NRC·CNRC

Herzberg Institute of Astrophysics

From Gl229B to HR8799bcd: 15 years of direct exoplanet imaging research

Christian Marois

Herzberg Institute of Astrophysics

Kyoto, Japan May 2009

National Research Council Canada

Conseil national de recherches Canada

Canada

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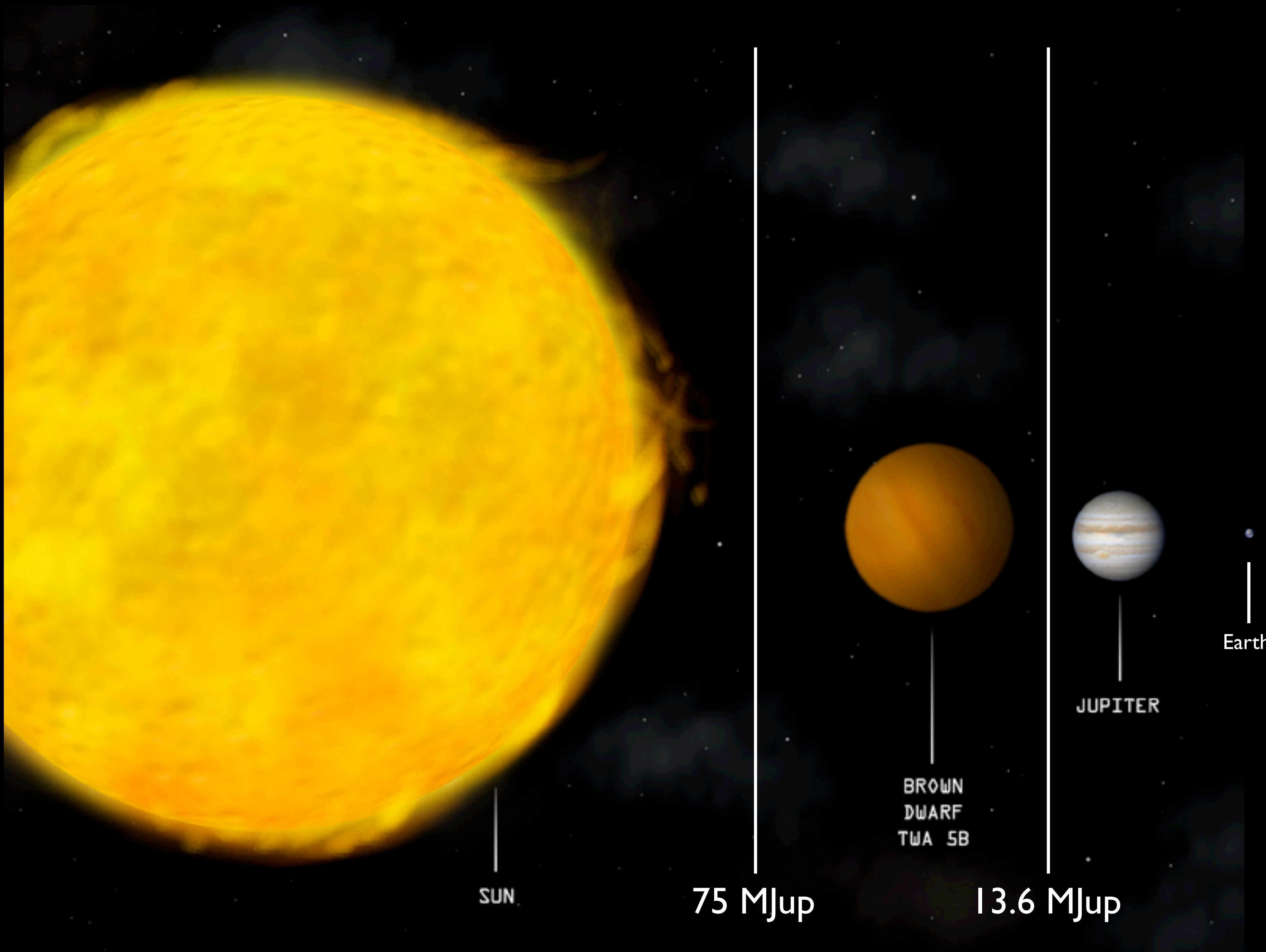
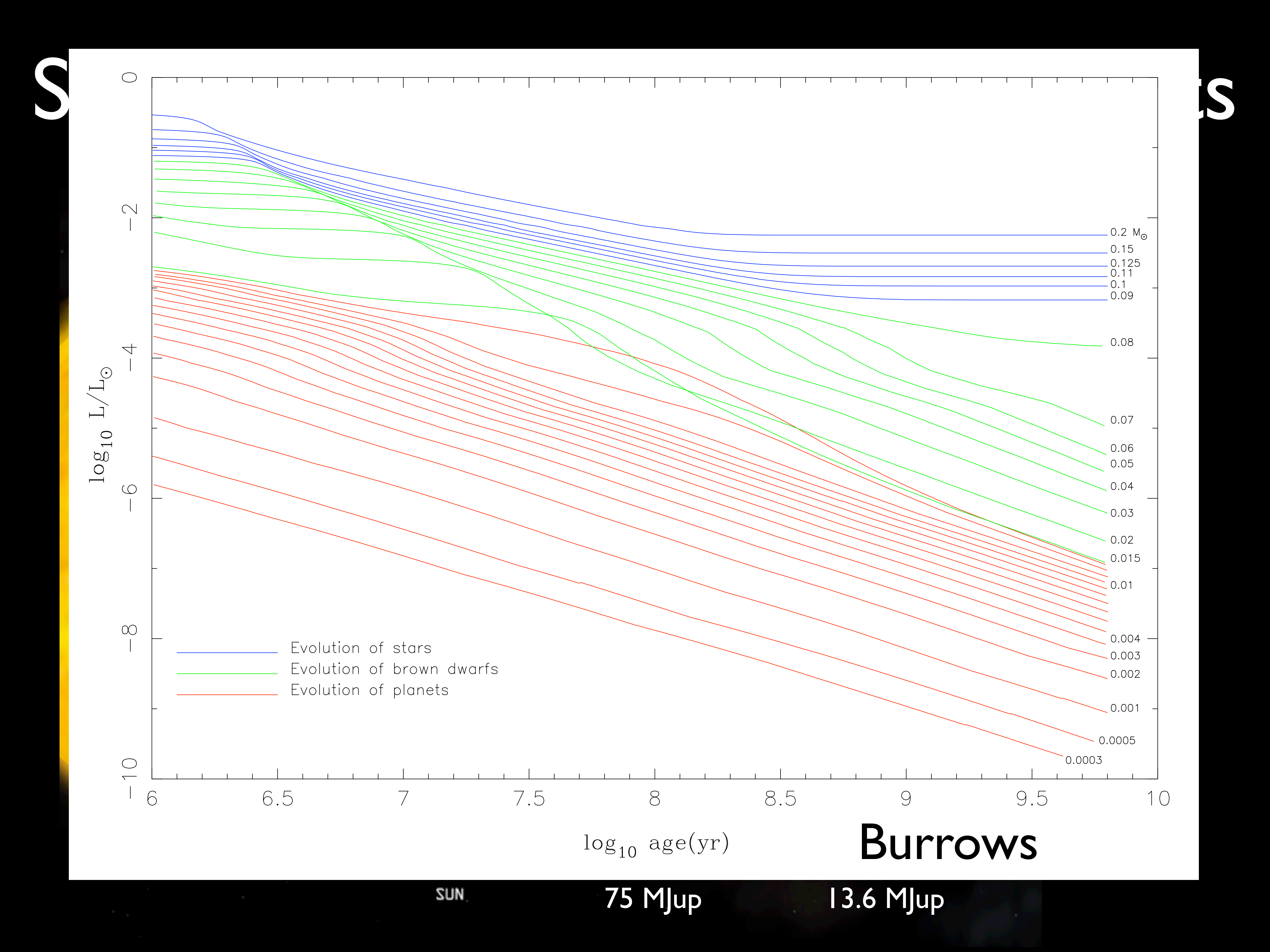
Stars vs Brown Dwarfs vs Planets




0
−2
−4
−6
−8
−10
6
6.5
7
7.5
8
8.5
9
9.5
10
log10 L/L⊙
log10 age(yr)
0.2 M⊙
0.15
0.125
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.015
0.01
0.004
0.003
0.002
0.001
0.0005
0.0003
Evolution of stars
Evolution of brown dwarfs
Evolution of planets
Burrows
SUN
75 MJup
13.6 MJup

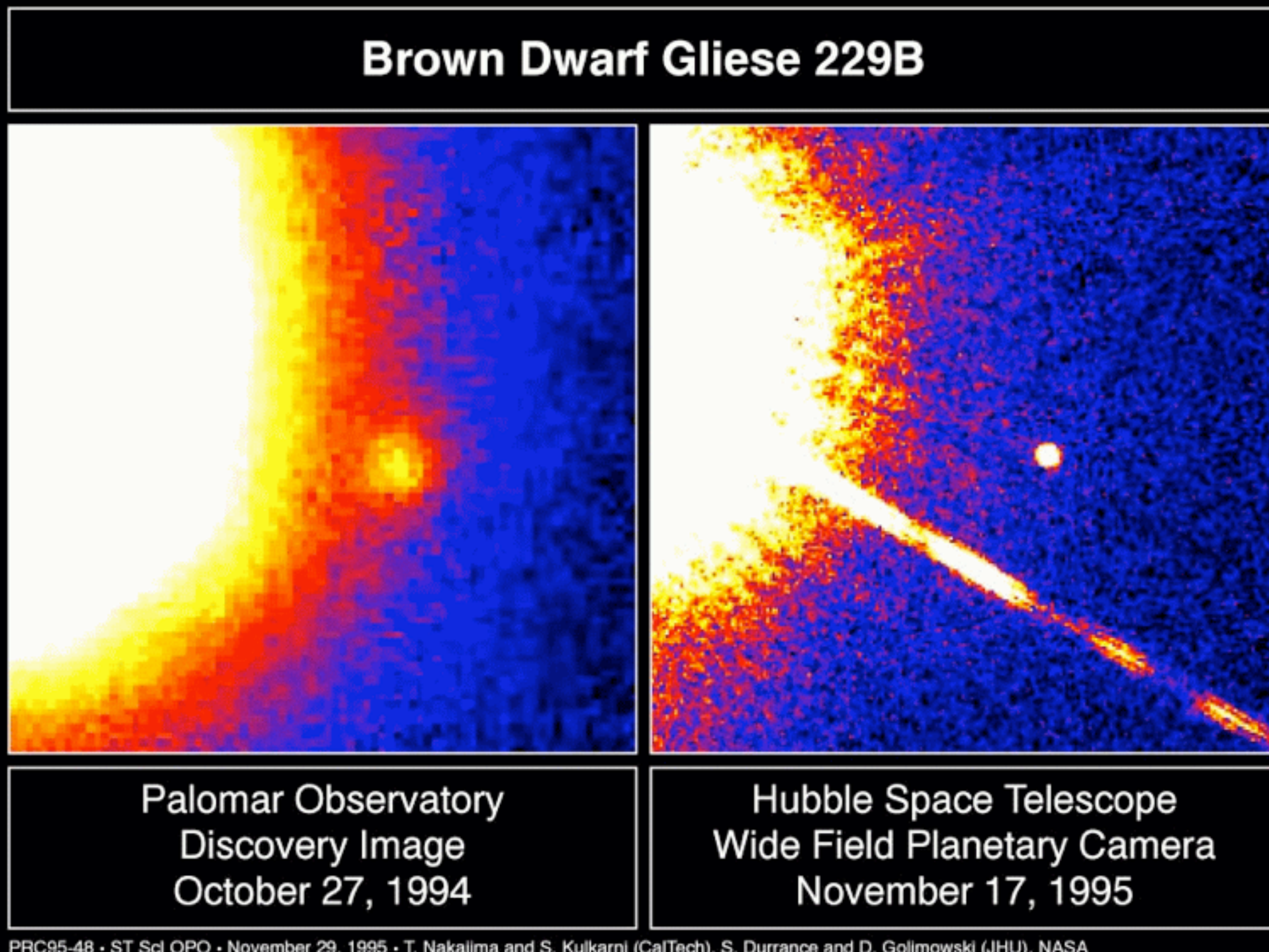
The challenge

Everest mount (10km)

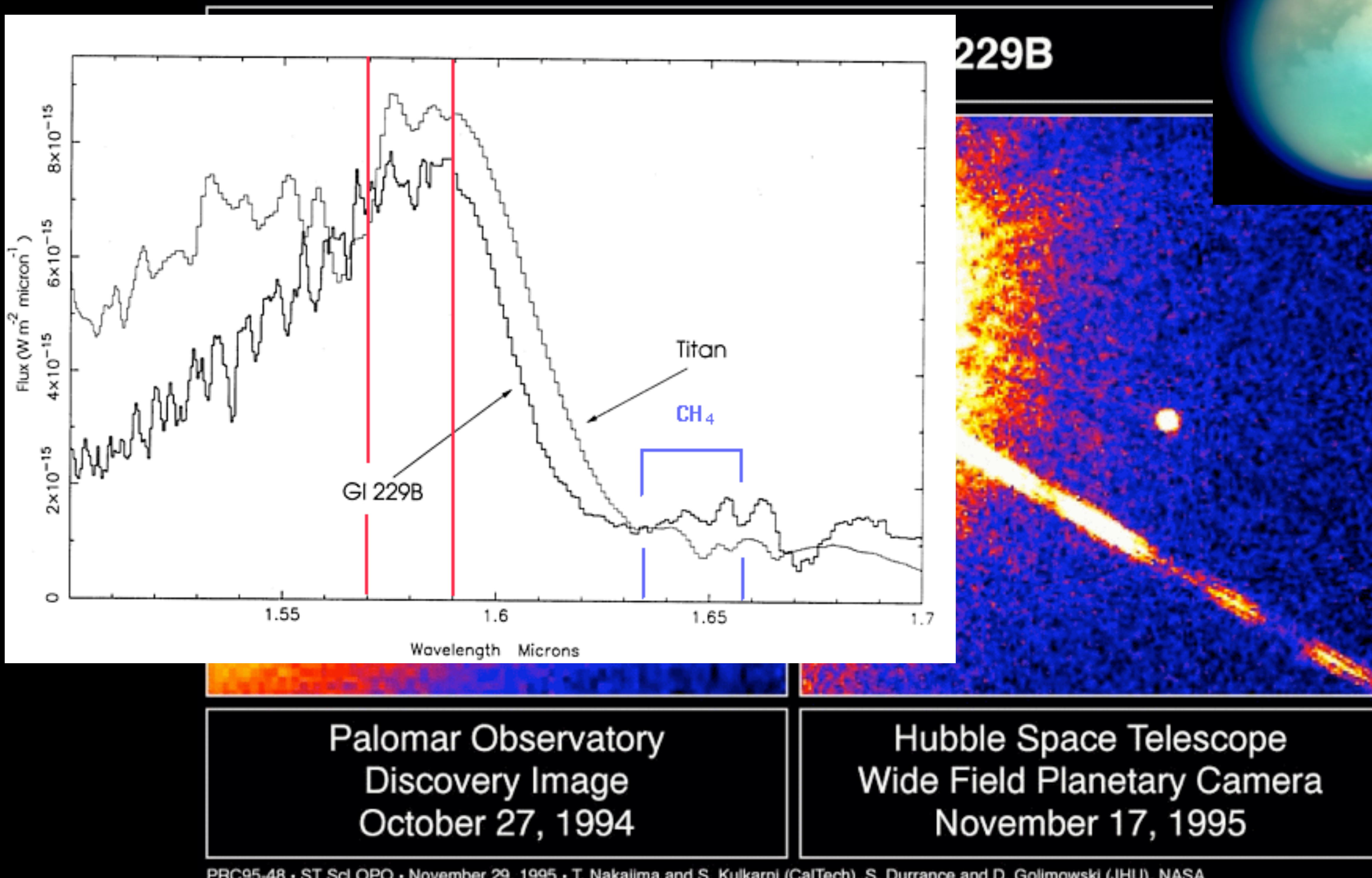
Jupiter: basketball

Earth: ant

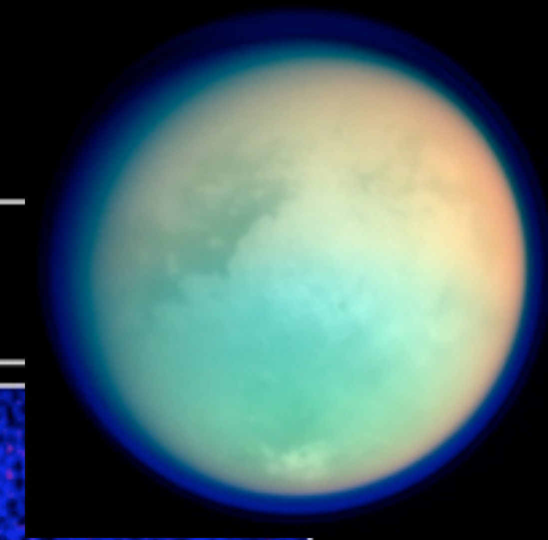
Gl229B


Brown Dwarf Gliese 229B
Palomar Observatory
Discovery Image
October 27, 1994
Hubble Space Telescope
Wide Field Planetary Camera
November 17, 1995
PRC95-48 • ST ScI OPO • November 29, 1995 • T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA

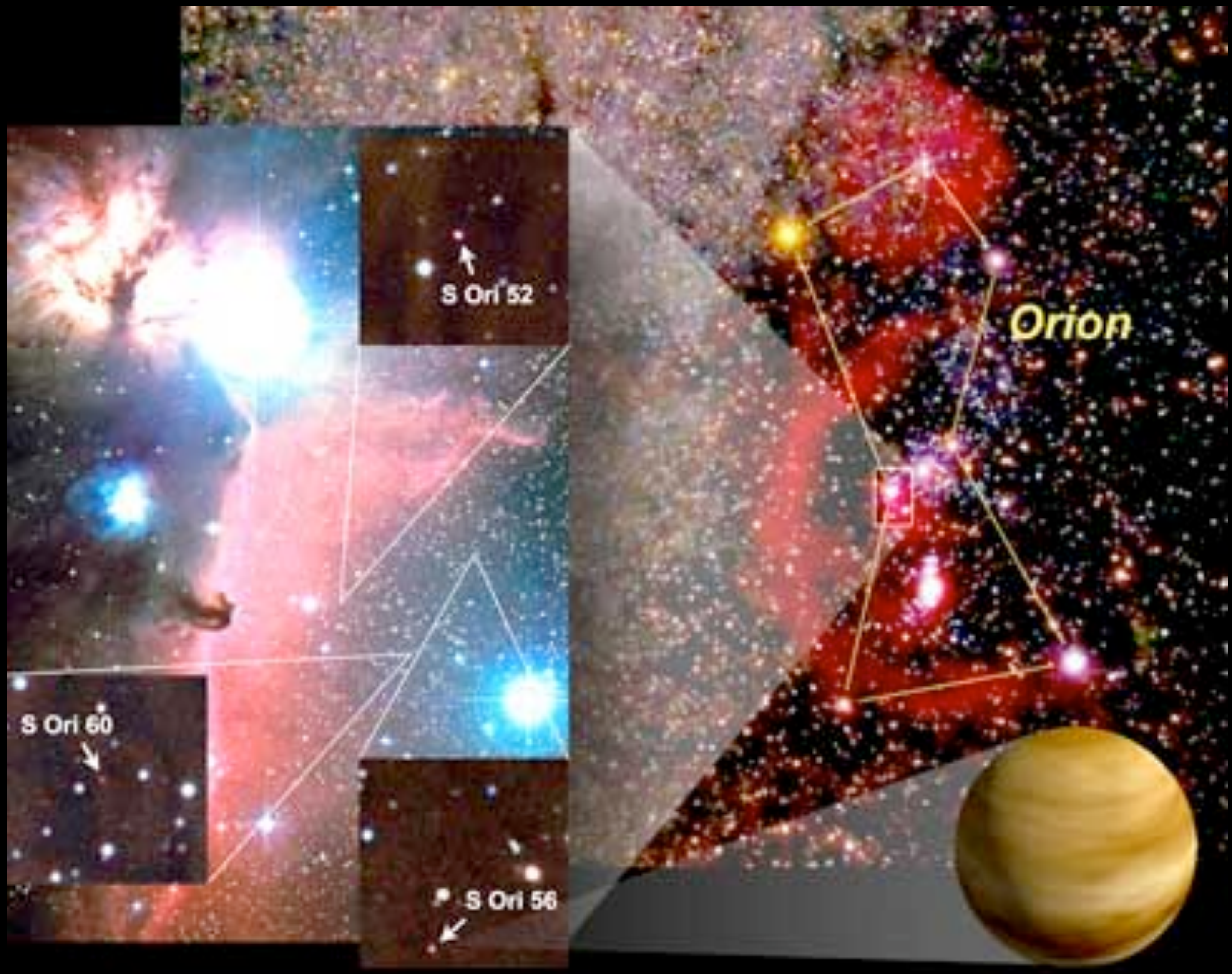
Gl229B



Flux (W m^{-2} micron^{-1})
0
2×10^{-15}
4×10^{-15}
6×10^{-15}
8×10^{-15}
1.55
1.6
1.65
1.7
Wavelength Microns
Titan
Gl 229B
CH$_4$
229B
Palomar Observatory
Discovery Image
October 27, 1994
Hubble Space Telescope
Wide Field Planetary Camera
November 17, 1995
PRC95-48 • ST ScI OPO • November 29, 1995 • T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA



Star Forming Region

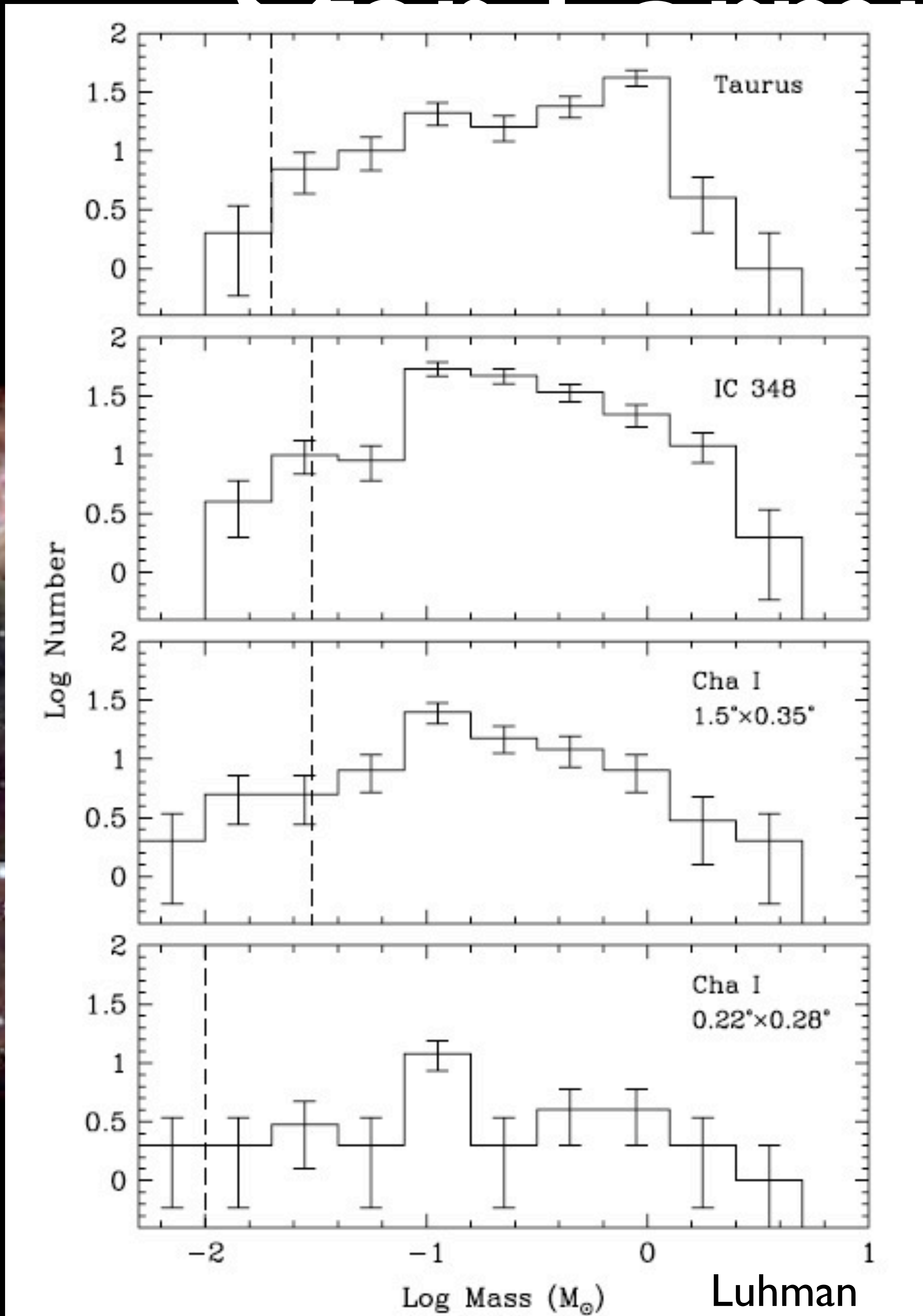


Zapatero Osorio et al. 2000

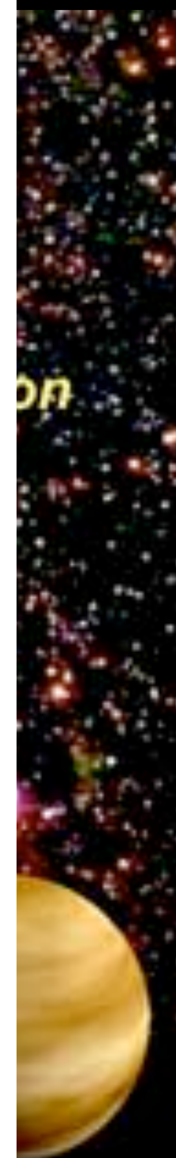
5-15 MJup

Free-floating in star forming regions?

Star Forming Region



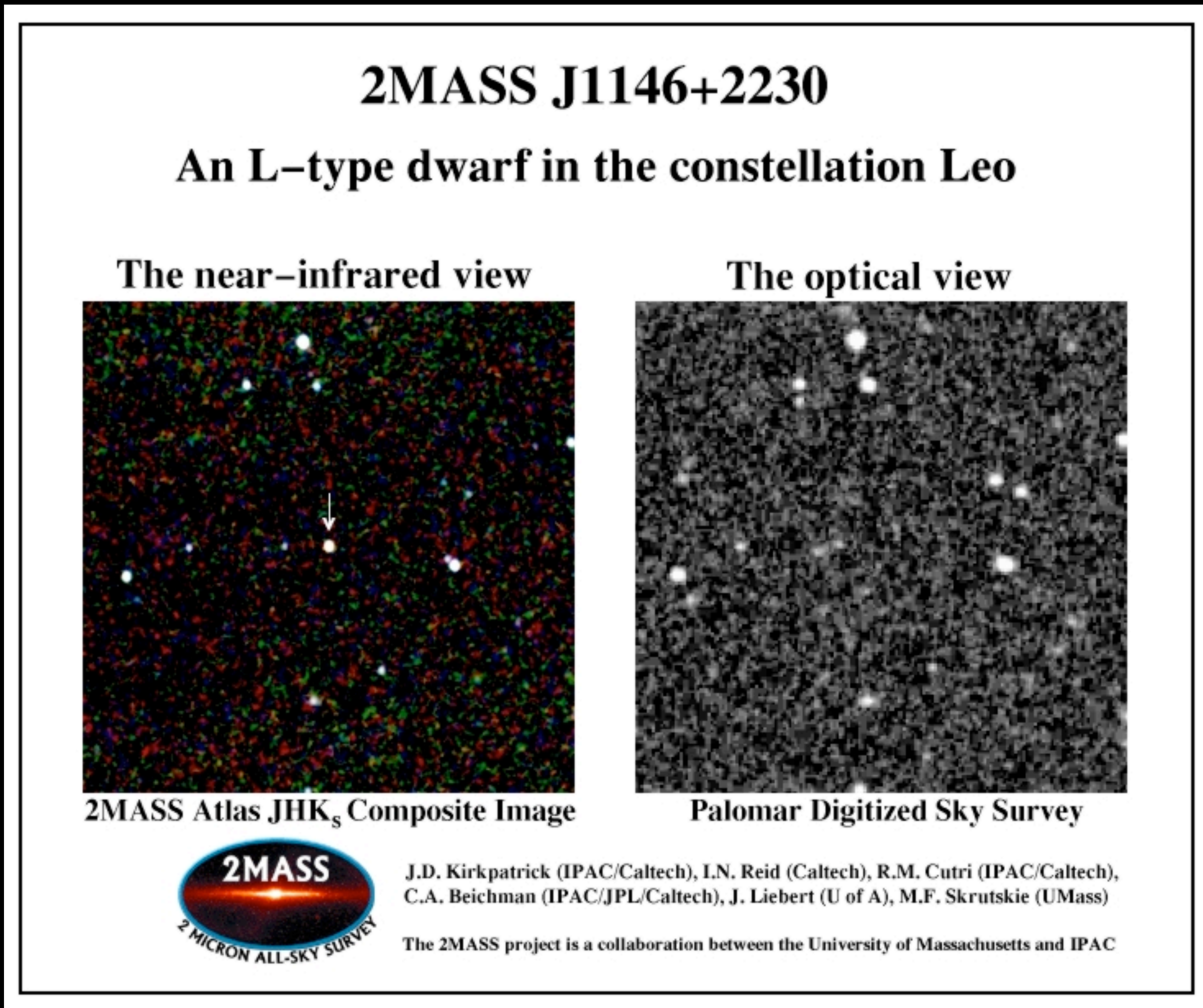
Luhman



5-15 MJup

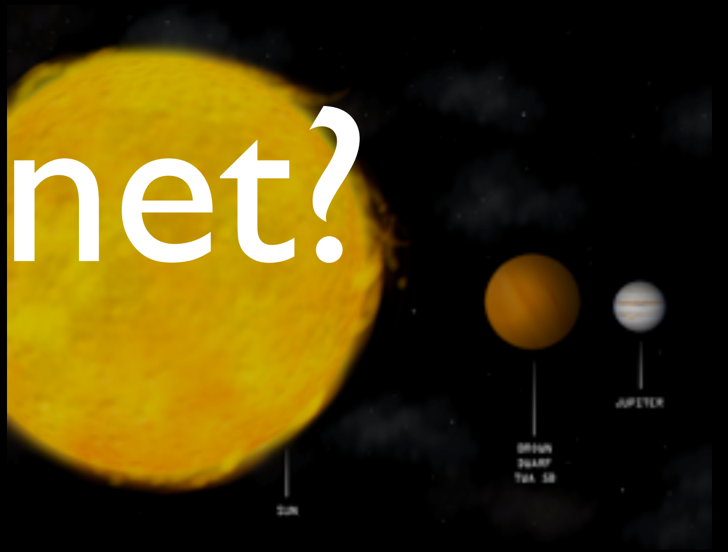
Free-floating in star forming regions?

2MASS



Free-floating in space?

What is an exoplanet?



- Less than 13.6 Jupiter mass (13.6-75MJup = brown dwarfs)

- In orbit around a star

- Form in a disk (?)

- Initial formation energy, than cool down with time.

  "hot start model"

  "core accretion model"

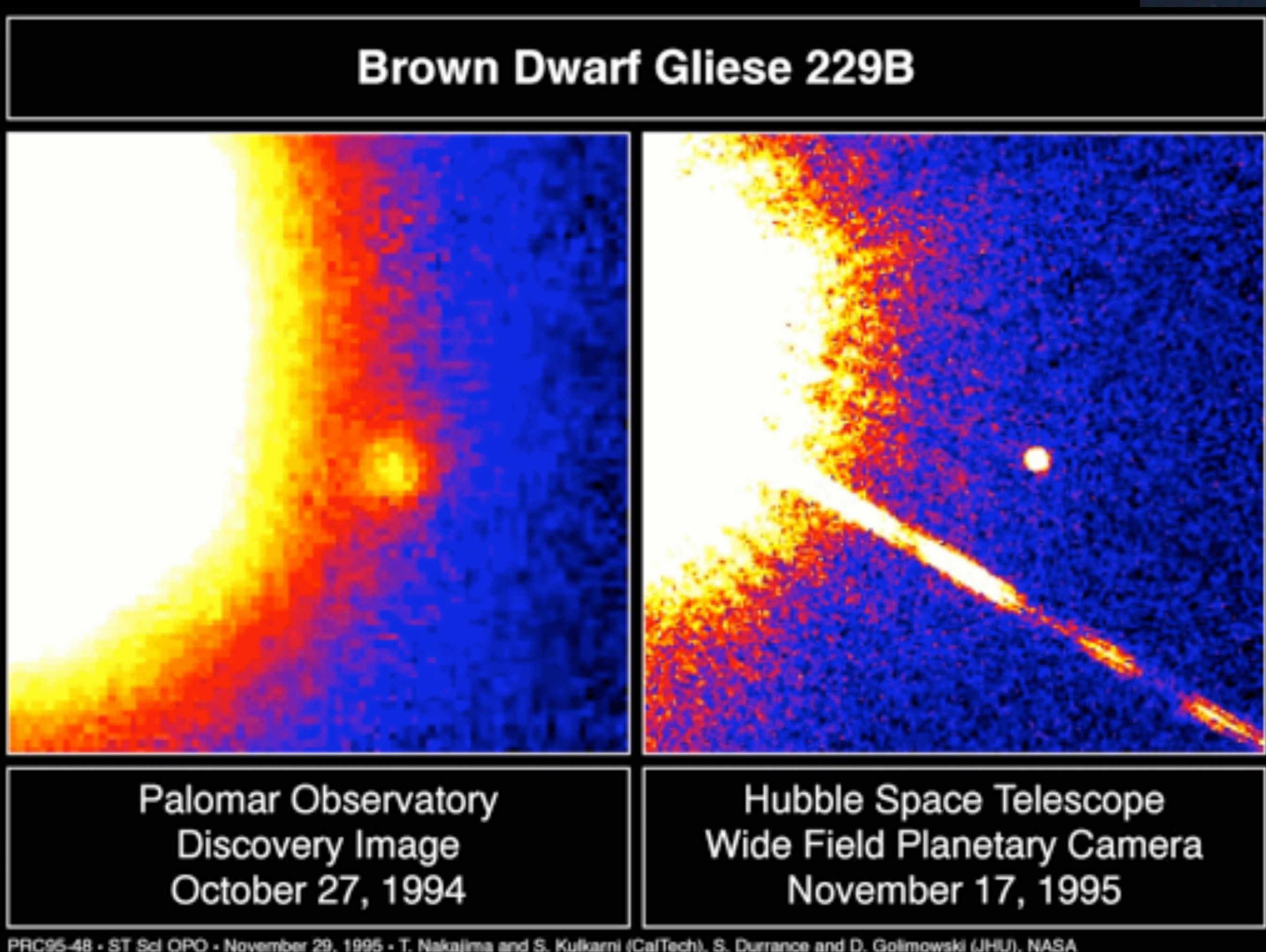
Designing a Direct Imaging Exoplanet Survey

- Need to be able to resolve the system

- Need to be able to see the planets before they cool down

Find nearby & young stars

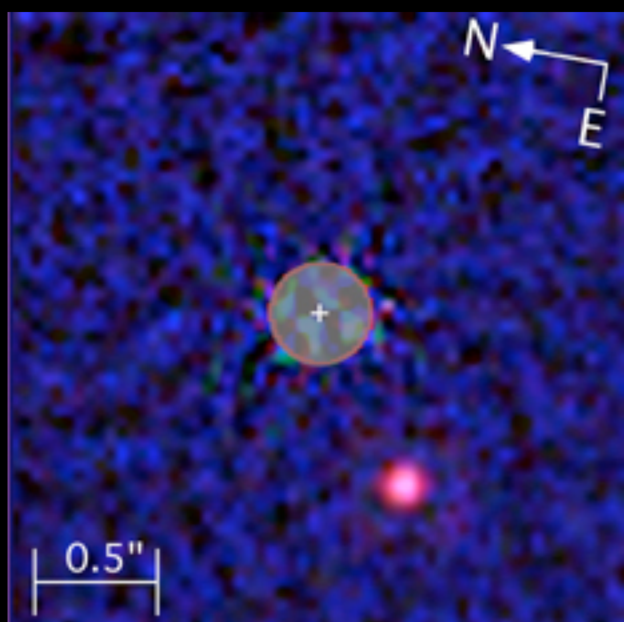
Palomar AO Survey



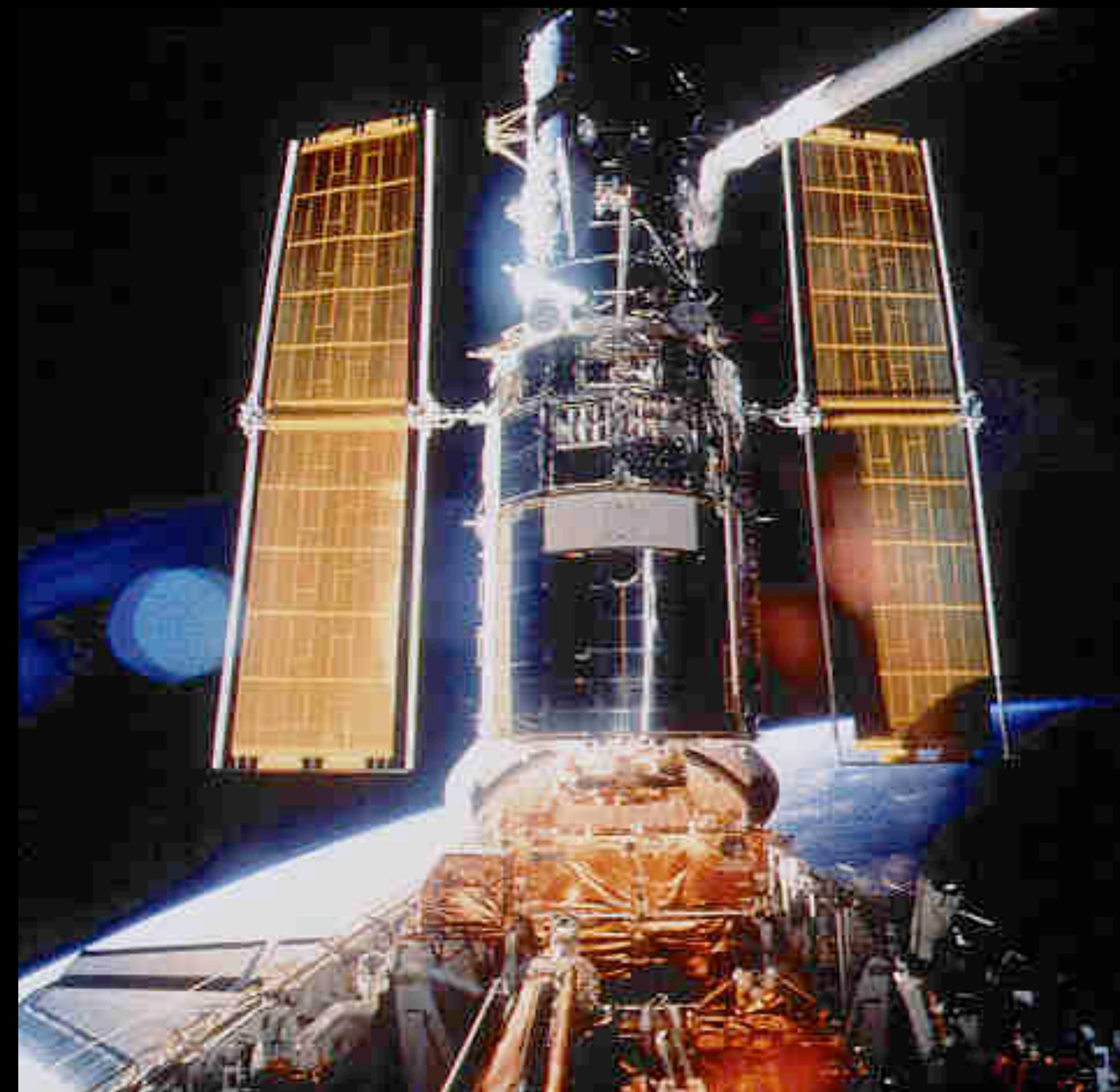
Ben Oppenheimer et al. : < 8pc survey (163 stars)

Stan Metchev et al. : 266 stars 3Myr-3Gyr at Palomar & Keck - BD statistics 28-1590AU 3.2% [+3.1-2.7]

Young star HST survey



2M1207b



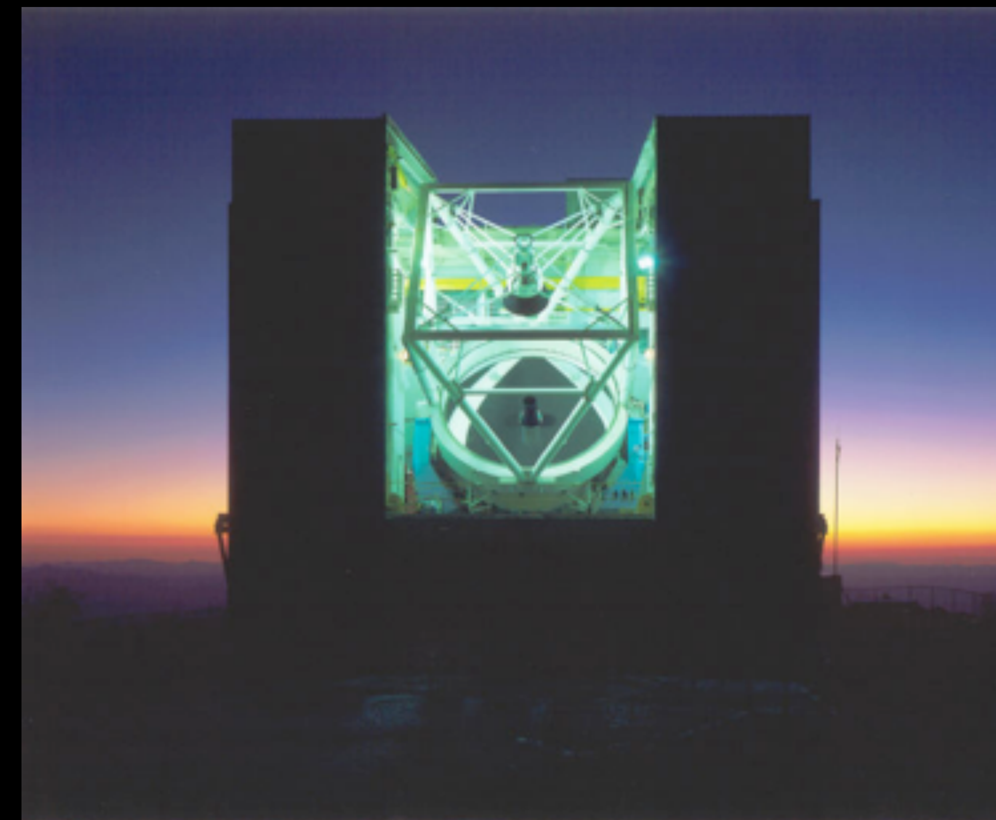
116 nearby young stars - NICMOS 2 coronagraph

Inseok Song et al.

