Survey of high contrast imaging instrument concepts

D. Mawet, ESO
SPHERE Paranal instrument scientist

Sagan Summer workshop, 2014-07-21

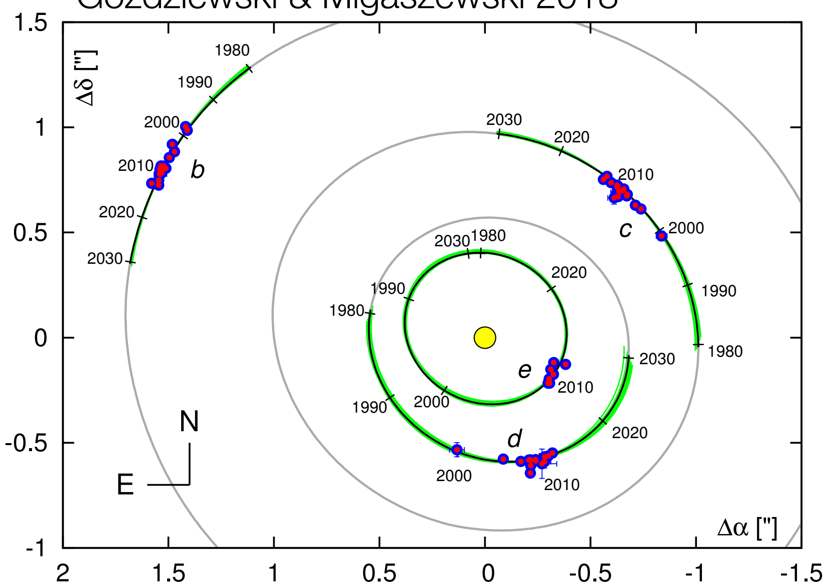
Acknowledgements: B. Oppenheimer, P. Hinz, D. Defrere, A. Skemer, L. Close, B. Macintosh, O. Guyon, N. Jovanovic, G. Vasisht, J.-L. Beuzit, J. Kasdin, T. Fusco, J.-F. Sauvage, and many others.

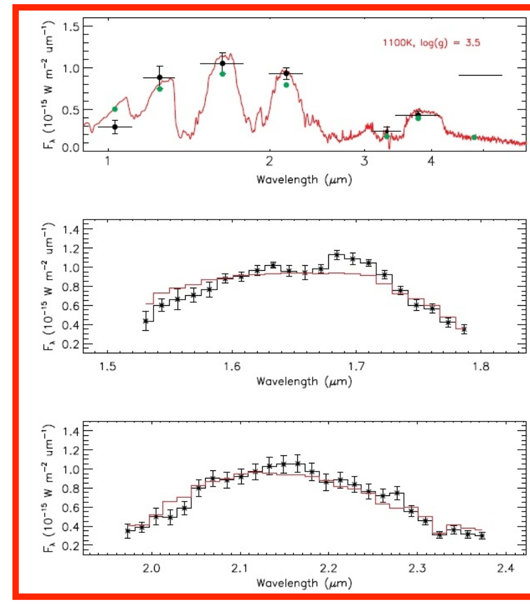
Content

- High contrast imaging is the richest technique for exoplanet science
- The mother of high contrast imagers: HST
- Basics of high contrast imagers:
  - Building blocks
  - The order matters
- Highlights of 1st generation high contrast AO imagers
- 2nd generation high contrast XAO imagers are here!
- The future:
  - On the ground: ELTs
  - In space: JWST, AFTA-WFIRST & EXO-C/S

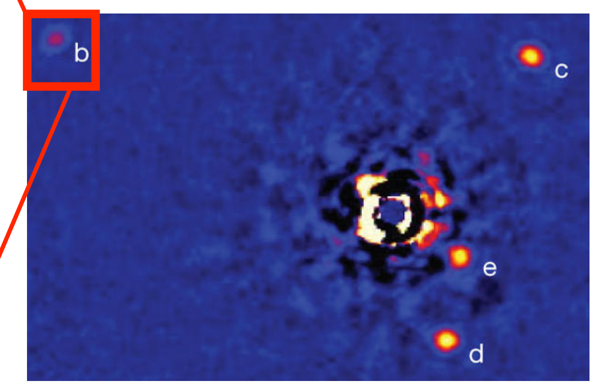
High contrast imaging is the richest technique

Gozdziewski & Migaszewski 2013

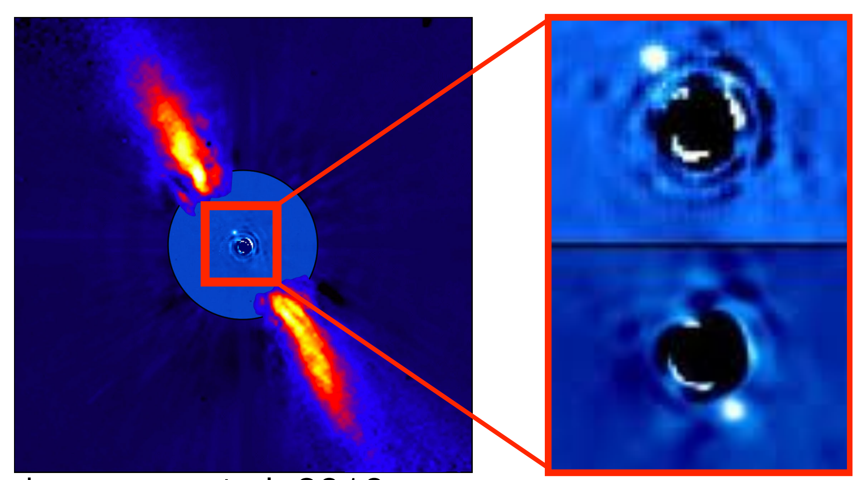




Barman et al. 2011



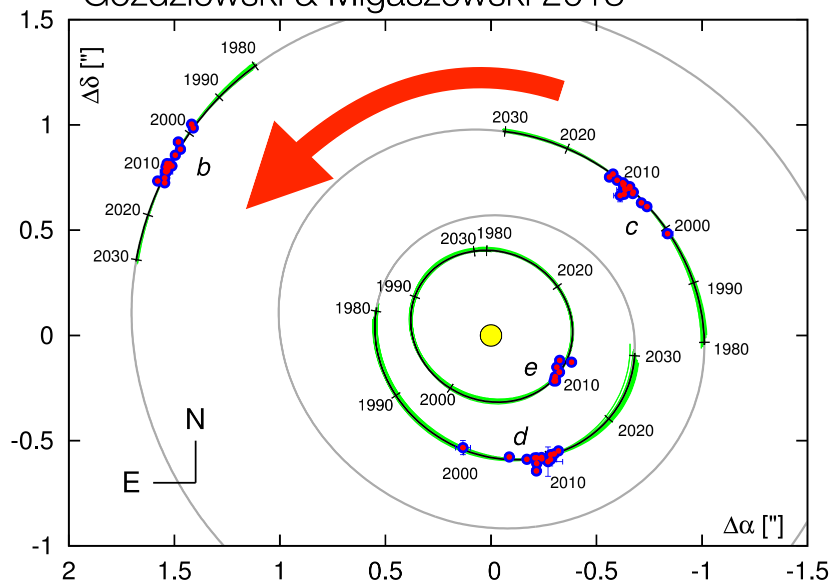
Marois et al. 2010



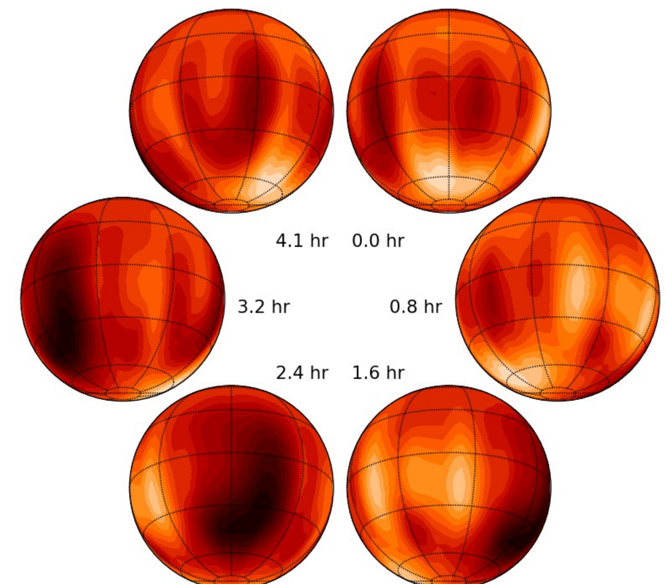
Lagrange et al. 2010

High contrast imaging is the richest technique

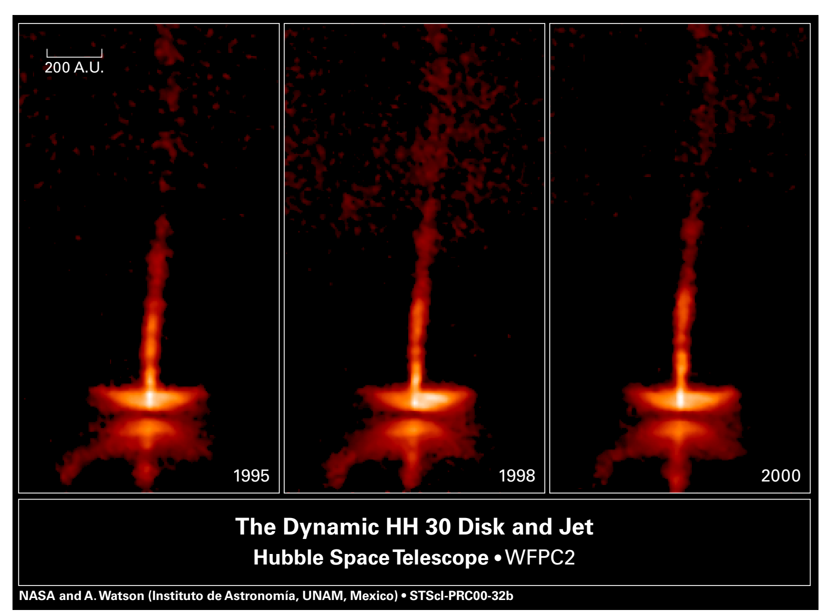
Gozdziewski & Migaszewski 2013



f(t)



LU16: Crossfield et al. 2013



... and the most difficult one (contrast, IWA)

1st generation medium-high contrast imagers

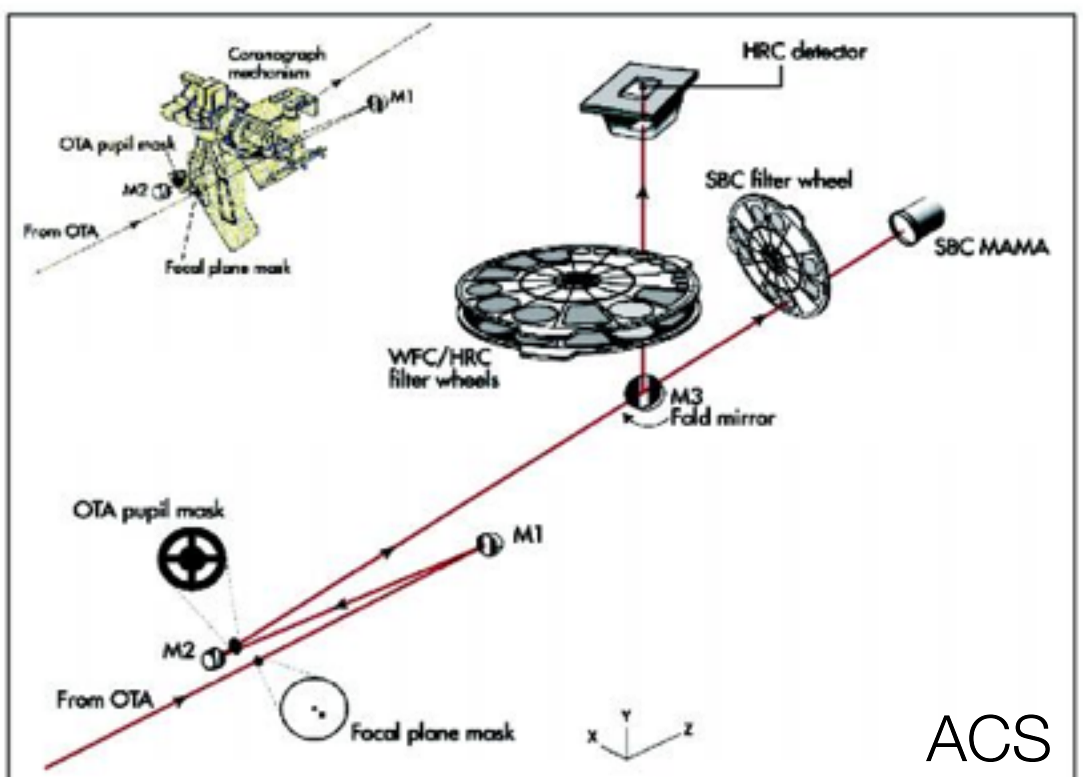
Instrument	Telescope	AO	Wavelength (μm)	Ang. res. (mas)	Coronagraph
WFPC2†	HST	NA	0.12–1.1	10–100	...
WFPC3	HST	NA	0.2–1.7	17–150	...
NICMOS†	HST	NA	0.8–2.4	60–200	Lyot
ACS†	HST	NA	0.2–1.1	20–100	Lyot
STIS	HST	NA	0.2–0.8	20–60	Lyot
NAOS-CONICA	VLT	16-SH	1.1–3.5	30–90	Lyot/FQPM/APP/VC
VISIR	VLT	no	8.5–20	200–500	FQPM/VC
COME-ON+-ADONIS†	3.6-m ESO	8-SH	1–5	60–280	Lyot
PUEO-TRIDENT†	CFHT	8-SH	0.7–2.5	4–140	Lyot(/CIA)
COMICS	Subaru	NA	8–25	200–500	...
HICIAO	Subaru	14-C	1.1–2.5	30–70	Lyot
CanariCam	GTC	NA	7.5–25	150–470	...
KeckAO-NIRC2/OSIRIS	Keck	16-SH	0.9–5.0	20–100	Lyot(/VC, 2015)
LWS†	Keck	no	3.5–25	70–500	...
MIRLIN†	Keck	no	8.0–20	160–400	...
ALTAIR-NIRI	Gemini N.	no	1.1–2.5	30–70	Lyot
NICI†	Gemini S.	9-C	1.1–2.5	30–70	Lyot
T-ReCS†	Gemini S.	no	1.1–2.5	30–70	...
Clio/PISCES	MMT	16-SH	1–5	30–70	APP
Lyot project†	AEOS	30-SH	0.8–2.5	60–140	Lyot/FQPM
PALAO(WCS)†-PHARO	Hale 200”	16-SH	1.1–2.5	60–140	Lyot/FQPM/VC
AO-IRCAL	Shane 120”	8-SH	1.1–2.5	100–150	...

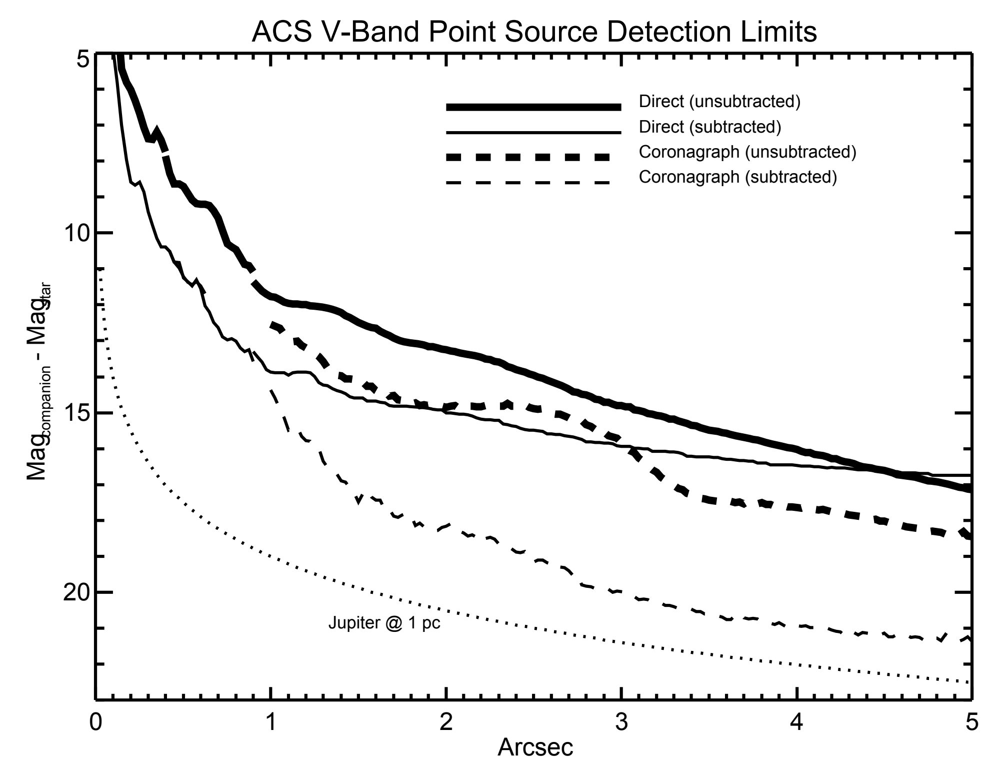
The mother of all high contrast imagers

High contrast imaging in space enabled by **stability**

HST only had classical Lyot unoptimized coronagraphs, but its unmatched stability benefited, and still benefits all of its imagers: WFC2/3 (nc), STIS (bars), NICMOS (hole), ACS (proper masks)

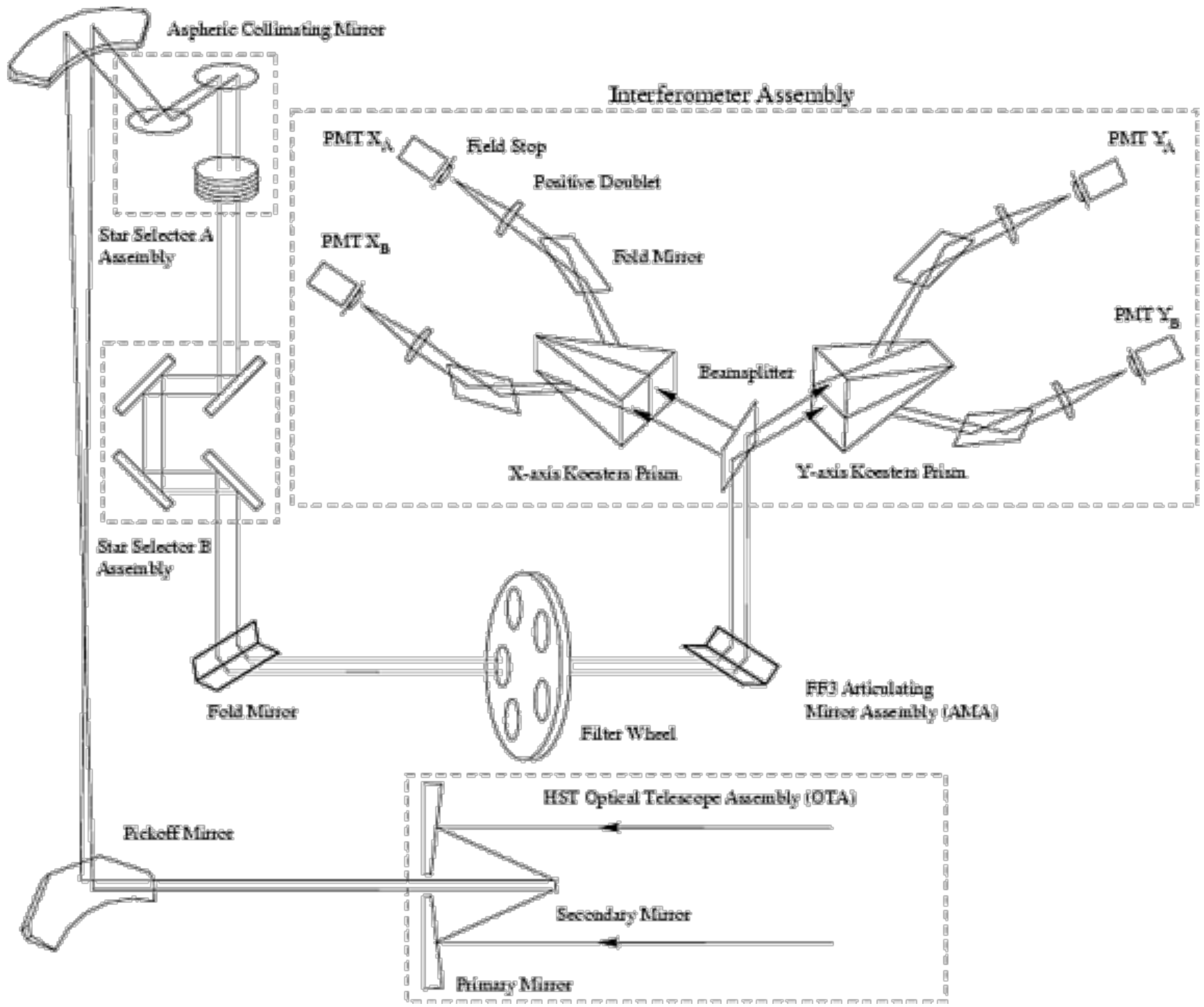
…so much so that archival data mining is producing wealth of results





Krist et al. 2006

Its secret: 3 fine guidance sensors (FGS)



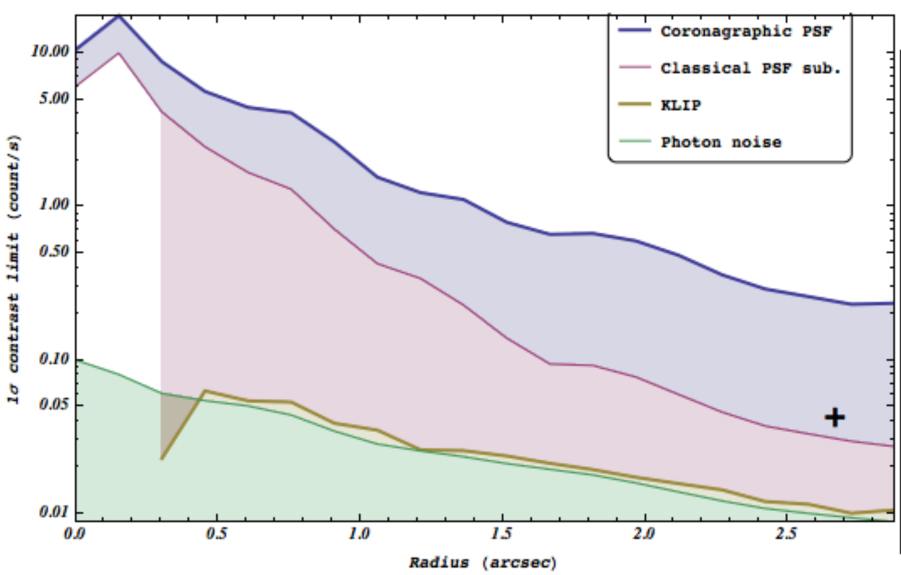
~1 mas pointing accuracy over > 10 min

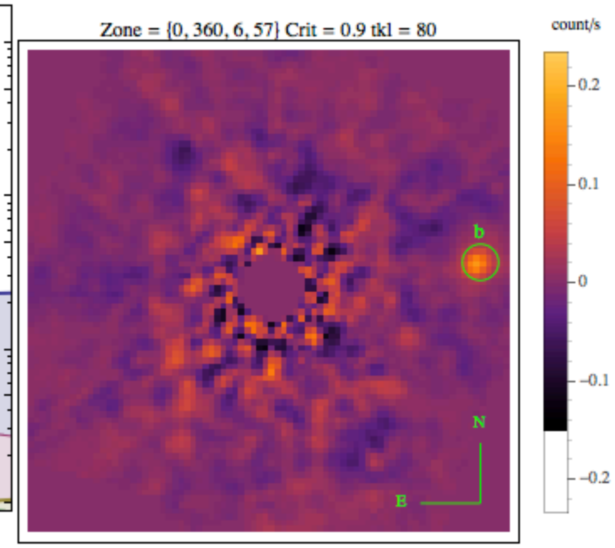
70' FoV, R < 17

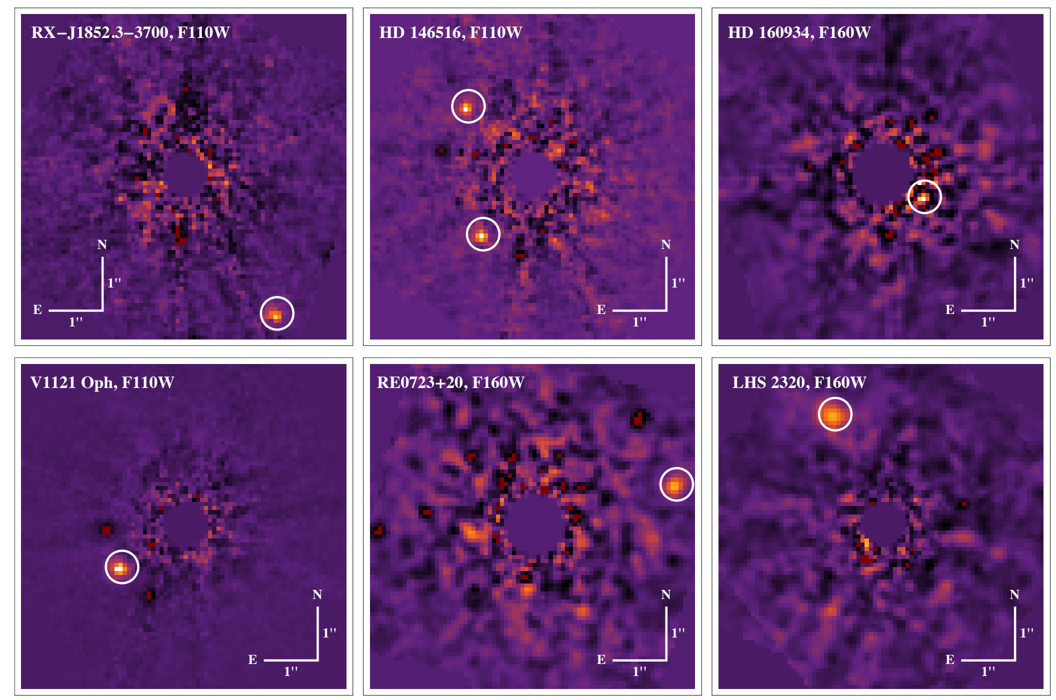
ALICE: an overwhelming harvest

Soummer, Pueyo, Perrin, Choquet, et al

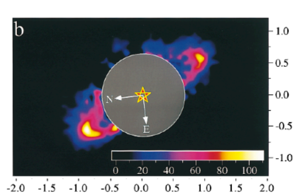
Laurent's talk
+
Elodie's
POP/POSTER



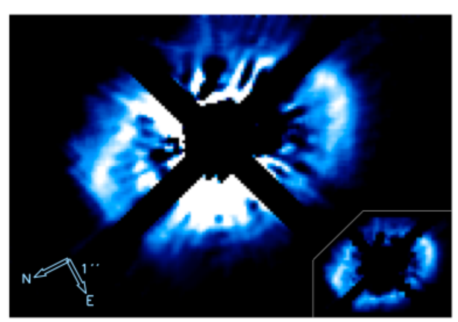




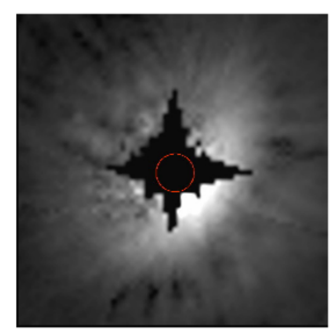
Schneider et al. 1999



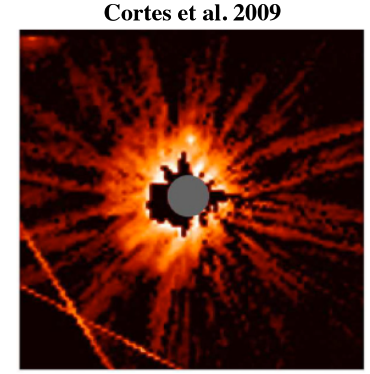
Augereau et al. 1999

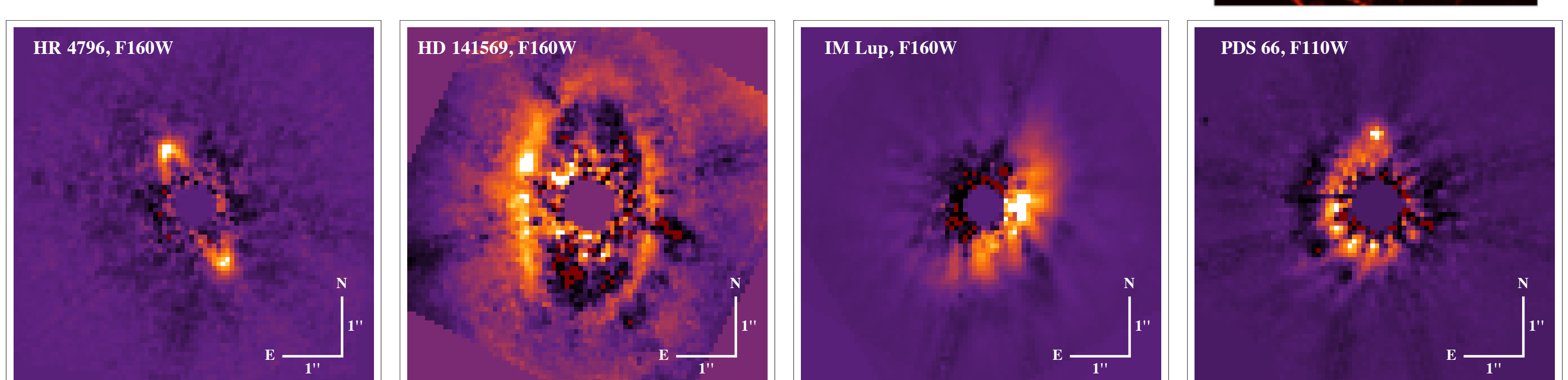


Pinte et al. 2008

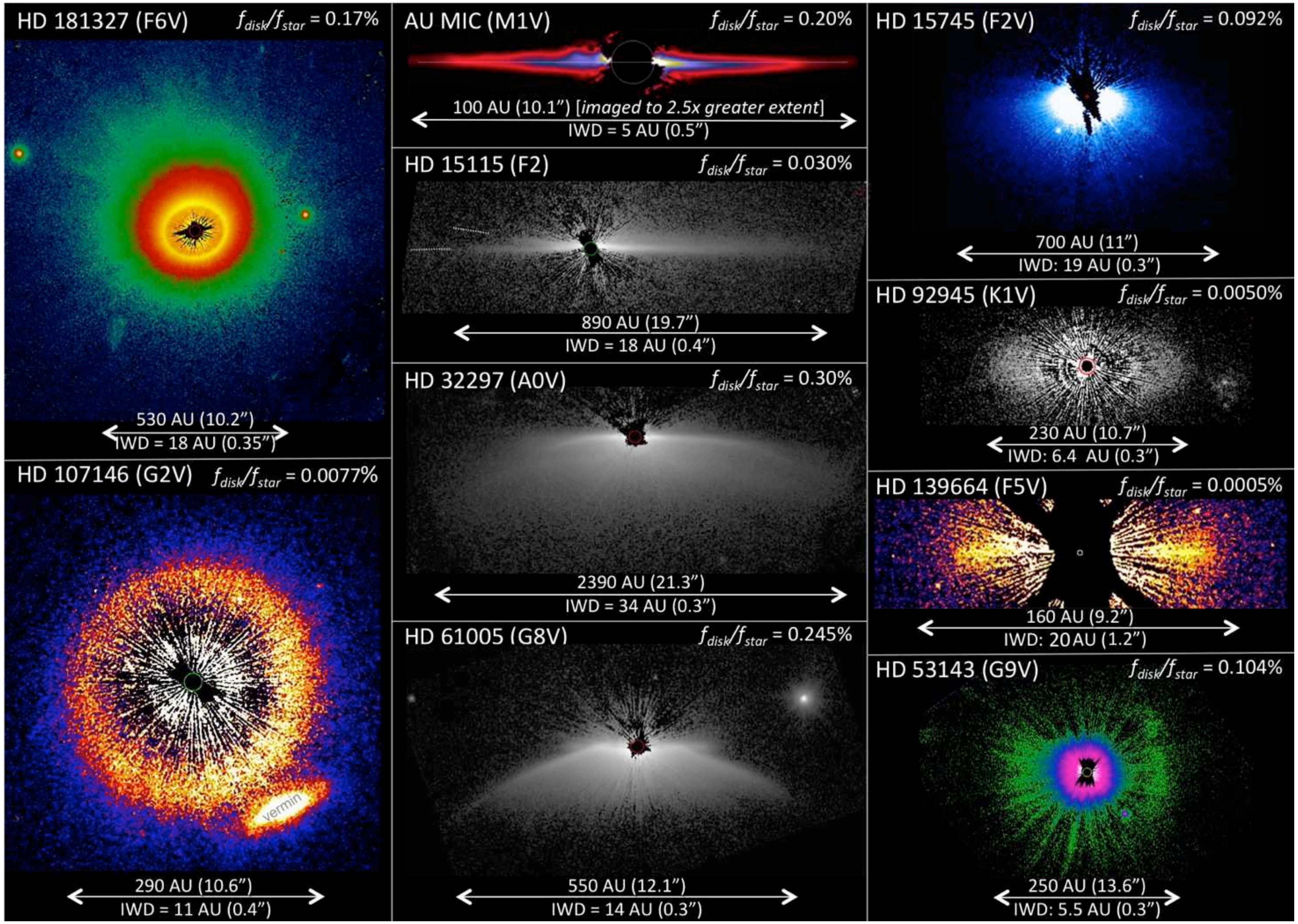


Cortes et al. 2009





Lessons learned applied to new programs



Schneider et al. 2014 (STIS)

Not a level-playing field!

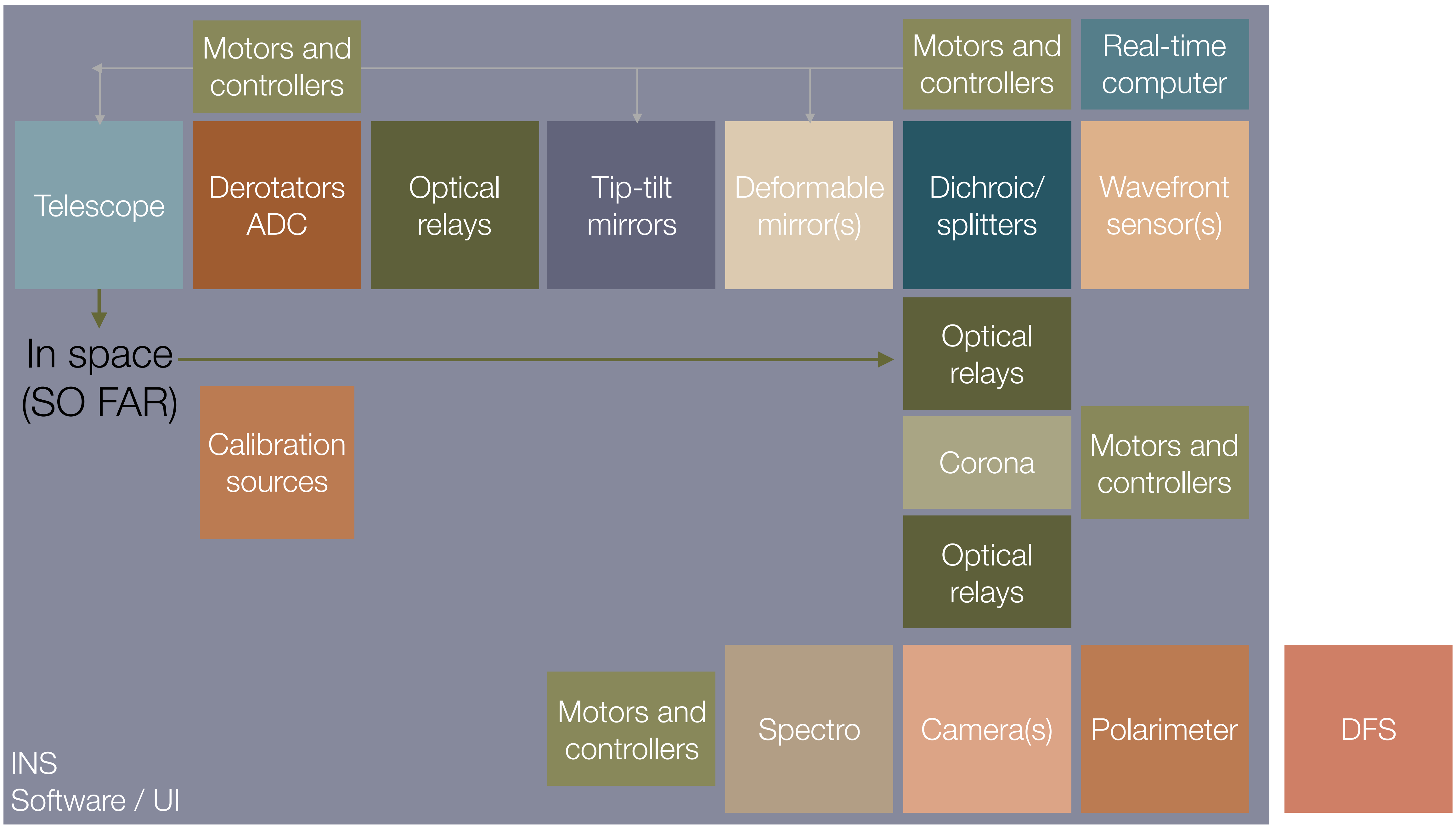
High contrast imaging through this
requires some well thought out architecture!

Building blocks of direct imaging instruments

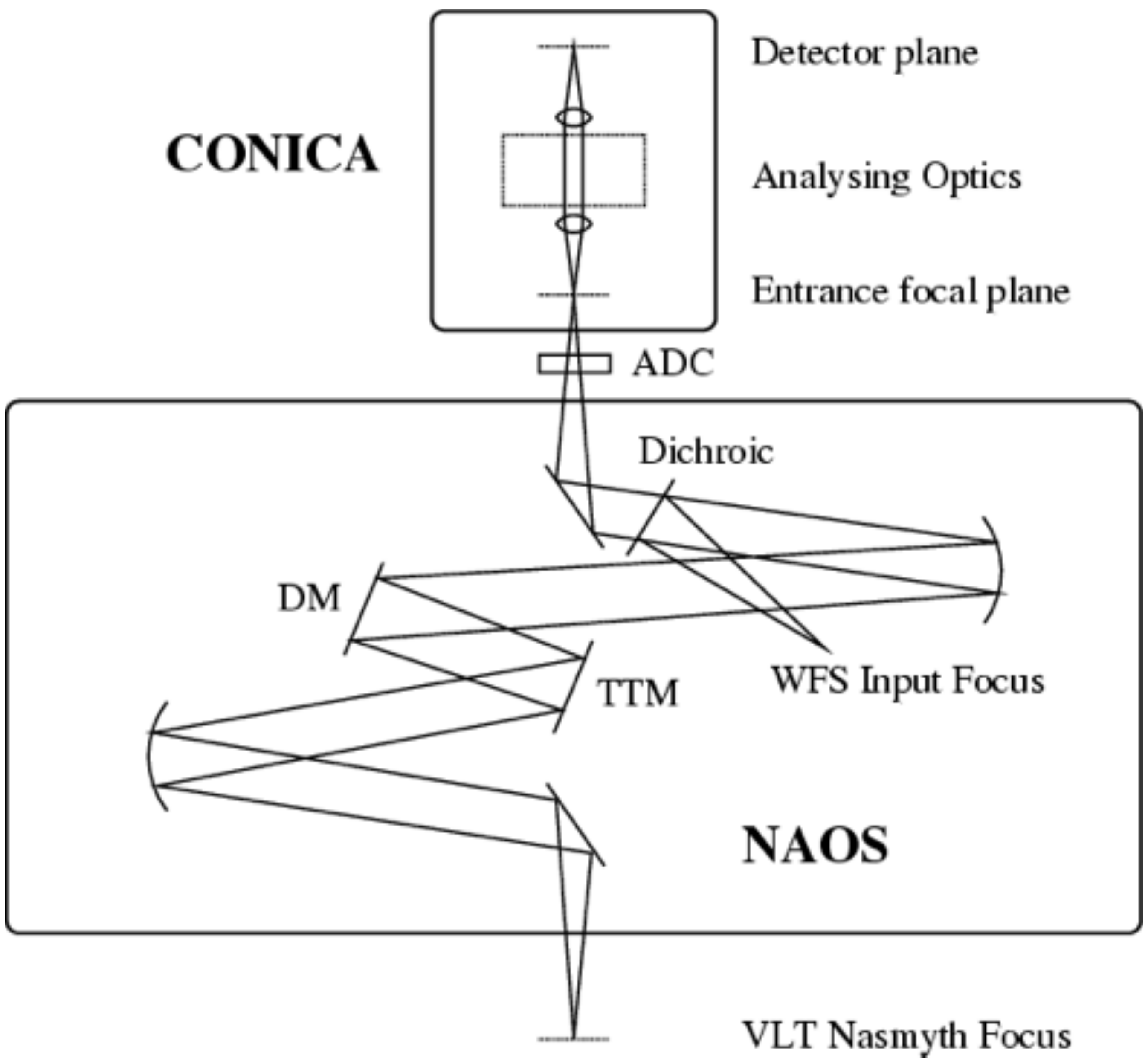
Telescope	Coronagraph(s)	Deformable mirror(s)	Wavefront sensor(s)
Camera(s)	INS Control Software / UI	Real-time computer	Motors and controllers
Spectrograph/ Polarimeter	Calibration sources	DFS: pipeline/archive	Tip-tilt mirrors
Dichroic/splitters	High quality optical relays	ADC	Derotators

Architecture: order matters

- All high contrast imagers are based on a variant of the following
- Devil is the details of their respective implementation

