LkCa 15 b: A Young Exoplanet Caught at Formation

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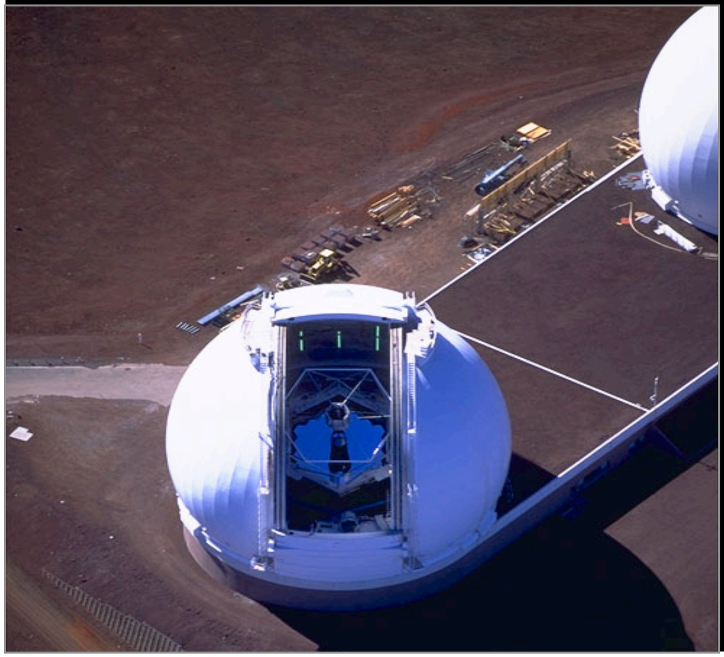
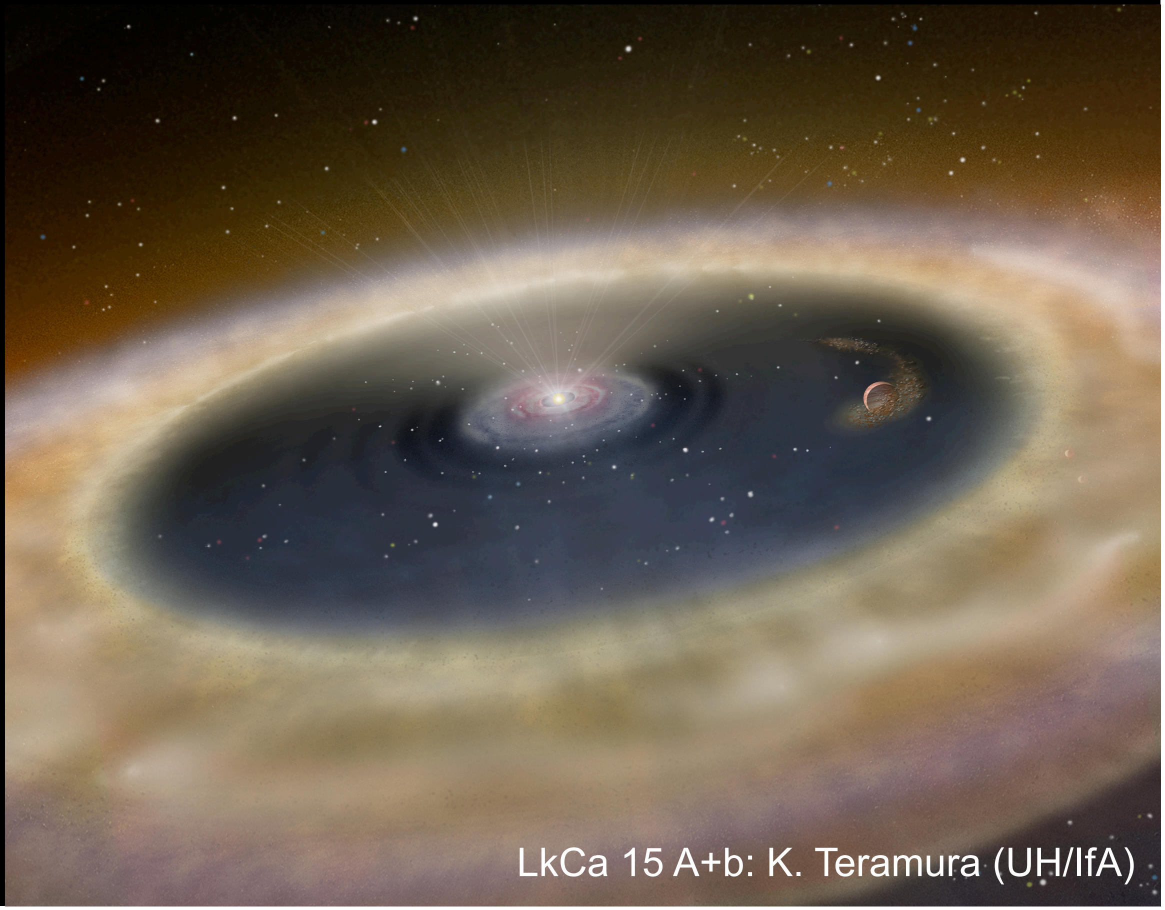
Michael Ireland (Macquarie University)

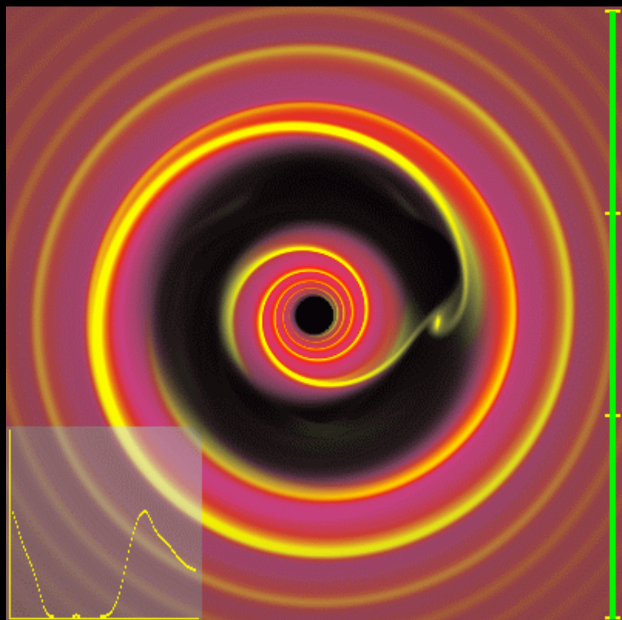
arXiv:1110.3808





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

The Case for Newly-Formed Planets

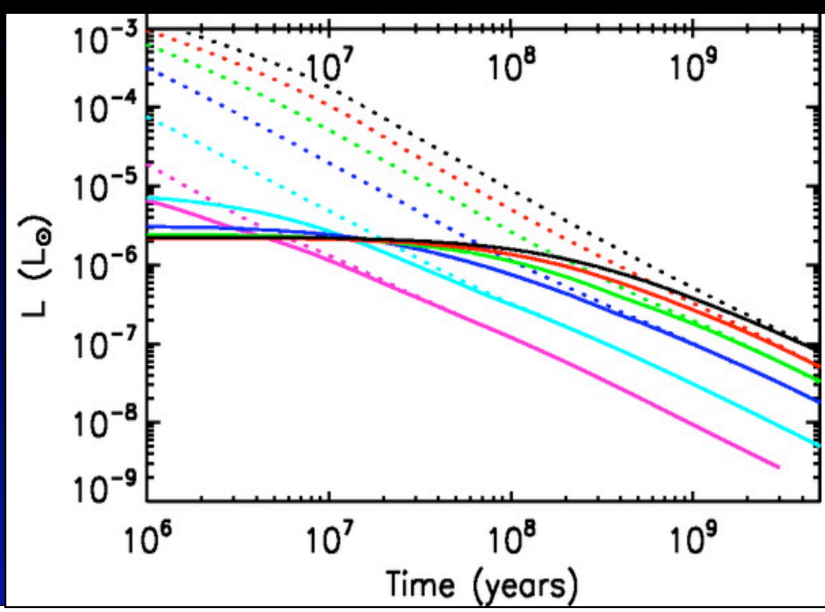


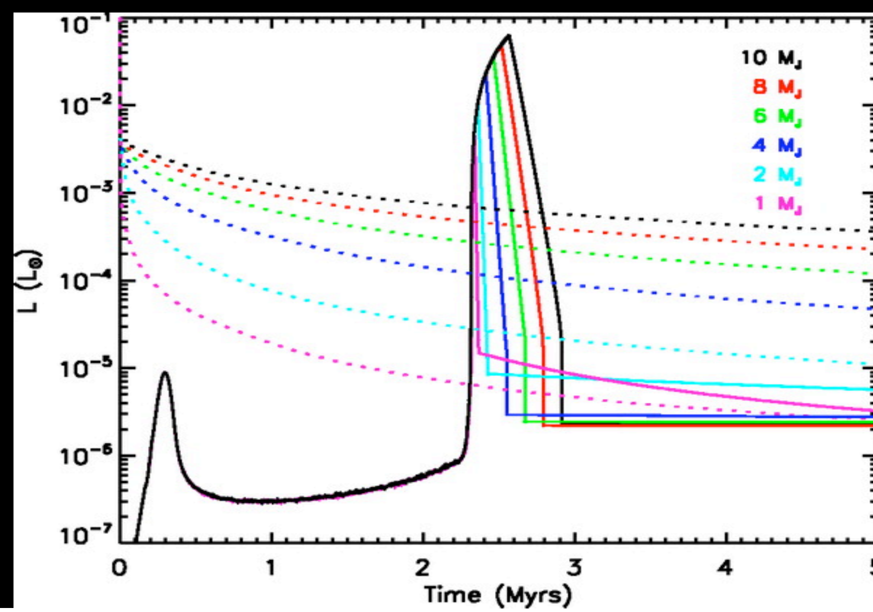
Young planets are primordial

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).

