SGL Coronagraph Simulation

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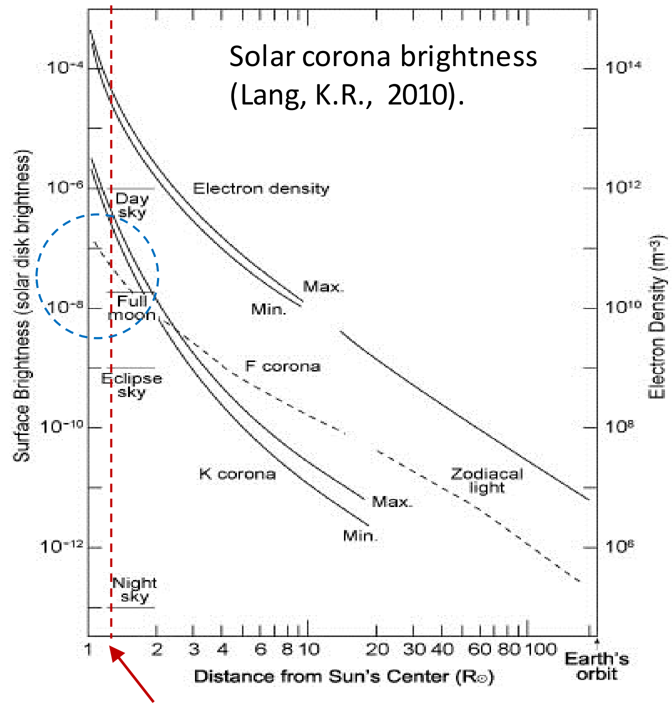
SGL Coronagraph

- Typical exoplanet coronagraphs:
  - Light contamination from the unresolved, close *parent star* is the limiting factor:

    0.1” Earth sized: ~1e-10; 0.5” Jupiter sized:~ 1e-9

- In SGL:
  - Light from the parent star focused ~1e3 km away from the imaging telescope
  - The Sun is an extended source ($R_\odot$: 1~2 arcsec)
  - The Einstein ring overlaps w/ the solar corona

➢ *The Sun light need only to be sufficiently suppressed (to < solar corona level) at the given Einstein’s ring location: ~a few e-7, notionally*



~ approx. Einstein’s ring location

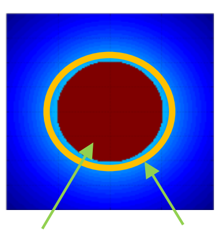
~ original “coronagraph” in solar astronomy (Sun angular radius size: $R_\odot$ ~960 arcsec)

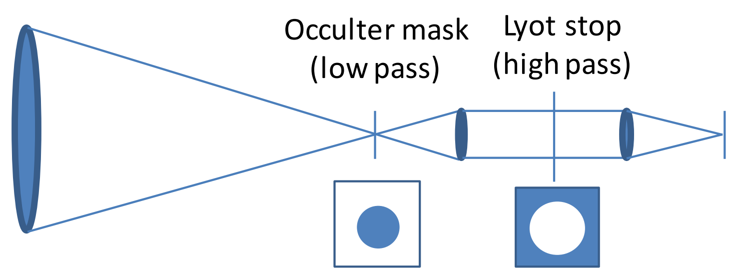
SGL Coronagraph Simulation General Setup

- Classic Lyot coronagraph architecture
  - ***Occulter mask***: remove central part of PSF
  - ***Lyot stop***: further remove residual part at pupil edge

  } Amplitude only

- Extended source model
  - **The Sun disk**: a collection of incoherent off-axis point sources, of uniform brightness
  - **Solar corona**: ~1e-6/r^3 power law radial profile brightness ($r/R_\odot >= 1$)
- Instrument parameters considered:
  - Telescope diam, SGL distance, occulter mask profile, Lyot mask size
- Fourier based diffraction modeling





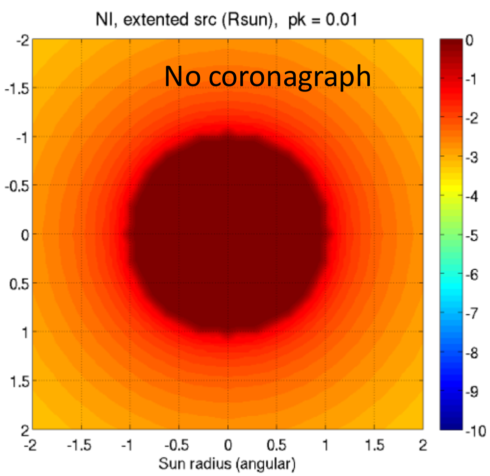
SGL Coronagraph Simulation -1

Opaque Disc Hard-edged Occulter

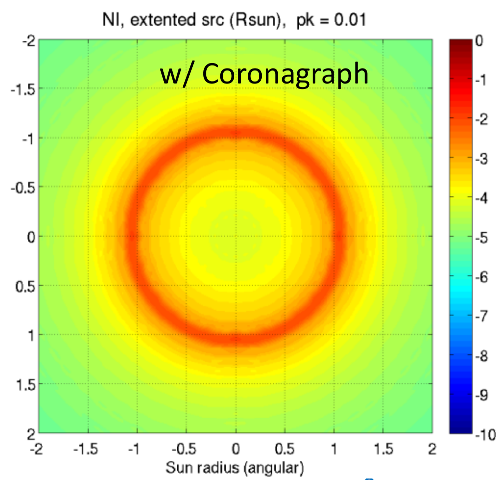
Basic parameter assumptions/ranges:

- Telescope pupil diam = 1~2m
- SGLF distance = 650 ~ 900 AU
- Occulter: radius = inner E-ring radius, 1.09~1.28 $R_\odot$
- Lyot stop: diam = 0.5~0.99*pupil_diam
- Solar sampling = 0.05 ~0.025 $R_\odot$ (~ 0.0438 arcsec)
  - ➔ ~5k point sources whose angular coordinates sqrt(α^2+β^2) ≤ $R_\odot$
- Monochromatic: λ =0.6um
- Normalized to peak intensity without occulter ("normalized intensity", NI)

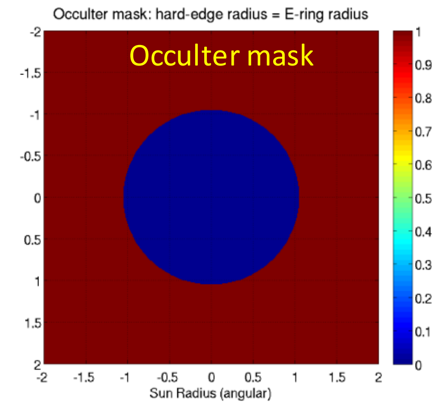
Hard Edge Occulter: A First Look



(Sun radius ~12 λ/D)

