Exoplanet Nulling Coronagraphy with Arbitrary Apertures

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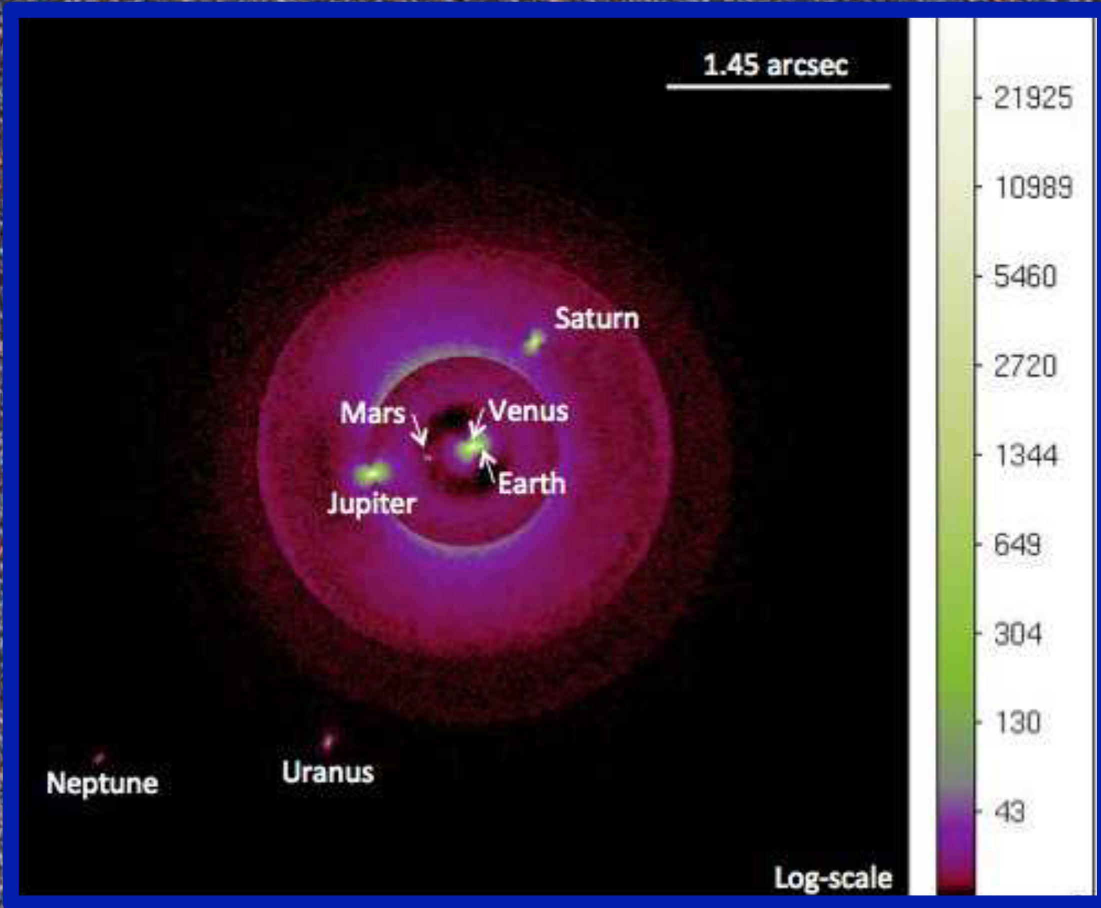


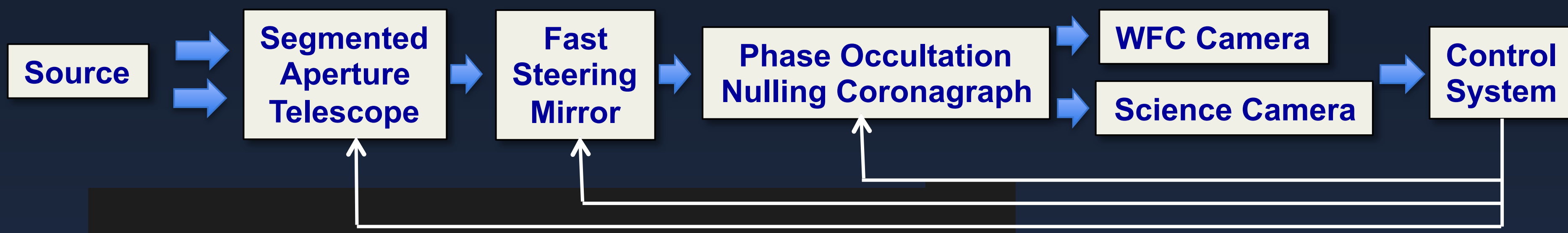
Synopsis

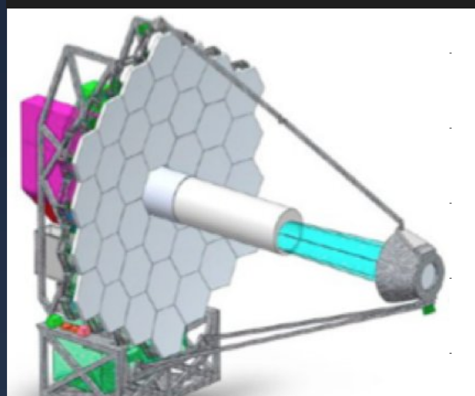
- ***GOAL***: Spectroscopy & imaging of earth size exoplanets & biomarkers
- ***Past Approaches***: STABLE off-axis unobscured filled aperture telescope employing a high contrast coronographic instrument, e.g. TPF-C
  - Large lightweight monolithic primary mirror
  - Telescope stability ~30 picometer (contrast stability of $2x10^{-11}$) per observation
  - ~1000x more stable than JWST
- ***Alternative Approach***: Leverage JWST segmented telescope technology
  - Low order wavefront control, closed loop ~1/minute, but w/ on-board processing throughout flight
  - Deployable segmented mirrors for large >8m, as large as 20m ?
  - Use *Phase Occultation Nulling Coronagraph* (PONC):
    - Pupil plane nulling ⬄Allows segmented, and arbitrary, apertures
    - Telescope stability to 2 nm / minute (differential control)
    - PONC differential stability to 15 pm / minute
    - Facilitates its own differential fine wavefront control

