Performance of hybrid externally occulted Lyot solar coronagraph

Raphael Rougeot – ESA, PROBA-3

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Who am I?

- System Engineer
  at the European Space Agency within Proba-3 project team.

- *Educational Background:*
  - Ecole Polytechnique, Palaiseau, France.
  - ISAE Supaero, Toulouse, France .
  - Université Paul Sabatier, Toulouse, France.

- **Article:** Rougeot R., Flamary R., Galano D., Aime, C., A&A (2016)
  "Performance of hybrid externally occulted Lyot solar coronagraph"

Outline

1. Proba-3 mission
2. The corona of the Sun
3. Solar coronagraphy
4. Numerical study of performance
5. Observed intensities
6. Sizing the Lyot mask and stop
7. Conclusion

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Proba-3

- In-orbit demonstration of precise **Formation Flying**.

- Two spacecraft flying **150m apart**, control with at a millimetre accuracy.
  - The Occulter Spacecraft will carry a 1.5m diameter occulting disc.
  - The Coronagraph Spacecraft will fly the solar coronagraph ASPIICS.

Proba-3

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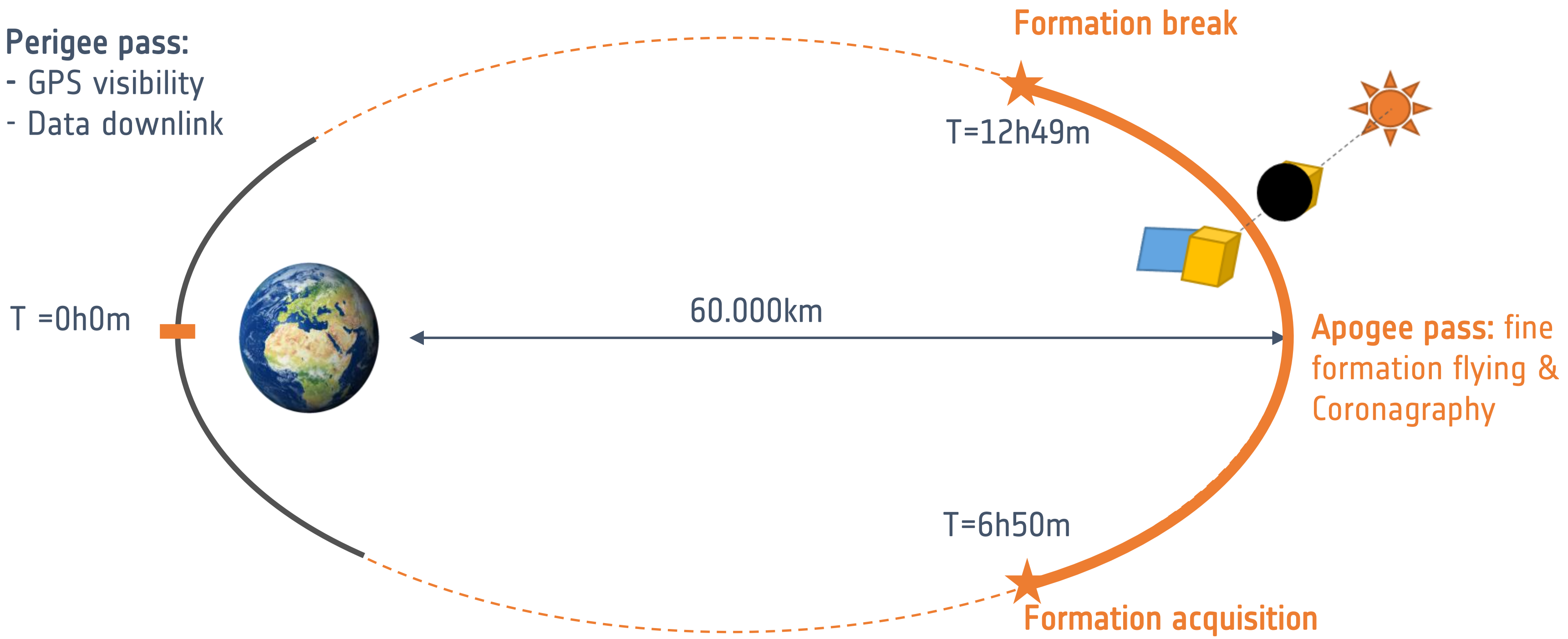
- Two spacecraft flying **150m apart**, control with at a millimetre accuracy.
  - The Occulter Spacecraft will carry a 1.5m diameter occulting disc.
  - The Coronagraph Spacecraft will fly the solar coronagraph ASPIICS.
- Launch scheduled in December 2019.

Proba-3


Perigee pass:
- GPS visibility
- Data downlink
Formation break
T=12h49m
T =0h0m
60.000km
Apogee pass: fine formation flying & Coronagraphy
T=6h50m
Formation acquisition

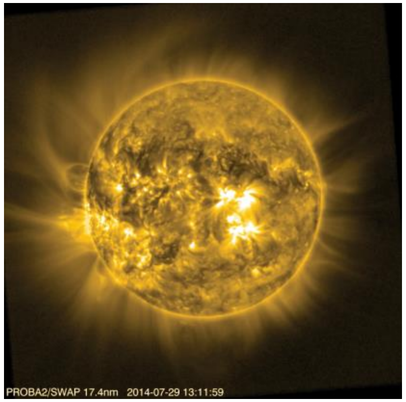
Outline

The corona of the Sun

- Fully ionized, magnetized plasma in a dynamic state.
- From ~5000kms to 20-30 solar radii.
- **Temperature** of 10^6K ≫ 6000K at the Sun's surface.
  Aschwanden, 2005.

- Three "layers" of corona:
  - K-corona (continuum, Thomson scattering)
  - F-corona (Fraunhoffer rays)
  - E-corona (emission lines)

- Large scale structures (streamers, loop arcades, holes)
  Fine scale structures (plumes, rays, loops)
  ~ arcsec (November & Koutchmy 1996, Zhukov et al. 2000)

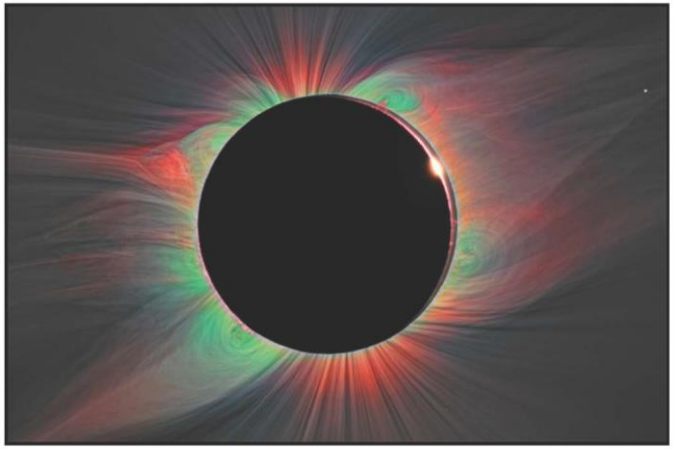


Proba-2 (SWAP) on 29/07/2014

Questions to be addressed

- Physical processes that govern the quiescent solar corona.
- Nature at different scales.
- Heating processes, role of waves (Alfven, MHD modes).
- Solar wind acceleration.

- Coronal Mass Ejections (CME).
- Formation, structures.
- Acceleration, interaction, shock.



Habbal et al., 2010. Emissions from FeX/FeXI and FeXIII/FeXIV on white light image (01/08/2008)

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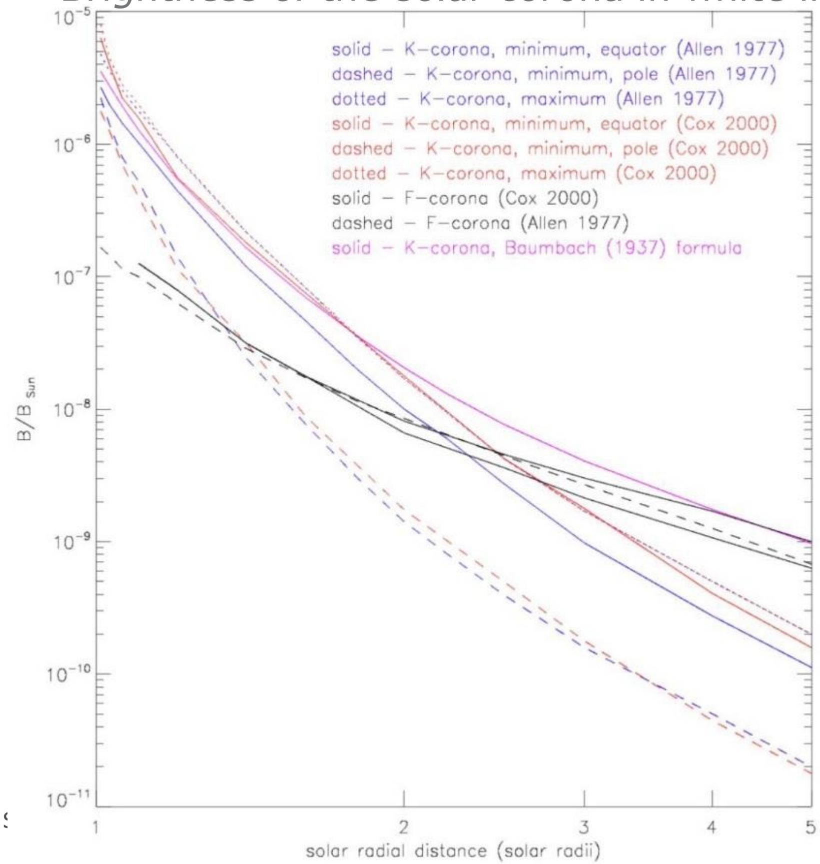
Principle of coronagraphy

Practically, it is impossible to observe directly the corona of the Sun in white light without perfect eclipse conditions.

$$B_{corona} \sim 10^{-6} \ to\ 10^{-9} B_{sun}$$

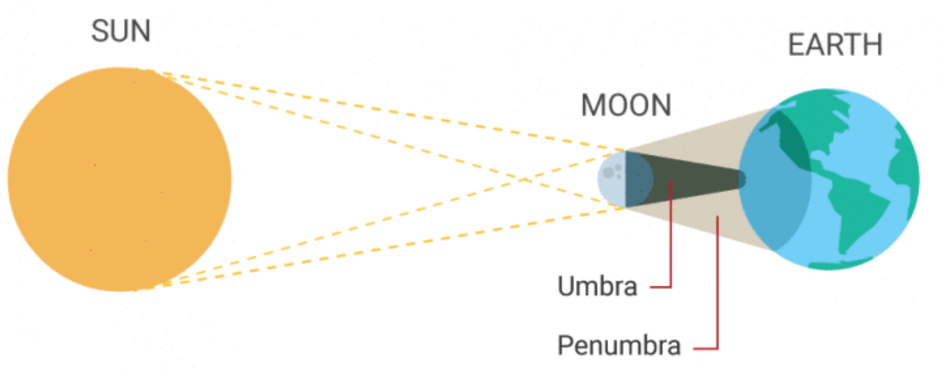
Brightness of the solar corona in white light



Allen, 1997
Cox, 2000

Principle of coronagraphy

- First on-ground observations during solar eclipses by the Moon.

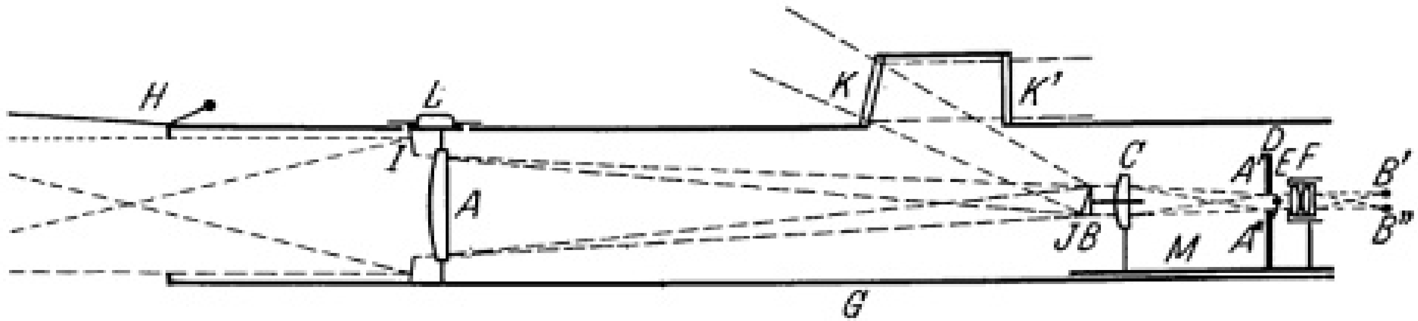


$$\frac{R_{Moon}}{D_{Moon}} \gtrsim \frac{R_{Sun}}{D_{Sun}}$$

- *Constraints:* rare events, precise location on Earth, short observation time, atmosphere turbulence and scattering.

Lyot coronagraph

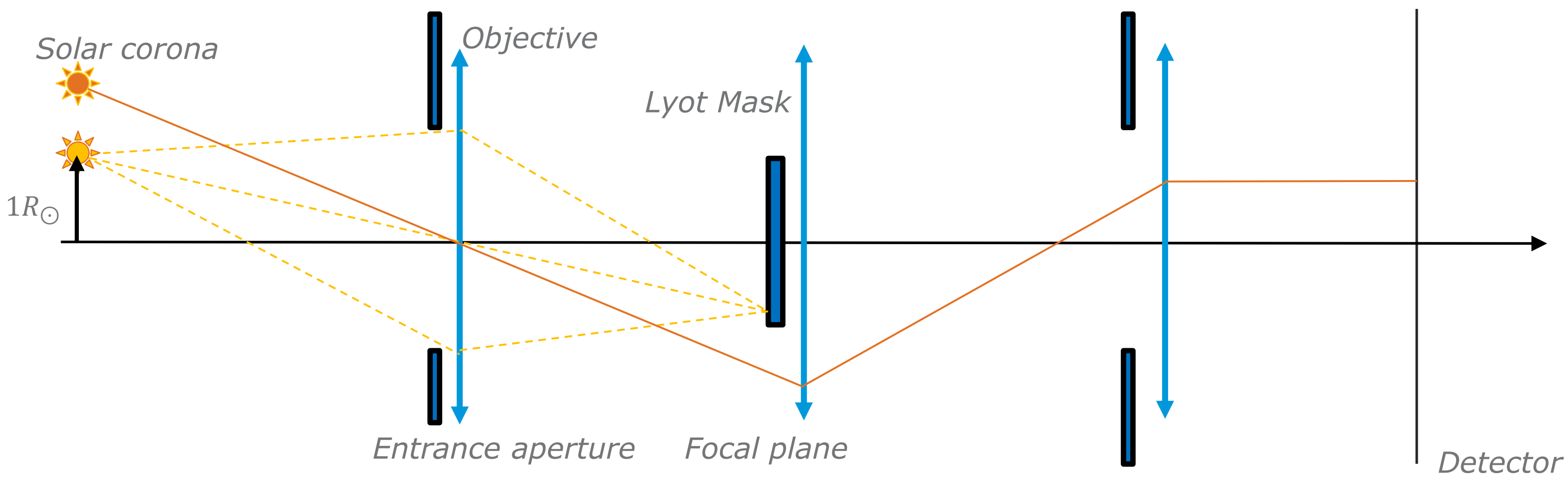
- First solar coronagraph was designed in 1930's by French astronomer Bernard Lyot (Lyot, 1939, Dollfus, 1983).



