Far & Extreme UV Astrophysical Spectral Telescope

Team Green – Summer School Alpbach 2022

Alpbach Summer School 2022
Team Green

Michele Berretti, Alexandros Binios, Victoria Foss, Jana Gillmayr, Justin Jacobs, Viktoria Kutnohorsky, Filip af Malmborg, Davide Manzini, João Matias, Filippo Oggionni, Agnessa Pedersen, Laurynas Sisovas, Mirko Viviano

Tutors: Greta De Marco, Charlotte Götz

Outline

- Science Case (Filip af Malmborg)
- Payload Concept & Measurement Requirements (Davide Manzini)
- Mission Profile & Analysis (Filippo Oggionni)

Mission Statement

To further our understanding of the formation of high-energy events in Sun-like stars and the EUV radiation incident on exoplanet atmospheres.

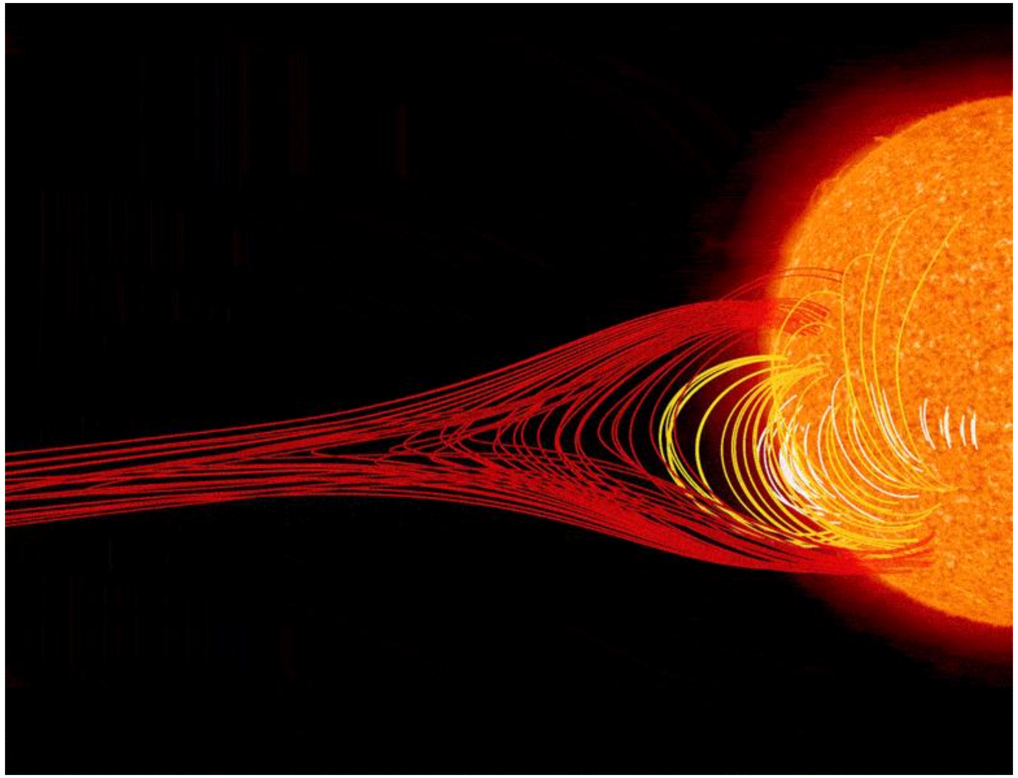
Science Case

Primary scientific questions

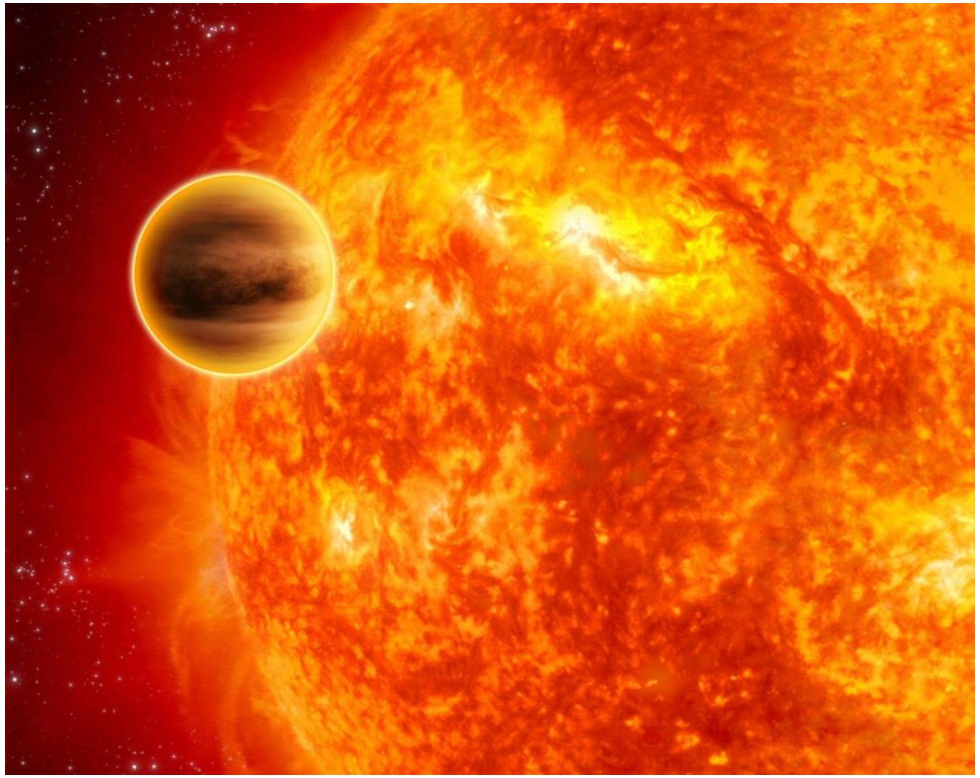
A. How do stellar properties affect the formation of energetic transient events?

B. What is the EUV radiation environment experienced by exoplanets orbiting nearby stars?

Primary scientific questions



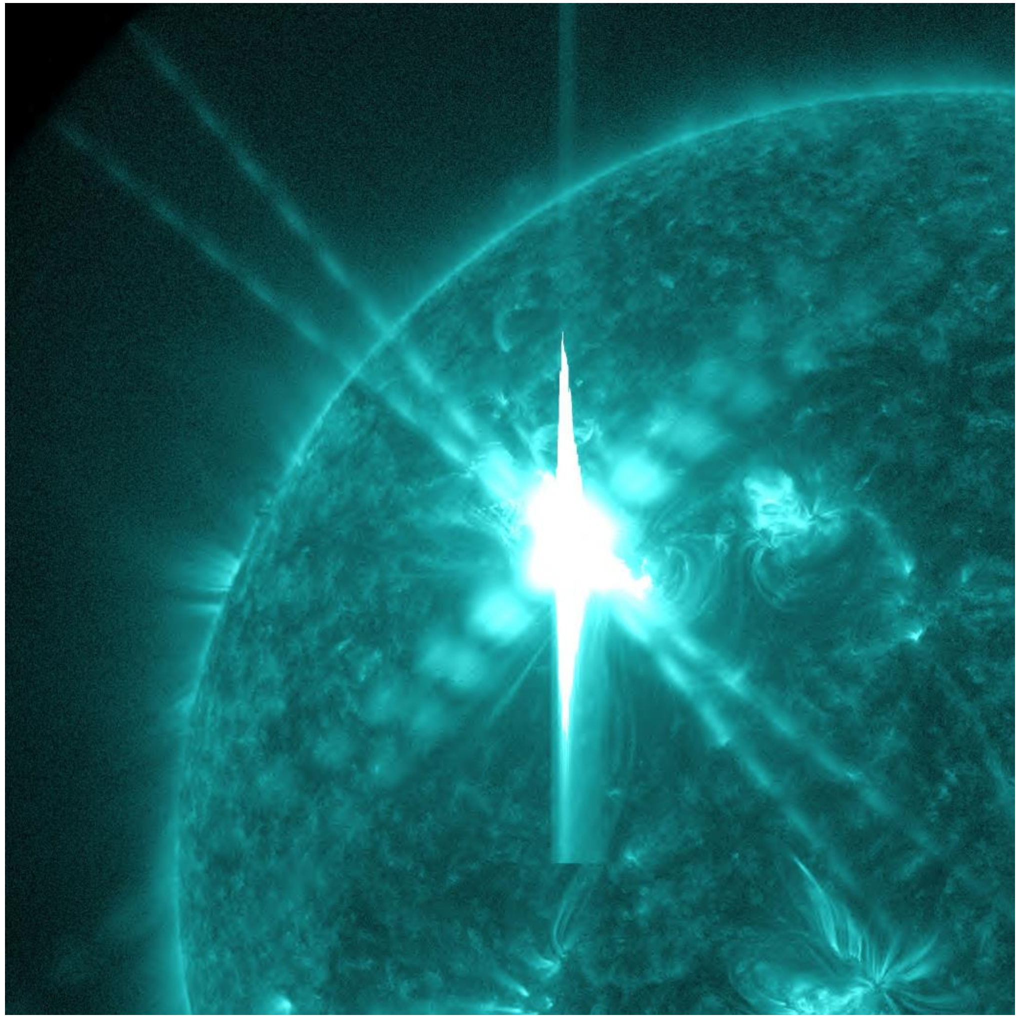
[LINA TRAN, NASA'S GODDARD SPACE FLIGHT CENTER, 2017]



[NASA/JPL-Caltech, 2021]

Transient events - flares

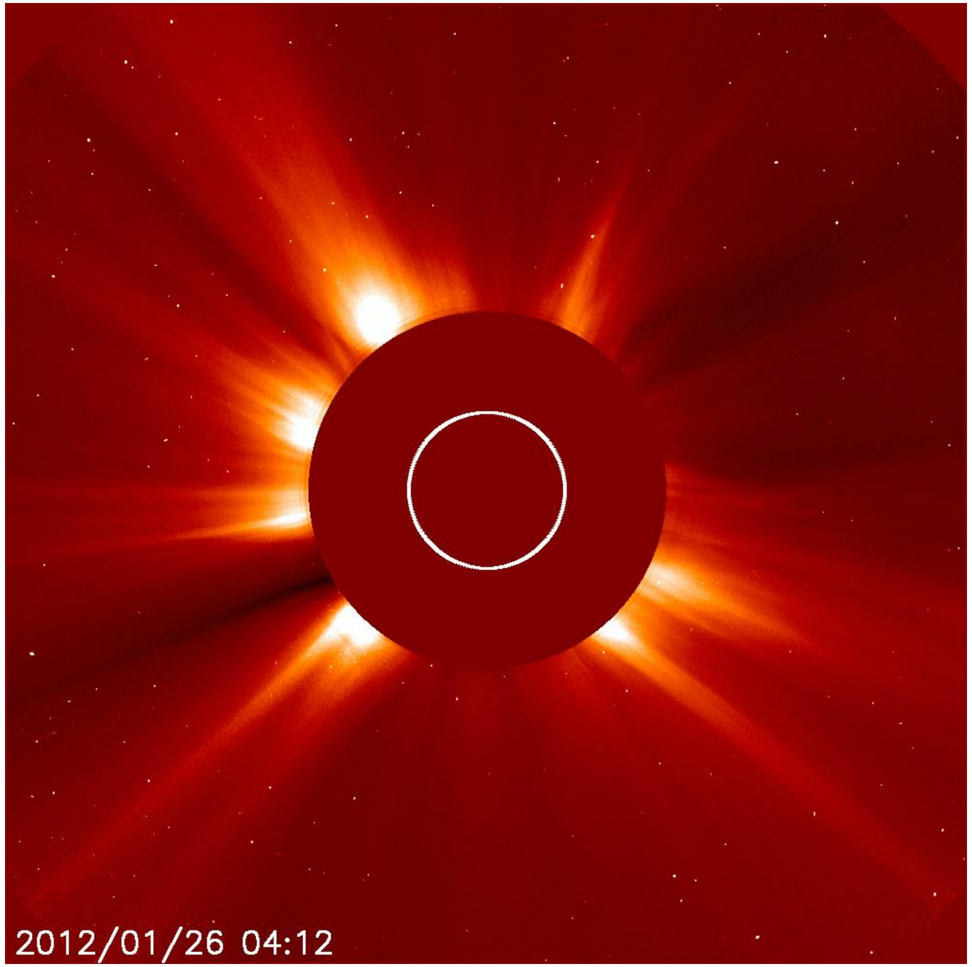
- Stellar flares are intense localized eruptions of electromagnetic radiation in stellar atmospheres
- Distributed over the full EM spectrum, have been observed in most stars
- Typical duration (sun): 5 minutes
- Typical frequency (sun): 1-2/hour



[NASA/SDO/AIA]

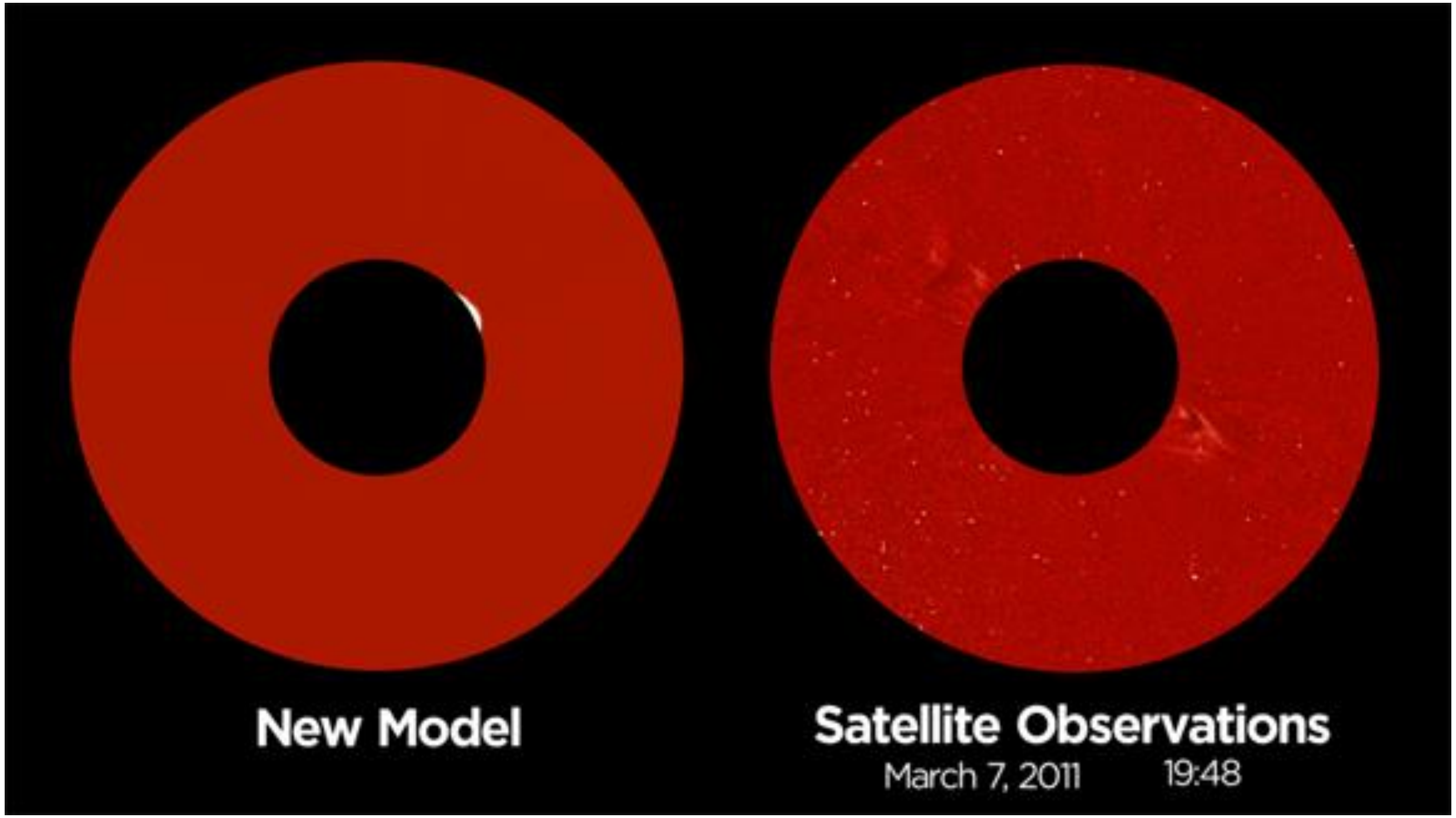
Transient events - CMEs

- A coronal mass ejection (CME) is an eruption of magnetized plasma from a star’s corona
- Primary cause of geomagnetic storms
- Exact physical mechanism is not known
- Assumed to be caused by destabilization of large-scale magnetic structures and resulting reconfiguration by magnetic reconnection [Kaiser et al., 2008]



[SOHO mission gallery, https://soho.nascom.nasa.gov/gallery]

CMEs - Our Current Understanding

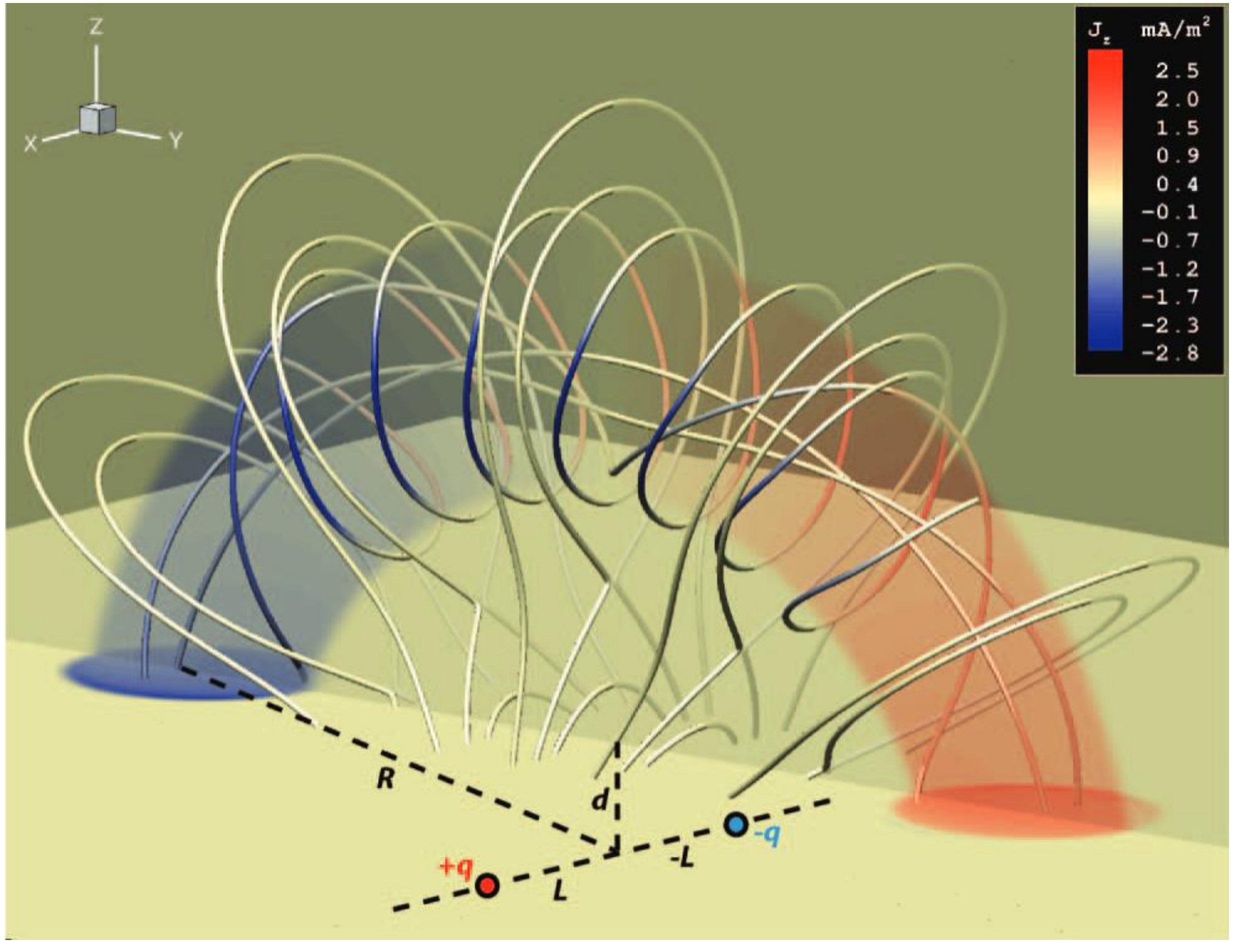


[Kilpua et al., 2019]

Unanswered questions:

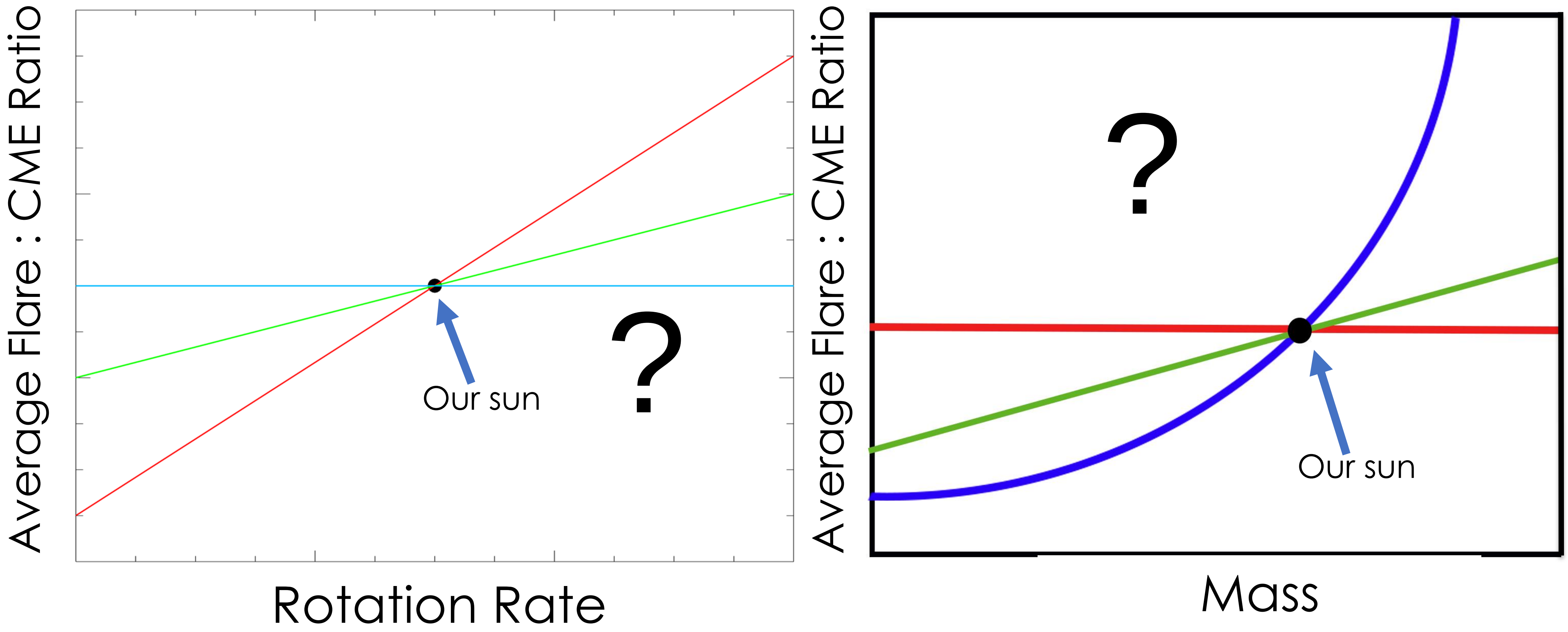
- What triggers a CME?
- Connection between CMEs and flares?
- Does their frequency correlate to stellar properties?

