Direct Characterization of Exoplanet Atmospheres using Fourier Transform Spectroscopy

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Eugene Serabyn[2]

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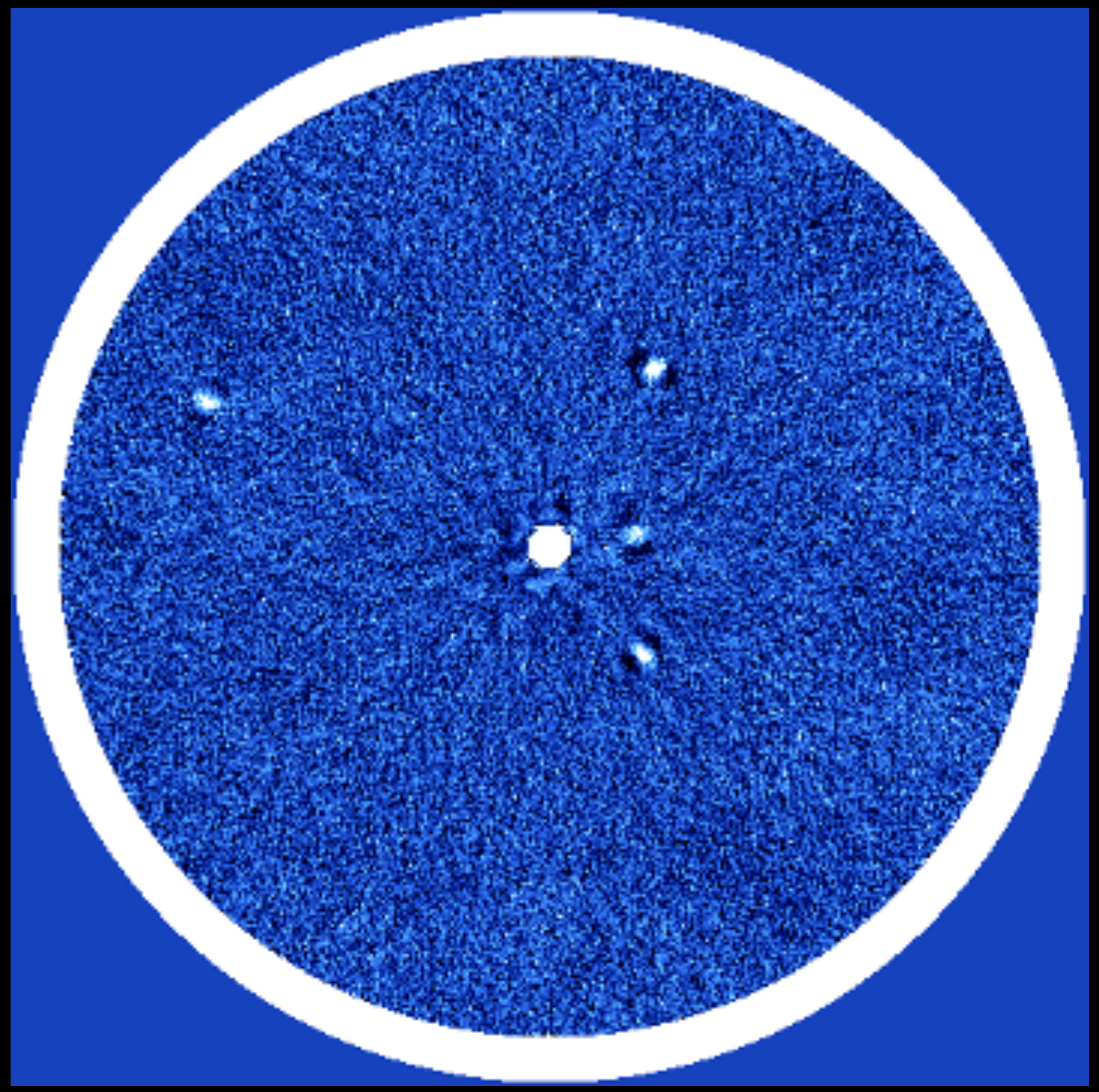
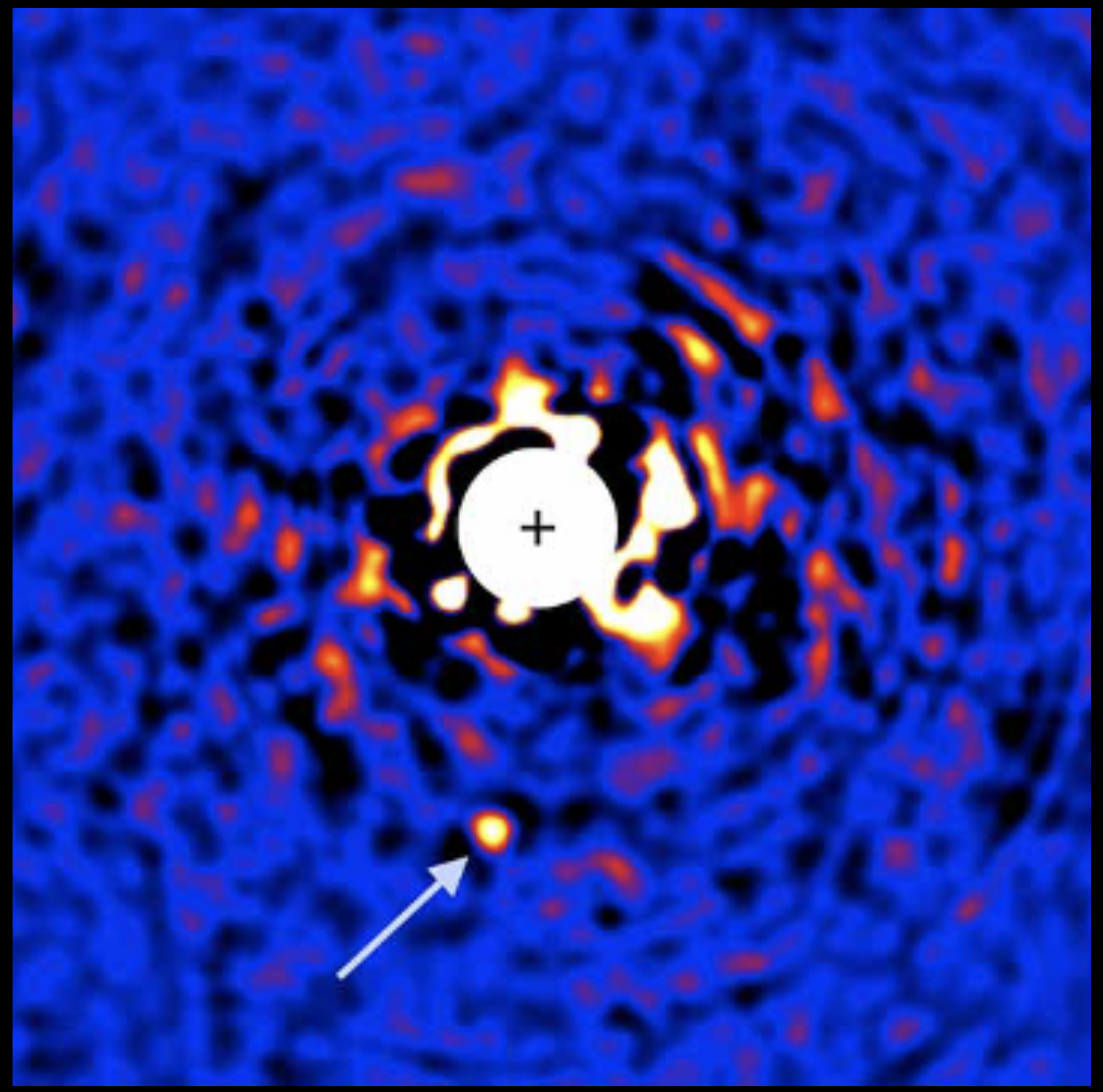
ExSoCal 2023

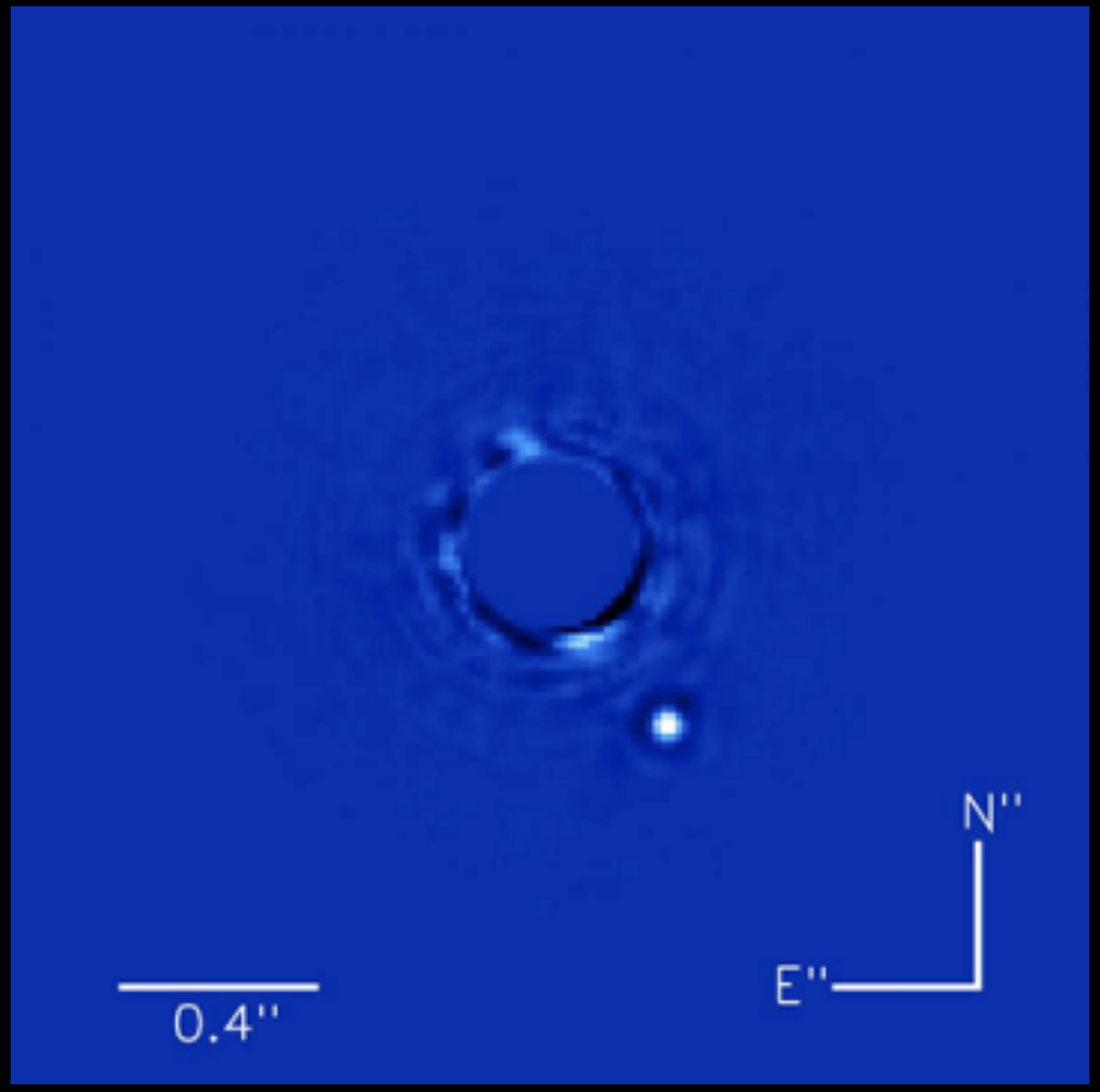
Directly imaged exoplanets from ground based telescopes



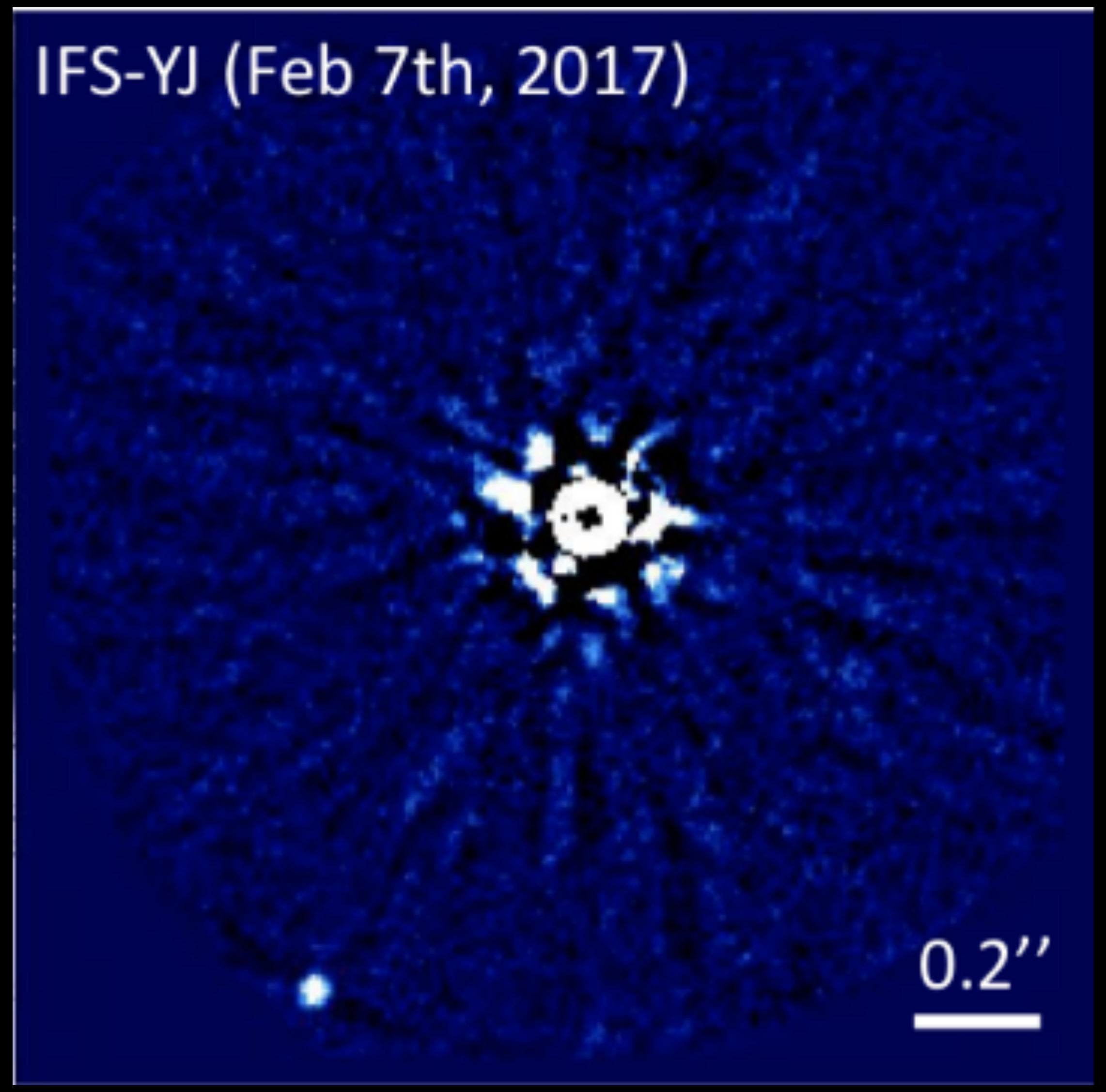
HR 8799 b, c, d, e
Mass: 5, 7, 7, 7 MJ
a : 68, 38, 24, 14.5 AU
Marois et al. 2008, 2010
Image: Keck/NIRC2



51 Eridani b
Mass: 2-10 MJ
a : 13 AU
Macintosh et al. 2015
Image: GPI



beta Pictoris b
Mass: 13 MJ
a : 12 AU
Lagrange et al. 2008
Image: GPI



HIP 65426
Mass: 9 MJ
a : 90 AU
Chauvin et al. 2017
Image: SPHERE

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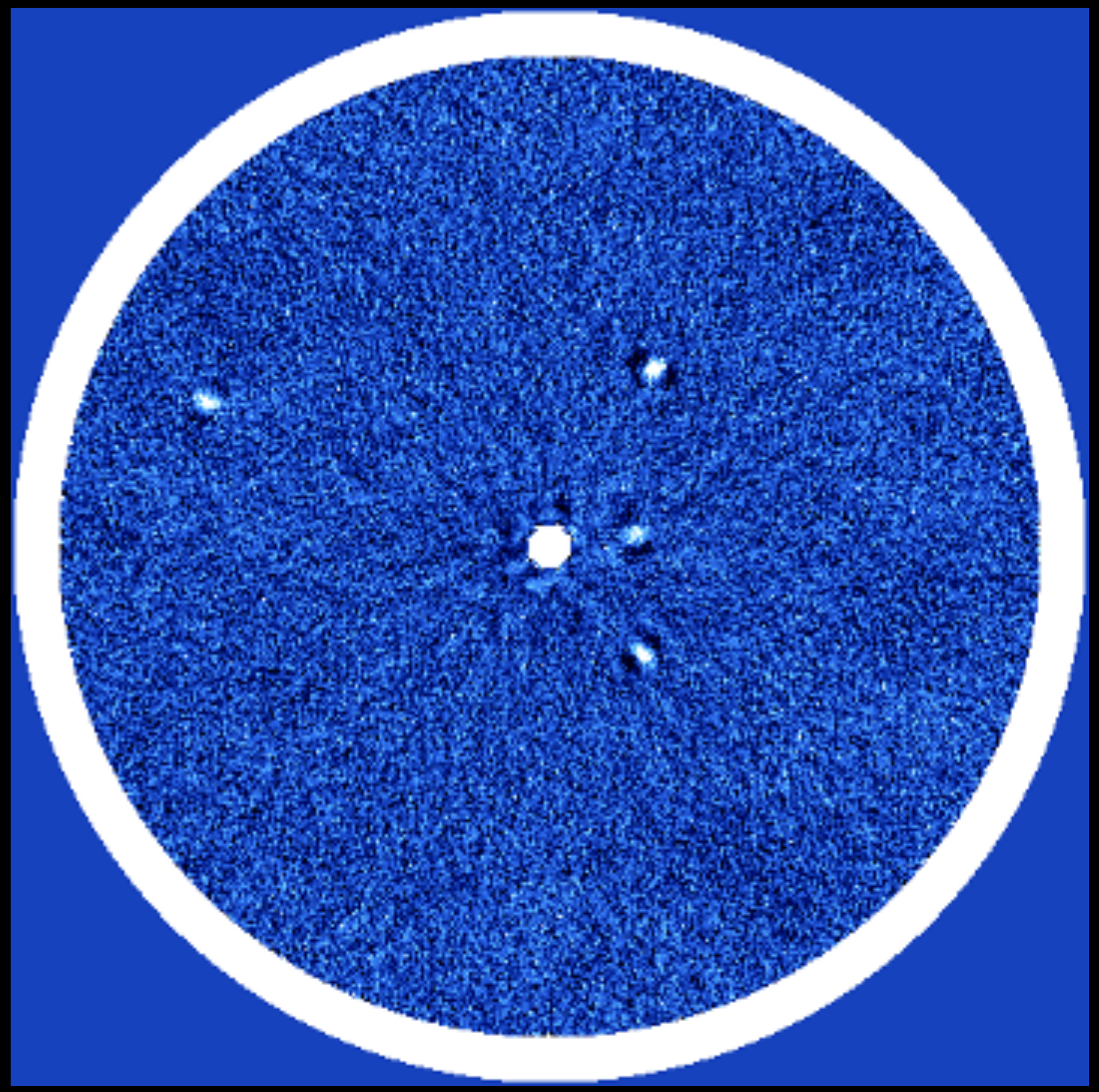

