Astrometry of Visual Binaries with Adaptive Optics

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collaboration with:
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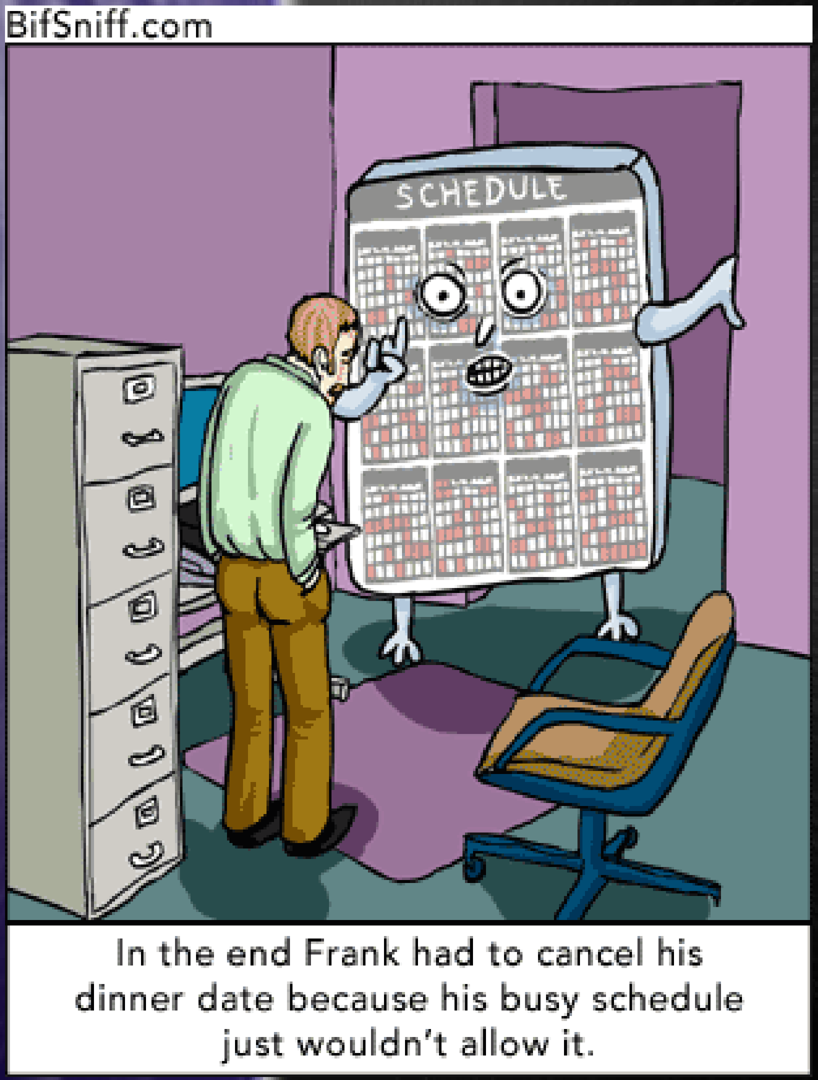
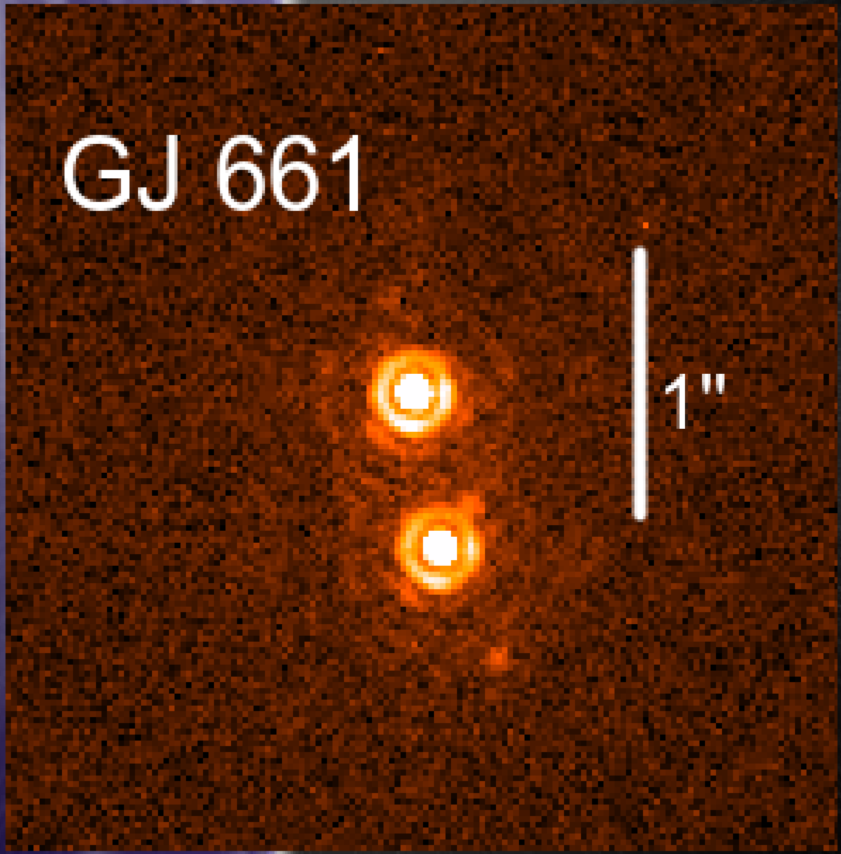
"The universe is a procession with measured and perfect motion"
Walt Whitman, "Leaves of Grass" 1855

Schedule:



- Why and what?
- Detecting planets with astrometry
- Observations
- Problems and things to remember (AO, FOV, PSC, AR)
- Precision, stability & mass limits
- Summary

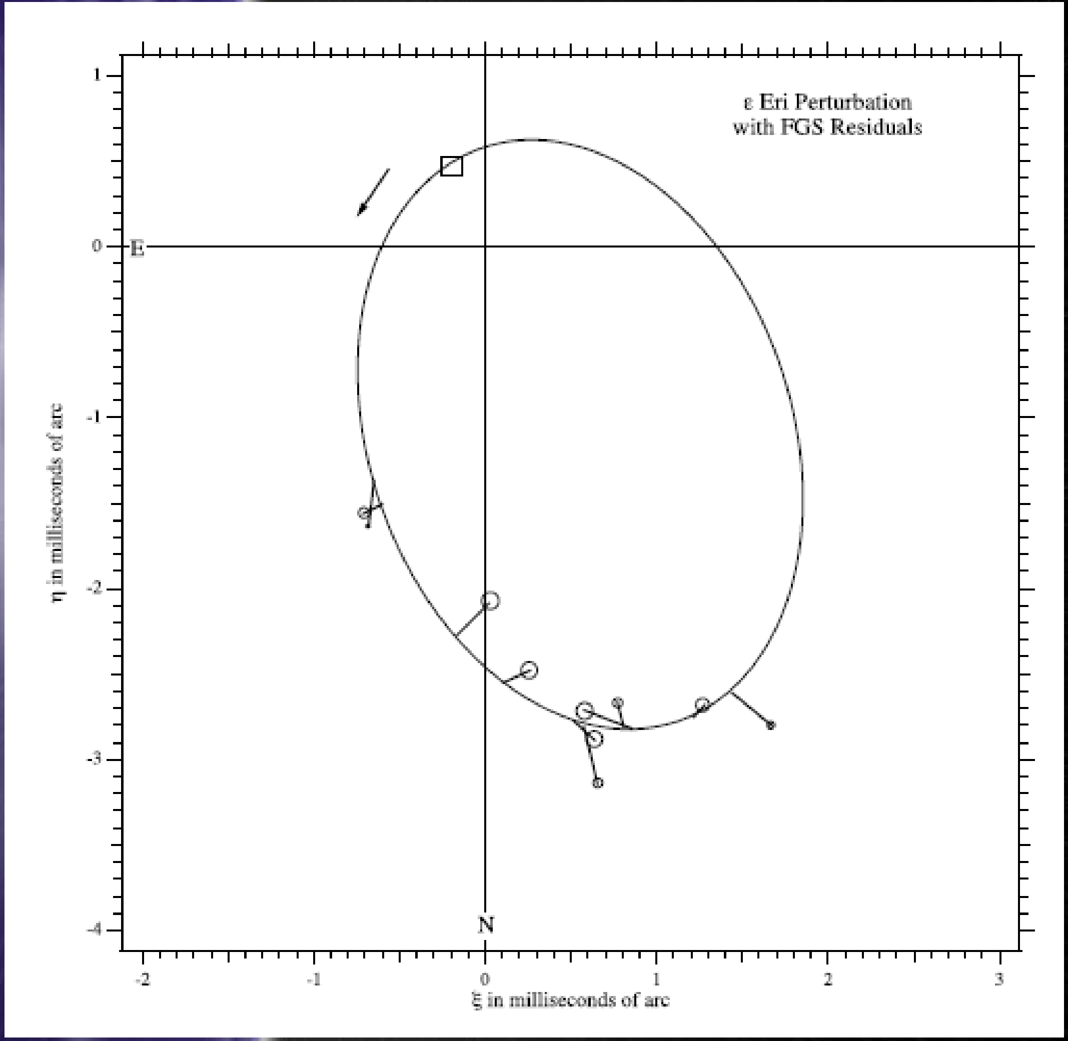
Why?



