D. MAWET, JULY 2016

SURVEY OF DIRECT IMAGING: TECHNIQUES AND RESULTS

DIRECT IMAGING OF EXOPLANETS

- Direct imaging: taking actual pictures of exoplanets
- Demographics at young ages and large separations
- Direct detection enables detailed characterization:
    - Orbital evolution, dynamical interactions
    - Remote sensing of their atmospheres
    - Formation and disk interaction

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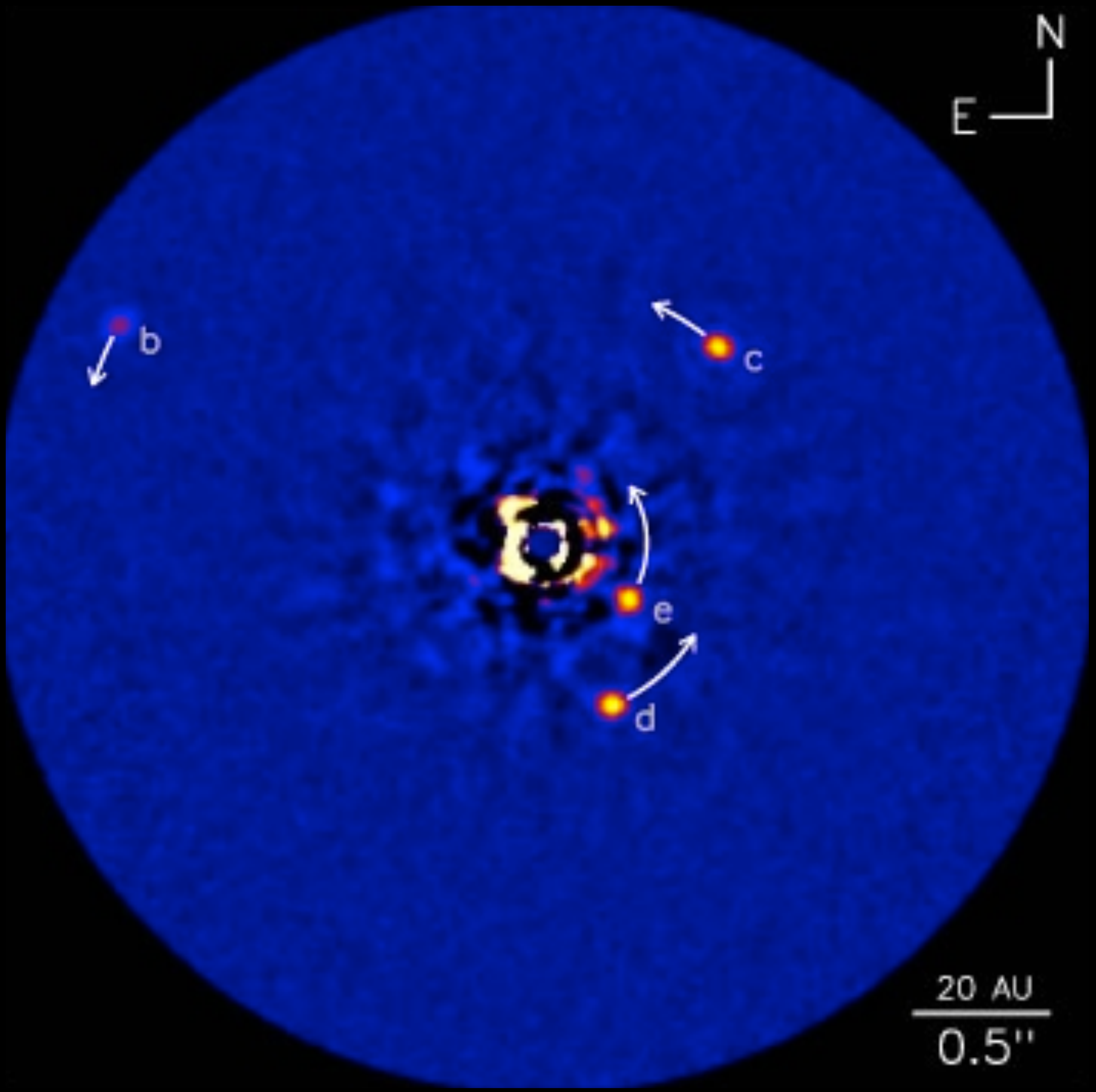
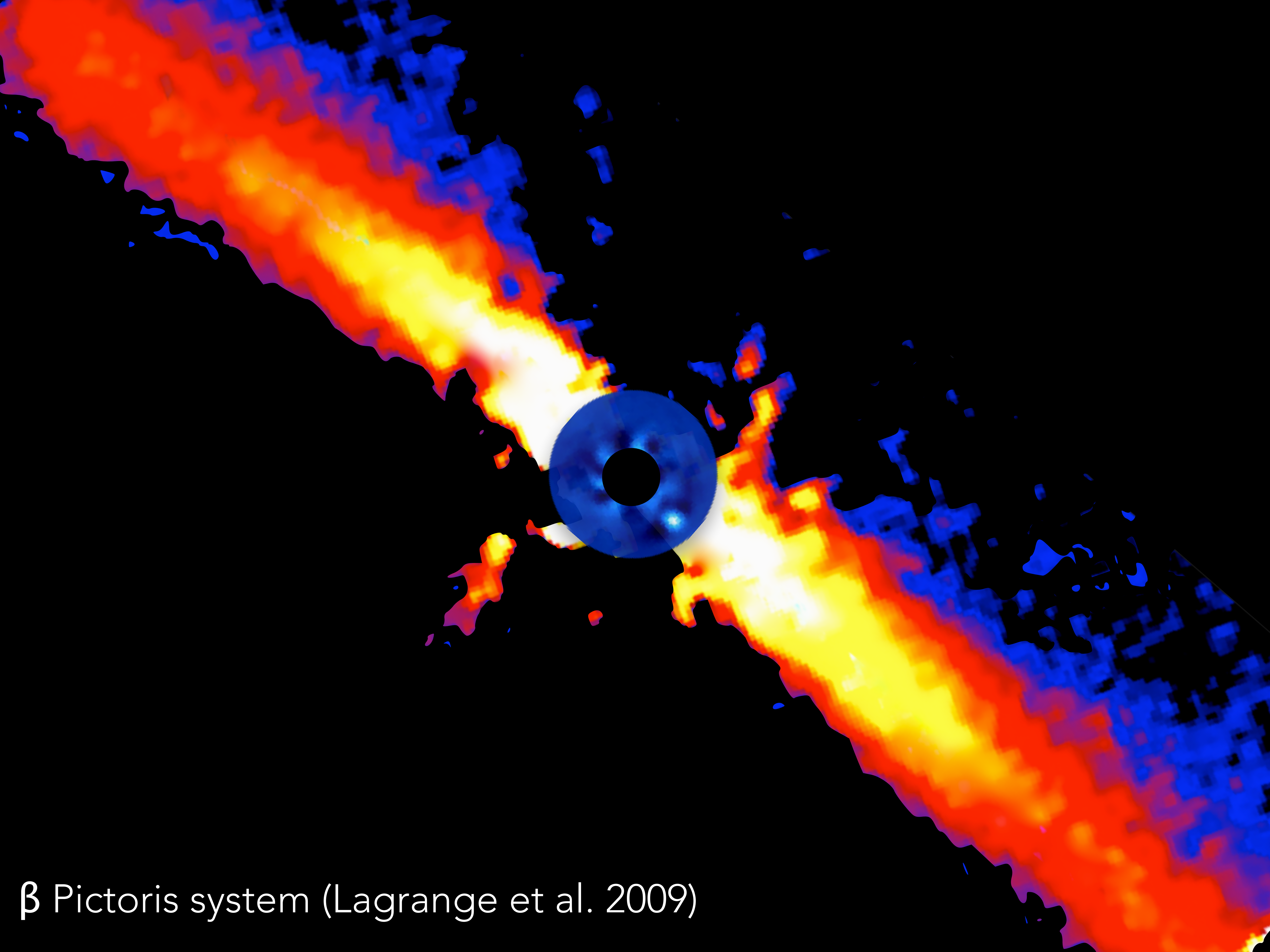
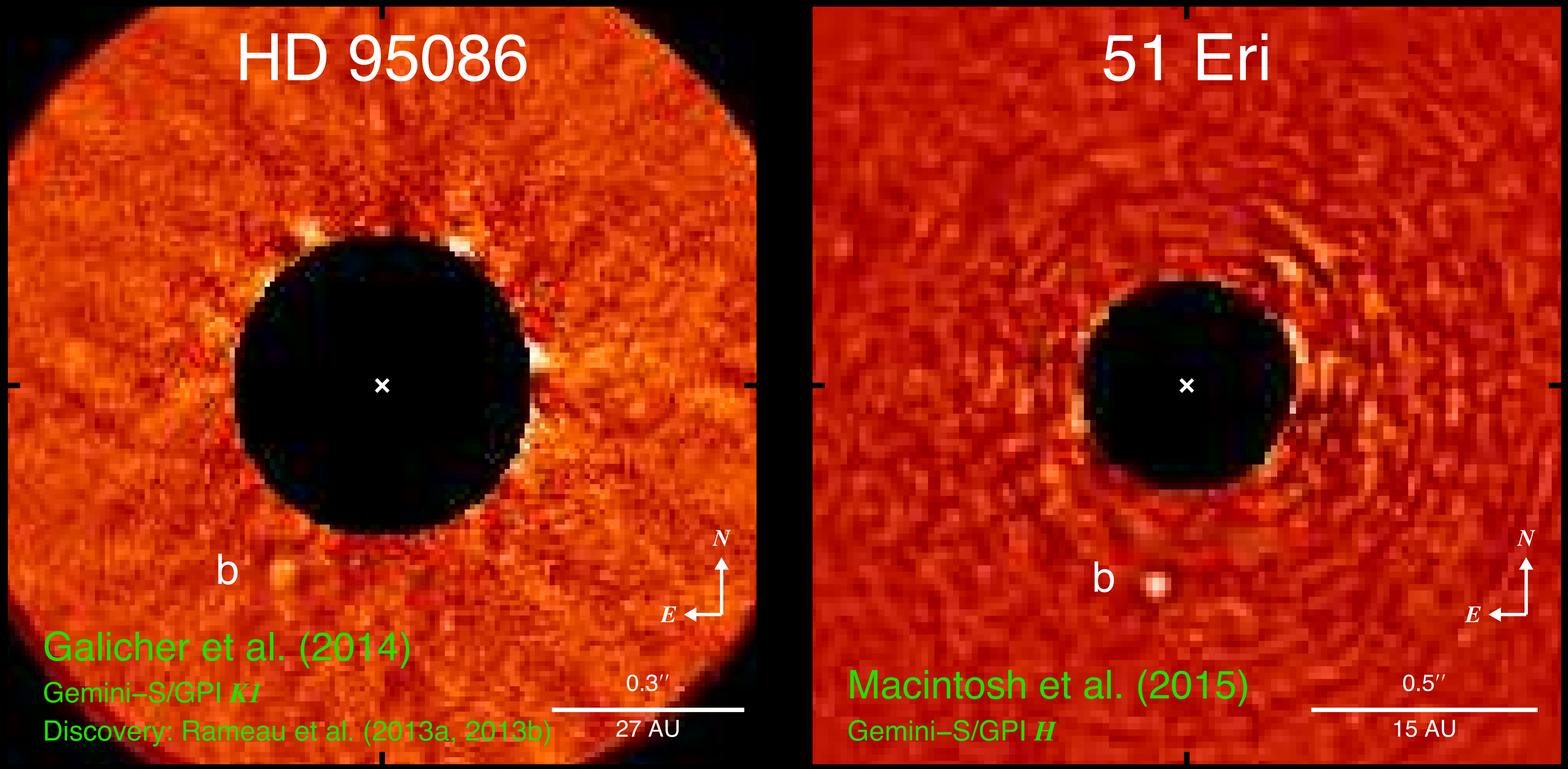
HR8799'S 4 GIANT PLANETS



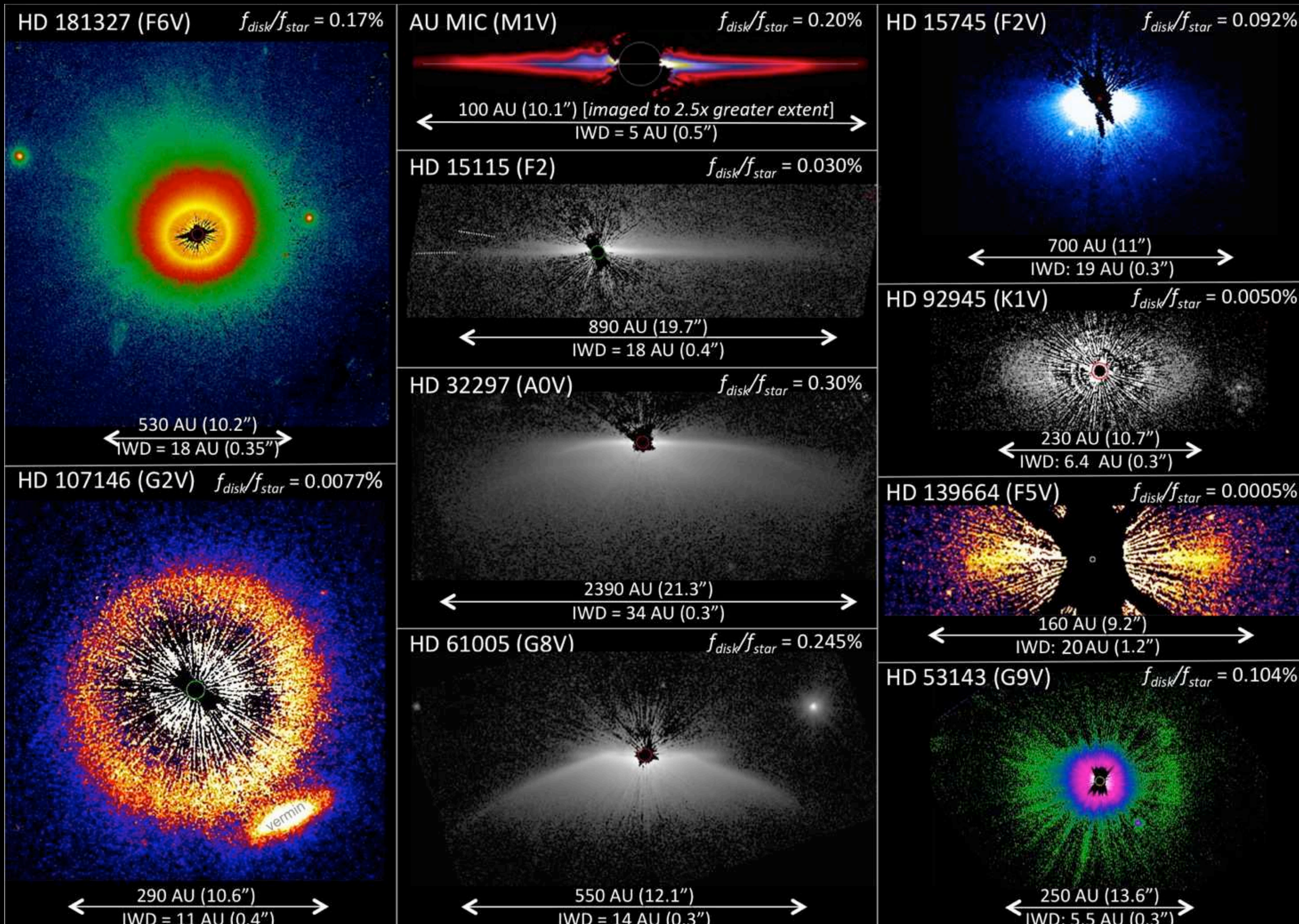
Marois et al. 2008 (2010)



β Pictoris system (Lagrange et al. 2009)


HD 95086
b
N
E
Galicher et al. (2014)
Gemini–S/GPI K1
Discovery: Rameau et al. (2013a, 2013b)
0.3″
27 AU
51 Eri
b
N
E
Macintosh et al. (2015)
Gemini–S/GPI H
0.5″
15 AU

DISKS AS SIGNPOSTS OF PLANETS



Schneider et al. 2014 (HST-STIS)

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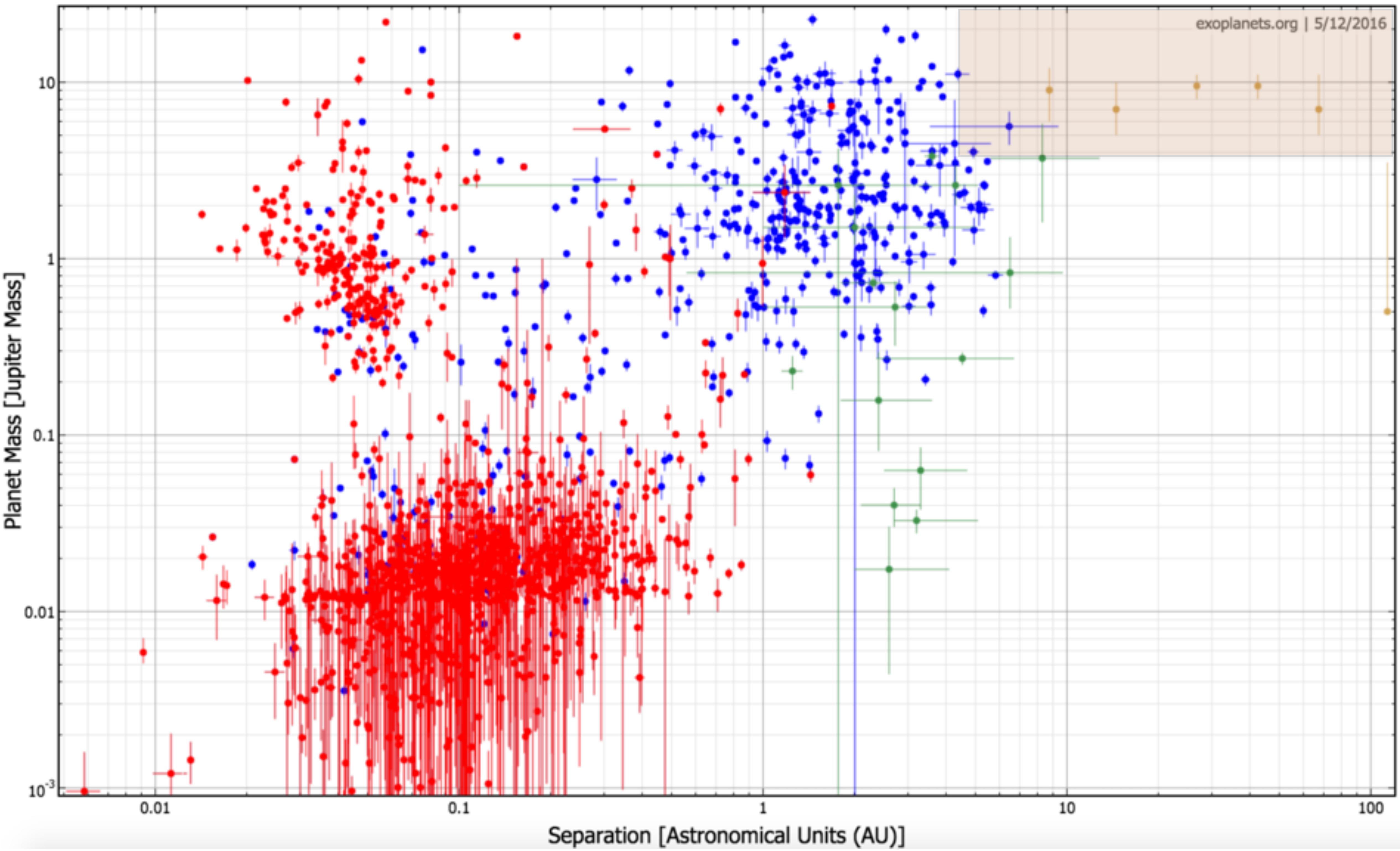
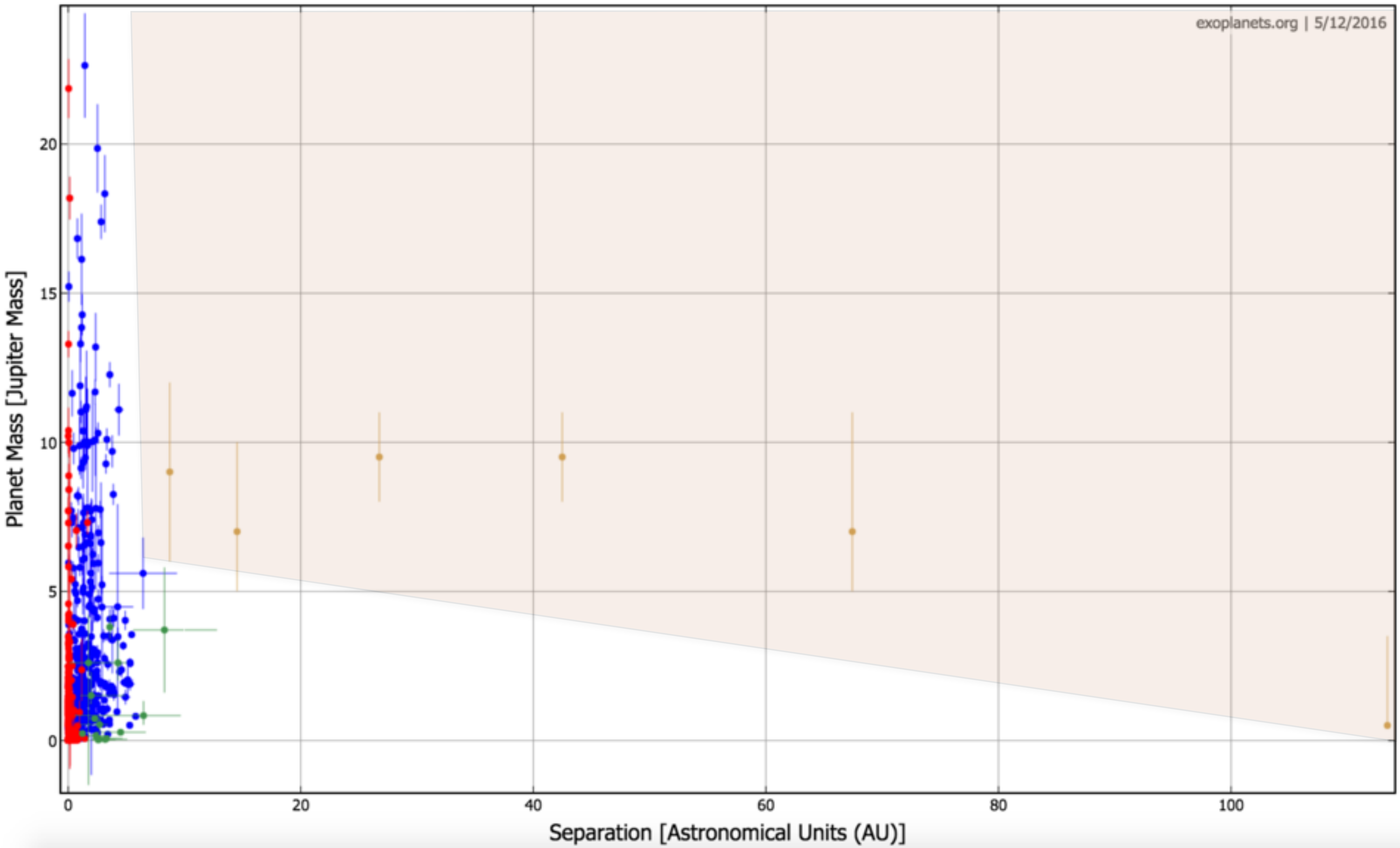


exoplanets.org | 5/12/2016
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100
Separation [Astronomical Units (AU)]


exoplanets.org | 5/12/2016
Planet Mass [Jupiter Mass]
Separation [Astronomical Units (AU)]
0
5
10
15
20
0
20
40
60
80
100

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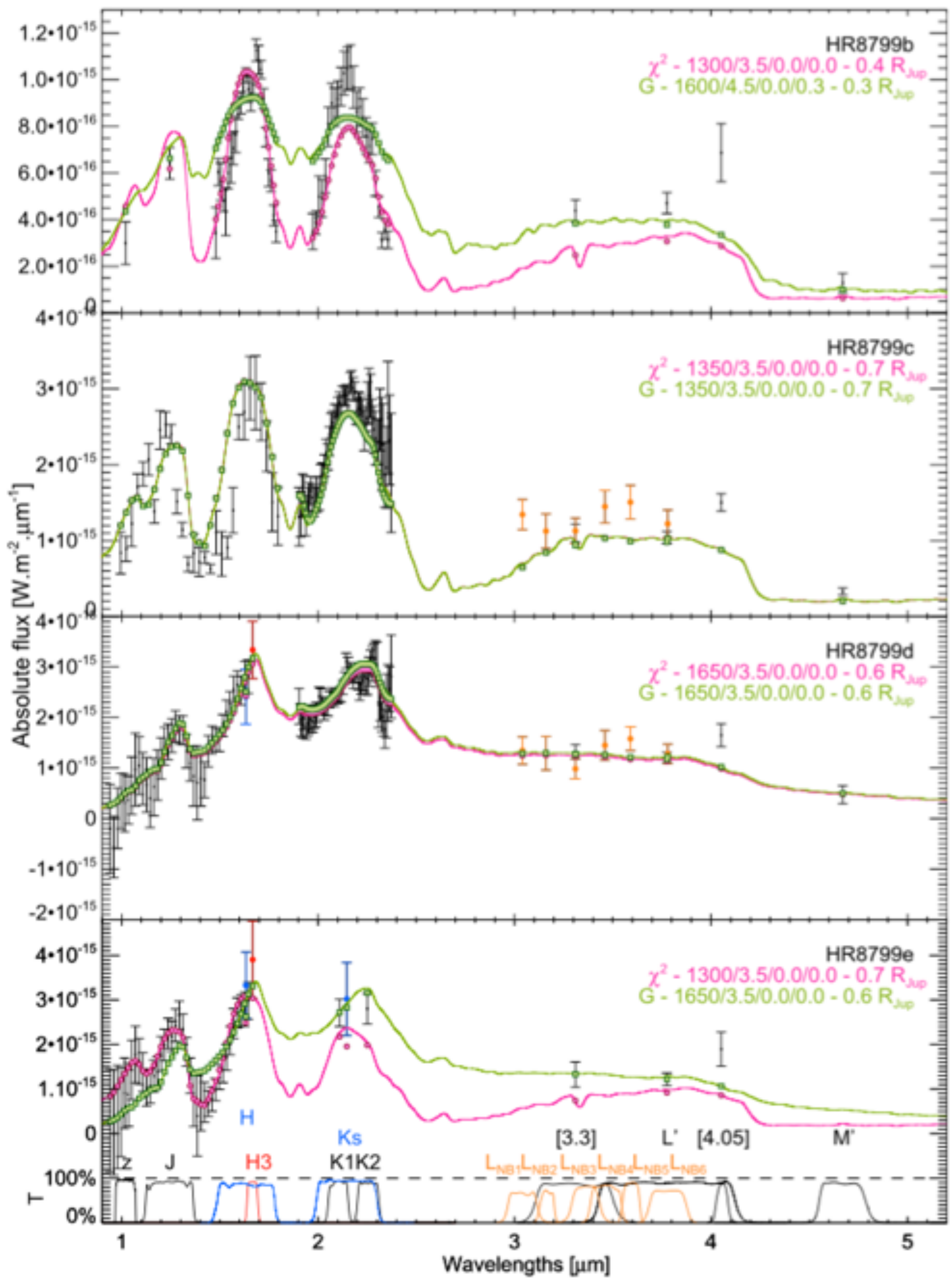
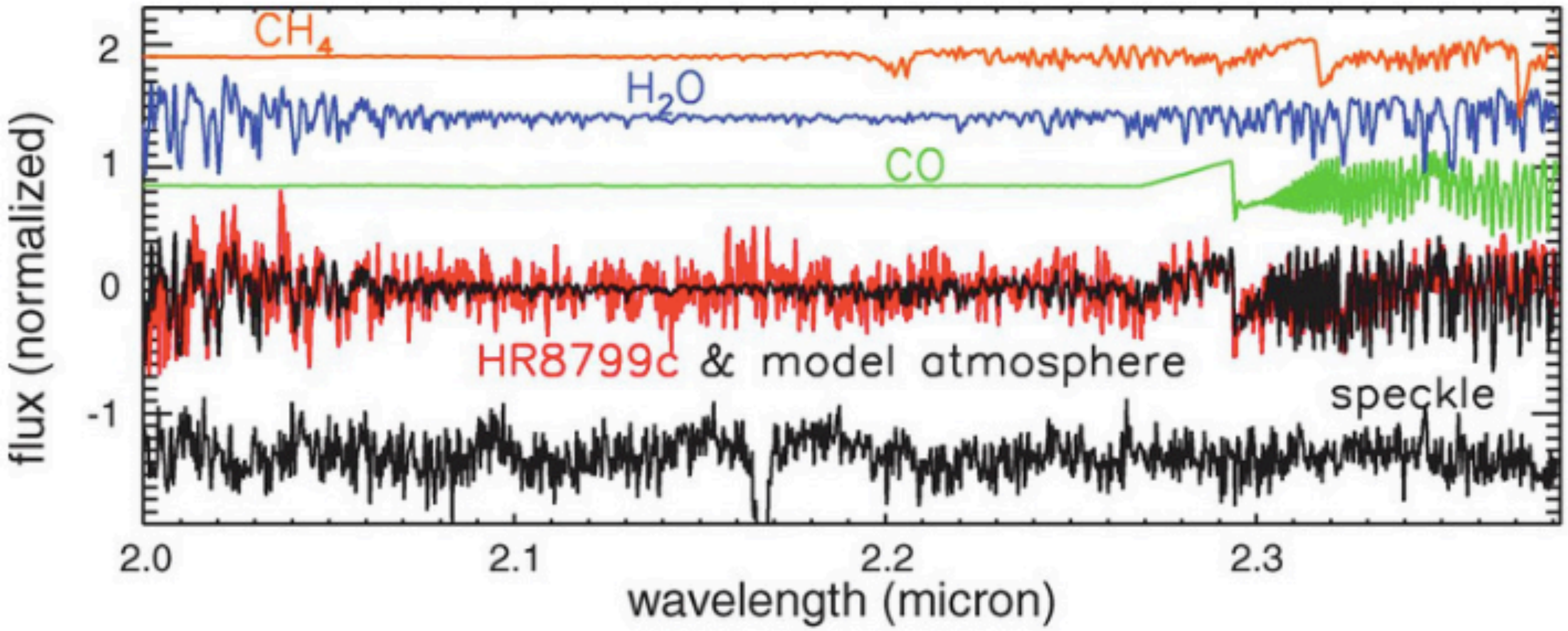
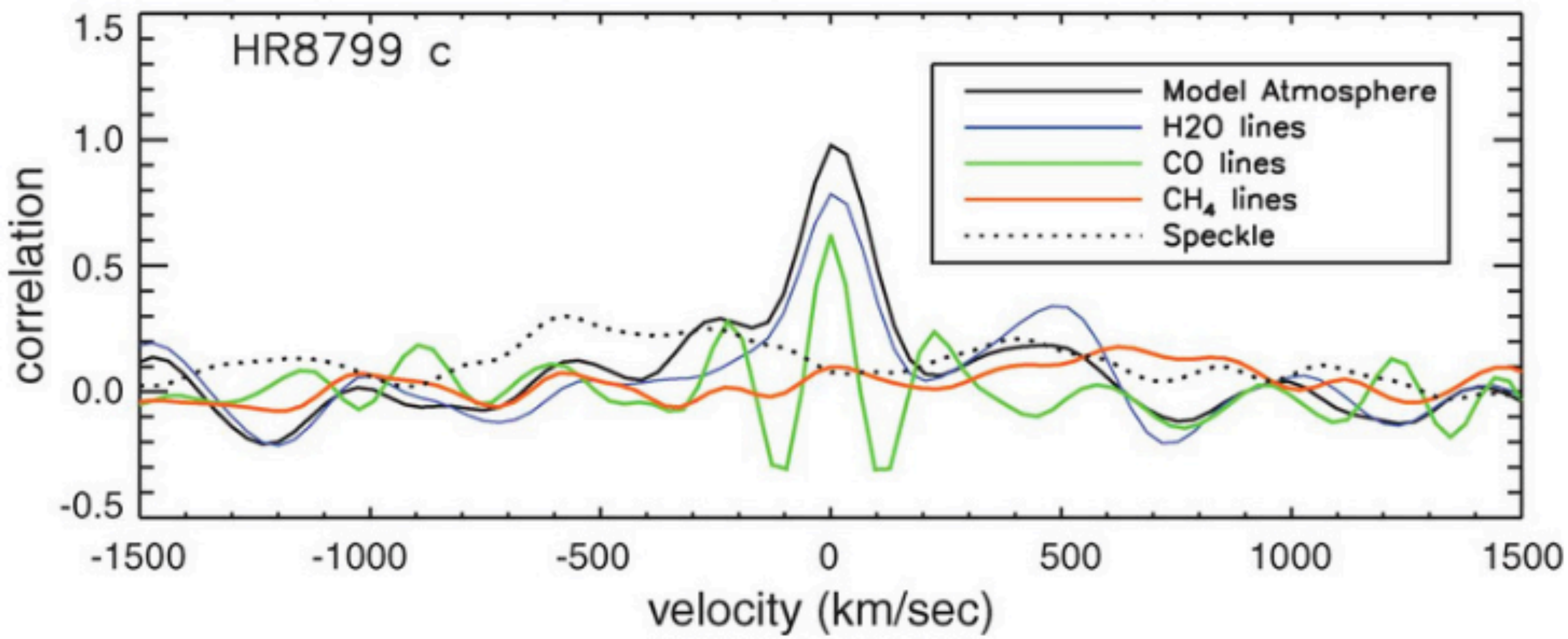


