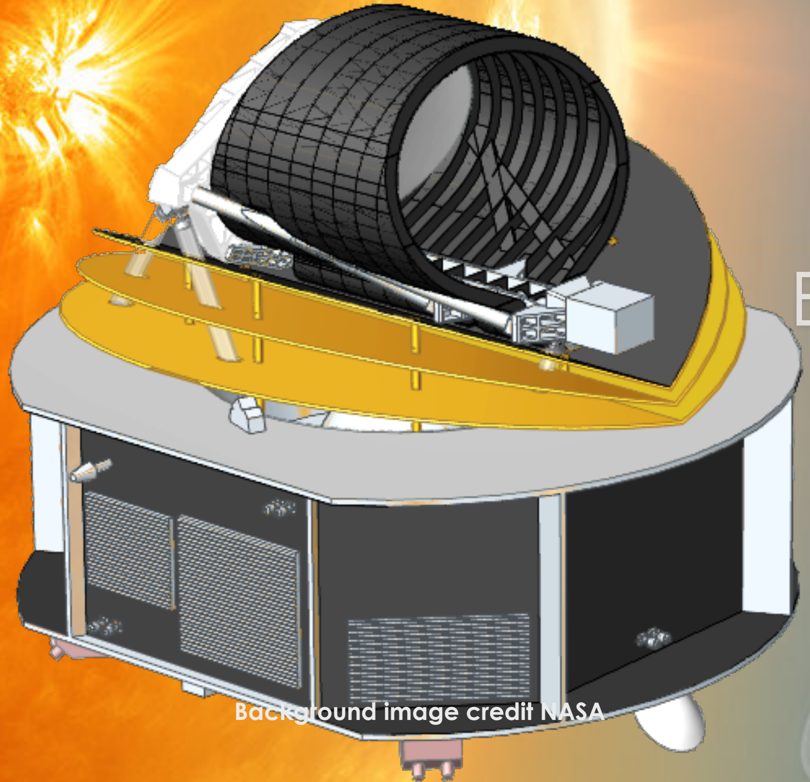
ARIEL

Enabling planetary science across light-years



Background image credit NASA

PLANETS ARE UBIQUITOUS

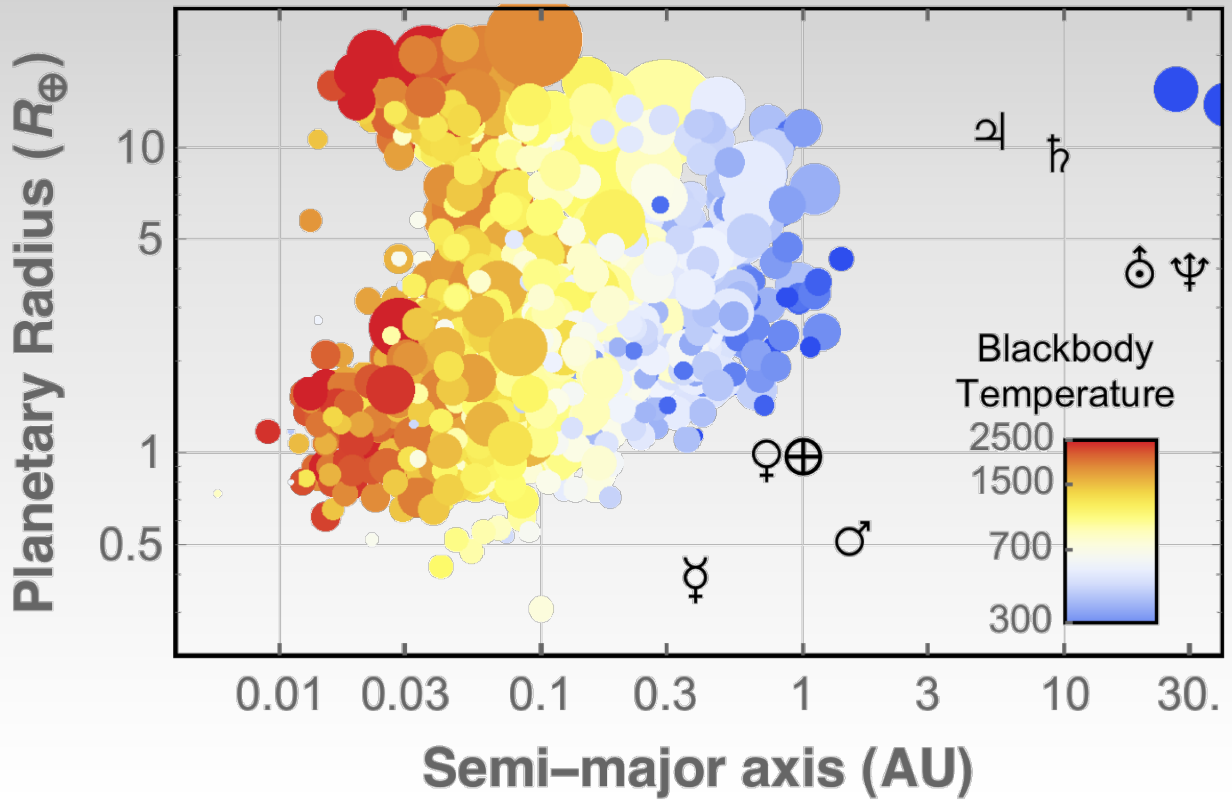
OUR GALAXY IS MADE OF GAS, STARS & PLANETS

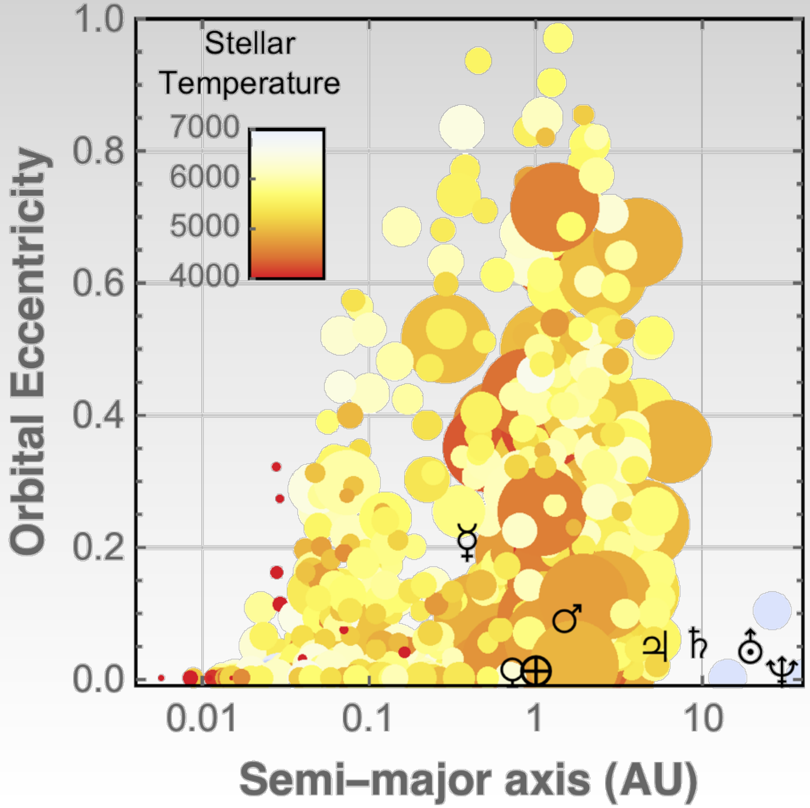
There are at least as many planets as stars

Cassan et al, 2012; Batalha et al., 2015;

EXOPLANETS TODAY: HUGE DIVERSITY

3700+ PLANETS, 2700 PLANETARY SYSTEMS KNOWN IN OUR GALAXY





TRUTH IS STRANGER THAN FICTION!

THE SOLAR SYSTEM IS NOT THE STANDARD MODEL IN OUR GALAXY

Credit films: “Interstellar”, “Pitch Black”, “Star wars”

KEY EXOPLANET QUESTIONS

- How diverse are exoplanets chemically?
- Does chemical diversity correlate with other parameters?
- How do planets form?
- How do planets evolve?

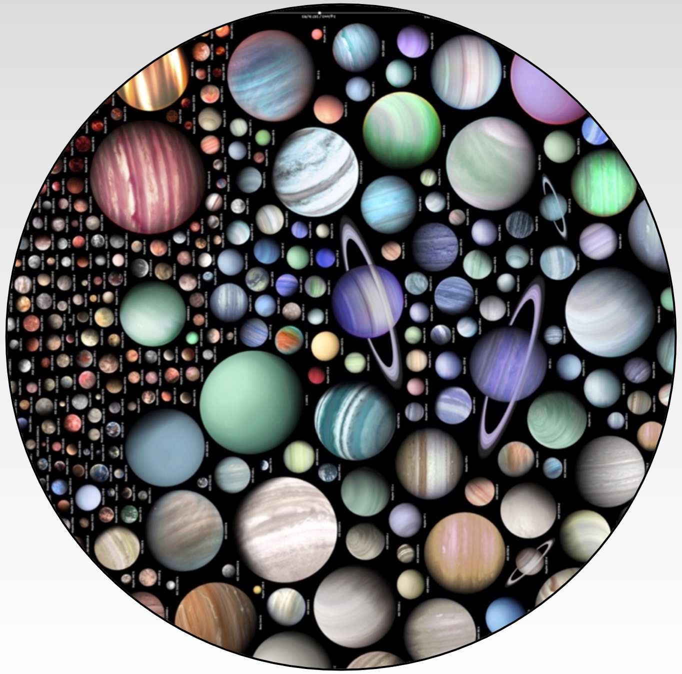
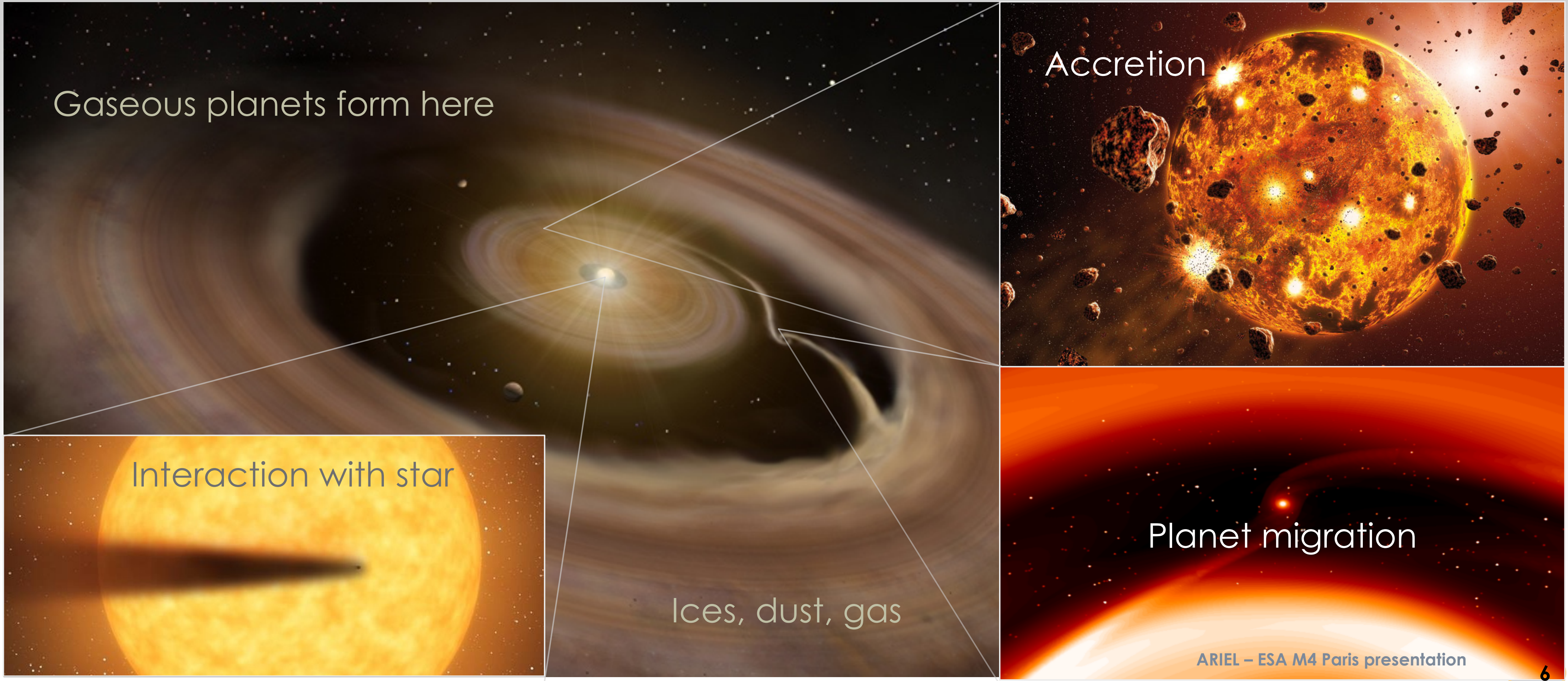


Image credit: Halcyon Maps & Martin Vargic

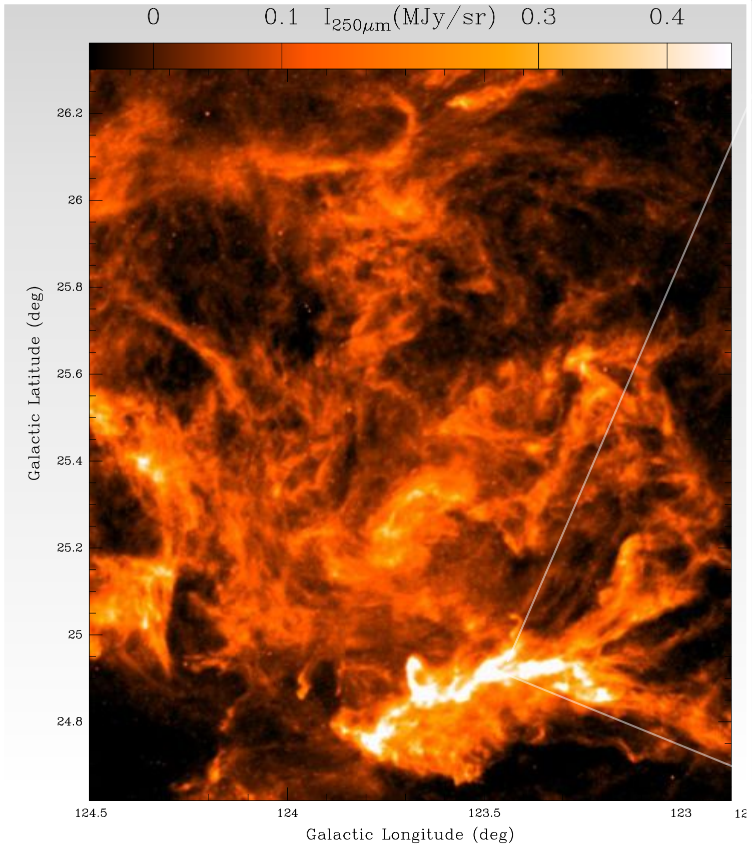
HUGE DIVERSITY: WHY?

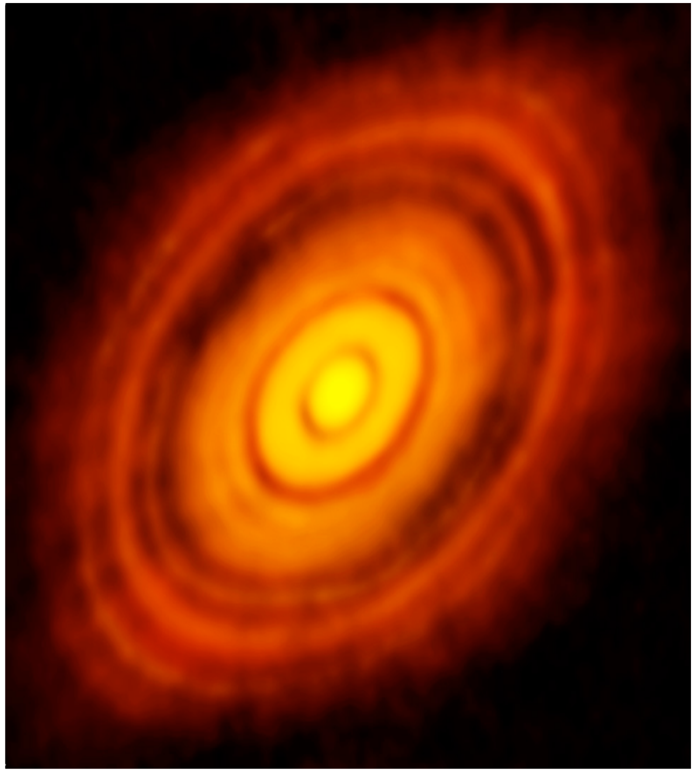
FORMATION & EVOLUTION PROCESSES? MIGRATION? INTERACTION WITH STAR?



STAR & PLANET FORMATION/EVOLUTION

WHAT WE KNOW: CONSTRAINTS FROM OBSERVATIONS – HERSCHEL, ALMA, SOLAR SYSTEM





?

Measured elements in Solar system

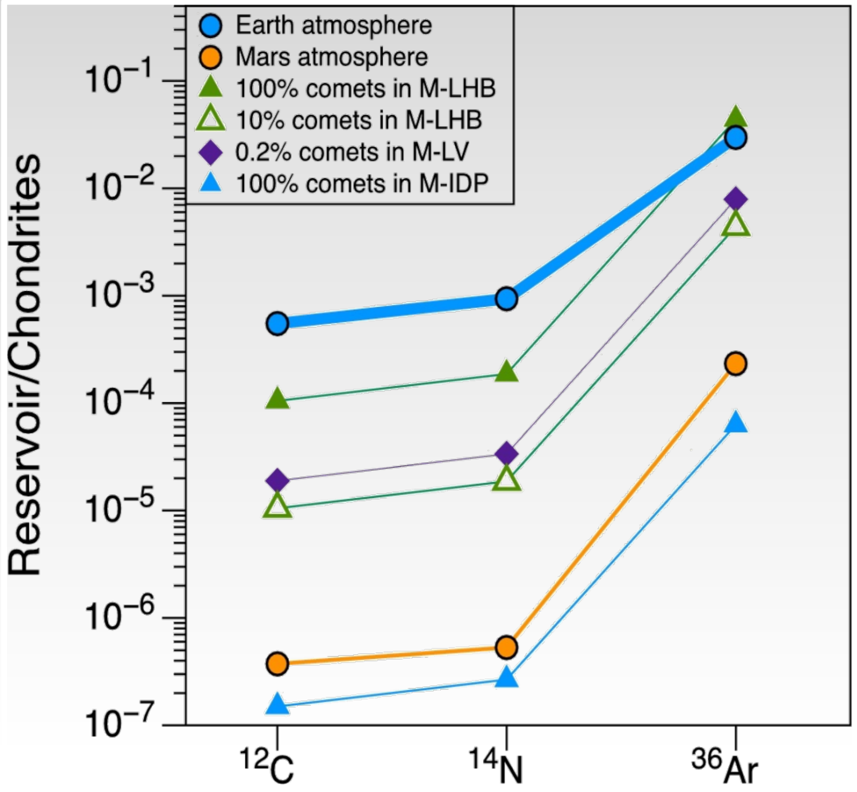
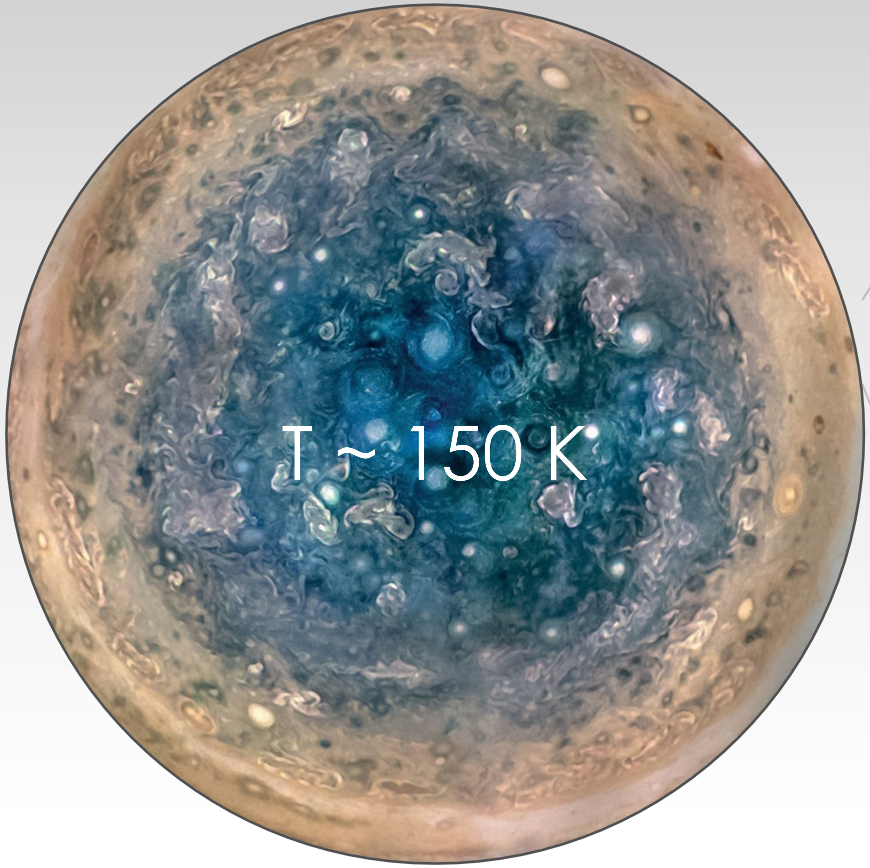


Image credit ESA-Herschel, ALMA (ESO/NAOJ/NRAO), Marty et al, 2016; André, 2012;

THE SUN'S PLANETS ARE COLD

SOME KEY O, C, N, S MOLECULES ARE **NOT** IN GAS FORM



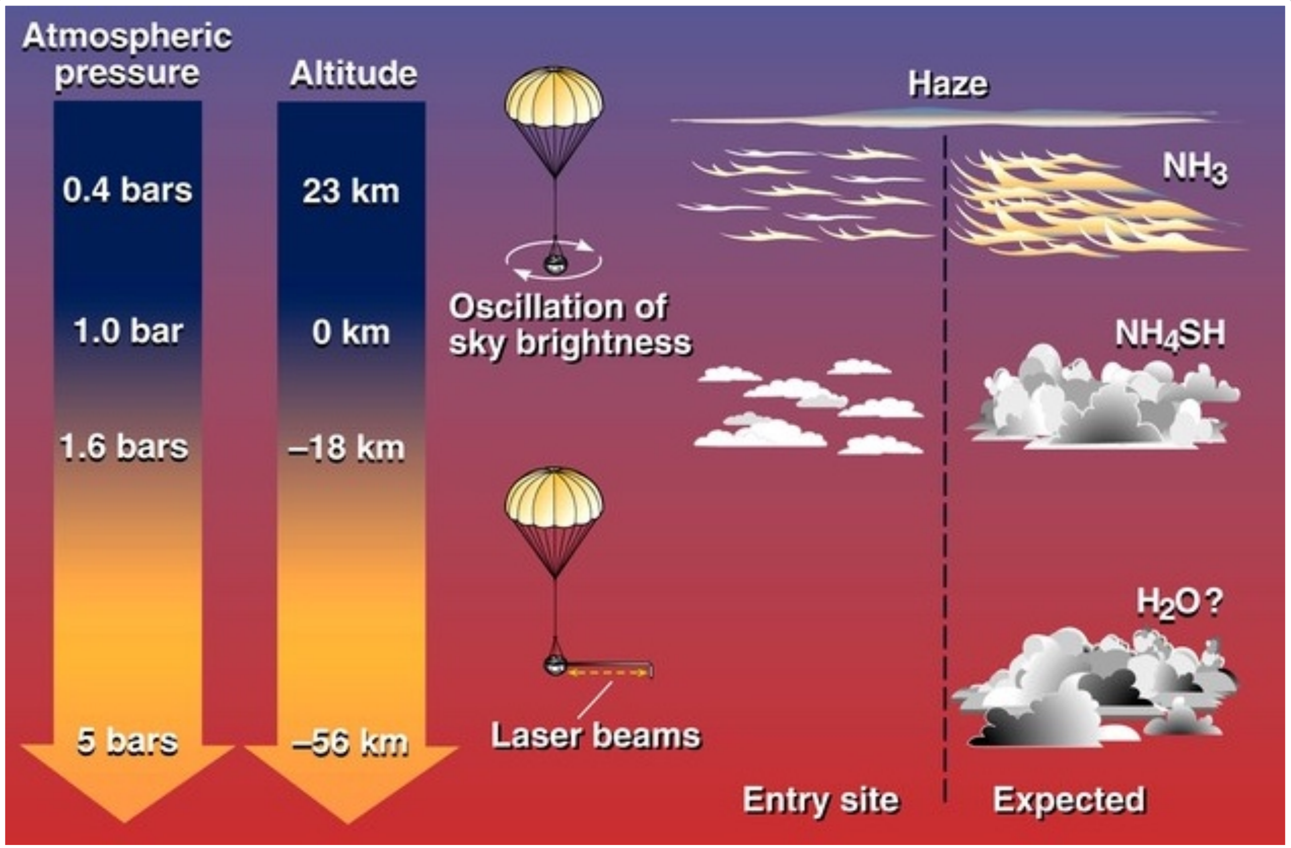
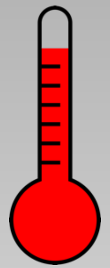
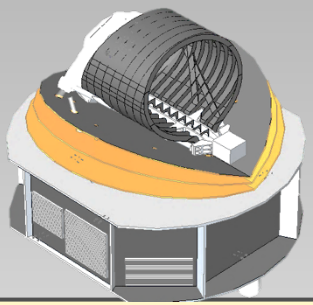


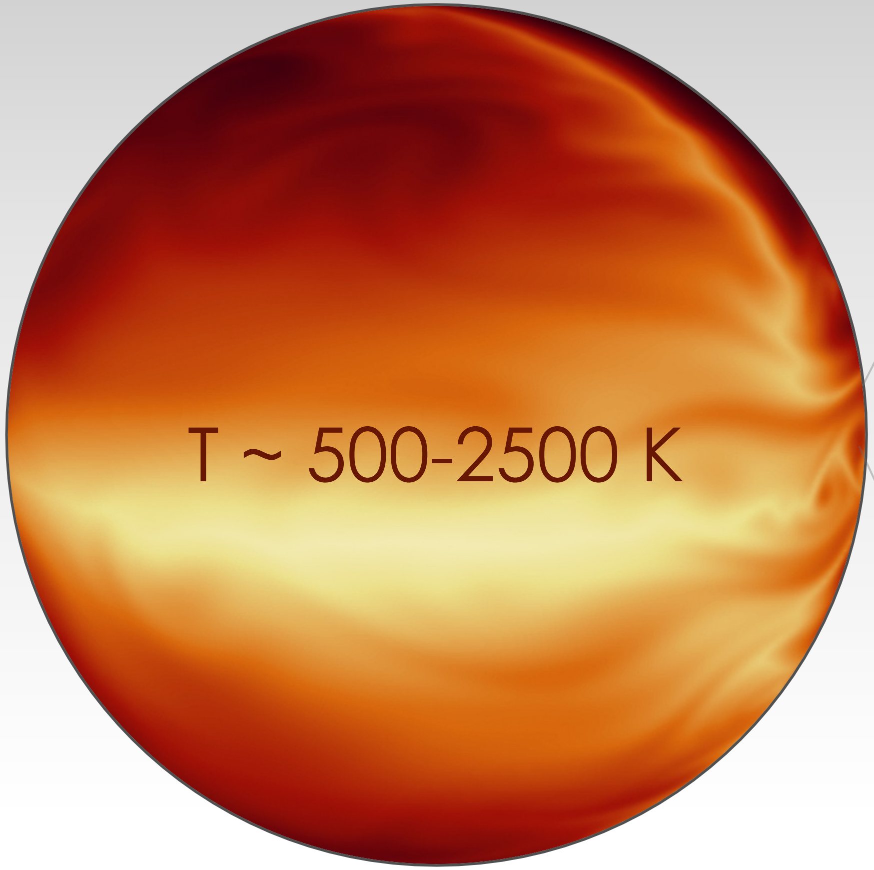
Image credit NASA Juno mission, NASA Galileo

