Potential for improving coronagraphic instrument on the Astro2020 flagship through continued technology innovation

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Outline

- Motivation for continuing to improve coronagraphic instrument designs
- How much improvement is possible (i.e. before we reach fundamental physics limits)?
- What technologies can reach physics limits?
- Example technology: PIAA-Vortex coronagraph (Kevin Fogarty)
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On a flagship, there is a strong motivation to improve instrument performance

- Instruments are often performance bottlenecks
  - unless they are physics-limited

- Instrument technology research and development:
  - small fraction of mission cost
  - large impact on
    - mission performance
    - requirements relaxation
    - risk reduction
  - large, leveraged ROI on investment (“better” is NOT the enemy of “good enough”)
    - until physics limits are reached, or investment becomes a significant fraction of mission cost

- Flagship instrument development should aim to reach physics limits
  - at least while development cost is a small fraction of mission cost
More powerful instruments are necessary to guard against “yield erosion”

<table>
<thead>
<tr>
<th>Mission</th>
<th>Originally expected/desired yield</th>
<th>Actual or currently expected yield</th>
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<tbody>
<tr>
<td>Kepler</td>
<td>~25 Earth analogs (Borucki et al. 2003)</td>
<td>o(1)</td>
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<tr>
<td>Roman CGI</td>
<td>~25 reflected light planets (circa 2013-2015)</td>
<td>o(1)</td>
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<tr>
<td>Astro2020 flagship</td>
<td>~25 characterized potentially habitable planets</td>
<td>?</td>
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- There are more ways in which expected science yields can decrease than increase
- So, yields they tend to get worse as a mission concept matures
Large mission studies recommend thorough, early, well-funded trades and technology development

- Finding: “During the Pre-Phase-A period, requirements development and architecture trades are often over-constrained, driving the mission unnecessarily toward very expensive solutions[...]”

- Recommendation: “[...]Conduct requirements analyses and architecture trades during pre-phase-A that quantify science vs. cost, thereby preventing unnecessary adoption of very expensive solutions[...]”
  - SMD’s large mission study report (https://science.nasa.gov/about-us/large-mission-study)

- “Inadequate funding for concept studies, concept, and technology development”

- “annual funding [should be] provided in the early stages of development, to cover feasibility studies, technology developments and prototype development,”
Two of the top recommendations of Astro2020 decadal survey:

The decadal survey recommends a large (~6m diameter) Infrared/Optical/Ultraviolet space telescope with high-contrast imaging and spectroscopy as the first mission to enter the Great Observatories Mission and Technology Maturation Program. This is an ambitious mission with the goal of searching for biosignatures from habitable zone exoplanets and providing a powerful new facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade with a target launch in the first half of the 2040’s.

Given the large costs and development timescales for the next generation of space telescopes, the decadal survey recommends that NASA create the Great Observatories Mission and Technology Maturation Program as a new approach for planning and implementing large missions. The program would provide early investment in technology development for multiple mission concepts to lower the risks and costs of projects before they become too complex, large, and costly. The first entrant for the maturation program should be a large Infrared/Optical/Ultraviolet space telescope. The second entrants should be strategic Far-Infrared and X-ray missions.

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Expected ExoEarth candidate yields from current coronagraph designs

Stark C., et al., 2019
Expected ExoEarth candidate yields from current coronagraph designs

Can we access this region?

Stark C., et al., 2019
Abstract representation of coronagraphs as linear operators

1. Choose an orthonormal basis of pupil plane modes (identifying noise modes to be suppressed)
2. Choose desired attenuation for each mode (0 for noise modes and 1 for signal modes is best)
3. Choose an orthonormal basis of science plane modes onto which passed pupil plane modes are to be mapped (this will almost always be a simple imaging system for passed modes)

Belikov et al. 2021 (also see Guyon et al. 2006)
Yield simulations of Exo-Earth candidates

Optimal coronagraphs achieve 2-4 greater yield than currently baselined coronagraphs (for a fixed bandwidth and system QE)

- Gap between obstructed and unobstructed apertures can be closed!
  - Enabling larger aperture for the same cost, and/or risk reduction / cost savings

- Caveats: optimal coronagraph yields
  - Show where theoretical limits are, but not how to get there practically
  - May or may not require exotic architectures
  - Are partially based on IWA improvements, which may have other limitations
  - Useful as a target, guide, and inspiration for coronagraph design
What coronagraph parameters should we focus on improving?