Original design of Lyot's coronagraph in his article of 1931

- *Main principle:* create **artificial eclipse conditions** to reveal the corona of the Sun.
- *Advantages:* daily observations, long observation time…
- *Constraints:* atmosphere turbulence, instrumental scatter…

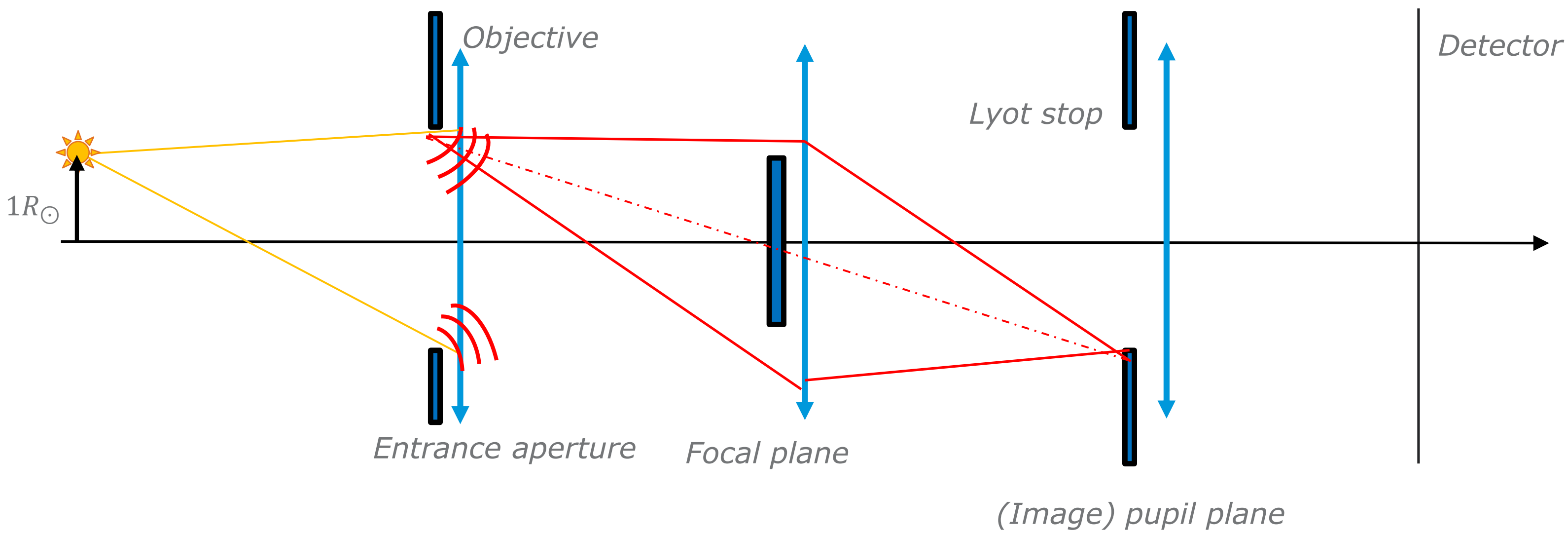
Lyot coronagraph



- The objective focuses **the sunlight** on the focal plane where an occulting disc or a rejecting mirror is set: **the Lyot Mask**.

- **The light from the solar corona** is not blocked and can be observed.

Lyot coronagraph

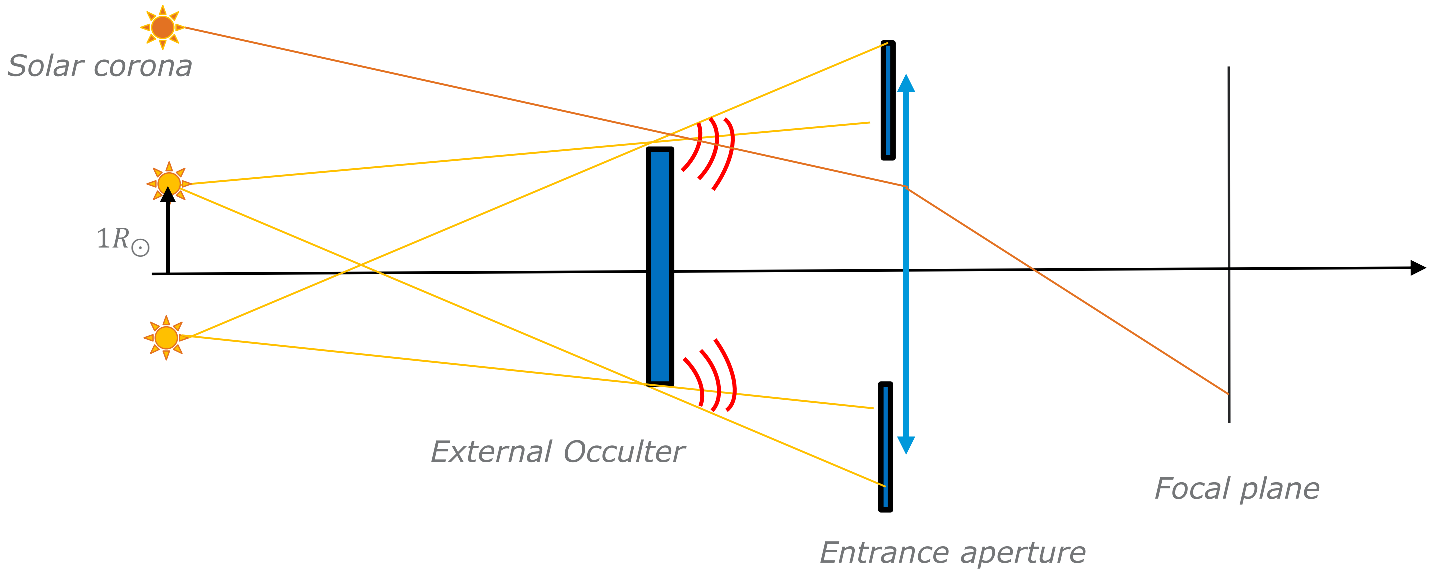


- Because of the wave nature of light, **diffraction of sunlight** contaminates the observations, and has to be removed as well.
  A field stop blocks this diffracted light on the pupil plane: **the Lyot stop**.

Development of solar coronagraphy

- The classical Lyot coronagraph is said internally occulted.

- **External occultation technique** (Evans, 1948).
  The solar coronagraph is then said externally occulted.
  The external occulter diffracts and scatters sunlight as well.



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- Occulting discs with **complex shapes**, to lower the scattered light:
  - toothed discs (Purcell & Koomen, 1962, Fort et al., 1977).
  - multiple discs (Newkirk & Bohlin, 1963, Lensky, 1981).
  - torus, barrel, cone (Exp. studies: Bout et al., 2000, Landini et al., 2011).

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Development of solar coronagraphy

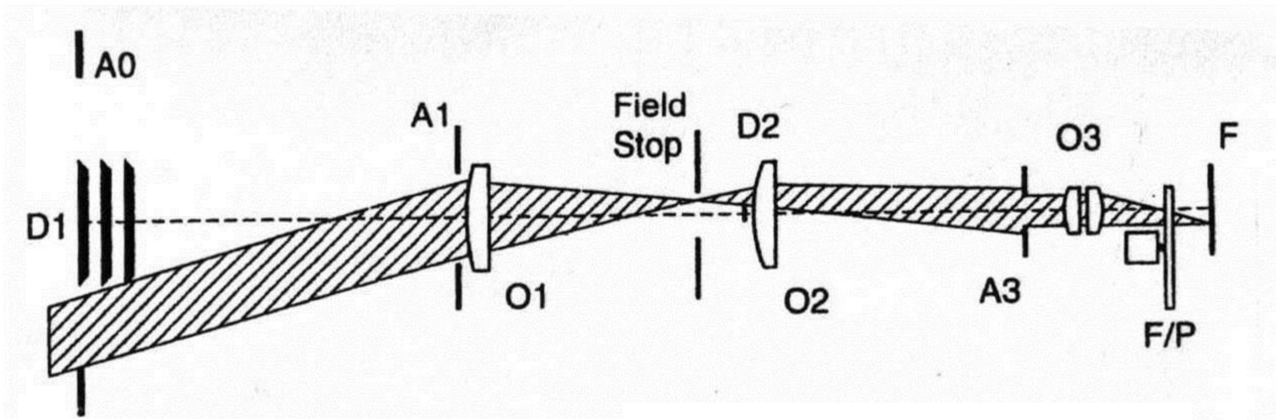
- Spaceborne coronagraphy: review described in Koutchmy, 1988.
  Advantages: get rid off atmosphere turbulences/scattering.

- LASCO solar coronagraphs of the SOHO mission (Brueckner et al., 1995)
  Three solar coronagraphs (C1, C2 and C3) of different concepts.

- LASCO C2
  - External occulter (multiple sharp thread discs on a cone)
  - Classical Lyot coronagraph with a Lyot mask/Lyot stop
  - **Hybrid externally occulted Lyot solar coronagraph**

LASCO C2 & C3

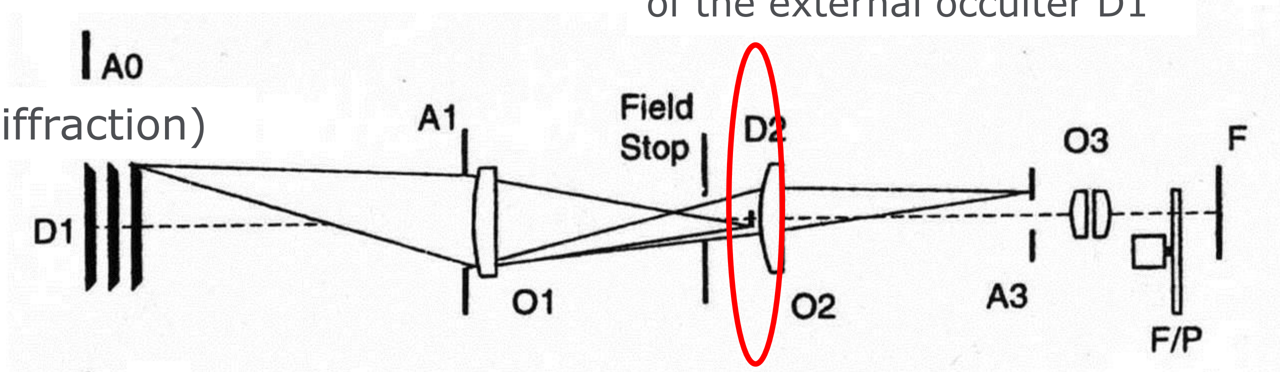
Hybrid externally occulted Lyot solar coronagraph



Ray bundle from the solar corona

Image conjugate plane
of the external occulter D1

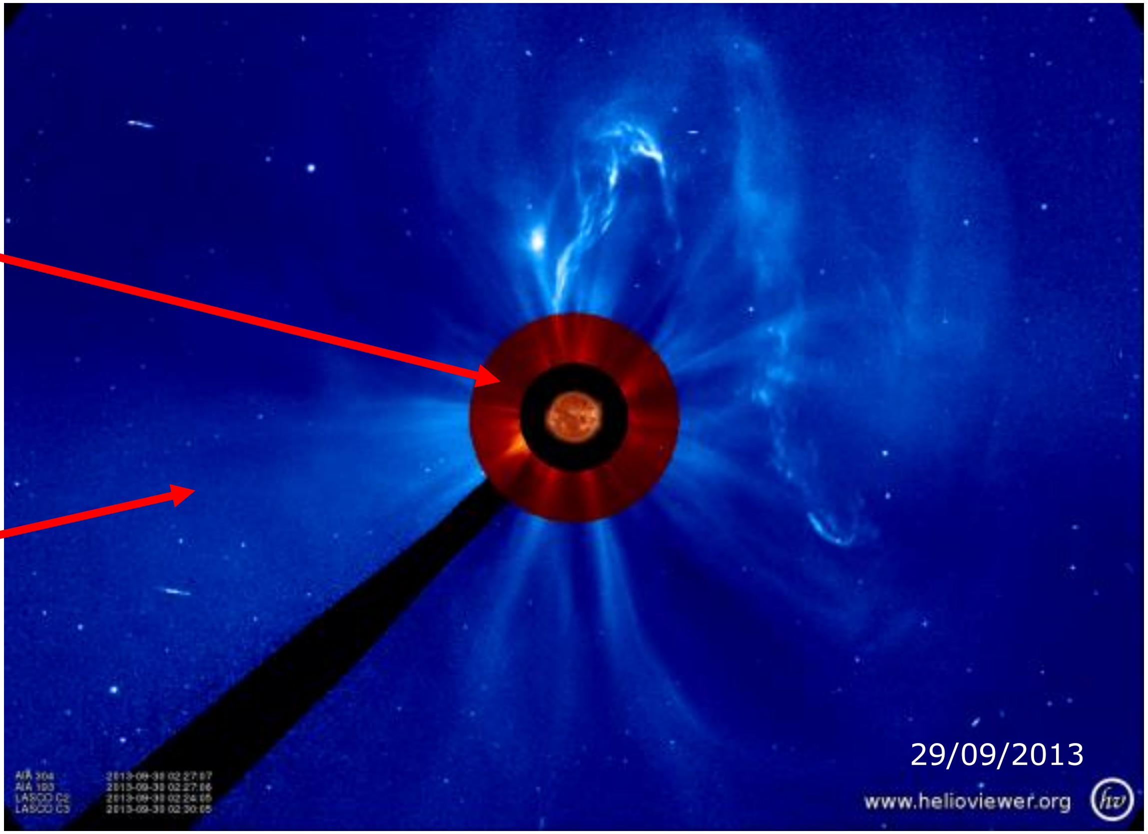
Stray light (diffraction)



Conceptual diagram for LASCO C2 and C3 (Brueckner et al., 1995)

C2 FoV: 1.5 – 6 R_{sun}

C3 FoV: 3.7 – 30 R_{sun}



The resulting CME from the filament eruption observed by the SOHO LASCO C2 and C3 coronagraphs. The solar disk is an SDO 304/193 Angstrom image.

ASPIICS coronagraph

- ASPIICS is based on the same concept as LASCO C2
  Hybrid externally occulted Lyot solar coronagraph
  Lamy, 2010, Renotte, 2015, and Galy, 21015

- *Advantages:* Formation Flying provides a long-baseline (150m).
  The instrument is split into two spacecraft.
  For the same occultation, the resolution/signal of the corona is better.

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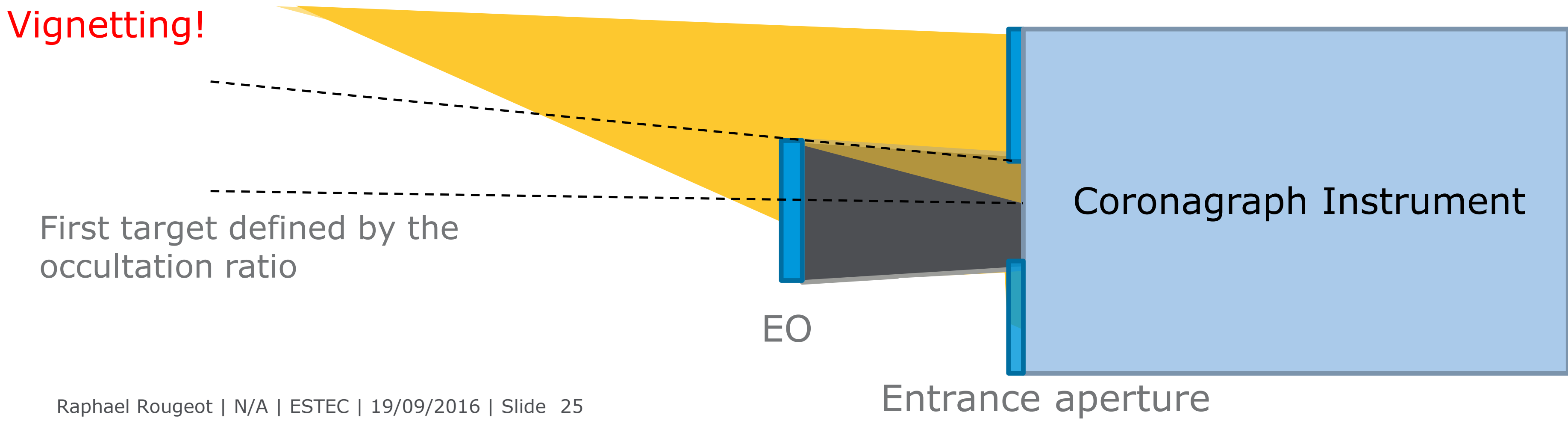

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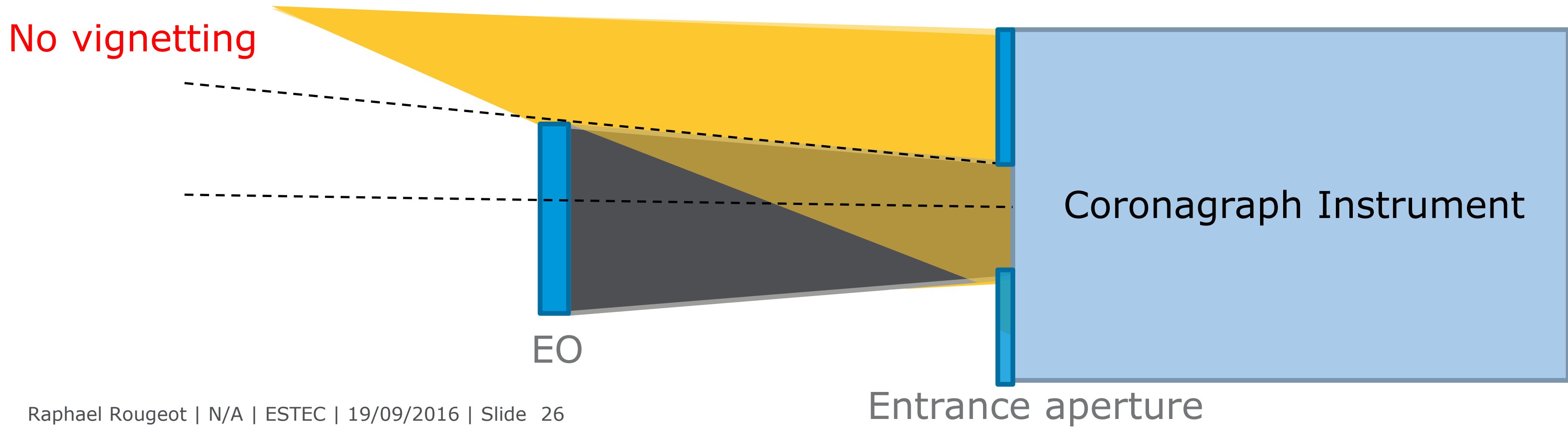

Outline

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- Need of analyzing the **end-to-end performance** of solar coronagraphs through **dedicated analytical study**.

