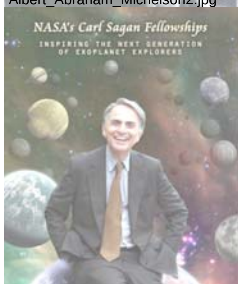
http://en.wikipedia.org/wiki/File:
Albert_Abraham_Michelson2.jpg



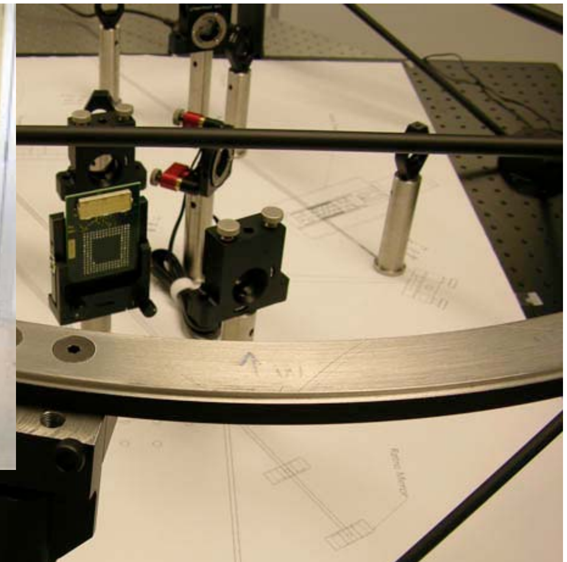
http://nexsci.caltech.edu/sagan/

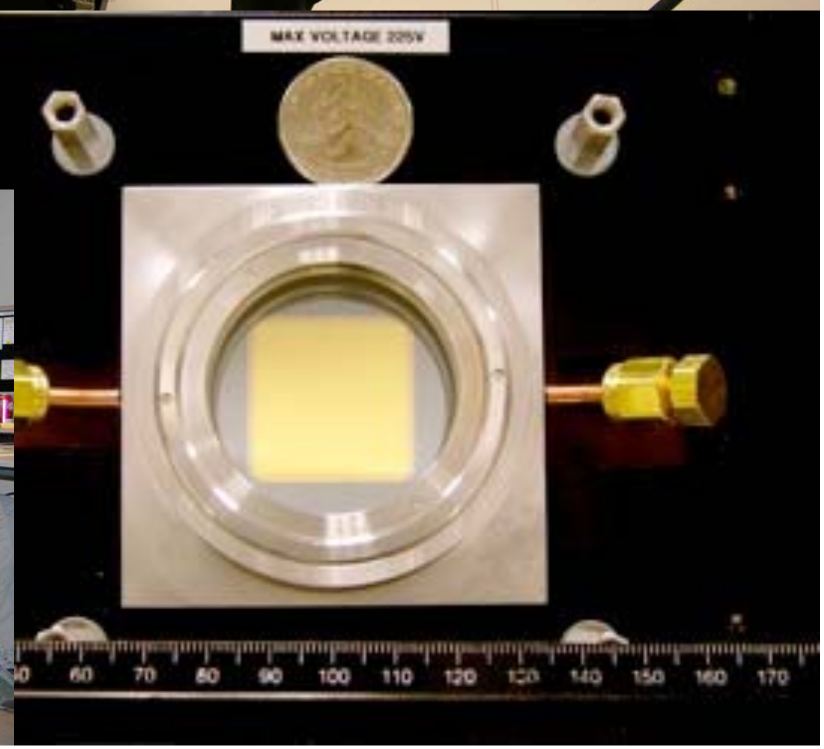
A high-contrast adaptive-optics imaging search for brown dwarfs

Katie Morzinski
UC Santa Cruz/Center for Adaptive Optics
with Bruce Macintosh et al.

Michelson/Sagan Symposium
NExScI, Caltech
13 Nov. 2009

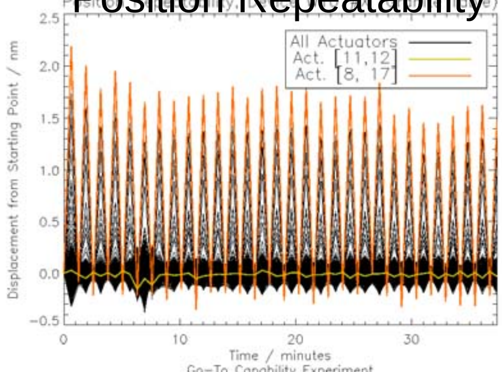
(c) Robert Hurt




MAX VOLTAGE 225V

Testing MEMS deformable mirrors at UCSC's LAO (for GPI) and on-sky at Lick Observatory

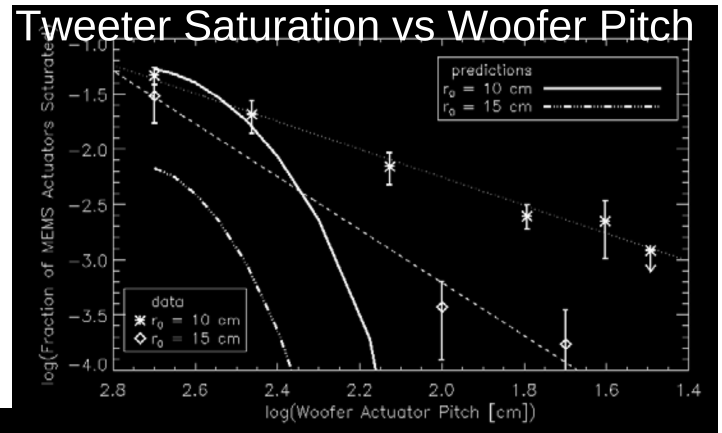
Position Repeatability



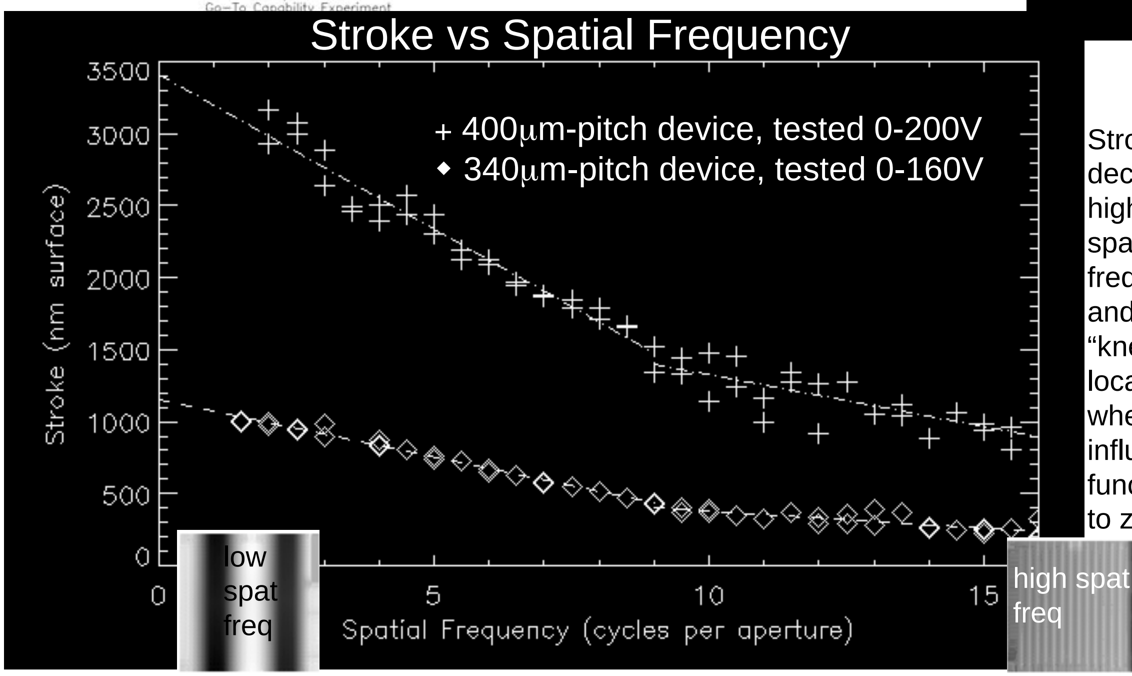
Sub-nanometer stability, position repeatability, and hysteresis demonstrated in the LAO.

Saturation was a 3-4 σ event for r0=15cm with a 1.5um-stroke MEMS. Broad influence functions cause mid-to-high spatial frequencies to saturate more than predicted analytically from the fitting error equation.