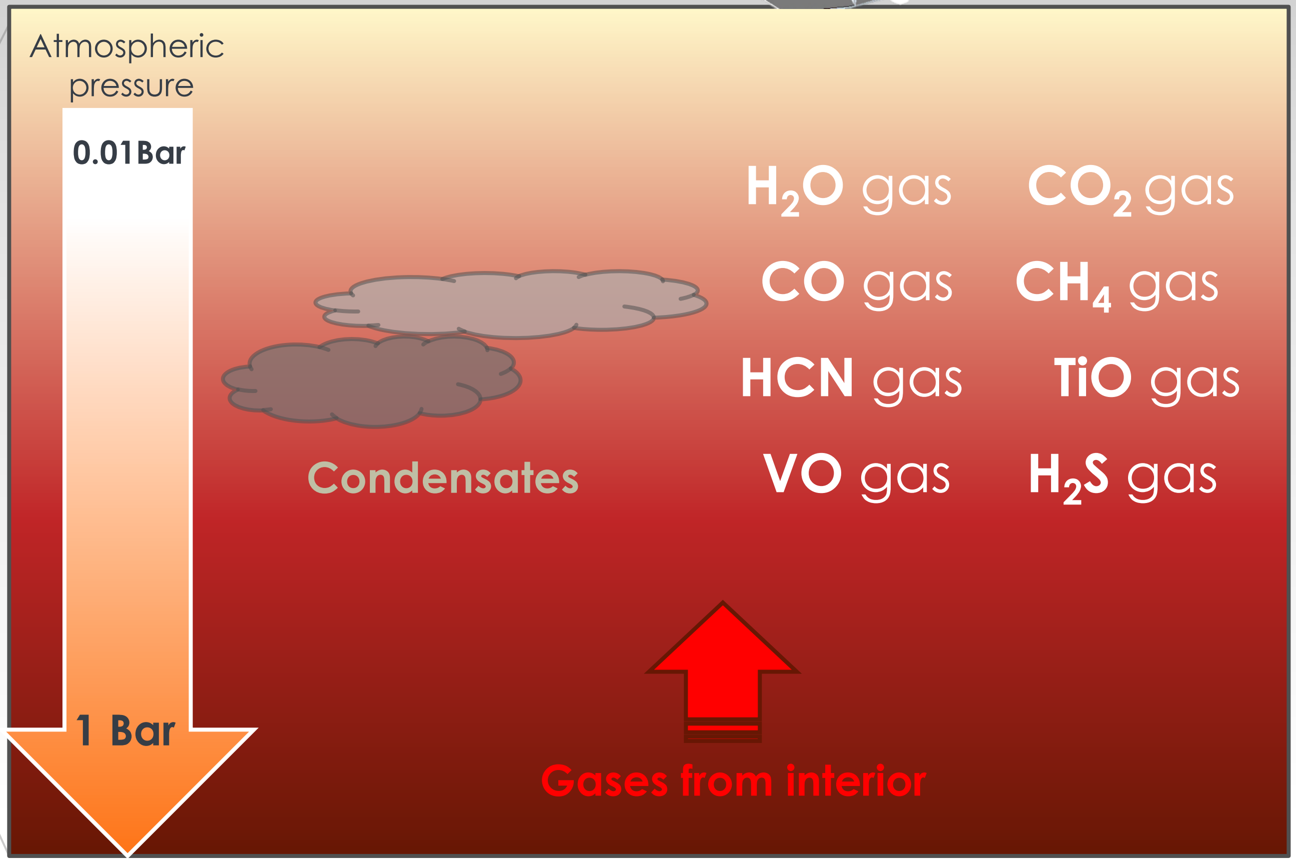
WARM/HOT EXOPLANETS

O, C, N, S (Ti, VO, Si) molecules are in gas form



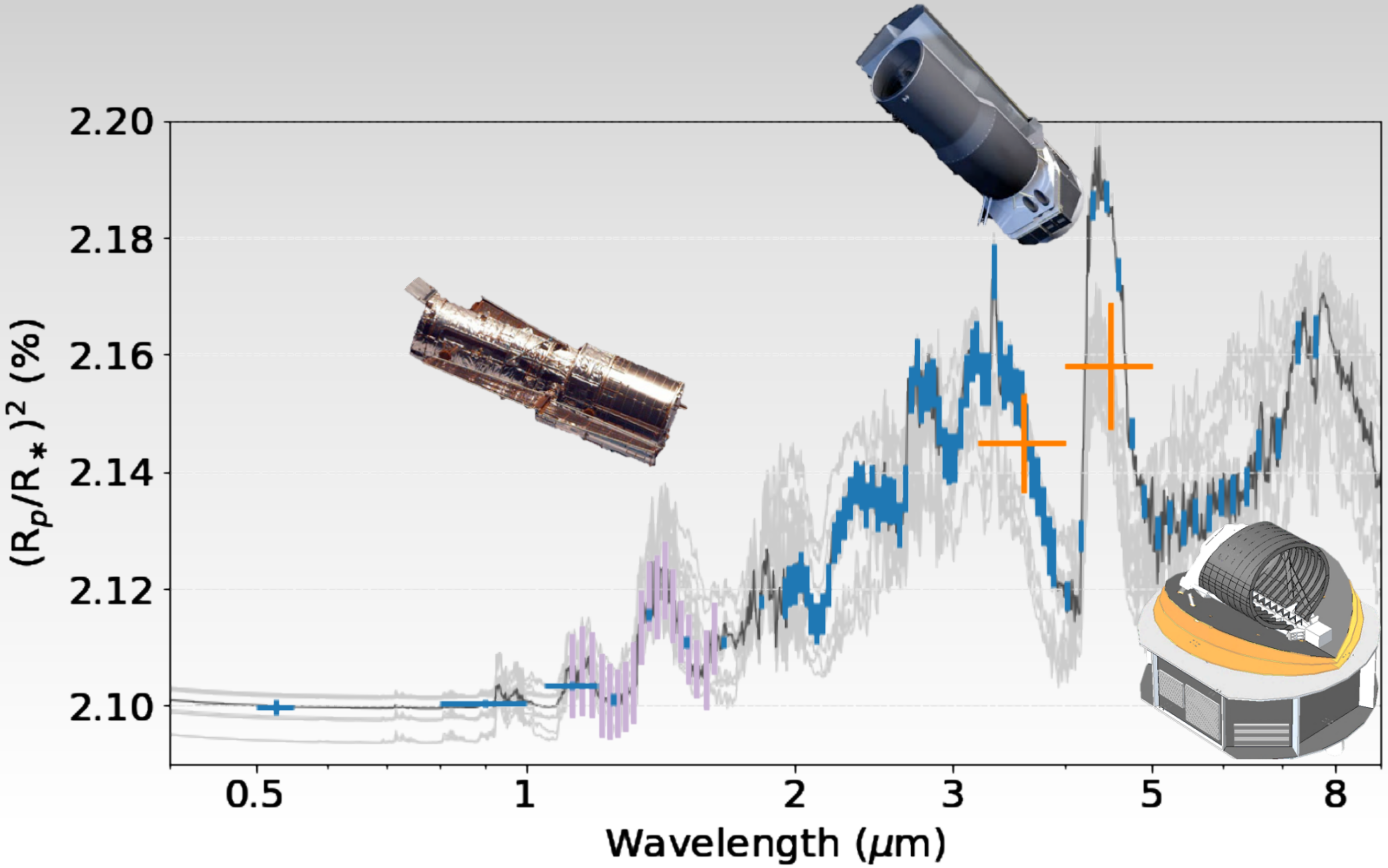






CHEMICAL MEASUREMENTS TODAY

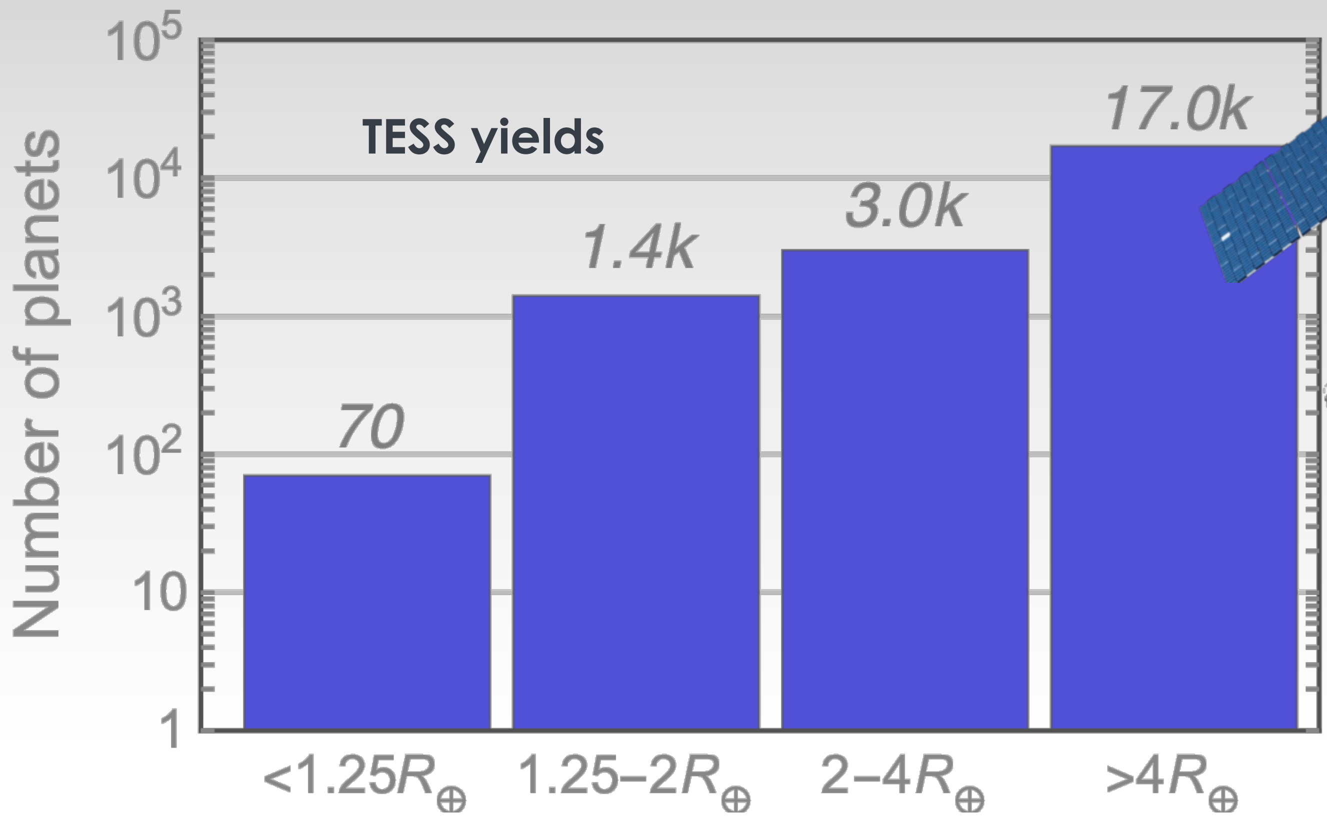
SPECTROSCOPIC OBSERVATIONS WITH CURRENT INSTRUMENTS (HUBBLE, SPITZER)

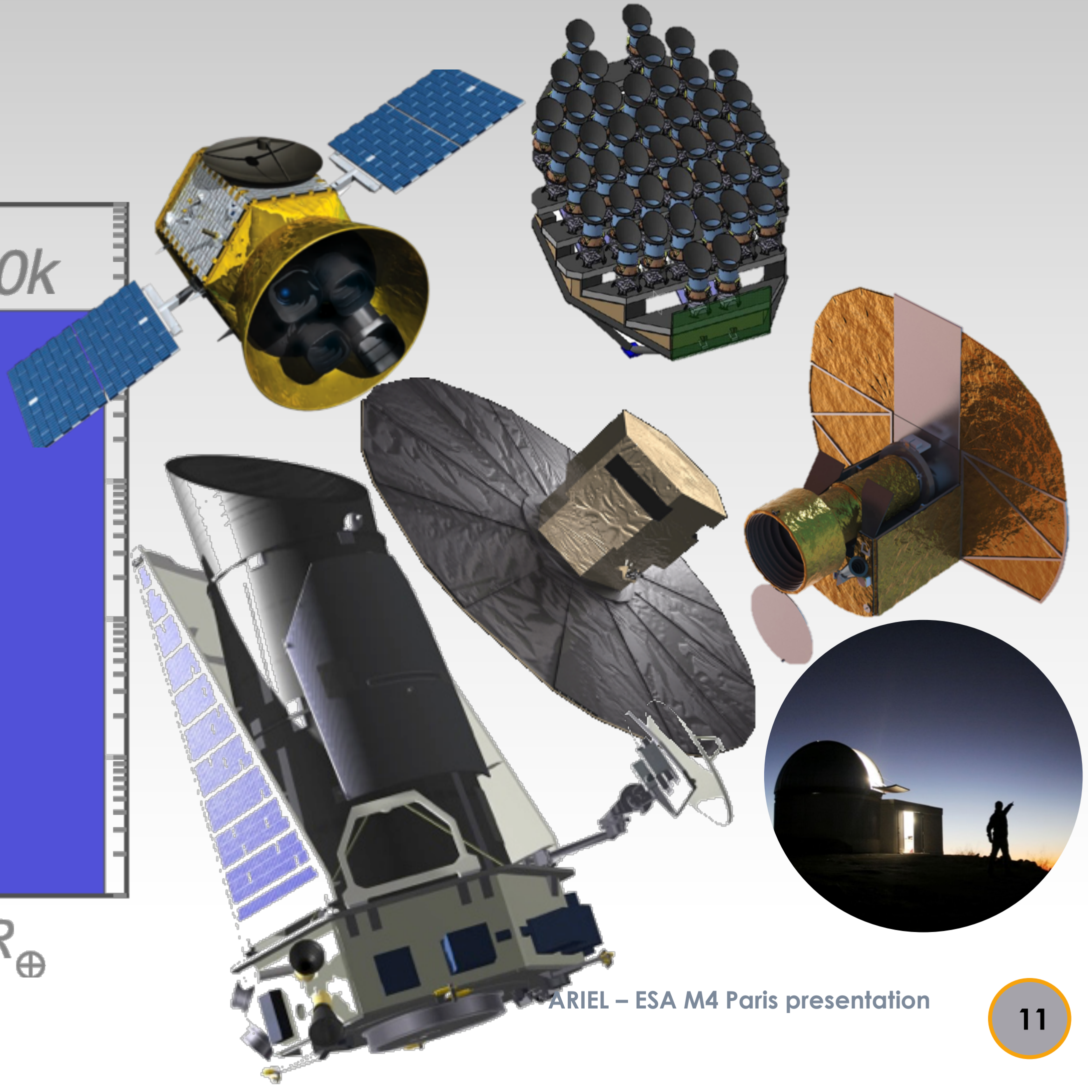


- Precision of 20 ppm can be reached today by Hubble-WFC3
- Current data are sparse, instruments not absolutely calibrated
- < 40 planets analysed
- Not enough wavelength coverage
- Degeneracy of interpretation

LARGE POPULATION OF WARM/HOT PLANETS

TODAY AND IN THE NEXT DECADE

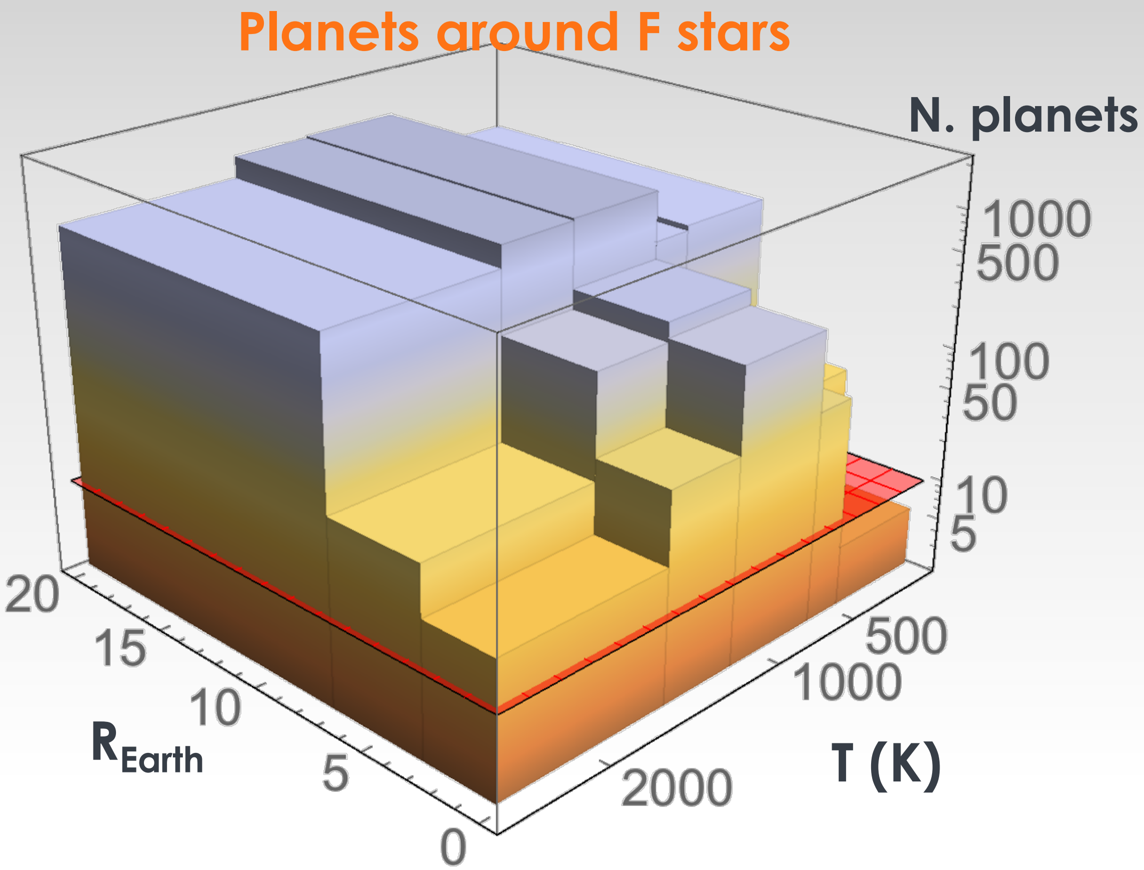




Sullivan et al., 2015

LARGE POPULATION OF WARM/HOT PLANETS

SELECTED OUT OF 10,000 PLANETS OPTIMAL FOR CHEMICAL OBSERVATIONS



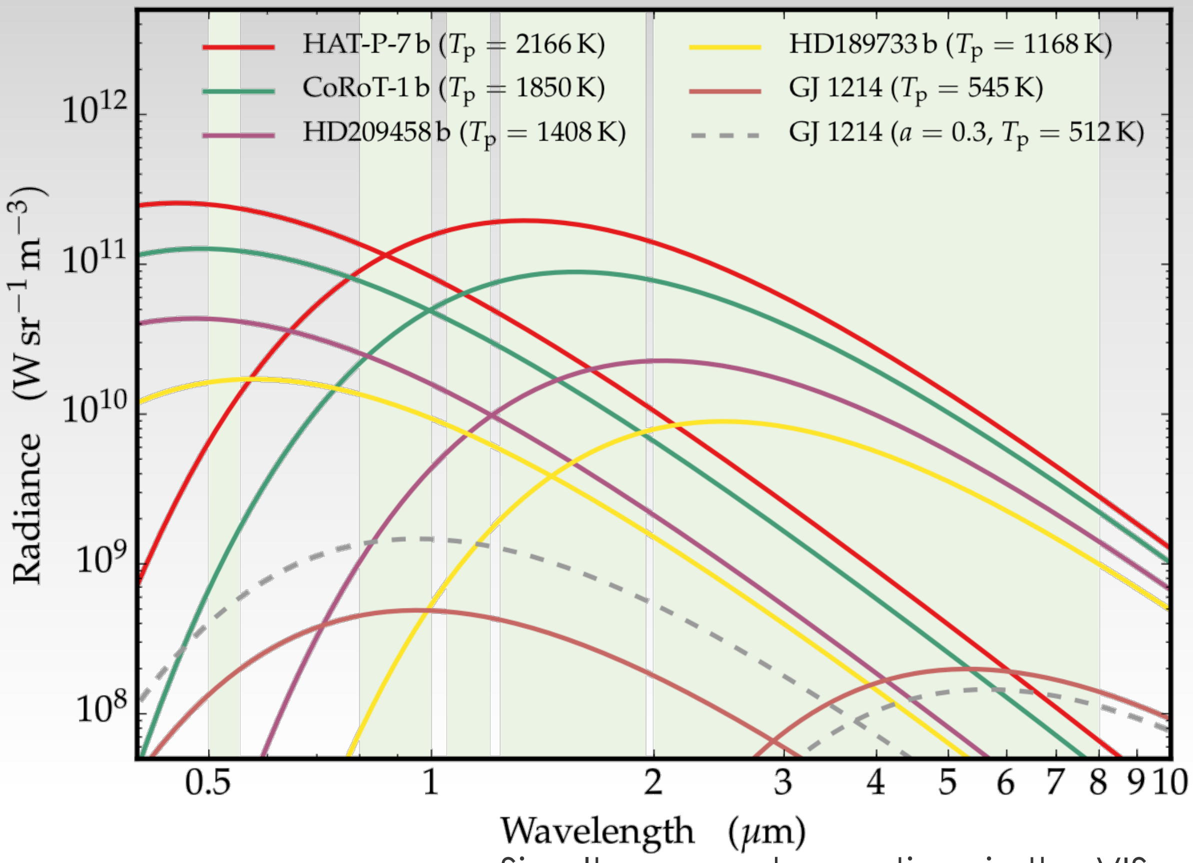
Parameter space to be sampled:

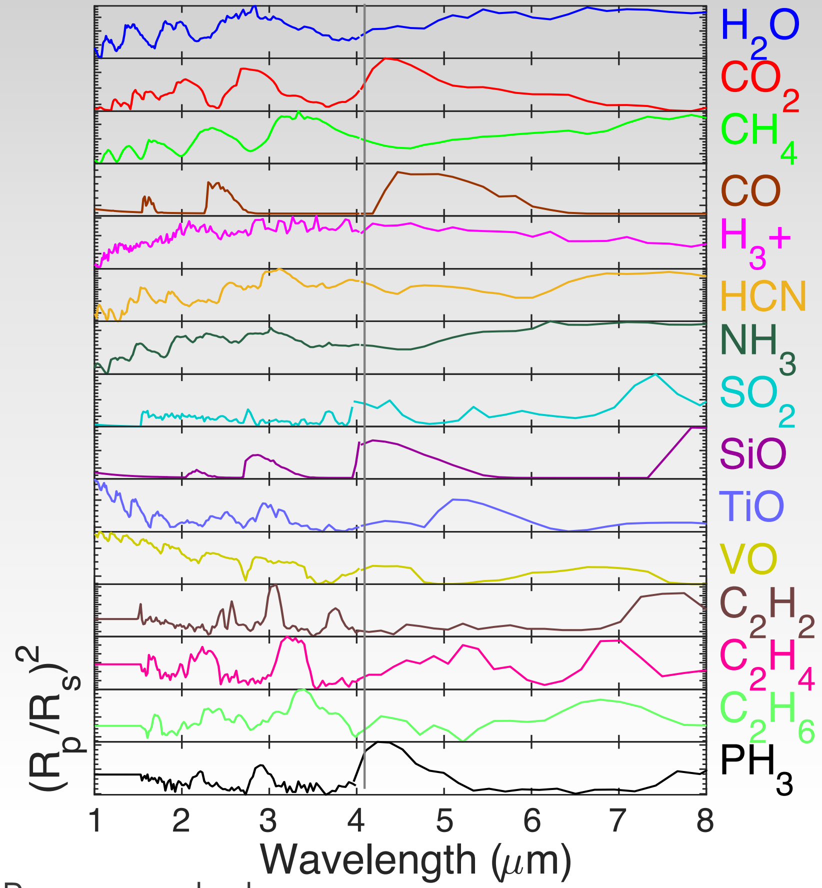
- Planet size (density)
- Temperature
- Stellar type
- Metallicity

The sample should have ~ 1000 planets

A CHEMICAL SURVEY OF A LARGE POPULATION

SCIENCE REQUIREMENTS: **EXOPLANET RADIATION, MOLECULAR** & CLOUD SIGNATURES, STAR ACTIVITY





Simultaneous observations in the VIS and IR are needed

A CHEMICAL SURVEY OF A LARGE POPULATION

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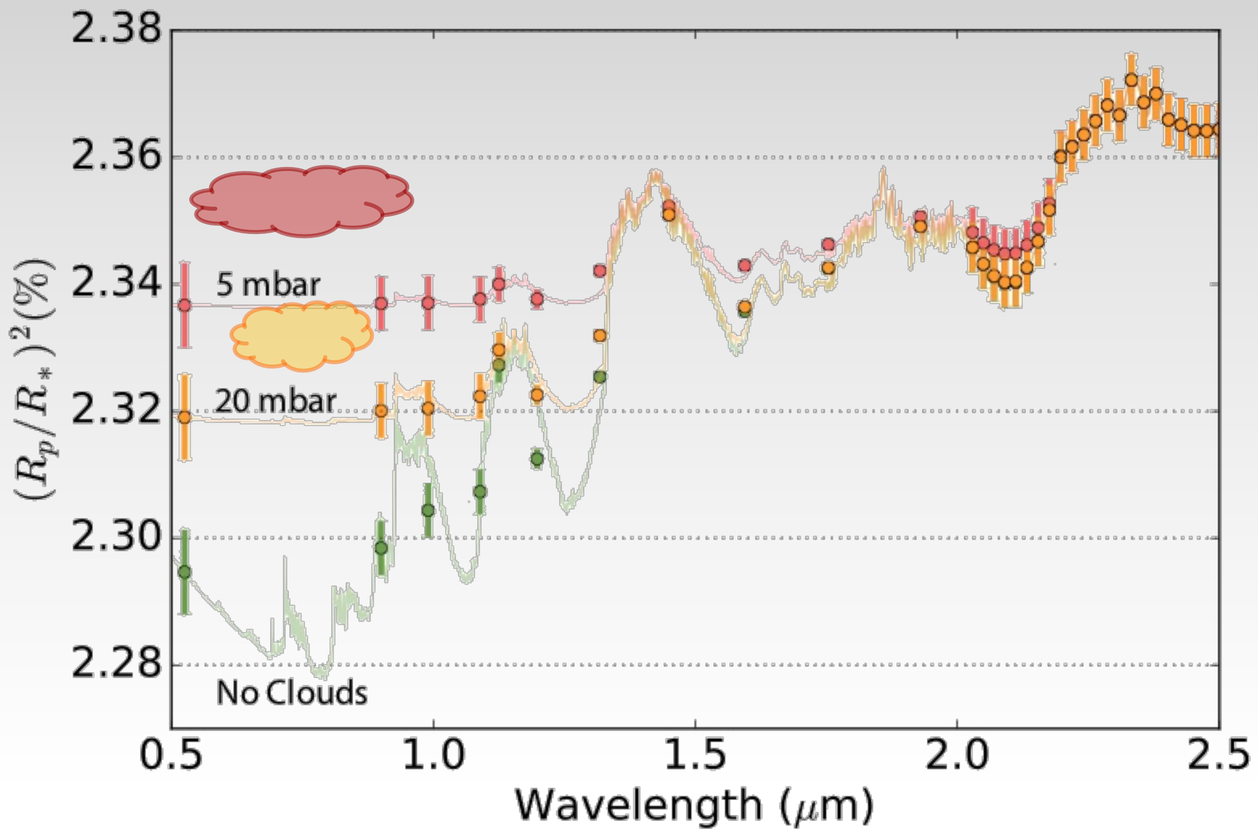
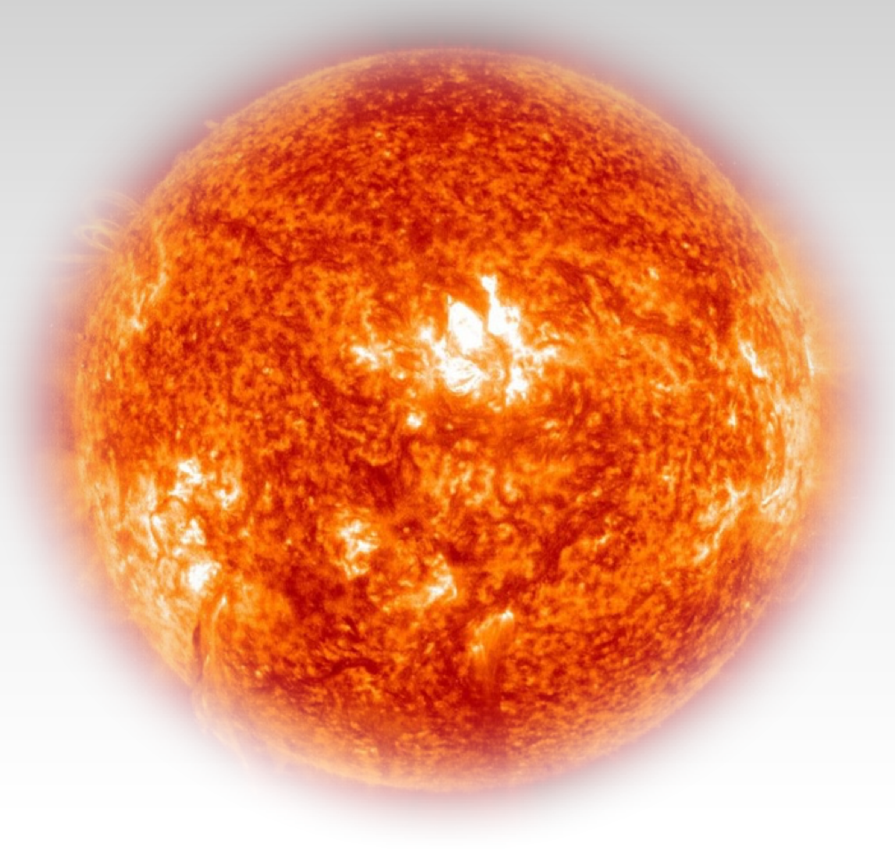
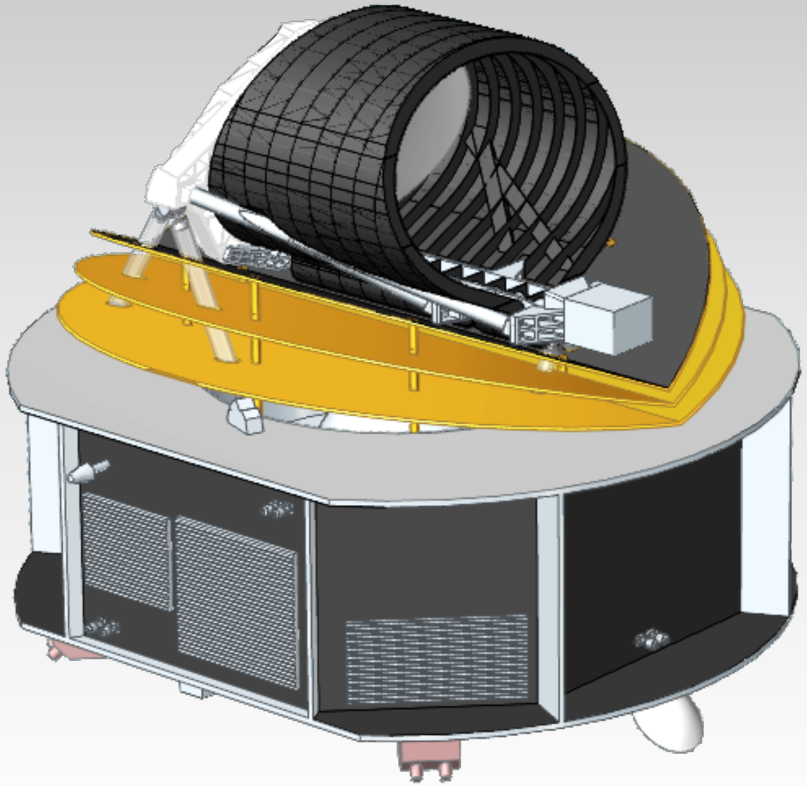