- Coronagraph contrast is of course critical and challenging, but
  - diminishing returns once \( o(10^{-10}) \) contrast is reached (because zodi / exozodi starts to dominate)
  - is NOT fundamentally limited by coronagraph architecture (for point sources): requires primarily time and effort in the lab
- Coronagraph “efficiency” (throughput, IWA, tolerance to stellar size, etc.) is also very critical
  - IS fundamentally coronagraph architecture-limited: decisions made without a thorough trade can be very costly
  - Requires continued innovation (TRL0-4)

Stark et al. 2019
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Which technologies may reach physics limits?

- Blue and green probably require churning through ~20 technologies/architectures (because many may fail)
  - an order of magnitude more effort than what can be supported by current ROSES calls
  - Still a tiny fraction of mission cost
- Should not be afraid of <TRL3 technologies: “In Exoplanets, 4 years is a lifetime” – Eric Mamajek
Hardware Implementation: Photonic Lantern SMF Out, Into Optical Chip


(Jeff Jewel, JPL)
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PIAA-Vortex Coronagraph: High Performance on Obstructed Pupils

- Enables an obstructed aperture version of Astro2020 flagship, with yields potentially comparable to unobstructed apertures.
  - Mitigates several key mission risks
  - Access to on-axis trade space may improve science performance
- Based on high-maturity components, but requires more design optimization and system-level testing.
- Addresses the trade-off between throughput, sensitivity, and IWA that limits on-axis performance.

Absil et al. 2017
Belikov et al. 2010
PIAA-Vortex combines the advantages of PIAA and Vortex coronagraphs.
PIAA-Vortex enables robustness to tip/tilt errors and stellar angular size.
PIAA-Vortex aims to improve yields and lower Astro2020 risk.

- We expect an on-axis yield improvement over existing designs of a factor of > 1.6
  - Parametric extrapolation of yield from apodized vortex (accounting for better throughput, etc.) with obstruction, but ignoring struts and segments for now…

- Relaxation of requirements on tip/tilt and stellar angular size by factor of ~10.

- Stay tuned for more in-depth presentation of results at SPIE Montreal.
There are other technologies improve Astro2020 flagship CGI performance

- Several other promising coronagraph architectures

- Spectral bandwidth
  - No fundamental limit (can be “brute-forced” by many narrowband CGIs in parallel)

- Binary star suppression

- More efficient wavefront control methods
  - Pogorelyuk et al. 2020
  - Fogarty et al.
  - etc.

- Better quantum efficiency of CGI components (coatings, cameras, etc.)

- Post-processing and DRM improvements

- …
Conclusions

- On a flagship, there is very high value in improving instruments (all the way to physics limits)
  - Instrument is a small fraction of mission cost, but high impact on performance
  - A more powerful instrument can also significantly relax mission requirements and reduce risk

- Coronagraphic state of the art is still far from physics limits
  - 2-4x exoEarth yield improvement still possible, simply by improving coronagraph efficiency
  - Additional improvements are possible from bandwidth, WFC, QE, etc.

- There are many technologies can result in a breakthrough in performance:
  - Existing coronagraph architectures still have plenty of mileage left (but unclear whether they can reach physics limits)
  - Emerging technologies such as photonic chips are on the horizon, may be possible to raise to TRL6 by 2030 (especially by interdisciplinary engagement with telecommunications engineers)

- Need to accelerate technology innovation for Astro2020 mission
  - A coordinated effort, rather than independent groups
  - Taking full advantage of this opportunity probably requires an order of magnitude greater effort than current ROSES opportunities can support
Backup slides
How far can we improve…

Throughput (log scale)

Sky angle (λ/D, log scale)

… contrast (for stars with >0 diameter / tip/tilt aberrations)

… planet throughput?