Lyon, Hicks, Clampin, Petrone
Phase-Occultation Nulling Coronagraphy
http://arxiv.org/abs/1504.05747
(2015)

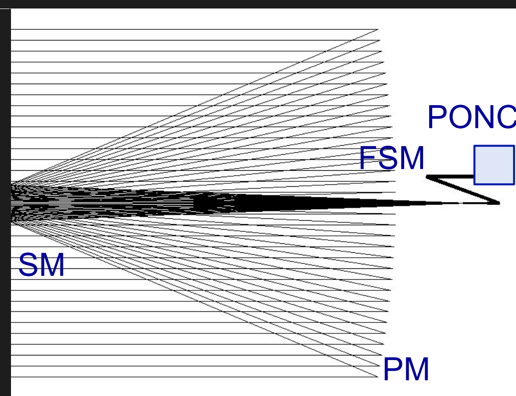
- ***PONC => New approach to exoplanet imaging***
  - Achieved lab results achieved with GSFC VNC testbed (not a PONC):
    - 5.5 x 10^{-9} at IWA = 2 λ/D (28 milli-arcseconds for assumed 8m telescope)
    - For sensing / control at 2 λ/D narrowband w/o phase occultation
  - Broaderband (40 nm) nearly complete at 10^{-9} (SAT/TDEM milestone)
  - Next milestone (2016) validates with macroscopic segmented aperture
  - Proposed milestone (>2016) PONC w/ segmented aperture
  - PONC component technologies at or are pushing towards TRL-6
  - PONC instrument to TRL-5/6 by 2018/19 possible to prepare for 2020 Decadal
    - Requires influx of funds.

Architecture Overview with PONC

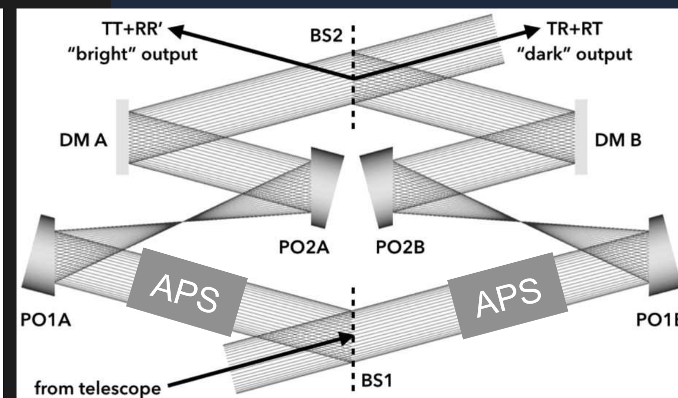




Example of ATLAST/LUVOIR (Postman et.al. (2009)



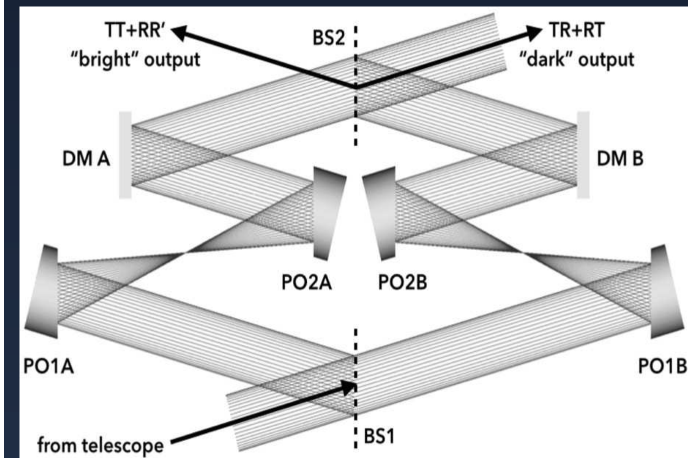
Telescope Raytrace

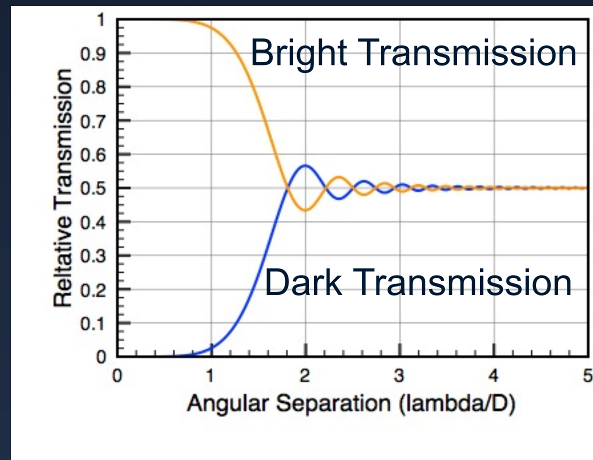


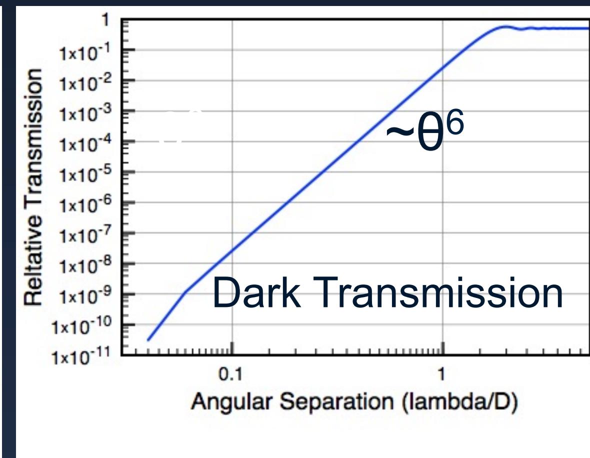
Phase Occultation Nulling Coronagraph

- On-board closed-loop control
- Segment level piston, tip, tilt
- SM 6-DOF control
- PONC
  - fine wavefront/amplitude control
  - polarization (passive)
  - broadband
  - ~1/minute

