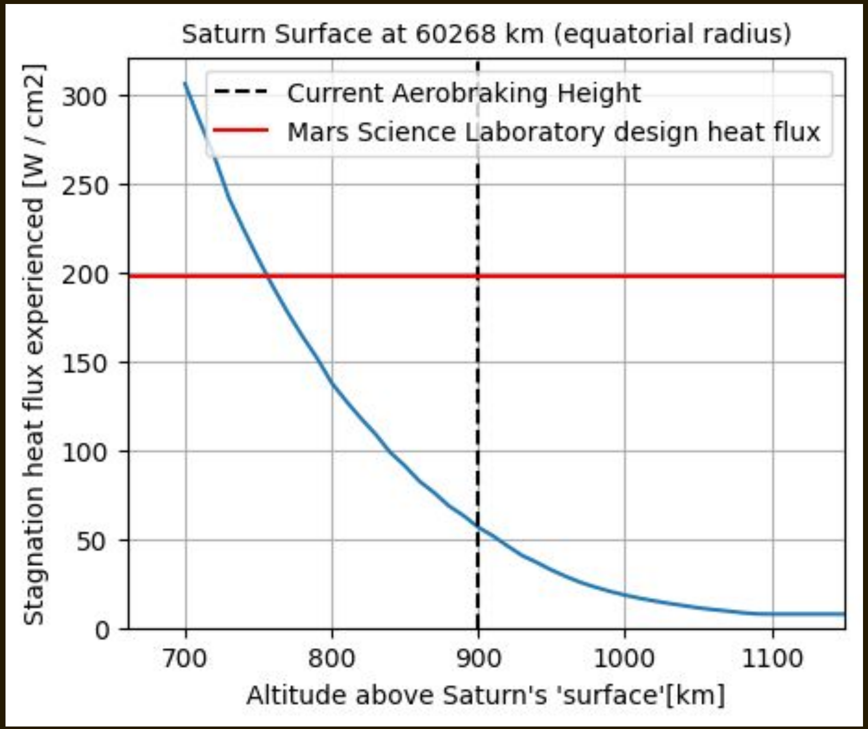
Orbit design: **Insertion**

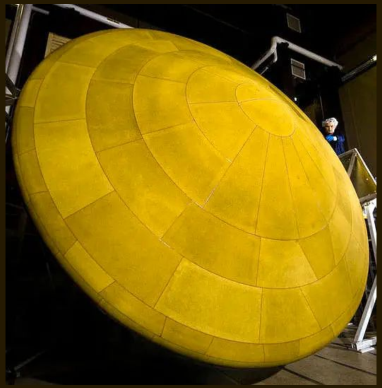
Heat flux analysis:

- Aerobraking corridor
  400 km wide

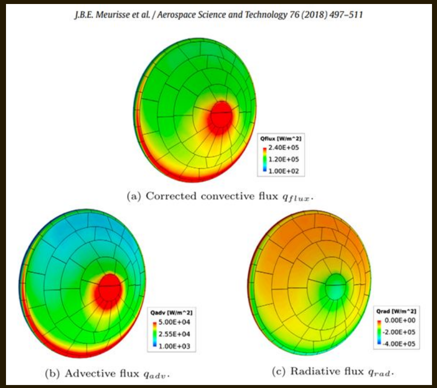
- Very gradual entry to avoid overheating and excessive heat shield ablation

- Heat shield design:
  50 kg PICA shield
  3 cm thickness, 1.4 m radius





[NASA]



[J. B. E. Meurisse ,2018]

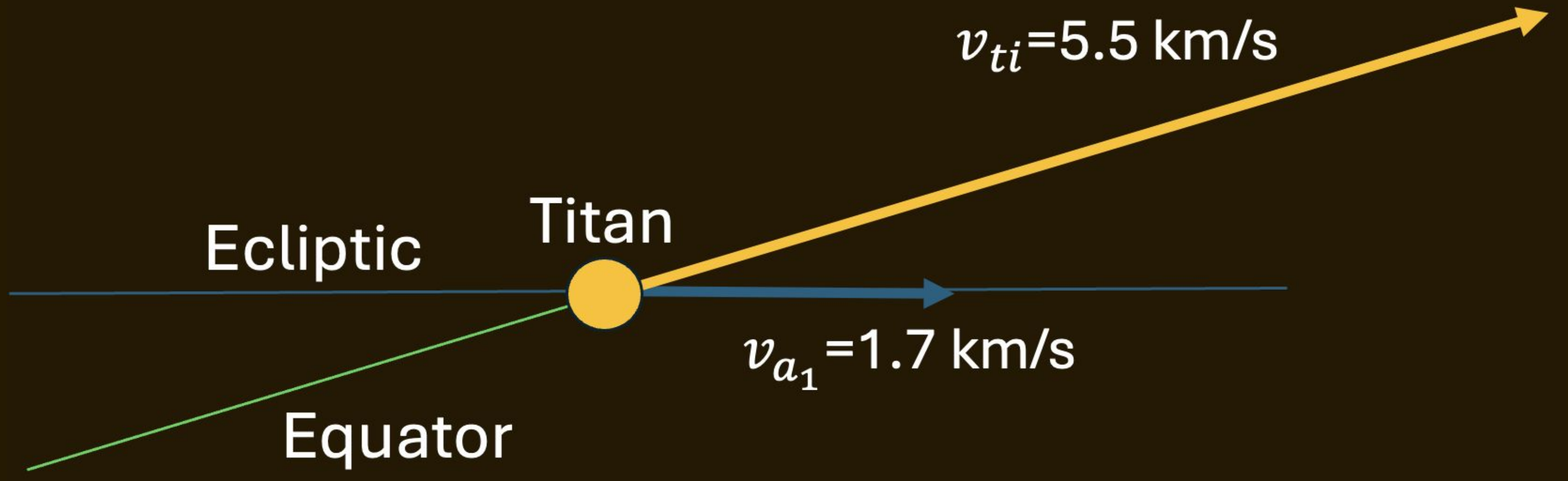
Orbit design: **Insertion**

1. Chemical burn at the closest approach to Saturn (insertion into a highly elliptical orbit)

2. Lowering of the periapsis into edge of Saturn's atmosphere - beginning of aerobraking maneuver

3. Swing-by Titan to reduce inclination w.r.t equator to 0.006 deg:

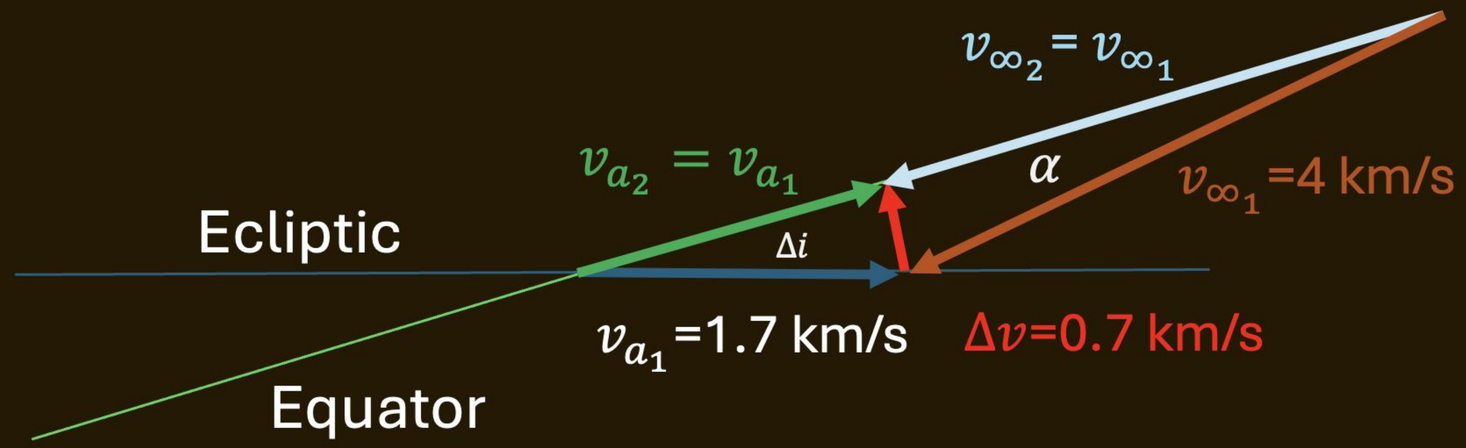
- $r_{pa} = r_{ti}$ = 1,221,870 km
- V_{ti} = 5.5 km/s
- V_{ap} = 1.7 km/s



Orbit design: **Insertion**

3. Swing-by Titan to reduce inclination w.r.t equator to 0.006 deg:

- V_{inf}= 4 km/s, ΔV=0.7 km/s
- Turning angle of 11.1 deg
- Impact parameter = 5600 km
- Closest approach = 5000 km > Rt = 2500 km



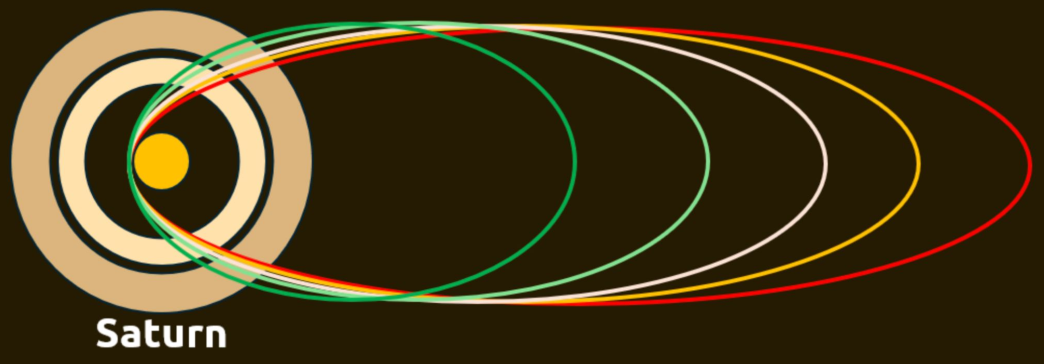
Orbit design: **Insertion**

1. Chemical burn at the closest approach to Saturn (insertion into a highly elliptical orbit)

2. Lowering of the periapsis into edge of Saturn's atmosphere - beginning of aerobraking maneuver

3. Swing-by Titan to reduce inclination w.r.t equator to 0.006 deg

4. Continue aerobraking



Orbit design: **Insertion**

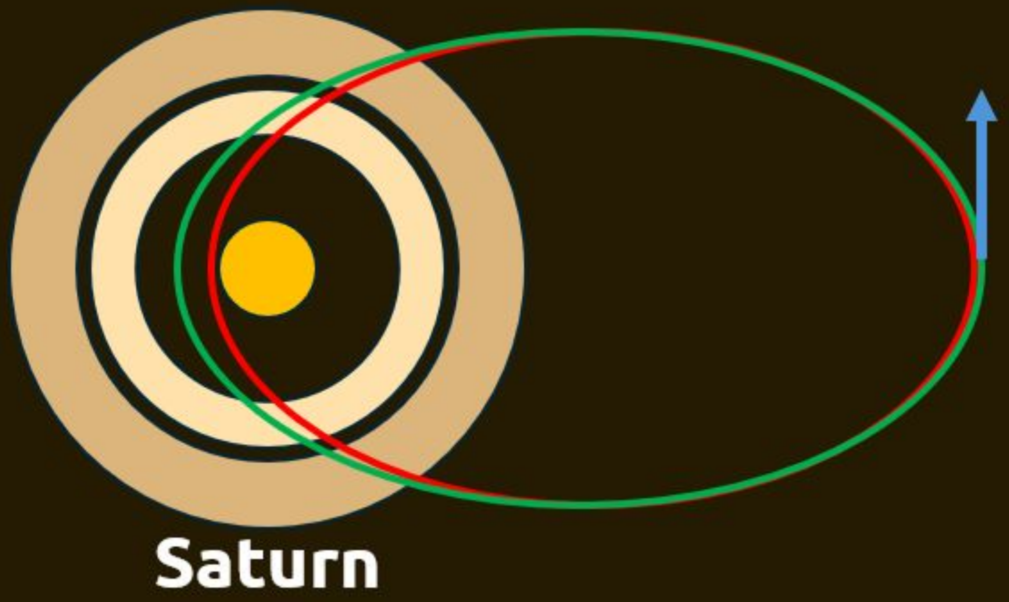
1. Chemical burn at the closest approach to Saturn (insertion into a highly elliptical orbit)

2. Lowering of the periapsis into edge of Saturn's atmosphere - beginning of aerobraking maneuver

3. Swing-by Titan to reduce inclination w.r.t equator to 0.006 deg

4. Continue aerobraking

5. Get periapsis out of the atmosphere:
- r_a = 141,750 km, r_p = 65,000 km
- ΔVs = 200 m/s, m_{ps} = 62 kg
- Science orbit reached!



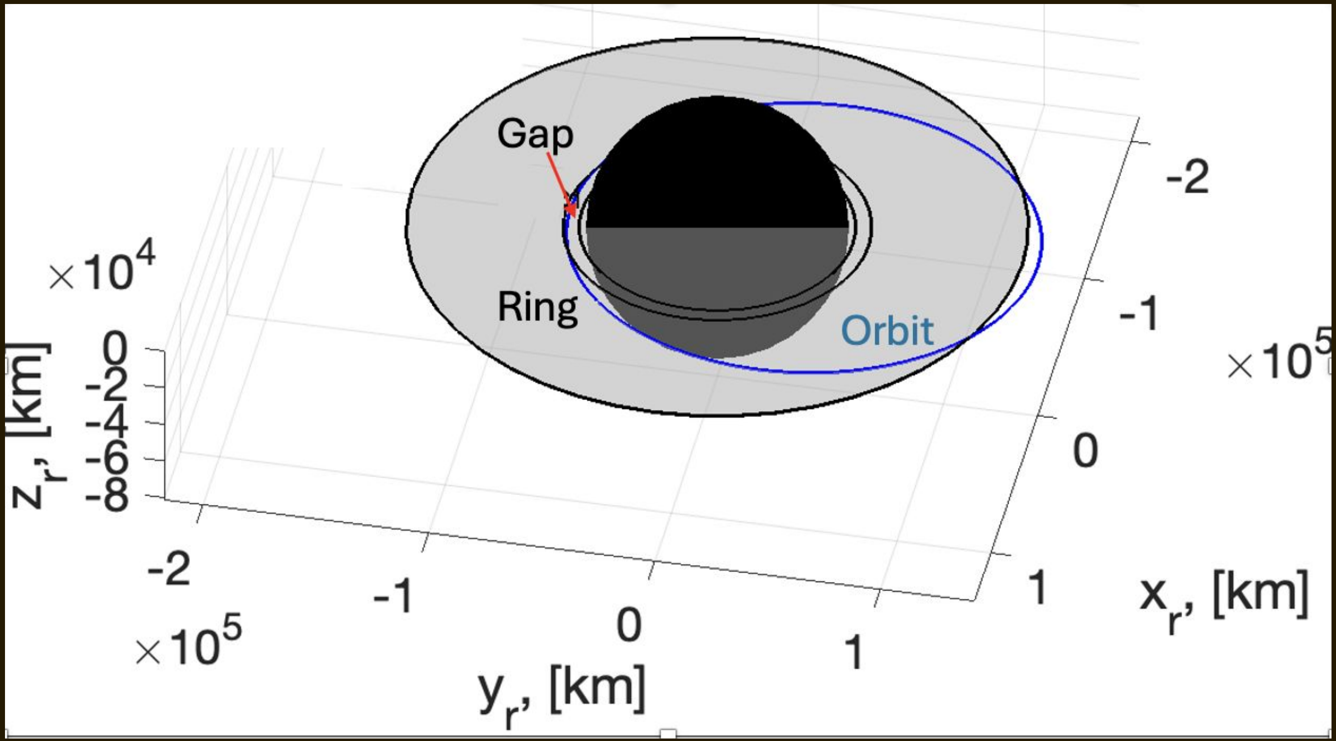
Orbit design: **Science orbit**

Characteristics:

- Inclination = 0.006 deg
- Periapsis in gap

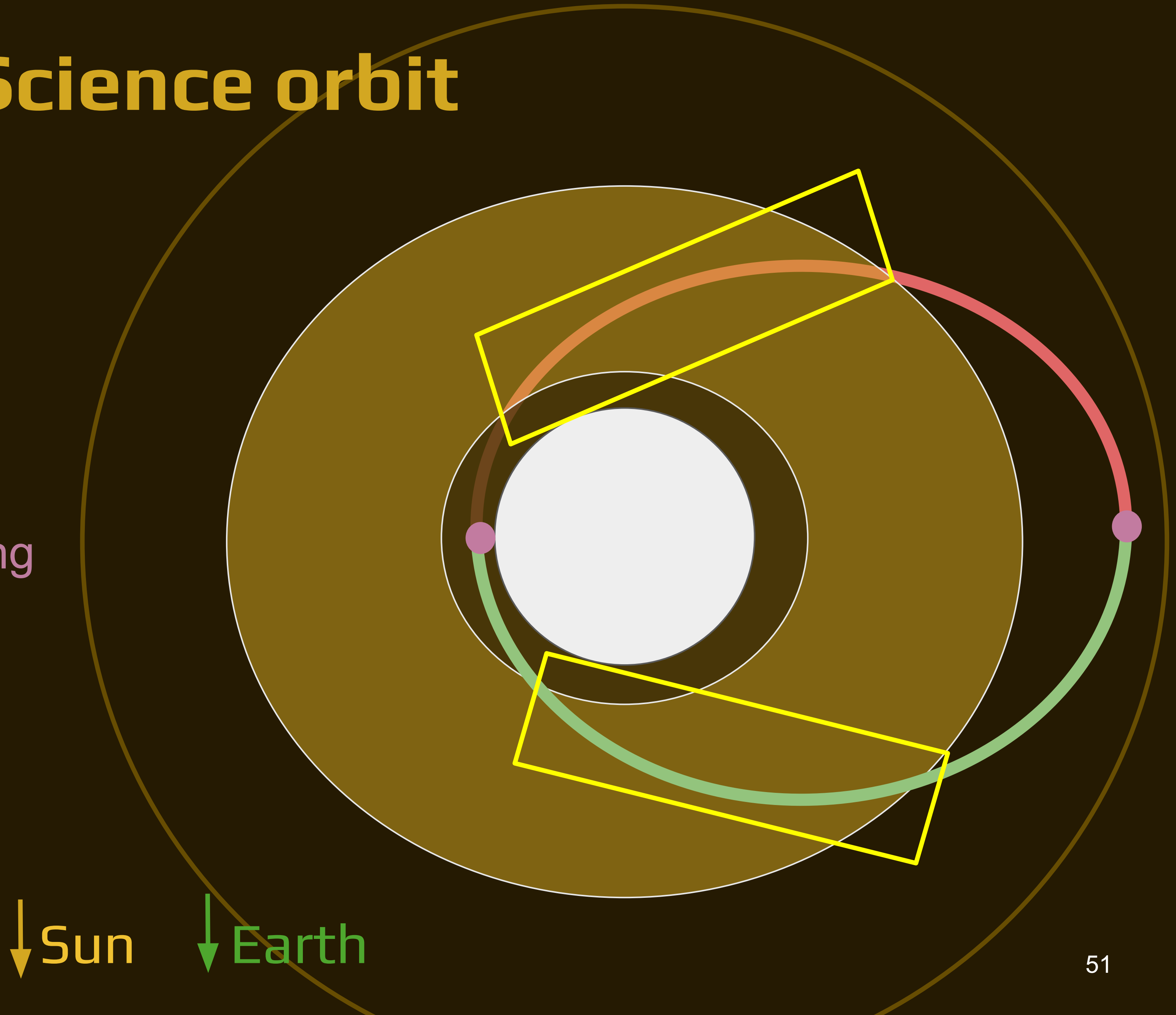
  $\rightarrow r_p = 65{,}000$ km
- Apogee outer rim ring F

  -> r_p = 141,750 km



Orbit design: **Science orbit**

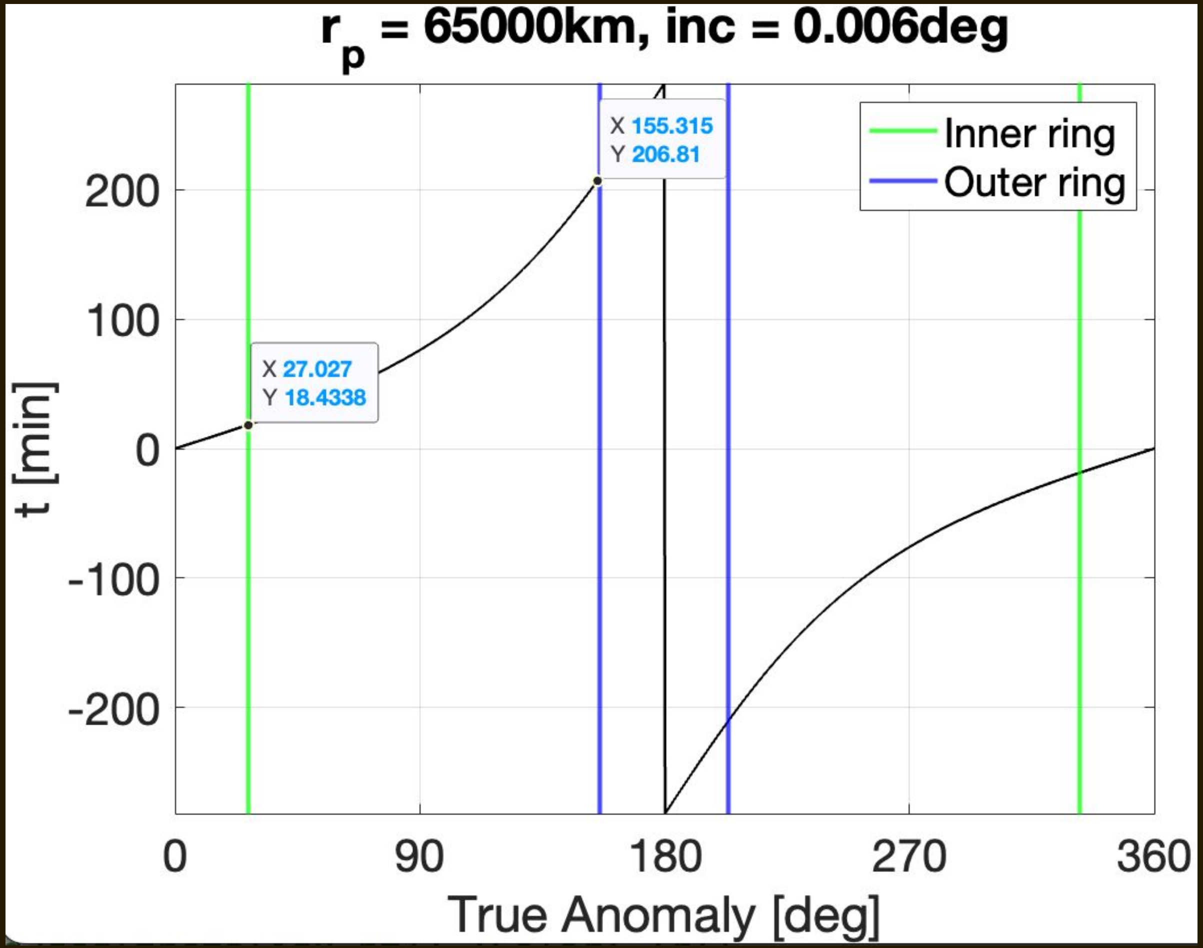
- Observable area
- Over the ring
- Below the ring
- Crossing of the ring



Orbit design: **Science Orbit**

Best observation time:

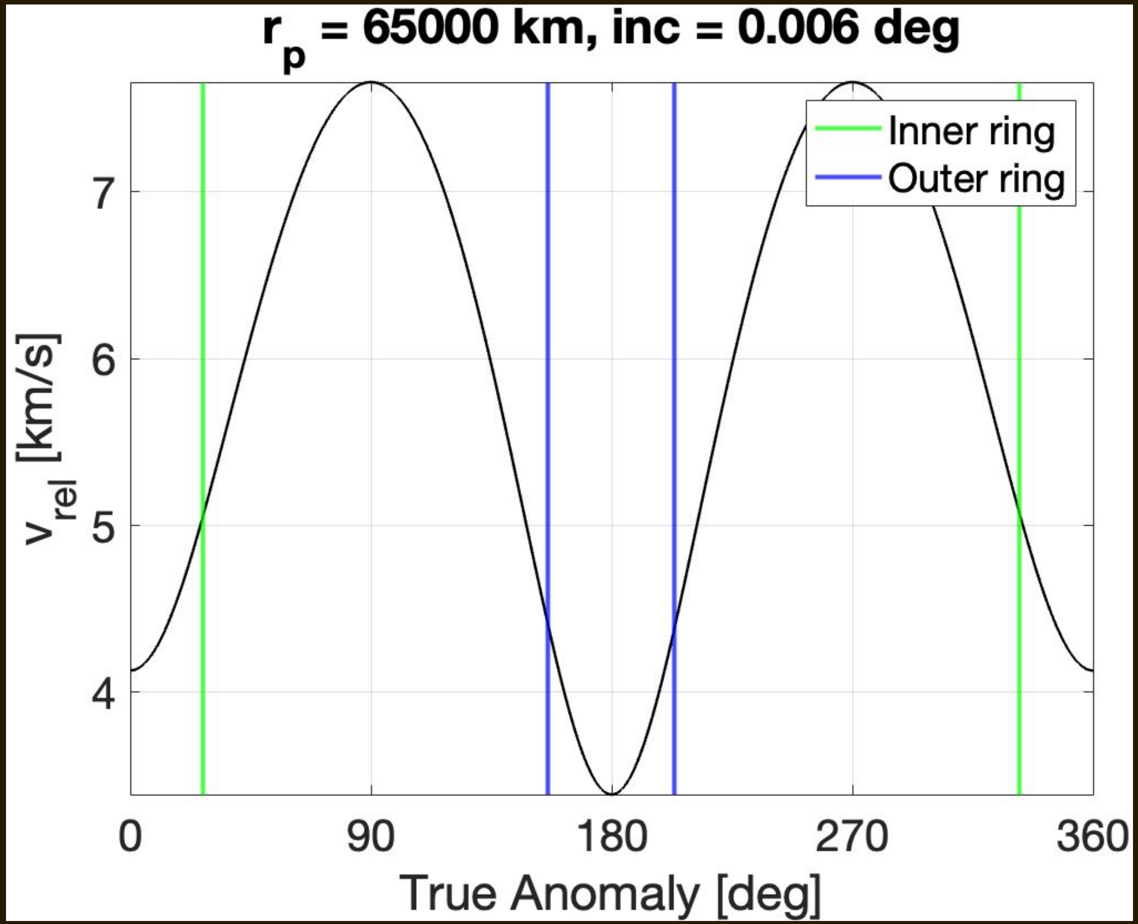
- 10 km observation window
- Period = 9h 30 min
- Above/below = 6 h
- Beyond = 3h 30 min



