Far infraRed Observation Spectrography Telescopes

FROST

FFG

esa

INTERNATIONAL SPACE SCIENCE INSTITUTE

Hallerstrasse 6 • CH-3012 Bern • Switzerland

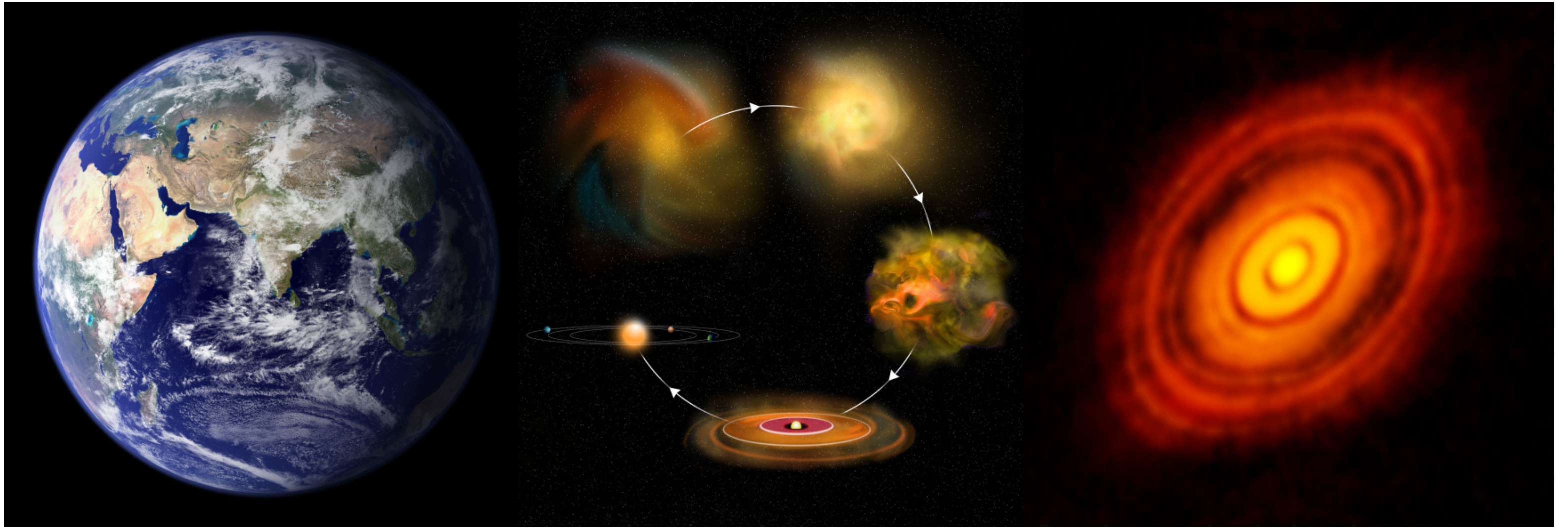
AUSTROSPACE

I. Science

Motivation

Where do we come from?

How do structures in the universe form?



Images from: NASA / NRAO

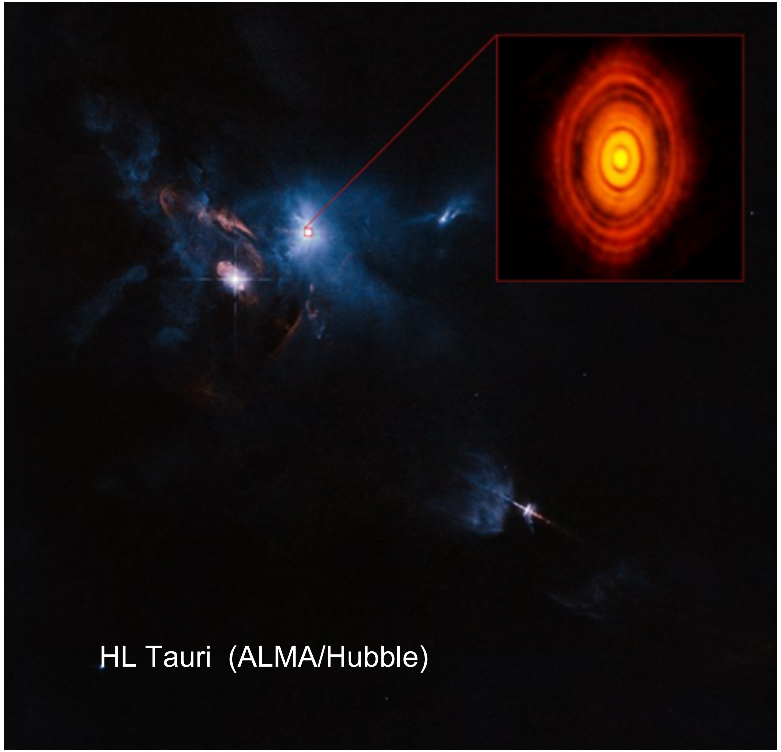
Protoplanetary disks

- Found in stellar nebulae
- Dense disk of dust and gas
- Theorised place of birth of planets

Unknowns:

- Composition & formation of disks
- Evolution & formation of planets

Focus on inner disks of T Tauri stars - our heritage



HL Tauri (ALMA/Hubble)

Dust diagnostics in protoplanetary disks

From experiments and models we know:

- Dust-... **coupling** dependent on the **dust size distribution**

- **Chemistry** is controlled by the **temperature** and its gradient and hence the **composition**

Our Mission

We will observe **inner protoplanetary disks** to **precisely constrain:**

- **Grain Size Distribution**
- **Temperature Gradient**
- **Composition**

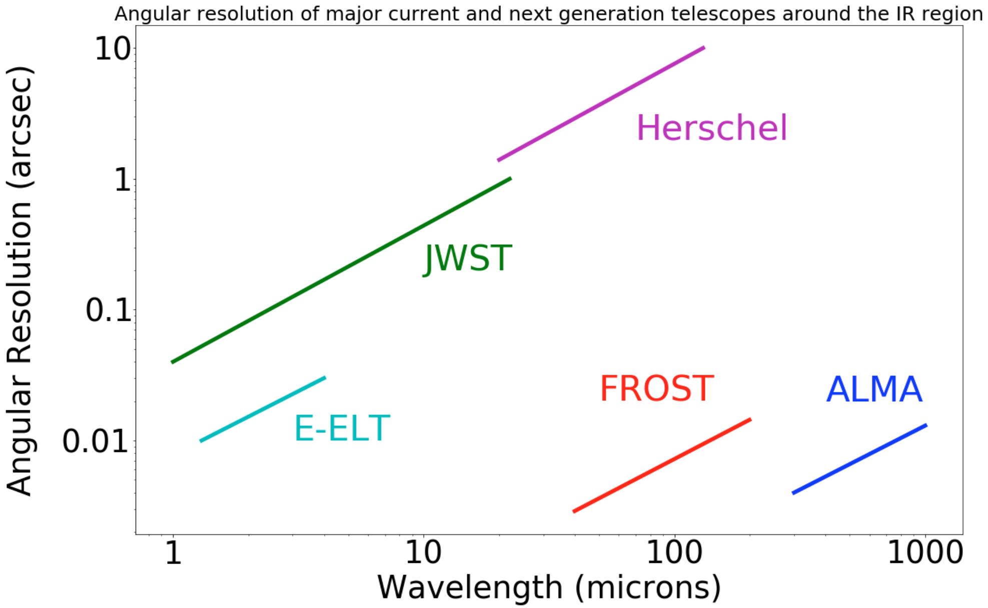
Allowing us to compare **models of disk evolution leading to planet formation.**

To understand the next steps to **planet formation,** we will improve our knowledge of:

- **Dust growth mechanisms**
- **Location of the mechanisms**
- **Disk geometry and structure: How gaps, rings and planets are formed**

Our Mission

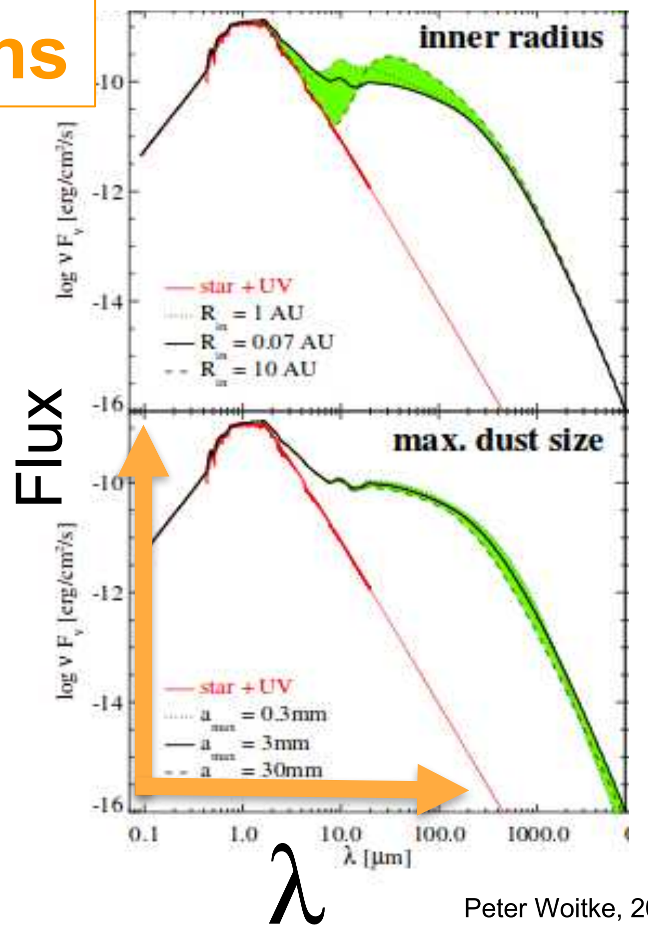
1. Why study the Far IR?
2. Why go into space?
3. What information do we need?



How we find dust size distributions

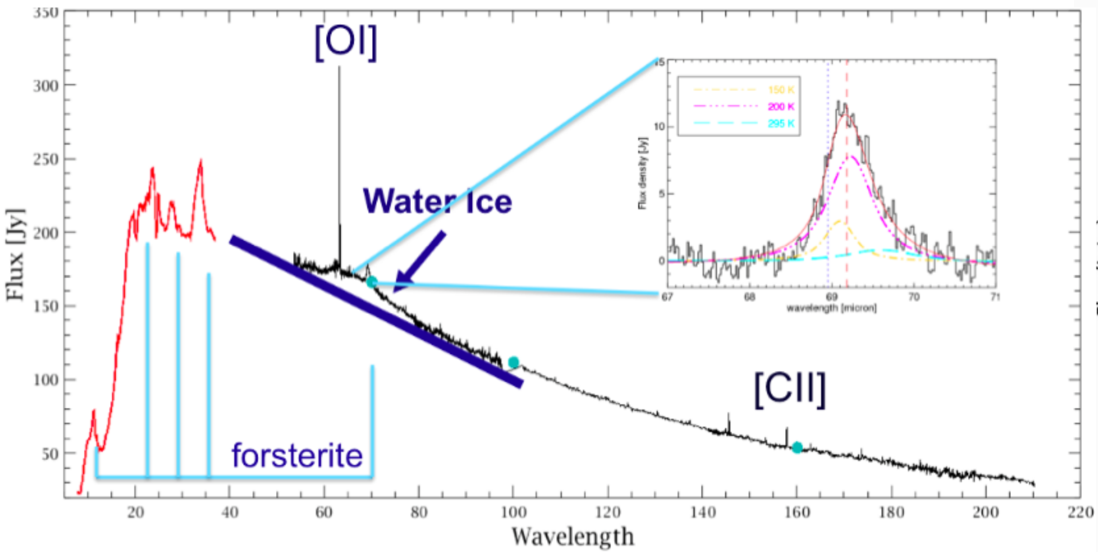
Current observations do not allow us to distinguish different size distributions

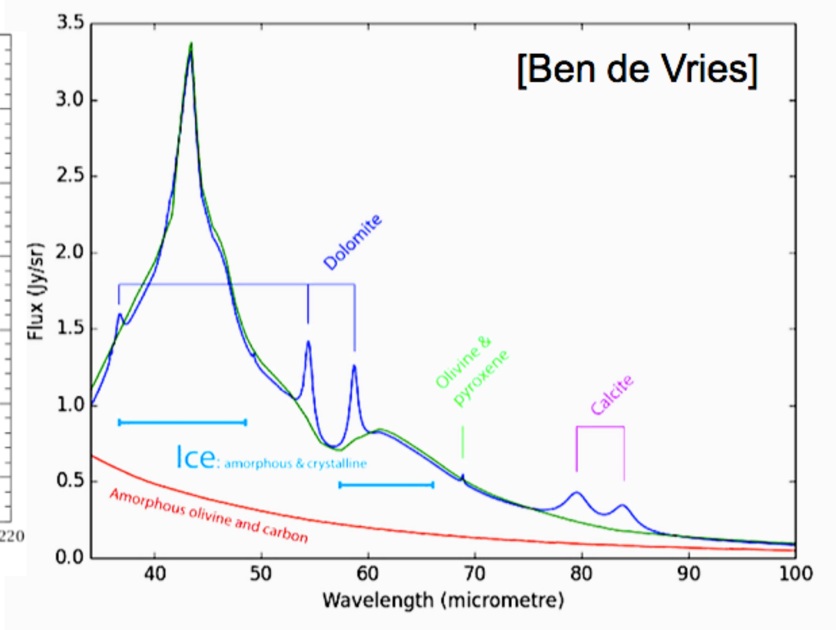
Dust size distribution is hard to constrain without good angular resolution



Peter Woitke, 2015

How we will find composition

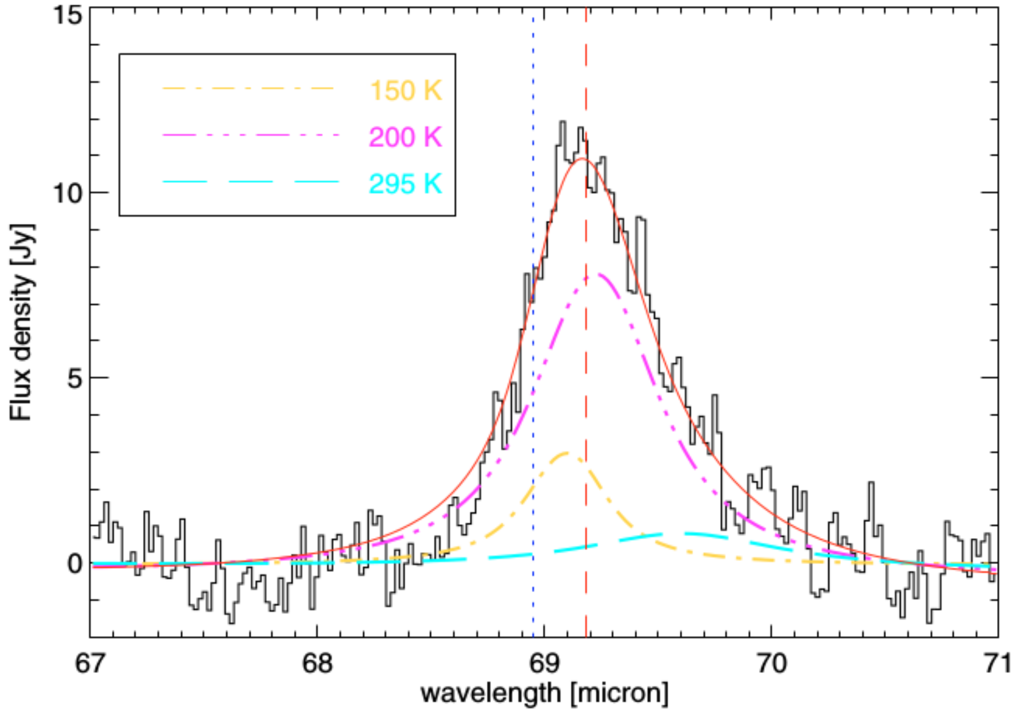




L.B.F.M Waters, 2015

How we will find temperature

Can measure temperature if peaks of the features in time



Sturm, 2010

How we will find time and spatial evolution

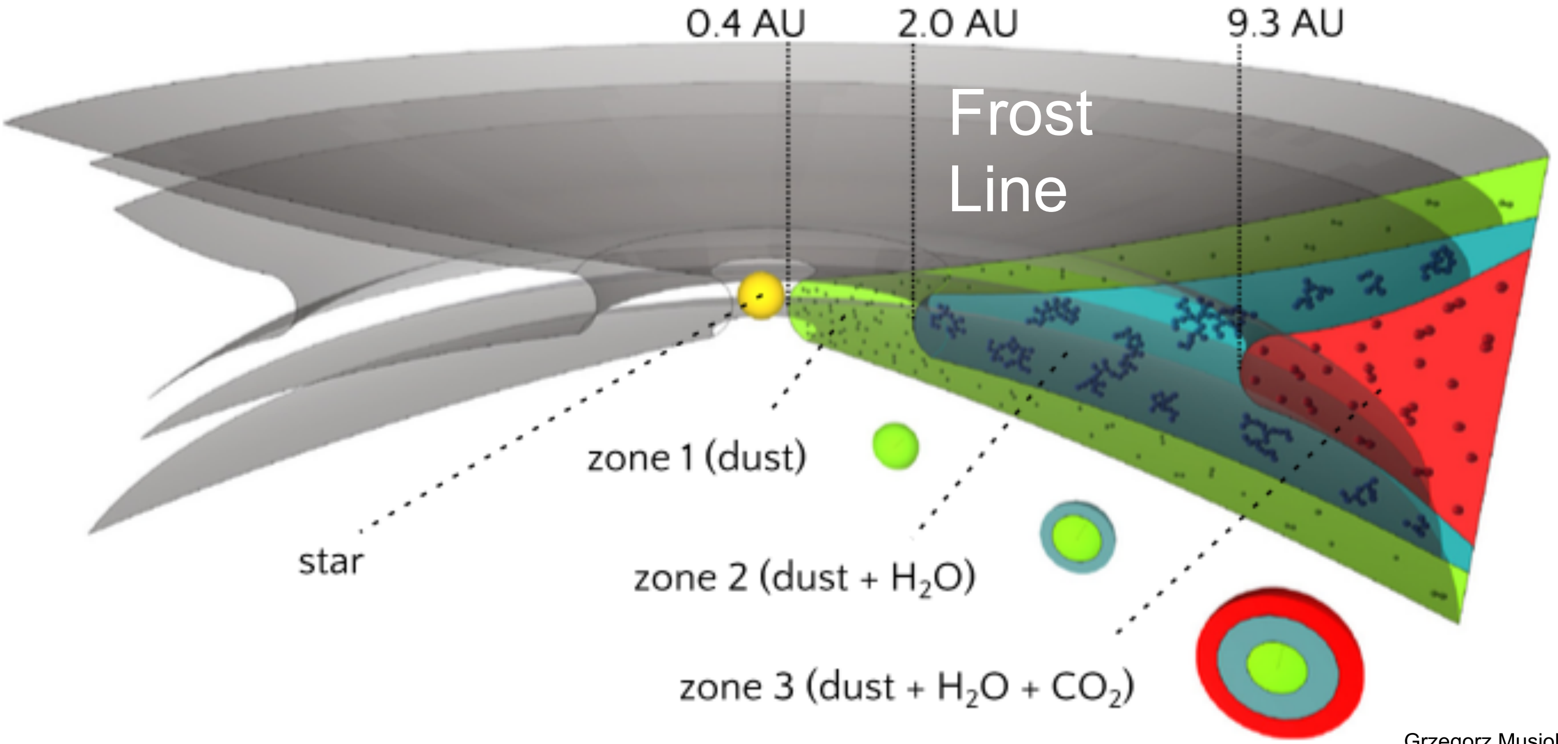
We are interested in changing

Dust Size Distribution and **Temperature**

Observations taken over different **radial distance** gives us the gradient of the dust size **distribution**, and **temperature**.

