October 12, 2017
NASA Exoplanet Science Institute
Pasadena, CA

Observational needs for the confirmation and characterization of exoplanets

Direct imaging surveys

Paul Kalas (UC Berkeley)

(with thanks to Jason Wang, Rob De Rosa, Eric Nielsen, James Graham, Tom Esposito, Mike Fitzgerald, Bruce Macintosh and everyone on the GPI Team)

NASA NExSS gpi Exoplanet Survey NSF

The observational needs for direct imaging were recognized very early by NASA

NASA/CP—1998-10155

Exozodiacal Dust Workshop

Conference Proceedings

Edited by D. E. Backman,
Franklin and Marshall College, Lancaster, Pennsylvania

L. J. Caroff, S. A. Sandford, and D. H. Wooden
NASA Ames Research Center, Moffett Field, Californ

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

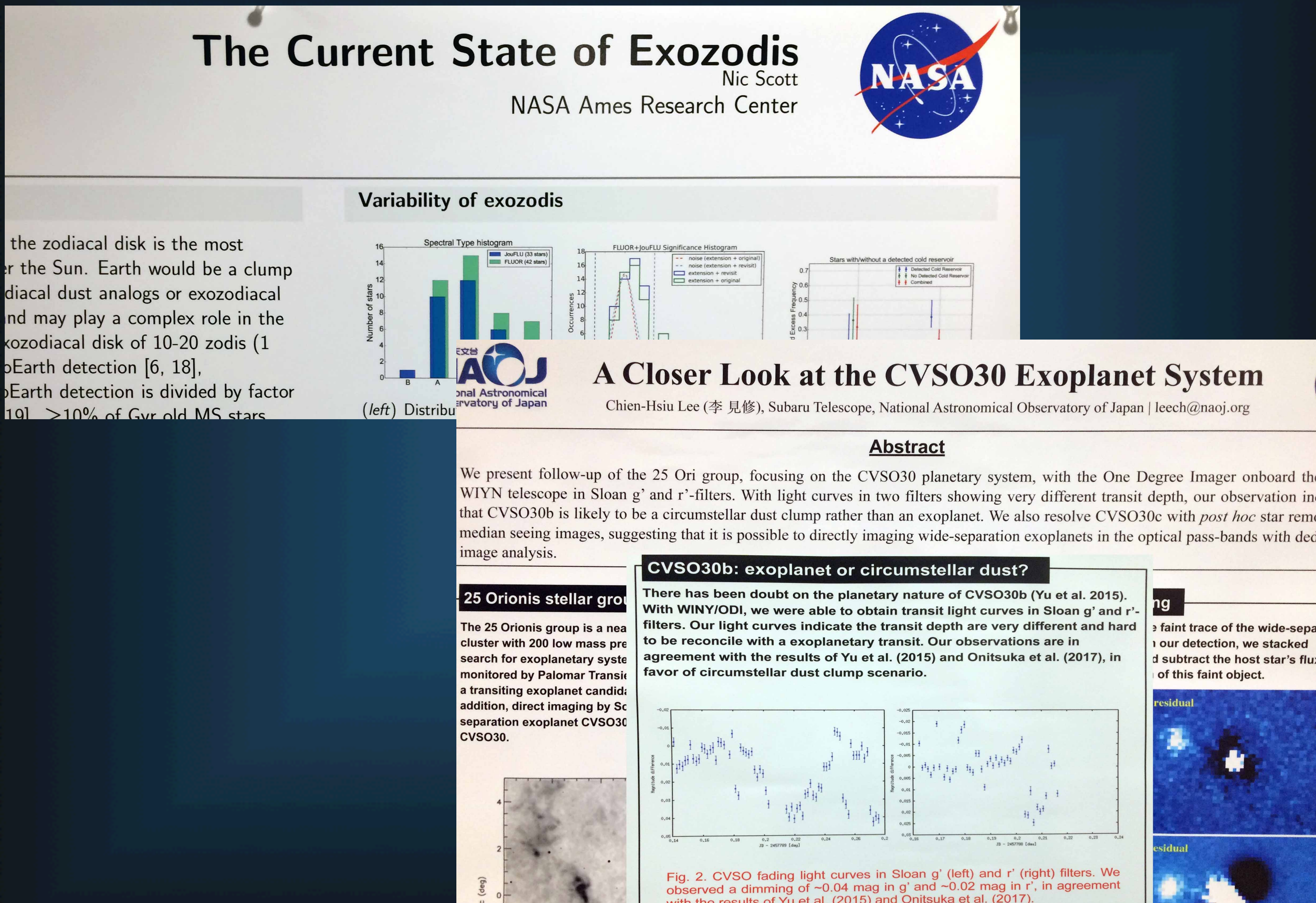
Translation: Know thy zody as you prepare to know thy exoplanets through imaging.

Goals of the Workshop

One of NASA's fundamental goals is to search for evidence of life outside of the Earth. An important element of that goal is to search other stellar systems for terrestrial-sized planets in the so-called "habitable zone," image those planetary systems that contain such likely sites for life, and through spectroscopy or other means, look for unambiguous signs of the presence of life. To this end, conceptual studies are already underway to define the Terrestrial Planet Finder (TPF) mission. TPF will be a space-based spatial interferometer, working at infrared wavelengths to detect and characterize Earth-like planets in orbits around nearby stars that are within 10-15 pc of the Sun. Launch of TPF is planned for 2011.

It is expected that a significant limitation to unambiguous planet detection and study will be background thermal emission from warm dust within a given planetary system--the exozodiacal dust cloud. At present, the amount, distribution, and composition of the exozodiacal dust, particularly the warm component, is essentially unknown. This lack of knowledge leads to significant uncertainties in the requirements on TPF for such fundamental parameters as sensitivity and angular resolution, with matching uncertainties in the final design.

Zody-related Posters at Know Thy Stars



Observational needs of direct imaging

I. **Precursor needs** - observations needed to plan direct imaging surveys (we call it the target list instead of the "input catalog")

II. **Follow-up observing needs** - to conifrm and characterize directly imaged planetary systems.

III. **Future needs** – to directly image Earth twins.

Science Motivation

What is the distribution of outer giant planets as a function of planet mass and semi-major axis?

And as a function of spectral type…
multiplicity,
metallicity,
birth environment, etc.

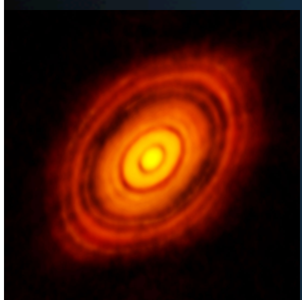
Not to mention as a function of debris disk properties or other planets in the system (papers by Knutson, Ngo, Bryan, et al.)

And as a function of stellar ages (evolution),
direct imaging holds the promise of imaging all the planets from 1 Myr to 10 Gyr.

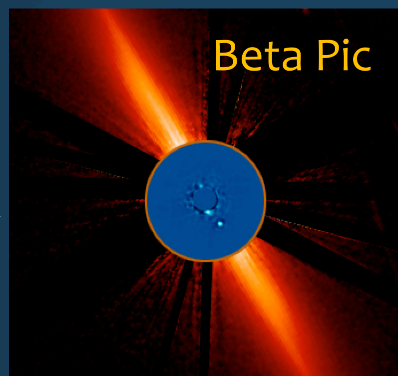
Direct Imaging Probes Evolution

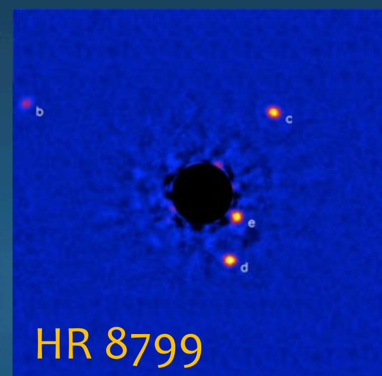
1 Myr 10 Myr 100 Myr 1 Gyr

HL Tau

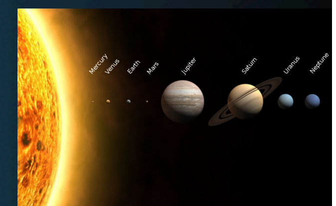


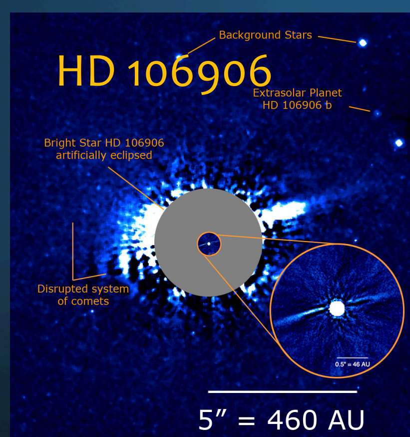
??

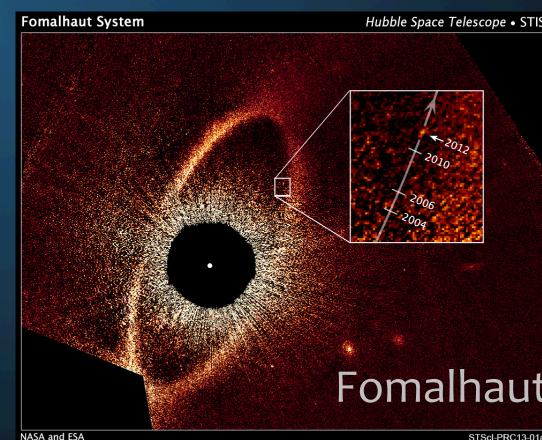




??







Paul Kalas – UC Berkeley

Practical Constraints

- $\lambda \sim 1.6\ \mu$m   (adaptive optics correction of the atmosphere is most effective at near infrared wavelengths)

- Inner Working Angle, IWA ~ 0.1-0.3″ (λ / D ~ 0.05″ for an 8-m telescope in the NIR)

- m_v brighter than ~10th mag (need photons from a natural guide star for the AO system to correct atmosphere)

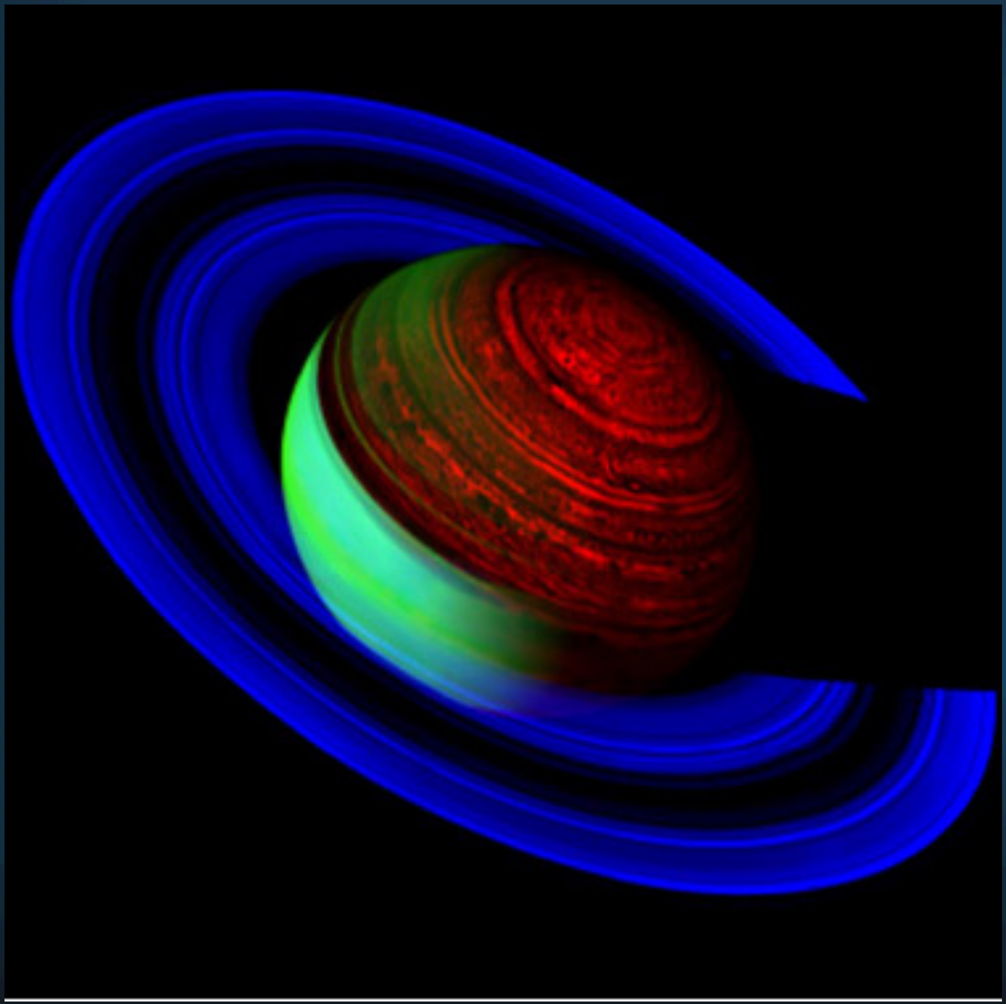
Inner Working Angles from Beichman (2010) review

INNER WORKING ANGLE AND PHYSICAL RESOLUTION

Telescope (m) / Wavelength (μm)	5.0 / 1.65	6.5 / 2.2	6.5 / 4.4	6.5 / 11.4	8.0 / 1.65	30.0 / 1.65
Inner Working Angle (mas)						
NIRCAM/Wedge ($4\lambda/D$)	—	280	560	—	—	—
NIRCAM/Sombrero ($6\lambda/D$)	—	420	850	—	—	—
"MMT-like" ($4\lambda/D$)	—	—	560	—	—	—
TFI/Nonredundant Mask ($0.5\lambda/D$)	—	35	70	—	—	—
MIRI/FPQM ($1\lambda/D$)	—	—	—	365	—	—
Palomar/P1640 ($2.5\lambda/D$)	170	—	—	—	—	—
GPI/SPHERE ($2.5\lambda/D$)	—	—	—	—	105	—
TMT Coronagraph ($2.5\lambda/D$)	—	—	—	—	—	30
Physical Resolution (AU) at 10 pc						
NIRCAM/Wedge ($4\lambda/D$)	—	2.8	5.6	—	—	—
NIRCAM/Sombrero ($6\lambda/D$)	—	4.2	8.5	—	—	—
"MMT-like"($4\lambda/D$)	—	—	5.6	—	—	—
TFI/Nonredundant Mask ($0.5\lambda/D$)	—	0.4	0.7	—	—	—
MIRI/FPQM ($1\lambda/D$)	—	—	—	3.7	—	—
Palomar/P1640 ($2.5\lambda/D$)	1.7	—	—	—	—	—
GPI/SPHERE ($2.5\lambda/D$)	—	—	—	—	1.1	—
TMT Coronagraph ($2.5\lambda/D$)	—	—	—	—	—	0.3
Physical Resolution (AU) at 50 pc						
NIRCAM/Wedge ($4\lambda/D$)	—	14	28	—	—	—
NIRCAM/Sombrero ($6\lambda/D$)	—	21	42	—	—	—
"MMT-like" ($4\lambda/D$)	—	—	28	—	—	—
TFI/Nonredundant Mask ($0.5\lambda/D$)	—	1.8	3.7	—	—	—
MIRI/FPQM ($1\lambda/D$)	—	—	—	18	—	—
Palomar/P1640 ($2.5\lambda/D$)	9	—	—	—	—	—
GPI/SPHERE ($2.5\lambda/D$)	—	—	—	—	5	—
TMT Coronagraph ($2.5\lambda/D$)	—	—	—	—	—	1.5