- **Because we want to discover planets!**
- To do that astrometrically, we need to go down to ~100 μas precision
- ... possible (and was done) with interferometers
- ... but using a single-mirror telescope is easier, faster and cheaper
- Visual binaries make that business a bit easier

Planets detected astrometrically

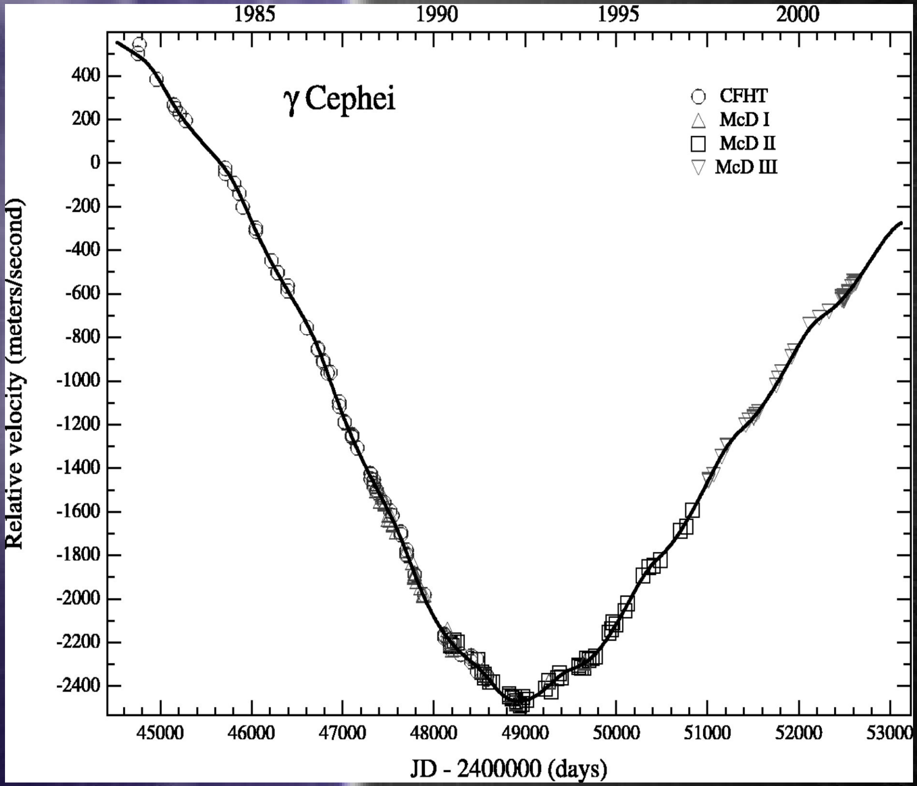
DISCOVERED:



DETECTED: several

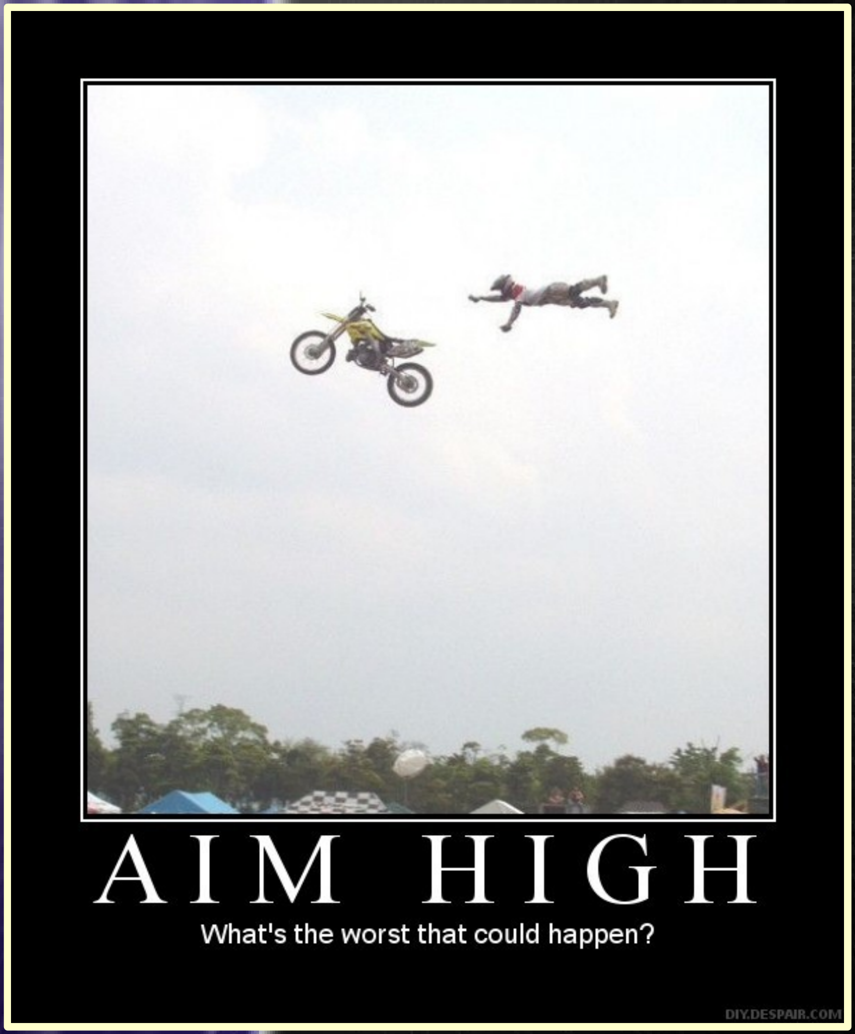
eps Eridani (Benedict et al. 2006)