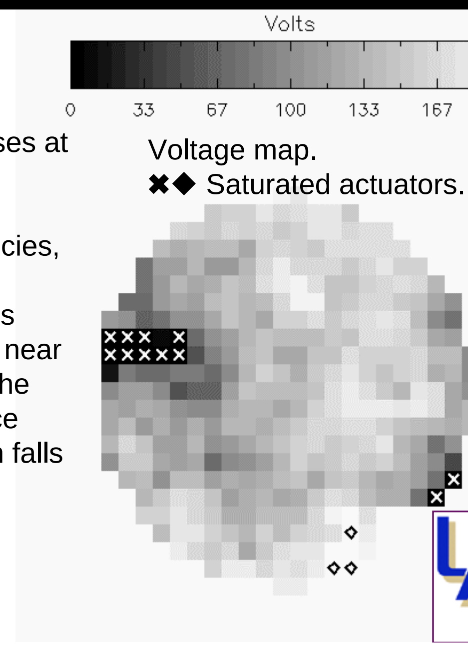
Tweeter Saturation vs Woofer Pitch



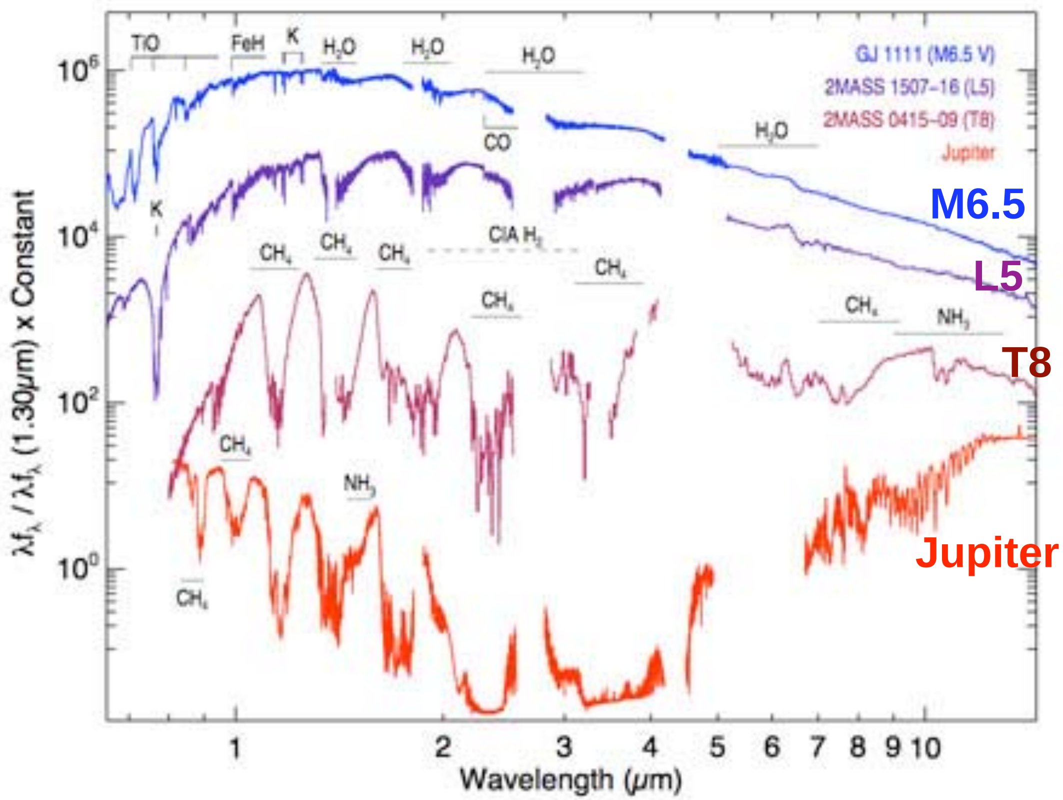
Stroke vs Spatial Frequency

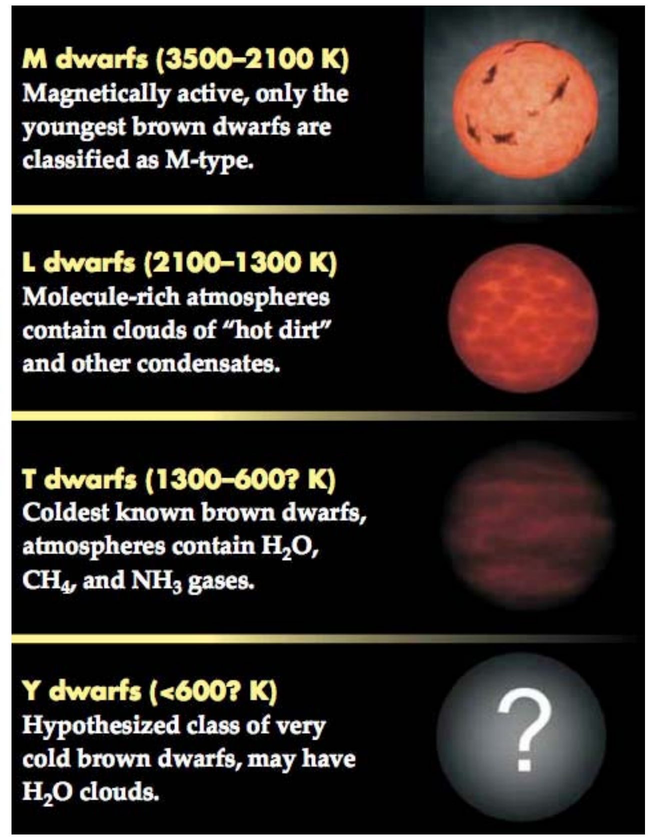


Stroke decreases at higher spatial frequencies, and the "knee" is located near where the influence function falls to zero.



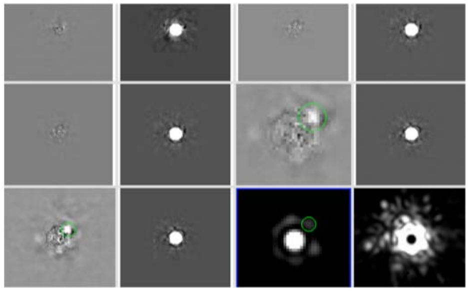
Brown dwarfs, at 75 > M_{BD}/M_{Jup} > 13, are (1) laboratories for model atmospheres and (2) cross-overs between star and planet formation





Burgasser 2009 arXiv:0903.1390 / Burgasser 2008 Physics Today; Mark Marley spectra; Robert Hurt BD illustrations


Imaging low-mass companion



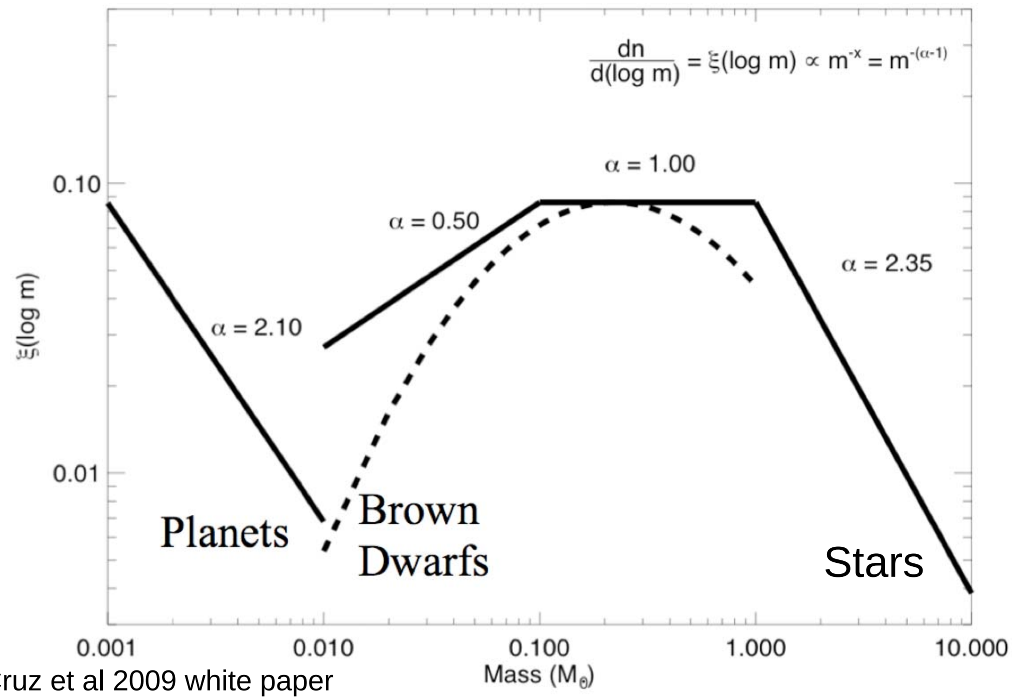
We are using Keck and Lick NGS AO to look for faint companions to Hyades stars

- Brown dwarfs:
  - Characterize colors
  - Match model atmospheres
- Binary stars:
  - Astrometric masses
  - Binary fraction
- Mass function:
  - Low-mass stars
  - Brown dwarfs

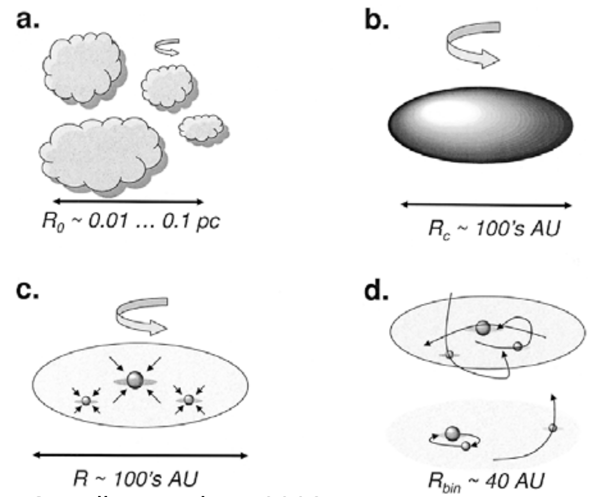
Outline:

- Why we want to find brown dwarf secondaries
- Why we chose to search the Hyades cluster
- How the survey was done
- How the data were/are being analyzed (LOCI)
- Which stars had candidates for follow-up
- What we've found so far

Brown dwarfs probe interesting mass regime in the IMF to aid understanding of star formation processes



Cruz et al 2009 white paper



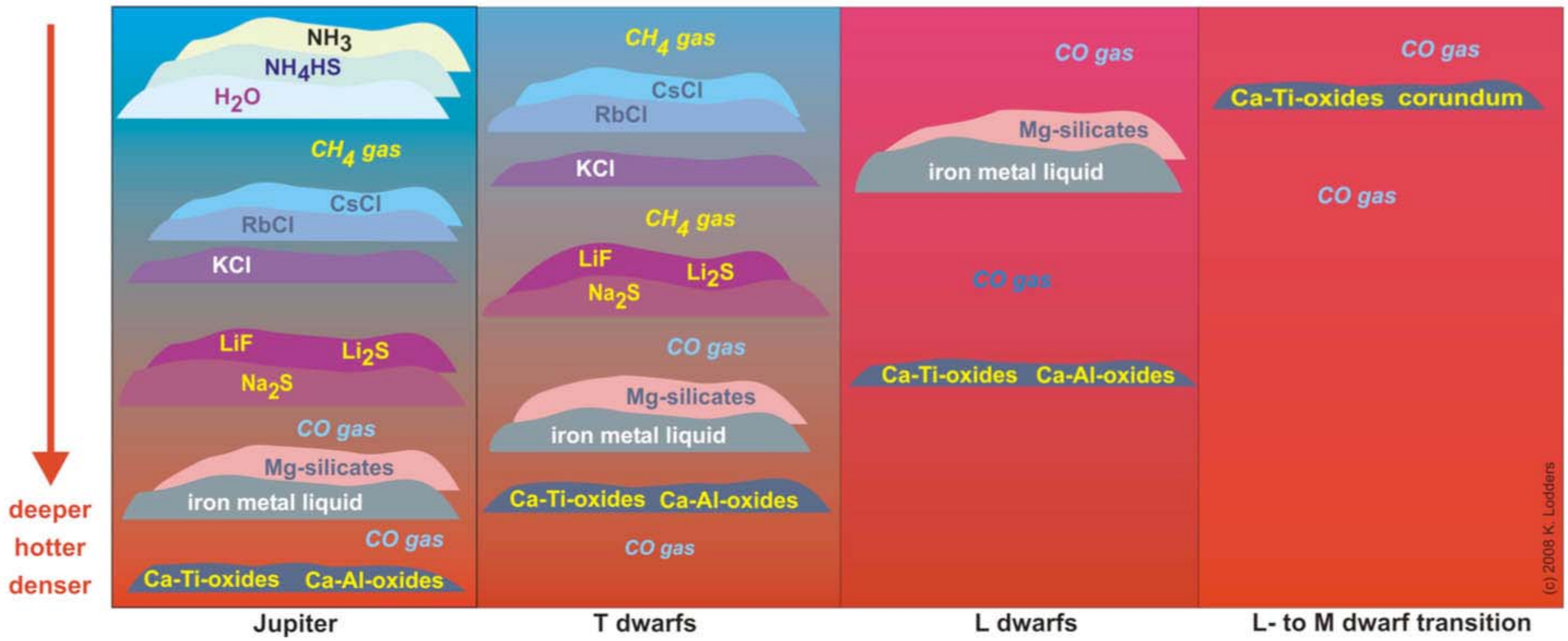
Sterzik & Durisen 2003

Binary star formation also not well-understood.

Initial mass function not uniform over star–brown dwarf–planet regimes, implying varying formation mechanisms

Observations:
Mass function
Binary fraction
Separation distribution

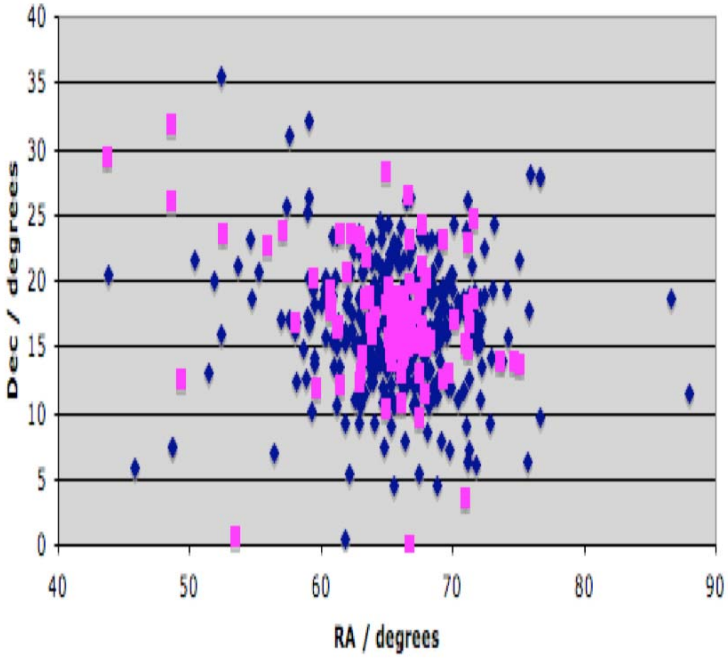
Physical & chemical properties of clouds in BD atmospheres not well known; Depend on temperature, pressure, mixing, kinetics, patchy cloud deck, etc.