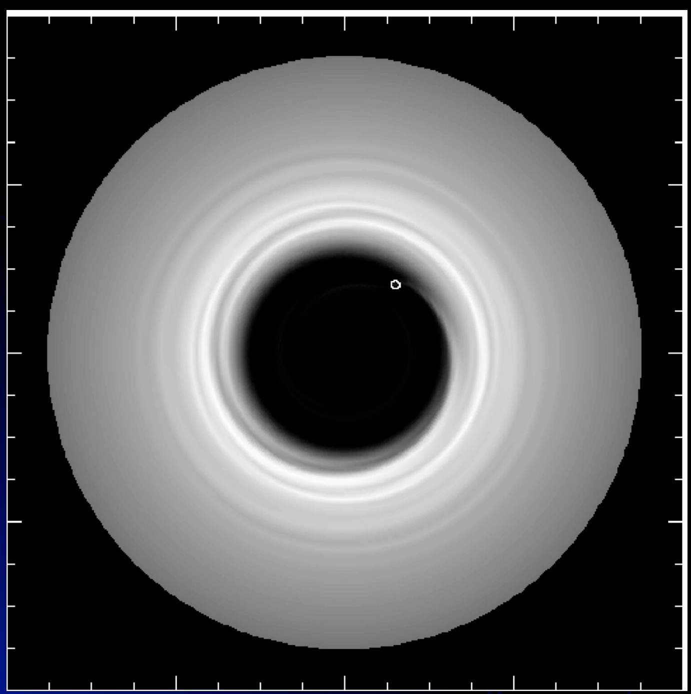




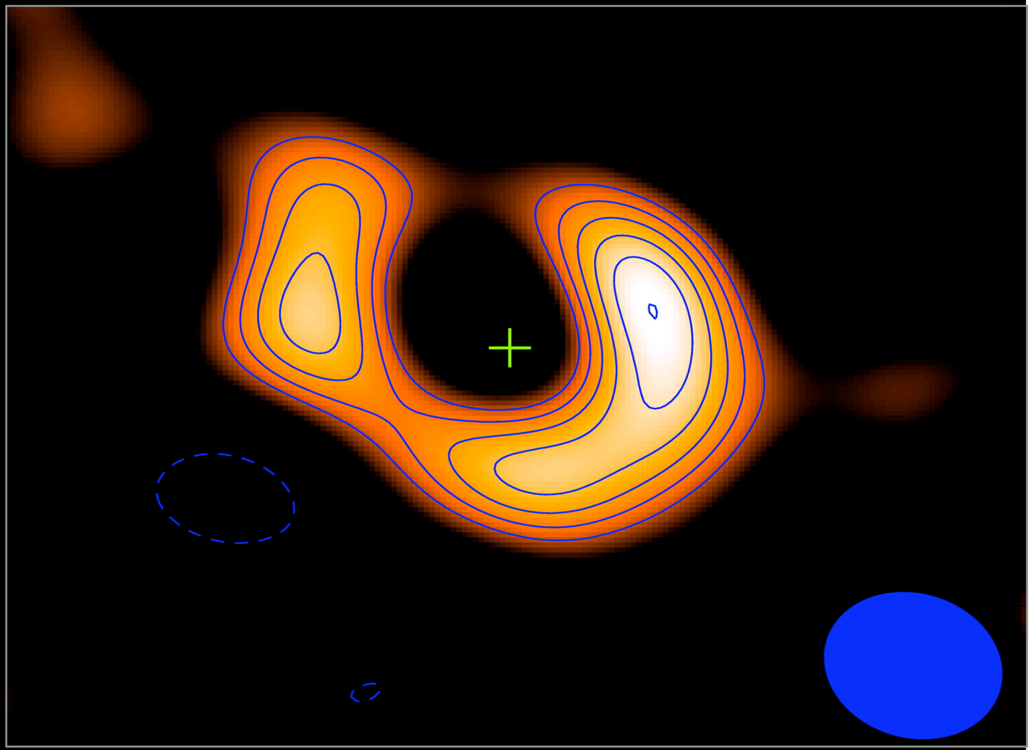
Sites of Ongoing Planet Formation

Transitional Disks

Some protoplanetary disks have large cleared gaps – perhaps signposts of ongoing planet formation?



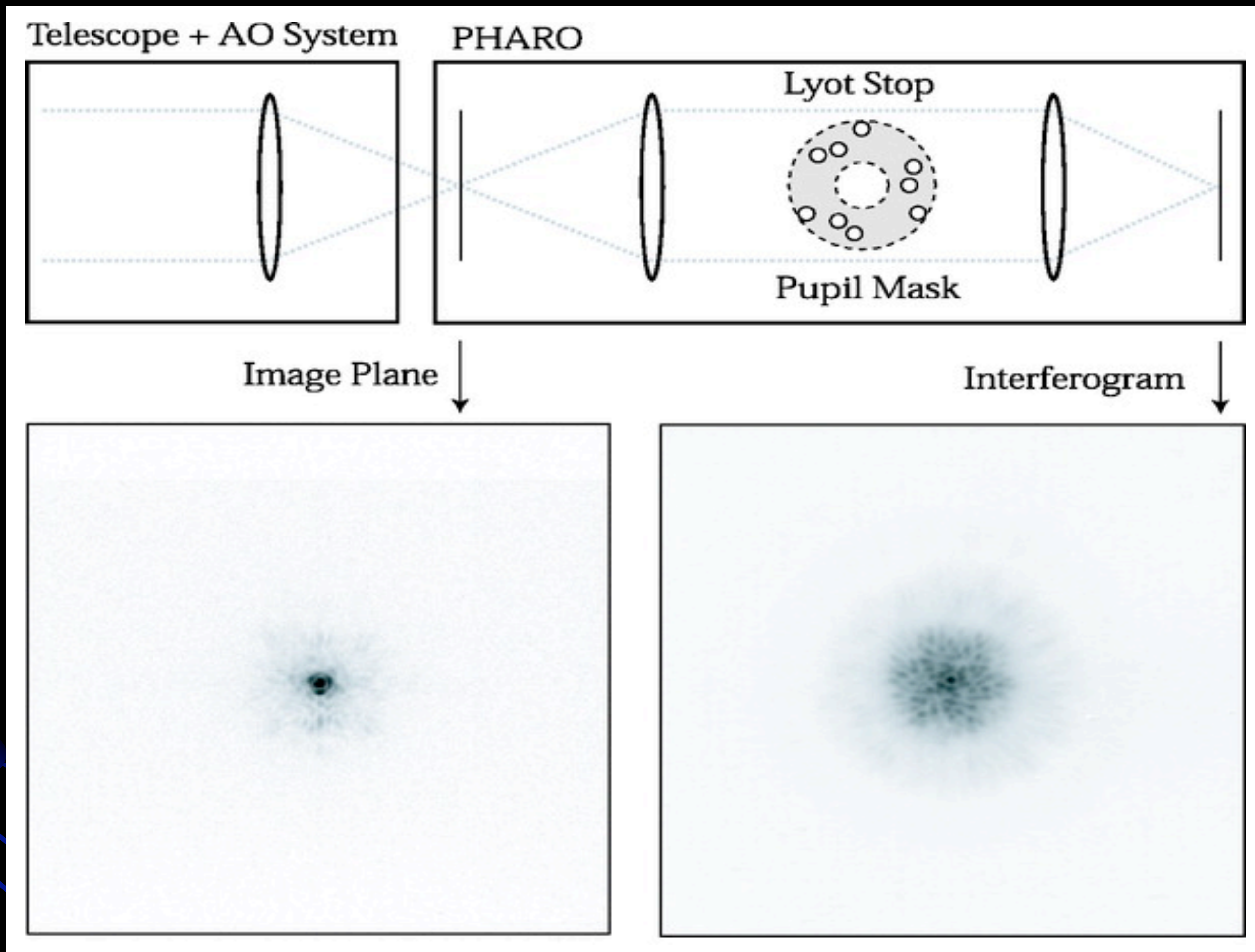
CoKu Tau/4 (Model; Quillen et al. 2004)



LkHa 330 (Submm image; Brown et al. 2009)

