ARIEL

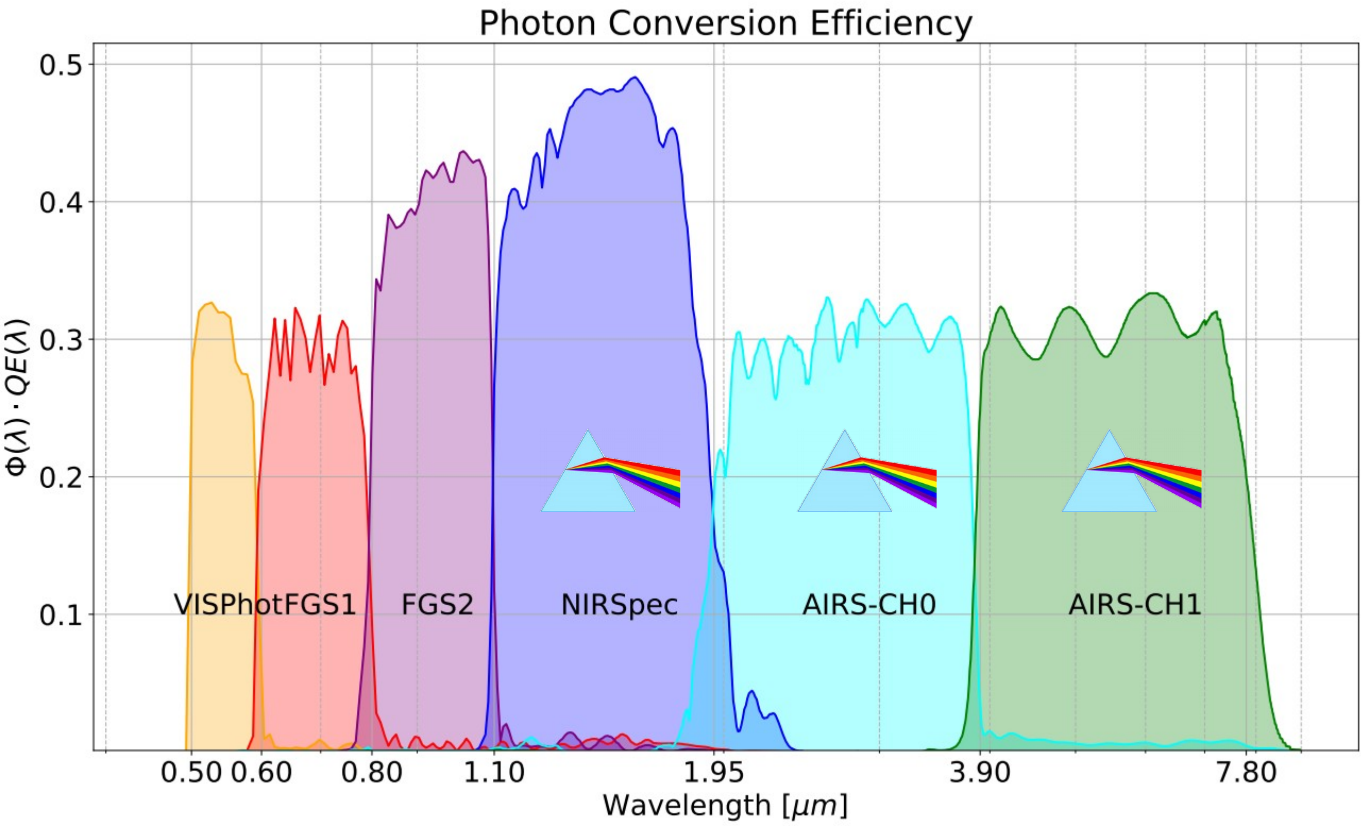
Performance modelling
and
predictions of performance

E. Pascale
and
The ARIEL Simulation Working Group

Science requirements

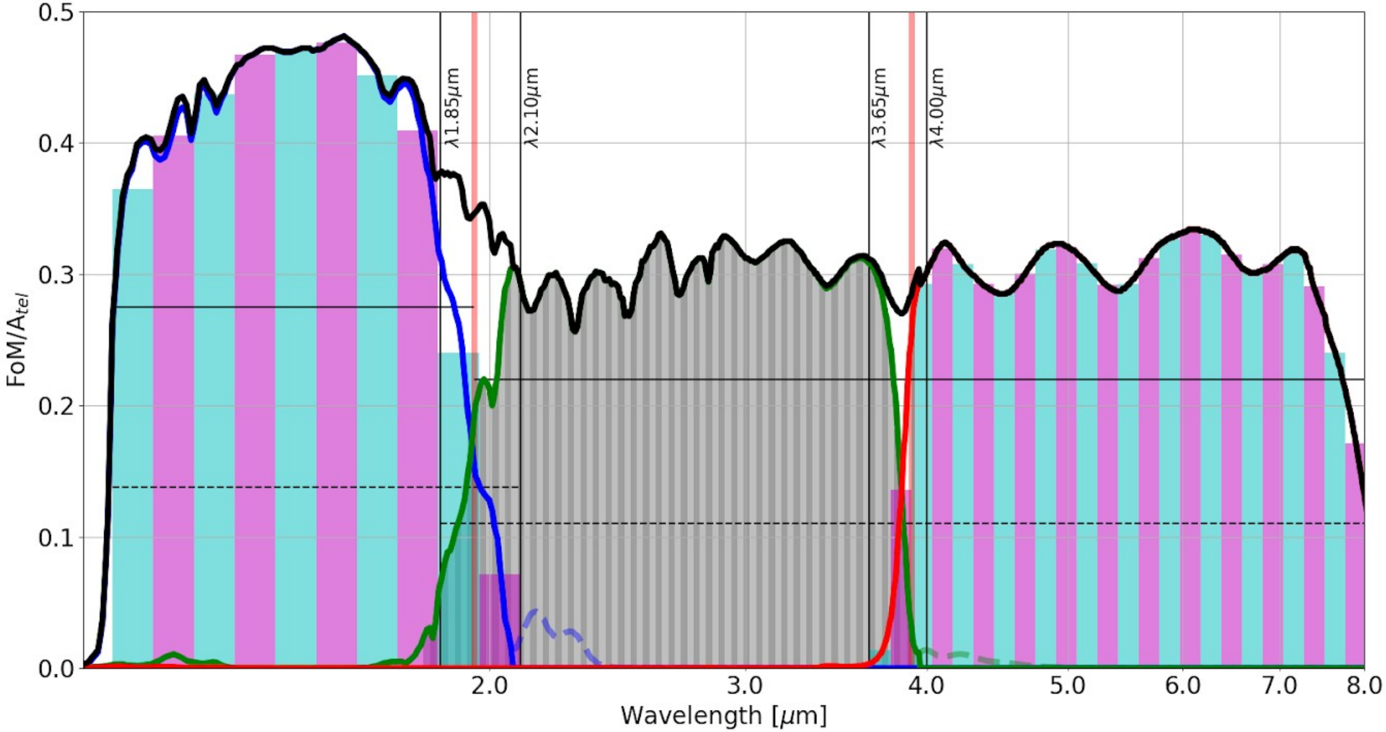
- Study the atmospheres of a statistically large and diverse sample of exoplanets.
- ARIEL can survey a core sample of about 1000 exoplanets during the nominal mission lifetime.
- To deliver its science mandate, ARIEL
  - has an integrated payload design to deliver simultaneous detection over the 0.5 to 7.8μm band of the electromagnetic spectrum
  - is designed to achieve high photometric stability over a time scale of hours
  - designs-out known systematic effects, implementing lessons learned from ground and space instrumentation deployed (HST, Spitzer, etc.)

Photometric and spectroscopic bands



Channel	λ_{min} [μm]	λ_{max} [μm]	R
VISPhot	0.5	0.6	
FGS1	0.6	0.8	
FGS2	0.8	1.1	
NIRSpec	1.1	1.95 [2.10]	>15
AIRS/CH0	1.95 [1.85]	3.9 [4.0]	> 100
AIRS/CH1	3.9 [3.65]	7.8	> 30

Spectral overlap for continuous



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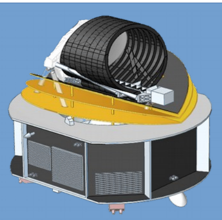
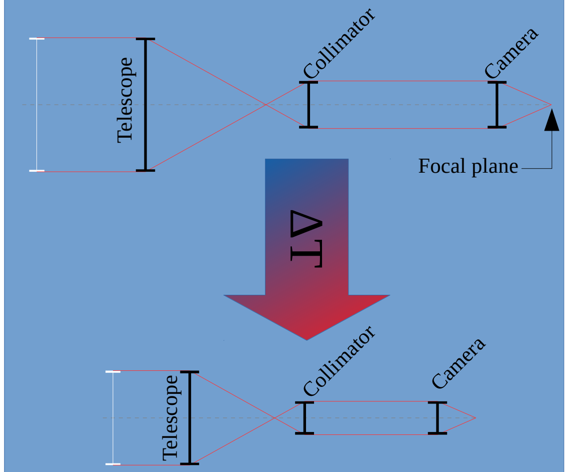
Noise and systematics