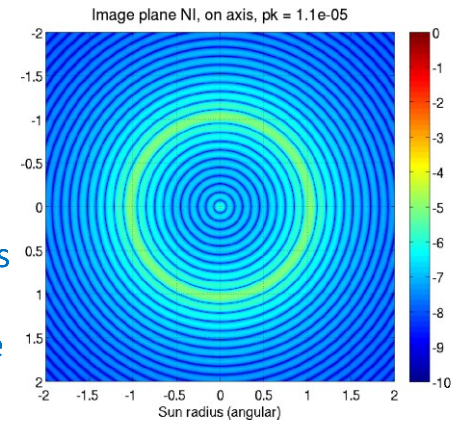


Extended Source



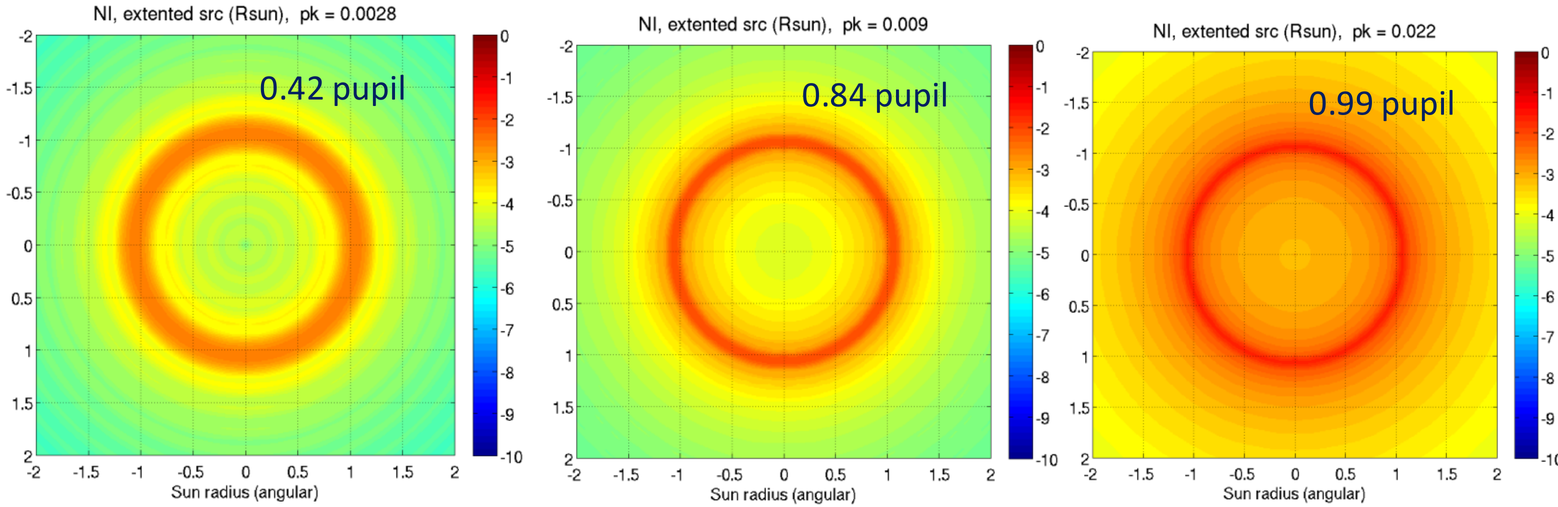
- Telescope diam = 1m
- SGLF distance = 650 AU
- Occulter radius ~ inner E ring radius
- Lyot stop diam = 0.84* pup_diam

If single on-axis point source



NI: e-2~e-3 @ E-ring ~1.09$R_{\odot}$

Hard Edge Occulter – Lyot Stop Size

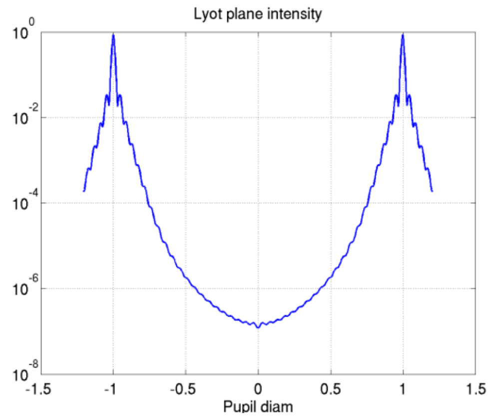


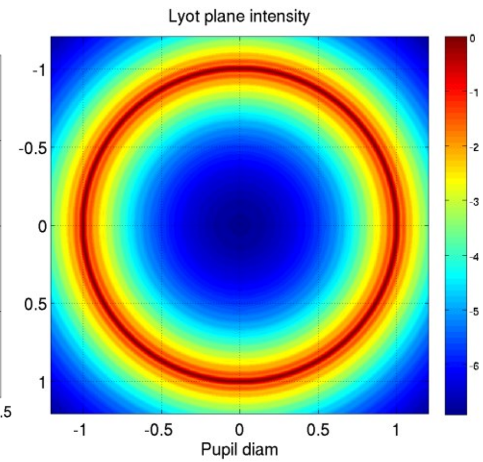
1m telescope + 650 AU SGLF

- High residual Sun light @ Lyot plane (annular peak around pupil diam)

