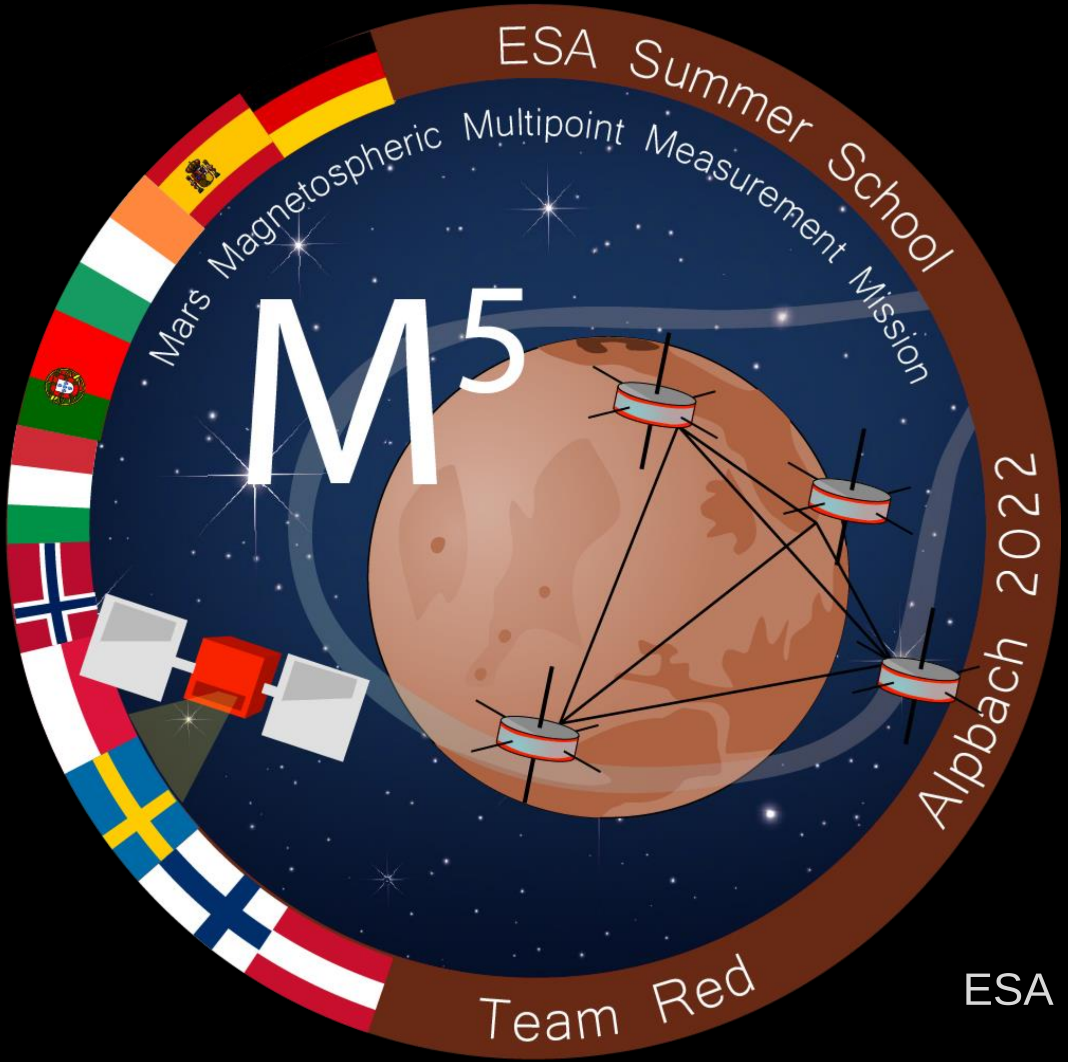


Red Team: M5

Mars
Magnetospheric
Multipoint
Measurement
Mission

ESA Summer School, Alpbach 2022

Science Motivation

Science Case

Systems Engineering

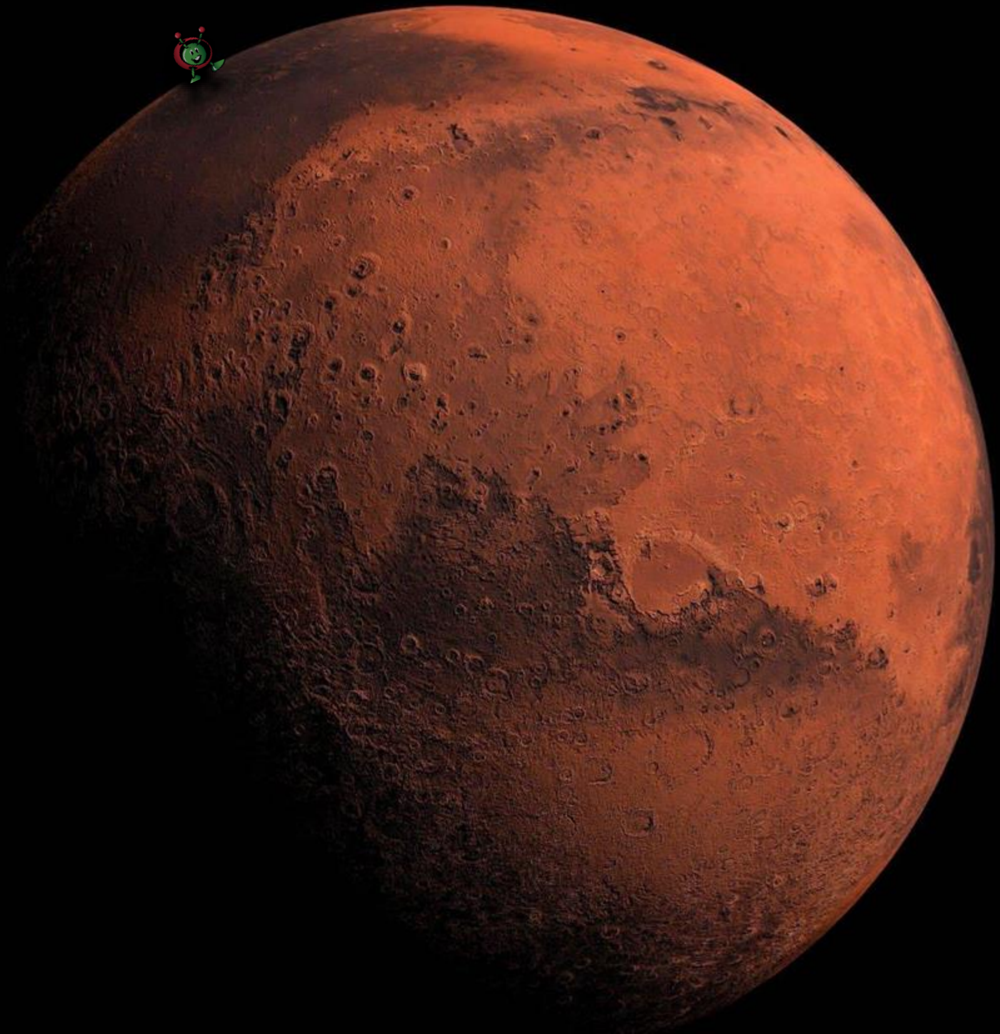
Programmatics

Sara Östman

Leonard Schulz

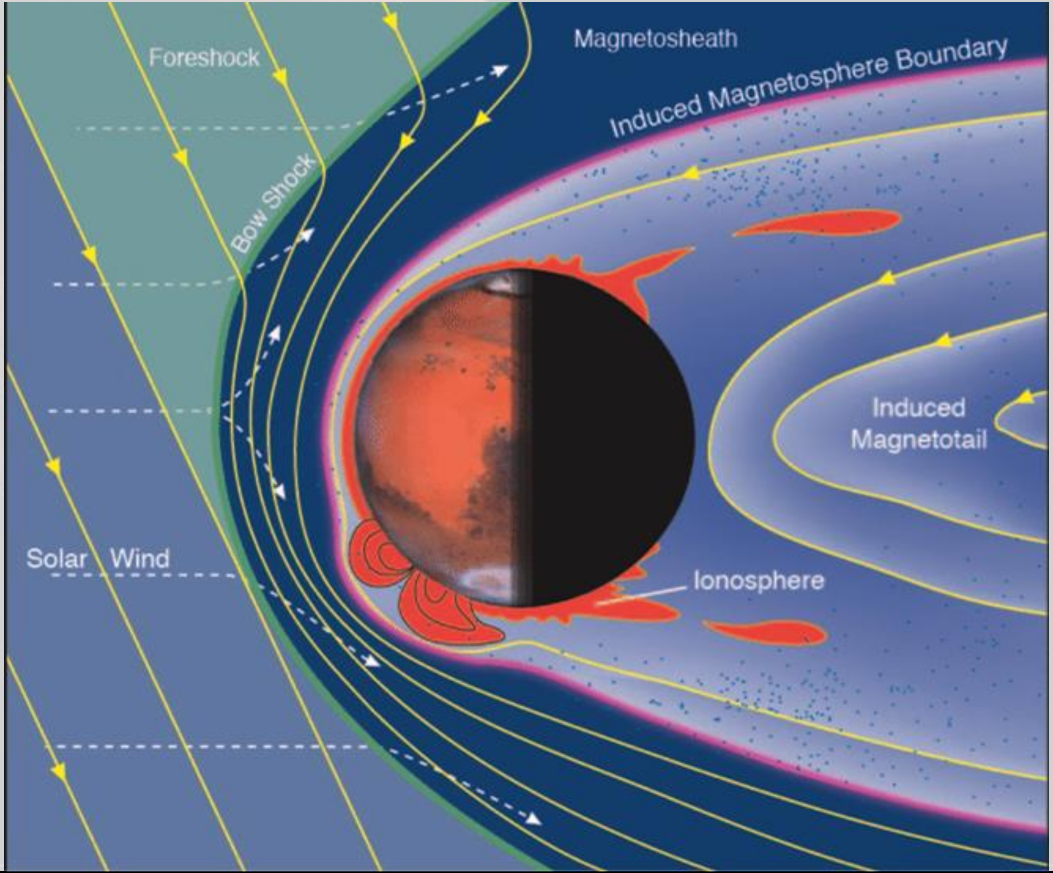
Ville Lundén

Cormac Larkin



Our target

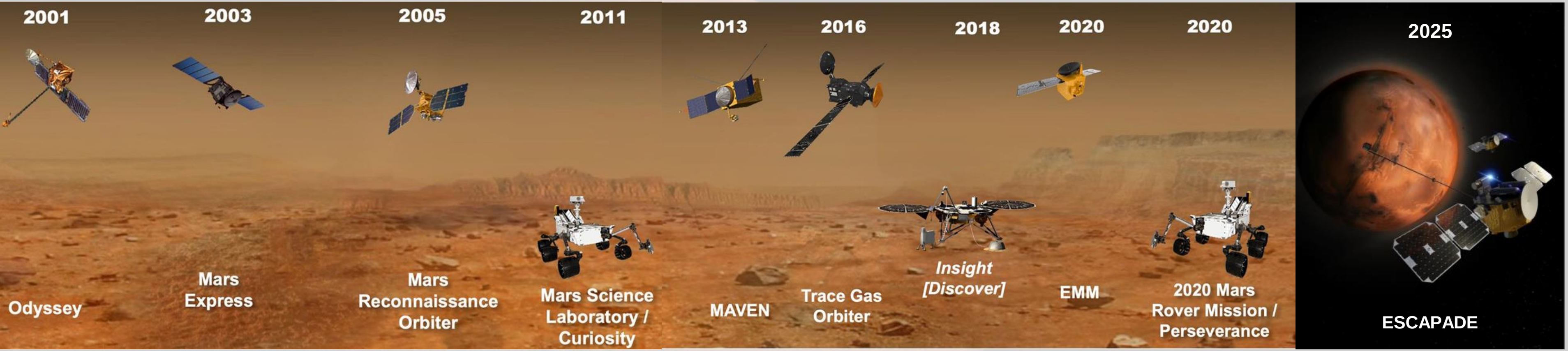
The Martian Magnetosphere



Mars magnetic reconnection: Harada Y., et. al.. (2018)

Figure: Grandin, Maxime. (2017)

We are not the first

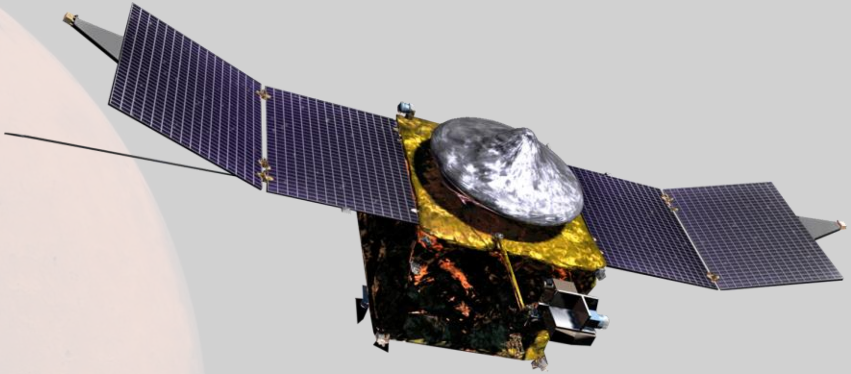


Looking for water	Atmospheric escape
Surface study for human space exploration	Communication relays
Looking for bio-signatures	Plasma

MAVEN & EscaPADE Missions

MAVEN

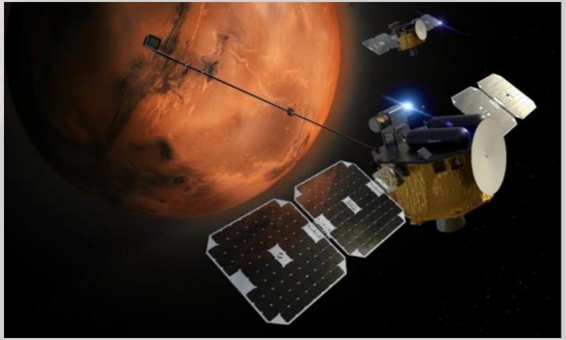
- Atmospheric loss
- Single S/C



Images: NASA

EscaPADE:

- Hybrid magnetosphere, collisional atmosphere, and energy transport.
- Double S/C



What we Don’t Know and why it’s Important

How does the magnetosphere change with **solar wind conditions**?

- To know how the atmosphere evolves over time, we need to know how it changes with changing solar wind conditions
- To protect people and technology, we need to know how the system responds to different conditions

What is the energy transport across **different scales** in the Martian environment?

What does the Martian **magnetotail** region look like?

What we Don't Know and why it's Important

How does the magnetosphere change with **solar wind conditions**?

What is the energy transport across **different scales** in the Martian environment?

- Energy transport processes in space plasmas span different spatial and temporal scales, and are vital to understanding the dynamics of the complete system

What does the Martian **magnetotail** region look like?

What we Don’t Know and why it’s Important

How does the magnetosphere change with **solar wind conditions**?

What is the energy transport across **different scales** in the Martian environment?

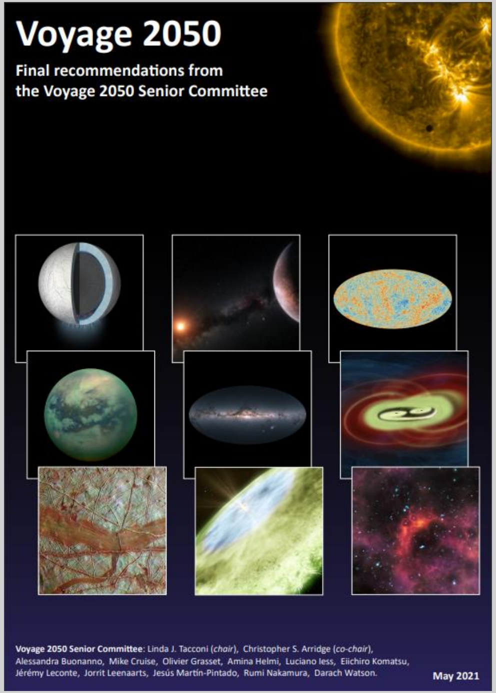
What does the Martian **magnetotail** region look like?

- The solar wind transports energy to the magnetosphere in the tail region
- Mass is transported away from the Martian system at the tail
- We don’t know whether magnetic reconnection occurs in the magnetotail, which would vastly change the dynamics of the tail and the whole system

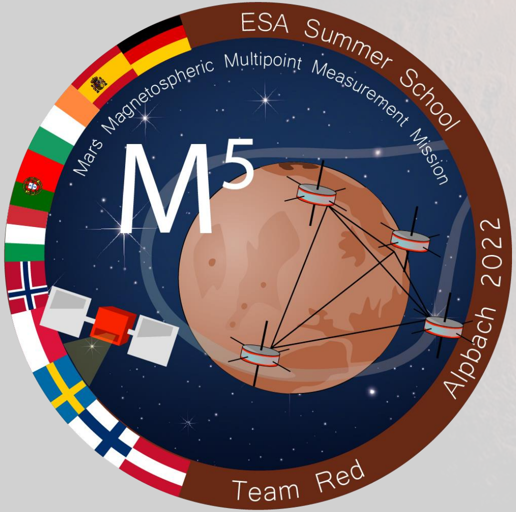
… and we are not the Only Ones who Think so

ESA Voyage 2050 Senior Committee Report:

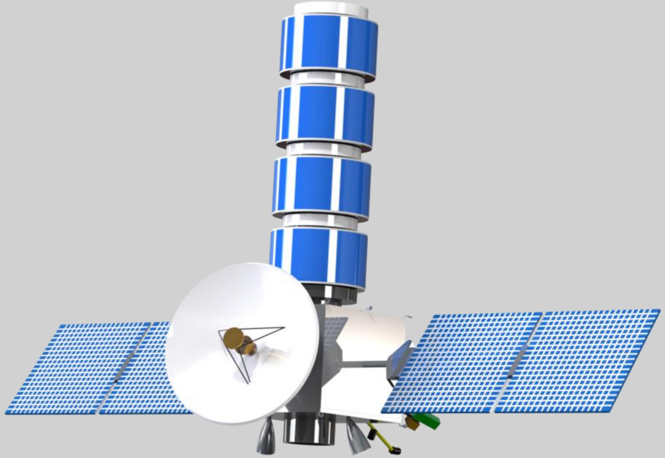
- "The key difficulty in understanding the plasma energization lies in the two-way nature of the **intrinsic multiscale physics** of plasmas: processes on the large scales affect the small-scale physics and processes on the small scales affect the large-scale evolution of plasmas."
- "[...] planetary objects such as **Mars**, Jupiter, and comets enable the study of different types of magnetospheric interaction, including interactions with induced magnetospheres. It further addresses fundamental questions of **planetary evolution** such as atmospheric escape over geological time scales."
- "[...] relevant to Mars' environment in the Voyage 2050 era in relation to **astronaut safety** and the protection of space infrastructure in Mars orbit."



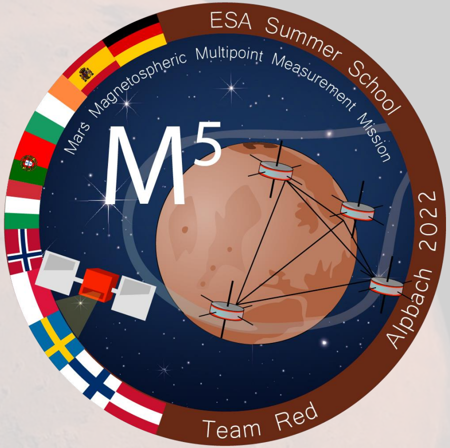
Scientific Theme



"Understand how the variable solar wind conditions influence the dynamics and energy transport of the Martian induced magnetosphere."



Science Questions



Q1: How do the Martian magnetospheric system's **structure** and **dynamics** depend on **solar wind** conditions?

Q2: How is **energy transported** within the Martian magnetospheric system on ion scales and above?

Science Motivation

Science Case

Systems Engineering

Programmatics

Sara Östman

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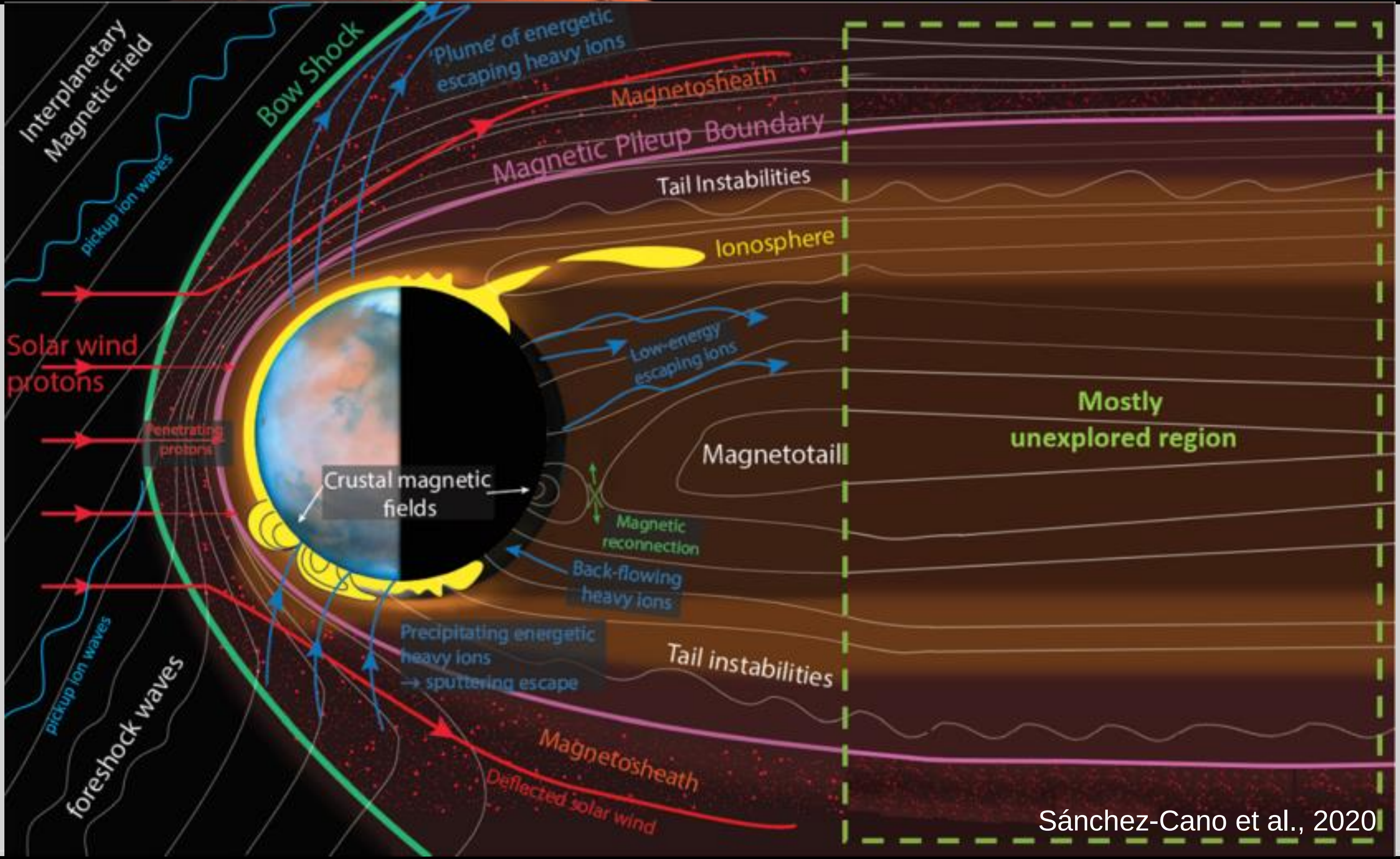
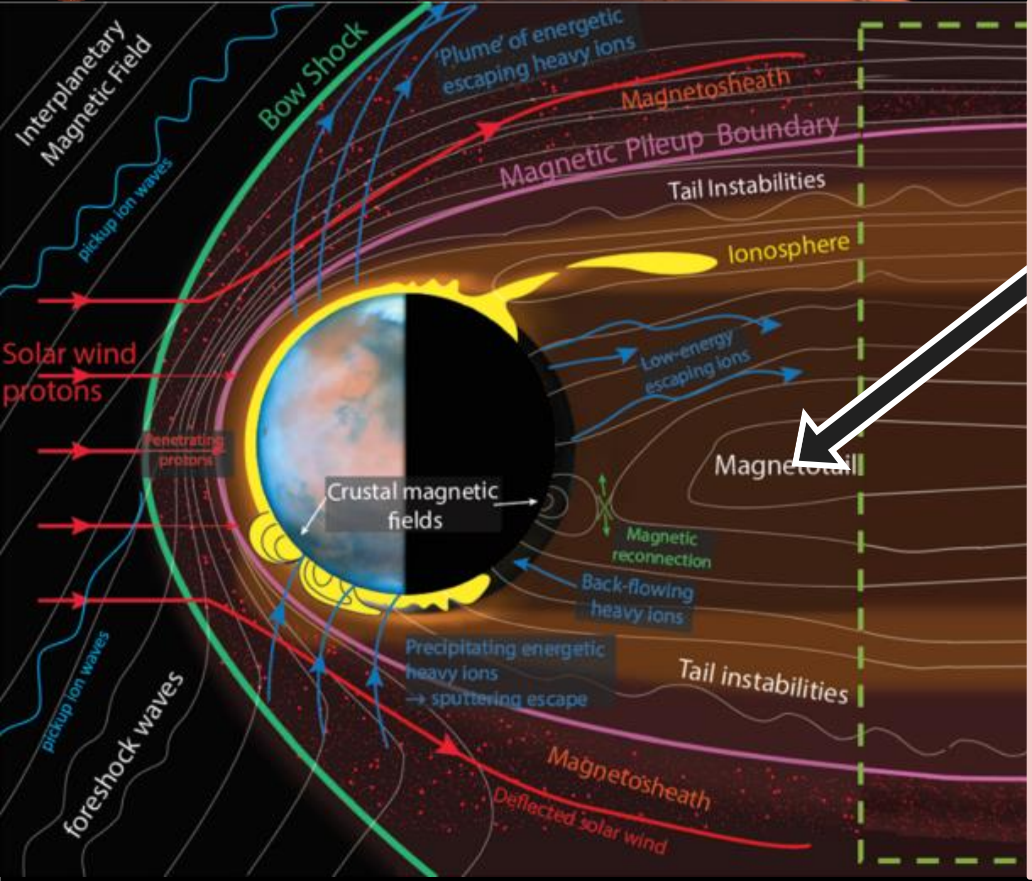
Science Questions and Objectives

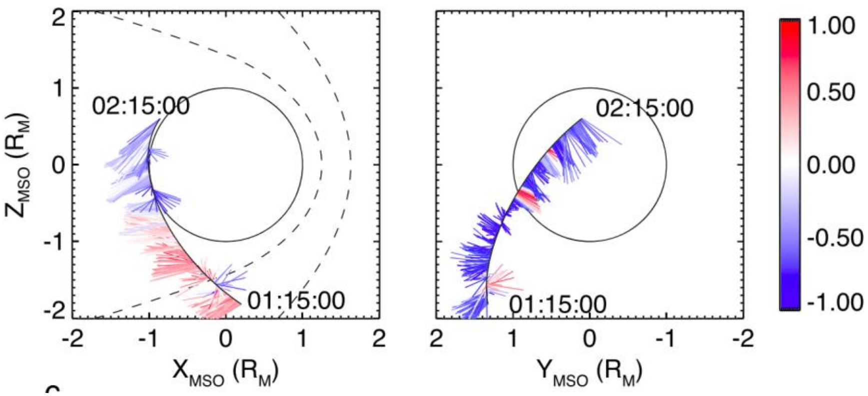
Primary Science Questions	Science Objectives
Q1: How do the Martian magnetospheric system's **structure** and **dynamics** depend on **solar wind** conditions?	• O1.1: What are the dynamics and orientation of **boundary** regions, with particular interest for their dependence upon solar wind conditions? • O1.2: What is the structure of the Martian **magnetotail** on different scales, with particular interest for its dependence upon solar wind conditions? • O1.3: What is the dynamical structure of the **current system** in the Martian magnetosphere, with particular interest for its dependence upon solar wind conditions?
Q2: How is **energy transported** within the Martian magnetospheric system on ion scales and above?	• O2.1: Is magnetic **reconnection** observed in the magnetosphere tail, and if so, where and how? • O2.2: What are the direction and temporal evolution of low frequency plasma **waves**?

Structure of Martian Induced Magnetosphere



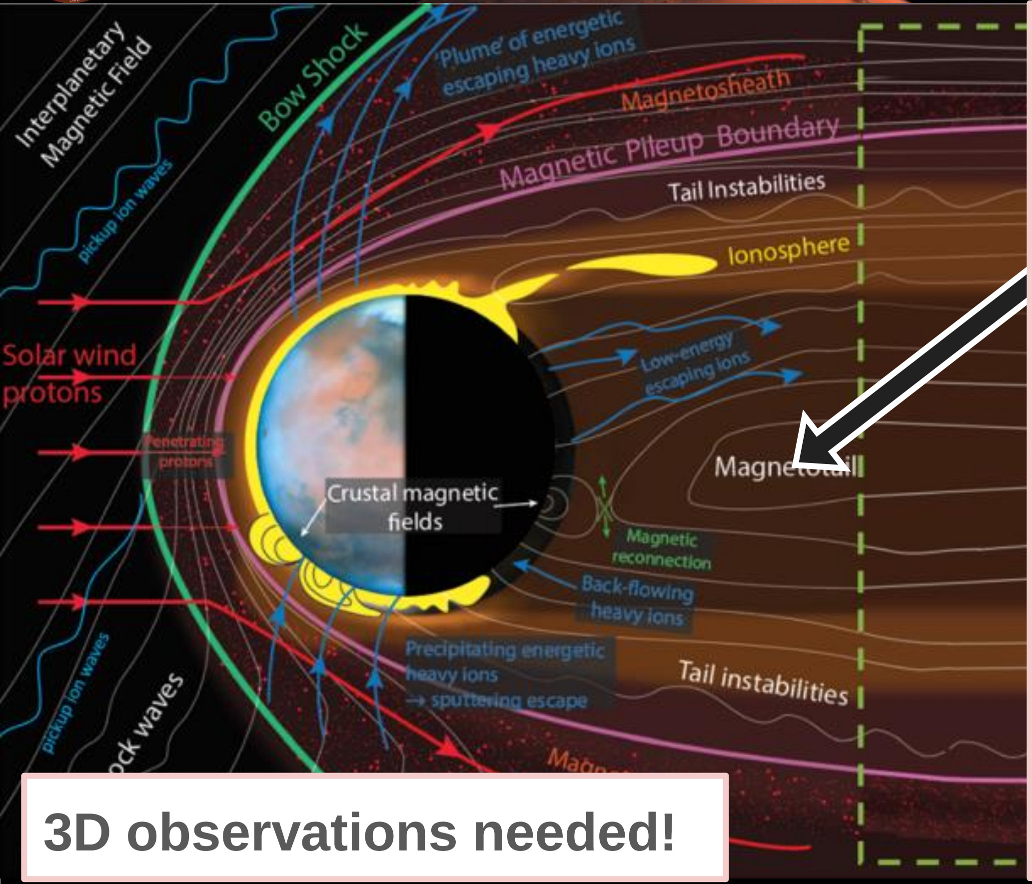


O1.1: What is the **structure of the Martian magnetotail** on different scales, with particular interest for its dependence upon solar wind conditions?



