

NIRCam Coronagraphy of HR8799 b



Example Science Program #36

This article discusses a relatively simple high contrast imaging science program using JWST [NIRCam Coronagraphy](#): the spectrophotometric characterization of the outermost exoplanet previously imaged around the young star HR8799.

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See also: [JWST Coronagraphic Observation Planning](#)

This article describes the preparation of an [Exposure Time Calculator \(ETC\)](#) workbook to directly image a known exoplanet at a relatively wide angular separation of 1.7", yet still benefitting from [NIRCam Coronagraphic Imaging](#) as the host star is very bright and the expected contrast is around 14 magnitudes in K-band. Using the ETC, one can quickly assess the feasibility of such program and calculate signal-to-noise ratios (SNRs) through various long-wavelength (LW) [filters](#). This article does not give details on how to design an [APT](#) file as that is explained thoroughly and for a more complex case in the science use case [MIRI and NIRCam Coronagraphy of the Debris Disk Archetype around Beta Pictoris](#).

This article will focus on the first four of these five steps of [planning](#) this JWST coronagraphic observation:

1. Choose instrument(s), filter(s) and coronagraph(s) based on the science goals and to some extent on the [contrast](#) and separation of the science target. When assessing feasibility, observers may need to use models to extrapolate shorter-wavelength measurements to 2–5 μm , for instance to determine companion contrasts at NIRCam wavelengths. Additionally, the user will want to use the [JWST Coronagraphic Visibility Tool \(CVT\)](#) to examine the target's visibility and available position angles versus time.
2. Select a PSF subtraction strategy. The [recommended standard sequence](#) is two rolls on a science target, followed by a PSF calibrator, all observed back-to-back in sequence.

3. Calculate the necessary exposure times using the ETC coronagraphic capabilities. You may want to upload custom spectral models for cool substellar atmospheres.
 4. Select a PSF reference star. This should be based on proximity, brightness, spectral type match, and avoidance of binaries.
 5. Set up observations in the [Astronomer's Proposal Tool \(APT\)](#); assess overheads and total program time; iterate as desired. It is important to consider significant overheads: [slews and rolls](#), [guide star acquisitions](#), target acquisitions, etc.
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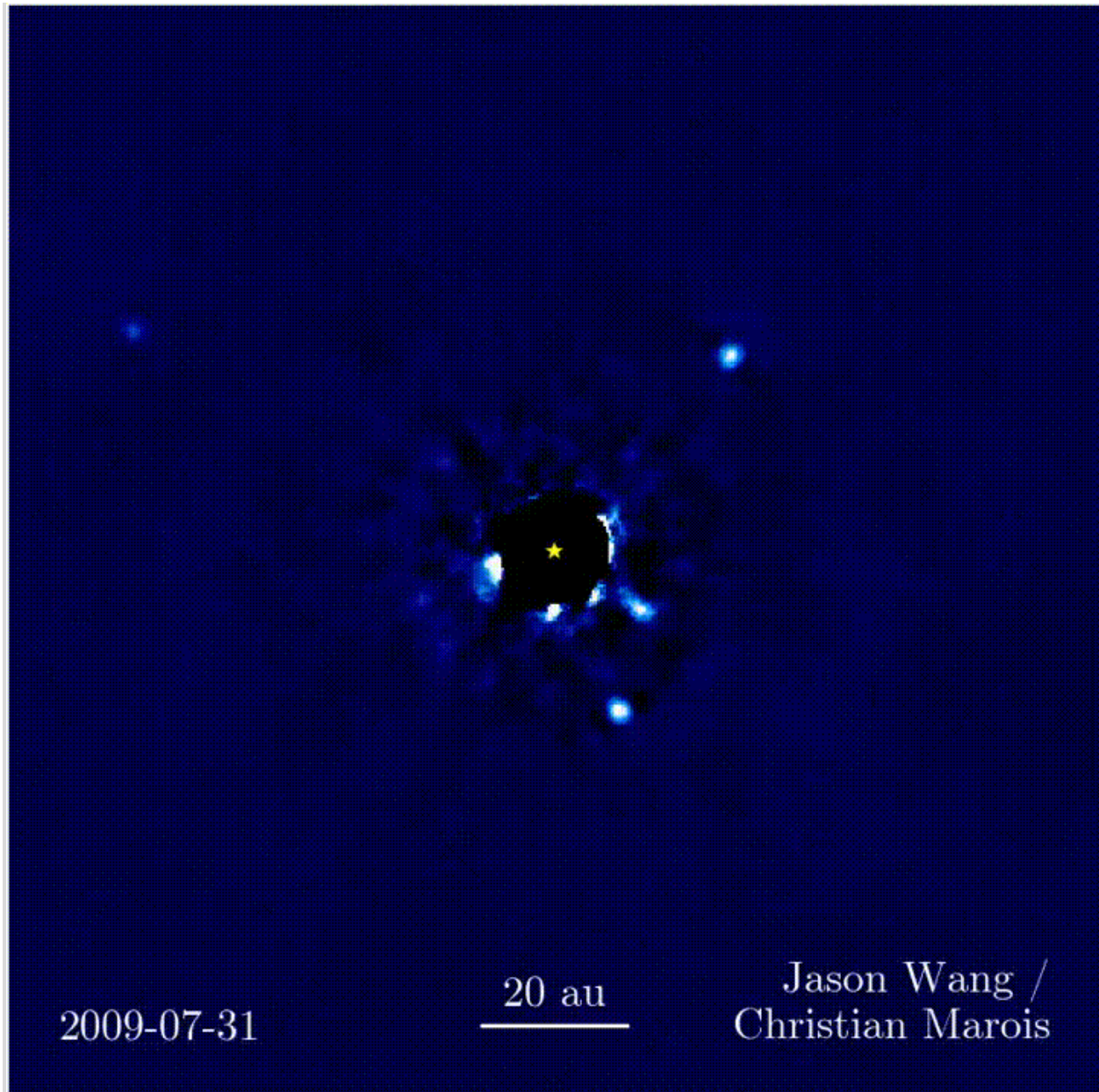
Characterizing HR8799 b