Keck AO survey

Kaisler, Macintosh, Zuckerman, Song et al.
M. Liu
Stan Metchev

VLT/Arizona AO survey



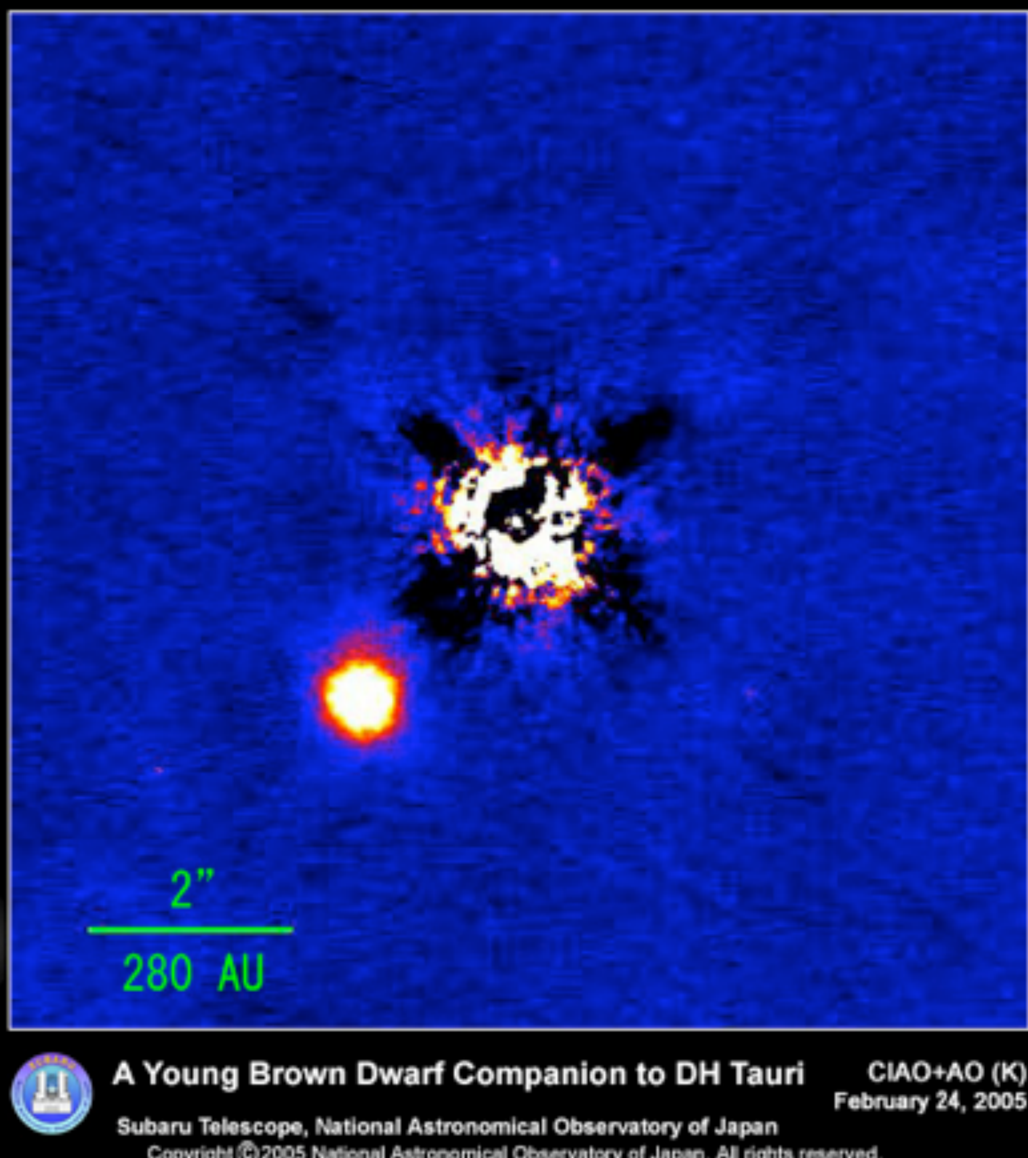
Laird Close/R. Lenzen SDI-camera
60 stars survey (B. Billers)
Nielson 20-100AU >4MJup <20%

Chauvin et al.

Phil Henz Clio L-band IR camera
<6pc survey

Neuhauser et al

Subaru AO survey

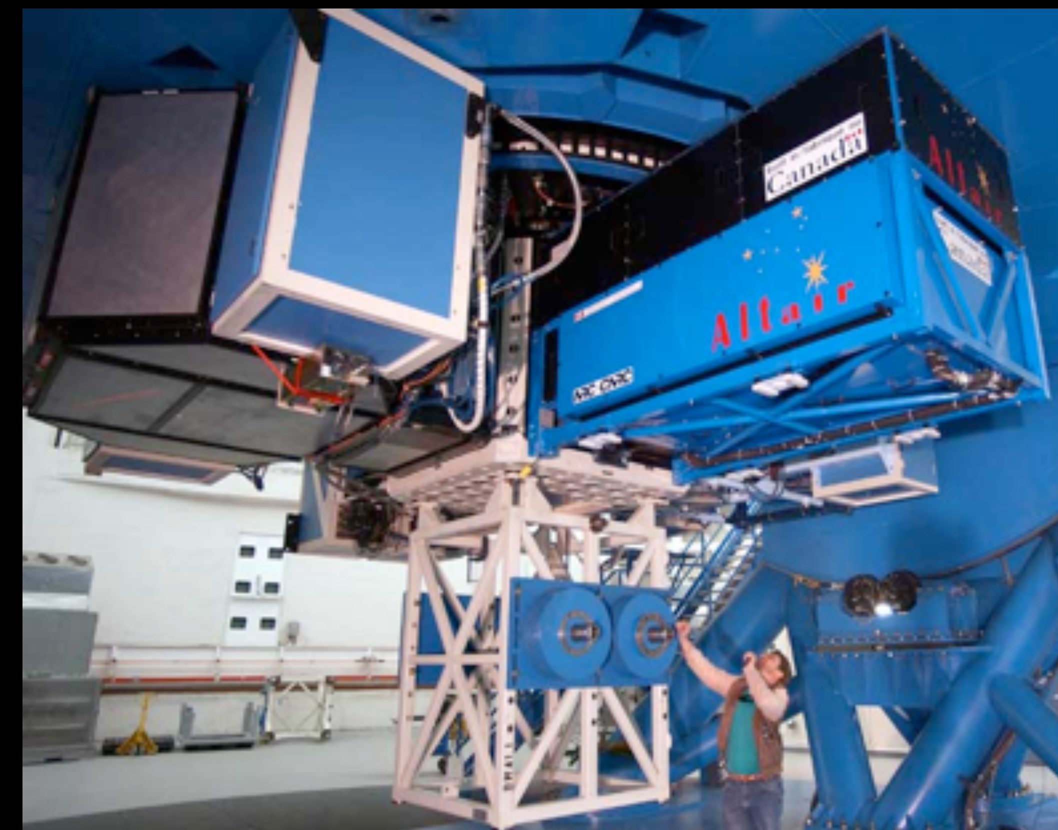


Nakajima < 20 pc survey
Motohide Tamura TTauri star survey

Gemini AO survey

Altair commissioning ~2003

Altair@Gemini N



David Lafreniere: GDPS (2004-2007) 86 GKM stars <300 Myr

Christian Marois: IDPS (2007-now) ~100 AF stars <300 Myr & some dusty AF stars

David Lafreniere: Young star associations

Markus Janson: ~10 OB stars

Our Gemini Survey History

- 2002: ADI initial idea

- 2003: Initial ADI testing at Gemini North (Altair SV).

- 2004-2007: 86 GKM stars ADI survey at Gemini North - no detection (Lafreniere et al. 2007).

- 2007-now: 80 AF stars ADI survey (Gemini North, Keck II & VLT).

- 2007-now: Young star association (Lafreniere)

Angular Differential Imaging

Image 1

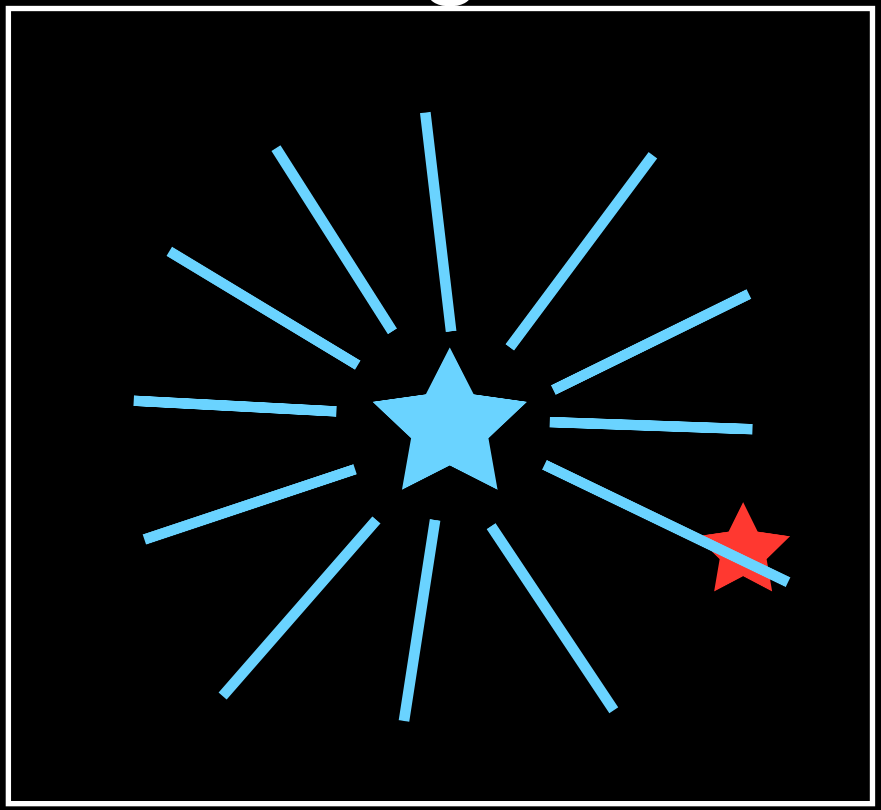
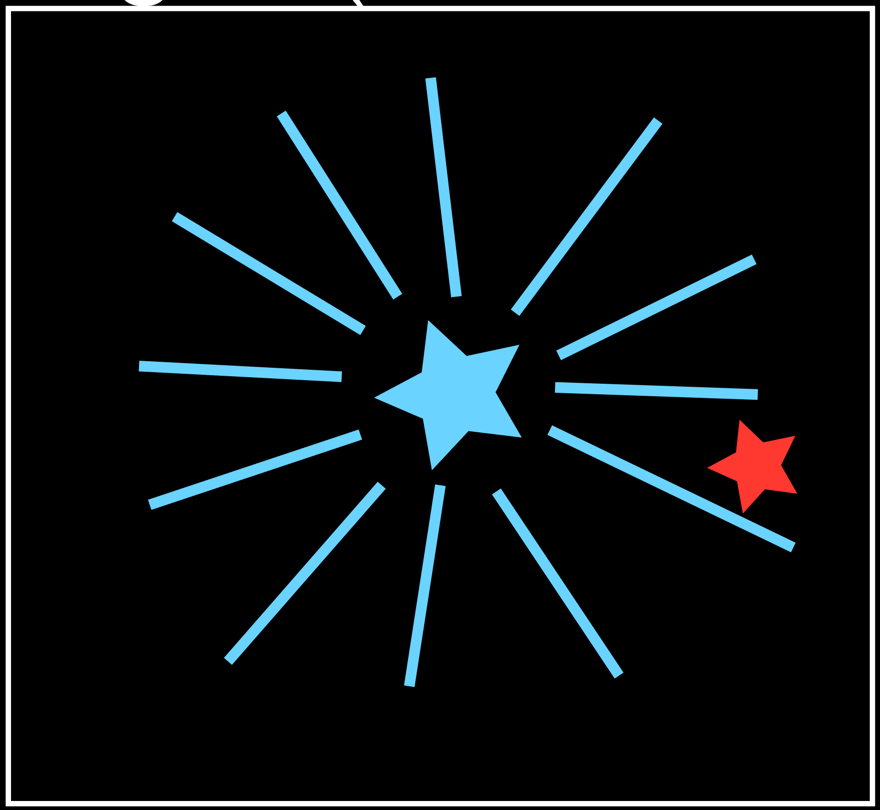


Image 2 (+ 5 minutes)



Angular Differential Imaging

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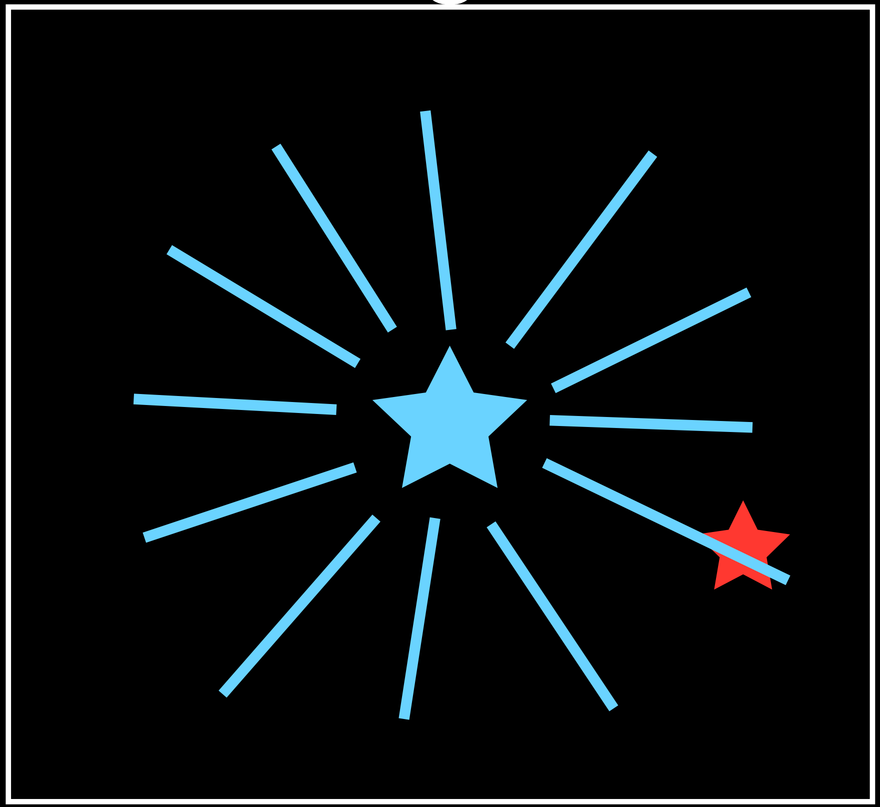
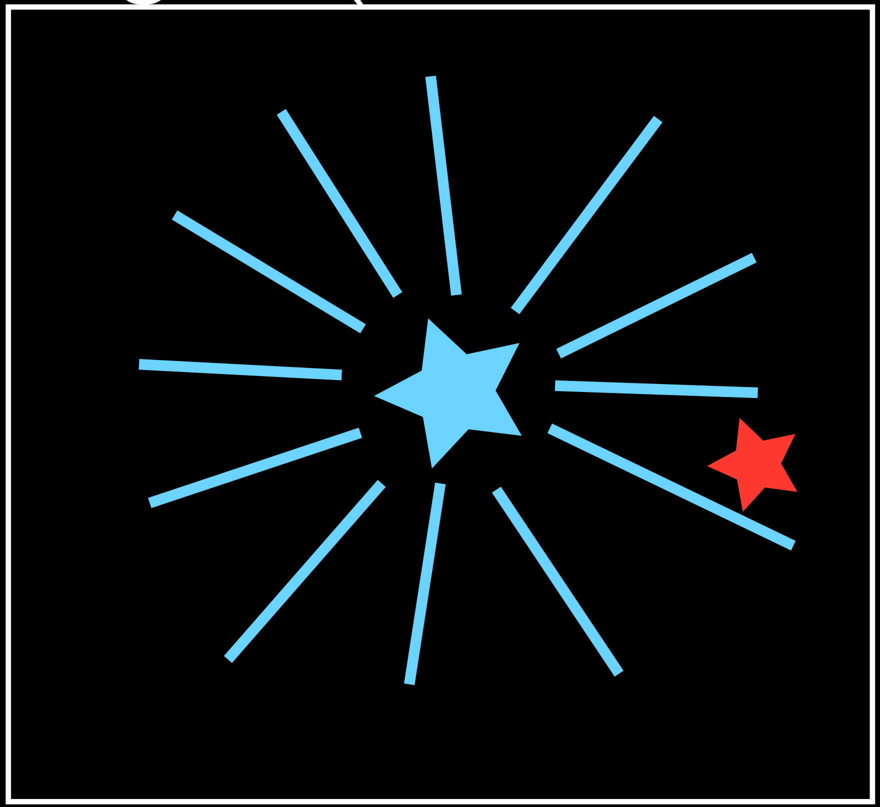
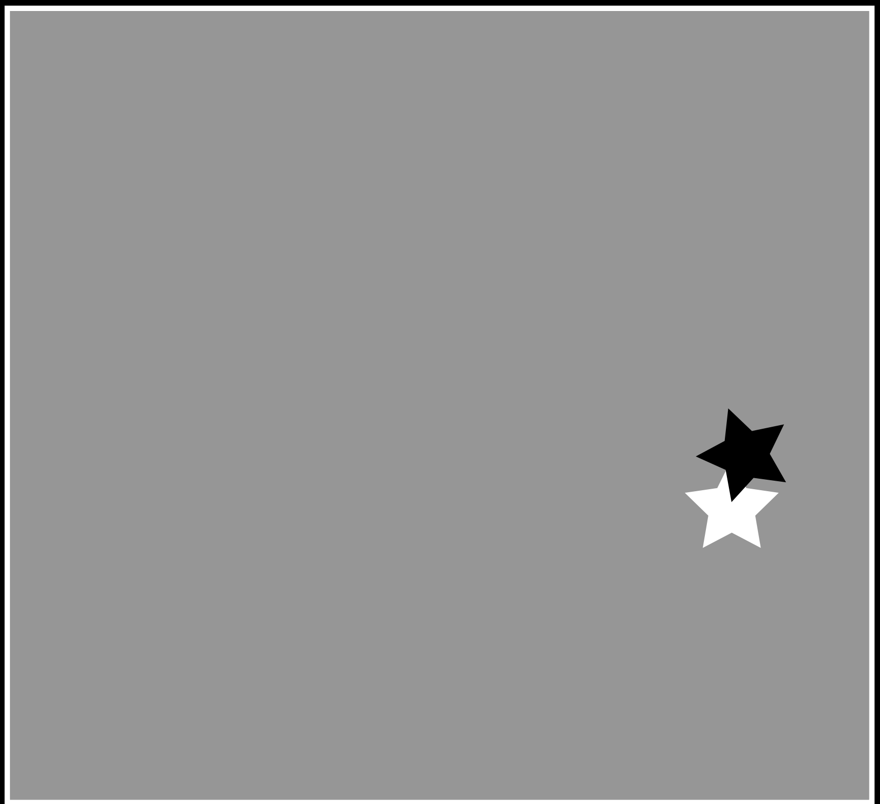


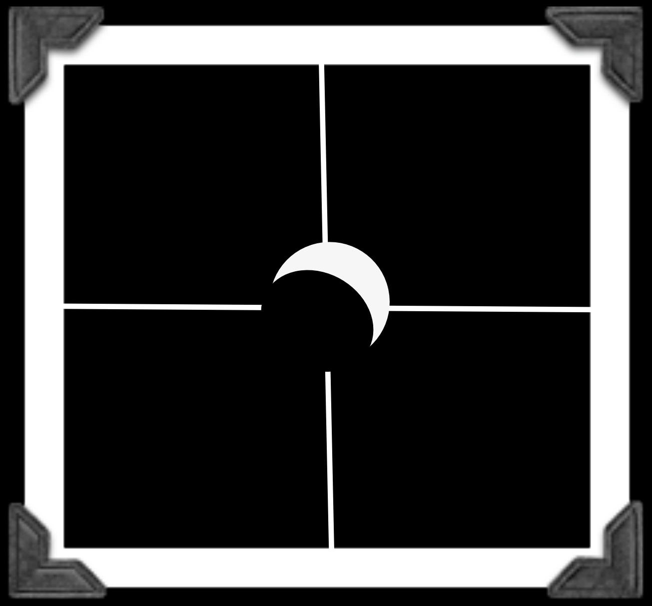
Image 2 (+ 5 minutes)

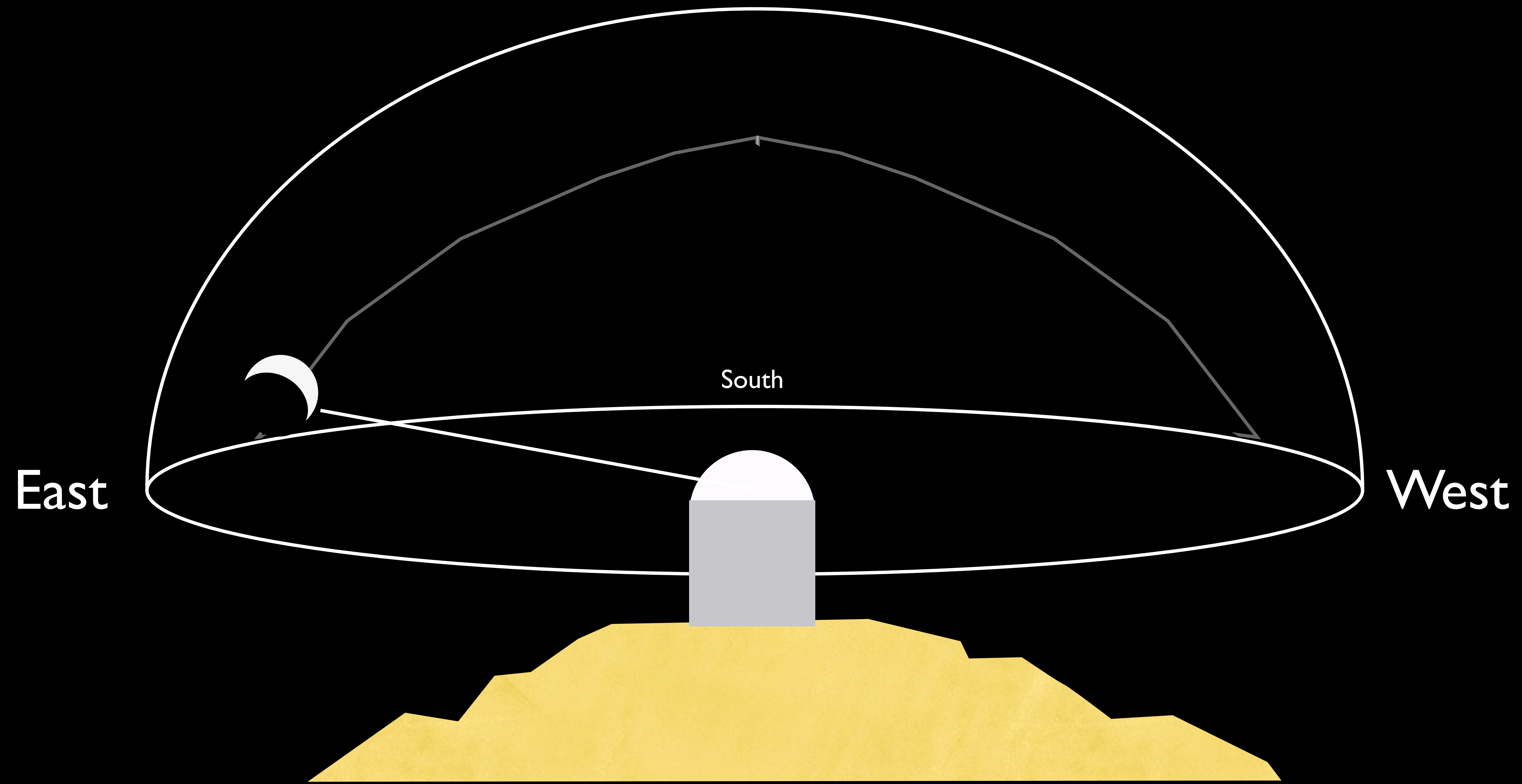


Subtraction



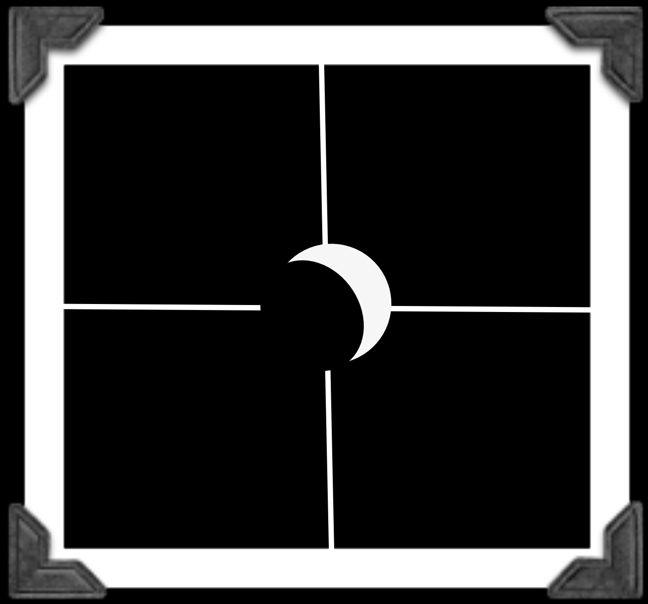
Angular differential imaging

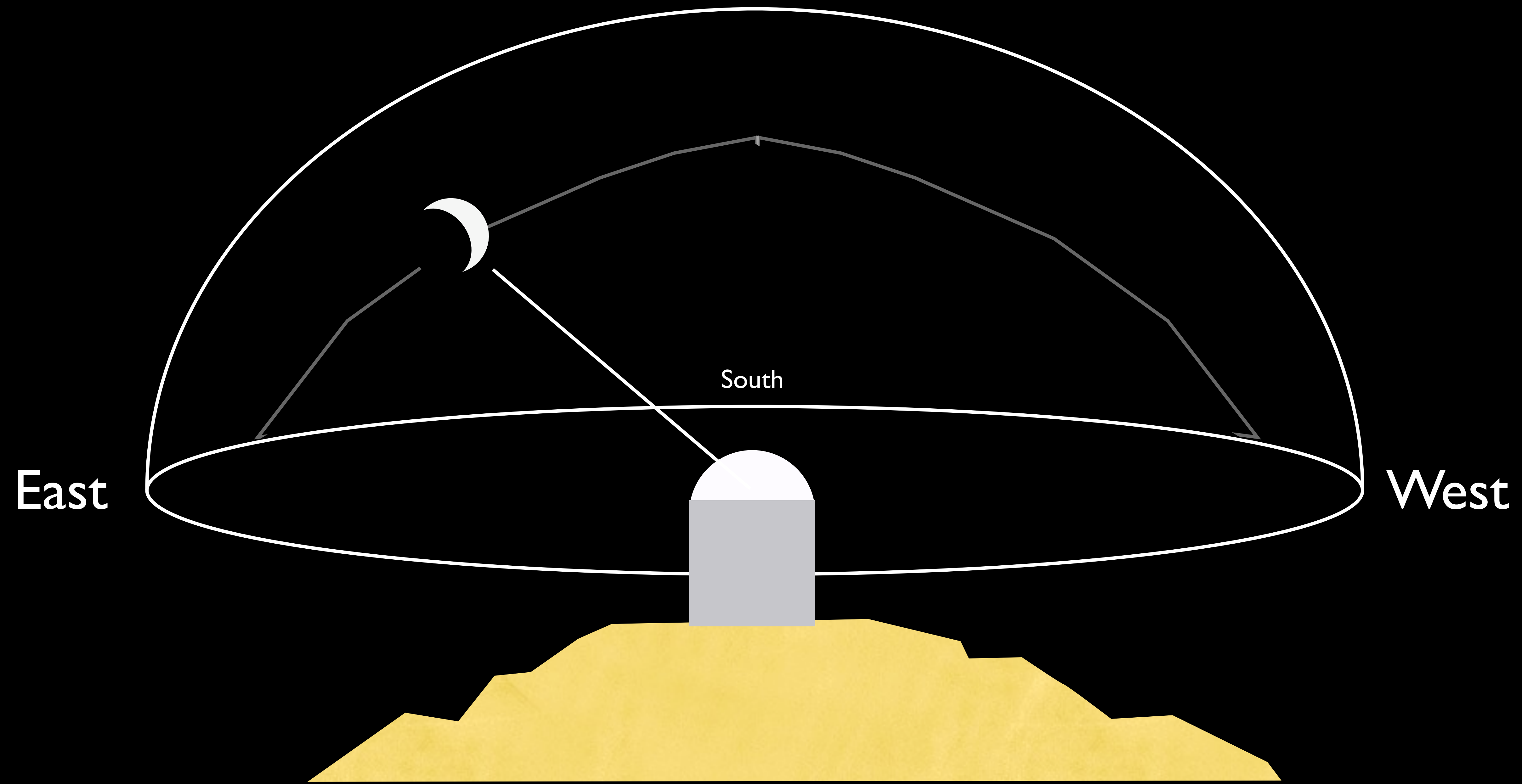




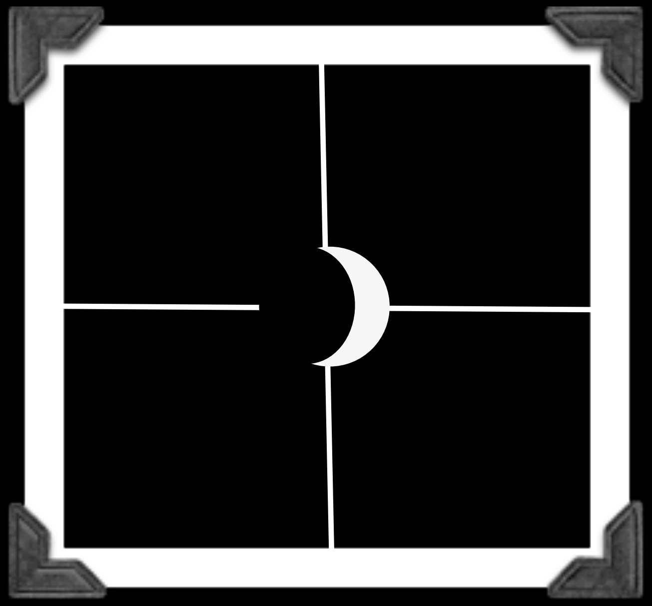
Angular differential imaging

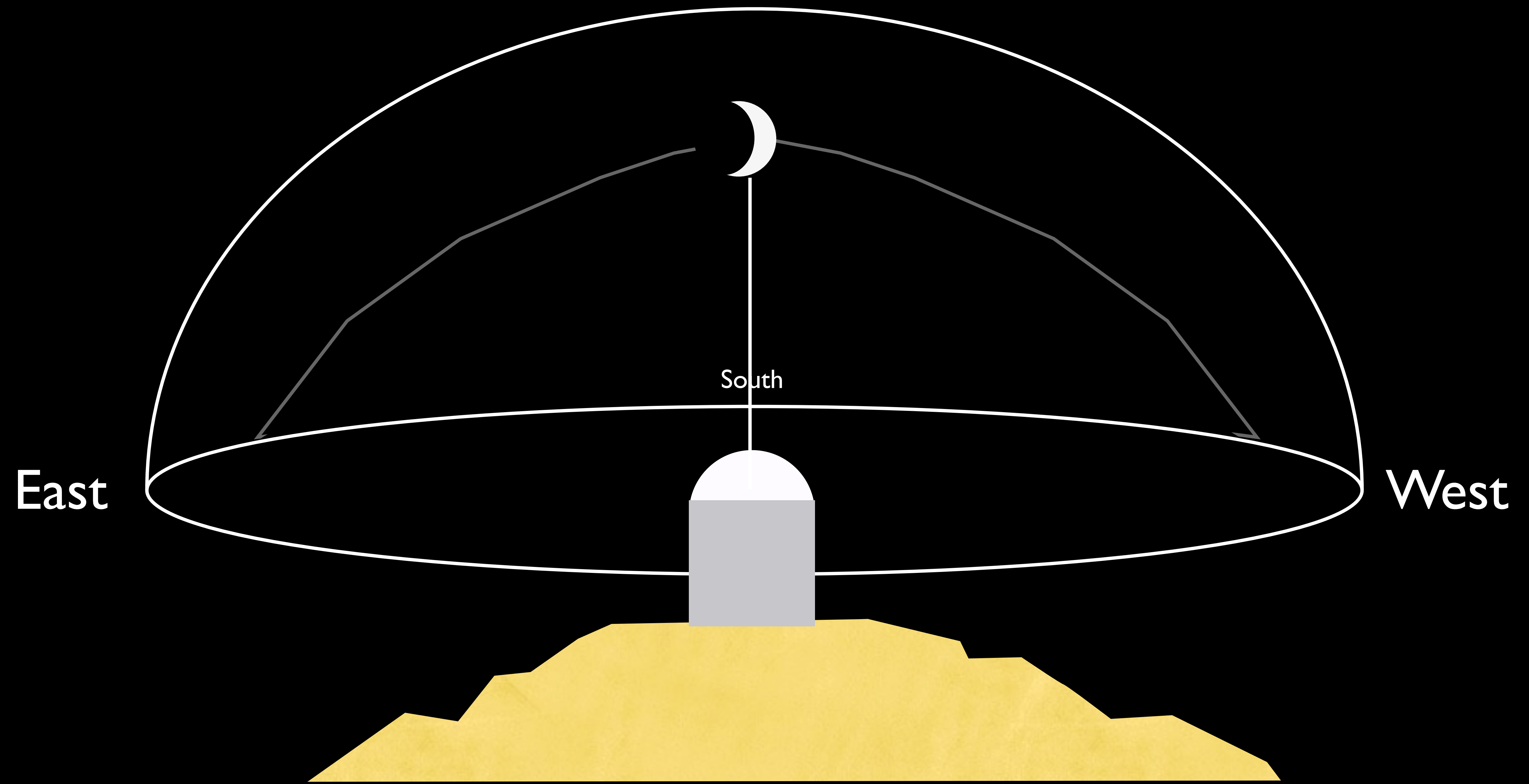
Camera





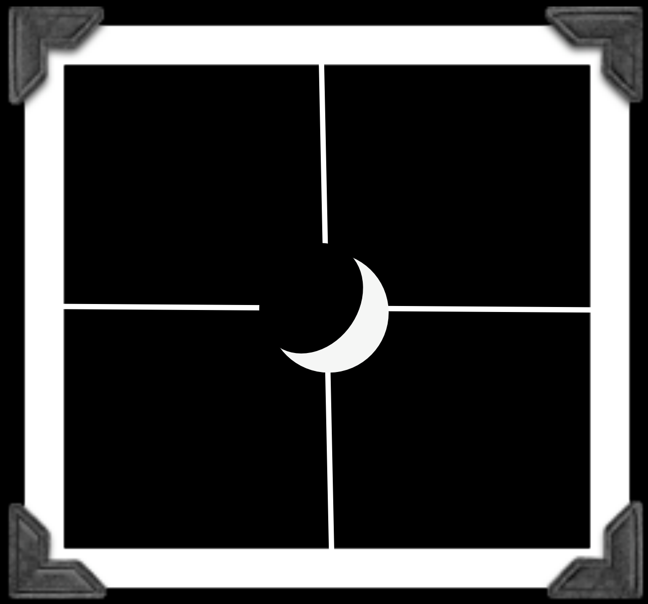
Angular differential imaging

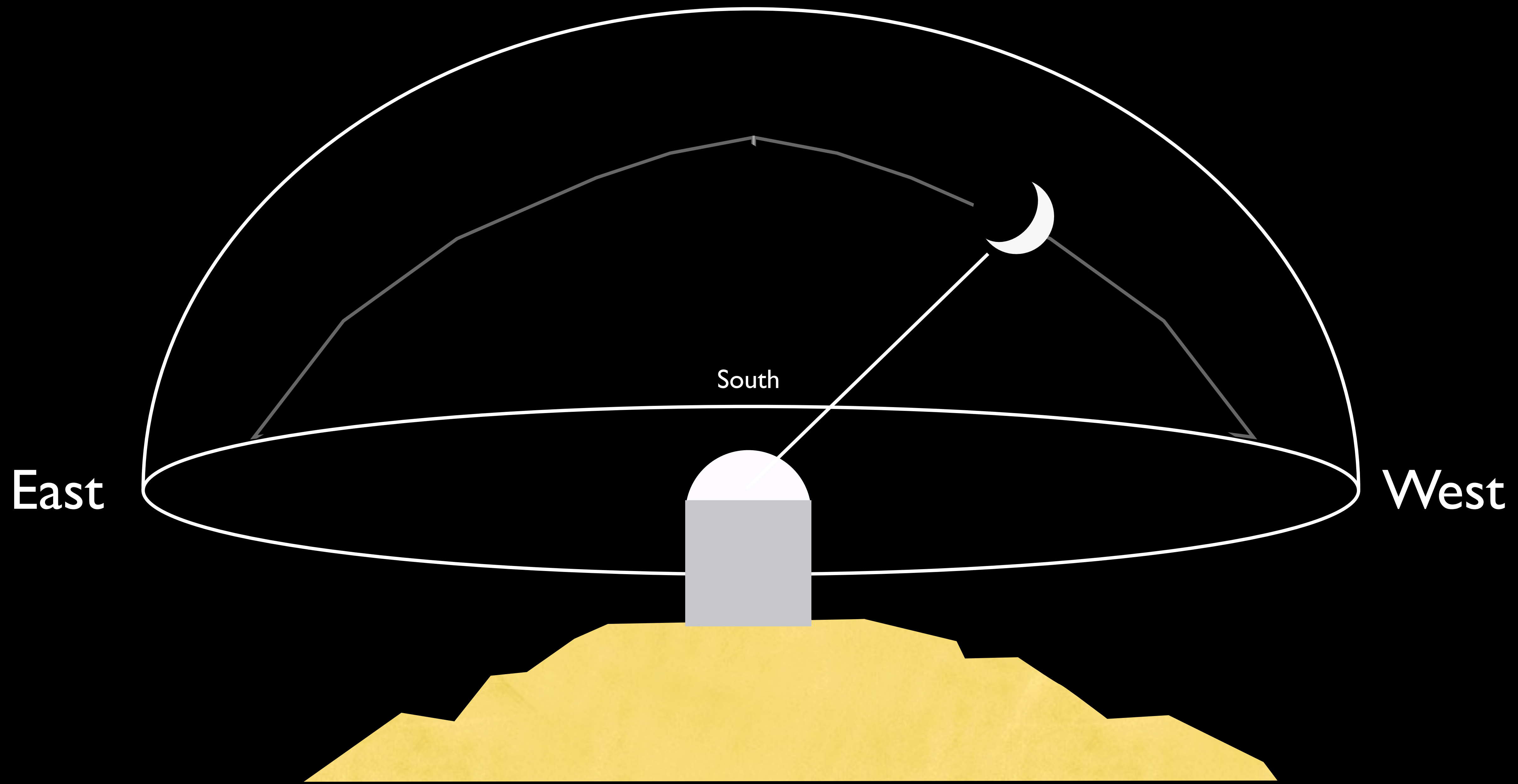




Angular differential imaging

Camera





Angular differential imaging

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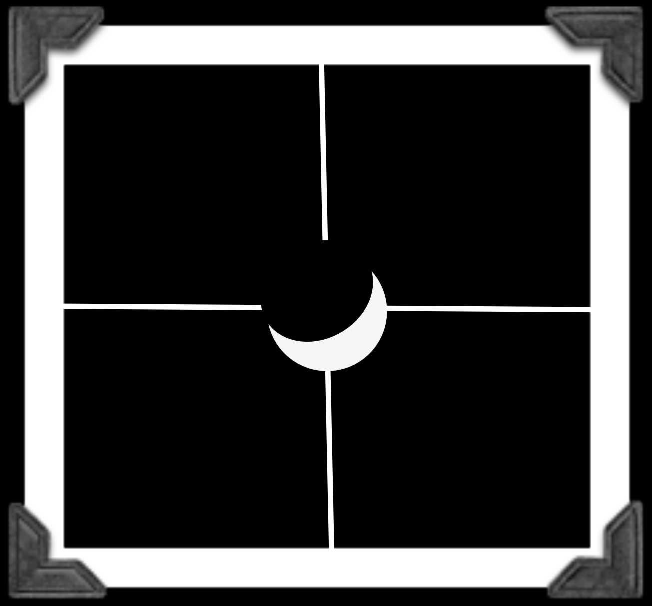

