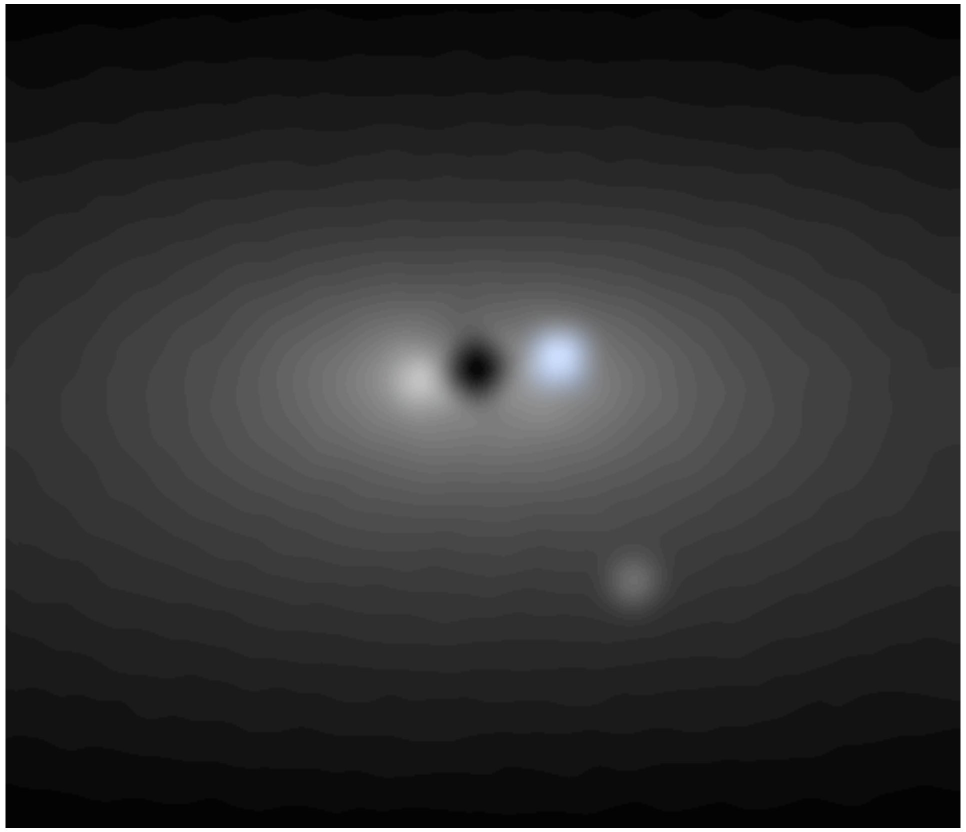
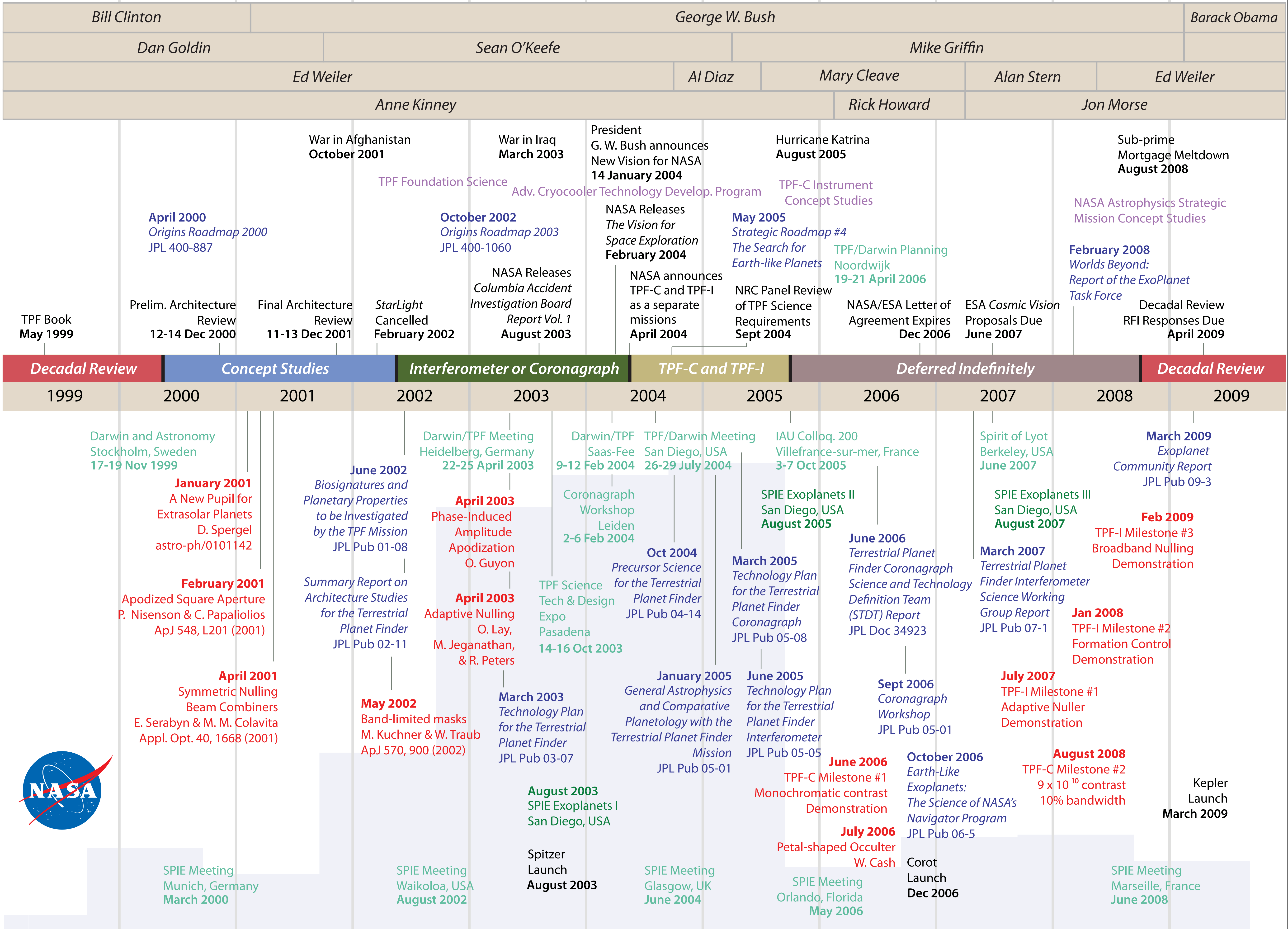
A Starshade for JWST: Science Goals and Optimization

Rémi Soummer (STScI)
November 12th, 2009

and the New Worlds Probe team
W.Cash et al.





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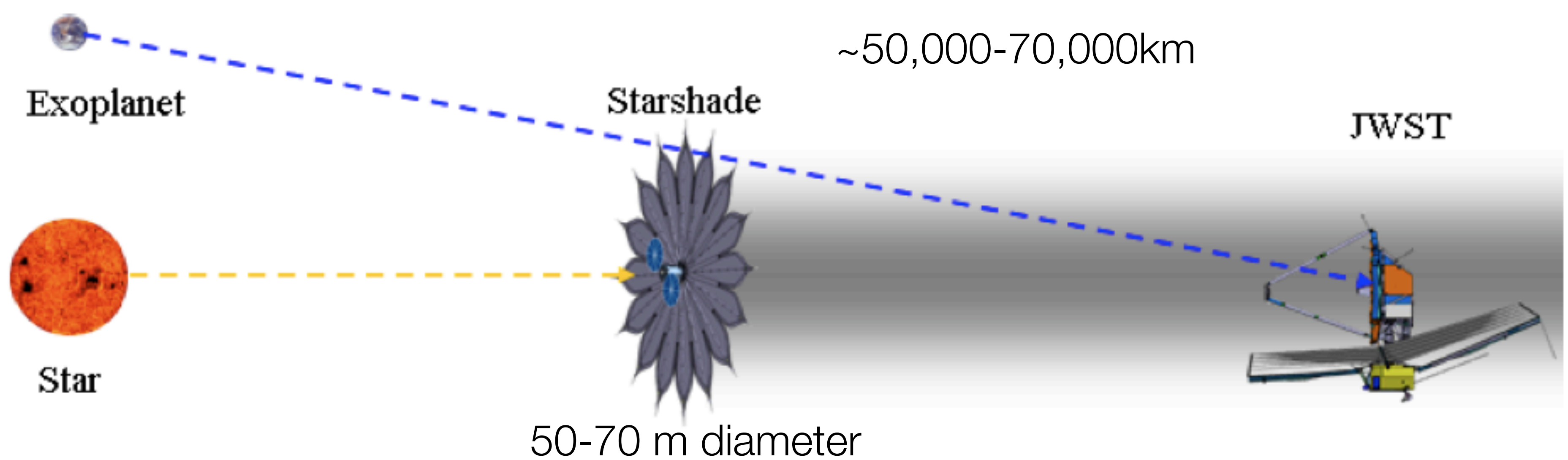
Peter R. Lawson 30 July 2009