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- Few theoretical/analytic studies (Fort, 1977, Lensky, 1981, Aime et al.)
  Experimental/laboratory studies
  (Bout et al., 2000, Venet et al., 2010, Landini et al., 2011)

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- Few theoretical/analytic studies (Fort, 1977, Lensky, 1981, Aime et al.)
  Experimental/laboratory studies
  (Bout et al., 2000, Venet et al., 2010, Landini et al., 2011)

- The performance of hybrid externally occulted Lyot coronagraph has never been analytically/extensively studied.
  This is what we did!

  Rougeot R., Flamary R., Galano D., Aime C., A&A (2016)
  "Performance of hybrid externally occulted Lyot solar coronagraph"

Numerical study of diffraction

- *Objectives:* analytical (theoretical) performance of solar coronagraphs, especially the hybrid externally occulted Lyot coronagraph.

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- *Method:* analytical.
  - Sun defined as a collection of point sources.
  - Diffraction from the EO (Aime, 2013).
  - **Coherent propagation** process inside the coronagraph (Aime, 2002).
  - Incoherent summation of elementary intensities.

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  - Coherent propagation process inside the coronagraph (Aime, 2002).
  - Incoherent 2D-summation of elementary intensities from every solar point sources.

- *Results:* **theoretical performance** in stray light rejection.
  - comparison of different coronagraphic systems.
  - study on sizing the dimension of the Lyot mask and stop.

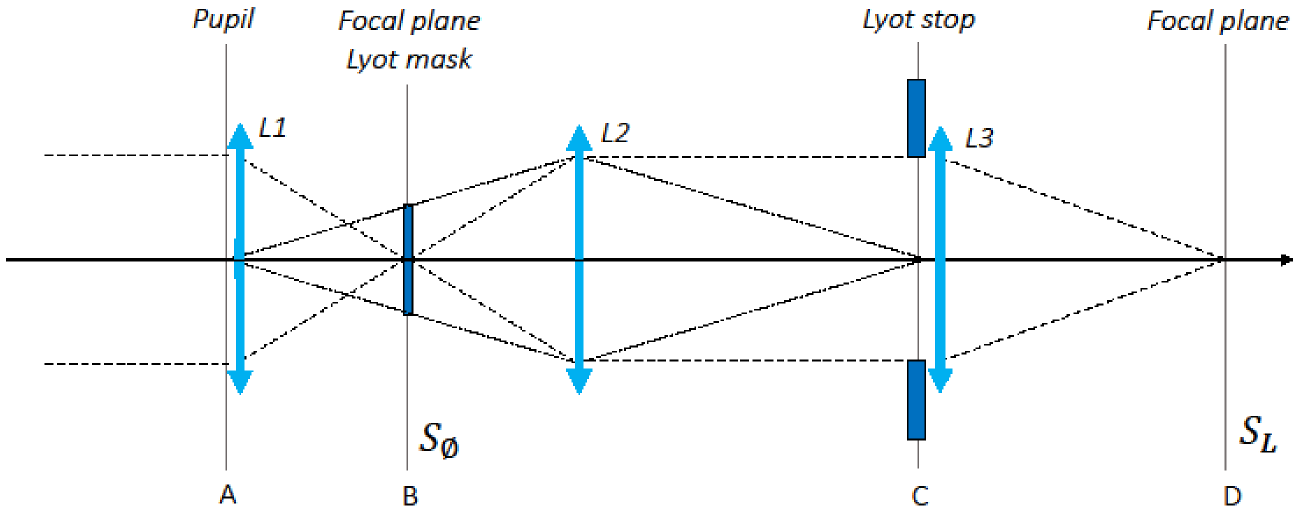
Fourier Optics

- *Frame of work:* **Fourier Optics** (Born & Wolf, 2006, Goodman, 2005) Fresnel free space wave propagation of light.

- *Assumptions:*
  - **Ideal perfect optics.**
  - All planes of interest are parallel and aligned ➔ axis-symmetry.
  - Small angles.

Definition of the system

- Different key planes are used to describe the classical Lyot coronagraph:
  - **Plane A**: the pupil plane. The entrance aperture + L1.
  - **Plane B**: the focal plane. Lyot mask + L2.
  - **Plane C**: the pupil plane (image). Lyot stop + L3.
  - **Plane D**: final focal plane. Detector.



Aime, 2002

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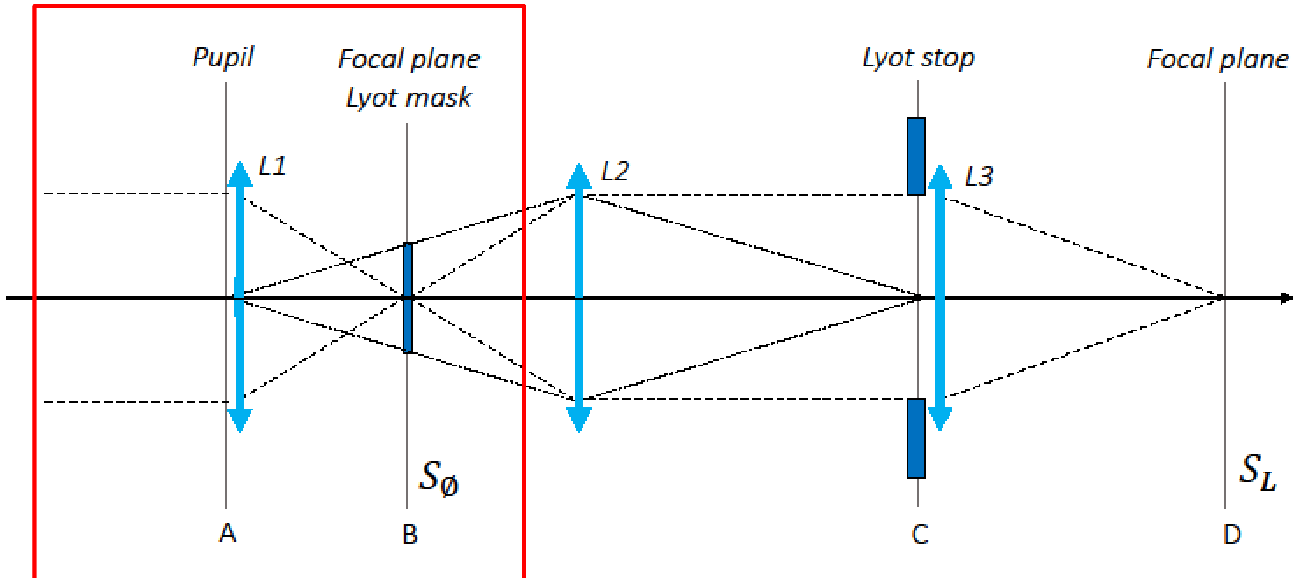

$S_\emptyset$ the reference telescope

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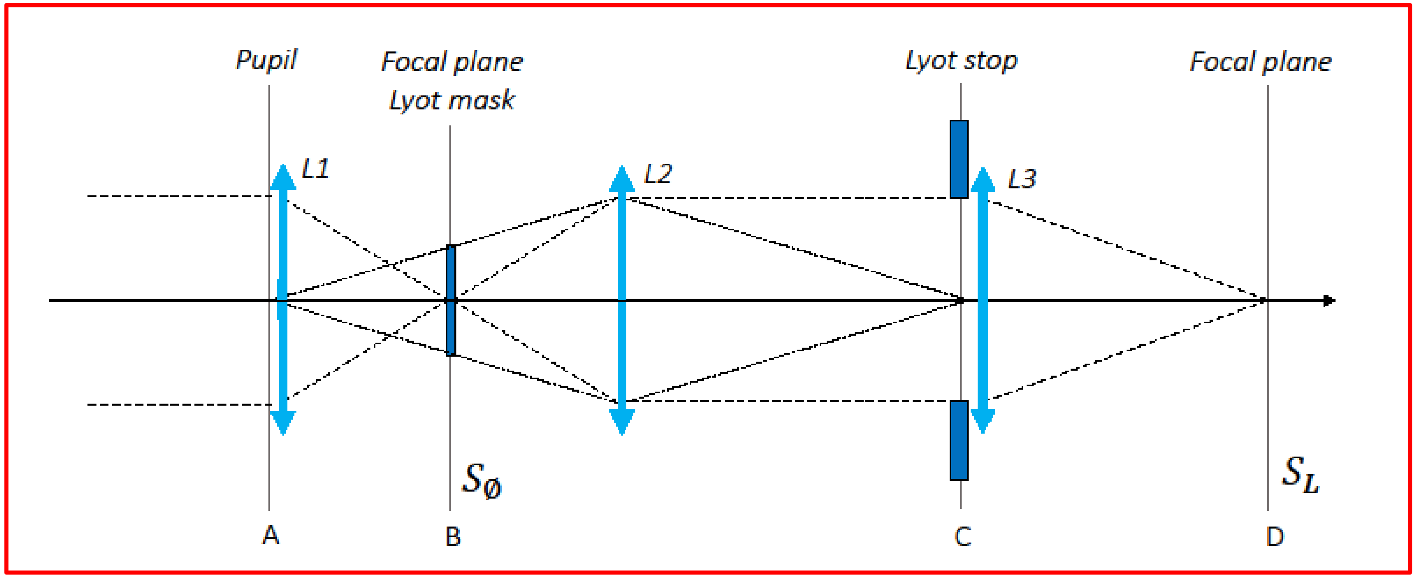
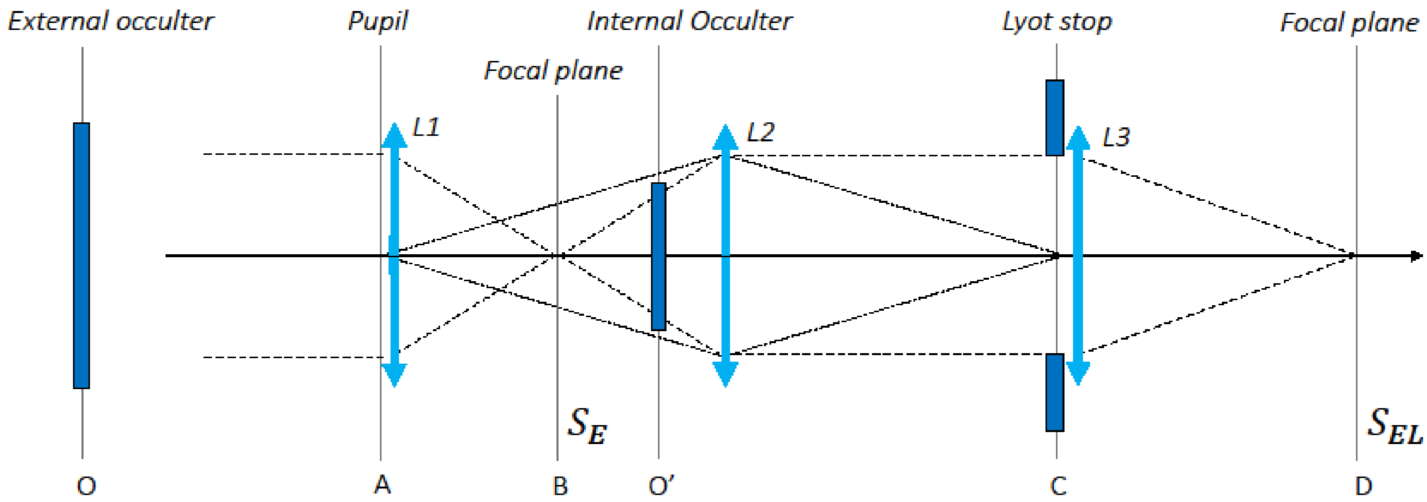


S_L the classical Lyot coronagraph (internally occulted)

Definition of the system

- Two other planes have been added:
  - **Plane O**: the external occulter plane.
  - **Plane O'**: Image conjugate plane of plane O. Internal occulter + L2



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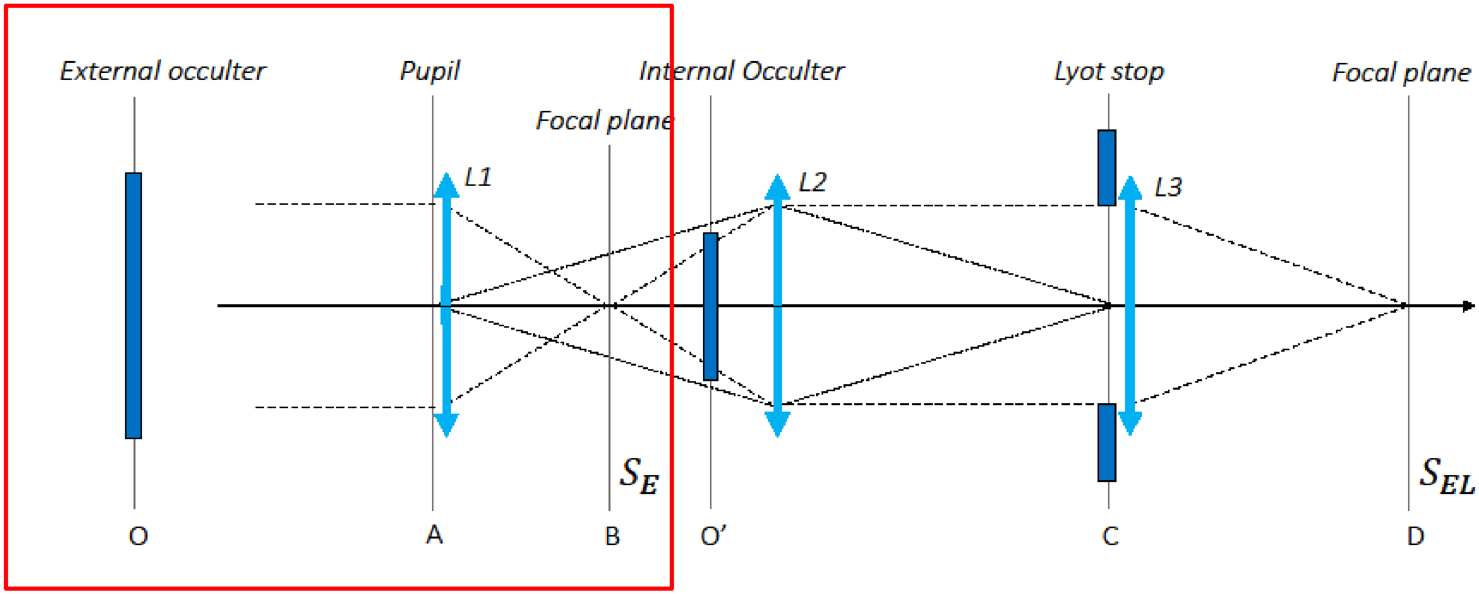

S_E the externally occulted coronagraph

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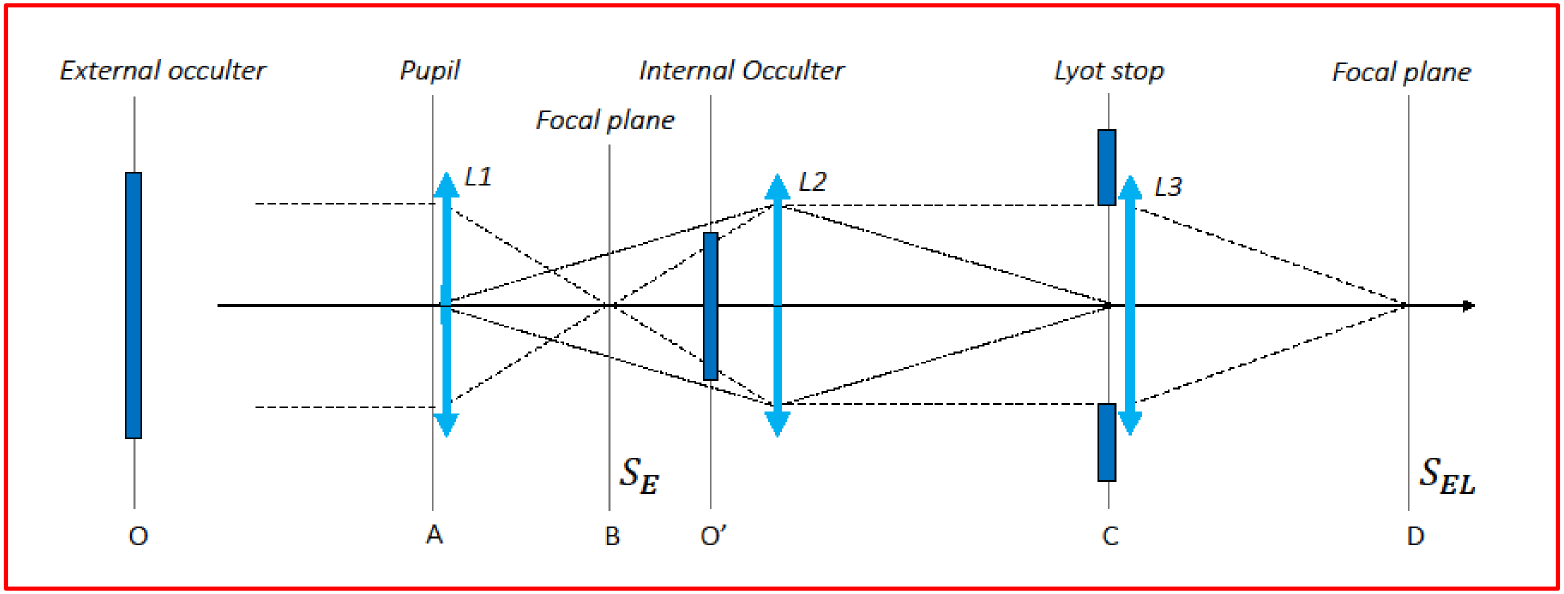


S_{EL} the hybrid externally occulted Lyot coronagraph

Parameters of the study

- The parameters for our numerical study are matched to ASPIICS configuration.