Science goals

In this science use case, we will observe the brown dwarf companion HR8799 b using one of NIRCam's round [Lyot coronagraphs](#). HR8799 b is the outermost planet orbiting this young F-type star, which harbors a total of four gaseous giant planets in the range of 5–9 M_{Jupiter} (Marois et al., 2008, 2010). The effective temperature of HR8799 b is $\sim 870\text{K}$ and its K-band magnitude is ~ 14 . The host star HR8799 is 40 pc from us. The goals of this program are to:

- Characterize the atmosphere of this benchmark exoplanet at 2.5 to 5 μm especially with filters/bands which are not accessible from the ground due to the Earth's atmosphere (otherwise they have already been done by ground-based instruments with adaptive optics).
- Compare to atmospheres of other exoplanets and field brown dwarfs.

Figure 1. The power of direct imaging: multi-epoch animation of the orbital motion of HR8799 bcde planets from 2010 to 2015



Direct, high-contrast imaging of the multi-planet system around HR8799 between 2010 (discovery of the innermost, fourth planet with Keck) to 2015 (GPI data). Credit: Jason Wang and Christian Marois (GPIES Team). In this science use case, we will concentrate on planet b, the outermost but faintest one at a separation of 1.7" and position angle $\sim 70^\circ$ (in 2019).