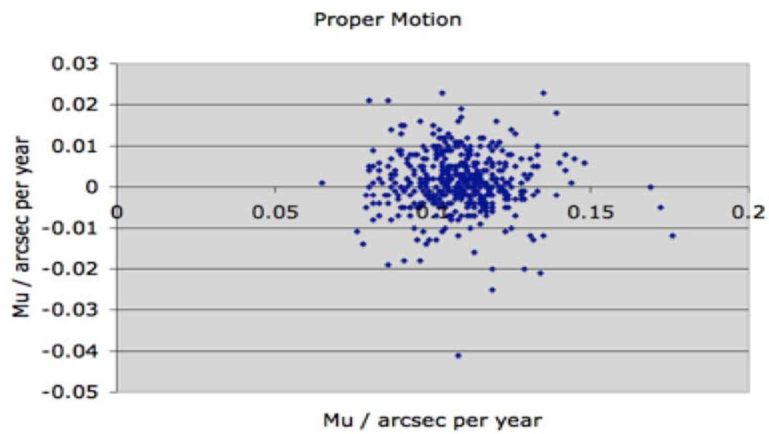


Burgasser et al. 2009 white paper / after Lodders & Fegley 2006

The Hyades open star cluster is well-suited for an HCAO imaging survey

Surveyed 88 G2V–K7V stars in Hyades (M_V~4.7–7.6)

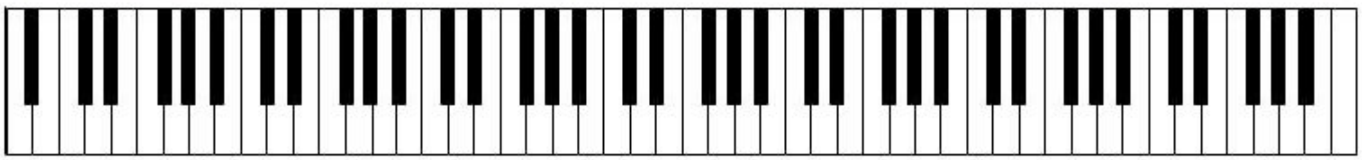


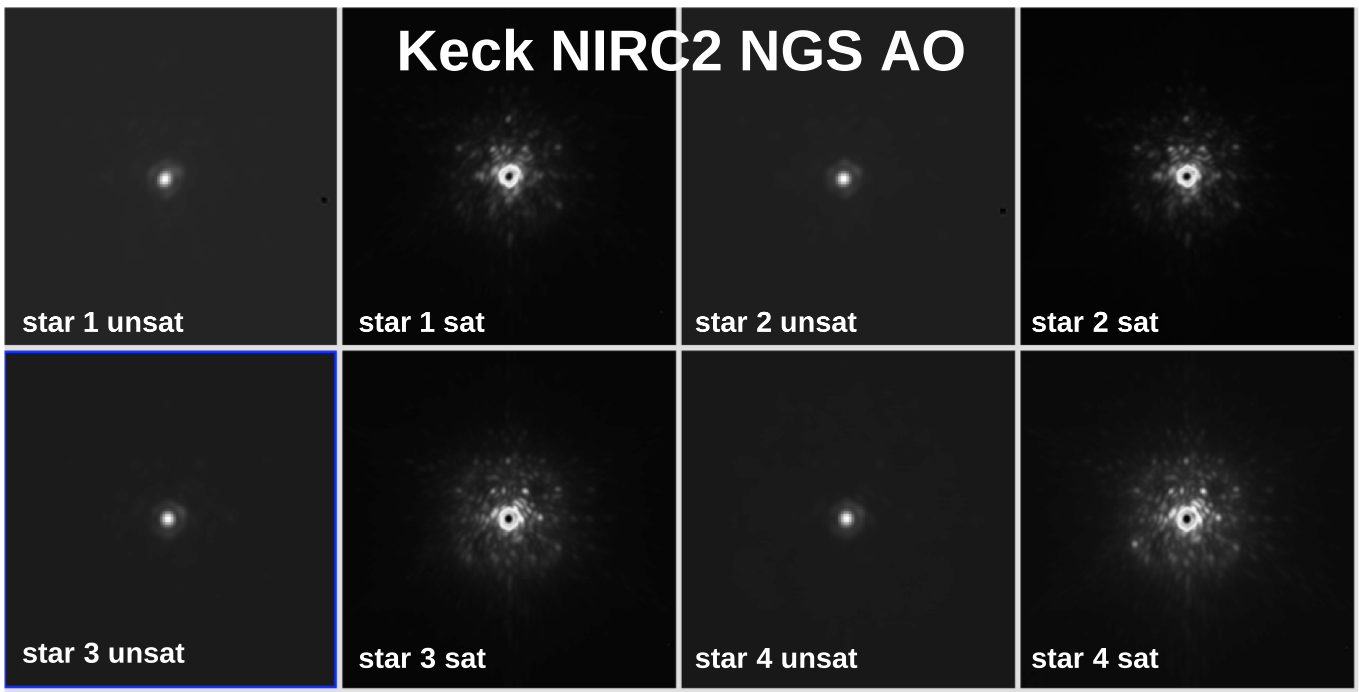


- 625 Ma old
- 46 pc away
- [Fe/H]=+0.11
- 10 degree tidal diameter / subtends ~300 square degrees
- approx 400 members
- 0.11”/yr mean proper motion

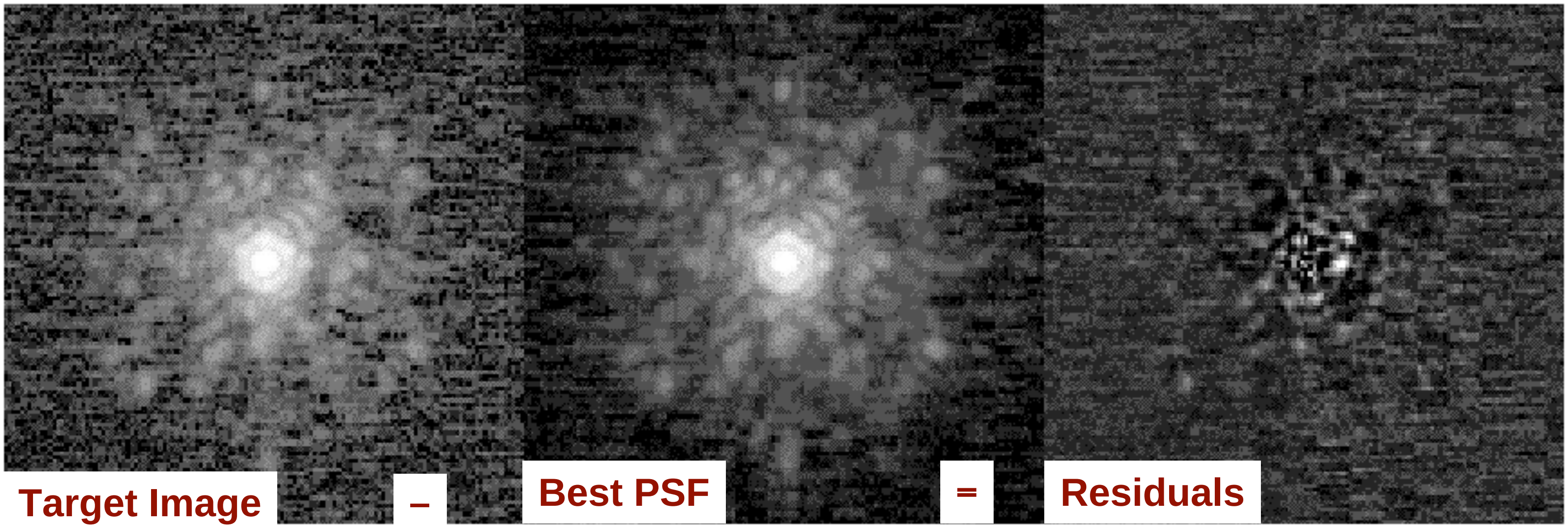
Perryman et al. 1998

Epoch 1: 88 Hyads in 10 hrs @Keck (2005-6); Snapshot images: Short & long exposures





Locally Optimized Combination of Images (LOCI) used to find best PSF to subtract

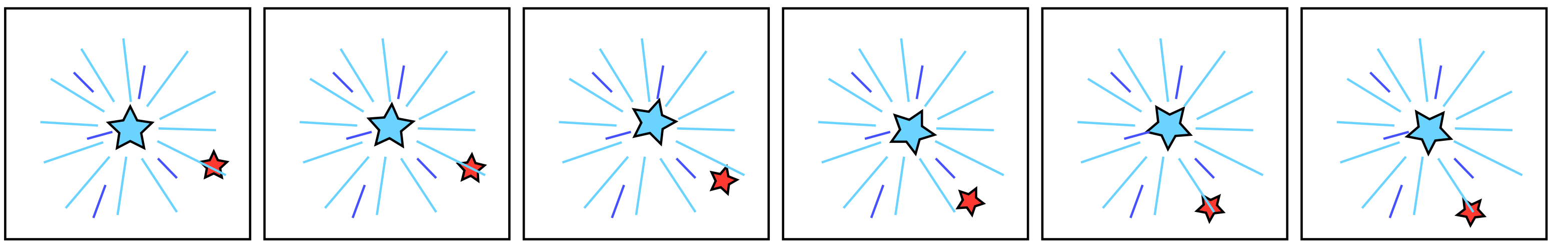


“Best PSF” = minimizes residuals in least-squares sense

“Locally optimized” = each region of image is analyzed independently for best PSF; then tiled back together

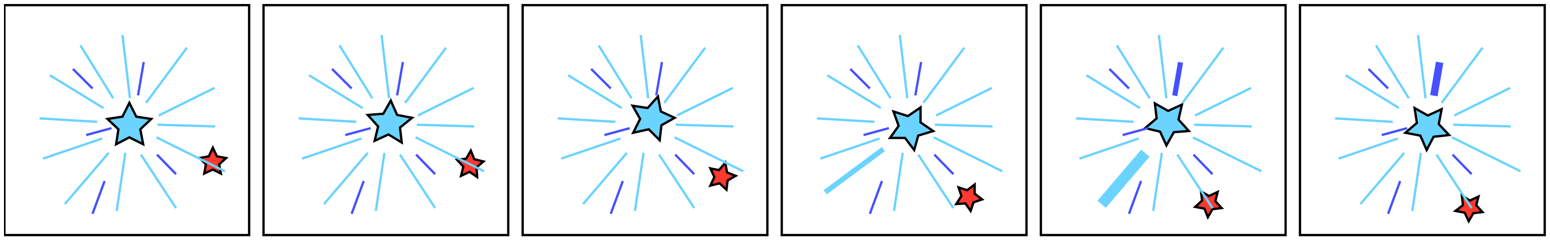
LOCI from Lafreniere et al 2007 ApJ 660

Locally Optimized Combinaton of Images (LaFreneiere et al 2007)