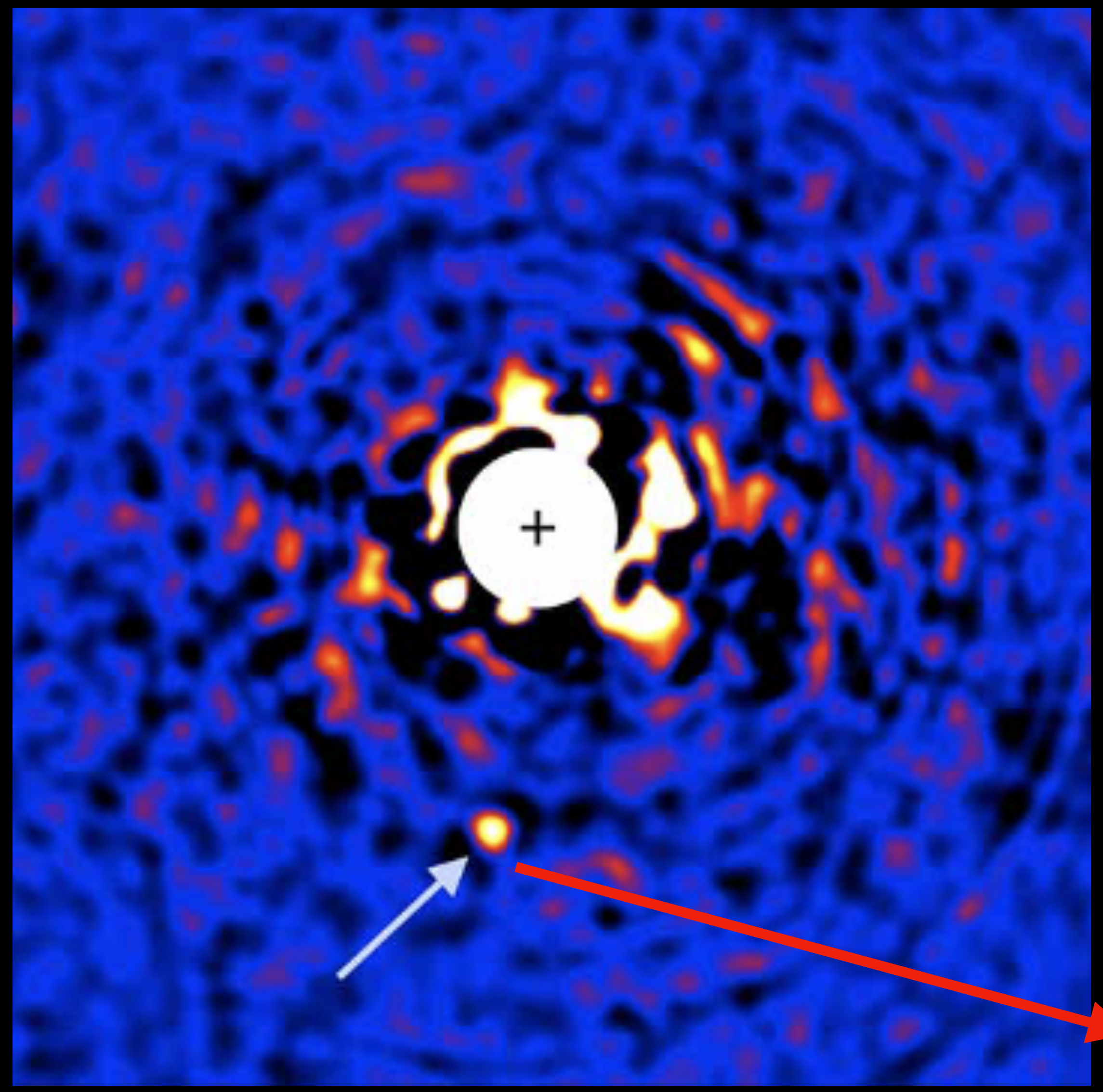

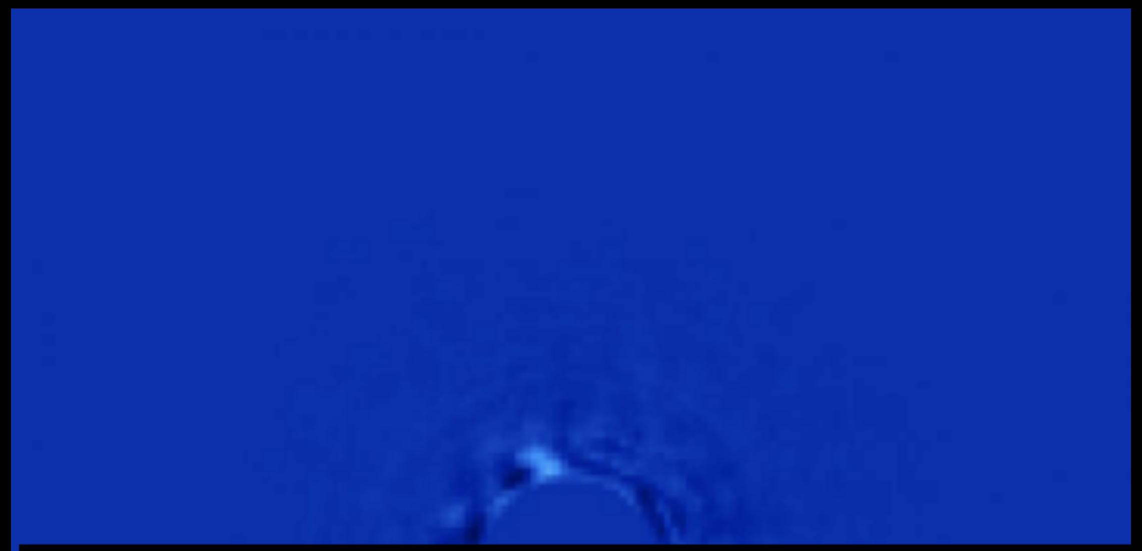

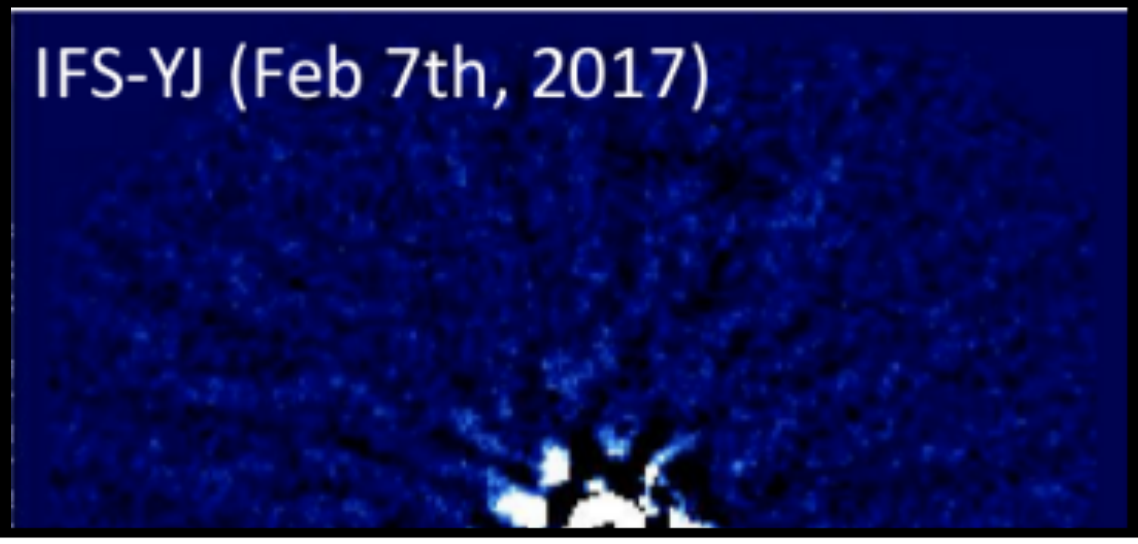

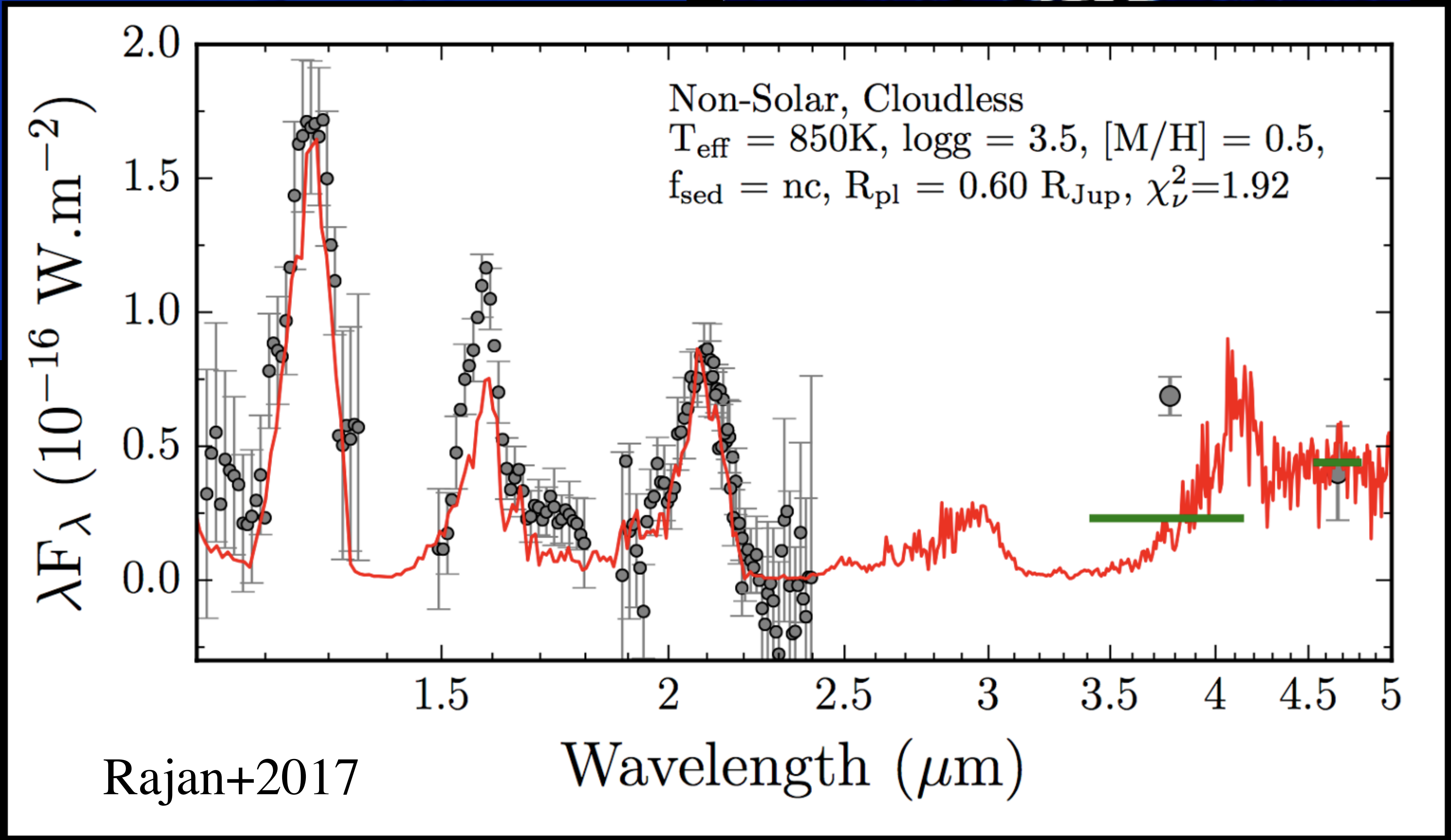

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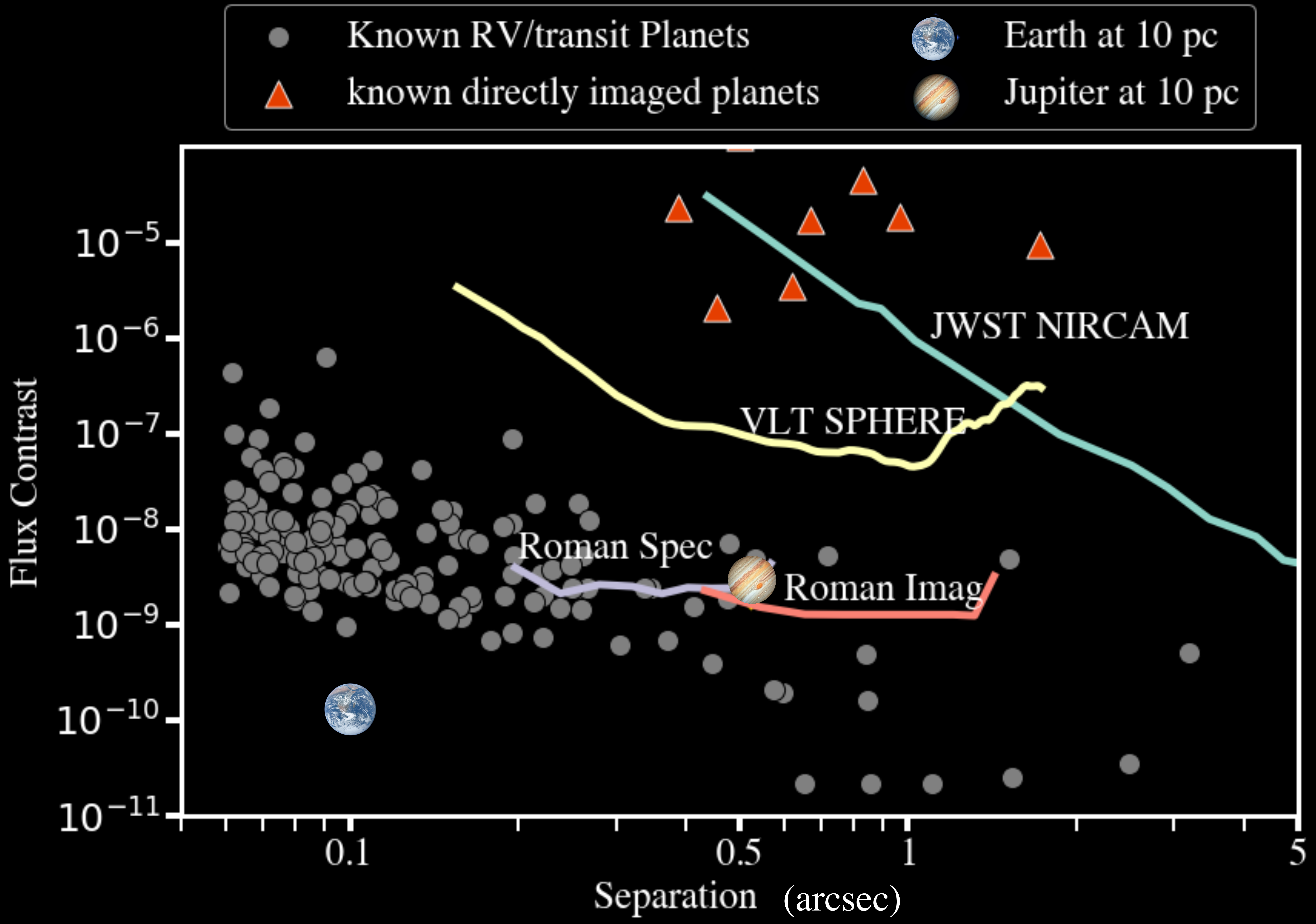
Astro 2020 recommends direct imaging from space



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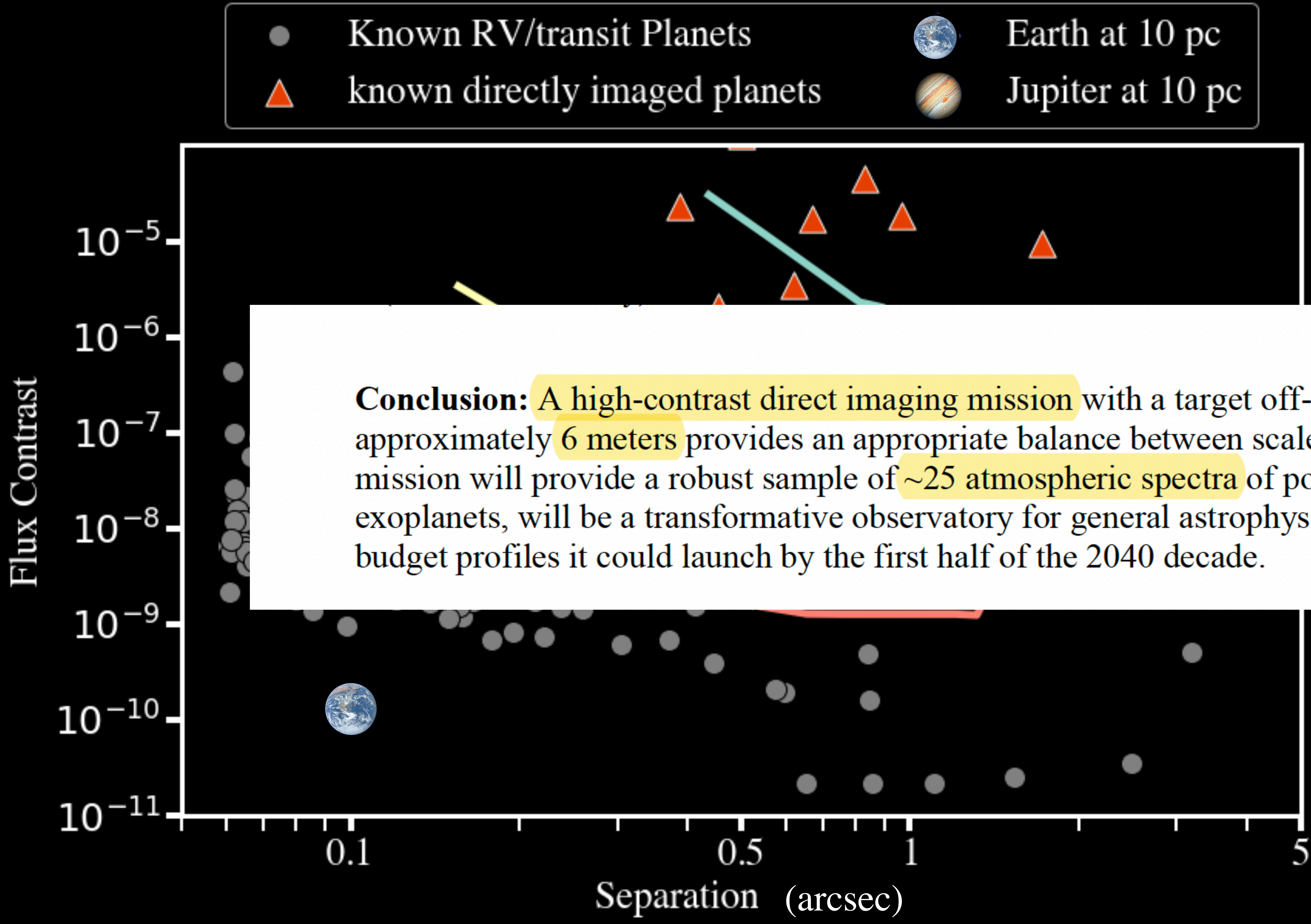