Observing strategy and planning

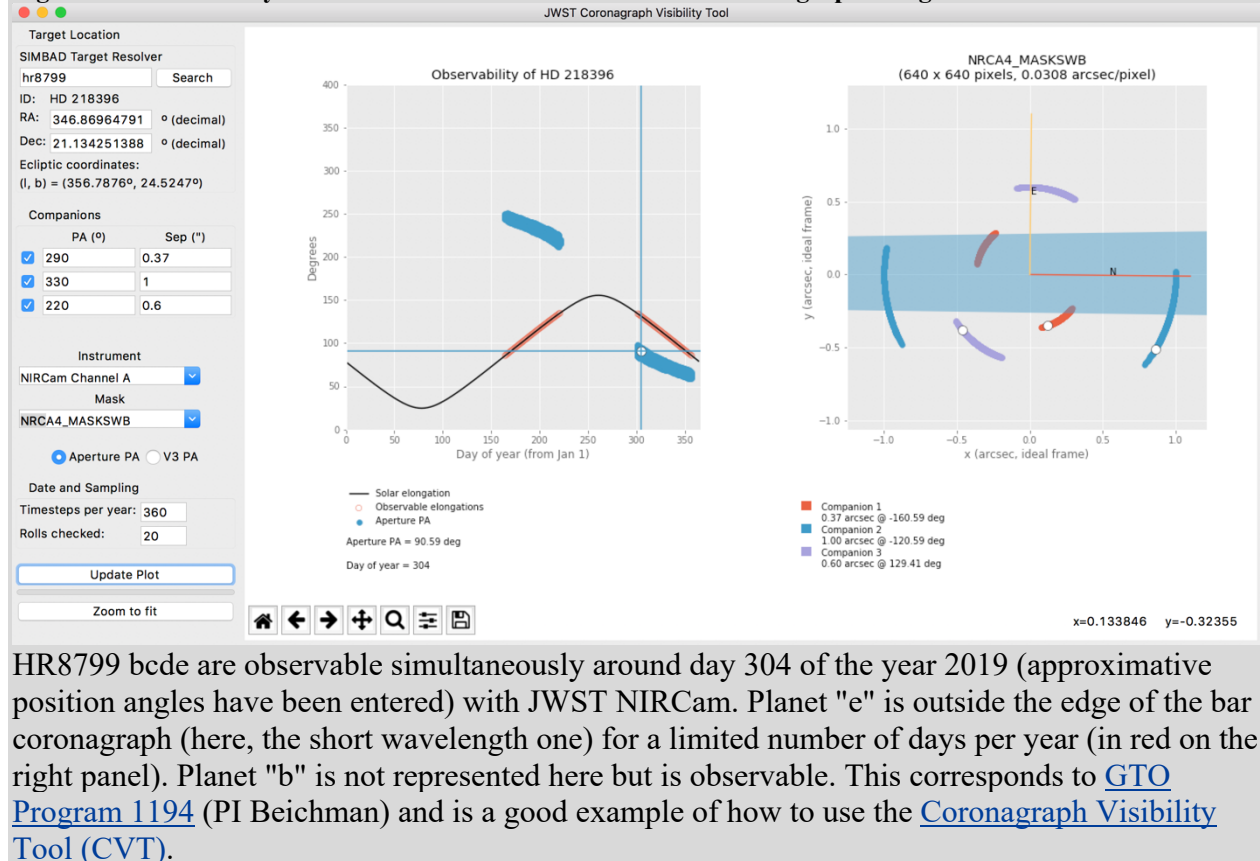
Choosing the coronagraphic setup

HR8799b is at a separation of 1.7". If the goal of this proposal is solely to characterize this planet and not the other three planets in the system (HR8799 c, d, and e at smaller angular distances),

then the best long-wavelength (LW) [coronagraphic mask](#) is MASK430R because it allows observations in ten different LW [filters](#) with central wavelengths from 2.5 to 4.6 μm while providing a small enough [inner working angle](#) (IWA) of 0.82" and a better attenuation than MASK335R for wavelengths above 3.5 μm (at least five or six filters).

If the goal were to image all four planets, including the very challenging planet "e" at an angular distance $< 0.35''$, then the only suitable coronagraphic setup would be the MASKLWB (bar / wedge occulter) and a complex and very time critical strategy (Figure. 2) involving an engineering mode aperture to position the star at the narrow end of the bar coronagraph. This article does not go into that level of planning. [GTO Program 1194](#) will attempt exactly that and the [APT file](#) can be downloaded on the same page.

Figure 2. Observability of HR8799 bcde with the MASKSWB coronagraph using the CVT



HR8799 bcde are observable simultaneously around day 304 of the year 2019 (approximative position angles have been entered) with JWST NIRCcam. Planet "e" is outside the edge of the bar coronagraph (here, the short wavelength one) for a limited number of days per year (in red on the right panel). Planet "b" is not represented here but is observable. This corresponds to [GTO Program 1194](#) (PI Beichman) and is a good example of how to use the [Coronagraph Visibility Tool \(CVT\)](#).