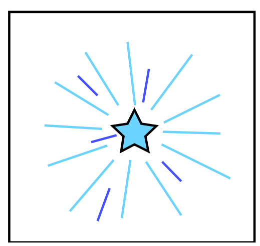
slide courtesy Bruce Macintosh

Locally Optimized Combinaton of Images (LaFreneiere et al 2007)



0* 0.4* 0.3* 0.1* 0.2*

-



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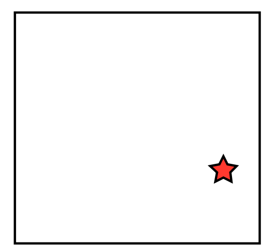


slide courtesy Bruce Macintosh

LOCI algorithm minimizes the sum of the squared residuals of the PSF subtraction

T = target image
R = reference PSF image
O^T = optimization area on target image (O^T>>PSF core)
S^T = subtraction area on target ($S^T \leq O^T$)
O^R & S^R = optimization and subtraction areas on reference PSF, respectively
c = reference weights (coefficients)
i = summing over pixels in image
j & k = summing over images

$$\sigma^2 = \sum_i (O_i^T - O_i^R)^2$$

$$O^R = \sum_k c^k O^k$$

$$= \sum_i (O_i^T - \sum_k c_k O_i^k)^2$$

$$\frac{\partial \sigma^2}{\partial c_j} = \sum_i 2(O_i^T - \sum_k c_k O_i^k)(-O_i^j)$$

$$= -2\sum_i (O_i^j O_i^T + \sum_k c_k O_i^k O_i^j) = 0$$

$$\sum_k c_k (\sum_i O_i^k O_i^j) = \sum_i O_i^j O_i^T$$

$$Ax = B$$

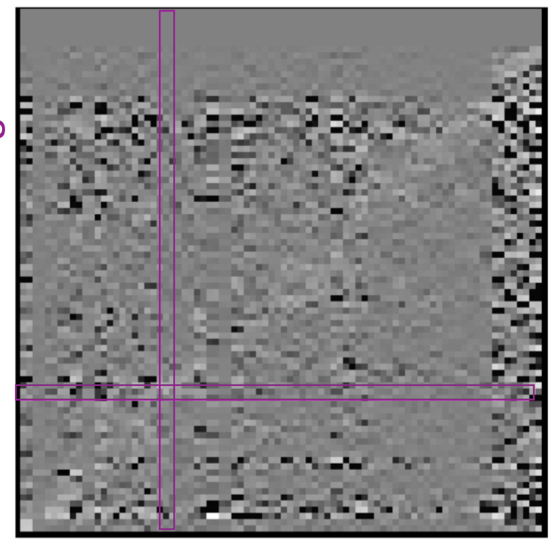
$$x_k A_{kj} = B_j$$

$$x_k = A_{kj}^{-1} B_j$$

$$A_{kj} = \sum_i O_i^k O_i^j$$

$$x_k = c_k$$

$$B_j = \sum_i O_i^j O_i^T$$

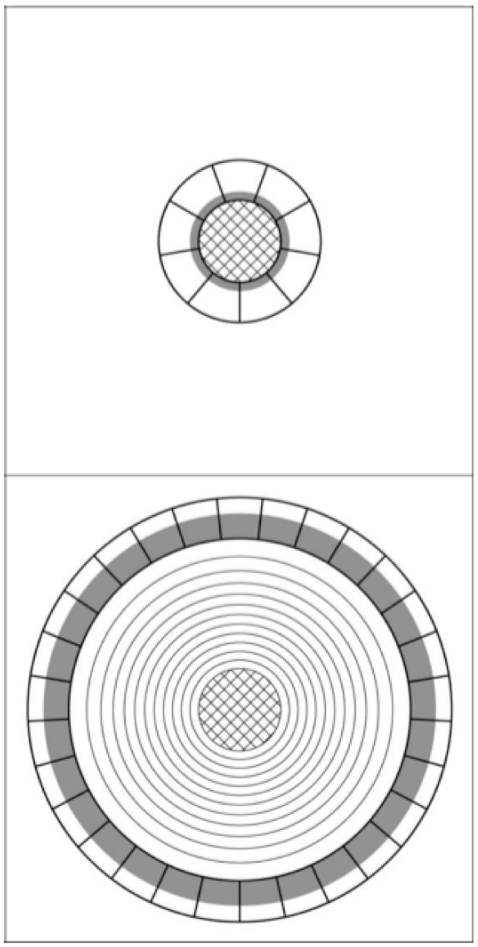


$$S_i^R = \sum_j c_i^j S_i^j$$

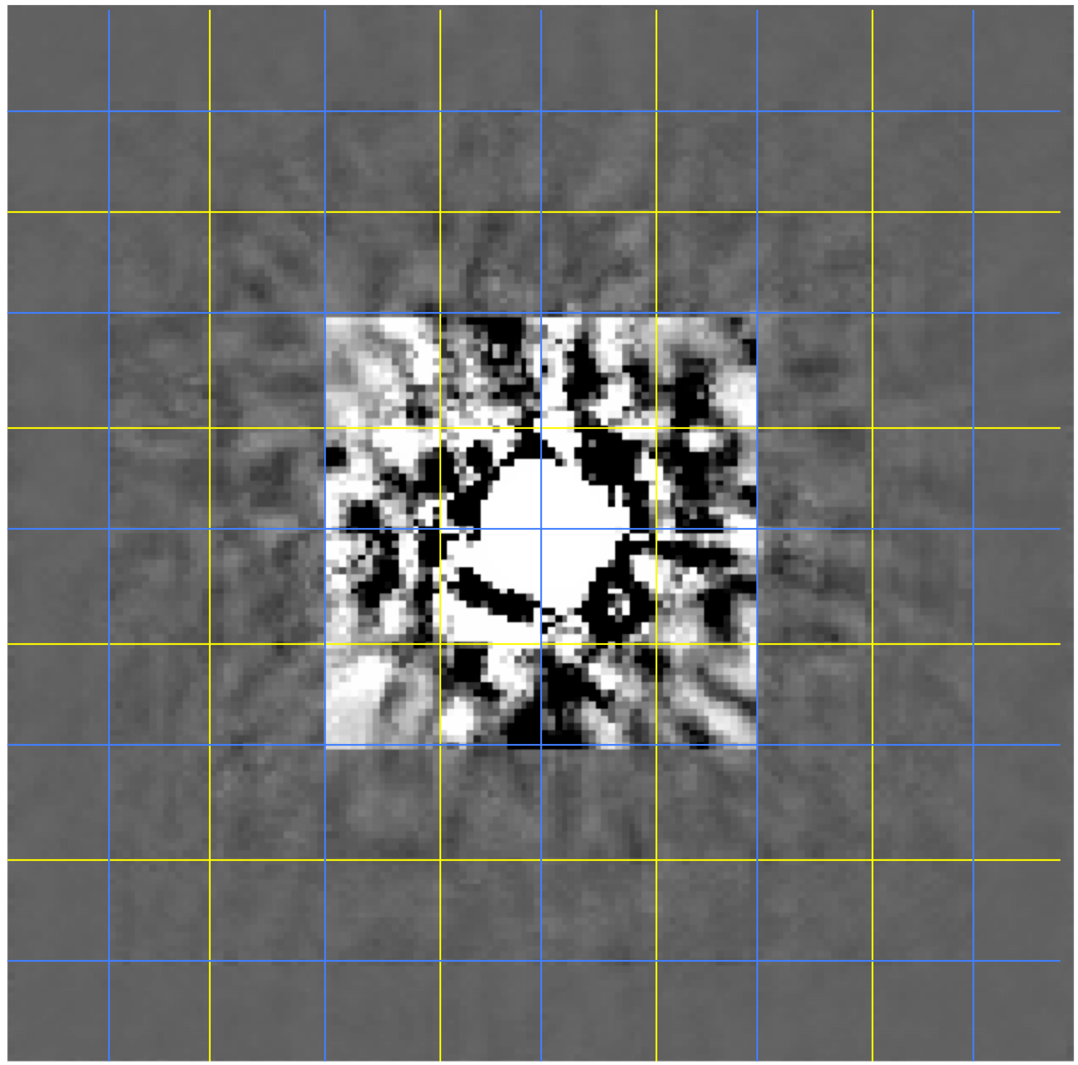
$$residual = T - R$$

Lafreniere et al 2007 ApJ 660

Size of optimization region >> size of PSF core



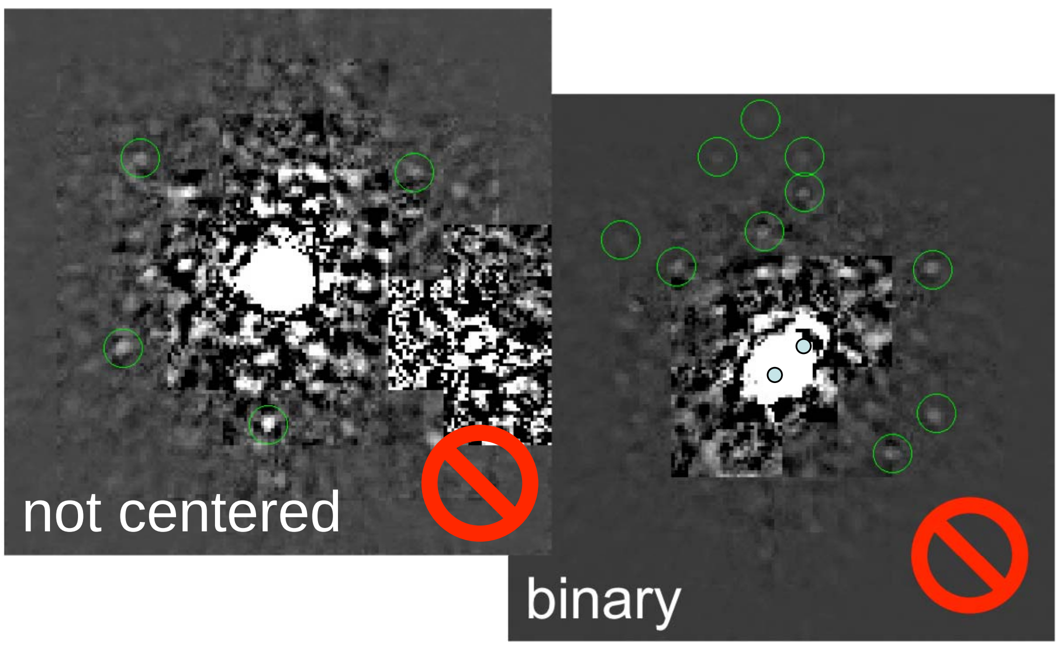
Lafreniere et al 2007 ApJ 660



Practicalities – observing strategies, binary stars, accurate photometry, etc.