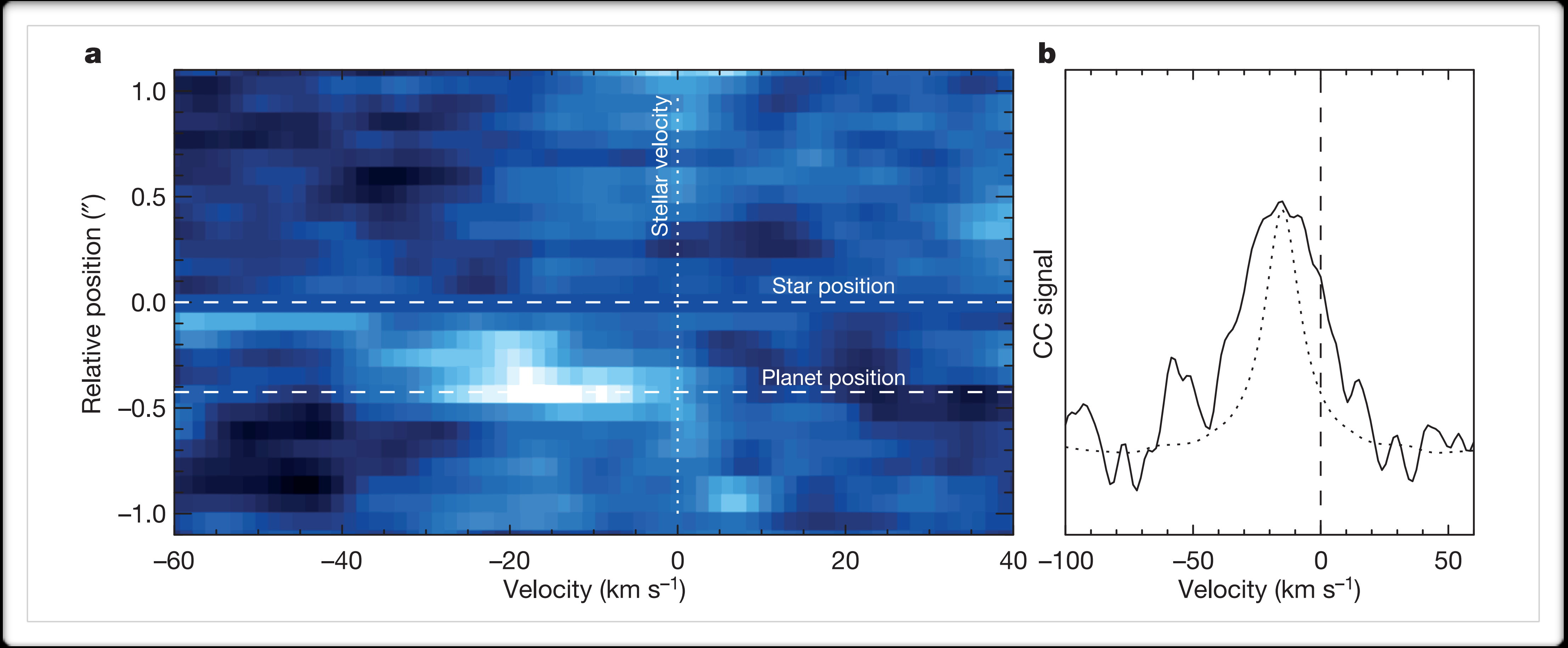
Bonnefoy et al. 2014





Konopacky et al. 2013

MEASURE PLANET SPIN



Snellen et al. 2014

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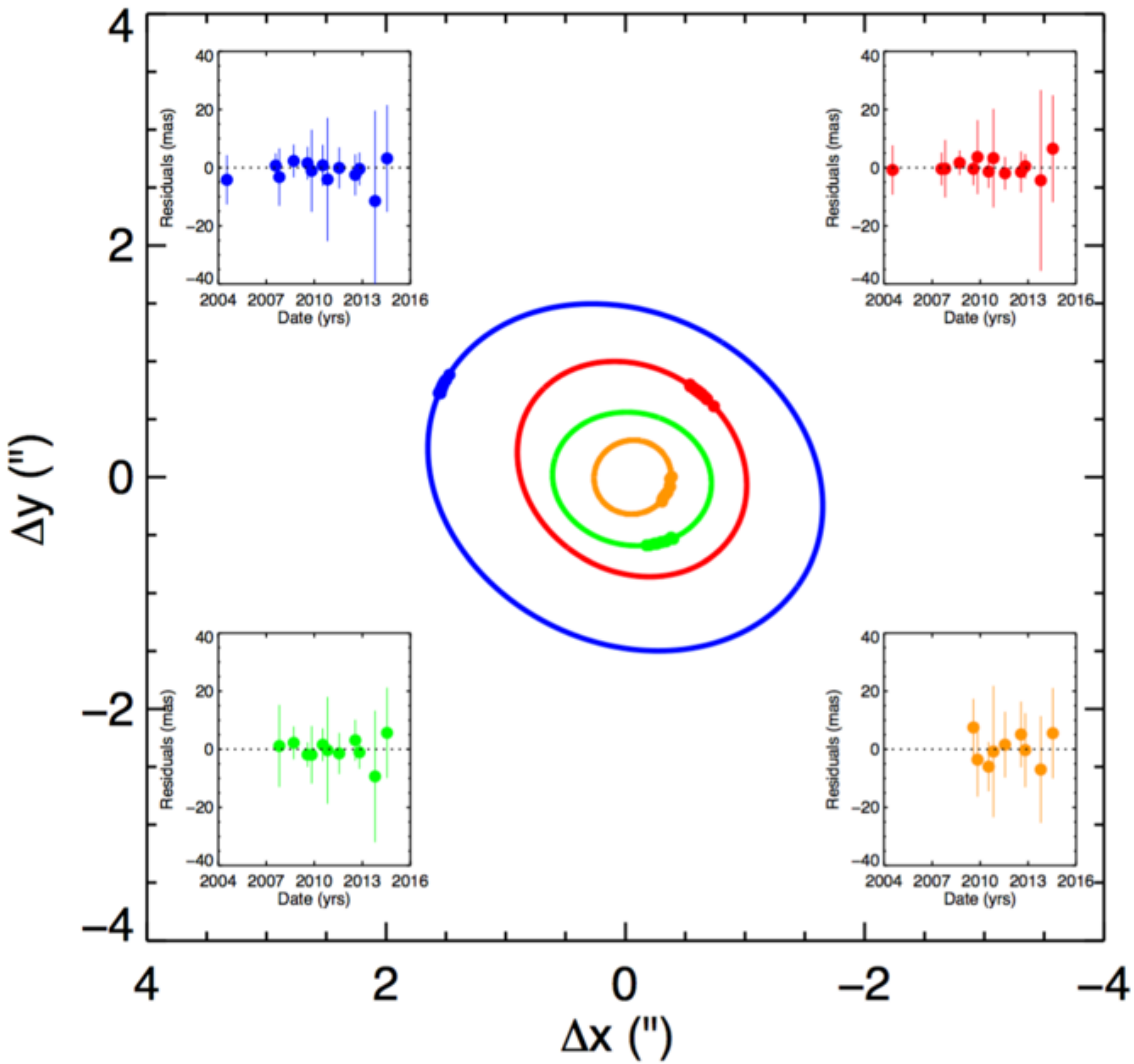
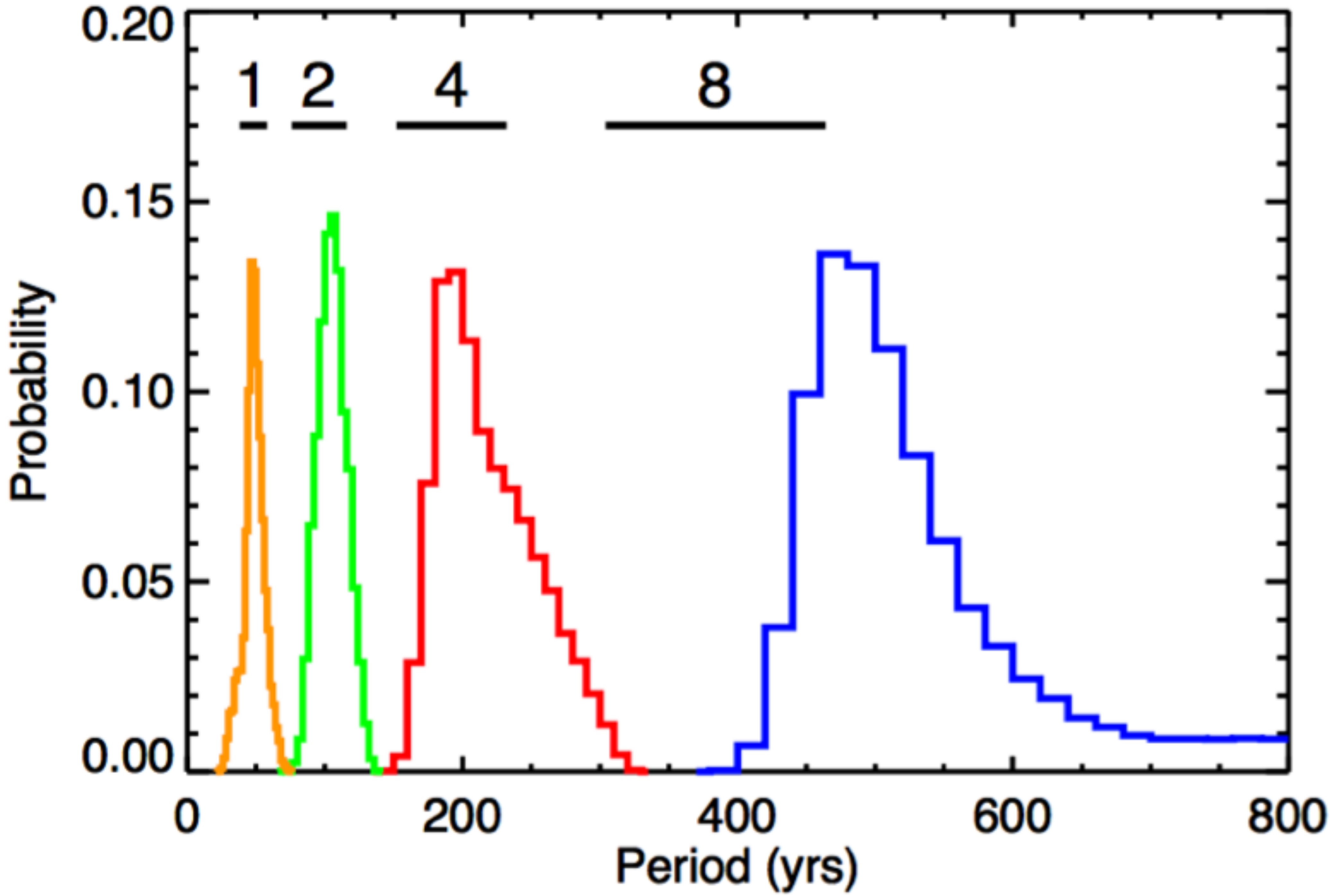


Konopacky et al. 2016



Konopacky et al. 2016

BETA PICTORIS B ORBITAL MOTION MOVIE

M. MILLAR-BLANCHAER et al. (2015)

Credit: M. Millar-Blanchaer (Dunlap Institute) & F. Marchis (SETI Institute)

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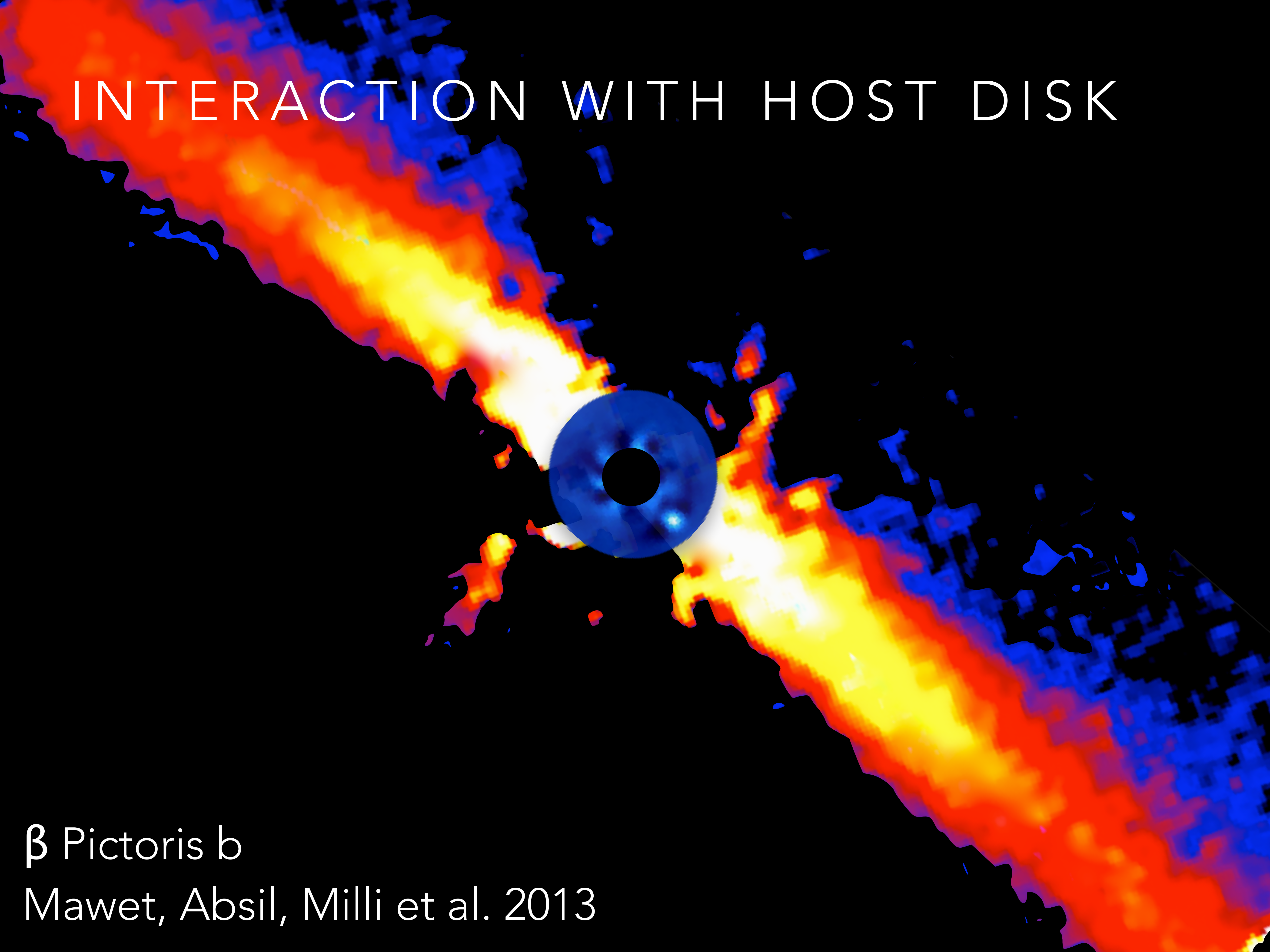
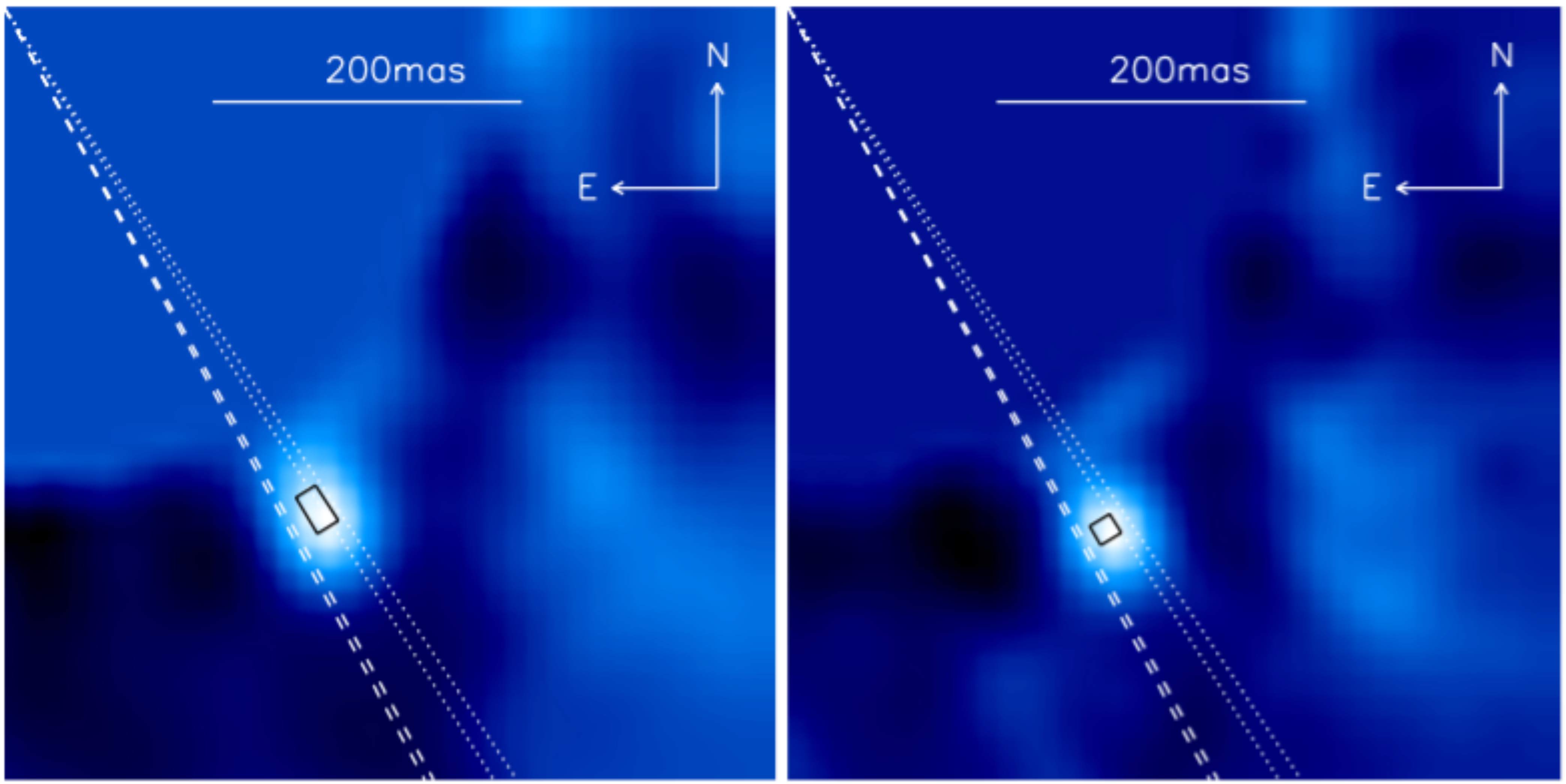

INTERACTION WITH HOST DISK
β Pictoris b
Mawet, Absil, Milli et al. 2013



Lagrange et al. 2012

HIGH CONTRAST IMAGING

HIGH CONTRAST IMAGING

Where are the planets?

HIGH CONTRAST IMAGING

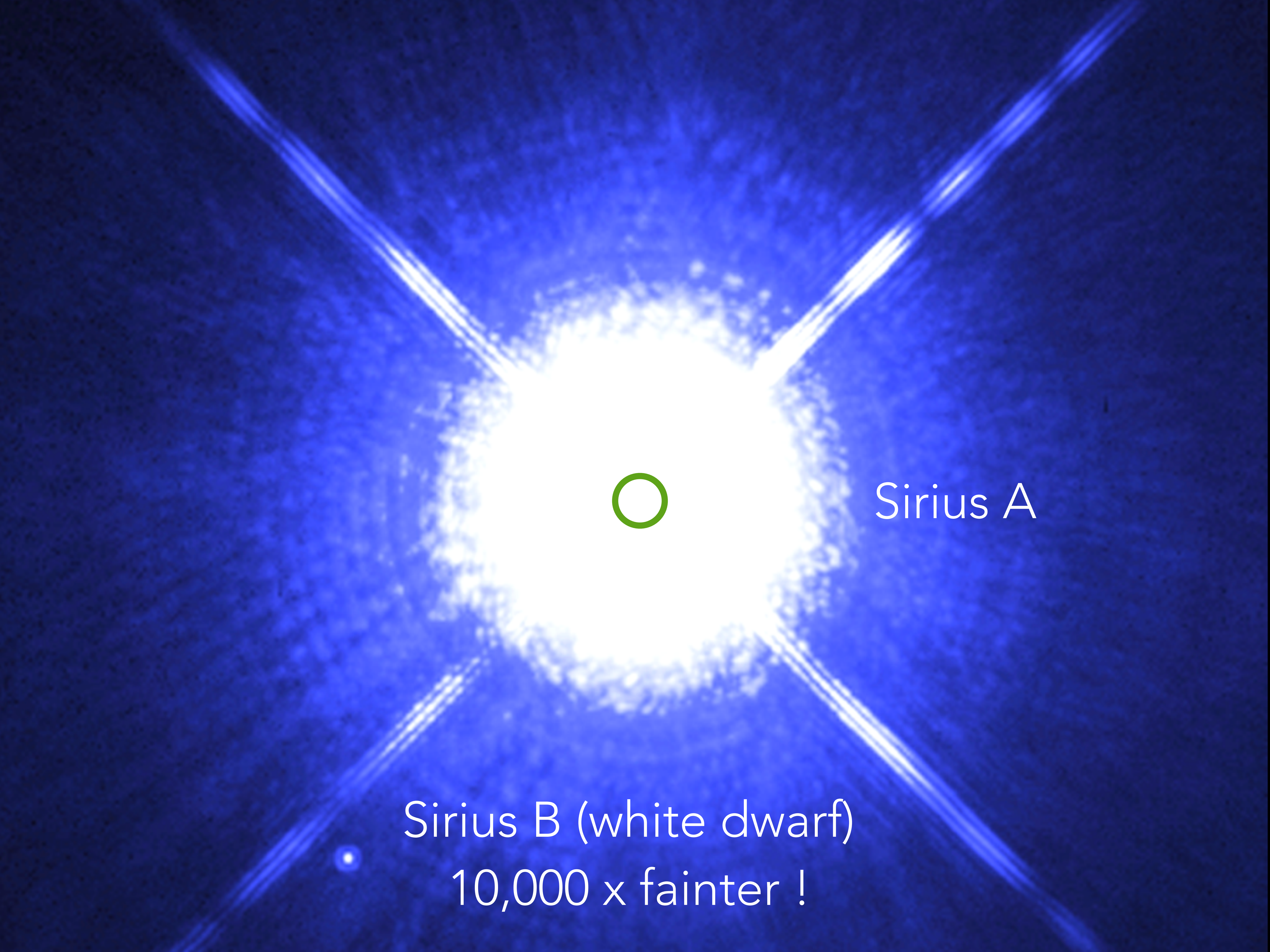
Let's zoom in
adjust contrast

HIGH CONTRAST IMAGING

All the point sources in the field of view are stars!

HIGH CONTRAST IMAGING

Stars are bright!


Sirius A
Sirius B (white dwarf)
10,000 x fainter !

"Imaging exoplanets directly is equivalent to spotting a tiny ember flying off a blazing campfire 200 km away, while looking through a dirty window."