Choosing the PSF reference star

See also: [Selecting Suitable PSF Reference Stars for JWST High-Contrast Imaging](#)

The PSF reference star should satisfy the following criteria:

- Relatively nearby (not more than a few degrees away from HR8799)
- Close match in spectral type
- Close in magnitude, if possible a bit brighter
- Not a binary
- Not a variable star

Using [SearchCal](#), we find that HD 218261 is an ideal match at a distance of only 1.24°, enabling a [slew time](#) of approximately 500 s between the two sources.

In addition, it is slightly brighter than HR8799 and can therefore be observed with slightly less total time, yielding the same level of counts. Finally its spectral type is close and therefore the [sensitivity loss due to the spectral mismatch](#) should be negligible.

Figure 3. SearchCal results for a suitable PSF reference star for HR8799

The screenshot shows the SearchCal application window with the following sections:

- Query Parameters:**
 - 1) Instrumental Configuration: Magnitude Band: K, Wavelength (K) [μm]: 2.2, Max. Baseline [m]: 10.0
 - 2) Science Object: Name: HR 8799, RA 2000 [hh:mm:ss]: 23 07 28.7155, DEC 2000 [+/-dd:mm:ss]: +21 08 03.305, Magnitude (K): 5.24
 - 3) SearchCal Parameters: Min. Magnitude (K): 3.24, Max. Magnitude (K): 7.24, Scenario: Faint (selected), Radius [arcmin]: 240.0
- Found Calibrators (226 sources, 220 filtered):**

Index	dist	SIMBAD	SpType	RAJ2000	DEJ2000	ObjTypes	V	K
1	4.703E-6	HD 218396e	A5V	23 07 28.7143	+21 08 03.3072	,Planet*,PI7,PI	5.953	5.24
2	1.243	HD 218261	F6V	23 06 31.8862	+19 54 39.0708	,PM*,PM*,UV*,IR,X	6.44	5.144
3	0.997	HD 218172	F8IV	23 05 35.3270	+20 14 27.3588	,Star*,IR	7.26	5.85
4	2.371	HD 217588	F5	23 01 35.0395	+19 53 31.3296	,PM*,UV*,IR,PM*	7.02	5.726
5	3.365	HD 216625	F8	22 54 07.4105	+21 55 09.0300	,Star*,IR	9.428	5.65
6	1.623	BD+21 4867	F0	23 01 22.3224	+21 55 09.0300	,Star*,IR	9.428	5.65
- Filters:**
 - Reject stars farther than: Maximum RA Separation (mn): 600.0, Maximum DEC Separation (degree): 10.0
 - Reject stars with magnitude: below: 4.0, and above: 6.0
 - Reject Spectral Types (and unknowns): O, B, A, F, G, K, M (all checked)
 - Reject Luminosity Classes (and unknowns): I, II, III, IV, V, VI (IV, V, VI checked)
 - Reject Visibility below: vis2: 0.5
 - Reject Visibility Accuracy above (or unknown): vis2Err/vis2 (%): 2.0
 - Reject Variability (checked)
 - Reject Multiplicity (checked)
 - Reject Invalid Object Types (checked)
 - Diameter quality: Maximum chi square: 2.0, Maximum relative error (%): 10.0

At the bottom, it shows "searching calibrators... done." and "Provided by JMMC".

Using SearchCal and a "faint" catalog scenario, we find that the best suited PSF reference star for HR8799 is HD 218261. The two stars are only 1.24° apart and HD 218261 is slightly brighter than HR8799.

Signal to noise calculations with the ETC

We created an [ETC workbook](#) "from scratch".

