Exoplanet Survey

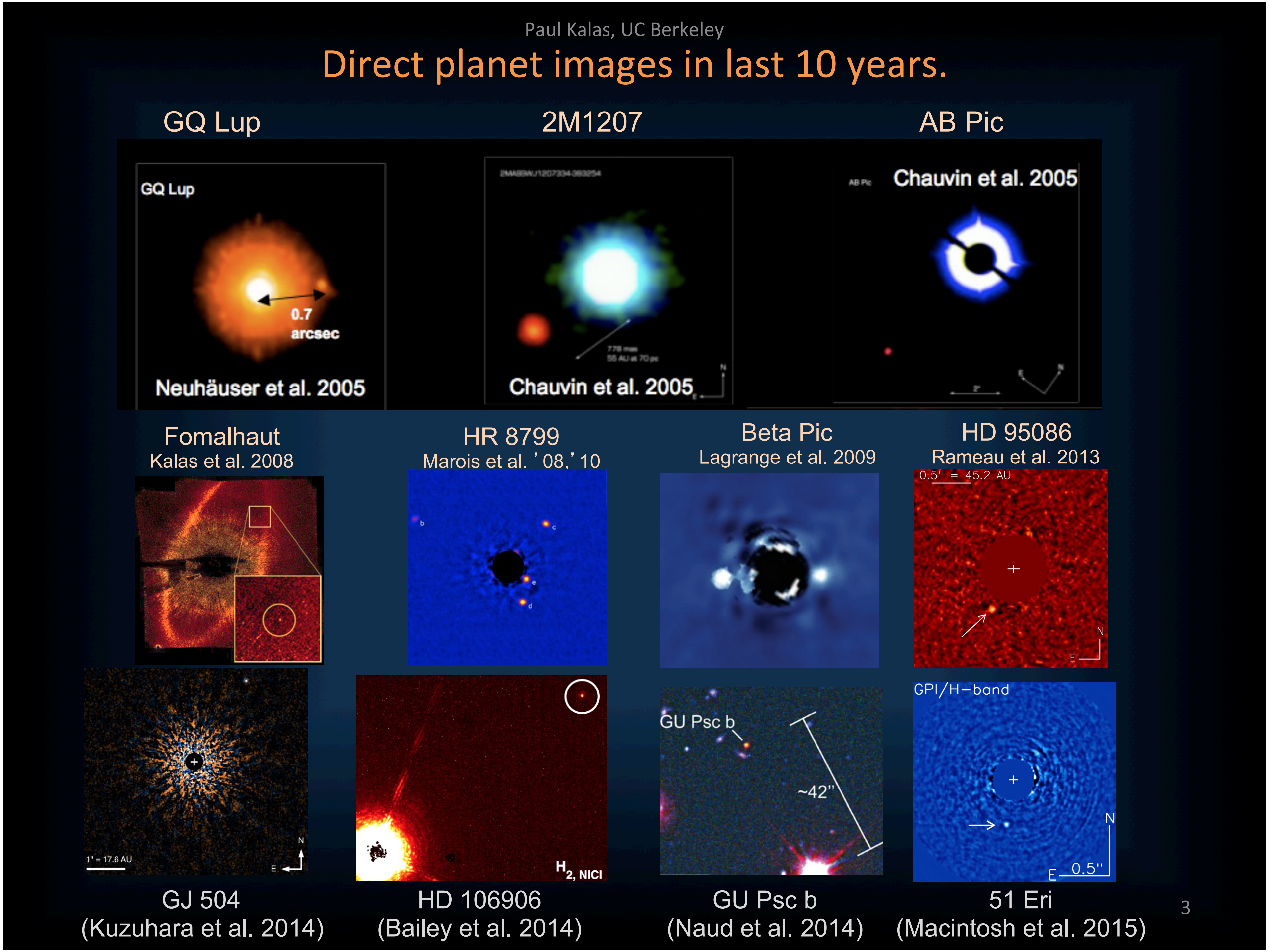
Ex Imago Mundi:
The current scientific revolution from imaging exoplanets

Paul Kalas (UC Berkeley)

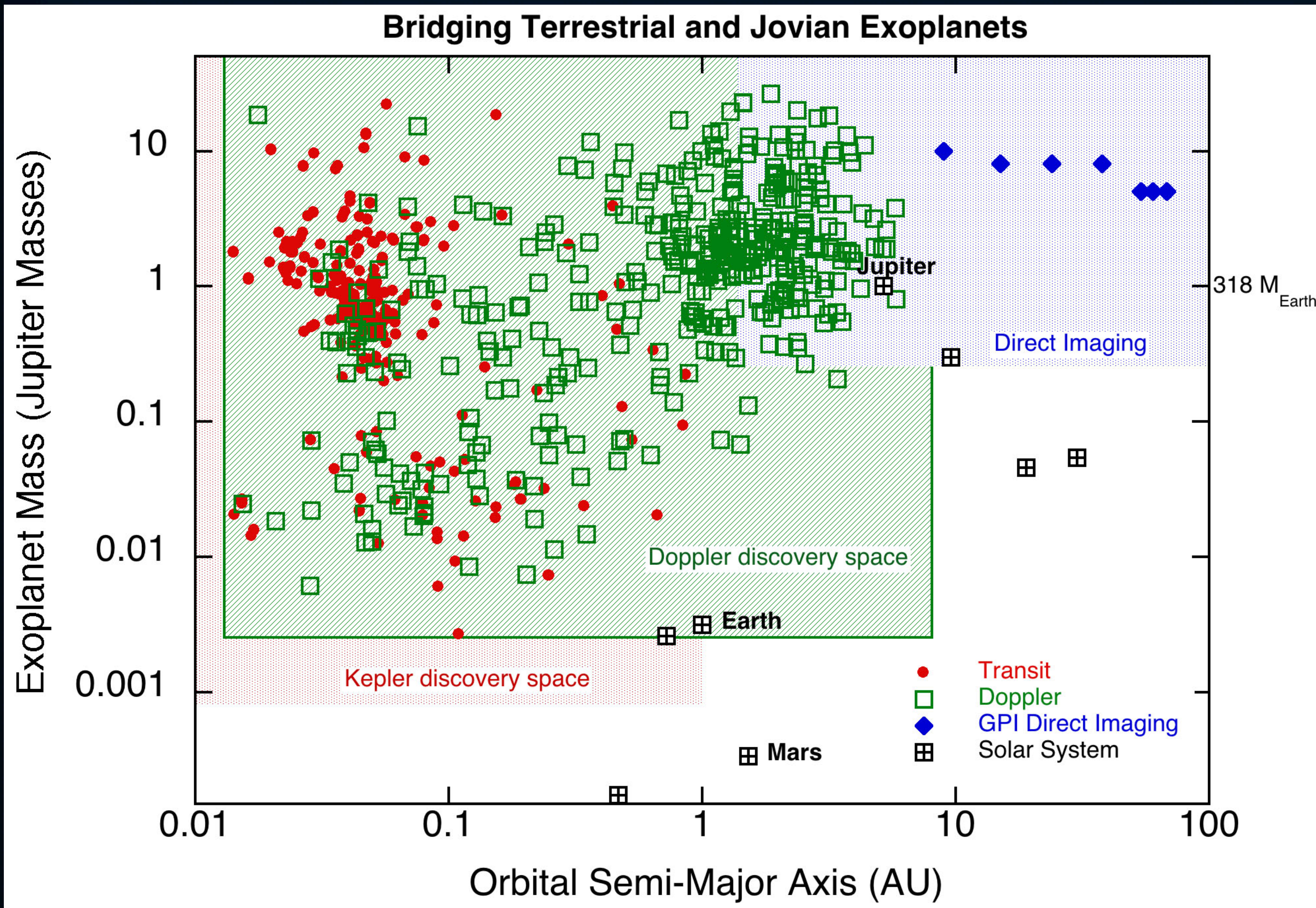
James Graham, Grant Kennedy, Brenda Matthews, Gaspar Duchene
Mark Wyatt, Mike Fitzgerald, Mark Booth, Jean-Francois Lestrade
Mark Clampin, Andrew Shannon, Jane Greaves
And the GPIES Consortium (PI Macintosh)

Outline

- Context and motivation for direct imaging
- Techniques
- Overview of the “revolution”
- Examples from the Gemini Planet Imager
  - Beta Pictoris
  - 51 Eri
  - HD 106906 and comparison to Fomalhaut

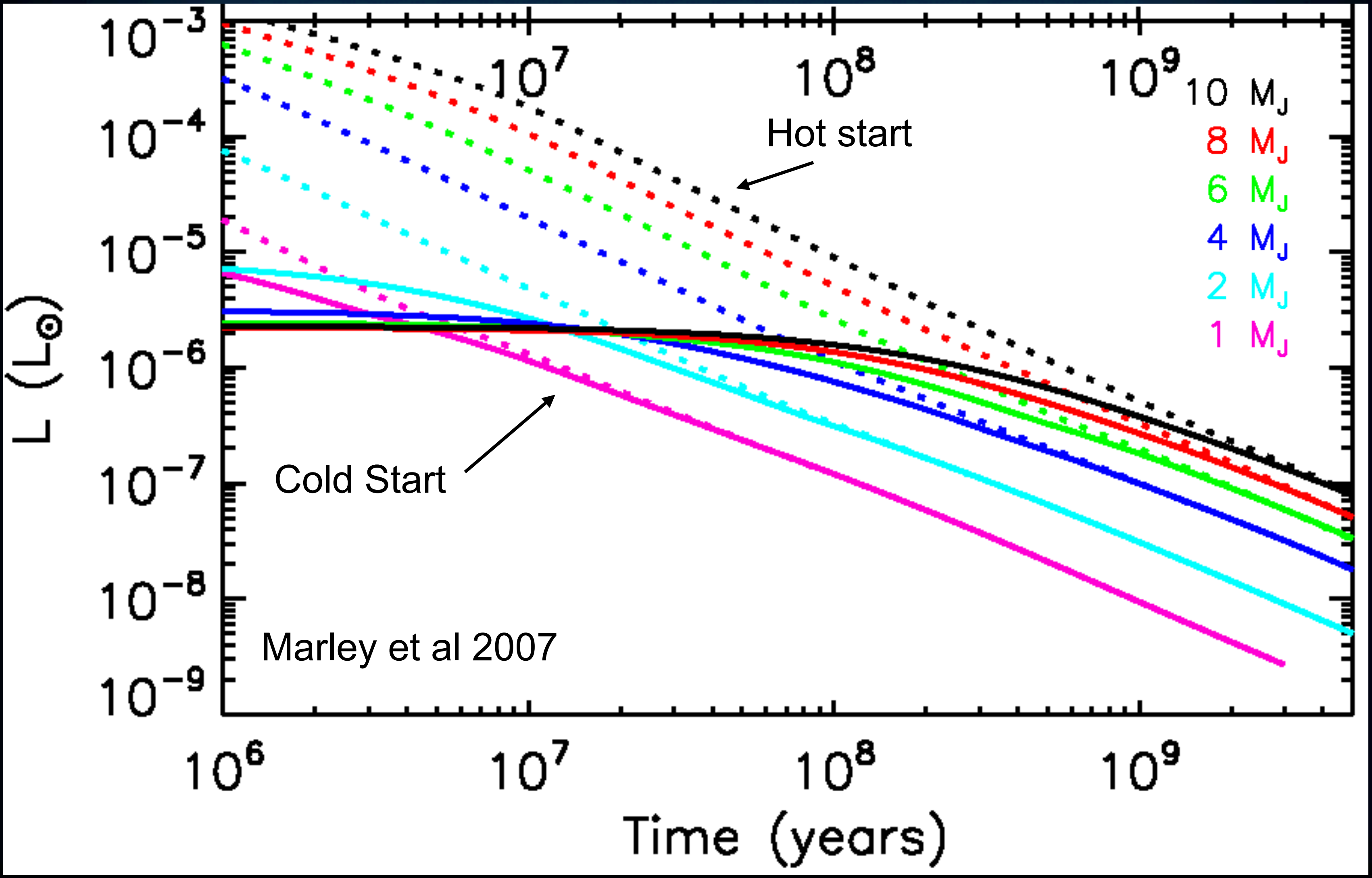

Paul Kalas, UC Berkeley
Direct planet images in last 10 years.
GQ Lup
2M1207
AB Pic
GQ Lup
0.7
arcsec
Neuhäuser et al. 2005
Chauvin et al. 2005
Chauvin et al. 2005
Fomalhaut
Kalas et al. 2008
HR 8799
Marois et al. ’08, ’10
Beta Pic
Lagrange et al. 2009
HD 95086
Rameau et al. 2013
0.5'' = 45.2 AU
N
E
1'' = 17.6 AU
N
E
H2, NICI
GU Psc b
~42''
GPI/H–band
N
E
0.5''
GJ 504
(Kuzuhara et al. 2014)
HD 106906
(Bailey et al. 2014)
GU Psc b
(Naud et al. 2014)
51 Eri
(Macintosh et al. 2015)
3

Unsolved Problem: Detections of planets beyond 5 AU



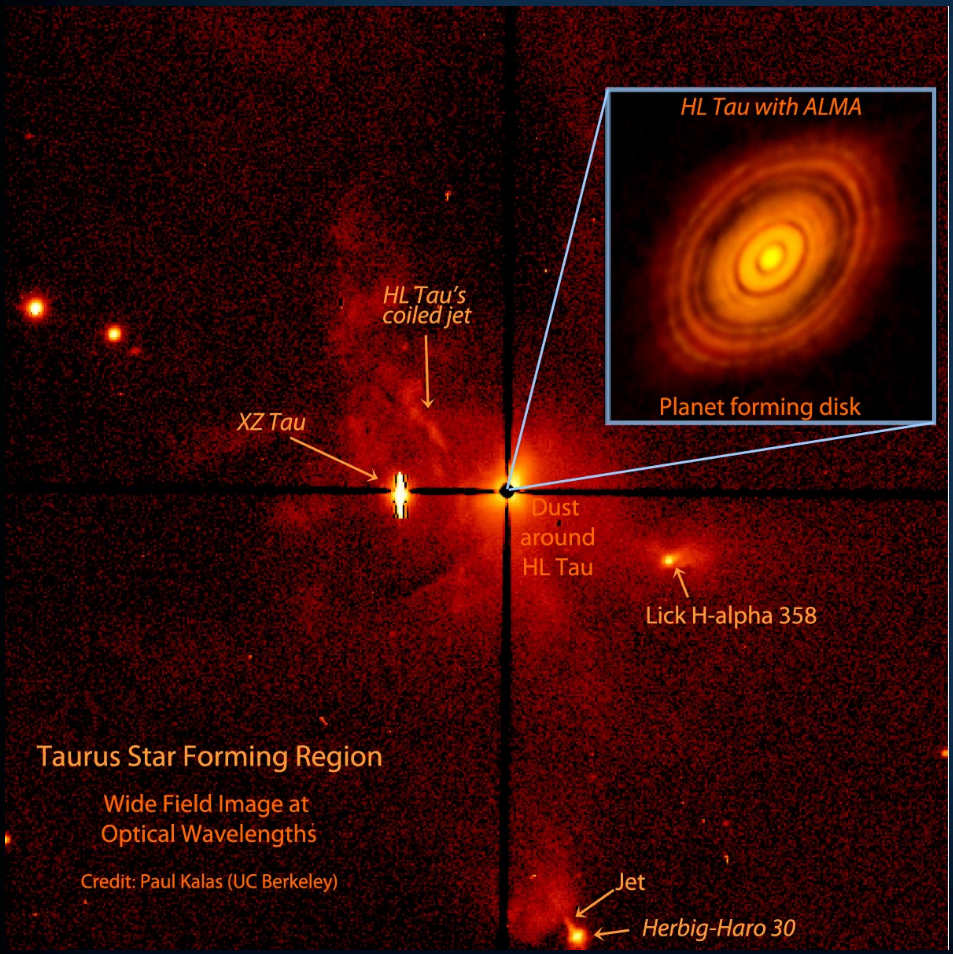
Mass estimate depends on models & age determination

How do planet form?
Hot Start vs. Cold Start

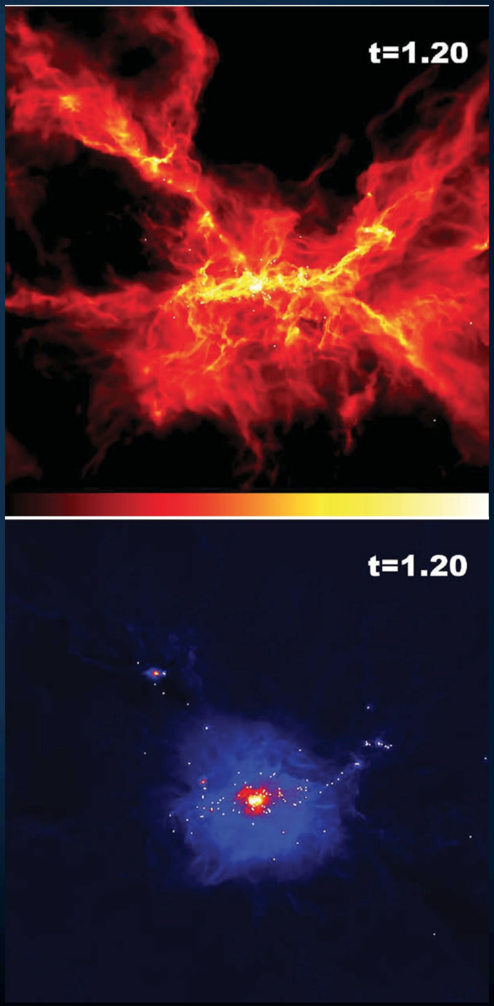


"Where do planets form?"

Form like our planets core accretion in a disk?
Yes, of course.



Form like stars by gravitational instability?
Open question



Bate et al 2012

Paul Kalas, UC Berkeley

Direct detection planet candidates

Host	SpT	Distance (pc)	Separation (AU)	Mass (M_J)	Age (Myr)	Reference
Fomalhaut	A3V	7.69	119	<1.0	440 ± 40	Kalas et al. '08
GJ 504	G0V	17.6	44	3 - 9	160 ± 100	Kuzuhara et al. '13
Beta Pic	A5V	19.3	8	7 - 12	8 - 20	Lagrange et al. '08
51 Eri	F0IV	29.4	13	2	20 ± 6	Macintosh et al. '15
HR 8799	A5V	39.4	68,38,24,15	5-13	30 - 160	Marois et al. '08,' 10
AB Pic	K2	47.3	258	11 - 16	30 – 40	Chauvin et al. '05
GU Psc	M3	48 ± 5	2000±200	11 ± 2	100±30	Naud et al. '14
2M1207	M8	52.4	54	2 – 7	5 – 12	Chauvin et al. '04
HD 95086	A8III	90 ± 3	55-60	5 ± 2	17 ± 4	Rameau et al. '13
HD 106906	F5V	92 ± 6	650	11 ± 2	13 ± 2	Bailey et al. '13
GQ Lup	K7	156 ± 50	100	8 – 36	2 ± 1	Neuhauser et al. '05
CT Cha	K7	160±30	440	11 - 37	<2	Schmidt et al. '08

Visible light: Fomalhaut, HD 106906, GQ Lup
Orbital motion: Fomalhaut, HR 8799, β Pic and GQ Lup
What is a planet? Formation matters?