Angular separation:

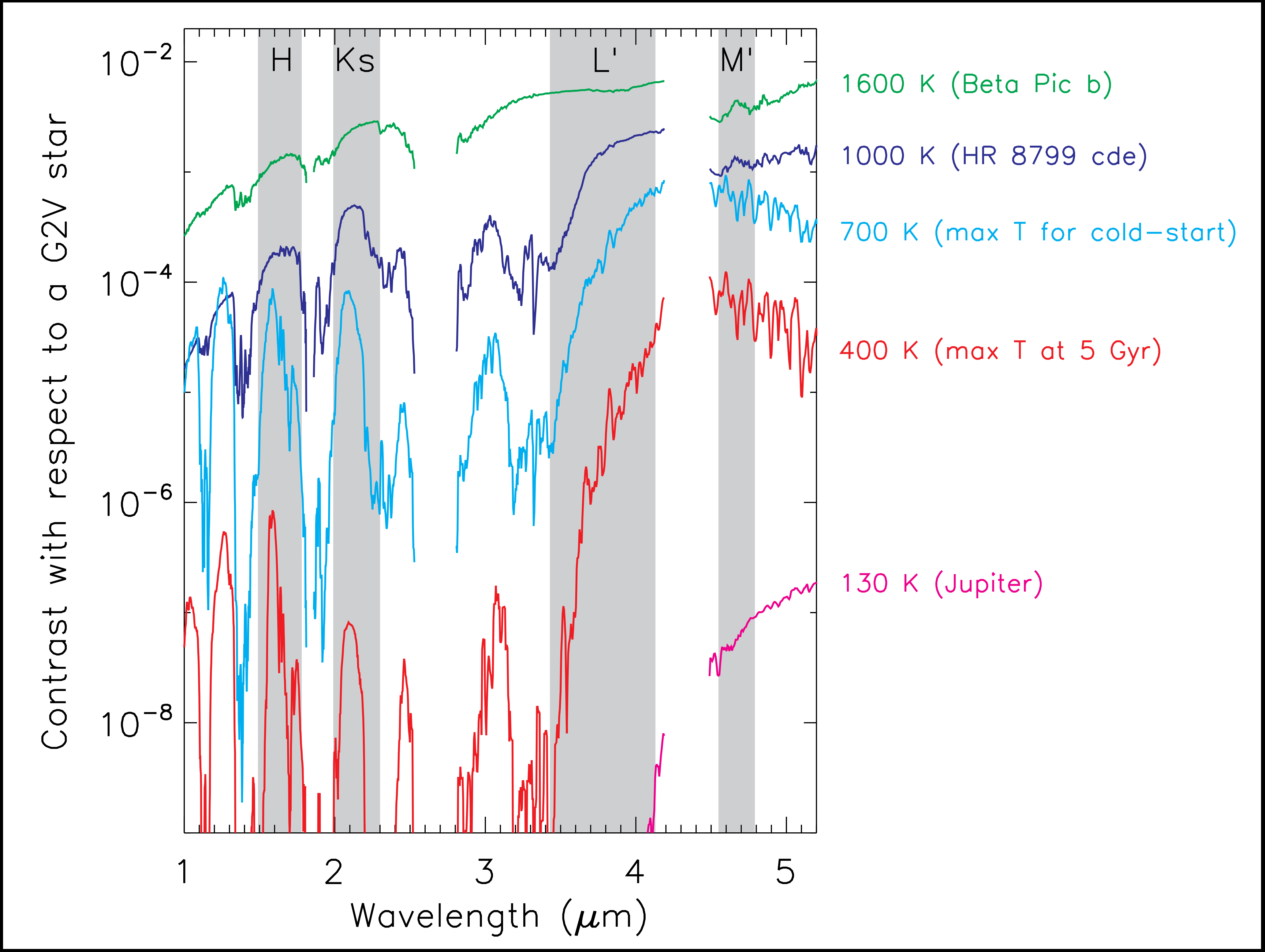
0".1, or 0.5 μrad

Planet to star contrast:

10^{-6} (hot young giant planets),

10^{-10} Earth-like planets around Solar-type stars

GIANT PLANET CONTRAST

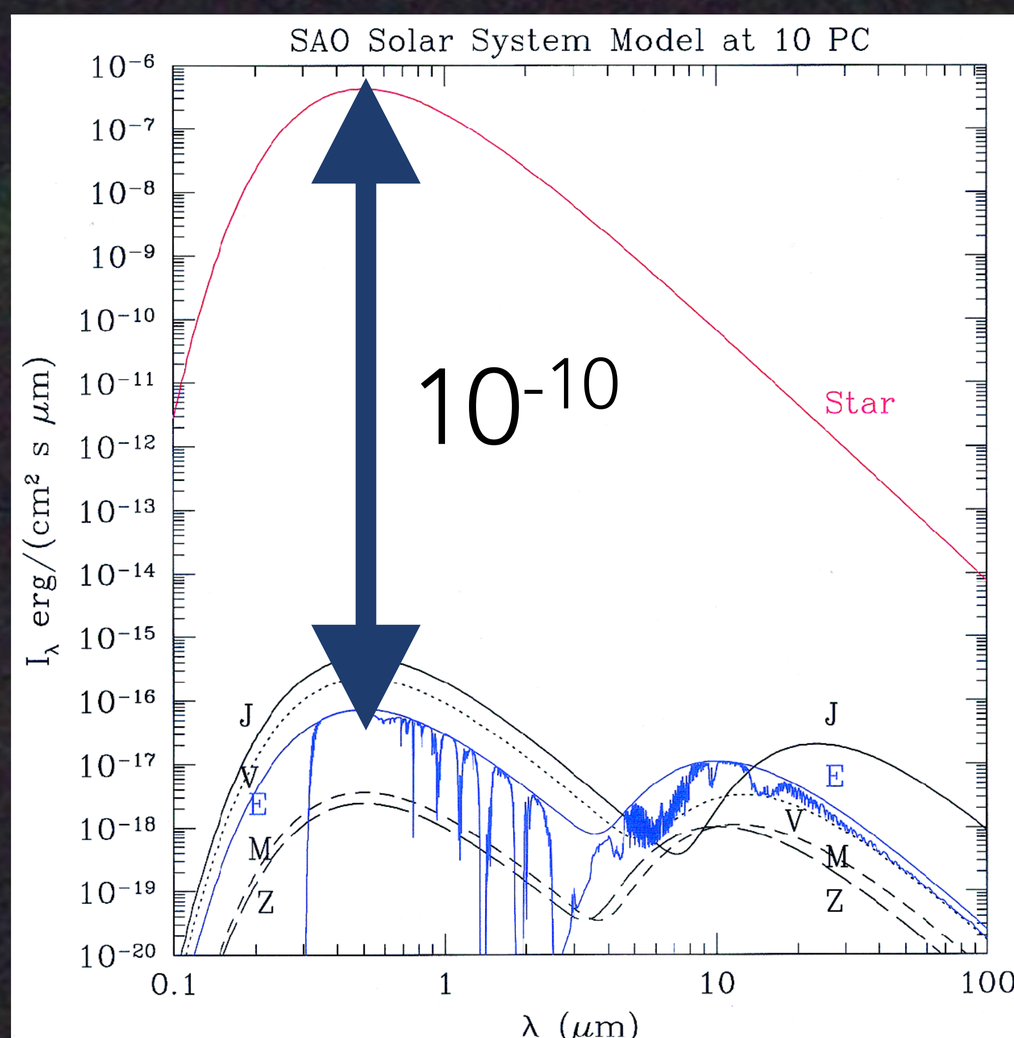


Skemer et al. 2014

(VERY) PALE BLUE DOT

Taken on Feb 14, 1990, by Voyager 1 from 3.7 billion miles

10^{-10}



DesMarais et al. 2002

4 PILLARS OF HIGH CONTRAST IMAGING

- Adaptive optics
- Coronagraphy
- Differential imaging
- Post-processing

- Know your star (age, L, distance, proper motion, etc.)!

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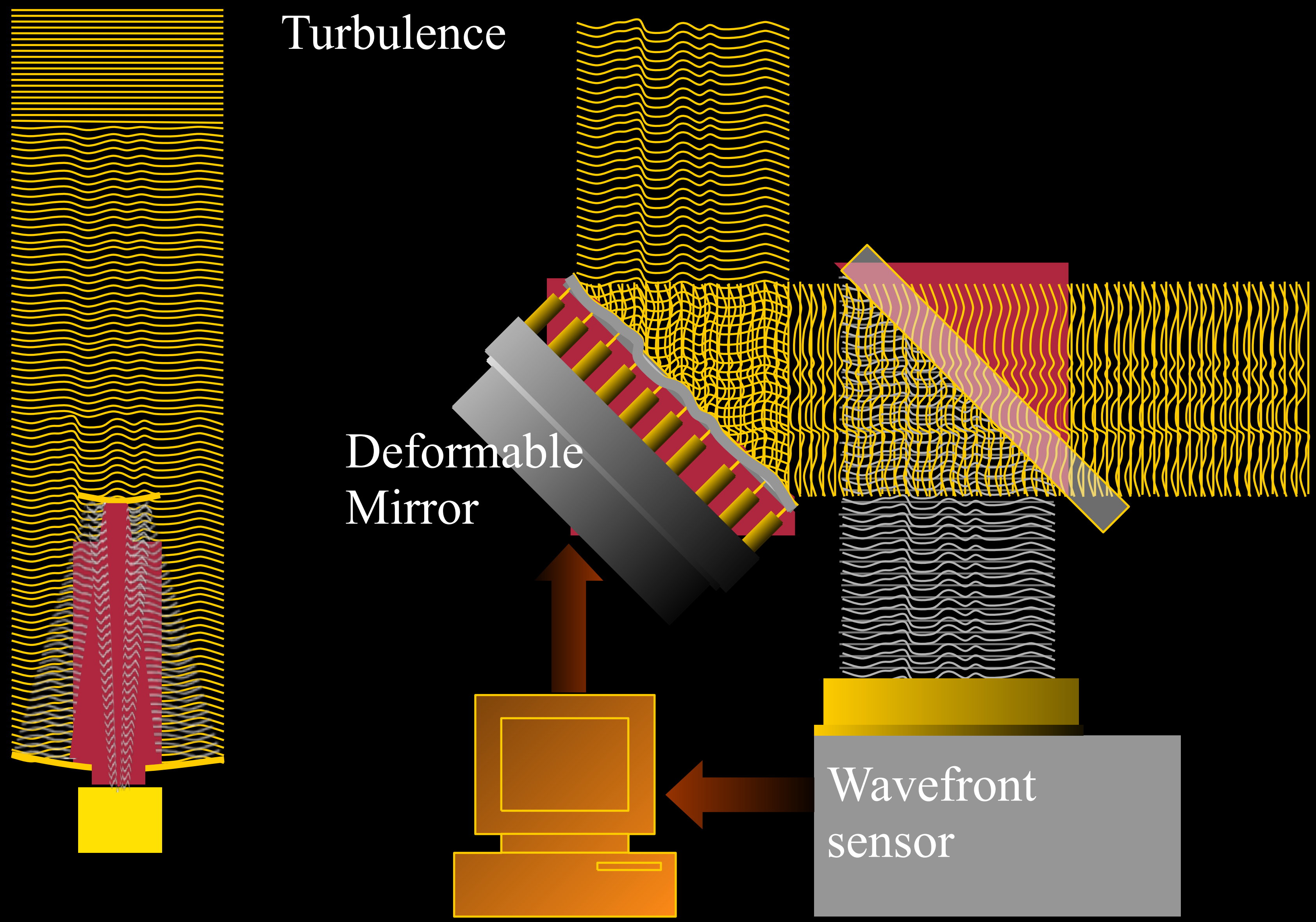
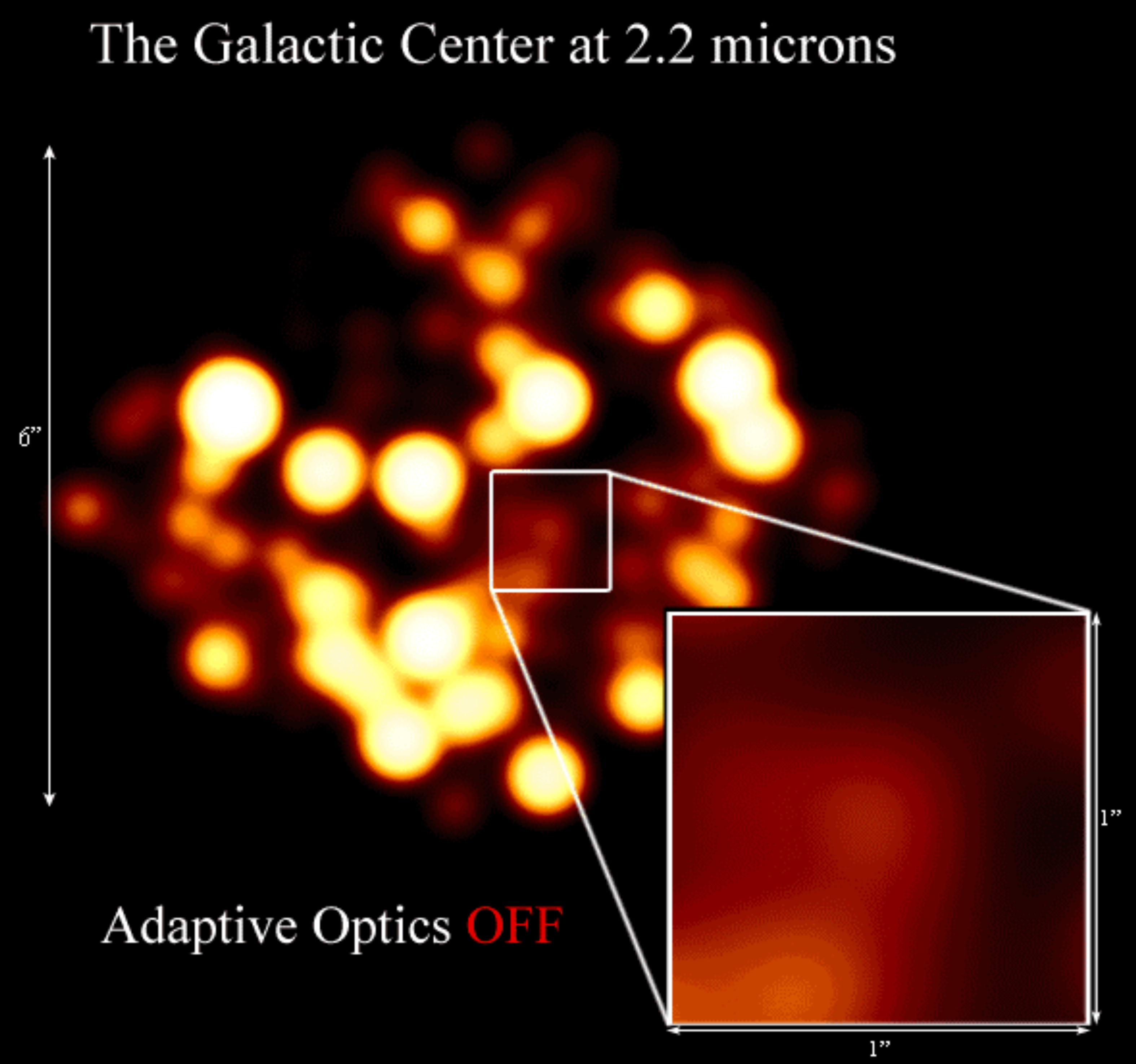
ADAPTIVE OPTICS 101



ADAPTIVE OPTICS IN ACTION



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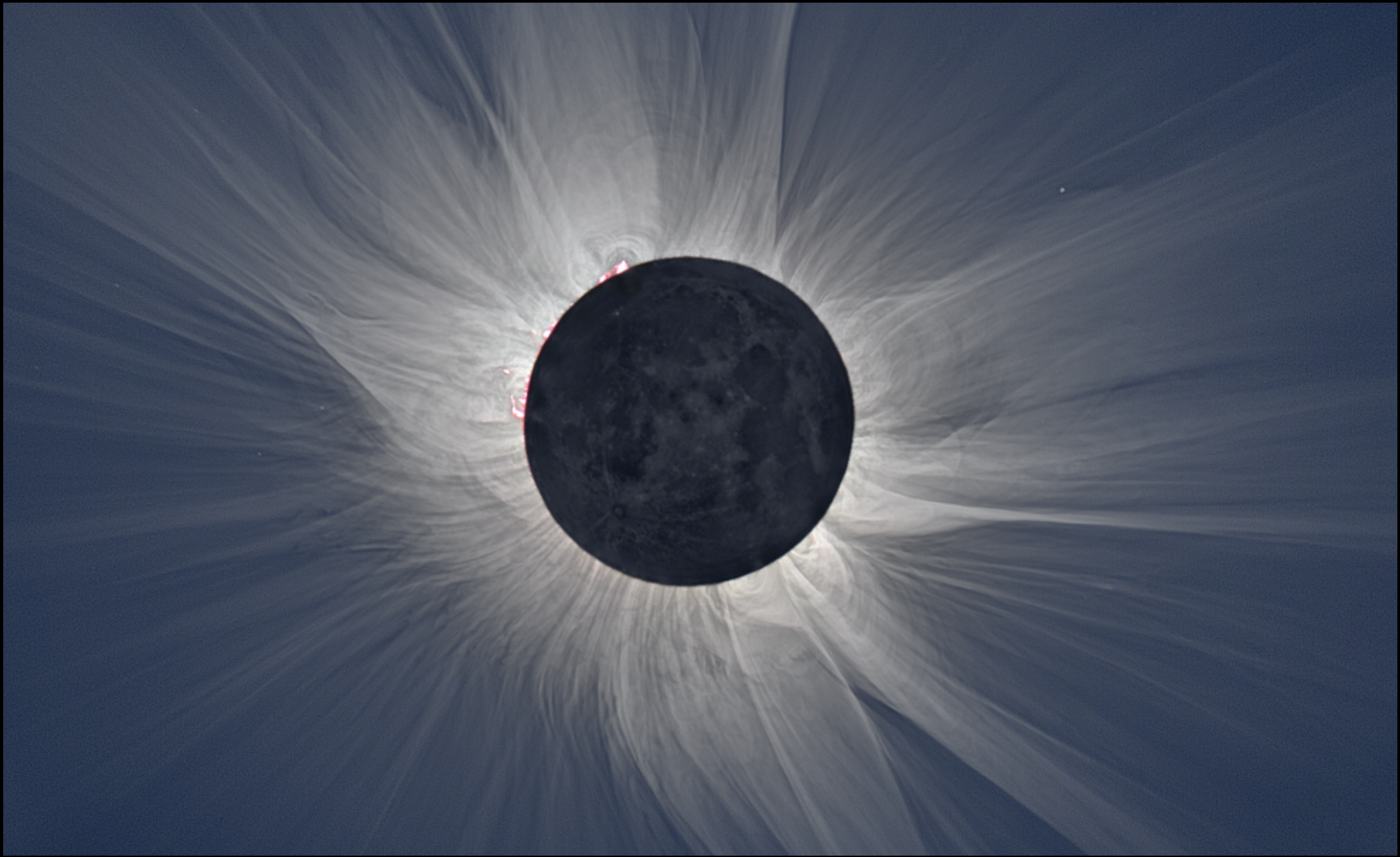
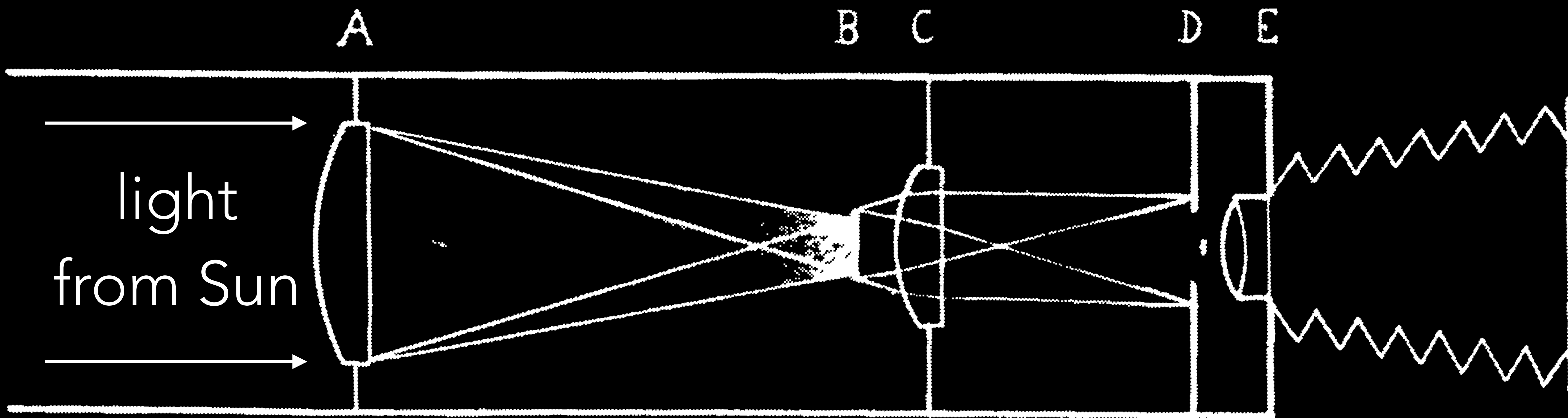
CREATING ARTIFICIAL ECLIPSES



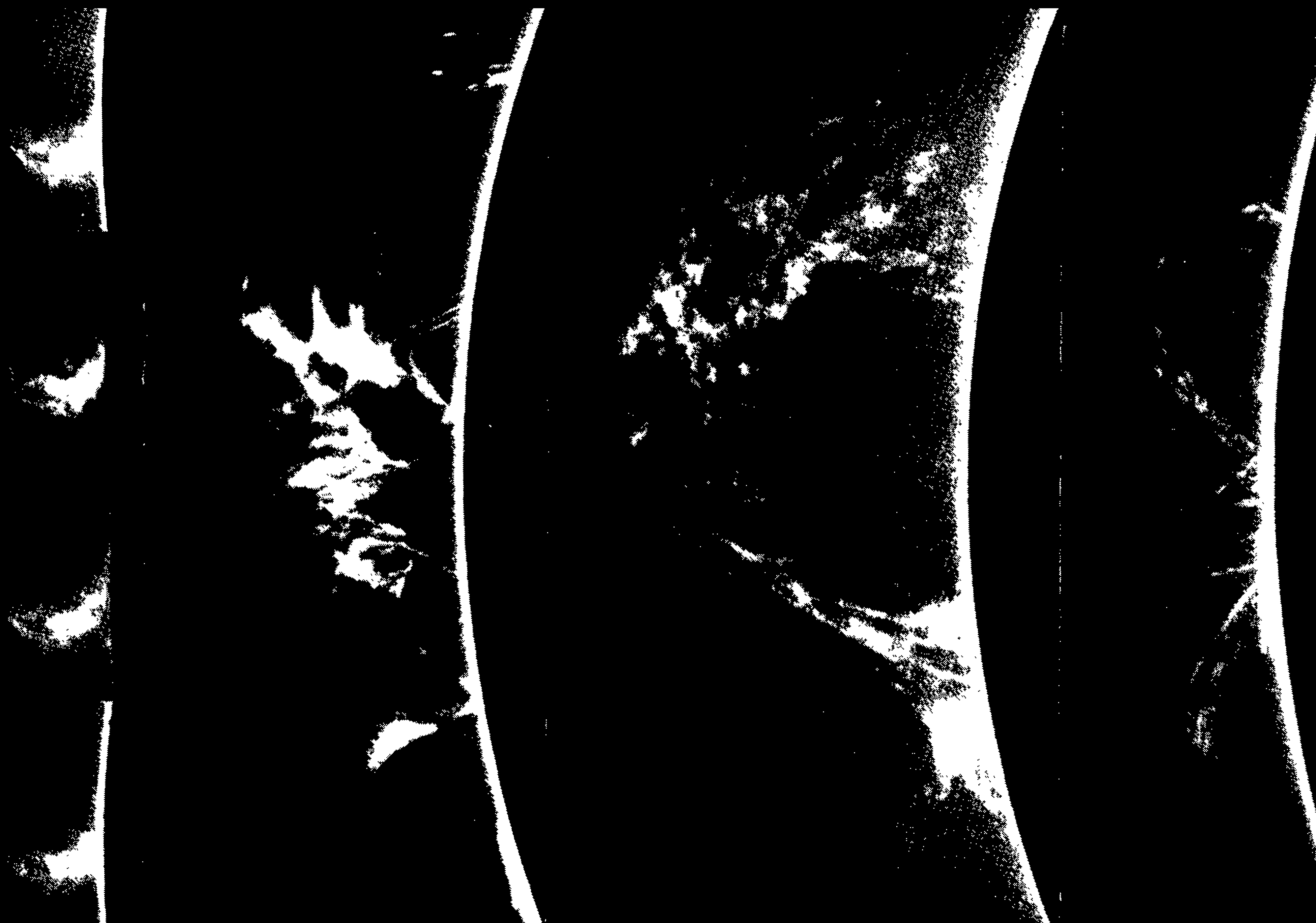
CORONAGRAPHY, BERNARD LYOT 1930

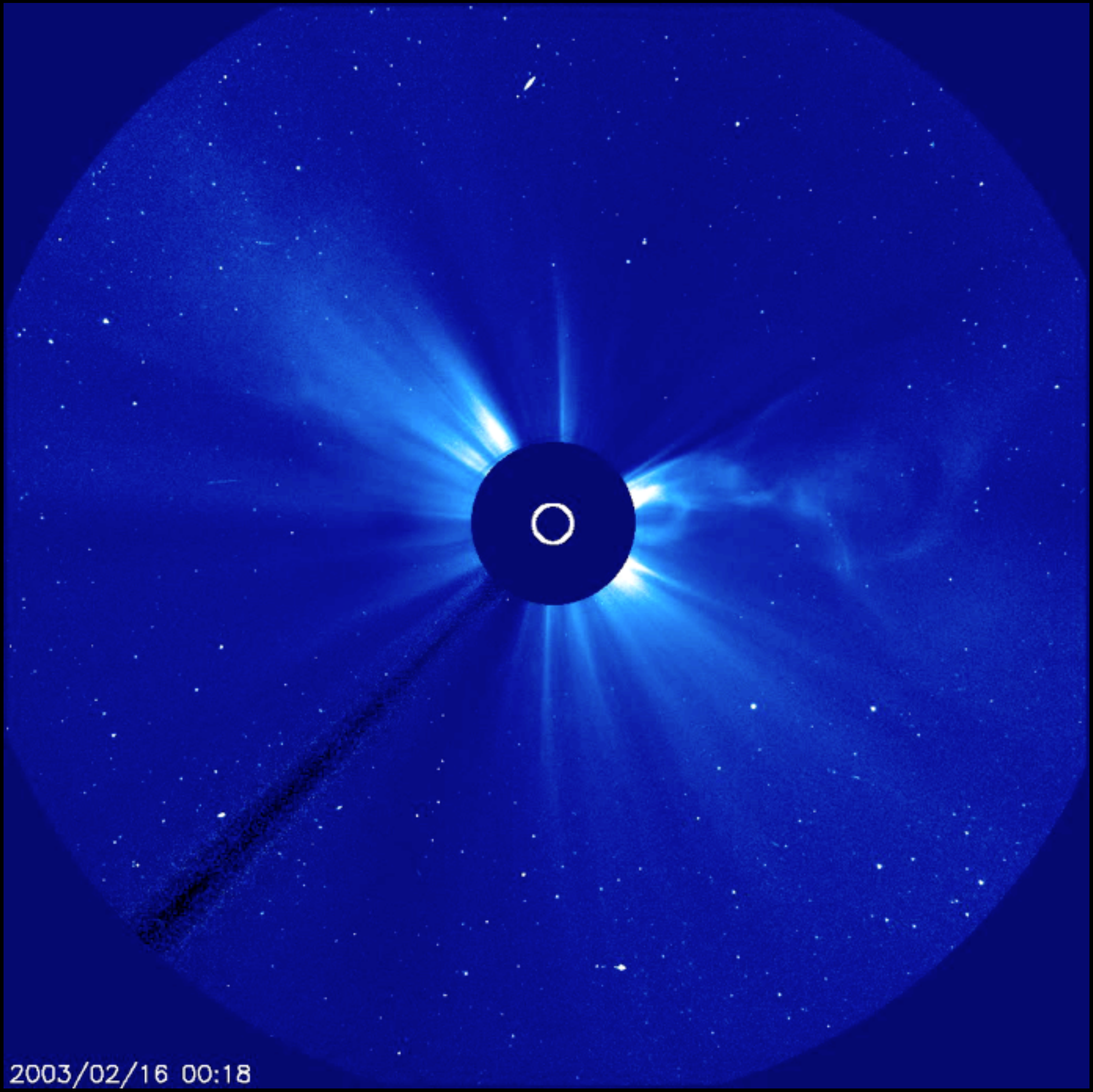
"The rareness of total eclipses of the Sun, their short duration and the distances one has to travel to observe them have, for more than half a century, led astronomers and physicists to seek for a method which enables them to study the corona at any time."

LYOT'S CORONAGRAPH



SOLAR CORONA IN 1930S WITH LYOT'S CORONAGRAPH!