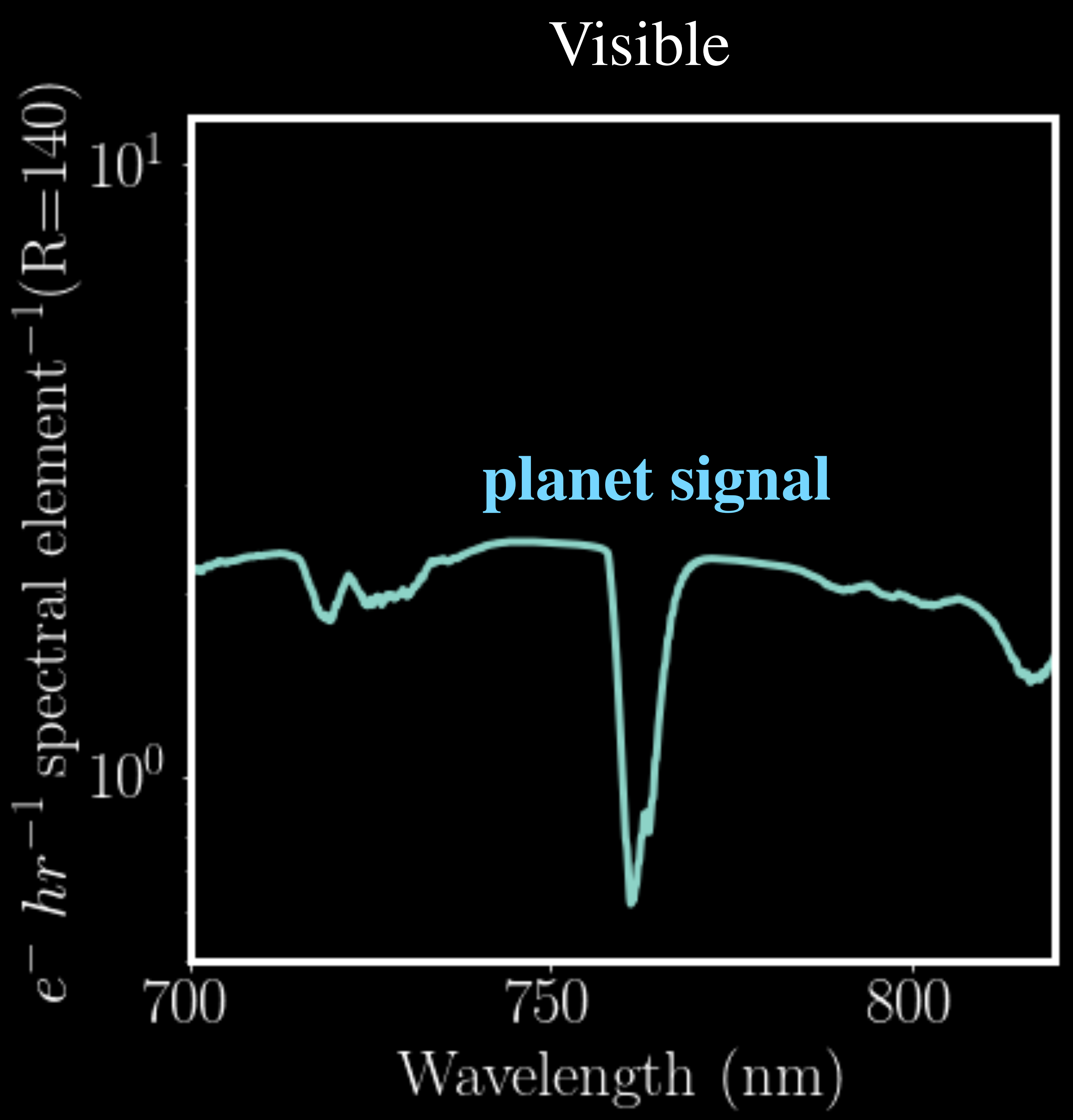
Conclusion: A high-contrast direct imaging mission with a target off-axis inscribed diameter of approximately 6 meters provides an appropriate balance between scale and feasibility. Such a mission will provide a robust sample of ~25 atmospheric spectra of potentially habitable exoplanets, will be a transformative observatory for general astrophysics, and given optimal budget profiles it could launch by the first half of the 2040 decade.

Integral Field Spectrograph (IFS)

Rizzo et al. 2021

IFS signal rate and noise rate

Target: an Earth analog from 10 pc



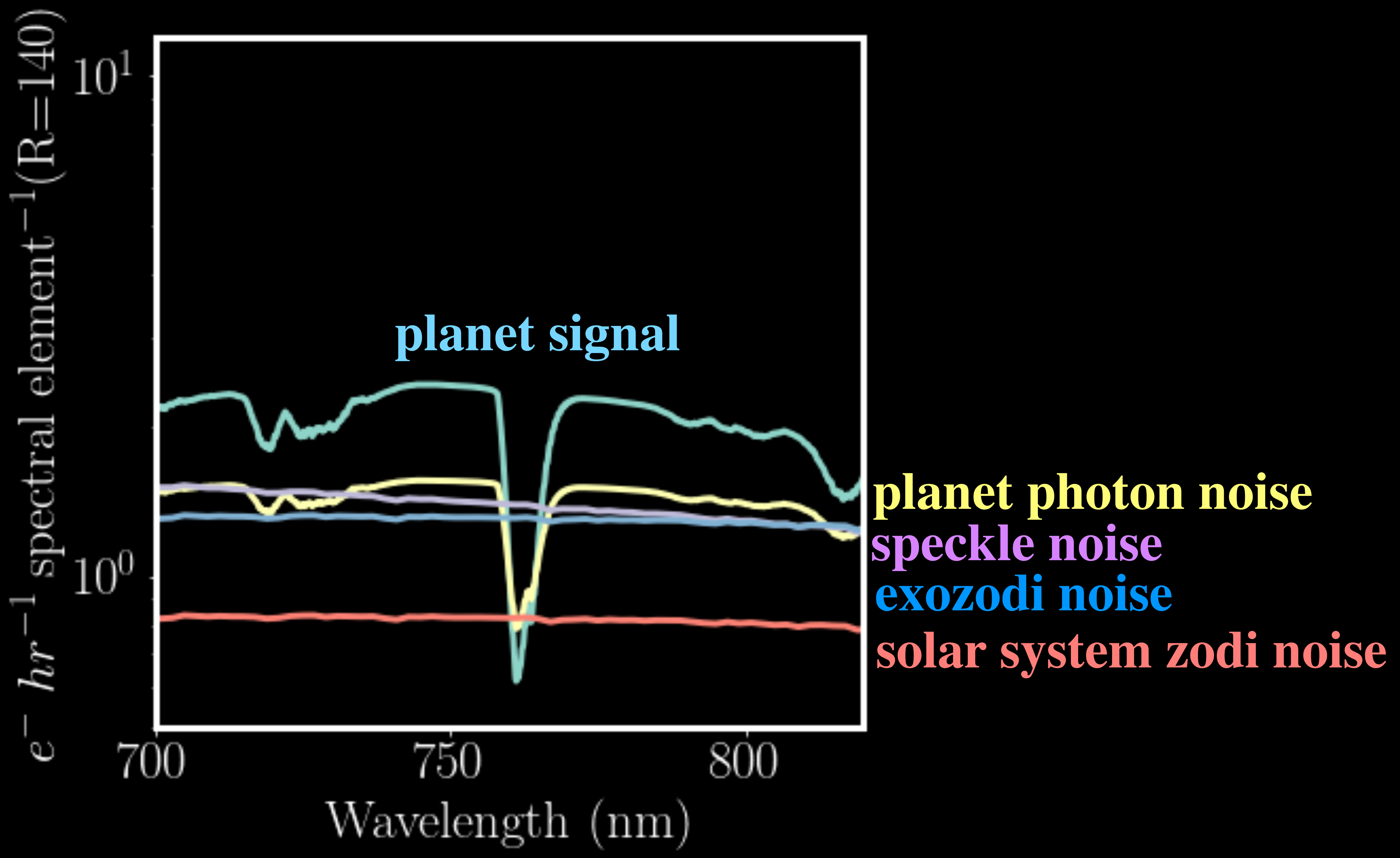
Dark current values from Morrissey+2023

Zhang, Bottom, Serabyn, submitted

IFS signal rate and noise rate

Target: an Earth analog from 10 pc

Visible



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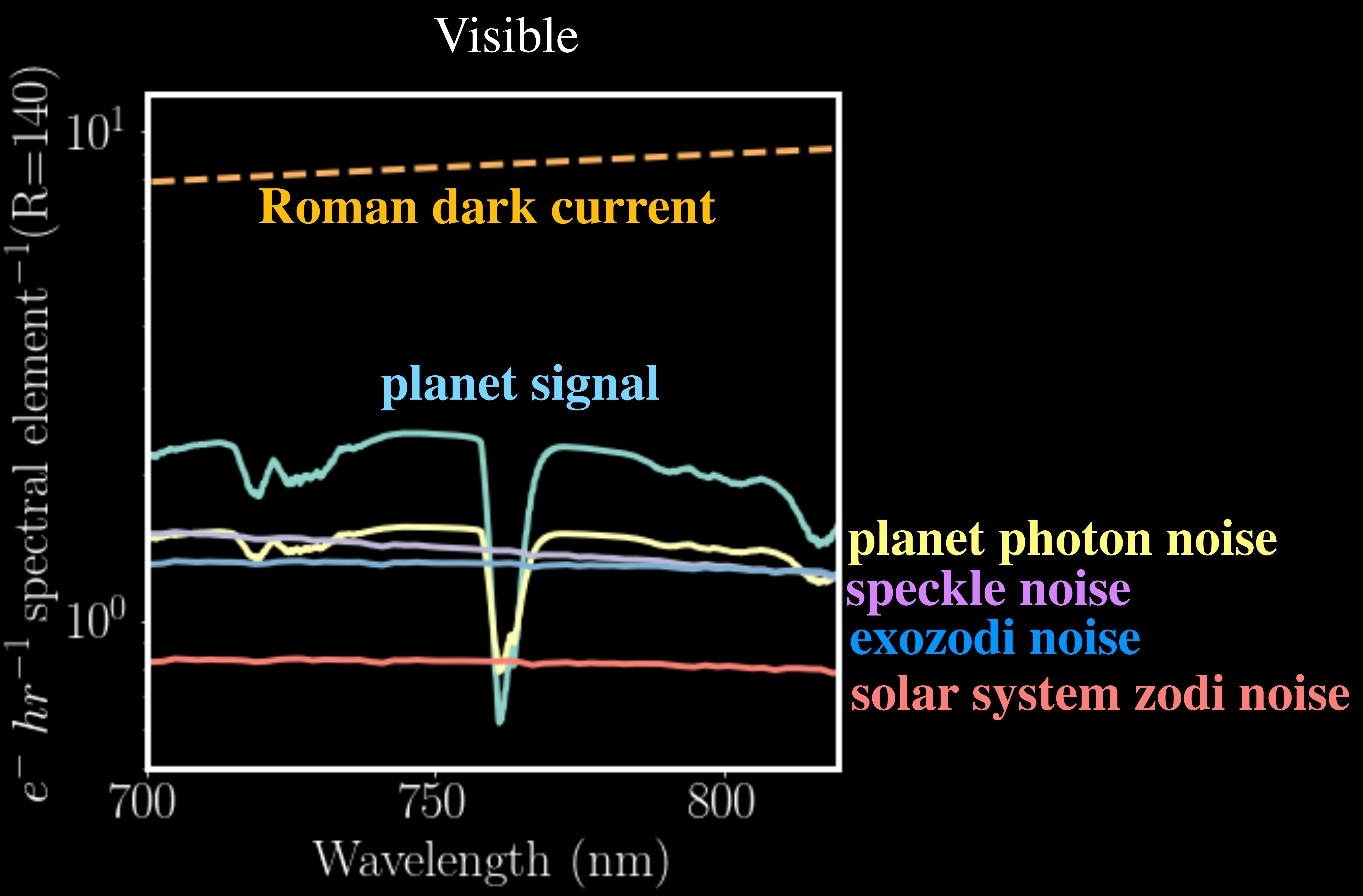

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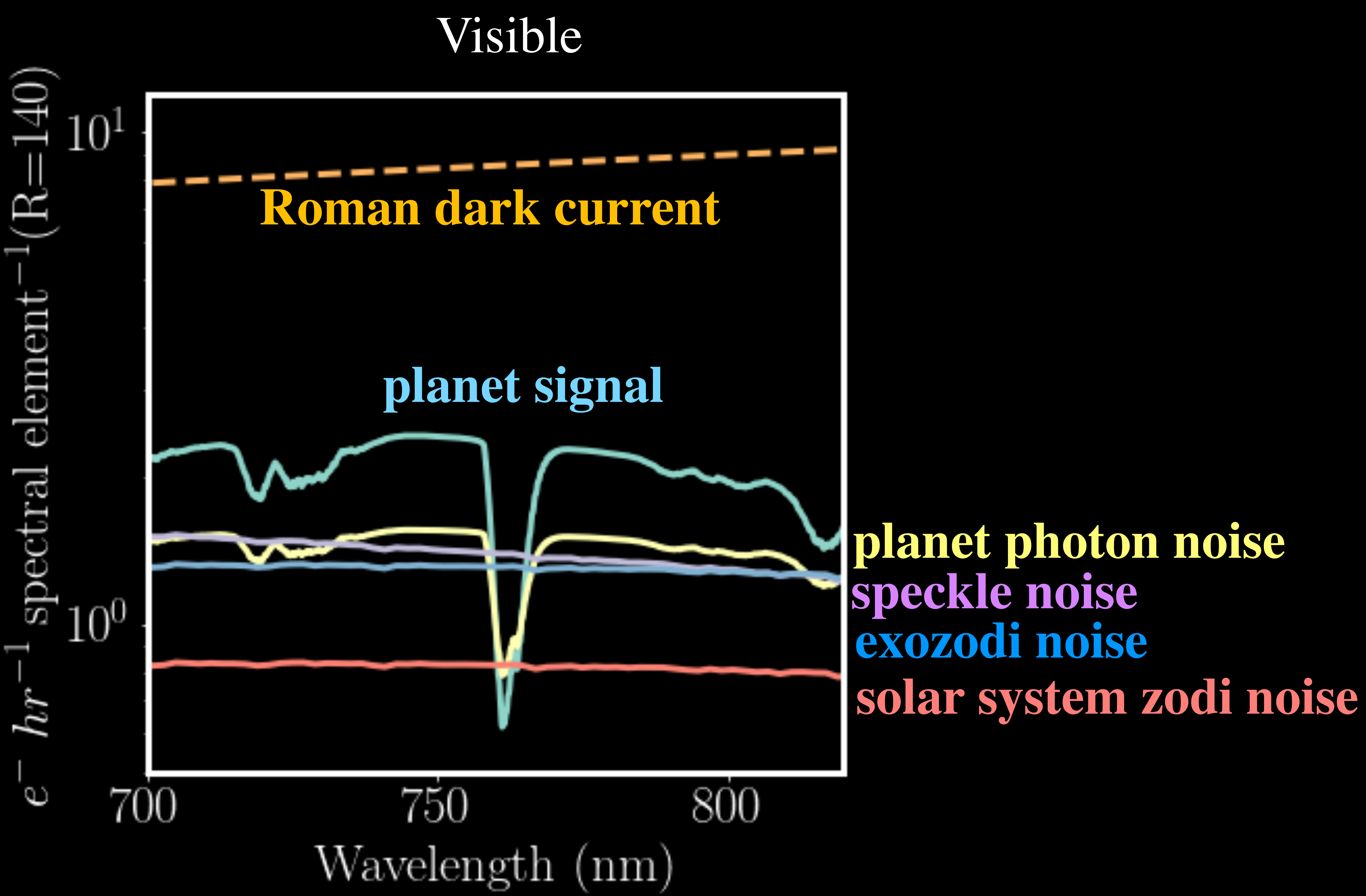