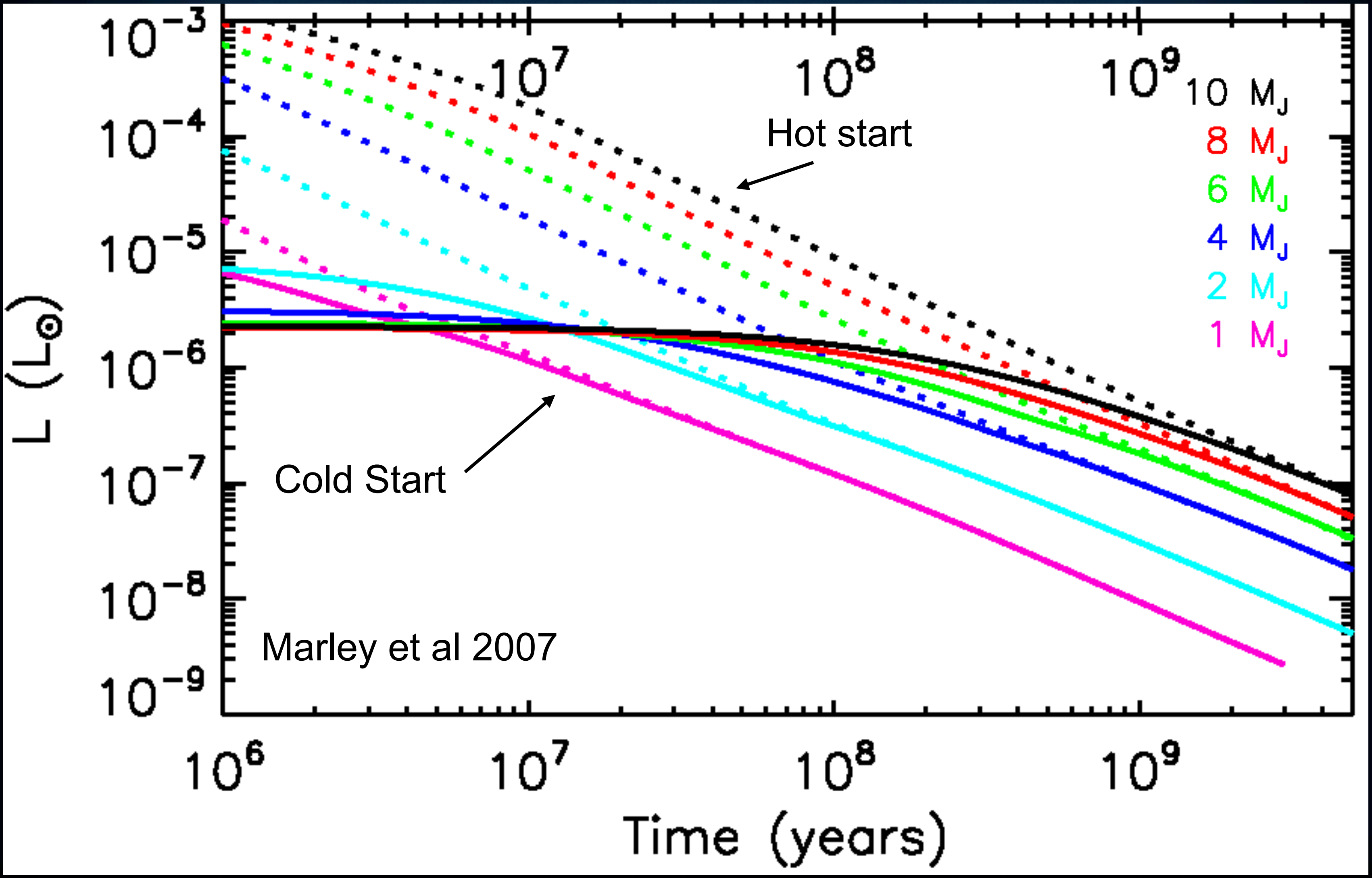
How do you increase the sample of directly imaged outer planets to better understand these issues?

Techniques

How do you separate the planet light from the starlight?

First trick – Target Selection

Observe young targets in the infrared because planets are more luminous at early times



Second Trick: Instrumentation

From Space: HST, Spitzer, Herschel

From the ground: Adaptive Optics

Southern Hemisphere:	Gemini Planet Imager VLT/SPHERE MagAO
Northern Hemisphere	Palomar 1640 Subaru HiCIAO+SCeXAO Large Binocular Telescope

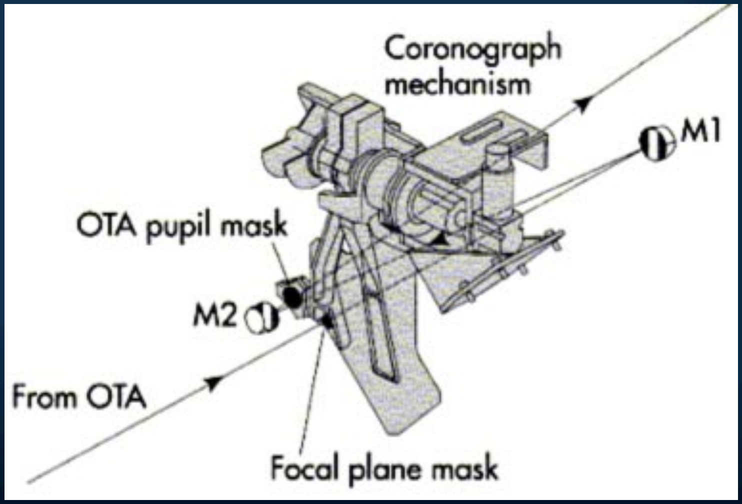
General Properties:

1) Extreme Strehl ratios, better than 85% at H
2) Extreme contrast; ΔH > 15 mag at 0.5" radius

HST Advanced Camera for Surveys

2002 STS-109

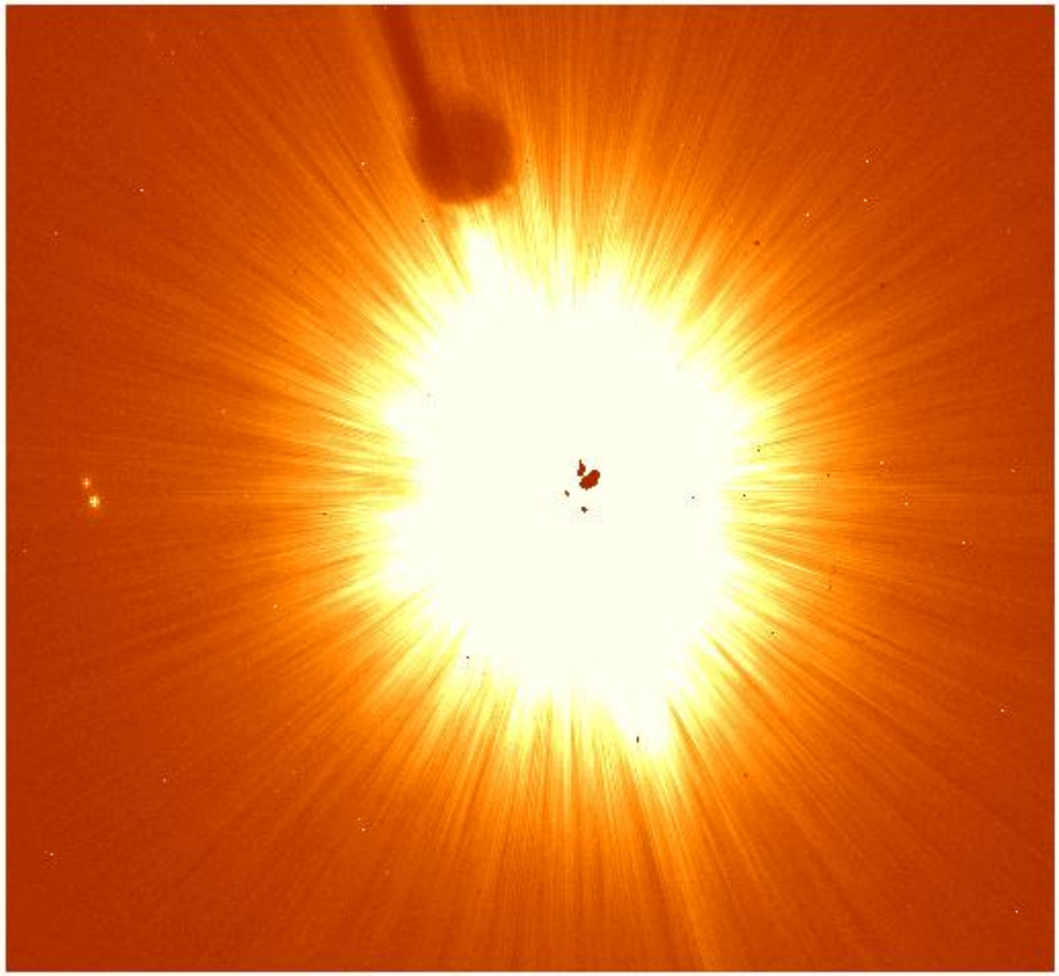
- ***High Resolution Channel (HRC)***
  - **Optimized for NUV band**
  - **26" x 29" field of view**
  - **0.025"/pixel plate scale**
  - **Stellar Coronograph mode**



Coronagraphy and Subtraction of the PSF

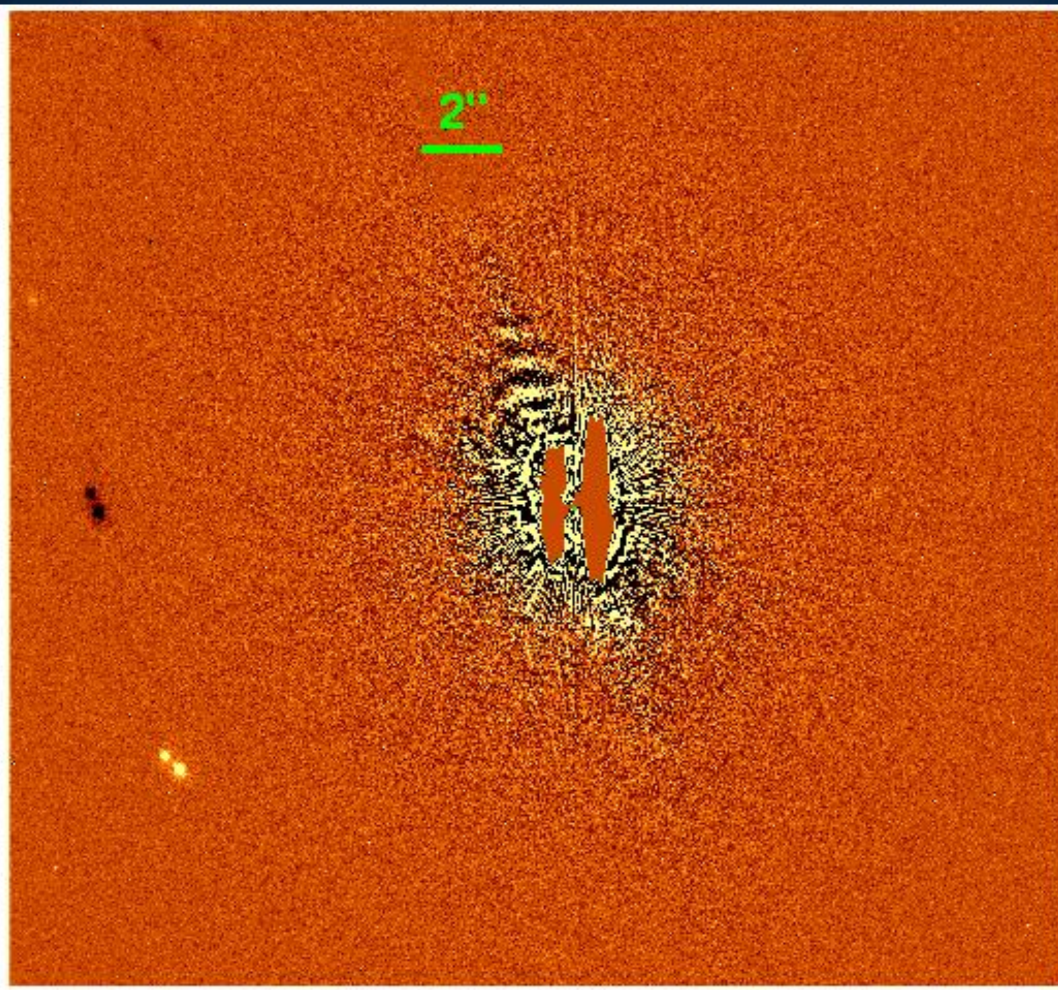
Advanced Camera optical coronagraph aboard HST.

ζ Lep, V=3.5, SpT=A2V, d = 22 pc, τ_{IR} = 0.1 x β Pic



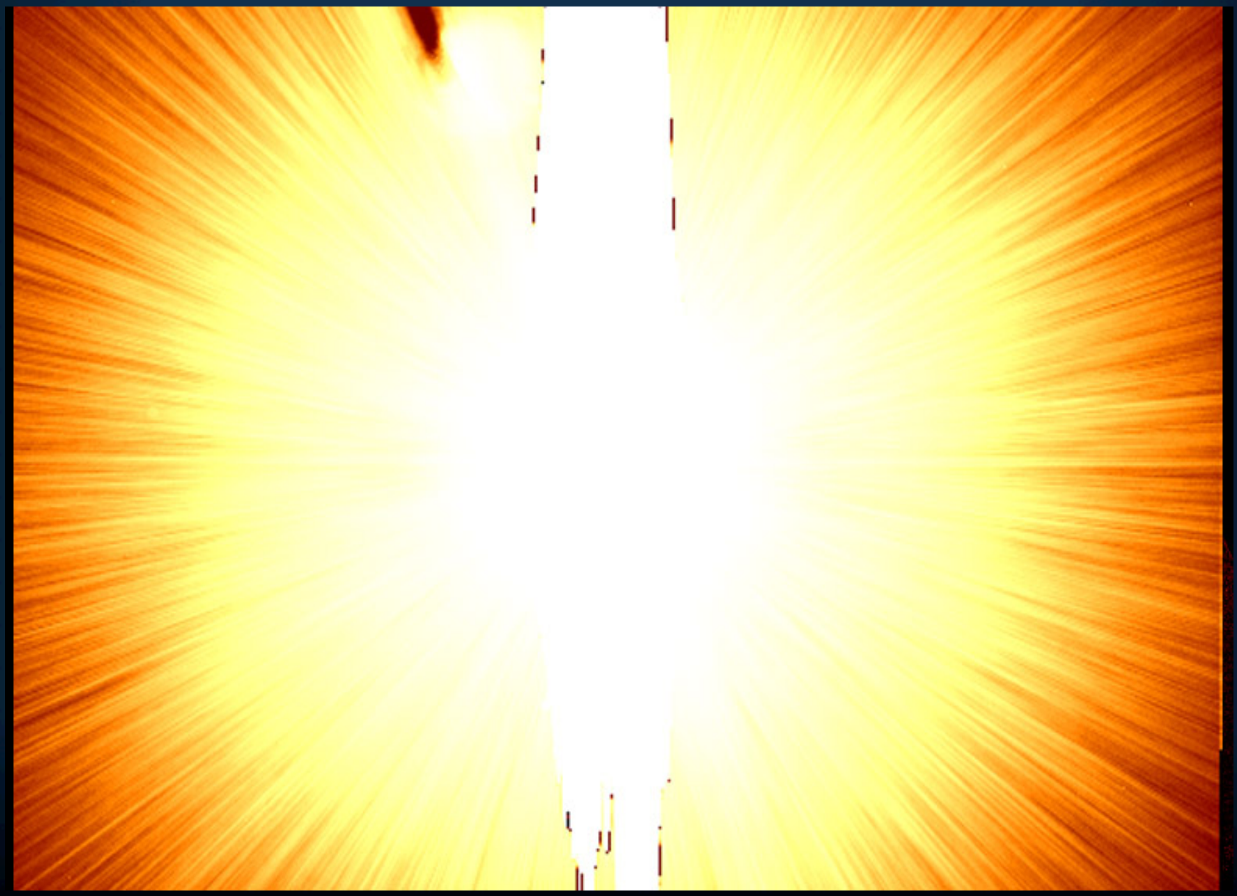
Telescope Roll with PSF Self Subtraction

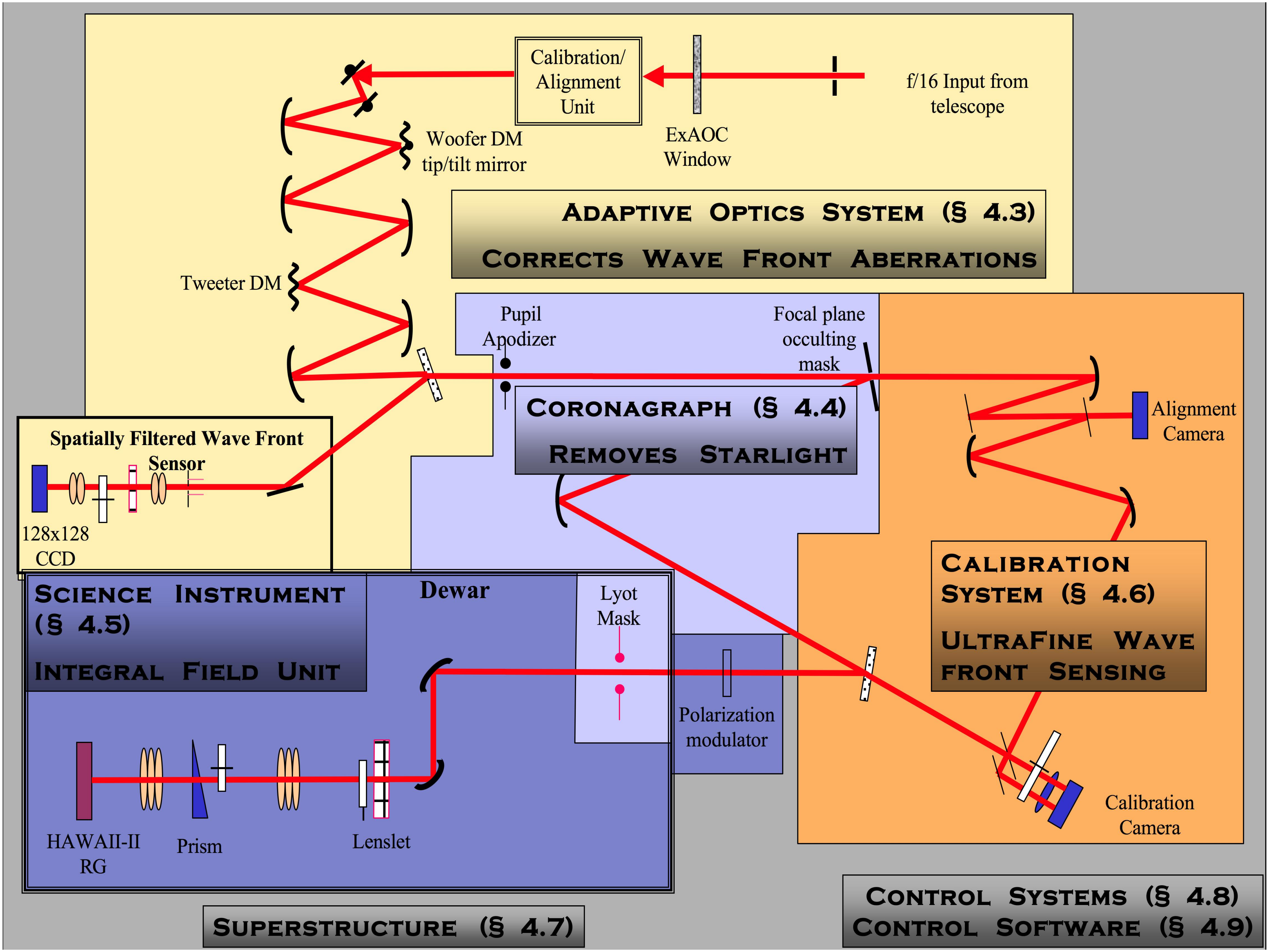
ζ Lep, V=3.5, SpT=A2V, d = 22 pc, τ_{IR} = 0.1 x β Pic



