Detector Modeling Workshop: Modelling detector interference (in the infrared)

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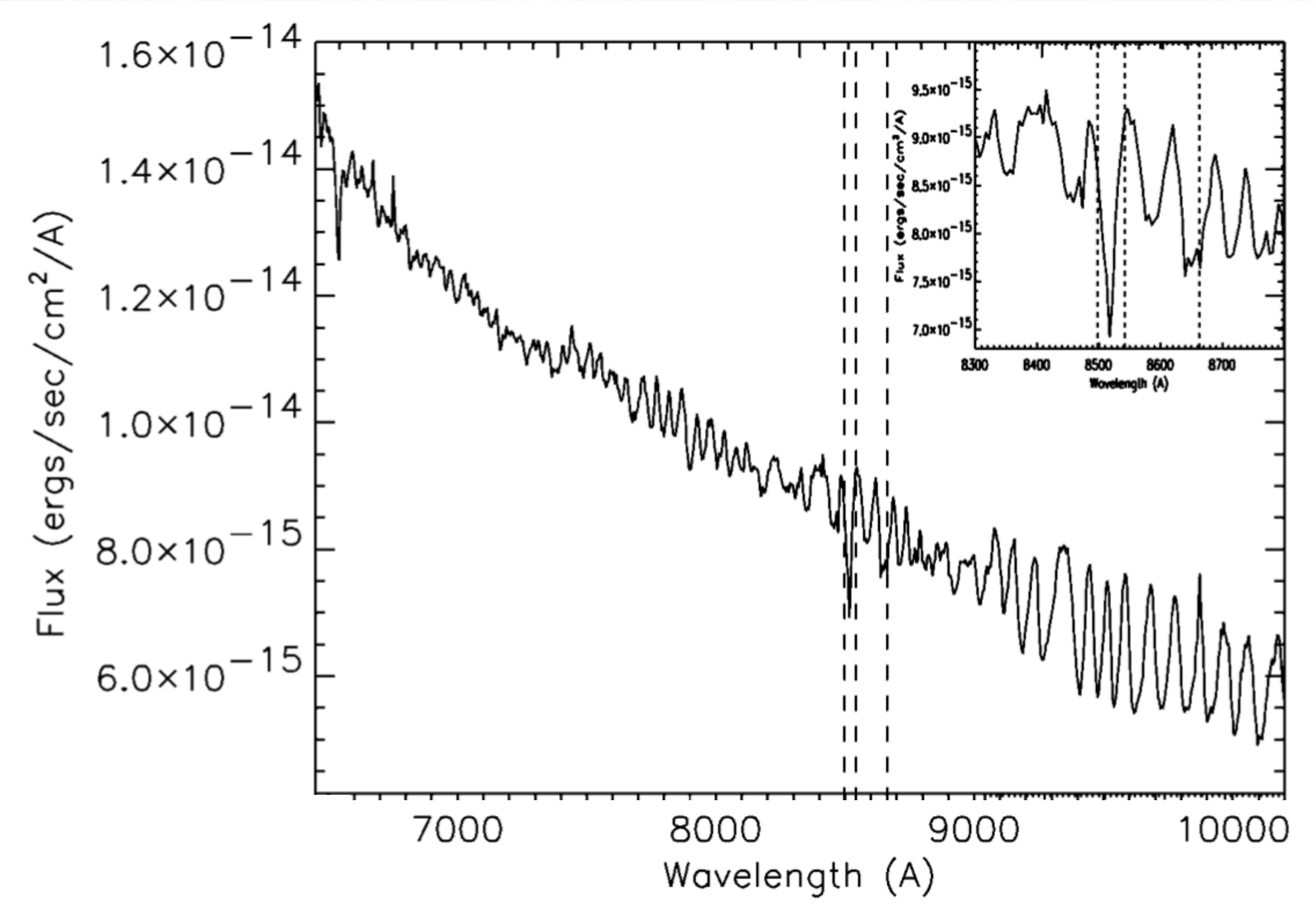
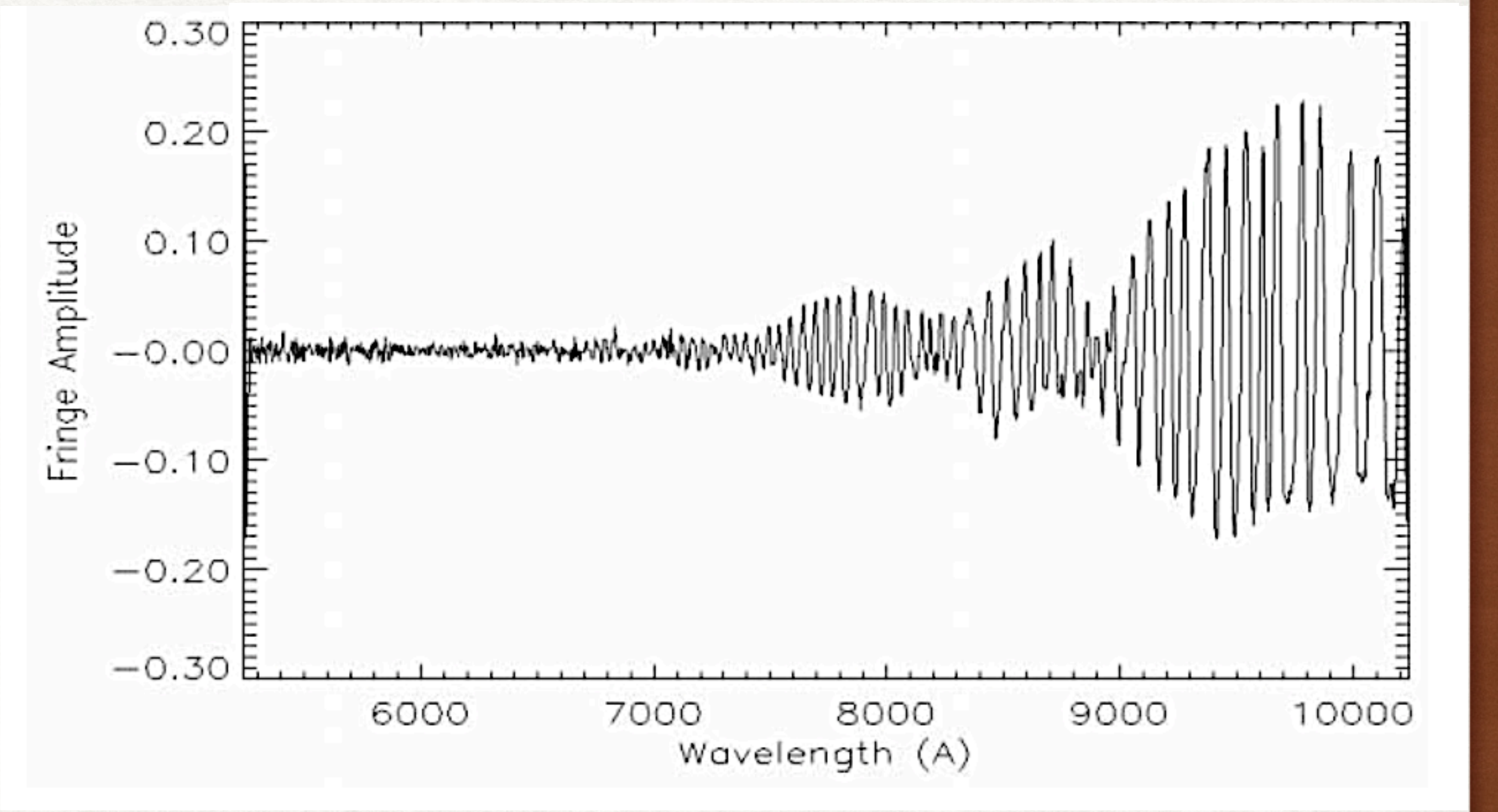
DETECTOR INTERFERENCE - SOME EXAMPLES

- Hubble Space Telescope - STIS CCD data



HST/STIS spectrum of F-type star with CaII triplet.

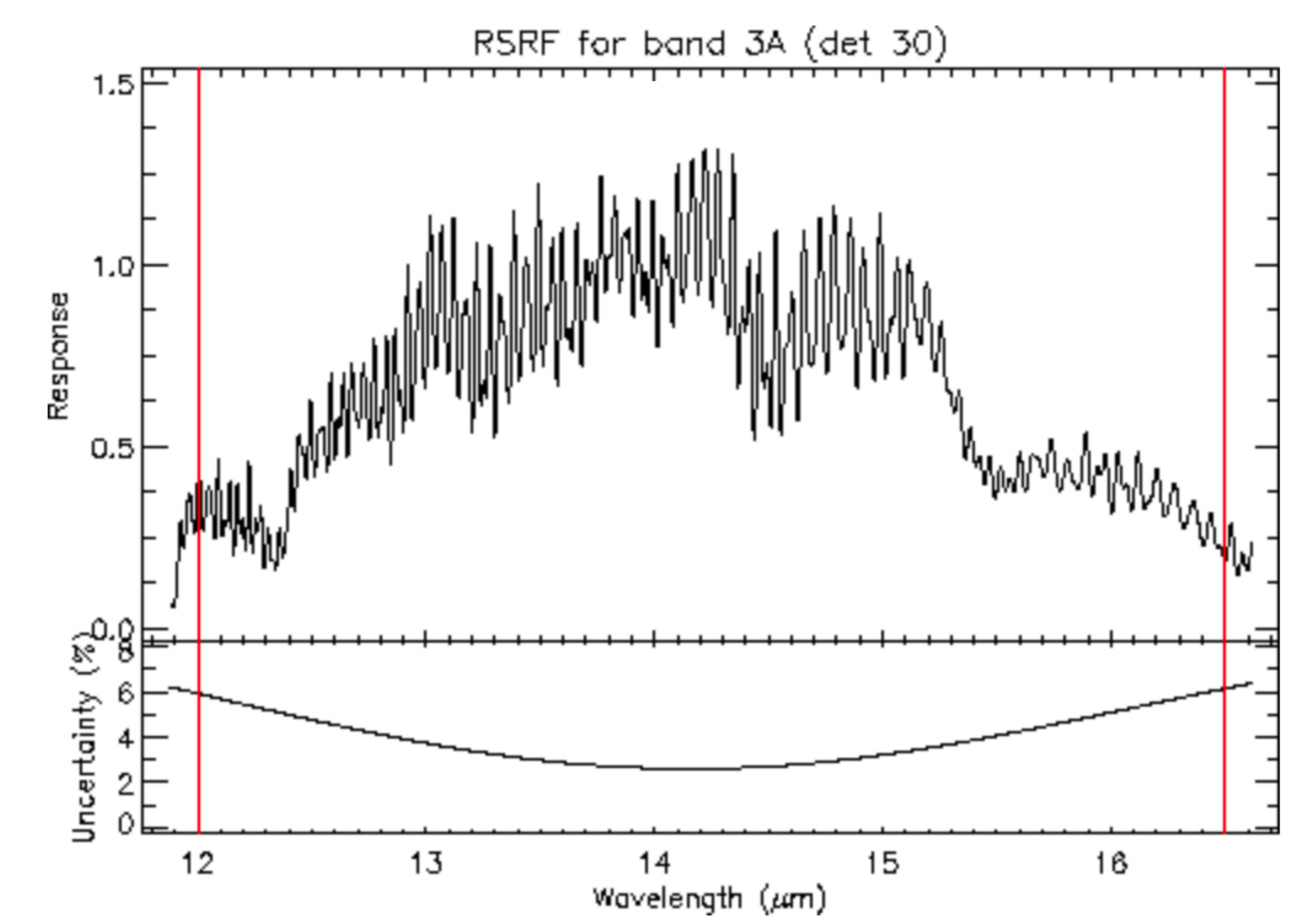


Extracted fringe modulation from STIS internal calibration source spectrum.