Type of uncertainty	Source	Mitigation Strategy
Detector noise	Dark current noise	Choice of low-noise detectors
	Readout noise	
	Gain stability	Calibration, post- processing data analysis, choice of stable detectors.
	Persistence	Post-processing decorrelation. Continuously staring at a target for the whole duration of the observation.
Thermal noise	Emission from telescope, common optics and all optical elements	Negligible due to surface emissivity properties and in-flight temperatures of the payload.
	Temperature fluctuations in time	Negligible impact by design
Astrophysical noise	Photon noise arising from the target	Fundamental noise limit, choice of aperture size (M1 diameter).
	Photon noise arising from local zodiacal light	Negligible over ARIEL band
	Stellar variability with time	Multi-wavelength stellar monitoring, post-processing decorrelation
Pointing jitter	RPE and PDE effects on the position, Spectral Energy Distribution, and detector intra/inter pixel response	Small RPE and PDE, Nyquist sampling, post-processing decorrelation
	Field stop losses	Spectrometer field stops sufficiently large



ARIEL made of aluminium

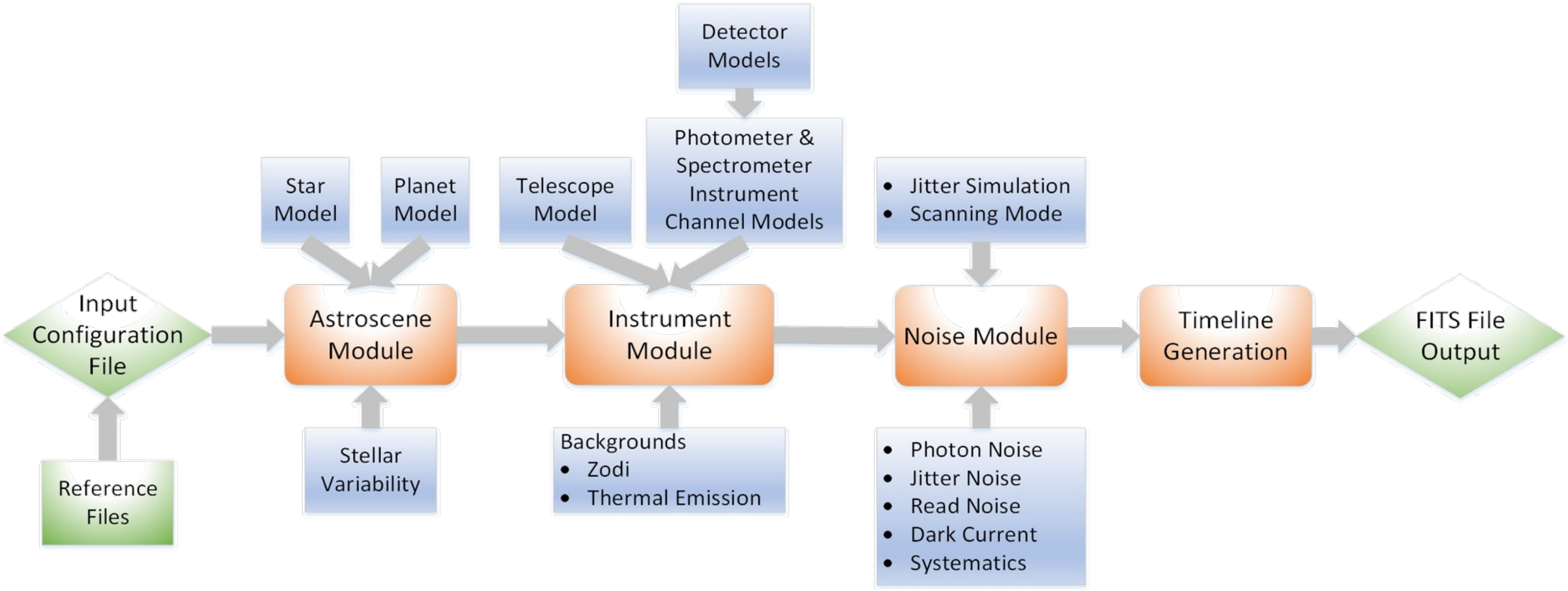


Largely not sensitive to thermal variations

Performance assessment / Design optimisation

- Use multiple performance simulators
  - Implement payload design
  - Take into account SVM-AOCS
  - Include noise and systematics
- Deliver
  - Timelines
  - Photometric stability estimates, and estimates of detection uncertainties
  - SNR achieved on ARIEL targets
    - Depends from target physical parameters