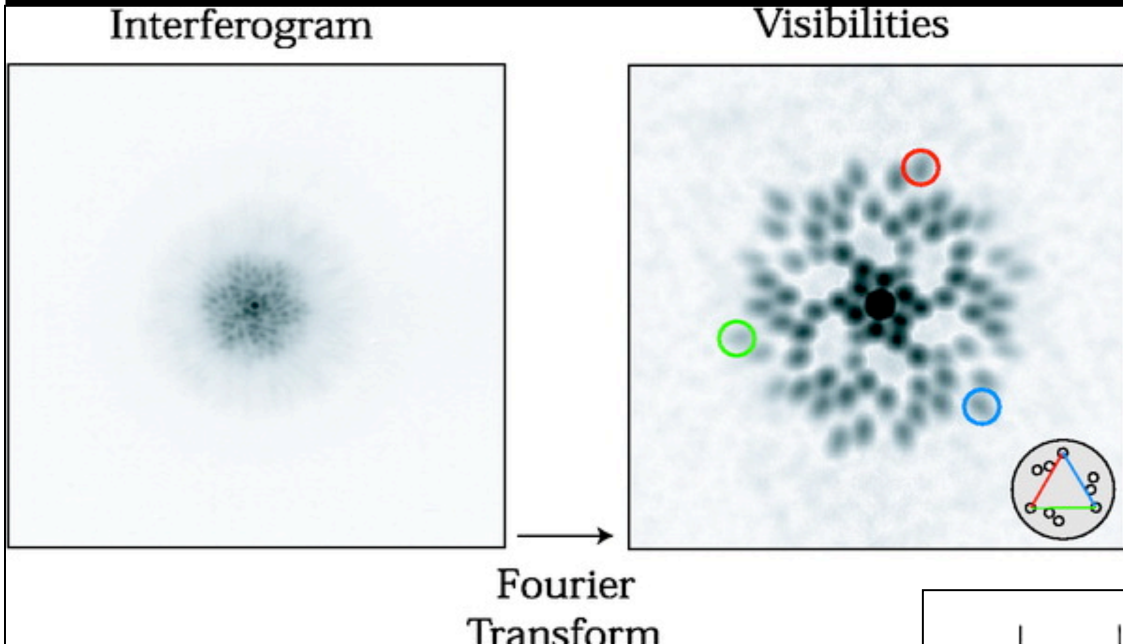
Problem: These are very distant (~150-250 pc), so resolution is a big obstacle.

Nonredundant Mask Interferometry



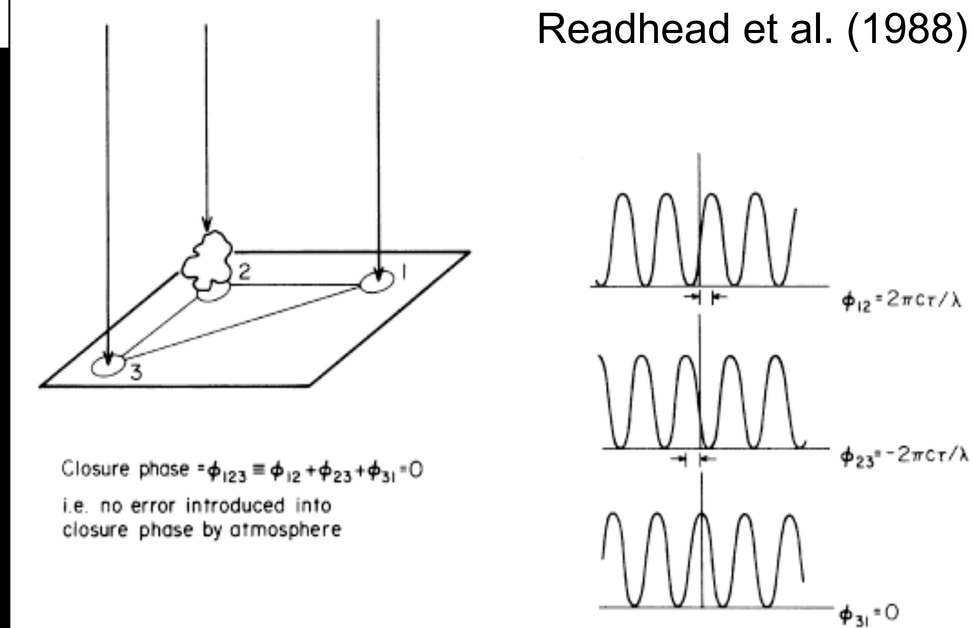
Placing an aperture mask in the pupil plane turn the single mirror into a sparse interferometric array. Fourier analysis techniques (i.e. closure phases) can be used to filter almost all noise from turbulence and AO errors. This yields very stable performance.

Closure Phases



$$\Phi = \Phi_{12} + \Phi_{23} + \Phi_{31}$$

In the closure phase, any phase error on aperture 1, 2, or 3 will cancel out.

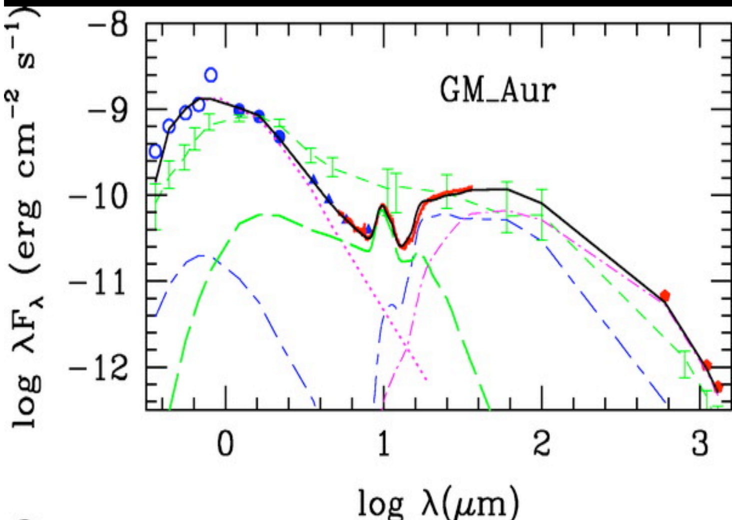


Readhead et al. (1988)

Almost all noise sources (most notably, speckles) are just phase errors that readily cancel. This improved PSF calibration delivers relatively deep contrast (8 magnitudes at L') even at the diffraction limit.

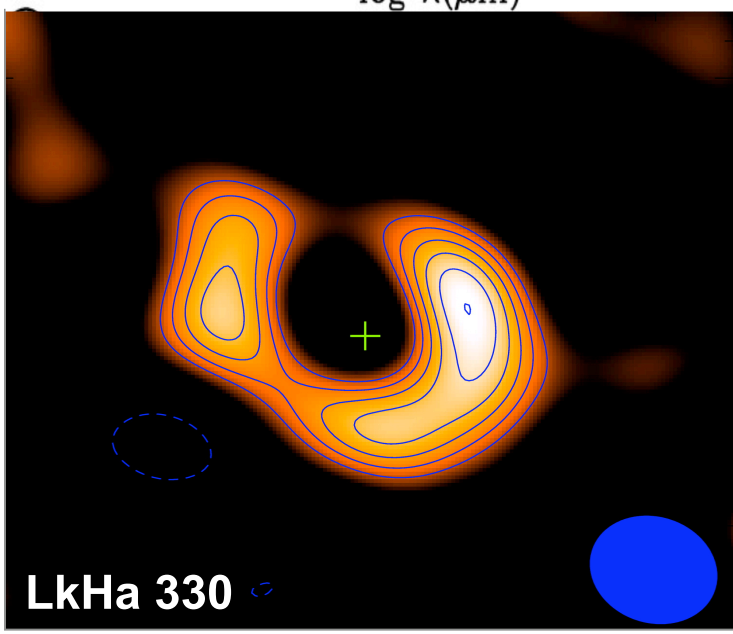
(See poster by S. Hinkley)

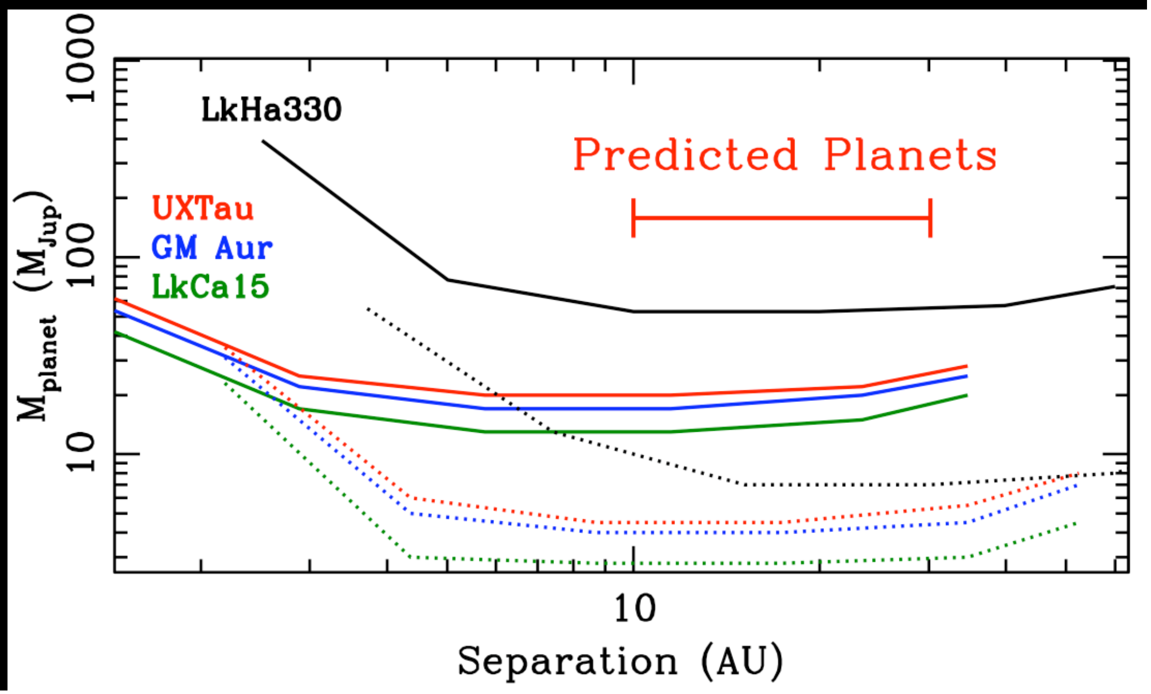
Following the Signposts of Planet Formation