Credit: E. M. Malumuth et al. 2003

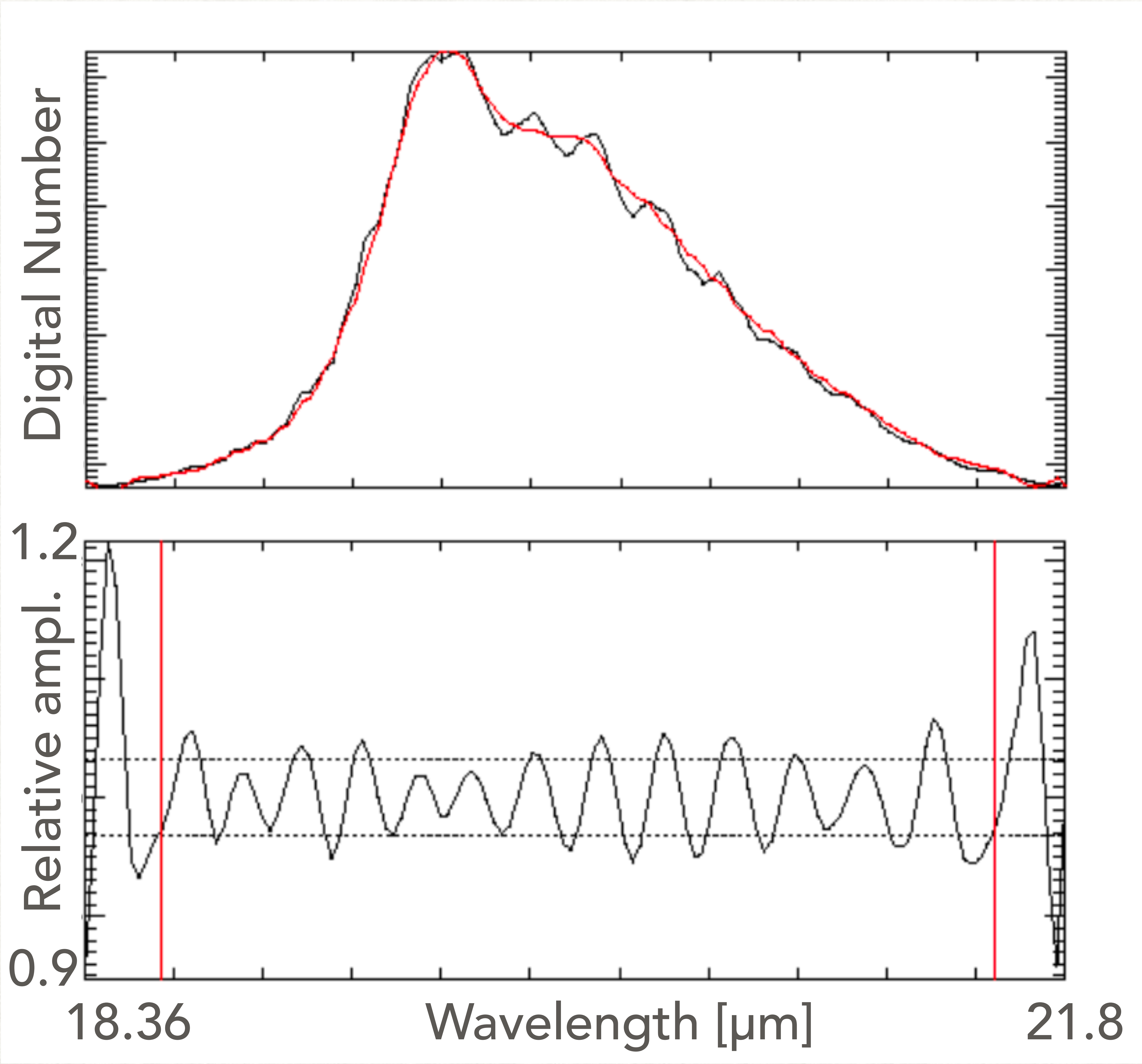
DETECTOR INTERFERENCE - SOME EXAMPLES

- Infrared Space Observatory - SWS BIB detector response

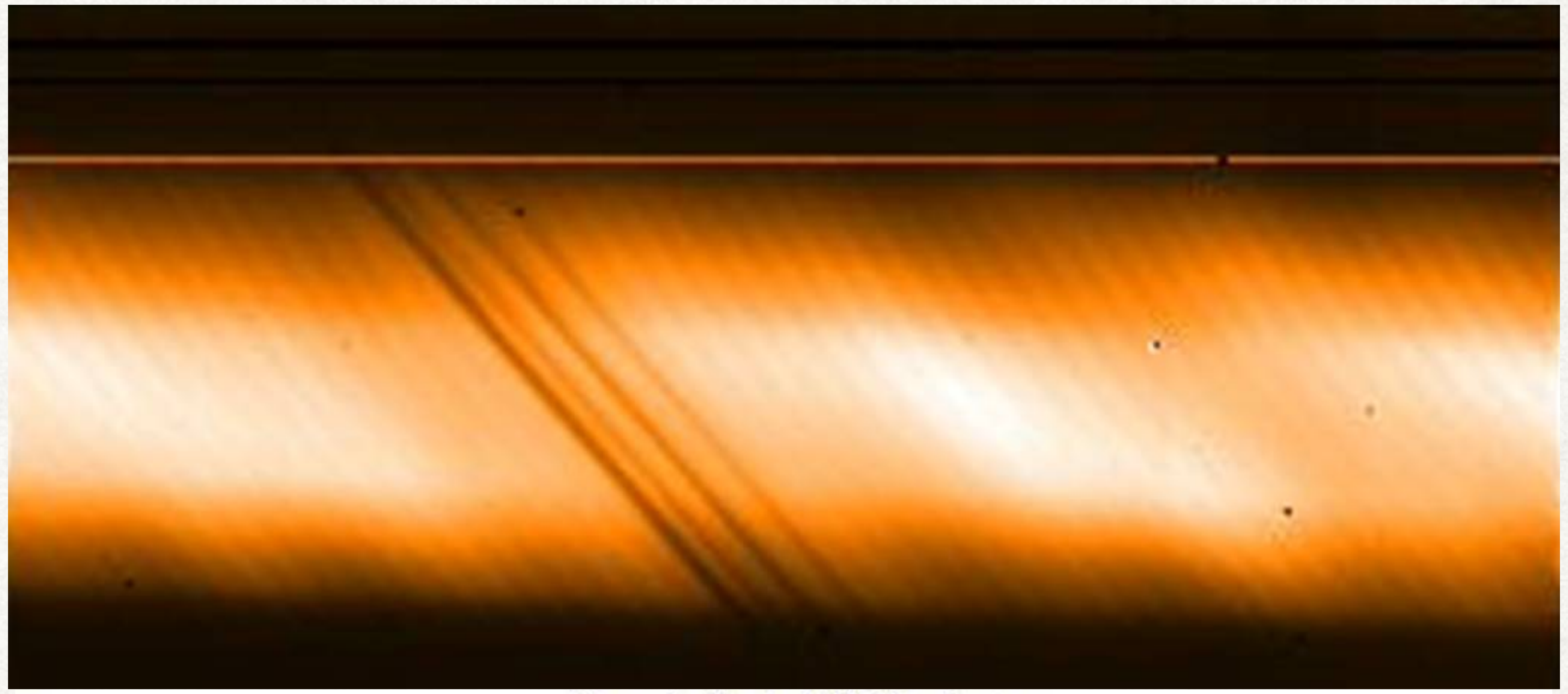


Credit: ISO SWS instrument handbook

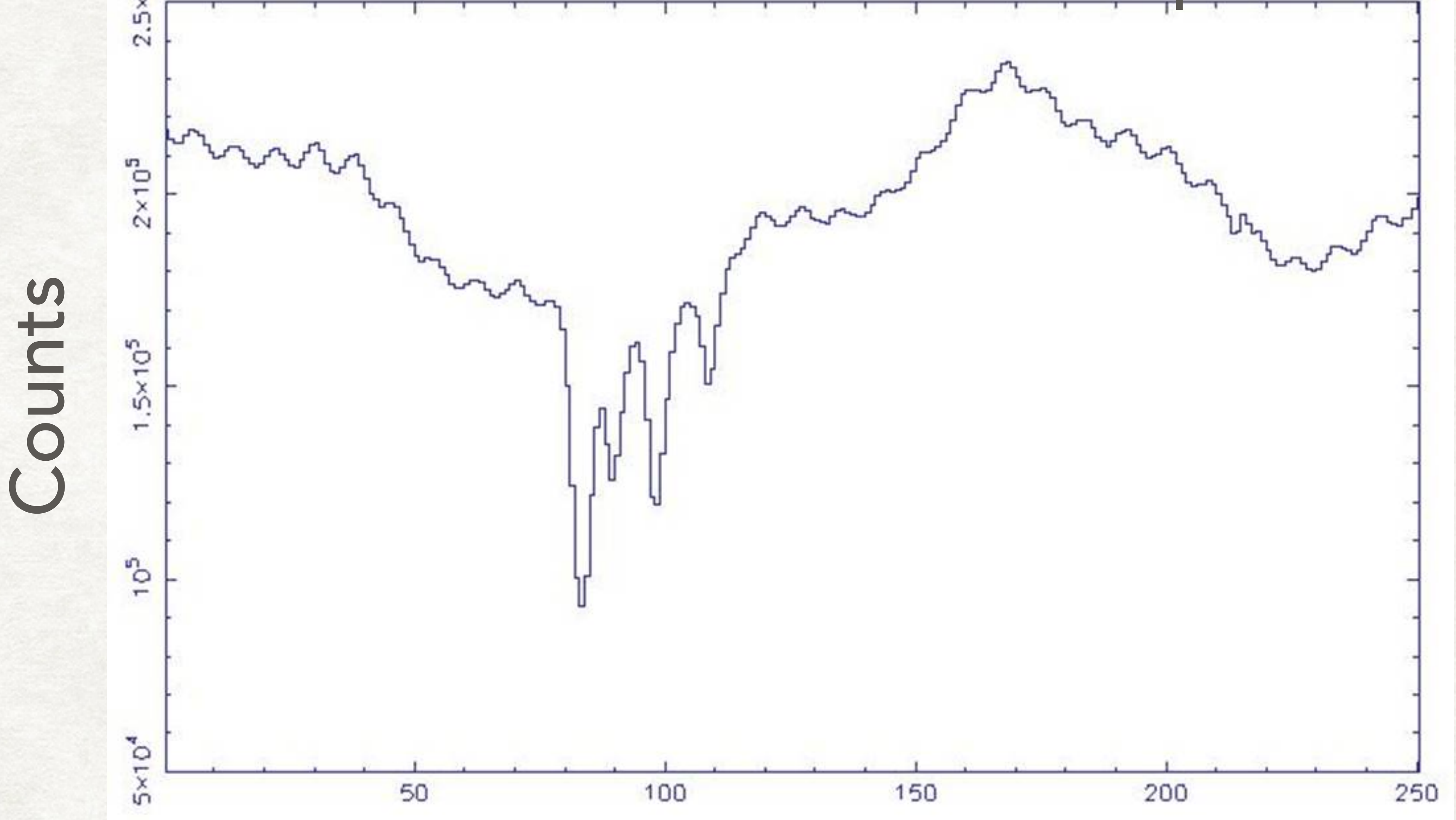
DETECTOR INTERFERENCE - SOME EXAMPLES