Simultaneous observations in the VIS and IR are needed

ARIEL – KEY FACTS

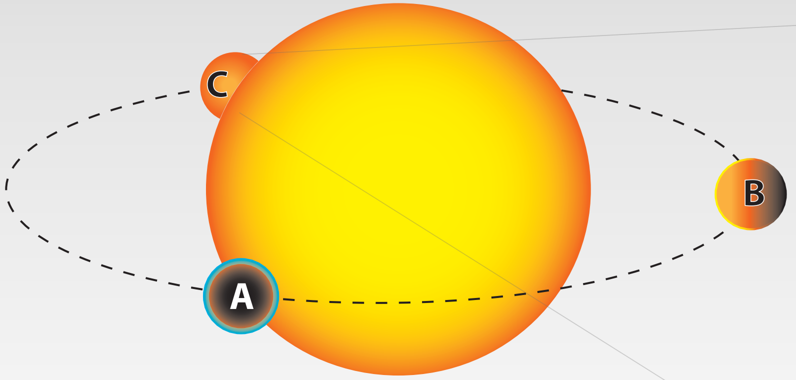
- 1-m telescope, spectroscopy from VIS to IR
- Satellite in orbit around L2
- ~1000 exoplanets observed (rocky + gaseous)
- Simultaneous coverage 0.5-7.8 micron
- Payload consortium: 11 ESA countries

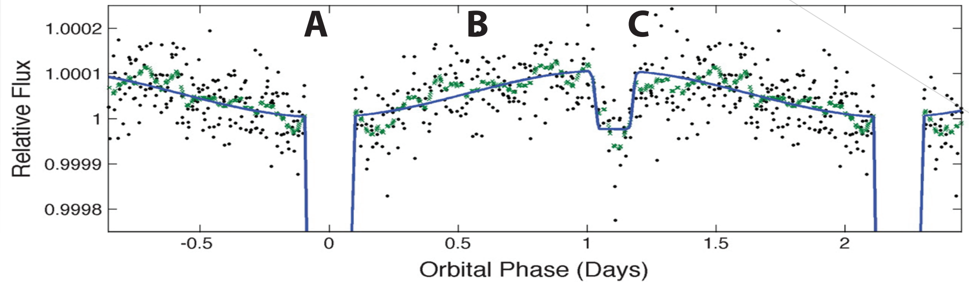


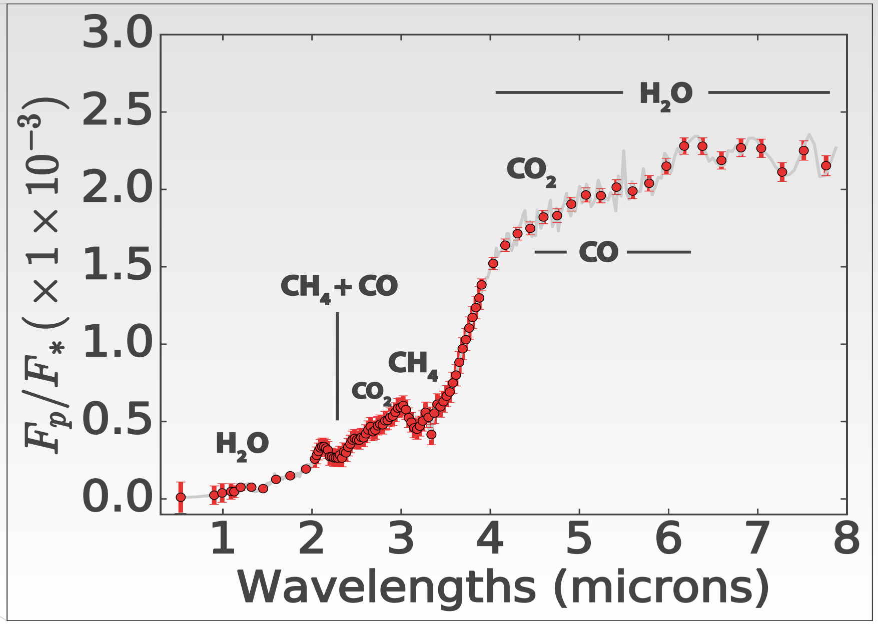
TRANSIT, ECLIPSE, PHASE-CURVE SPECTROSCOPY

AIMING AT 10 PPM STELLAR FLUX AT MULTIPLE WAVELENGTHS

Through stable instrument, external calibration & proven postprocessing analysis



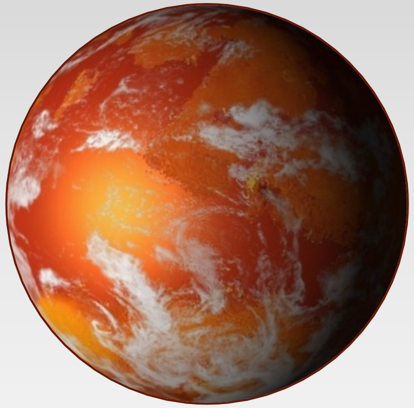




ARIEL KEY SCIENCE QUESTIONS

INDIVIDUAL PLANET

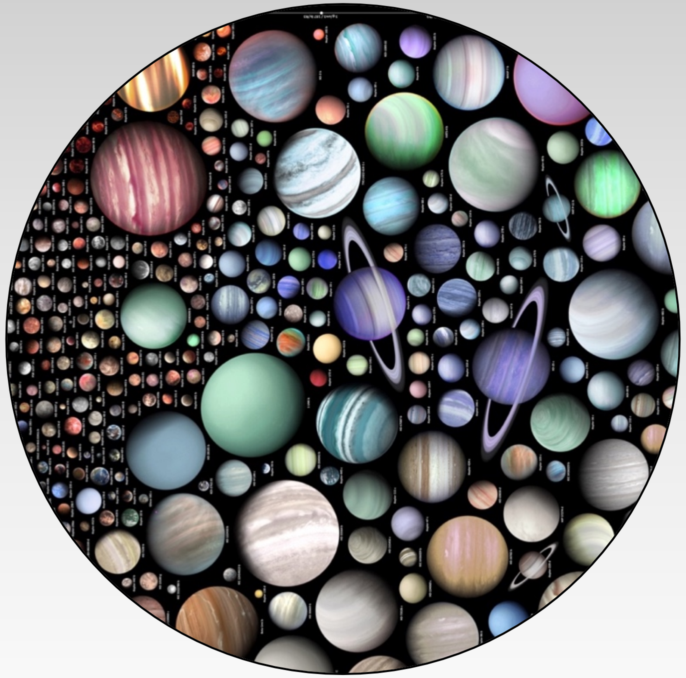
- **Individual planet: Instant & short-term variability**
    - Chemical composition
    - Atmospheric circulation + cloud pattern
    - Equilibrium or non-equilibrium chemistry?
    - Impact with stellar environment
- **Individual planet: Formation & long-term evolution**
    - Elemental composition
    - Coupling interior-atmosphere
    - Impact of stellar environment & system history



ARIEL KEY SCIENCE QUESTIONS

LARGE POPULATION OF DIVERSE PLANETS

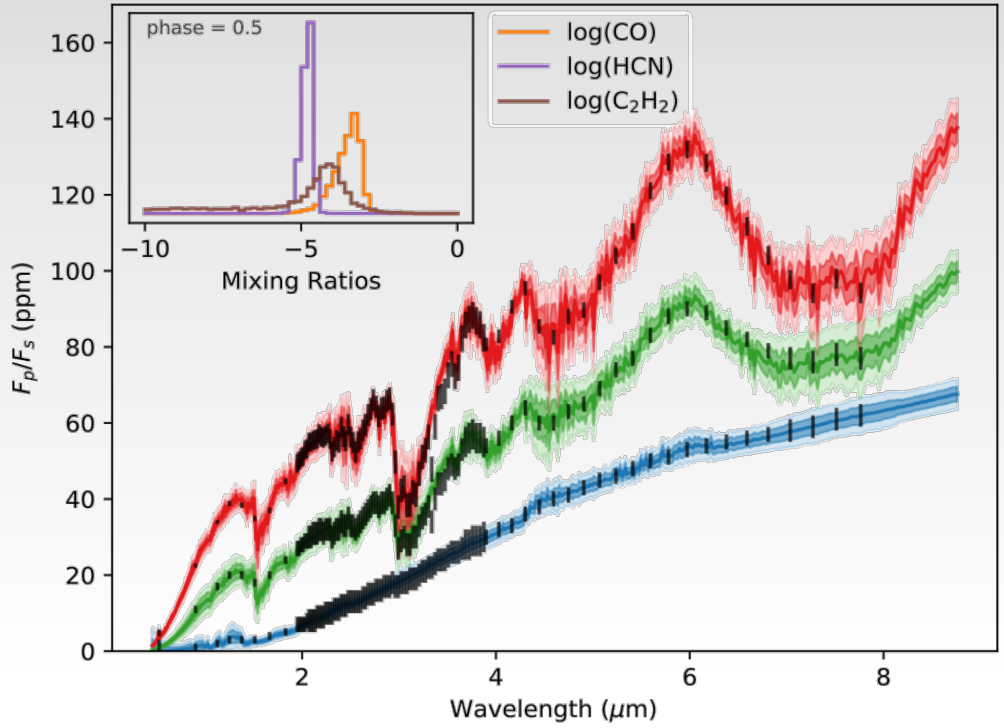
- **Large population: Instant & short-term variability**
    - Chemical diversity
    - Correlation chemistry - other parameters
    - Correlation clouds–temperature-stellar-type
    - How fast atmospheres change through time?
- **Large population: Formation & long-term evolution**
    - Correlation elemental composition planet provenance
    - Correlation elemental composition stellar metallicity
    - Coupling atmosphere-interior through time
    - Transition between terrestrial planets and sub-Neptunes

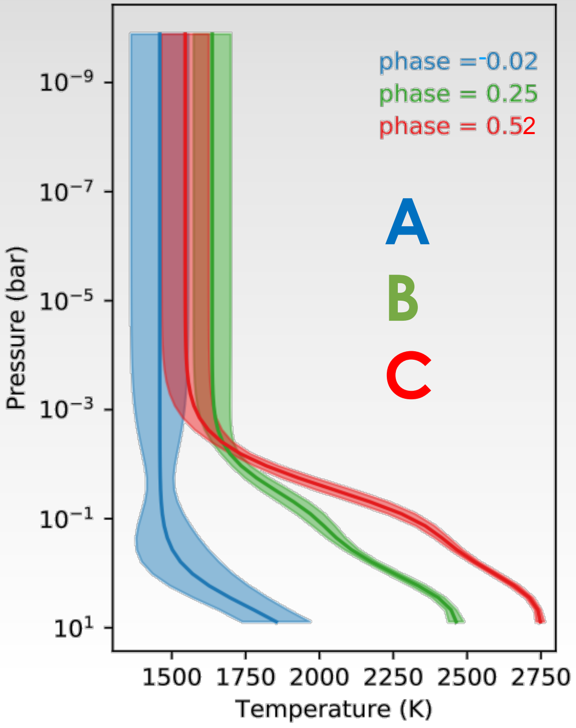


INSTANT & SHORT-TERM VARIABILITY

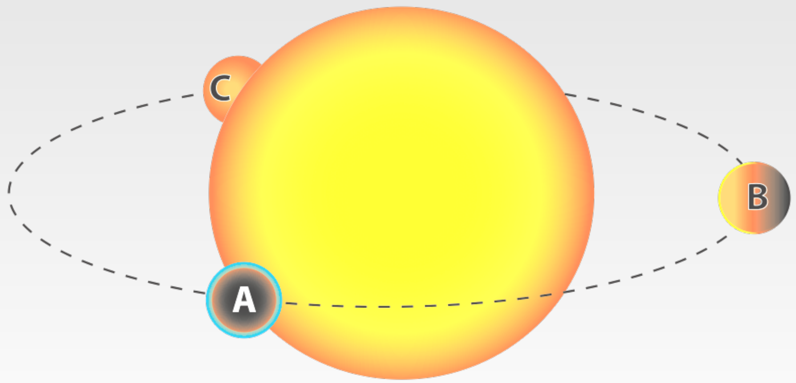
(NON)-EQUILIBRIUM CHEMISTRY? ATMOSPHERIC CIRCULATION? CLOUD PATTERN?

ARIEL phase-curve spectra, chemical composition & thermal profile





Planet orbiting around the star

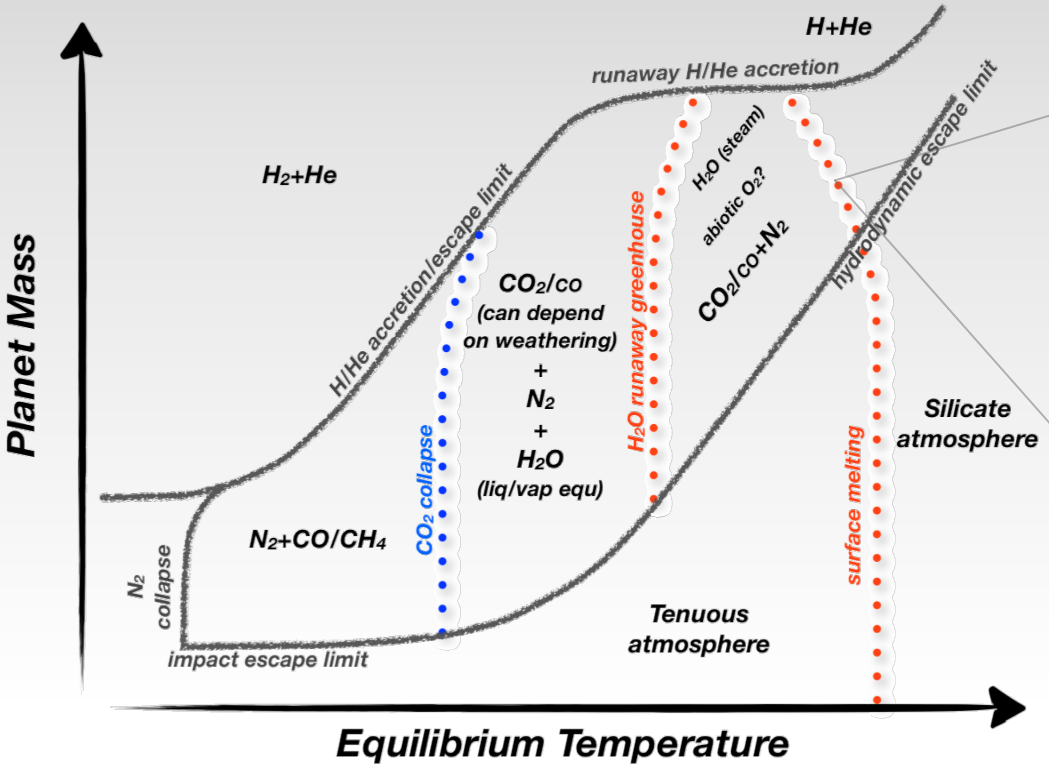


Snap-shots of an animation available at: http://bit.ly/2kGL4Wz

CHEMICAL DIVERSITY

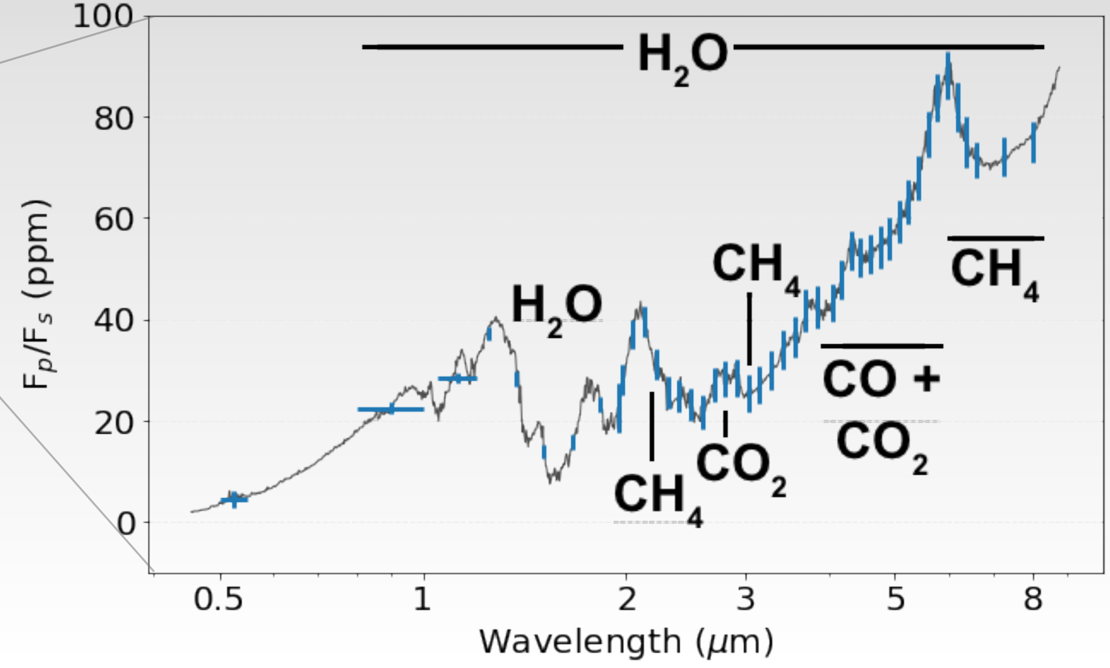
CORRELATION WITH ANY OTHER KEY PARAMETERS?

Is this plot true? Where are the transitions?



Forget & Leconte, 2013

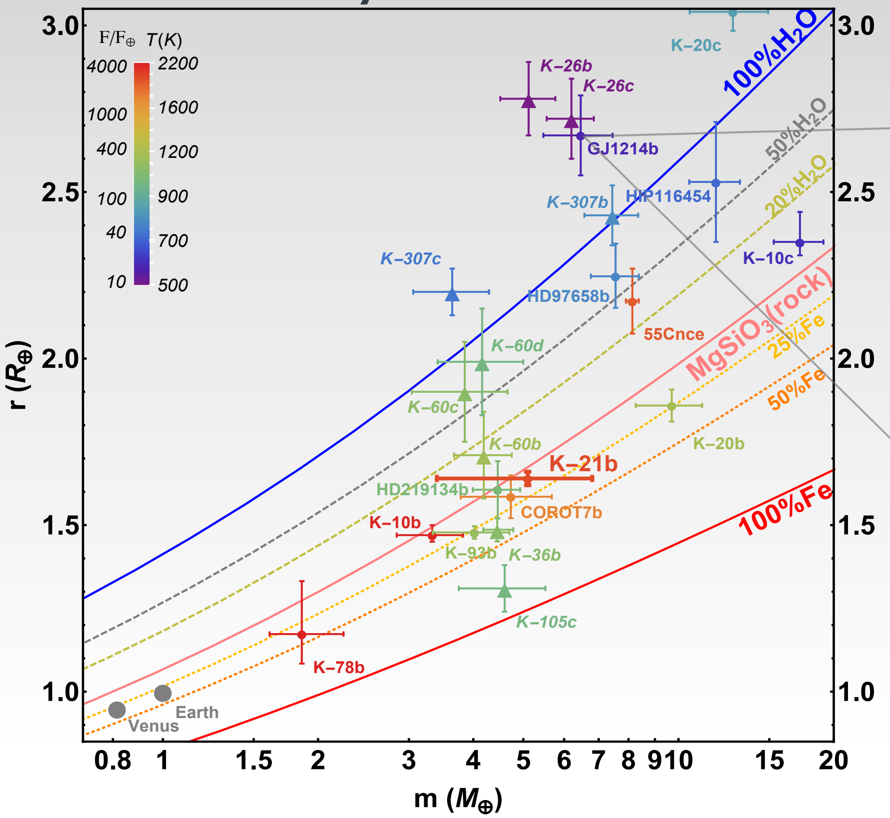
ARIEL observations x 1000 planets



CHEMICAL DIVERSITY

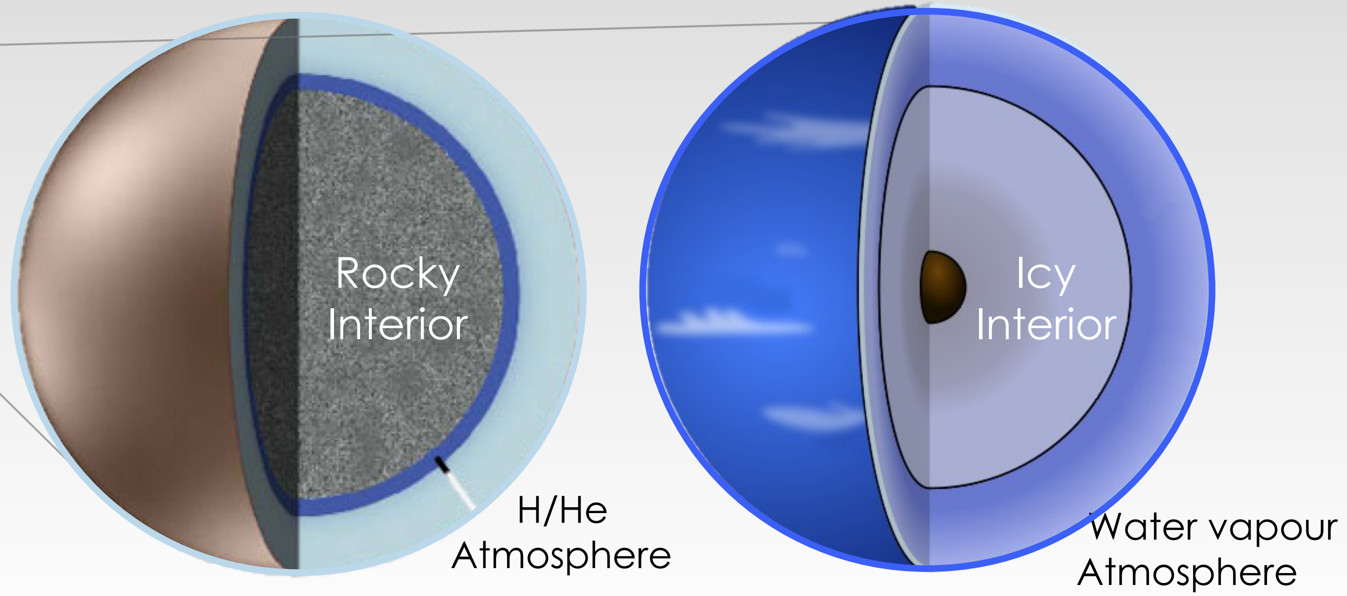
ARIEL WILL CLARIFY CORRELATION WITH THE DENSITY

Density observations



Lopez Morales et al. 2016; Valencia et al., 2013

Atmospheric composition through ARIEL will clarify the degeneracy

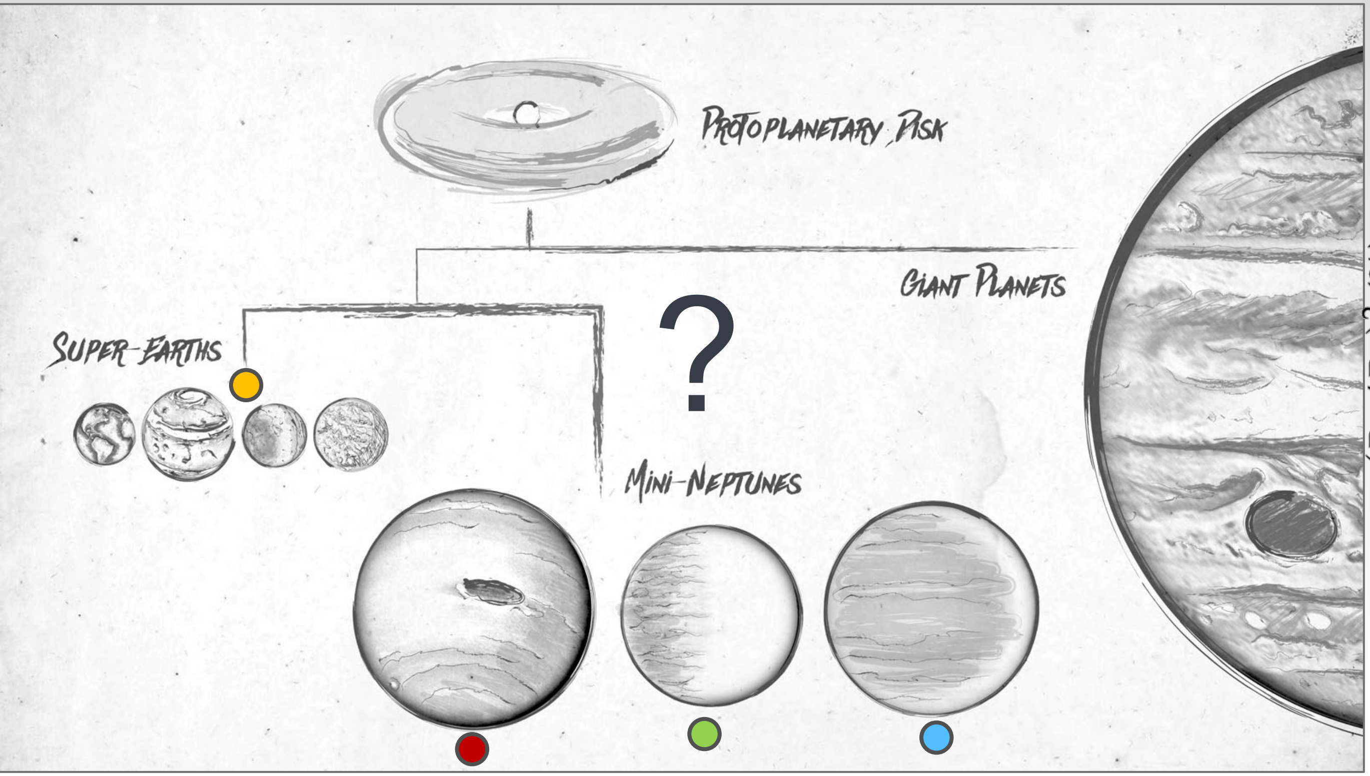


Same mean density – Different atmospheric signatures

TERRESTRIAL-SUBNEPTUNES TRANSITION

ARE SUPER-EARTHS BIG TERRESTRIAL PLANETS, SMALL NEPTUNES? IS H/HE STILL THERE?