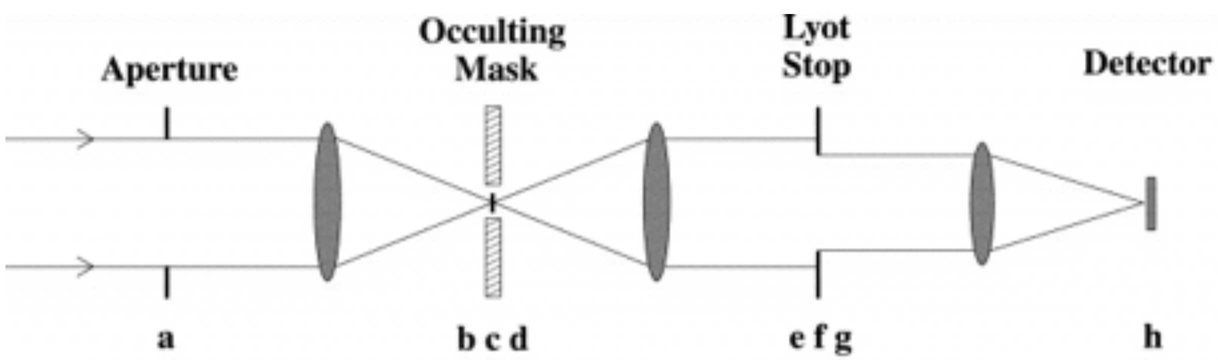


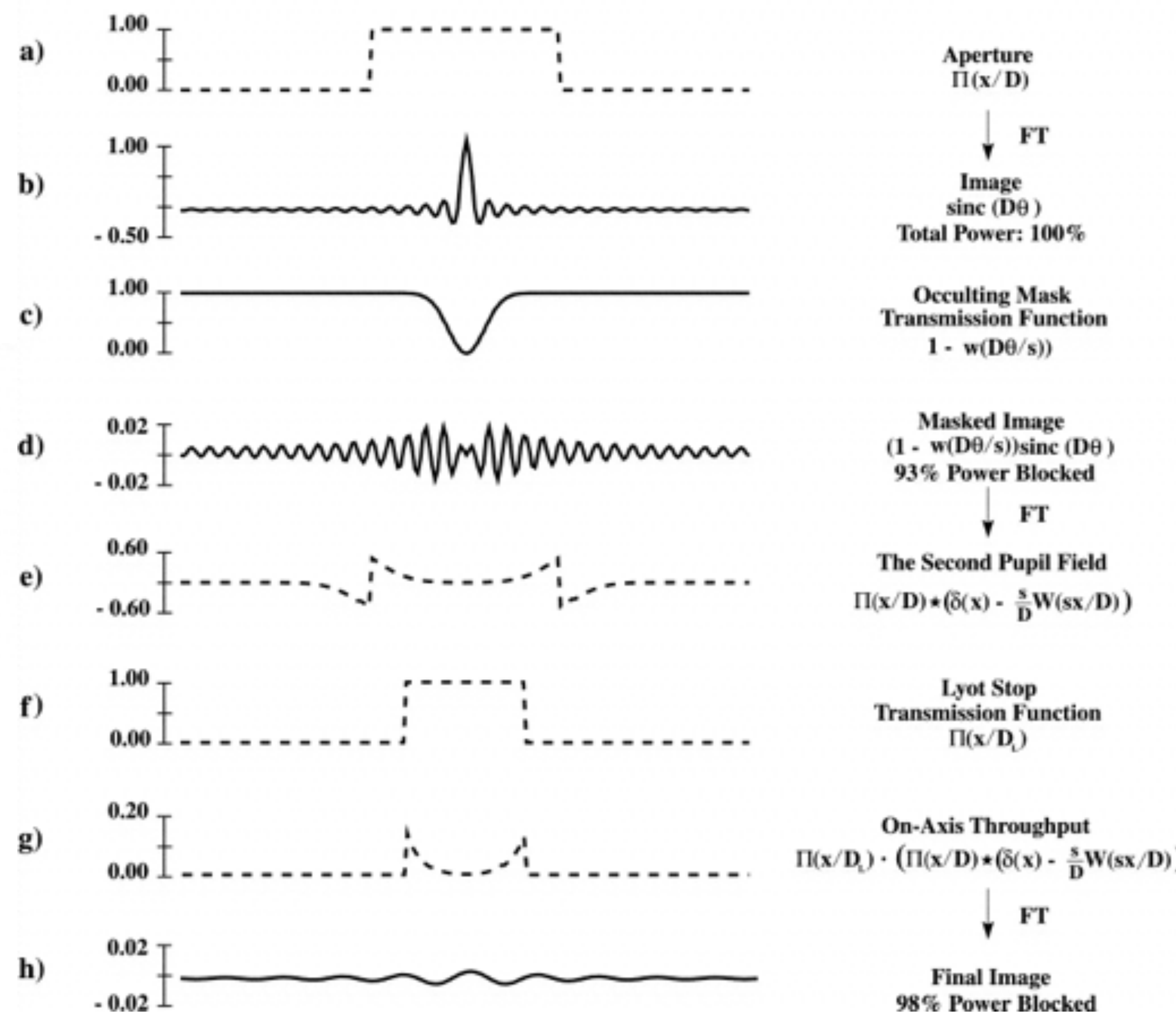

2003/02/16 00:18

DEFINITION AND TERMINOLOGY

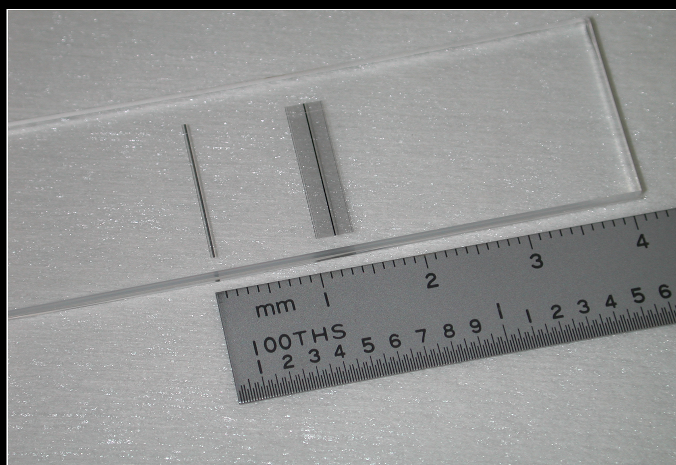
- *"A coronagraph is an optical device designed to suppress (or strongly attenuate) the on-axis coherent starlight while allowing the off-axis planet (or circumstellar disk) light to transmit through."*
- <u>Important definitions:</u>
    - **Contrast**: The ratio of the peak of the stellar point spread function to the noise at the planet location.
    - **Inner Working Angle**: The smallest angle on the sky at which the needed contrast is achieved and the planet is reduced by no more than 50% relative to other angles.
    - **Throughput**: The ratio of the open telescope area remaining after high-contrast is achieved.
    - **Bandwidth**: The wavelengths at which high contrast is achieved.
    - **Sensitivity**: The degree to which contrast is degraded in the presence of aberrations.

LYOT CORONAGRAPH CONT'D: STEP BY STEP

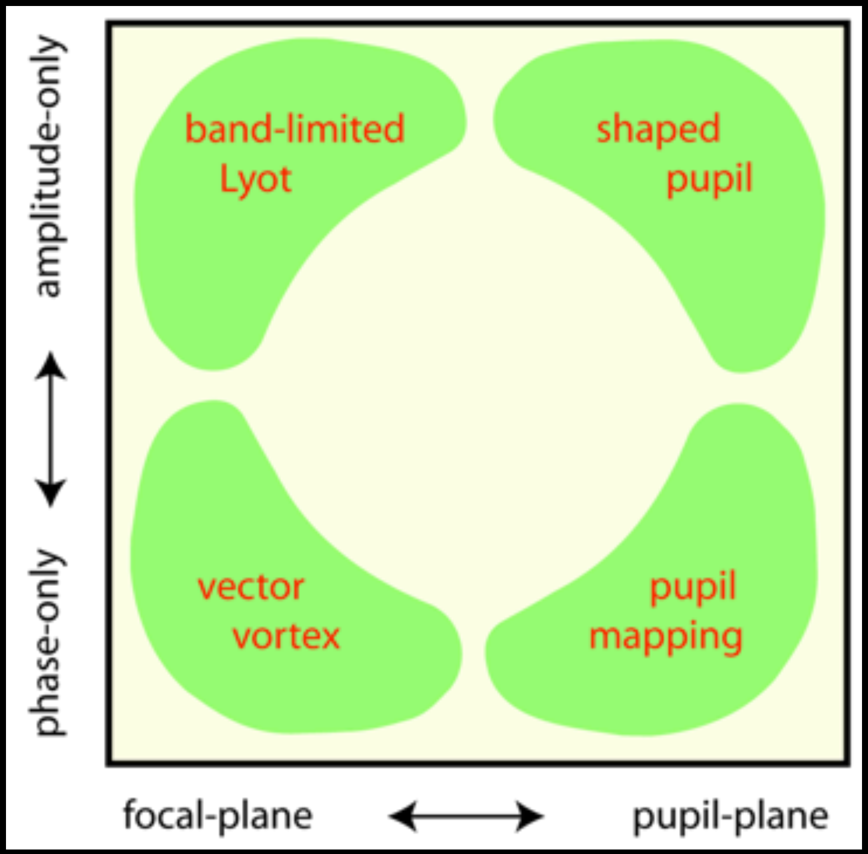


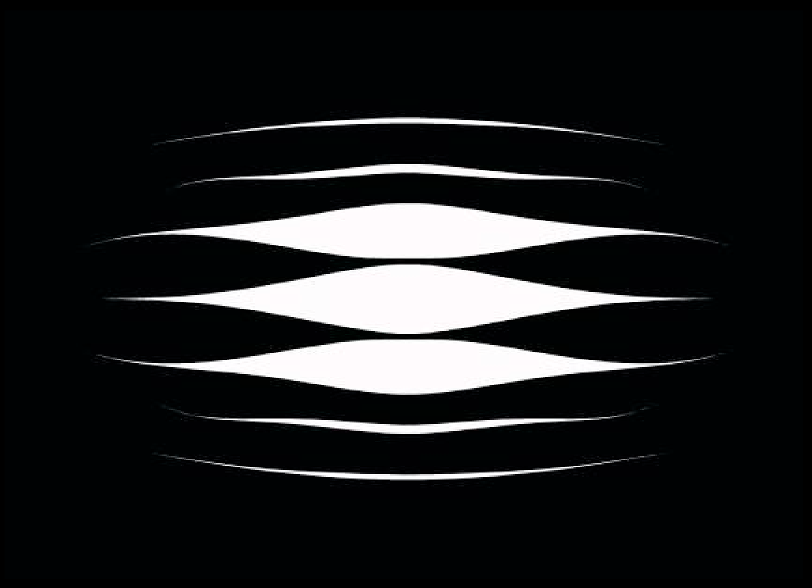


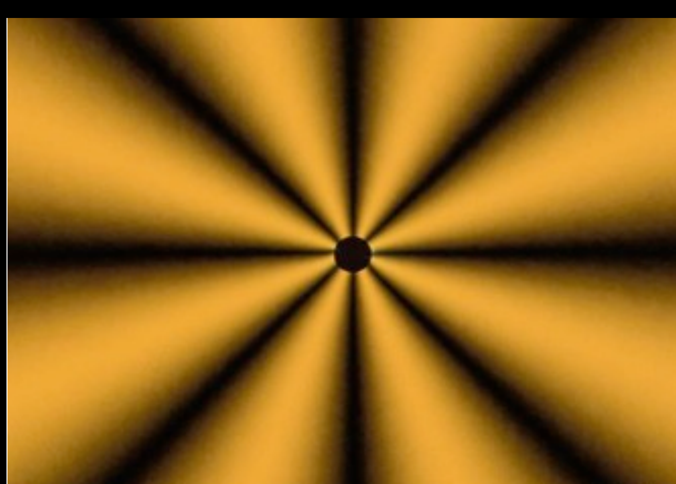
GAMUT OF CORONAGRAPHY

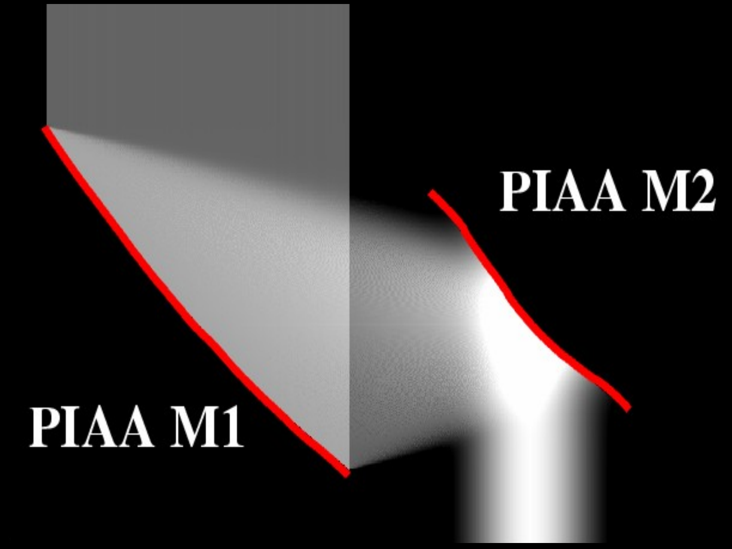


J. Trauger (JPL)

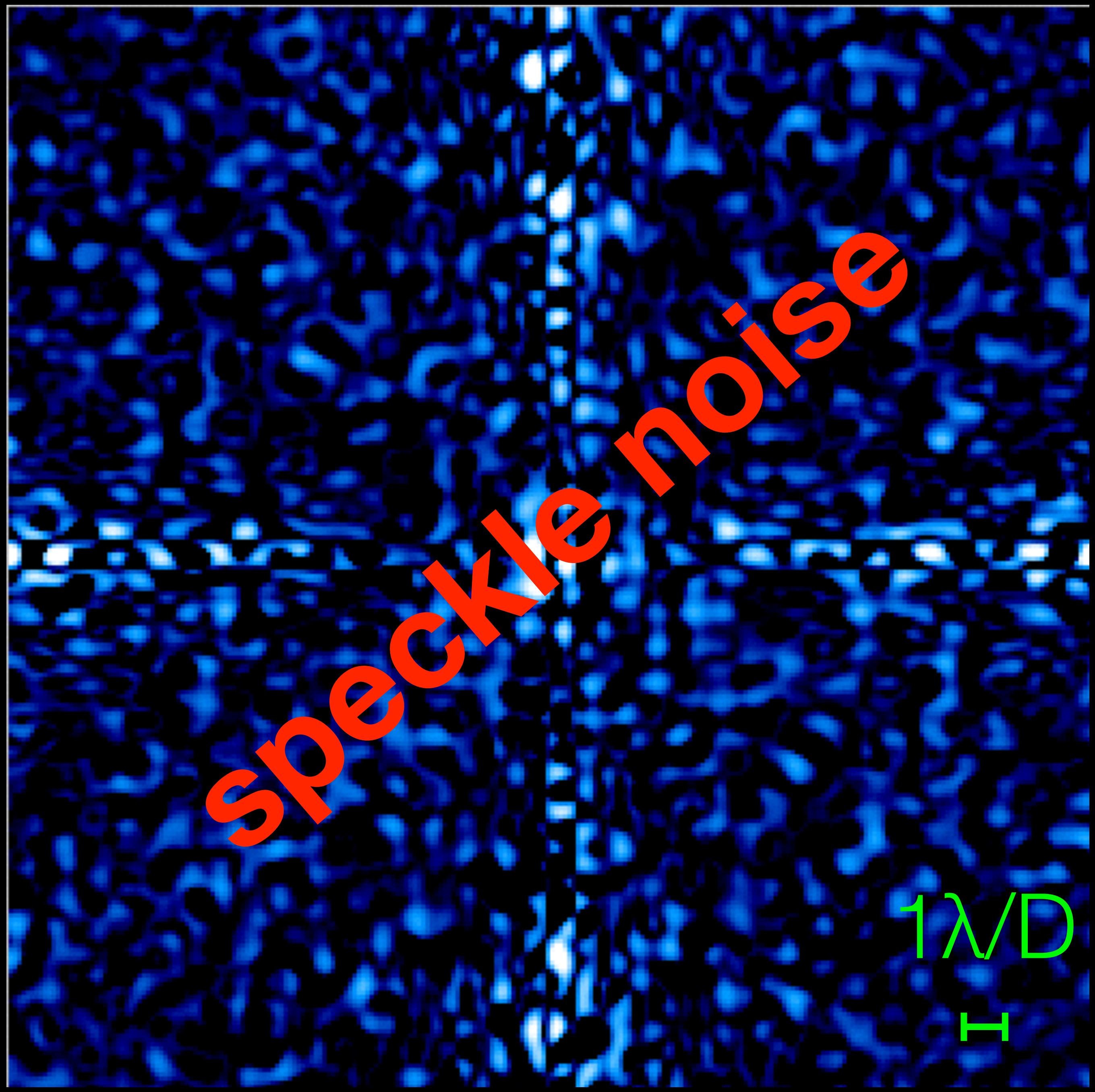


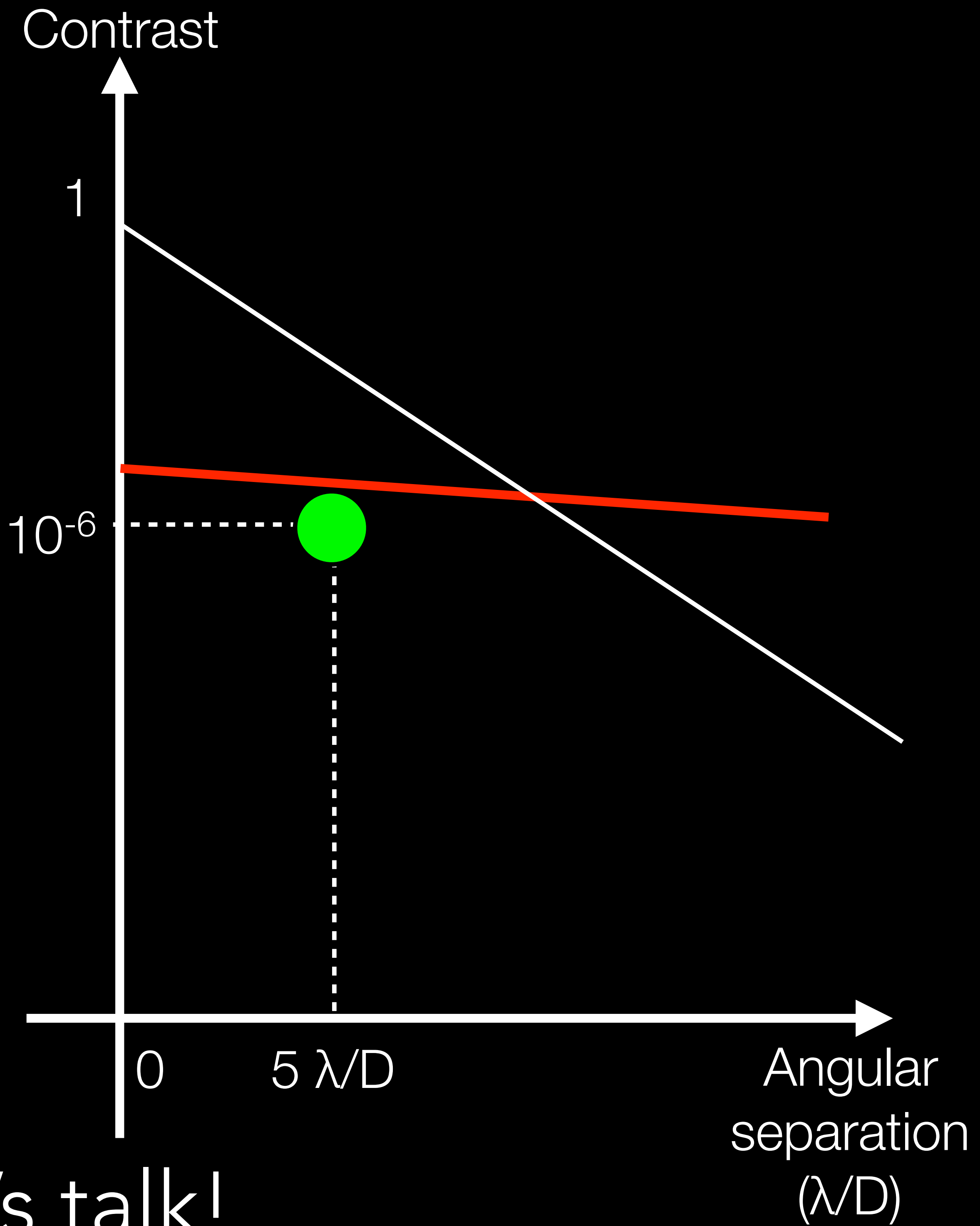






DO YOU SEE THE PLANET AFTER THE CORONAGRAPH? NO?





See Laurent's talk!

Red pill:
image plane
wavefront sensing
& control

Blue pill:
differential
imaging

I’ll have both!

WAVEFRONT CONTROL & CORONAGRAPH IN ACTION

4 PILLARS OF HIGH CONTRAST IMAGING

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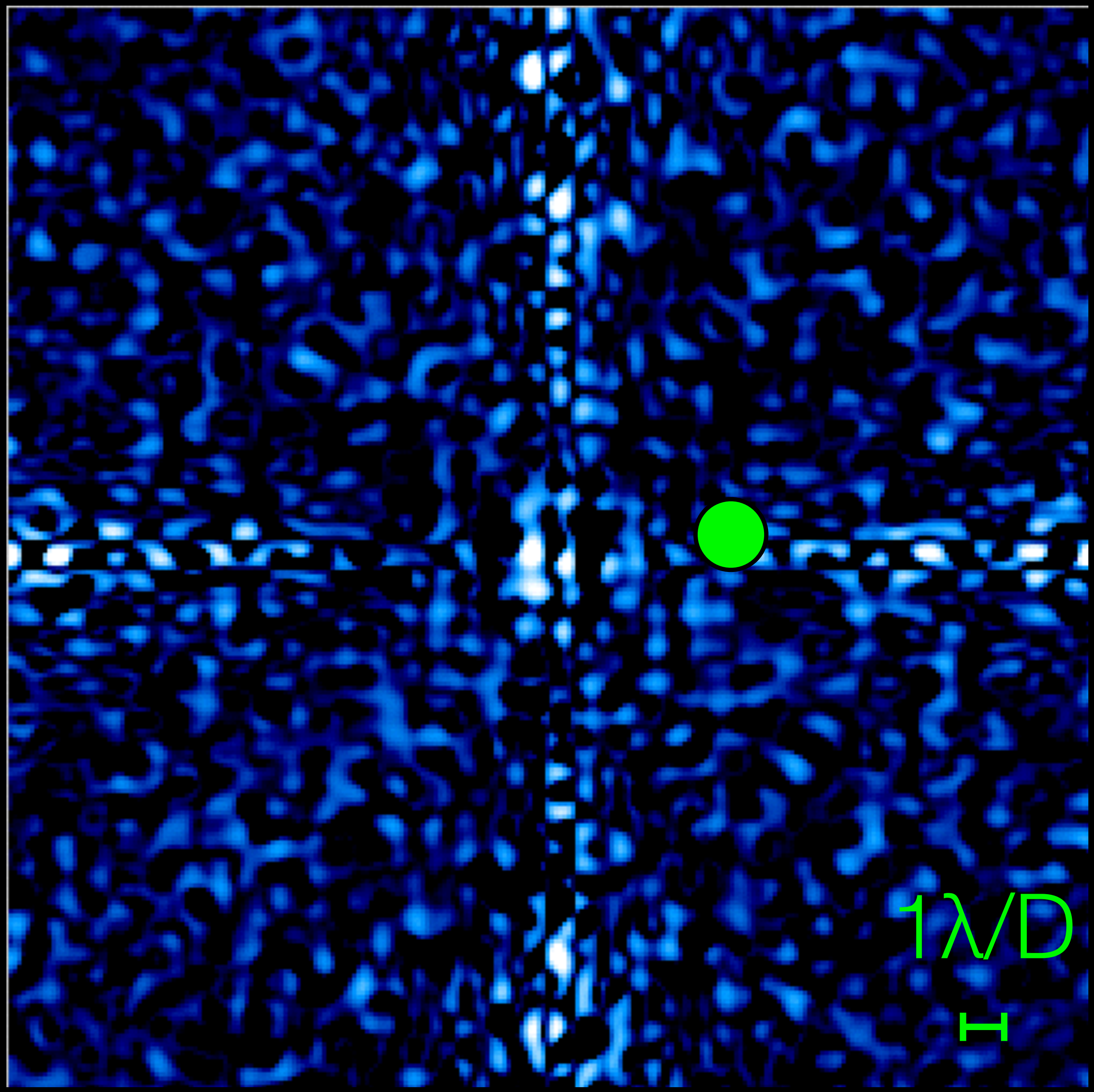
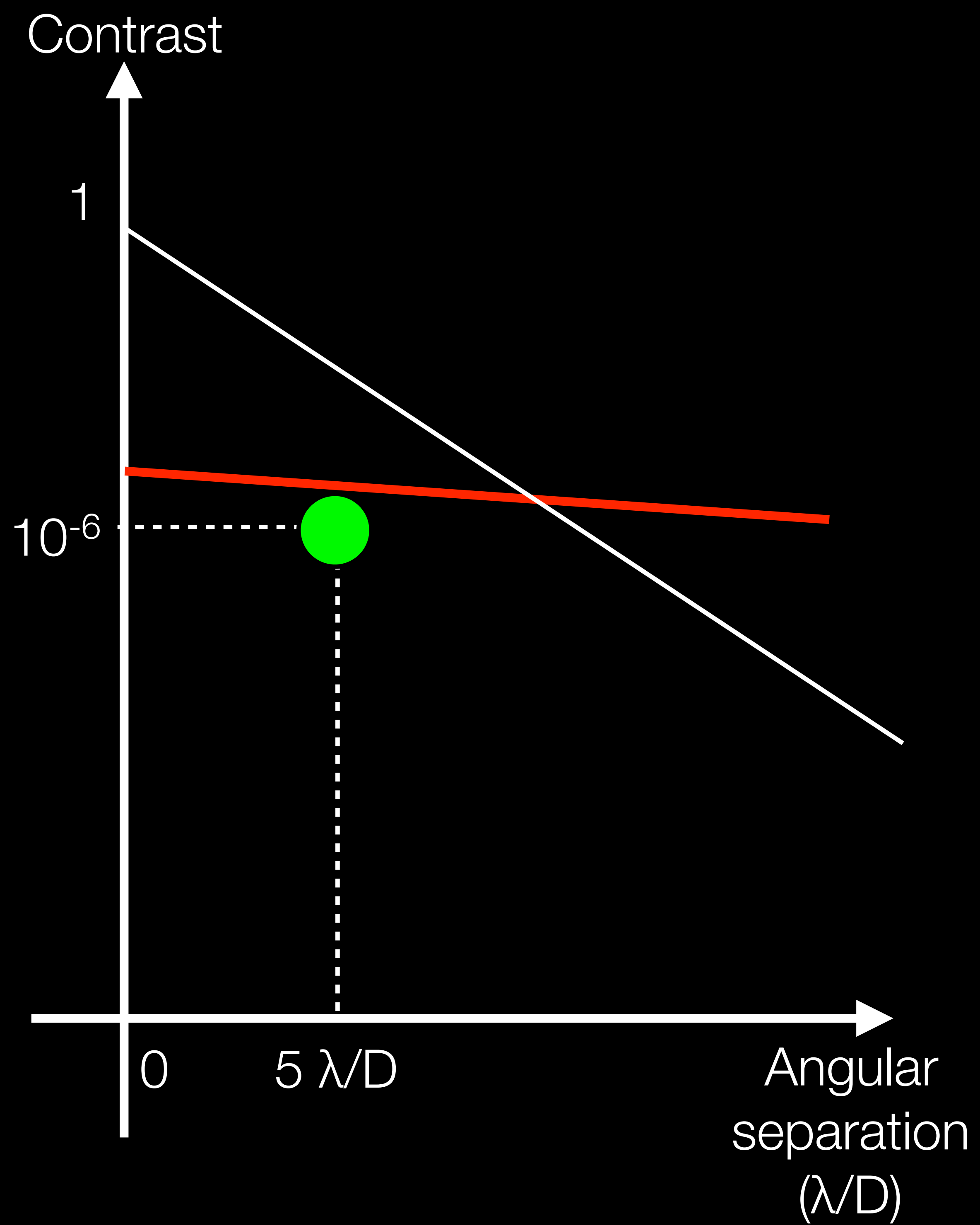
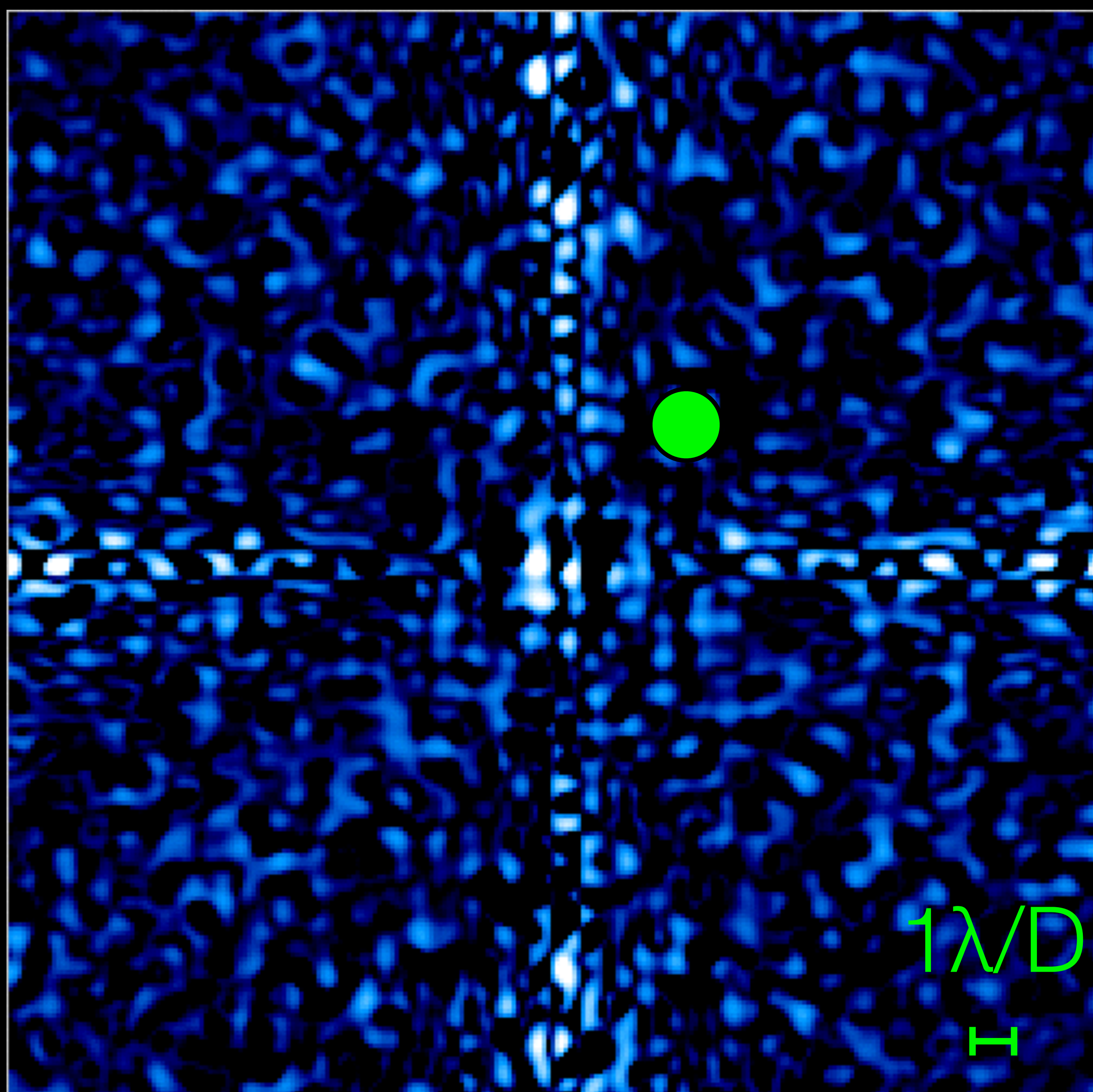
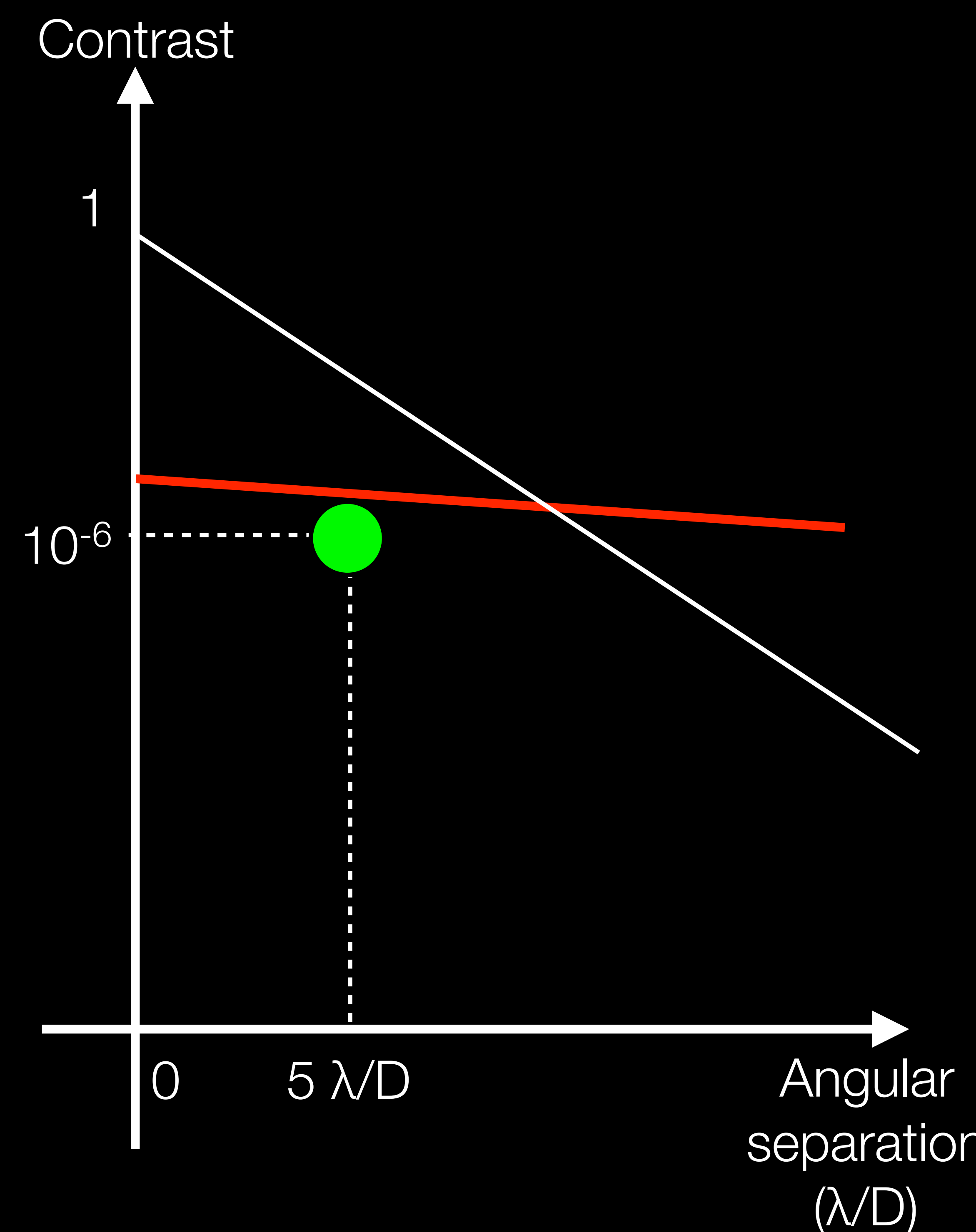
THE PLANET IS 10-1000 FAINTER THAN THE SPECKLE NOISE FLOOR