CMEs - Modelling



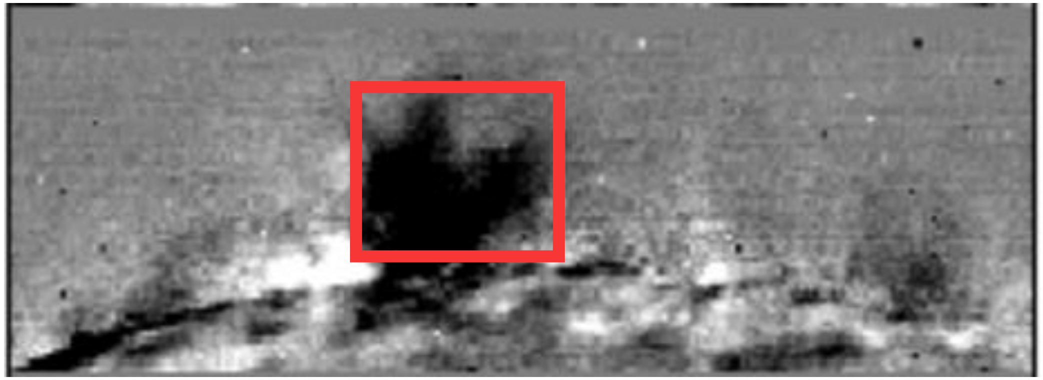
[Roussev et al., 2008]

CMEs – Model uncertainties



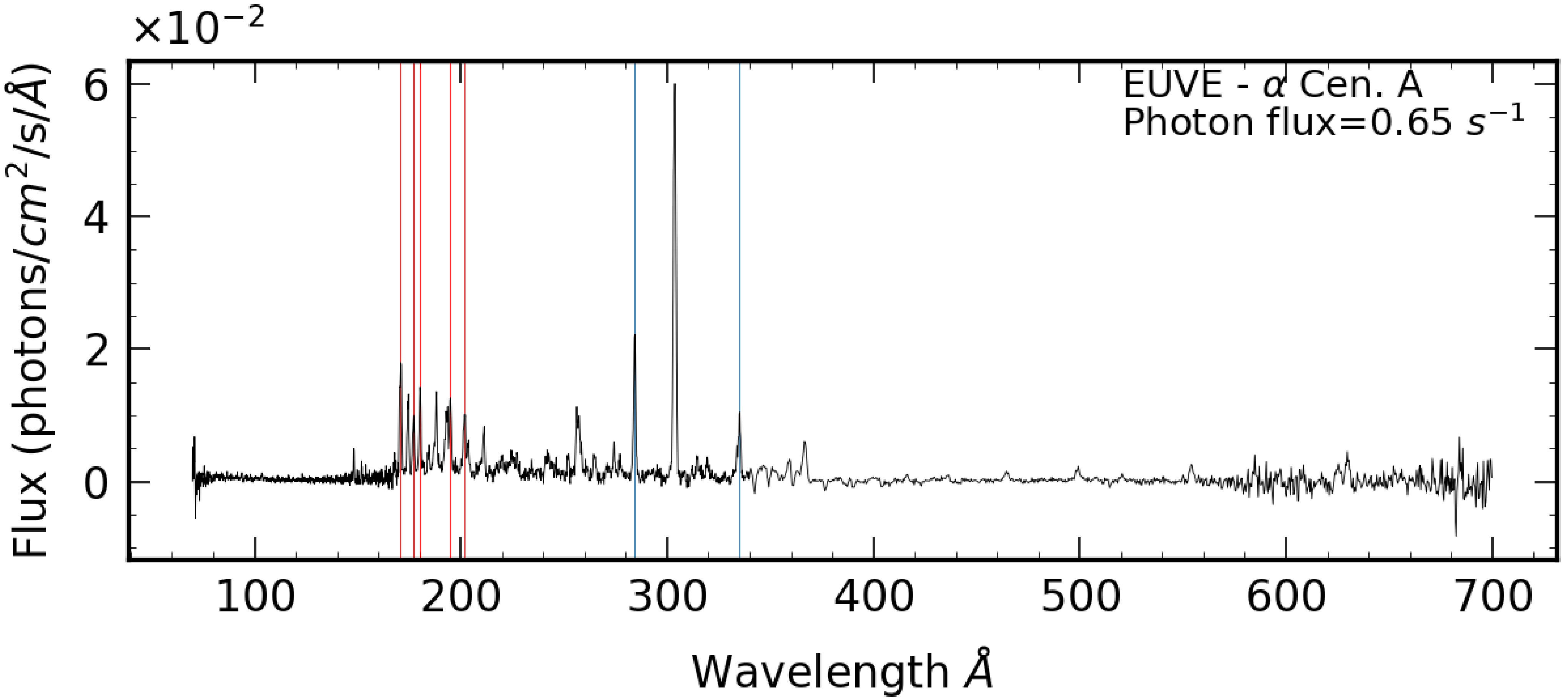
CME – Coronal Dimming

- We can detect CMEs on other stars by measuring **coronal dimming**
- Coronal dimming occurs due to mass loss in the corona
- In general, we expect a one-to-one correlation between CMEs and coronal dimming [Veronig et al., 2019]



Mg IX emission line at 368 Å as measured by SOHO [Harrison et al., 2003]

Coronal Dimming

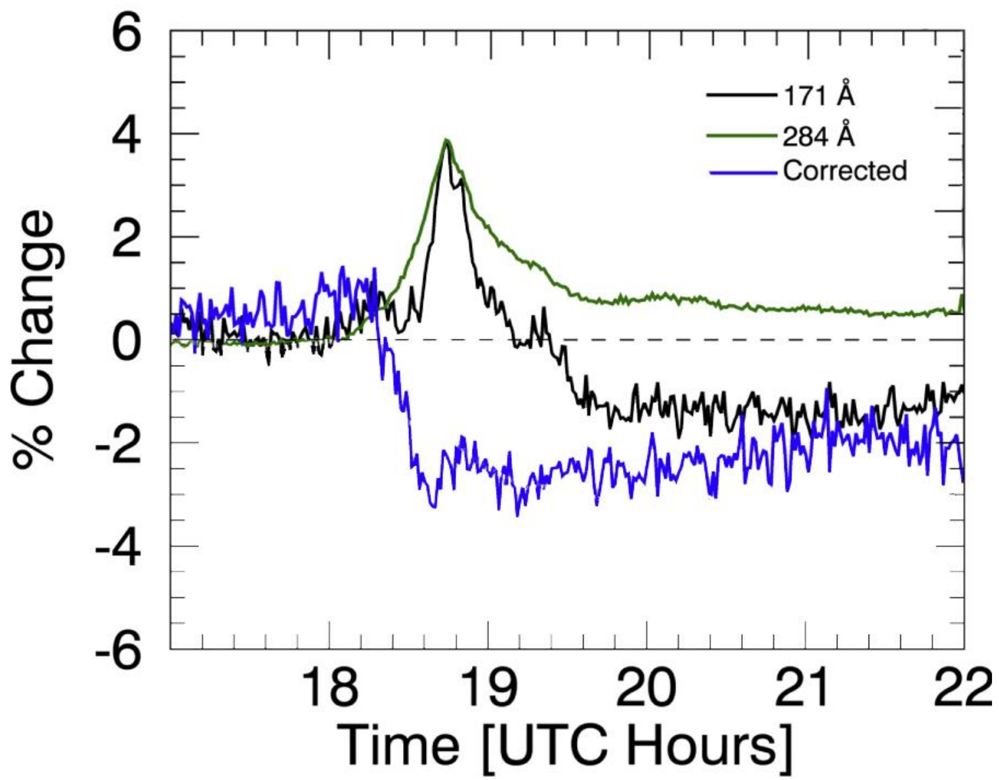


Coronal Dimming

Non-dimming (Fe IX–Fe XIII) / **Dimming** (Fe XIV–Fe XX)

Ion	Wavelength (Å)	Peak Formation Temperature (MK)
Fe IX	171	0.631
Fe X	177	0.933
Fe XI	180	1.15
Fe XII	195	1.26
Fe XIII	202	1.58
Fe XIV	211	1.86
Fe XV	284	2.19
Fe XVI	335	2.69
Fe XVIII	094	6.46
Fe XX	132	9.33

[Adapted from Mason et al., 2014]



[Adapted from Mason et al., 2014]

CME observations – Conclusion

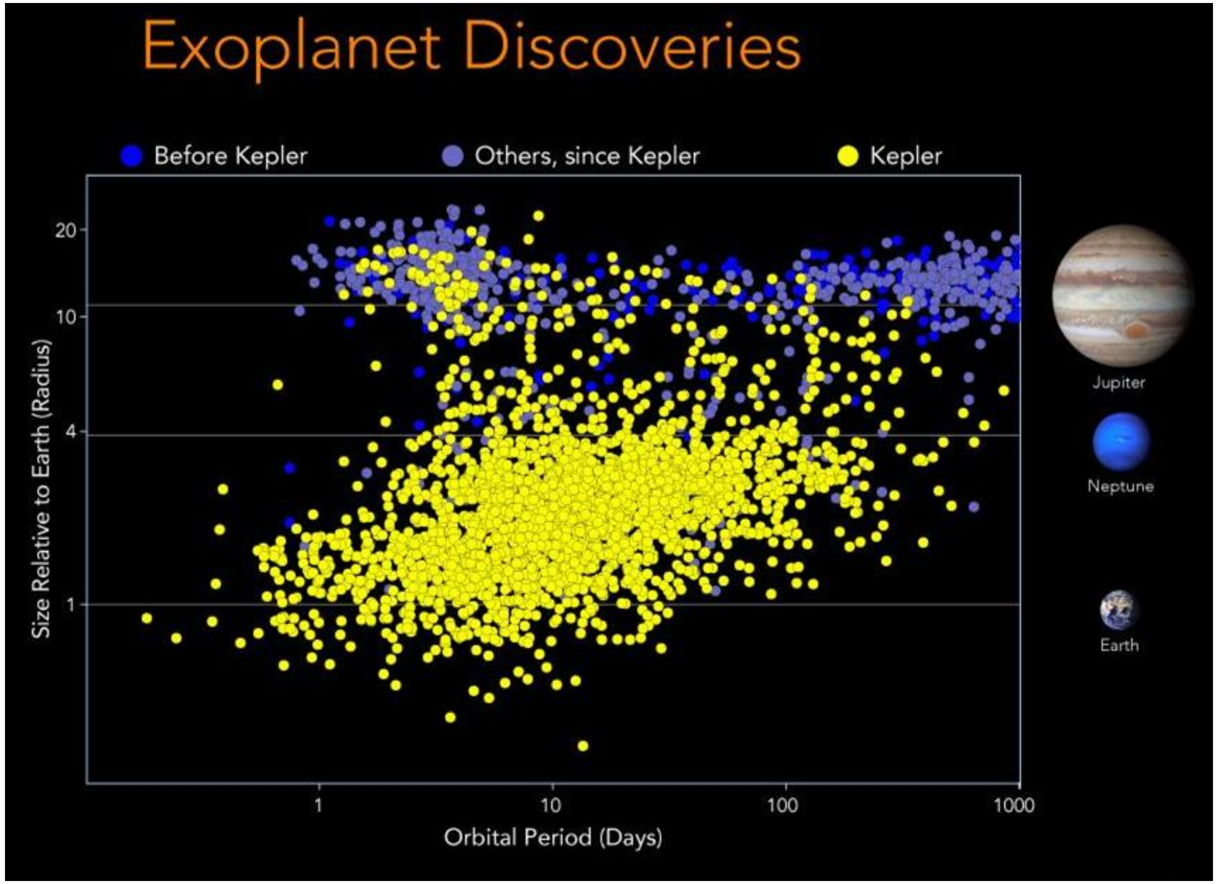
Req. ID	Requirement
FE-SCI-010	Observe 25 Sun-like stars and detect potential coronal mass ejections
FE-SCI-011/021	Measure coronal dimming and flares, including the onset and decay time of the events
FE-SCI-012	Observe at least 10 CMEs in each of the 25 stars

- Science results
  - Understanding of flare/CME ratio coupling to stellar properties
  - Improve models for CME formation

Exoplanets

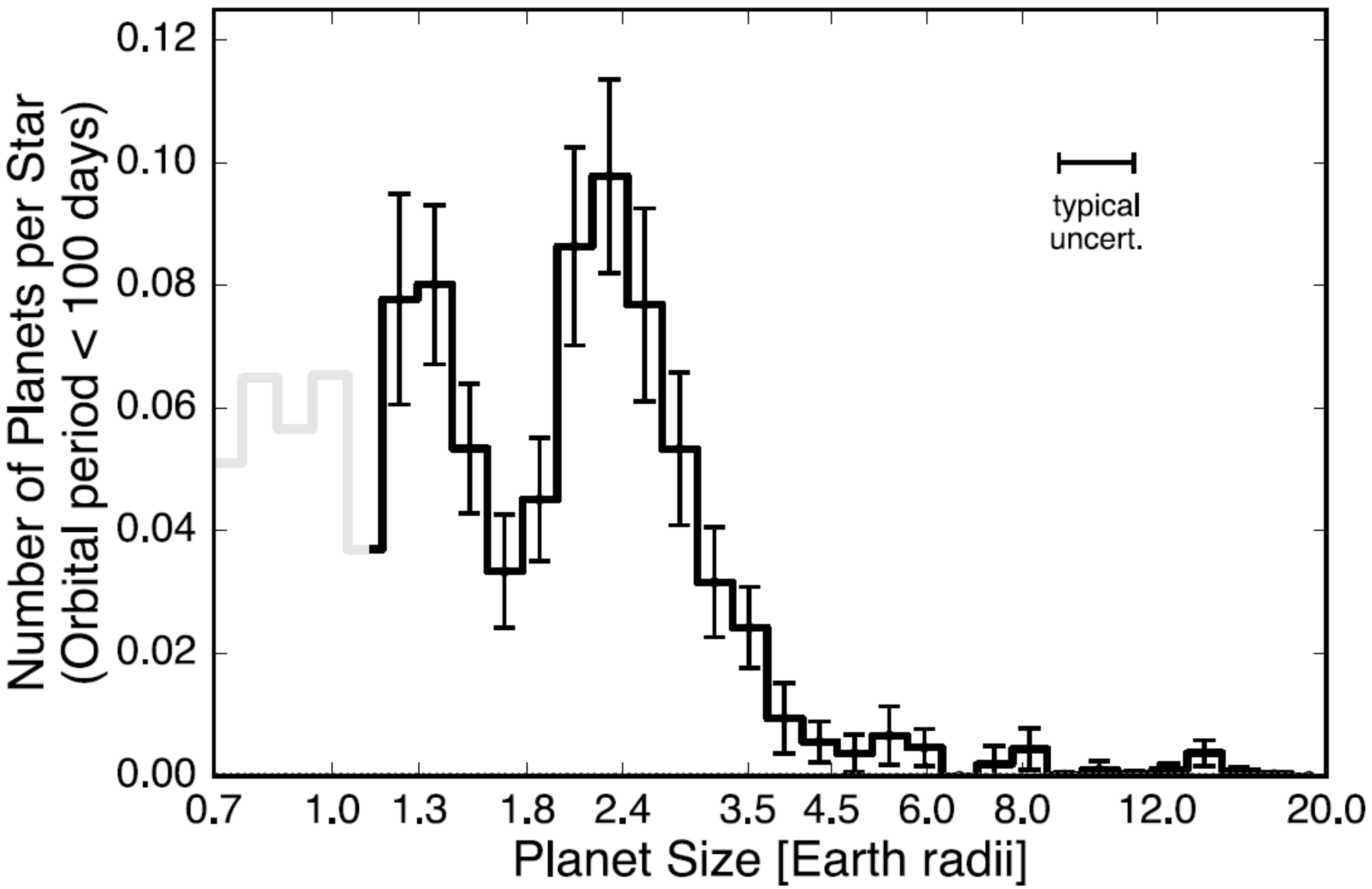
- 4531 exoplanets have been observed in 3363 systems
- Kepler meant a huge leap forward
- 166 ‘Earth-like’ rocky planets ($<1.6\ R_E$)
- 1389 ‘super-Earths’

[Values as of 2021]



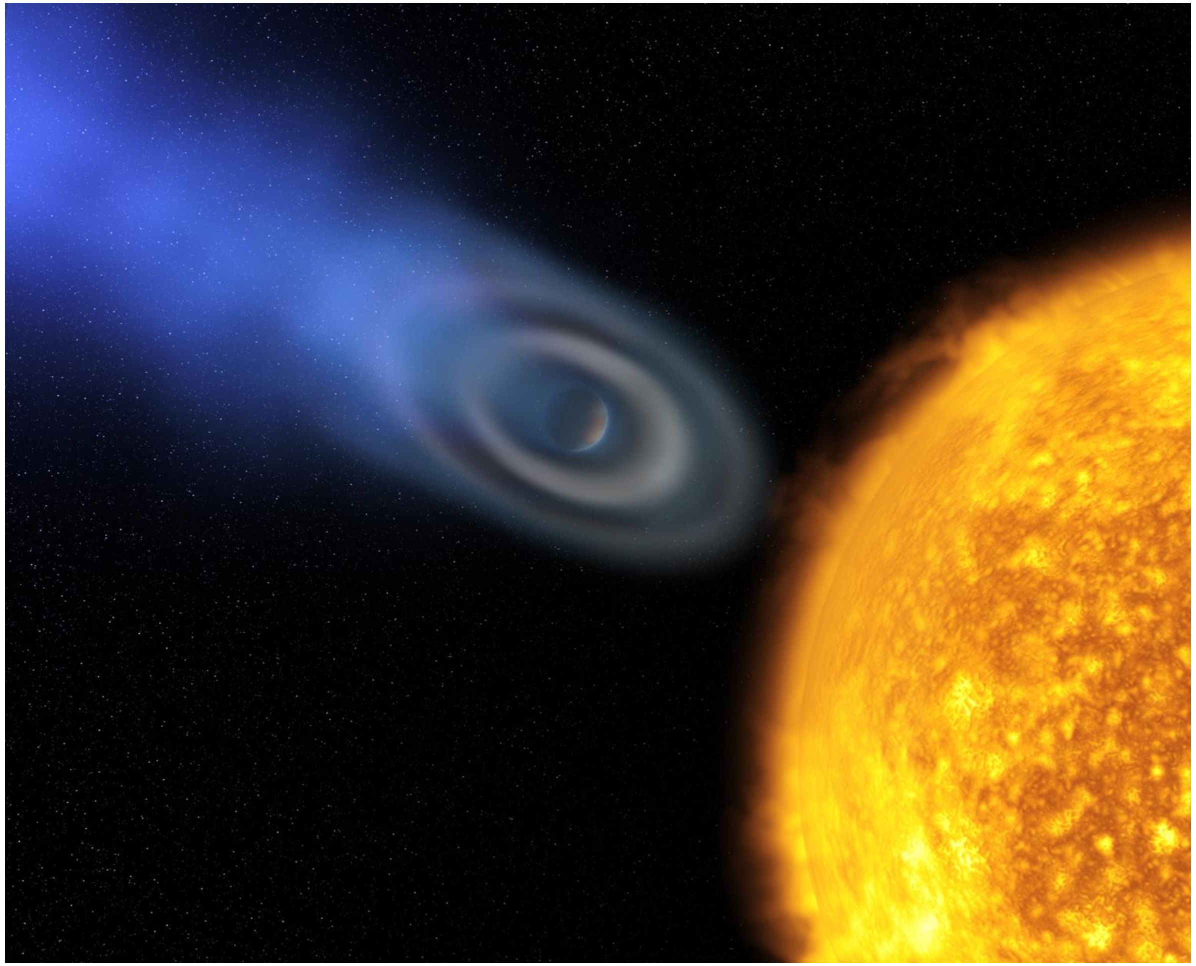
[https://www.nasa.gov/content/kepler-multimedia]

Exoplanet atmospheres – Kepler valley



[Fulton et al., 2017]

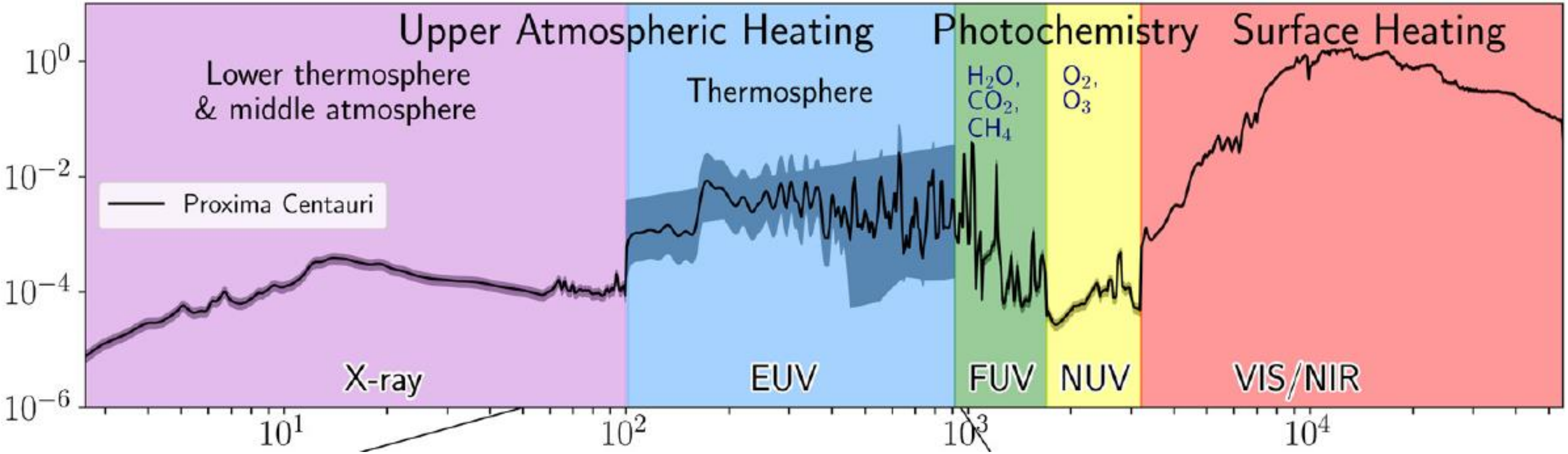
Atmospheric heating



[European Space Agency and Alfred Vidal-Madjar (Institut d'Astrophysique de Paris, CNRS, France)]

Atmospheric heating - EUV domination

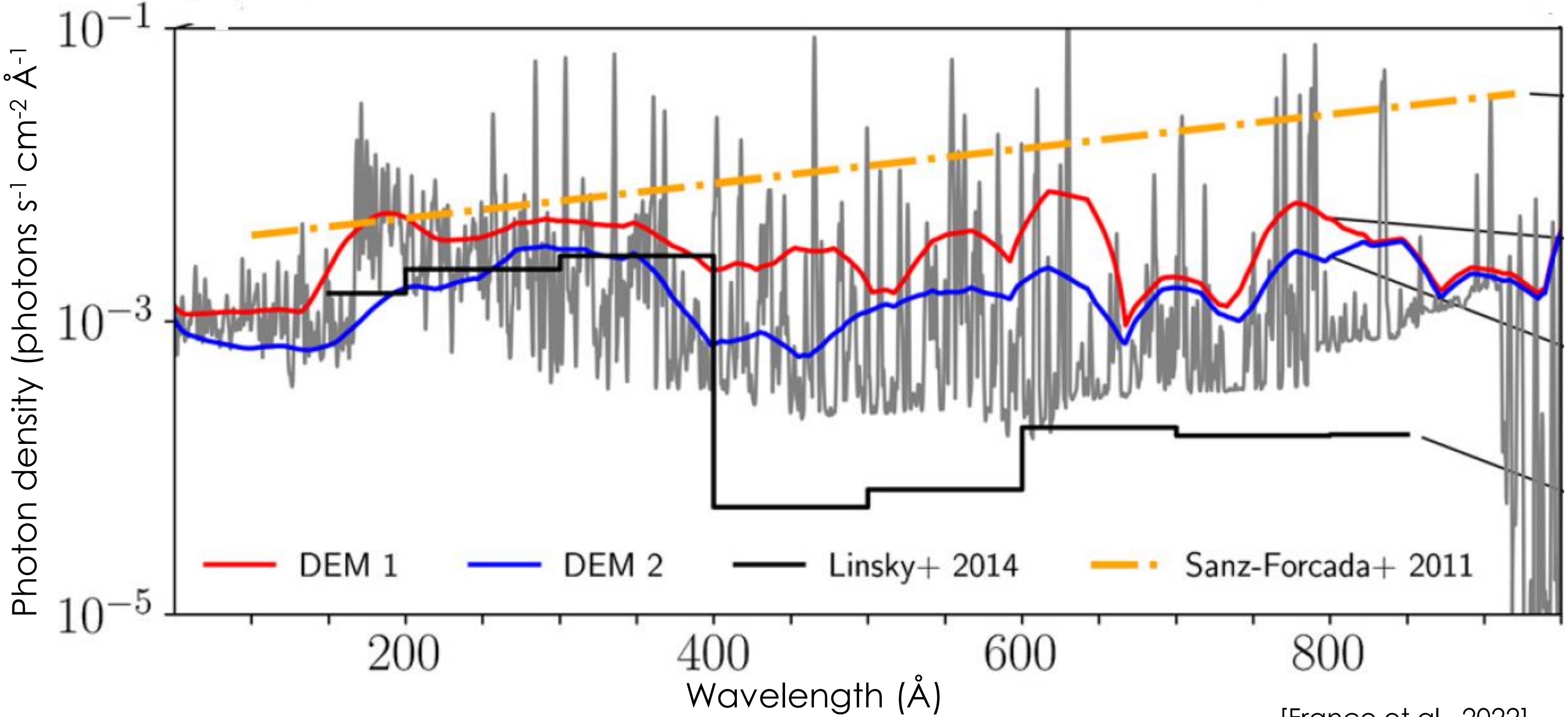
Photon density (photons s^{-1} cm^{-2} Å^{-1})



Wavelength (Å)

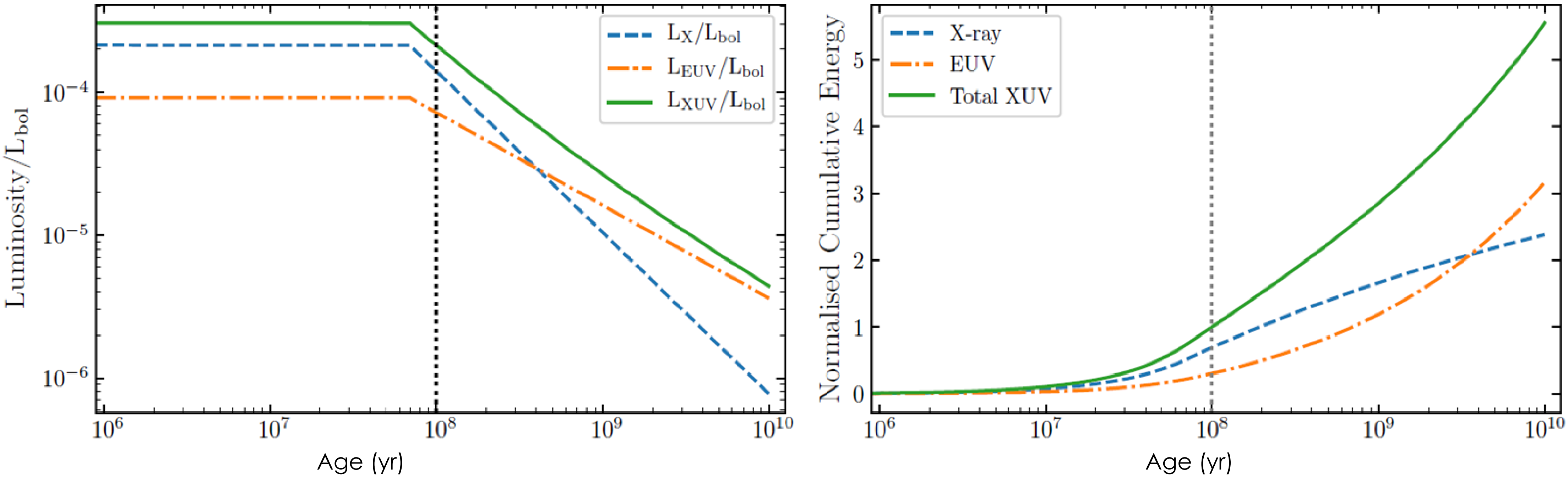
[France et al., 2022]

