Orbital Motion and Multi-Wavelength Monitoring of LkCa15 b

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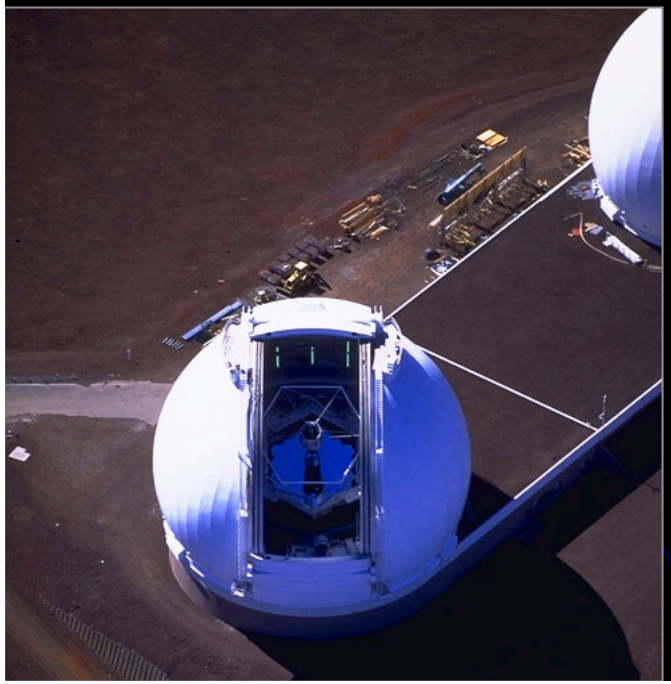
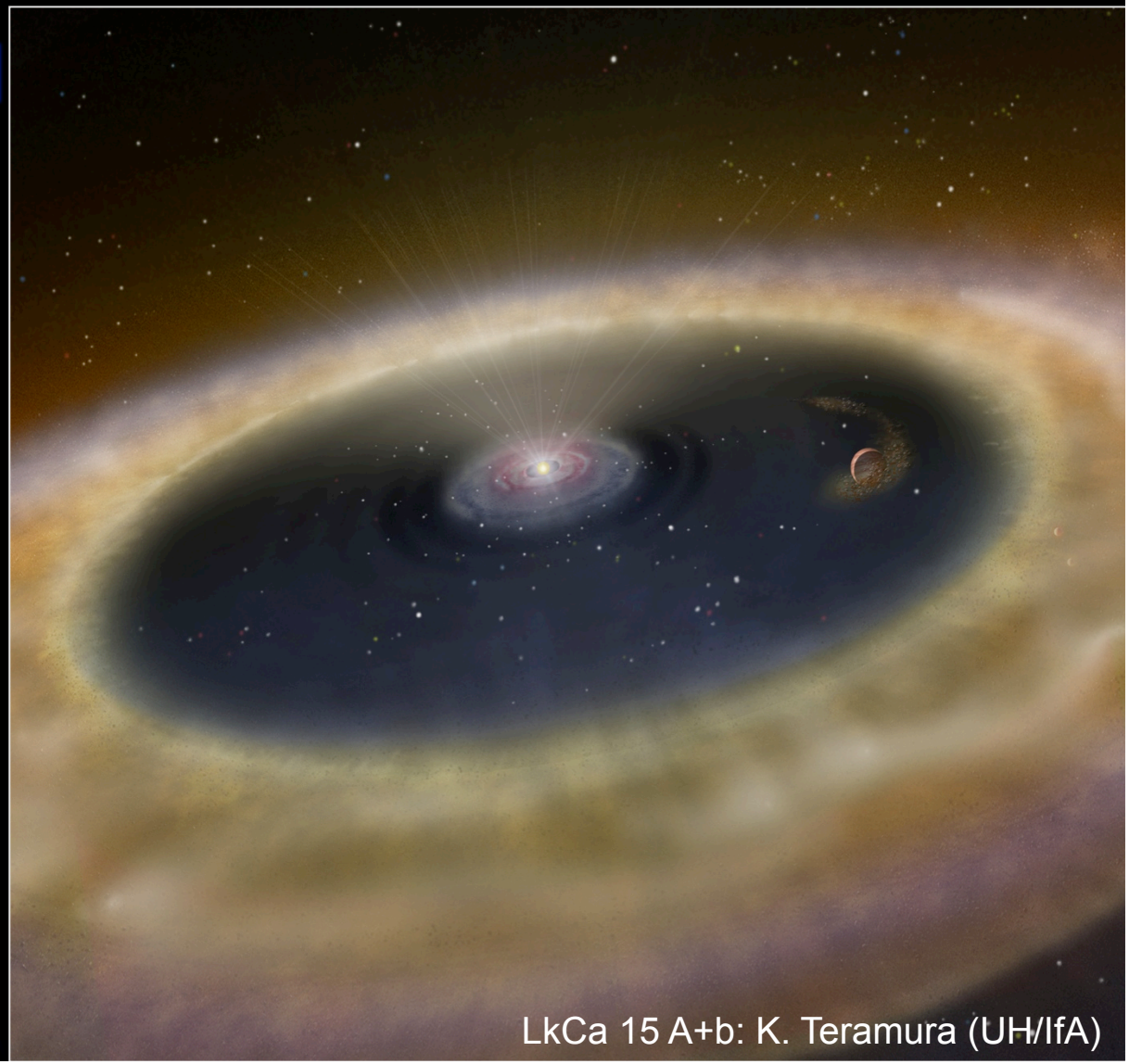
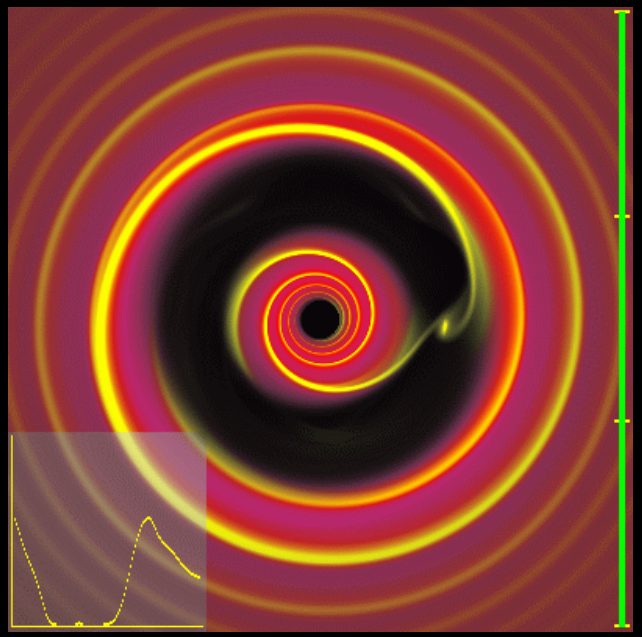




LkCa 15 A+b: K. Teramura (UH/IfA)

The Case for Newly-Formed Planets



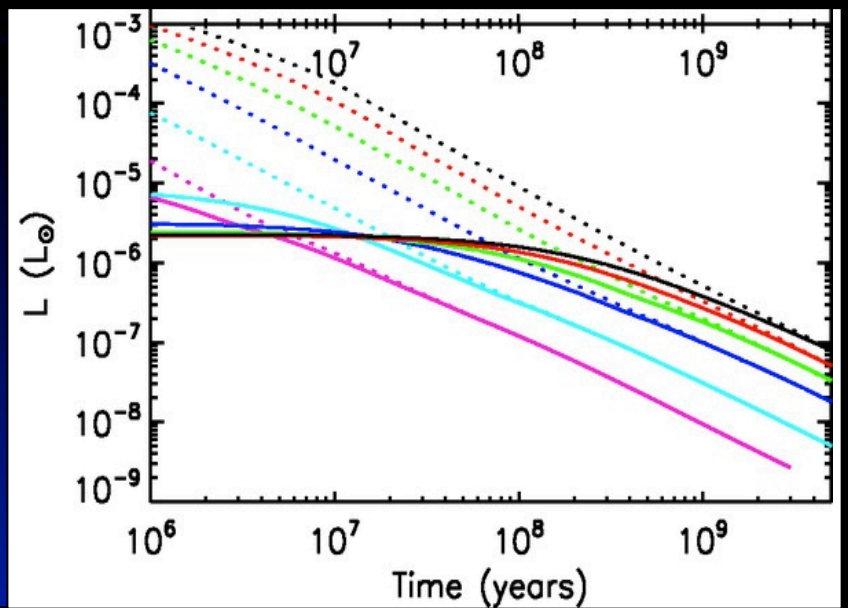
Young planets are primordial

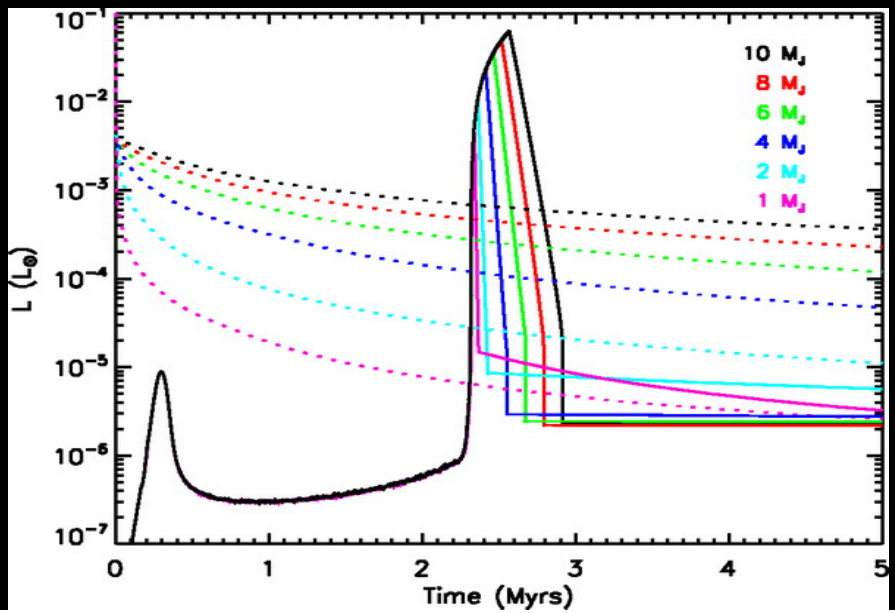
Planets migrate based on interactions with the protoplanetary gas disk (left; Armitage & Rice 2005) or other planets and planetesimals

Young planets are bright(er)