Thursday, November 12, 2009

Context

- Terrestrial Planet Finder
- NASA is interested in new strategies consistent with current budget
  - Mission concept studies
  - Exoplanet Community Report
  - Possibility of a “medium-class” mission (~$700M)
- Discovery proposal 3 years ago (Cash et al.)
- Medium mission
  - “small coronagraph” e.g. PECO 1.4 m
  - occulter possible if host telescope available
  - small interferometer e.g. FKSI

New Worlds Probe (NWP) Concept



- Science capabilities given JWST instruments (what can we detect? biomarkers?)
- Observing time, available stars, Field of Regard, DRM
- Operations (alignment, planning & scheduling, target acquisition, overheads)
- Starshade itself

External Occulters: early ideas

- Lyman Spitzer, in American Scientist 1962
  - *"This method involves the use of a large occulting disk far in front of the telescope to reduce the light from the star."*
  - *"In the same way that the diffracted light from a telescope mirror can be reduced by a smooth reduction of the reflectivity towards zero at the edge, the shadow behind an occulting disk can be made much blacker if the transparency of the disk varies smoothly at the edge of the disk rather than abruptly; a reduction of intensity within the shadow by an order of magnitude was achieved with the use of an occulting disk edged with sharp spikes".*

External Occulters: early ideas

- Gordon Woodcock 1974

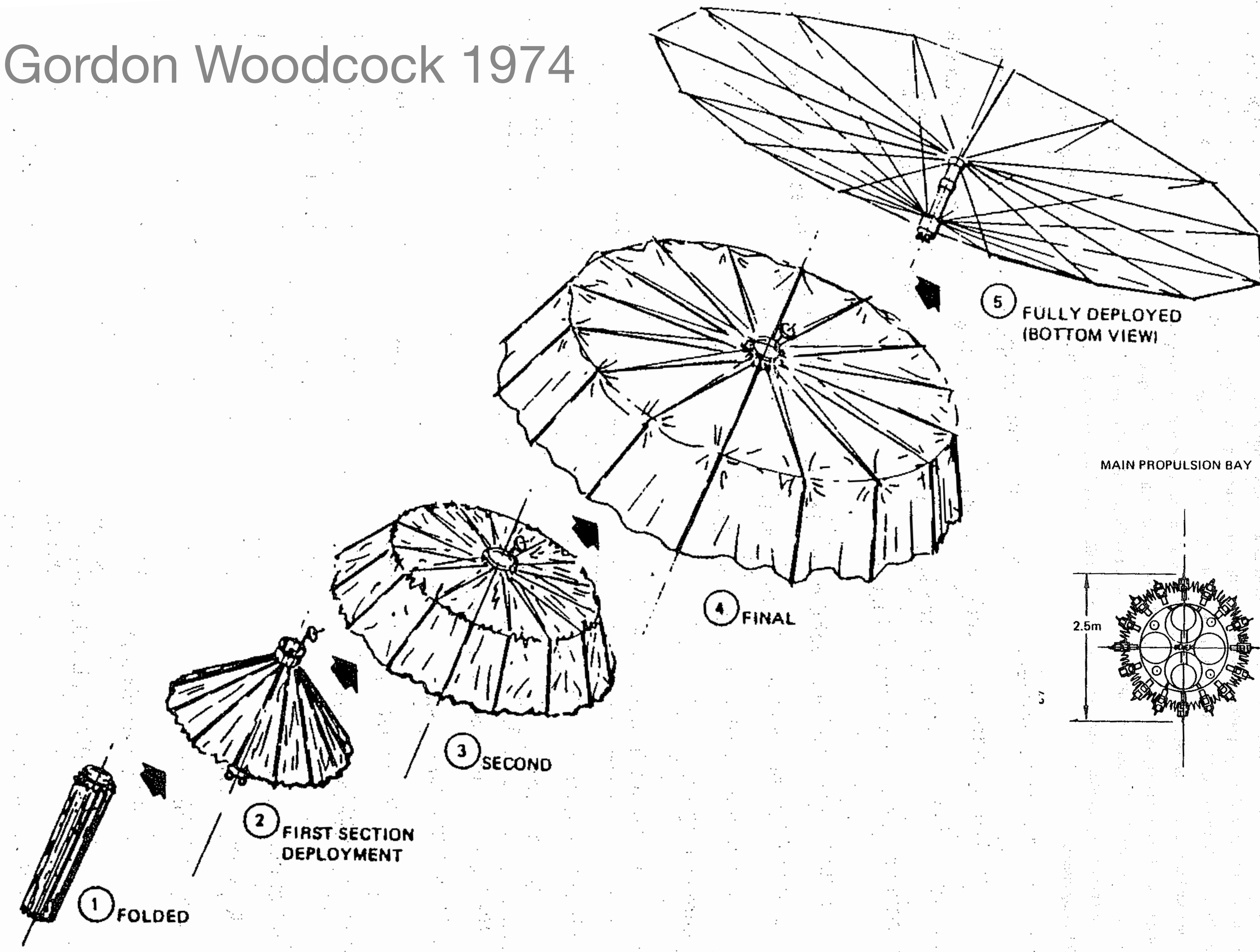


Figure D-6: Occulting Disk Spacecraft Deployment of 50-m Disk

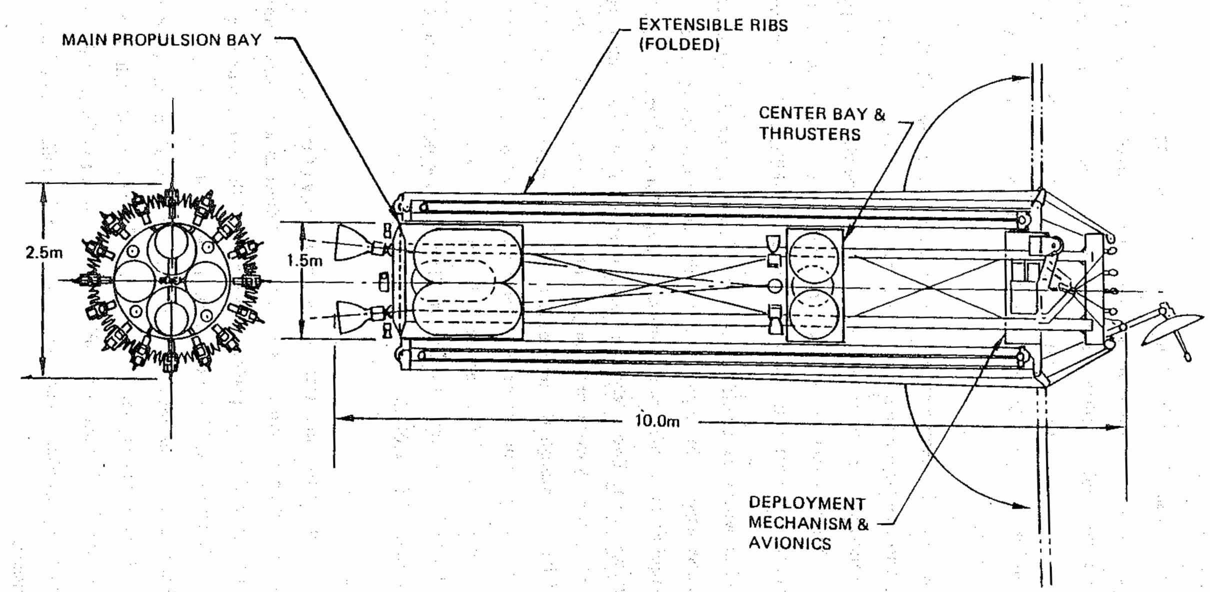


Figure D-5: Occulting Disk Spacecraft Folded for Transportation

External Occulters: early ideas

Acta Astronautica Vol. 12, No. 3, pp. 195–201, 1985
Printed in Great Britain.

0094-5765/85 $3.00 + .00
Pergamon Press Ltd.

CONCEPT OF A SPACE TELESCOPE ABLE TO SEE THE PLANETS AND EVEN THE SATELLITES AROUND THE NEAREST STARS†

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(*Received* 19 *January* 1984; *in revised form* 13 *June* 1984)

Abstract—The Space Telescope will be launched in 1986 and will improve considerably our observational possibilities, but not the visibility of outer planetary systems.

The solar system as seen from Alpha Centauri is presented, as well as the nearest stars and the main cameras of the Space Telescope.