Observing Strategies

- Stellar positioning constant on chip
  - Static PSF errors ➔ No dithering
- Sky subtracted in darks and by LOCI ➔ No skies



LOCI Practicalities

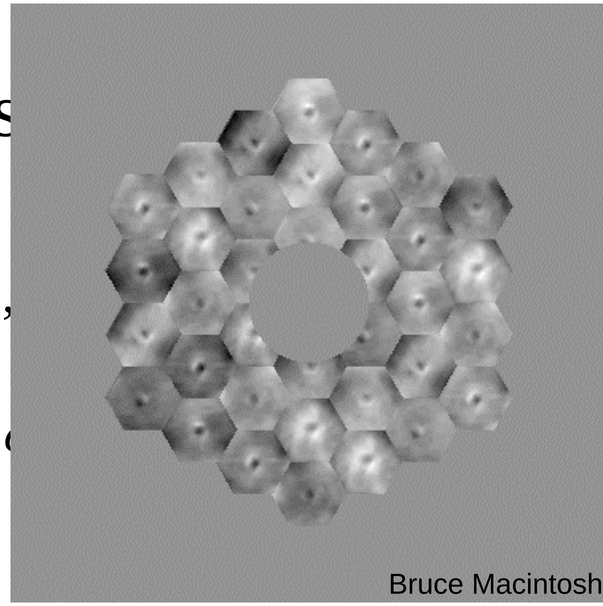
- Deep (saturated) images ➔ Mask out central saturated region
- Centering is critical
  - Binaries ➔ Re-center on each component
- Coefficients can be positive or negative
  - Double-check any companions found
- Photometry
  - LOCI can also remove flux from companion
  - Calibrate by inserting artifical point-sources

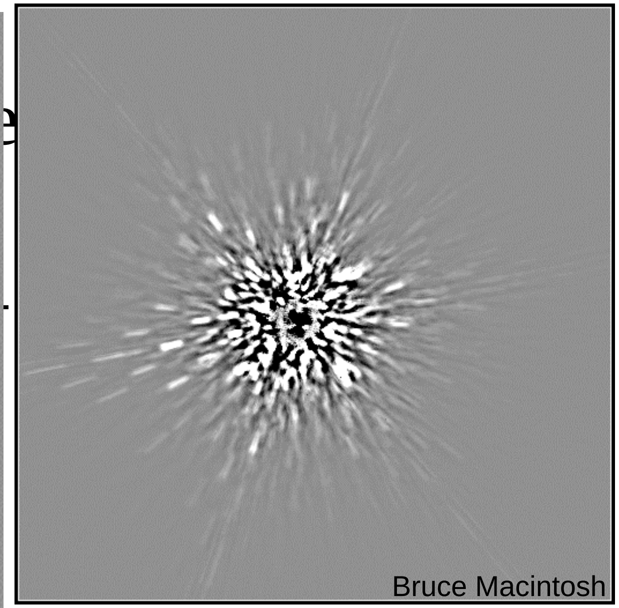
Taylor expans

$e(\xi,\eta) = FT(A(x,$

$= a + i(a*$

$p(\xi,\eta) = |e(\xi,\eta)|^2$





$= (a + i(a*\phi) - \frac{a*\phi*\phi}{2} + \ldots)(a^* - i(a^* * \phi^*) - \frac{a^* * \phi^* * \phi^*}{2}$

$= aa^*$ Diffraction pattern term

$+i[a(a^* * \phi^*) - a^*(a*\phi)]$ Pinned speckle term

$+(a*\phi)(a^* * \phi^*)$ Halo term

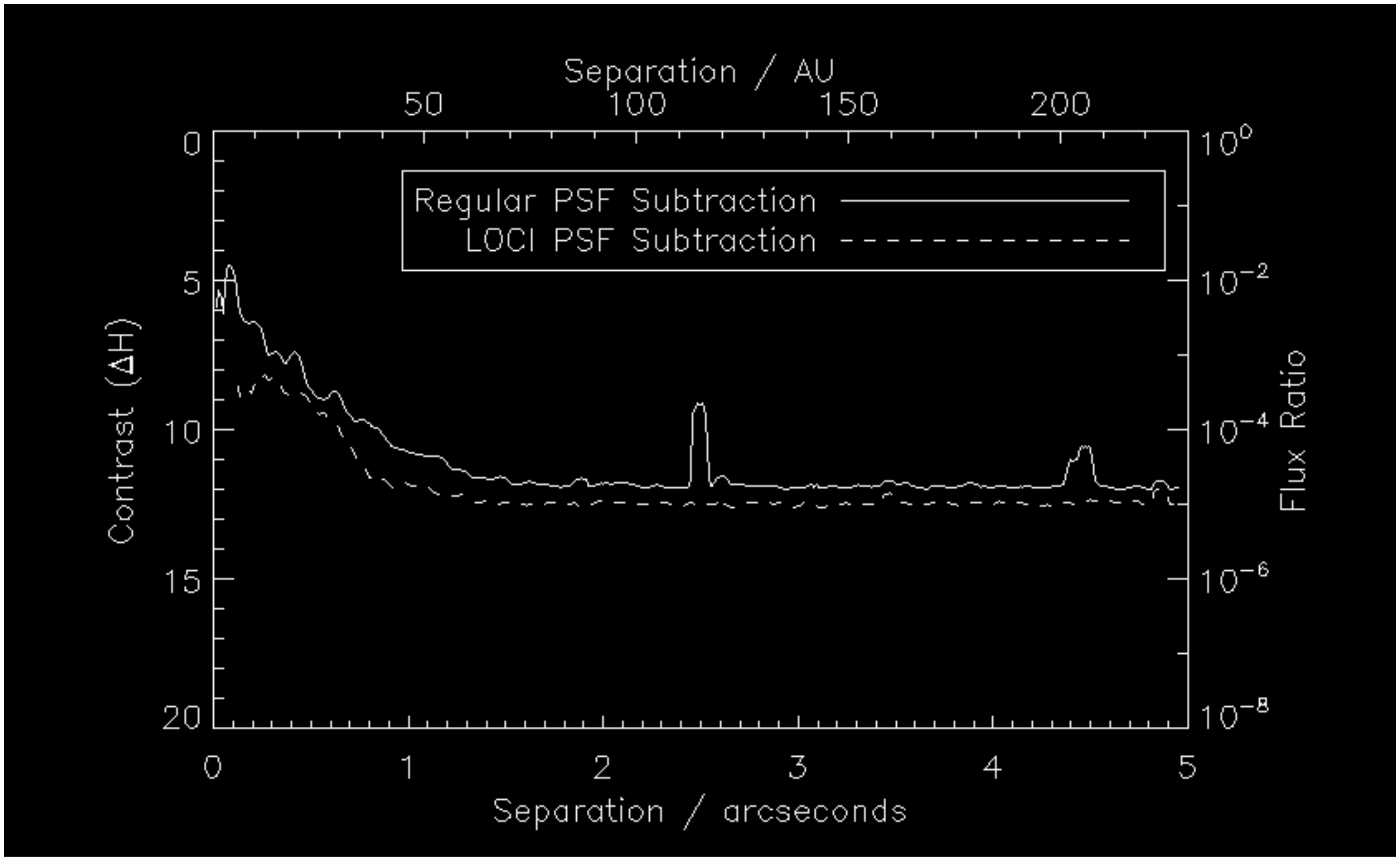
$-\frac{1}{2}\,|a(a^* * \phi^* * \phi^*) + a^*(a*\phi*\phi)|$ Strehl term

--results in symmetric speckles

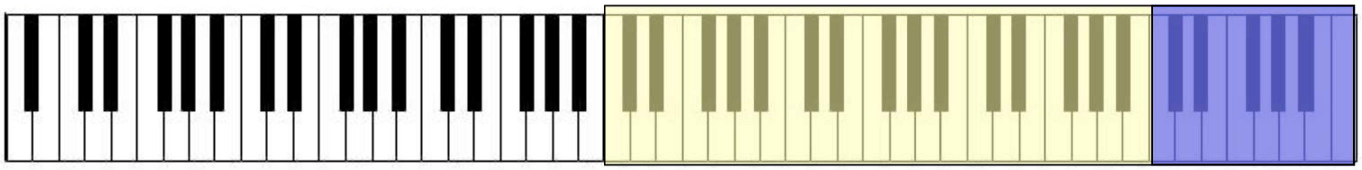
$+\ldots$

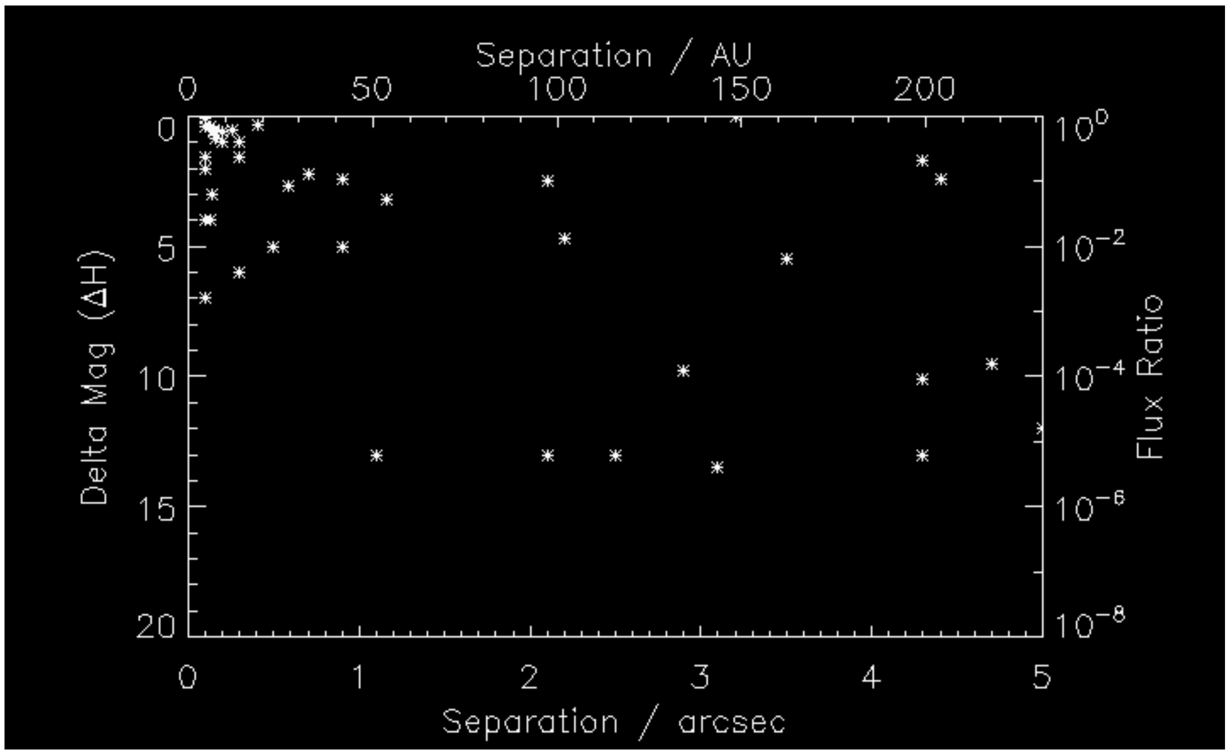
(from Sivaramakrishnan et al 2002 and Perrin et al 2003; also via Macintosh et al 2005)