The final images make it look easy – not the case

Fomalhaut Imaged behind the occulting spot of the Advanced Camera for Surveys aboard the Hubble Space Telescope

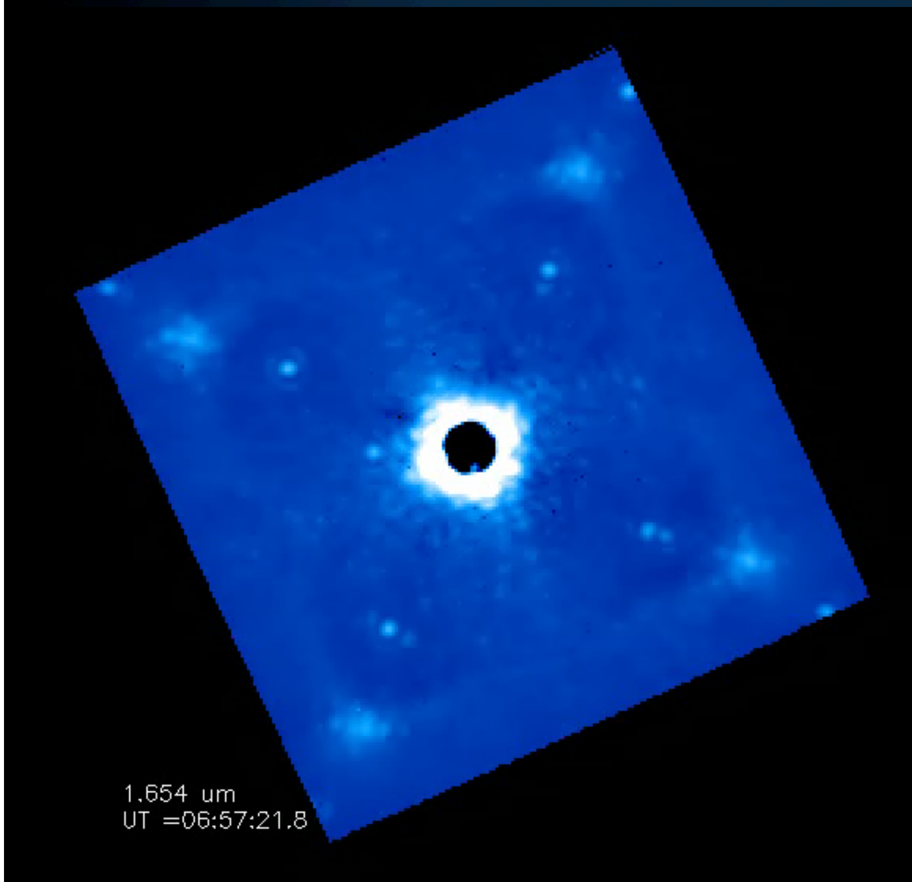


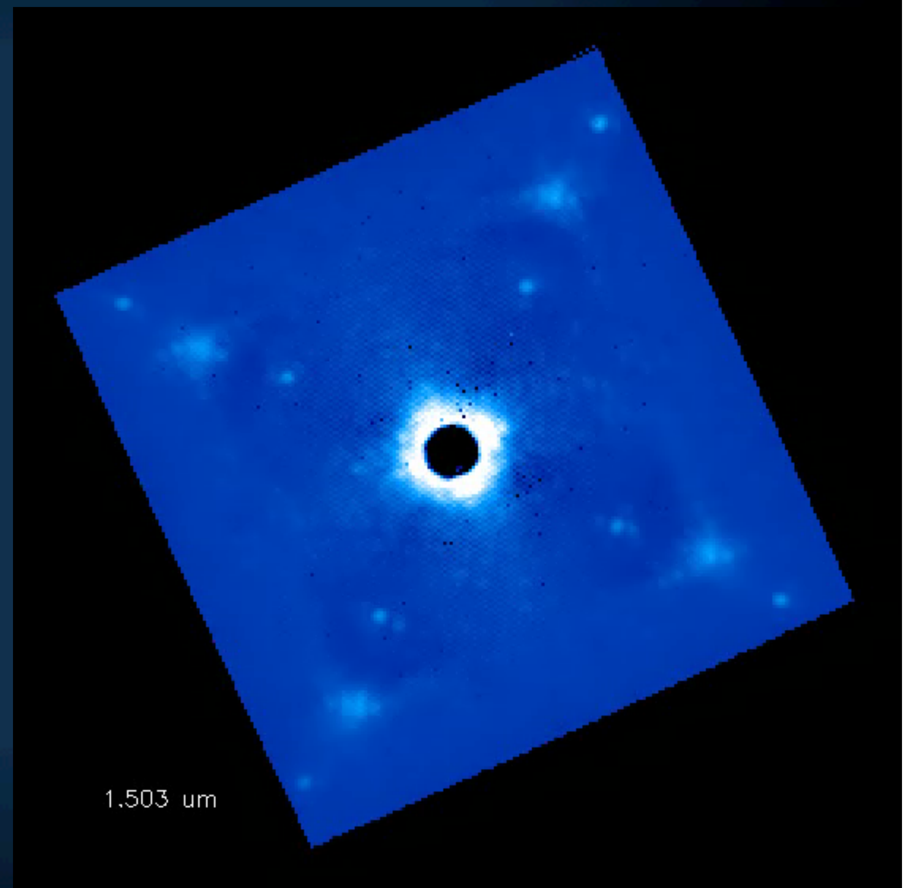

Calibration/ Alignment Unit
ExAOC Window
f/16 Input from telescope
Woofer DM tip/tilt mirror
Tweeter DM
Adaptive Optics System (§ 4.3)
Corrects Wave Front Aberrations
Pupil Apodizer
Focal plane occulting mask
Coronagraph (§ 4.4)
Removes Starlight
Alignment Camera
Spatially Filtered Wave Front Sensor
128x128 CCD
Calibration System (§ 4.6)
UltraFine Wave Front Sensing
Science Instrument (§ 4.5)
Integral Field Unit
Dewar
Lyot Mask
Polarization modulator
HAWAII-II RG
Prism
Lenslet
Calibration Camera
Superstructure (§ 4.7)
Control Systems (§ 4.8)
Control Software (§ 4.9)

β Pictoris b with the Gemini Planet Imager

Sky rotates in detector frame

No rotation, but increasing λ moves the speckles produced from the starlight

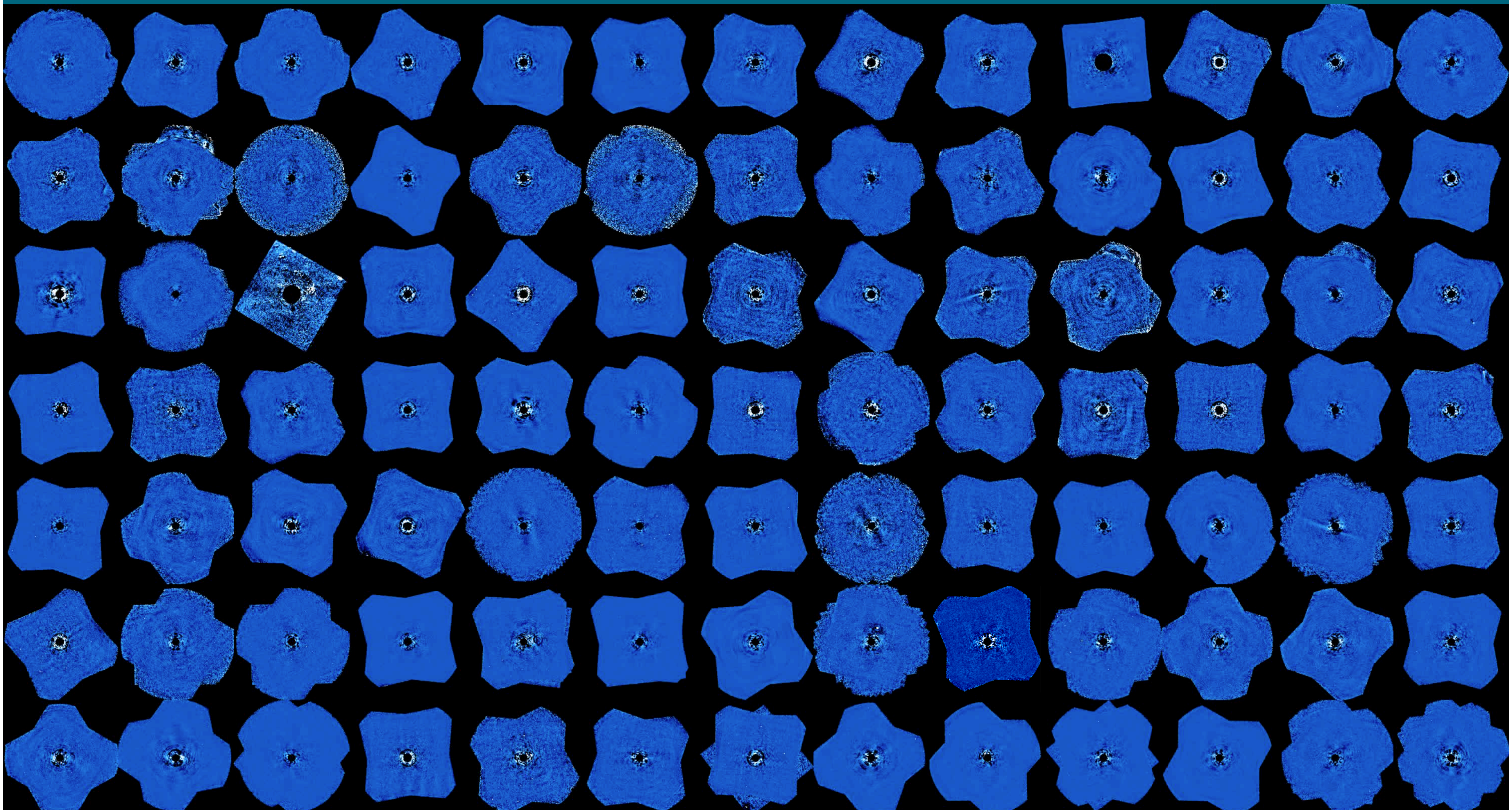




Figures by P. Ingraham

GPIES: “Spot the planet”

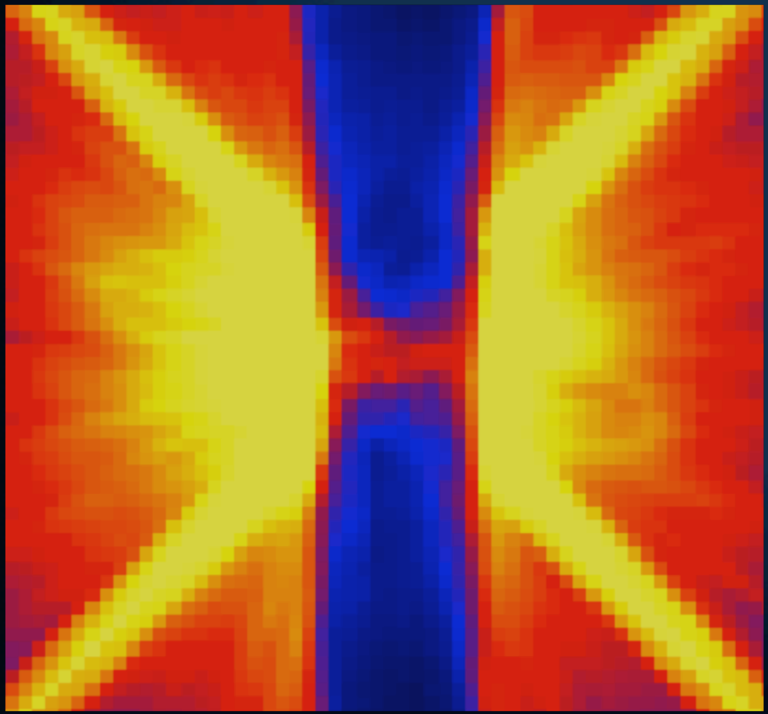
credit: Rob de Rosa (UC Berkeley)



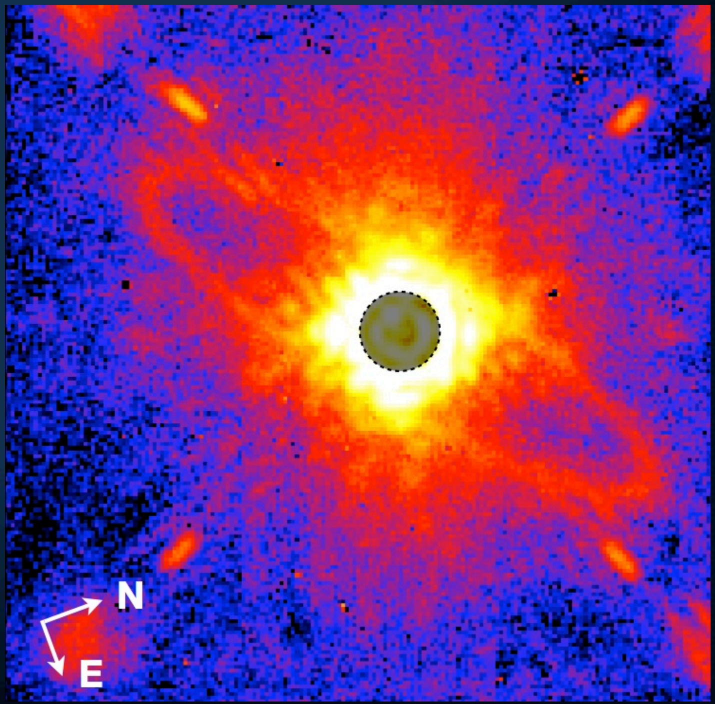
New Adaptive Optics Systems are Remarkable

Raw images in ~60 seconds integration.
No data processing.
No PSF subtraction.

Space: HST/STIS



Ground: Gemini Planet Imager



Perrin et al. 2014

Paul Kalas, UC Berkeley

Something like science fiction:

Live views of exoplanetary systems

Overview of the Revolution

Overview of the Revolution

From Space: HST, Spitzer, Herschel

From the ground: Extreme Adaptive Optics

Southern Hemisphere:	Gemini Planet Imager (Gemini South) SPHERE (VLT) MagAO (Magellan)
Northern Hemisphere	Palomar 1640 Subaru HiCIAO+SCeXAO Large Binocular Telescope

General Properties:

1) Extreme Strehl ratios, better than 85% at H
2) Extreme contrast; ΔH > 15 mag at 0.5" radius
3) Spectroscopy & polarimetry available
4) Anyone can apply for GPI & SPHERE
(but some targets are protected)

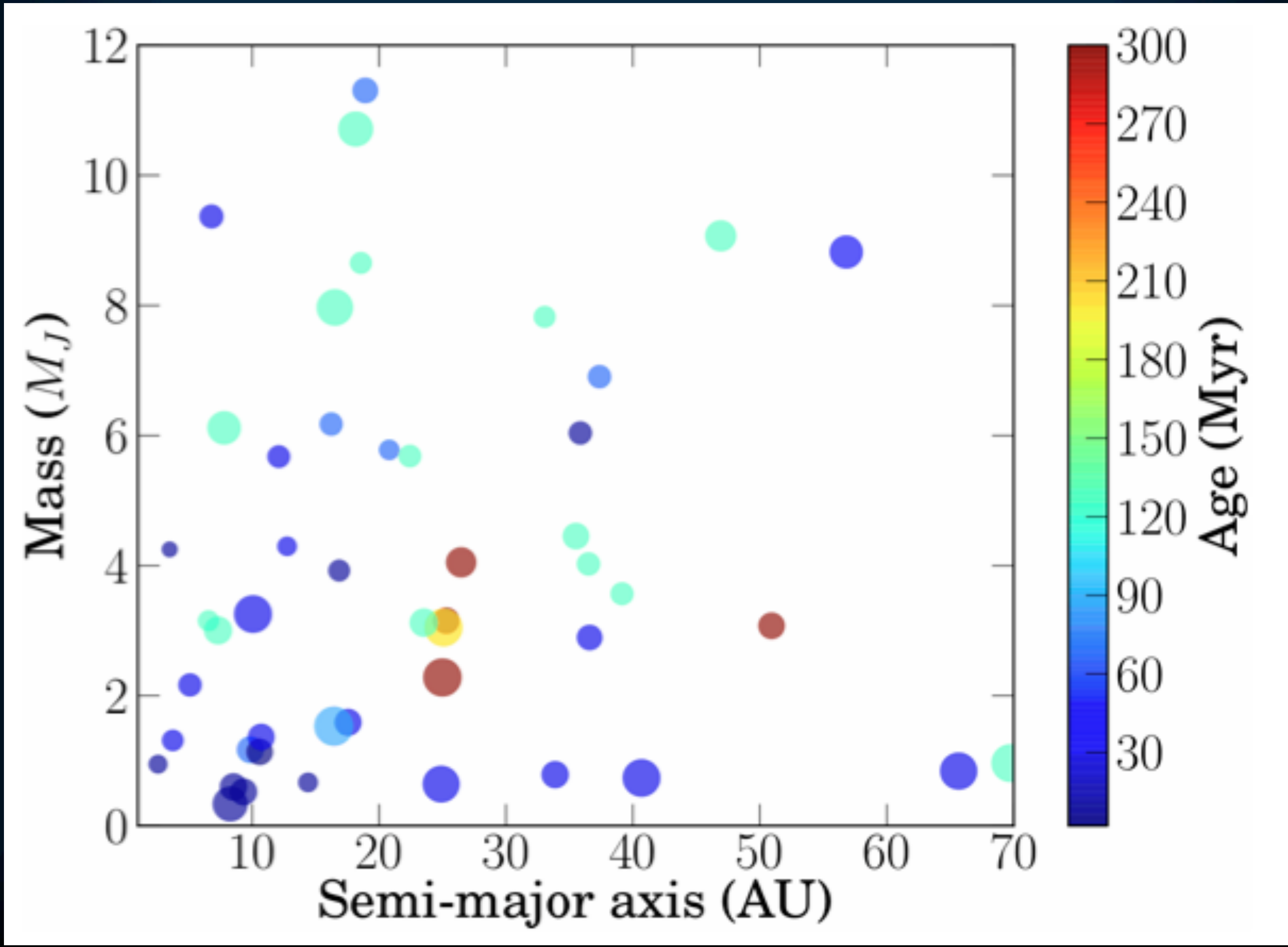
GPIES: GPI Exoplanet Survey

Scope: 890 hours awarded for a 600 star planet survey
PI: Bruce Macintosh (Stanford)
Project Scientist: James Graham (UC Berkeley)
Debris Disk Leads: Paul Kalas (UC Berkeley) & Mike Fitzgerald (UCLA)