- Reduce Lyot stop size ➔ **lower the peak leakage but also widen it**

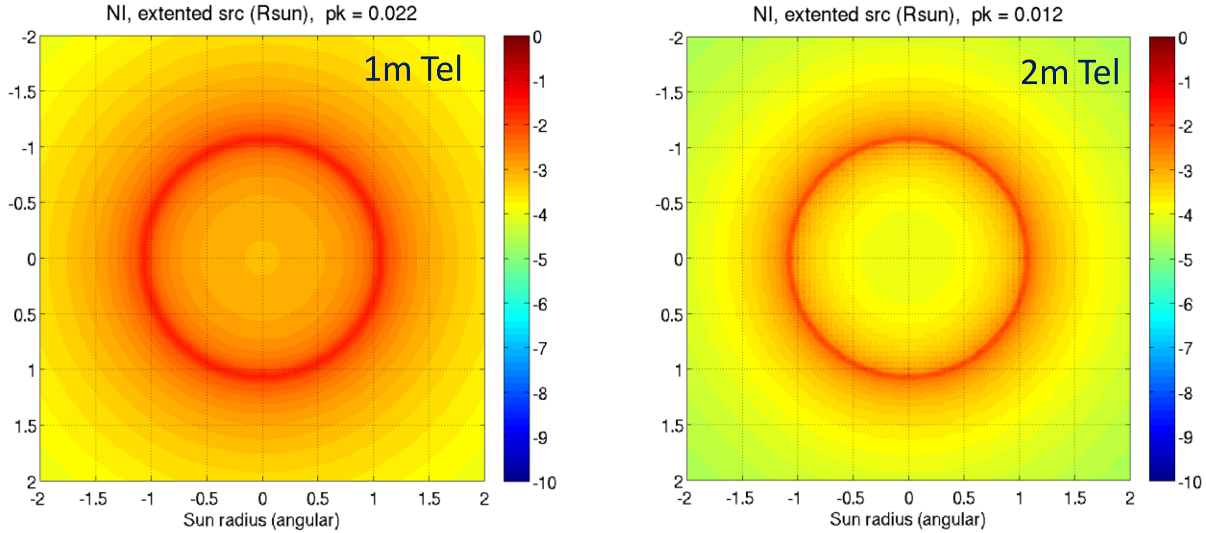
  ➔Some improvement





Typical Lyot plane intensity ⇦ ***before*** applying Lyot stop

Hard Edge Occulter – Telescope Diam

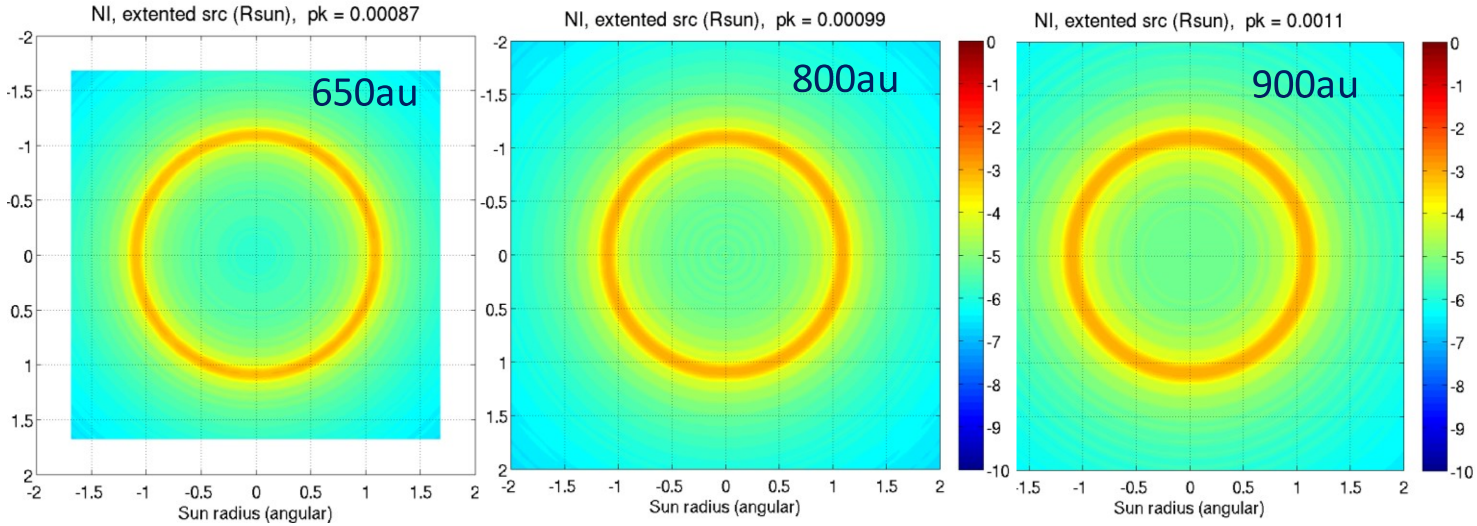


650 AU SGLF + 0.99 pup diam Lyot

- 1m telescope (left) vs 2m telescope (right)

Significant improvement

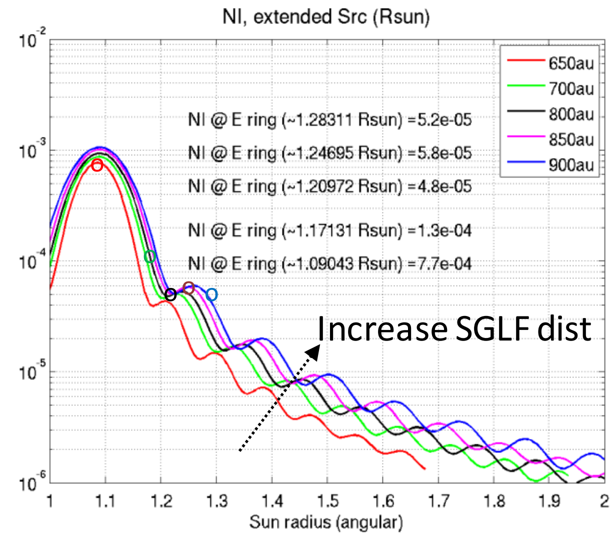
Hard Edge Occulter – SGL Distance



2m telescope + 0.5 pupil diam Lyot stop

- Increase SGLF distance ➔ E-ring location farther away from residual peak ➔ effective (but not monotonic) to improve NI

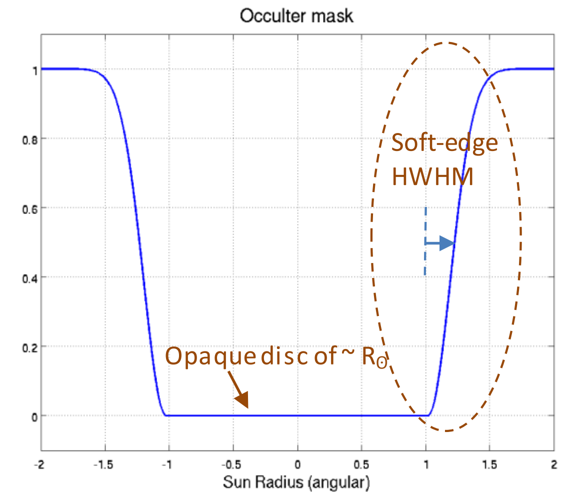
➔ SGL ~800au, NI @ E –ring = 4.8e-5



SGL Coronagraph Simulation -2

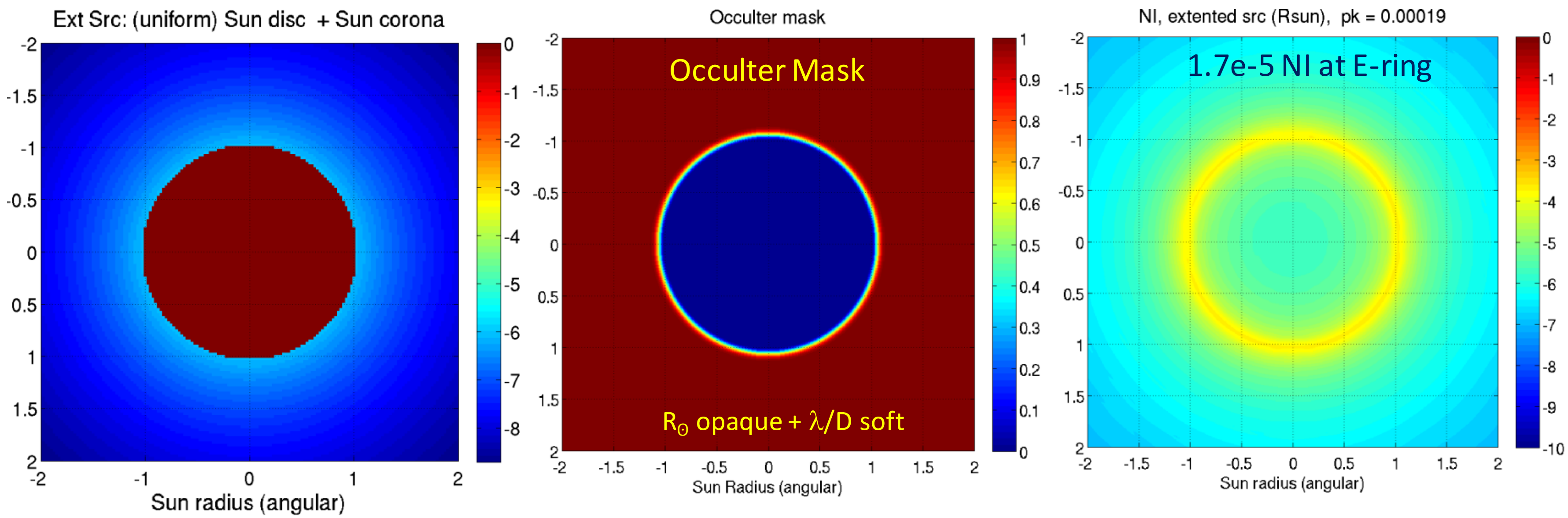
Opaque Disc Soft-edged Occulter

- Pupil diam = 2, 2.5 m
- SGLF distance = 600 ~ 1000AU
- Source: Sun disc + corona (~1/r^3, up to 2 $R_{\odot}$)
- Solar sampling: 0.025 $R_{\odot}$ (~ 0.0438 arcsec) ➔~5k point sources
- Occulter:
  - Opaque disc radius of ~$R_{\odot}$
  - Soft (Gaussian) edge width: FWHM = 0.5 ~2*(E_ring - $R_{\odot}$)
- Lyot stop: diam = 0.5 *pupil diam
- Monochromatic: λ =0.6um
- Normalized to peak intensity without occulter ("normalized intensity", NI)