Spitzer Space Telescope - IRS (P. Morris 2003)



Ammonia band at 11.52μm



Michelle spectrum (UKIRT)
- Courtesy of Dr. Alistair Glasse

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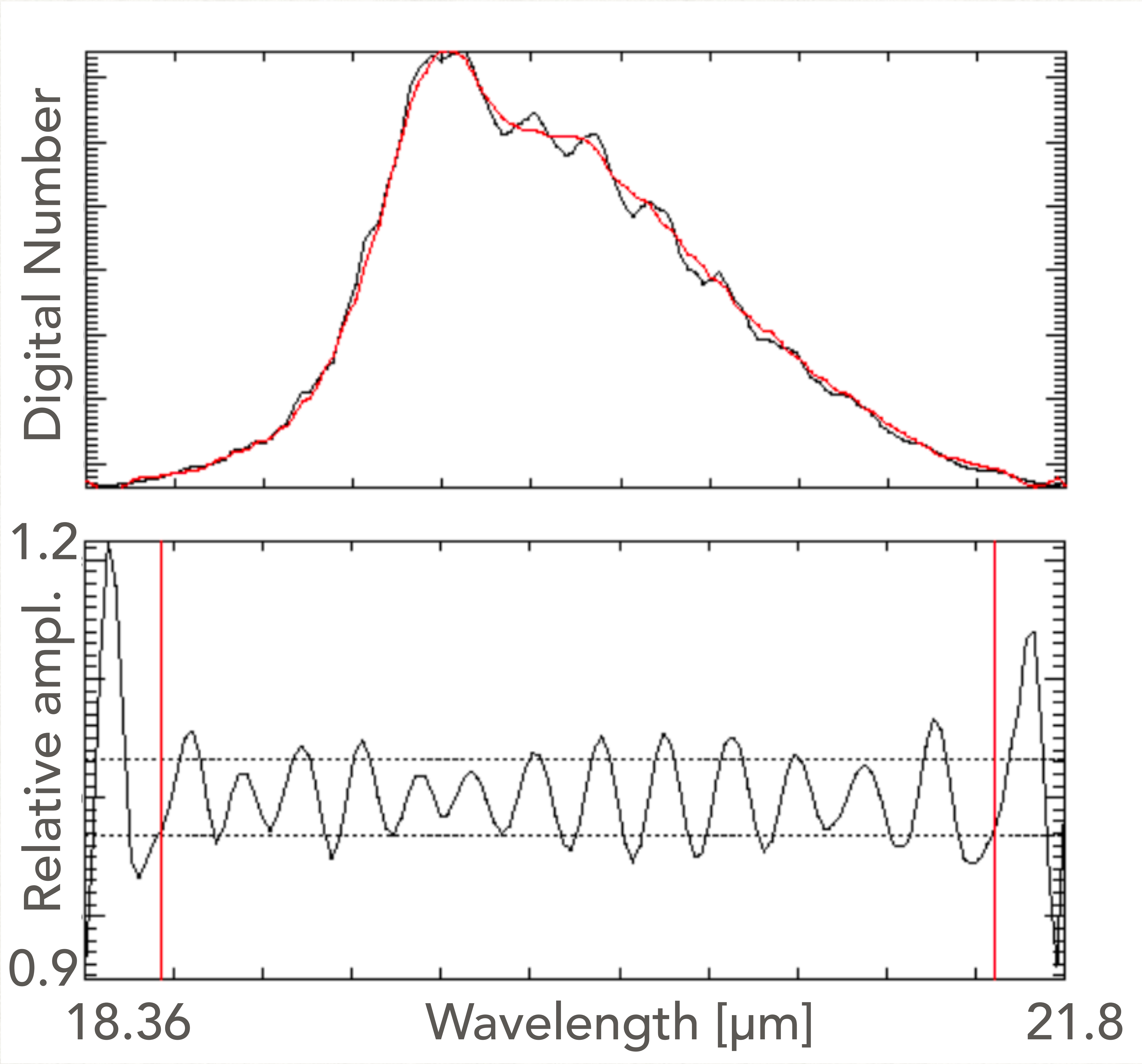

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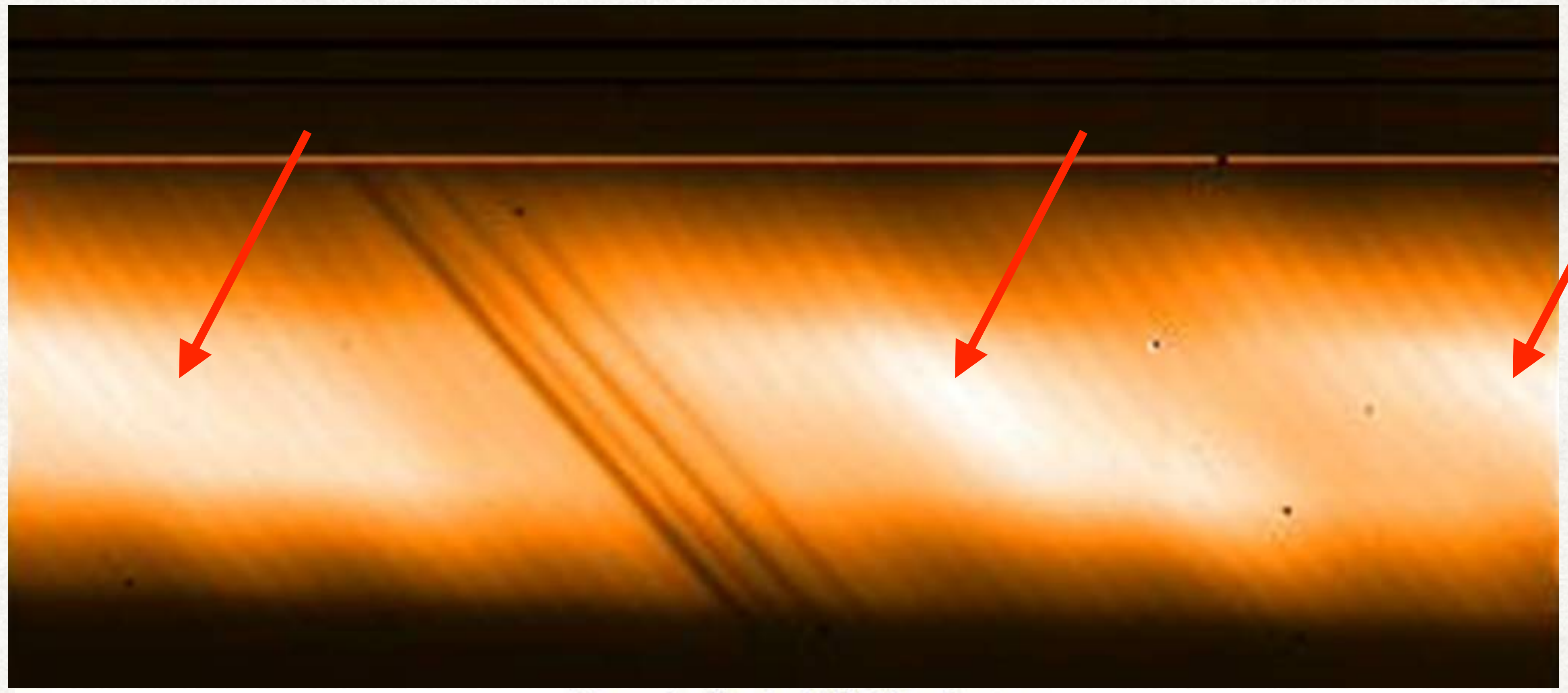