Planets in binaries



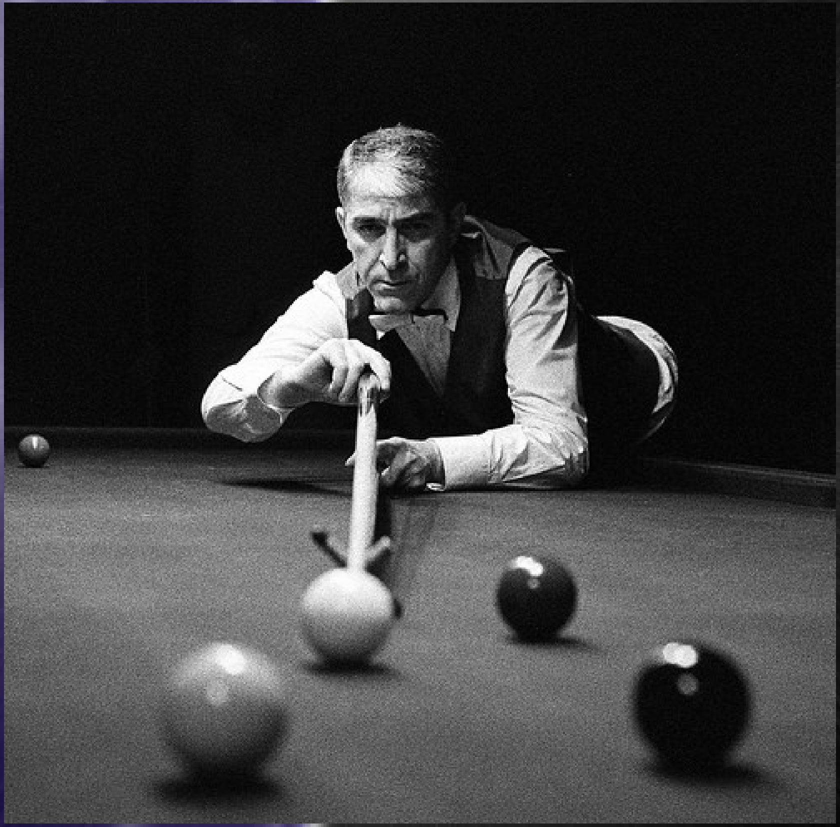
- P-, **S-** and L-type
- Most of the planets were found around single stars
- Most of planet-harboring binaries are very wide (~100 AU and much more)
- It is not confirmed if the binarity makes planet formation easier or not (rather not)
- Dynamics is much more interesting

Aims (what):



- Check if the CCD astrometry of visual binaries and multiples with Adaptive Optics (AO) can be a tool for searching for exoplanets in binaries.
- Estimate the precision possible to achieve by ***obtaining a random scatter*** of the measurements (the biggest fun)
- Give the requirements needed for making precise measurements

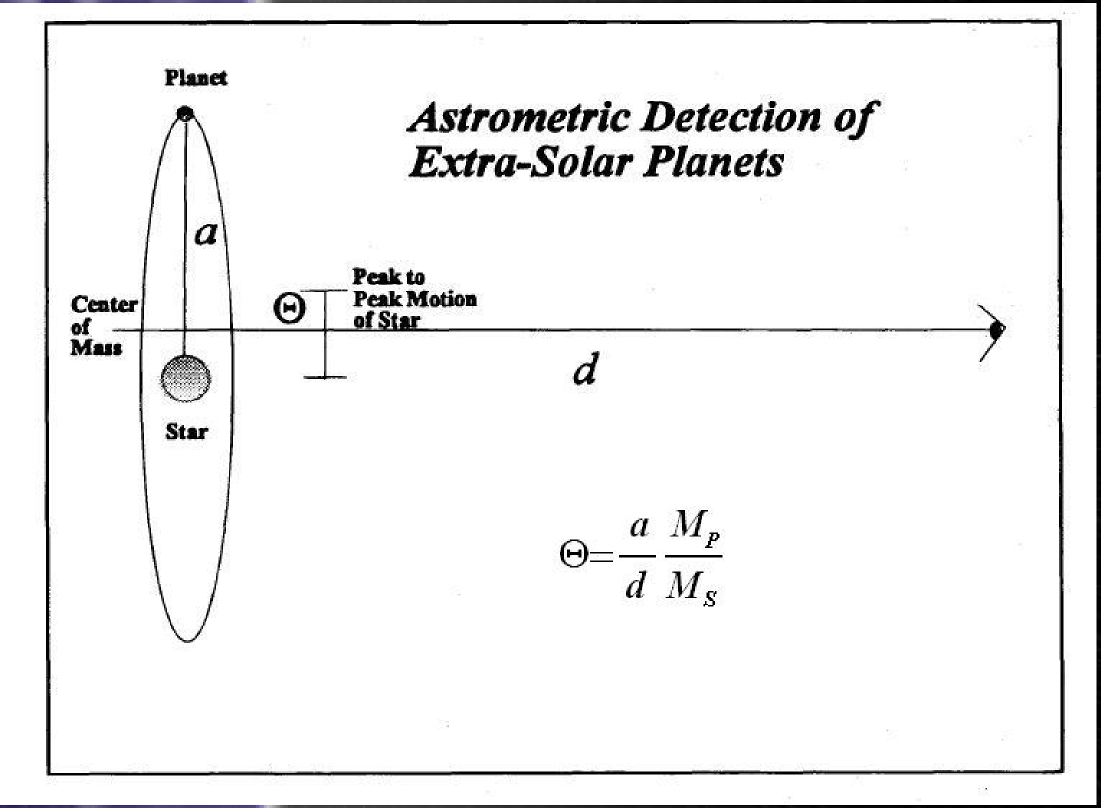
So far, so good...
Some precision records:



- Pravdo & Shaklan (1996): ~150 μas
- Seifhart et al. (2007): ~50 μas
- Cameron et al. (2008): <100 μas
- Us (2008): 38 μas

(HST and interferometry not included)

Detecting (S-type) planets with astrometry



Pravdo & Shaklan, 1996

$\Theta > 3\sigma_\rho$

Detection limit:

$a\, M_P > 3\sigma_\rho\, d\, M_S$

$a\, M_P\ [AU\ M_J] > 1.5625\ \sigma_\rho\ d\, M_S\ [mas\ pc\ M_\odot]$

Observations

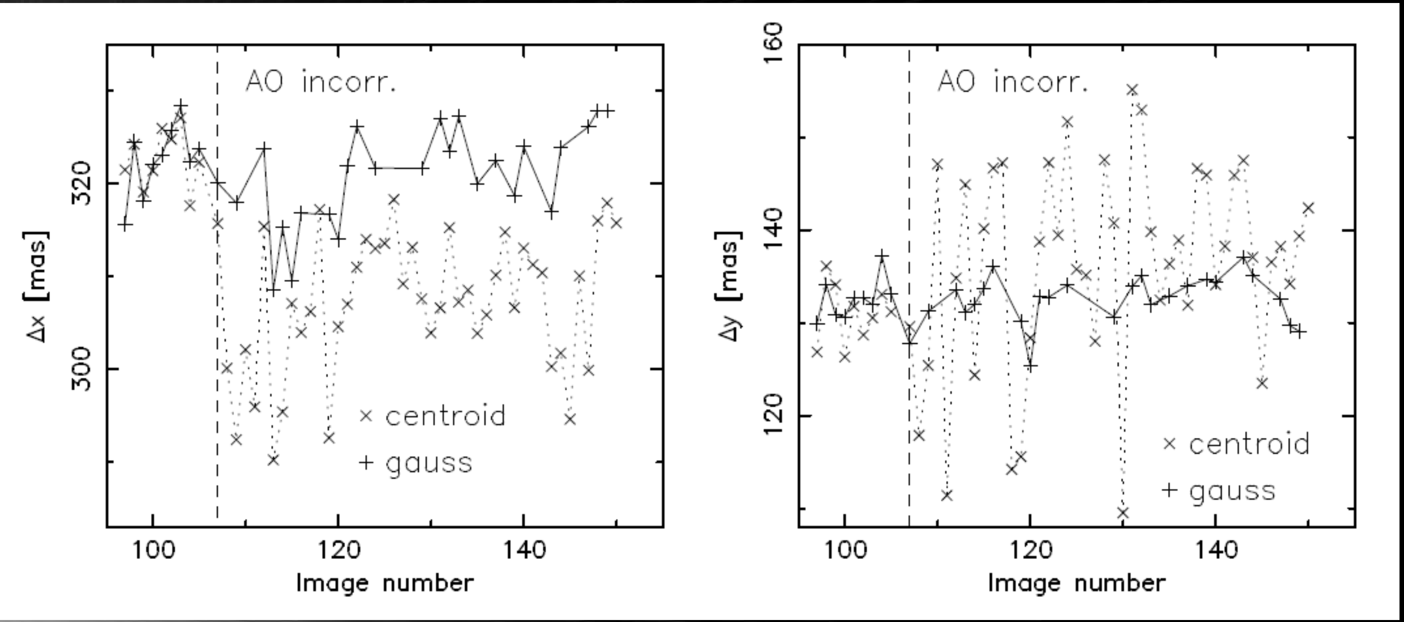
- 8 nights between Mar. and Nov. 2002
- 9 objects observed with Hale telescope + PHARO (Mt. Palomar): GJ 195, 352, 458, 507, 661, 767, 860, 873, 9071 and NGC 6871
- 3 objects observed with Keck II telescope + NIRC2 (Mauna Kea): 56 Per, GJ 300, 569
- J and K bands + AO
- Dithering + field rotation (Keck II)
- Scales: 39.91, 25.10 (Hale); 39.686 i 9.942 *mas/pix* (Keck II)
- NO DEDICATED CALIBRATION OBJECTS