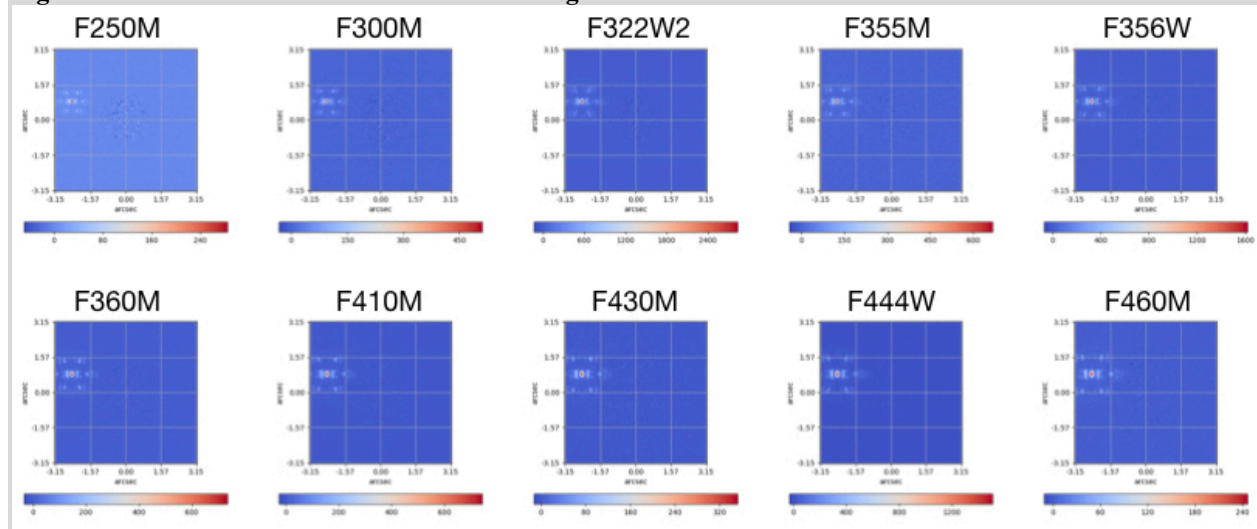
The scene is composed of three sources:

- HR8799: central star, $K = 5.24$ (renormalized through the Johnson K filter)
- HR8799b: off-axis planet at 1.7" separation ($[-2.4", 0.8"]$) as $\{x, y\}$ offsets, the "SNR source" in the Calculations/Extraction tab)
- HD 218261: off-axis PSF reference (or "PSF Subtraction source"), $K = 5.24$ (also renormalized through the Johnson K filter). For the calculations, the ETC will artificially place this source at a distance of $|100,100|$ pixels.

The target acquisition (TA) is done in "Bright" mode (with the neutral density filter). With the BRIGHT1 [readout pattern](#), an SNR of ~ 150 is easily achievable in less than 1 s. This is important to guarantee a good and very similar centering (good, sub-pixel registration) of both HR8799 and the PSF reference star.

Figure 4 displays the "Detector" images with background and noise obtained after an "optimal" subtraction of the PSF reference (scaled photometrically) to the science target. HR8799b is revealed easily with SNRs ranging from ~ 124 to ~ 273 and contrasts at the planet separation from 3×10^{-5} to 1.5×10^{-6} as shown in Figure 5.