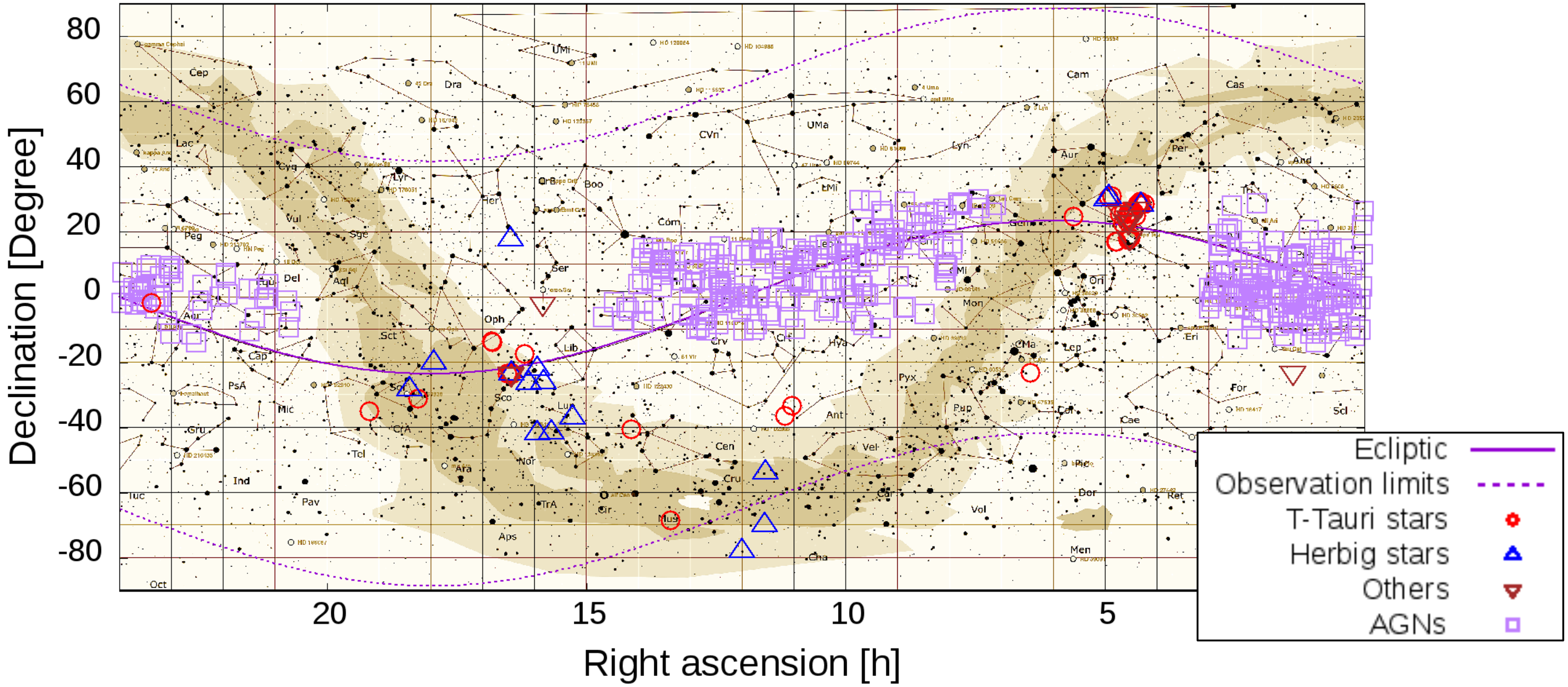
Repeated at some later time, we may observe **inclined disks**, **outburst** from stars and variations in features of **silicates**.

How we find out about planetary formation



Grzegorz Musiolik, et al, 2016

Star distribution over galactic plane



Mission Requirements

REQ.ID	Requirement	Value	Reason
SR-01	Number of observable objects	100 disks	Good sample of disk lifetimes
SR-02	Maximum observable distance	140 parsec	Enough objects within this distance
SR-03	Minimum observable flux	10^{-14} W/m^2	Theoretical estimate for dimmest disks
SR-04	Spatial resolution at 140 parsec	0.7 AU	Constrain frost line position accurately
SR-05	Disk size at 140 parsec	10 AU	Inner disk size

Mission Requirements

REQ.ID	Requirement	Value	Description
SR-06	Reference wavelength	69 um	Measure forsterite
SR-07	Wavelength range	40 - 200 um	To detect most important features
SR-08	Signal to noise ratio	S/N = 100	To detect features in the continuum
SR-09	Spectral Frequency resolution	R = 1600 (0.1 um)	Observe peak shift to measure temperature

Hypothesis

Grains will be larger around the **frost line**, because of coagulation with the ice

Observation of mainly **silicate features** before the frost line

Around older stars, the disks are **less dense / gaps in rings** are wider

Where do our solar system models and data fit in?

Key Mission Drivers

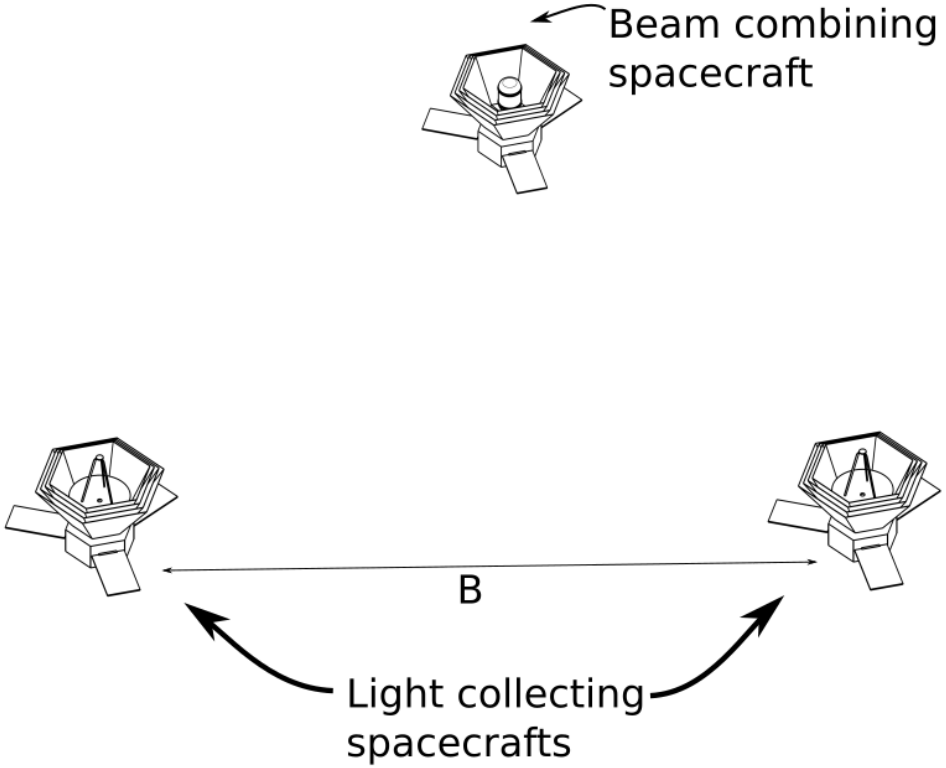
- Far Infrared Wavelengths
- High angular resolution **1000x Herschel**
- High spectral resolution

II. Payload Concept

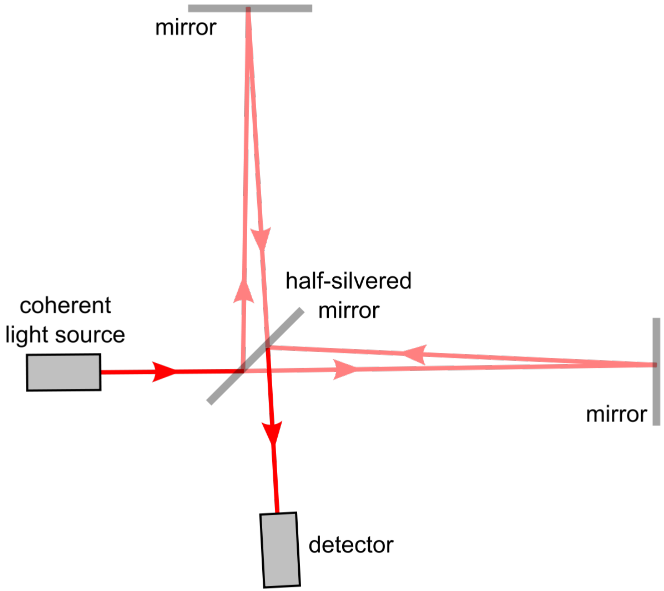
Measurement principle

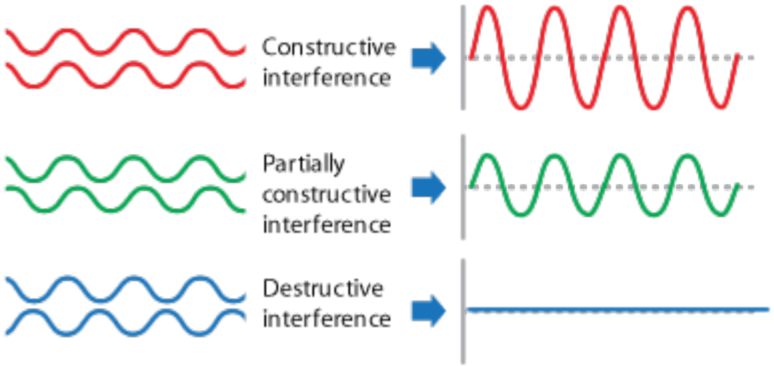
Basic principle:
“Far infrared spectroscopy using interferometry with Fourier Transform Spectroscopy (FTS)”

Basic solution:
“Three free-flying spacecrafts, two for light collecting, and one for beam combination with Fourier Transform Spectroscopy”



Basics of interferometry



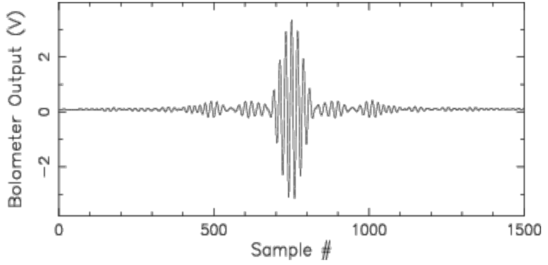


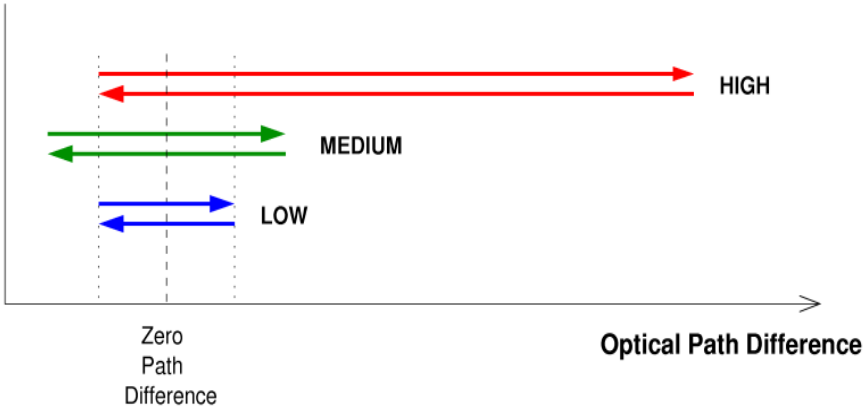
References:
http://www.fortebio.com/interactions/Spring_2012/images/BLI_figures5-6.png (Visited 26/7/2017)
https://upload.wikimedia.org/wikipedia/commons/thumb/e/e7/Interferometer.svg/1200px-Interferometer.svg.png (Visited 26/7/2017)

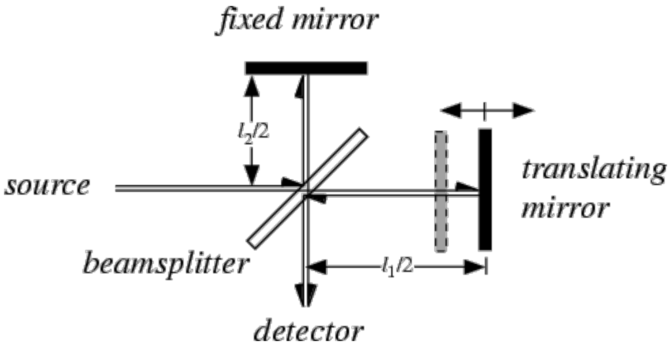
Basics of Fourier Transform Spectroscopy

$$R = \frac{\lambda}{\Delta\lambda} = \frac{\sigma}{\Delta\sigma}$$

$$OPD = \frac{1}{2\Delta\sigma}$$







References:
http://scienceworld.wolfram.com/physics/fimg192.gif (Visited 26/7/2017)
http://herschel.esac.esa.int/Docs/SPIRE/html/spire_om.html (Visitid 24/7/2017)

Payload requirements (1)

Req. ID	Requirement	Value	Description	Ref. Req. ID
PL-01	Baselines per target	15	# of baselines	SR-05
PL-02	Pointing accuracy	0.43''	(Beam width)/20*	SR-04, SR-05
PL-03	Detector NEP	$1.7\times10^{-19}\frac{W}{\sqrt{Hz}}$		SR-09
PL-04	Primary Mirror Size	2 m	Primary mirror	SR-09
PL-05	Tip tilt mirrors	mm	Beam direction	SR-05
PL-06	Dichroic mirrors	<40 µm, 40-80 µm, 80-120 µm, 120-160 µm, 160-200 µm	Dichroic mirror reflections	SR-07

References:
*"FIRI, A Far-InfraRed Interferometer for ESA",F. Helmich, R. Ivison

Payload requirements (2)

Req. ID	Requirement	Value	Description	Driving Req. ID
PL-07	FTS delay line movement	2.5 cm, 100 nm precision*	Folded light once	SR-10
PL-08	OPD delay line	100 nm precision*	-	SR-05, SR-06
PL-09	Knowledge of LCS position with respect to BCS	10 μm precision*	Length of the baseline	SR-05, SR-06
PL-10	Baseline range	230-3500 m	Minimum and maximum baseline	SR-05,SR-06
PL-11	Beam diameter	3 cm	Minimum size to avoid too much dispersion	SR-05, SR-06

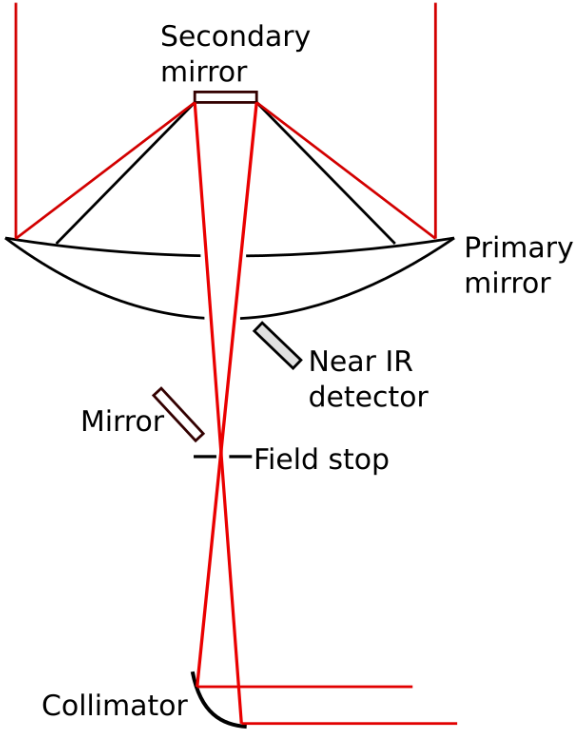
References:
*"Far Infrared Interferometer Technology reference Study", A. Lyngvi, ESA, IAC

Payload requirements (3)