Orbit design: **Science Orbit**

Relative velocity to ring particles:

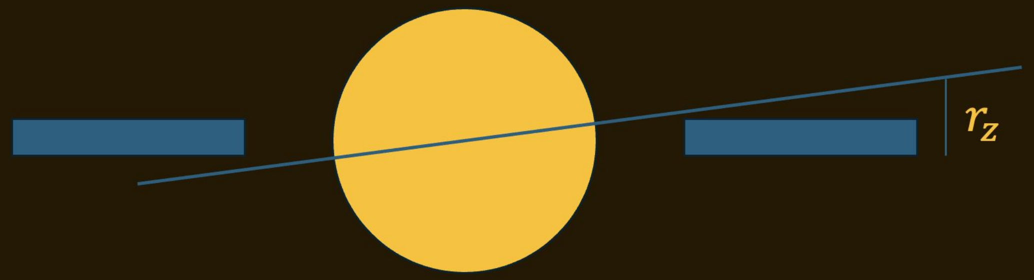
- Average = 6.5 km/s

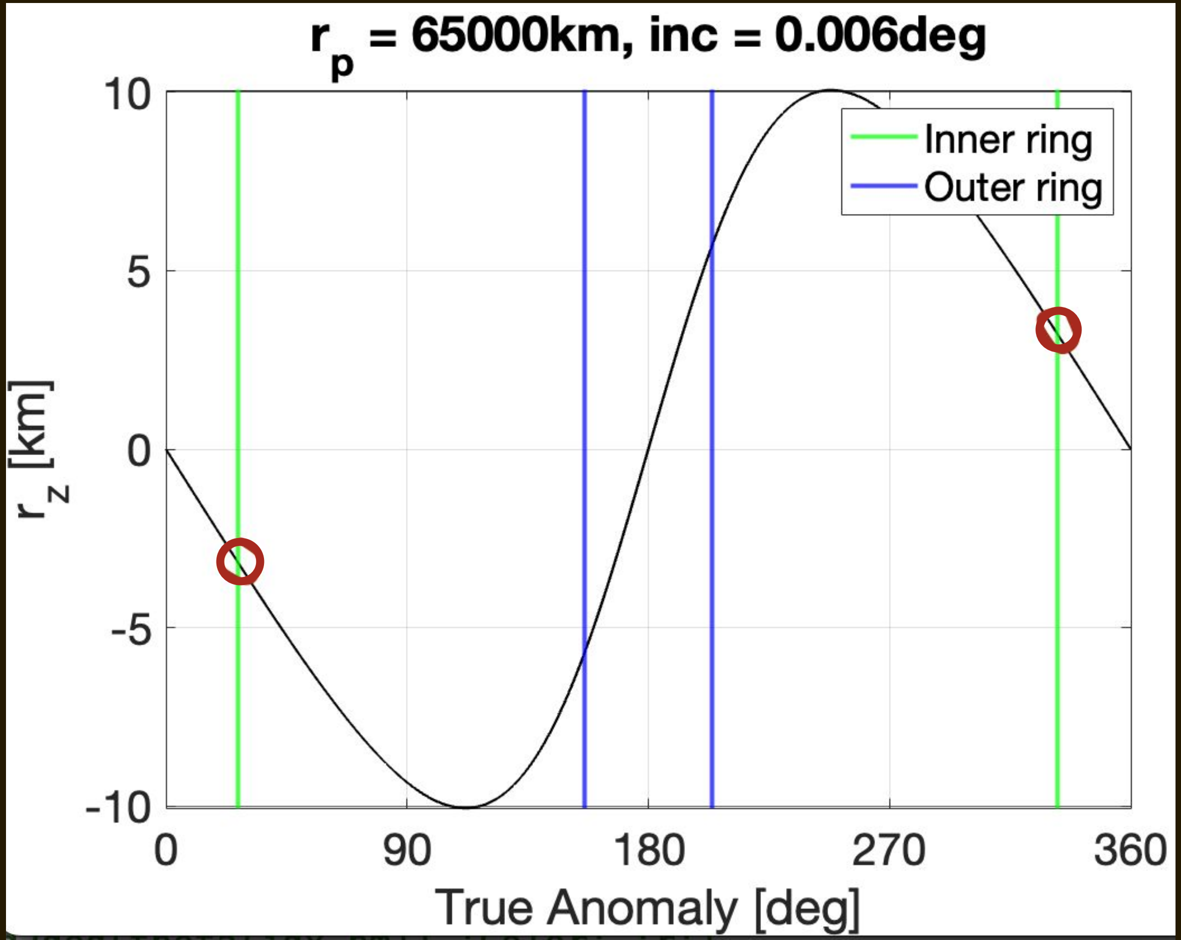


Orbit design: **Science Orbit**

Vertical distance to rings plane:

- Minimum height over the ring = 3.8 km
- Thickness of the ring = 30 m
- We're safe!

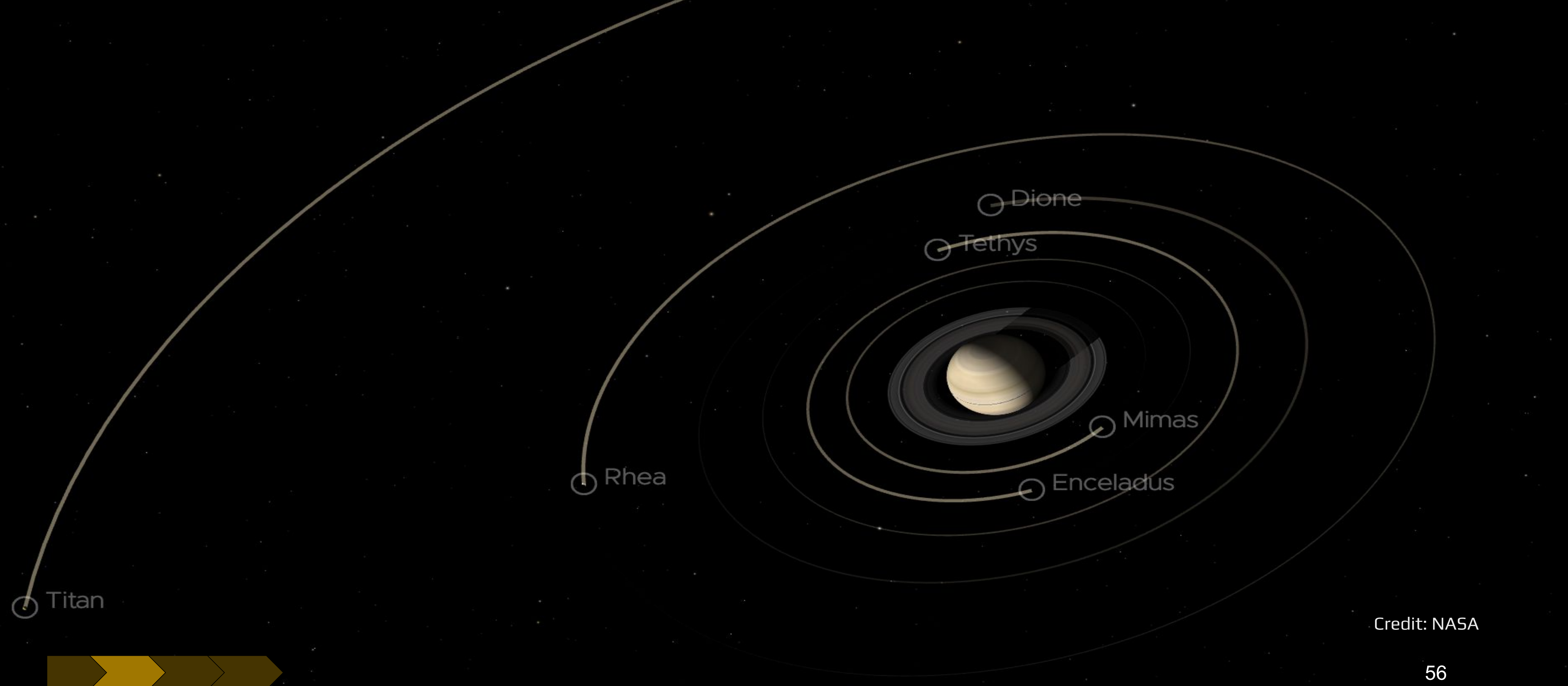




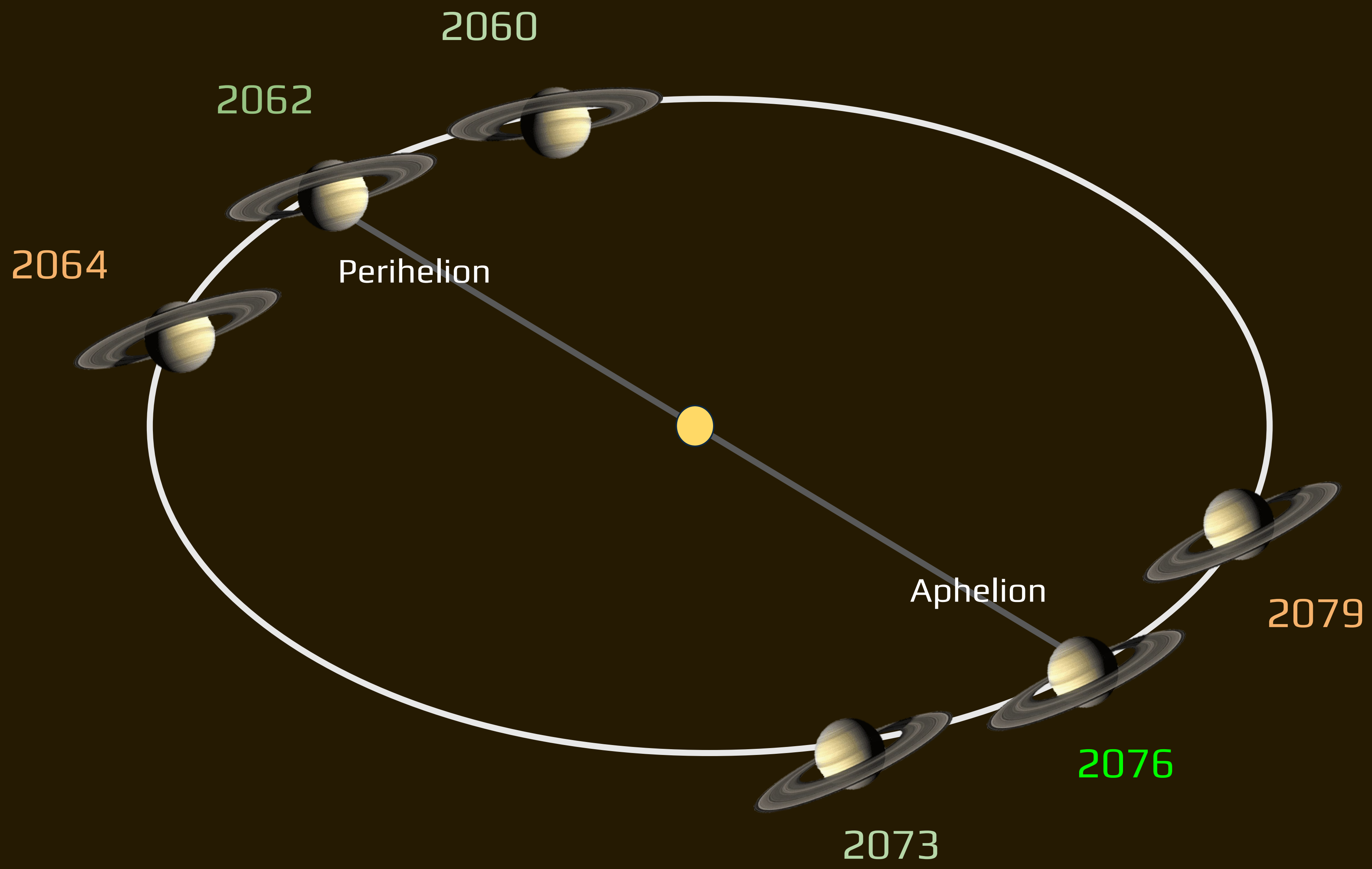
Orbit design: ΔV and use of propellant over time

Stage	ΔV (m/s)	Propellent left (kg)
Pre launch		664
Earth to saturn	5372	194
Saturn orbital injection	180	132
Start Aerobraking	10	129
Aerobraking	5600	129
Cranking with titan	700	129
Science orbit injection	200	61
Rest of fuel used for Station keeping	170	61

Concept of Operations (ConOps)



Credit: NASA


2060
2062
2064
Perihelion
Aphelion
2079
2076
2073

ConOps

LEOP	Transfer	Orbit Insertion	Science Phase	End of Life
Single launch Ariane 64 Check-out phase	Low thrust electric transfer Interplanetary trajectory	Insertion into science orbit around Saturn	4 operational modes	Decommissioning of S/C
Earliest: 2061 Optimal wrt. Saturns position.	**+12 years**	**+2 years**	**+3 years**	**2078 or later**

ConOps

4 operational modes

Extended science

Opportunistic science

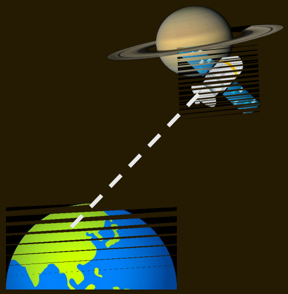
Decommissioning of S/C

2078 →

ConOps: Operational Modes

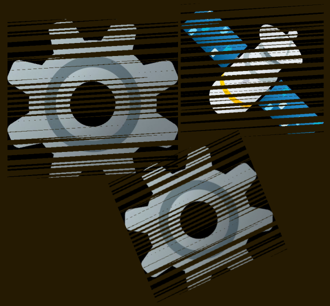
Science

- Scanning
- Tracking
- Sampling



Communication

- Bulk data downlink
- TT&C



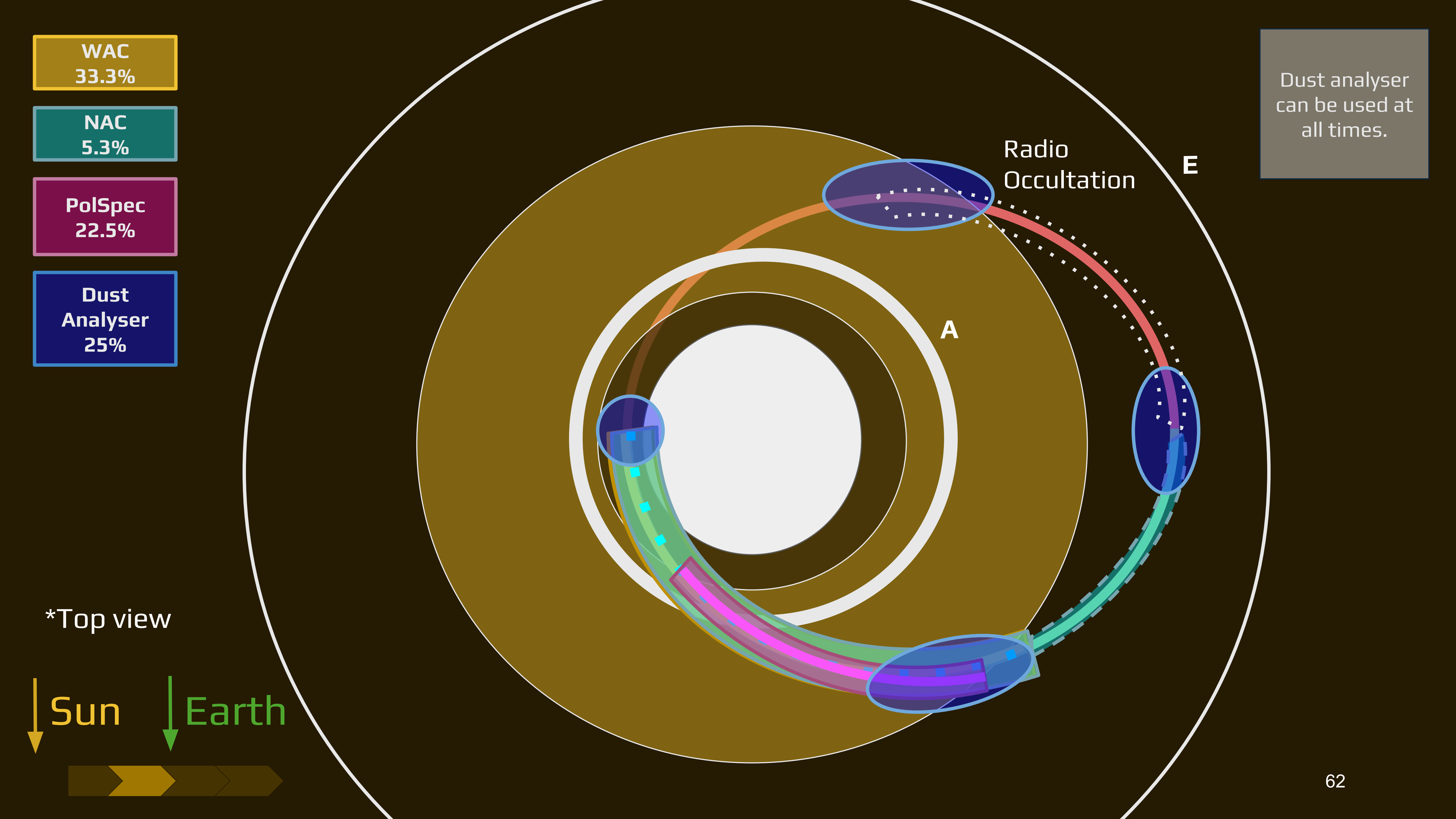
Maneuver

- Thrusters
- TT&C
- AOCS

Safe

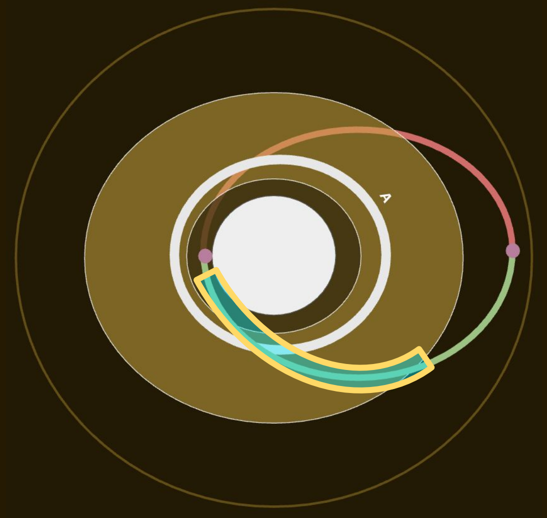
- Sun pointing
- C&DH is in safe-mode
- Emergency communication via MGA

ConOps: **Science Mode**



WAC
33.3%
NAC
5.3%
PolSpec
22.5%
Dust
Analyser
25%
Dust analyser can be used at all times.
Radio
Occultation
E
A
*Top view
Sun
Earth