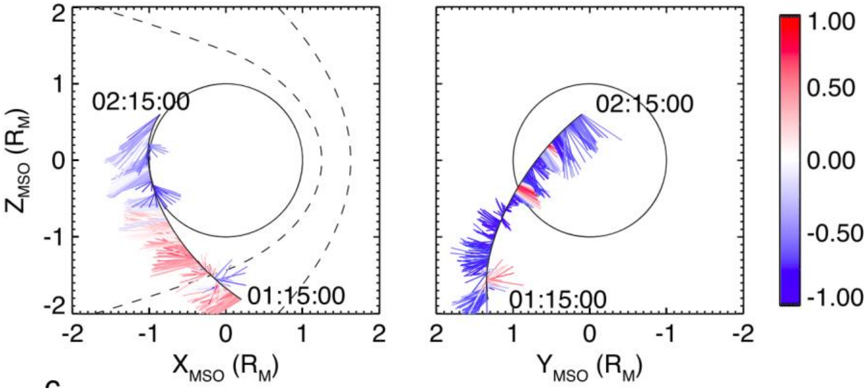
DiBraccio et al., 2017

Sánchez-Cano et al., 2020



3D observations needed!

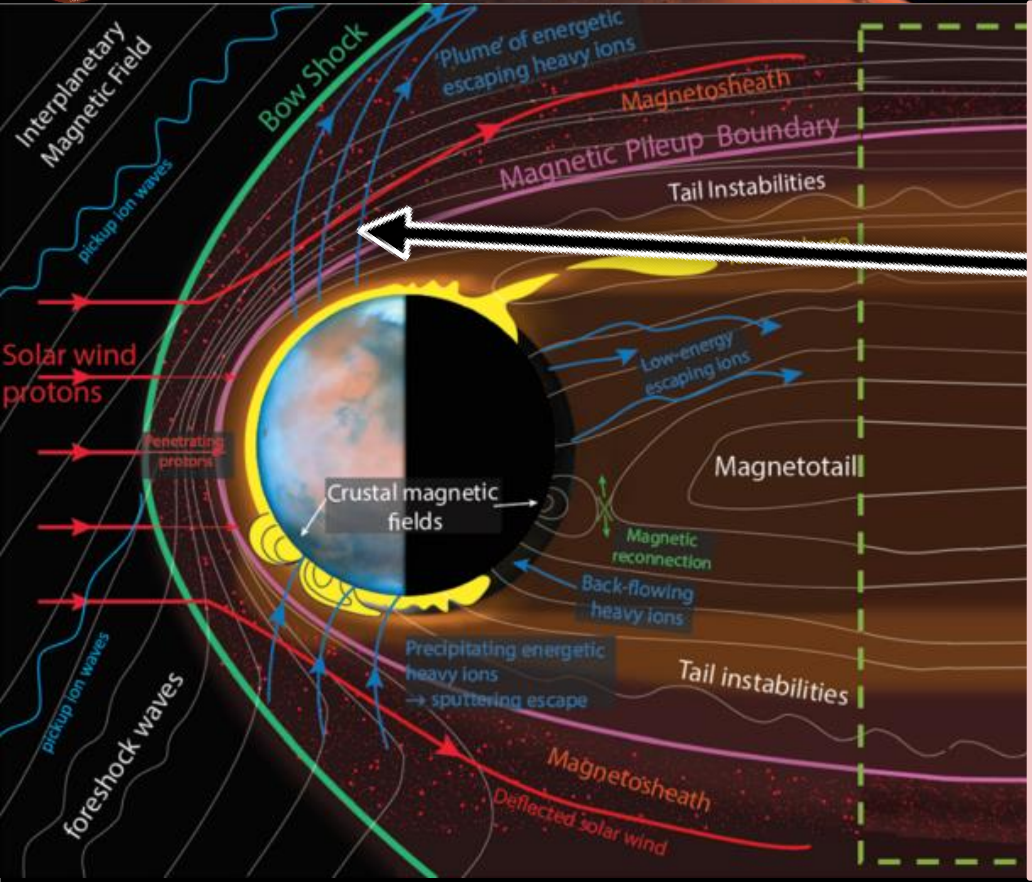
O1.1: What is the **structure of the Martian magnetotail** on different scales, with particular interest for its dependence upon solar wind conditions?



DiBraccio et al., 2017

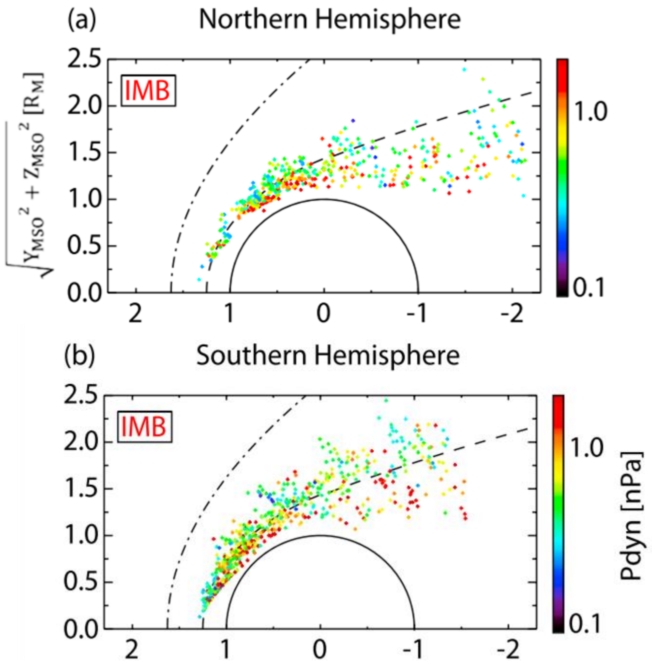
Sánchez-Cano et al., 2020

SQ1: How do the Martian magnetospheric system's structure and dynamics depend on solar wind conditions?



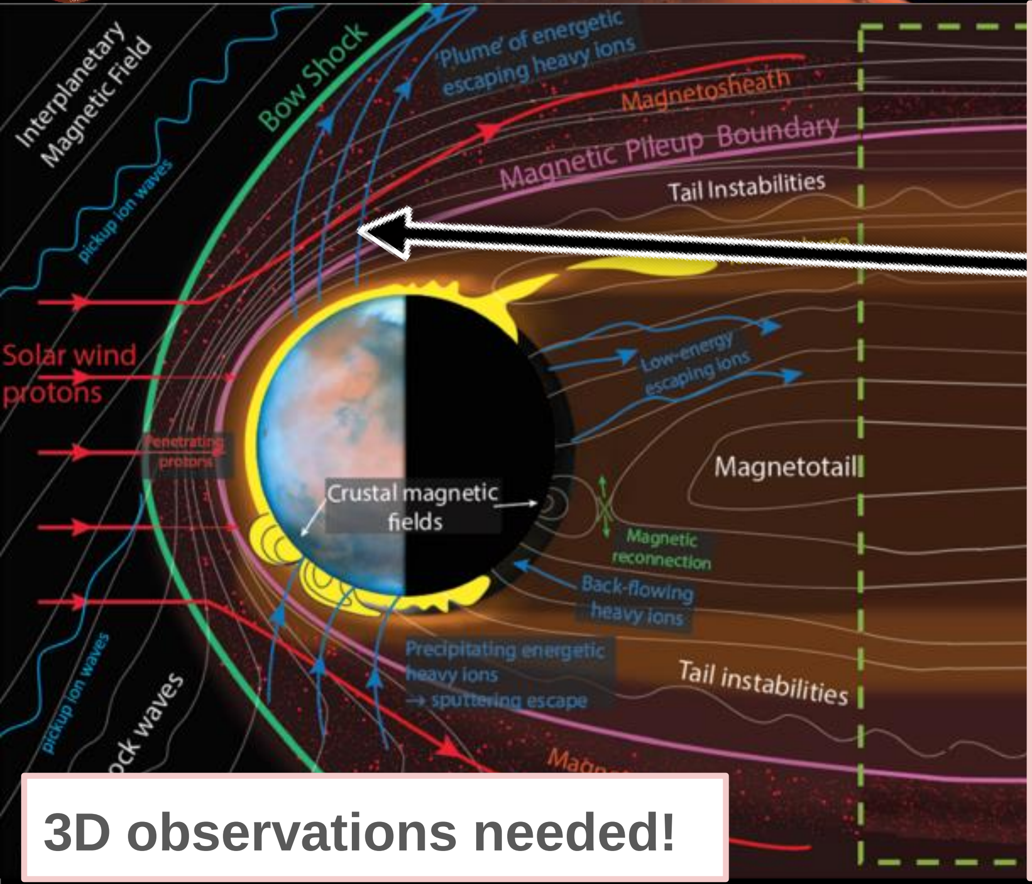
Sánchez-Cano et al., 2020

O1.2: What are the dynamics and orientation of **boundary regions**, with particular interest for their dependence upon solar wind conditions?



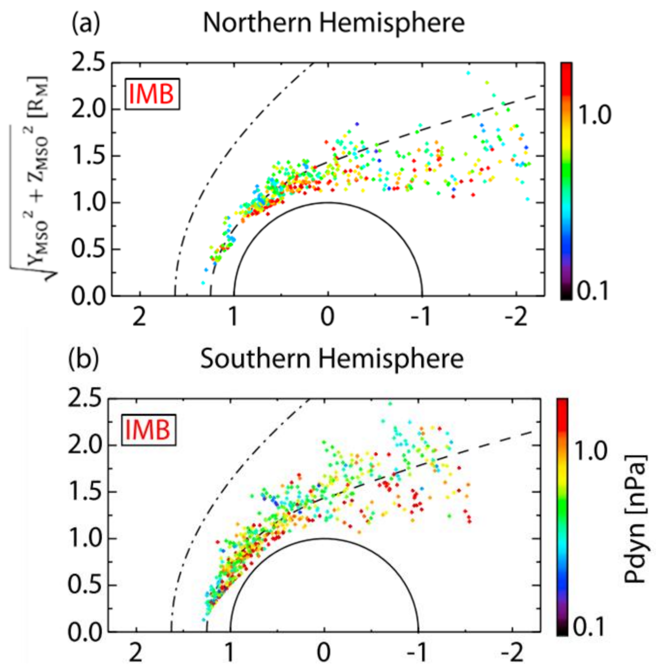
Matsunaga, 2017

SQ1: How do the Martian magnetospheric system's structure and dynamics depend on solar wind conditions?



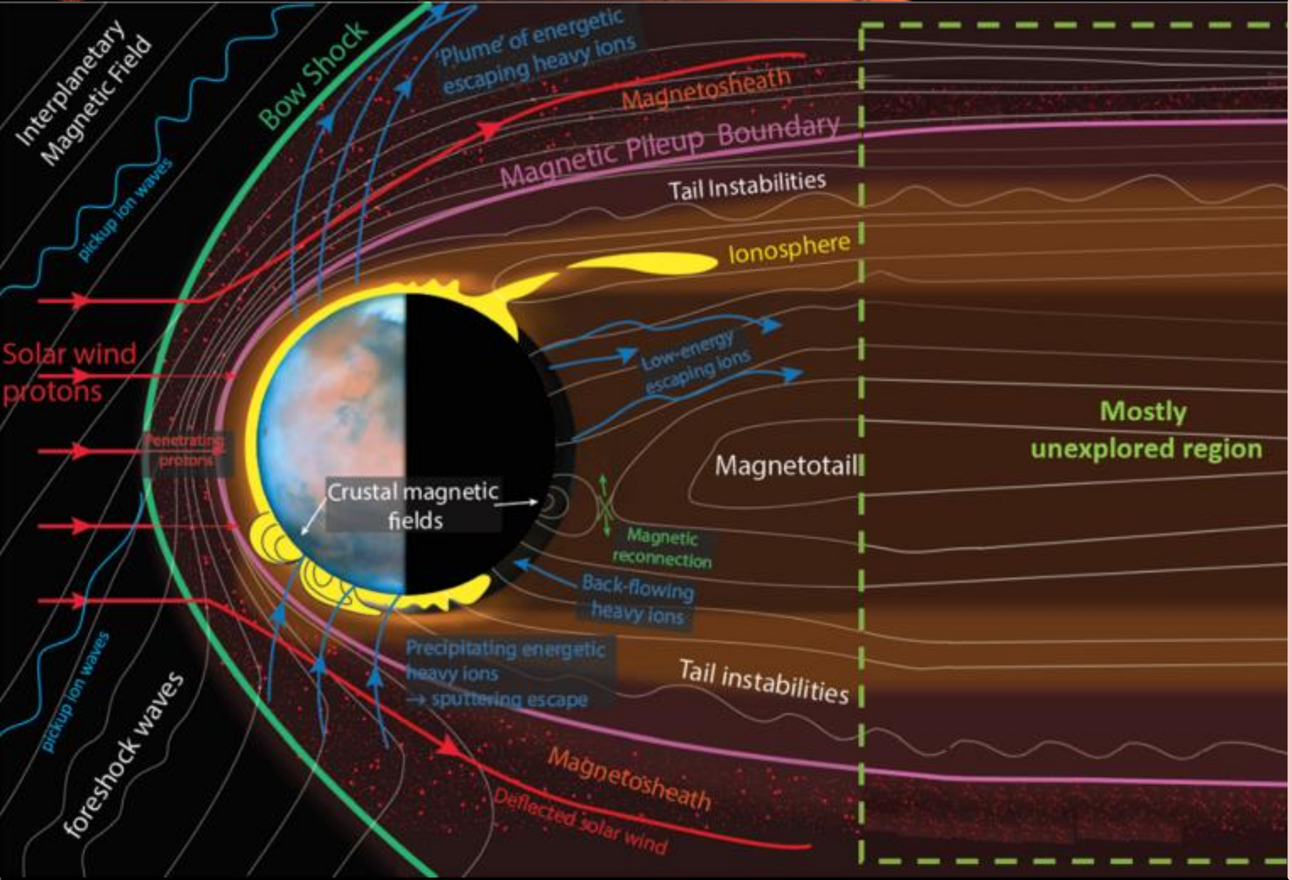
3D observations needed!

O1.2: What are the dynamics and orientation of **boundary regions**, with particular interest for their dependence upon solar wind conditions?

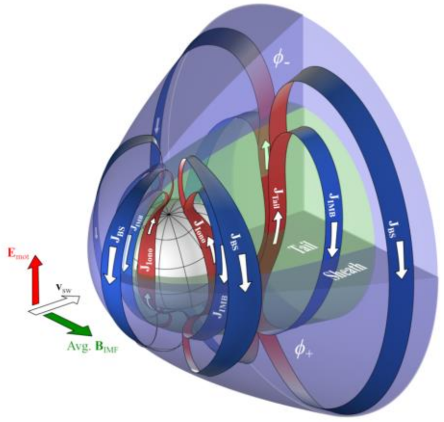


Matsunaga, 2017

Sánchez-Cano et al., 2020



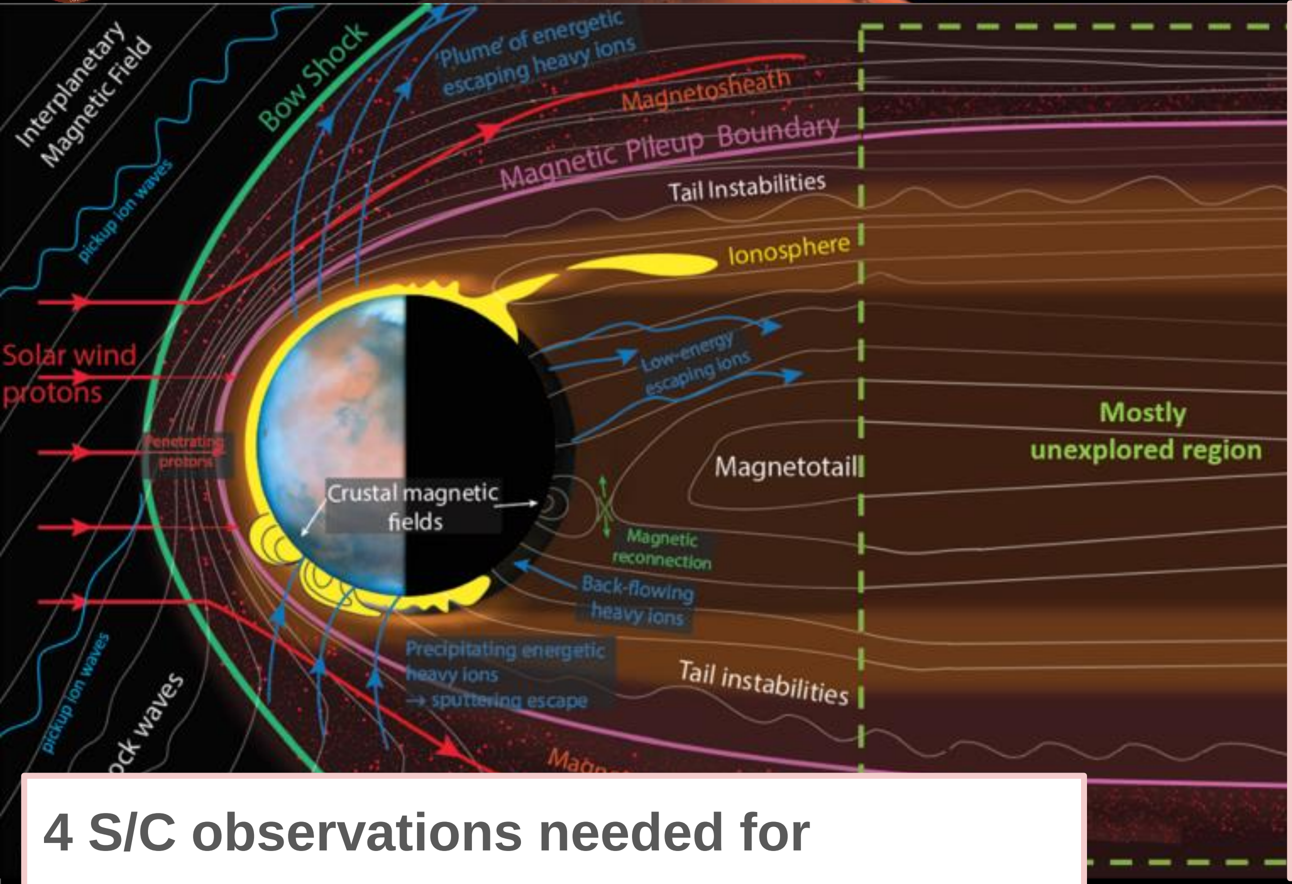
O1.3: What is the dynamical structure of the **current system** in the Martian magnetosphere, with particular interest for its dependence upon solar wind conditions?



Ramstad, 2019

Sánchez-Cano et al., 2020

SQ1: How do the Martian magnetospheric system's structure and dynamics depend on solar wind conditions?



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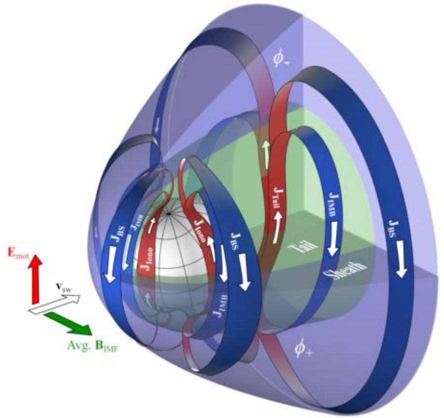
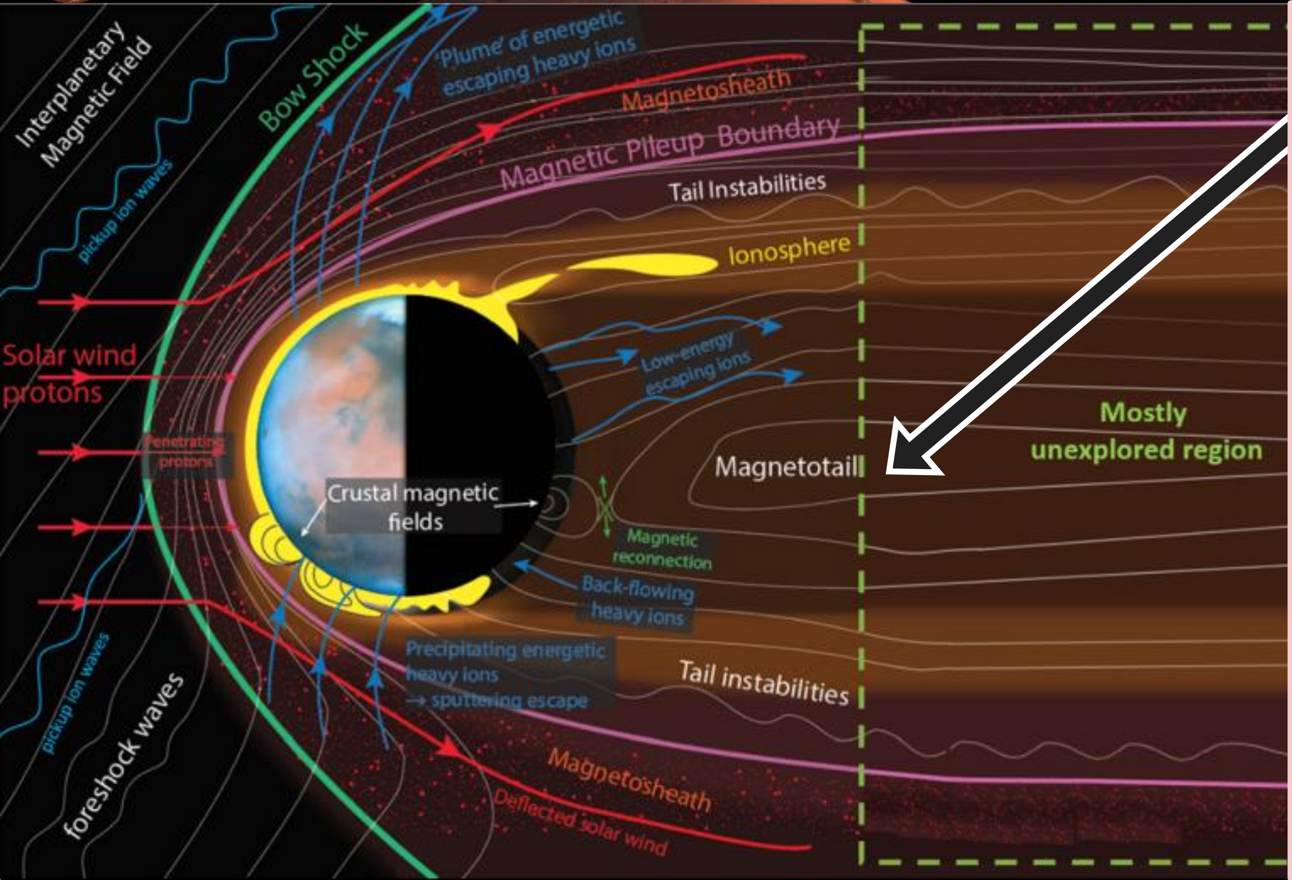


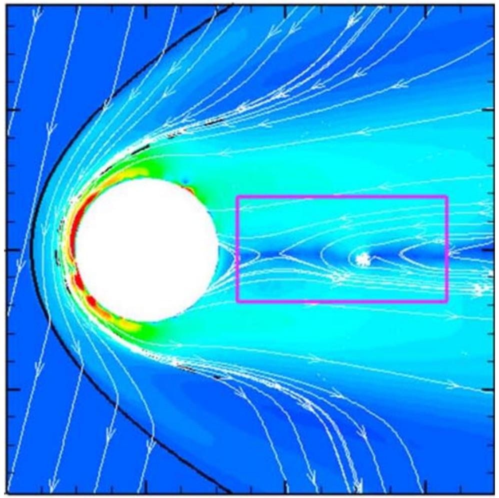
Ramstad, 2019

4 S/C observations needed for Curlometer method!

SQ2: How is energy transported within the Martian magnetospheric system on ion and above scales?

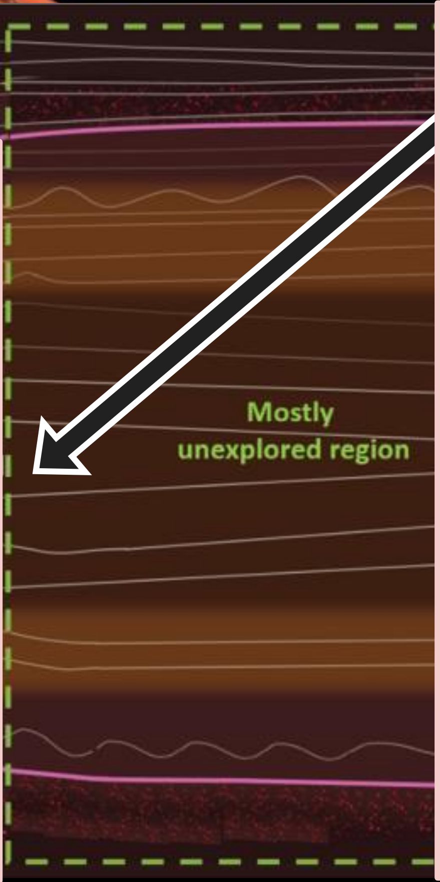


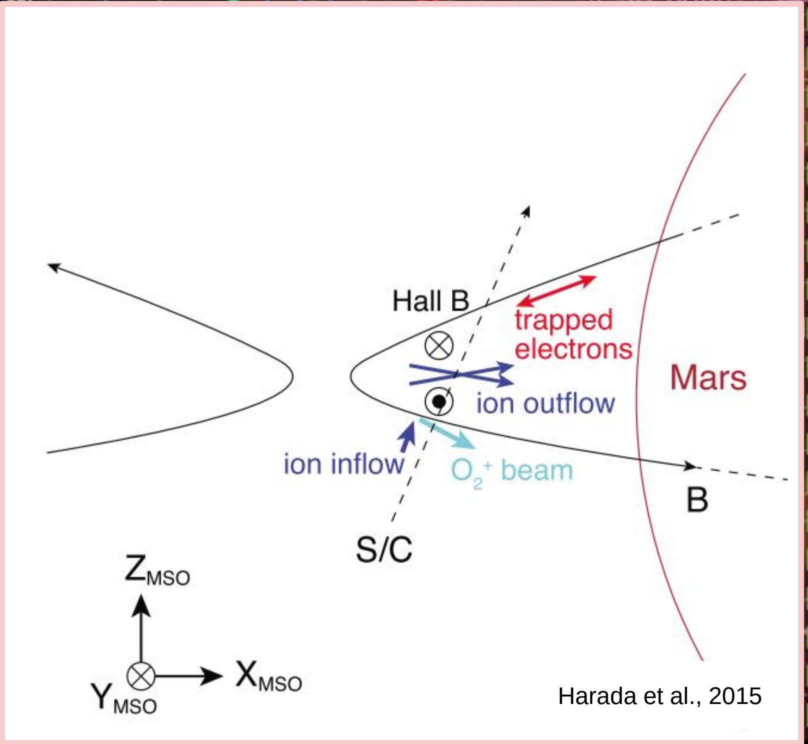
O2.1: Is **magnetic reconnection** observed in the magnetosphere tail, and if so, where and how?



Ma et al., 2017

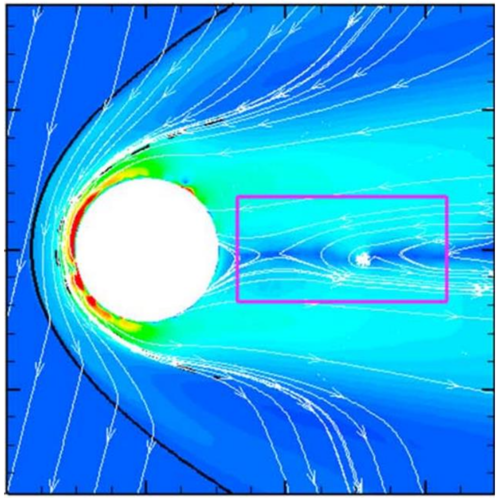
Sánchez-Cano et al., 2020





Harada et al., 2015

O2.1: Is **magnetic reconnection** observed in the magnetosphere tail, and if so, where and how?