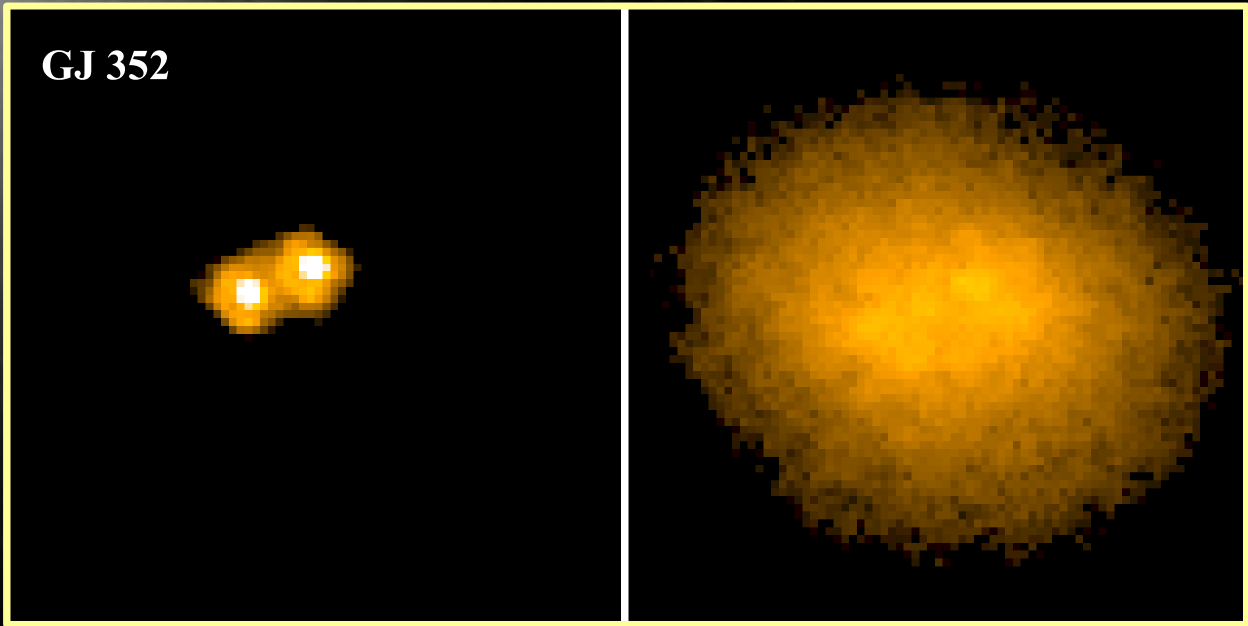
Star	Sp. Type	Magn.	(Band)	$\pi\,[mas]$	Comment	Telescope
56 Per B	???	8.7	(V)	24.00(.91)	double	Keck II
GJ 195 A	M1	10.16	(V)	72.0(.4)	—	Hale
GJ 195 B	M5	13.7	(V)	72.0(.4)	—	Hale
AG+45 517	???	11	(V)	???	field	Hale
GJ 300 B	K7III	8.39	(J)	166(11)	double, field	Keck II
GJ 352 A	M4	10.07	(V)	94.95(4.31)	—	Hale
GJ 352 B	M4	10.08	(V)	94.95(4.31)	—	Hale
GJ 458 A	M0	9.86	(V)	65.29(1.47)	—	Hale
GJ 458 B	M3	13.33	(V)	65.29(1.47)	—	Hale
GJ 507 A	M0.5	9.52	(V)	75.96(3.31)	—	Hale
GJ 507 B	M3	12.09	(V)	75.96(3.31)	—	Hale
GJ 569 Ba	M8.5V	11.14	(J)	101.91(1.67)	double(?)	Keck II
GJ 569 Bb	M9V	11.65	(J)	101.91(1.67)	—	Keck II
GJ 661 A	M3	10.0	(V)	158.17(3.26)	—	Hale
GJ 661 B	M4	10.3	(V)	158.17(3.26)	—	Hale
GJ 767 A	M1	10.28	(V)	74.90(2.93)	—	Hale
GJ 767 B	M2	11.10	(V)	74.90(2.93)	—	Hale
GJ 860 A	M3	9.59	(V)	249.53(3.03)	variable	Hale
GJ 860 B	M4	10.30	(V)	249.53(3.03)	flare	Hale
CCDM 22281...H	???	13.8	(V)	???	field	Hale
GJ 873 A	M3.5e	10.09	(V)	198.07(2.05)	flare	Hale
GJ 873 B	G	10.66	(V)	198.07(2.05)	double, field	Hale
GJ 9071 A	K7	10.2	(V)	72(4)	—	Hale
GJ 9071 B	M0	14	(B)	72(4)	—	Hale

Data

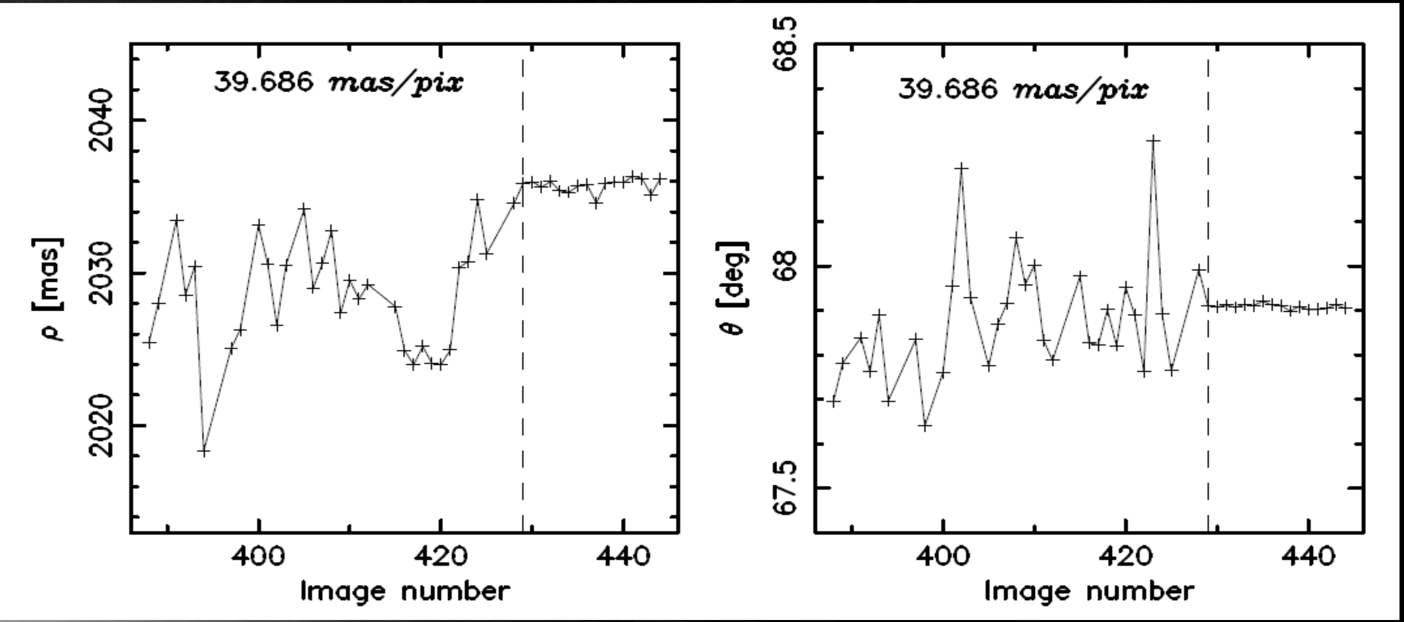
- Over 30,000 CCD frames
- Standard reduction with *IRAF* package
- Calculating centroids and fitting elliptical gaussoids
- Checking the influence of systematic effects with Allan variance