Parameters	Value
Wavelength	$\lambda = 550nm$
Angular radius of the Sun	$R_{\odot} = 0.00465421rad$
Distance to the Sun	$\infty\ (1AU)$
Radius of the External Occulter	$R = 710mm$
Distance plane O – plane A	$z_0 = 144.348m$
Radius of the entrance pupil	$R_p = 25mm$
Focal length (plane A – plane B)	$f = 330.385m$

Outline

Objectives

- *What do we want?*
  - Quantify the **level and the distribution of residual sunlight** (diffraction).
  - For the three coronagraphic systems, on the final focal plane.
  - Address the question of sizing the Lyot mask and stop.

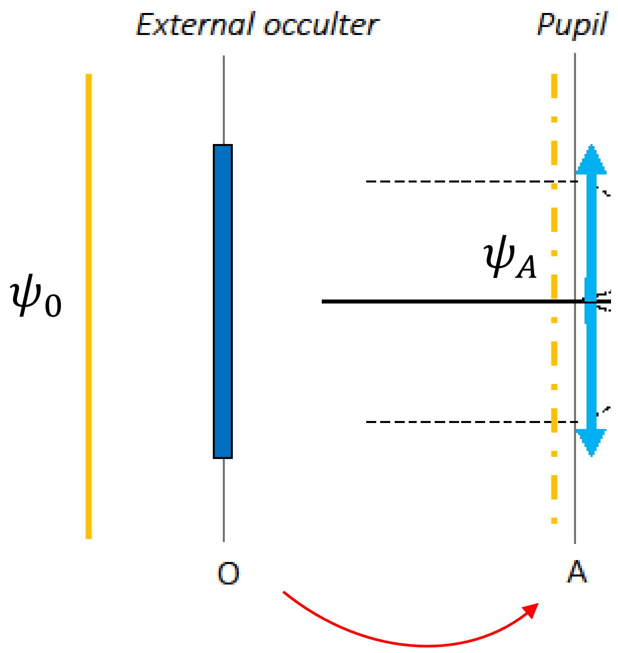
- *What did we do?*
  - Computation of the coherent propagation for every solar point sources.
  - Computation of the incoherent 2D-summation of elementary intensities.
  - For the three coronagraphic systems, on every plane.

- We will now go through the results plane after plane
  A → B → O’ → C → D

Diffraction from the external occulter

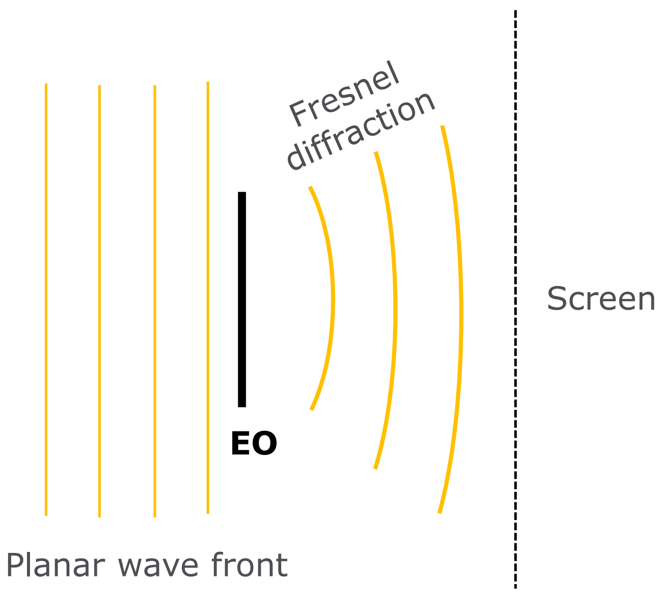
- Approach from Aime, 2013, A&A 558, 138
  "Theoretical performance of solar coronagraphs
  using sharp-edged or apodized circular external occulter".

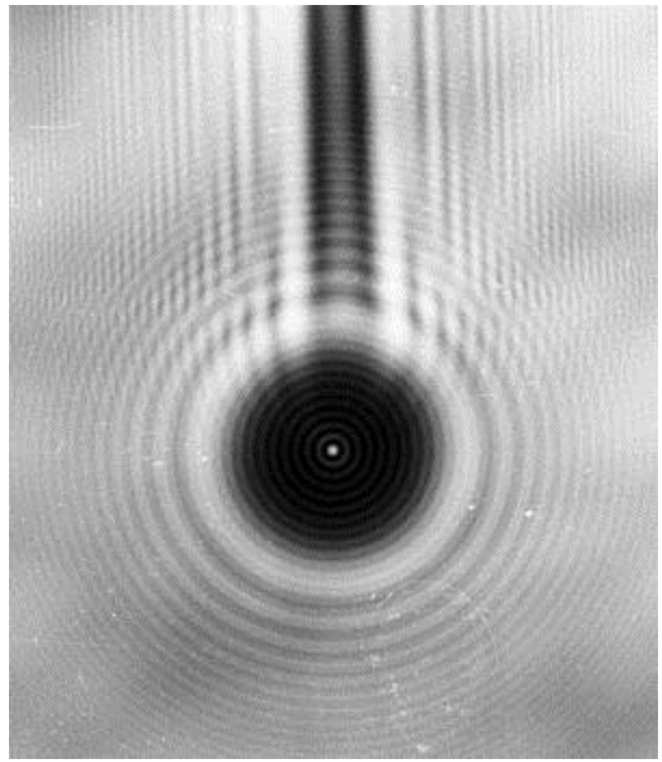
- **Fresnel diffraction** of planar wave front
  from a point source at infinity
  by a perfect sharp-edged occulting disc.



Plane A: Diffraction from the external occulter

Bright spot of Arago from the on-axis point source (Plane A)

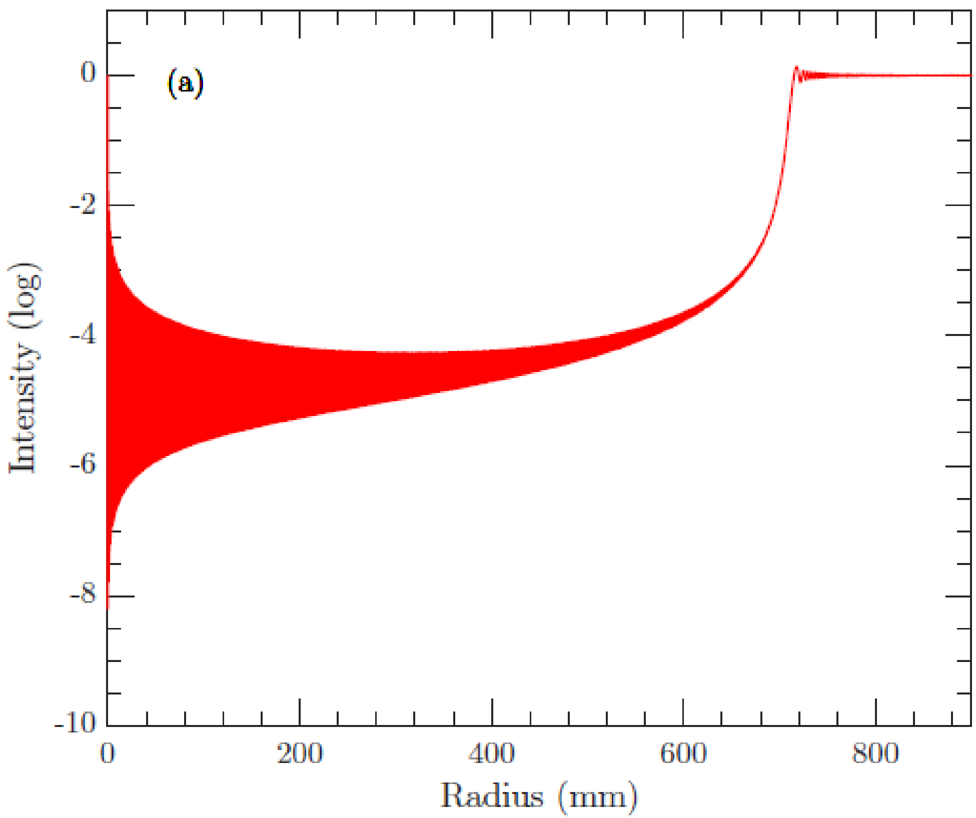


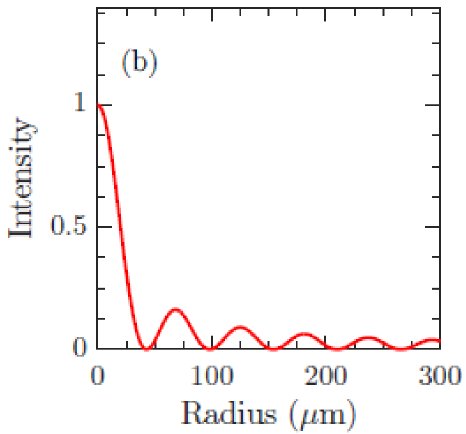


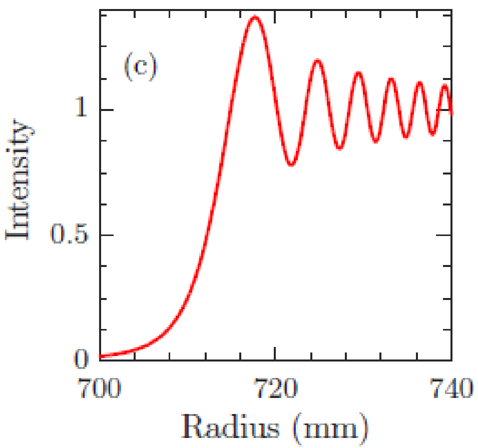
Credit: Minerva.union.edu

Diffraction from the external occulter

Bright spot of Arago from the on-axis point source (Plane A)
Computation using Nintegrate in *Mathematica* (Wolfram, 2012)