Gas giants are more luminous in the infrared when they are young

Thermal infrared emission from giant planets



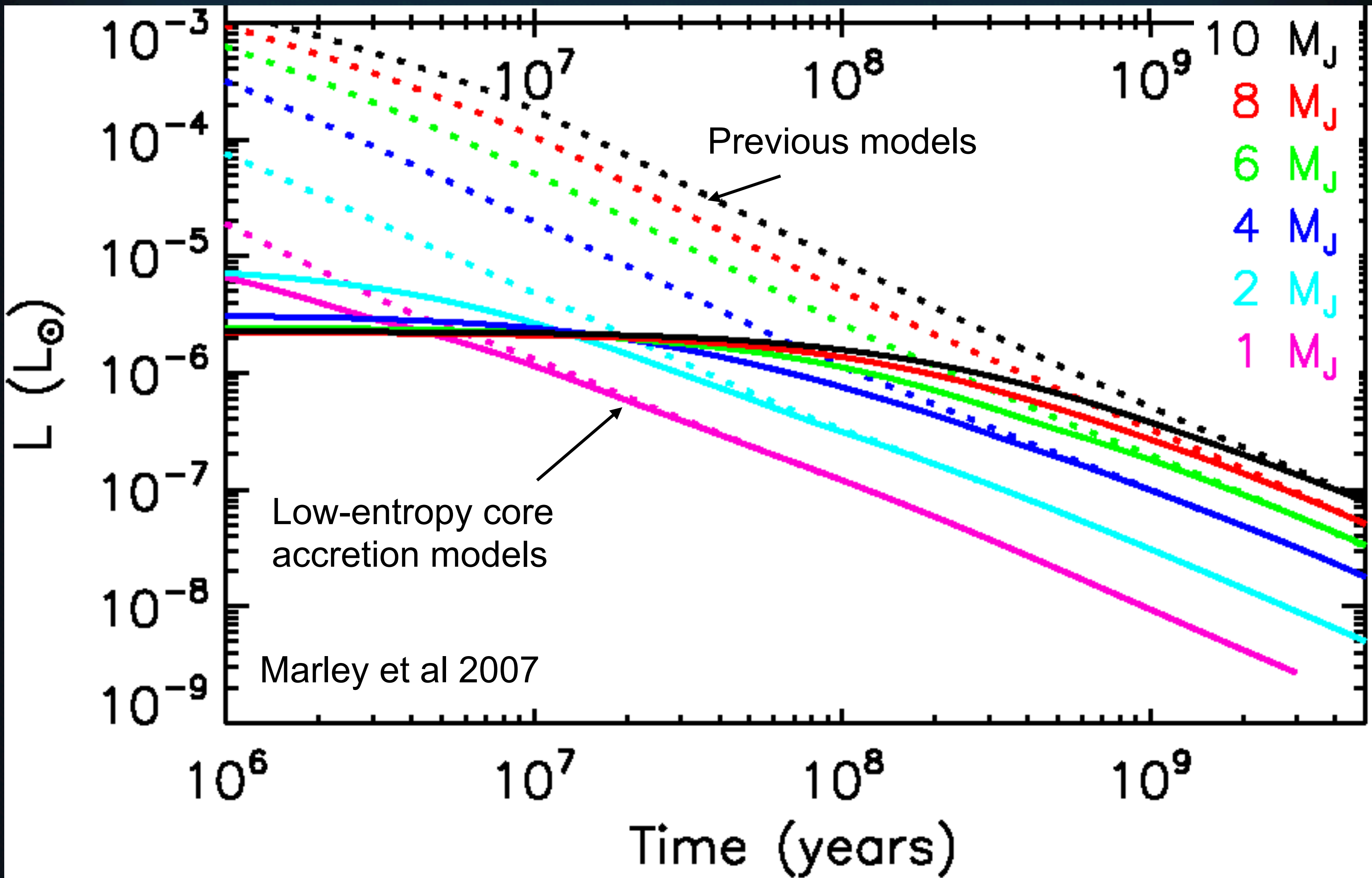
Optical to infrared composite image of Saturn

5 micron thermal emission shown in red

(Cassini Mission 2007)

Exoplanets more luminous in the infrared when they are young

Hot Start (dotted) vs. Cold Start (solid)



If we obtain a spectrum of a planet, the spectrum can give us a temperature, but then we need the age to infer the planet mass.

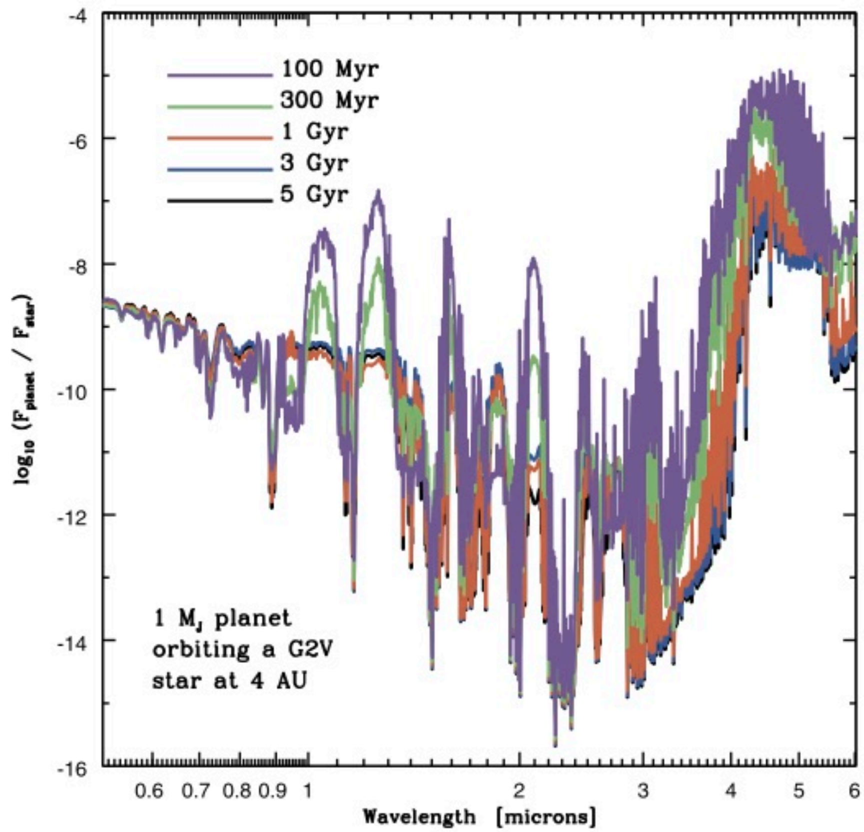


FIG. 6.—Planet-to-star flux ratio from 0.5 to 6.0 μm for a 1M_J EGP orbiting a G2 V star at 4 AU as a function of age. The ages are 0.1, 0.3, 1, 3, and 5 Gyr. An inner flux boundary condition $T_{\rm eff}$ from the evolutionary calculations of Burrows et al. (1997) has been employed. The effect of clouds is handled in the radiative transfer calculation in a completely consistent fashion. See Table 2, Fig. 2, and text for details and discussion.

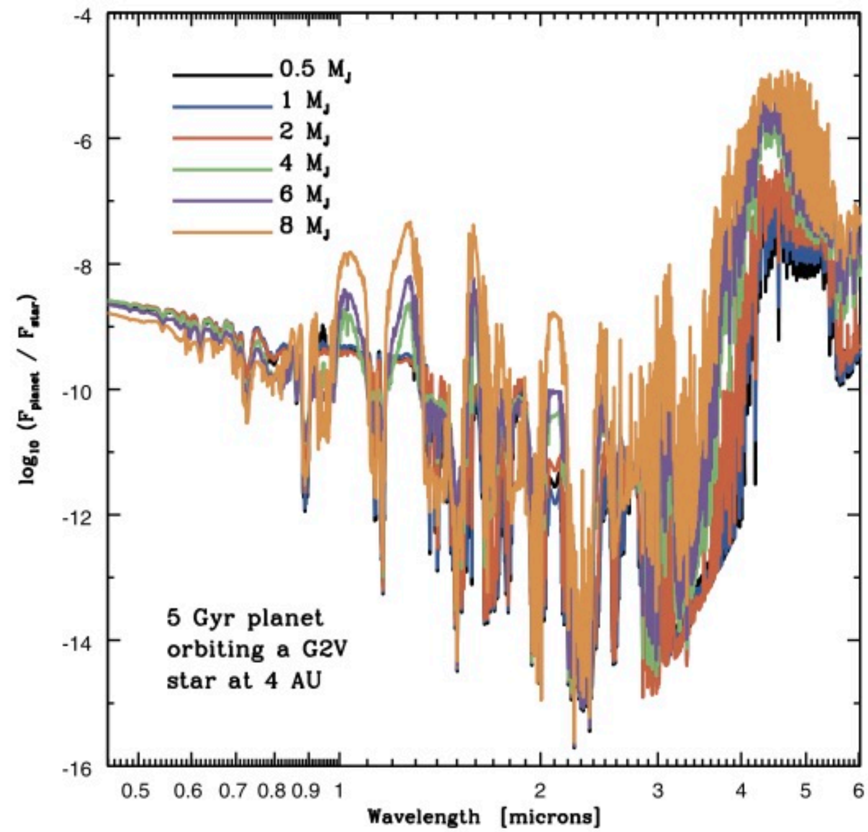


FIG. 7.—Similar to Fig. 6, but the planet-to-star flux ratio from 0.4 to 6.0 μm for a 5 Gyr EGP orbiting a G2 V star at 4 AU, as a function of EGP mass. The masses represented are 0.5M_J, 1M_J, 2M_J, 4M_J, 6M_J, and 8M_J. See Table 3 and text for a discussion.

Or, if we can obtain a spectrum of a planet, the spectrum can give us a temperature, but then we need the age to infer the planet mass.

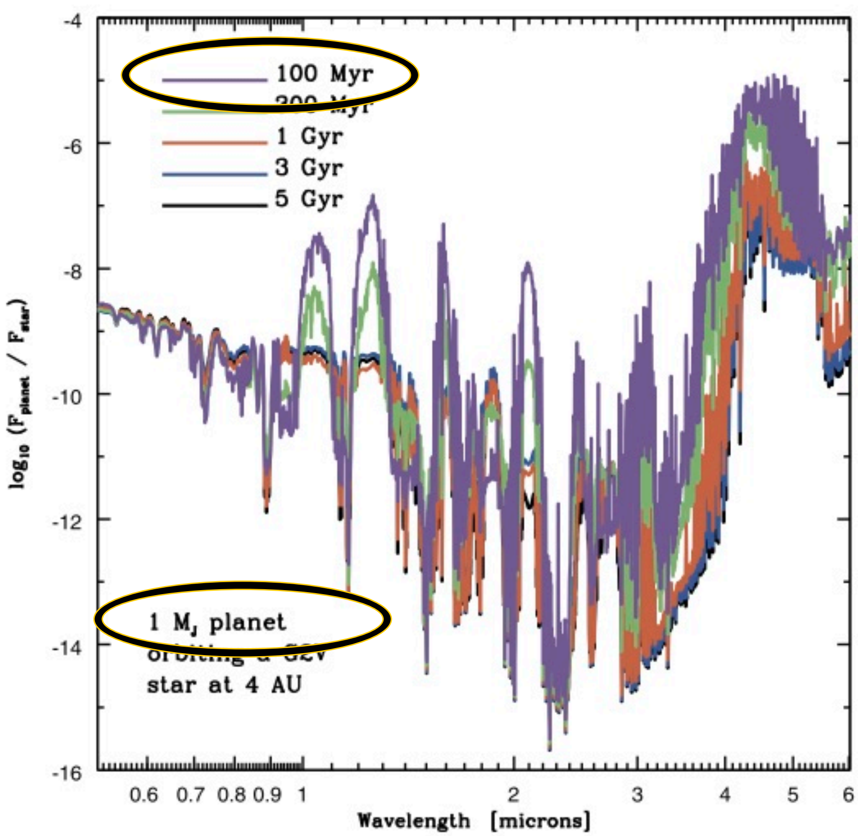


FIG. 6.—Planet-to-star flux ratio from 0.5 to 6.0 μm for a 1M_J EGP orbiting a G2 V star at 4 AU as a function of age. The ages are 0.1, 0.3, 1, 3, and 5 Gyr. An inner flux boundary condition $T_{\rm eff}$ from the evolutionary calculations of Burrows et al. (1997) has been employed. The effect of clouds is handled in the radiative transfer calculation in a completely consistent fashion. See Table 2, Fig. 2, and text for details and discussion.

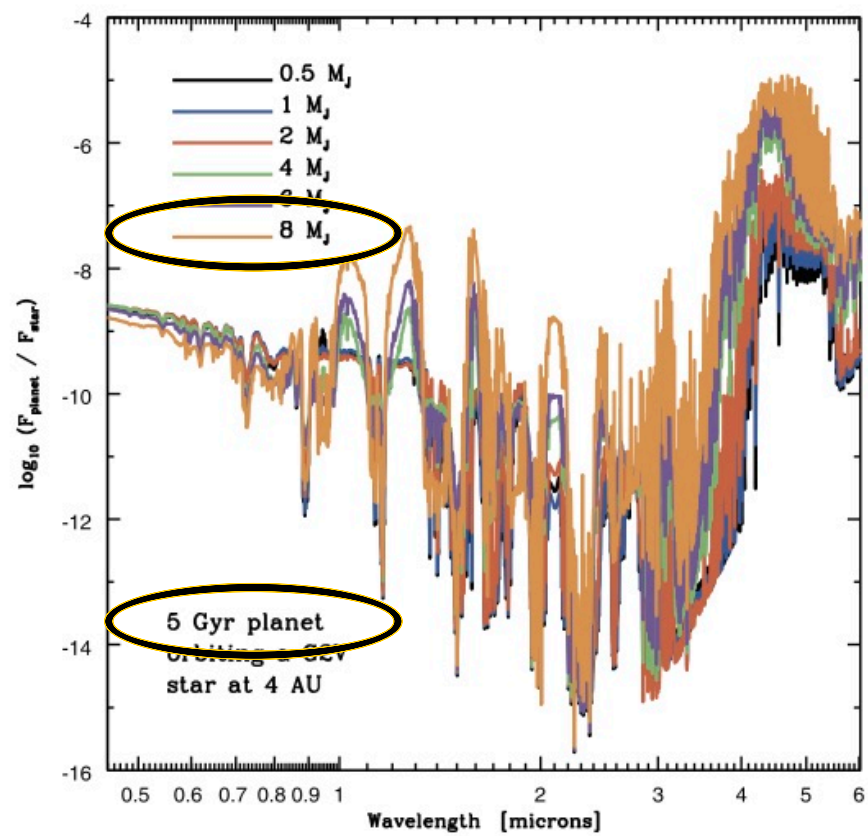


FIG. 7.—Similar to Fig. 6, but the planet-to-star flux ratio from 0.4 to 6.0 μm for a 5 Gyr EGP orbiting a G2 V star at 4 AU, as a function of EGP mass. The masses represented are 0.5M_J, 1M_J, 2M_J, 4M_J, 6M_J, and 8M_J. See Table 3 and text for a discussion.