Ma et al., 2017

Sánchez-Cano et al., 2020

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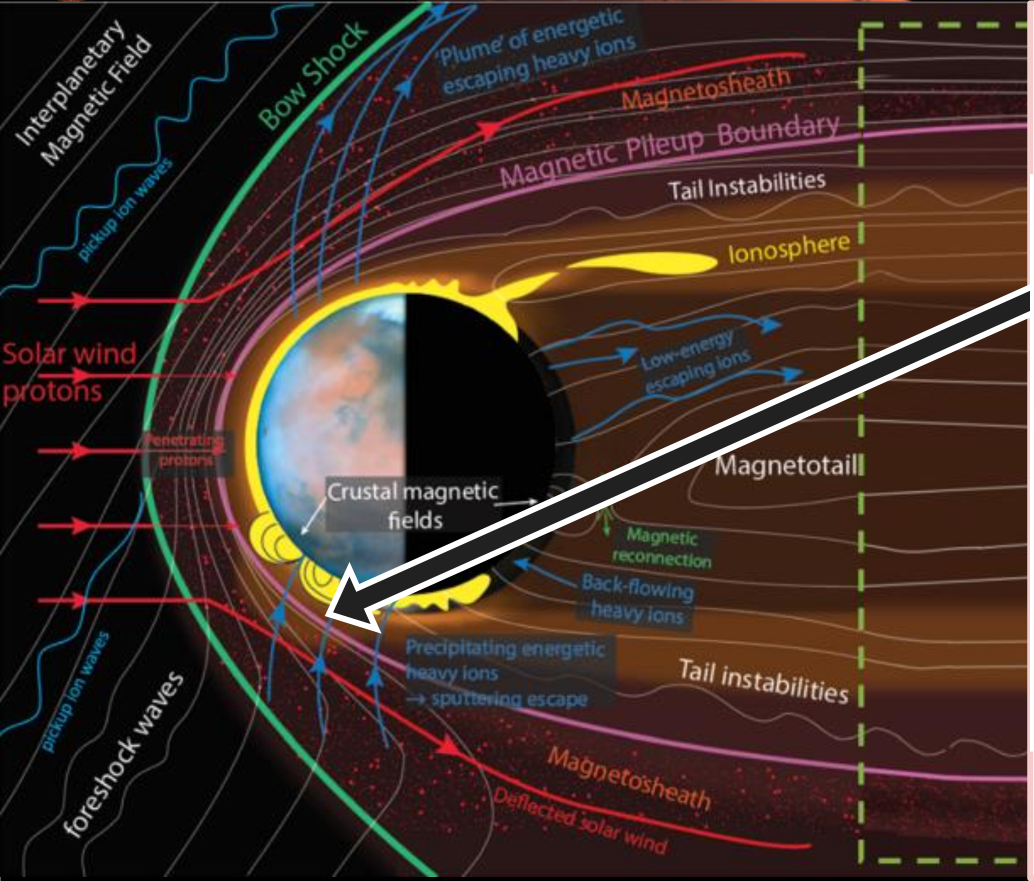
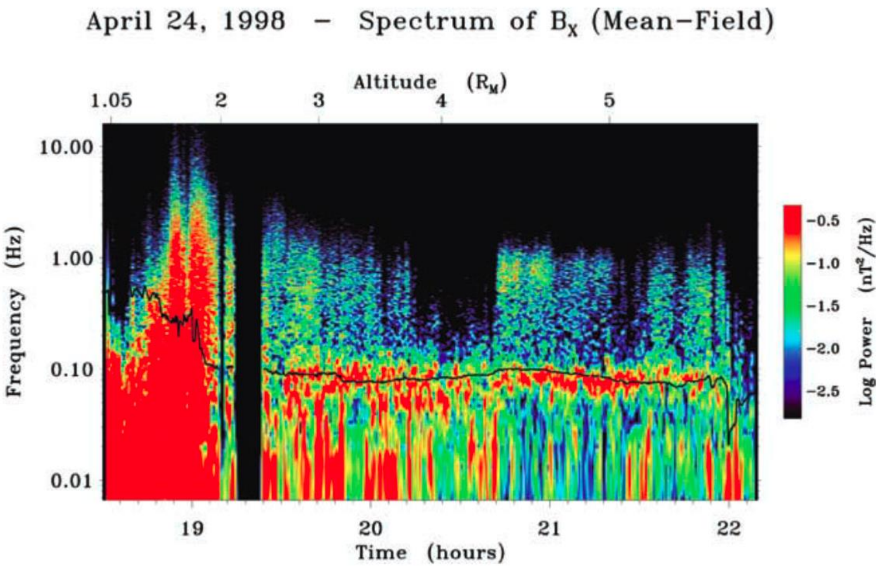


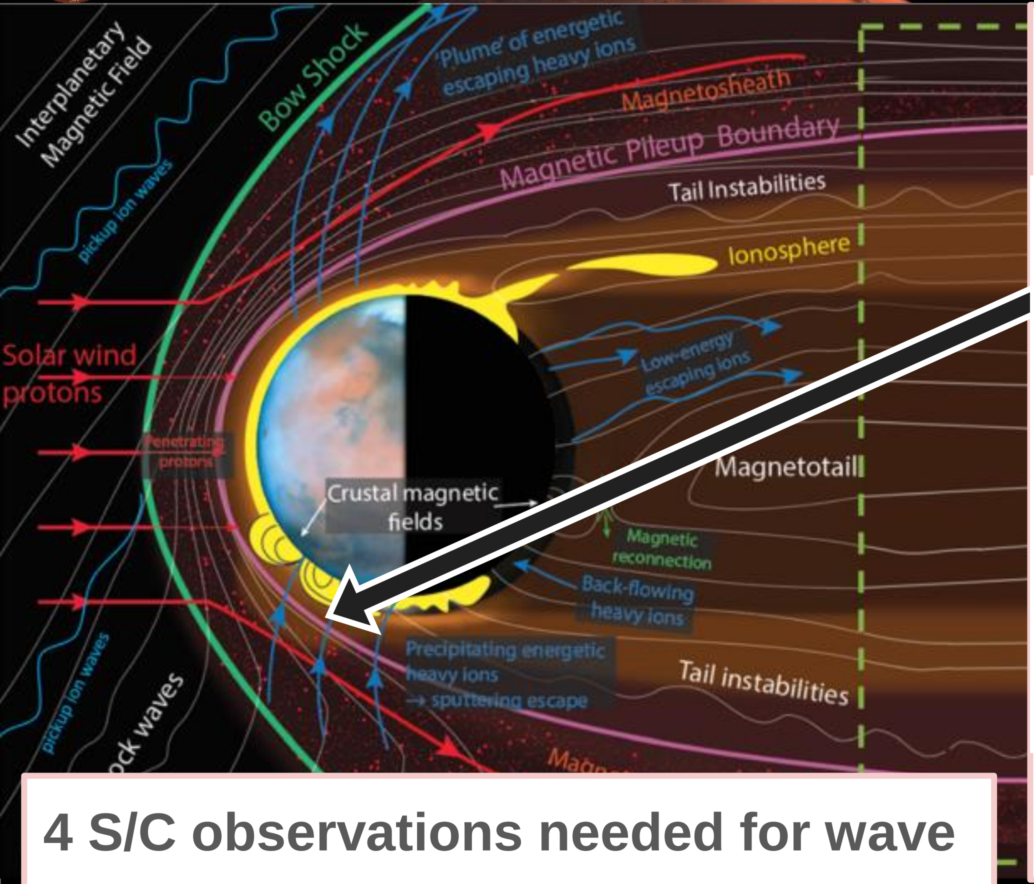
Sánchez-Cano et al., 2020

O2.3: What are the direction and temporal evolution of low frequency plasma **waves**?

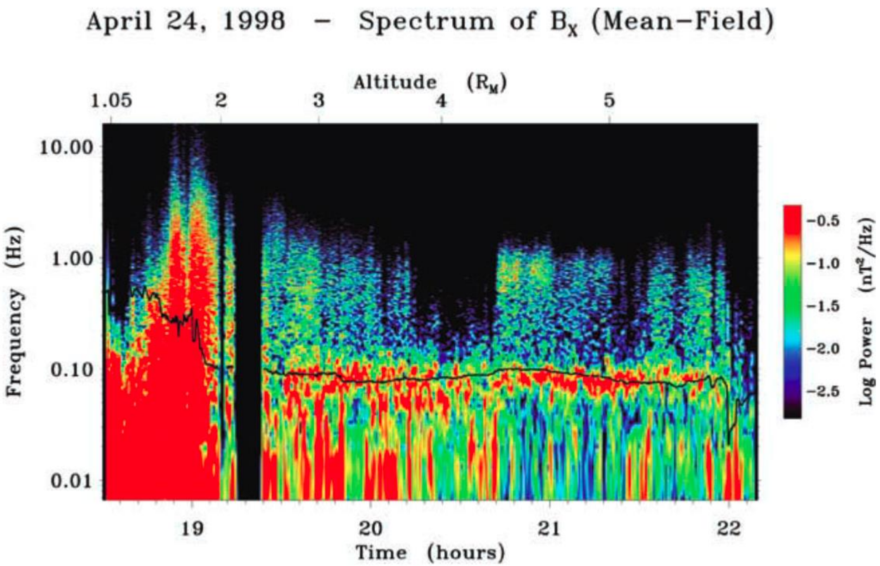


Brain et al., 2002

SQ2: How is energy transported within the Martian magnetospheric system on ion and above scales?



O2.3: What are the direction and temporal evolution of low frequency plasma **waves**?



Brain et al., 2002

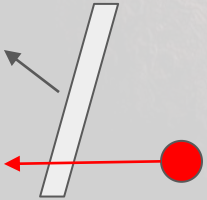
4 S/C observations needed for wave telescope technique!

Secondary Science Questions and Objectives

Secondary Science Questions	Secondary Science Objectives
Q3: How does the solar wind propagate through the solar system?	• O3.1: What are the temporal variations of the upstream solar wind conditions at Mars?
Q4: Excluding magnetic reconnection, are there other processes driving the energy transport at the Martian magnetotail?	• O4.1: Are other energy transport processes observed at the Martian magnetotail that exhibit signatures different to magnetic reconnection?

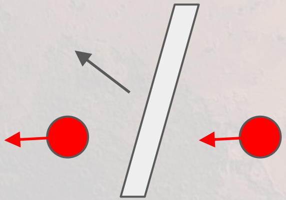
3D Picture is Needed → 4 Spacecraft

1 Spacecraft



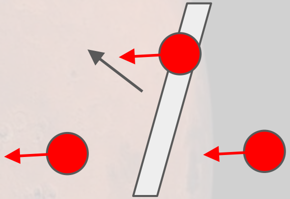
There is a boundary

2 Spacecraft



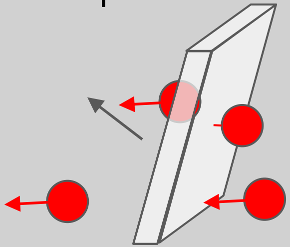
How thick is the boundary or is it moving?

3 Spacecraft



Where is the boundary in 2D?

4 Spacecraft



Where is the boundary in 3D, what is its orientation?

3D Picture is Needed → 4 Spacecraft

- Three dimensional mapping of magnetosphere currents (**Curlometer**)

  Solving **Ampere's Law** to get currents requires **3D gradients**

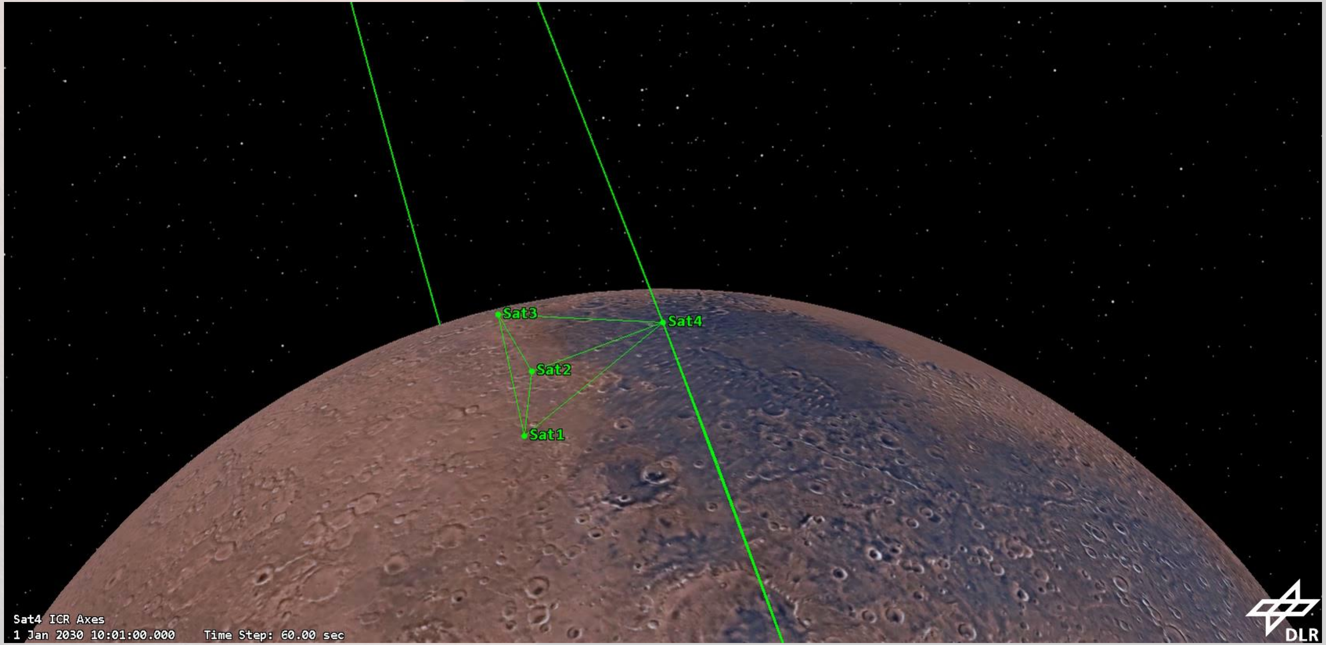
  $$\nabla \times \vec{B} = \mu_0 \vec{J}$$

- Separation of wave direction and time dependence (**Wave telescope**)

  Fourier transform estimation: Get wave vectors and time dependency of waves

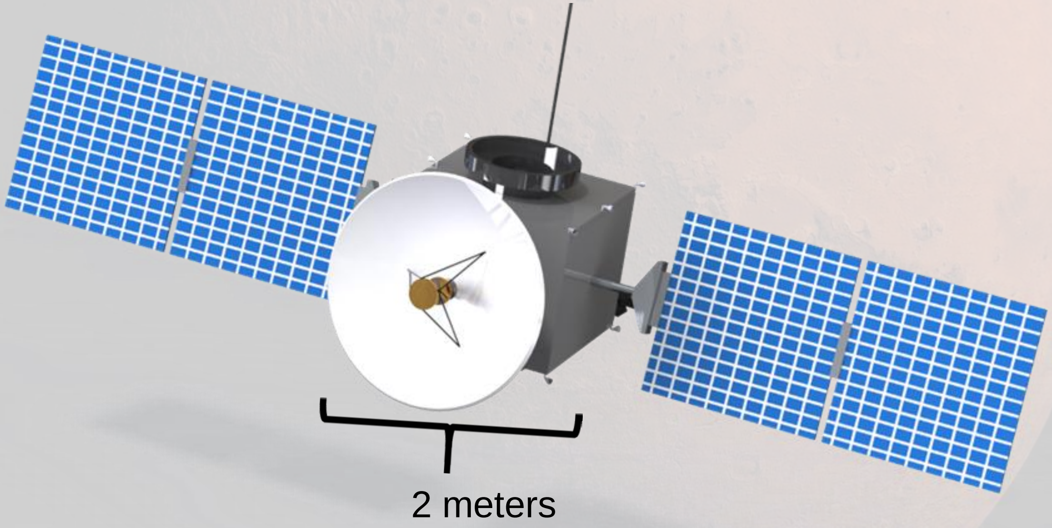
Formation MFO

- Tetrahedron
- MFO will fly in a Cartwheel-Helix formation
- Distance between spacecraft: ~100 km (H^+ gyroradius)

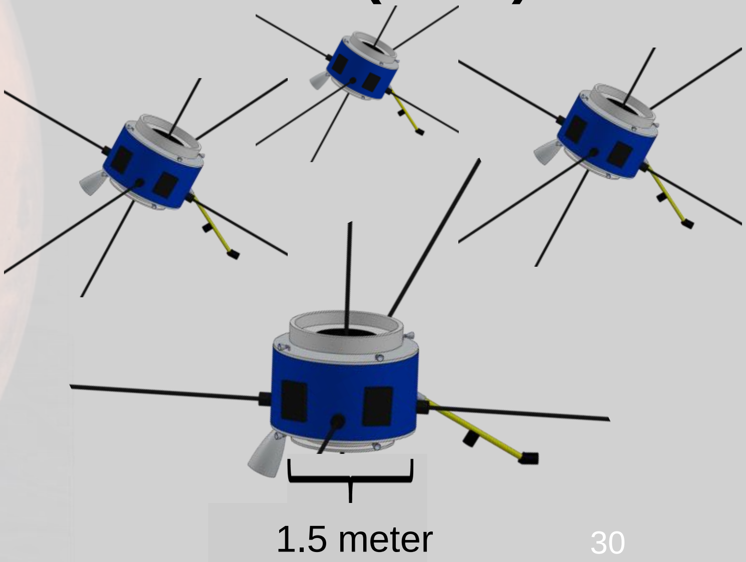


The Orbiters

Solar Wind Observatory (SWO)

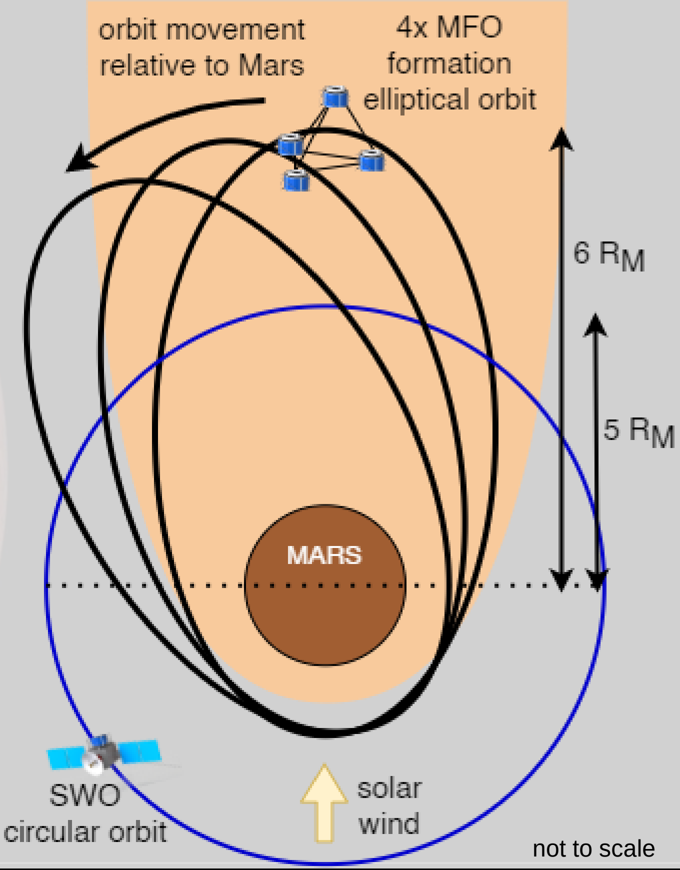


Magnetospheric Formation Orbiters (MFO)



Mission Outline: 4 + 1 Spacecraft

- 1 Solar Wind Observatory (SWO)
  - Solar wind probe
  - Data relay to Earth
  - Circular orbit for similar upstream solar wind coverage during the whole Martian year
- 4 Magnetospheric Formation Orbiters (MFO)
  - Tetrahedral formation with base length of ~100 km
  - Elliptical orbit to probe both the magnetotail and frontal boundary regions (BS, MPB) during a Martian year and satisfy timing requirements
- Physical observables
  - Solar wind monitor: B, Ions, Electrons
  - Tetrahedron: B, E, Ions, Electrons



What do we Require to Measure This?

Science questions	**Science objectives**	Magnetometer	Ion spectrometer	Electron spectrometer	Langmuir probe	Dipolar antennas
		DC Vector magnetic field	Ion distribution functions	Electron distribution functions	Density, temperature	DC Vector electric field
SQ1: **Dynamics, solar wind**	SO1.1: Boundaries	● ••••	● •			
	SO1.2: Tail structure	● ••••	● •	●	••••	
	SO1.3: Current system	● ••••	●	●		
SQ2: **Energy transport**	SO2.1: Reconnection	••	••			
	SO2.2: Waves	••••			••••	••••
Second. SQ3	*SO3.1: Solar wind*	●	●	●		
Second. SQ4	*SO4.1: Other processes*	••	••	••		••

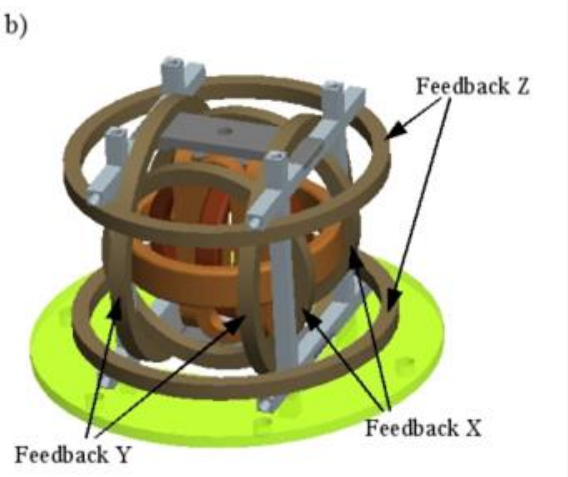
Science Objectives → Measurement Requirements→ Instrument Requirements→ Orbit Requirements→ Functional Requirements

Measuring Magnetic Fields

Measurement Requirement
- *Absolute range: 3000 nT*
- *Absolute accuracy: 0.5 nT*
- *Temporal resolution: 128 samples/sec*

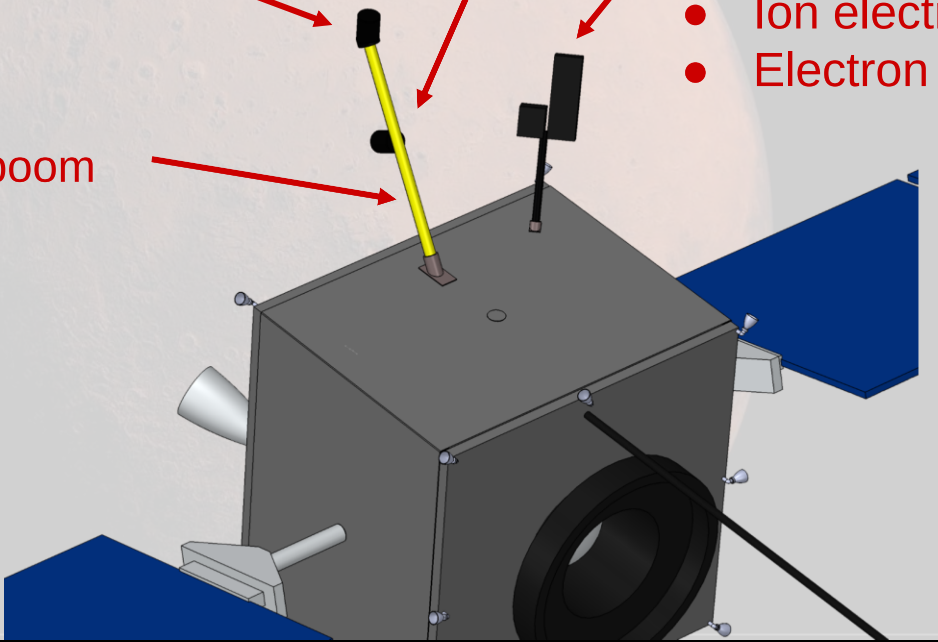
Instrument Requirement
- *Range: 3000 nT*
- *Offset stability: 0.5 nT / 12h*
- *Absolute vector accuracy: 0.05%*
- *Resolution: 20 pT*
- *128 vectors/s*
- *Attitude knowledge: <0.05°*

Fluxgate Magnetometer

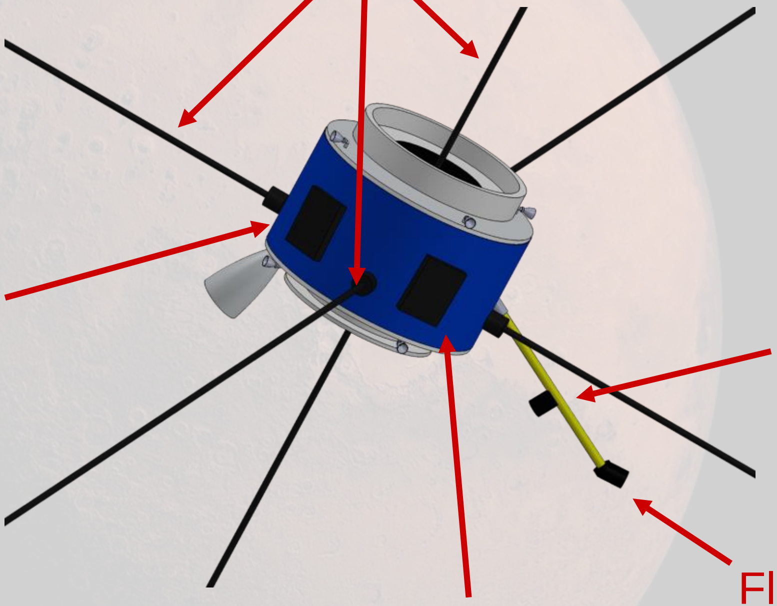


Credit: THEMIS instrument team

Instruments on Solar Wind Observatory (SWO)

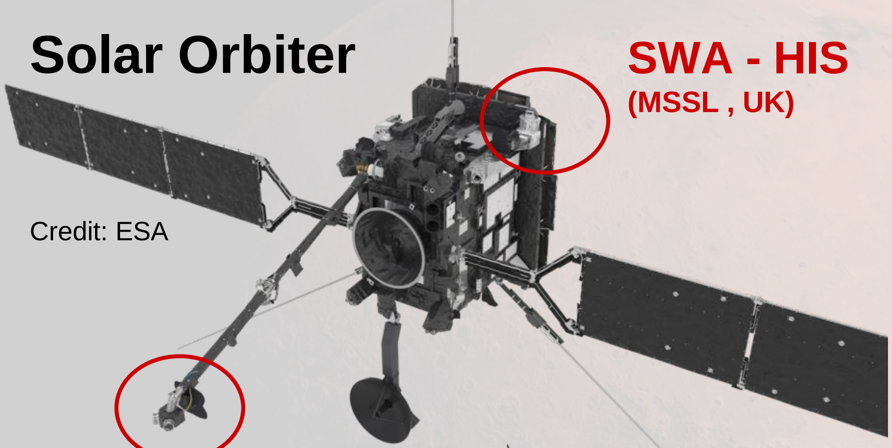


Instruments on Magnetospheric Formation Orbiter (MFO)



Instrumental Heritage for SWO

Solar Orbiter

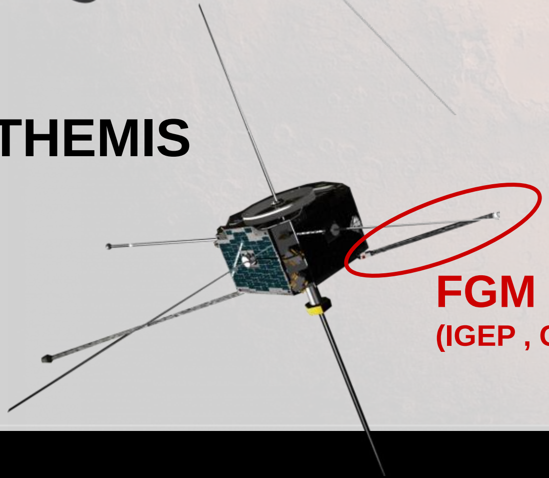


SWA - HIS
(MSSL , UK)

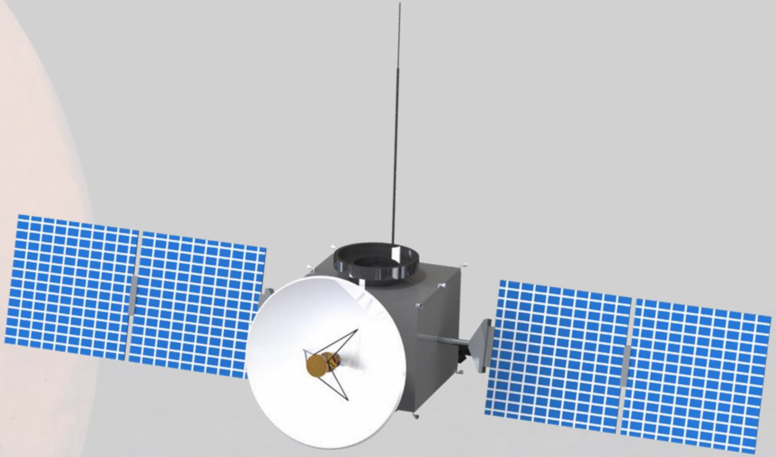
Credit: ESA

SWA - EAS
(IRF, Sweden)

THEMIS

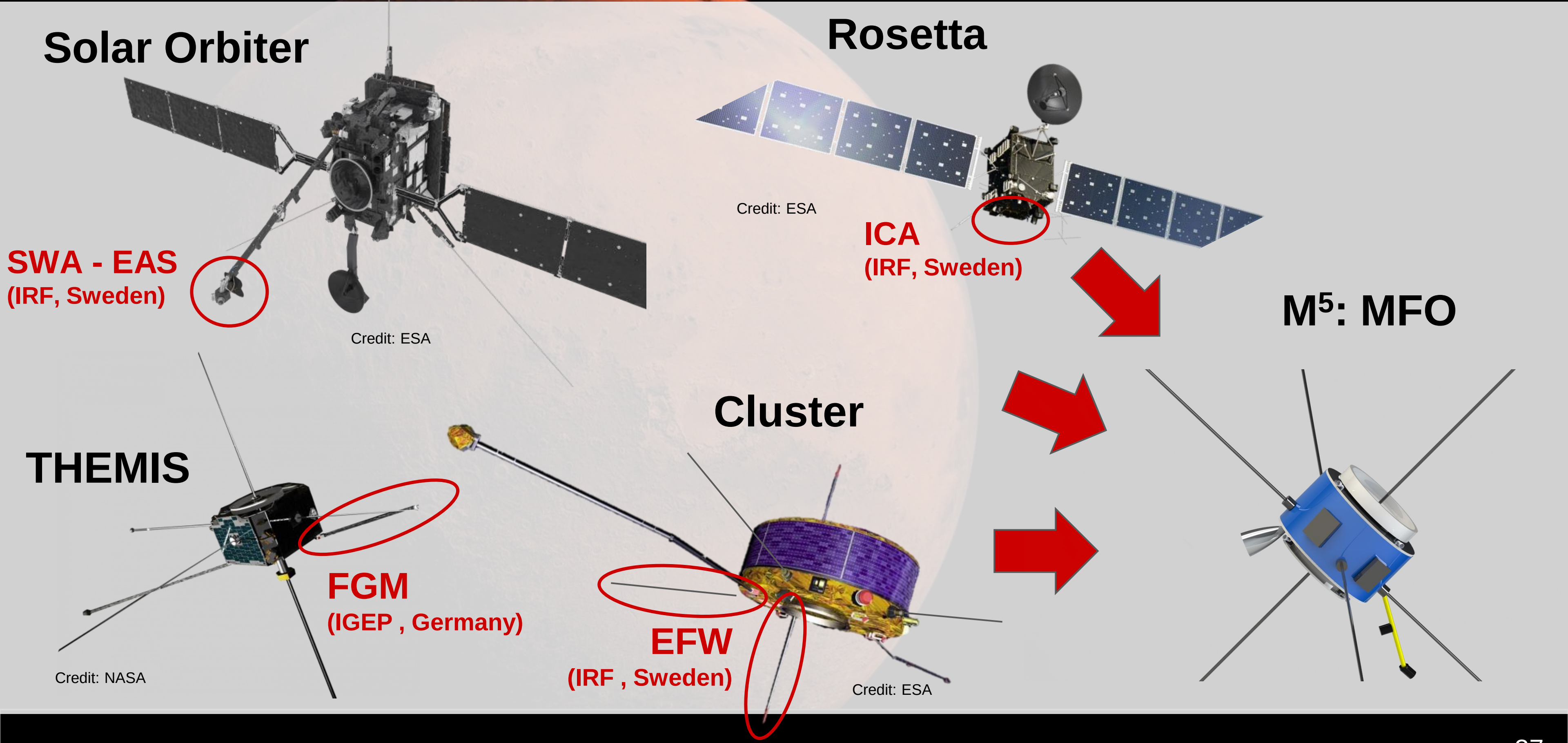


FGM
(IGEP , Germany)

