The Coronagraph Tree of Life
(non-solar coronagraphs)

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Quick overview of coronagraph designs
attempt to group coronagraphs in broad families

Where is the performance limit? What sets this limit?
Source characteristics, wavefront quality
Exoplanets

How many planets around other stars?
How do they form, evolved?
Mass, size, composition?
Rocky planets with atmospheres?

Could have life evolved on other planets?
Intelligent life somewhere else?
Direct imaging of planets similar to the ones in our solar system is very difficult

A planet is faint (compared to its star) and very close to its star.

In visible:

Earth is $1 \times 10^{10}$ times fainter than Sun
Jupiter is $1 \times 10^9$ times fainter than Sun

In IR (10 um):

Sun/Earth = $1 \times 10^6$

Saturn eclipses the Sun
Earth as seen by Voyager 1

Many Coronagraph Choices...

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<th>Coronagraph</th>
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<th>reference</th>
<th>Design goal adopted</th>
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<td>Interferometric Coronagraph</td>
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<td>Achromatic Interferometric Coronagraph</td>
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<td>Conventional Pupil Apodization and Shaped-Pupil®</td>
<td>CPA</td>
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<td>Phase-Inward Amplitude Apodization Coronagraph</td>
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<td>Improvement on the Lyot concept with amplitude modes</td>
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<td>Band limited, 4th order</td>
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<td>Phase Mask</td>
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<td>Roddier &amp; Roddier (1987)</td>
<td>with mild pupil pupil apod.</td>
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<td>Optical Diffraction</td>
<td>OD</td>
<td>On et al. (2006)</td>
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*The Visible Field Achromatic Interferometric Coronagraph (VIFC) and Band limited 4th order (BLS) coronagraphs belong to the same class of pupil-shaping 4th order coronagraphs, and are simply 2 ways of achieving the same result. Thus can be designed to have exactly the same performance. In this Table, the VIFC is shown with small DIAs and 2 orthogonal shear directions, while the BLS is designed with a larger DIA and 2 shears in the same direction. To reflect this similarity, they are referred to as VIFC/BL4(4) for the small DIA option (listed as VIFC in this Table) and VIFC/BL4(4) for the large DIA option (listed as BLS in this Table).

1 The CPA design adopted here is a continuous apodization (rather than binary apodization/shaped pupil) which maximizes the radiometric improvement at 40 AU. More optimal designs exist under other conditions: CPA with high contrast at specific position angles for observations at 3.5 AU or high throughput CPA for observations at 4 AU.

2 CPA, APLC, APLCn - r is the radius in λ, d, of the mask within which the circular pupil function is invariant to a Hankel transform. This parameter is half of the mask diameter defined in Soummer et al. (2003).

3 OD = 0.6. Minimum mask transmission at 75% Lyot pupil mask radius = 0.65 times pupil radius.
### 4 main branches, 4 different approaches

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<th>&quot;Interferometric&quot; coronagraphs</th>
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<td>( \text{VNC} )</td>
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<td>Phase Induced Amplitude Apodization Coronagraph</td>
<td>( \text{PIAA} )</td>
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<td>Lyot Coronagraph</td>
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<td>( \text{APLC} )</td>
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<td>Apodized Pupil Lyot Coronagraph</td>
<td>( \text{APLC} )</td>
<td>( \text{APLC} )</td>
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<td>Multistep APLC</td>
<td>( \text{APLCn} )</td>
<td>( \text{APLCn} )</td>
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<td>Band Limited, 4th order</td>
<td>( \text{BL4} )</td>
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<tr>
<td>Band Limited, 8th order</td>
<td>( \text{BL8} )</td>
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<tr>
<td>Phase mask</td>
<td>( \text{PM} )</td>
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<td>Optical Vortex Coronagraph, topological charge ( m )</td>
<td>( \text{OVCm} )</td>
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<td>( \text{AGPMC} )</td>
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<td>( \text{ODC} )</td>
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External Occulter

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### "Interferometric" coronagraphs

- Nulling interferometer on a single pupil telescope
  - Creates multiple (at least 2) beams from a single telescope beam
  - Combines them to produce a destructive interference on-axis and constructive interference off-axis

<table>
<thead>
<tr>
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<th>( \text{APKC} )</th>
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<td>Common Path AIC</td>
<td>( \text{CPAIC} )</td>
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</tr>
</tbody>
</table>