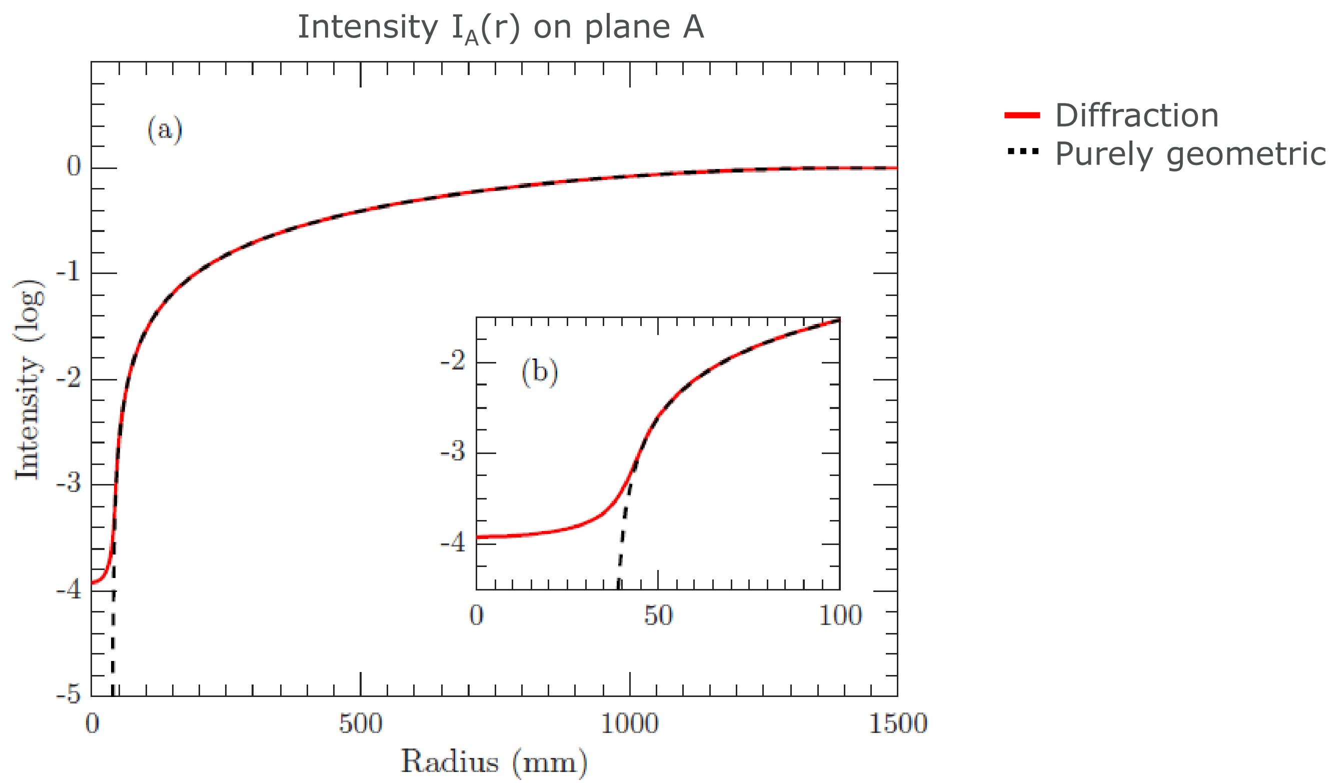






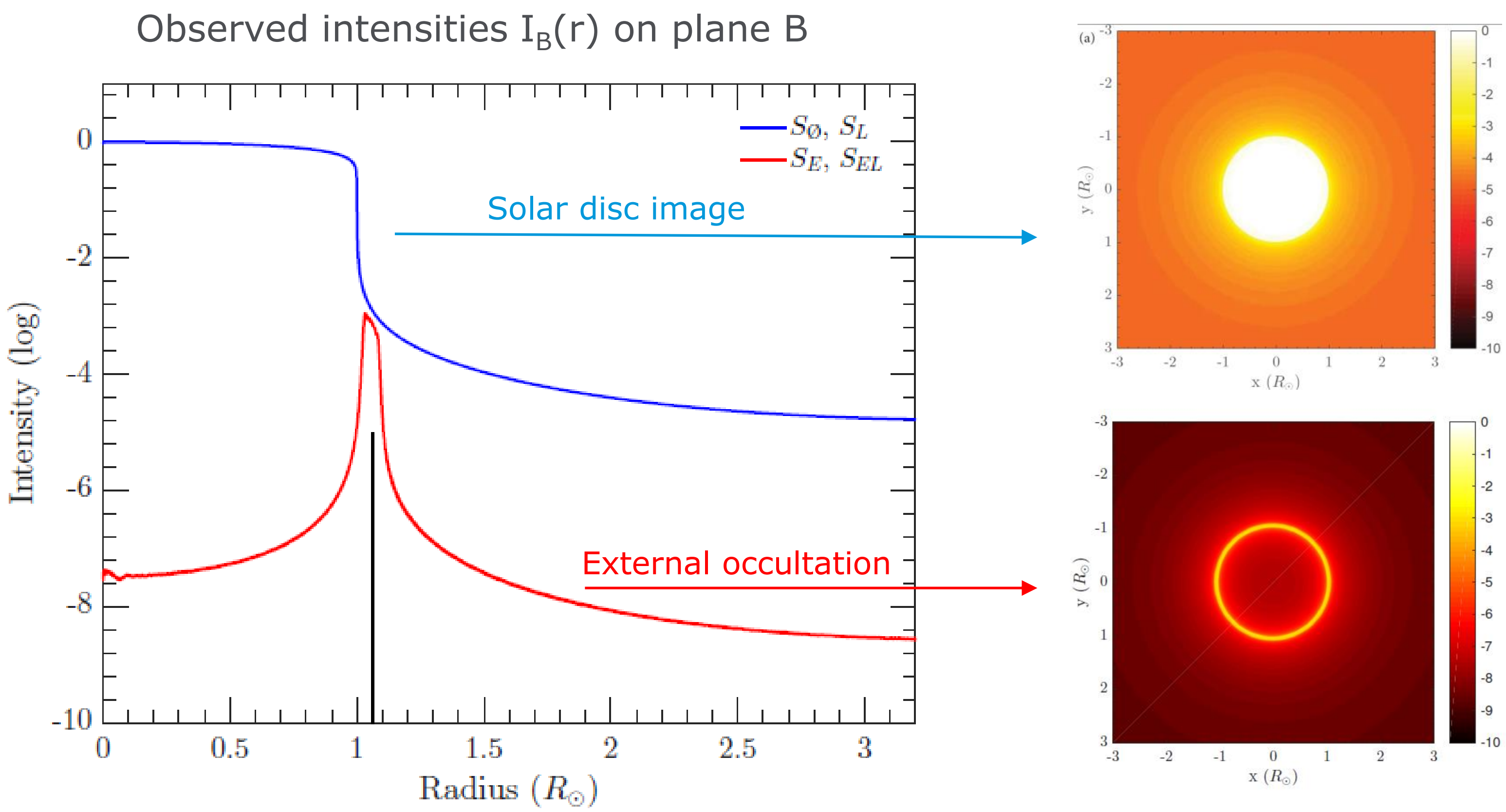
Plane A: penumbra profile

Including the **external occulter** on plane O



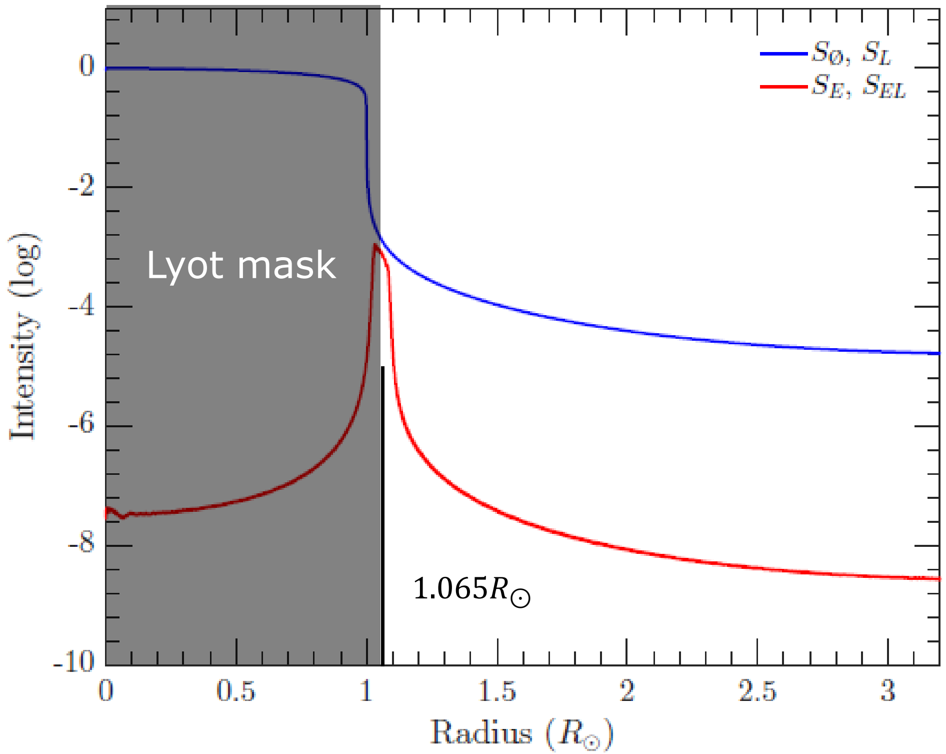
Rejection to 10^{-4}
Bout et al., 2000

Plane B: focal plane



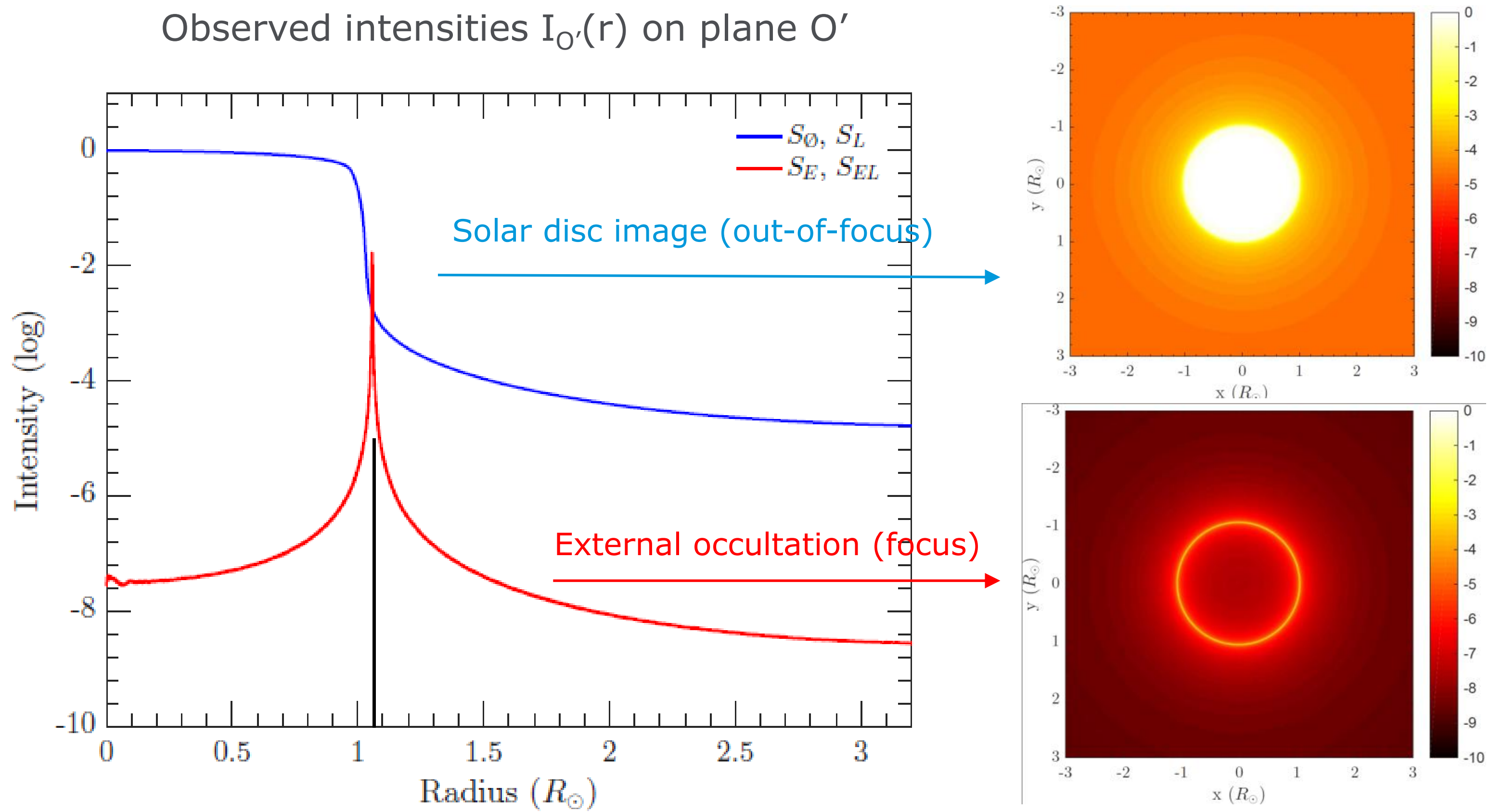
Plane B: focal plane

Observed intensities $I_B(r)$ on plane B



Plane O': image plane of the EO

Observed intensities $I_{O'}(r)$ on plane O'



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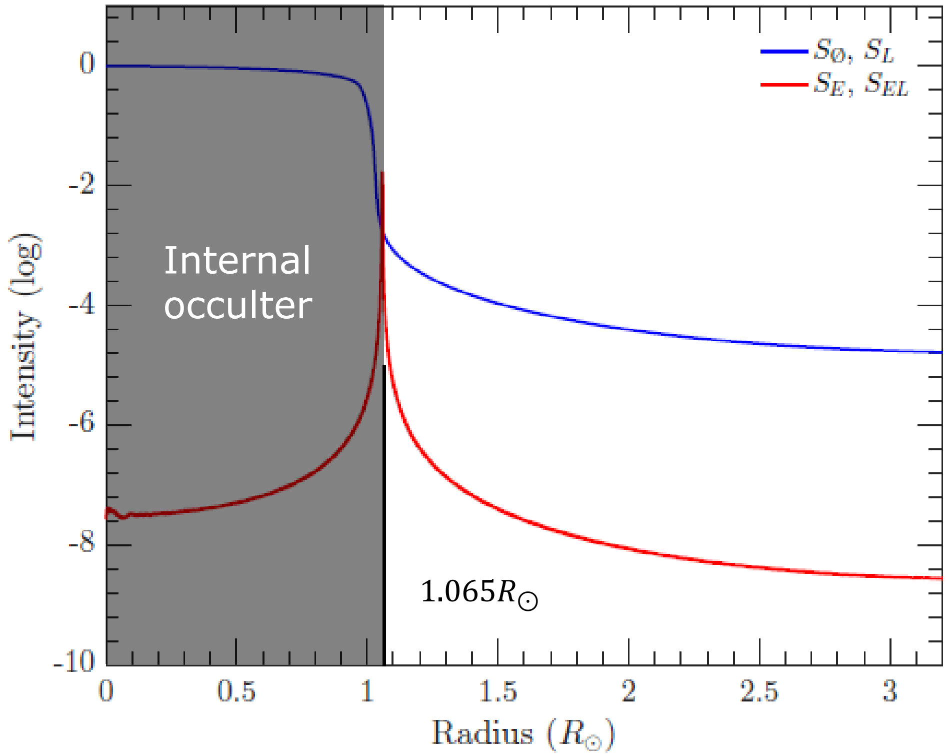
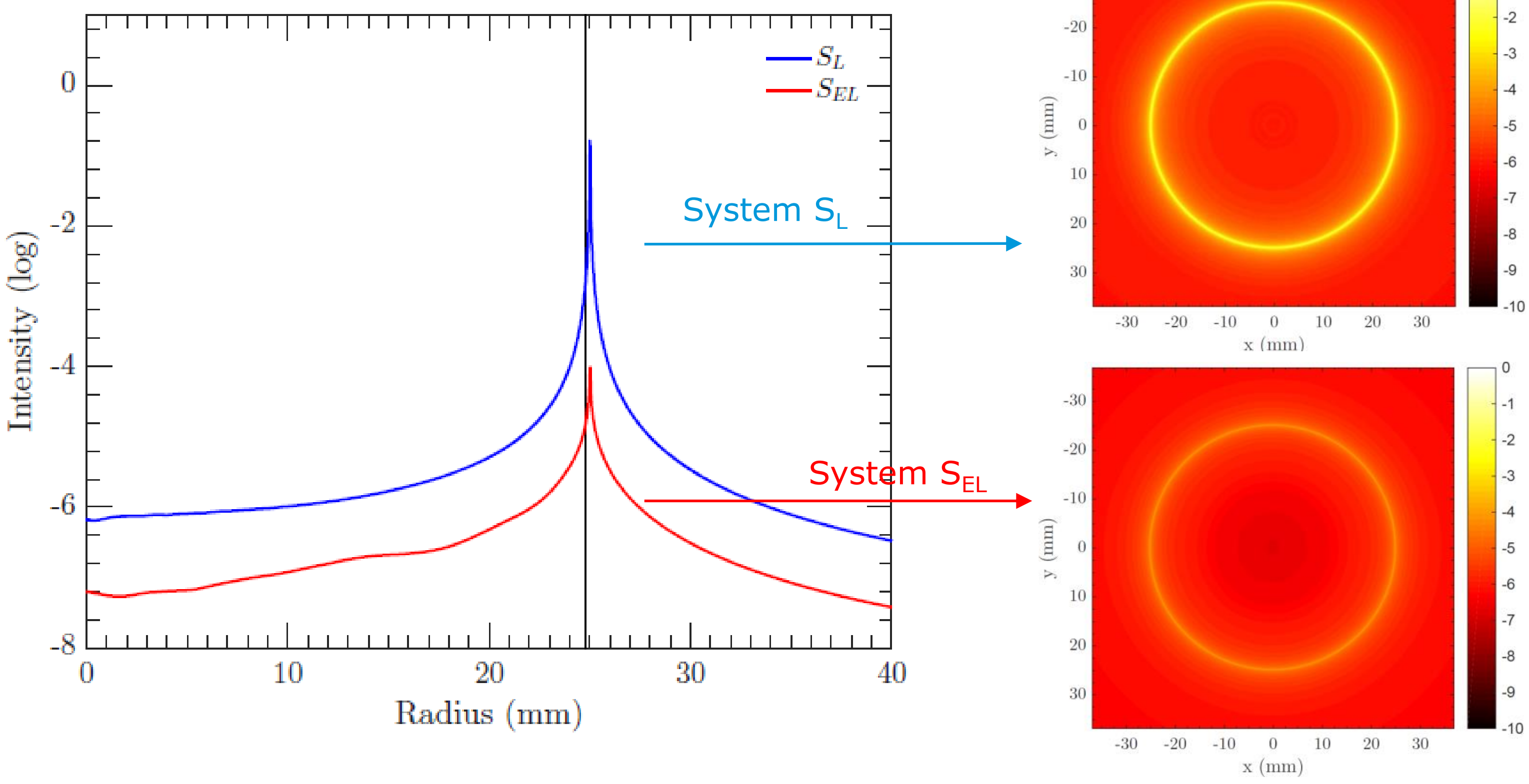


