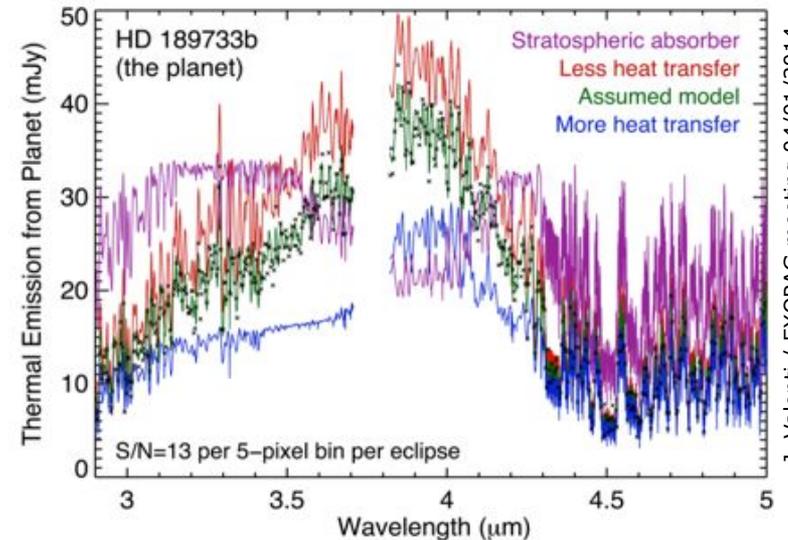
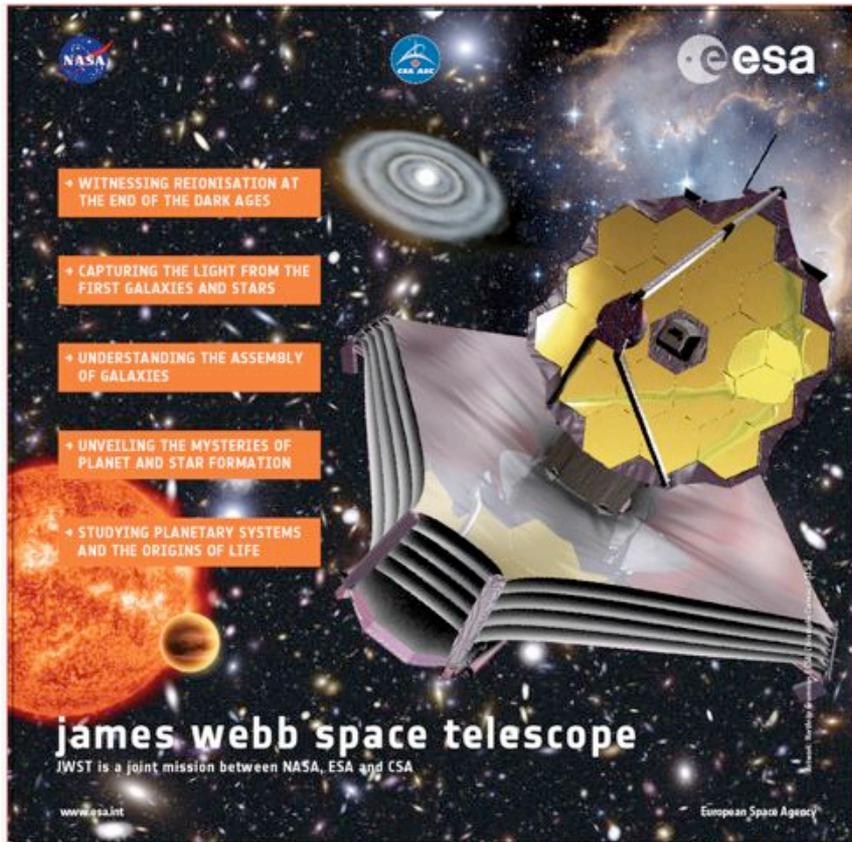


# Exo-planet transit spectroscopy with JWST/NIRSpec

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G. Giardino /



J. Valenti / EXOPAG meeting 04/01/2014



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- **Operational timeline and limitations.**
  - Timeline; limitations.
- **Simulations.**
  - What for?; photon noise floor; some systematics;

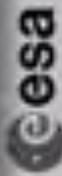
# Instrument overview NIRSpec in a nutshell



- **NIRSpec (Near-InfraRed Spectrograph) is part of ESA's contribution to JWST.**
- **To fulfill its share of JWST science goals, NIRSpec had to have the following capabilities:**
  - Deep multi-object spectroscopy at low (around 100) and medium (around 1000) resolution over a "wide" field of view.  
**→ NIRSpec's MOS mode.**
  - Spatially-resolved, single-object spectroscopy at "high" (a few thousands) spectral resolution over a "small" (a few arc seconds) field of view.  
**→ NIRSpec's IFU mode.**
  - High-contrast slit spectroscopy at various spectral resolutions, including an aperture for extra-solar planet transit observations.  
**→ NIRSpec's SLIT mode.**

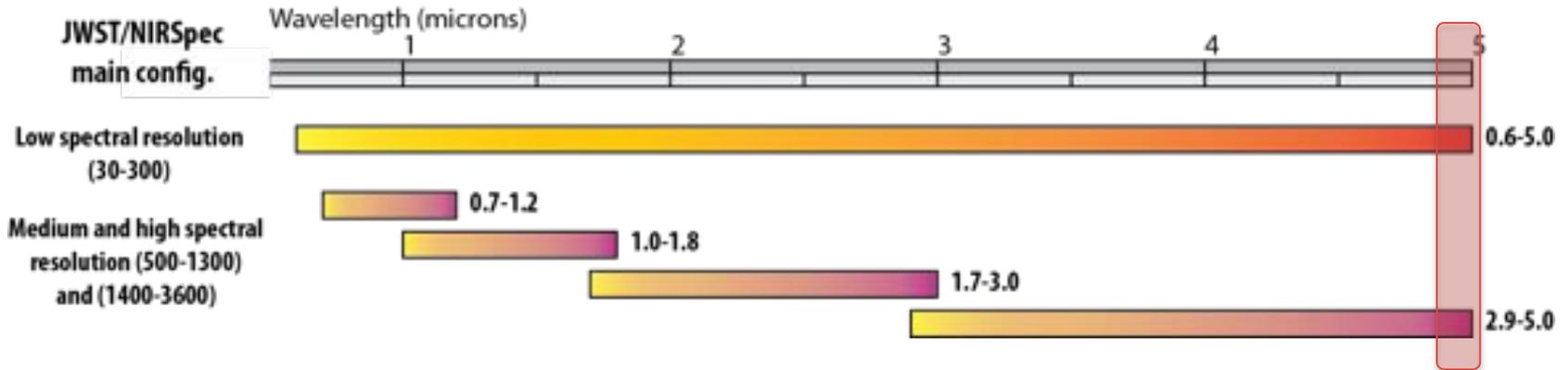


# Instrument overview NIRSpec in a nutshell

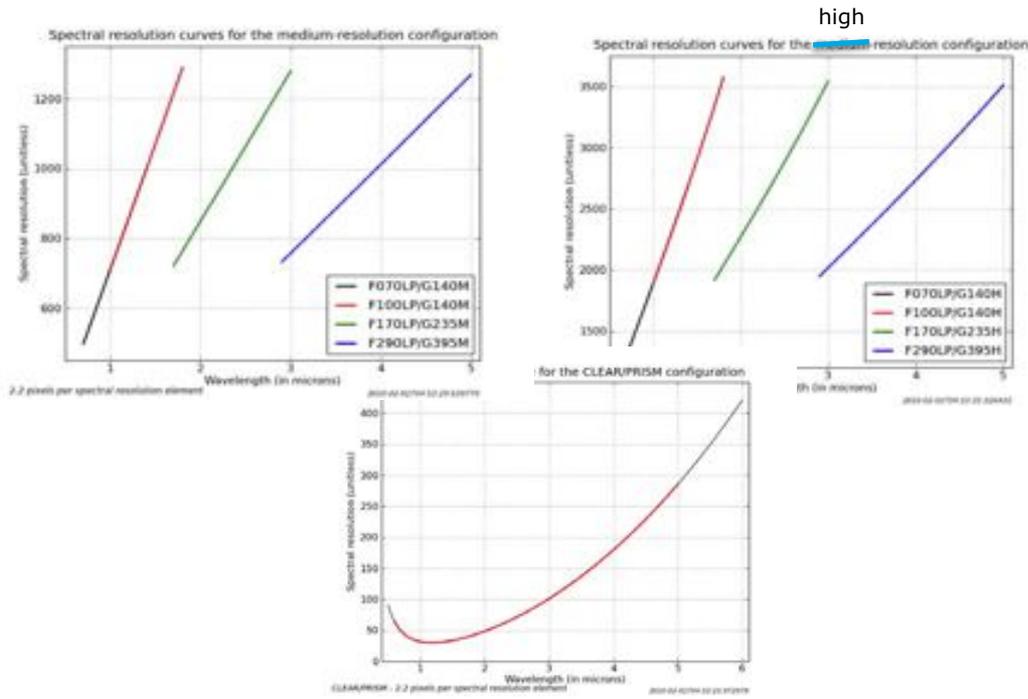


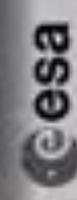
JWST/NIRSpec	MOS		<p><b>Multi-object spectroscopy with 0.2"-wide mini-slits.</b></p>	<ul style="list-style-type: none"> <li>- <b>9 square arcmin. field of view</b></li> <li>- Low spectral resolution (30 to 300), prism-based mode covering the 0.6-5.0 micron range in one exposure.</li> <li>- Medium spectral resolution (500 to 1300), grating-based mode covering the 0.7-5.0 range</li> </ul>
	IFU		<p><b>IFU spectroscopy with a 0.1" sampling.</b></p> <p>(IFU made of 30 slices for a total of 900 "spaxels")</p>	<ul style="list-style-type: none"> <li>- <b>3"x3" field of view</b></li> <li>- Low spectral resolution (30 to 300), prism-based mode covering the 0.6-5.0 micron range in one exposure.</li> <li>- Medium (500 to 1300) and high (1400-3600) spectral resolution modes, covering the 0.7-5.0 range in 4 exposures.</li> <li>- <b>IFU and MOS cannot be used at the same time.</b></li> </ul>
	SLIT		<p><b>High-contrast slit spectroscopy.</b></p> <p>(including with a 1.6"x1.6" square aperture for extra-solar planet transit observation)</p>	<ul style="list-style-type: none"> <li>- <b>5 slits available</b></li> <li>- <b>All spectral resolution modes available.</b></li> <li>- <b>SLIT can be used simultaneously to IFU or MOS.</b></li> </ul>

# Instrument overview NIRSpec in a nutshell



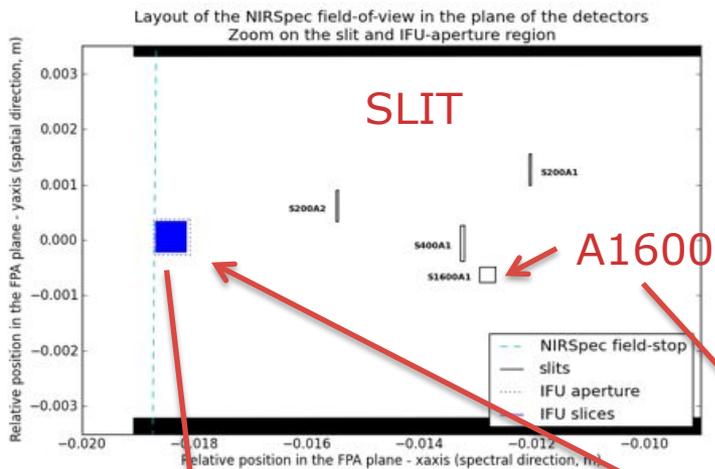
Actually extends up to the detector cut-off wavelength (5.3-5.4 microns). Overlap with MIRI.





