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SCIENCE INSTITUTE

EXPANDING THE FRONTIERS OF SPACE ASTRONOMY

The JWST Exposure Time Calculator

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JWST Master Class

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Table of Contents

- History and design philosophy
- Basic algorithm and architecture
- Strategies
- Detector readout and noise
- Reference database
- ~~Scenes and sources~~
- The JWST Background
- Special effects
- Benchmarks and testing
- A collaborative environment
- The Pandeia engine



First things first – where can I find the ETC?

jwst.etc.stsci.edu

Welcome to the JWST Exposure Time Calculator

Quick Start

Create User

Login

Work Anonymously

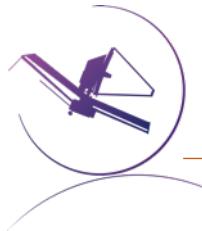
News

Welcome to version 1.5 of the JWST ETC!

This release features new instrument modes, accuracy improvements, usability enhancements, and more: see the [Release Notes](#) for details, and be sure to review the [Known Issues](#) for this release.

When you log in to the 1.5 ETC, your old workbooks will be marked "Out of Date":

- When you load them, they will open in Read-Only mode: this ensures that your previous results are not overwritten and remain available to you for reference.
- If you copy an out of date workbook, and load the copy, all its calculations will be automatically updated for you with the current version of the software.
- For more information, see [ETC Releases and Out-of-Date Workbooks](#).



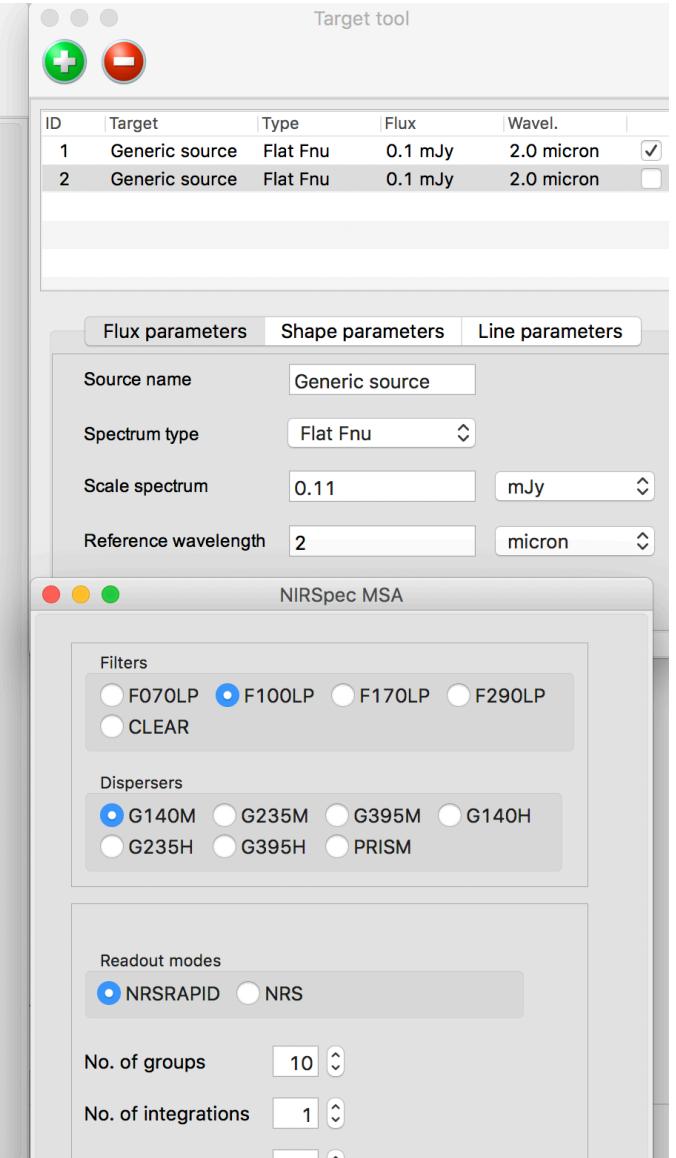
Some history

- Imaging
 - NIRCam SW+LW, NIRISS, MIRI
- Slit spectroscopy
 - NIRSpec FS, MIRI LRS
- IFU spectroscopy
 - NIRSpec IFU, MIRI MRS
- Multi-object spectroscopy
 - NIRSpec MSA
- Slitless spectroscopy
 - NIRISS WFSS, NIRCam WFSS
- Time Series Observations
 - MIRI LRS, NIRISS SOSS, NIRCam grism+weak lens
- Coronagraphy
 - NIRCam spots + wedges, MIRI Lyot, MIRI 4QPMs
- Aperture Masking Interferometry
 - NIRISS AMI
- Target Acquisition
 - All instruments

- The JWST ETC is required to support all science modes and related target acquisition.
- Originally, it was envisioned that the JWST ETC would be similar to the HST ETC.
- It became clear that using the HST ETC as a basic design was not viable.
- Works ok for imaging, but not for:
 - the advanced JWST modes
 - JWST detector noise / non-destructive readout
 - Supporting modern user interaction and collaborations
- Something more modern was needed.



2012: The first prototype





Some history, cont'd

2013: Recommendations to satisfy the ETC requirements for all observing modes within a common framework.

- 1) The ETC should use a three-dimensional (two spatial and one spectral) framework.
- 2) The ETC should use a PSF library, for instance as generated by the WebbPSF tool.
- 3) The noise propagation should include correlated noise.
- 4) Post-observation additions of multiple exposures, subtraction of backgrounds, extraction of photometry and spectroscopy [...] should be explicitly modeled under the unifying concept of “observing strategy”.
- 5) The ETC engine should have a stable API supporting different clients, including APT, a user web form and a standalone application.
- 6) ETC calculations should be sufficiently fast to support efficient comparative parameter studies, as well as inverse problems.
- 7) The ETC should be template-based for all three main inputs (instrument configuration, target design, observing strategy).

February 12, 2016

Accordingly:

The JSTAC would like to recommend that the Exposure Time Calculators (ETC) that has been under development should be released to the science community as soon as practical. The ETC should be populated with the best-available measured or model numbers from the instruments and the telescope, and the current best estimates of likely backgrounds.



The production ETC

Exposure Time Calculator Edit ▾ Expand ▾

anon_12898 ▾ Help ▾

Calculations Scenes and Sources Upload Spectra Caveats and Limitations

MIRI ▾ NIRCam ▾ NIRISS ▾ NIRSpec ▾ ⓘ

ID	Mode	λ	Scn	(s)	SNR	▲
3	nirspec mos	1.15	1	440.21	1.83	✓
2	miri imaging	5.61	1	277.50	7.97	✓
1	nircam lw_imaging	2.50	1	1954.09	87.84	✓
-	-	-	-	-	-	-

Scene ★ Backgrounds Instrument Setup Detector Setup Strategy

NIRSpec Multi-Object Spectroscopy

Grating/Filter Pair G140M/F100LP

Slitlet Shape 3 shutters (-1,0,1)

The source selected in the Strategy tab will be placed in shutter 0.

MSA Location Quadrant 3 center

These relative directions are when looking through the MSA towards the sky.

Wavelength range: (0.97 ~ 1.89)

Total System Throughput

NIRSPEC MOS G140M F100LP

λ (μ m)

Calculation selected: 3, Mode: nirspec mos

Reset Calculate

Images ⓘ

Calculation selected: 3, Mode: nirspec mos

2D SNR Detector Saturation Groups Before Saturation

SNR

microns

arcsec

Plots ⓘ

ApFlux ApBackground SNR SNR (time) Contrast

Signal to Noise

SNR

Reports ⓘ

Calculation selected: 3, Mode: nirspec mos

Report Warnings Errors Downloads

Instrument Filter/Disperser: f100lp/g140m

Extraction Aperture Position (arcsec): [0.00, 0.00]

Wavelength of Interest used to Calculate Scalar Values (microns): 1.15

Size of Extraction Aperture (arcsec): N/A

Total Time Required for Strategy (seconds): 440.21

Total Exposure Time (seconds): 440.21

Maximum Fraction of Saturation: 8.7e-4

Maximum Number of Groups Before Saturation: >9999

Extracted Flux (e-/sec): 0.09

Standard Deviation in Extracted Flux (e-/sec): 0.05

Extracted Signal-to-Noise ratio: 1.83

Input Background Surface Brightness (MJy/sr): 0.46

Total Background Flux in Extraction Aperture (e-/sec): 0.11

Total Sky Background Flux in Extraction Aperture (e-/sec): 0.11

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the “pandeia” project



3D ETC engine
(pandeia.engine)

**Reference
database**
(pandeia_data)

- Throughputs
- Detector noise
- PSFs

...

Web Application
(jwst/etc.stsci.edu)

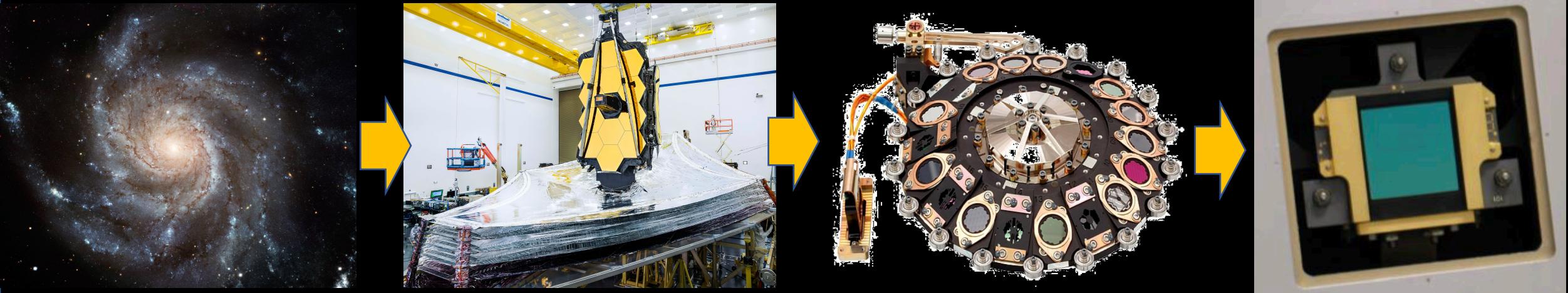
- User interface
- Collaborative functionality

**JWST
Background
Model**

Also available via
jwst_backgrounds



Engine algorithm: Overview





Engine algorithm: The scene cube

1. Create astrophysical scene

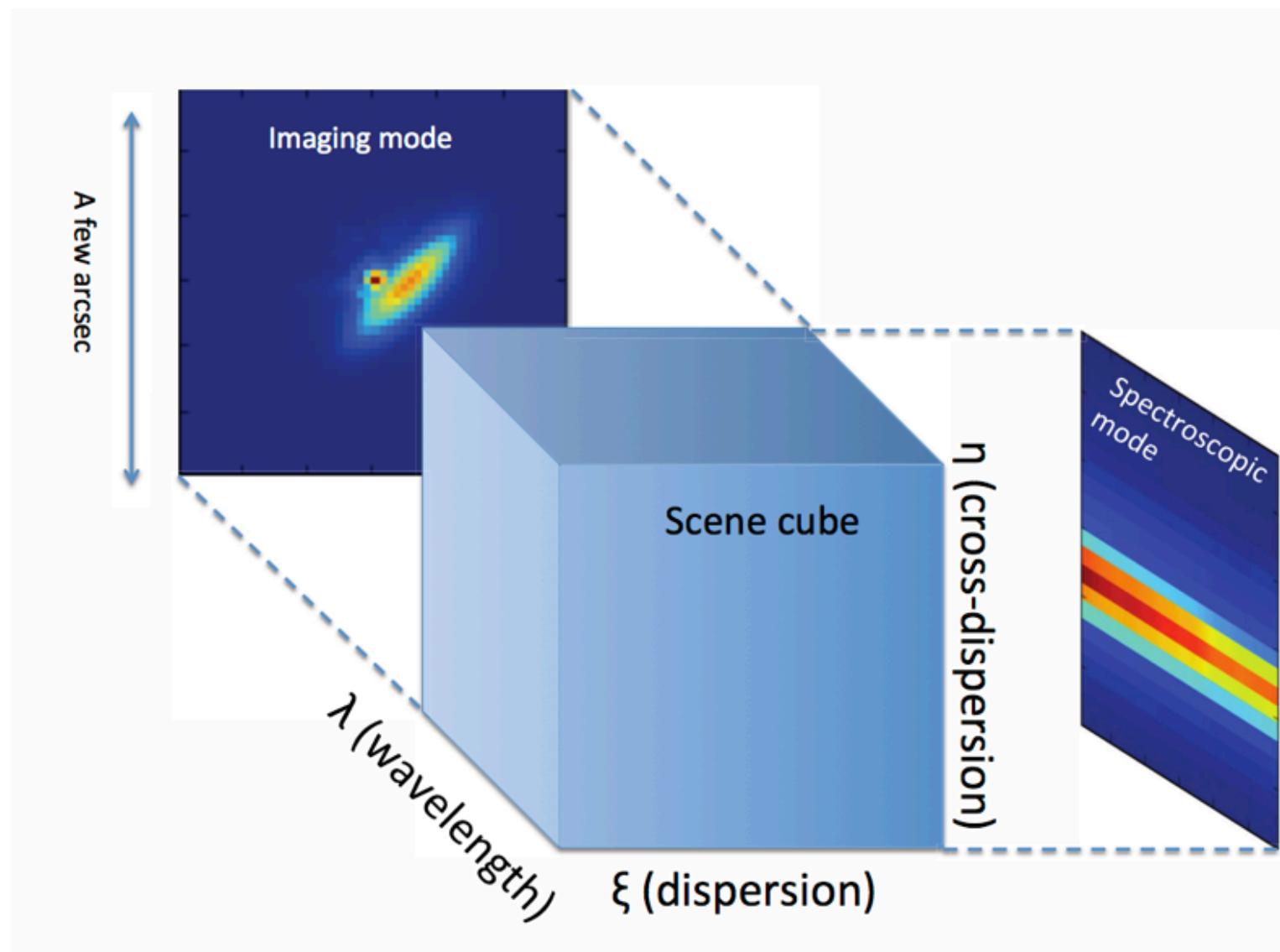
- Abstract cube in surface brightness
- Jy/sq. arcsec (wavelength)