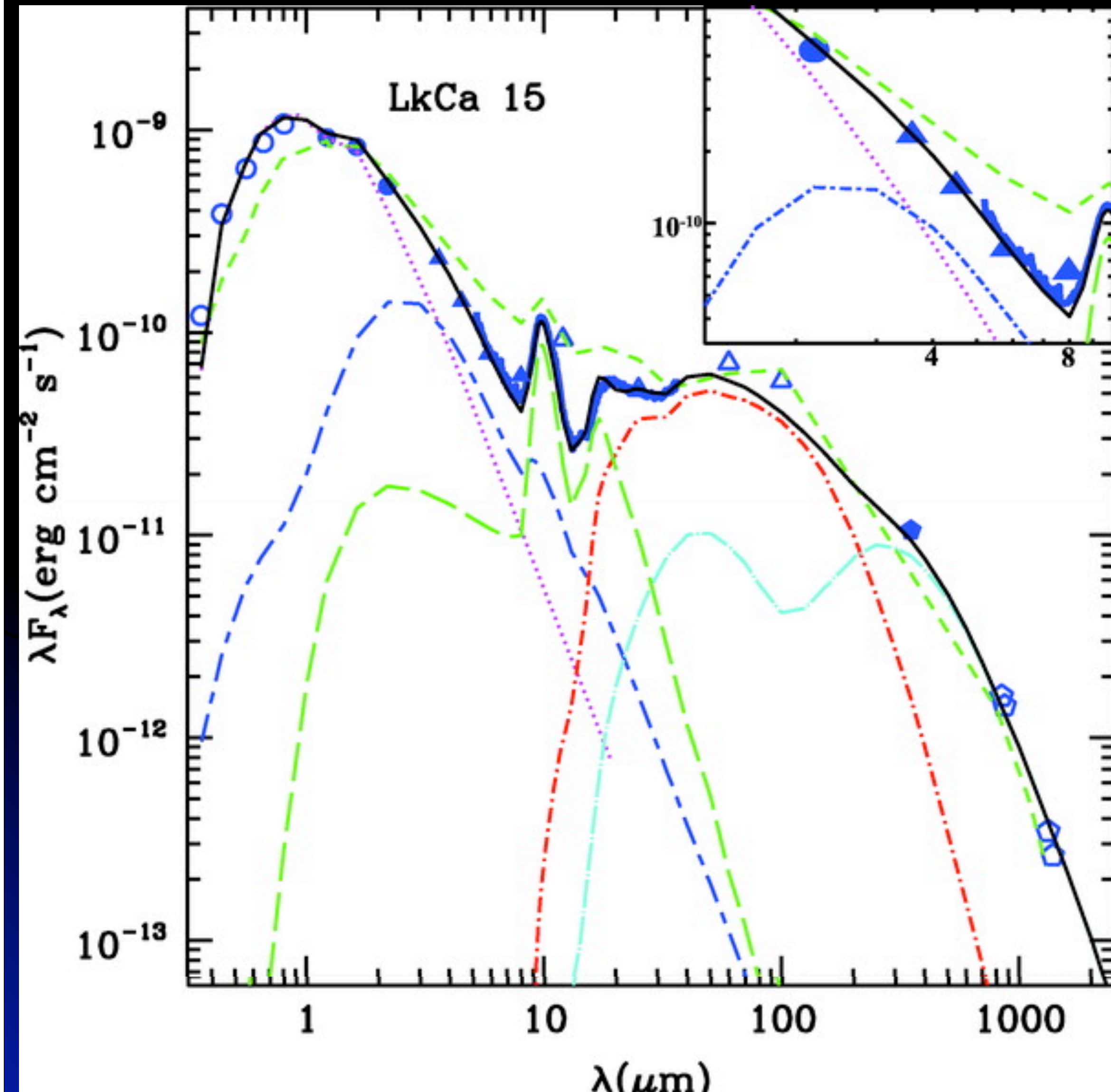
If we're going to find planets anywhere, these are the places to look!

We're observing all of the transitional disks with large gaps (>25 AU), starting with those that have been confirmed with submm or optical/NIR imaging.





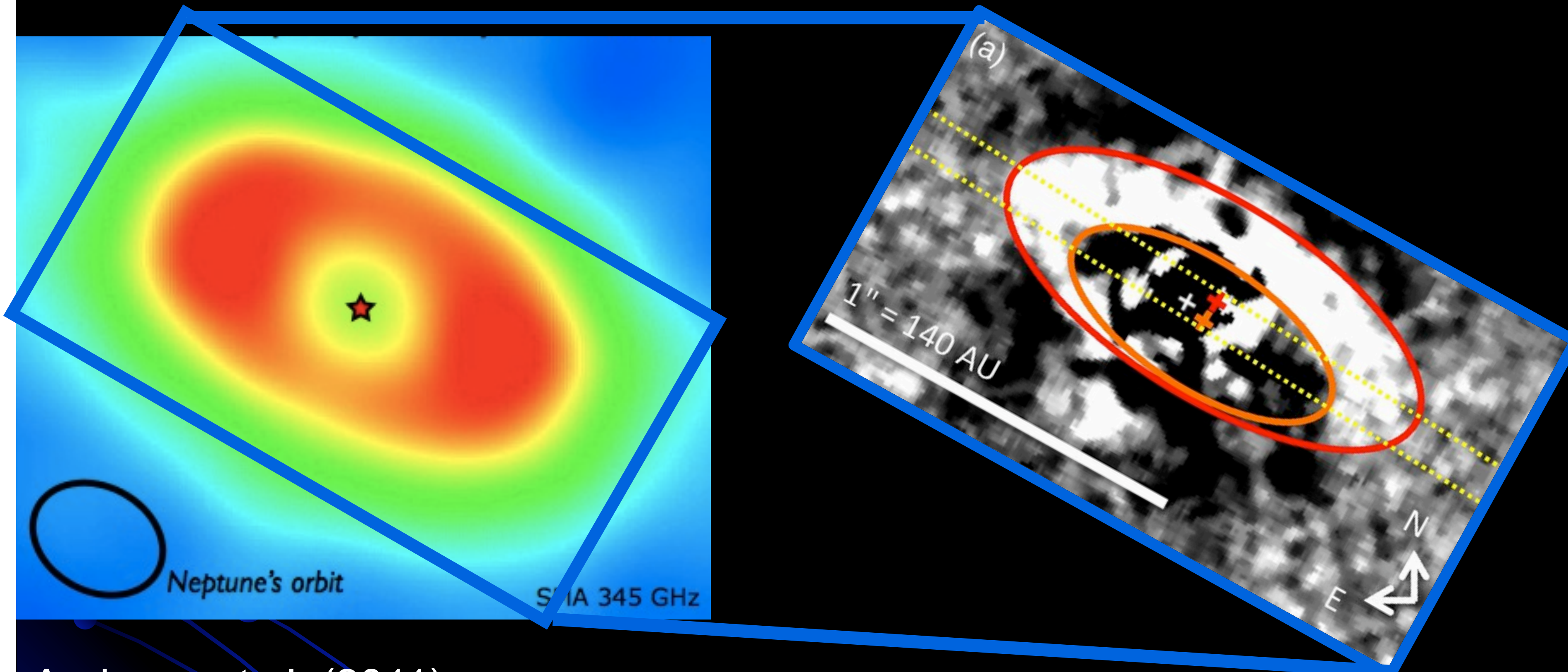
Target #2: LkCa15



One of the best-studied transitional disks – massive disk, big gap, young stellar age.

Espaillat et al. (2007)
Optical-IR-MM SED
(Gapped Disk)

Target #2: LkCa15



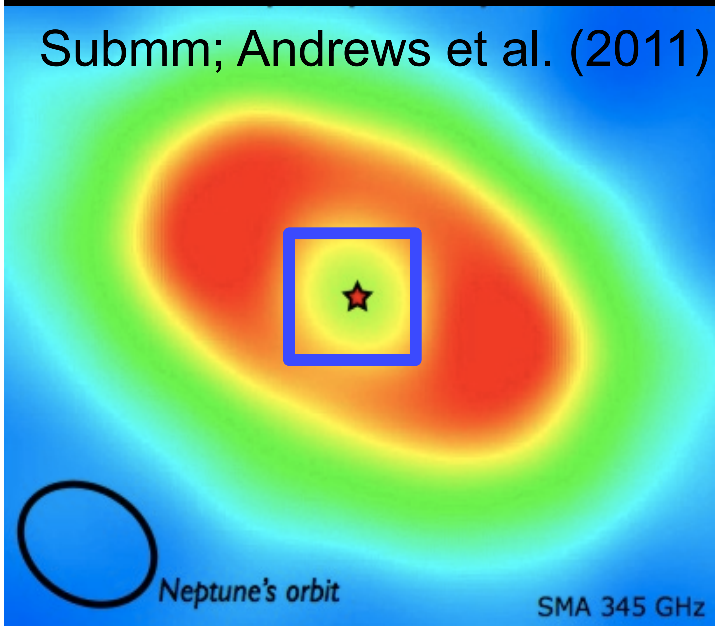
Andrews et al. (2011)
SMA, Sub-mm Image
(Dusty Outer Disk)