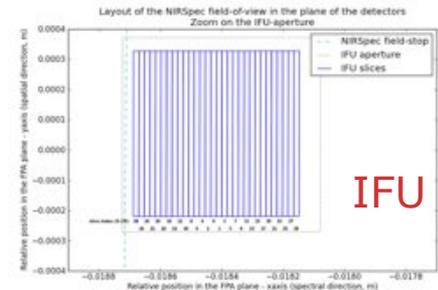
# Instrument overview NIRSpec in a nutshell

## A complex field-of-view layout

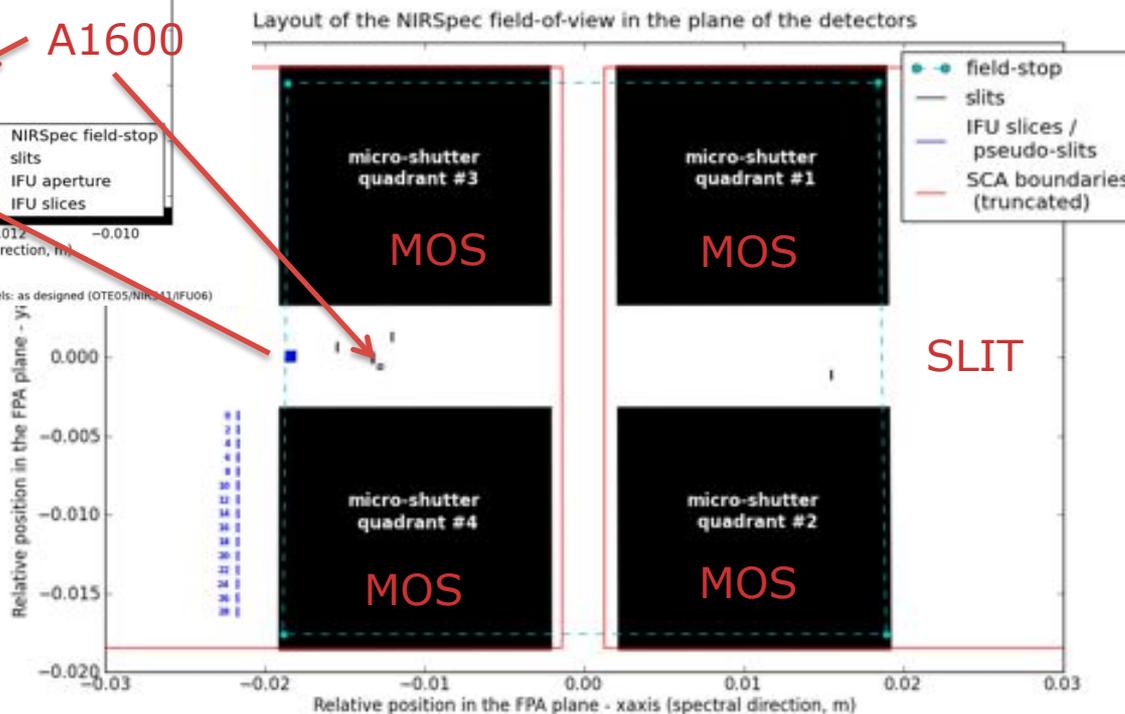


p\_figure\_fullLayoutFPA.py - version 1.0 - 2012-07-03T18:45:37.305833

Models: as designed (OTE05/NIR541/IFU06)



p\_figure\_fullLayoutFPA.py - version 1.0 - 2012-07-03T18:45:37.305833 Models: as designed (OTE05/NIR541/IFU06)



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Models: as designed (OTE05/NIR541/IFU06)

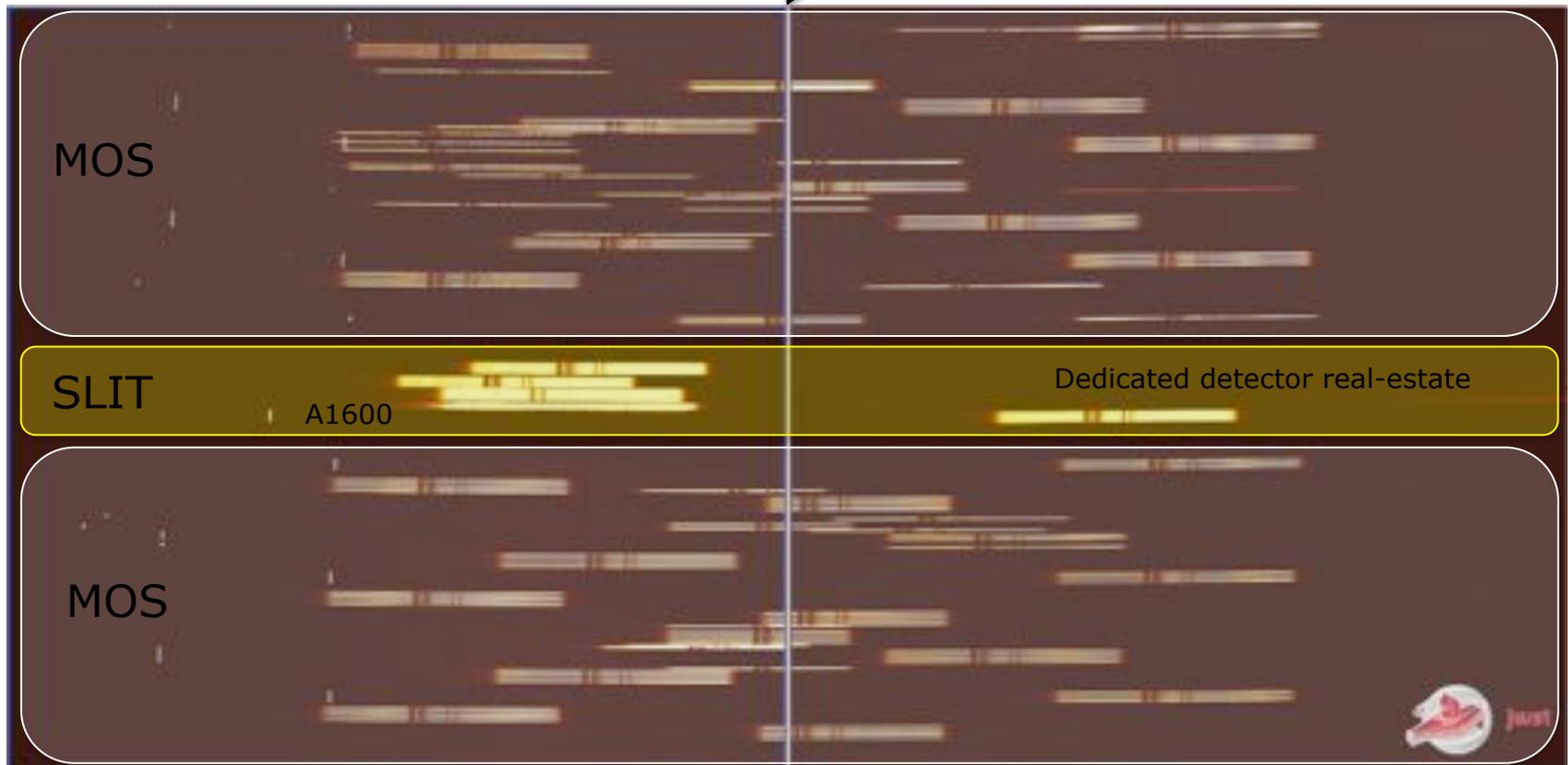
# Instrument overview NIRSpec in a nutshell

Layout in the detector plane: MOS+SLIT – short spectra

**Gap** between the detectors corresponding to approximately 145 pixels.

Detector #1 (SCA491)

Detector #2 (SCA492)



JWST/NIRSpec - FM2 cryogenic test campaign 01/2013

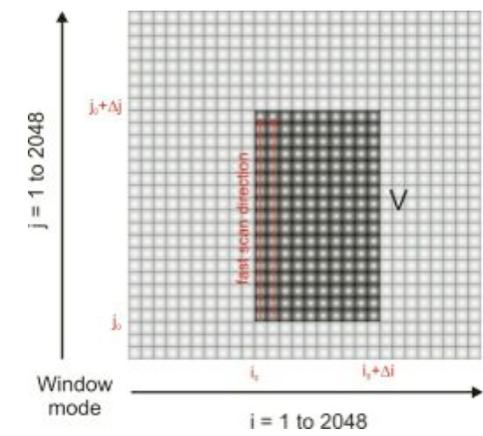
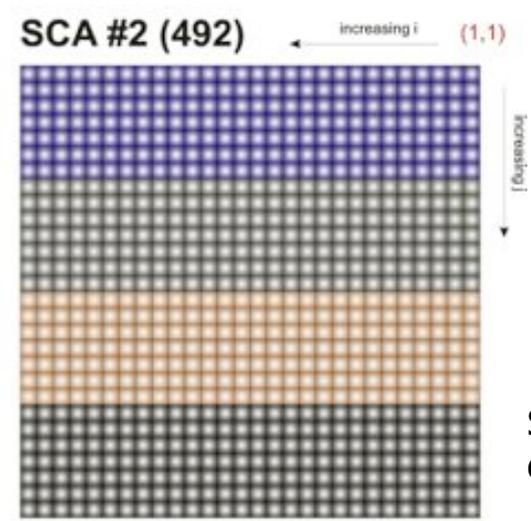
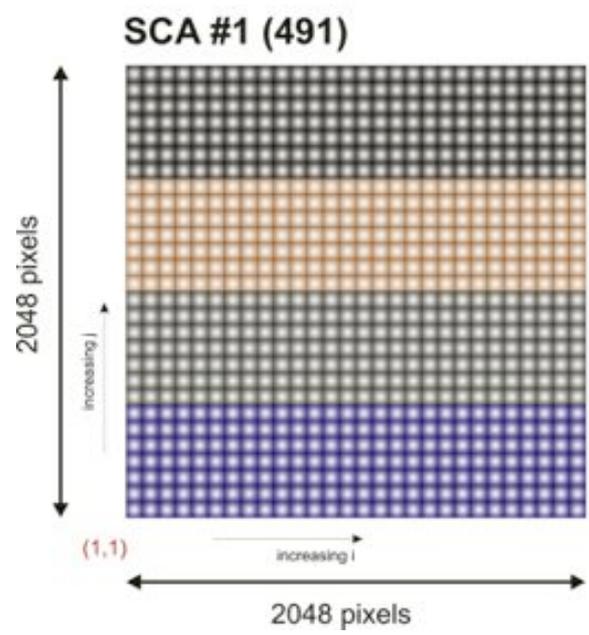
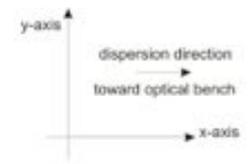
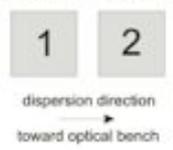




# Instrument overview NIRSpec in a nutshell - Detectors

- **MULTIACCUM** readout scheme presented yesterday.
- **Three different modes: full-frame, stripe and window.**
  - Full-frame & stripe modes: 4 outputs read in parallel.
  - Window mode: 1 output only.