2. Sample scene in angular and wavelength space

- Conserve flux, resolve lines, a oversample JWST resolution
- Point sources centered in mini 2x2 pixel grids.
- Jy/sq. arcsec (wavelength)

3. Convolve each wavelength plane with *monochromatic* PSF

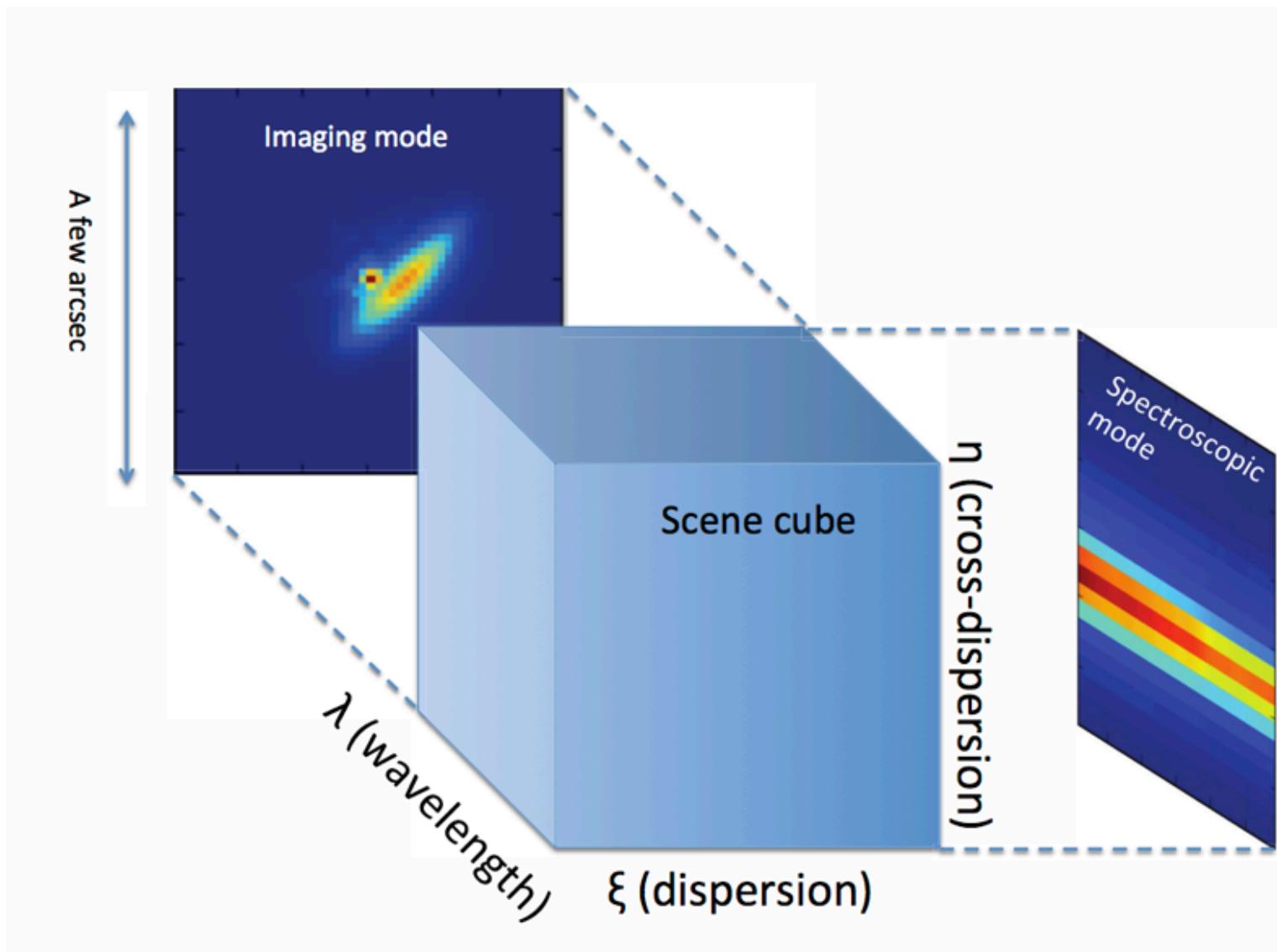
- PSF shape is color-dependent!
- Jy/sq. arcsec (wavelength)





Engine algorithm: The scene cube

4. Multiply by telescope throughput and convert to a photon rate
 - Photons/s/sq. arcsec/micron (wavelength)
5. Multiply by instrument throughput + detector quantum efficiency (QE)
 - Depending on filter/disperser
 - Electrons/s/sq. arcsec/micron (wavelength)
6. Project cube onto rate image (more on this later)
 - Electrons/s/pixel





Engine algorithm: Scene projections

Imaging projection

$$F(x, y) = \int S_{\lambda}^{\text{rate}}(\xi, \eta, \lambda) d\lambda \quad [\text{electrons/s/pixel}]$$

Spectral projection

$$\begin{aligned} F(\lambda, y) &= \frac{d\lambda}{dx} \int S_{\lambda}^{\text{rate}} \times M_{\text{slit}}(\xi, \eta) d\xi \\ &= \frac{d\lambda}{dx} \sum_i S_{\lambda}^{\text{rate}} \times M_{\text{slit}}(\xi_i, \eta_j) \quad [\text{electrons/s/pixel}] \end{aligned}$$

Slitless projection

$$F(x, y) = \int S_{\lambda}^{\text{rate}}(\xi(x, y, \lambda), \eta(x, y), \lambda) \sqrt{\left(\frac{d\xi}{d\lambda}\right)^2 + 1} d\lambda$$



Engine algorithm: The detector level

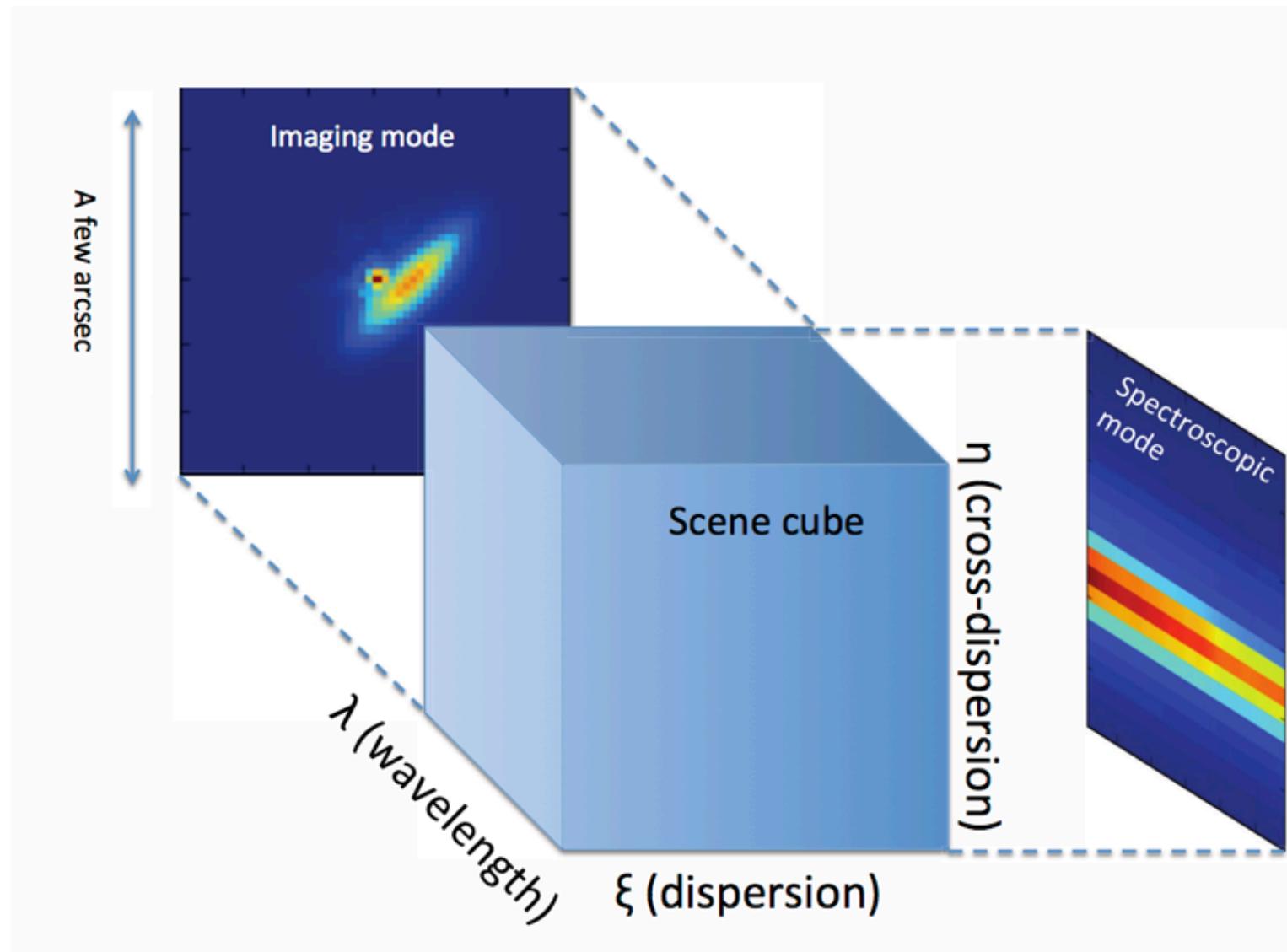
7. Apply MULTIACCUM noise formula to the rate image.

- Creates a noise image
- Standard deviation in Electrons/s/pixel

8. Extract photometry or 1D spectra by applying linear noise propagation

- Use both rate and noise image
- Dimensionless signal-to-noise ratio

9. Celebrate! That was a lot of work.





ETC Strategies

- A **strategy** is a prescription for how to go from a detector image to an extracted product.
- Strategies can be
 - Aperture photometry
 - Aperture spectral extraction
 - IFU extraction with a background observation ("nod off scene")
 - Coronagraphic contrast'
 - ...
- Strategies are implemented as classical error propagation.

$$F_{tot} = \sum_i a_i F_i$$

Total flux rate in measurement

Flux rate in pixel i

$$\sigma^2(F_{tot}) = \bar{a} C \bar{a}^T$$

Variance of measurement

scalar weight of pixel i

covariance matrix of pixels (1,2,...,N)



Strategy example: Imaging aperture photometry

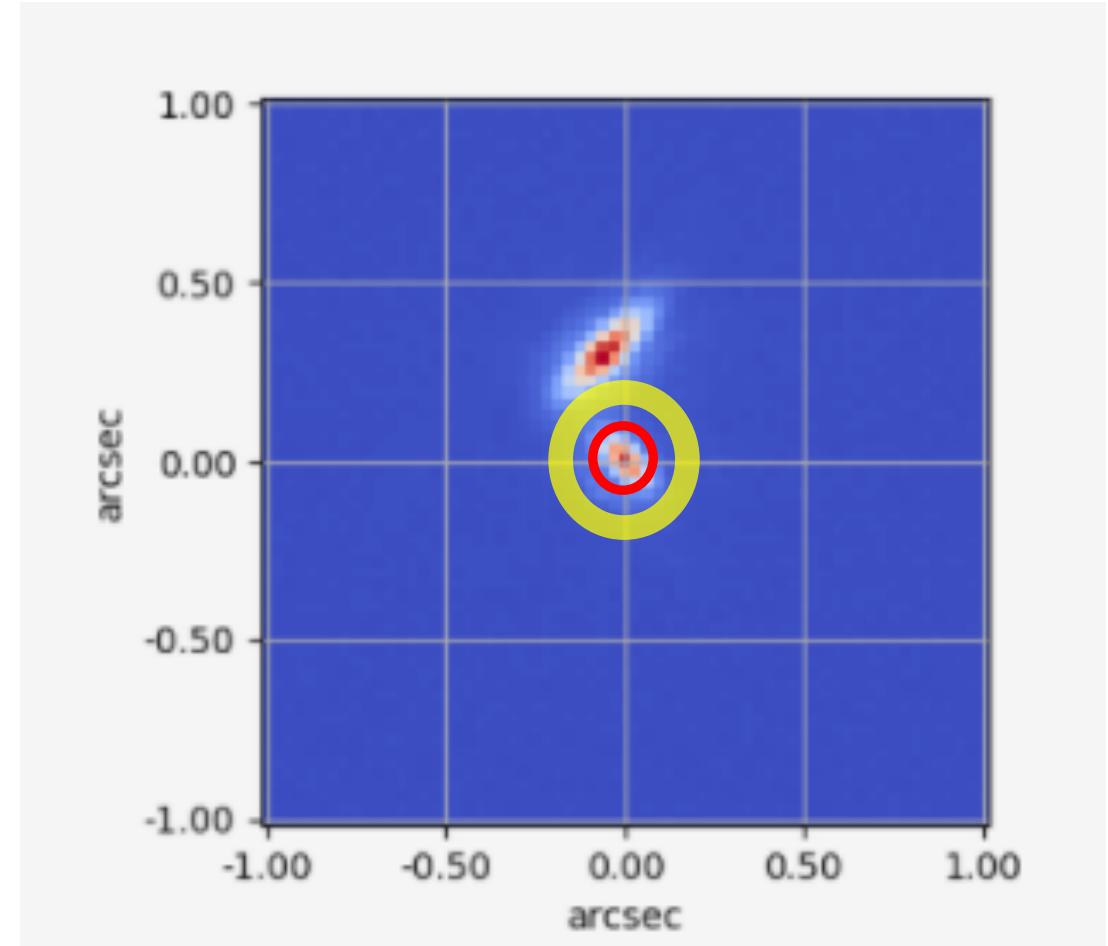
$$F = K \sum_i^{N_A} \left(F_i^{\text{aperture}} - \frac{1}{N_B} \sum_j^{N_B} F_j^{\text{background}} \right)$$

$$a_i = \begin{cases} K, & i \in A \\ -KN_A/N_B, & i \in B \end{cases}$$

In the ETC, “noiseless background” means that the background term is 0. That is, the background level is “magically” perfectly subtracted.