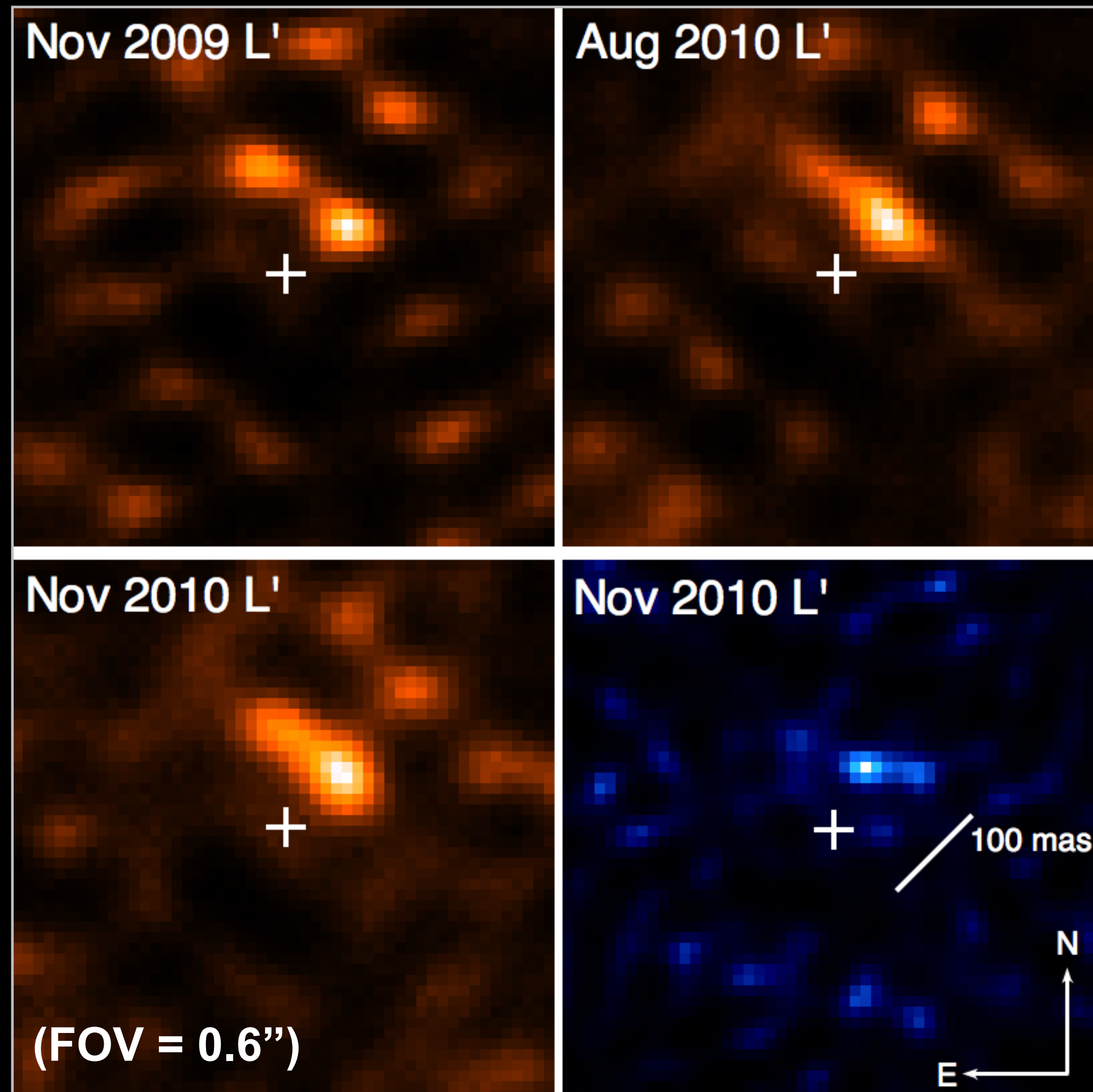
Thalmann et al. 2010
HiCIAO, H-band Image
(Inner Disk Wall)

Taurus star-forming region

T~2-3 Myr; d~150 pc; M_*=1 M_{sun}; M_{disk}=55 M_{Jup}

LkCa15 b: A Planet in a Cleared Gap?





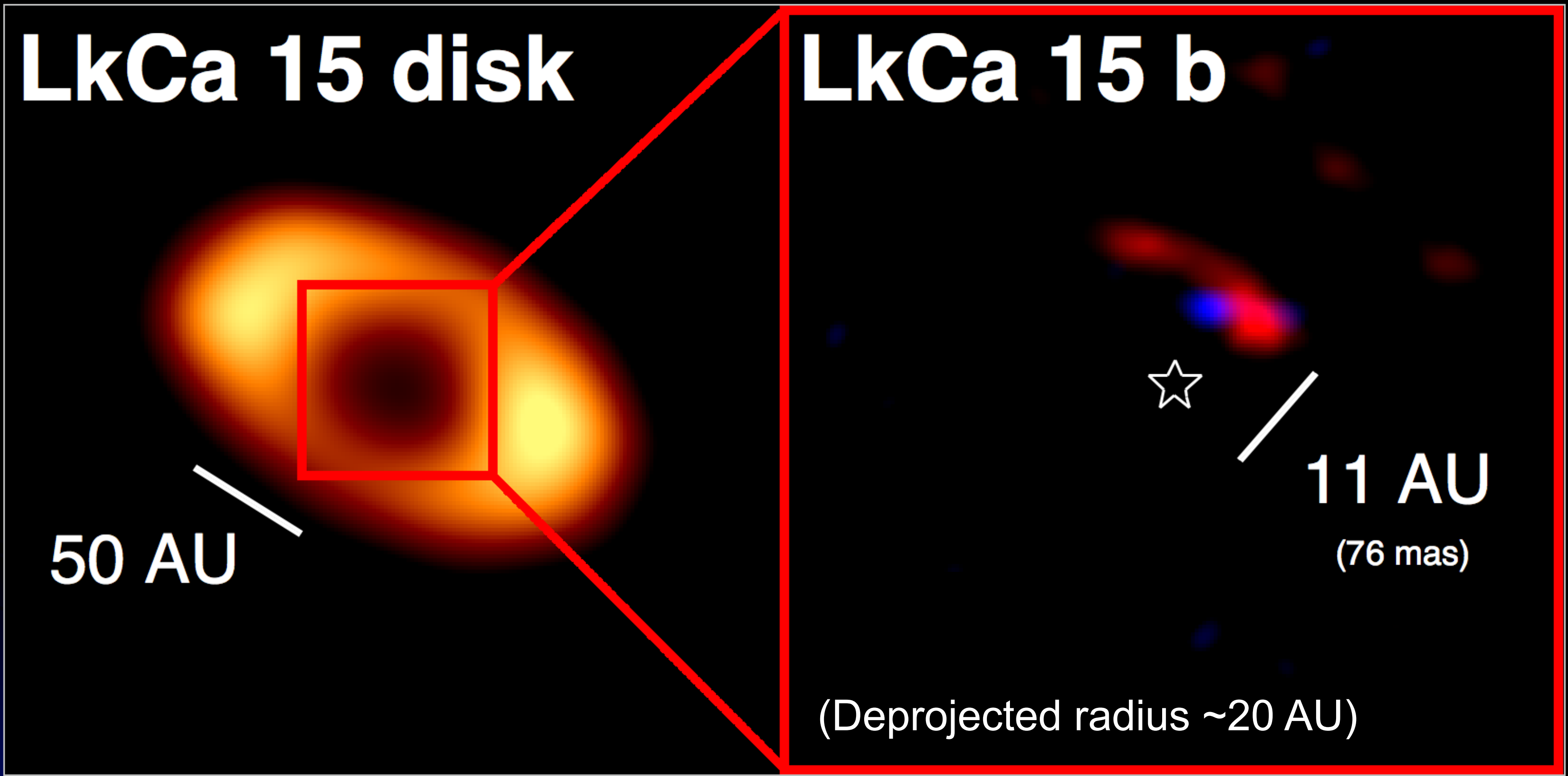
We see a central source that's relatively blue (hot?) and leading/trailing sources that are relatively red (cool?).

ΔK=6.8 mag

ΔL=5.5 mag

(The hot-start models say 6/12 M_{Jup} for the central/total flux.)

