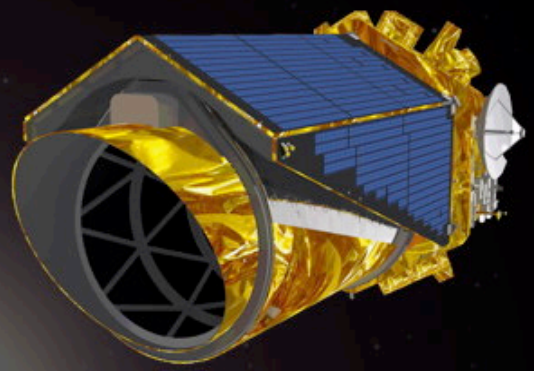
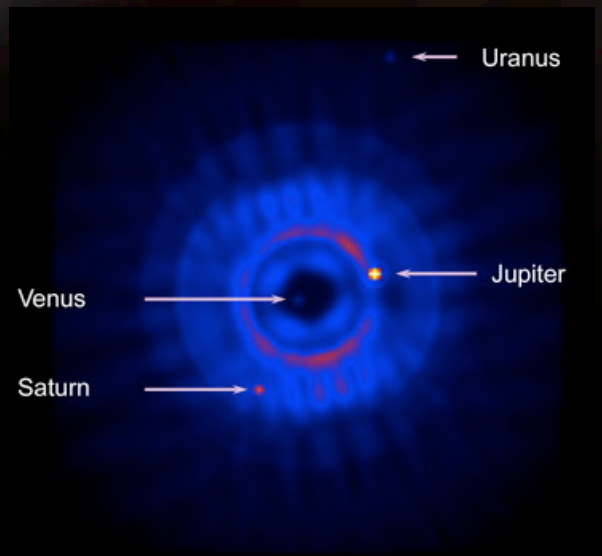
ExtraSolar Imaging Planetary Coronagraph (EPIC)



Missions for Exoplanets
Pasadena, CA
April 21-23, 2009



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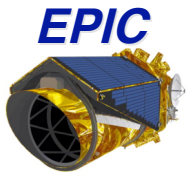
EPIC Overview



- **Science: Discovery & Characterization**
  - Key science: Dust/debris disks, Jovians, superEarths, 1-2 terrestrials possible
  - Science floor => Characterize >15 known RV selected gas giant planets
  - 125 mas IWA @ 500 nm, contrasts 10^9 to 4 x 10^9 from 480 - 960 nm
- **Mission**
  - EELV to Heliocentric Earth-trailing, 5 yr mission (7 yr goal) (similar to Spitzer orbit)
- **Instrument**
  - Single 1.65 m unobscured telescope feeding Visible Nulling Coronagraph (VNC)
  - Imaging Camera (FOV 4.5” x 4.5” & 10” x 10”) w/ spectral filters
  - Dispersive spectrometer (to R = 50), Limited polarimetry w/ filters
  - Active & passive null control, 2 MEMS segmented mirrors w/ Spatial Filter Array
  - Fine pointing S/C + FSM, 4 mas (3σ) @ 30 Hz
  - Mass 1356 kg (wet), Pwr < 785 W, Ka w/ HGA, X-band w/ Omni < 0.5 GB/day
- **Testbeds & Technology**
  - White light nulling demonstrated, closed-loop nulling control with MEMS DM
  - Development & integration of SFA underway, SBIRs for MEMS DM ongoing
  - Achromatic phase shifters 4-plate solution developed, higher fidelity approach underway
- **Costing**
  - EPIC is only ASMC mission costed both by GSFC IDC *and* JPL Team-X
- **EPIC is mature & achievable for < $850M**
  - Proposed twice as Discovery mission (w/ 1.5 m aperture)
  - Multiple design iterations, error budgeting and costing
  - Stressing technologies and risks associated with VNC

EPIC costed independently by GSFC IDC & JPL Team-X

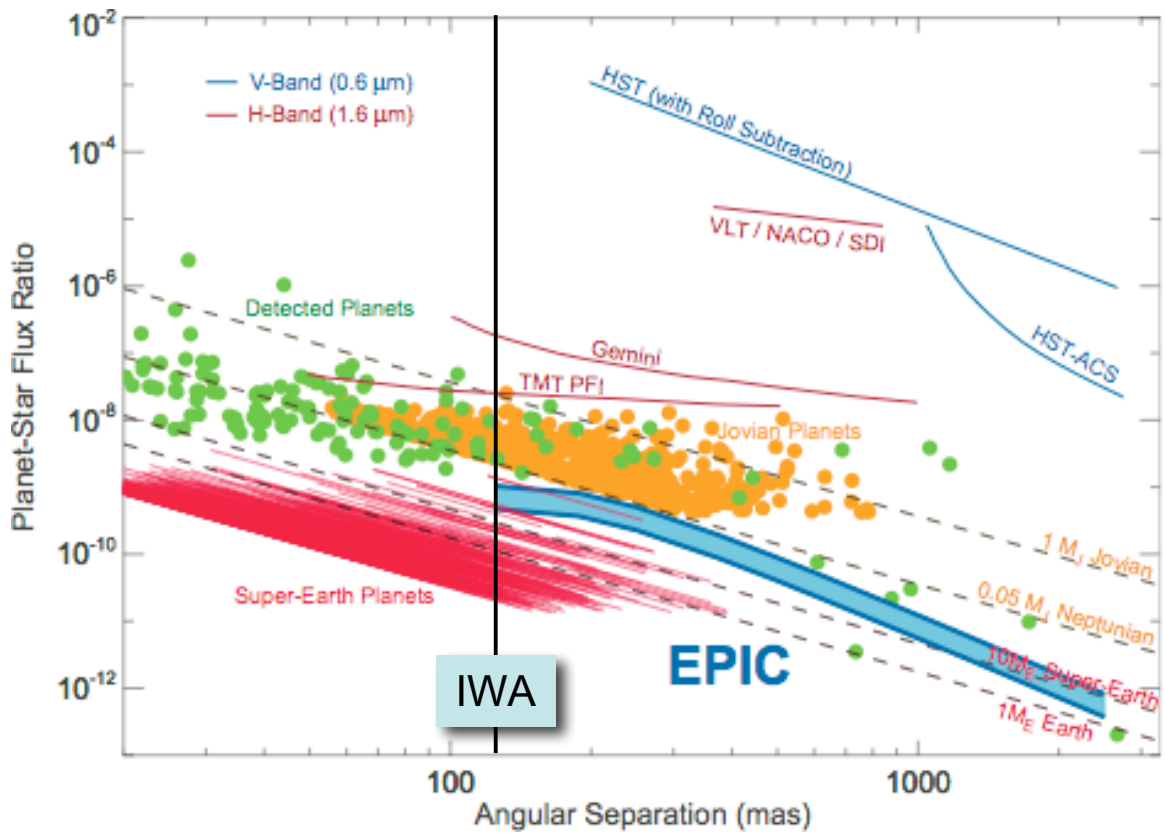
Science & Discovery Space

Gas Giants and Dust Disks

- EPIC's achievable contrast range allows gas giants & intermediate gas planets.

- EPIC can potentially detect some superEarths & and some terrestrials with higher null control bandwidth

  - Orange dots:
    $1M_J$ Jupiters @ 3 AU (luminosity corrected)
  - Red lines:
    $1M_E$ Earths at inner, outer HZ (luminosity corrected)
  - Green dots:
    all currently detected planets (RV, imaging, transits)
  - Blue lines:
    EPIC's contrast drift per 7,000 sec