Occulter mask radial profile

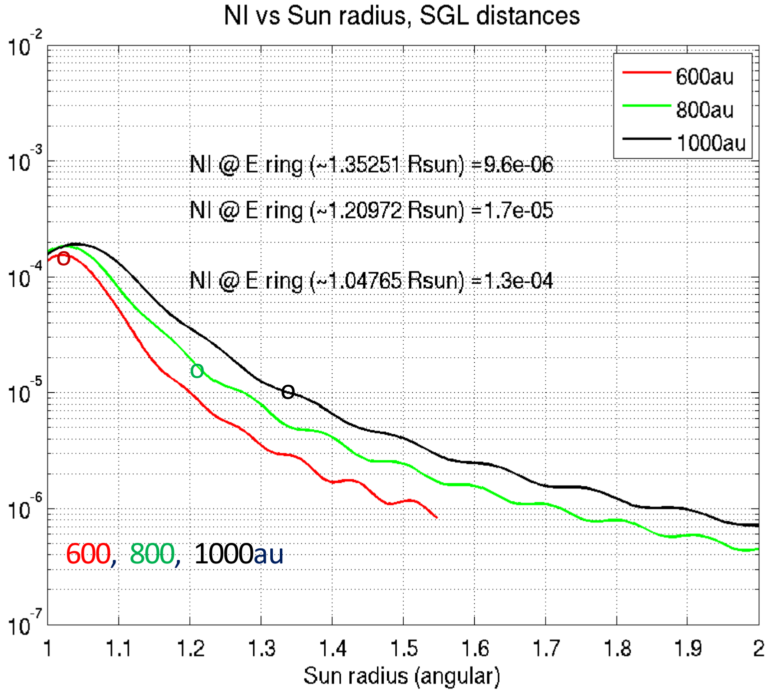
Soft Edged Occulter, First Look

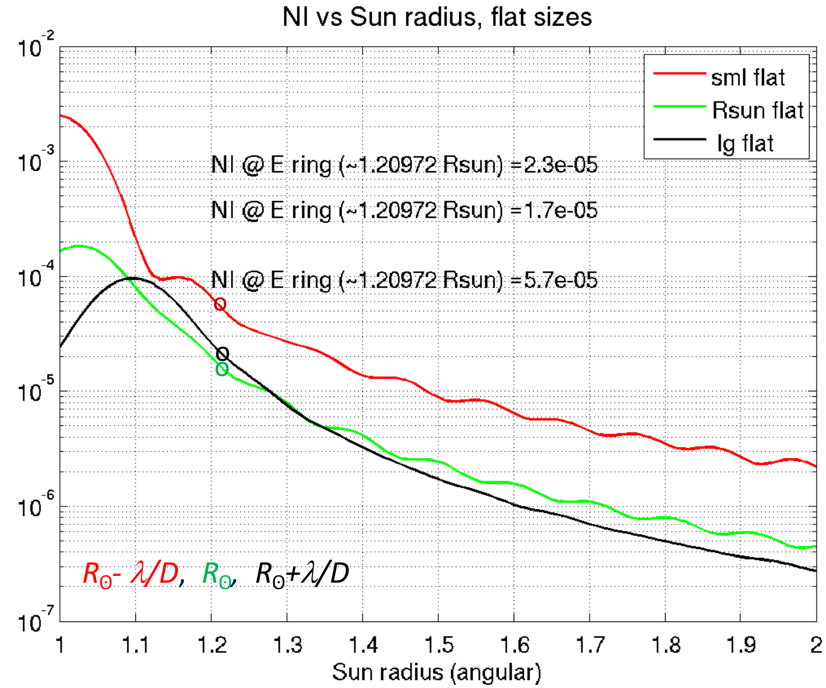


2m telescope, 0.5 pup_diam Lyot stop, 800au SGL

Improved NI =1.75e-5 @ E -ring

SGL Dist, Opaque Disc Size

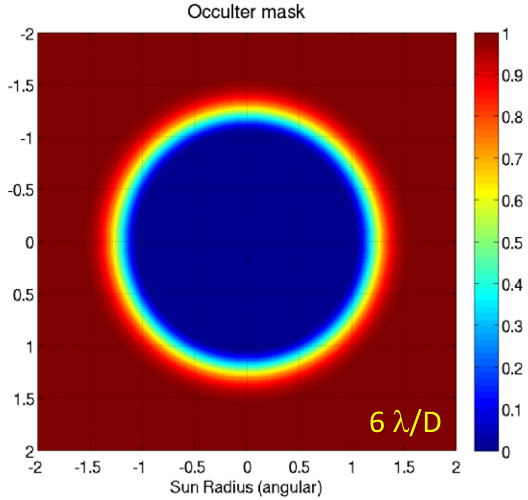


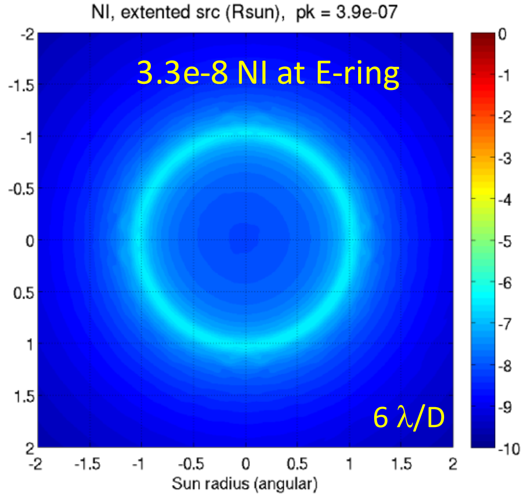


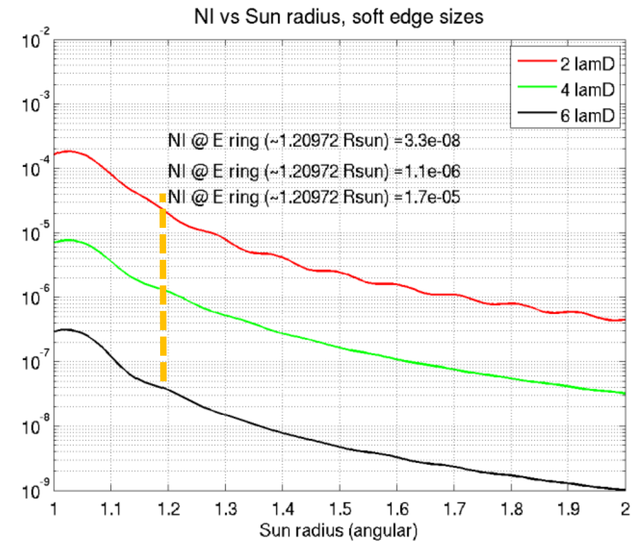
2m telescope, 0.5 pup_diam Lyot stop, 800au SGL

- SGLF distance: **the larger the better**
  But decreased benefit once >800au
- Opaque disc radius: **same as $R_\odot$ better**
  Unless very large SGL dist (>1000au)