- \( \text{Baudouz et al. 2000, Tavrov et al. 2005} \)
  - Destructive interference between pupil and flipped copy of the pupil
  - Achromatic PI phase shift and geometrical flip performed by going through focus

<table>
<thead>
<tr>
<th>Visible Nulling Coronagraph, X &amp; Y shear, 4th order</th>
<th>( \text{VNC} )</th>
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<td>( \text{Shao et al., Menesson et al. 2003} )</td>
<td>( \text{VNC} )</td>
<td>( \text{VNC} )</td>
</tr>
</tbody>
</table>
  - Destructive interference between 2 copies of the pupil, sheared by some distance.
  - 4th order null obtained by cascading 2 shear/null

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<tr>
<th>Pupil Swapping Coronagraph</th>
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<tr>
<td>( \text{Guyon &amp; Shao, 2006} )</td>
<td>( \text{PSC} )</td>
<td>( \text{PSC} )</td>
</tr>
</tbody>
</table>
  - Destructive interference between pupil and a copy of the pupil where 4 quadrants have been swapped
Achromatic Interferometric Coronagraph (AIC)

Baudoz et al. 2005, PASP, 117, 1004 (Hybrid AIC, no 180 deg ambiguity)
Tavrov et al. 2005, Opt. Letters, 30, 2224 (Common path AIC)

Visible Nuller Coron. (VNC)

Small shear : high throughput, low IWA
Large shear : low throughput, small IWA
The 2 shears can also be colinear

Will fly soon on sounding rocket (PICTURE)

Mennesson, Shao ... 2003, SPIE 4860, 32
Pupil Swapping Coronagraph (PSC)

Same basic principle as VNC, higher throughput
Guyon & Shao, 2006, PASP

Pupil Apodization

Since Airy rings originate from sharp edges of the pupil, why not change the pupil?

Conventional Pupil Apodization/ Shaped pupil CPA
Kasdin et al. 2003
Make the pupil edges fainter by absorbing light, either with a continuous or "binary" (shaped pupil) mask

Achromatic Pupil Phase Apodization PPA
Yang & Kostinski, 2004
Same as CPA, but achieved by a phase apodization rather than amplitude

Phase Induced Amplitude Apodization Coronagraph PIAAC
Guyon, 2003
Perform amplitude apodization by remapping of the pupil with aspheric optics

Phase Induced Zonal Zernike Apodization PIZZA
Martinache, 2003
Transform a pupil phase offset into an amplitude apodization thanks to a focal plane Zernike mask
Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

+ Simple, robust, achromatic
- low efficiency for high contrast

Jacquinot & Roisin-Dossier 1964

Pupil Phase Apodization (PPA)

Achromatic solutions exist.

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)
Lossless apodization by aspheric optics.

Phase-Induced Zernike Zonal Apodization (PIZZA)

Zernike phase contrast transforms pupil phase aberration into pupil amplitude modulation. This property is used to produce an amplitude apodization.

Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

Lyot & Improvements on the Lyot concept

Lyot coronagraph combines pupil plane and focal plane masks to remove starlight.

Focal plane mask removes central part of PSF. What is left (Airy rings) is mostly due to the outer parts of the pupil (the edges) -> a pupil mask (Lyot mask) removes these edges.

Well suited for solar coronagraphy
For high performance stellar coronagraphy, the original Lyot concept is limited because of a painful tradeoff between throughput, starlight rejection and inner working angle:
Higher contrast -> edges are wider -> lower throughput
Smaller IWA -> edges are wider -> lower throughput

Improvement on the Lyot concept
Part I: Amplitude masks

<table>
<thead>
<tr>
<th>Apodized Pupil Lyot Coronagraph</th>
<th>APLC</th>
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<tr>
<td>Soummer et al. 2003, Abe et al.</td>
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<tr>
<td>Modify (amplitude apodization) the entrance pupil to match it perfectly to the focal plane mask</td>
<td></td>
</tr>
<tr>
<td><strong>Multistep APLC</strong></td>
<td><strong>APLC1</strong>, <strong>APLC2</strong>, <strong>APLC3</strong>...</td>
</tr>
<tr>
<td>Cascade APLCs to improve the contrast / reduce Inner Working Angle</td>
<td></td>
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</tbody>
</table>

| Band Limited, 4th order | BL4 |
| Band Limited, 8th order | BL8 |
| Kuchner & Traub, 2002; Kuchner et al., 2005 |
| Modify (amplitude apodization) the focal plane mask to match it perfectly to the pupil. Deeper 8th order null more immune to low order aberrations |
Apodized Pupil Lyot Coronagraph (APLC) = Prolate Apodized Lyot Coronagraph (PALC)

Lyot Coronagraph with apodized entrance pupil. Prolate apodization is optimal, and can bring contrast to $10^{-10}$. Focal plane mask is smaller than Central diffraction spot: challenging to achromatize.