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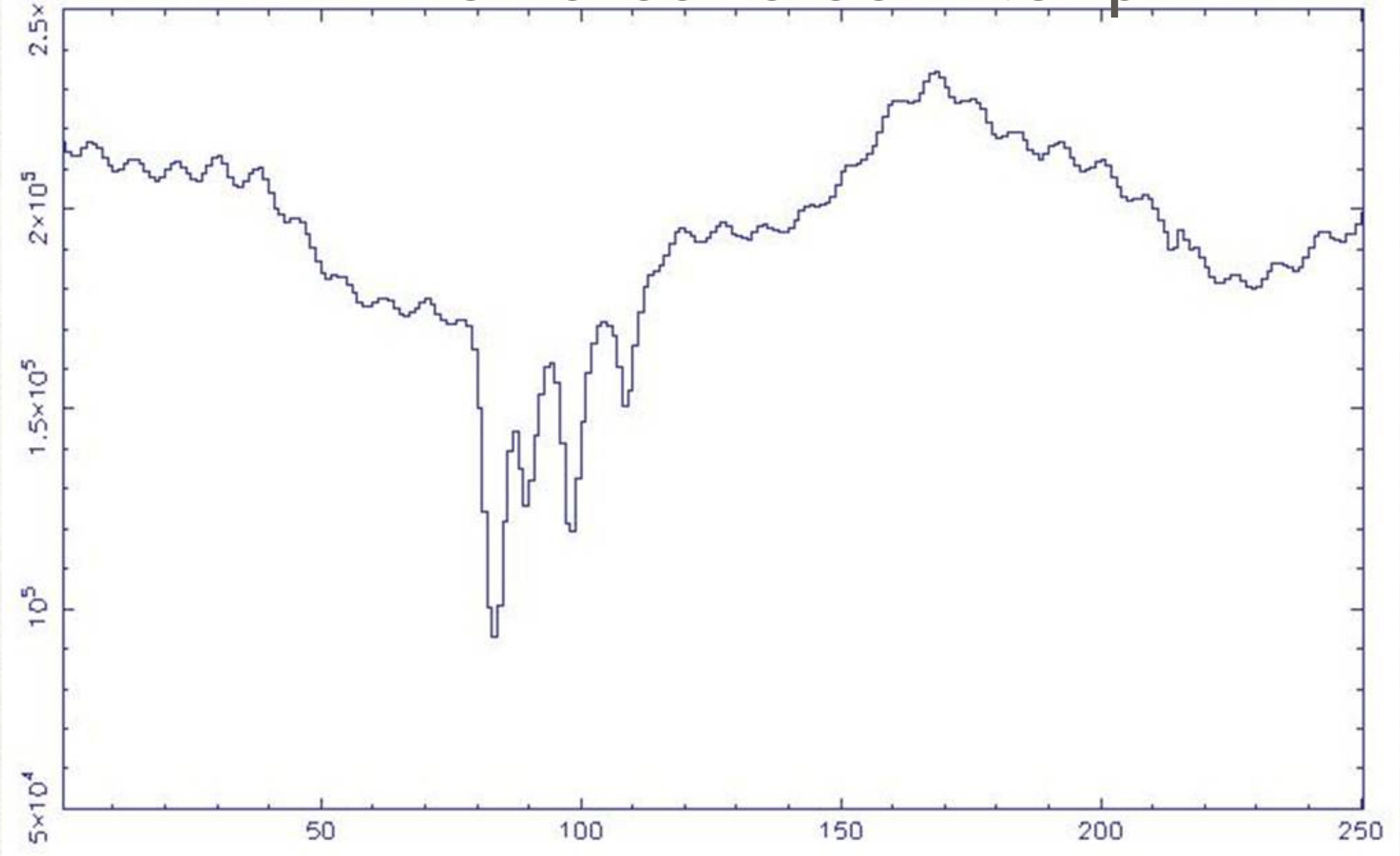

Michelle spectrum (UKIRT)
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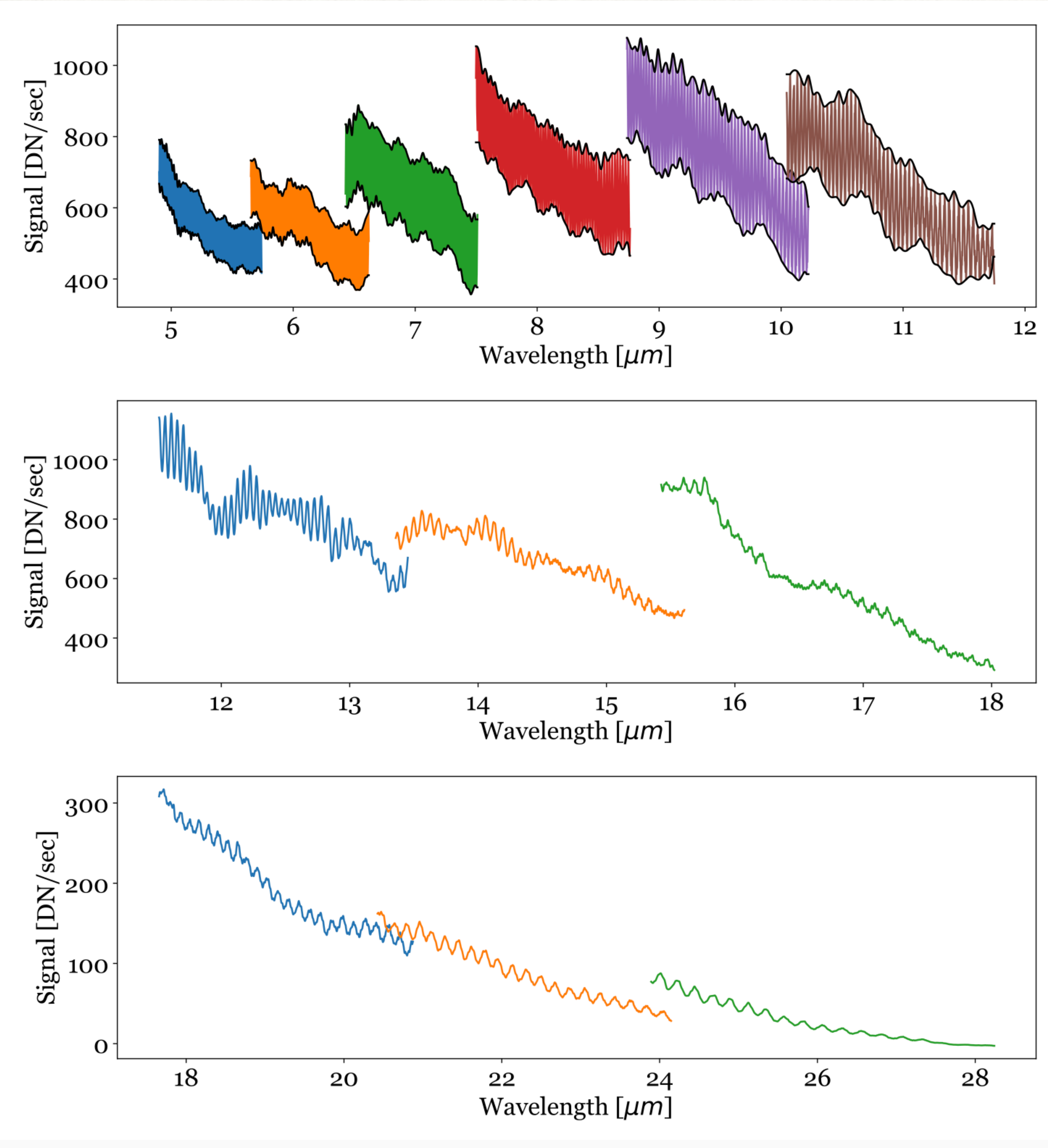
DETECTOR INTERFERENCE - JWST/MIRI/MRS

- The JWST/MIRI/MRS instrument is an integral field spectrometer operating in the 5-28μm wavelength range. It uses two Si:As blocked impurity band (BIB) detectors of 1024x1024 pixels, operated at a temperature of ~7 Kelvin.

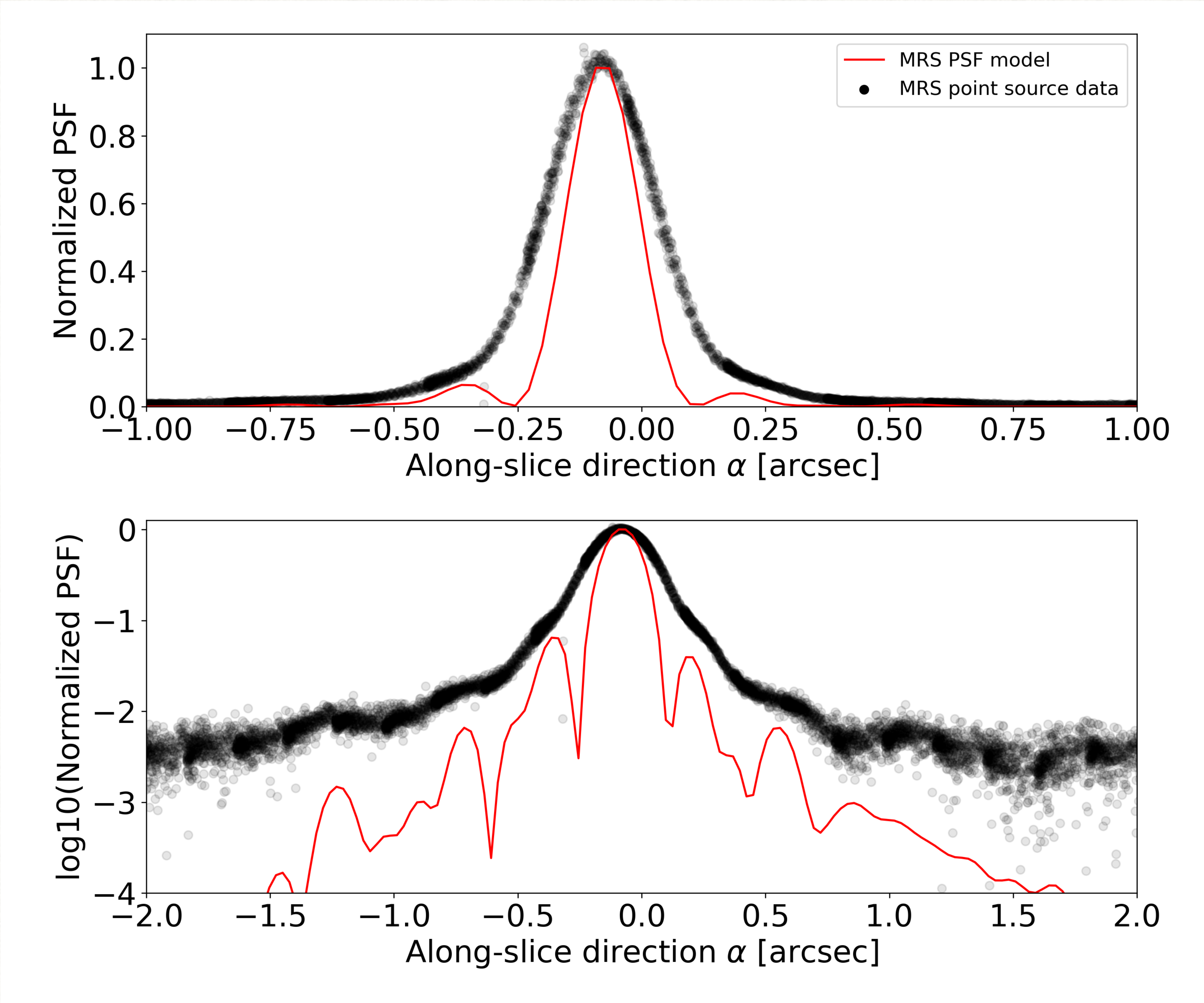
- The MRS has a spectral resolution of ~3500 at 5μm and ~1000 at 25μm, and records fringes that modulate the spectral baseline by 10-30%.