… IWA?
How far can we improve…

Throughput (log scale)

Sky angle ($\lambda/D$, log scale)

… contrast (for stars with >0 diameter / tip/tilt aberrations)

… IWA?

… planet throughput?
How far can we improve...

Throughput (log scale)

Sky angle (\(\lambda/D\), log scale)

• Pioneering work on this question:
  • Guyon et al. 2006

• New results (Belikov et al. 2021):
  • Formal SVD-based analytical framework
  • Generalization to obstructed apertures
  • Optimal performance boundary
  • Implications for exoplanet yields
“First principles” reasoning

A good framework for thinking is physics, the “first principles” reasoning. Boil things down to their fundamental truths, and reason up from there, as opposed to reasoning by analogy. Through most of our life, we get through life by reasoning by analogy, which essentially means copying what other people do, with slight variations. And you have to do that, otherwise mentally, you wouldn't be able to get through the day. But, when you want to do something new, you have to apply the physics approach. Physics is about discovering new things that are counter-intuitive.

-- Elon Musk
Sampling of existing research / applications of photonic chips in astronomy
1. GLINT

https://www.naoj.org/Projects/SCEXAO/scexaoWEB/050devmodules.web/040glint.web/indexm.html

Martinod et al. 2021
General concept for high contrast imaging
PIMMS used by SCExAO

A photonic integrated multimode microspectrograph (PIMMS) in which the dispersing element is an array waveguide grating (AWG). The input light from the Subaru telescope focus (Mauna Kea Observatory, Hawaii, USA) is cleaned by the adaptive-optics system (SCExAO) before being fed to the instrument. Courtesy of Nick Cvetcojevic, Observatoire de la Côte d’Azur, France.
Integrated beam combiner used by GRAVITY

Figure 1. (Left) An image of the integrated photonic beam combiner used by GRAVITY. The circuit which is used to combine the light from the four 8-m telescopes at the VLT via a series of splitters and couplers can clearly be seen. The wafer is approximately the size of two US quarters and monolithic (i.e. a single component) as opposed to classical bulk optic beam combiners. This image was reproduced based on Figure 3 in Perraut et al. (2018). This device was designed and manufactured by CEA/LETI (Grenoble, France). (Right) the superior spectrum obtained for HR8799e with GRAVITY compared to previous results. This figure was reproduced from the Gravity Collaboration et al. (2019).

Jovanovic et al. 2019
Exoplanet Missions

This decade's big wave: exoplanet transits

NASA Missions

EPA/European Missions

W. M. Keck Observatory

Large Binocular Telescope Interferometer

NN-EXPLORE

VLT (Breakthrough/ESO 10 micron imaging)

ELTs (2020s)

Hubble

CoRoT

Spitzer

Kepler

TESS

JWST

PLATO

CHEOPS

Gaia

Roman

Next big wave? (2020s and 30s): Direct imaging of exoplanets from space and from ground

Ground Telescopes with NASA participation

1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA

1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
Shoulders of giants

- Guyon et al. 2006
- Jewell et al. 2018
- Miller, various
- Solgaard, various
Coronagraph performance parameters

- Parameters I will focus on:
  - Contrast of stellar leakage (due to stellar size / telescope low-order aberrations)
  - Inner Working Angle
  - Planet throughput

- Parameters I will not consider:
  - Bandwidth (no physics limit)
  - Wavefront control efficiency (important, but orthogonal problem)
Examples of pupil and image plane orthonormal bases

Pupil plane tip/tilt modes \( \{ v_n^m(r) \} \)

Corresponding Science Plane modes \( \{ u_n^m(\theta) \} \)
Technology progress schematic

- Where are the physics limits?
- Will currently developing technologies reach physics limits?
- What technologies can reach physics limits?
- How much will it cost and how long will it take?
ID: IT1A, IT1B
Likelihood: 5 (LUVOIR-A), 4 (LUVOIR-B)
Consequence: 4

Statement: Given the size of LUVOIR, there is a possibility that existing integration and test facilities may not be able to accommodate the fully integrated observatory segment, resulting in the need to construct new facilities.