Principle of PONC
Pupil Plane Transmission



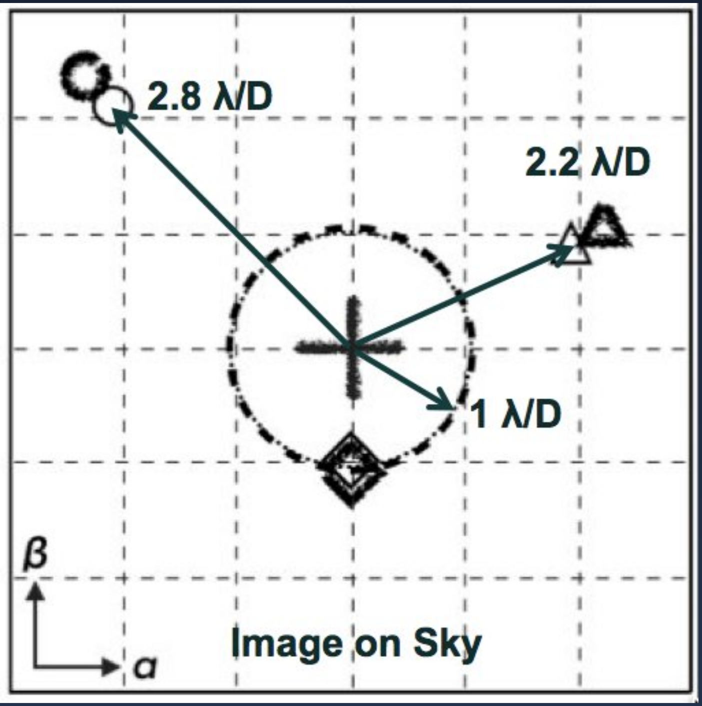


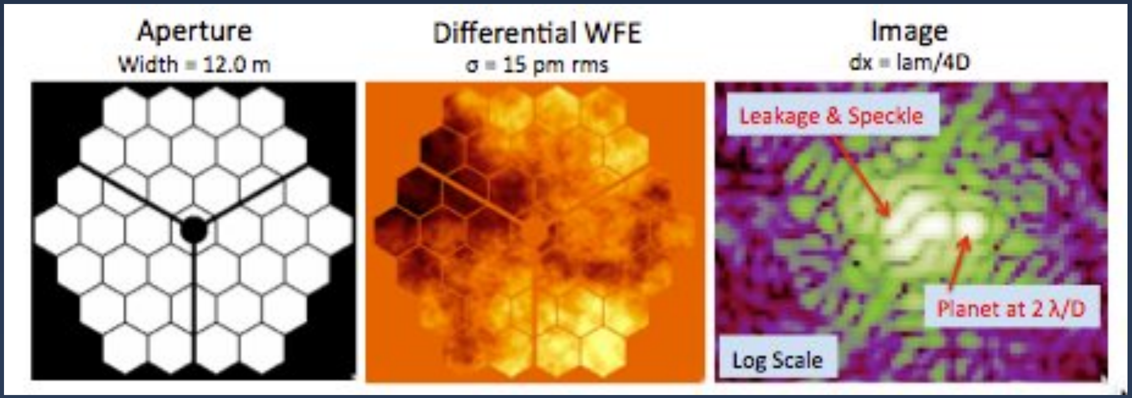


- Single modified ***Mach-Zehnder*** interferometer (aka nuller)
- Telescope light split into two paths ("arms" @ BS-1)
- PO optics cancel SA3, coma, astigmatism, leaves 3rd order distortion
- Field distortion is $\sim\theta^3$ with field angle => Contrast is $\sim\theta^6$
  - **Star**: on-axis ($\theta = 0$) <I> = zero (star),
  - **Planet**: off-axis ($\theta > 0$) <I> $\sim\theta^6$
- Recombined @ BS-2 => 2 output channels:
  - *Bright* => on-axis star light for control => pupil, or infocus, image
  - *Dark* => off-axis planet light for science => in-focus image

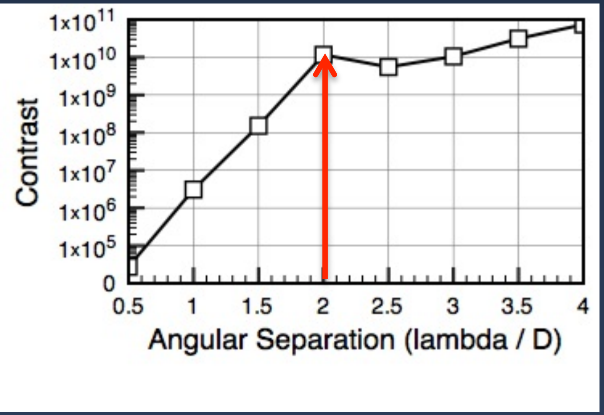
Principle of PONC
Focal Plane Transmission

- PONC on-axis (Star) acts like conventional nuller
- Off-axis (Planet) PONC induces differential distortion plus path length phase shift between two arms
- Causes PSFs from each arm to shift apart with increasing field angle
- Net effect is destructive interference of Star (aka nulling) and unbalanced destructive (aka transmission) interference of planet