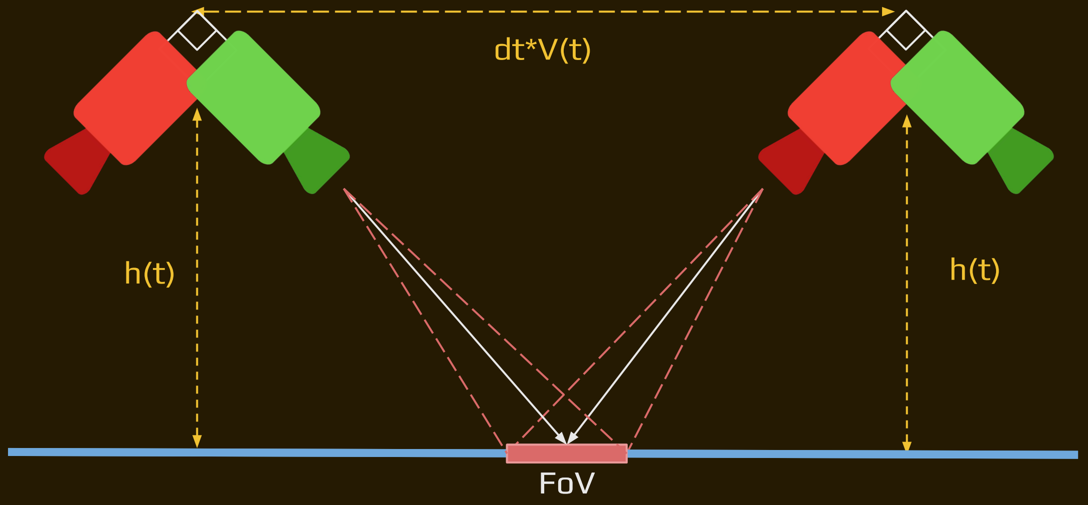
ConOps: **Science Mode**

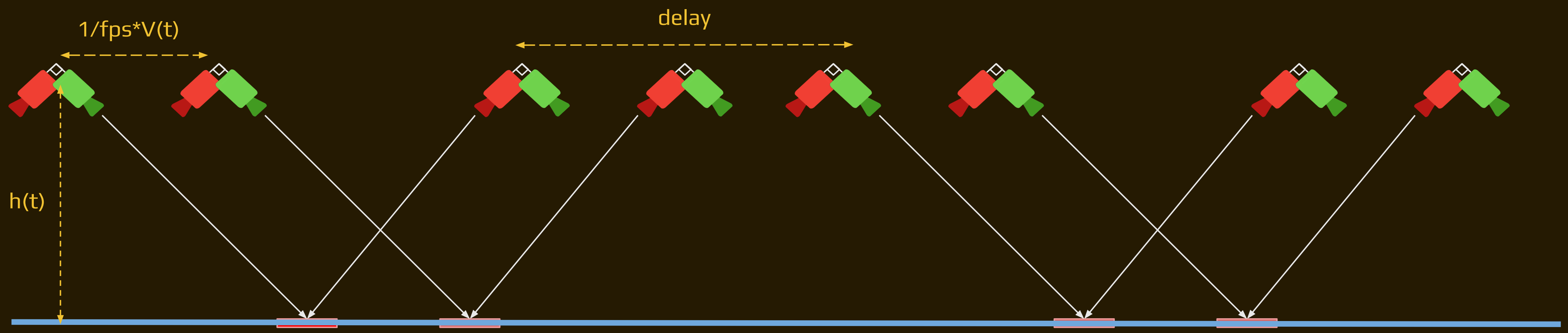


SCANNING

WACs

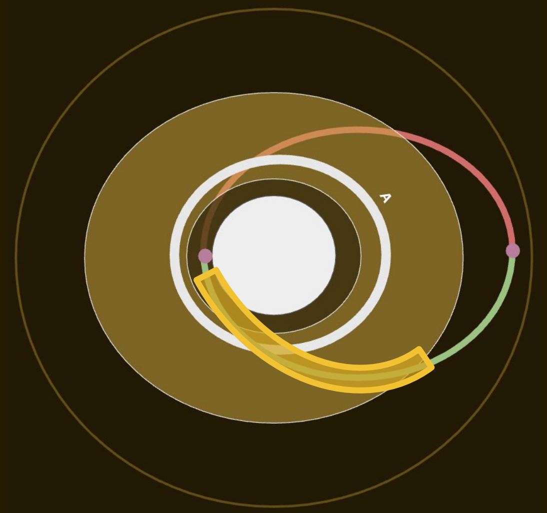
NACs





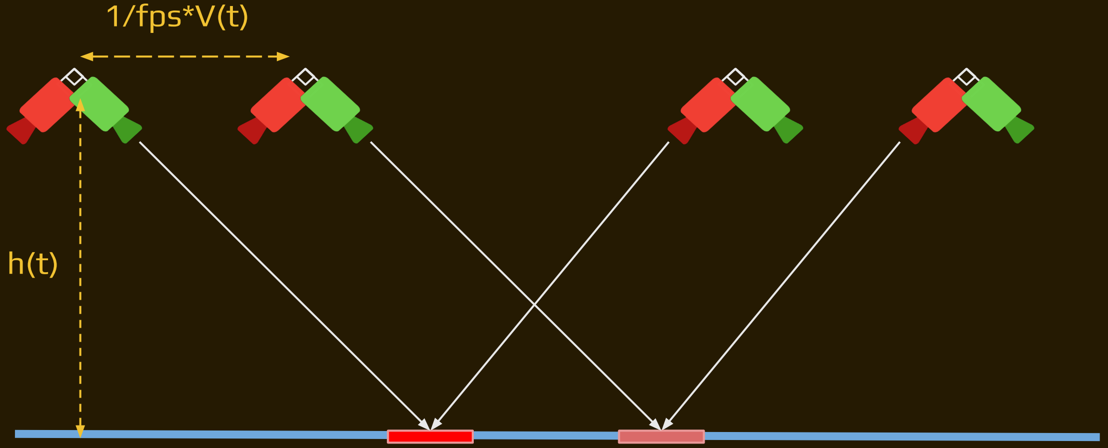
ConOps: **Science Mode**

Total coverage with fps > 8



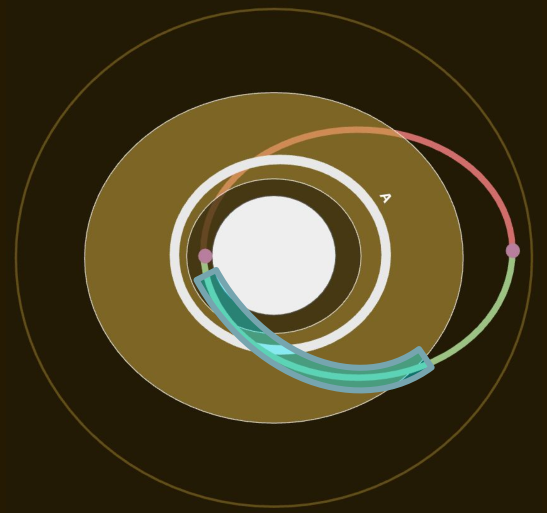
SCANNING

WACs



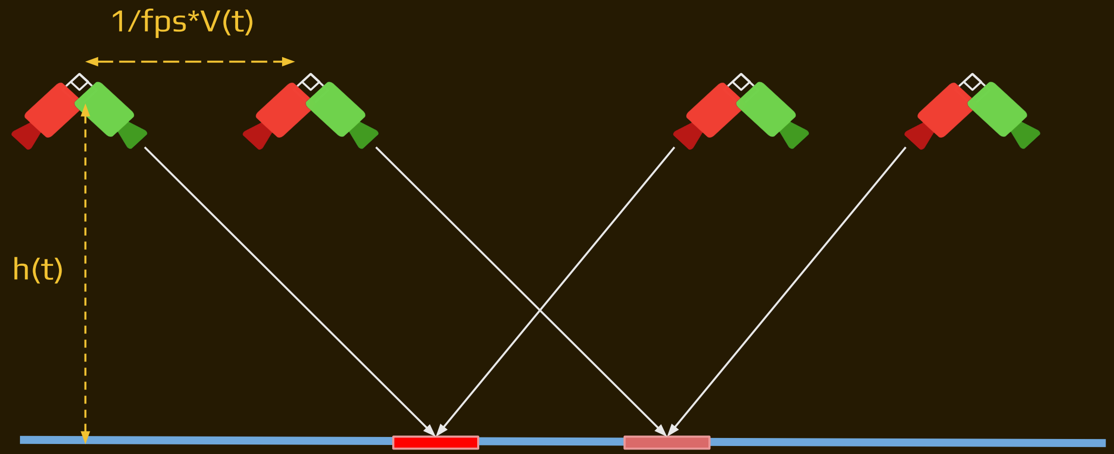
DETECTION

ConOps: **Science Mode**

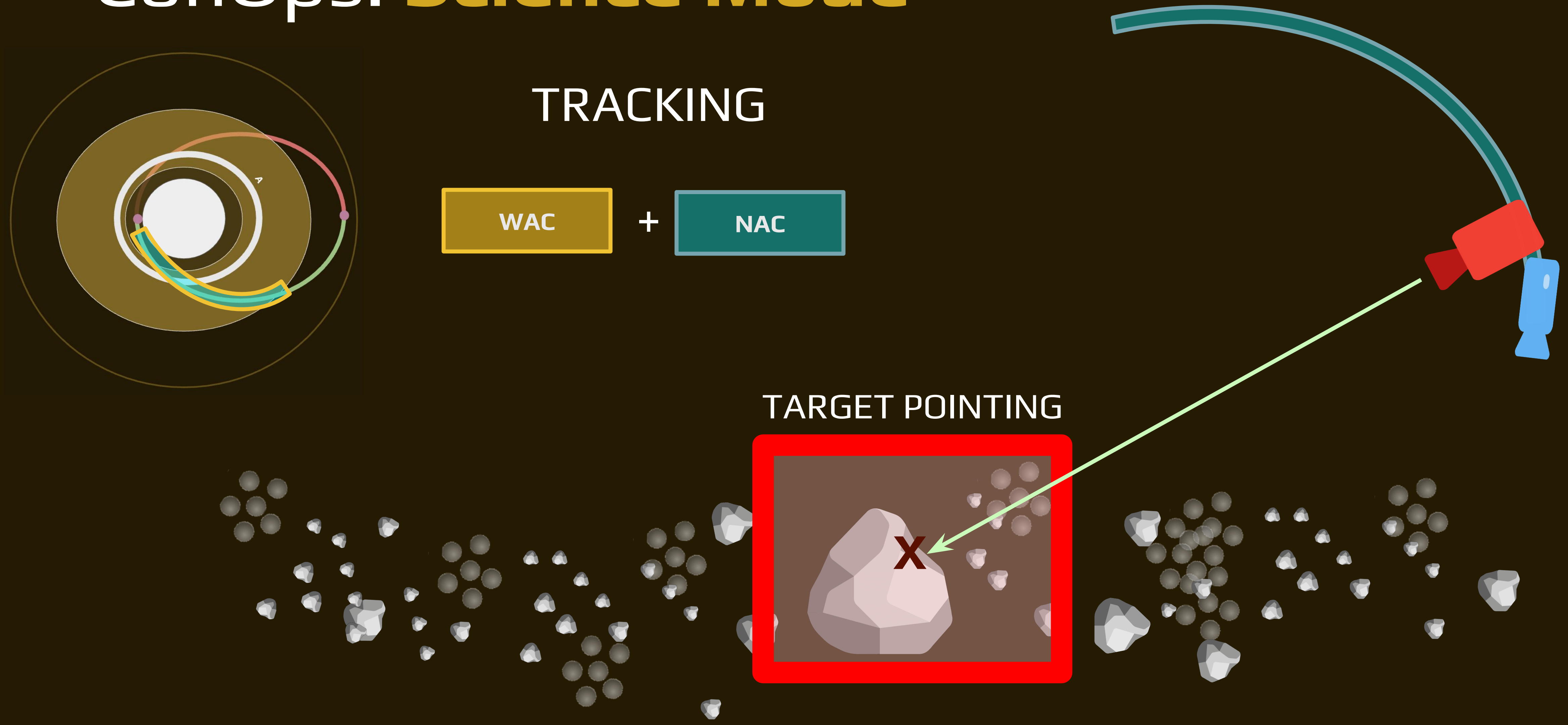


SCANNING

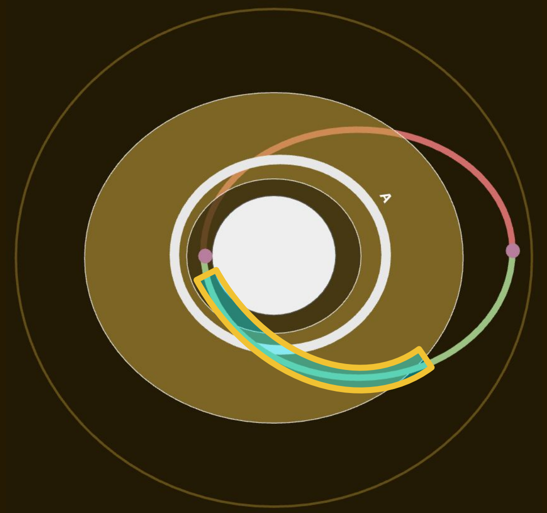
NACs

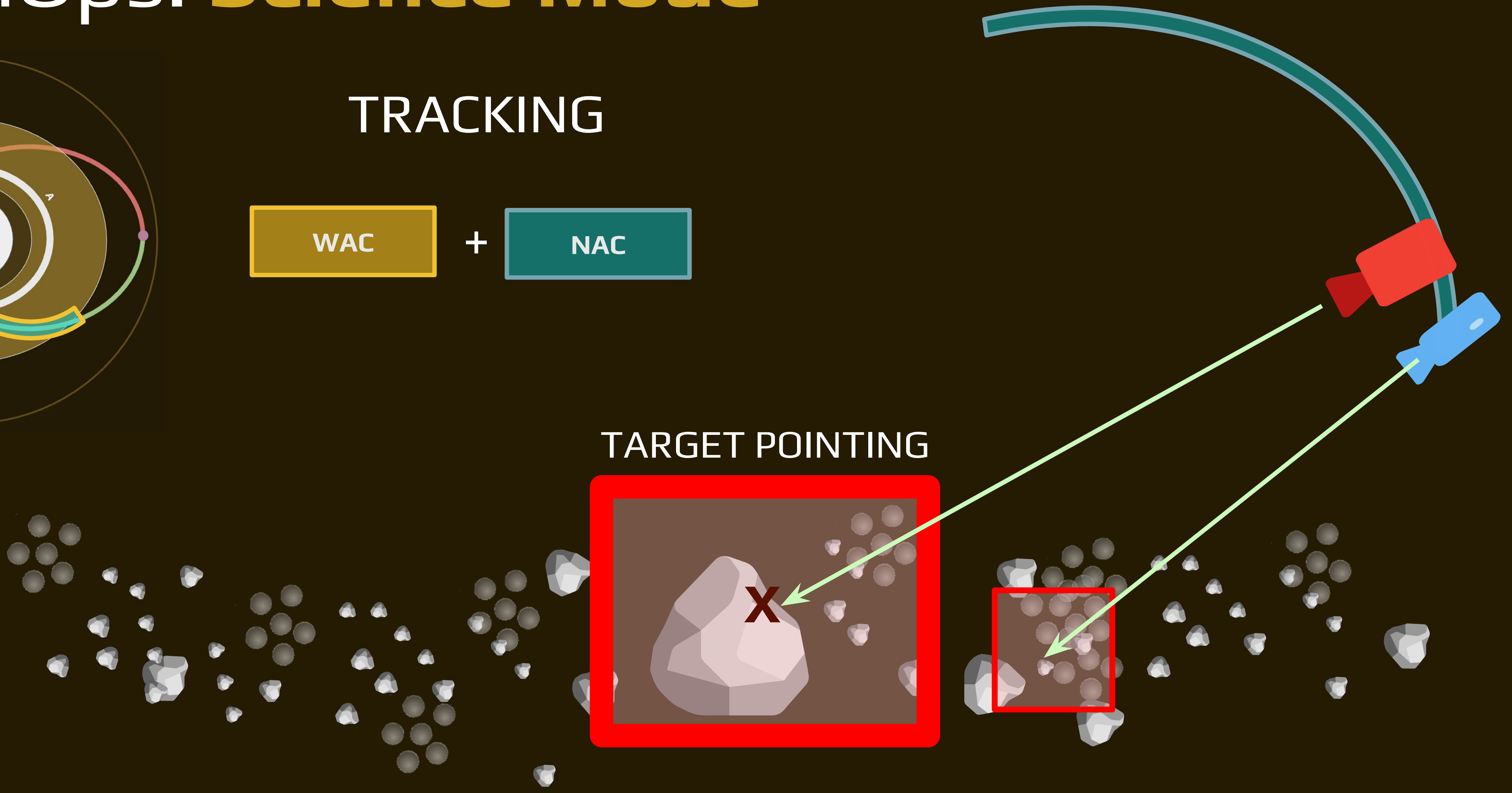


ConOps: **Science Mode**

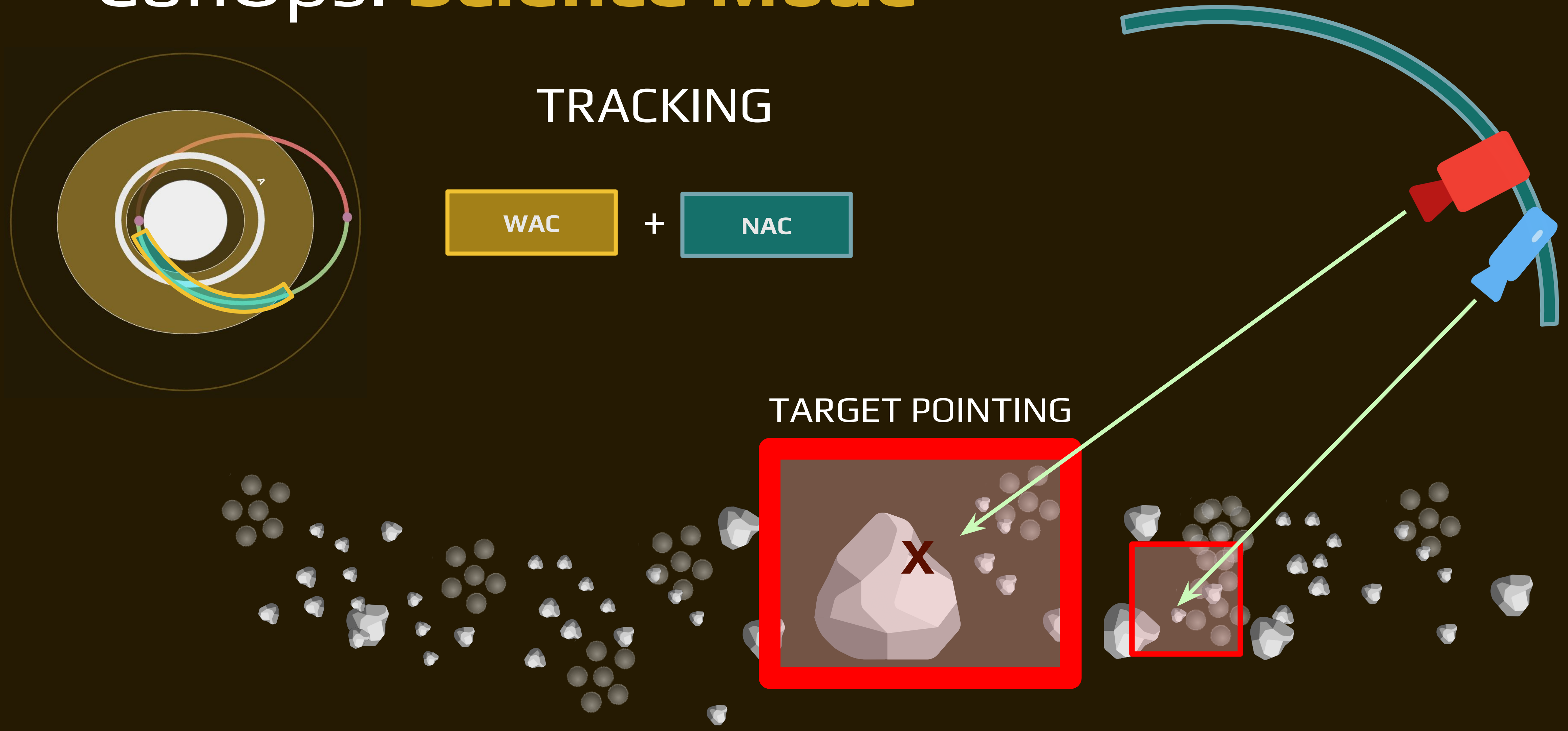


ConOps: **Science Mode**

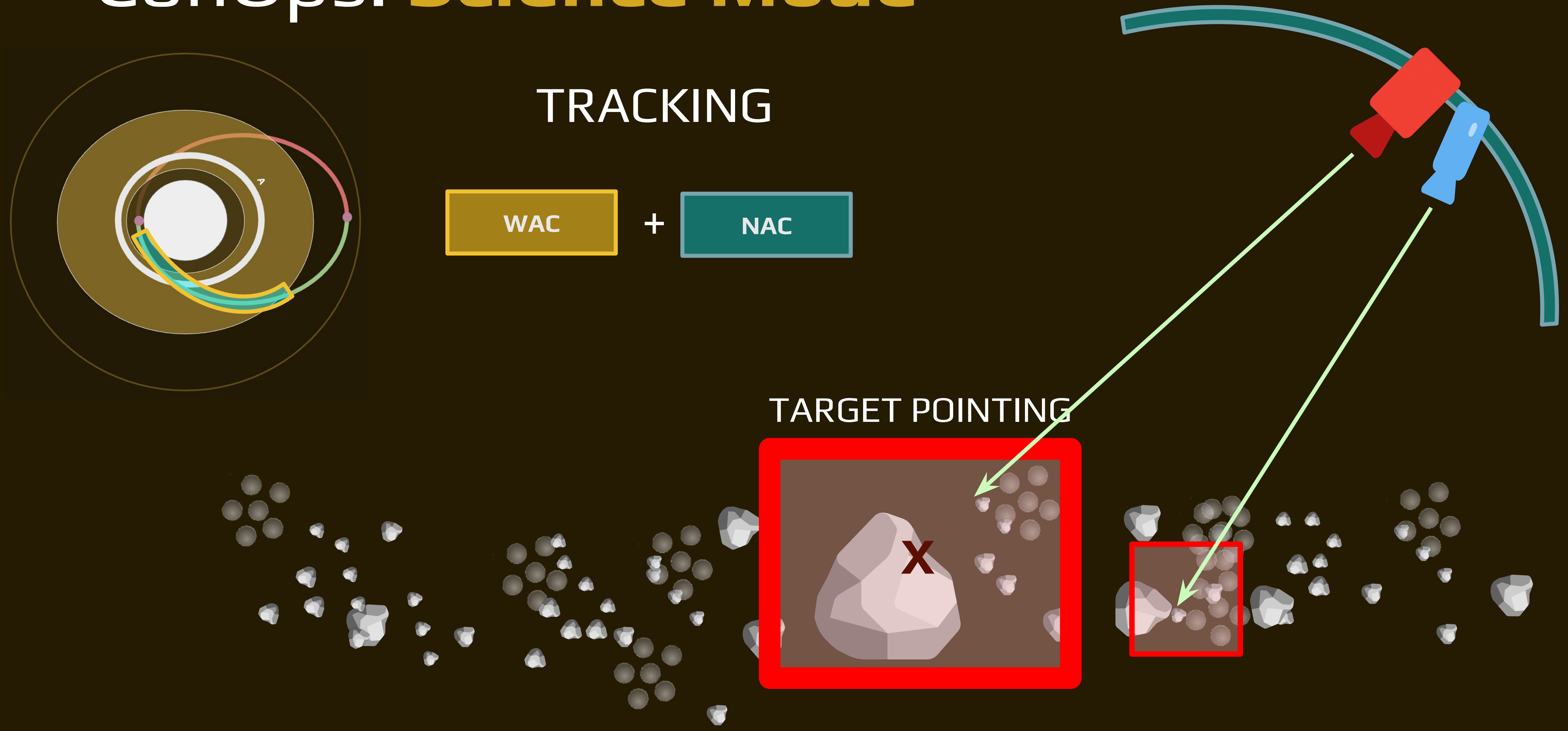




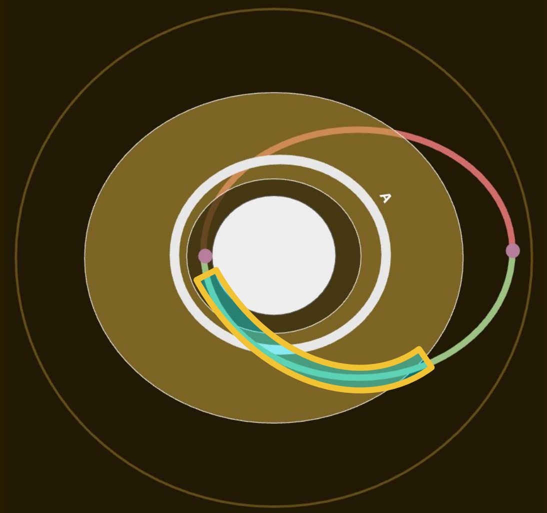
ConOps: **Science Mode**

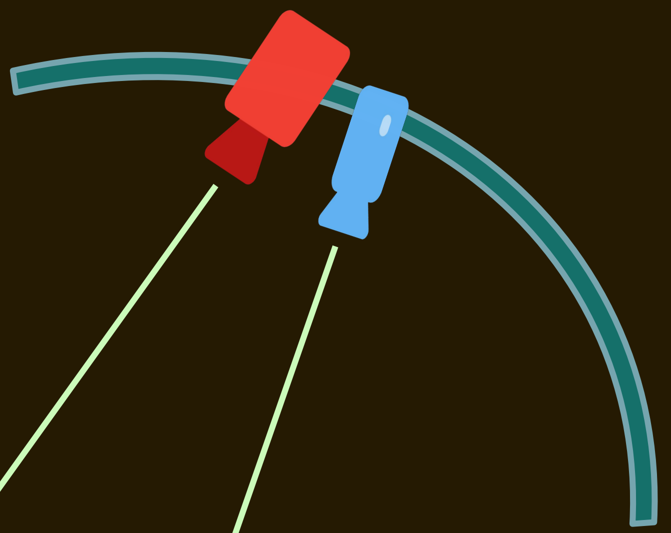


ConOps: **Science Mode**



ConOps: **Science Mode**



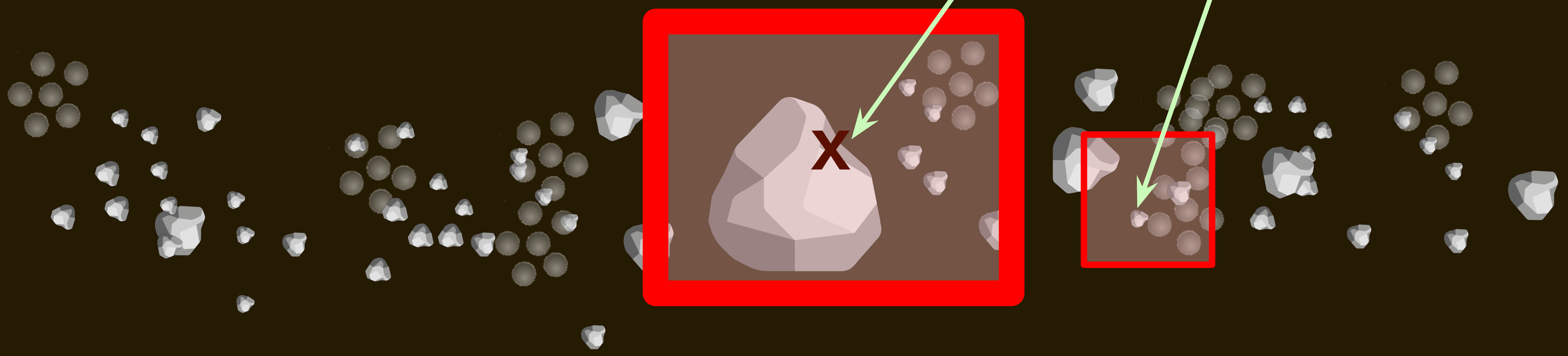


TRACKING

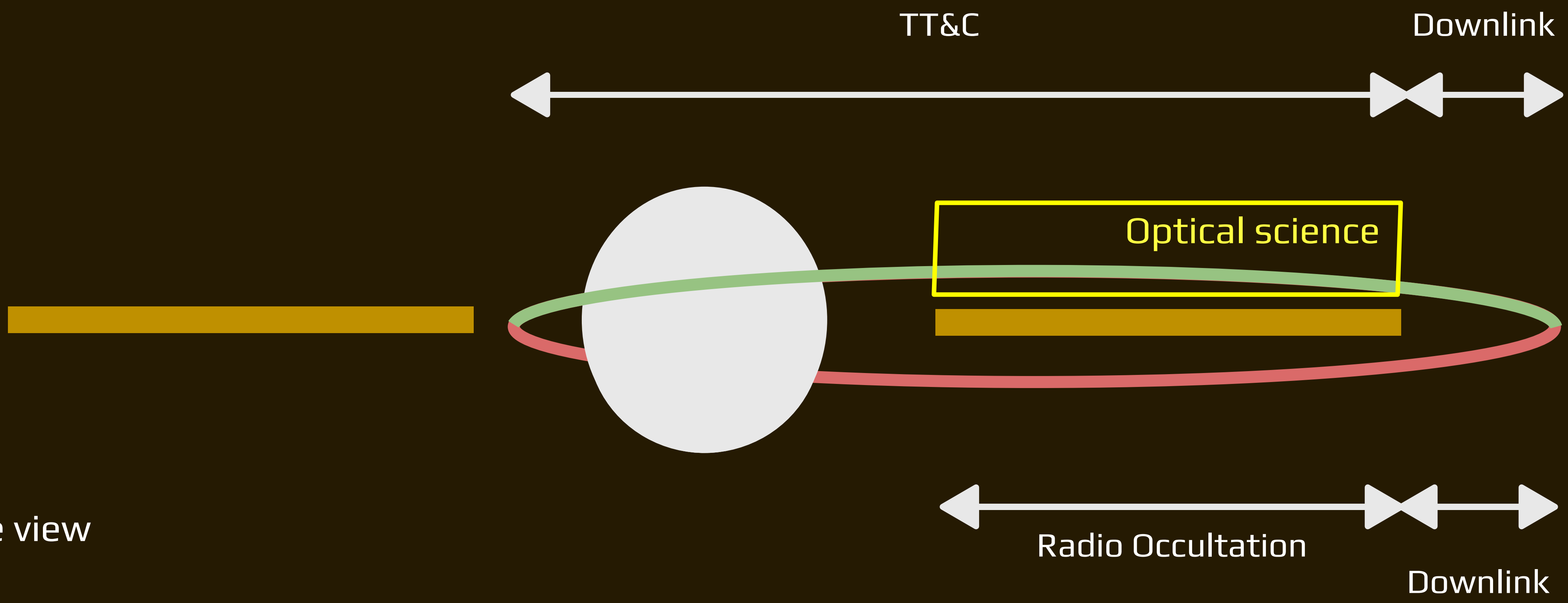
WAC + NAC

Tracking time 5-8 s
Velocity resolution 2.5 cm/s

TARGET POINTING



ConOps: **Communication Mode**



*Side view

Mission Design Drivers

01	Orbital Mechanics	• **Planet alignment** for **transfer** • **Low distance** from Saturn's rings
02	Instrument Requirements	• **Illumination** of the rings • **Resolution** and **data processing** • **Attitude stability**
03	Communication	• **Link budget** and **up-time** • **Distance** • **Orbital and Solar system geometry**