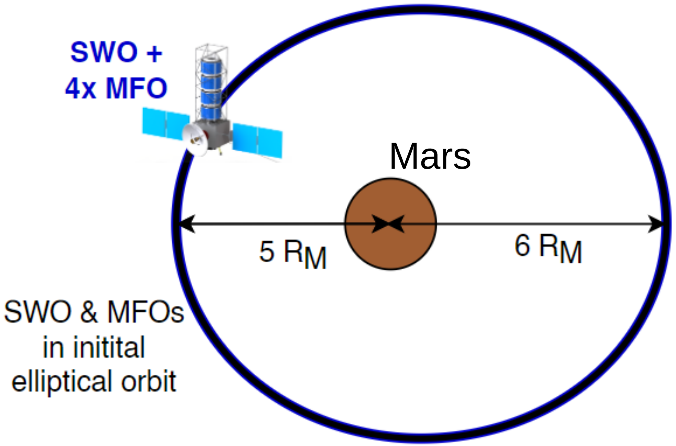


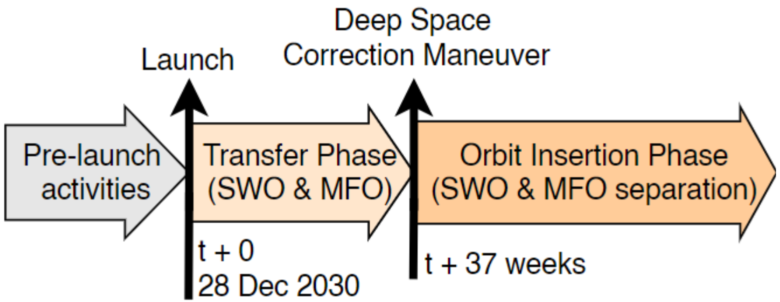
M⁵: Solar Wind Orbiter

Instrumental Heritage for MFOs

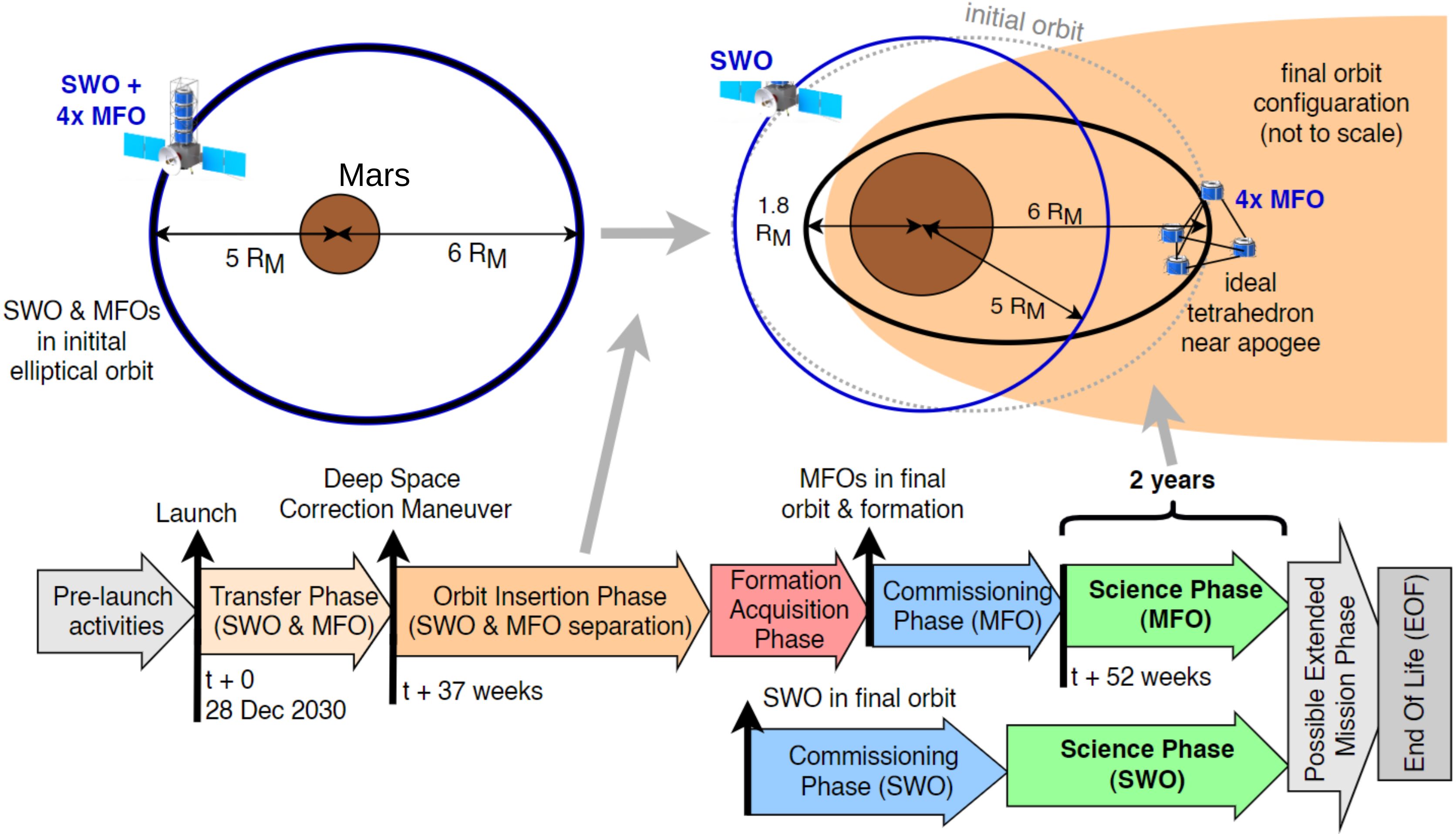


Orbital Timeline





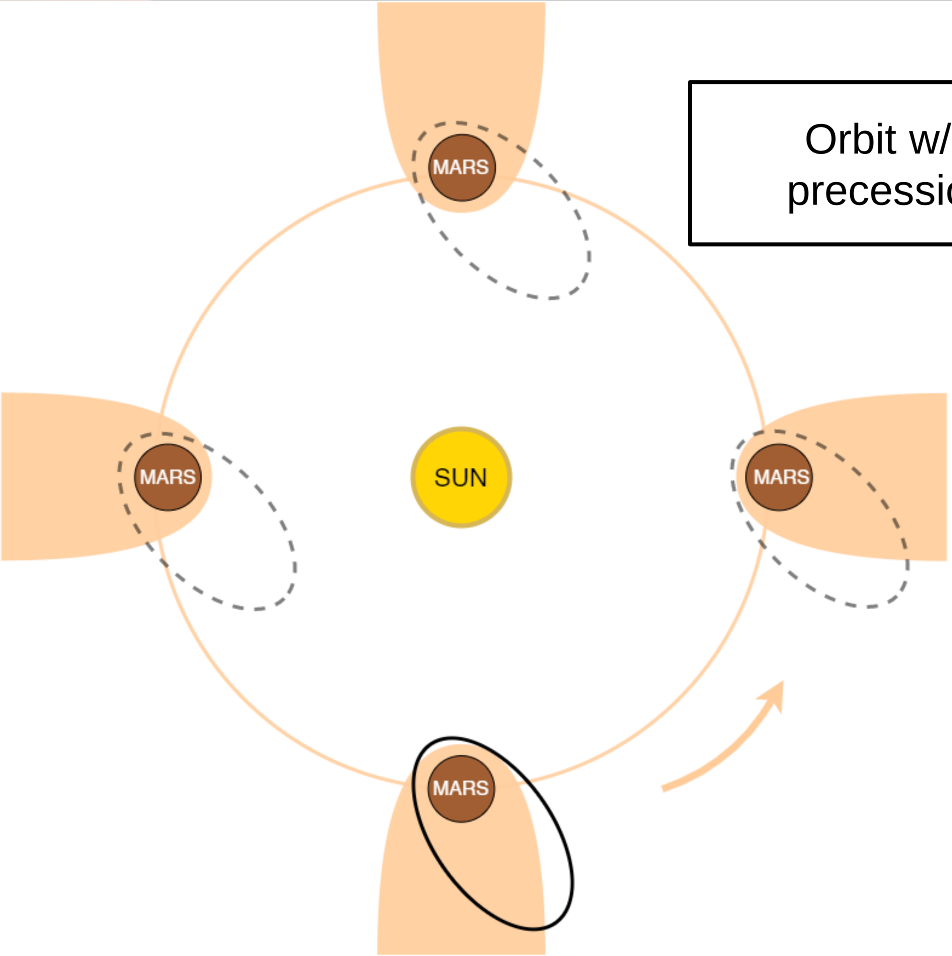
Orbital Timeline



Orbit Precession in Martian Year

Orbit throughout the Martian year:

- Martian year: 687 sidereal days
- Time for apogee within tail boundaries very limited: **only 49 days**

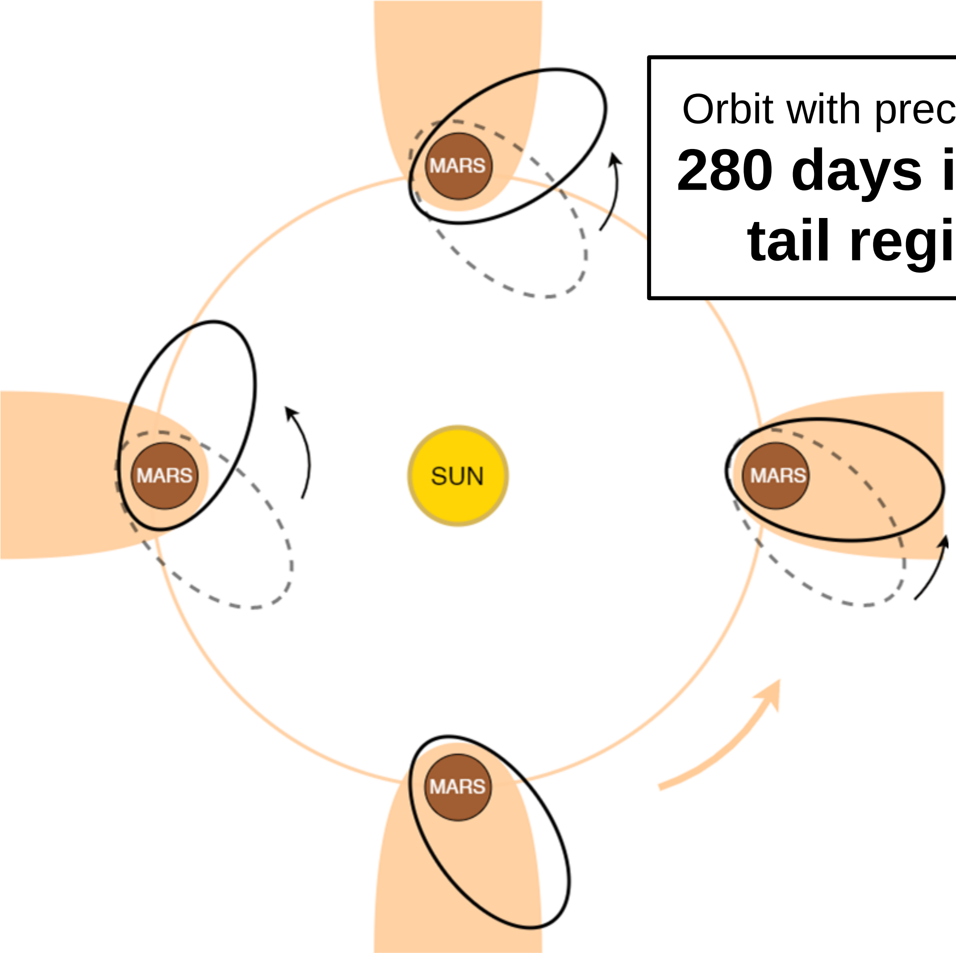


Orbit w/o precession

Orbit Precession in Martian Year

Orbit throughout the Martian year:

- Martian year: 687 sidereal days
- Time for apogee within tail boundaries very limited: **only 49 days**

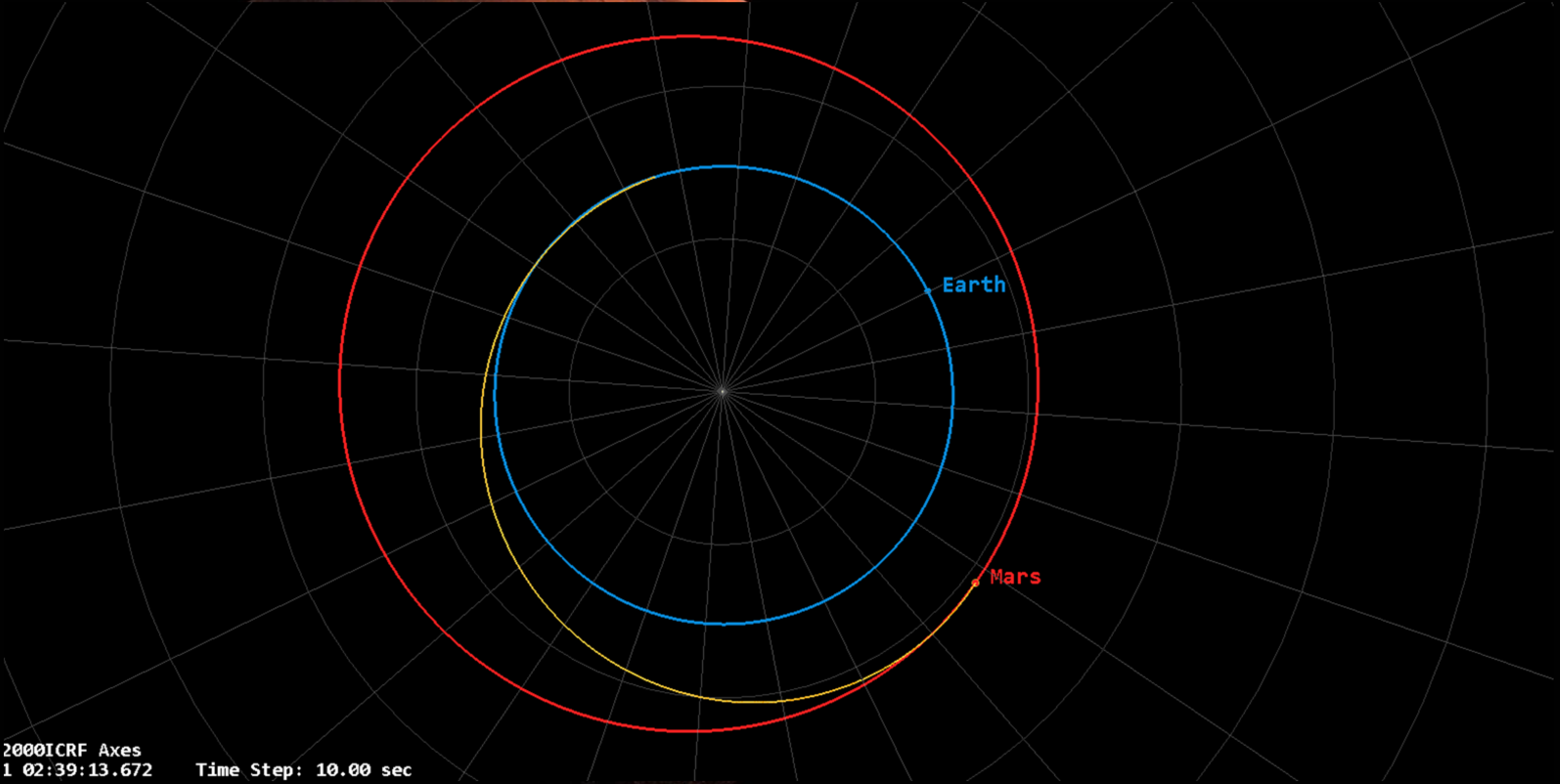


Orbit with precession:
280 days in the tail region

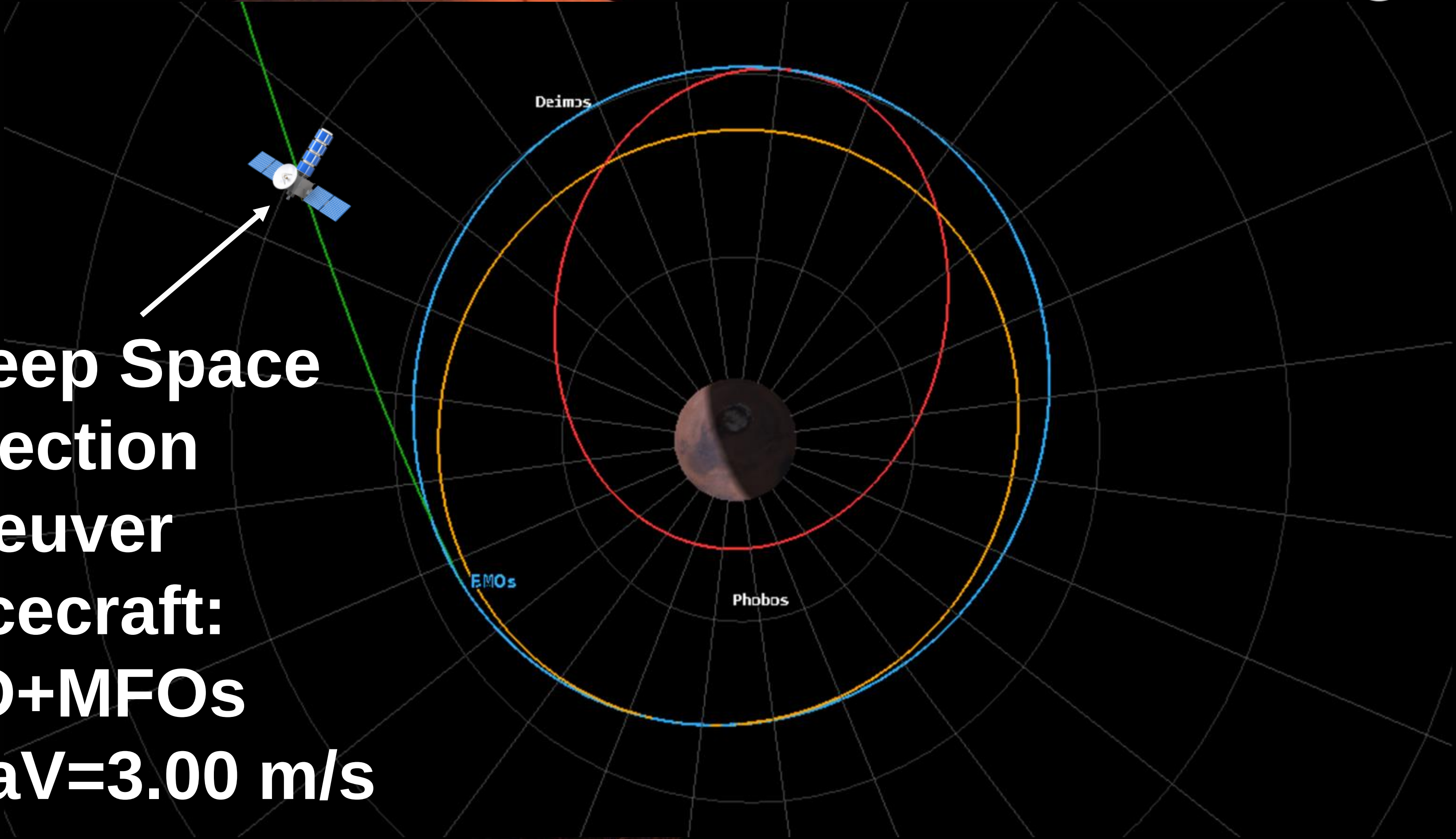
Extend time in tail?
→ **J2 perturbation**
(due to Mars oblateness)