All 12 MRS spectral bands

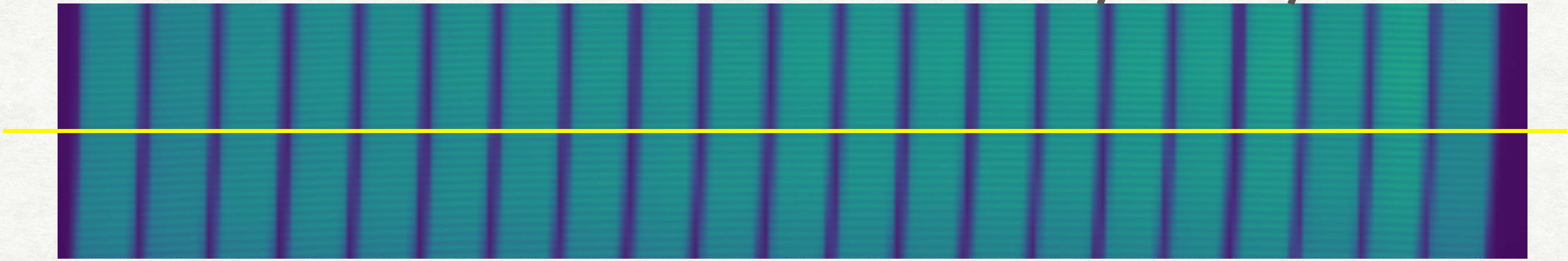
DETECTOR INTERFERENCE - JWST/MIRI/MRS

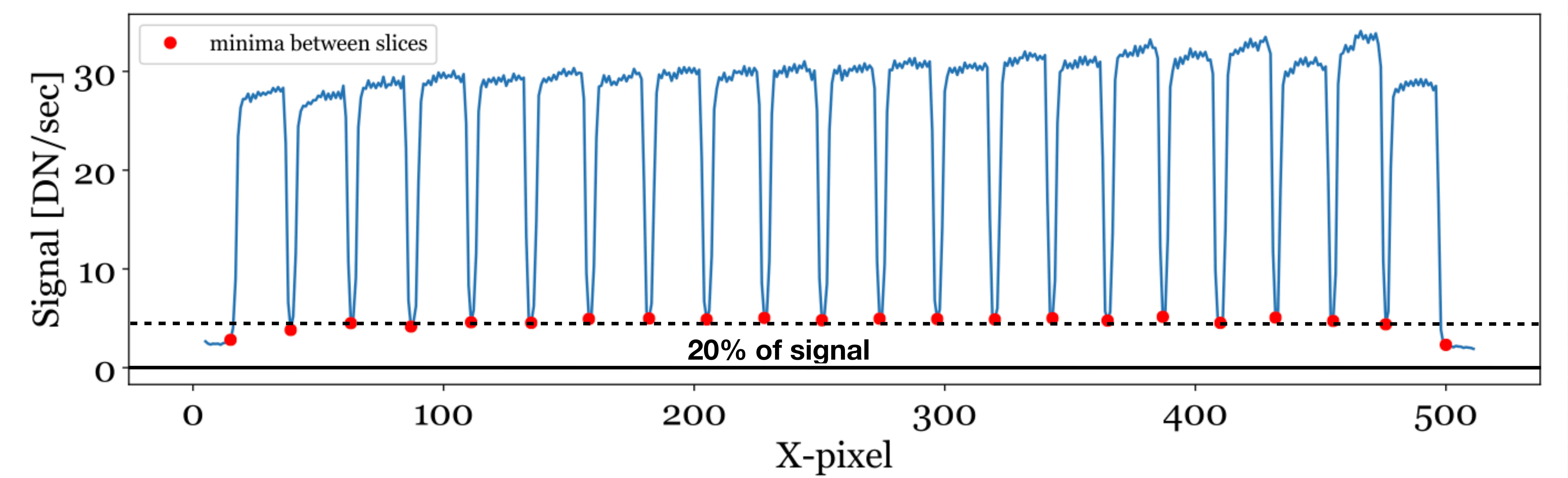
- As an integral field spectrometer, the MRS records spectral and spatial information simultaneously.
- It was noticed during the ground test campaigns that the MRS PSF was much broader than expected (based on a diffraction-limited model). This also impacts the background estimation.



Observed broadening of MRS PSF (PhD thesis, Argyriou 2021)

DETECTOR INTERFERENCE - JWST/MIRI/MRS





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HISTORICAL APPROACHES TO A CORRECTION

- HST/STIS: "A fringe flat is obtained by observing a tungsten continuum lamp through a narrow slit and dividing out the broad spectral shape of the lamp from the resulting image.” [E. M. Malumuth et al. 2003]
- ISO/SWS: Division by a Spectral Response Function (SRF), followed by an empirical residual fringe correction. [D. Kester, D. Beintema, D. Lutz, 2003]
- Spitzer/IRS: Empirical fringe fitting using sinusoidal model. [P. Morris 2001]
- UKIRT/Michelle: Signal filtering [Priv. comm. Alistair Glasse]

HISTORICAL APPROACHES TO A CORRECTION

Method	Pros	Cons
On-board calibration lamp	Repeatable measurements	> Mass, power, volume cost > Single illumination pattern
SRF using celestial standard	Gives an absolute calibration reference	> Observing time cost > Fringes depend on local detector properties
Empirical fringe fitting	Accounts for fringe signal profile	Danger of overfitting (e.g. periodic spectral features)
Filtering	Simplest solution	Smooths spectrum features

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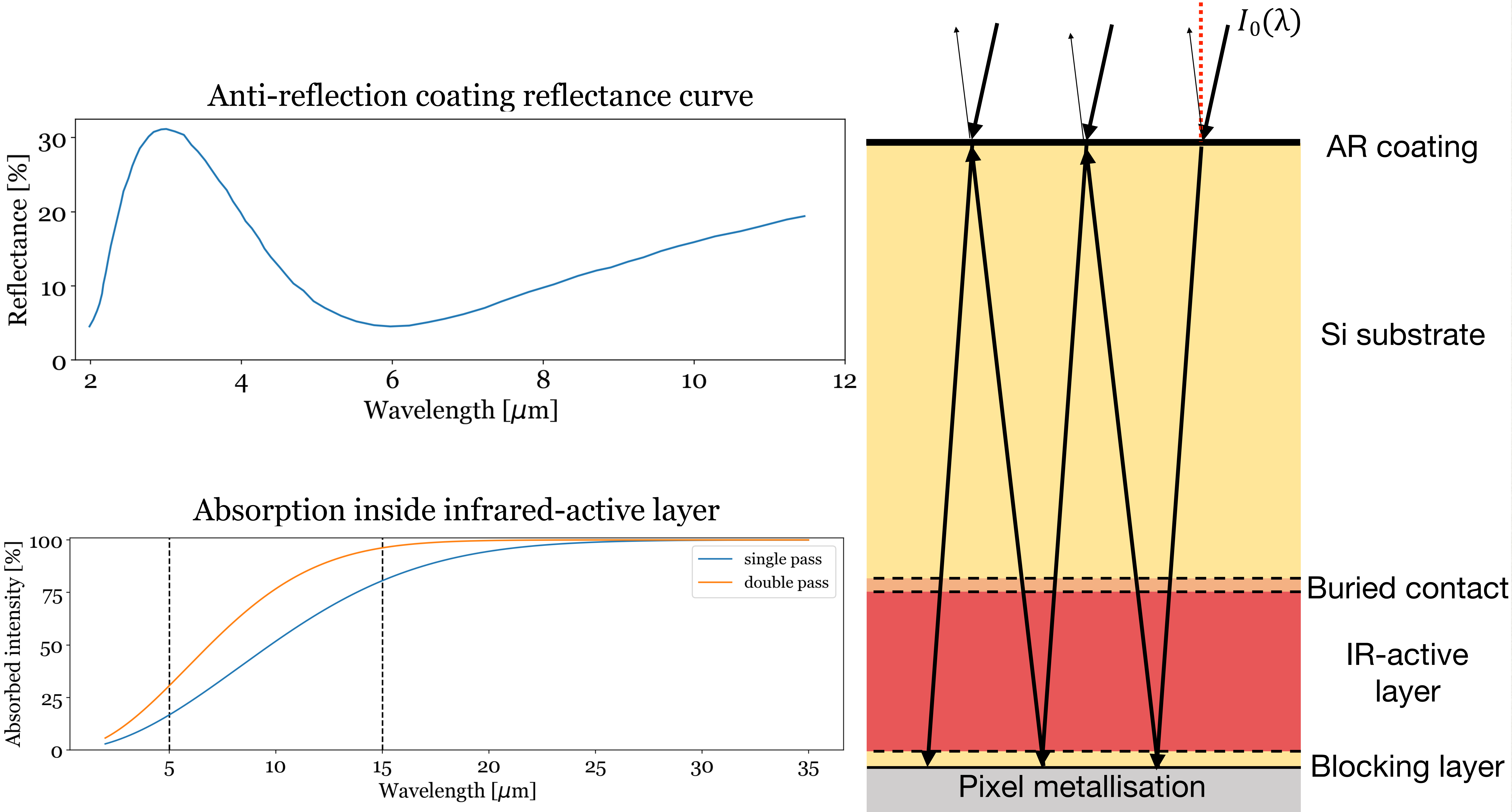
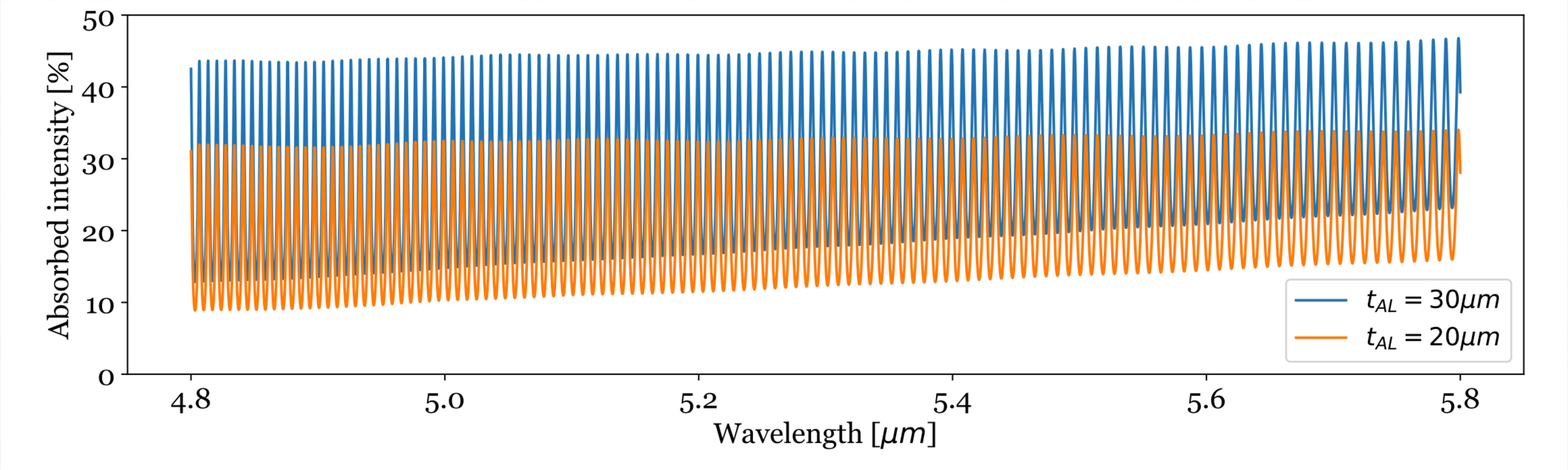
- Detector interference
- Historical approaches to calibrating the systematic effect
- <u>Understanding the physical problem and modelling it</u>
- Standardising available software and lessons for future missions