Mission Constraints

• Mass • Size	**Launcher**	01
• **Illumination of the rings** constrains the **launch window**	**Science**	02
• **High radiation near Saturn**	**Environment**	03

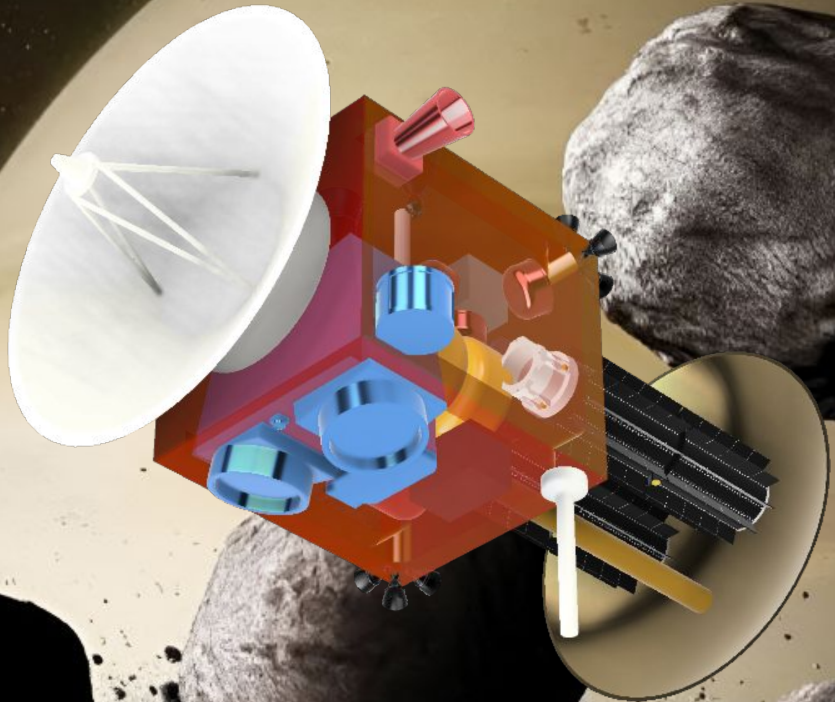
System Design

Science → Mission Design → **System Design** → Program Execution

- Product Tree
- Mass and power budget
- Subsystems
- Ground segment

Product Tree

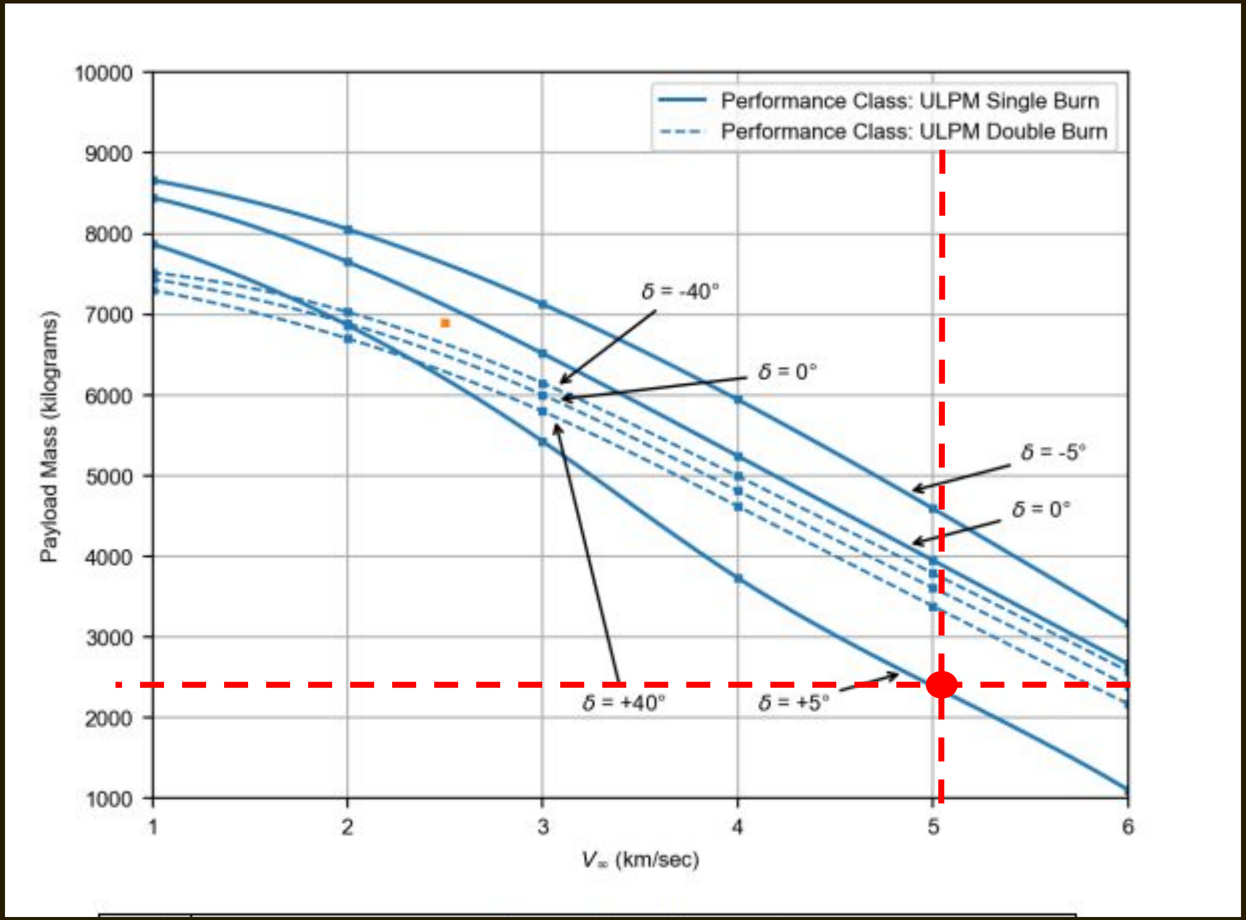
- Ground Segment
- Spacecraft
  - Power
  - Propulsion
  - Structures & Mechanisms
  - Thermal Control
  - TTC
  - AOCS
  - C&DH
- Payloads



Mass budget

Aiming for:

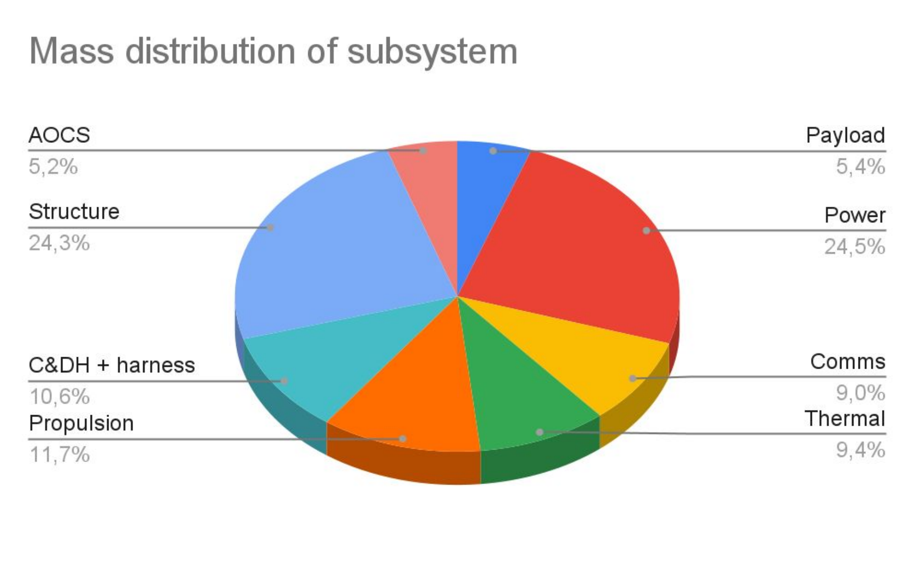
- 1500 kg at launch (Ariane 64)
- V_∞ = 5.2 km/s at Earth
- 1014 kg Saturn arrival mass
- Mass limited due to thrust level of ion engine.



Credit: ESA, Ariane

Mass budget

Subsystem:	Mass (kg)	Equipment margin (kg) (percentage depend)	System margin (kg) 20%
Payload	40.83	42.9	51.45
Power	176	193.6	232.32
Comms	65	71.25	85.5
Thermal	70	74.5	89.4
Propulsion	87.1	92.21	110.65
Structures	160	192	230.4
AOCS	38.2	40.72	48.89
C&DH & Harness	79.7	83.69	100.42
		Total dry mass:	949.03
		Propellant:	158.57
		Total wet mass:	**1107.60**



93.60 kg over budget!

Power budget

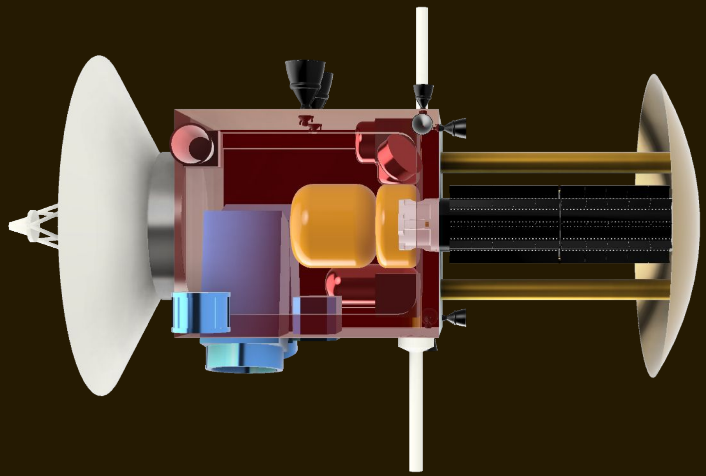
Subsystem	LEOP	Interplanetary Transfer	Measurement	Downlink
Payload	77	0	77	0
Comms	40	2	200	200
Thermal	10	10	10	10
Propulsion	438,72	**660**	0	0
C&DH	30	30	53	41
Structure	0	0	0	0
AOCS	132,6	15,32	132,6	132,6
Total	728,52	**728,52**	472,6	383,6

Subsystems: **Propulsion System**

- Requirement: Provide sufficient capability for successful orbital maneuvering and attitude control.

- Layout
  - 1 Hall effect thruster PPSX00- deep space maneuvering.
    - Mass: 3.2 kg
    - Power: 640 W
  - 6 bipropellant (MMH & N2O4) chemical engines (for insertion and maneuvering around Saturn)
    - MASS: ~3.9 kg
  - Tanks + plumbing.
    - Mass: ~80 kg

[Safran]



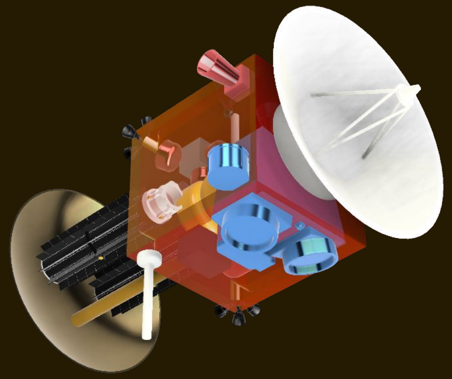
Subsystems: **Power Subsystem**

- Requirement: Satisfy the total system power consumption at all phases of operation.
- Current estimate of the system power draw: 700 W (transfer), 320 W (Saturn).
- NASA Next Gen RTGs, scaled to meet this demand.
    - Also providing heat to the s/c
    - Currently TRL 5/6, first flight planned ~2030
- 200 Wh sized battery to handle power peaks, however 100% uptime of RTGs expected.

Subsystems: **Thermal Control**

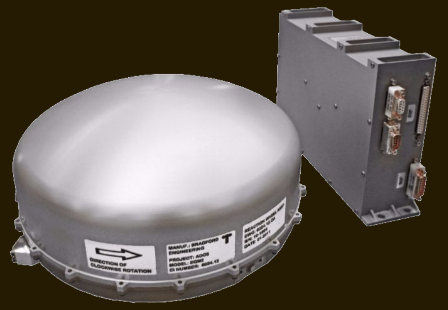
- Preliminary 1-node Thermal Equilibrium calculation:
  - Cube with 1 m side length, 2m antenna dish
  - low ε low α surfaces (bare aluminum)
  - RTGs do not transfer any heat
- ~20 W of heating required at Venus
  - due to low internal power consumption in coast phase
- ~200 W of heating required at Saturn
- Detailed analysis needed, highly dependant on sc geometry
- Some instruments may require active cooling

Subsystems: **Attitude & Orbit Control Subsystem**



- Requirement

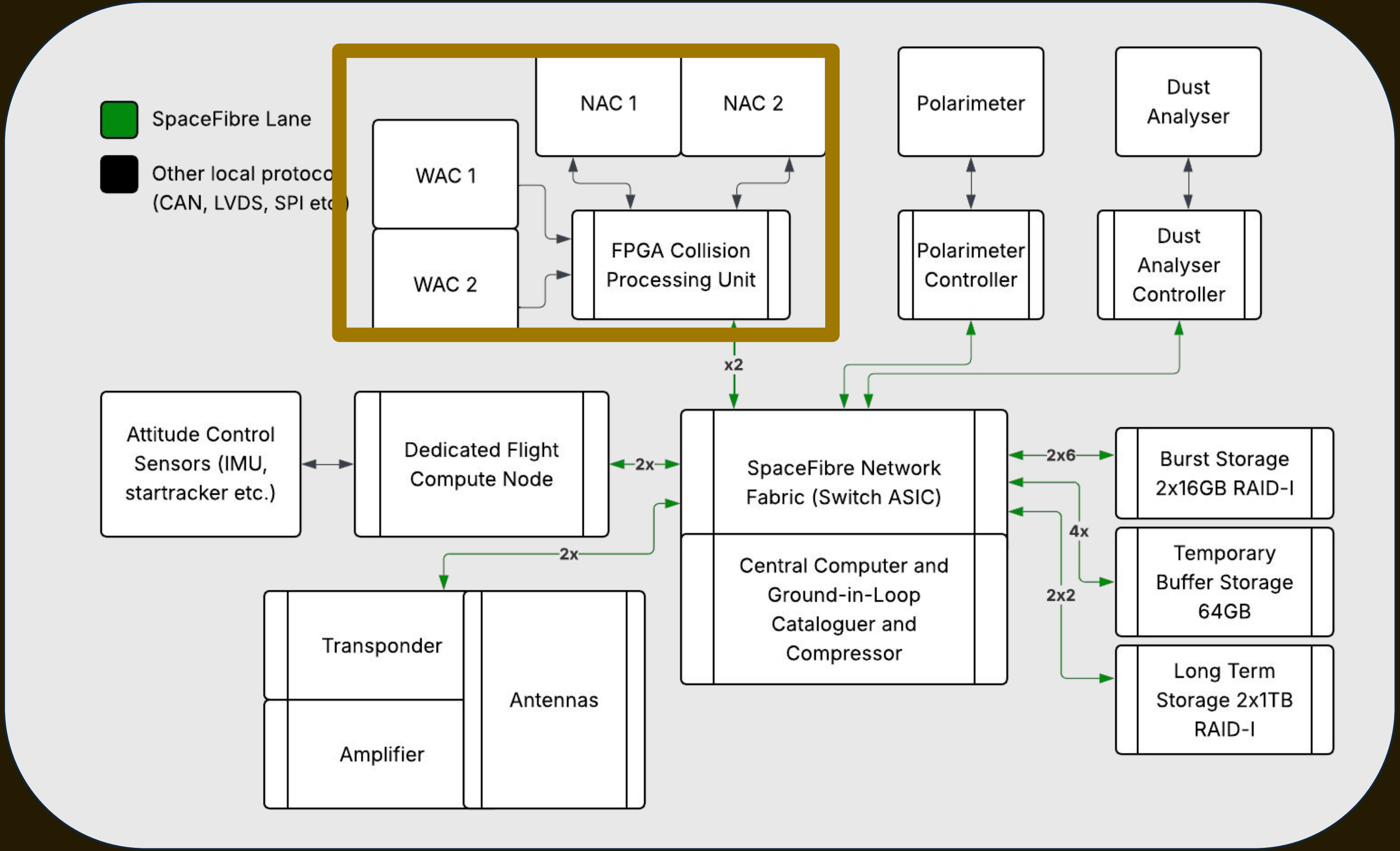
  Pointing accuracy of 0.03 (communication)
  Pointing accuracy of 0.3° (science operation)
  Slew rate of 11.5°/s (tracking mode)
- Maximum disturbance torque: mNm - µNm
- Sensors: Star tracker + 3 IRU.
- Actuators:
  - 4 reaction wheels (1 for redundancy)
  - 6 thrusters



[Bradford Engineering BV]

Subsystems: C&DH - Architecture Drivers

- High Throughput
- On-board Processing - Stereo Camera
- Fault Tolerance
- Radiation Hardening
- Neural Networks for image processing

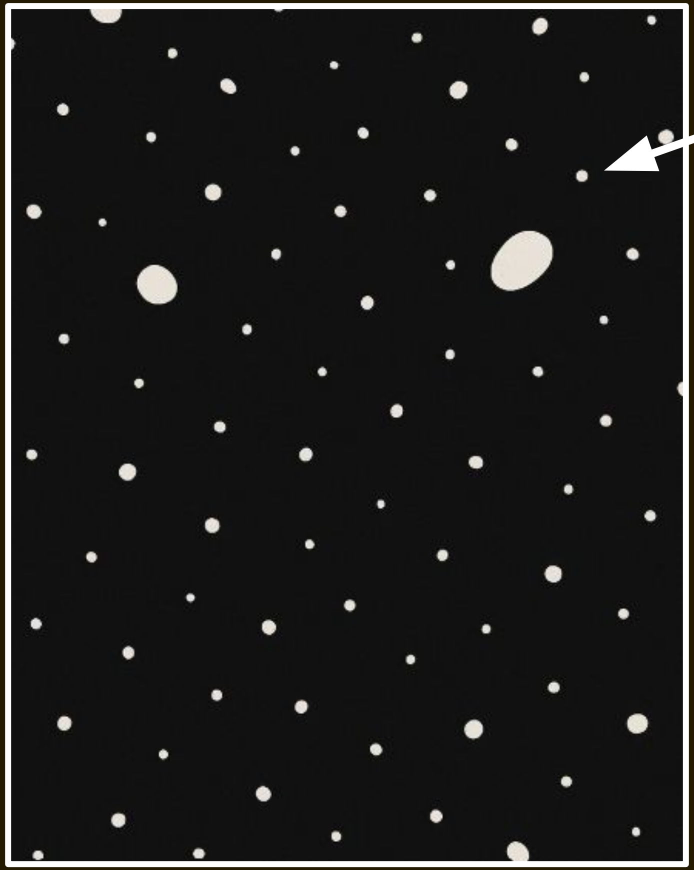


Subsystems: C & DH - Data Budget (per Orbit)

Instrument / Data Type	Peak/Typical Raw per Orbit (~9.5hrs)	Peak/Typical After RT Processing	Post-Processing / Compression	Expected After Processing
Stereo NACs (5FPS@4096² or 20FPS@2048²)	450 GB / 105 GB	122.6 MB / 49 MB	CCSDS 122.0 lossless (~2:1) for ROIs	61.3 MB (peak)* / 19.6 MB (typical)
Stereo WACs (5FPS@1024²)	71.2 GB	19.4 MB / 7.8 MB	CCSDS 122.0 lossless (~2:1) for ROIs	9.7 MB / 3.9 MB
Polarimeter	1.8 GB / –	–	Compute Stokes vector (4 floats)	1.1 MB
Dust Analyser	0.85 GB / –	–	Extract 64-ch mass spectra + metadata (160 B/event)	16 MB
Telemetry & Housekeeping	17 MB / –	2 MB / –	Delta-encode & threshold	2 MB
Ground-in-Loop Catalogue	50 MB / –	2 MB / –	n/a	2 MB

*Peak data exceeds single orbit budget and compromises in following orbit modes must be taken for these instances.

Subsystems: **C & DH - Data Budget Metadata**



({x, y}, {Vx, Vy}, d, h, t, Var, Var, Var)

- The metadata for a NAC frame is broken down into 7 32b floats and 3 additionally budgeted for future scoping, at each particle of interest
- An average of 1 ROI snapshot per frame is budgeted
- Particle count is calculated to range between 25-50, 50 is budgeted.

Subsystems: C&DH - Data Budget

Data Type	Volume (per Orbit)
Telemetry & Housekeeping	2 MB
Ground-in-Loop Catalogue	2 MB
Subtotal	**4 MB**
Remaining for Science Requests	**61.5 MB**

- Total downlink per orbit is **65.5MB** within **3 hrs 10 mins** of the 9.5 hour orbit
- **70%** of the remaining 61.5 MB (~43.1 MB) is allocated to **ground-requested** or **scheduled** data
- The final ~18.4 MB serves as **margin** for unexpected needs, burst-mode science, or communications interruptions.

- Full images, raw datasets and other preprocessed data can be requested from the ground in advance in order to ensure the full data is preserved and stored

Subsystems: **C&DH - Autonomous Operations**

- 70 minutes one-way signal travel time
- Autonomous Operations:
  - Collision avoidance (very rare, expecting only μm sized particles)
  - Science event detection and targeting
  - Target acquisition and attitude adjustment in tracking mode

Subsystems: **TT&C Subsystem**

- Requirement: Transmit TT&C and Downlink Data
- Antennas:
  - 2x LGA (S-Band, for LEOP),
  - 1x MGA for safe mode (sun pointing)
  - 1x HGA (X and Ka-Band), Dish diameter 2 m, Power ~120 W electric
  - HGA reused for radar occultation experiments
  - HGA gimbaled for TT&C during Science Phase.
- TT&C/Housekeeping download at all times.
- Bulk downlink of data during Communications phase (33%).
  - Data rate: 65 MB/orbit assuming 1.5 hrs per orbit/4 hrs per day
- Additionally, Doppler, D-DOR Ranging

Ground Segment

- ESA ESTRACK 35 m Antennas
- May require time-sharing, currently considering 50% availability

Program Execution

Science → Mission Design → System Design → **Program Execution**

- Cost
- Risk Assessment
- Preparation for Saturn's environment
- Development
- Descoping options
- Public outreach

Cost

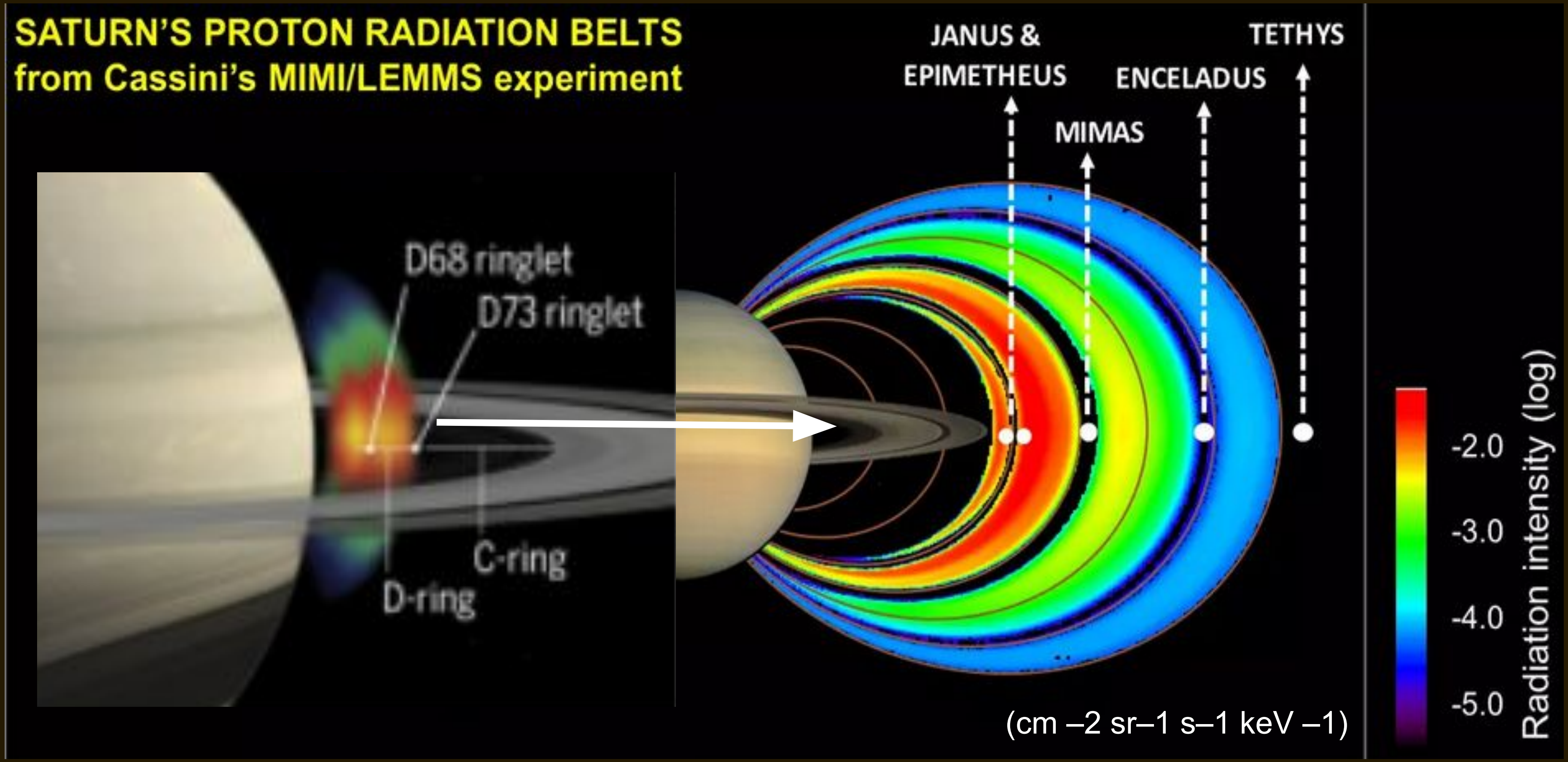
- **ESA L-class** mission
- Total cost 1.1 B€

	Cost in M€	
ESA mission	110	
S/C	300	
Power (RTGs)	250	
MOC	80	
SOC	70	
SUM	810	
Contingency	121.5	
Launcher	170	including RTG
Cost At Completion	1102	

Risk Assessment

	Very unlikely	Unlikely	Possibly	Likely	Very likely
Catastrophic	**Separation** **Gravity assist** **RTG**	**Collision** **AODCS**	**Shield** **Atmospheric modeling**		
Significant	**Orbit Insertion**	**Communications** **Instruments**	**TRL delay** **Missed launch window**	**Particle collision**	
Moderate		**Components**	**Degradation of mirror**	**Higher throughput**	**Single event upset**
Low			**Dust contamination**	**Loss of expertise**	**Unexpected costs**
Negligible					

Preparation for Saturn's environment



Radiation testing requirements for deep space missions:

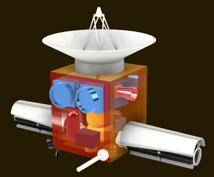
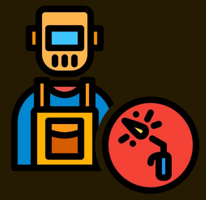
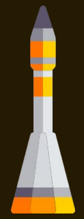
- TID testing: 1-10 Mrad(Si)

  SEE testing: heavy ions and protons

  DD testing: protons and neutrons

- Extensive shield testing
- Extensive TRL development

Development

2045–2047	2047–2049	2049–2053	2053–2057	2057–2061	2061–2078
2 years	2 years	4 years	4 years	4 years	17 years
					
Phase 0	**Phase A**	**Phase B**	**Phase C**	**Phase D**	**Phase E**
Mission analysis and identification	Feasibility studies	Preliminary definition	Detailed design	Qualification and production	Operations phase
		PDR	STM and EM	Building FM	
			CDR	AIT	

Descoping options

Decision process:

- What is the scientific significance?
- What is the impact on mission success?
- Can we find an alternative measurement method if the instrument is removed?