Plane C: image plane of the pupil

Observed intensities $I_C(r)$ on plane C



Plane C: image plane of the pupil

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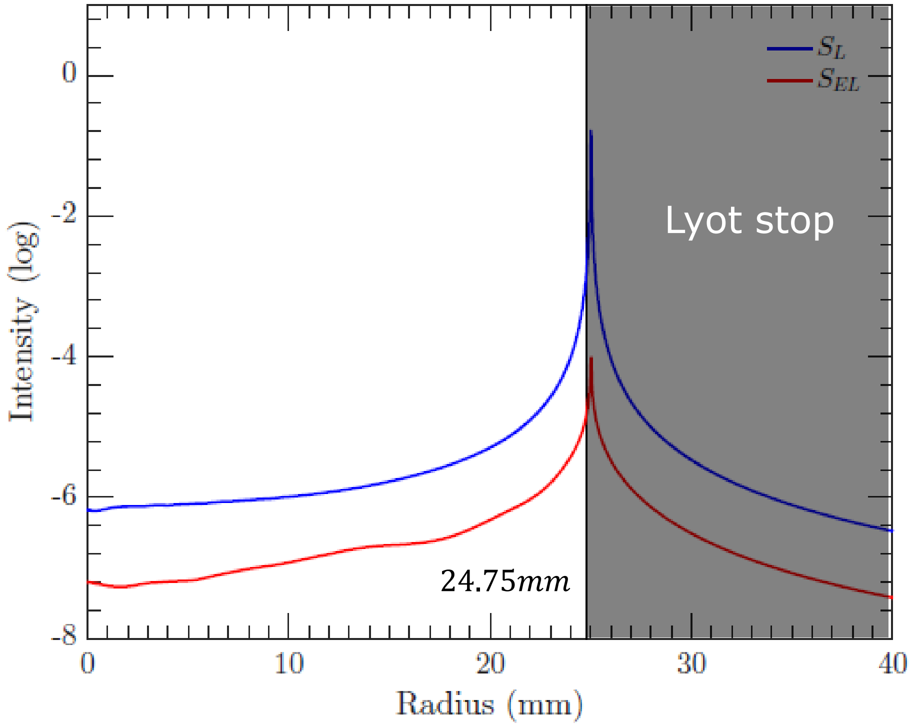
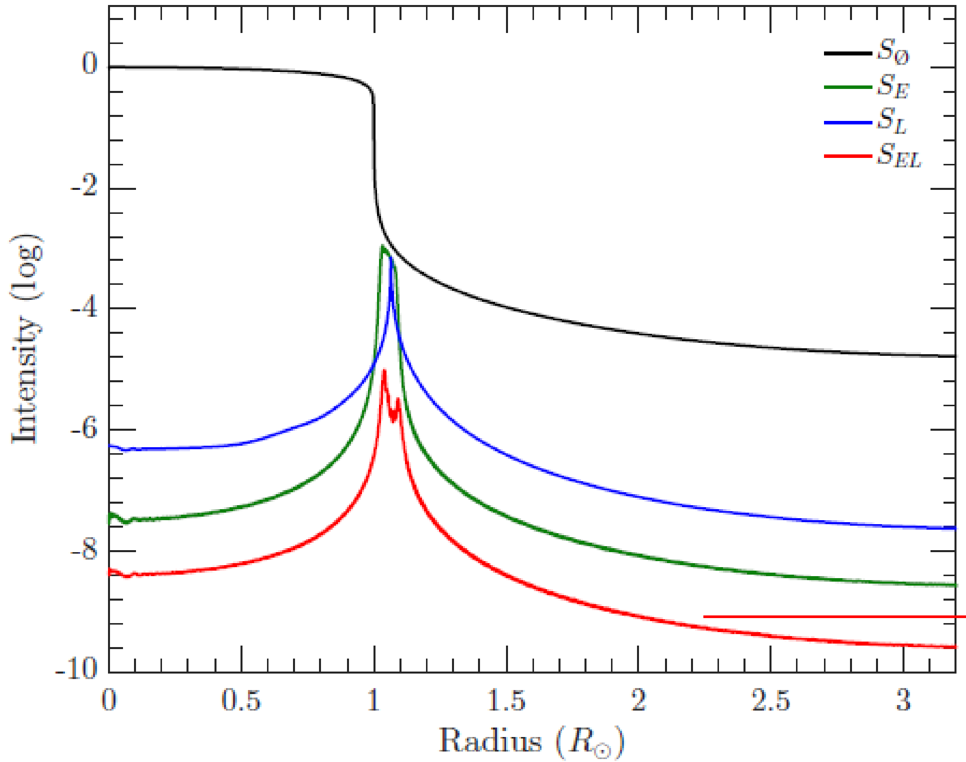
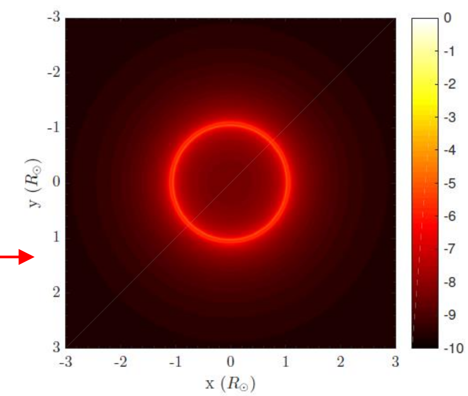


Plane D: final focal plane

Final observed intensities





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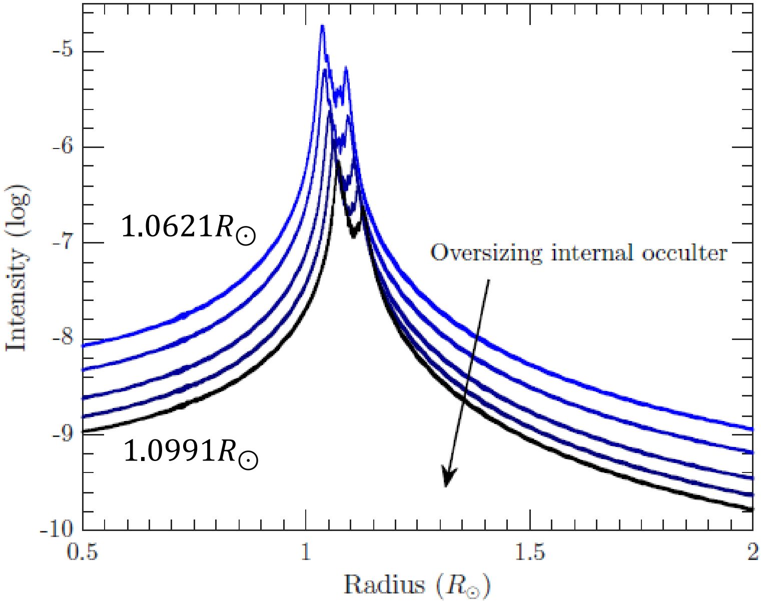
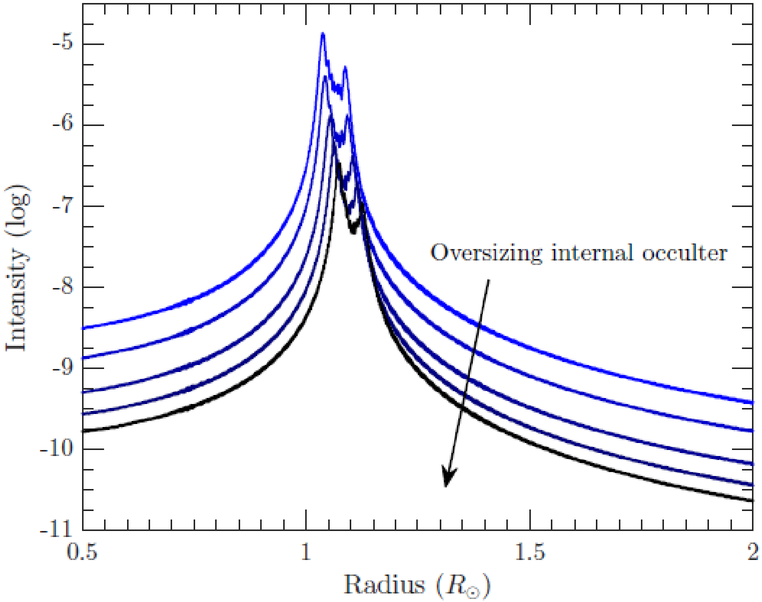
Sizing the internal occulter

Final observed intensities $I_D(r)$ of the hybrid coronagraphic system S_{EL}



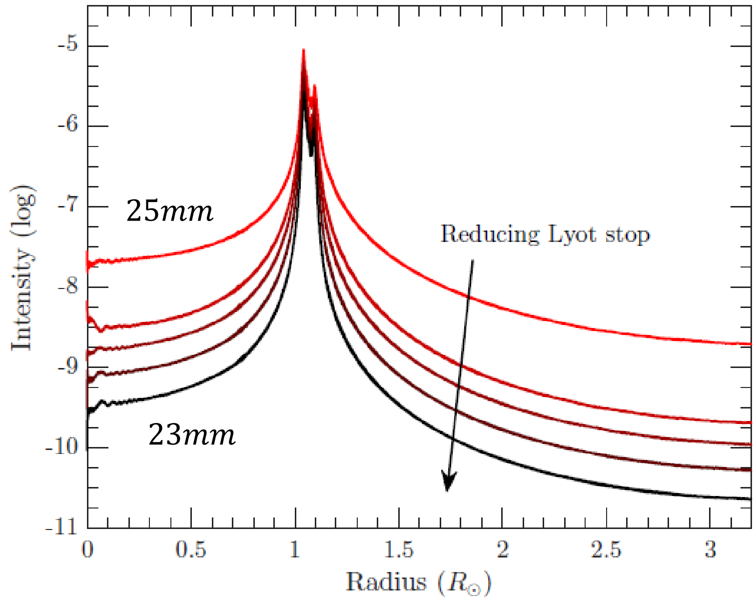
Lyot stop of 24.75mm



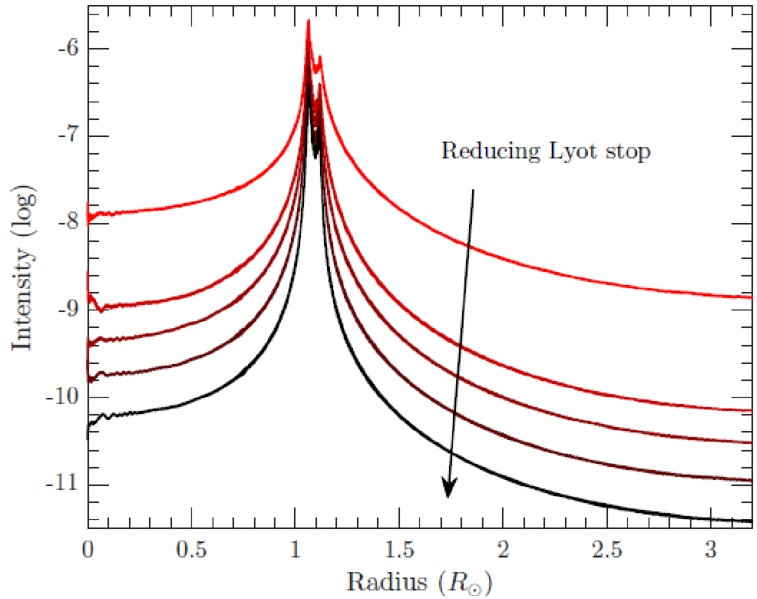
Lyot stop of 24.00mm

Sizing the internal occulter

Final observed intensities $I_D(r)$ of the hybrid coronagraphic system S_{EL}



Internal occulter of $1.0674 R_\odot$

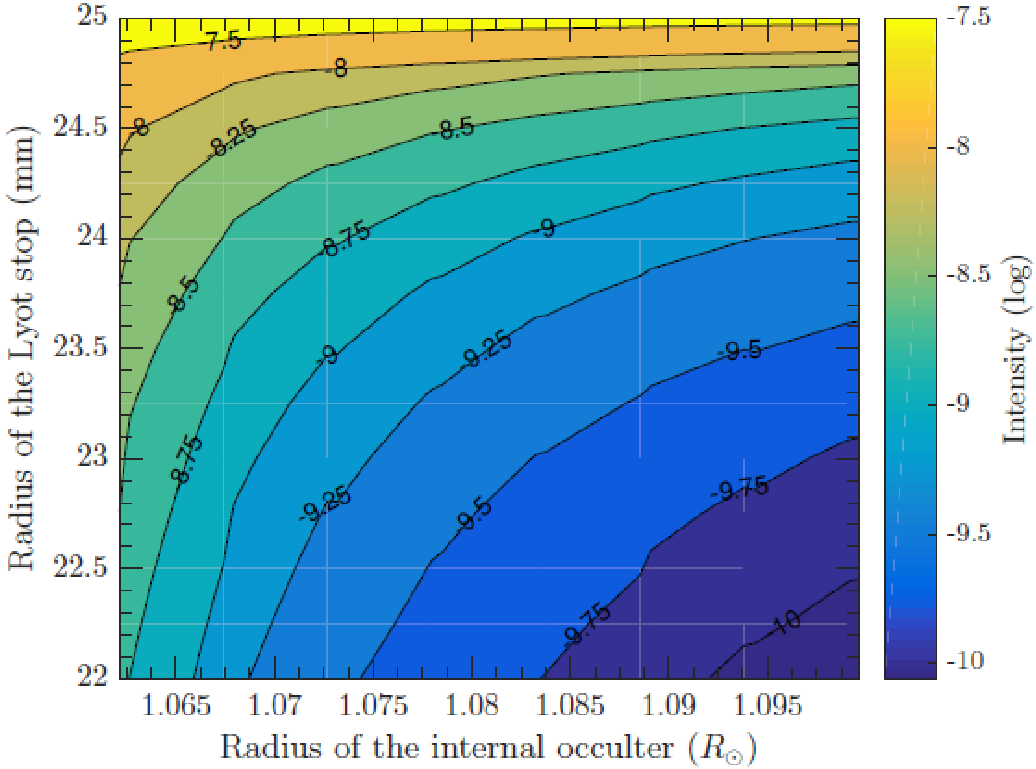


Internal occulter of $1.0779 R_\odot$

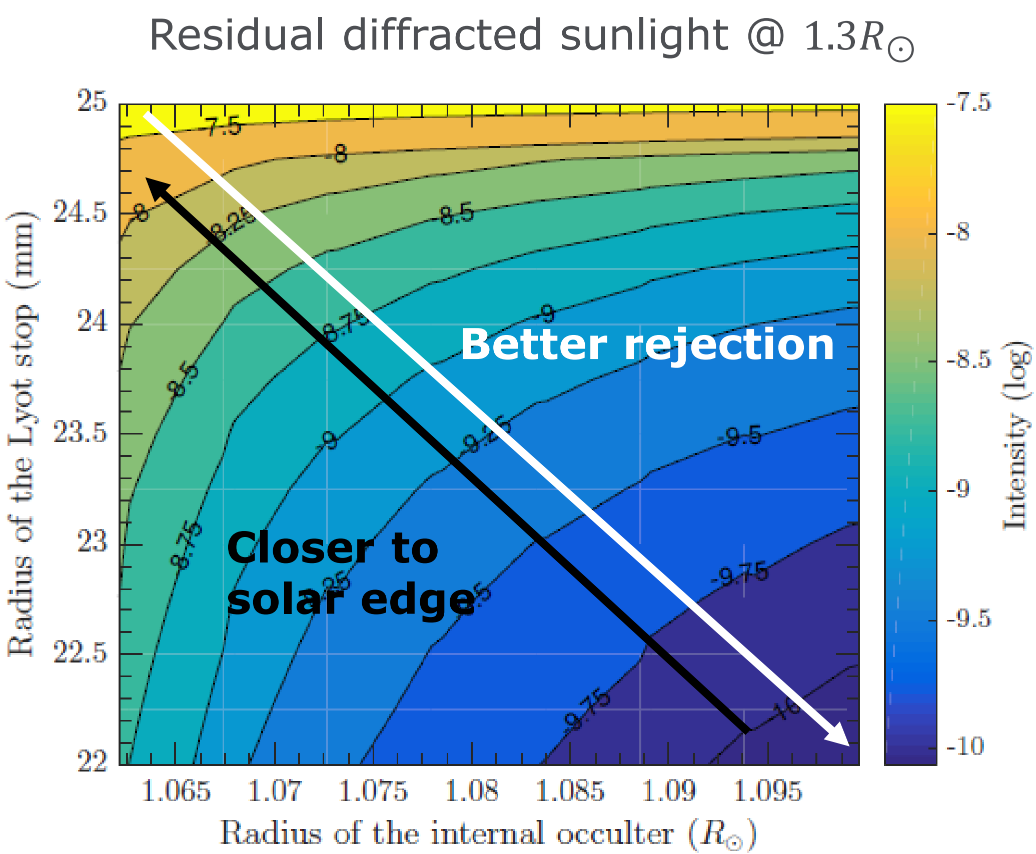
European Space Agency

Dimension of the IO and the Lyot stop

Residual diffracted sunlight @ $1.3R_\odot$



Dimension of the IO and the Lyot stop



Outline

1. Proba-3 mission
2. The corona of the Sun
3. Solar coronagraphy
4. Numerical study of performance
5. Observed intensities
6. Sizing the Lyot mask and stop
7. Conclusion

Conclusion

- *Objectives:* to develop an analytical and numerical study of the theoretical performance of solar coronagraphs such as ASPIICS.