Sketch of the FPA geometry



Slow readout direction = dispersion direction

# Instrument overview

## NIRSpec in a nutshell - Detectors

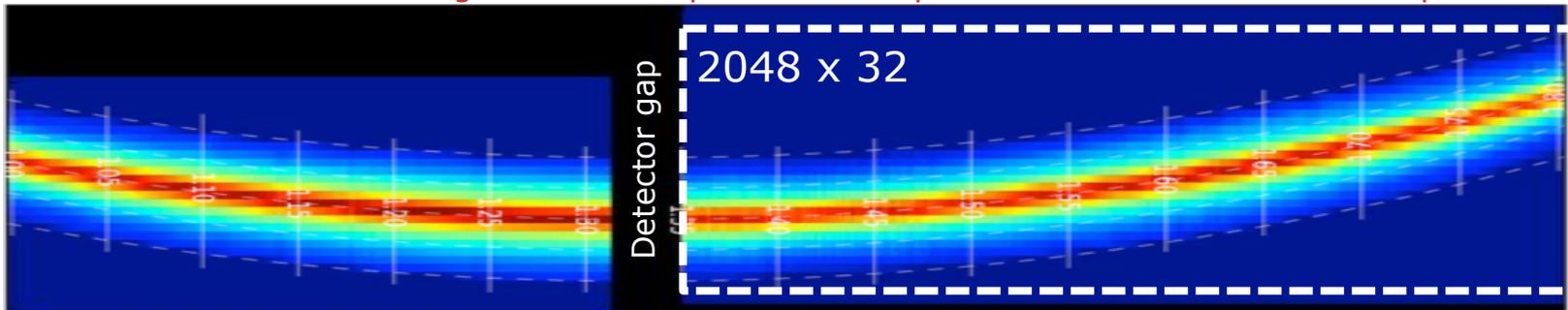
- **NIRSpec's window mode (single output) and its rules...**
  - One single rectangular window per SCA.
  - The size of the windows must be identical in both SCAs but their origin can be different.
  - The size of the window must be expressed as powers of 2 (e.g. 64×128) with a minimum size of 8 pixels along a given axis.
  - The number of pixels in a window must be larger or equal to 1024.
- **The "idle" time between exposures is ALWAYS filled with full-frame resets (4 outputs).**
  - Constraint linked to the design of the focal plane electronics.
  - Strong change in dissipation power in the ASIC when switching between 1 and 4 outputs.
- **→ thermal disturbance between window-mode exposures (specific to NIRSpec).**

# Instrument overview

## Spectroscopy with the A1600 aperture

- In order to accommodate the needs of transit spectroscopy, one of the 5 slits of NIRSpec has been turned into an aperture of 1.6" x 1.6" (labeled A1600).
  - Can be used with all spectroscopic configurations.
  - Large enough to get rid of systematics related to aperture losses.
  - Not wide enough to use the "spatial-scanning" strategy recently used for HST spectroscopic observations.

A1600 high-resolution spectrum for a point-source with a continuum spectrum

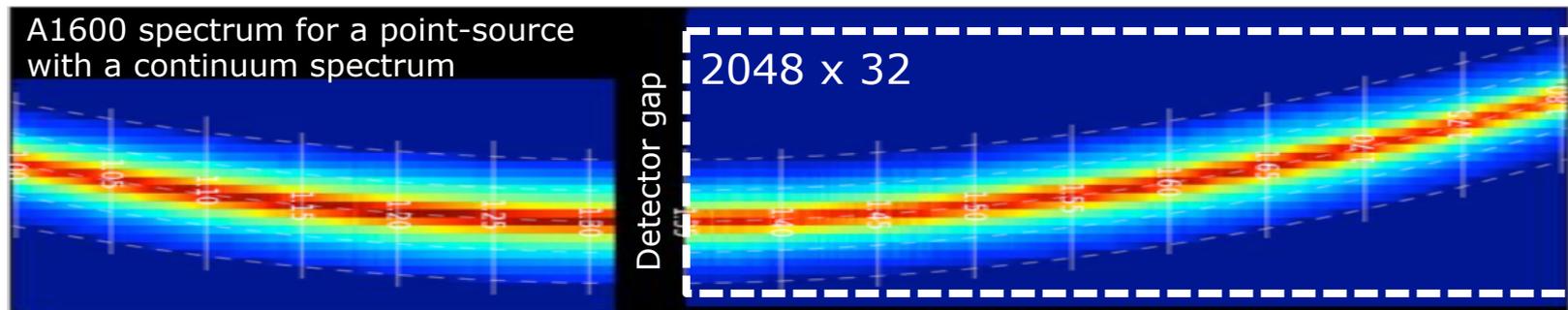


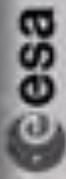
- Note the "missing wavelengths" due to the detector gap in this **high spectral resolution** configuration (145 spectral pixels; 4 to 8e-2 microns).
- **No gap at low/medium resolution** (the spectra fit onto a single detector).

# Instrument overview

## Spectroscopy with the A1600 aperture

- **The baseline for transit spectroscopy is to use sub-arrays (so-called “window mode”).**
  - Full-frame readout time (4 outputs): 10.6 seconds.
  - 2048x32 window (1 output):  $\sim 0.76$  seconds.
  - 512x32 window (1 output, short spectra):  $\sim 0.19$  seconds.
- **The baseline is to retrieve all the data (no on-board frame averaging).**
  - As we use a single output, data rate should not be an issue.
- **The baseline is to use a minimum of 2 groups (i.e. a pair of readouts following a reset).**
  - No fixed number of groups. Single group option possible.

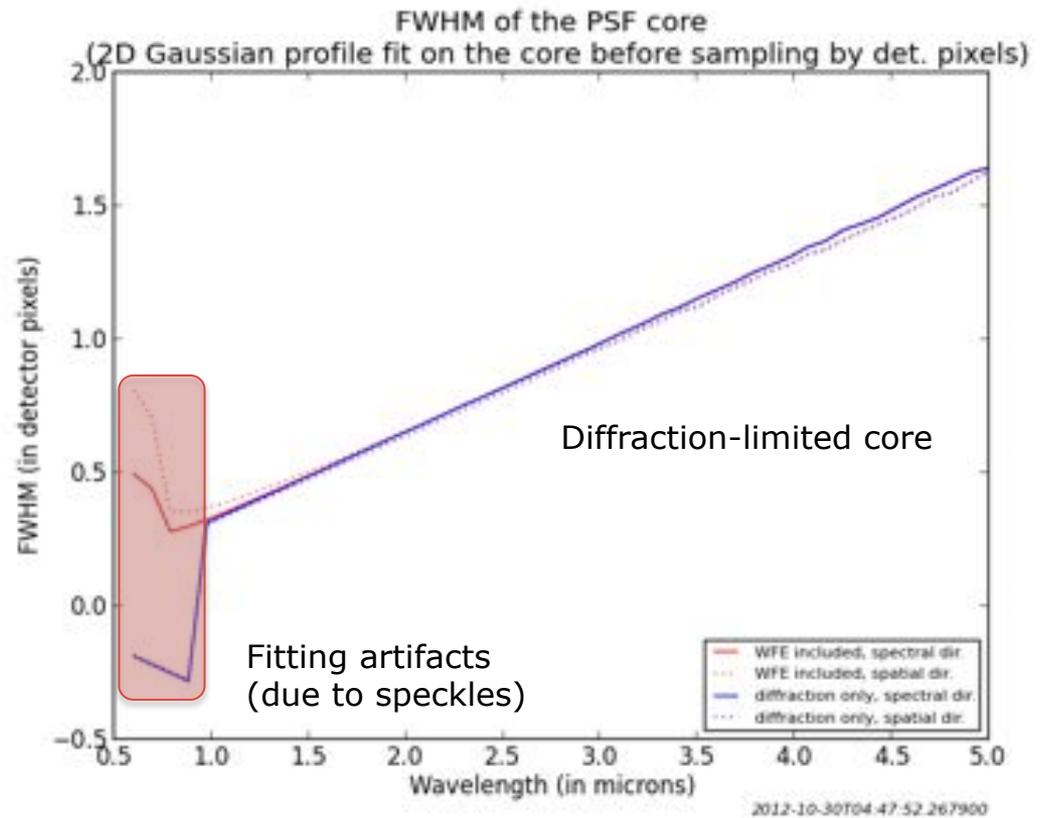
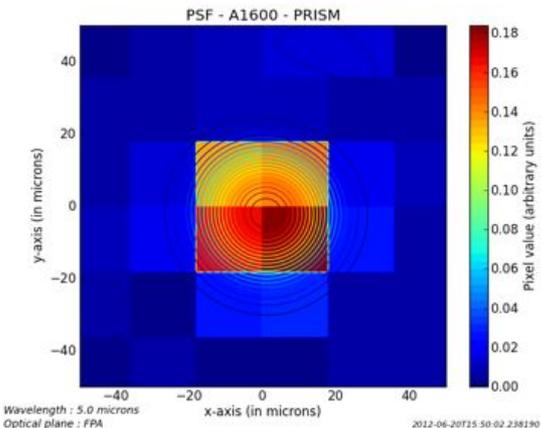
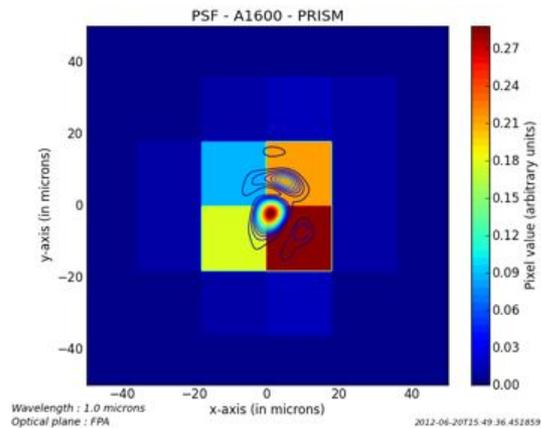




# Instrument overview

## Spectroscopy with the A1600 aperture

- The PSF of JWST+NIRSpec exhibits a narrow “diffraction-limited” core over almost its complete wavelength range.
- This core is under-sampled by the 100mas pixels.