Perform Background
Subtraction Using

- background region
- noiseless sky background

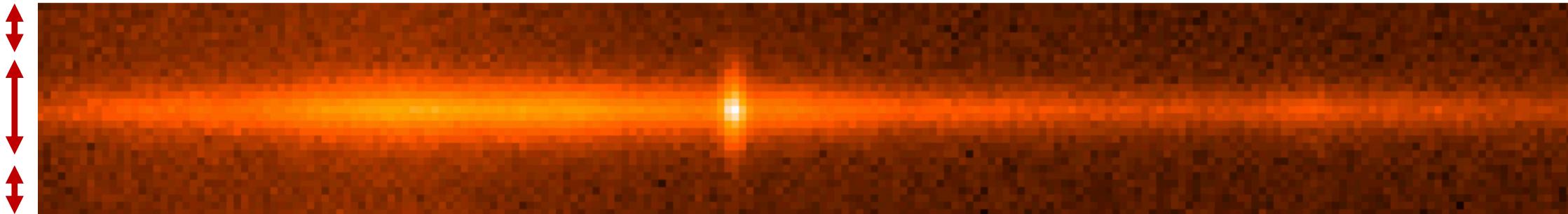


Note that the apertures are not currently drawn in the ETC

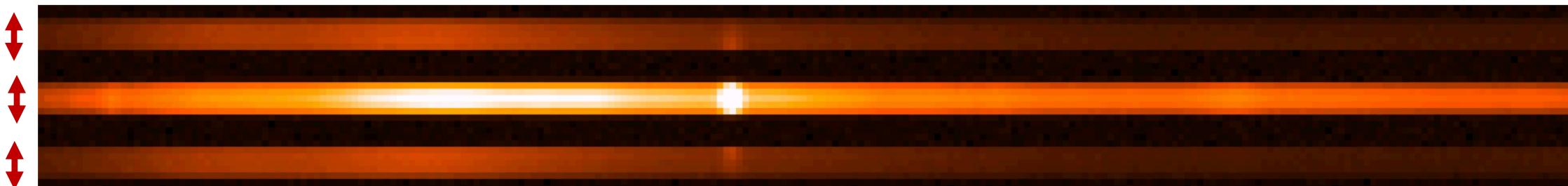


Spectroscopic strategies

Aperture extraction / fixed slit



Full shutter extraction / -2,0,2 shutter pattern

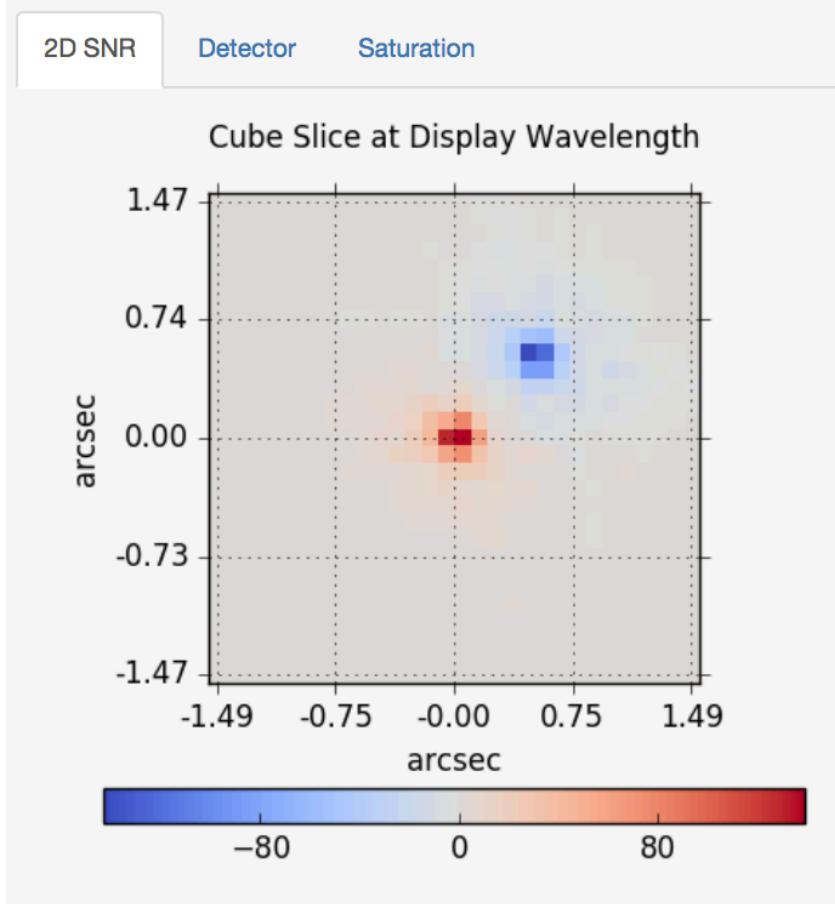




Multi-dither strategies – IFUs and coronagraphy

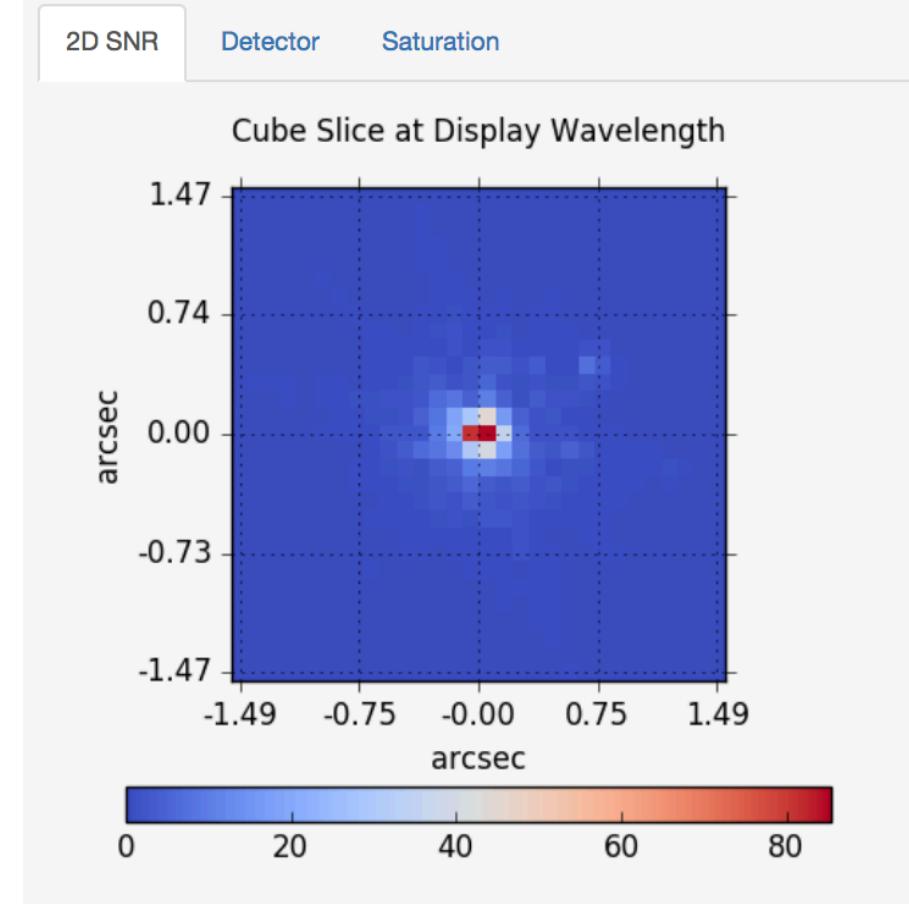
Scene ★ Backgrounds Instrument Setup Detector Setup Strategy

✓ IFU Nod In Scene
IFU Nod Off Scene



Scene ★ Backgrounds Instrument Setup Detector Setup Strategy

IFU Nod In Scene
✓ IFU Nod Off Scene

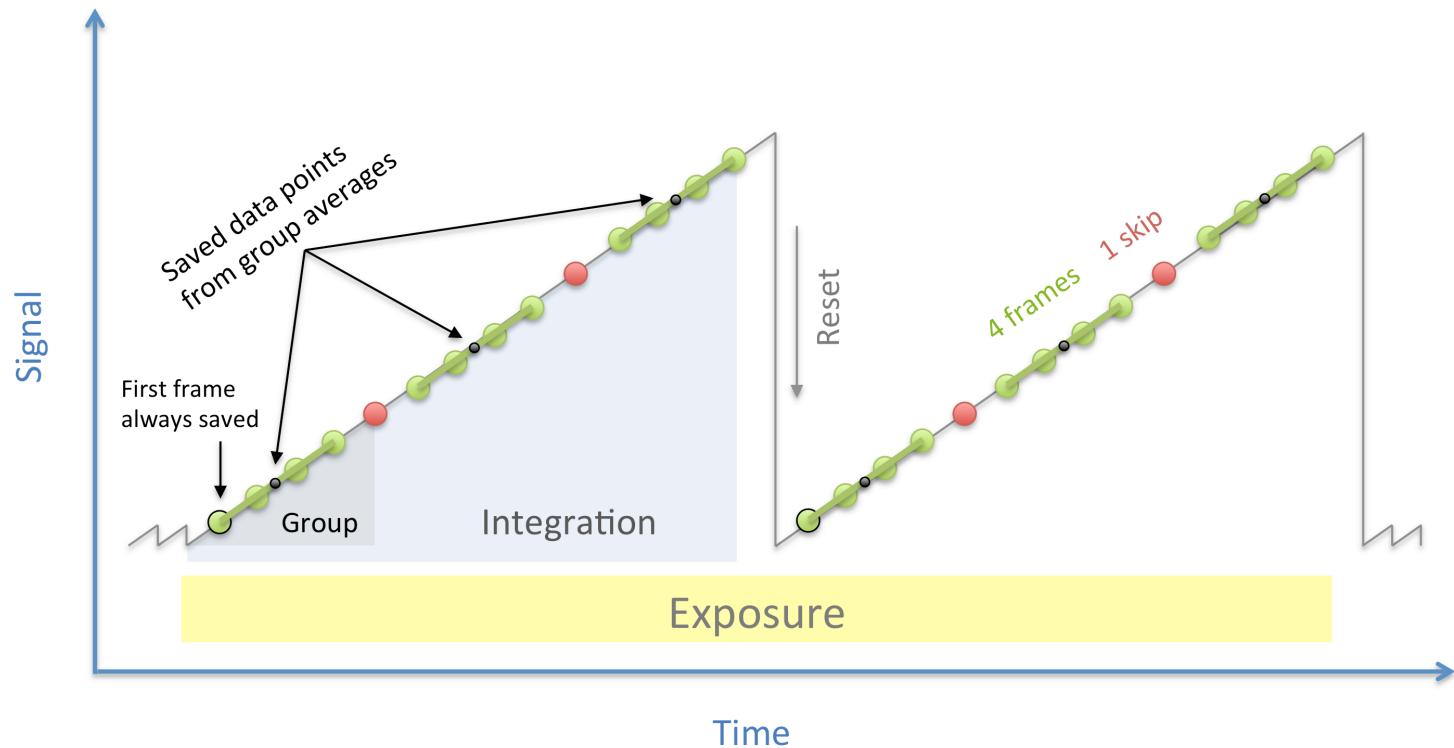




Frames, groups, integrations, and exposures

- **Subarray** = the window on the detector that is being read out
- **Frame** = one complete read of the detector or subarray
- **Group** = a set of consecutive frames that are averaged (some may be skipped)
- **Integration** = one non-destructive ramp
- **Exposure** = a set of consecutive integrations at the same pointing
- **Dither** = an exposure at a new pointing

The combination of readout pattern, ngroups, nints, nexps is called "Detector Setup"