As a possible improvement the action of a distant and star-shaped screen is described; that screen is 100 to 800 meters and placed 10^5 to 10^6 km in front of the telescope: it allows one to avoid the dazzling effect of the stars and to look for planets such as Jupiter and Saturn up to 20 to 40 light-years. Such planets as Earth and Venus are a little less visible.

The visibility of satellites such as the Moon is discussed: it remains at the limit of our technical possibilities.

This conceptual paper does not consider in detail the technical difficulties involved.

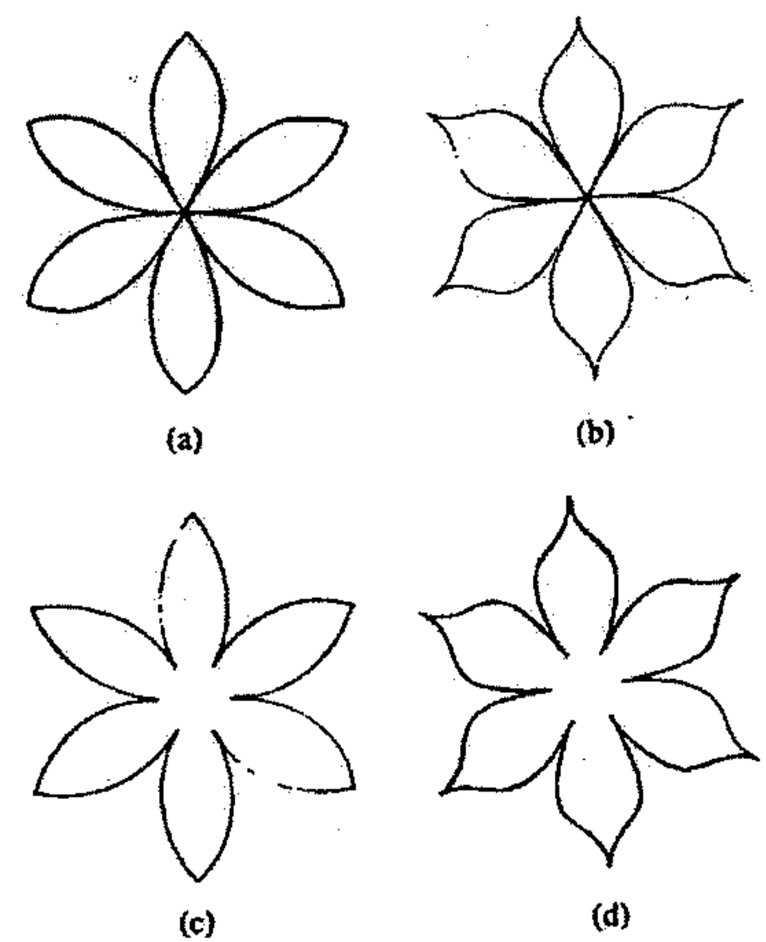


Fig. 4. The shape of some possible screens for various ψ functions. (a) $\psi = \psi_2$. (b) $\psi = \psi_3$. (c) $\psi = \psi_4$. (d) $\psi = \psi_5$.

External Occulters

Shadow is not optimum, spot of Arago-Poisson

Much better shadow

Star shaped occulter (approximation of the continuous apodization)

Umbras

Boss

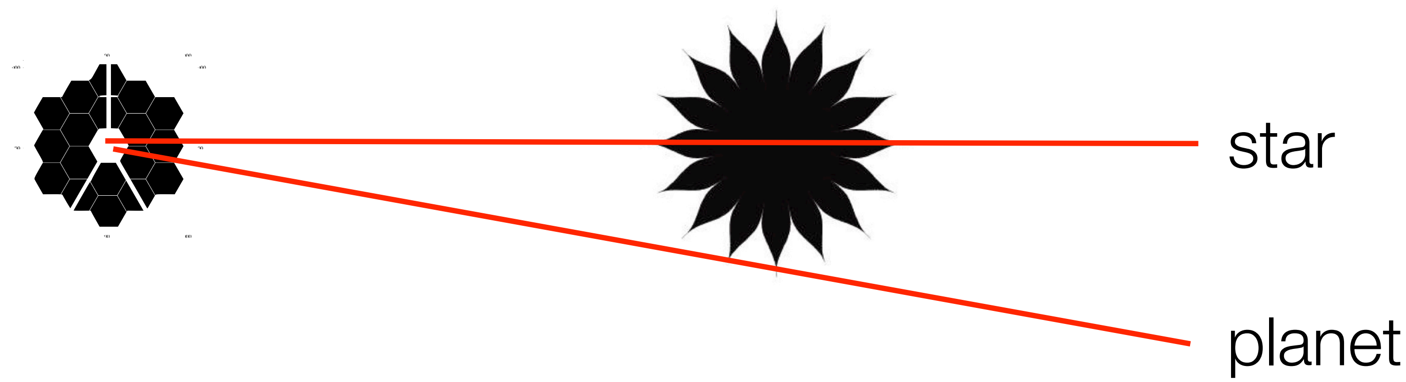
2000~2002

Web Cash: analytical functions, e.g. ‘hypergaussian’

Bob Vanderbei: optimal numerical solutions

Parameters for the Starshade

- Define a geometric inner working angle (IWA)
  - IWA ~ D/z



  - Shadow properties (Fresnel propagation) ~ $D^2/\lambda z$
- there is a minimum distance & size for a given set of IWA, contrast, bandwidth and other constraints.
- occulter diameter (and distance) increase with
  - decreasing IWA
  - telescope diameter
  - bandwidth (easier on the blue side than red side)
  - contrast