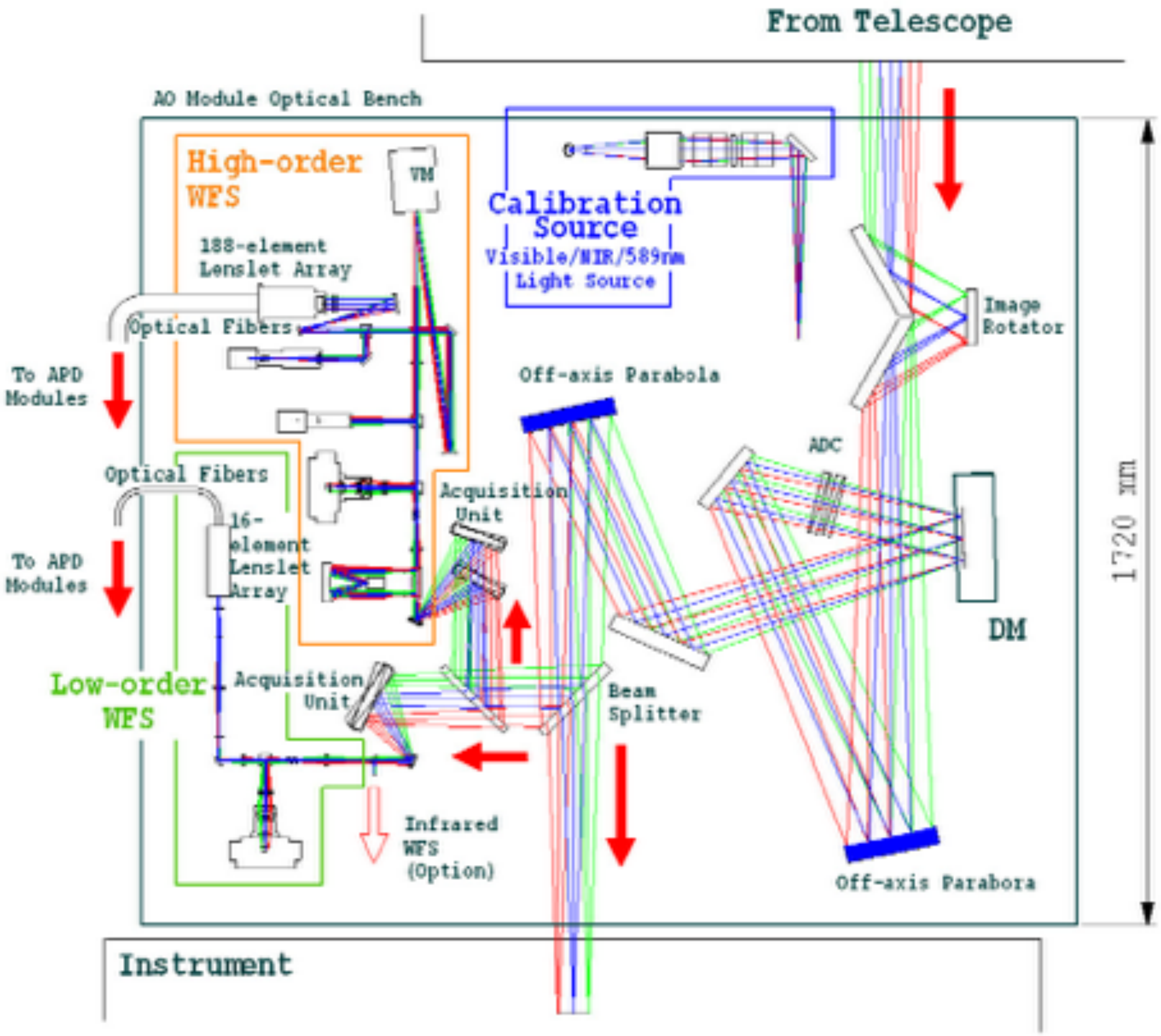


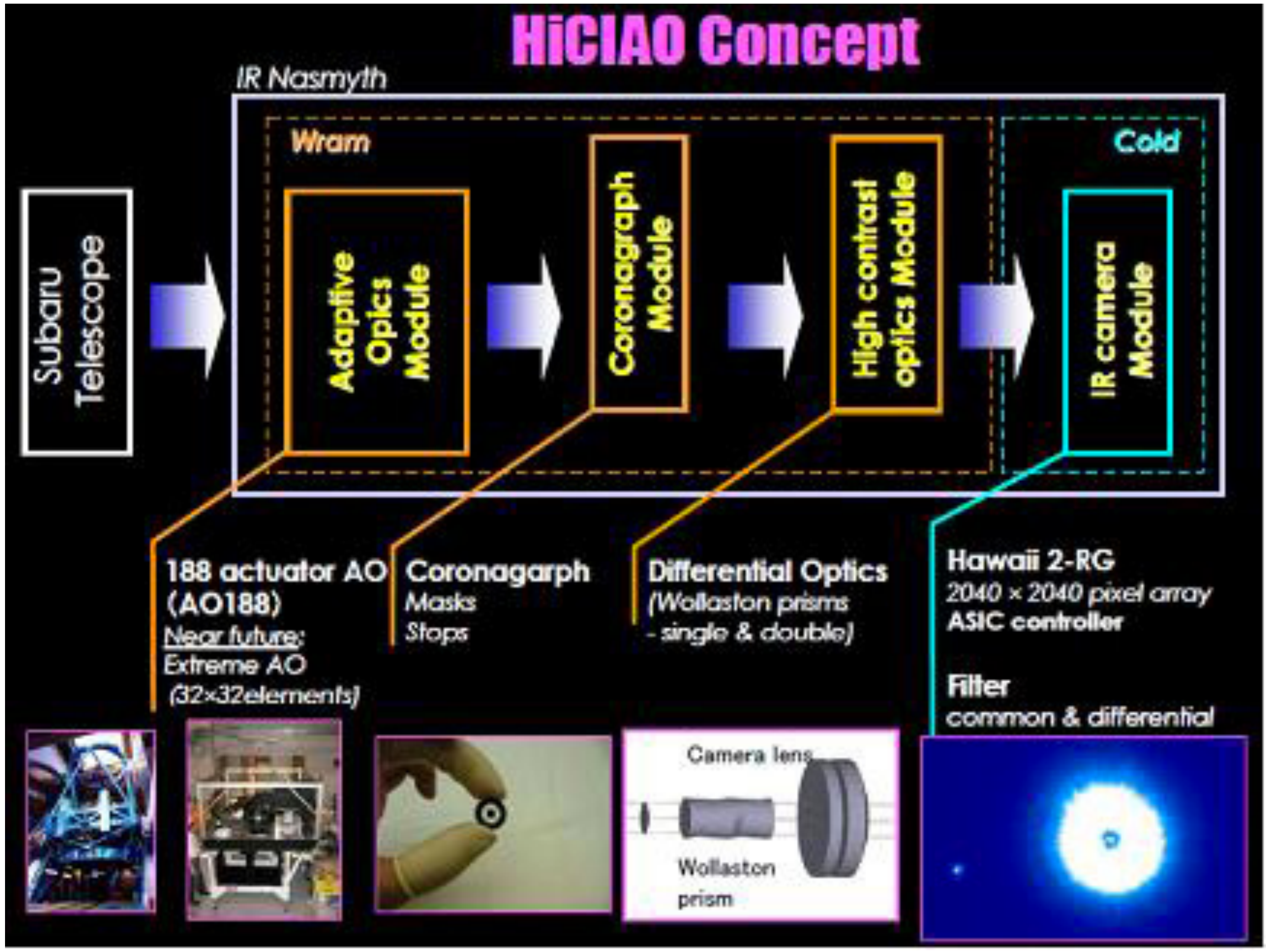
VLT: NAOS-CONICA



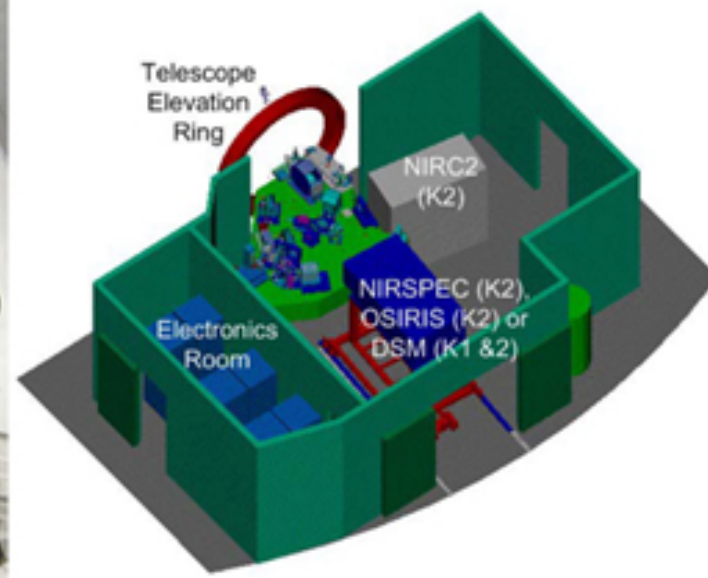
10 years of AO at the VLT

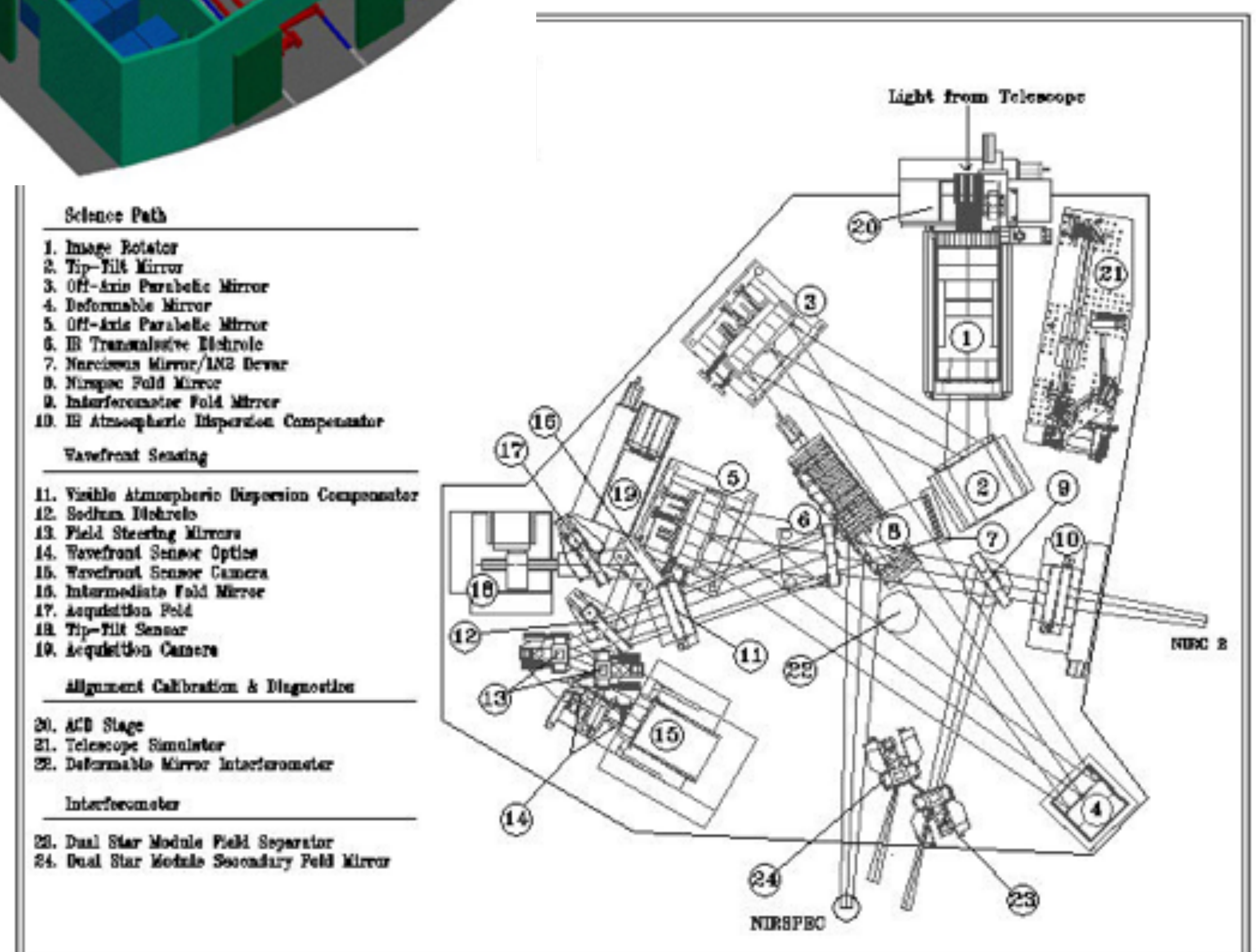
Subaru: AO188 - HICIAO





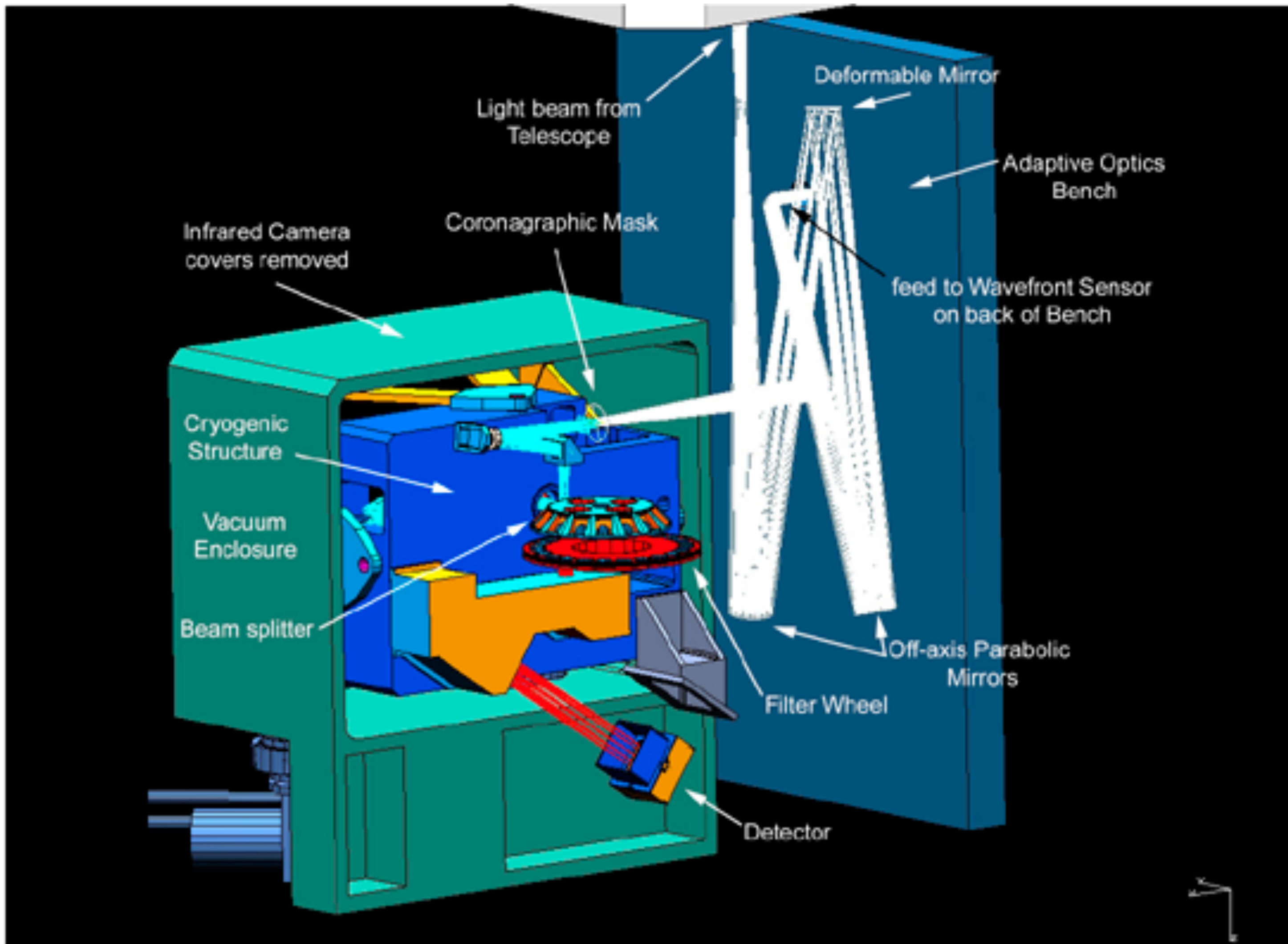
Keck: AO-NIRC2



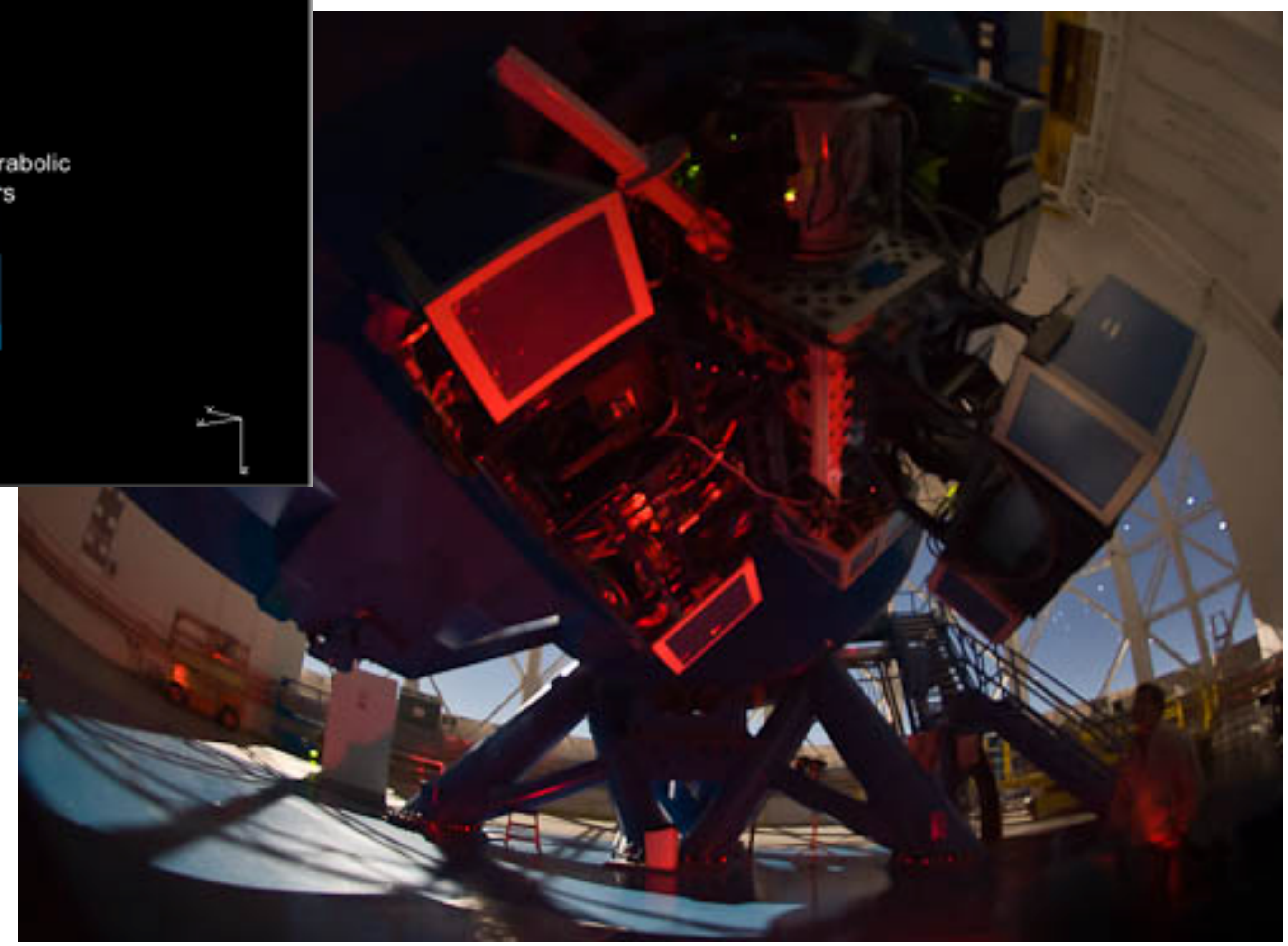


Transitioning to a new regime

Gemini: NICI

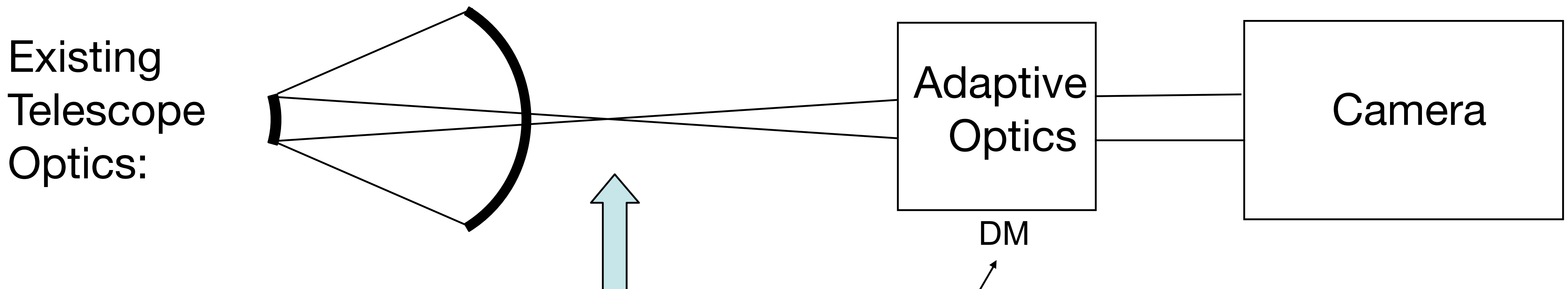


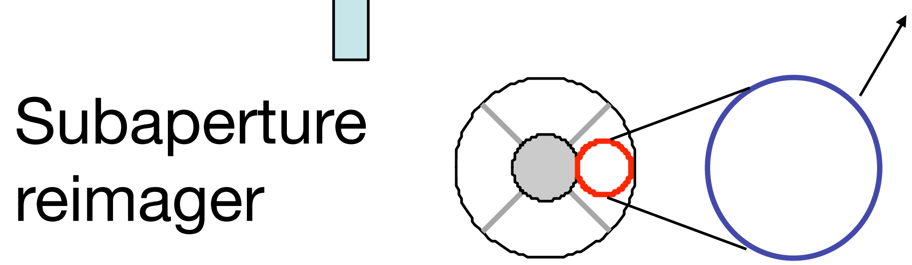
SDI built in!



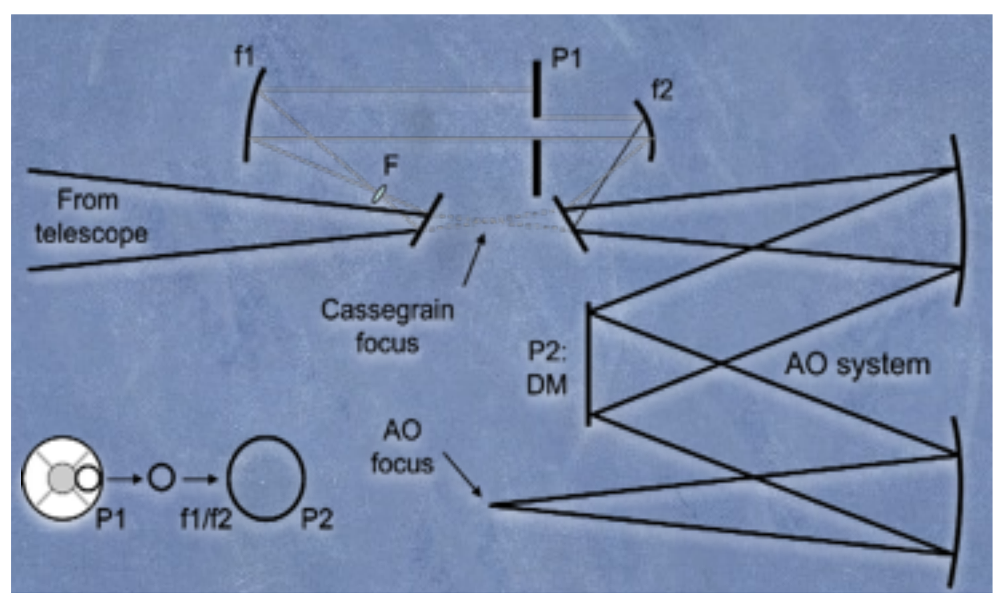
Palomar WCS

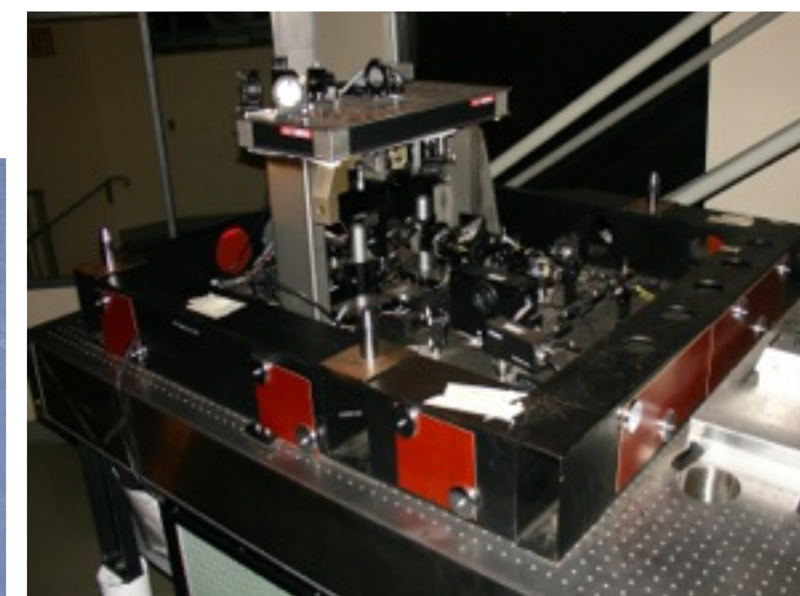
Serabyn et al. 2007



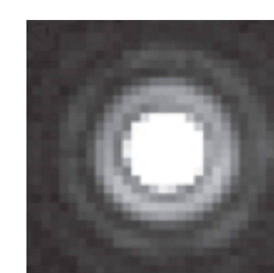


- Keep pupil location at DM
- Magnify pupil (by f1/f2)
- Center sub-pupil on DM
- Maintain F# to AO system
  ⇒post-AO optics unchanged

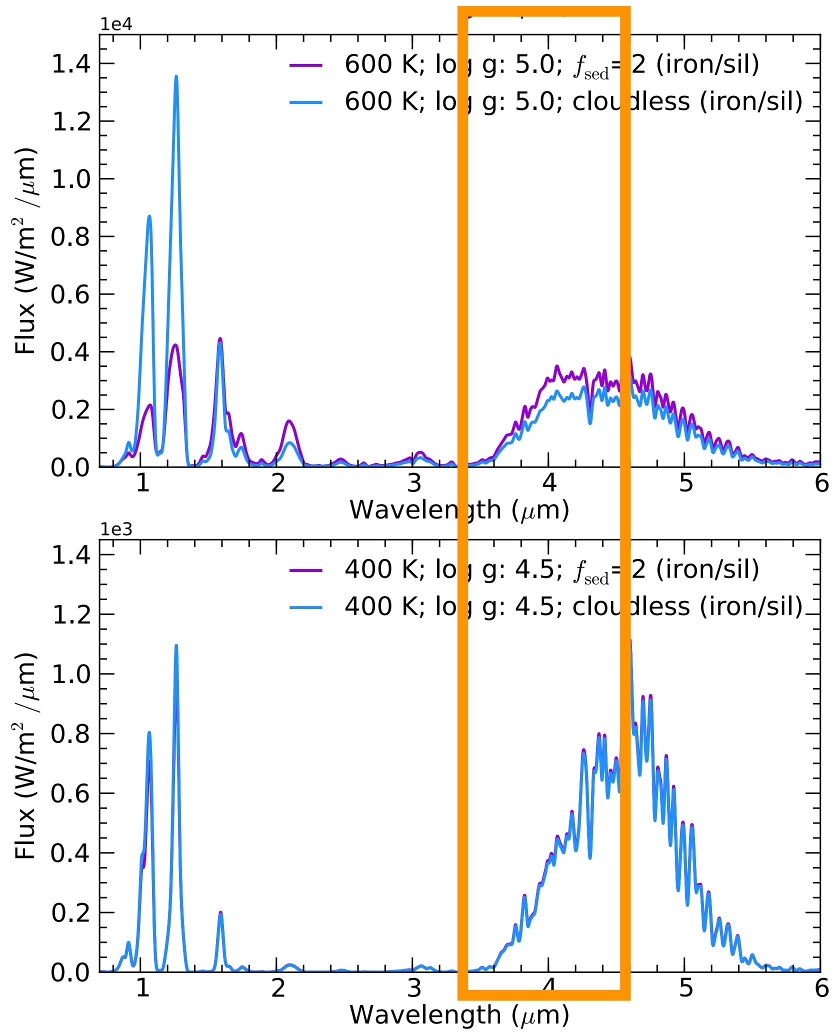




Result: >90% Strehl Ratio (how close the PSF is to the theoretical one for the perfect system)

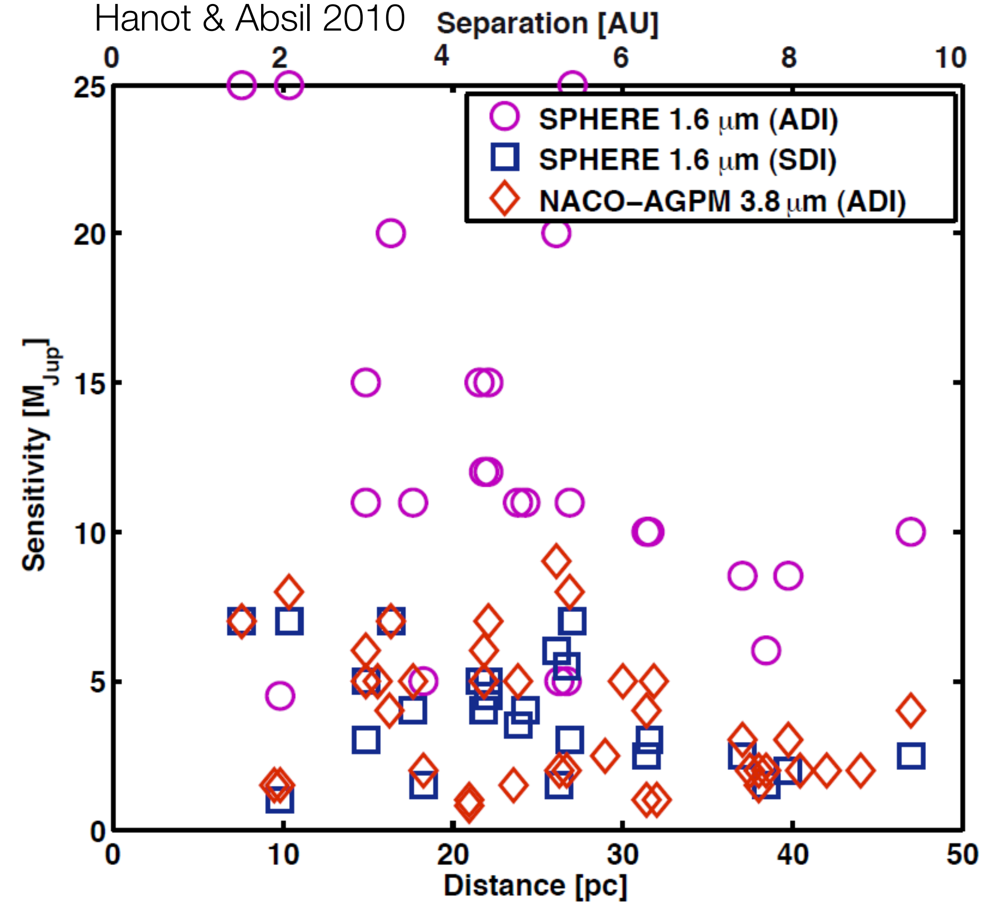


1st gen untapped potential: L' band imaging



Morley et al. 2012

Hanot & Absil 2010



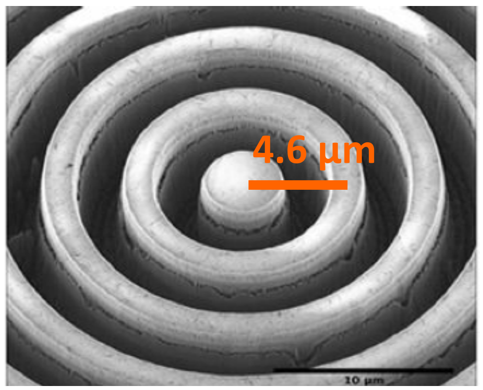
- Technical advantage:
  - Untapped potential: free high Strehl
  - Vortex coronagraph to compensate for loss in resolution

C. Delacroix
POP/POSTER

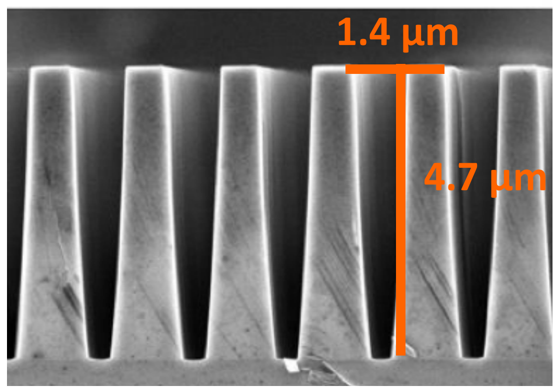
Mid-IR vortex at Paranal

Mawet et al. 2005, 2013, Delacroix et al. 2013, Absil et al. 2013

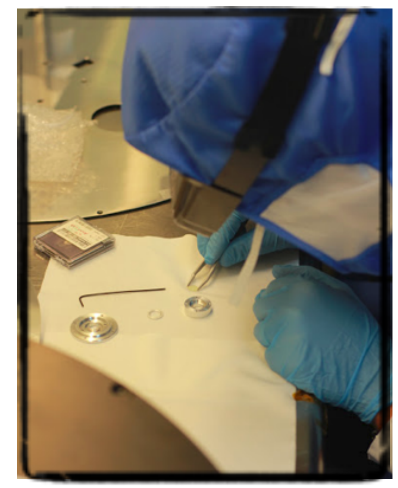
N band (Feb 2012)



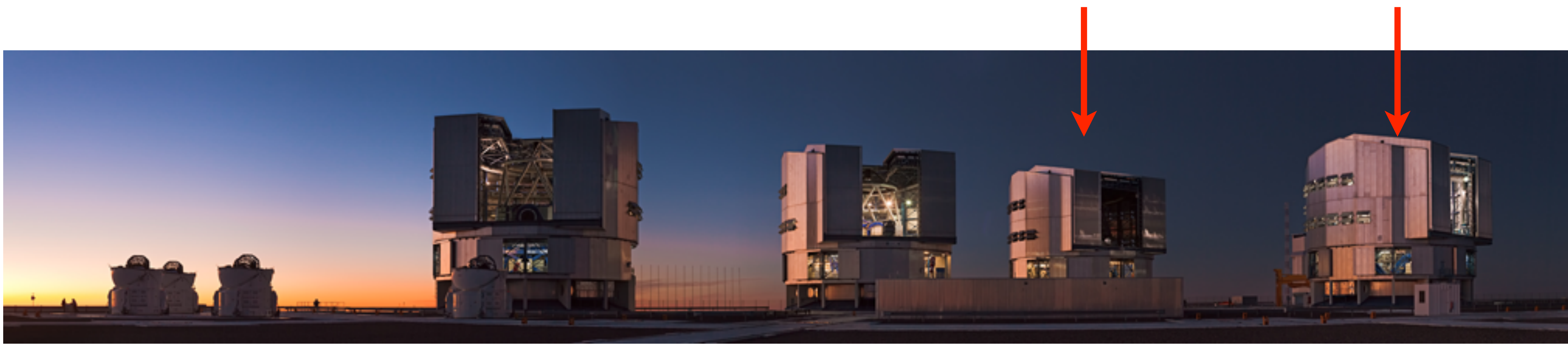
L band (Sep 2012)



8 years of R&D

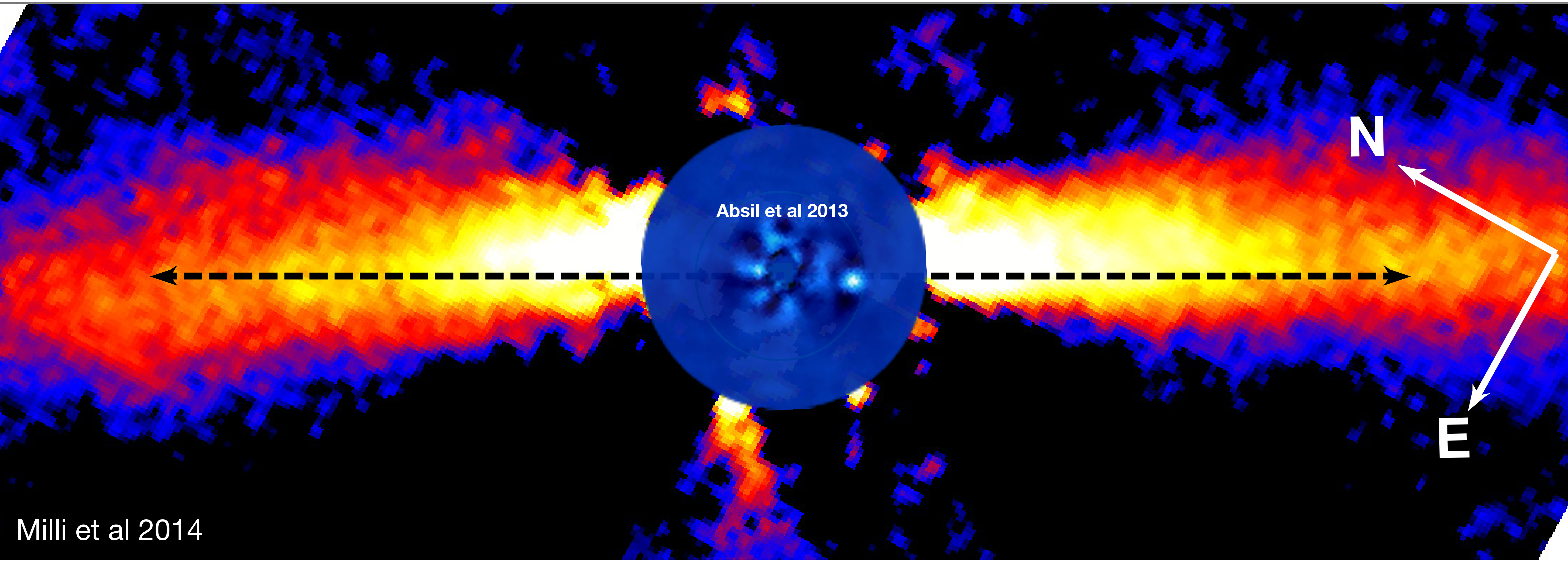


@ Paranal observatory



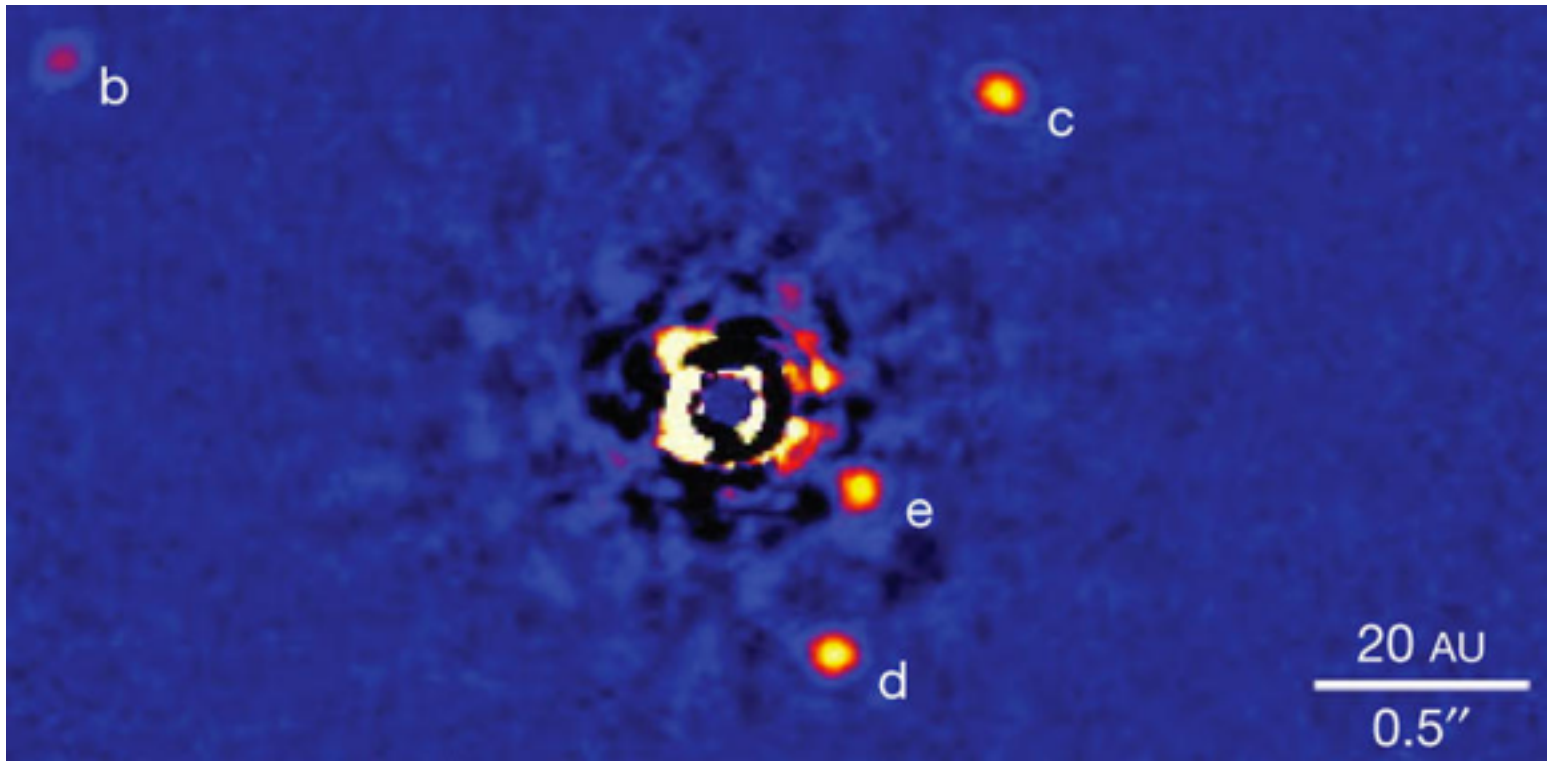
J. Milli
POP/POSTER

L-M band high contrast imaging:
1st generation's continuous hegemony



Beth and Travis talks

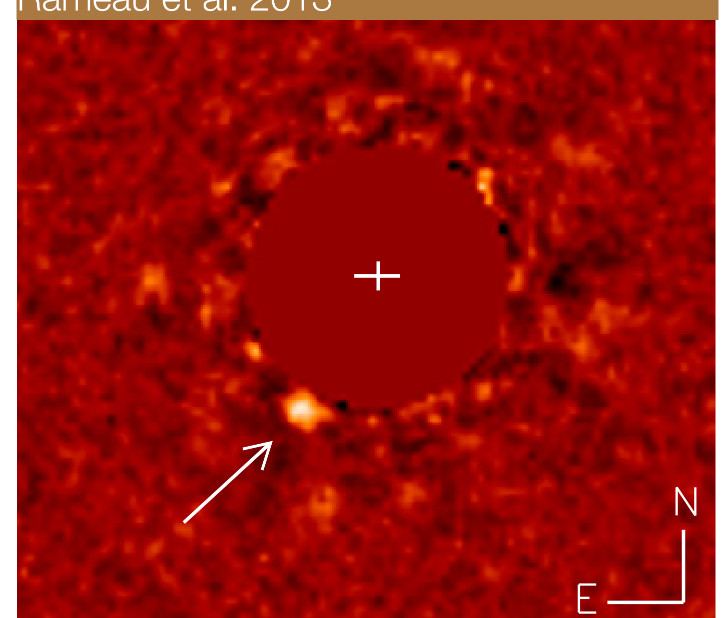
Science highlights from 1st generation



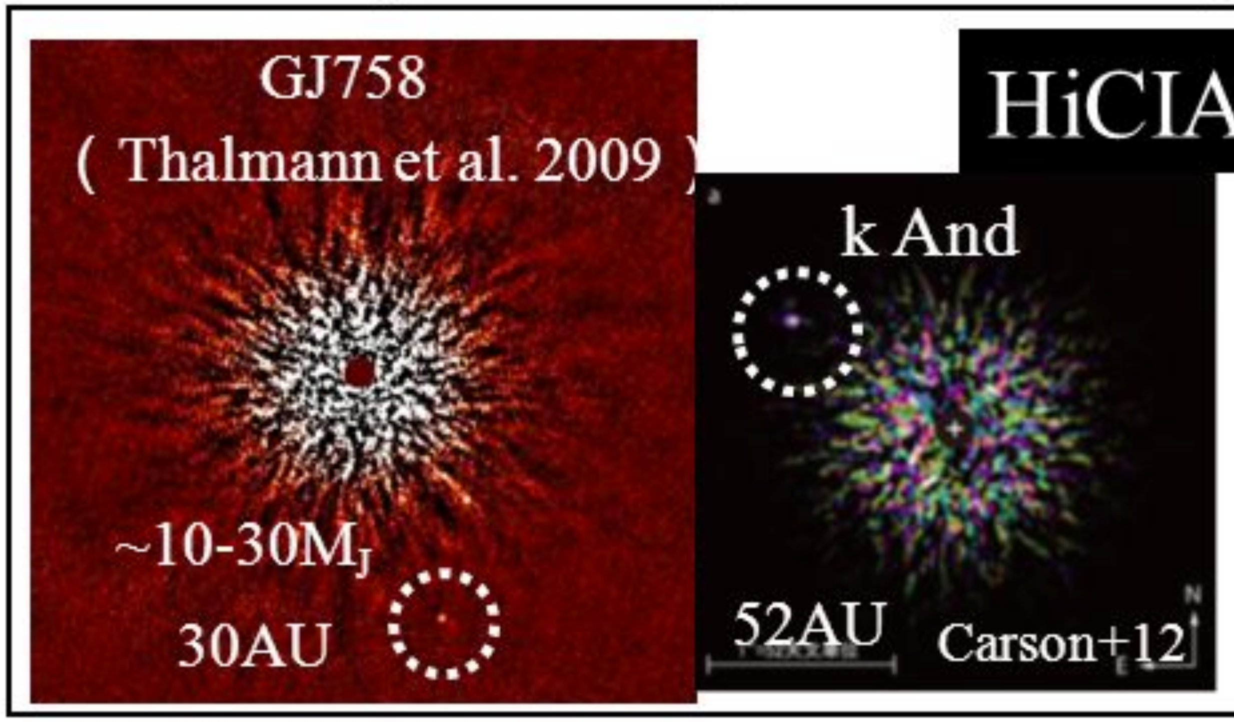
Keck-NIRC2: HR8799, 4-planet system (Marois et al. 2008-10)

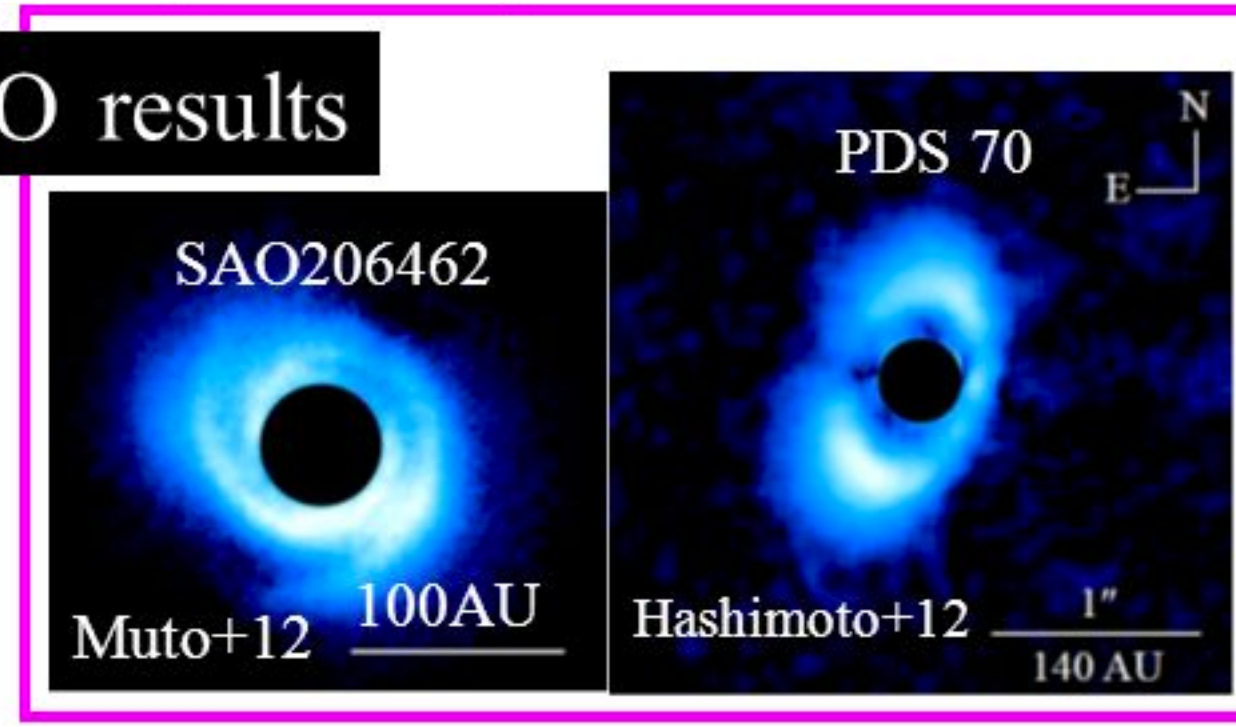
NACO: 1st “exoplanet” imaged (Chauvin et al. 2004)

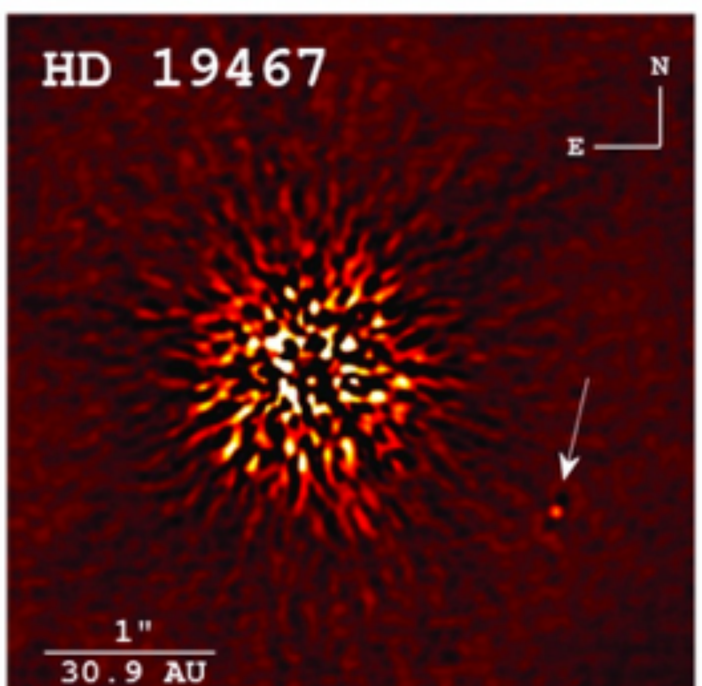
HD95086 with NACO (L’)
Rameau et al. 2013



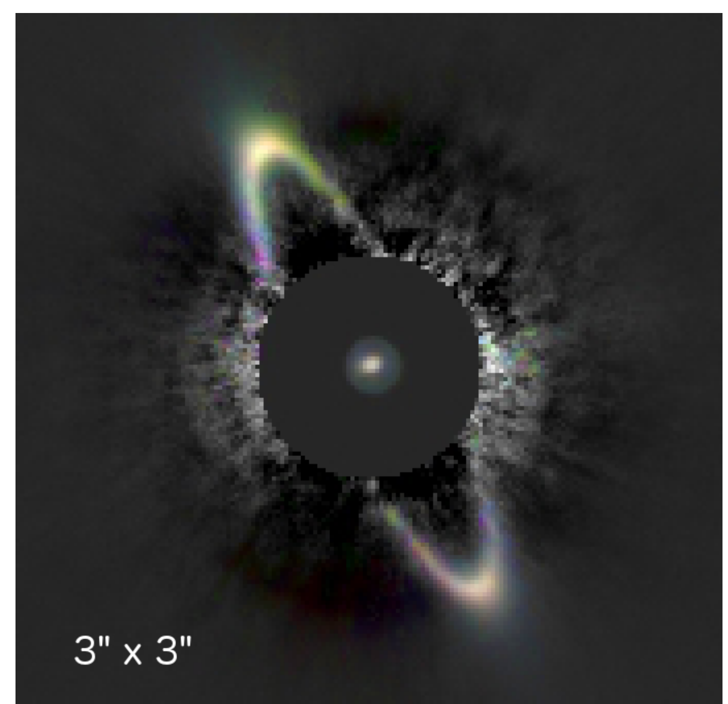
Science highlights from 1st generation







Keck-NIRC2: brown dwarf companion (Crepp et al. 2014)



NICI: HR4796 debris disk (Wahhaj et al. 2014)

2nd generation high contrast imaging instruments

2nd generation = 1st generation on steroids

- Extreme AO, **C = (1-S) / N²** (Serabyn et al. 2007):
    - High density DM
    - High density, low noise, faster WFS
- Better optics => excellent wavefront quality
- Optimized for stability => slow thermal & mechanical drifts
- Speckle control strategies are fully built in!