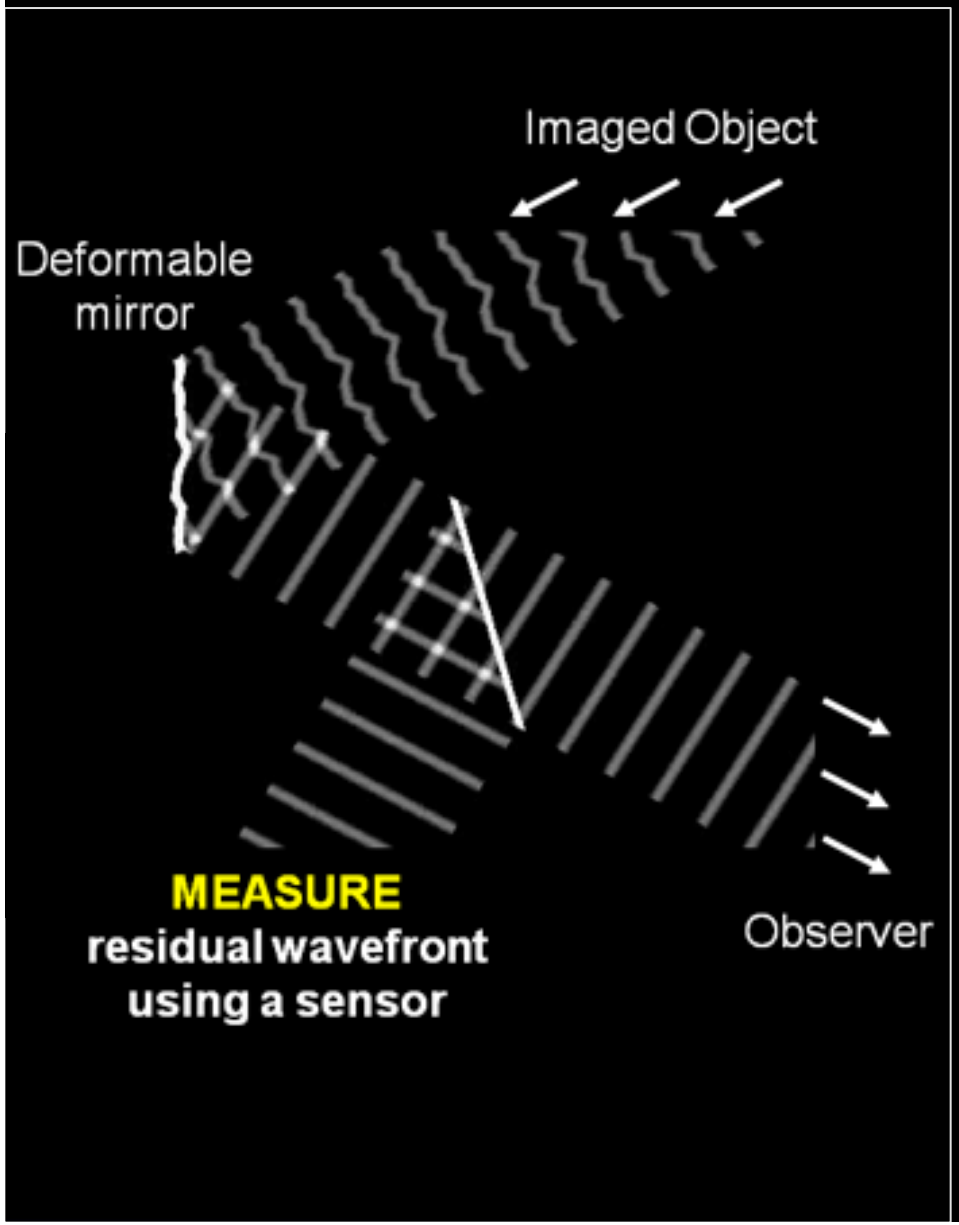
Hot start or cold start aside, young planet should be orders of magnitude brighter (below; Marley et al. 2007; Baraffe et al. 2003).

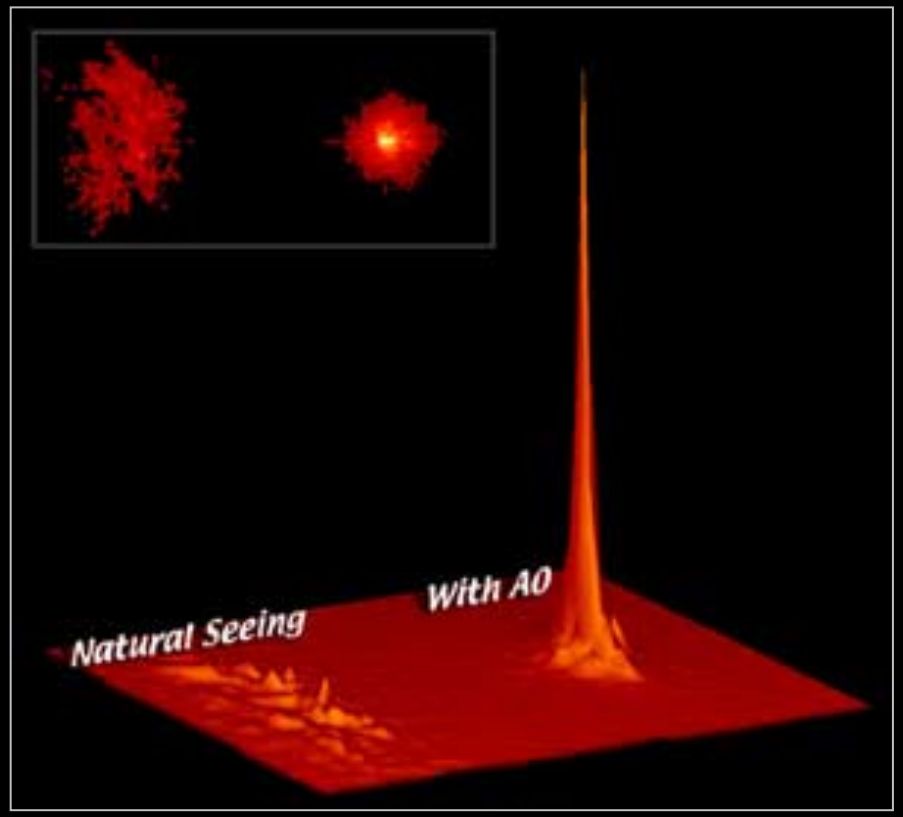
BUT: Young Stars are far away (5AU=0.05")





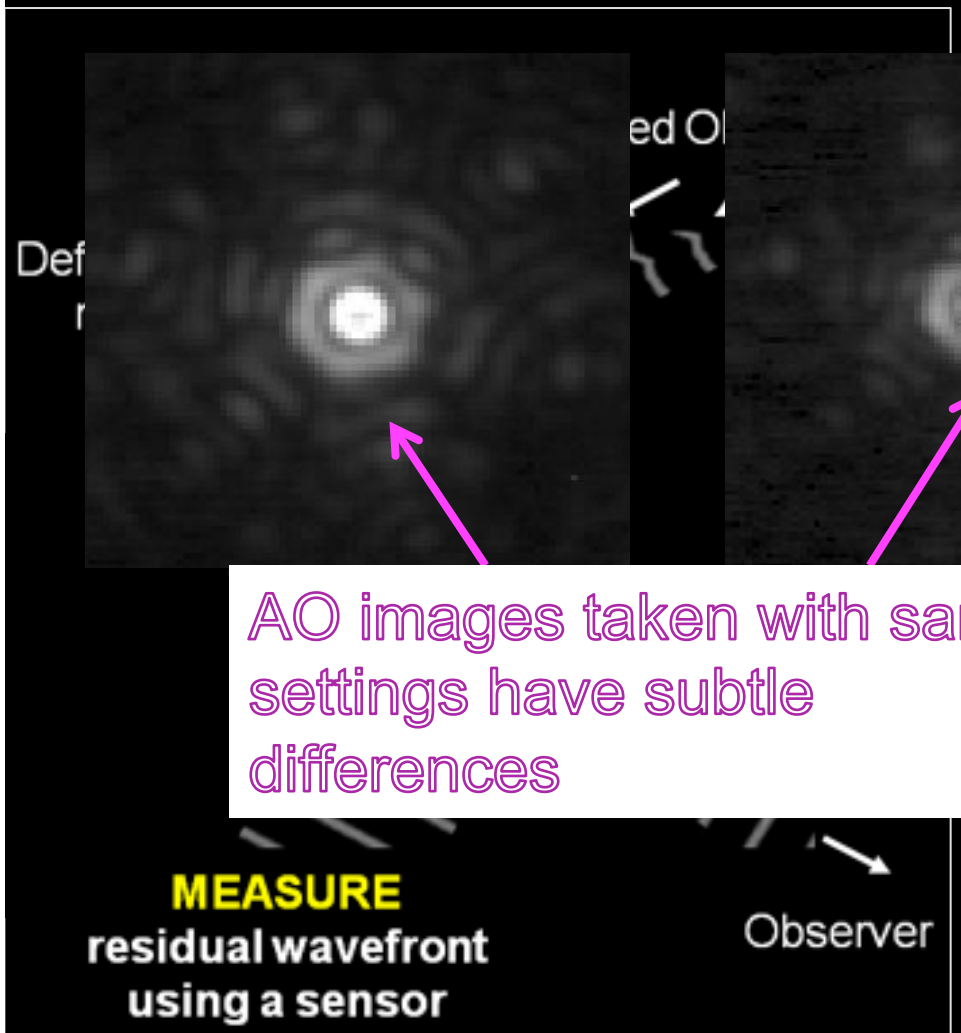
Solution, Part 1: Adaptive Optics



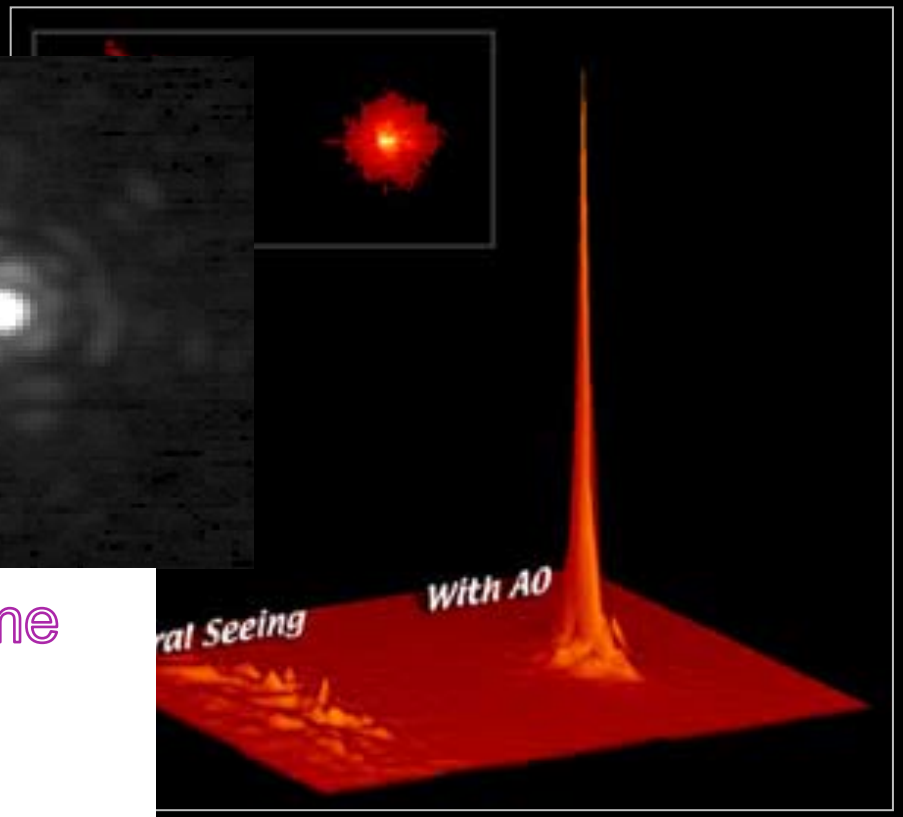


Correct the turbulence introduced by the atmosphere, and hence concentrate the light of the primary star away from the planet.

Solution, Part 1: Adaptive Optics



AO images taken with same settings have subtle differences



Correct the turbulence introduced by the atmosphere, and hence concentrate the light of the primary star away from the planet.

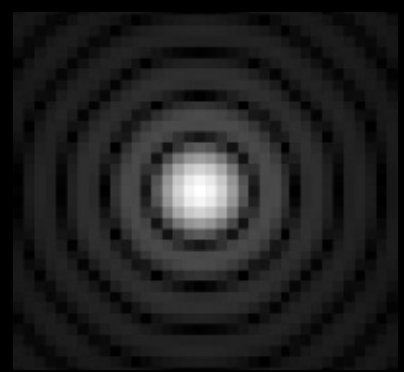
Solution: Maybe LOCI?