- Const. Ω (RAAN) change over time

Transfer Orbit



Insertion Orbit

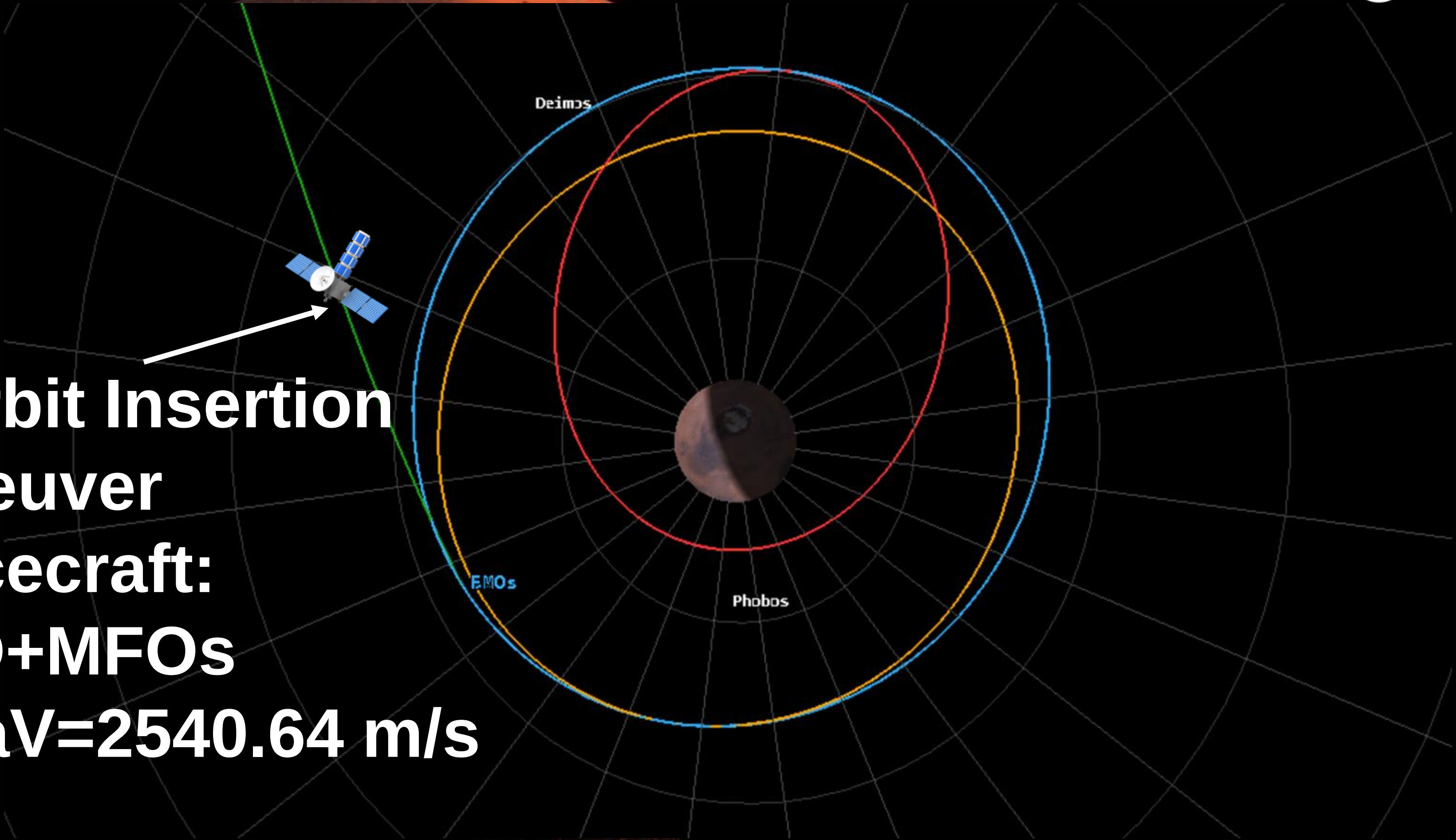


1: Deep Space Correction Maneuver

Spacecraft: SWO+MFOs

DeltaV=3.00 m/s

Insertion Orbit

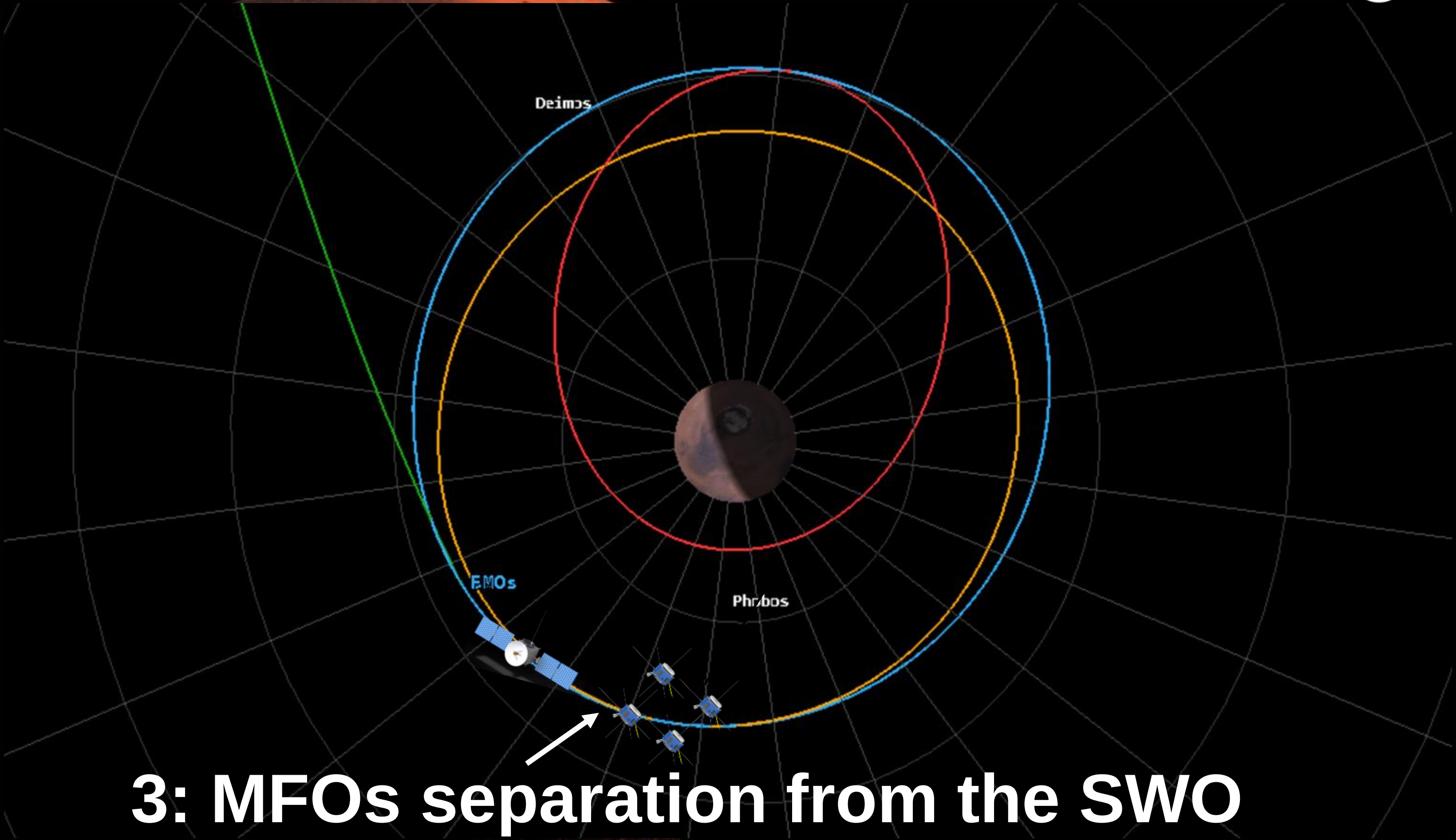


2: Orbit Insertion Maneuver

Spacecraft: SWO+MFOs

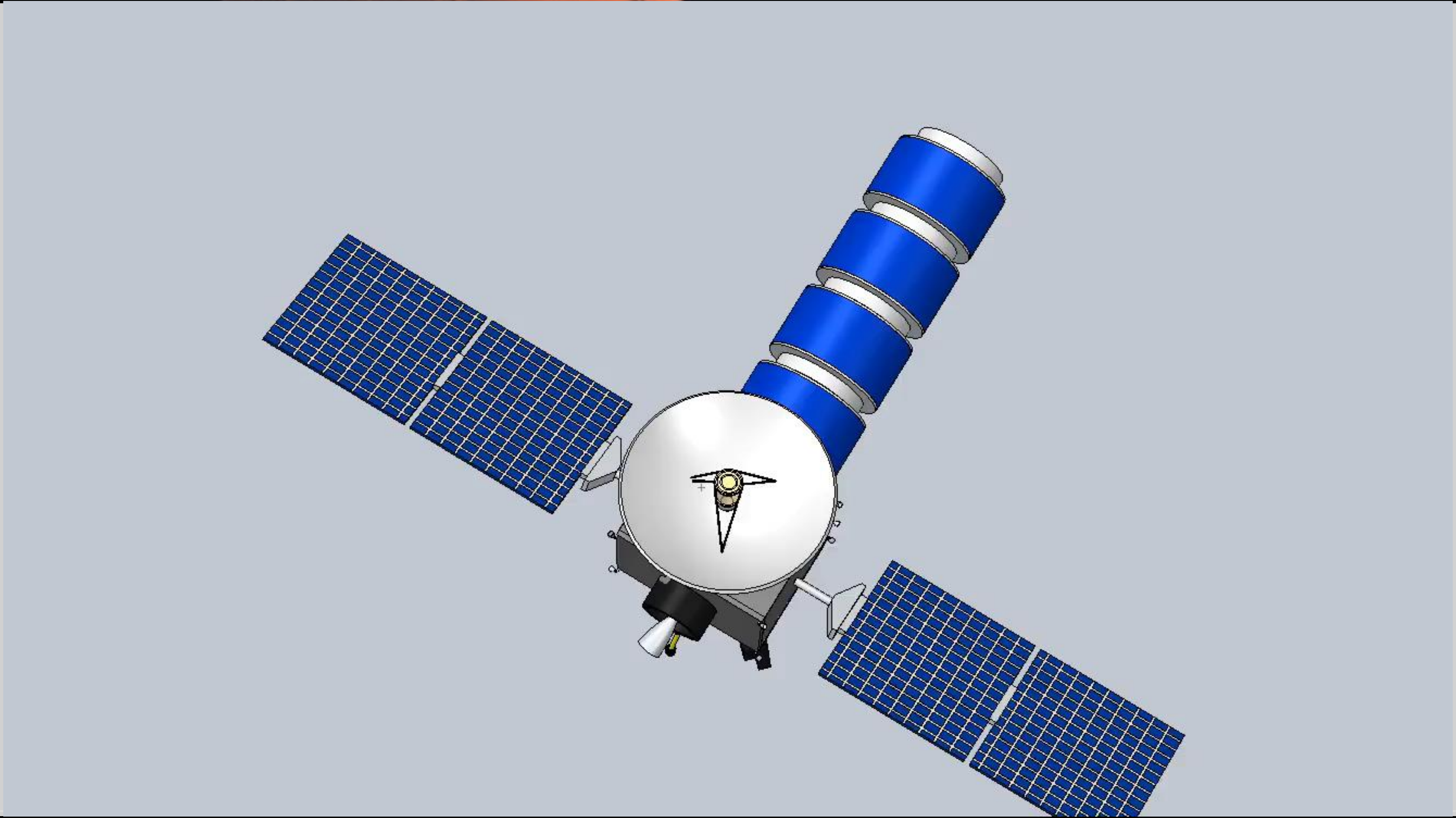
DeltaV=2540.64 m/s

Insertion Orbit

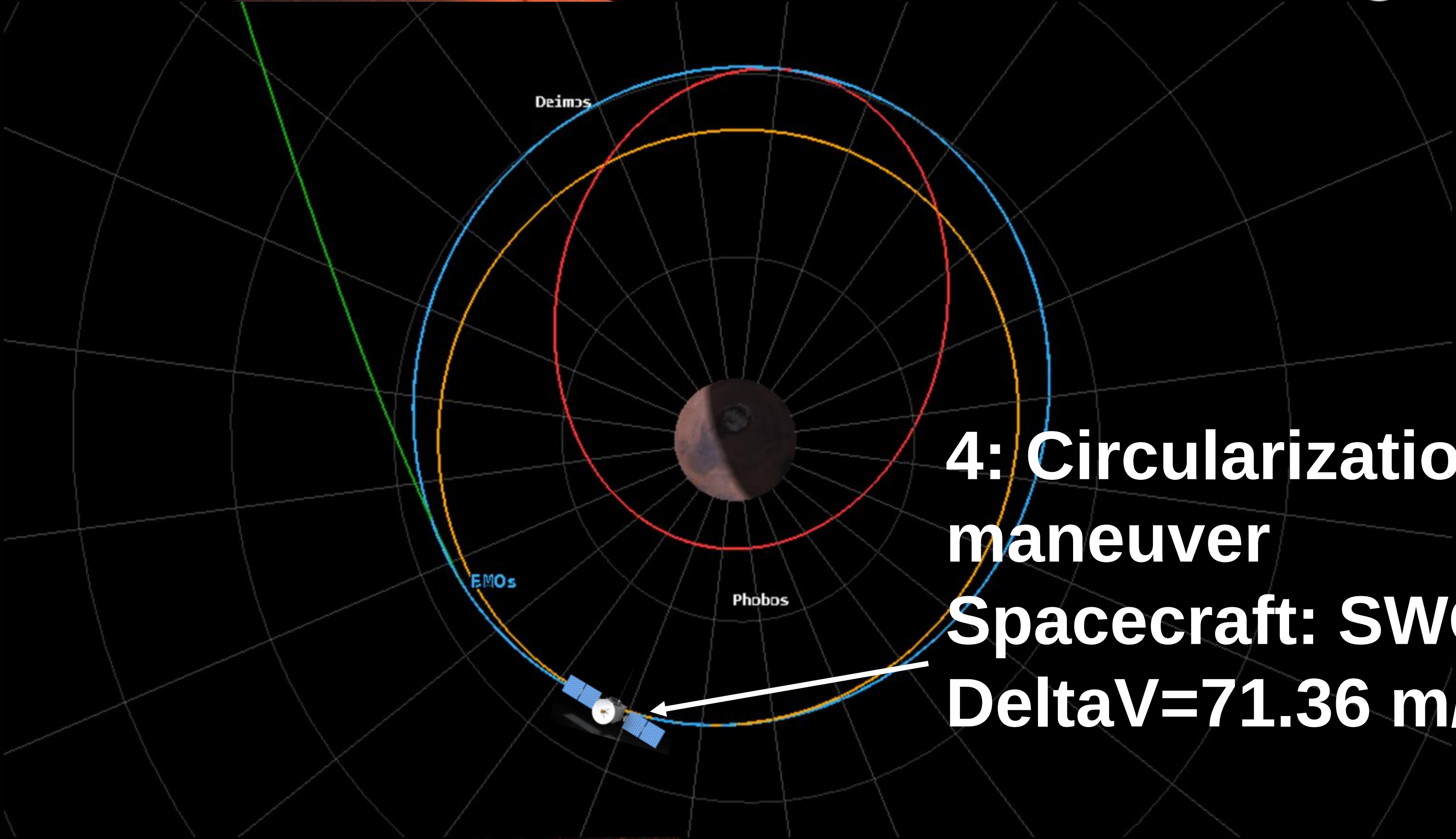


3: MFOs separation from the SWO

Constellation Separation



Insertion Orbit

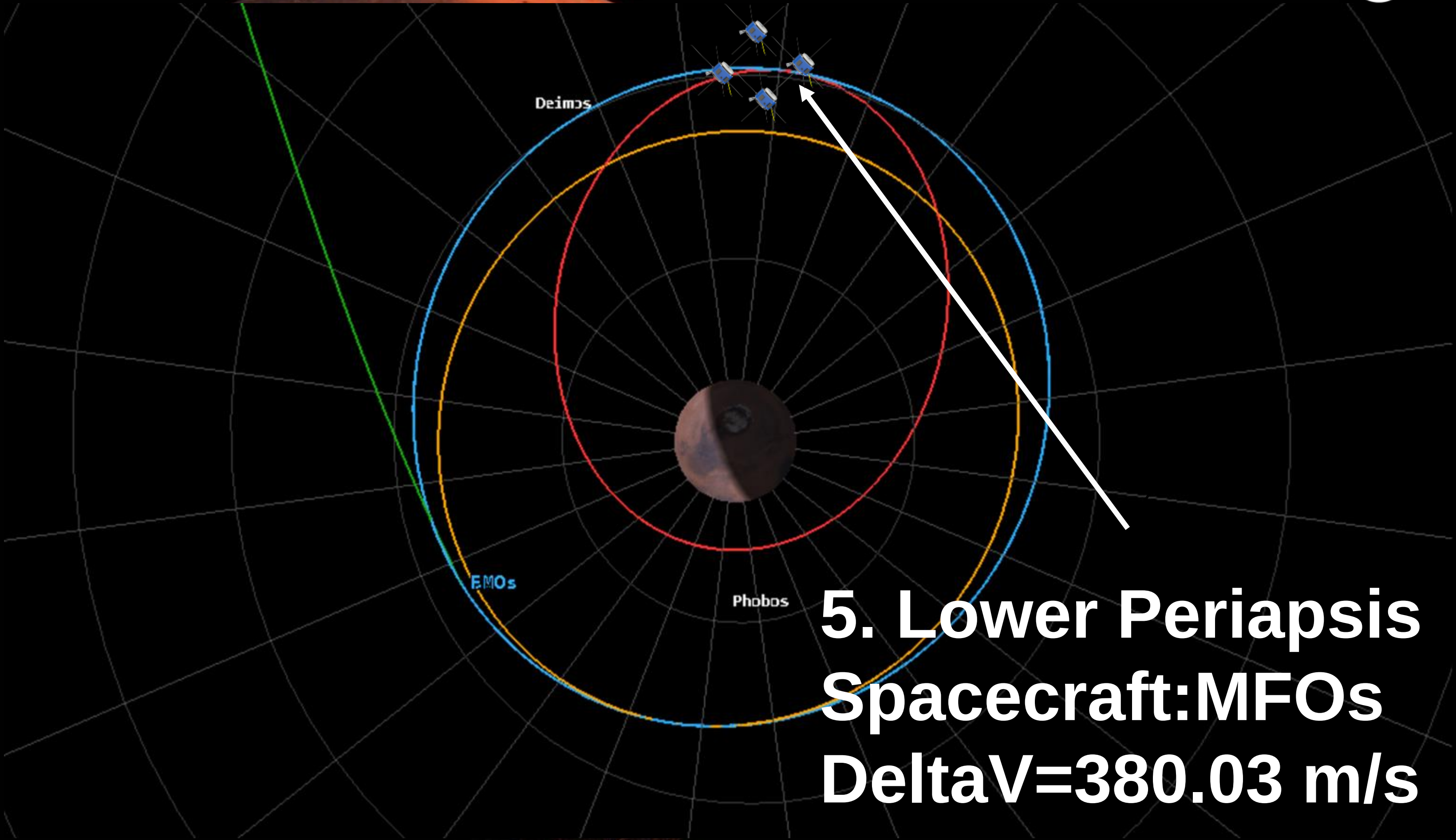


4: Circularization maneuver

Spacecraft: SWO

DeltaV=71.36 m/s

Insertion Orbit

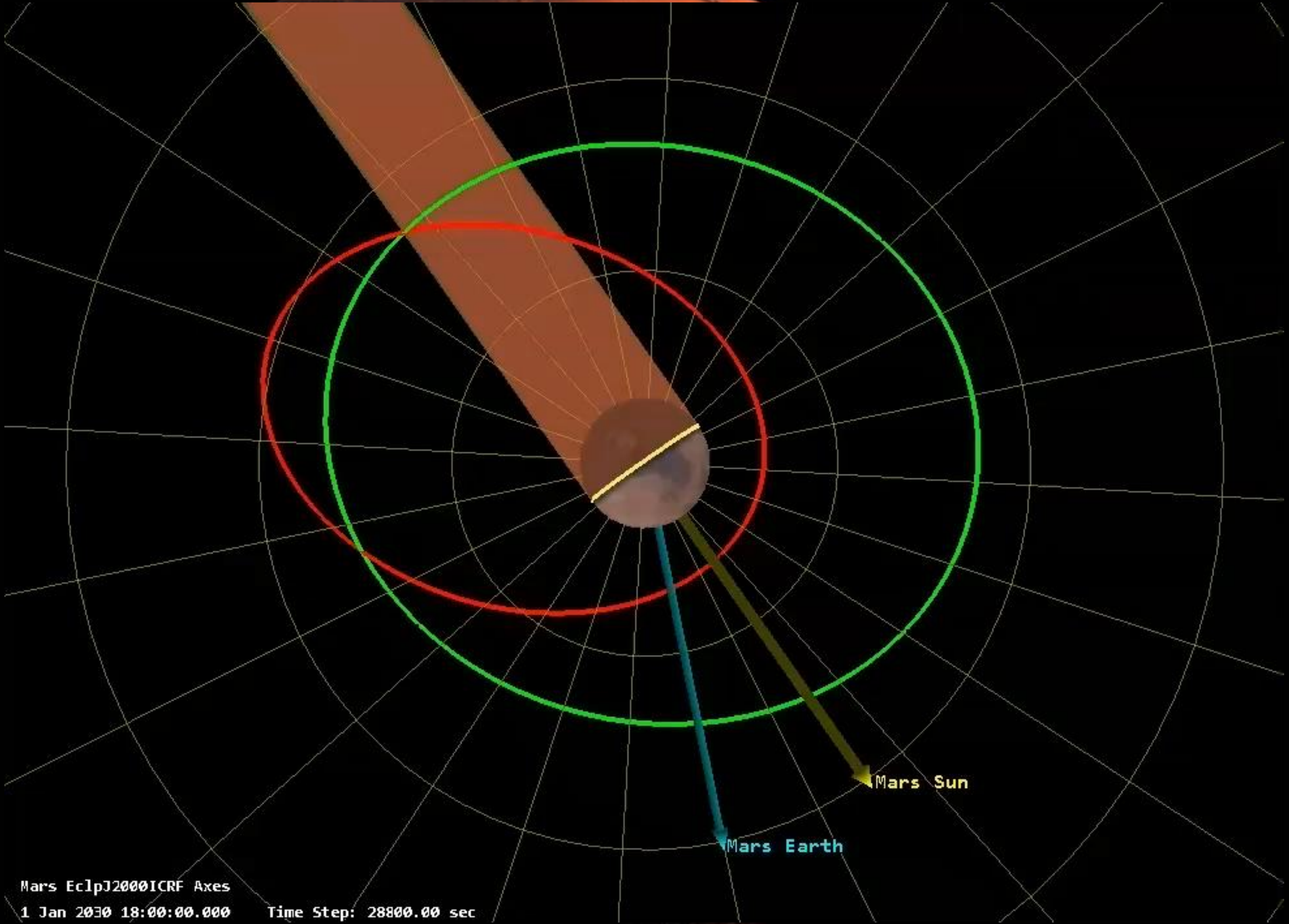


5. Lower Periapsis
Spacecraft:MFOs
DeltaV=380.03 m/s

Delta-V Budget

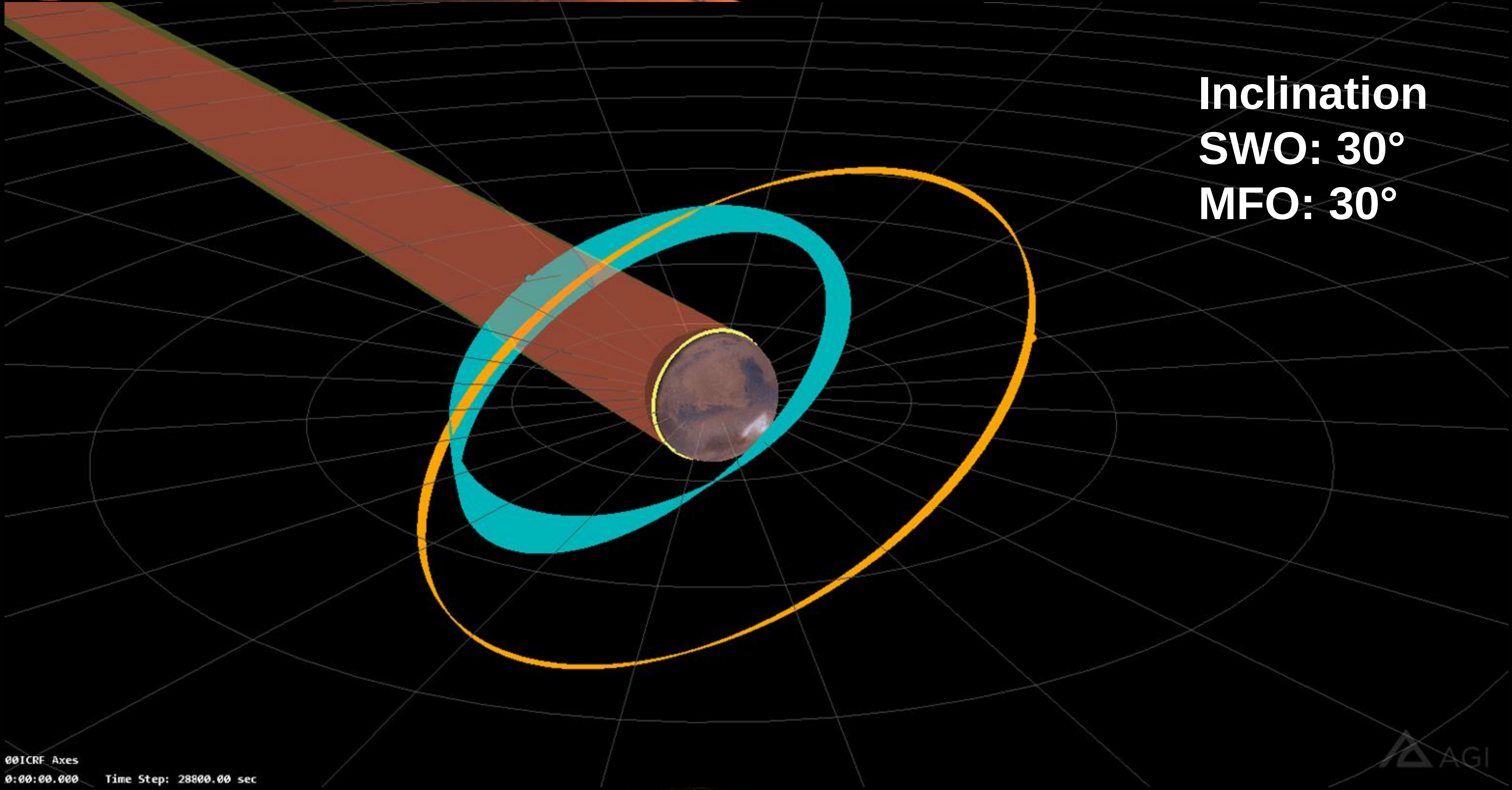
Spacecraft	Maneuver	Delta-V [m/s]	Propellant Mass [kg]
SWO + 4 ╳ MFOs	Deep Space Correction Maneuver	(3,2) 30	6,4
SWO + 4 ╳ MFOs	Orbital Insertion	2668	3552
SWO	Circularization	75	21
4 ╳ MFO	Lower Periapsis	1596	50
4 ╳ MFO	Formation	1600	43
		TOTAL: 5969	**3672,8**

Martian Orbit



Inclination
SWO: 30°
MFO: 30°

Martian Orbit

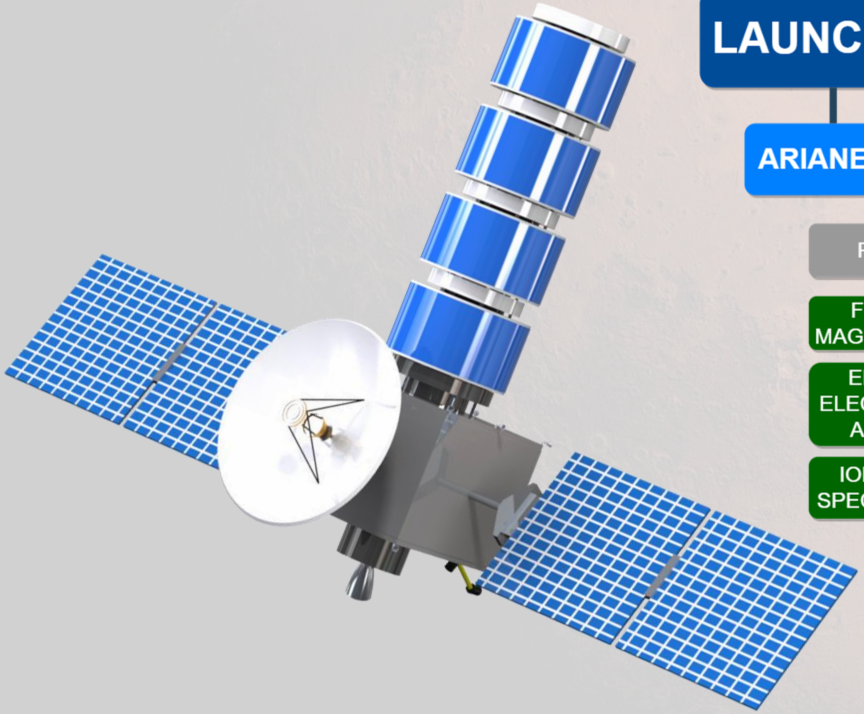


Inclination
SWO: 30°
MFO: 30°

Science Motivation → **Science Case** → **Systems Engineering** → **Programmatics**

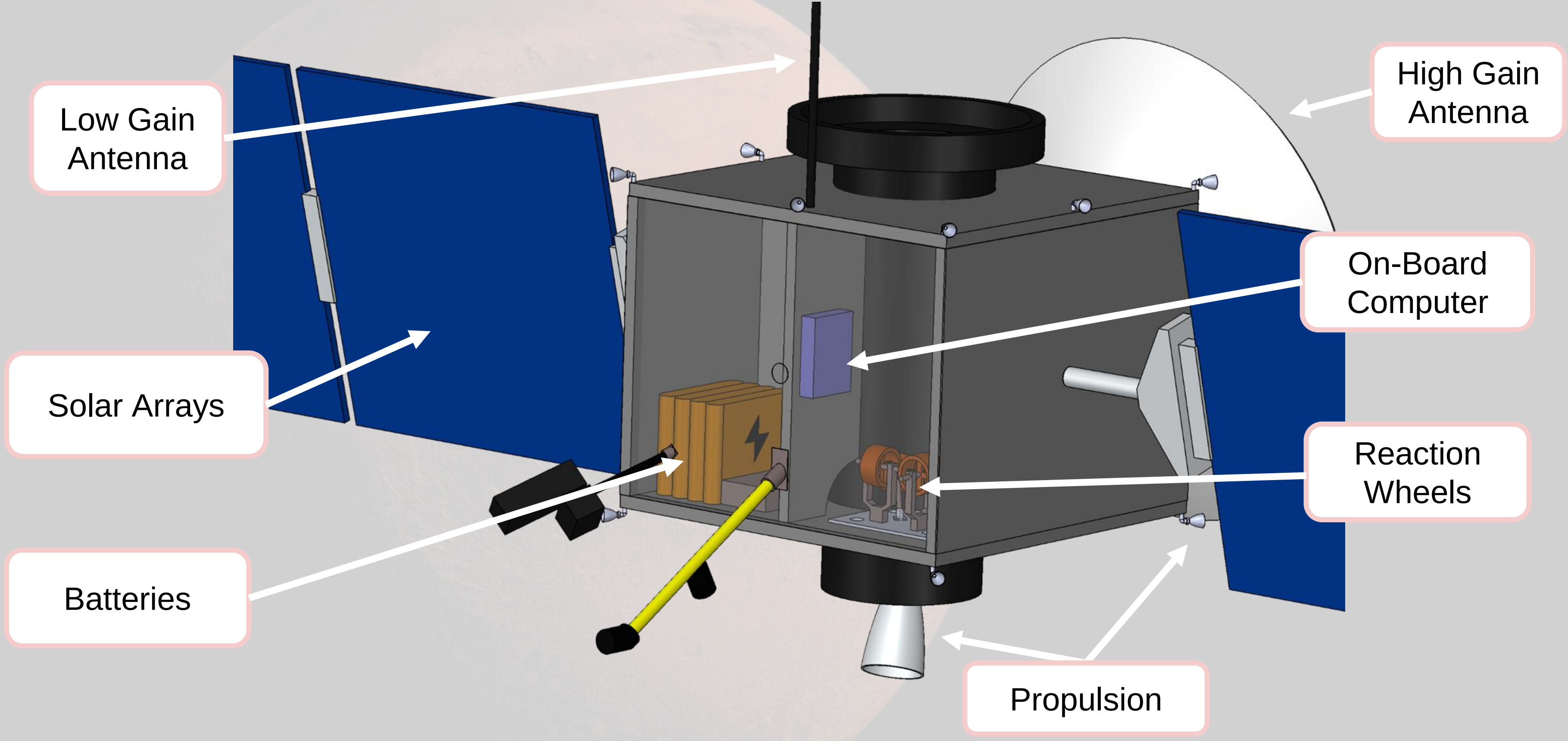
Sara Östman | Leonard Schulz | **Ville Lundén** | Cormac Larkin

System Overview

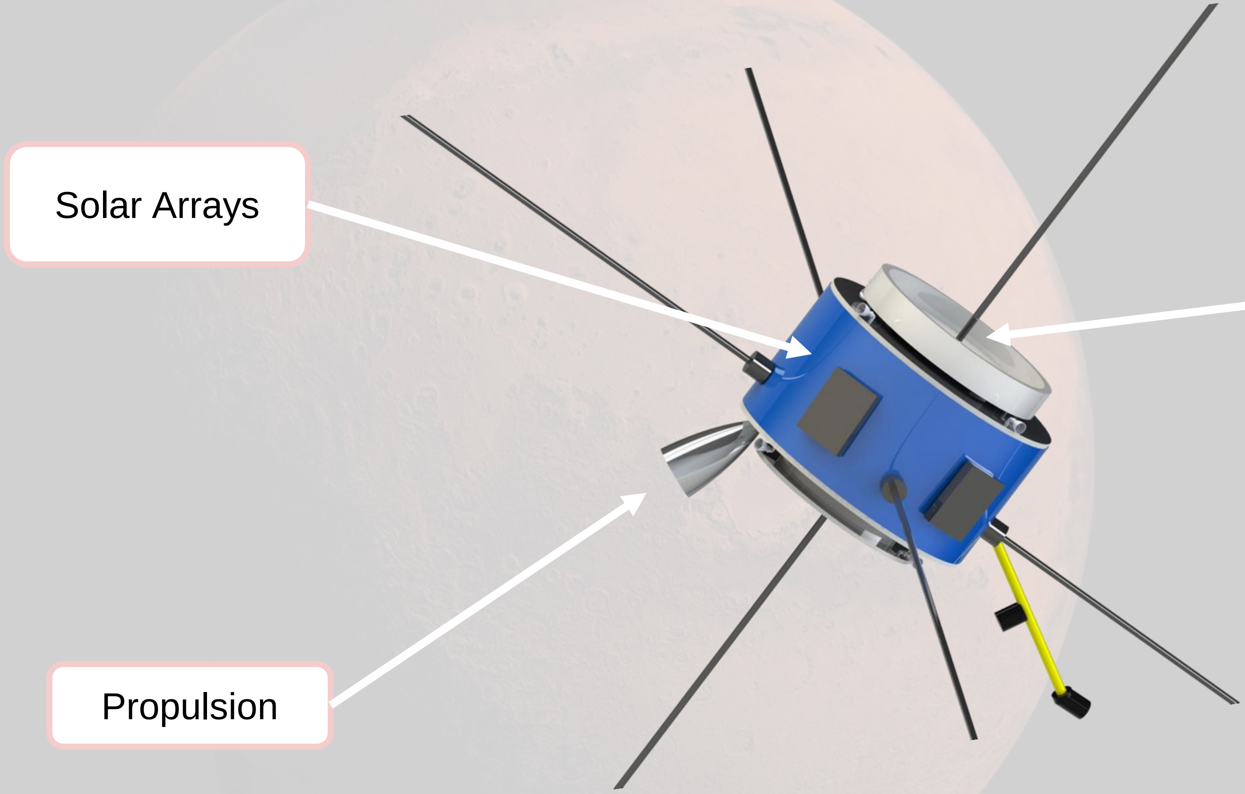


- **M5**
  - **LAUNCHER**
    - ARIANE 64
  - **SPACE SEGMENT**
    - SOLAR WIND ORBITER
      - PAYLOAD
        - FLUXGATE MAGNETOMETER
        - ELECTRON ELECTROSTATIC ANALYSER
        - ION ENERGY SPECTROMETER
      - PROPULSION
      - OBC
      - EPS
      - COMMS
      - THERMAL
      - ATTITUDE CONTROL
      - STRUCTURE
    - 4x MAGNETOSPHERIC FORMATION ORBITER
      - PAYLOAD
        - FLUXGATE MAGNETOMETER
        - ELECTRON ELECTROSTATIC ANALYSER
        - ION ENERGY AND MASS SPECTROMETER
        - ION ELECTRO-STATIC AND TOF VELOCITY ANALYSER
        - LANGMUIR PROBE
      - PROPULSION
      - OBC
      - EPS
      - COMMS
      - THERMAL
      - ATTITUDE CONTROL
      - STRUCTURE
  - **GROUND SEGMENT**
    - CEBREROS (SPAIN)
    - MALARGÜE (ARGENTINA)
    - NEW NORCIA (AUSTRALIA)