Instrument	Telescope	AO	Wavelength (μm)	Ang. res. (mas)	Coronagraph
P3K-P1640/SDC	Hale 200"	64-SH	1.1–2.4	45-90	APLC/VC
SPHERE	VLT	40-SH	0.5–2.4	15-55	Lyot/APLC/FQPM
GPI	Gemini South	48-SH	0.9–2.4	23-55	APLC
SCExAO	Subaru	14-C & 48-P	0.55–2.4	15-55	PIAA/SP/VC
MagAO-Clio2/VisAO	Magellan	25-Pyramid	0.55–5	18-160	Lyot(+APP)
LMIRCAM	LBT'	30-Pyramid	2–5	60–120	APP+VC

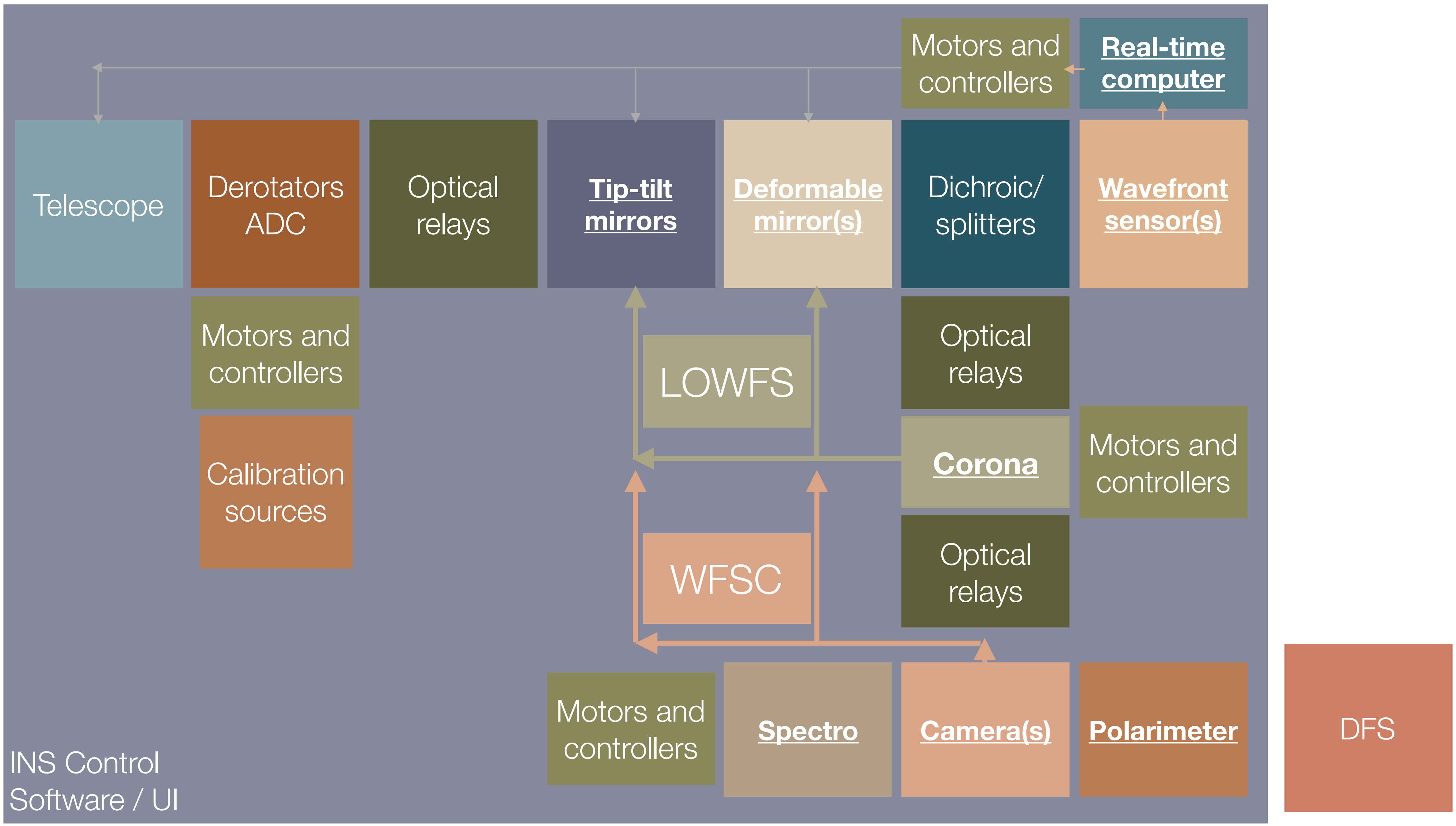
2nd generation: deal with speckle headaches

Red pill:
image plane
wavefront sensing

Blue pill:
differential
imaging

I'll have both!

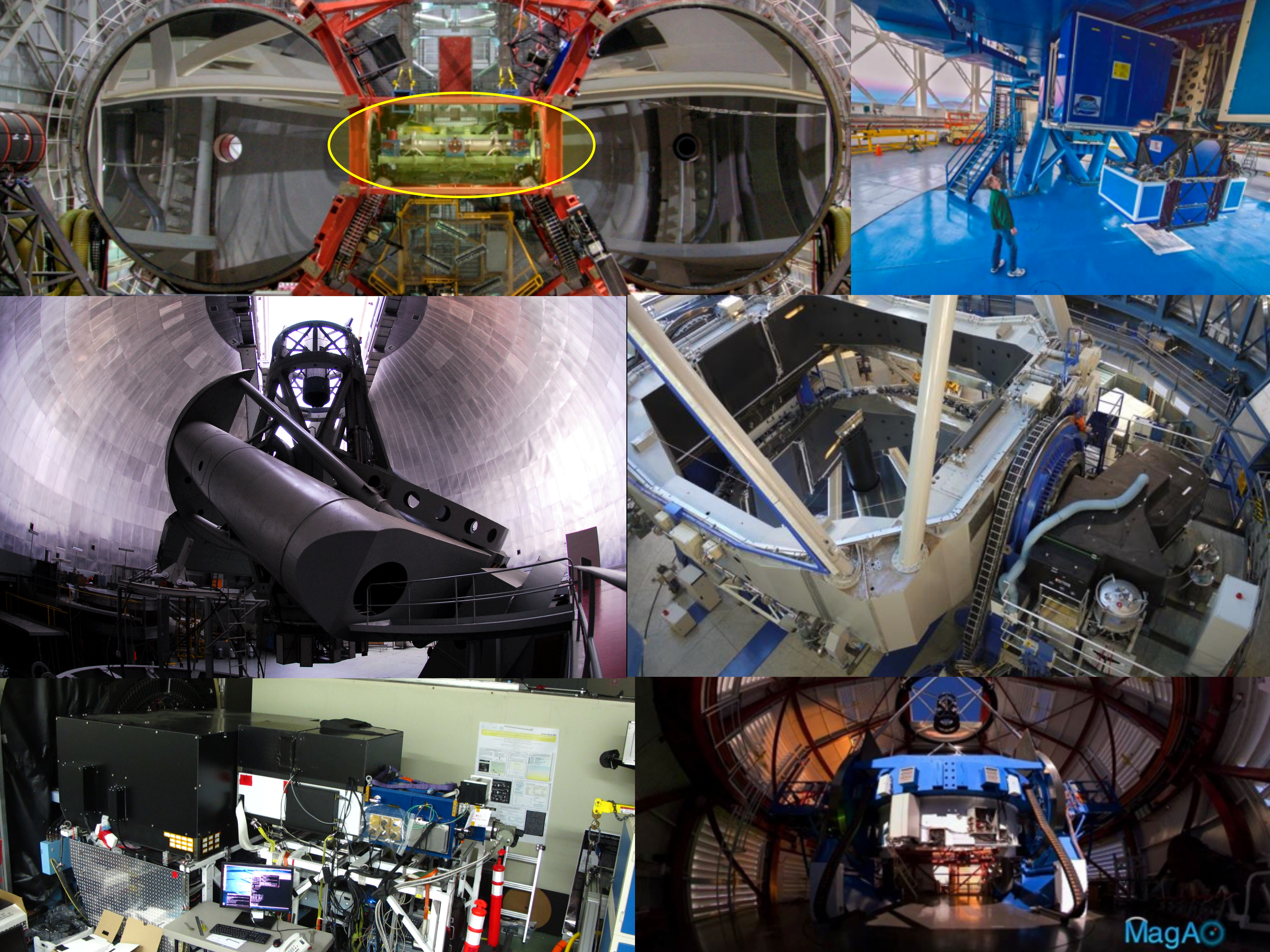
Similar architecture + a few (critical) tweaks



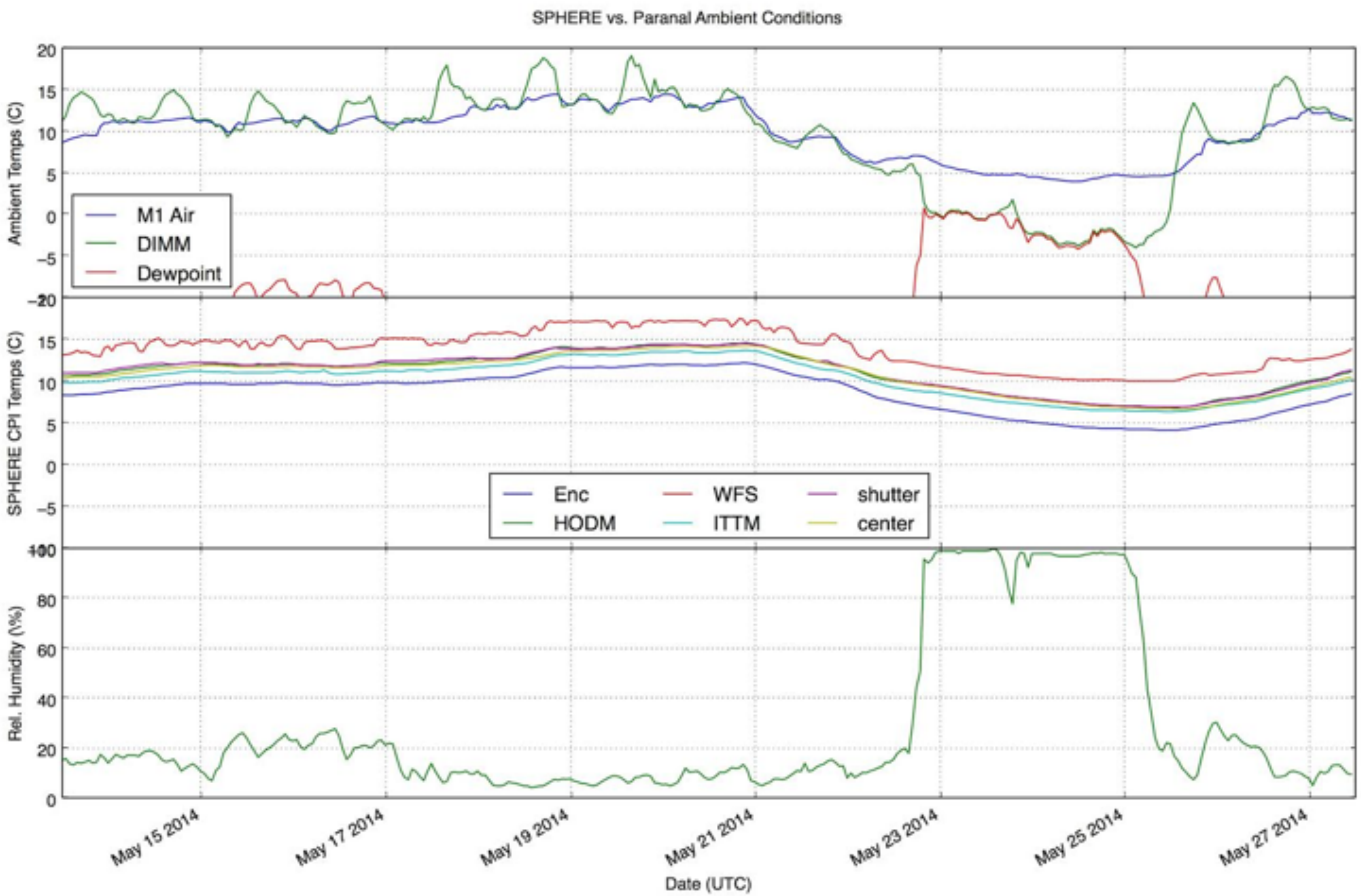
SAME ARCHITECTURE FOR NEXTGEN SPACE-BASED CORONAGRAPHS!

Configuration - environment - telescope interaction

	Telescope	Location	Focus	Note
P3K	Hale 200-inch	CA	Cassegrain	Equatorial mount
LBT	LBT	AZ	Combined	ASM
MagAO	Magellan	Chile	Nasmyth	ASM, Rotating
SCExAO	Subaru	Hawaii	Nasmyth	Modular
GPI	Gemini S	Chile	Cassegrain	Small, light weight
SPHERE	VLT	Chile	Nasmyth	Heavy, stable (damped)


MagAO

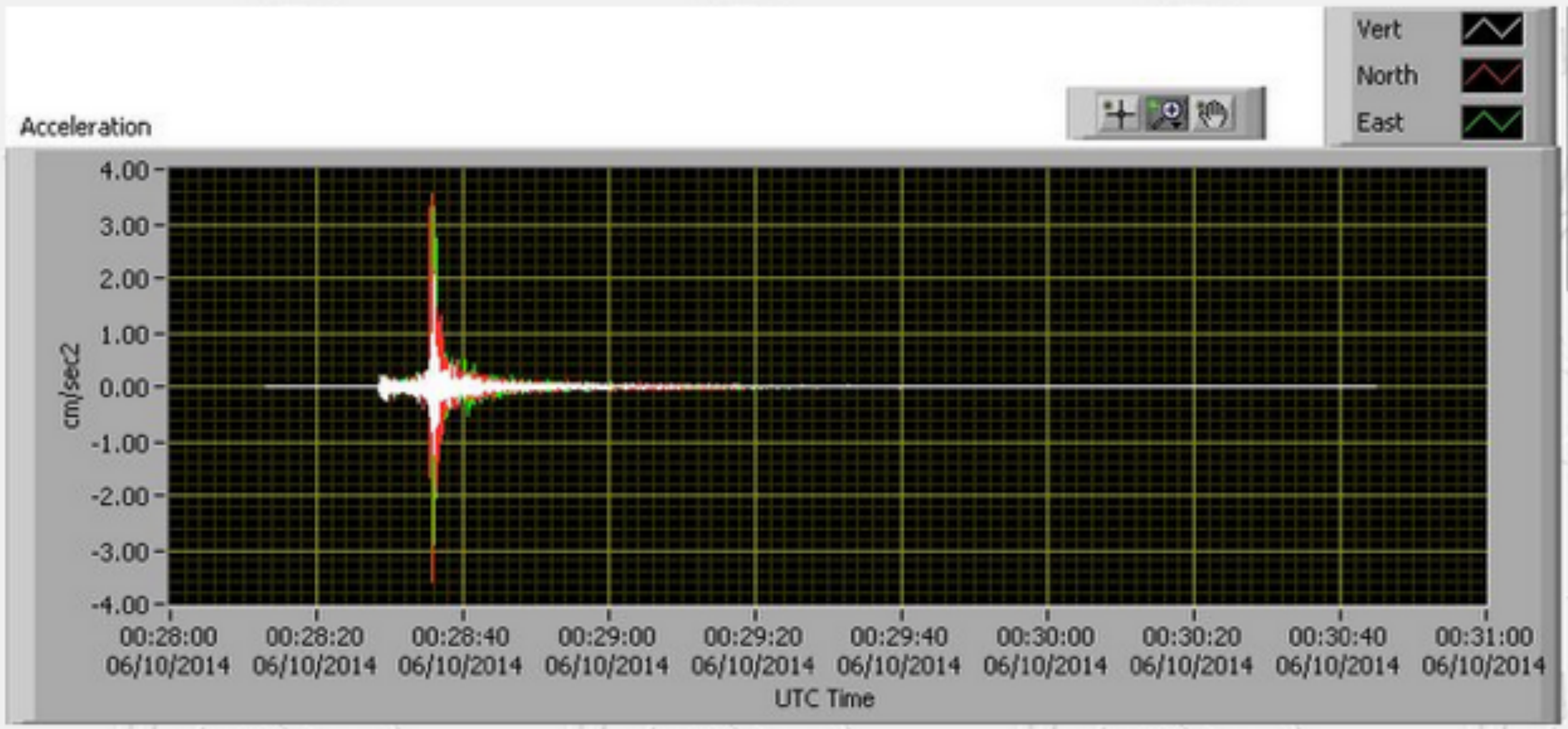
Wild weather conditions!
J. O'Neal, ESO



+ monsoon, wildfires (+ strikes, bbq)

Coronagraphs are allergic to dust…

Earthquakes!



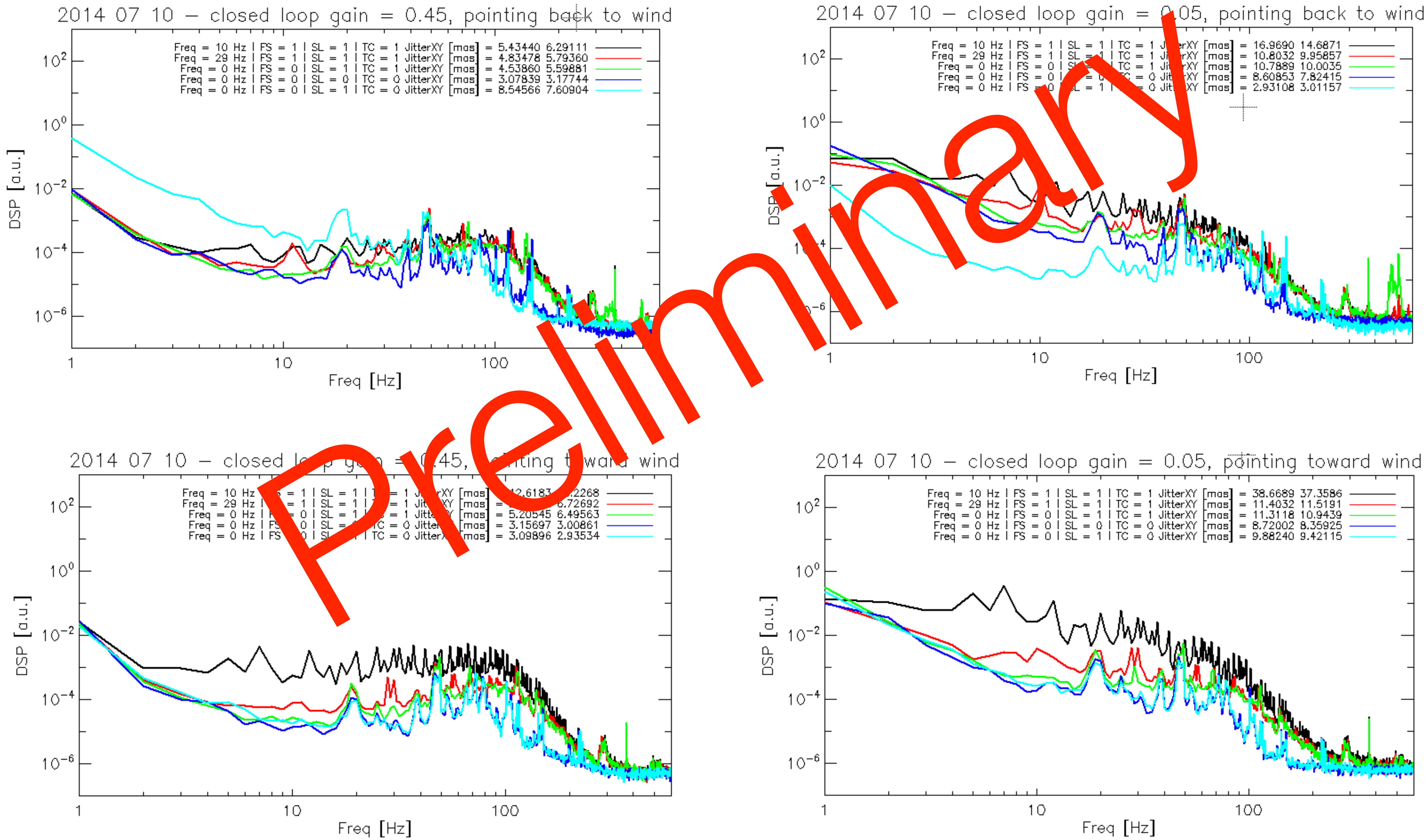
Risk Level	No Risk
Date Event UTC	2014/06/10
Time Event UTC	0:27:43
PGA [cm/sec2]	3.542089
Distance [kms]	72.48
Ritchter	4.291263
Mercalli	3.147778

Date Time	PGA [cm/sec2]	Distance [kms]	Ritchter	Mercalli
2014/06/10 00:27:43	3.542089	72.48	4.291263	3.147778
2014/06/02 20:03:41	1.454716	44.4	3.852664	1.988334
2014/05/30 15:37:29	0.3813578	358.48	5.559597	0.2439977
2014/05/29 02:28:09	0.319964	214.96	4.259342	1.530346E-02
2014/05/17 00:17:21	0.5842438	281.68	5.016644	0.7997823
2014/05/16 17:13:10	2.711451	256.32	5.530533	2.799605
2014/05/15 16:44:45	0.4939594	38.4	2.581523	0.5810738
2014/05/14 03:43:46	2.675448	347.92	5.775005	2.78219
2014/05/06 10:32:23	0.8144505	78.24	4.117043	1.232594
2014/05/06 03:26:21	0.70921	123.04	4.091603	1.052325
2014/05/05 20:07:05	2.866613	199.12	5.437913	2.872107
2014/05/05 06:09:07	0.3794087	49.36	2.901212	0.2373217
2014/05/03 21:36:38	1.120628	344.88	6.085762	1.648385
2014/05/01 01:55:42	0.7334946	-0.08	5.094975	1.096191
2014/04/29 23:45:05	0.6151029	-0.16	4.673129	0.8668435

Date Time	PGA [cm/sec2]	Distance [kms]	Ritchter	Mercalli
2014/04/29 04:09:35	0.6087596	447.76	6.070396	0.8533374
2014/04/23 18:17:32	1.231517	111.76	4.596357	1.771321
2014/04/21 20:56:23	3.840531	63.44	4.505048	3.253174
2014/04/21 00:59:31	2.604788	324.48	5.91458	2.747317
2014/04/19 18:44:41	3.007996	48.88	3.679722	2.934832
2014/04/17 13:25:02	0.3931395	288.8	4.71149	0.2836399
2014/04/13 05:18:34	0.5309814	229.52	4.568206	0.6752379
2014/04/11 23:24:22	0.3296065	194.32	5.165696	5.398721E-02
2014/04/07 04:12:56	0.9974644	77.36	3.917838	1.496692
2014/04/06 08:01:14	0.4256831	51.76	3.018063	0.3872593
2014/04/04 04:38:40	0.5687134	211.44	4.76265	0.7646803
2014/04/04 01:44:24	0.4409721	404.56	5.636302	0.4332334
2014/04/03 05:34:09	0.3480419	526.4	5.857316	0.1248946
2014/04/03 02:53:25	2.785169	535.84	6.666691	2.834555
2014/04/03 02:04:55	0.5995262	501.2	5.935338	0.8334245

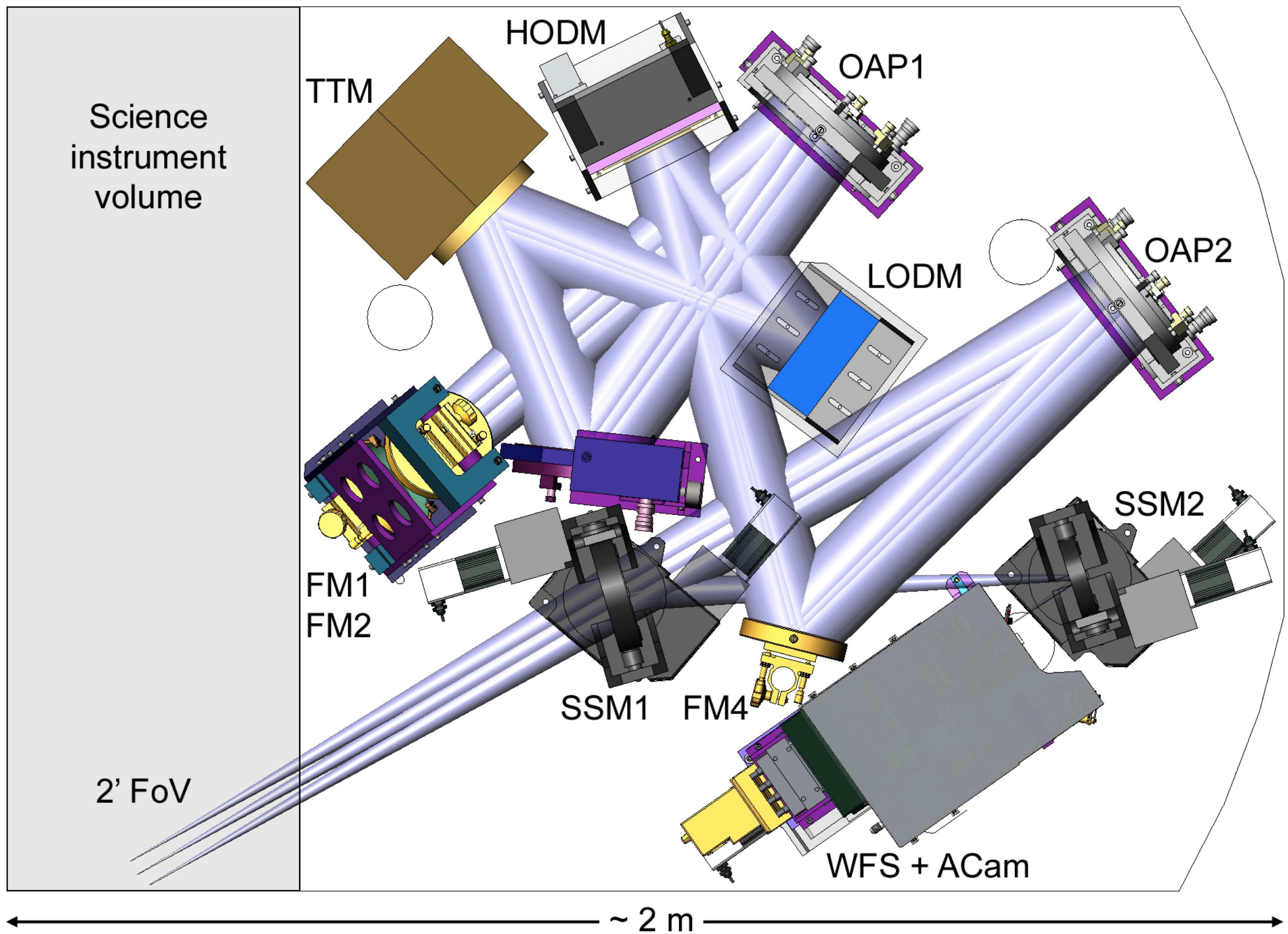
Wind shake - Vibrations - M2 control

Sauvage & Fusco et al.



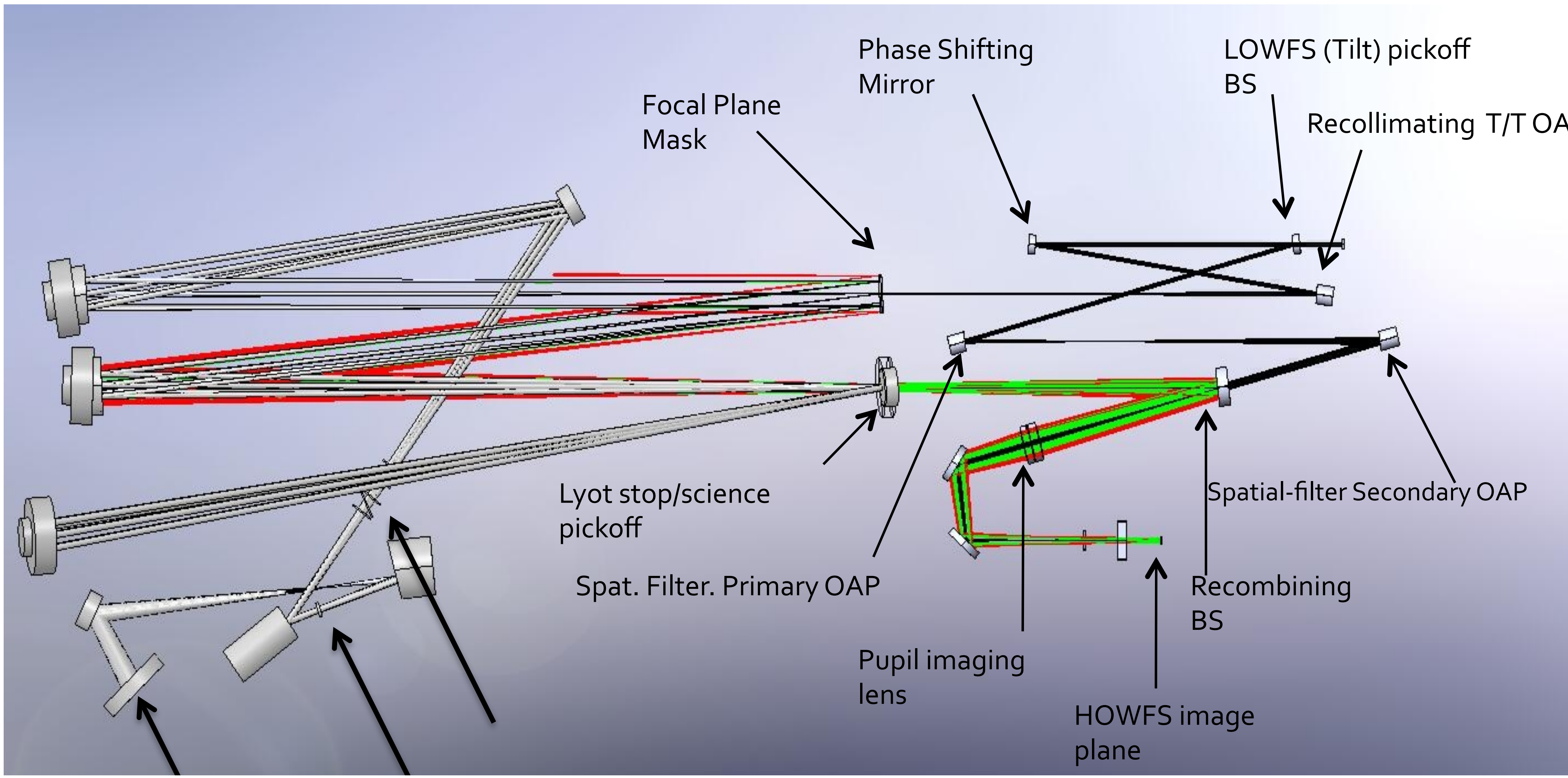
Palm-3000

Dekany et al.



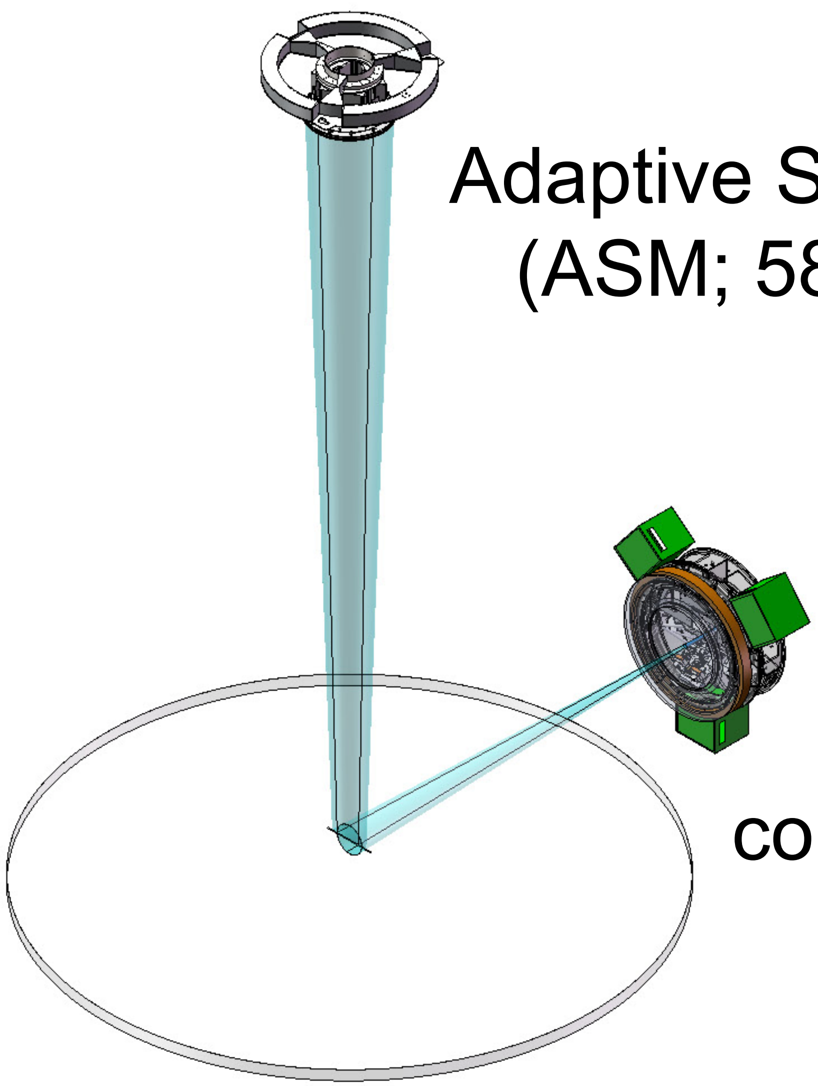
Project 1640

Oppenheimer et al.



Mag AO

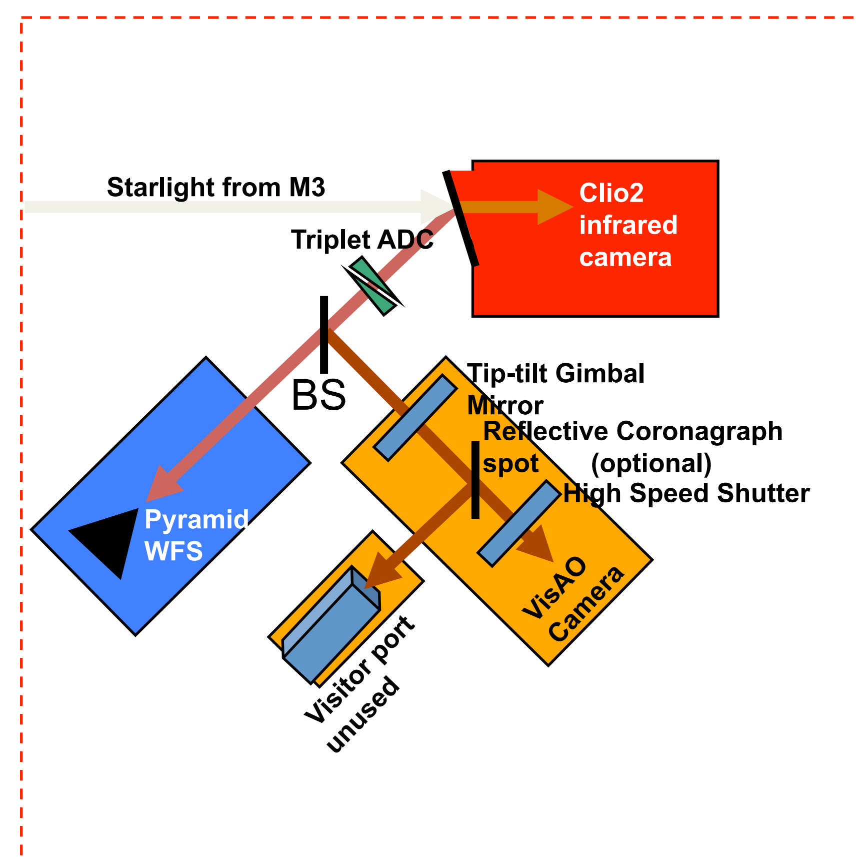
Close et al. 2014



Adaptive Secondary Mirror
(ASM; 585 actuators)

Pyramid
WFS 378
modes
controlled at 1KHz

ASM

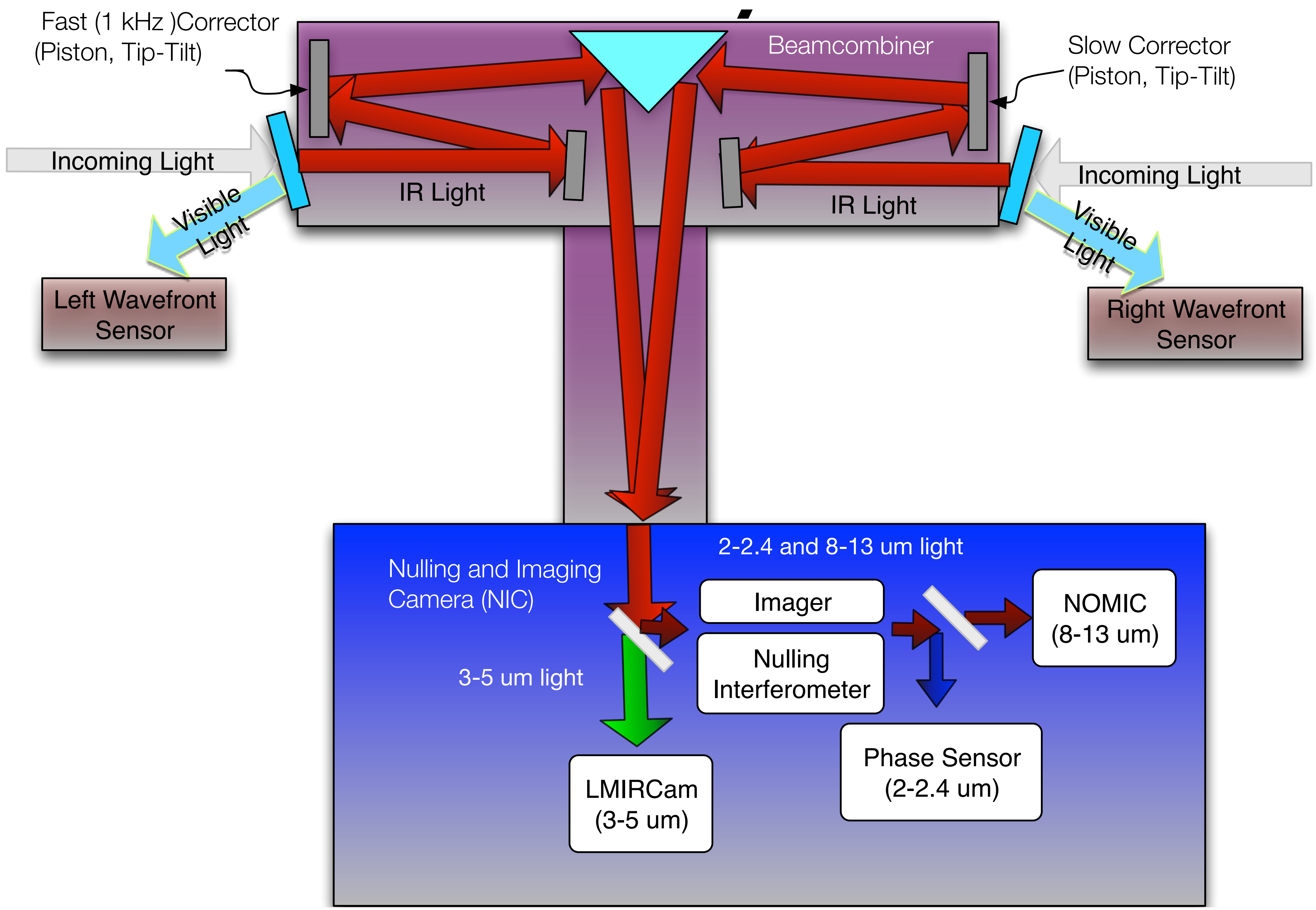


1kHz
AO loop

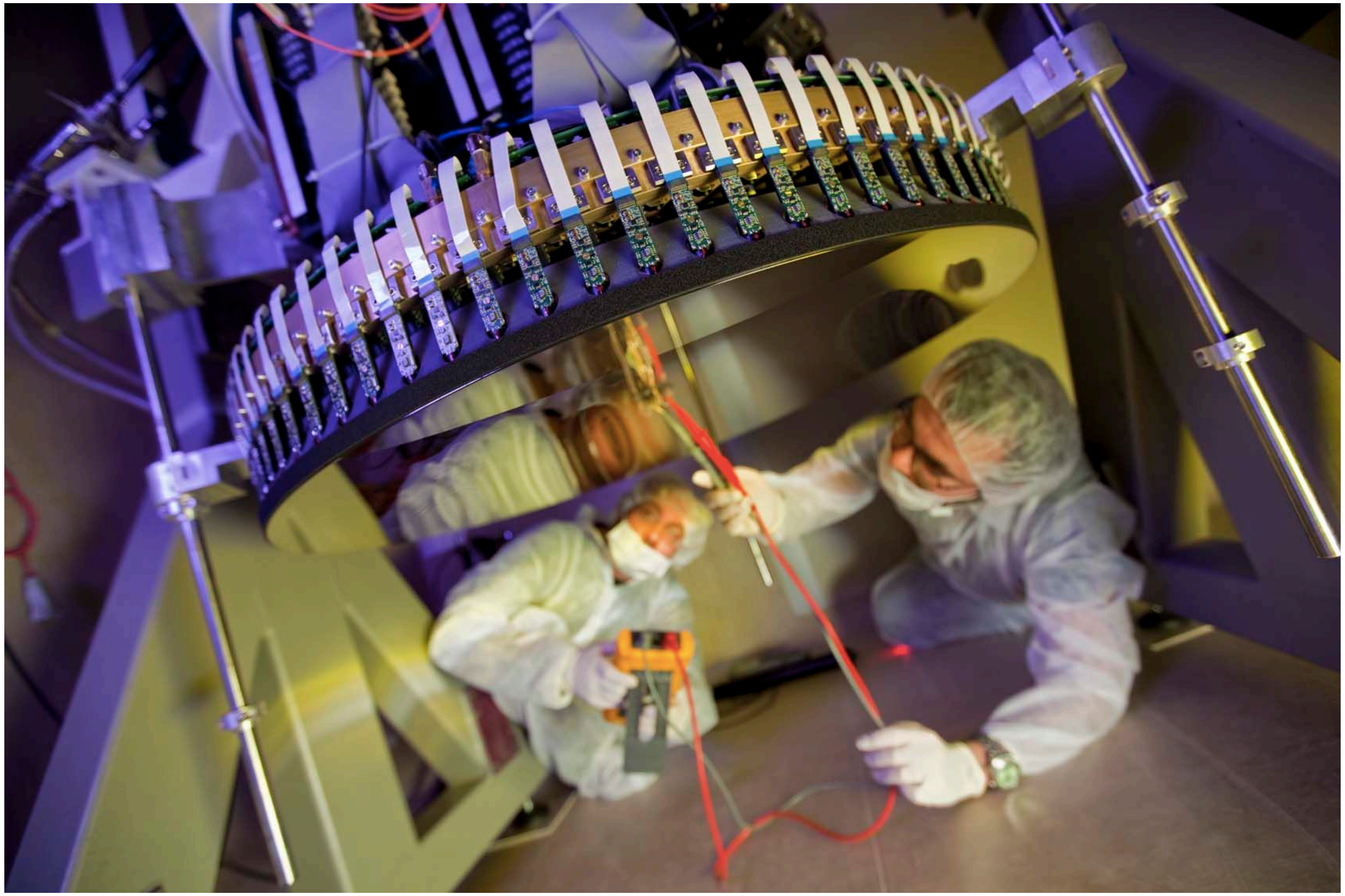
NAS ring

LBT(I)

Hinz et al.