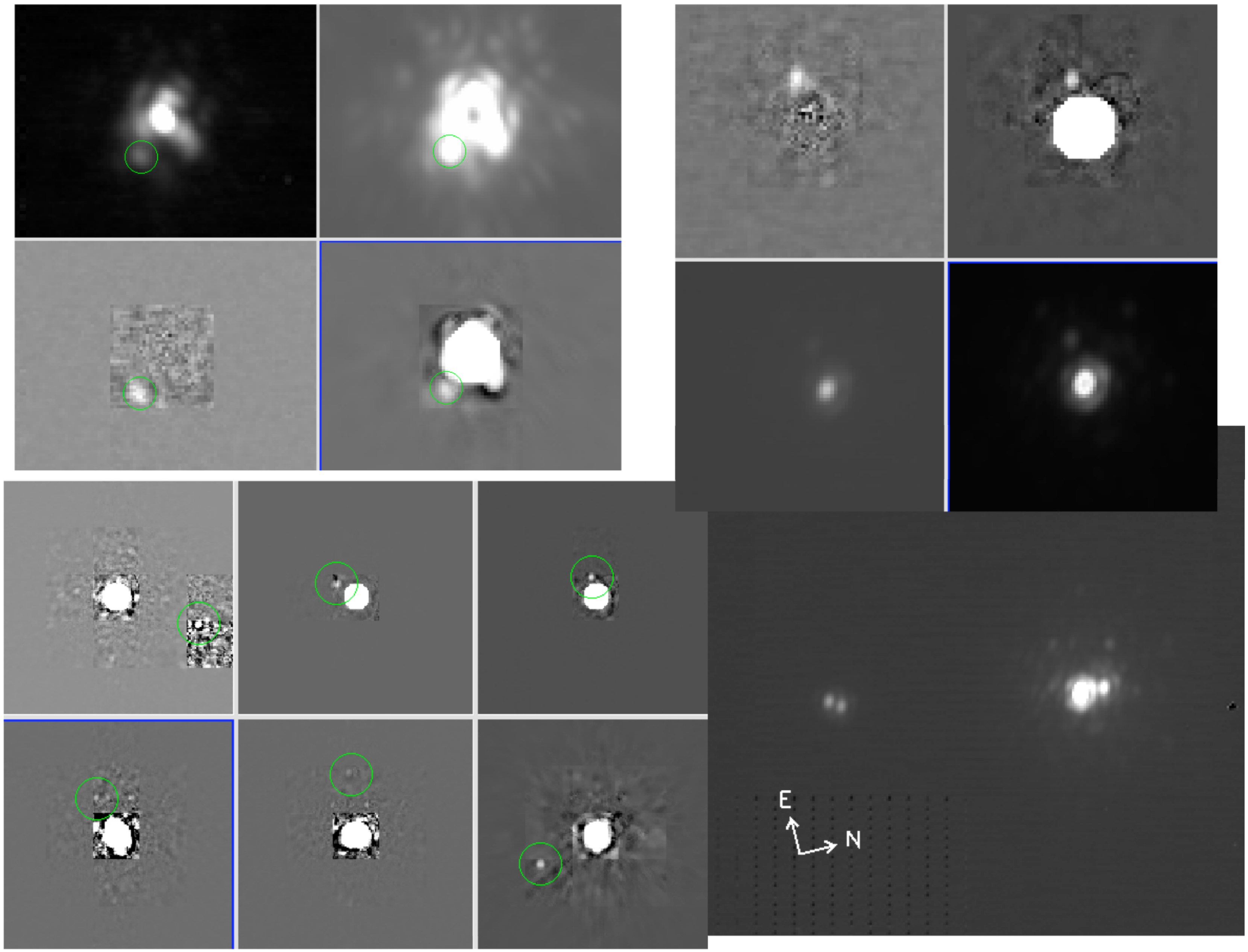
LOCI PSF subtraction allows for 3-σ detection at contrast 10^{-4}–10^{-5}

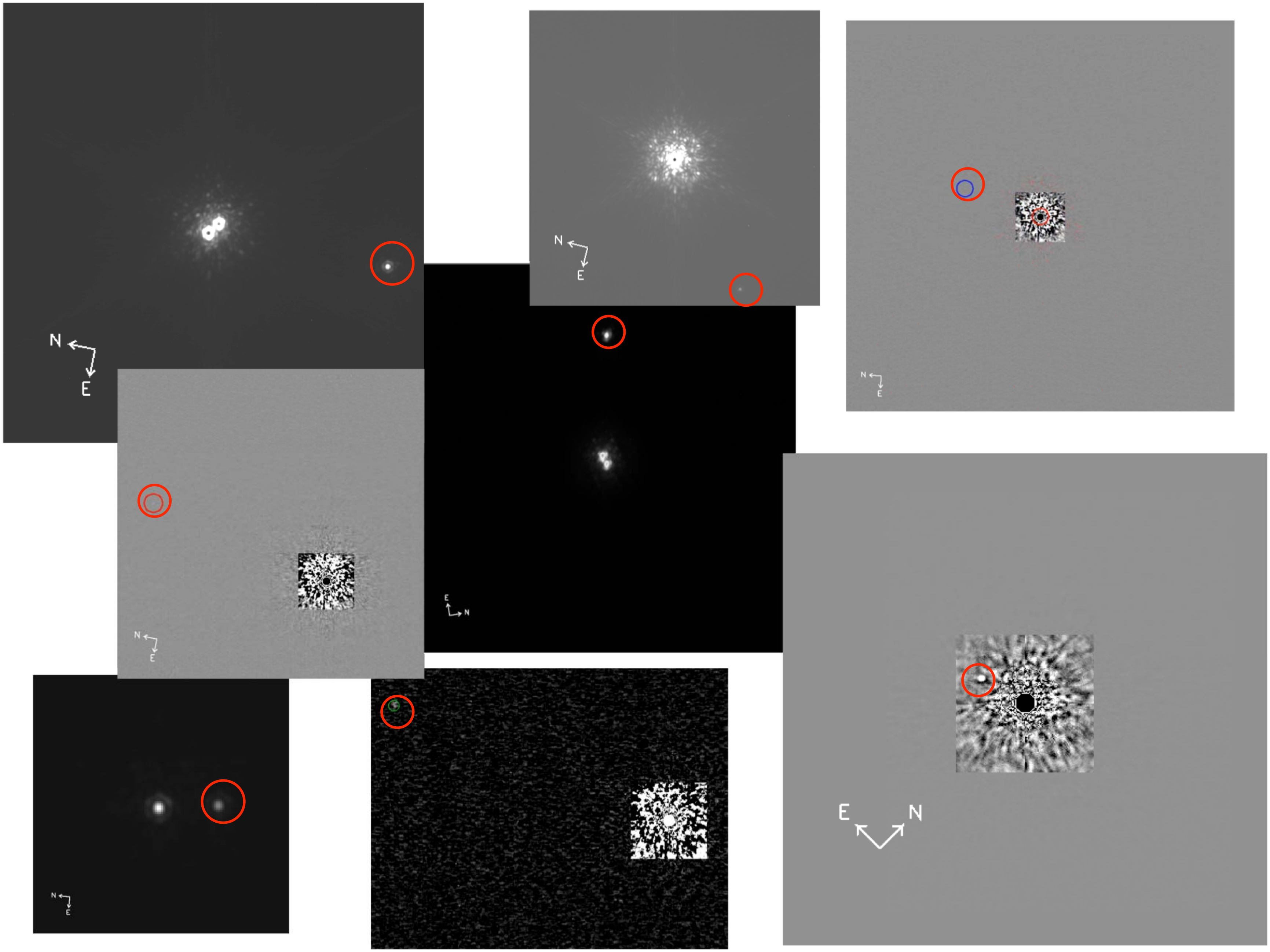


~45 candidate multiples; ~10 candidate BDs; Follow-up in Fall 2009 with Keck (5 hrs) & Lick