EUV heating models - Uncertainties



[France et al., 2022]

Atmospheric heating - Timescales



[King and Wheatley, 2020]

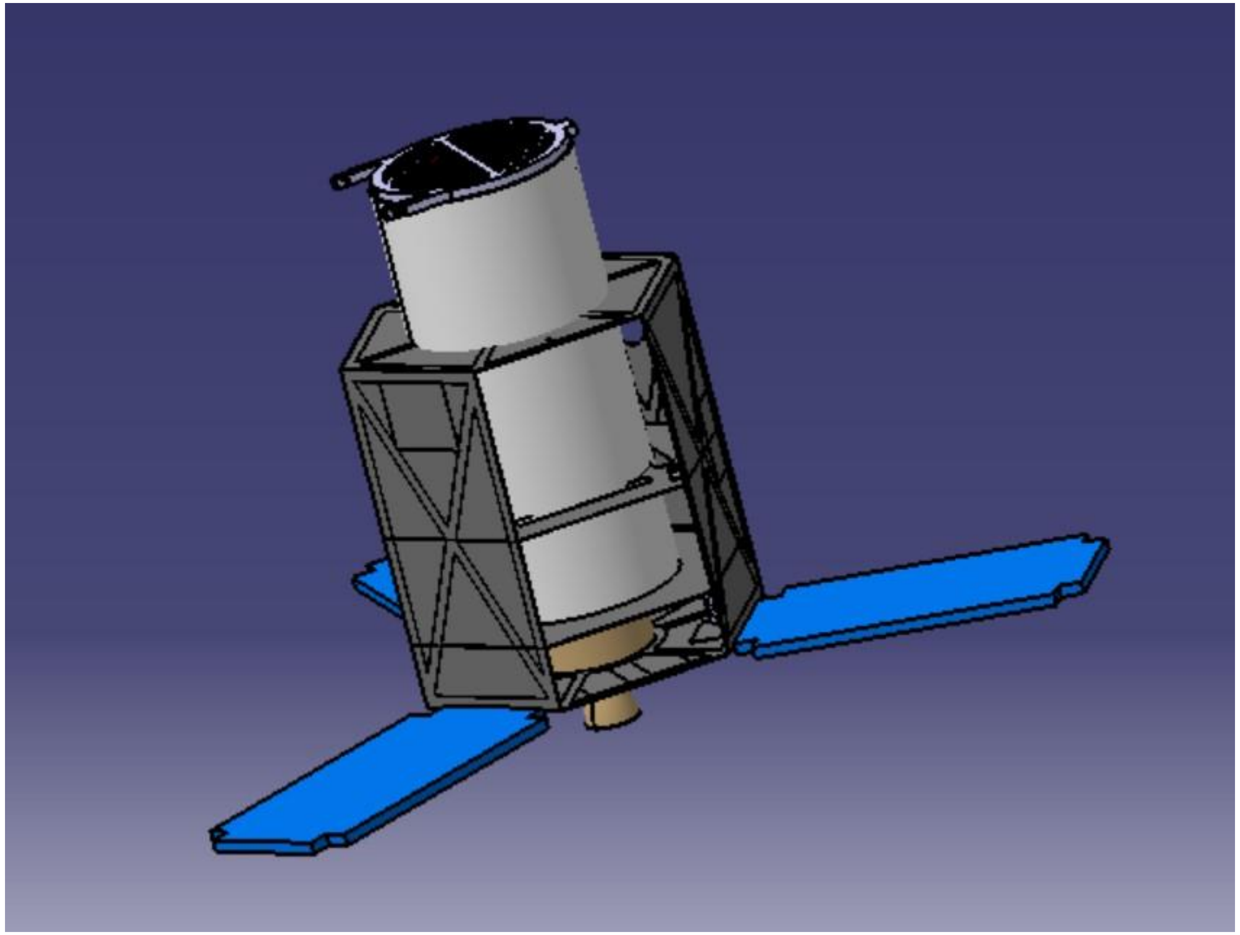
Maybe EUV energy is delivered over a longer timescale?

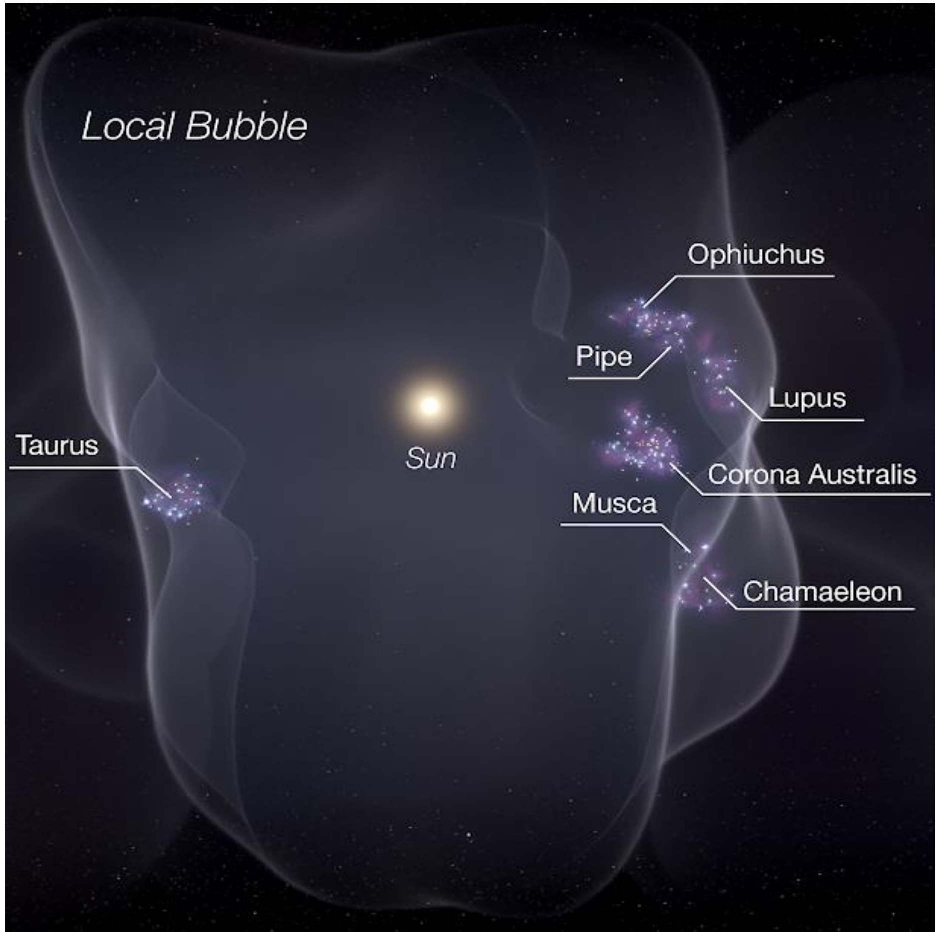
Exoplanet heating - Conclusion

Req. ID	Requirement
FE-SC-040	Measure EUV/FUV spectra and intensity for 500 stars
FE-SC-050	Measure EUV short-term variability for those same stars

- Science results:
  - Correlation between EUV flux/variability and atmospheric loss
  - Explanation for the Kepler valley
  - Establishment of EUV heating loss timescale

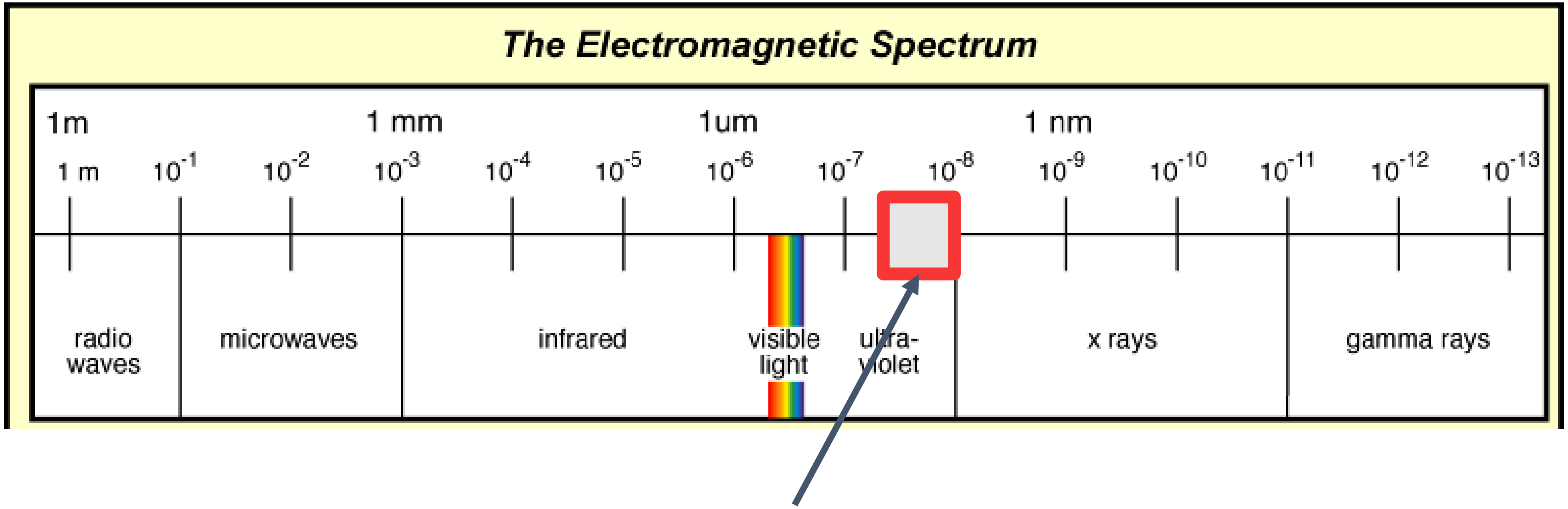
FEAST - An EUV telescope





[Zucker et al., 2022]

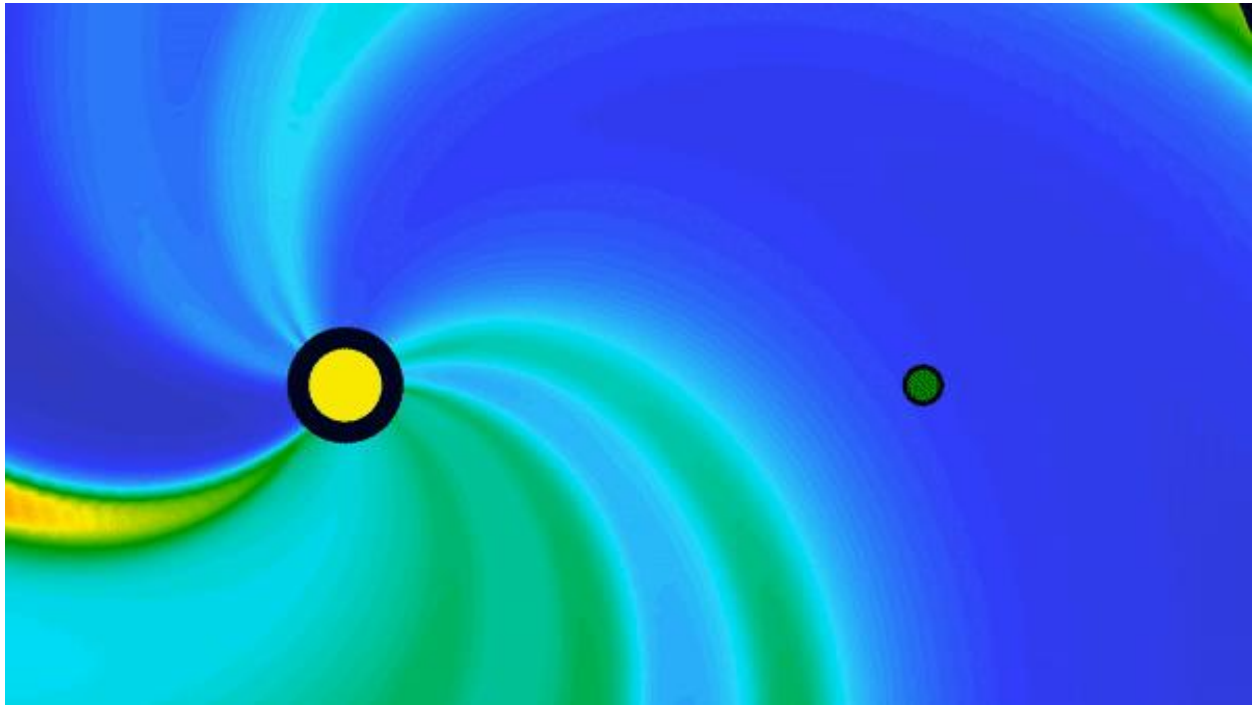
FEAST - The bigger picture



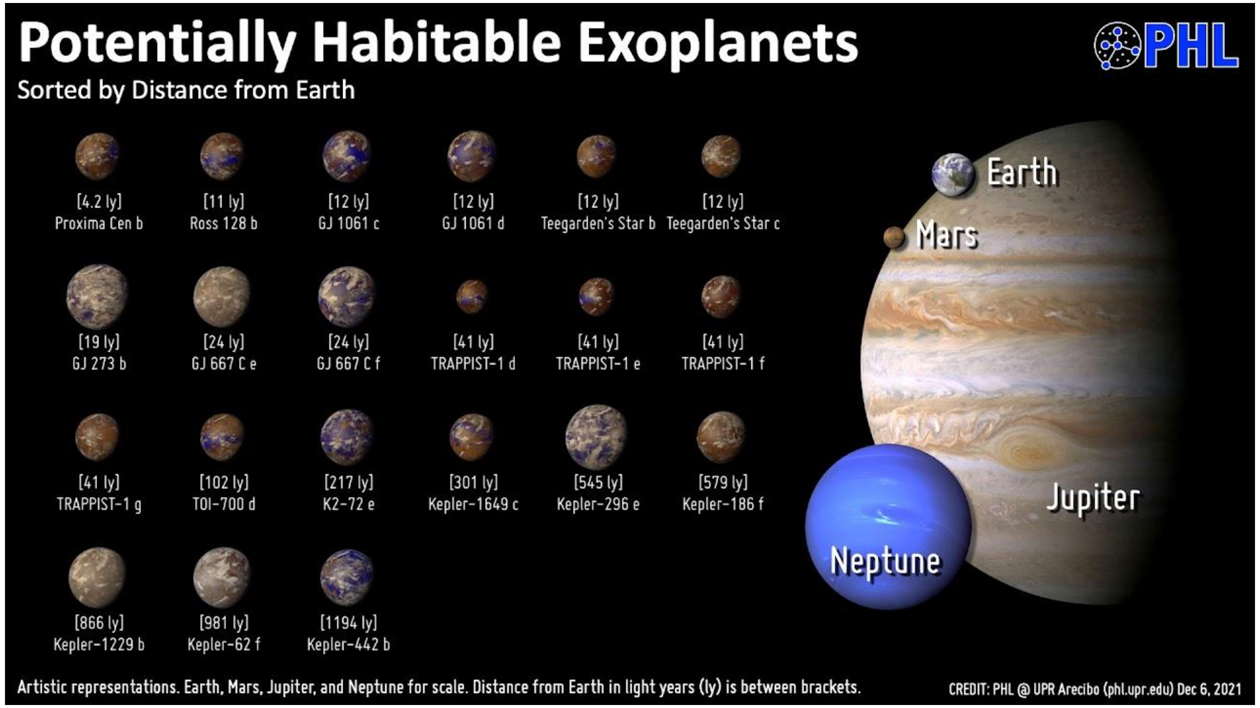
Unknown territory!

[Image: http://www.columbia.edu/~vjd1/electromag_spectrum.htm]

FEAST - The bigger picture

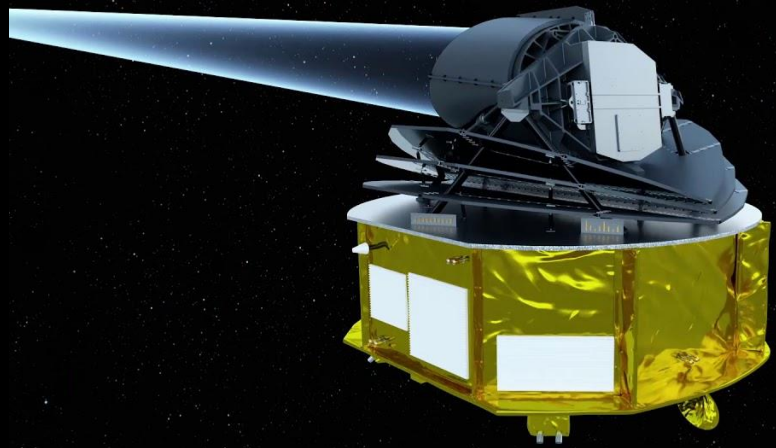


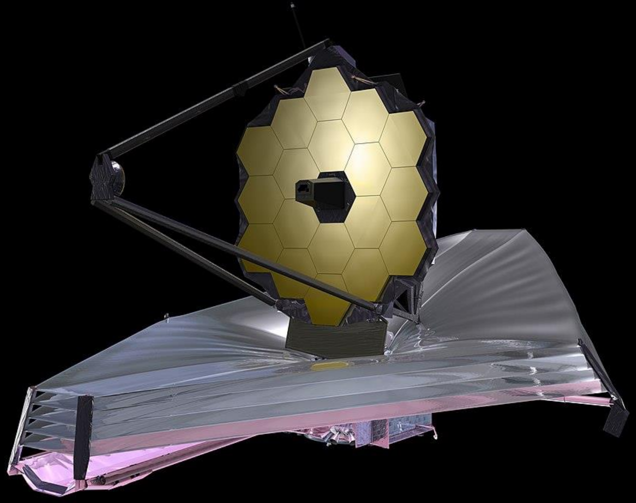
[NWS Youtube, 2011]

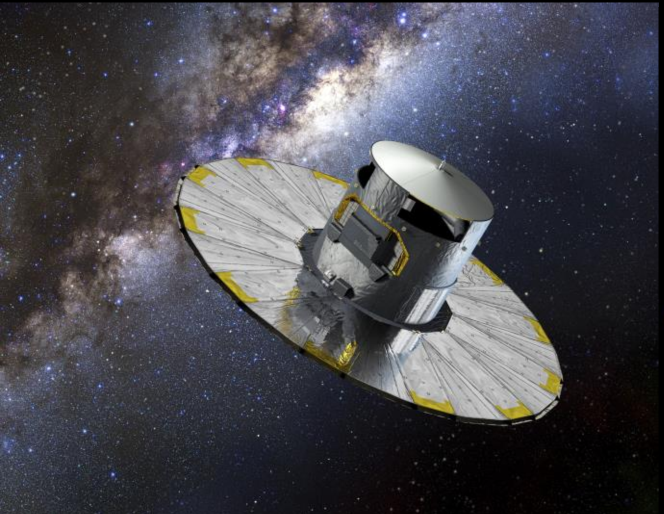


[PHL @UPR Arecibo, 2021]

Synergy with other missions





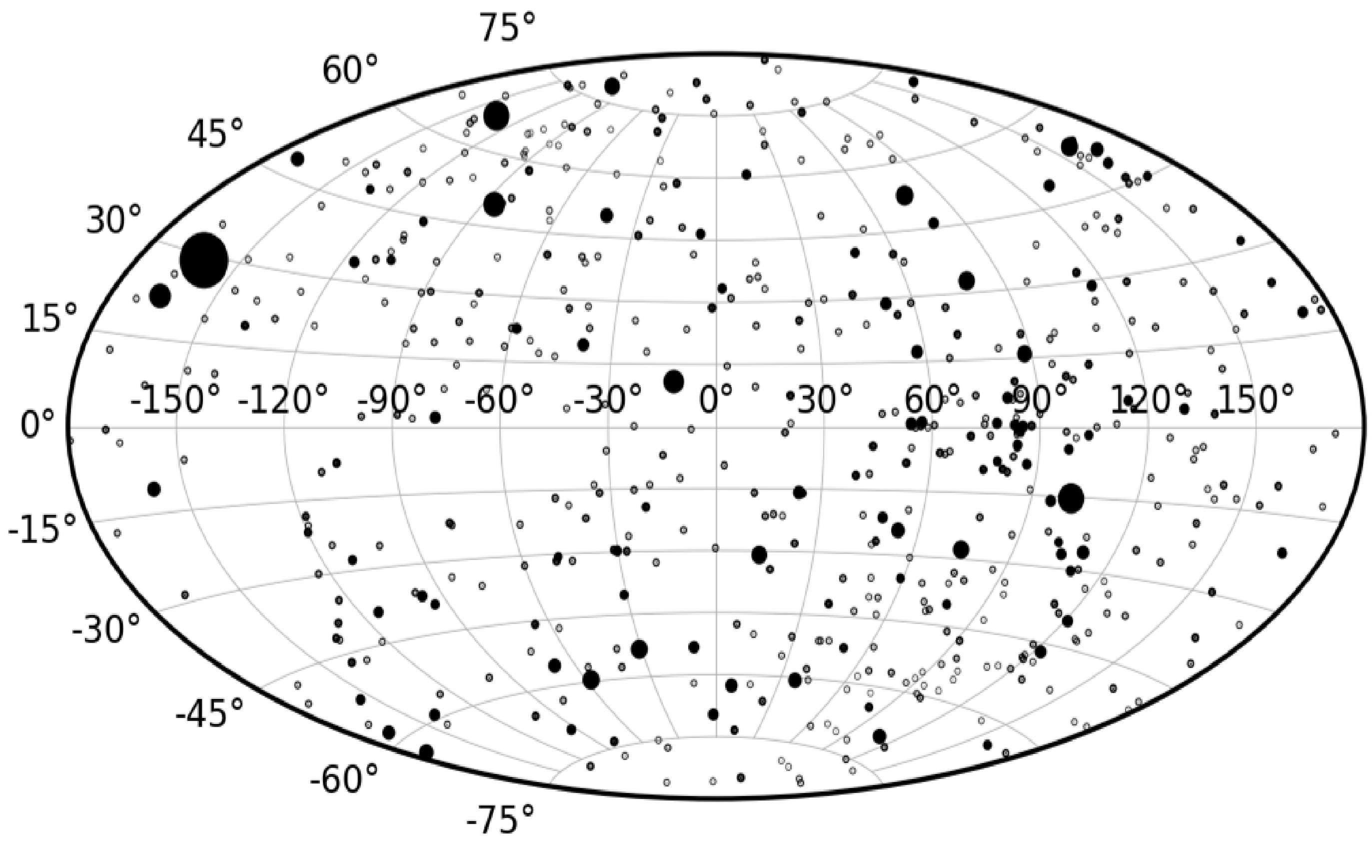


- EUVE: Target selection
- Hubble, Gaia: stellar parameter catalogues
- Kepler, JWST, ARIEL, Cheops, PLATO: exoplanet data

[NASA, ESA/STFC RAL Space/UCL/UK Space Agency/ ATG Medialab]

Observational scheme

- 500 stars in "snapshot" mode, 10 hr observations
  - FE-SCI-051
- 25 stars in "stare" mode, 1 week observations
  - FE-SCI-012
- Total mission cycle time: 460 days
- 4 cycles → 5 year mission



Secondary scientific questions

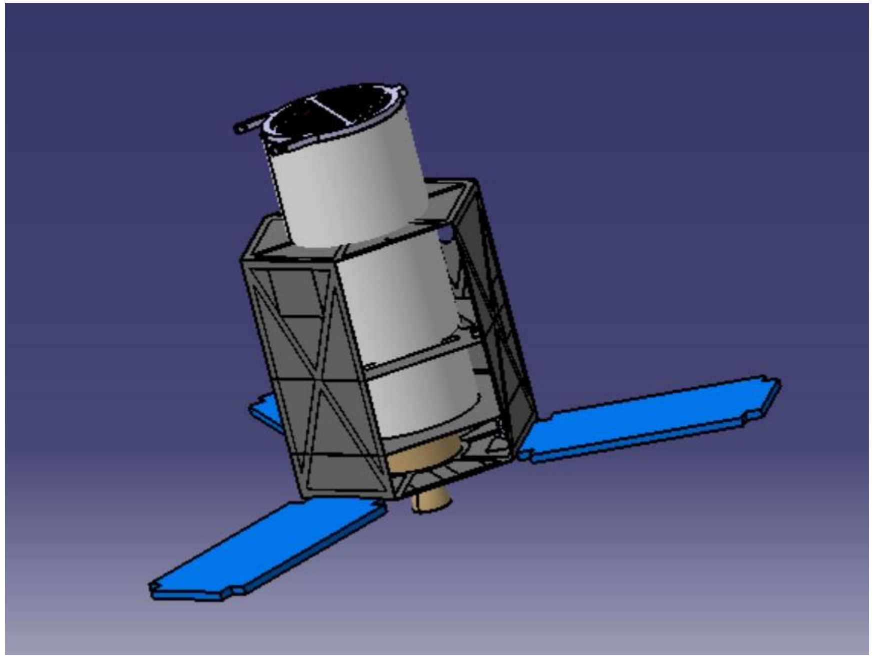
1. How are stellar properties such as mass and activity coupled to not only CME formation but also total EUV flux? How does this relation evolve over long timescales?