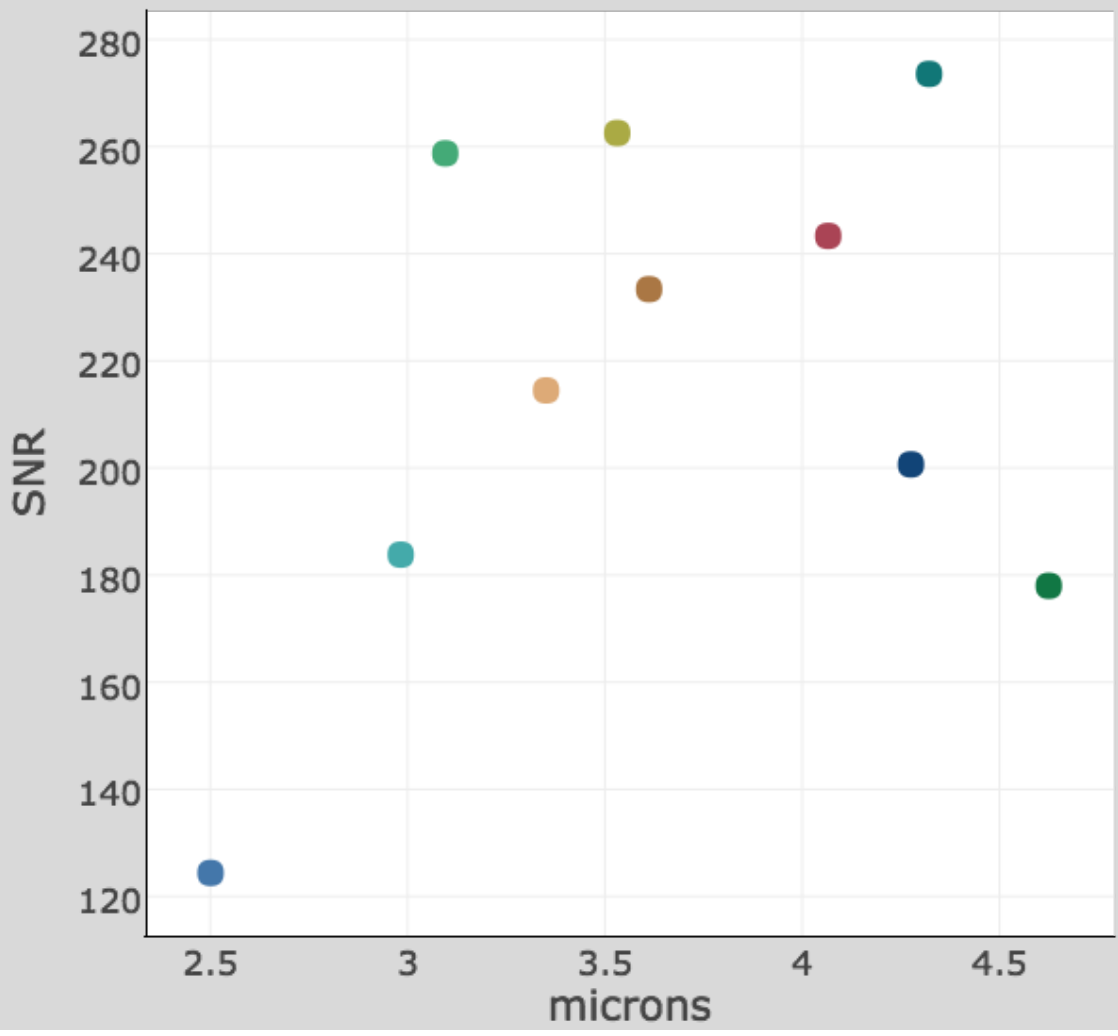
Figure 4. Detector scene as a function of wavelength for all 10 filters offered with MASK430R