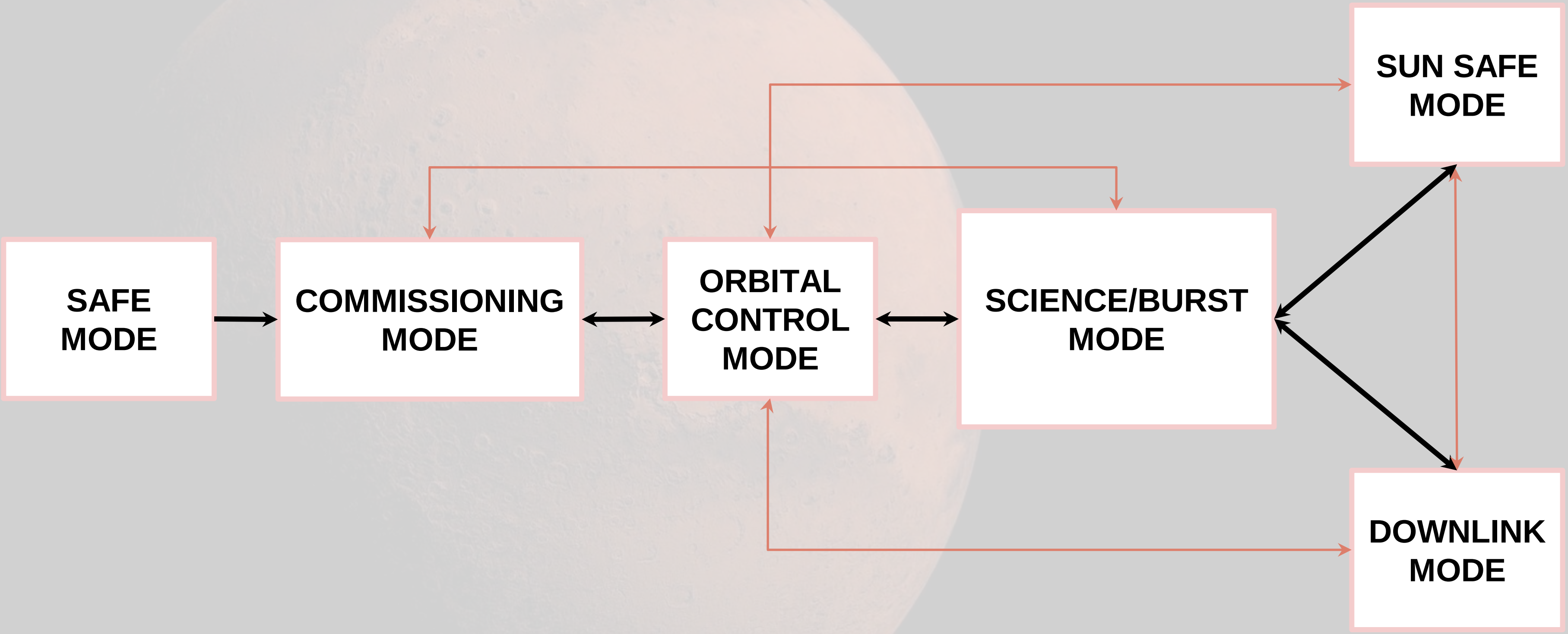
Solar Wind Observatory

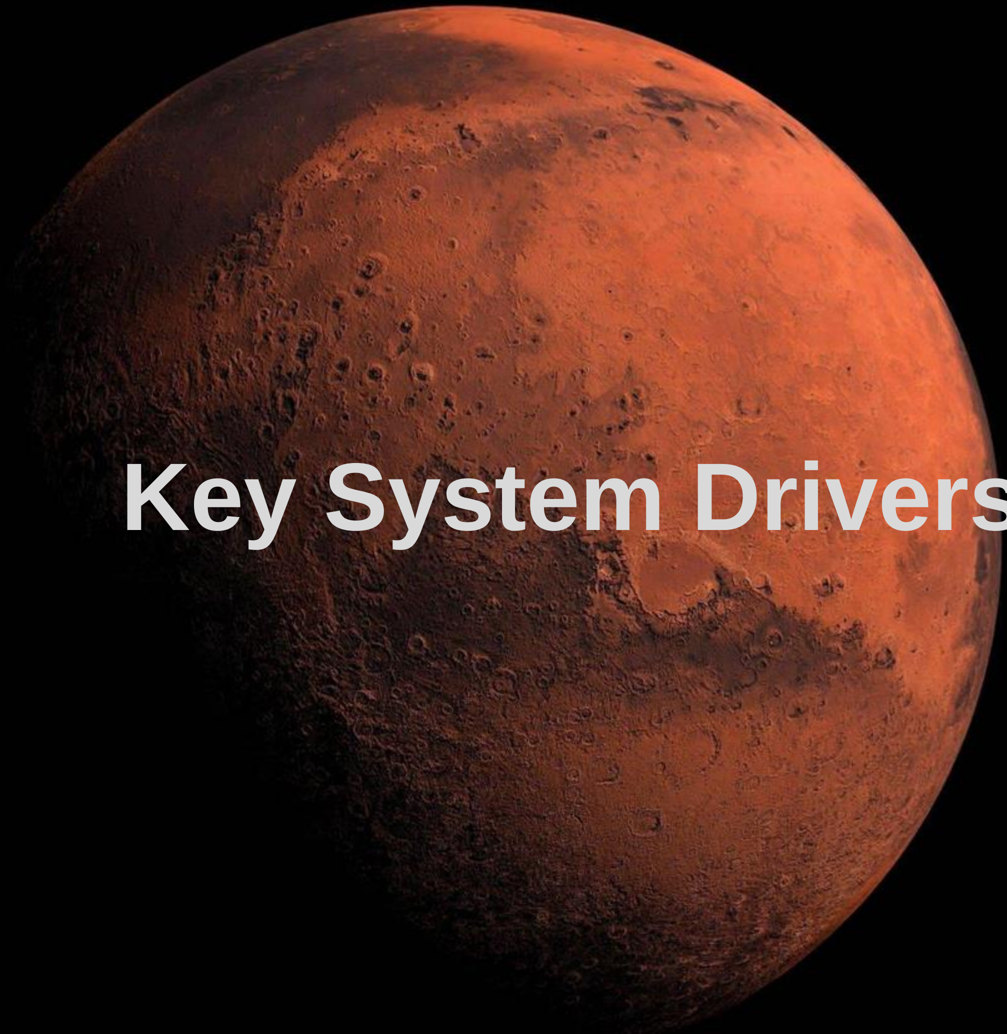


Magnetospheric Formation Orbiter



State Mode Diagram





Key System Drivers

Instrument Data Rates

Solar Wind Observatory
7.3 kbps

Magnetospheric Formation Orbiter
24 kbps

x1 x4

Maximum
105 kbps

- **150 Gbit on-board memory**

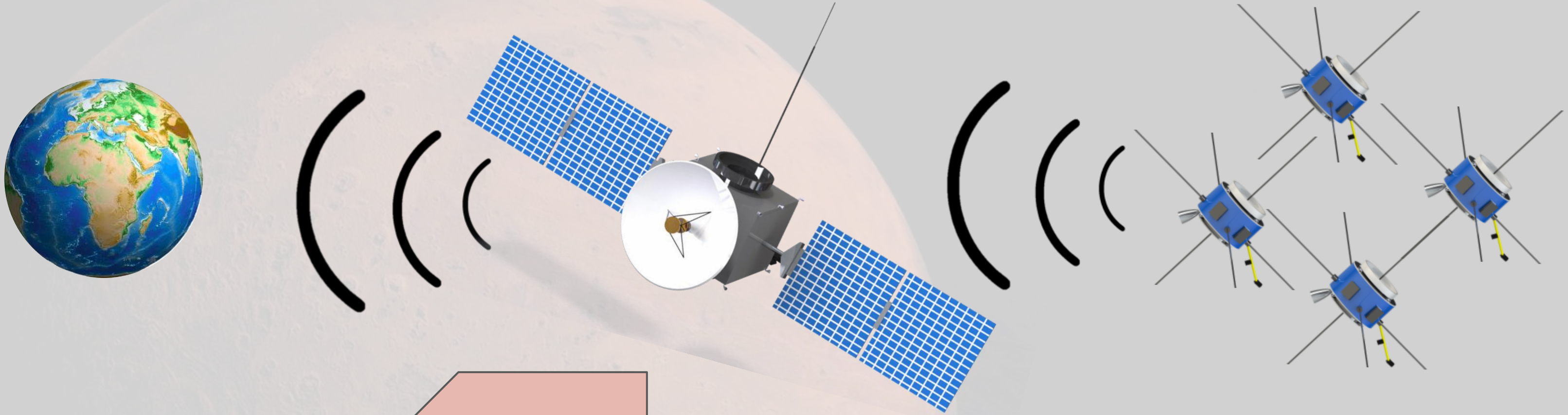
SWO Data Rate		
Instrument	**Data rate [kbps]**	**Measurement time [% of orbit]**
Solar Wind Electron Analyzer	1.5	65
Solar Wind Ion Analyser	2.0	65
Fluxgate magnetometer (2 per s/c)	3.8	65
TOTAL:	**7.3**	

MFO Data Rate		
Instrument	**Data rate [kbps]**	**Measurement time [% of orbit]**
Solar Wind Electron Analyzer	1.5	50
Solar Wind Ion Analyser	2.0	50
Fluxgate magnetometer (2 per s/c)	1.9	50
Suprathermal and Thermal Ion Composition instrument	10.0	50
Electric Field Instrument	6.0	50
Langmuir probe	3.0	50
TOTAL:	**24.4**	

Ground Segment

- ESA Deep Space Antennas:
  - Cebreros (Spain)
  - Malargüe (Argentina)
  - New Norcia (Australia)
- Downlink 3–5 times a week

Link Budget



256–4 kbps

25–0.45 Mbps

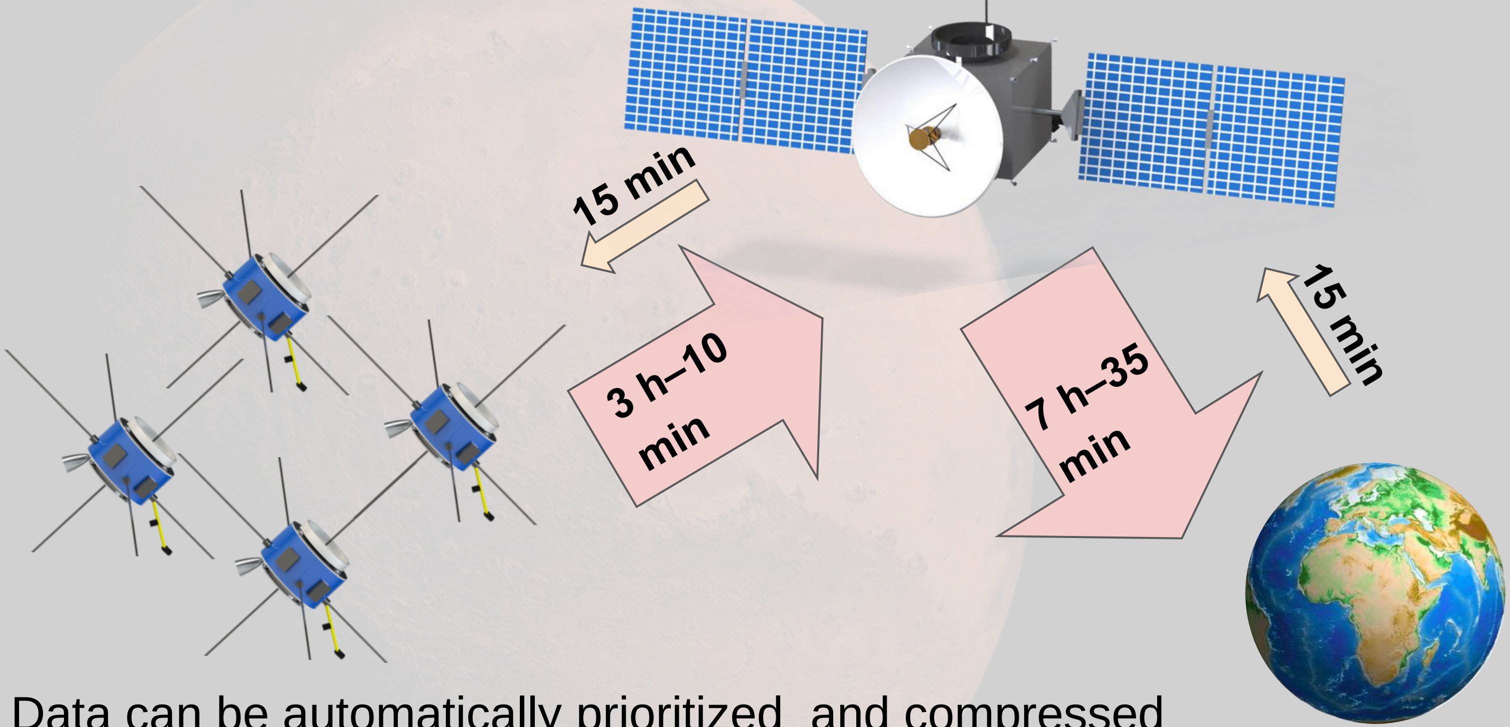
475–38 kbps

475–38 kbps

X- Band ~ 8,4 GHz

S- Band ~ 2,5 GHz

Downlink Times for 24 h Data

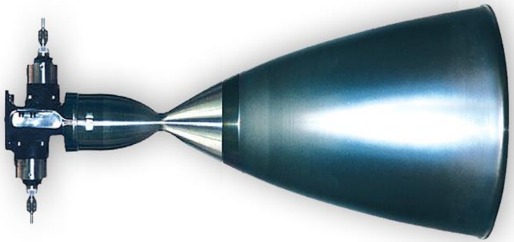


- Data can be automatically prioritized and compressed onboard → reduced downlink time

Orbit & Attitude Control – SWO

- **12 thrusters** in total using MMH/N204 or Hydrazine monopropellant.
- **4 reaction wheels** (3 + 1 spare) for standard pointing and attitude control (heritage: Cluster)
- **2 star trackers** (heritage: Cluster)

Heritage: ExoMars



1 x *400N Bipropellant Thruster*
Image: Orbital Propulsion center

Heritage: Planck

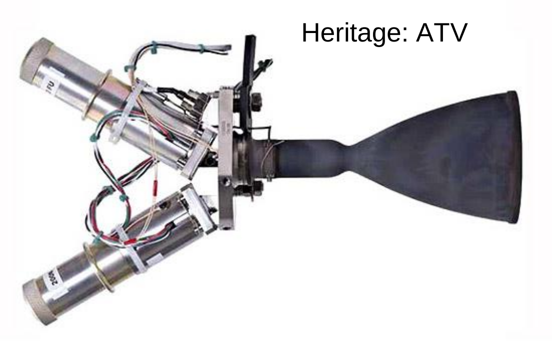
3 x *20N Hydrazine Thruster*
Image: Orbital Propulsion Center

Heritage: THEOS

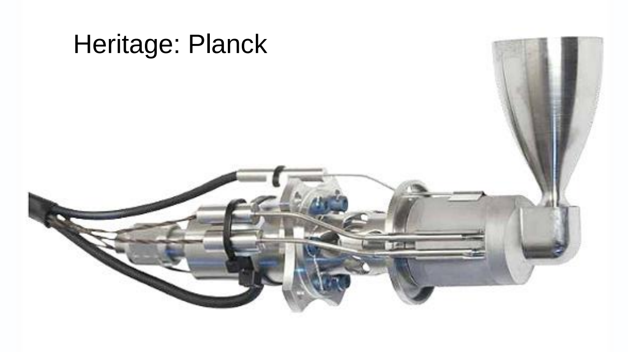
8 x *1N Hydrazine Thruster*
Image: Orbital Propulsion Center

Orbit & Attitude Control – MFO

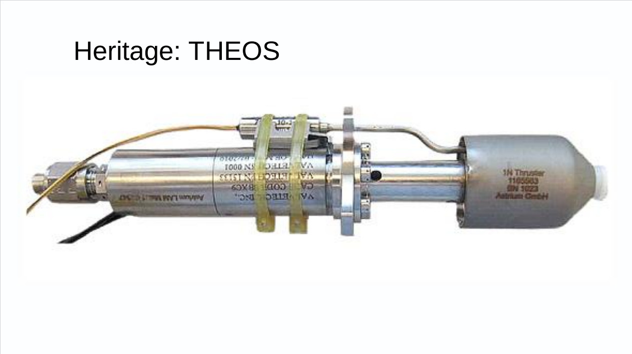
- **12 thrusters** in total using MMH/N204 or Hydrazine monopropellant.
- Spin stabilized
- **2 star trackers** (heritage: Cluster)



1 x *200N Bipropellant*
Image: Orbital Control System



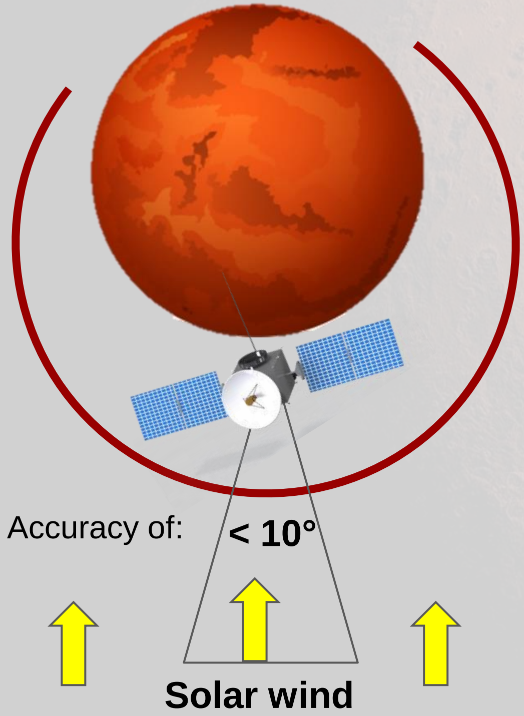
3 x *20N Hydrazine Thruster*
Image: Orbital Propulsion Center



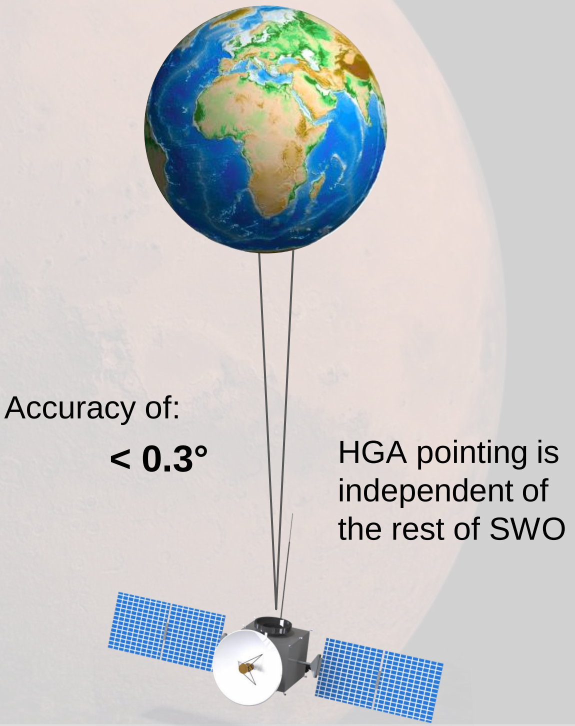
8 x *1N Hydrazine Thruster*
Image: Orbital Propulsion Center

Pointing Stability

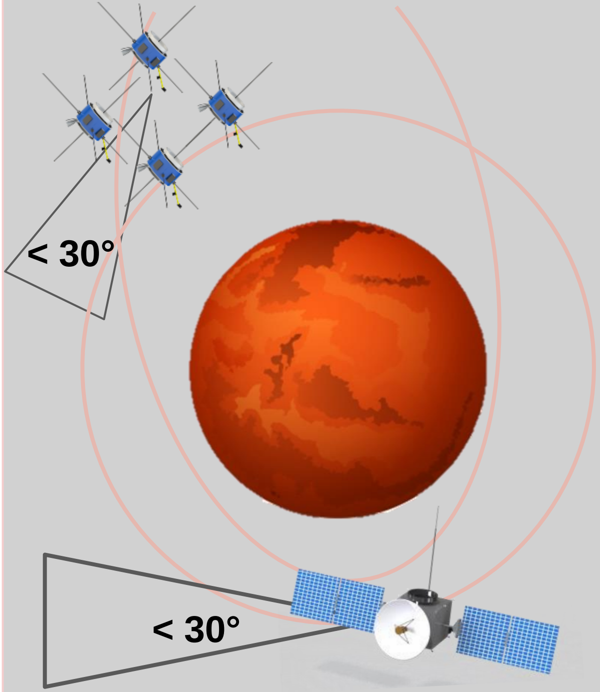
SWO: Solar wind instruments during science mode



SWO: HGA pointing error to Earth



LGA (dipole) requires alignment with orbital plane normal



Power Budget – SWO

- 3000 Wh Silver-Cadmium batteries (heritage: Cluster)
- Total power **consumption range: 240 W to 440 W**
- Total **power generation in Sun: 400 W**
- Maximum **eclipse time 9 %** of orbit
- Batteries fully charged between eclipses
- Degrading of components over lifetime has been considered

	EPS	OBC	COMMS	PAYLOAD	ADCS	PROPULSION	HEATER	TOTAL	MARGINS
CONSUMPTION (W)	5	10	0–400	1–35	24–44	0–30	0–200	**240–440**	35–82
MARGINS	10%	10%	20%	10%	20%	10%	20%		

Power Budget – MFO

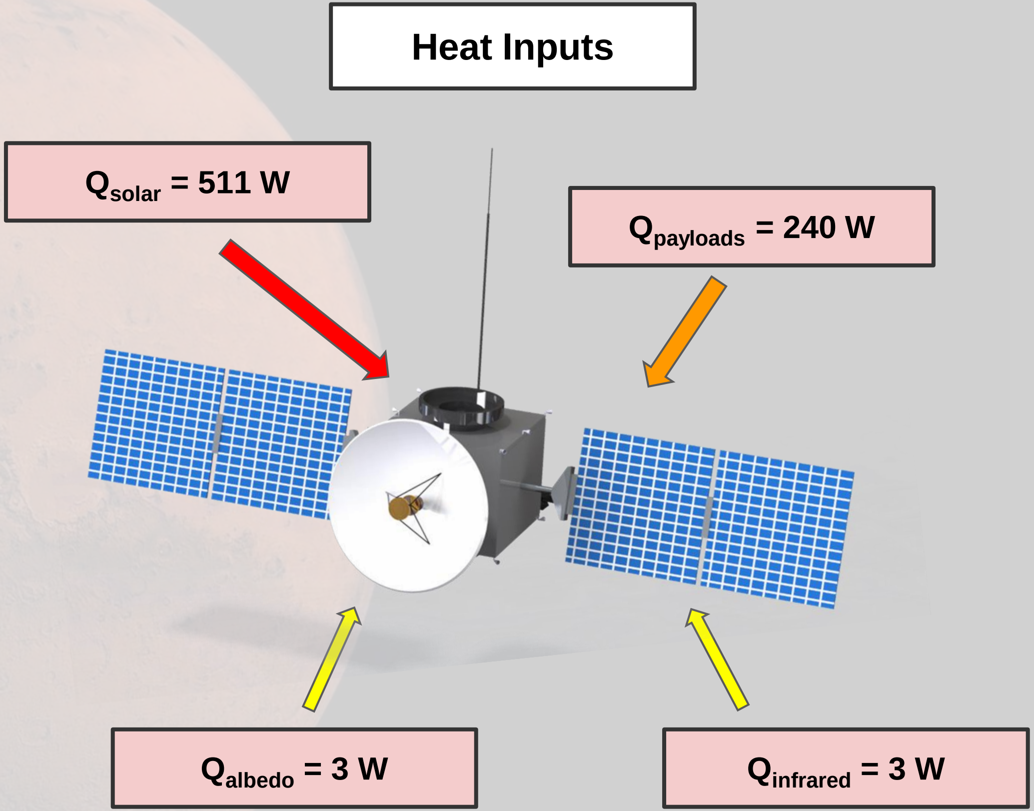
- 1500 Wh Silver-Cadmium batteries (heritage: Cluster)
- Total power **consumption range: 150W to 250W**
- Total **power generation in Sun: 250 W**
- Maximum **eclipse time 14 %** of orbit
- Batteries fully charged between eclipses
- Degrading of components over lifetime has been considered

	EPS	OBC	COMMS	PAYLOAD	ADCS	PROPULSION	HEATER	TOTAL	MARGINS
CONSUMPTION (W)	5	10	0–200	1–26	0–10	0–30	24–134	**150–240**	6.4–44
MARGINS	10%	10%	20%	10%	20%	10%	20%		

Thermal Control Analysis – SWO

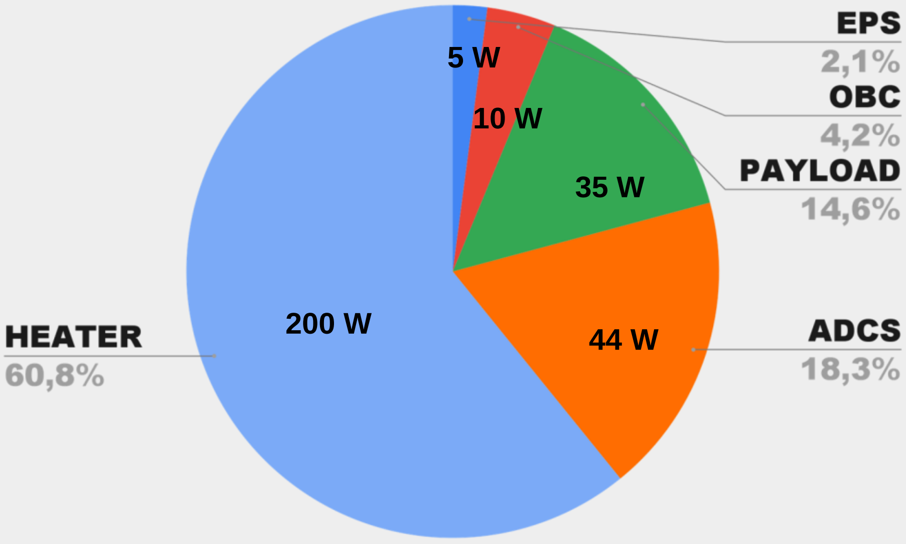
HEAT INPUTS	
Hot Case (ºC)	58
Cold Case (ºC)	−6

ORBITAL INPUTS	
Eclipse time (min)	70
Max. orbital altitude (km)	16948

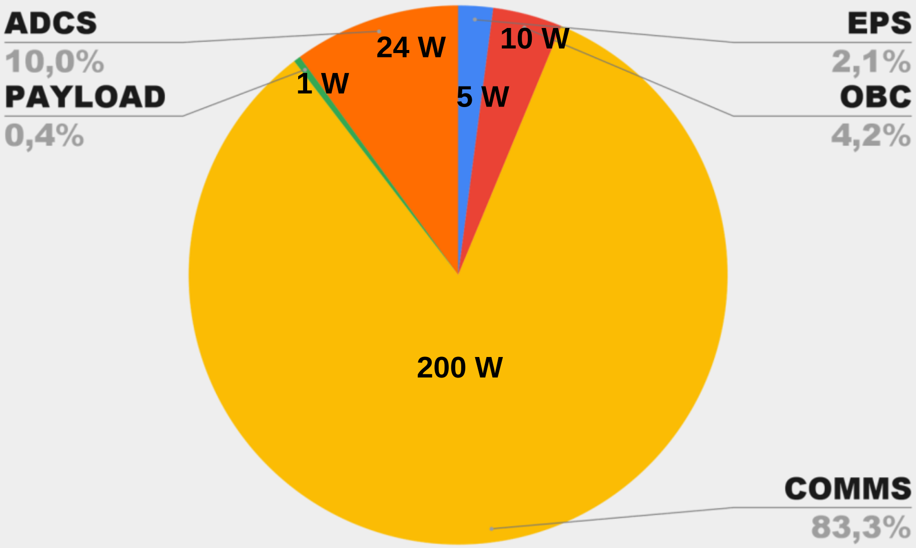


Thermal Budget – SWO

Power Dissipation: 240 W



Science Mode



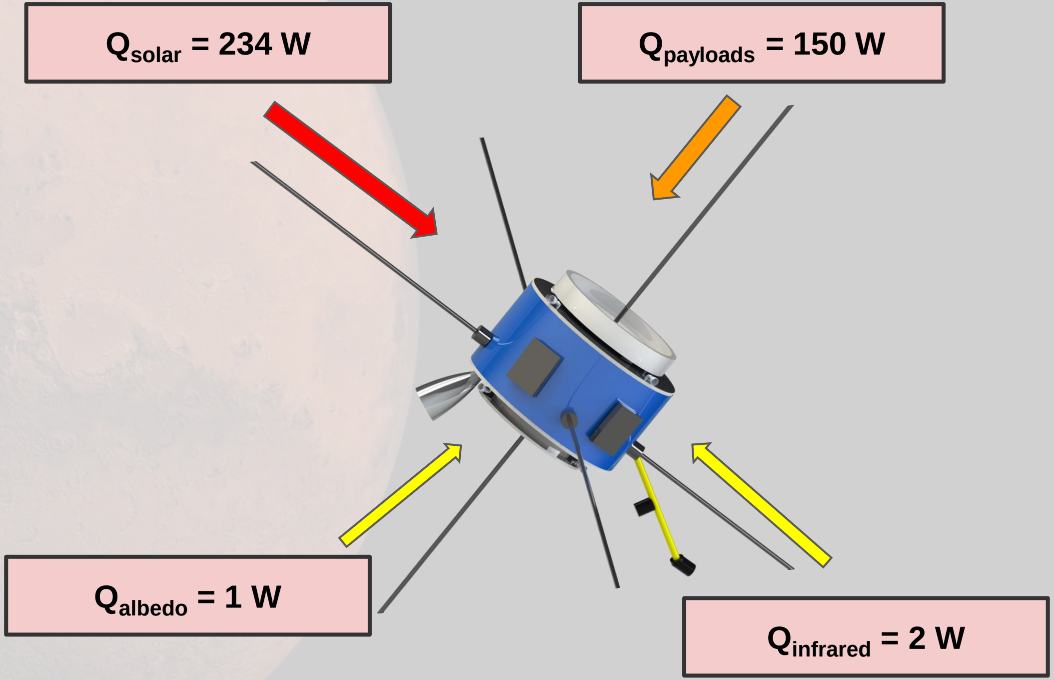
Downlink Mode

Thermal Control Analysis – MFO

TEMPERATURE	
Hot Case (ºC)	32
Cold Case (ºC)	−14

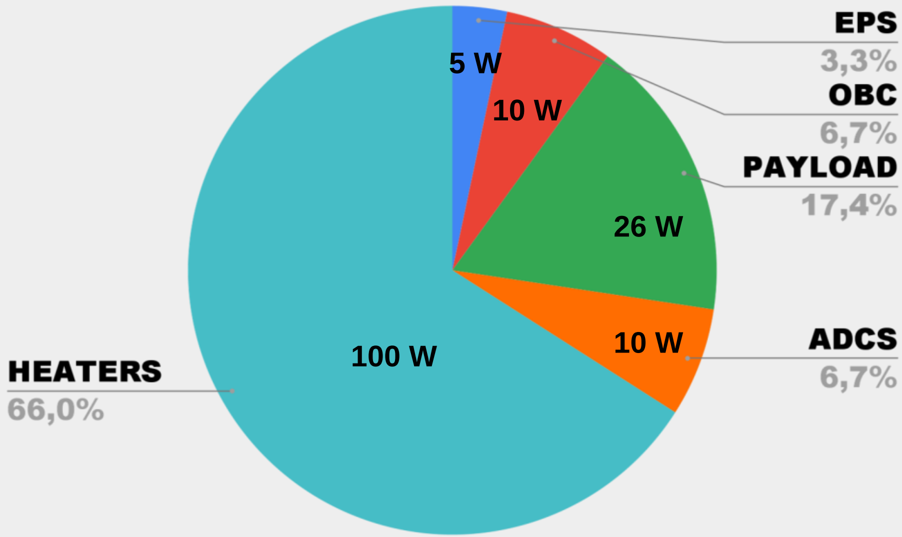
ORBITAL INPUTS	
Eclipse time (min)	112
Max. orbital altitude (km)	20337
Min. orbital altitude	5762

Heat Inputs

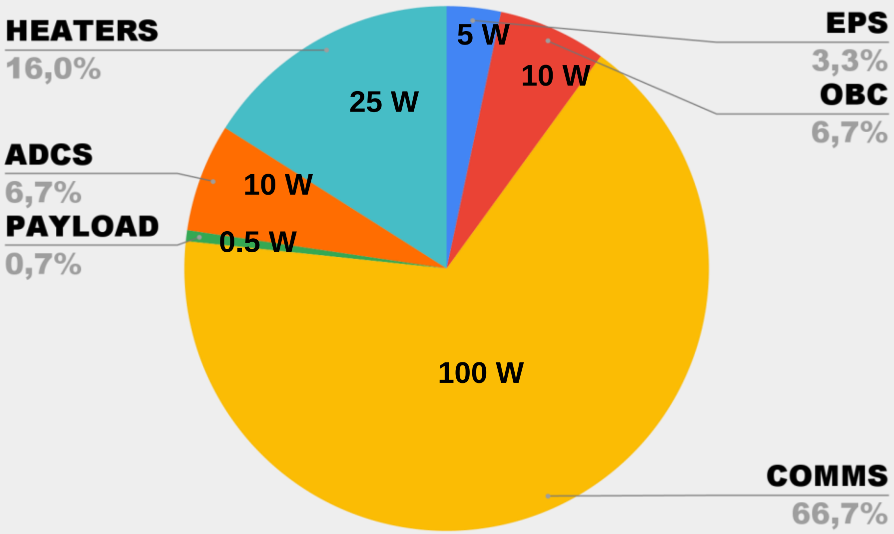


Thermal Budget – MFO

Power Dissipation: 150 W



Science Mode



Downlink Mode

Mass Budget

Solar Wind Observatory
4549 kg

Magnetospheric Formation Orbiter
300 kg

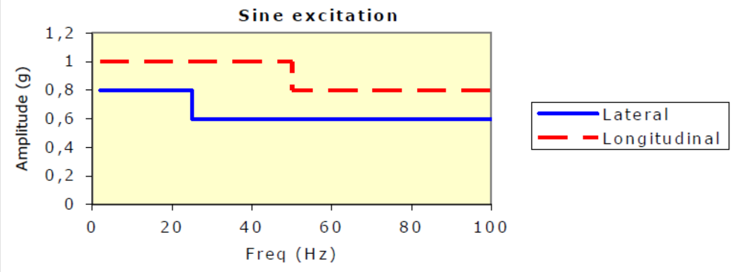
x1

x4

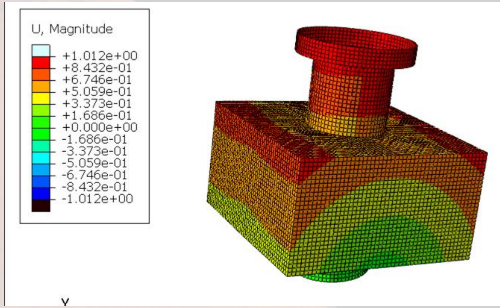
Total
5749 kg

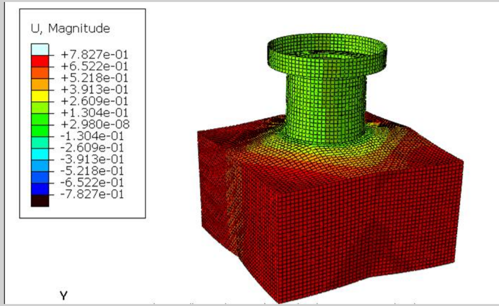
Subsystem	SWO [kg]	1 MFO [kg]	Margin
Main Structure + Adapter	340	35	20,00%
Batteries + Solar Panels	56	74	5,00%
Payload (Instruments)	20	22	5,00%
Antenna	12	10	5,00%
On-board Computer	6,5	6,5	5,00%
Attitude & Orbit Control	30	17	10,00%
Thermal	23	8	20,00%
Dry mass (without margins)	465	164	20,00%
Dry mass (inc.margins)	558	197	
Propellant (inc. margin)	3711	103	10,00%
TOTAL (kg):	**4549**	**300**	