2. What is the relationship between EUV and FUV variability in solar-mass stars?

3. How do CMEs affect planetary atmospheres?

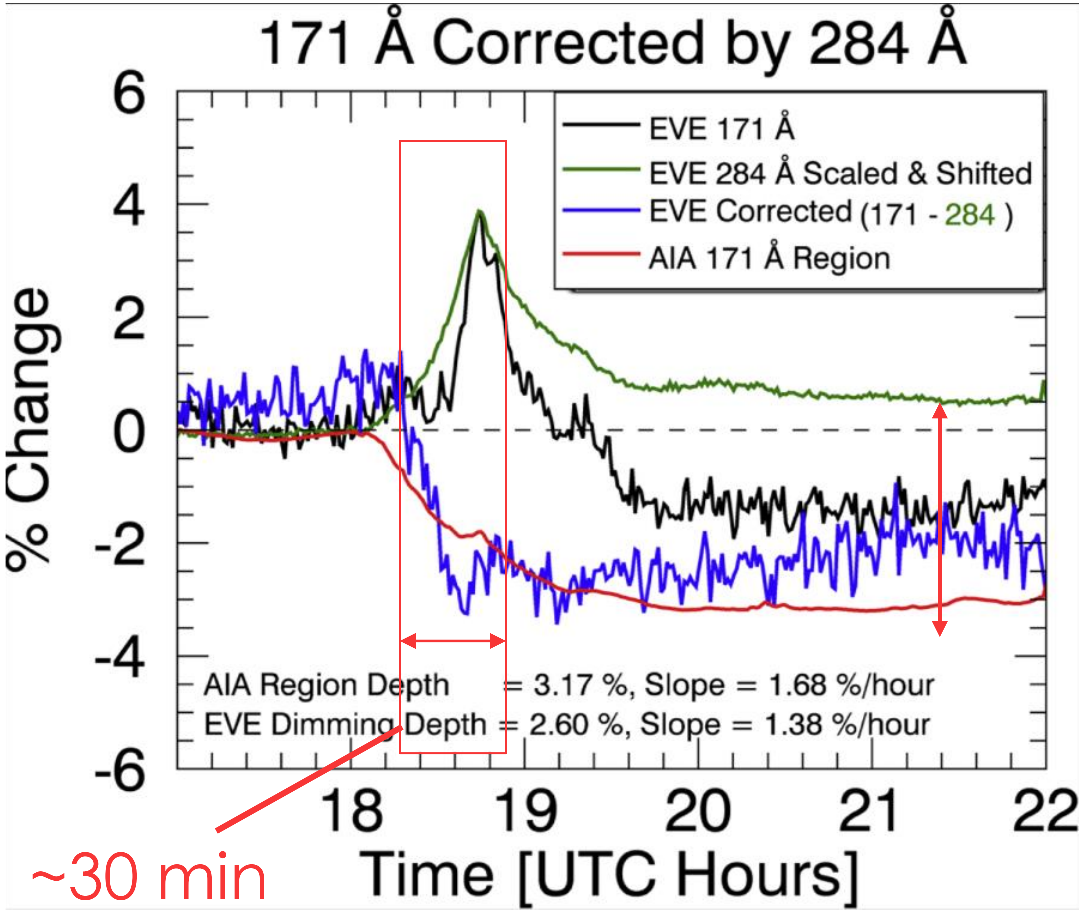
Science case - summary

- We propose an EUV/FUV spectral telescope
- Two main science objectives:
  - Understanding the formation of coronal mass ejections
  - Improving models for EUV-driven evaporation of exoplanet atmospheres
- Fills an important gap in our scientific knowledge



Measurement Requirements

EUV Measurement requirements: CMEs

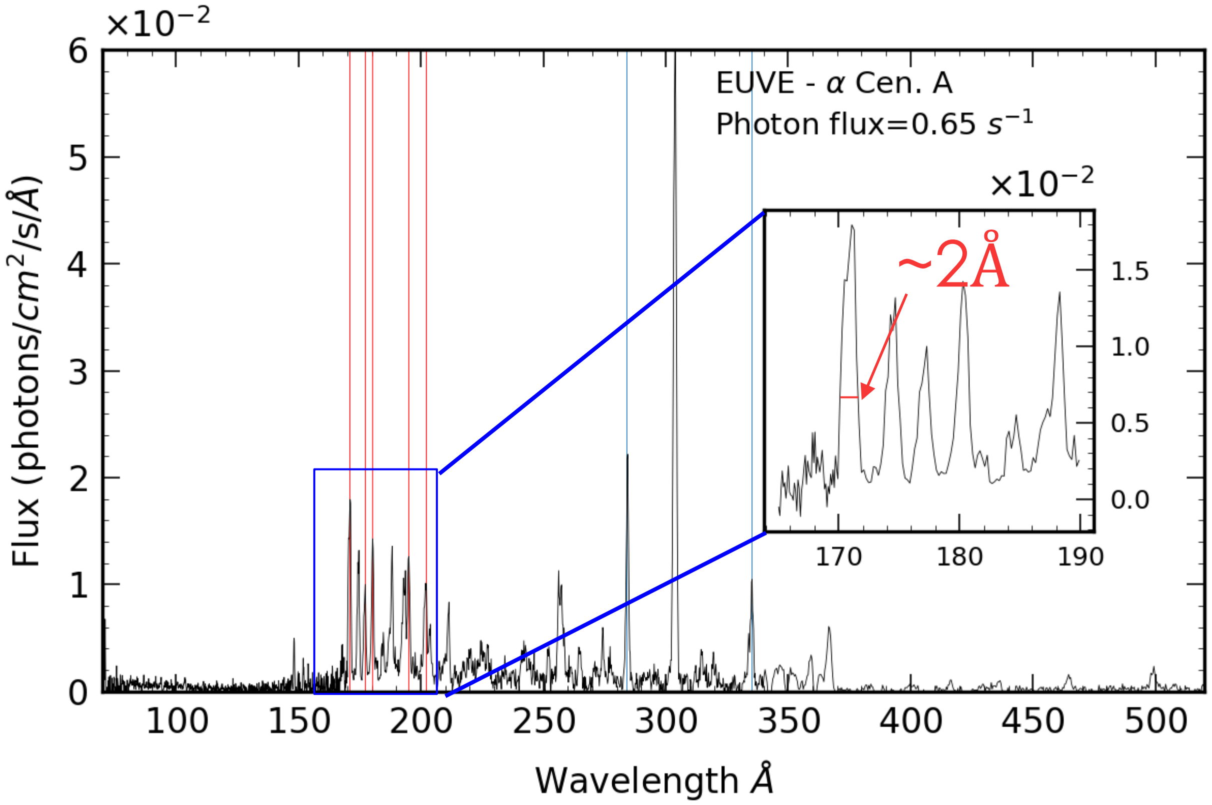


[Mason et al., 2014]

FE-SCI-011: Measure coronal dimming		
FE-MEA-030	Δt_{obs}	10 min
	SNR	100

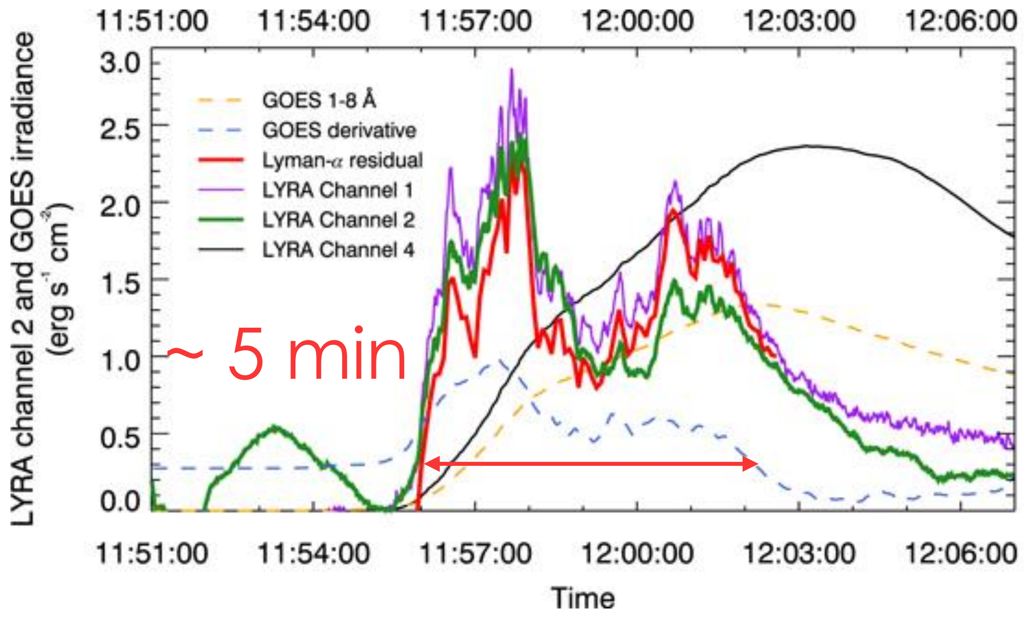
~4 % change in intensity

EUV Measurement requirements: CMEs



FE-SCI-011: Detect CMEs		
FE-INS-010	Range	150 – 700 Å
FE-INS-020	Δλ	0.5 Å

EUV Measurement requirements: Flares

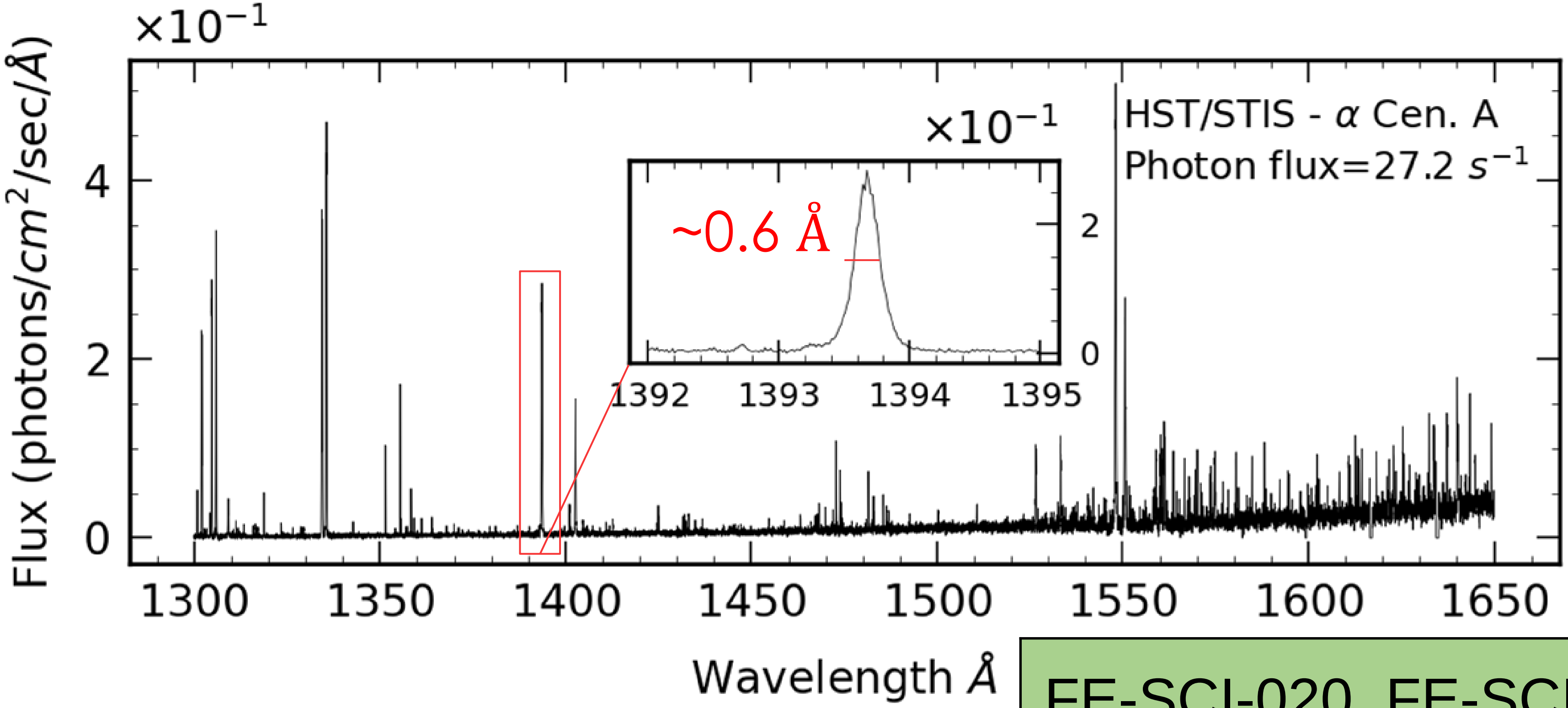


Channel	Bandpass	Irradiance	Increase
Ch. 3 (Al)	1 – 800 Å	4.2 → 30.0 ergs/s/cm²	614 %
Ch. 4 (Zr)	1 – 200 Å	1.45 → 25.5 ergs/s/cm²	1650 %

[M. Dominique, *et al.*, 2018]

FE-SCI-021: Measure stellar flares		
FE-MEA-080	Δt_{obs}	1 min

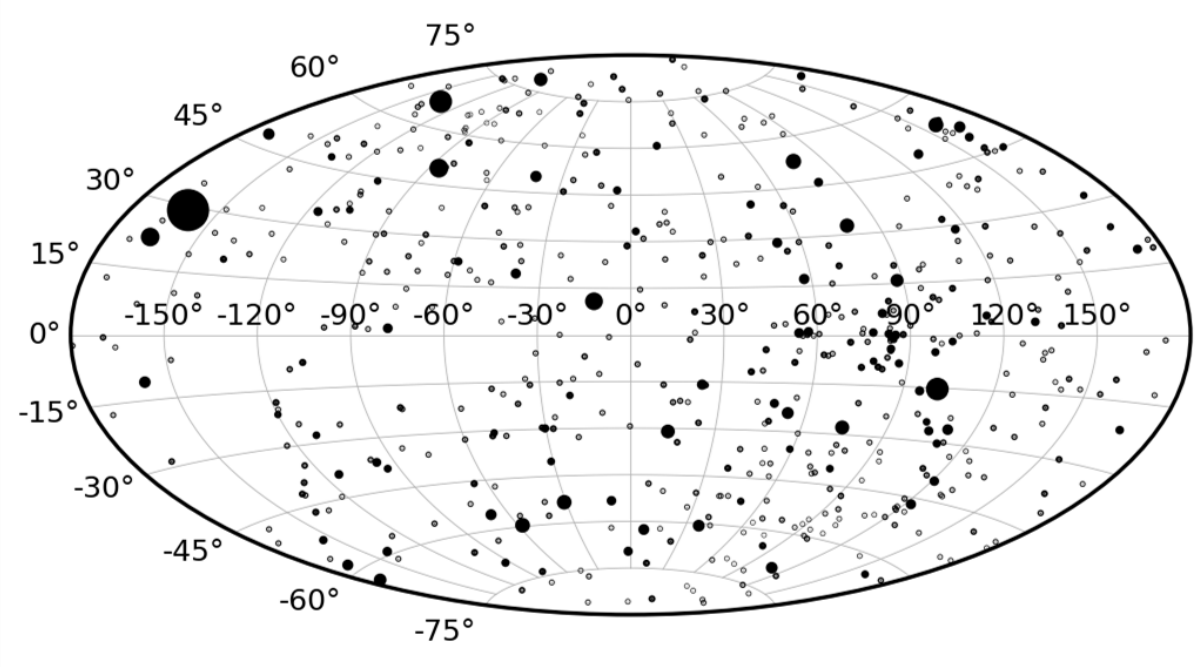
FUV Measurement requirements

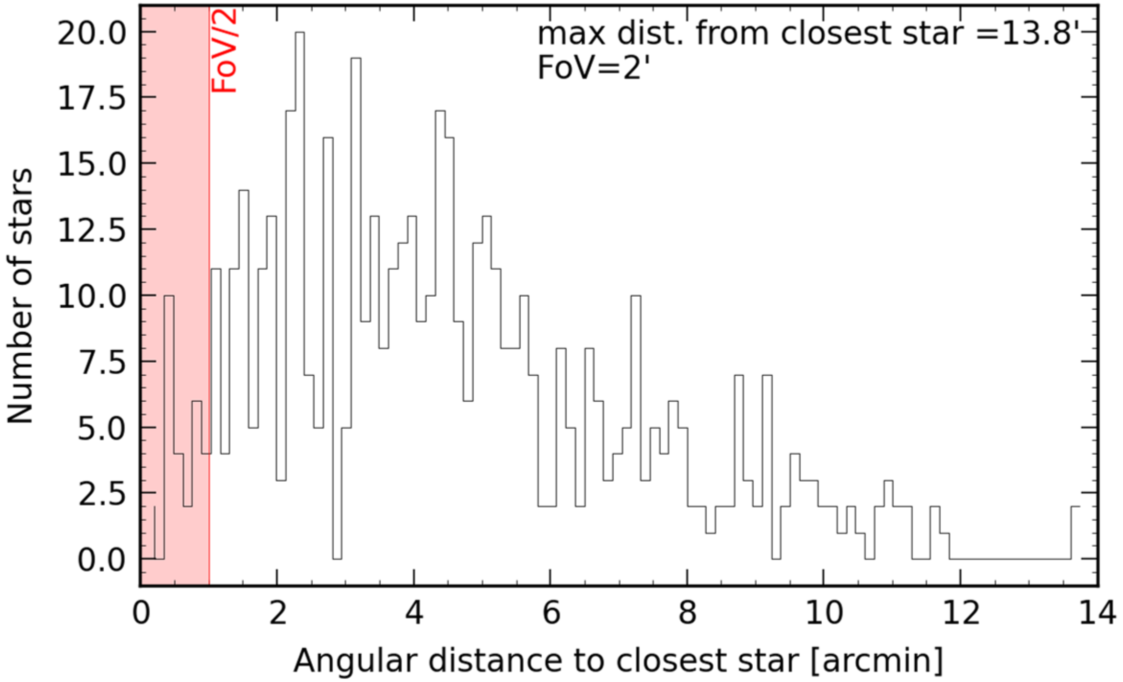


FE-SCI-020, FE-SCI-021, FE-SCI-040		
FE-MEA-050	Δλ	0.2 Å
FE-MEA-050	Range	1300 – 1650 Å

FoV calculation

FE-SCI-010, FE-SCI-020, FE-SCI-040, FE-SCI-050: Isolate single target		
FE-MEA-070	Field of View	2 arcmin



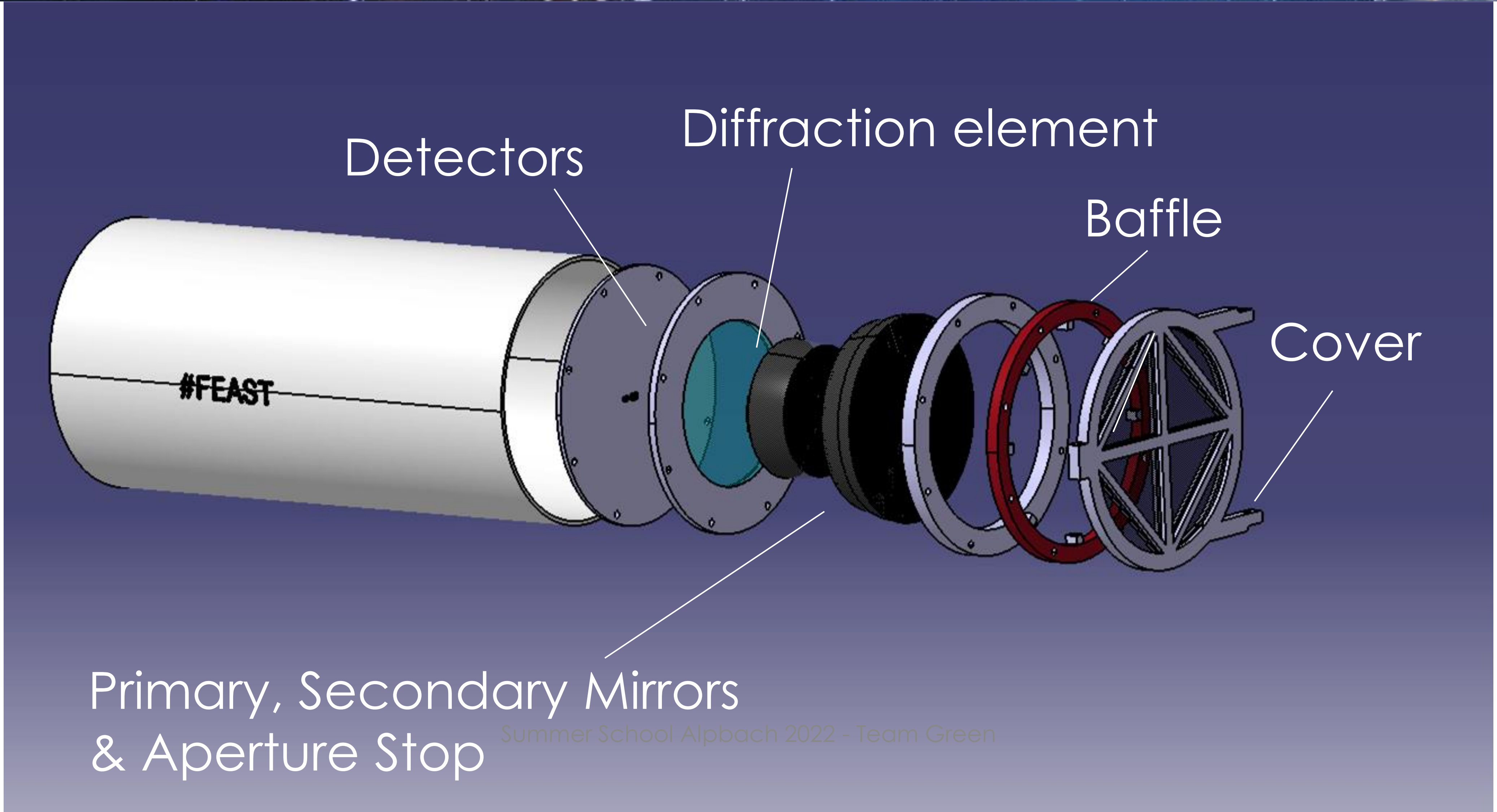


Measurement Requirements - summary

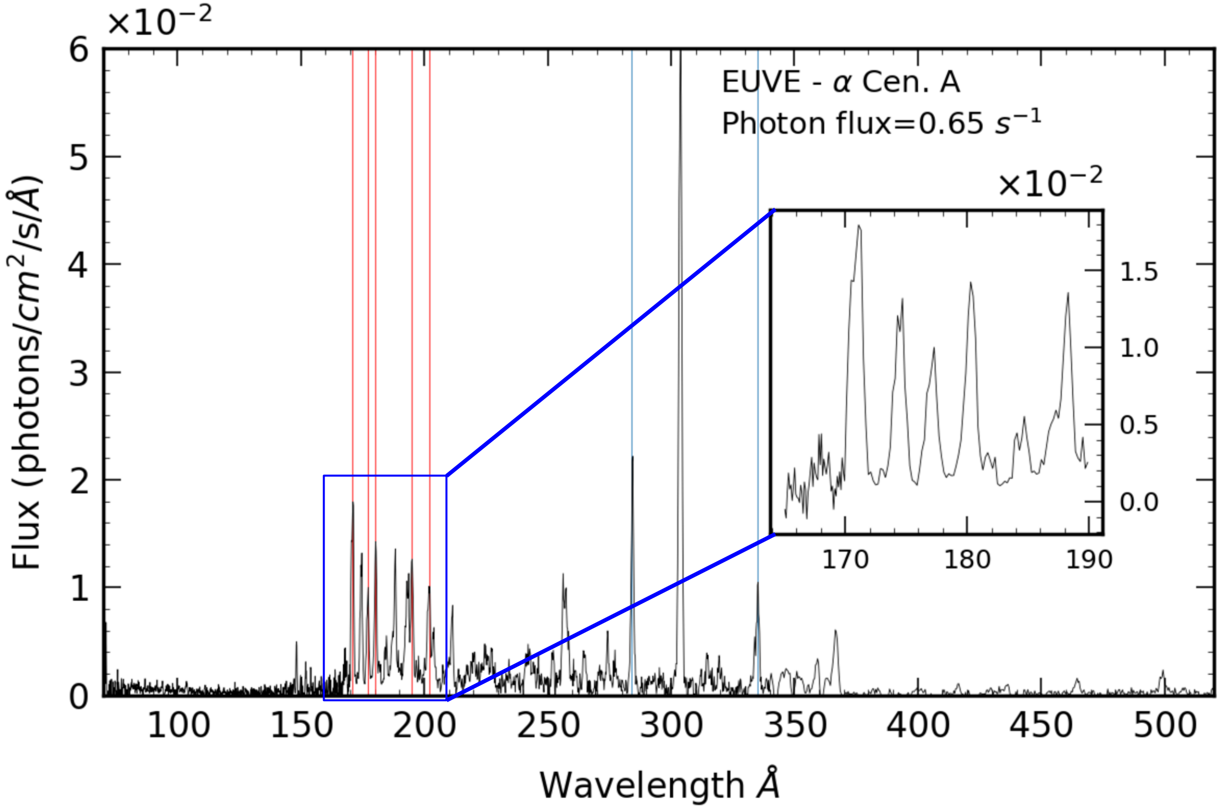
FE-MEA-010	EUV wavelength range 150 – 700 Å
FE-MEA-020	EUV spectral resolution of 0.5 Å
FE-MEA-030	S/N = 100, at 171, 284 Å Δt_{obs} = 10 minutes
FE-MEA-040	FUV wavelength range 1300 – 1650 Å
FE-MEA-050	FUV spectral resolution of 0.2 Å
FE-MEA-060	S/N = 100 at 1321, 1445 Å Δt_{obs} = 1 minute
FE-MEA-070	Field of view 2 arcmin
FE-MEA-080	Temporal resolution < 1 min

Payload Concept

Instrument Scheme



Effective Area



Photon Count 600 s in 171 & 284 Å lines

N_{171} = 0.0218 x **A** x 600 = 13 x **A**

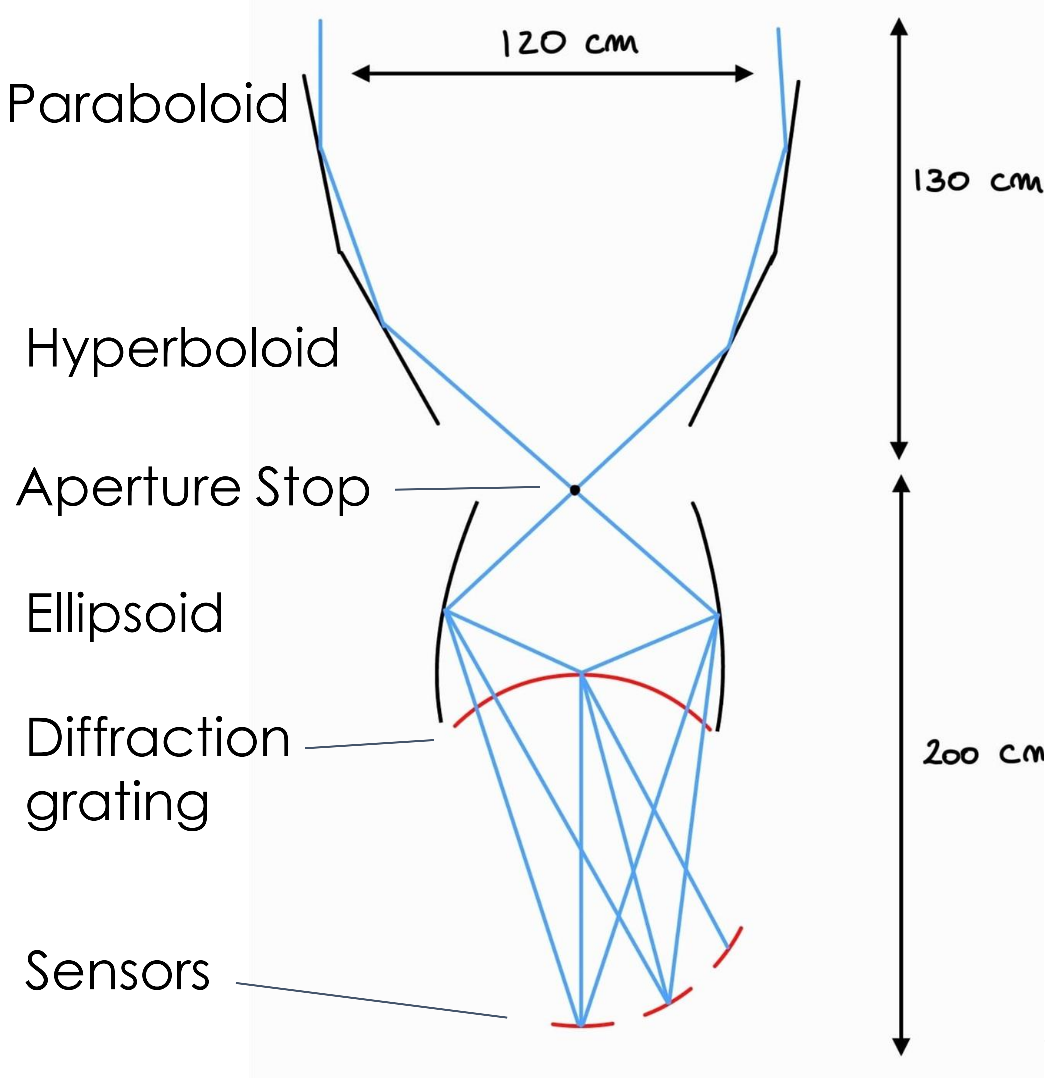
N_{284} = 0.0189 x **A** x 600 = 11.34 x **A**

SNR = √N = 100 ⟶ **A = 880 cm²**

97x better than EUVE!