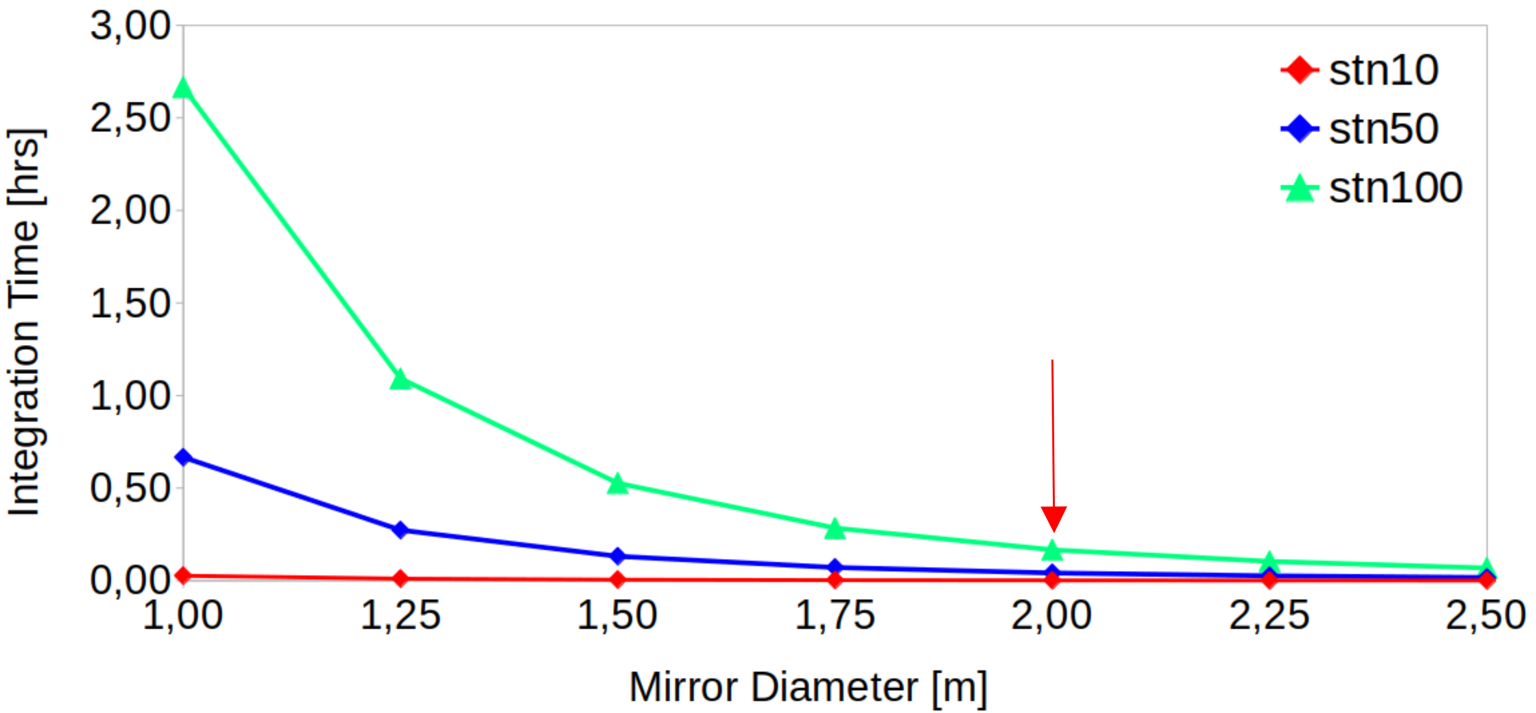
Req. ID	Requirement	Value	Description	Driving Req. ID
PL-12	Baseline Rotation	180°	Through an entire observation	SR-01
PL-13	Observation Time per object	32.5 h	For all wavelengths and baselines	SR-03

Light Collecting Spacecrafts (LCS)

Payload	Per spacecraft	Purpose
Primary mirror	1	Light collection
Secondary mirror	1	Light collection
Collimation mirror	1	Light correction
Tip tilt mirror	2	Light direction
Field stop	1	Stray light
Near IR detector	1	Fine guiding sensor

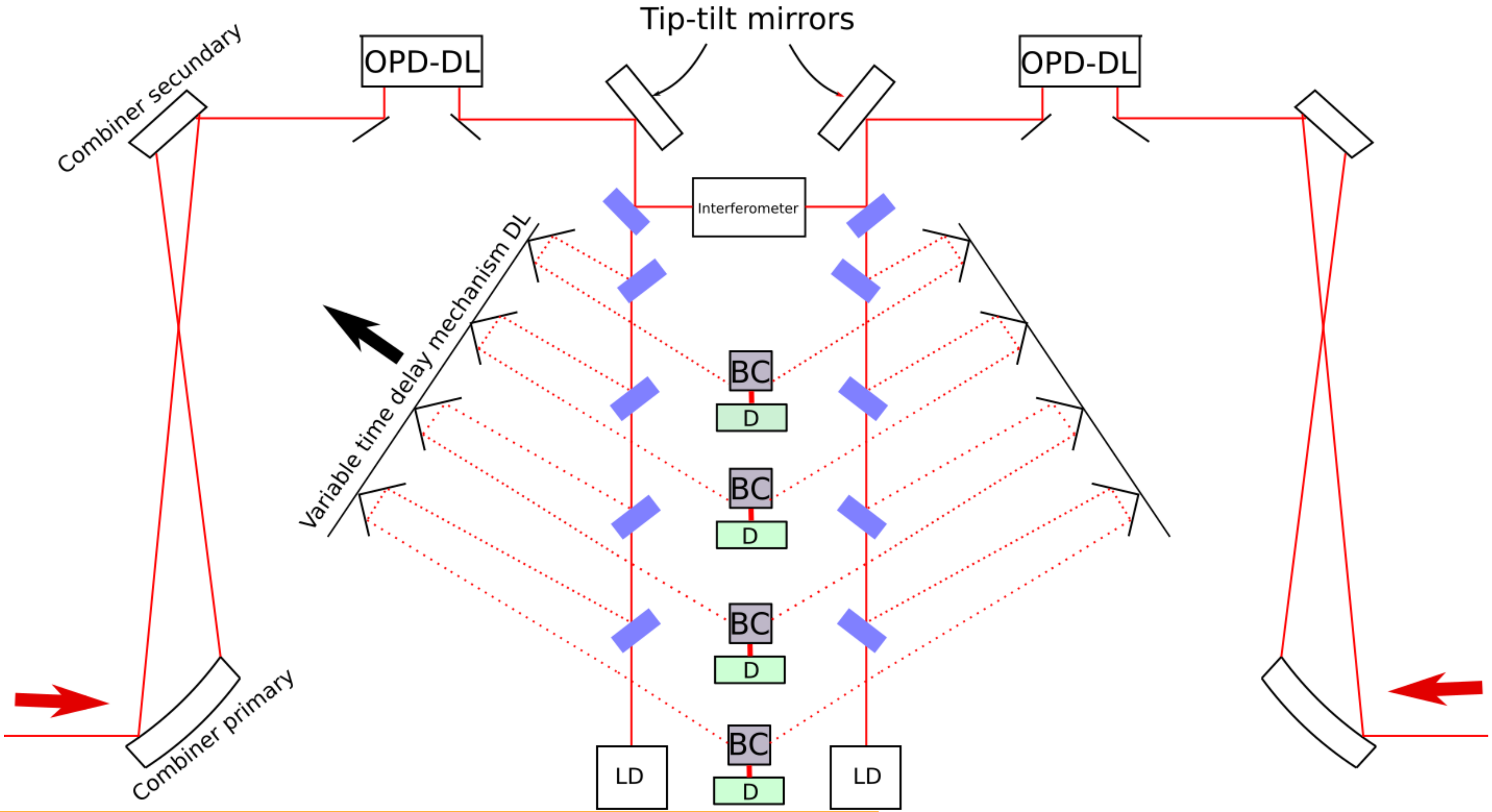


Light Collecting Spacecrafts (LGS)
Primary mirror size



Beam Combining Spacecraft (BCS)

Payload	Number
Combiner primary	2
Combiner secondary	2
Tip tilt mirrors	2
Dichroic mirrors	10
Interferometer for distance measurement	1
Corner cube mirror	8
OPD correction delay lines	2
FTS delay line	1
Beam combiners	4
Bolometer detector	4



References:

"FISICA (Far Infrared Space Interferometer Critical Assessment) Metrological problems and system requirements for interferometric observations from space", Iafolla et. al. , IEEE, 2014

Solution - OPD correction

Delay lines to compensate Optical Path Difference (OPD) between telescope constellation - Equalisation and fine tuning

+ FTS

Precision	Sub nm
Operating temperature	40 K
Mirror type	Corner cube retro reflector
Developed for	DARWIN

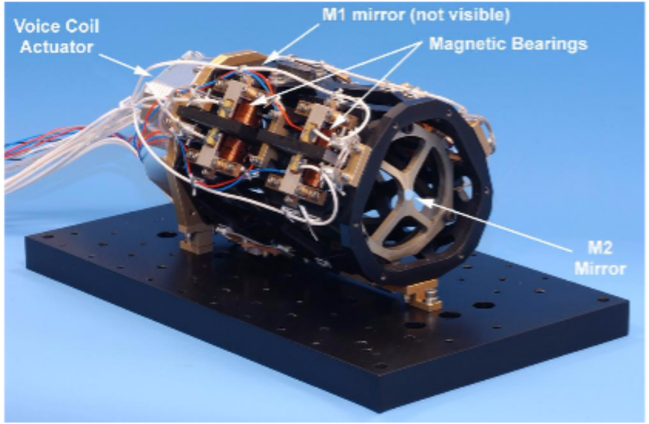


Figure 2 – Dynamic ODL

References:
“The DARWIN Breadboard Optical Delay Line Verification Programme” T.C. van den Dool et. al., Advances in Stellar Interferometry, 2006

Fourier transform spectroscopy

$\Delta\lambda = 0.1\ \mu m \rightarrow \Delta\sigma = 2.5\ m^{-1}$

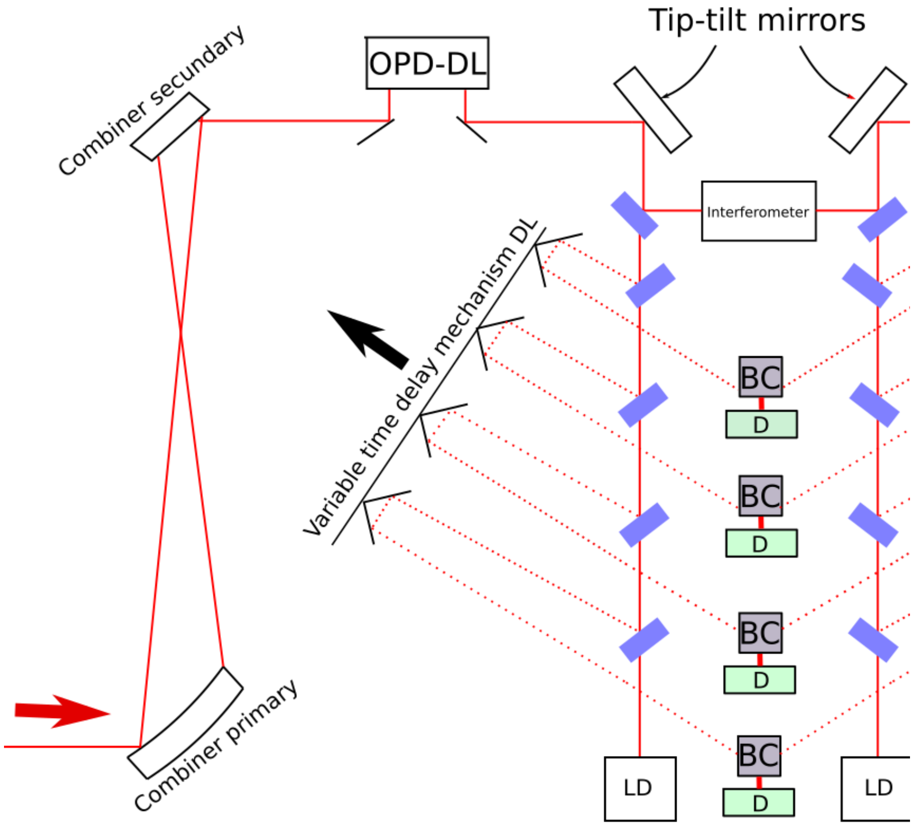
To meet this requirement, the time variable delay distance, **D**, must be calculated, $D = \frac{1}{2\Delta\sigma} = 0.2\ m$

Scan detector over 1600 points

→ 4 detectors $\rightarrow \frac{1600}{4}$ = 400 points

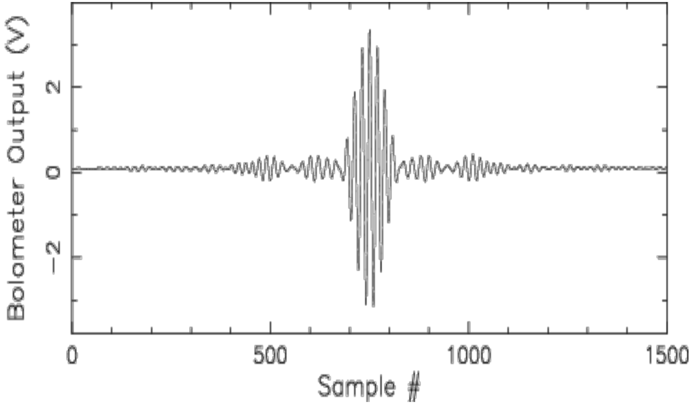
With folding of the light ~ 10 cm

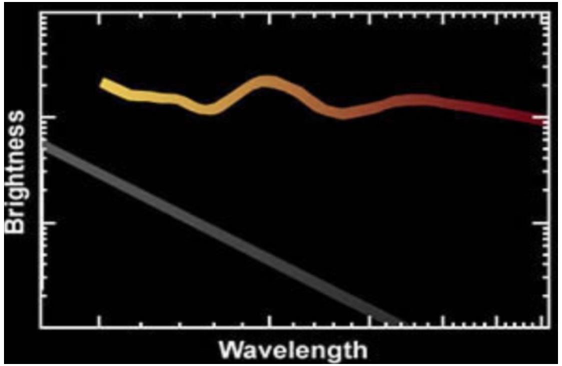
To do FTS with a resolution of $\Delta\lambda = 0.1\ \mu m$



References:
"Fourier Transform Spectroscopy", J.B.Bates, 1977, Comp. and Maths with Appls. Vol 4
http://herschel.esac.esa.int/Docs/SPIRE/html/images/fts-scans.png (visited 25/7/2017)

Resulting data from FTS





Level 1	Raw Data
Level 2	Reconstructing the signal
Level 3	FTS
Level 4	Calibration (Subtracting the background and instrument noise)
Level 5	Archive the Data (Instrument+ Science)

References
https://spie.org/Images/Graphics/Publications/TT61_Fig1.3.jpg (Visited 24/7/2017) ; http://scienceworld.wolfram.com/physics/iimg117.gif (Visited 24/7/2017)

Detector - TES Bolometers

Transition Edge Sensors (TES) Bolometers, developed by SRON in the Netherlands → Must be custom made

$$NEP = 1.7\times10^{-19}\frac{W}{\sqrt{Hz}}$$

- Operating Temperature of 50mK
- Already fabricated and currently under going testing

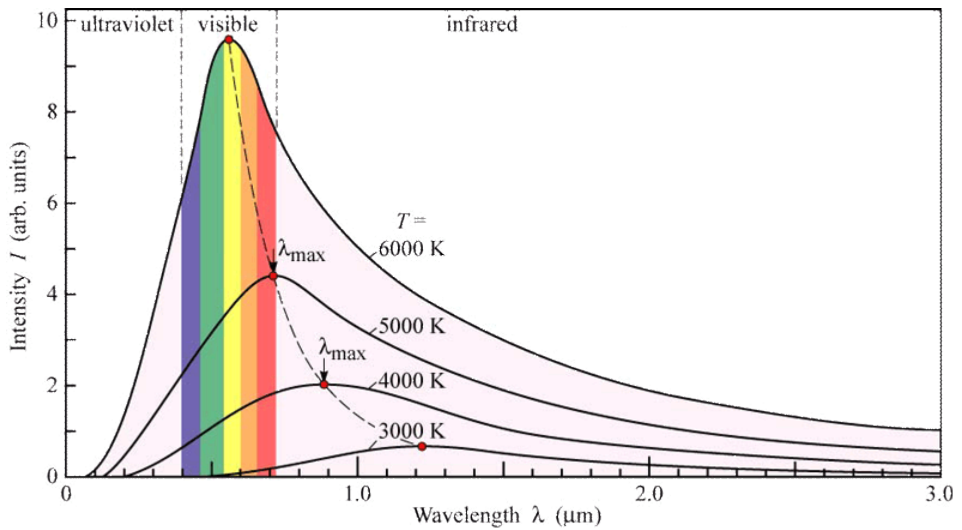
Detector calibration

Using a moving mirror to choose the light going to the detectors:

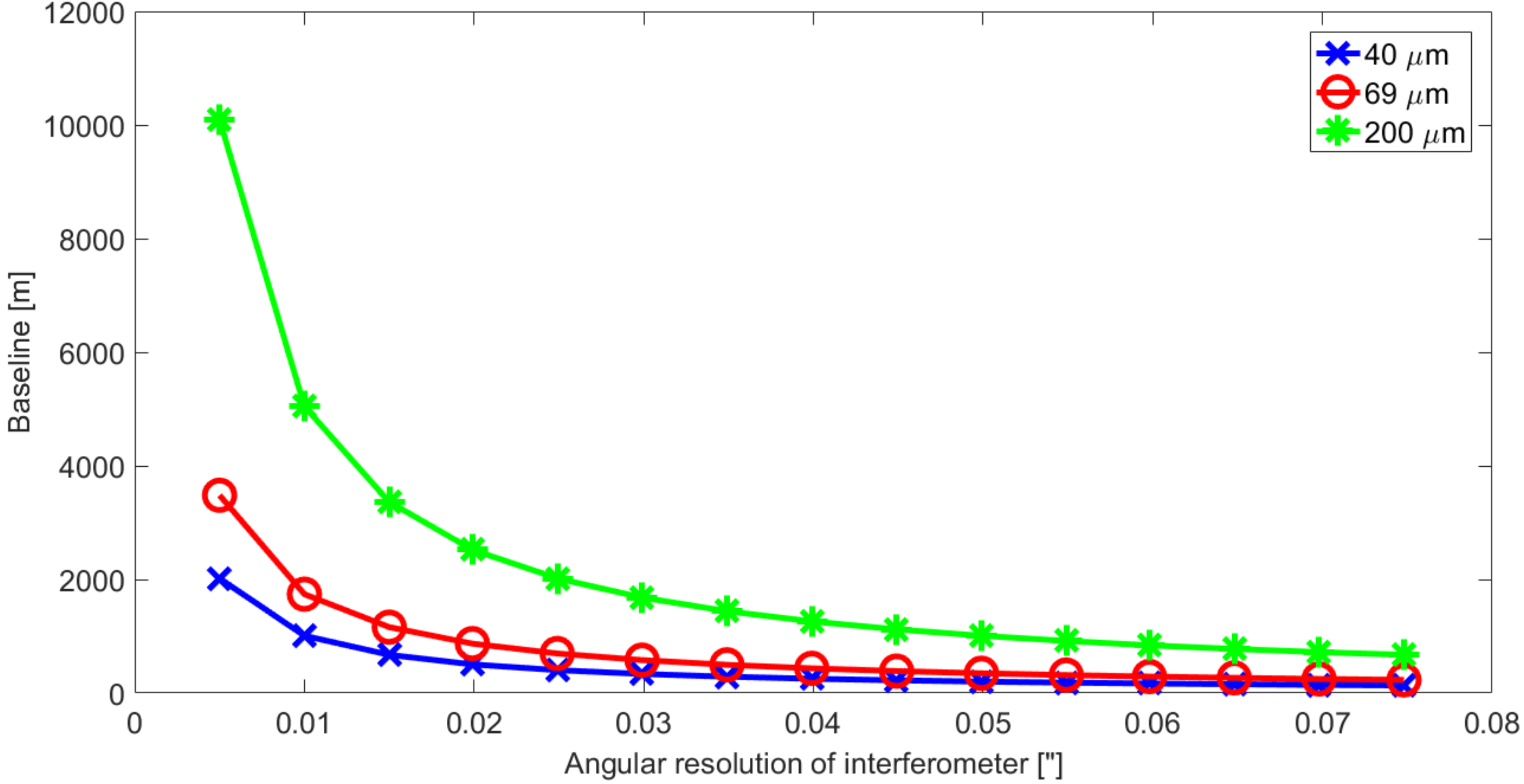
→ either from the observation light and calibrations sources.