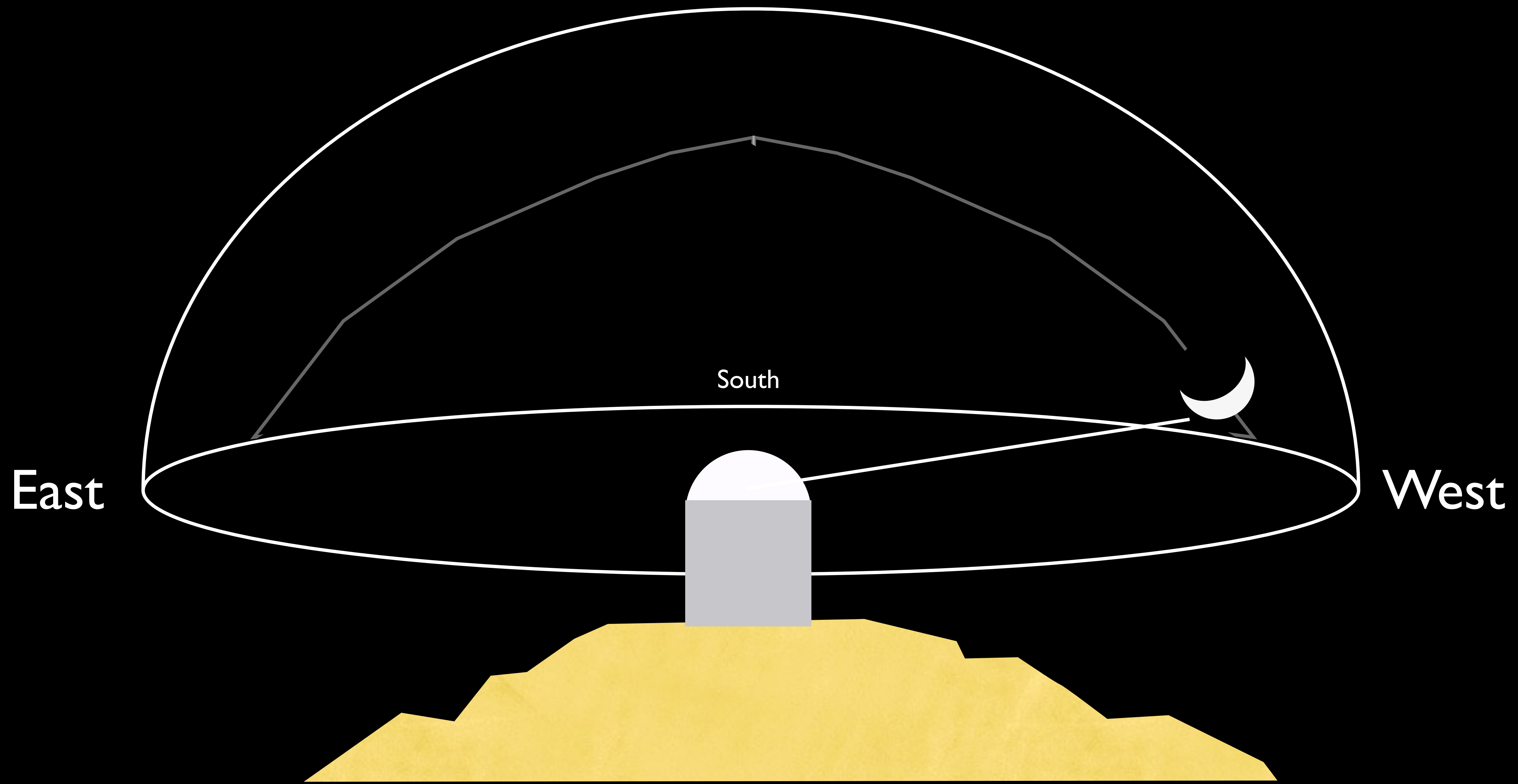

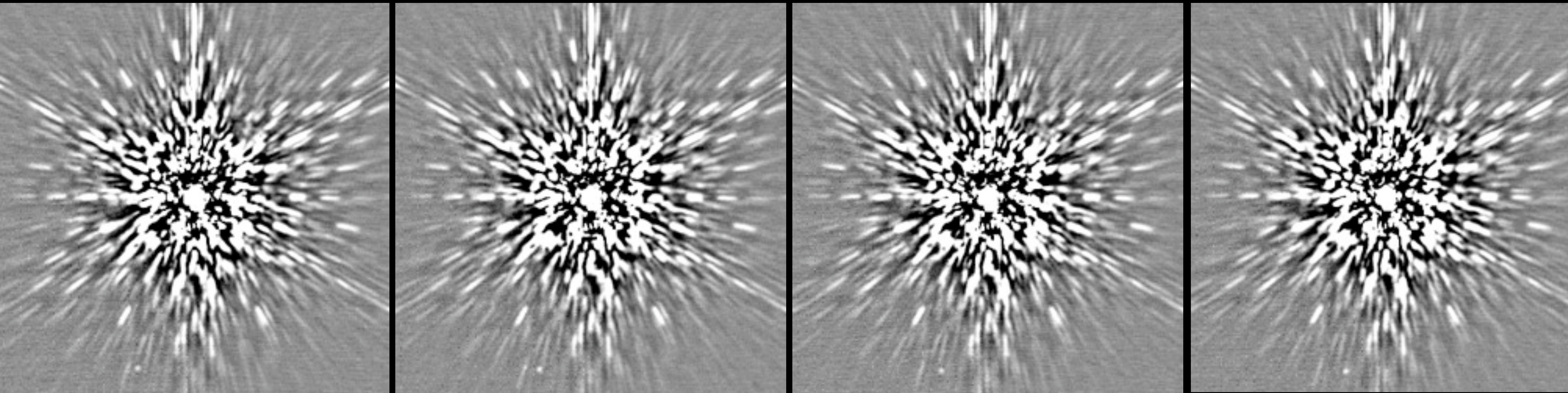

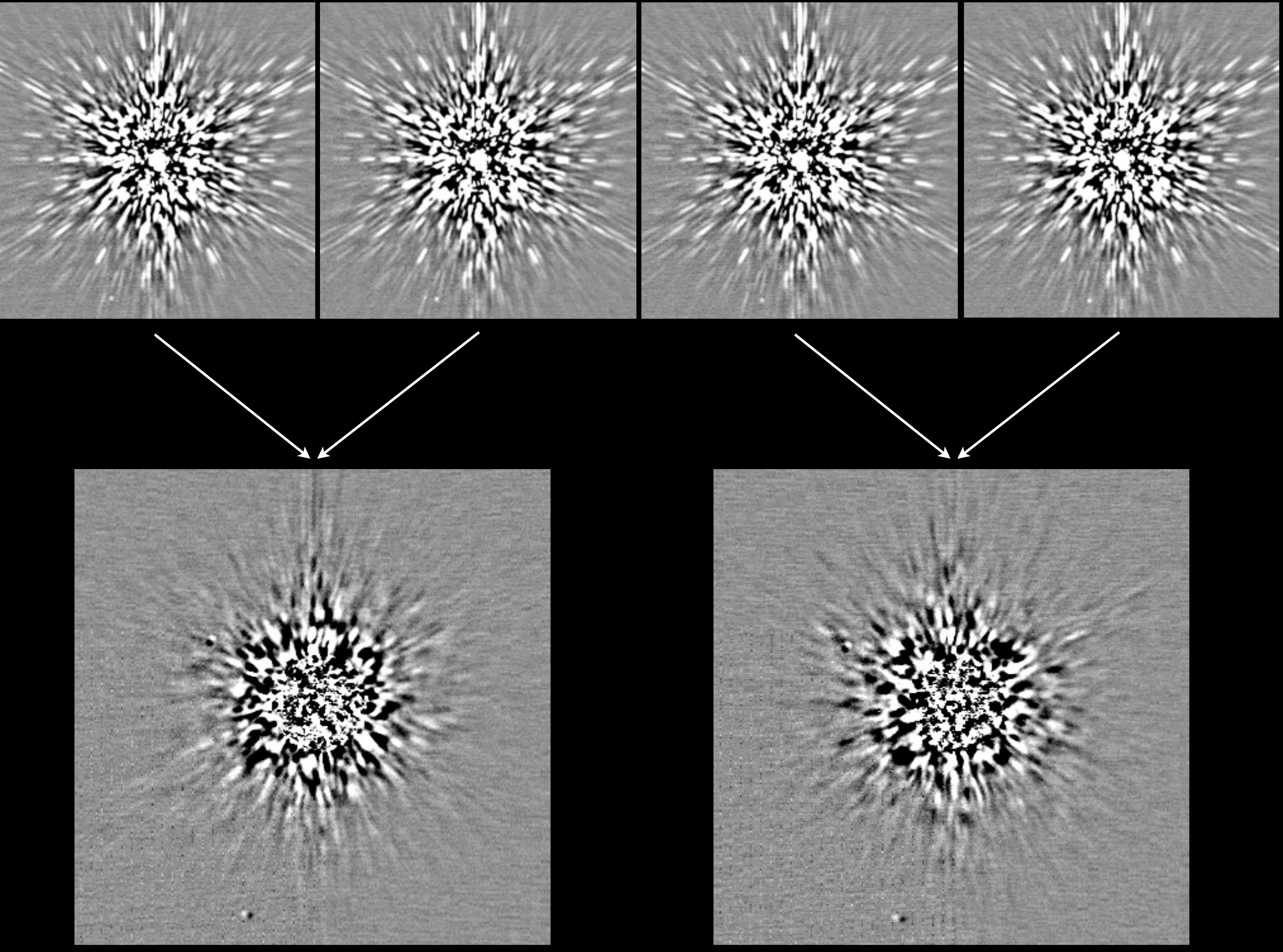

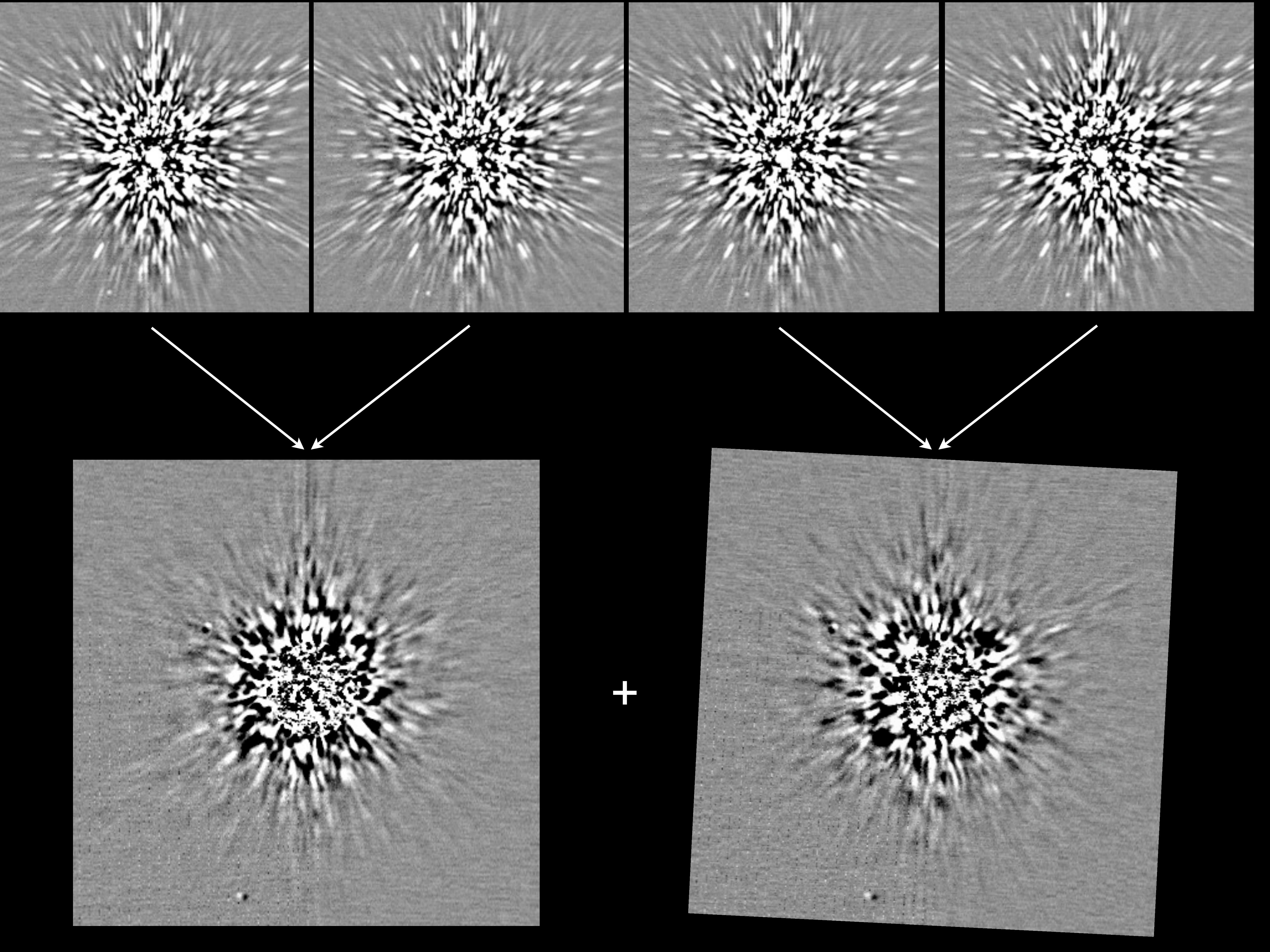

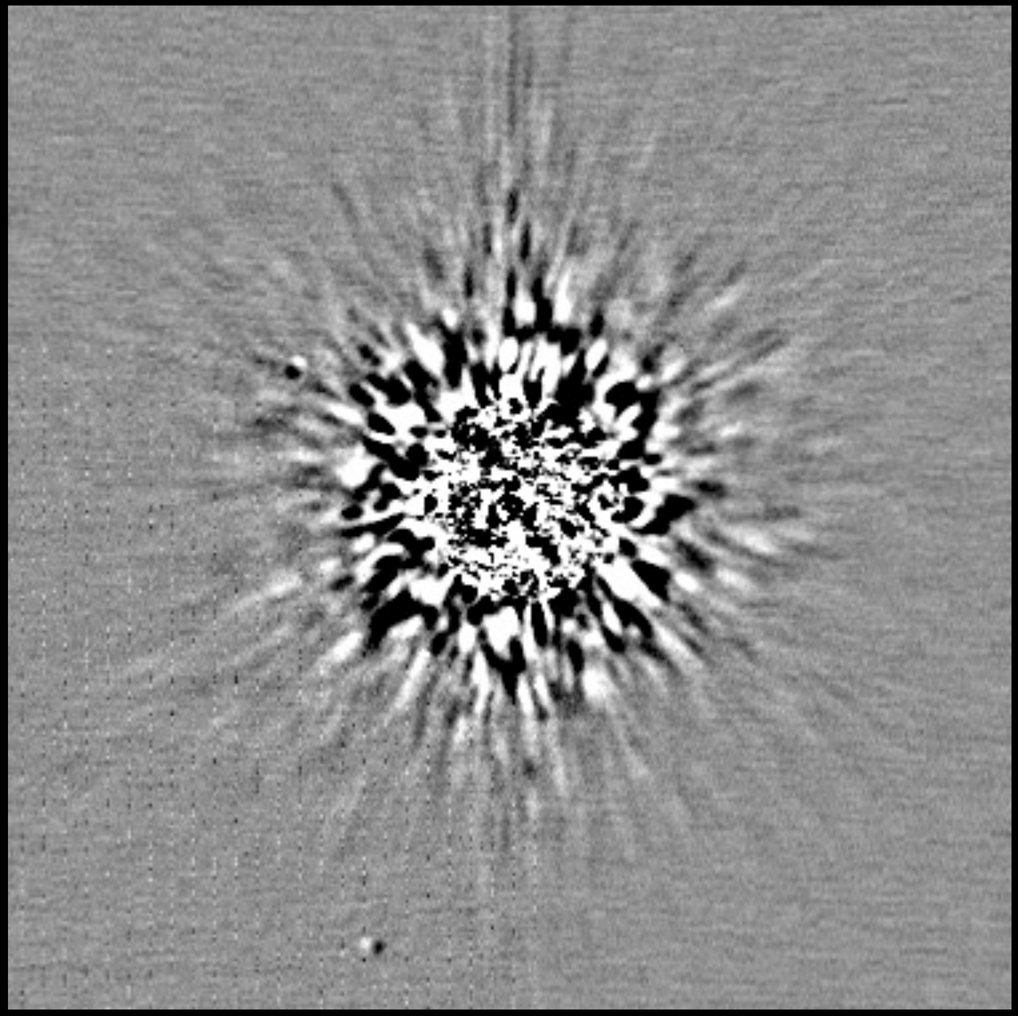

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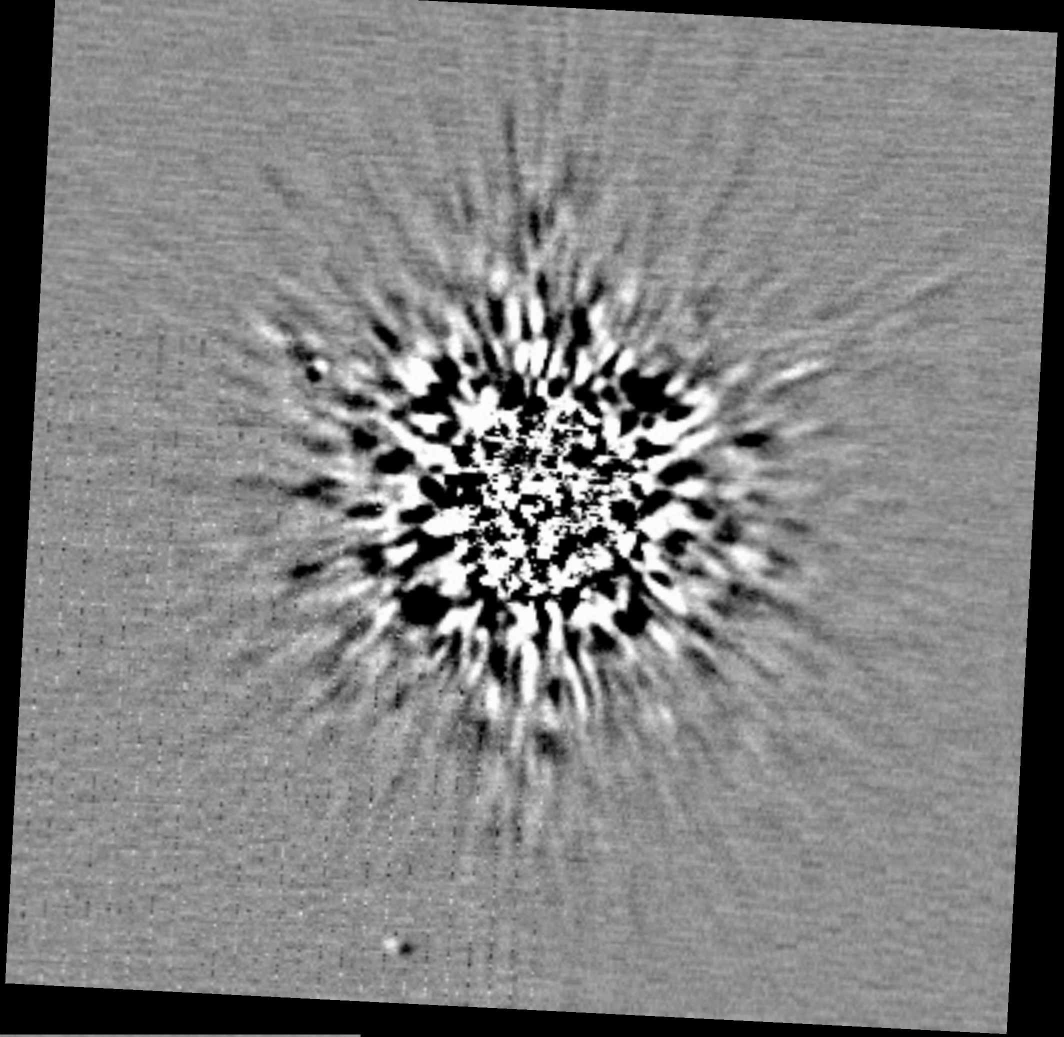

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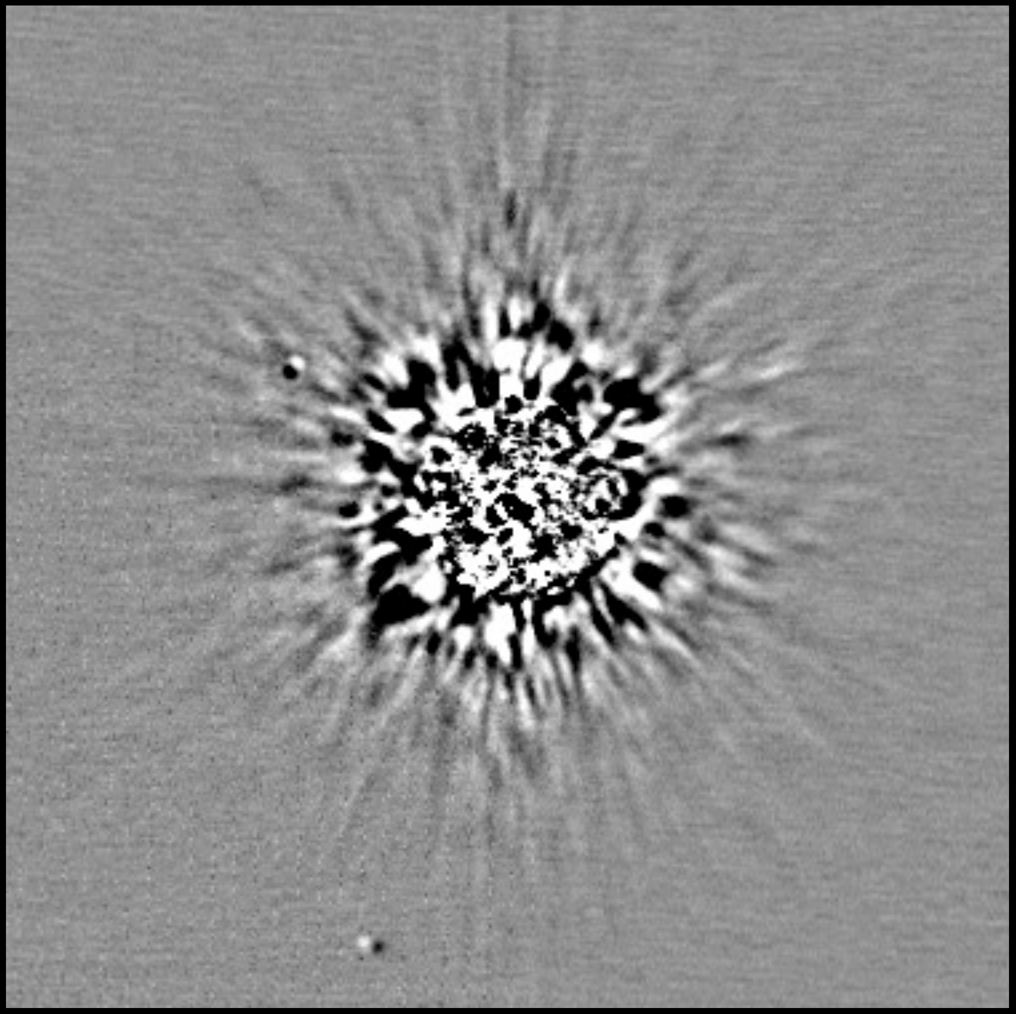
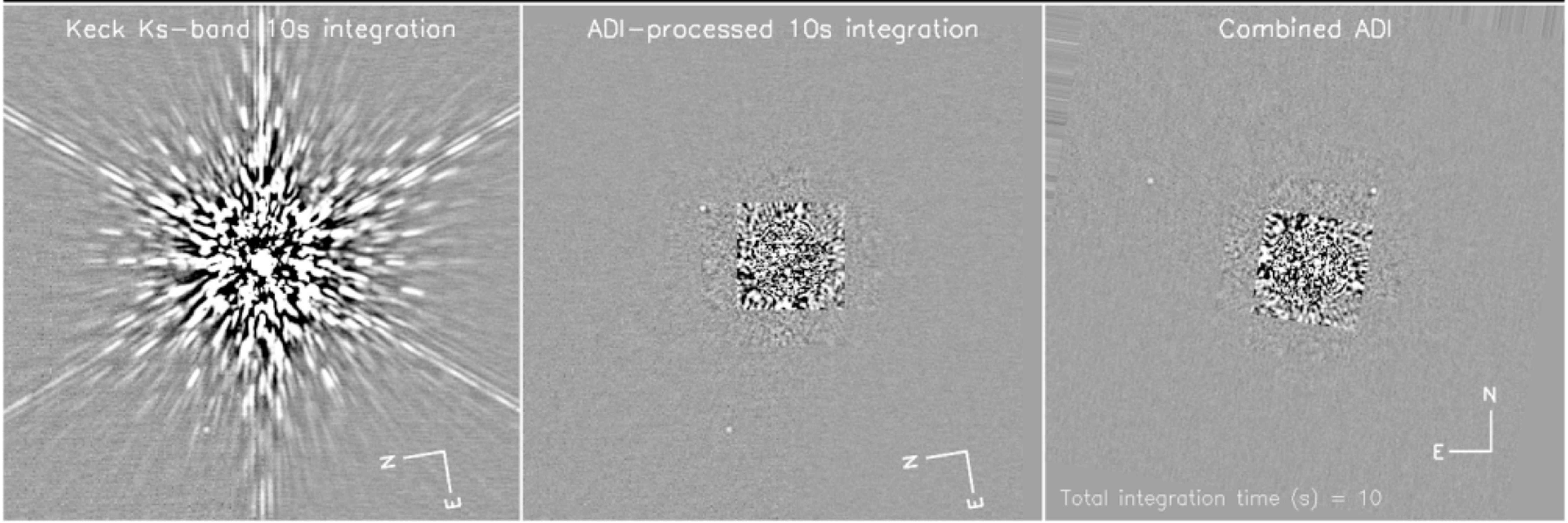


Angular Differential Imaging (ADI)



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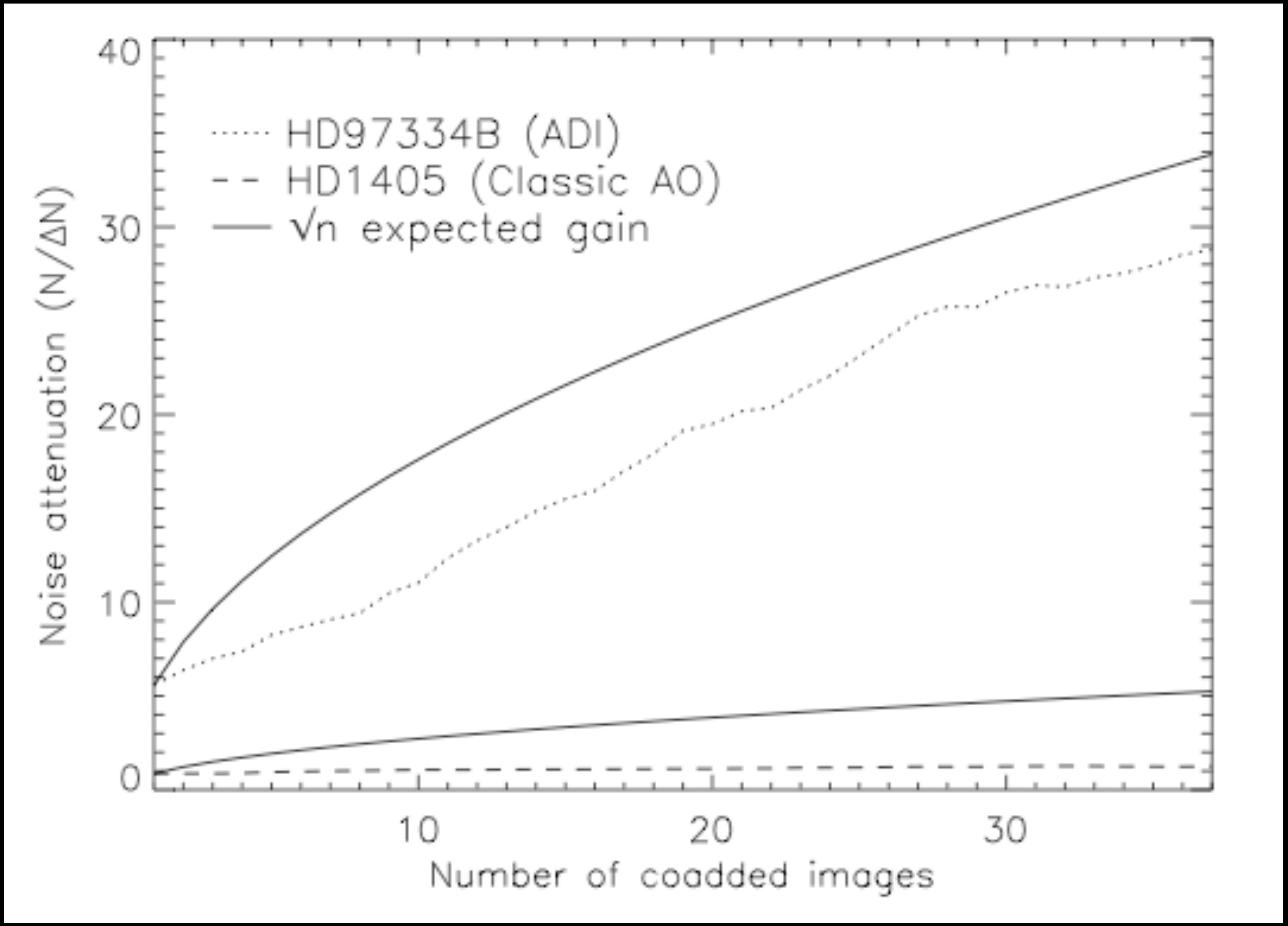
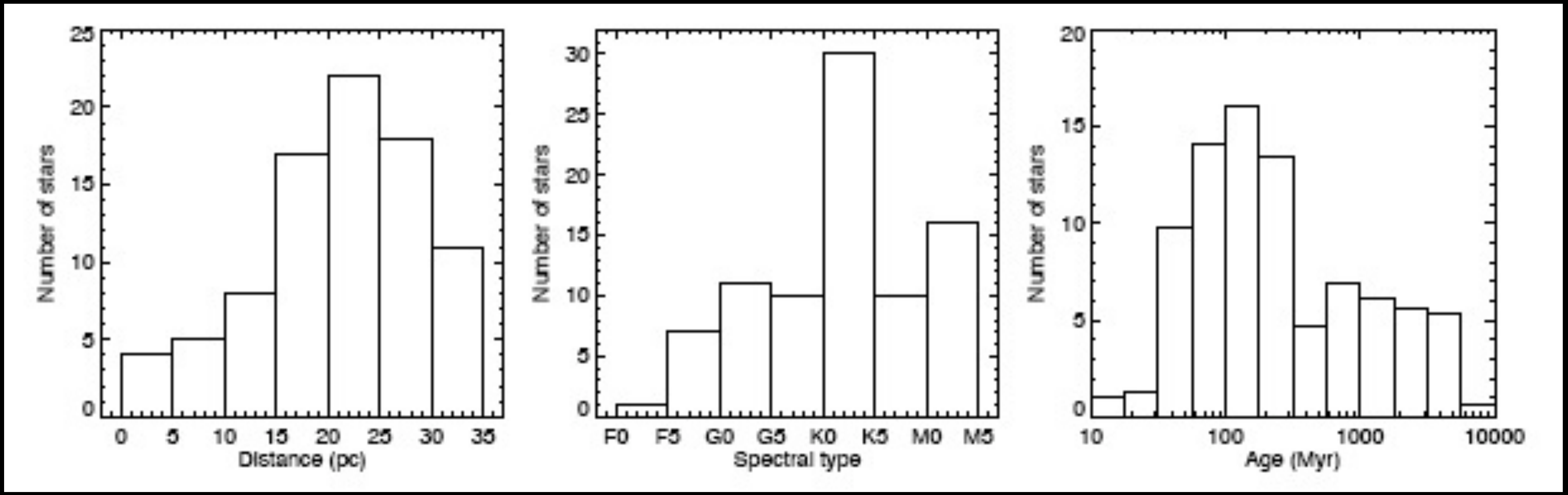
National Research Council Canada

ADI gain

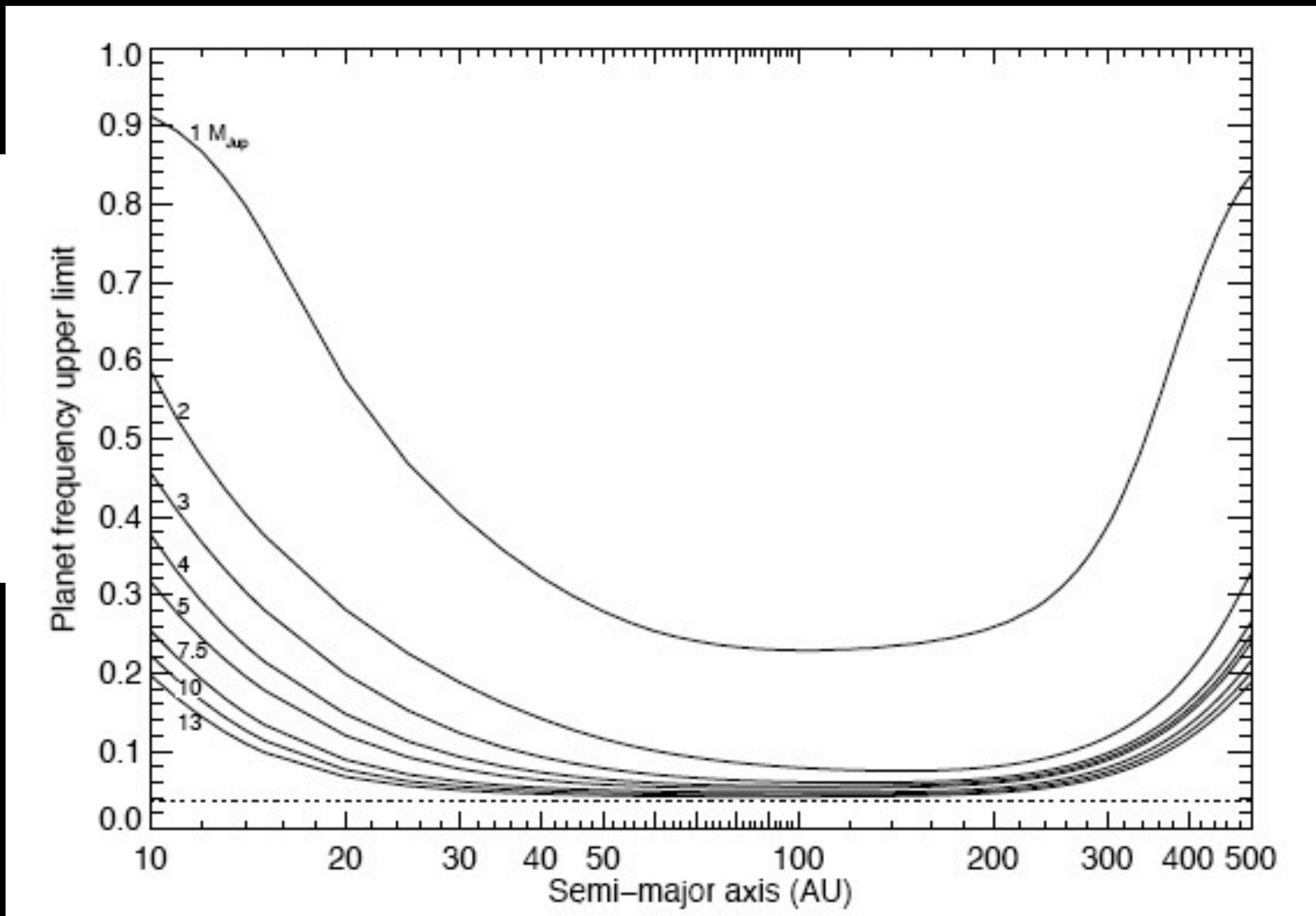


40
30
20
10
0
10
20
30
Noise attenuation (N/ΔN)
Number of coadded images
HD97334B (ADI)
HD1405 (Classic AO)
√n expected gain