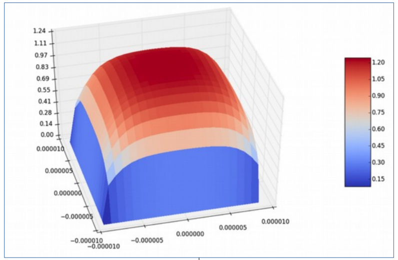
ExoSim: ARIEL time domain simulator



Sarkar 2018, 2020

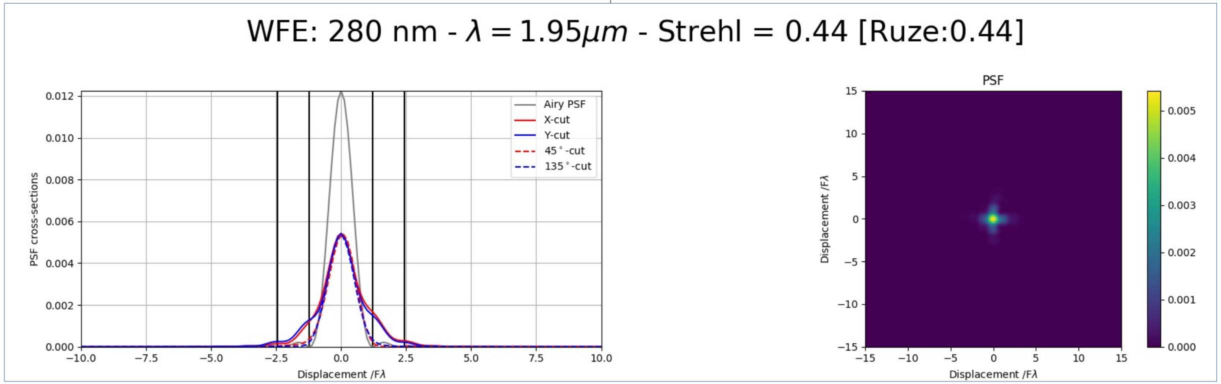
ExoSim: a realistic focal plane

Intra-pixel response

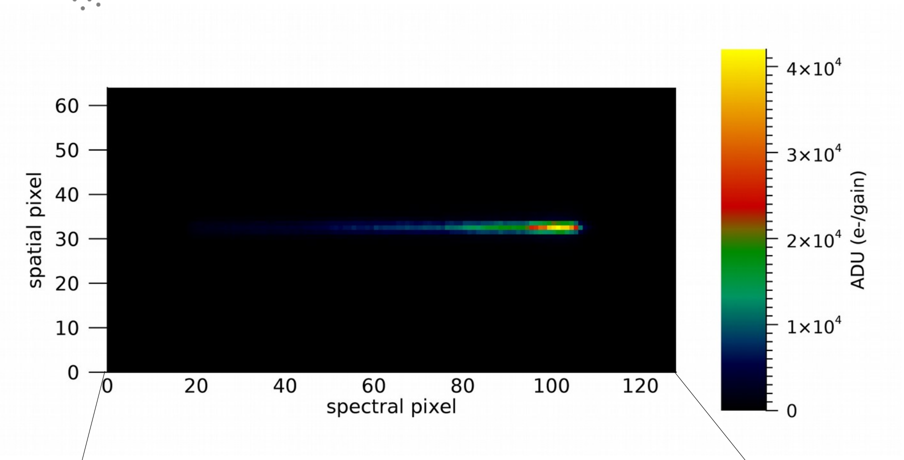


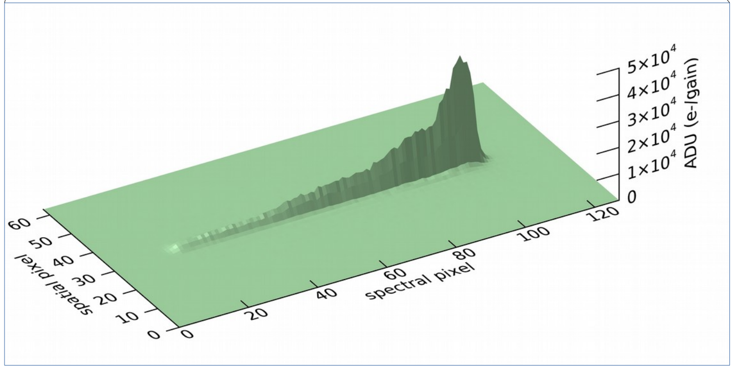
CONVOLUTION

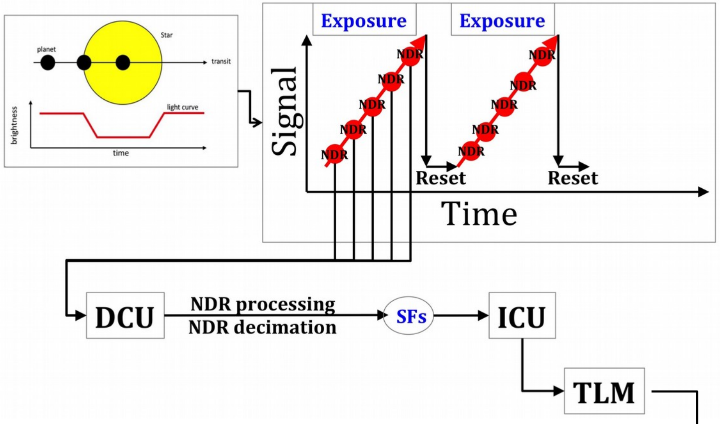
PRF vs λ



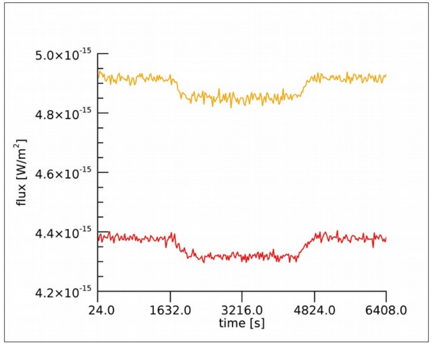
ExoSim: simulates focal plane detection





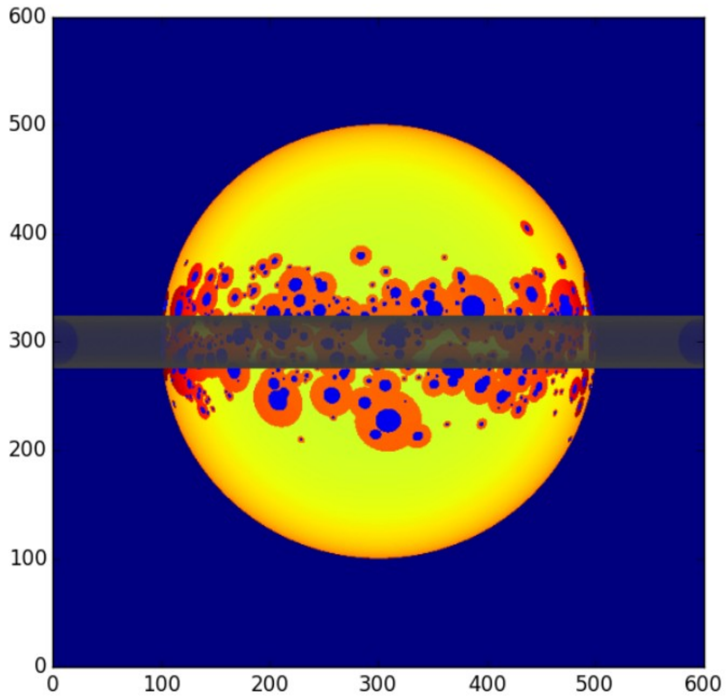


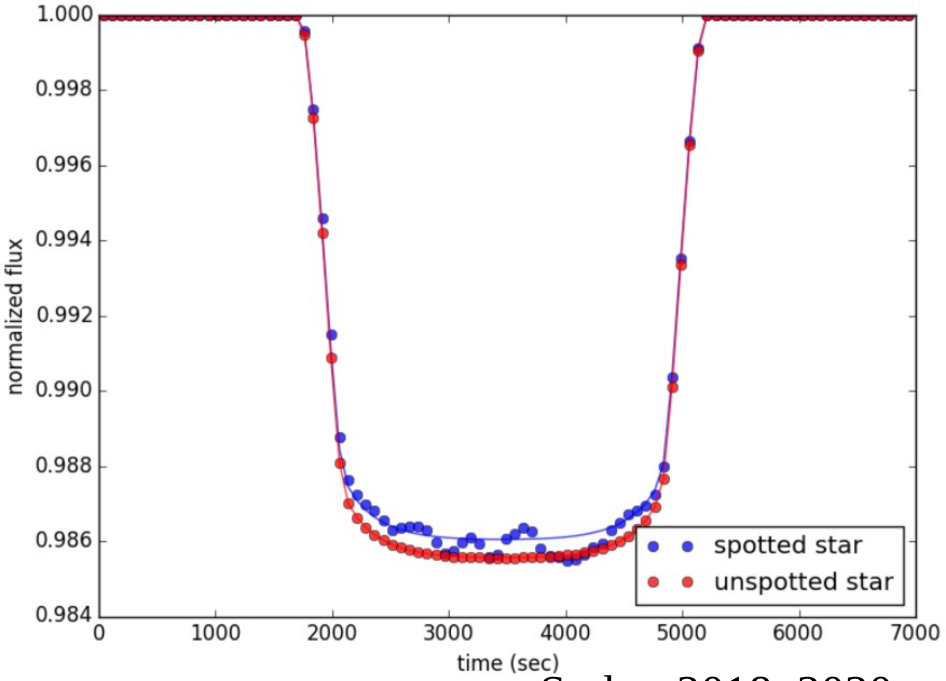
ADaRP



Sarkar 2018, 2020

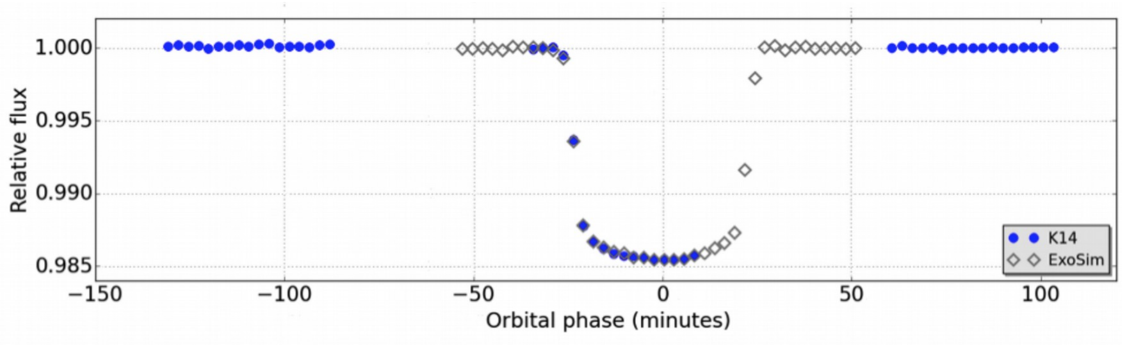
Simulation of astrophysical systematics





Sarkar 2018, 2020

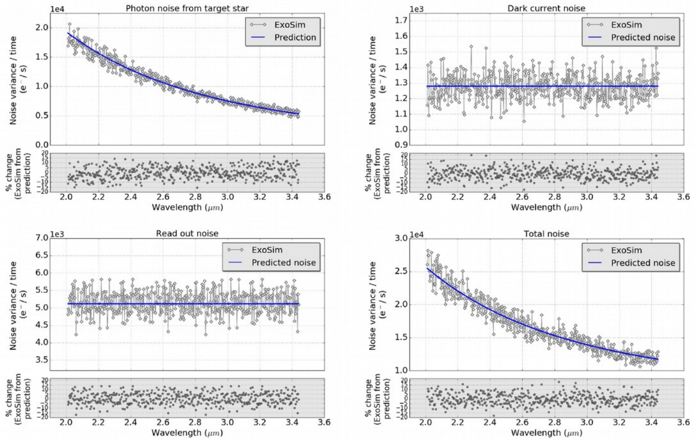
ExoSim is reliable



ExoSim configured to simulate WFC3

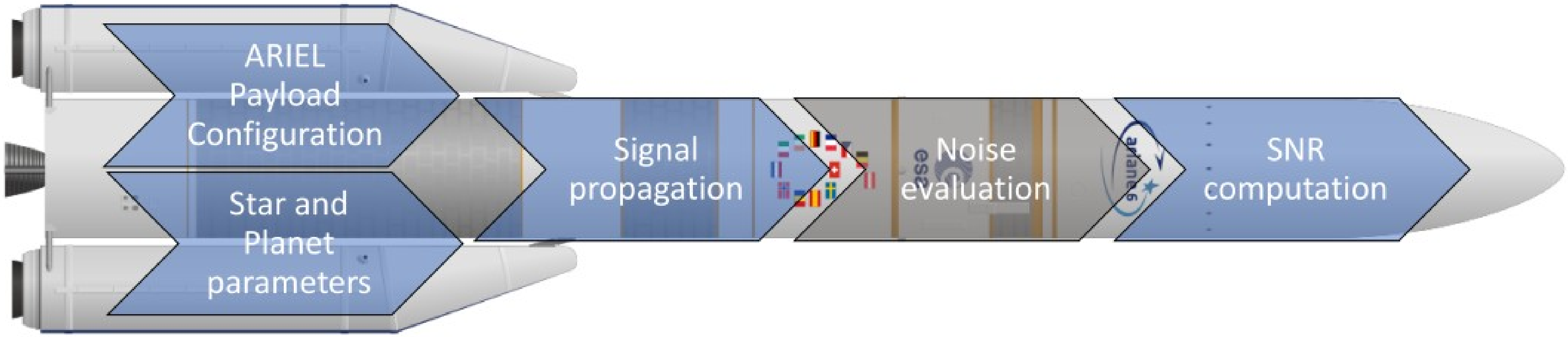
- Blue points: GJ 1214b white light curve of a transit of GJ 1214b (From Kreidberg 2014)
- Open points: ExoSim