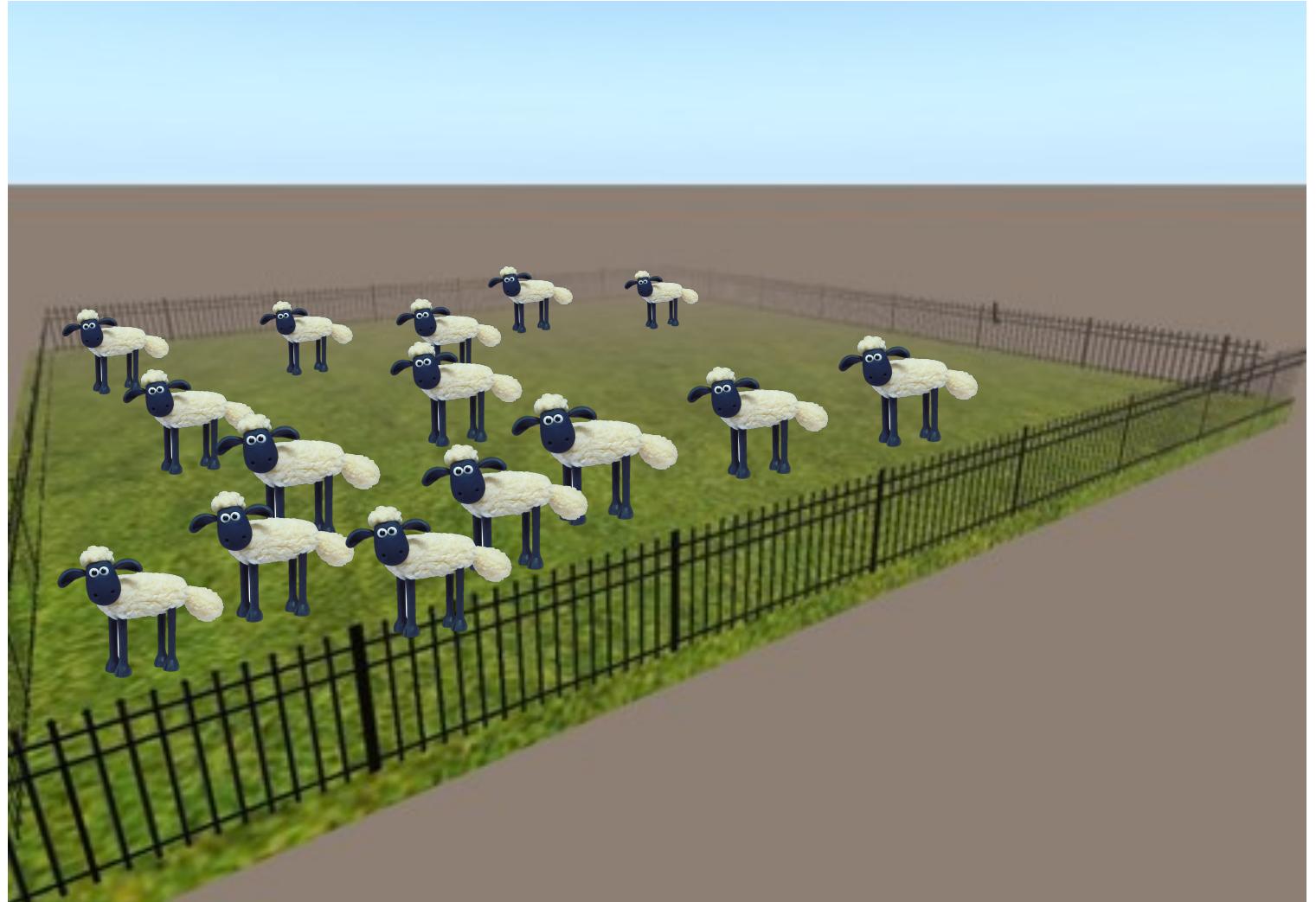




Why use MULTIACCUM non-destructive readout



- When you count the same sheep multiple times, you reduce the read noise.
- Some sheep are correlated.





MULTIACCUM: Now with math

$$Var[S_{total}] = \frac{6}{5} \frac{(n^2+1)(n-1)}{n(n+1)} bt_g \left[1 - \frac{5}{3} \frac{m^2-1}{m(n^2+1)} \frac{t_f}{t_g} \right] + 12 \frac{(n-1)}{mn(n+1)} \sigma_{ron}^2 \quad (36)$$

Variance of slope

Roberto 2009

m = Number of frames per group

n = Number of groups per integration

Take-home message:

The read noise decreases as the root of the number of frames per integration ($m*n$)



Exposure time, measurement time and saturation time

"exposure time" – The array-based time the detector is operating during a single expose command, including resets but excluding the initial synchronization time. This time includes all integrations in an exposure, but no repetitions per pointing, per tile, or per observation.

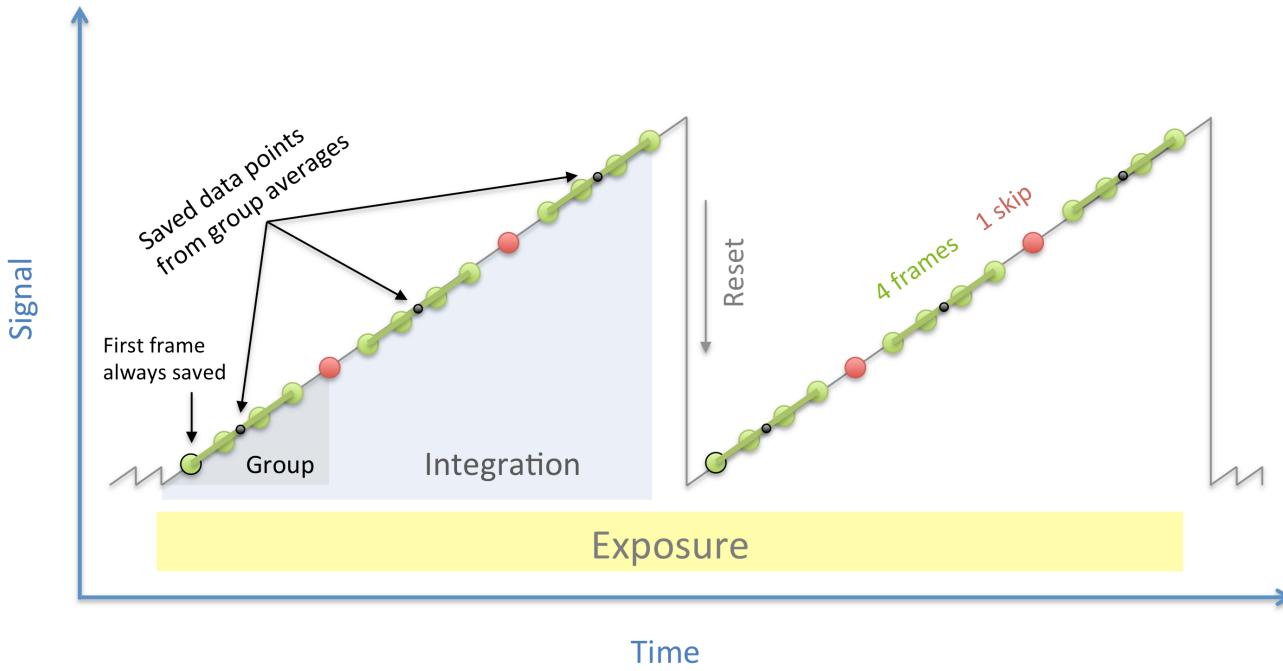
"measurement time" – The pixel-based time interval between the first and last measurements of a pixel in an integration times the number of integrations per exposure. Here a measurement is a value used on the ground to determine count rate.

"saturation time" – The pixel-based time interval from the reset of a pixel to the final read of that pixel in an integration times the number of integrations per exposure. This time depends on exposure parameters, not target brightness or instrument throughput.

"exposure duty cycle" – The pixel-based measurement time divided by the array-based exposure time.

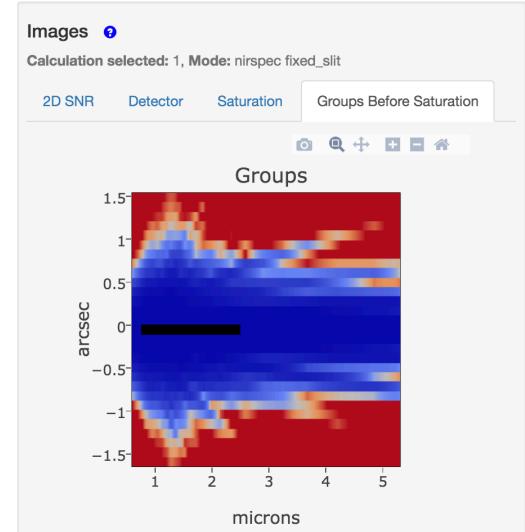
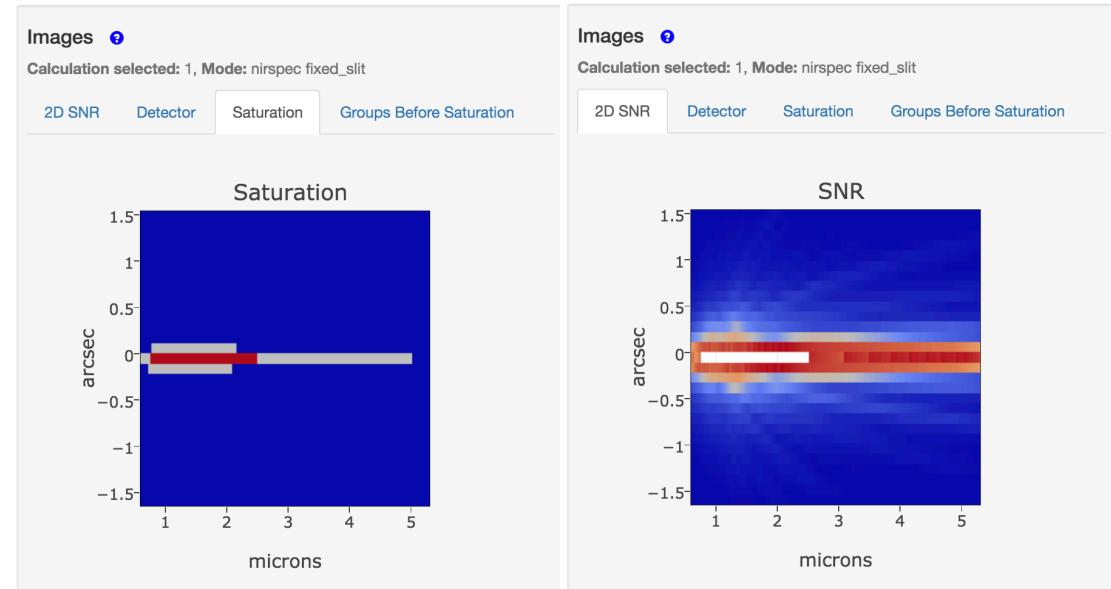


How is saturation treated in the ETC?



Two types of saturation:

- **Partial saturation** - the integration saturates before it completes, but more than the minimum number of groups are unsaturated.
- **Full saturation** – the integration saturates before the minimum number of groups is reached.
- The minimum ngroups is usually 2.