Descoping priorities:

1. Dust Analyser
2. Cut one WAC

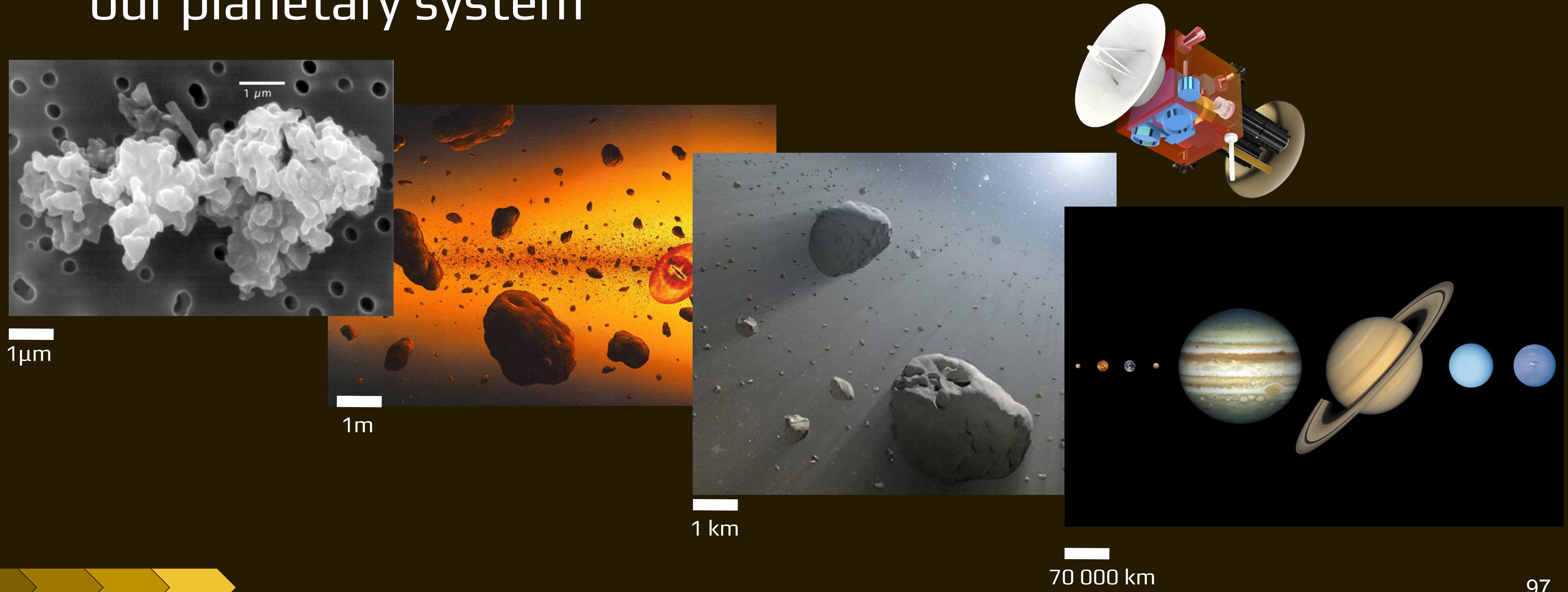
Public Outreach

- “Name your moonlet” website
- Active media presence
- University seminars
- Student participation

  Invite students from all around Europe to apply to become silent participants in the mission development operations (Inspired by DART)
- Traveling exhibits with spacecrafts models and interactive activities

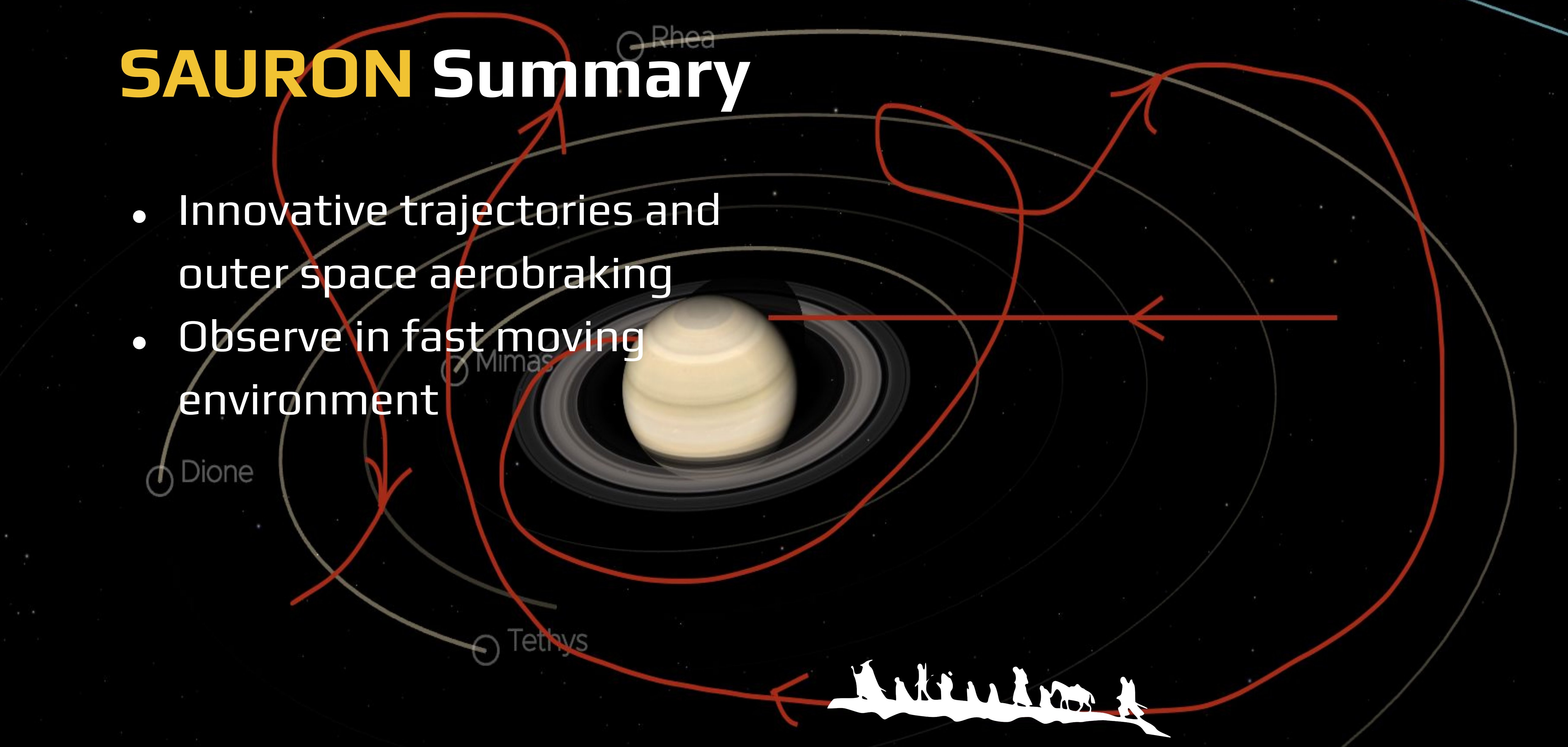
SAURON Summary

- Complex & ambitious mission to investigate the origins of our planetary system



SAURON Summary

- Innovative trajectories and outer space aerobraking
- Observe in fast moving environment



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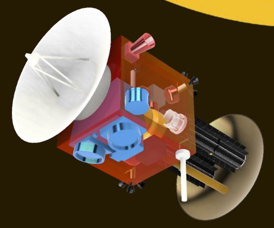
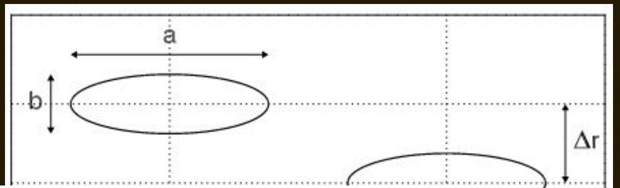


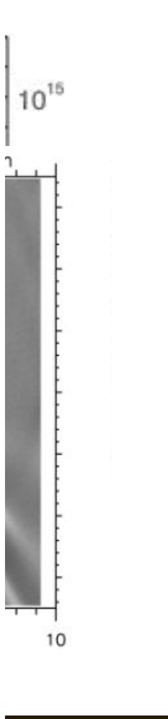
BACKUP SLIDES

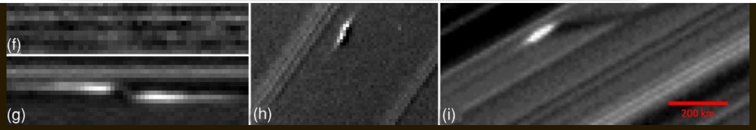
How do planetesimal form?

Propeller Moons

- Propeller moons creates turbulences within the ring (stochastic migration).
- Location:~ 60 % (more than 150 objects identified by Tiscareno in 2007) in mid A-ring (between 126s). Structure,750 km and 132,000 from saturn center) exist in annulus between 50 and 100 km.
- Estimation of 10e7 propellers (for Δr>0.25 km) homogeneously distributed (Tiscareno et al, 2007).
- Size : 50m > D >2 km (moon) particles around (1 to 10 cm for lowest ones of Propellers : meters to one thousand.
- Simulations expects 1± 0.7 cm/s for dispersion velocity .
- Brighter zone (interactions with light increase the optical depth) in low density ring due to freeing of regolith? Or disruption of self-gravity wakes ? (Tiscareno et al. 2010). Simulation too expensive for small particles but same shape founded in protoplanetary disk simulation.

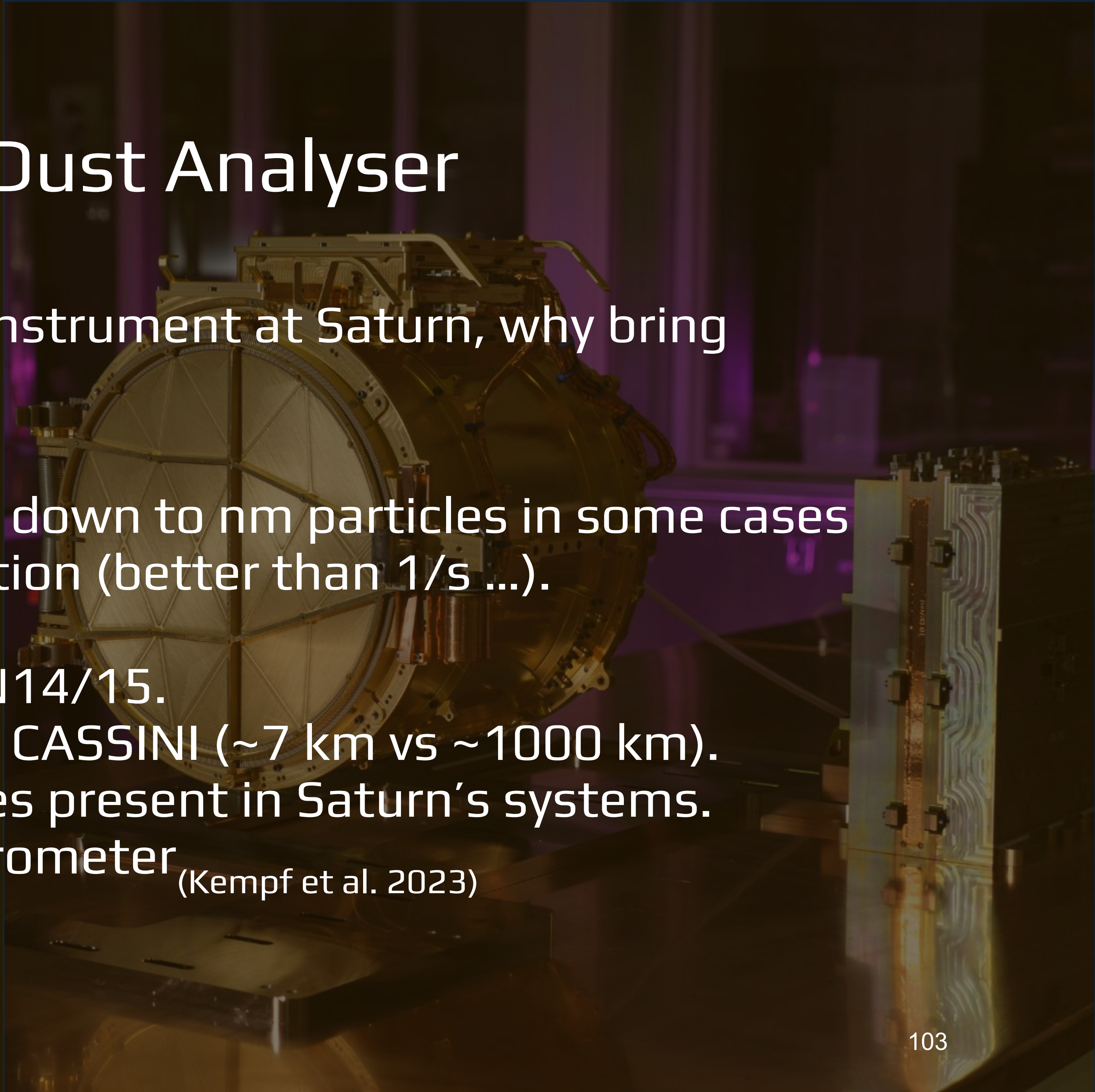






Instrumentation: Dust Analyser

- There already was a Dust Instrument at Saturn, why bring another?
  - 30 year old Technology.
  - Better mass resolution, down to nm particles in some cases
  - Higher temporal resolution (better than 1/s ...).
  - 3D trajectories.
  - Isotopes! H/D 016/18 N14/15.
  - Closer approaches than CASSINI (~7 km vs ~1000 km).
  - Also Interstellar particles present in Saturn's systems.
  - SUDA typically 100 micrometer (Kempf et al. 2023)



Dust Analyser

- Why analyse dust again when Cassini already did?
- Old tech: higher mass- and temporal resolution, 3D detection & isotope analysis
- SUDA Europa clipper
- Science Requirement
- Instrument Requirement

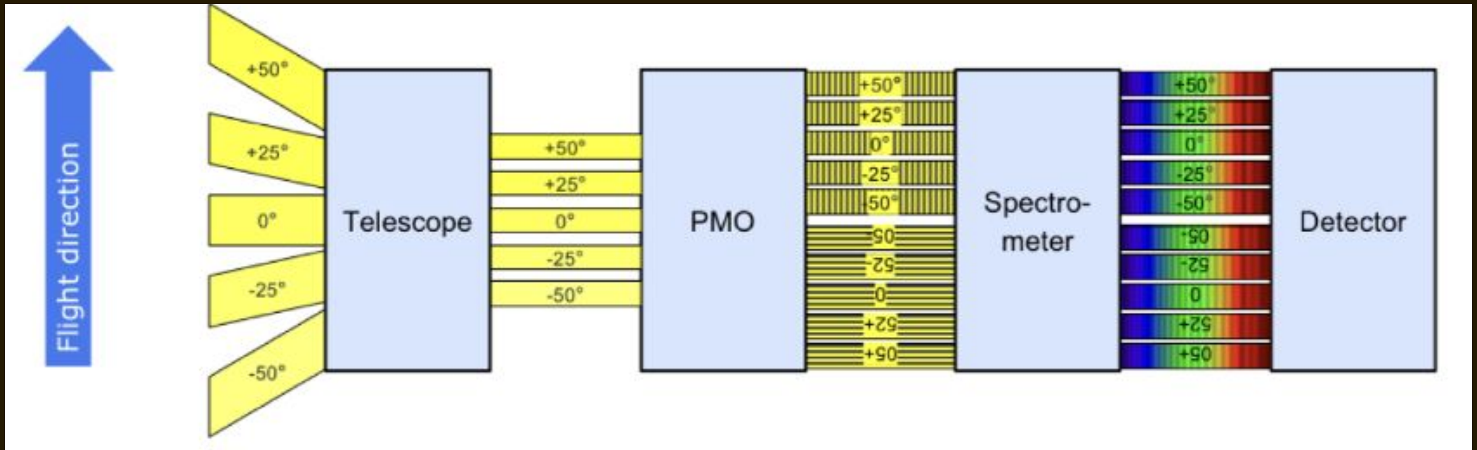
Payload

- Science Requirement
- Instrument Requirement
- TRL

Technology Readiness

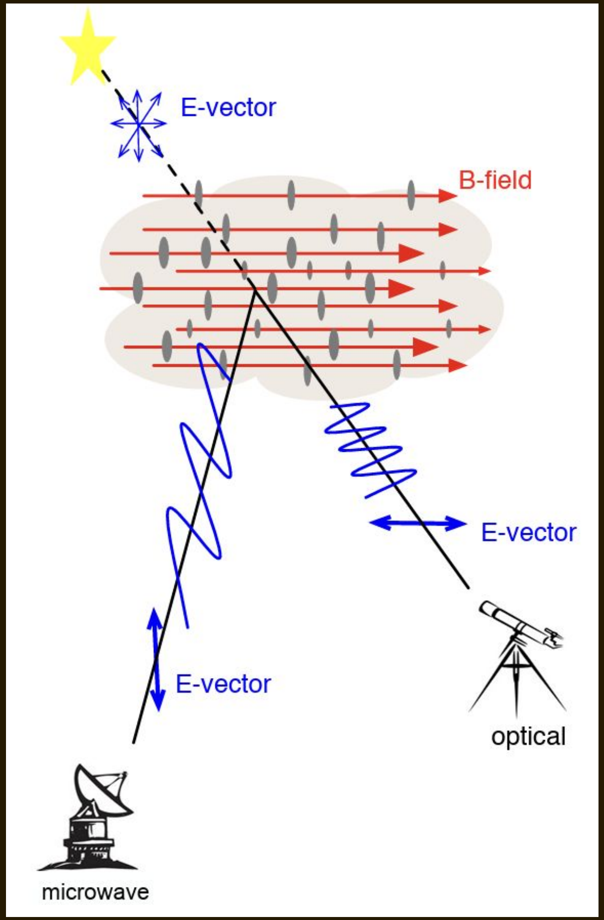
Technology	Narrow Angle Camera	Wide Angle Camera	Dust Analyser	Radar	Polarimeter	Magnetometer
TRL	7	8	5		7	6
Concerns						

Spectro-polarimeter



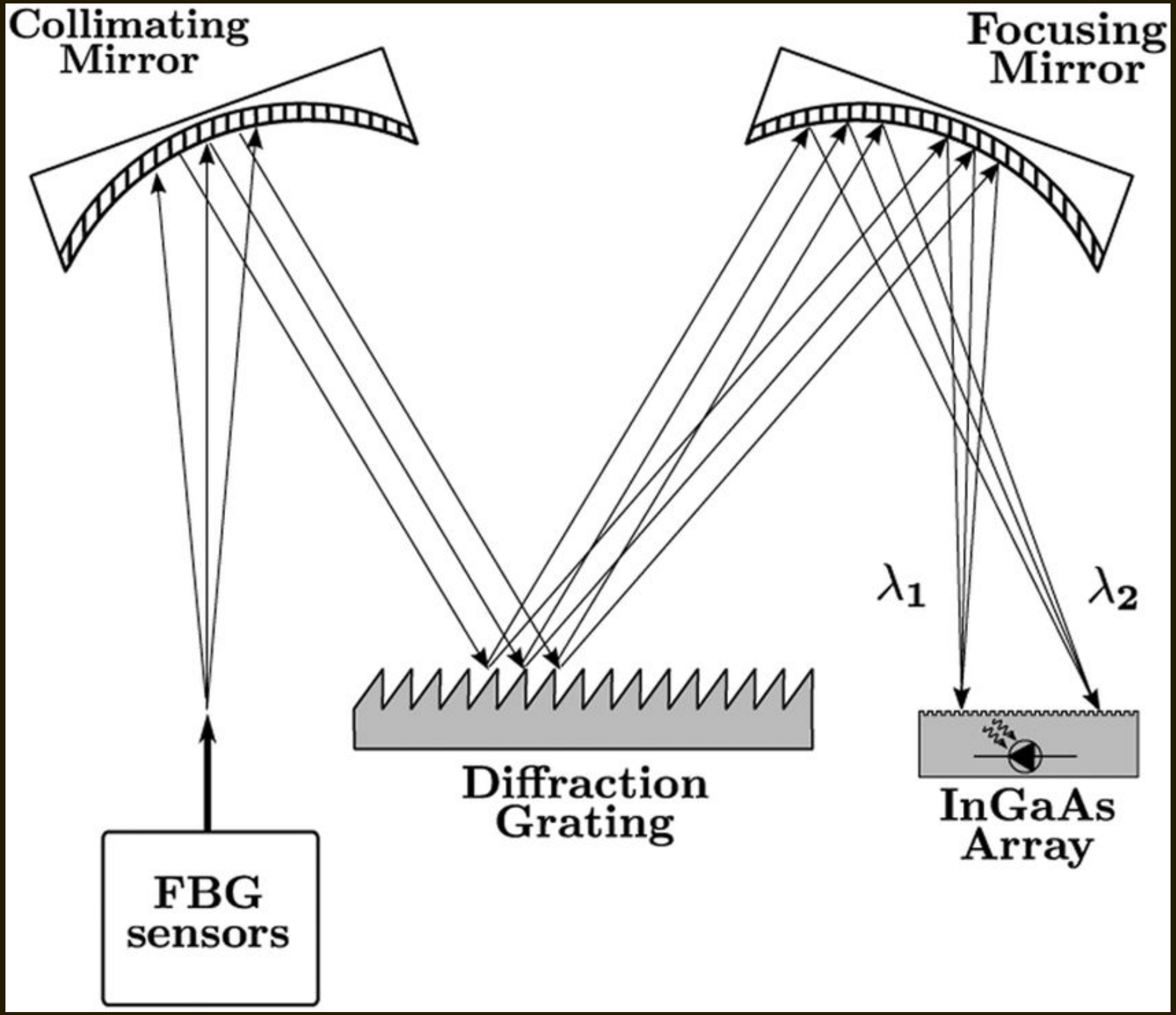
Credit: SPEXone, PACE project

Polarization



Credit: Tassis et al. 2018

Spectrometer: working principle



Instrumentation:

Magnetometer

Science Requirement:

- **SO-2.2:** Measure Saturn's planetary magnetic field.
- **SO-2.2:** Look for non axis-symmetric components.
  - Get as close as possible.