Output pupil (in Lyot plane) is prolate itself, and can serve as input for another Lyot coronagraph: Multistep APLC.

Adopted for Gemini Planet Imager (GPI) and Subaru HiCIAO.

Aime & Soummer 2004, SPIE, 5490, 456
Abe

Band-Limited mask Coronagraph (BL4, BL8)

Focal plane mask optimized to maintain fully dark central zone in pupil (band-limited mask).

4th or 8th order extinction.

Kuchner & Traub 2002
Kuchner 2005

Fig. 4 — Simplest band-limited mask, analogous to a single-baseline masking interferometer. (a) Mask. JET an/1 averaged by an input pupil. Dark areas are opaque. (b) Conjugate of the mask. AE with (c). This occulting stop can be used with any aperture shape, but for the circular aperture shown in (c), the corresponding Lyot stop in (d).
Improvement on the Lyot concept
Part II: Phase masks in focal plane

<table>
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<th>Phase mask</th>
<th>PM</th>
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<td>Roddier &amp; Roddier, 1997</td>
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<td>Smaller IWA, higher efficiency thanks to PI-shifting (ampl = -1) focal plane phase mask instead of traditional opaque (ampl = 0) mask. Requires mild pupil amplitude apodization</td>
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<td>APKC</td>
</tr>
<tr>
<td>Rouan et al., 2000; Abe et al., 2001</td>
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<tr>
<td>PI phase shift in 2 opposite quadrants of the focal plane, 0 phase shift in the other 2 quadrants. Less chromatic than PM.</td>
<td></td>
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<td>Optical Vortex Coronagraph, topological charge m</td>
<td>OVCm</td>
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<tr>
<td>Angular Groove Phase Mask Coronagraph</td>
<td>AGPMC</td>
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<tr>
<td>Palacios, 2005</td>
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<tr>
<td>Phase shift is proportional to position angle in focal plane</td>
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<tr>
<td>Optical Differentiation Coronagraph</td>
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<tr>
<td>Oti et al., 2005</td>
<td></td>
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<tr>
<td>Combined phase and amplitude mask in focal plane</td>
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Phase Mask Coronagraph (PM)

Lyot-like design with PI-shifiting (-1 amplitude) circular focal plane mask:
- smaller mask
- smaller IWA
Requires mild prolate pupil apodization.

Phase shift needs to be achromatic
Mask size should be wavelength dependant
  Dual zone PM coronagraph mitigates chromaticity

2nd order null only.

Roddier & Roddier 1997, PASP, 109, 815 (basic concept)
Guyon & Roddier 2000, SPIE, 4006, 377 (pupil apodization with PM)
Soummer et al. 2003, A&A, 397, 1161 (pupil apodization with PM)
4 Quadrant Phase Mask (4QPM)

Lytot-like design with PI-shifting (-1 amplitude) of 2 oppose quadrants in focal plane:
- Does not require pupil apodization.
- Less chromatic
Phase shift still needs to be achromatic

2nd order null only.

Used on VLT for science obs.


Achromatic Phase Knife Coronagraph (APKC)

Same basic principle as 4QPM. Addresses chromaticity problem with dispersion along one axis.

Optical Vortex Coronagraph (OVC)

Phase in focal plane mask = Cst x PA

Fig. 2. (a) Intensity profile, $|U(x', y')|^2$ of a beam containing an optical vortex. (b) Surface profile of a VPM.

Fig. 3. Comparisons for $\alpha_2 = \alpha_{\text{MIN}}$ and $A_x^2/A_y^2 = 100$. (a) Lyot coronagraph where $R_{\text{OM}} = R_{\text{MIN}}$. (b), (c), (d) Vortex coronagraphs where $m = 1$, $m = 2$, $m = 3$, respectively. In (c) the starlight is essentially eliminated, revealing a high-contrast image of the planet when $m = 2$.

Optical Differentiation Coronagraph (ODC)

Optimized version of a single axis phase knife coronagraph.

Fig. 3. Simulated images at different planes in the optical differentiation coronagraph illustrating its principle of operation. (a) Image of the star PSF multiplied by the modified differentiation mask. (b) Intensity distribution just before (b) and after (c) the Lyot stop plane. (d) Final image detected at the CCD plane. Images are displayed in different intensity scales.
External Occulter

Place large occulter far in front of the telescope: works really well but some practical challenges...