UNDERSTANDING THE PROBLEM (MIRI/MRS)



UNDERSTANDING THE PROBLEM

- Assuming certain properties for the thickness of the detector layers and their optical functions (i.e. the index of refraction and extinction coefficient), fringes are modelled by solving the Fresnel continuity equations. Given conservation of energy, the metric of interest is the absorbed intensity A. Mathematically, A = 1-T-R, where T is the transmitted intensity and R is the reflected intensity.



MODELLING DETECTOR INTERFERENCE

- Modelling fringes accurately involves knowing the geometric and refractive properties of the detector layers (CCD/BIB/etc).

Table 6.1: Optical and geometric properties of MIRI MRS SW detector layers.

Layer	Material	Geometric thickness	Comments
Ambient	Vaccuum	inf.	
Anti-reflection coating	Zinc Sulphide (ZnS)[a]	0.72 μm	Optimized reflectivity at 6 μm
Inactive layer	Silicon (Si)[b]	460.5 $\pm 6.6 \mu m$	Pure silicon (zero extinction)
Buried contact (electrode)	Antimony-doped silicon	uncertain	Material is assumed based on Woods et al. (2011).
Active layer	Arsenic-doped silicon[c,d]	30 μm	- Thickness variation much less than $1 \mu m$ - Arsenic concentration N=$5 \cdot 10^{17} cm^{-3}$ - Contingency array (identical to IRAC)
Blocking layer	Silicon (Si)	4 μm	Pure silicon (zero extinction)
Pixel metalization	Aluminium (Al)[e]	inf.	

[a] Optical constants for ZnS acquired from Amotchkina et al. (2020).

[b] Optical constants for Si acquired from Frey et al. (2006), evaluated at 6K.

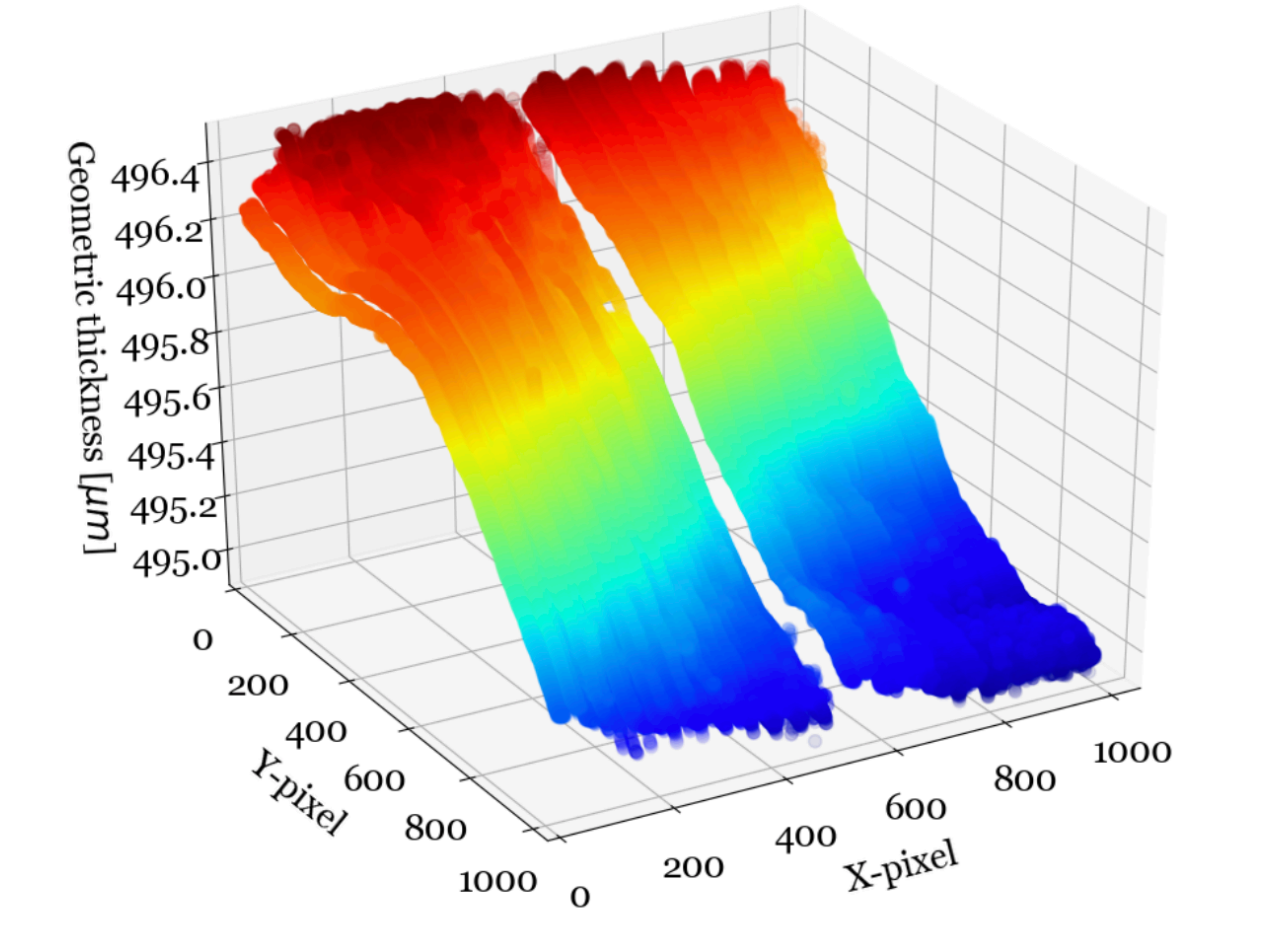
[c] Arsenic has +1 electron in its outer shell, thus the active layer is n-doped (operates with free electrons, i.e. electron carriers). This is in contrast to Germanium (Ge) and Galium (Ga) which have -1 electron on their outer shell and as a result are p-doped (operate with free holes, i.e. hole carriers), Germanium and Galium being two other chemical elements often used in astronomical detectors.

[d] Optical constants for Si:As acquired from Woods et al. (2011).

[e] Optical constants for Al acquired from Ordal et al. (1988).

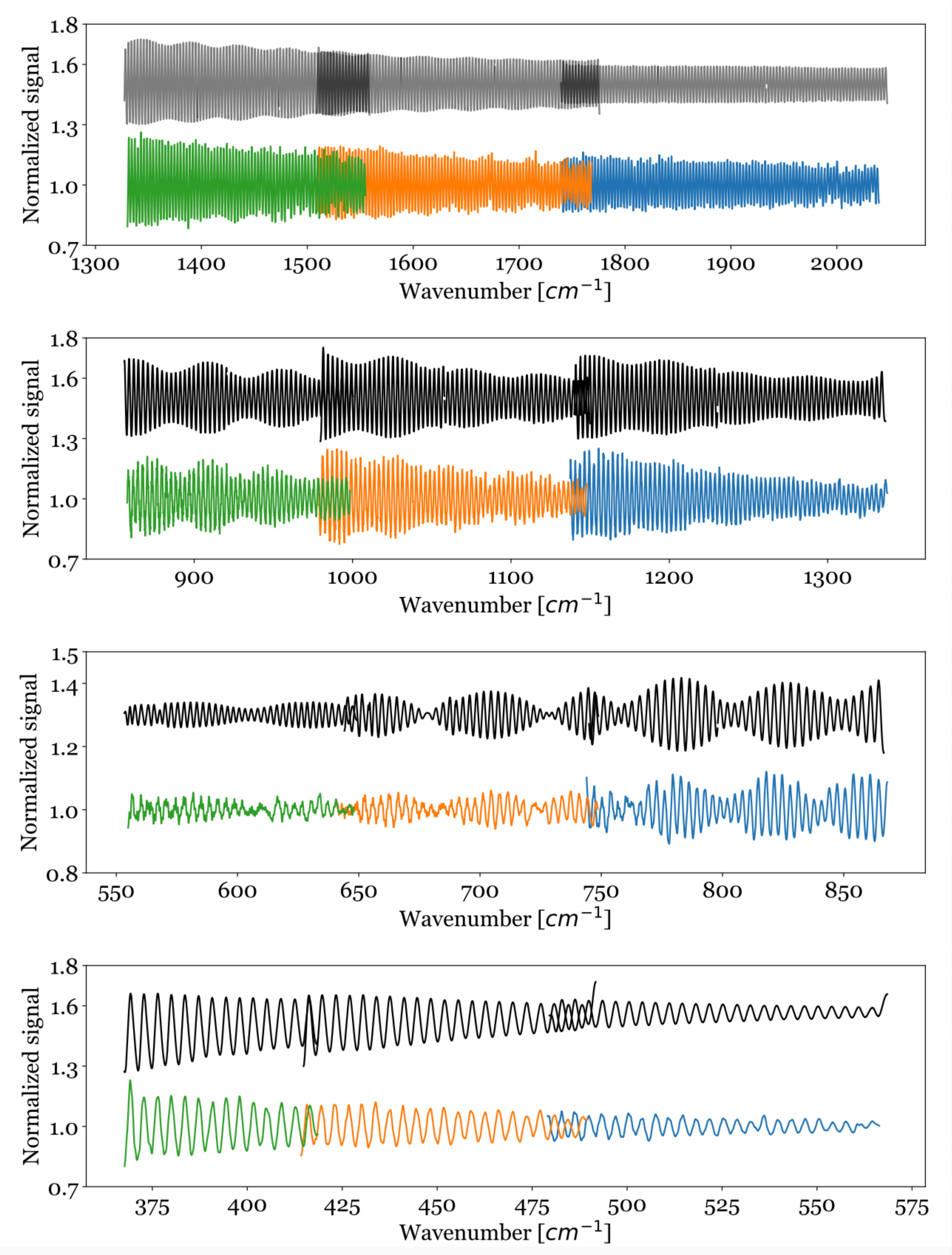
MODELLING DETECTOR INTERFERENCE

- Fringes can be used to derive the detector geometric thickness (separation between fringe peaks relates to the optical thickness of the detector).