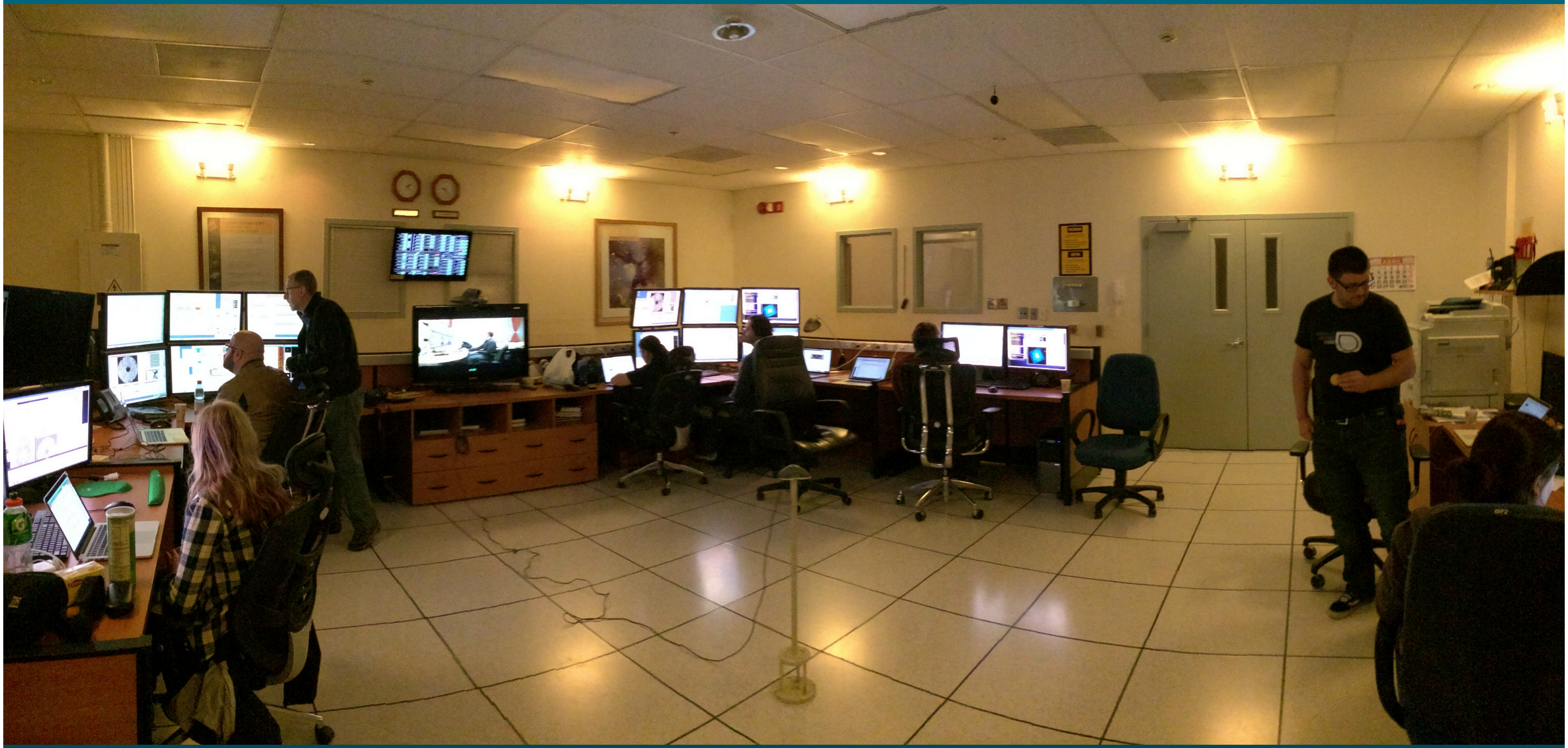
1. Produce the first imaging census of giant planet populations in the 5-50 AU range
2. Elucidate the formation pathways of Jovian Planets
3. Understand the atmospheres of young Jovians
4. Detect dusty debris disks and understand the dynamical evolution with respect to planetary architecture.

GPIES: GPI Exoplanet Survey

Expected detection rate: 4% - 8% (cold vs. hot start) or 25-50 exoplanets

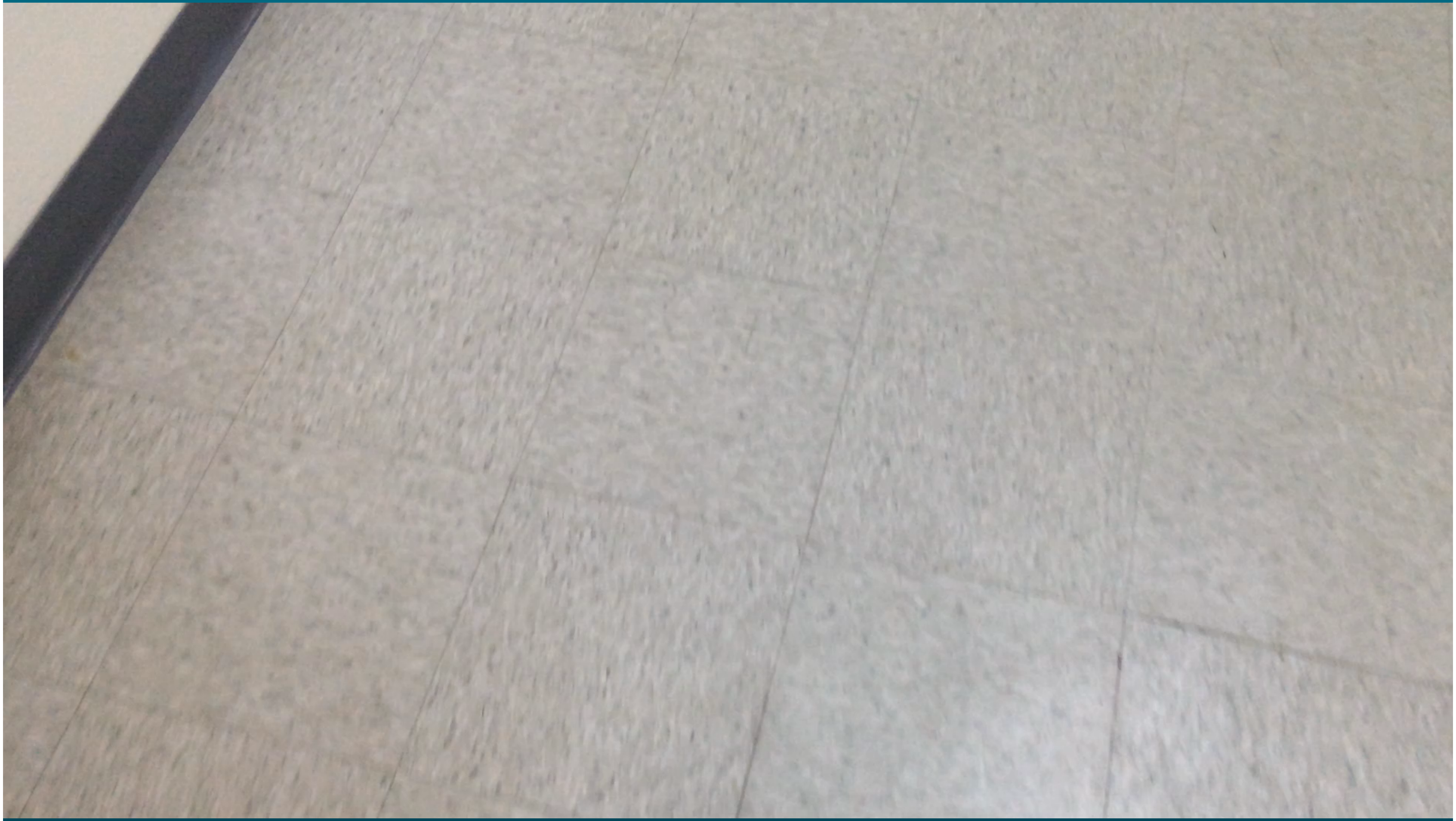


Gemini Planet Imager



Early May 2015 Campaign Observing Run

Commissioning finished early 2014
Just one small bug



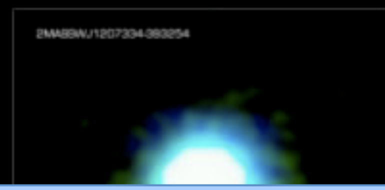
Examples from the Gemini Planet Imager

Example #1: β Pic b

Direct planet images in last 10 years.

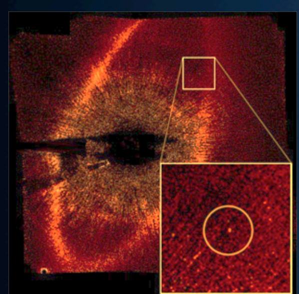
GQ Lup

2M1207



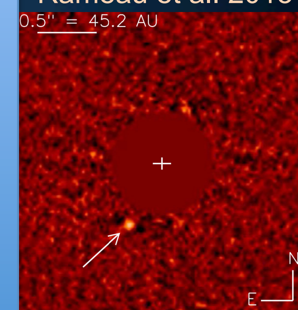
AB Pic

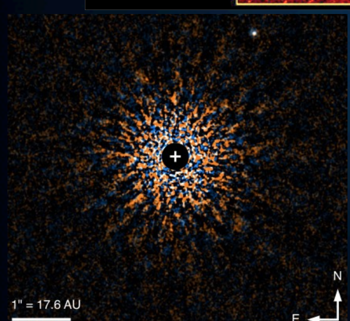
Fomalhaut
Kalas et al. 2008



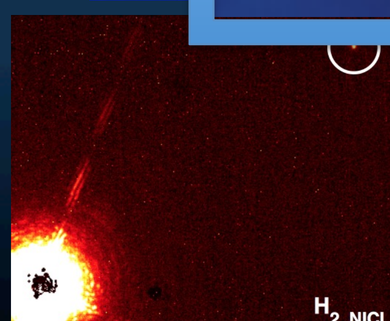
H
Marois

HD 95086
Rameau et al. 2013

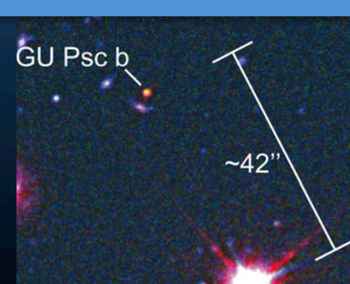




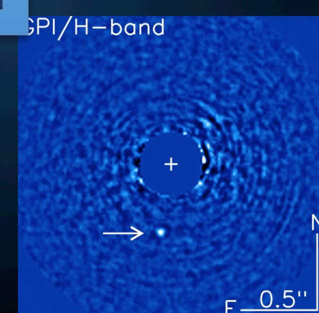
GJ 504
(Kuzuhara et al. 2014)



HD 106906
(Bailey et al. 2014)



GU Psc b
(Naud et al. 2014)



51 Eri
(Macintosh et al. 2015)

10 second introduction to β Pic

- First "planetary system" ever detected by direct imaging (1984) – an extended debris disks seen in scattered light.
- A5V star
- 20 Myr old
- 19 pc away
- Debris disk is asymmetric – evidence for planetary perturbations.

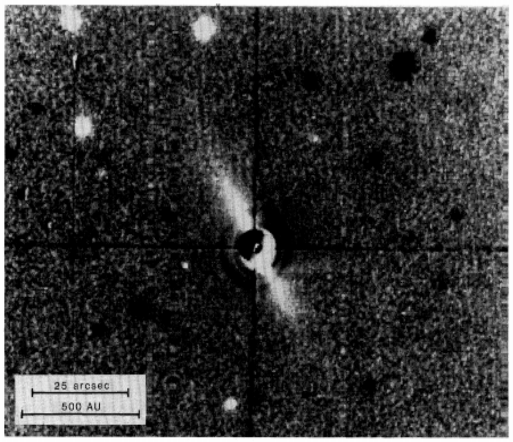
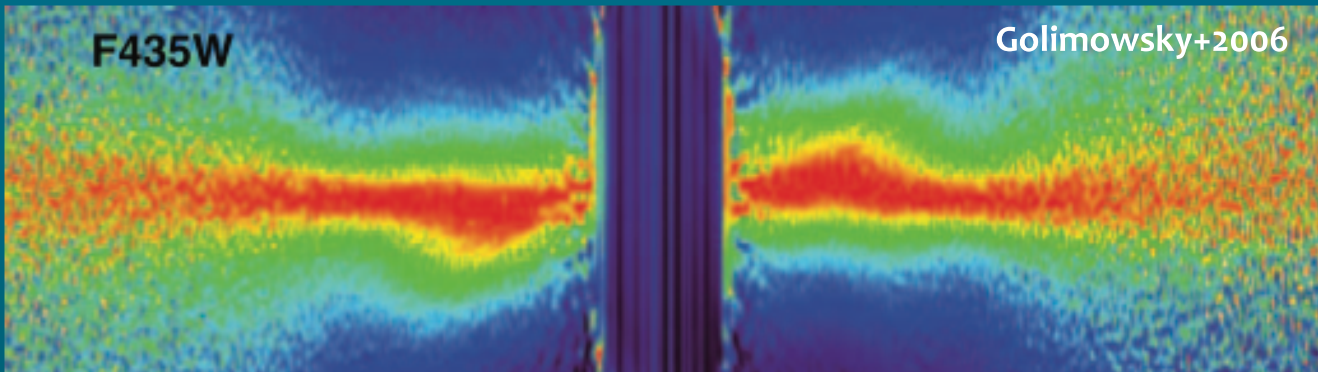
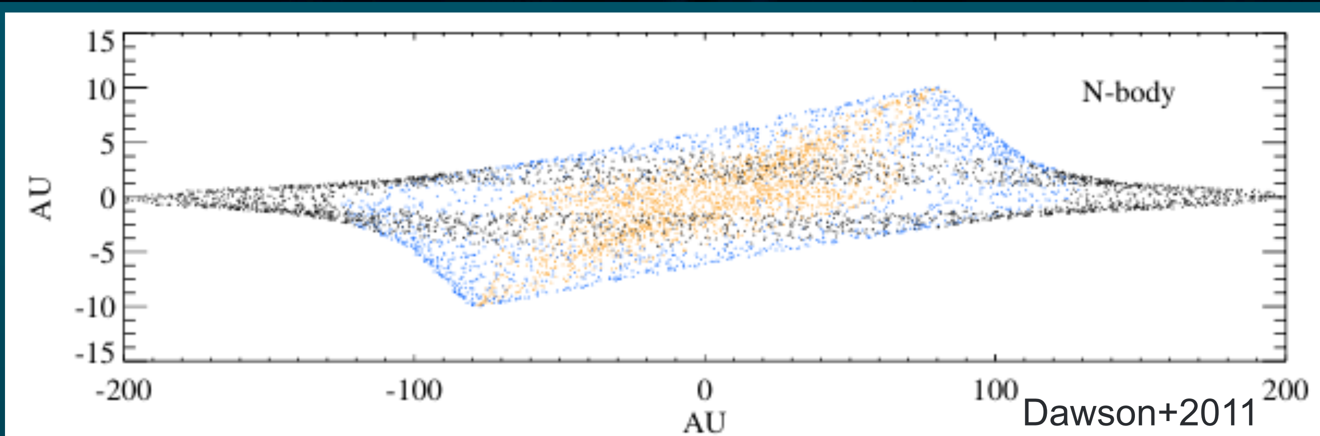


Fig. 1. Ratio image (β Pictoris divided by α Pictoris) showing the edge-on circumstellar disk extending 25 arcsec (400 AU) to the northeast and southwest of the star, which is situated behind an obscuring mask. North is at the top. The dark halo surrounding the mask is caused by imperfect balance in the ratioing process. For further explanation, see text.

Smith & Terrille 1984





Dynamical Question

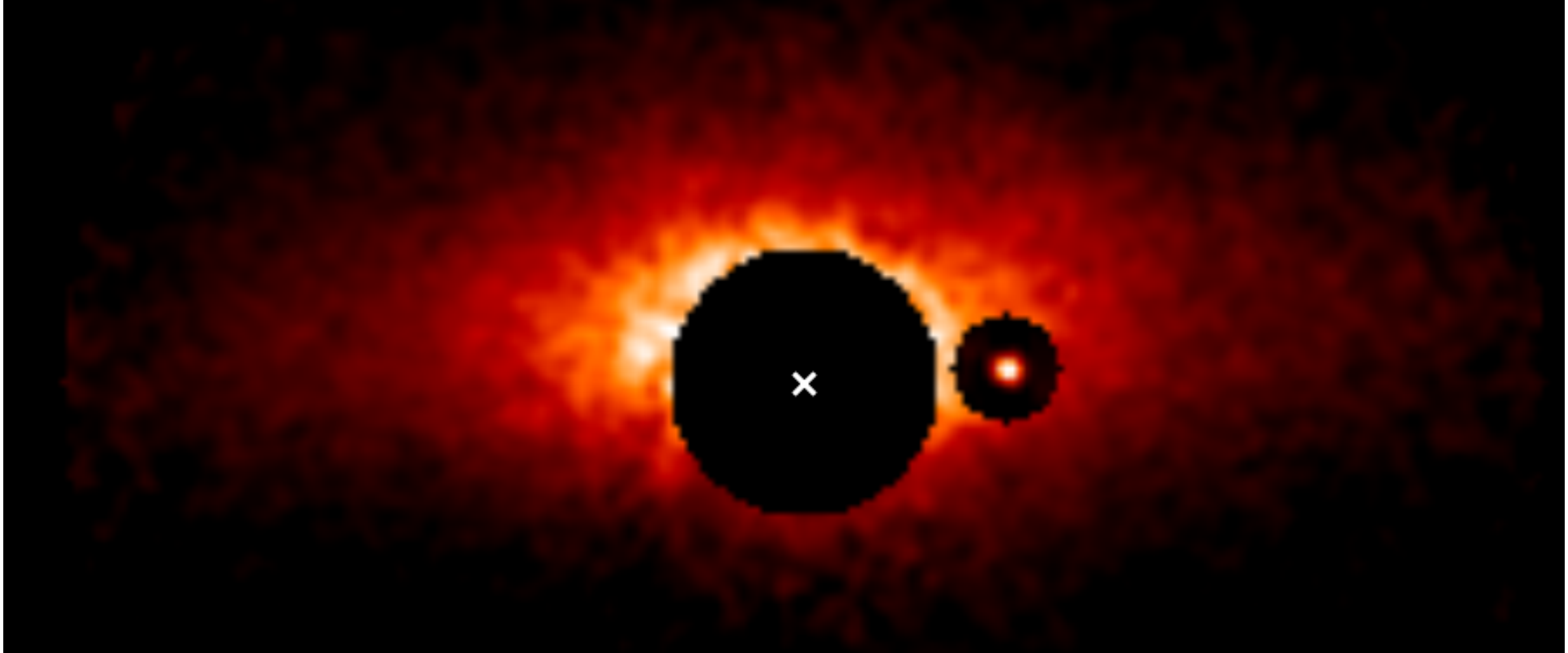
The disk is seen edge-on, but there is an apparent vertical warp at ~80 AU.

The planet was discovered recently, but the astrometry is difficult, and there is a debate on its orientation relative to the disk.

Dynamical models suggest an inclined planet can produce the warp, but is β Pic b the perturber?