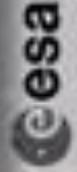


# Bright star limit



- **Computation of the saturation limits for NIRSpec – The rules...**
  - Currently, the pixel saturation in NIRSpec is set by the ADC and this corresponds to roughly 77 000 electrons.
  - The minimum integration contents is one reset followed by two reads and we do not want pixel saturation to be reached before the second read.
  - 2048x32 (512x32) window for the grating (prism) modes.
- **The inputs...**
  - As required telescope collecting area and throughput.
  - Using the JWST+NIRSpec photon conversion efficiency values presented at NIRSpec acceptance review.
  - Taking the worst case of a PSF centered on a pixel.
  - As these estimates are usually conservative in the “wrong” direction, the derived limiting fluxes have been decreased by 15% to be on the safe side.
- **Need to have a consistent approach across the instruments...**

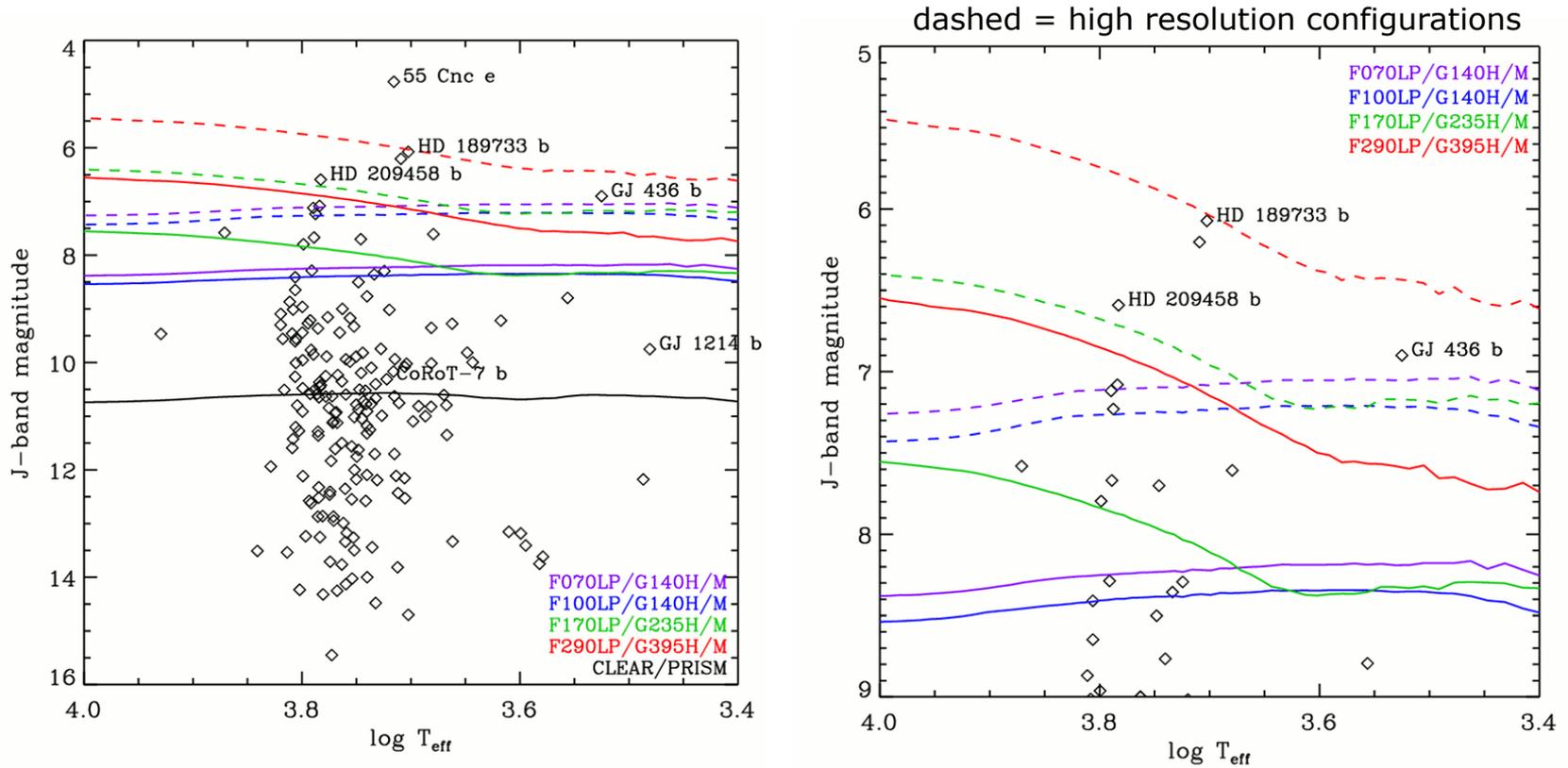
# Bright star limit



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See: <http://www.cosmos.esa.int/web/jwst/exoplanets>

- **Good coverage at high spectral resolution. Much stronger limitations at low spectral resolution.**



Sources below the lines can be observed in the full wavelength range of the given mode. The black symbols denote the host stars of known transiting exoplanets (data taken from exoplanets.org on 7 June 2013). The plot on the right shows the magnitude limits for the gratings in more detail. The difference in shape between the curves is due to the combined effect of i) using J-band magnitudes as the reference, ii) the spectral resolution of NIRSpec, and iii) the spectral energy distribution of the stars.

European Space Agency

# Bright star limit Pushing the limit



- **Pushing the limit.**
  - Tuning the detector gain to get rid of the limit set by the ADC and reach the real pixel saturation. → gain of 10-20 % (not large).
  - Changing the detector bias level. → **potentially a gain by a factor 2.**
- **Feasibility study conducted by B. Rauscher and his team using NIRSpec SCAs with the new design.**
  - Two SCAs have been tested including one which is “in family” with the selected flight SCAs (i.e. flight representative).
  - Report posted on NGIN (“JWST NIRSpec High Bias for Increased Well Depth Test”, B. Rauscher et al.).



# Bright star limit Pushing the limit



- **Confirmed the results obtained by the team at ESO that the detectors are not damaged when the bias is pushed to 1V (baseline is 0.25V).**
  - **Key performance elements when operating at high bias.**
    - Allows to achieve well depths of typically 180 000 electrons.
    - Population of hot pixels increased by a factor 10.
  - **Major caveat.**
    - Anomalous persistence present during several hours after changing the bias voltage (one way or another).
    - Typical wait-time of 6 hours before the persistence is back to acceptable levels.
- ➔ **On NIRSpec side, we consider this rules out using a “high-bias” mode as the baseline for the window mode (we want to preserve the capability to switch rapidly between full-frame and window mode).**
- ➔ **Still the possibility for a “campaign” approach if scientifically justified.**

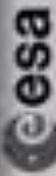
# Target acquisition

## Accuracy of the positioning of the source

- **A common misunderstanding is to mix up the needs in terms of source centering in the A1600 aperture and those in terms of stability of its positioning during the transit spectroscopy.**
    - Aperture is 16-pixel wide. Geometrical PSF losses are limited to a few percent. Need to have a fairly large offset ( $> 1$  pixel = 100 mas) to increase them significantly.
    - Note that percent-level modeling of the losses is tricky especially at short wavelengths where speckles contribute a lot.
  - **Robustness with respect to the source centering is expected to be quite good but has not yet been assessed.**
    - Expecting the 10-15 mas required accuracy of the baseline target acquisition to be much better than necessary in our case.
- **Work needed.**
- **Baseline target acquisition may be usable even when the number of reference sources is fairly small.**

# Target acquisition

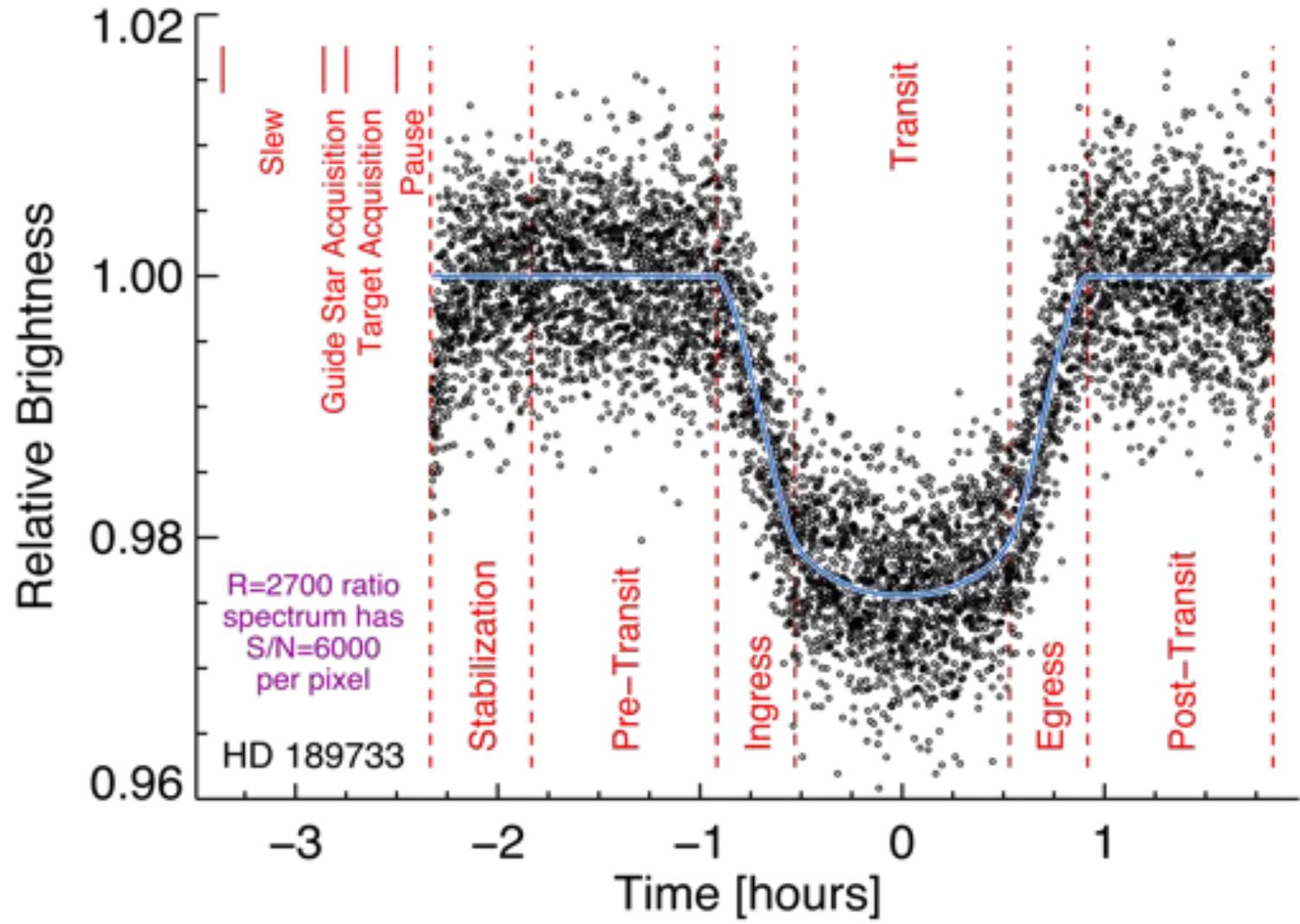
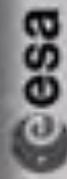
## Bright Object Target Acquisition (BOTA)



- **Recently STScI and the NIRSpec operation working group have been discussing the implementation of TA scheme specific to the A1600 aperture.**
  - Imaging the host star in the A1600 aperture, computing its centroid and using it to derive the slew necessary to center it.
- **On-going discussion.**
  - Bright star limit in imaging is even more of a problem; need to use a 32x32 pixel window (minimum allowed size).
  - Sanity check will be needed as the required initial pointing accuracy is still 1 arcsec (1 sigma). This is large compared to the size of the aperture.
    - Actual accuracy is expected to be better than that.
  - When should we use it? Criteria?