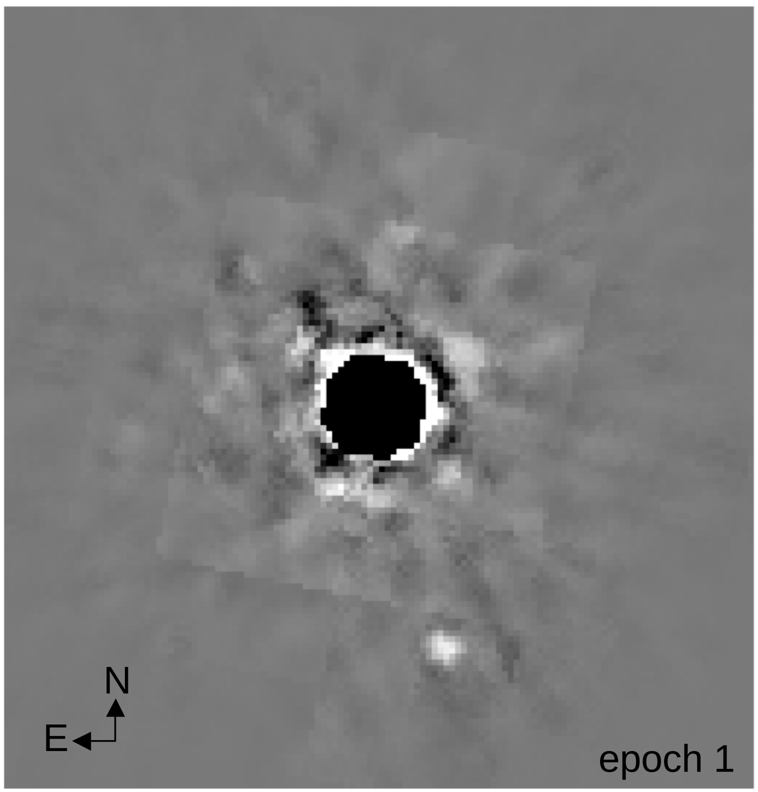


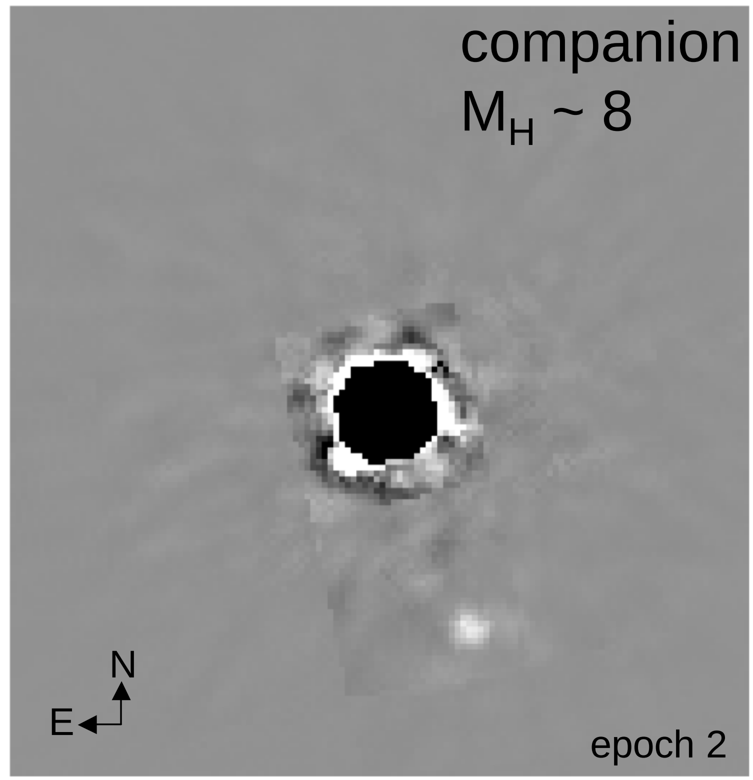


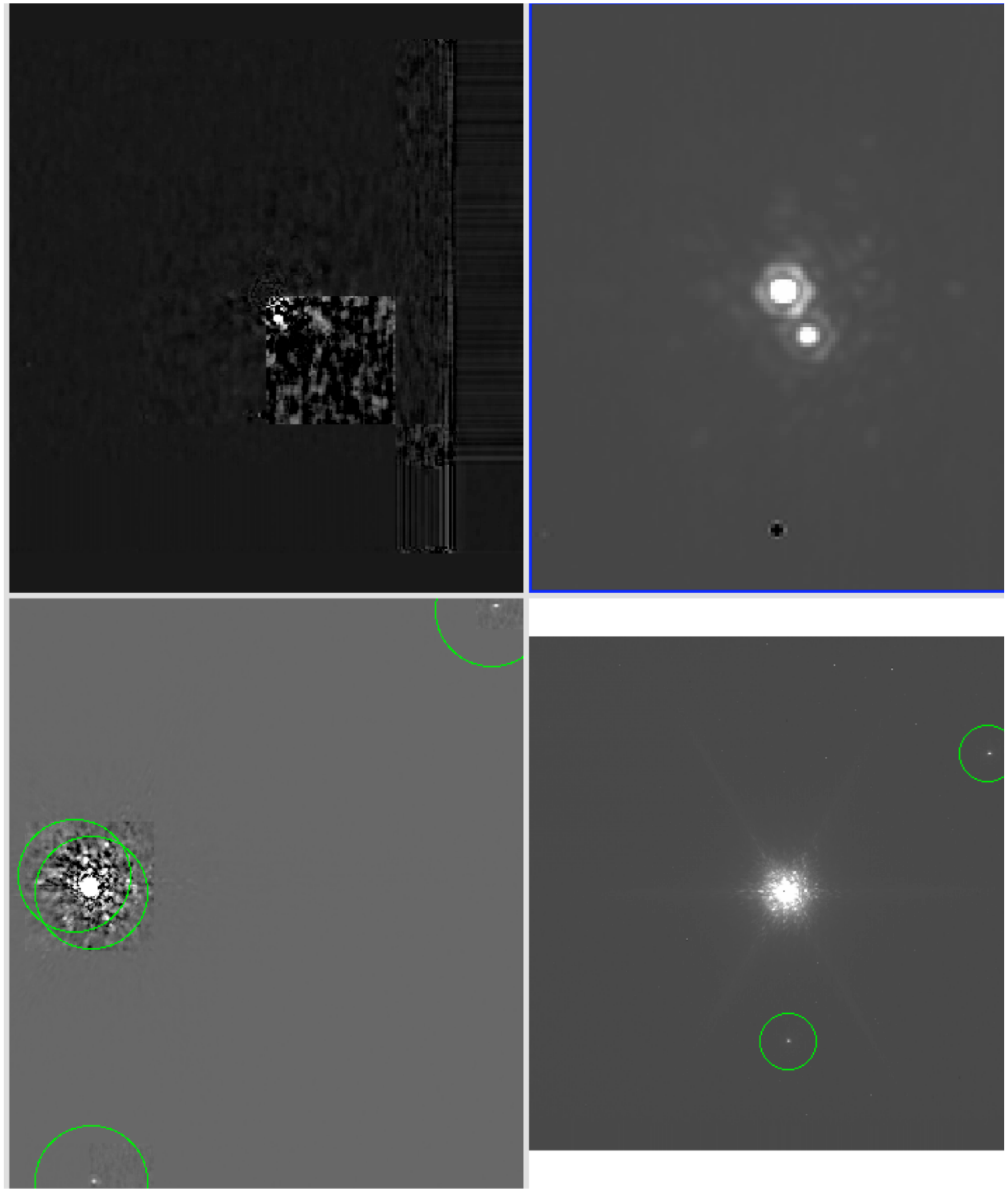

E
N

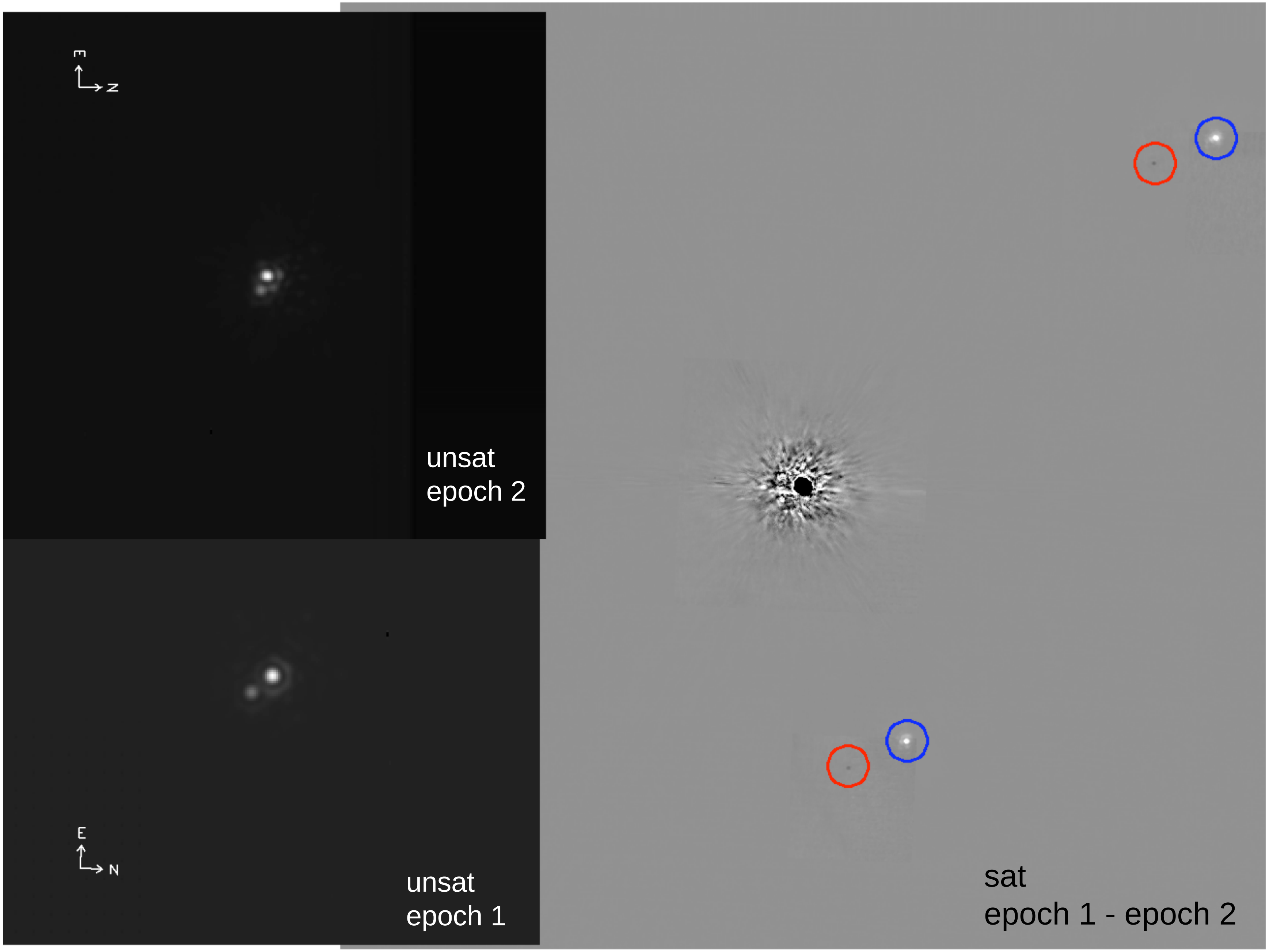

N
E
N
E
N
E
E
N
N
E
E
N
N
E

Comparing epoch 1 to epoch 2 verifies any co-moving companions








E
N
unsat
epoch 2
E
N
unsat
epoch 1
sat
epoch 1 - epoch 2

Minimum mass detectable ~0.03-0.02M_{sun} or spectral class late-L to early-T

t (Gyr) = 0.500

DUSTY models -- L dwarfs

M/Ms	Teff	L/Ls	g	R	Li/Li0	Mv	Mr	Mi	Mj	Mh	Mk	Ml'	Mm
0.020	901.	-5.14	4.65	0.111	1.000	43.80	35.89	32.23	22.56	18.57	15.59	12.11	11.67
0.030	1170.	-4.73	4.86	0.106	1.000	33.93	28.57	25.49	18.78	15.91	13.65	11.09	11.10
0.040	1461.	-4.36	5.01	0.104	1.000	27.41	23.50	20.90	15.94	13.81	12.20	10.51	10.62
0.050	1751.	-4.06	5.11	0.103	0.954	22.45	19.47	17.10	13.18	12.07	11.35	10.23	10.36
0.055	1902.	-3.91	5.15	0.103	0.561	21.42	18.64	16.25	12.60	11.73	11.20	10.16	10.32