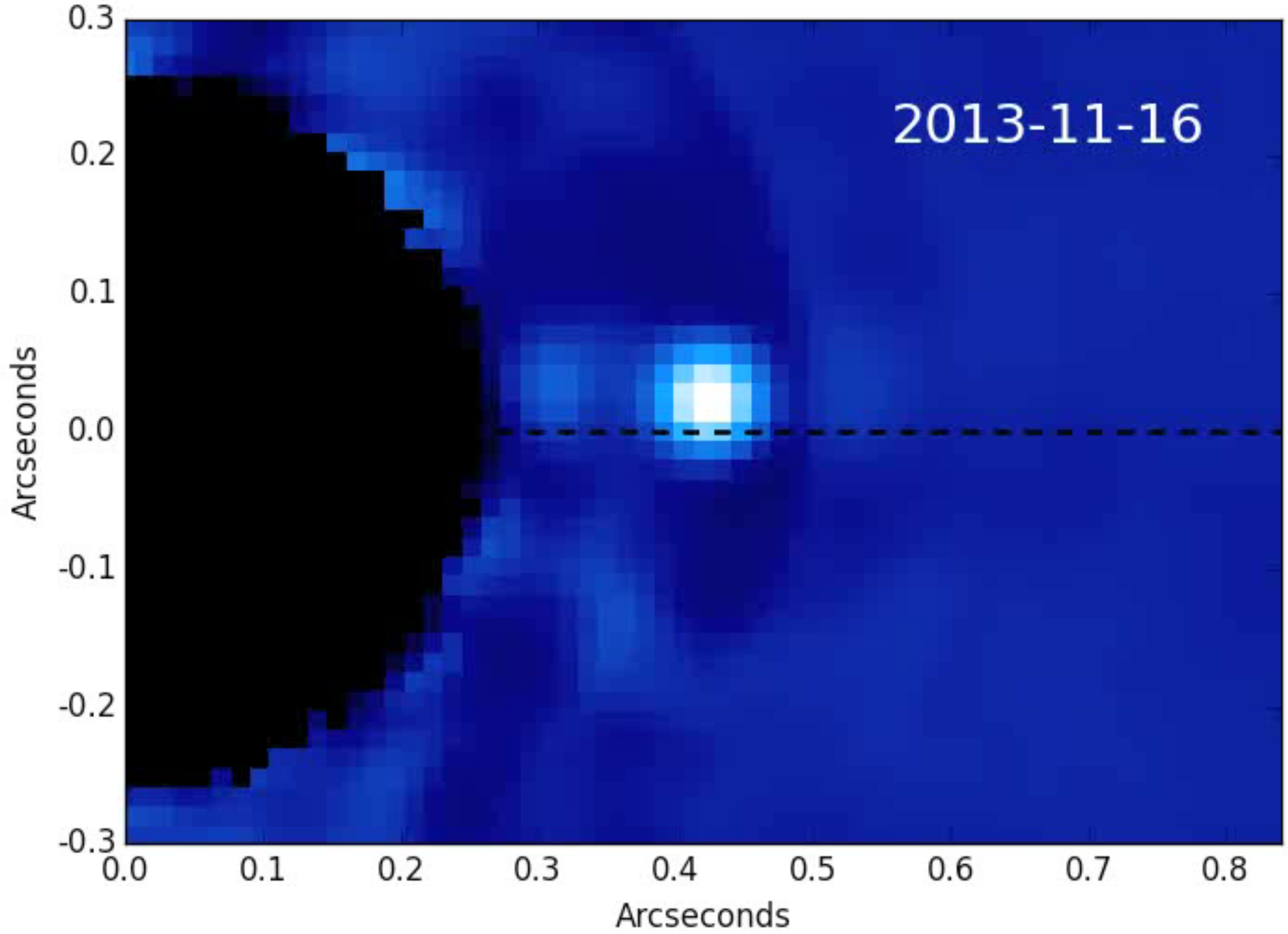
Beta Pictoris as seen by GPI:

A polarized disk detection and multi-epoch astrometry of the directly imaged planet



Max Millar-Blanchaer, 2015, in prep

Multi-epoch astrometry of Beta Pic b



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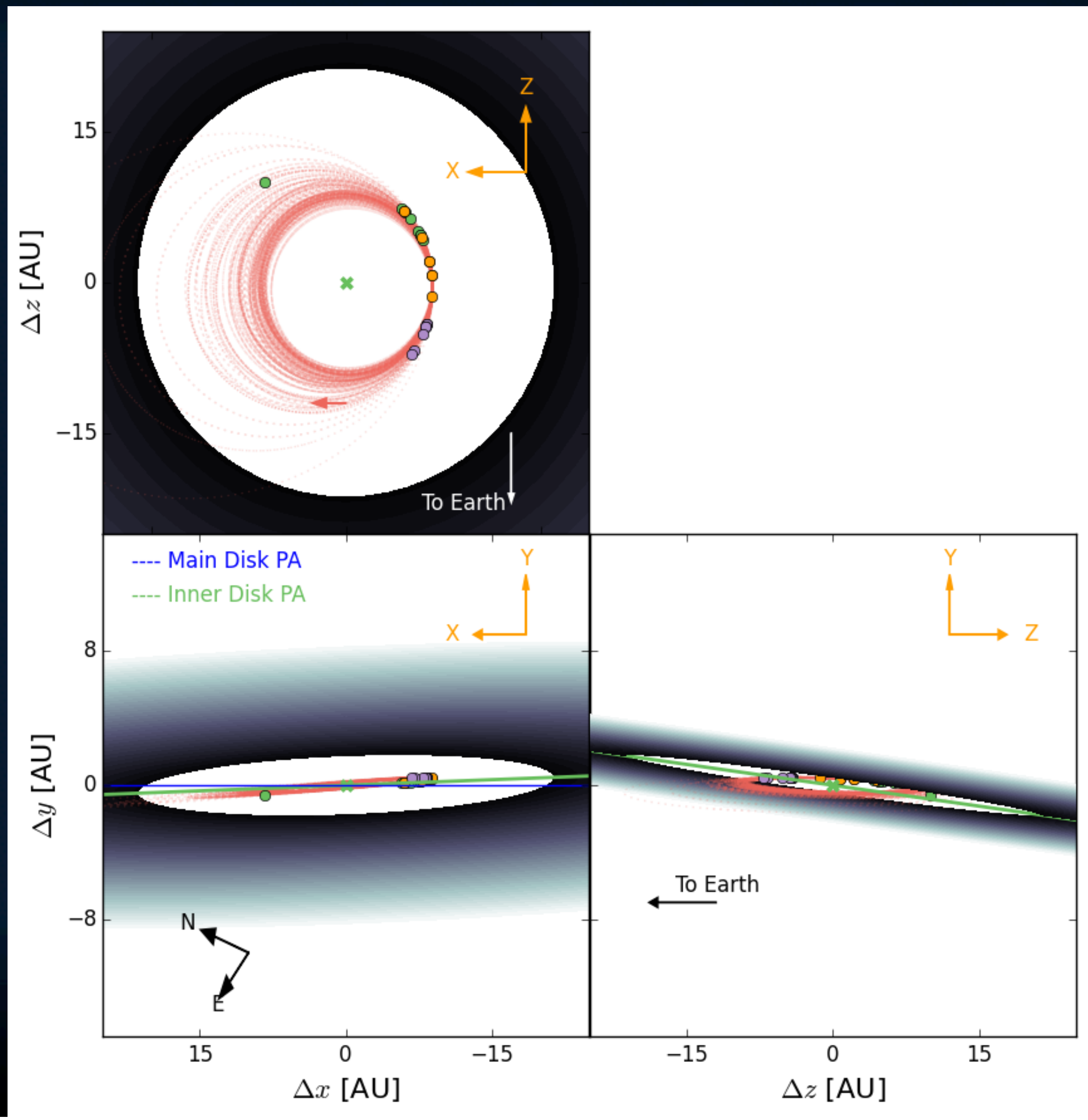
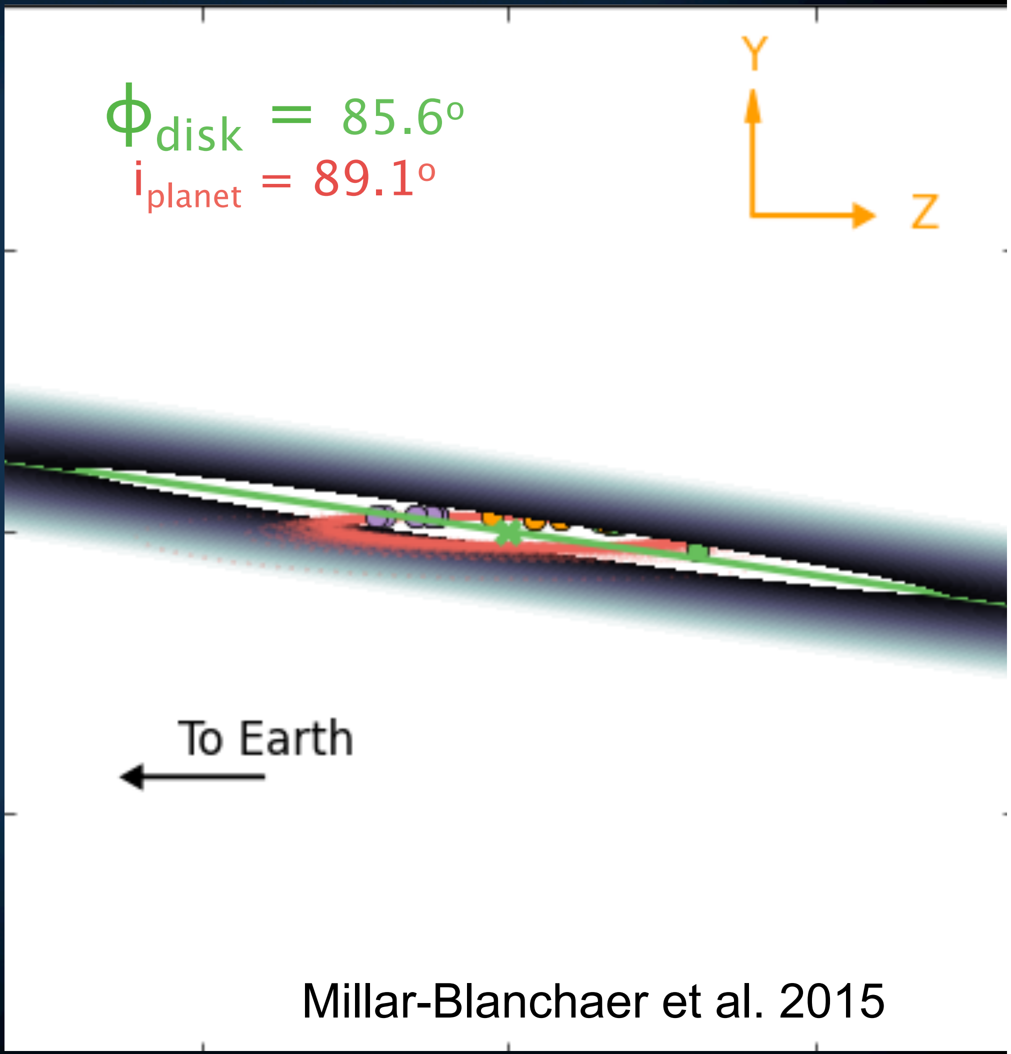
3D model of the system



Disk-Planet Interactions

The mutual inclination between the orbital planes of the planet and the disk is ~5˚.

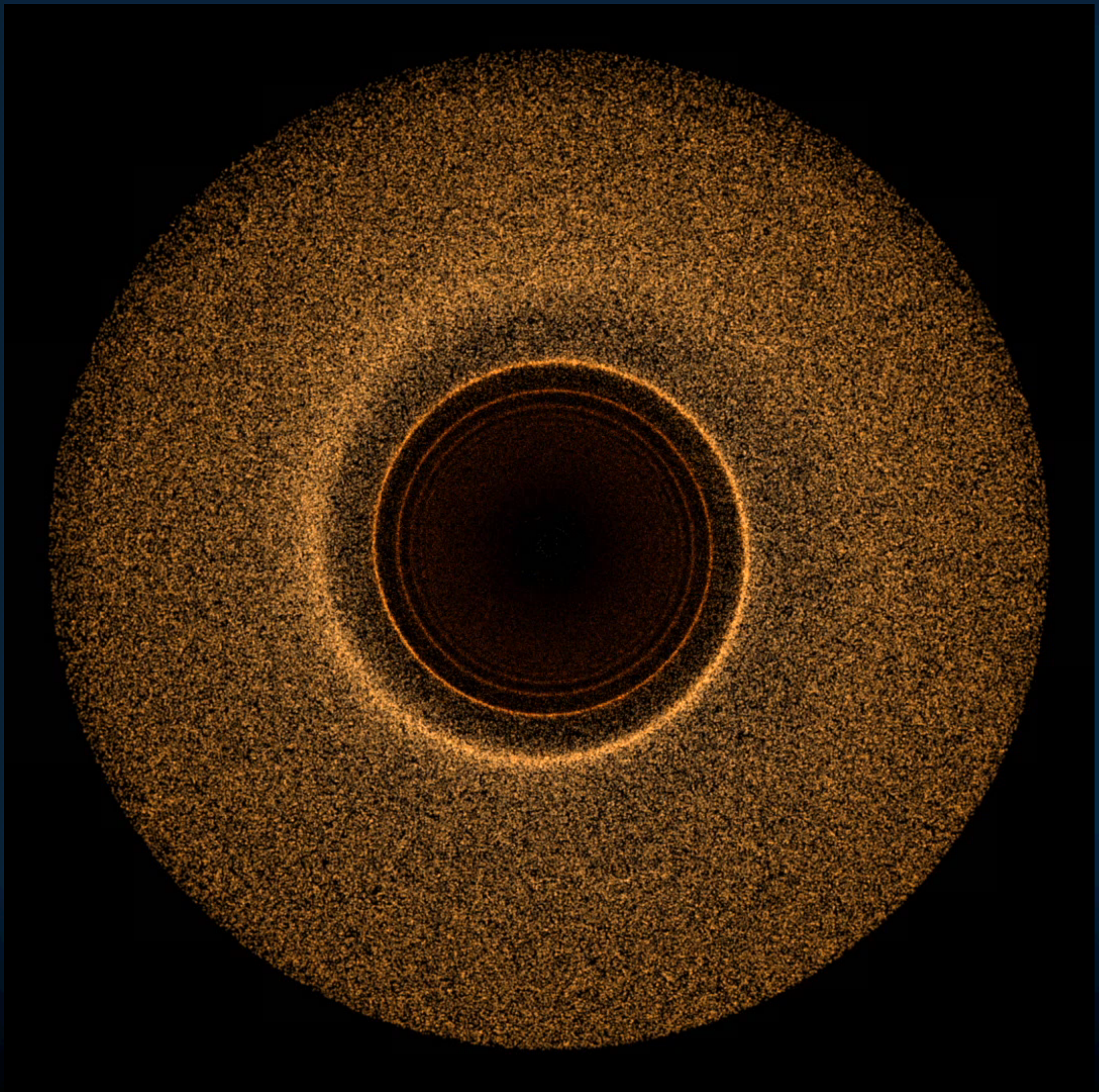
β Pic b is most likely the planet responsible for the disk warp.



Millar-Blanchaer et al. 2015

Most recent dynamical model

(breakthrough) by Nesvold & Kuchner 2015



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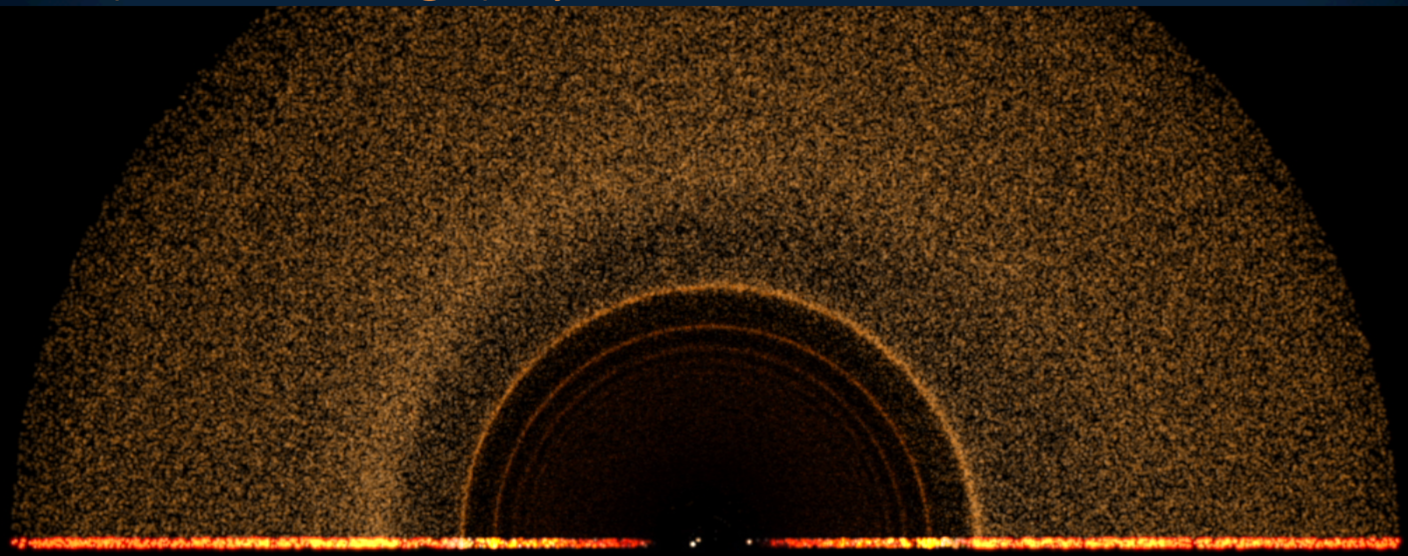