FE-MEA-030, FE-MEA-060		
FE-INS-010	Effective Area	880 cm^2

Instrument scheme

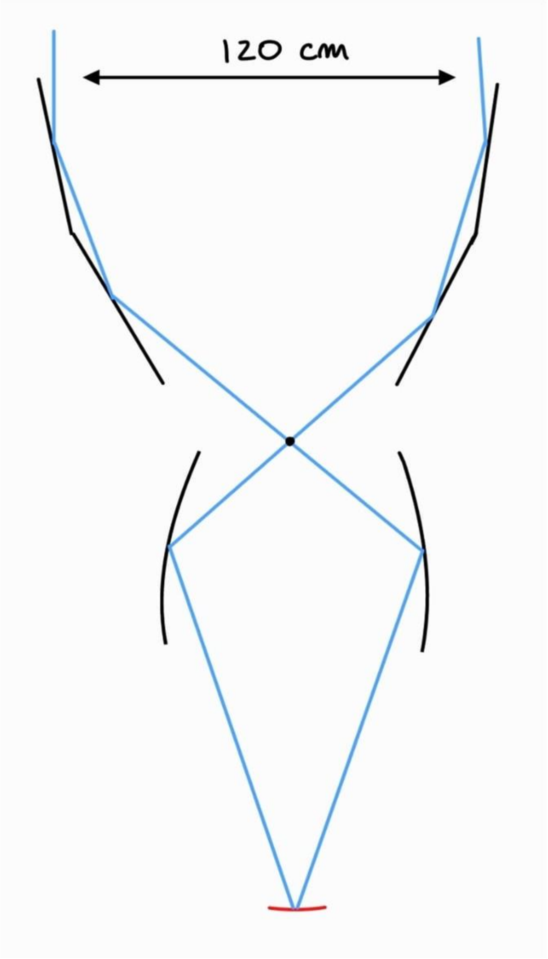


- Entrance Baffle
- Optics
  - Primary mirror
  - Aperture stop
  - Secondary mirror
- Diffraction Element
- Detectors
  - EUV and FUV detectors
  - Fine guidance system

Front to Focus: 330 cm

Mirror

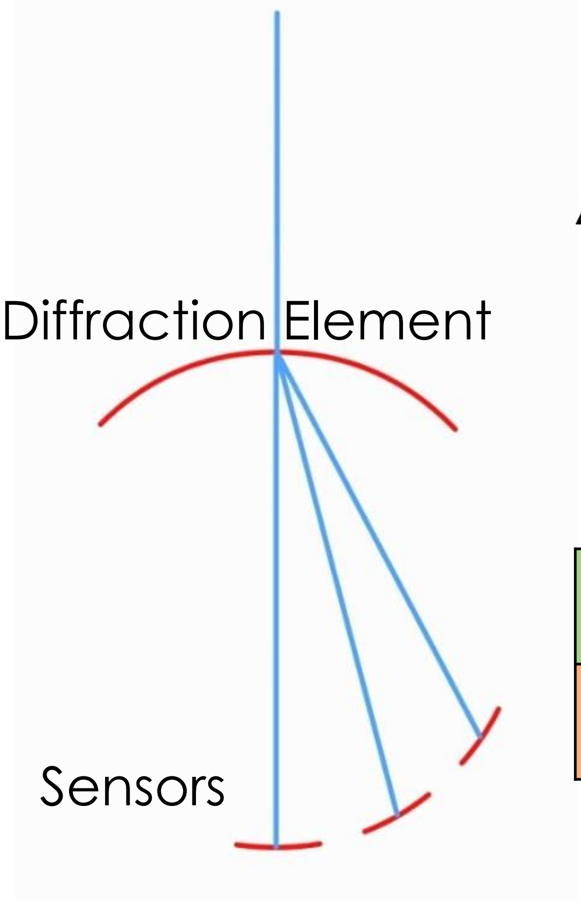
Hettrick-Boyer 1



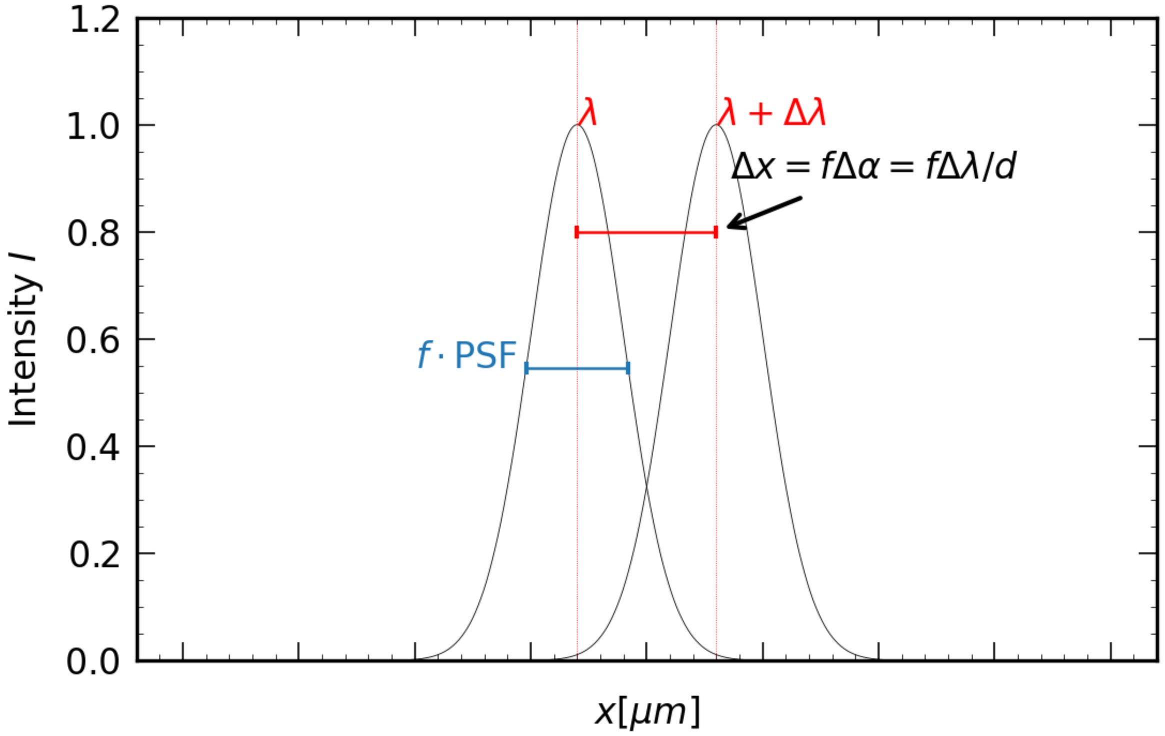
FE-MEA-010: 150 – 700 Å range		
FE-INS-010	Critical Angle ϑ_c	7.9º
FE-INS-011	Surface Roughness	15 Å
FE-MEA-020, FE-MEA-050: wavelength resolution		
FE-INS-022	PSF (Point Spread Function)	1”
FE-MEA-070: field of view		
FE-INS-030	Aperture Stop	⌀ 0.5 mm
FE-INS-010 + Typical detector efficiencies		
	Mirror Diameter	1.2 m

Diffraction element

Transmission Grating in Rowland Torus Geometry

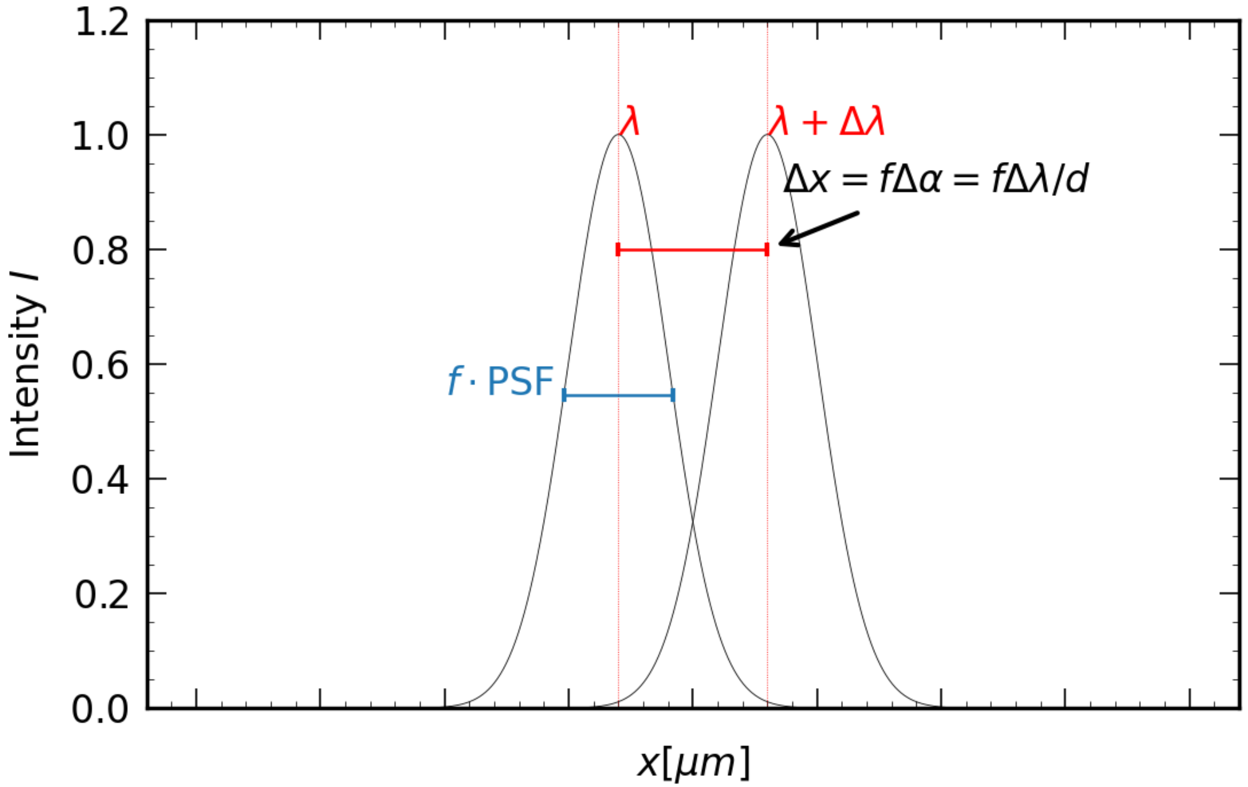


$$\Delta\alpha \approx \frac{\Delta\lambda}{d} > \mathrm{PSF} = 1"$$



FE-MEA-020, FE-MEA-050			
FE-INS-040	1/d (lines per mm)	>250	**Chosen val. 1/d = 500**

EUV Detector



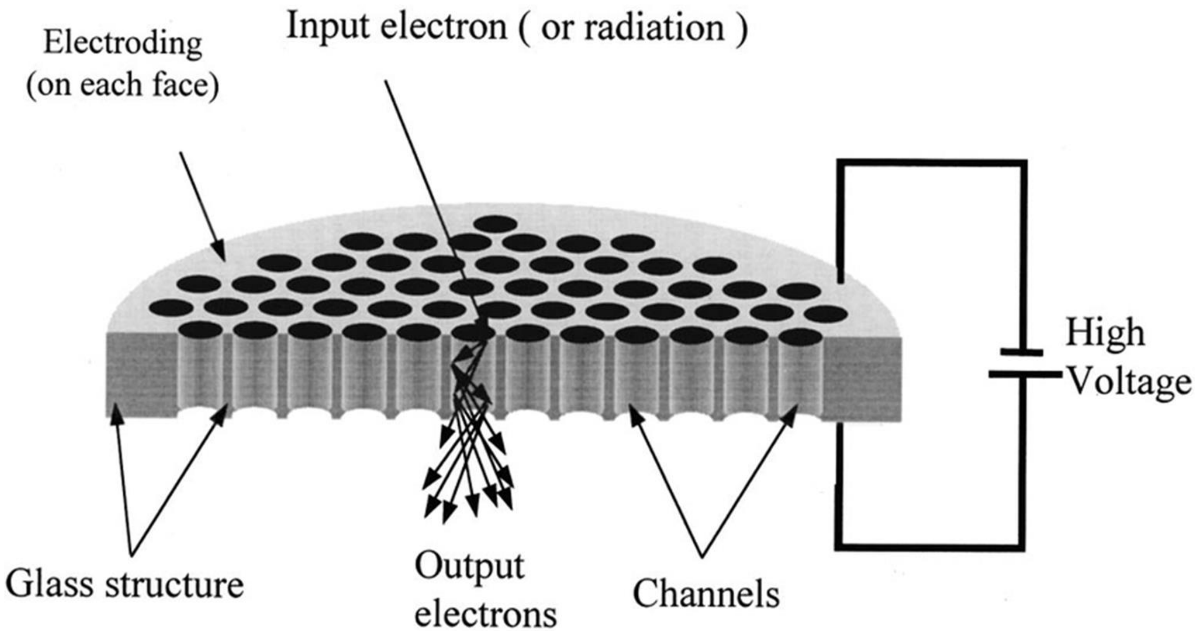
Wavelength range	150 – 700 Å
Wavelength resolution	0.5 Å

Expected photon count	609 photons/s
Expected data rate	6.2 kb/s

FE-INS-041	Pixel linear max size	45 μm
	Sensor linear size	27.5 mm

Microchannel plate: MCP 34-10 (TRL6)

Physical specs	
Effective area	⌀ 28 mm
Channel diameter	10 µm
MPC Diameter	34 mm
Thickness	0.46 mm
Bias angle	10°
Height	11 mm

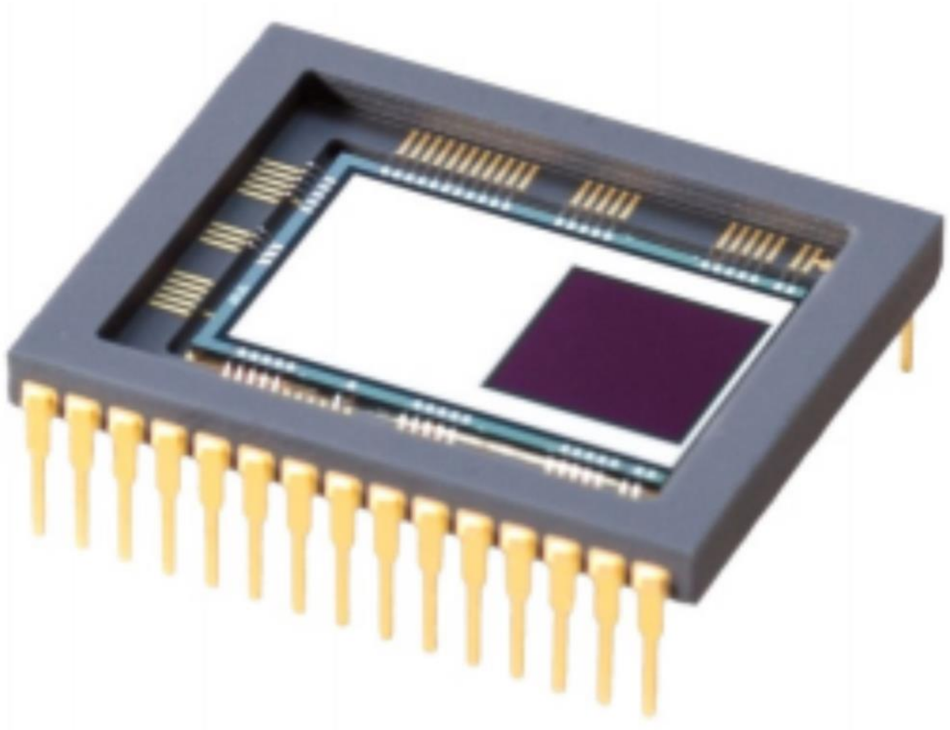


[Yi, Whikun et al., 2001]

Delta-Doped EMCCD: CCD97s with L3CCDs (TRL6)

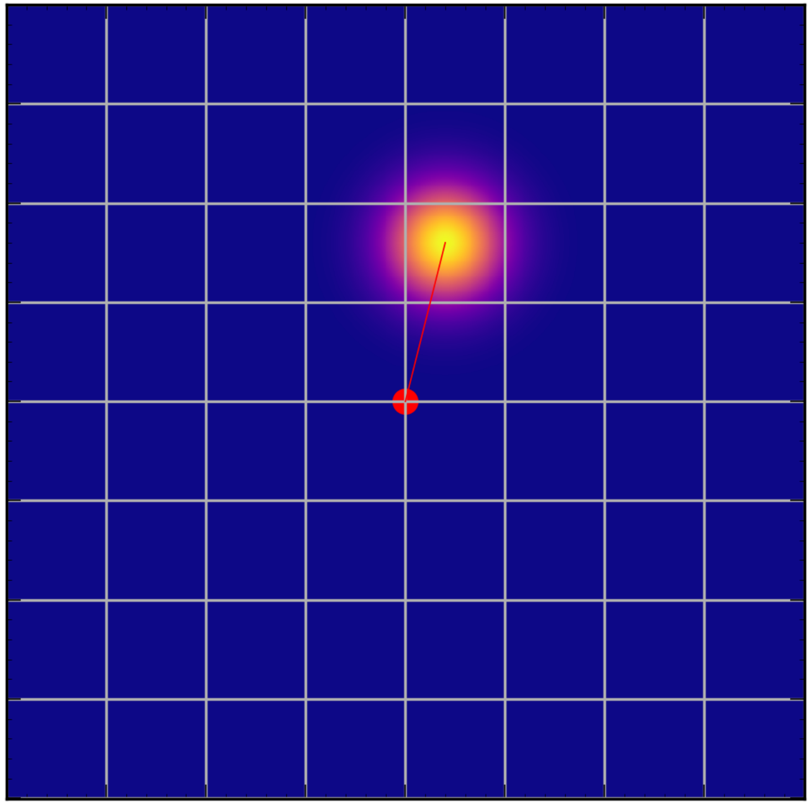
Physical specs	
Pixel format	(512 x 512) px
Pixel size	(16 x 16) µm
Detection efficiency	~ 55 %

Expected photon count	3×10^5 photons/s
Expected data rate	346 kb/s



[teledyneimaging]

FUV – Fine Guidance Sensor



Delta-Doped EMCCD (FUV)

Pixel size	16 µm
Pixel Number	(512 x 512) px
Nominal pointing accuracy	1.15”

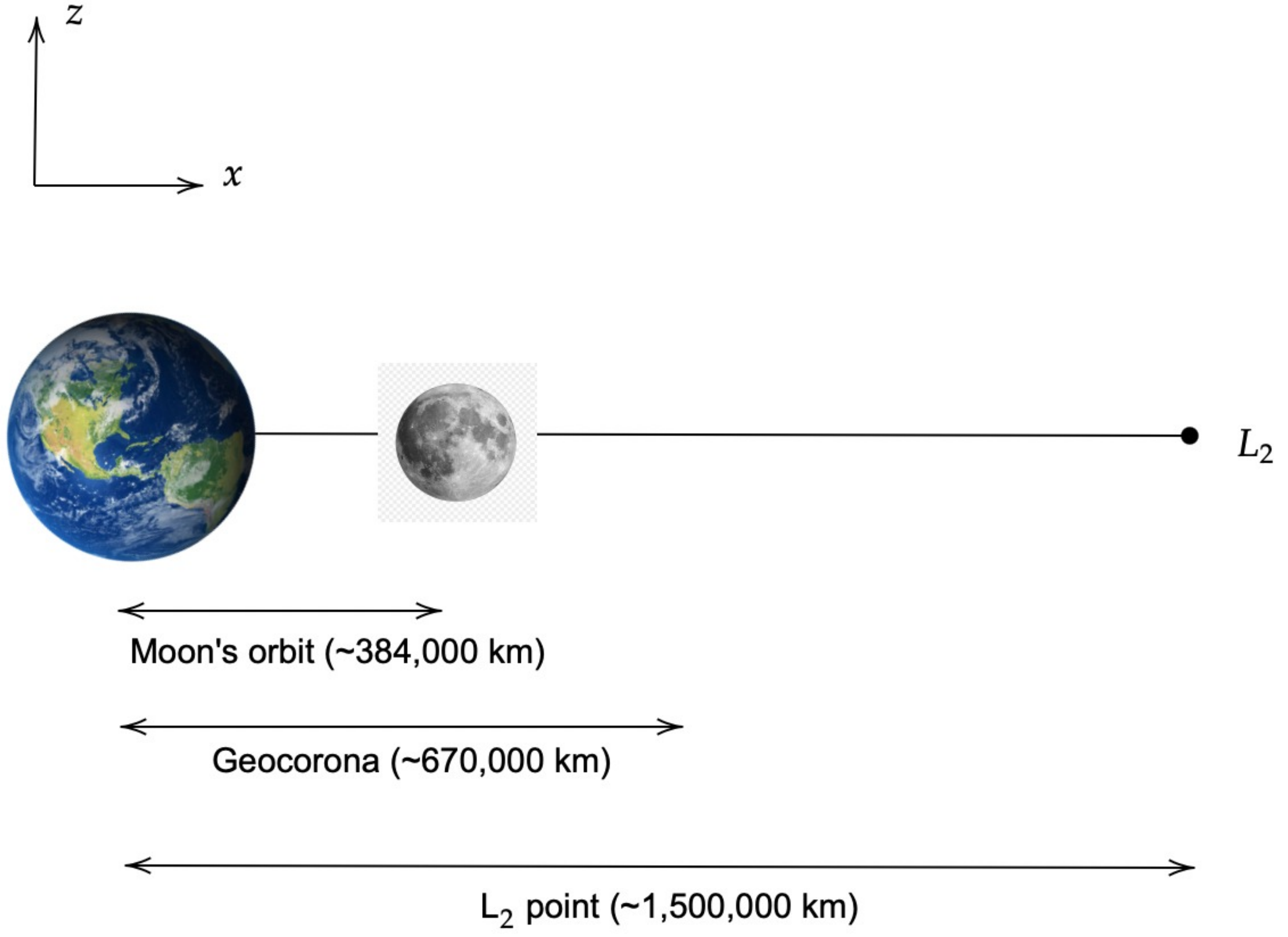
Cross-calibration and redundancy

Measure of the integrated flux

Mission Profile

Where do we go?