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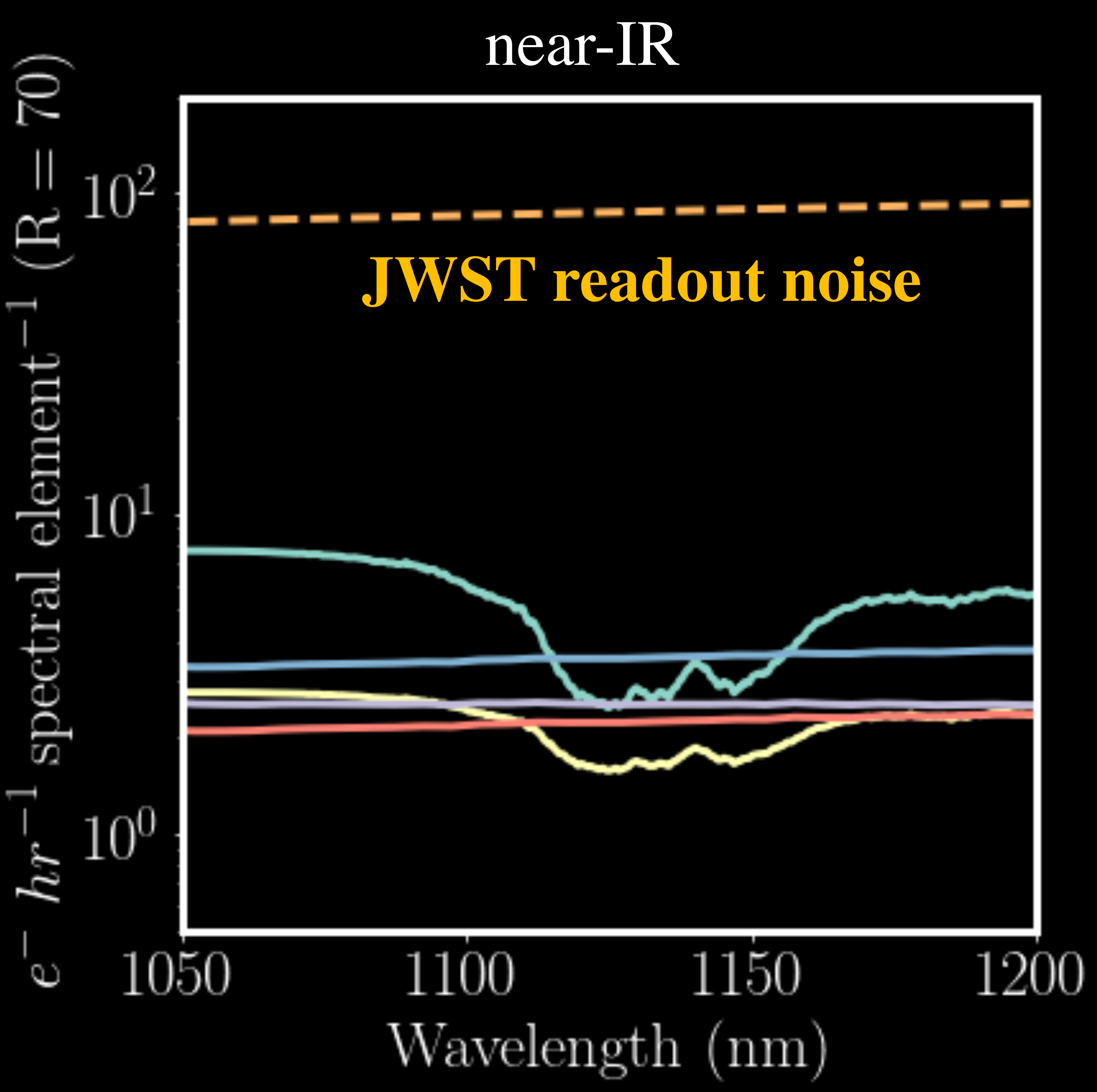
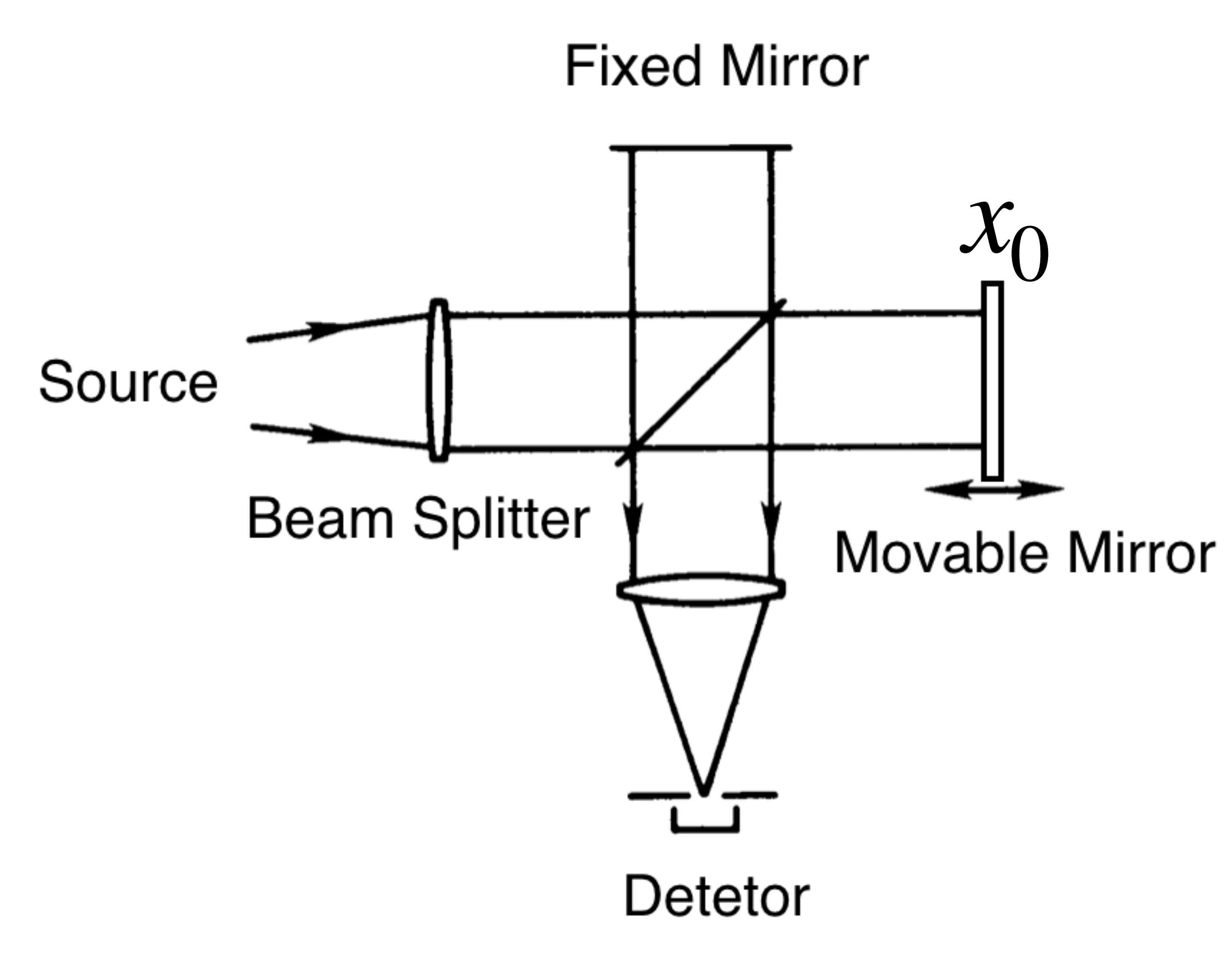


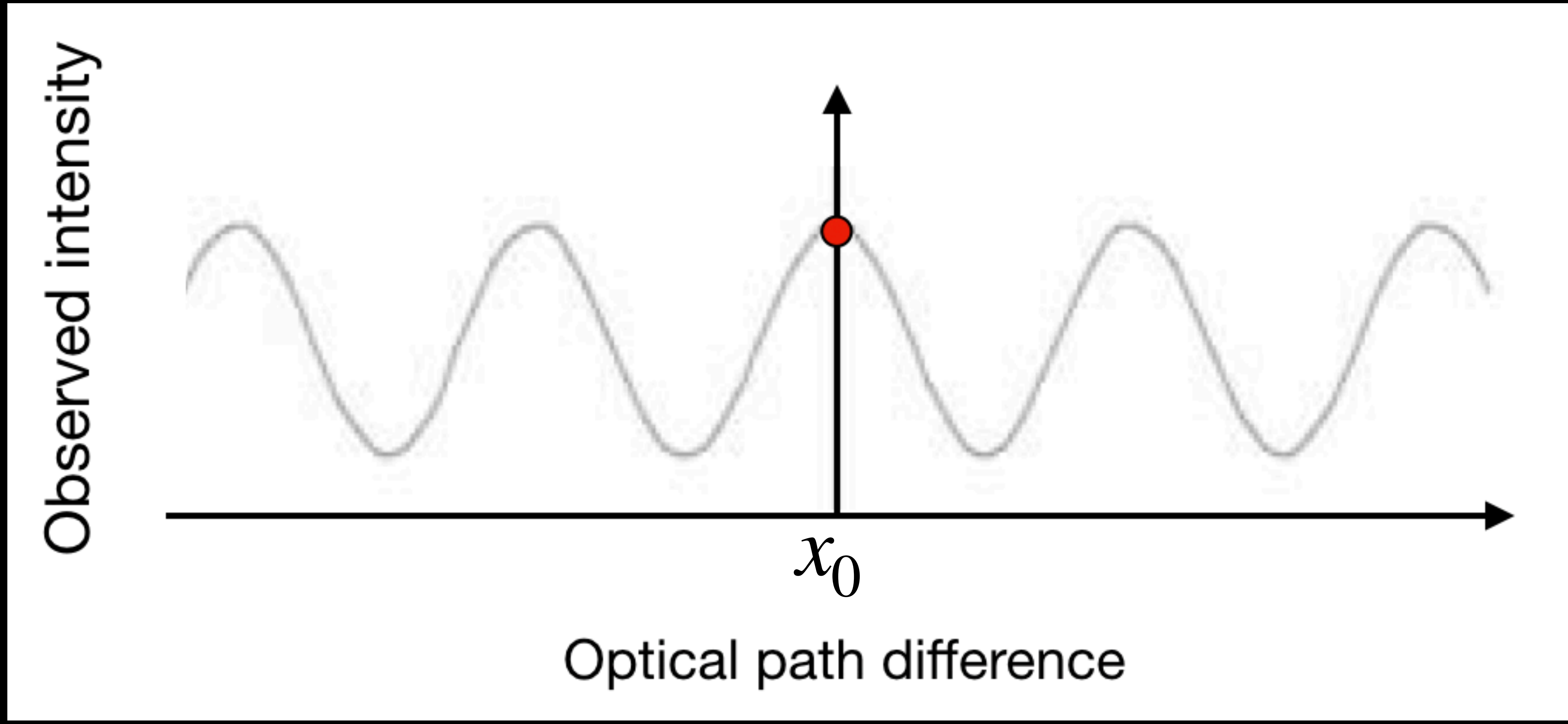
Readout noise values from Birkmann+2021

Zhang, Bottom, Serabyn, submitted

Imaging Fourier Transform Spectrograph (iFTS)



Interferogram



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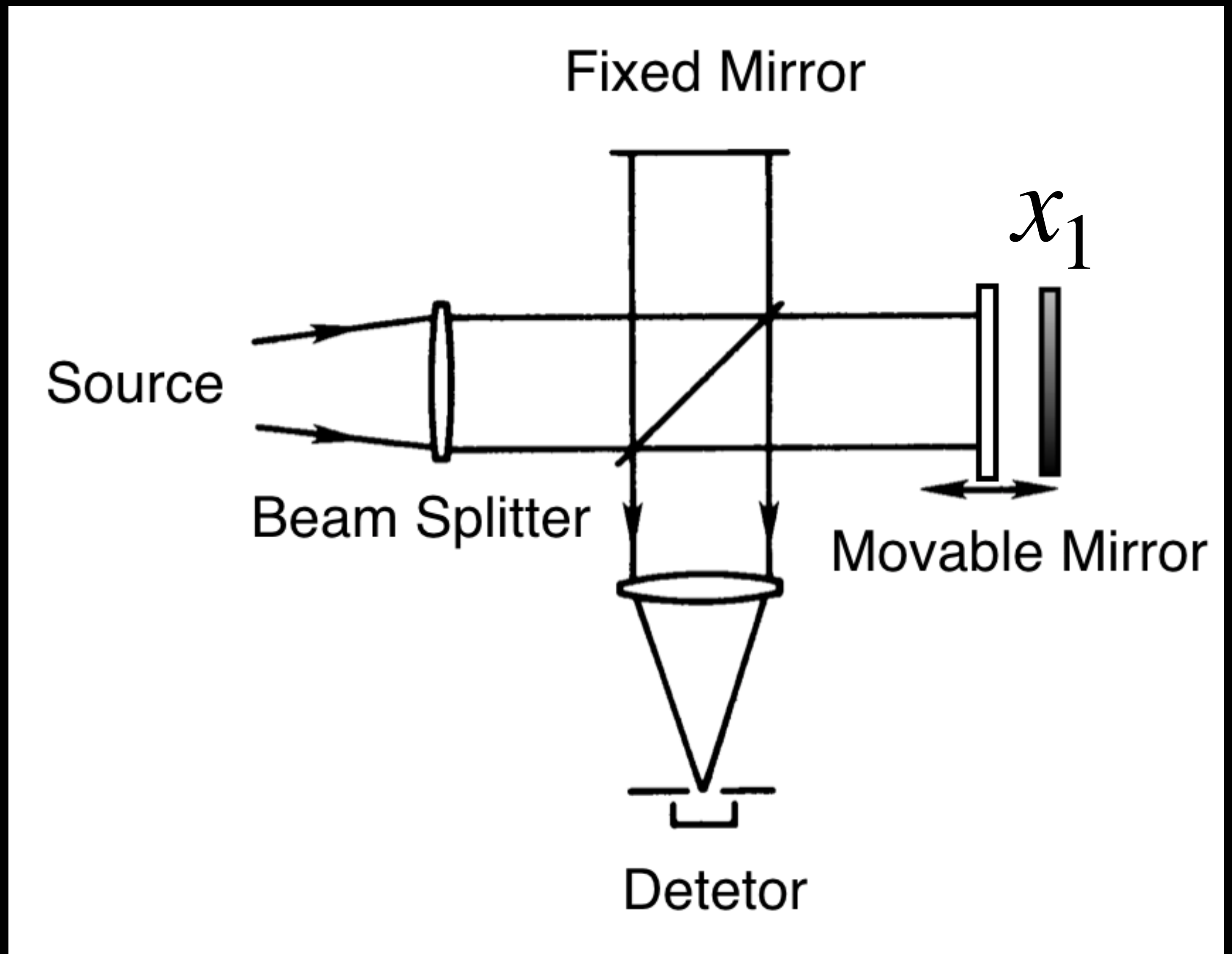
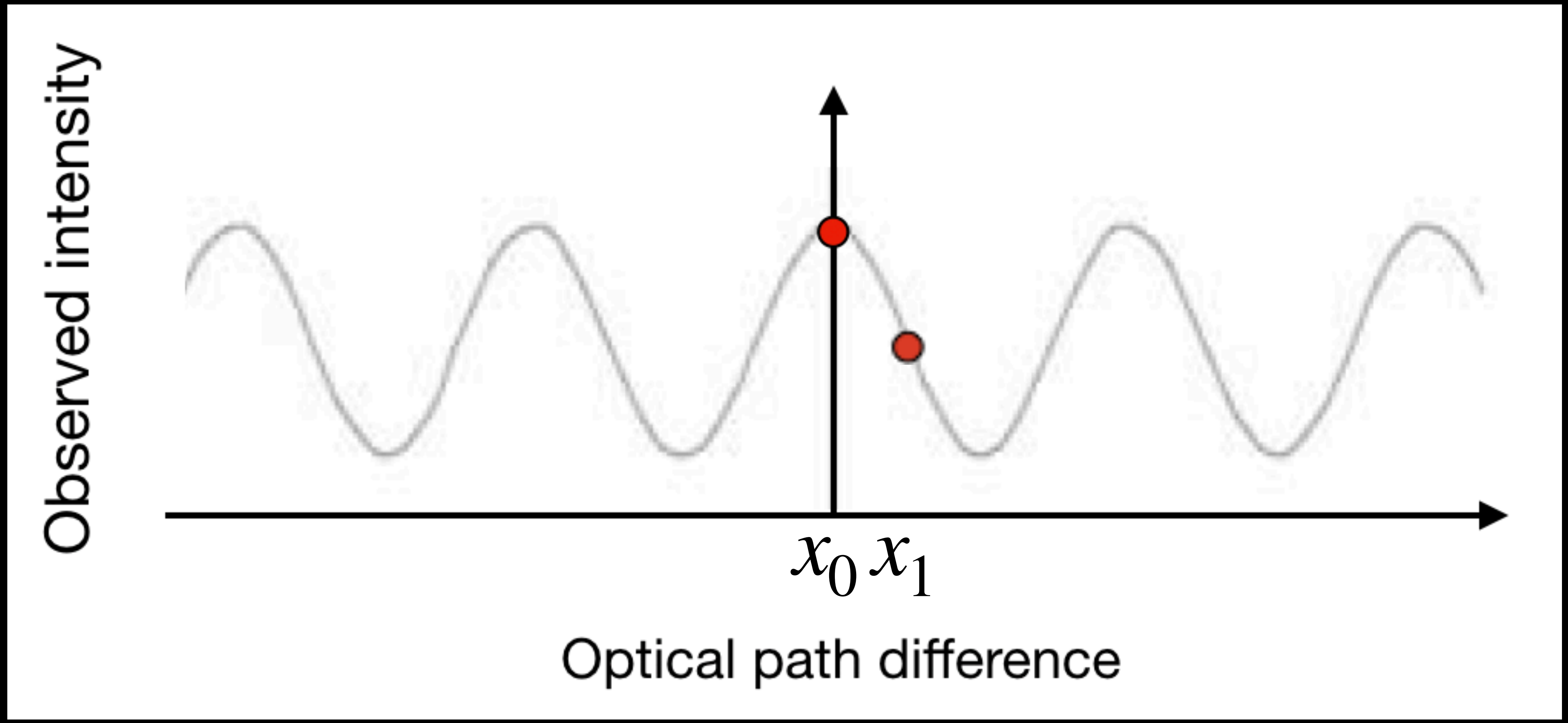