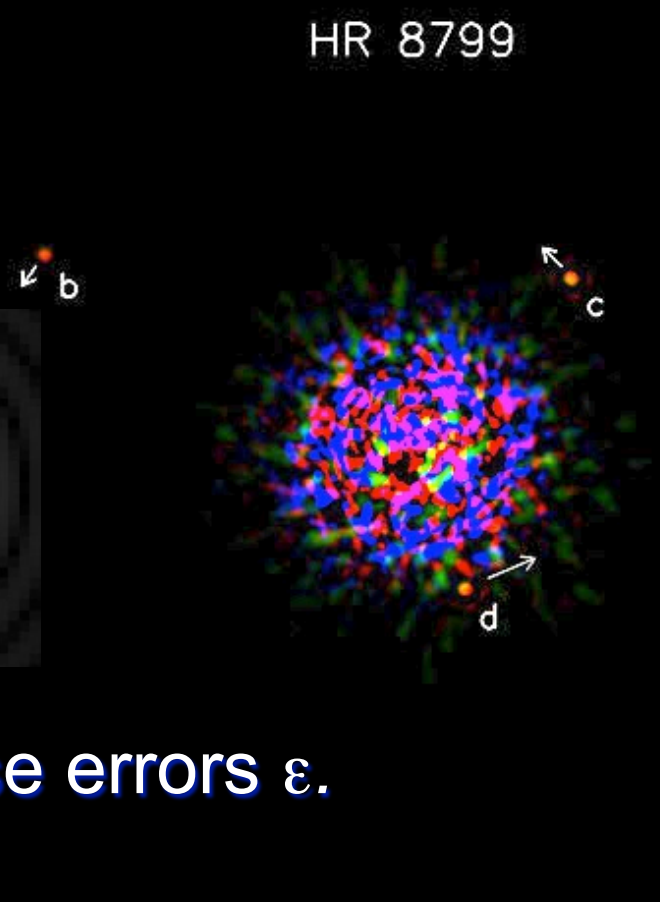
- At larger separations (~4 times the diffraction limit), Angular Differential Imaging and "LOCI" have been very successful.
- But a speckle at (x,y)

has amplitude ~

$|E_0(x.y)+ E_\sigma(x.y)|^2$, with

$E_\sigma = \mathcal{F}\ [\varepsilon(u,v)\ ]$



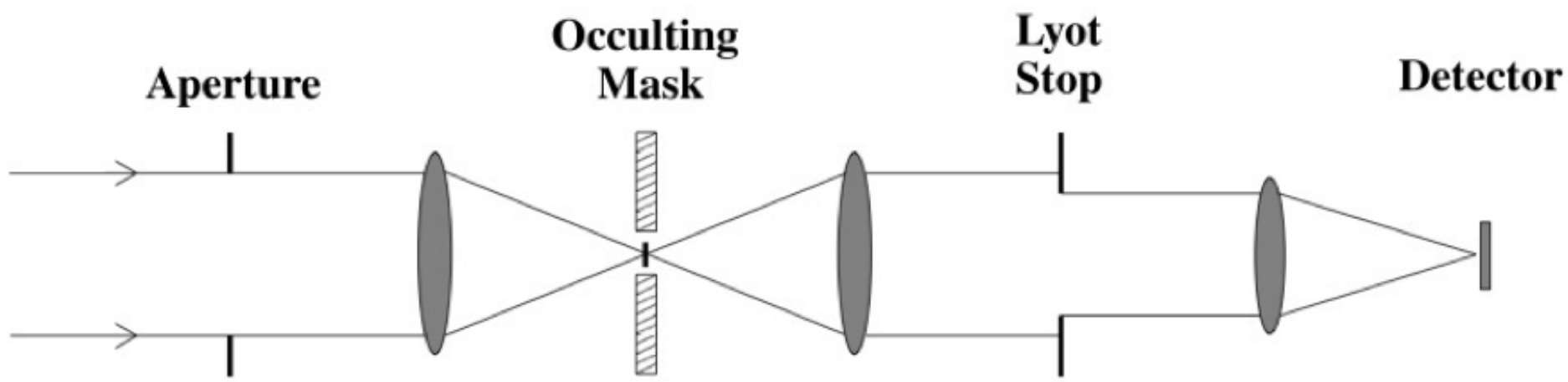


- Speckles are

first-order in pupil-plane phase errors ε.

Solution: Maybe Coronagraphy?

- Coronagraphy eliminates the off-axis diffraction-limited electric-field E_0.
- Errors are *second-order* in pupil-plane phase-abberation ε… if the coronagraph is perfect.



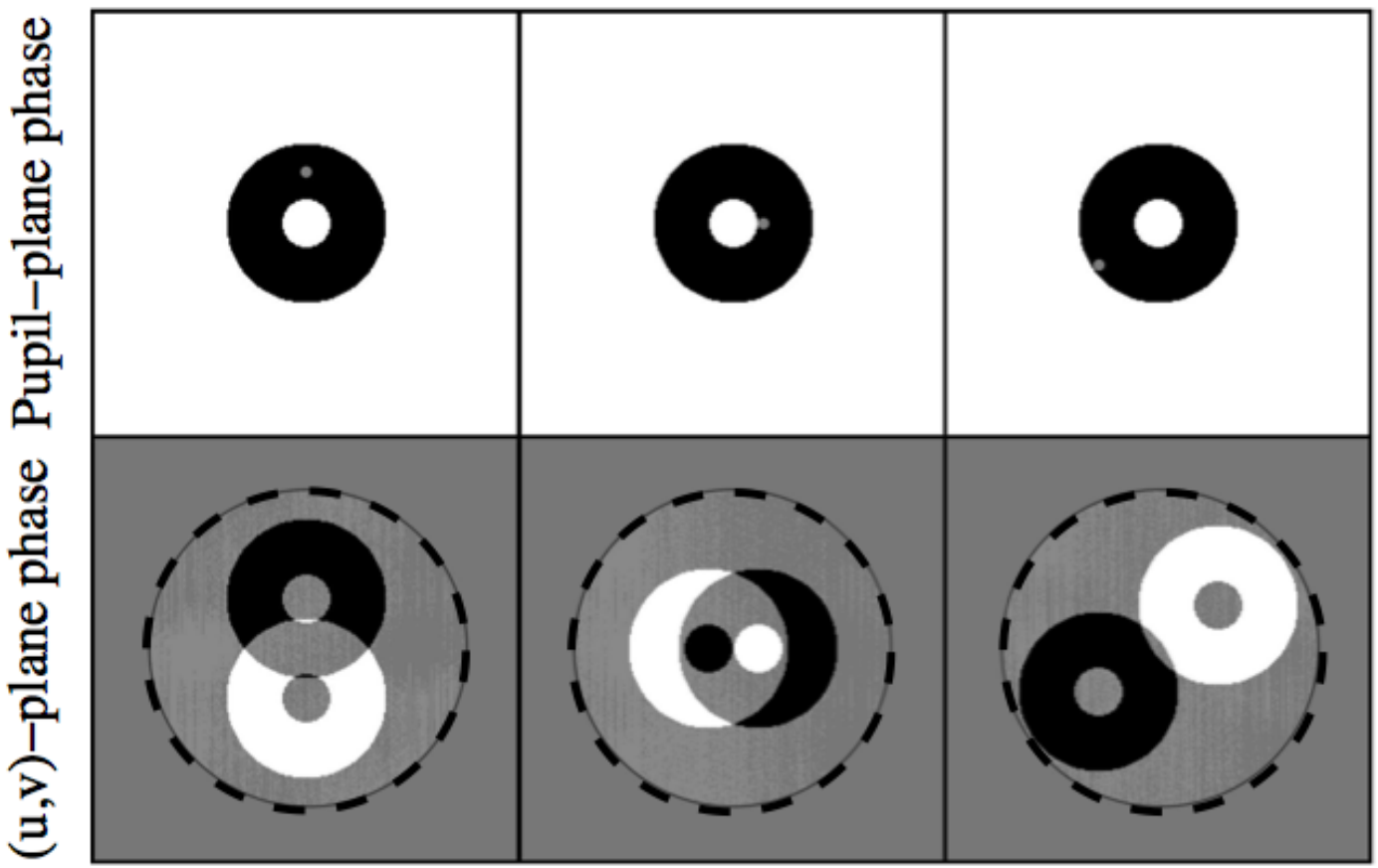
(From Sivaramakrishnan et al 2001)

Solution, Part 2: Kernel Phase

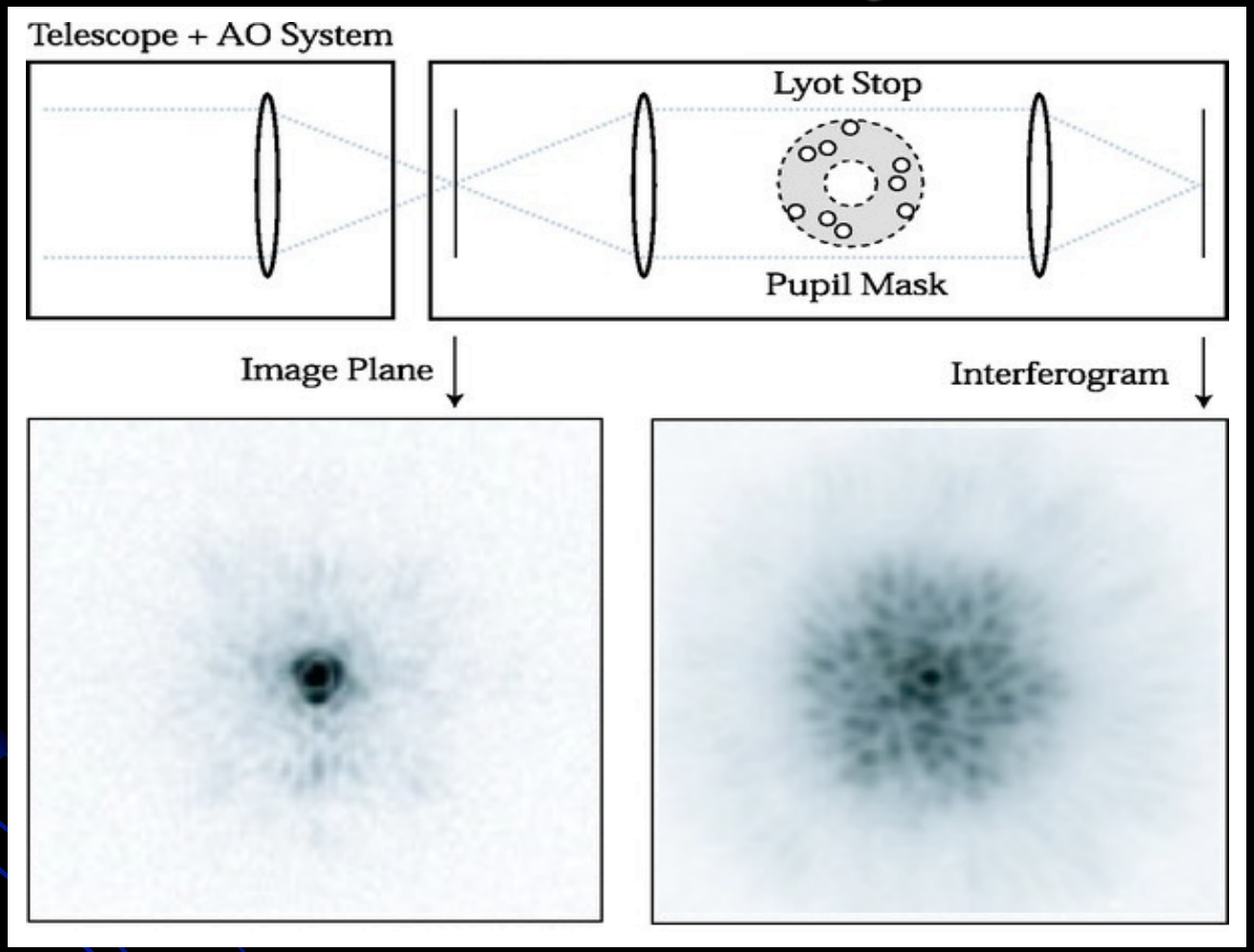
There is *always* more phase information in the (u,v)-plane than the pupil-plane. This information is the *Kernel-Phase* (Martinache 2010) and is *third-order* in phase errors.