Precursor Needs: Stellar Ages

Soderblom et al. (2014) PPIV

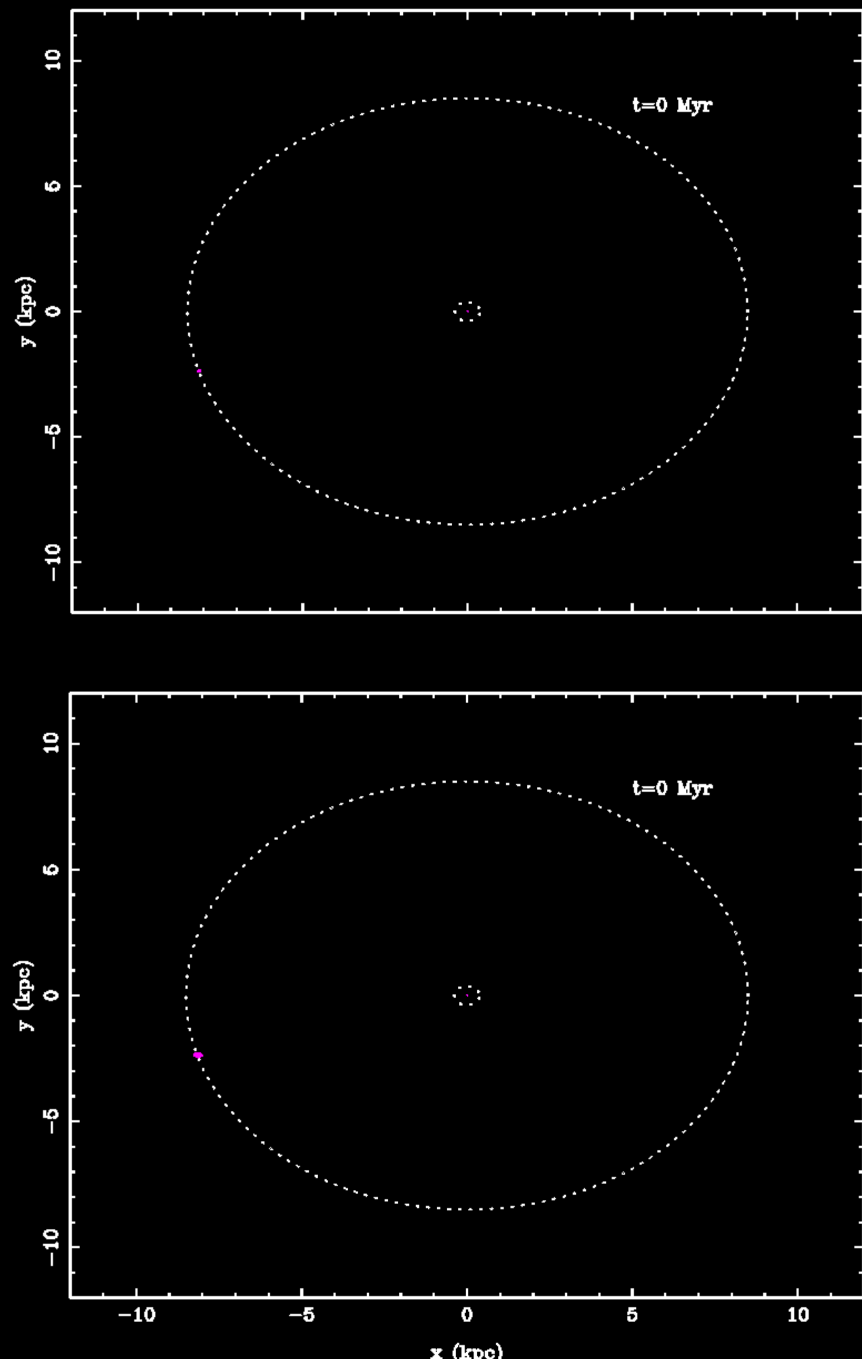
	1-10 Myr	~10-100 Myr	>100 Myr
$<0.1\ M_\odot$	isochrones, gravity, $R \sin i$, seismology?	LDB, isochrones, gravity	LDB, isochrones
0.1-$0.5\ M_\odot$	isochrones, gravity, $R \sin i$, disks	isochrones, Li, gravity	rotation/activity
0.5-$2.0\ M_\odot$	isochrones, disks	Li	rotation/activity
$>2.0\ M_\odot$	isochrones, seismology, R-C gap	isochrones, seismology	isochrones

The individual techniques within each cell are listed in order of reliability

Table 2: Useful age-dating methods for various mass- and age ranges in the H-R diagram

See various reviews:

Zuckerman & Song (2004) ARAA, 42, 685
Soderblom (2010) ARAA, 48, 581
Soderblom et al. (2014) PPIV
Jeffries (2014)
Papers by Mamajek, Hillenbrand, et al.

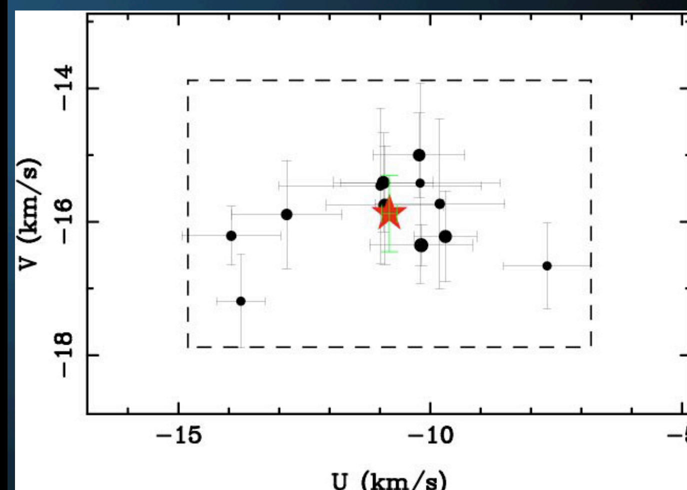


Kinematic ages

Forming stellar kinematic groups

At t=0 stars form in region 1 pc in radius, have velocity dispersion Δv.
Follow motion in galactic potential well.

Δv = 1 km/s

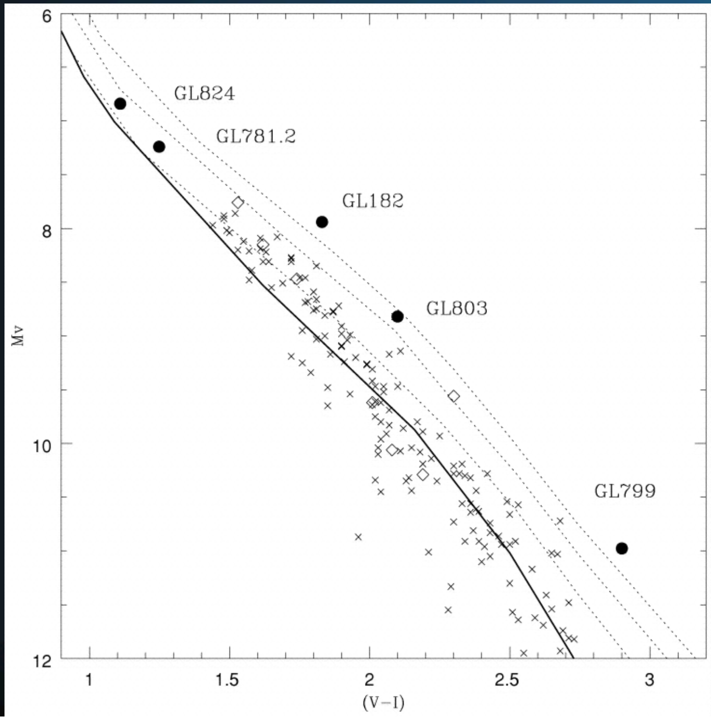


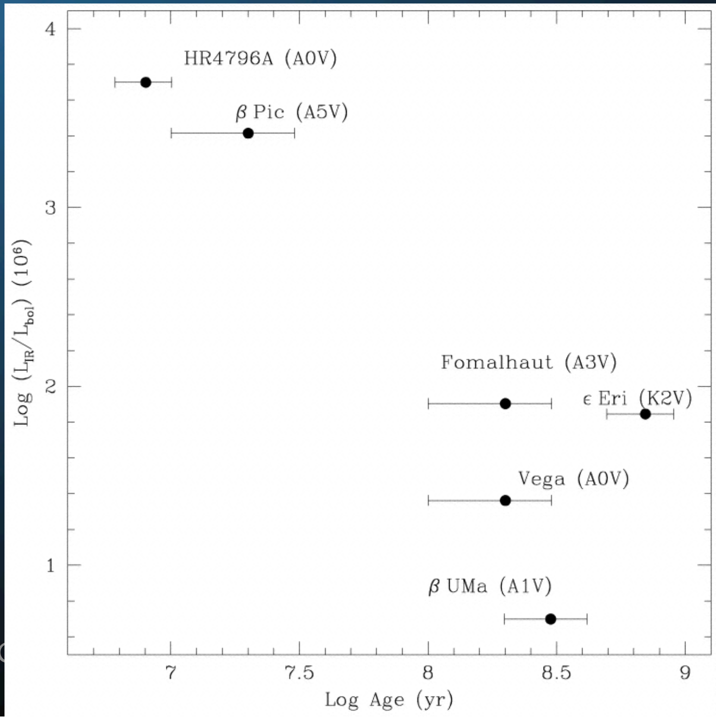
Δv = 3 km/s

The β Pic moving group

Barrado y Navascues et al. 1999

1. Original sample ~1000 stars
2. Calculate U, V, W using Hipparcos α, δ, μ,, π, and Rv from literature
3. Identify close matches in V $_{\beta\ \mathrm{Pic}}$, ±2 km/s (stars oscillate in U and W)
   2 km/s = 2 pc/Myr, If t>20 Myr, separation >40 pc
4. Find 6 candidates for a β Pic moving group
5. Estimate ages with CM diagram+isochrones, X-ray vs. (B-V), vs. Pleides & Hyades
6. **2** / 6 candidates are 20 Myr ± 10 Myr, V < 1 km/s, coeval with β Pic

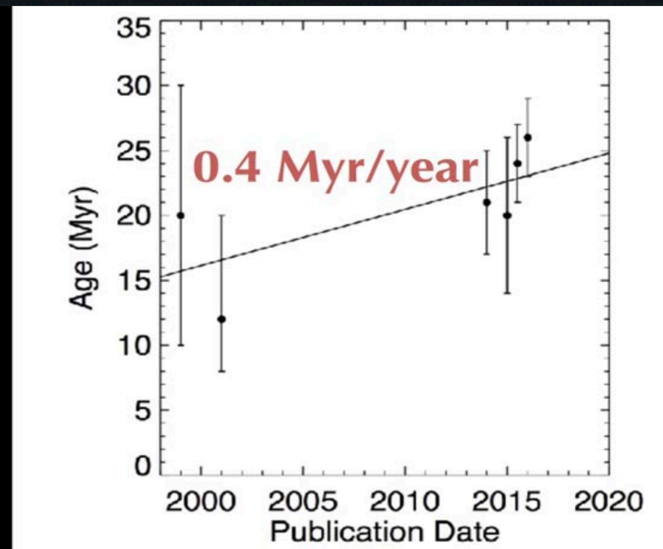




Recall Eric Nielsen's talk on a new age determination for the BPMG by studying binaries

The Age of the β Pic Moving Group

20 ± 10 Myr — Barrado y Navascues et al. 1999
12 (+8, -4) Myr — Zuckerman et al. 2001
21 ± 4 Myr — Binks & Jeffries 2014
20 ± 6 Myr — Macintosh et al. 2015
24 ± 3 Myr — Bell et al. 2015
26 ± 3 Myr — Nielsen et al. 2016



Many papers also search for new members (and exclude interlopers)

THE ASTROPHYSICAL JOURNAL, 562:L87–L90, 2001 November 20

THE β PICTORIS MOVING GROUP

B. ZUCKERMAN AND INSEOK SONG
M. S. BESSELL R. A. WEBB

17 members

See also:
Lepine & Simon 2009
Rice et al. 2010
Schlieder et al. 2010
Kiss et al. 2011

TABLE 2

MEASURED AND DERIVED QUANTITIES[a]

Quantity	HIP 23309	HIP 29964[b] (HD 45081)	HIP 76629 (HD 139084)	HIP 88399 (HD 164249)	β Pic (HIP 27321)
$\mu_{R.A.}$ (mas yr^{-1}):					
PPM	35	−11	−51	6.6	9.4
Hipparcos	36	−8	−53	3.5	4.7
$\mu_{decl.}$ (mas yr^{-1}):					
PPM	76	75	−97	−93	79
Hipparcos	73	71	−106	−86	82
Radial velocity (km s^{-1})	17.8 ± 0.8	15.0 ± 1.0	0.5 ± 0.9	0.1 ± 3.0	20.2 ± 0.4
T_{eff} (K)	3810	4288	5250	6420	8500
$B-V$	1.421	1.11	0.82	0.458	0.171
V	10.01	9.77	8.06	7.01	3.85
$V-I_C$	1.79	1.34	0.93	...	0.18
J	...	7.55	...	...	3.55
H	...	6.99	...	...	3.47
K	...	6.81	...	...	3.49
Li 6708 EW (mÅ)[c]	294	357	261	92	...
Hα EW (Å)[d]	−0.81	−0.65	0.49	1.46	−
ROSAT (counts s^{-1})	0.33	1.03	1.42	0.15	...

[a] Radial velocity, Li, and Hα EWs for HIP 23309, 29964, and 76629 are from our echelle spectra; $B-V$, V, $V-I_C$ for HIP 23309 and 29964 are from L. Berdnikov (2001, private communication); J, H, and K for HIP 29964 are from the Two Micron All Sky Survey catalog; radial velocity for β Pic is from Barrado y Navascués et al. 1999. Colors and V for HIP 76629 are from Cutispoto et al. 1999.

[b] Cutispoto et al. 1999 list a set of measurements for HIP 29964; radial velocity = 16.2 ± 0.7 km s^{-1}, $v \sin i$ = 17 ± 2 km s^{-1}, $(B-V)$ = 1.13, V = 9.80, and $(V-I_C)$ = 1.32. Average radial velocity of our value, 15.0 km s^{-1}, and Cutispoto et al.'s was used to calculate (U, V, W).

[c] Measured lithium equivalent widths corrected for the contribution of an Fe I λ6707.44 line. Corrections are 25, 19, 13, and 6 mÅ for HIP 23309, 29964, 76629, and 88399, respectively (Soderblom et al. 1993).

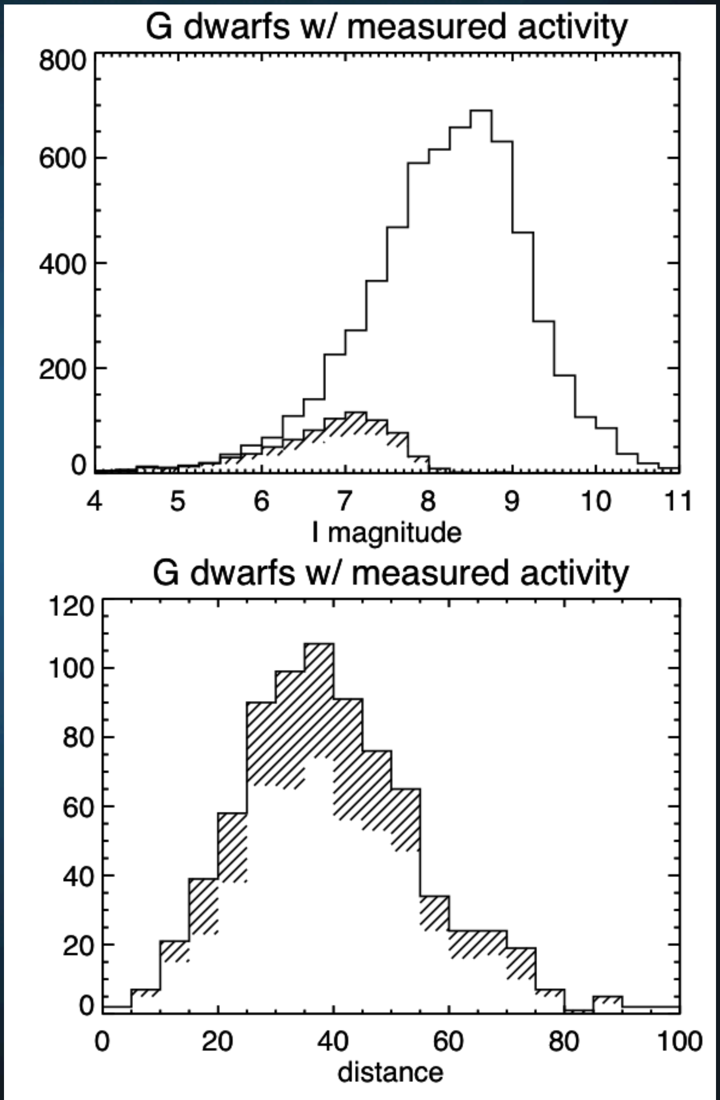
[d] Line core equivalent widths of Hα. The minus sign indicates emission.