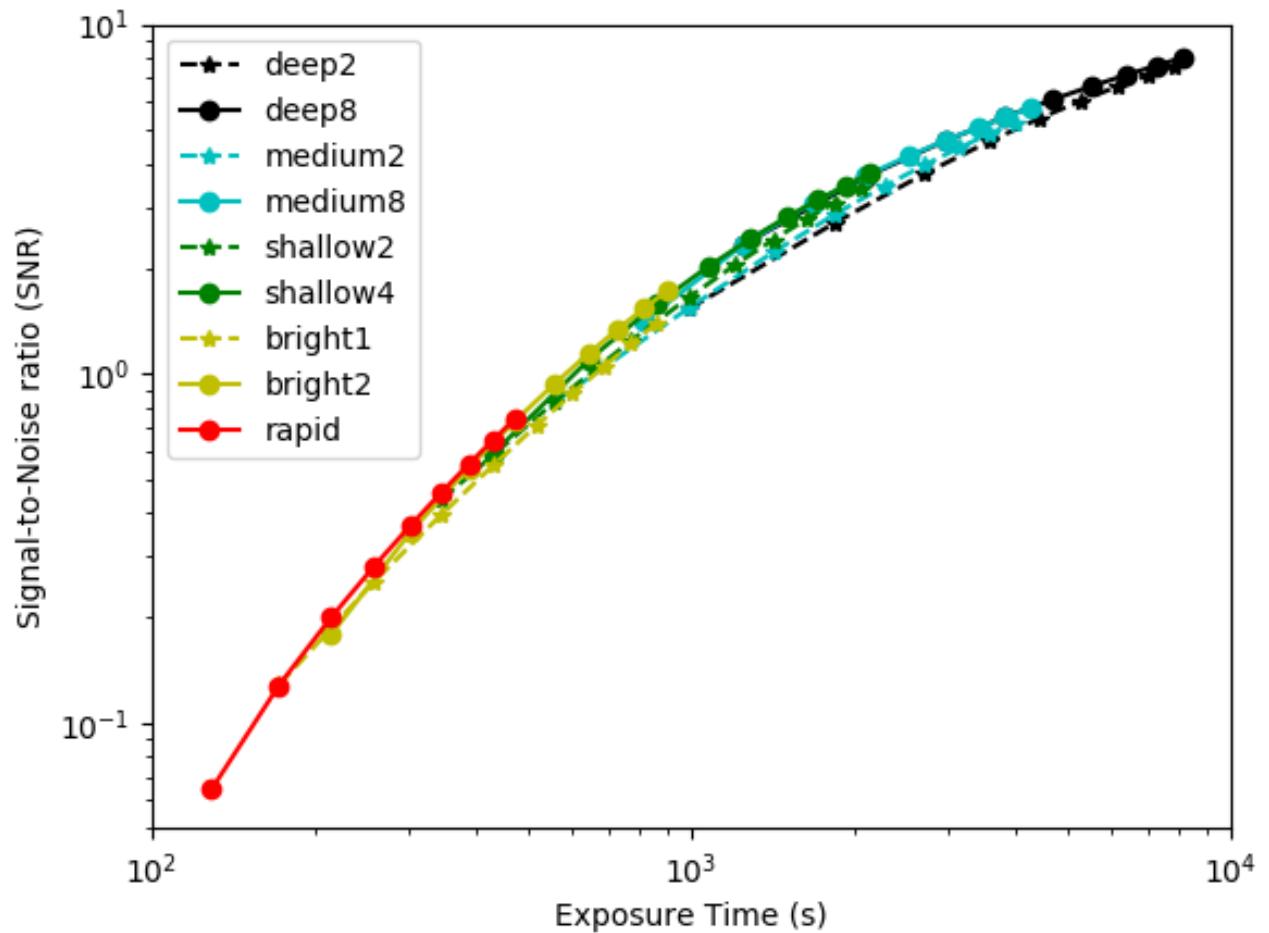




Finding the best exposure parameters

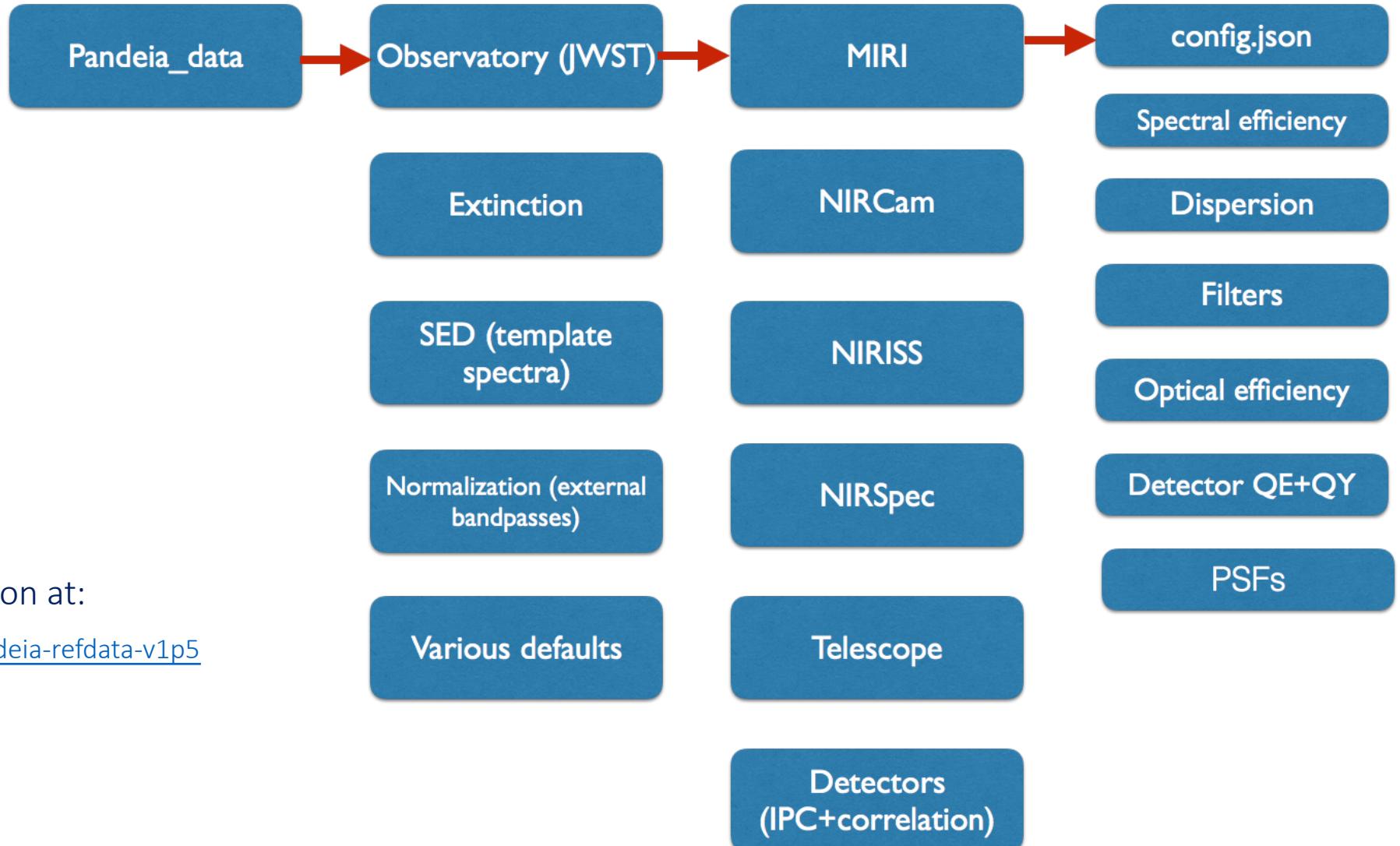
Selecting the optimal combination of readout pattern, ngroups, nints and nexps is a trade-off.

- More frames decreases read noise.
- Shorter groups increases data volume.
- Longer groups increases the chance of a cosmic ray hit during the group.
- Shorter groups/longer integrations make cosmic ray corrections better.
- Shorter integrations make ramp fits more uncertain in the presence of non-linearity.
- More dithered exposures decreases flat field errors.
 - Note: In the ETC all exposures are assumed to be dithered, except for time-series observations.
- Patterns that skip a lot of frames have higher read noise, but have slightly better duty cycle.





Pandeia reference data



Download the latest version at:

<https://stsci.app.box.com/v/pandeia-refdata-v1p5>

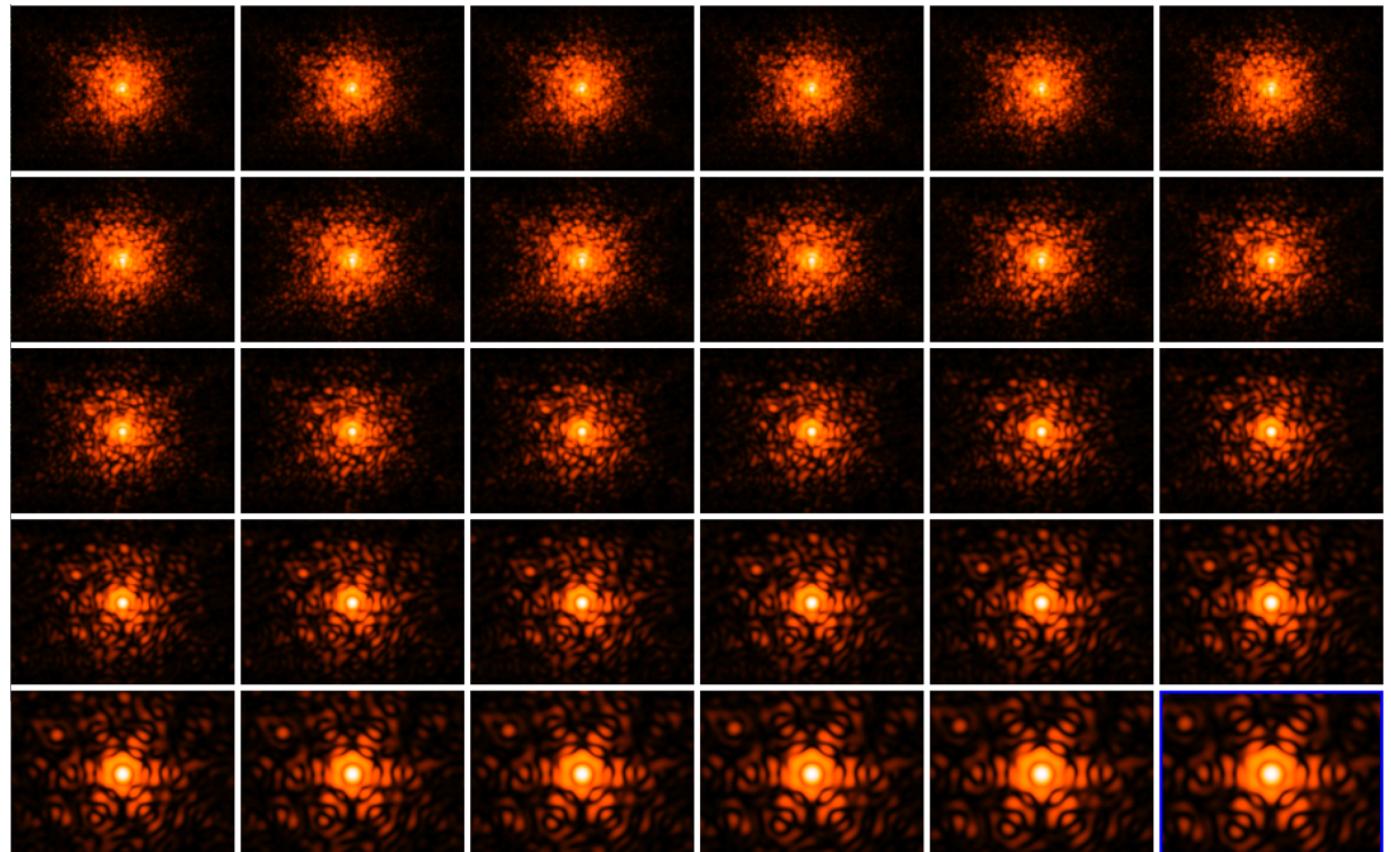


PSF library

- Uses WebbPSF to calculate point spread functions including realistic wavefront errors.
[WebbPSF Tool](#)
- Almost 5000 individual monochromatic PSFs.
- Subsampled by integer factor of pixel size.

Fun fact: The observed PSF depends on the color of the astronomical source.

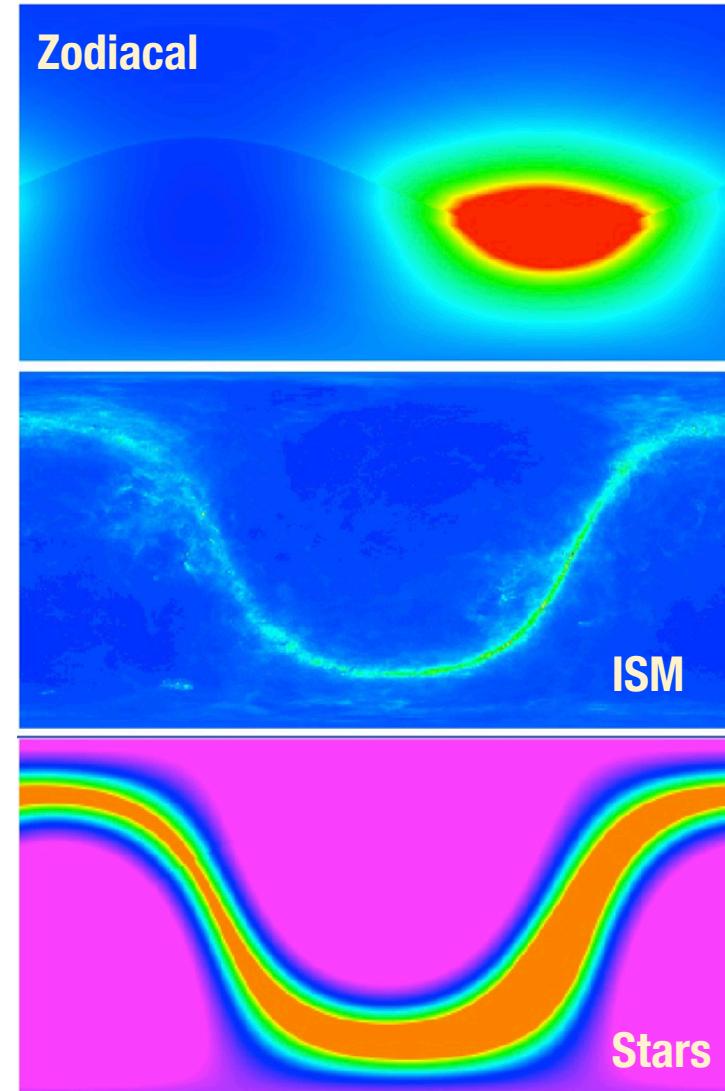
NIRCam SW PSFs (0.6-5.2 micron)





The JWST Background Model

- JWST uses a dynamic “background model generator” (BMG)
- Components of the background are:
 - Galactic interstellar medium+stars
 - Zodiacal light (position+time dependent)
 - Out-of-field stray light (position+time dependent)
 - Telescope+spacecraft thermal emission
- Two ways to use backgrounds in the ETC:
 - **“Dated background”**: The actual background for a given RA, Dec, and date.
 - **“Dateless background”**: Given RA, Dec, the low (10%), medium (50%), or high (90%) percentile of the background range over a full year.