At least *half* of the Fourier phase info. is independent of pupil phase (1st order)

$$\mathbf{\Phi_F} = \mathbf{A} \cdot \mathbf{\Phi_P}$$



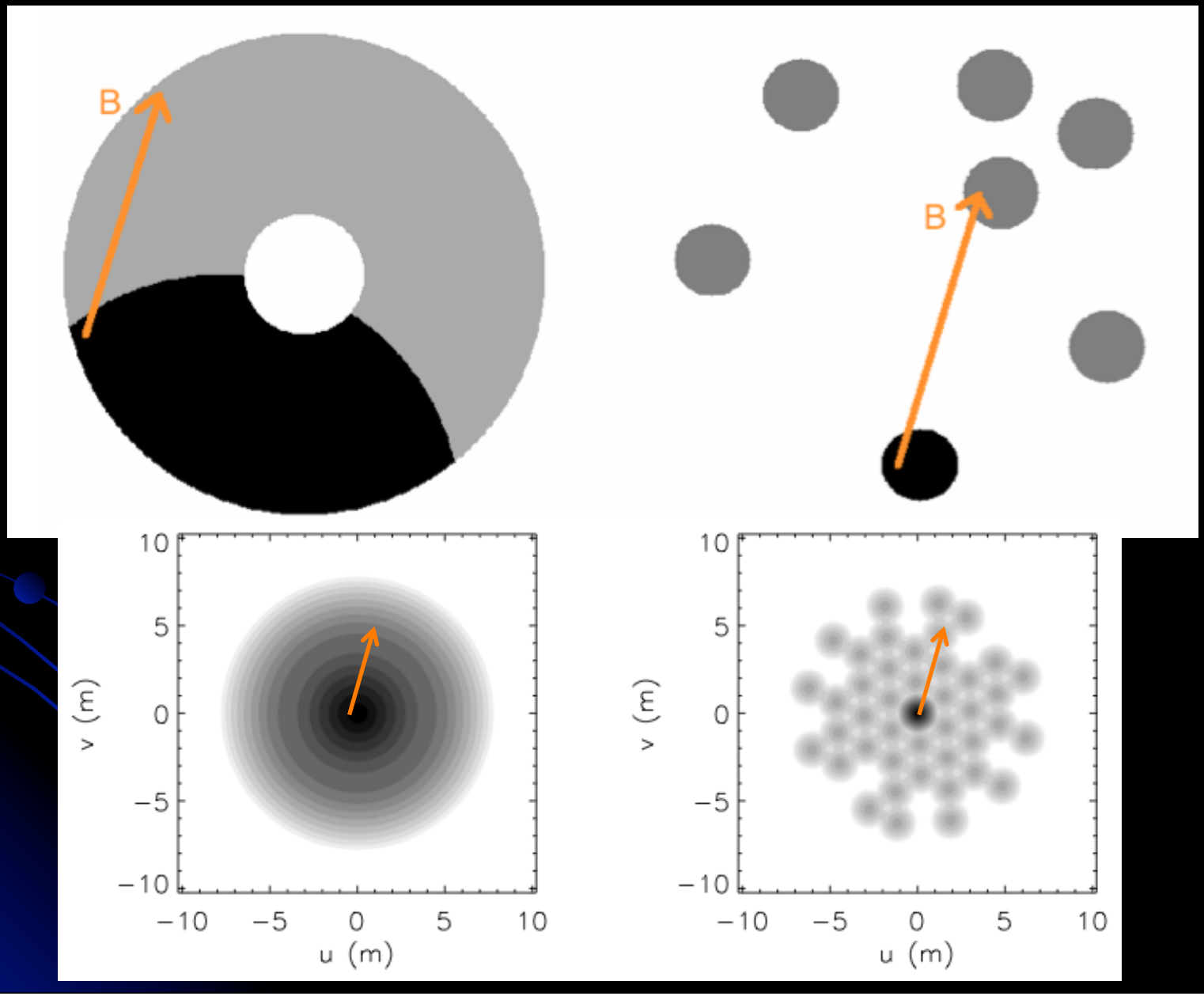
Interferometry



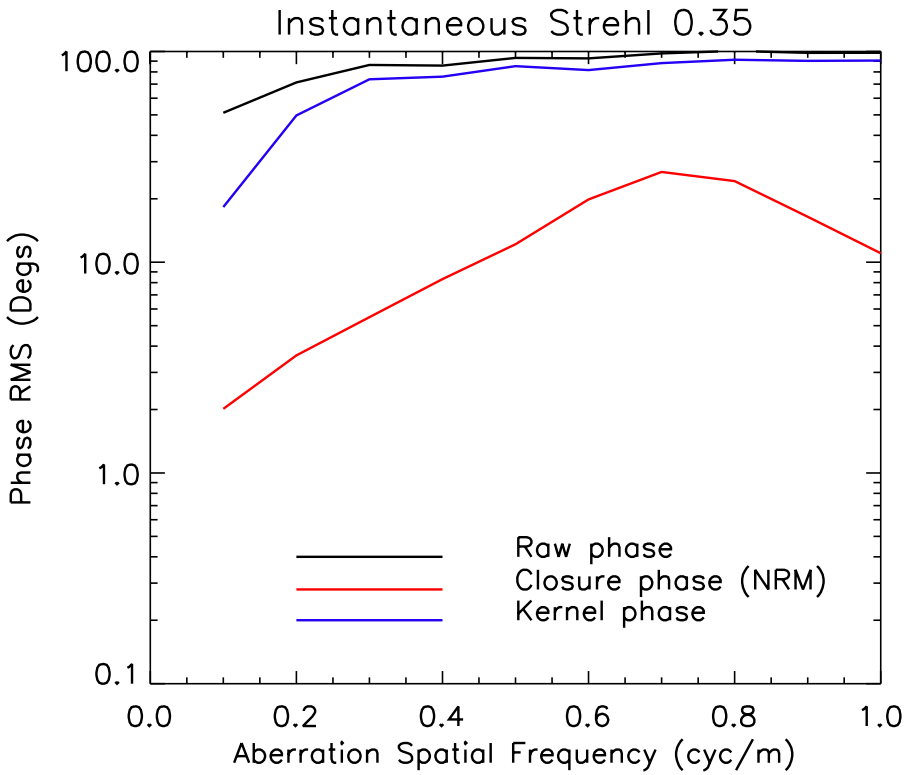
Nonredundant Mask Interferometry (NRM): Place an aperture mask in the pupil plane, turning the single mirror into a sparse array.

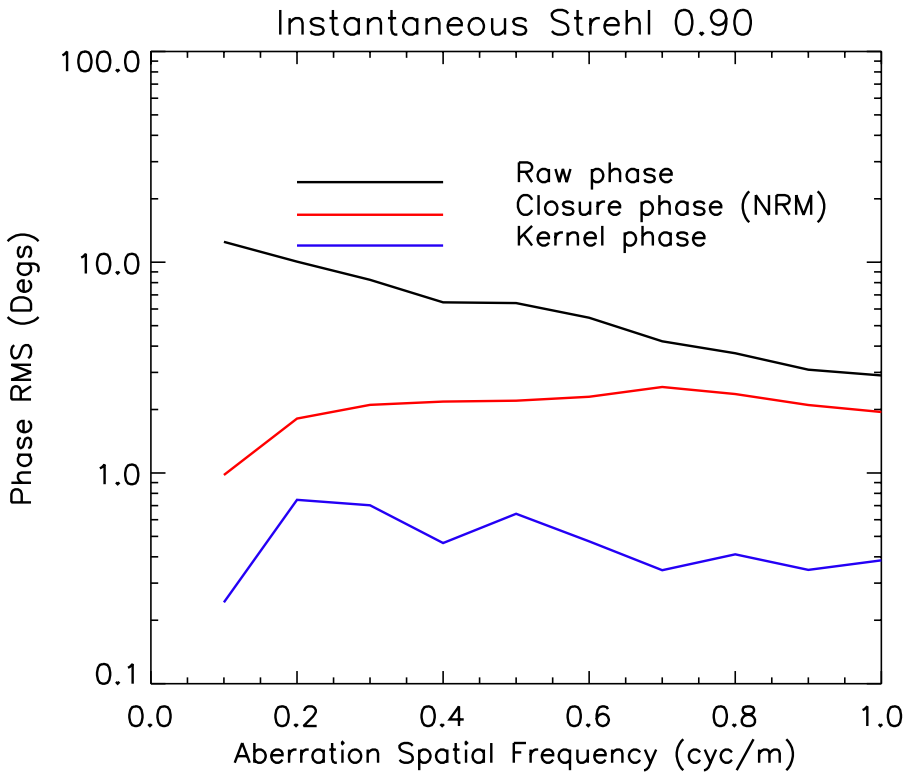
(A. Kraus talk on Friday for more details including large surveys…)