Cash et al. 2005, SPIE, 5899, 274
Cash 2006, Nature

Removing starlight: What are the options ???

Block light before it enters the telescope: create an eclipse
  -> External Occulter

Remove light in the telescope, where it is most concentrated, in the focal plane... but this doesn't work that well: something also needs to be done in the pupil plane
  -> Lyot coronagraph & improvements

Build a nulling interferometer
  -> Interferometric coronagraphs

The problem is with the pupil edges: change the pupil to make a friendly PSF
  -> pupil apodization coronagraphs
Coronagraph Performance

Defining a performance metric independant of coronagraph design

Commonly used metrics: IWA, throughput, discovery space

IWA: what limit? ... 50% of max throughput?
Throughput: how does coronagraph throughput change with separation?
Discovery space: complex geometries?
Overlap effects between star image and planet image.

Useful throughput
fraction of the planet's light that can be isolated from the stellar light
**Useful Throughput**

Proposed definition:
*Amount of planet light which can be isolated from stellar light.*

Isolated = it is possible to gather this planet light without having gathered more starlight than planet light.

Useful Throughput is function of planet position & contrast

Measuring Useful throughput
Pixel #i has
Starlight          Si
Planet light      Pi

- order pixels in decreasing Pi/Si
- take first N pixels until:
  Sum(Si) = Sum(Pi)
- Sum(Pi) is the useful throughput

If on-axis star fully cancelled, Useful Throughput = total planet light in detector(s)

---

**Useful Throughput**

If no background, Useful Throughput is **representative of the coronagraph performance**.
Exposure time ~ prop to 1/Useful Throughput

For Discovery: Radially averaged Useful Throughput
For Characterization: Peak Useful Throughput

Still somewhat a little arbitrary: can we detect planet light in much brighter stellar light?
Useful throughput for $1e10$ contrast

Point source / Radially averaged throughput
Useful throughput for 1e10 contrast

Coronagraph unified Model and Theoretical Performance Limits
**Coronagraph model**

 Linear system in complex amplitude
 Fourier transforms, Fresnel propagation, interferences, every wavefront control schemes: all are linear

U is fixed by optical configuration, and is independent of the source position on the sky.

**Coronagraph model**

What is the theoretical performance limit of coronagraphy?

Coronagraph is a linear filter which removes starlight.
If:
planet = 0.2 x starlight wavefront + 0.8 x something else
then:
coronagraph throughput for planet < 0.8

What is the vector C that maximizes C.A(planet) but keeps C.A(star position) < C.A(planet position)^sqrt(1e-10)?
Coronagraph needs to remove (project) from the incident wavefront the "flat" on-axis component. The amplitude of this component, as a function of angular separation, is by definition the ideal PSF of the optical system.

-> Maximum theoretical throughput
   = 1 – PSF  (1-Airy for circular aperture)

This conclusion is independant of how well the coronagraph needs to cancel on-axis light.
Could we build this "ideal" coronagraph?

Assume fixed planet position; previous equations yield vector C that needs to go inside matrix U. Equivalent to build coronagraph such that one output has all the light if input $A = C$.

This can be done with beam splitters. Input $A=C$ is fully coherent, made of N individual beams. Combine beams 1 and 2 such that all the light is in one of the 2 outputs. Combine this output with beam 3 such that all the light is in one of the 2 outputs. .......

At the end, ALL of the light is in one "pixel"

Could we build this "ideal" coronagraph?

Previously, we assumed fixed planet position. Can this work simultaneously for all planet positions?

YES!

Instead of trying to build one output optimal for a given planet position, we can concentrate ALL starlight into a single output. The other outputs will have no starlight (plane perp to starlight component).
Useful throughput for 1e10 contrast

What can (will) go wrong?

Chromaticity?
Sometimes very serious practical challenge, but it is not a fundamental limit:
- design of achromatic components
- multiple narrow bands

Stellar angular size?

Zodi, exozodi, complex background?
Yes, sometimes... need to minimize how much zodi/exozodi mixed with planet: make PSF sharp
Stellar Size

Measuring Useful Throughput with stellar size

Star is modelled as an incoherent cloud of point sources, uniformly distributed on the stellar surface.
Useful throughput of existing coronagraphs

Point source / Radially averaged throughput

Useful throughput

Angular separation (λ/d)

Useful throughput of existing coronagraphs

Radially averaged throughput

stellar radius = 0.01 λ/d
Useful throughput of existing coronagraphs

Useful throughput – average, 0.1 l/d
Useful throughput – peak, 0.1 l/d

---

Why is it so serious?