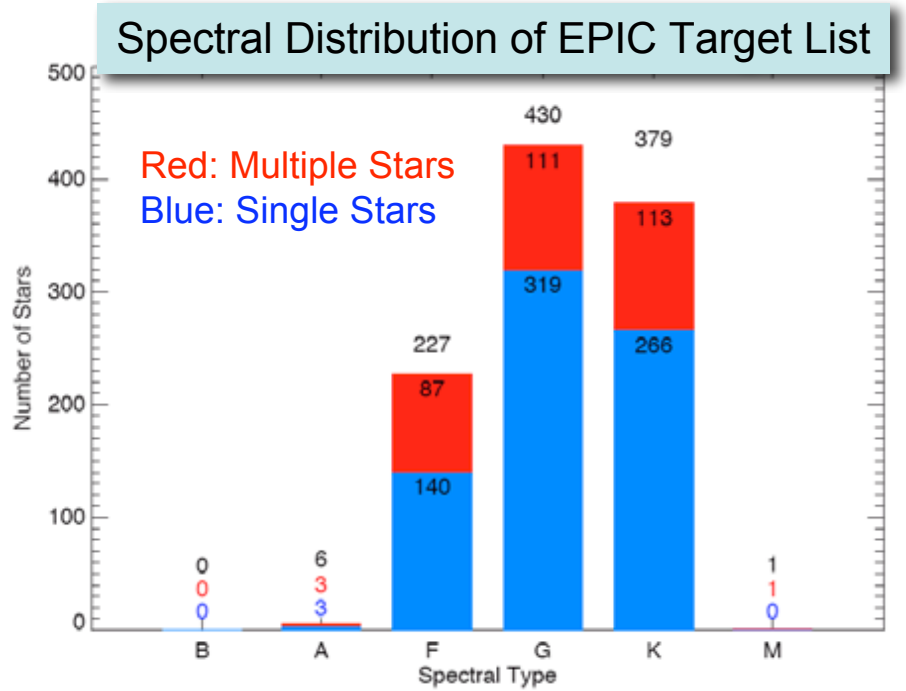


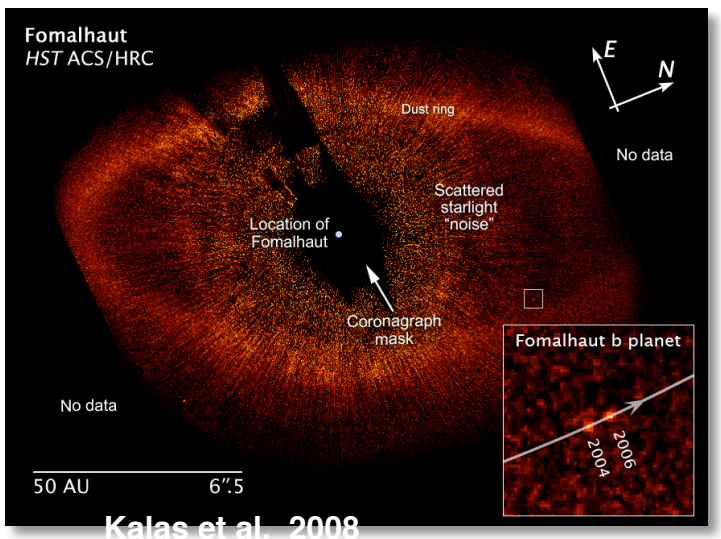
EPIC discovery space 0ptimized for gas giants beyond 125 mas with contrasts to $<10^9$

EPIC's Target Distribution

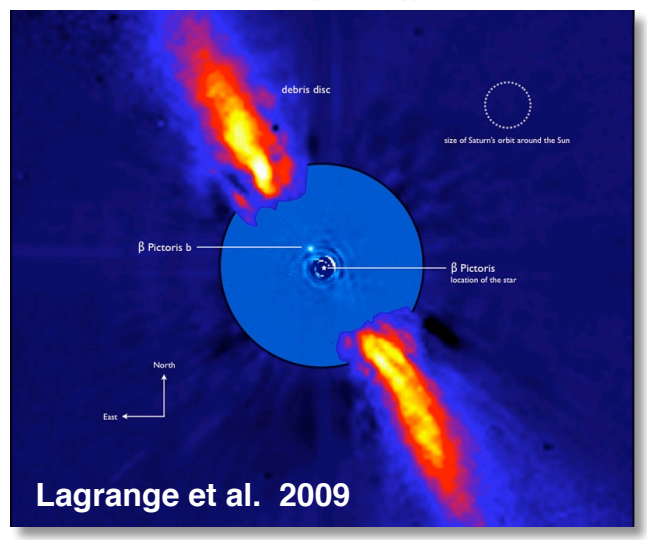
Jovians & Dust Disks

- ***Image & Characterize*** extrasolar giant planets and their environments
  <u>This includes binaries</u>
- ***Target list*** *of 1044 mostly F, G, K stars*
  - 315 are multiple star systems
  - 17 binary star systems within 10 pc
  - 109 within 20 pc
- ***Zodi Dust*** down to < 1 Zodi at 125 mas
  - dust structure/gaps infers exoplanets
  - Place brightness limits for future missions





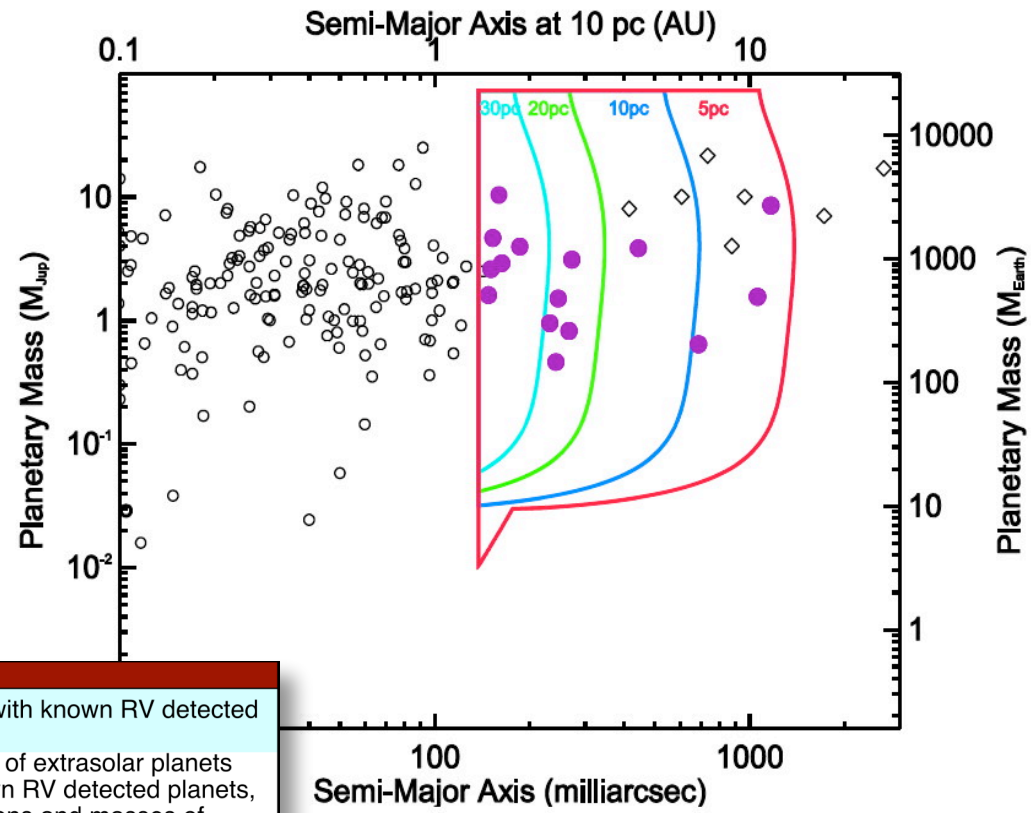
Kalas et al. 2008



Lagrange et al. 2009

EPIC's Discovery Space

- ***Contours***: planet semi-major axis vs mass in which Jovian's can be detected for distances of 5, 10, 20, 30 pc.
- ***Open circles***: RV detected planets
- ***Closed circles***: RV subset observable w/ EPIC => *minimum science floor*
- ***Diamonds***: coronagraph detected planets

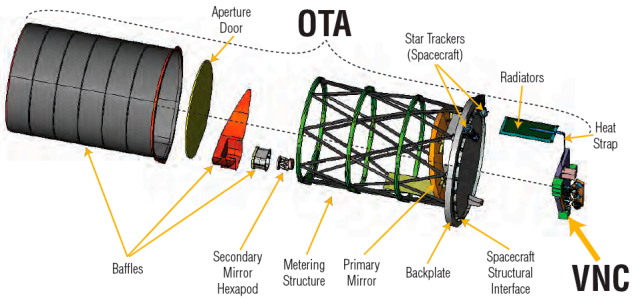


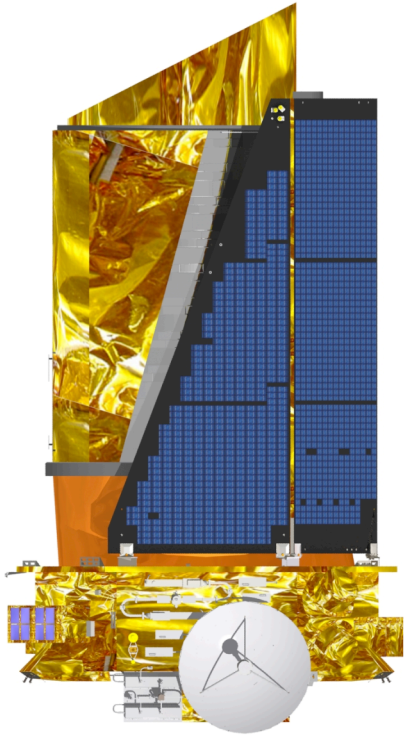
Science Goal	Science Investigation
Determine the properties of RV selected gas giant planets and characterize their atmospheres	Directly image extrasolar in systems with known RV detected planets, - Characterize the atmospheres of extrasolar planets detected in systems with known RV detected planets, - Determine the orbital inclinations and masses of planets in these systems - Map and Characterize the exozodiacal structures in these systems
Investigate the diversity of planetary system architectures	Survey nearby exosolar systems to search for extrasolar planets and debris disk structures. - Characterize the atmospheres of extrasolar planets detected in systems - Determine the orbital inclinations and masses of planets in these systems - Map and Characterize the exozodiacal structures in these systems

- Jovians can be detected from < 0.1 M_J to Brown Dwarfs
- Minimal science floor is 15 RV