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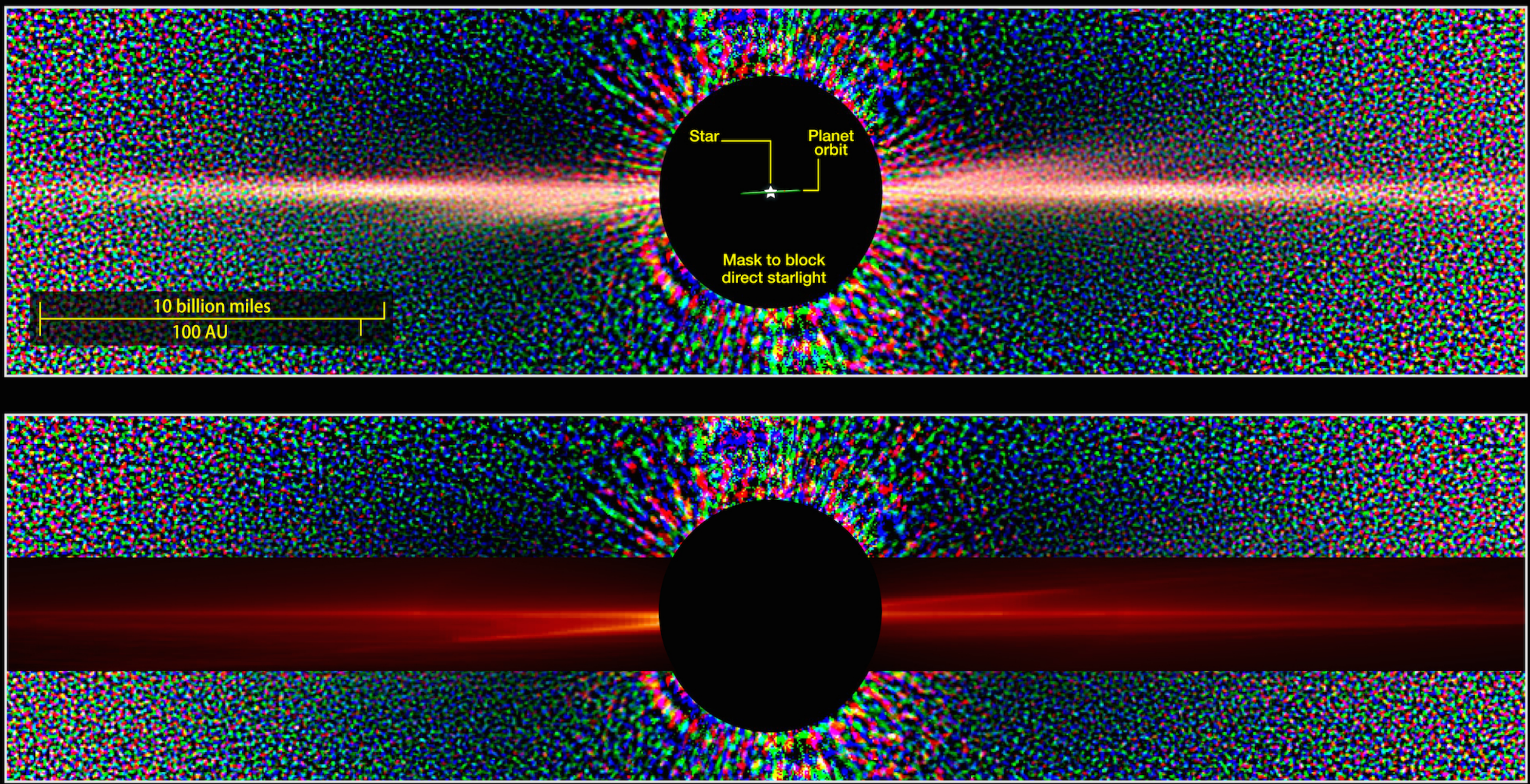
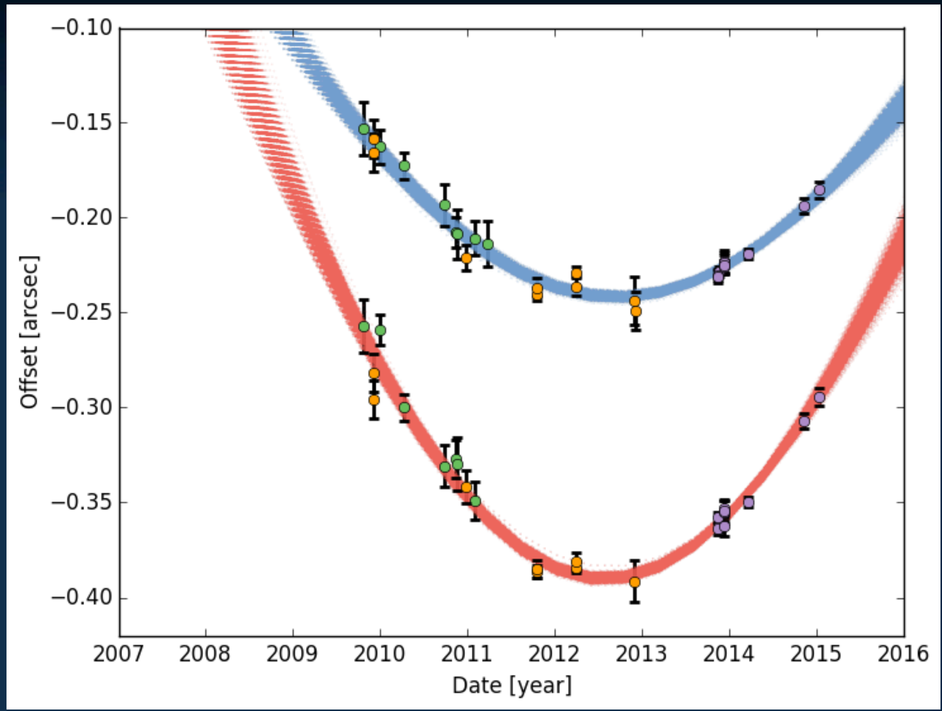


Beta Pic b orbit solutions and transit probability



Millar-Blanchaer et al. 2015

$i_{planet} = 89.11^\circ \pm 0.36^\circ$

0.5% transit probability in 2017 for the planet

But the Hill sphere has $R_H \sim 1.2$ AU

Circumplanetary material (rings, moons, etc.) will transit the star

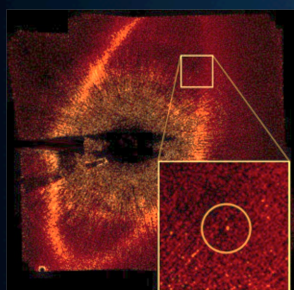
Examples from the Gemini Planet Imager

Example #2: 51 Eri b

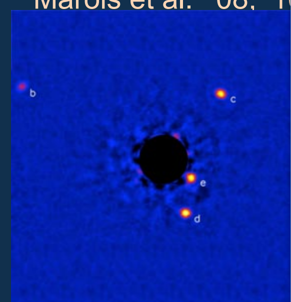
Direct planet images in last 10 years.

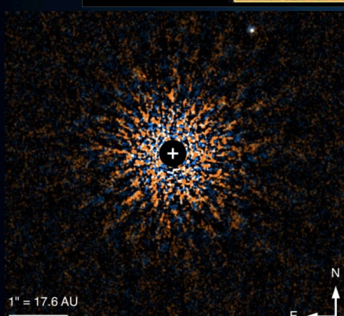
GQ Lup | 2M1207 | AB Pic

Fomalhaut
Kalas et al. 2008

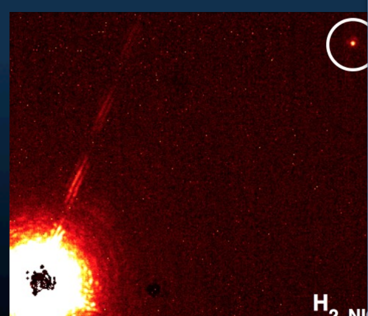


HR 8799
Marois et al. ’08,’ 1

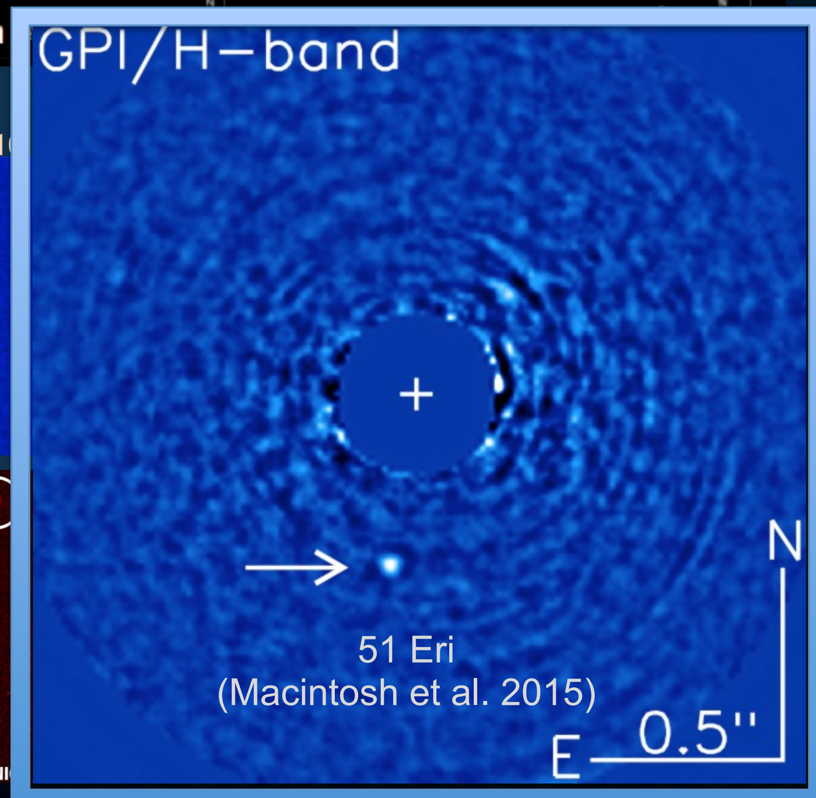




GJ 504
(Kuzuhara et al. 2014)



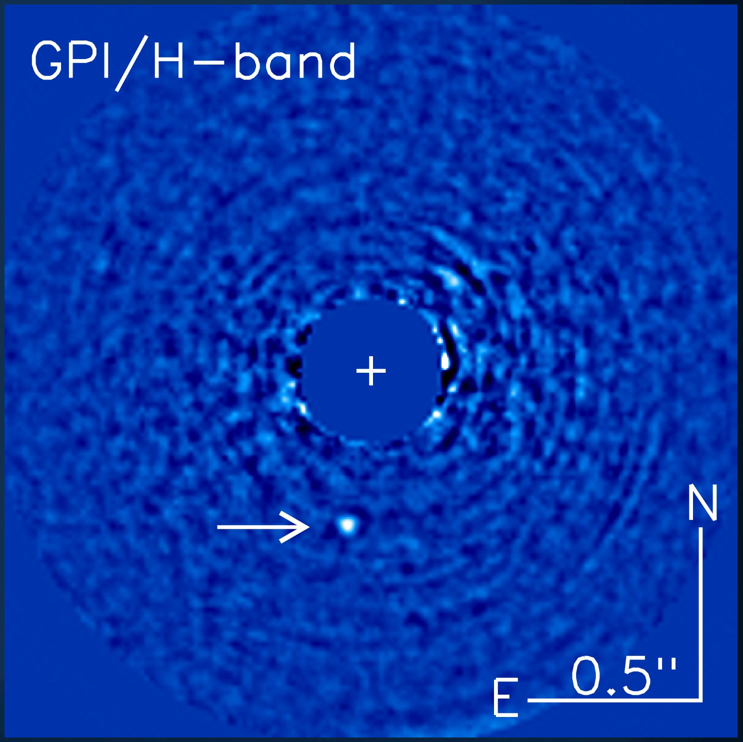
HD 106906
(Bailey et al. 2014)



GU Psc b
(Naud et al. 2014)

First GPIES exoplanet discovery: 51 Eridani b

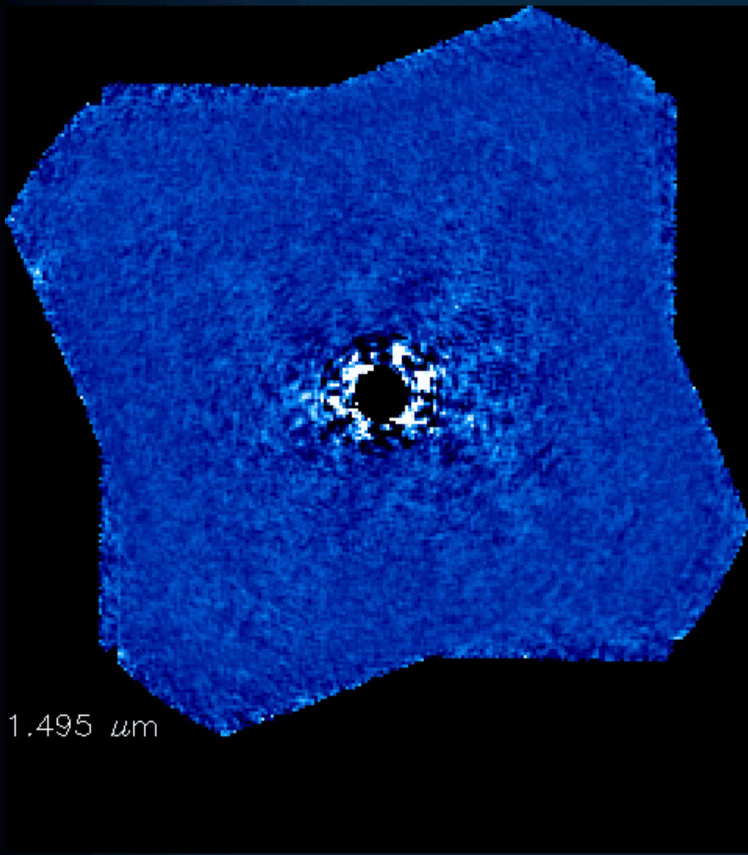
- Star: 20 Myr (β pic moving group) F0 star at 29 pc
- Observed by GPI December 2015
- T=650 K, 2×10^{-6} L_{sun}
- No common proper motion yet, but probability (background) < 10^{-5}
- Mass 2 Jupiter masses (hot-start)
- Projected separation 13 AU

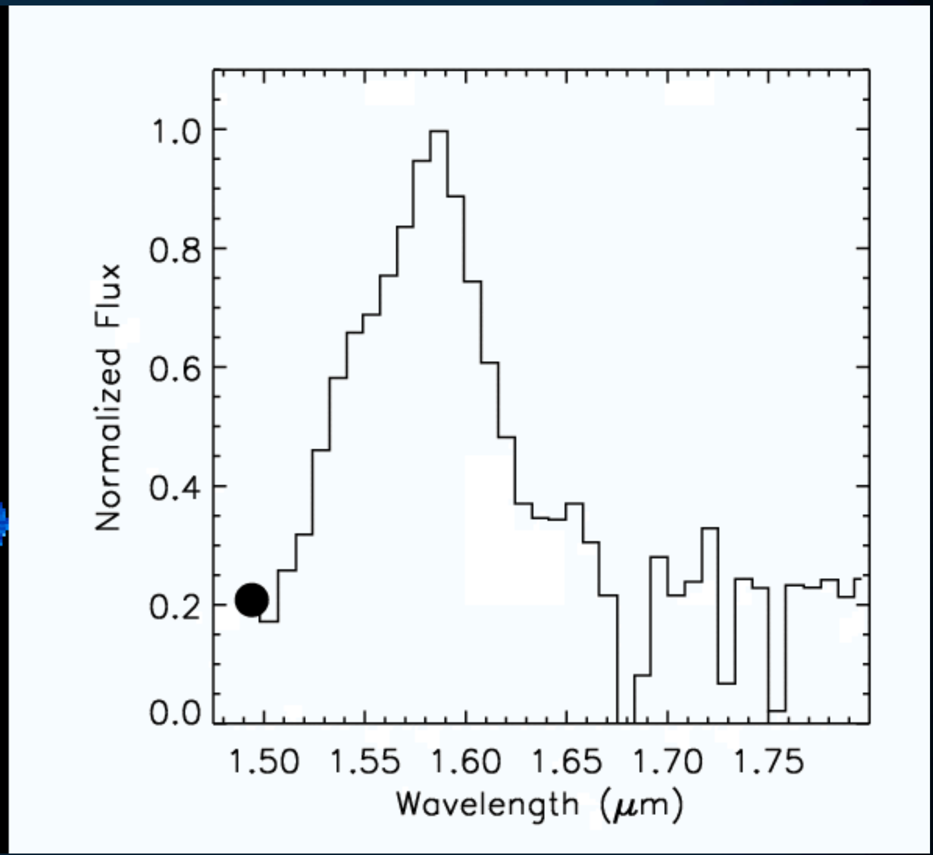


Macintosh et al. 2015, Science, submitted

First GPIES exoplanet discovery: 51 Eridani b

Methane signature in H-band (37 spectral channels, R=45 spectra)





Animation by Rob de Rosa (UC Berkeley)

51 Eri b

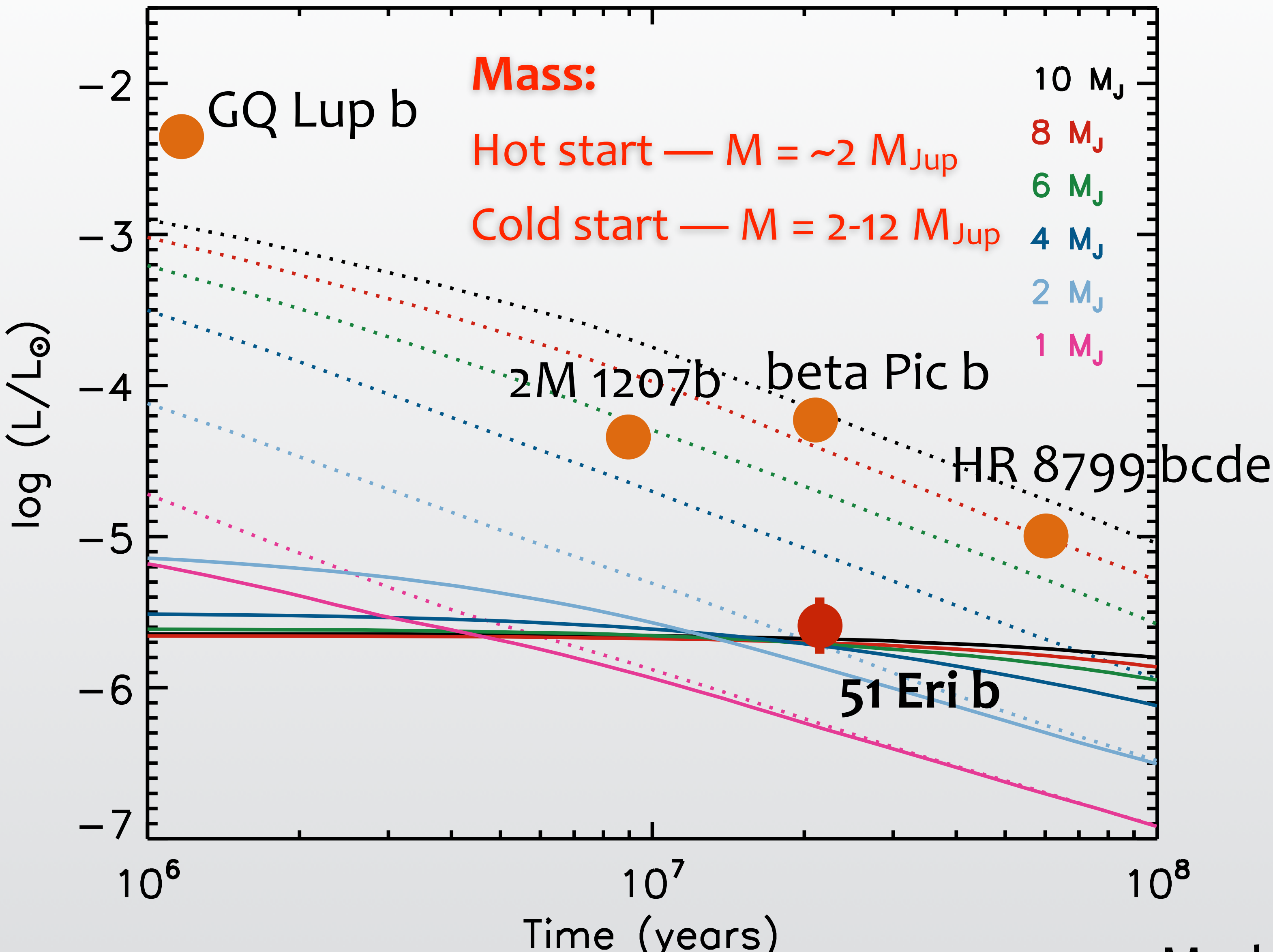
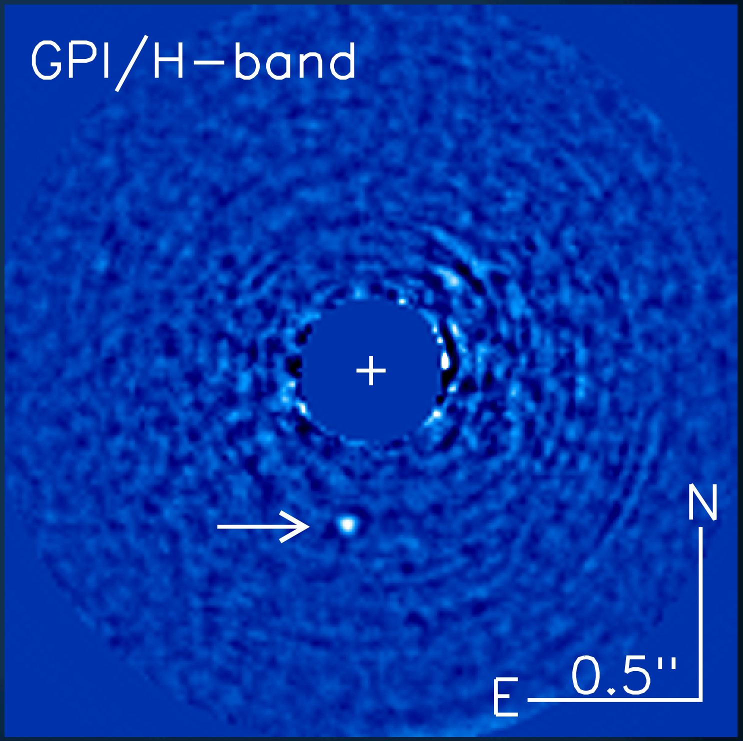


Figure by Rob deRosa

Marley+07

Summary: 51 Eridani b

- First exoplanet discovery from the new generation adaptive optics surveys.
- About 2 years to go in the survey with 500 more stars to image.
- 51 Eri b has 2 Jupiter masses
- Projected separation 13 AU – orbital motion and common proper motion will be forthcoming.