Example with Wavefront Error



Key Points and Issues

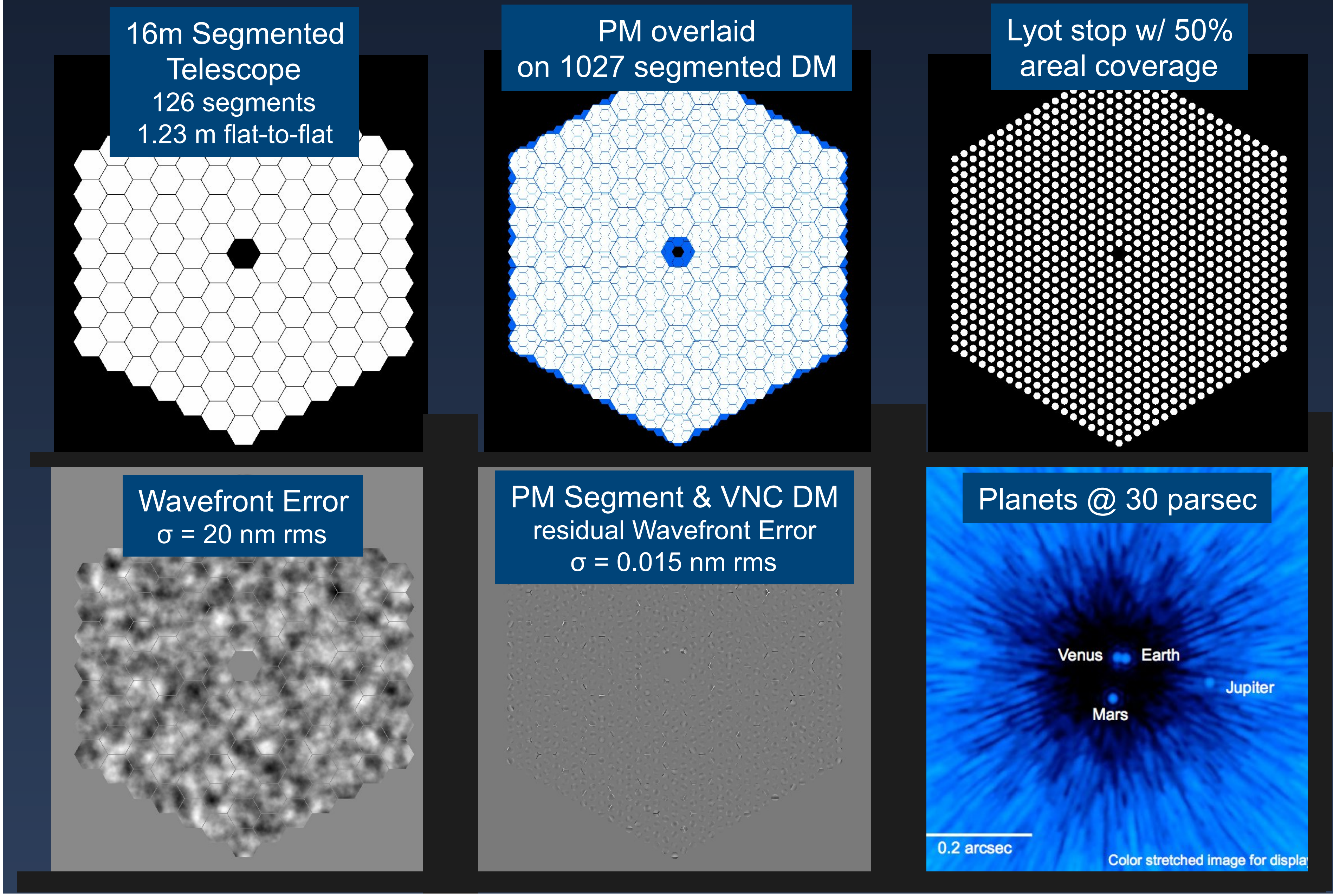
Key Points:

- Viable for Segmented Apertures
- Differential wavefront/amplitude control:
  - Lowers sensitivity to telescope WFE & drift (common mode)
  - Single hex-pack DM + spatial filter array
  - <u>or</u> 2 DMs, 1 @ pupil, 1 @ Fresnel plane
- Inner working angle = 2 λ/D (28 mas for 8 m)
- Contrast to $<10^{-10}$
- Broadband with achromatic phase shifters
- "Flattening" of central conic region may desensitize wrt pointing
- Resolved stellar source sensitivity $\sim\theta^6$

Issues:

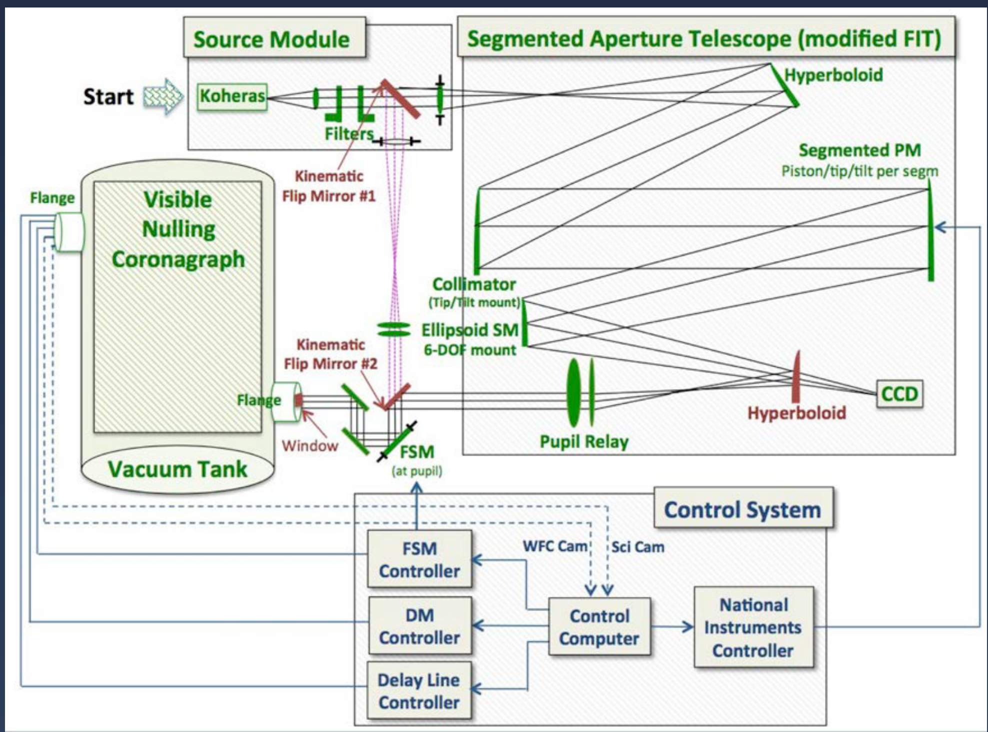
- Sensitive to re-imaged telescope pupil shift, roll & magnification
- PSF has 2-lobes (post-processing to minimize ?)
- Peak theorectical throughput limited to 50% (less w/Lyot)
- Manufacture / alignment tolerances of PO optics still in-progress
- Best optical surface design still in-progress