Mission Overview

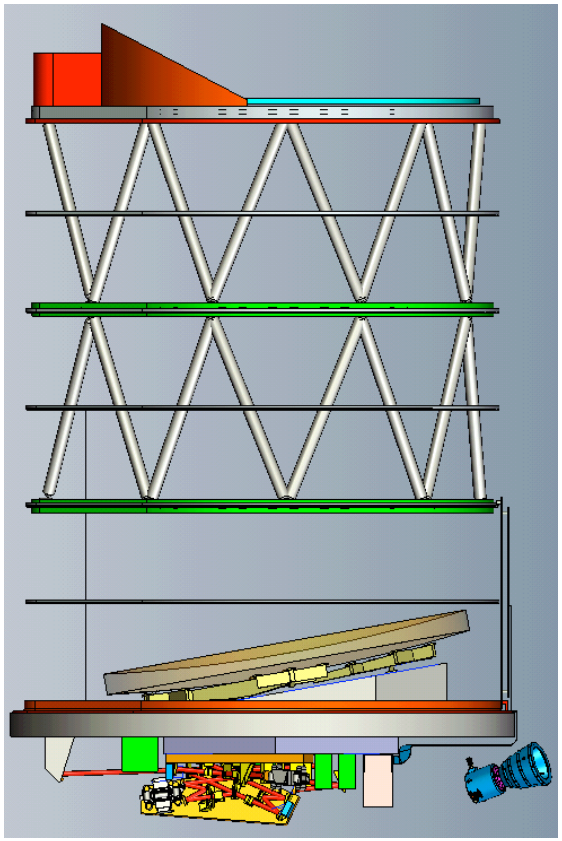
Spacecraft	Performance
Pointing	Spacecraft + Fine Steering Mirror
	Stability (Jitter): 4 mas (3 σ)
	Coarse Pointing: 2.5'' (3 σ)
	Abs. Pointing Knowledge: 5''
Power	785 W
Mass	1356 kg wet mass
Orbit	Heliocentric, trailing Earth's orbit
Launcher	EELV
Redundancy	Class B: Essential spacecraft functions and key instruments are typically fully redundant
Mission Lifetime	5 years
Communications	Ka-Band via HGA
	X-Band via Omni
	<0.5 Gbs/Day





Science Payload

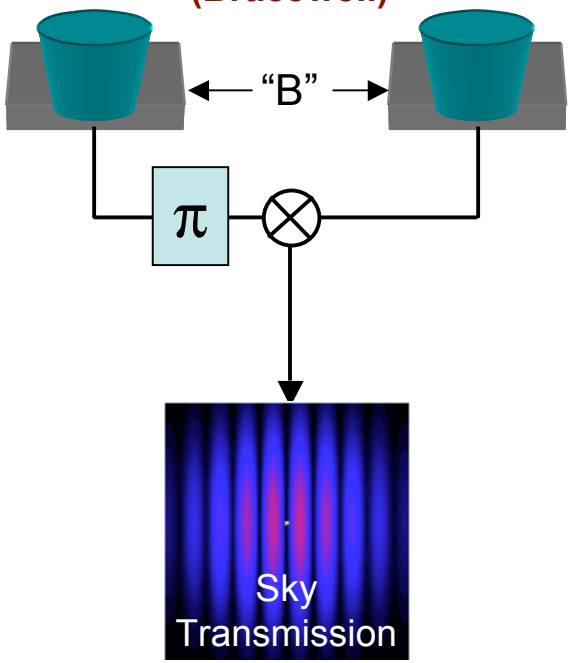
Science Payload	Performance
Telescope Optics	1.65 meter aperture off-axis primary
	- Wavefront error <55 nm
	- Wavefront error stability <12 nm
Coronagraph Design	Visible Nulling Coronagraph - Shears pupil in X: Shears pupil in Y --> θ^4 null - Phase control: Tip/Tilt/Piston multimirror array - Amplitude control: Fiber spatial filter array (SFA) - Instrument throughput: 18% - Bandpass: 20%
Science modes	$\geq 10^9$ contrast @ $2\lambda/D$: 4.5"x4.5" FOV
	$\geq 10^7$ contrast @ $2\lambda/D$: 10"x10" FOV
	R = 20 – 50 spectroscopy over 480 - 960 nm.
Sensors	Photon counting CCD detectors
	CCD Format: 512 x 512 pixels
	Readnoise: zero in photon counting mode
	Quantum Efficiency: 85% @ 700 nm



- Filled aperture off-axis (unobscured) Cassegrainian telescope
  1.65 m aperture, feeds light into Visible Nulling Coronagraph (VNC)
- Pointing control system with w/ Fine Steering Mirror in Loop
- VNC suppresses starlight increasing planet/star contrast
  and performs active and passive null control
- Two science instruments: Imager w/ filter & dispersive spectrometer

Starlight Suppression via Visible Nulling Coronagraph

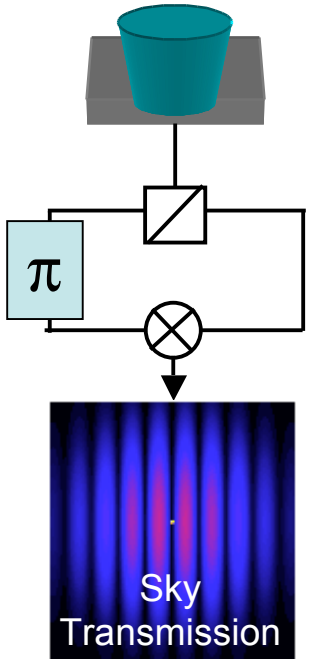
Nulling Interferometer
(Bracewell)



$$T^{\{2\}} = \sin^2\left(\pi \frac{B}{\lambda}\theta\right) \sim \theta^2$$

N - Telescopes
B - Baseline

Nulling Coronagraph



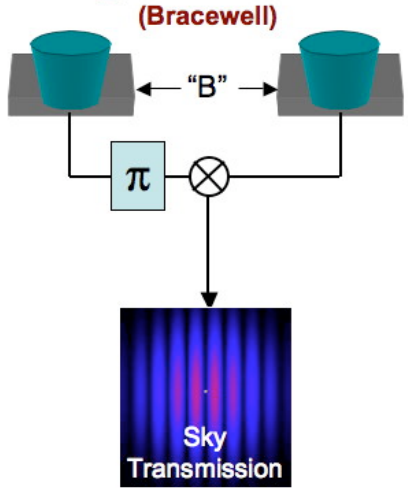
$$T^{\{2\}} = \sin^2\left(\pi \frac{sD}{\lambda}\theta\right) \sim \theta^2$$

N - Shears
D - Pupil Diameer

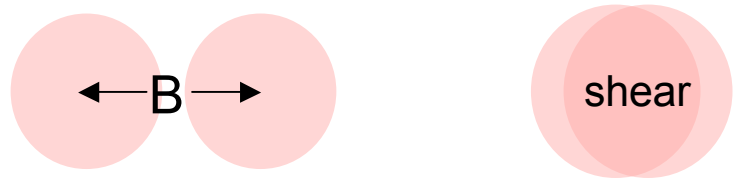
$$\sum_{j=1}^{N} e^{i\phi_j} = 0 \qquad Null \sim \theta^N$$

Visible Nulling Coronagraph Principle

Nulling Interferometer
(Bracewell)

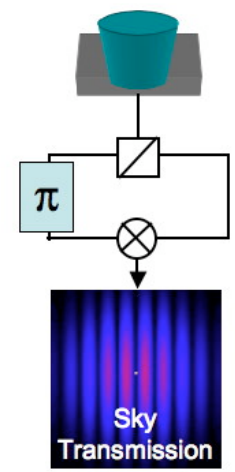


$T^{\{2\}} \sim \theta^2$



VNC is Hybrid of interferometer where ***baseline separation*** is **emulated by shearing**

Nulling Coronagraph



$T^{\{2\}} \sim \theta^2$

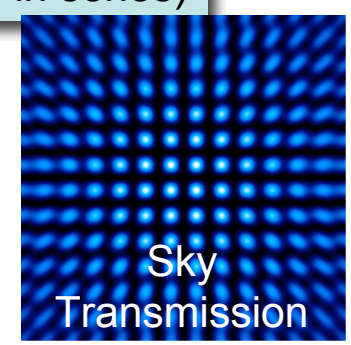
EPIC has X-shear followed by Y-shear (2 nullers in series)