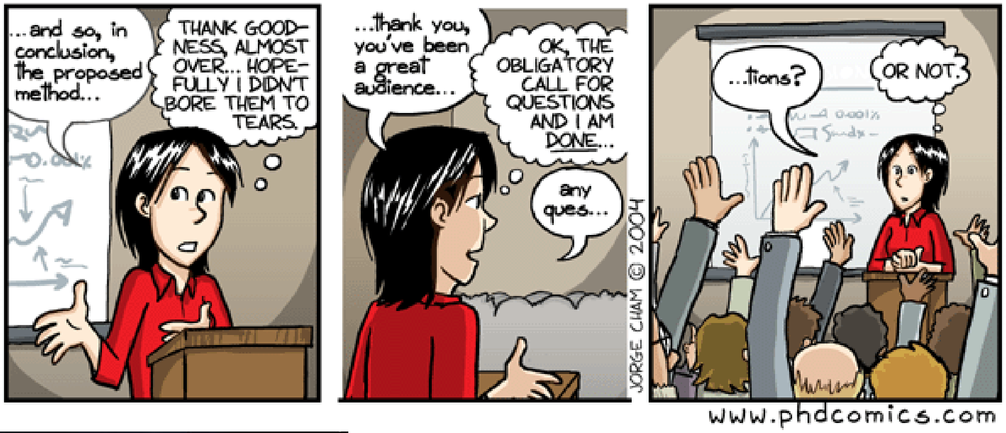
- *We did:* analytically
  - **Novel computation of theoretical end-to-end performance**.
  - Computation of the stray light rejection.
  - Comparison of different coronagraphic systems.
  - Study on sizing the dimension of the Lyot mask and stop.

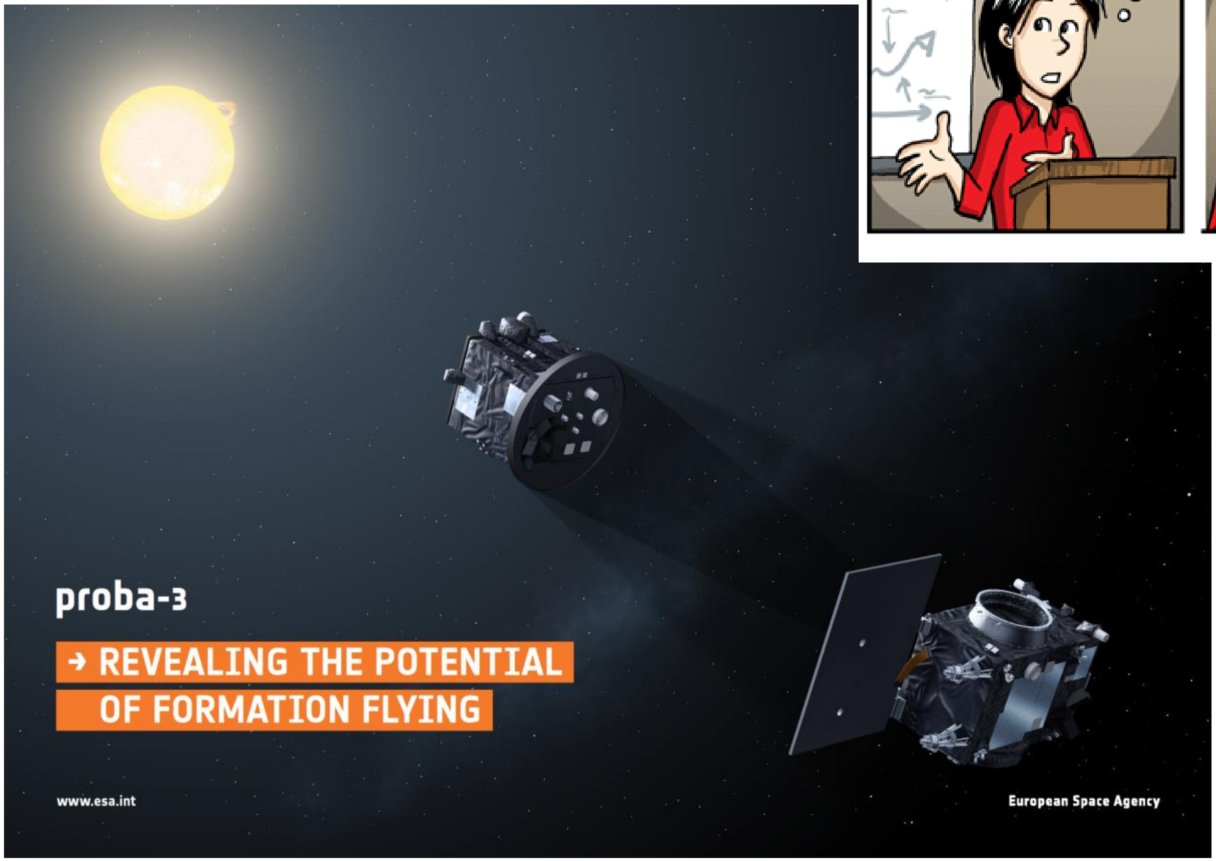
- *Conclusion:*
  - We proved the performance of the hybrid externally occulted Lyot coronagraph.
  - Support to the solar astronomer and ASPIICS design.

Future activities

- Misalignment (in case of FF), tilt…
- Other types/shapes of occulters.
- Apodization of the entrance pupil.
- Non-perfect optics, deviation from the ideal model.
- Experimental assessements, confrontation.

Questions?


...and so, in conclusion, the proposed method...
THANK GOODNESS, ALMOST OVER... HOPEFULLY I DIDN'T BORE THEM TO TEARS.
...thank you, you've been a great audience...
OK, THE OBLIGATORY CALL FOR QUESTIONS AND I AM DONE...
any ques...
JORGE CHAM © 2004
...tions?
OR NOT.
www.phdcomics.com


proba-3
→ REVEALING THE POTENTIAL OF FORMATION FLYING
www.esa.int
European Space Agency

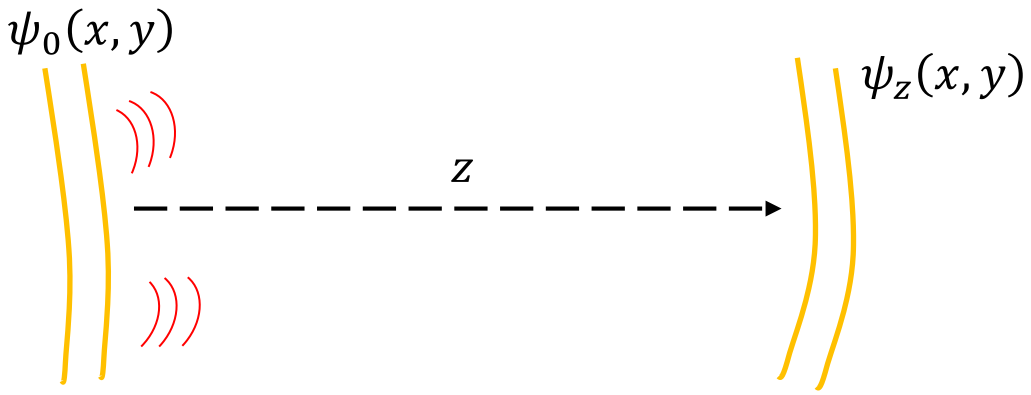
Outline

Wave propagation

- **Fresnel free space wave propagation of light**
- Propagation over a distance z

  Convolution by free space propagator $\frac{1}{i\lambda z}\exp\left(+i\pi\frac{x^2+y^2}{\lambda z}\right)$

$$\psi_z(x,y) = \frac{e^{i\pi\frac{x^2+y^2}{\lambda z}}}{i\lambda z} \times FT\left[\psi_0(x,y) \times \frac{1}{i\lambda z}\exp\left(+i\pi\frac{x^2+y^2}{\lambda z}\right)\right]$$



Wave propagation

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- Converging (perfect) lens of focal *f*: $\exp\left(-i\pi\frac{r^2}{\lambda f}\right)$

- Propagation to the **focal plane**: $z = f$

Wave propagation

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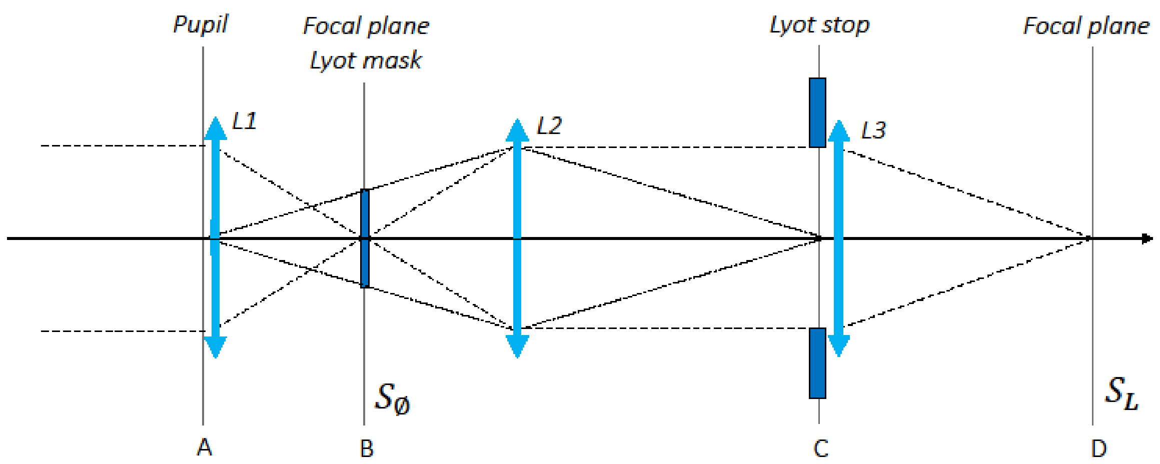
- Propagation to the **focal plane**: $z = f$

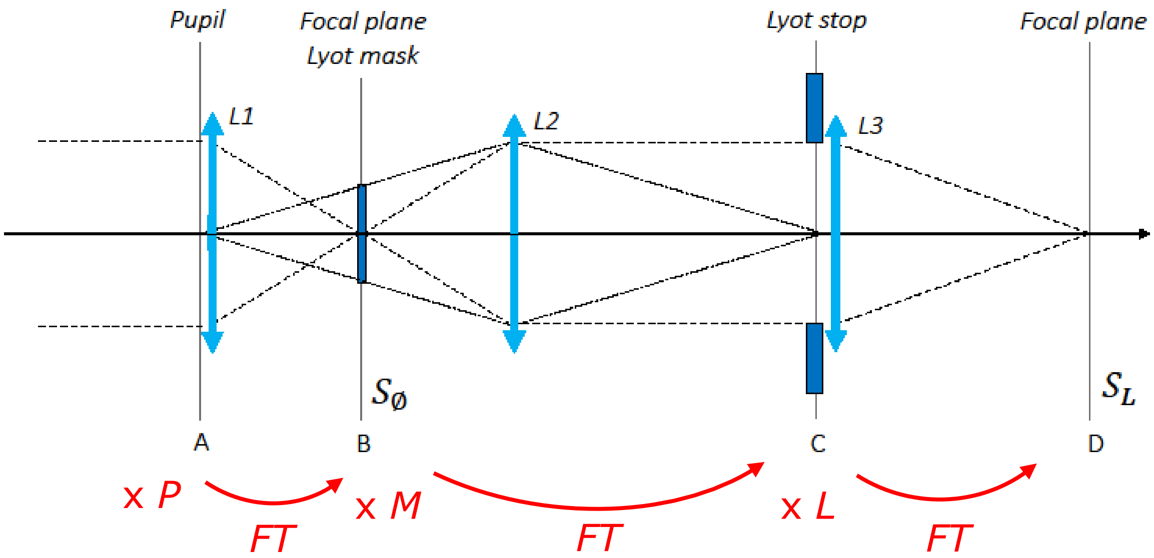
  A **simple Fourier transformation** of the incoming wave front!

$$\psi_{z=f}(x,y) = \frac{e^{i\pi\frac{x^2+y^2}{\lambda f}}}{i\lambda f} \times FT[\psi_0(x,y)]$$

Wave propagation



Wave propagation

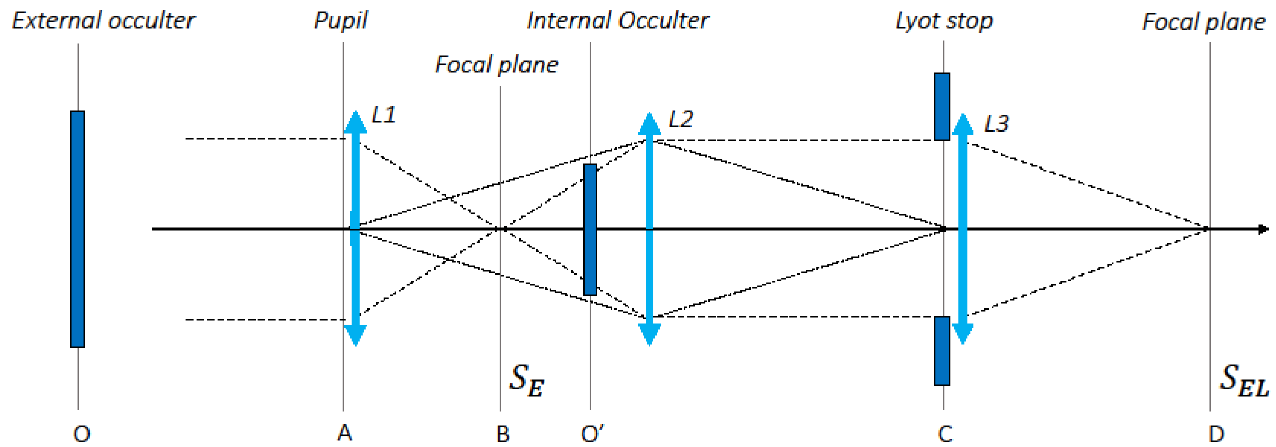


- Ψ_A : Planar incoming wave front

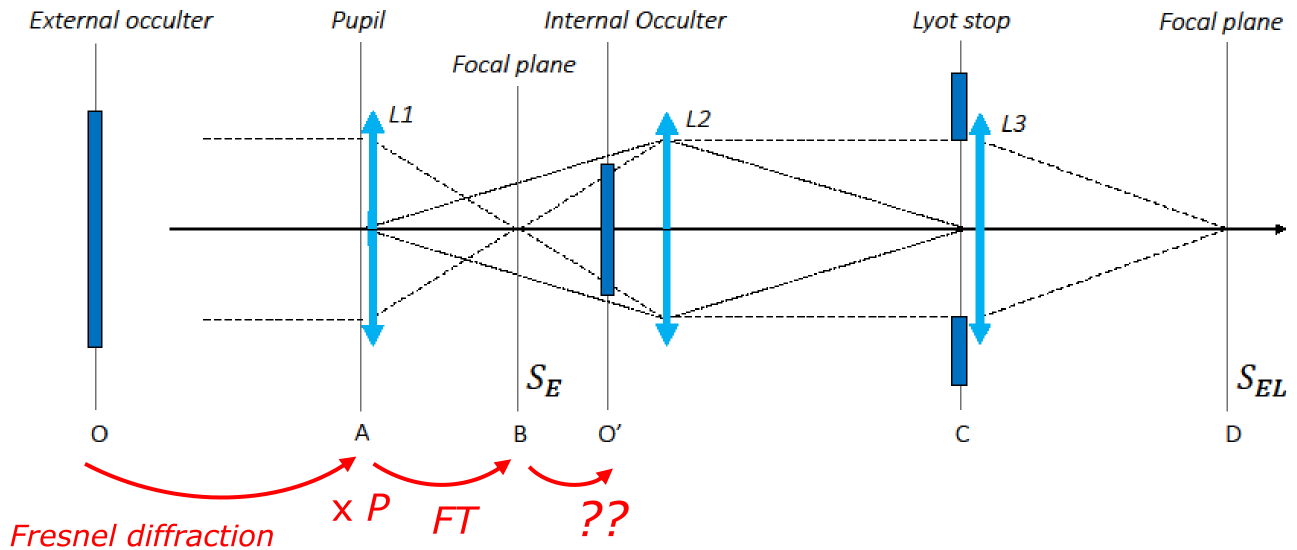
$$\Psi_B = FT[\Psi_A \times P]$$
$$\Psi_C = FT[\Psi_B \times M]$$
$$\Psi_D = FT[\Psi_C \times L]$$

Aime, 2002

Wave propagation



Wave propagation



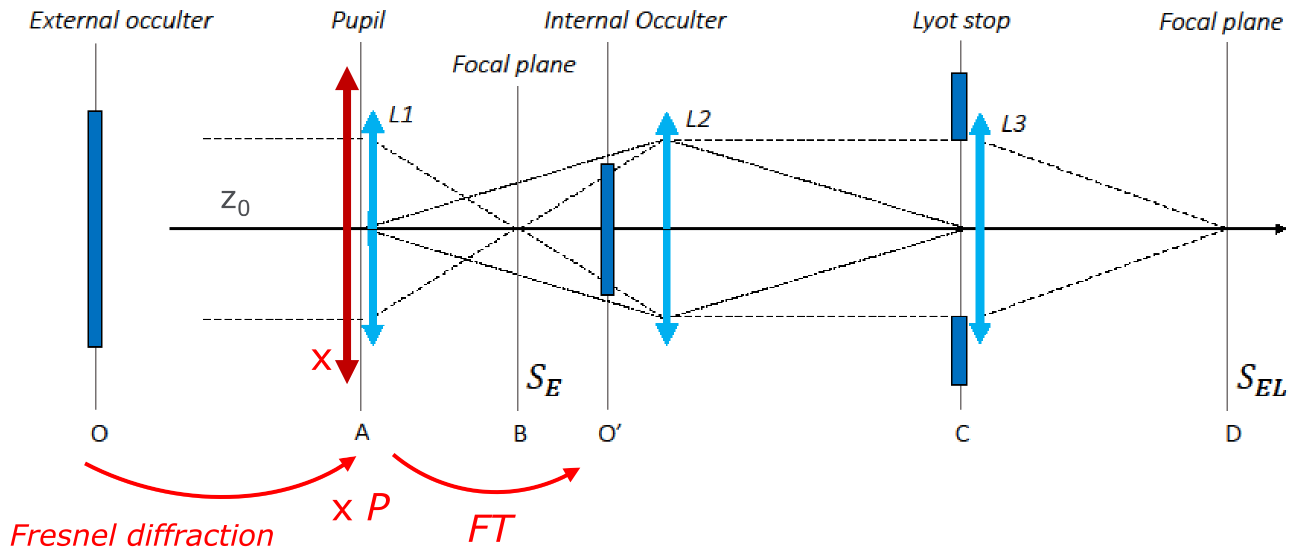
- Ψ_A : Fresnel diffraction induced by the EO (Arago's spot)

$$\Psi_B = FT[\Psi_A \times P]$$

$\Psi_{O'}$ = Propagation to O'?