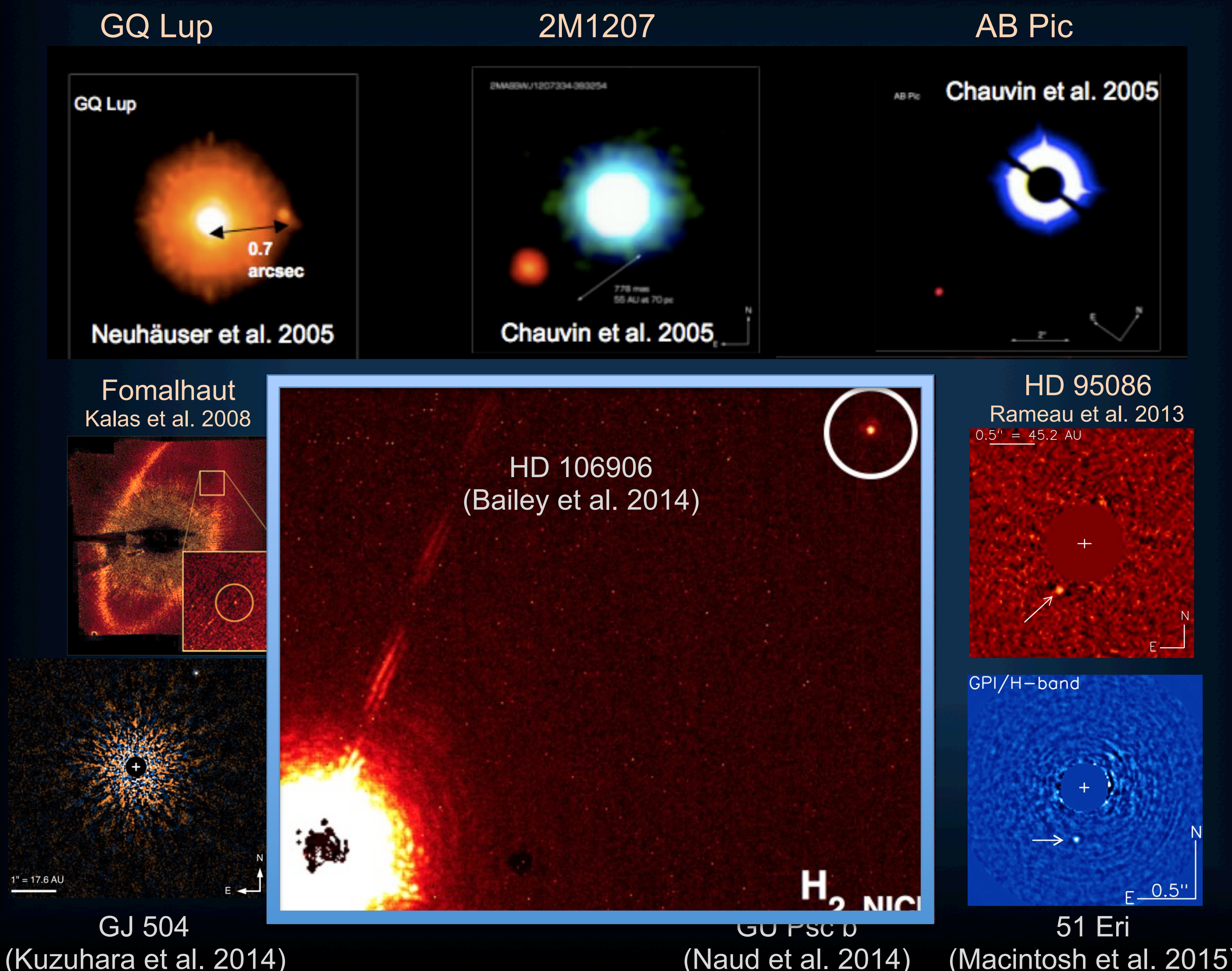
Macintosh et al. 2015, Science, submitted

Examples from the Gemini Planet Imager

Example #3: HD 106906

Paul Kalas, UC Berkeley

Direct planet images in last 10 years.



Some dynamical history questions:

If HD 106906b formed in the natal circumstellar disk surrounding the primary, how was it ejected to >654 AU in possibly a non-coplanar orbit?

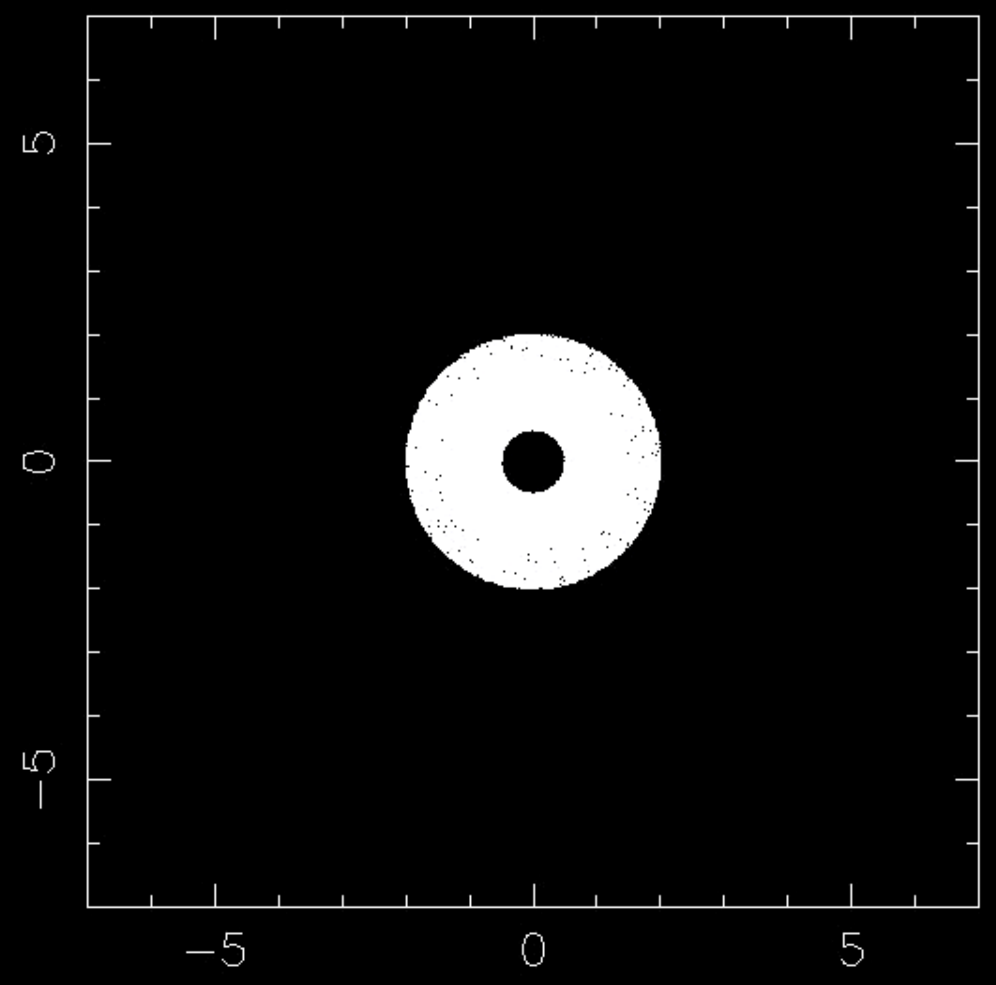
Planet-planet scattering.

If so, where is the other planet which must be at least as massive as HD 106906b, and how is it that the inner disk is relatively symmetric if two giant planets recently interacted strongly with each other?

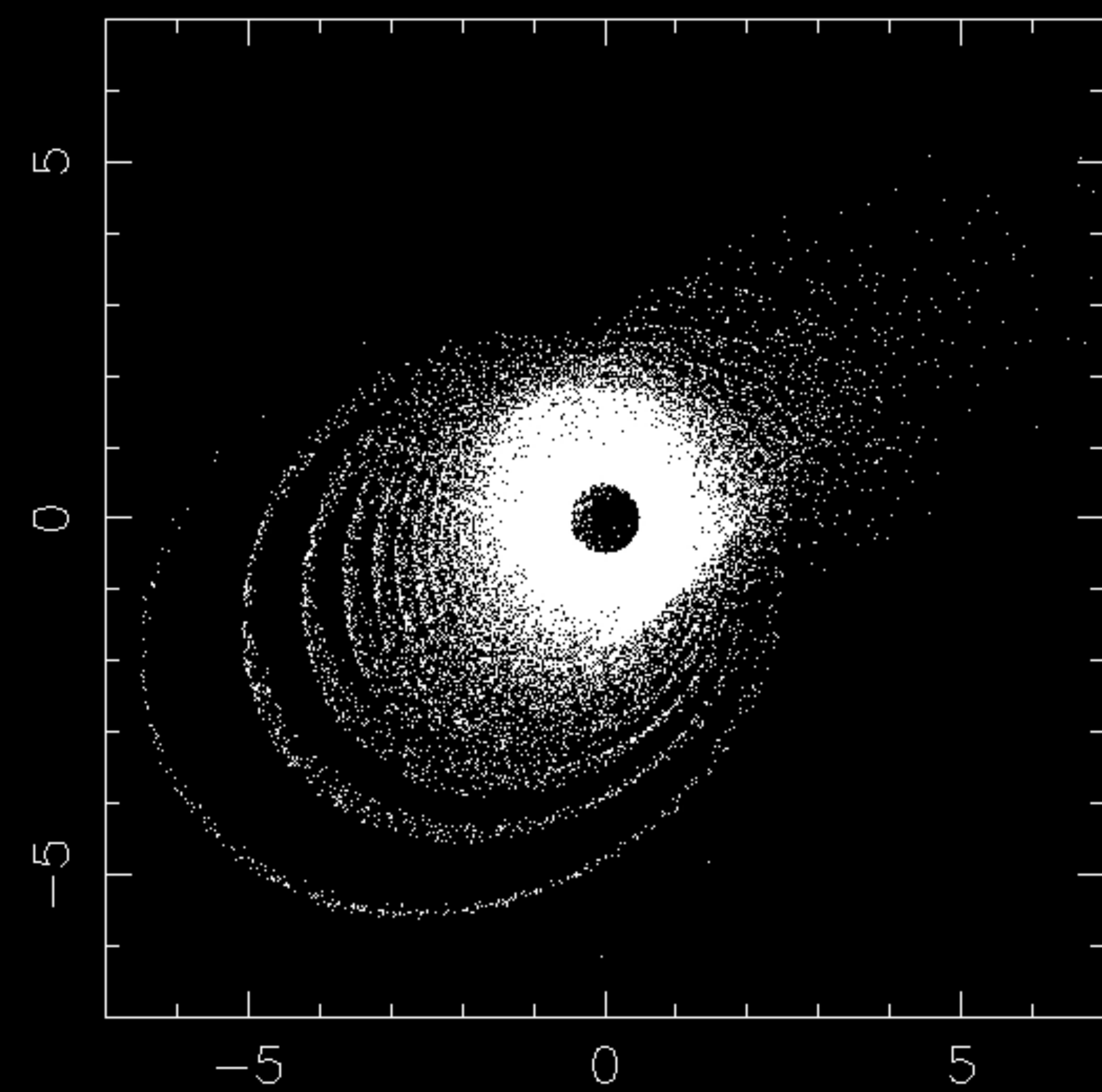
Or…HD 106906b did NOT form in the natal circumstellar disk, but instead it is an interloper or captured object.

Stellar flyby interactions.

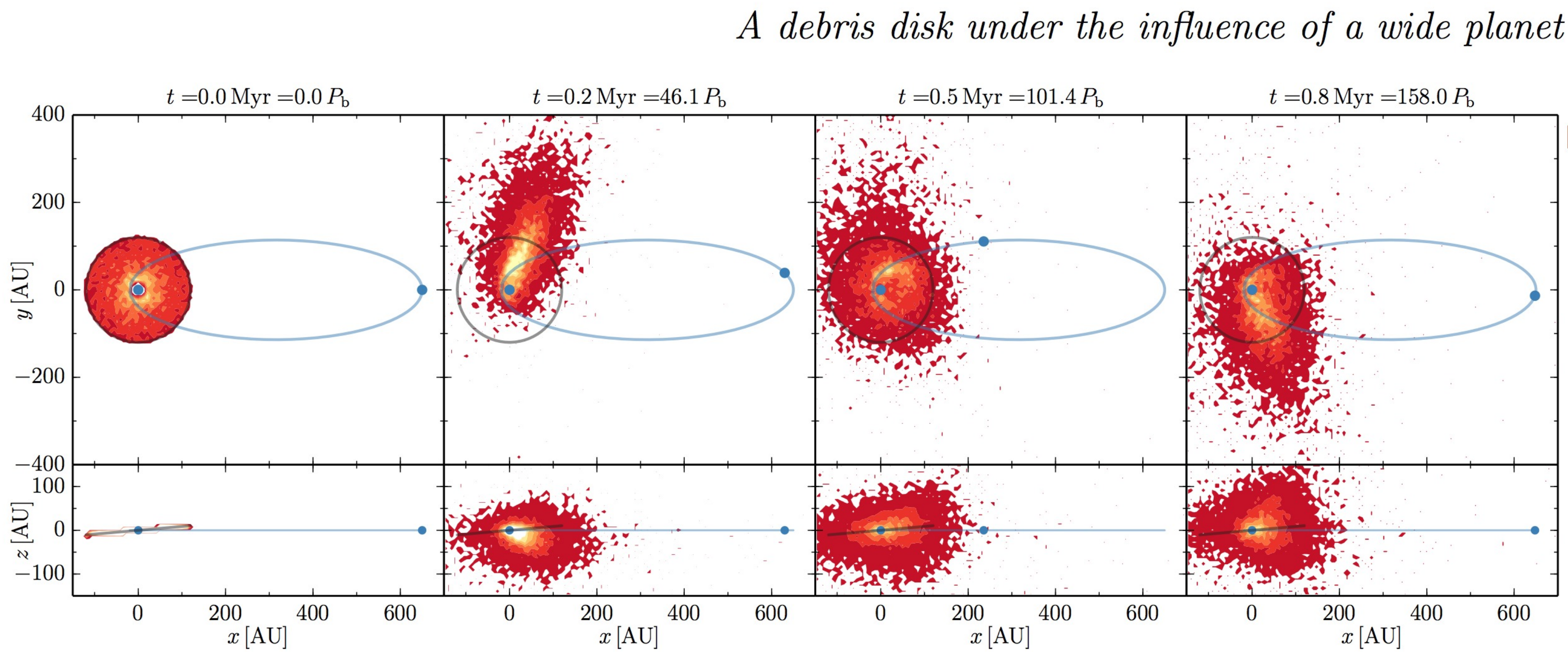
But HD 106906b is not a star, does it have enough mass to perturb a disk around a 1.5 solar mass star?



Larwood & Kalas 2001



5
0
−5
−5
0
5



Jilkova et al. 2015; Periastron 20 AU, inclination 5 degrees

After several tens of orbits extreme asymmetries develop.

But, it's not clear, yet, if the disk can simultaneously have:

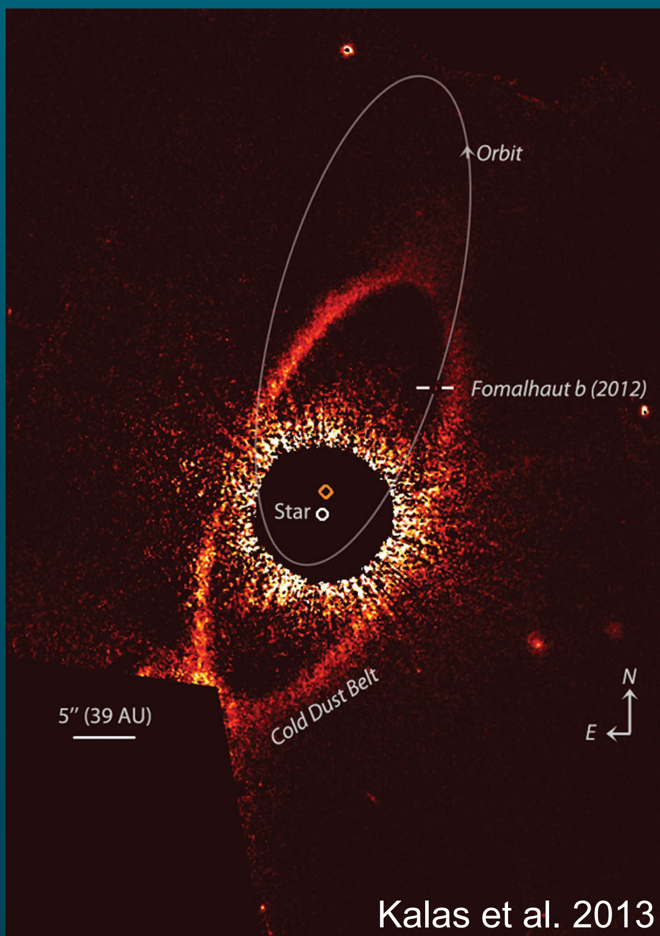
A significant vertical asymmetry on one side,

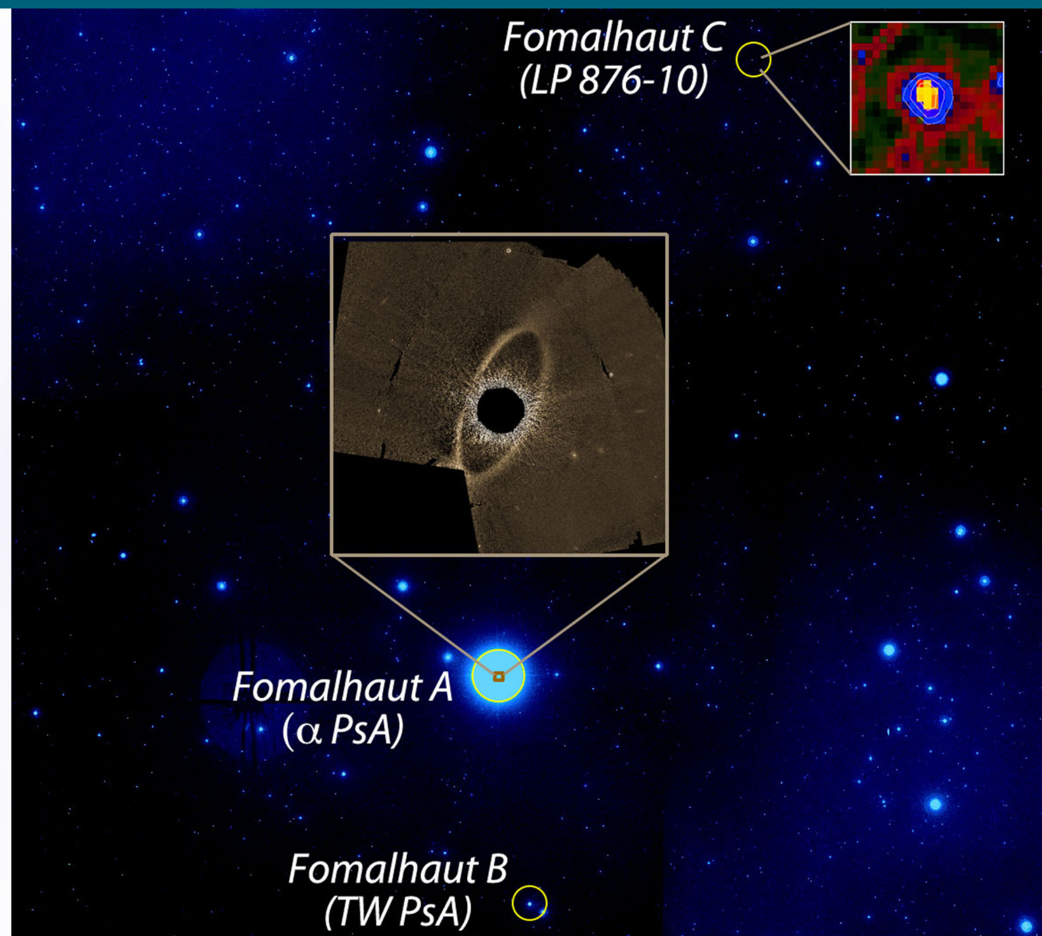
AND a length asymmetry on the other side,

AND maintain a more symmetric inner hole.