Soft Edge Occulter – Edge Width



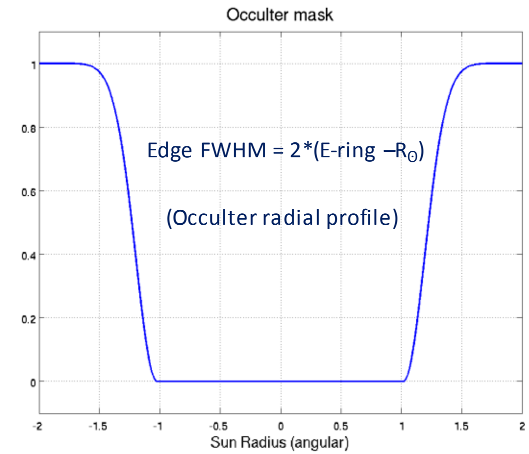




2m telescope, 0.5 pup_diam Lyot stop, 800au SGL

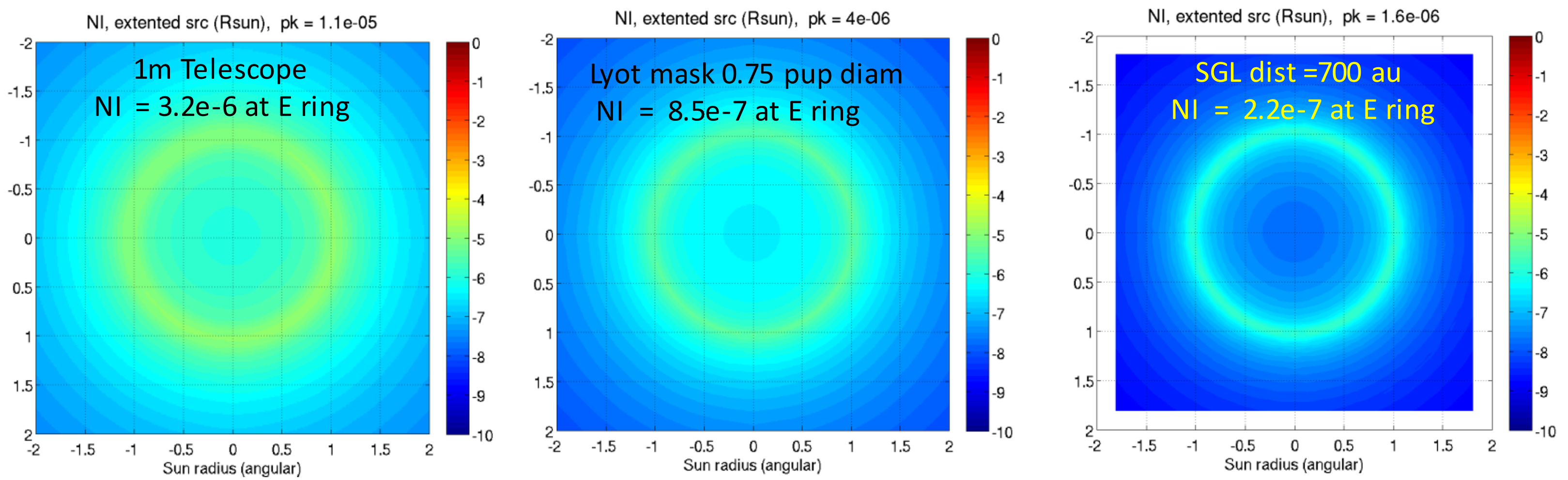
- Occulter = opaque disc of $R_\odot$ + Gaussian edge stitched together (various FWHM)

  2, 4, 6 λ/D ~= 0.5, 1, 2*(E-Ring – $R_\odot$)



Most effective design parameter so far

Soft Edge Occulter – Parameter Sensitivities

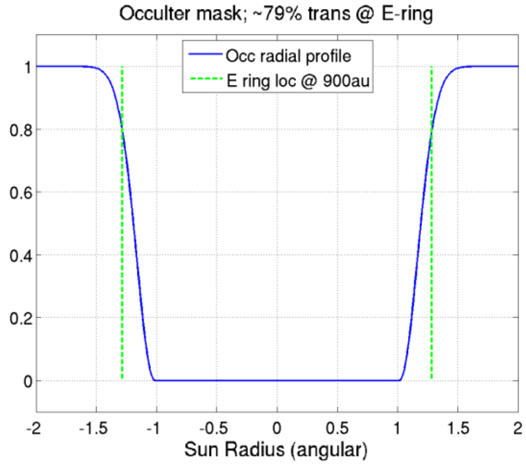


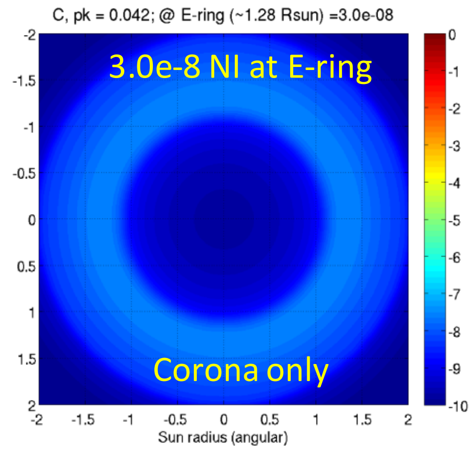
2m telescope, 0.5 pup_diam Lyot stop, 800au SGL, opaque disc of $R_\odot$ + 2*(E-ring-$R_\odot$) soft edge stitched

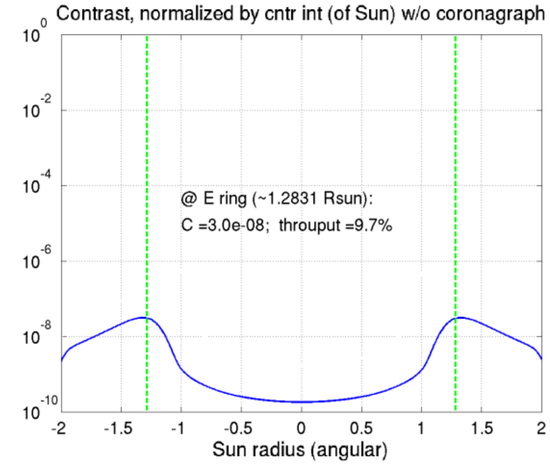
Change one parameter at a time w/o optimizing remaining parameters:

- Smaller telescope size (0.5X): huge diff (~100X)
- Larger Lyot mask size (1.5X): large diff (~20X)
- Smaller SGLF dist (0.875X): moderate diff (~5X)

Sun vs Corona at E-ring – 900au





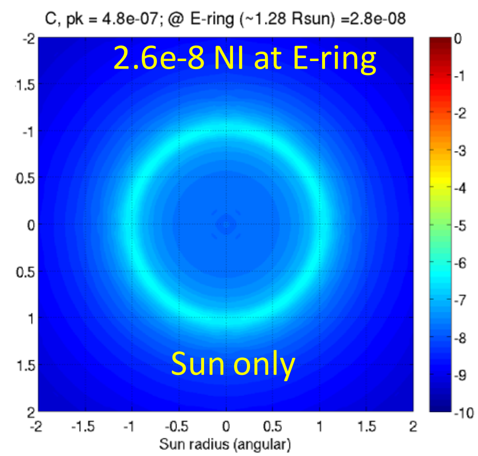


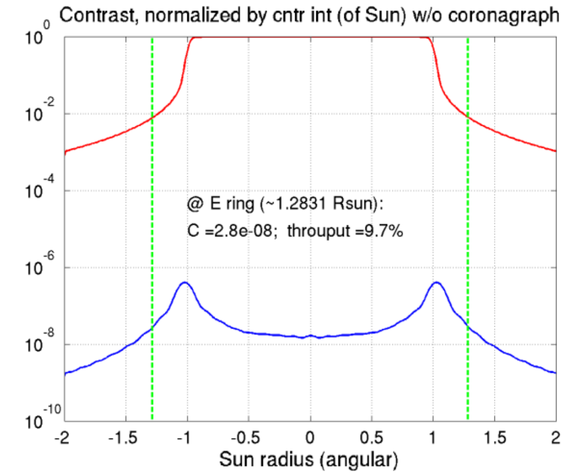
- 2m Tel, 900au SGLF, 0.5 pupil Lyot, 1.25*(E-ring- $R_{\odot}$) soft edge, 79% occulter transm (amp) @ E-ring

- NI at E-ring:

  2.8e-8 Sun vs 3.0 e-8 corona

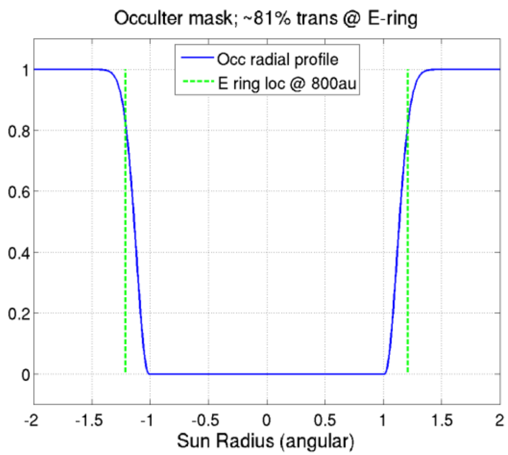
- E-ring core PSF thrput*: ~ 9.7%

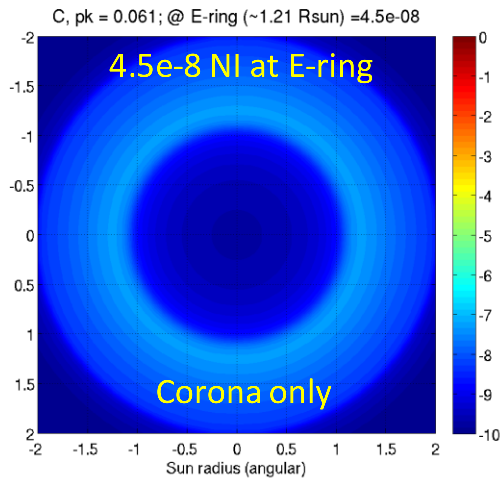


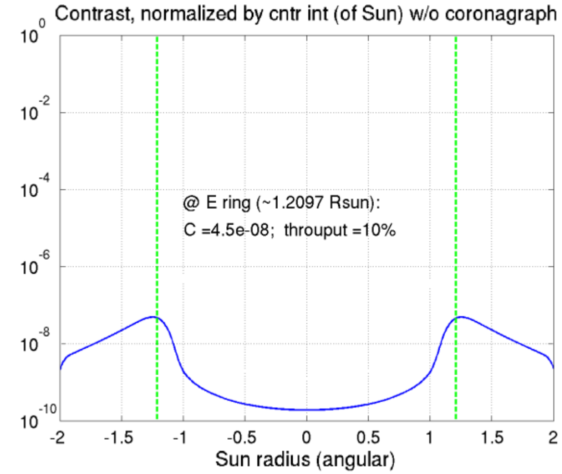


*Intensity of all pixels w/n ± λ/D of a pnt src at E-ring

Sun vs Corona at E-ring – 2.5m Tel





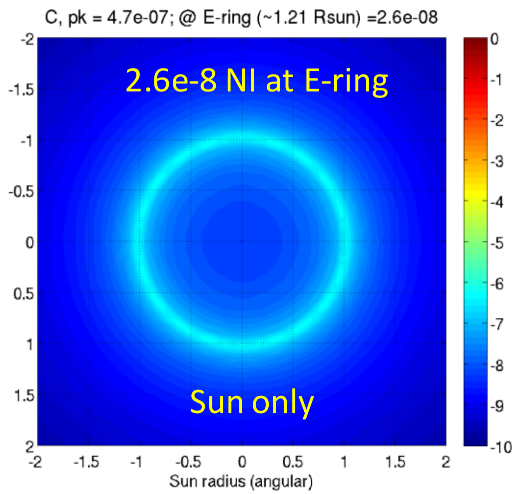


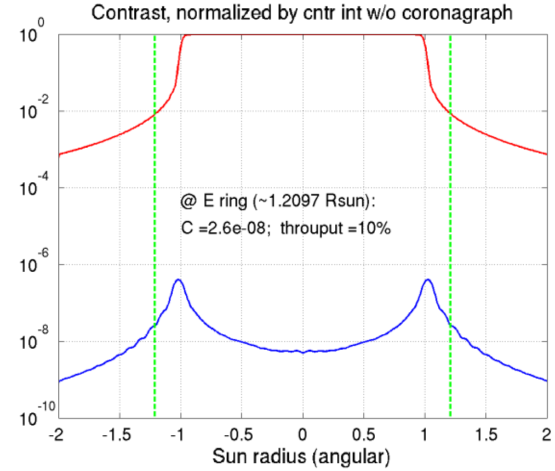
- 2.5m Tel, 800au SGLF, 0.5 pupil Lyot, 1.2*(Ering- $R_{\odot}$) soft edge, 81% occulter transm

- Contrast at E-ring:

  2.6e-8 Sun vs 4.5 e-8 corona

- E-ring core PSF thrput: ~ 10%





Summary & Future Work

- A preliminary Lyot coronagraph designed for SGL:
  - 2~2.5m telescope; SGLF distance: 800~900 AU
  - Occulter mask: Opaque disc of radius $R_\odot$ + 1.2*(E-ring- $R_\odot$) soft edge
  - NI 2.6e-8 Sun light suppression vs 4.5e-8 corona

    (Better than 2e-7 needed b/c soft edge occulter mask reduces planet light at E-ring also)
  - Core PSF throughput (E-ring): ~ 10%

- On design parameters evaluated:
  - Occulter soft edge profile most effective
  - Telescope size, SGL distance, Lyot stop also help

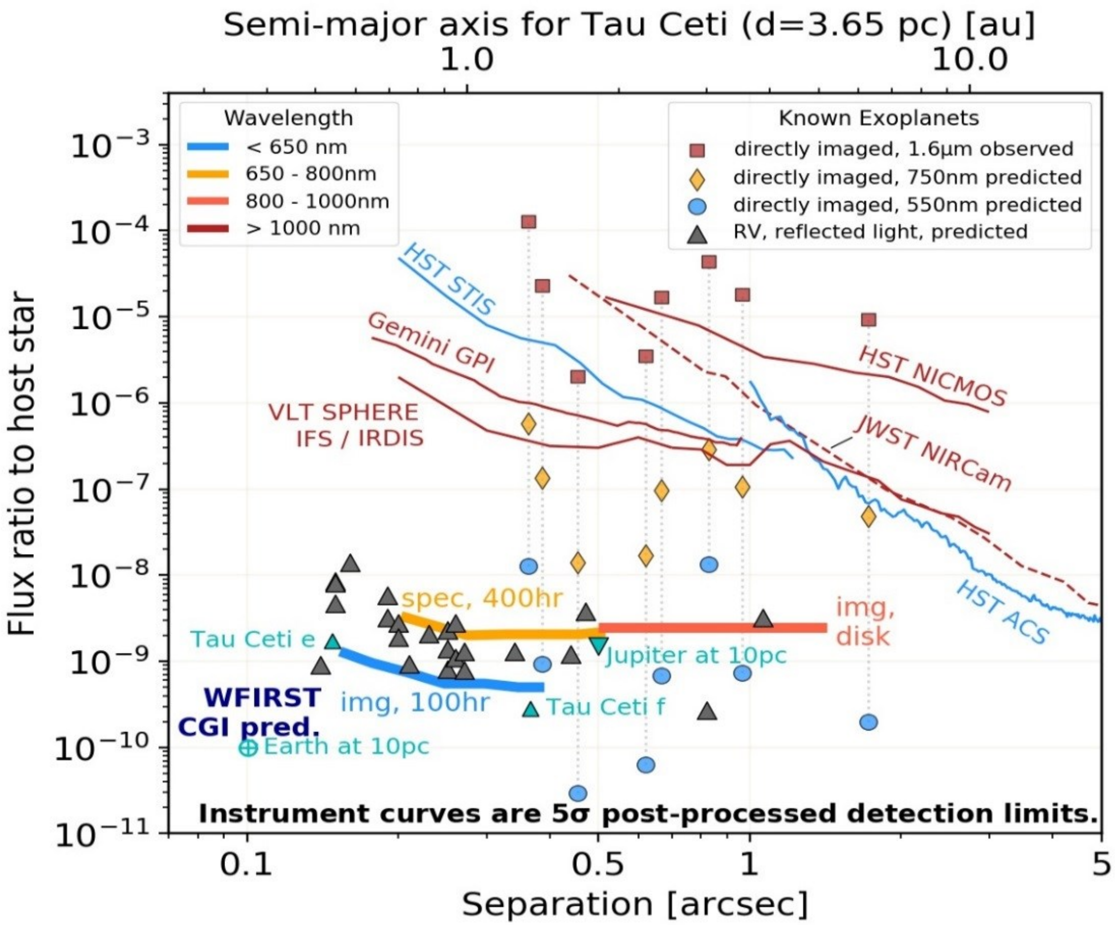
- Future work in coronagraph design tradeoff