Structure - Modal Analysis



Direction	Frequency band (Hz)	Sine amplitude (g)
Longitudinal	2-50	1.0
	50-100	0.8
Lateral	2-25	0.8
	25-100	0.6





Lateral Frequency:

79.905 Hz

Longitudinal Frequency:

217.88 Hz

- Both lateral and longitudinal frequencies satisfy the launch requirements

Technology Readiness Level – System

System Component (SWO)	TRL
Reaction wheel system	9
Propulsion system	6
Star tracker	6

System Component (MFO)	TRL
Reaction wheel system	9
Propulsion system	6
Star tracker	6

TRL 4	Component and/or breadboard functional verification in laboratory environment.
TRL 5	Component and/or breadboard critical functional verification in laboratory environment.
TRL 6	Model demonstrating the critical functions of the element in a relevant environment
TRL 7	Model demonstrating the element performance for the operational environment
TRL 8	Actual system completed and accepted for flight ("Flight Qualified")
TRL 9	Actual system "flight proven" through successful mission operations

Technology Readiness Level – Instruments

System Component (SWO)	TRL
3-axis fluxgate magnetometer	6
Electron electrostatic analyzer	6
Ion energy spectrometer	6

System Component (MFO)	TRL
3-axis fluxgate magnetometer	6
Electron electrostatic analyzer	6
Ion electrostatic and TOF velocity analyzer	6
Electric dipole antennas	6
Langmuir probes	6

Technology Readiness

TRL 4	Component and/or breadboard functional verification in laboratory environment.
TRL 5	Component and/or breadboard critical functional verification in laboratory environment.
TRL 6	Model demonstrating the critical functions of the element in a relevant environment
TRL 7	Model demonstrating the element performance for the operational environment
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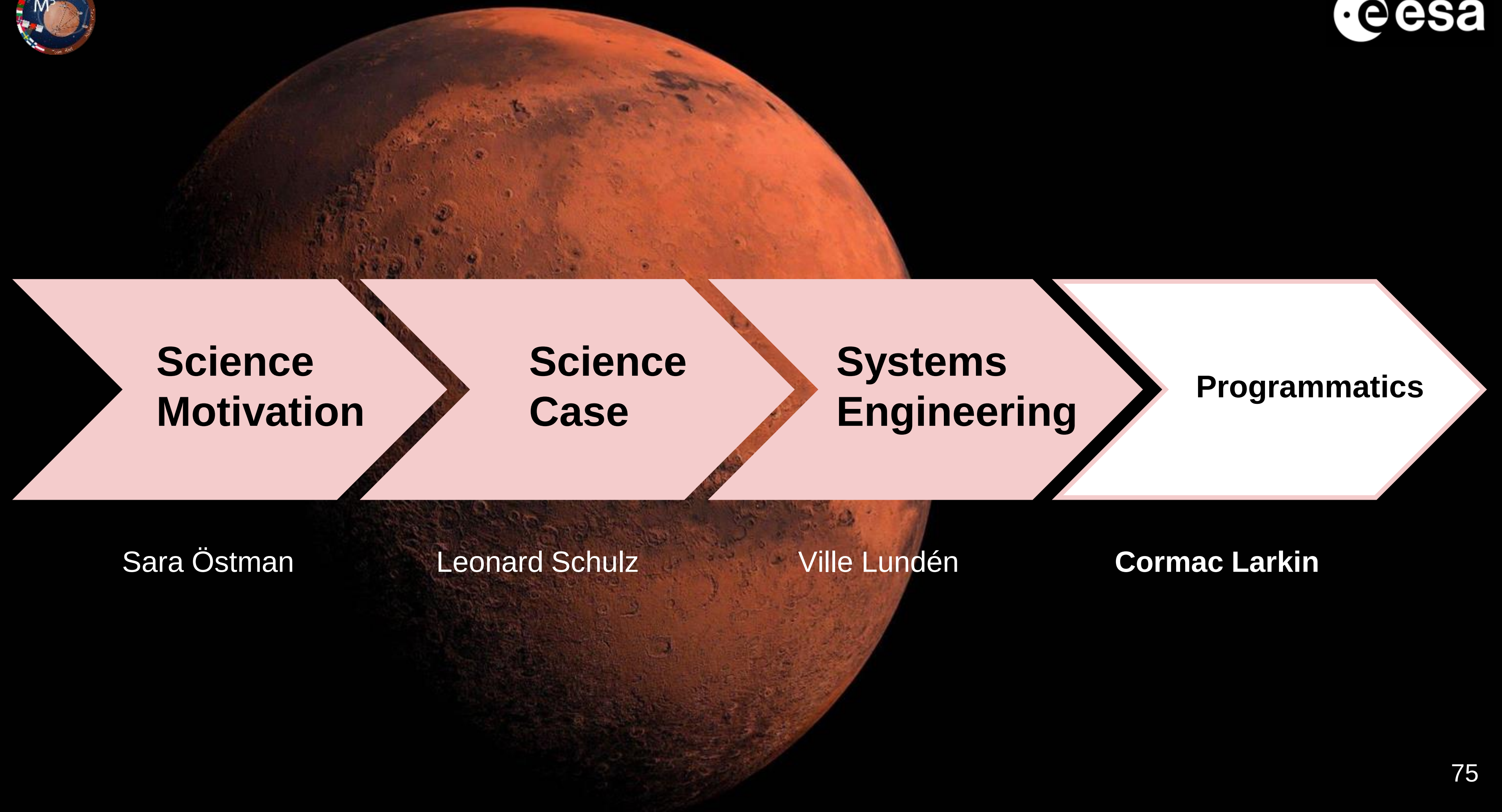
Science Motivation
Science Case
Systems Engineering
Programmatics
Sara Östman
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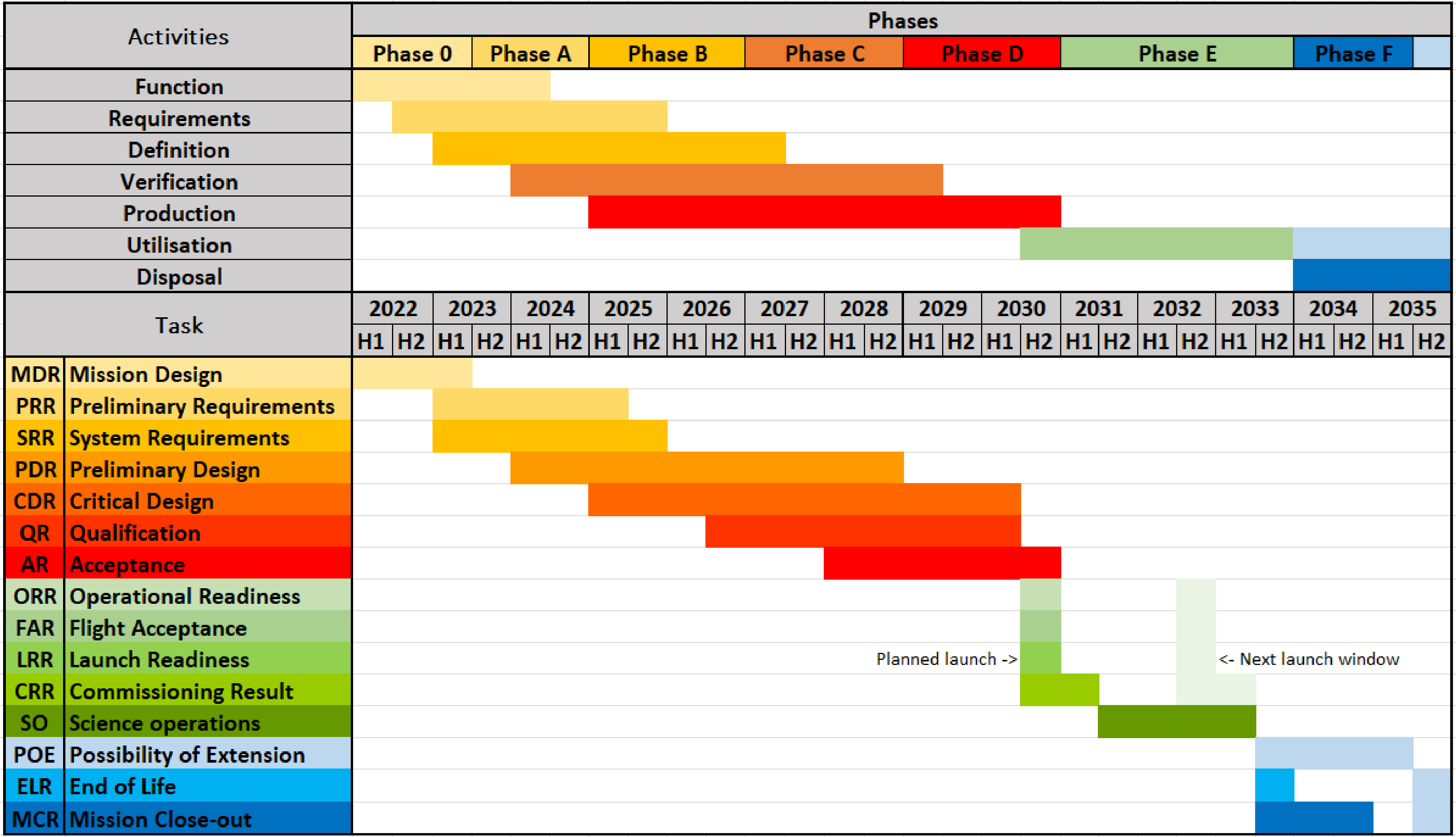

Activities
Phases
Phase 0
Phase A
Phase B
Phase C
Phase D
Phase E
Phase F
Function
Requirements
Definition
Verification
Production
Utilisation
Disposal
Task
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
H1
H2
MDR Mission Design
PRR Preliminary Requirements
SRR System Requirements
PDR Preliminary Design
CDR Critical Design
QR Qualification
AR Acceptance
ORR Operational Readiness
FAR Flight Acceptance
LRR Launch Readiness
CRR Commissioning Result
SO Science operations
POE Possibility of Extension
ELR End of Life
MCR Mission Close-out
Planned launch ->
<- Next launch window

Science Operations

- Science data transmitted from ground stations to ESAC in Madrid
- Science data can be reduced at ESAC and shared with partners

Image credit: ESA

Data Products

Level	Description	Data Product
Raw	Raw telemetry data	
L0	Unprocessed instrument & payload data	CCSDS packets
L1	Partly or uncalibrated time-series data	
L2	L1 with derived parameters and full science calibrations	Research-grade data
L3	L2 with spatial and temporal resampling	
L4	Merged open-source database	Mission-Level Data Product

Risk Assessment

Severity		A - Remote	B - Unlikely	C - Possible	D - Likely	E - Near Certain
	5	Low	Medium	C5 - Loss of SWO C5 - SWO orbit insertion failure High	Very high	Very high
	4	Low	B4 - Loss of MFO Low	Medium	High	Very high
	3	Very low	Low	C3 - (Partial) misalignment of formation Low	Medium	High
	2	Very low	Very low	Low	Low	Medium
	1	Very low	B2 - Launcher Unavailable Very low	Very low	Low	Low

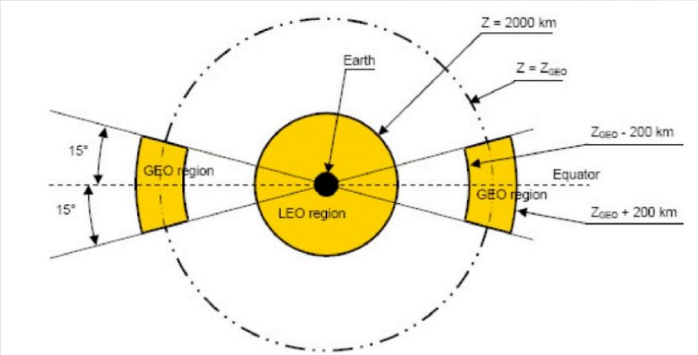
Likelihood

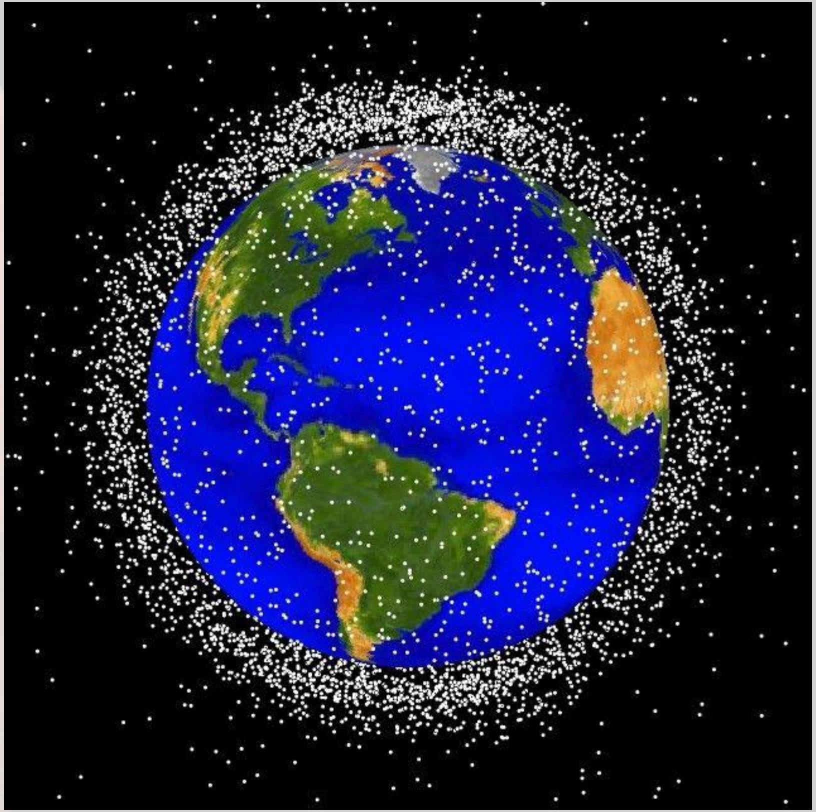
Key Risk Mitigation

Code	Risk	Mitigation
C5 C5	Loss of SWO SWO orbit insertion failure	Possibly use MRO for communication between MFO and Earth, but lose solar wind monitoring Total Mission Loss
B4	Loss of MFO	Add fifth MFO for redundancy or lose some science objectives
C3	(Partial) misalignment of formation	Use more propellant at expense of mission lifetime
B2	Launcher not available	Use alternative launcher or delay launch

Space Debris Mitigation

- Compliance with ESSB-HB-U-002, ESA Space Debris Mitigation Compliance Verification Guidelines
- Compatible with planned orbital insertion
    - No debris left in protected orbits





Planetary Protection

ECSS-U-ST-20C standard - Mission as proposed is Category III and all requirements given in 5.3.2.1 are feasible

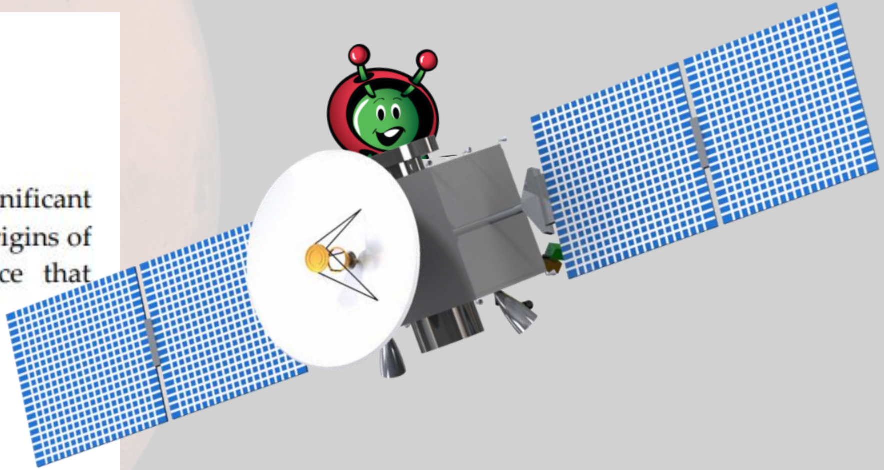
4.2.4 Category III

4.2.4.1 Description

Fly-by and orbital missions to a target body for which there is significant scientific interest relative to the process of chemical evolution and the origins of life and for which scientific opinion provides a significant chance that contamination by a spacecraft can compromise future investigations.

4.2.4.2 Applicability

Mars, Europa, Enceladus.



Cost

Instruments contributed by member states (also possibly international partners)

Element	**% of total Cost at Completion**	**Amount in M€**
ESA Space Segment	47%	700
A64 Launcher	10%	150
Mission & Science Ops	15%	225
ESA Project	11.5%	175
Margin	16.5%	250
	Total	**1500**

Mission envelope

Element	Request	Comments	Status
ESA Cost at Completion	≤ 550 M€ - M-Class ~1500 M€ - L-Class	Includes all elements to be funded by ESA	Not Anticipated Expected
Science objectives and instruments	Any science objective can be proposed - M-Class Specific themes - L-Class	The science instruments must be defined in relation with the science objectives.	Objectives well aligned with Voyage 2050 Senior Committee Report
Launcher	Ariane 62 (M) Ariane 64 (L)	Non European launcher excluded.	Ariane 64 probably required
Spacecraft dry mass	≤1500 kg - M-Class ~6000kg - L-Class	Recommended upper limit in view of the cost target	Not Anticipated Expected
Platform and Science Payload TRL	TRL 5-6 by mission adoption		Yes, all TRL ≥ 6
International collaboration	Can be envisaged		Possible, not required
Spacecraft and science operations	Nominal duration of science operations typically <3 years	Other schemes may be considered subject to feasibility.	Yes for primary science objectives

L-Class Plus required due to mass and complexity

Space Safety for Astronauts on Mars

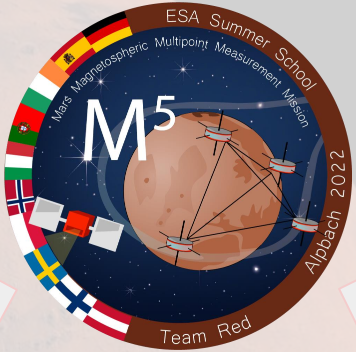
Encourage interest in STEM

OUTREACH OBJECTIVES

Value for money

Social responsibility

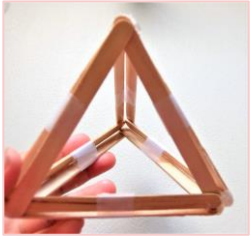
Outreach



Public lectures

Social Media

School activities



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Mars Magnetospheric Multipoint Measurement Mission 2030✨
First Multipoint Mars Space mission 🚀

POSTS TAGGED

Our team

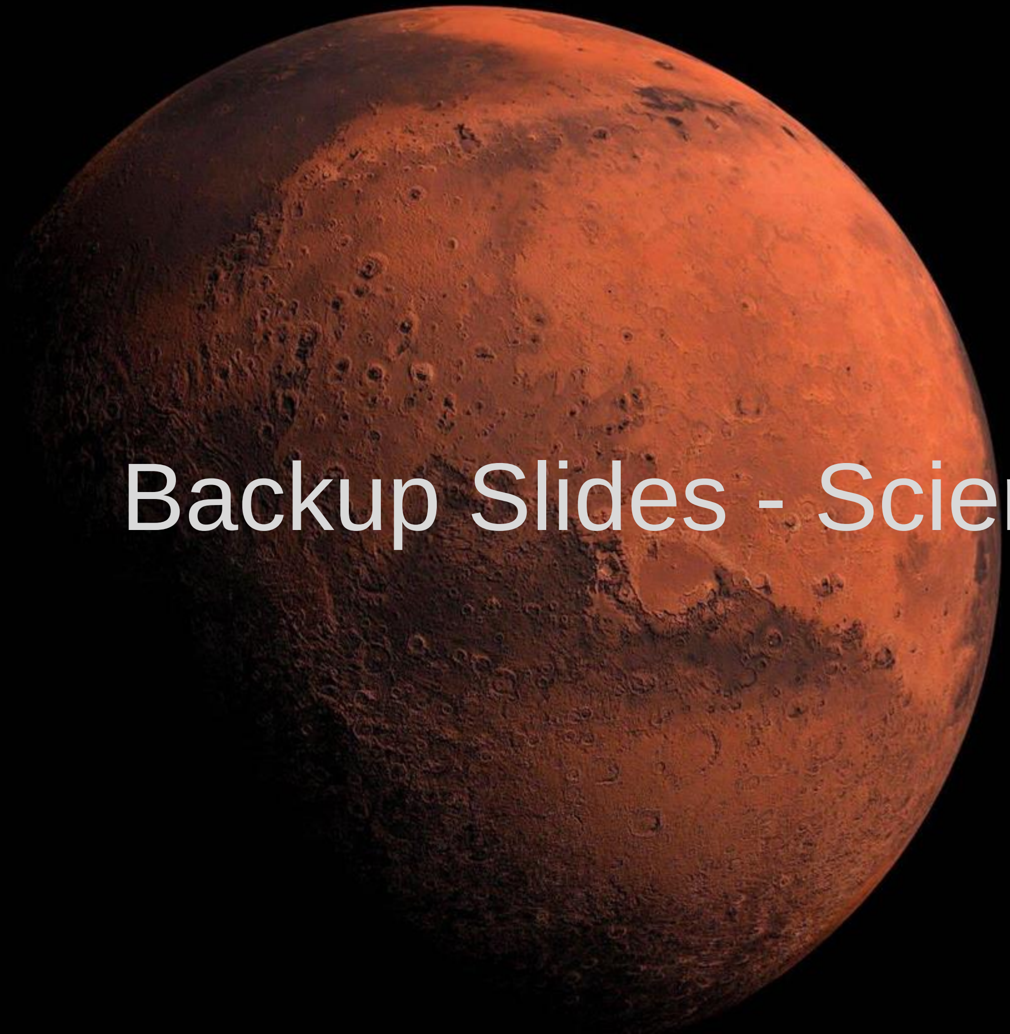
Science: Leonard Schulz (Lead), Pietro Dazzi, Sara Östman, Daniel Teubenbacher

Payload: Markus Baumgartner-Steinleitner (Lead), Marianne Brekkum, Adam Cegla, Sofia Lennerstrand

System Engineering: Ville Lundén (Lead), Vasco Castro Pires, Alessia De Iuliis, Jonas Gesch, Inés Terraza Palanca

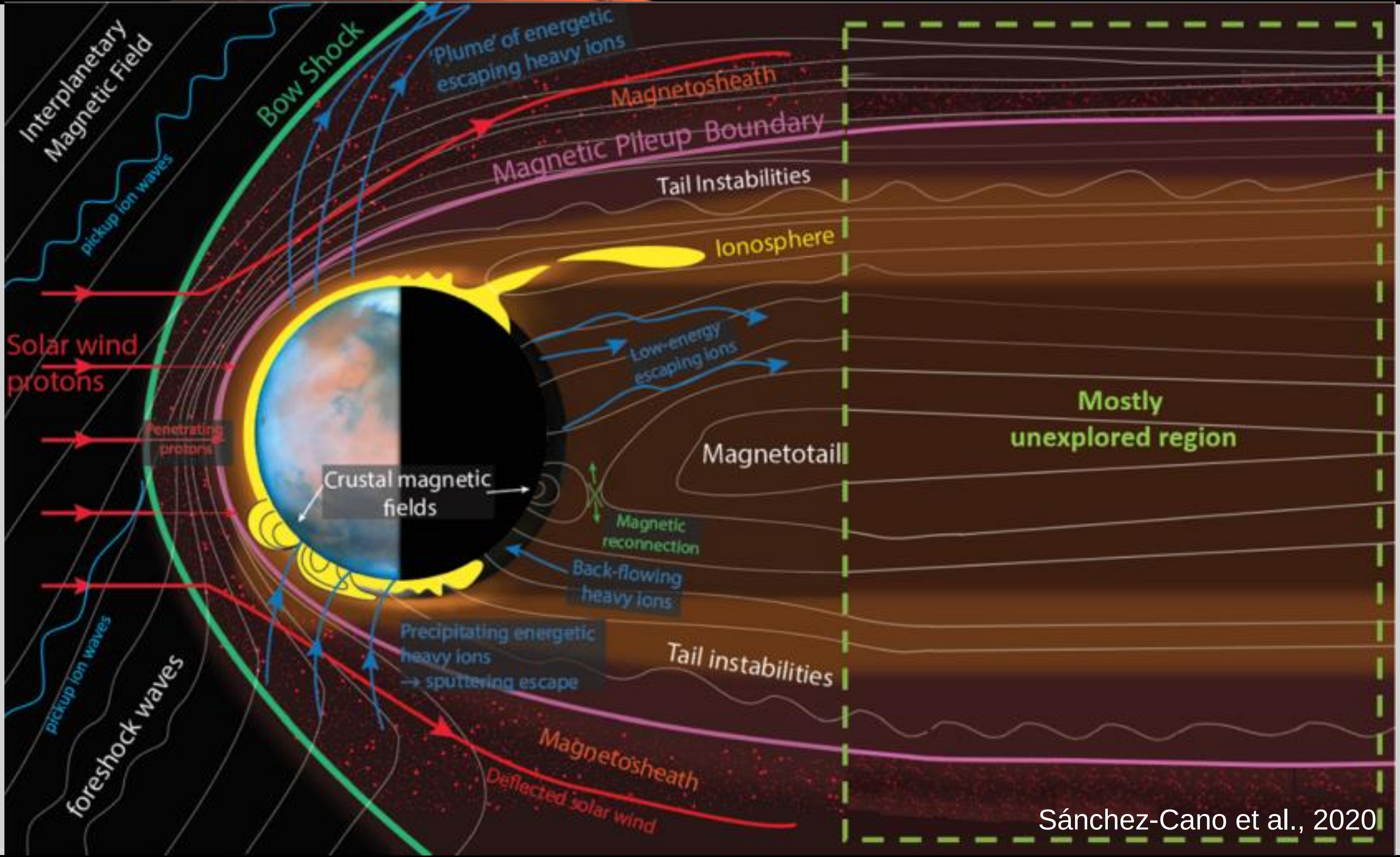
Mission Lead: Cormac Larkin

Tutors: Florine Enengl and Markus with a c Hallmann



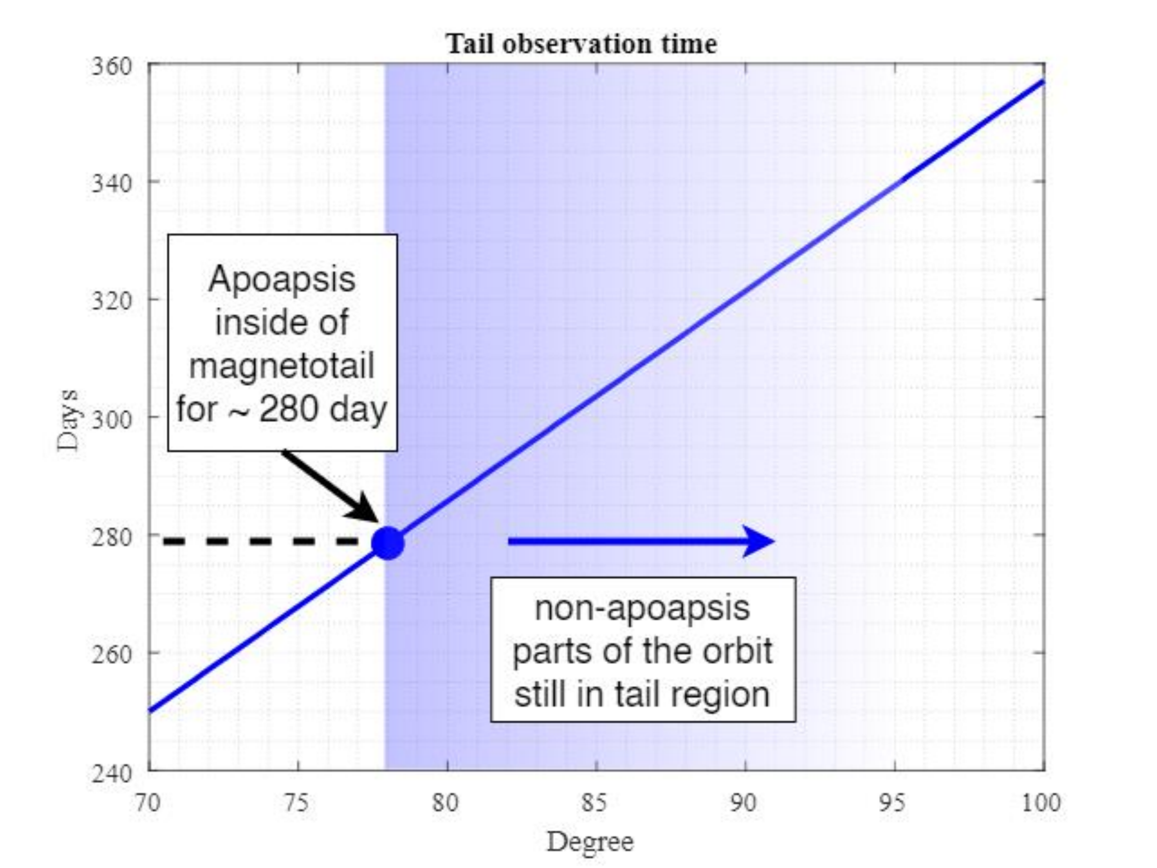
Backup Slides - Science

Structure



Sánchez-Cano et al., 2020

Orbit Time in Tail



Ion Gyroradius

	Magnetic field	Energy	Gyroradius
Solar Wind	3 nT	1 keV	2400 km
Magnetosheath	10 nT	50-500 eV	160-500 km
Near tail	20 nT	10 eV	30 km