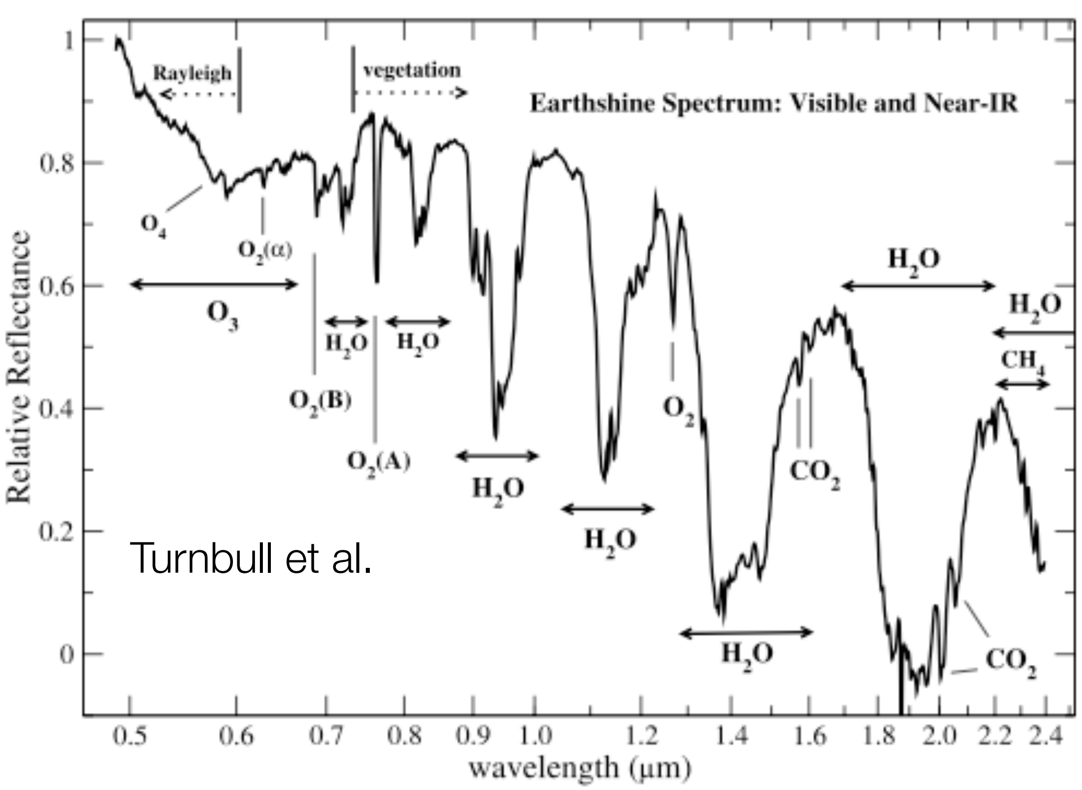
James Webb Space Telescope

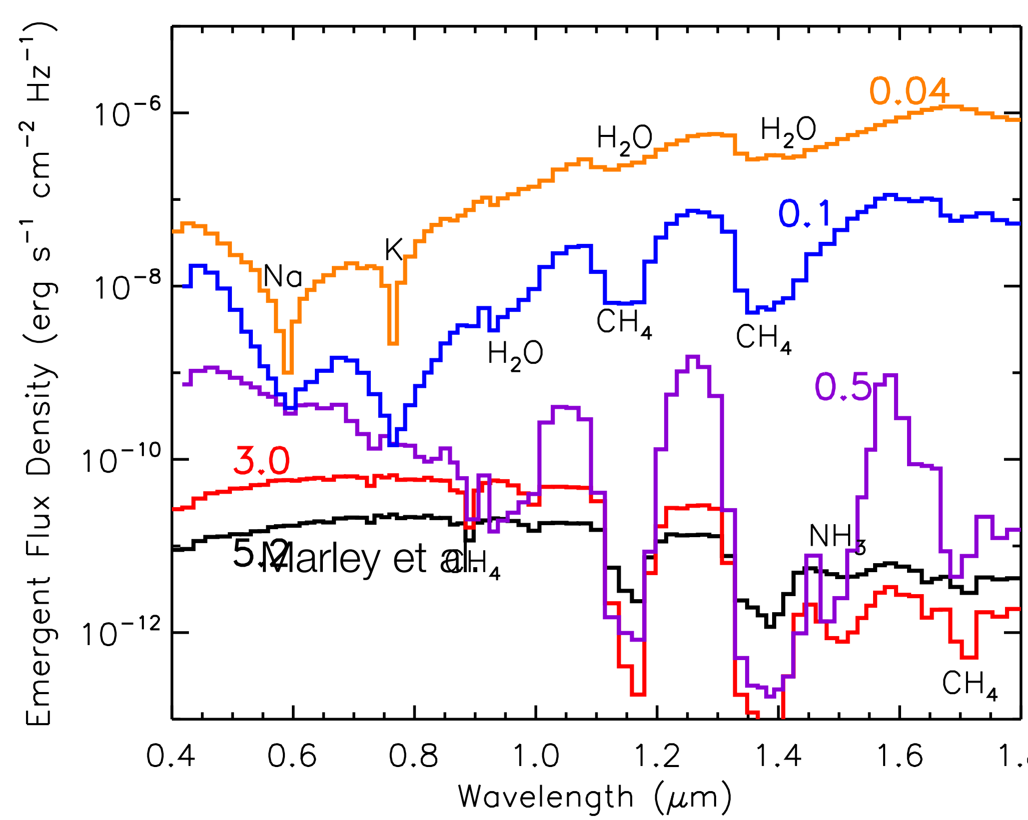
- Observatory
  - 6.5 m, segmented
  - modest optical quality (diffraction limited at 2 microns, SR=80%)
  - Imaging and spectroscopy from 0.6 to 25 microns
- Near Infrared Camera (NIRCam)
  - 2 instruments: short arm (0.6-2.3 μm) and long arm (2.4-5.0 μm)
  - several filters, broadband and medium band
- Near Infrared Spectrograph (NIRSpec)
  - 0.6-5.0 μm, R=40-100 (prism) and R=1000

- Mid Infrared Imager (MIRI)
- Tunable Filter Imager (TFI)

NWP: Science Goals Summary

- Can we design an occulter to image and characterize and Earth-like planet?
  - contrast goal 1e-10
  - characterize habitability & possible biomarkers, near infrared: O_2, H_2O, CO_2, CH_4
  - possibility of thermal emission as well? (radius and temperature)
- Characterization of giant planets is interesting in the near infrared
- Imaging & Spectroscopy from 0.6 to 1.7 µm covers large science program





NWP: Science Goals Summary

- 1) Find and characterize planetary systems including terrestrial planets in the habitable zone
  - 20 - 30 nearby extrasolar systems can be observed and mapped
  - If η_{earth} is >0.5, there is a high probability of observing ~5 terrestrial planets
  - With ~3 revisits each, we can characterize their atmospheres, and establish the terrestrial planet's habitable zone residency. Rotation? Biomarkers? Oxygen?
- 2) Characterize known RV planets (Jupiters, Neptune, super Earths)
  - Mass: disentangle m *sin(*i) with inclination measurement
  - Atmospheric composition, gravity, temperature & radius if emitted light can be measured
- 3) Determine brightness and structures of exozodiacal disks.

NWP Can Perform a Variety of Exoplanet Science

Large-separation RV planets

Planet Name	M sin(i)	period	sma	excentricity	separation	contrast
Epsilon Eridani b	1.6	2502	3.4	0.70	1.059	2.97E-09
GJ 832 b	0.6	3416	3.4	0.12	0.688	2.95E-09
55 Cnc d	3.8	5218	5.8	0.03	0.443	1.02E-09
HD 160691 c	3.1	2986	4.2	0.57	0.273	1.96E-09
Gj 849 b	0.8	1890	2.4	0.06	0.267	6.17E-09
HD 190360 b	1.5	2891	3.9	0.36	0.247	2.22E-09
47 Uma c	0.5	2190	3.4	0.22	0.243	2.97E-09
HD 154345 b	0.9	3340	4.2	0.04	0.232	1.94E-09
Ups And d	4.0	1275	2.5	0.24	0.186	5.41E-09
HD 62509 b	2.9	590	1.7	0.02	0.163	1.19E-08
HD 39091 b	10.4	2064	3.3	0.62	0.160	3.15E-09
14 Her b	4.6	1773	2.8	0.37	0.153	4.44E-09
47 Uma b	2.6	1083	2.1	0.05	0.151	7.66E-09
Gamma Cephei b	1.6	903	2.0	0.12	0.148	8.16E-09
HD 217107 c	2.5	4210	5.3	0.52	0.142	1.23E-09
HD 89307 b	2.7	3090	4.2	0.27	0.126	1.98E-09
HD 10647 b	0.9	1040	2.1	0.18	0.121	7.73E-09
HD 117207 b	2.1	2627	3.8	0.16	0.115	2.39E-09
HD 181433 d	0.5	2172	3.0	0.48	0.115	3.79E-09
HD 70642 b	2.0	2231	3.3	0.10	0.114	3.13E-09
HD 128311 c	3.2	919	1.8	0.17	0.106	1.10E-08
GJ 317 b	1.2	693	1.0	0.19	0.104	3.78E-08
HD 216437 b	2.1	1294	2.7	0.34	0.102	4.68E-09

NWP: Imaging

- Imaging capabilities with NIRCam
  - Several Broadband filters and medium band filters
  - SNR=10 detection of Earth at 10pc (solar-system zodiacal disk) in:
    - *23 hours with F070W*
    - *7.3 hours with F090W*
    - *5.8 hours with F115W*
    - *11 hours with F200W*
  - Super Earth (5 Earth-mass, same density & albedo)
    - *2.7 hours with F070W*
    - *0.85 hours with F090W*
    - *0.7 hours with F115W*
    - *1.3 hours with F200W*
  - Emitted light detection at 4-5 microns (with relaxed IWA 200-250 mas and closer occulter - If thermal emission from occulter is acceptable)