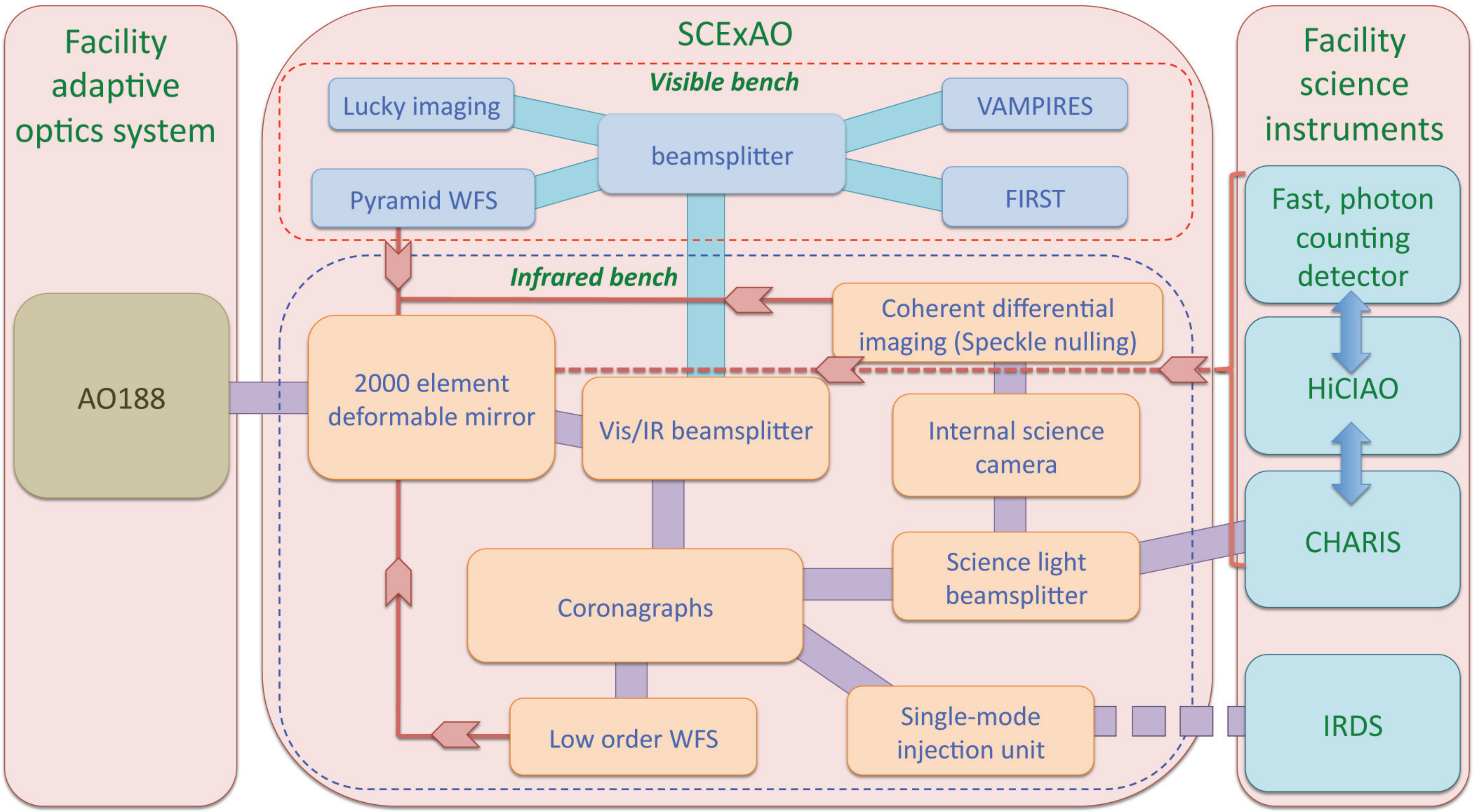


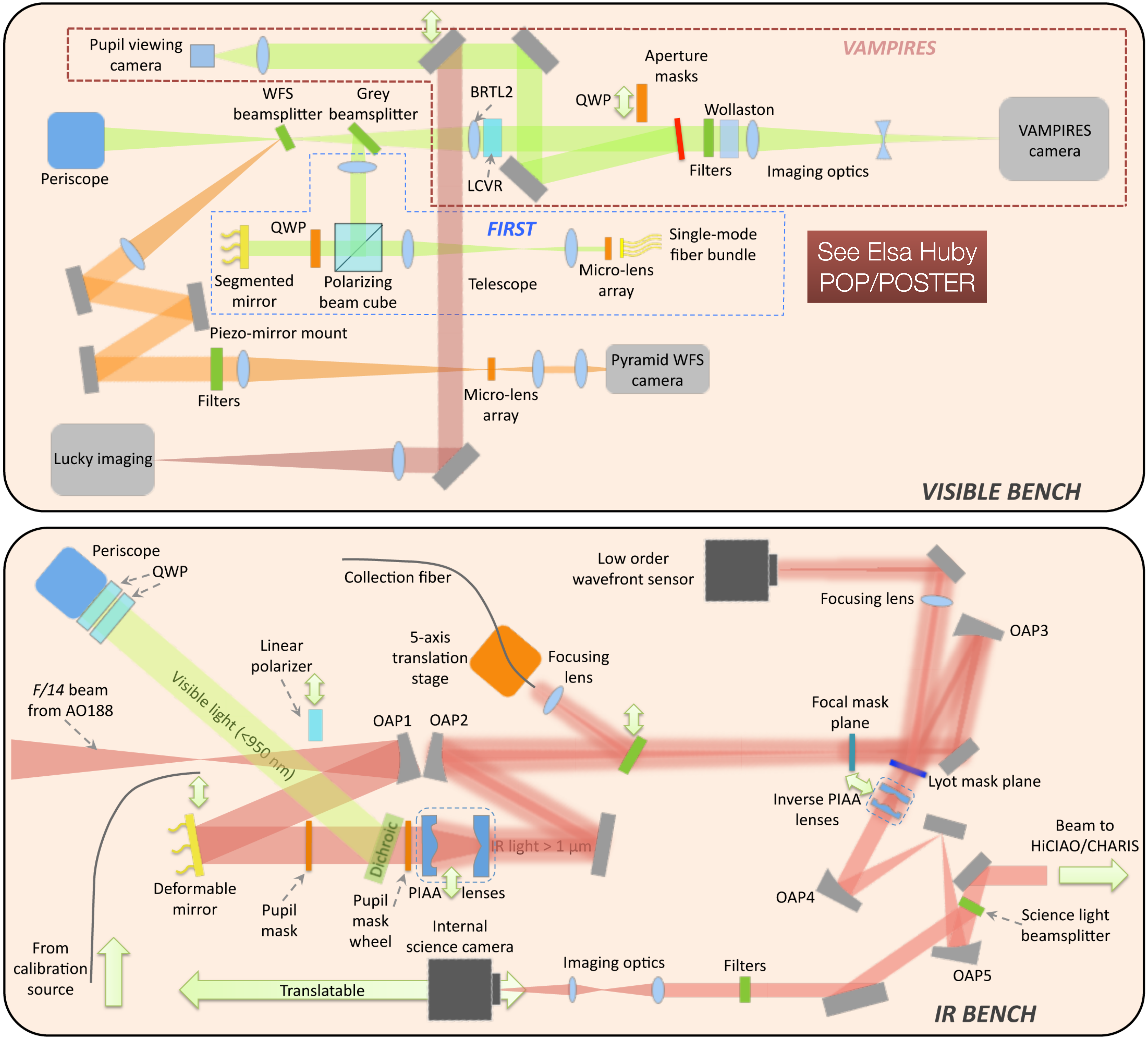
LBT and Mag AO ASM



Excellent for mid-IR imaging (minimize # of optical surfaces)

SCExAO
Guyon et al.

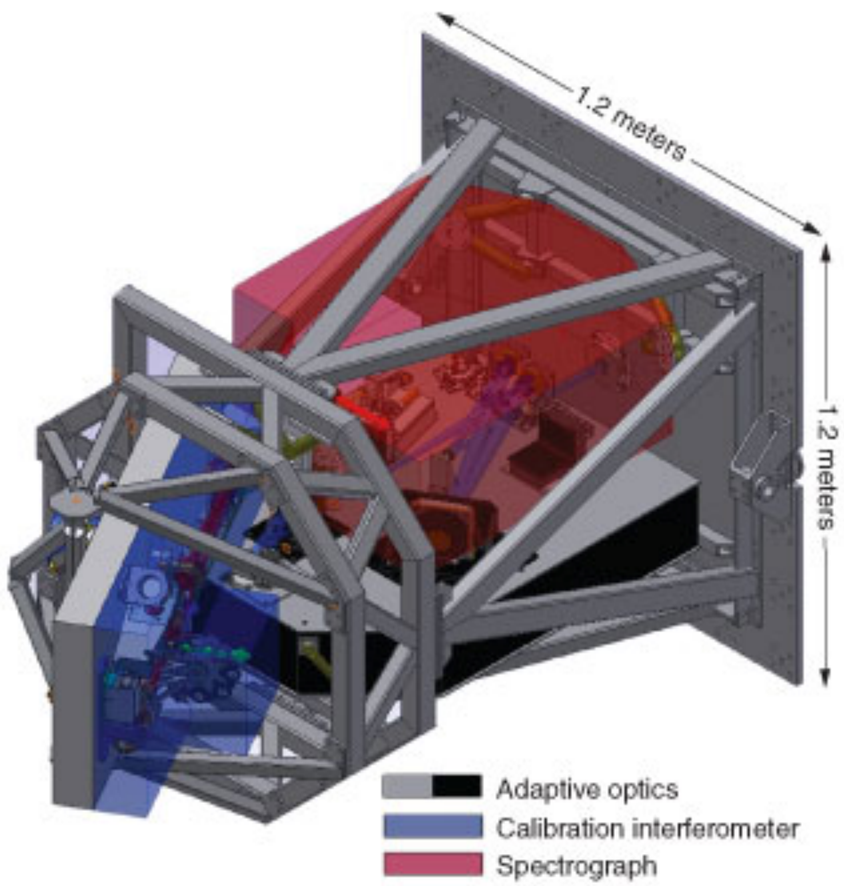


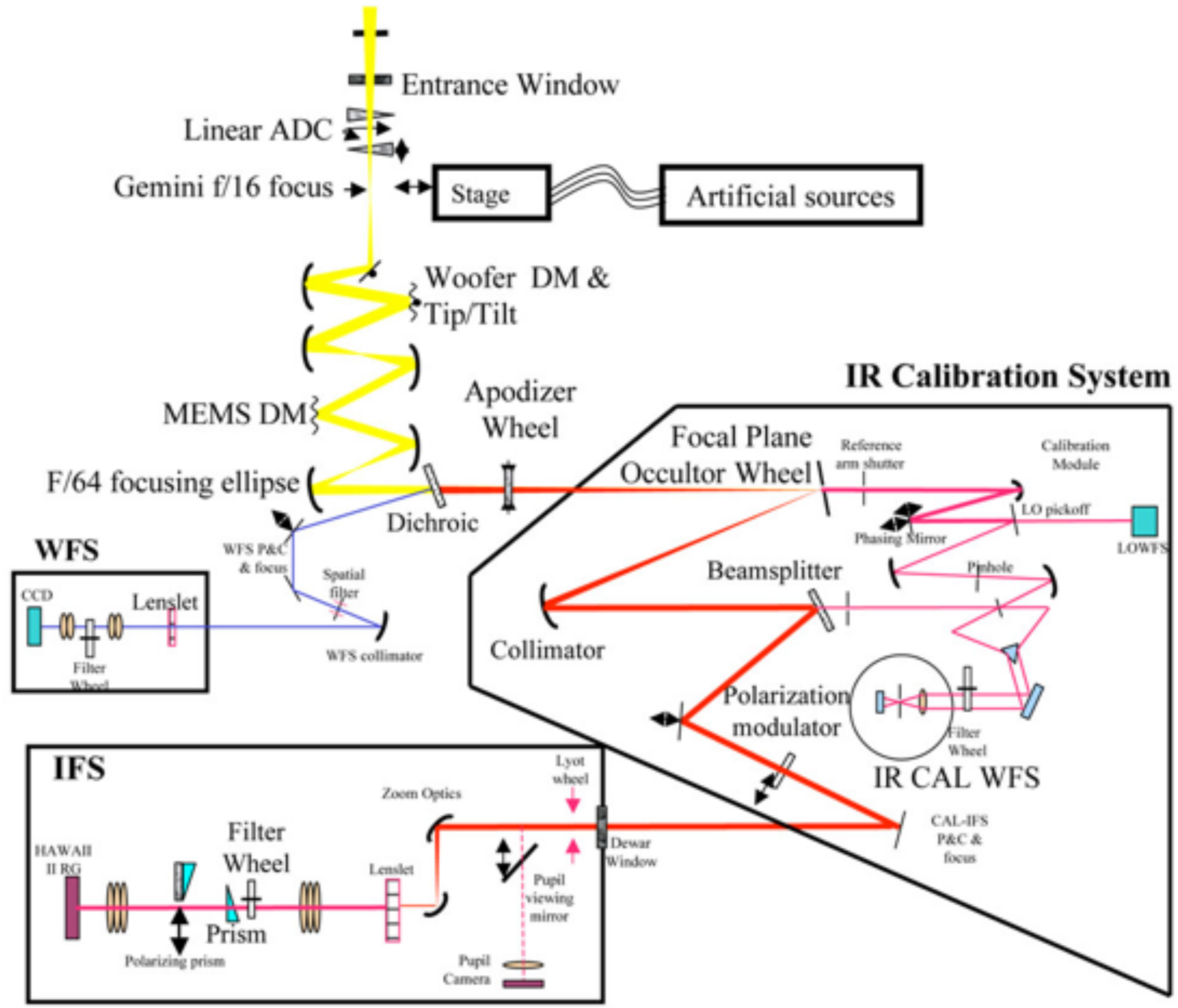


Pupil viewing camera
VAMPIRES
Aperture masks
QWP
BRTL2
WFS beamsplitter
Grey beamsplitter
Wollaston
VAMPIRES camera
Periscope
LCVR
Filters
Imaging optics
FIRST
QWP
Single-mode fiber bundle
See Elsa Huby POP/POSTER
Segmented mirror
Polarizing beam cube
Telescope
Micro-lens array
Piezo-mirror mount
Pyramid WFS camera
Filters
Micro-lens array
Lucky imaging
VISIBLE BENCH
Periscope
QWP
Collection fiber
Low order wavefront sensor
Focusing lens
OAP3
5-axis translation stage
Focusing lens
Linear polarizer
Visible light (<950 nm)
F/14 beam from AO188
OAP1
OAP2
Focal mask plane
Lyot mask plane
Inverse PIAA lenses
Dichroic
IR light > 1 µm
Beam to HiCIAO/CHARIS
Deformable mirror
Pupil mask
Pupil mask wheel
PIAA
lenses
OAP4
Science light beamsplitter
Internal science camera
From calibration source
Imaging optics
Filters
OAP5
Translatable
IR BENCH

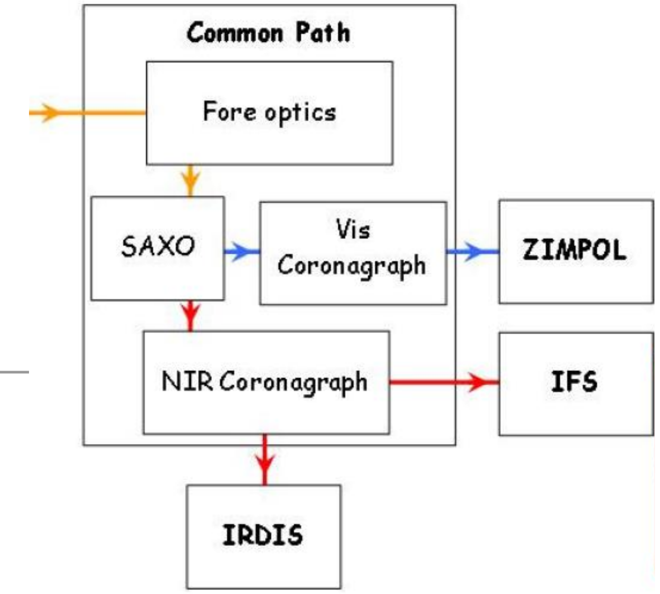
Gemini planet imager

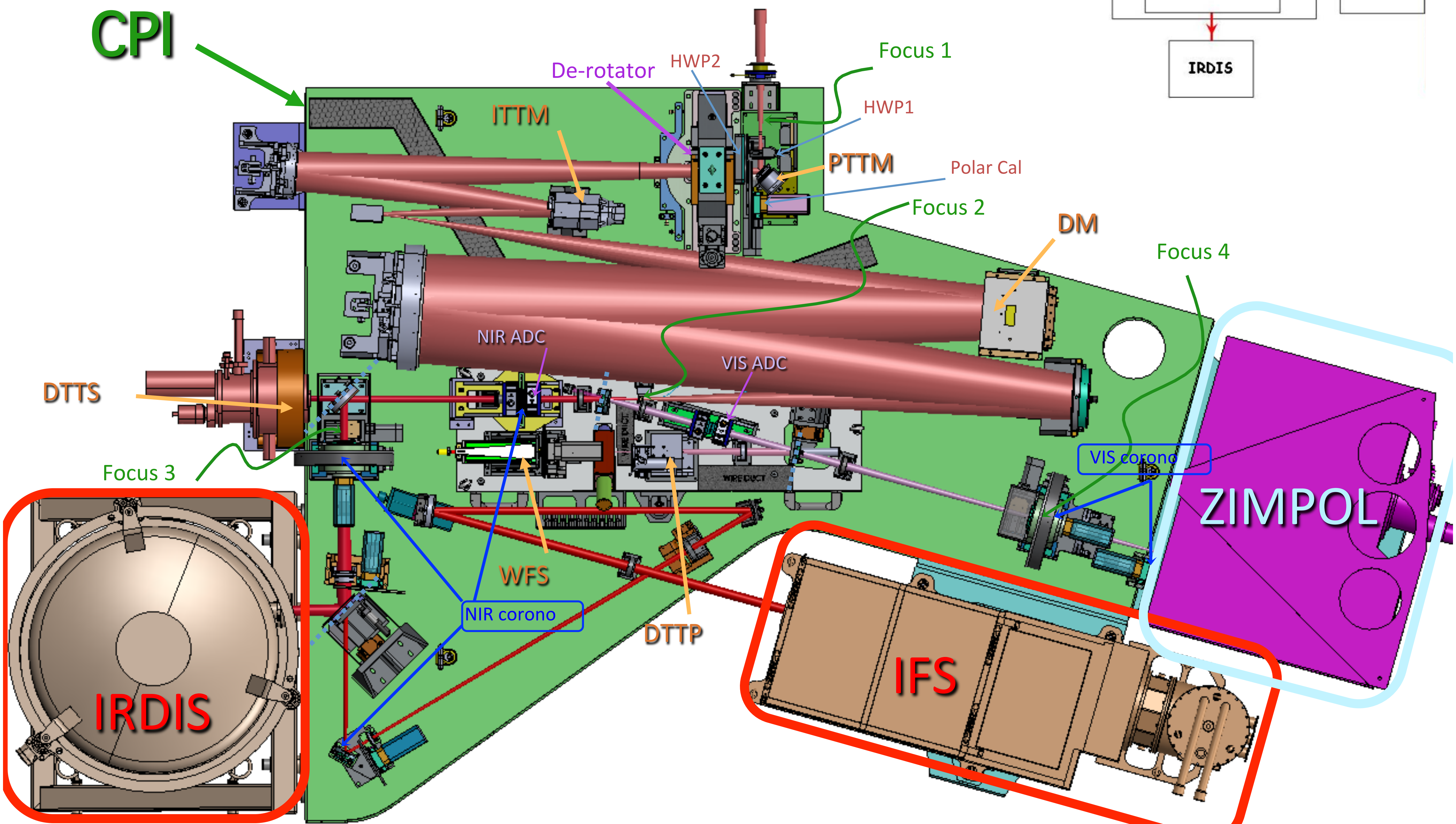
Macintosh et al.





SPHERE
Beuzit et al. 2014



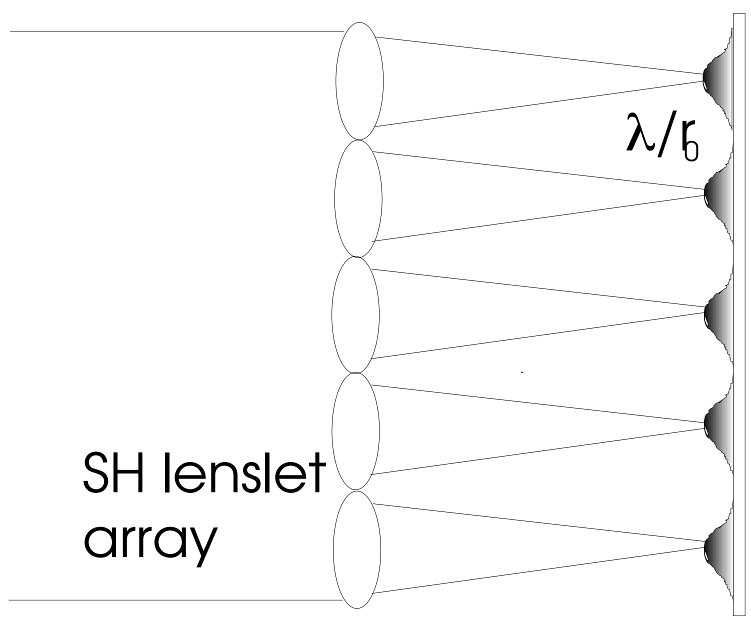


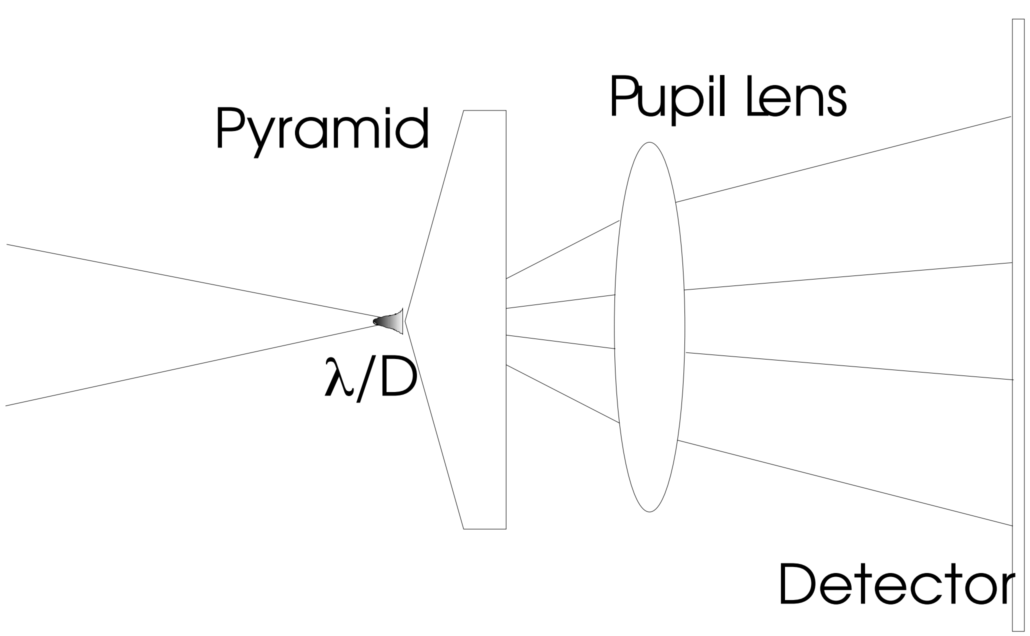
Wavefront sensing

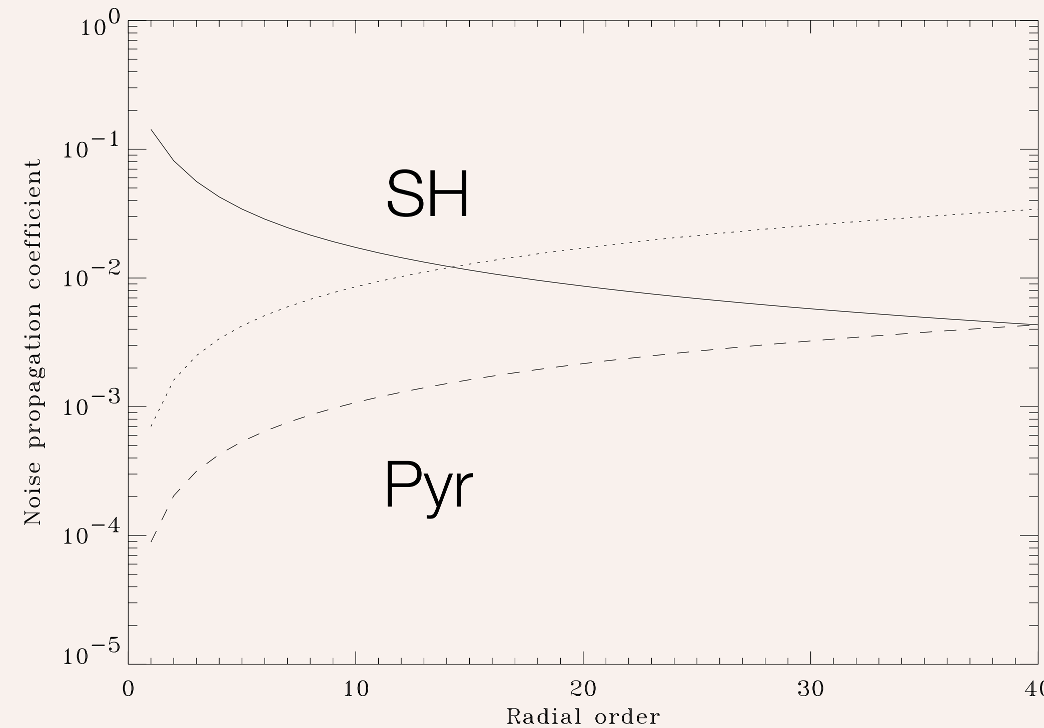
	Shack-Hartmann	Spatial filter	Pyramid	Modulation	Curvature
P3K	x	x			
LBT			x	x	
MagAO			x	x	
SCExAO			x		AO188
GPI	x	x			
SPHERE	x	x(*)			

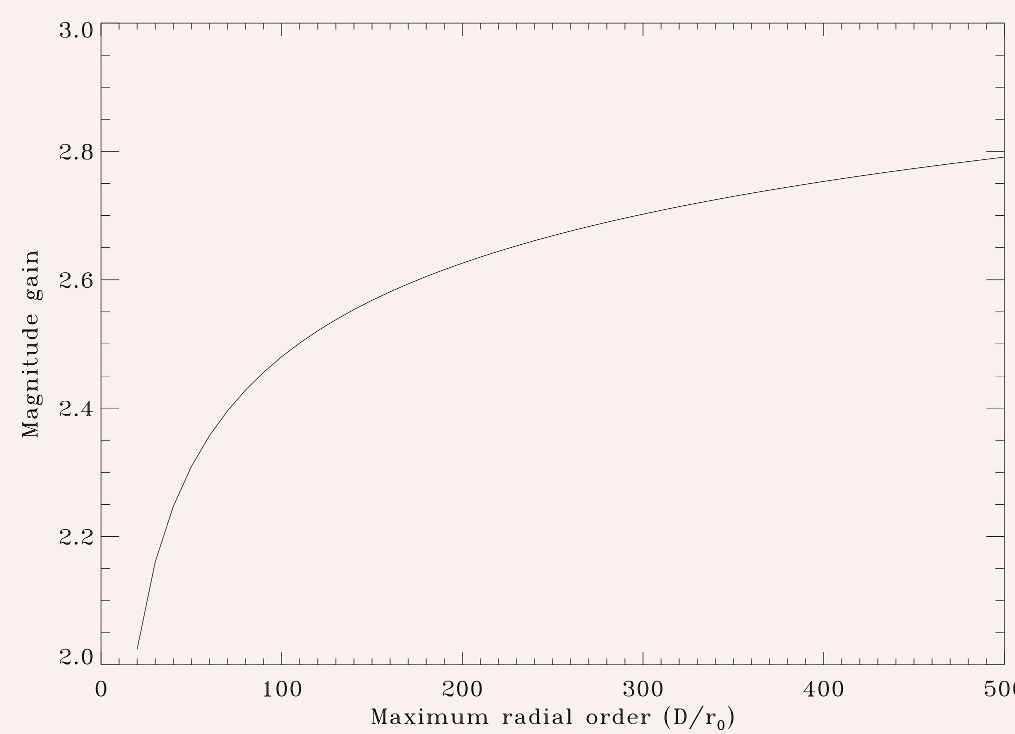
Shack-Hartmann vs Pyramid WFS

Ragazzoni & Farinato 1999



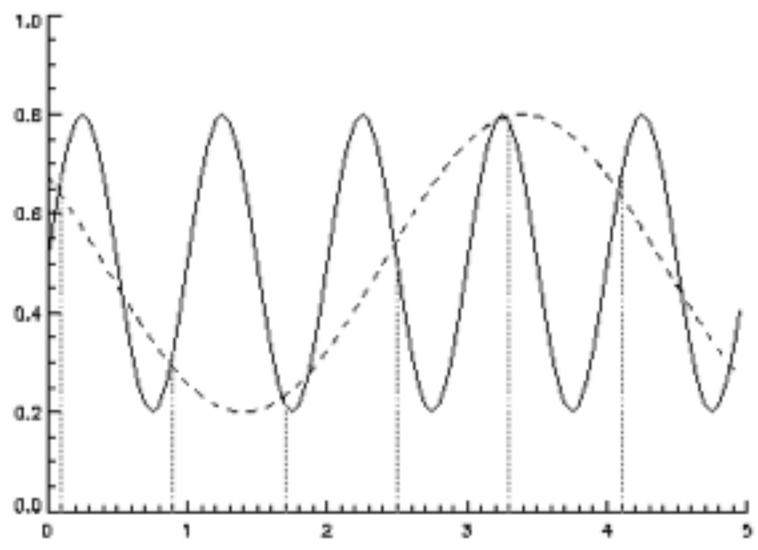


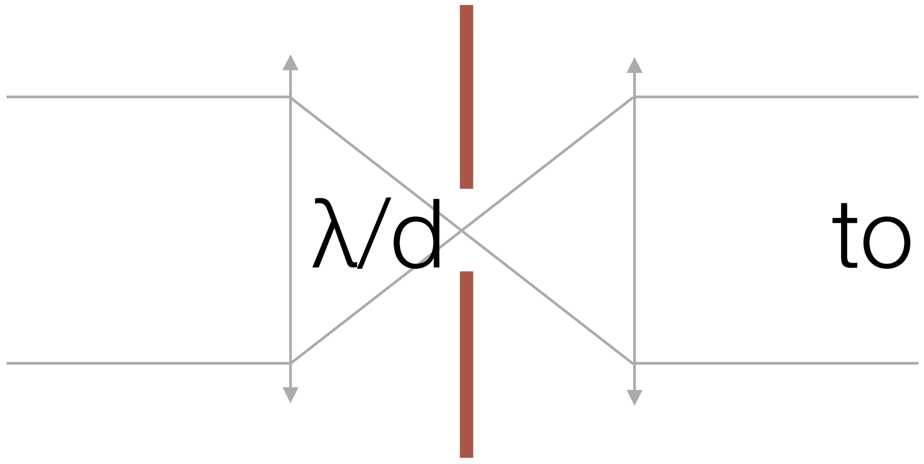


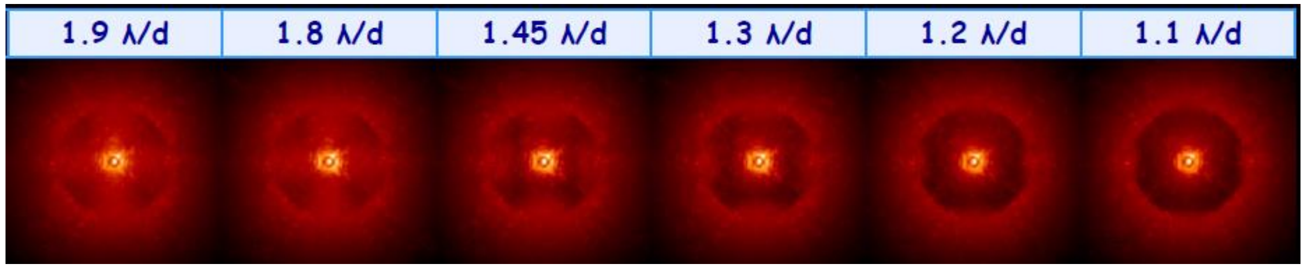


Spatial filtering for SH WFS

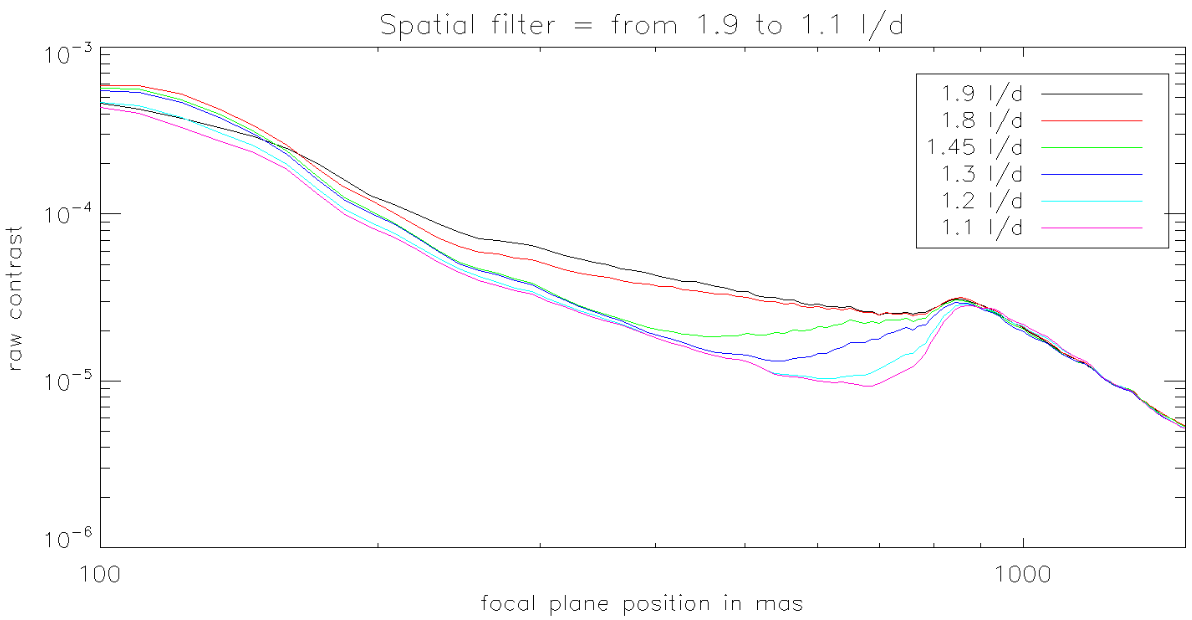
Poyneer & Macintosh 2006







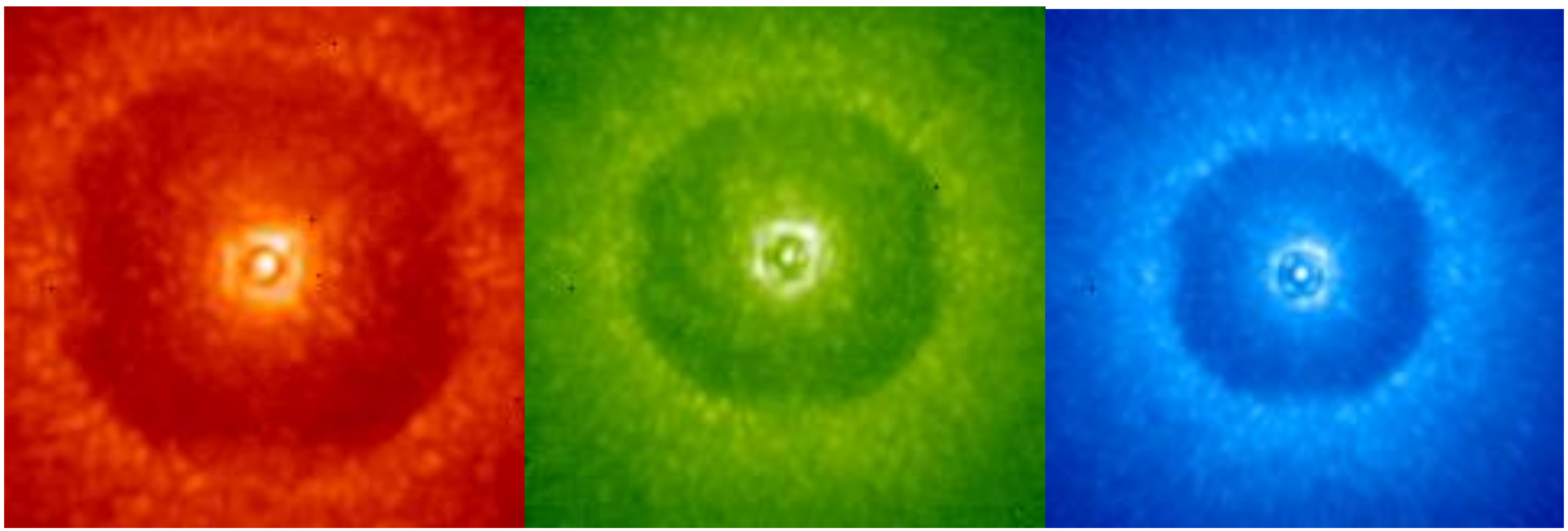
SPHERE
SF-SH on sky!