ExoSim has also been validated
- Against model predictions
- Against radiometric model (Puig 2015) developed at ESA during phase/A study



Sarkar 2018, 2020

ArielRad: ARIEL radiometric model



- Simulates detection using a radiometric model of the science payload
- Accounts for stationary noise processes
- Also accounts for processes that are either non-stationary or require a time-domain simulation by importing relevant ExoSim outputs: e.g. pointing jitter

- Estimates signals, noise, SNR, and payload metrics for all candidate targets, in ARIEL
  - ✓ Reconnaissance Survey Tier
  - ✓ Deep Survey Tier
  - ✓ Benchmark/Reference Planets Tier

Mugnai 2020

ArielRad Noise Model

$$\frac{Var(S)}{S^2} = \begin{cases} \left[\frac{\sigma_R^2}{R^2} \left(1 + \frac{N_{pix} I_D}{k \eta_s QE N_0} \right)^2 + \frac{\sigma_t^2}{\Delta t^2} + \frac{\sigma_{\eta_s}^2}{\eta_s^2} + \frac{\sigma_{\eta_{opt}}^2}{\eta_{opt}^2} + \frac{\sigma_{QE}^2}{QE^2} \right] \times \frac{\Delta t}{T} + \\ + g_\gamma \frac{1+X}{k \eta_s QE N_0} \times \frac{1}{\epsilon T} + \\ + \frac{N_{pix} I_D + N_{pix} \sigma_{rd}^2 / (\epsilon \Delta t)}{(k \eta_s QE N_0)^2} \times \frac{1}{\epsilon T} + \\ + p_0^2 \end{cases}$$

(gain terms)

(photon noise term)

(dark current and read noise)

(Payload noise floor)

$$\sigma_{rd}^2 = \frac{12(n-1)}{n(n+1)} \sigma_{rd0}^2 \qquad g_\gamma = \frac{6(n^2+1)}{5n(n+1)}$$

margins

On the left, the general expression of the ARIEL noise model

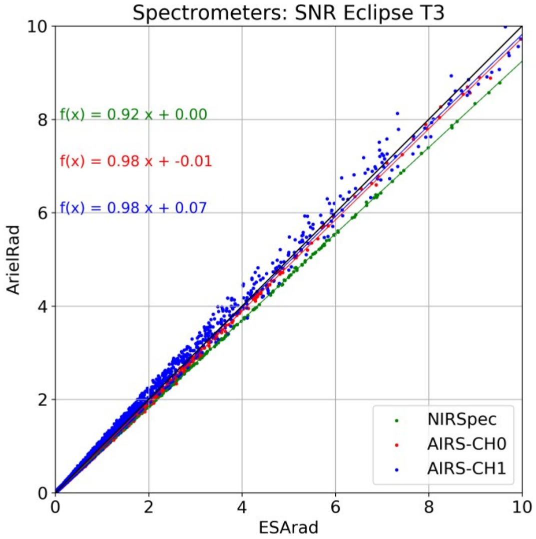
- Gains: effects that multiplies the astronomical signal true value
- Photon noise
- Detector: dark current + read noise
- Floor: time-coloured noise and systematics.

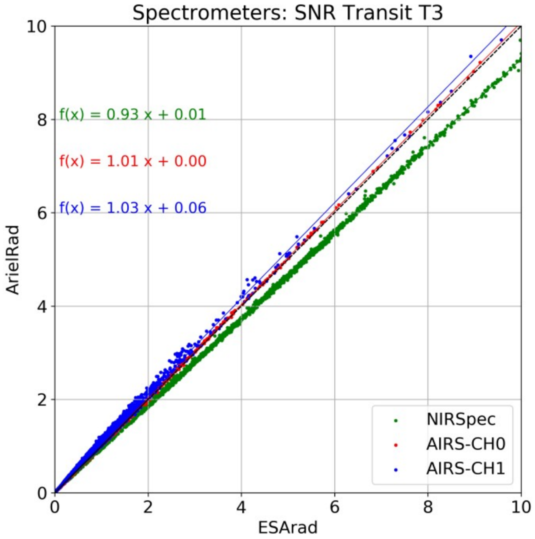
ArielRad: validation

Channel	GJ 1214	HD 209458	HD 219134
	Percent variation		
VISPhot	-0.8	-0.5	-0.4
AIRS-CH0	-2.9	1.0	1.2
AIRS-CH1	4.4	2.5	2.8

Comparison of detector saturation times estimated by ExoSim and ArielRad: validates instrument model

Comparison of SNR on atmospheric detection between ArielRad and Puig 2015 model: validates planet modelling.





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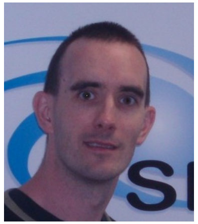
Simulations Community Support

- Support payload design optimisation activities
- Performance verification
  - Compliance with Science Requirements
  - Estimate goal science objectives
  - Ancillary science investigation

All estimates include margins:
- 20% on standard deviations
- 20ppm noise floor
- Larger than expected detector noise
- Lower than expected electronic stability

- Ground Segment support
  - See P. Malaguti and Chris poster and presentation



Simulations Community Support

- Support astrophysical community by providing detection performance estimates

generic ARIEL target performance estimate

Name	Wavelength	BandWidth	LeftBinEdge	RightBinEdge	totalNoise	NoiseOnTransit	NoiseOnTransitFloor
		[micron]			[ppm √hr]	[ppm]	[ppm]
VISPhot	0.55	0.10	0.50	0.60	43	43	47
FGS1	0.70	0.20	0.60	0.80	43	42	47
FGS2	0.95	0.30	0.80	1.10	41	40	45
…	…	…	…	…	…	…	…
NIRSpec	1.13	0.06	1.10	1.16	64	63	66
NIRSpec	1.44	0.07	1.40	1.47	43	43	47
…	…	…	…	…	…	…	…
AIRS-CH0	2.07	0.02	2.06	2.08	68	67	70
AIRS-CH0	2.08	0.02	2.07	2.09	68	67	70
…	…	…	…	…	…	…	…
AIRS-CH1	6.38	0.21	6.27	6.48	94	92	94
AIRS-CH1	6.48	0.21	6.38	6.59	97	95	97
…	…	…	…	…	…	…	…

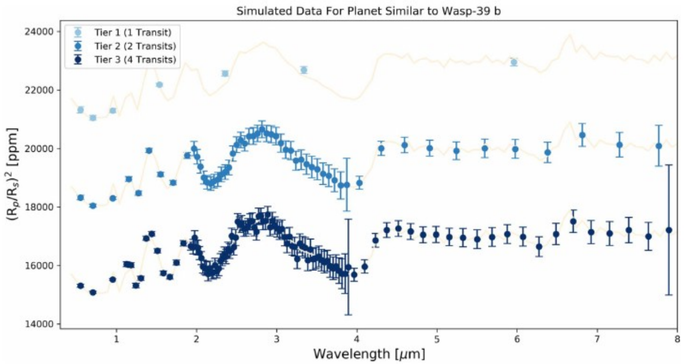
End-to-end simulations

Forward

Detection

Model
Chemistry/thermodynamics

COMPARE



Retrieve

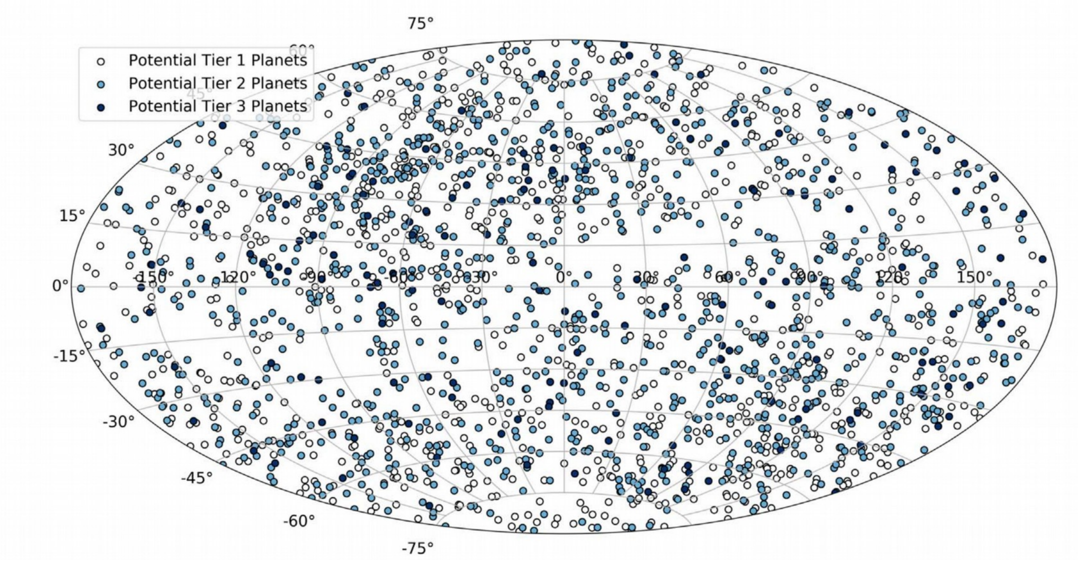
Lorenzo Mugnai

Quentin Changeat

Ahmed Al-Refaie

ARIEL Mission Reference Sample (MRS)