The GDPS ADI Survey

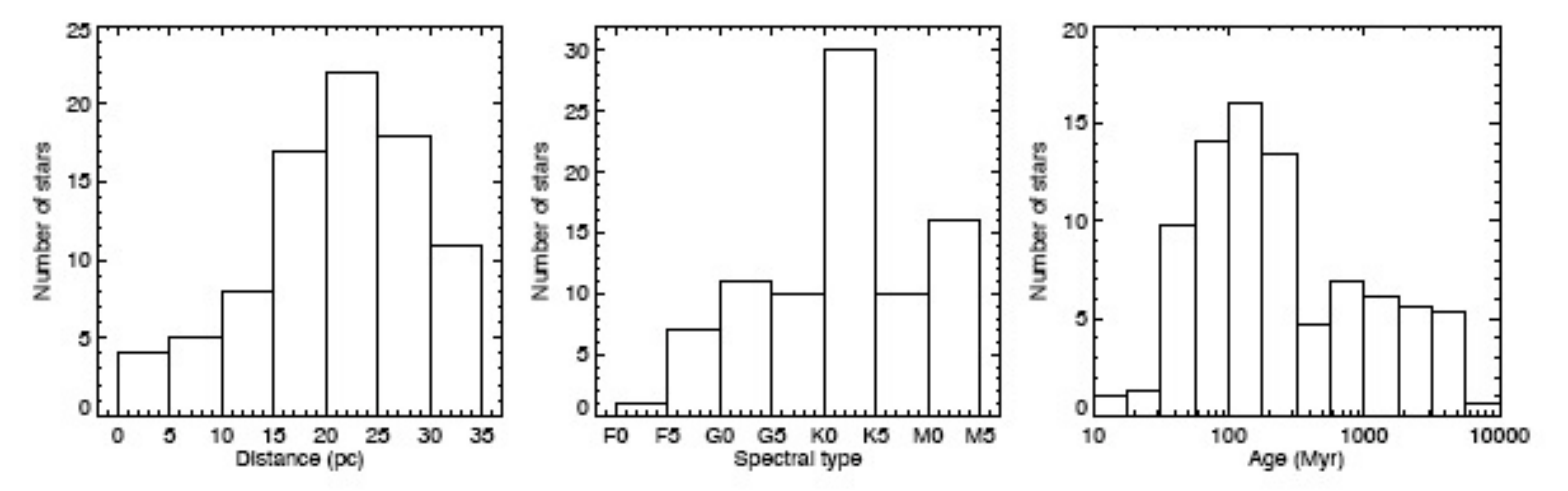


The GDPS ADI Survey



No detection

The IDPS survey



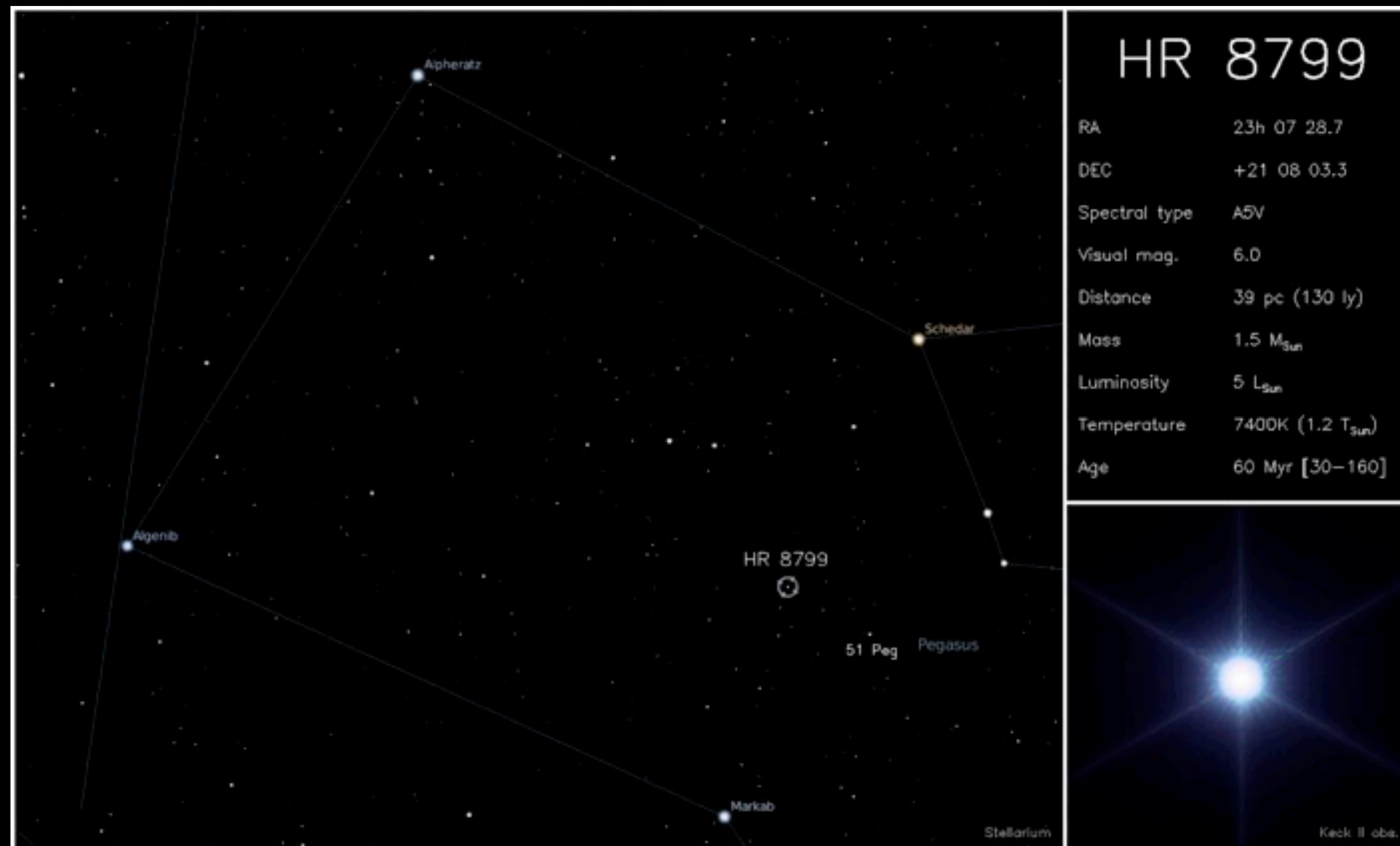
Remove the late type bias

Focus on young & close AF-type stars + some dusty

Combine the Gemini N, Keck and VLT

HR 8799 Characteristics

- A5V star
- V~6
- 39 pc (130 ly)
- Pegasus



- Lambda Boo, Gamma Dor and Vega-like star (disk ~90AU)

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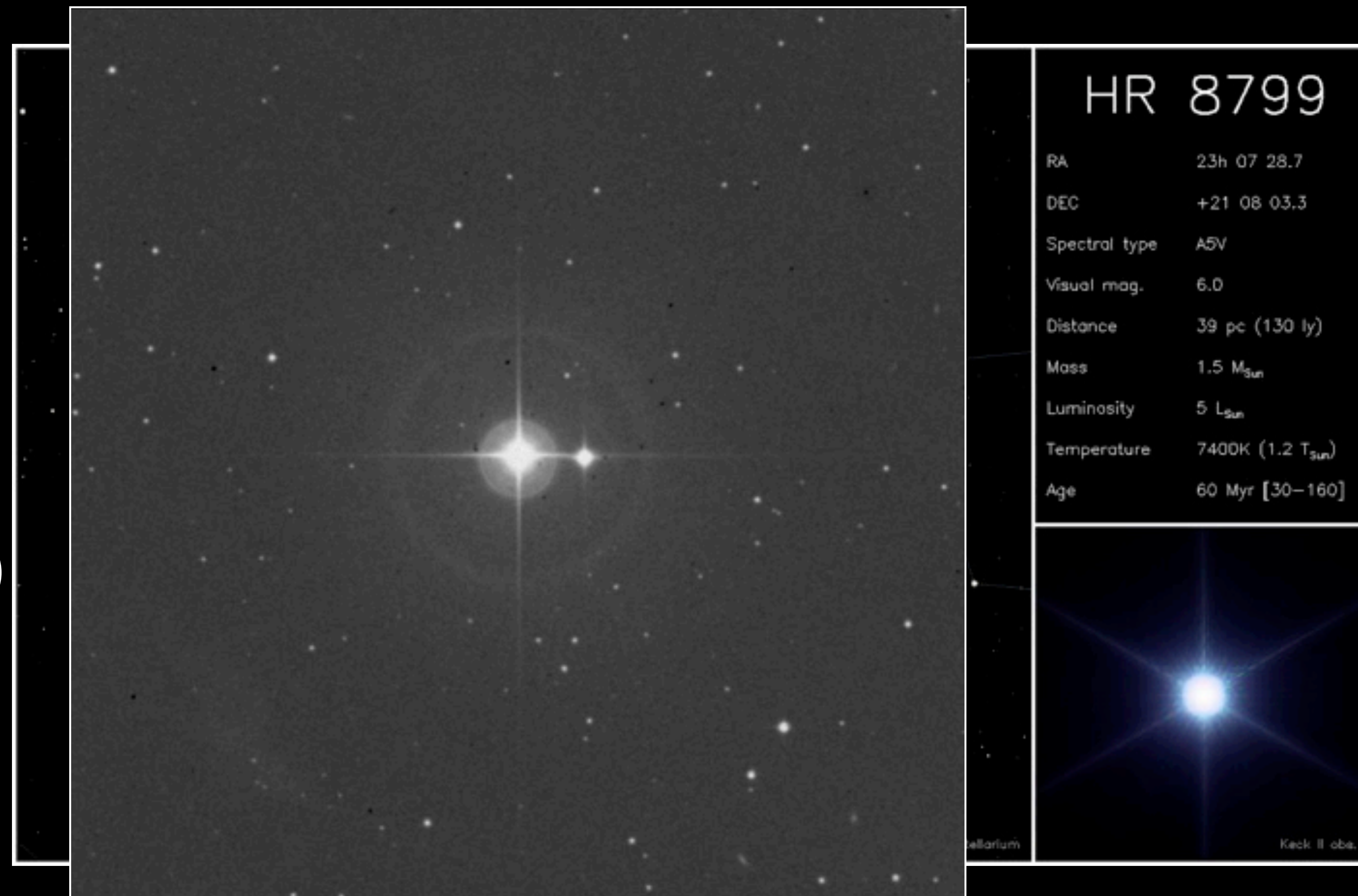

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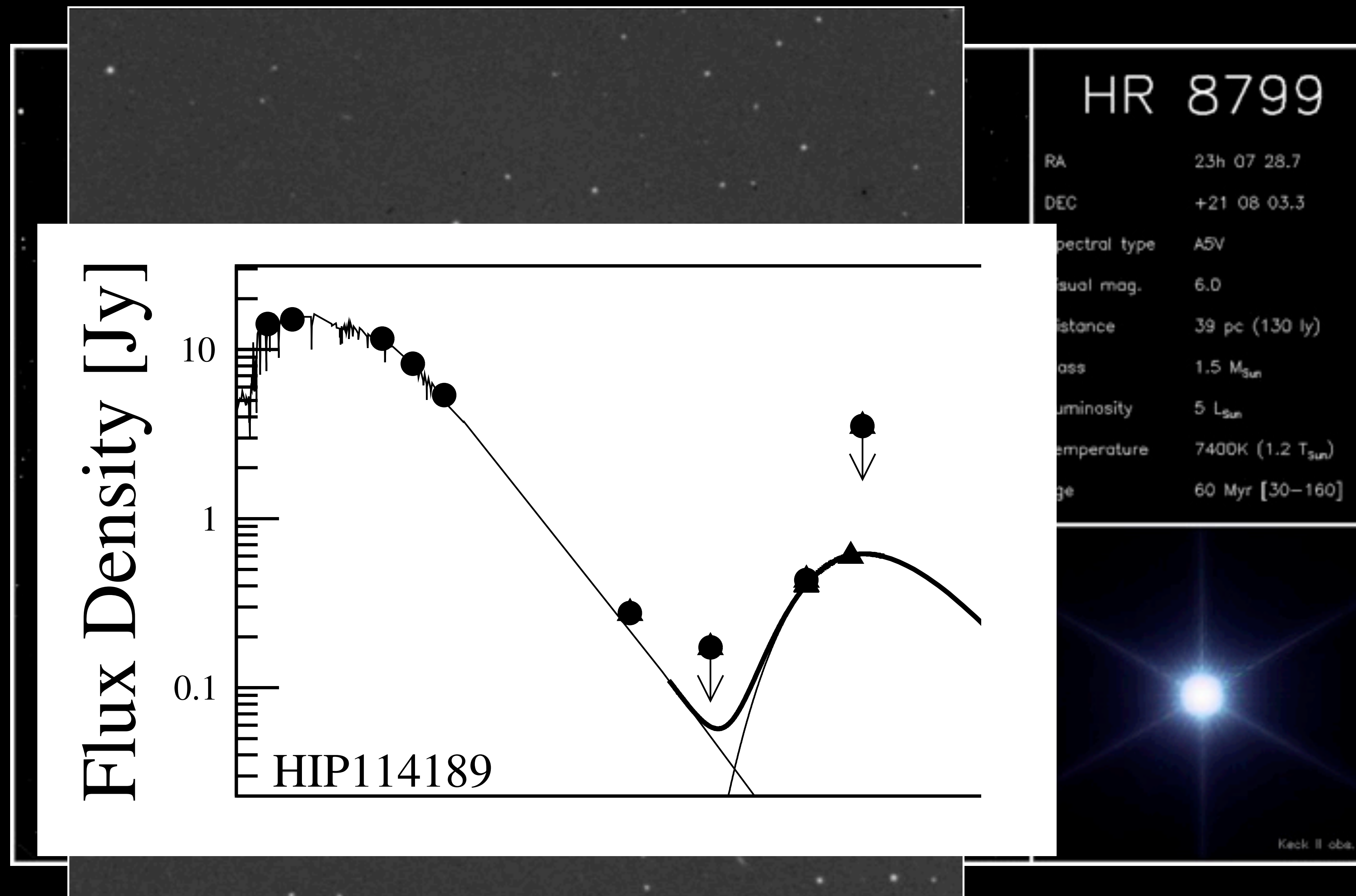
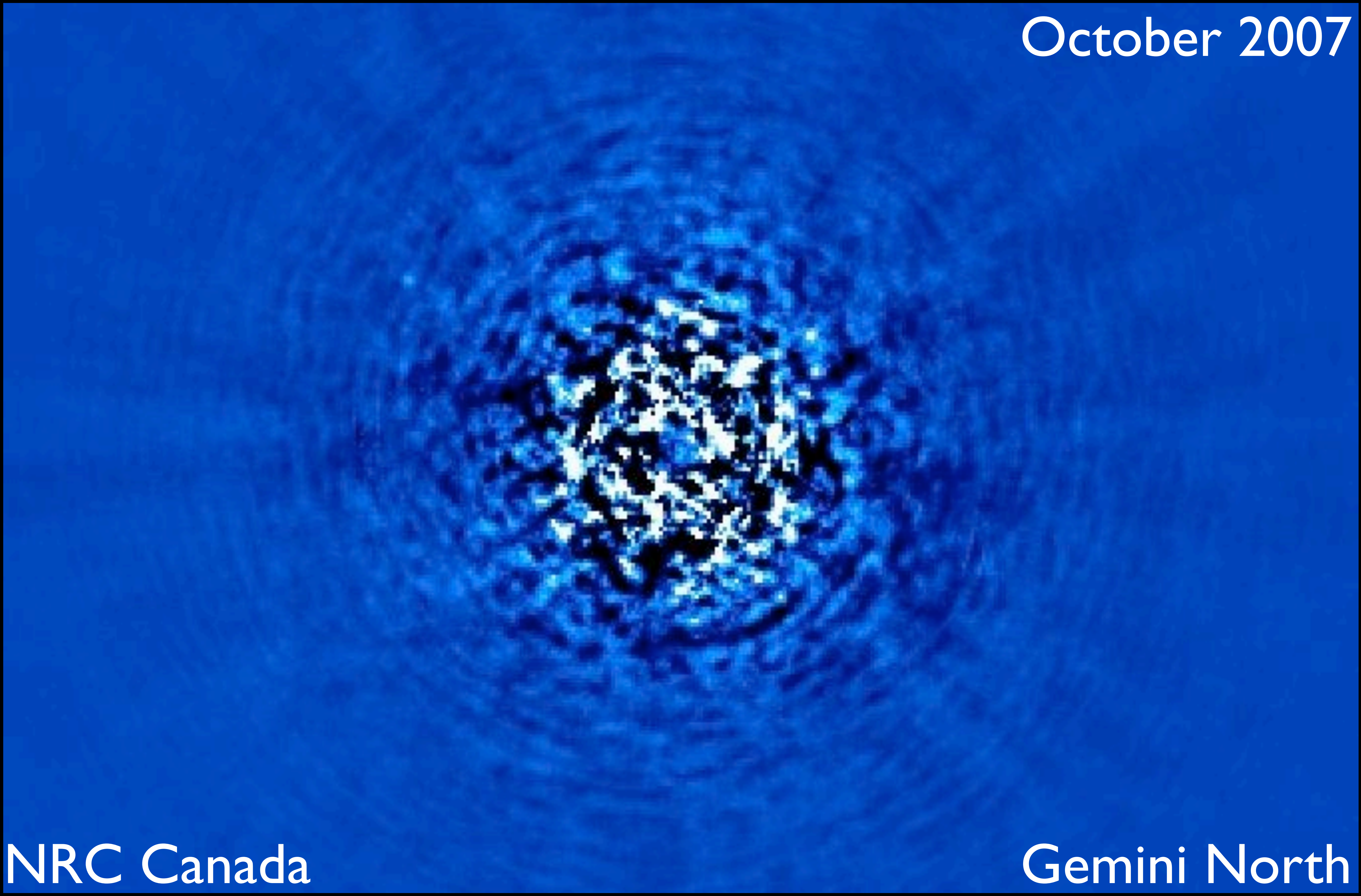
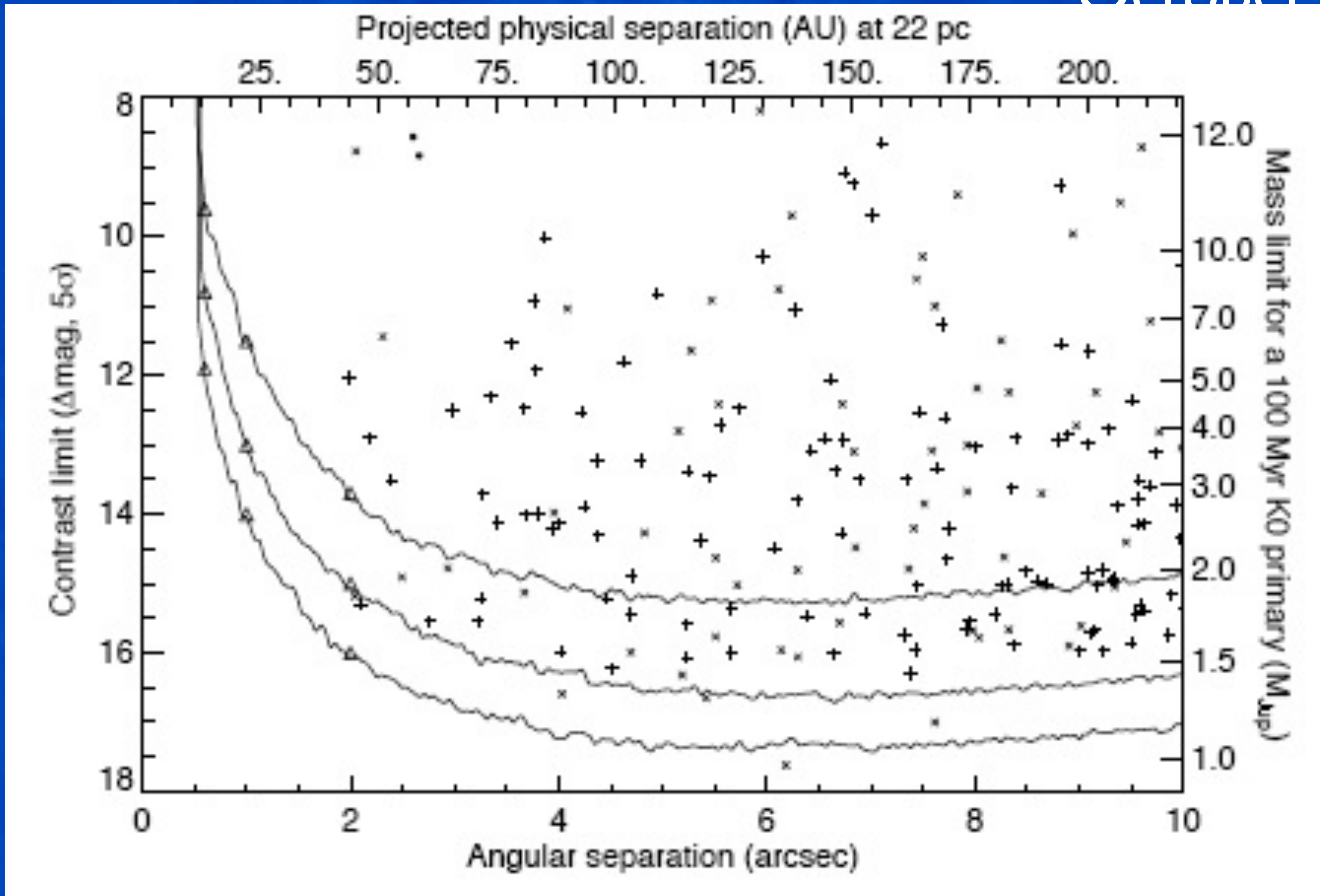


The Initial Discovery (March 2008)



The Initial Discovery (March 2008)

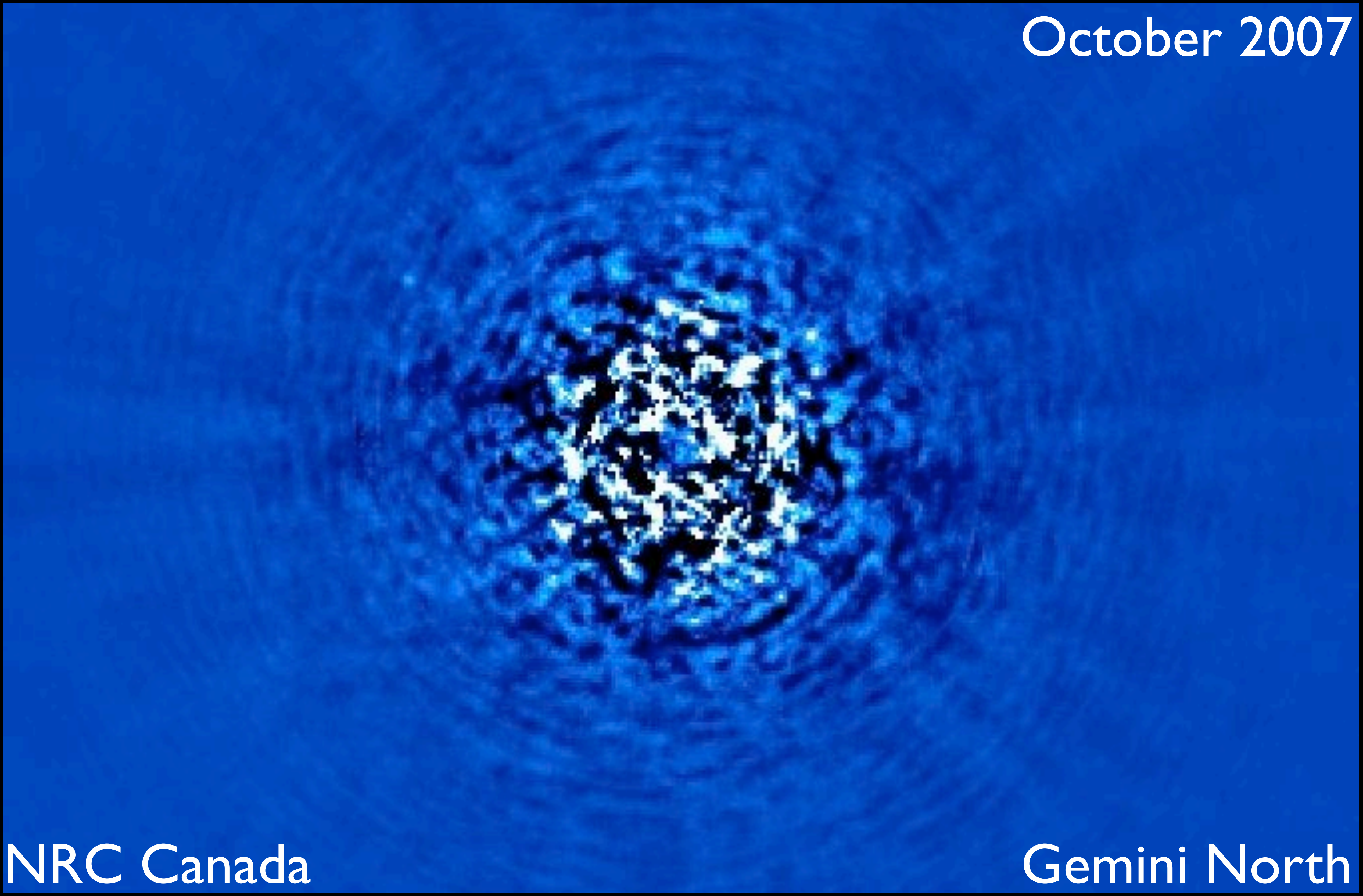
October 2007



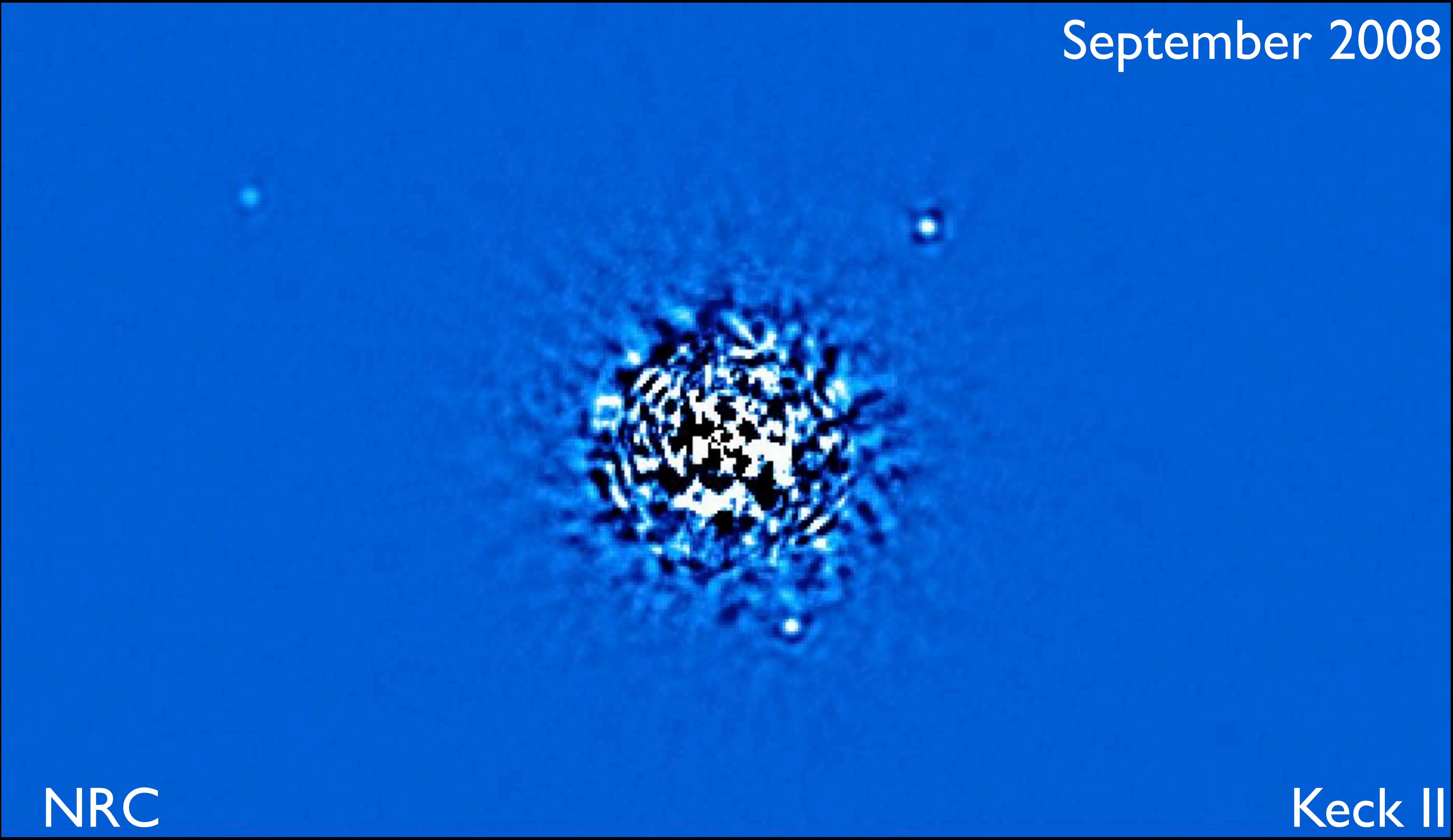
NRC Canada

Gemini North

The Initial Discovery (March 2008)



A third planet!



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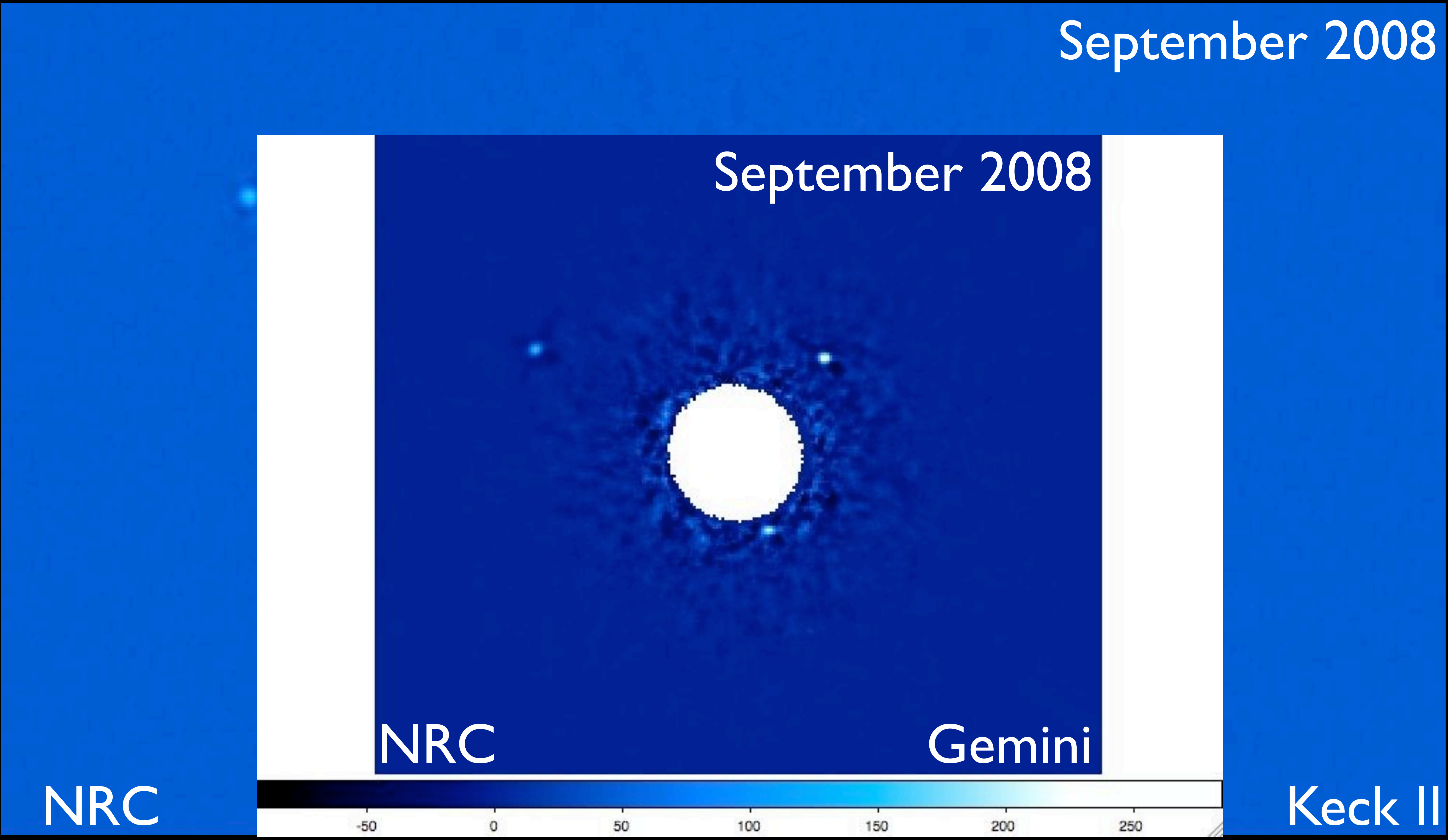
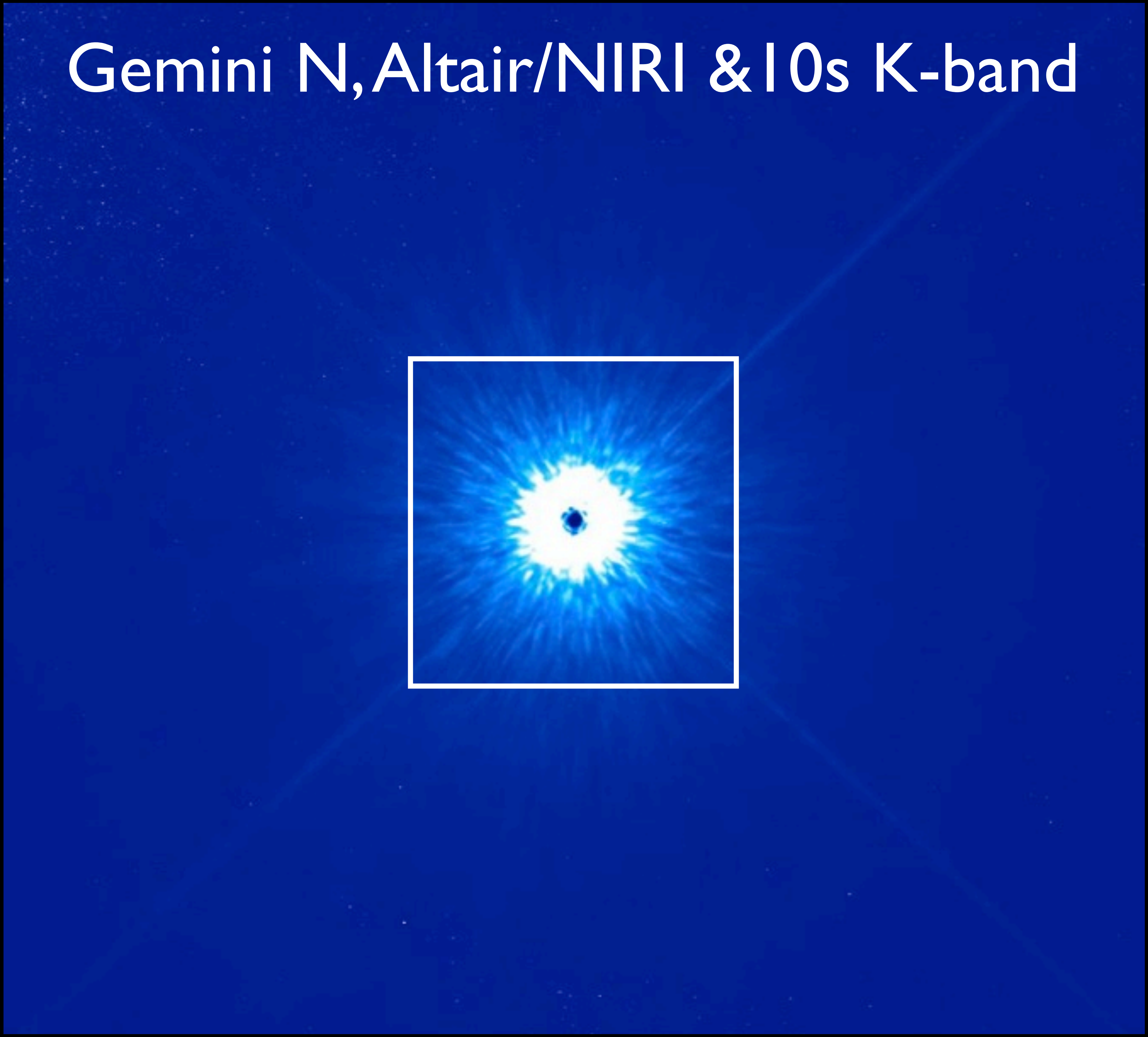


A system not that easy to see...