Interferogram



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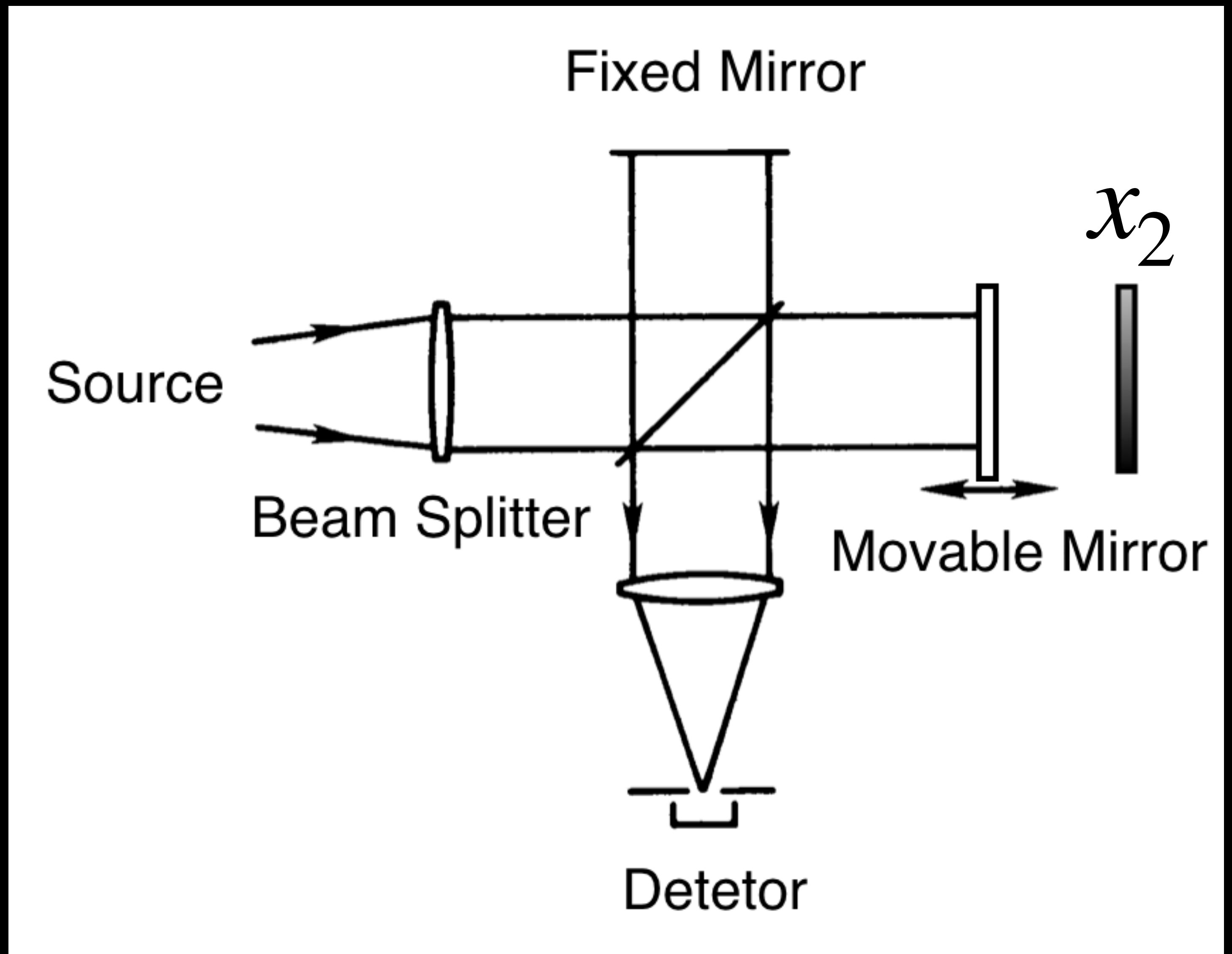
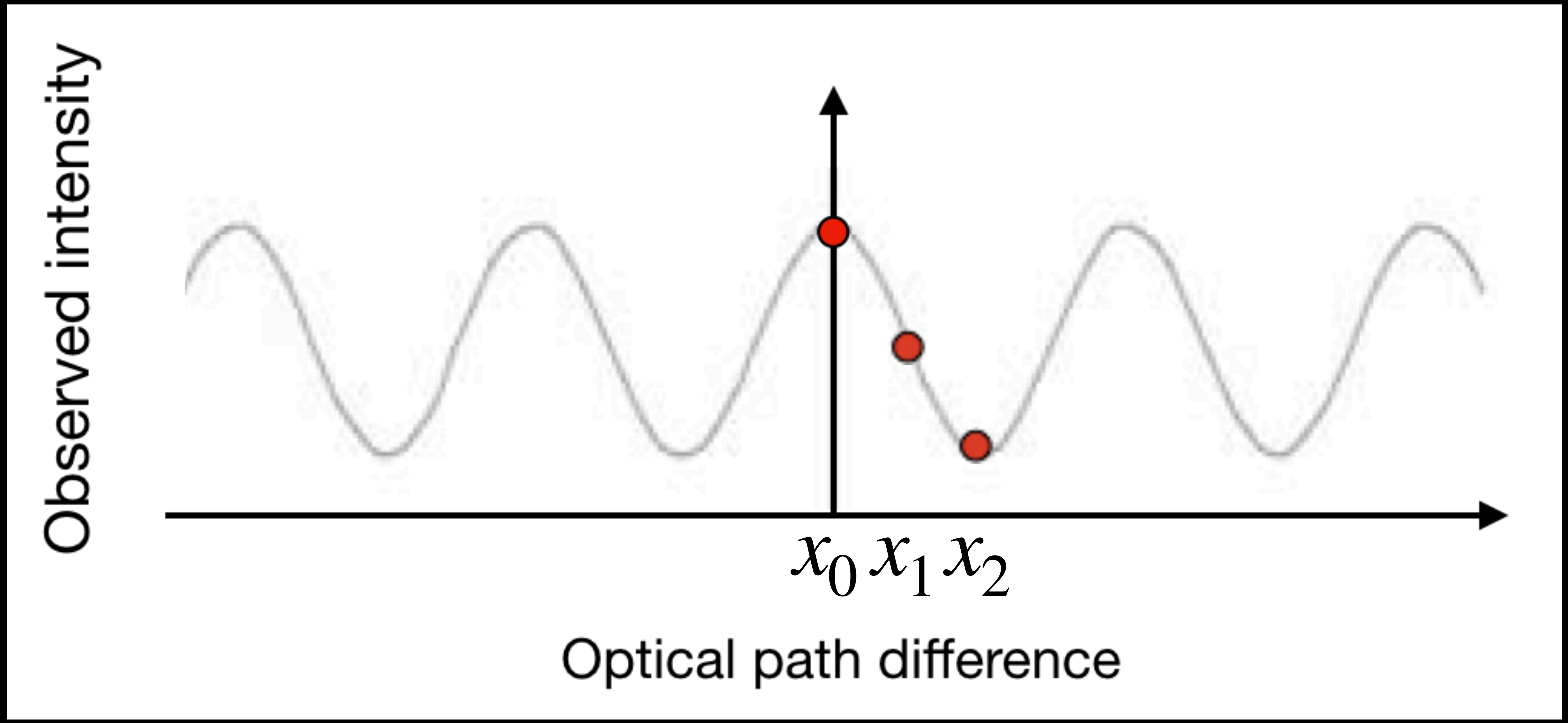
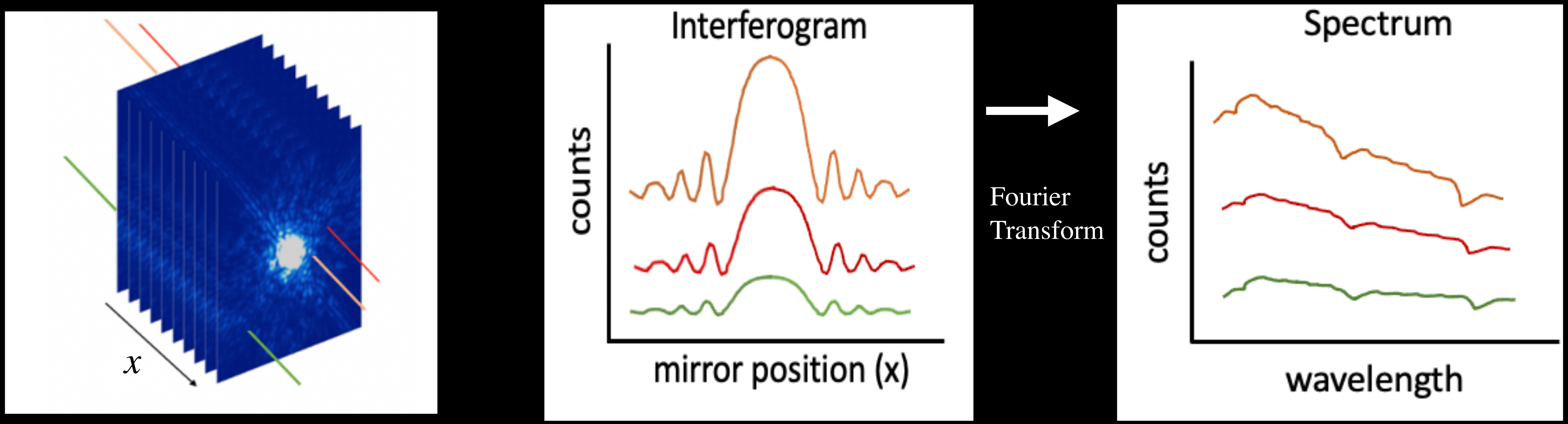


Interferogram

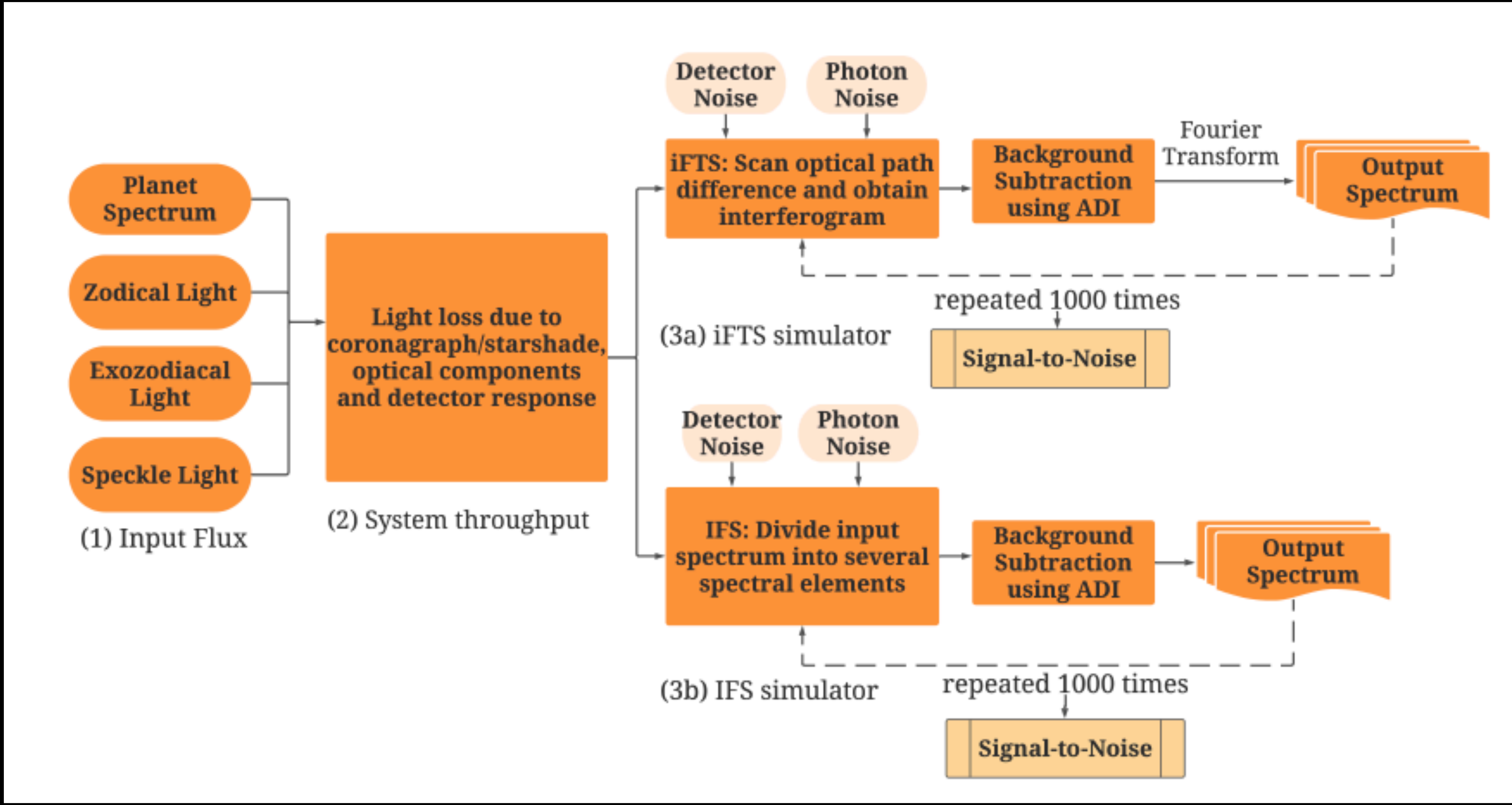


Imaging Fourier Transform Spectrograph (iFTS)

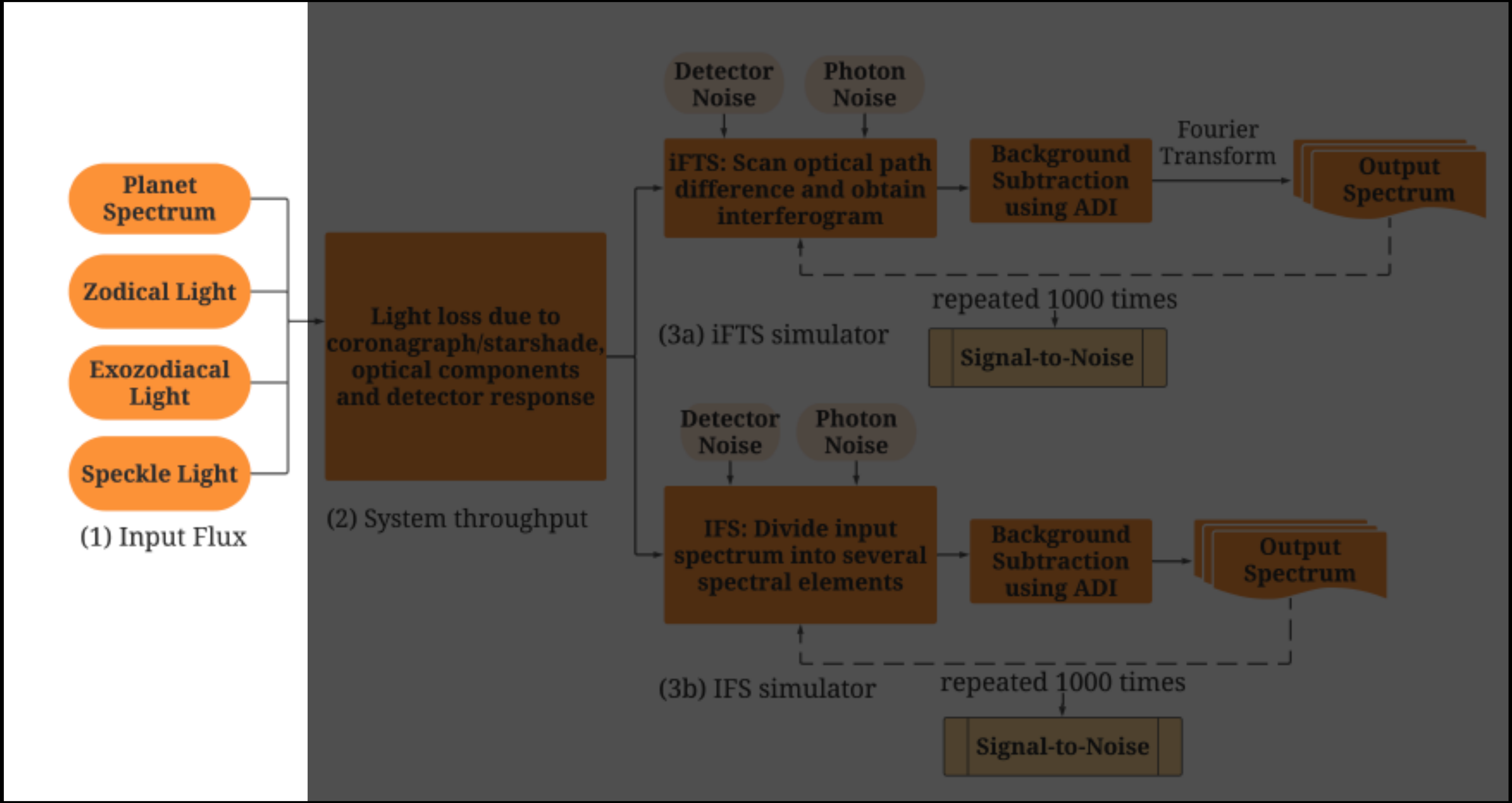
- Pros: No dispersion, use much fewer pixels, less detector noise
- Cons: higher photon noise