→ **Work in progress.**

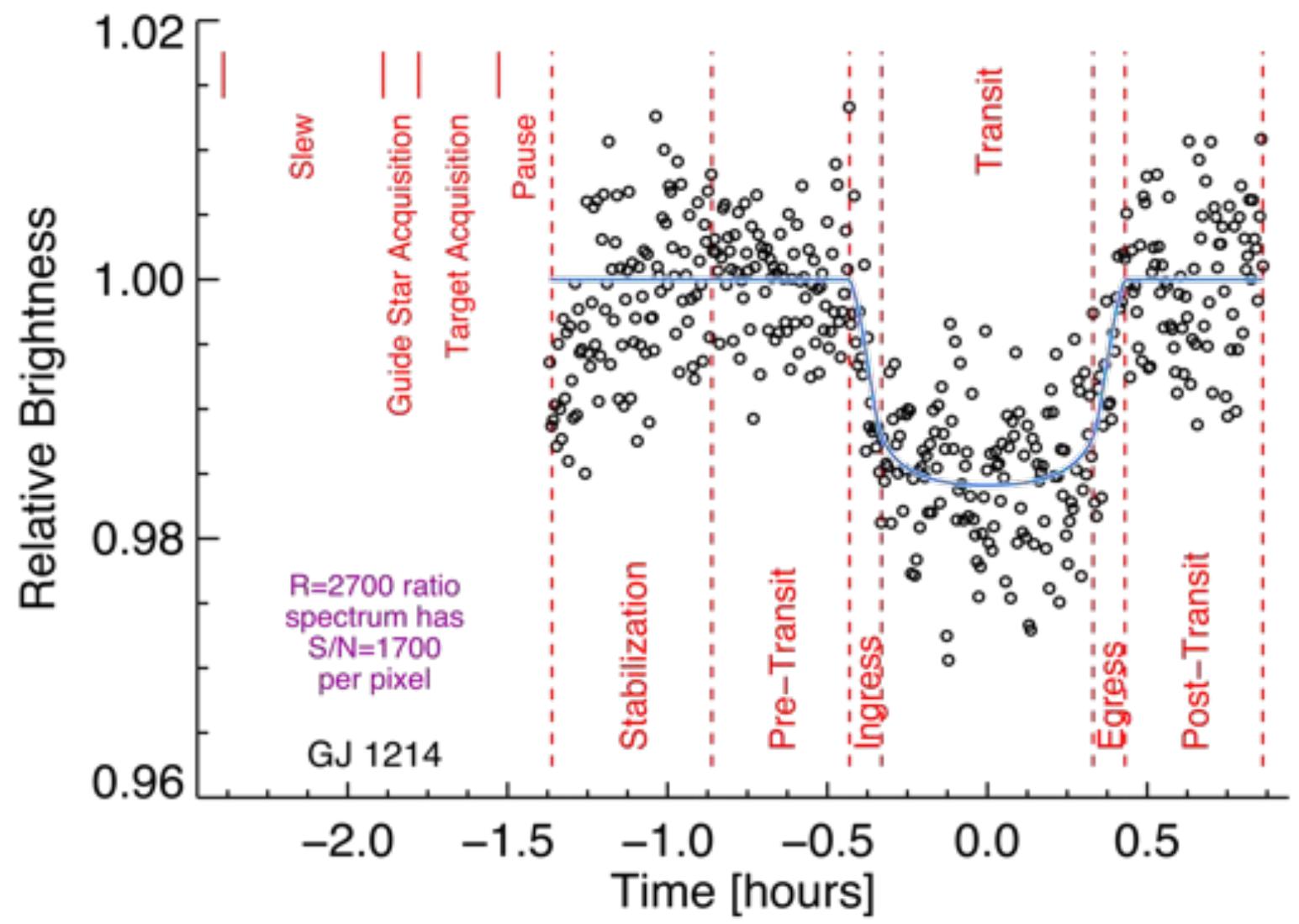
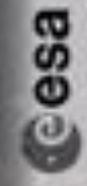
# Operational timeline



Credit: J. Valenti



# Operational timeline



Credit: J. Valenti



# Constraints and disturbances.

- **High-gain antenna repointing. [constraint]**
    - Every  $\sim 3$  hours (10ks), 1 minute duration.
    - Associated with a 100 mas perturbation during the repointing.
    - Was initially associated to a mandatory change of visit (i.e. need to restart the timeline introducing huge disturbances).
- Change not mandatory anymore thanks to the work of STScI (acquisition continues but data will be flagged as bad during the repointing).**
- **Maximum visit duration is now 1 day (to be confirmed) to allow momentum dump.**



# Disturbances and constraints

- **Maximum number of integrations per exposure. [constraint]**
    - Maximum of 65365 integrations per exposure.
    - For the shortest integrations (reset-read-read) and the baseline window sizes this corresponds to 12.5 (49.2) hours for the prism (gratings).
  - **The problem is that we go back to full frame between exposures.**
    - Switching back to 4 outputs. Thermal disturbances in the detector system.
- **Do as much as possible within single exposures...**



# Disturbances and constraints

- **Disturbances at the start of a visit.**
  - Slewing, moving mechanisms...
  - Starting an exposure...
- **Stabilization time needed.**
- **Need for a “pause” before starting the first exposure is TBD.**
  - The switch from “idle” to window mode could be a significant disturbance and this would be an argument to start the exposure immediately.
  - Seems to have unwanted consequences on the operation side (activity with ill-defined duration).

→ **Work in progress.**

# Simulations

## Generic considerations...



- **Many different approaches possible depending on the scope of the simulations.**
- **Evaluation of the impact of the systematics. Getting some grip on the actual performances of the instrument.**
  - ➔ focus of the presentation. See later.
- **Advertise the capabilities of the instrument to the community. Provide inputs to the community so they can assess the feasibility of their own projects.**
  - ➔ for me (PF) this should be the focus of a lot of the discussions at this meeting; I would advocate for a strong coordination to provide a JWST-level picture.

# Simulations

## Generic considerations...



- **Support development of specific ETCs. Linked to previous bullet.**
  - ➔ discussion / coordination needed (so far the development of the ETCs is decoupled from the instrument teams).
- **Support data challenges.**
  - ➔ timeline to be discussed; “garbage in garbage out” problem for this type of simulations; NIRSpec IPS software used to generate simulated raw exposures.
  - ➔ Specific presentation today.



# Simulations

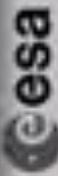
## Photon & readout noise floor and systematics



Noise contributions	Key elements
Photon + readout noise	Noise floor. Provides a benchmark.
Changes in aperture losses levels due to changes in the source position.	Can be seen as NIRSpec specific (use of an aperture).
Intra-pixel sensitivity changes.	NIRSpec PSF core is under-sampled.
Accuracy of the flat-field correction	Not addressed in this presentation.
PSF variations	Not addressed in this presentation.
Unknowns!	



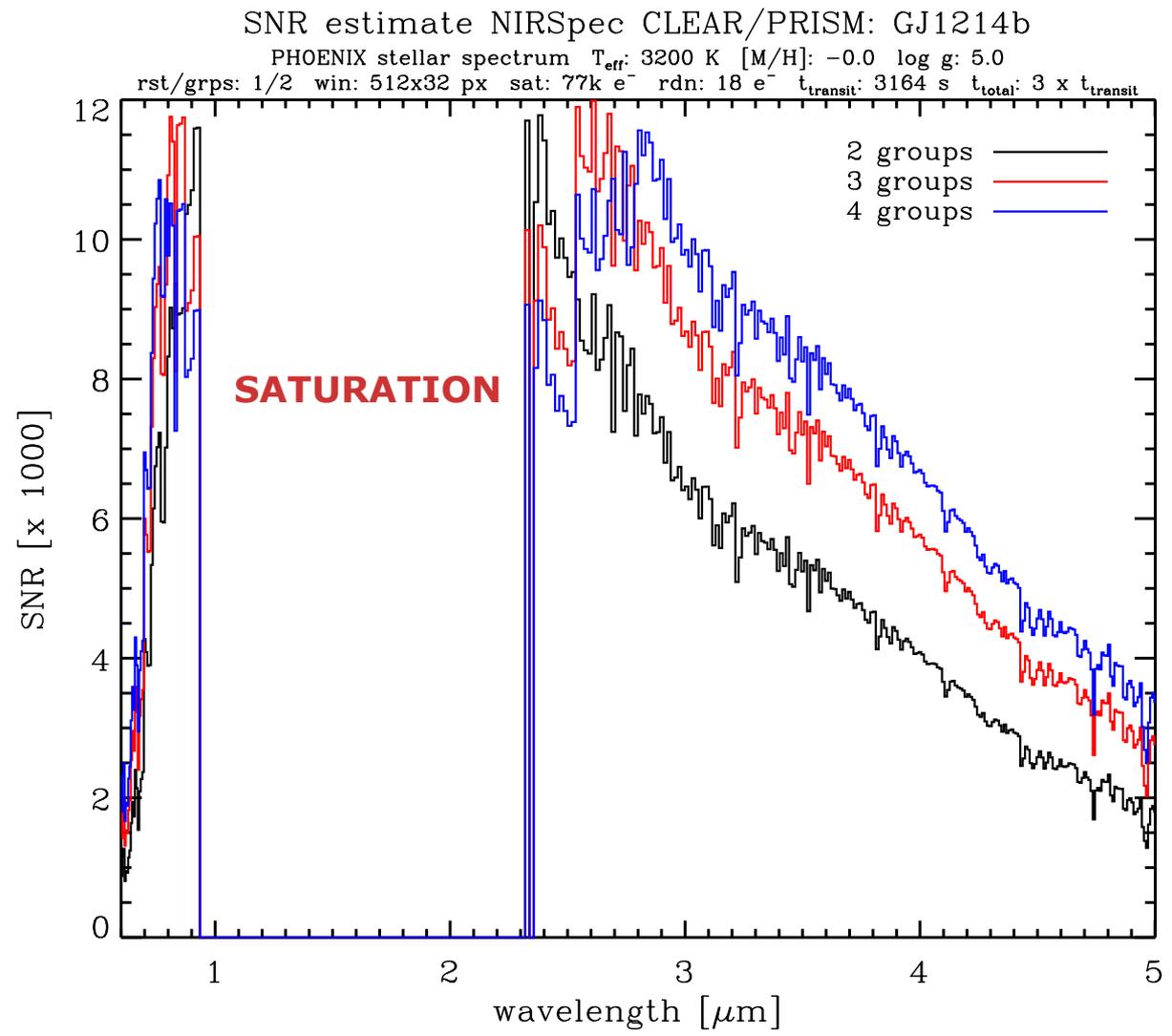
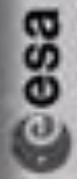
# Simulations Photon & readout noise floor



- **Very basic first step, gives you the theoretical limit.**
  - First assessment of what is possible or not, regardless of (poorly known) systematics.
  - Provides a benchmark for the evaluation of the importance / impact of various disturbances.
- **Large parameter space as the results depend a lot on the transit parameters.**
  - Generic cases: we will need to agree on their parameters to get a consistent picture from one instrument to the next.
  - Examples: easier but we need to agree on a set of examples and use cases. => sharing the same inputs and transit parameters.
- **Simulations for the faint-end are fairly straight forward, things become more complicated at the bright end.**
  - Overheads become important and have some discrete jumps.
  - The saturation limit is not constant with wavelength.