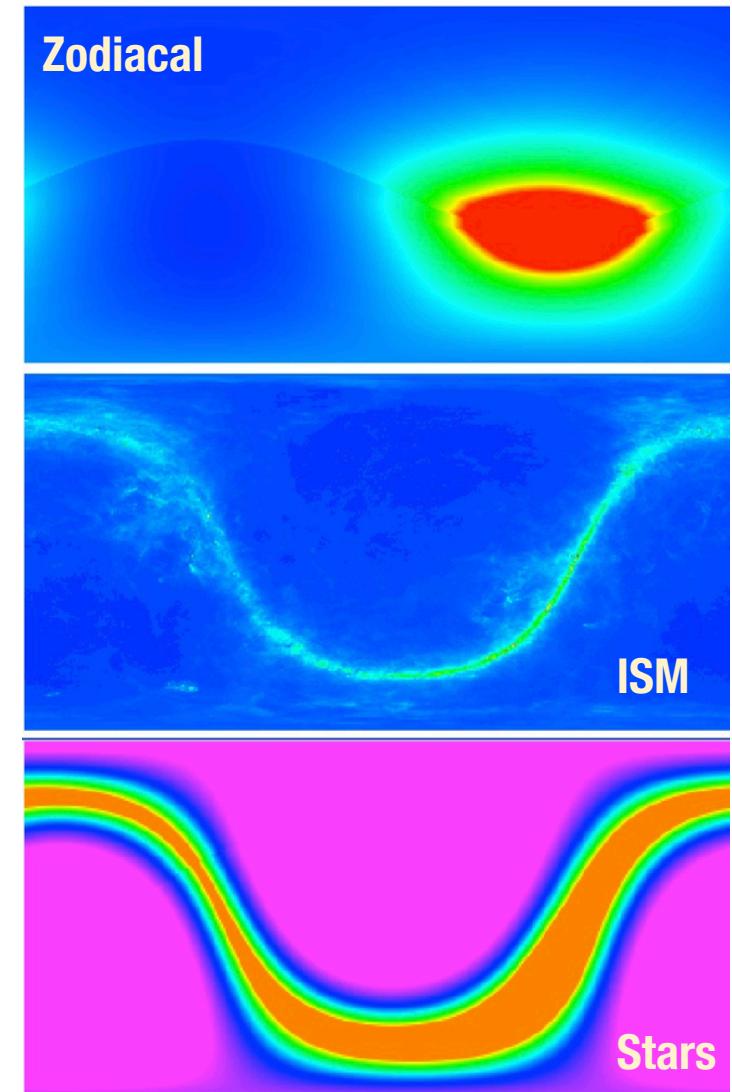
A. Noriega-Crespo



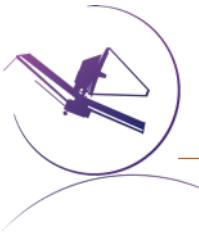
Zodiacal and Galactic backgrounds

- Zodi+ISM heritage from Spitzer's operational system (IPAC)
 - Data are from COBE/DIRBE
 - ISM "cirrus" uses fixed spectrum, including PAHs. Intensity set by Schlegel et al. extinction maps, which were fits to IRAS + DIRBE/COBE data
 - Wainscoat et al. 1998 star counts model

Fun fact: Benchmark sensitivities computed for (J2000, 17:26:44 -73:19:56) on June 19.

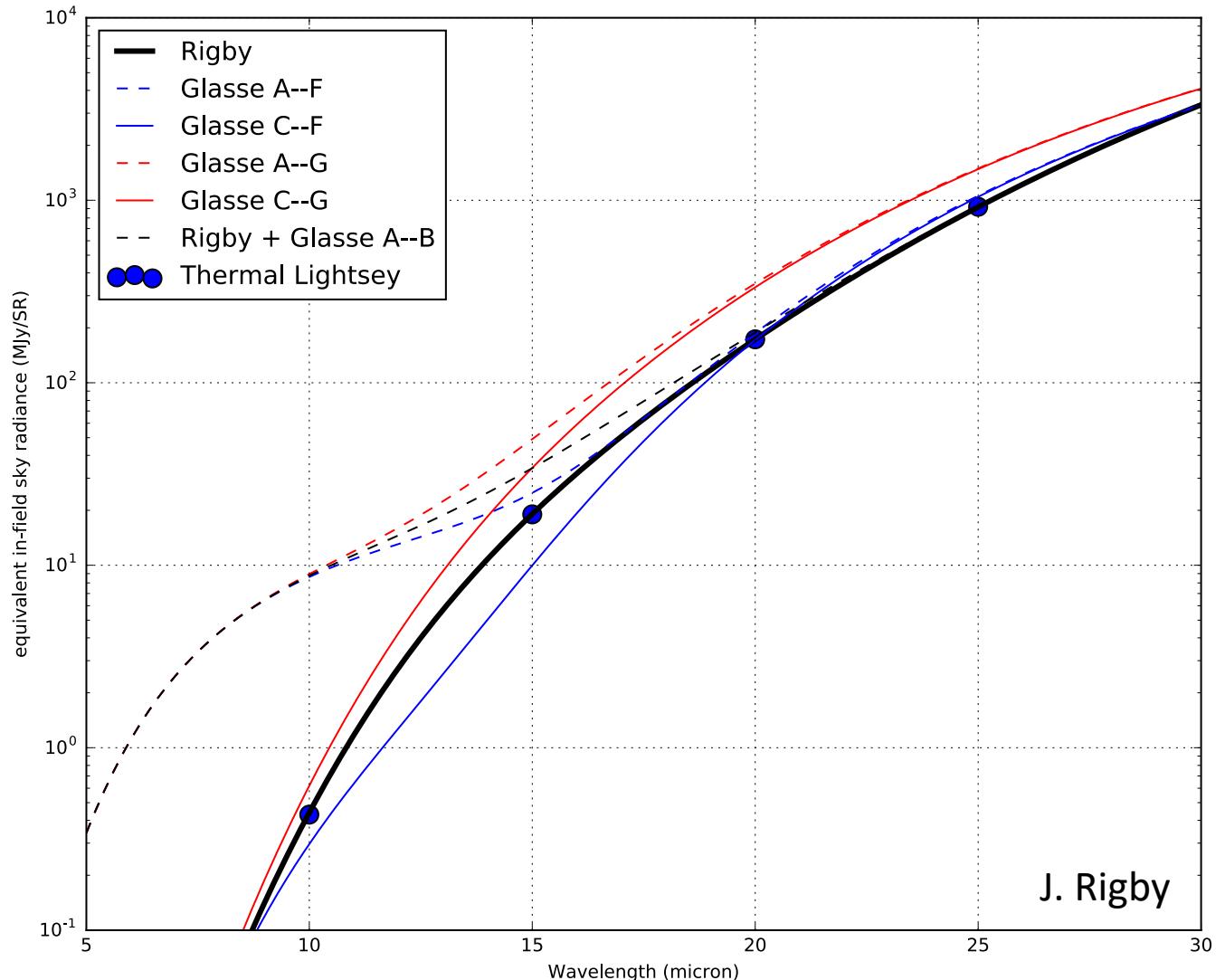


A. Noriega-Crespo



Thermal self-emission

- Thermal emission from JWST itself is the dominant background at $\sim>15\mu\text{m}$.
- Sum of 20 blackbodies (P. Lightsey, J. Rigby).
- Produces backgrounds of 0.74 and 174 MJy/SR at 10 and 20 micron. (Reqs. are 3.9 and 200 MJy/sr). Temperatures are as expected: $T(\text{sun shield})=89\text{K}$, $T(\text{primary mirror})=54\text{K}$ (hottest segments).
- Blackbody model agrees with Lightsey calculations at 15, 25 micron to within 0.5%.

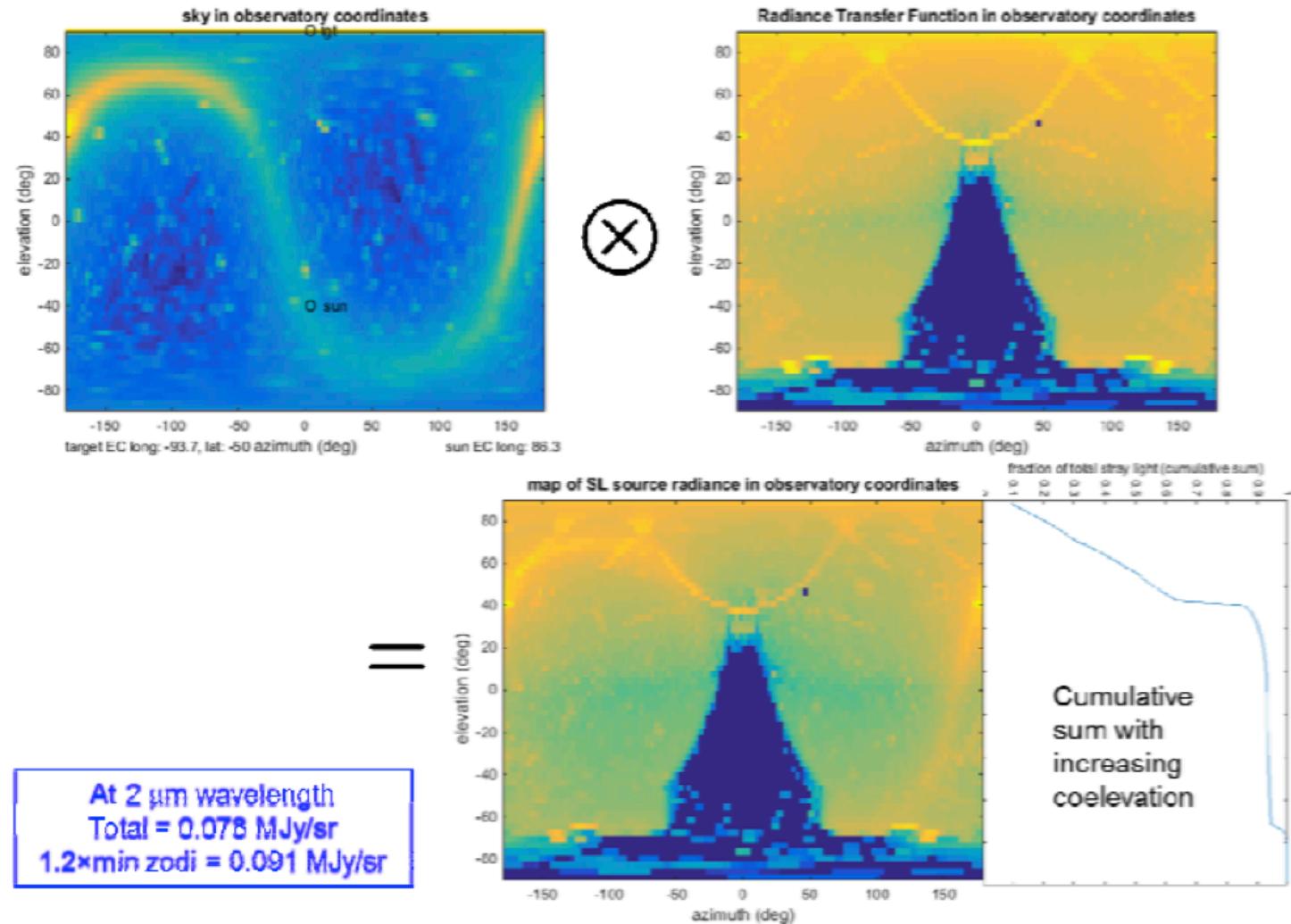


Thermal-only curve (black line) + Glasse et al. 2015 SPIE (red and blue solid lines.)
Zodiacal model of Glasse (dashed lines.) Figure from J. Rigby