Instrument Requirement:

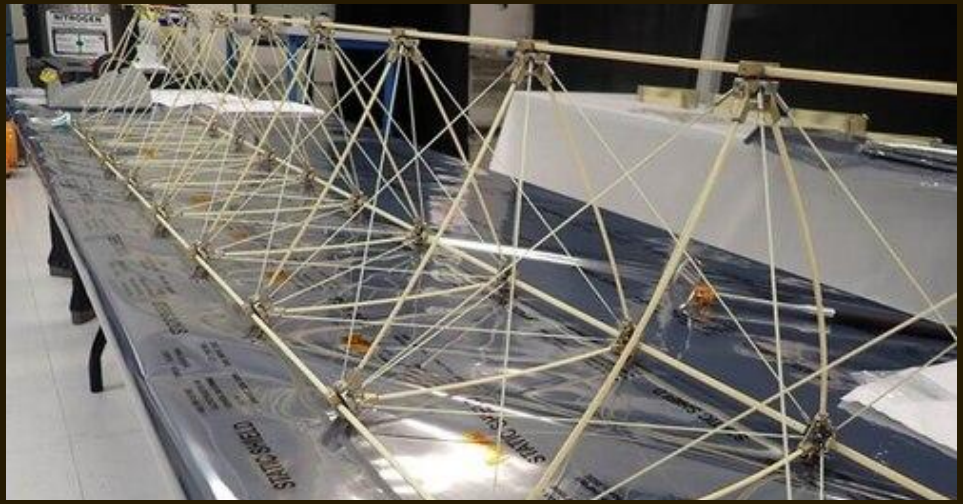
- Aim for 10s of pT Resolution.

Instrumentation:

Magnetometer

- CASSINI could not find out why Saturn's magnetic field is so symmetrical.
- Mounted on a ~3 m boom. More magneto cleanliness of the SC is possible but expensive.
- Second magnetometer at half length of the boom.

Mass	5 kg + Mass of Boom ~ 30 kg
Size	250x250x500 mm
Power	5 W
TRL	7 (very common instrument, only 1 has orbited Saturn)



Cassini's Thermal Solution

- Very cold environment, but lots of heat from RTGs
- Minimize exposure to varying environment (0.67 to 10 au), passive techniques.
- HGA as global shade, isolated from SC, low α/ε paint
- Thermal blankets, except for radiators and apertures
- Utilization of RTG heat.
- Small electrical and radioisotope heaters for instruments with low temperature range.
- Basically kept everything between -30°C and 50°C.

Our Thermal Solution

- Overall similar to Cassini, we have 1 RTG less, overall smaller Spacecraft.
- Preliminary Thermal Equilibrium calculation:
  - Cube with 2m side length.
  - aluminized kapton surface.
- Without RTG heat: -100°C, way too cold!
- With the RTG waste heat: 33°C at Saturn, comfortable!
- Venus flyby could go up to 66°C, a bit too warm.
- Have not chosen a solution yet, but many options.
- HGA as shield, different surfaces, louvers...
- Specific instruments could get hot during manoeuvers.

Control & Data Handling

- Central C&DH Computer with **Integrated SpaceFibre Switch**: single backplane hosts **ground-in-loop** and **compression** software, mass-memory controllers and FPGA-based on-board processing
- Instrument Controllers as SpaceFibre End-Points: each payload (stereo NAC, wide-angle camera, polarimeter, mag/dust analyser) plugs into its own **multi-lane link** for data, telemetry and commands
- **Tiered Storage** over SpaceFibre Fabric: high-speed NVMe "**burst**" SSD for image bursts, mid-rate flash "**temp**" buffer, and **bulk** NAND archive—all accessed via dedicated SF lanes
- Deterministic **QoS** via Virtual Channels: VCs 0–3 for **guaranteed science streams**, 4–7 scheduled **housekeeping**, 8–9 **pre-emptive** command/control, with **hardware-enforced priorities** and lane-fail recovery
- **SpaceFibre** - ultra-low latency, scalable aggregate bandwidth (6.25 Gbit/s per lane, >100 Gbit/s total), built-in fault tolerance and flow control for mission-critical reliability

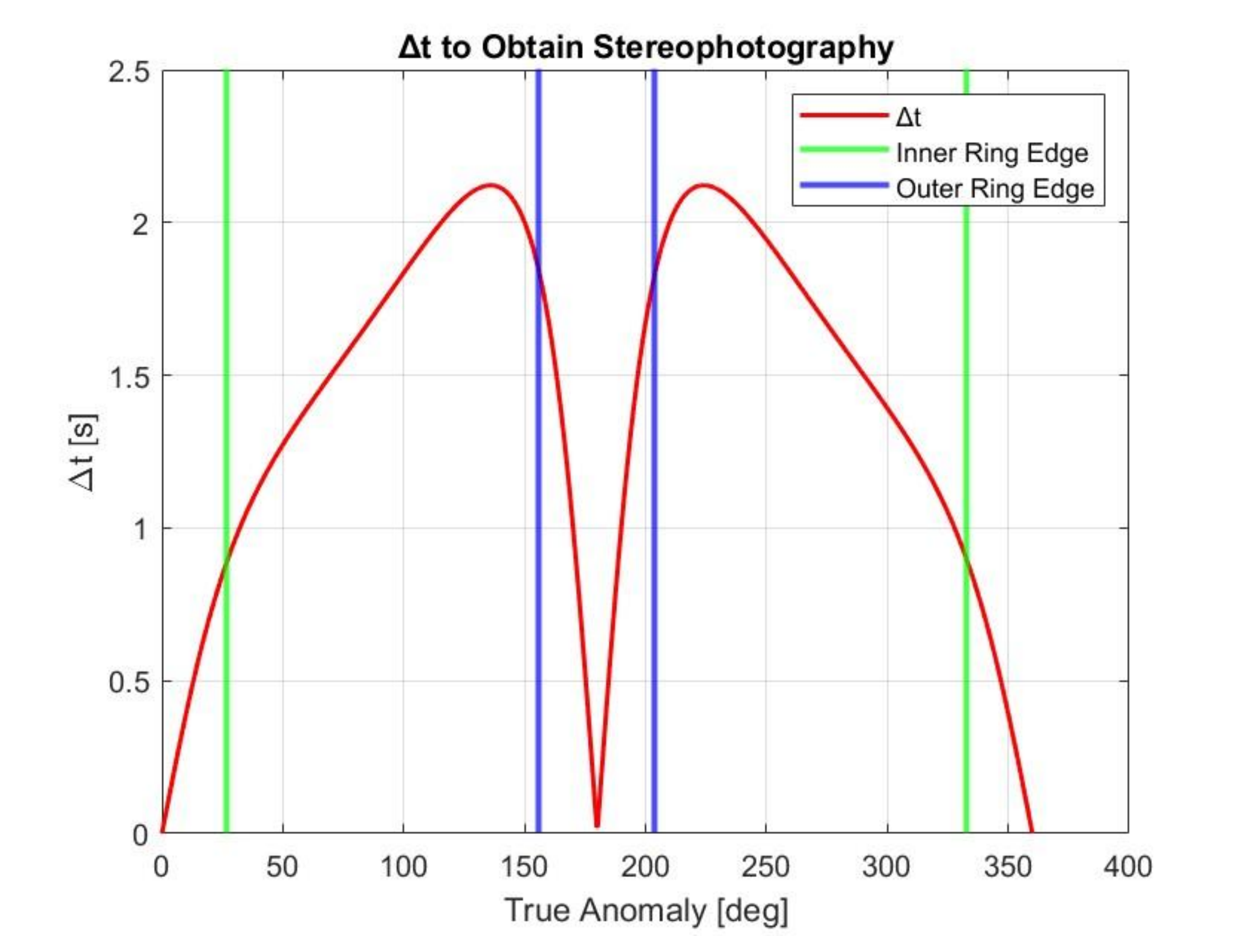
Control & Data Handling

Class	Traffic	VC(s)
Class 1 – Command & Control	Uplink commands & ACKs between the Central Computer and all instrument controllers	8–9 (highest priority, preemptive)
Class 2 – Housekeeping Telemetry	Periodic health & status frames from each instrument controller to the Central Computer	4–7 (scheduled time-triggered slots)
Class 3a – Stereo NAC data	Post-filter science frames from the Stereo NAC Controller into the Burst Bank	VC 0 (guaranteed-bandwidth)
Class 3b – Wide-Angle Camera data	Science frames from the WAC Controller into the Burst Bank	VC 1 (guaranteed-bandwidth)
Class 3c – Polarimeter data	Science data from the Polarimeter Controller into the Temp Bank	VC 2 (guaranteed-bandwidth)
Class 3d – Mag & Dust data	Science data from the Mag/Dust Shared Controller into the Temp Bank	VC 3 (guaranteed-bandwidth)
Class 4 – Storage Ingress	Internal bulk writes into Burst, Temp and Long-Term Storage via the SpaceFibre switch	Best-effort within storage-ingress lanes
Class 5 – Ground-in-Loop Processing	Browse-product & event-log assembly, final formatting performed by the Central Computer (no separate processor)	Best-effort within existing Central Computer lanes

INSTRUMENTS

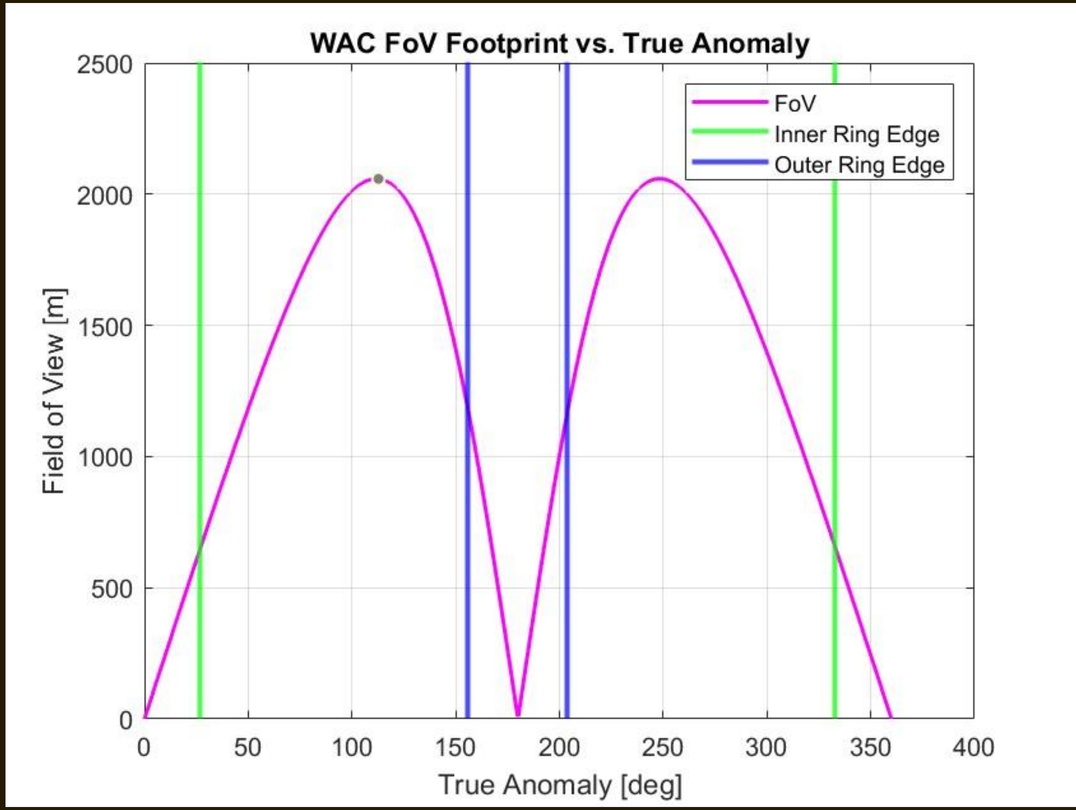
Instrumentation: Stereo camera system

MIN 0.8 s
MAX 2.1 s

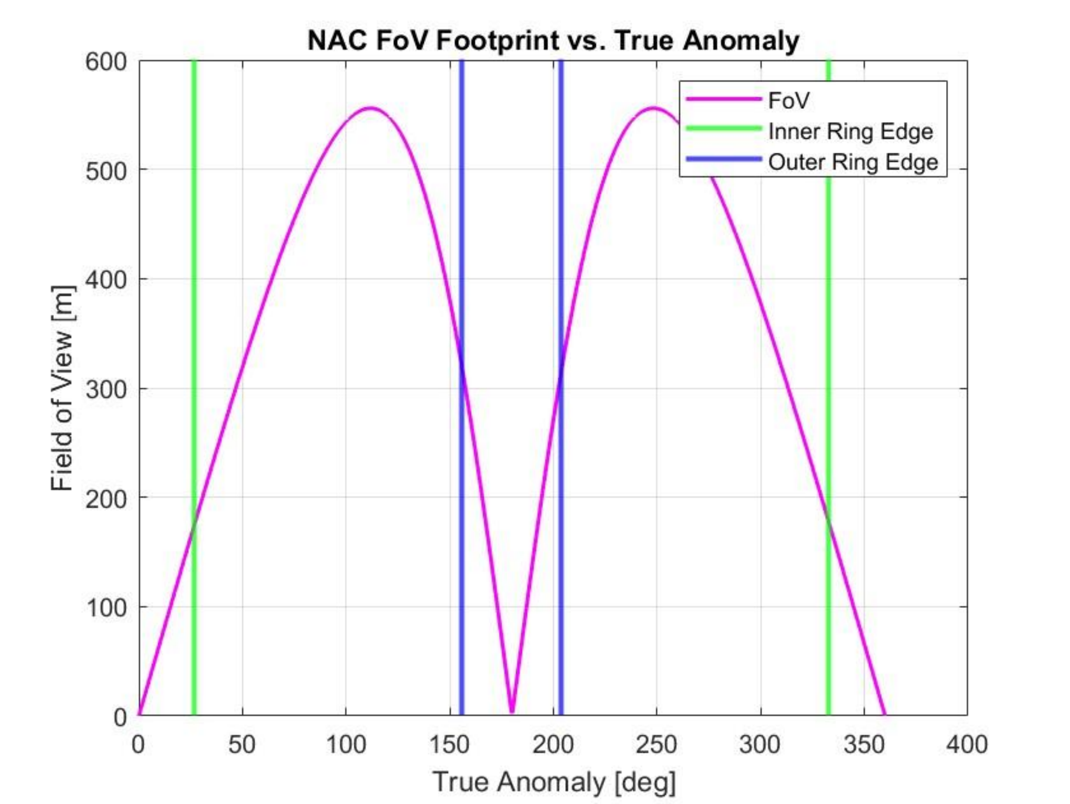


Instrumentation: Stereo camera system

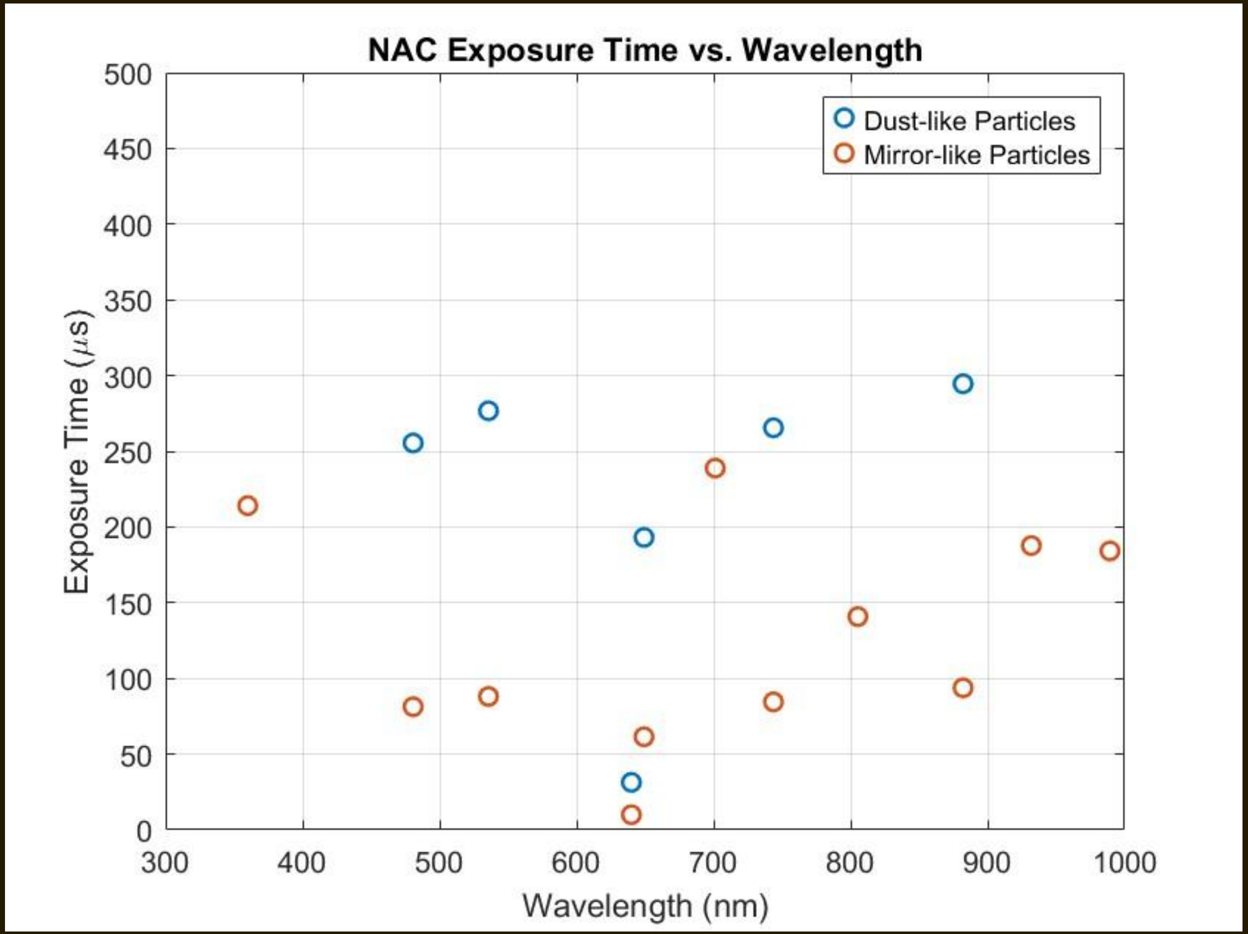
MIN 687 x 687 m
MAX 2058x2058 m



MIN 183 x 183 m
MAX 555 x555 m



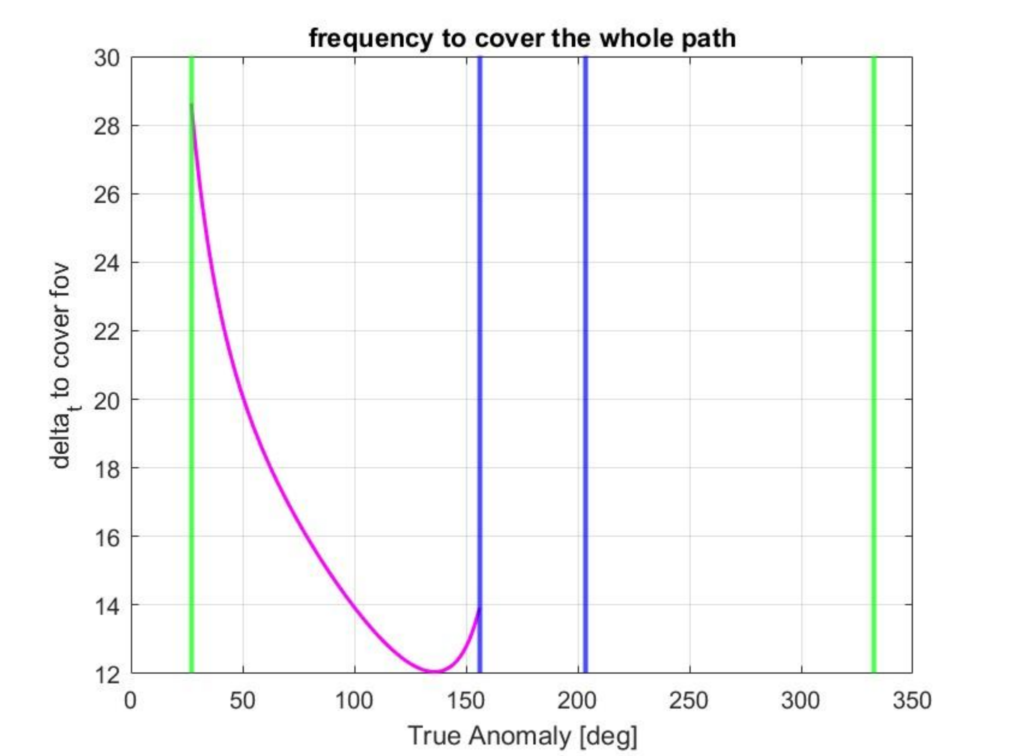
Instrumentation: Stereo camera system



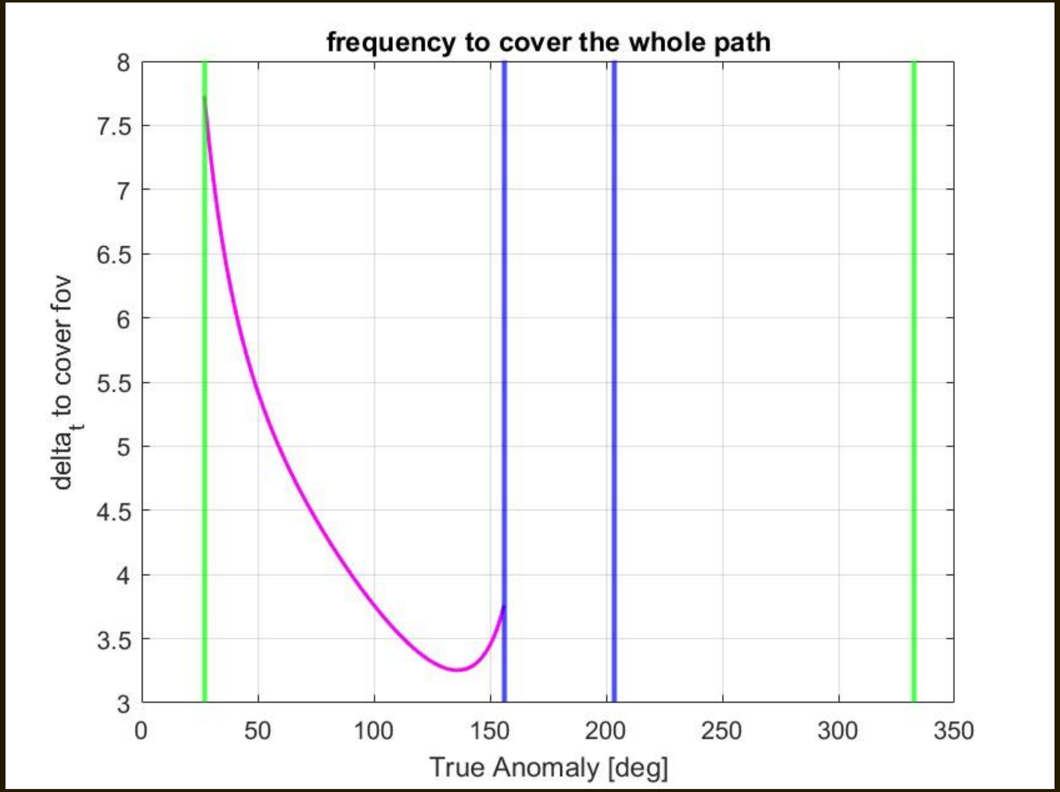
MIN Mirror 10 micro s
MIN Dust 33 micro s

Instrumentation: Stereo camera system

NAC



WAC



Instrumentation: MUV spectrometer

Science Requirement:

- Further analyze dust composition to look for the unknown UV absorber(s)

Instrument requirements:

- Broaden Cassini's range to include MUV absorption peaks [180 - 340] nm
- Use the MUV channels of MAVEN (NASA) Ultraviolet Spectrograph

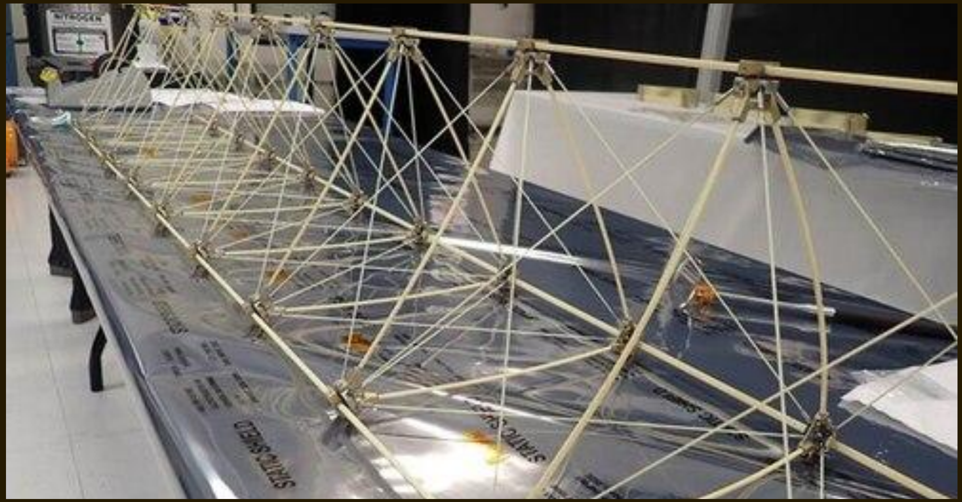
Mass	11 kg
Size	617 x 541 x 231 mm^3
Power	15 W
TRL	9 (MAVEN payload)

a lot of text

Instrumentation: Magnetometer

- CASSINI could not find out why Saturn's magnetic field is so symmetrical.
- A higher sensitivity Magnetometer could look for weak non axis-symmetric components.
- Cassini had 1nT vs 8pT on Europa-Clipper (Dougherty et al 2002) (Kivelson et al 2023).
- Mounted on a ~3 m boom, mechanism has a large volume requirement, potential problem.