Formation scenarios for small planets



ARIEL observations for small planets

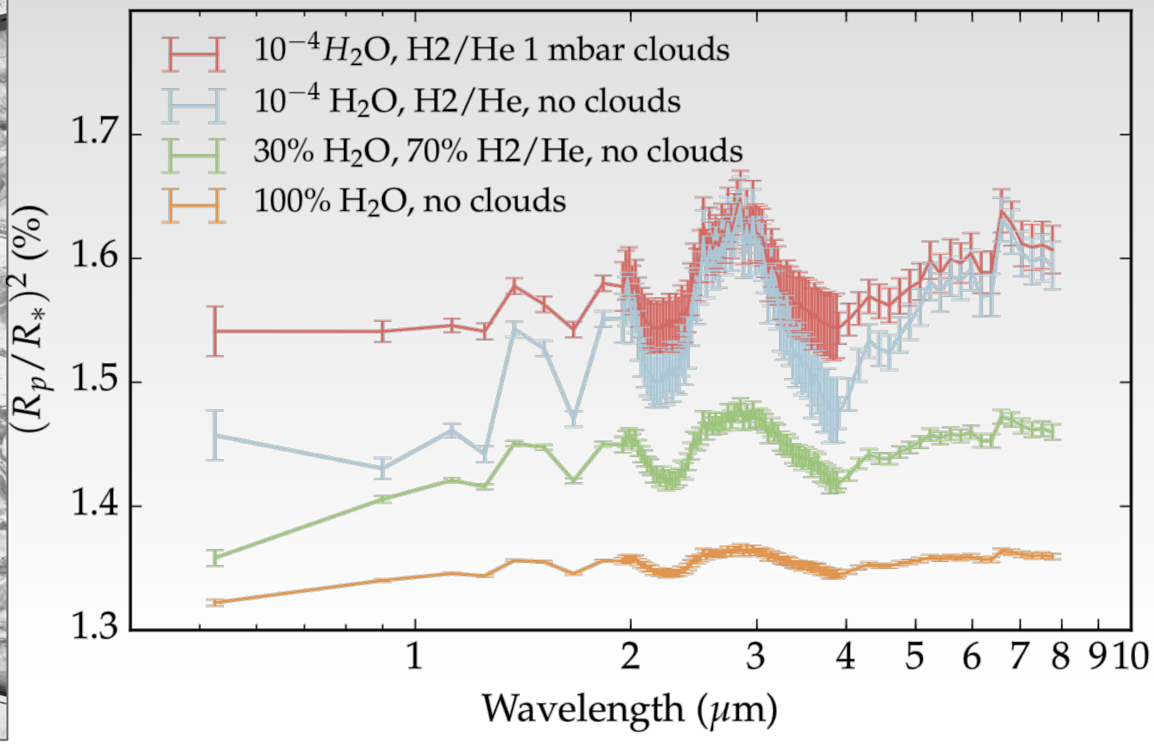
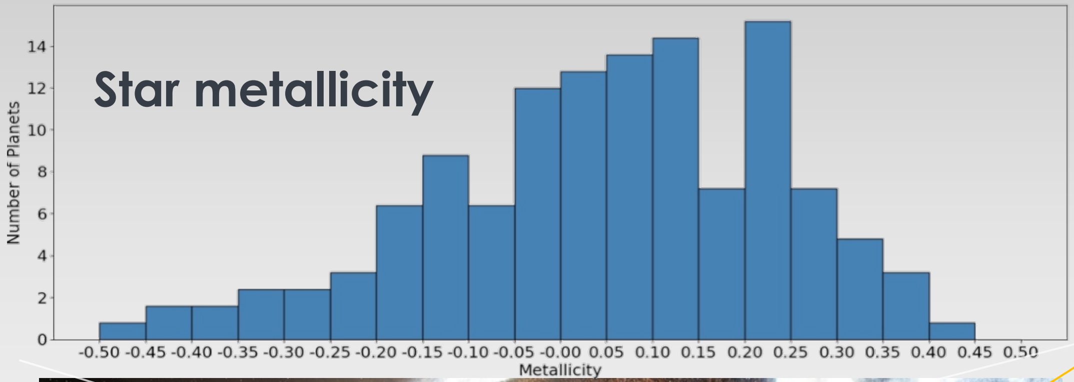
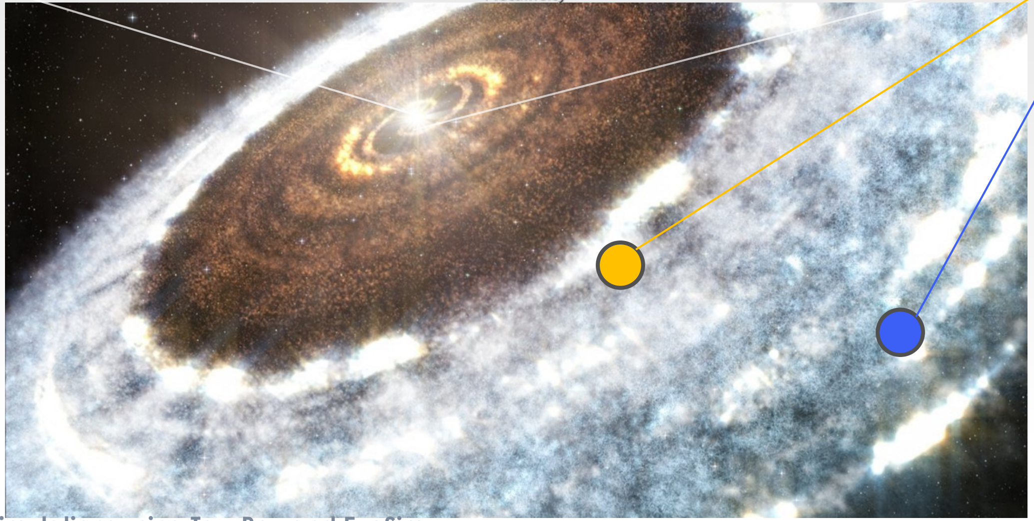


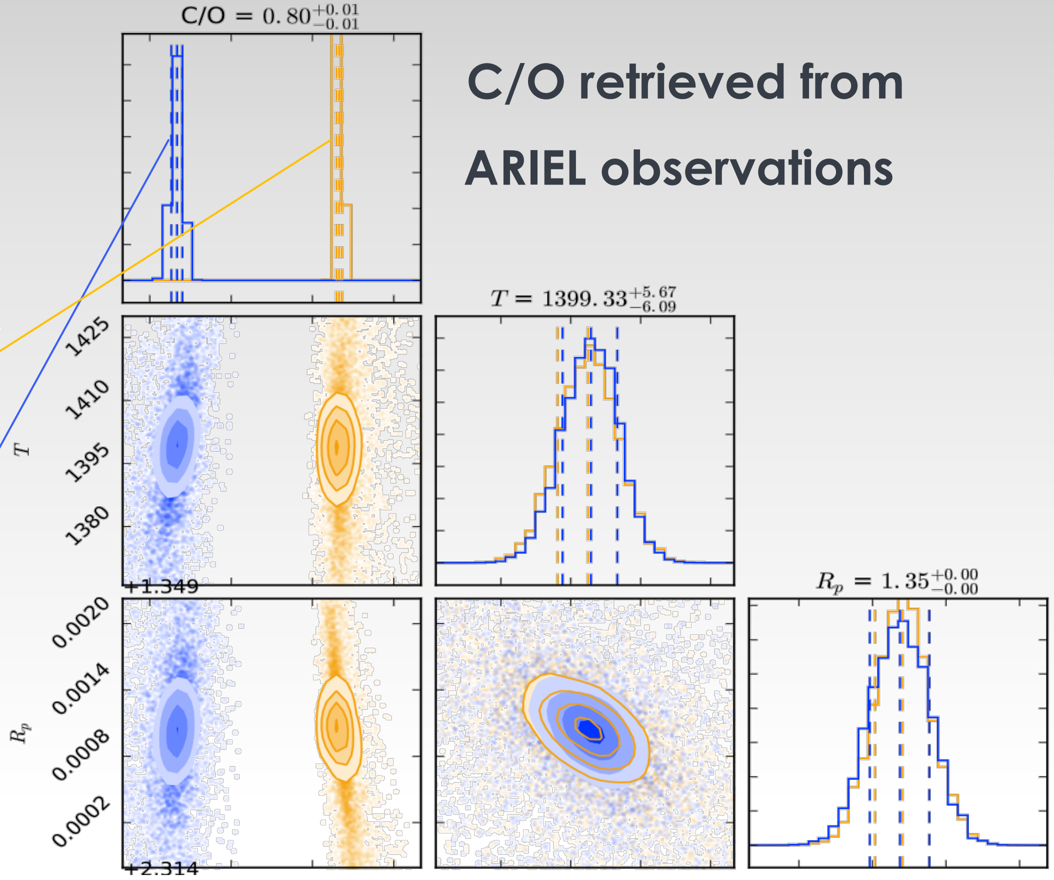
Image credit NASA/Kepler/Caltech (T Pyle). Simulations using Tau-Rex and ExoSim

IS ELEMENTAL COMPOSITION CORRELATED …

…TO EXOPLANET PROVENANCE OR STELLAR METALLICITY?







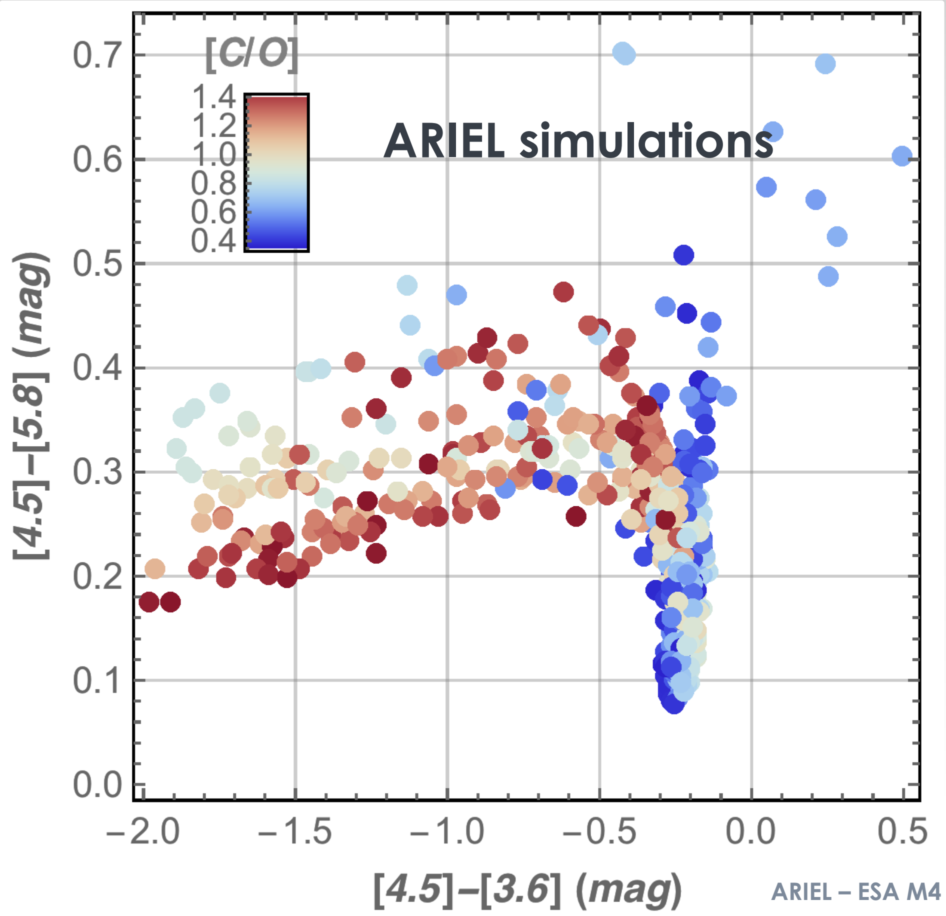
C/O retrieved from ARIEL observations

Simulations using Tau-Rex and ExoSim

POPULATION ANALYSIS

COLOUR-MAGNITUDE DIAGRAMS, CLOUD-CHARACTERISATION

- Colour-colour diagrams and colour-magnitude diagrams in the IR and VIS will allow to identify **families of planets**

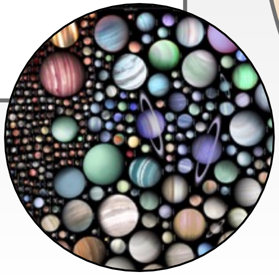


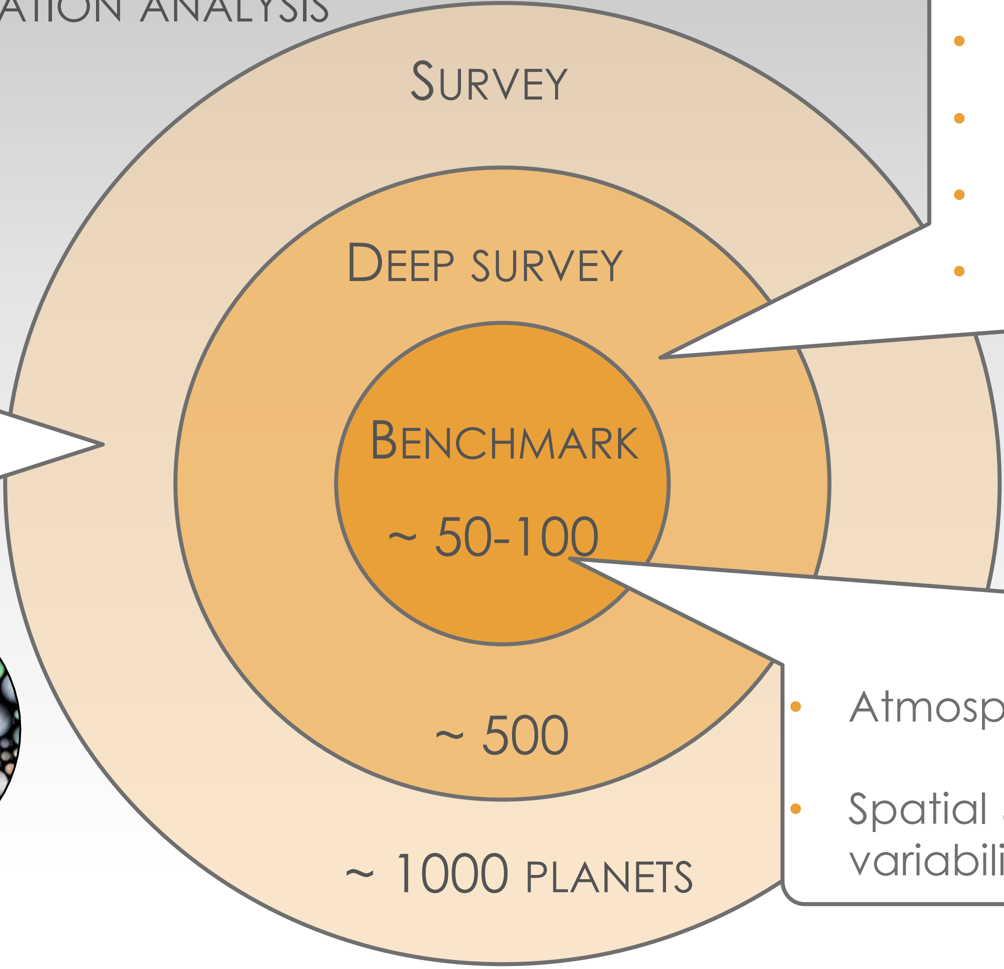
Simulations using approach and data from: Triaud 2015; Moliere et al., 2016

ARIEL 3-TIER APPROACH

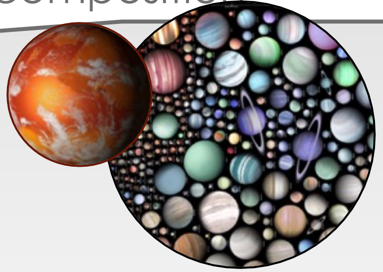
INDIVIDUAL PLANETS & POPULATION ANALYSIS

- What fraction of planets have clouds?
- Have small planets still retained H/He?
- Colour-colour diagrams
- Refinement of orbital/planet parameters in IR

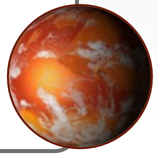




- Main atmospheric component
- Trace gases
- Thermal structure
- Cloud characterization
- Elemental composition

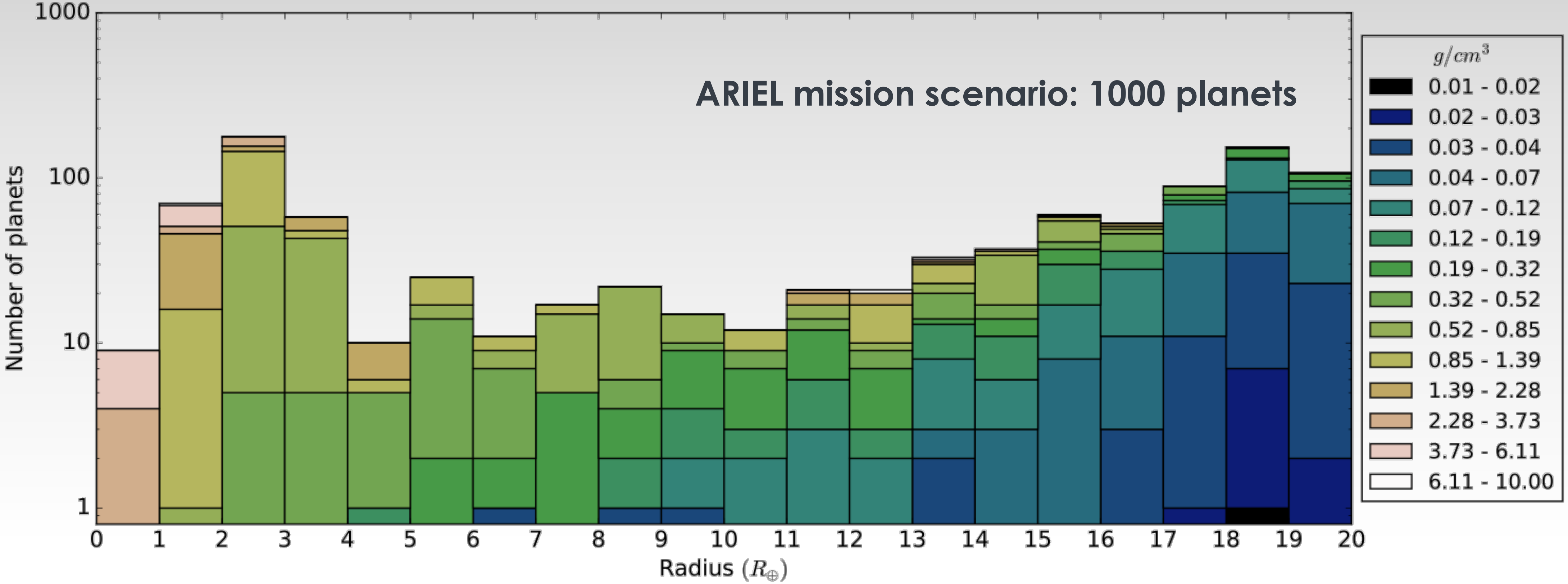


- Atmospheric circulation
- Spatial & temporal variability



DIVERSITY PROBED IN ARIEL CORE SAMPLE

PLANET SIZE, DENSITY, TEMPERATURE, STAR TYPE, METALLICITY



Zingales et al., 2017

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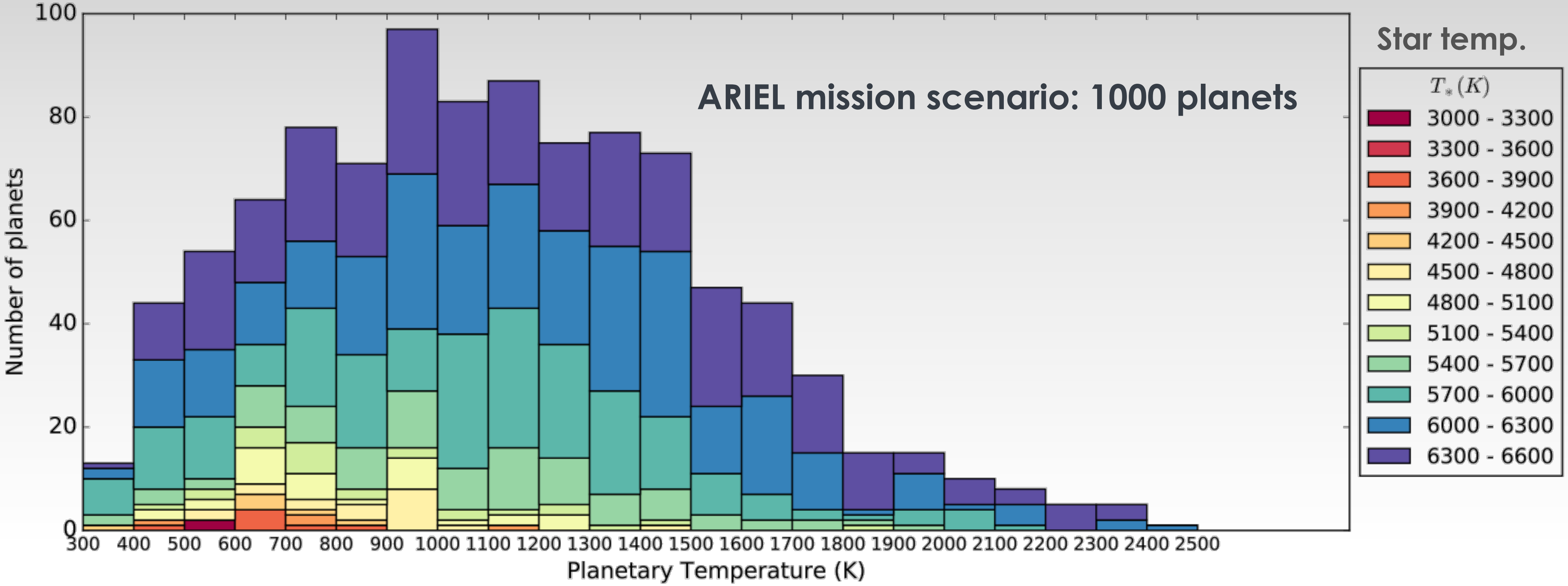
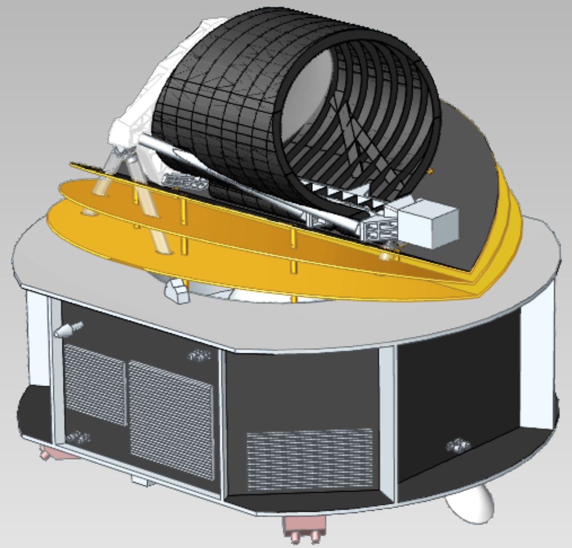
PLANET SIZE, DENSITY, **TEMPERATURE, STAR TYPE**, METALLICITY



Zingales et al., 2017

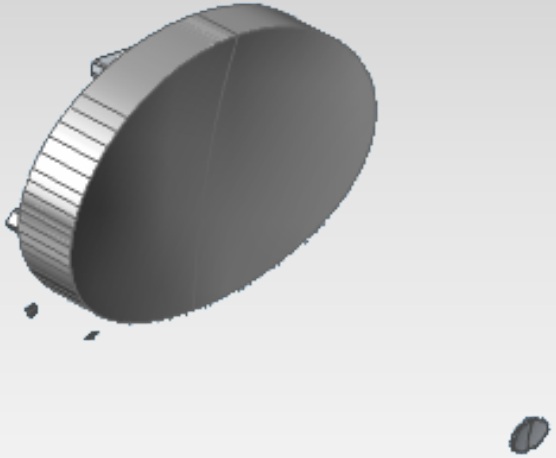
ARIEL – KEY REQUIREMENTS

- > 0.6m^2 collecting area telescope, high throughput
- Diffraction limited performance beyond 3 microns; minimal FoV required
- Observing efficiency of > 85%
- Brightest Target: K_{mag} = 3.25 (HD219134);
- Faintest target: K_{mag} = 8.8 (GJ1214)
- Photon noise dominated
- Temporal resolution of 90 seconds (goal 1s for phot. channels)
- Average observation time = 7.7 hours, separated by 70° on sky from next target
- Continuous spectral coverage between spectral bands.



Channel Name	Wavelength (μm)	Spectral Resolution Reqt / Design
VisPhot	0.5 – 0.55	Photometer
FGS-1	0.8 – 1.0	Photometer
FGS-2	1.05 – 1.2	Photometer
NIRSpec	1.25 – 1.95	R≥10 / 20 – 25
AIRS-Ch0	1.95 – 3.9	R≥100 / 102 – 180
AIRS-Ch1	3.9 – 7.8	R≥30 / 30 – 64

ARIEL – PAYLOAD & S/C CONFIGURATION



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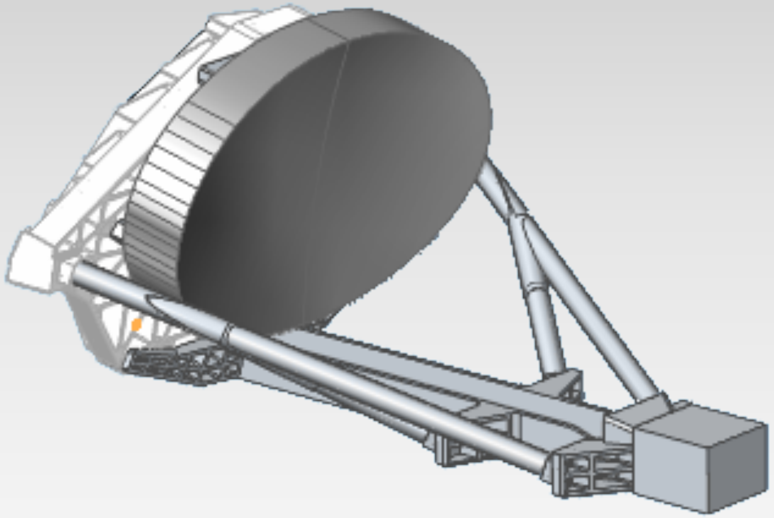

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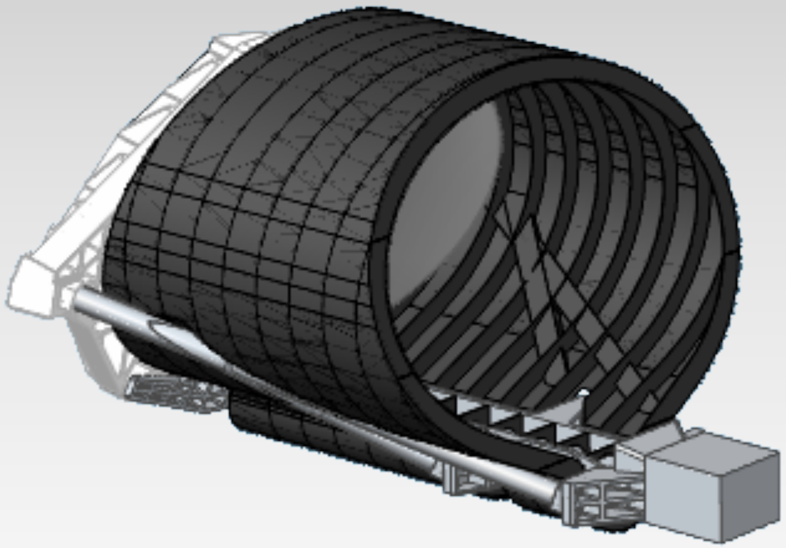

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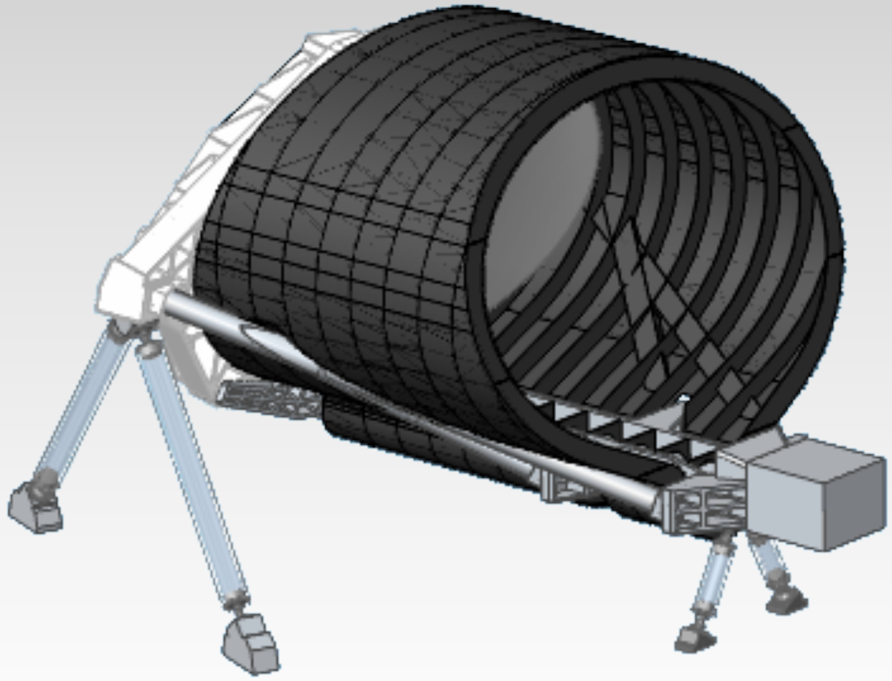

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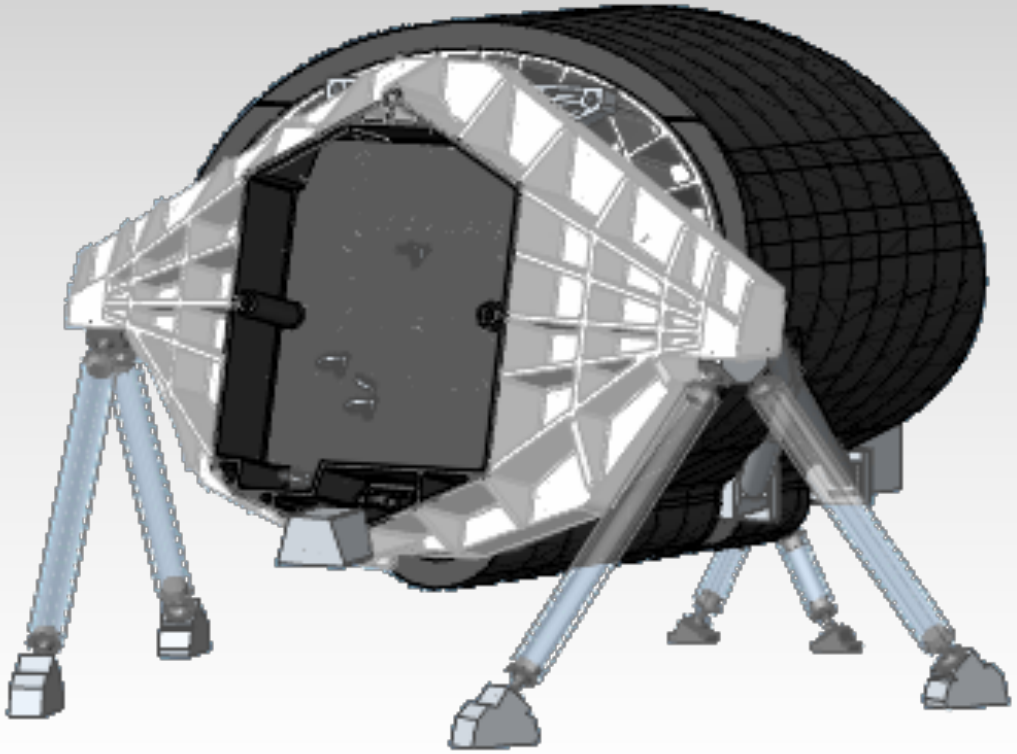

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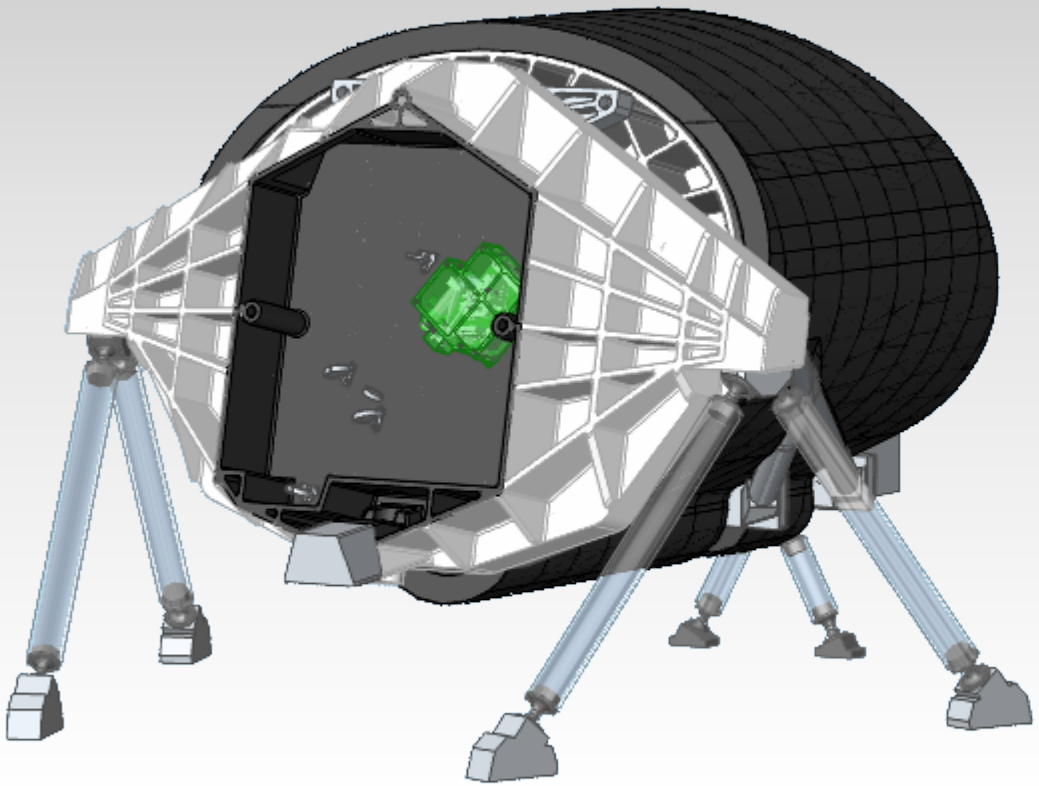