Fusco et al. 2014

Spatial filtering is critical for high contrast

Fusco et al. 2014

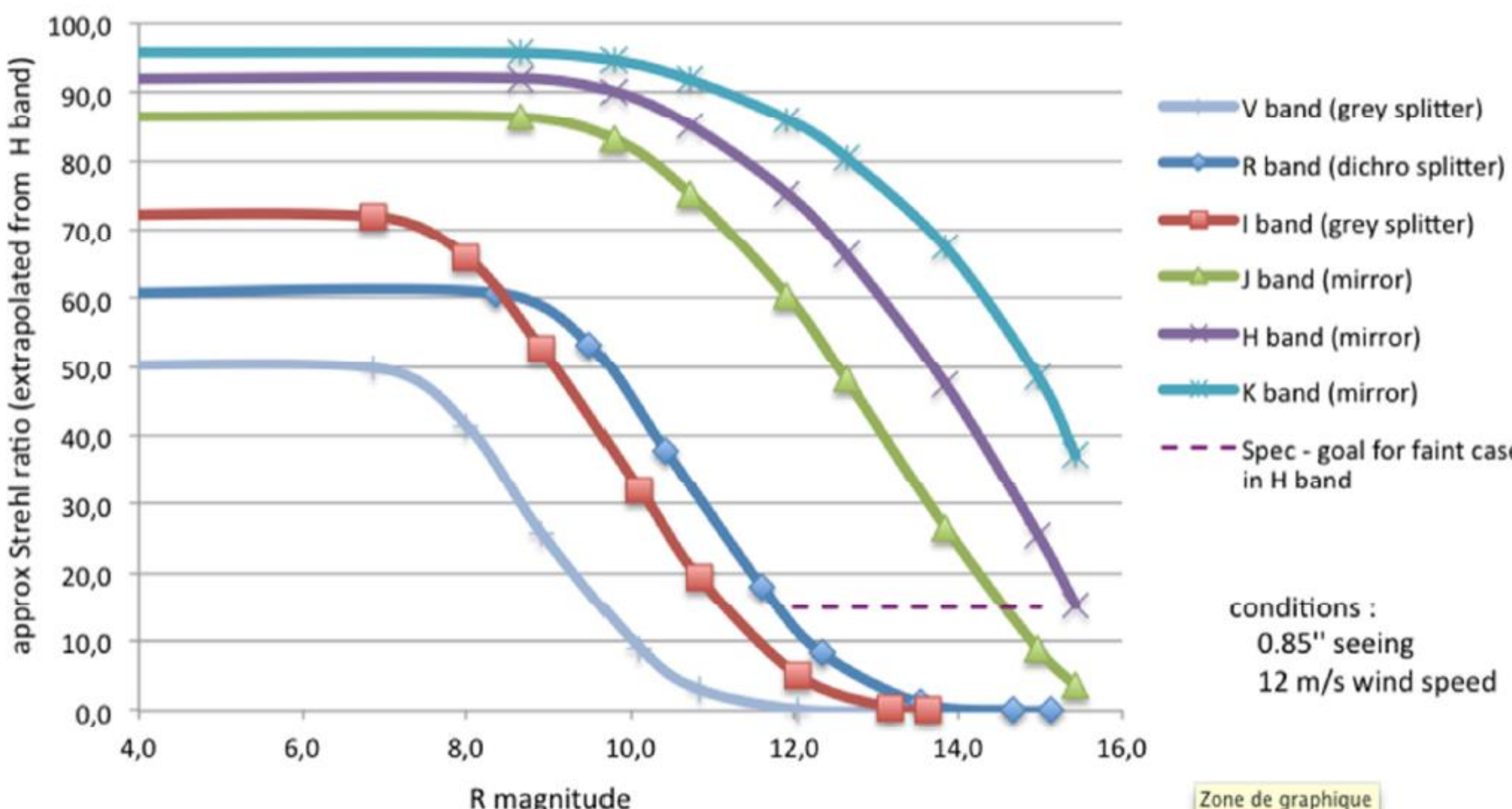


H J Y

Low-noise cameras

- EMCCD allows for very low readout noise
- Super-sensitive WFS

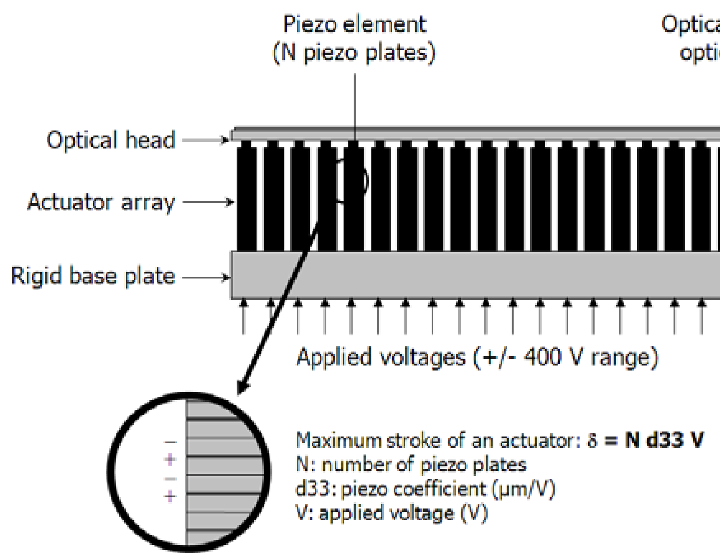
SPHERE
(verified on sky,
closed loop
on R~15.9)

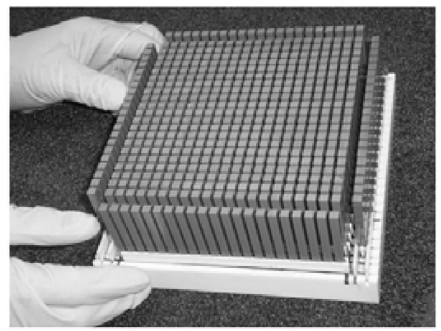


DM technology

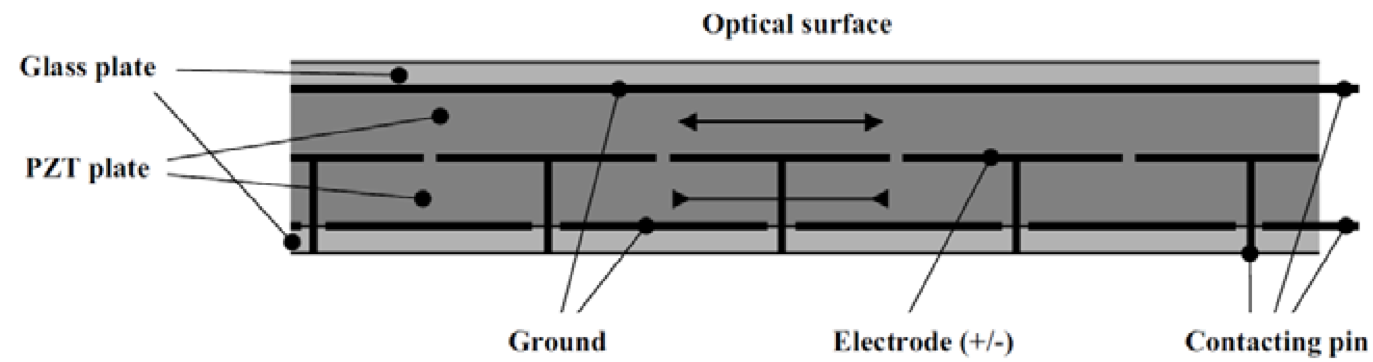
	LODM	HODM	ASM
P3K	PMN, Xinetics (241)	PMN, Xinetics (3k)	
LBT			Voice coil (672)
MagAO			Voice coil (585)
SCExAO	Bimorph (188)	MEMS, BMC (2k)	
GPI	PZT, CILAS (97)	MEMS, BMC (2k)	
SPHERE		PZT, CILAS (1.6k)	

Stacked array electrostrictive effect (PMN, PZT)

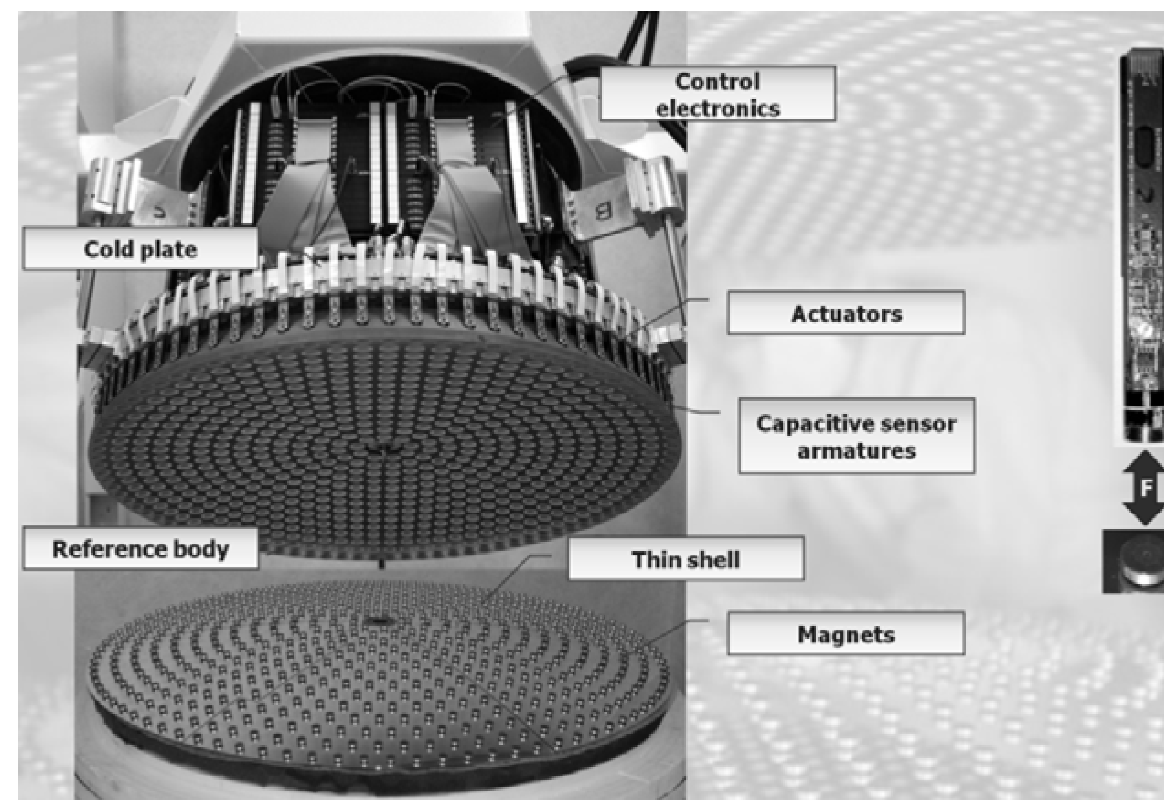




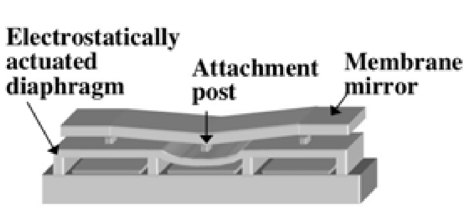
Bimorph lateral electrostrictive

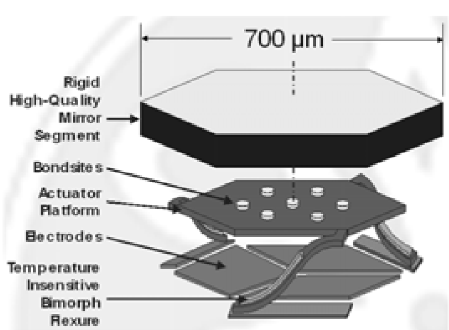


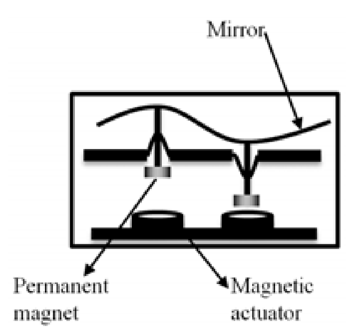
Voice coil Magnetic



MEMS (electro/magneto)

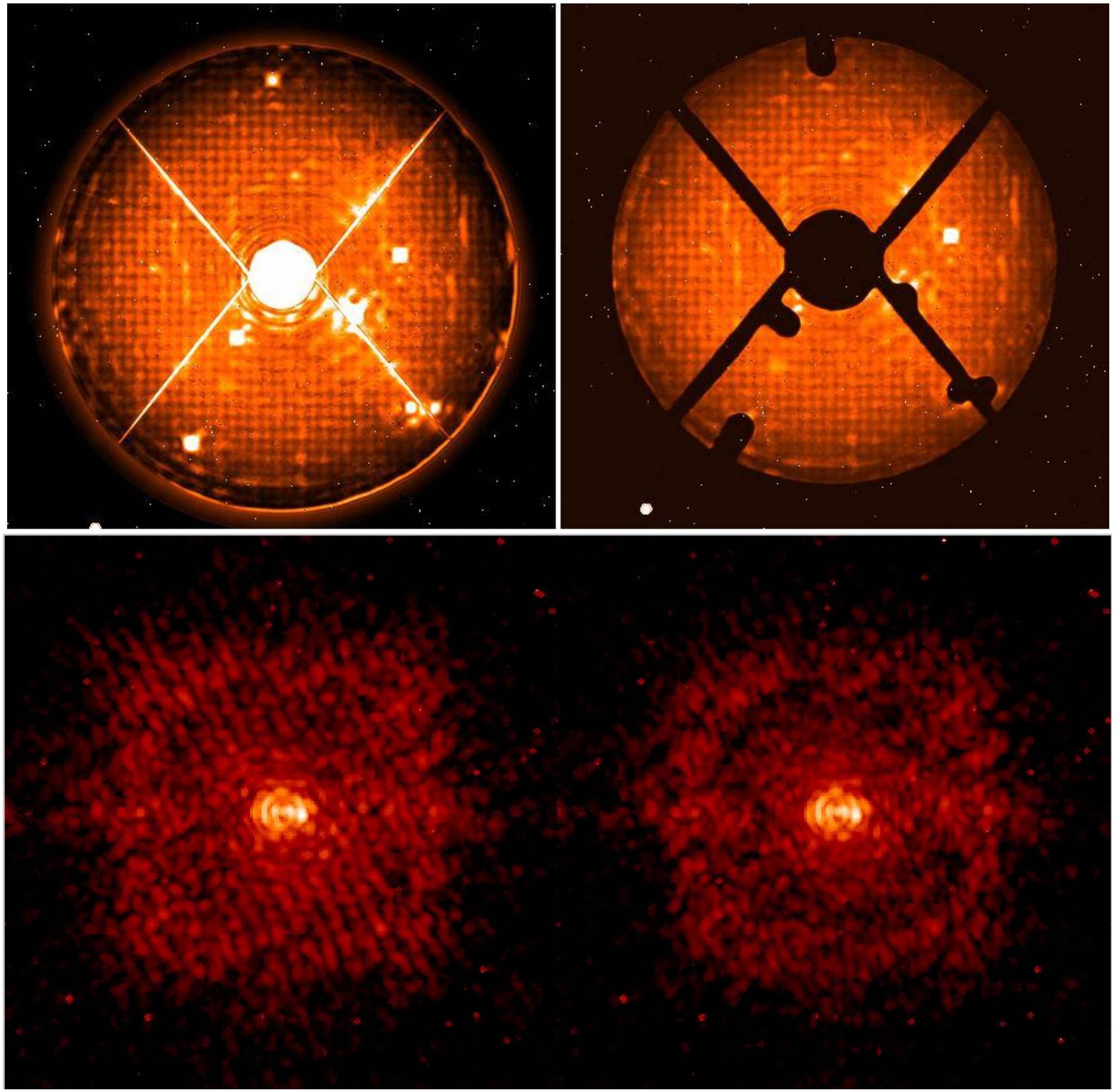




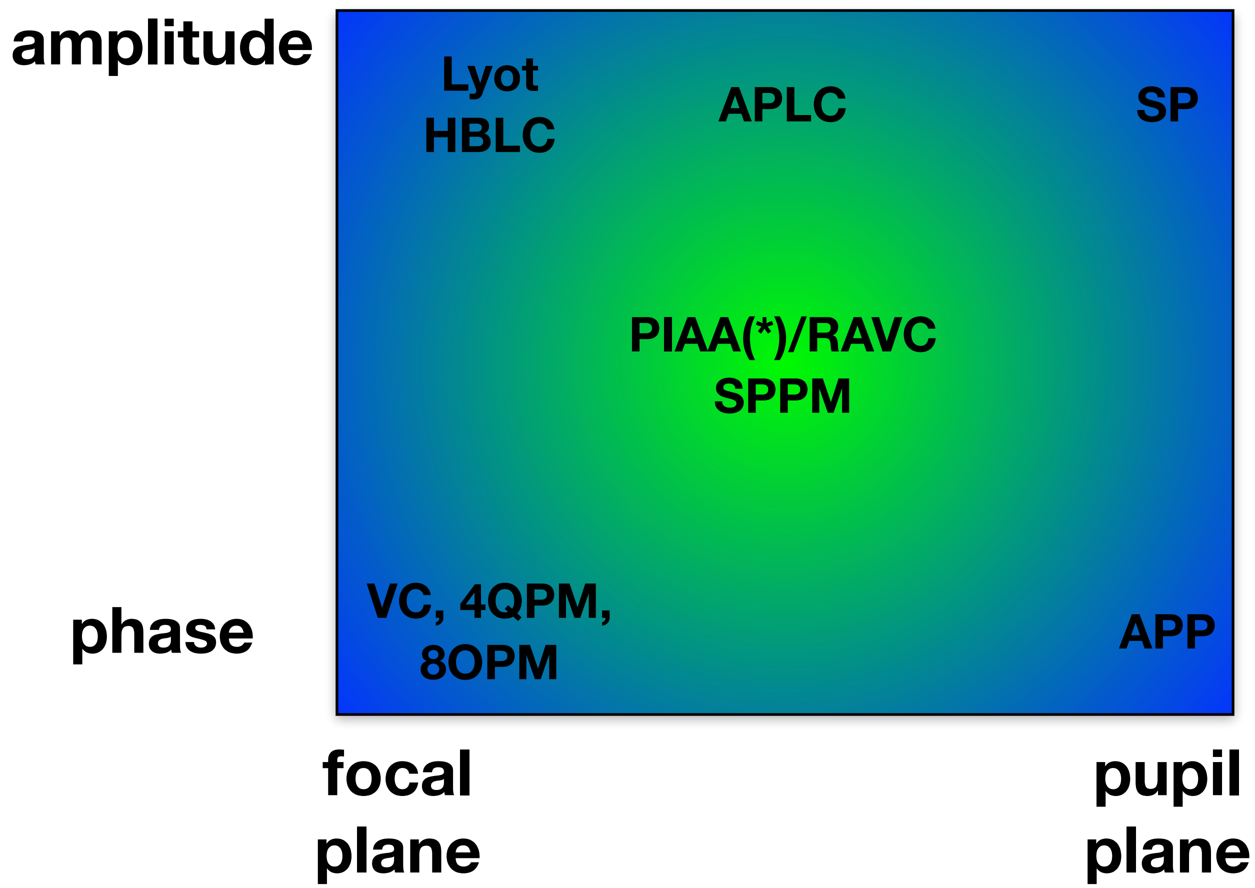


Madec et al. 2012

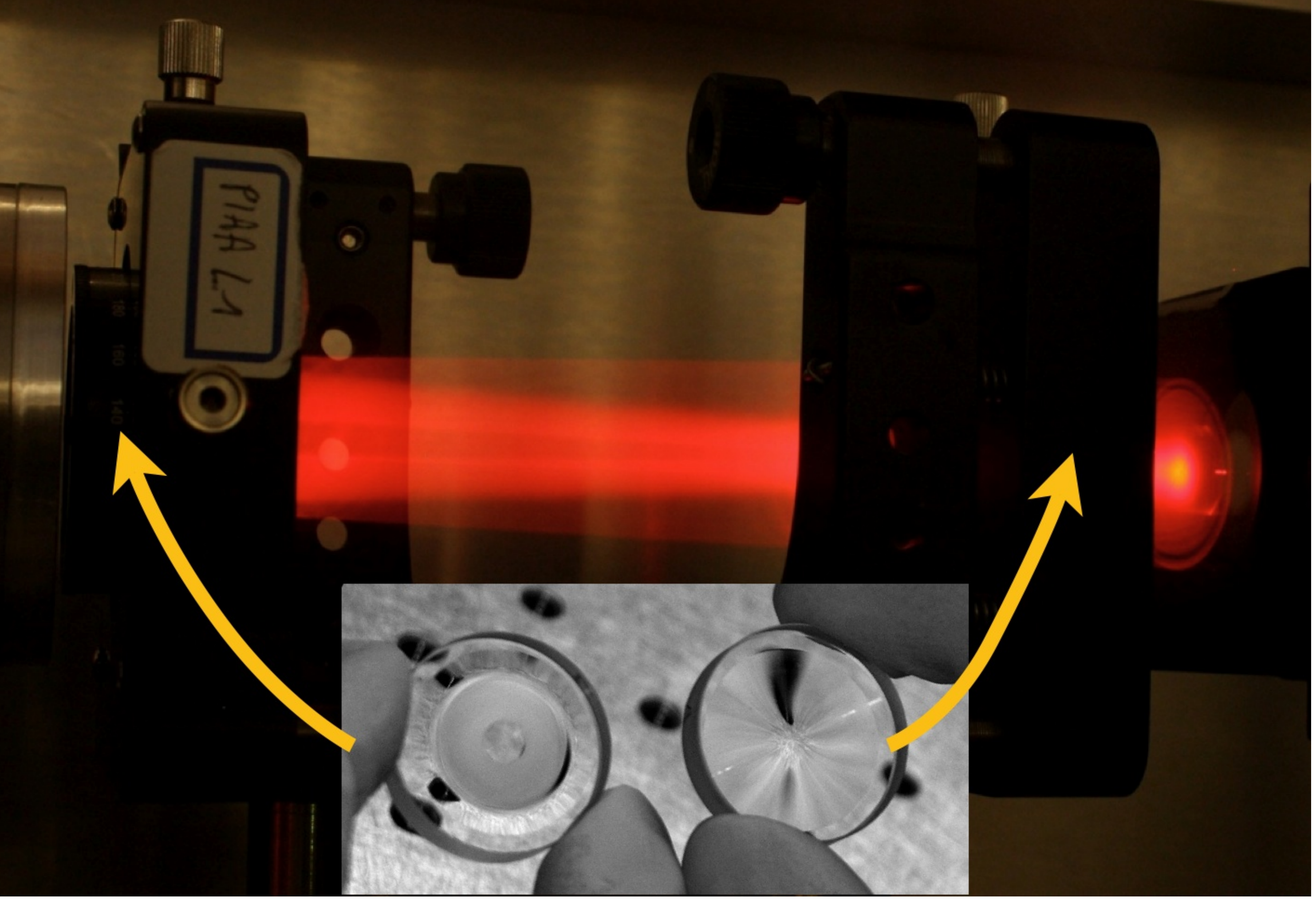
Dead actuators are contrast killers

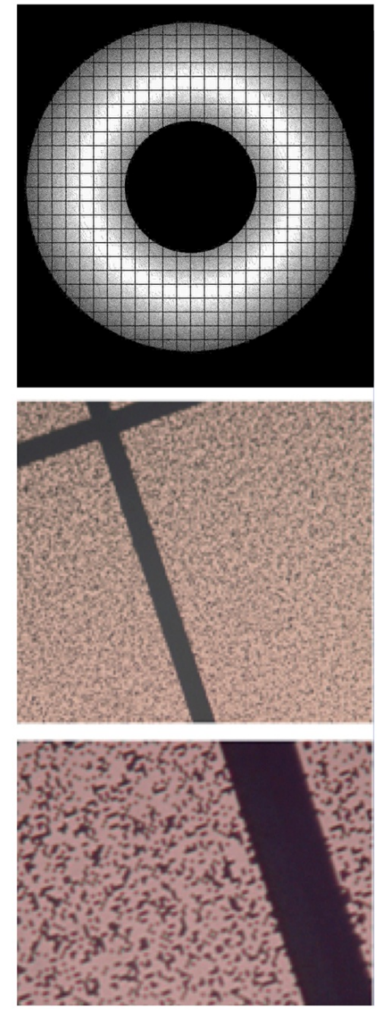


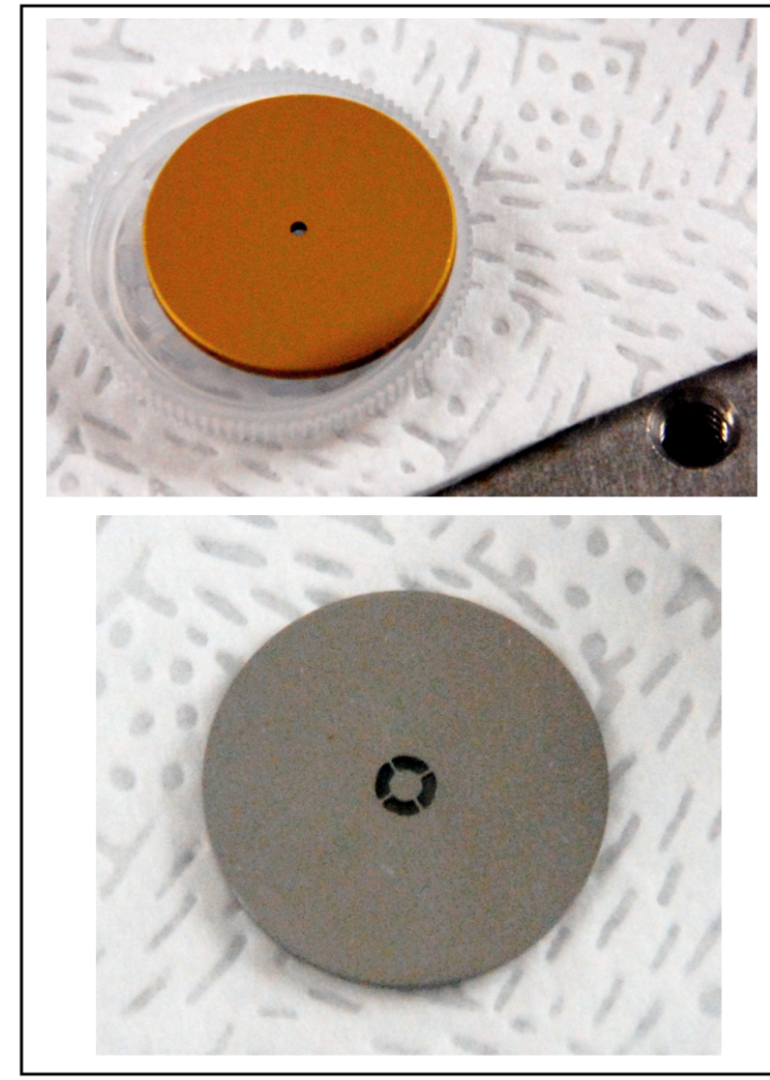
Coronagraph choices

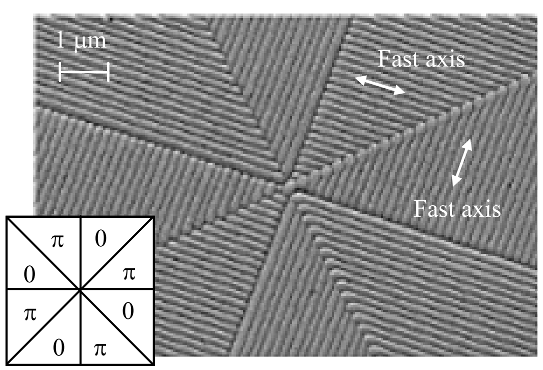


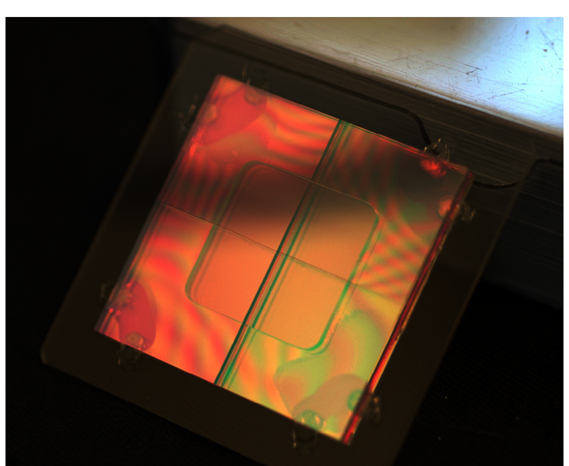
	Lyot	APLC	SP	4QPM/8OPM	(RA)VC	PIAA	APP
P3K	PHARO	P1640			(SDC)/ PHARO		
LBT					LMIRCAM		LMIRCAM
MagAO							Clio2
SCExAO			x	x	x	x	
GPI		x					
SPHERE	x	x		x			

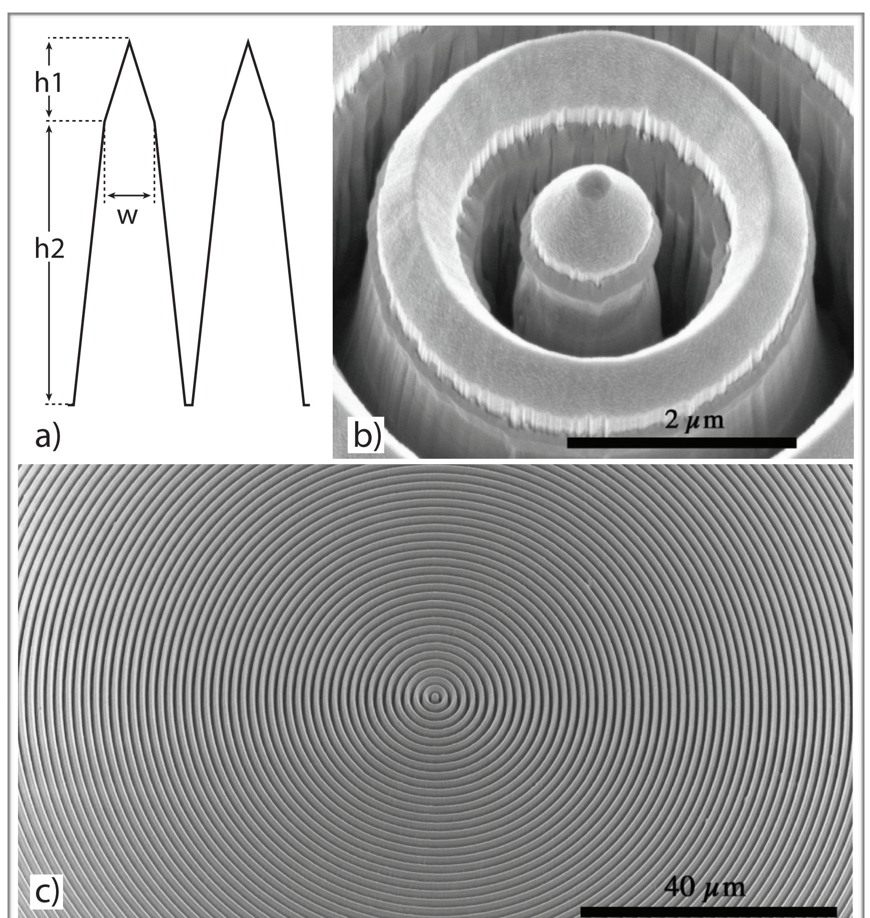


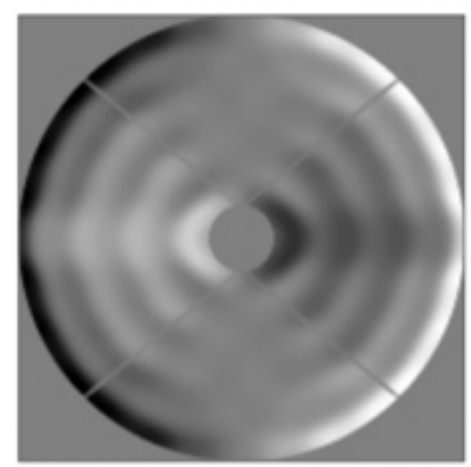


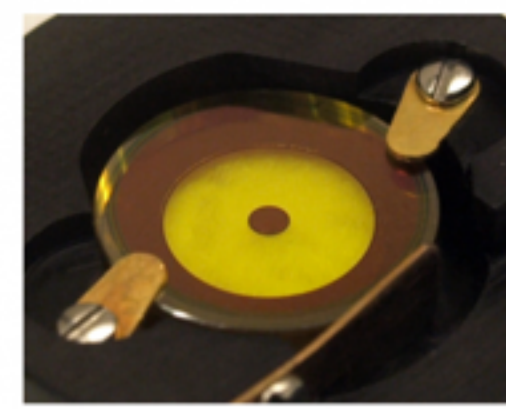


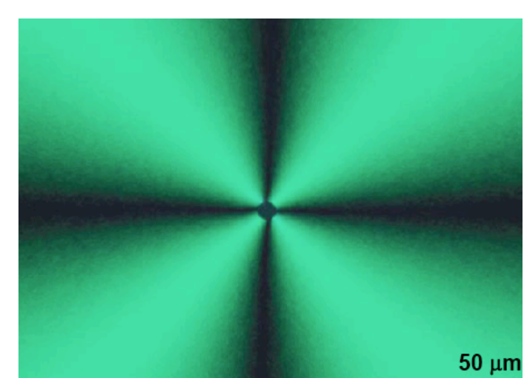






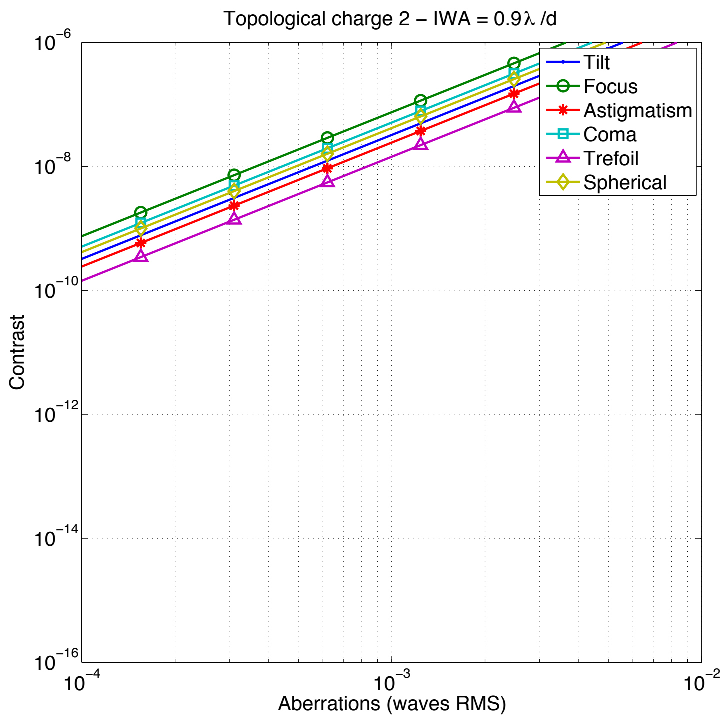




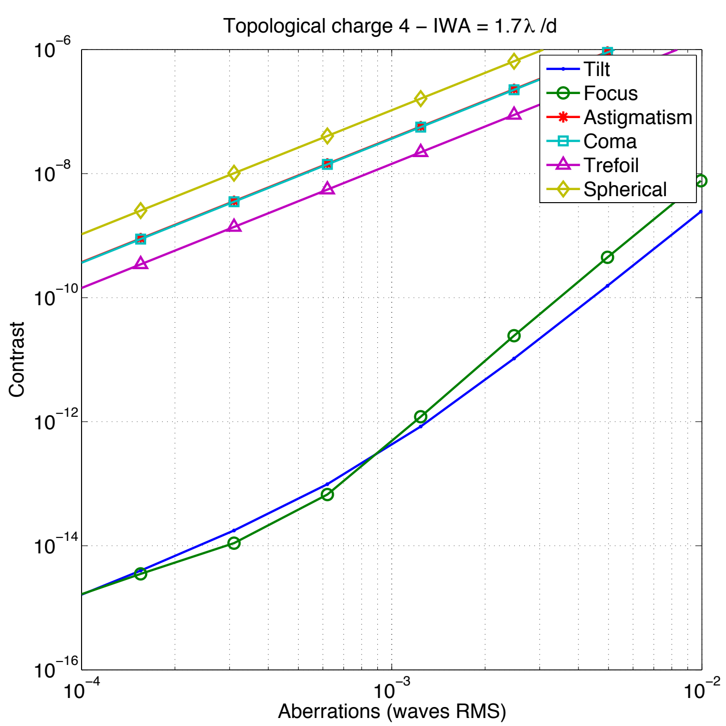


CoronAgraphs

2nd order coronagraphs (very small IWA): VC2 / 4QPM / PIAA



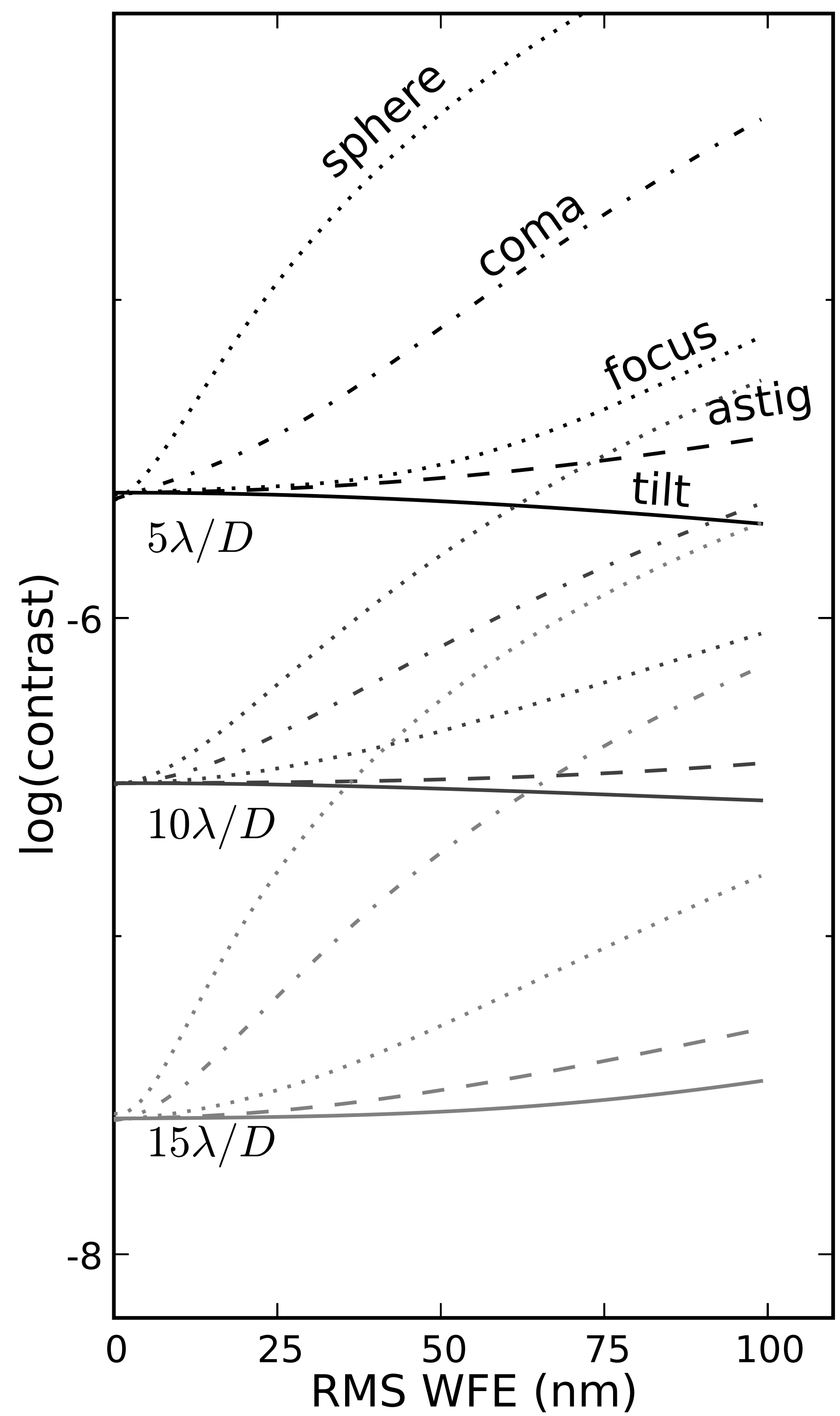
4th order coronagraphs: BL4 / VC4 / PIAA*



Mawet et al. 2010

APLC

Sivaramakrishnan et al.

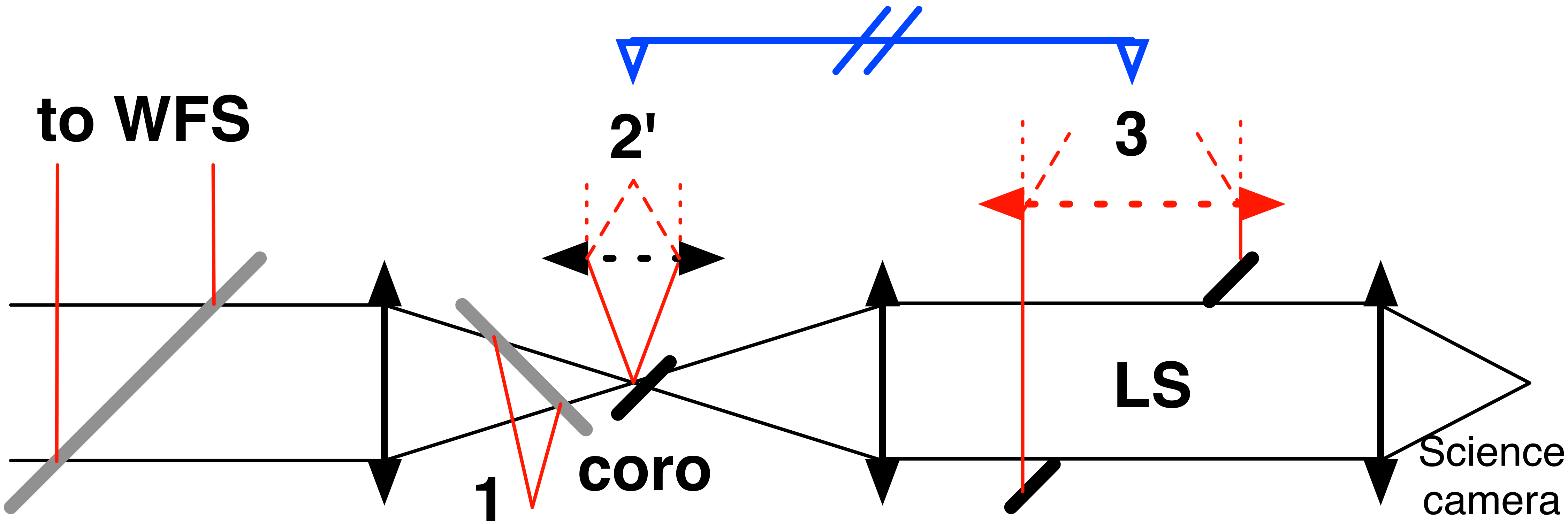


SP and APP insensitive to tip-tilt

Spec: 10^{-2} λ

Goal: 10^{-3} λ

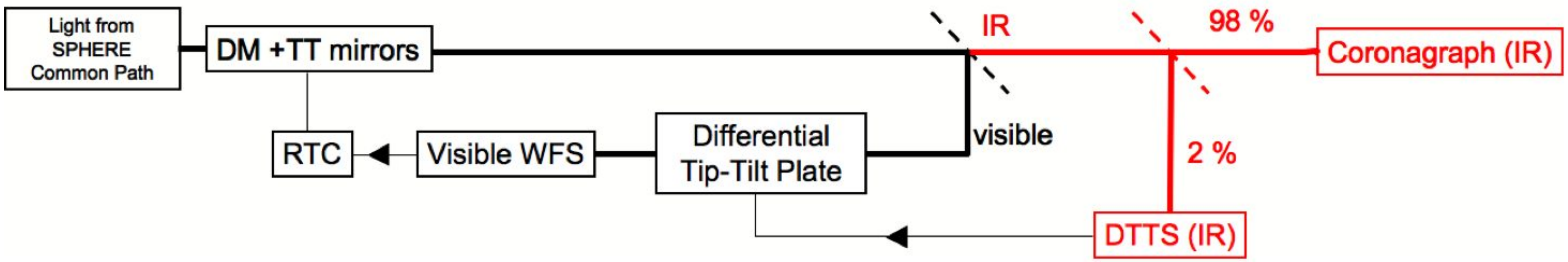
Low Order Wavefront Sensor (LOWFS)

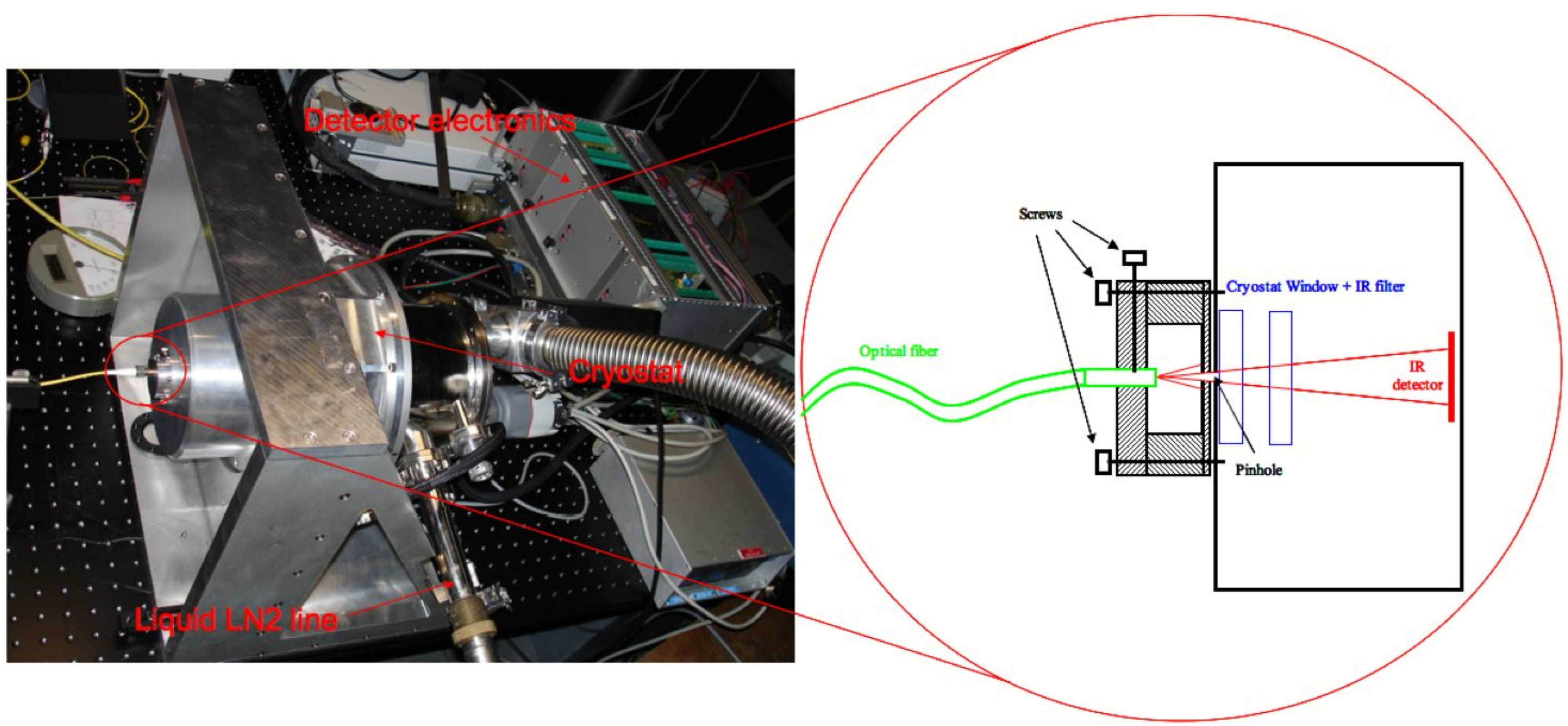


- P3K: CAL (P1640) + pseudo-SCC (SDC) — 3
- GPI: CAL — 2’-3
- SCExAO: CLOWFS, LSLOWFS — 2’ and 3
- SPHERE: DTTS, PTTS — 1
- LBT/MAgAO: NA

SPHERE DTTS

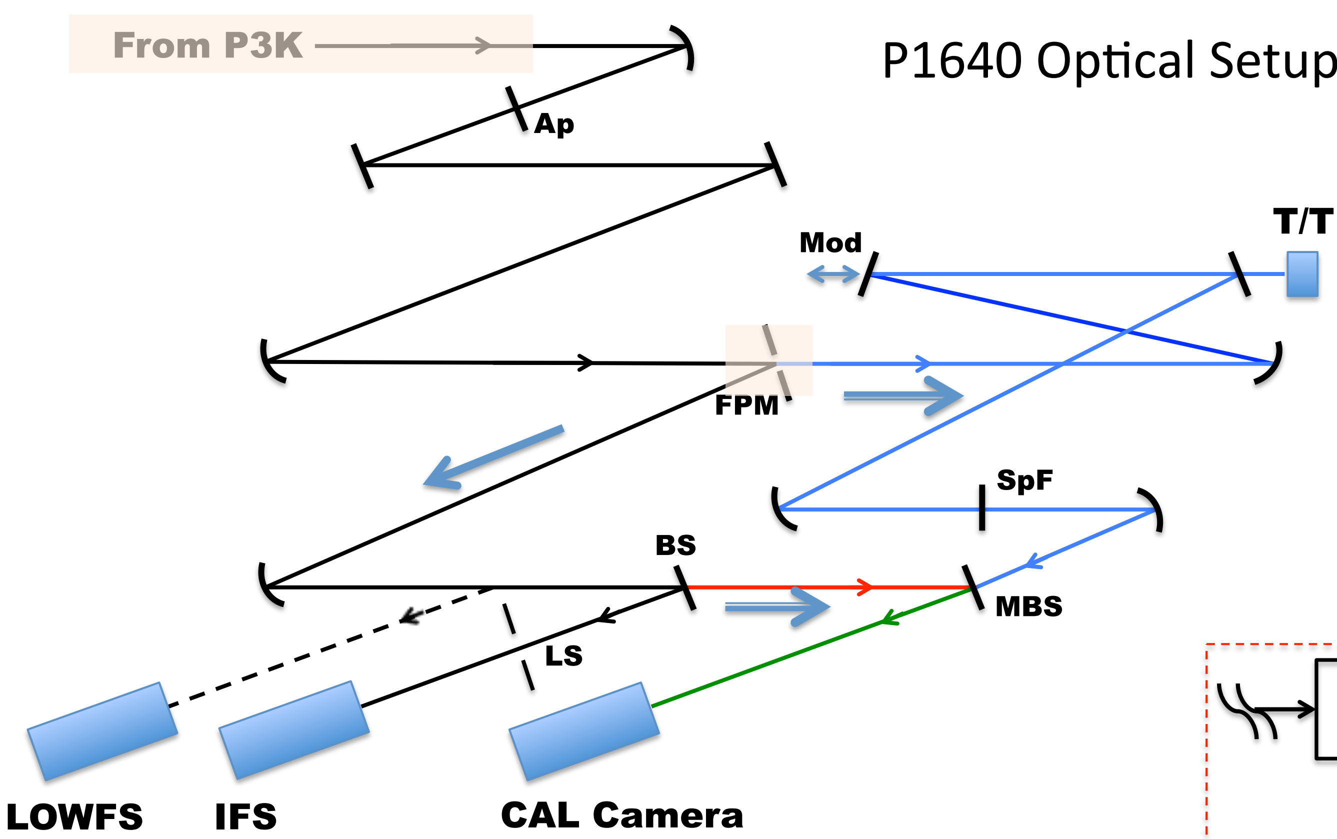
Baudoz et al.