Comparison of HD 106906 with Fomalhaut

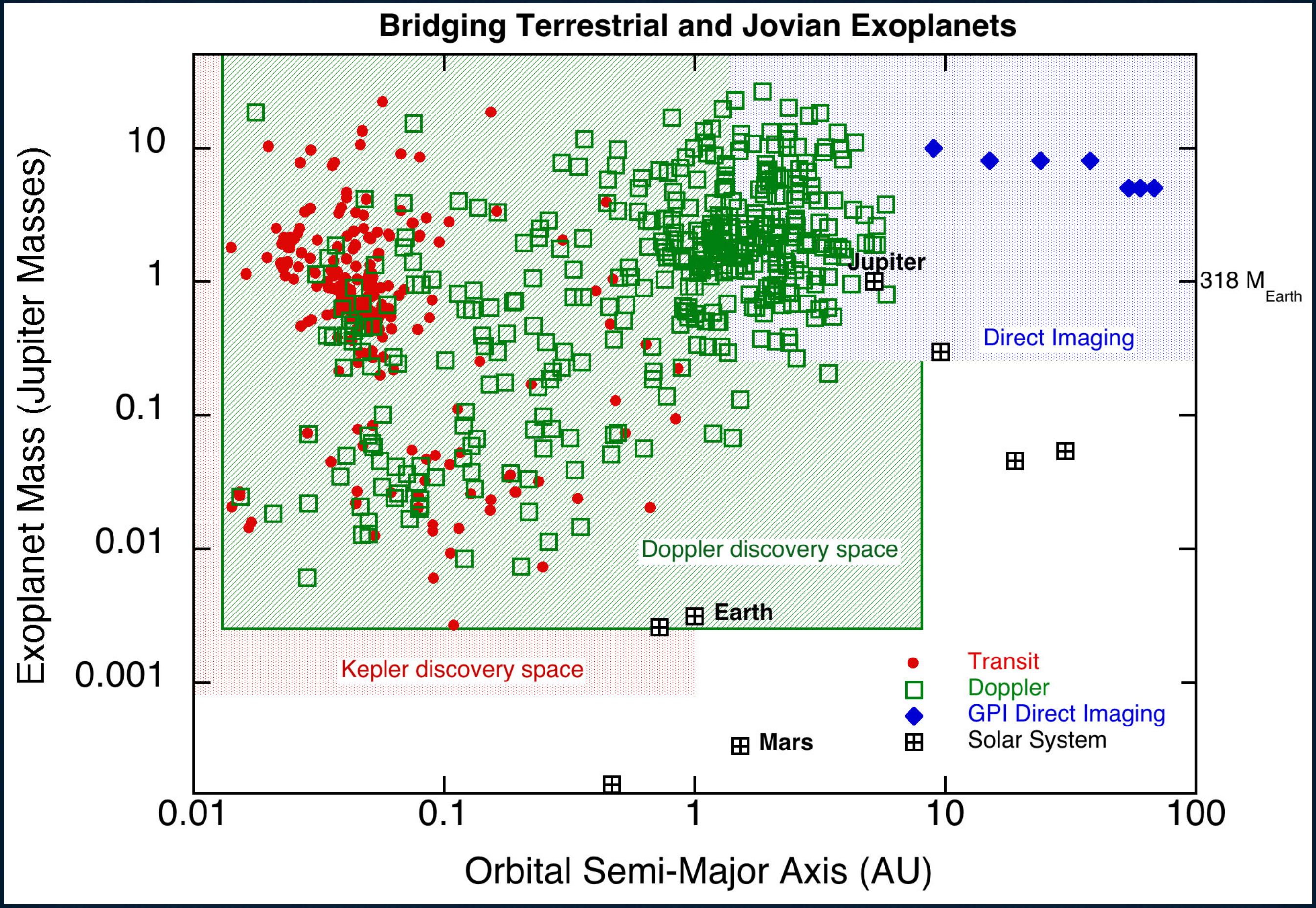
Planet may be interacting with debris belt, but not uniquely proven yet.
Other stars could be interacting with the system.





What’s the big picture here?

Direct detections of planets beyond 5 AU



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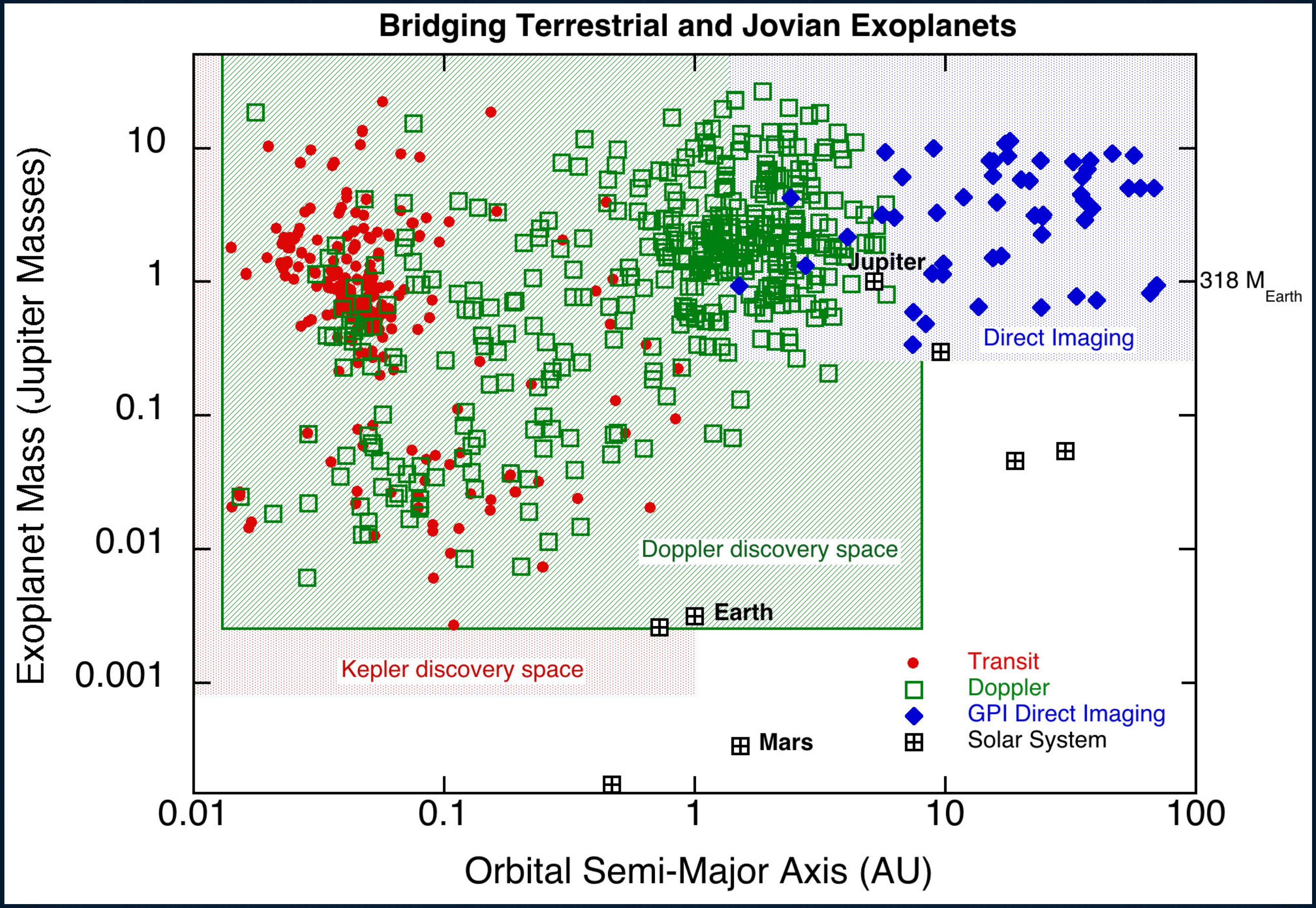
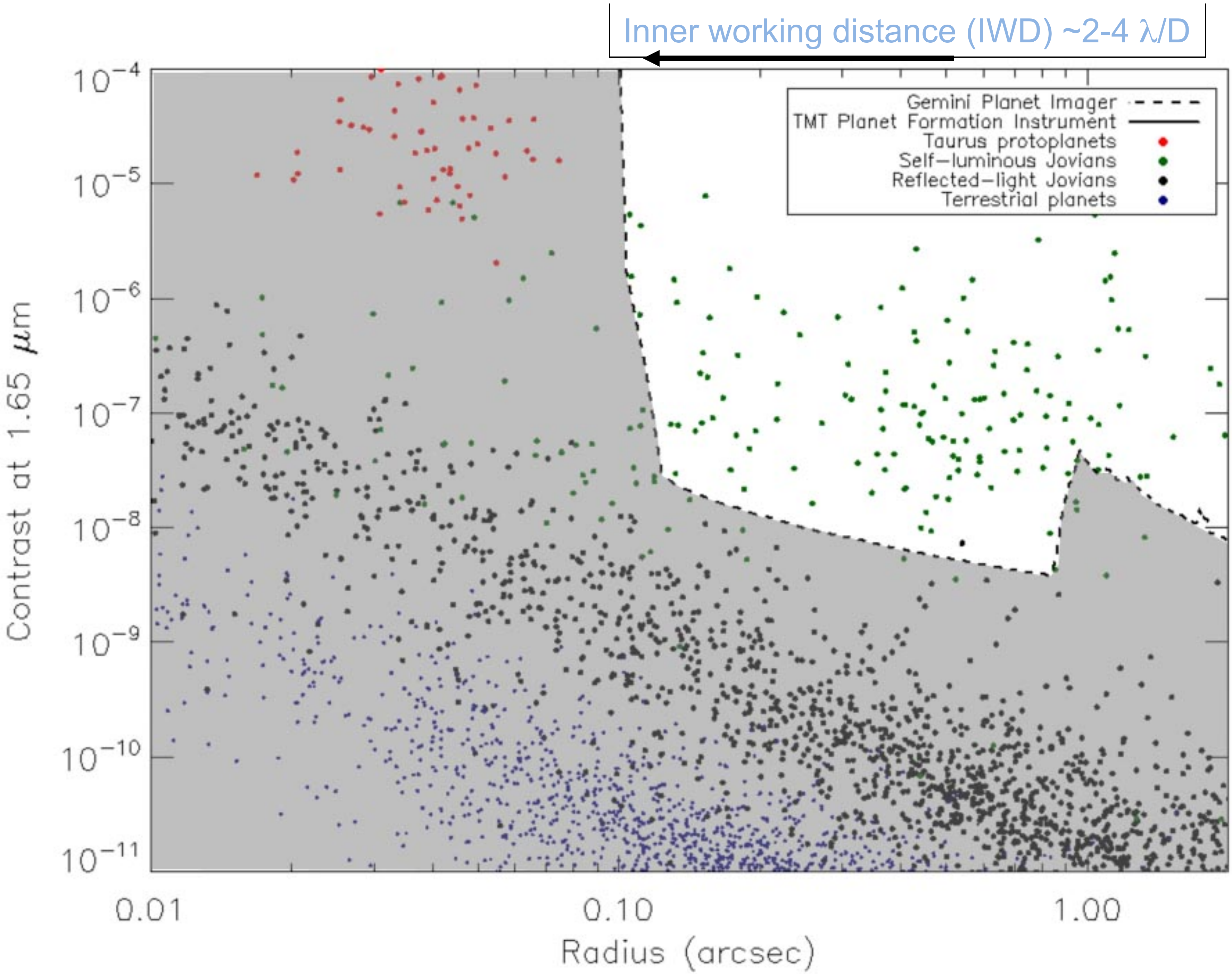
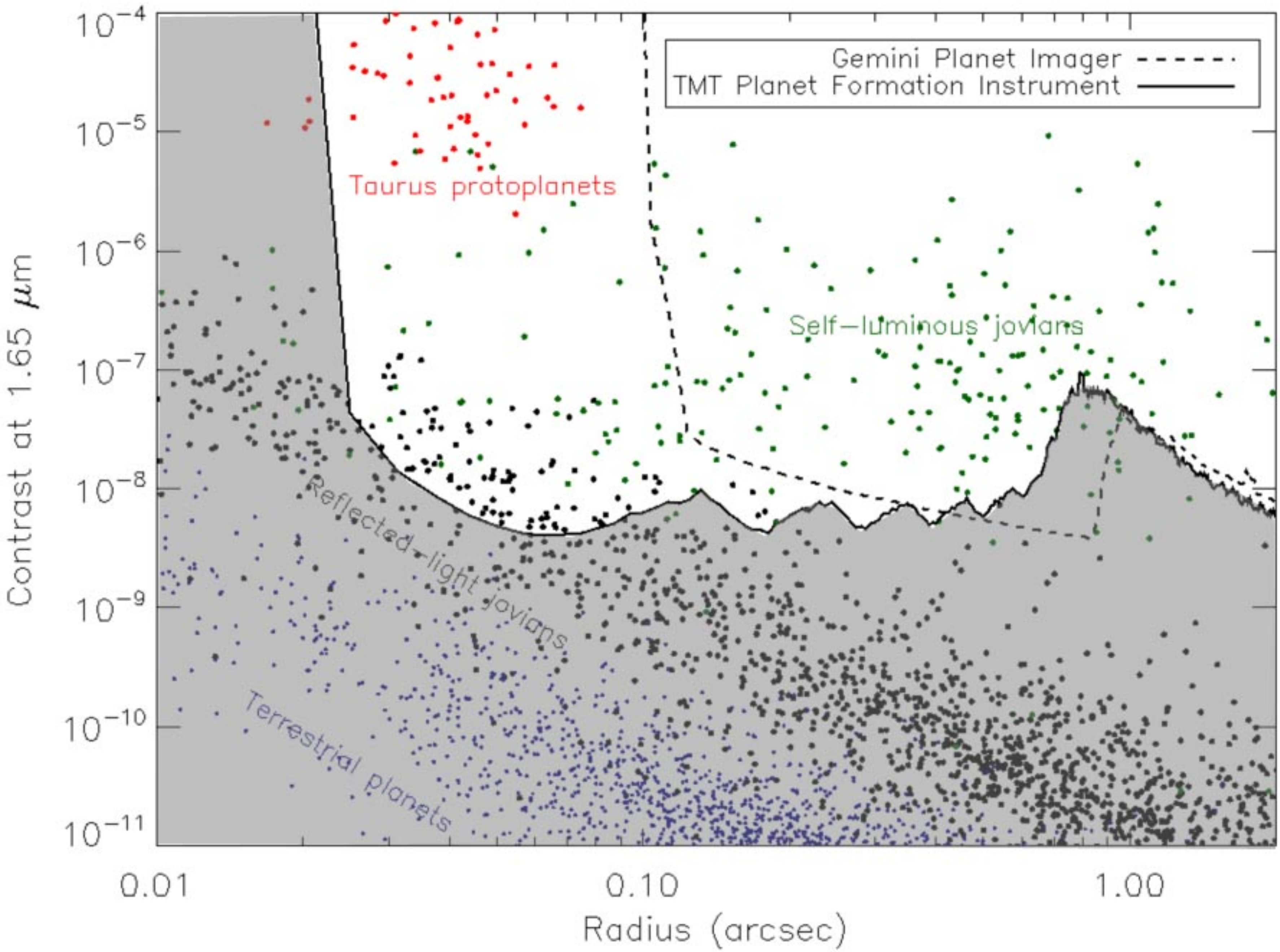
Direct detections of planets beyond 5 AU



GPI Exoplanet Survey (GPIES): 2014-2018, 600 stars
Expect ~10-20 new direct detection of exoplanets



Inner working distance (IWD) ~2-4 λ/D
Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self−luminous Jovians
Reflected−light Jovians
Terrestrial planets
Contrast at 1.65 μm
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
0.01
0.10
1.00
Radius (arcsec)



Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self-luminous jovians
Reflected-light jovians
Terrestrial planets
Contrast at 1.65 μm
Radius (arcsec)
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
0.01
0.10
1.00

Summary

- Ground based, high-contrast imaging is now poised to conduct a census of gas giants around young stars.
- Among the Gemini Planet Imager results, we've learned:
  - Beta Pic's planet is inclined relative to the main disk and is most likely responsible for the vertical warp.
  - Beta Pic b orbital plane is nearly edge-on to our line of sight and the planet or circumplanetary material will transit the star in 2017
  - 51 Eri b is a newly discovered planet with 2 MJ that will test competing theories of planet luminosity evolution.
  - The HD 106906 debris disk is resolved for the first time with GPI and we now know that it appears misaligned with the planet at 650 AU.

Exoplanet Survey

Ex Imago Mundi:
The current scientific revolution from imaging exoplanets

Paul Kalas (UC Berkeley)

James Graham, Grant Kennedy, Brenda Matthews, Gaspar Duchene
Mark Wyatt, Mike Fitzgerald, Mark Booth, Jean-Francois Lestrade
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And the GPIES Consortium (PI Macintosh)

Exoplanet Survey

~~Ex Imago Mundi:~~
Ex Imagine Mundi
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