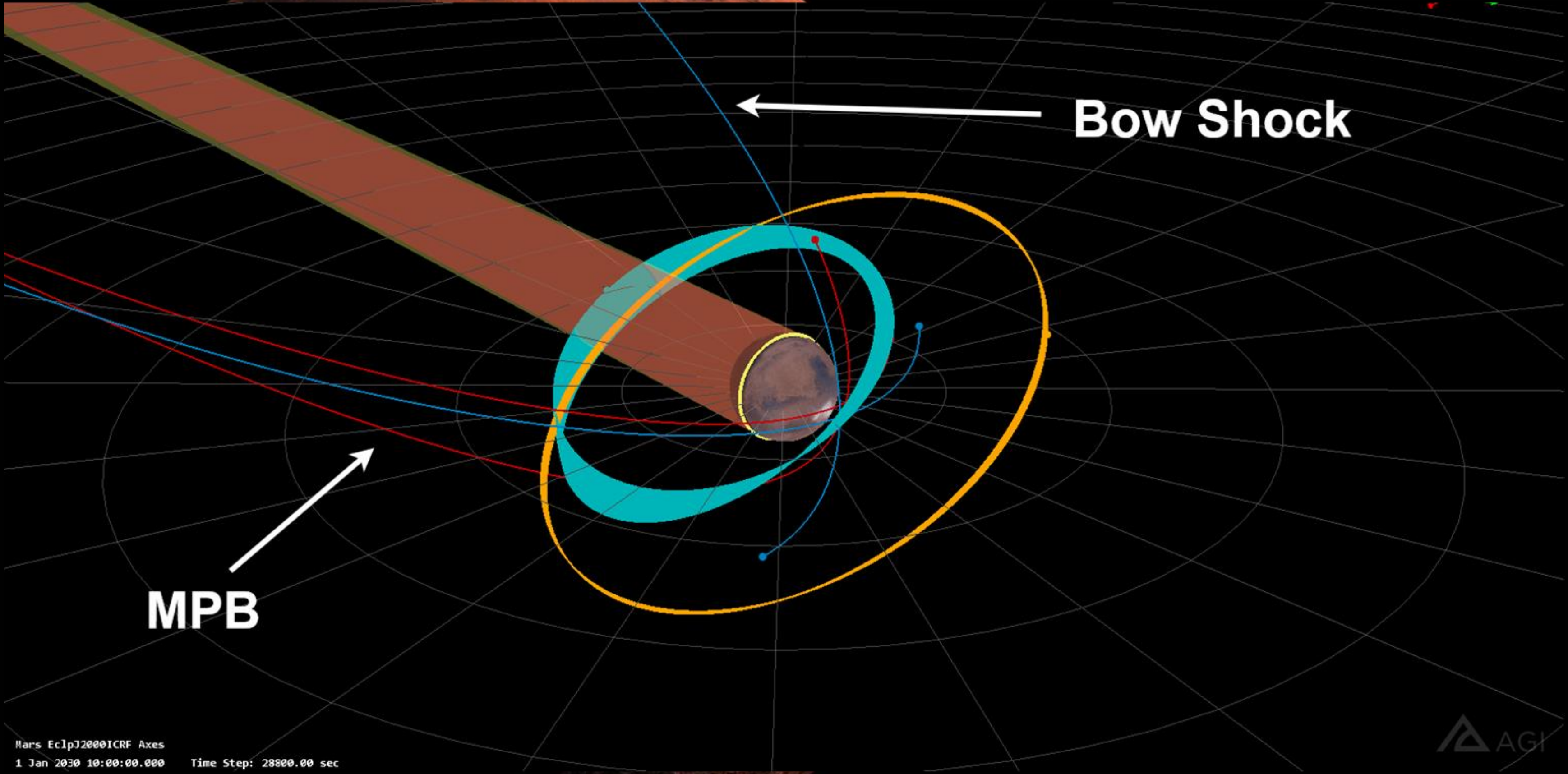
$$r_g = \frac{\sqrt{2Em}}{|q|B}$$

m is the mass, E is the energy, q is the electric charge, and B is the strength of the magnetic field

Additional source $r_{gi,tail}$: Harada, Y., et al. (2015)

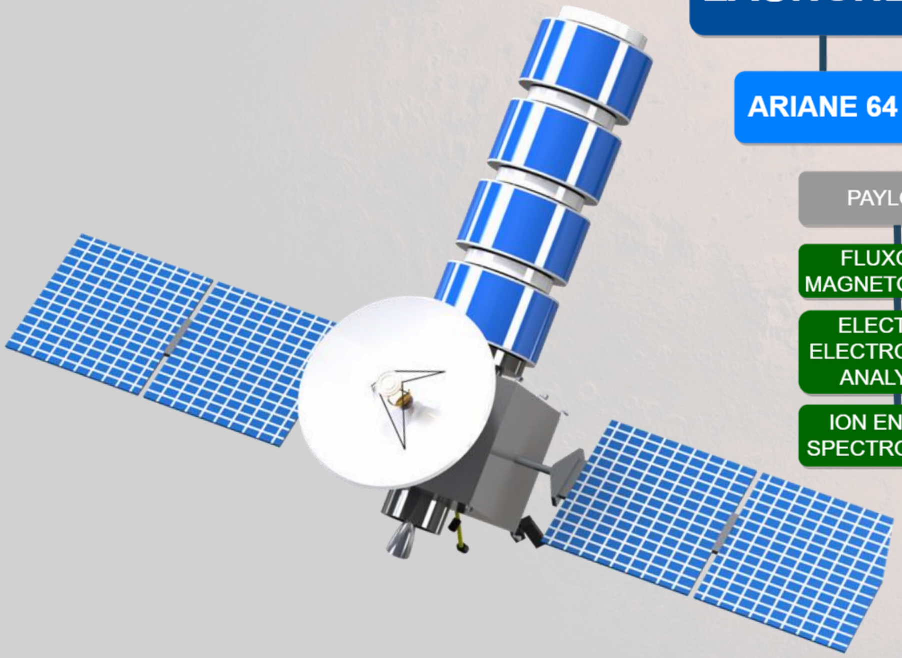
Source Magnetosheath E_{H+}; Nilsson, H., Stenberg, G., Futaana, Y. et al. (2012)

Martian orbit, bow shock and MPB



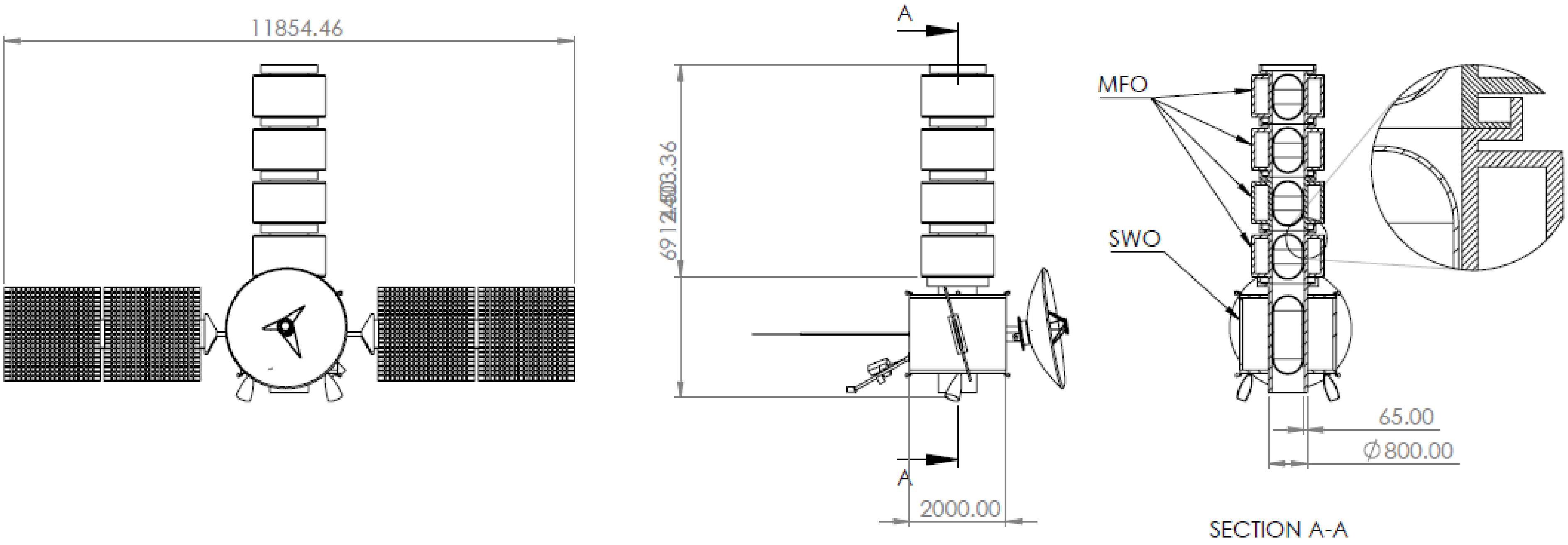
Backup Slides - Engineering

System Overview



- **M5**
  - **LAUNCHER**
    - ARIANE 64
  - **SPACE SEGMENT**
    - **SOLAR WIND ORBITER**
      - PAYLOAD
        - FLUXGATE MAGNETOMETER
        - ELECTRON ELECTROSTATIC ANALYSER
        - ION ENERGY SPECTROMETER
      - PROPULSION
      - OBC
      - EPS
      - COMMS
      - THERMAL
      - ATTITUDE CONTROL
      - STRUCTURE
    - **4x MAGNETOSPHERIC FORMATION ORBITER**
      - PAYLOAD
        - FLUXGATE MAGNETOMETER
        - ELECTRON ELECTROSTATIC ANALYSER
        - ION ENERGY AND MASS SPECTROMETER
        - ION ELECTRO-STATIC AND TOF VELOCITY ANALYSER
        - LANGMUIR PROBE
      - PROPULSION
      - OBC
      - EPS
      - COMMS
      - THERMAL
      - ATTITUDE CONTROL
      - STRUCTURE
  - **GROUND SEGMENT**
    - CEBREROS (SPAIN)
    - MALARGÜE (ARGENTINA)
    - NEW NORCIA (AUSTRALIA)

Structure - Details and General Dimensions



State Modes

- **Safe Mode:** Used to travel to Mars to ensure the power for different subsystems is off and power is saved.
- **Commissioning Mode:** Turn on instruments and payloads to perform testing and health check.
- **Orbital control Mode:** Maneuvering with thrusters.
- **Science Mode:** Instruments are on and measuring.
- **Burst Mode:** Science Mode with increased data rate (only MFO).
- **Sun Safe Mode:** Entered automatically when battery voltage drops below the setted voltage threshold. Several high-consuming energy functions cannot be performed, such as payload and downlink execution, in order to extend operating life.
- **Downlink Mode:** Transmit data.

Magnetic Cleanliness

- Strict magnetic cleanliness required to comply with magnetic field accuracy and resolution requirements
  - All fluxgate magnetometers on 5 m long booms
  - All soft magnetic materials should be avoided on the spacecraft, in particular close to the magnetometers
  - All current loops should be minimized and compensated for where possible
  - Magnetic dipole moments of the spacecraft should be compensated for

Link Budget SWO

BEST CASE: Closest position

LINK BUDGET	[dB]
EIRP	**21,7**
Antenna Pointing Loss	**−1,1**
Transmission Loss	**−165,8**
Rx G/T	**−13**
Boltzmann's constant (k)	**228,6**
Data Rate	**−53**
Final EB/EN	**18,5**
LINK BUDGET (Mbps)	**25,15**

TRANSMISSION LOSS	
Range (km)	**400000000**
Transmission	**0,65**
Spaceloss (dB)	**−267,6**

WORST CASE: Furthest position

LINK BUDGET	[dB]
EIRP	**66,8**
Antenna Pointing Loss	**−1,1**
Transmission Loss	**−284,8**
Rx G/T	**50,3**
Boltzmann's constant (k)	**228,6**
Data Rate	**−53**
Final EB/EN	**6,8**
LINK BUDGET (Mbps)	**0,48**

TRANSMISSION LOSS	
Range (km)	**55000000**
Transmission	**0,65**
Spaceloss (dB)	**−284,8**

Mass Budget

Subsystem	SWO [kg]	1 MFO [kg]	Margin
Main Structure	288,0	35,0	1,20
Battery x 2	37,8	18,9	1,05
Payload (Instruments)	21,0	22,0	1,05
Antenna	12,7	10,5	1,05
On-board Computer	6,8	6,5	1,05
Attitude & Orbit Control (thrusters, star tracker, reaction wheels)	33,0	18,3	1,10
Thermal	32,8	10,8	1,20
Solar panels (panels + power system)	47,3	68,3	1,05

Subsystem	SWO [kg]	1 MFO [kg]	Margin
Rail Structure (we can delete this)	0,0	0,0	1,20
Launcher Adapter	100,0	0,0	
Overall Margins (20%)			1,20
Final mass budget	**SWO [kg]**	**1 MFO [kg]**	**Margin**
Dry mass (without margins)	546,6	179,5	
Dry mass (with margins)	695,3	228,3	
Propellant	764,8	251,2	1,10
TOTAL (kg):	**1453,7**	**529,7**	

Power Budget - SWO

- ~3000 Wh Silver-Cadmium batteries (heritage from Cluster)
  - Large capacity to ensure batteries are not depleted over 15 % per charge cycle to increase battery lifetime

MODE	CONSUMPTION (W)							Total production: 700 W	
	EPS (TBC)	OBC (RAD-750)	COMMS	PAYLOAD	ADCS (TBC)	PROPULSION	HEATER	TOTAL CONSUMPTION (W)	MARGINS (W)
Safe Mode	5	10	0	1	24	0	200,0	240	41,98
Science Mode	5	10	0	35	44	0	146,0	240	61,5
Commissioning Mode	5	10	0	1	24	0	200,0	240	41,98
Downlink mode	5	10	400	1	24	0	0,0	440	81,98
Sun Safe mode	5	10	0	1	24	0	200,0	240	41,98
Orbital control mode	5	10	0	1	44	30	150,0	240	35,38
MARGINS	10%	10%	20%	10%	20%	10%	20%		

Power budget - MFO

- ~1500 Wh Silver-Cadium batteries (heritage from Cluster)
  - Large capacity to ensure batteries are not depleted over 15 % per charge cycle to increase battery lifetime

MODE	CONSUMPTION (W)							Total production: 250 W	
	EPS	OBC	COMMS	PAYLOAD	ADCS	HEATERS	PROPULSION	POWER BUDGET (W)	MARGINS (W)
Safe Mode	5,0	10,0	0,0	1,0	0,0	134,0	0,0	150,0	14,9
Science Mode	5,0	10,0	0,0	26,1	10,0	99,0	0,0	150,1	16,6
Burst Mode	5,0	10,0	0,0	26,1	10,0	99,0	0,0	150,1	16,6
Downlink mode	5,0	10,0	200,0	1,0	10,0	24,0	0,0	250,0	44,1
Orbital control mode	5,0	10,0	0,0	1,0	10,0	74,0	50,0	150,0	14,1
Commissioning Mode	5,0	10,0	0,0	1,0	0,0	134,0	0,0	150,0	14,9
Sun Safe Mode	5,0	10,0	0,0	1,0	0,0	134,0	0,0	150,0	1,5
MARGINS	0,1	0,1	0,2	0,1	0,2	0,1	0,1		

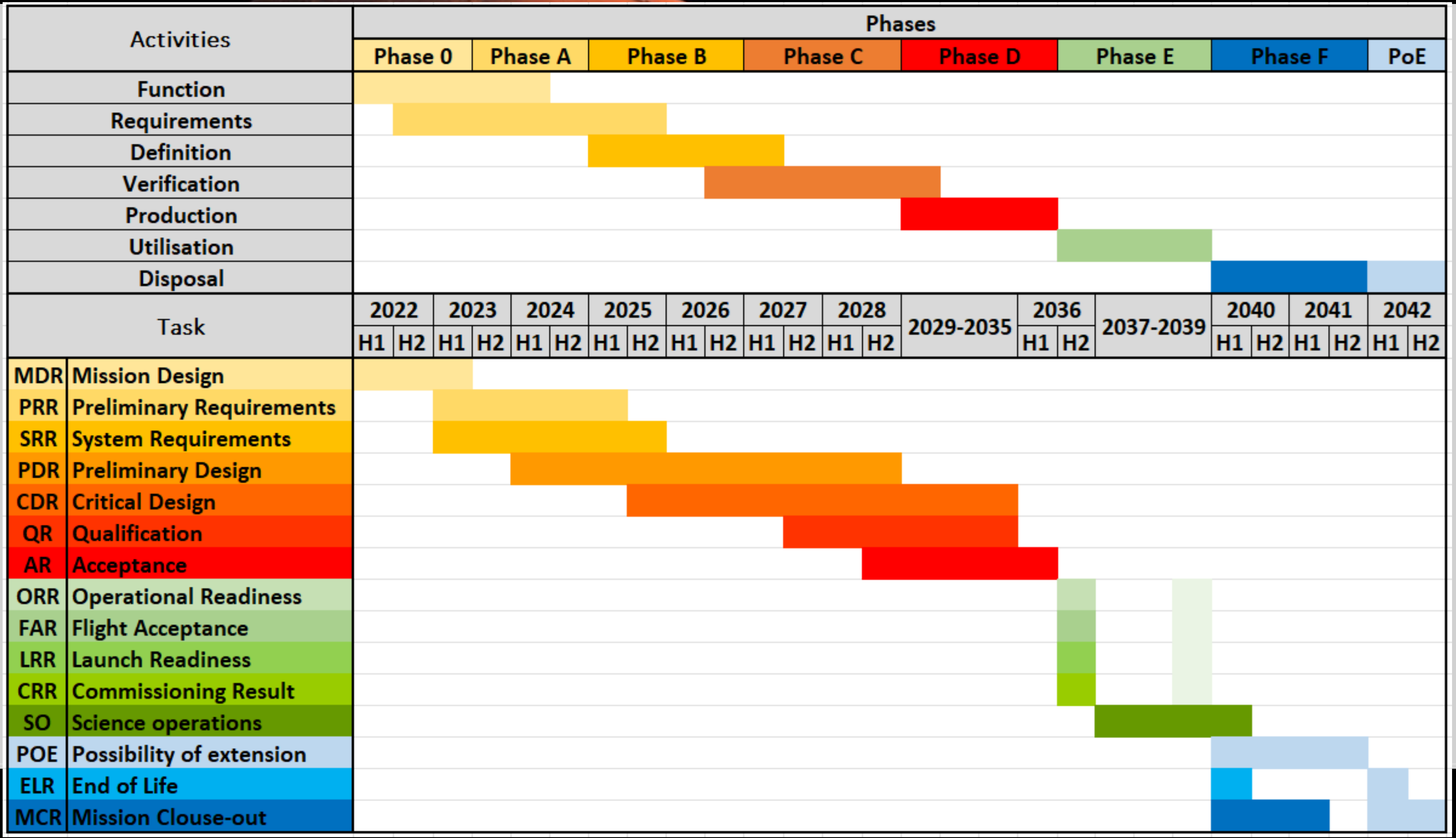
Thermal budget - SWO

MODE	HEAT DISSIPATION (W)							Allowed range: 80 W to 280 W	
	EPS (TBC)	OBC (RAD-750)	COMMS	PAYLOAD	ADCS (TBC)	PROPULSION	HEATER	TOTAL DISSIPATION (W)	MARGINS (W)
Safe Mode	5,0	10,0	0,0	1,0	24,0	0,0	200,0	240,0	42,0
Science Mode	5,0	10,0	0,0	35,0	44,0	0,0	146,0	240,0	61,5
Commissioning Mode	5,0	10,0	0,0	1,0	24,0	0,0	200,0	240,0	42,0
Downlink mode	5,0	10,0	200,0	1,0	24,0	0,0	0,0	240,0	42,0
Sun Safe mode	5,0	10,0	0,0	1,0	24,0	0,0	200,0	240,0	42,0
Orbital control mode	5,0	10,0	0,0	1,0	44,0	30,0	150,0	240,0	35,4
MARGINS	0,1	0,1	0,2	0,1	0,2	0,1	0,2		

Thermal budget - MFO

MODE	DISSIPATION							Allowed range: 80 W to 280 W	
	EPS	**OBC**	**COMMS**	**PAYLOAD**	**ADCS**	**HEATERS**	**PROPULSION**	**TOTAL DISSIPATION (W)**	**MARGINS (W)**
Safe Mode	5,0	10,0	0,0	1,0	0,0	134,0	0,0	150,0	14,9
Science Mode	5,0	10,0	0,0	26,1	10,0	99,0	0,0	150,1	16,6
Burst Mode	5,0	10,0	0,0	26,1	10,0	99,0	0,0	150,1	16,6
Downlink mode	5,0	10,0	100,0	1,0	10,0	24,0	0,0	150,0	24,1
Orbital control mode	5,0	10,0	0,0	1,0	10,0	74,0	50,0	150,0	14,1
Commissioning Mode	5,0	10,0	0,0	1,0	0,0	134,0	0,0	150,0	14,9
Sun Safe Mode	5,0	10,0	0,0	1,0	0,0	134,0	0,0	150,0	1,5
MARGINS	0,1	0,1	0,2	0,1	0,2	0,1	0,1		

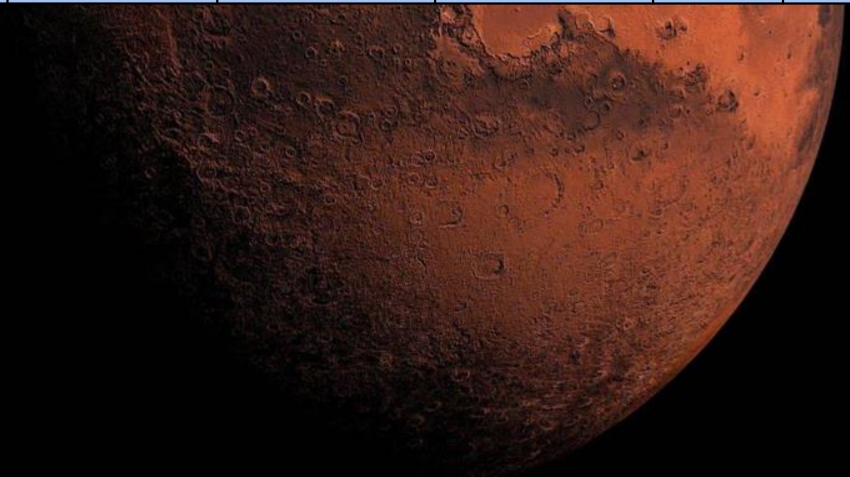
Alternative launch schedule



MMMMM (M5) Science Traceability Matrix

Primary Science Questions	Tier 1 Science Objectives	Measurement	Measurement Requirements		Instrument	Instrument requirements	Orbital Requirements	Functional Requirements
			General measurement requirements	Multi-point and scale requirements				
Q1: How do the Martian system's magnetotail and magnetospheric boundary region structure and dynamics depend on solar wind conditions?	O1.1. What are the dynamics and orientation of boundary regions, with particular interest for their dependence upon solar wind conditions?	*O1.1.1. The vector magnetic field at multiple points, separated below boundary scales, at the boundary regions.*	*Measure at the nose of the magnetospheric region:* *- Absolute range: 3000 nT* *- Absolute accuracy: 0.5 nT* *- Temporal resolution: 32 samples/sec*	*4 S/C. Measure with a distance of ~100km.*	*3-axis fluxgate magnetometer*	*- Range: 3000 nT* *- Offset stability: 0.5 nT / 12h* *- Absolute vector accuracy: 0.05%* *- Resolution: 20 pT* *- 32 vectors/s* *- Attitude knowledge: <0.05°*	*Measurements shall be made when the solar wind observatory is in the upstream solar wind. The measurements shall be made at the nose of the magnetospheric region from 1.2 RM to 1.8 RM, extending from the nose to at least -1 RM outside of the bow shock and inside of the IMB (using the empirical model of Trotignon et al., 2006). The crossing time from BS to IMB shall be in the order of 10 min. The spacecraft shall be in a 3D configuration with separations in the order of 100km.*	*A four spacecraft formation orbiting Mars as a 3D constellation of separations in the order of 100 km.*

		O1.1.3. The ion density and bulk velocity at multiple points, separated below boundary scales, at the boundary regions.	*Measure at the nose of the magnetospheric region:* *- Energy range: 1 eV to 30 keV.* *- Energy resolution (DeltaE/E): 25%* *- Temporal resolution: 5s* *- FOV: 360° x 90°* *- Detect H+, O+, O2+, CO2+*	*1 S/C*	*Ion electrostatic and TOF velocity analyzer*	*Electrostatic analyzer:* *- Energy range: 1 eV to 30 keV.* *- Energy resolution (DeltaE/E): 25%* *- Temporal resolution: 5s* *- Angle coverage: 360° x 90°* *Carbon foil TOF analyzer:* *- Proton flight of time 12 to 7 ns* *- Anode detection resolution: 22.5°*	*Measurements shall be made when the solar wind observatory is in the upstream solar wind. The measurements shall be made at the nose of the magnetospheric region from 1.2 RM to 1.8 RM, extending from the nose to at least -1 RM outside of the bow shock and inside of the IMB (using the empirical model of Trotignon et al., 2006). The crossing time from BS to IMB shall be in the order of 10 min. The spacecraft shall be in a 3D configuration with separations in the order of 100km.*	*A four spacecraft formation orbiting Mars as a 3D constellation of separations in the order of 100 km.*



		O1.1.4. The vector magnetic field, in the upstream solar wind.	*- Measure upstream of the solar wind: - Absolute range: 500 nT - Absolute accuracy: 0.5 nT - Temporal resolution: 32 samples/sec*	*1 S/C*	*3-axis fluxgate magnetometer*	*- Range: 500 nT - Offset stability: 0.5 nT / 12h - Absolute vector accuracy: 0.05% - Resolution: 20 pT - 32 vectors/s - Attitude knowledge: <0.05°*	*The measurements shall be made with a distance to the boundary measuring spacecraft constellation of at least 4 RM. The measurements in the solar wind shall be taken at least 50% of the time.*	*A single spacecraft with a circular orbit around Mars of at least 5 RM, with instruments pointed at the solar wind, if applicable.*
		O1.1.6. The ion density and bulk velocity of different mass species (to detect higher mass ions in CME events), in the upstream solar wind.	*Measure upstream of the solar wind: - Energy range: 10 eV/q to 25 keV/q. - Energy resolution (DeltaE/E): 25% - Temporal resolution: 5s - FOV: 180° x 40° - Detect H+, He++, higher mass*	*1 S/C*	*Ion energy spectrometer*	*Electrostatic analyzer: - Energy range: 10 eV/q to 25 keV/q. - Energy resolution (DeltaE/E): 25% - Temporal resolution: 5s - Angle coverage: 180° x 40° Differentiation between H+ and He++ by E/q*	*The measurements shall be made with a distance to the boundary measuring spacecraft constellation of at least 4 RM. The measurements in the solar wind shall be taken at least 50% of the time.*	*A single spacecraft with a circular orbit around Mars of at least 5 RM, with instruments pointed at the solar wind, if applicable.*

		O1.1.6. The ion density and bulk velocity of different mass species (to detect higher mass ions in CME events), in the upstream solar wind.	Measure upstream of the solar wind: - Energy range: 10 eV/q to 25 keV/q. - Energy resolution (DeltaE/E): 25% - Temporal resolution: 5s - FOV: 180° x 40° - Detect H+, He++, higher mass	1 S/C	Ion energy spectrometer	Electrostatic analyzer: - Energy range: 10 eV/q to 25 keV/q. - Energy resolution (DeltaE/E): 25% - Temporal resolution: 5s - Angle coverage: 180° x 40° Differentiation between H+ and He++ by E/q	The measurements shall be made with a distance to the boundary measuring spacecraft constellation of at least 4 RM. The measurements in the solar wind shall be taken at least 50% of the time.	A single spacecraft with a circular orbit around Mars of at least 5 RM, with instruments pointed at the solar wind, if applicable.

	O1.2. What is the structure of the Martian magnetotail on different scales, with particular interest for its dependence upon solar wind conditions?	*O1.2.1 The vector magnetic field at multiple points, separated at ion kinetic scales, measured at different positions in the tail region.*	*Measure in the tail region: - Absolute range: 3000 nT - Absolute accuracy: 0.5 nT - Temporal resolution: 32 samples/sec*	*4 S/C. Measure with a distance of ~100km. Also take different maesurements in the whole of the tail.*	*3-axis fluxgate magnetometer*	*- Range: 3000 nT - Offset stability: 0.5 nT / 12h - Absolute vector accuracy: 0.05% - Resolution: 20 pT - 32 vectors/s - Attitude knowledge: <0.05°*	*Measurements shall be made when the solar wind observatory is in the upstream solar wind. The measurements shall be made inside the outer boundary regions of the magnetotail. The spacecraft shall be in a tetrahedron configuration with separations in the order of 100km.The S/C constellation shall stay in the tail for at least 1h.*	*A four spacecraft formation orbiting Mars as a tetrahedron configuration of separations in the order of 100 km.*

		O1.2.2. The electron density and temperature, measured at different positions in the tail region.	*Measure in the tail region:*	*4 S/C. Measure with a distance of ~100km. Also take different maesurements in the wohle of the tail (~1000km scale).*	*Langmuir probe*		*Measurements shall be made when the solar wind observatory is in the upstream solar wind. The measurements shall be made inside the outer boundary regions of the magnetotail. The spacecraft shall be in a tetrahedron configuration with separations in the order of 100km.The S/C constellation shall stay in the tail for at least 1h.*	*A four spacecraft formation orbiting Mars as a tetrahedron configuration of separations in the order of 100 km.*

		O1.2.3. The ion density, bulk velocity, temperature, measured at different positions in the tail region.	*Measure in the tail region:* *- Energy range: 1 eV to 30 keV.* *- Energy resolution (DeltaE/E): 25%* *- Temporal resolution: 5s* *- FOV: 360° x 90°* *- Detect H+, O+, O2+, CO2+*	*1 S/C. Also take different maesurements in the wohle of the tail (~1000km scale).*	*Ion electrostatic and TOF velocity analyzer*	*Electrostatic analyzer:* *- Energy range: 1 eV to 30 keV.* *- Energy resolution (DeltaE/E): 25%* *- Temporal resolution: 5s* *- Angle coverage: 360° x 90°* *Carbon foil TOF analyzer:* *- Proton flight of time 12 to 7 ns* *- Anode detection resolution: 22.5°*	*Measurements shall be made when the solar wind observatory is in the upstream solar wind. The measurements shall be made inside the outer boundary regions of the magnetotail. The spacecraft shall be in a tetrahedron configuration with separations in the order of 100km.The S/C constellation shall stay in the tail for at least 1h.*	*A four spacecraft formation orbiting Mars as a tetrahedron configuration of separations in the order of 100 km.*