The calibrations sources we need:

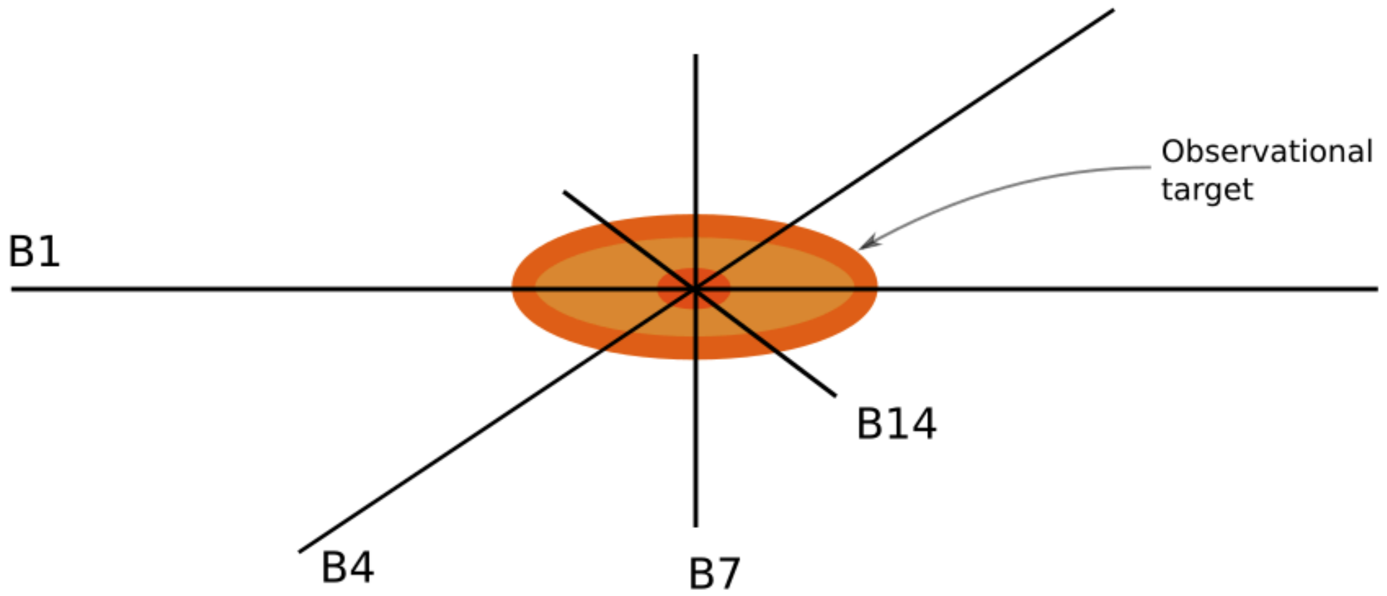
- Cold target (4K)
- Blackbody (Warm target)



Observation Strategy - Optimizing baseline



Rotation of the baseline



Pointing accuracy of spacecrafts

Pointing accuracy : 1/20th of the primary beam*

$$PA = \frac{\theta_T}{20} = \frac{1.22 * \frac{\lambda}{D}}{20}$$
$$\Leftrightarrow PA = 0.43''@69\mu m$$

References:

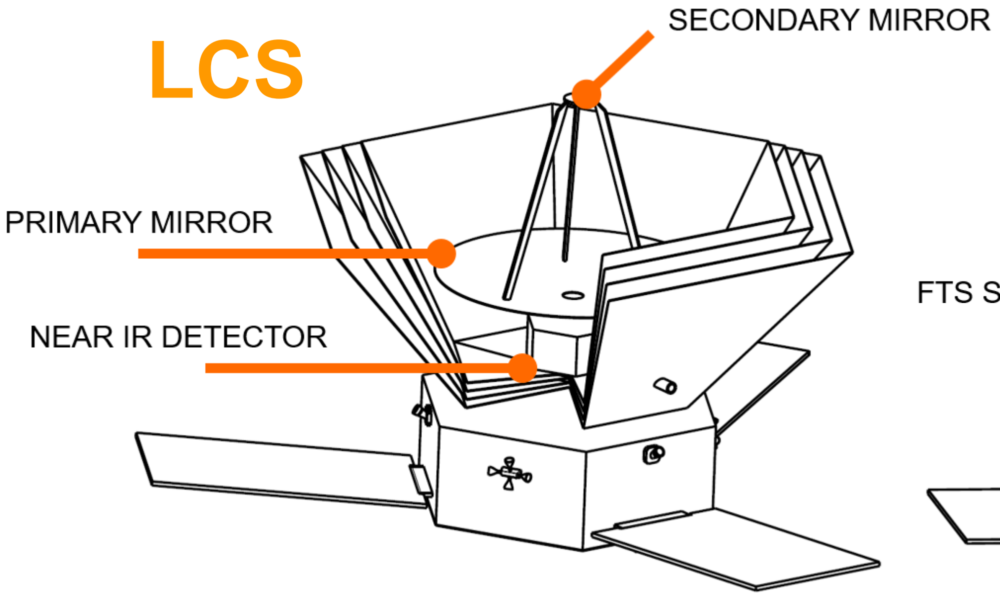
*"FIRI, A Far-InfraRed Interferometer for ESA",F. Helmich, R. Ivison

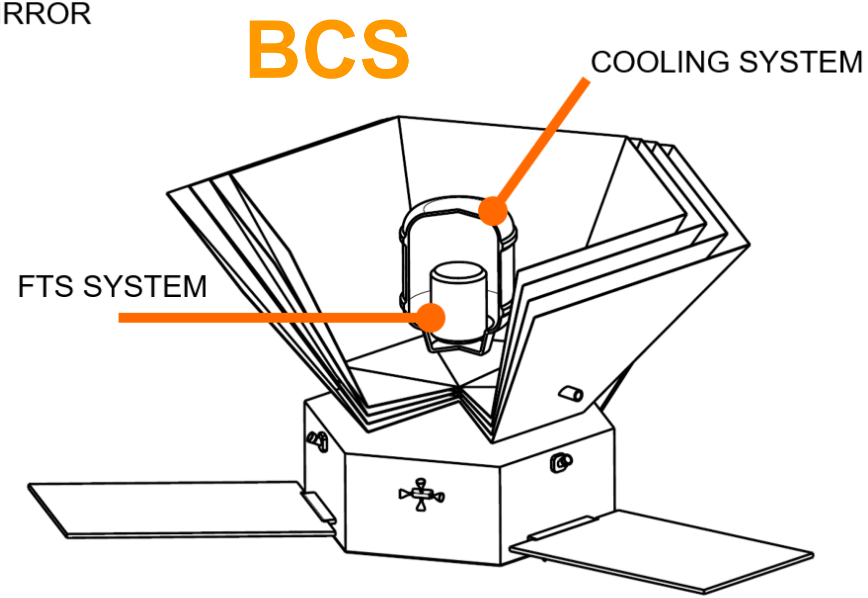
Key Mission Drivers

- Free flying interferometry in space
- Pointing accuracy
- Beam combination procedure
- Baseline stability
- Delay line system

III. Mission Profile

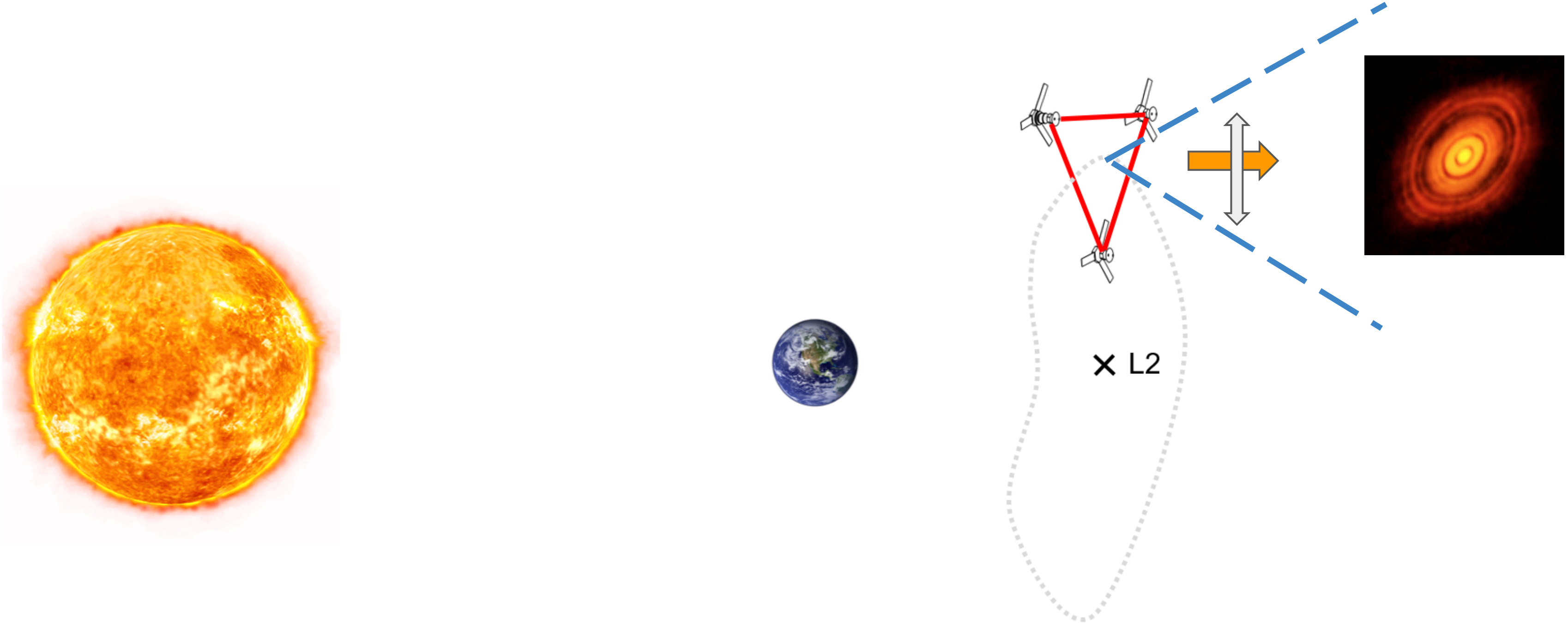
Satellite Design Overview





- Mission lifetime: 3 years
- 3 spacecrafts: 2x LCS, 1x BCS
- Free formation flight with high precision

Mission Overview



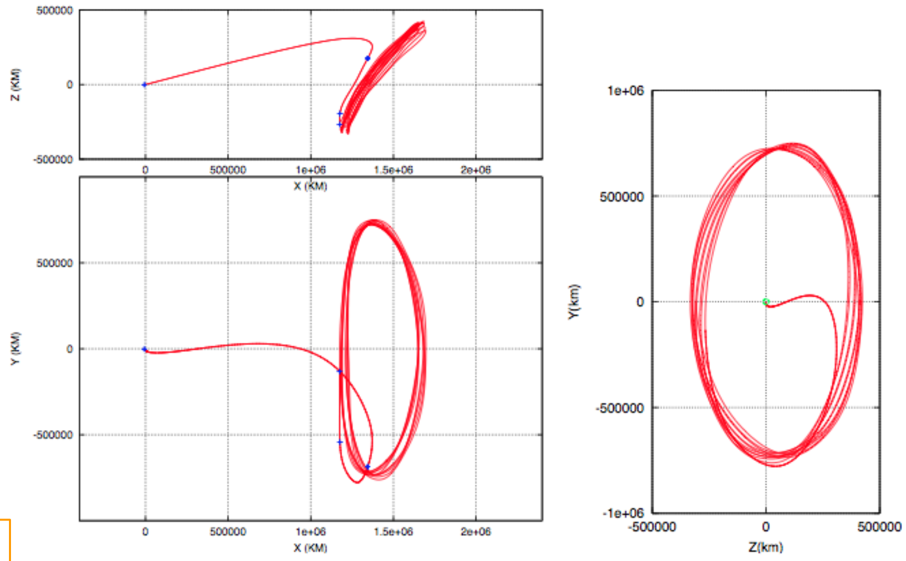
Target Orbit

Large-amplitude Lissajous (LAL) orbit around the L2 point:

8e5km semi-axis, 6 month period

Distance to earth ~1.5e6km

- Avoiding eclipses
- Low Δv for orbit insertion orbit
- Low station keeping costs
- Low perturbations → *crucial for formation flight*



Reference:

DARWIN System Assessment Study 2007, Herschel/Planck CReMA 2006

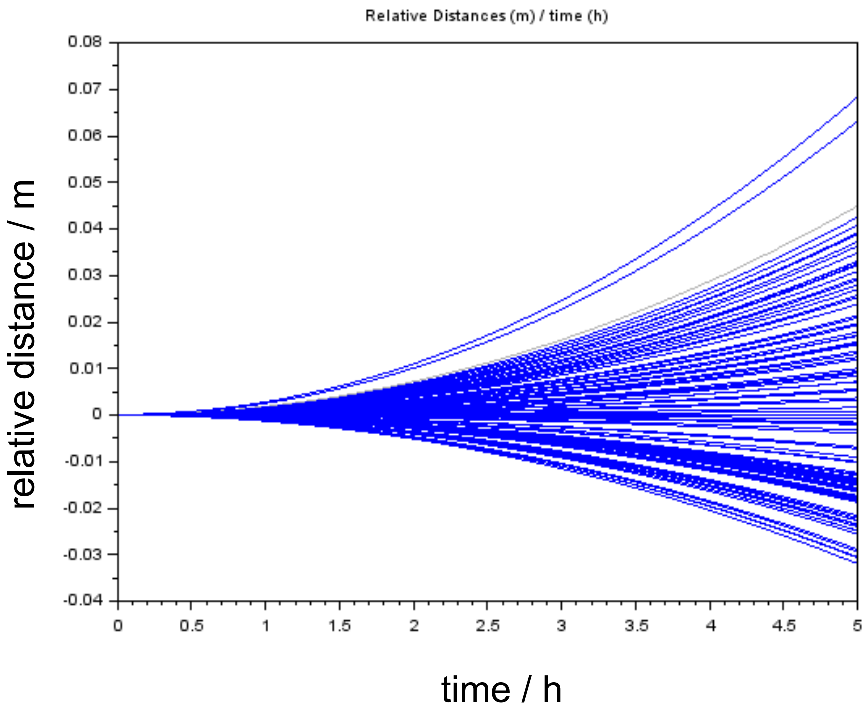
Target Orbit Disturbances

Gravitational forces if not on LAL

Force due to solar pressure

Worst-case disturbance force 80uN
→ relative distance error after 5h
observation: 6.5m if not compensated

S/Cs at 1000m distance from LAL



Radiation at Orbit

Solar Cycle 25 will appear sometime in late-2019.

In 2030 we expect a solar minimum

We may approximate the needed radiation resistance requirement from this knowledge.

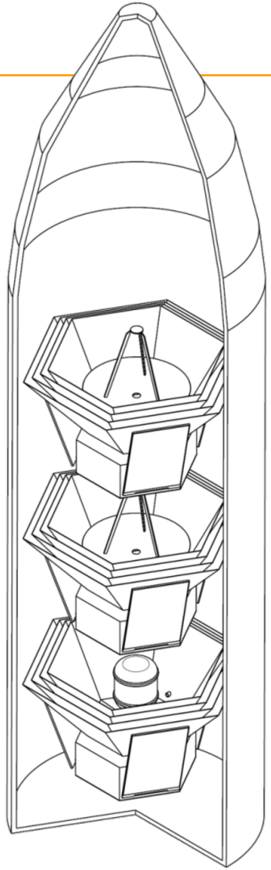
Herschel saw approximately **one memory bit flip per day** during in 2008-2013.