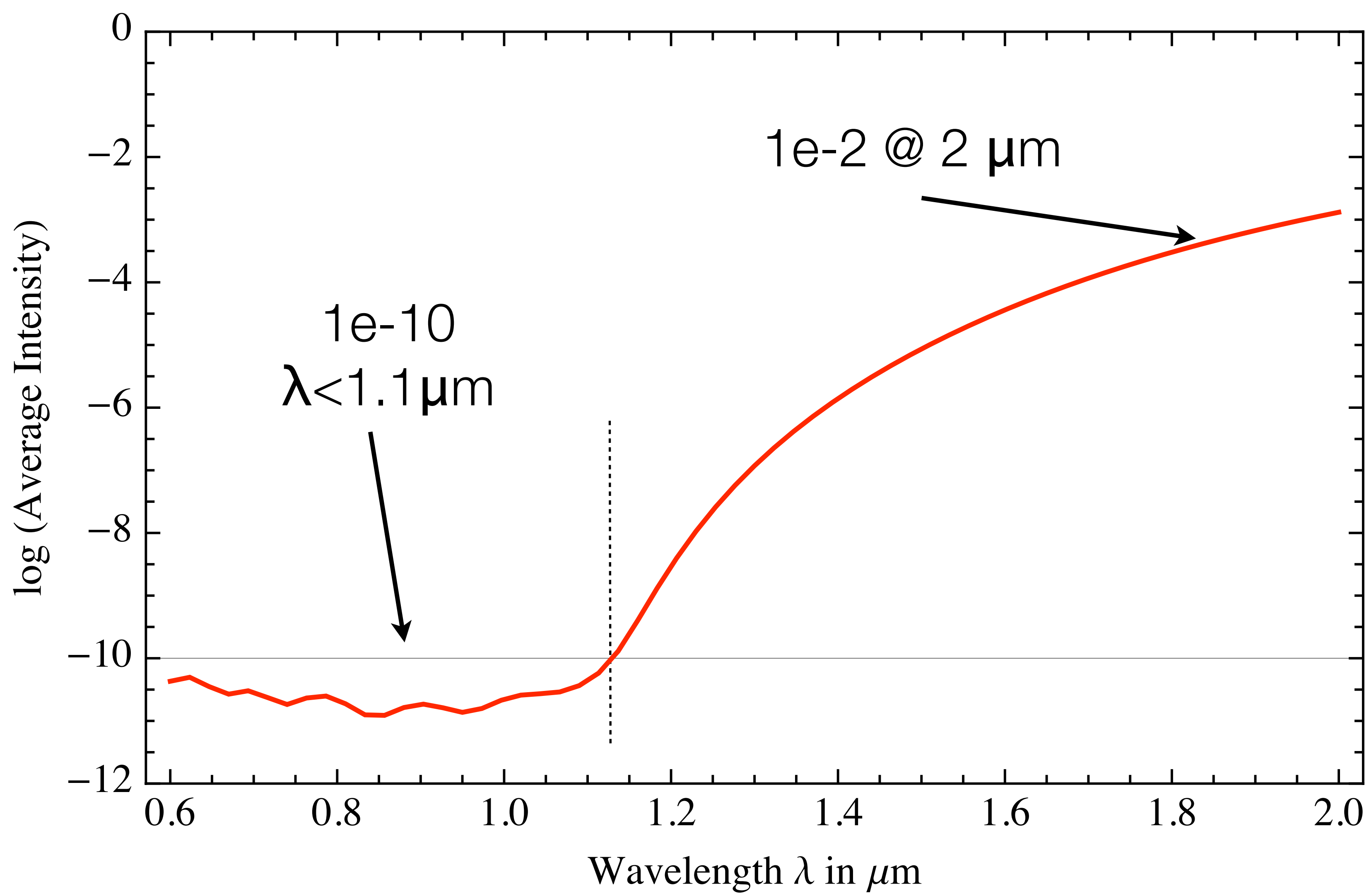
NWP: Spectroscopy

- Spectroscopic capabilities with NIRSpec
  - Use a target acquisition filter to reduce detector sensitivity range.
    - *F140W (0.8-2.0 μm) most interesting for science*
    - *F110W (1.0-1.2 μm) for small starshade*

  - SNR=5 *spectrum* of Earth at 10pc (solar-system zodiacal disk) in:
    - *$3x10^5$ between 1.0 and 1.7 micron*
    - *$1.3x10^6$ below 1.0 micron*
    - *resolution R=30-50*
  - SNR=5 *spectrum* of Super-Earth at 10pc ($5M_E$, solar-system zodiacal disk) in:
    - *$4x10^4$ between 1.0 and 1.7 micron*
  - Super Earth O_2 detection in *10^6+ s at R~100 with grating*
  - *Giant planet R=1000 spectrum in $5x10^5$ to 10^6s*
  - *R=2700 possible on bright young giants?*

Red Leak

- NIRCam's detector is sensitive up to 2.5 µm
  - smaller range but imaging
- NIRSpec's detector is sensitive up to 5.0 µm, filter substrate up to 2.7 µm
  - larger range but dispersed *spectrum*

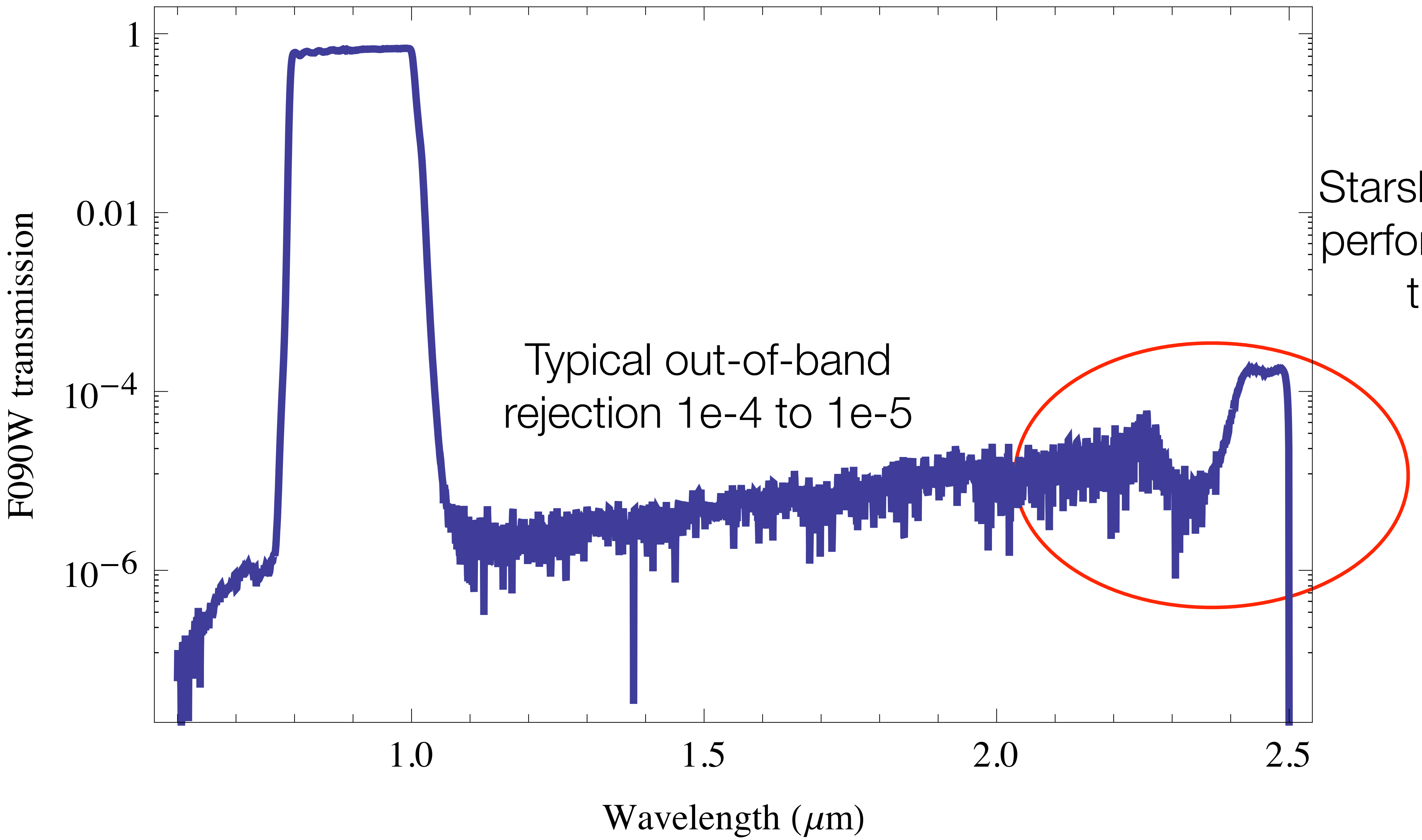


Available filters

- NIRSpec “Target Acquisition” filters
  - F140X : 0.8 µm < λ < 2.0 µm
  - F110W: 1.0 µm < λ < 1.2 µm
    - *F140X has a red bump of about 7-8% at ~3 micron*
- NIRCam filters
  - F070W, F090W, F115W, F150W
- Baseline design:
  - 0.6/0.8 to 2.0 micron (overlap NIRcam & NIRSpec range)
  - core science up to 1.7/1.8 µm (relax contrast beyond)
  - constraints at 2.5 µm & 5.0 µm for NIRcam & NIRSpec