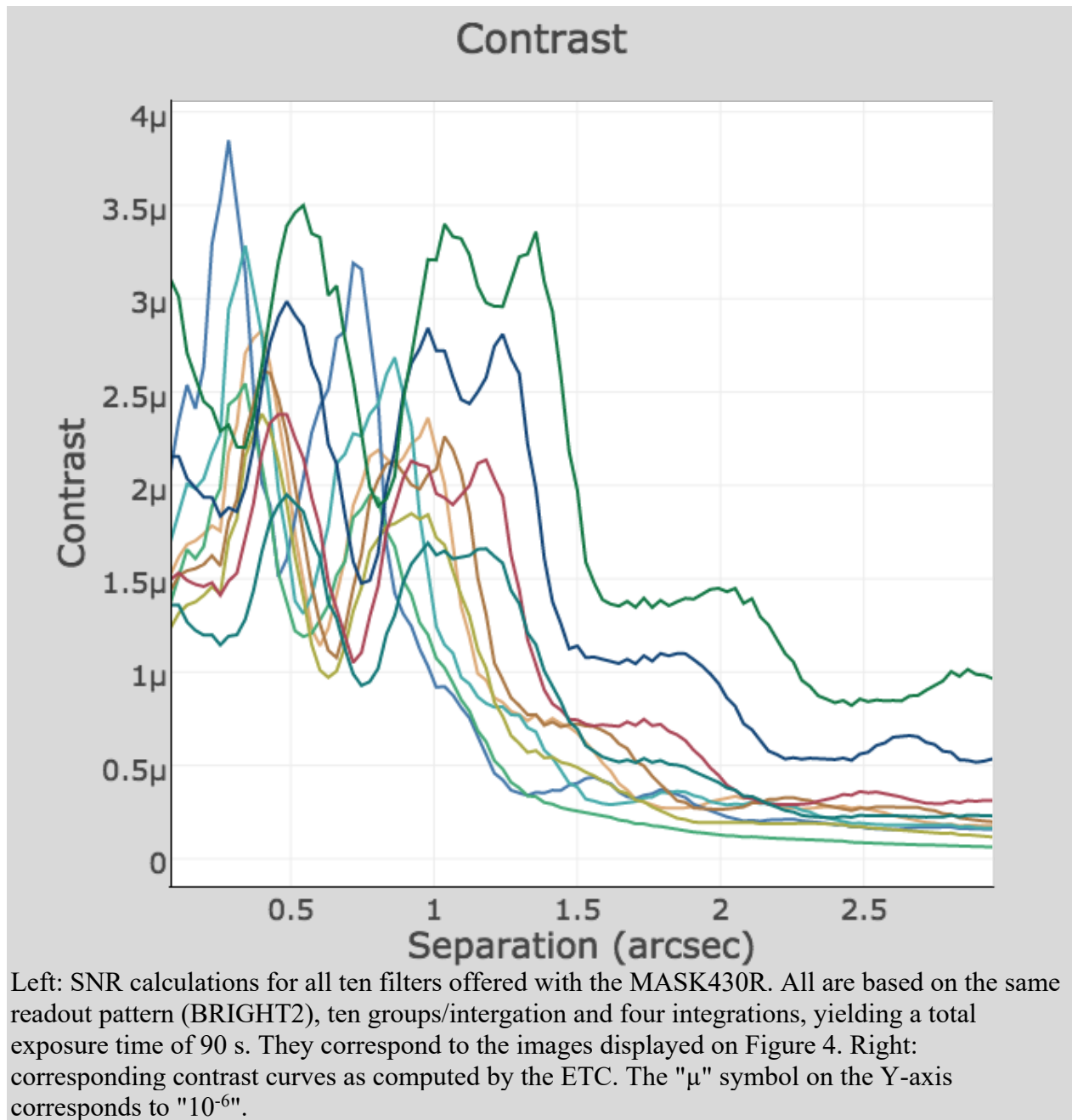


ETC-generated detector scenes for the ten filters available for use with MASK430R. All are based on the same readout pattern (BRIGHT2), ten groups/integration and four integrations, yielding a total exposure time of 90 s. The central star, HR8799 has been optimally subtracted with the reference star HD218261 (whose flux has been rescaled in each filter bandwidth to avoid over-subtraction). These calculations correspond to the SNRs plotted on Figure 5. They are optimistic provided that the ETC assumes a perfect centering behind the coronagraph for both stars. Note the PSF size increasing with wavelength as well as the radial dispersion of the side lobes with wide filters ("W" in the name).

Figure 5. SNR as a function of wavelength and contrast as a function of angular separation