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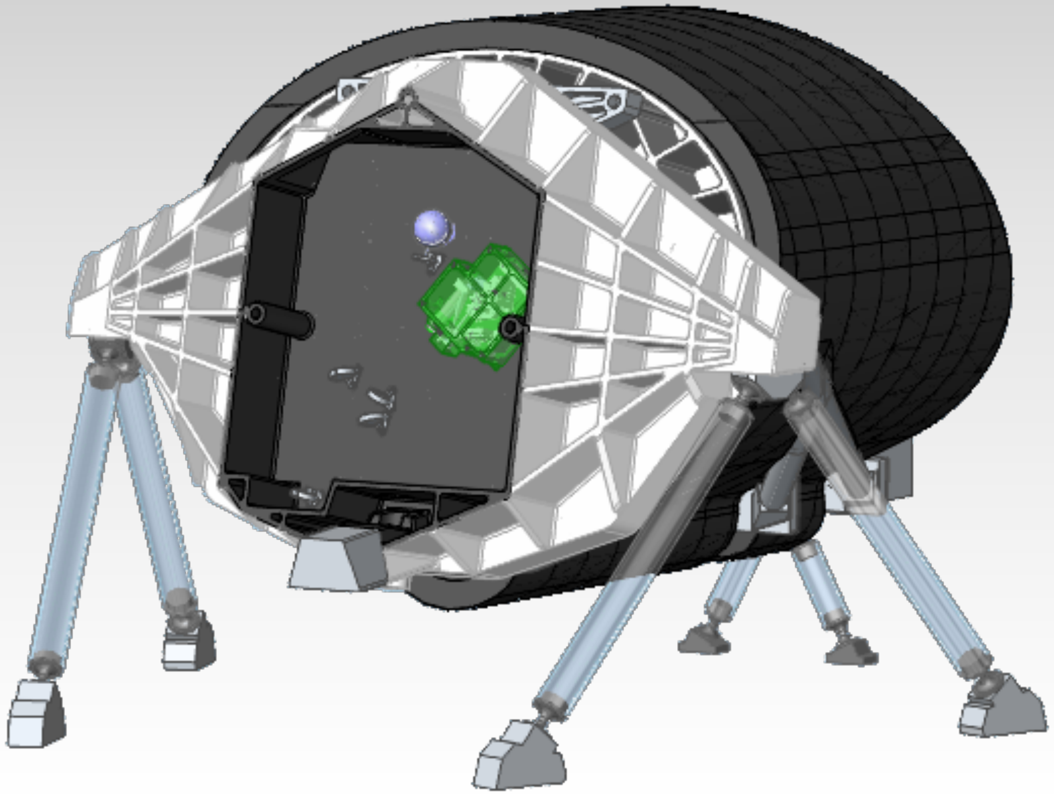

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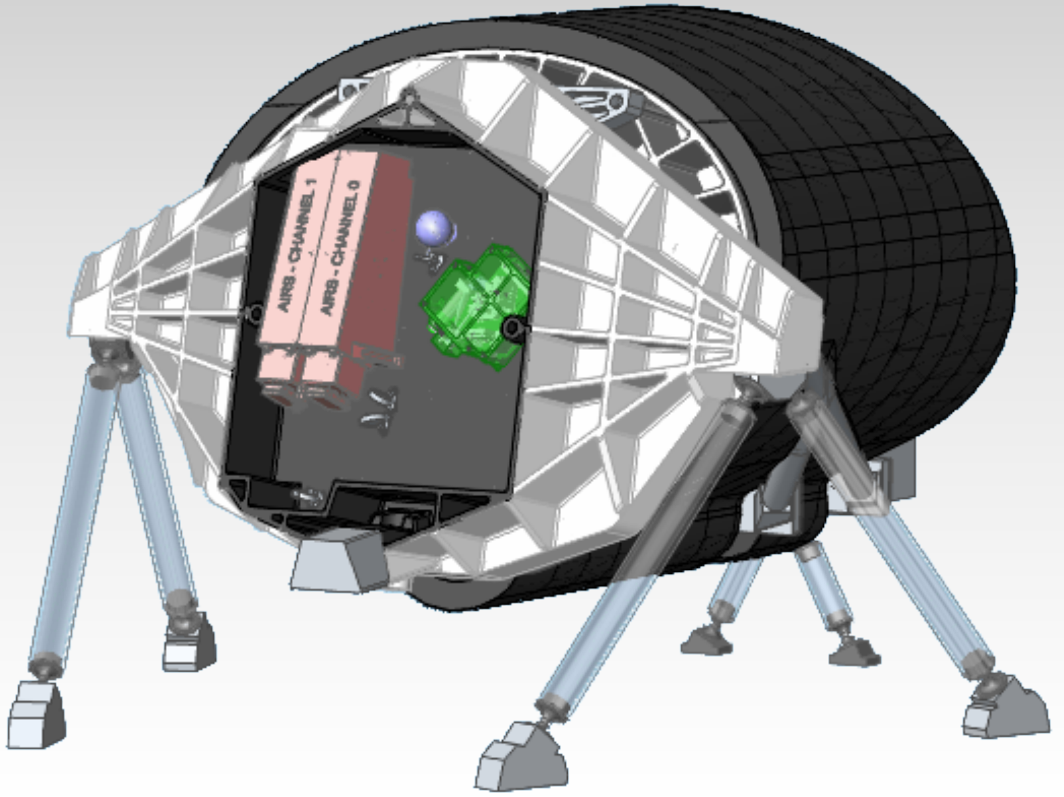

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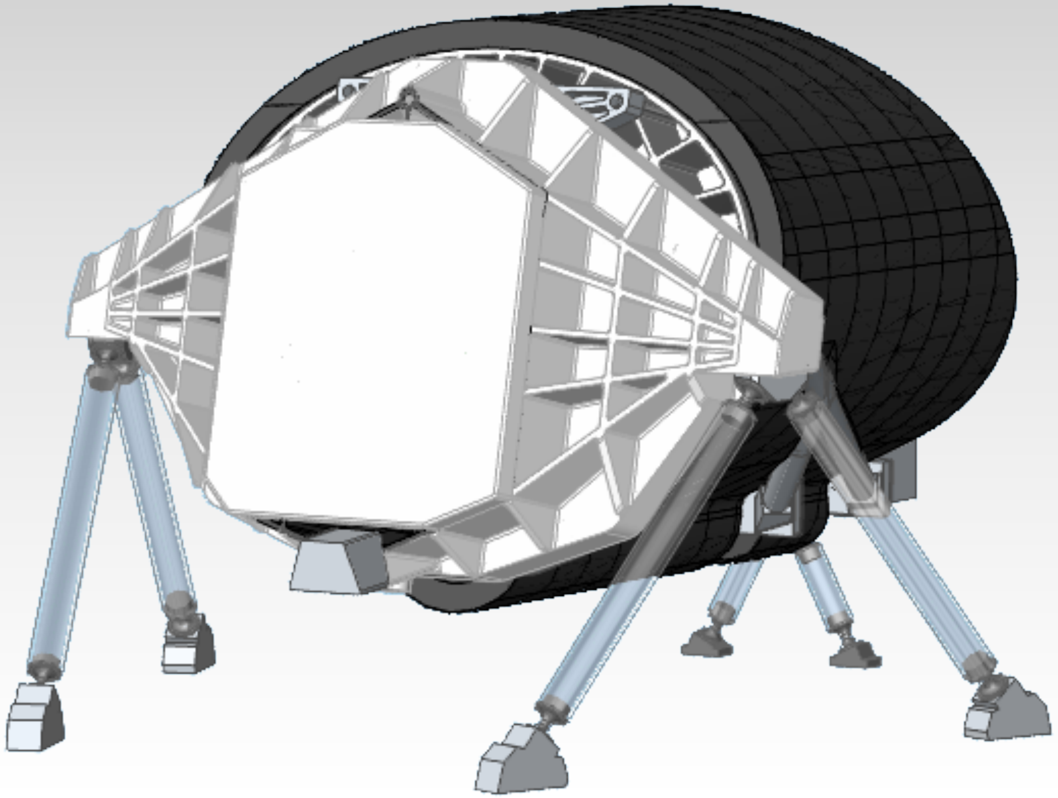
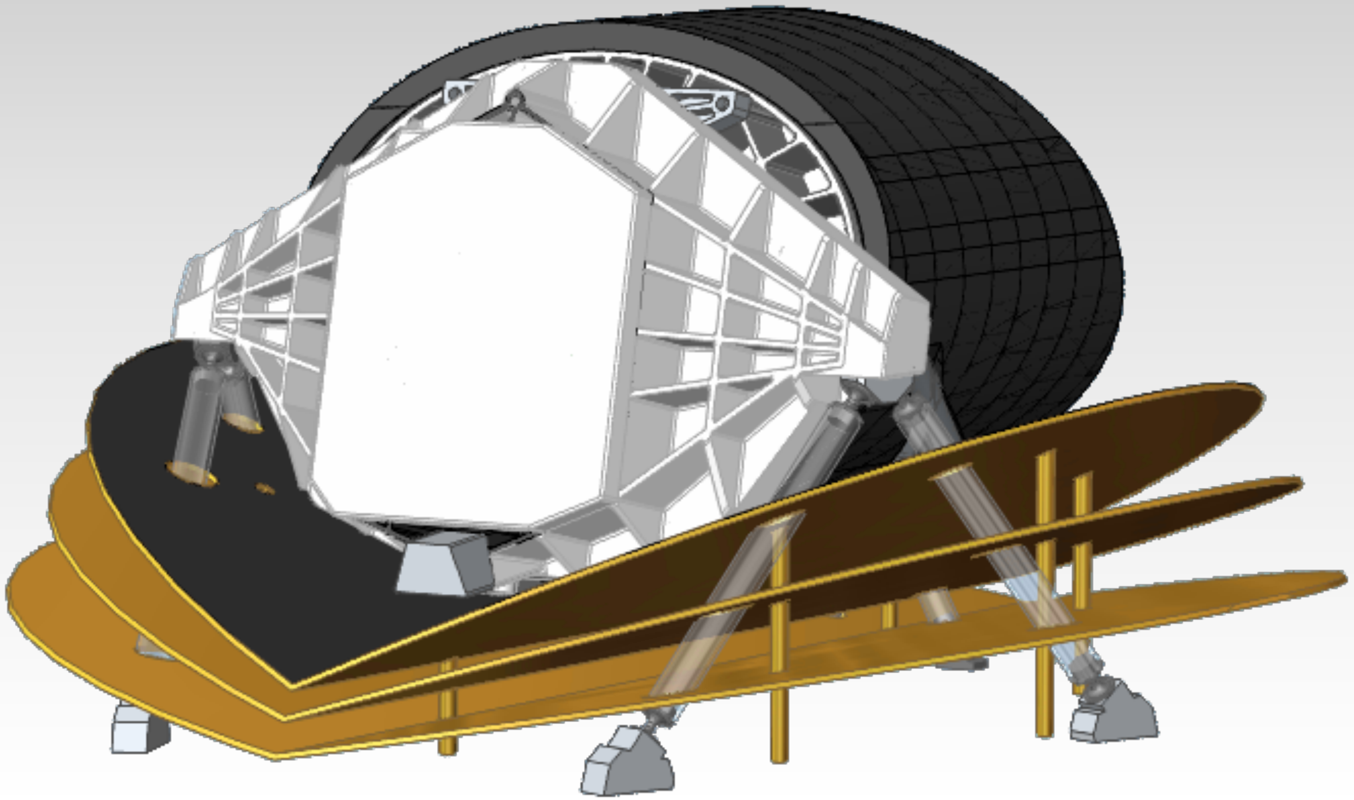
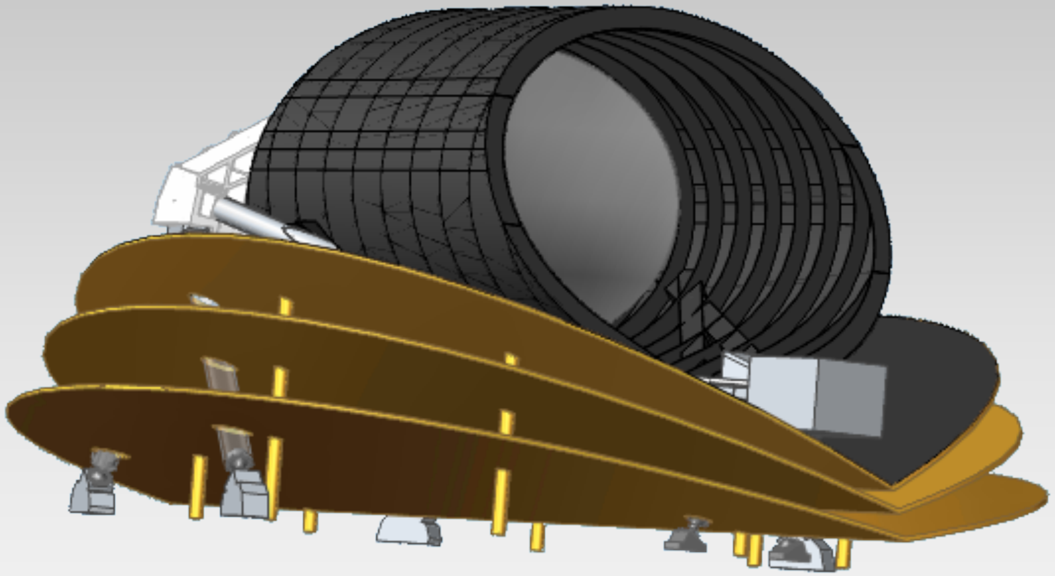


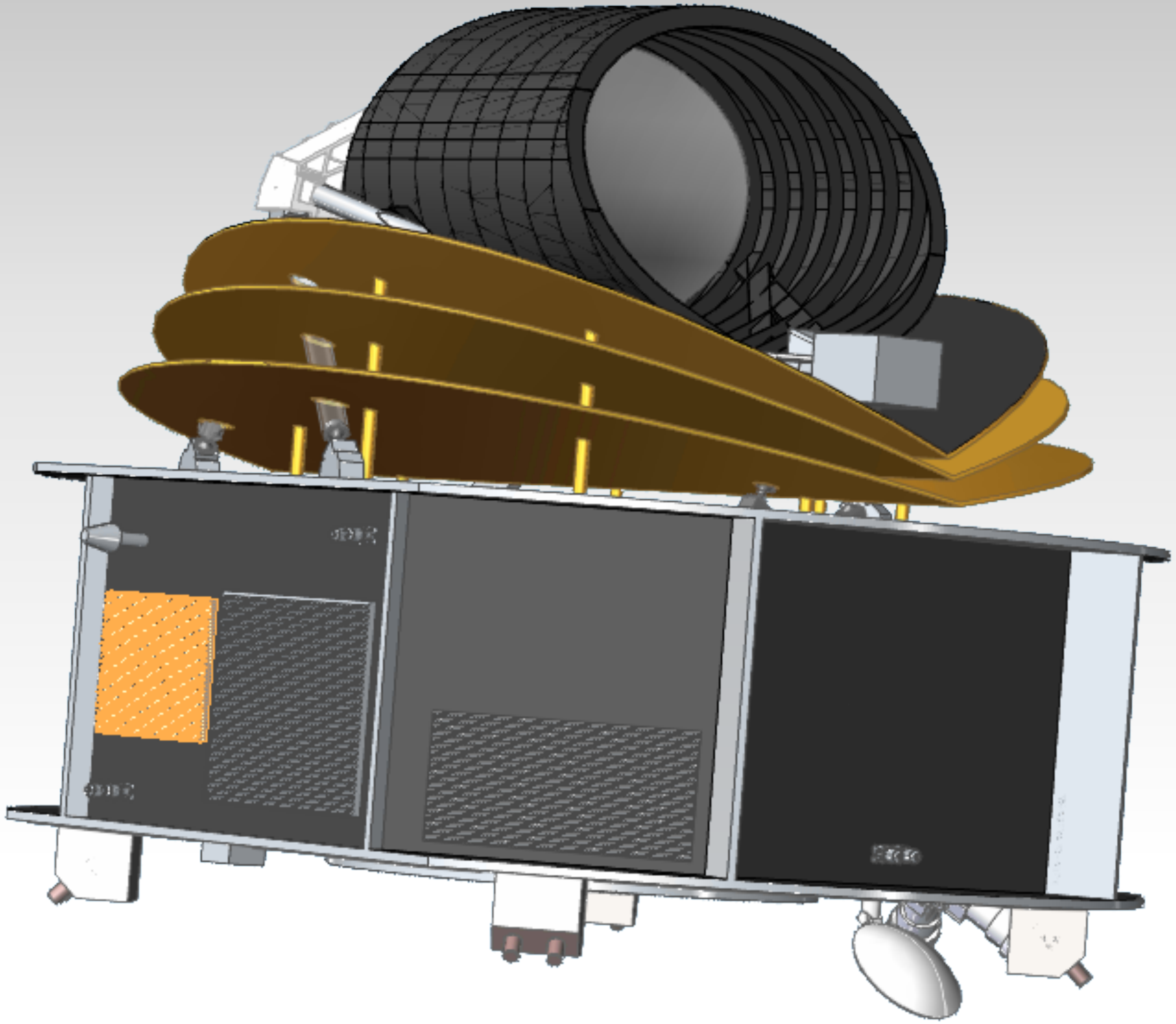
ARIEL – PAYLOAD & S/C CONFIGURATION



ARIEL – PAYLOAD & S/C CONFIGURATION

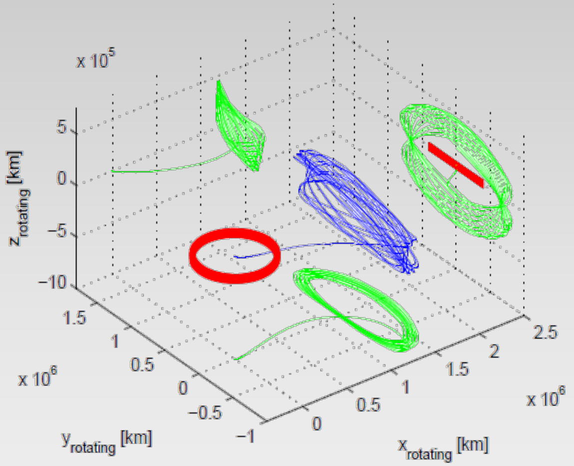


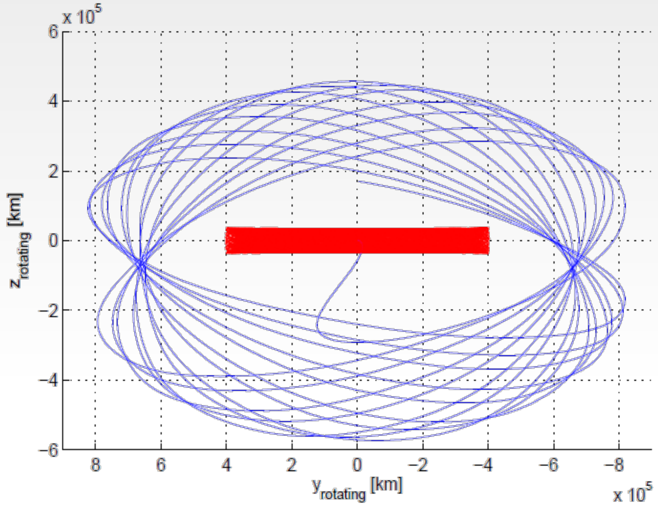
ARIEL – PAYLOAD & S/C CONFIGURATION

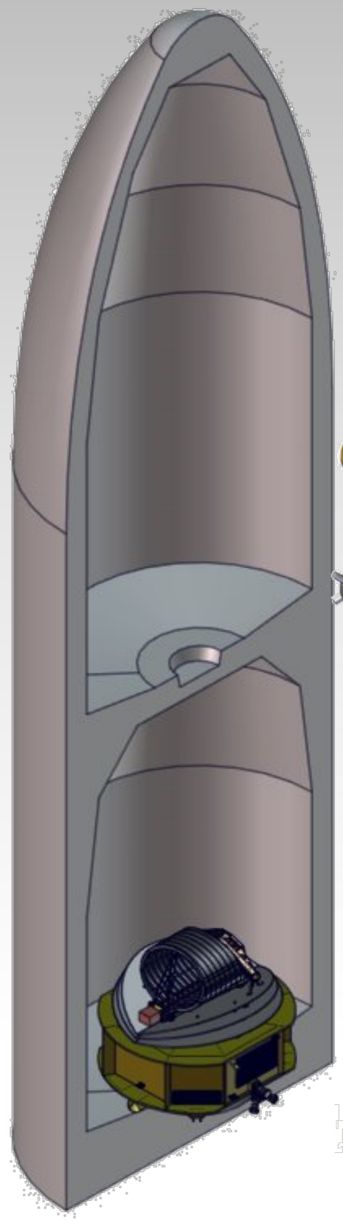


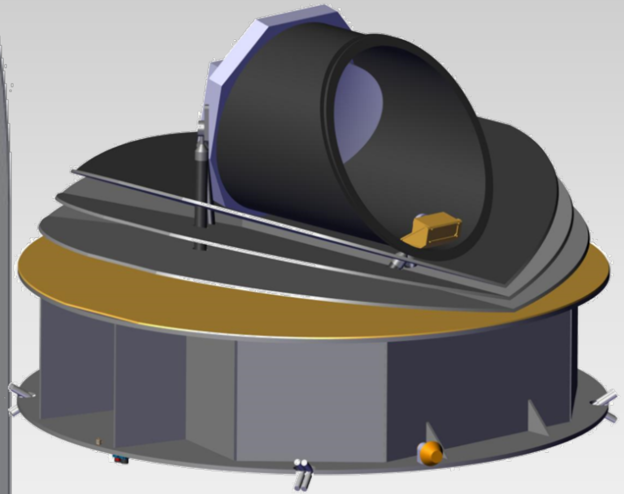
ARIEL – MISSION DESIGN

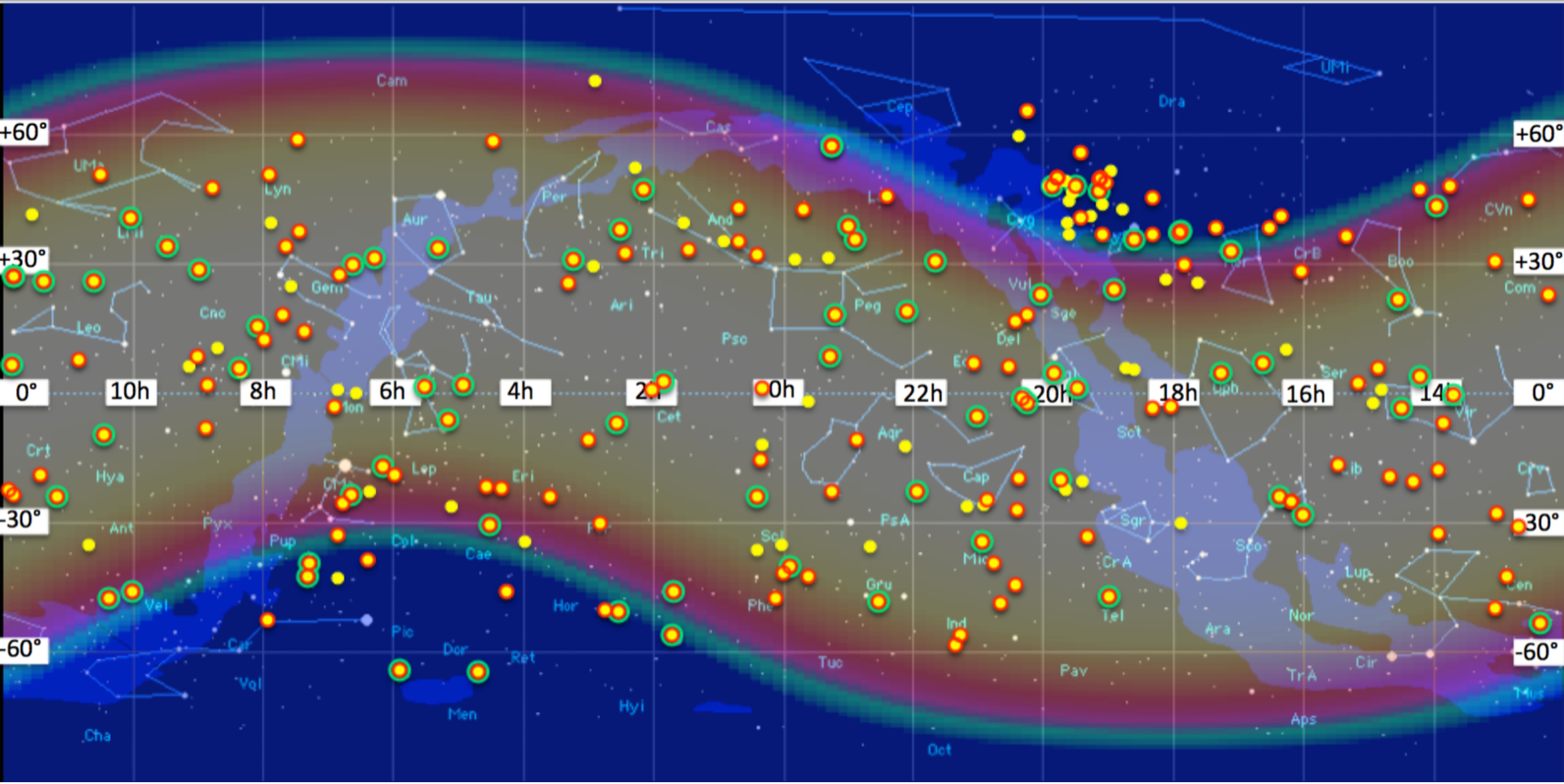
- Launch direct to large amplitude orbit around L2 by Ariane 6-2
    - Alternative flight profiles possible including shared launch
- Six months: transfer to L2, cooldown, commissioning and performance verification phase; followed by 3.5 years of routine science operations
- Wet Mass: < 1300kg
- Power: < 957 W
- Data Rate: 25 Gbits / day