Launcher

Proposed Launcher: ***Ariane 6 4***

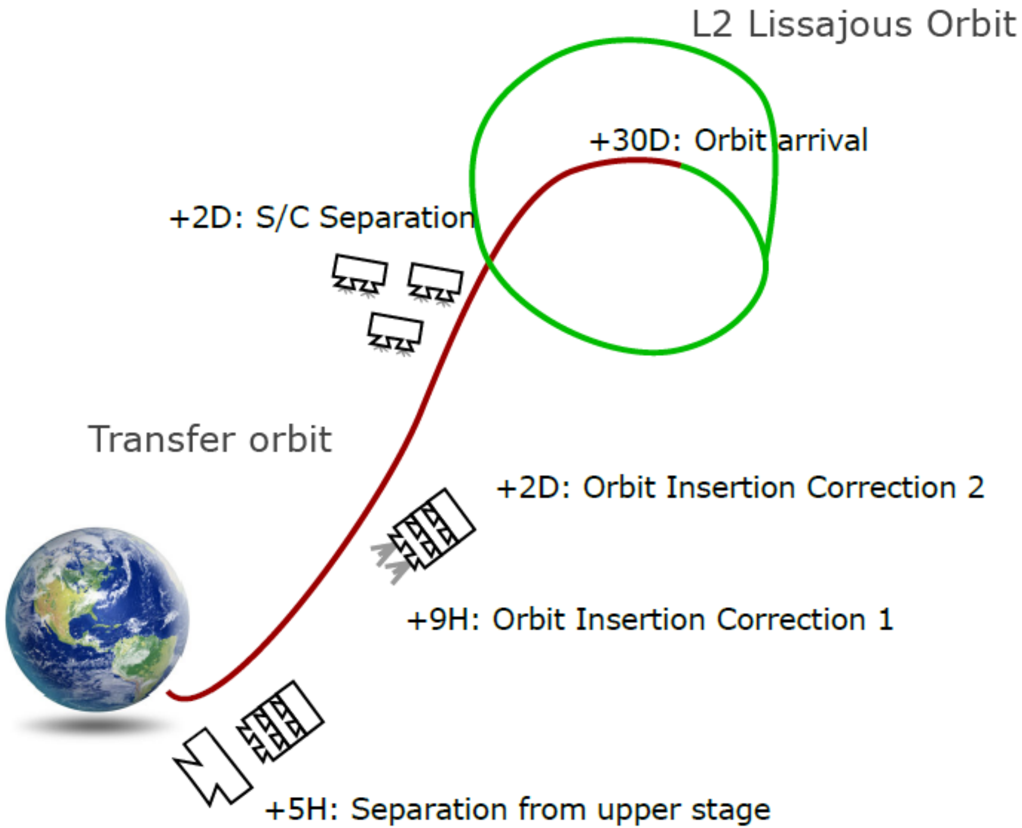
Expected performance to L2: >**7t**

Custom structure for combined satellite launch

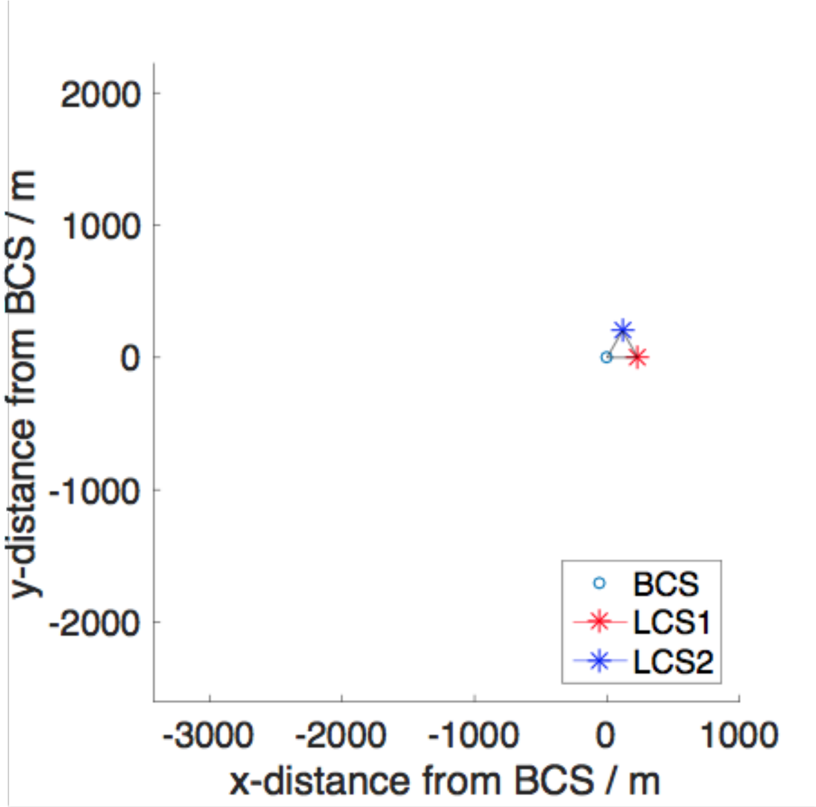


Reference:
ESA Ariane 5 and Ariane 6 Handbook

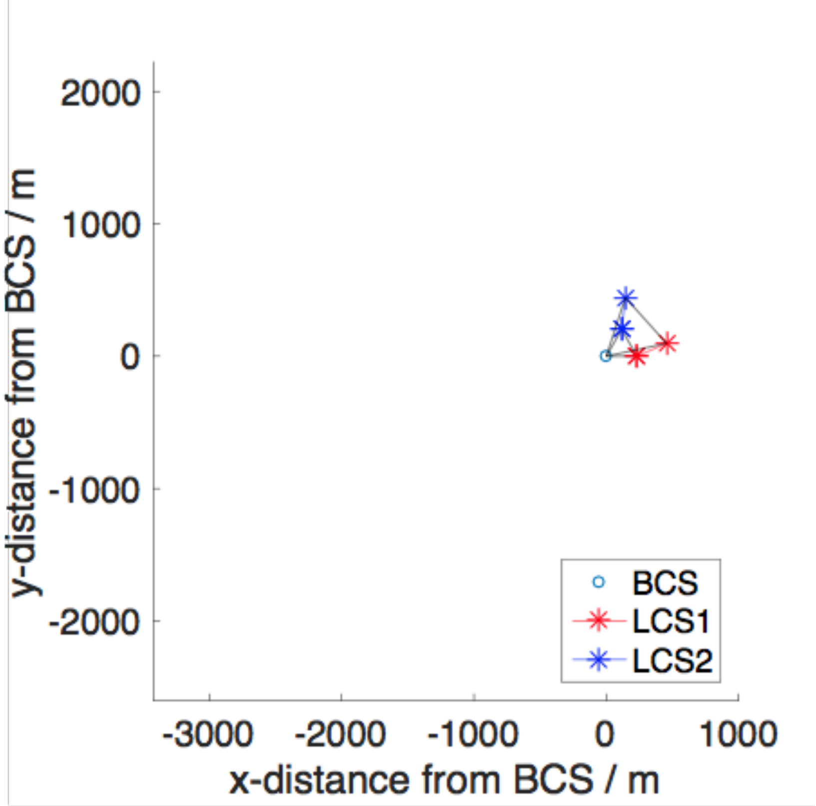
Orbit Insertion and S/C Deployment



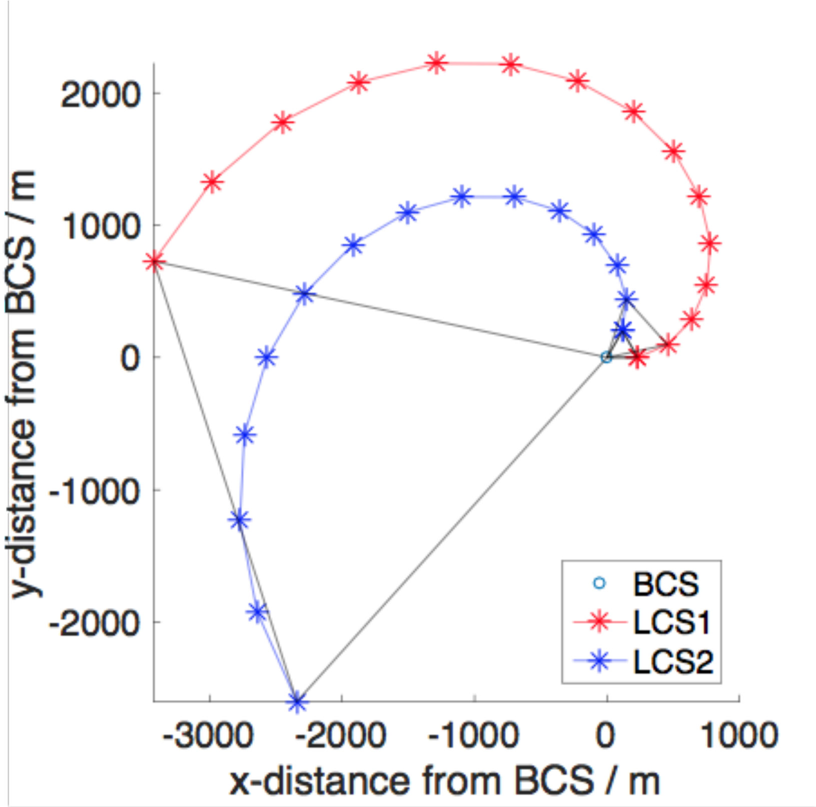
Reconfiguration of Baselines



Reconfiguration of Baselines



Reconfiguration of Baselines



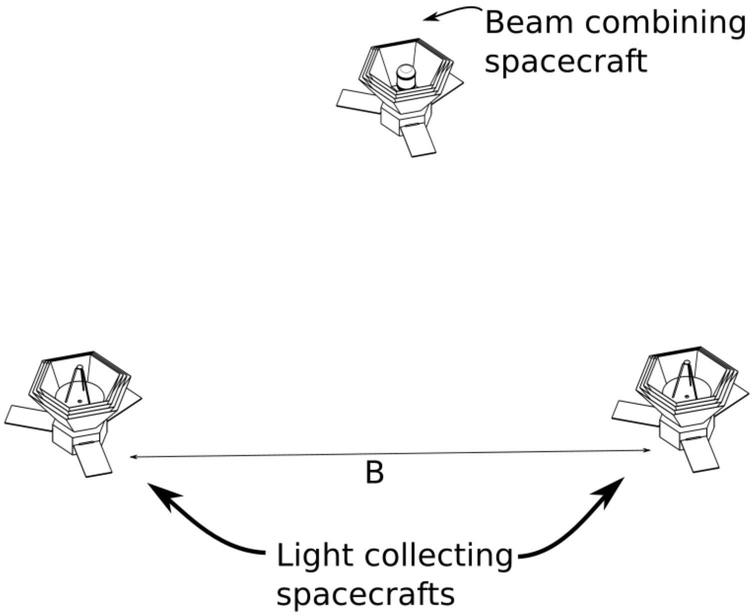
Formation Flight Control Subsystem

Req.ID	Formation Flight requirement	Driving Req.ID
FFS-01	Absolute distance error between the S/Cs: 10 mm	PL-02
FFS-02	Relative distance error between the S/Cs: 10 um	PL-02

Optical Lock-In

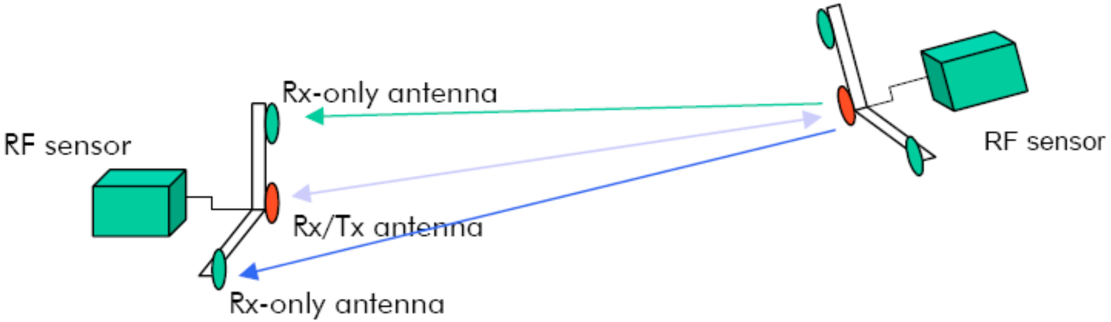
Procedure before starting the observation:

- **<u>1st stage:</u>** Coarse positioning
- **<u>2nd stage:</u>** Control the distance with high accuracy with precision metrology system
- **<u>3rd stage:</u>** Control delay lines using fringe sensor to get proper optical path length



Metrology System 1st Stage

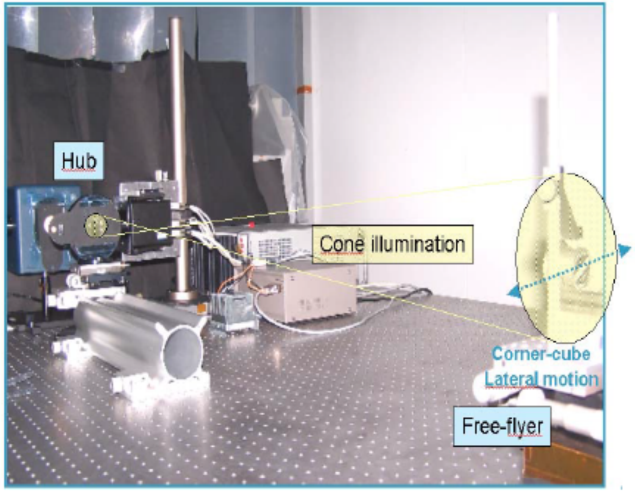
System	Formation Flying Radio Frequency, CNES
Function	Coarse position and pointing determination
Measurement Range	3m-30km
Accuracy	1cm, 1deg
Used in	PRISMA (2010)



Metrology System 2nd Stage

System	ULLIS Absolute Precision Sensor
Accuracy	better than 100um

System	FRLS Fine Relative Lateral Sensor
Accuracy	few nm
Noise	10 nm/√(Hz)



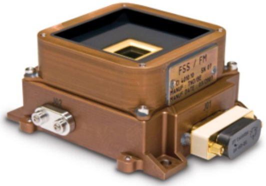
Reference:
Alcatel Alenia Darwin Summary Report

ADCS subsystem

Req.ID	Requirement	Value	Driving Req.ID
AS-01	Three-axis controlled	-	-
AS-02	Absolute pointing accuracy to target	0.43 ‘’	PL-02
AS-03	Pointing stability between LCS and BCS	0.1’’/s	PL-02

ADCS subsystem

# of units per spacecraft	Hardware	Function
2	**High precision star tracker**	Angular position knowledge
6	**Sun sensors**	Sun position/angular knowledge
1	**Fyber gyro**	3-Axis Angular rate, angular position
4	**8 Nms Reaction Wheel**	Disturbance rejection, fine pointing
1 on BCS	**Fine guidance sensor**	Precise angular position determination
1 on LCS	**Detector for fine guidance**	Precise angular position determination



Propulsion Subsystem

Req.ID	Requirement	Value	Driving Req. ID
PS-01	Orbit insertion and disposal maneuver	-	-
PS-02	Change the baseline (LCS are moving to change the baseline)	3200 m within 90 h	PL-01
PS-03	Relative position	< 1 um	PL-06
PS-04	Wheel unloading	-	-

Two-Stage Propulsion System

1. Coarse-Propulsion System:
    a. Higher thrust and impulse is needed for reconfiguration
    b. Monopropellant hydrazine (higher specific impulse)

2. Micro-Propulsion System:
    a. mN-Thruster with high resolution for fine positioning
    b. Coldgas Thrusters

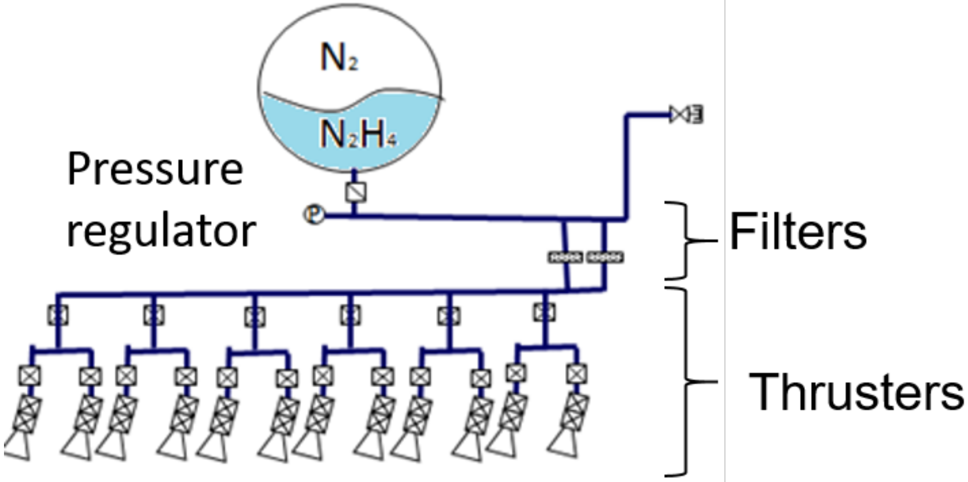
Coarse-Propulsion Subsystem: Δv Budget

Type of Maneuver	**LCS Δv (m/s)**	**BCS Δv (m/s)**
Orbit insertion and launcher dispersion	25	100
Reconfiguration and retargeting	325	-
Station keeping incl. wheel unloading	12	12
Disposal (End-of-life disposal concepts, Colombo, 2014)	25	25
Sum	**387**	**137**

numbers given for the overall lifetime of the mission

Coarse-Propulsion Subsystem

Monopropellant 1N thrusters (Aerojet)	
Number	12
Pressurant	5.49 kg N2 (LCS) 4.54 kg N2 (BCS)
Propellant	335 kg N2H4 (LCS) 250 kg N2H4 (BCS)
Initial pressure	8 MPa
Radius of tank	0.25 m (LCS) 0.22 m (BCS)
Material of tank	Aluminium
Minimum impulse bit	0.02 Ns

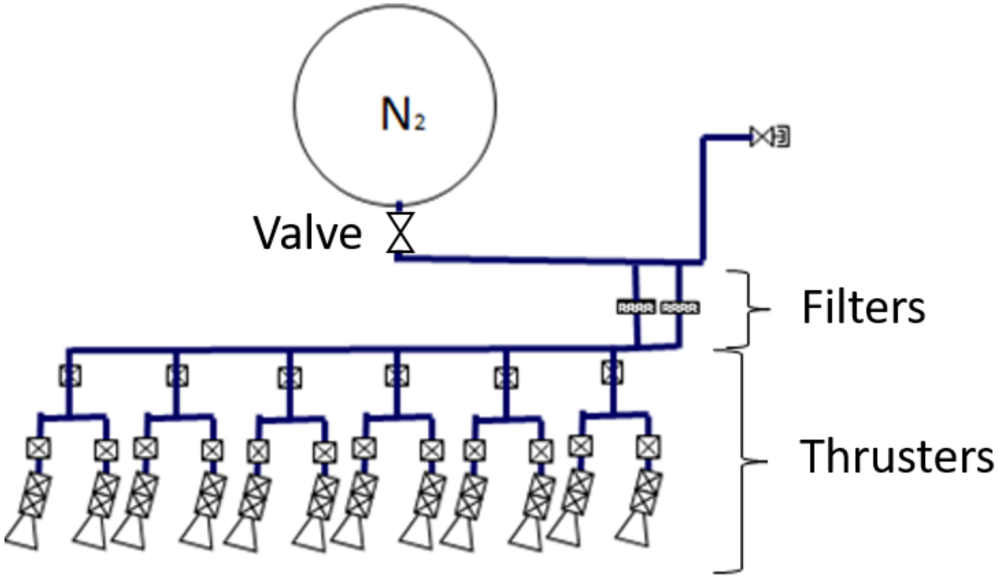


Micro-Propulsion Subsystem: Δv Budget

Type of Maneuver	LCS Δv (m/s)	BCS Δv (m/s)
Formation Flight Precision Control	5.5	5.5
Solar Pressure Compensation	0.5	0.5