Starshade optimization

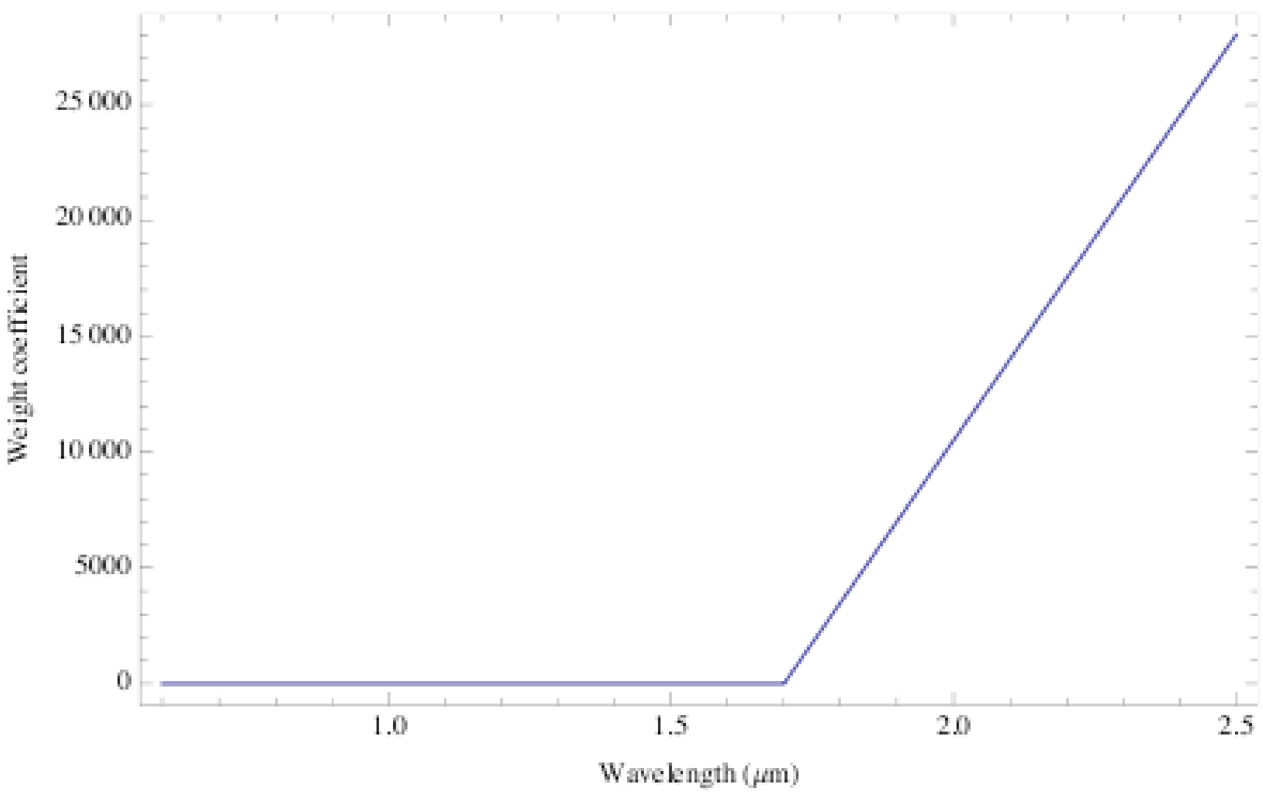
- Example of NIRCam filter F090W + detector + dichroic
  - similar transmissions for other filters (not final parts)

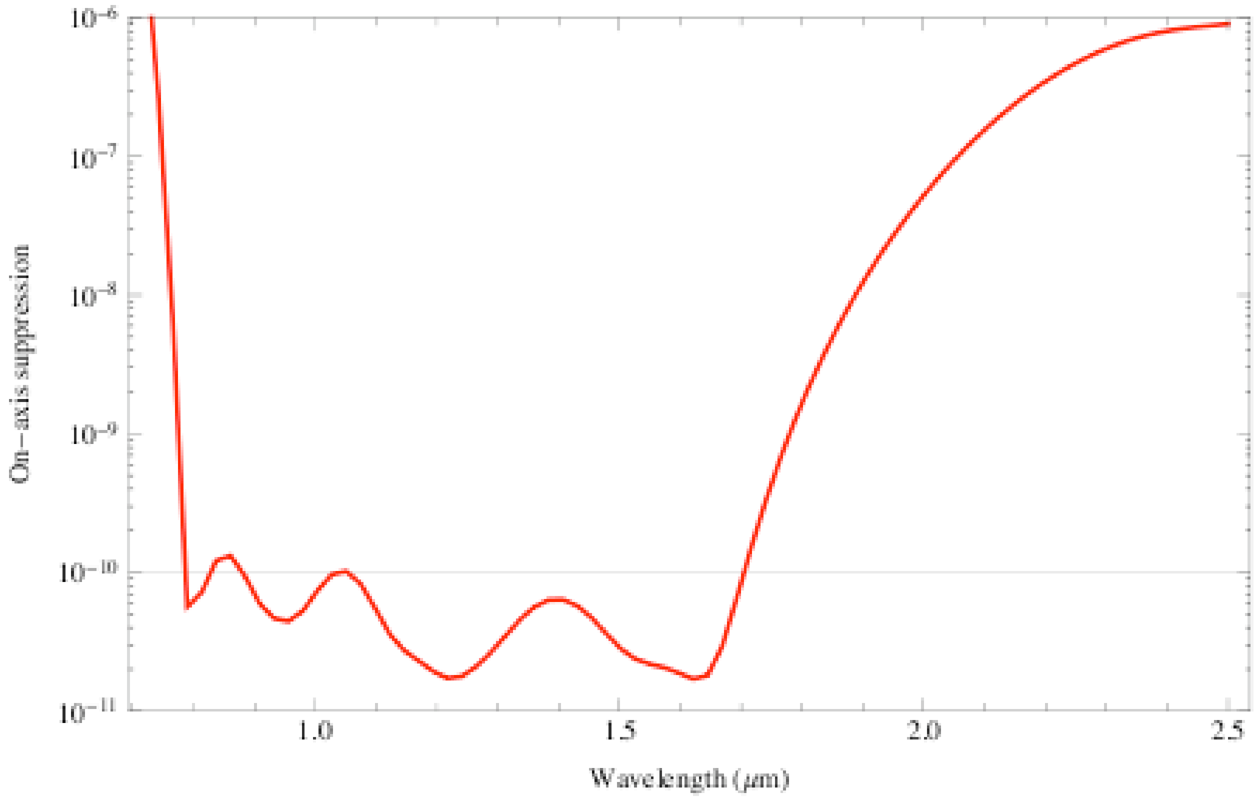


Starshade needs to perform at ~1e-6 in this region

Starshade optimization

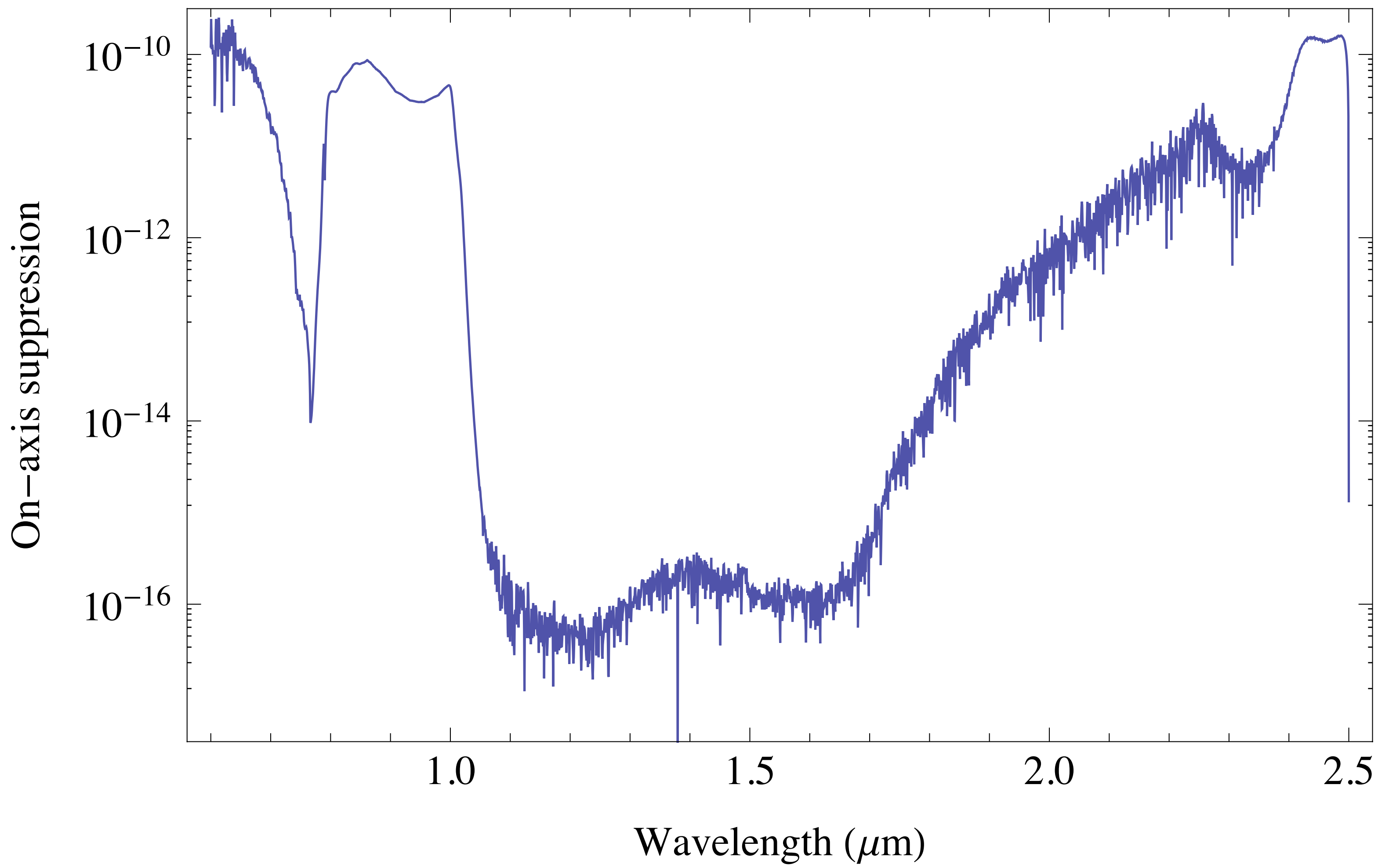
- weighted optimization
    - NIRcam constraint at 2.5 micron (overall suppression of 1e-10
    - Contrast relaxed beyond 1.7 µm (science) up to 1e-6 at 2.5 µm (red leak)