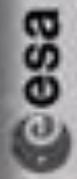
# Simulations Photon & readout noise floor



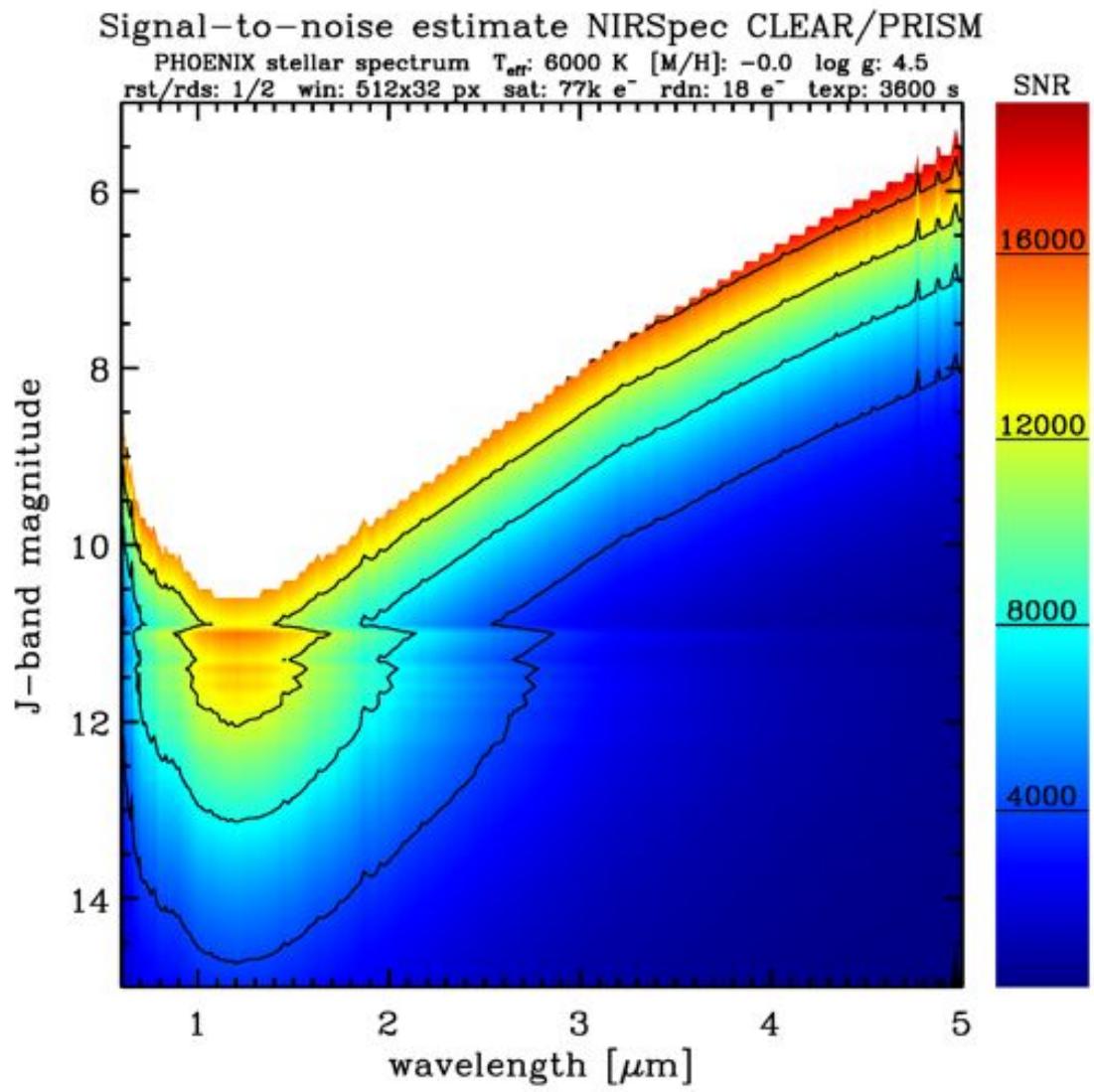
At the limit of what NIRSpec can do at low spectral resolution.



# Simulations Photon & readout noise floor



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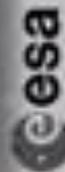


A different view.  
Highlights the jumps associated to increases in the number of groups (and the associated increases in operational efficiency).

The prism configurations correspond to a fairly extreme case.



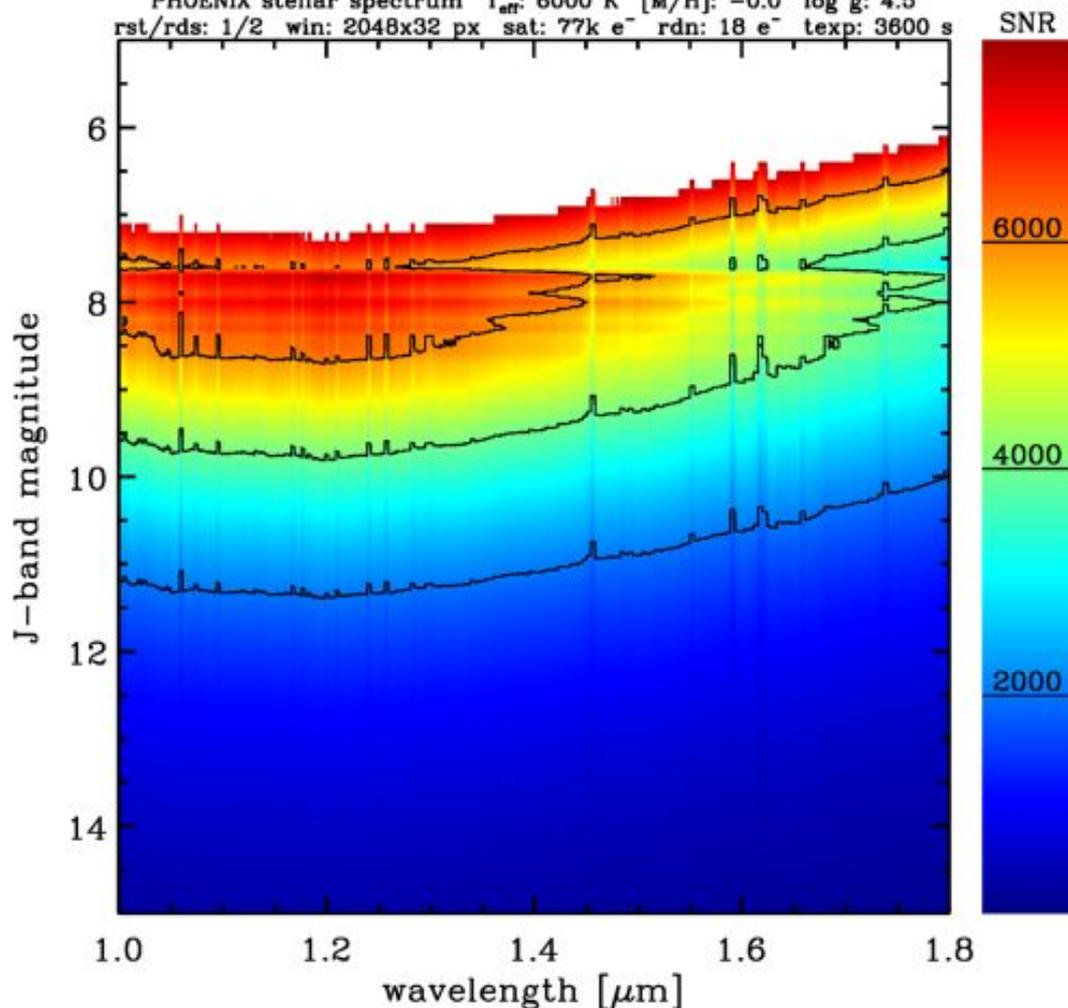
# Simulations Photon & readout noise floor



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Signal-to-noise estimate NIRSpec F100LP/G140H

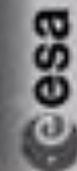
PHOENIX stellar spectrum  $T_{\text{eff}}$ : 6000 K [M/H]: -0.0 log g: 4.5  
rst/rds: 1/2 win: 2048x32 px sat: 77k e<sup>-</sup> rdn: 18 e<sup>-</sup> texp: 3600 s



The situation is less extreme in the case of the gratings (lesser changes in spectral resolution).



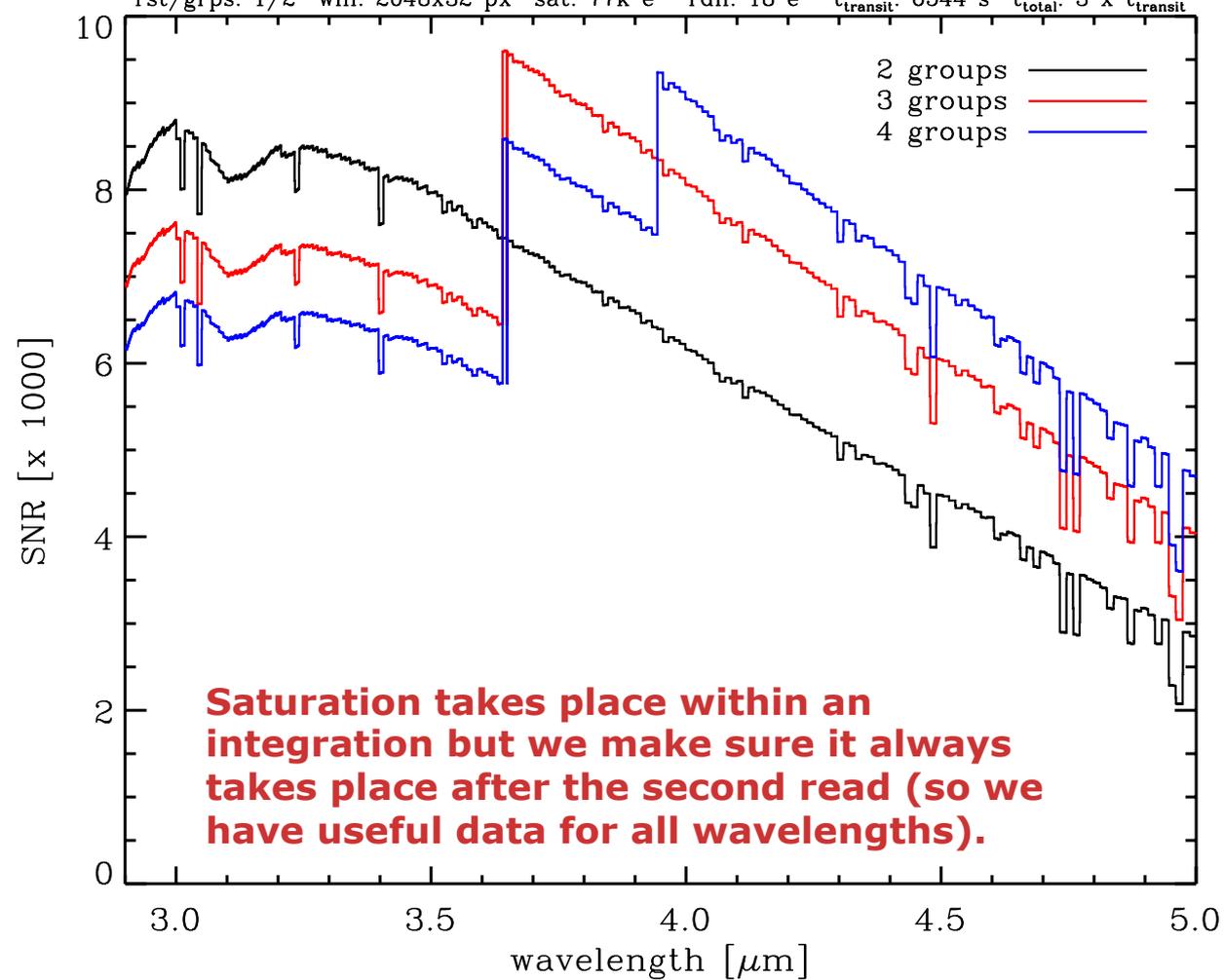
# Simulations Simulations Photon & readout noise floor