Stellar size makes light incoherent
Sun diam = 1% of Sun-Earth distance

No hope of fixing this by wavefront control, the coronagraph has to deal with it!

In a stellar size limited coronagraph, remaining speckles have opposite complex amplitude from one side of the star to the other. Adding complex amplitude can only increase intensity.
Graphical representation of the coronagraph throughput

Central star is made of a group of vectors, ALL of which need to be cancelled to some degree.

Need to remove more than 1 mode from the incoming wavefront (how many and how well depends on the star size and desired contrast)
Theoretical limit with increasing stellar radius (monochromatic light)

0 l/d -> IWA ~ 0.5 l/d
0.1 l/d -> IWA ~ 2 l/d

Fig. 5.— Upper limit on the off-axis throughput of a coronagraph for different stellar radii.

An "ideal" coronagraph for extended source with discrete beam splitters
# modes removed linked to null depth and predicts coronagraph behaviour at small angular separation

2nd order null: only B0 removed at small angular separation, B1 and B2 dominate, and their amplitude is prop to separation

Predictions:
As source moves away, PSF does not change, but its intensity is prop to square of separation

180 deg ambiguity in image

Coronagraphic PSFs at small angular separation

2nd order null

6 modes removed x^3, y^3, xy^2, x^2y dominate

More complex interactions between modes
Zodi / Exozodi

With "good" coronagraph (small sharp PSF), planet likely to stand out of the background (zodi+exozodi) for nearby system.

What makes things worse:
- distance to system
- increasing lambda
- poor angular resolution
- complex PSF structure (multiple peaks, diffraction in some directions ...)

Coronagraph design

Diffractive Efficiency Factor (DEF): how much more background light is mixed to the planet's PSF than in the simple non-coronagraphic telescope case (Airy + background).
The ultimate coronagraph dream:

Can we ... 
Reach the perfect limit for source size > 0 
AND 
have diffractive efficiency factor (DEF) = 1 ?

*By the way, it would be nice if it were optically simple*

Yes, it is possible!

But no optically simple implementation known

(lots of beam splitters)

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Numerical Simulations
for Exo-Earths imaging
Example:
HIP 56997 (G8 star at 9.54pc)
0.55 micron, 0.1 micron band
Planet at maximum elongation (80 mas)
Earth albedo = 0.3 (C=6e9)
4h exposure, 0.25 throughput, perfect detector

Exozodi : 1 zodi
System observed at time when zodi is minimal

Each image is 20x20 lambda/d
1 zodi, 50% detection at SNR = 7

In 8m plot (right), line = 2 months open shutter time with 6 visits per target, 1 year, excluding overhead (pointing) -> number of targets limited by mission life

Side benefits of high performance coronagraph

(1) High throughput enables high contrast
   - more photons for wavefront control: makes it easier to catch up with non-predictable drifts & vibrations

(2) High throughput + good angular resolution reduces need for revisits
   - for closeby objects, proper motion confirmation < day
   - less confusion with exozodi clumps and/or other planets

(3) Short exposure time per visit: high overheads

(2)+(3) : more characterization for initial visits?
Wavefront Control
**Extreme-AO from the ground: raw contrast at 0.5” with 8m telescope**

**How much contrast?**

- **100**
- **1e3**
- **1e4**
- **1e5**
- **1e6**
- **1e7**
- **1e8**
- **1e9**
- **1e10 (TPF)**

**AO speed:**
- **1kHz**
- **6kHz**
- **40kHz**
- **250kHz**

**Star mV (theory):**
- **14**
- **11**
- **8**
- **5**
- **2**
- **-1**

**Star mV (with current WFS):**
- **10.5**
- **7.5**
- **4.5**
- **1.5**
- **-1.5**
- **-4.5**

**Problems to be solved**

- Amplitude correction (scintillation)
- Scintillation chromaticity
- Refraction index chromaticity
- Wavefront phase chromaticity
- Optics quality

**Larger Telescopes**
Wavefront Control on coronagraphs

Wavefront (optics/atmosphere) not expected to be rock steady on large pupil.