PONC with Segmented Aperture Telescope



Summary and the Future

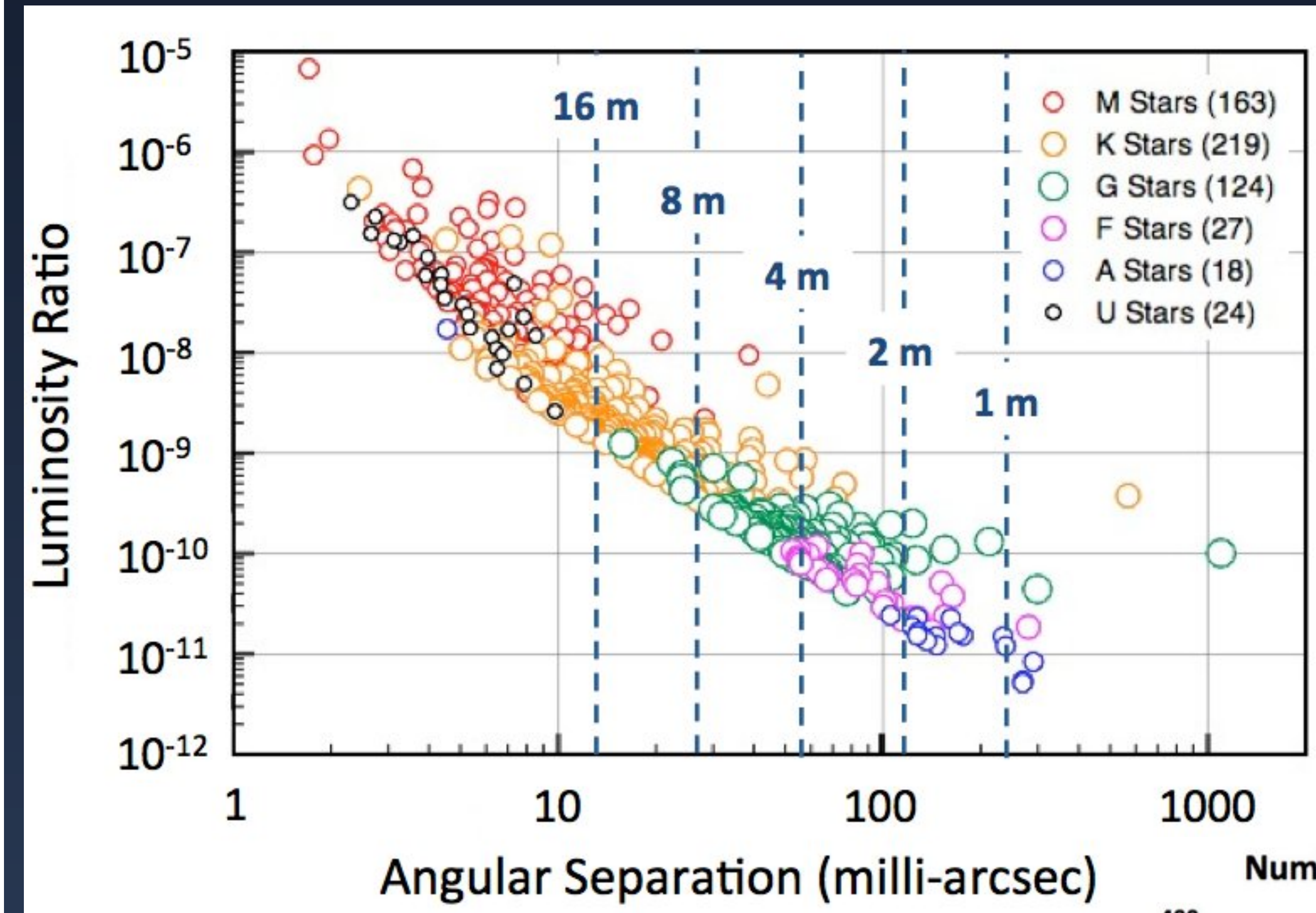
- Exoplanet direct imaging / spectroscopy require large apertures (>8 meters)
- Large Apertures should leverage existing segmented aperture technology
- Coronagraph(s) need to adapt to segmented apertures
- Approaches that levy less stressing telescope requirements are desired
- Phase Occulting Nulling Coronagraph may be such an approach, however:
  - Needs more detailed modeling / analysis, with detailed instrument design
    - IRAD and SIF (FY15/16) and DR&T efforts (FY16)
  - Lab demo of PONC approach:
    - SAINT*: Segmented Aperture Interferometric Nulling Testbed*



SAINT: Benchtop segmented (actuated) telescope coupled to PONC to demonstrate coupled control & hi-contrast imaging

Also…

Terrestrial Exoplanets and Telescope Size

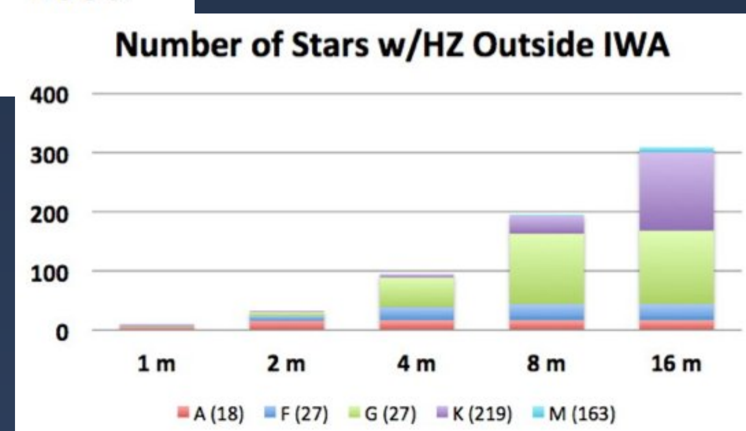


Assumes:

- $\eta_{EARTH1} = 1$
- Planets all Earth diameter
- V-band 500 – 600 nm
- IWA = 2 λ/D

See for example:

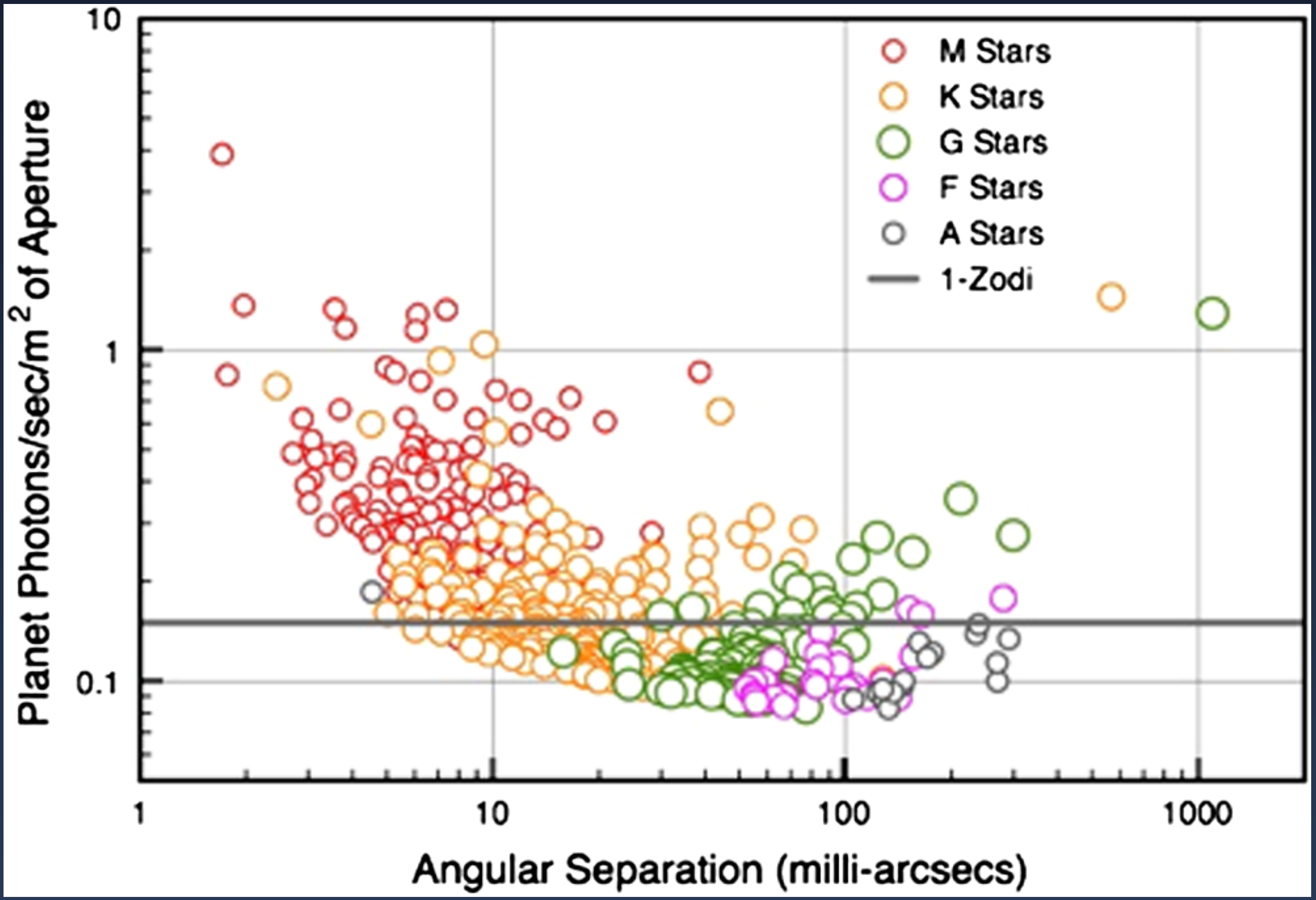
Lyon, Clampin, JOE 51 (2012)



To resolve reasonable number of terrestrials from host star =>

- Aperture must be ≥ 8m
- Area ≥ 50 m^2

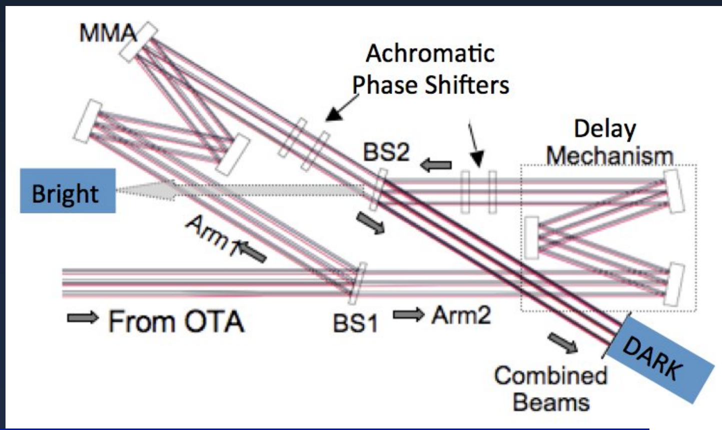
At least 8 meter Apertures are Required



Most G-stars > 30 mas

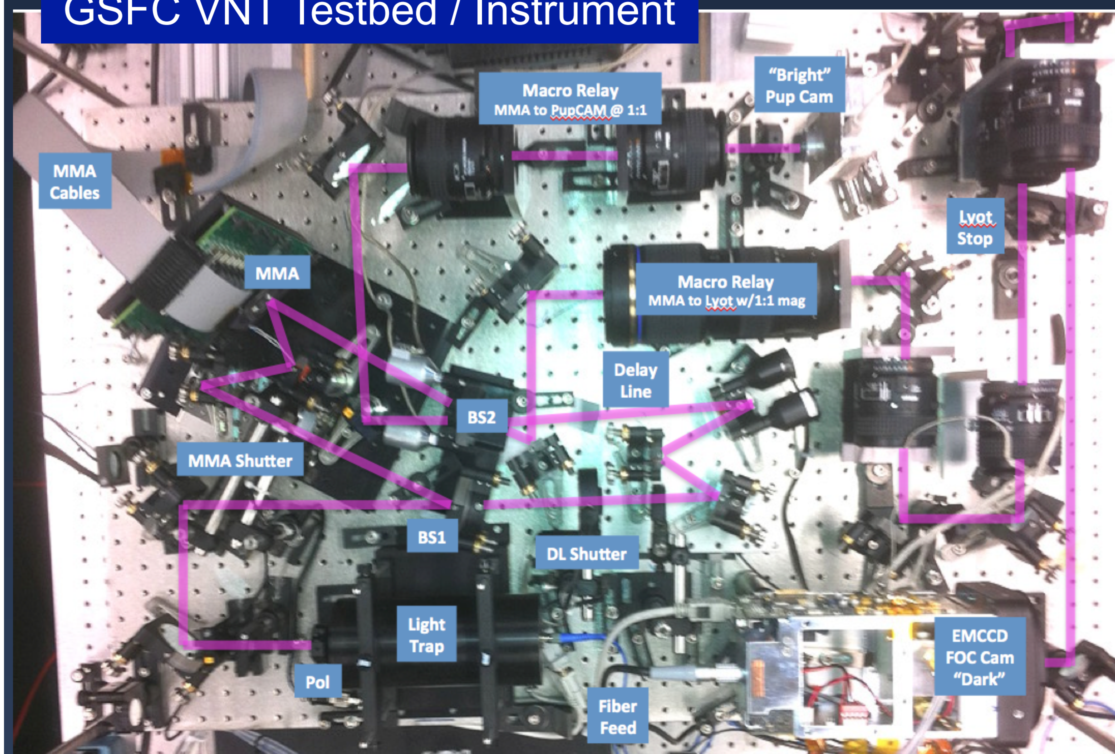
D = 8 m
A = 50 m^2
=> Yields ~10 photons/sec
Spectra R=100 => ~0.1 photon/sec