  Reduce telescope size and/or SGL distance requirements; more practical mask
  - Other mask profiles: Apodized occulter or Lyot stop? phase + amp occulter mask?
  - Other architectures: external (starshade, sawtooth)? hybrid external + internal occulter?
  - Broadband performance

Backups

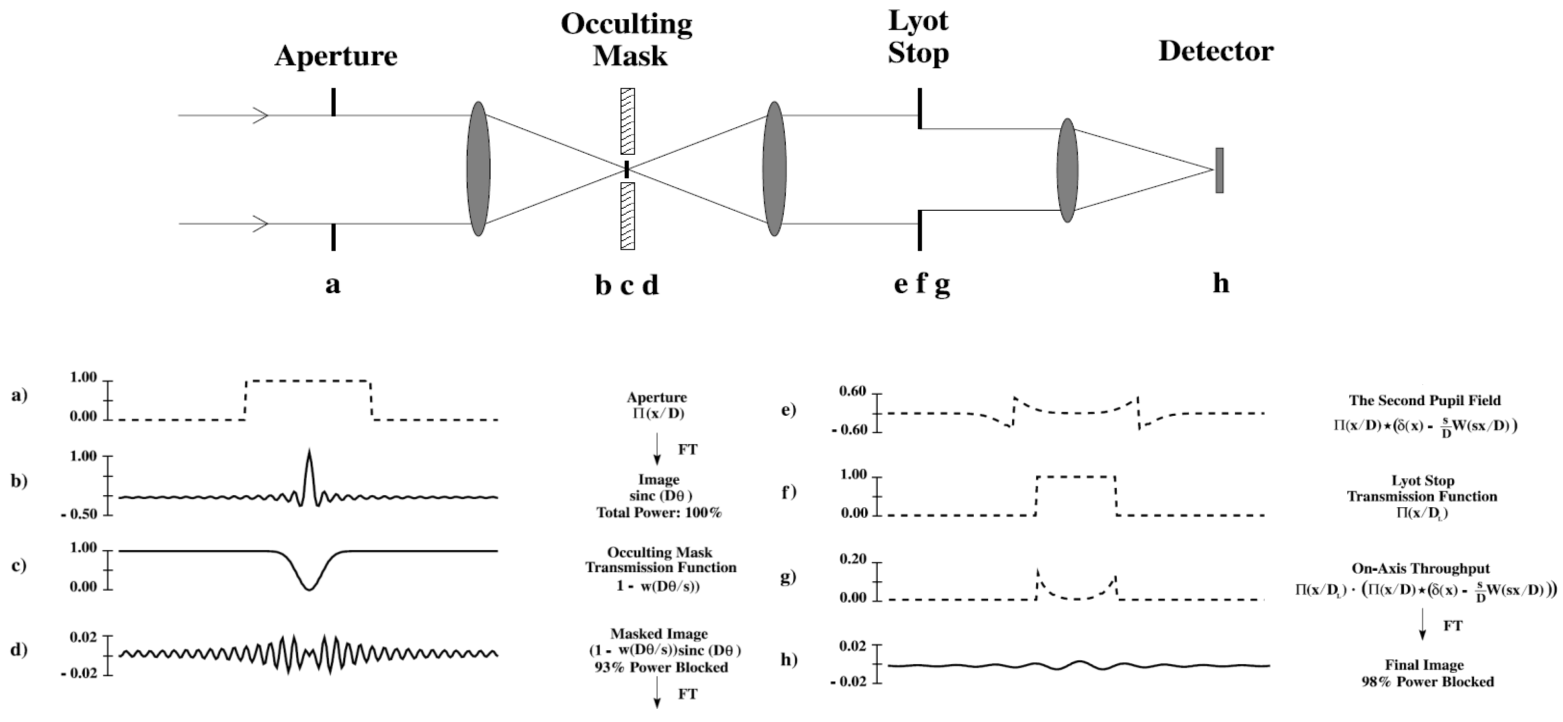
Exoplanet Coronagraph Example

Predicted WFISRT-CGI Performance



Predicted WFIRST-CGI performance on a V=5 star, in the context of known planetary systems and current instrumentation (Bailey, V., 2018)

Lyot coronagraph principles



(Sivaramakrishnan et al. 2001)

A Few Definitions

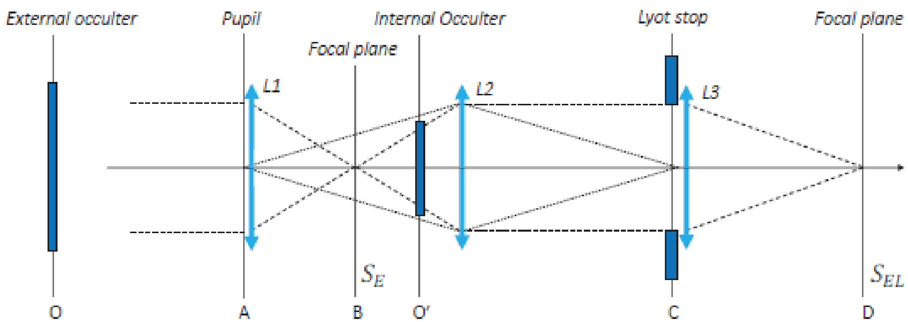
- Fourier based diffraction modeling
  1. For each pnt src (a tilted plane wave depend on its location): start from entrance pupil → normalize the field to have intensity of 1 at pupil → FFT to occulter plane and multiply w/ occulter mask → inverse FFT and multiply w/ Lyot mask → one more FFT to the image plane → find intensity
  2. Add intensities from all ~5k pnt src .

- On normalization:
  a) No coronagraph (occulter and Lyot out), image plane intensity of all ~5k pnt src; its peak at center is the normalization factor
  b) Now w/ coronagraph (occulter and Lyot in), image plane intensity of all ~5k pnt src. Then divided by peak value from a).

- Coronagraph planet core throughput at E-ring
  - Most loss come from Lyot stop mask: ~ 0.42 radius, → 17.64% area
  - Occulter mask (amplitude) also significant: ~80% transmission at E-ring→ intensity 64%
  - "Core" PSF w/o coronagraph (intensity of all pixels w/n $\pm \lambda/D$ of a pnt src at E-ring): ~84%

  → ~ 0.176*0.64*0.84 = 0.09

Hybrid External + Internal Occulters for Solar Corona



Parameter	Value
Wavelength	$\lambda = 550$ nm
Angular radius of the Sun	$R_\odot = 0.0046542$ rad
	$= 960$ arcsec
Distance to the Sun	∞ (1 AU)
Radius of the external occulter	$R = 710$ mm
Distance plane O – plane A	$z_0 = 144.348$ m
Radius of the pupil	$R_p = 25$ mm
Focal length of the telescope	$f = 330.385$ mm

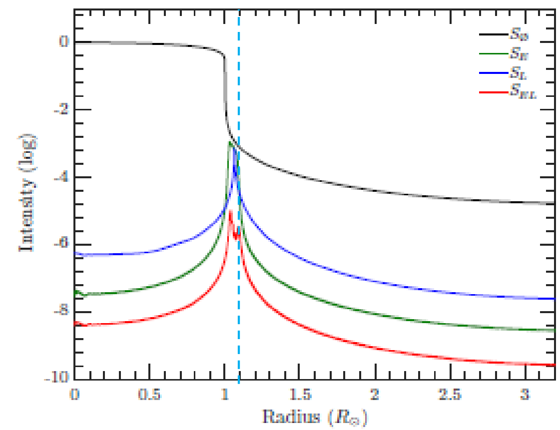


Fig. 10. Observed intensities as final response in the focal plane, in logarithmic scale. The transverse radius is given in solar units. The intensities are normalized to the mean solar brightness. Black: system $S_\emptyset$ given by $I_B(r)$ in plane B. Blue: system S_L given by $I_D(r)$ in plane D. Black: system S_E given by $I_B(r)$ in plane B. Red: system S_{EL} given by $I_D(r)$ in plane D.