4-Shear

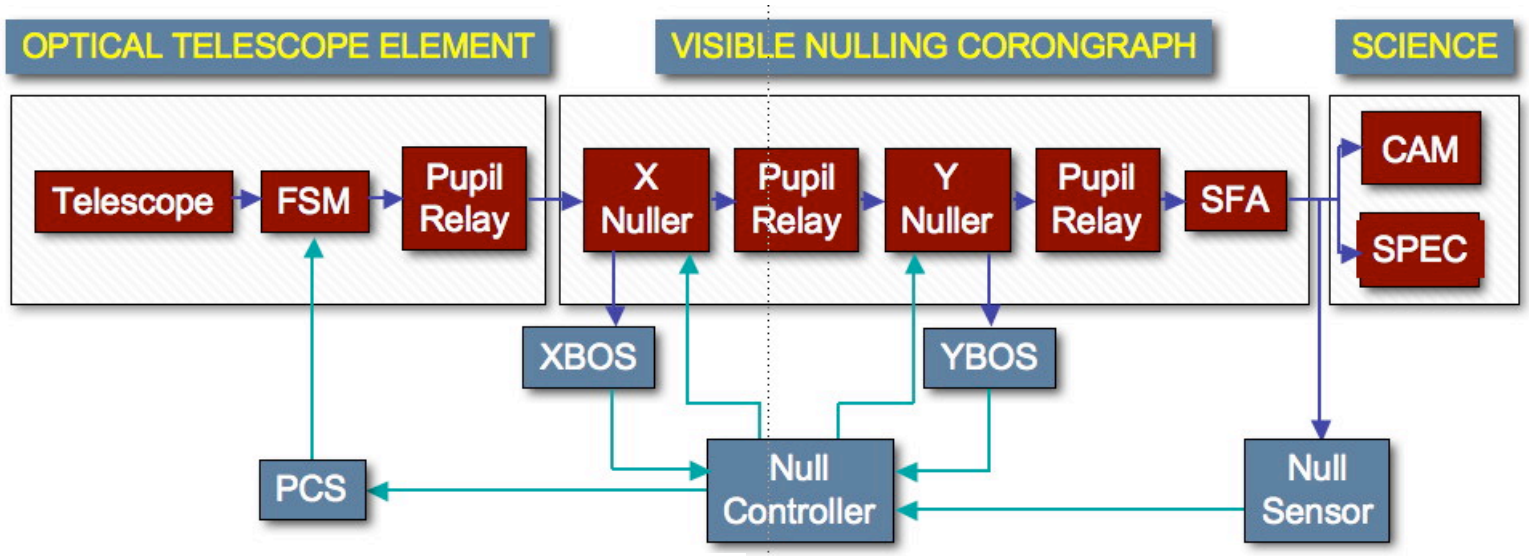
$$T^{\{4\}} \sim \theta^4$$

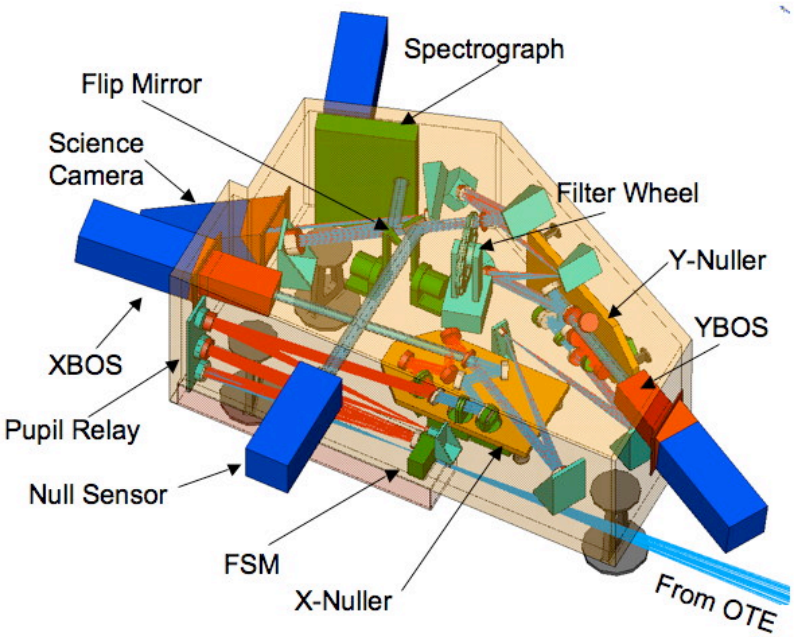
$$IWA = \frac{1}{s}\frac{\lambda}{2D}$$

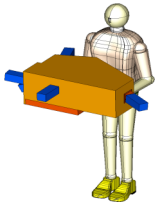
$$s = 0.25 \Rightarrow IWA = 2\frac{\lambda}{D}$$



Instrument Overview





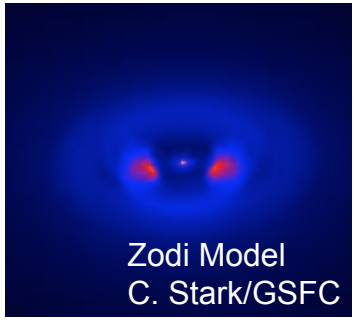


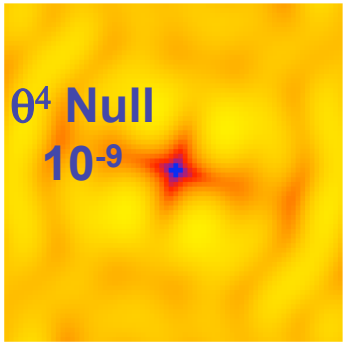
- XBOS used for fine pointing
- XBOS, YBOS, Null Sensor used for coarse & fine null control
- YBOS & Science Cam used for in-situ null control monitoring

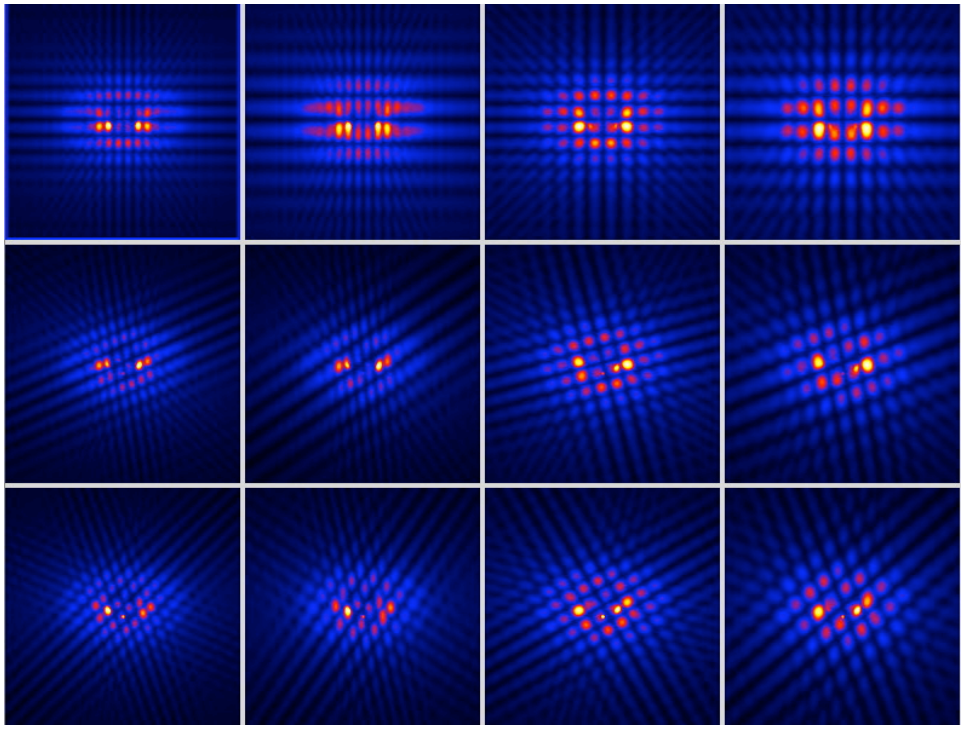
Most optics within VNC are Flats
<2 cm diameter
Size limited by DM technology

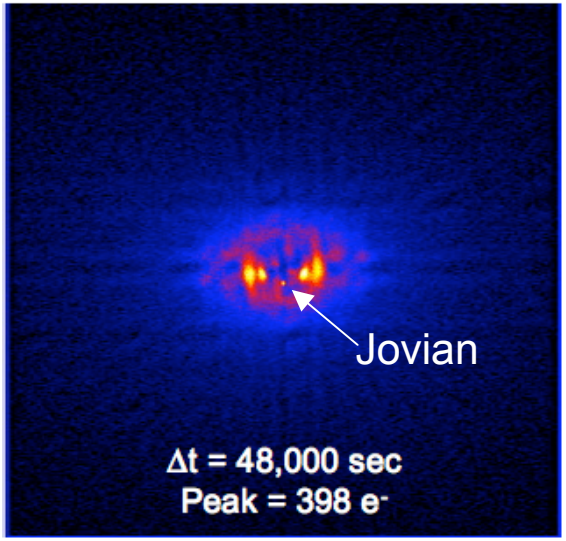
Detection Concept

- ***Discovery***
  - Location of planet is unknown then a search strategy is employed
  - 3 S/C rolls [0, 15, 30^0] and 4 X-Y Shear combinations
- ***Characterization***
  - Planet location known, optimally tune shear/roll to transmission maxima
  - Perform spectroscopy
- ***Dust/Debris disks*** **(Extended Scenes)**
  - Baseline 3 S/C rolls, 4 X-Y shears, however more (or less) are possible