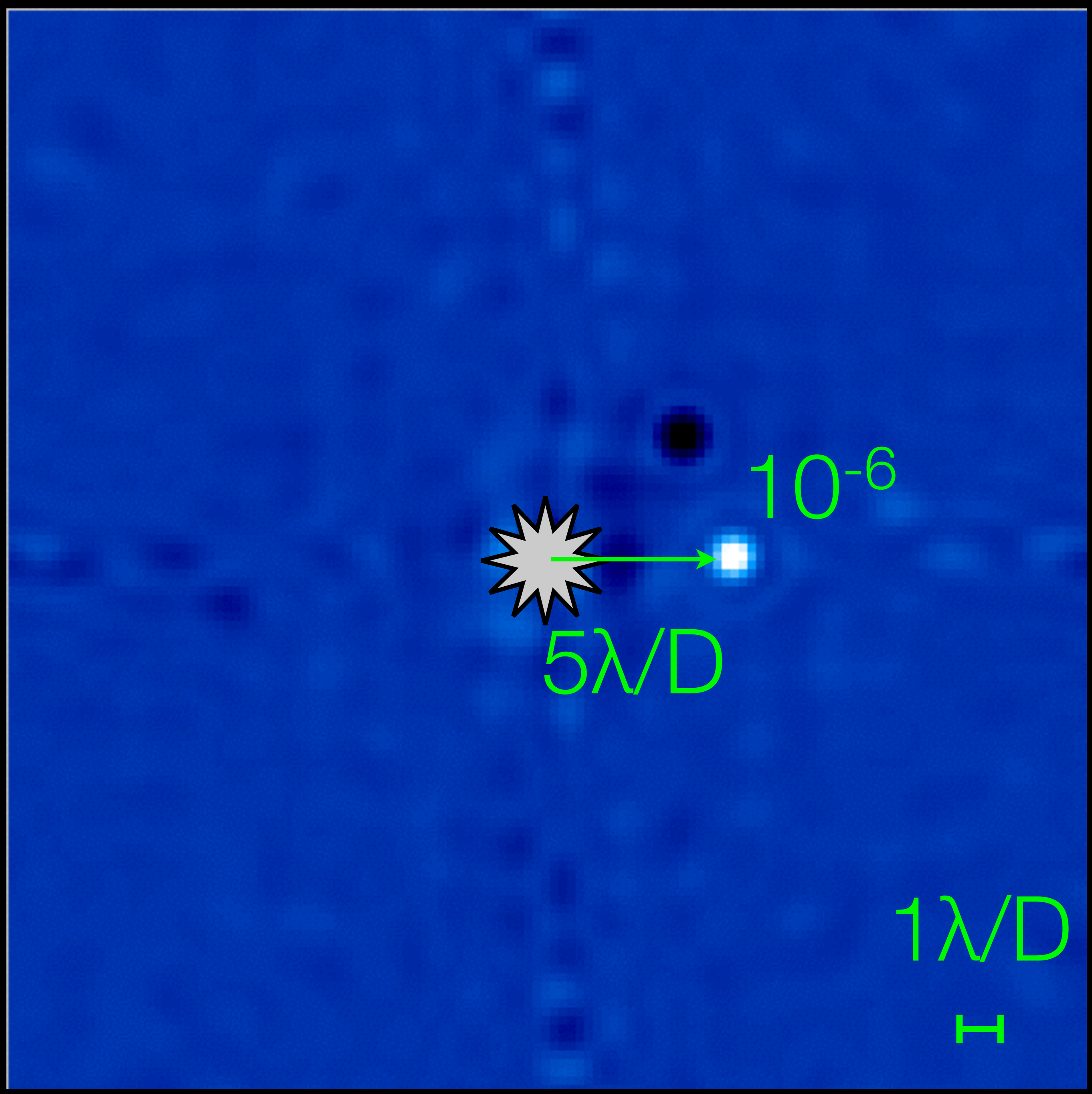


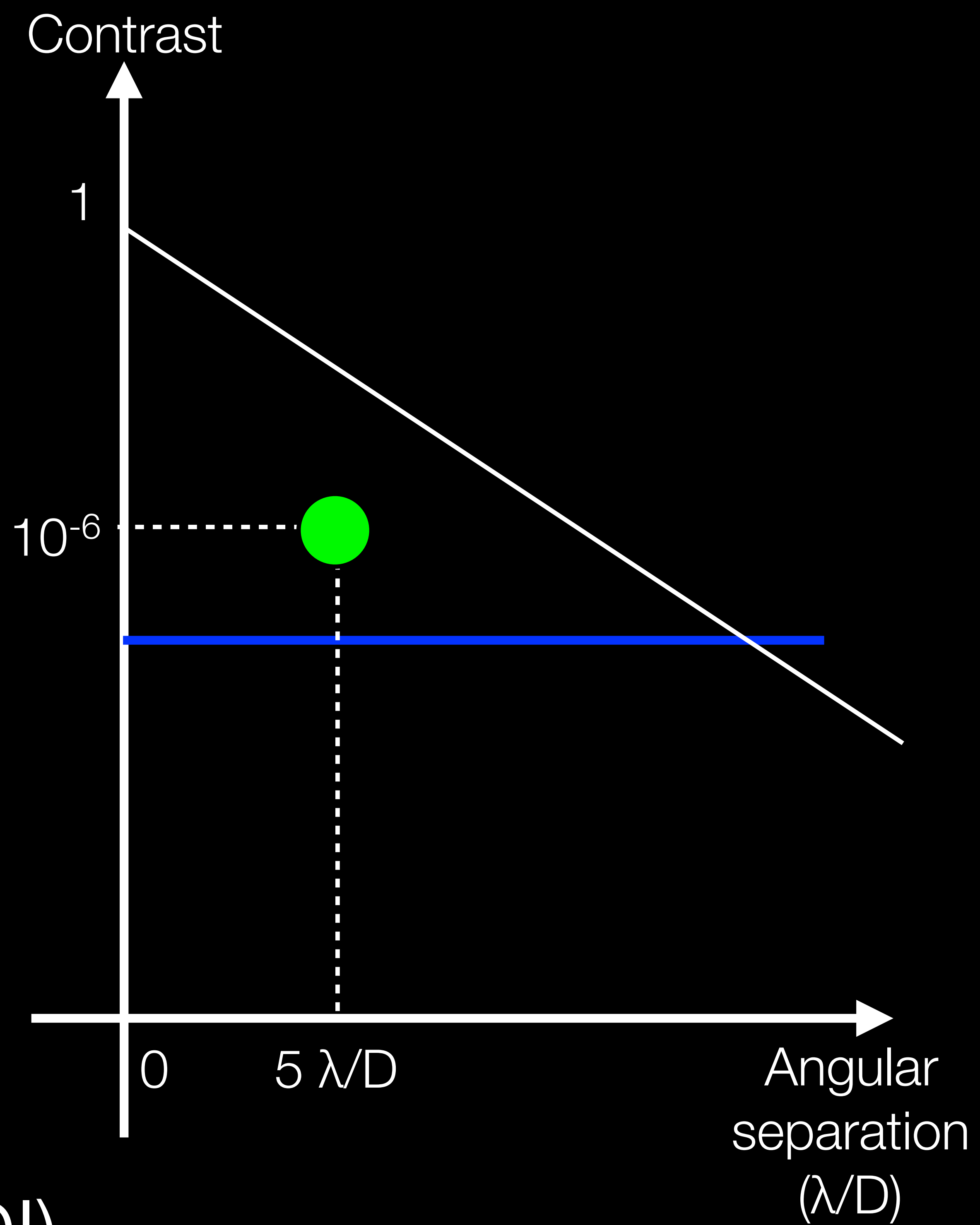
ROLL TELESCOPE BY 45°





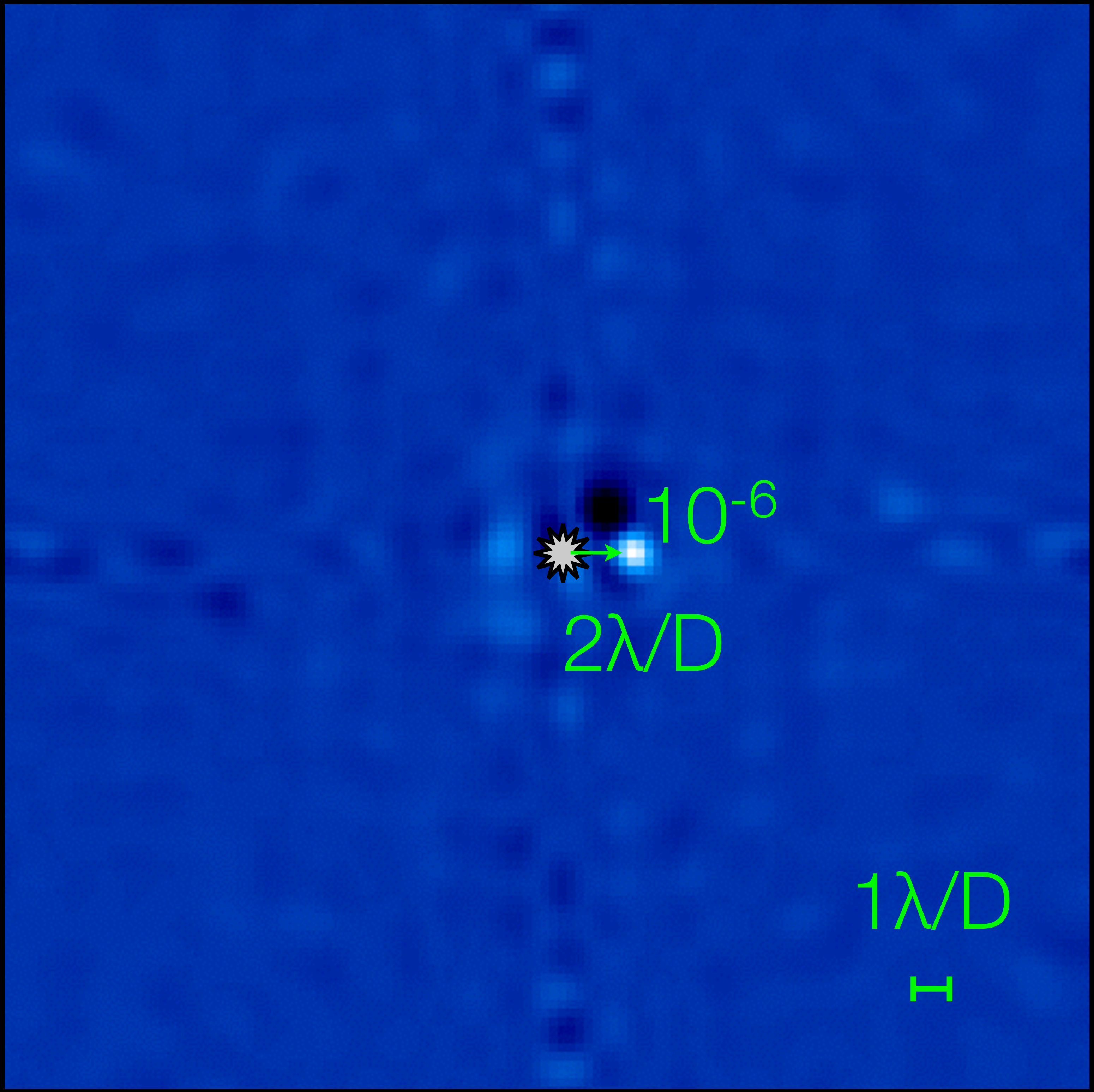
SUBTRACT BOTH IMAGES



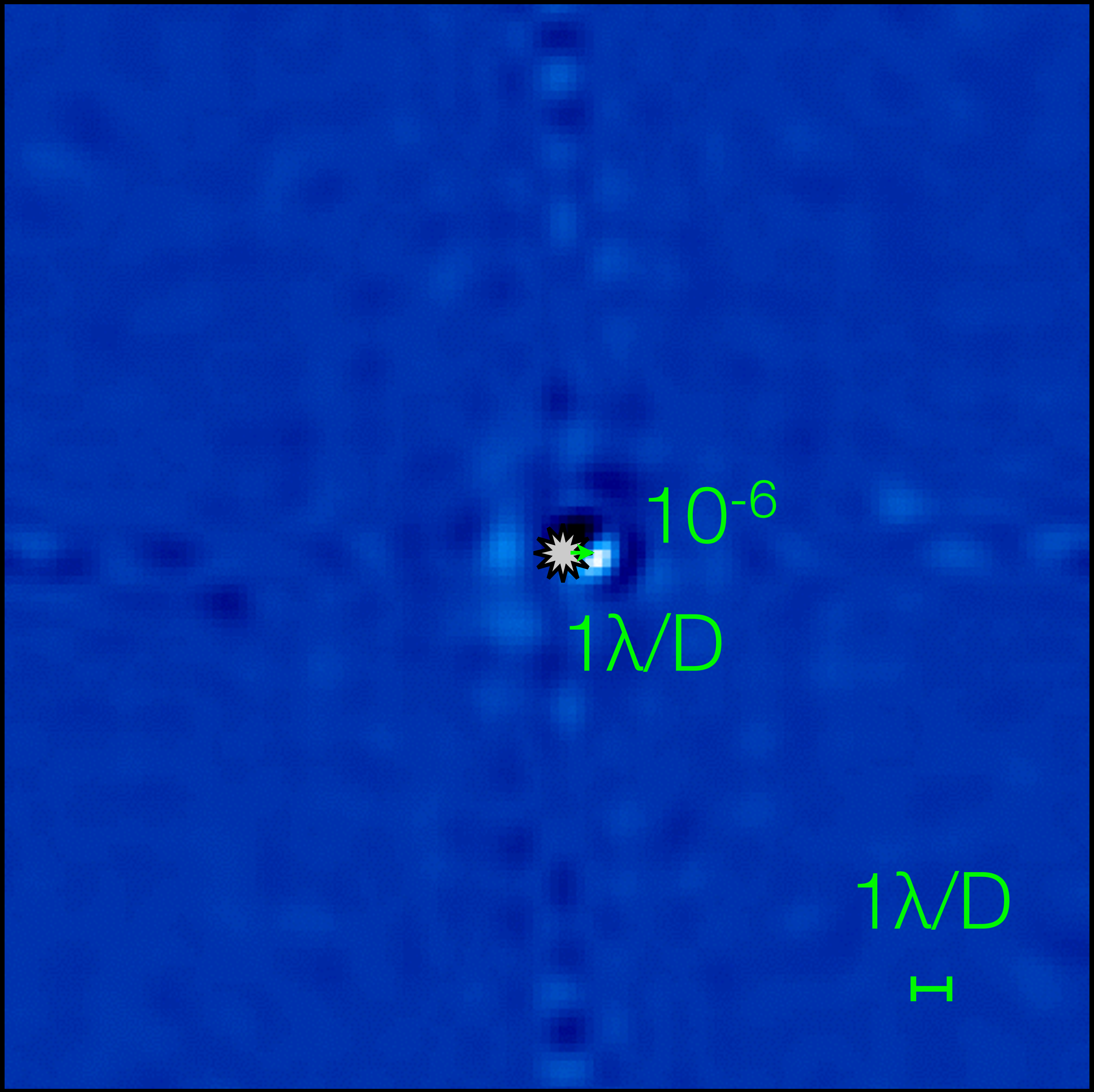


Angular differential imaging (ADI)

ADI AT SMALL ANGLES (IWA)



EXOPLANET SIGNAL SELF-SUBTRACT



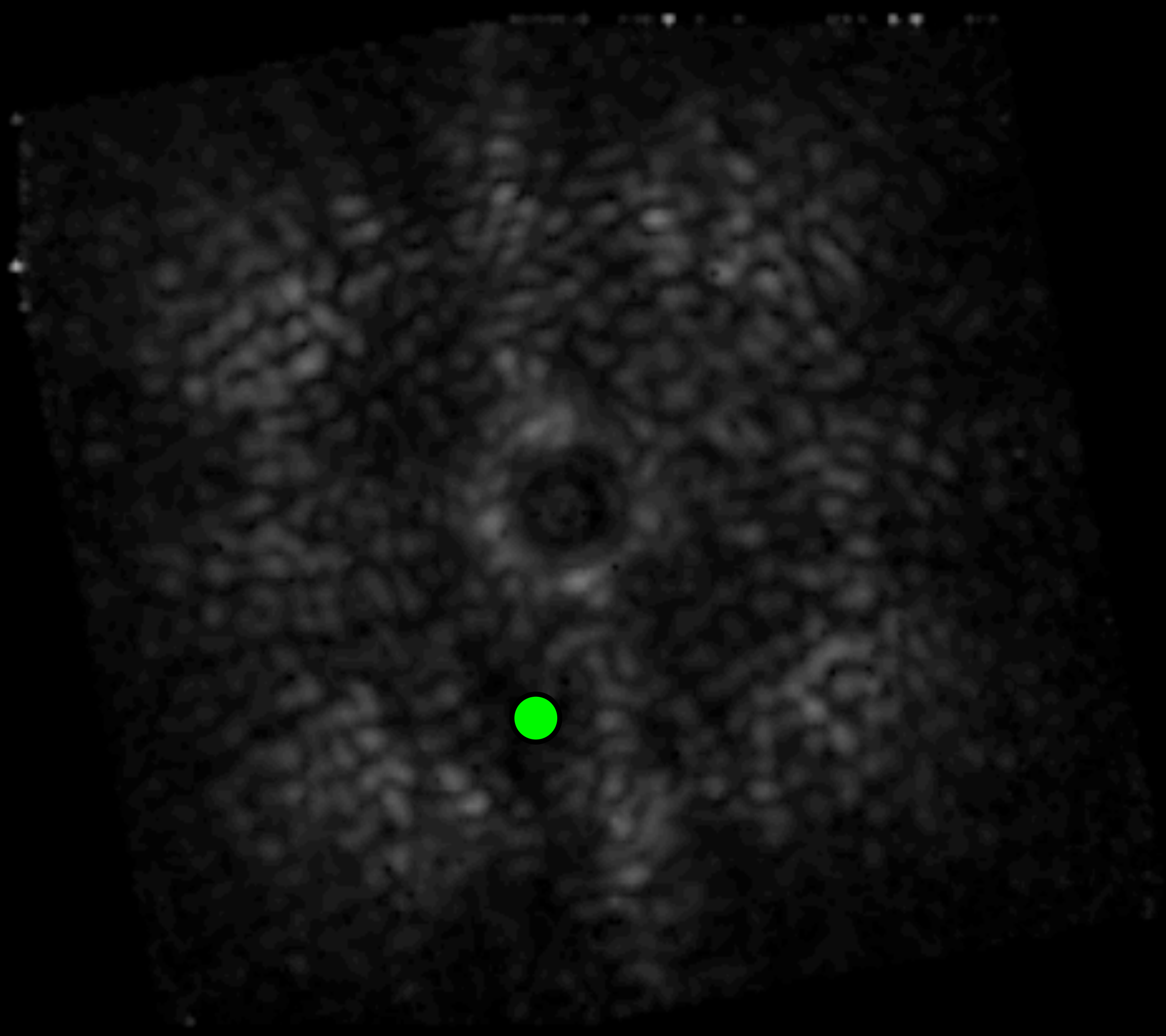
SPECTRAL DIFFERENTIAL IMAGING (SDI)

- Requires dual beam imagers or integral field spectrographs = hyperspectral imaging

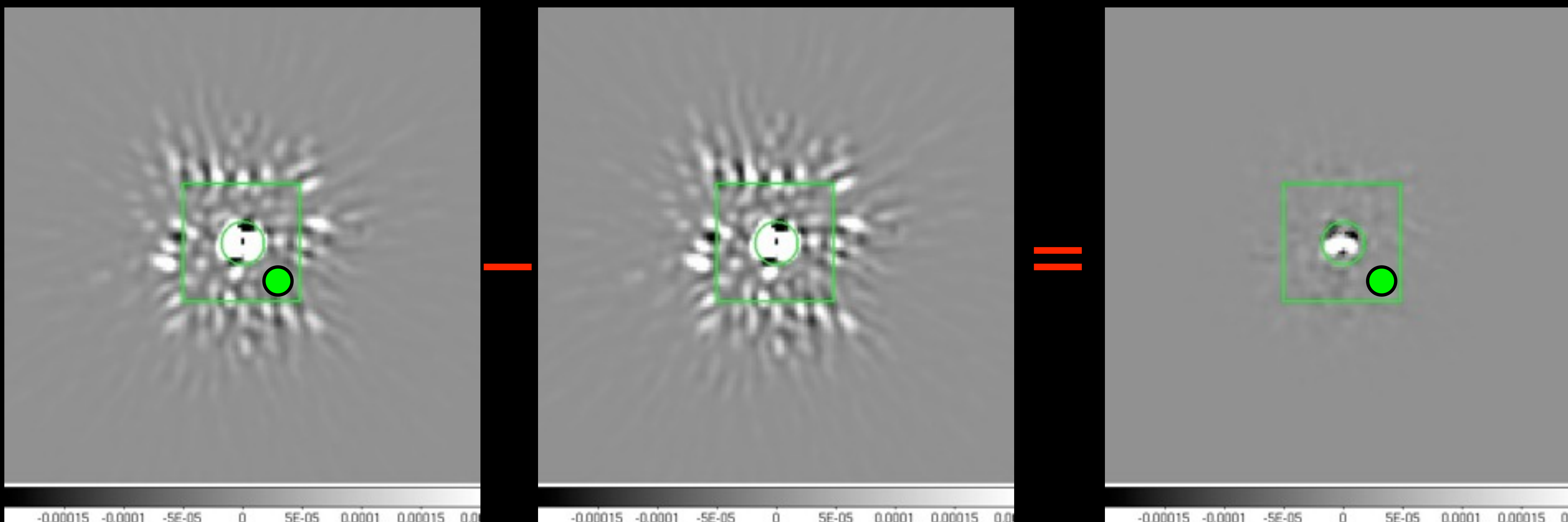
- Speckles scale as λ

- Real objects don't move

- Suffers from self subtraction at small IWA too



REFERENCE STAR DIFFERENTIAL IMAGING (RDI)



- Observe another similar star close in time, with as little telescope motion as possible
- Polarization differential imaging (PDI)

  ➡ NO geometrical limitations at small IWA

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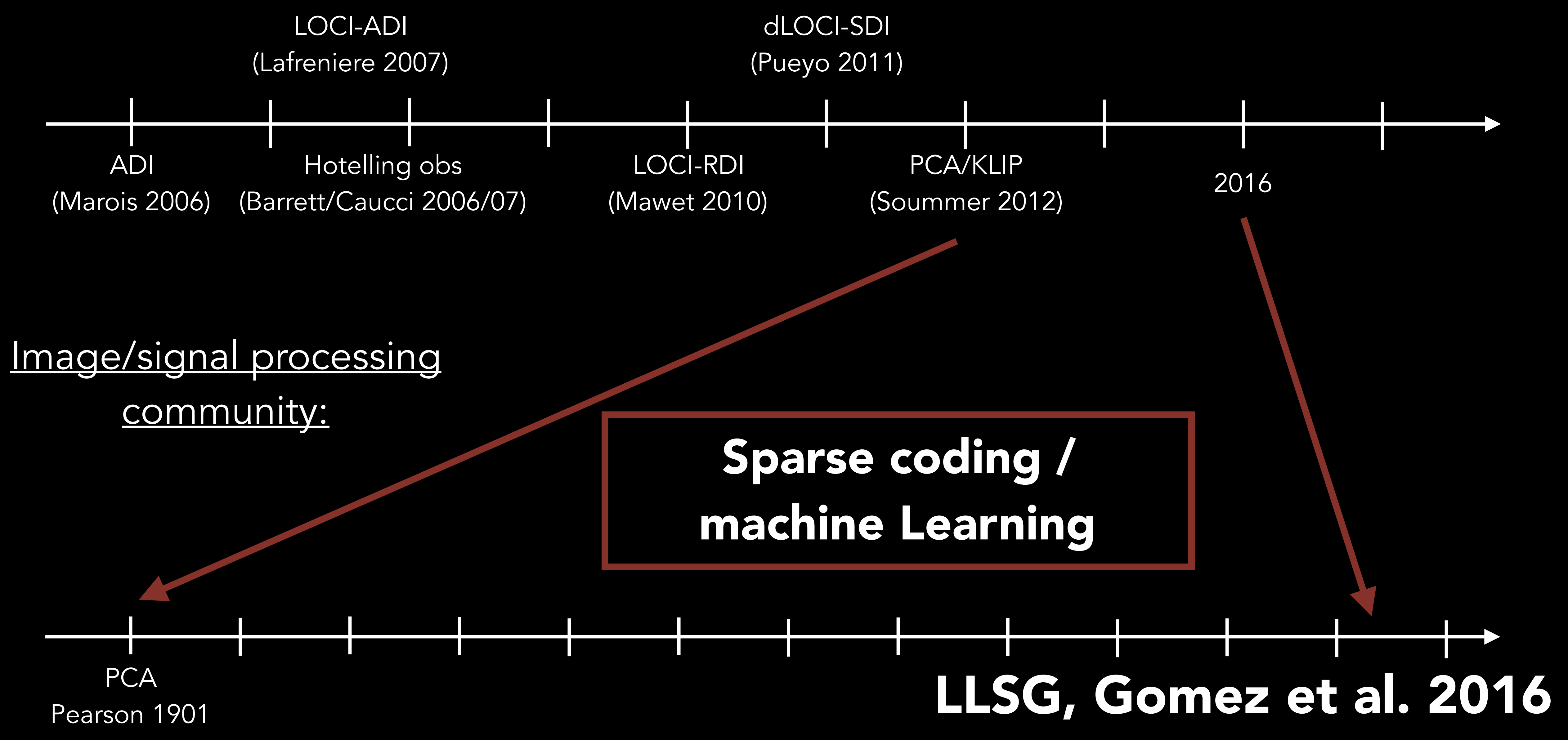
OPTIMAL WAY OF COMBINING DATA