Kernel-Phase Versus SAM/NRM



Poor Strehls: Aperture-Masking Wins

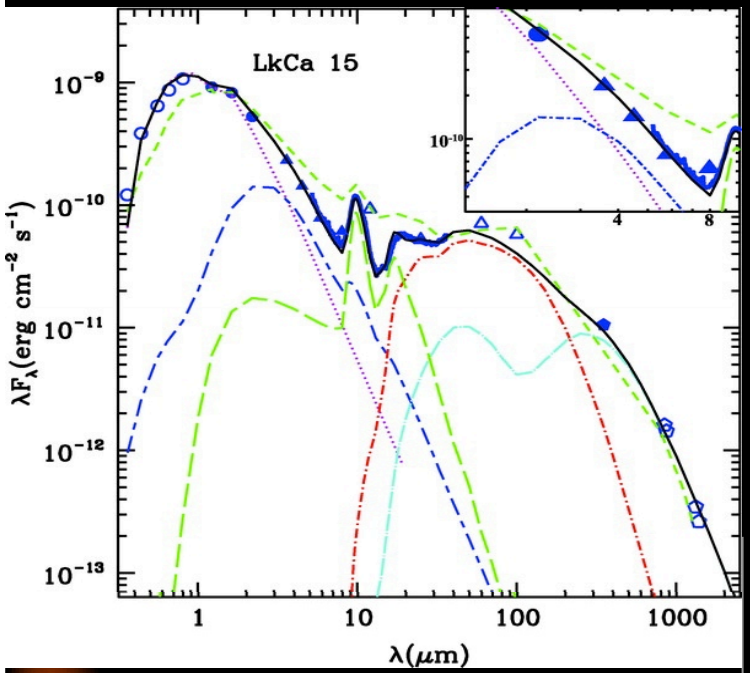




NGAO or L/M bands: Kernel-phase wins

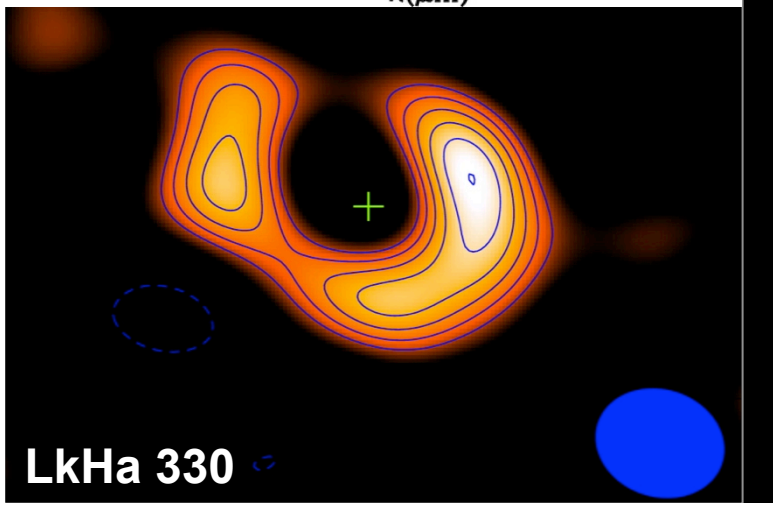
Back to Astronomy…

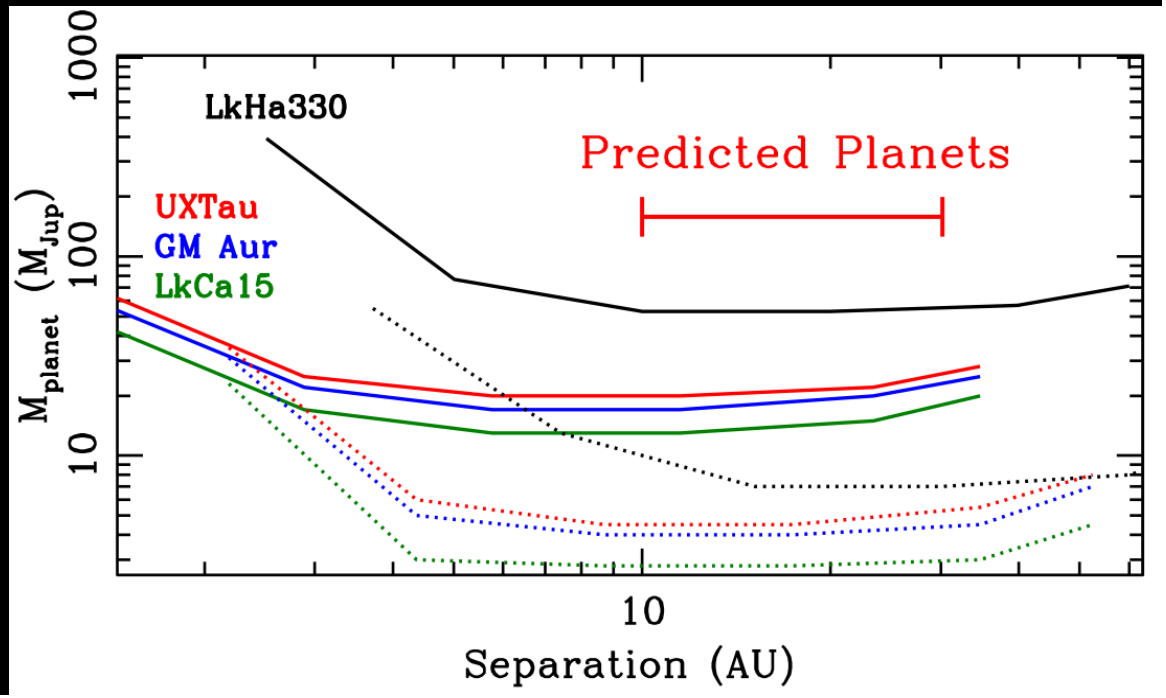
Following the Signposts of Planet Formation



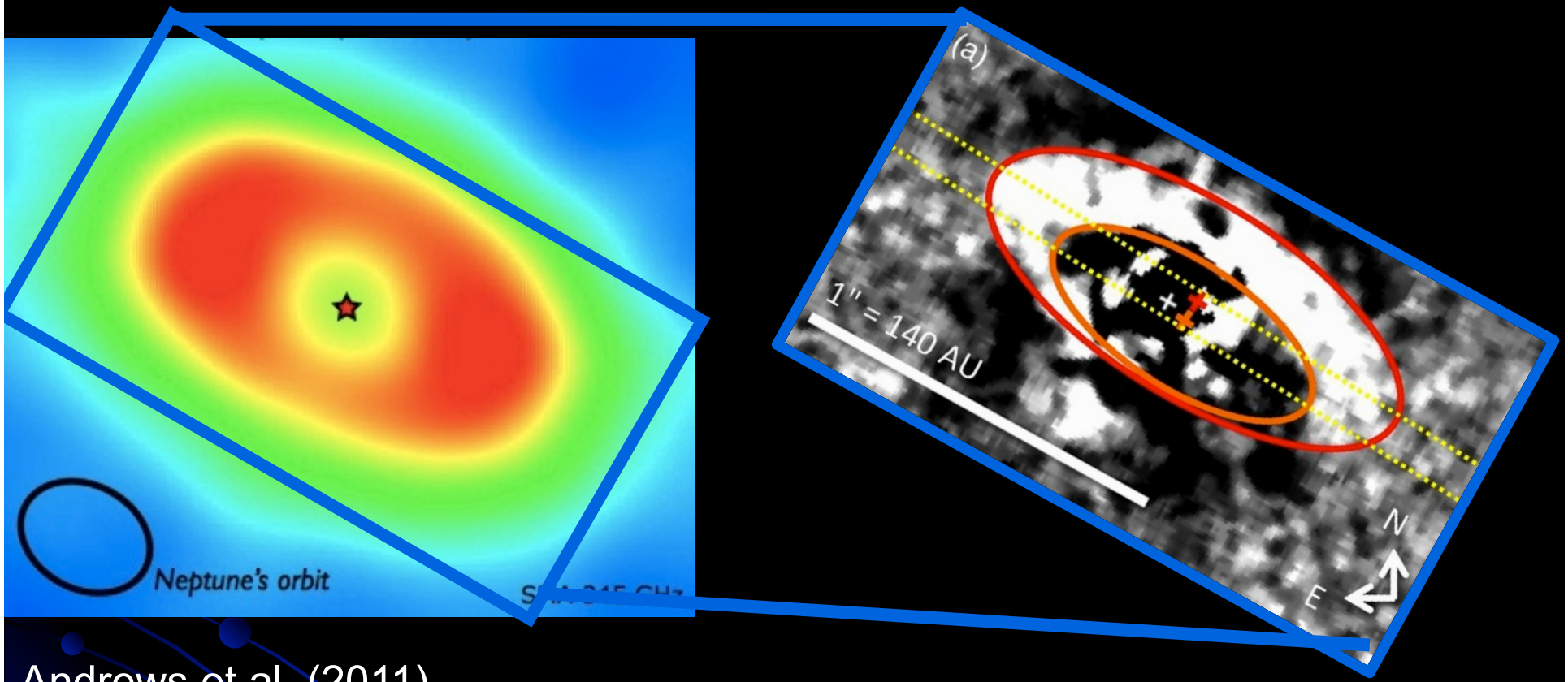
If we're going to find planets anywhere, transitional disks are the places to look!

Observe at reddest possible wavelength (L'), and invest 4+ hours per target. We want to hit the contrast limit of our current capabilities.





LkCa15

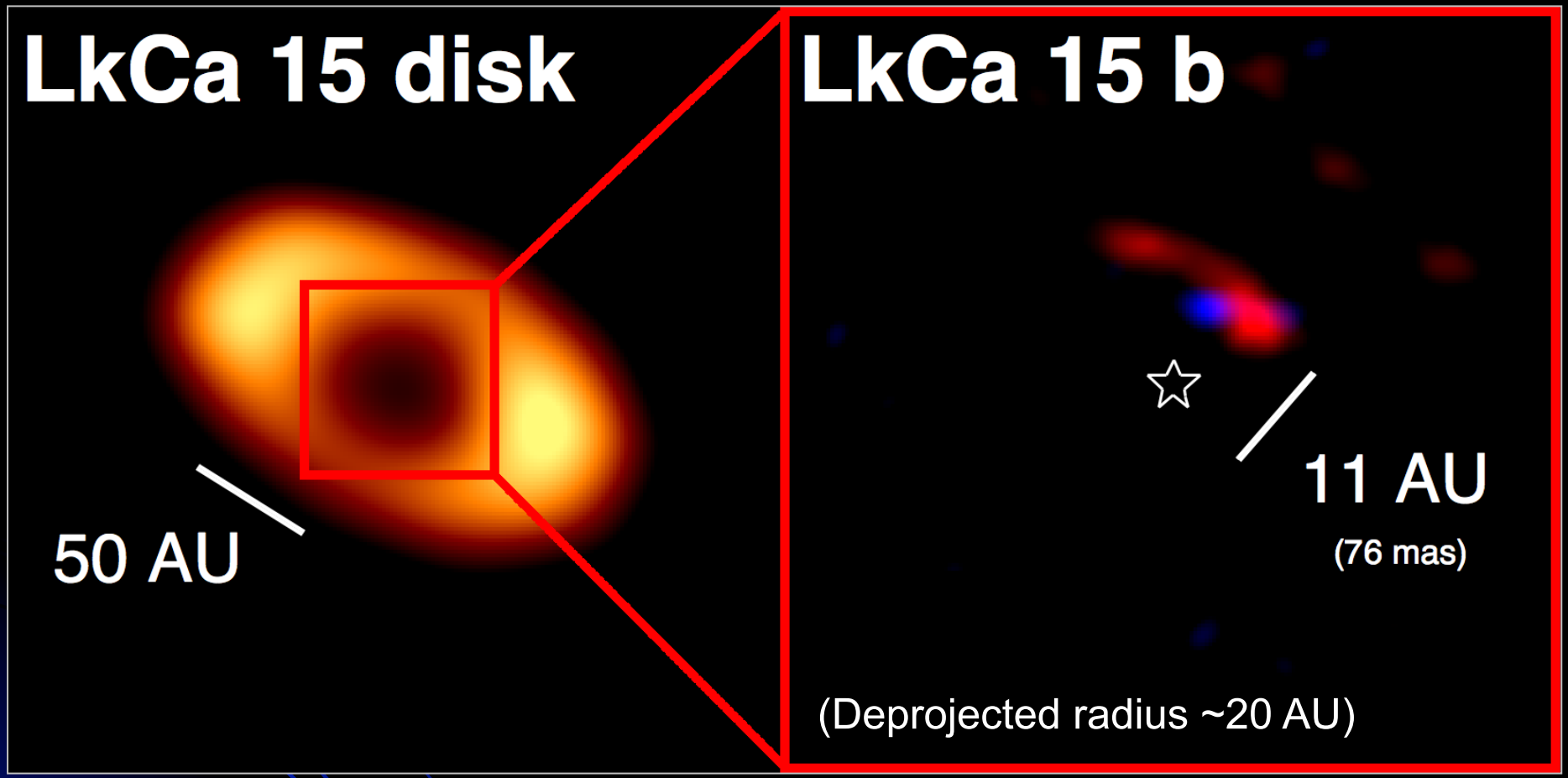


Andrews et al. (2011)
SMA, Sub-mm Image
(Dusty Outer Disk)

Thalmann et al. 2010
HiCIAO, H-band Image
(Interpreted as inner Disk Wall)

One of the best-studied transitional disks –
A ~50 M_J disk, a ~46 AU gap, a 1 $M_\odot$, 2-3MYr star.

K&I 2012: Image Reconstruction



Andrews et al. (2011)
SMA, Sub-mm Image
Dusty Outer Disk

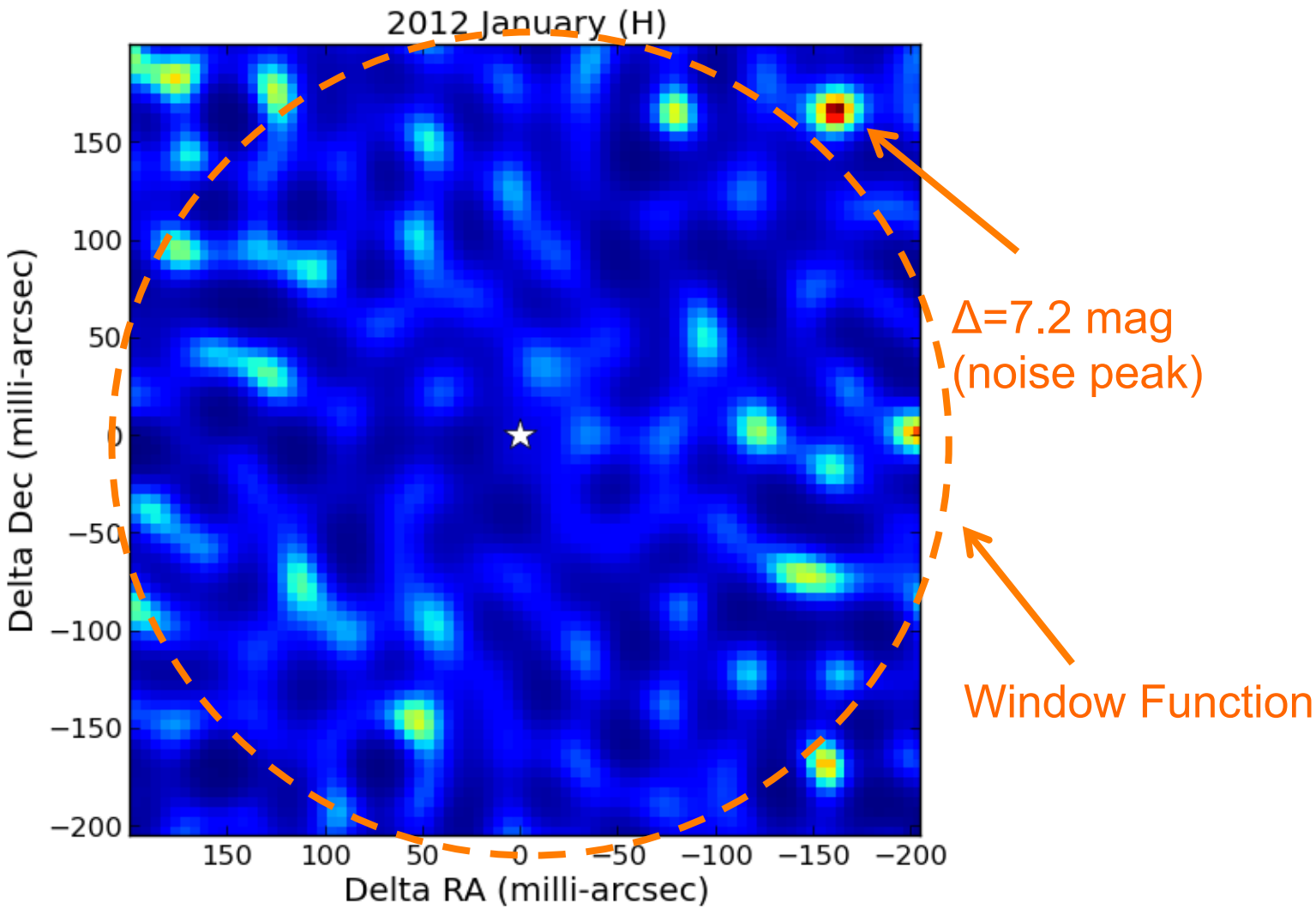
Reconstructed Multicolor Image
Blue=K', Red=L'
Planet + Co-orbital material?