GPI Target Selection Programs

- Jenny Patience & Inseok Song lead the team for target selection (Starting from ~5 years before the instrument was commissioned, with help from Wright, Bessel, Zuckerman & others)
  - Drawing up candidate lists
  - Observing programs for age indicators

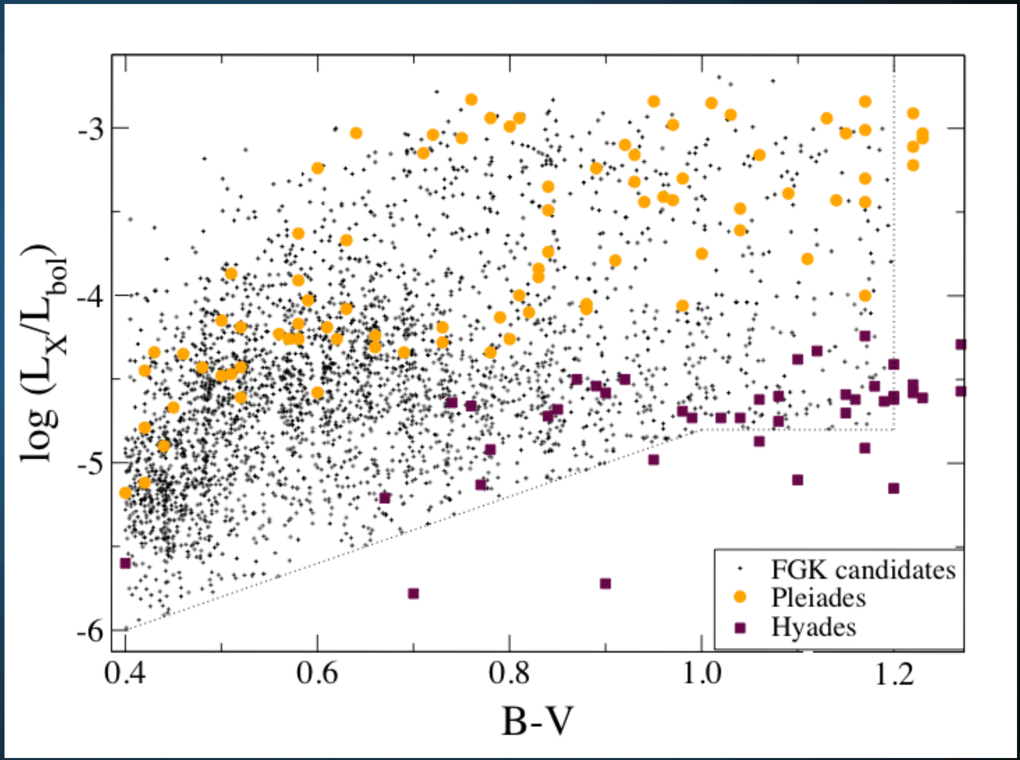
Adolescent Stars

- Goal is to identify adolescent (0.1–2 Gyr) F, G, K, & M stars by their levels of chromospheric activity.
- HIPPARCOS catalog ≈ 7500 G, K, & M dwarfs < 60 pc and *I* < 9 mag.
  - More than 1900 of these potential GPI targets have measured activity
  - About 500 show activity levels consistent with ages of less than 2 Gyr.



X-ray Selected FGK Stars

- Selected 3052 X-ray bright Tycho-2 stars
  - Prioritized into four groups by
    - Proper motion (distance proxy)
    - Galactic latitude
    - *I*-band mag.
    - X-ray luminosity
  - Spectra (*R*~15,000) for top 1500 stars to get age estimates
- Seven runs at Siding Spring



A Stars

- Attractive GPI targets
  - Many debris disks around A stars show evidence for planetary perturbations (β Pic, Fomalhaut, HR 4796A, etc.)
  - Necessarily young
    - F0V (1.6 $M_{\odot}$) has a 2.1 Gyr main sequence lifetime
  - Poor RV targets
  - Rare & bright– poorly represented in transit searches
- AO target vetting program
  - Sample of 334 10-700 Myr A stars from Hipparchos based on CMD
    - Divided into <100 Myr and >100 Myr
    - Used Gemini, Palomar, CFHT, & Lick to observe ~ half of the sample

We reject binaries/multiples. Why?

- In case of a relative bright companion within ~3″, difficult to close the AO loops on the primary.
- Dynamical argument – giant planet would be unstable.

From Theory: Artymowicz & Lubow 1994

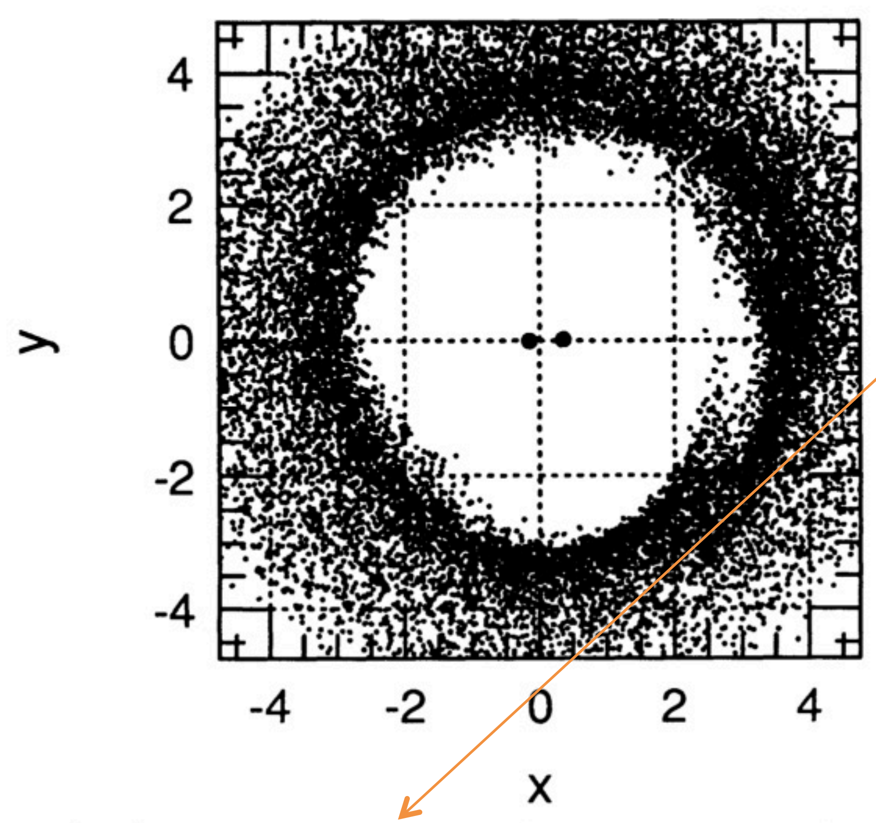


FIG. 10.—A gap out to $r \approx 2.8a$ surrounding a $\mu = 0.3$, $e = 0.5$ binary. The gap is much larger than in Fig. 9, extending to between 4:1 and 5:1 orbital commensurabilities. Stars are at their 50th periastron passage.

Circumbinary disk

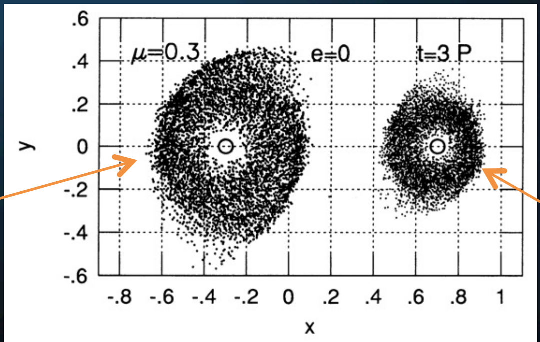
r ~ 3 a

Assuming μ =0.3, e=0.5

r ~ 2 a

Assuming μ =0.3, e=0.0

Also explores outer edges for circumprimary and circumsecondary disks



r ~ 0.5 a

r~0.2 a

See Mariangela Bonavita talk

From Observations: see talk from Adam Kraus

3:40 pm	*Afternoon Break*	
	Session Chair:	Knicole Colon (NASA GSFC)
4:10 pm	**Invited Talk:** Stellar Companions and Properties from High Resolution Imaging	David Ciardi (Caltech/IPAC-NExScI)
4:40 pm	The Impact of Binary Companions on Planetary Systems	Adam Kraus (UT Austin)
4:55 pm	Stellar Companions of Exoplanet Host Stars in K2	Rachel Matson (NASA Ames)
5:10 pm	Robo-AO KOI Survey: LGS-AO Imaging of Every Kepler Planetary Candidate Host Star	Carl Ziegler (University of North Carolina, Chapel Hill)

THE IMPACT OF STELLAR MULTIPLICITY ON PLANETARY SYSTEMS, I.: THE RUINOUS INFLUENCE OF CLOSE BINARY COMPANIONS

Adam L. Kraus[1], Michael J. Ireland[2], Daniel Huber[3,4,5] Andrew W. Mann[1], Trent J. Dupuy[1]

First and only use of "ruinous"
in the title of a paper
for entire history of astronomy
written in English

Direct Imaging of Extrasolar Planets:
The GPI Exoplanet Survey (GPIES)

890 hours of Gemini South telescope time makes this the largest and most systematic direct-imaging exoplanet survey to date (rivaled only by the VLT SPHERE GTO program.)

Enable both new discoveries and a robust statistical measurement of the giant planet occurrence rate in the 5-50 AU range – the crucial transition between Doppler surveys showing the giant planet frequency at <5 AU, and previous imaging searches sensitivity primarily to >50 AU.

Explore the architecture of other planetary systems through the properties of circumstellar debris disks, and characterize the atmospheres of young giant planets at high SNR.

486 out of 890 hours executed (*H*-band survey for planets & disks; J,K follow-up on planets)

340 out of 600 targets observed

Mid-survey statistics paper *in prep* led by Eric Nielsen.

GPIES Target Properties

Young A,F,G,K,M stars (D<75pc, Age<~300Myr)
Sco-Cen A/F stars (D<150pc, age ~10 Myr)

Plus resolved debris disk sample

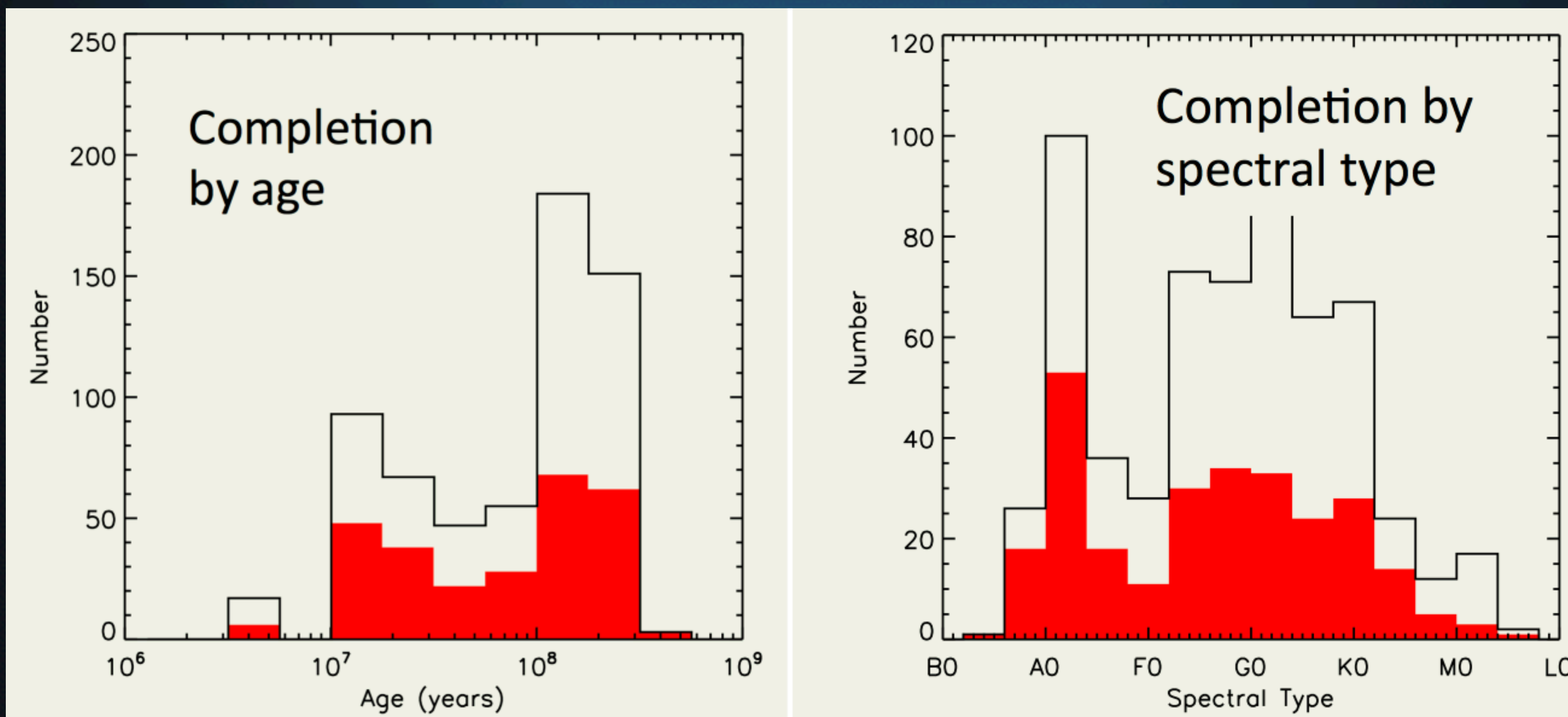
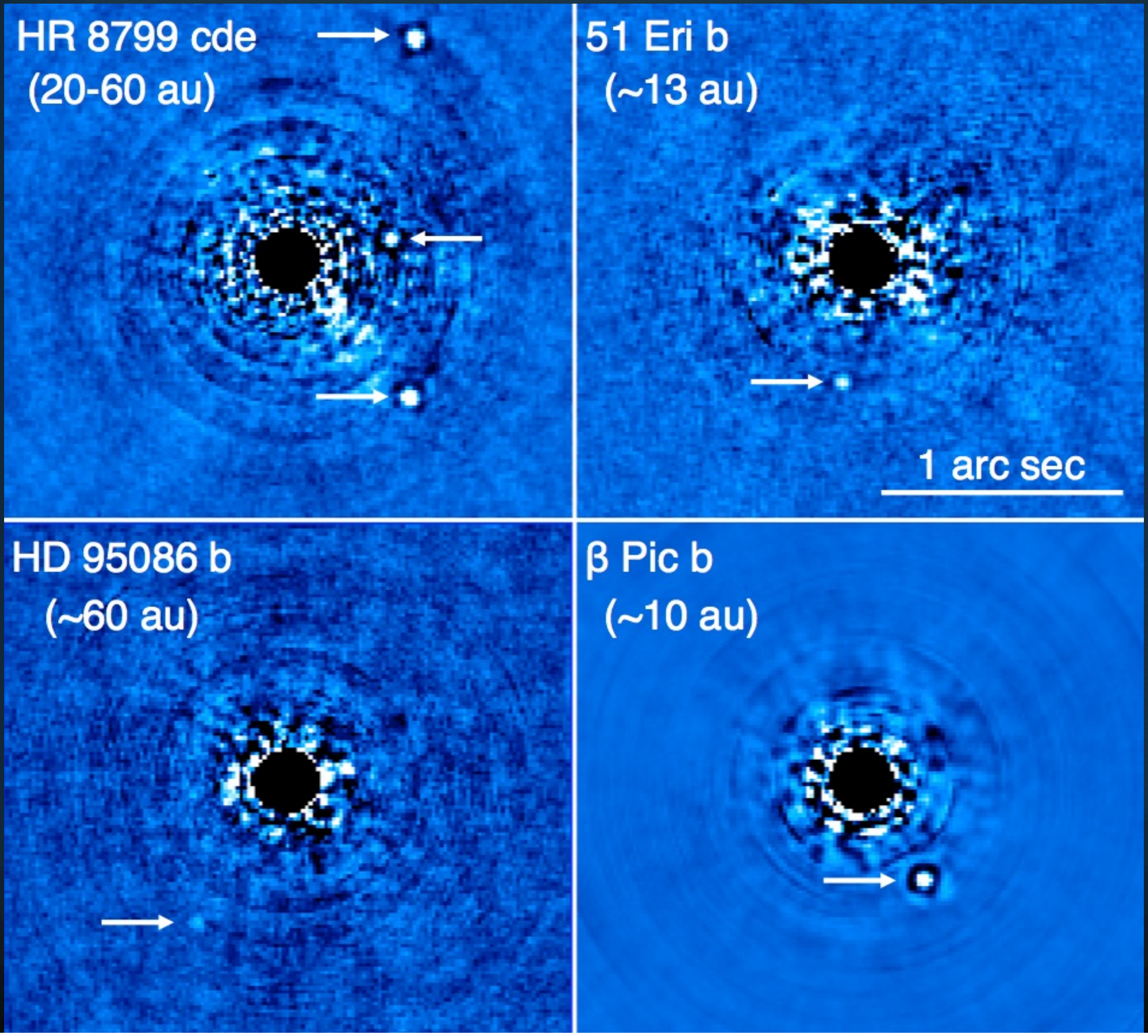