Approach: Research. A preliminary survey of existing facilities has been completed as part of this study. While it appears that large enough facilities exist for most integration and test activities, a full accounting of required optical and mechanical ground support equipment has not been completed. As the architecture continues to develop in Pre-Phase A, a thorough assessment of available facilities and their capabilities will be completed, and a facility development plan will be created. This plan will identify any facility gaps, and specify which existing facilities will need to be upgraded and which facilities may need to be constructed.
Stage 1 – Focus on enabling science and technology; begin Stage 1 now

Stage 2 – Begin the Decadal Survey recommended “Great Observatories Maturation Program”; conduct Analysis of Alternatives (AoA) and science / technology / architecture trades; begin Stage 2 in a few years (driven by planning and budget availability)

Stage 3 – Pre-formulation and decision to start the next Great Observatory; begin after Stage 2 AoA complete (Decadal Survey estimates 6 years for Stages 2 and 3)
• It is important / critical to concurrently develop science and technology, starting now (Nick Siegler, Jay Falker, Aki Roberge, John Ziemer)

• Need quantitative understanding of integrated science trade space & hardware implications (Aki Roberge)

• Understanding the driving parameters and sensitivities in design, which requires system models of the science, observatory, data processing (John Ziemer)

• In addition to working to close technology gaps and reduce risk, it is also very important to reduce total mission cost, and pursue emerging technologies that may enable that (Jay Falker)

Note: above are paraphrases and are not exact quotes
How can Ames contribute to Astro2020 precursor science?

- Provide a model of exoplanet demographics for IR/O/UV mission (as we did with SAG13)
  - especially for binary stars and possibly specific to each individual IR/O/UV target for exoplanet search

- Model exoplanet spectra, assess sensitivities to mission parameters, and how to maximize retrieved information
  - Using laboratory and theoretical data as input parameters

- Optimize / Improve turnaround time of coronagraph modeling tools (e.g. as we did with the SCDA effort: Segmented Coronagraph Design and Analysis) which links technology to science

- Conduct observations to provide potential targets, or better characterize star system parameters, for IR/O/UV exo-Earth imaging flagship (e.g. JWST and Toliman observations of Alpha Centauri)
Pursue rapid, vigorous technology innovation to achieve:
- Breakthrough improvements in mission performance (for exo-Earth characterization)
- Significant reductions in mission risk and lifecycle cost
- This addresses some of the top recommendations in SMD Large Mission Study report (https://science.nasa.gov/about-us/large-mission-study)

Potentially breakthrough technologies we are already pursuing:
- PIAA-Vortex coronagraph
  - Significantly improves IR/O/UV mission exo-Earth yield (reduces astrophysics risks)
  - Significantly relaxes requirements on telescope (reduces technical risk and cost)
- Multi-Star Wavefront Control
  - Improves IR/O/UV mission exo-Earth yield, and diversifies science into binaries
  - Reduces risk and lifecycle mission cost by enabling more targets that are better / brighter / closer

Technologies we are exploring:
- Photonic chips
  - In theory, can achieve physics limits and improve science by a factor of 3
  - Relaxes requirements on telescope (on-axis, jitter-tolerant)
- Predictive / machine-learning-based wavefront control

Thinking bigger: an “innovation center”, with a staff of 10-20 technology innovators, tasked with inventing technologies that may be risky but potentially breakthrough
- High return on investment in terms of mission cost savings and improving science margin
  - Example: even if only 1-2 technologies succeed by improving mission performance or reducing risk by 10%, that could save a lot on a $10B mission
  - Quantifying ROI on breakthrough technologies deserves a deeper look by flagship technology strategy teams, and ARC can inform that
- Cost of technology innovation is low compared to total flagship cost, but impact is high
How can Ames contribute to Astro2020 IR/O/UV flagship mission long-term?