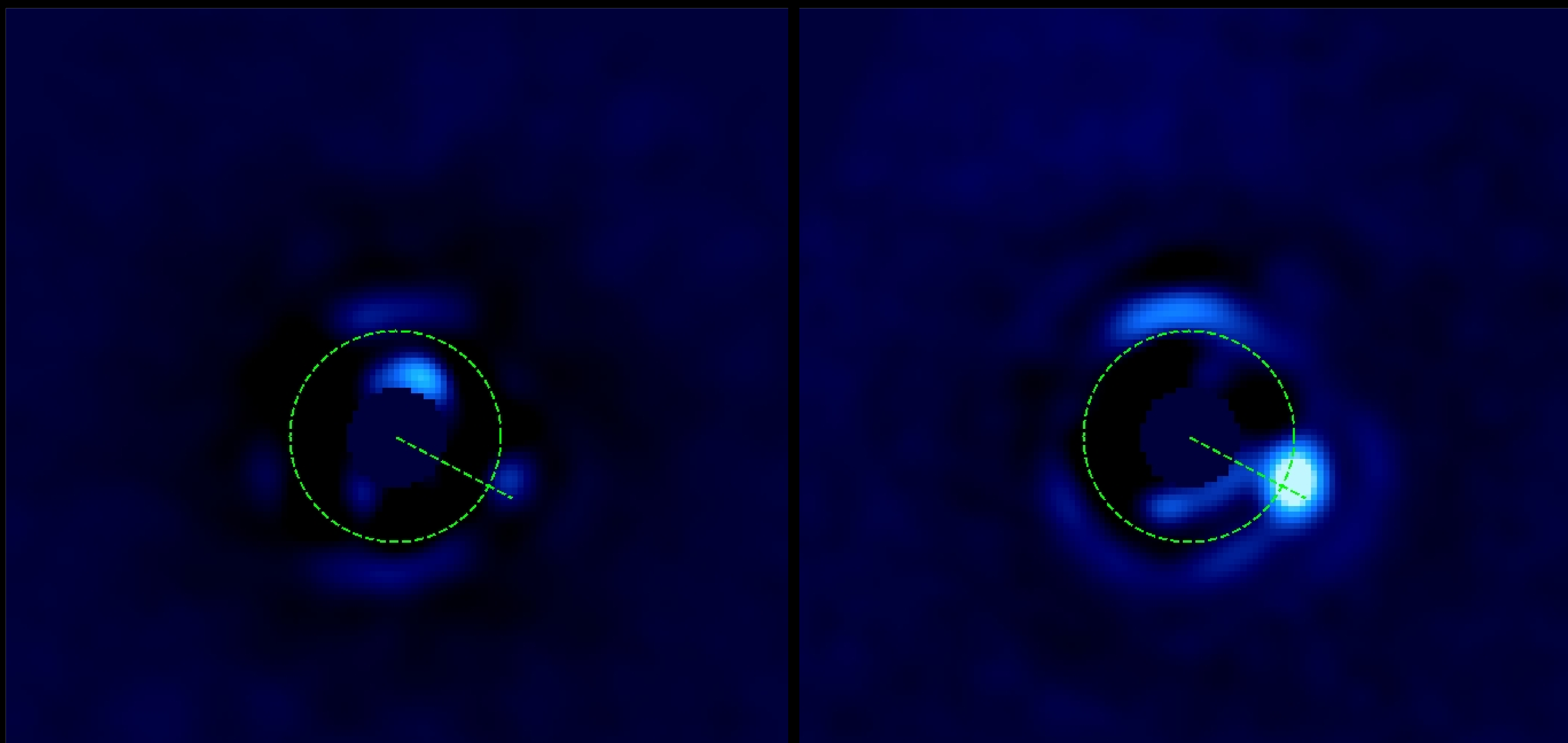


See Laurent’s talk!

MACHINE LEARNING?

- For a given instrument, during its 10+ year lifetime, a library of 1000s realizations of reference images can be assembled
- Using PCA-like methods, a low-rank approximation of the PSF can be built
- This method can be very powerful as it is not affected by the self-subtraction bias of ADI, and SDI

EXAMPLE: LEARNING THE LOW-RANK APPROXIMATION FROM A LIBRARY OF REFERENCE IMAGES



ADI RDI

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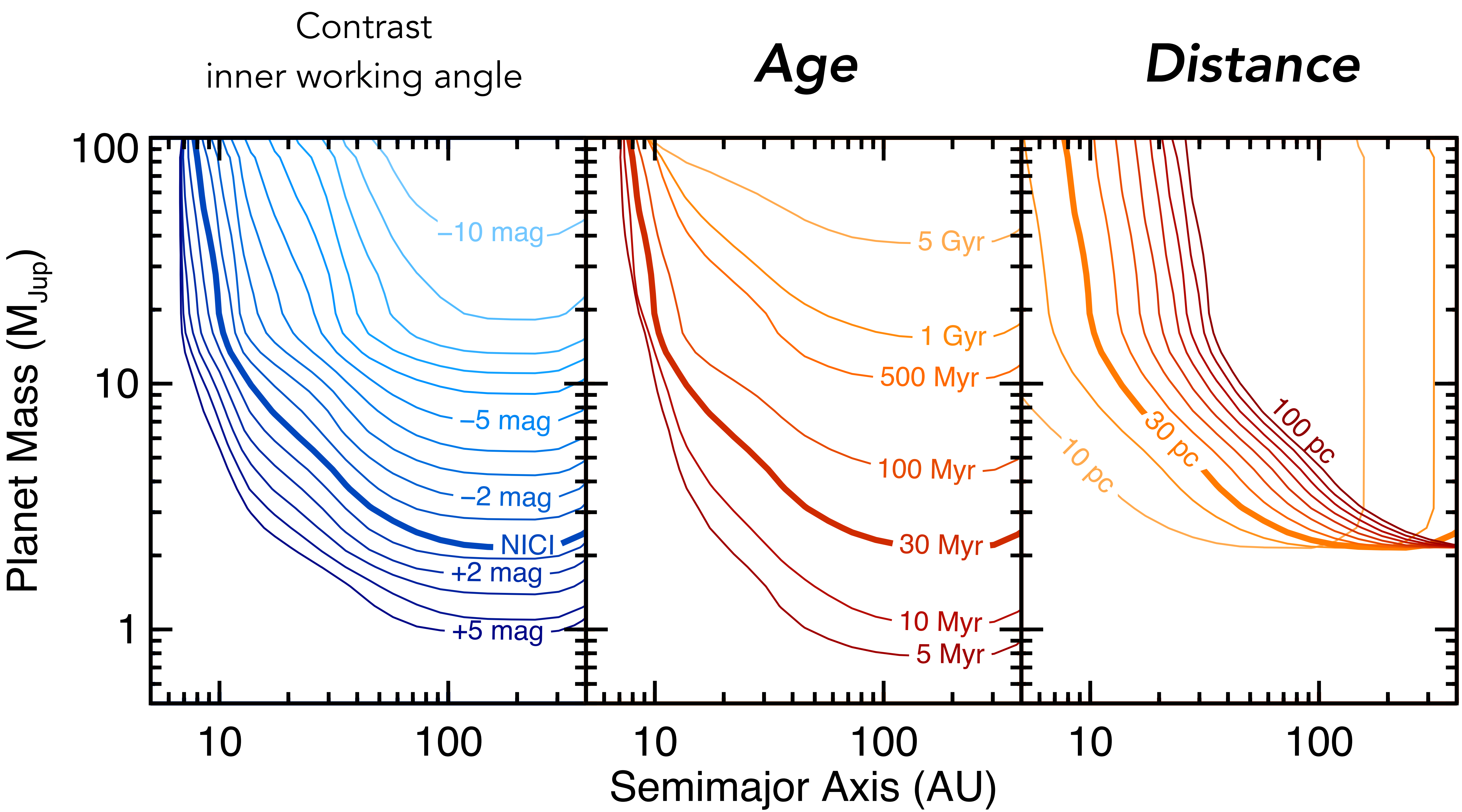
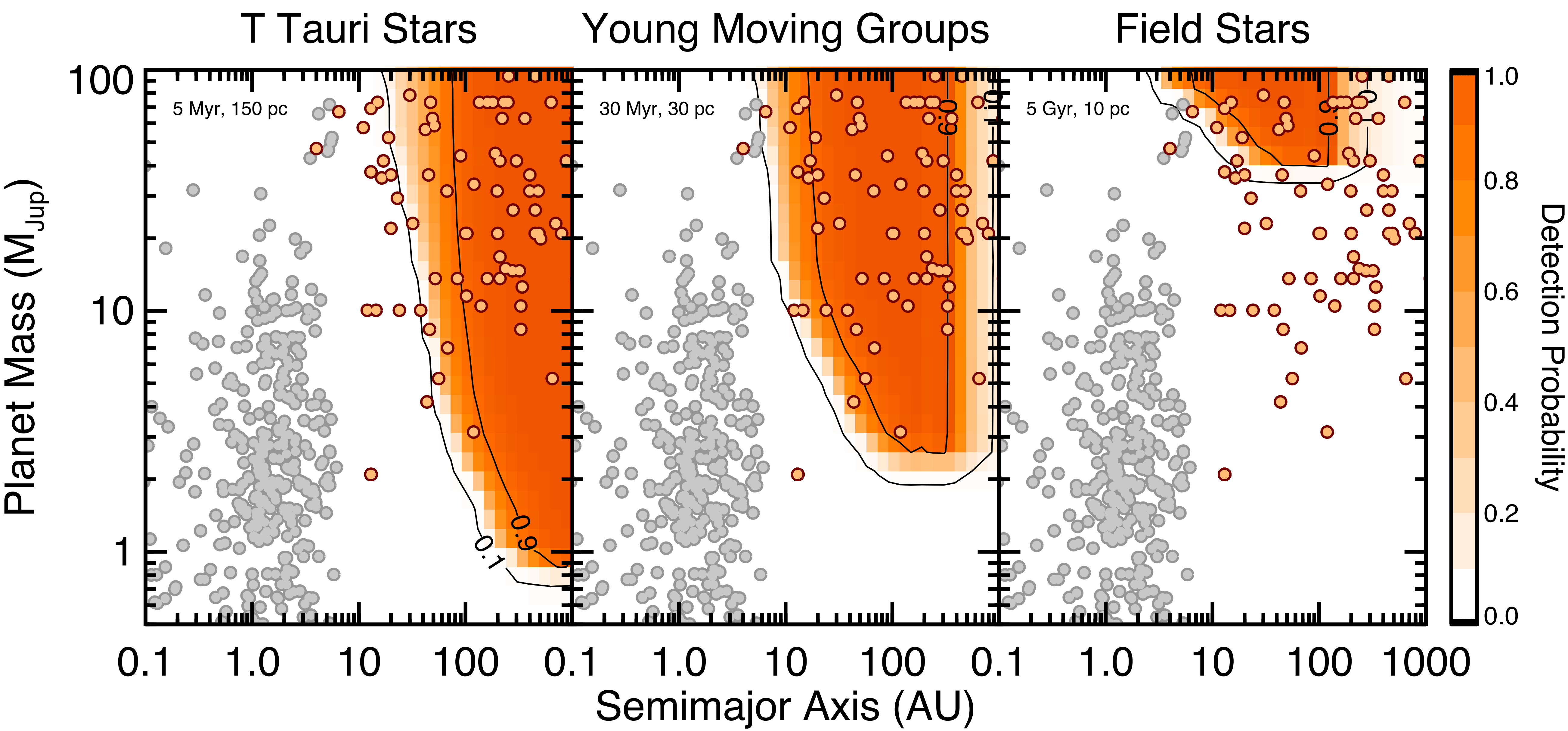
DIRECT IMAGING SENSITIVITY DRIVERS

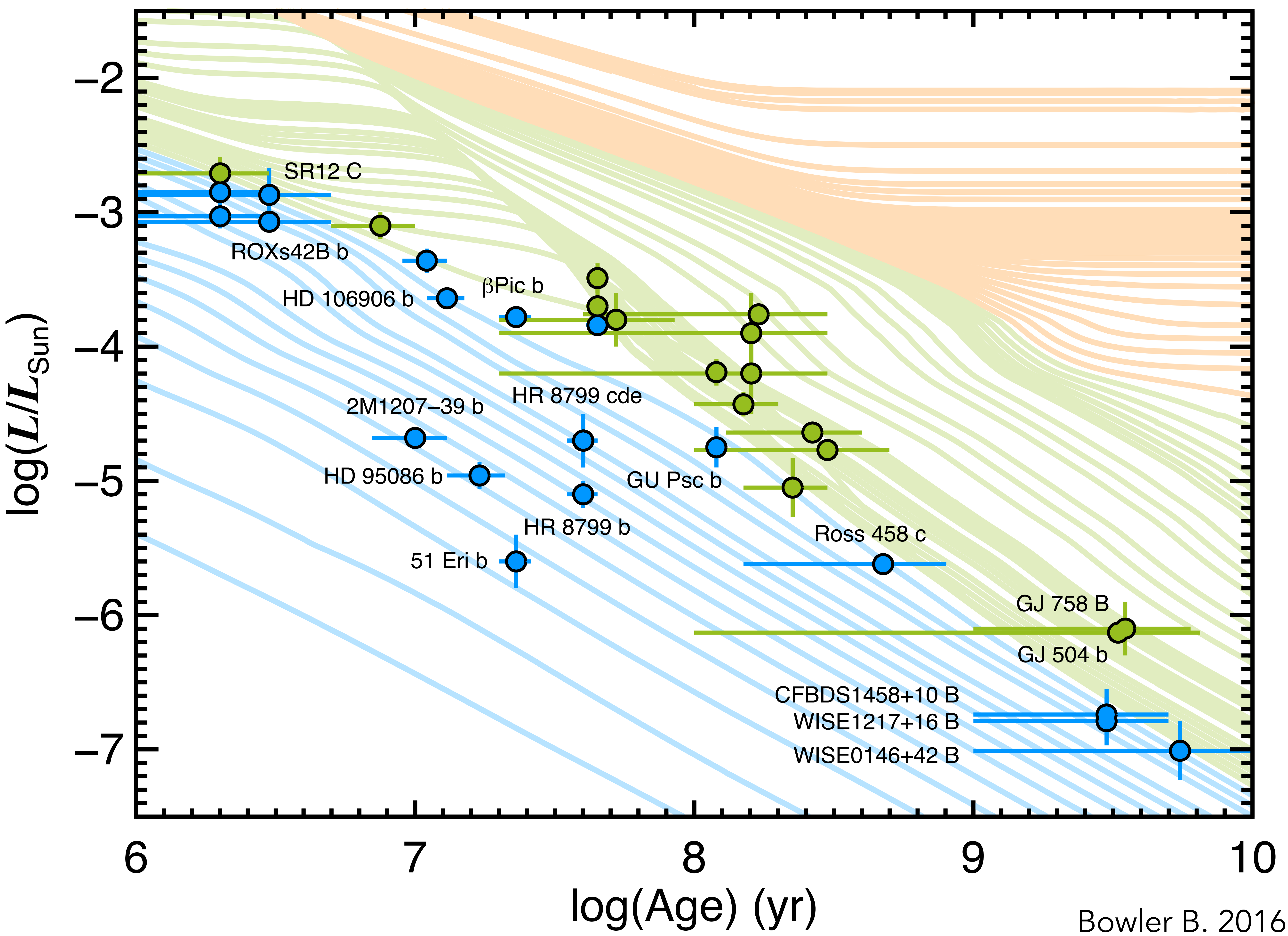


Bowler B. 2016

INFLUENCE OF STAR SAMPLE ON DIRECT IMAGING SENSITIVITY



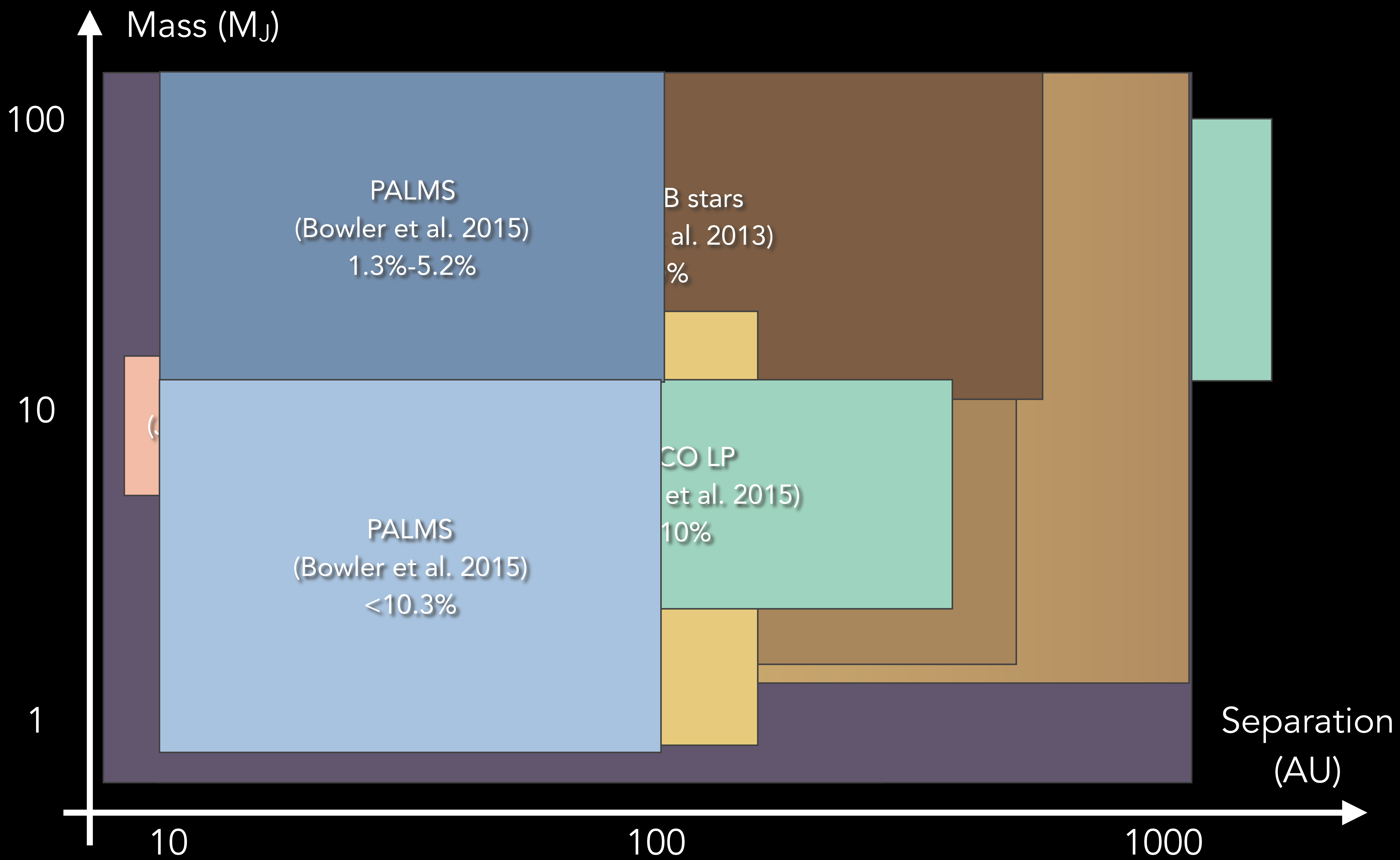
Bowler B. 2016


SR12 C
ROXs42B b
HD 106906 b
βPic b
2M1207−39 b
HR 8799 cde
HD 95086 b
GU Psc b
HR 8799 b
51 Eri b
Ross 458 c
GJ 758 B
GJ 504 b
CFBDS1458+10 B
WISE1217+16 B
WISE0146+42 B
log(L/L_Sun)
log(Age) (yr)
Bowler B. 2016

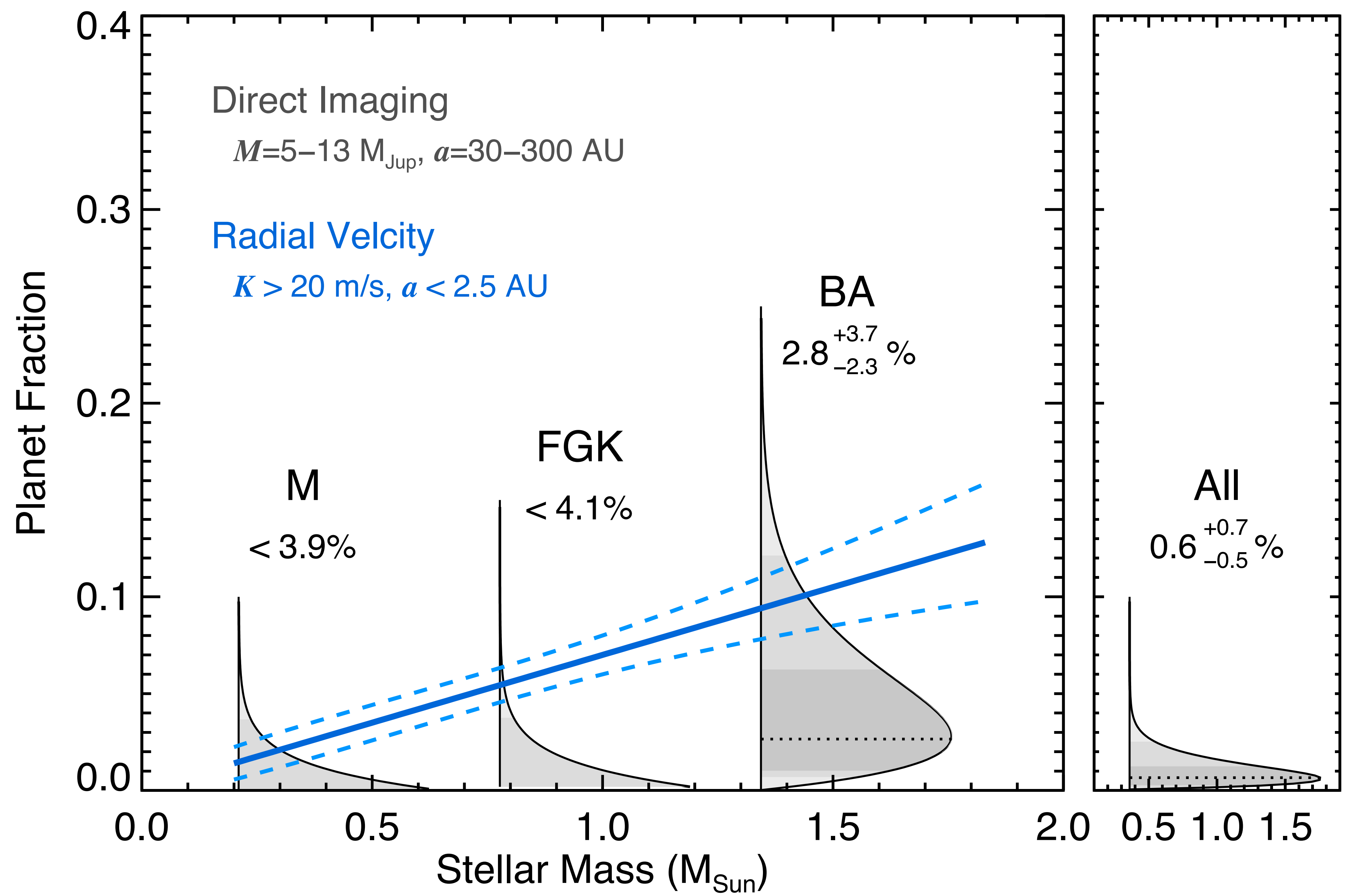
RESULTS OF FIRST GENERATION DIRECT IMAGING SURVEYS

Reference	Telescope	Instr.	Mode	Filter	FoV (″×″)	#	SpT	Age (Myr)
Chauvin et al. (2003)	ESO3.6m	ADONIS	Cor-I	H, K	13 × 13	29	GKM	≲50
Neuhäuser et al. (2003)	NTT	Sharp	Sat-I	K	11 × 11	23	AFGKM	≲50
	NTT	Sofi	Sat-I	H	13 × 13	10	AFGKM	≲50
Lowrance et al. (2005)	HST	NICMOS	Cor-I	H	19 × 19	45	AFGKM	10–600
Masciadri et al. (2005)	VLT	NaCo	Sat-I	H, K	14 × 14	28	KM	≲200
Biller et al. (2007)	VLT	NaCo	SDI	H	5 × 5	45	GKM	≲300
	MMT		SDI	H	5 × 5	–	–	–
Kasper et al. (2007)	VLT	NaCo	Sat-I	L'	28 × 28	22	GKM	≲50
Lafrenière et al. (2007)	Gemini-N	NIRI	ADI	H	22 × 22	85		10–5000
Apai et al. (2008)[a]	VLT	NaCo	SDI	H	3 × 3	8	FG	12–500
Chauvin et al. (2010)	VLT	NaCo	Cor-I	H, K	28 × 28	88	BAFGKM	≲100
Heinze et al. (2010a,b)	MMT	Clio	ADI	L', M	15.5 × 12.4	54	FGK	100–5000
Janson et al. (2011)	Gemini-N	NIRI	ADI	H, K	22 × 22	15	BA	20–700
Vigan et al. (2012)	Gemini-N	NIRI	ADI	H, K	22 × 22	42	AF	10–400
	VLT	NaCo	ADI	H, K	14 × 14	–	–	–
Delorme et al. (2012)	VLT	NaCo	ADI	L'	28 × 28	16	M	≲200
Rameau et al. (2013c)	VLT	NaCo	ADI	L'	28 × 28	59	AF	≲200
Yamamoto et al. (2013)	Subaru	HiCIAO	ADI	H, K	20 × 20	20	FG	125 ± 8
Biller et al. (2013)	Gemini-S	NICI	Cor-ASDI	H	18 × 18	80	BAFGKM	≲200
Brandt et al. (2013)	Subaru	HiCIAO	ADI	H	20 × 20	63	AFGKM	≲500
Nielsen et al. (2013)	Gemini-S	NICI	Cor-ASDI	H	18 × 18	70	BA	50–500
Wahhaj et al. (2013)[a]	Gemini-S	NICI	Cor-ASDI	H	18 × 18	57	AFGKM	~100
Janson et al. (2013)[a]	Subaru	HiCIAO	ADI	H	20 × 20	50	AFGKM	≲1000

Chauvin et al. 2015


Mass (M_J)
100
10
1
PALMS
(Bowler et al. 2015)
1.3%-5.2%
B stars
al. 2013)
%
(
CO LP
et al. 2015)
10%
PALMS
(Bowler et al. 2015)
<10.3%
Separation
(AU)
10
100
1000

OCCURRENCE RATES FROM FIRST GENERATION SURVEYS



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DIRECT IMAGING DISCOVERIES

TABLE 1
Directly Imaged Planets and Planet Candidates with Masses $\lesssim 13\ M_{\rm Jup}$