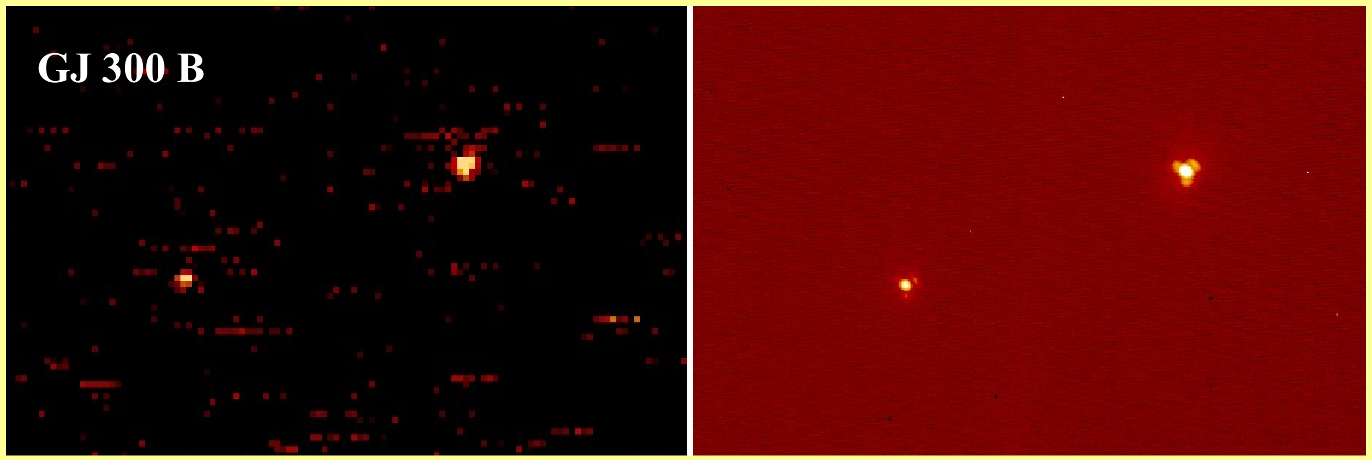
AO correction quality





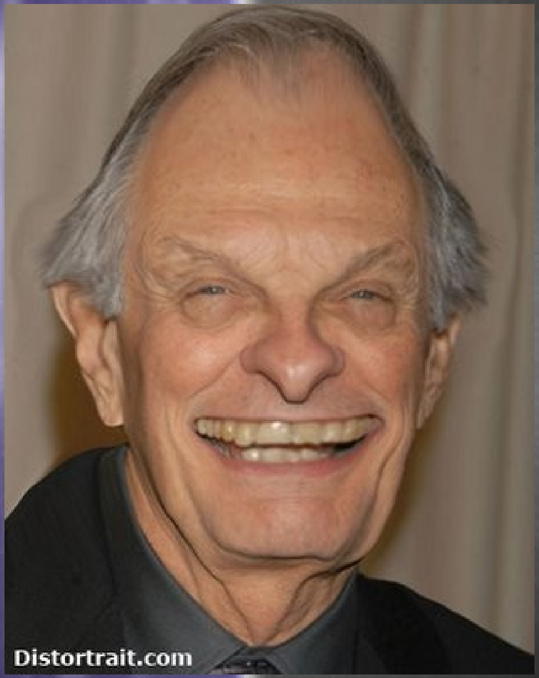
Field of view





Problems occur when most of the star's light is collected by 1 pixel

Pixel scale calibration



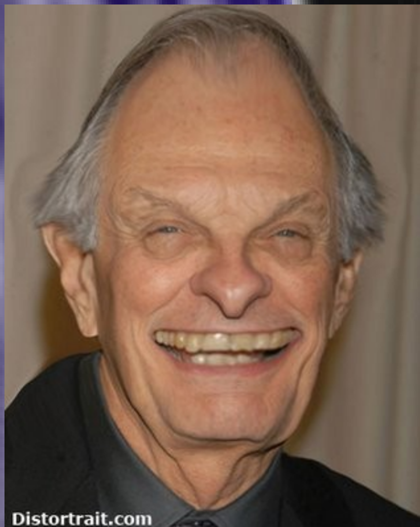
HALE:

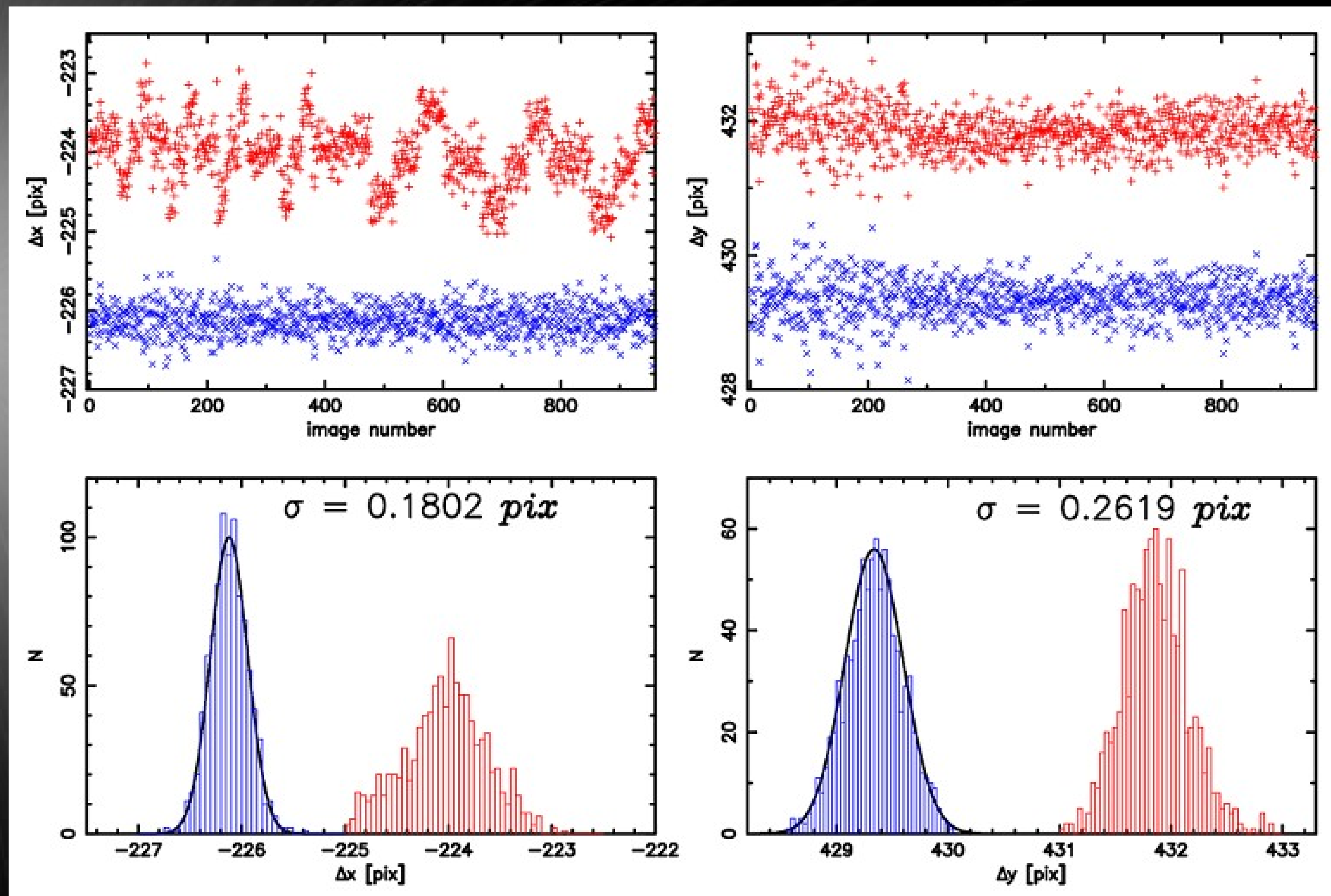
- Complicated model of geom. distortion, beam tilt and gravity variations by Metchev (2006)
- For 1 night average pixel scale and North vector from Metchev & Hillenbrand (2004)
- For the rest of the nights: own calibrations based on NGC 6871