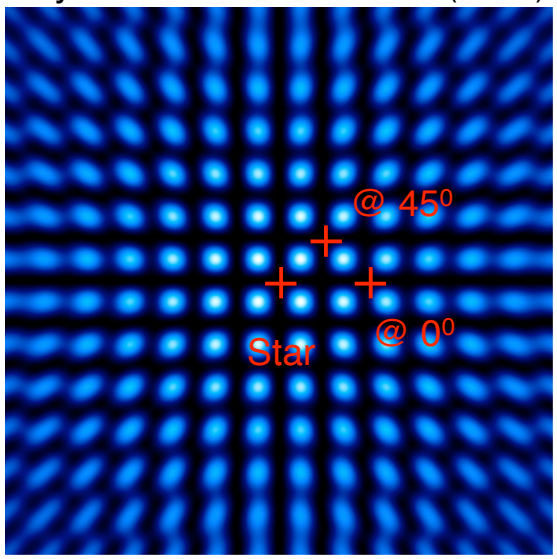




EPIC Can Image Planets around Binaries

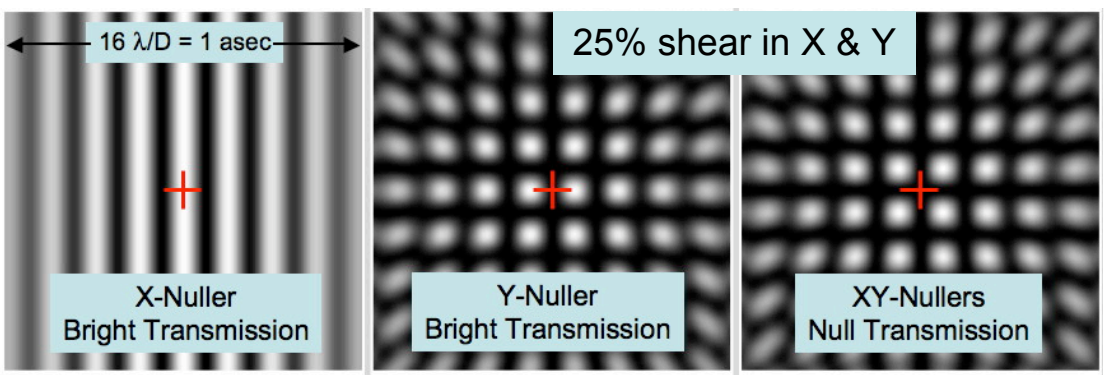
- EPIC can detect planets & charaterize planets around binaries
  (~53% of close G stars are binary
  Duquennoy & Mayor 1991, Ficher & Marcy 1992)
- Shear/Roll to place star & binary companion
  on transmission minimum
  planet on transmission maximum
- Transmission minimum are ~zero along X & Y
  45^0 minima are less deep that primary minima
- Arbitrary binary separation within coronagraphic FOV

Sky Transmission Pattern (R=10)



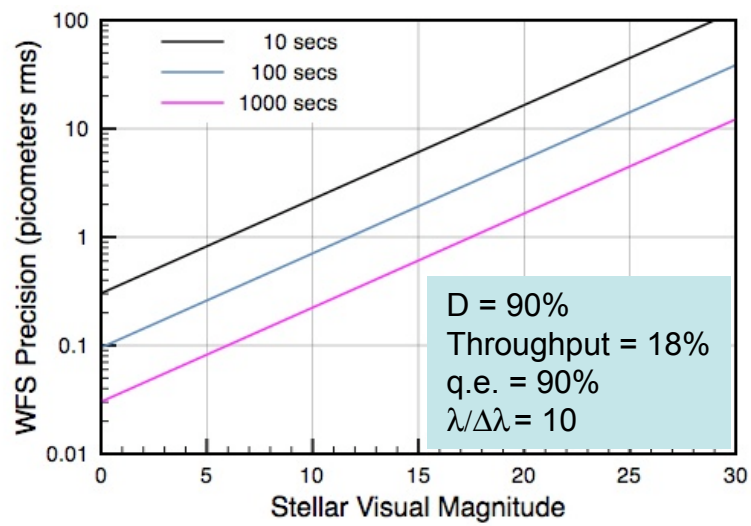
Null Control

- All internal coronagraphs limited by ***wavefront control***
  - Trades spectral bandwidth, stability per time step (temporal bandwidth) & photon rate
- ***4 Sensing Regimes***
  - Dark Channel (non-optimal use of photons => long integration times)
  - EPIC ⇨ **Dark/Bright Incoherent (optimal w/o additional optics)**
  - Dark/Bright Coherent (optimal w/ additional optics)
  - Metrology (optimal overall but requires many optics/complexity)
- ***EPIC is its own Interferometer***
  - 3 output ports: X-bright, Y-bright, XY-null
  - Energy conservation allows all star photons used for WFC w/o beam recombiners
  - Requires detectors at output ports & system level stability / control step
- EPIC can sense to 2 pm WFE in < 100 sec to 15th magnitude

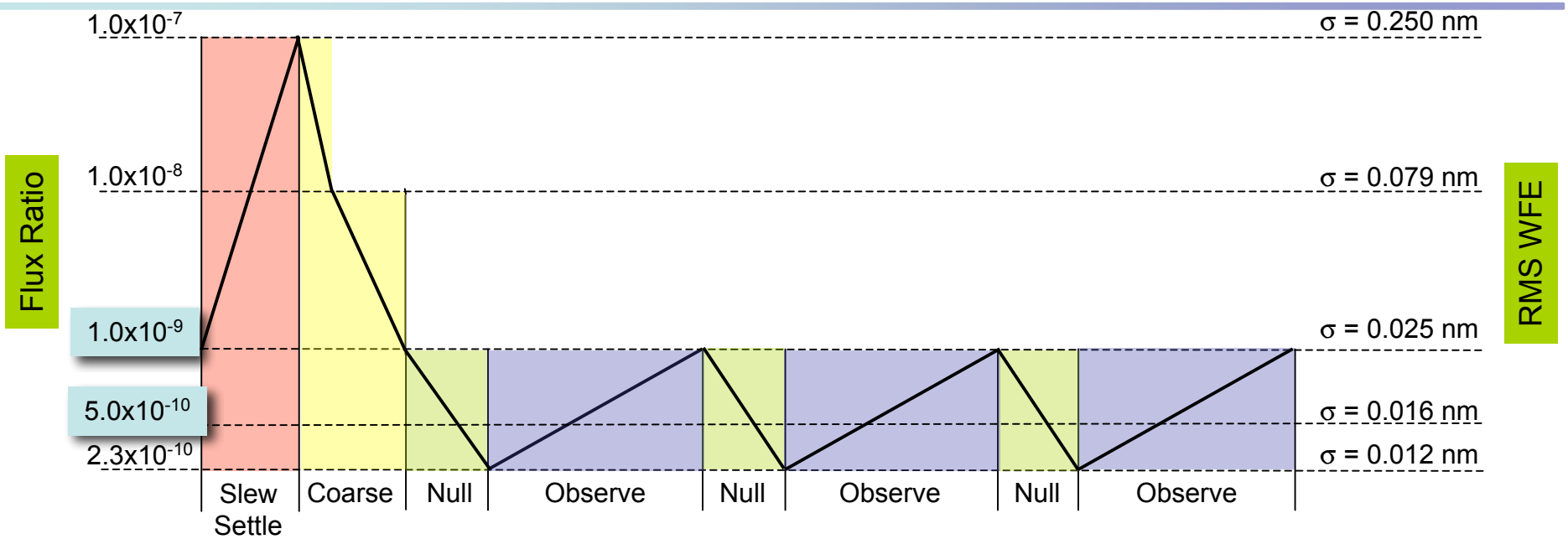


Transmission patterns sum to unity

$$T(\alpha,\beta)=\begin{cases} I_B^{(X)}/I_0=\cos^2(\pi s_x\alpha) \\ I_B^{(Y)}/I_0=\sin^2(\pi s_x\alpha)\cos^2(\pi s_y\beta) \\ I_N^{(XY)}/I_0=\sin^2(\pi s_x\alpha)\sin^2(\pi s_y\beta) \end{cases}$$