1. Participation on strategic teams, STDTs, and workgroups

2. Organize workshops to:
   1. Significantly accelerate technology innovation
   2. Bring different interdisciplinary communities together (e.g. to see what lab data is needed for modeling)

3. Lead development of breakthrough technologies that were incubated at Ames (if selected for flight)

4. Conduct laboratory experiments and theoretical calculations to provide input parameters (line lists, optical constants…) for exoplanet models

5. Contribute instrument modes (as we did with Roman CGI), especially for characterizing exoplanets around Alpha Centauri and other binaries

6. Lead modeling of exoplanet spectra, simulate observations, and conduct spectral retrieval

7. Lead science observations, especially ones with Ames-developed technologies and/or contributed modes
Summary: what can we do with different levels of investments this decade into ARC contribution to IR/O/UV mission?

<table>
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<tr>
<th>Benefit to NASA: IR/O/UV science / technical performance and risk mitigation</th>
<th>Benefit to NASA: IR/O/UV lifecycle cost savings</th>
<th>Benefit to ARC</th>
<th>Small investment o($100K / year)</th>
<th>Medium investment o($1M/year), including funded proposals</th>
<th>Large investment o($10M / year), possibly distributed across several centers</th>
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<tbody>
<tr>
<td>Precursor science (slide 5)</td>
<td>Enables / enhances science &gt;95% chance of medium science risk reduction</td>
<td>&gt; 95% chance of o($100M) savings</td>
<td>Early participation on IR/O/UV flagship teams that can lead to greater roles in the future; growth of science capabilities</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Small group pursuing 2-3 breakthrough technologies (slide 6)</td>
<td>enhances instrument performance ~30% chance of large risk reduction</td>
<td>~$30% chance of o($1B) savings</td>
<td>Possibility of establishing a strong role on IR/O/UV coronagraphic instrument</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Additional activities (slide 7)</td>
<td>Enables / enhances science and technical performance ~80% chance of medium reduction</td>
<td>Medium chance of o($100M) savings</td>
<td>Role on IR/O/UV teams; greater synergies, both within ARC, and with teams outside of ARC</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>“Innovation center” pursuing ~20 breakthrough technologies for IR/O/UV coronagraphic instrument (and possibly other exoplanet technologies) (slide 8)</td>
<td>&gt; 95% chance of high reduction</td>
<td>&gt; 95% chance of o($1B) savings</td>
<td>New unique core competency for NASA in tech innovation, and strong role for IR/O/UV and future missions, such as leading instruments and (non-flagship) missions</td>
<td>X</td>
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Caveat: for now, this table is based on educated guesses and back-of-the-envelope calculations, rather than detailed quantitative assessments. In case there is interest in pursuing these directions, we can conduct more accurate quantitative assessments.
Coronagraph metrics

very common metric: contrast curve

(Arguably) more informative metric: point source throughput curve

Lab demonstration at HCIT, 10% band, Lyot coronagraph

Seo et al. 2019
Coronagraph metric #1: “Energy Throughput”

Define “Energy throughput” as

$$T_C(\theta) = \frac{\|CE_\theta\|^2}{\|E_\theta\|^2}$$
Is it possible to fully suppress a (point-like) star?

Throughput (linear scale)

Sky angle

Exactly 0
(10^-∞ contrast)
Is it possible to fully suppress a (point-like) star?

**YES!**

Throughput (linear scale)

Exactly 0 (10^-∞ contrast)

Sky angle
Is it possible to fully suppress a star with >0 diameter?
Is it possible to fully suppress a star with >0 diameter?

No… (Belikov et al. 2021)
Motivation

• Investments in potentially breakthrough technologies to improve the performance of CGI systems has very high benefits
  • mitigating risk for the Astro2020-recommended mission objectives
  • achieving even greater discoveries by future missions
  • ensuring that older technologies do not limit future mission performance

• How CGI technology investments in 2020s will mitigate mission risk for Astro2020 flagship and beyond
  • create exoplanet yield margin by improving CGI performance (leading to 2-3x greater yields¹)
  • significantly reduce mission risk by making the instrument more robust¹
  • provide an option to consider a less costly telescope (e.g. on axis and/or less stable and/or smaller ³)

• Several new technologies have the potential to significantly improve CGI performance and be advanced to TRL5 by the end of the decade
  • New advances in traditional CGI technologies¹
  • Photonic circuits²
  • New wavefront control algorithms³
  • It is likely there are others (possibly machine learning, more sensitive detectors, coatings with better reflectivity, etc.)