See B. Edwards presentation

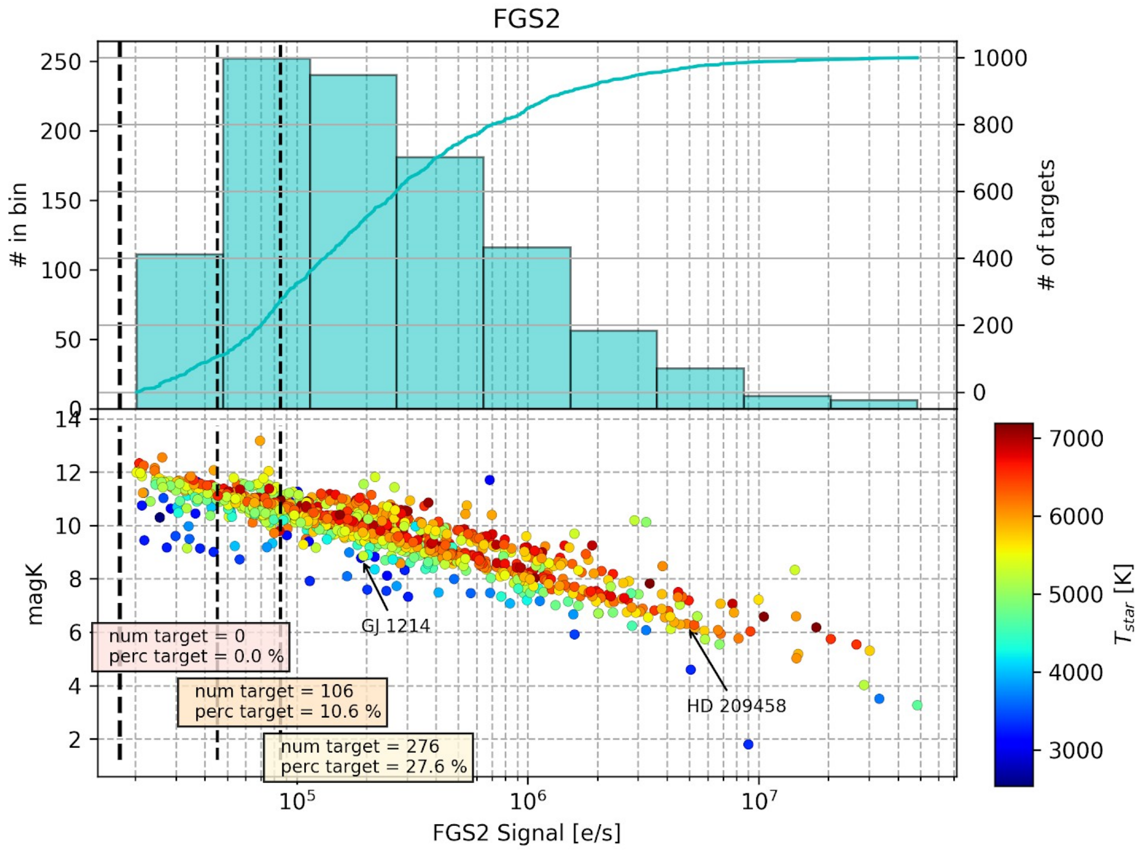


Bounds Used to Classify Potential Planets to Ensure a Varied Population of Planets within the Mission Reference Sample

Parameter	Class	Bounds
Stellar Effective Temperature	M	$T_s < 3955$ K
	K	3955 K $< T_s <$ 5330 K
	G	5330 K $< T_s <$ 6070 K
	F	6070 K $< T_s <$ 7200 K
Planetary Radius	Earth/super-Earth	$R_p < 1.8\ R_\oplus$
	Sub-Neptune	$1.8\ R_\oplus < R_p < 3.5\ R_\oplus$
	Neptune	$3.5\ R_\oplus < R_p < 6\ R_\oplus$
	Jupiter	$6\ R_\oplus < R_p < 16\ R_\oplus$
	Massive Jupiter	$R_p > 16\ R_\oplus$
Planetary Equilibrium Temperature	Temperate/warm	$T_p < 500$ K
	Very warm	500 K $< T_p <$ 1000 K
	Hot	1000 K $< T_p <$ 1500 K
	Very hot	1500 K $< T_p <$ 2500 K
	Ultra hot	$T_p > 2500$ K