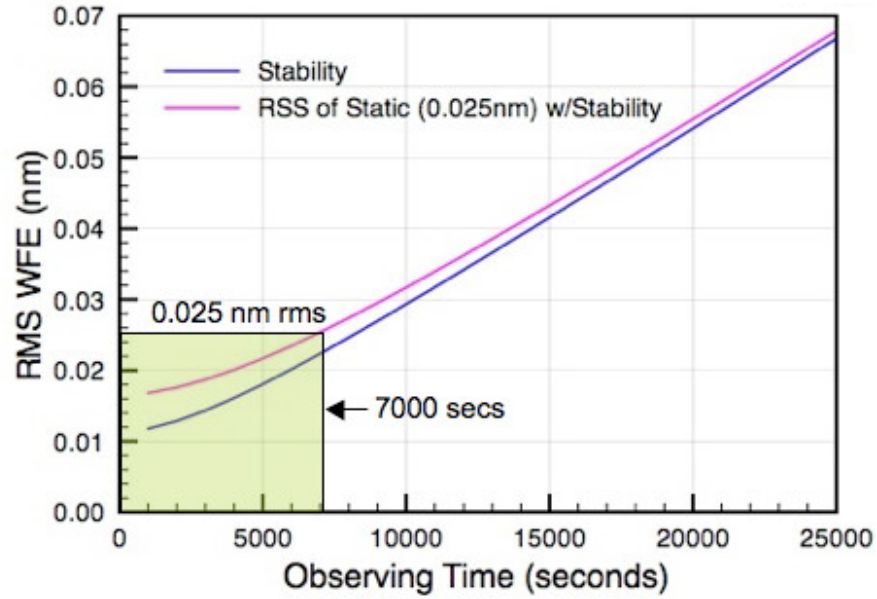
Observing & Null Control

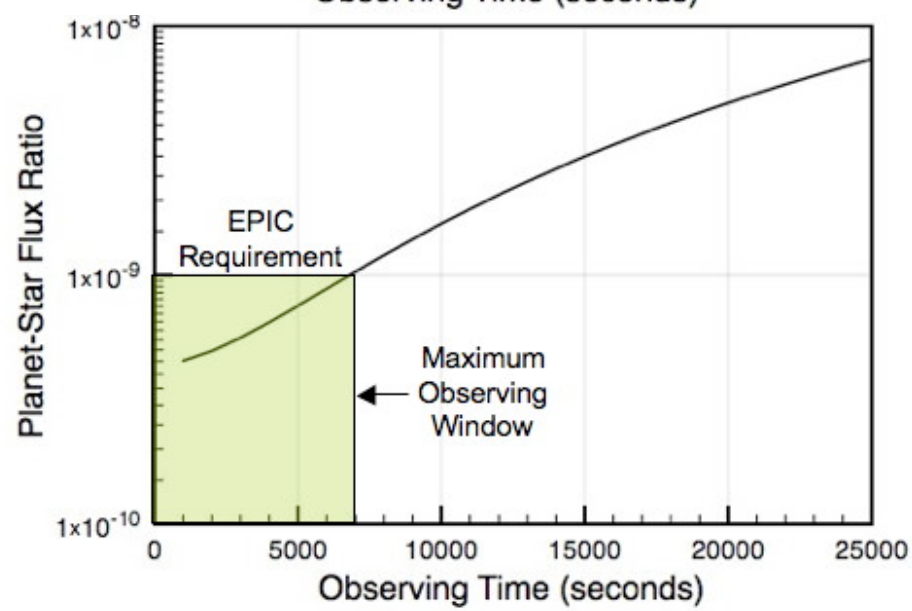


- During ***slew & settle*** growth in rms WFE degrades contrast
- ***Coarse*** null control begins before settle is completed
  - Includes tracking global piston and coarse phasing using BOS and NULL
  - Thermal isolation gives small ΔT drifts
- Fine ***Null*** Control brings rms WFE from 0.025 (start) to < 0.012 (end) nm rms WFE
  - Yields planet-star flux ratios between 1×10^{-9} and 5×10^{-10} => enables Jovians & dust disks
  - Short term (time <2000 sec) planet-star flux ratios < 5×10^{-10} => enables bright Earths / SuperEarths at contrasts of ~2×10^{9}
- During ***Observation*** null drifts σ from 0.012 to 0.025 nm
- Observing windows (7000 sec) iterated w/ null control (~1000 sec) until observation sequence complete, then slew to new target and start over.

Null & Contrast Stability

- Based on Structural/Thermal/Optical models of VNC & OTE
- Top plots WFE (nm rms) vs Δt time with all contributors
- Bottom plots planet-star flux ratio vs observing time.
- EPIC's reqmt of 10^{-9} reached in 7000 sec
- 1st 2000 sec => flux ratios of < 5 x 10^{-10}





Requirements Scaling

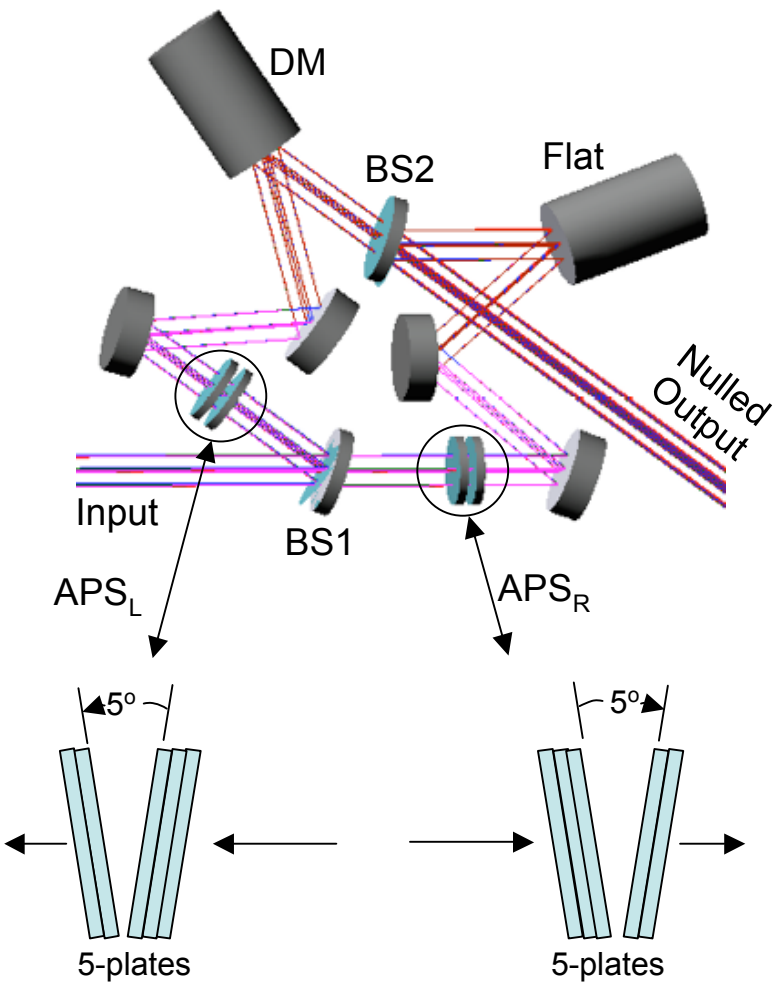
Contrast @ 125 mas	Units	Disks 10^8	Jovians 10^9	Earths 10^{10}
Residual WFE	nm RMS WFE	0.038	0.012	0.004
WFE drift per control step	nm RMS WFE	0.070	0.022	0.007
RMS Reflectivity error	%	0.158	0.050	0.016
Polarization Error	degrees	0.032	0.010	0.003
Pointing precision (LOS jitter)	mas (3σ)	7.310	4.100	2.245
Beam Walk per WF control step	mas (3σ)	7.310	4.100	2.245
Pupil Plane Null Depth =		**9.80E-07**	**9.84E-08**	**9.82E-09**
Contrast at 125 mas (2 λ/D) =		**1.00E+08**	**1.00E+09**	**1.00E+10**

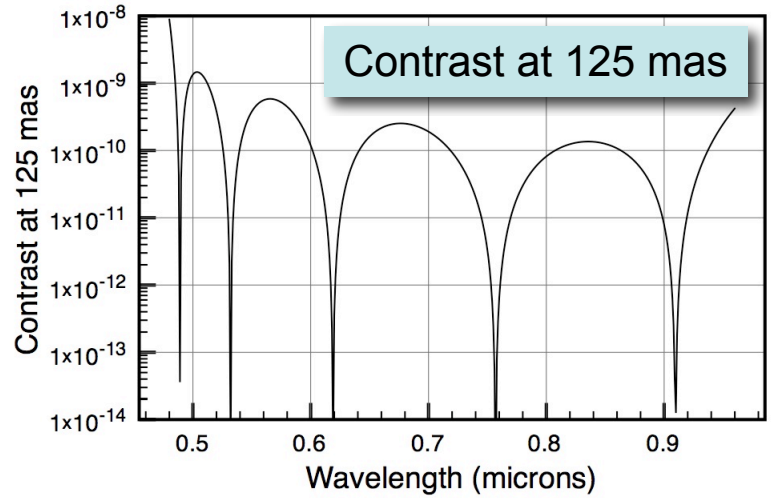
- EPIC Requirements shown in RED at end of observing sequence
  - following null control step WFE is 12 pm & drifts to 25 pm rms.
  - RMS Reflectivity error is differential mismatch between nuller arms not OTA reflectivity error, and is 0.0005 (0.05%)
  - Pointing precision is 4.1 mas 3σ
  - Beam Walk specified same as pointing => allocates all of worst case (3σ) lineal pointing drift onto beam walk on non-pupil OTE optics.
- Requirements for Jovians are achievable w/short null control times
- Earths => demanding tolerances but can in principle be achieved for short times just following a null control step

Technologies

Achromatic Phase Shifters (APS)

APS Allows broadband null *and* broadband null control





- APS Glass Solution

  M. Bolcar optimized over glass catalogs to *min OPD, reflectivity, beam walk, differential polarization and ghosts vs* λ:

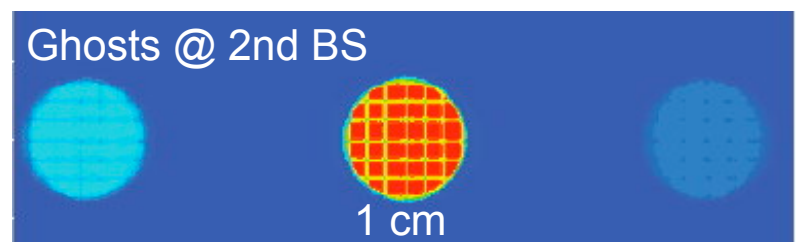
  $\langle C \rangle = 2.4 \times 10^{-10}$, $\sigma_C = 6.0 \times 10^{-10}$

  Differential Reflectivity < 0.023%

  Chromatic Beam Walk < 1.5 um

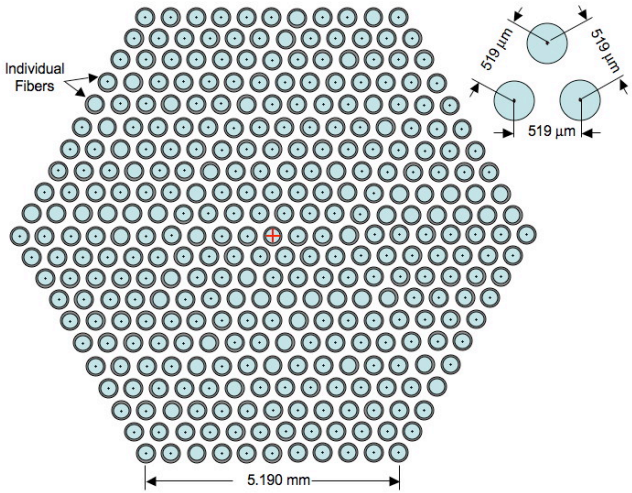
  Differential Polarization < 0.0032^0

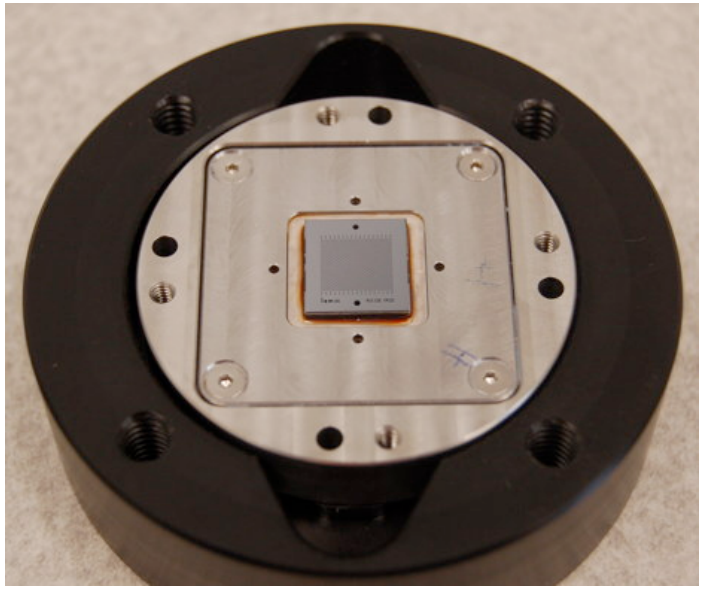
- 'Set and Forget' soln over 480 - 960 nm

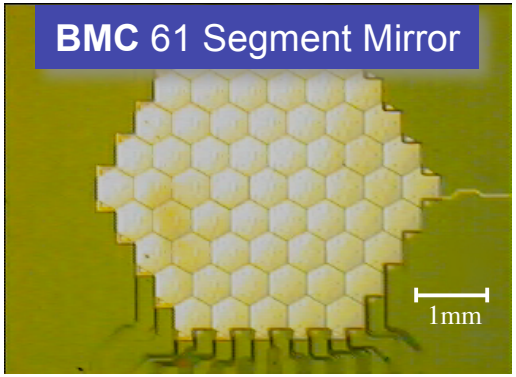


Technologies

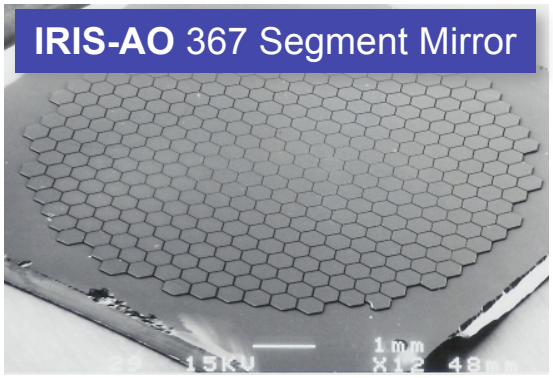
Coherent Fiber Bundles, aka *Spatial Filter Array*
Segmented Deformable Mirros, aka *Multiple Mirror Array*