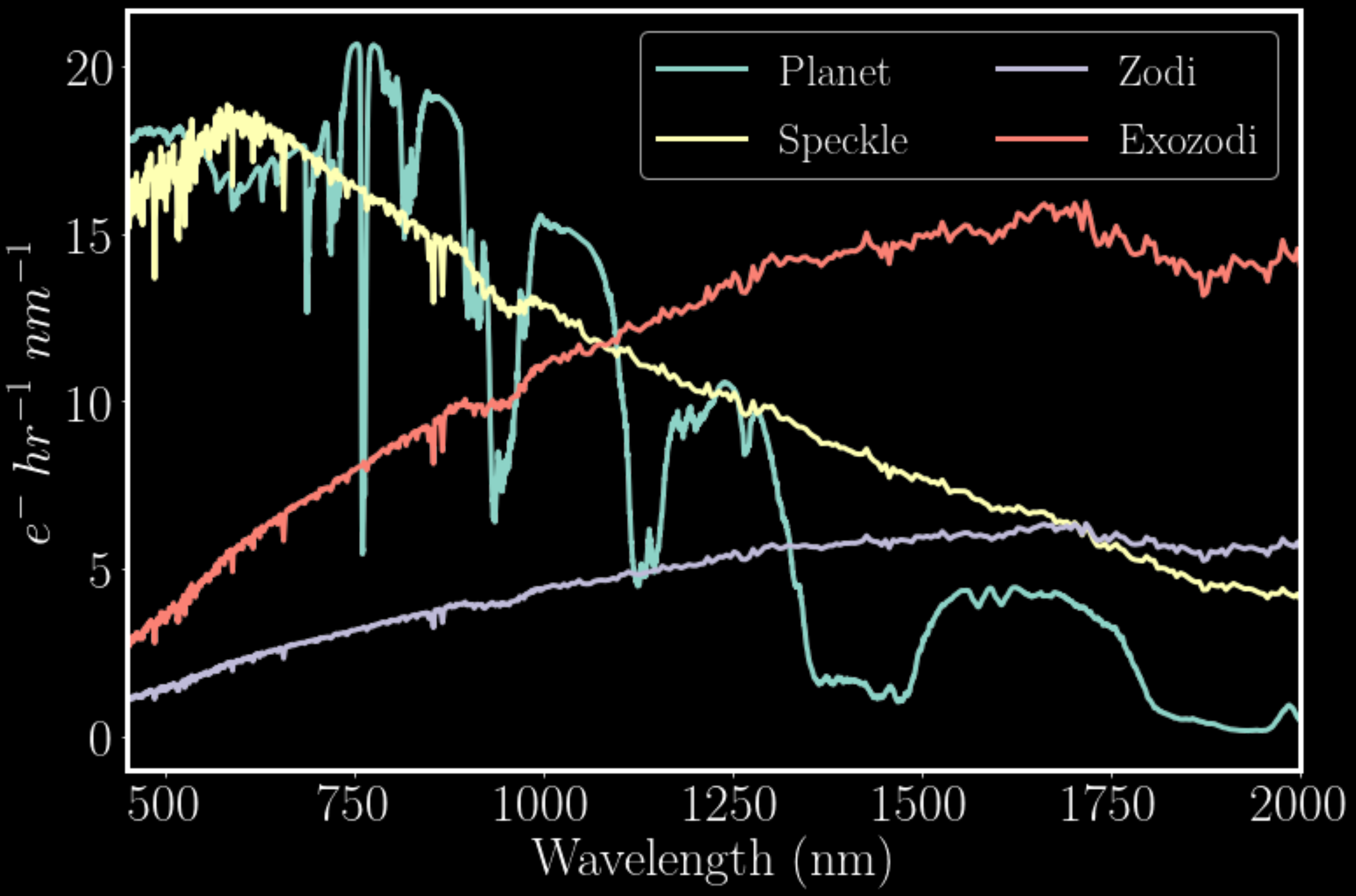
Numerical Simulation



Numerical Simulation

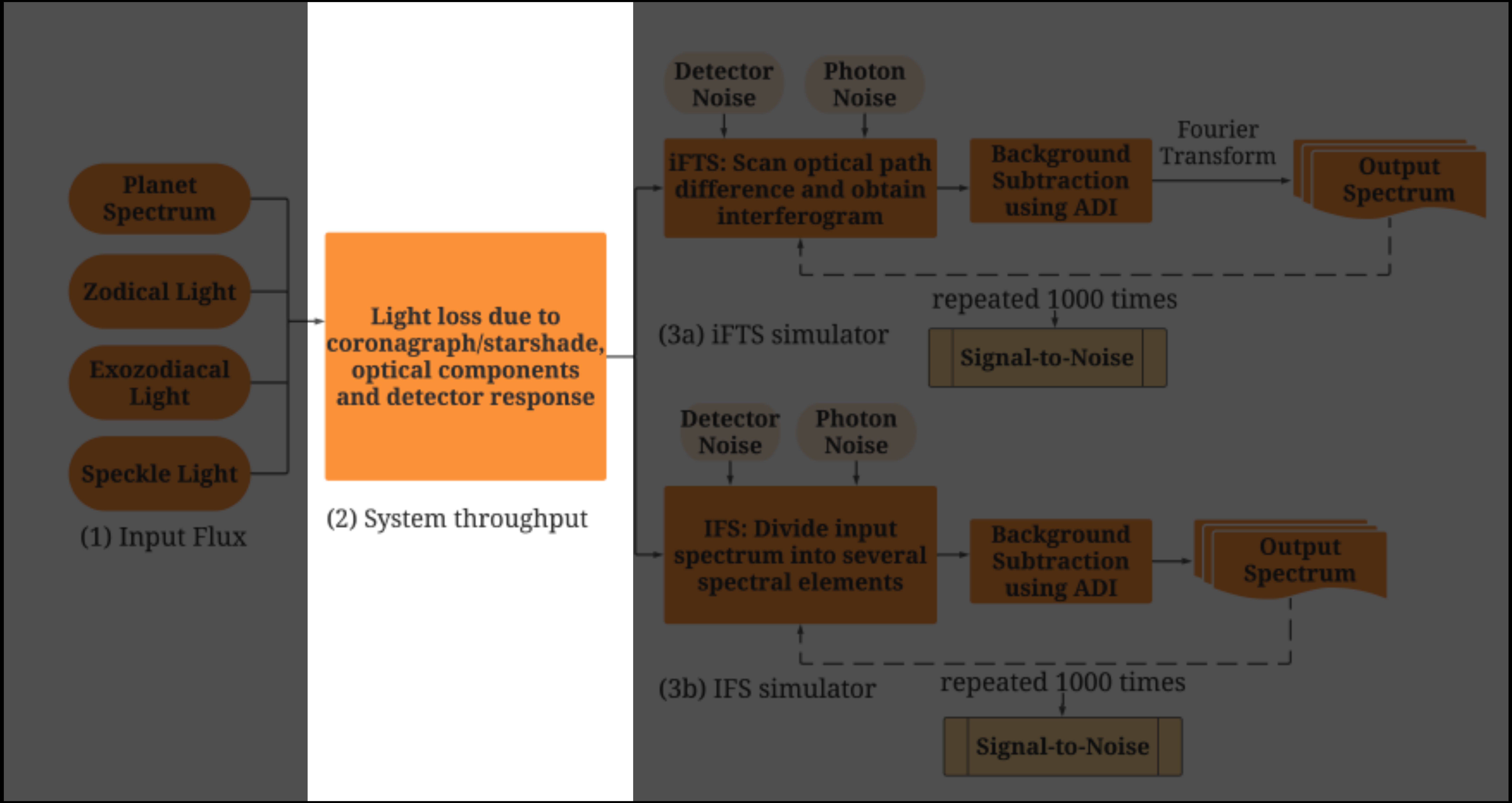


Input spectra



- Fiducial Target: an Earth twin orbiting a Sun-like star at 1 AU at 10 pc away
- Speckle: 10^-10 starlight
- 23 mag/arcsec^2 zodiacal light
- one 22 mag/arcsec^2 exo-zodiacal light

Numerical Simulation



Instrument Parameters

Diameter

6 m

Throughput

$$\tau_{tot} = \tau_{optical} * \tau_{coronagraph} * \tau_{QE}$$

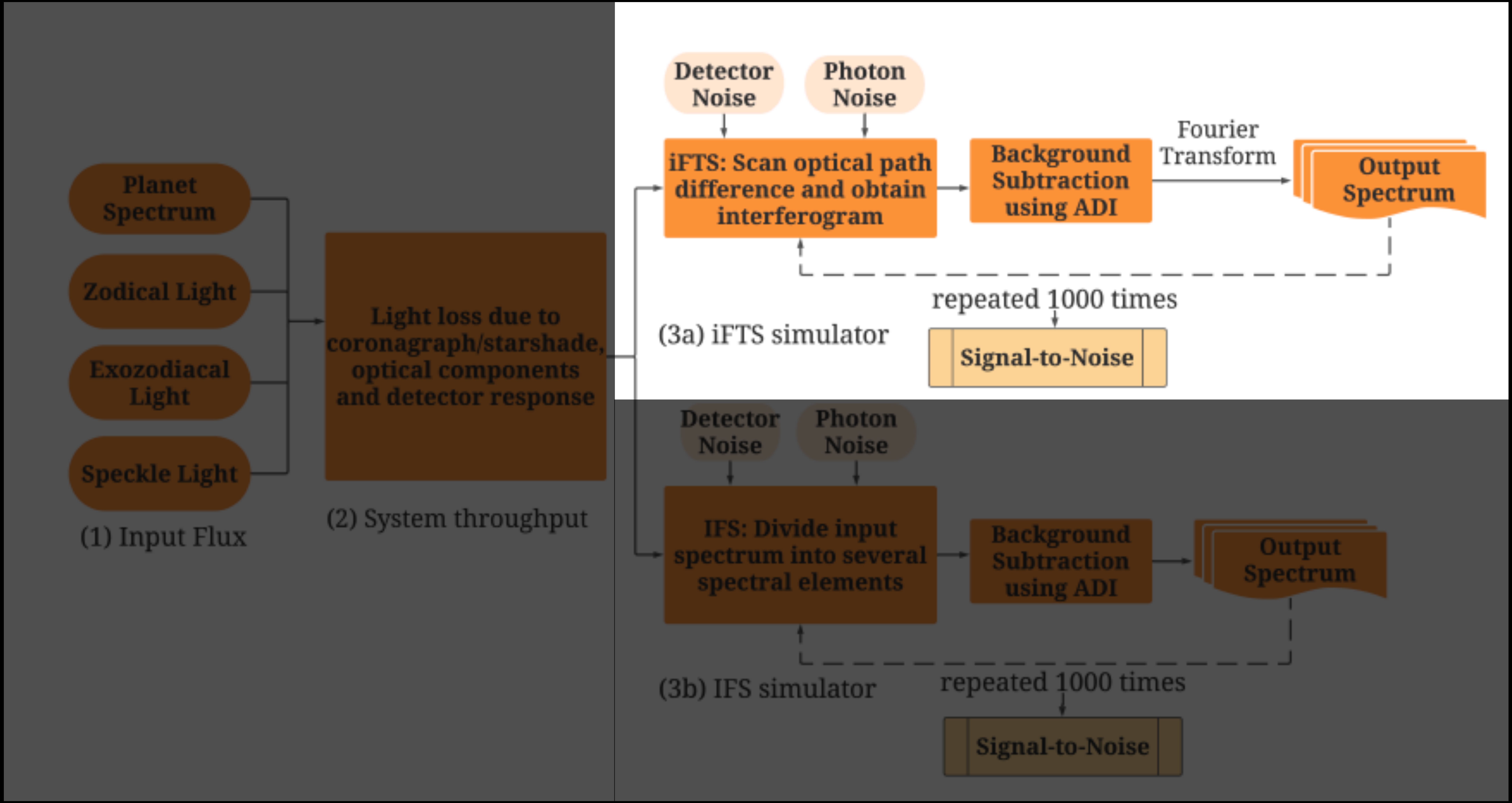
Resolution

VIS: 140, NIR:70

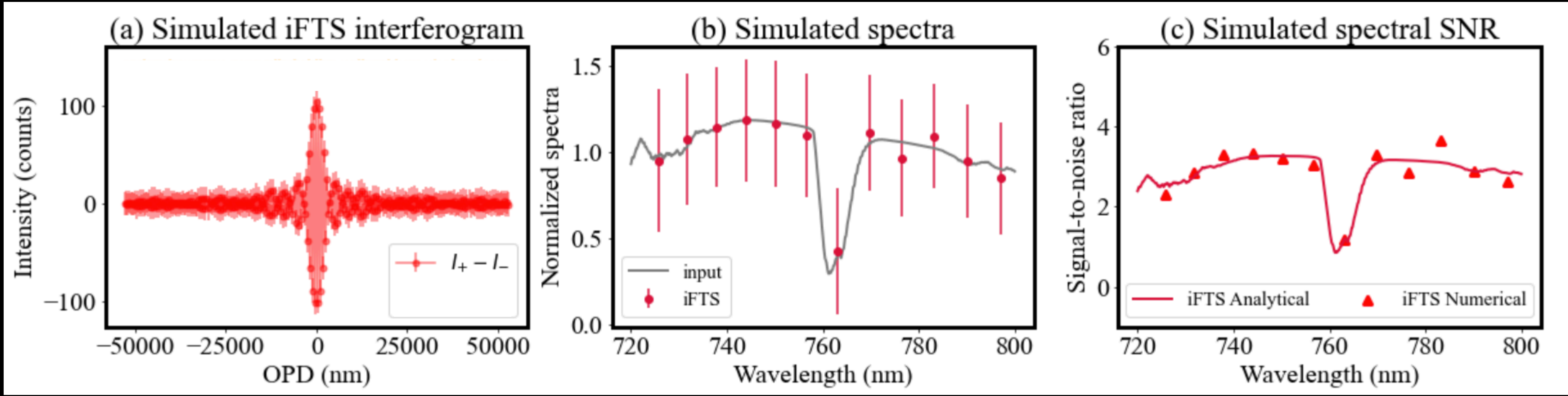
Detector Noise

1. Current level: ROMAN and JWST
2. Future level: HabEx and LUVOIR

Numerical Simulation



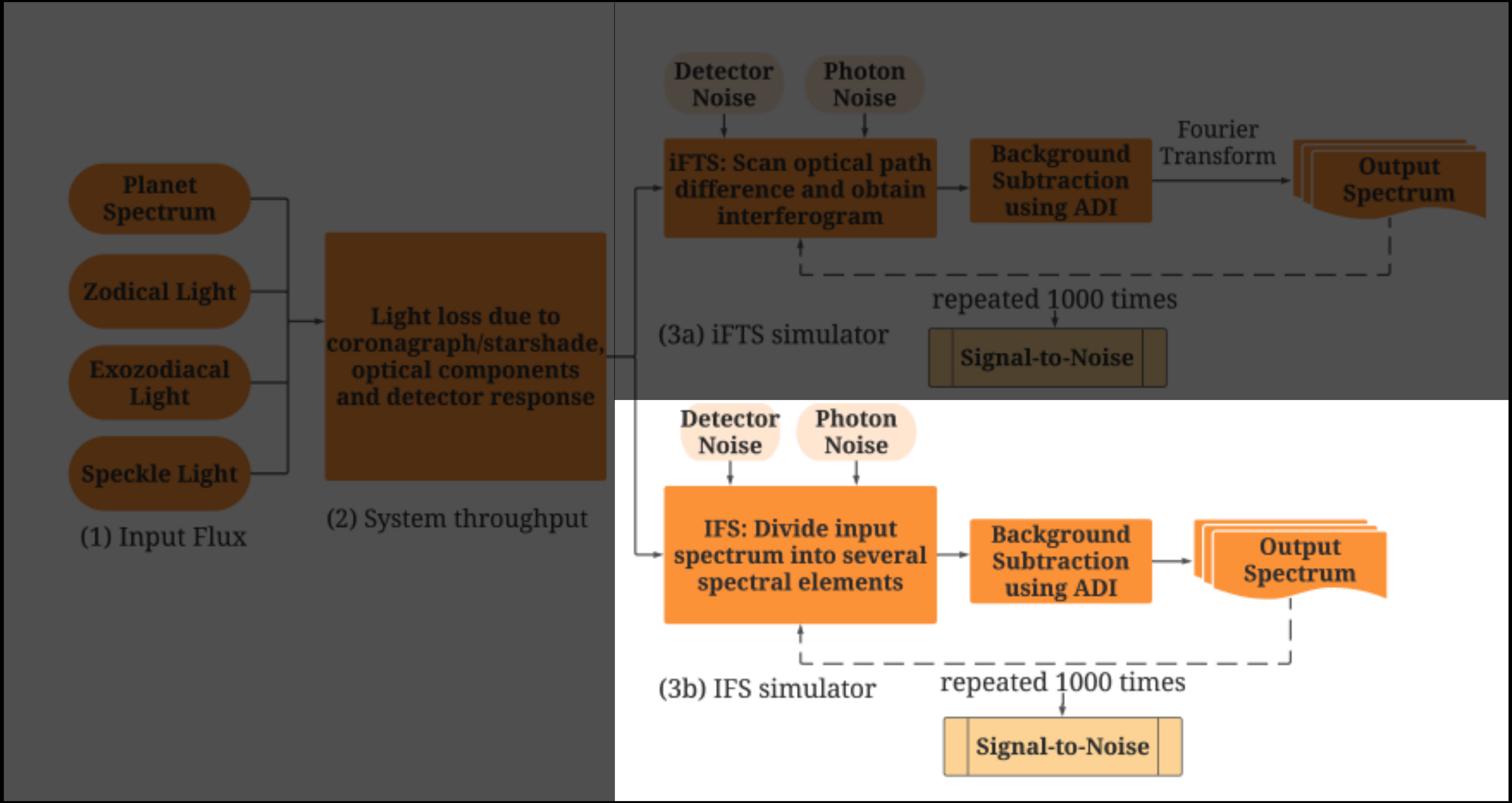
iFTS: comparing numerical SNR with analytical SNR



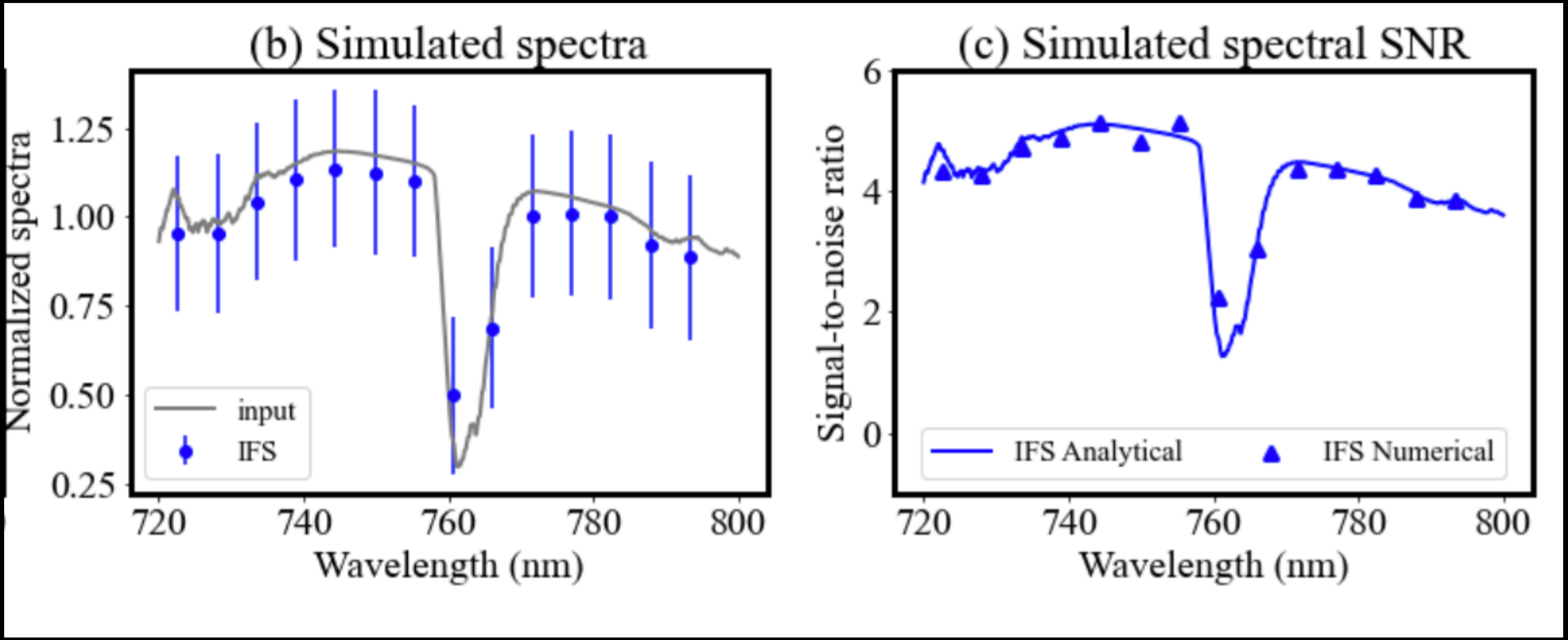
$$\mathrm{SNR_{FTS}} = \frac{c_p * \Delta\lambda_{ILS} * T_{exp}}{\sqrt{2}\sqrt{[\int(c_p + 2c_b)d\lambda + 2c_d N'_{pix}]T_{exp}}}$$

Photon Noise **Detector Noise**

Numerical Simulation



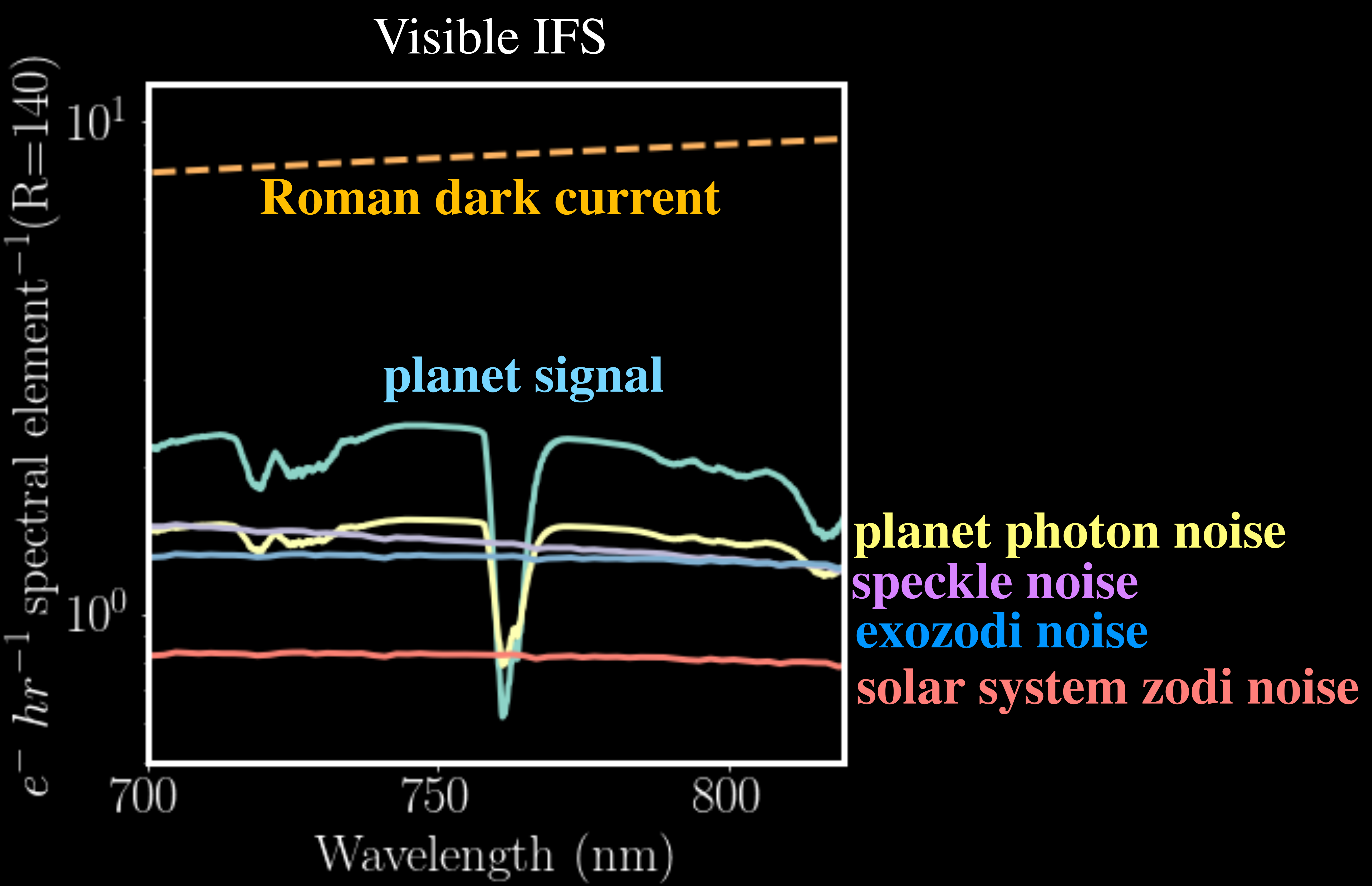
IFS: comparing numerical SNR with analytical SNR