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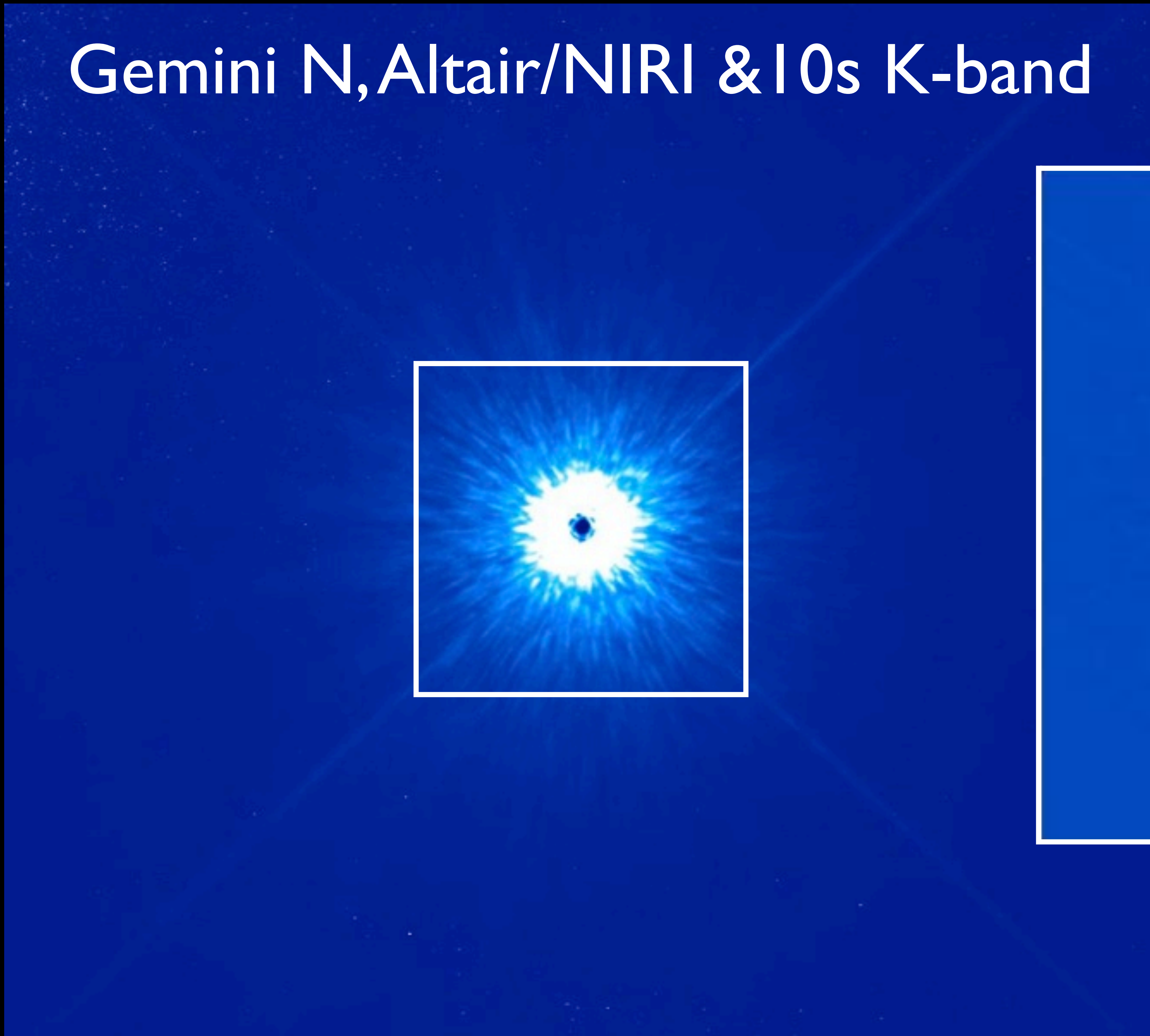
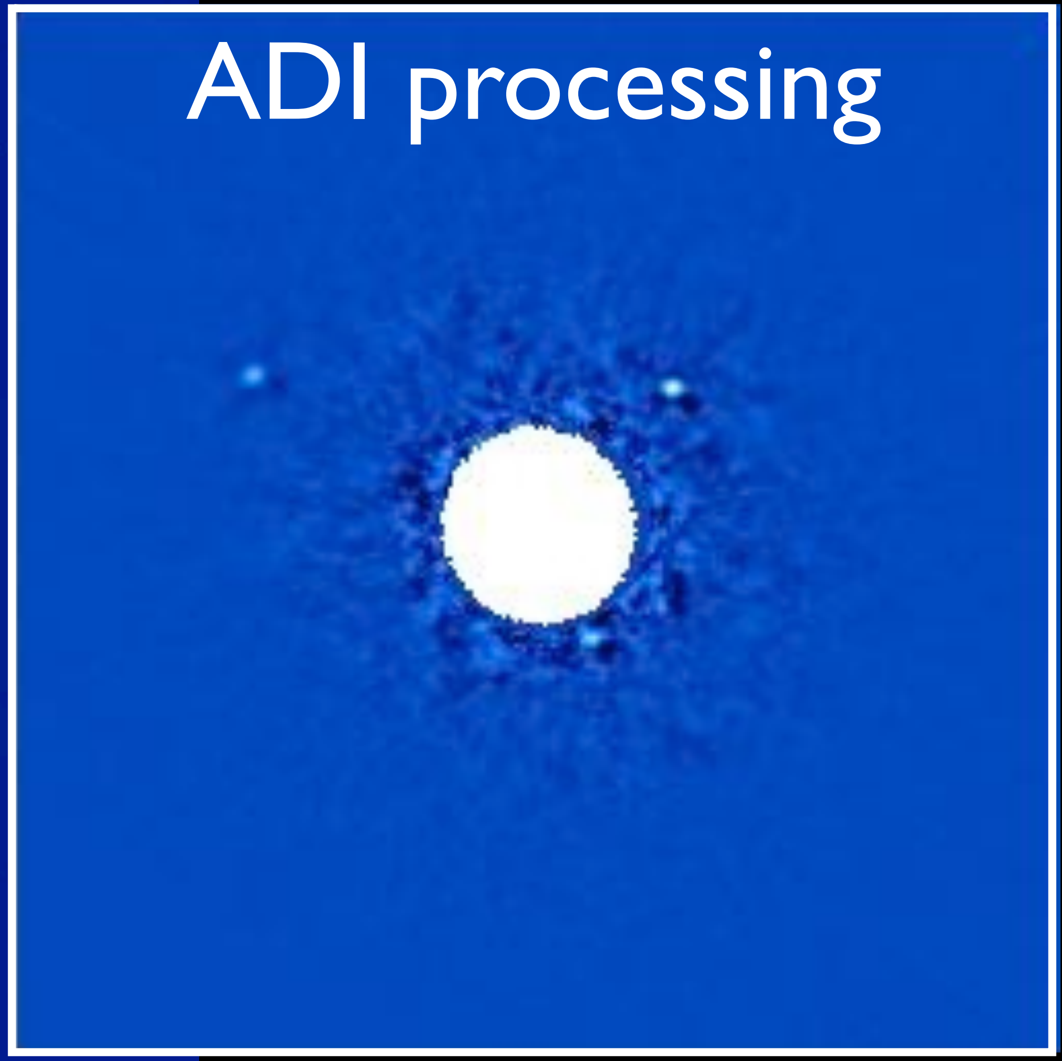
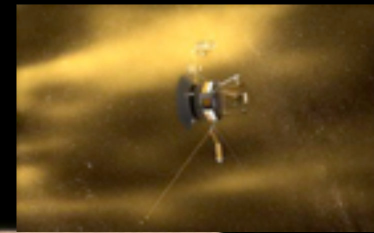
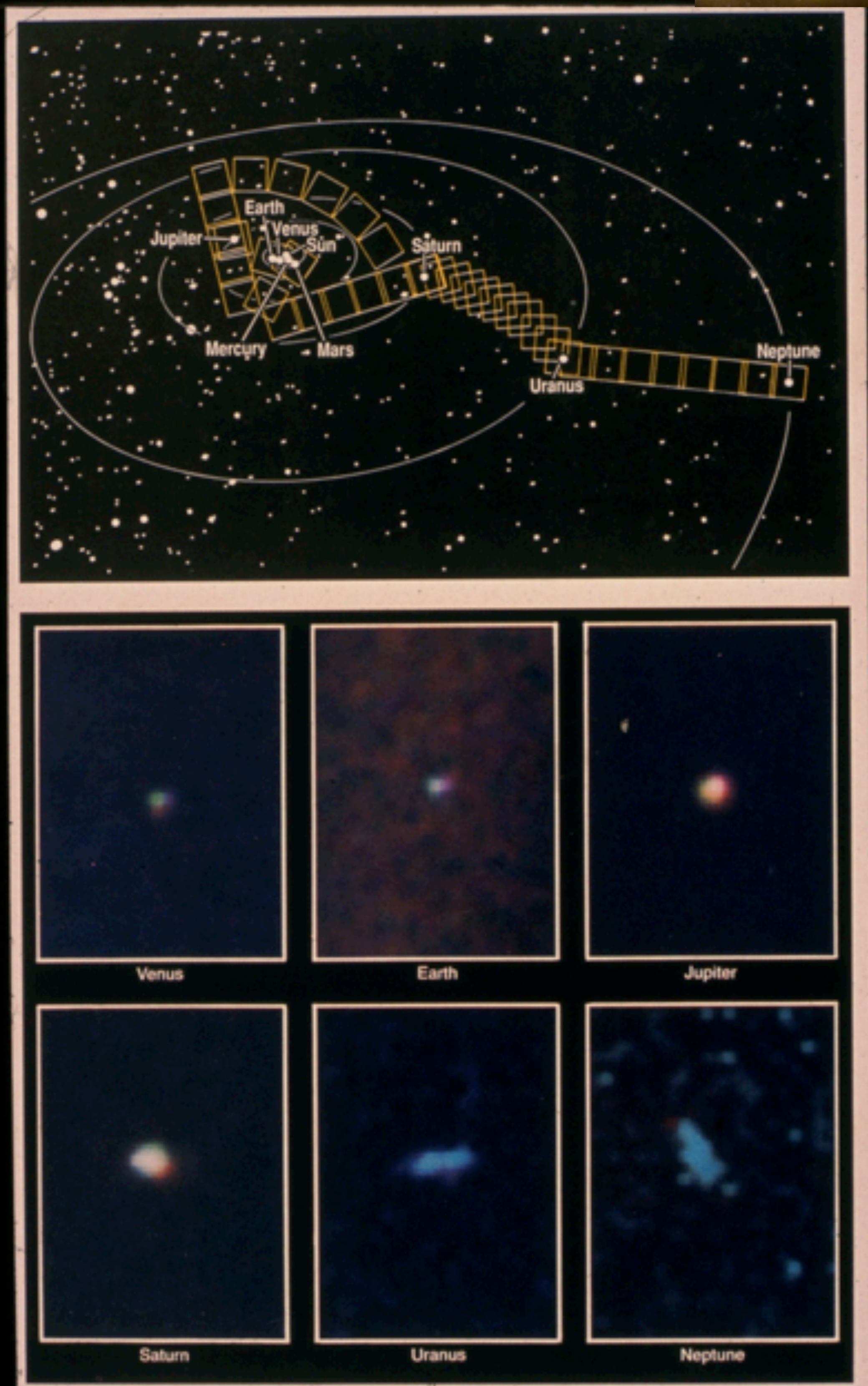


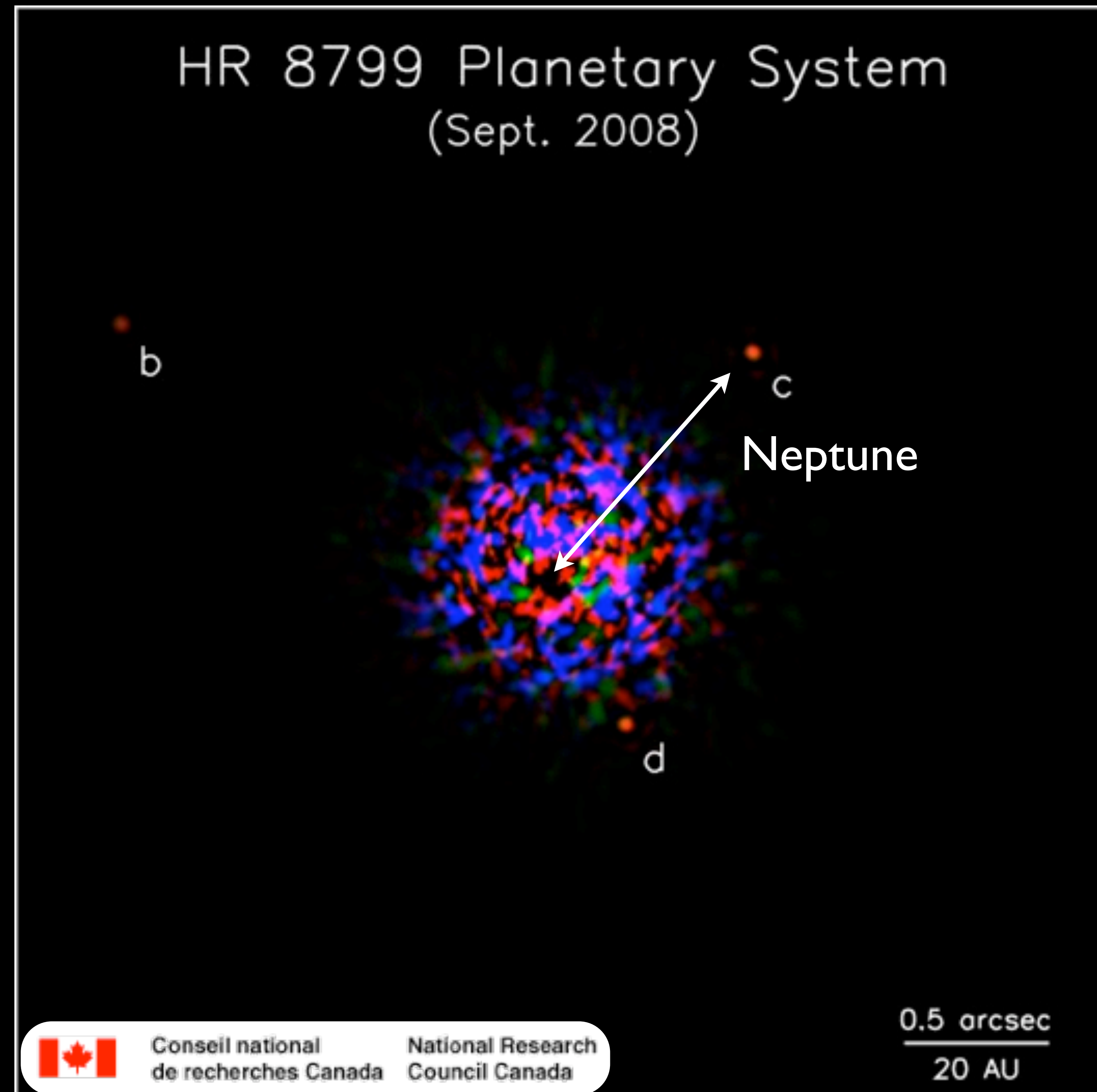


Voyager 1 (43 AU)
18 cm diameter





Keck 2 (130 ly), 10m diameter



8 200 000 AU

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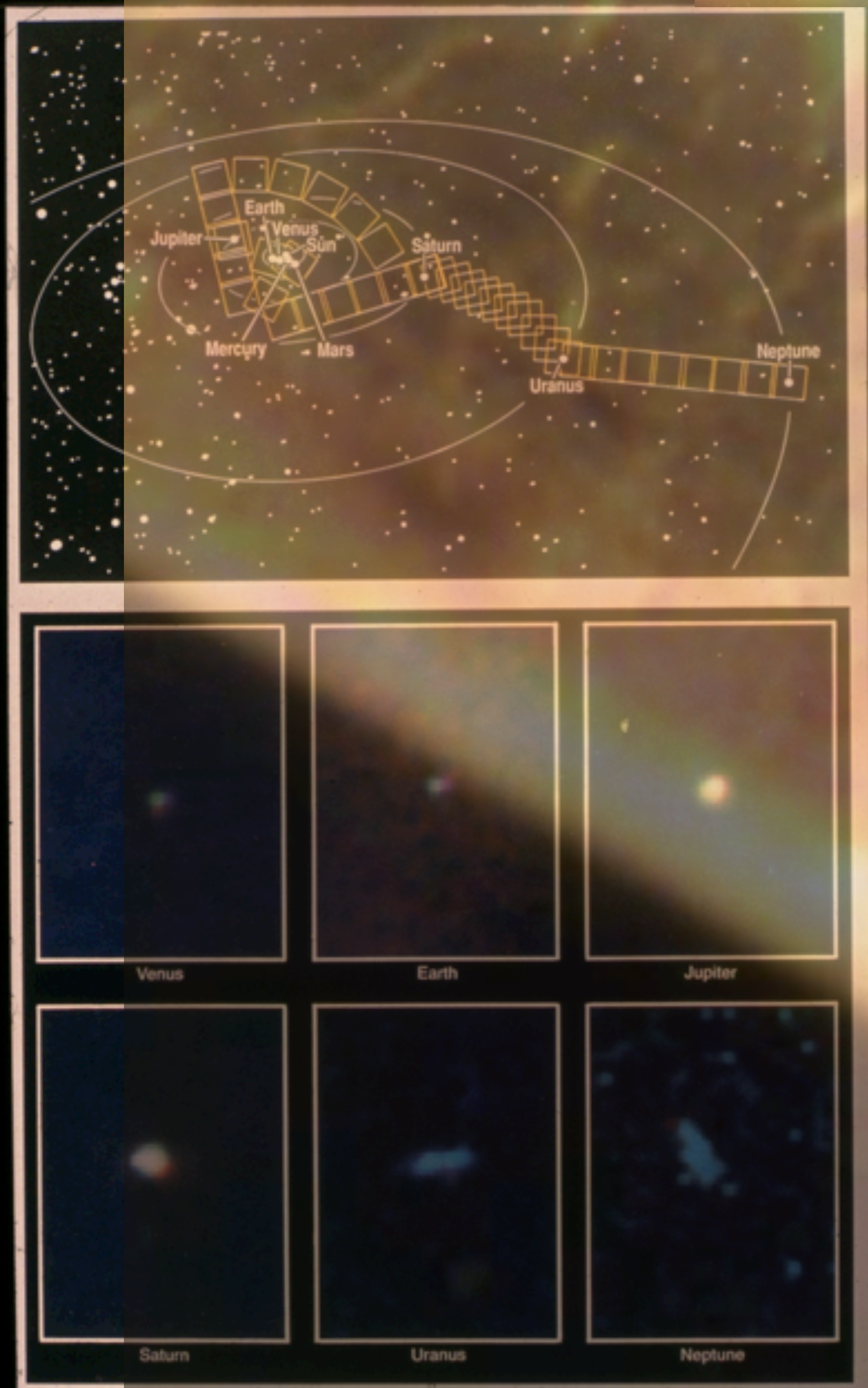

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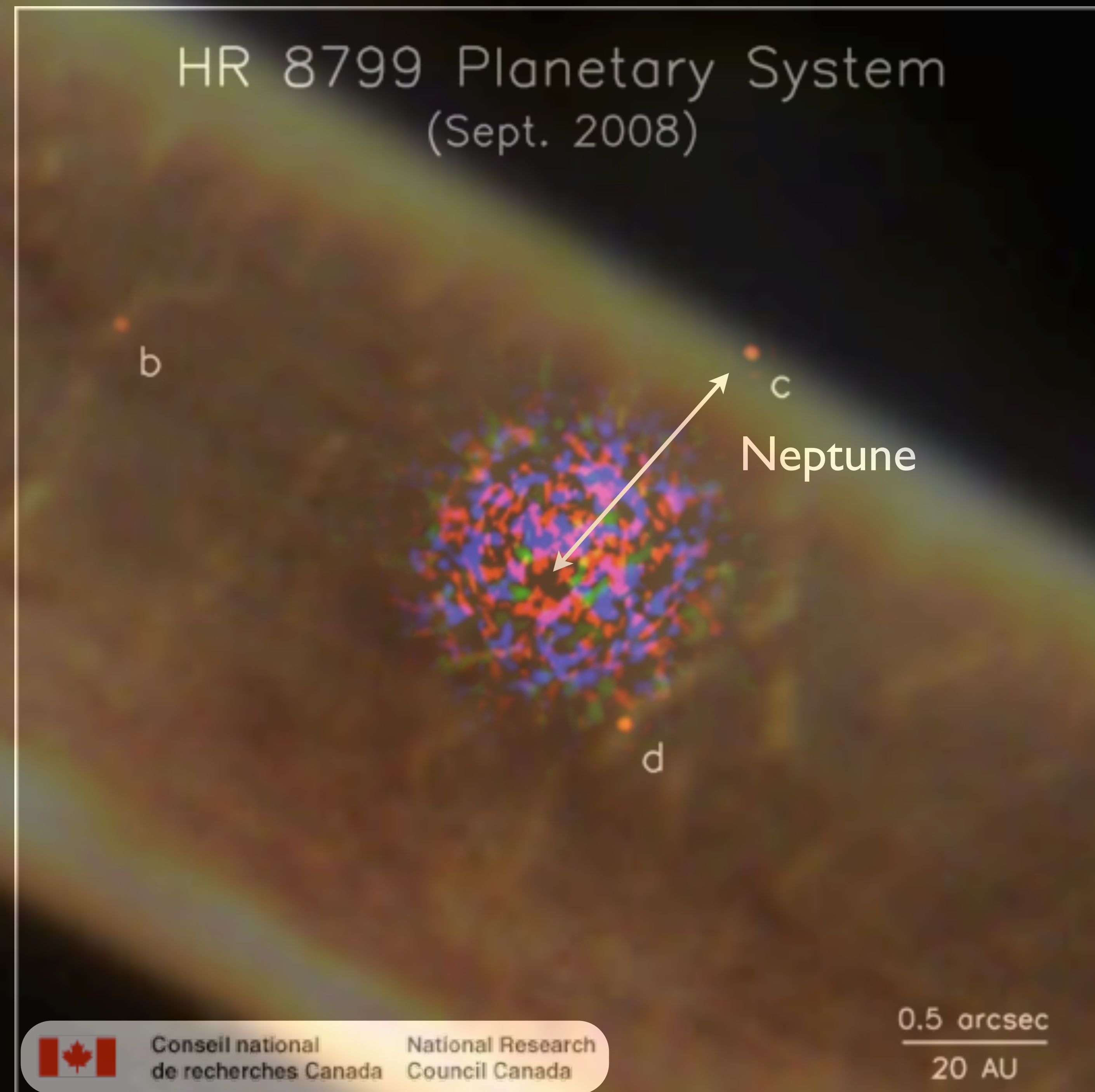

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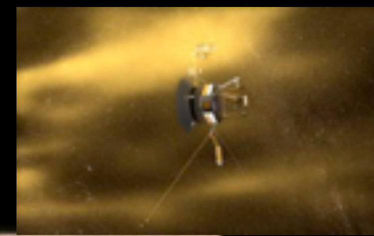
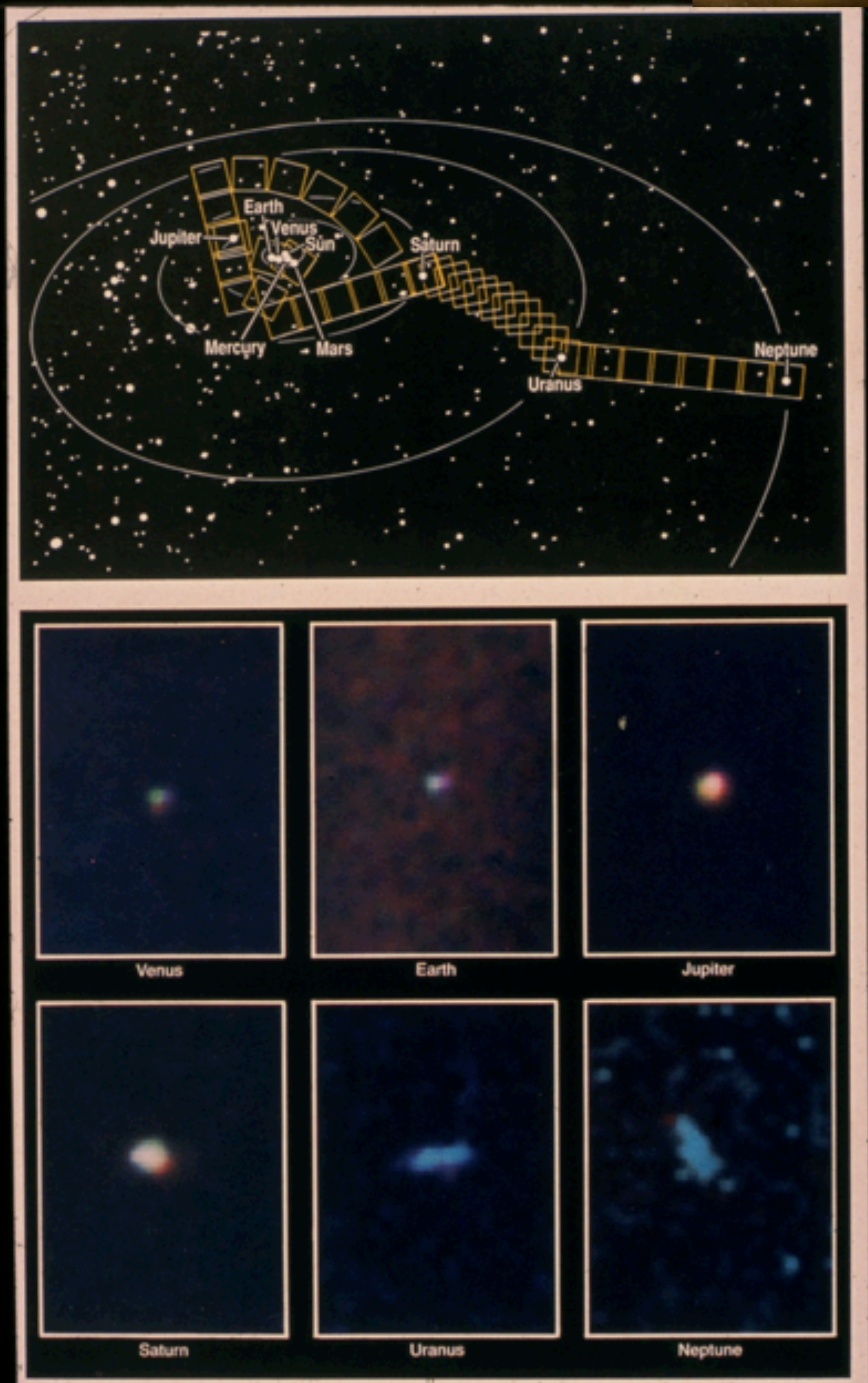
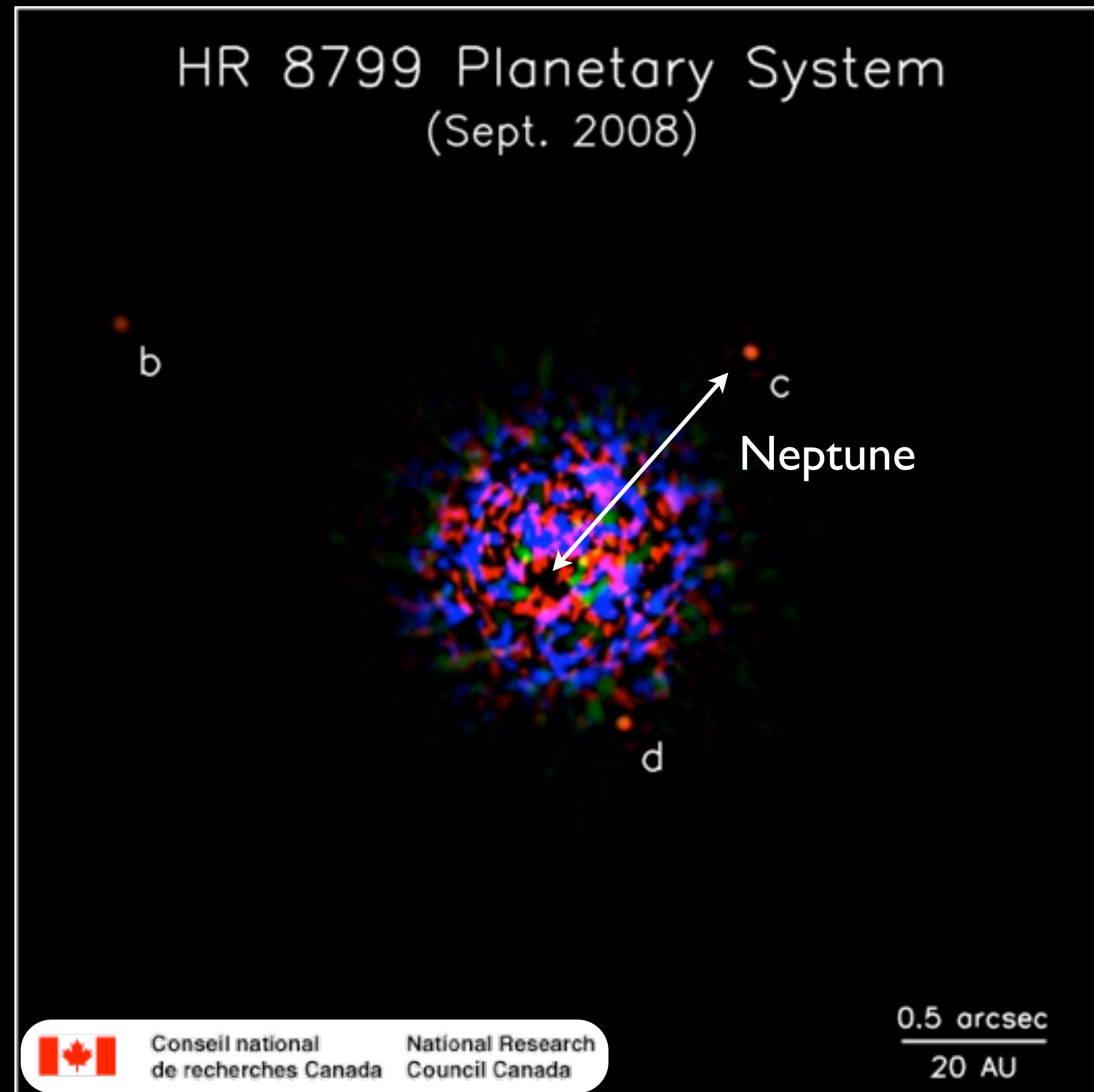


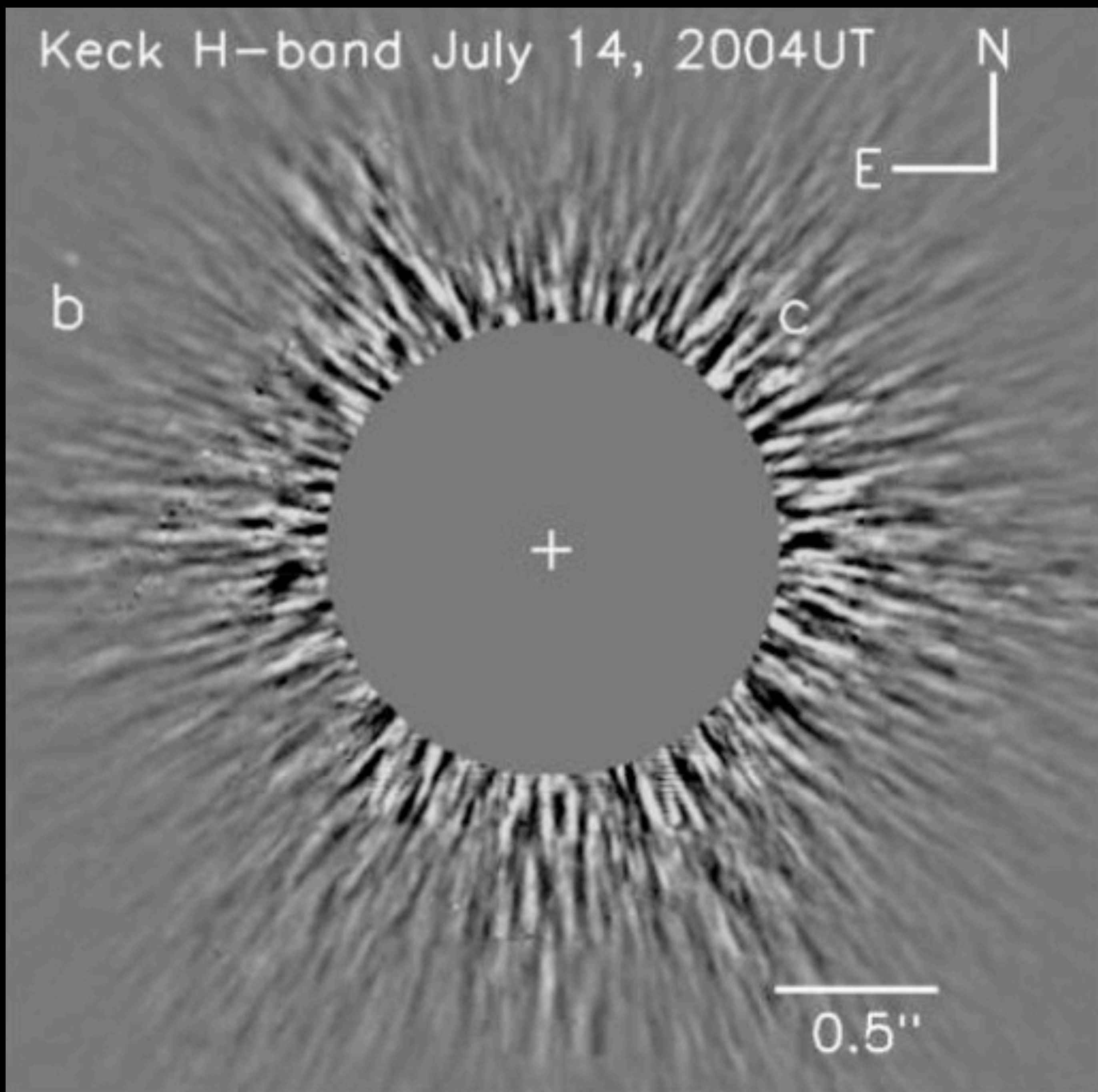


Keck 2 (130 ly), 10m diameter

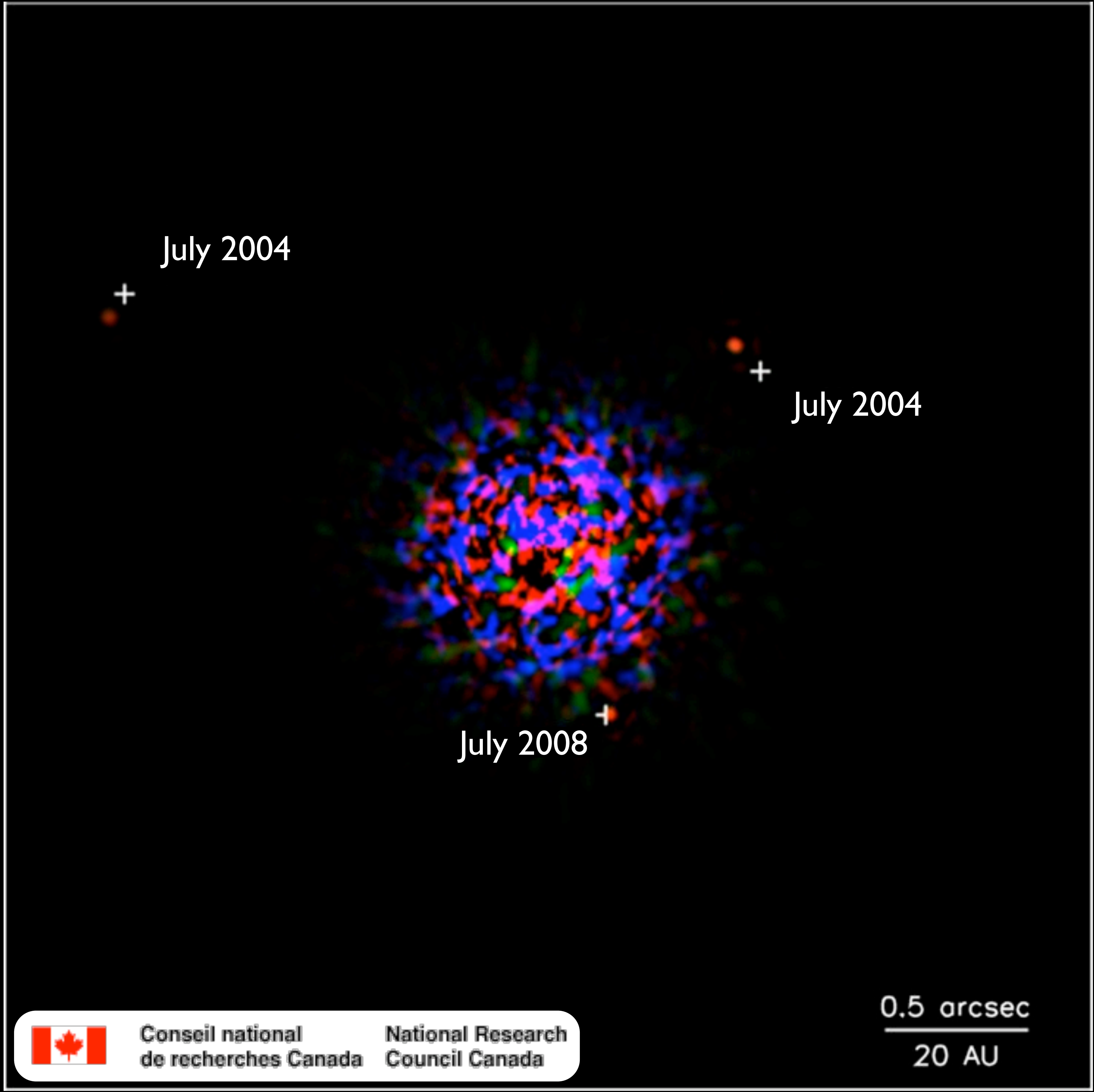


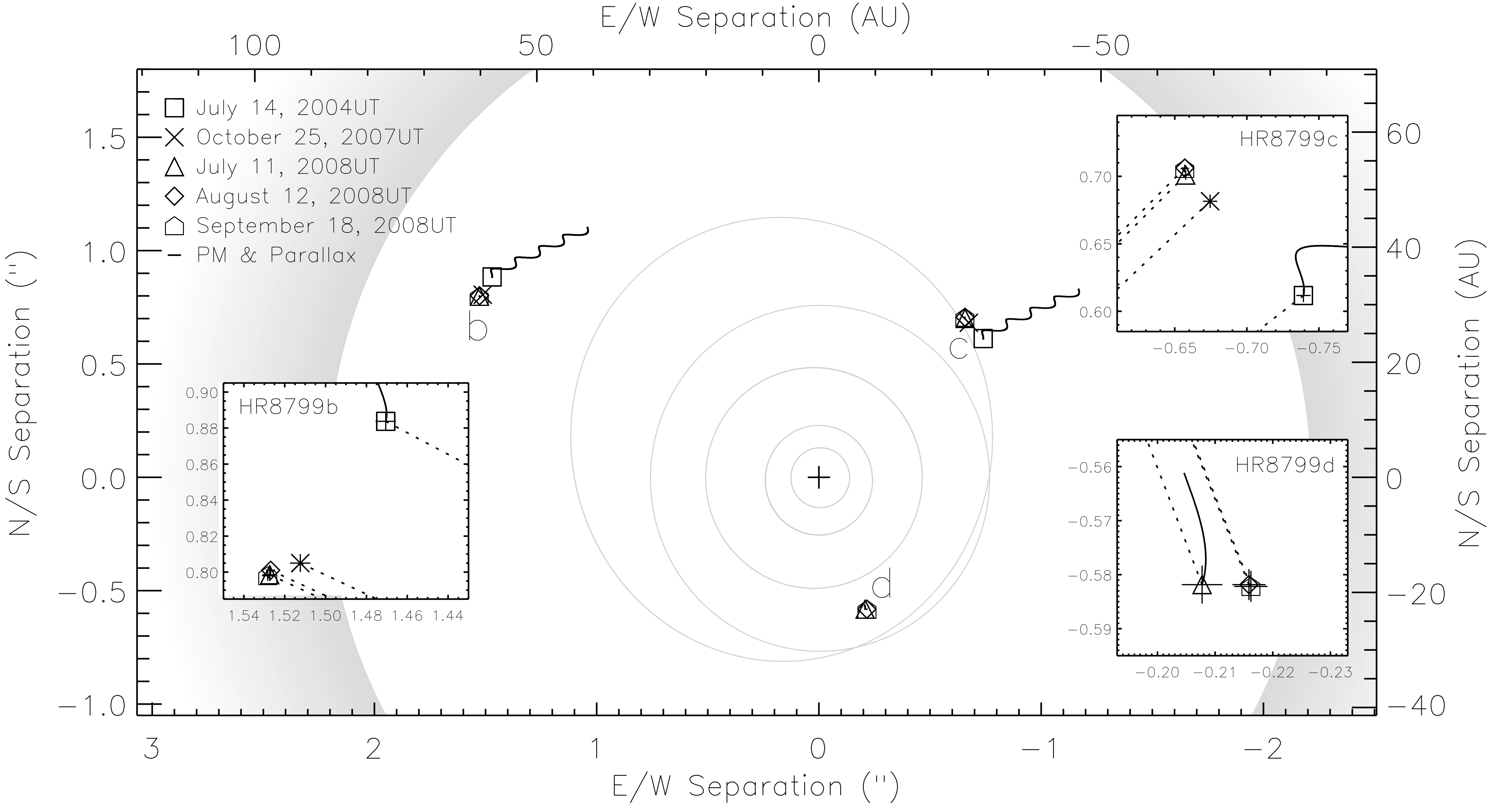
8 200 000 AU

Keck 2004 old data



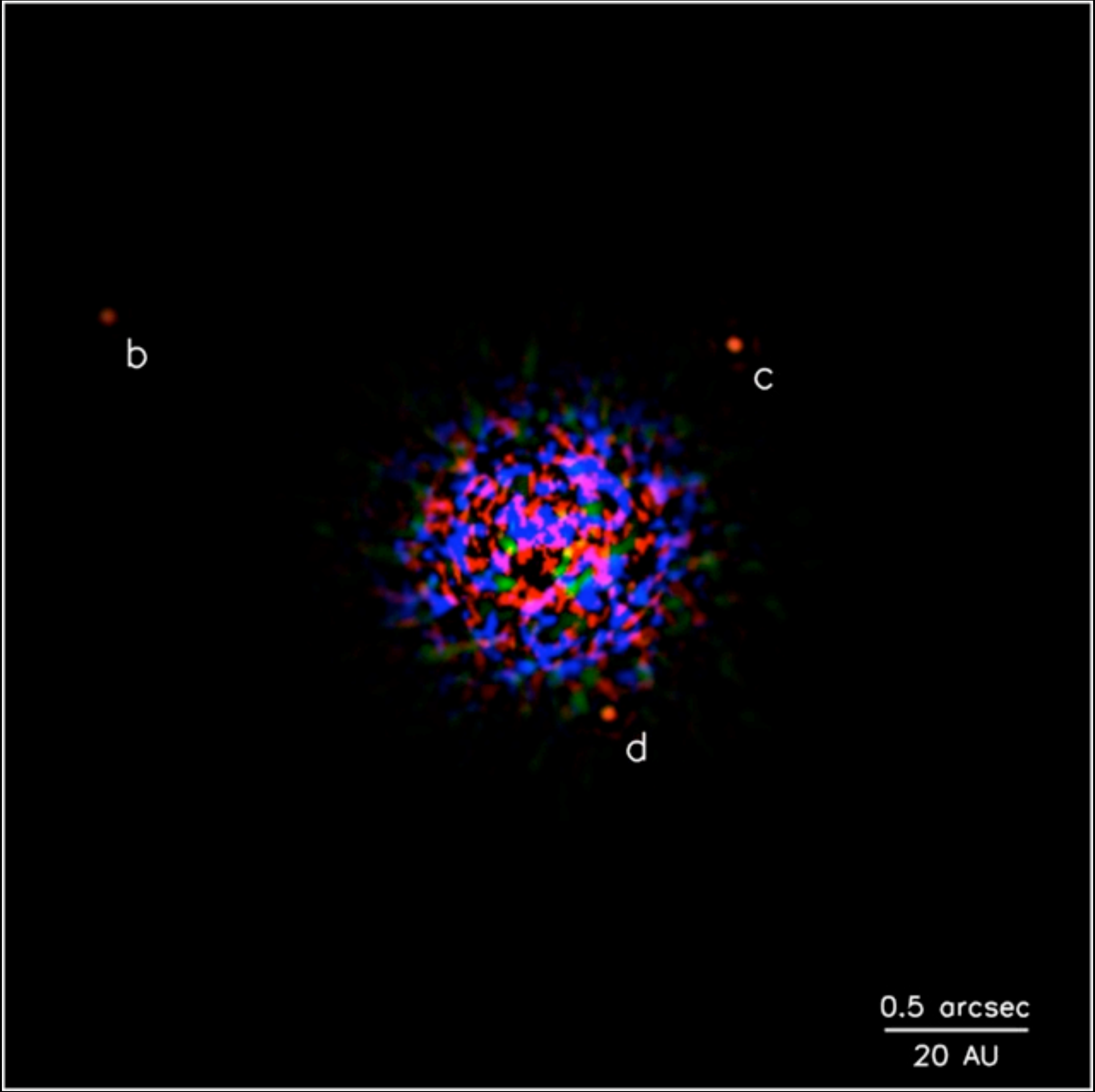
Add 4 more years of orbital motion!