Signal to Noise

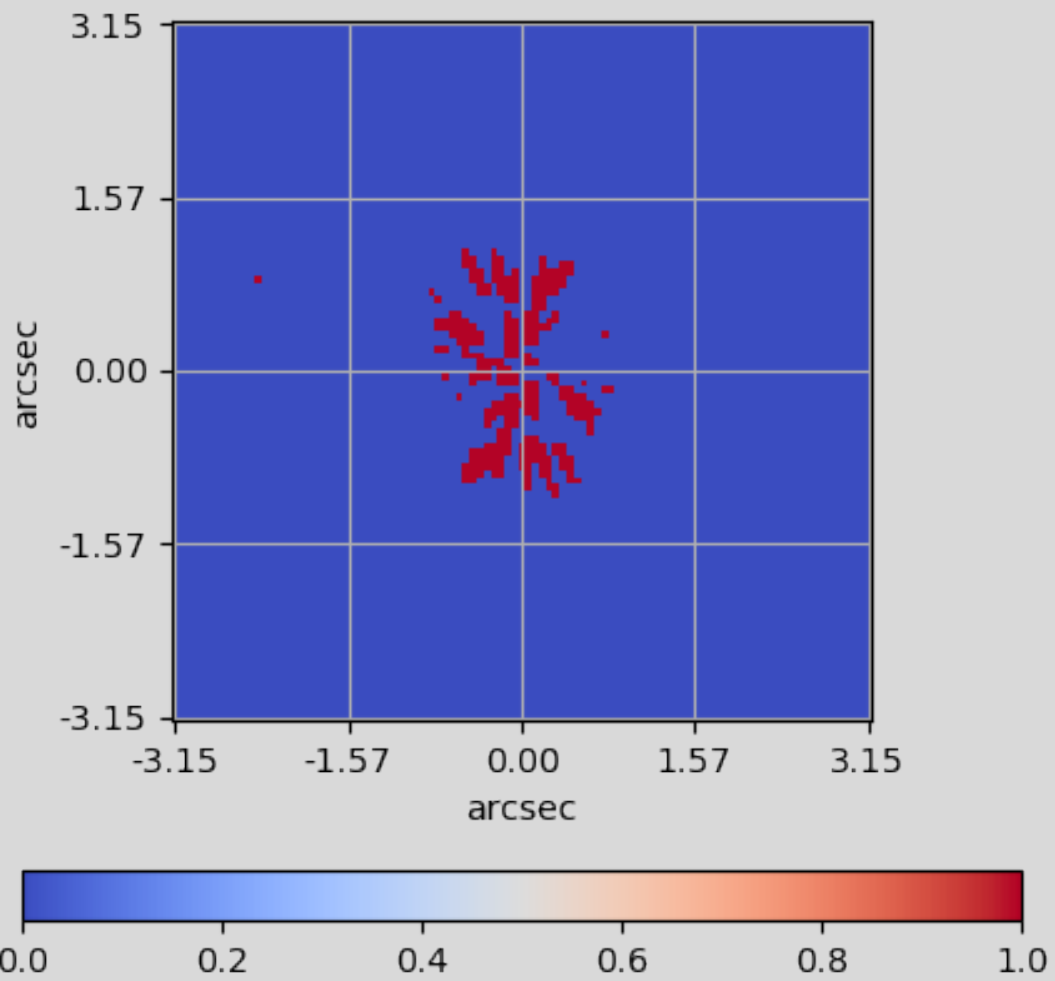




Left: SNR calculations for all ten filters offered with the MASK430R. All are based on the same readout pattern (BRIGHT2), ten groups/integration and four integrations, yielding a total exposure time of 90 s. They correspond to the images displayed on Figure 4. Right: corresponding contrast curves as computed by the ETC. The "μ" symbol on the Y-axis corresponds to "10⁻⁶".

For these calculations we kept the same readout pattern and number of groups and integrations on purpose to have a meaningful first comparison. In four of the ten filters, we observe a significant partial saturation (from 1 to 50 pixels), the worst case being for the widest filter, F322W2, as shown in Figure 6.

Figure 6. Saturation for the F322W2 filter and warning message from the ETC



Reports

Calculation selected: 10, Mode: nircam coronagraphy

Report

Warnings

Errors

Downloads

- Partial saturation: There are 50 saturated pixels at the end of a ramp. Partial ramps may still be used in some cases.

The readout pattern chosen (BRIGHT2) causes the star(s) to saturate partially in four of the filters. F322W2 is the most critical here with a "Report" (right hand side of the ETC workbook) indicating "50 saturated pixels at the end of a ramp". In the case of HR8799b this would not matter as the planet lies in a non-saturated area. However, it would affect the recovery of planets "c," "d," and "e" at a separation $< 1''$.

Preparation of the APT file

Please refer to the detailed science use case on [MIRI and NIRCcam Coronagraphy of the Beta Pictoris Debris Disk](#). It contains all the necessary information to build [non-interruptible Coronagraphic Observation Sequences with APT](#) as well as how to perform the time accounting.

HR8799 b is relatively easy to characterize with NIRCcam. About 90 s of total integration time per filter yield an SNR of about 100 to 270.

Note for this outermost planet, which is at $1.7''$ (far from the IWA of the coronagraph and thus not in the speckle-limited regime), it is not necessary to observe the PSF reference star with a [small grid dither pattern](#). As shown by these ETC calculations, the planet is easily and unambiguously detected without risk of over-subtraction of the PSF.

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