SNR estimate NIRSpec F290LP/G395H: HD189733b

PHOENIX stellar spectrum  $T_{\text{eff}}$ : 5000 K [M/H]: -0.0 log g: 4.5

rst/grps: 1/2 win: 2048x32 px sat: 77k e<sup>-</sup> rdn: 18 e<sup>-</sup>  $t_{\text{transit}}$ : 6544 s  $t_{\text{total}}$ : 3 x  $t_{\text{transit}}$



Balancing the signal to noise by playing with the number of groups per integration.



## A few words about pointing stability...

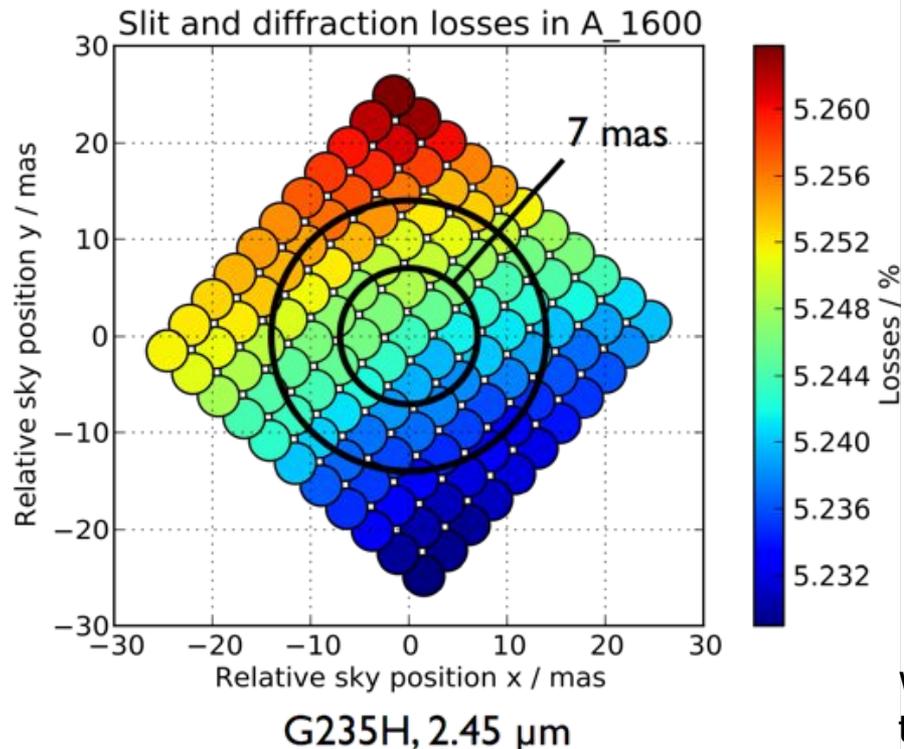


- **Understanding JWST pointing stability is critical if we want to assess the impact of systematics in NIRSpec's transit spectroscopy observations.**
- **Need to go deeper than the top level image motion requirement of 7 mas over 10ks.**
  - What happens when we push beyond 10 ks (see timeline discussion)?
  - We need to understand what happens over very different time scales.
    - Within one integration (< minute), from one integration to the next (several minutes to several tens of minutes), between in and out of transit (hours).
    - Jitter versus drift...
- **Work in progress (at least on NIRSpec side).**



# Simulations Changes in slit losses due to drifts

- Changes in the source centering within the A1600 aperture during a visit will change the radiometric response of the instrument.
  - More concerned by long-term drifts than by random jitter during integrations.



**Prior to any calibration,** changes at the  **$4 \times 10^{-5}$  relative level** are predicted for a drift level of 7 mas (1 sigma).

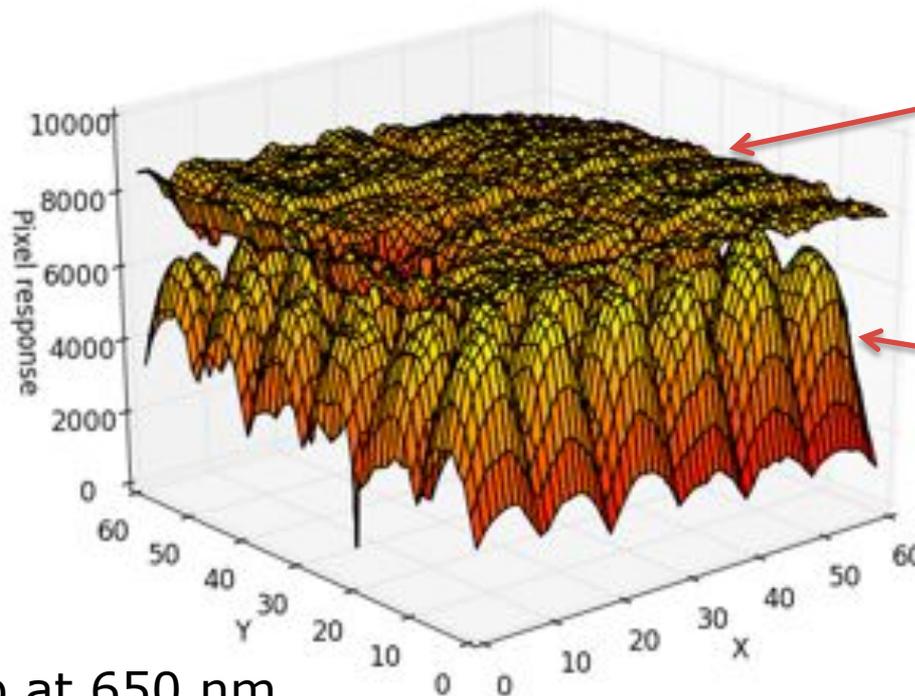
Worst case as this is the complete image motion budget.

Work conducted by B. Dorner (PhD thesis).

# Simulations

## Effect of intra-pixel sensitivity changes

- **Looking at the impact of intra-pixel sensitivity.**
  - Using existing intra-pixel sensitivity maps provided by R. Doyon. To be updated soon with maps for the new detectors.
  - Work conducted by G. Giardino.



Map at 650 nm.

**The “flat” map is the relevant one for our analysis.**

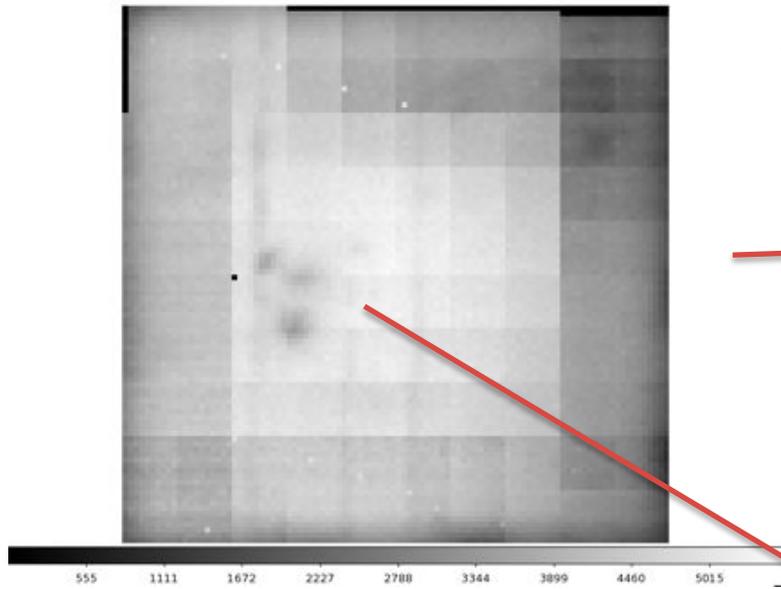
The “domes” correspond to the amount of light collected by a given pixel as a function of the position of the source.

**“Not collected” is different from “lost”.**

# Simulations

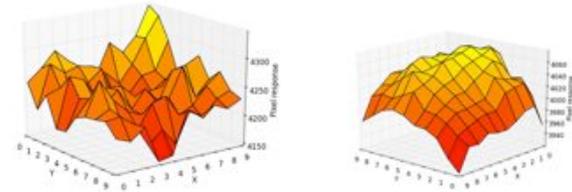
## Effect of intra-pixel sensitivity changes

- **From the measured maps to a generic simulation.**
  - What is a representative intra-pixel sensitivity map?
  - Exploring various solutions.

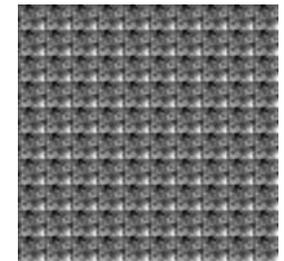


Measurements at 1550 nm.

Trying different "super-pixel" maps  
(median, average, worst...).