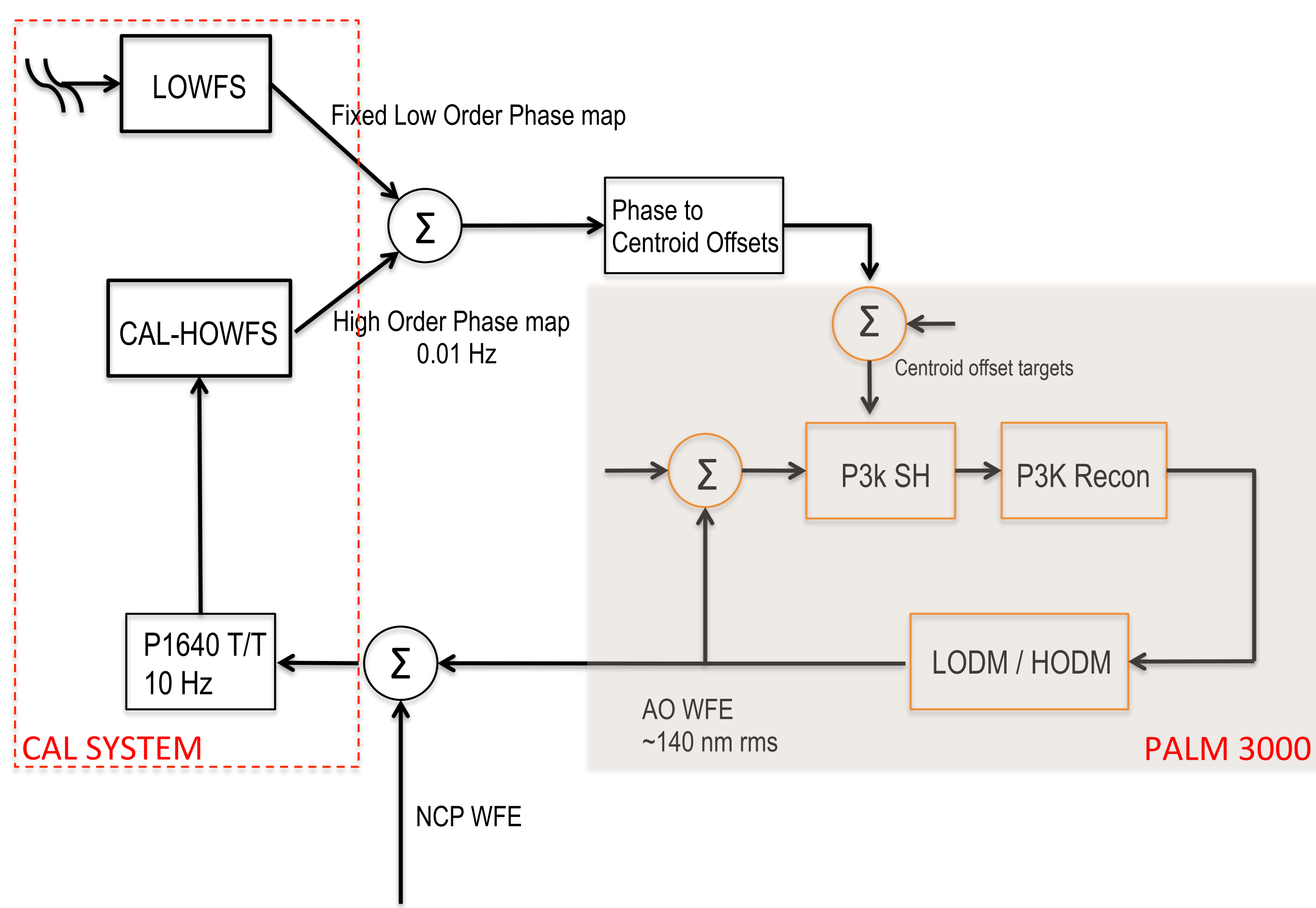




P1640 CAL system

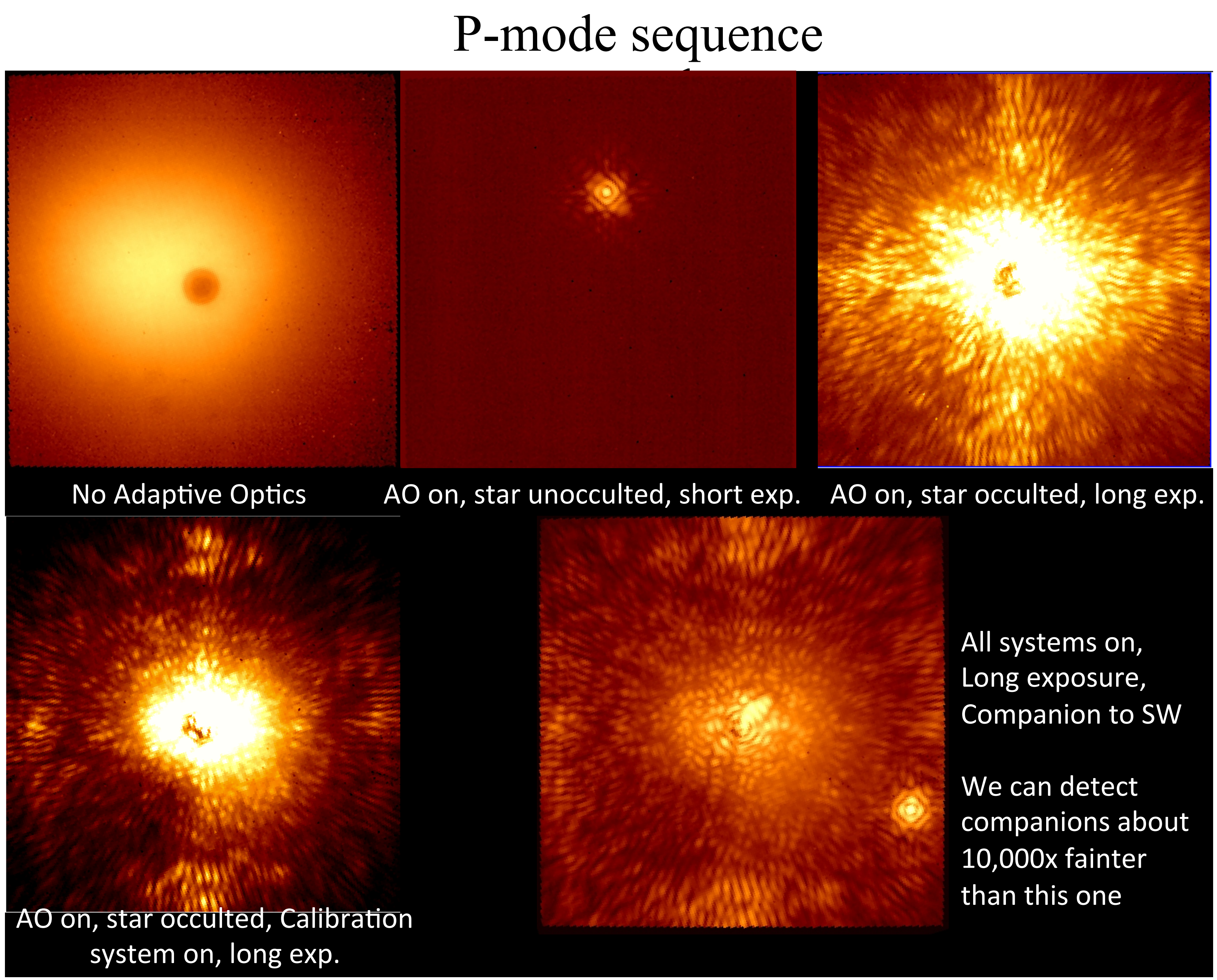
Vasisht et al.





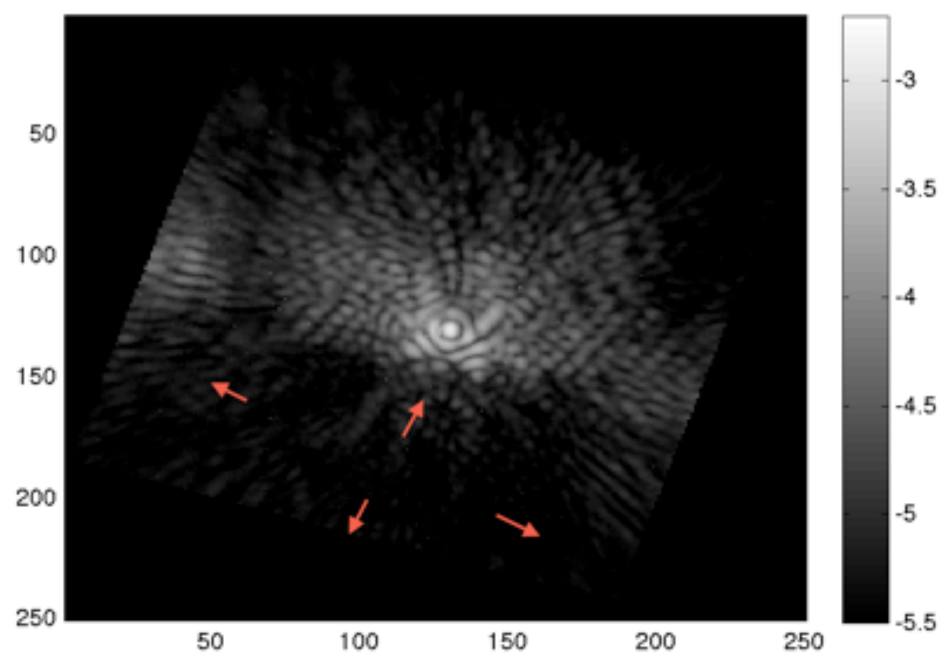
P1640 CAL system in action

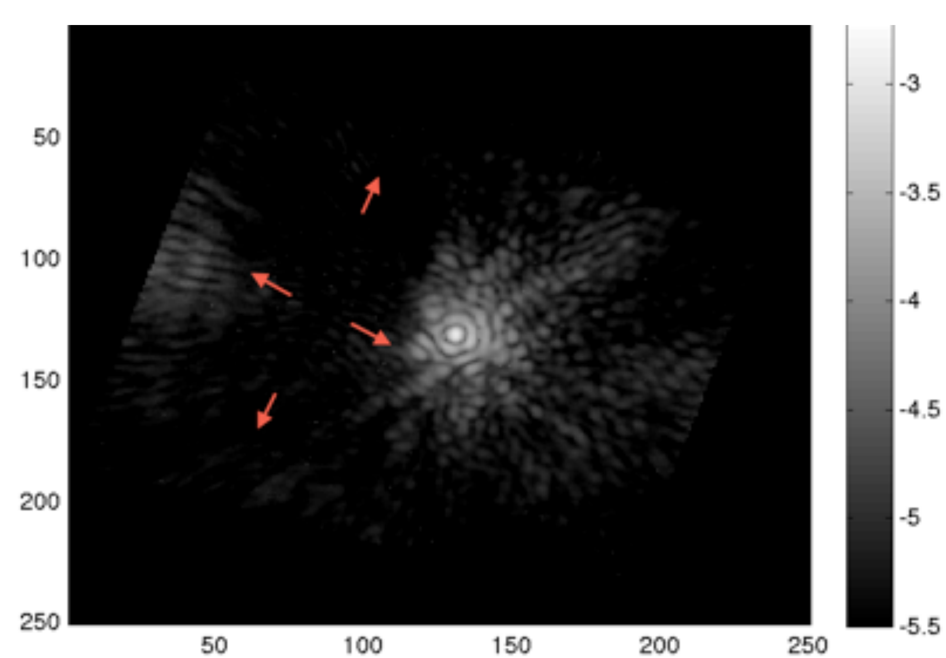
Vasisht et al.

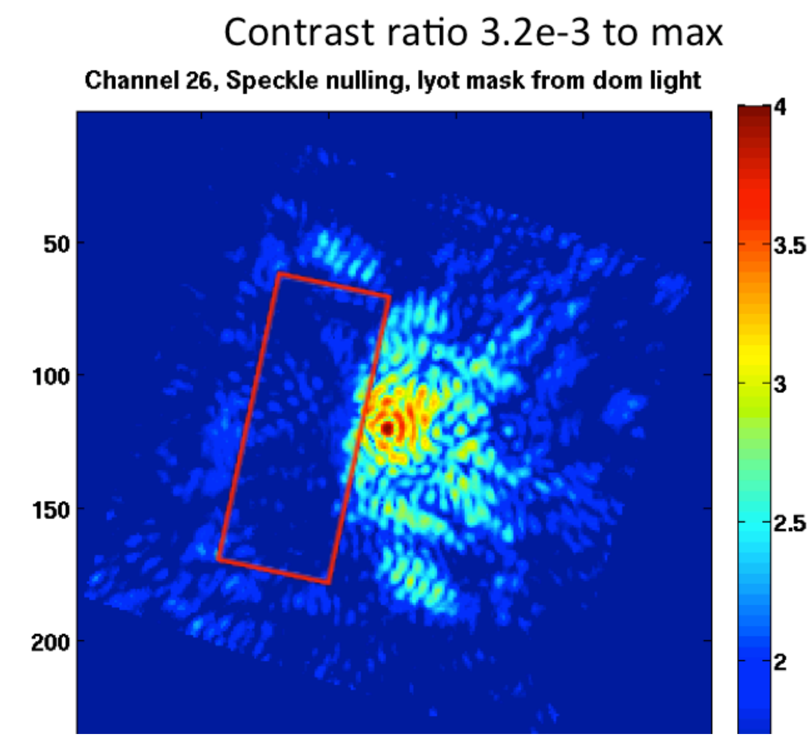


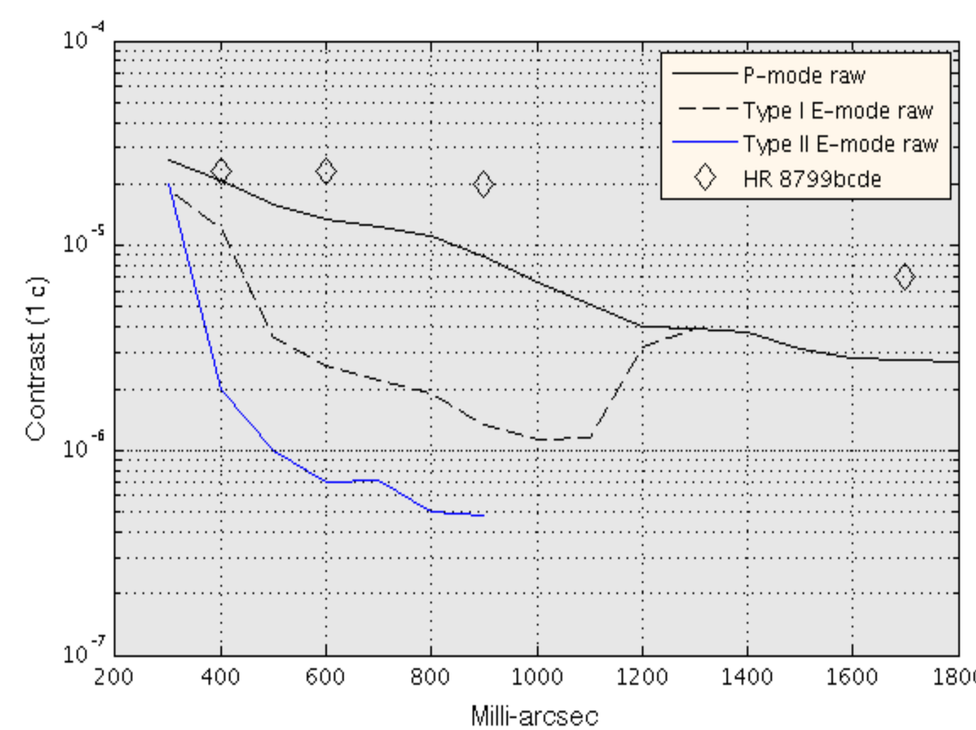
P1640 CAL system doing E-field correction

Vasisht et al.



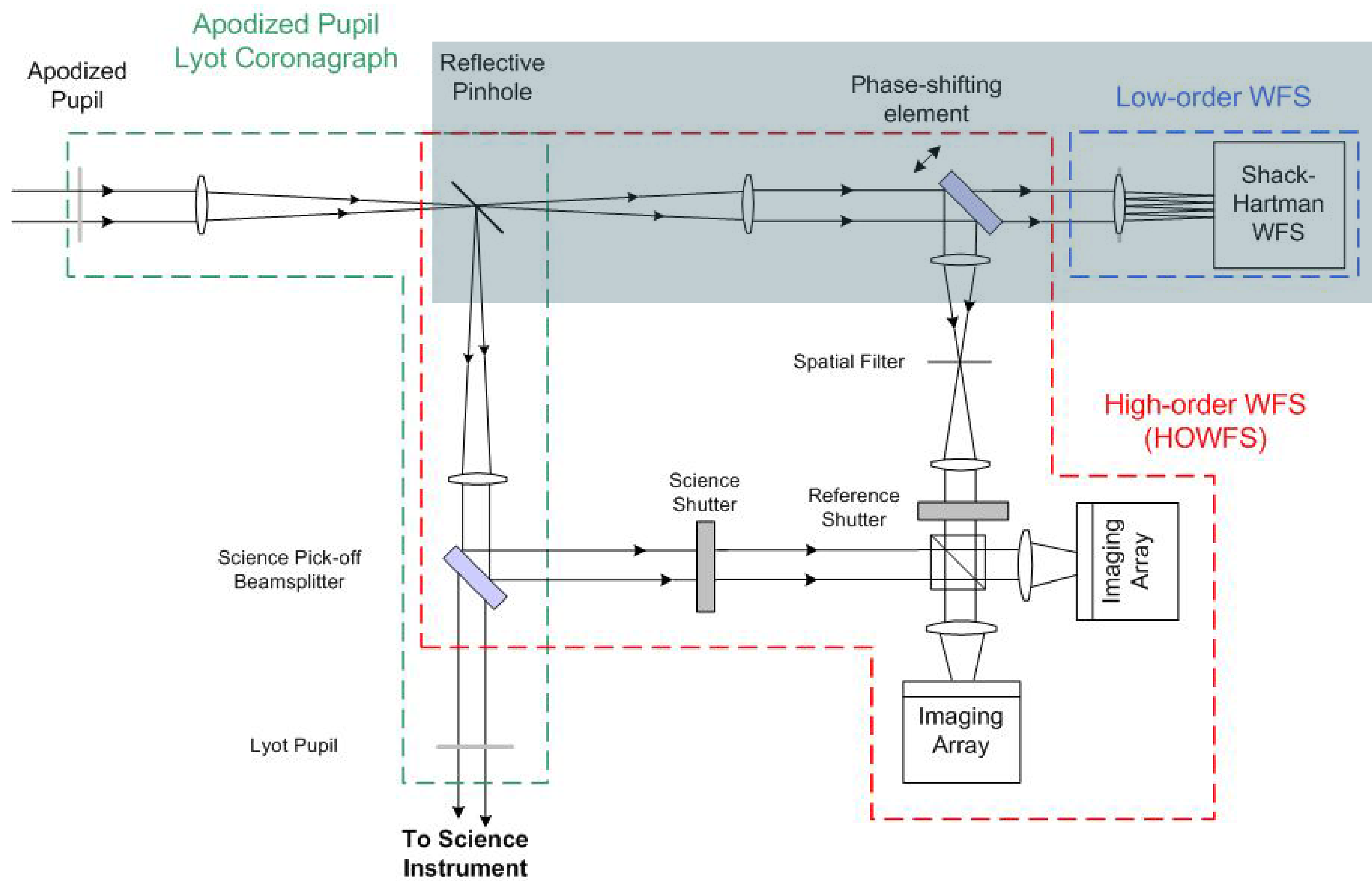






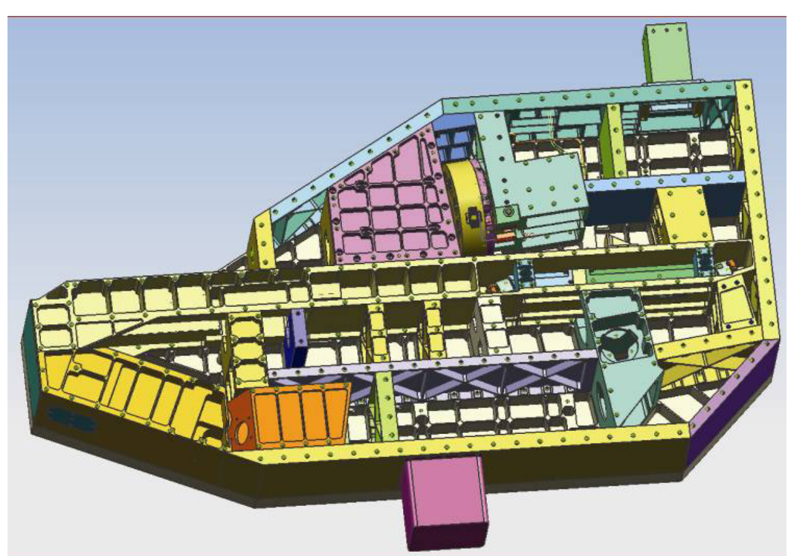
GPI CAL system

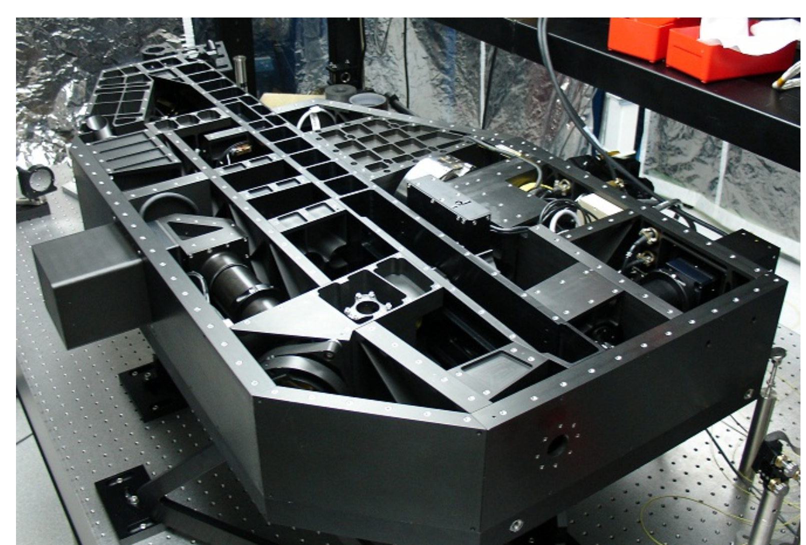
Wallace et al.



Only this part
is currently being used

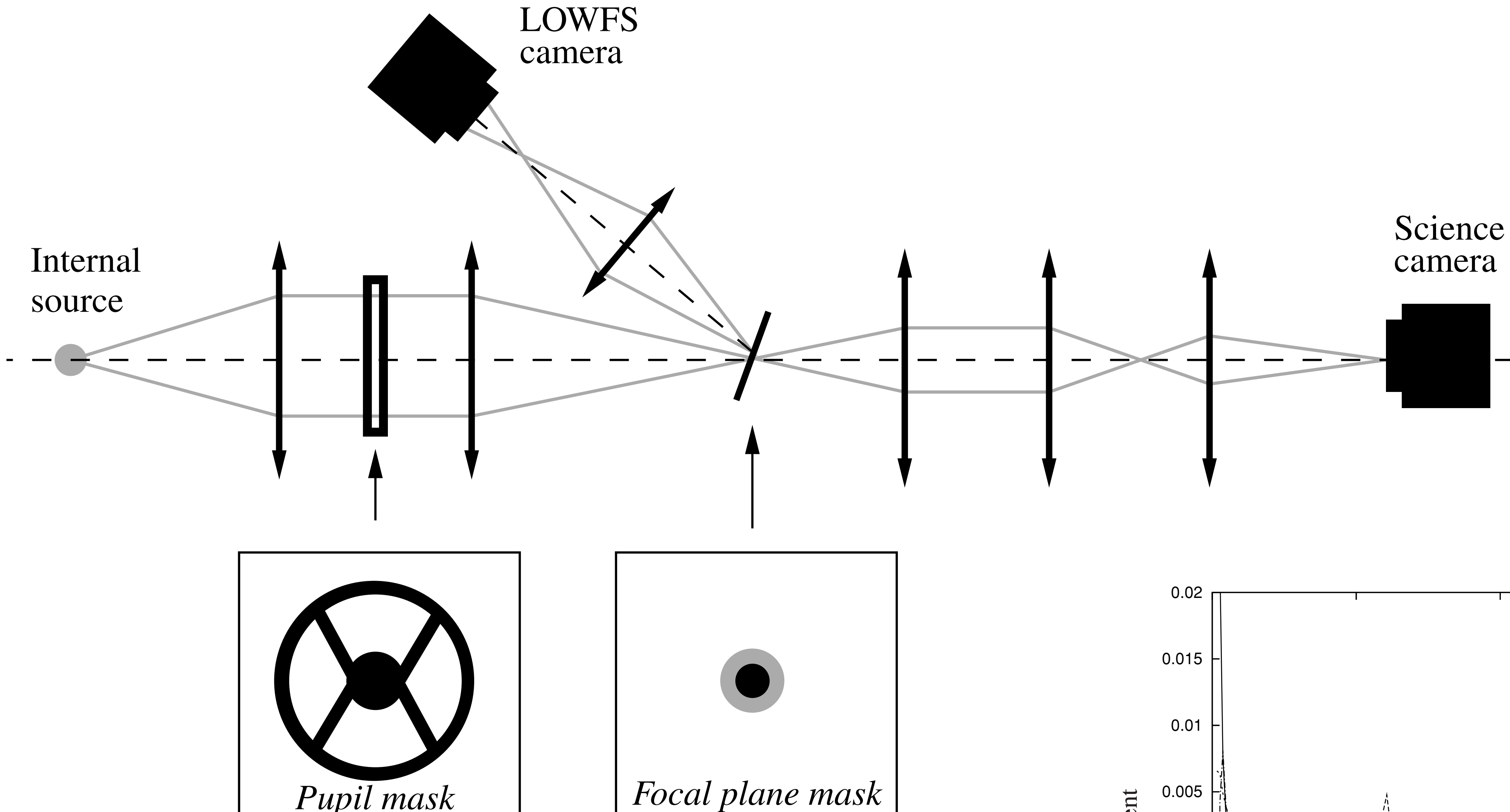
HOWFS to be commissioned



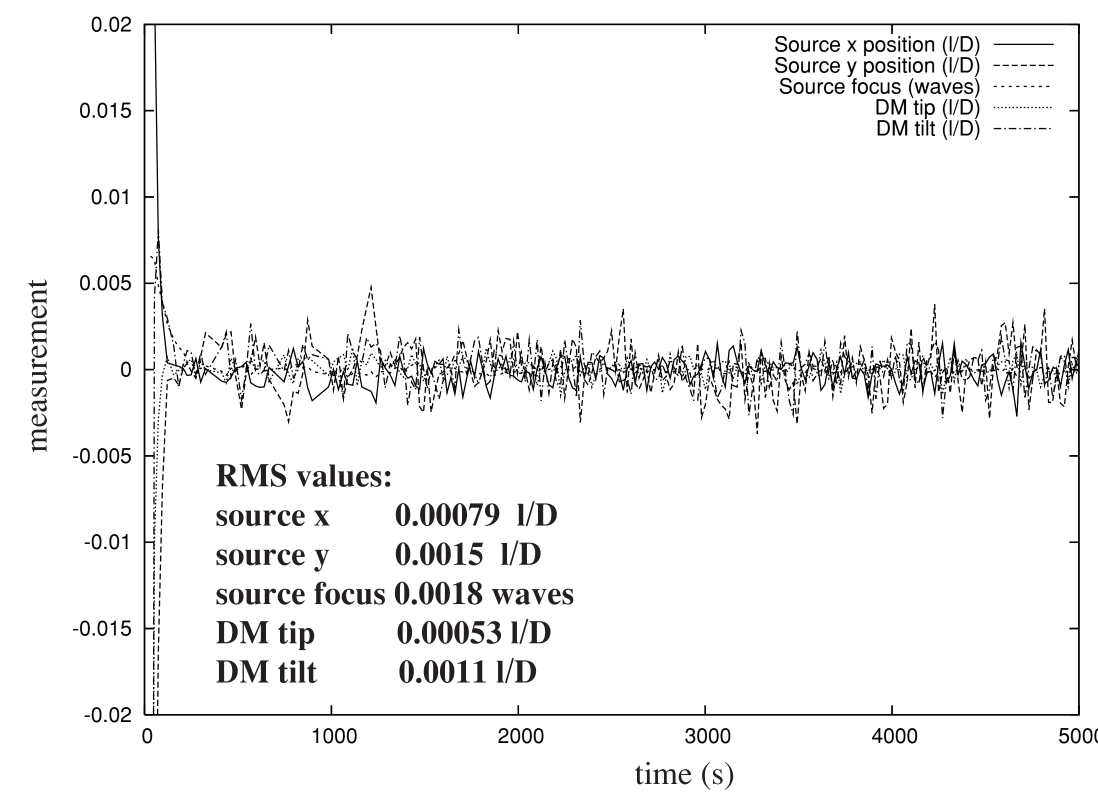


SCExAO LOWFS, option I

Guyon et al. 2009



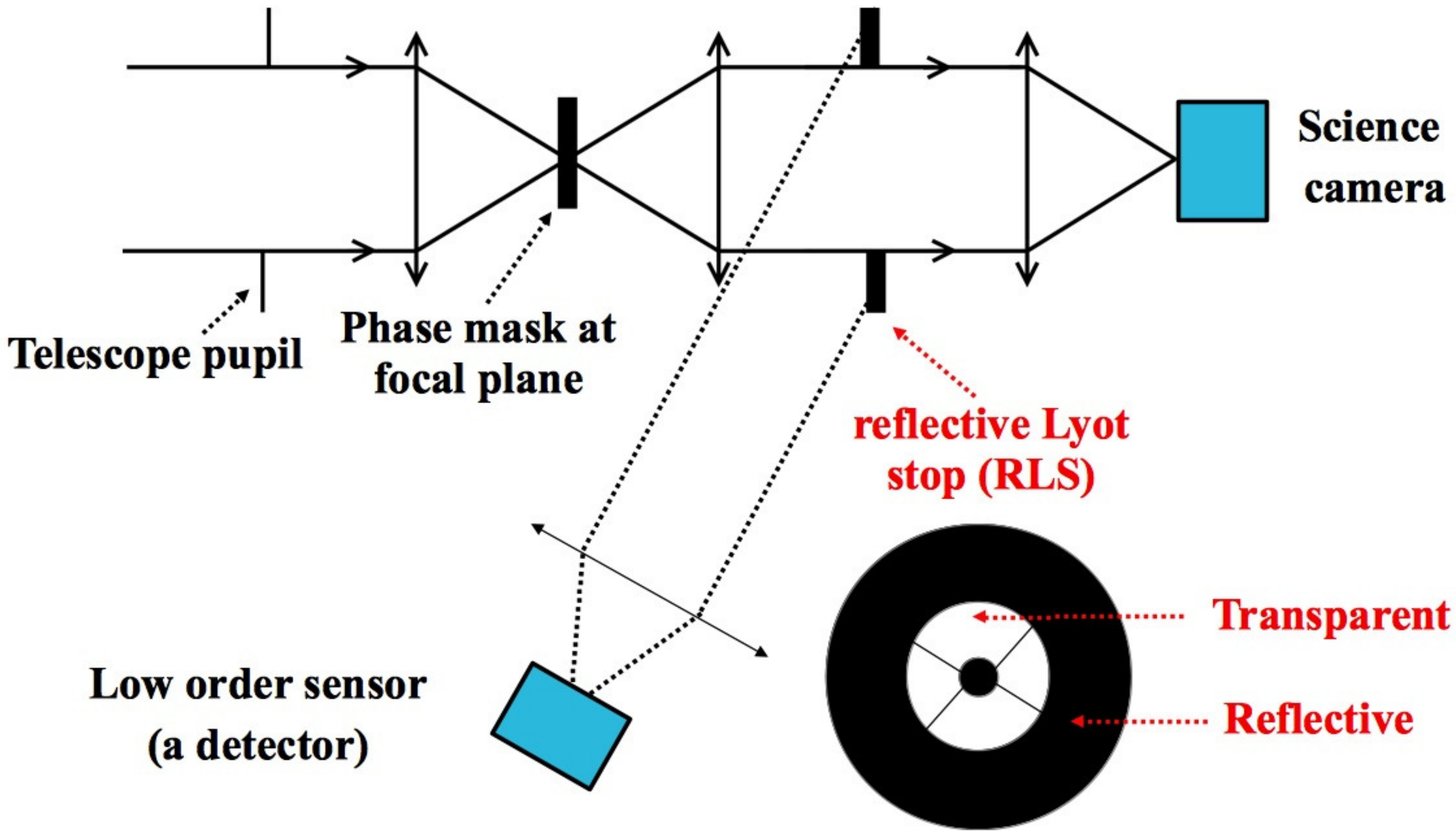
Note: reflection from the spot can be used from any reflective masks



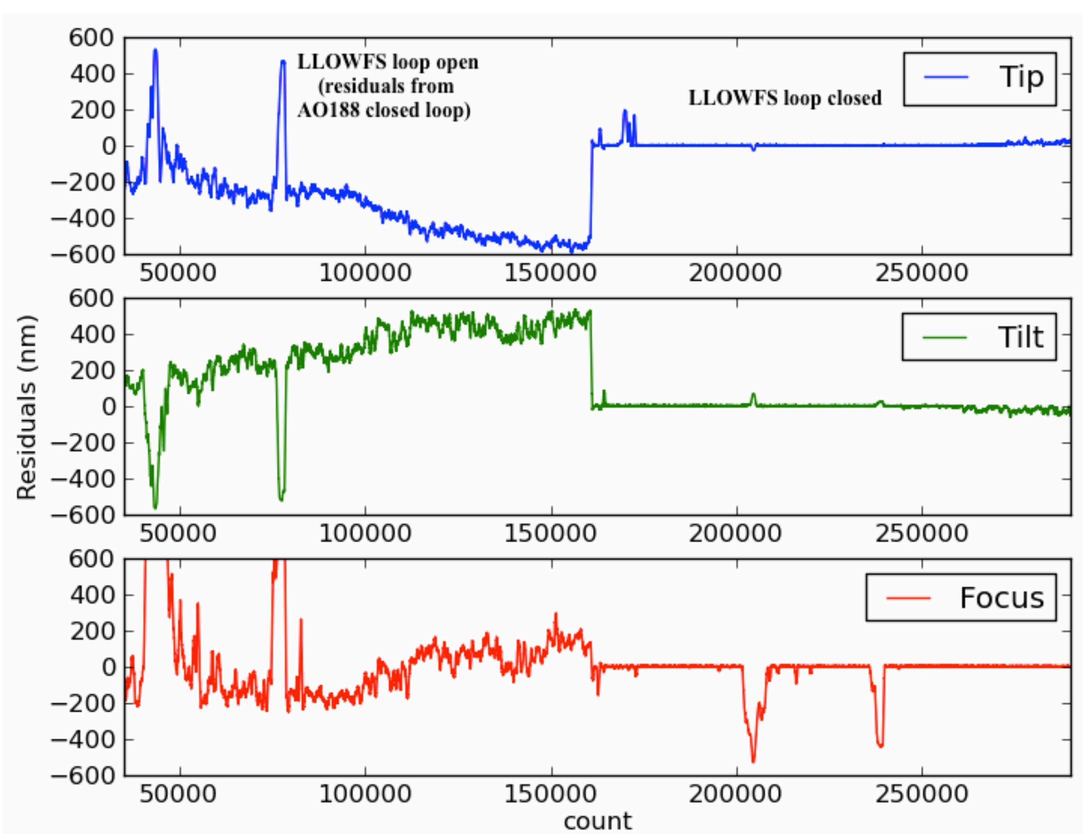
G. Singh
POP/Poster

SCExAO LOWFS, option II

Singh et al. 2014



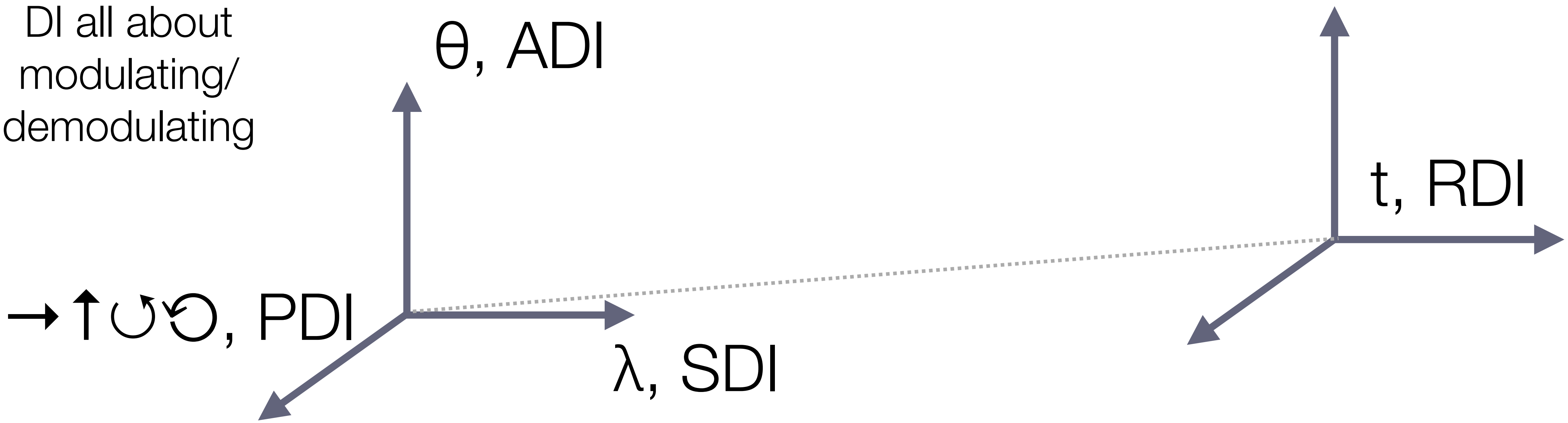
~0.01 λ/D in the lab
closing loop on sky with VVC



Differential imaging techniques and corresponding data reduction methods

See Laurent's talk
"Overview of Data Reduction Methods"
+ Tuesday hands-on session

DI all about modulating/ demodulating

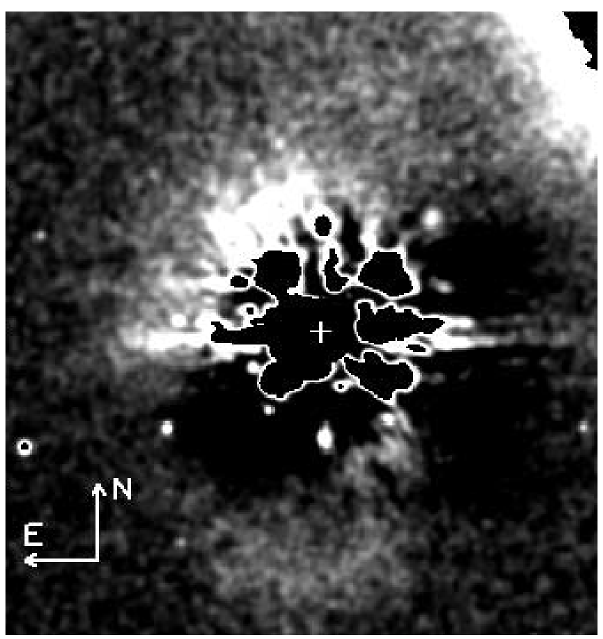


	RDI	ADI	SDI-IFS	SDI-DBI	PDI	CDI
P1640	x		x			x
LBT	x	x				
MagAO	x	x		x		
SCExAO	x	x	x(*)			x
GPI	x	x	x		x	
SPHERE	x	x	x	x	x	

Performance and early science results

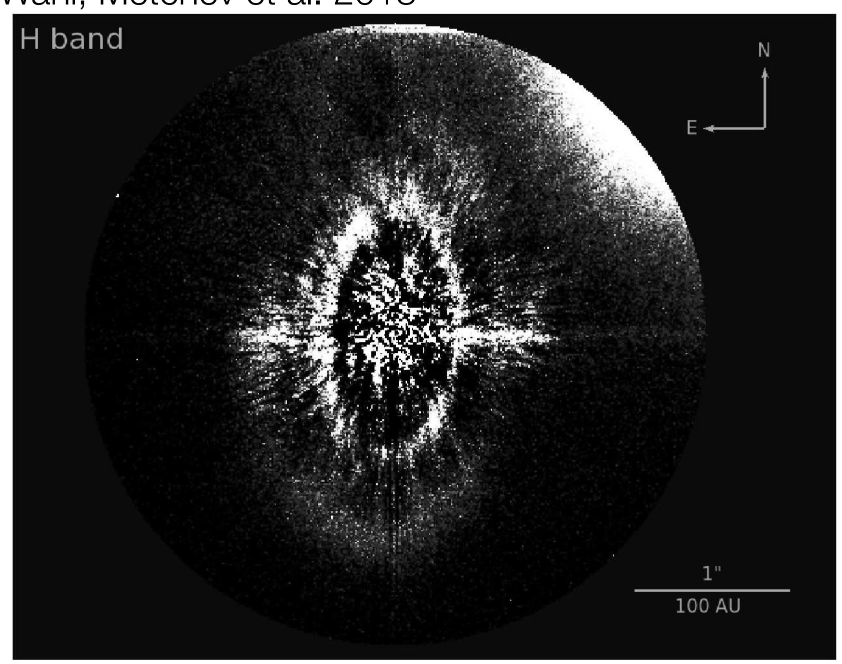
10 years of progress pioneered at Palomar