Name	Mass ($M_{\rm Jup}$)	Luminosity ($\log(L_{\rm Bol}/L_{\odot})$)	Age (Myr)	Proj. Sep. (AU)	NIR SpT	Orbital Motion?	Pri. Mult.	Pri. Mass ($M_{\odot}$)	References
Close-in Planets (<100 AU)									
51 Eri b	2 ± 1	–5.6 ± 0.2	23 ± 3	13	T4.5–T6	Yes	S	1.75	1, 2, 3
HD 95086 b	5 ± 2	···	17 ± 4	56	···	No	S	1.6	4, 5
HR 8799 b	5 ± 1	–5.1 ± 0.1	40 ± 5	68	~L/Tpec	Yes	S	1.5	6–9
LkCa 15 b[a]	6 ± 4	···	2 ± 1	20	···	Yes	S	1.0	10–13
HR 8799 c	7 ± 2	–4.7 ± 0.1	40 ± 5	38	~L/Tpec	Yes	S	1.5	6–9
HR 8799 d	7 ± 2	–4.7 ± 0.2	40 ± 5	24	~L7pec	Yes	S	1.5	6, 8, 9
HR 8799 e	7 ± 2	–4.7 ± 0.2	40 ± 5	14	~L7pec	Yes	S	1.5	8, 9, 14
β Pic b	12.7 ± 0.3	–3.78 ± 0.03	23 ± 3	9	L1	Yes	S	1.6	15–18
Planetary-Mass Companions on Wide Orbits (>100 AU)									
WD 0806-661 b	7.5 ± 1.5	···	2000 ± 500	2500	Y?	No	S	2.0[b]	19–21
Ross 458 c	9 ± 3	–5.62 ± 0.03	150–800	1190	T8.5pec	No	B	0.6, 0.09	22–26
ROXs 42B b	10 ± 4	–3.07 ± 0.07	3 ± 2	140	L1	Yes	B	0.89, 0.36	27–31
HD 106906 b	11 ± 2	–3.64 ± 0.08	13 ± 2	650	L2.5	No	B	1.5	32, 33
GU Psc b	11 ± 2	–4.75 ± 0.15	120 ± 10	2000	T3.5	No	S	0.30	34
CHXR 73 b	13 ± 6	–2.85 ± 0.14	2 ± 1	210	≥M9.5	No	S	0.30	35
SR12 C	13 ± 2	–2.87 ± 0.20	3 ± 2	1100	M9.0	No	B	1.0, 0.5	29, 36
TYC 9486-927-1 b	12–15	···	10–45	4500	L3	No	S	0.4	37, 38
Planetary-Mass Companions Orbiting Brown Dwarfs									
2M1207–3932 b	5 ± 2	–4.68 ± 0.05	10 ± 3	41	L3	No	S	0.024	39–42, 9
2M0441+2301 Bb	10 ± 2	–3.03 ± 0.09	2 ± 1	1800/15	L1	Yes	B/S	0.2, 0.018	43–45

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DIRECT IMAGING DISCOVERIES

Candidate Planets and Companions Near the Deuterium-Burning Limit

1RXS J1609–2105 B	14 ± 2	–3.36 ± 0.09	11 ± 2	330	L2	No	S	0.85	46–49
2M0103–5515 b	13–35	–3.49 ± 0.11	45 ± 4	84	…	Yes	B	0.19, 0.17	50, 51, 9
2M0122–2439 B	12–27	–4.19 ± 0.10	120 ± 10	52	L4	No	S	0.4	51, 52
2M0219–3925 B	14 ± 1	–3.84 ± 0.05	45 ± 4	156	L4	No	S	0.11	53
AB Pic B	13–30	–3.7 ± 0.2	45 ± 4	250	L0	No	S	0.95	54, 55, 39
CFBDSIR J1458+1013 B	5–20	–6.74 ± 0.19	1000–5000	2.6	Y0:	Yes	S	0.01–0.04	56, 57
DH Tau B	8–22	–2.71 ± 0.12	2 ± 1	340	M9.25	No	S	0.5	58, 35, 13
Fomalhaut b	$\lesssim$2	…	440 ± 40	119	…	Yes	S	1.92	59–62
FU Tau B	$\sim$16	–2.60	2 ± 1	800	M9.25	No	S	0.05	63
FW Tau b	$\sim$10–100	…	2 ± 1	330	pec	No	B	0.3, 0.3	27, 29, 64
G196-3 B	12–25	–3.8 ± 0.2	20–85	400	L3	No	S	0.43	65–67, 51, 42
GJ 504 b	3–30	–6.13 ± 0.03	100–6500	44	T:	Yes	S	1.16	68–71
GJ 758 B	10–40	–6.1 ± 0.2	1000–6000	29	T8:	Yes	S	1.0	72–75
GSC 6214-210 B	15 ± 2	–3.1 ± 0.1	5–10	320	M9.5	No	S	0.9	48, 29, 76, 77
HD 100546 b	$\sim$10 ± 5	…	5–10	53	…	No	S	2.4	78–80
HD 100546 c	<20	…	5–10	13	…	No	S	2.4	81
HD 203030 B	12–30	–4.64 ± 0.07	130–400	490	L7.5	Yes	S	0.95	82, 83
HN Peg B	12–31	–4.77 ± 0.03	300 ± 200	800	T2.5	No	S	1.07	84, 85
κ And b	12–66	–3.76 ± 0.06	40–300	55	L1	No	S	2.8	85–87
LkCa 15 c[a]	<10	…	2 ± 1	15	…	Yes	S	1.0	12, 13
LkCa 15 d	<10	…	2 ± 1	18	…	Yes	S	1.0	12, 13
LP 261-75 B	12–26	–4.43 ± 0.09	100–200	450	L4.5	No	S	0.22	88, 51
ROXs12 B	16 ± 4	…	8 ± 3	210	…	Yes	S	0.9	27, 31
SDSS2249+0044 A	12–60	–3.9 ± 0.3	20–300	17/2600	L3	No	S/S	…	89
SDSS2249+0044 B	8–52	–4.2 ± 0.3	20–300	17	L5	No	S	0.03	89
VHS1256–1257 b	10–21	–5.05 ± 0.22	150–300	102	L7	No	B	0.07, 0.07	90, 91
WISE J0146+4234 B	4–16	–7.01 ± 0.22	1000-10000	1	Y0	Yes	S	0.005–0.016	92
WISE J1217+1626 B	5–20	–6.79 ± 0.18	1000–5000	8	Y0	No	S	0.01–0.04	93

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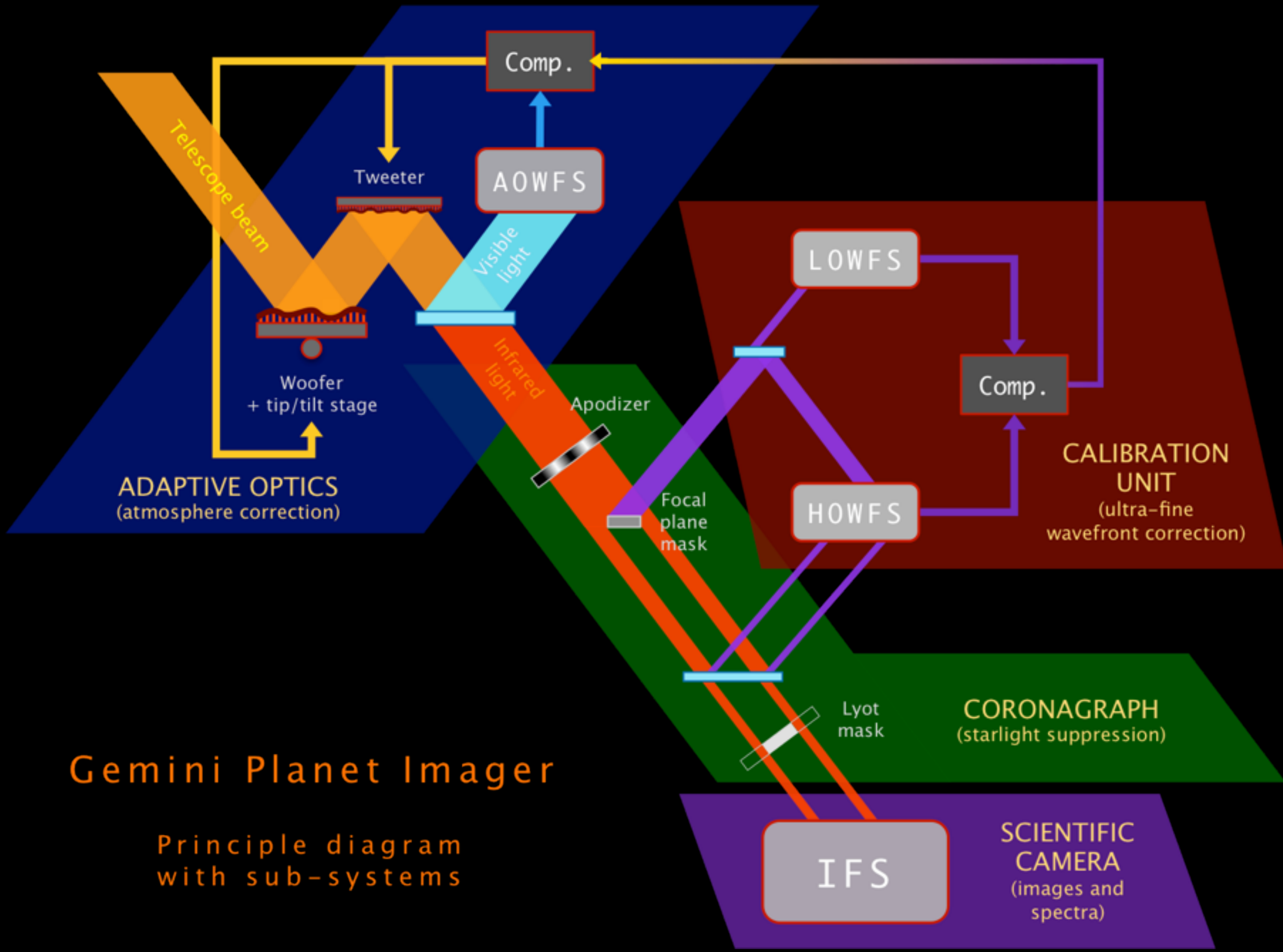
SECOND GENERATION DIRECT IMAGING FACILITIES

2ND GENERATION:
1ST GENERATION ON STEROIDS

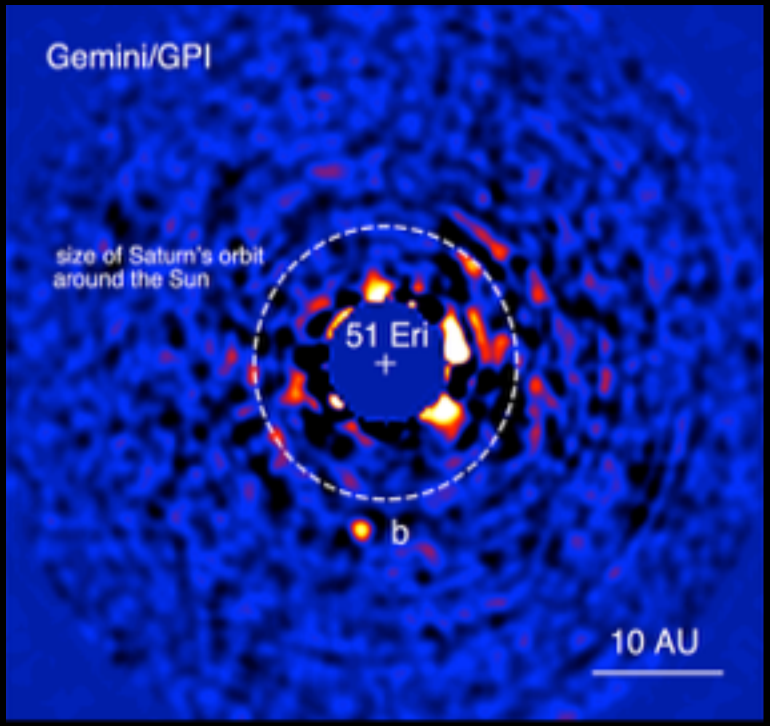
- More DOF, faster AO
- Better optics => excellent wavefront quality
- Optimized for stability => slow thermal & mechanical drifts
- Speckle control strategies are fully built in!

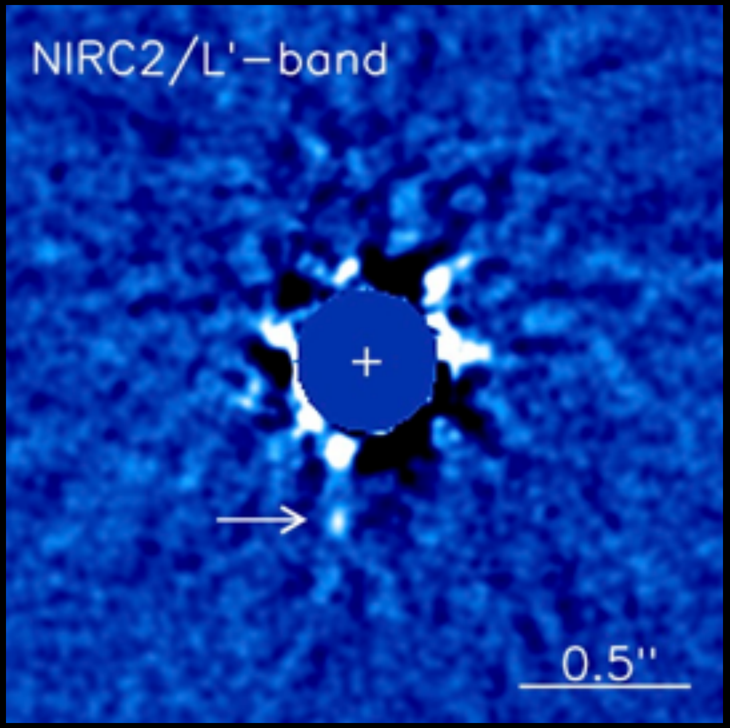
Instrument	Telescope	AO	Wavelength (μm)	Ang. res. (mas)	Coronagraph
P3K-P1640/SDC	Hale 200”	64-SH	1.1–2.4	45-90	APLC/VC
SPHERE	VLT	40-SH	0.5–2.4	15-55	Lyot/APLC/FQPM
GPI	Gemini South	48-SH	0.9–2.4	23-55	APLC
SCExAO	Subaru	14-C & 48-P	0.55–2.4	15-55	PIAA/SP/VC
MagAO-Clio2/VisAO	Magellan	25-Pyramid	0.55–5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

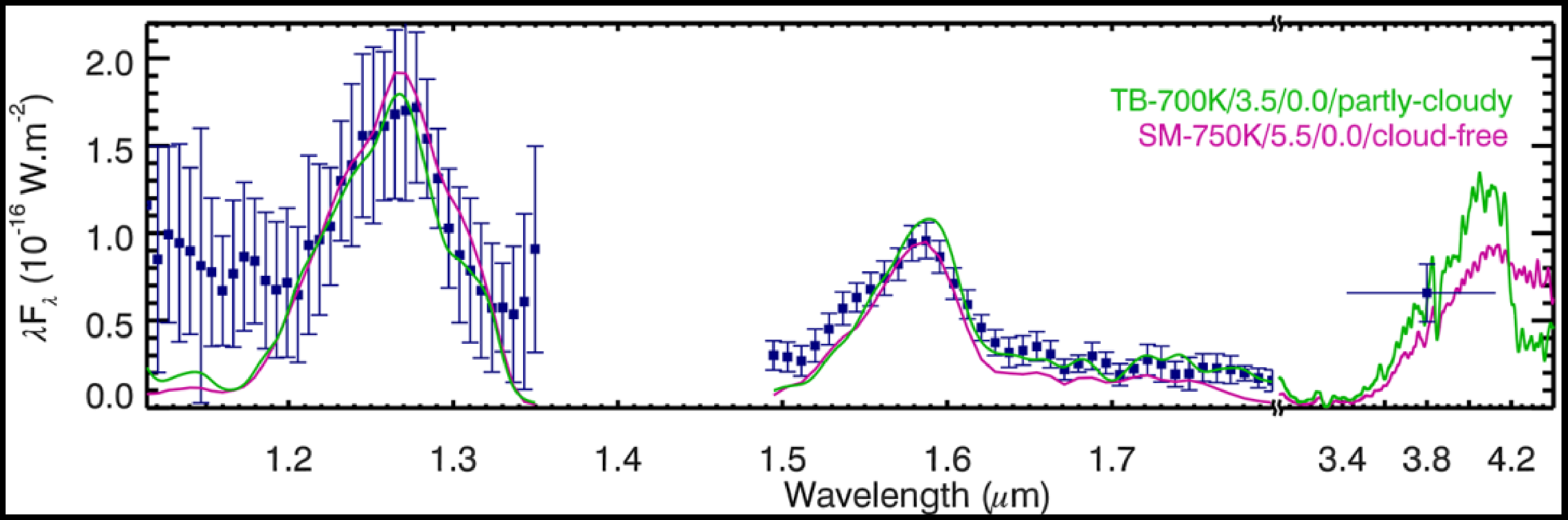

Comp.
Telescope beam
Tweeter
AOWFS
Visible light
Woofer
+ tip/tilt stage
Infrared light
Apodizer
ADAPTIVE OPTICS
(atmosphere correction)
LOWFS
Comp.
Focal plane mask
HOWFS
CALIBRATION UNIT
(ultra-fine wavefront correction)
Lyot mask
CORONAGRAPH
(starlight suppression)
Gemini Planet Imager
Principle diagram
with sub-systems
IFS
SCIENTIFIC CAMERA
(images and spectra)

RECENT RESULT FROM GPI

51 Eri b

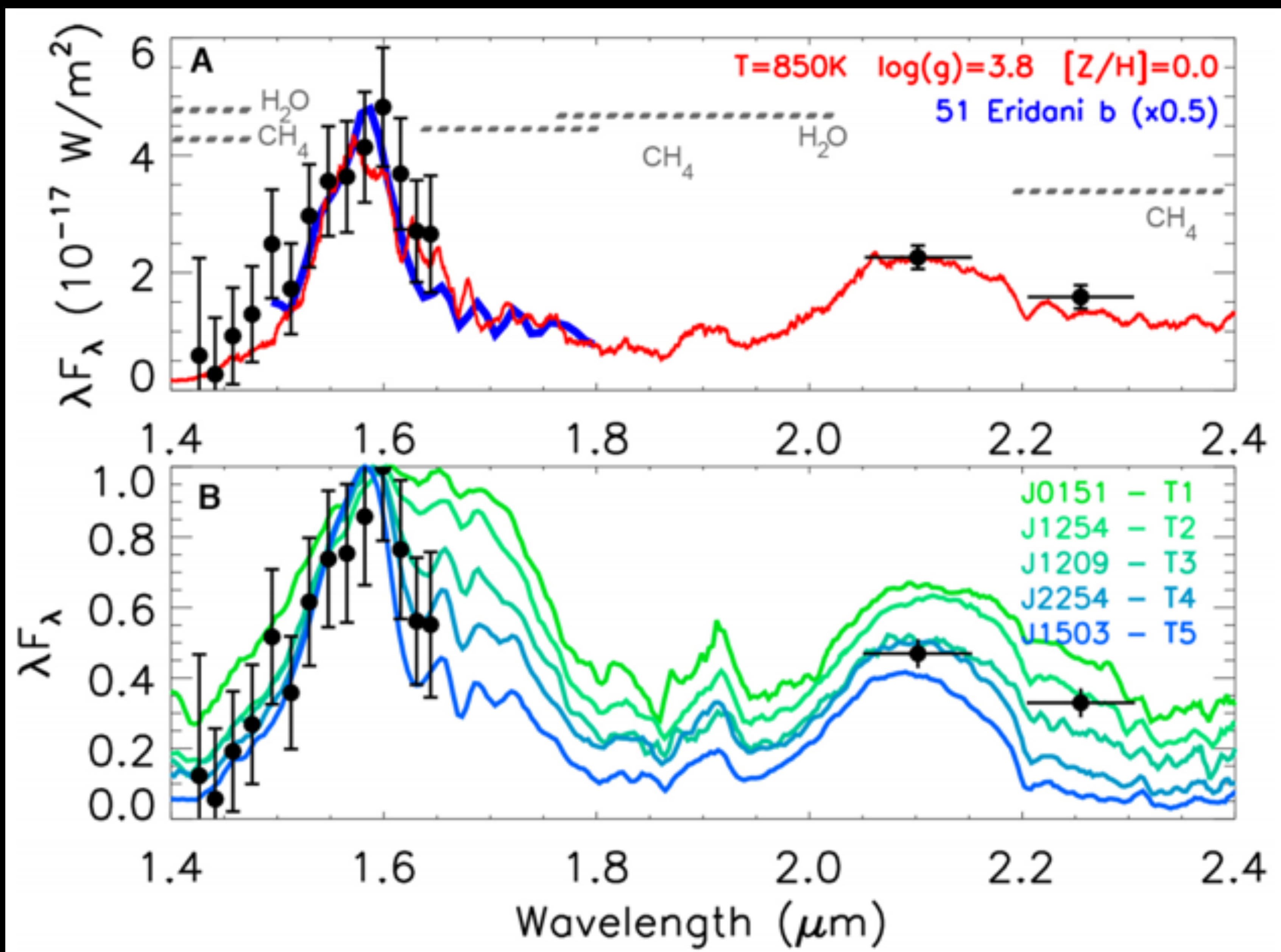


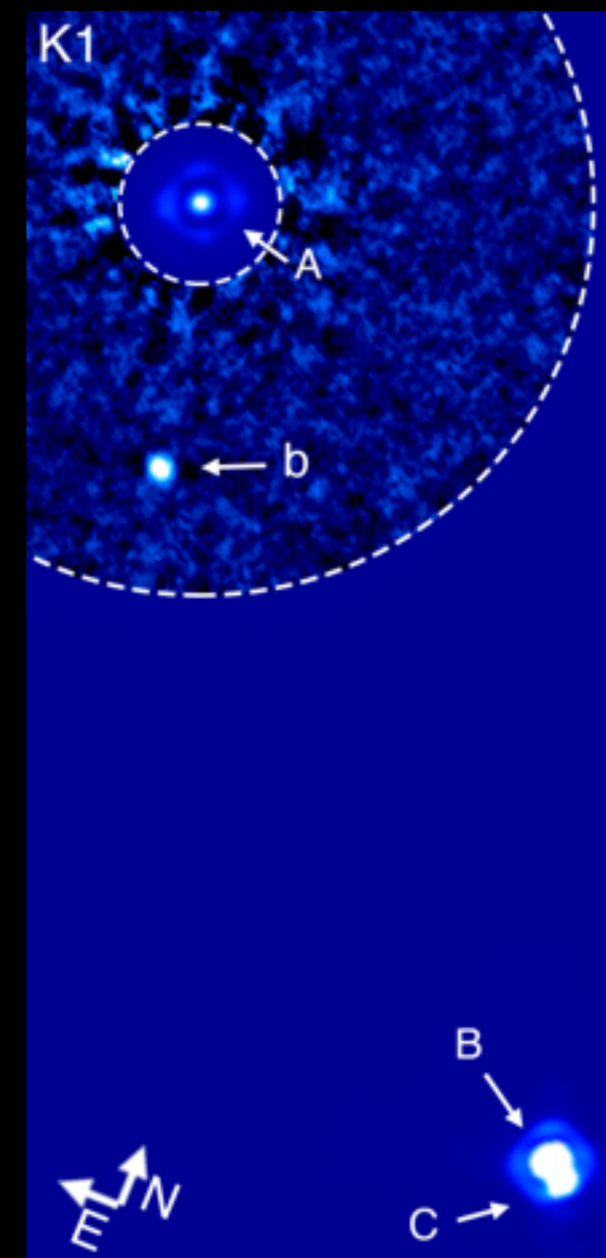




RECENT RESULT FROM SPHERE

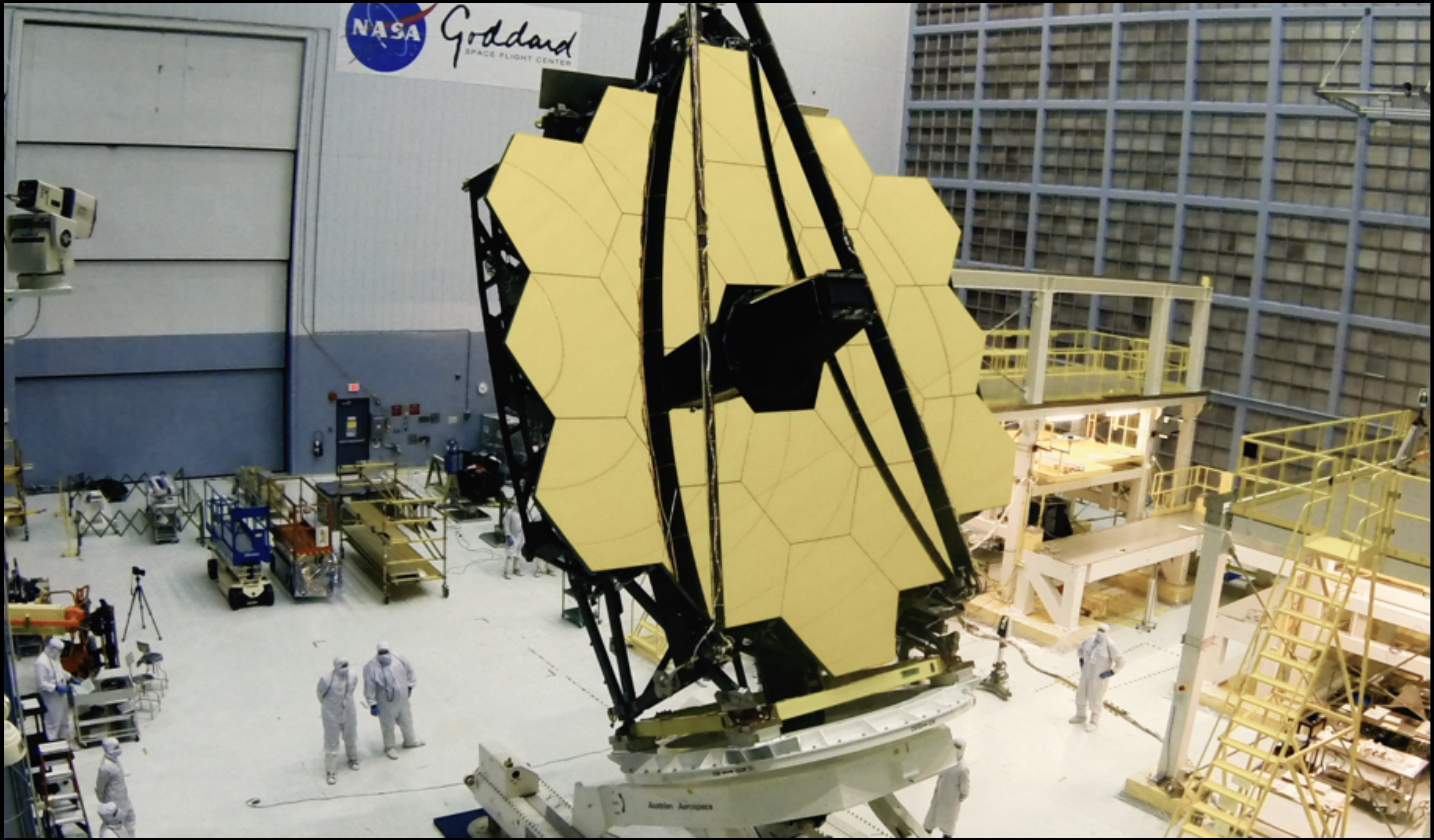
HD 131399Ab





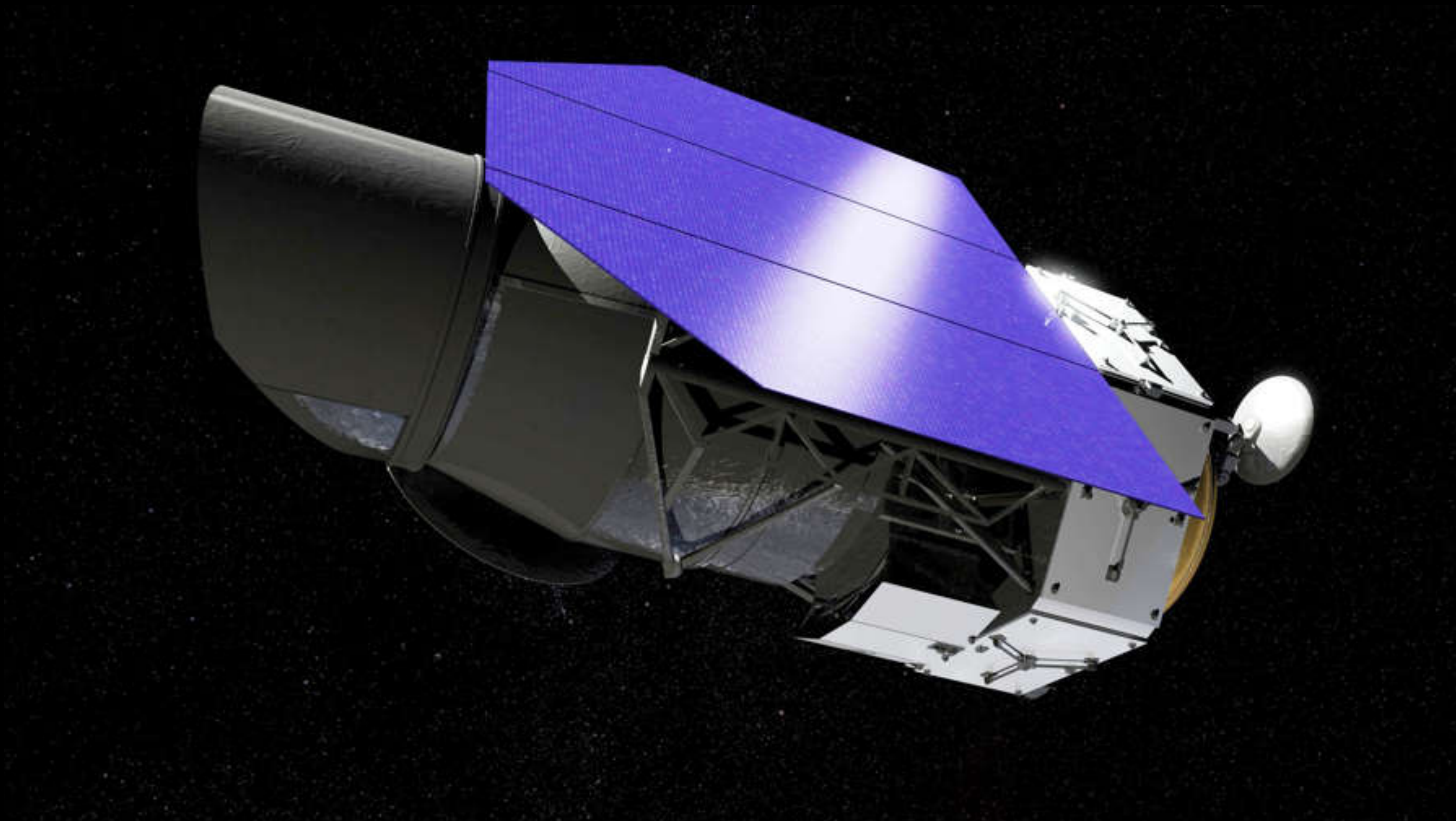
THE FUTURE OF DIRECT IMAGING

JAMES WEBB SPACE TELESCOPE

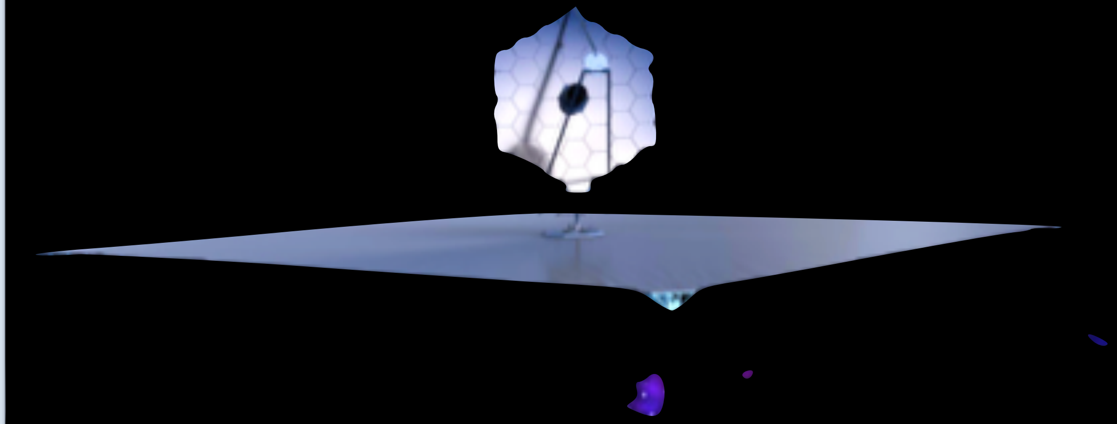


See Chas's talk on Friday!