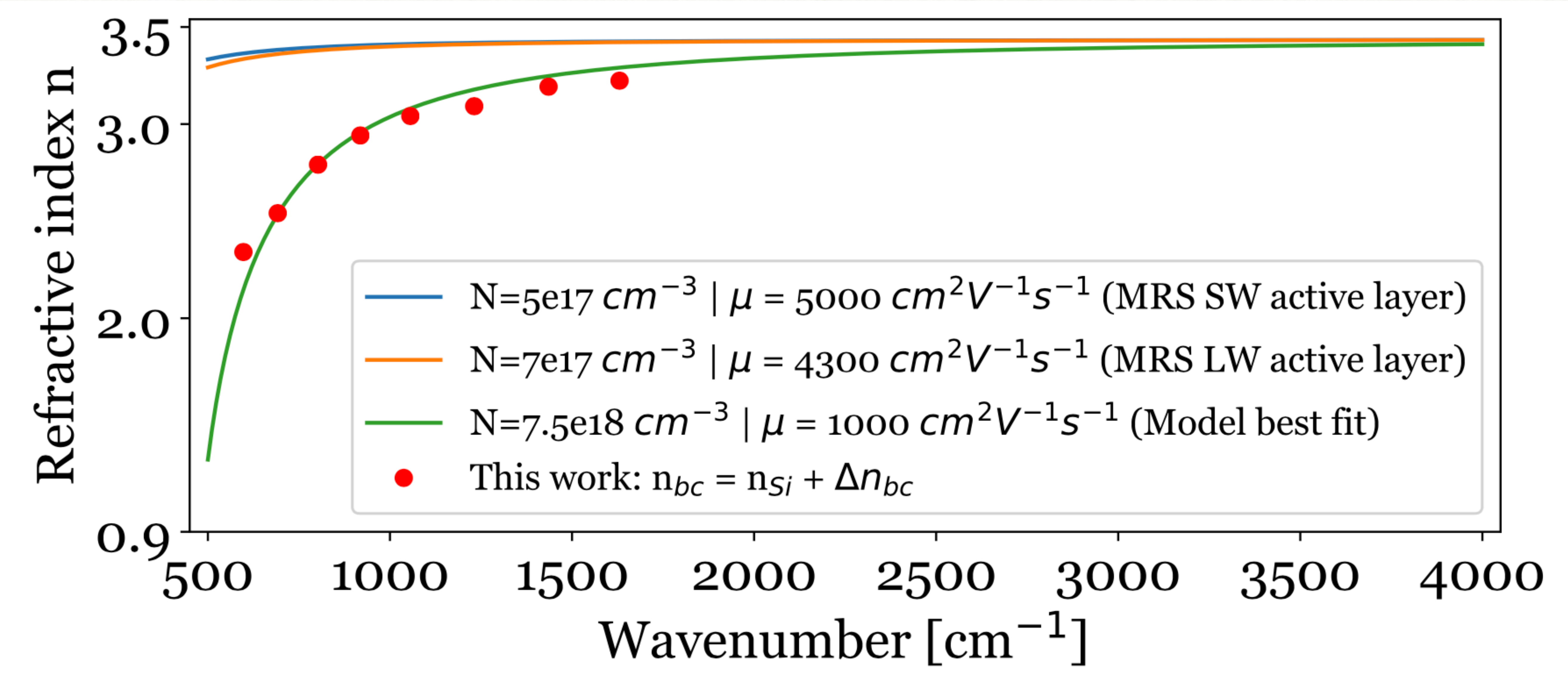
MODELLING DETECTOR INTERFERENCE

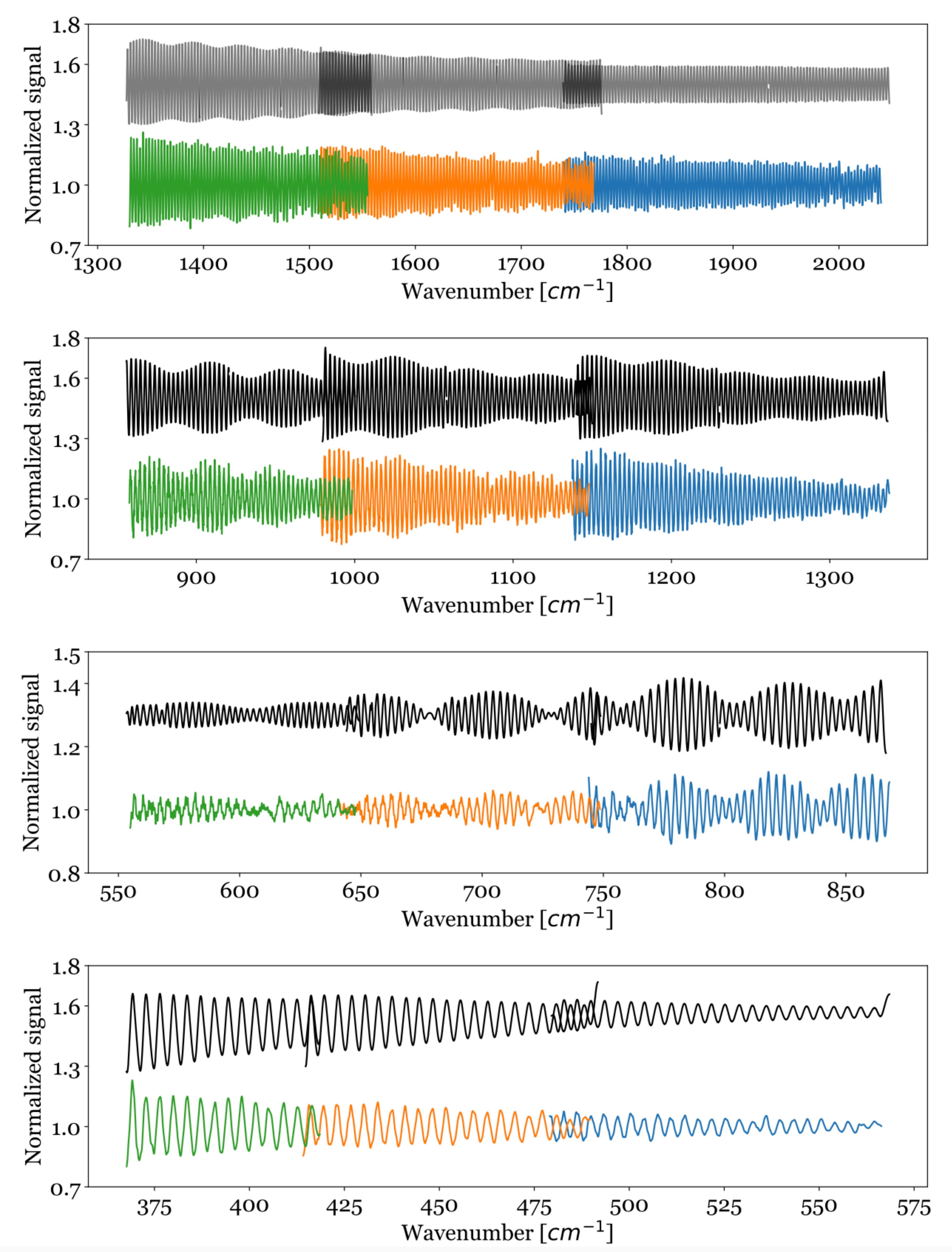
- On the right the simulated MRS fringes are shown in black and the fringes extracted from the data are shown in blue/orange/green.
- The fringes are simulated using the Transfer-Matrix Method (TMM), commonly employed to study, for example, the performance of solar cells.



MODELLING DETECTOR INTERFERENCE

- In I. Argyriou, G.H. Rieke, M.E. Rester et al. 2020, I used the analytical model to indirectly derive the doping concentration of the MRS detector buried contact.
- The buried contact, previously assumed to be transparent, was found to be the cause of the low-frequency modulation in MRS spectra.