July 2004
July 2004
July 2008
0.5 arcsec
20 AU
Conseil national
de recherches Canada
National Research
Council Canada



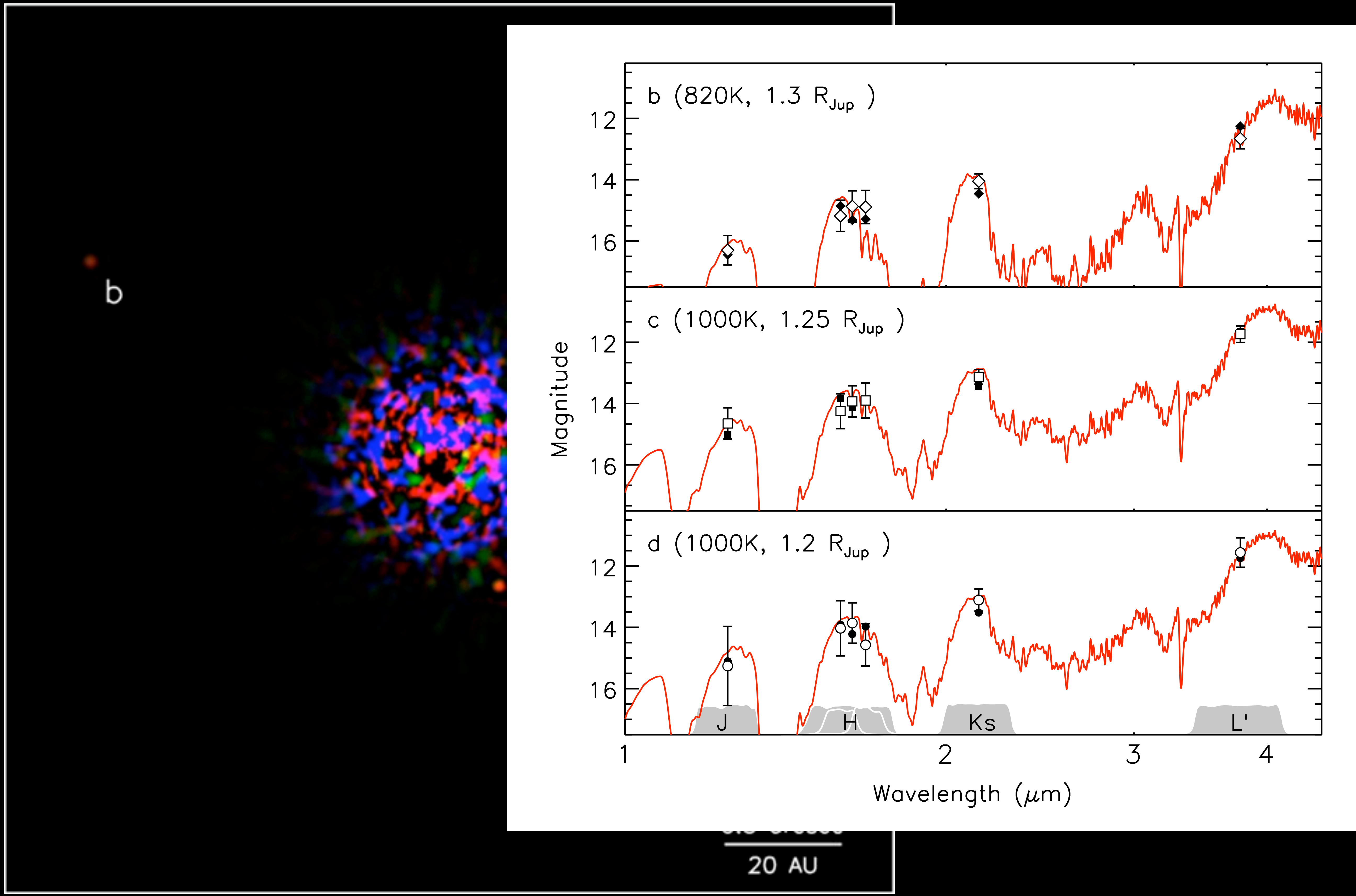
E/W Separation (AU)
100
50
0
−50
July 14, 2004UT
October 25, 2007UT
July 11, 2008UT
August 12, 2008UT
September 18, 2008UT
PM & Parallax
N/S Separation ('')
N/S Separation (AU)
b
c
d
HR8799b
HR8799c
HR8799d
E/W Separation ('')

Multi-band photometry @ Keck



HR 8799 age?

Multi-band photometry @ Keck



HR 8799 age?

HR 8799 Age Estimation

- Low in the HR diagram, under Pleiades.

- Galactic Space motion consistent with being young - between TW Hya and Pleiades

- Lambda Boo & Gamma Dor stars generally considered young.

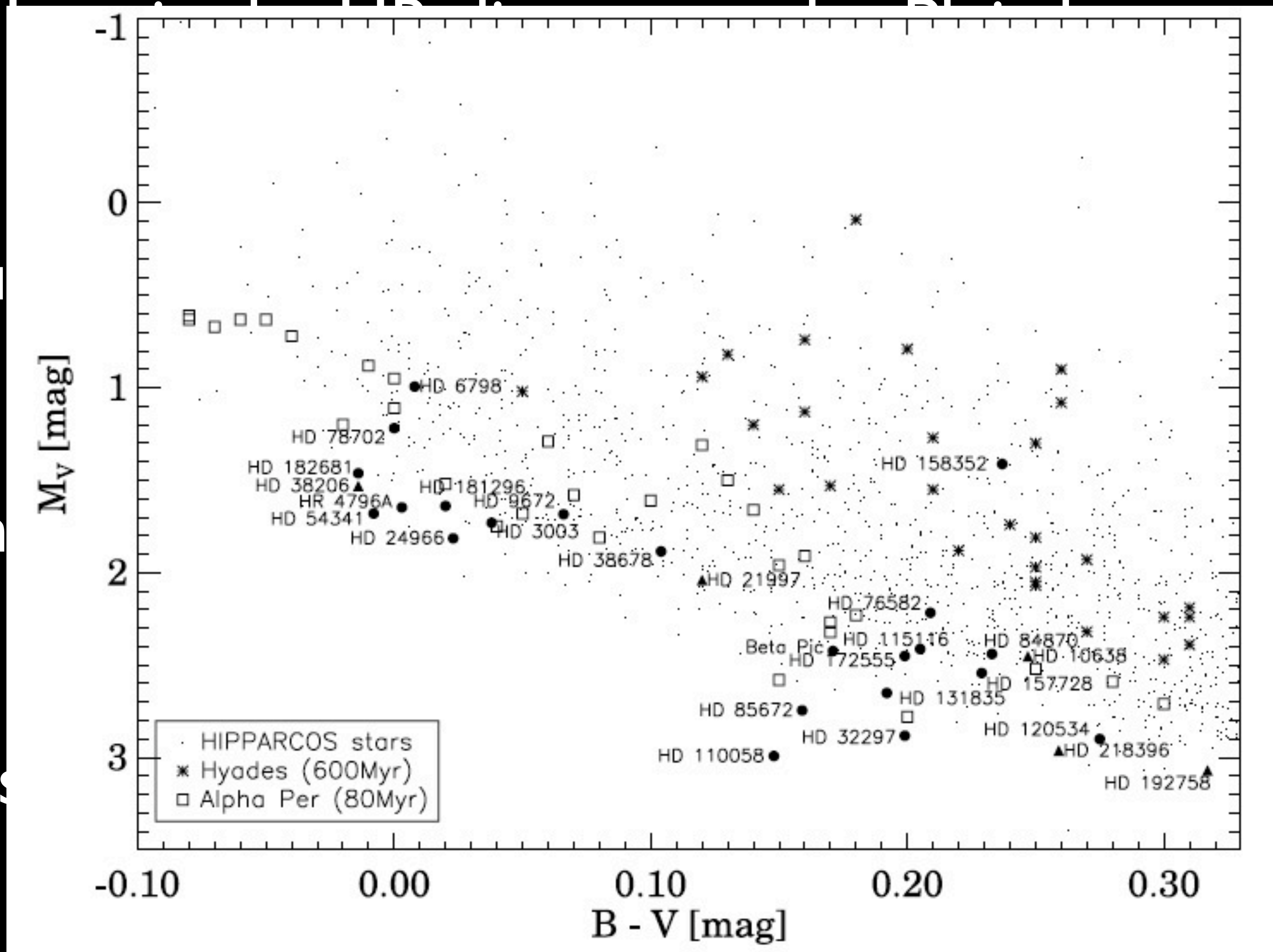
- Massive debris disk - lower probability at older ages.

- Isolated field star.

HR 8799 age = 30-160 Myr

HR 8799 Age Estimation

- you
- con
- der ages
- isolated field star.



HR 8799 age = 30-160 Myr

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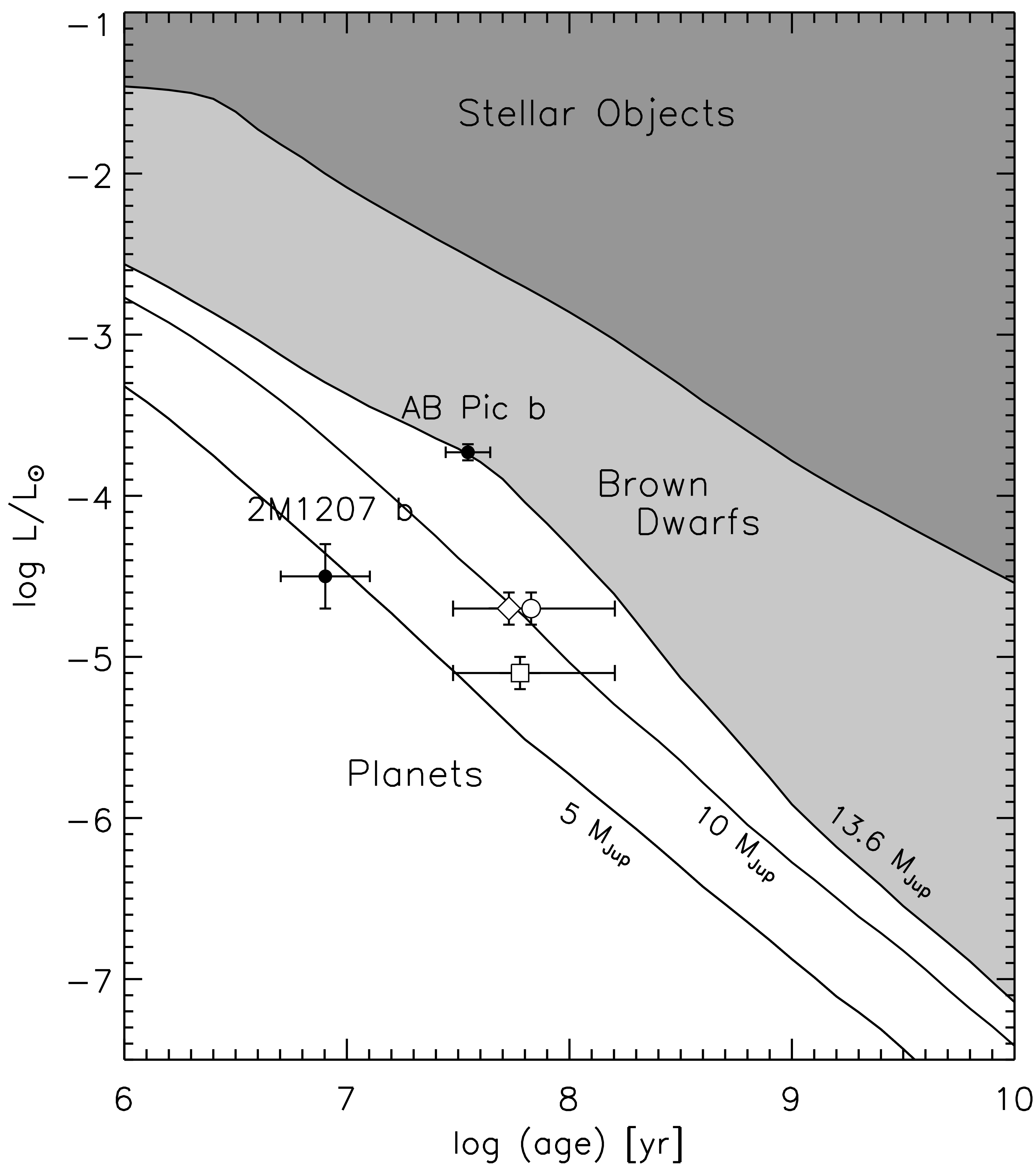
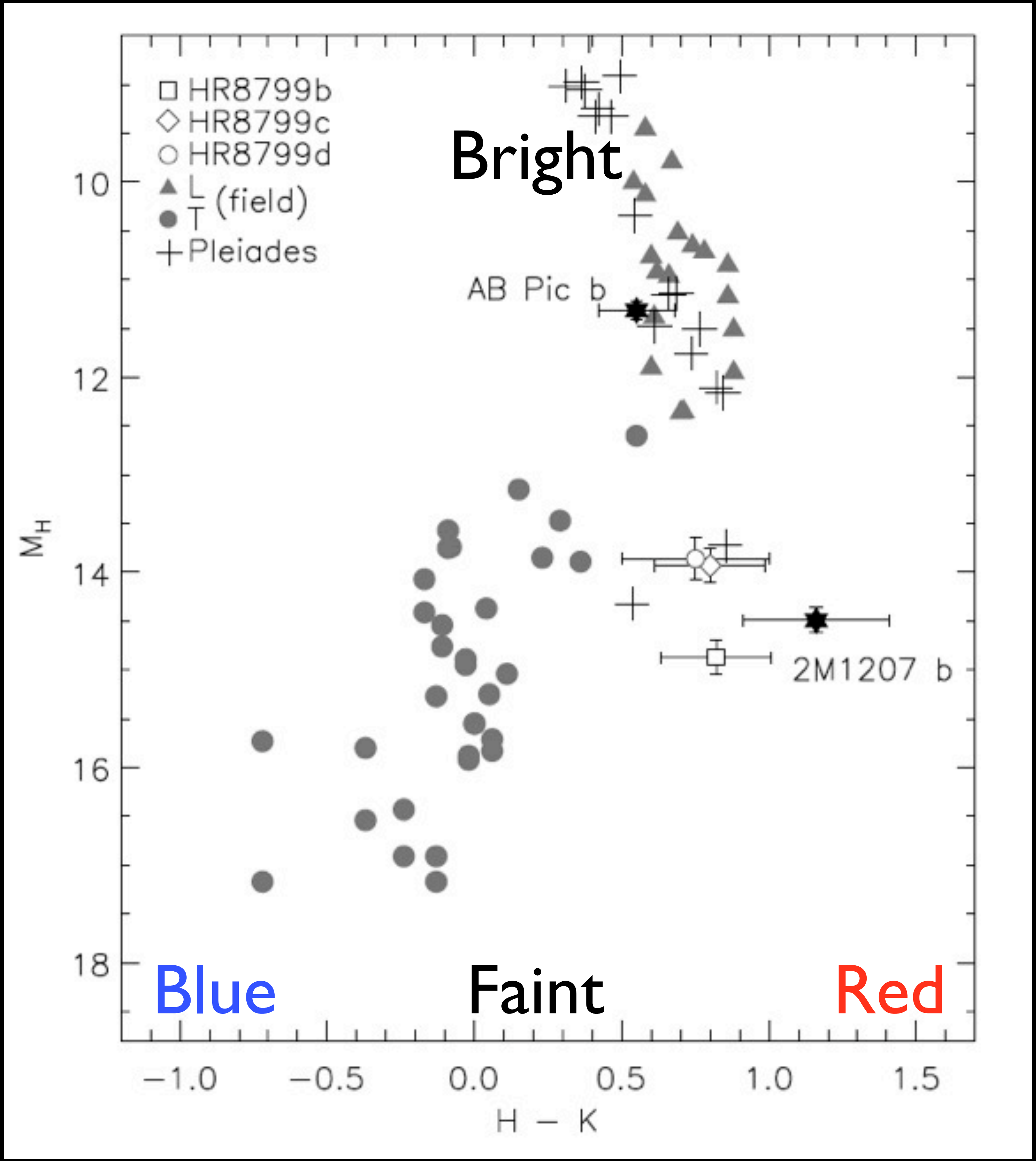
HR 8799 age = 30-160 Myr

Mass, radius & Teff estimations from cooling tracks



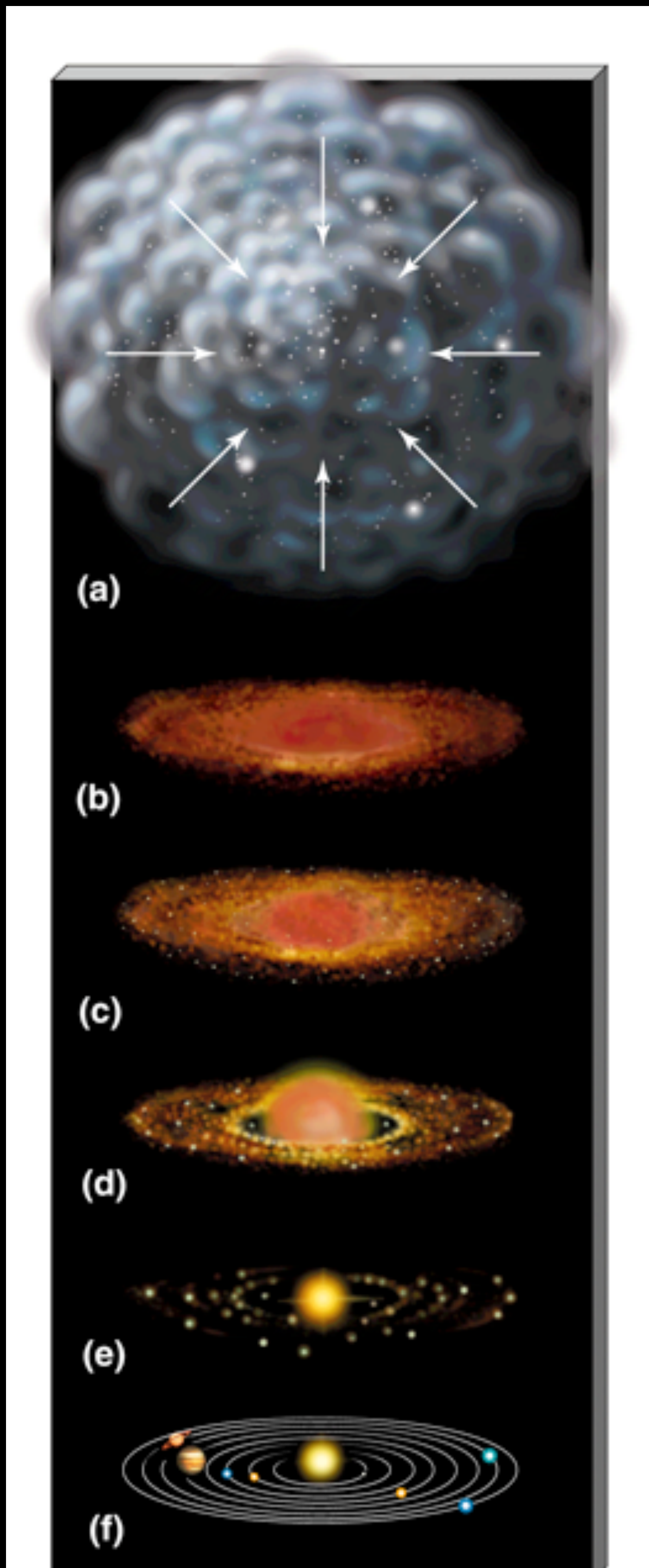
The 3 planet's colors are more consistent with Pleiades low mass ~11MJup objects and 2M1207b than field BDs.



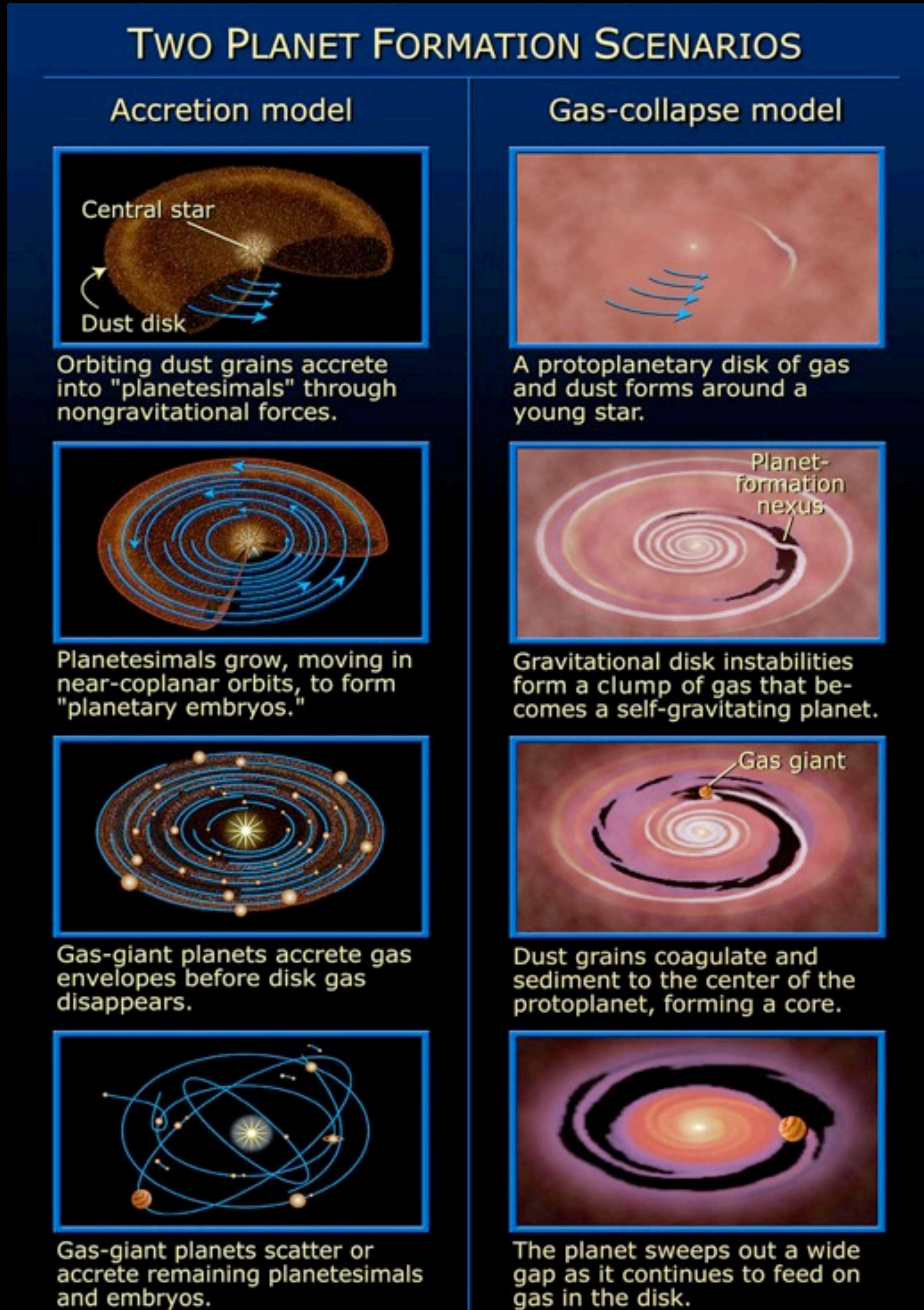
Physics untested - No corresponding objects in the field.

Planetary System Formation

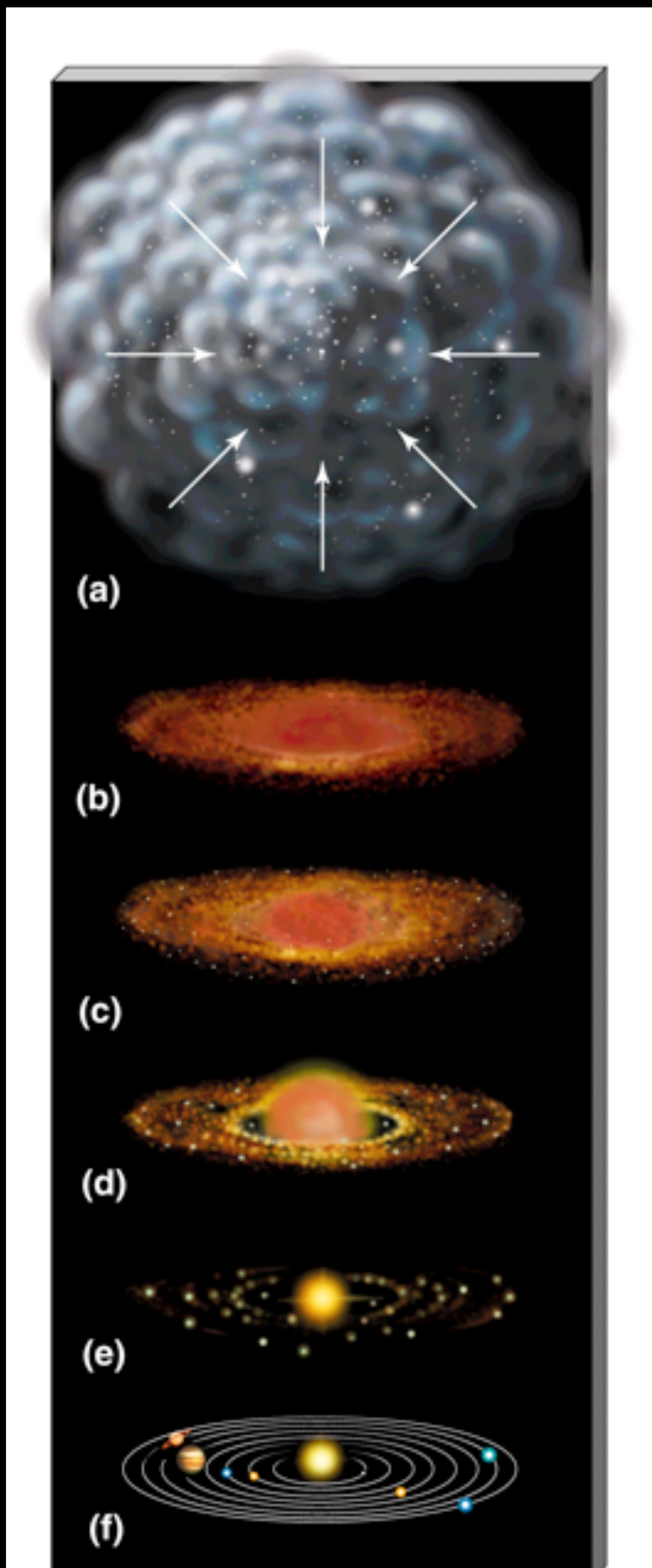
Solar system

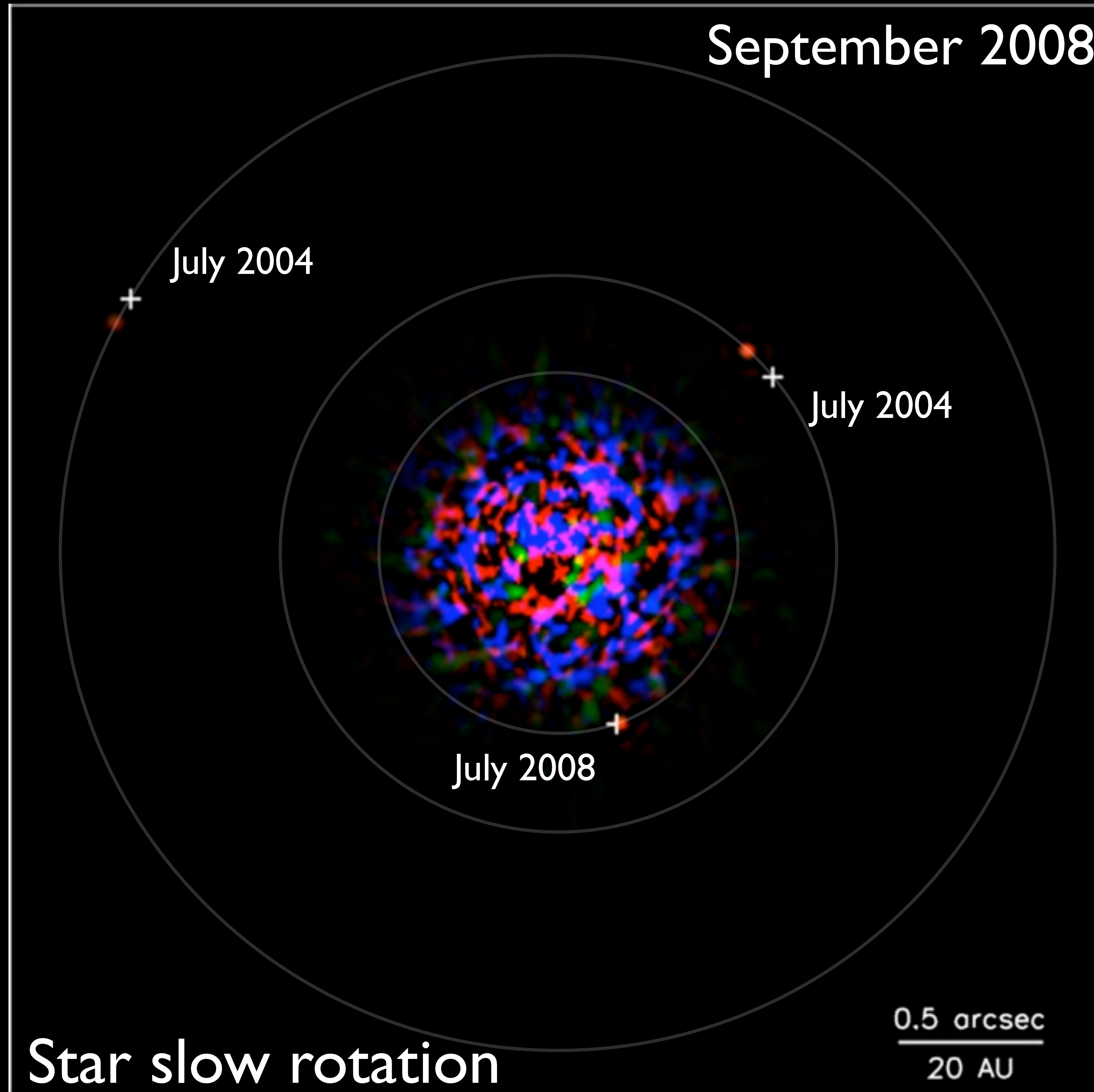


one theory of how gas-giant planets form
Moonrunner Design


TWO PLANET FORMATION SCENARIOS
Accretion model
Gas-collapse model
Central star
Dust disk
Orbiting dust grains accrete into "planetesimals" through nongravitational forces.
A protoplanetary disk of gas and dust forms around a young star.
Planetesimals grow, moving in near-coplanar orbits, to form "planetary embryos."
Planet-formation nexus
Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.
Gas-giant planets accrete gas envelopes before disk gas disappears.
Gas giant
Dust grains coagulate and sediment to the center of the protoplanet, forming a core.
Gas-giant planets scatter or accrete remaining planetesimals and embryos.
The planet sweeps out a wide gap as it continues to feed on gas in the disk.