KECK II:

- Simple model of geom. distortion from Thompson et al. (2001)
- Pixel scale the same as nominal

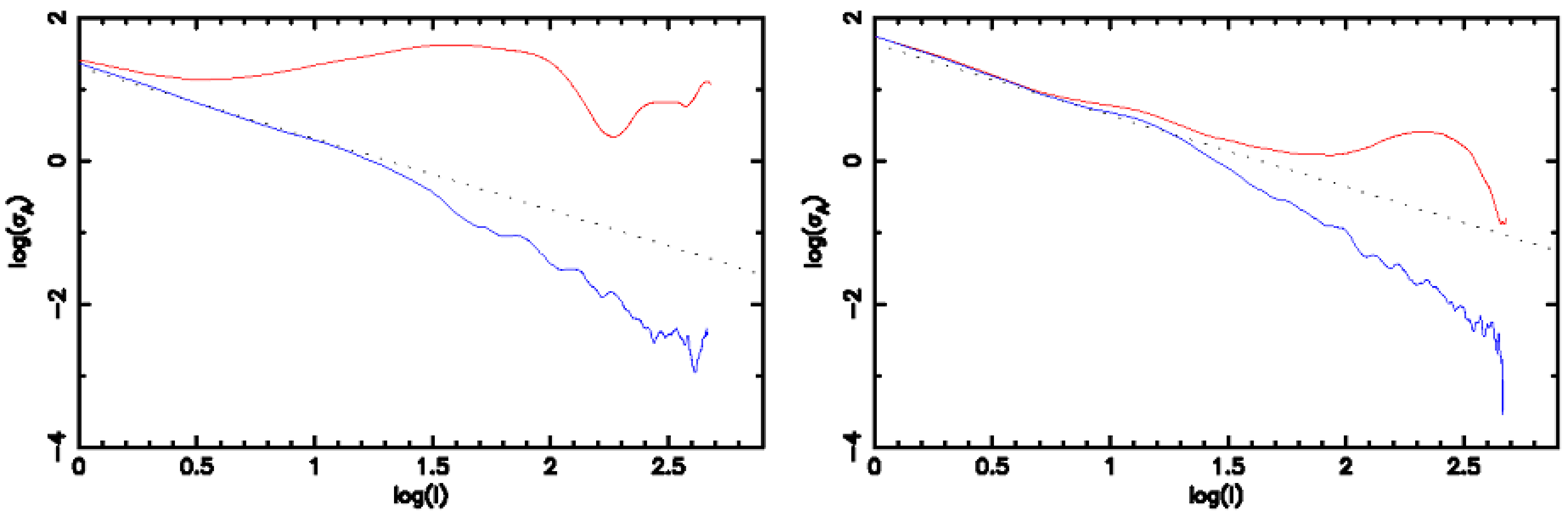
...and the results





Allan (not Alda) variance

$$\sigma^2_{Ax} = \frac{1}{2(M+1-2l)} \sum_{n=0}^{M-2l} \left(\frac{1}{l} \sum_{m=0}^{l-1} r^x_{n+m} - r^x_{n+l+m} \right)^2$$



Allan Alda's pictures: http://distortrait.blogspot.com

Atmospheric Refraction

$$R \equiv z_t - z_a \simeq 206265 \left(\frac{n^2 - 1}{2n^2} \right) \mathrm{tg}\, z_t \quad [arcsec]$$

$$n(\lambda, p, T, p_w) = 1 +$$

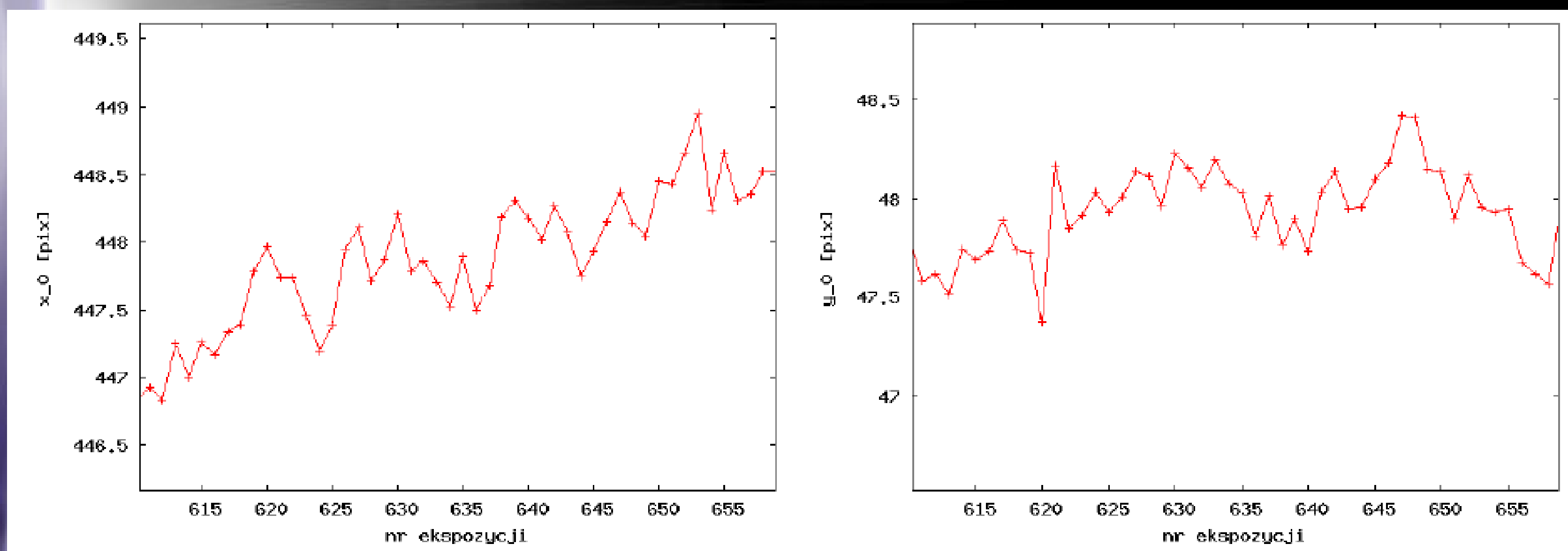
$$+ \left[64.328 + \frac{29498.1}{146 - \lambda^{-2}} + \frac{255.4}{41 - \lambda^{-2}} \right] \frac{pT_s}{p_s T} 10^{-6} -$$