Micro-Propulsion Subsystem

Coldgas 0.001N thrusters (AMPAC-ISP)	
Number	12
Propellant	20 kg N2
Initial pressure	6 MPa
Radius of tank	0.4 m
Material of tank	Aluminium
Thrust range	1 uN - 0.001 N



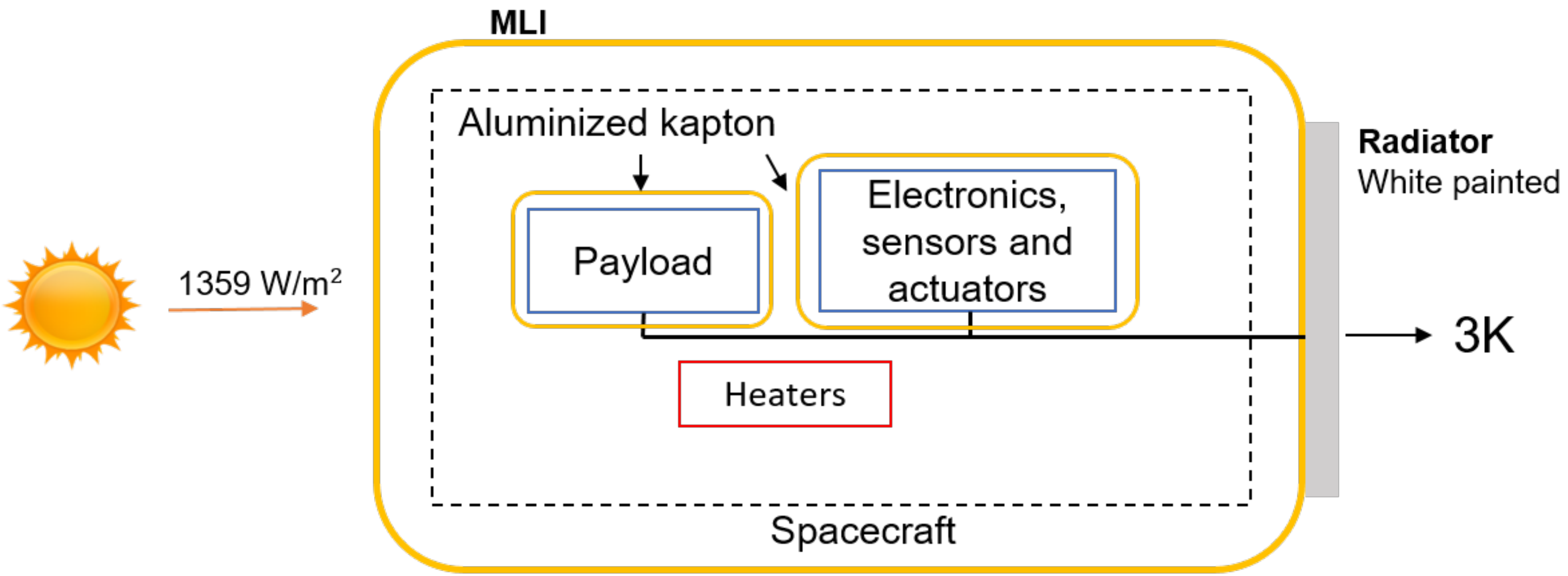
Fully redundant and balanced system

Similar system used in EUCLID

Thermal Control Subsystem

Req.ID	Requirement	Value	Driving Req. ID
TCS-01	Mirror temperature	60 K	PL
TCS-02	Delay line temperature	40 K	PL
TCS-03	Detector (Bolometer) temperature	50 mK	PL
TCS-04	Power to dissipate	650 W (BCS) 300 W (LCS)	PL
TCS-05	Protect spacecraft from external environment	1359 W/m^2	-

Thermal Control Subsystem



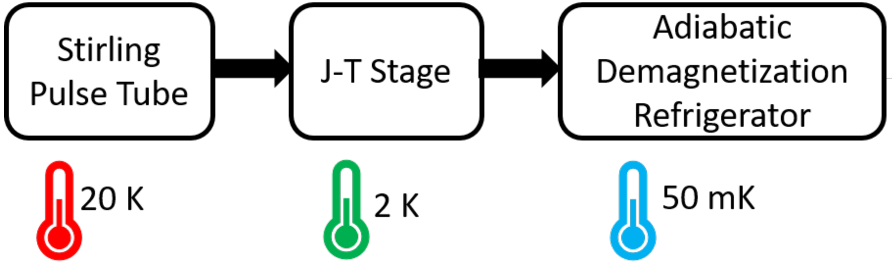
Thermal Control Subsystem

Mirrors cooling (LCS)

Passively cooled

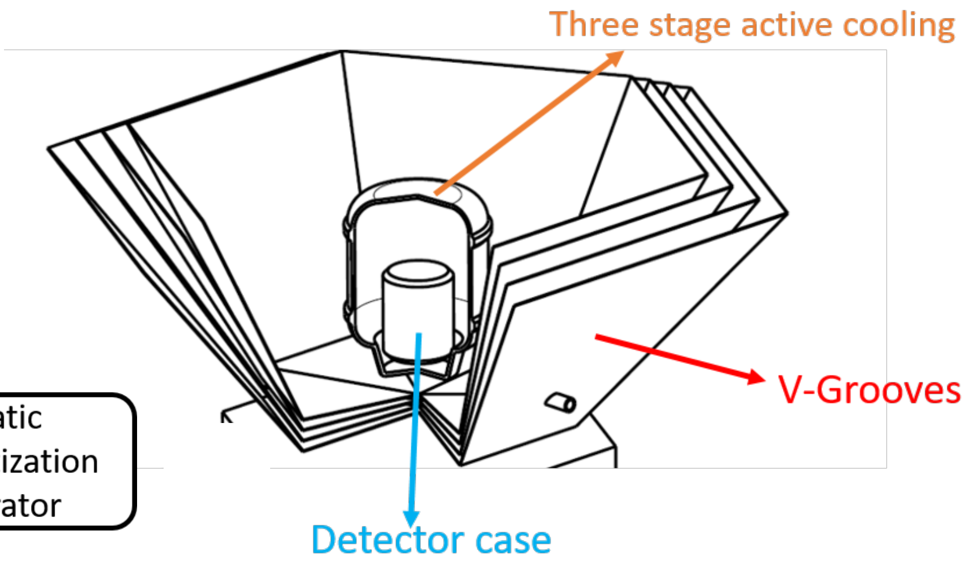
V-Grooves, MLI

Detector cooling (BCS only)



Mass = 400 kg

Power = 1 kW



On-Board Computer (OBC)

Req.ID	Requirement	Value	Driving Req.ID
OB-01	ADCS & Formation Flight Control System	-	-
OB-02	Process data and housekeeping	-	SR-01

ERC32 processor (up to 16 MIPS)

Used on **LISA Pathfinder**, etc.

Mass: 13.6 kg

Dimensions: 307 x 242 x 263 mm

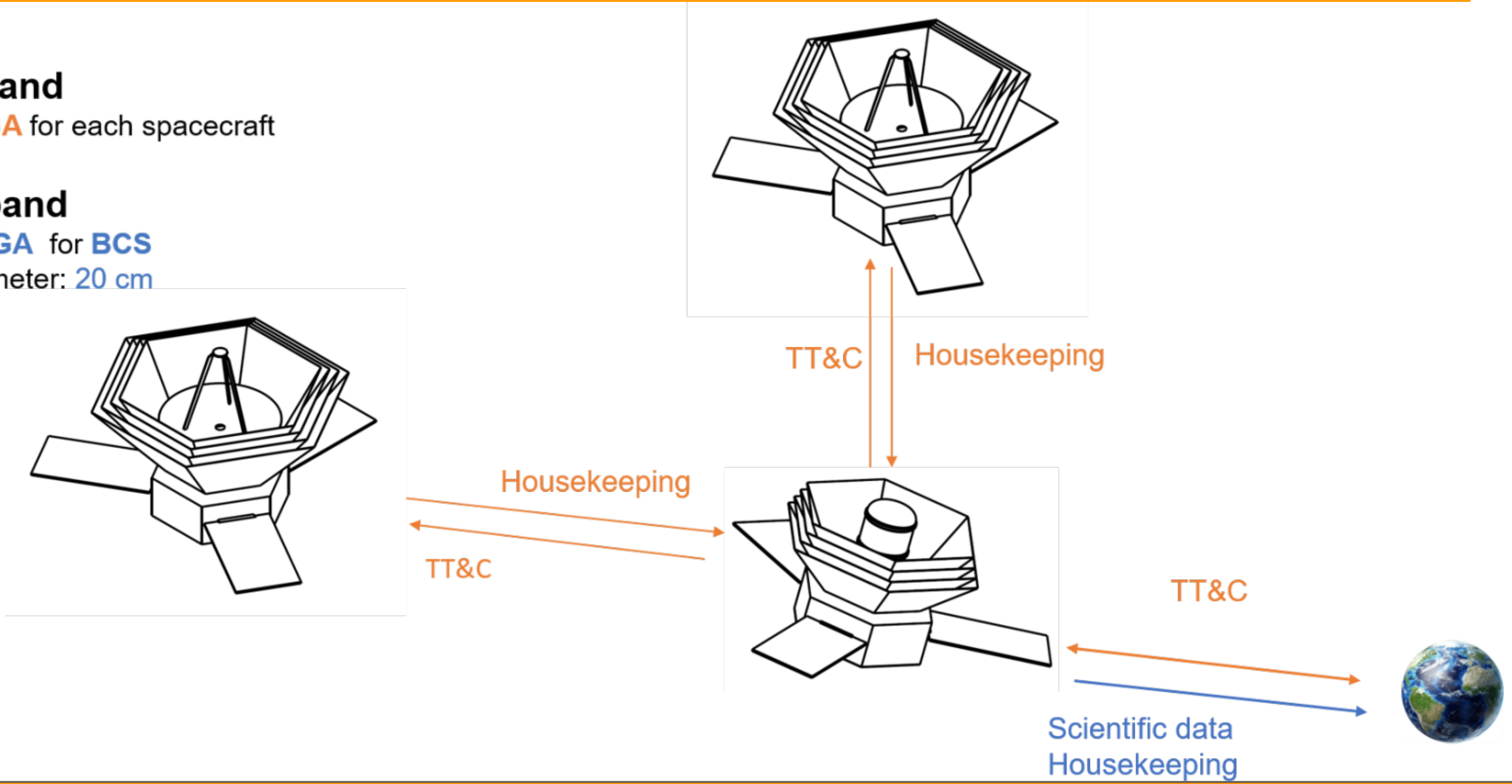
Power: 35 W

Telecommunication Subsystem

Req.ID	Requirement	Value	Driving Req.ID
TS-01	Science downlink datarate	50 Mbps	-
TS-02	Housekeeping datarate	512 kbps	-
TS-03	TT&C datarate	1 Mbps	-

Telecommunication Subsystem

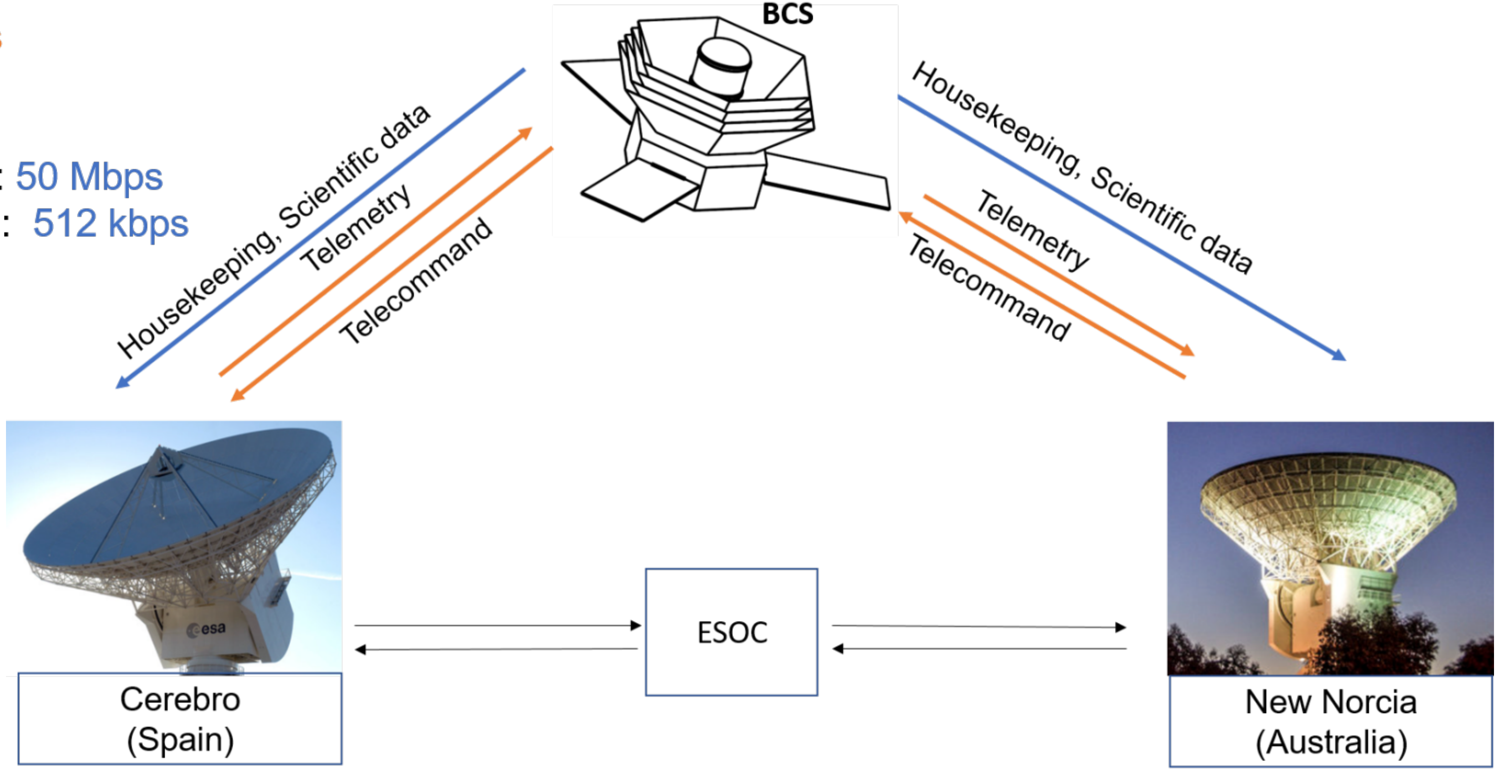
- **S-band**
  2 LGA for each spacecraft
- **X-band**
  1 MGA for BCS
  Diameter: 20 cm



Operation & Ground Segment

S-band
TT&C: 1 Mbps

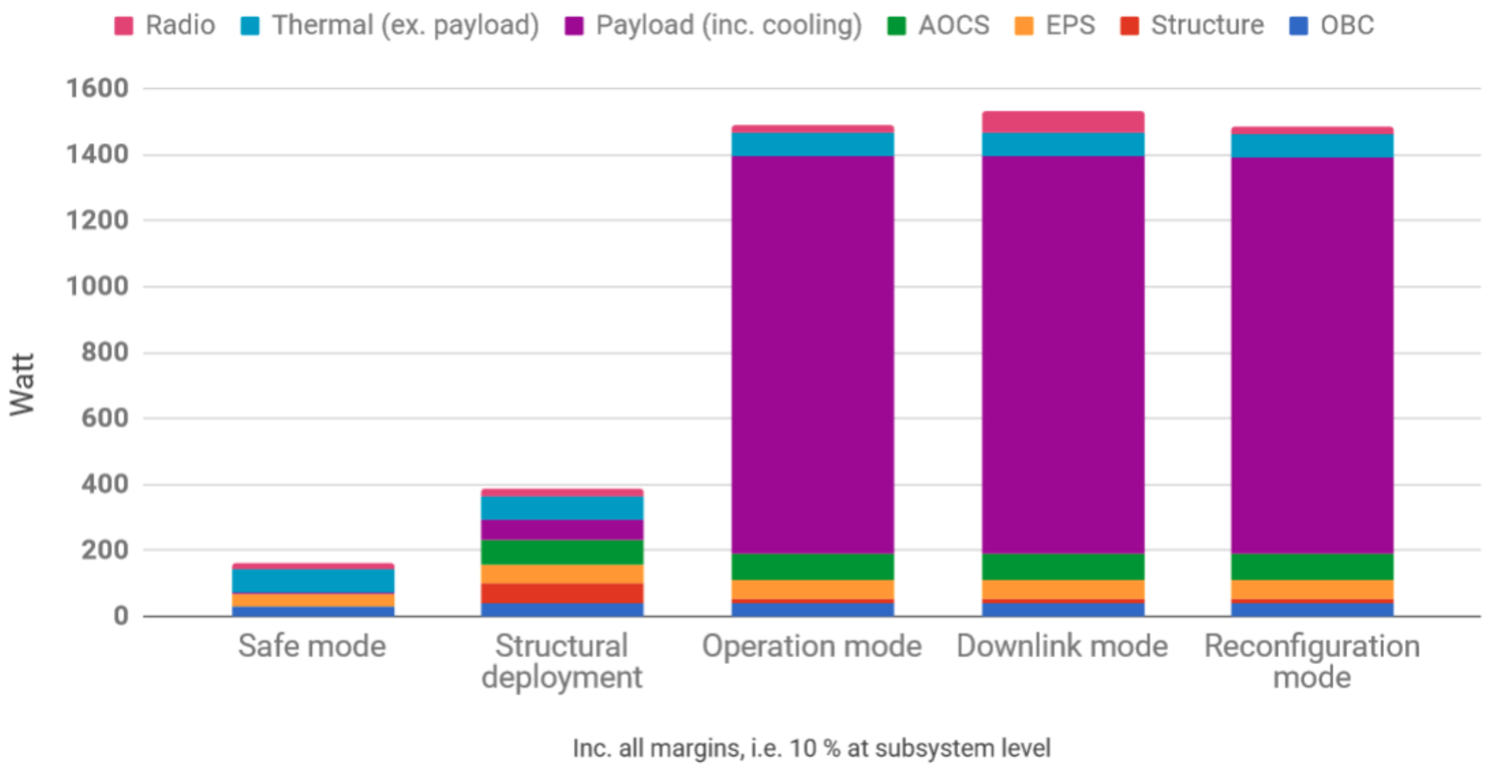
X-band
Scientific data: 50 Mbps
Housekeeping: 512 kbps