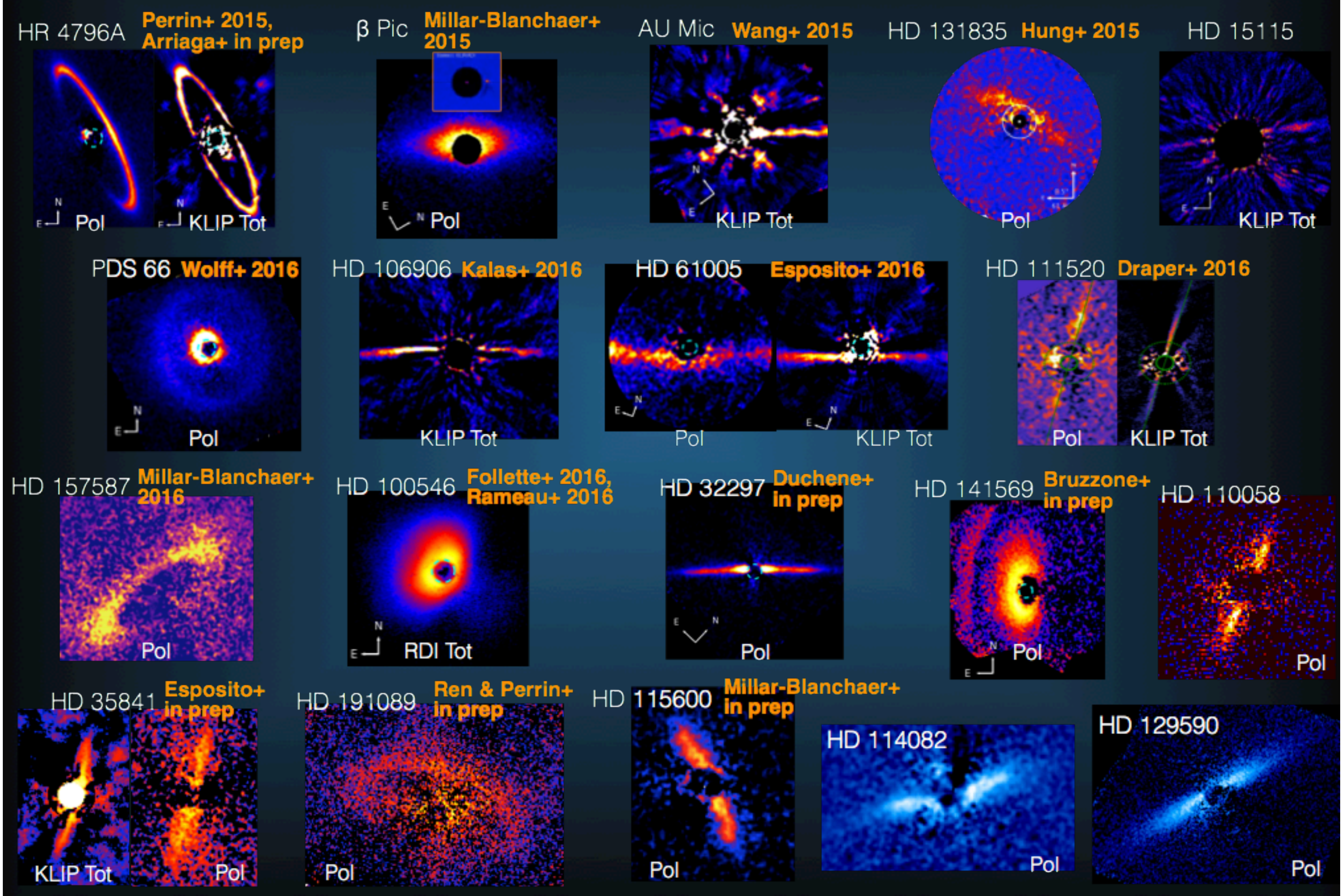
Image credit: Rob De Rosa

Direct Imaging of Extrasolar Planets:

The GPI Exoplanet Survey (GPIES)



GPIES Disk Gallery



Outline

I. Precursor needs - observations needed to plan direct imaging surveys

II. Follow-up observing needs - to confirm and characterize directly imaged planetary systems.

III. Future needs – to directly image Earth twins.

Recent comprehensive review

Publications of the Astronomical Society of the Pacific, 128:102001 (38pp), 2016 October

Imaging Extrasolar Giant Planets

Brendan P. Bowler
McDonald Observatory and the University of Texas at Austin, Department of Astronomy,

"Survey of Surveys" since 2007:

VLT/MMT (Biller) - Gemini/GDPS (Lafreniere) - MMT (Heinze) - VLT/NaCo (Chauvin, Rameau) - Subaru/SEEDS (Tamura) - Gemini/NICI (Liu) - IDPS (Marois) - PALMS (Bowler) - VLT/NACO-LP (Beuzit) - P1640 (Oppenheimer) - LEECH (Skemer) - SPHERE (Beuzit) - MagAO (Close) - SCExAO (Guyon) - GPIES (Macintosh).

Plus smaller surveys by Apai, Janson, Kalas, Meshkat, Oppenheimer, Song, et al.

Table 3
The Frequency of 5–13 $M_{\rm Jup}$ Planets on Wide Orbits

Sample	Number of Stars	Occurrence Rate (10–100 au)	Occurrence Rate (30–300 au)	Occurrence Rate (10–1000 au)	Occurrence Rate (100–1000 au)
BA	110	$7.7^{+9.0}_{-6.0}$%	$2.8^{+3.7}_{-2.3}$%	$3.5^{+4.7}_{-2.5}$%	<6.4%
FGK	155	<6.8%	<4.1%	<5.8%	<5.1%
M	119	<4.2%	<3.9%	<5.4%	<7.3%
All Stars	384	$0.8^{+1.2}_{-0.5}$%	$0.6^{+0.7}_{-0.5}$%	$0.8^{+1.0}_{-0.6}$%	<2.1%

Note. Assumes circular orbits, logarithmically flat planet mass-period distributions, and hot-start evolutionary models from Baraffe et al. (2003). All binaries within 100 au of the host stars have been removed. Occurrence rates are 68% credible intervals and upper limits are 95% confidence values.

We just directly imaged a possible planet, now what?

- Is it really a planet? (versus a speckle, a background star, or a companion low mass star or brown dwarf)
- Flux (relative to star – we work in contrast units), color and spectra?
- What is the age of the star?
- What is the mass of the planet?
- Is the star really a single star? (RV can be helpful)
- Is there a debris disk? (see talks by Tiffany Meshkat & Samantha Lawler)
- If there is a debris disk, what properties help understand the planet?
- Which theory of planet evolution is favored?
- Variability of the planet ("weather") – time domain studies
- Polarization of the planet.
- Circumplanetary rings and moons?

Case study: HD 131399Ab

Jason Wang's talk

12:10 pm	*Lunch Break*	
	Session Chair:	Rachel Street (LCO)
1:40 pm	**Invited Talk:** Observational Needs for Direct Imaging Surveys	Paul Kalas (UC Berkeley)
2:10 pm	First Constraints on the Frequency of Sub-stellar Companions on Wide Circumbinary Orbits	Mariangela Bonavita (University of Edinburgh, IfA)
2:25 pm	The Cautionary Tale of HD 131399 Ab	Jason Wang (C Berkeley)
2:40 pm	Occurrence of Giant Planets Around Stars with Dusty Debris Disks	Tiffany Meshkat (Caltech/IPAC)
2:55 pm	Debris Disks in STIPs	Samantha Lawler (NRC-Herzberg)
3:10 pm	*Afternoon Break*	
	Session Chair:	Samantha Lawler (NRC-Herzberg)
3:40 pm	**Invited Talk:** Observational Needs for Microlensing Surveys	Rachel Street (LCO)
4:10 pm	Using AO Follow-up to Characterize Microlensing Exoplanets	Calen Hendersen (Caltech/IPAC-NExScI)
4:25 pm	Microlensing Exoplanet Mass Measurement in the WFIRST Era	Aparna Bhattacharya (NASA GSFC)

Case studies for the "know thy star" theme

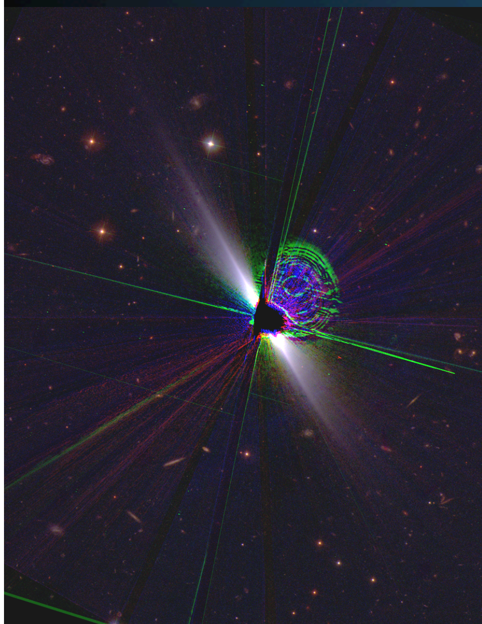
- β Pic – timely with a connection to disks & transit science
- ~~HR 8799~~
- ~~Fomalhaut~~
- ~~51 Eri~~
- ~~HD 106906~~
- ~~HD 95086~~

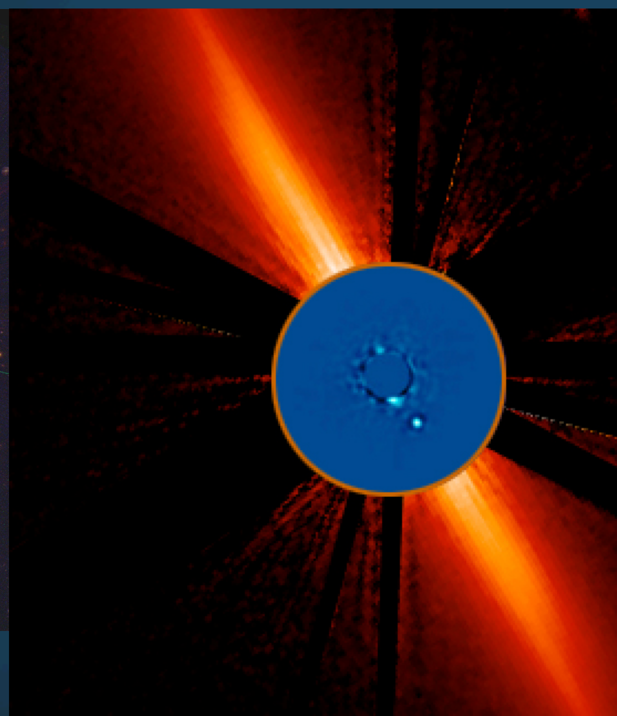
Case study: Beta Pic b

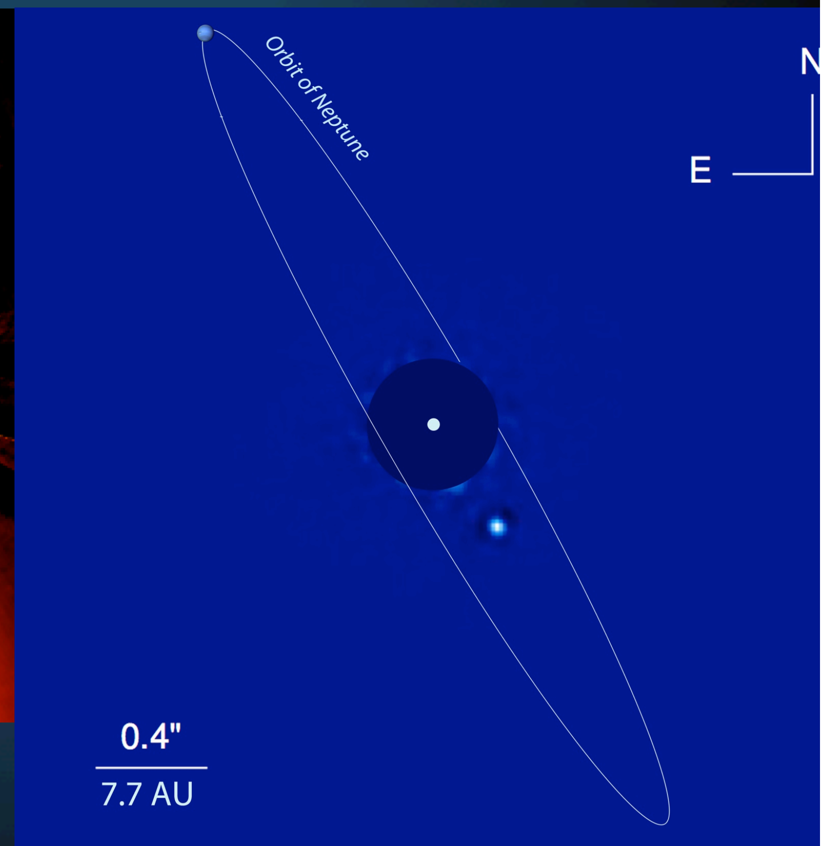
Huge, edge-on debris disk imaged in scattered light in 1984

Planet Beta Pic b announced by Lagrange et al. 2009, imaged by many groups including GPI