WFIRST-CORONAGRAPH



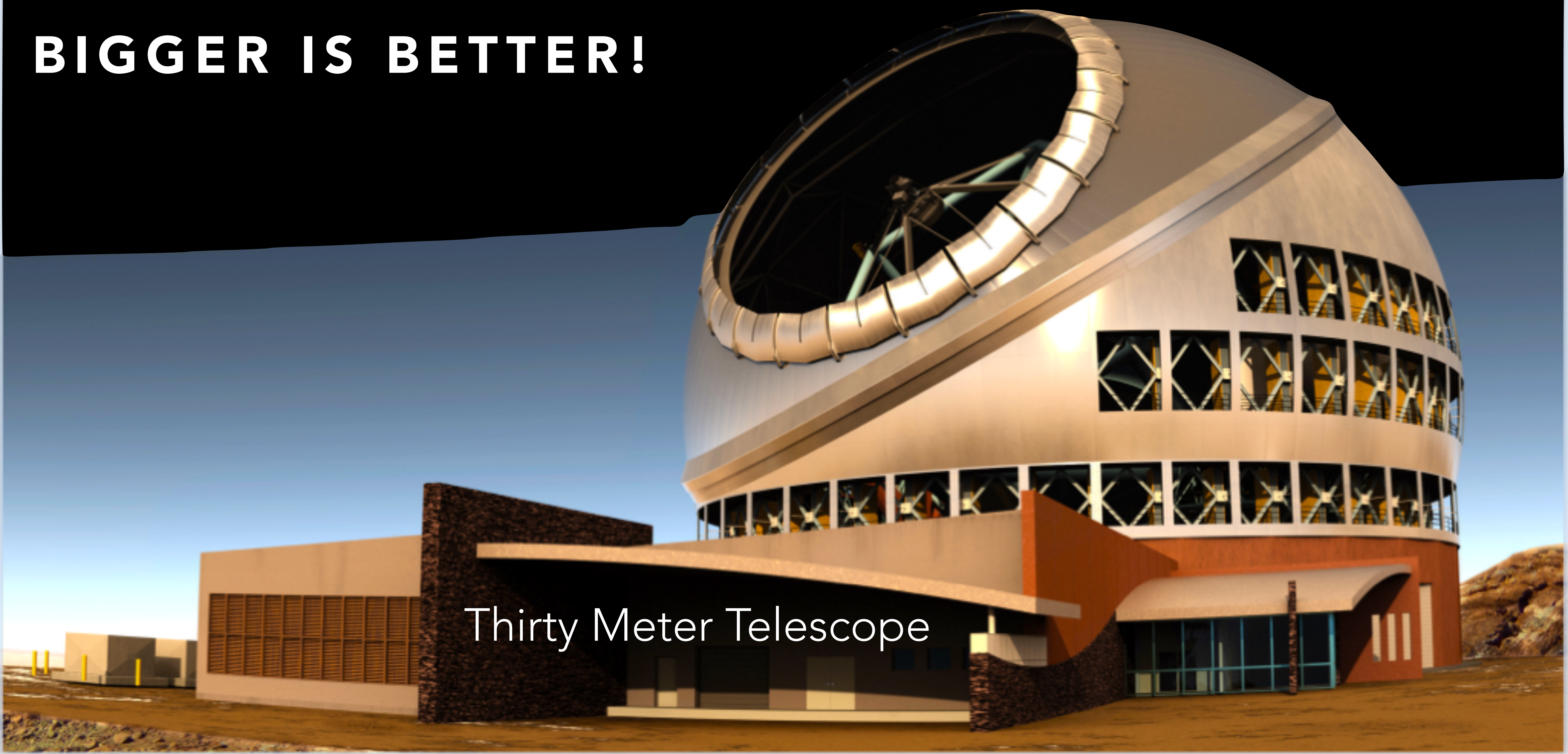
See Nikole’s talk on Friday!



LUVOIR/HabEx

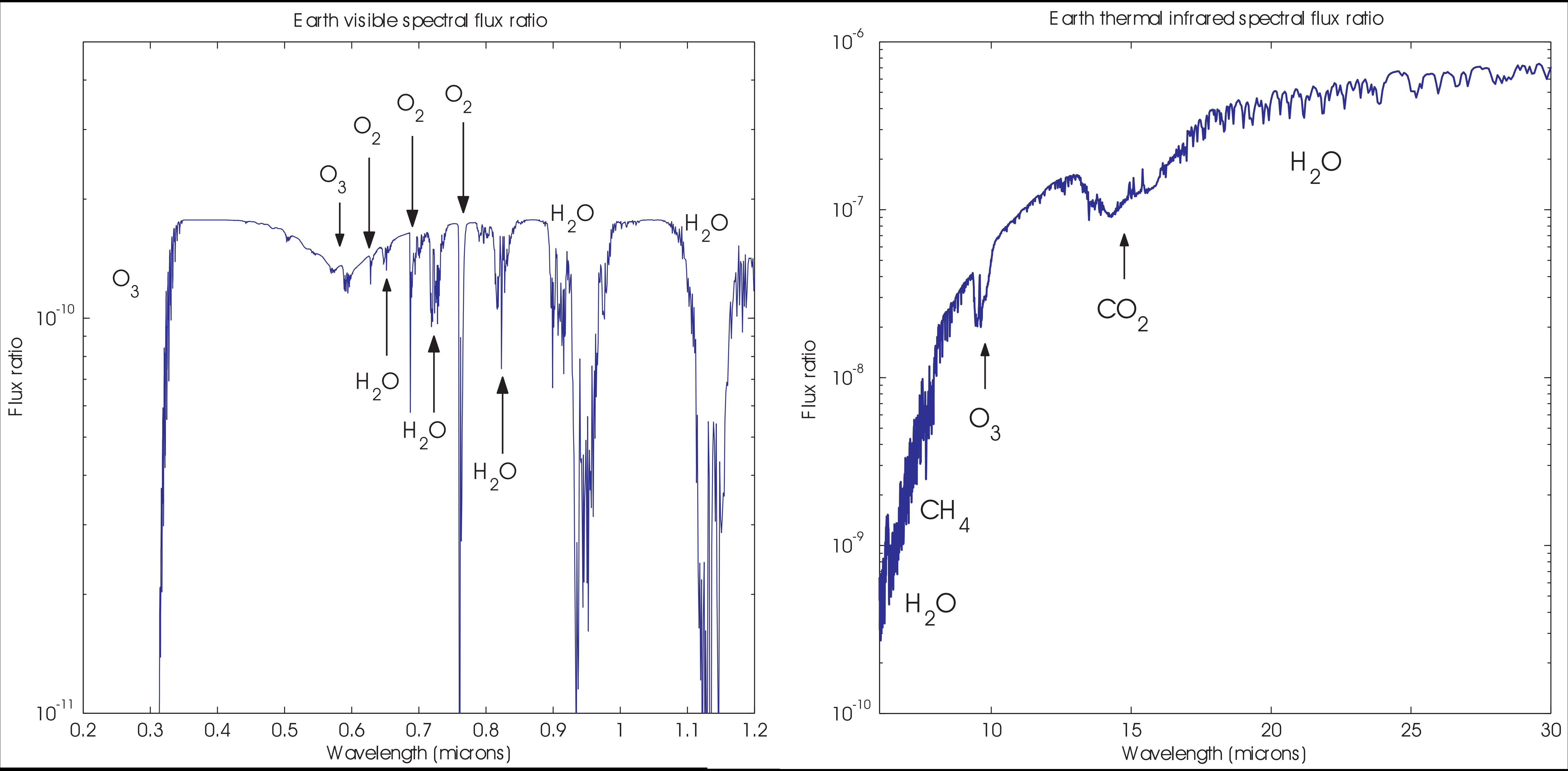
TELESCOPES OF TOMORROW WILL BE BIGGER!

BIGGER IS BETTER!

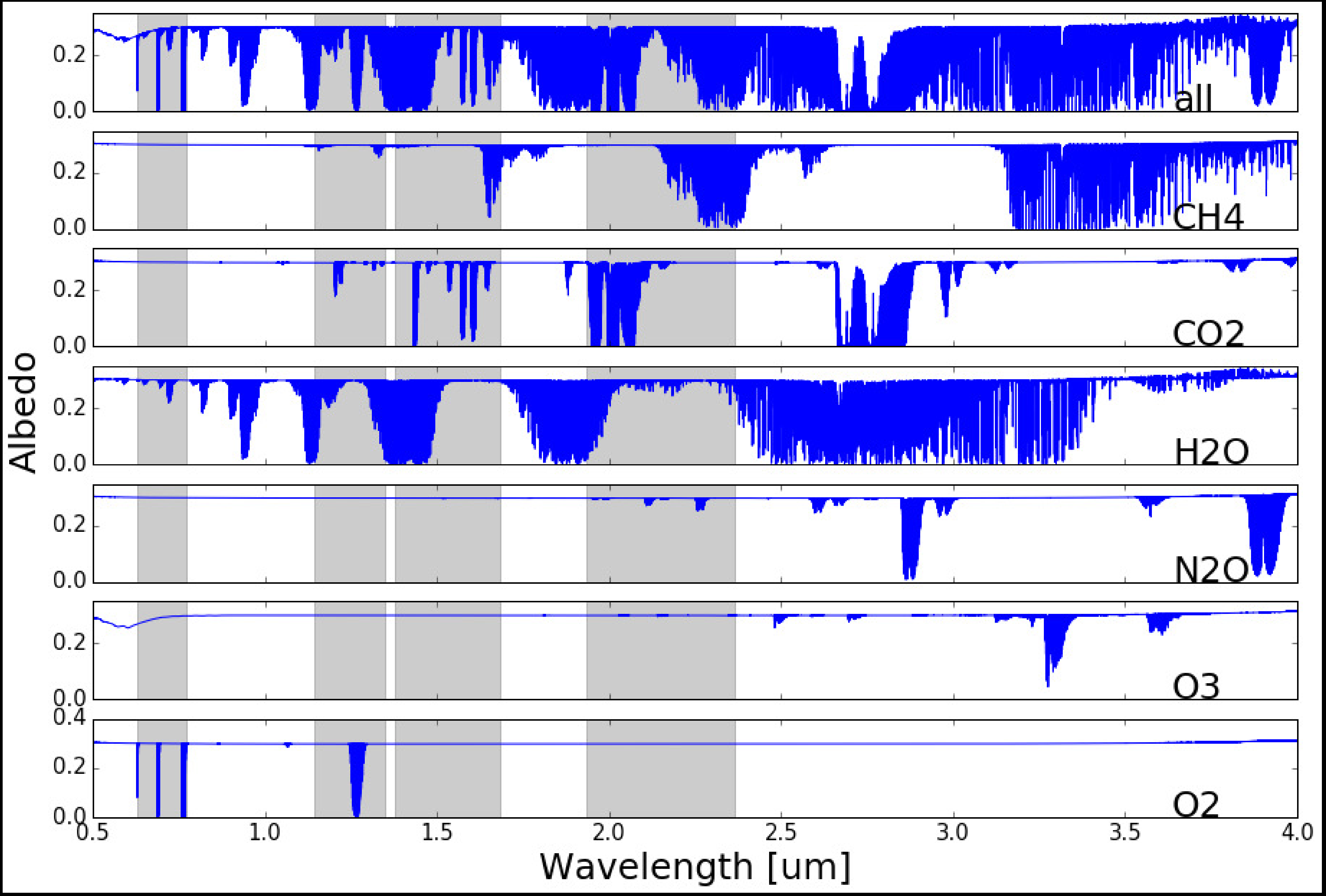


Thirty Meter Telescope

BIOSIGNATURES AT LOW R

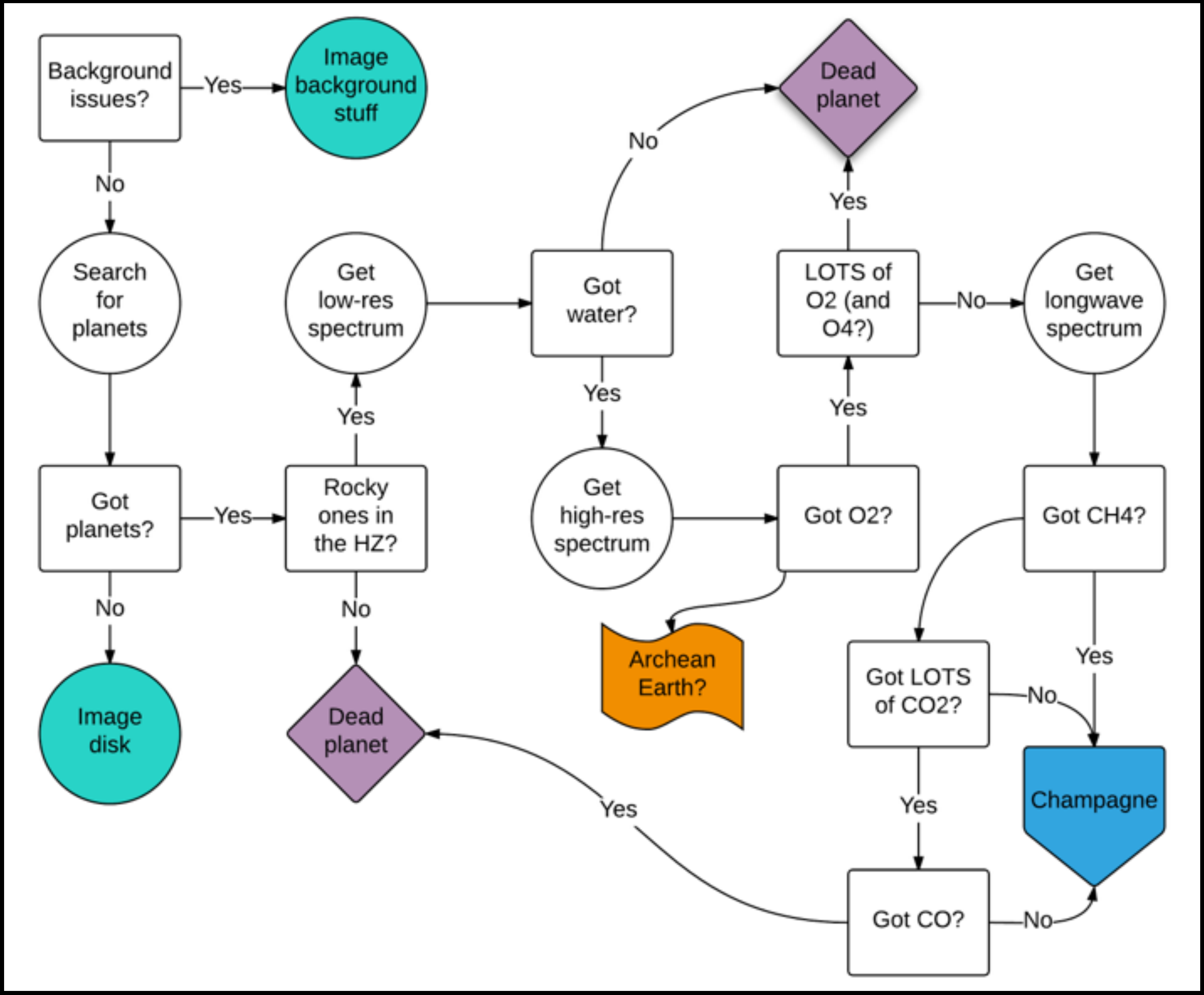


BIOSIGNATURES AT HIGH R



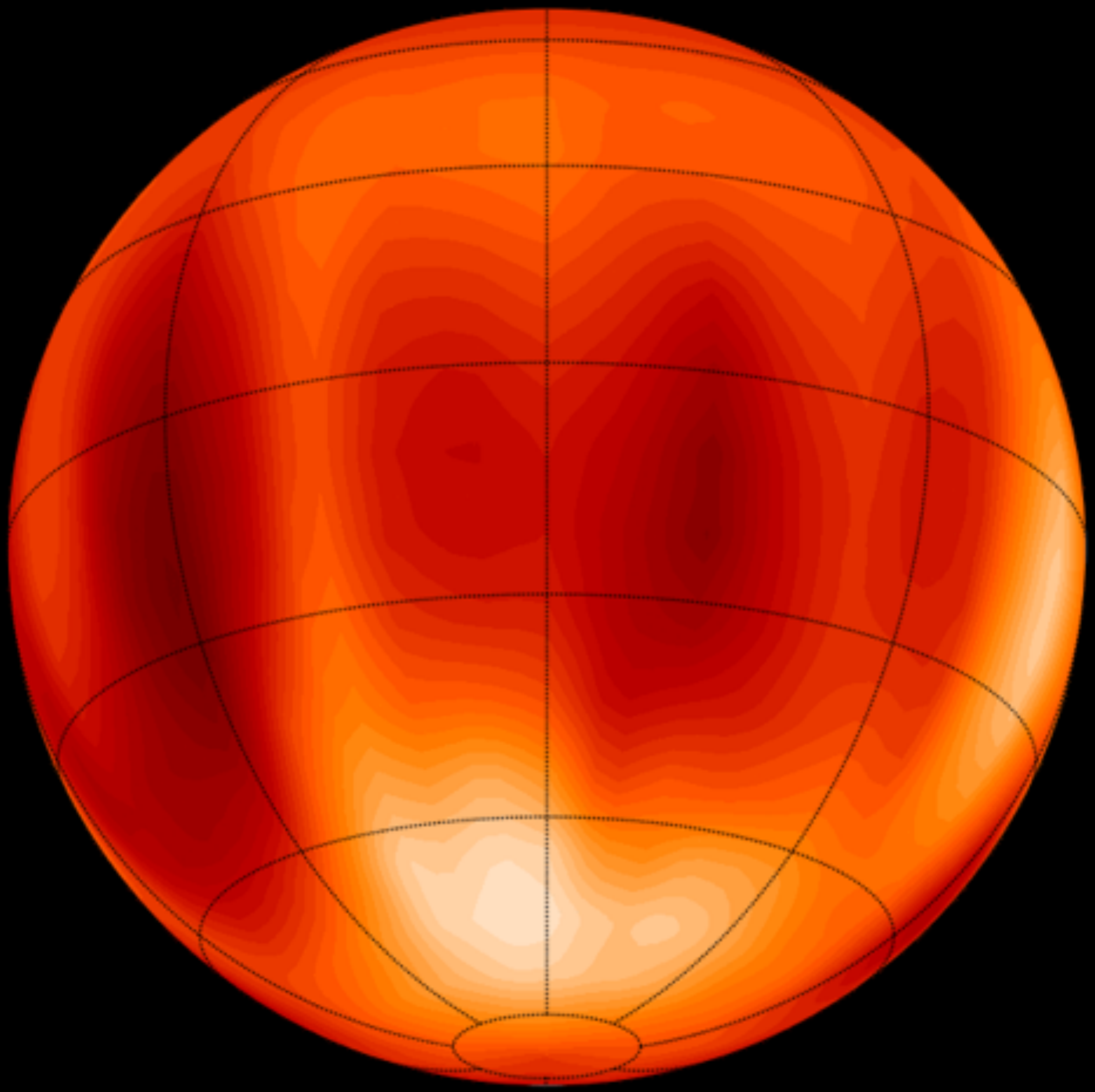
Wang J., Mawet D., Hu R., Benneke B. 2016, in prep

BIOSIGNATURE DECISION TREE



Shawn Domagal-Goldman et al. 2016, in prep

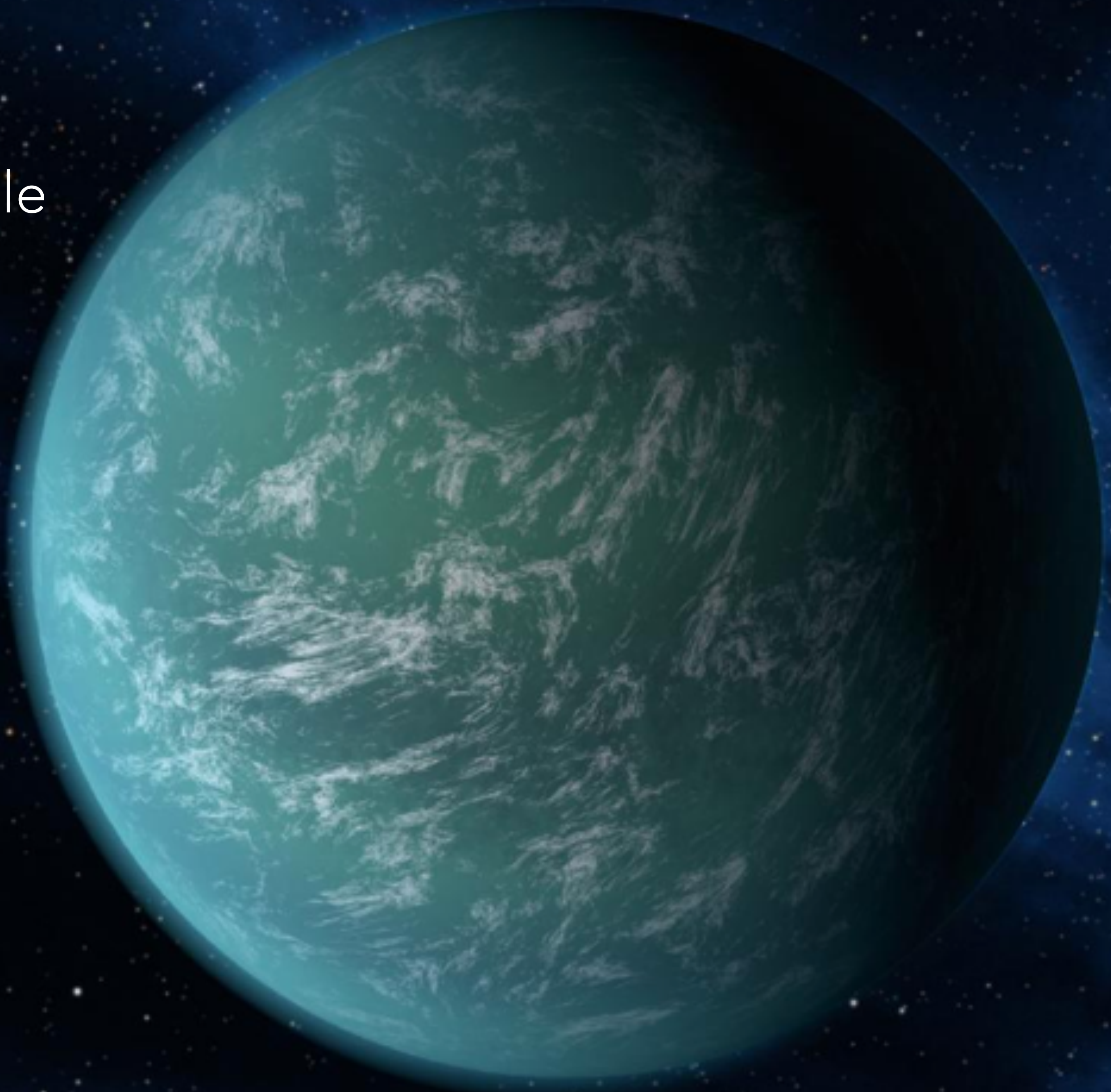
DOPPLER MAPPING OF GIANT PLANETS

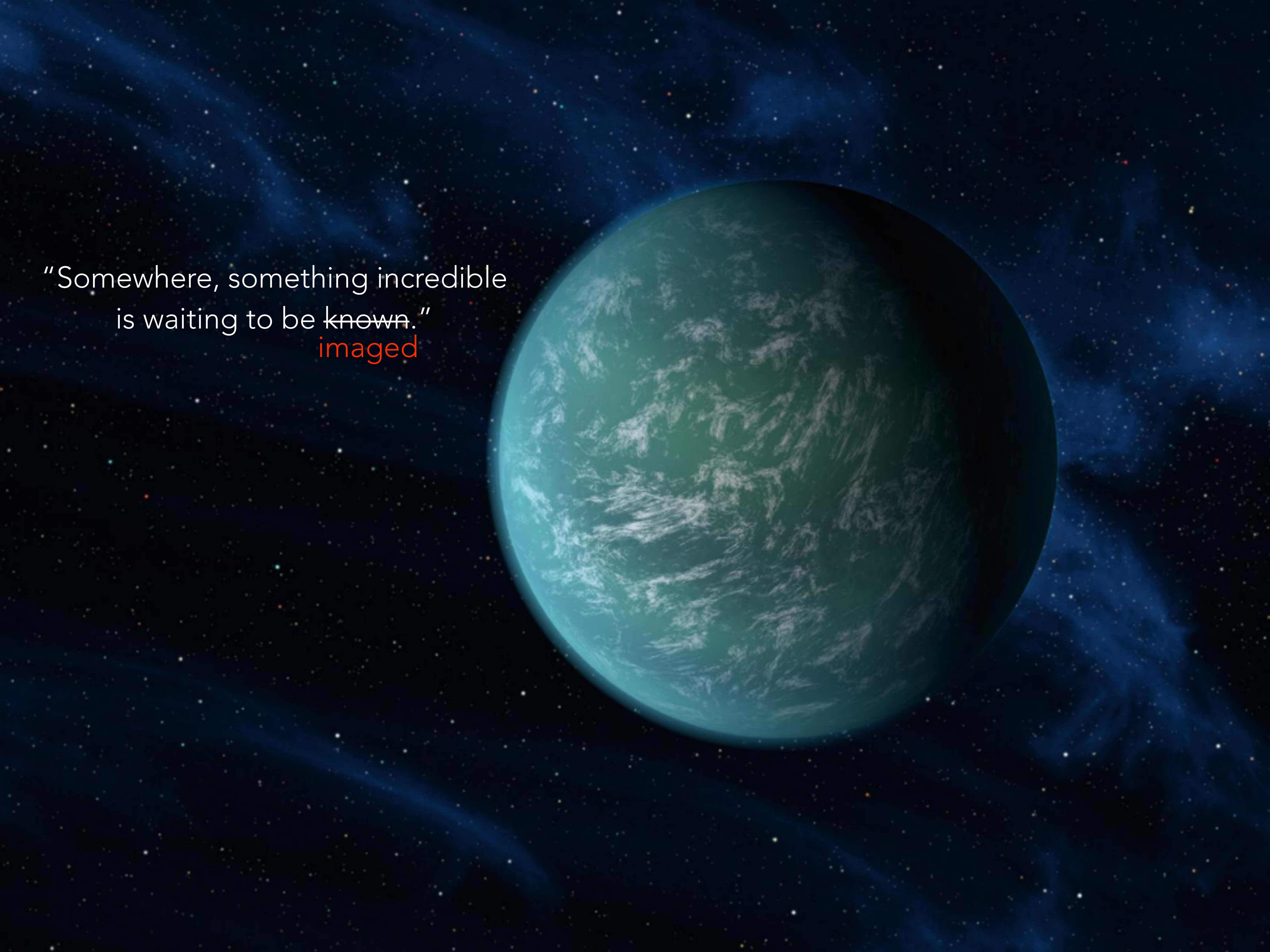


Crossfield et al. 2014

"Somewhere, something incredible is waiting to be known."

–CARL SAGAN




"Somewhere, something incredible
is waiting to be ~~known~~."
imaged