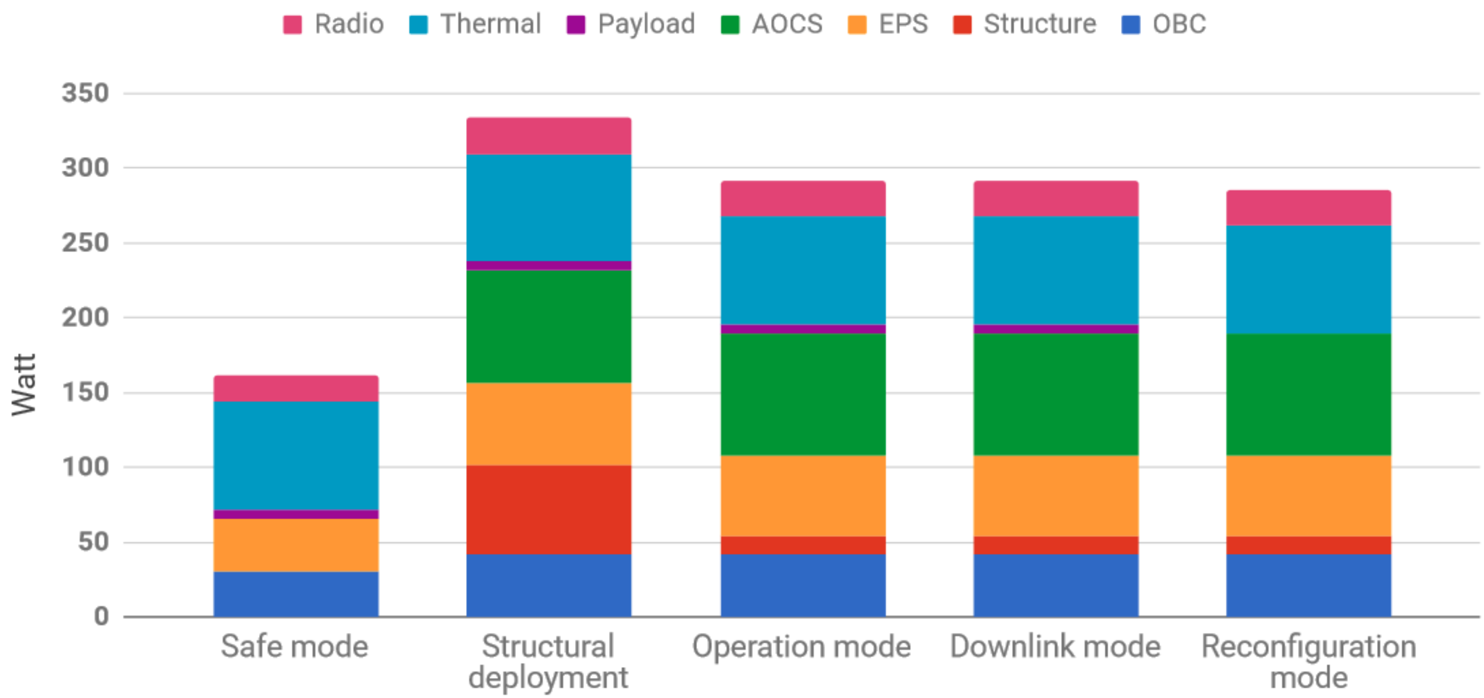
Electric Power Subsystem

Req.ID	Requirement	Value	Driving Req.ID
EPS-01	Power for LCS	350 W	-
EPS-02	Power for BCS	1.6 kW	-
EPS-03	Solar aspect angle	+/- 60°	EPS-01/EPS-02

Electric Power Budget - BCS

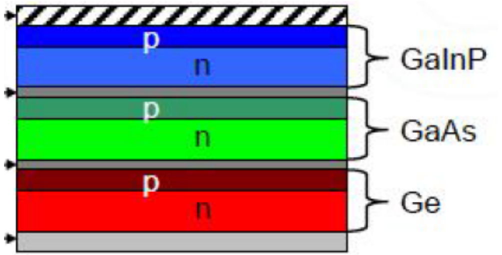


Electric Power Budget - LCS



Inc. all margins, i.e. 10 % for subsystem level

Electric Power Subsystem



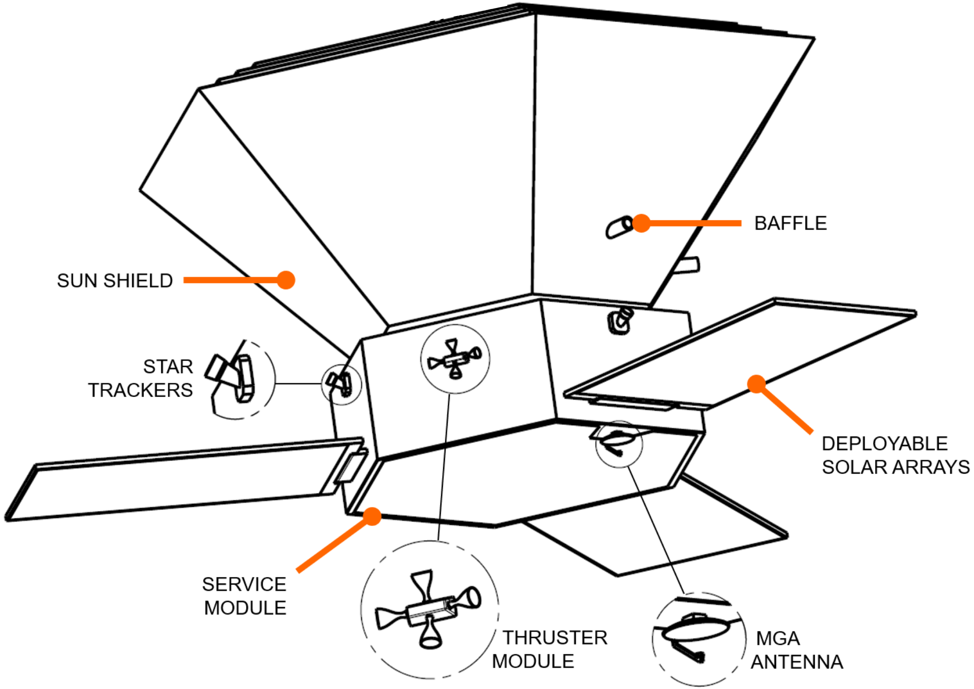
Solar cells
Type: **5 μm triple-junction GaAs**
Area: **9.9 m^2 (BCS)**
2.4 m^2 (LCS)

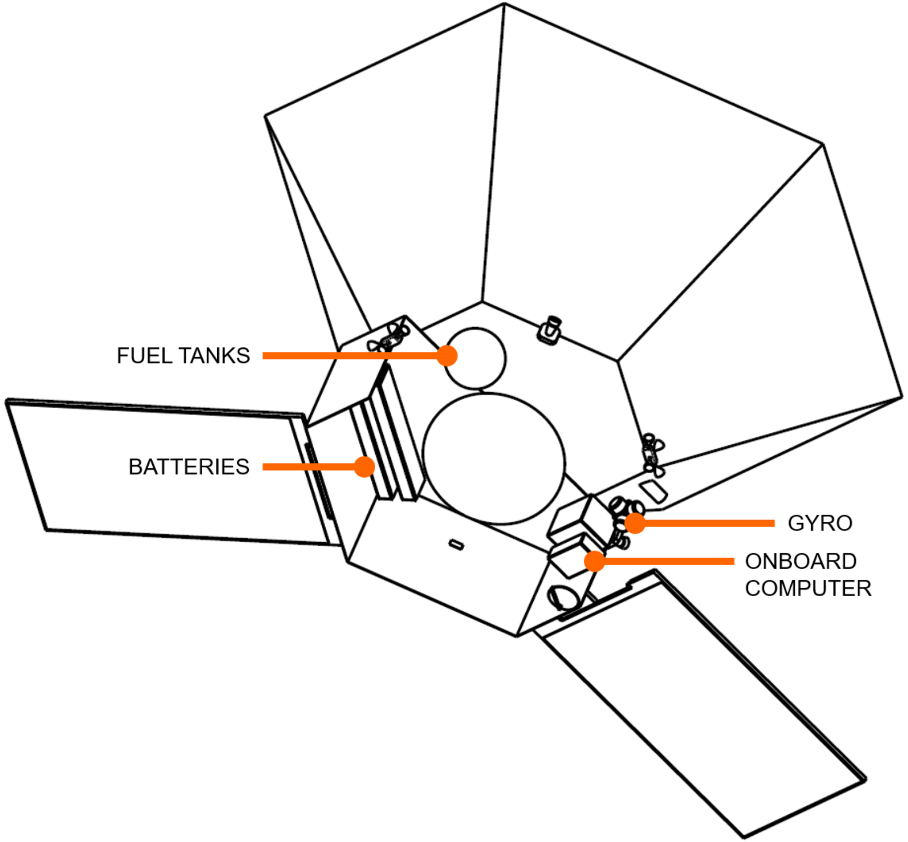
Regulator

Battery
Type: **Sony 18650HC**
Configuration: **46p 9s**
Capacity: **2.6 kWh**
DoD: **40 %**
Autonomy: **3 hrs**

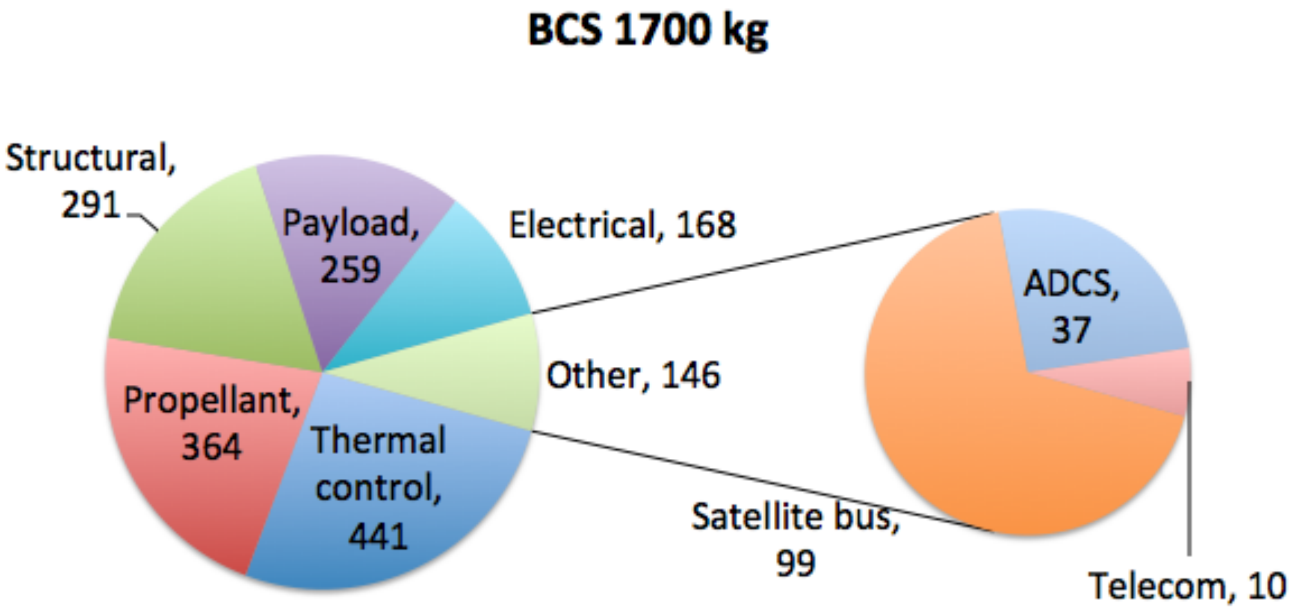
LOADS

Spacecraft Layout



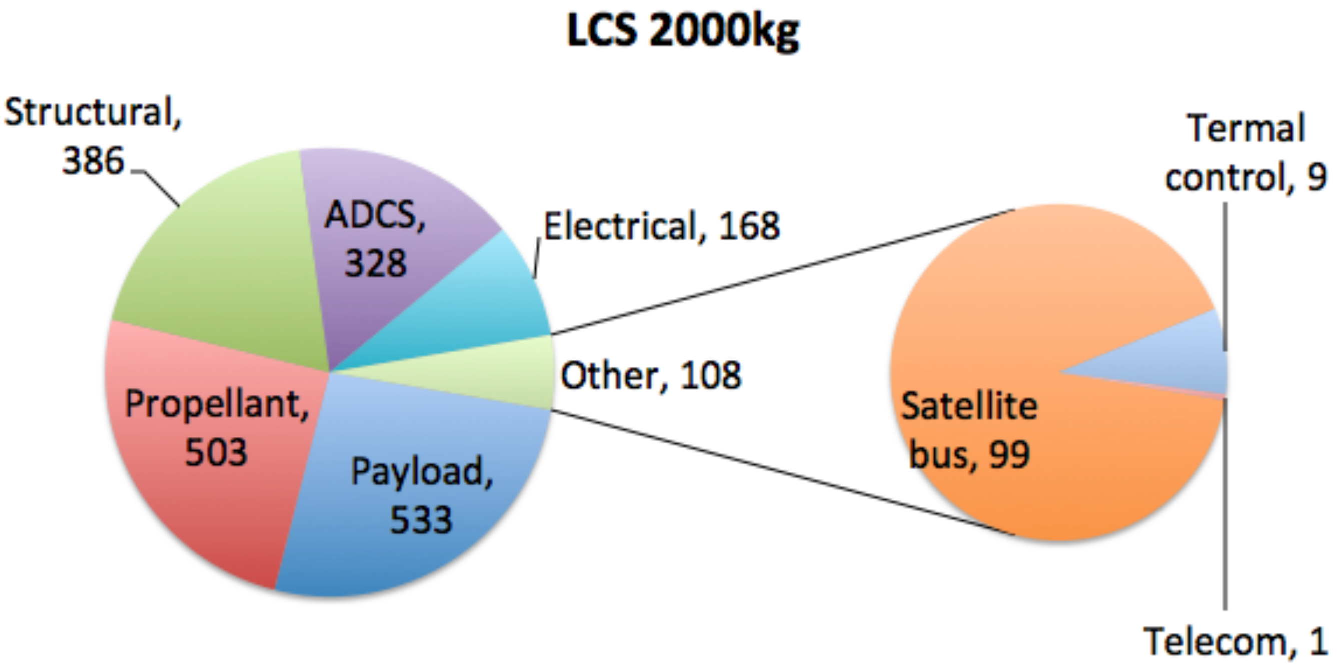


Mass Budget BCS



Margins:
5-20% on equipment level
20% on subsystem level

Mass Budget LCS



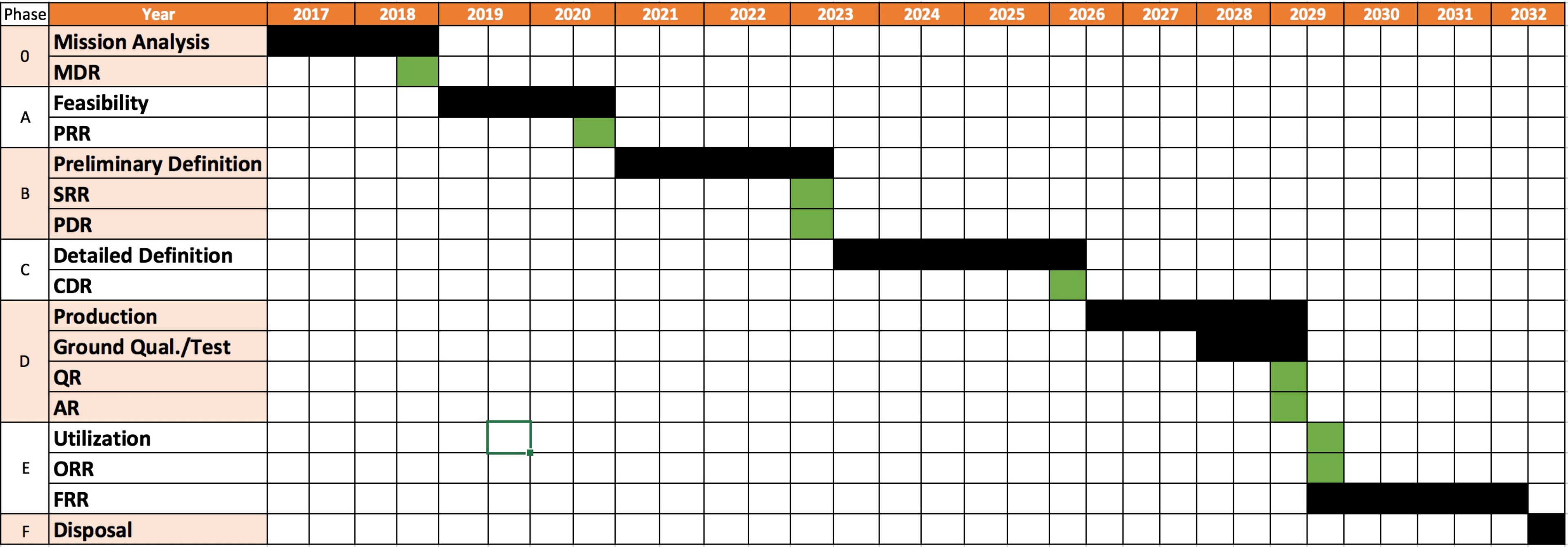
Margins:
5-20% on equipment level
20% on subsystem level