Need to **simultaneously** answer 2 questions:
(1) How much wavefront aberration is acceptable?
Open-loop wavefront sensitivity
(2) How well can it be corrected (= how well can it be detected = how rapidly can it be sensed vs. How fast does it change)?
Wavefront sensing efficiency

Together, these 2 answers will set the open loop wavefront stability requirement

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Low-order aberrations

Low IWA coronagraphs require smaller low-order aberration (especially true for tip-tilt).
Stellar angular size = tip-tilt!!
Stellar angular size analysis can be generalized to low order aberrations & help match coronagraph design with wavefront errors

Larger IWA coronagraphs (CPA for example), tolerate larger aberrations but cannot detect them unless they are large.

We can always expect low-order aberrations to be at the level where they start to impact contrast at the IWA.
UNLESS... we use the light on the focal plane occulter
Example of a Dedicated Low-Order Wavefront Sensor (LOWFS)

Use "for free" light from central star

This example will work for:
- CPA
- BL4, BL8
- PIAA
- APLCs

Same general principle can be applied to other coronagraphs (PM, 4QPM, OVC)

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Dedicated Low-Order Wavefront Sensor (LOWFS)

*Figure 6.* Noisy inside and outside focus images obtained by the LOWFS (top left). Photon noise is included in this simulation, where $10^{17}$ photons entered the telescope pupil. These images were simulated at 550nm with a 50pm error per Zernike for the first 10 Zernikes. Wavefront reconstruction from these 2 frames accurately recovers low order wavefront aberrations (right), to an accuracy level which exceeds the requirement for $10^{-5}$ contrast. Simulated science focal plane and LOWFS (bottom left), computed from the wavefront estimation, match the noisy images acquired by the LOWFS (top left).
Deriving Wavefront stability requirements (example: TOPS, 1.2m telescope with PIAA)

Table 1. Wavefront control requirements for $10^{10}$ contrast. Wavefront tolerances are given at the entrance of the PIAA. A coronagraph system including PIAA, focal plane occulter, and inverse PIAA was simulated at 550 nm to derive these requirements. The sampling time necessary to measure the corresponding level of aberration at SNR=3 is given here for an rms = 5 star.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Required control accuracy</th>
<th>Sensing</th>
<th>SNR=3 sampling time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip / tilt</td>
<td>0.9 nm rms/mode</td>
<td>LOWFS</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Focus</td>
<td>43 pm rms</td>
<td>LOWFS</td>
<td>1 s</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>70 pm rms/mode</td>
<td>LOWFS</td>
<td>1 s</td>
</tr>
<tr>
<td>Mid spatial frequ</td>
<td>1.5 pm rms/mode</td>
<td>Science CCEs &amp; LOWFS</td>
<td>5 min</td>
</tr>
<tr>
<td></td>
<td>[40 pm rms total, 10 pm actuator]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High spatial frequ</td>
<td>Strehl ratio &gt; 0.36</td>
<td>none, relies on optical quality of components</td>
<td>-</td>
</tr>
</tbody>
</table>

Tip/Tilt stable to 0.9nm within ~5 s
Focus stable to 43 pm within ~10 s
Mid Spatial frequ stable to 1.5 pm within ~50 min
(assuming correction bandwidth = 0.1 sampling bandwidth - PESSIMISTIC)

Deriving Wavefront stability requirements

**1.2m telescope / $10^{10}$ contrast:**
Tip/Tilt stable to 0.9nm within ~5 s
Focus stable to 43 pm within ~10 s
Mid Spatial frequ stable to 1.5 pm within ~50 min

Bigger telescope:
- faster sensing (more photons) – sampling time ~ $1/D^2$
  - 4m telescope: 11 times faster (50 min -> 4.5 min)
- input wavefront less stable

Lower throughput / larger IWA coronagraph
- slower sensing
- more tolerant to low-order aberrations
Conclusions

- In last few years, many coronagraph concepts have been proposed and studied. Several of them are being tested in the lab and/or on telescopes. Direct imaging of exoEarths looks especially attractive and within reach of ~2m visible space telescope.

- Stellar size and low order aberrations are very important and fundamental limitation (loss of coherence) – especially critical when trying to go to small separations.

- Theoretical limits identified but not (yet) practical to build. There is still room for improvement, but not huge improvement (Max gain = factor 2 in # of accessible terrestrial planets).

More info...

**Coronagraph Theory**:  

**Coronagraph designs**:  
Tuesday afternoon “Coronagraph Theory & Innovation”

**Wavefront Control**:  
Wednesday morning “Wavefront control, Observing techniques and methods”

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