Orbit at ~9.7 AU has P ~ 22 years



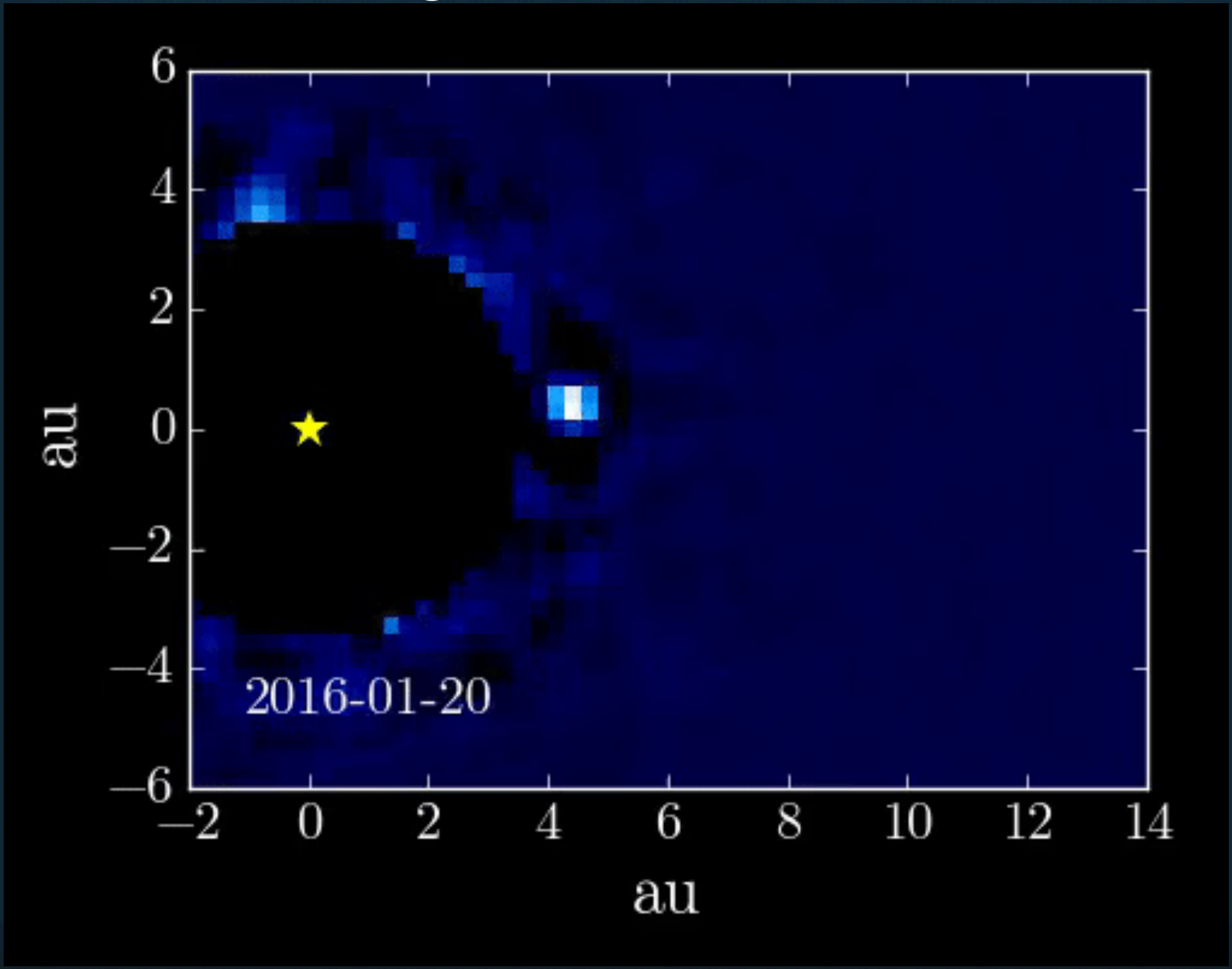




Puzzling asymmetries due to unseen perturber.

But is the orbit it exactly edge-on?

Orbital motion of beta Pic b as directly imaged with the Gemini Planet Imager 2013-2016



Animation: Jason Wang

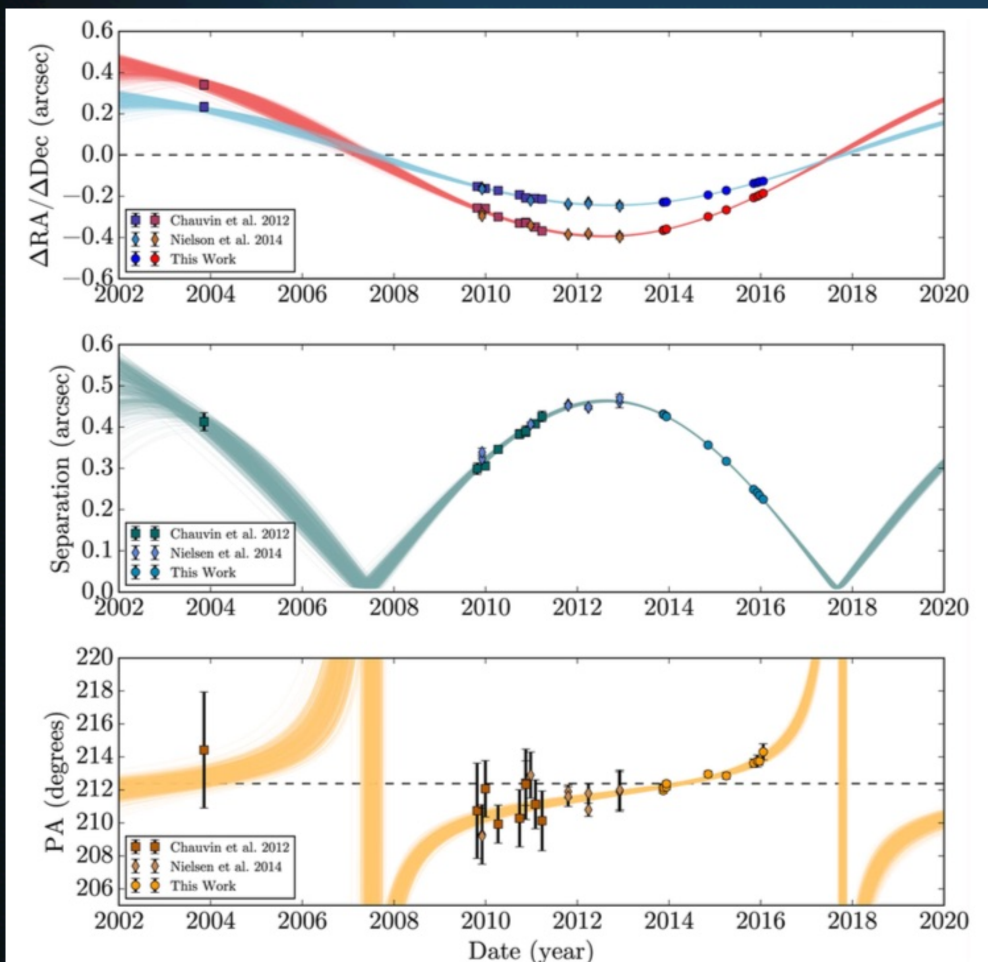
The Astronomical Journal, 152:97 (16pp), 2016 October
doi:10.3847/0004-6256/152/4/97
© 2016. The American Astronomical Society. All rights reserved.

CrossMark

THE ORBIT AND TRANSIT PROSPECTS FOR β PICTORIS b CONSTRAINED WITH ONE MILLIARCSECOND ASTROMETRY

Jason J. Wang[1], James R. Graham[1], Laurent Pueyo[2], Paul Kalas[1], Maxwell A. Millar-Blanchaer[3],
Jean-Baptiste Ruffio[4], Robert J. De Rosa[1], S. Mark Ammons[5], Pauline Arriaga[6], Vanessa P. Bailey[4], Travis S. Barman[7]

jwang@berkeley.edu



Beta Pic b Orbital Parameters

a = 9.66 AU (~22 year orbit)

e = 0.08 (low eccentricity)

i = 88.81° ± 0.10 (90° = edge-on)

For a transit need, >89.95°

The planet will NOT pass in front of the star!

Closest approach in projection is 10 mas, or 0.2 AU.

The Hill sphere radius r_H = 1.2 AU. It transits!

$$r_H \approx a(1 - e)\sqrt[3]{\left(\frac{m}{3M}\right)}$$

M = planet mass = 13 M_J

M = star mass = 1.8 M_{Sun}

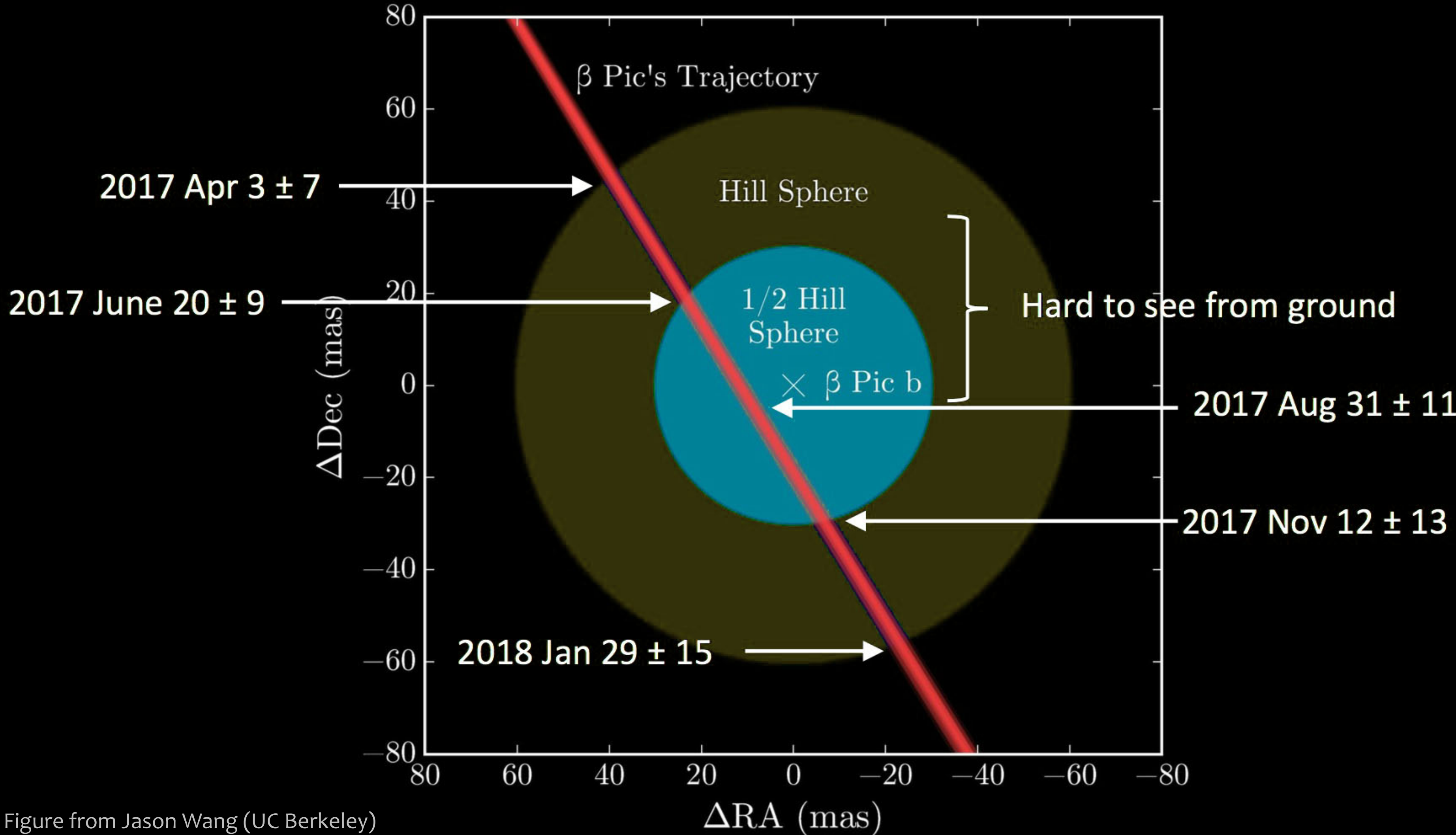
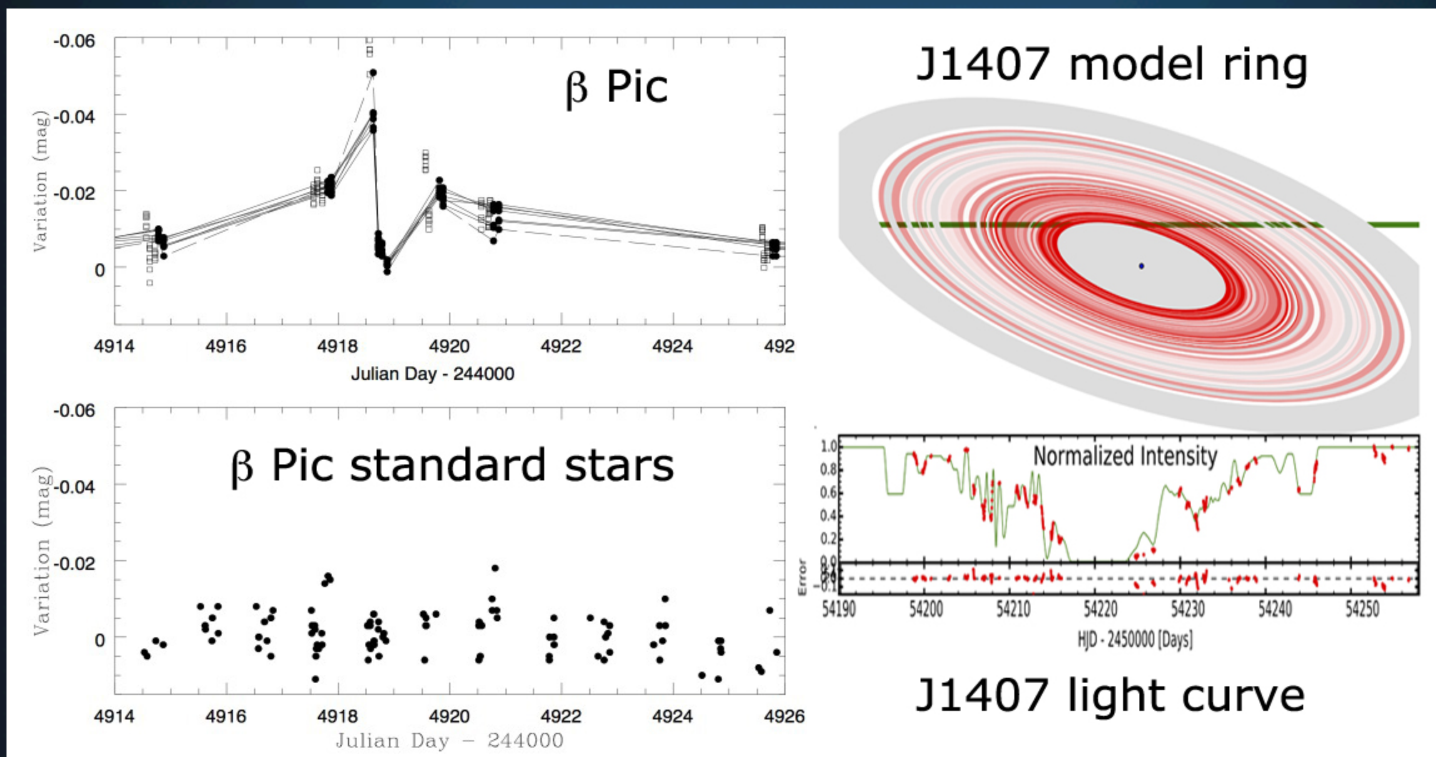


Figure from Jason Wang (UC Berkeley)

What are we expecting?

In principle:
Moons as large as Ganymede (r = 2630 km) would give transit depths of 6×10^{-6} (6.5 μmag).
Moons as large as Earth (r = 6371 km) would give transit depths of 4×10^{-5} (0.04 mmag).
The transit duration is ~45 hours, but very hard to obtain photometric precision for a moon.

Ring signatures ARE possible. E.g. J1407 light curve; various depths over many days.