- Geocoronal background is very high in LEO and GEO
  - 3 – 5 orders of magnitude larger than typical signal
- Can be remedied by filters, which cuts S/N and kills temporal resolution
- → L2 orbit is necessitated by FE-SCI-011



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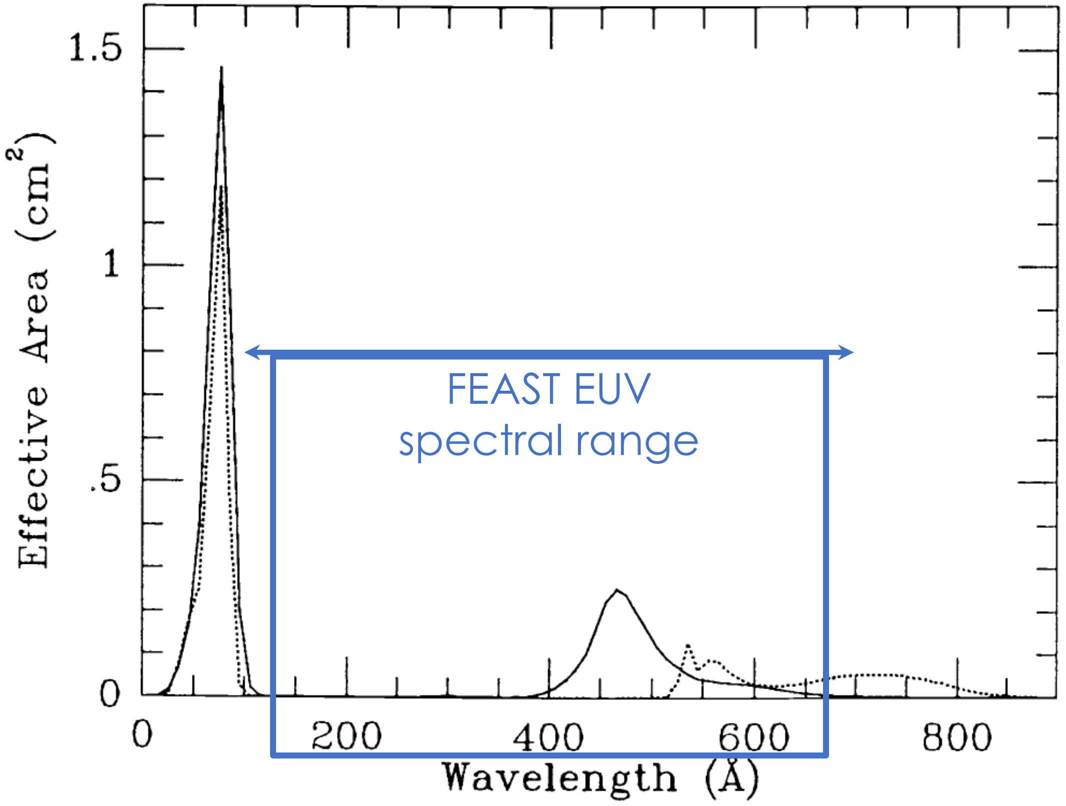


[Finley et al, 1986]

Launch and Transfer

FE-MIS-007:	The target orbit of the mission is a Halo orbit around the Sun-Earth L2 equilibrium point.

- Launch on Ariane 6.2
- Transfer orbit to L2 with Ariane's Vinci upper stage
  (Delta V = 2.5 km/s)
- Target orbit insertion with own chemical propulsion system
  (Delta V = 40 m/s)

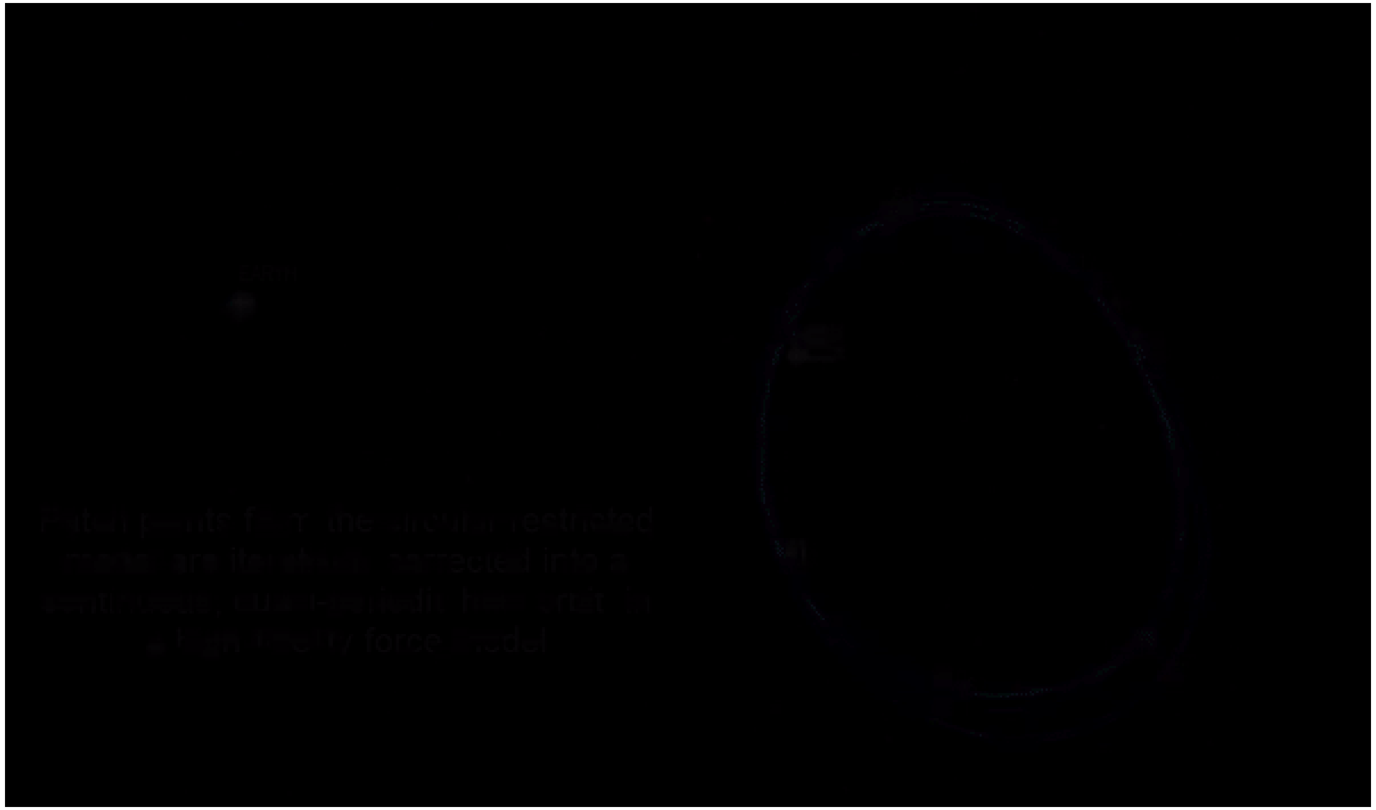
[Ariane Group]

[Ariane Group]

Target Orbit

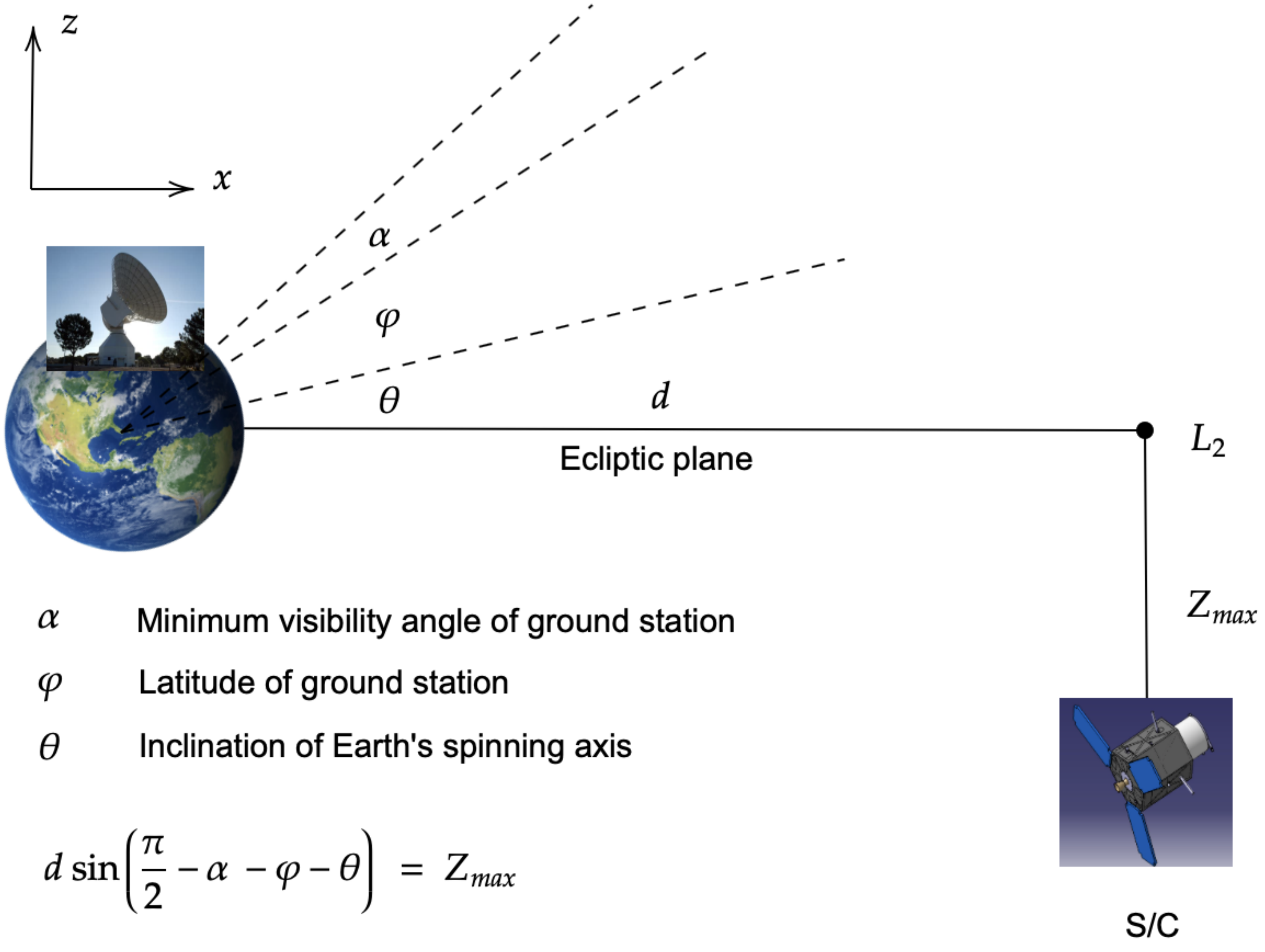
FE-MIS-100:	The target orbit of the mission is a Halo orbit around the Sun-Earth L2 equilibrium point.

- Halo orbit around L2
- Out-of-plane amplitude constrained by ground station visibility
- No constraints on the in-plane motion
- Orbit is unstable → station-keeping



Target Orbit

- Maximum out-of-plane amplitude: 645,000 km
- No constraint on in-plane amplitude
- Delta V orbit maintenance: 6 m/s/year



α	Minimum visibility angle of ground station
φ	Latitude of ground station
θ	Inclination of Earth's spinning axis

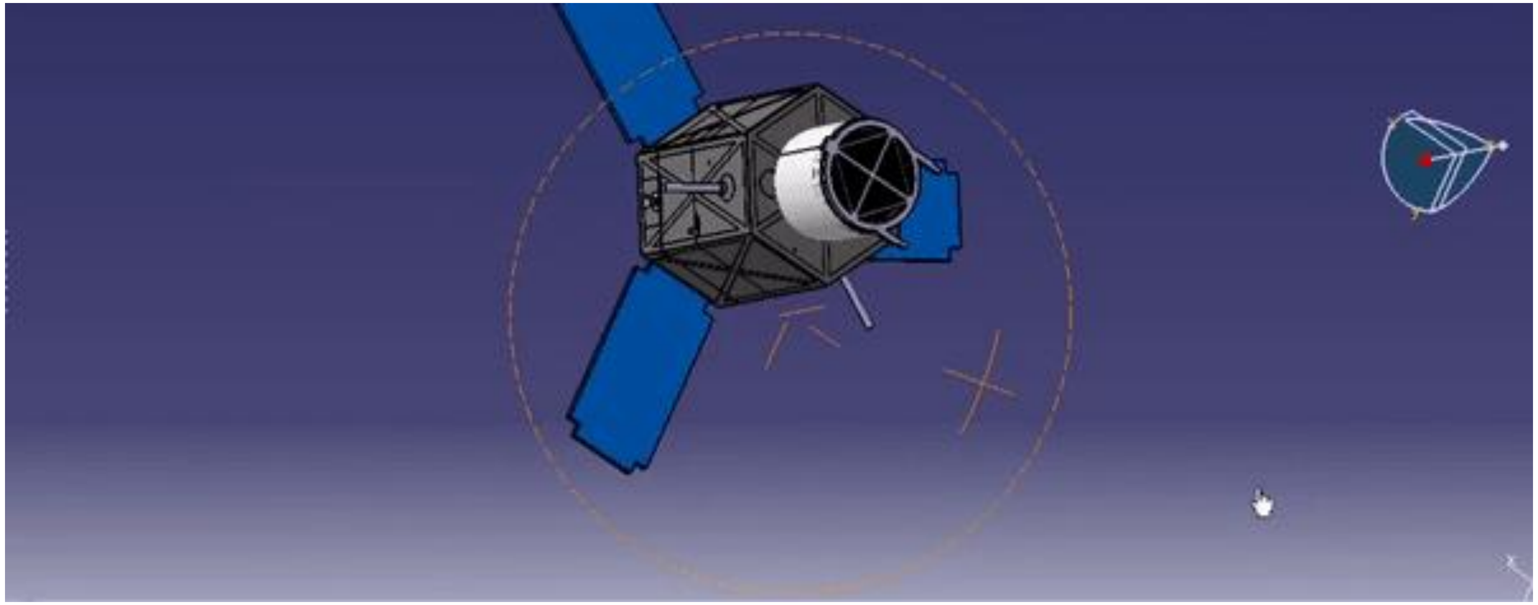
$$d \sin\left(\frac{\pi}{2} - \alpha - \varphi - \theta\right) = Z_{max}$$

Spacecraft Modes

	Launch	Snapshot	Staring	Communication	Safe
AOCS Mode	N/A	Nominal	Nominal	Ground Station Acquisition	Sun Acquisition
Payload Mode	Survival	Snapshot	Staring	Survival	Survival
TT&C Mode	Low Gain	Low Gain	Low Gain	Low + Med Gain	Low Gain
Duration	1 month	10 hours	1 week	2 hours	5 hours
Total Power Demand	213 W	827 W	827 W	364 W	213 W

Spacecraft Systems

- Propulsion System
- Thermal System
- Attitude Determination & Control System (ADCS)
- Telemetry, Tracking & Control (TT&C)
- Electric Power System (EPS)
- On-Board Computers (OBCs)
- Structure



Propulsion System

FE-MIS-100:	Halo orbit around L2
FE-MIS-040:	Orbit insertion maneuver into the target orbit
FE-MIS-090:	Nominal mission duration shall be 5 years

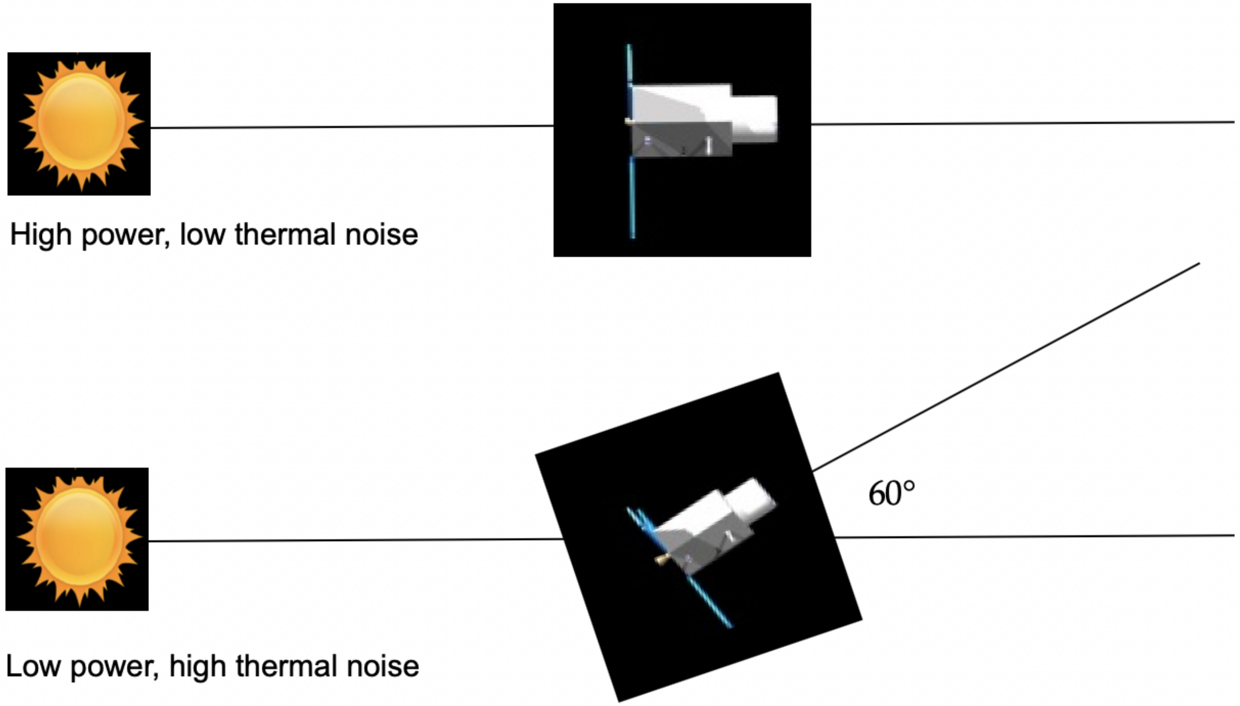
- **Tradeoff:** EP vs. chemical
- Total Delta V: ~236 m/s
  - Orbit insertion
  - Orbit maintenance (L2 is unstable + wheel offloading)
  - End-of-Life disposal
- Propellant mass: ~236 kg

Engine type	MRE-1.0 (secondary) MRE-1.5 (primary)
Isp	218 s
Nozzles	12
Propellant	Hydrazine
Tanks	2 titanium tanks

Thermal System

FE-MIS-030: Thermal control of the spacecraft

- Stable thermal environment, S/C in constant sunlight
- Modeled as a cylinder + cube
- Thermal loads:
  - Sunlight
  - Electronics
- Heaters needed for batteries, hydrazine tank, detectors



Sun Shield

FE-MIS-030: Thermal control of the spacecraft

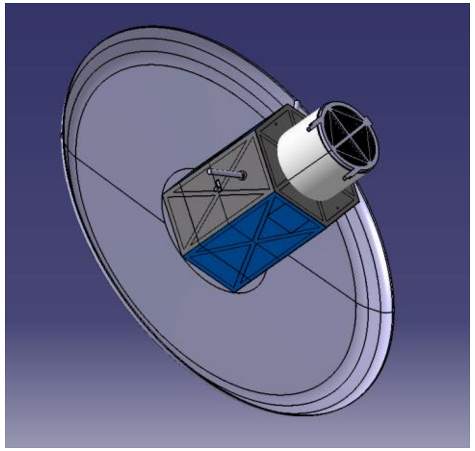
- Issues:
  - thermal expansion
  - thermal noise
  - temperature gradient

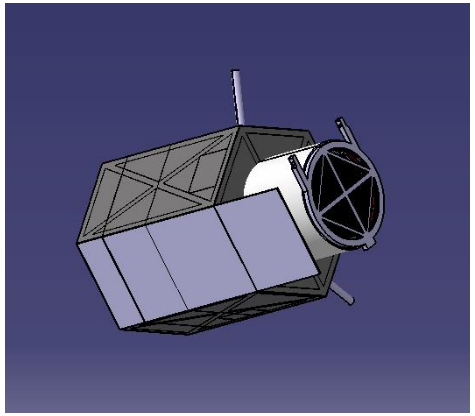
Tradeoff:

- Circular deployable MLI sunshield (heavier, e.g. GAIA)

vs.

- Body-mounted carbon sunshield (constrains the number of observable stars, e.g. EUCLID)





Attitude Control System

FE-MIS-010:	Three-axis stabilized
FE-MIS-020:	Pointing accuracy of 1.3 arcsec for 1 week

- Sensors:
  - 3 Sun Sensors
  - 2 Gyros
  - 2 AstroTrackers
  - FGS (Delta Doped EMCCD)
- Actuators:
  - 4 Reaction Wheels in a 123 configuration (1 redundant)
  - 4 Smaller Reaction Wheels for finer adjustment movements of the S/C in order to comply with the FGS requests

[Sodern]

Telemetry, Tracking & Command

FE-MIS-060:	Downlink bandwidth of 168.24 Mb/s
FE-MIS-070:	Data storage up to 30 GB

Tradeoff:

- gimballed antenna for communication during science operations

vs.

- data downlink once per week in one ground pass

- Ground Station: New Norcia
- 2 hour daily communication window
- Medium Gain - Parabolic Cassegrain X band
  - Gain: 33 dB
  - Beamwidth angle: 15°
- Low Gain - Omnidirectional S band (x2)
  - Gain: 7 dB
  - Beamwidth angle: 180°

Uplink (kb/s)		Downlink (Mb/s)	
Telecommand	24	S/C Health	0.02
		Payload Health	0.01
		Science Data	168.21
Total	**24**	**Total**	**168.24**

Electric Power System

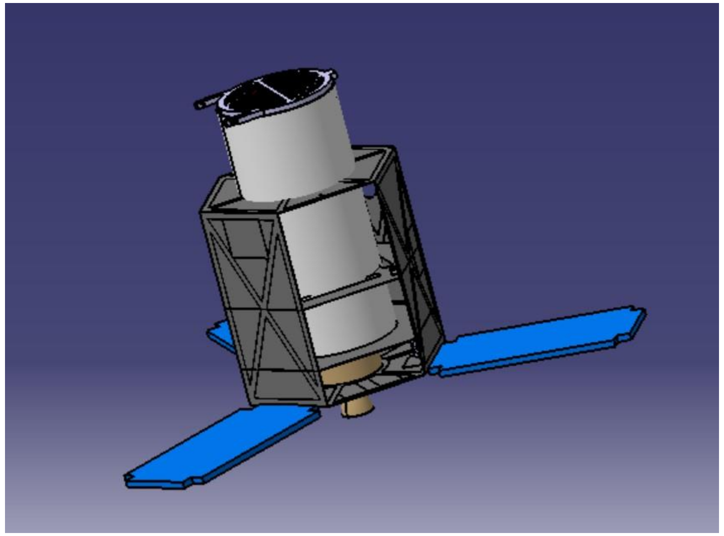
FE-MIS-070:	827 W in science operations mode.
FE-MIS-071:	5 hours in non-Sun pointing configuration (safe mode)

Tradeoff:

- single-axis + constraint on pointing
- double-axis rotation

- Triple-junction GaAs solar cells with single-axis gimble
  - BOL efficiency: 26 %
  - Degradation (5 years): 14.5 %
  - Area: ~7.09 m²

- Batteries:
  - Primary(for solar array deployment, communication)
  - Secondary (safe mode):
    - Li-Ion battery packs (for redundancy)
    - Total capacity: ~368 Wh



On-Board Computers

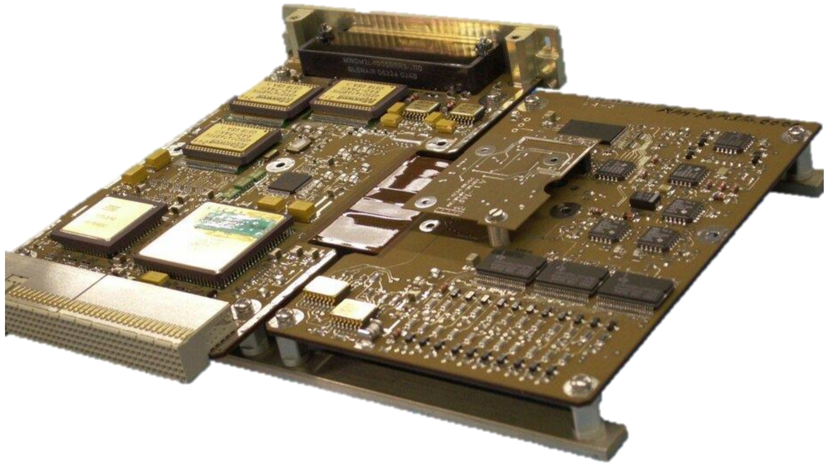
FE-MIS-120:	No data loss due to control unit failure

- **Main driver:** payload instrument data generation
- **Tradeoff:** redundancy, processing power

- 8 On-Board Computers
  - General-purpose processor module
  - Hot redundancy
  - Mesh network topology

- Payload instrument data buffer: 17 MB

- Mass memory unit: 30 GB storage
  - Science data (1 week)
  - Service module and payload health (1 month)



[ESA]