Multicolor Image Reconstruction



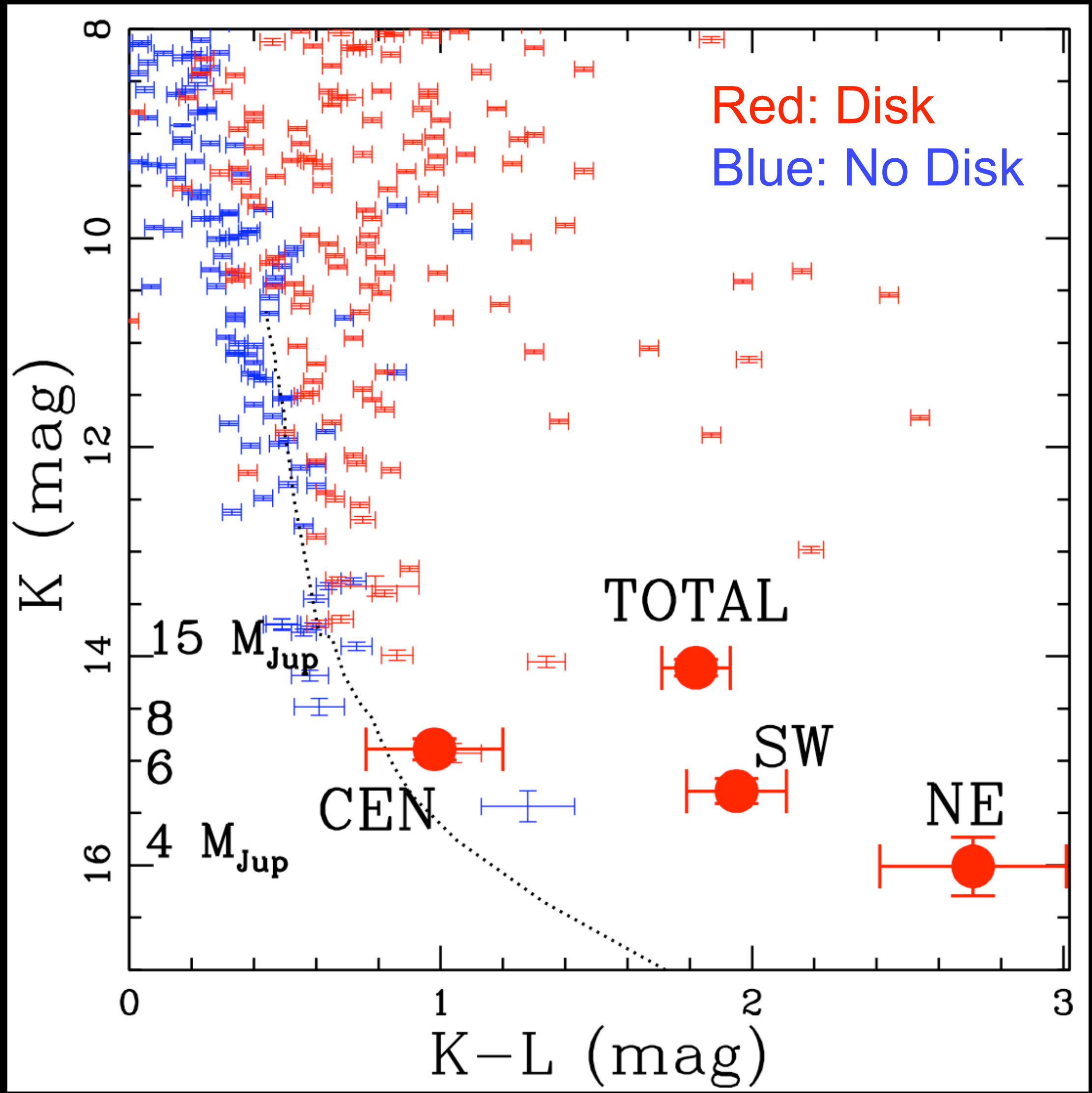
Andrews et al. (2011)
SMA, Sub-mm Image
Dusty Outer Disk

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

Luminosities and Colors

Points show all free-floating Taurus members. Our detection falls at the very faint end (or below)

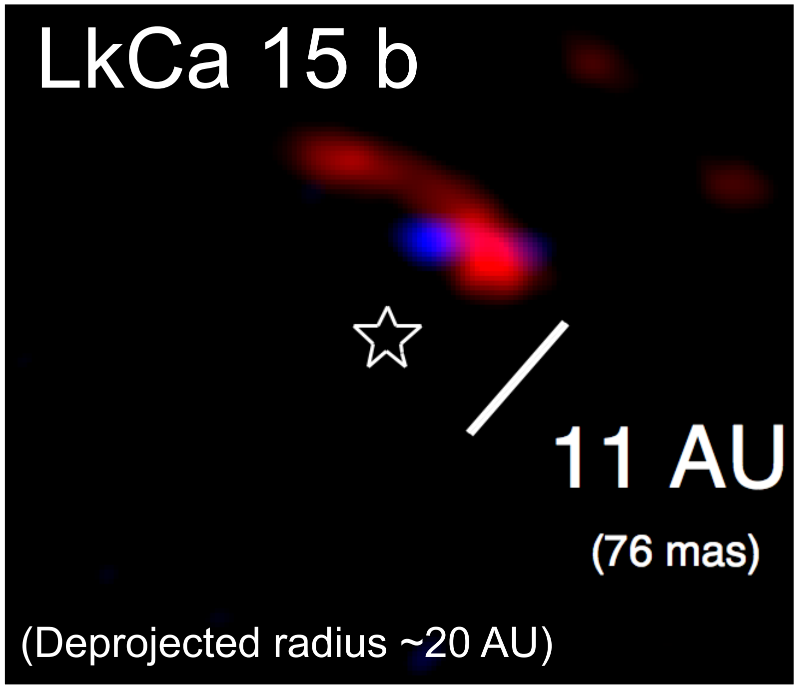
Hot start models estimate ~6 M_{Jup}



(K photometry from 2MASS, L photometry from Luhman et al. 2010.)

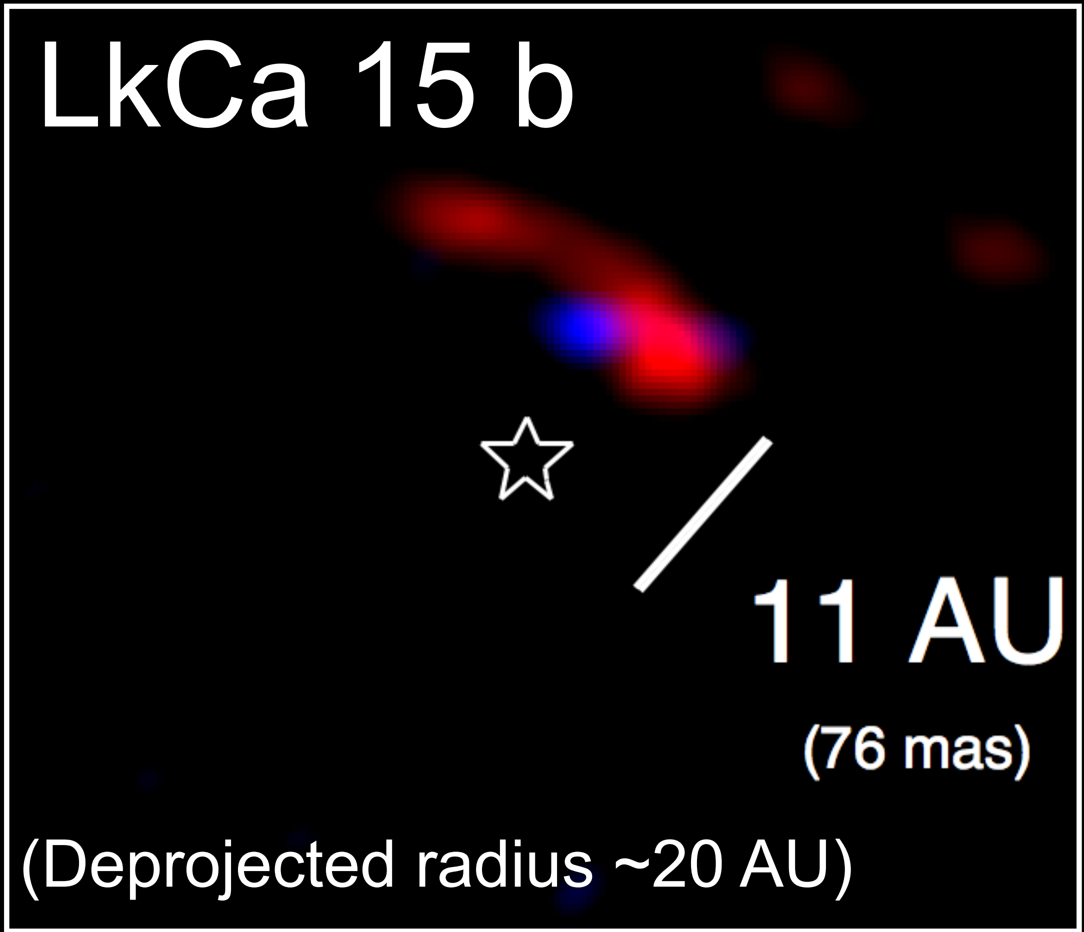
Rejected Non-Planet Explanations

- Background object?
  - Comovement says **NO**. Besides, the probability of chance alignment is very low (~10^{-5}).
- Thermal disk emission
  - Much too far from the star, but also too close to be the inner wall. **NO.**
- Reflected Light?
  - Geometry says **MAYBE**. Energetics and colors say **NO**. Total L' flux is over 1% of the primary star flux!
- A binary companion
  - Luminosity is too low, and morphology doesn't match known edge-on disks. Also, no sign of submm counterpart. **NO.**