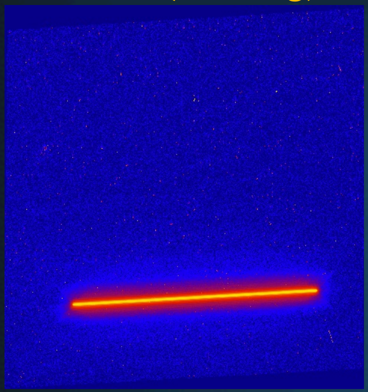
Lecavelier des Etangs+1997

Kenworthy & Mamajek 2015

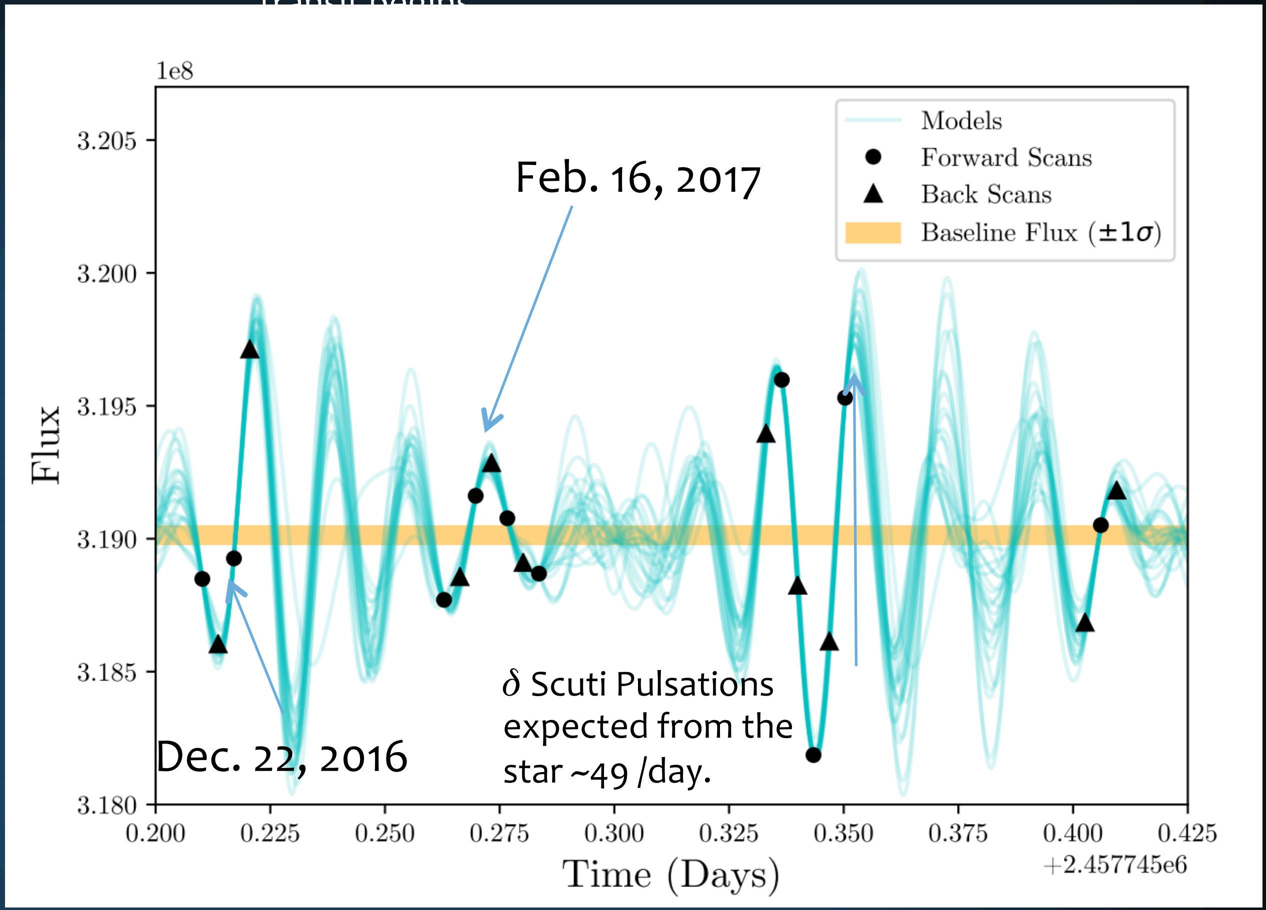
Hubble Space Telescope Spatial Scanning for Precision Photometry

Baseline observations to determine photometric uncertainties with our method before the Hill sphere transit begins

GO-14621 (PI Wang)



WFC3/UVIS, F953N, 0.5 arcsec/sec



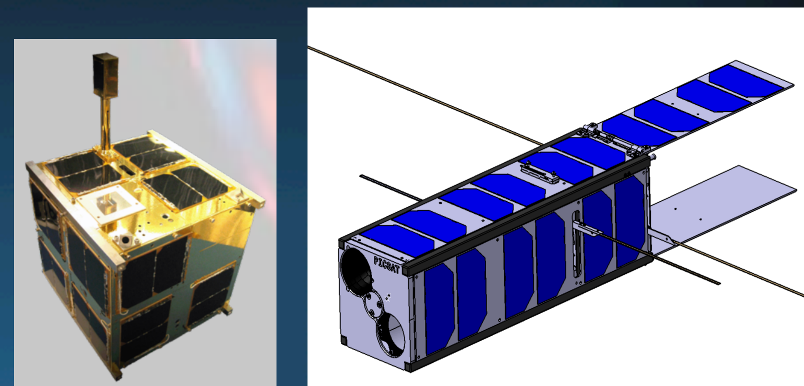
1.5x 10^{-3} fractional offset in the mean stellar flux between December and February.

Defines the precision to which we could detect a ring occultation, optical depth $\tau \sim 10^{-3}$.

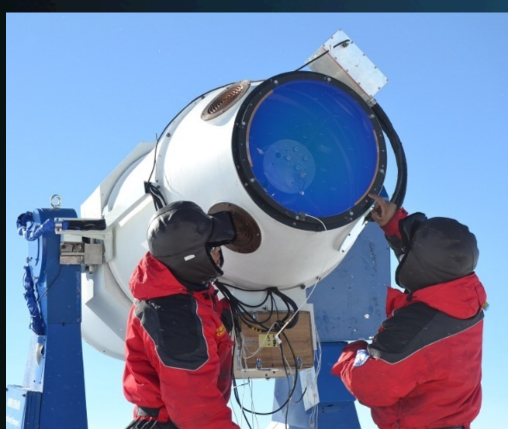
Data Reduction: Kevin Stevenson (STScI)
Analysis: Jason Wang (UC Berkeley)
δ Scuti pulsations modeled as quasiperiodic Gaussian processes

International Transit Monitoring Efforts

Hubble Space Telescope
J. Wang, P. Anthony-Wilson



Nanosats
K. Zwintz, S. Lacour



Antarctic Telescopes
L. Wang, T. Guillot

bRing
M. Kenworthy, E. Mamajek

Spectroscopic Monitoring
B. Lomberg, E. de Mooij

Outline

I. Precursor needs - observations needed to plan direct imaging surveys

II. Follow-up observing needs - to confirm and characterize directly imaged planetary systems.

III. Future needs – to directly image Earth twins.

Future Needs: GAIA

- Moving groups – more targets, better ages.
- Star-Star encounters.
- Star-Sun encounters

Moving groups – more targets (esp. late type), better ages.

Young Stars & Planets Near the Sun
Proceedings IAU Symposium No. 314, 2015
J. H. Kastner, B. Stelzer, & S. A. Metchev, eds.

© International Astronomical Union 2016
doi:10.1017/S1743921315006250

A Pre-Gaia Census of Nearby Stellar Groups

Eric E. Mamajek

These groups got a grade of either "Pass" or "Satisfactory"

Table 1. Catalog of Stellar Groups Within 100 pc

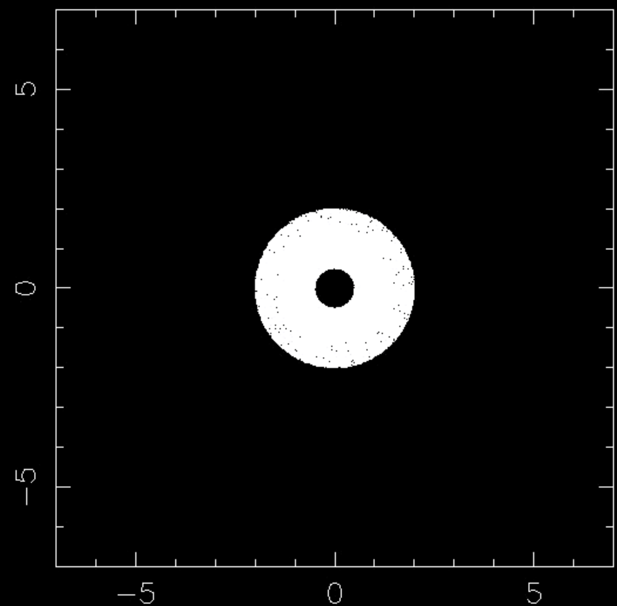
Group ...	Dist pc	Ref. ...	U km/s	V km/s	W km/s	$\sigma_U, \sigma_V, \sigma_W$ km/s	σ_v km/s	Ref. ...	Age Myr	Ref. ...
β Pic	$\sim 15^a$	1	-10.9	-16.0	-9.2	0.3, 0.3, 0.3	1.5	2	23 ± 3	2
AB Dor	20.1 ± 1.6	3	-7.6	-27.3	-14.9	0.4, 1.1, 0.3	1.0	3	150^{+50}_{-30}	4
UMa	25.2 ± 0.3	5	14.6	1.8	-8.6	0.4, 0.7, 1.0	1.4	5	530 ± 40	6
Car-Near	33 ± 1	5	-24.8	-18.2	-2.3	0.7, 0.7, 0.4	1.3	5	~ 200	7
β Tuc	43 ± 1	5	-9.6	-21.6	-0.7	1.0, 1.3, 0.6	1.1	5	45 ± 4	4
Tuc-Hor	~ 48	9	-10.6	-21.0	-2.1	0.2, 0.2, 0.2	1.1	8	45 ± 4	4
Hyades	46.5 ± 0.5	10	-42.3	-19.1	-1.5	0.1, 0.1, 0.2	0.3	11	750 ± 150	6
Columba	~ 50	1	-12.2	-21.3	-5.6	1.1, 1.2, 0.9	...	...	42 ± 5	4
TW Hya	53 ± 2	12	-11.2	-18.2	-5.1	0.4, 0.4, 0.4	0.8	12	10 ± 3	4
Carina	~ 65	1	-10.5	-22.4	-5.8	1.0, 0.6, 0.1	...	...	45 ± 10	4
Coma Ber	87 ± 1	10	-2.4	-5.5	-0.6	0.1, 0.1, 0.1	0.4	13	560 ± 90	14
32 Ori	92 ± 2	4	-11.8	-18.5	-8.9	0.4, 0.4, 0.3	~ 1	5	22 ± 4	4
η Cha	94 ± 1	15	-10.2	-20.7	-11.2	0.2, 0.1, 0.1	1.5	15	11 ± 3	4
χ^1 For	99 ± 6	5	-13.1	-22.1	-3.7	0.4, 0.5, 1.1	...	5	$\sim 50?$	5

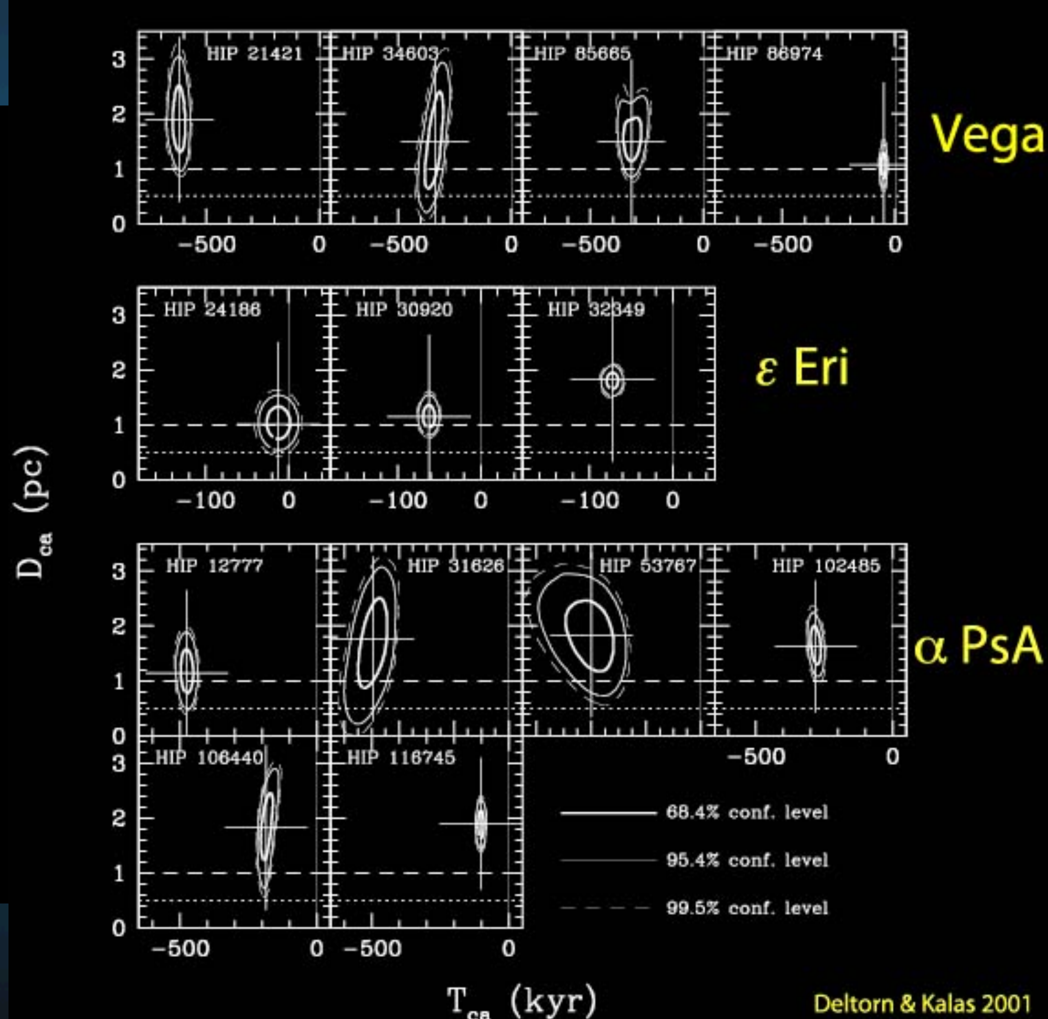
Failed the class
(retake the test with GAIA)

Argus
Oct-Near
Her-Lyr
Castor
IC 2391 Supercluster
Local Association
Polaris
Chereul 3 & 2
Latyshev 2