- *"Performance of the hybrid externally occulted Lyot Solar coronagraph," Rougeot R., et al., Astronomy & Astrophysics, 599, A2 (2017)*

F# = 1.5^2/(4*.55um*144) = **7102**; $\mathbf{D_{tel}/D_{ss}}$ = 0.035; **IWA** = 1.5m/(2*144)*2.06e5 = 1073 as

Starshade Scaling

Starshade light suppression performance specified by *(for point src like host star)*:

- Fresnel #: F#= $D^2_{ss}/4\lambda Z$
- Telescope /physical size of the shadow for a given F#, so $D_{tel} \propto D_{ss}$
- IWA = $D_{ss}/(2Z)$*rad2as

Typical starshade design parameters:

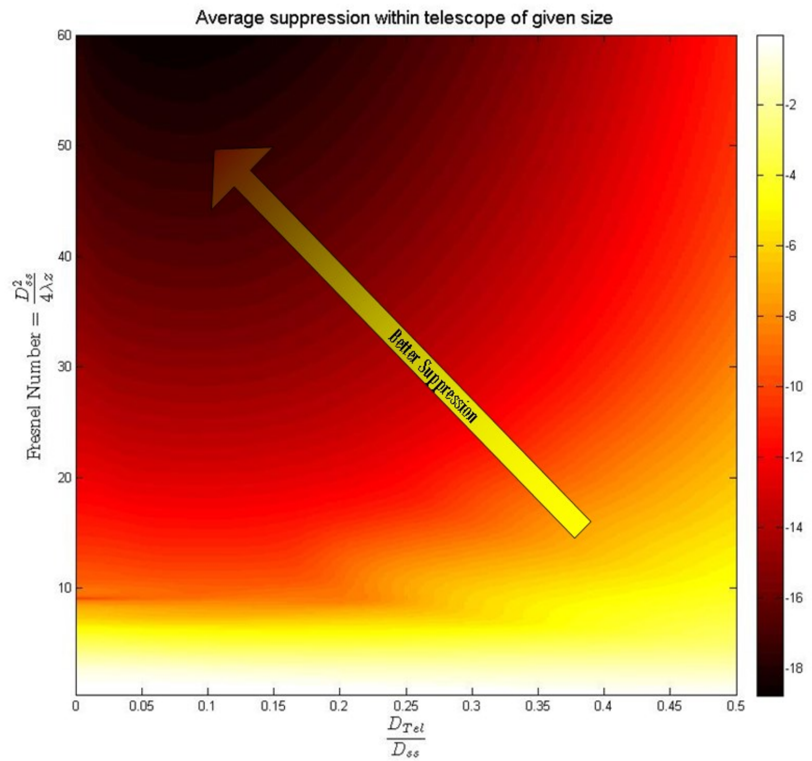
F#=16; **D_{tel}/D_{ss}** = 0.08; **IWA** = 77mas
D_{tel} = 4m; D_{ss}=50m; Z = 67,000km; λ =0.6um,

For reference, Solar corona (*Rougeot R., et al, 2017*)

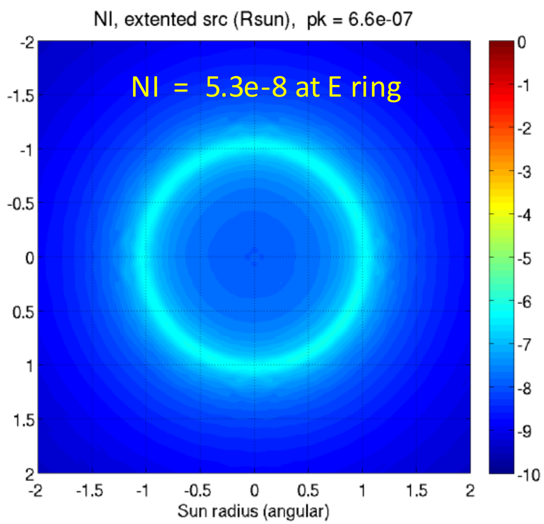
F# = 1.5^2/(4*.55um*144) = **7102**; **D_{tel}/D_{ss}** = 0.035; **IWA** = 1.5m/(2*144)*2.06e5 = 1073 as

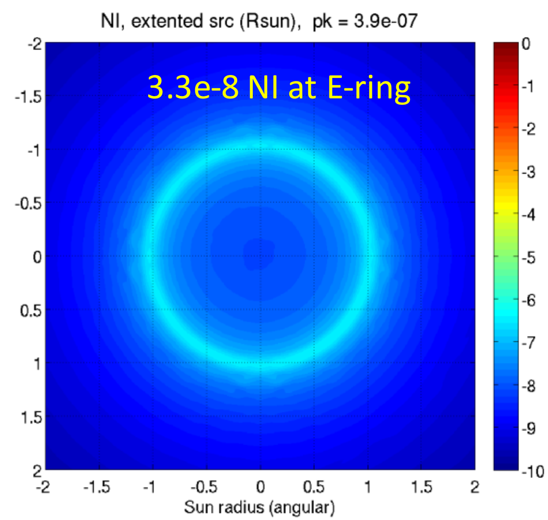
(Glassman, T., et al., SPIE, 2009)

For point source



Sun Brightness



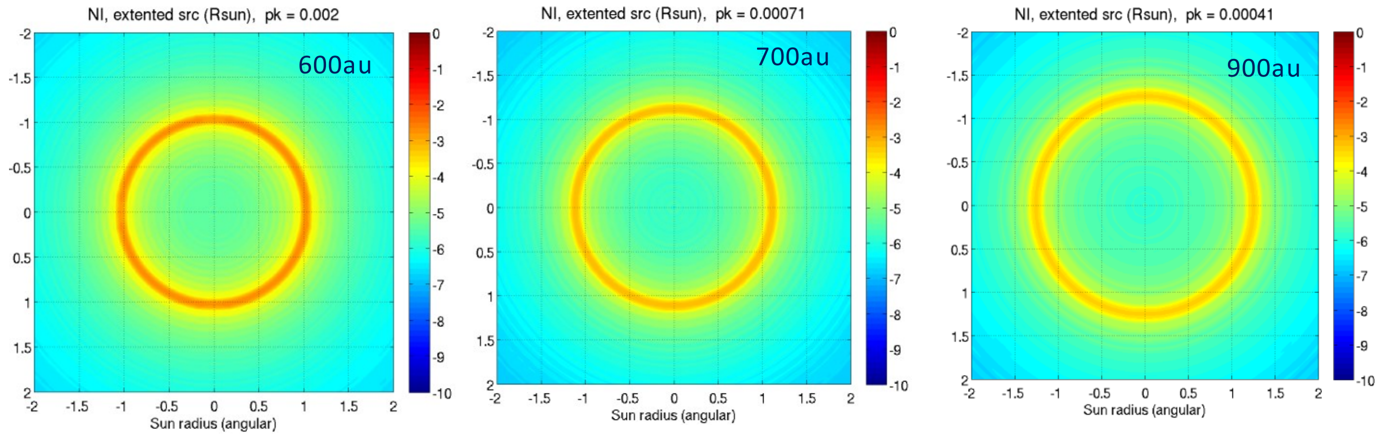


2m telescope, 0.5 pup_diam Lyot stop, 800au SGL

Uniform solar brightness (left) vs non-uniform solar brightness* (right)

* Hamme, V., 1993, APJ, 106, 5

Hard Edge Occulter – SGL Distance -2



- 2m telescope + 0.5 pupil diam Lyot stop
- Occulter size ***proportion*** to SGL distance
- Larger the SGL distance, lower the peak NI, but shifted diffraction pattern nullifies most benefit → not effective

NI ~ 4e-4 @ E-ring