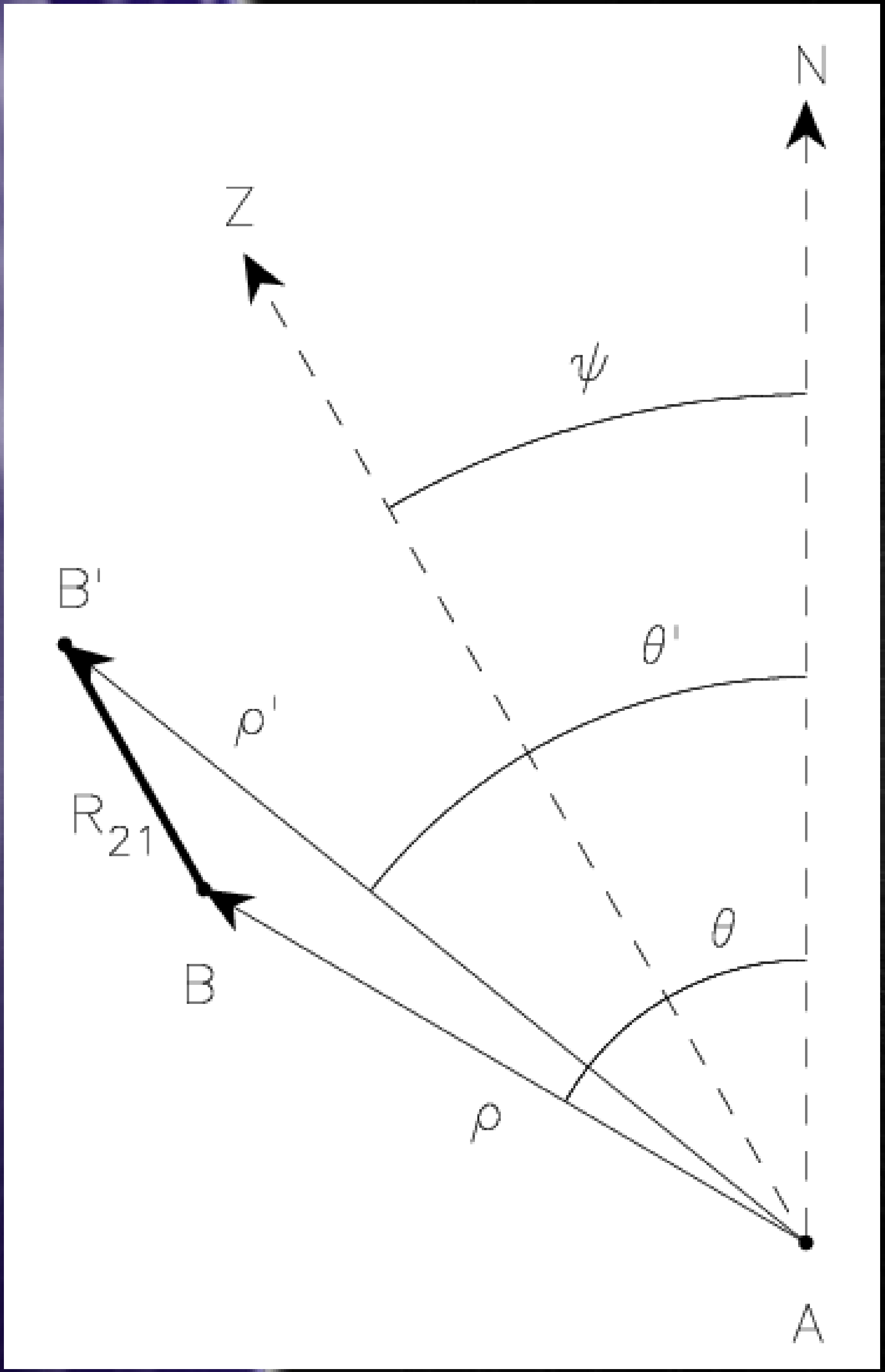
$$-43.49 \left[1 - \frac{0.007956}{\lambda^2} \right] \frac{p_w}{p_s} 10^{-6}$$

Roe 2002

On star's position:

- The AO system guides in visual
- The observation is in IR
- Wavelength dependency leads to a movement of the star along the chip

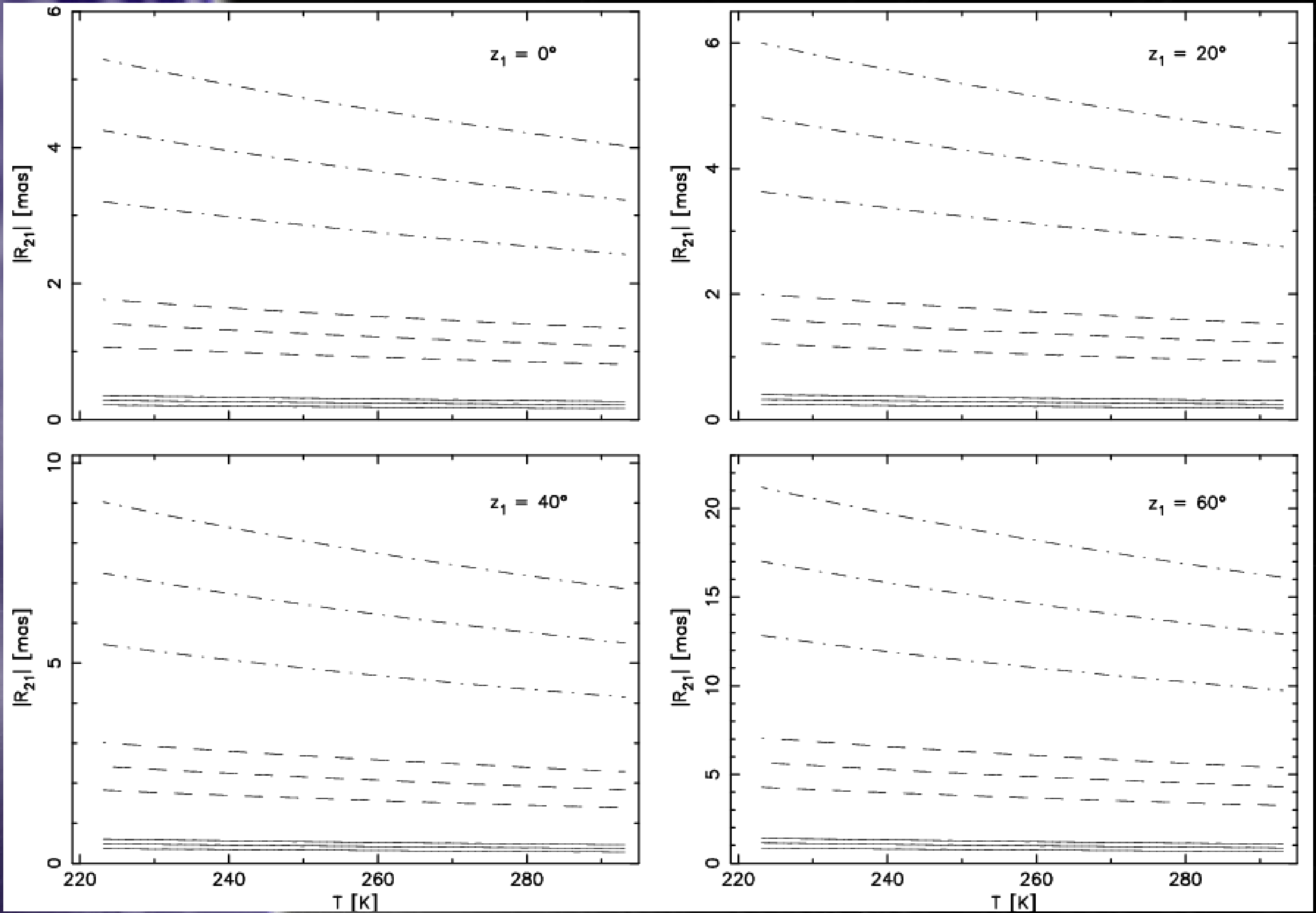




On relative astrometry:

- Stars at different zenithal distances z_1 and z_2
- ...thus are affected by different refractions
- Apparent shift by a vector R_{21} along the Z direction (opposite to Z)
- Second star seen at position B relatively to point A, while in reality is at position B'