Stray light

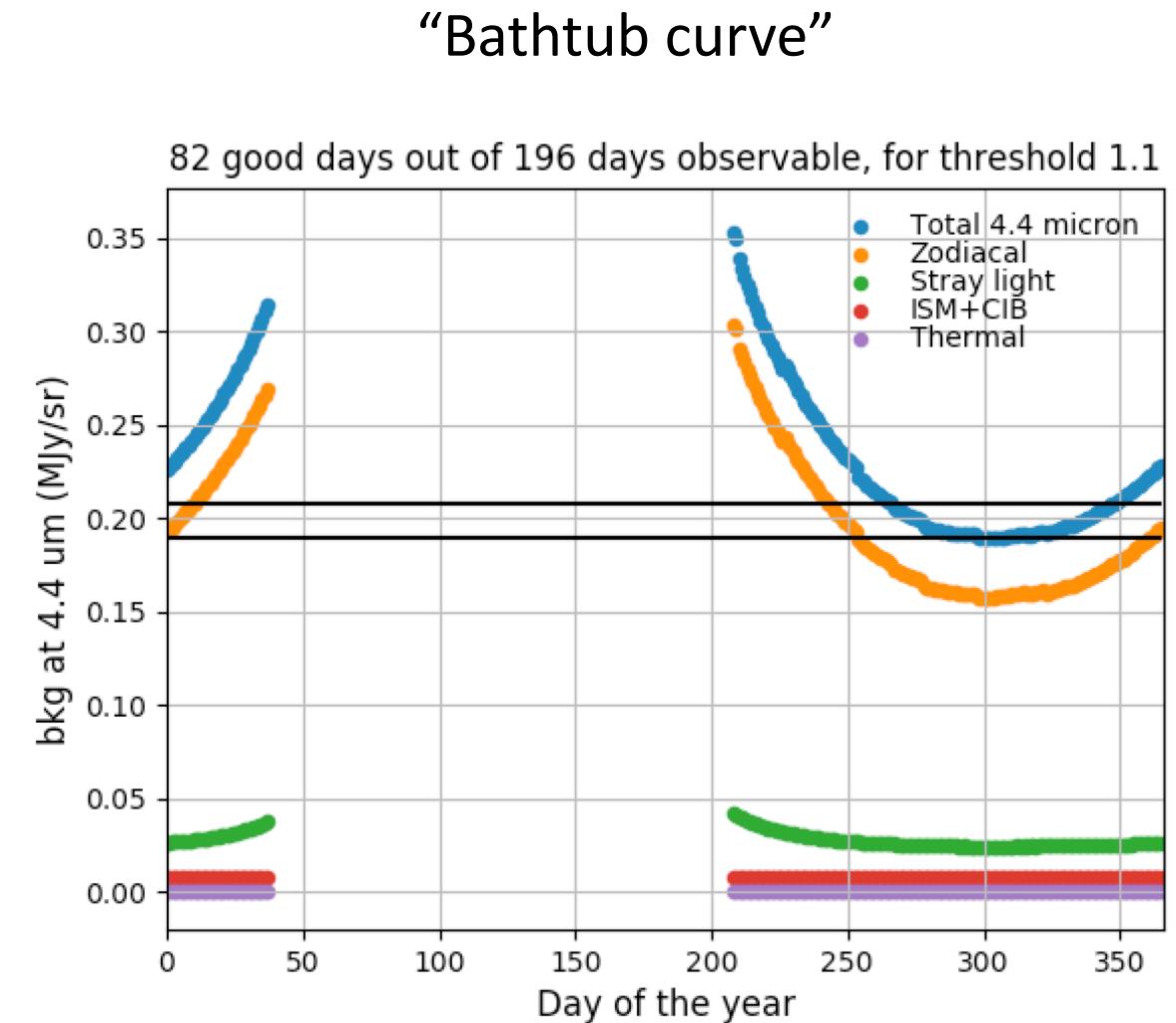
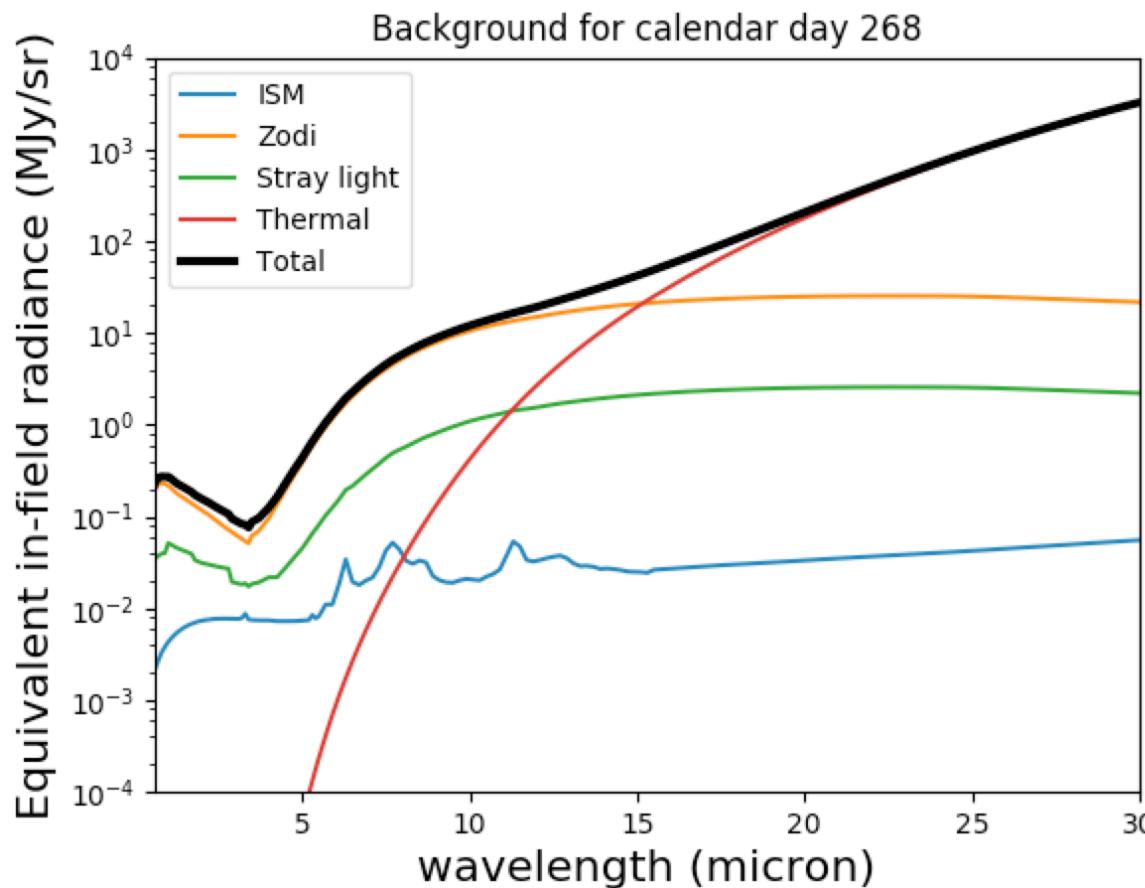
- The background model calculates the stray light for a given position and date, following Lightsey 2016 SPIE.
- Radiance Transfer Functions (RTFs) from Lightsey, at 0.7, 1, 2, 3, 5, 10, 15 micron.
- Sky map from Galactic + Zody engine (for that position, for that date)
- Interpolate RTFs at other wavelengths.





The JWST Backgrounds Tool (JBT)

pip install jwst_backgrounds

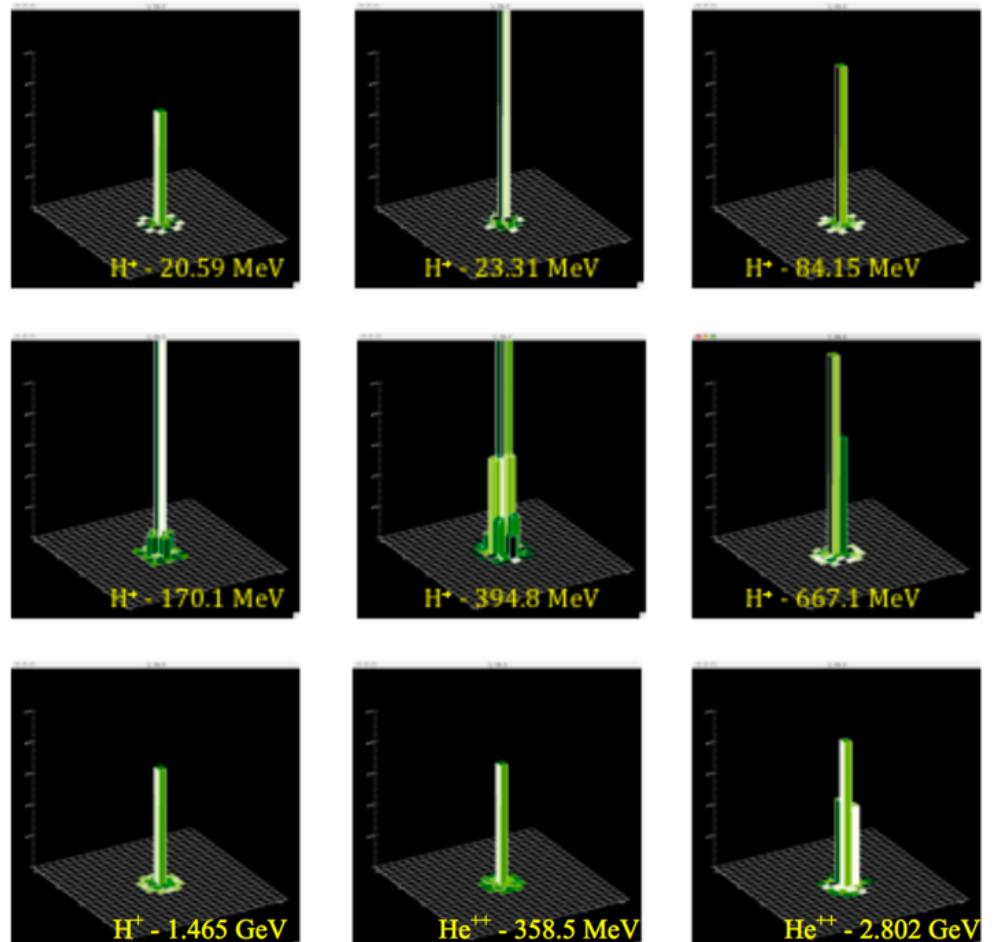


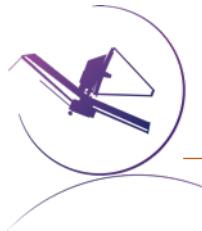


Cosmic Rays

- Conservative treatment of cosmic rays
- Best known L2 CR rate (Gaia, Herschel)
- Purely statistical treatment
- CR hits effectively lead to loss of measurement time.
- Assume $\frac{1}{2}$ of the ramp (on average) is lost per CR hit.
- Assume N pixels affected by each CR (currently N=5).
- In practice, CR hits do not affect SNR significantly for integrations < 1000 s.
 - Integrations > 1000 s are not recommended.

Roberto 2009

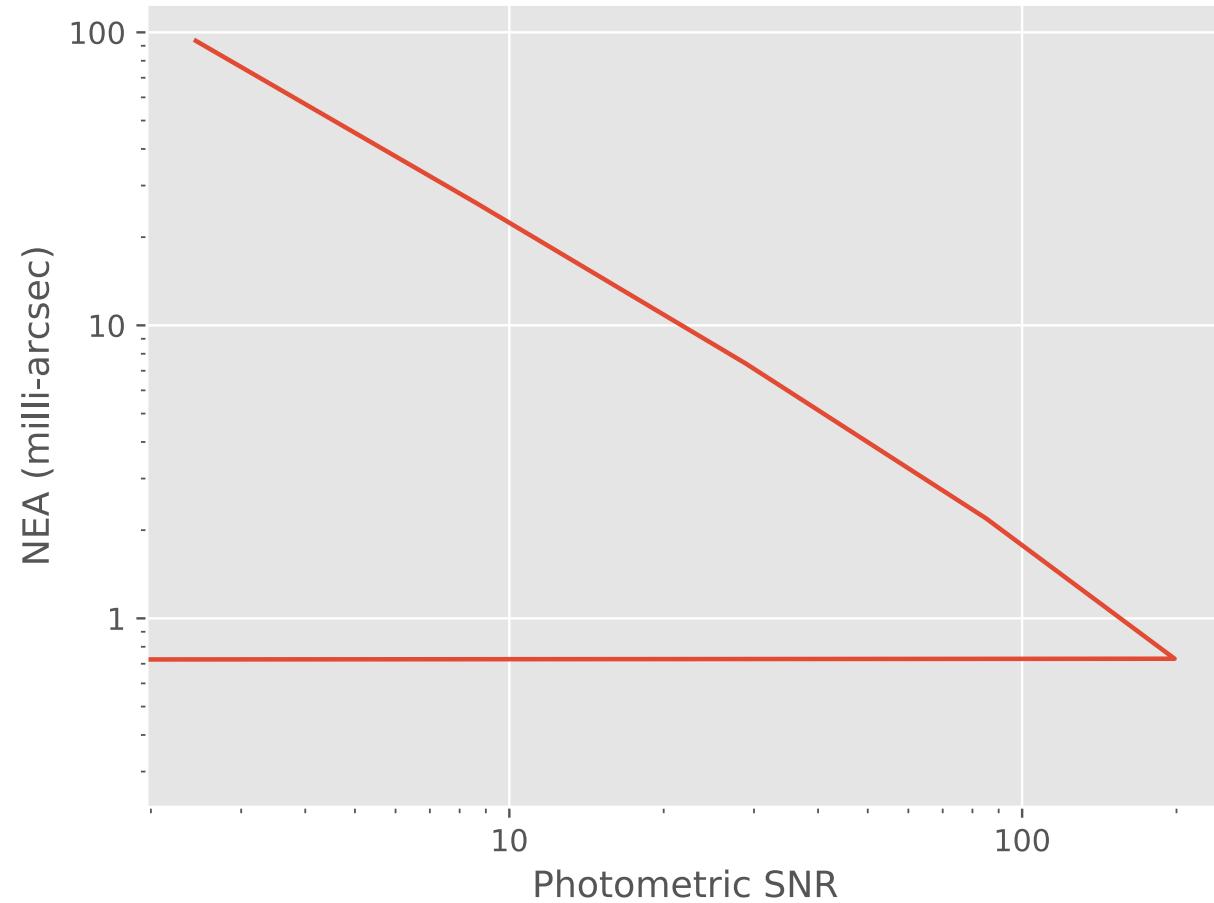




Target acquisition

- Different than regular science data!
- Models the *GENTALOCATE* algorithm used by the on-board software.
 - Only uses first, middle and last group.
 - On-board software removes cosmic rays by taking:
 - $\text{Median}([\text{middle-first}]/[\text{last-middle}])$
- Less sensitive than science imaging.
- Fixed square aperture (e.g., 3x3 or 5x5 pixels).
- Can sustain some saturation.

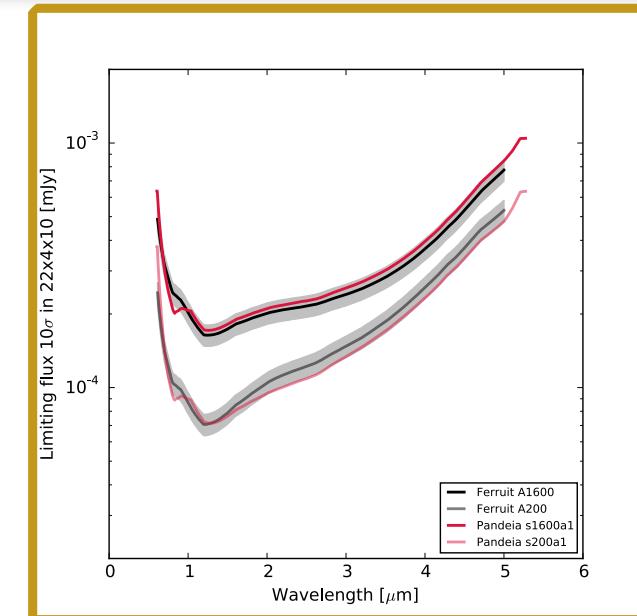
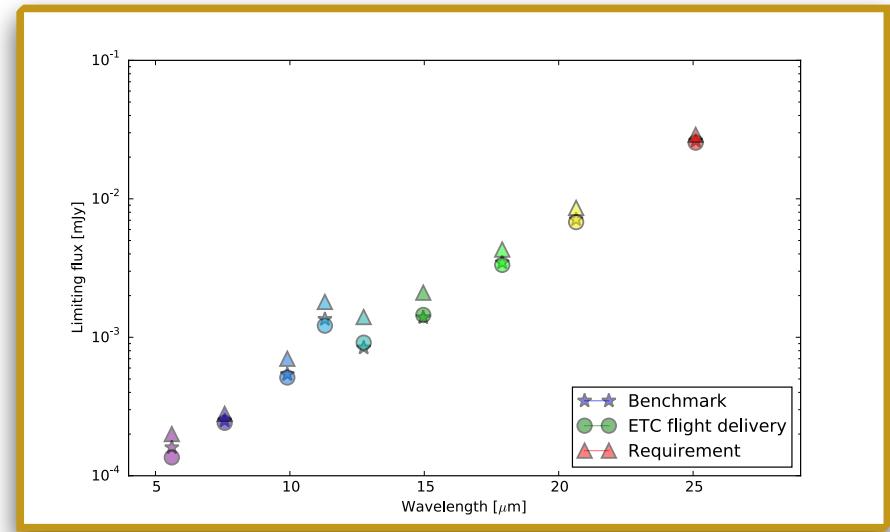
Astrometric precision predicted by the ETC





How do we know it is correct?