Mass	5 kg
Size	250x250x500 mm
Power	5 W
TRL	7 (very common instrument, only 1 has been in Saturn)



CONOPS

Concept of operation: Science phase

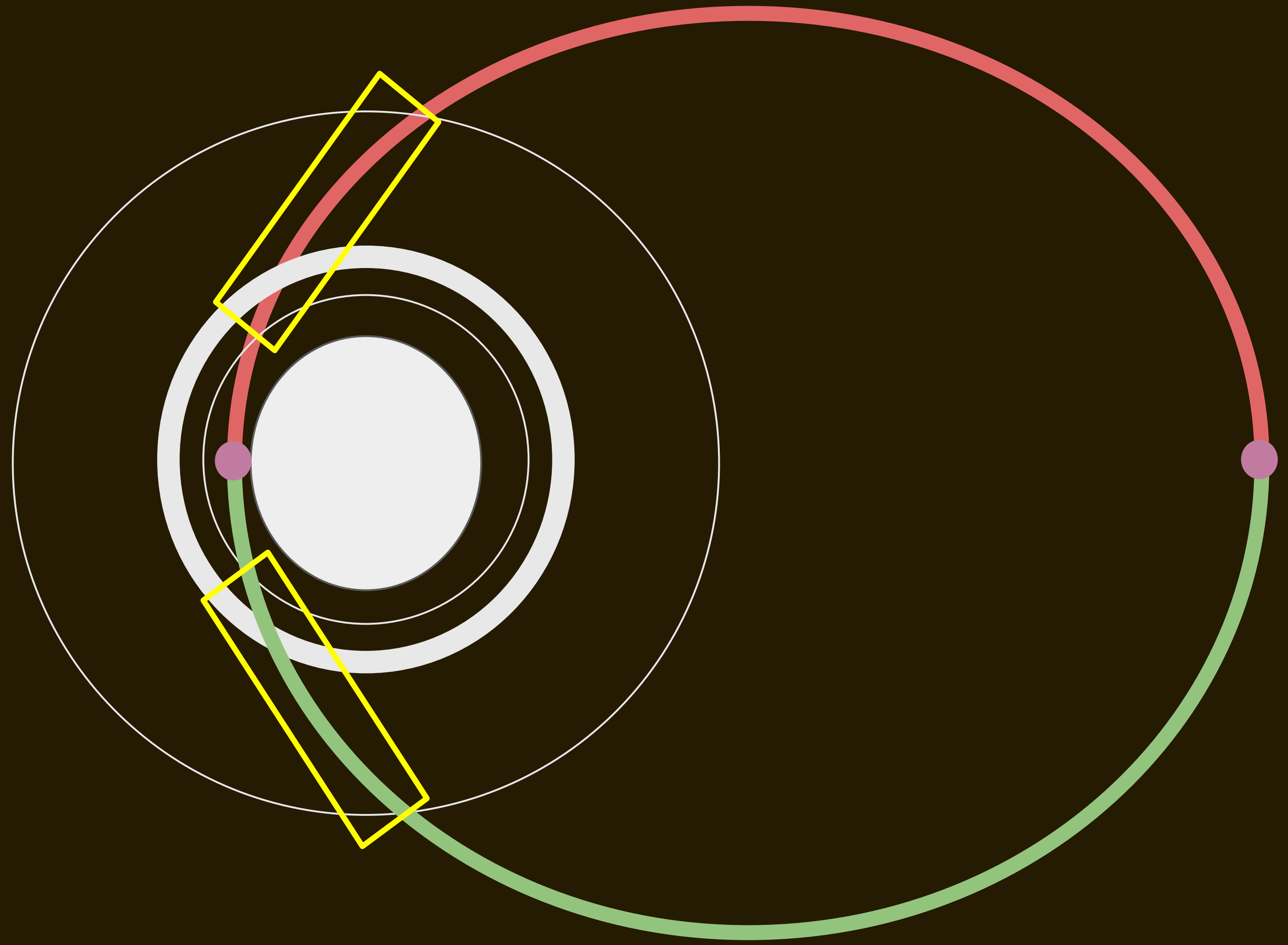
Above the ring plane (observable area)	Ring plane crossing in the gap	Below the ring plane (observable area)	Below the ring plane (no measurement area)	Ring plane crossing	Over the ring plane (no measurement area)
Aphelion: illuminated Perihelion: non-illuminated Smallest distance to the rings above the D-ring	In situ measurements. Cross section images	Perihelion: illuminated Aphelion: non-illuminated Smallest distance to the rings above the D-ring.	Communication mode	Communication mode Outer side of the rings.	Communication mode

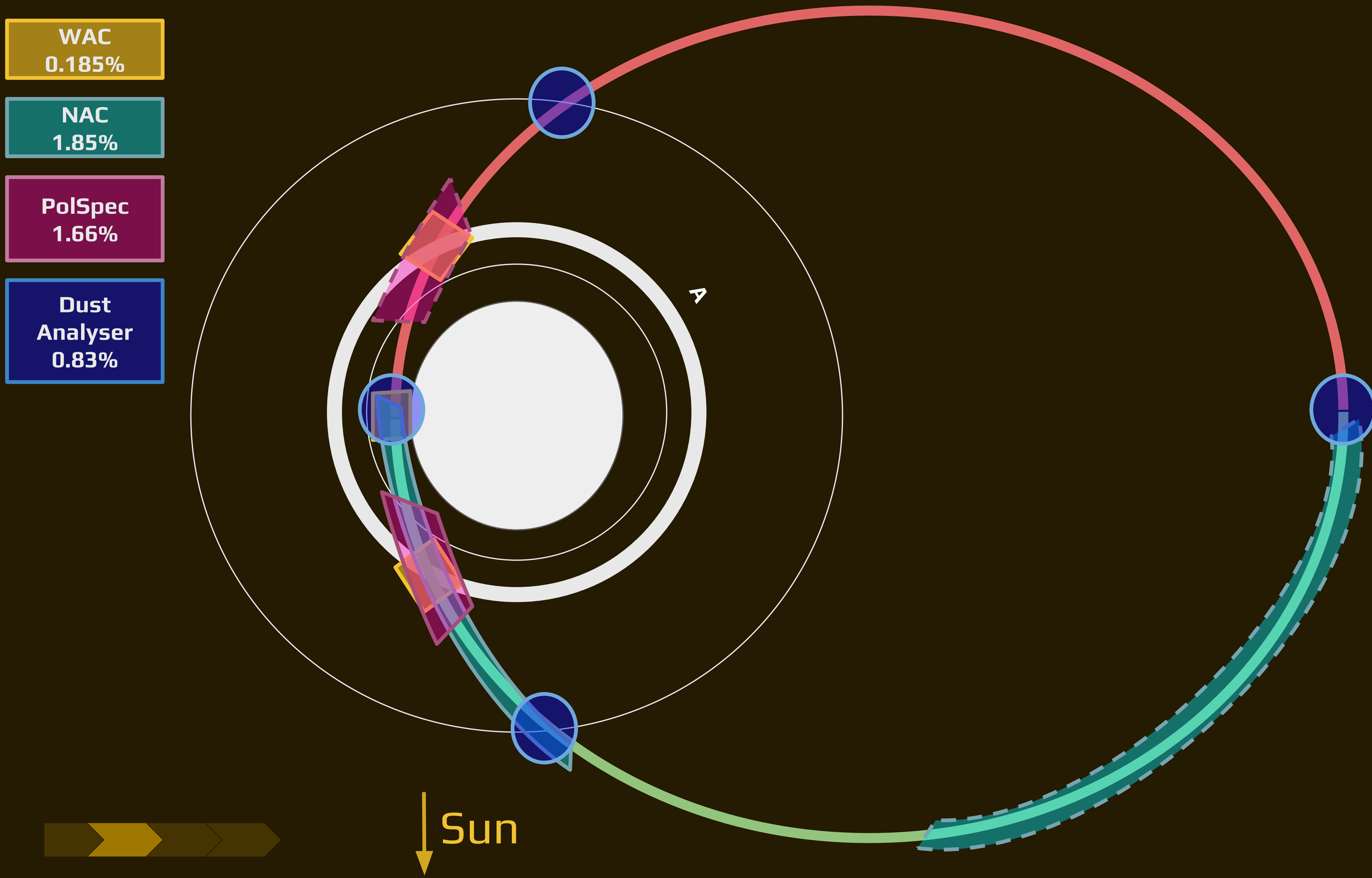
Science Phase - Instrument Operations

	Observation Phase						
Instrument	**Above the ring plane** (observable area)	**Ring plane crossing in the gap**	**Below the ring plane** (observable area)	**Below the ring plane** (non-observable area)	**Ring plane crossing**	**Over the ring plane** (non-observable area)	**COMMENT**
Narrow Angle Camera (200-1100 nm)	X	X	X	*	X	*	Requires sun illumination for operation. * Outreach images
Wide Angle Camera (300-1000 nm)	X	X	X				Can aid startracker.
Radio Science Experiment (comms system, Ka-band) 10 mm to 10 cm	X	X	X	X	X	X	Dependent on Earth's position
Magnetometer	X	X	X	X	X	X	
Dust analyser (Mass Spectrometer)	X	X	X	X	X	X	
SPEXone polarimeter	X	X	X	X	X	X	

Science Phase - Operational Phases

- Observable area
- Over the ring plane
- Below the ring plane
- Crossing of the ring plane





Dust analyser can be used a all times.

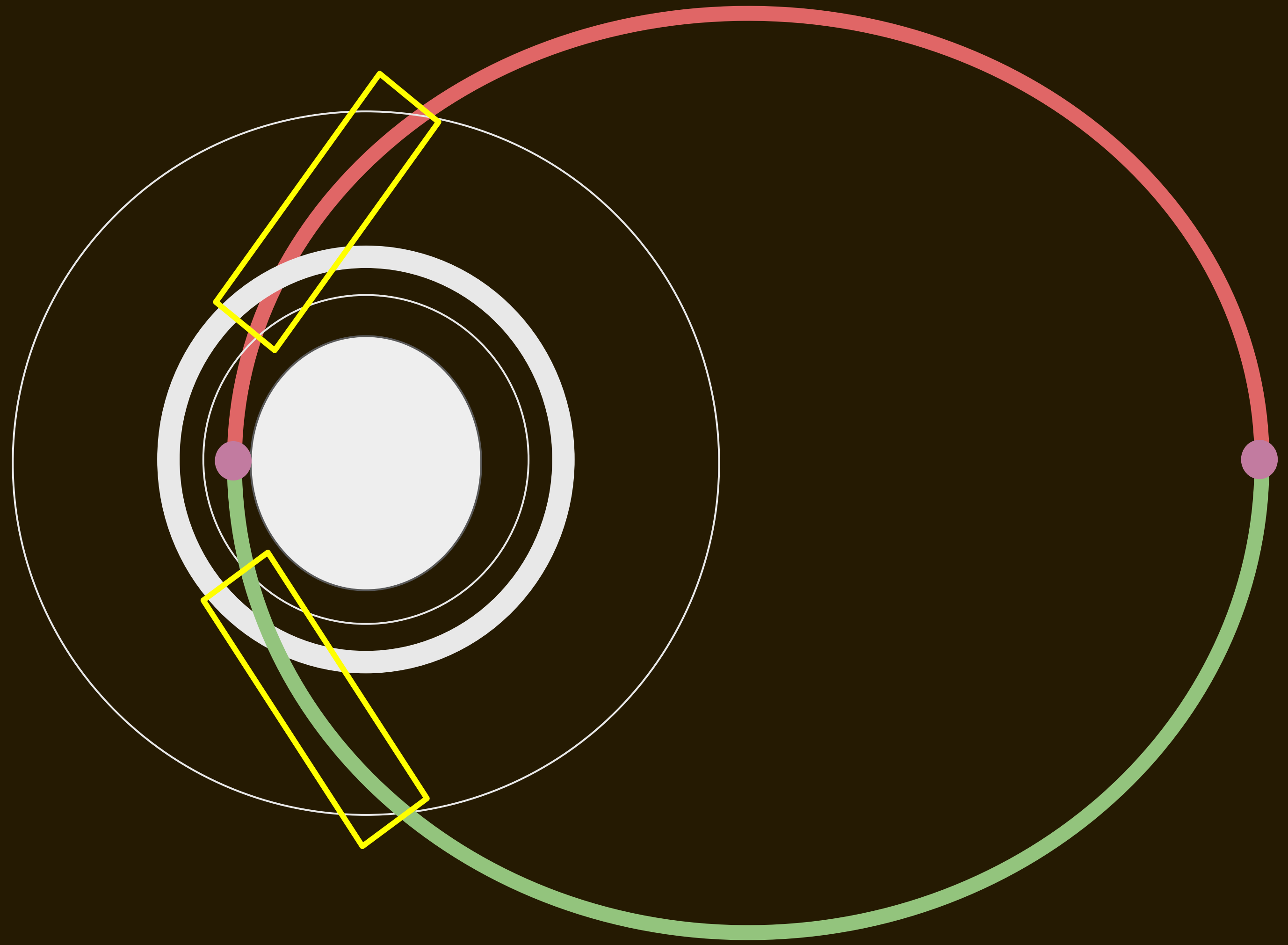
Magnetometer is on at all times (100%).

Radio Science Experiments are dependent of Earth's position.

Position	Earth year		
Pre- Perihelion	2001	2030.5	2060
Perihelion	2003	2032.5	2062
Post Perihelion	2005	2034.5	2064
Pre- Aphelion	2014	2044	2073.5
Aphelion	2017	2046.5	2076
Post Aphelion	2020.5	2050	2079

Orbit Design: Operating around Saturn

- Observable area
- Over the ring plane
- Below the ring plane
- Crossing of the ring plane



Timeline

2025 — 2027 — 2029 — 2033 — 2037 — 2041 — 2046

Phase 0 (2025)

Mission analysis and identification

Phase A (2027)

Feasibility studies

Phase B (2029)

Preliminary definition

Phase C (2033)

Detailed definition

STM and EMI

Test and validation

Phase D (2037)

Qualification and production

CDR

Building flight model

Assembly integration and testing

Set date for launch

Phase E (2041)

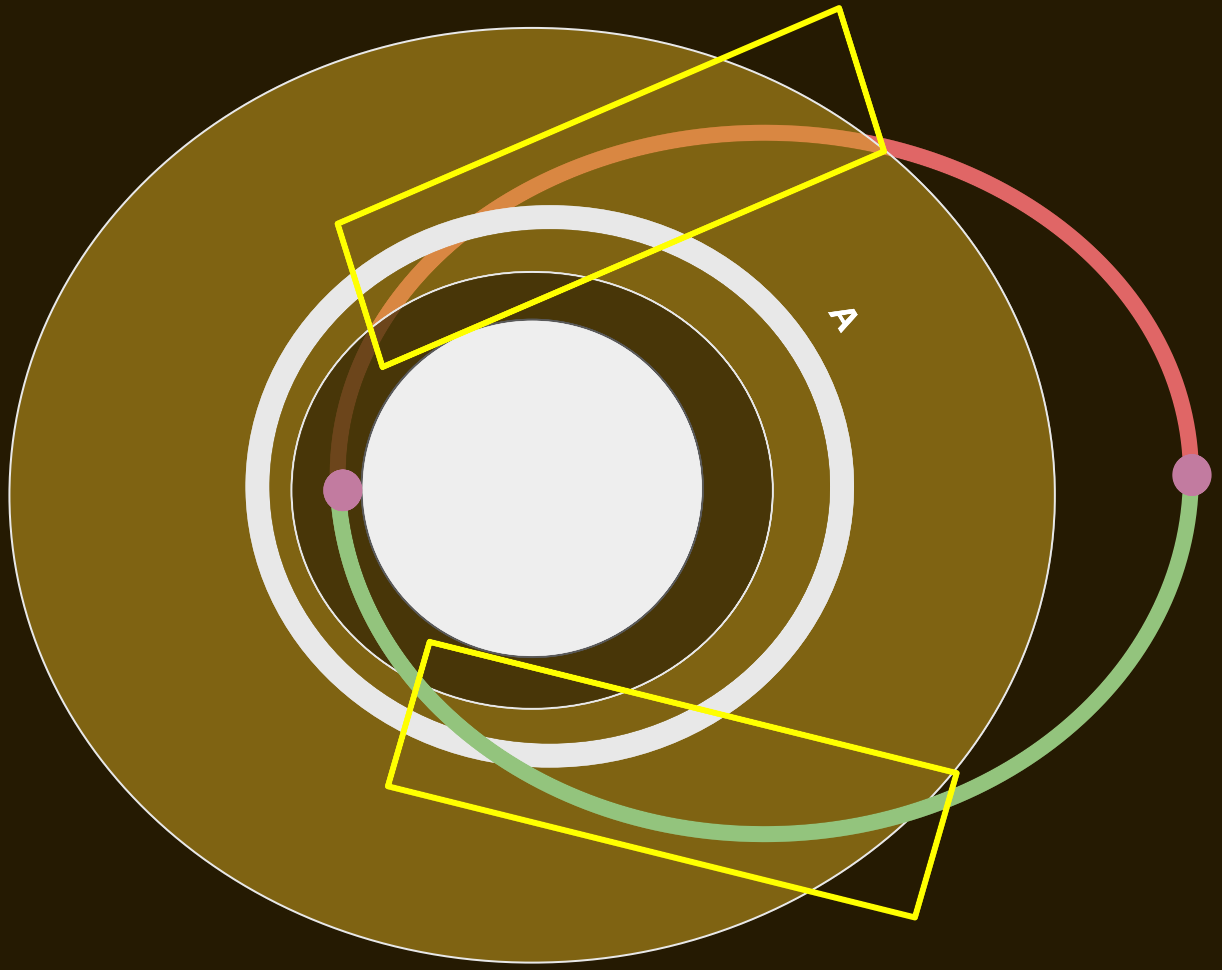
Operations phase (ConOps)

launch to operation

Concept of Operations: Orbit

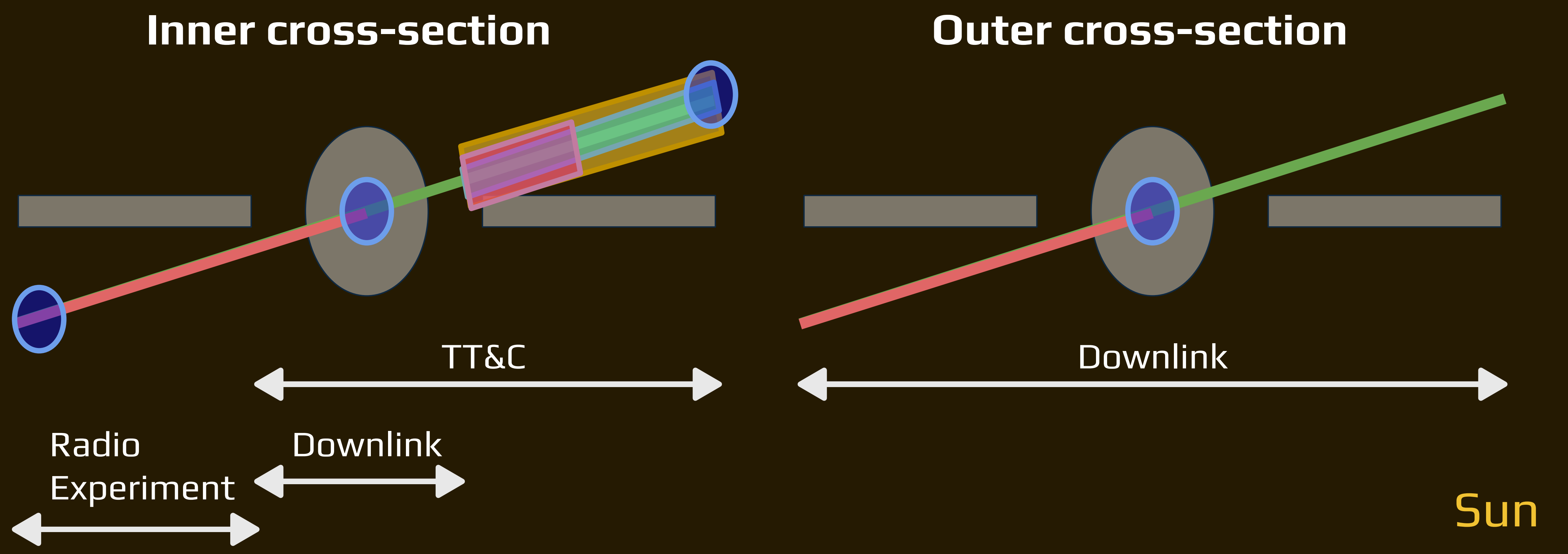
unsure, fix

- Observable area
- Over the ring plane
- Below the ring plane
- Crossing of the ring plane

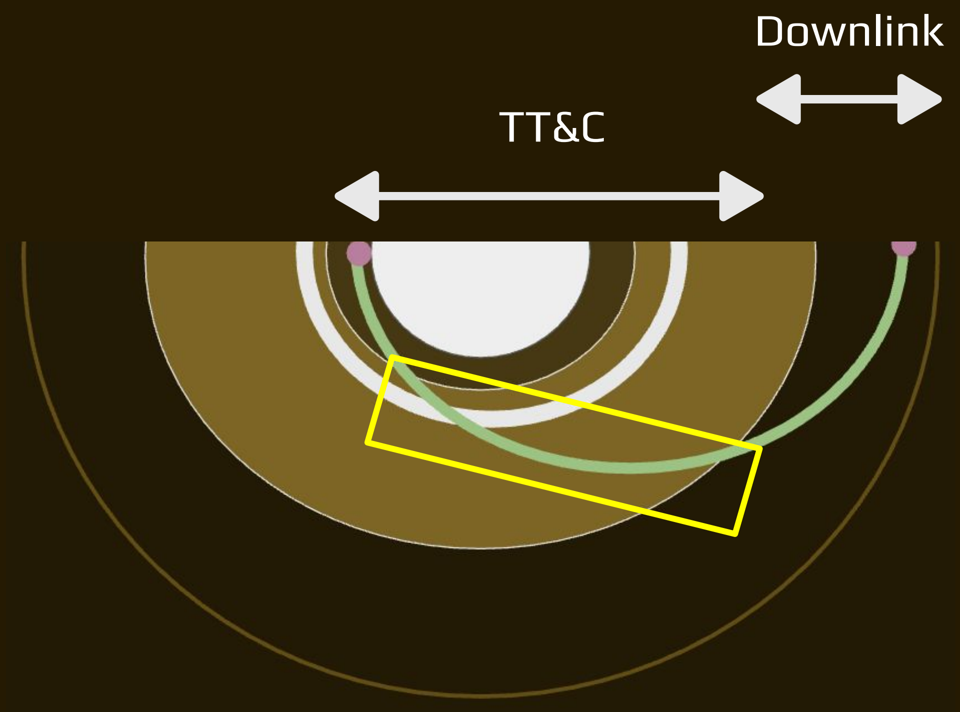


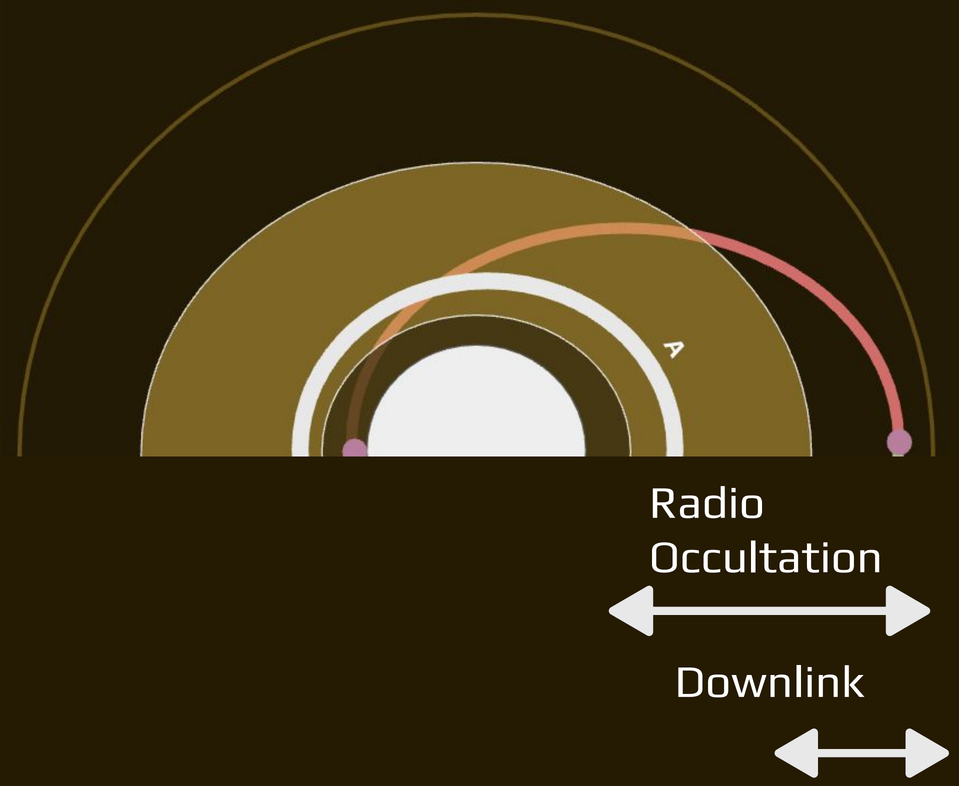
Sun Earth

Concept of operation: Science phase



Concept of operation: **Science phase**





Operational Modes **Science**

Scanning

goal: cover as much area as possible

Nominal image acquisition:

- **WAC** - 100% over illuminated rings
  - Stereo mode
  - 2 fps
- **NAC** - Sample observable are randomly characterise the ring surface
  - Stereo mode
  - 5 fps

Operational Modes: **Science**

Tracking

Focus on propellant moonlets

- **WAC** - Keep pointing on “track point” for 5-8 s.