VNC Technologies



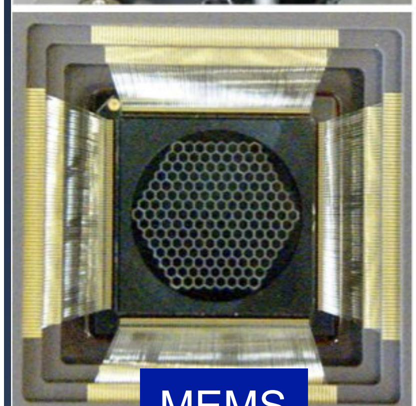
- GSFC VNC testbed => IRAD, SAT/TDEM
- Operates in vacuum tank, currently tank sealed w/air
- Technologies funded under SBIR & SAT/TDEM
  - DM multiple SBIRs funded (IRIS-AO Inc.)
  - DM undergoing environmental test FY14 (SAT/TDEM)
- All Technologies at > TRL-6 or will be by end of 2015

GSFC VNT Testbed / Instrument

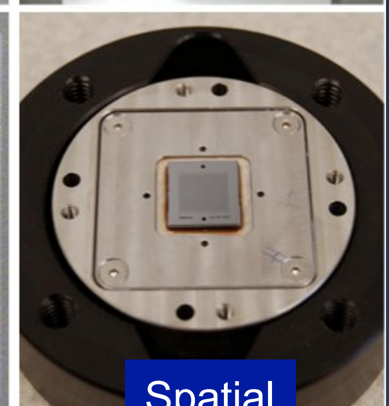


Delay Line

FSM

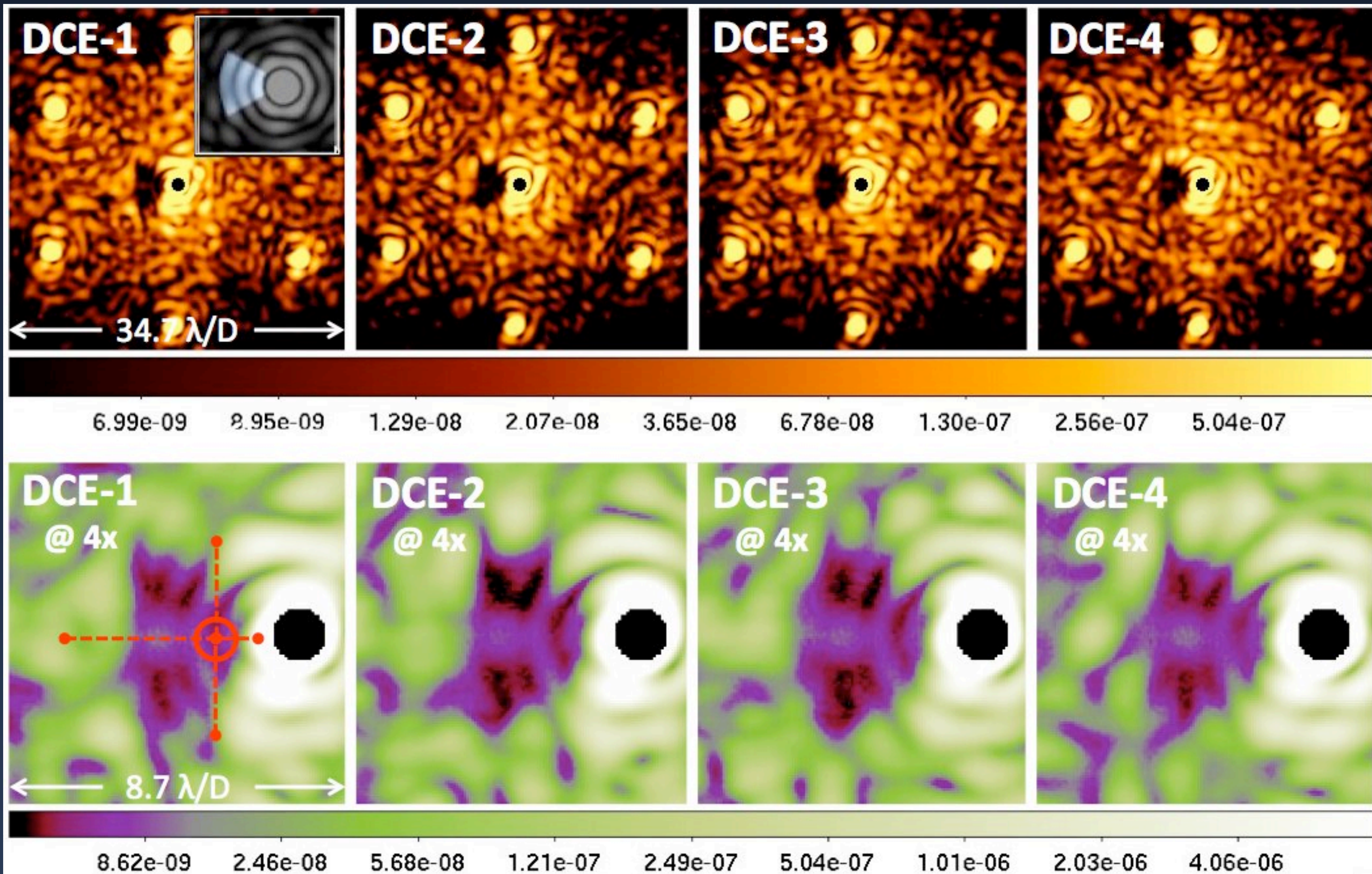


MEMS DM



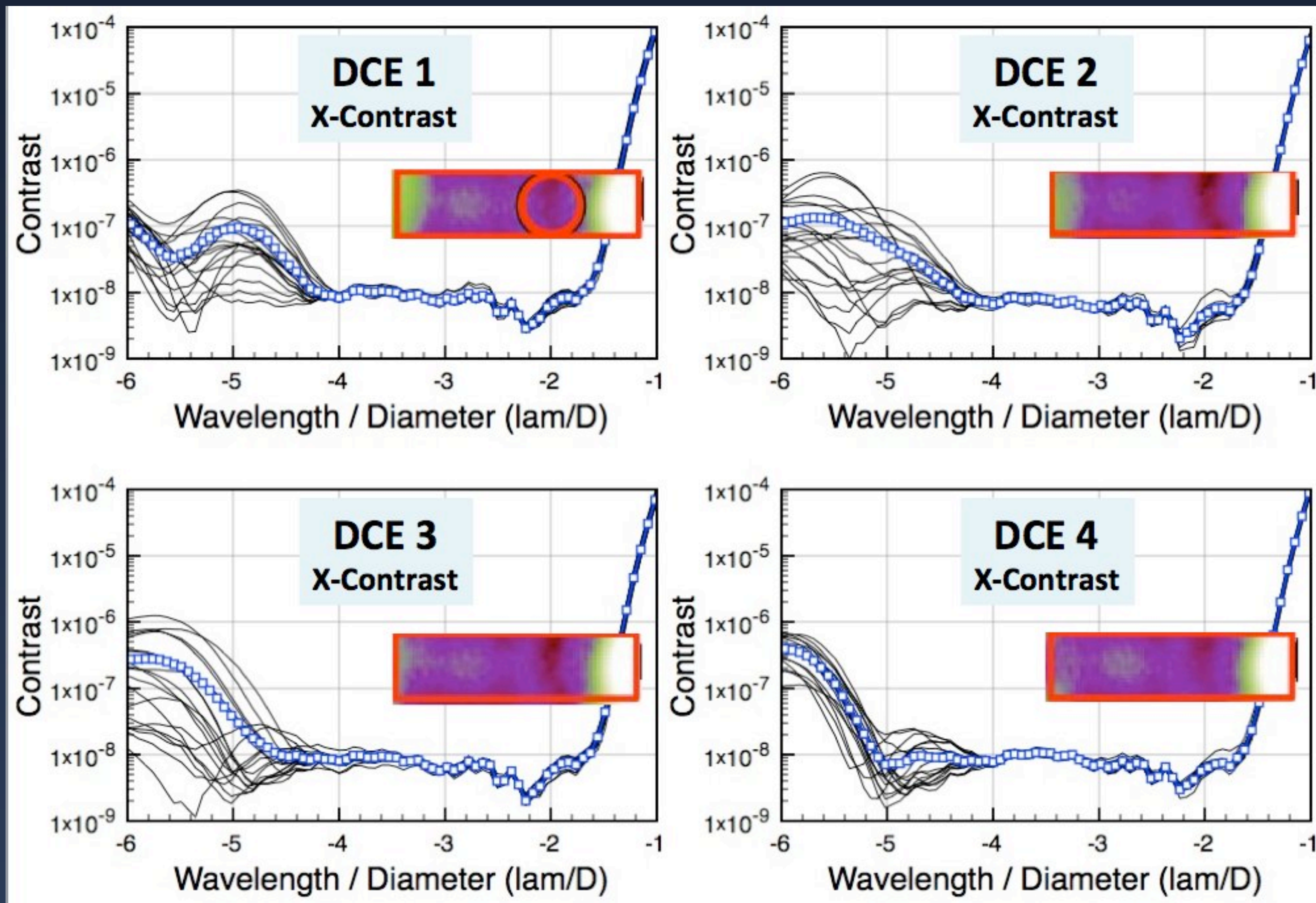
Spatial Filter Array

GSFC VNC Lab Results



4 DCEs, 50,000 control steps, last 3,800 averaged per DCE

GSFC VNC Lab Results



GSFC Contrast Results

- Worst case <C> is for DCE1
  $5.51 \pm 0.13 \times 10^{-9}$
  - to >99.99% confidence
  - at 2 λ/D
  - Narrowband (λ=633 nm, Δλ=1.2 nm)
  - Result is consistent with models & error budgets
- Met first milestone per TAC review Feb 2013
- Highest recorded contrast for any nulling coronagraph