- Benchmarked to sensitivity calculations provided by instrument teams.
- Benchmark requirement: 10% in signal-to-noise ratio for 90% of calculations
- In comparing a 3D to a 1D calculation, 10% is considered reasonable.
- Compared calculated limiting sensitivities (10 sigma in 10,000 s) for all major instrument modes to independent calculations provided by the instrument teams.
- Using the same reference data and parameter assumptions.
- Since the benchmark, many parameters and some reference data have changed -> ETC is the best available estimate of JWST performance.





How to use the ETC with APT

NIRCam Imaging Mosaic Properties Special Requirements Comments

Module ALL Subarray FULL

Dither Parameters Primary Dither Type: INTRAMODULEBOX Primary Dithers: 3 Subpixel Dither Type: STANDARD Subpixel Positions: 3

#	Short Filter	Long Filter	Readout Pattern	Groups/Int	Integrations/Exp	Total Dithers	Total Integrations	Total Exposure T...	ETC Wkbk.Calc ID
1	F115W	F444W	SHALLOW4	10	3	9	27	14494.639	16003.3

Filters

Scene ★ Backgrounds Instrument Setup Detector Setup Strategy

Subarray: FULL Readout pattern: SHALLOW4

Groups: 10 Integrations: 3 Exposures: 9

Total exposure time: 04:01:34 (14494.63 s)

Total integrations: 27

Calculation selected: 1, Mode: nircam sw_imaging

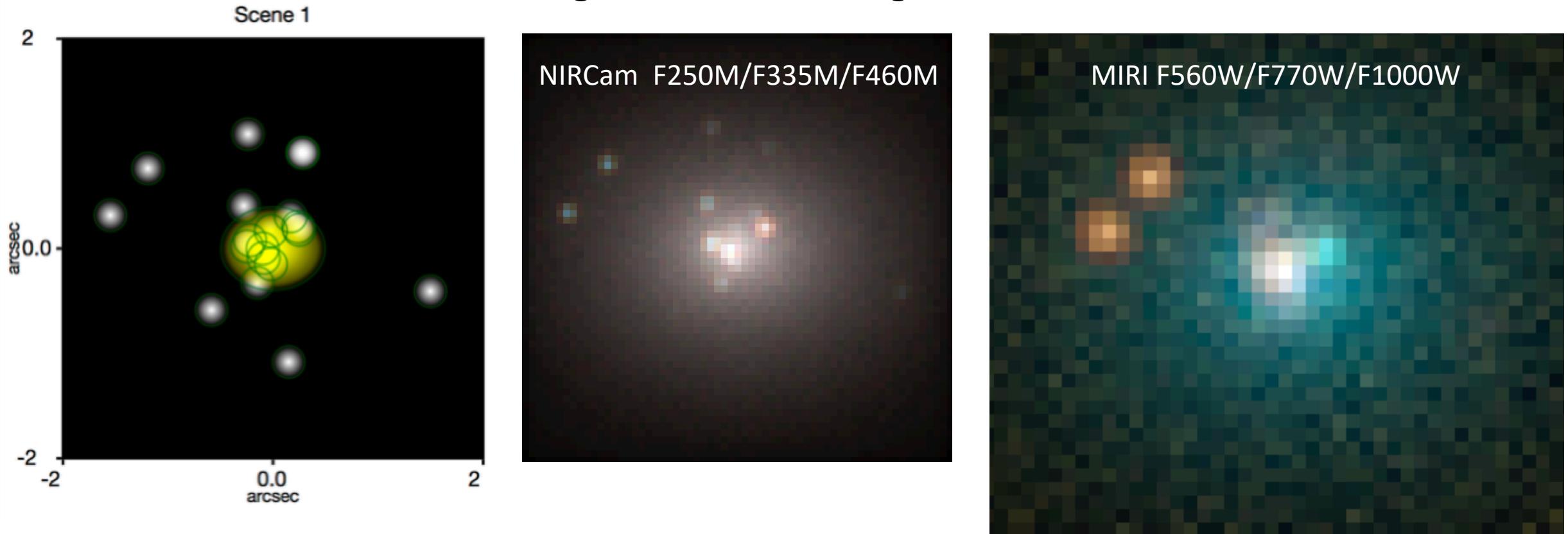
Reset Calculate

APT ETC



Advanced use: imaging

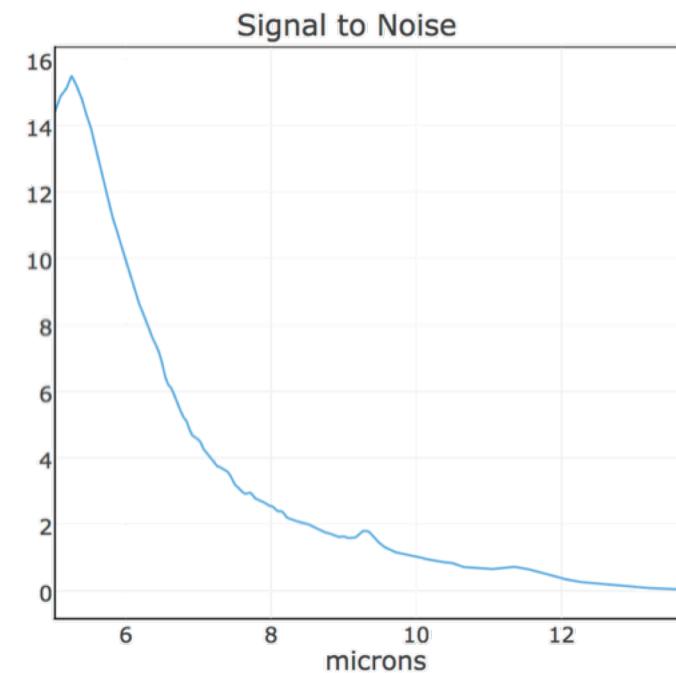
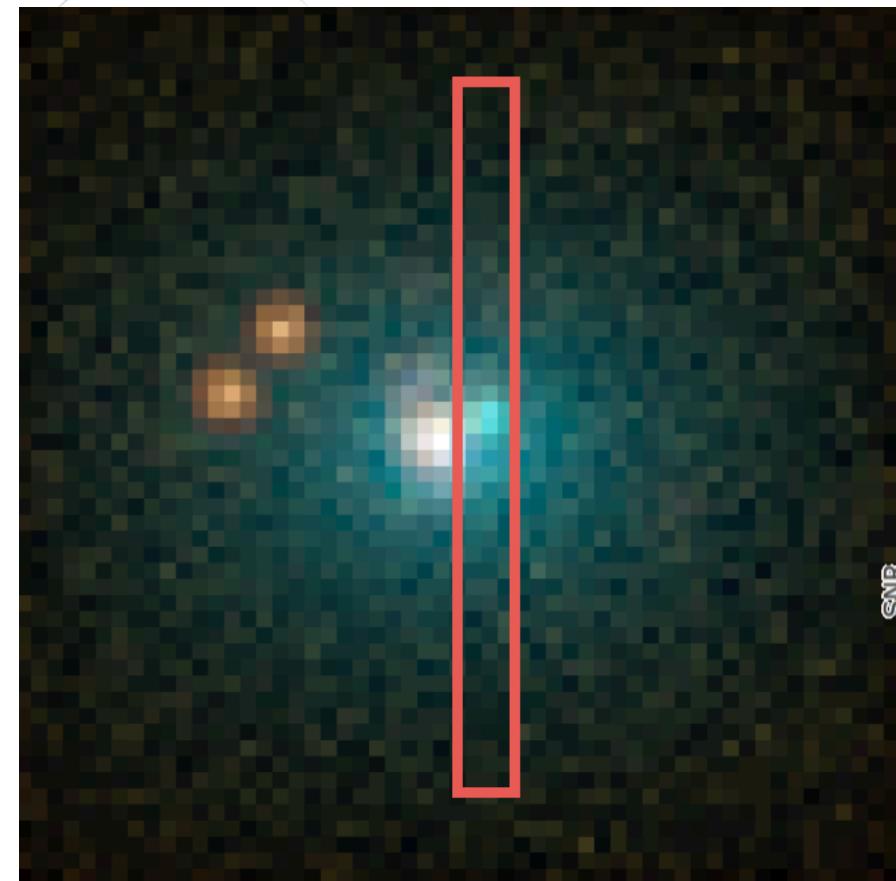
Red bulge with star-forming knots at $z=0.5$



→ Color composites generated from ETC products



Advanced use: Spectroscopy



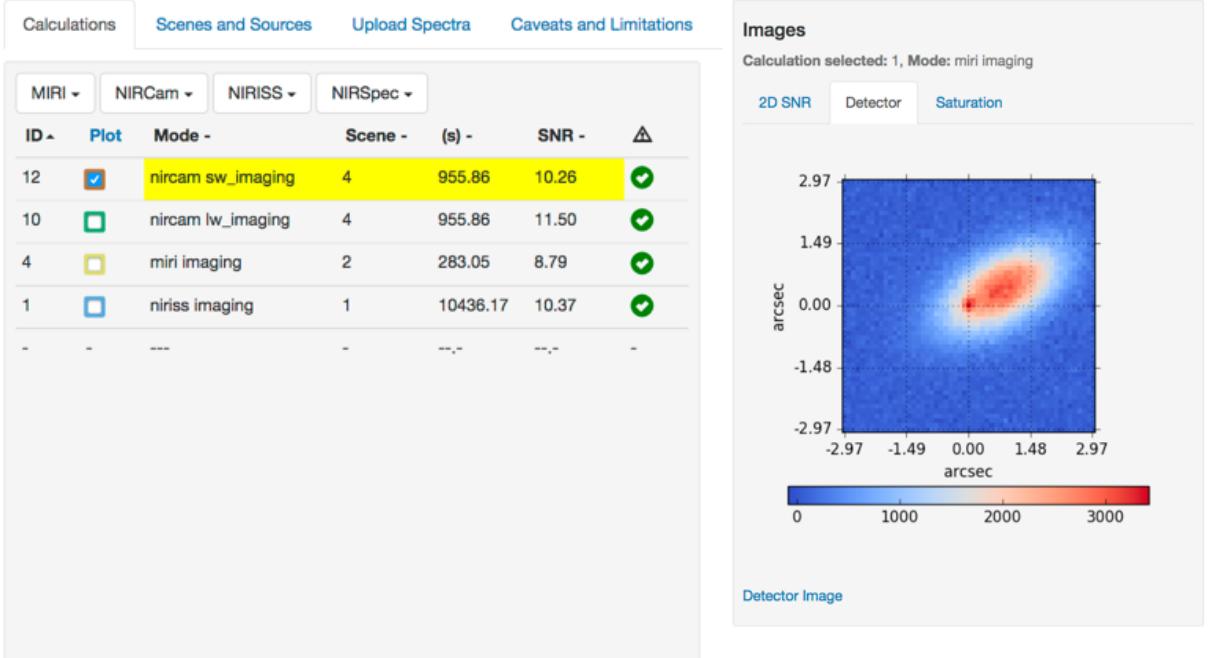
Fun fact: In spectroscopic modes extraction apertures are one wavelength pixel wide.

NIRSpec MSA

A 1D spectrum from NIRSpec MSA showing a series of absorption features. The spectrum is color-coded blue.



The ETC web application: A collaborative work environment



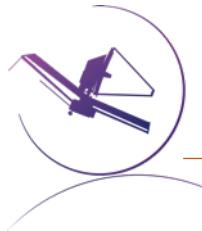
- Workbooks: Organize and save your ETC calculations
- Build your own sources and scenes library
- Analyze and compare different instruments and modes
- Share your work with your team

User Access Permissions for Small Body Examples for JWST Solar System London Workshop

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ETC engine available as a Python module

- Python module
- More functionality than available in the web application
- Advanced scripting
 - Parameter space exploration
 - Complex scenes / many sources
 - Any JWST science mode accessible within one framework
- pip install pandeia.engine
- <https://pypi.org/project/pandeia.engine/>

Fun fact: The engine is a compact, general code, currently only ~16,600 lines of code, excluding standard libraries.



Did I do it right? Summary checklist

There are many parameters affecting the predicted ETC sensitivities.

That's the point of having a versatile tool, but comes with some responsibility.

- ✓ Think about your background subtraction strategy.
- ✓ Think about what extraction aperture is optimal (point or extended sources).
- ✓ Is your background correct for your target – enter the actual RA, DEC. Investigate time dependency.
- ✓ Check that your extraction aperture does not contain contaminating flux from other sources.
- ✓ Is your selected readout pattern giving you the best SNR?