New Observations

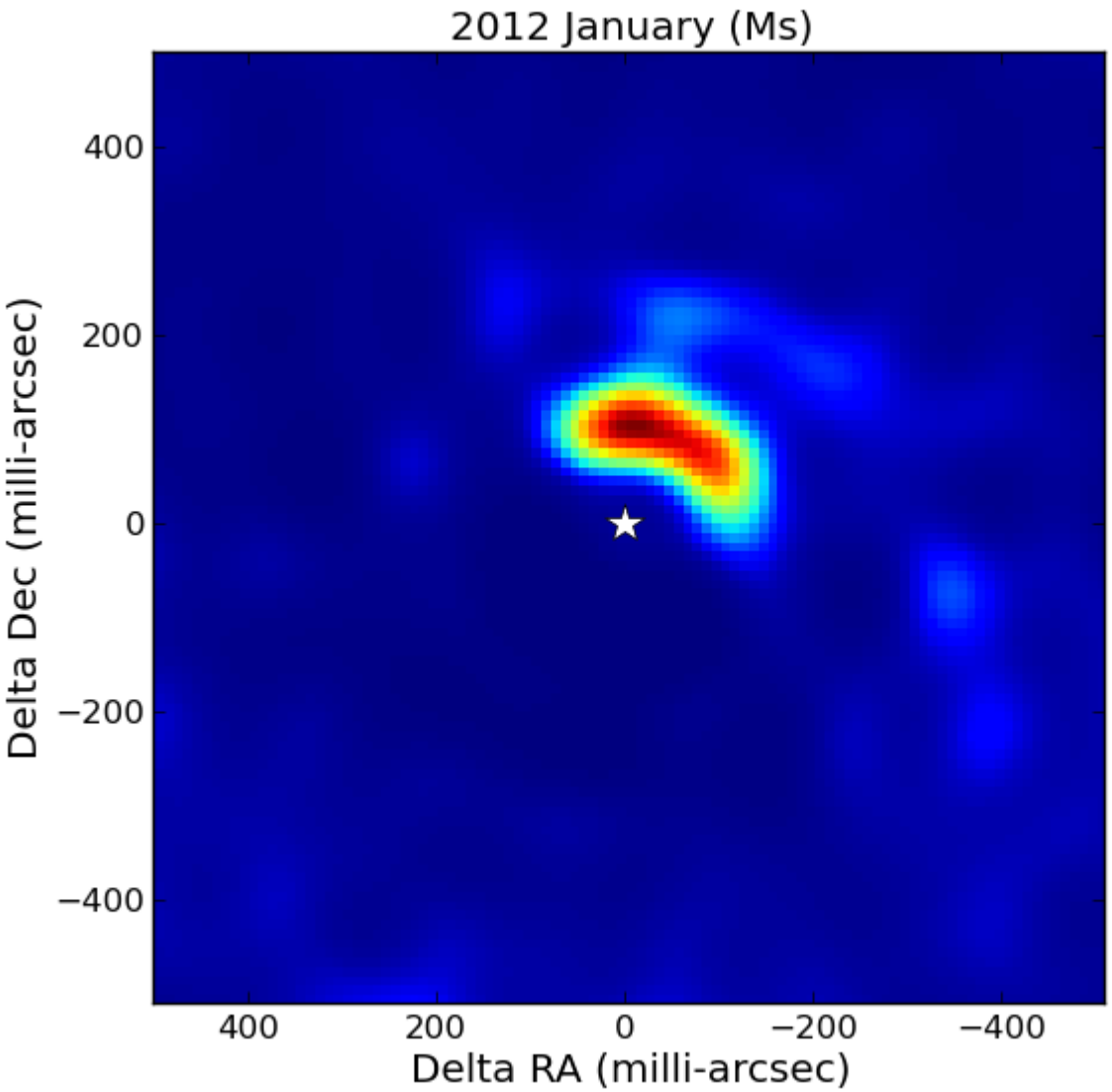
- Poor weather since 2010 has meant different filters taken at different times…

Date	Filters
2008 Dec	K (shallow)
2009 Nov	L
2010 Nov	K,L
2012 Jan	H,M
2012 Aug	L
2012 Dec	K,L

H-band (Jan 2012, nearly *6 hours*)



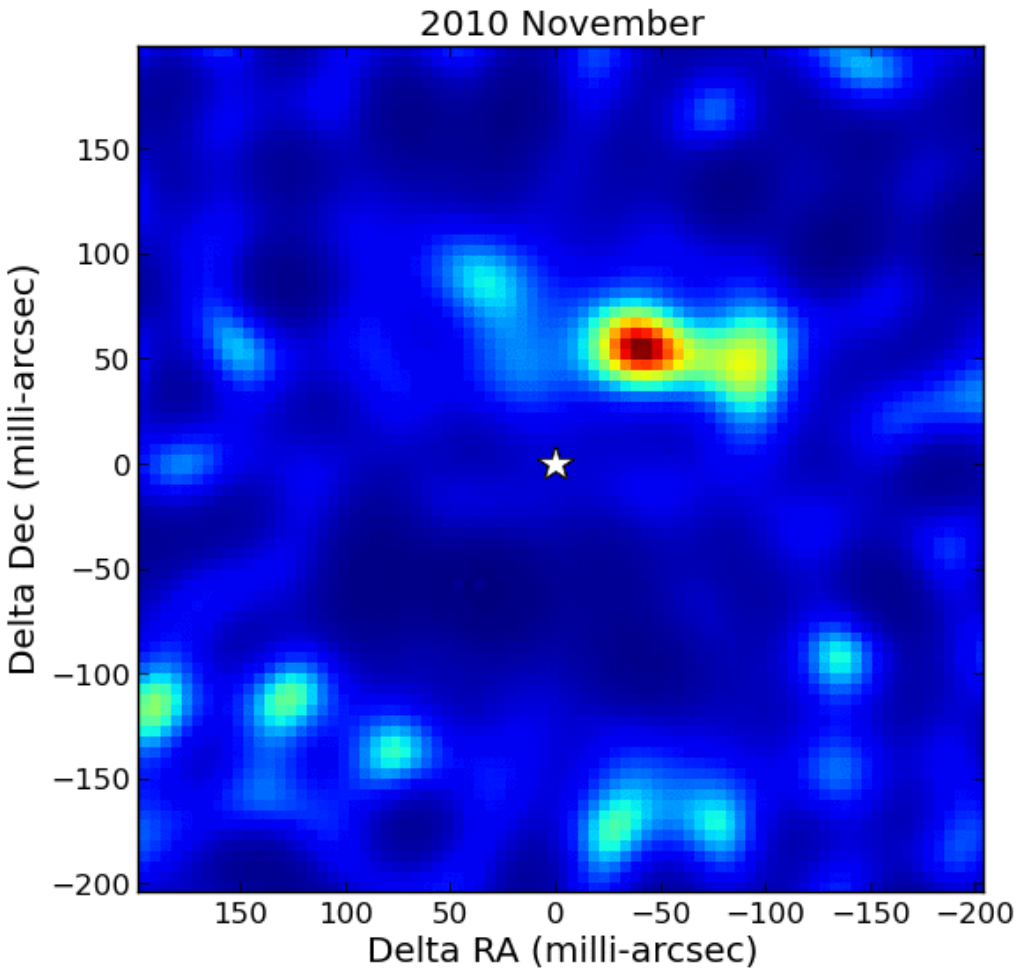
M-band (Jan 2012)

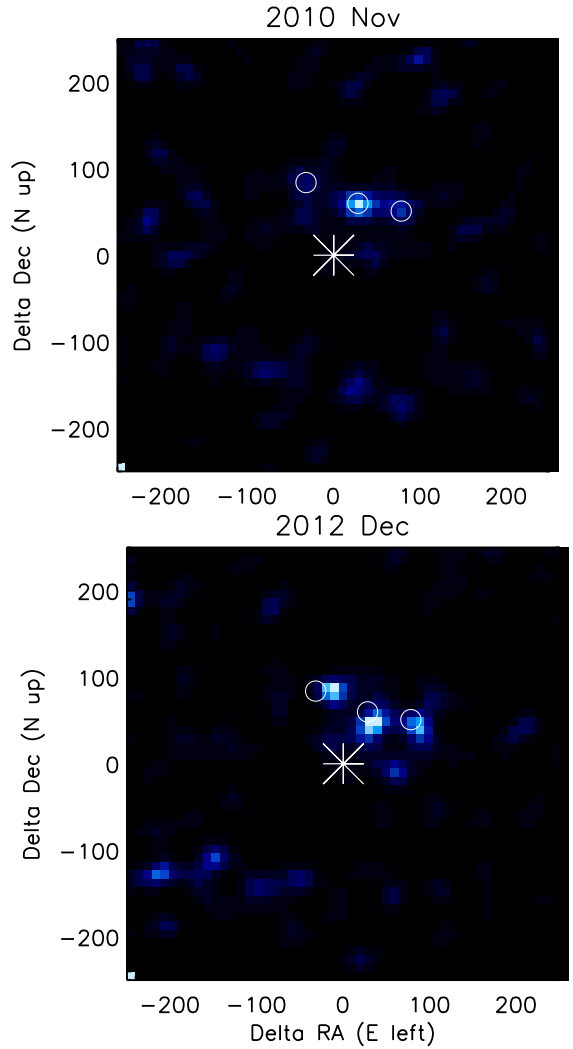


- Kernel-phase (full pupil) imaging
- Contrast Δ= 3.5 mag
- ~80 milli-arcsec arc similar to L-band