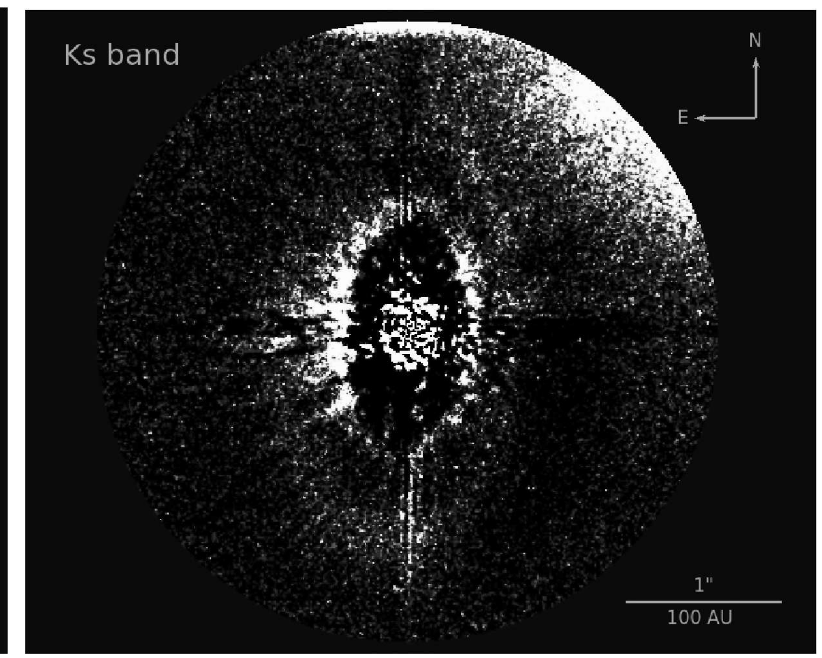
Boccaletti et al. 2003



PALAO

Wahl, Metchev et al. 2013





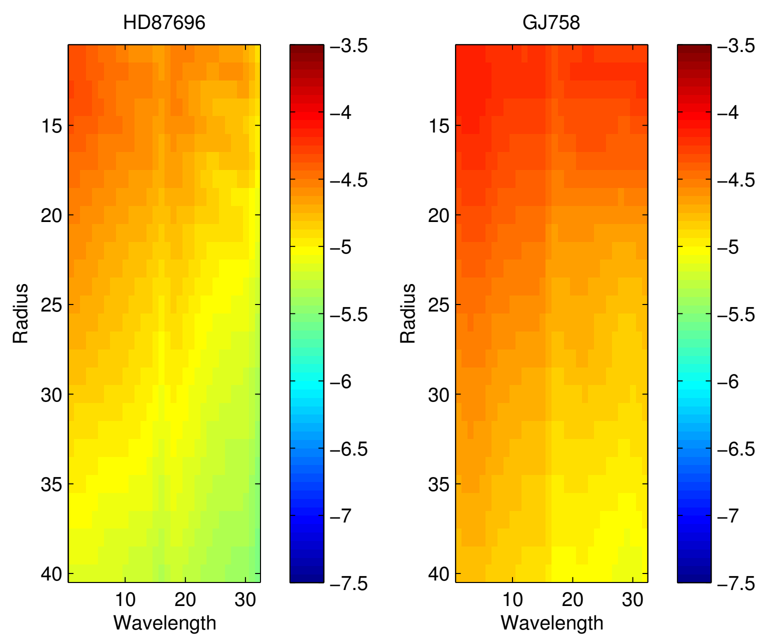
P3K

See Aaron Veicht,
Ricky Nilsson,Jonathan Aguilar
POP/POSTER

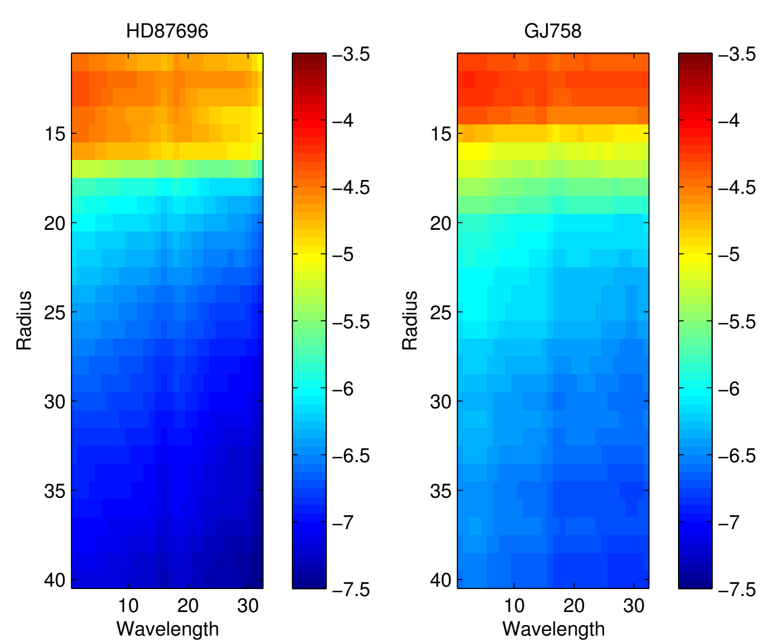
P3K-P1640, the first XAO - IFS on sky

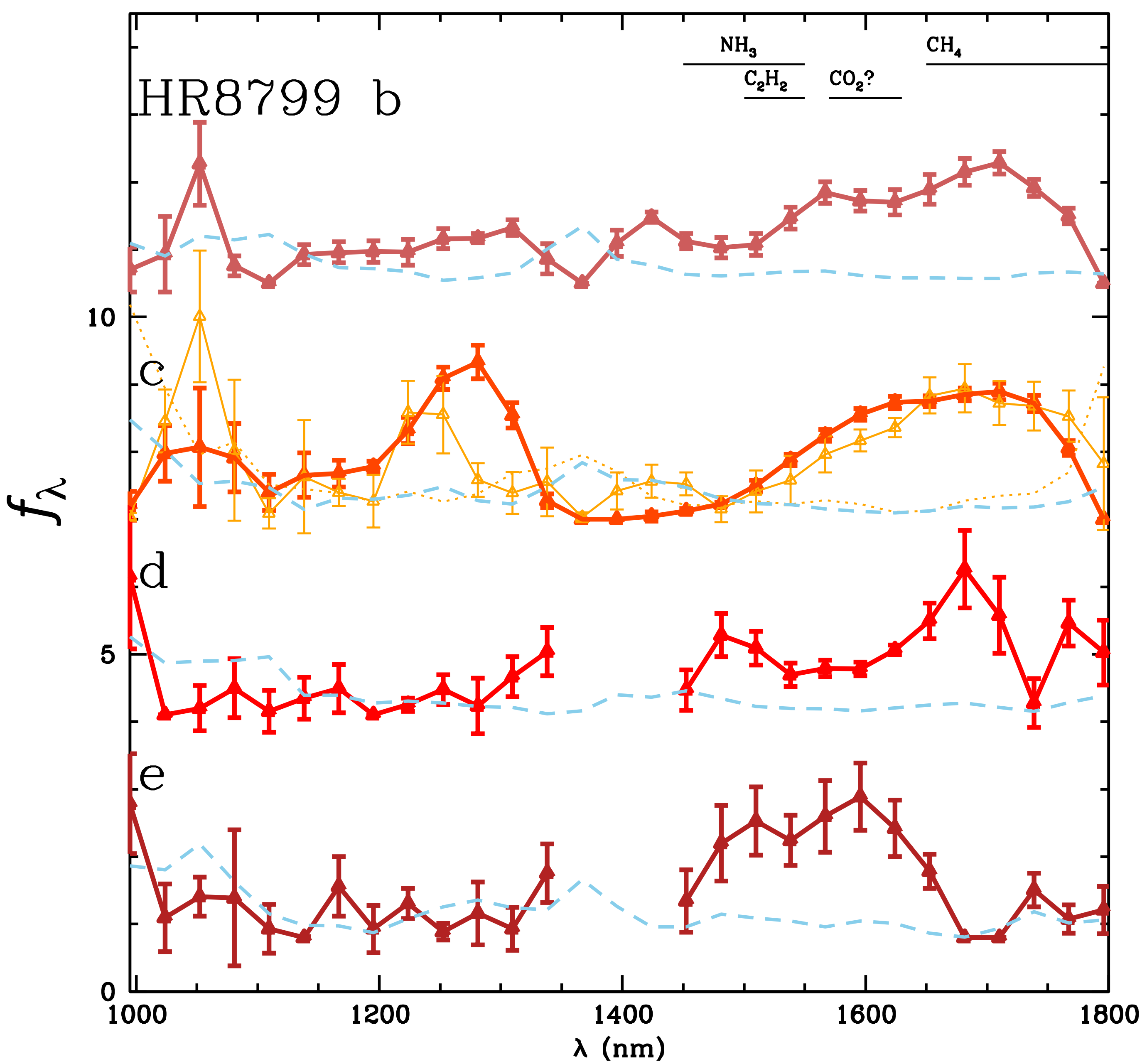
Oppenheimer et al.

No Post Processing



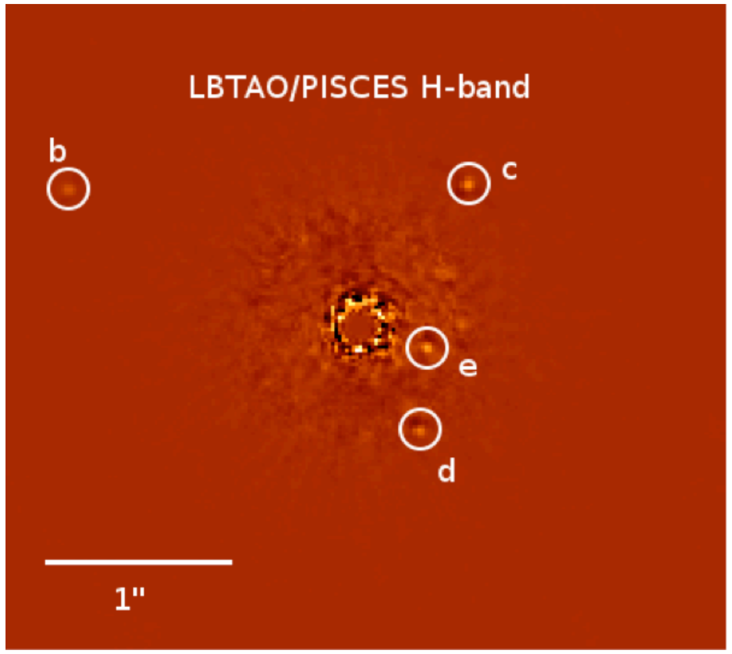
After S4 Speckle suppression

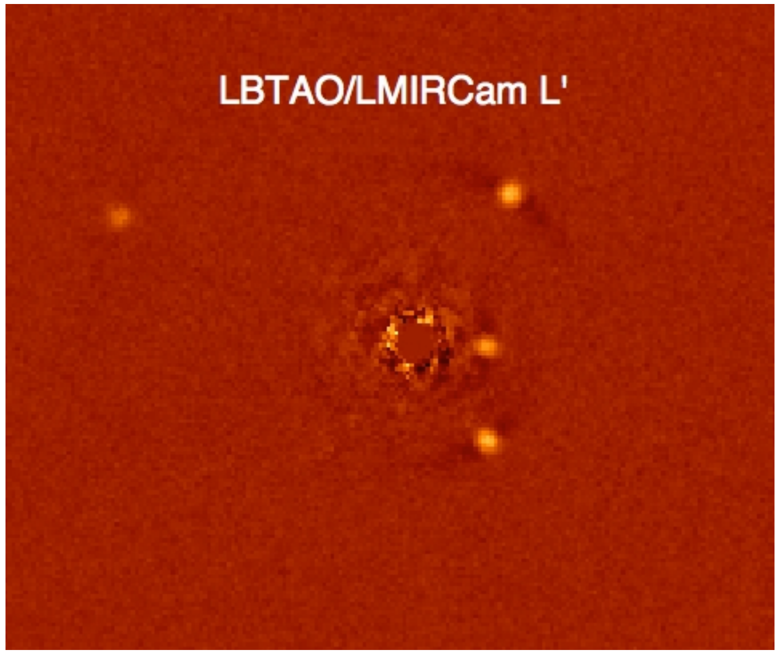


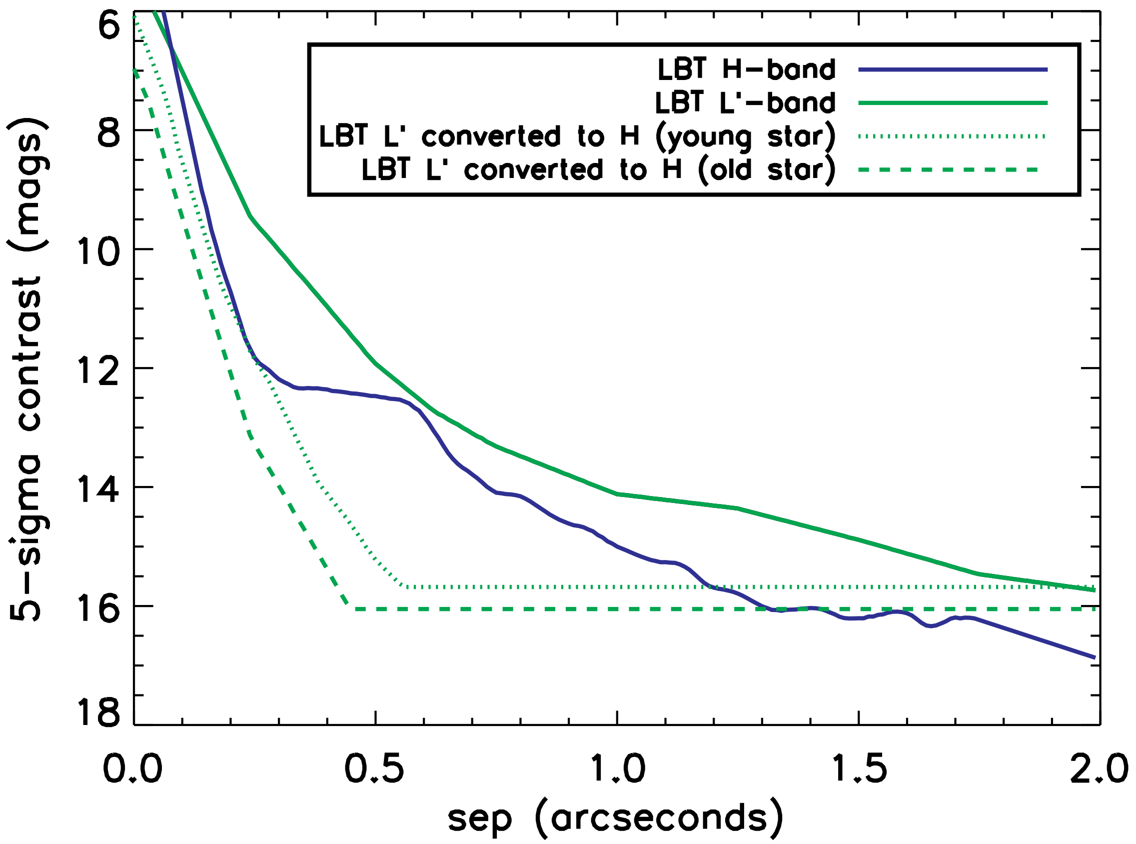


LBT: L' high contrast imaging at its best

Skemer et al. 2012, 2014

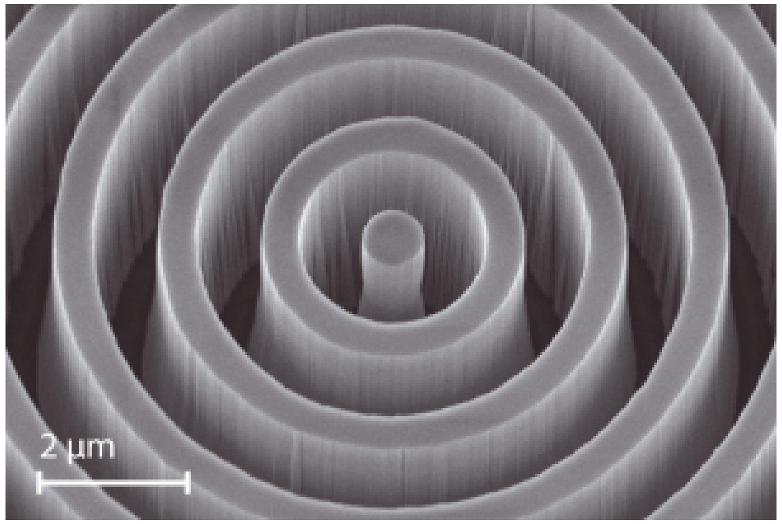


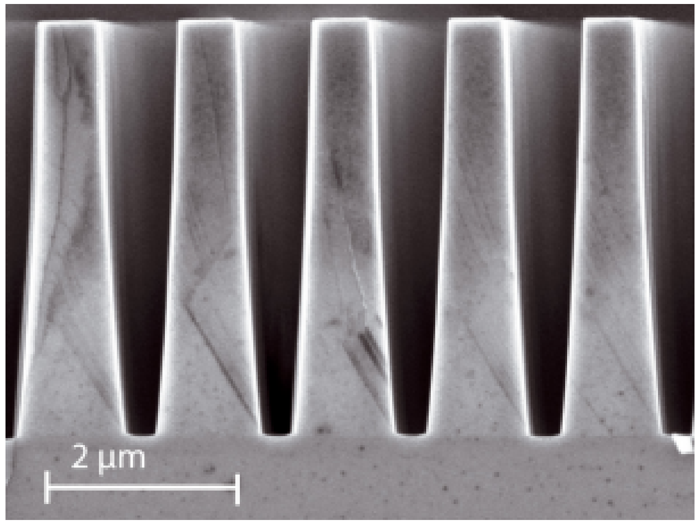


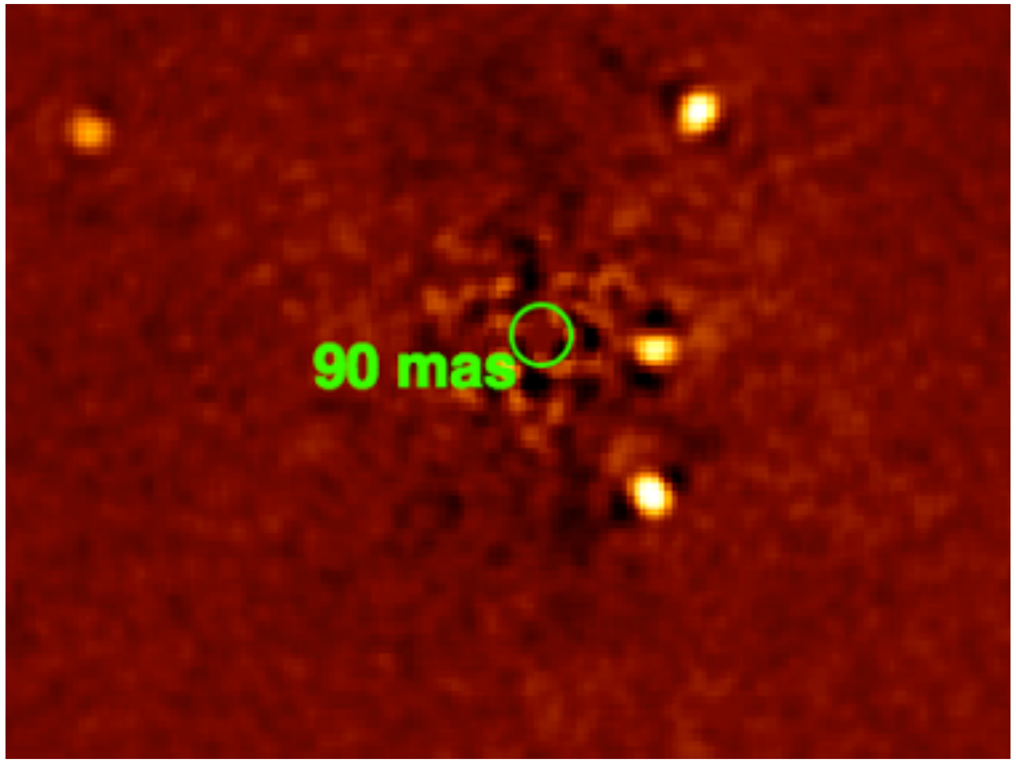


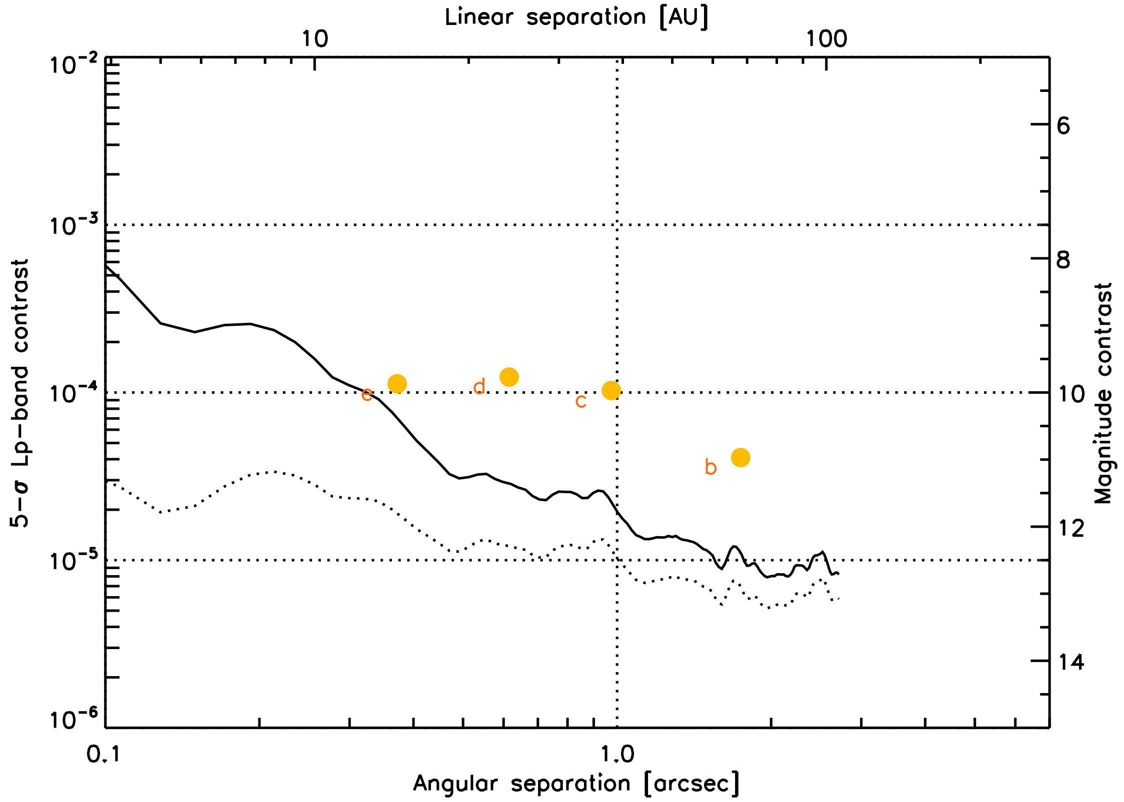
L’-band vortex at LBT

Defrere et al. 2014





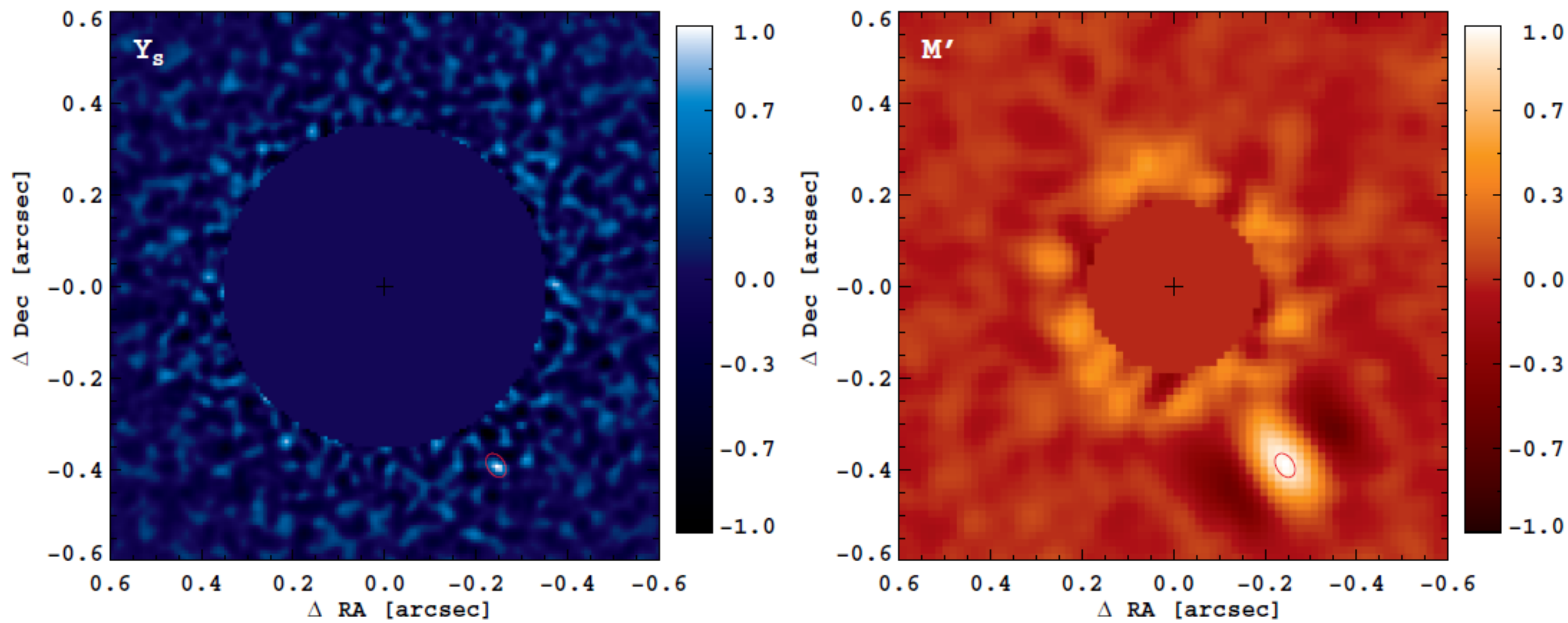


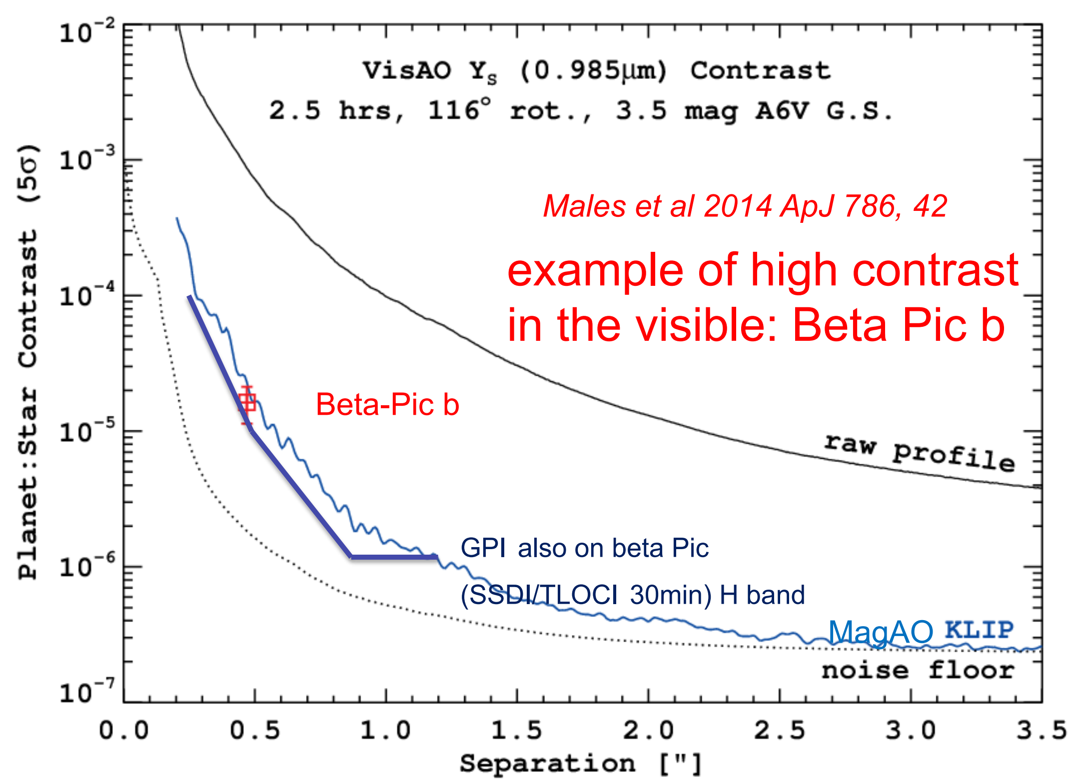


See Jared Males POP/POSTER

Mag AO: visible AO!

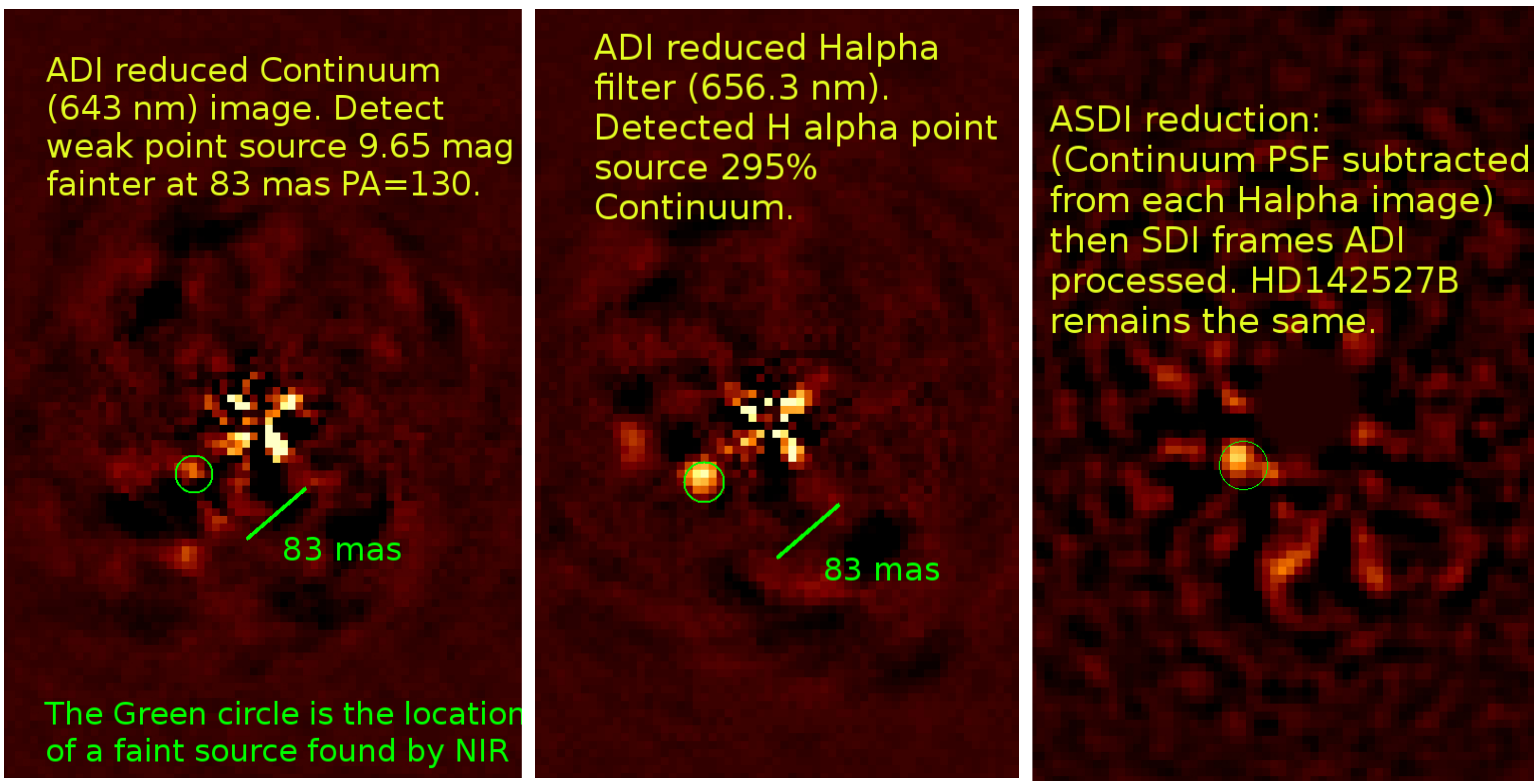
Claus, Males, Morzinski et al.





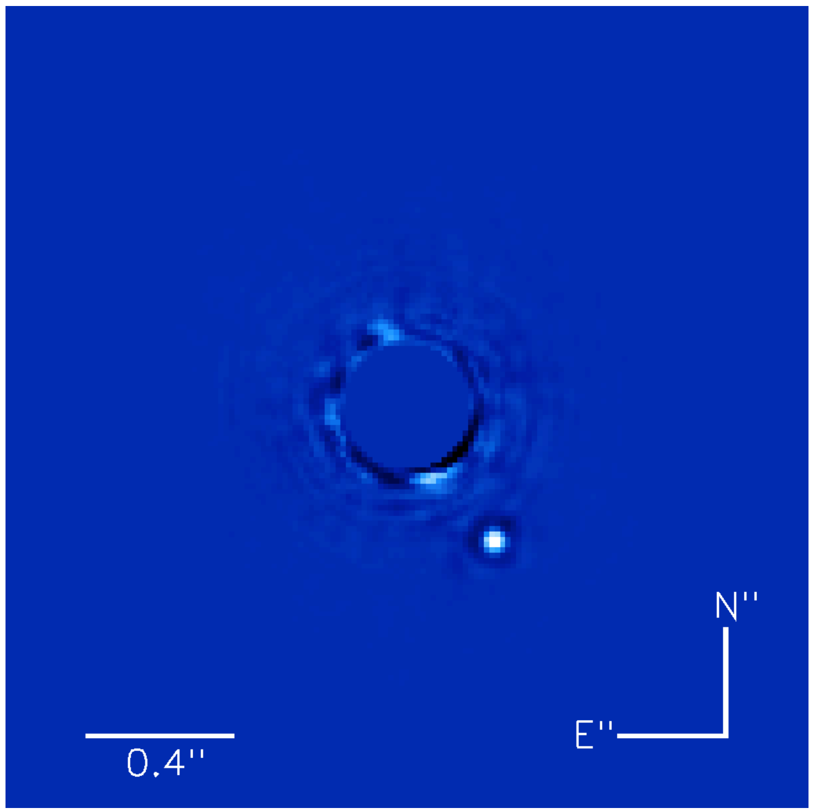
See Kate Folette POP/POSTER

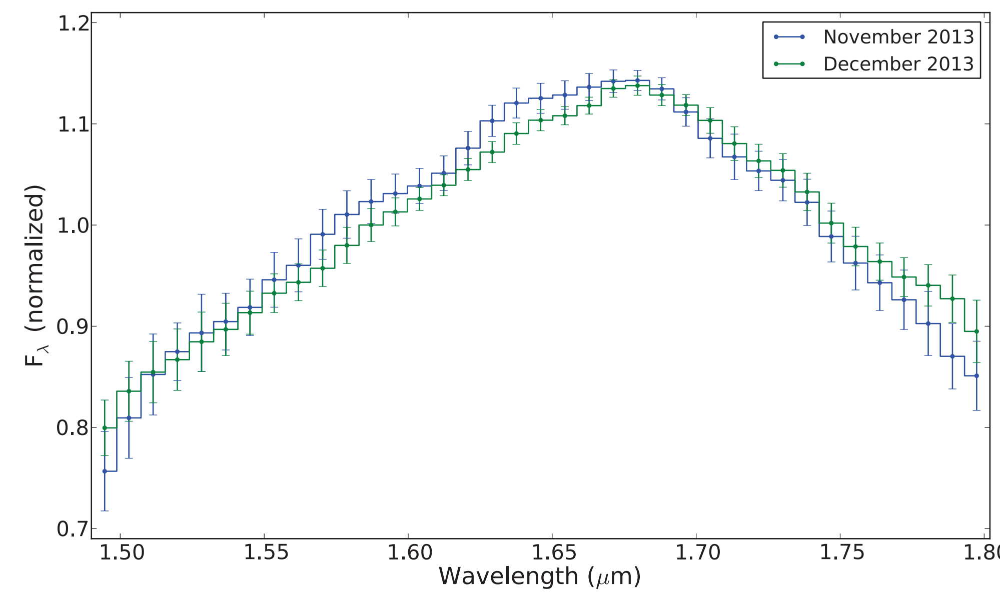
Mag AO: Hα SDI

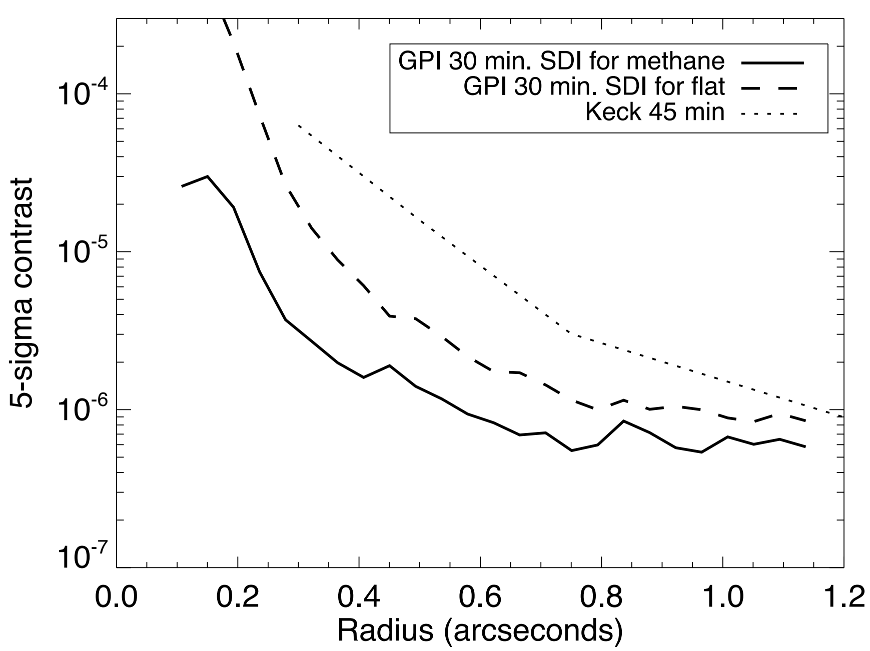


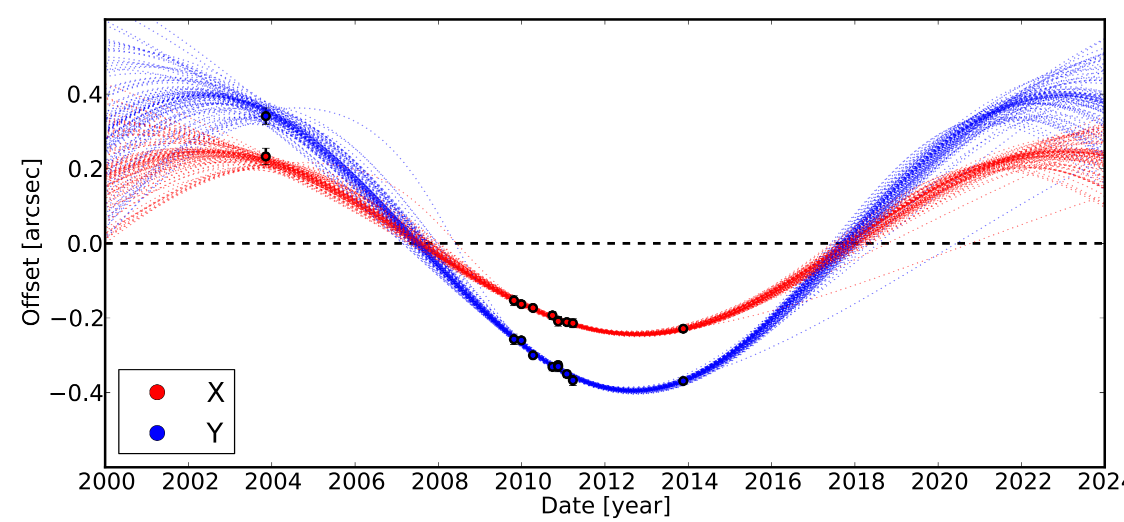
Close et al. 2014

GPI early exoplanet science
Macintosh et la. 2014; Chilcote et al. 2014



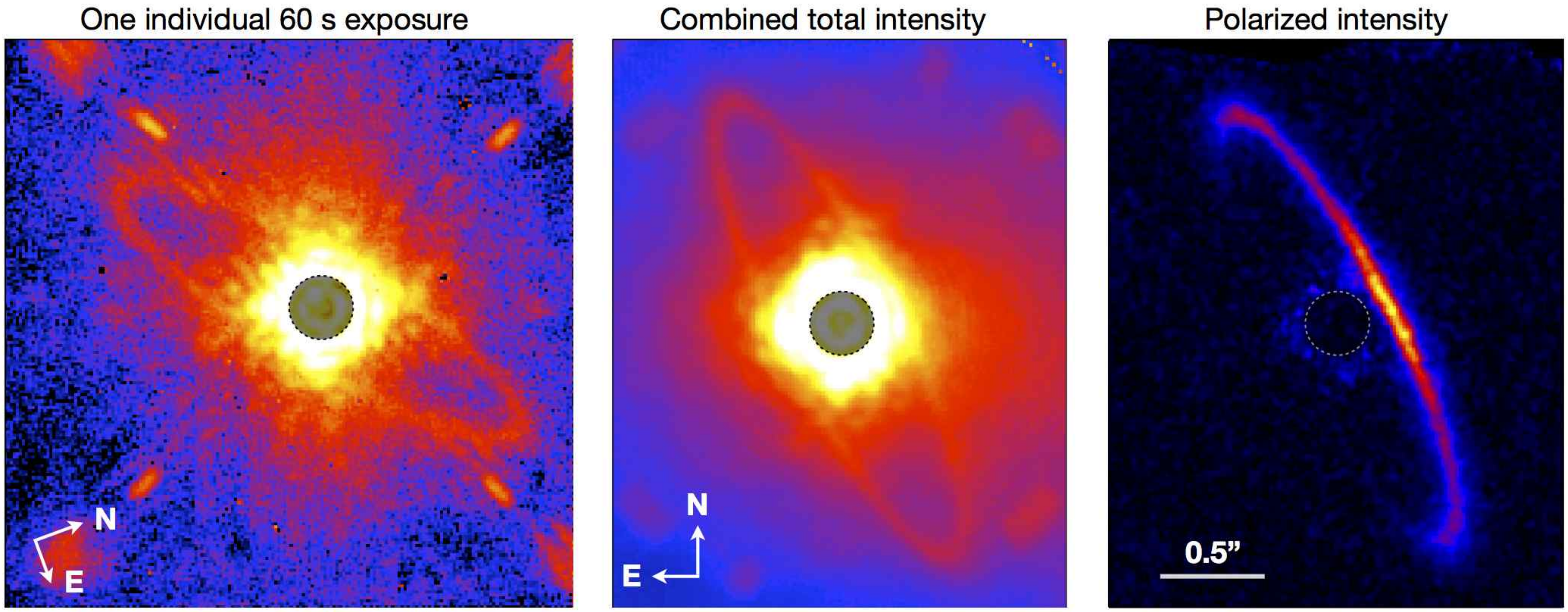




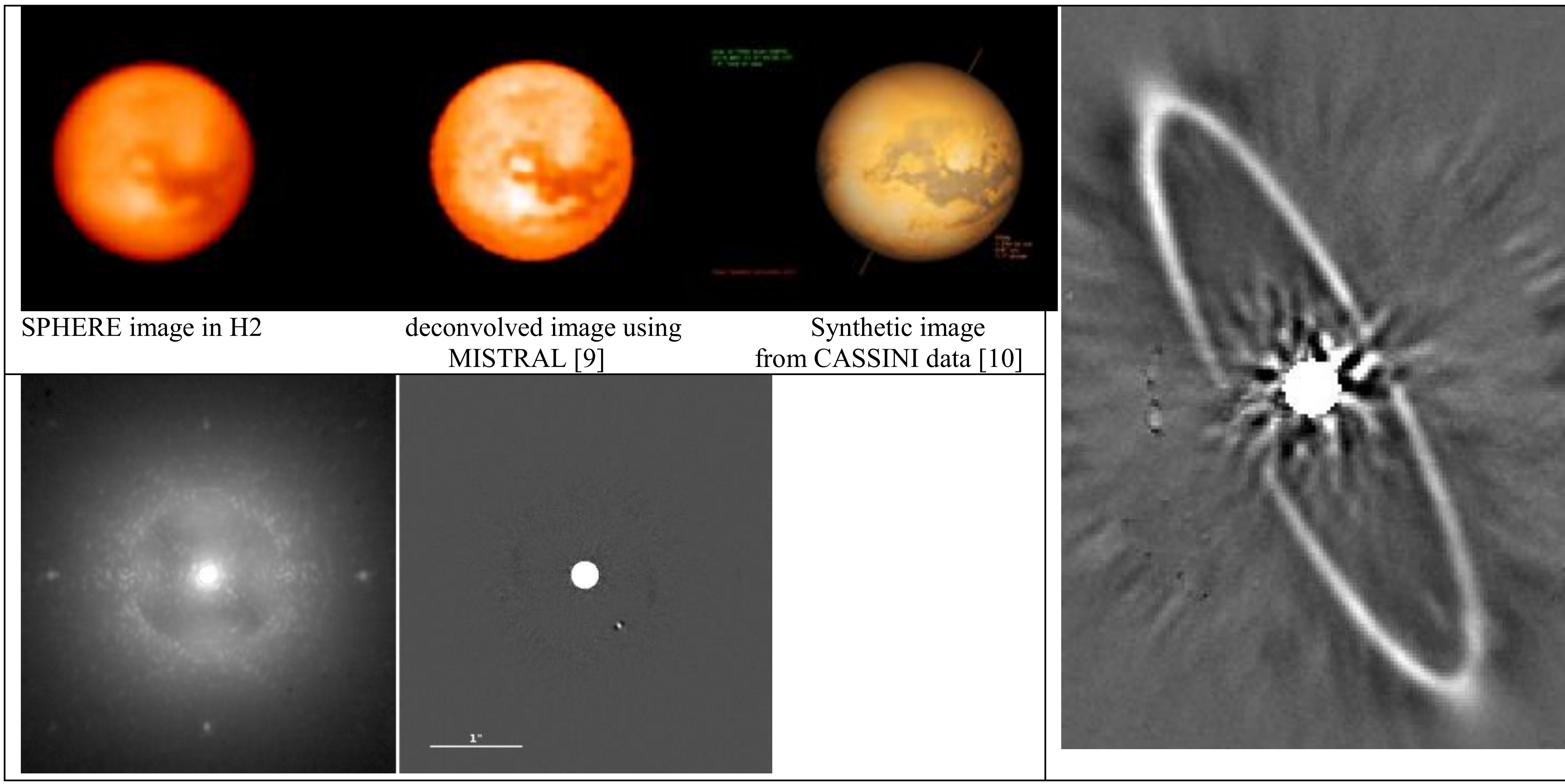


GPI early exoplanet science

Perrin et al. 2014



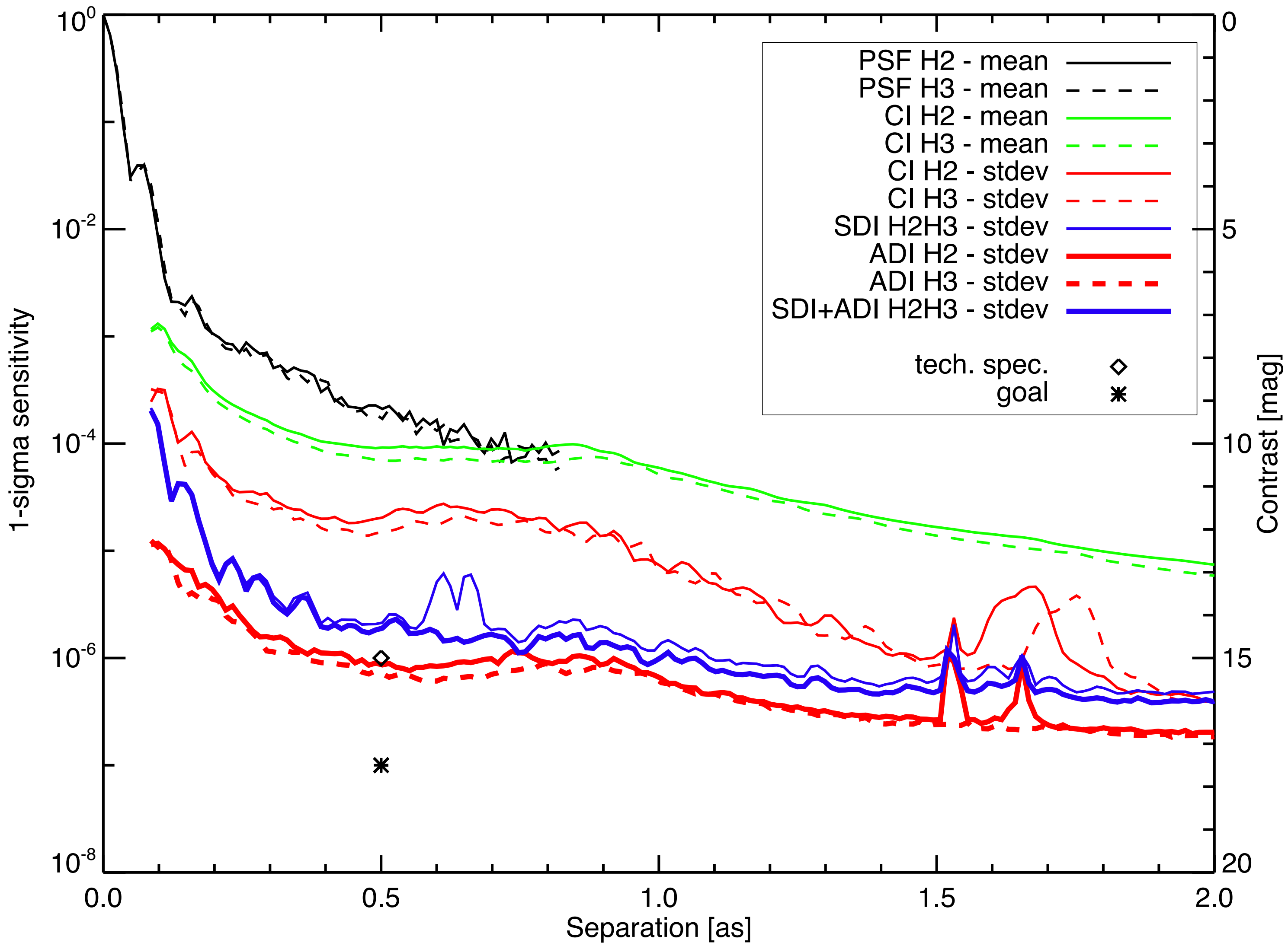
SPHERE first light!