HR 8799 Planetary System Probably formed in a disk





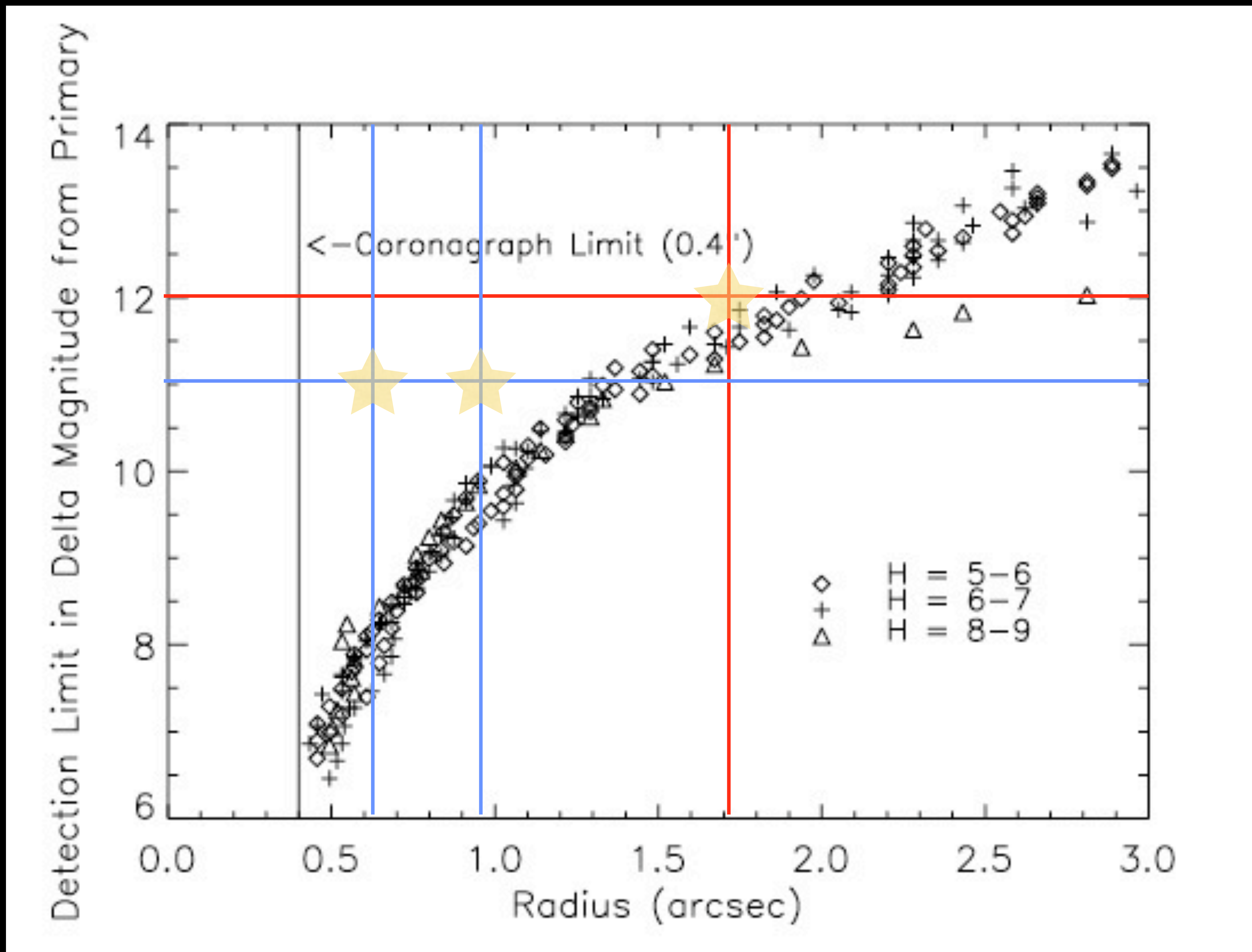
HR 8799bcd Characteristics

HR 8799	Separation (AU)	Period (years)	Temperature (K)	Radius (RJup)	Mass (MJup)
b	68	~460	820	1.30	7
c	38	~190	1000	1.25	10
d	25	~100	1000	1.20	10

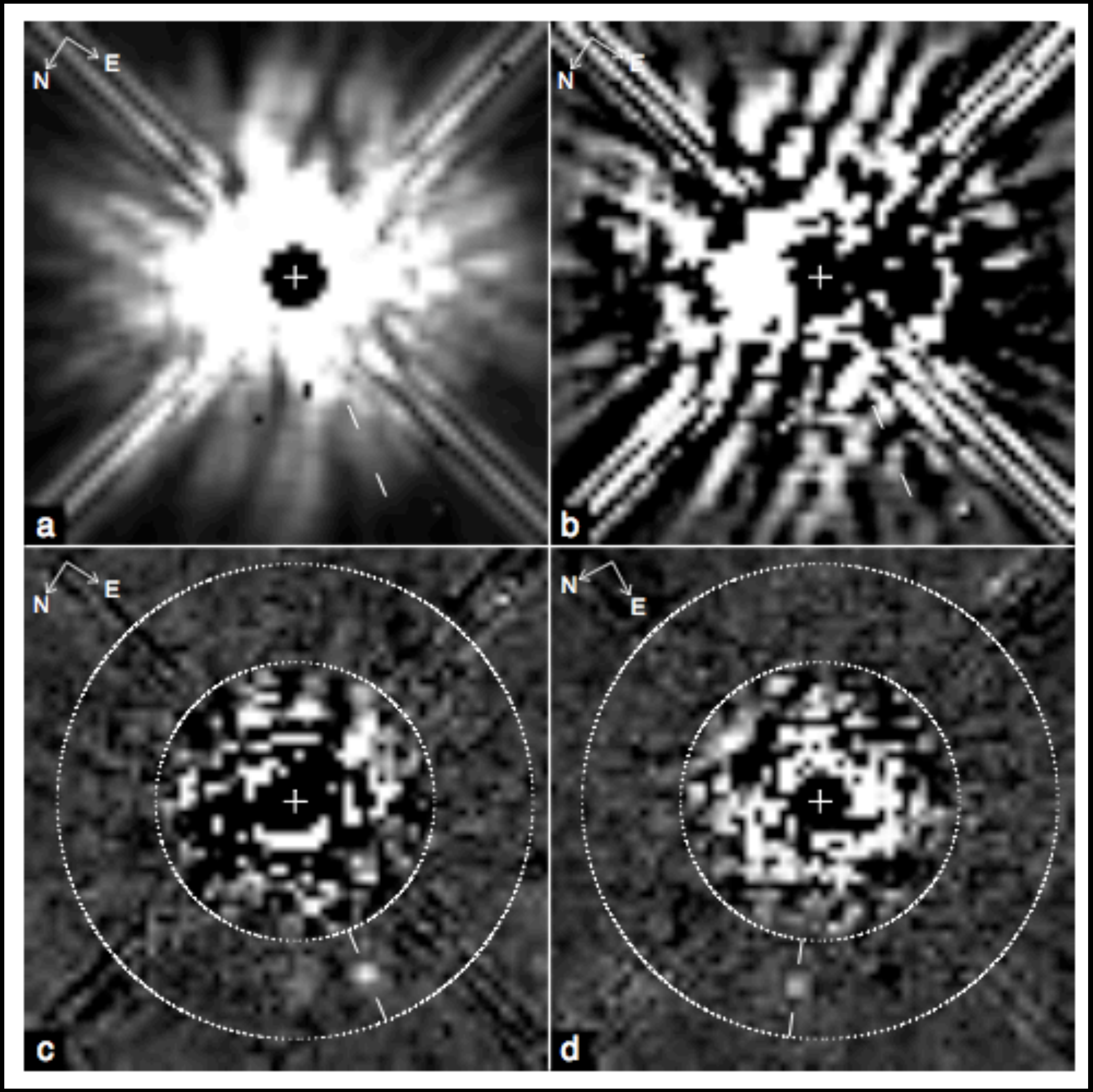
Circular
face-on

60 Myr

E. Becklin 1998 HST data



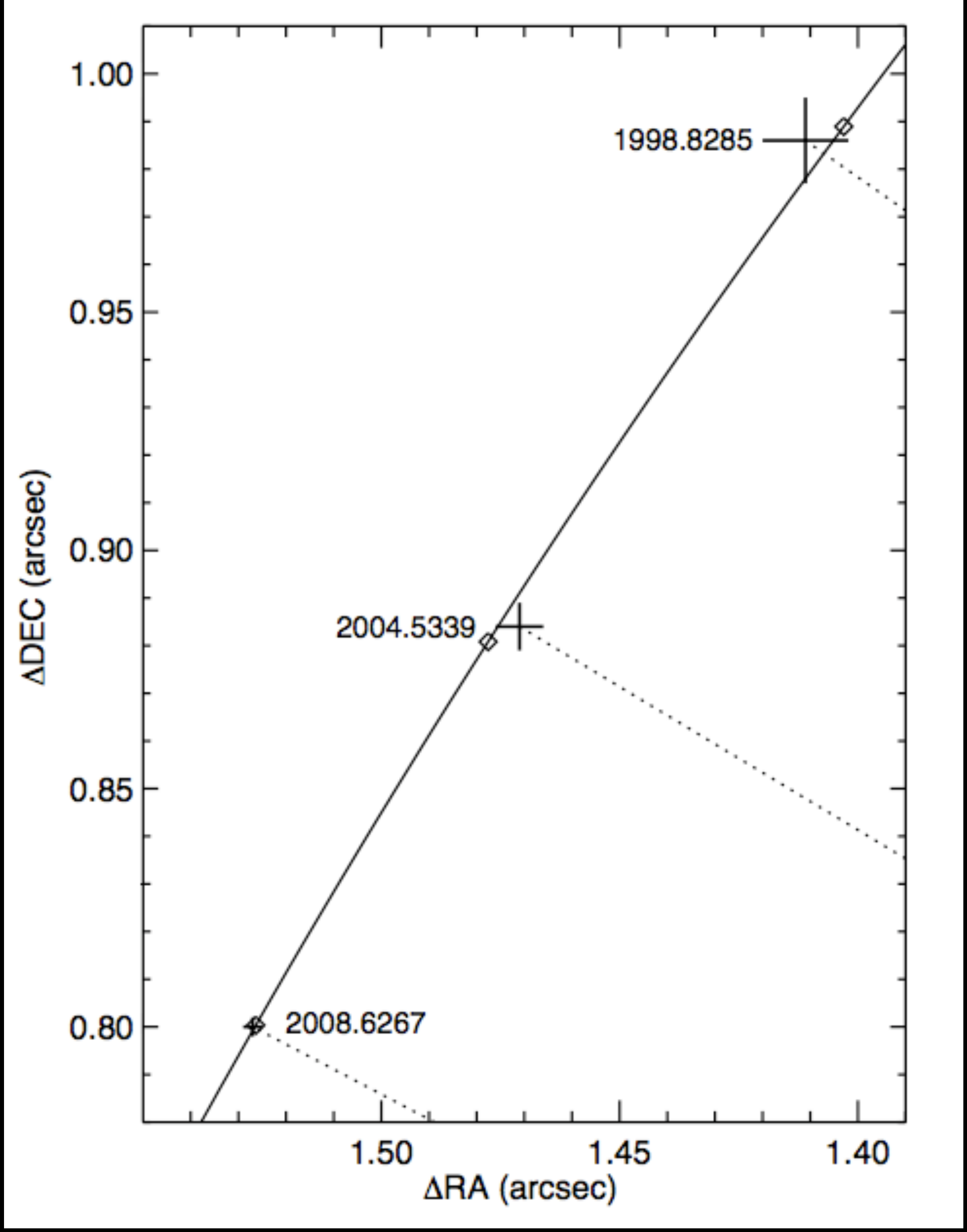
Lefreniere et al. 2009



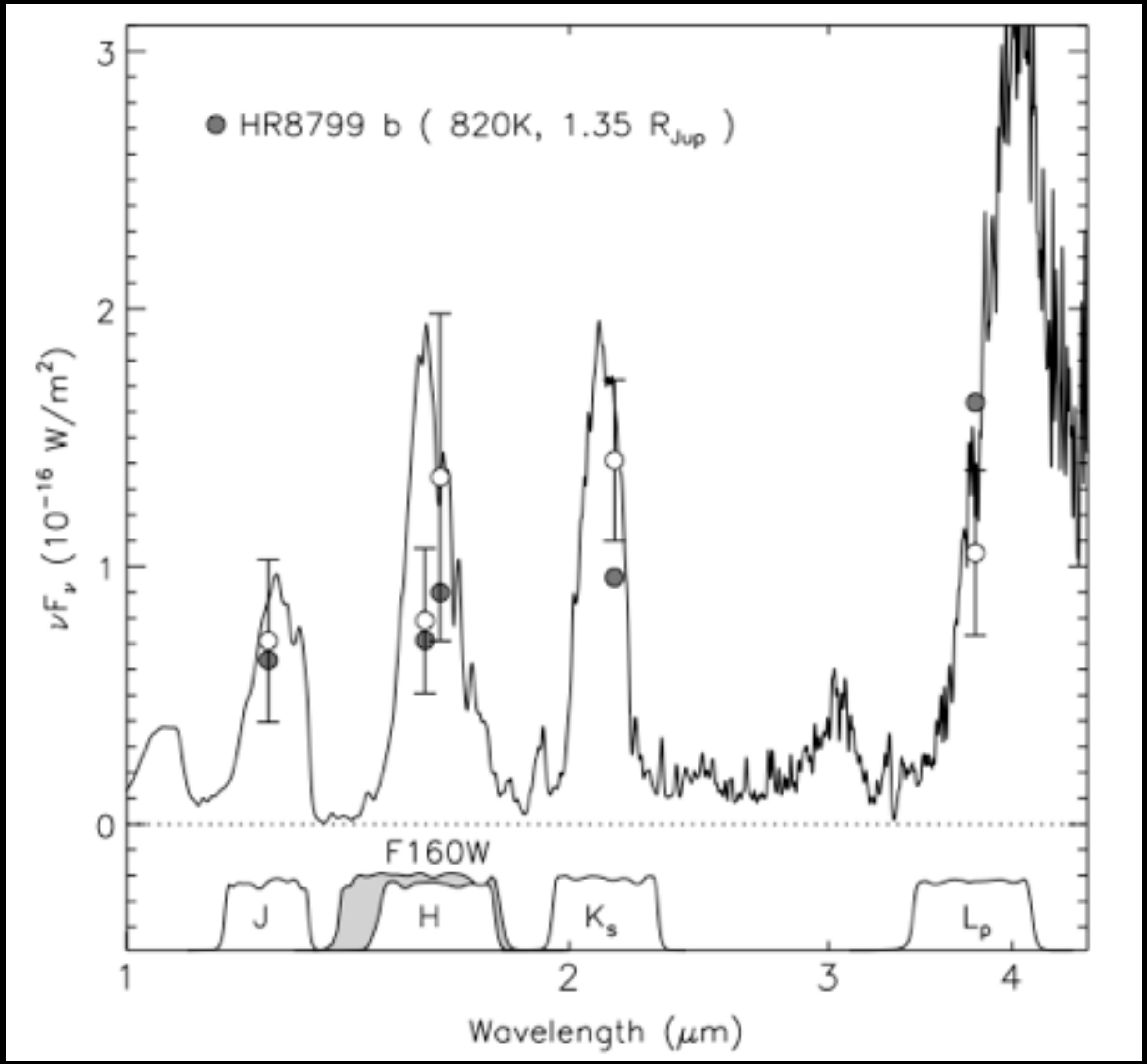
~10x better PSF subtraction!

New 1998 epoch!

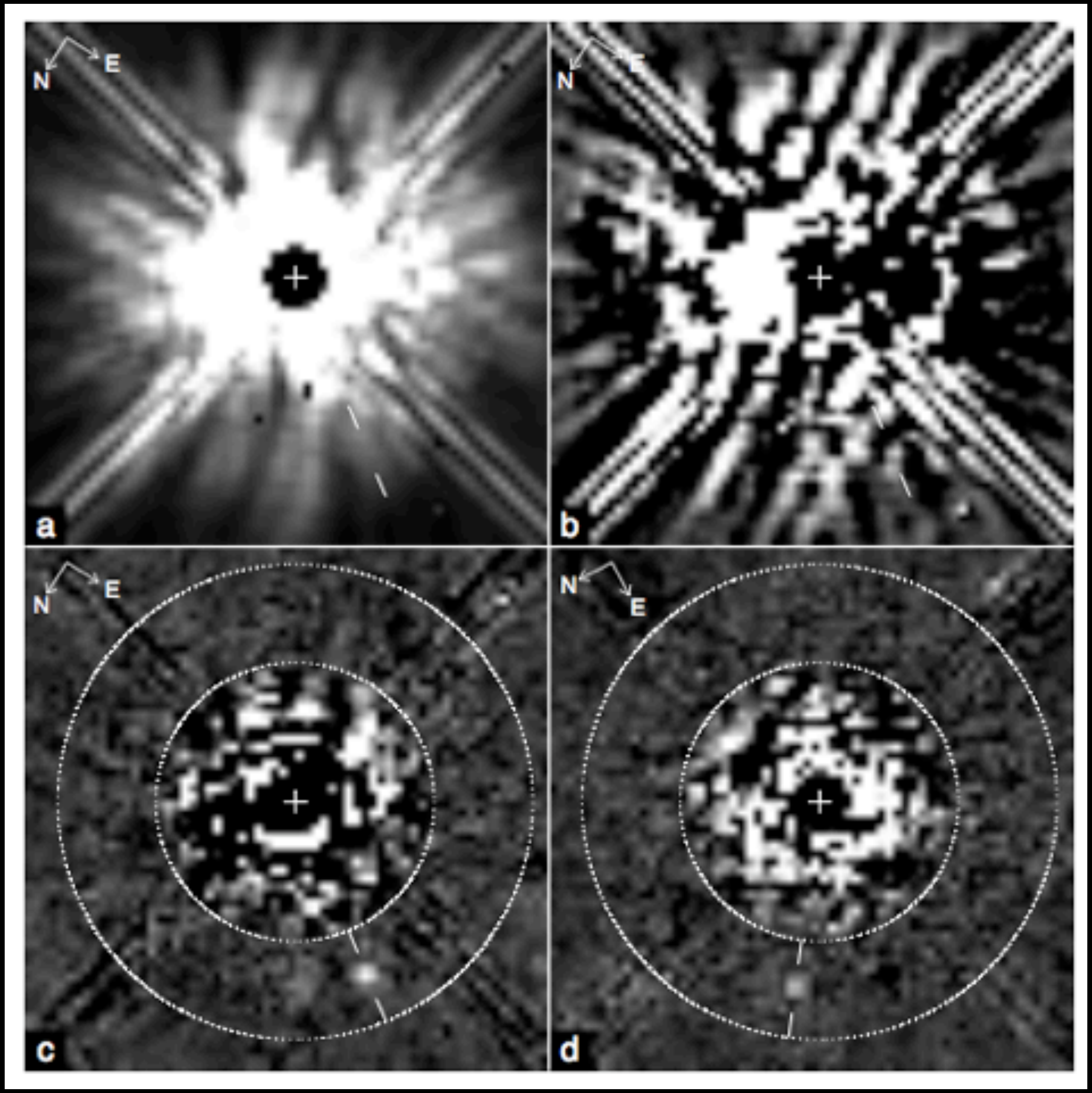
Lefreniere et al. 2009, submitted



F160W point consistent with water bands!



2nd HST paper in prep.



Lefreniere et al. 2009

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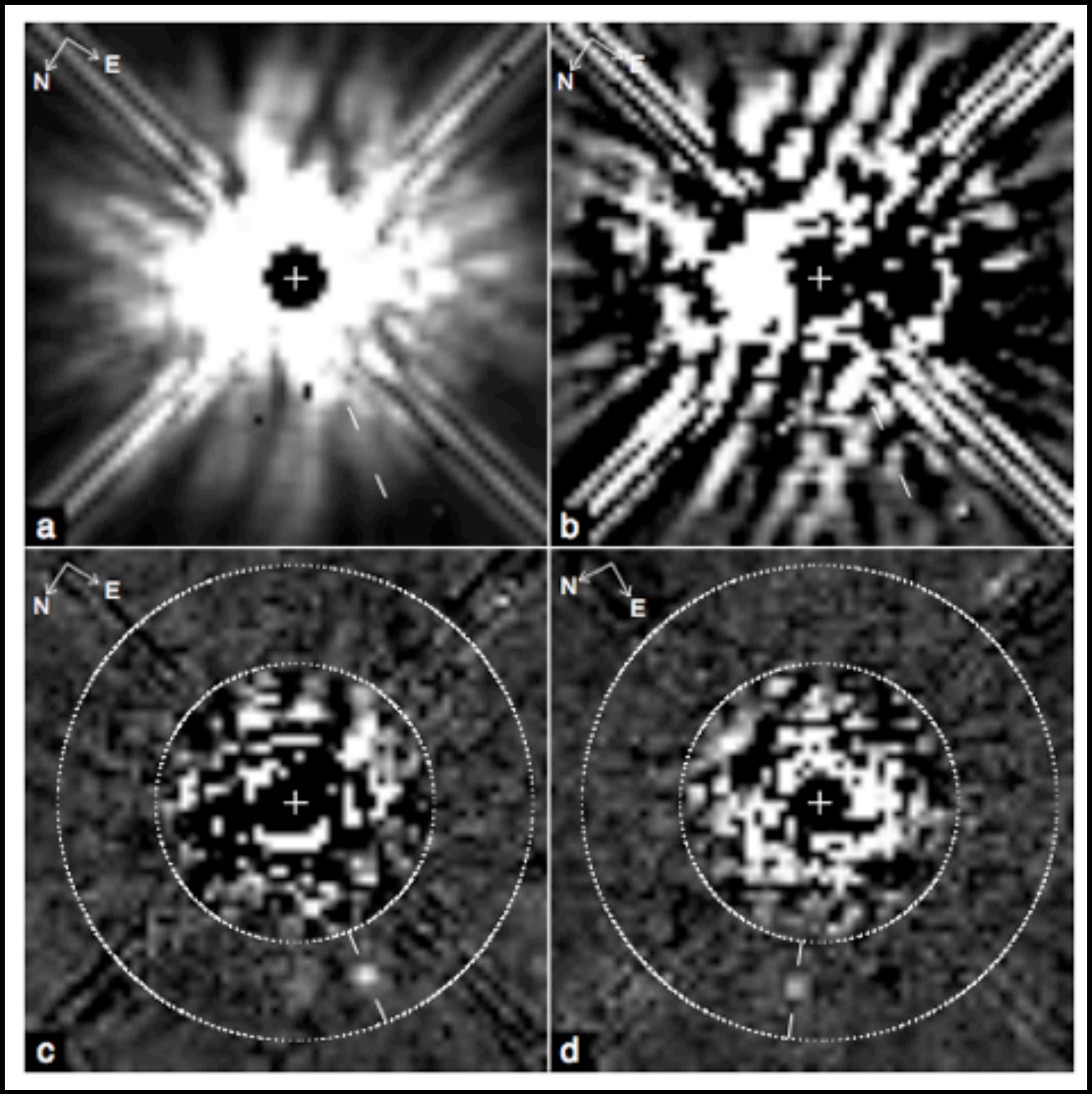
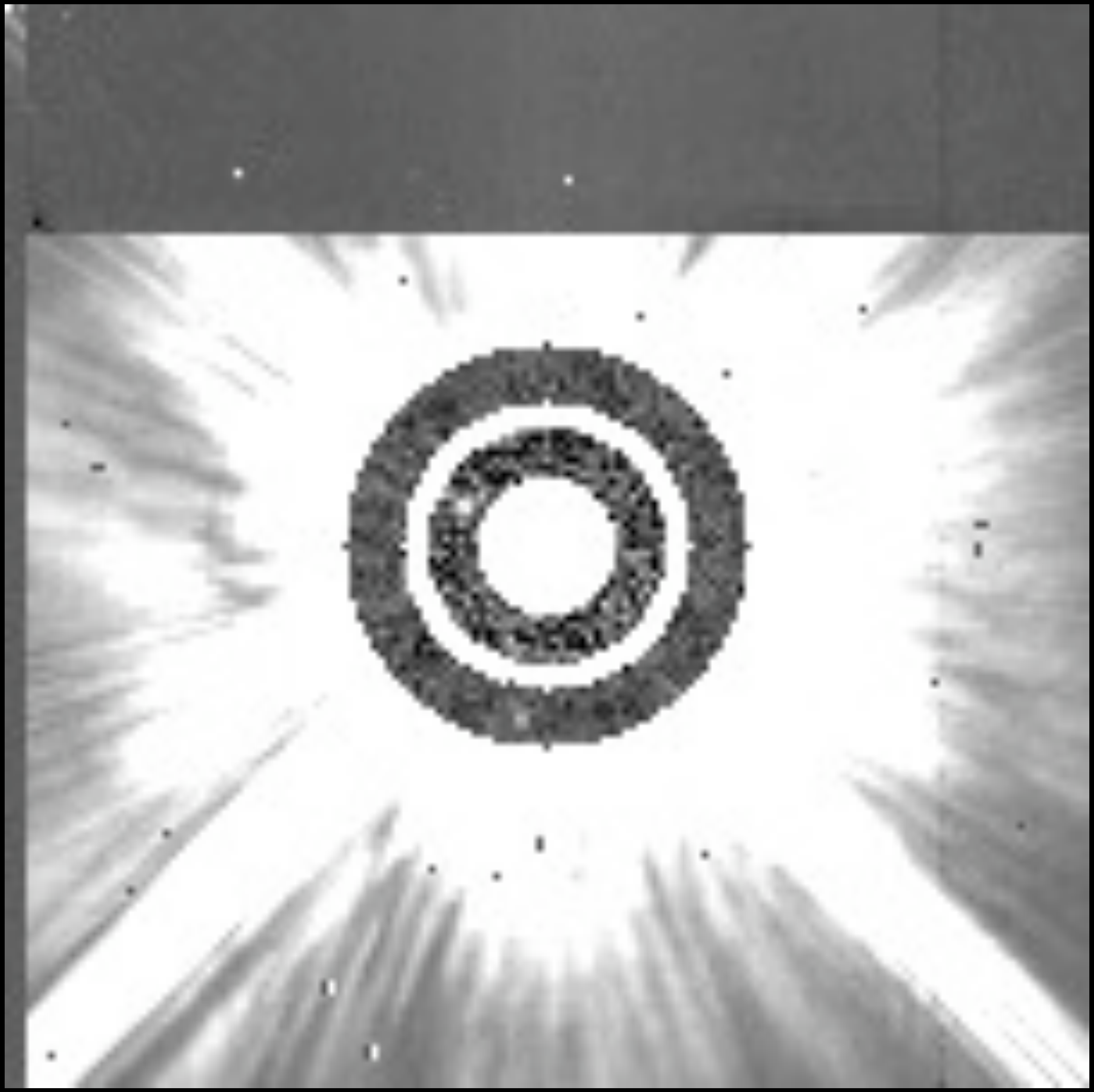


Lefreniere et al. 2009

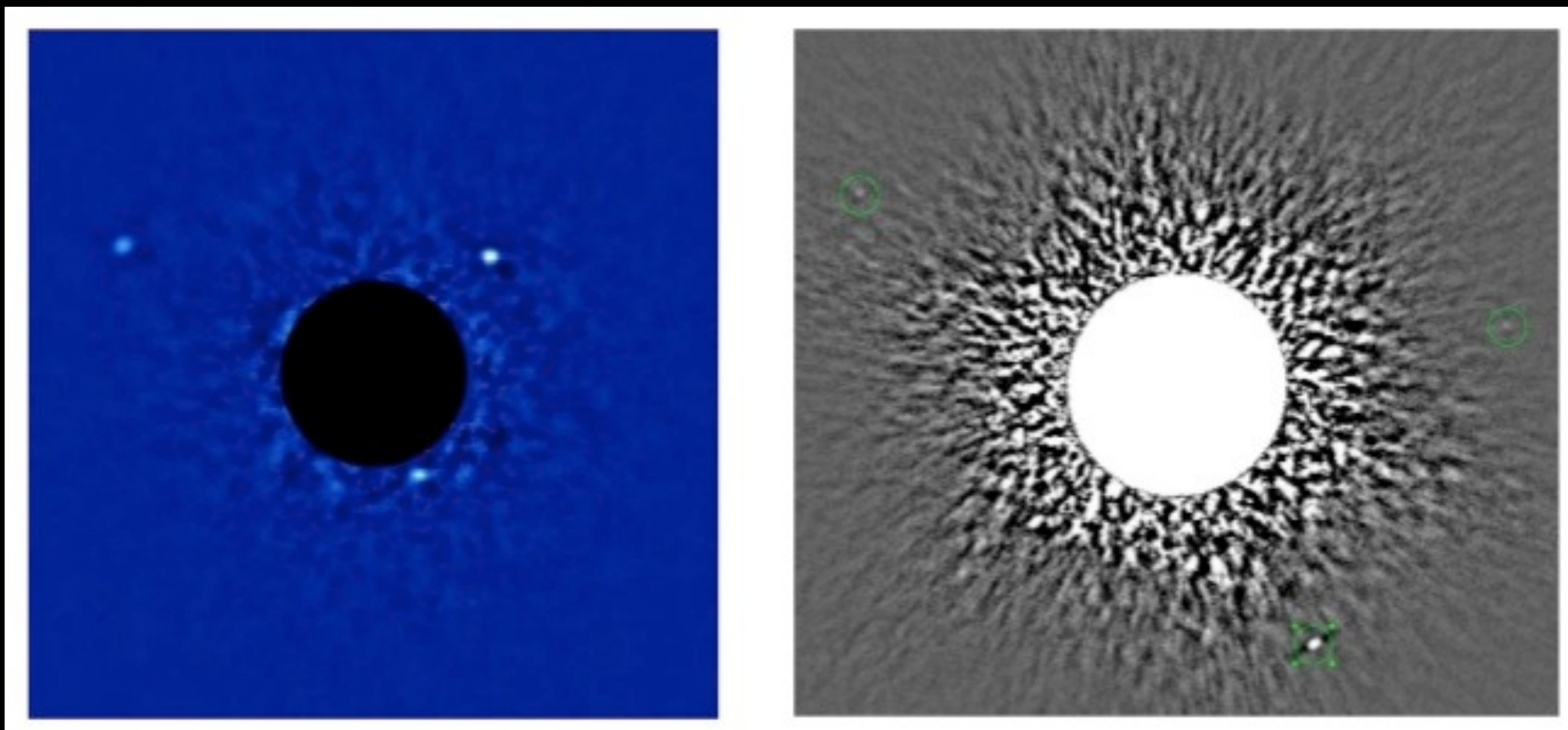


Marois et al., in prep.

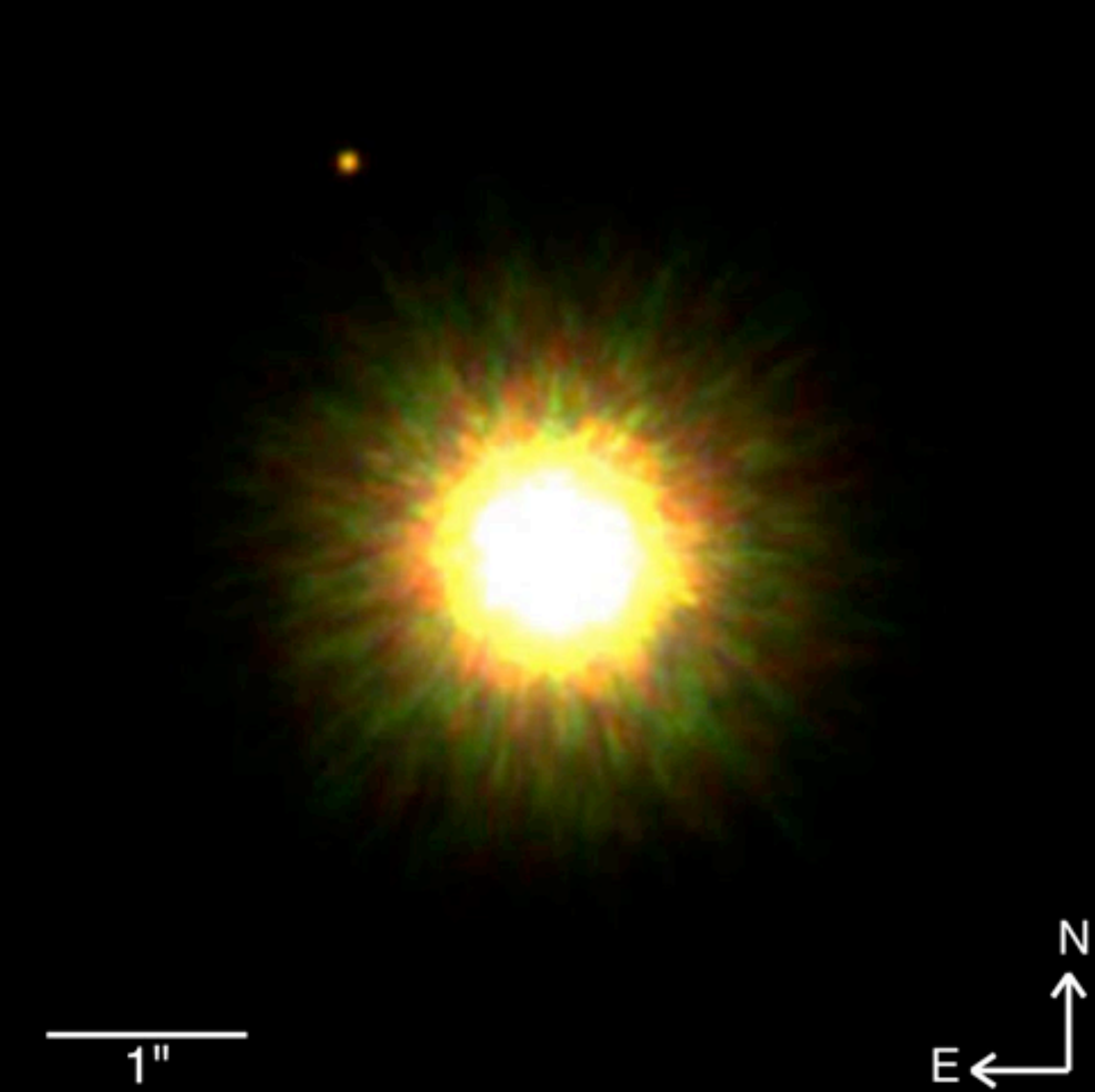
Finalizing the current AO survey (2010)

- Nearly 100 massive stars have been observed
- 79 candidates (3 real!)
- Increasing the survey to 250 stars (250h for 2009B)
- Now with NICI, NIRI, Nirc2 & Conica

Finalizing the current AO survey (2010)



1RXS J160929.1-210524

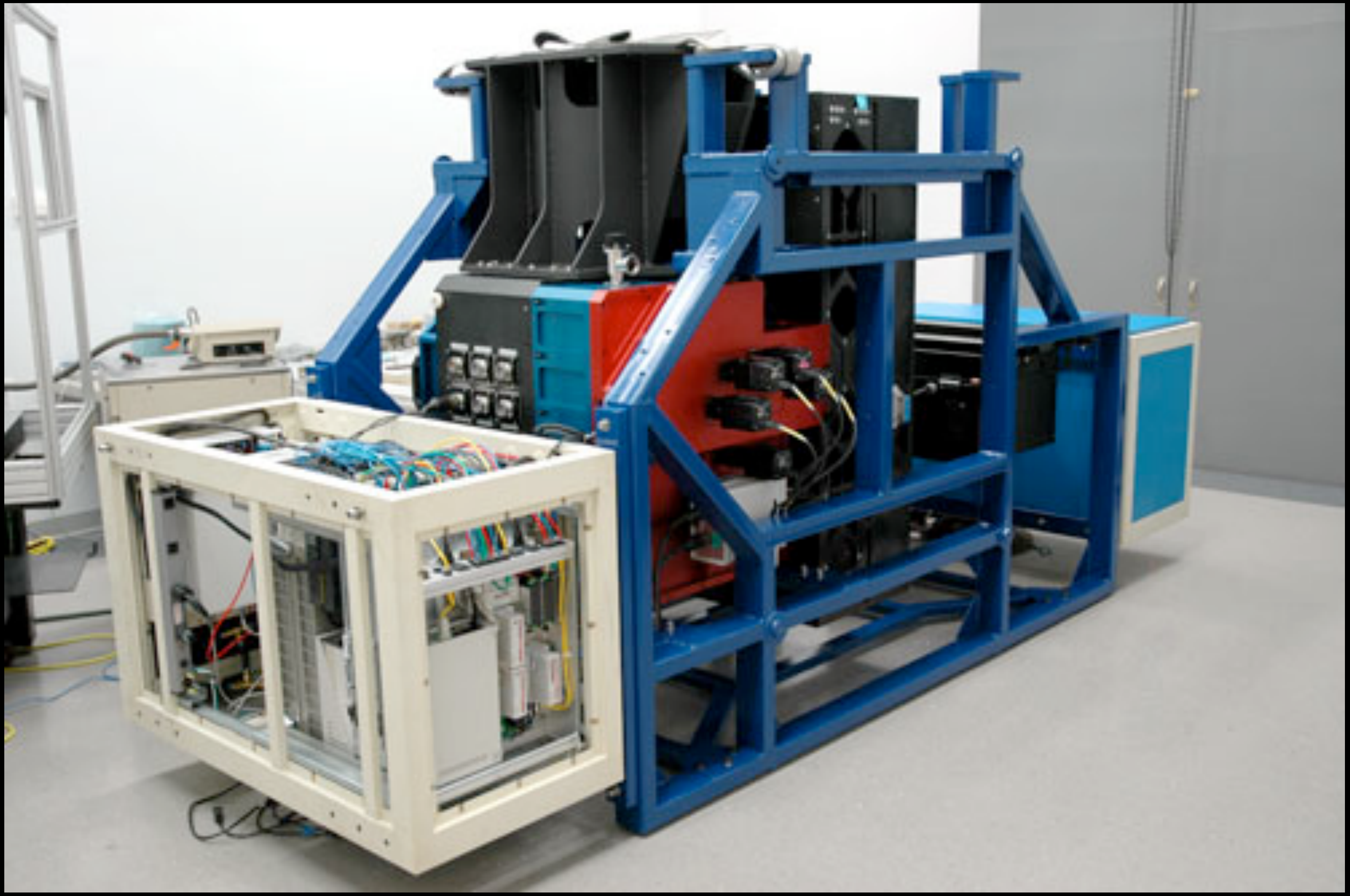


Lafreniere et al. 2008

330 AU & 8 MJup

Bound?