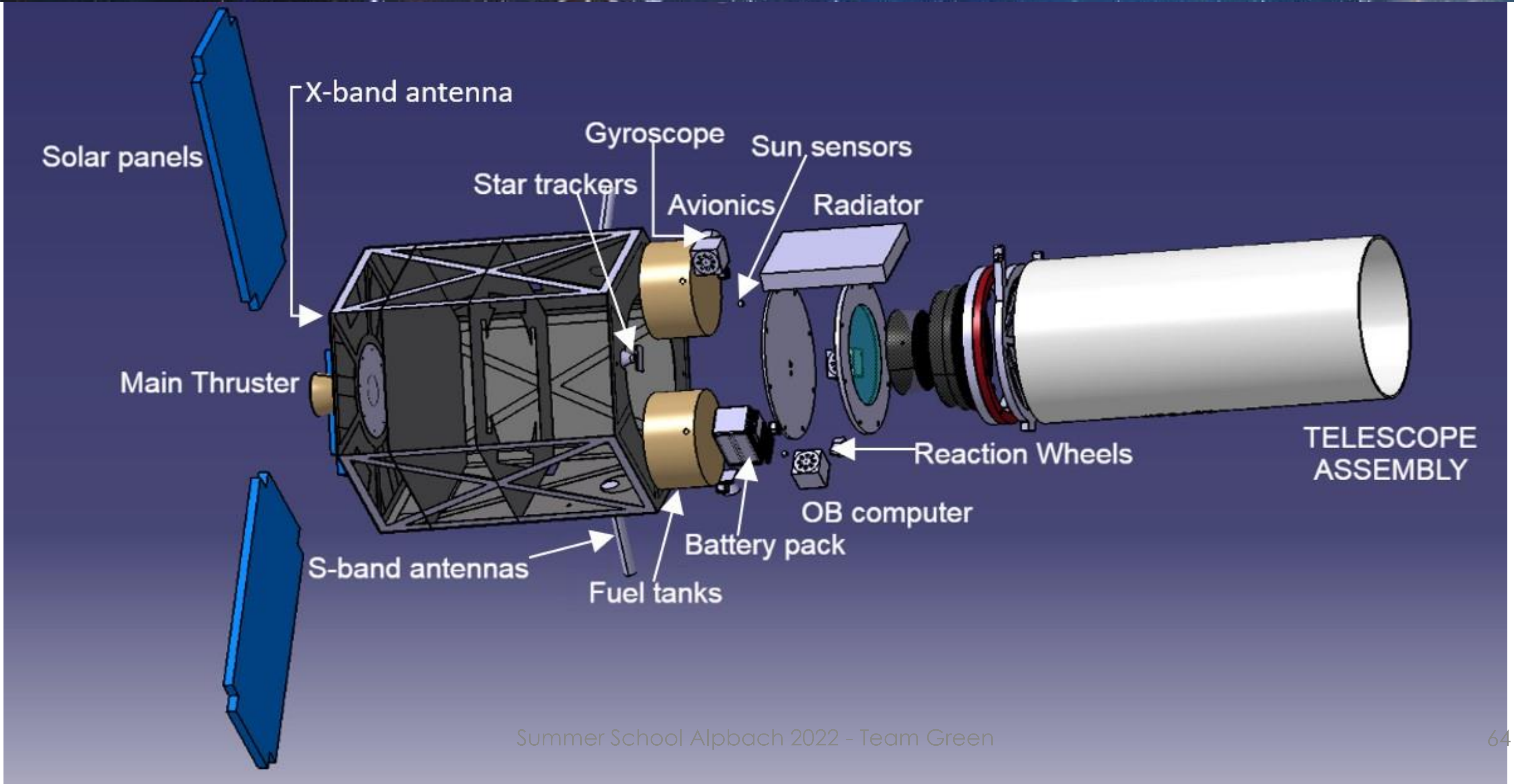
Structure

FE-MIS-110:	Spacecraft survives launch environment

- Material: Silicon Carbide
  - Low thermal expansion coefficient
  - High thermal conductivity
  - High Young modulus

- Truss and panel primary structure
  - CNC milling

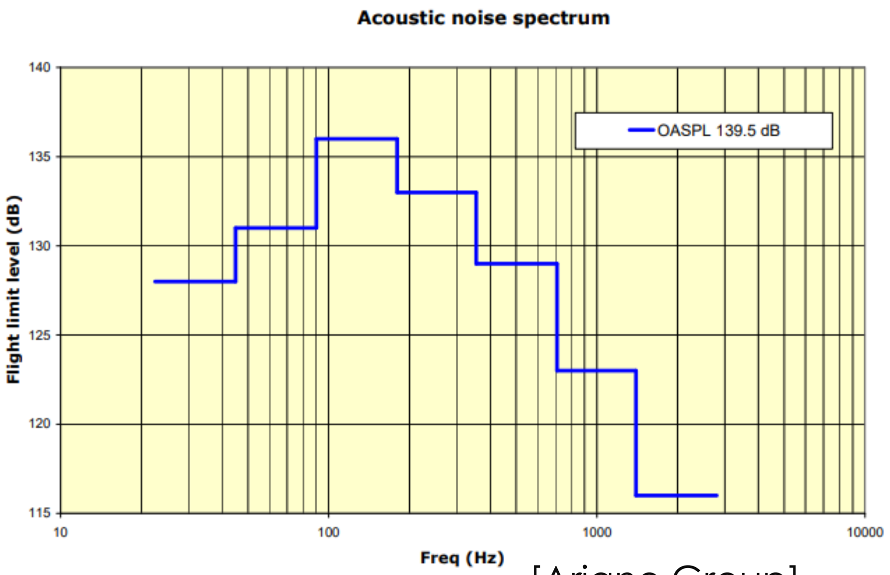
Structure



X-band antenna
Solar panels
Gyroscope
Sun sensors
Star trackers
Avionics
Radiator
Main Thruster
Reaction Wheels
TELESCOPE ASSEMBLY
OB computer
Battery pack
S-band antennas
Fuel tanks

Testing

- TVAC test
- Environmental testing (Helmholtz cage, EMI)
- Vibration/shock tests
- Detumbling



[Ariane Group]

[ESA]

Mass budget

		Total (kg)	Total + Margin (kg)	% of dry mass
Service module	**Propulsion**	105	150	10 %
	EPS	111	166	11 %
	Thermal	140	168	11 %
	TT&C	40	48	3 %
	Structure	406	487	31 %
	ADCS	35	71	5 %
	OBC	40	48	3 %
	Total		1136	68 %
Payload module		420	420	25 %

Dry Mass	1557 kg
Wet Mass	1674 kg

Power Budget

	Nominal Power (W)	Safe Mode (W)
Payload Module		
MCP	260	0
EMCCD	0.1	0
CCD	0.1	0
Payload Total	**260**	**0**
Service Module		
Heaters	150	38
TT&C	10	10
Propulsion	0	30
OBCs	100	25
ADCS	55	64
EPS	125	13
Service Total	**495**	**262**
Grand Total +20 %	**906**	**314**

Delta-v Budget

Operation	Orbit Delta [m/s]
Initial L2 orbit injection	40
Orbit Station-Keeping (per year)	6
Required orbit Station-Keeping (goal)	30 (42)
End of life disposal	30
Total	**118**
Total +100 % Margin	**236**

Mission Analysis

Mission schedule

Project phases		Timeline in Years																	
		1	2	3	4	5	6	7	8	9	10	10,5	11,5	12,5	13,5	14,5	15,5	16,5	17,5	…
0	Feasibility study																			
A	Preliminary mission studies																			
B	Detailed definition studies																			
C	Design, development																			
D	Testing, evaluation																			
E1	Launch & early orbit phase																			
E2	Nominal operations																			
E3	Mission extension																			Extended
F	Disposal																			

Risk assessment

Before mitigation

Probability of Risk Scenario	1	2	3	4	5
5					
4					
3					MCP OBCs
2			Thermal	EPS	CCD
1			Orbit insertion	Propulsion Launch	AOCS TT&C OBDH

Severity of Risk Scenario

With mitigation

Probability of Risk Scenario	1	2	3	4	5
5					
4					
3					
2		EPS Thermal			
1			Propulsion Orbit insertion OBDH	AOCS OBCs TT&C Launch	CCD MCP

Severity of Risk Scenario

Cost assessment

Cost category	Amount (M€)
Industrial costs	
Spacecraft bus	250
Payload	150
Total industrial costs	400
ESA project costs (25 % of industrial costs)	100
Operations	100
Total	600
Total with 20 % contingency	720
Launch	90
Total mission cost	**810**

Descoping options

- Main mission driver:
  - Size of the mirror and instruments
  - Drives both cost and mass budget

- Descoping means losing ability to resolve CME evolution and less possible targets
  - → Partly compromises both science objectives

Public outreach Plan

- Social Media
- Cooperation with educational institutes

[http://www.lesbullesdefleury.com/79-activites/143-les-ateliers-astronomie-jouez-aux-apprentis-astronomes-et-decrochez-la-lune.html]

Do not forget to follow us on:

- Instagram → @feast_mission
- Twitter → @FeastMission

Conclusion

[Lifescience] [Pixabay]

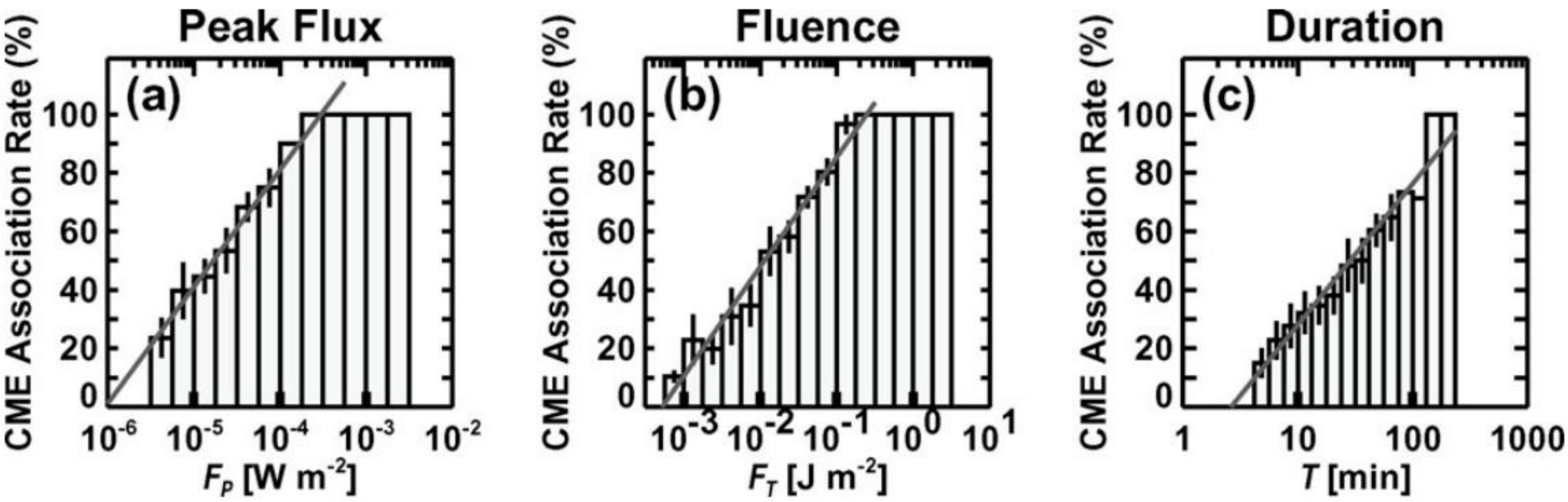
Far & Extreme UV Astrophysical Spectral Telescope

Team Green – Summer School Alpbach 2022

Backup Slides

Data management

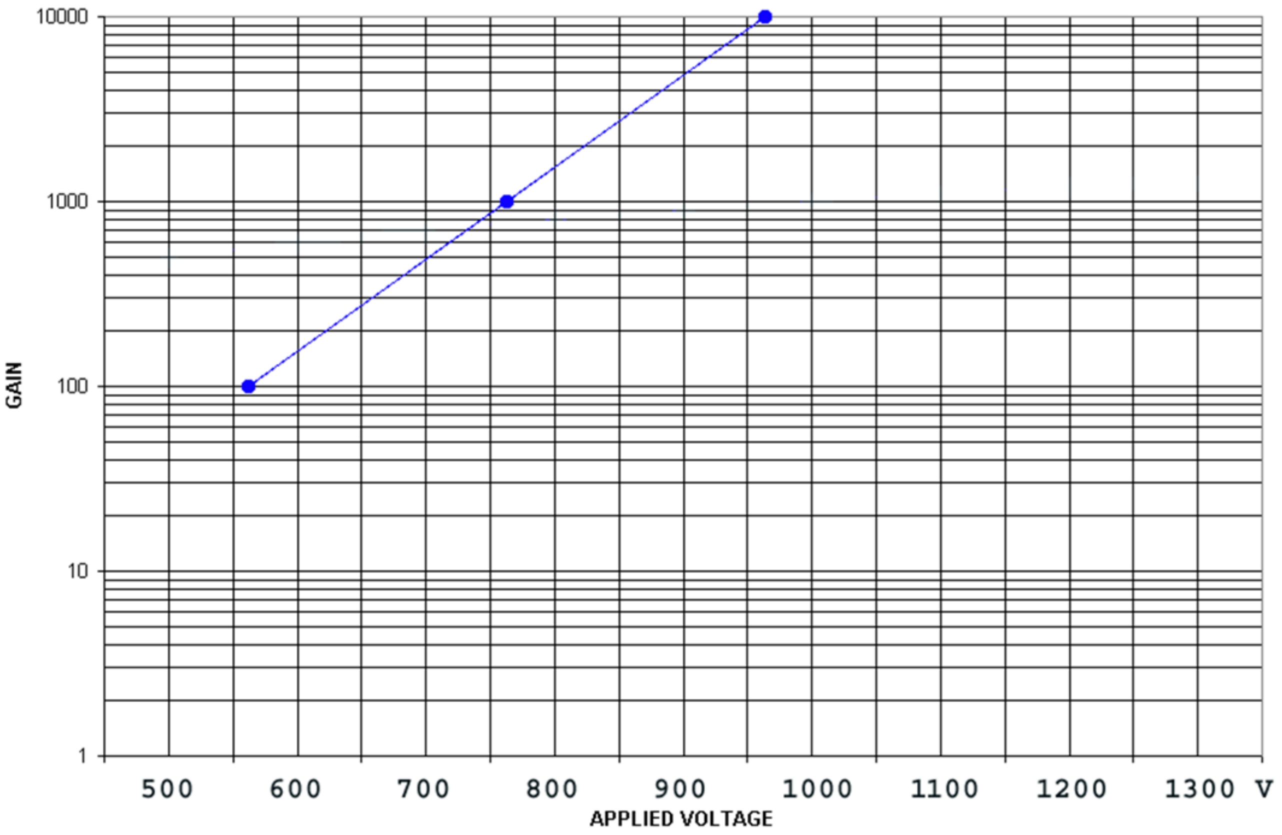
- First data: 1 week (after launch)
- Data press release: 2 weeks
- Calibration and data preparation: 3 months
- Public data access : after 3 months
  - Dedicated FEAST science archive (ESA)
  - MAST (Mikulski Archive for Space Telescopes) NASA Platform



[Yashiro & Gopalswamy 2009]

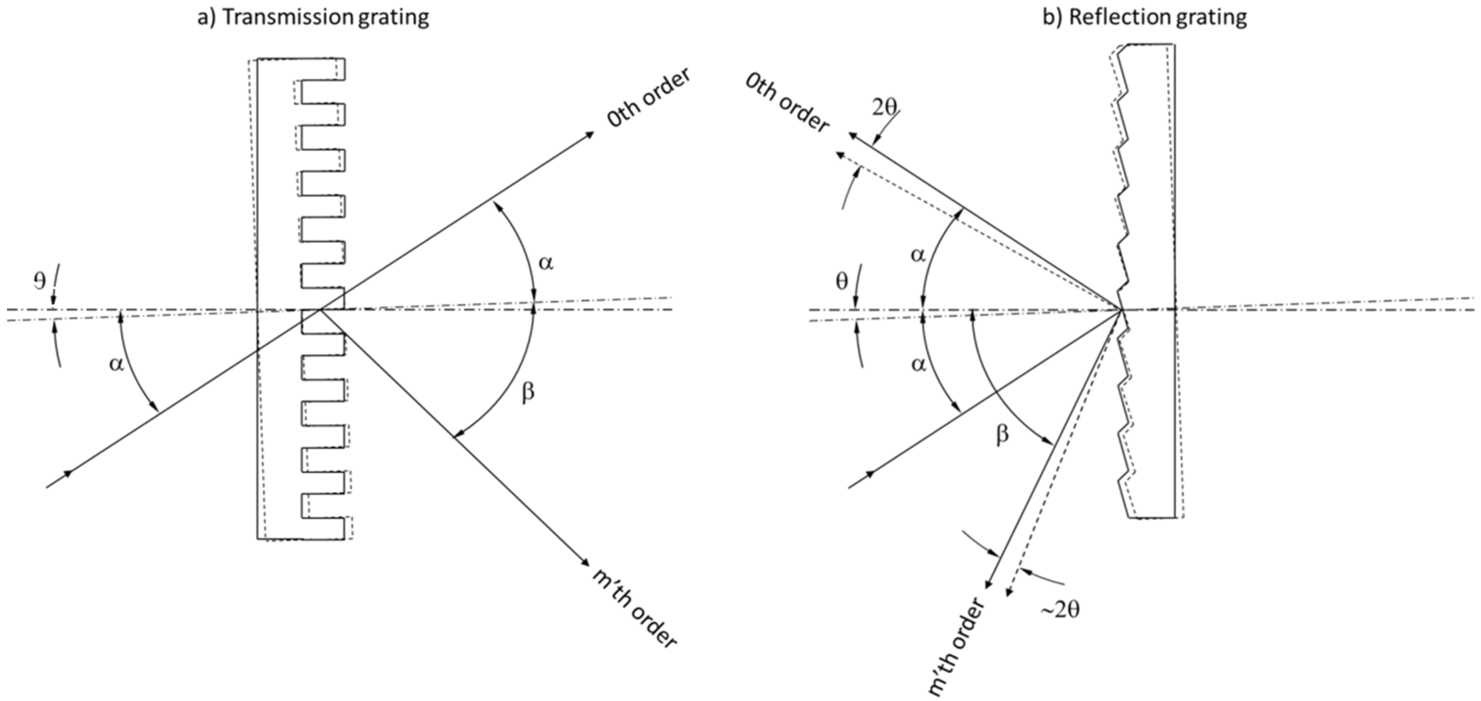
Microchannel plate: MCP 34-10 (TRL6)

Electrical specs	
gain of 1000	960 V
2 MCP	10^7 Gain
3 MCP	10^9 Gain
Strip current	< 20 µA
Dark current	0.52 pA/cm^2
Power consumption	TBC



Transmission Grating

- Beam splitting elements or as dispersion elements for wavelength separation
- Diffraction of light in different angles to give a diffraction pattern.



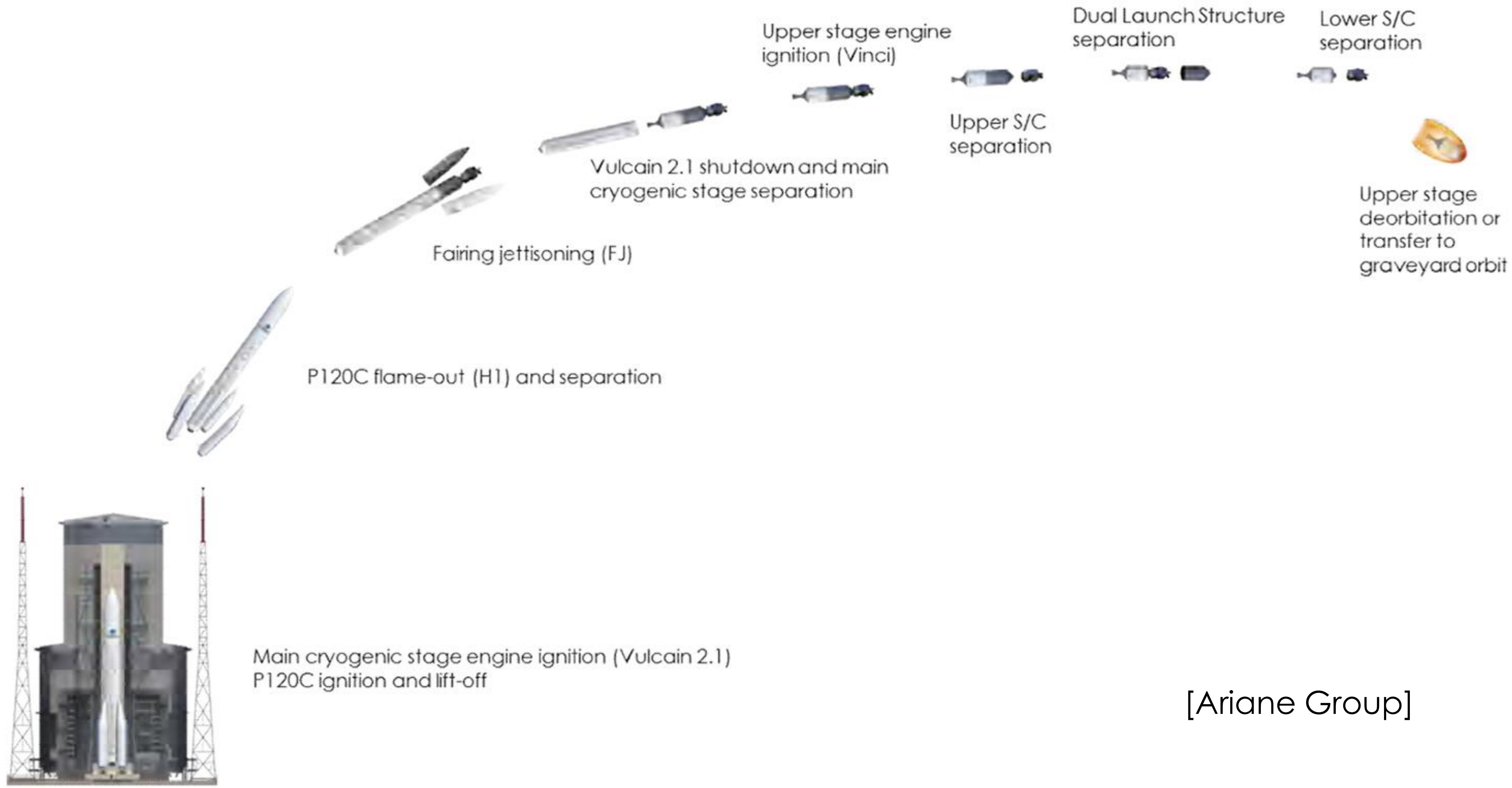
Ibsen Photonics, “Transmission grating angle sensitivity”

Transmission Grating

LETG Configurations (TBC)				
Configuration	Wavelength Range / Å	Energy Range / keV	Resolving Power (E / ΔE)	Plate scale
LETG / HRC-S	1.2 - 175	0.07 - 10.0	>1000 (50-160 Å) ~20 xλ (3-50 Å)	48.8 microns / arcsec
LETG / ACIS-S	1.2 - 60	0.2 - 10.0		

Brinkman et al. 2000, ApJ, 530, L111

Launch and Transfer



[Ariane Group]

Telemetry, Tracking & Command

- **Main driver:** payload data rates, ground station coverage
- **Tradeoff:** ground station selection, coverage window vs operation cost, antenna sizing, power consumption

- Ground Station: New Norcia
    - NNO-1 (35 m) and NNO-2 (4 m) antennas

- 2 hour daily communication window

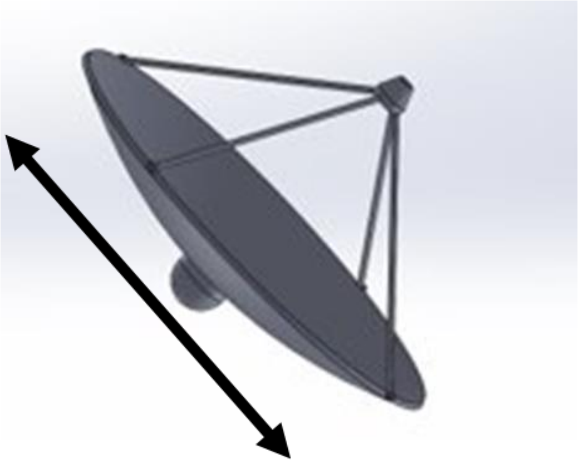
- S/X band frequency
    - Compatibility across ESTRACK

- Mission Control: ESOC

[ESA]

Telemetry, Tracking & Command

- Medium Gain - Parabolic Cassegrain X band (x1)
  - Gain: 33 dB
  - Beamwidth angle: 15°
  - Power: 100 W
- Low Gain - Omnidirectional S band (x2)
  - Gain: 7 dB
  - Beamwidth angle: 180°
  - Power: 10 W