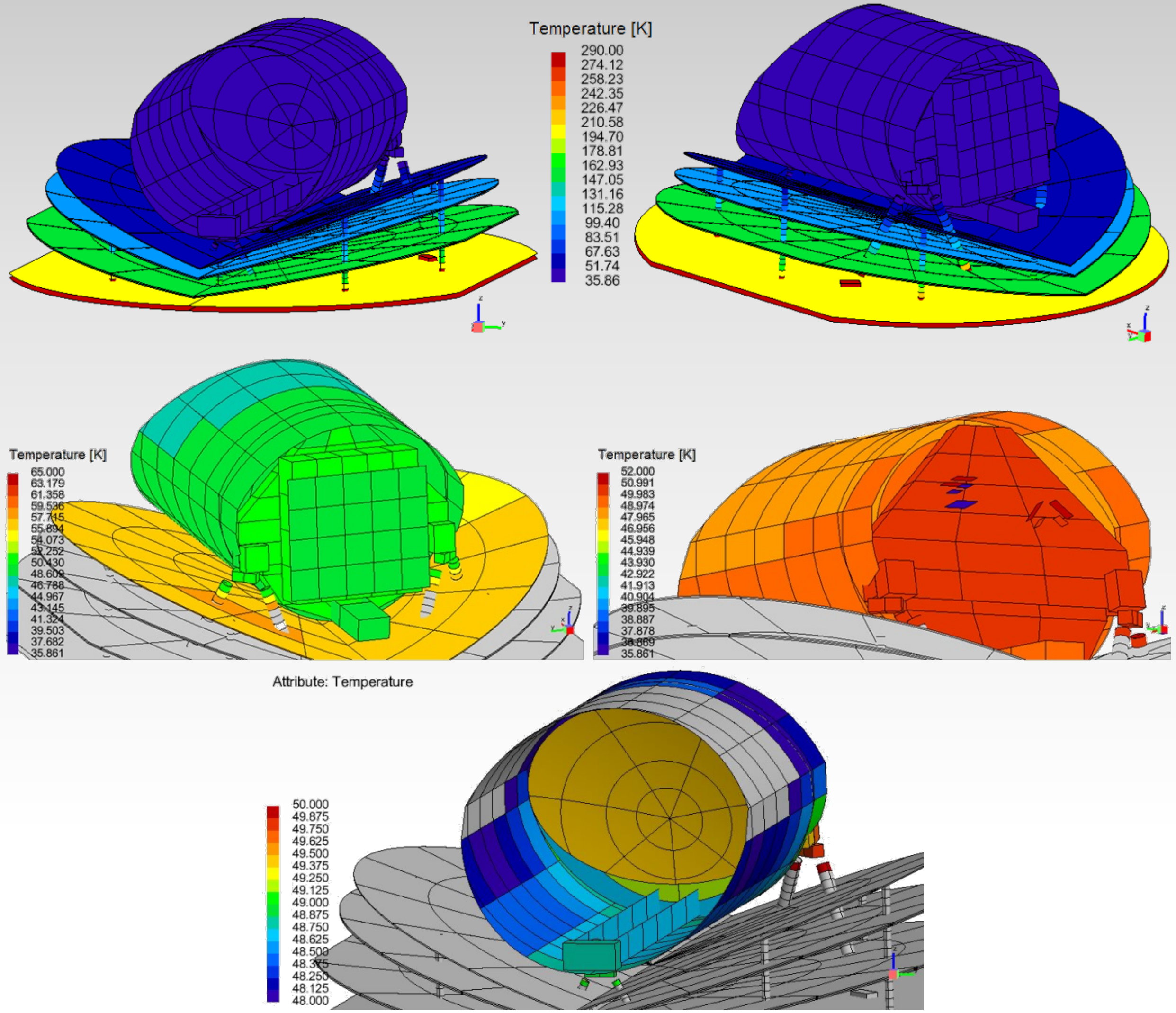


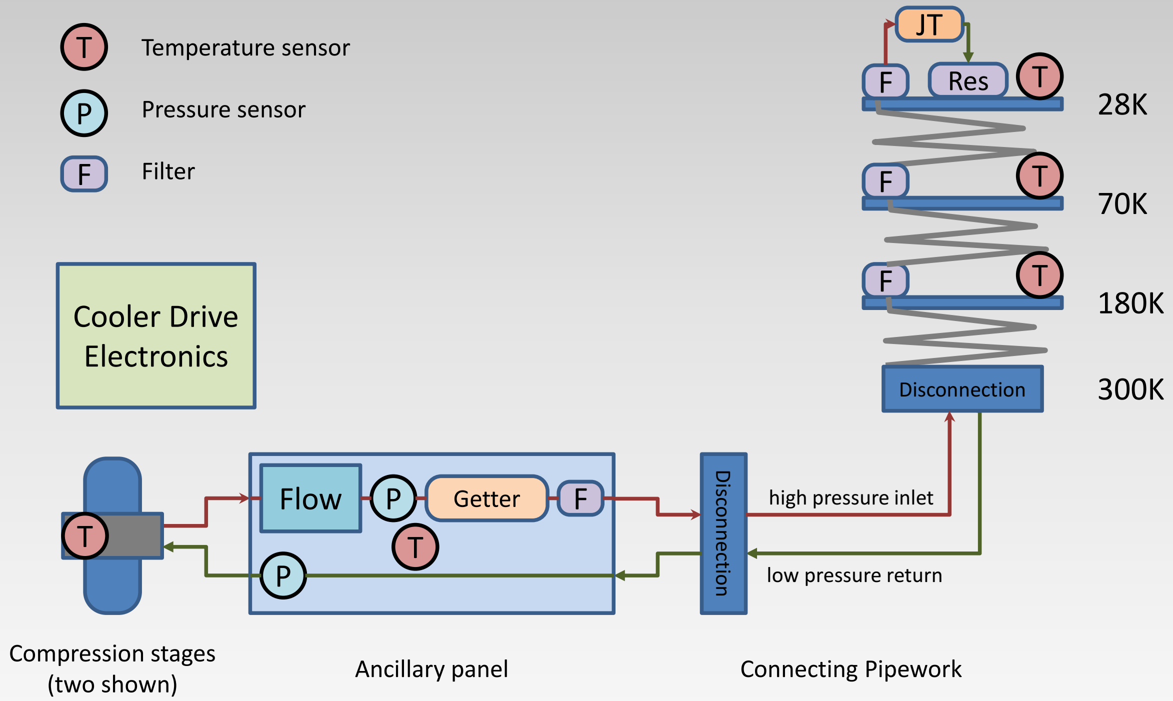


Instantaneous Sky Visibility 100% 80% 60% 40%

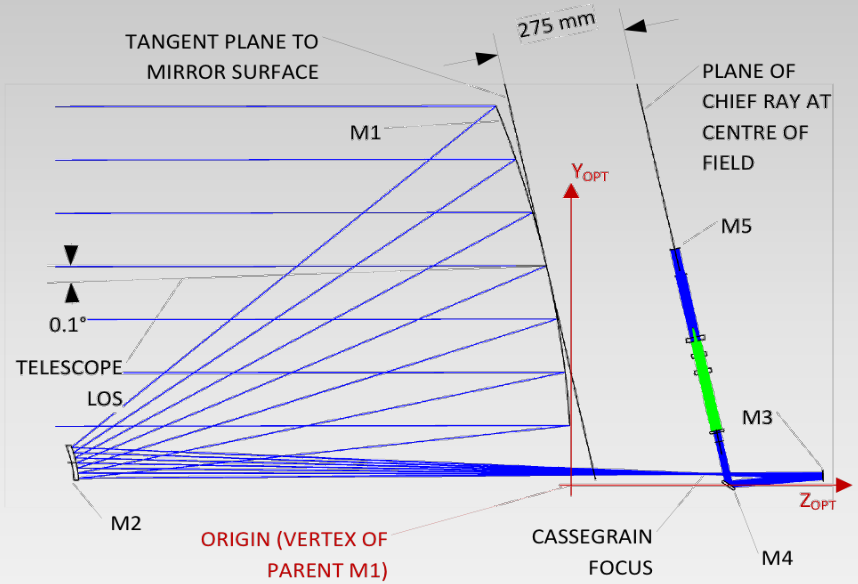
Survey
Deep
Benchmark

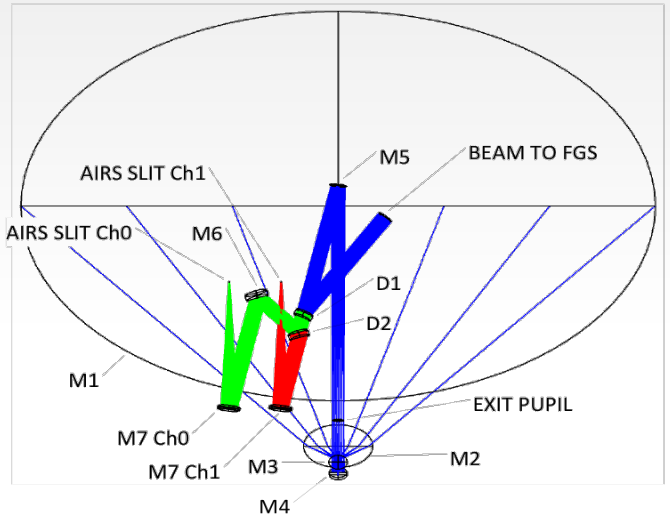
PAYLOAD: THERMAL CONFIGURATION



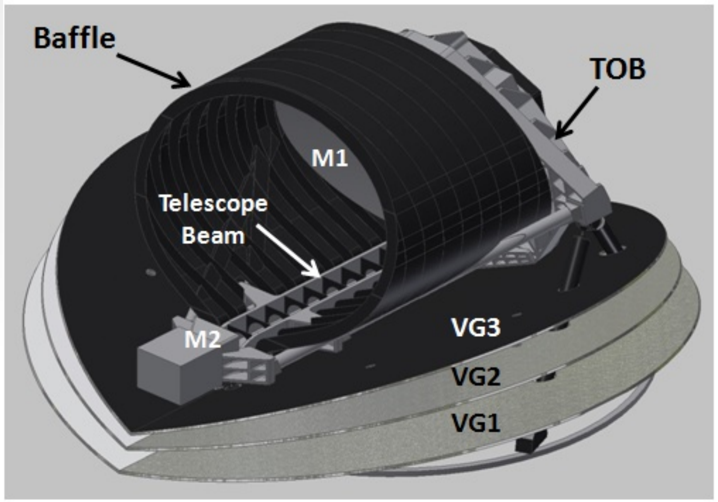


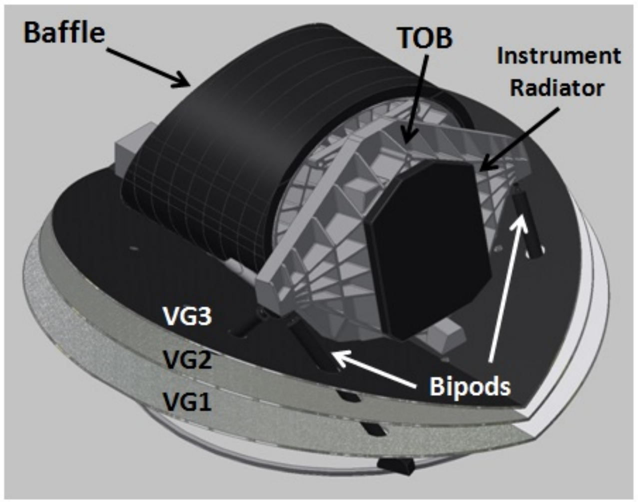
PAYLOAD: TELESCOPE & COMMON OPTICS



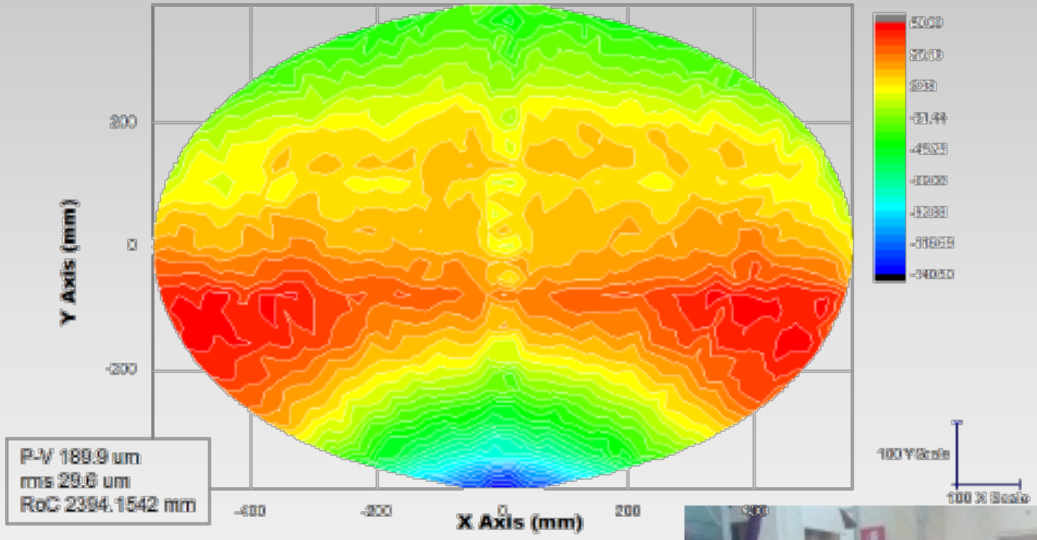


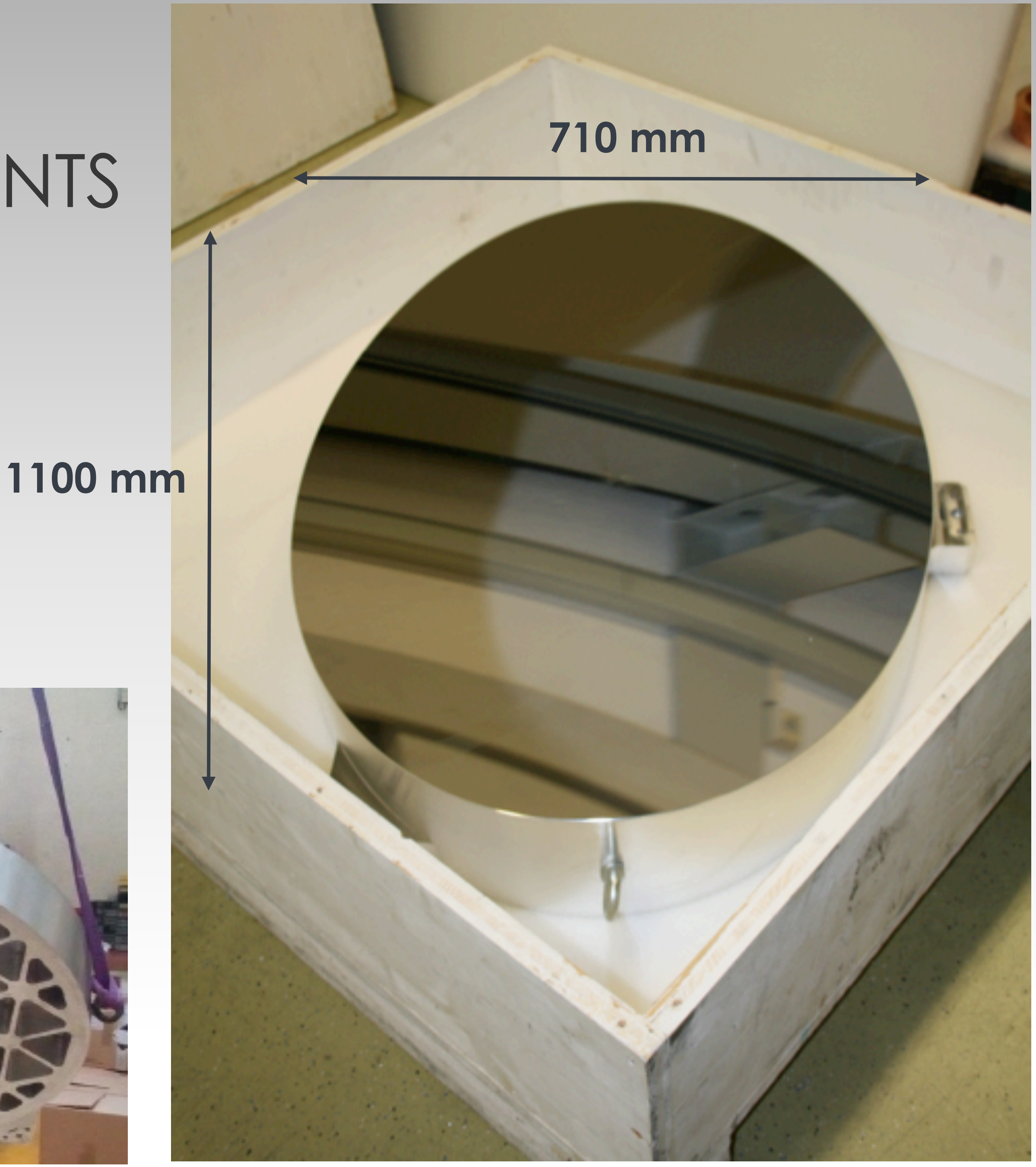
- Eccentric pupil Cassegrain telescope (M1 + M2) plus off-axis paraboloidal mirror (M3) and plane folding (M4)
- Collecting area of > 0.6 m^2 with diffraction limited performance for wavelengths ≥ 3 μm across 30” FoV
- Throughput at EOL of > 78% across wavelengths 0.5 – 7.8 μm
- Dichroics separate various spectral & photometric channels



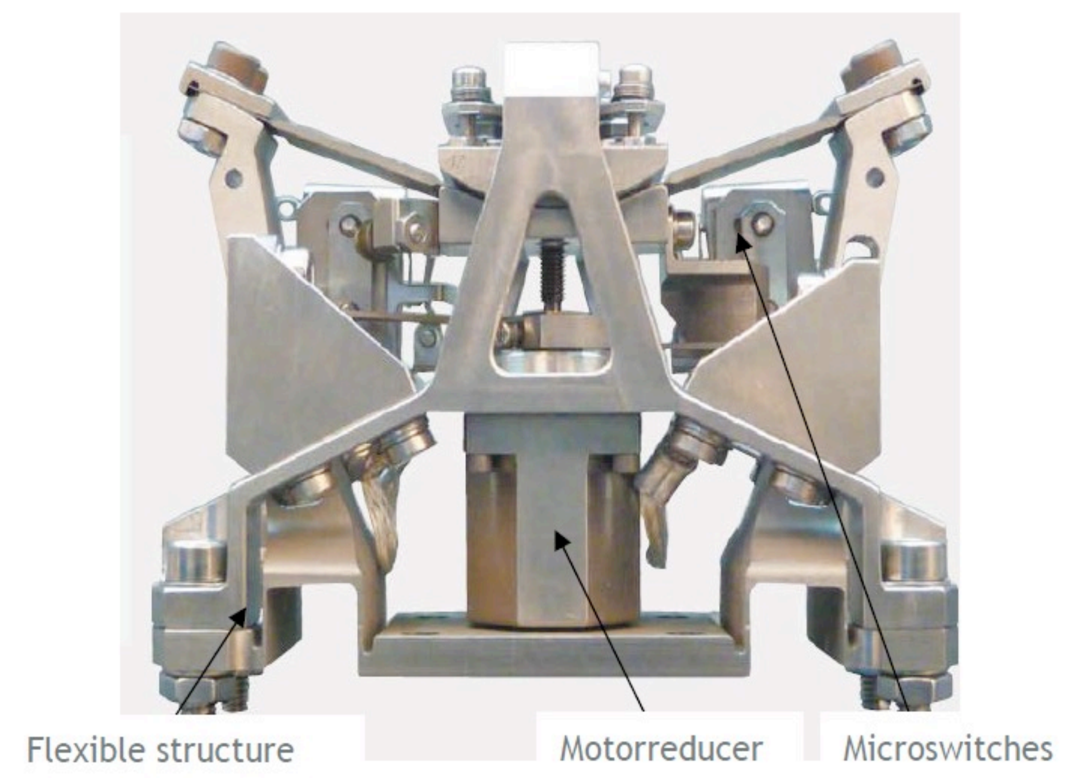


PAYLOAD: TELESCOPE BREADBOARD DEVELOPMENTS

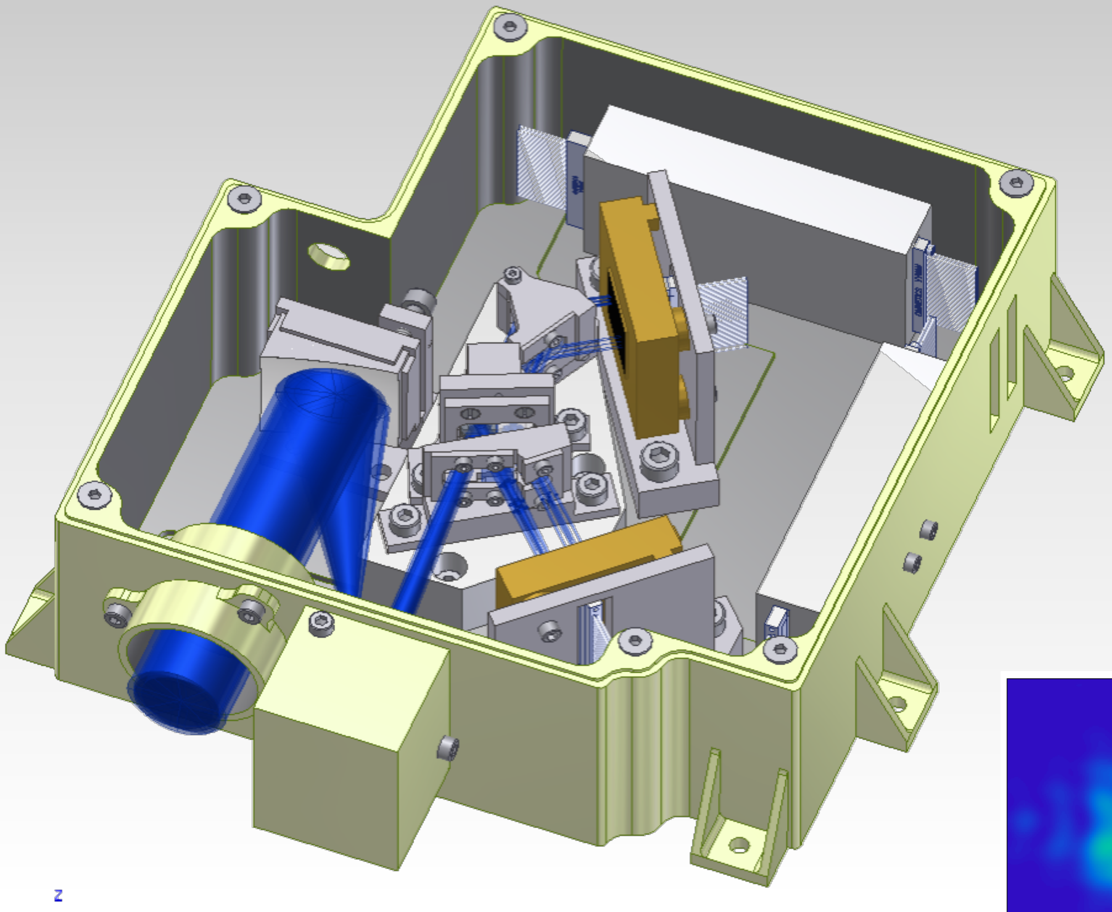


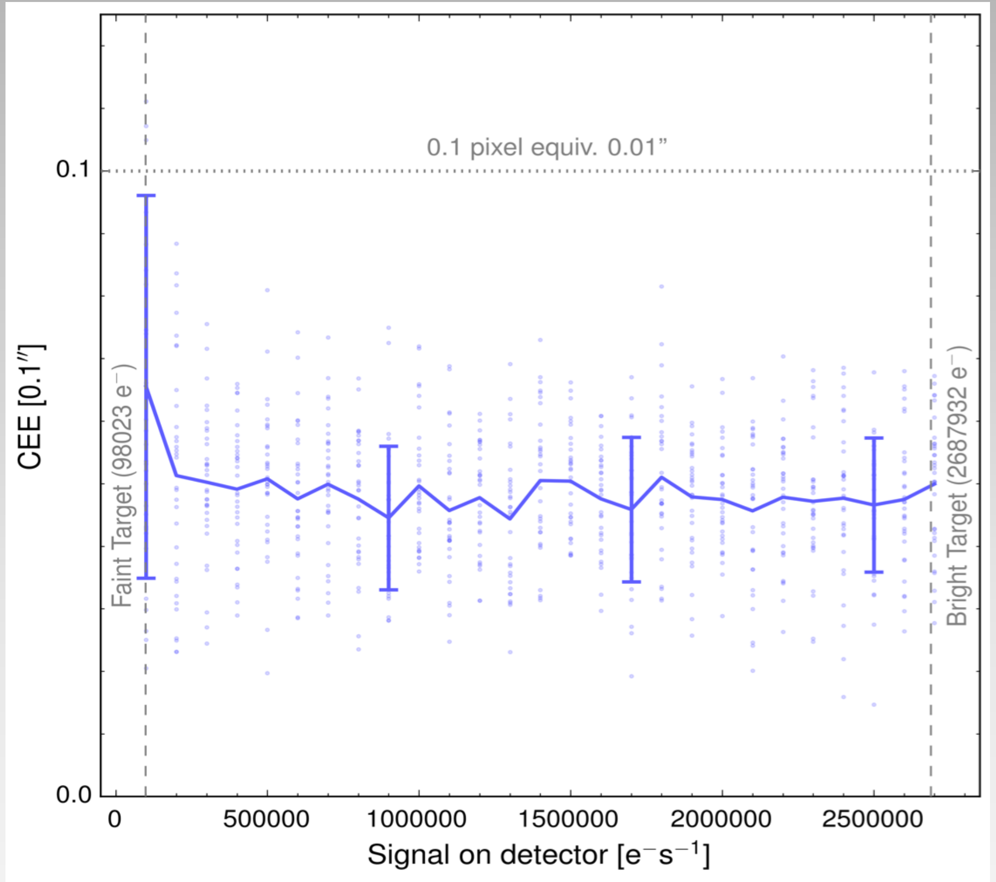


PAYLOAD: TELESCOPE DEVELOPMENTS

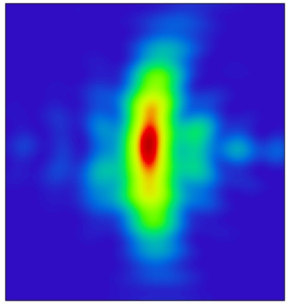


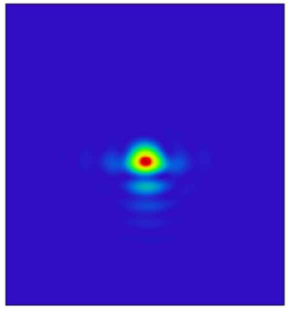
PAYLOAD: FGS / NIRSPEC





Monte-Carlo simulation of centroiding error for FGS for all brightness levels showing <10mas centroiding error in presence of all noise sources

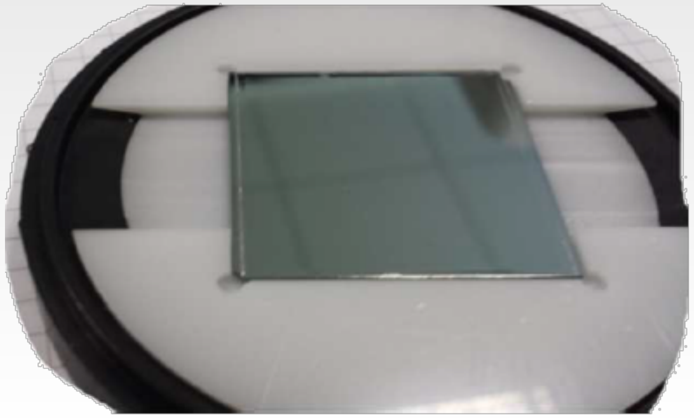




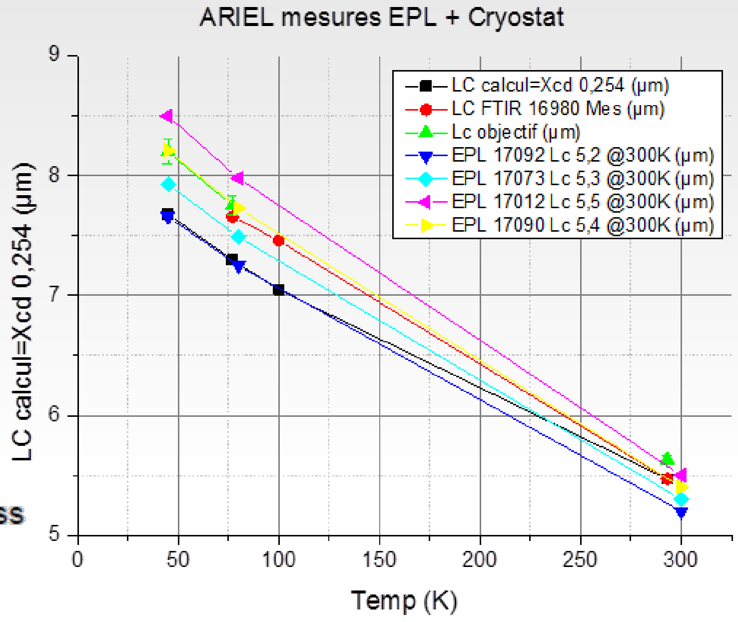
PSFs on 5x5 pixels: 0.55 μm 1.95 μm

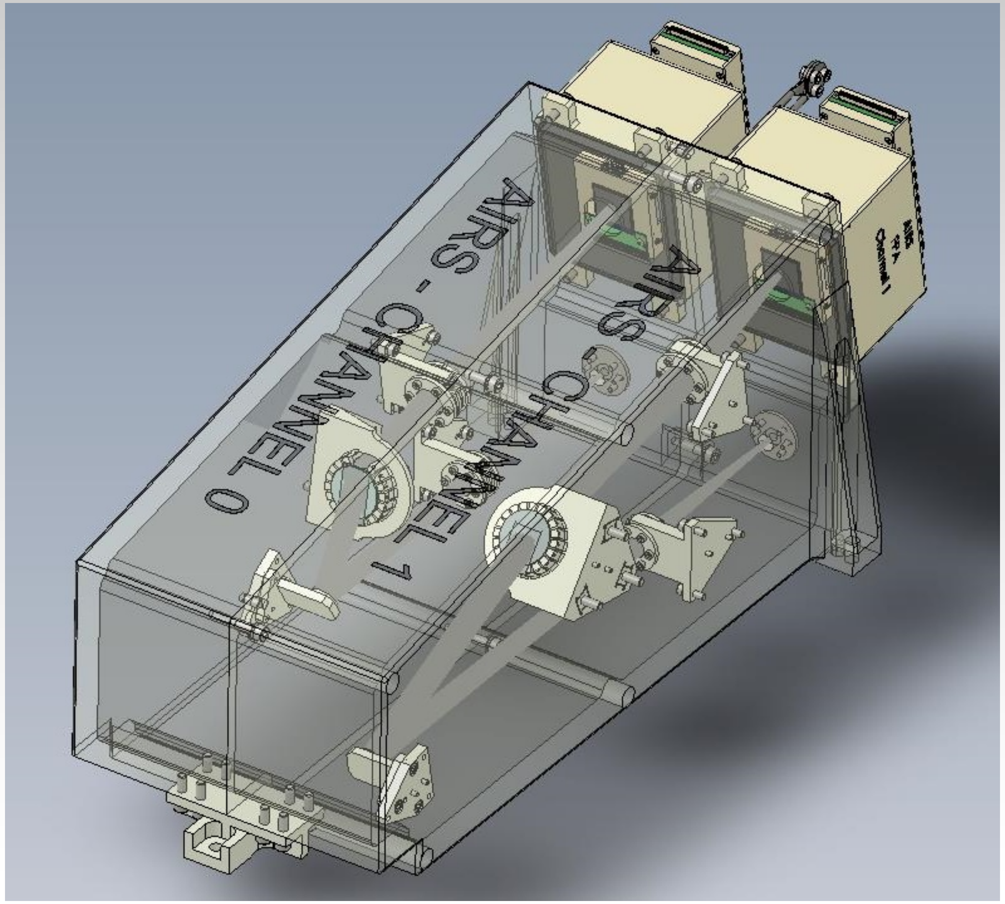
PAYLOAD: AIRS

- Two channels of prism spectrometers with similar design
- Detectors baselined Teledyne H1RG and derivatives, but design open to European detector alternatives currently being developed