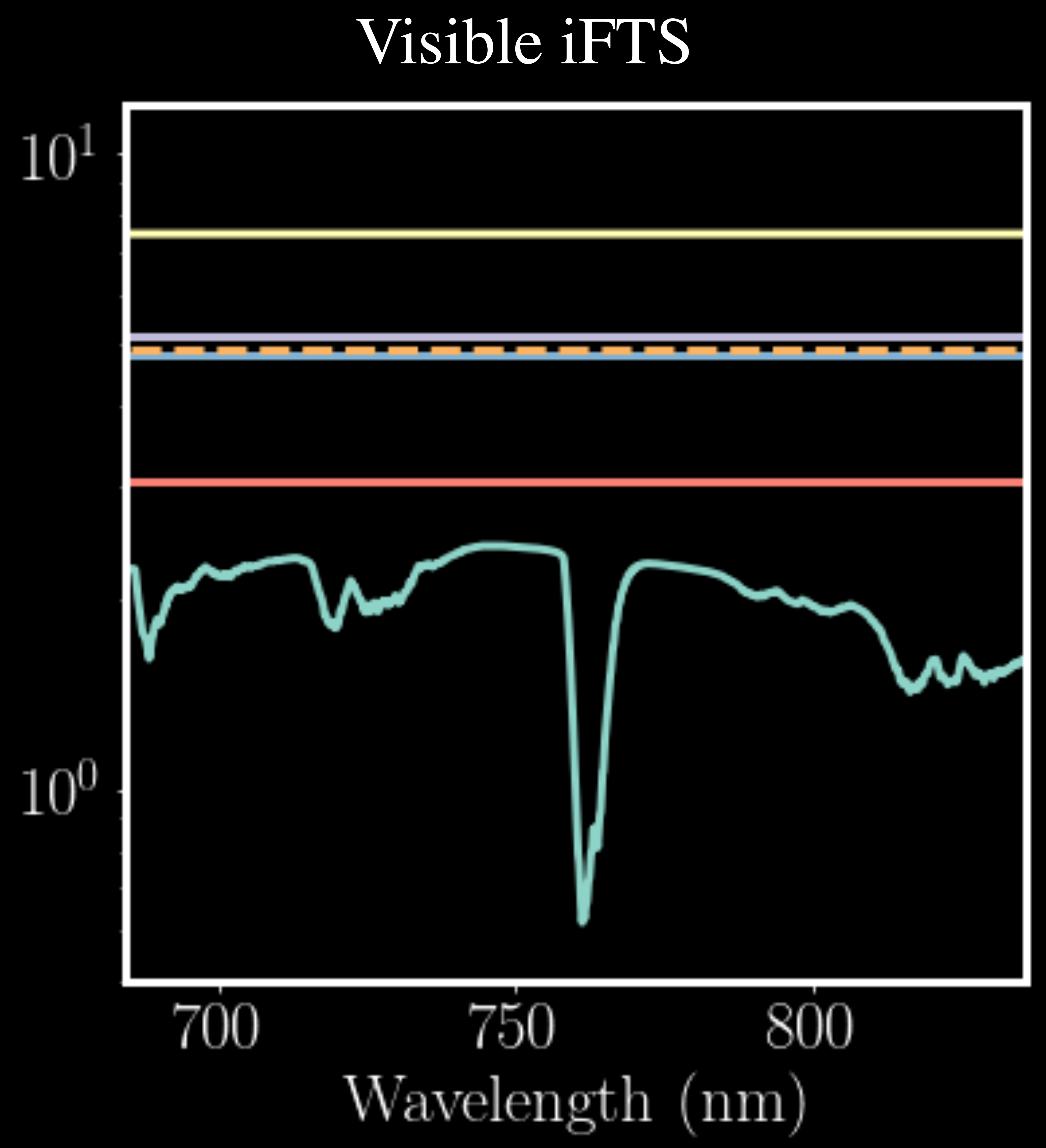
$$SNR_{IFS} = \frac{c_p * \Delta\lambda * T_{exp}}{\sqrt{[(c_p + 2c_b)\Delta\lambda + 2c_d N_{pix}]T_{exp}}}$$

Photon Noise   Detector Noise

Visible: an iFTS is limited by the photon noise



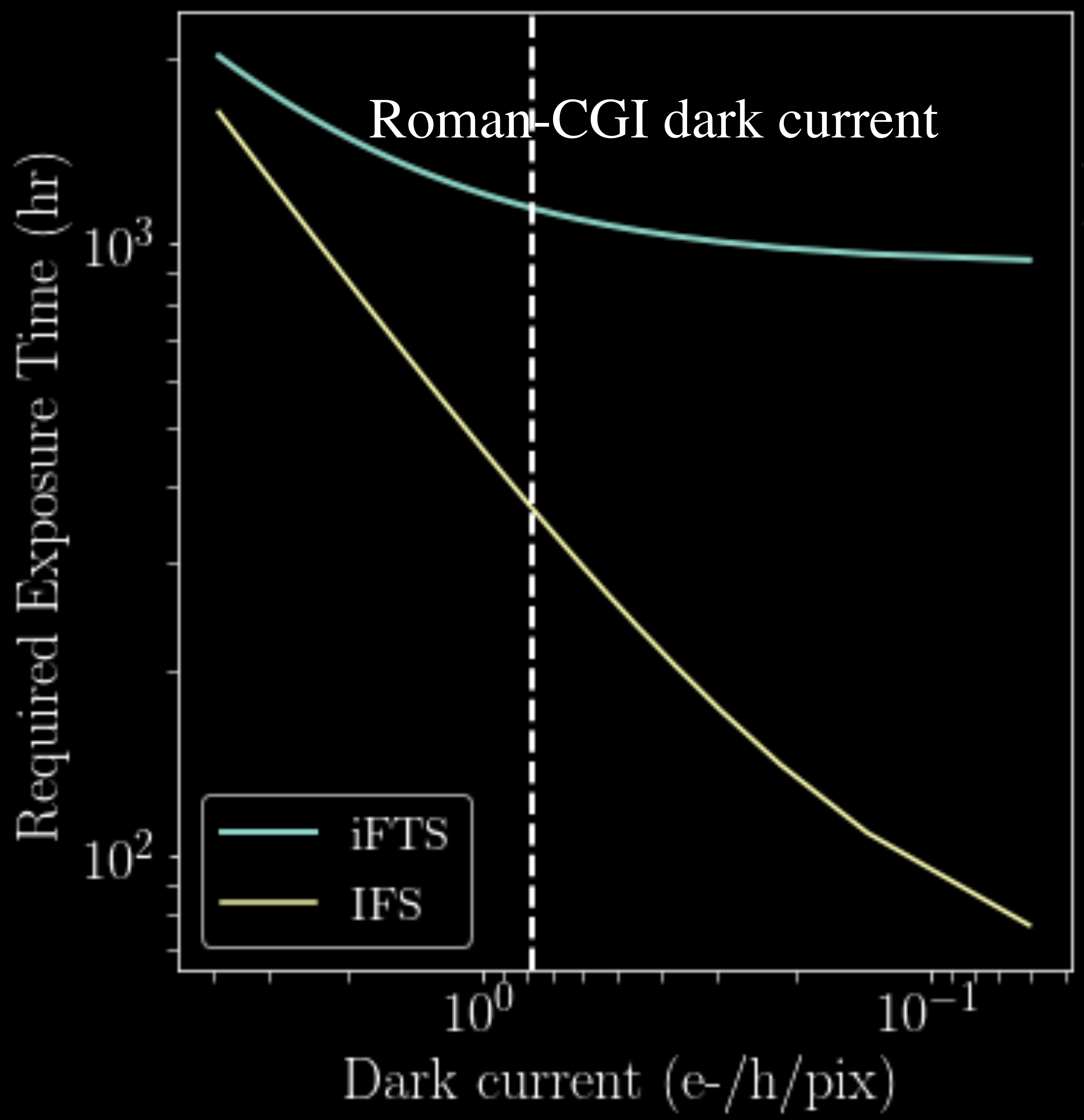
Dark current values from Morrissey+2023



Zhang, Bottom, Serabyn, submitted

Visible: required exposure time to achieve SNR of 5

Target: an Earth analog from 10 pc



Dark current values from Morrissey+2023

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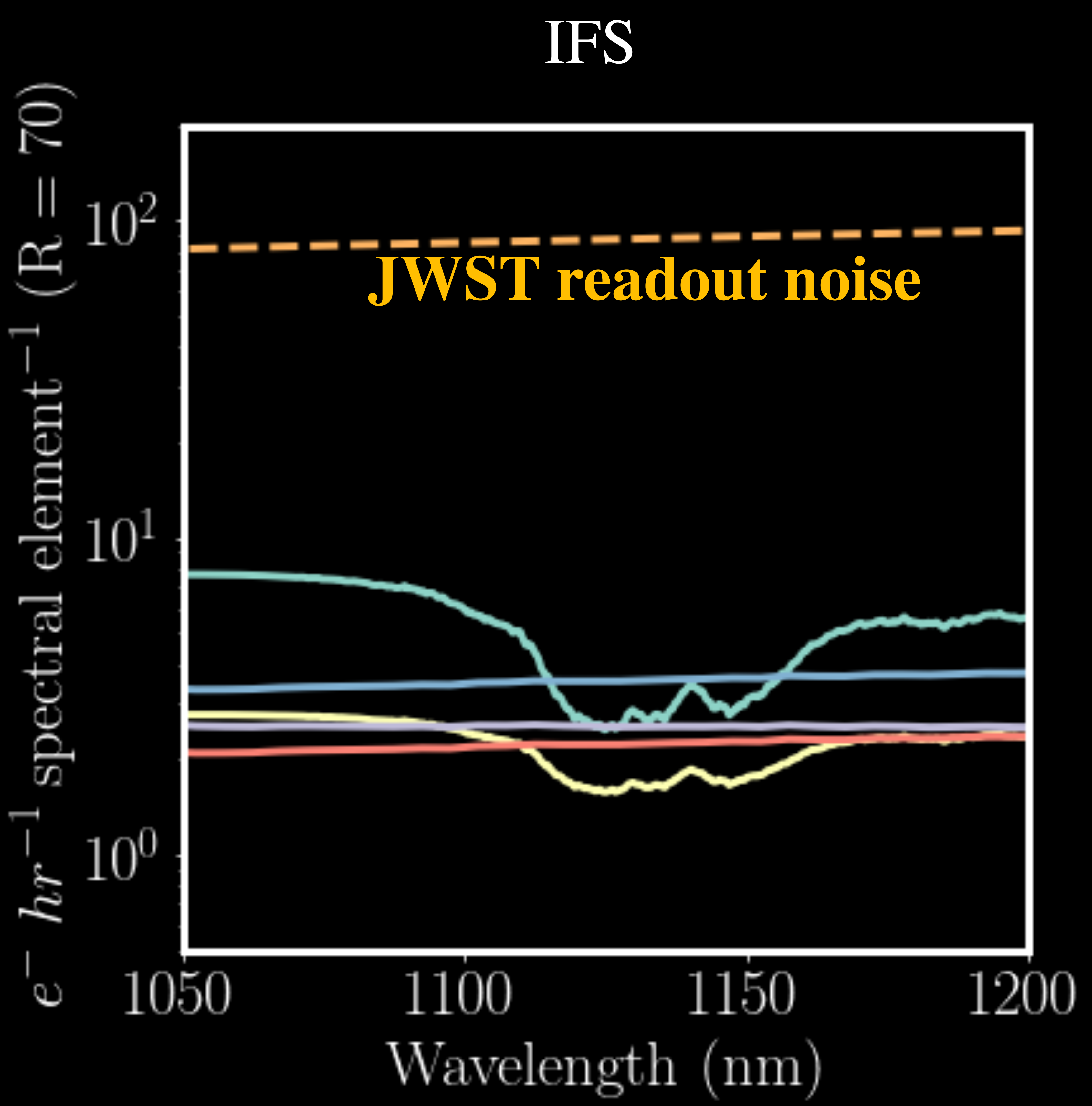
near-IR: the results depend on the instrument parameters



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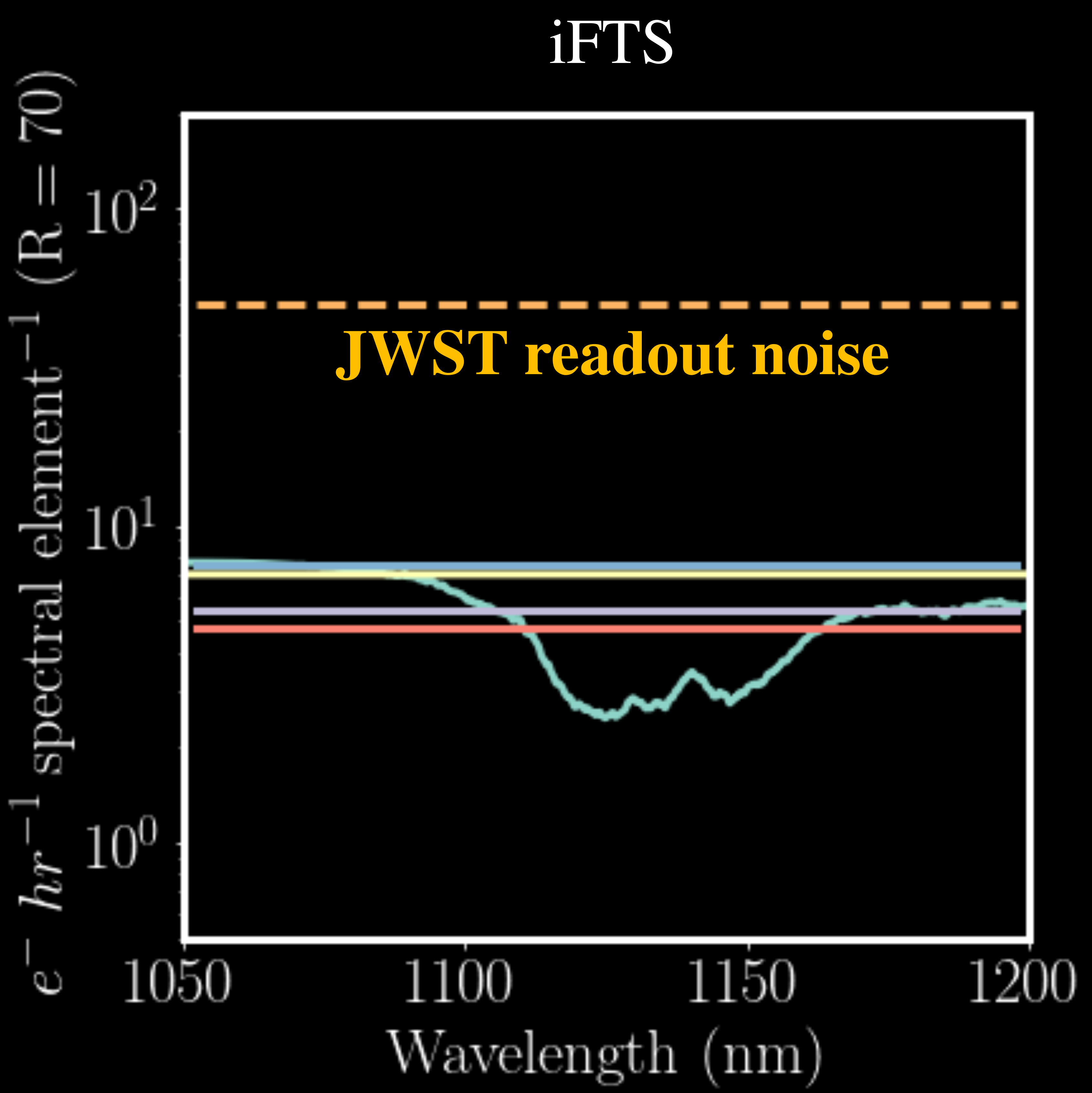

near-IR: required exposure time to achieve SNR of 5

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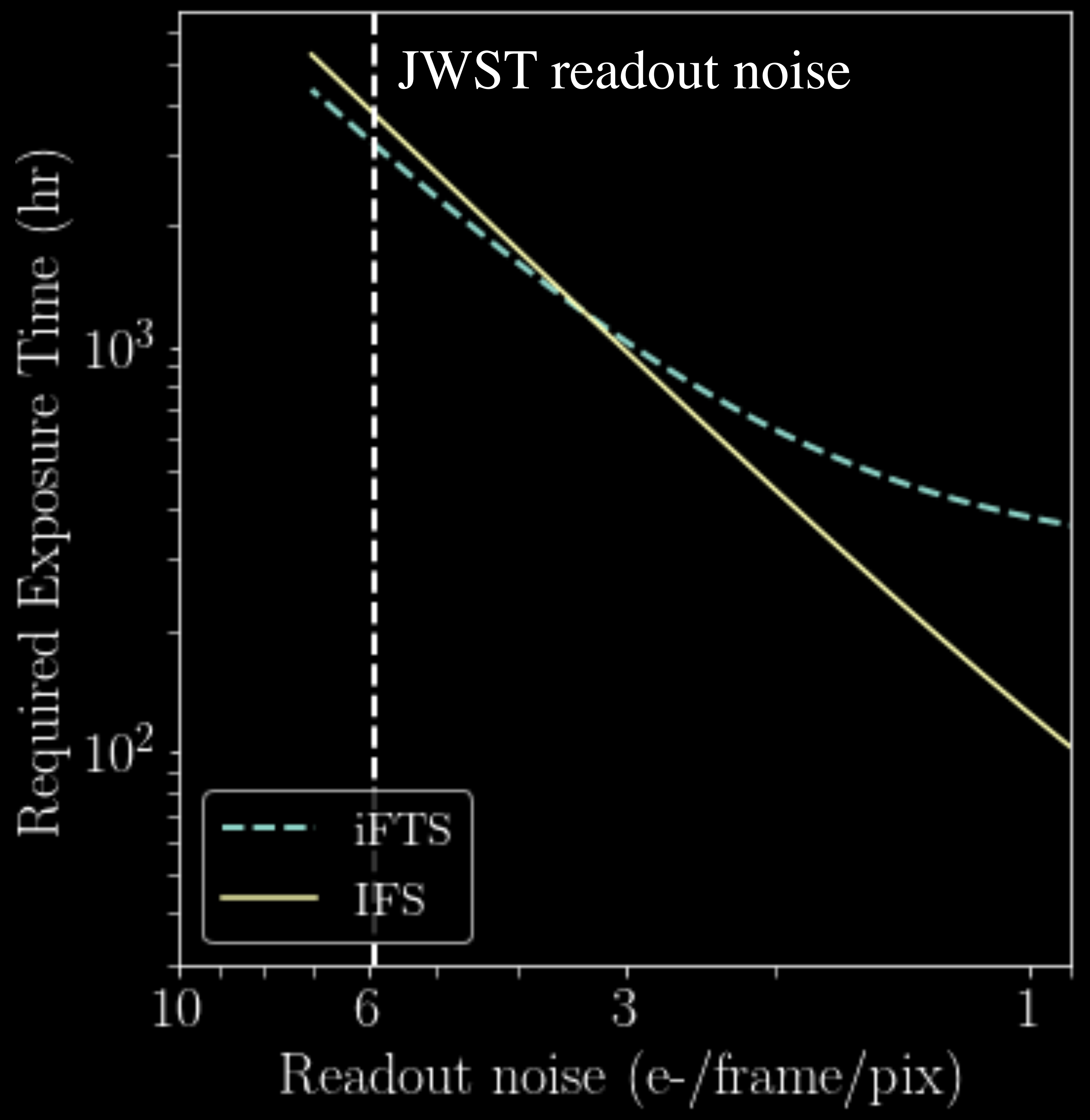