Starshade optimization

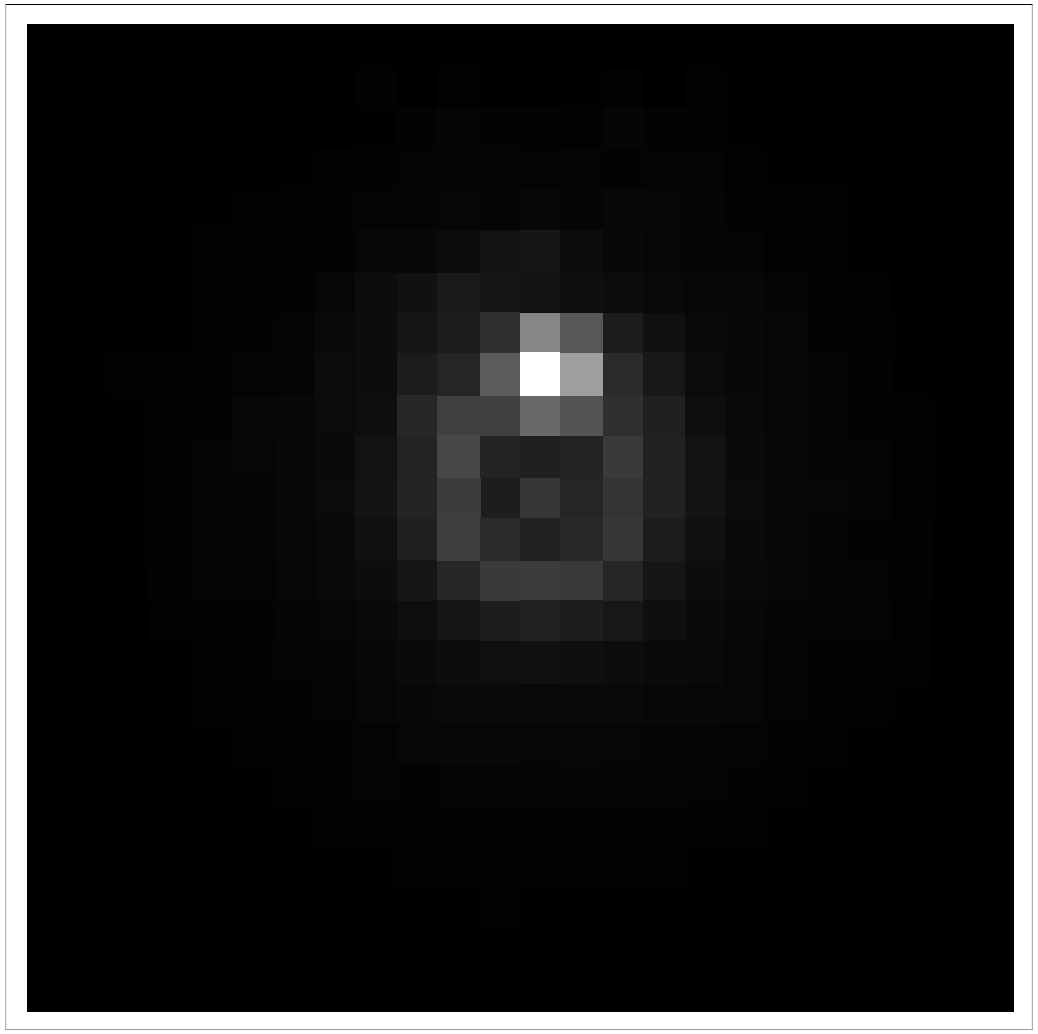
- Overall on-axis transmission including starshade + OTE + detector + dichroic + actual filter
- The contribution form the star leakage is negligible in the error budget (perfect starshade)



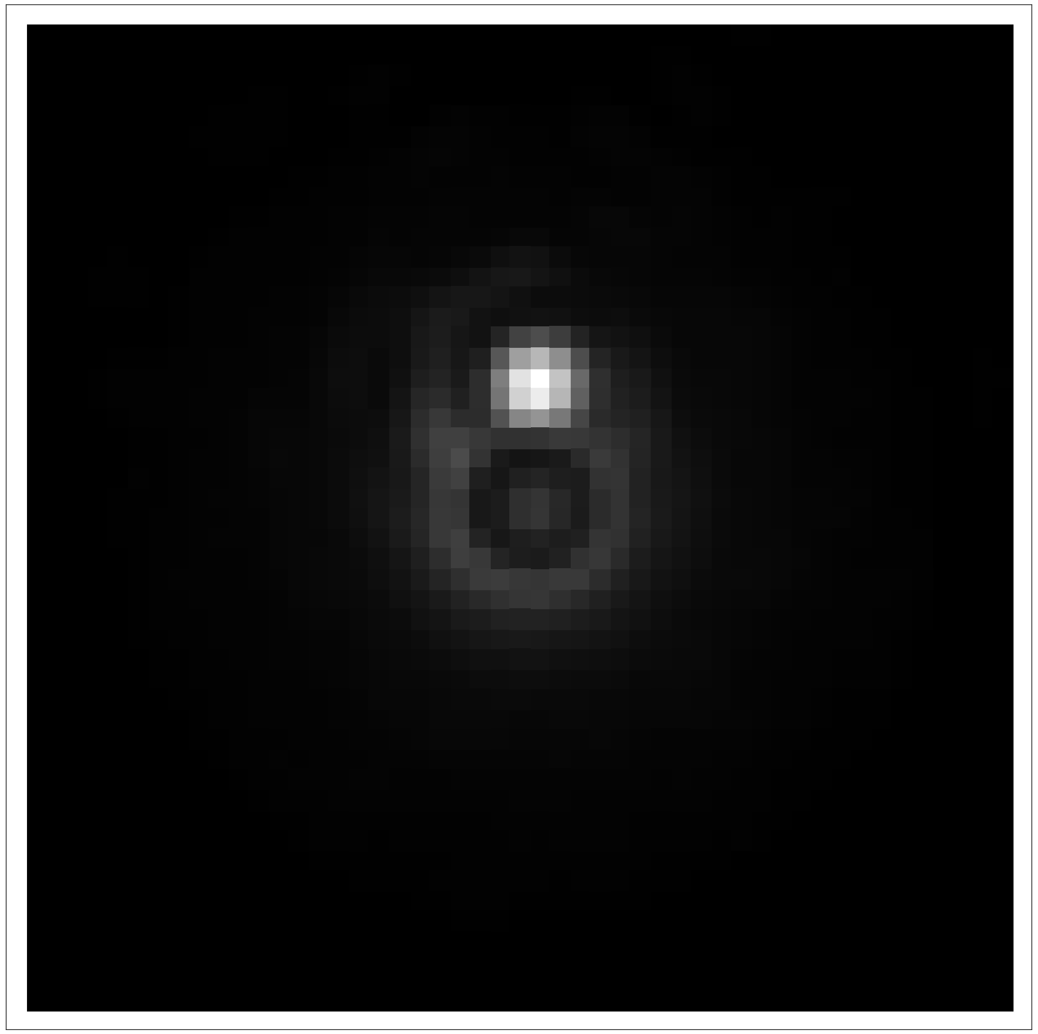
NWP Simulated Solar System Detection

- Sun-Earth at 10pc with zodiacal disk
  - Simulation for F090W for a 7h exposure
  - Includes perfect starshade 70m (tip-tip) at 72193km
  - Actual F090W transmission + starshade leak up to 2.5 µm