Trying various  
locations in the  
measured map

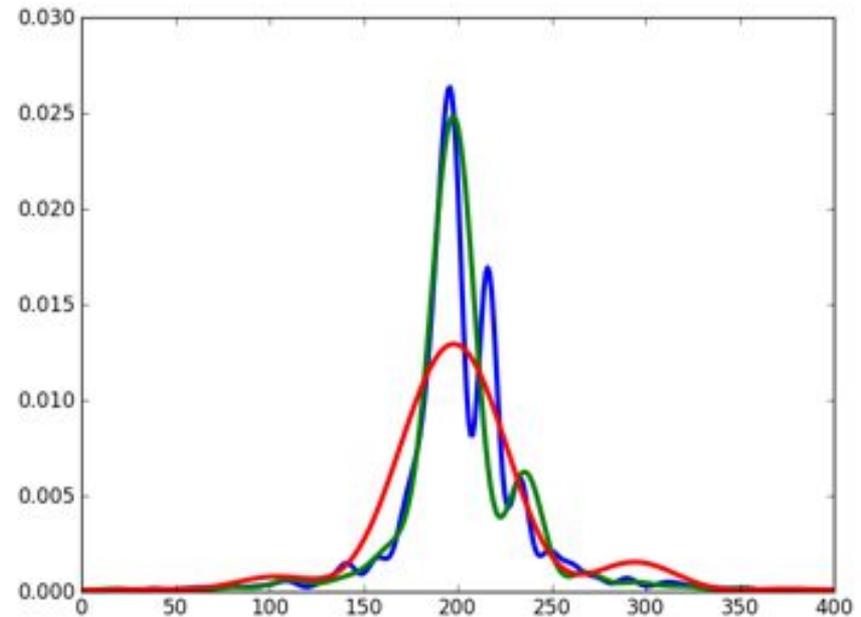
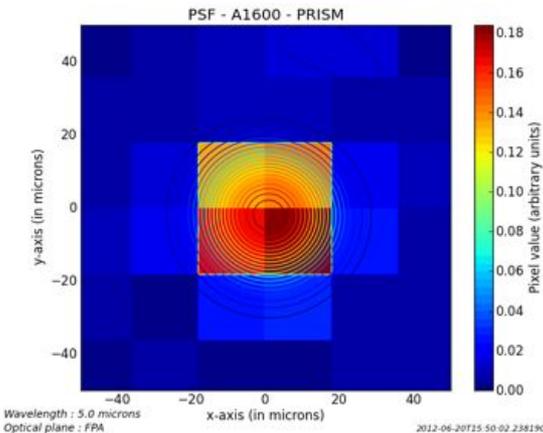
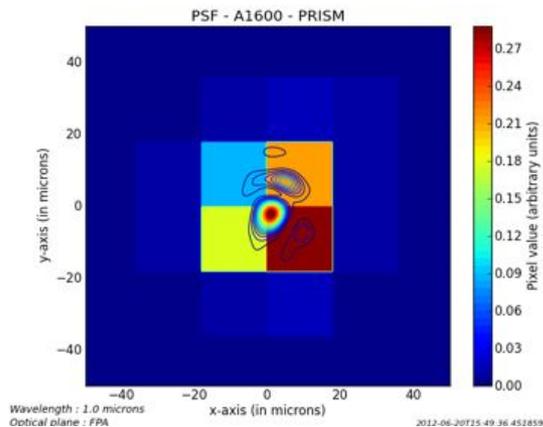


Tiling

# Simulations

## Effect of intra-pixel sensitivity changes

- **Injecting the PSF shape in the simulations.**
  - 1D profiles (continuum spectrum).
  - Simulations conducted both with simplified (Gaussian) profile and with representative profiles (PSF models).





# Simulations

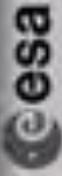
## Effect of intra-pixel sensitivity changes



- Work in progress but overall the results indicates that in the case of NIRSpec, **the intra-pixel sensitivity is likely to contribute at levels of a few  $10^{-4}$  [prior to any calibration].**
- **Probably a major contribution for transit spectroscopy with NIRSpec.**
- **Working on developing mitigation / calibration strategies.**
- **Work in progress.**
  - Results to be updated once the new maps are available.
  - Mitigation / calibration strategies.



# Simulations Highlighting NIRSpec capabilities.



- **Filling the template tables.**
    - Primary advertisement for the instrument capabilities.
    - We need to agree on the inputs and the assumptions.
- We need to discuss how we can achieve that in order to provide a consistent set of inputs for the white paper update.**

# Simulations Highlighting NIRSpec capabilities.

- Example of NIRSpec capabilities. Slides extracted from J. Valenti's presentation at the NASA EXOPAG meeting.

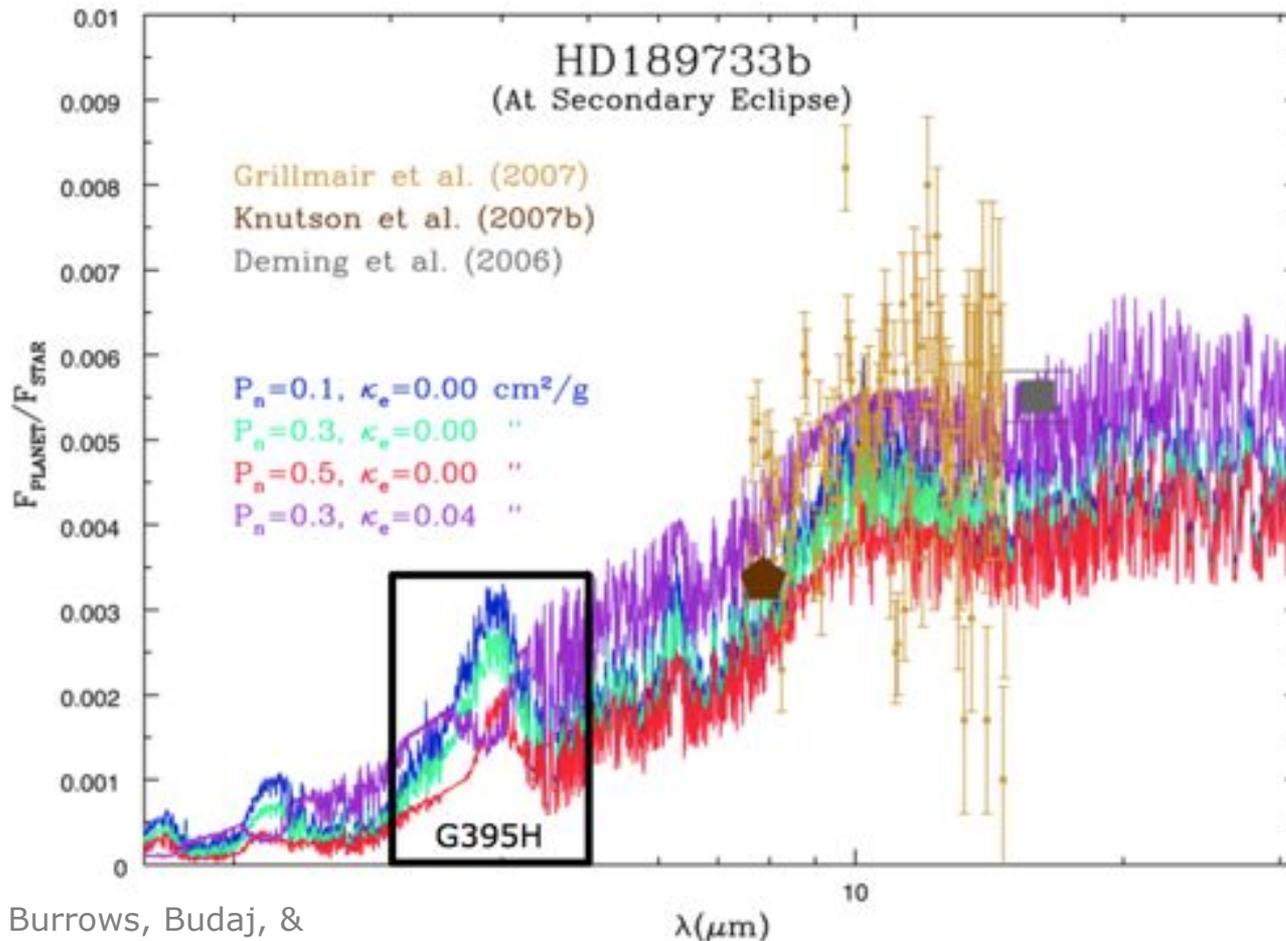
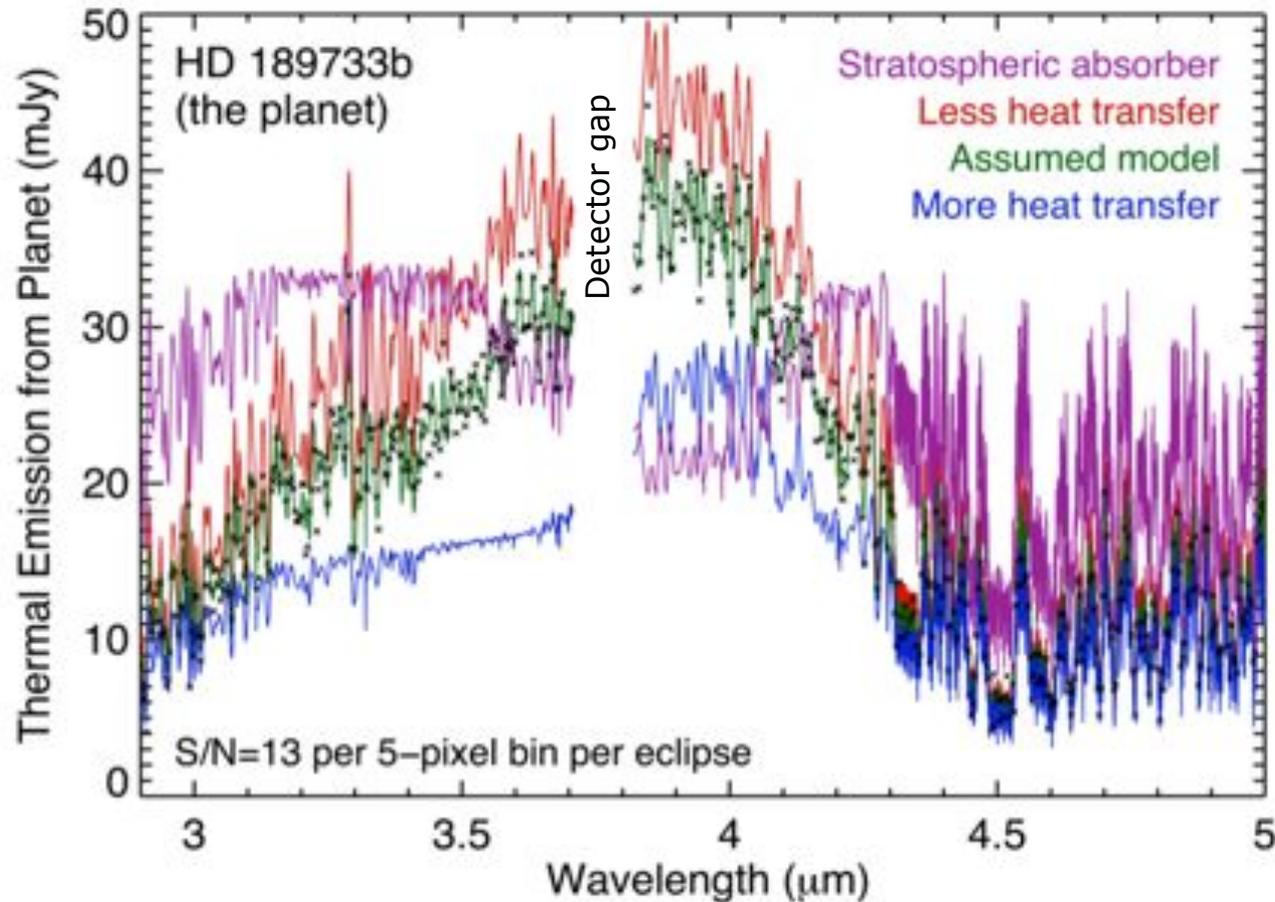


Figure 4b of Burrows, Budaj, & Hubeny (2008)

# Simulations Highlighting NIRSpec capabilities.

- **Thermal emission from a hot Jupiter (secondary eclipse)**
  - Credit for the slide: J. Valenti (STScI).



Adapted from Figure 4b of  
Burrows, Budaj, & Hubeny (2008)