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Conclusion

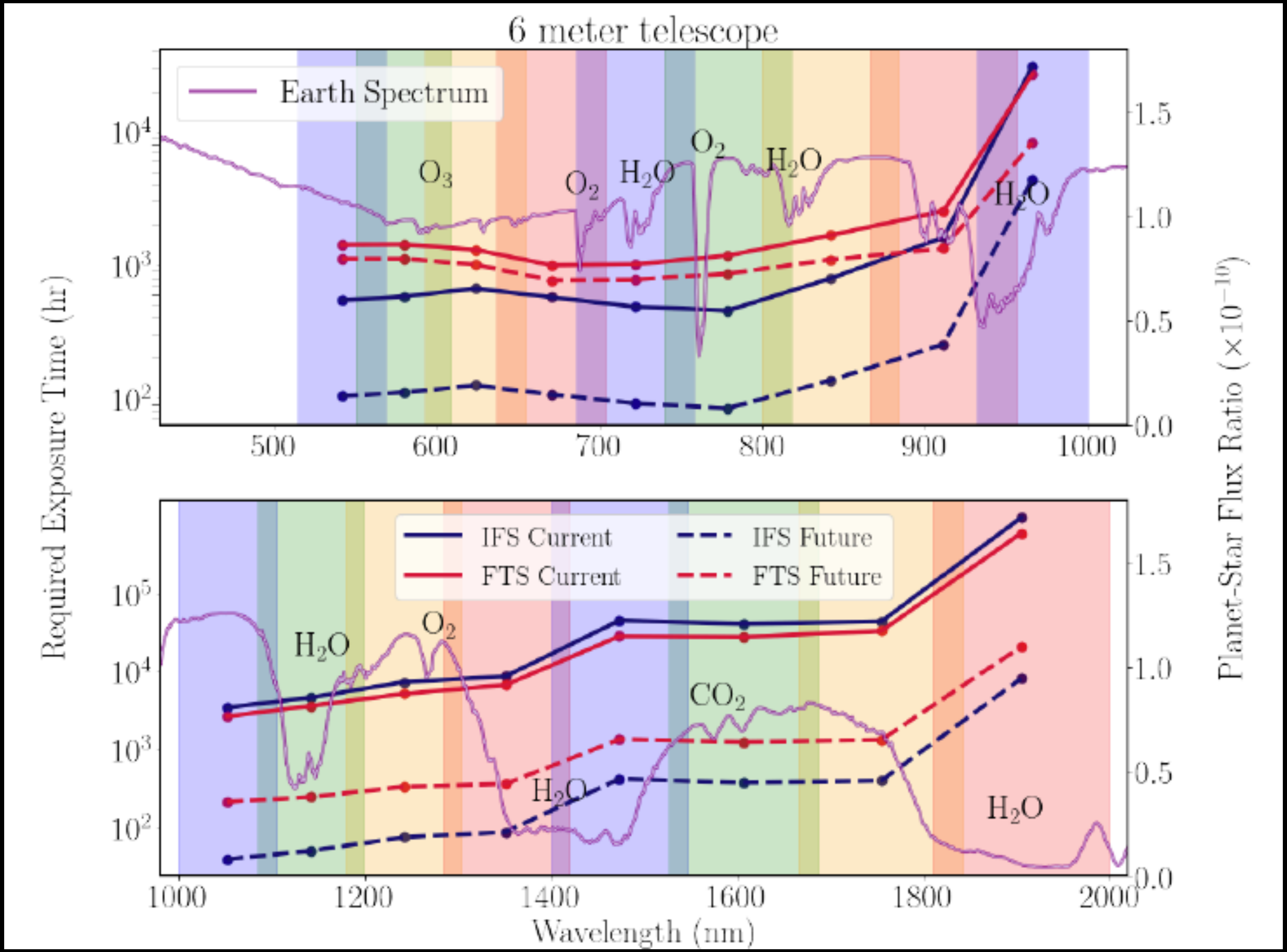
1. In Optical, an iFTS is limited by photon noise
2. In near-IR, an iFTS remains a promising option, determined by the detector noise.
3. Our simulation highlights the need for better detectors.

Thanks!

Back Up

required exposure time to achieve SNR of 5 in different filters

Target: an Earth analog from 10 pc



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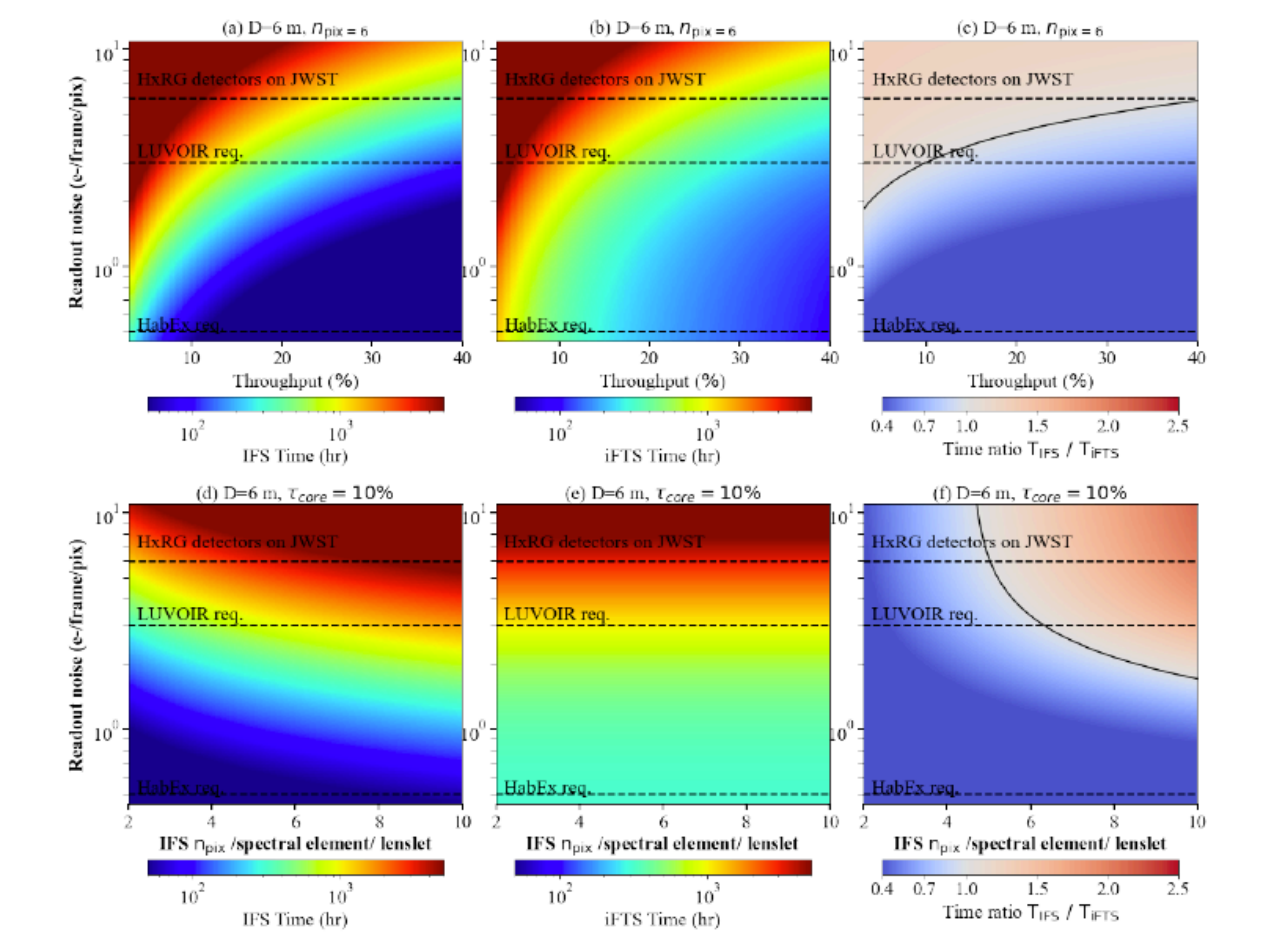
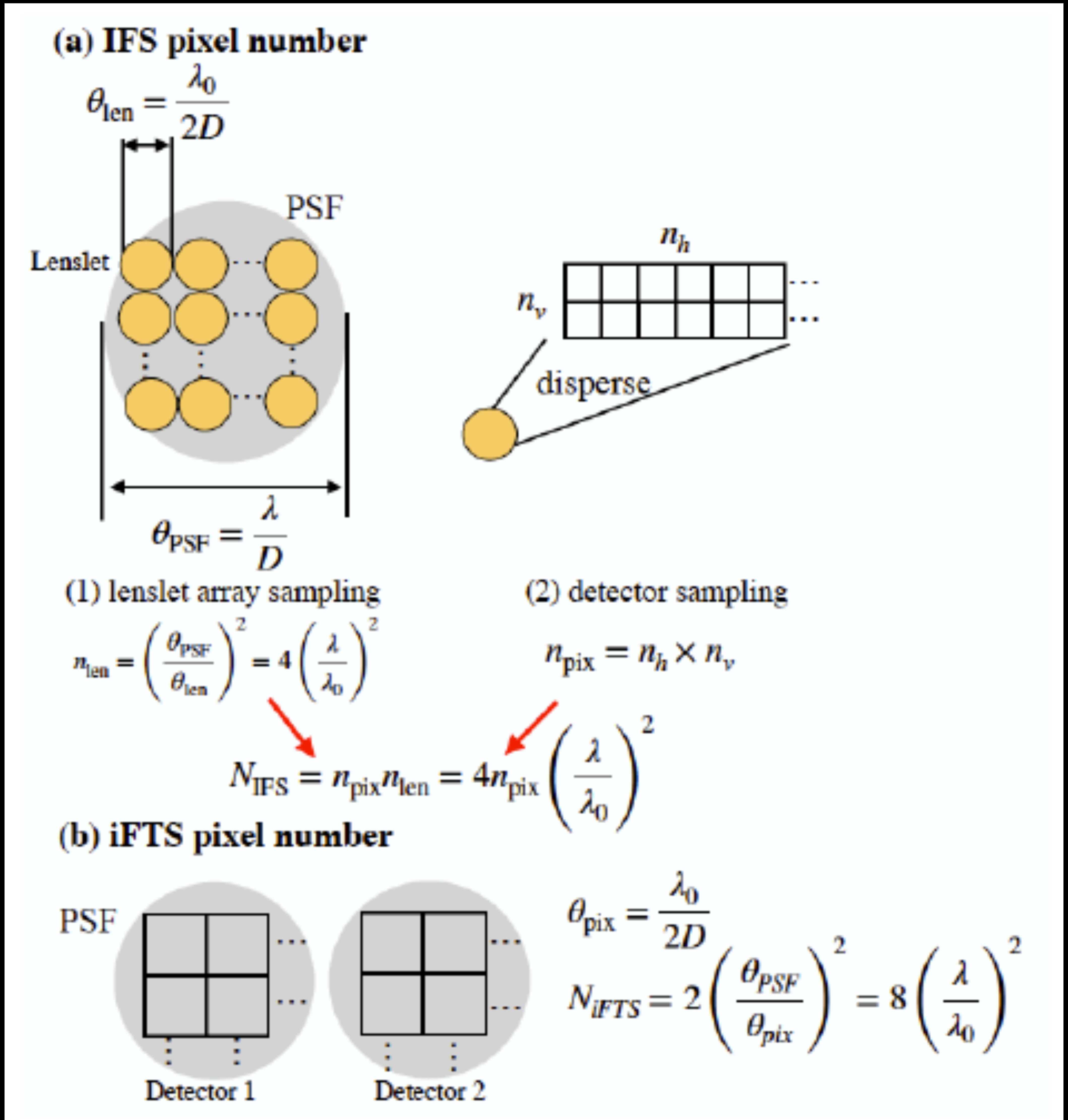


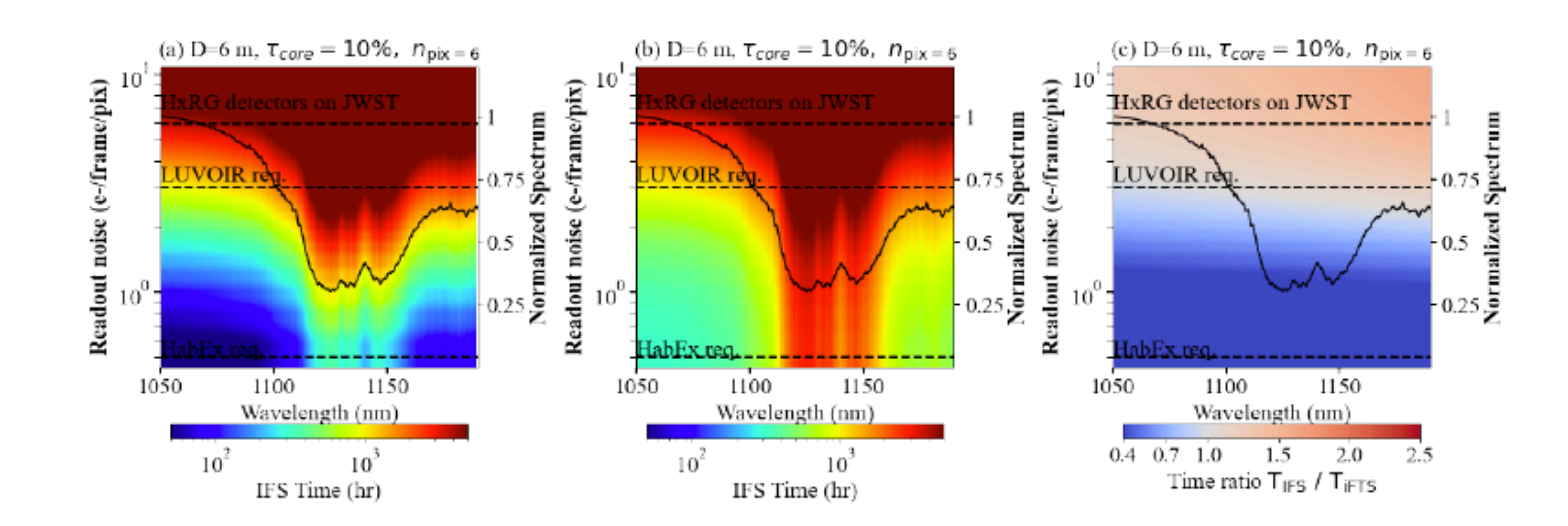
(a) D=6 m, $n_{pix} = 6$
(b) D=6 m, $n_{pix} = 6$
(c) D=6 m, $n_{pix} = 6$
HxRG detectors on JWST
LUVOIR req.
HabEx req.
Readout noise (e-/frame/pix)
Throughput (%)
IFS Time (hr)
iFTS Time (hr)
Time ratio T_{IFS} / T_{iFTS}
(d) D=6 m, τ_{core} = 10%
(e) D=6 m, τ_{core} = 10%
(f) D=6 m, τ_{core} = 10%
IFS n_{pix} /spectral element/ lenslet

Backup!



(a) IFS pixel number
$\theta_{\mathrm{len}} = \frac{\lambda_0}{2D}$
PSF
Lenslet
n_h
n_v
disperse
$\theta_{\mathrm{PSF}} = \frac{\lambda}{D}$
(1) lenslet array sampling
$n_{\mathrm{len}} = \left(\frac{\theta_{\mathrm{PSF}}}{\theta_{\mathrm{len}}}\right)^2 = 4\left(\frac{\lambda}{\lambda_0}\right)^2$
(2) detector sampling
$n_{\mathrm{pix}} = n_h \times n_v$
$N_{\mathrm{IFS}} = n_{\mathrm{pix}} n_{\mathrm{len}} = 4 n_{\mathrm{pix}} \left(\frac{\lambda}{\lambda_0}\right)^2$
(b) iFTS pixel number
PSF
Detector 1
Detector 2
$\theta_{pix} = \frac{\lambda_0}{2D}$
$N_{iFTS} = 2\left(\frac{\theta_{PSF}}{\theta_{pix}}\right)^2 = 8\left(\frac{\lambda}{\lambda_0}\right)^2$

Backup!



(a) D=6 m, τ_{core} = 10%, $n_{pix=6}$
(b) D=6 m, τ_{core} = 10%, $n_{pix=6}$
(c) D=6 m, τ_{core} = 10%, $n_{pix=6}$
HxRG detectors on JWST
LUVOIR req.
HabEx req.
Readout noise (e-/frame/pix)
Normalized Spectrum
Wavelength (nm)
IFS Time (hr)
Time ratio T_{IFS} / T_{iFTS}

Instrument Parameters

Diameter

6 m

Throughput

$\tau_{tot} = \tau_{optical} * \tau_{coronagraph} * \tau_{QE}$

Resolution

VIS: 140, NIR:70

Detector Noise

1. Current level:
ROMAN and JWST
2. Future level:
HabEx and LUVOIR

iFTS Vs. IFS

$$\frac{T_{IFS}}{T_{FTS}} = \frac{[(c_p + 2c_b)\Delta\lambda + 2c_d N_{pix}]}{2[\int(c_p + 2c_b)d\lambda + 2c_d N'_{pix}]}$$

Photon Noise **Detector Noise**

iFTS Vs. IFS

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Photon Noise

Detector Noise