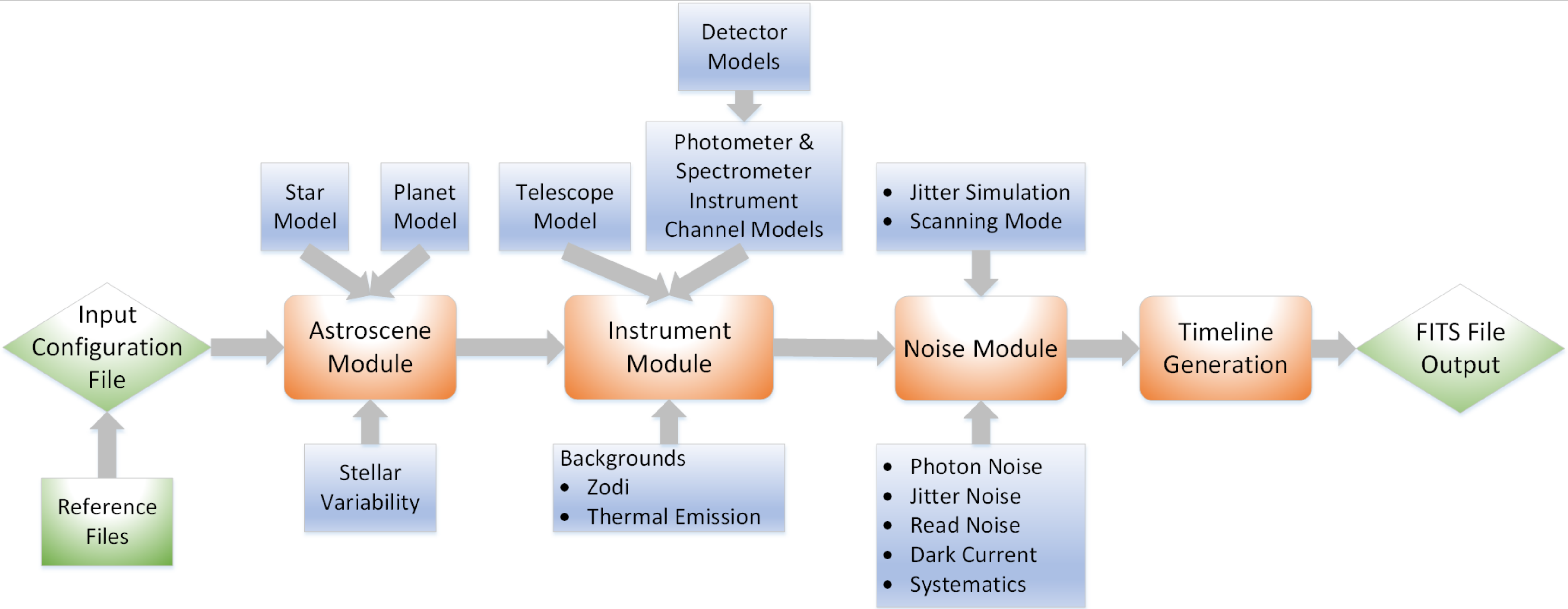


Hg$_{1-x}$Cd$_x$Te epilayer grown by LPE process
Size 36*38 mm²





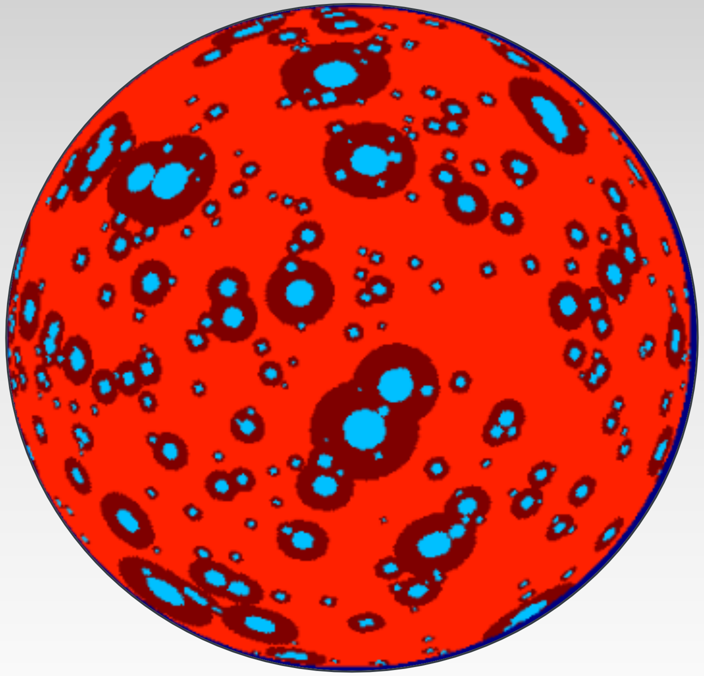
PERFORMANCE MODELLING: EXOSIM



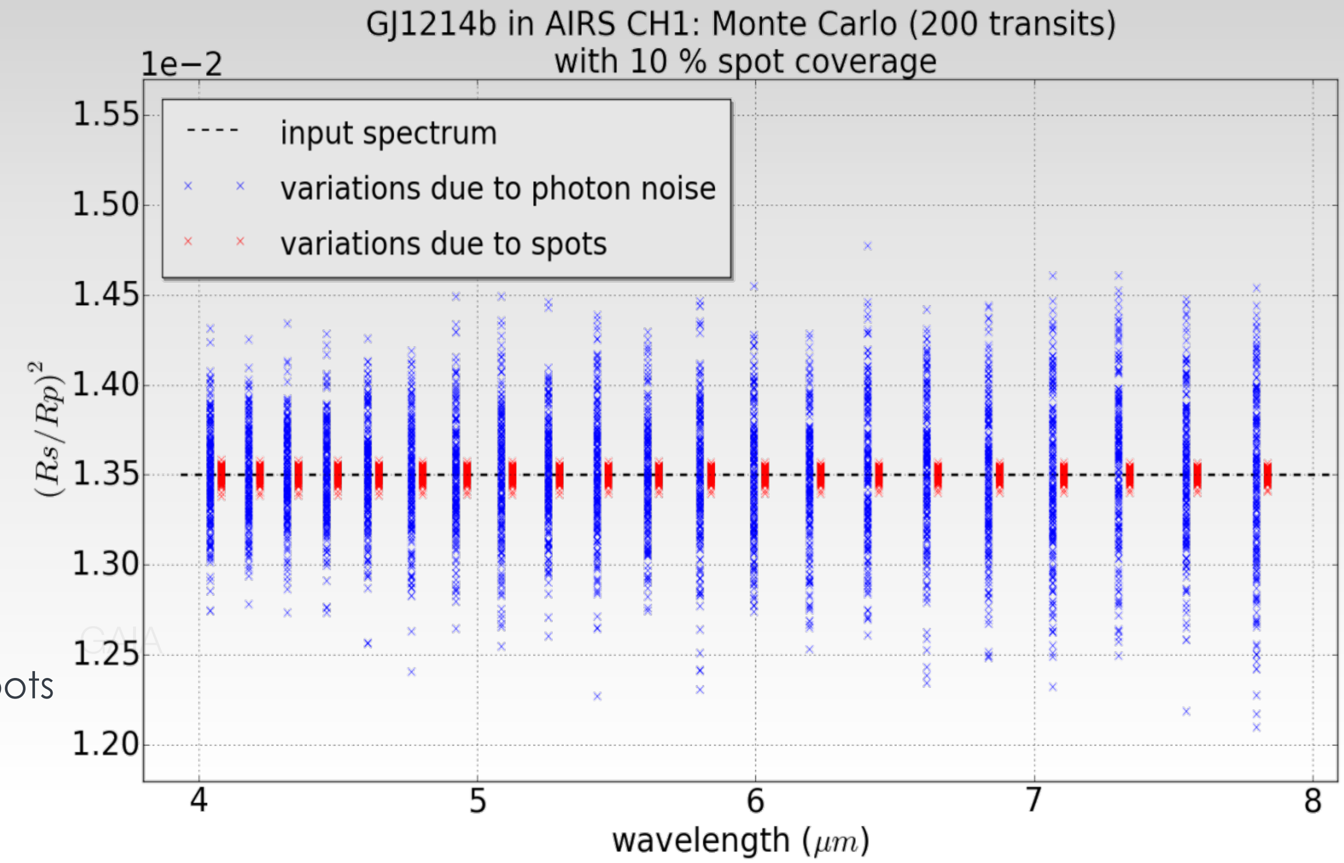
Sarkar et al, 2016; Pascale et al, 2014, Puig et al, 2014

EXOSIM: STELLAR SPOTS

STELLAR VARIABILITY: CORRECTING THE EFFECTS OF SPOTS



The example shows an extreme case: a star with 10% spots (the Sun is < 1%).
Cold spots are shown in light blue.
Hot faculae are in brown surrounding each spot.

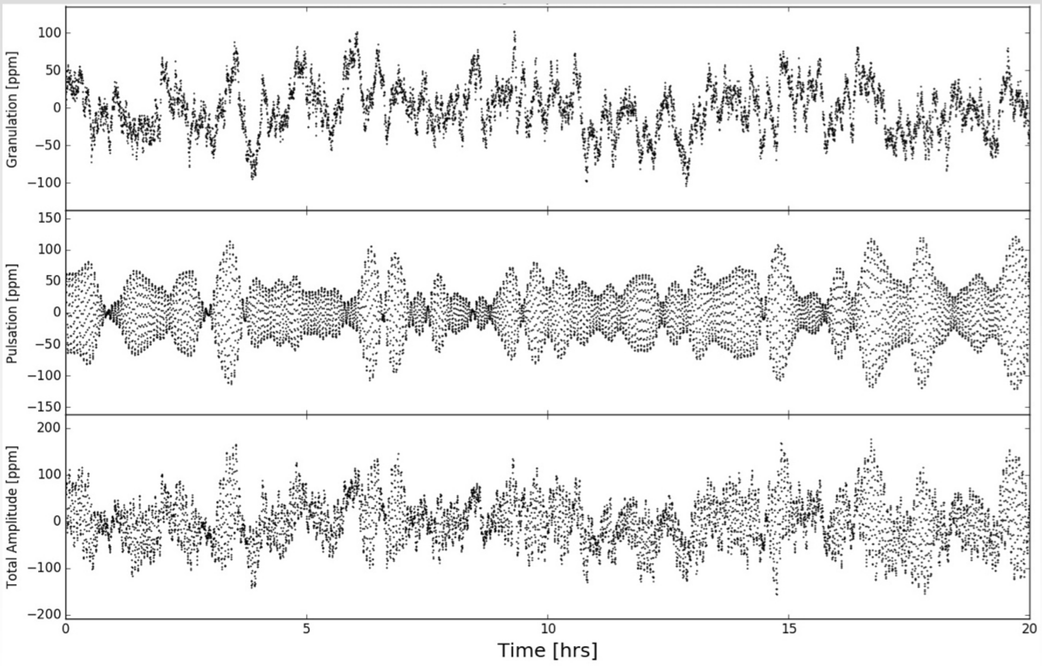


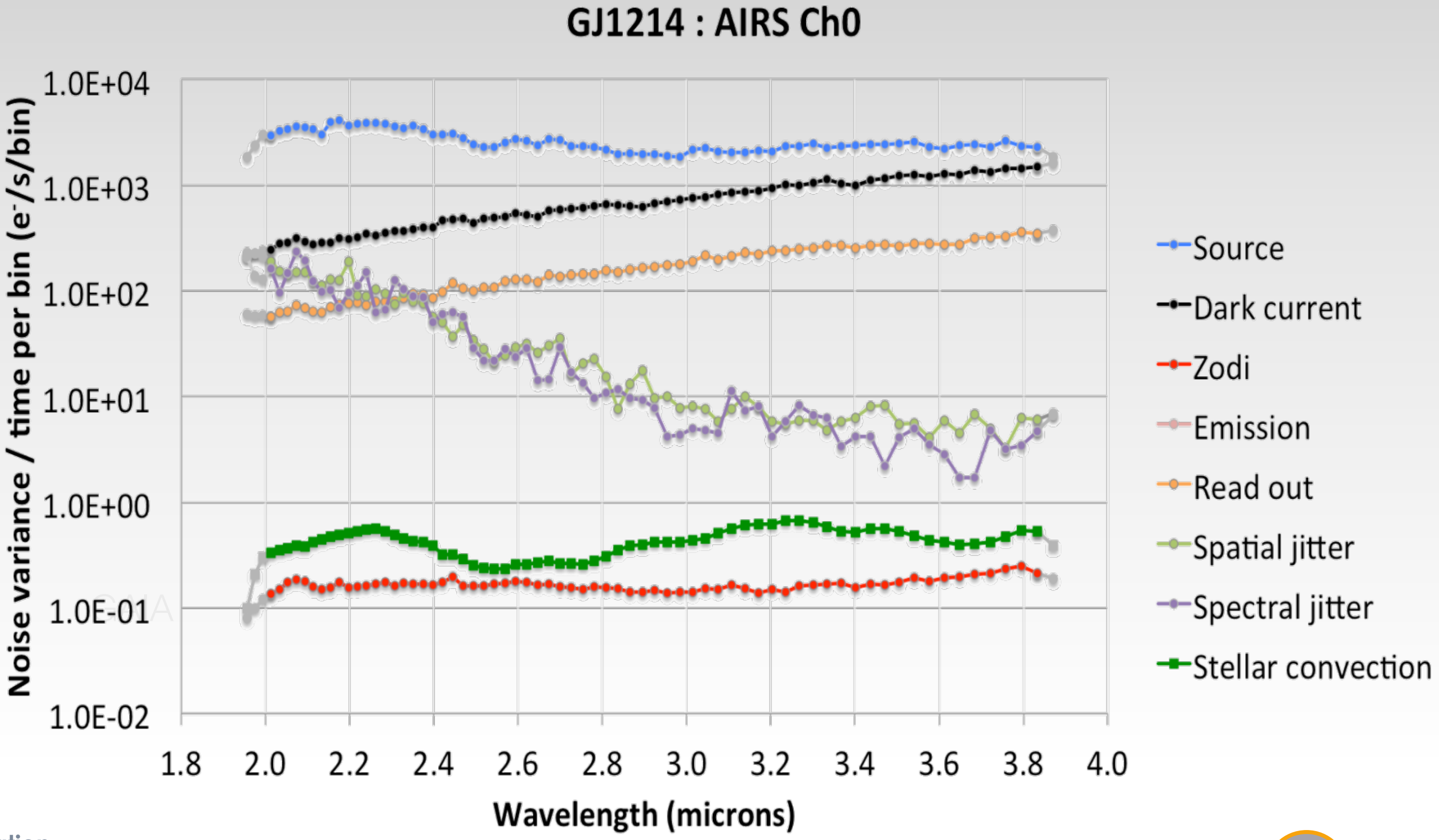
Sarkar et al, 2016; Herrero et al., 2015; Micela, 2015; Scandariato et al., 2015

EXOSIM: PULSATION AND GRANULATION

STELLAR VARIABILITY: CORRECTING THE EFFECTS OF PULSATION & GRANULATION

Simulated pulsations & granulations for M2V star

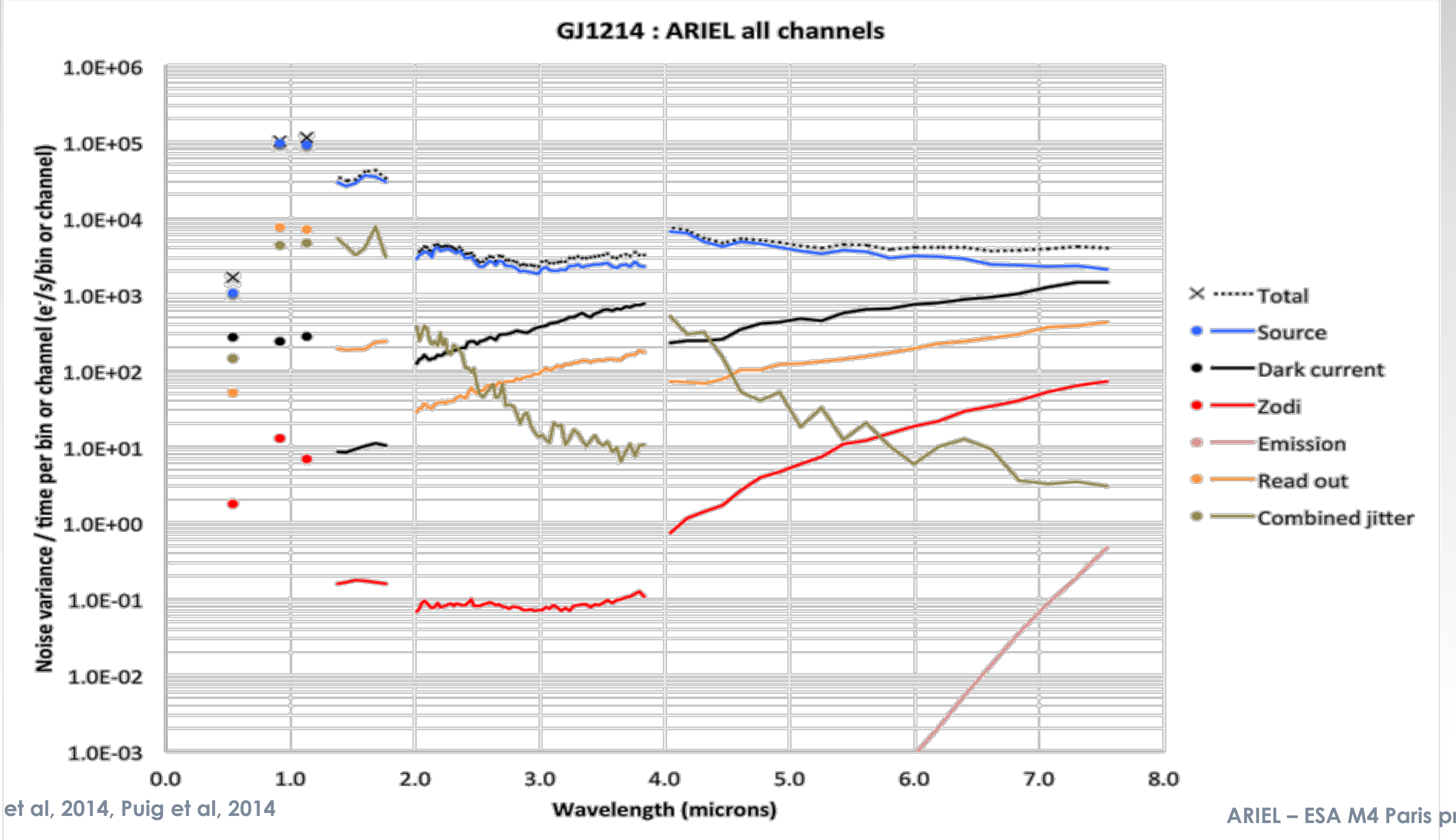




Sarkar et al, 2016; University of Leuven's simulations for pulsation & granulation

NOISE BUDGET – FAINTEST TARGET

ARIEL IS PHOTON NOISE LIMITED FOR ALL TARGETS



Sarkar et al, 2016; Pascale et al, 2014, Puig et al, 2014

GROUND SEGMENT & DATA POLICY

- ESA provided MOC and SOC are complimented and supported by distributed consortium Instrument Operations and Science Data Centre (IOSDC).

- **Science community extensively engaged prior to launch and during operation in definition of target list through Science Team and whitepapers**

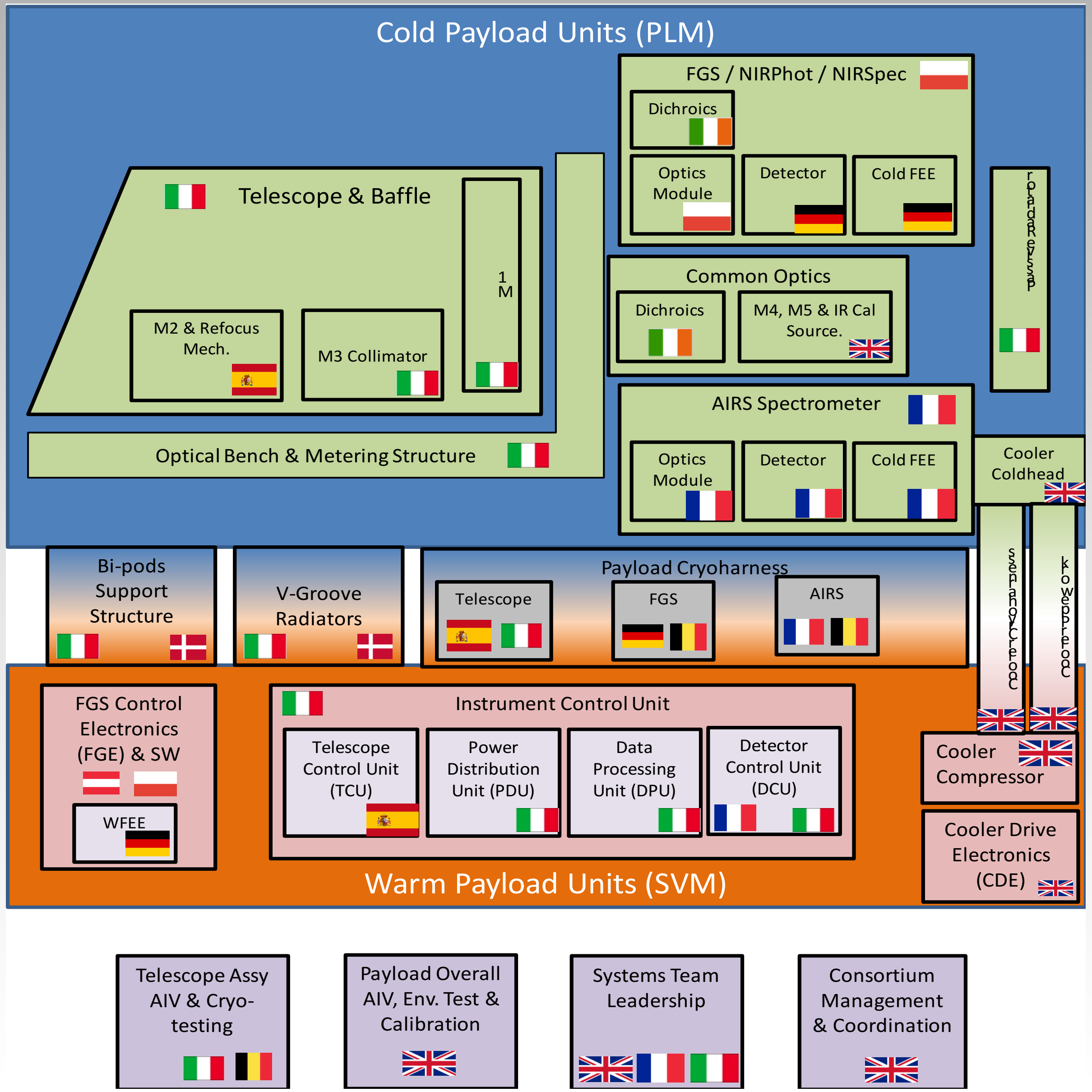
- Long term observation planning defined by IOSDC, reviewed throughout operations

- **Open Data Policy: All data released quarterly once required SNR reached**

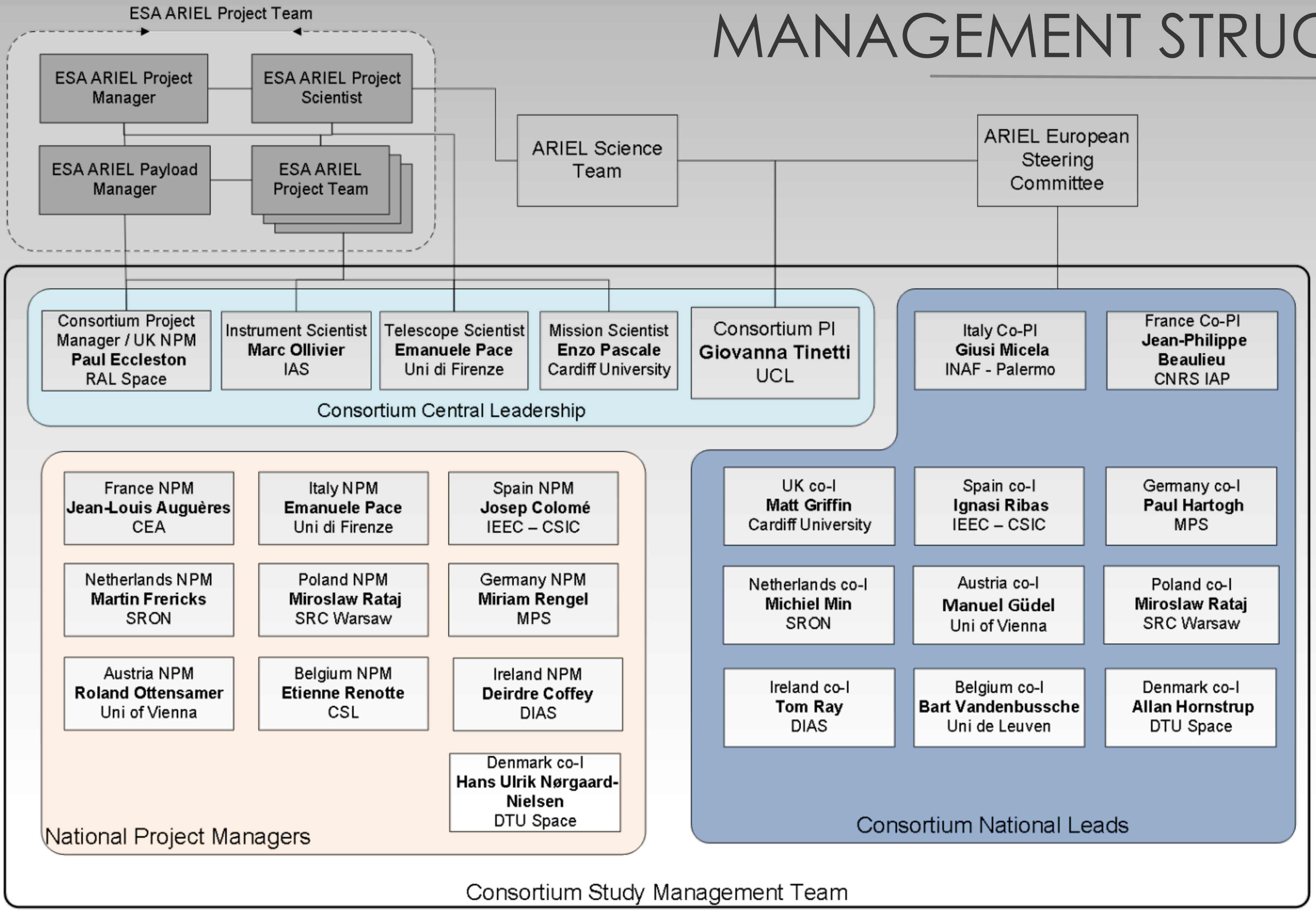
Data Level	Description	Comments
Level 0	Raw Telemetry	As sent from MOC to SOC
Level 1	Raw Spectral cubes of frames	Formatted cubes of raw detector images
Level 2	Extracted target spectra (star + planet)	In physical units as f(time) with instrument signatures removed
Level 3	Individual spectra of planets	Stacking of multiple revisits & extraction of planet spectra

MISSION RESPONSIBILITIES

- Clear division between ESA / Prime & single Payload Consortium
- Responsibilities within payload are clearly defined
  - Based on modular design and test approach to simplify interfaces and management
- Ground Segment responsibility share between ESA and Consortium also well defined and mature (MOC / SOC / IOSDC)



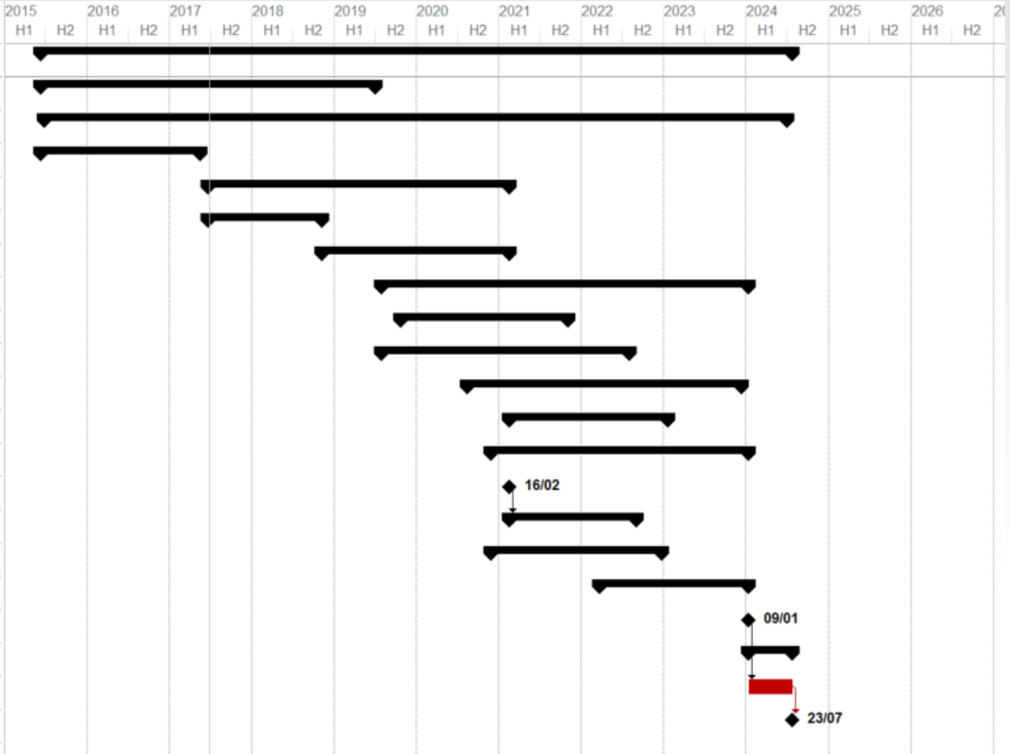
MANAGEMENT STRUCTURE



PROGRAM PLANNING

- **Schedule analysis shows feasibility for launch in 2026 with appropriate margin**
  - Technical development to retire key remaining risks planned for early phase B
- More details on overall M4 planning from ESA presentation shortly