Commissioning on-going

SPHERE early contrast performance

- Com1, improved since!
- M2 control issue solved => 92% Strehl at H
- tip-tilt rms within specs (3 mas)



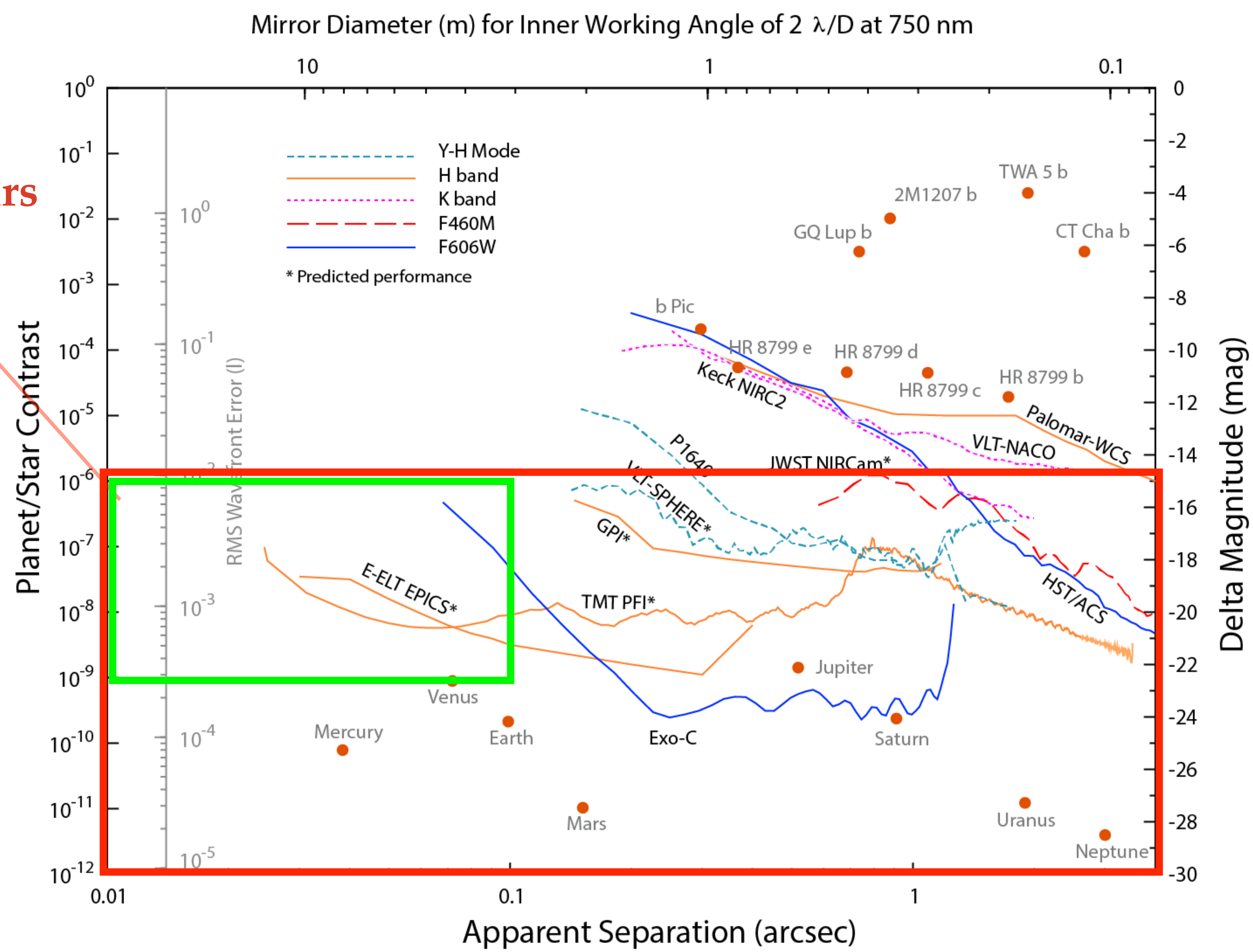
Summary

	Telescope/ Platform	WFS	DM	Coronagraph	LOWFS	DI
P3K/P1640/ SDC/PHARO	Cassegrain / Palomar 200 inch Hale telescope	SH	LODM/HODM (Xinetics)	APLC/RAVC/ VC	CAL + SH	SDI/RDI
LBT(I)	Combined focus / LBT	Pyramid	ASM	APP/VC (LMIRCAM)	N/A	ADI/RDI
MagAO	Nasmyth / Magellan	Pyramid	ASM	APP (Clio2)	N/A	ADI/RDI/SDI
SCExAO	Nasmyth / Subaru	Curvature (AO188) / Pyramid	LODM/HODM (CILAS(*)/BMC)	PIAA/VC	CLOWFS/ LSLOWFS	ADI/SDI/RDI
GPI	Cassegrain / Gemini South	SFSH	LODM/HODM (CILAS/BMC)	APLC	CAL + SH	ADI/SDI/PDI
SPHERE	Nasmyth / VLT	SFSH (EMCCD)	HODM (CILAS)	APLC/4QPM/ CLC	DTTS	ADI/SDI/PDI

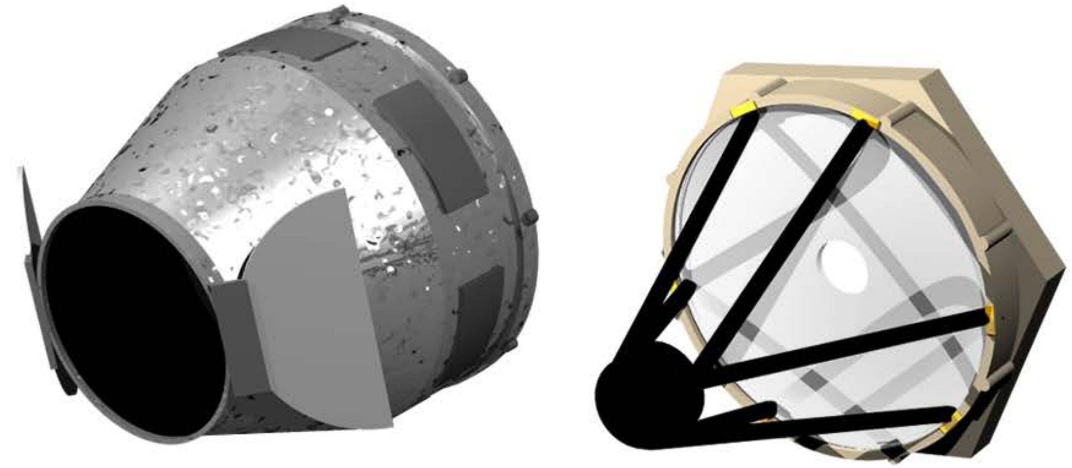
Future of high contrast imaging
from the ground and from space

Huge parameter space to explore, a single machine cannot do it all!

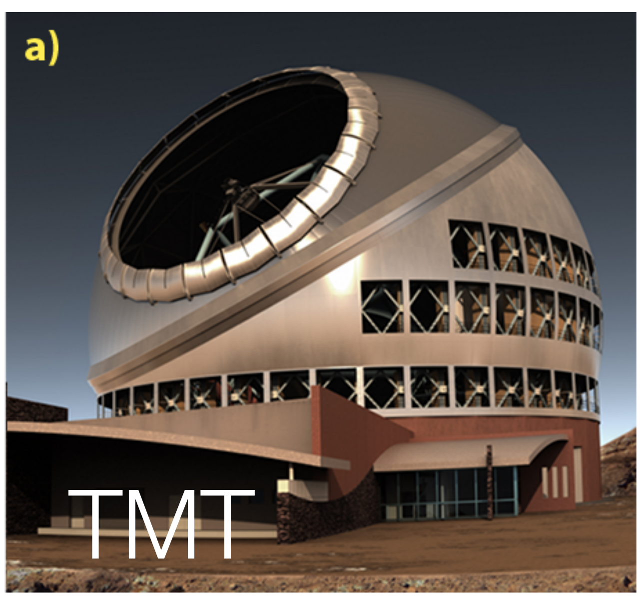
Habitable planets around nearest M stars

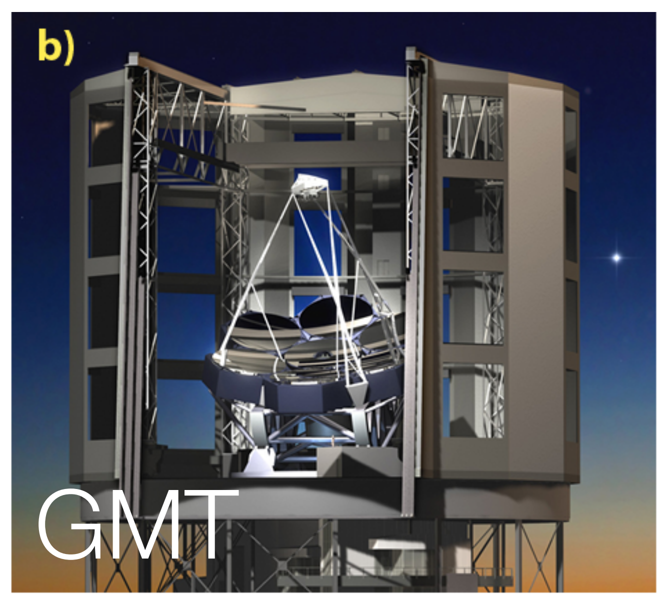


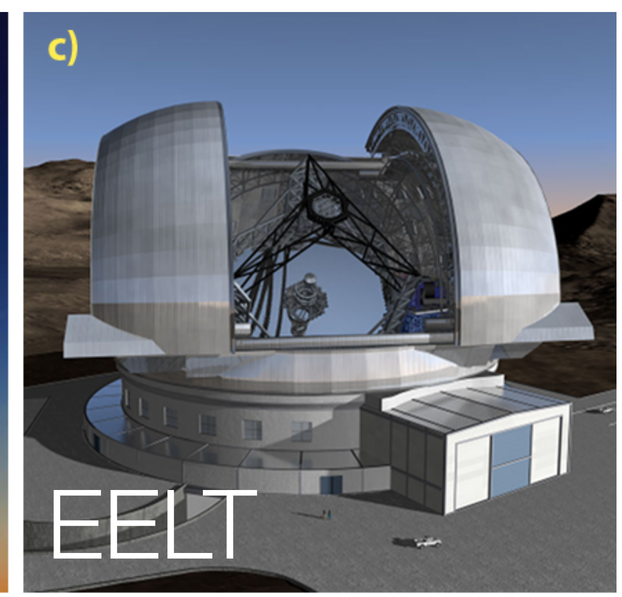
2020-2030 horizon



WFIRST-AFTA







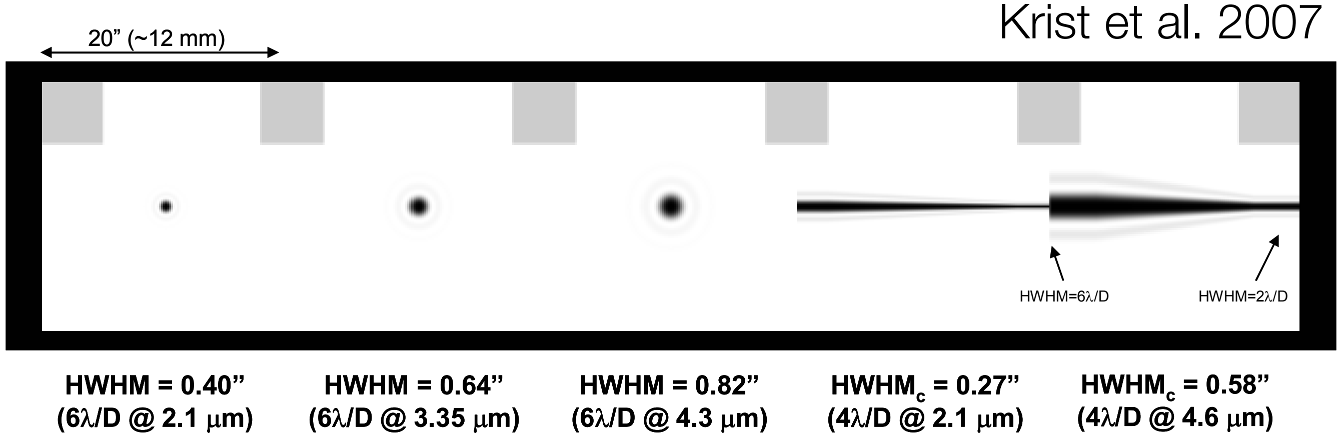
Challenge: diffraction and wavefront control over large, segmented and/or heavily obscured apertures

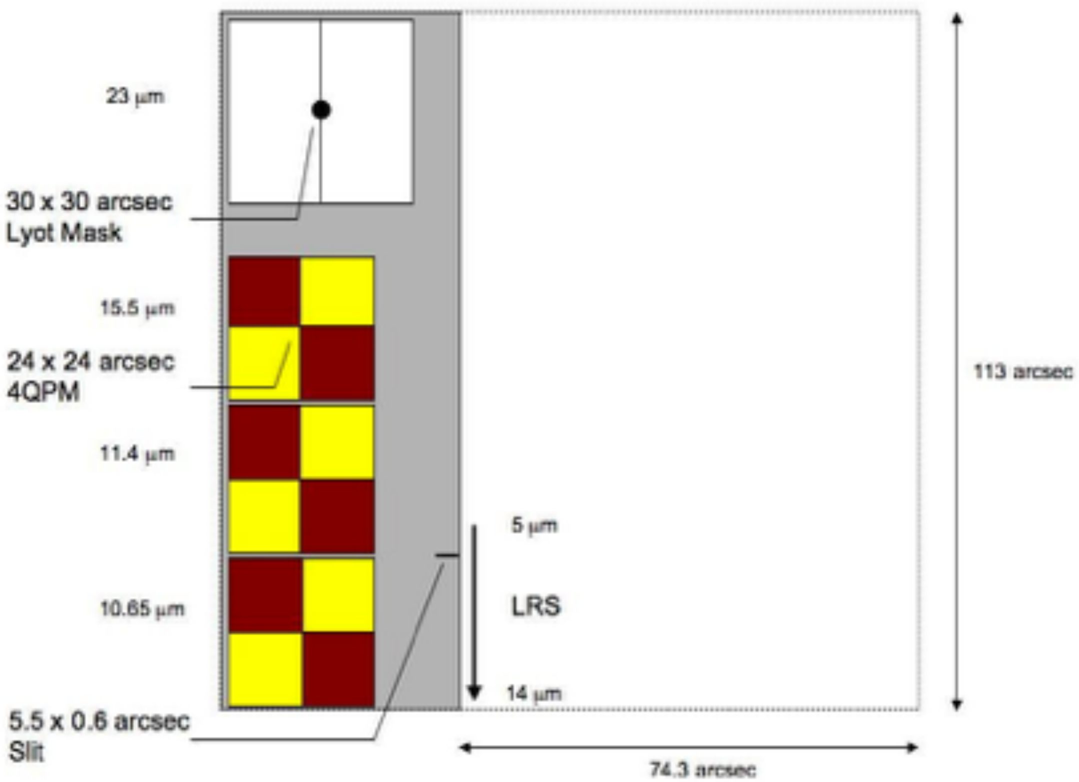
Marshall’s talk on Friday
“Coronagraphy with JWST”

In space: JWST

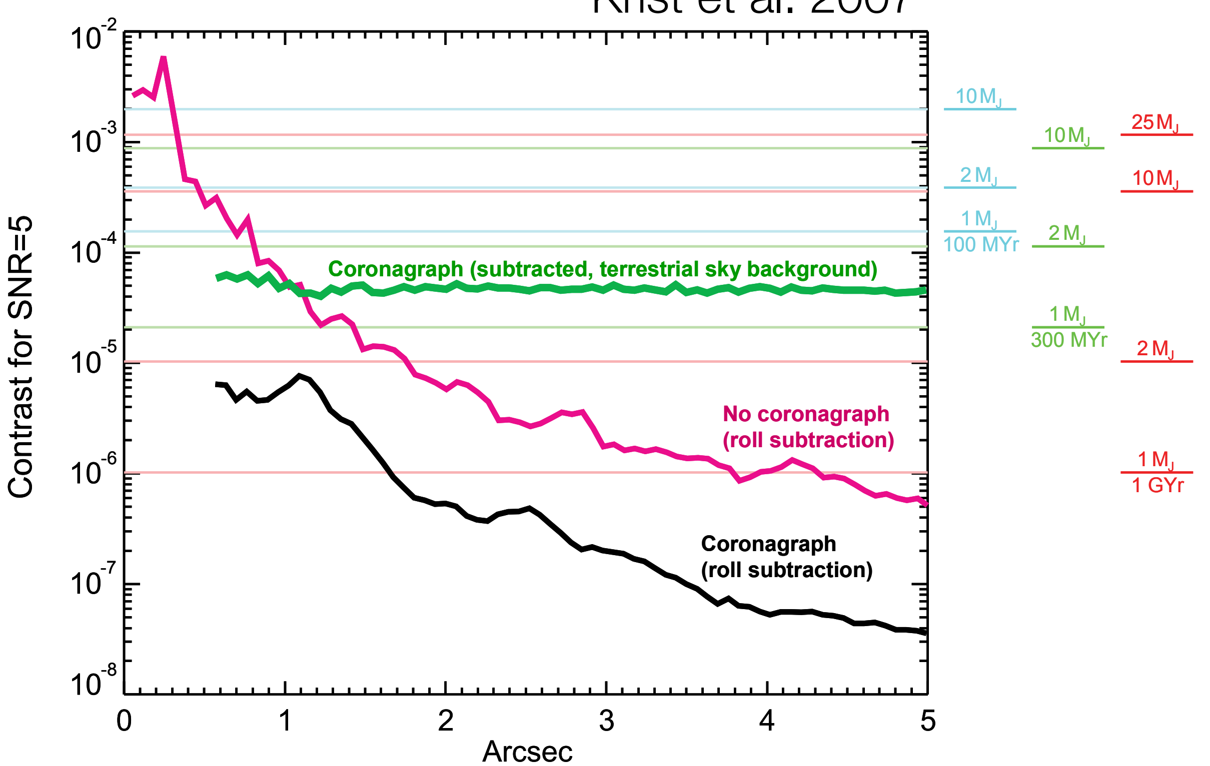
Mode	Instrument	Wavelength (microns)	Pixel Scale (arcsec)	Field of View
Coronography	NIRCam	0.6 – 2.3	0.032	20 x 20″
	NIRCam	2.4 – 5.0	0.065	20 x 20″
	MIRI	10.65	0.11	24 x 24″
	MIRI	11.4	0.11	24 x 24″
	MIRI	15.5	0.11	24 x 24″
	MIRI	23	0.11	30 x 30″

Krist et al. 2007



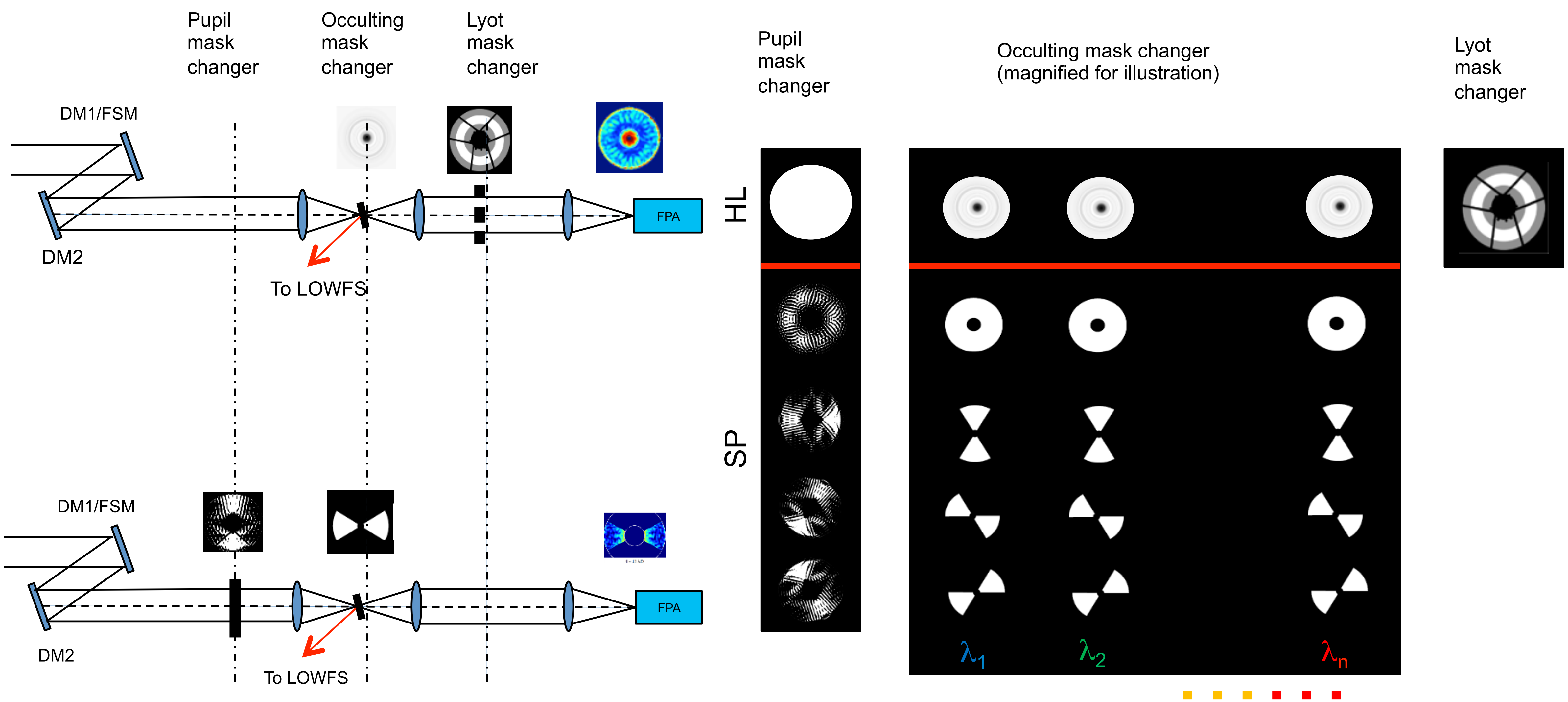


Krist et al. 2007



Bruce's talk on Friday
"The Next^2 Step: The AFTA Coronagraph"

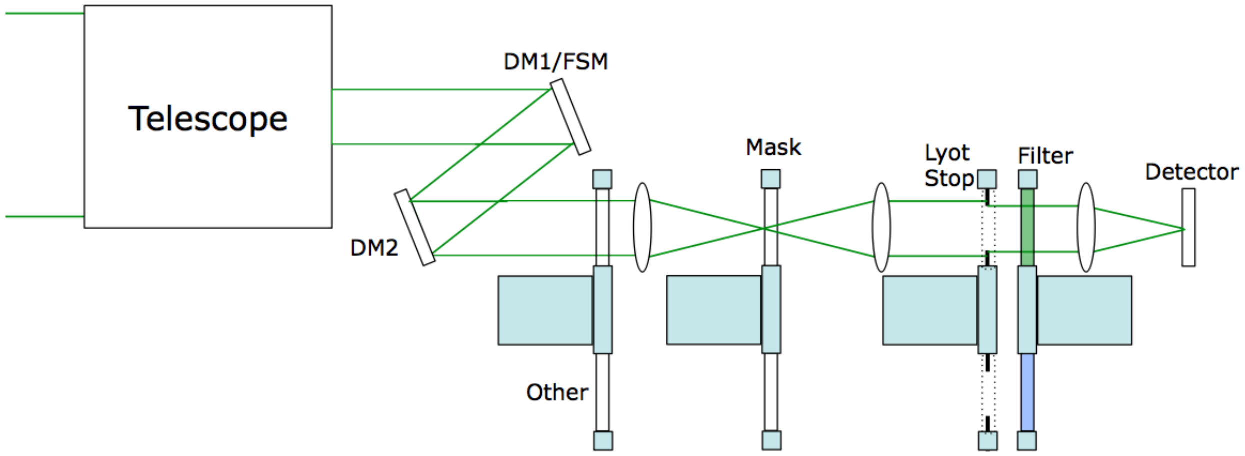
WFIRST - AFTA

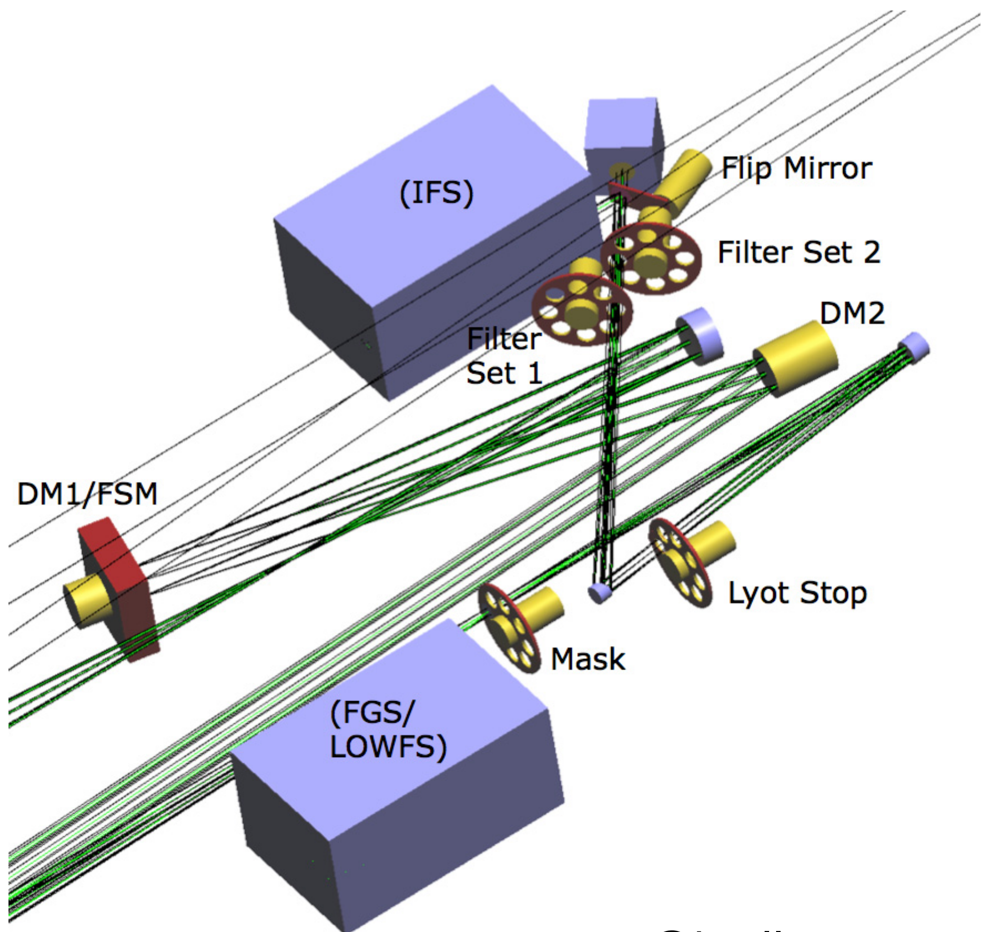


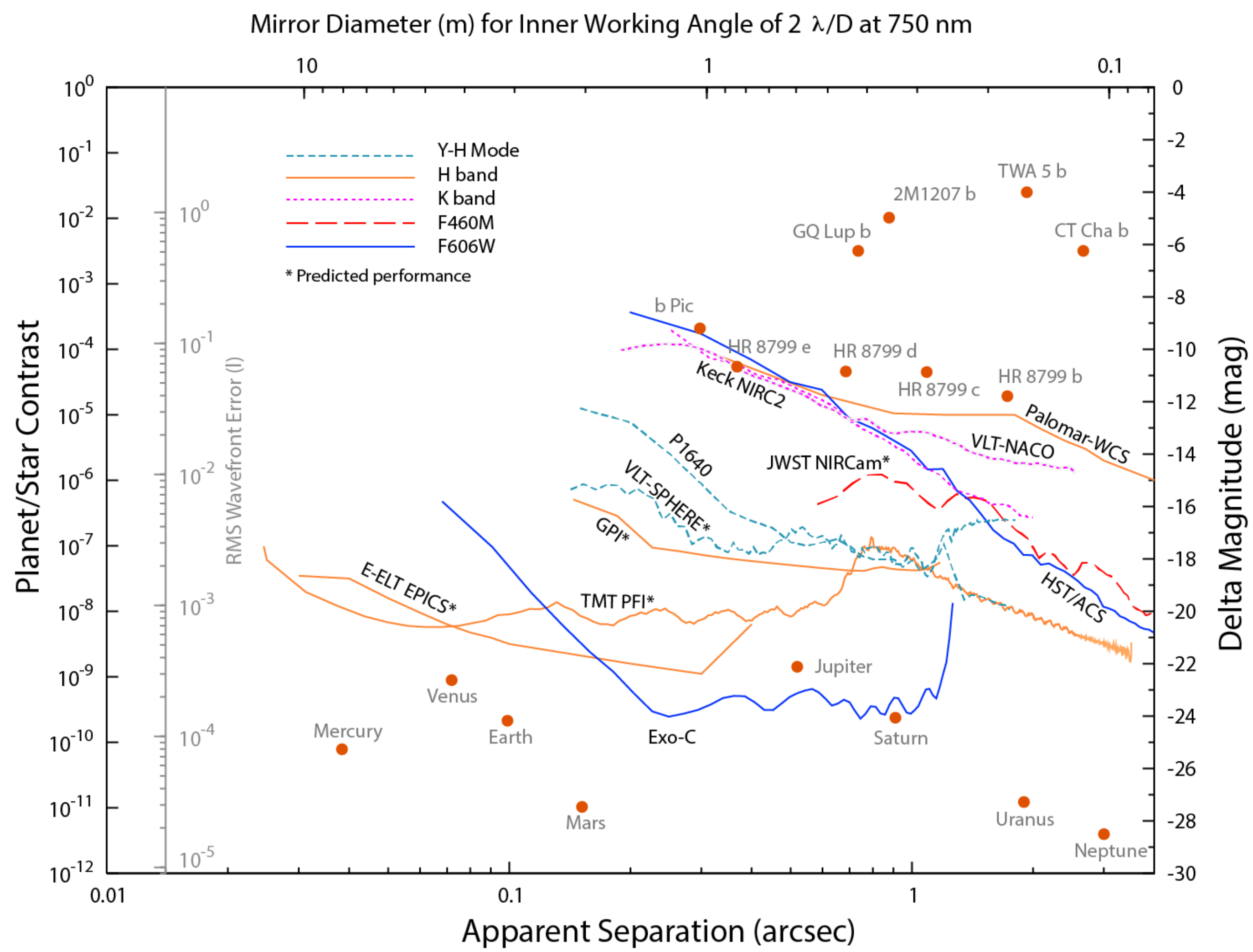
Challenges: pupil geometry, pupil geometry, pupil geometry!
+ optical aberrations, polarization, telescope time/availability

some say it could be our only/best shot
at a space-based coronagraph for the foreseeable future

EXO-C: backup to WFIRST-AFTA







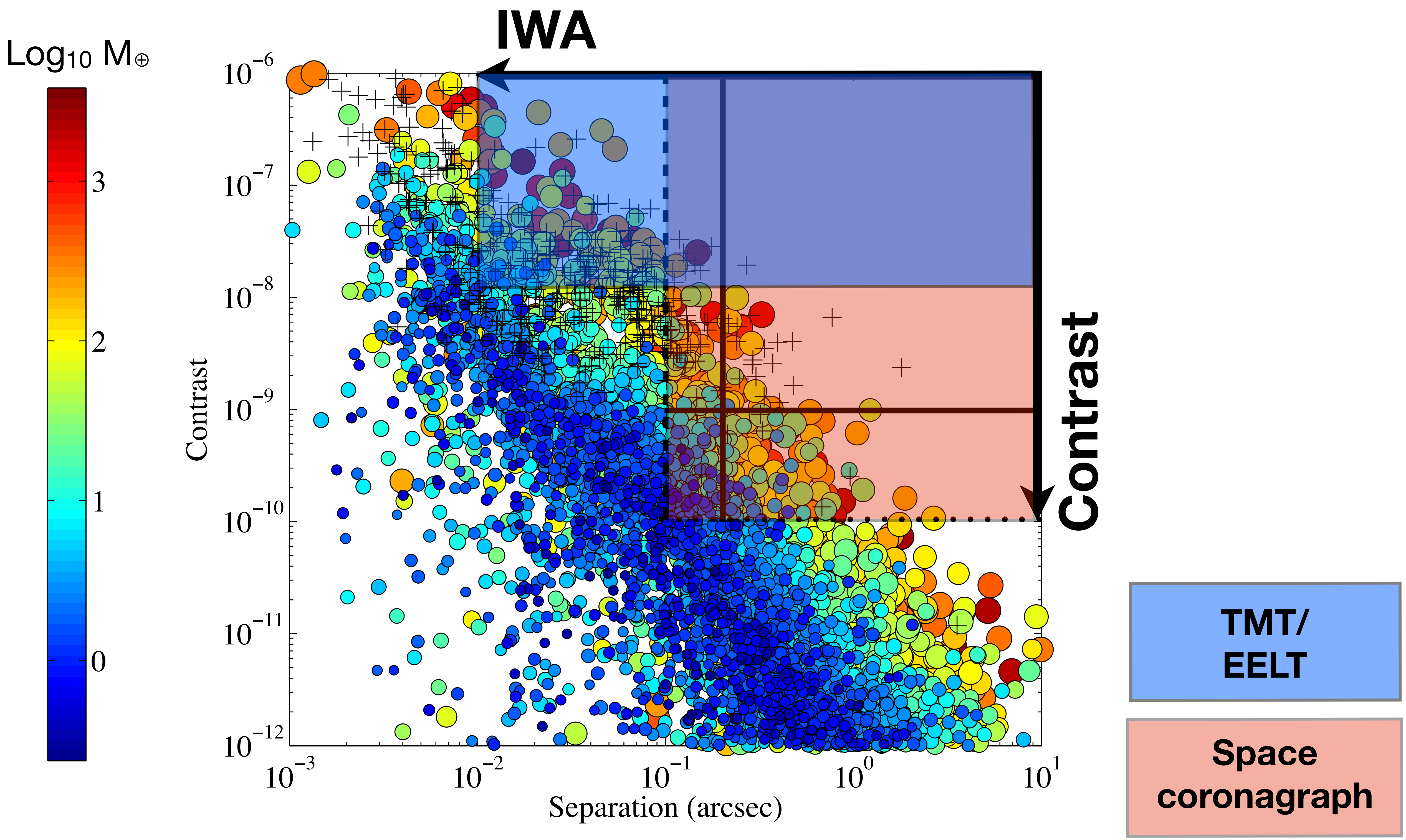
Challenges: 1.4-m aperture, budget

Aki's talk coming right up!

EXO-Starshade

Zooming in: synergy and complementarity!

Spergel et al 2013, WFIRST-AFTA

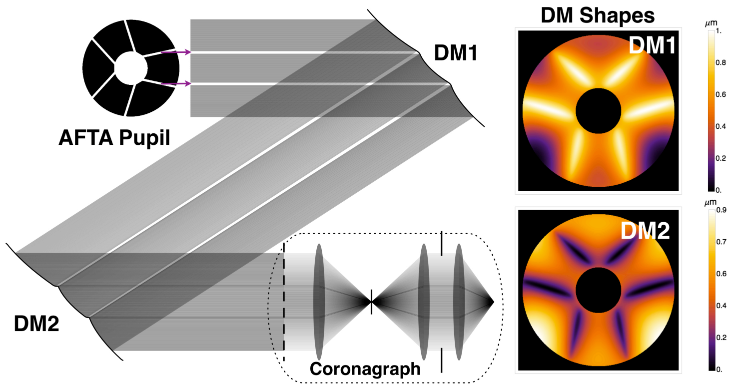


High contrast imaging with ELTs: still a lot to be done, invented, combined, optimized

- E-ELT: building on EPICS studies, Planetary Camera and Spectrograph (PCS) R&D roadmap written by ESO and made public to European Instituted
- TMT: Planet Finder Instrument (PFI) study from 2006 concluded VNC is the optimal way to deal with segments, not true anymore
- GMT: build on LBT experience, PIAA

Rebecca & Seth,
P. Pirron, JR Delorme
POP/POSTER

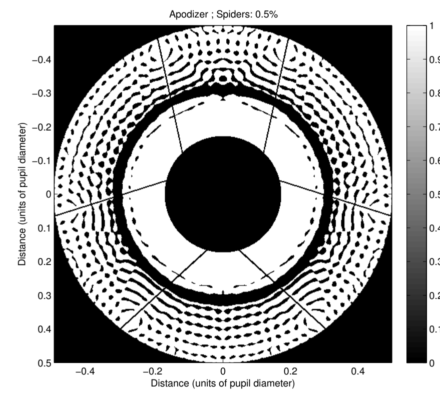
Synergistic developments



(Pueyo, Guyon, et al)

Remapping techniques

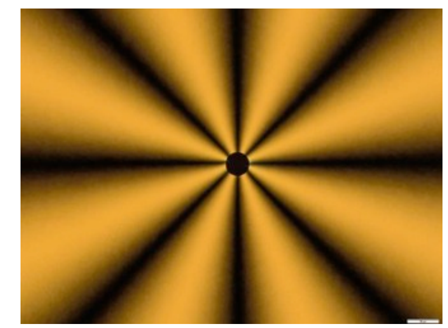
+



(Carlotti, Kasdin, Sivaramakrishnan, Soummer, Mawet, et al)

Apodizers

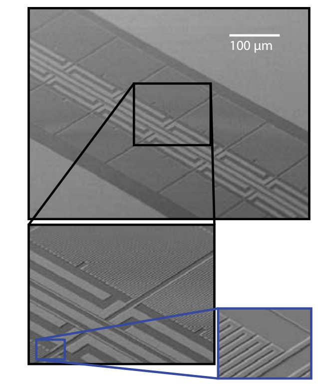
+



(Rouan, Baudoz, Mawet, Serabyn, et al)

Small IWA coronagraphs

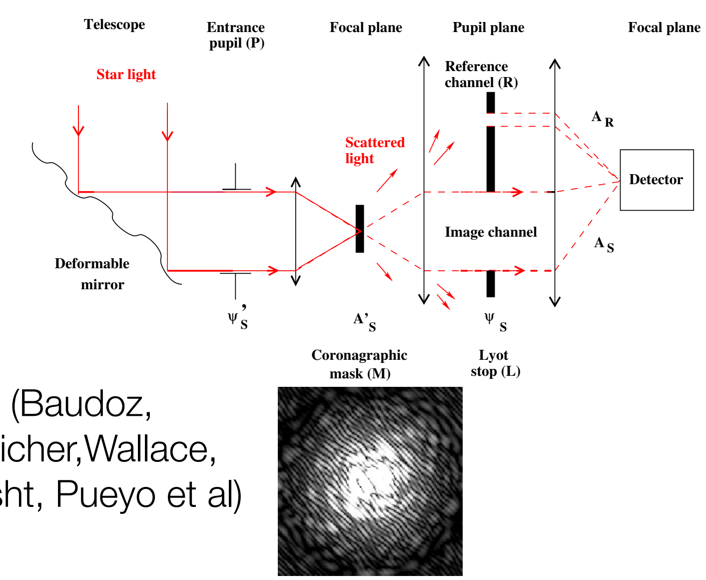
+



(Mazin et al)

MKIDS

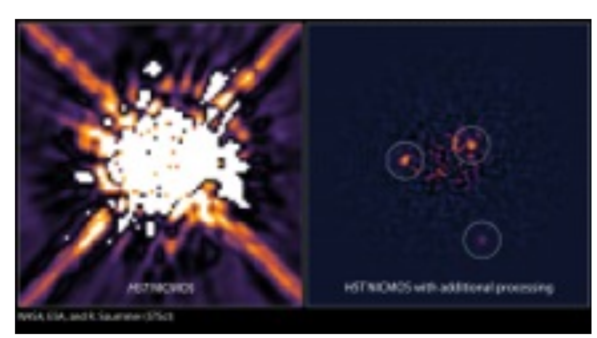
+



(Baudoz, Galicher,Wallace, Vasisht, Pueyo et al)

Post-coronagraphic WFS

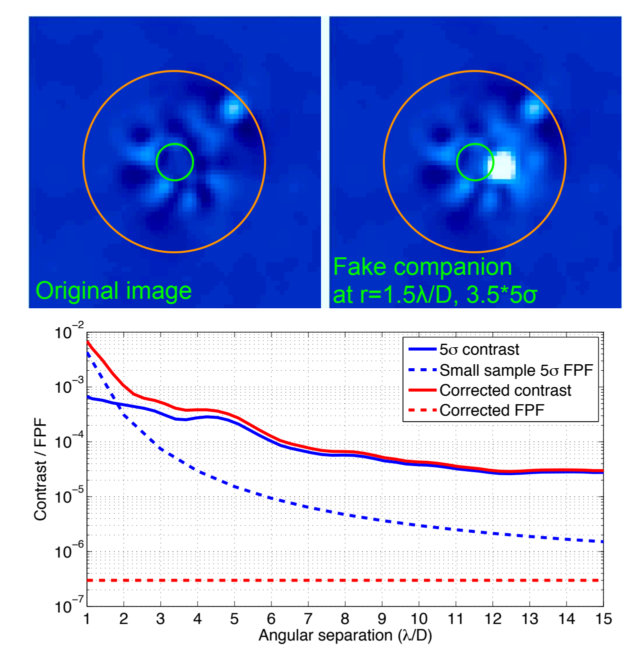
+



(Soummer, Pueyo, Marois, Lafreniere, Perrin, Currie, Mawet, etc…)

Post-processing advances

+



(Mawet et al. 2014, submitted)

Statistical significance

That’s all folks! Have fun out there!

SPHERE commissioning pics (J. Girard)