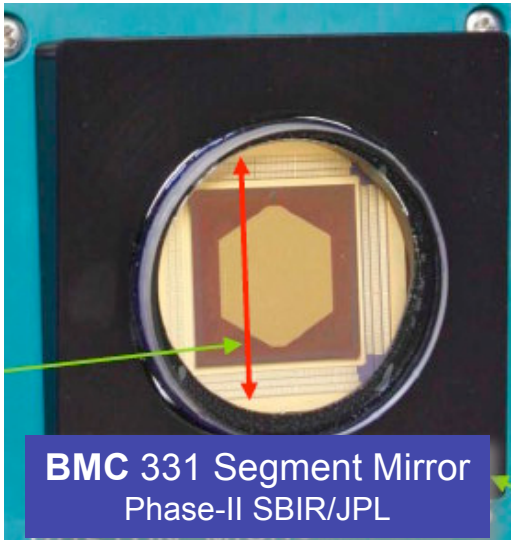




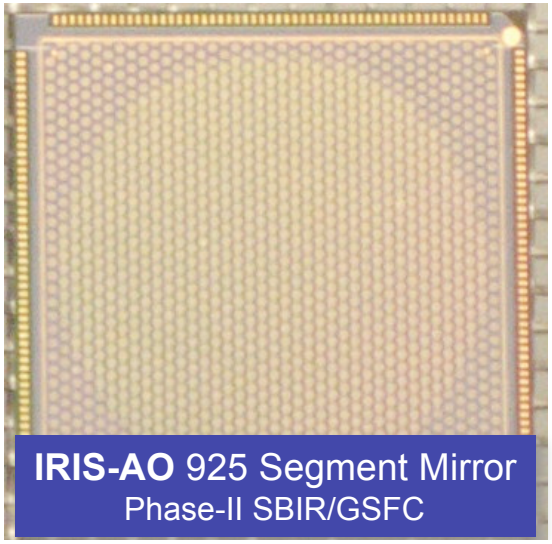
BMC 61 Segment Mirror



IRIS-AO 367 Segment Mirror



BMC 331 Segment Mirror
Phase-II SBIR/JPL



IRIS-AO 925 Segment Mirror
Phase-II SBIR/GSFC

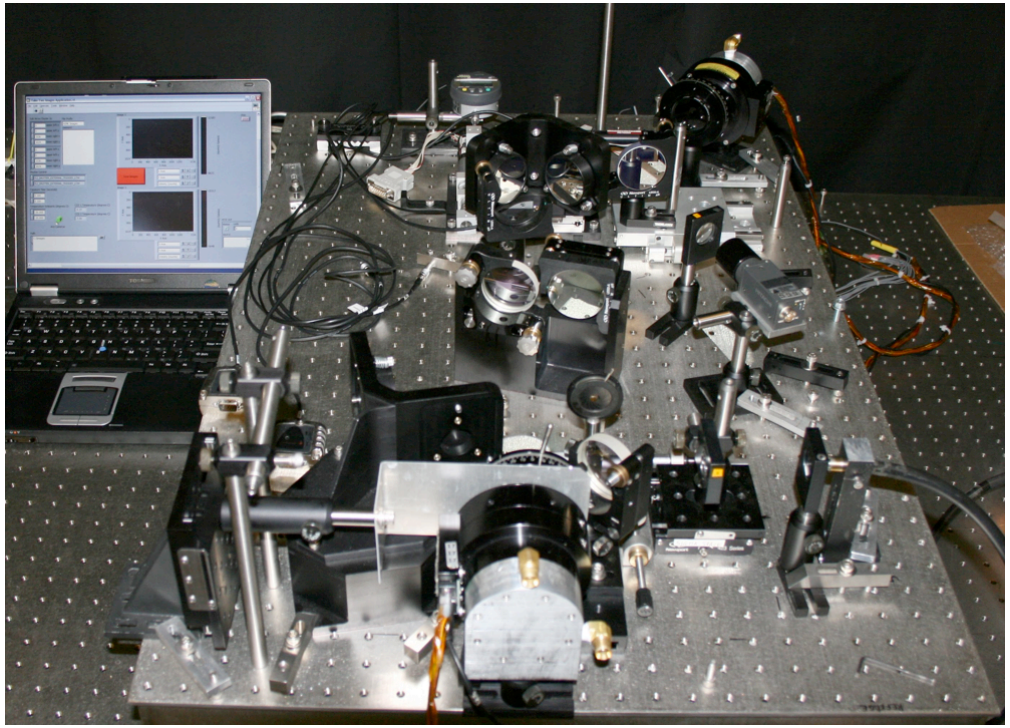
Technology Readiness Levels

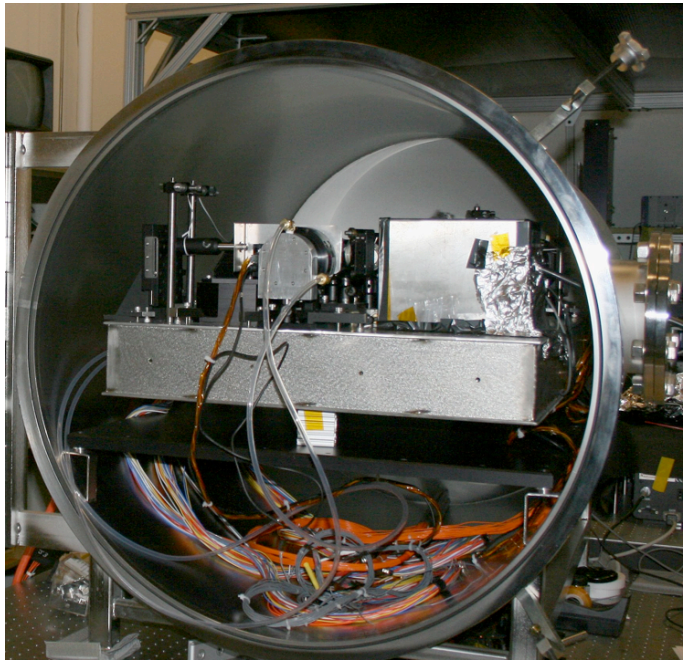
Component/ Subsystem	Heritage	TRL	Comments
Multiple Mirror Arrays	Boston Micromachines, TPF-C , Boston U/JPL PICTURE, Multiple SBIRs	4	Refer to Section C.1.
Spatial Filter Array (SFA)	Fiber optics flown on ISS, WMAP, EO1, GLAST, FiberGuide development and SBIR	4	Refer to Section C.2. Commercial alignment tolerances already exceed EPIC needs and vendors such as Fiberguide can build fiber arrays.
Beamsplitter Substrate & coatings	MDI, HMI, HST, GSFC/LMCO VNC Testbed	8	Commercially available material, SiO_2 and processing, process as matched pairs.
Achromatic Phase Shifter	MDI, HMI, HST, GSFC/LMCO VNC Testbed	5	Commercially standard materials, SiO_2 and BK7 and processing well understood, use as APS in VNC is new application
Nuller Structure	GP-B, LISA	6	Optically contacted stable structure.
Shear Mechanism	JWST NIRCam, MRO, HST, Spitzer	6	Modification of linear actuator using harmonic drive and ball screw
Null Control Strategy	BU/JPL PICTURE Mission, GSFC/LMCO VNC Testbed	4	Passive null control with SFA, active null control with MMA coupling to SFA.
E2V-L3 CCD	GSFC qualifying E2V-L3	5	Photon counting CCD.

TRL Advancement: Testbeds

- TRL advancement through multiple testbeds at GSFC & JPL
  - GSFC: Vacuum VNC testbed to achieve and hold contrasts [10^9 in >20% passband for > 1000 sec] with incoherent null control (testbed operational in the tank now)
  - GSFC: Null Control Breadboard, test DMs and SFA and develop control algorithms
  - JPL: APEP Testbed (P. Lawson), large facility class testbed, coherent null control

    M. Shao will discuss in more detail in next talk and see J. Sandhu's poster
- SBIRs w/ DM vendors (IRIS-AO, BMC) & SFA development via direct procurement & SBIR.

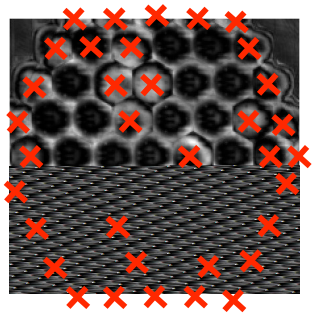




Testbed Results

- *Robust control* in white light developed ran continuously for 14 hours
- BMC-61 hex pack segmented DM run closed-loop (piston,tip/tilt control) for 14 hrs at 6.7 Hz
- Long term stability of < 2 nm rms Short term (so far) ~ 0.7 nm rms
- Open white light nulling in pupil to ~10^{-4}
- 10, 20% bandpass in progress
- Bad actuators masking in progress to assess focal plane results

- VNC testbed now in vacuum tank operational in tank w/ plumbing (chillers), electrical feed throughs and fiber feeds



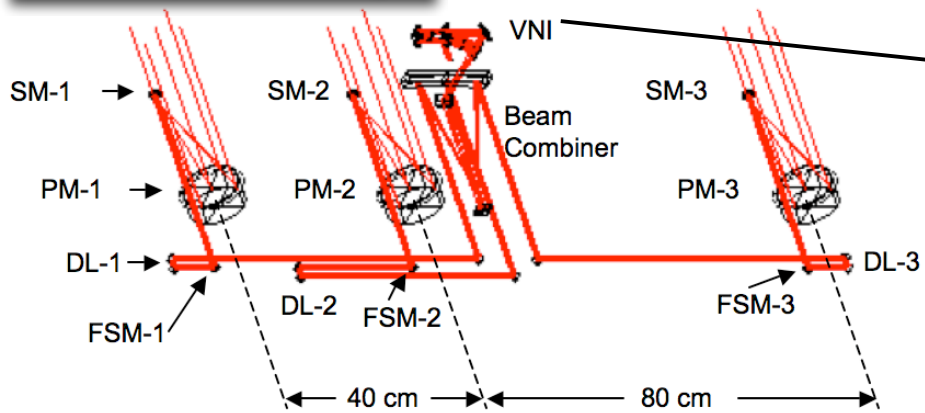
Time Steps (150 msec/step => 6.7 Hz)

Summary

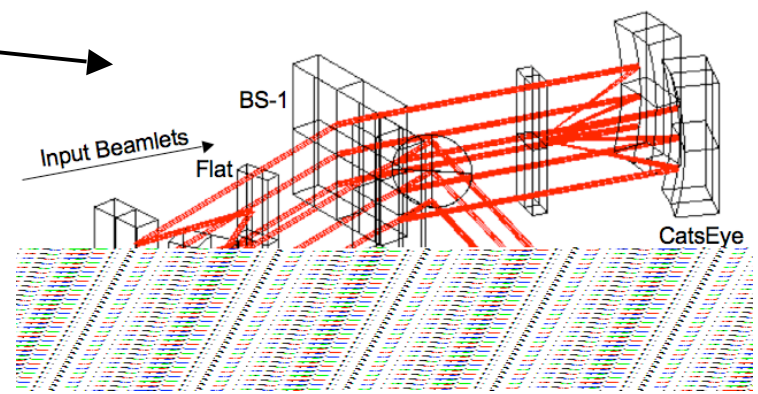
- **EPIC is mature & achievable mission for < $850M**
  - Proposed twice as Discovery mission (w/ 1.5 m aperture)
  - Only ASMC mission costed both by GSFC IDC *and* JPL Team-X
  - Multiple design iterations, error budgeting and costing
- **Risks associated w/ VNC technologies**
  - Technology development funding would help remedy this.
  - Buydown risks via ground testbeds (VNC & APEP), sub-orbital (PICTURE & BENI)) missions & ground instruments
- **If all goes well…**

BENI Design & Fabrication

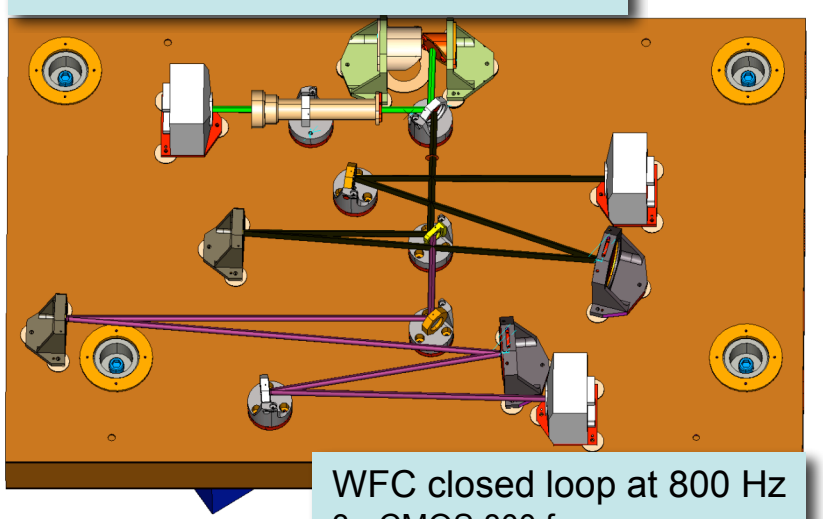
BENI Optical Design



Nuller Design



BENI Wavefront Control Board



WFC closed loop at 800 Hz
3 - CMOS 800 fps cameras
FPGA / DSP controller

BENI on Optical Bench

w/ existing 1.5 Baseline SVIP interferometer