1. Belikov et al. 2021
2. Jovanovic et al. 2019
3. Pogorelyuk et al. 2021
Proposed Approach
Deliverable #1: Panel + white paper (~5 pages)
on potential CGI breakthrough technology investments

● Goal: identify and discuss potentially breakthrough technologies that
  ● Have strong potential to significantly improve CGI
  ● Can conceivably be matured to TRL5 by the end of the decade

● Format:
  ● A diverse group of ~6 experts who focus on a particular topic (e.g. new traditional coronagraph tech, new WFC tech, photonics, etc.)
  ● Each expert leads a 1h breakout session with open attendance
  ● A 1h (or 1.5h) panel discussion
    ● First, each expert presents a slide of key results from the breakout session
    ● Open discussion between panel members and with the audience

● Location / date:
  ● Baseline: NASA Precursor Science Workshop I (Virtual, https://exoplanets.nasa.gov/exep/astro2020-precursor-sciws1/), 20-22 April 2022
  ● Alternatives:
    ● Exoplanets IV (Las Vegas, NV, 1-6 May, 2022)
    ● ExoPAG at 240th AAS meeting (June 12 – 16, 2022)

● Deliverable:
  ● A short (5page ?) white paper summarizing the panel findings and discussion

● Alternative approach: Same as above, but a longer and more in-depth dedicated workshop, either standalone or as a special session of one of the above meetings
Proposed Approach

Deliverable #2 – Series of Workshops / Report (~30 pages), describing the qualitative and quantitative benefits and costs of CGI Breakthrough Technology Investments

- **Goals:**
  - In-depth assessment of new CGI technologies (identified by panel, as well as potentially additional ones)
  - Initial design and feasibility studies (TRL0-3) of the most promising technologies over the next 1-3 years (with appropriate funding)

- **Format:**
  - Series of dedicated 1-day standalone workshops, 2 per year, hosted at ARC (or rotating between ARC and other institutions)
  - Similar to ExoPAG SAG (and maybe actually make it a SAG), i.e. open participation
    - Alternative: competitive or directed selection of a smaller group of experts

- **Deliverable:**
  - A longer (30 page ?) report:
    - summarizing all technologies that were studied
    - estimates of expected performance
    - estimates of cost and time of path to TRL5
    - recommendations of whether or not investment by NASA would benefit Astro2020 flagship
How close are state-of-the-art coronagraph designs to theoretical limits?

- Fundamental trade between IWA and tip-tilt sensitivity (or equivalently, stellar size)
  - For a ~12th order coronagraph, can have IWA of ~2.4 \( \lambda/D \) and be tolerant to 1 \( \lambda/D \) stellar diameters
- Optimal IWAs are quantized
- Substantial performance gap / opportunity for improvement remains even for unobstructed apertures

Performance of selected coronagraph designs compared to theoretical limits

Each asterisk represents a different coronagraph. Its y-coordinate is the IWA and the x-coordinate is the stellar diameter at which the peak contrast of leaked starlight becomes 1e-9.
The Circularly-Symmetric PIAA-Vortex
The Circularly-Symmetric PIAA-Vortex

PIAA-Vortex prescription is much flatter than traditional PIAA, resulting in significantly less off-axis PSF degradation.
Common wisdom is that challenges in $10^{10}$ contrast are too hard for integrated photonics (contrast, bandwidth, throughput, etc.)

But, the potential of photonics is very compelling...

Is common wisdom correct? What will it take to make a high-contrast imaging photonic integrated chip?

- Level of funding for CGI development on Astro2020 flagship may be greater than past projects
- Leveraging investments by industry (global photonics market is $597B in 2020, ~$1T by 2026)
"Bulk" electronics (ENIAC) → Integrated electronics

Technology evolution (or revolution)

Bulk Optics

Roman space telescope Coronagraphic Instrument
(current state of the art for space-qualified coronagraphs; tour de force technical achievement, like the ENIAC was)