- NAC -

Opportunistic Science

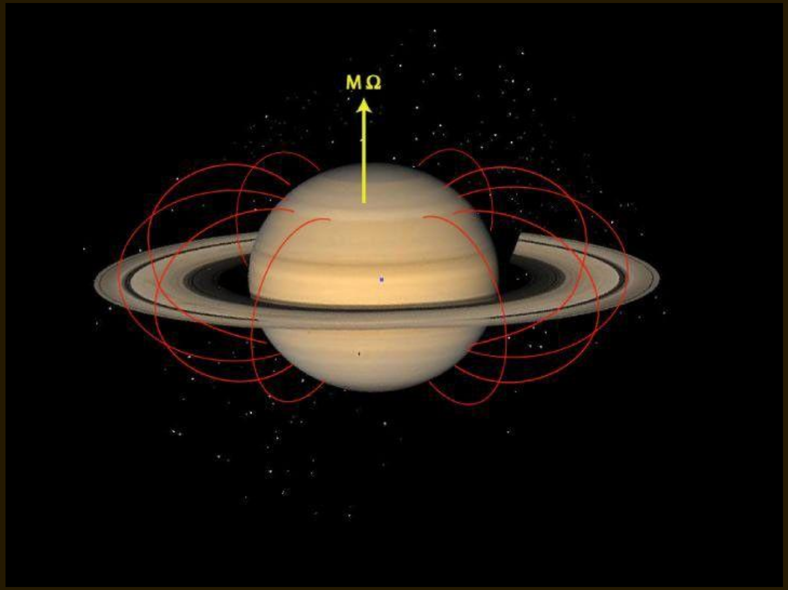
Science Objective	Sub Objectives
OS: Inspect small-scale variations in Saturn's exterior.	OS-1: Investigate small-scale variations in Saturn's **magnetic field**.
	OS-2: Study density variations in Saturn's **uppermost atmosphere**.

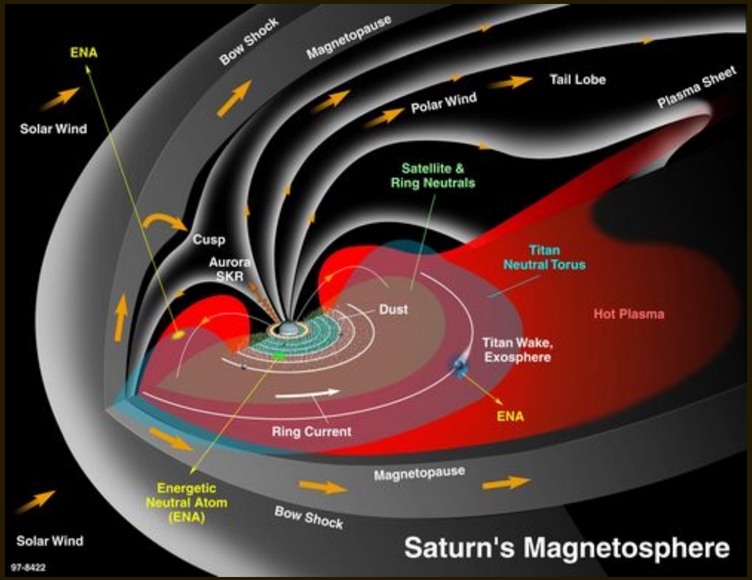
Opportunistic Science: Inspect small-scale variations in Saturn’s exterior.

OS-1: Investigate small-scale variations in Saturn’s magnetic field.

- Measure **high orders and degrees** of **Saturn’s external field**

10s of pt resolution

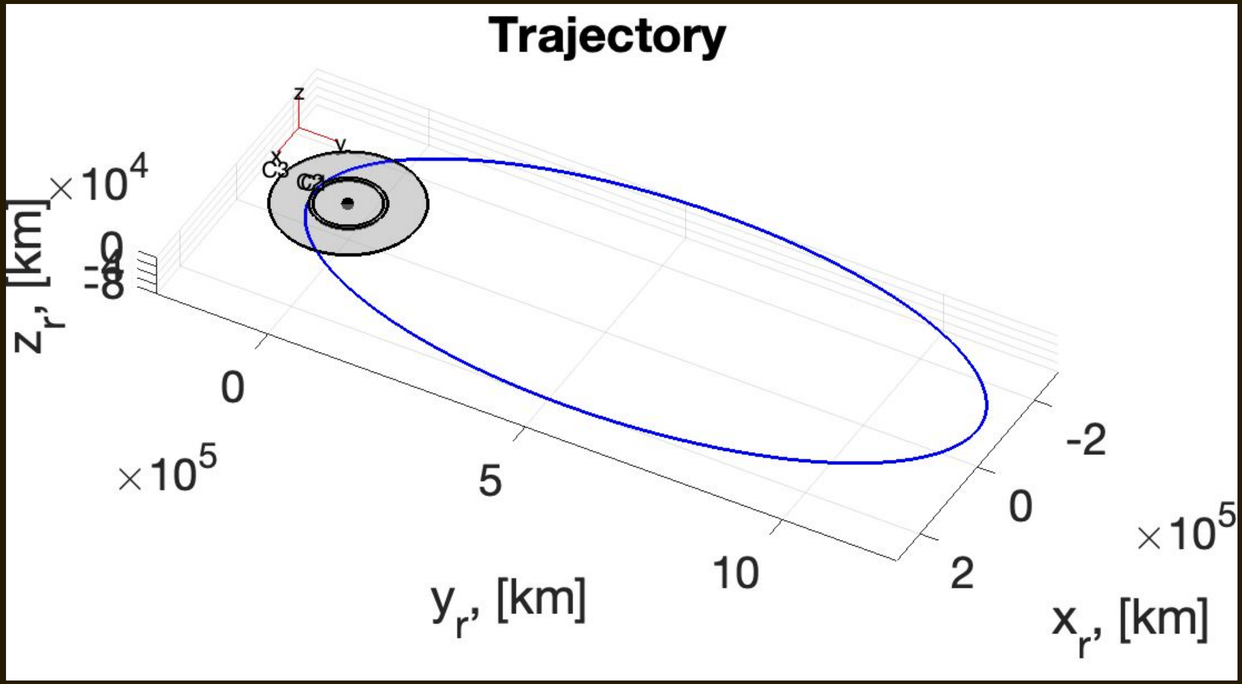




Orbit design: **Operating around Saturn**

Insertion orbit:
- Apogee at Titan
- Perigee in the gap
- Inclination 0.006 deg

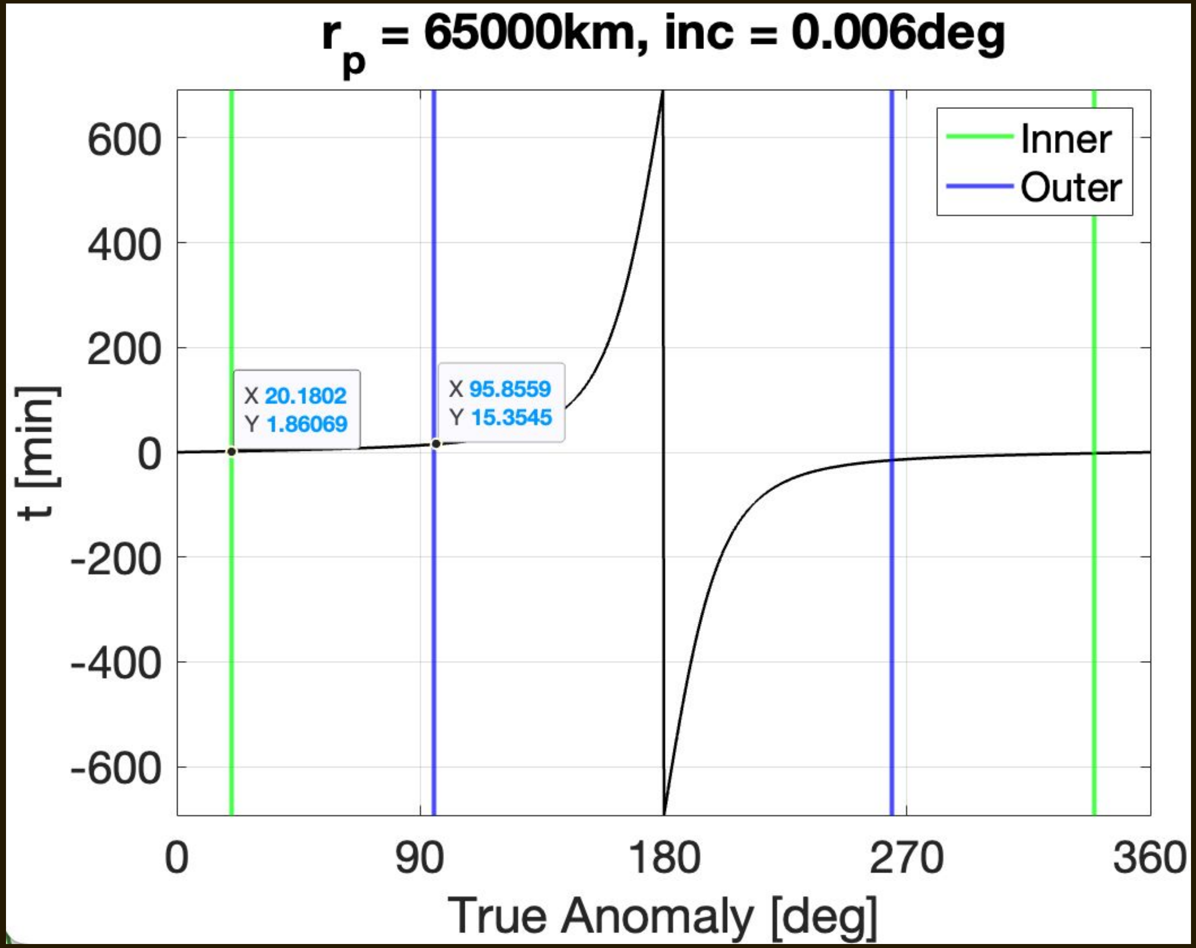
NOT GOOD ENOUGH!



Orbit design: **Operating around Saturn**

Insertion orbit:

- 10 km observation window
- Period = 23 h
- Obs time = 7 min
- Coms time = a lot
- Relative velocity = 13 km/s



We need to lower apogee! -> Aerobraking

Subsystem

- Requirement
- Budget
- TRL

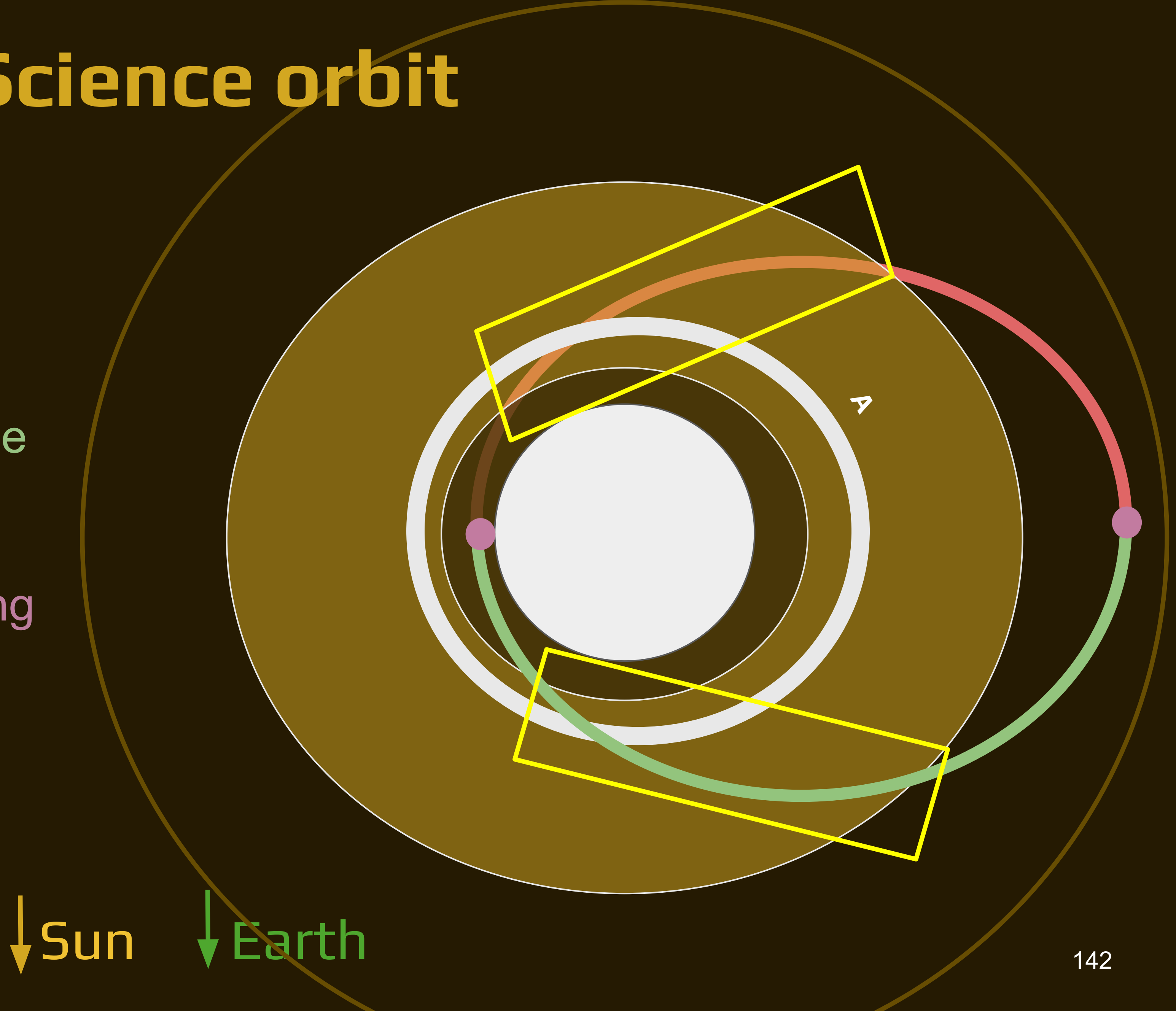
Subsystems: Control & Data Handling - Storage

- **Burst Bank**: A fast cache for large and fast instruments. RAID-1 for redundancy
- **Temp Bank**: A mid-speed buffer for less strained data, no redundancy as burst can operate backup
- **Bulk Memory**: The long-term archive for all processed science data awaiting downlink - again RAID-1 redundant
- Progression in storage technologies mean they are significantly lighter than in previous missions.

Storage Tier	Capacity	Redundancy	SF Lanes	Sustained Write BW	Total Mass	TRL
Burst Bank	2 × 16 GB (mirrored)	RAID-1 (2 modules)	12 (2×6 lanes)	~37.5 Gbit/s	2 kg	5
Temp Bank	64 GB	None	4	~25 Gbit/s	2 kg	7
Bulk Memory	2 × 1 TB (mirrored)	RAID-1 (2 modules)	4 (2 lanes × 2)	~25 Gbit/s	8 kg	6

Orbit design: **Science orbit**

- Observable area
- Over the ring plane
- Below the ring plane
- Crossing of the ring plane



Orbit design: **ΔV and use of propellant over time**

Stage	ΔV (m/s)	Wx	Consumed mass (kg)	Propellent left (kg)
Pre launch			0	664
Earth to saturn	5372	0.68	470	194
Saturn orbital injection	180	0.93	62	132
Start Aerobraking	10	0.99	3	129
Aerobraking	5600		0	129
Cranking with titan	700		0	129
Science orbit injection	200	0.93	68	61
Rest of fuel used for Station keeping	423			61

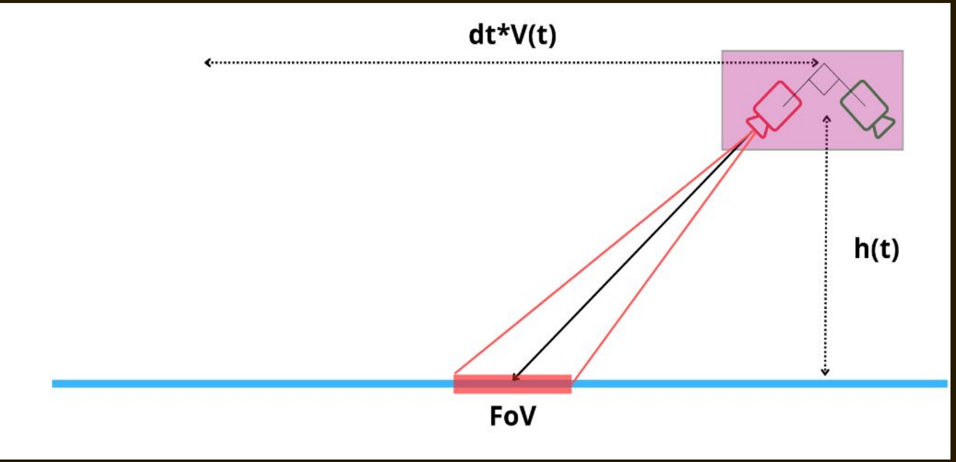
Using Xe

Bi-propellant
(MMH-N2O4)

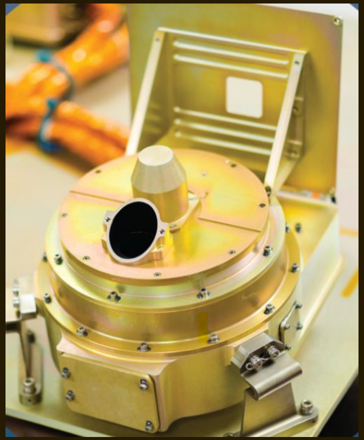
Instrumentation:
Wide Angular Cameras (WACs) Stereo System

Instrument Requirement:

- VIS range (280-900 nm)
- Pixel resolution 42 arcsec



Min. relative speed: 5 km/s @3.8 km
Max. relative speed: 7.65km/s @10 km

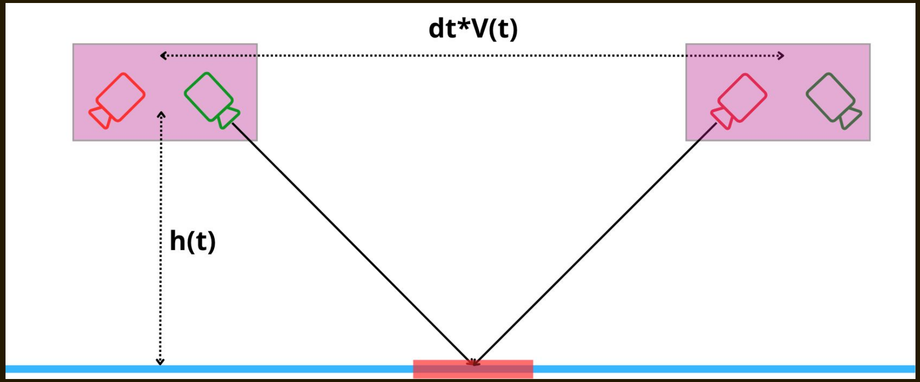


Offset dt 0.8 - 2 s

Optic	20 mm F/3.5
FoV	5.6 deg
Pixel res.	41 arcsec
Sensor	CCD 1024x1024 pixels
fps	20
Mass	2.68 kg each
Size	100x100x50 mm
Power	25 W each
TRL	7 (adaptation of SamCam, OSIRIS-REx mission)

Instrumentation:

Narrow Angular Cameras (NACs) Stereo System

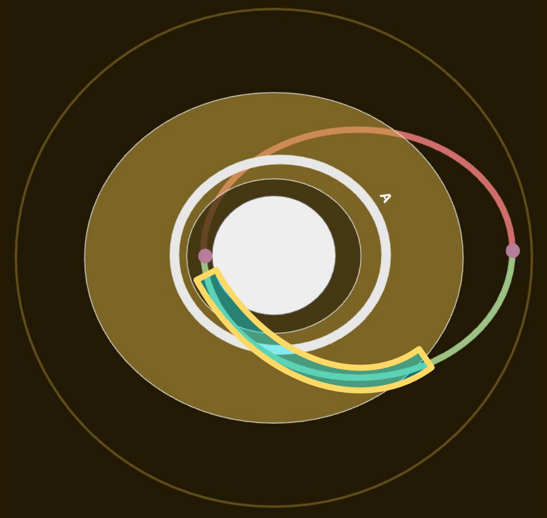


Optic	203 mm F/3
FoV	3.16 deg
Pixel res.	2.78 arcsec
Sensor	CMOS, 4046 x 4096 pixels
fps	30
Mass	9 kg each
Size	330x350x500 mm each
Power	32 W each
TRL	7 (adapted PolyCam, OSIRIS-REx mission)

Instrument Requirement:

- VIS band (280-900 nm)
- Pixel resolution 2.8 arcsec

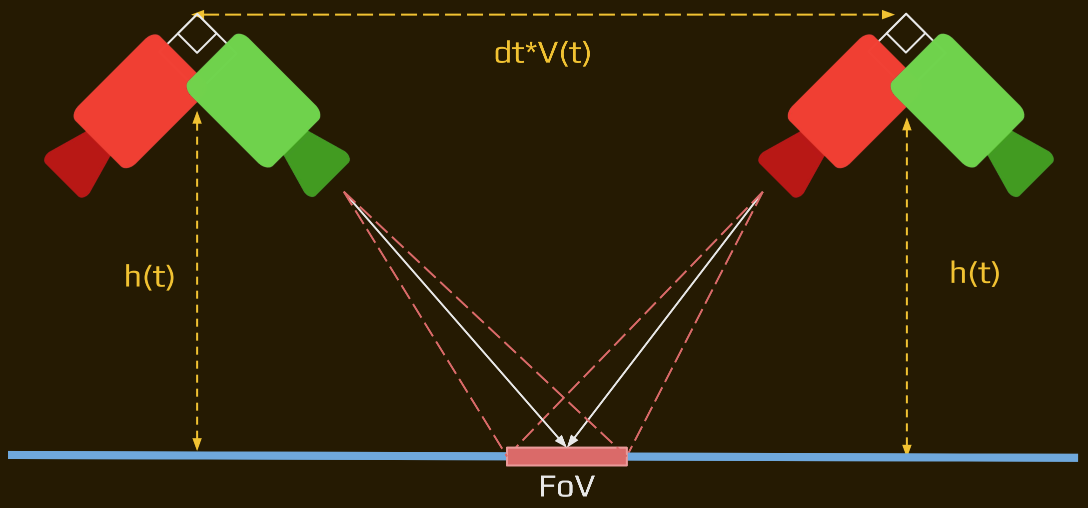
ConOps: **Science Mode**

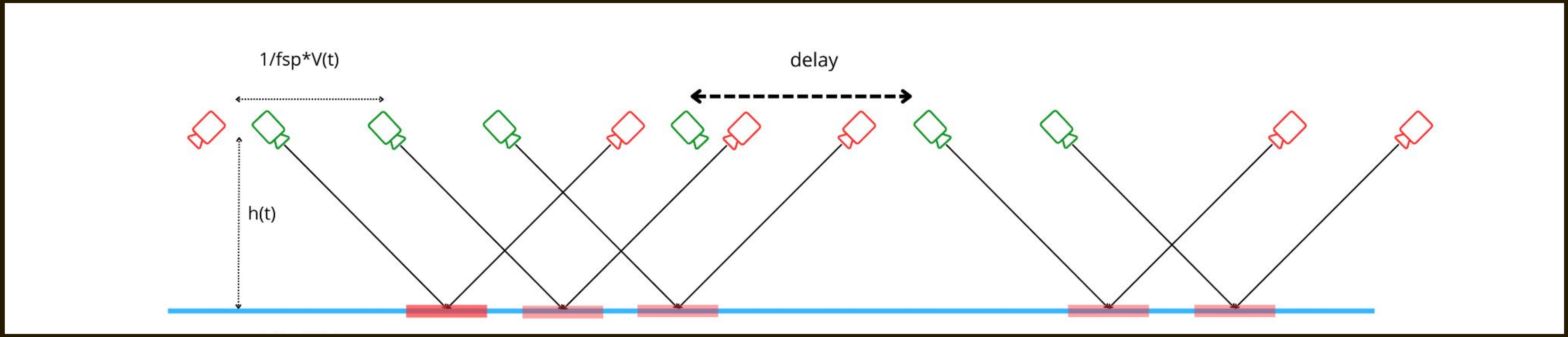


SCANNING

WACs

NACs





Risk Assessment

	Very unlikely to happen	Unlikely to happen	Possibly could happen	Likely to happen	Very likely to happen
Catastrophic consequences	Separation with launcher failure Gravity assist fails RTG failure	Collision with ring bodies AODCS failure	Shield failure Atmospheric modeling errors		
Significant consequences	Orbit Insertion failure	Communication loss Instruments failure	TRL delay Missed launch window	Particle collision	
Moderate consequences		Component failure	Degradation of the mirror surface	Higher throughput	Single event upset
Low consequences			Dust contamination on camera lens	Loss of expertise	Unexpected costs
Negligible consequences					

SAURON

ALPBACH SPACE AGENCY