Realization	DCE-1 Contrast x 10^{-9}	DCE-2 Contrast x 10^{-9}	DCE-3 Contrast x 10^{-9}	DCE-4 Contrast x 10^{-9}
1	5.86	5.25	3.95	5.36
2	5.40	4.09	4.71	4.64
3	5.15	3.98	4.72	4.79
4	4.88	3.80	4.29	4.61
5	4.93	3.87	4.35	4.66
6	5.06	3.95	3.95	4.80
7	5.54	3.96	5.03	4.98
8	5.54	3.61	5.01	5.02
9	5.31	3.65	4.96	5.45
10	6.30	3.93	4.88	5.12
11	5.23	3.75	4.90	6.11
12	4.89	3.67	4.63	5.21
13	5.05	3.99	4.94	4.94
14	4.98	4.24	4.41	5.26
15	5.77	3.73	4.84	5.09
16	5.52	3.41	4.13	5.30
17	6.68	3.42	4.27	6.31
18	6.64	3.50	4.28	5.07
19	5.98	3.91	4.25	5.08
Ave: <C> =	5.51×10^{-9}	3.88×10^{-9}	4.55×10^{-9}	5.15×10^{-9}
Sigma: σ =	5.65×10^{-10}	3.99×10^{-10}	3.64×10^{-10}	4.46×10^{-10}
Std Error =	$\pm 1.30 \times 10^{-10}$	$\pm 9.16 \times 10^{-11}$	$\pm 8.35 \times 10^{-11}$	$\pm 1.02 \times 10^{-10}$
Students-t =	34.61	66.82	65.21	47.40
Confidence =	> 99.99 %	> 99.99 %	> 99.99 %	> 99.99 %

Average over all 76 realizations	4.77×10^{-9}
Standard Dev (σ) over all 76 realizations	7.63×10^{-10}
Standard Error over all 76 realizations	8.76×10^{-11}
Contrast for 90% Confidence	5.68×10^{-9}