NICI@Gemini S



50 nights survey in 2-3 years
PI: M. Liu & L. Close

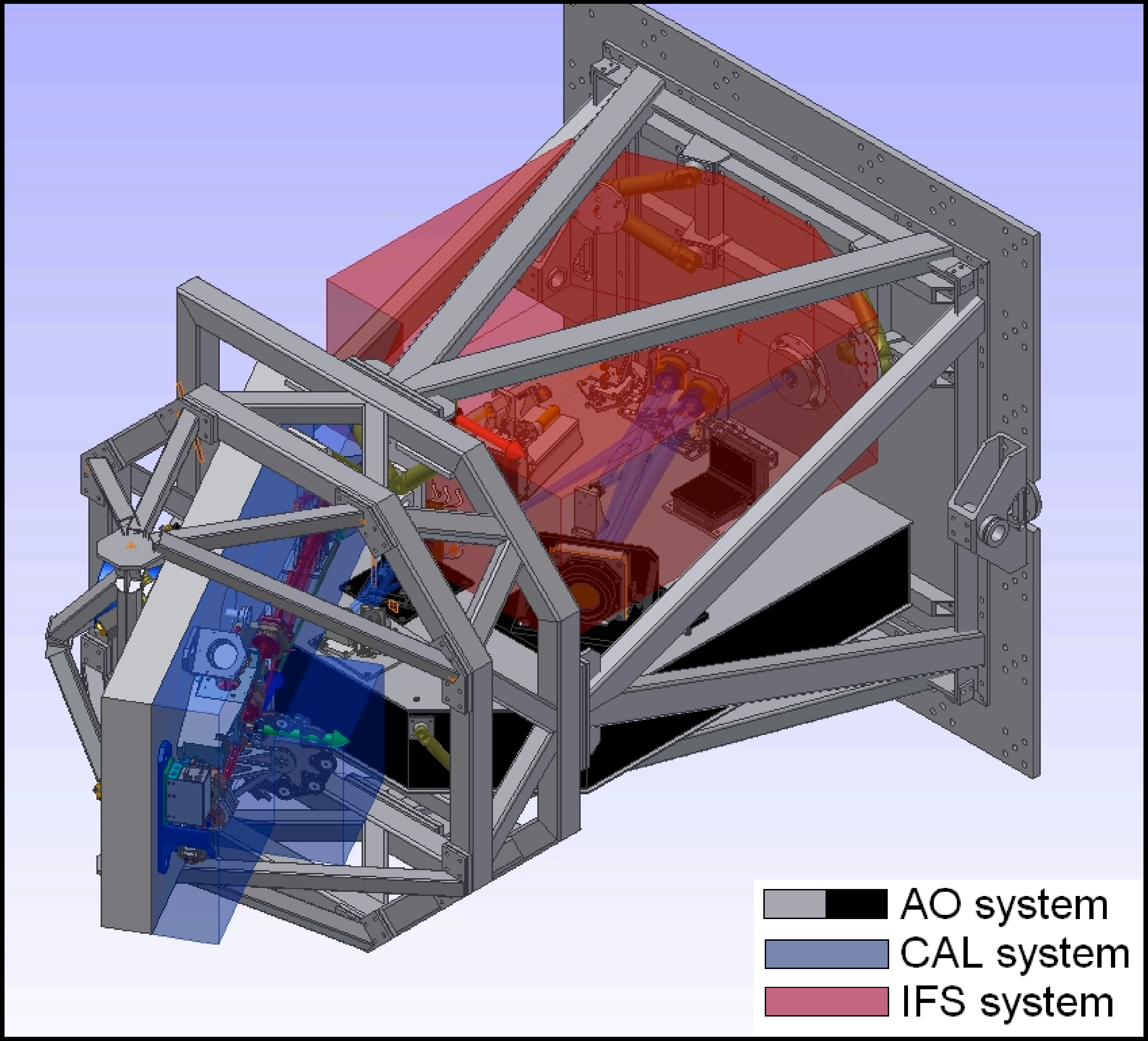
GPI@Gemini S/N

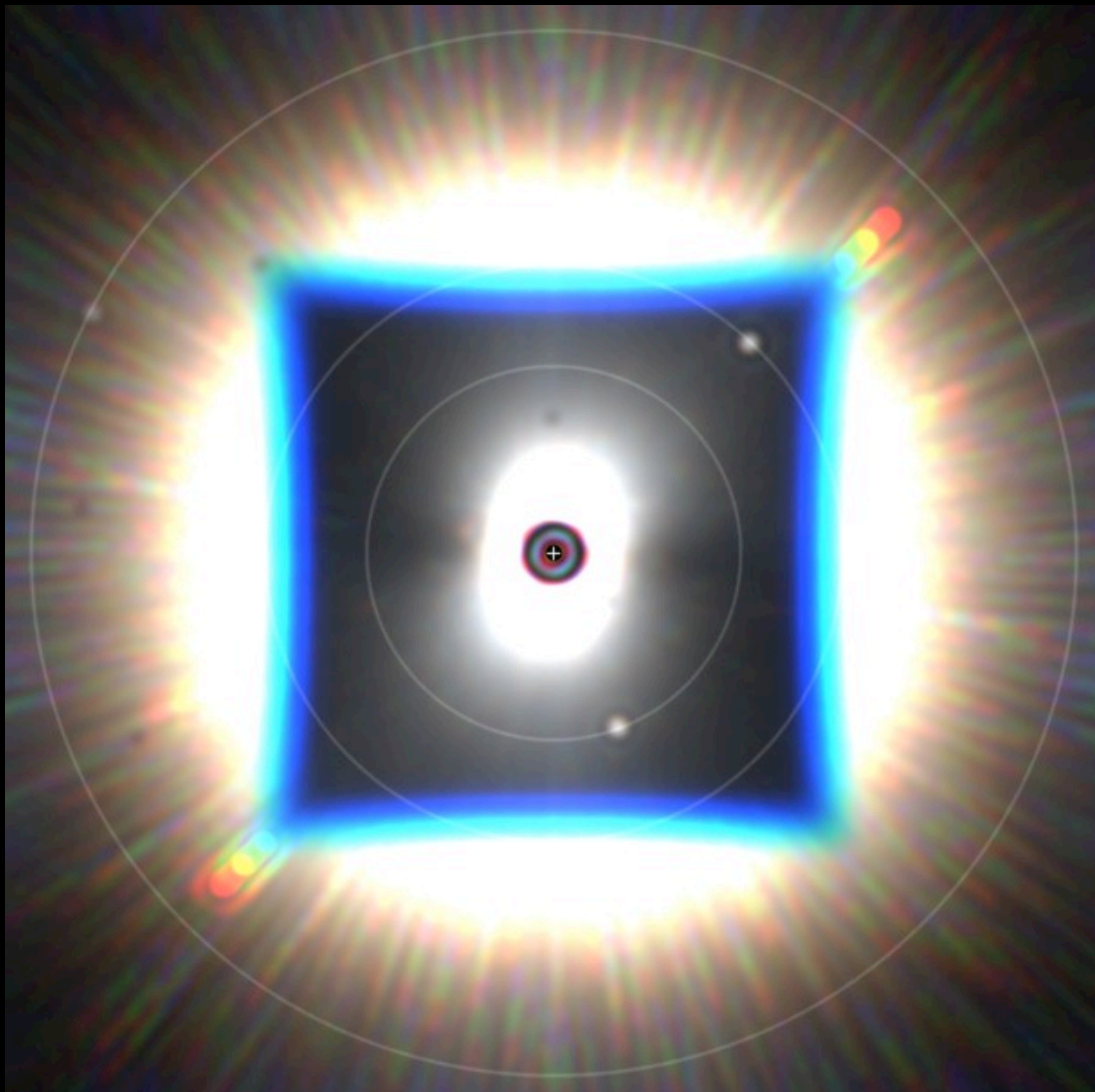
Gemini Planet Imager

Imageur de Planètes pour Gemini

Conseil national de recherches Canada

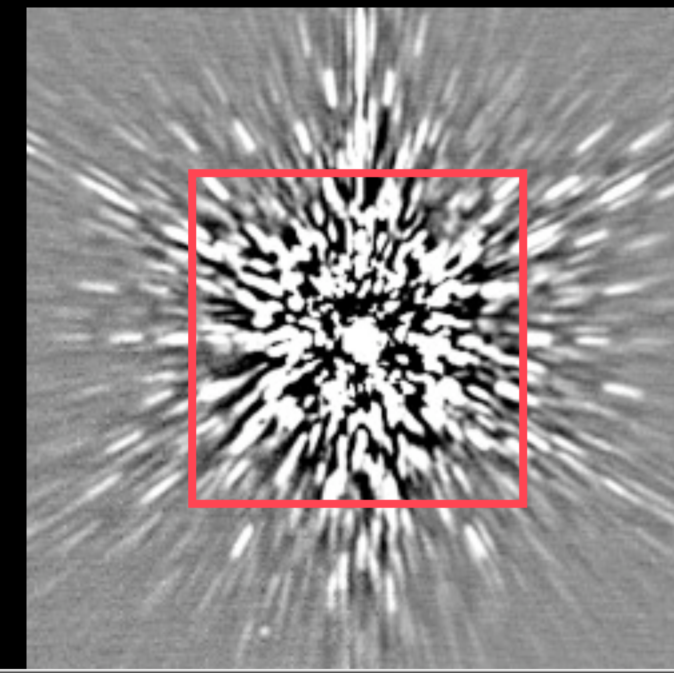
National Research Council Canada

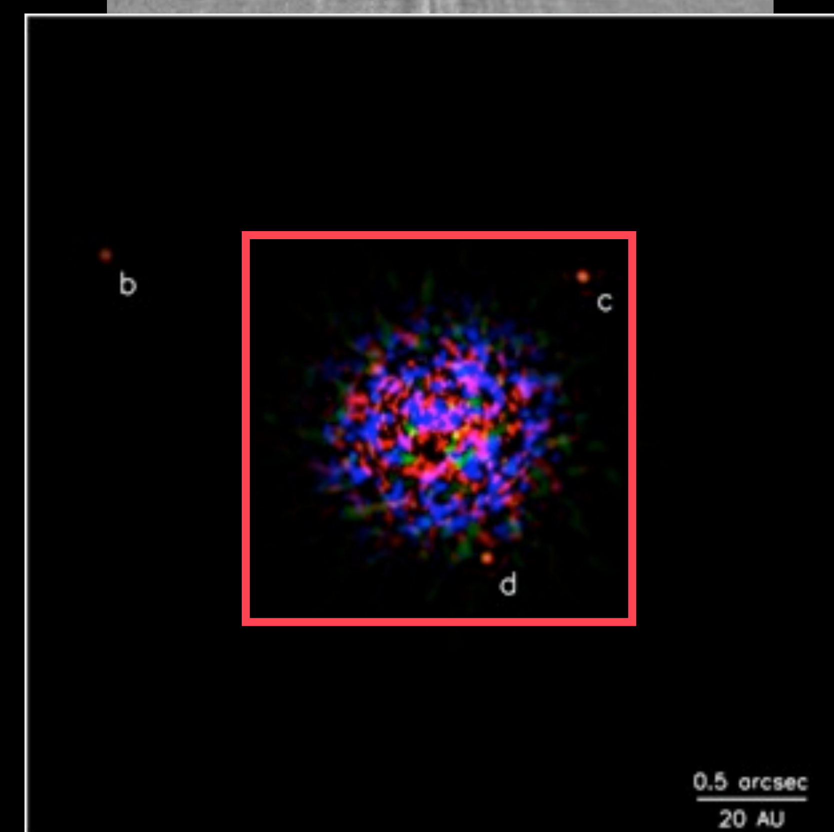




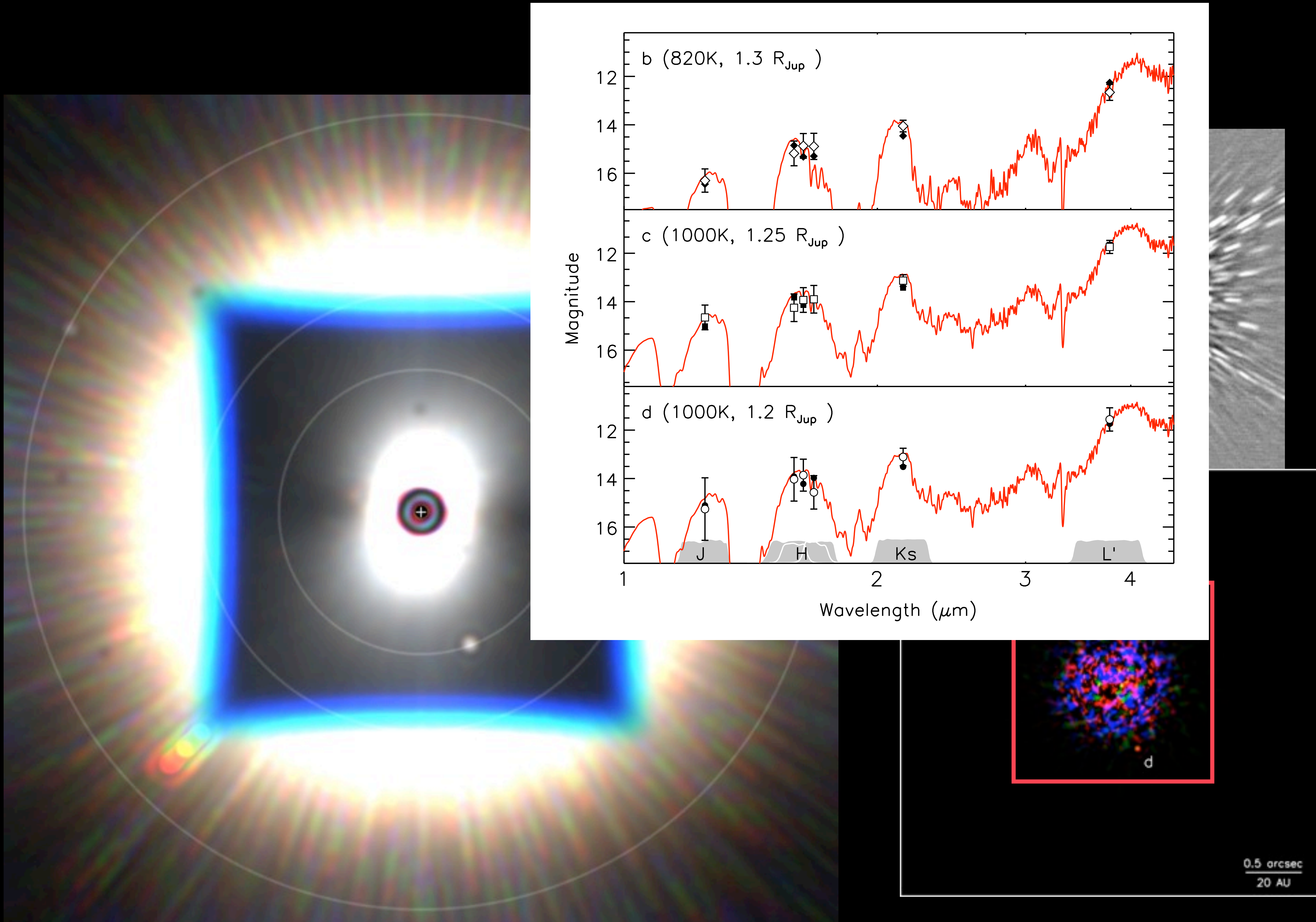
10s

10s





20 minutes (ADI)



10s

20 minutes (ADI)

- Direct exoplanet imaging - active on all 8-10m class telescopes equipped with an AO system (Gemini, Subaru, Keck, MMT & VLT).

- Gemini played a very important role in this field:
    - Development of a key observing strategy (ADI)
    - Lead one of the most complete imaging survey (GDPS)
    - Ongoing 2nd generation survey aimed at young/close more massive stars (IDPS)
    - Ongoing NICI survey
    - 2nd generation dedicated instrumentations: GPI (2011)

- Gemini commitment lead to the HR 8799 discovery, the first directly image multi-planet system. First at separations similar to the outer planets of our solar system + detected Keplerian orbital motion.

More to come...

Conclusions

- Direct exoplanet imaging - active on all 8-10m class telescopes equipped with an AO system (Gemini, Subaru, Keck, MMT & VLT).

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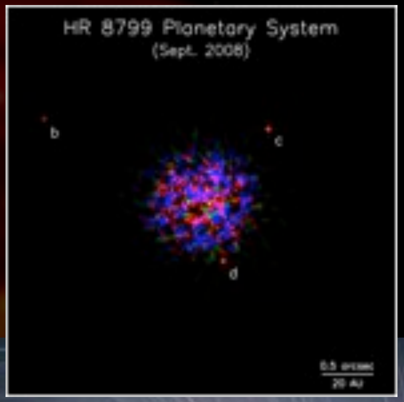


Conseil national de recherches Canada
National Research Council Canada

CRSNG NSERC

Fonds de recherche sur la nature et les technologies
Québec

NRC CNRC

Herzberg Institute of Astrophysics

Science at work for Canada

National Research Council Canada

Conseil national de recherches Canada

Canada

NRC CNRC

Herzberg Institute
of Astrophysics

Science
at work for
Canada

National Research
Council Canada

Conseil national
de recherches Canada

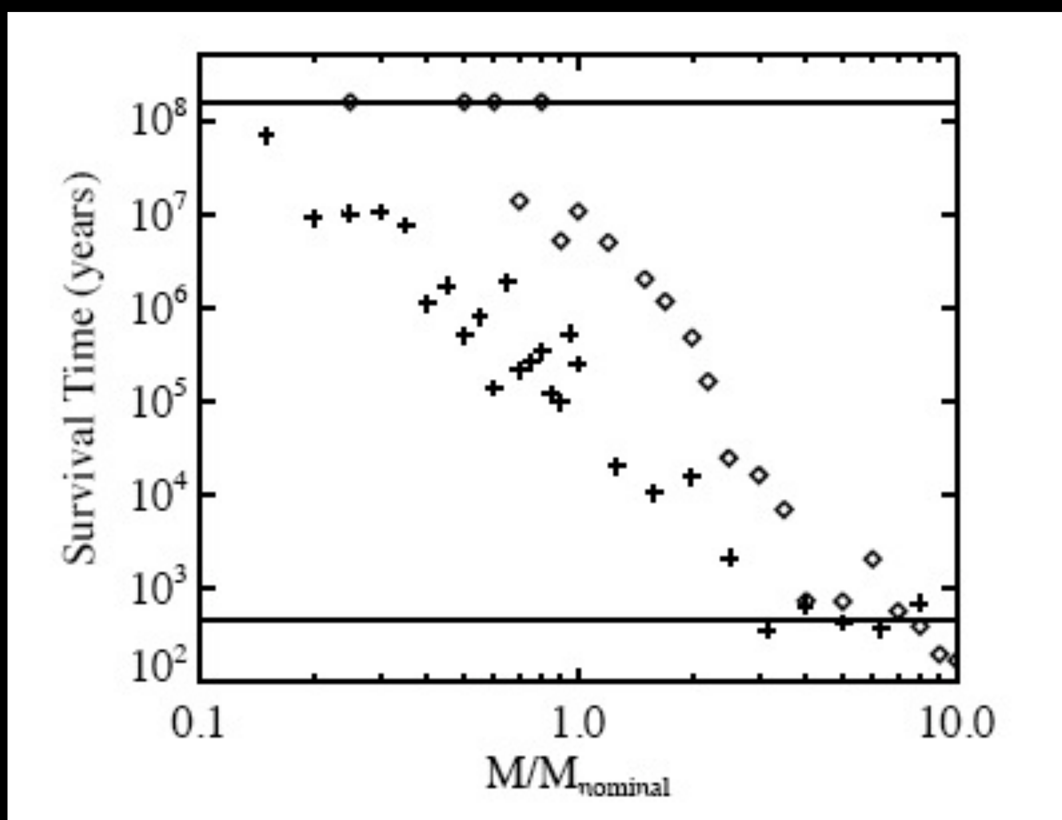
Canada

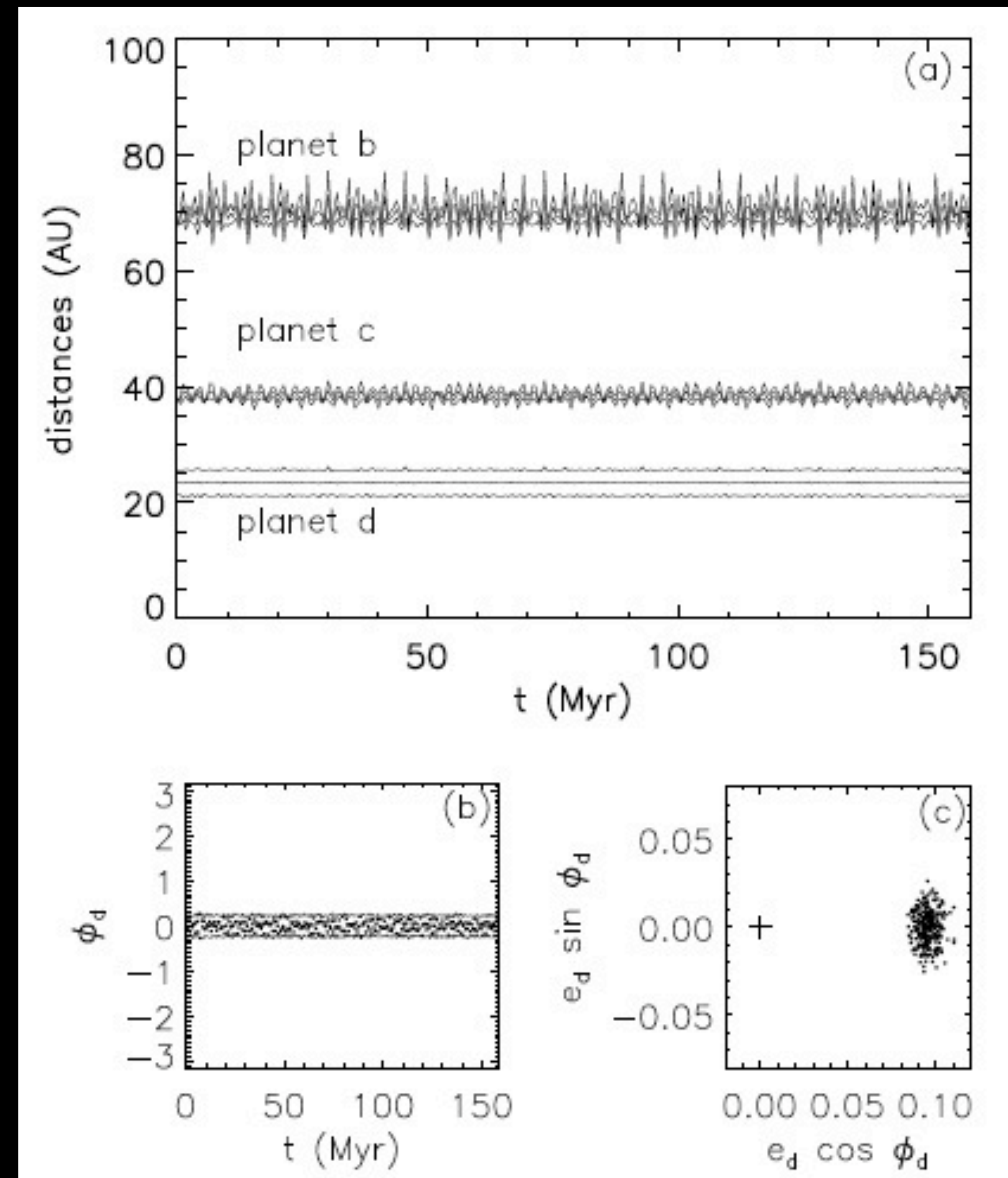
Dynamic Analysis

Fabrycky & Murray-Clay 2009

- Not perfectly face-on & not perfectly circular
- Non-resonance cases = masses need to be lower (< 2Mjup)
- 2:1 resonance for c & d: some cases stable for age
- 4:2:1 resonance: stable up to ~20 MJup.

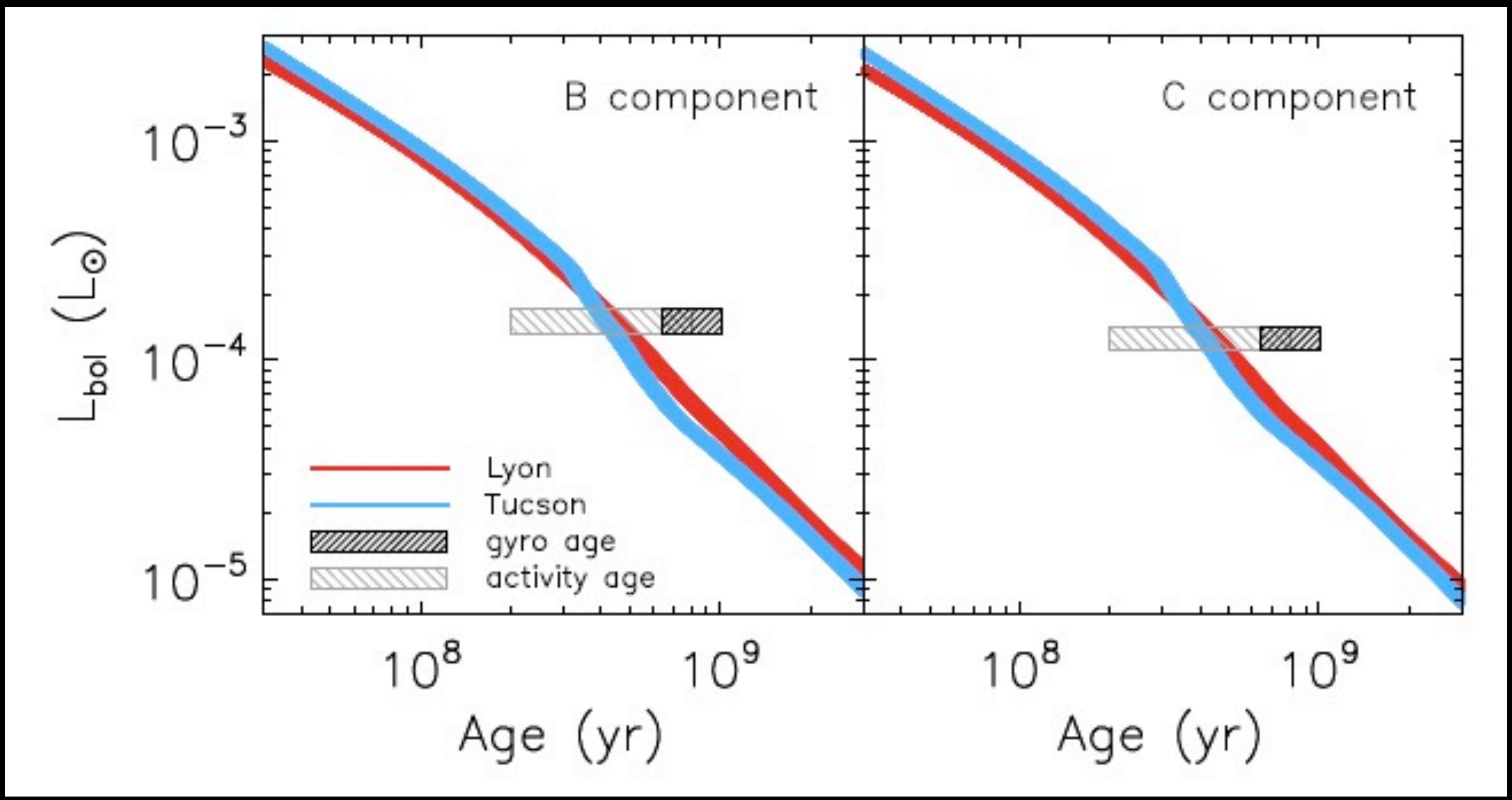
4:2:1 resonance





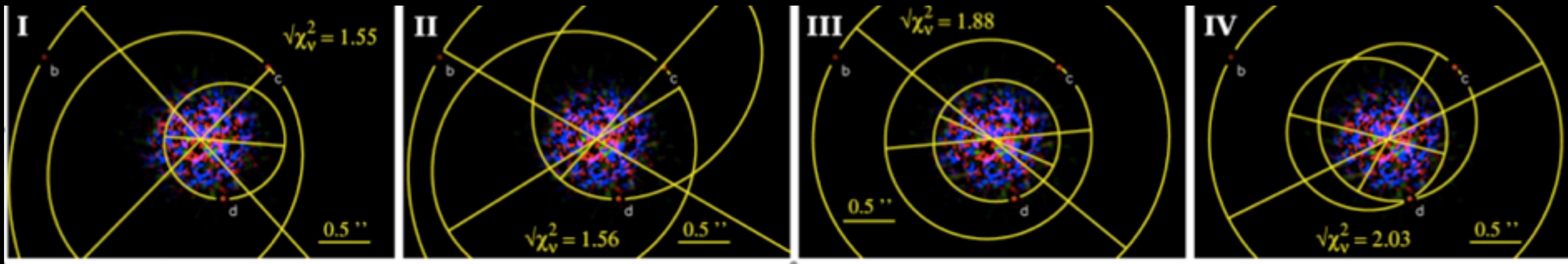
Younger age / model over predict mass / 4:2:1 resonance

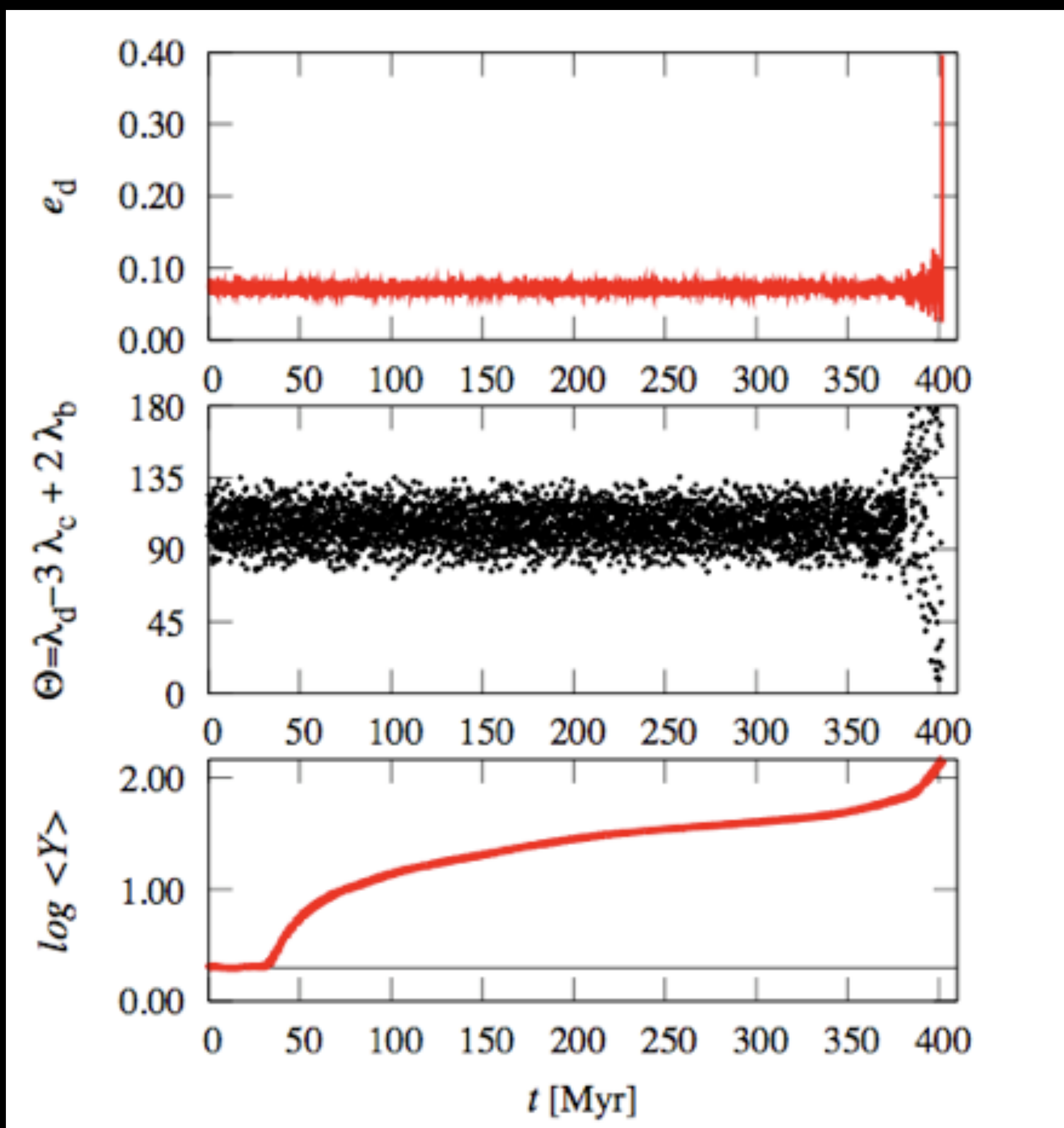
Do cooling tracks overestimate the mass?



Dupuy et al. 2008

Gozdziewski & Migaszewski 2009





4:2:1 resonance could be unstable in 400Myr

Planet d would be ejected from the system

Schmidt et al. 2009

TABLE 1. Observed properties of the directly imaged planet candidates.

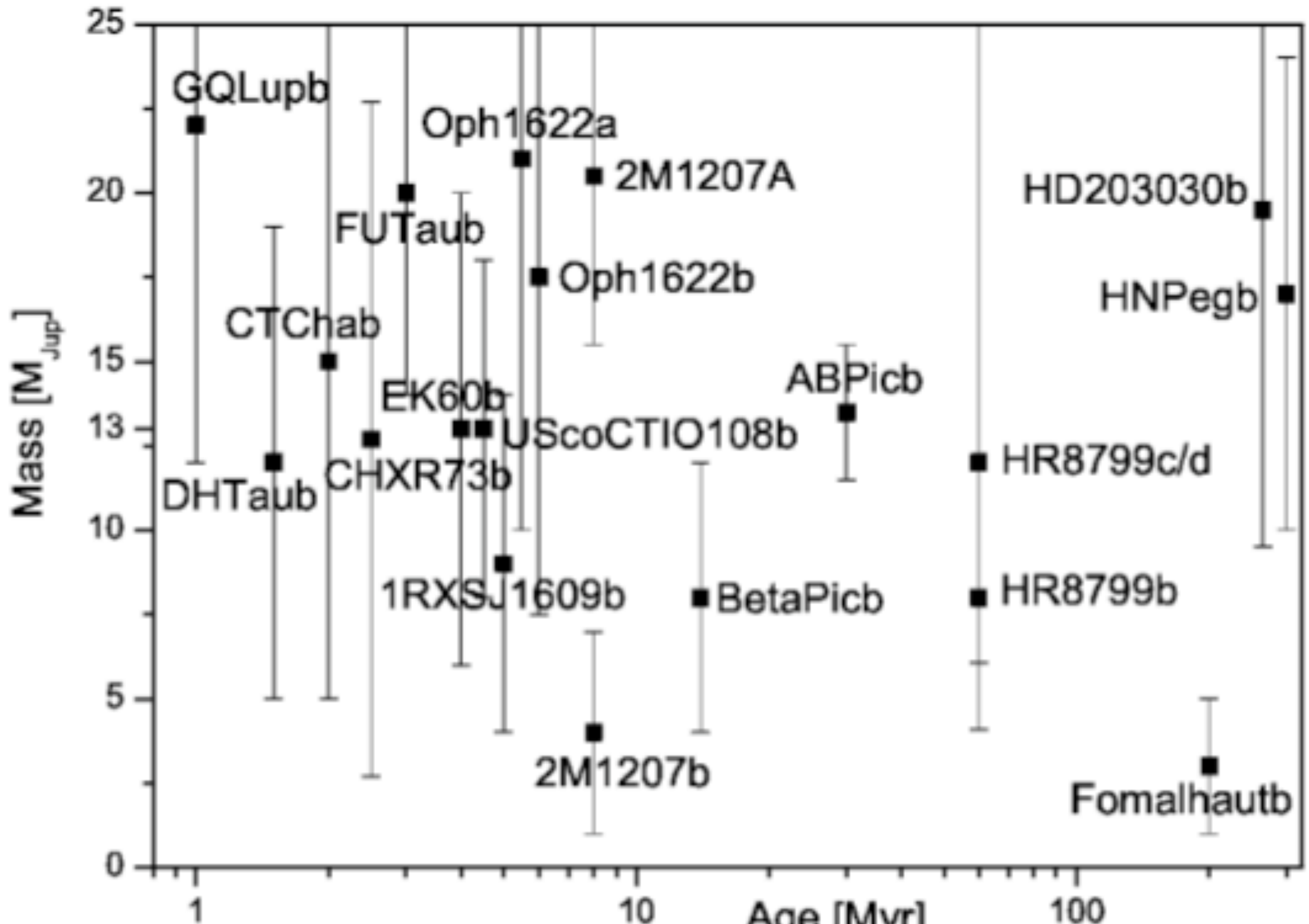
Object name	Luminosity $\log(L_{bol}/L_{\odot})$	Magnitude M_K [mag]	Temperature T_{eff} [K]	Age [Myrs]	References
Reference object (eSB2 brown dwarf - brown dwarf binary 2M0535):					
2M0535 A	-1.65 ± 0.07	5.29 ± 0.16	2715 ± 100	1 (0-3)	Stassun 2007
B	-1.83 ± 0.07	5.29 ± 0.16	2820 ± 105	1 (0-3)	Stassun 2007
Directly detected planet candidates:					
DH Tau b	-2.44		2750 ± 50	10	Itoh 2005
	-2.75 ± 0.10	8.31 ± 0.23		0.1-4	[17], [22]
GQ Lup b	-2.38 ± 0.25	7.67 ± 0.16	2650 ± 100	1-3	Neuh. 05, [32], [34]
2M1207 A	-2.76 ± 0.05	8.35 ± 0.05	2425 ± 160	5-12	Chauvin 05a, [11]
b	-4.75 ± 0.06	13.33 ± 0.12	1590 ± 280	5-12	[7], [16], [26], [31]
AB Pic b	-3.76 ± 0.06	10.85 ± 0.11	2040 ± 160	20-40	Chauvin 05b, [31]
Oph 1622 a	-2.61 ± 0.23	7.96 ± 0.56		5 (1-20)	Allers 2006, [2]
Oph 1622 b	-2.79 ± 0.23	8.42 ± 0.56		5 (1-20)	[8], [15]. [18]. [24]
SCR 1845 b	$M_H = 15.30 + 0.31 - 0.26$		(850)	$100\text{-}10^4$	Biller 2006
CHXR 73 b	-2.62 ± 0.21	8.00 ± 0.52	2600 ± 450	0.1-4	Luhman 2006, [33]
HD 203030 b	-4.69 ± 0.07	13.15 ± 0.14	late L	130-400	Metchev 2006
HN Peg b	-4.94 ± 0.04	13.80 ± 0.05	early T	100-500	Luhman 2007
USco 108 b	-3.14 ± 0.14	9.30 ± 0.34	(2350)	5 (1-10)	Béjar 2008
CT Cha b	-2.68 ± 0.21	8.83 ± 0.50	2600 ± 250	0.1-4	Schmidt 2008
1RXSJ1609 b	-3.57 ± 0.15	10.36 ± 0.35	early L	5 (1-10)	Lafrenière 2008
Fomalhaut b	≤ -6.5	$M_H \geq 23.5$		100-300	Kalas 2008
HR 8799 b	-5.1 ± 0.1	14.05 ± 0.08		20-1128	Marois 2008
c	-4.7 ± 0.1	13.13 ± 0.08		20-1128	[14]
d	-4.7 ± 0.1	13.11 ± 0.12		20-1128	[35]
β Pic b	$M_{L'} = 9.77 \pm 0.30$			8-20	Lagrange 2009
FU Tau b	-2.40 ± 0.09	7.44 ± 0.20		0.1-4	Luhman 2009
EK 60 b	-3.14 ± 0.18	9.28 ± 0.44		0.3-10	Kuzuhara (in prep.)

Schmidt et al. 2009

TABLE 2. Masses derived from evolutionary hot-start models.

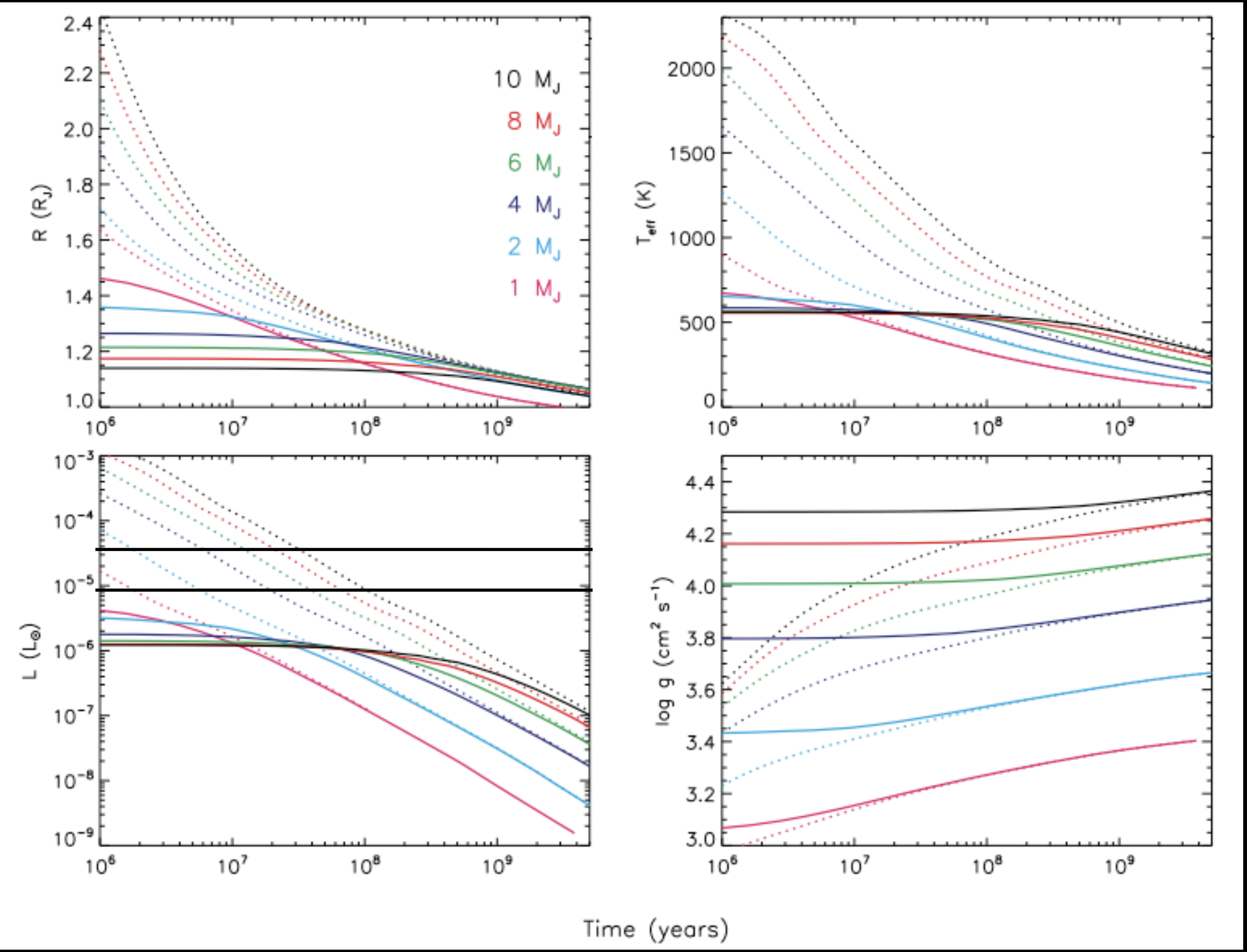
Object name	Burrows 97 (L, age)	Chabrier 00 (L, M_K, age)	Baraffe 03 (L, M_K, age)	Marley 07 ($\leq$ 10 Jup)	Baraffe 08 ($\geq$ 10 Myrs)	Wuchterl (Neuh05)
Reference object (eSB2 brown dwarf - brown dwarf binary 2M0335):						
2M0535 A	50 (45-60)	55 (30-60)	50 (45-80)			5-13
B	37 (33-46)	45 (40-50)	43 (40-65)			$\leq$ 13
Directly detected planet candidates:						
DH Tau b	14 (12-19)	11 (10-20)	10 (7-20)			5
GQ Lup b	19 (16-30)	22 (12-30)	17 (12-32)			1-5
2M1207 A	18 (18-19)	20 (17-23)	19 (15-21)			1-5
b	4 (3-5)	4 (2-5)	3 (1-4)	4 (3-5)	4	
AB Pic b	13.5 (13-14)	15 (11-20)	13 (11-20)			
Oph 1622 a	20 (14-55)	20 (10-40)	20 (9-40)			
Oph 1622 b	18 (10-40)	17 (7-25)	17 (7-23)			
SCR 1845 b		11.5-65	9-65			
CHXR 73 b	17 (12-23)	13 (10-25)	12 (8-25)			2-5
HD 203030 b	17 (12.5-30)	$\leq$ 30	18 (11-30)			
HN Peg b	17 (11.5-25)	17 (10-25)	17 (10-23)	$\geq$ 10		
USco 108 b	14 (7-17)	13.5 (5-17)	12 (5-18)			1-2
CT Cha b	17 (11-23)	13 (8-25)	12 (6-30)			2-5
1RXSJ1609 b	9.5 (4-14)	8 (3-13)	8 (3-12)	8 ($\geq$ 4)		
Fomalhaut b	$\leq$ 4		$\leq$ 3	$\leq$ 3	$\leq$ 2	
HR 8799 b	8 (4-36)	$\leq$ 35	6 (4-38)	7 ($\geq$ 3)	7 ($\geq$ 3)	
c	12 (6-50)	10 (6-46)	9 (6-48)	10 ($\geq$ 6)	$\geq$ 5	
d	12 (6-50)	10 (6-46)	9 (6-48)	10 ($\geq$ 6)	$\geq$ 5	
β Pic b		7.5 (6-10)	9 (6-12)			
FU Tau b	18 ($\leq$ 25)	20 (15-28)	17 (14-30)			
EK 60 b	14 (6-17)	13.5 (5-17)	12.5 (5-17)	$\geq$ 5		

Schmidt et al. 2009



+ SCR1845b, 100-10000 Myr, 9-65 M_{Jup}

Fortney et al. 2009



At 1 Gyr, b = 30 MJup and c/d = 40 MJup

But problematic...

- Inconsistent with several age indicators.
- At that age (1Gyr), models are though to be accurate no matter how they have formed.
- Stability models have problems with 7-10 MJup for 60 Myr - pointing the other way around that masses are probably equal or lower than our estimate.
- Probably impossible to have a stable 1 Gyr system that compact for that massive companions.

Very unlikely that the system is that old