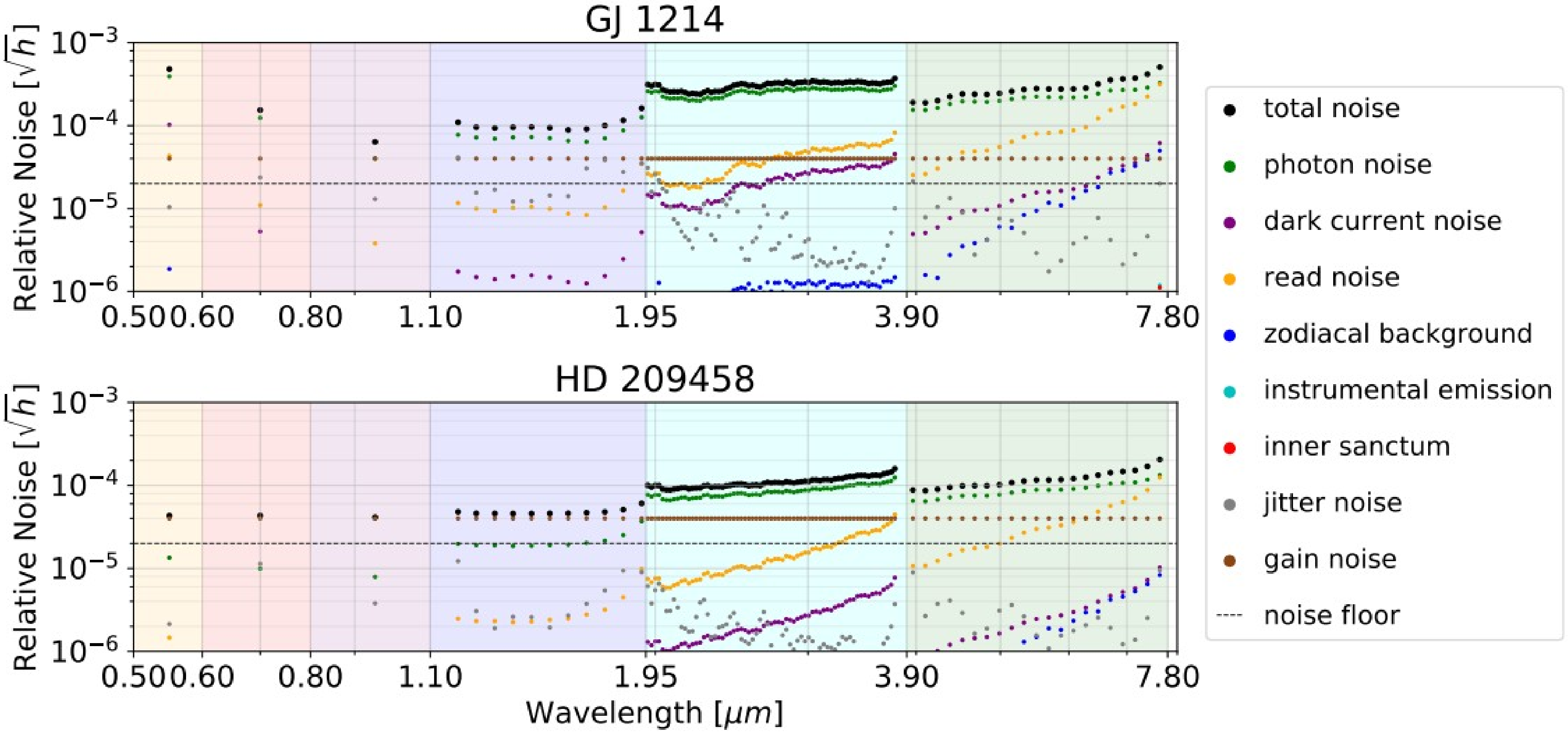
Edwards 2019

Sizing targets

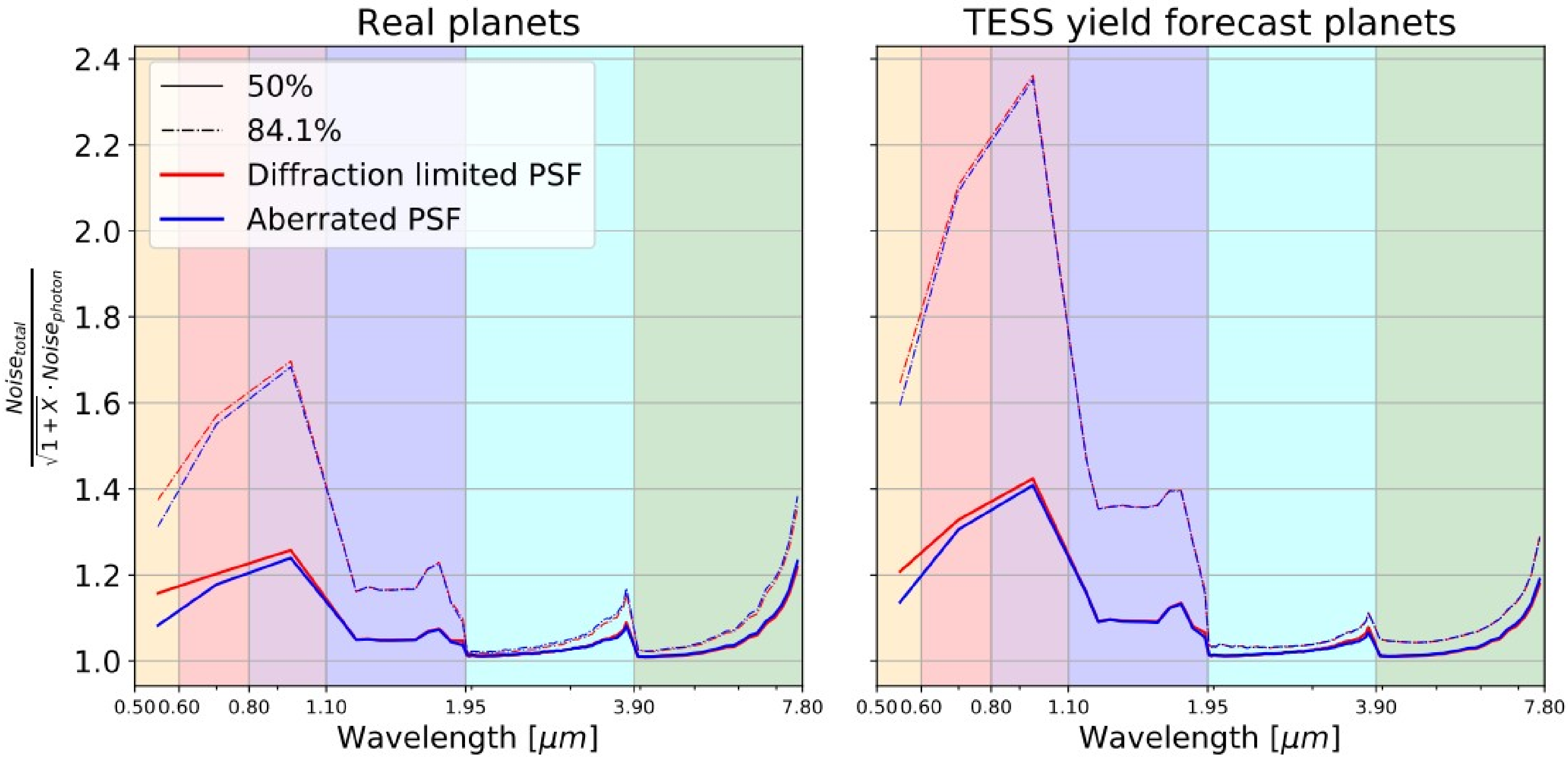


- HD 219134
  - K3B, T_{eff} = 4700K
  - magK = 3.3
- HD 209458
  - G0V, T_{eff} = 6000K
  - magK = 6.3
- GJ 1214
  - M4.5, T_{eff} = 3000K
  - magK = 8.8

ARIEL noise budget



Photon noise performance over MRS



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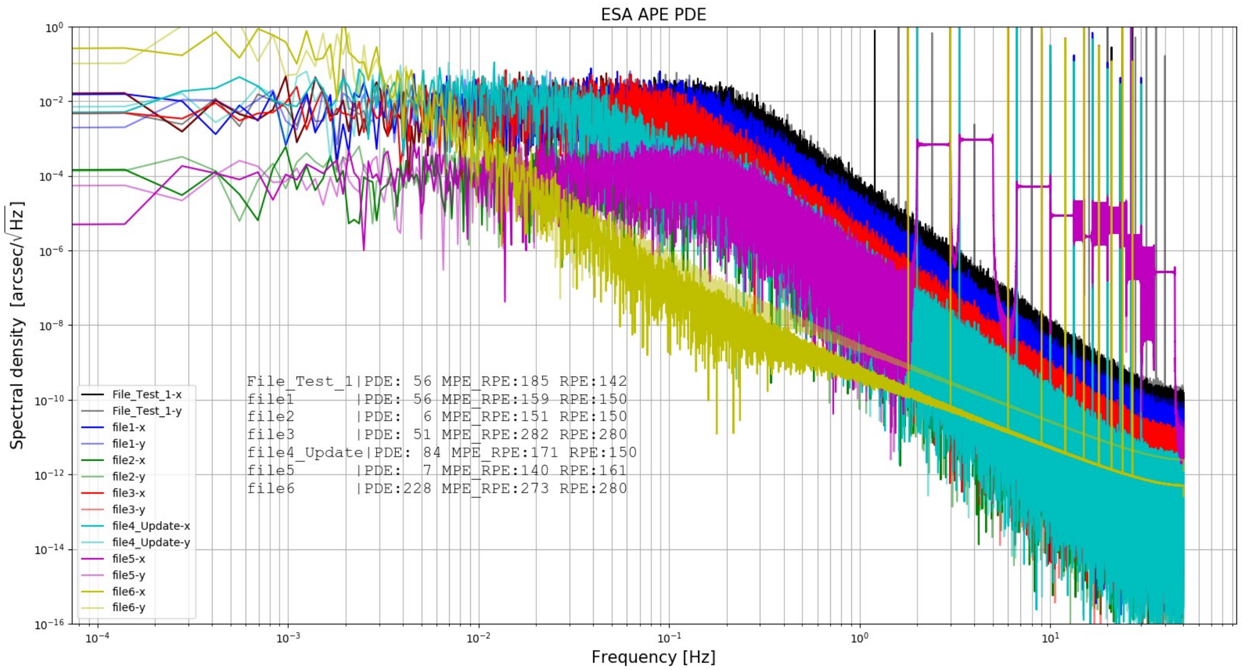
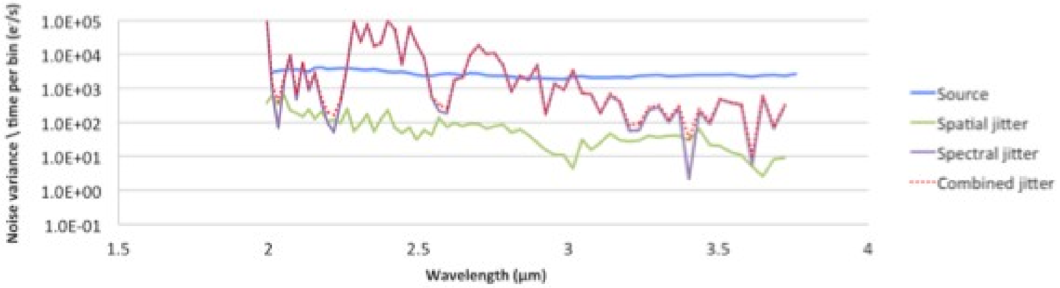
Attitude and Orbital Control System [AOCS]

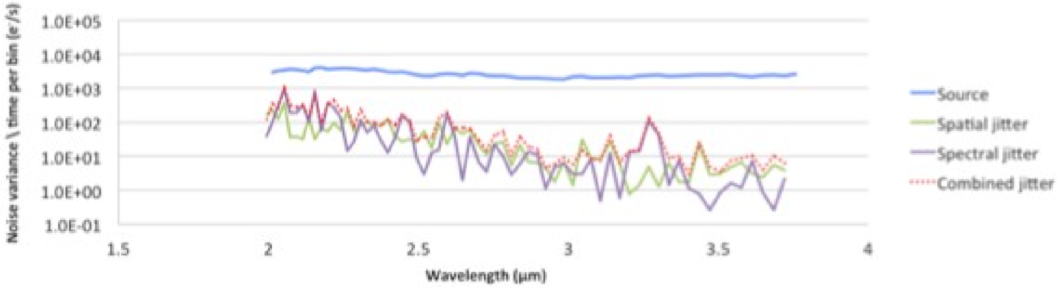


- Test-stressed payload design under uncountable AOCS solutions
- Diagram shows PSD of pointing errors for some of the models tested, and it does not give full credit to the non-stationary nature of the processes in some model.
- Some model is highly non-stationary and also includes “kicks” to the LoS stability.
- Some model has resonances at detector acquisition frequency

Pointing Stability



(A) No decorrelation



(B) Cross-correlation-Fourier

Common performance of AOCS models:

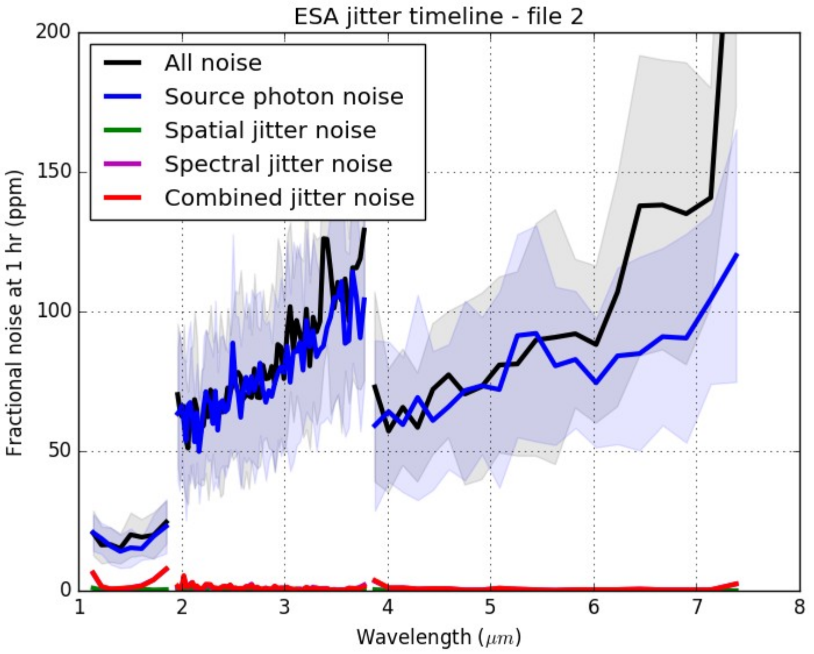
Stability ~ 1 pixel level at short time scales, mainly worst case vibrations from reaction wheels.

Stability ~ 1/10th pixel at longer time scales

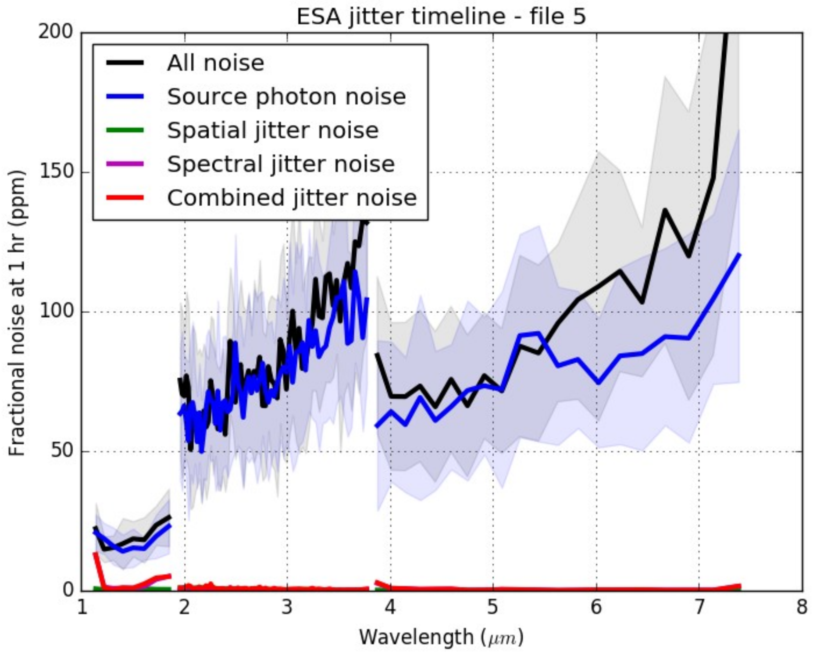
Requires detrending of spectral timelines

Pointing jitter: bright targets [HD 209458 – like]

Stationary processes only

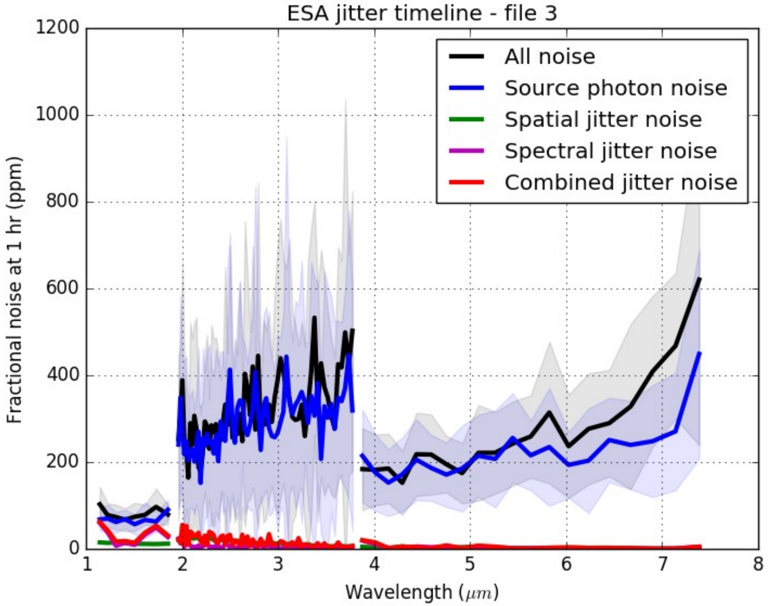


Non-stationary processes included



Pointing jitter: faint targets [GJ 1214 – like]

Stationary processes only

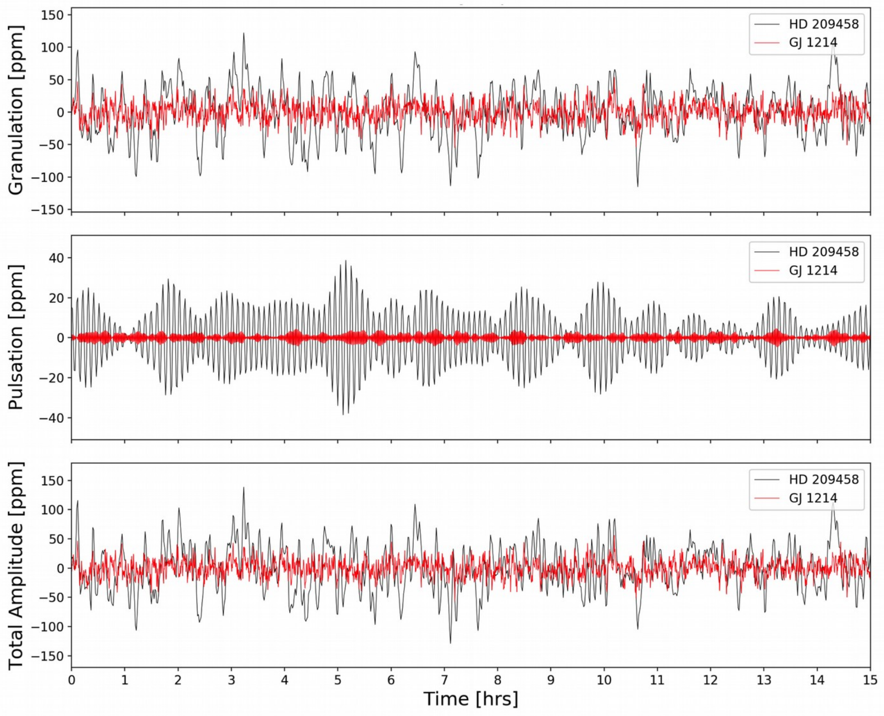


ARIEL is insensitive to diverse AOCS solutions

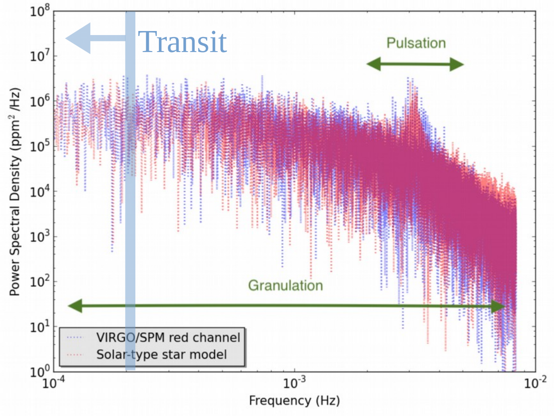
This has been achieved thanks to a careful instrument design that requires PSFs to be spatially Nyquist sampled