Hełminiak 2008



← $\Delta z = 15$ as

← $\Delta z = 5$ as

← $\Delta z = 1$ as

Hełminiak 2008

In every triplet:

- Top: $p = 1013.25$ hPa $= p_S$
- Middle: $p = 813.25$ hPa
- Lower: $p = 613.25$ hPa

Weather requirements

dz [as]	dT [K]	dp [hPa]	Sp.T	F.Ap.	dT [K]	dp [hPa]	Sp.T.	F.Ap.
$\sigma \sim 1\,mas$:								
	$z = 0°$				$z = 20°$			
1	n-n	n-n	no	no	n-n	n-n	no	no
5	n-n	100	no	no	n-n	100	no	no
15	10	50	no	no	1	50	no	no
	$z = 40°$				$z = 60°$			
1	n-n	n-n	no	no	n-n	100	yes	no
5	10	100	no	no	10	50	yes	no
15	10	50	no	no	5	10	yes	no
$\sigma \sim 100\mu as$:								
	$z = 0°$				$z = 20°$			
1	10	100	no	no	10	100	no	no
5	10	10	no	no	5	10	no	no
15	1	5	no	no	0.5	5	yes	no
	$z = 40°$				$z = 60°$			
1	10	50	no	no	10	10	yes	no
5	1	10	yes	no	1	5	yes	no
15	1	5	yes	no	5	10	yes	yes
$\sigma \sim 10\,\mu as$:								
	$z = 0°$				$z = 20°$			
1	1	10	no	no	1	10	yes	no
5	1	1	no	no	0.5	1	yes	no
15	0.1	1	no	no	0.1	0.5	yes	no
	$z = 40°$				$z = 60°$			
1	1	5	yes	no	1	1	yes	no
5	0.1	1	yes	no	0.1	0.5	yes	no
15	0.1	0.5	yes	no	0.05	0.1	yes	yes
$\sigma \sim 1\,\mu as$:								
	$z = 0°$				$z = 20°$			
1	0.1	1	no	no	0.1	1	yes	no
5	0.1	0.1	no	no	0.1	0.1	yes	yes
15	0.01	0.1	no	yes	0.01	0.05	yes	yes
	$z = 40°$				$z = 60°$			
1	0.1	0.5	yes	no	0.1	0.1	yes	no
5	0.01	0.1	yes	yes	0.01	0.05	yes	yes
15	0.01	0.05	yes	yes	0.005	0.01	yes	yes

Hełminiak 2008 (arXiv:0805.3369v2)

- Are we reaching the limit of ground-based astrometry?
- It CAN be impossible to measure positions with precision below 10 μas due to small variations of weather conditions in the telescope's vicinity

More encouraging – – detection limits

Overnight stability

Star (GJ No.)	Lowest σ $[mas]$	Dist. $[pc]$	Mass A $[M_\odot]$	Limit for A $[AU \cdot M_J]$	Mass B $[M_\odot]$	Limit for B $[AU \cdot M_J]$	Tel.
195	0.12	13.89	0.53	1.38	0.19	0.50	Hale
352	1.11	10.53	0.44	8.04	0.41	7.49	Hale
458	0.28	15.32	0.40	2.68	0.37	2.48	Hale
507	0.33	13.16	0.46	3.12	0.37	2.51	Hale
569B	0.11	9.81	0.071	0.116	0.054	0.088	Keck
661	0.038	6.32	0.379	0.16	0.34	0.15	Hale
767	0.09	13.35	0.44	0.83	0.40	0.75	Hale
860	0.048	4.01	0.34	0.10	0.27	0.09	Hale
873	0.57	5.05	0.36	1.62	unknown	unknown	Hale
9071	0.20	13.89	0.53	2.22	0.49	2.05	Hale

$$a\, M_P > 3\sigma_\rho\, d\, M_S$$

Hełminiak & Konacki 2008 (arXiv:0807.4139v1)

Statistics

- 76 measurements of binaries (and 50 of NGC 6871)
- Less than 20% with precision worse than 0.5 mas (due to small number of single frames or large difference in brightness)
- Almost 20% with precision better than 0.1 mas (best: GJ 661 and GJ 860)
- 84 calculated detection limits
- 6% larger than 6 *AU* M_J
- Almost 40% smaller than 1 *AU* M_J

Errata – are parallaxes really the same?

- First component at 10 pc
- Companion 100 AU further
- Distance to the second component:
- 10 pc + 100 AU =

  10.000484813 pc
- Parallaxes difference: **~5 μas**
- For 1st star at 5 pc: **~19.4 μas**

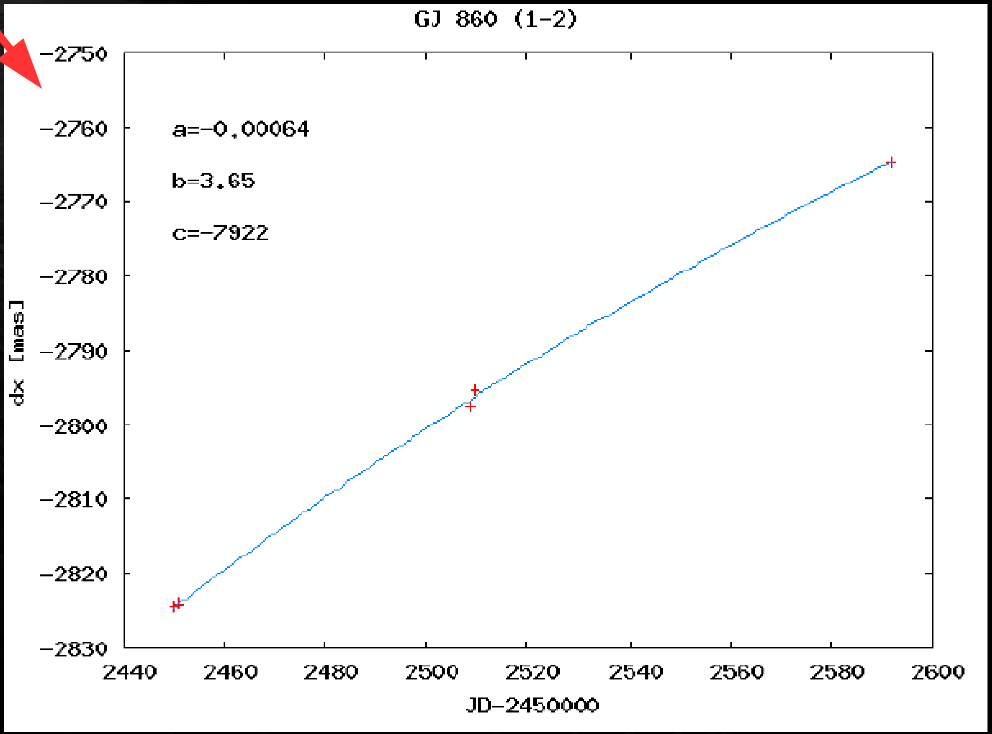
Yes... almost... Just be careful..

More about stability

Pair	rms [mas]
GJ 661 1-2	0.282
GJ 860 1-2	0.216
1-3	2.154
2-3	2.595
GJ 873 1-2	1.127
1-3	1.282
2-3	0.309
NGC 6871 1-2	0.412
1-3	0.470
1-4	1.271
1-5	0.872
2-3	0.345
2-4	1.324
2-5	0.717
3-4	1.304
3-5	0.763
4-5	2.671

Long-term stability (Hale only)

rms of a 2-nd order polynomial fit to results from at least 5 night



Summary

- We obtained one of the most precise astrometric measurements from the ground with a single-mirror telescope to date
- We emphasize the need of proper AO correction, FOV selection, distortion model and AR subtraction
- We conclude that Hale and Keck II telescopes are able to look for planets around many nearby stars
- We are waiting for some **EASY** questions :)

THANK YOU FOR YOUR ATTENTION