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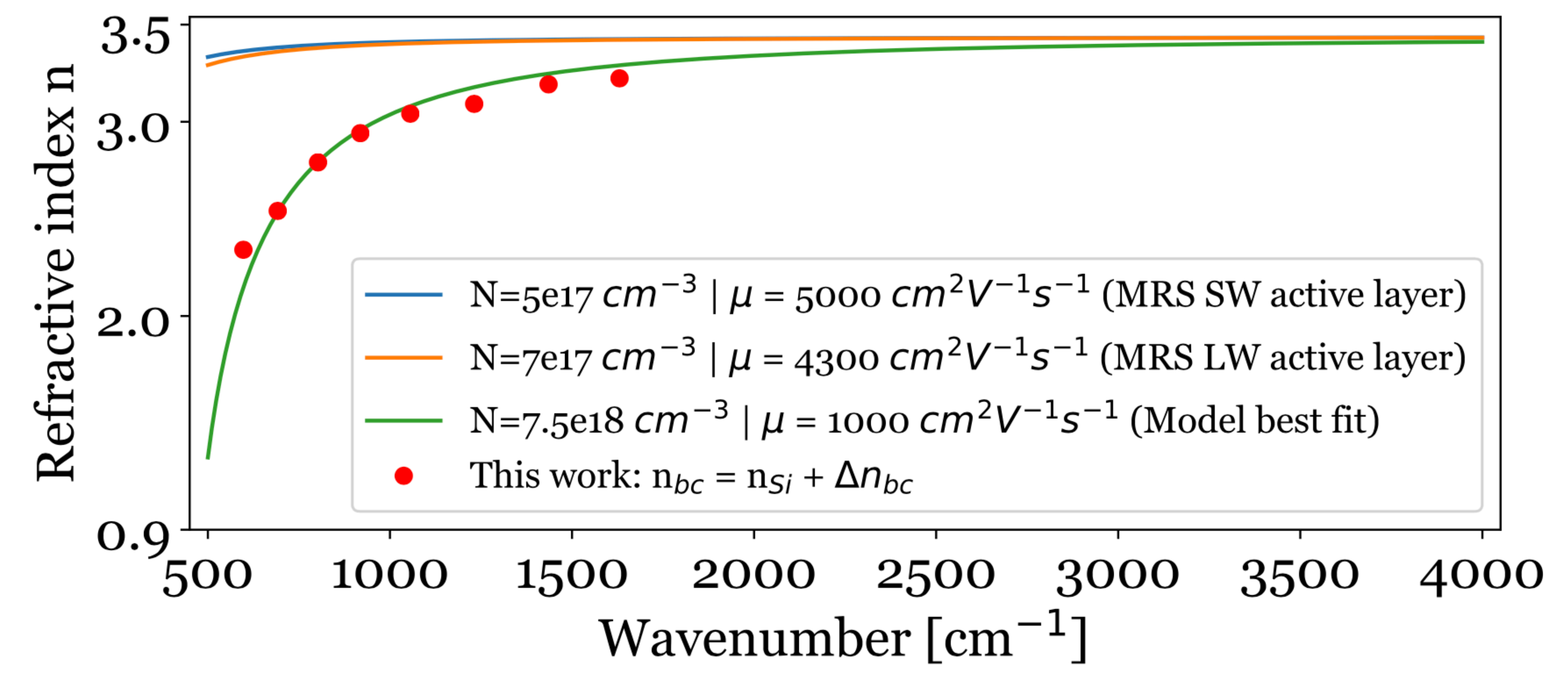
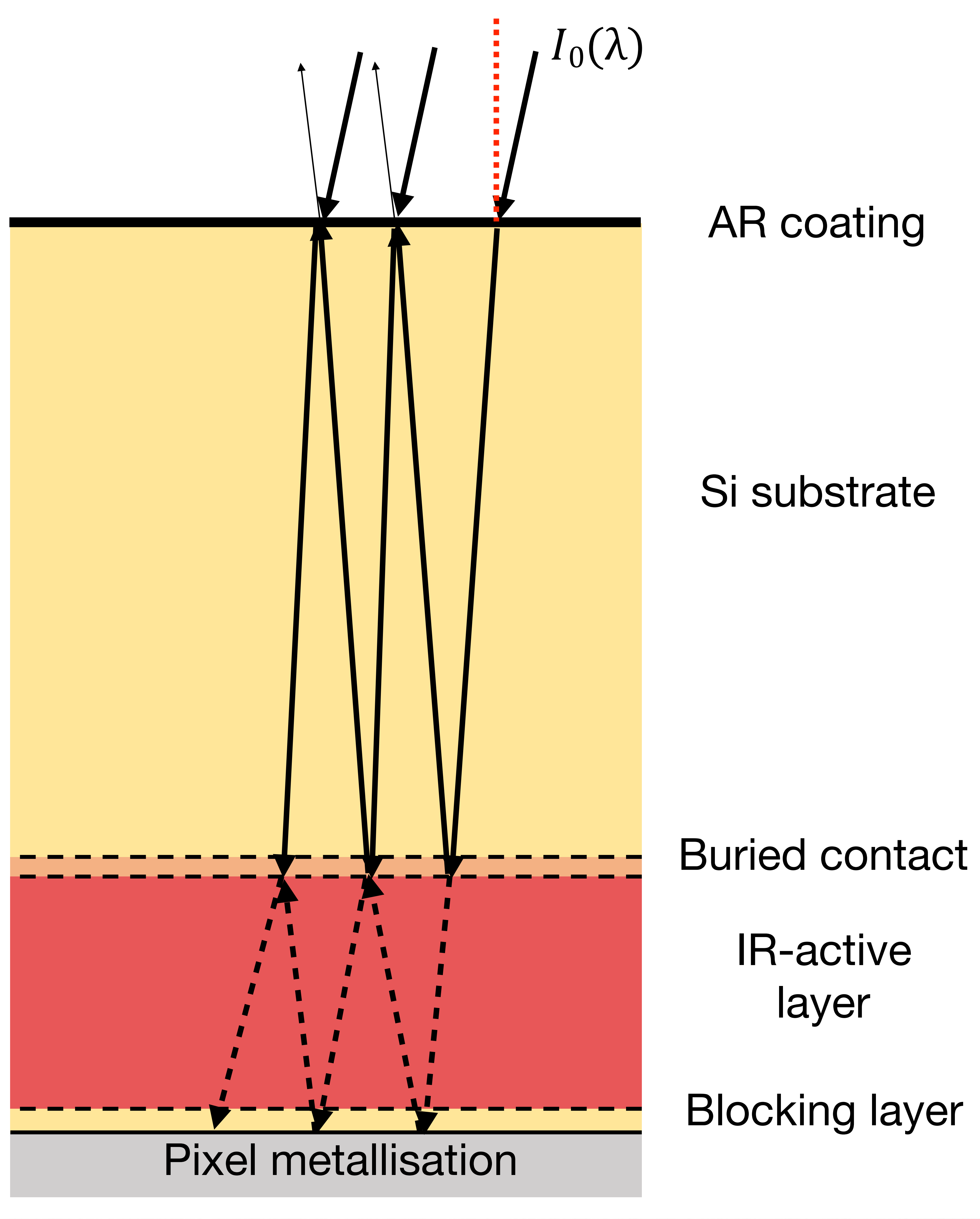
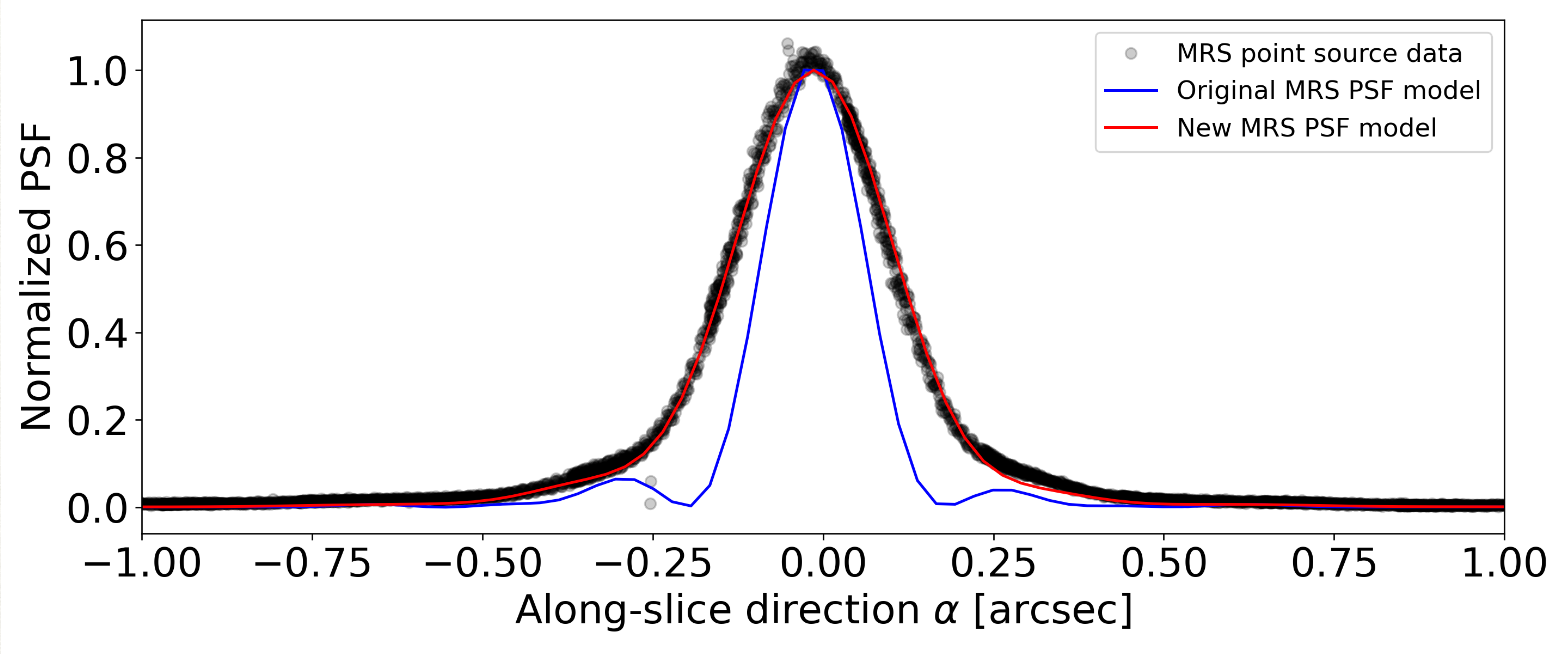




MODELLING DETECTOR INTERFERENCE

- What about the broadening in the spatial direction? Instead of looking at the variation with wavelength, we model the impact of the photon incidence angle.



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STANDARDIZING AVAILABLE SOFTWARE

- “IMD--Software for modeling the optical properties of multilayer films", written in IDL by David L. Windt (1998) http://www.rxollc.com/idl/
- "TMM--Multilayer optical calculations", written in Python by Steven J. Byrnes (2016) https://pypi.org/project/tmm/
- "GPU image model for MIRI (GimMIRI)”, written in C by Andras Gaspar (2020) https://github.com/merope82/GimMIRI

LESSONS FOR FUTURE MISSIONS

- If there is a possibility that photons will not be absorbed in a first pass through the detector, an effort should be made to quantify the resulting effect. The goal is to be proactive instead of reactive, as this can also inform instrument design.

- Available software to model the propagation of light through a layered medium (in combination with, e.g., Zemax / CodeV simulations), can help define calibration strategies early on in the mission.

Thank you for your attention.

Back-up slides

BACK-UP SLIDES