Mass Budget Total

Element	Mass
LCS1	2000 kg
LCS2	2000 kg
BCS	1700 kg
Structure and Adapter	500 kg
Boosted Weight	**6200 kg**

VI. Development Schedule

Timeline



MDR: Mission Definition Review
PRR: Preliminary Design Review
SRR: System Requirement Review
PDR: Preliminary Design Review
CDR: Critical Design Review

QR: Qualification Review
AR: Acceptance Review
ORR: Operation Readiness Review
FRR: Flight Readiness Review

Mission Design 1: Preliminary Design
Mission Design 2: Detailed Design

VII. Critical Risks

Technology Readiness Level (TRL)

Technology	TRL
OPD Correction system	TRL5
Interferometer	TRL5
Formation Flying	TRL5
Telescope	TRL8
Propulsion system	TRL9
Detector	TRL4
Telecom subsystem	TRL9
Electric power subsystem	TRL9
Metrology	TRL8

Technology Readiness Level (TRL)

Technology	TRL
OPD Correction system	TRL5
Interferometer	TRL5
Formation Flying	TRL5
Telescope	TRL8
Propulsion system	TRL9
Detector	TRL4
Telecom subsystem	TRL9
Electric power subsystem	TRL9
Metrology	TRL5

Technology Readiness Level (TRL)

Technology	TRL
OPD Correction system	TRL5
Interferometer	TRL5
Formation Flying	TRL5
Telescope	TRL8
Propulsion system	TRL9
Detector	TRL4
Telecom subsystem	TRL9
Electric power subsystem	TRL9
Metrology	TRL5

Technology Readiness Level (TRL)

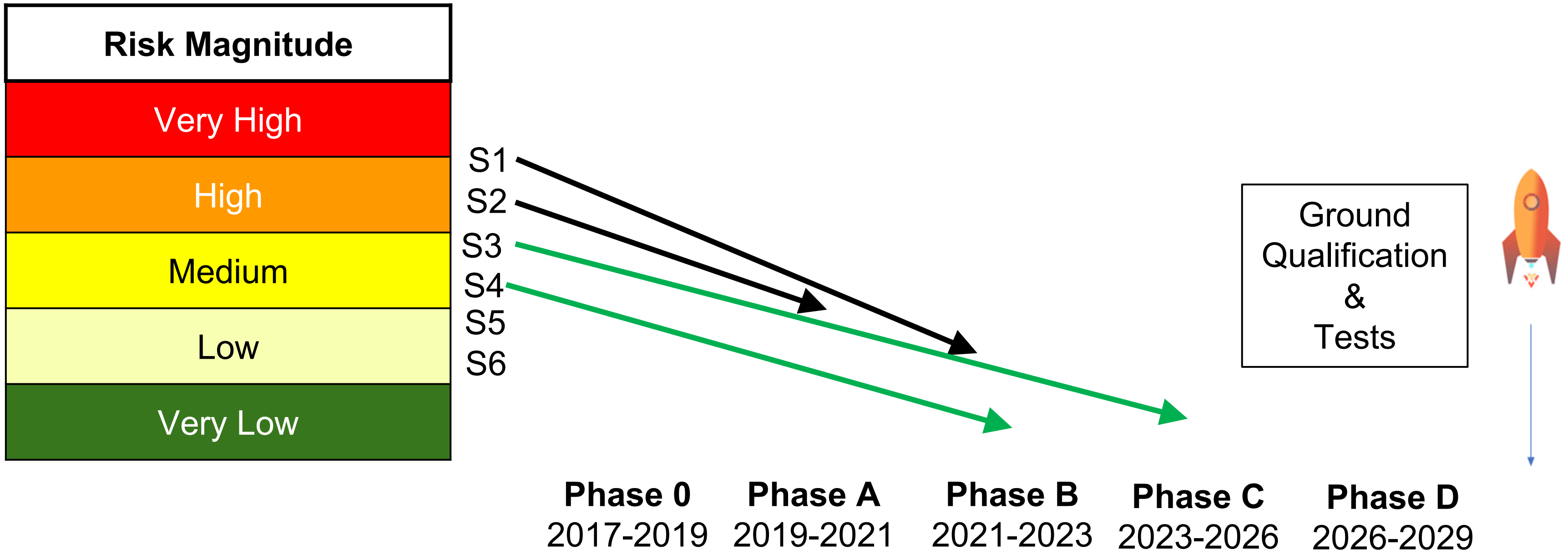
Technology	TRL
OPD Correction system	TRL5
Interferometer	TRL5
Formation Flying	TRL5
Telescope	TRL8
Propulsion system	TRL9
Detector	TRL4
Telecom subsystem	TRL9
Electric power subsystem	TRL9
Metrology	TRL5

Technology Readiness Level (TRL)

Technology	TRL
OPD Correction system	TRL5
Interferometer	TRL5
Formation Flying	TRL5
Telescope	TRL8
Propulsion system	TRL9
Detector	TRL4
Telecom subsystem	TRL9
Electric power subsystem	TRL9
Metrology	TRL5

Severity					
5	S6: Launch Failure Low	S4: OPD correction system Medium	S2: Interferometer High	Very high	Very high
4	Low	Low	S3: Detector Medium	S1: Formation Flying High	Very high
3	Very low	Low	S5: Deploying 3 spacecrafts at once Low	Medium	High
2	Very low	Very low	Low	Low	Medium
1	Very low	Very low	Very low	Low	Low
	A	B	C	D	E
	Likelihood				

Risk Trend



S1: Formation Flying
S2: Interferometer
S3: Detector

S4:OPD Correction System
S5: Deploying Three spacecrafts at once
S6: Launch

VIII. Cost Analysis & Descoping Options

Cost Analysis

Description	Million €
SpaceCraft 1 SerViceModule (Beam Combinator)	300
SpaceCraft 2 + SpaceCraft 3 (TelesCope)	510
2 Telescopes, PayLoadModules, Fine-Guidance-System	250
Total industrial cost	**1060**
P-L MI, FGS, metrology	350
cooling 50 mK	100
Total PayLoad	**450**
Project Operations ESA	212
SpaceCraft	1060
Operations (Mission Operations Center, Science Operations Center)	170
Launcher	175
Contingency 15 %	216
Total ESA CaC	**1833**
PayLoad (Member States)	**450**
Total K€	**2283**

Descoping options

- Choosing a detector which has already flown
- Reduce the mirror size
- SNR
- Lower the Mission Time
- Change the Formation Flying to a Boom

We are opened to the Scientific Community to propose **additional instruments**. Room and mass is available.

IX. Outreach

Social Media

@FROST_Telescope FROSTelescope

Follow updates on the **life** of the program, learn of the **dusty universe**, the formation of **stars** and **planets**.

On the day of the launch, a **special SnapChat filter** will be available worldwide.

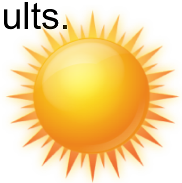
Crowdfunding

KissKiss BankBank®

Who does not want to have his or her **name on a spacecraft**?
Who would like to have a **baby planet wearing his or her name**?

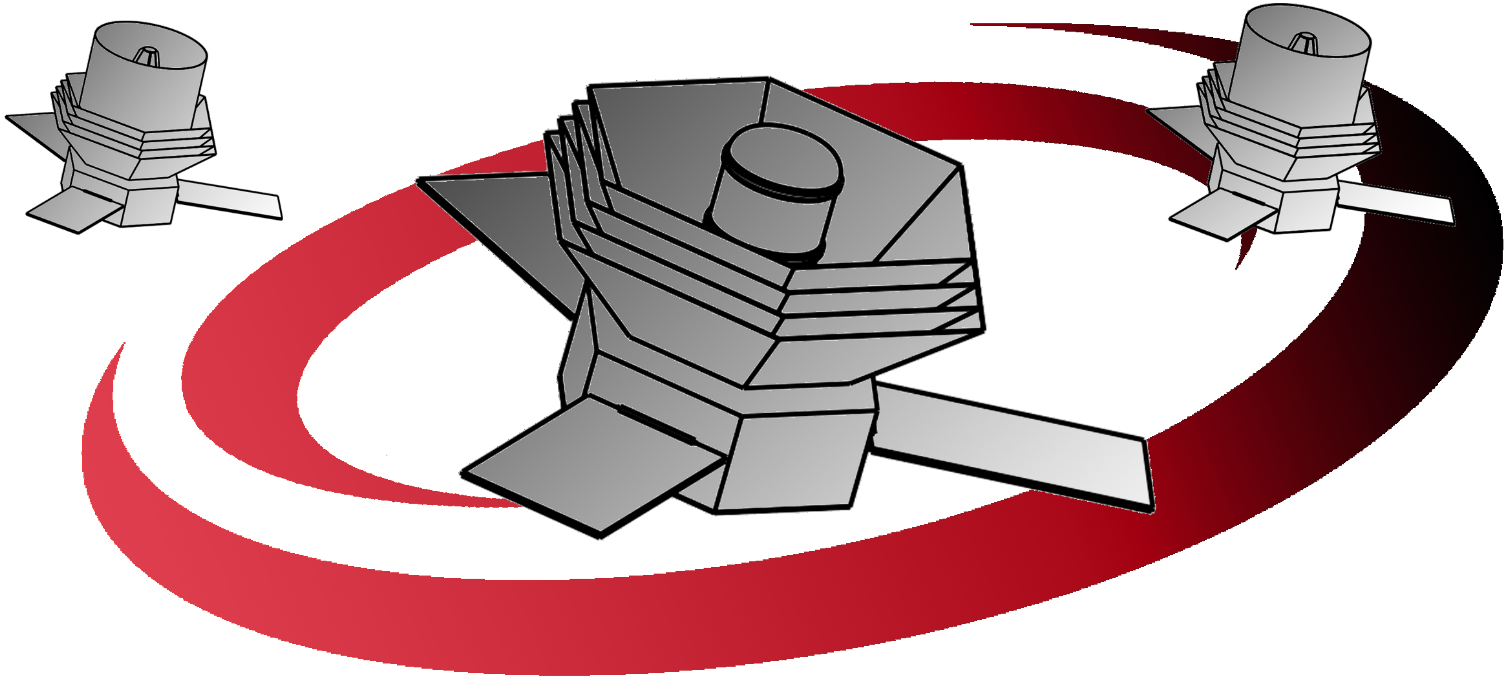
We can offer you that !

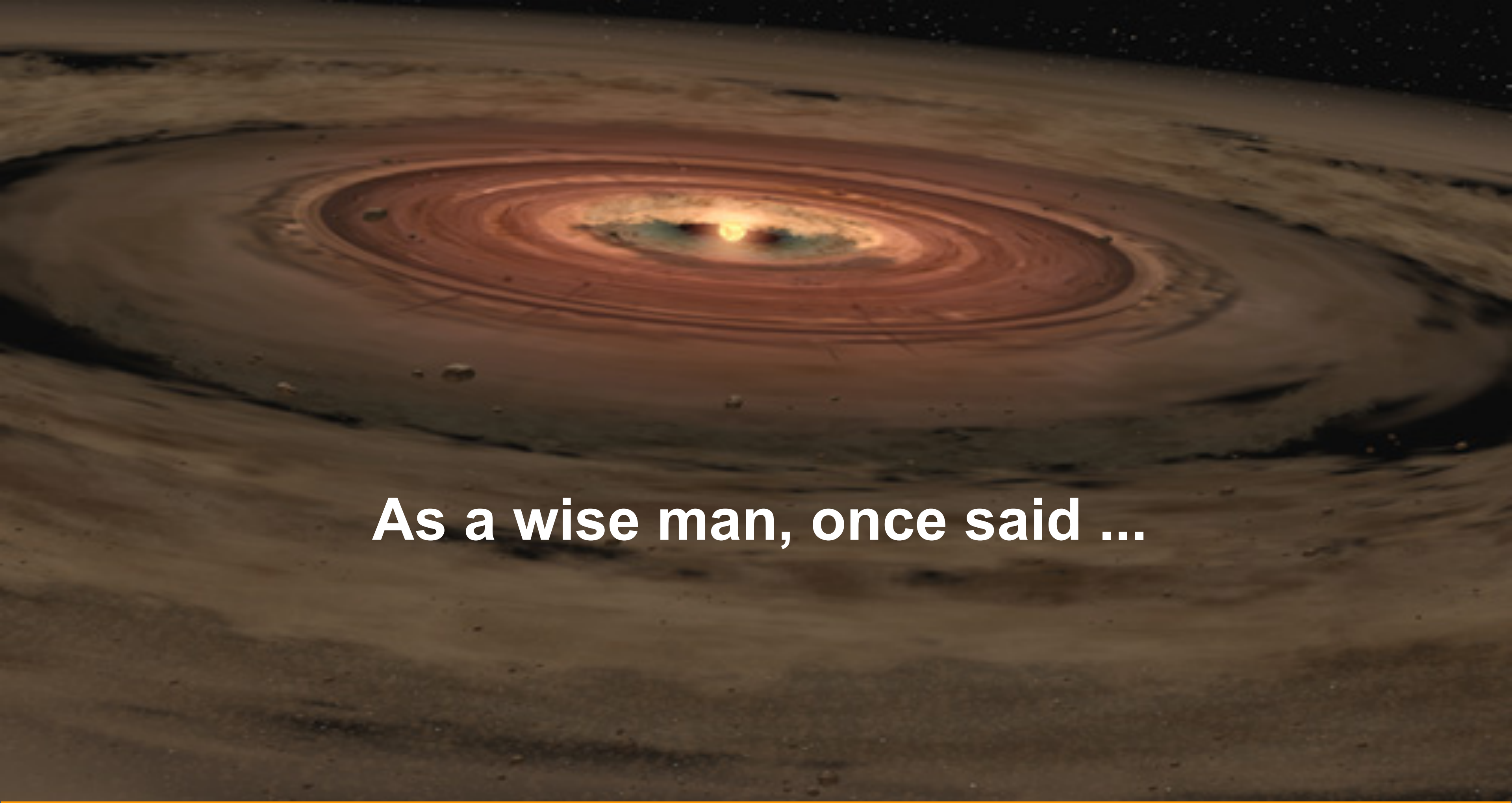
The money will be used to organise a **travelling exhibition** about the formation of stars and of planets for kids and young adults.



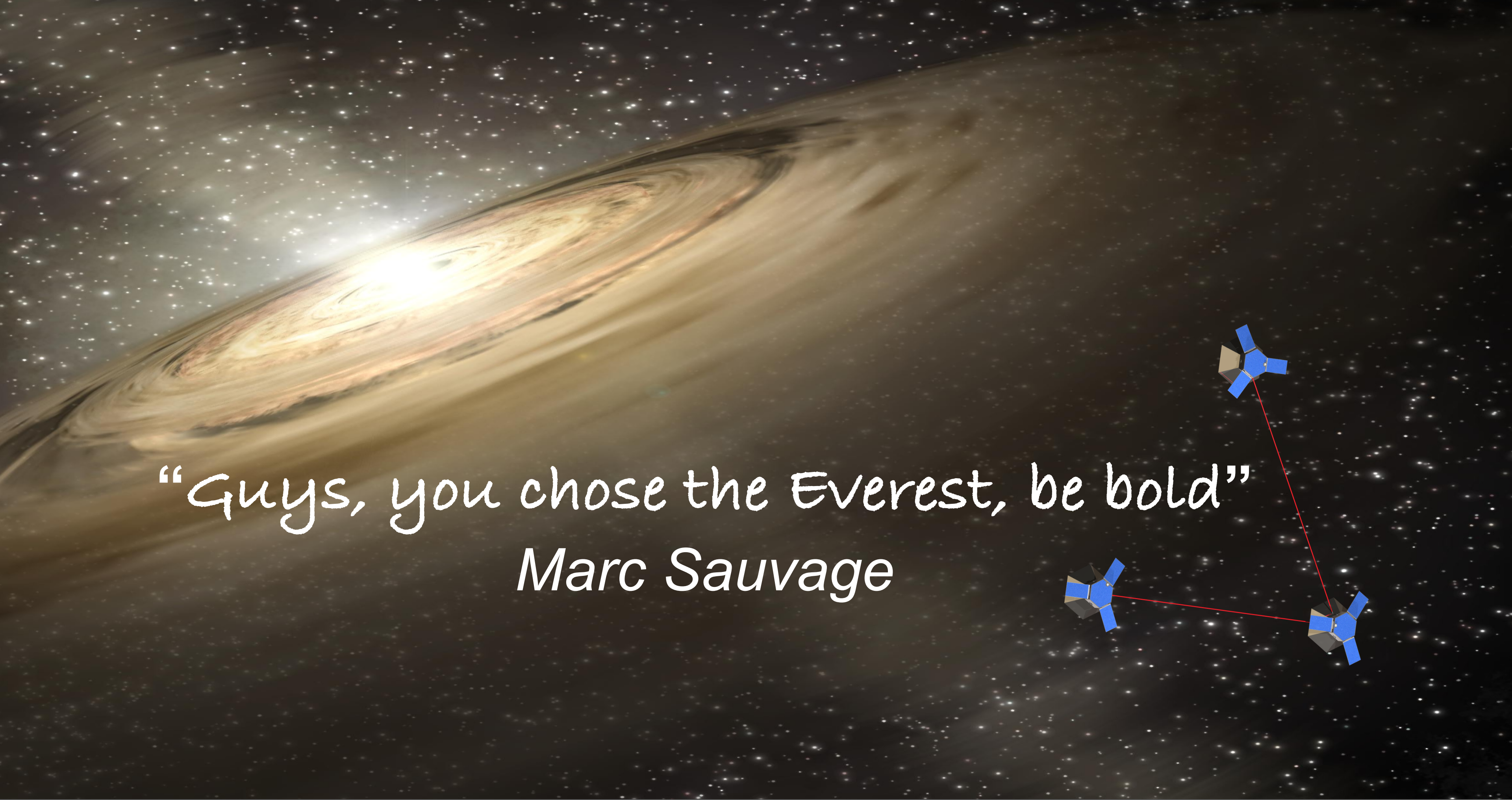
FROST

Far infraRed Observation Spectography Telescopes





As a wise man, once said ...



"Guys, you chose the Everest, be bold"

Marc Sauvage

Far infraRed Observation Spectrography Telescopes

FROST

Thank you !

Questions?

FFG

esa

INTERNATIONAL SPACE SCIENCE INSTITUTE

Hallerstrasse 6 • CH-3012 Bern • Switzerland

AUSTROSPACE