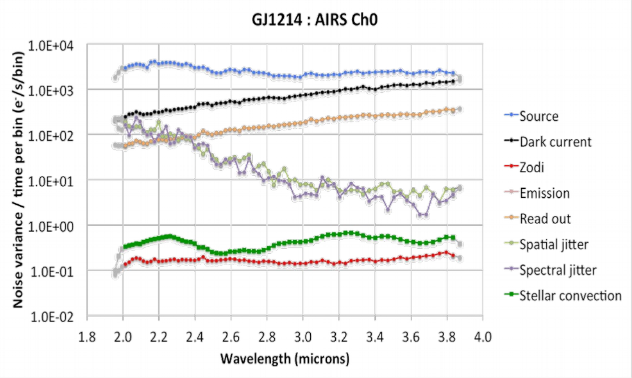
Stellar effects – Pulsation/Granulation

ExoSim simulation:
pulsation/granulation for M and G stars

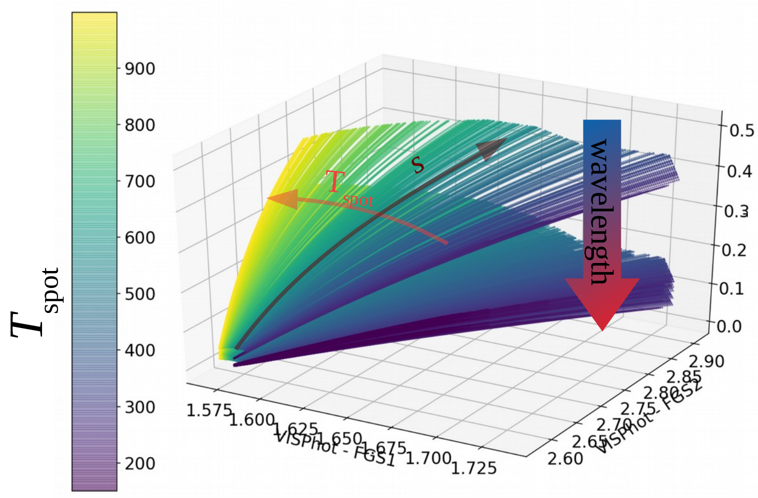


S. Sarkar 2018

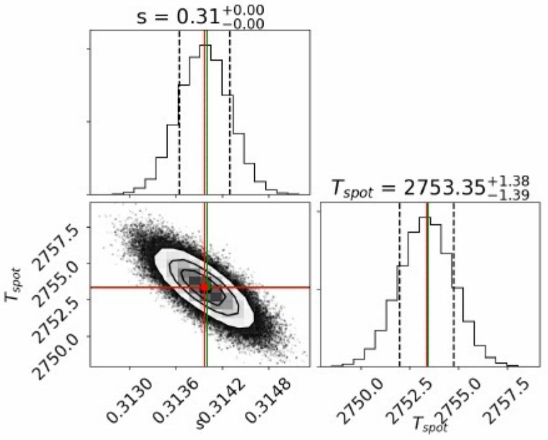


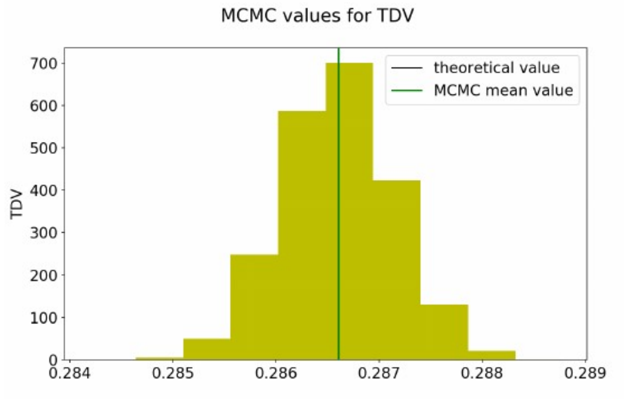


Stellar effects: spots not occulted



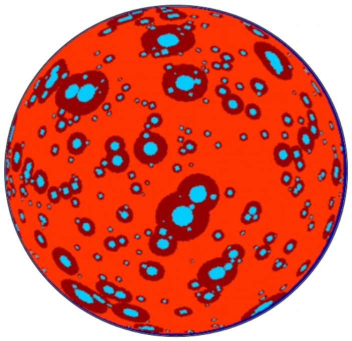
$$TDV = \frac{TD_{spot} - TD_0}{TD_0}$$

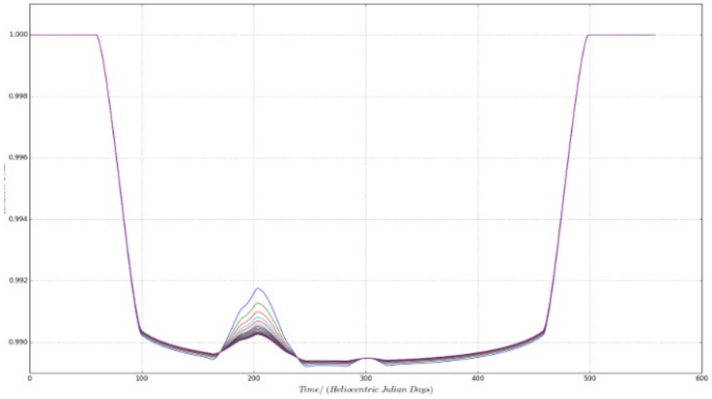


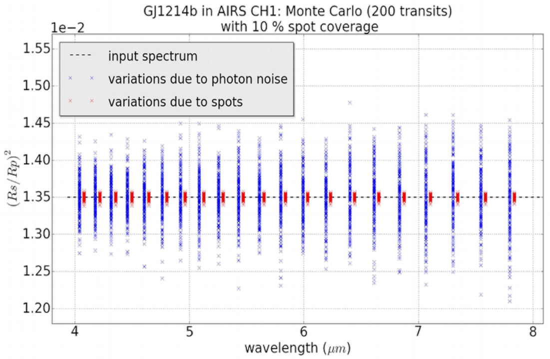


F. Amadio, Master Thesis, 2020

Stellar effects: spots







S. Sarkar and L. Johnson

See also presentation of G. Micela
for more on this topic, and
G. Cracchiolo’s poster contribution

Mission Performance

- For each target, the SNR of the detection is estimated
- The signal is
  - Transit: atmospheric height

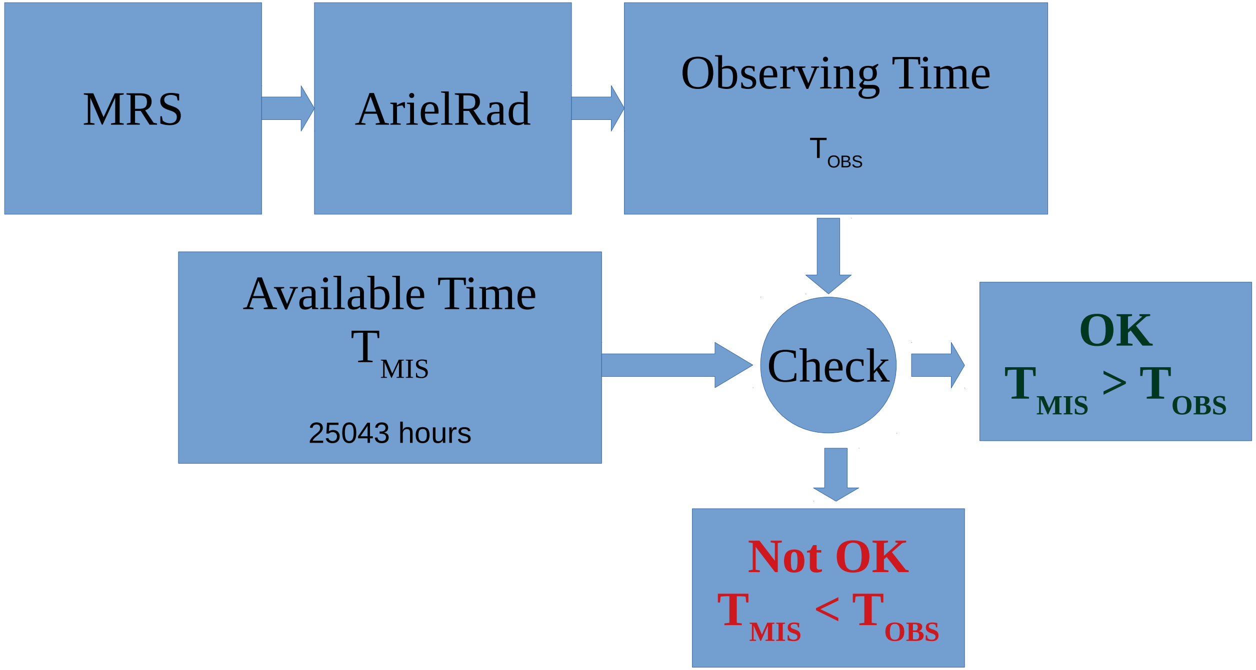
$$S = \frac{2 R_P n H}{R_*^2}$$

  - Eclipse: planet emission/reflection

$$S = \frac{BB(T_P)}{I_*^2} \frac{R_P^2}{R_*^2} + \alpha(\lambda) \frac{R_P}{a}$$

- The noise is from by ArielRad
- Atmosphere is detected when SNR ≥ 7, or
- ArielRad estimates the observing time needed to reach SNR = 7

Mission Performance



Mission Performance

Tier	N target	Total observing time [*h*]	Rel. observing time
Reconnaissance survey	398	6 384	26%
Deep survey	548	16 841	67%
Benchmark	49	1 679	7%
Total	995	**24 904**	100%
Available time		**25 044**	

Pessimistic estimate. Includes:
- 20% margin on noise
- pessimistic electronic stability assumptions made

Final remarks

- The ARIEL payload is designed to provide stable spectrometric and photometric measurements from a few ppm to ~10 ppm level from the Visible to the mid-IR
- Achieved thanks to
  - Integrated payload design
  - A payload design that accounts for known systematics
- ARIEL can survey the atmospheres of ~1000 targets during primary mission lifetime
- Performance predictions available to support science optimisation (targets, analysis methods, science exploitation preparation).