Earth at 10 pc, NIRCam F090W, ExpTime=7h

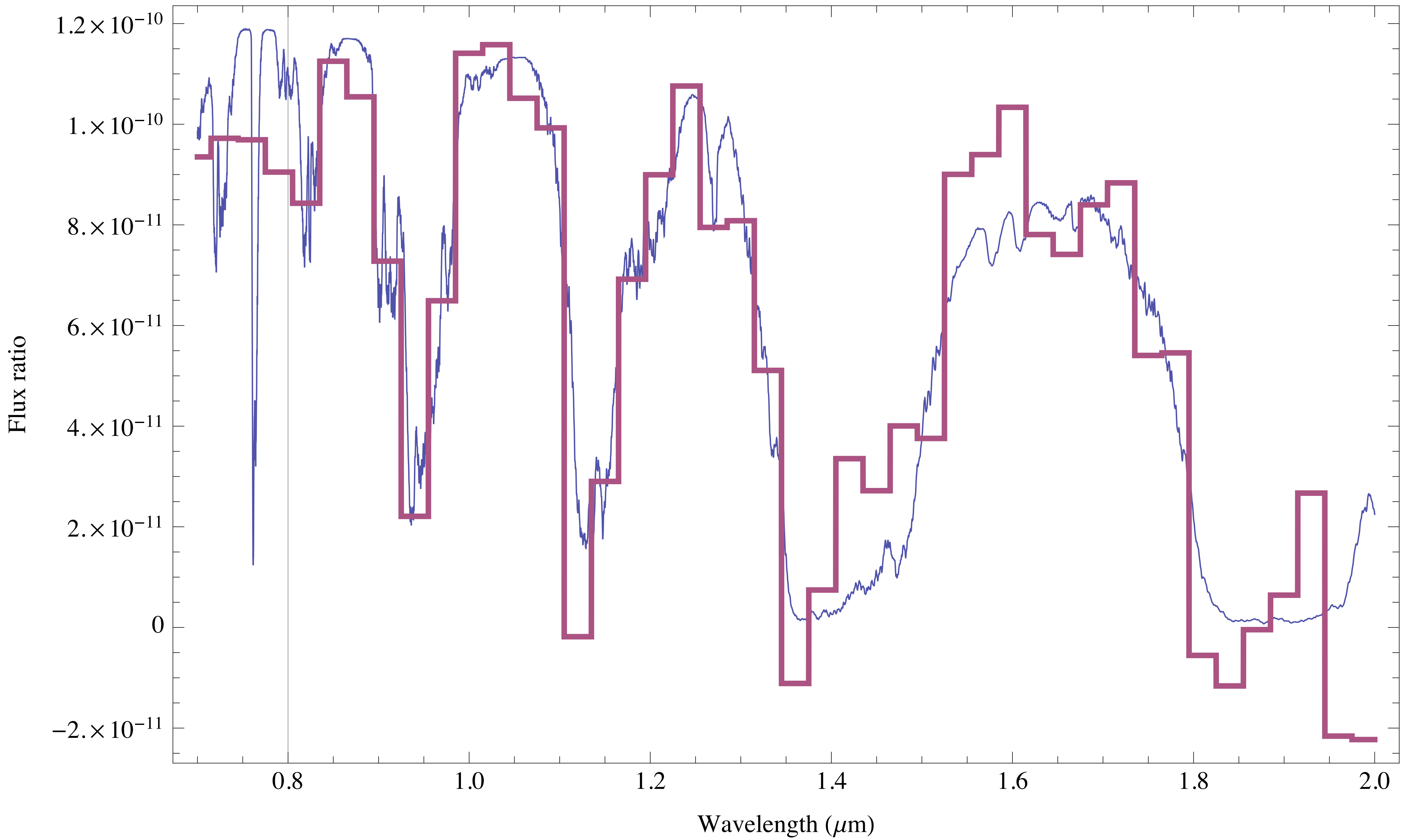


Earth at 10 pc, NIRCam F090W (Nyquist)



Earth Spectrum with NIRSpec

- SNR=5 spectrum of Earth at 10pc in 3×10^5s with prism (R=30-50)
  - does not include effects of out-of-band filter & varying sensitivity

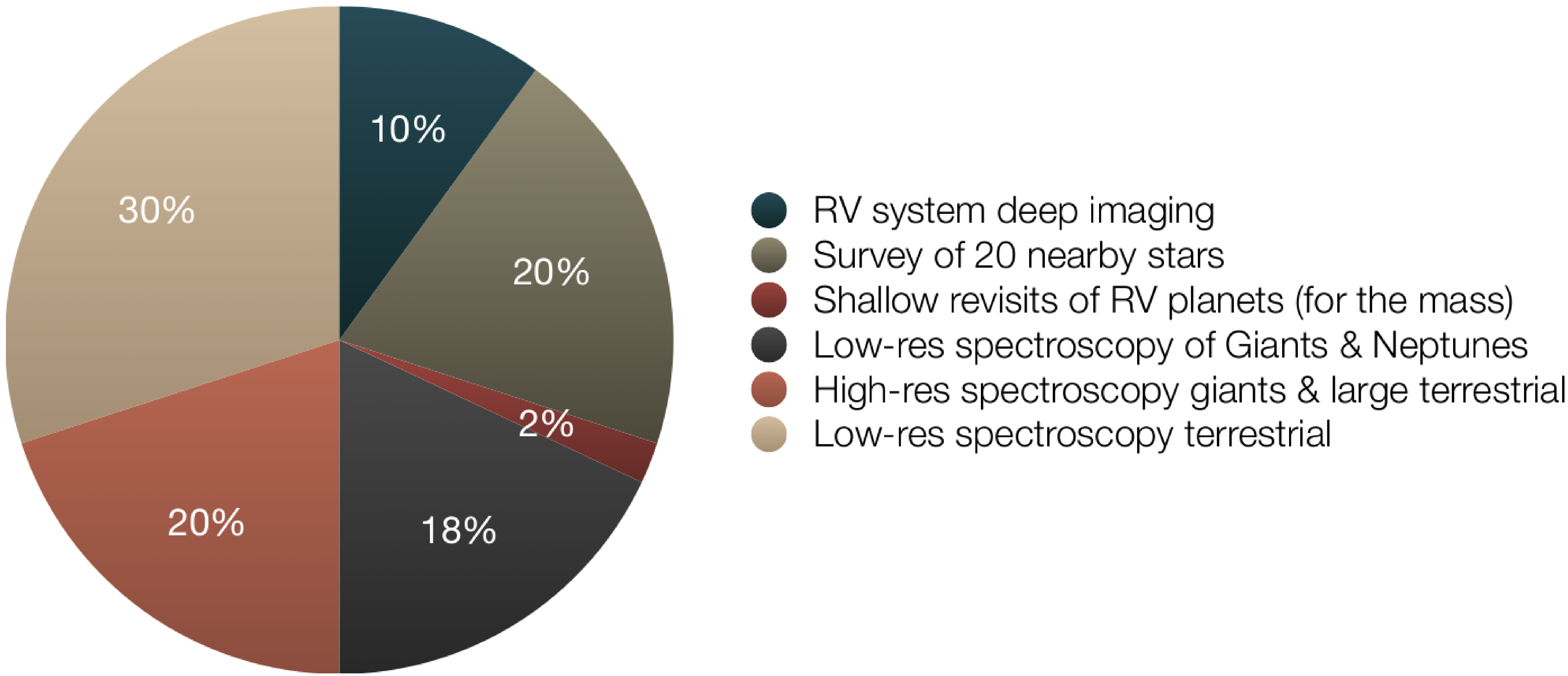


Sample NWP Science Exposure Time Allocation

- Plausible total exposure time: 7-9% (~10^7s) - Total slews ~60-80
  - Planetary system architecture: deep search of 10 best RV systems
    - *Detect outer planets, terrestrial planets, Probe habitable zone*
    - *Detect zodiacal dust and planet(s)-dust interaction and structures*
  - Deep survey of 20 nearby stars
    - *Probe habitable zone for terrestrial planets*
    - *Exo-Zodiacal dust brightness, structure and color/spectroscopy*
  - Shallow revisit of known 20 best RV systems
    - *Two visits to disambiguate inclination in RV detection (M.Sin i), test coplanarity*
  - Low-resolution spectroscopy of 20-30 giants and Neptunes
  - High-resolution spectroscopy 10 giant planets (2-3 mature, 6-9 young)
  - Low-resolution spectroscopy of 3-5 terrestrial planets

Sample NWP Science Exposure Time Allocation

- Total exposure time 7-9% of mission time (10^7s)
  - 1/3 imaging
  - 2/3 spectroscopy



Conclusions

- JWST + starshade excellent characterizer, short exposure times, high-resolution possible on brighter planets
- Limited for detection (max observing time ~ 7-9%)
- not limited by imperfect detector in most observing modes, near infrared is interesting
- better estimation of spectroscopic capabilities in progress