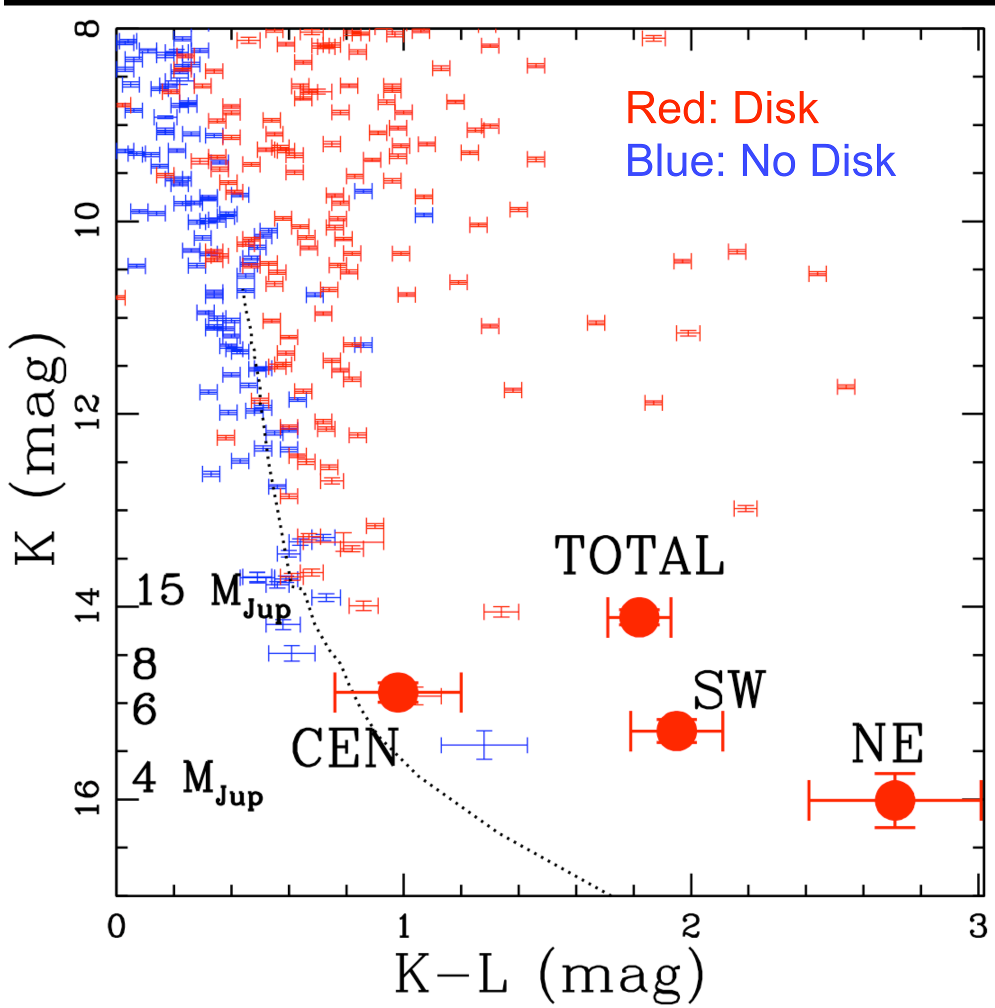
Morphology

A giant planet with warm dust in the circum-planetary environment...but what is the nature of this spatially resolved dust?



- **Circum-planetary?**
- **Co-orbital?**
- **What if it's not bound to the planet?**

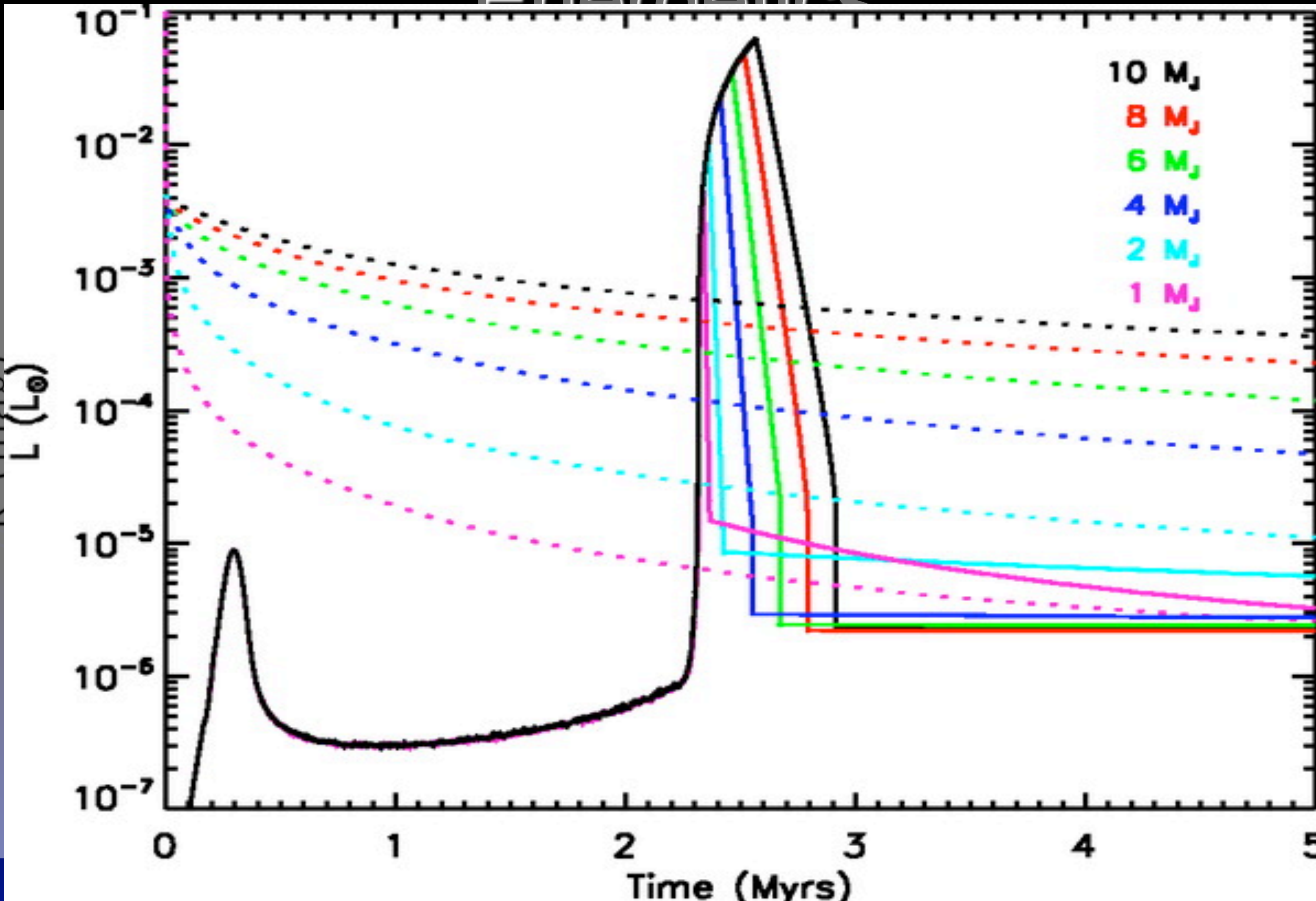
Energetics



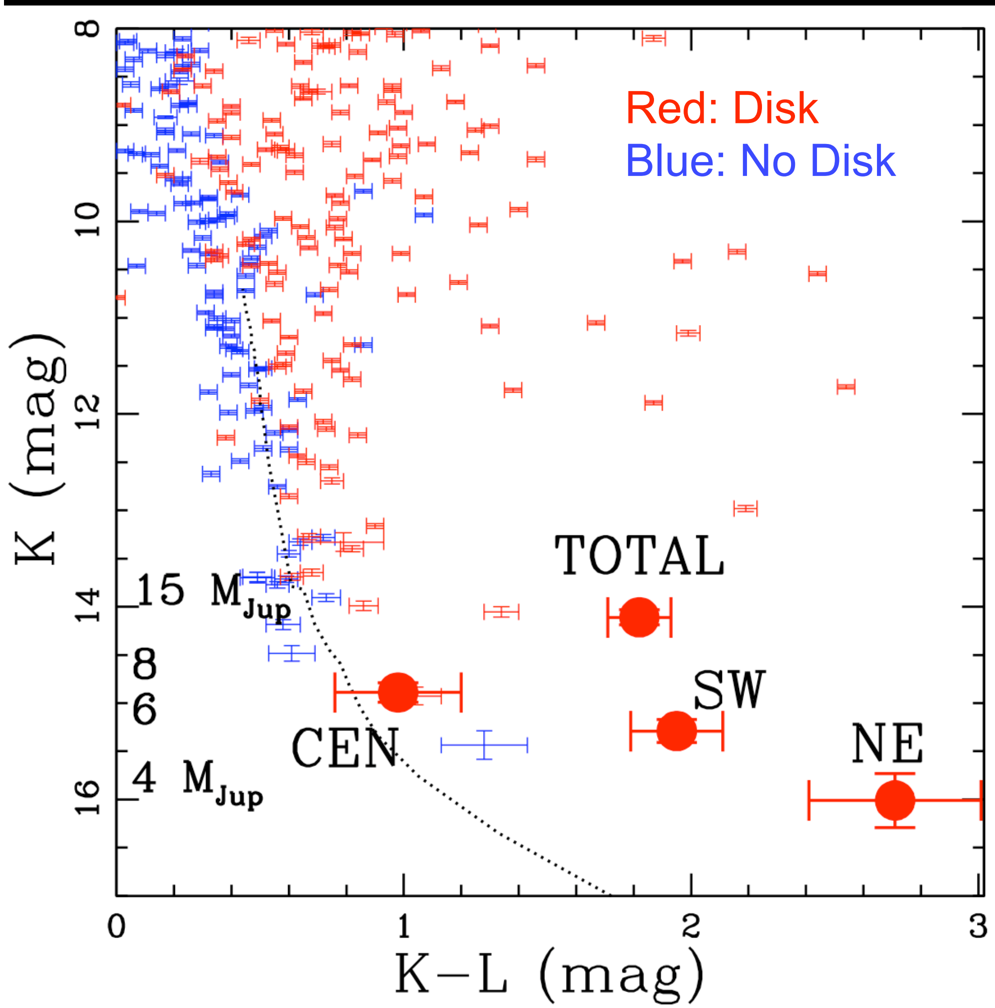
The entire resolved structure is extremely luminous!