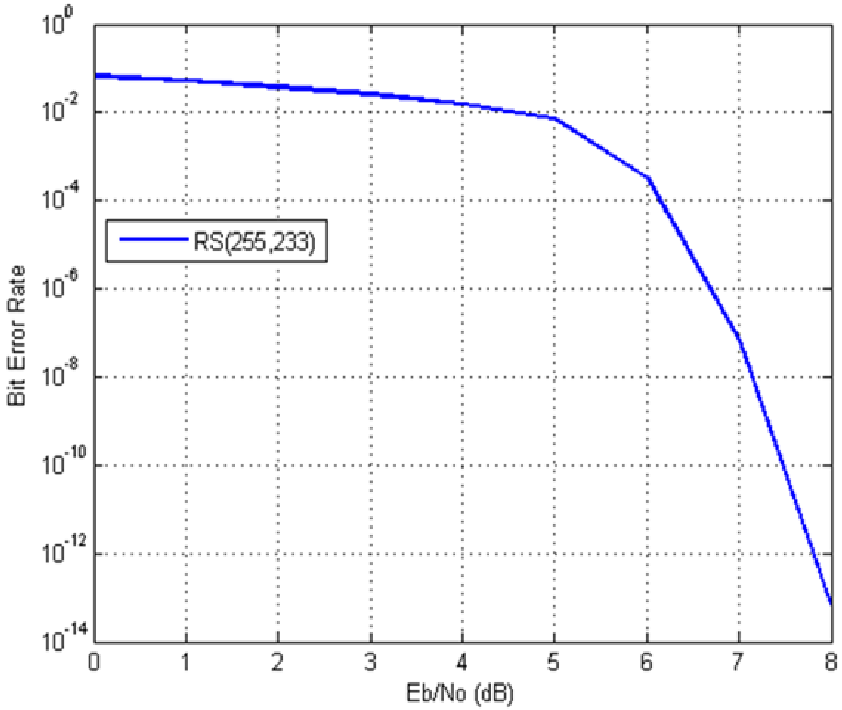


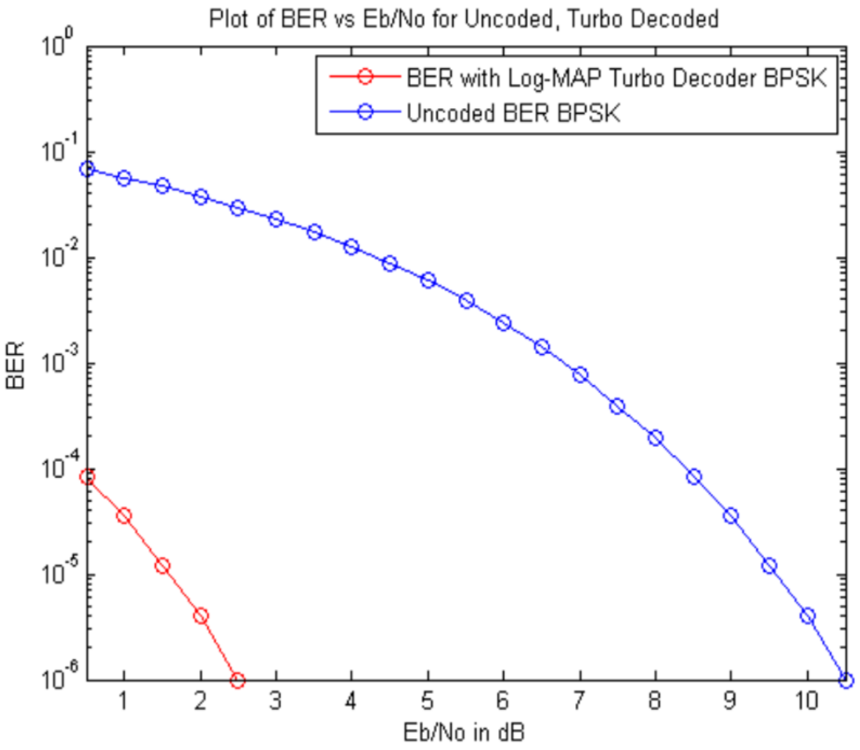
[SENER, NASA]

Uplink (kb/s)		**Downlink (Mb/s)**	
Telecommand	24	S/C Health	0.02
		Payload Health	0.01
		Science Data	168.21
Total	**24**	**Total**	**168.24**

Telemetry, Tracking & Command

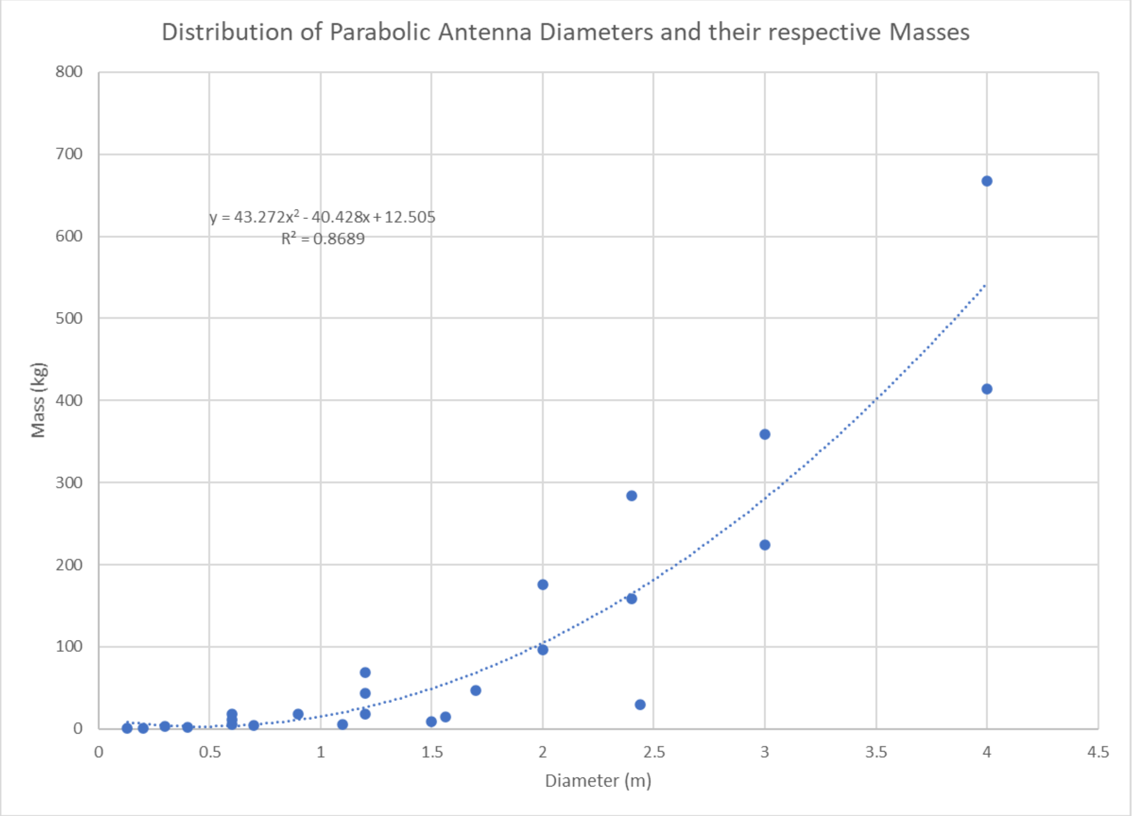
- Signal latency: 5 s
- Modulation: Binary Phase Shift-Keying
- Decoding: Reed-Solomon
- Required S/R: > 6.6 dB with 10 dB margin





Telemetry, Tracking & Command

- Medium Gain Link Budget
  - Turnaround ratio 749/864



Uplink		**Downlink**	
Frequency (MHZ)	7145	Frequency (MHz)	8242
Data rate (kbps)	24.0	Data rate (Mbps)	168.2
GS Tx EIRP (dBW)	138.0	S/R Needed (dB)	14.0
Path loss (dB)	-233.1	Path loss (dB)	-234.4
Atmospheric loss (dB)	-0.4	Atmospheric loss (dB)	-0.9
Implementation loss (dB)	-2.0	Line loss (dB)	-1.0
S/C Rx Gain (dB)	**-35.0**	GS Rx Gain (dB)	50.1
S/R Margin (dB)	**16.8**	**S/C Tx Power (W)**	**100.0**
Antenna efficiency	0.7	**Min S/C Tx Gain (dB)**	**33.8**
Minimum diameter (m)	0.762	**Beamwidth angle (°)**	**15.6**
Antenna mass (kg)	8.56		

Telemetry, Tracking & Command

- Low Gain Link Budget
  - Turnaround ratio 221/240

- Data rate sized by telecommands and spacecraft/instrument health

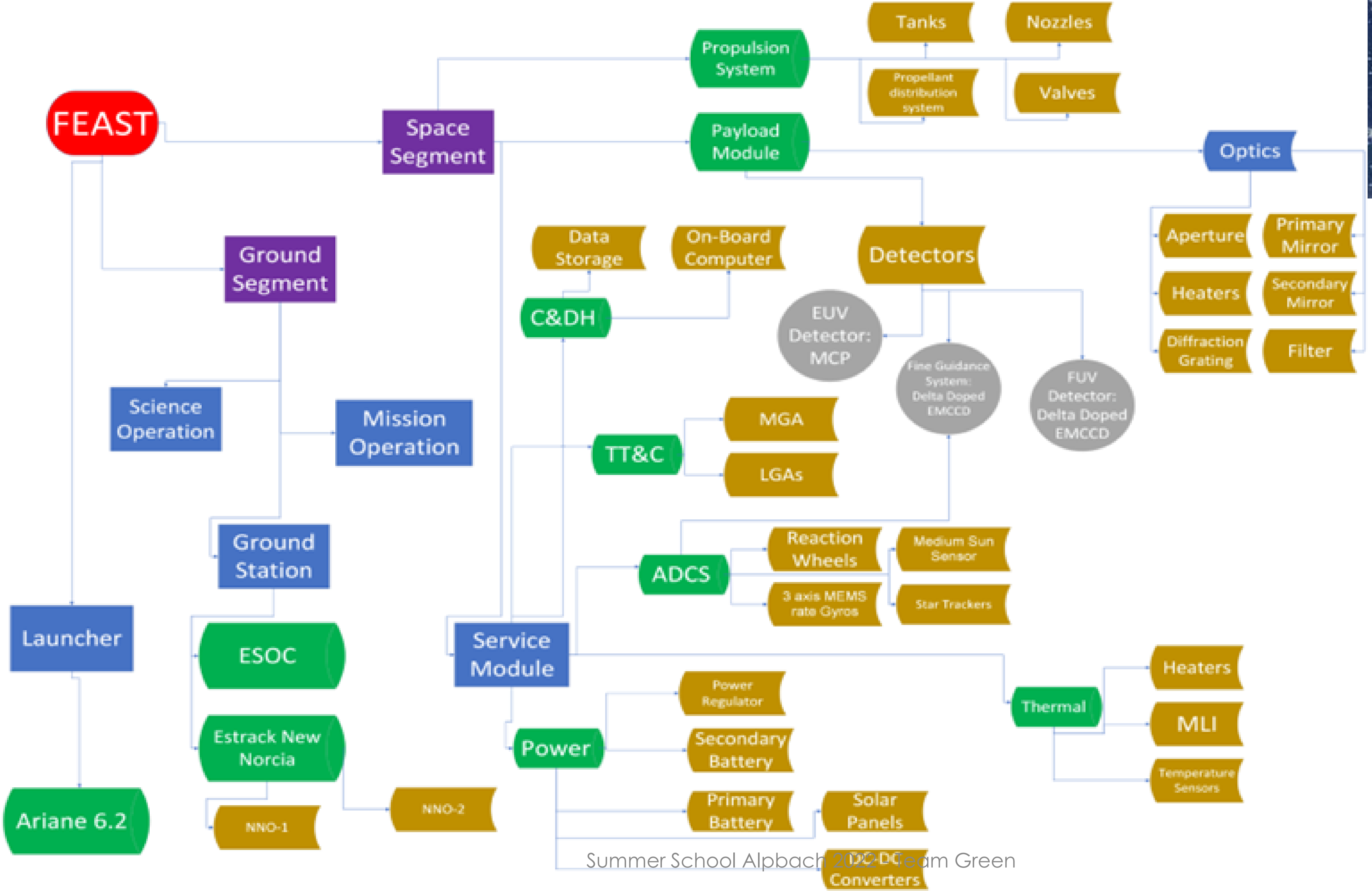
- Antenna selection based on NASA ICEE-C LGA design 3

Uplink		**Downlink**	
Frequency (MHZ)	2025	Frequency (MHz)	2199
Data rate (kbps)	2.0	Data rate (kbps)	25.0
GS Tx EIRP (dBW)	97.0	S/R Needed (dB)	14.0
Path loss (dB)	-222.2	Path loss (dB)	-222.8
Atmospheric loss (dB)	-0.4	Atmospheric loss (dB)	-0.9
Implementation loss (dB)	-2.0	Line loss (dB)	-1.0
S/C Rx Gain (dB)	**-20.0**	GS Rx Gain (dB)	37.5
S/R Margin (dB)	**13.5**	**S/C Tx Power (W)**	**10.0**
		Min S/C Tx Gain (dB)	**6.7**

Mass Budget

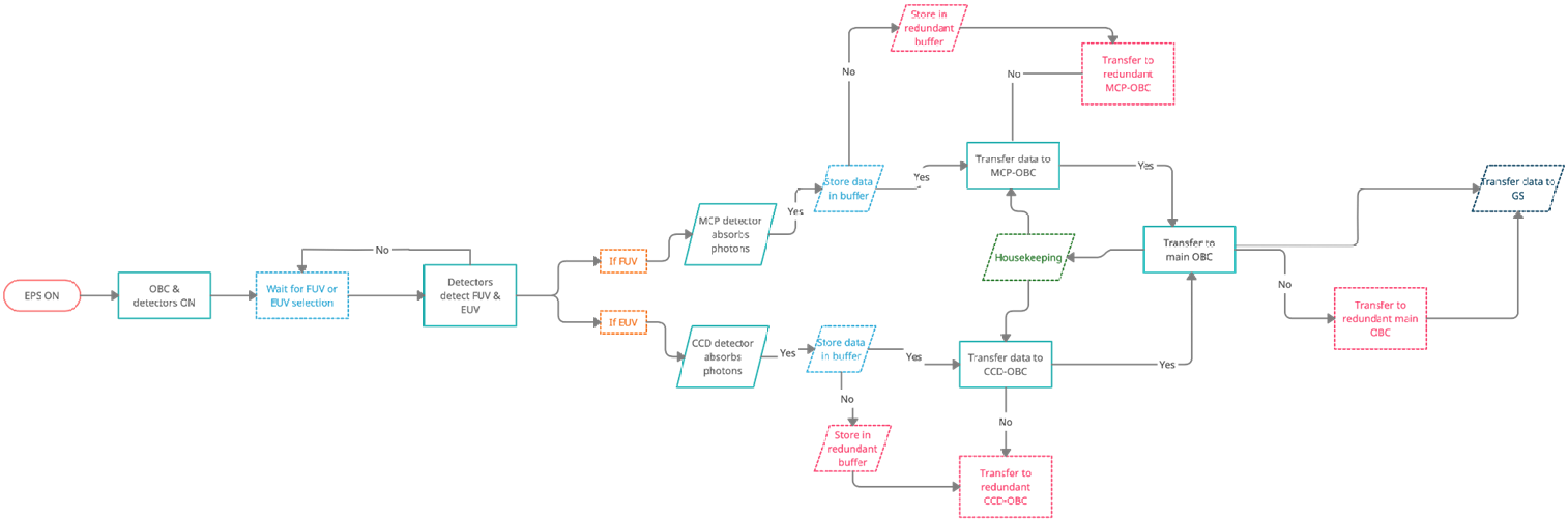
	Mass [Kg]	Mass with Budget [Kg]
Propulsion System	95.37	114.44
EPS	42.46	63.69
Thermal	11.00	13.20
Payload	420	420
TT&C	22.00	26.40
Total	637.73	765.28

System tree



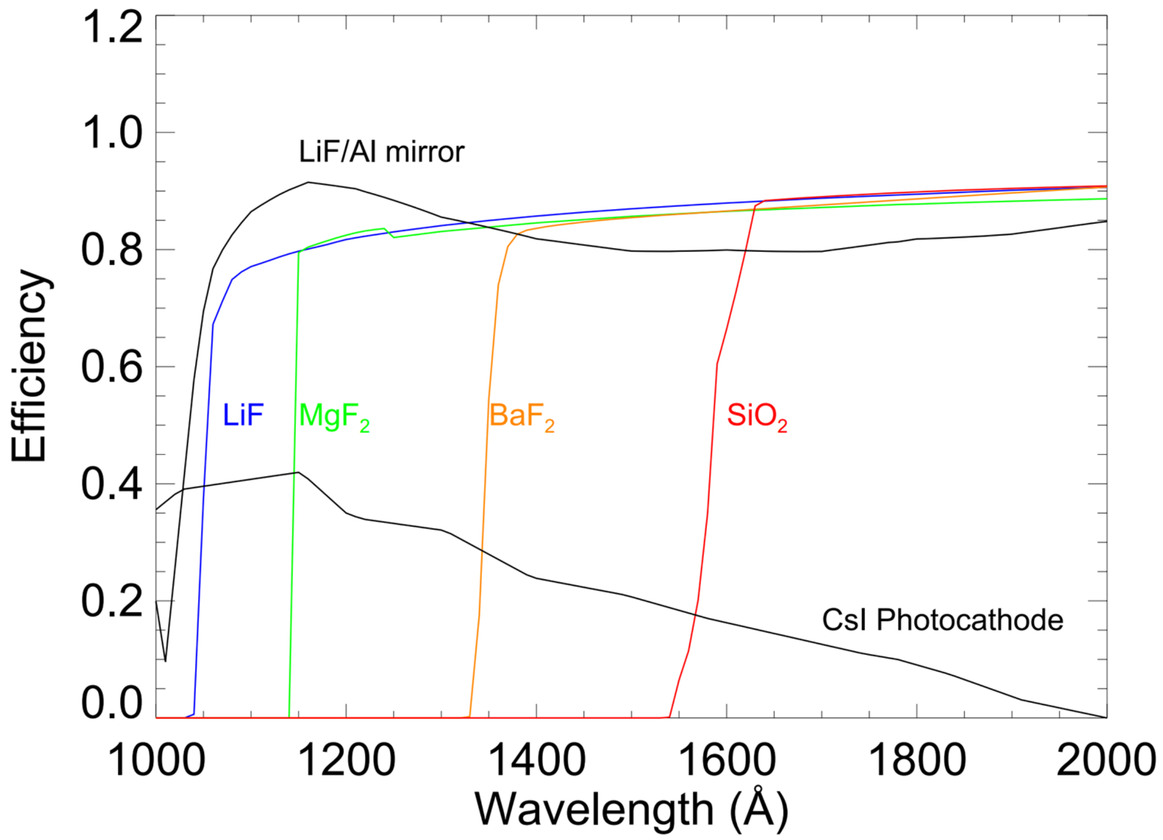
FEAST
Space Segment
Propulsion System
Tanks
Nozzles
Propellant distribution system
Valves
Payload Module
Optics
Aperture
Primary Mirror
Heaters
Secondary Mirror
Diffraction Grating
Filter
Detectors
EUV Detector: MCP
Fine Guidance System: Delta Doped EMCCD
FUV Detector: Delta Doped EMCCD
Data Storage
On-Board Computer
C&DH
TT&C
MGA
LGAs
ADCS
Reaction Wheels
Medium Sun Sensor
3 axis MEMS rate Gyros
Star Trackers
Service Module
Thermal
Heaters
MLI
Temperature Sensors
Power
Power Regulator
Secondary Battery
Primary Battery
Solar Panels
DC-DC Converters
Ground Segment
Science Operation
Mission Operation
Ground Station
ESOC
Estrack New Norcia
NNO-1
NNO-2
Launcher
Ariane 6.2

Dataflow for payload

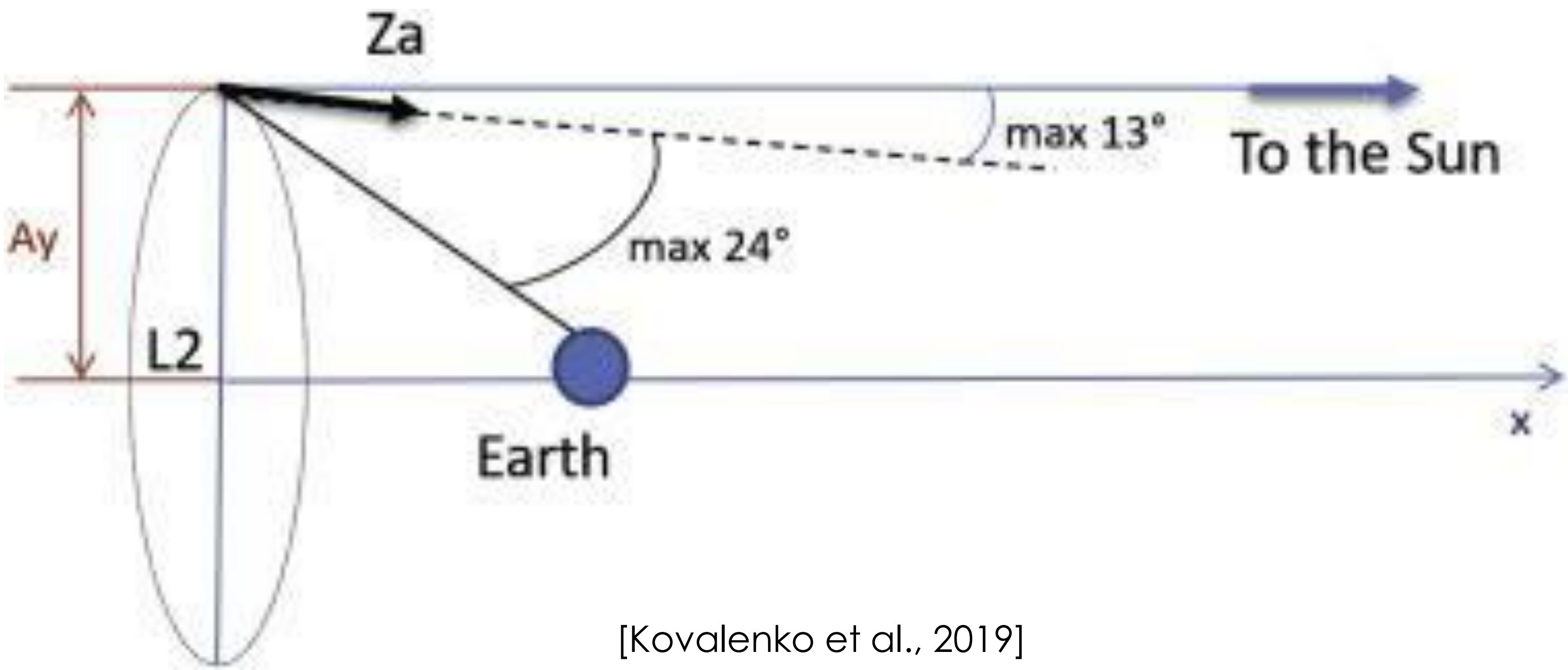


Diffraction Element

Filter: narrow band Lyman-a (1215 Å) rejection [Ravi1 et al., 2021]



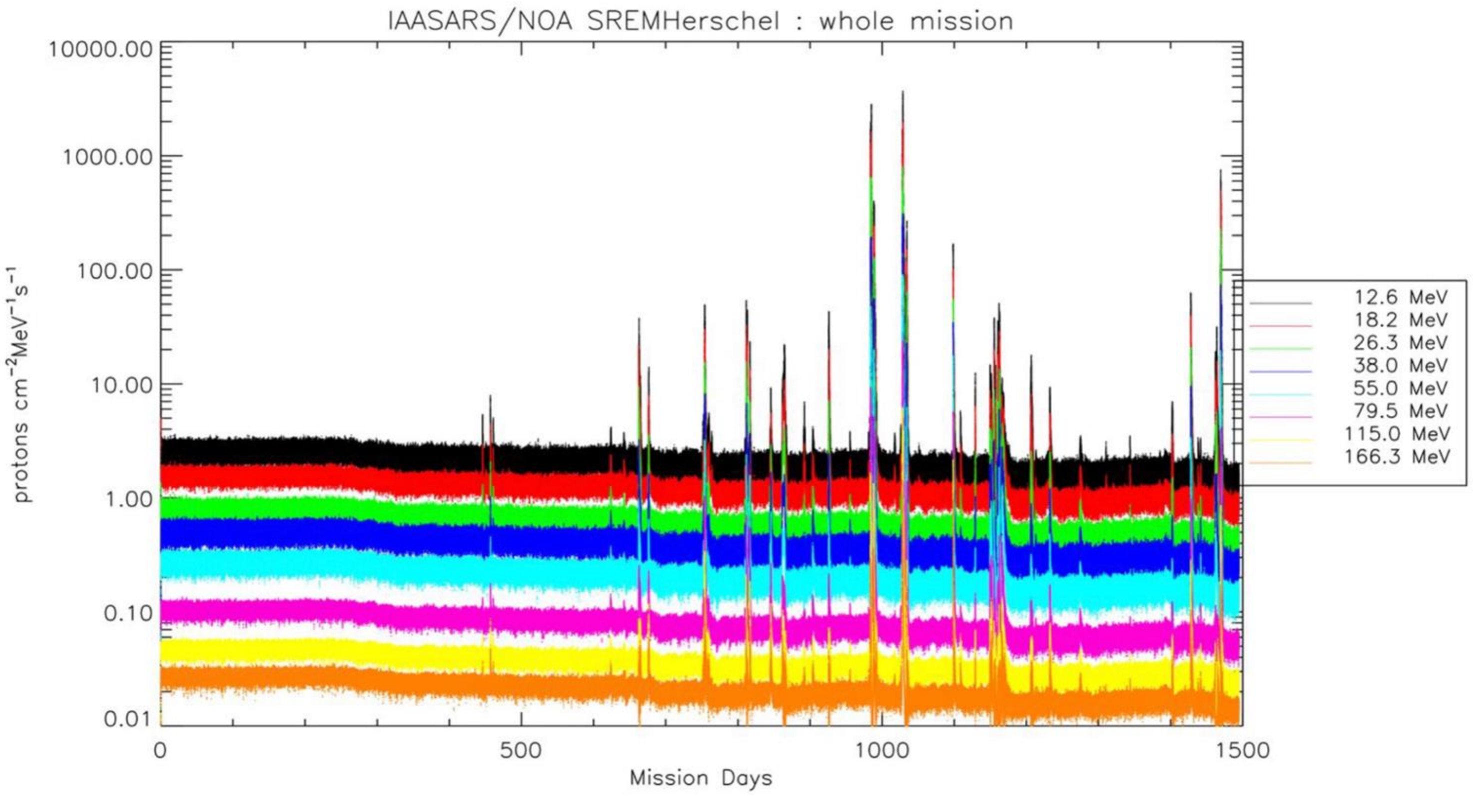
Target Orbit



[Kovalenko et al., 2019]

Radiation environment at L2

- Main sources of radiation:
  - cosmic rays
  - solar events
    - CME
    - Flare
- Fault Detection Isolation and Recovery (FDIR) system



[Herschel Observers' Manua., 2014]