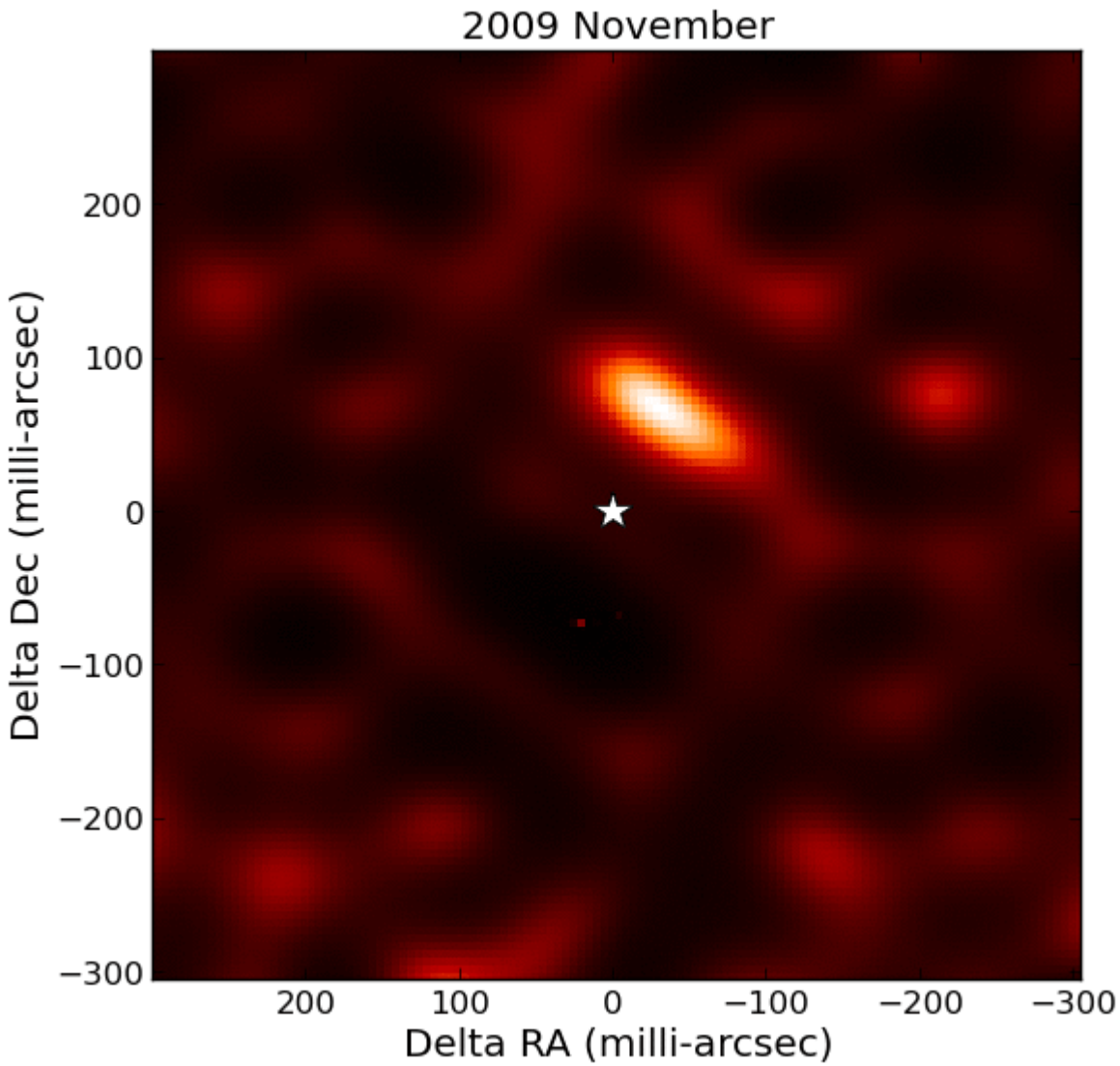
Orbital Motion? (K' filter)

~6 degrees/year motion (3-4 degrees deprojected) – consistent with Keplarian rotation (~100 year period for 1 $M_\odot$, 20 AU).

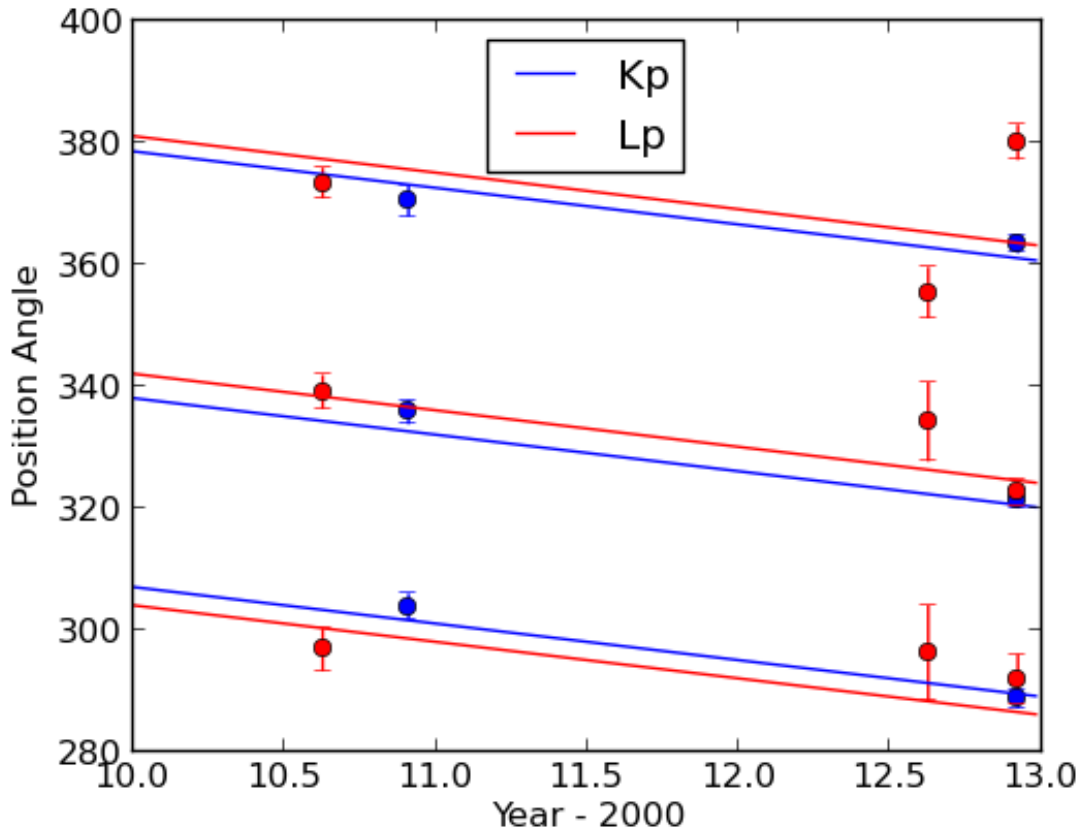




Orbital Motion? (L' filter)



Orbital Motion



- Imaging with super-resolution has artifacts: better to fit.
- For epochs fit well by 3 additional point-sources, all show clockwise rotation.
- 4 out of 6 blob/ colour combinations are statistically significant (up to 10 sigma)

Orbital Motion + CO 2-1

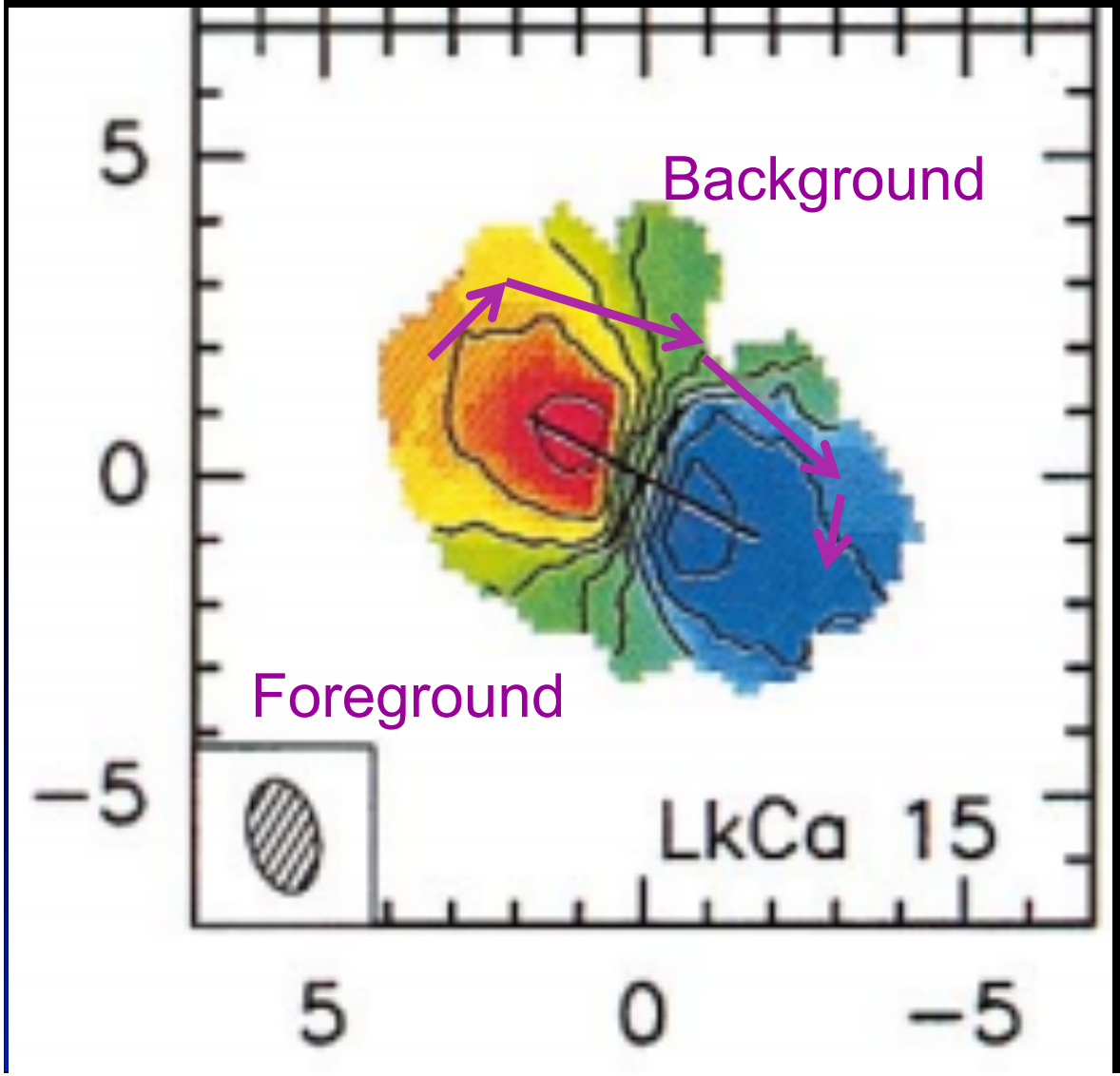
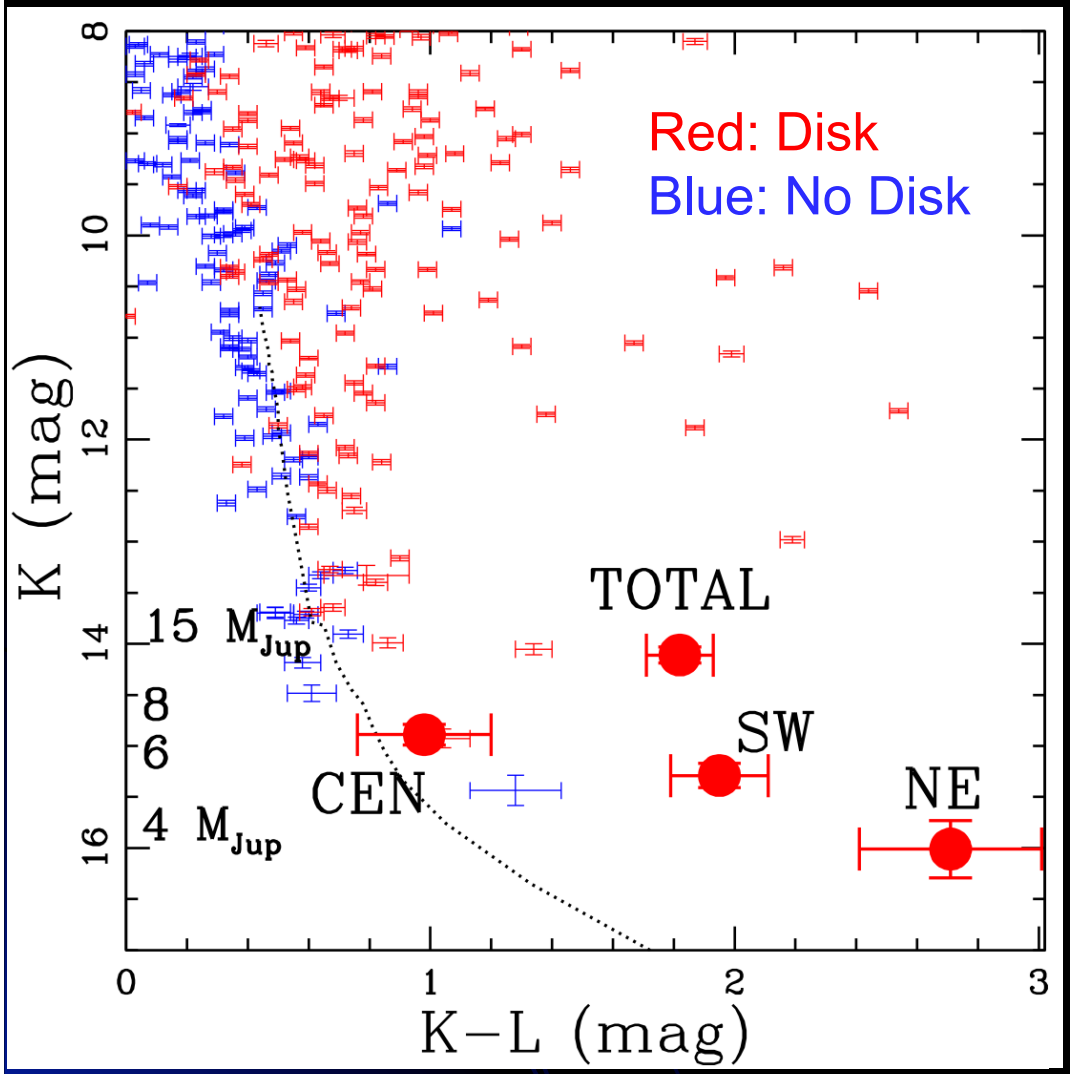