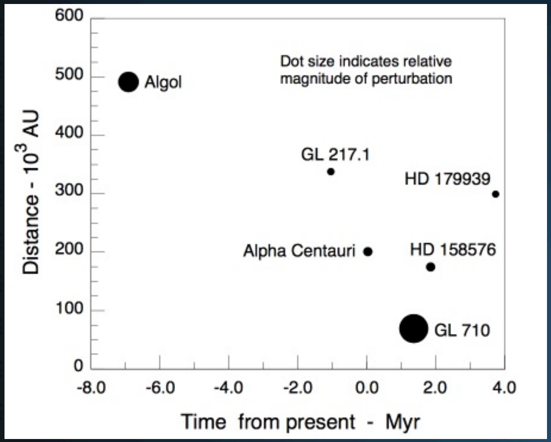
Know thy stellar neighborhood

Star-Star encounters

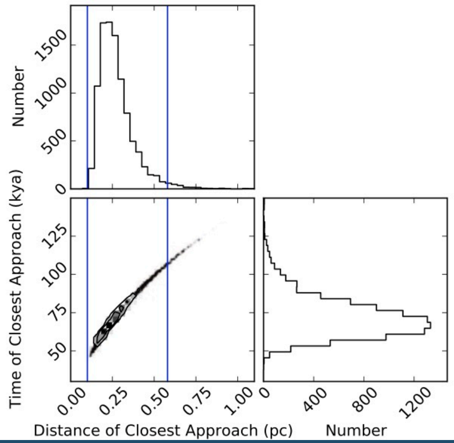




Star - solar system encounters

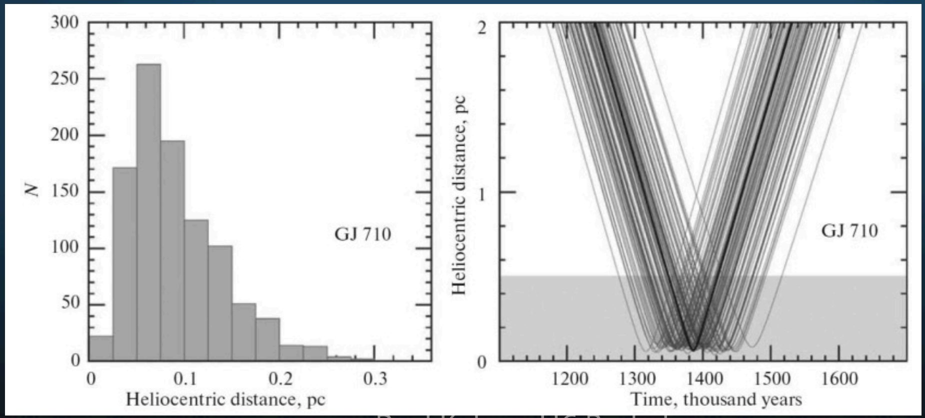


“Stellar encounters with the Oort cloud based on Hipparchos data” Garcia-Sanchez et al. 1999



“The closest known flyby of a star to the solar system” Mamajek et al. 2015

HIP 85605

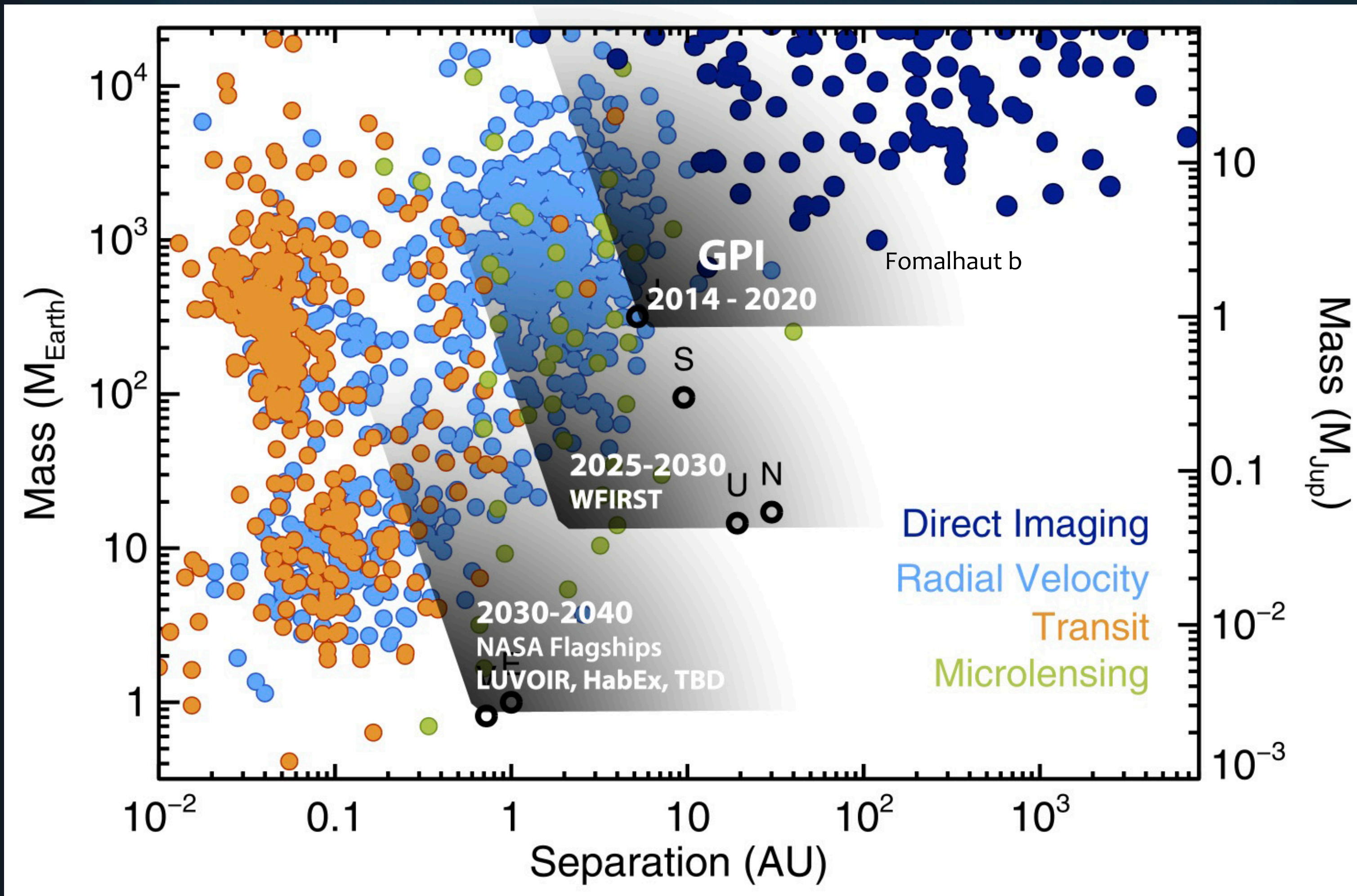


Using GAIA DRM1

Bobylev & Pajkova 2017

14,000 years in the future

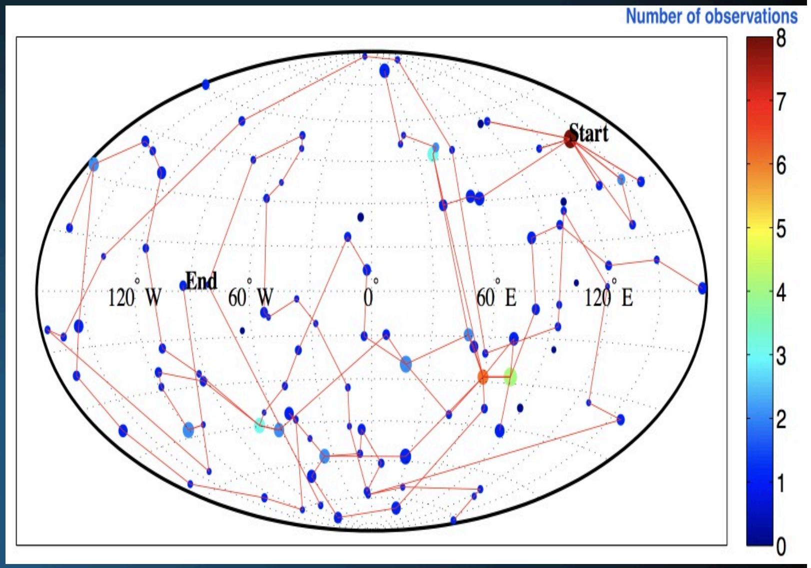
Observing Needs of Far-Future Images



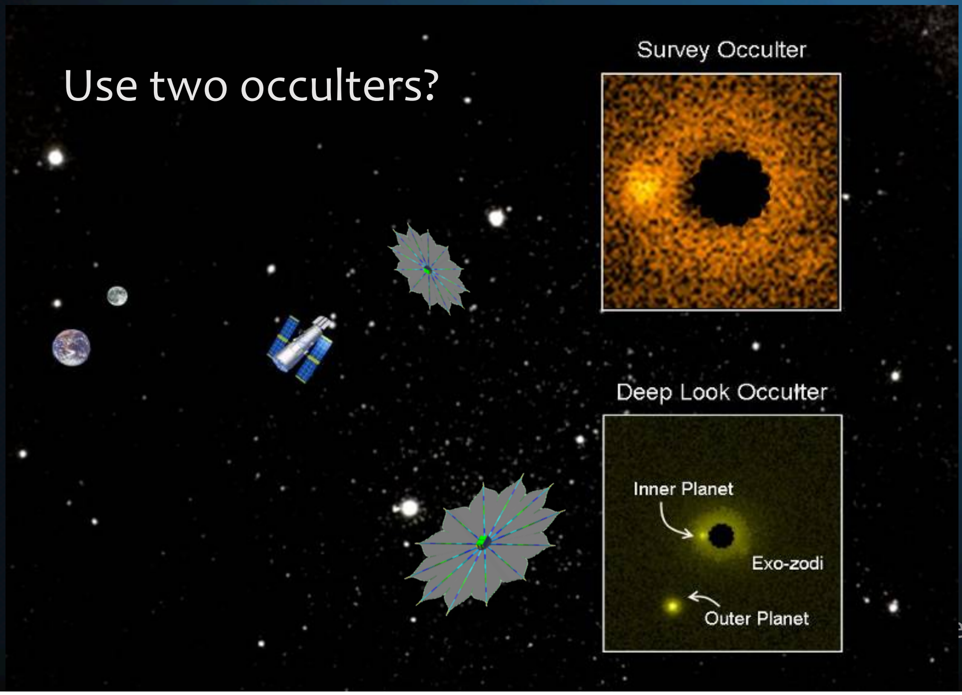
Background plot from Bowler 2016

External Occulter Missions

- Goal to detect and characterize HZ Earth-like planets
- Slew times measured in weeks
- 1/3 of the entire mission will be slewing
- Which targets, how many, and in what priority? Plus how do the answers change after each observation?



Savransky et al. 2010



Exozody strikes again.

Slide from Steve Warwick

Future needs: Know thy background stars

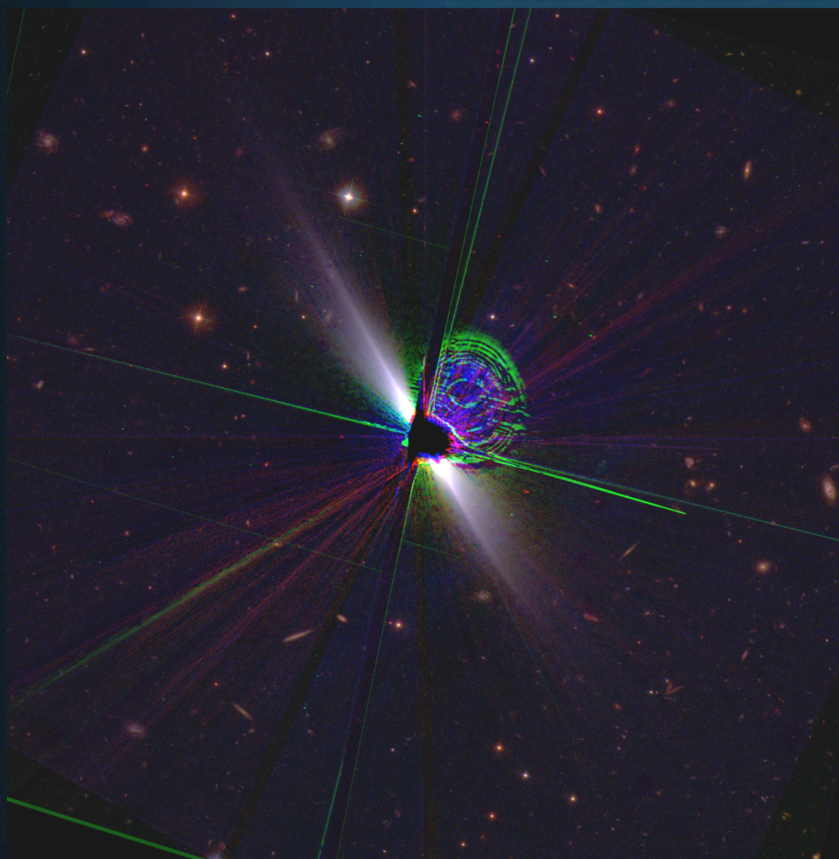
Deep fields for occulter pointings

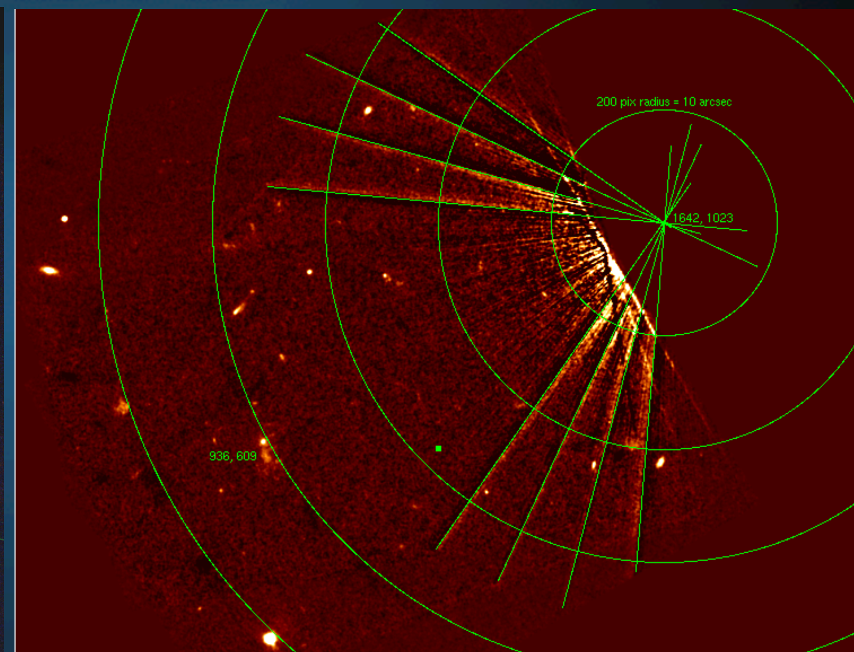
Some of the deepest optical images of β Pic (left) and ε Eri (right), but…

(1) these are young (<1 Gyr) and would not be occulter targets.

(2) The sensitivity limit of $m_V \sim 24$ mag isn't nearly as sensitive as needed

(3) Need long-lead time to image background surrounding >3 Gyr old stars



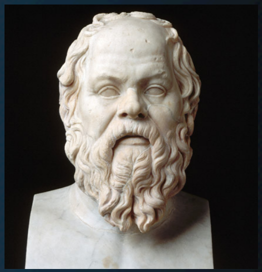


HST Deep Optical Images

Image credit: Paul Kalas

Summary

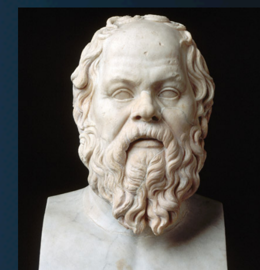
Basic Principles



- Socrates: “ὁ δὲ ἀνεξέταστος βίος οὐ βιωτὸς ἀνθρώπω” An unexamined life is not worth living…know thyself.
- Direct Imaging gurus: An unexamined star is not worth imaging… know thy star.

Summary

Basic Principles



- Socrates: “ὁ δὲ ἀνεξέταστος βίος οὐ βιωτὸς ἀνθρώπω” An unexamined life is not worth living…know thyself.
- Direct Imaging gurus: An unexamined star is not worth imaging… know thy star.

Consequences

- Socrates: was promptly executed.
- Direct imaging gurus: execute observations and discover planets.