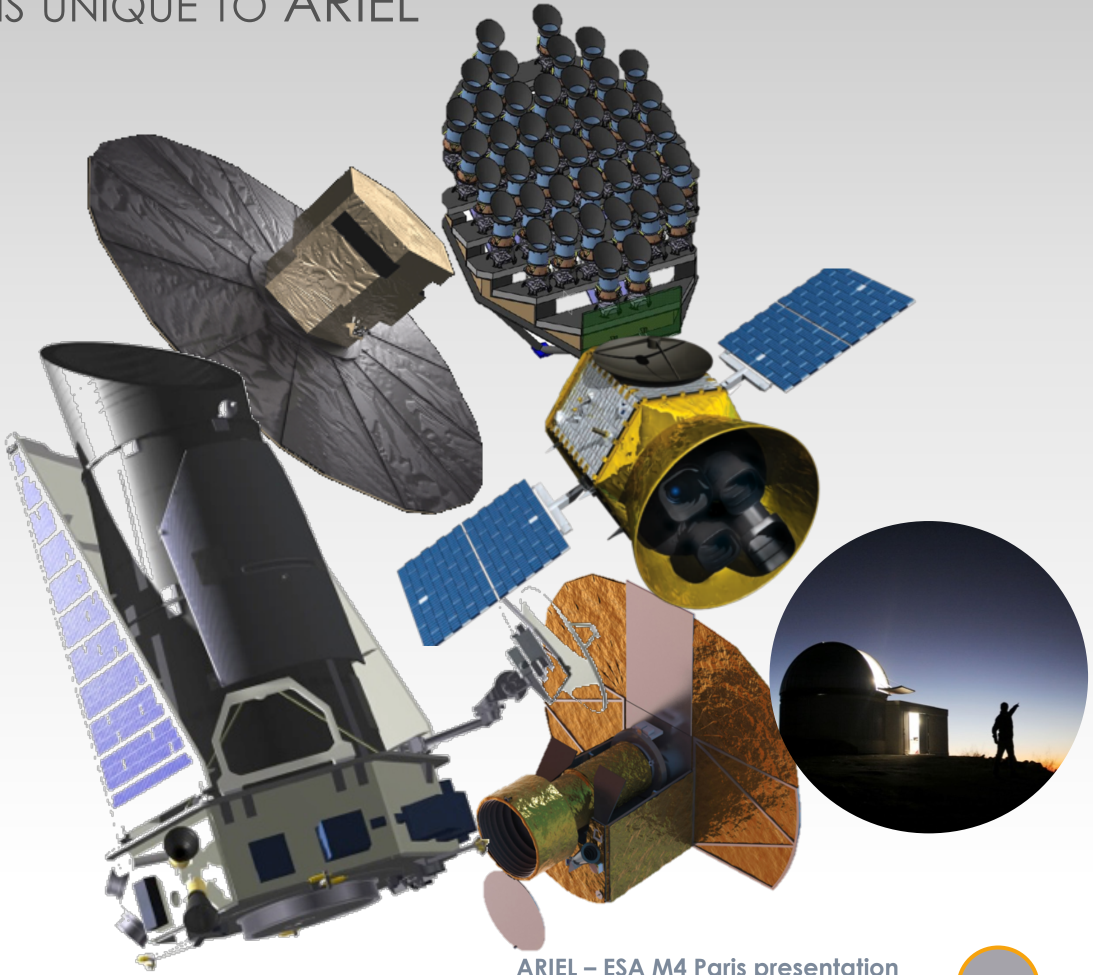
	Task Name	Duration	Start	Finish
1	**ARIEL Payload Project Overall Schedule**	**113.38 mons**	**Tue 09/06/15**	**Tue 23/07/24**
2	**Externally Imposed Milestones (ref ESA Presentation)**	**50.43 mons**	**Tue 09/06/15**	**Mon 01/07/19**
14	**Assumed Review Schedule**	**111.95 mons**	**Fri 26/06/15**	**Mon 01/07/24**
19	**Phase A Payload Study Detailed Schedule**	**24.02 mons**	**Tue 09/06/15**	**Mon 15/05/17**
107	**Phase BCD Payload Development Schedule**	**45.57 mons**	**Mon 19/06/17**	**Tue 16/02/21**
108	**Phase B1 Design Activities Schedule**	**17.29 mons**	**Mon 19/06/17**	**Wed 07/11/18**
159	**Phase B2CD Design Activities Schedule**	**28.29 mons**	**Thu 08/11/18**	**Tue 16/02/21**
180	**Hardware Program**	**55.29 mons**	**Tue 30/07/19**	**Tue 09/01/24**
181	**STM Payload Program**	**25.19 mons**	**Wed 23/10/19**	**Mon 01/11/21**
227	**PVM Payload Program**	**37.43 mons**	**Tue 30/07/19**	**Tue 02/08/22**
287	**QM Cooler System Program**	**41.43 mons**	**Wed 12/08/20**	**Tue 12/12/23**
310	FM Cooler System Program	23.81 mons	Wed 17/02/21	Tue 17/01/23
332	**pFM Payload Module Program**	**38.81 mons**	**Wed 25/11/20**	**Tue 09/01/24**
333	Design Confirmation at iCDR	0 mons	Tue 16/02/21	Tue 16/02/21
334	**PVM Program Design Feedback Inputs**	**19.1 mons**	**Wed 17/02/21**	**Wed 31/08/22**
339	**Module Level AIV Activities**	**25.86 mons**	**Wed 25/11/20**	**Fri 23/12/22**
367	**Payload Module Level AIV**	**22.38 mons**	**Tue 22/03/22**	**Tue 09/01/24**
397	Delivery of FM PLM to S/C Level AIV Earliest Readiness Date	0 mons	Tue 09/01/24	Tue 09/01/24
398	Payload Delivery	6.67 mons	Wed 10/01/24	Tue 23/07/24
399	Payload Level Project Margin (1 mon / yr from B1 KO)	28 wks	Wed 10/01/24	Tue 23/07/24
400	ARIEL Payload Delivery to S/C AIV (DRB / IFAR)	0 wks	Tue 23/07/24	Tue 23/07/24



SYNERGIES/COMPLEMENTARITIES WITH OTHER OBSERVATORIES

THE CHEMICAL SURVEY OF 1000 DIVERSE EXOPLANETS IS UNIQUE TO ARIEL

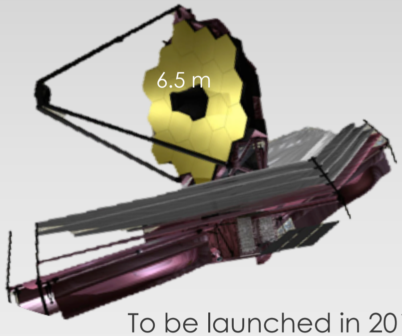
- Exoplanet detection missions: more planets for ARIEL!!!!
- Gaia & PLATO will also provide a better knowledge of the stellar environment
- Cheops will refine planet parameters



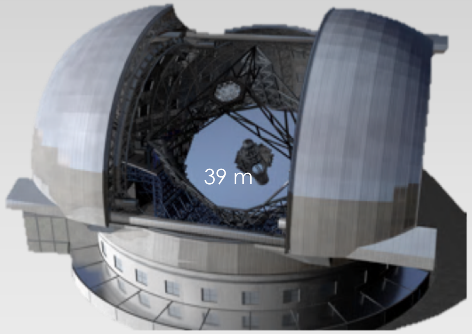
SYNERGIES/COMPLEMENTARITIES WITH OTHER OBSERVATORIES

THE CHEMICAL SURVEY OF 1000 DIVERSE EXOPLANETS IS UNIQUE TO ARIEL

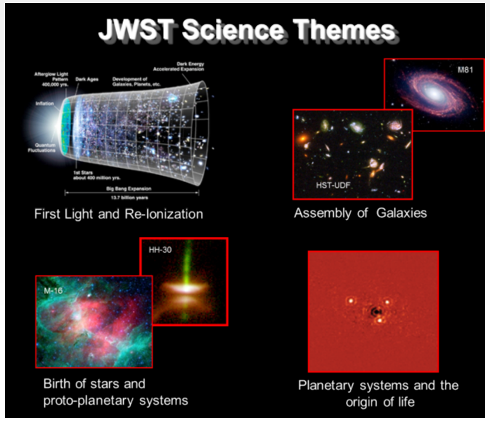
- Two observatories with IR spectroscopic capabilities
  - JWST (NIRISS, NIRCAM, NIRSPEC, MIRI)
  - ELT (MICADO, Harmoni, METIS, +)
- Not dedicated to exoplanets



To be launched in 2018

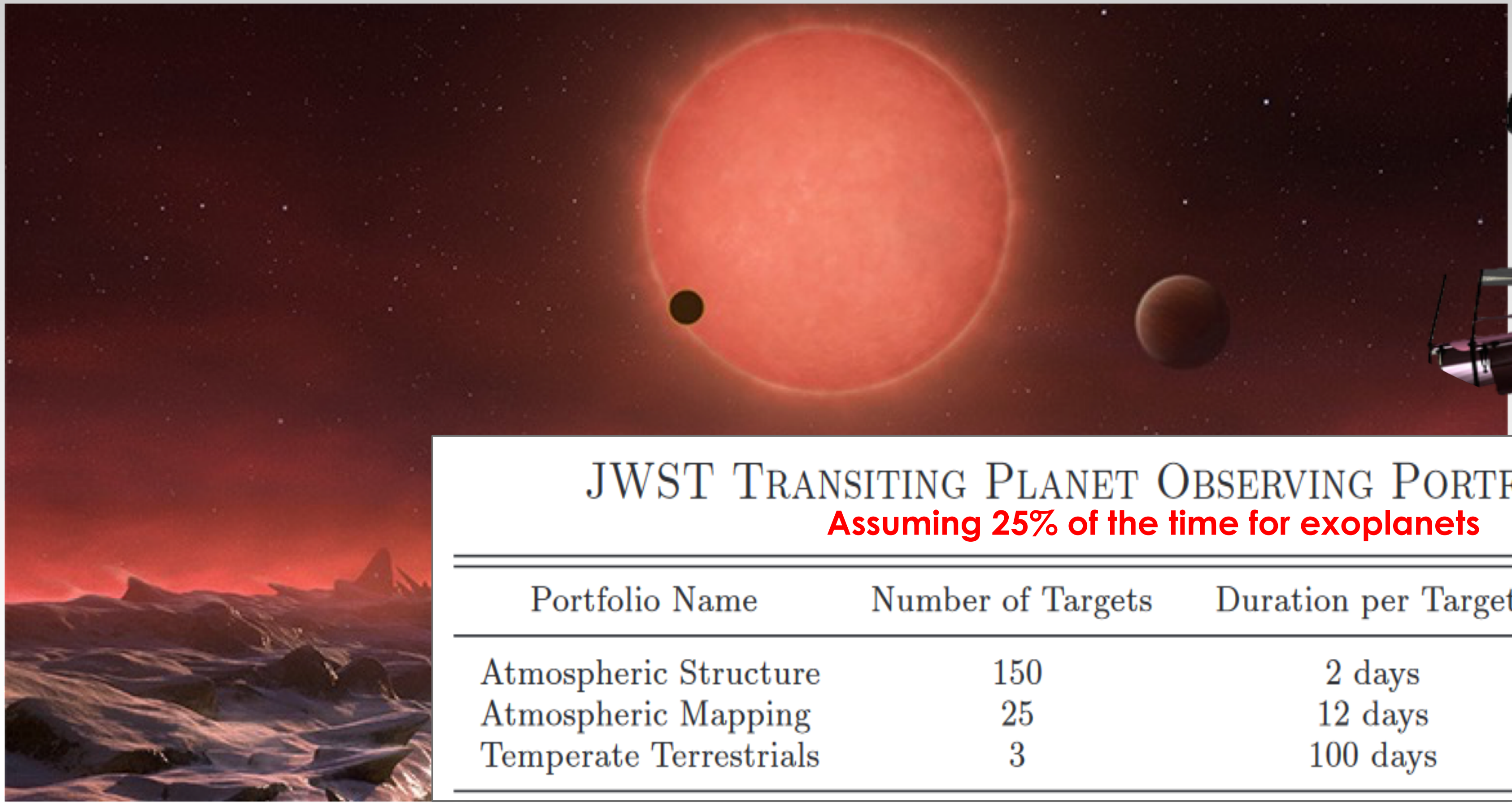


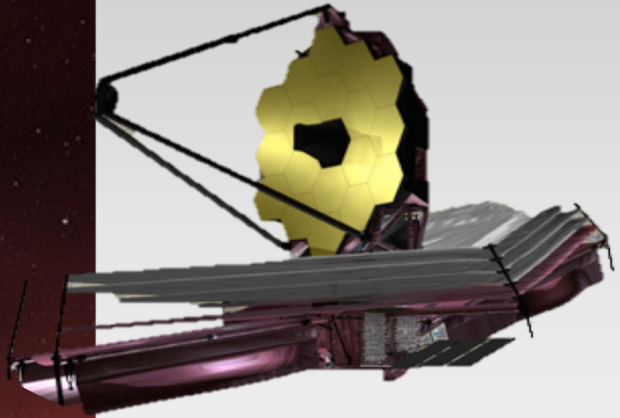
First light expected in 2024



SYNERGIES/COMPLEMENTARITIES WITH JWST

JWST CANNOT OBSERVE 1000 PLANETS





JWST TRANSITING PLANET OBSERVING PORTFOLIOS

Assuming 25% of the time for exoplanets

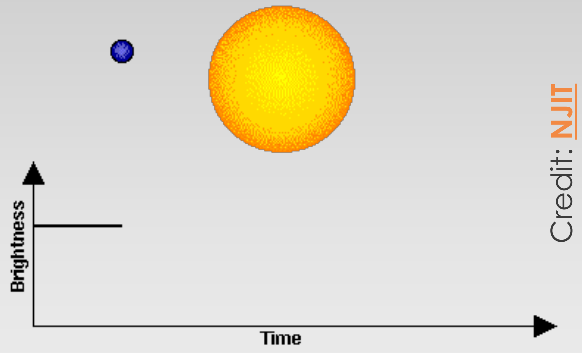
Portfolio Name	Number of Targets	Duration per Target	Total Time
Atmospheric Structure	150	2 days	300 days
Atmospheric Mapping	25	12 days	300 days
Temperate Terrestrials	3	100 days	300 days

Cowan et al. 2015

WHY 10 TIMES FEWER TARGETS THAN ARIEL ?

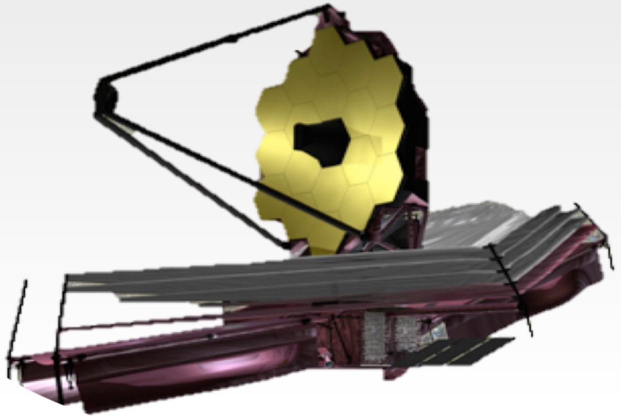
A LARGER TELESCOPE DOES NOT MAKE A TRANSIT SHORTER…

$$(S/N)_{jwst} \propto D_{tel} * t_{obs}^{(1/2)}$$ (Star Photon noise limited)



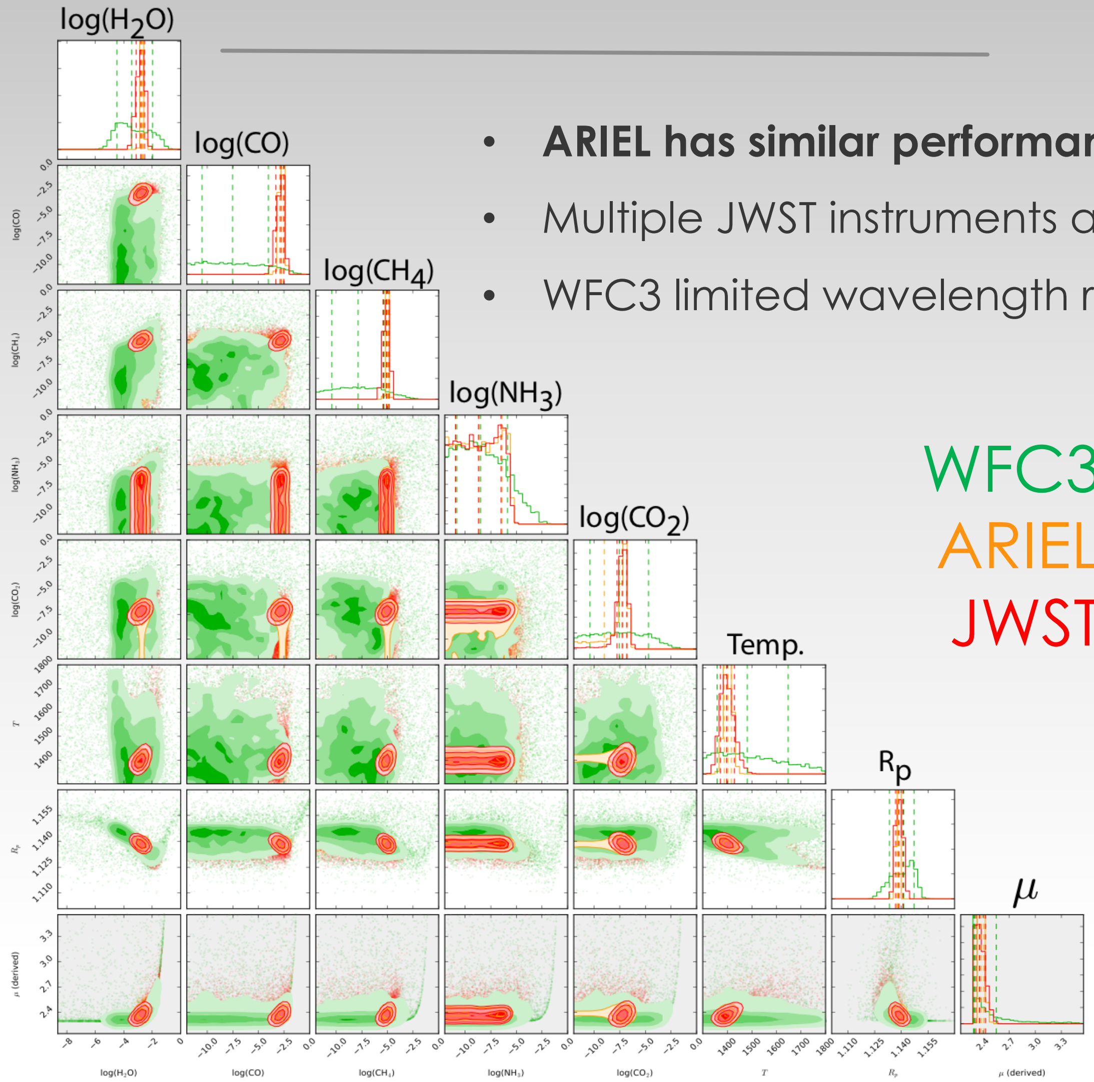
Typical observation ~ 6 hours

- Fixed observing time for a transit : T_{obs} = about 2 * $T_{transit}$
- JWST needs 4 instrumental settings (and then 4 transits) to cover the ARIEL wavelength range
- JWST limited time devoted to exoplanets (at best 25%)

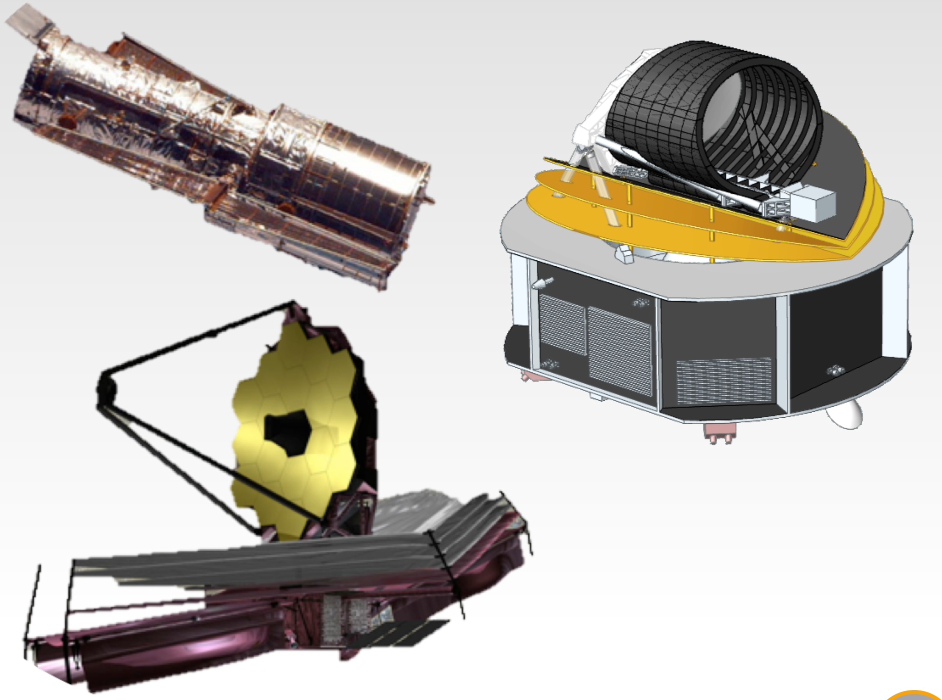


ARIEL OPTIMAL DESIGN & PERFORMANCES

- **ARIEL has similar performances to JWST for warm/hot planets around bright stars**
- Multiple JWST instruments are combined here
- WFC3 limited wavelength range gives highly degenerate solutions



WFC3
ARIEL
JWST



Simulations using Tau-Rex

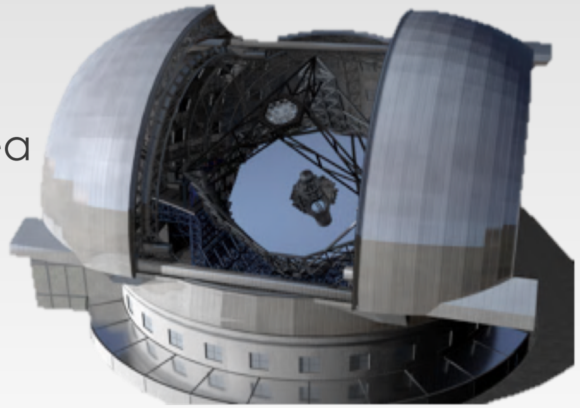
SYNERGIES/COMPLEMENTARITIES WITH ELT

ELT CANNOT OBSERVE 1000 PLANETS

- In the 3 instruments of first generation, METIS (L, M bands) will be well suited to exoplanets studies complementary to ARIEL

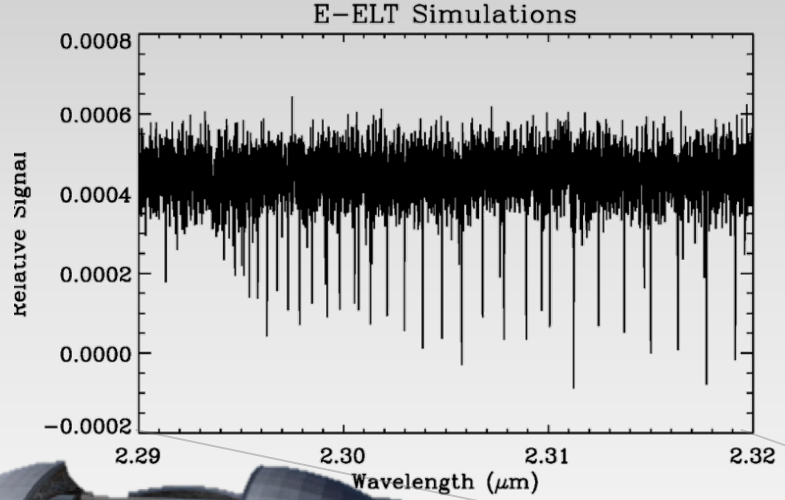
- Combining ELT High spectral resolution (R=100 000), large collecting area and high spatial resolution
    - access to individual molecular lines → access to line broadenings, line shifts → rotation, weak lines (see for example Snellen et al. β-Pic b)

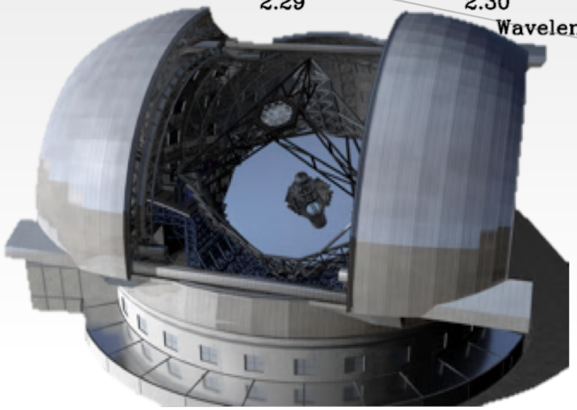
- High spectral resolution in the visible , near – IR, (HIRES) has to wait for second generation instrumentation plan (about 2030)

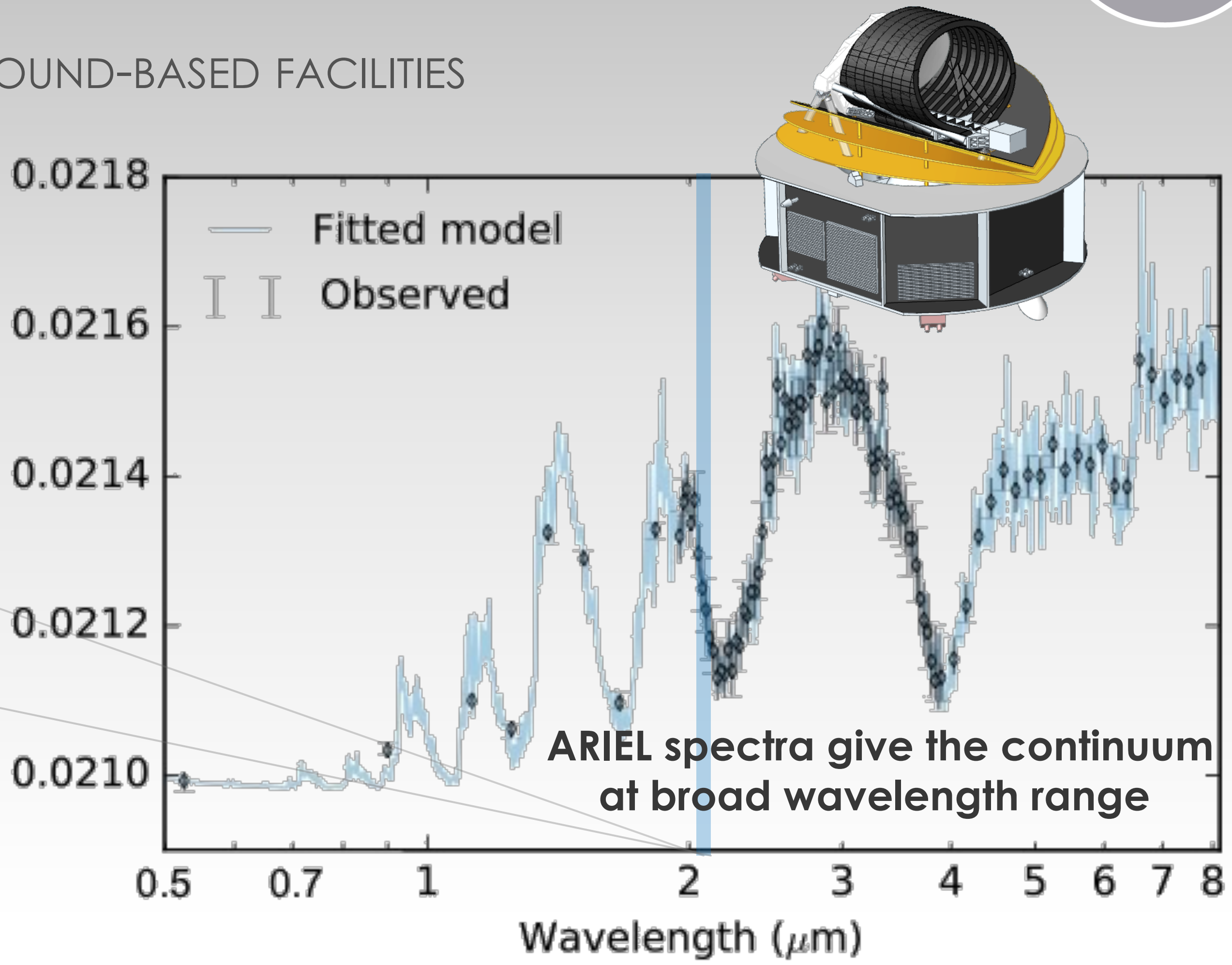


SYNERGIES/COMPLEMENTARITIES WITH ELT

HIGHLY COMPLEMENTARY TO LARGE, GROUND-BASED FACILITIES

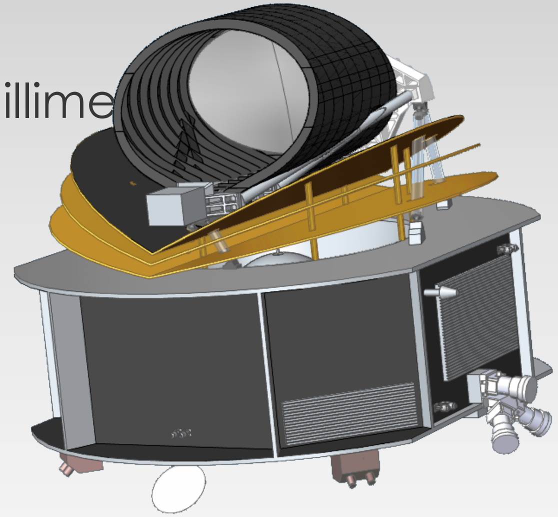






EUROPE IS WELL POSITIONED TO DO ARIEL

- Serious resources invested to be at the forefront of exoplanet detection (surveys from the ground, Corot, Cheops, PLATO)
- Builds on heritage from ESA's previous successful IR and sub-millimeter astronomical missions:
    - Instruments on the Infrared Space Observatory (ISO),
    - Instruments on Herschel Space Observatory,
    - MIRI for the forthcoming JWST
    - the Planck thermal system



- Solar System space instruments on Venus Express, Mars Express, JUICE, Cassini, Rosetta, Mars TGO…
- 12 ERC-funded programs to interpret exoplanet spectra, predict atmospheric dynamics, chemistry, formation and structure of the interior

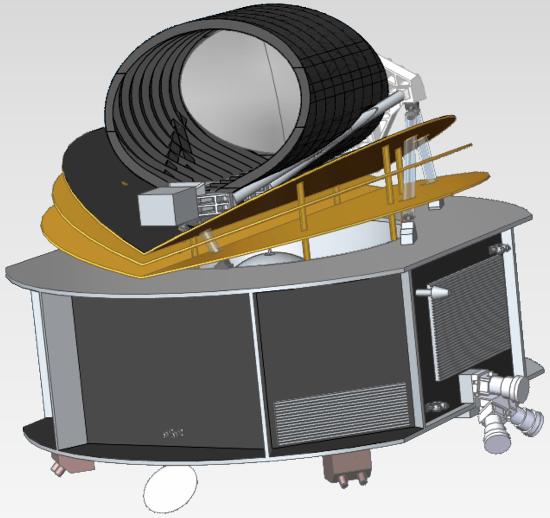
ARIEL – CONCLUSIONS

- ARIEL will enable us to understand why planets in our galaxy are so diverse and how they evolve

- ARIEL will do so by delivering the first chemical survey of ~ 1000 exoplanets, probing uniformly the gamut of planet and stellar parameters

- ARIEL will do for exoplanets what Herschel did for star formation and what ALMA is doing for disk evolution

- ARIEL science will provide a galactic perspective to the history and nature of our Solar System



Time is ripe for this endeavour and Europe is ready for it