Image Rotation + Doppler velocities uniquely determine disk orientation.

The preferred Thalmann (2010) orientation is confirmed – reflection not forward scattering to the NW

Simon et al (2001), IRAM

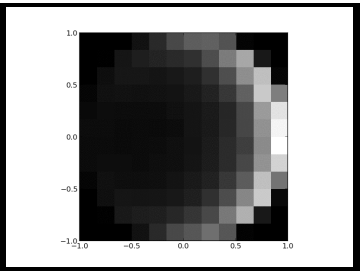
Luminosities and Colors



- The hot-start models (i.e., disk instability) predicted 6 M_{jup} for the central source. It's way too bright for cold-start models.
- The integrated luminosity of 3×10^{-3} $L_{\odot}$ is of course more luminous, but very red.

Points show all free-floating Taurus members from Luhman (2010). The point sources fall at the very faint end (or below).

Scattering?



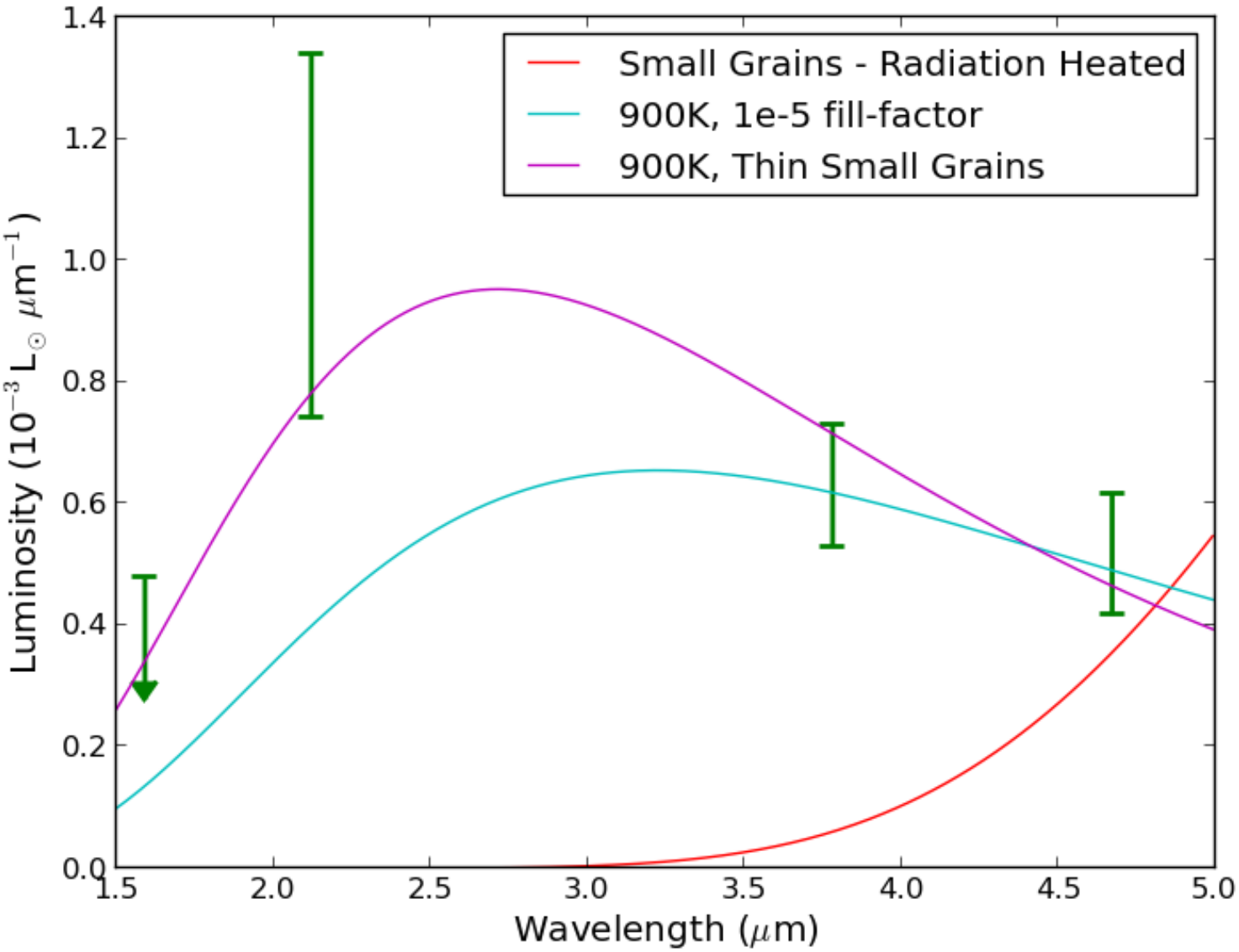
Three clouds of dust ~3AU in size (large planet Hill-sphere) can *just* intercept enough starlight to explain the L-band emission (albedo=1), but would struggle at M-band…

Emission is very *red*. Exotic/bright scattering needs a *forward scattering* geometry. We don't have this luxury.

Dust Type	τ=0.5	τ=1	τ=2
Dirty Ice	4.1	4.2	4.15
Silicate	1.35	1.02	0.95
"K Dark" dust	0.42	0.33	0.32

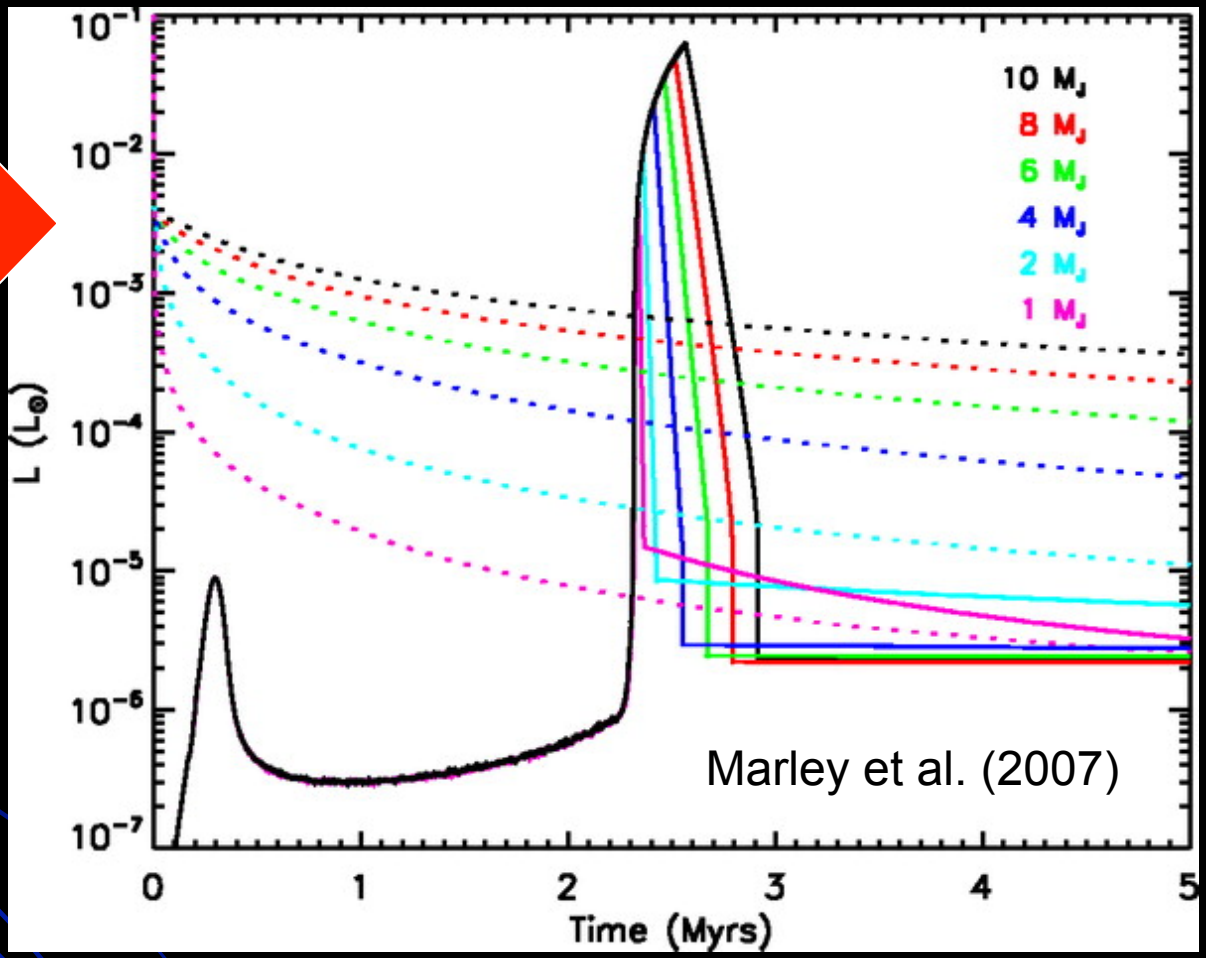
Filter	Contrast (mags)
H	> 6.8
K	4.8-5.6
L	4.1-4.7
Ms	3.5

Thermal Emission



Energy Source: Accretion Luminosity?

b



In core accretion, the luminosity should spike as it rapidly accretes its envelope; this phase corresponds to gap formation in the disk.

The transition disk stage is exactly the right time to look for planets, when even Jupiters might be detectable.

Lessons…

- Interpretation is hard, but would have been impossible without:
  1. mm CO disk measurements.
  2. mm disk continuum measurements.
  3. Medium resolution IR spectra.
  4. Detections at multiple wavelengths.
  5. Detections with the resolution to tell point-emission from extended emission.
  6. Orbital monitoring.

What comes next?

- Deep H-α observations (e.g. L. Close poster)
- Polarimetry + aperture-masking or kernel-phase.
- ALMA with resolutions smaller than 50 milli-arcsec (cycle 2, bands 7 and 9)

Remember: *Point-source planets are Boring – the real action happens at formation!*