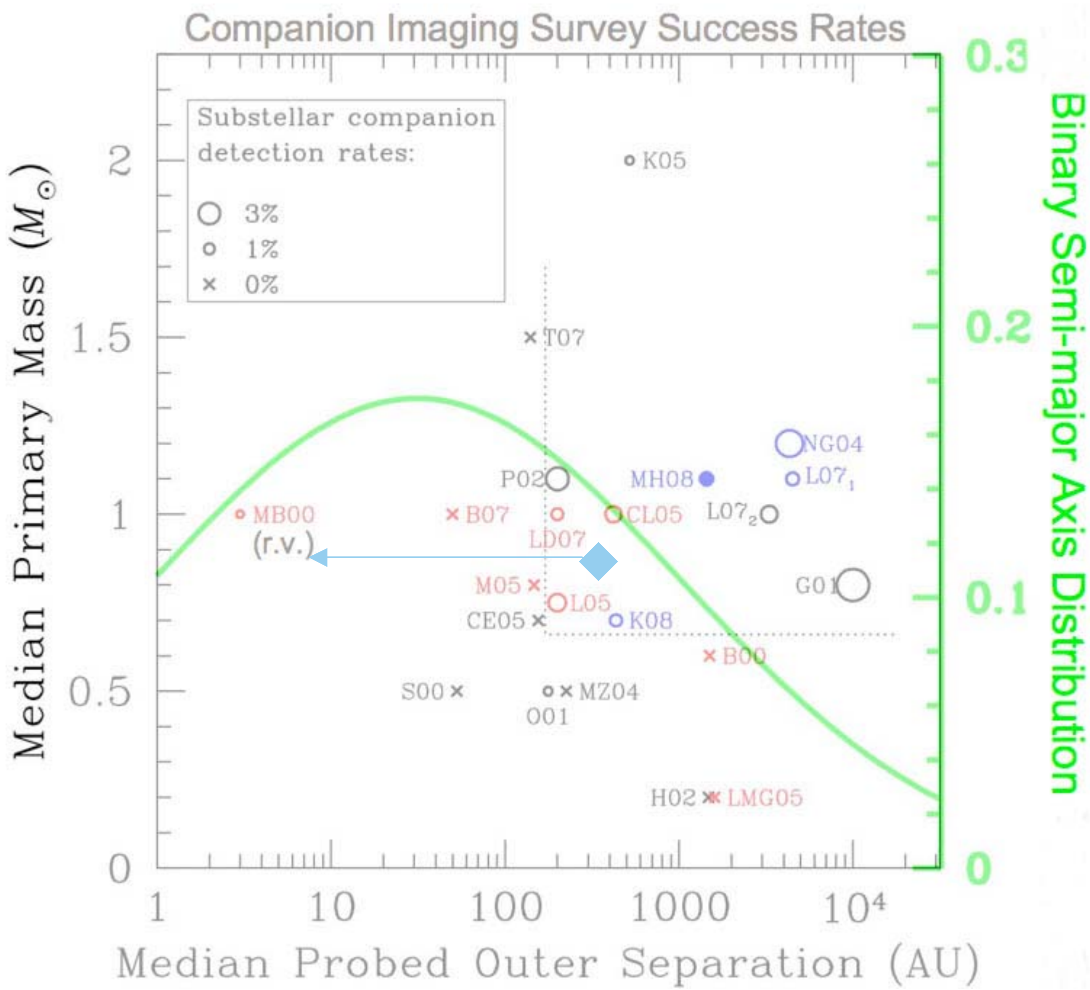
t (Gyr) = 0.500

COND models -- T dwarfs

M/Ms	Teff	L/Ls	g	R	Mv	Mr	Mi	Mj	Mh	Mk	Mll	Mm
0.0005	141.	-8.415	3.097	0.105	56.30	51.03	46.60	37.42	33.07	51.62	23.09	20.59
0.0010	203.	-7.753	3.365	0.109	47.57	42.88	38.99	31.61	29.15	43.23	20.93	18.68
0.0020	272.	-7.218	3.639	0.112	37.05	33.00	30.06	25.07	24.62	34.02	18.66	16.58
0.0030	322.	-6.913	3.805	0.113	32.02	28.23	25.75	22.05	22.27	29.03	17.52	15.53
0.0040	370.	-6.670	3.928	0.114	30.65	26.73	24.16	21.01	21.06	26.45	16.85	15.05
0.0050	409.	-6.496	4.027	0.113	29.60	25.57	22.94	20.20	20.11	24.54	16.32	14.67
0.0060	449.	-6.340	4.112	0.113	29.16	25.05	22.39	19.64	19.51	23.10	15.92	14.36
0.0070	488.	-6.200	4.185	0.112	28.71	24.51	21.80	19.10	18.91	21.68	15.52	14.06
0.0080	525.	-6.080	4.249	0.111	28.40	24.14	21.41	18.65	18.46	20.74	15.19	13.83
0.0090	564.	-5.963	4.307	0.110	28.14	23.82	21.07	18.21	18.04	19.95	14.88	13.63
0.0100	599.	-5.864	4.358	0.110	27.91	23.53	20.77	17.80	17.66	19.22	14.59	13.43
0.0120	759.	-5.447	4.432	0.110	27.20	22.73	19.91	16.38	16.29	16.82	13.51	12.68
0.0150	791.	-5.404	4.557	0.107	27.11	22.63	19.81	16.20	16.16	16.58	13.41	12.60
0.0200	936.	-5.133	4.704	0.104	26.53	22.07	19.27	15.33	15.34	15.37	12.78	12.21
0.0300	1264.	-4.636	4.905	0.101	24.97	20.77	17.95	13.90	13.87	13.69	11.70	11.68

http://perso.ens-lyon.fr/isabelle.baraffe/DUSTY00_models and http://perso.ens-lyon.fr/isabelle.baraffe/COND03_models

Likelihood of finding any brown dwarfs: Few percent; Out of 100 stars — 0-5 BDs



sensitivity limits

median companion mass

black: > 0.03 M_{sun}

blue: 0.013-0.03 M_{sun}

red: <0.013 M_{sun}

◆This Work (Morz et al)

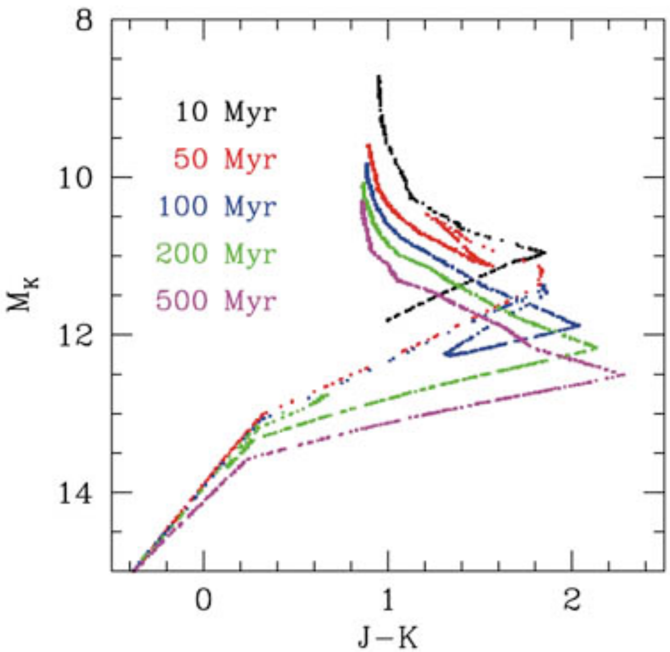
Metchev & Hillenbrand 2009 — Figure courtesy Stan Metchev

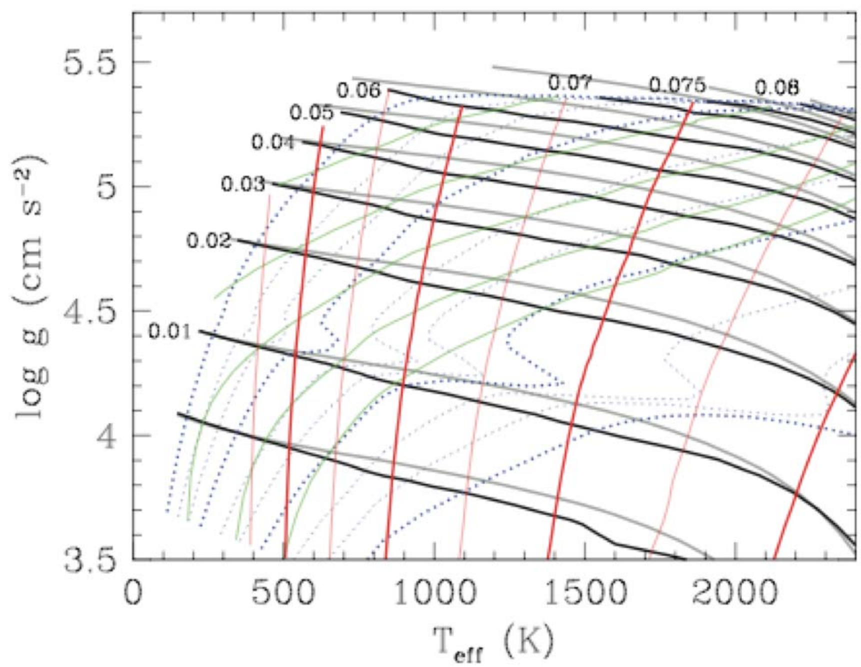
Further explanation of Metchev & Hillenbrand Figure 13--Substellar companion detection rates of published direct imaging surveys

Survey	Sample[a]	Stars	SpT[b]	Age[b] (Gyr)	Mass[b] $M_\odot$	d[b] (pc)	ρ_{out}[b] (AU)	Sensitivity[b] (M_{Jup})	N_{BD}	f_{BD} (%)	Label
Marcy & Butler (2000)	field	500	G5 ?	5.0	1.0 ?	···	3	0.5	2	0.40	MB00
Schroeder et al. (2000)	field	23	M1.5	5.0	0.5	3.5	53	30	0	0	S00
Brandner et al. (2000)	Cha T, Sco-Cen	24	M1.5	0.005	0.6	150	1500	3	0	0	B00
Oppenheimer et al. (2001)	field	164	M1	5.0	0.5	5.9	177	35	1	0.61	O01
Gizis et al. (2001)	field	60 ?	K ?	5.0	0.8 ?	< 25	10000	40	3	5.00	G01
Potter et al. (2002)	young field	31	G5 ?	0.5	1.1	20 ?	200 ?	30	1	3.22	P02
Hinz et al. (2002)	field	66	M3.5	5	0.2	5.8	1480	40	0	0	H02
Neuhäuser & Guenther (2004)	Tuc-Hor	25	G5 ?	0.035	1.2	60	4320	13	1	4.00	NG04
McCarthy & Zuckerman (2004)	young field	83	M1	0.3	0.5	15	225	30	0	0	MZ04
Masciadri et al. (2005)	young field	28	M0	0.012	0.8	21	147	5	0	0	M05
Carson et al. (2005)	field	80	K7	5	0.7	10.3	155	50	0	0	CE05
Luhman et al. (2005)	IC 348	150	M4.5	0.002	0.2	315	1600	6	0	0	LMG05
Lowrance et al. (2005)	young field	45	K5	0.15	0.75	30	200	10	1	2.22	L05
Chauvin et al. (2005b)	young field	50	K ?	0.035 ?	1.0 ?	60 ?	420 ?	5 ?	1	2.00	CL05
Kouwenhoven et al. (2005, 2007)	Sco OB2	199	A	15	2.0 ?	130	520	30	1	0.50	K05
Luhman et al. (2007b)	young field	73	G6	0.12	1.1	30	4500	13 ?	1	1.37	$L07_1$
Luhman et al. (2007b)	field	48	G3	5.0	1.0	22	3300	30 ?	1	2.08	$L07_2$
Tanner et al. (2007)	Taurus	15	K7	0.002	1.5	140	140	50	0	0.00	T07
Biller et al. (2007)	young field	54	K2	0.03	1.0	25	50	5	0	0	B07
Lafrenière et al. (2007)	young field	85	K0	0.1	1.0	22	200	2	1	1.18	LD07
Lafreniere et al. (2008)	IC 348	126	M2.5	0.002	0.29	160	960	13	0	0	L08
Kraus et al. (2008)	Upper Sco	82	M0	0.005	0.7	145	435	13	1	1.22	K08
Metchev & Hillenbrand (2008)	young field	100	G5	0.08	1.1	115	1440	13	2	1.98	MH

Metchev & Hillenbrand 2009

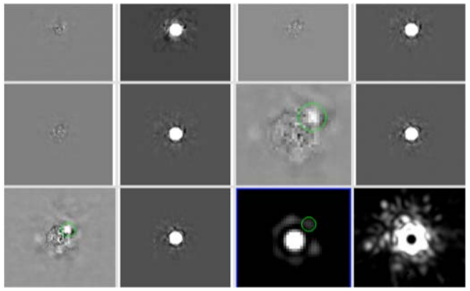
Constrain Hyades models with colors; Check against cloud sedimentation models





black lines = iso-masses, cooling in time
blue dotted lines = isochrones
red lines = iso-luminosities
green lines = iso-radii

Saumon & Marley 2008



Conclusion: AO plus LOCI PSF subtraction = high-contrast imaging to find faint Hyades companions

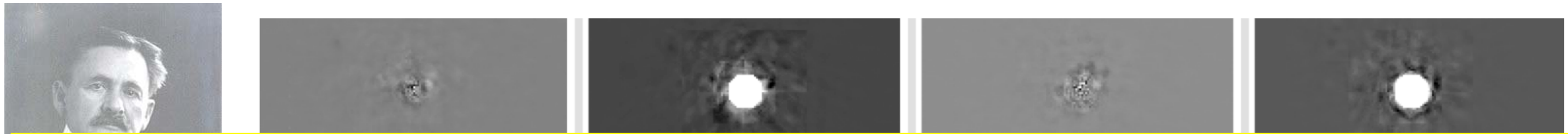
Thus far:

- 3 confirmed ~M-dwarf companions
- 6 confirmed back-ground objects

To do:

- Astrometry to confirm or reject co-moving membership
- Photometry to characterize companions
  - Insert artificial point sources to test photometry

- Stellar companions:
  - Binary fraction vs separation in Hyades
    - as compared to field stars
    - and to less-evolved clusters
  - Precise measurements of mass from astrometric & rv orbits
- Brown dwarfs:
  - Characterize color & spectrum for Hyades' age
  - Mass function in brown dwarf regime

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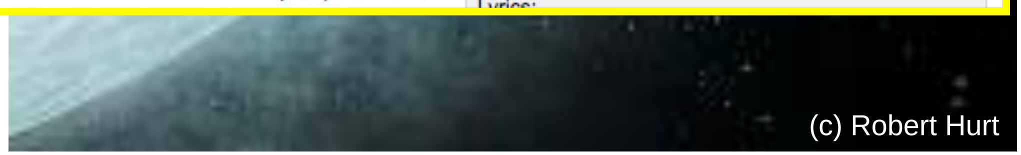
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