We can do better!

Wave propagation



- Ψ_A : Fresnel diffraction induced by the EO (Arago's spot)

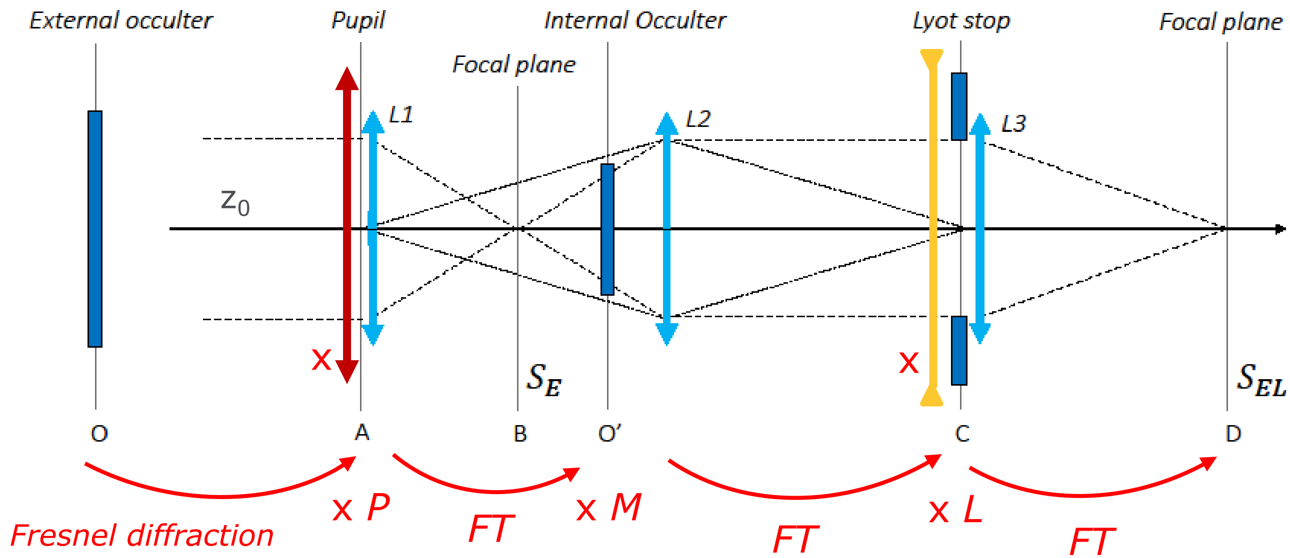
  ~~$\Psi_B = FT[\Psi_A \times P]$~~ We may skip plane B.

- "Virtual" **converging lens of focal $-z_0$**

  Plane O' becomes the new focal plane of the doublet ↕ + ↕.

$$\Psi_{O'} = \mathrm{FT}\left[\Psi_A \times P \times exp\left(-\frac{i\pi r^2}{\lambda z_0}\right)\right]$$

Wave propagation



- Ψ_A : Fresnel diffraction induced by the EO (Arago's spot)

$$\Psi_{O'} = \mathrm{FT}\left[\Psi_A \times P \times \exp\left(-\frac{i\pi r^2}{\lambda z_0}\right)\right]$$

$$\Psi_C = FT[\Psi_{O'} \times M] \times \exp\left(+\frac{i\pi r^2}{\lambda z_0}\right)$$

$$\Psi_D = FT[\Psi_C \times L]$$

Observed intensities

- **Sampling of the solar** disc by point sources (α, β)
  Limb darkening function *B* @550nm (Van Hamme, 1993)
  Shannon's criteria $\left(\frac{\lambda}{4R_p} = 1.13 arcsec\right)$

- On every plane:
  Incoherent integration, 2D-sum over the solar disc (Fredholm)

- *Axis-symmetry:* observed intensities are radial functions.

$$I_i(r) = \int_0^{2\pi} \underbrace{\left[\int_0^{R_\odot} B(\rho) \times |\Psi_i(\alpha, \beta, r, \theta)|^2 \rho d\rho\right]}_{\text{Weighted summation along one solar radius}} \mathrm{d}\theta \qquad i \in \{A, B, O', C, D\}$$

Circular average of the 2D-image

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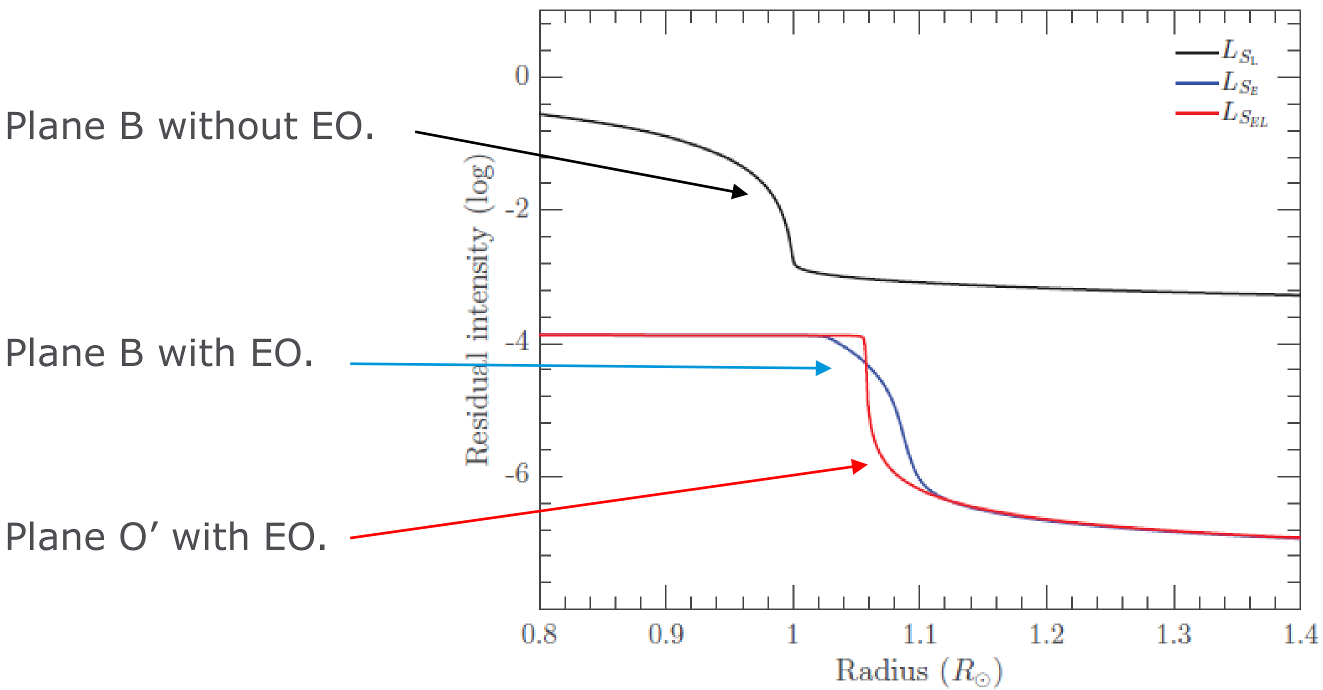
8. Appendix: wave propagation
9. Appendix: integrated residual light

Integrated residual light

$$L(r) = 2\pi \int_{r}^{3.2R_{\odot}} I(r) \times r dr$$

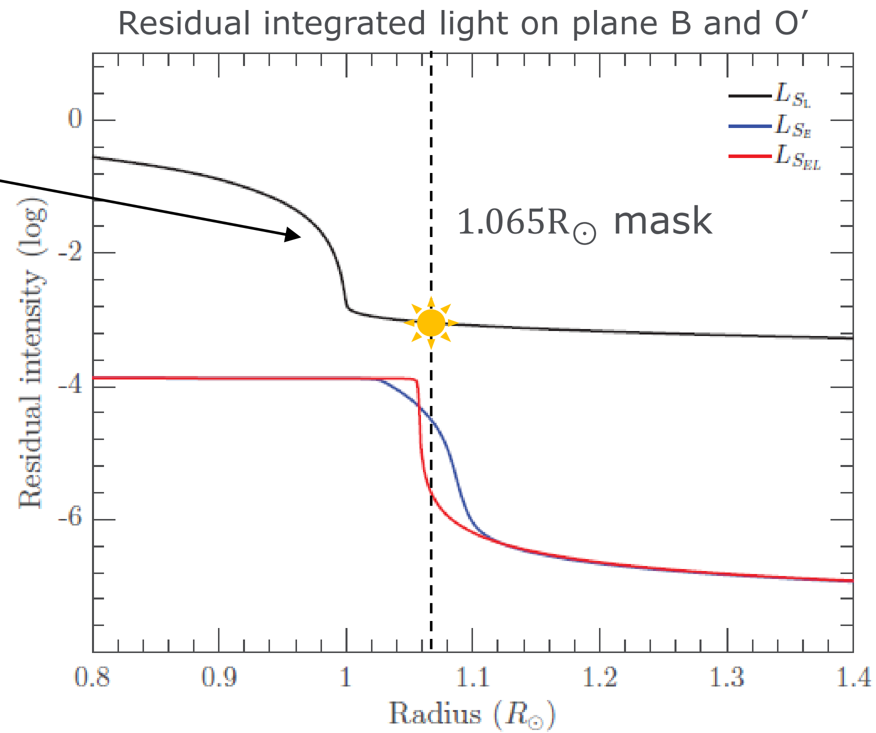
Residual integrated light on plane B and O’



Integrated residual light

Classical Lyot coronagraph: Lyot mask in plane B

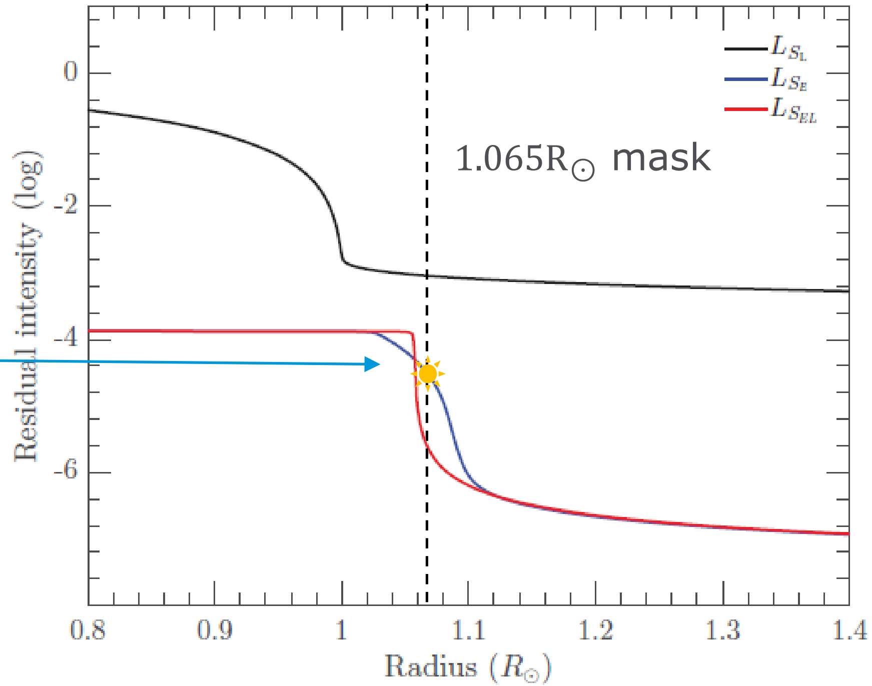
Plane B without EO.



Integrated residual light

Hybrid externally occulted Lyot coronagraph:
Internal pocuclter in plane B (wrong system)

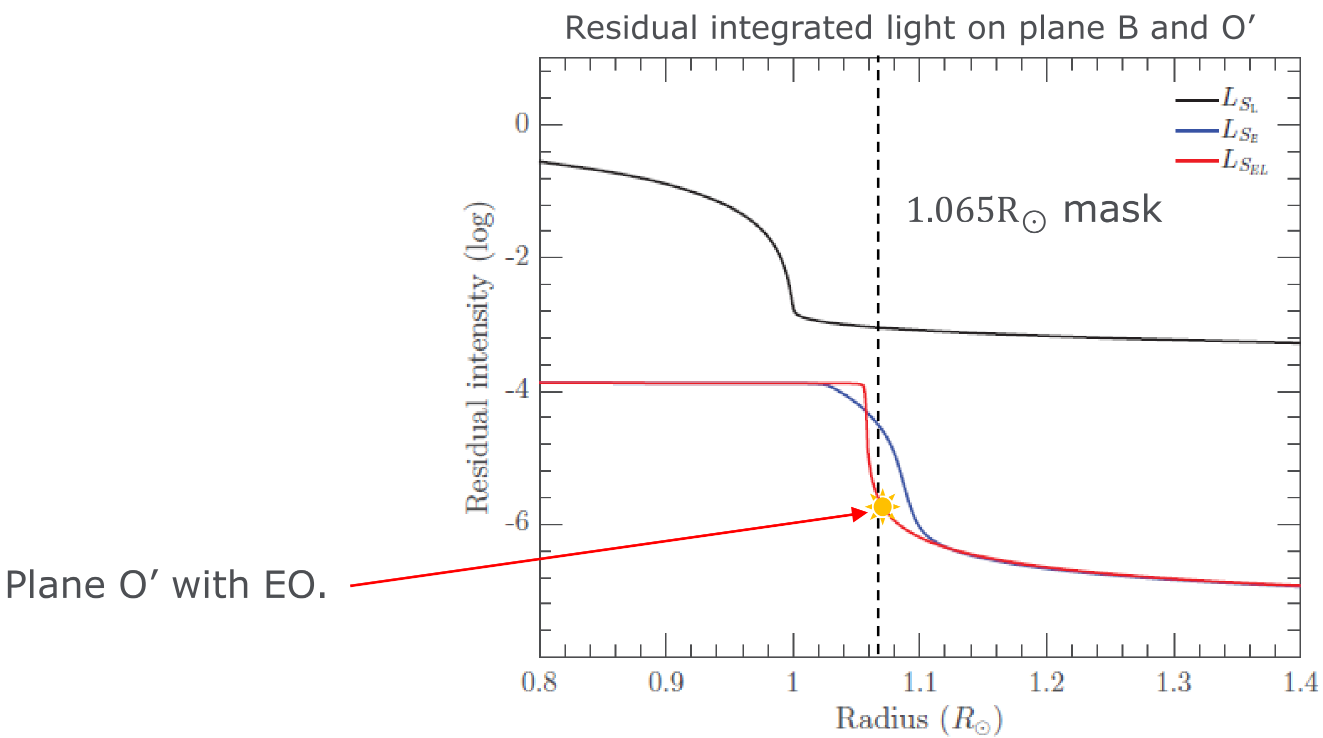
Residual integrated light on plane B and O′



Plane B with EO.

Integrated residual light

Hybrid externally occulted Lyot coronagraph:
Internal ocuclter in plane O'



This proves why the internal occulter is set in plane O' instead of plane B!