- Planet: Are we seeing photosphere or accretion luminosity?
- Resolved Material: This is harder. How do you heat material enough to glow at 3.5 microns – and keep it at that temperature? (~500-1000 K)

Energetics



Energetics



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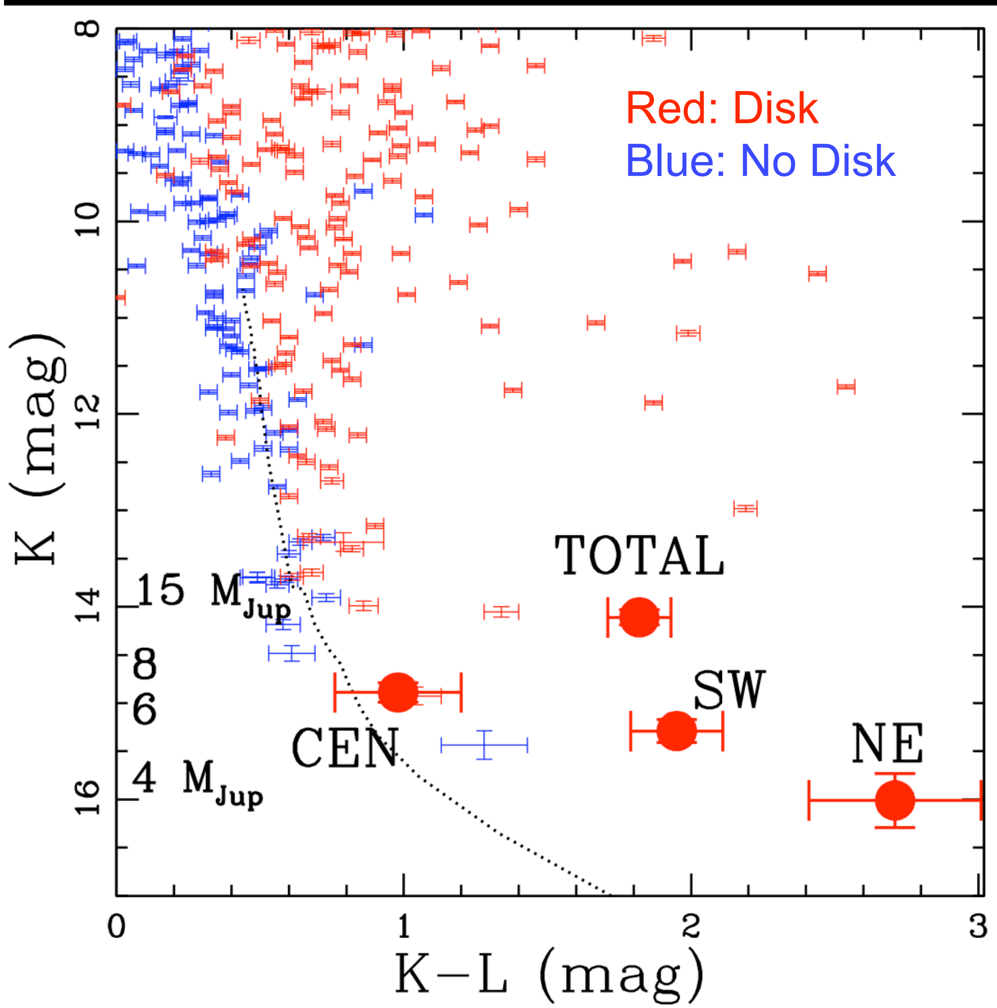
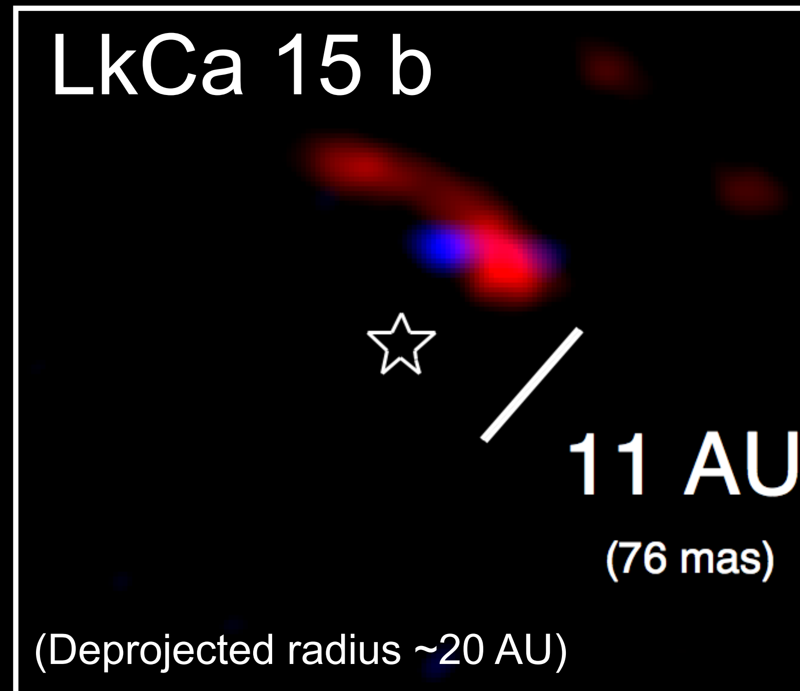


- **Direct Luminosity:**
  No way this can get the job done on 5-20 AU scales
- **Collisions:**
  Hard to do with collisions of planetesimals, but perhaps a shock or tide in a stream of accreting material?
- **Energy feedback:**
  The planet is accreting – feedback to the environment via winds?

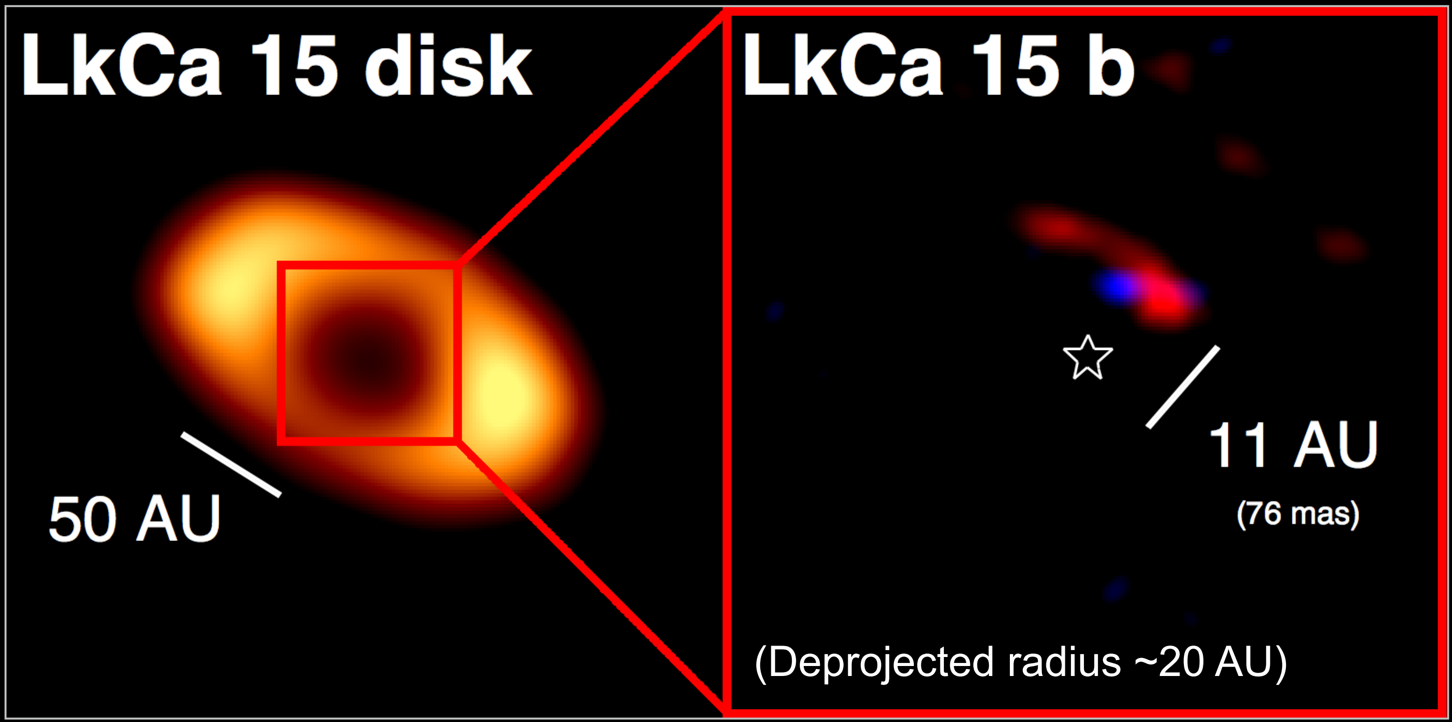
Implications of the Discovery

- Planet formation is not clean. **Do not expect point sources.**
- Some planets form well outside the snow line. **Disk instability, or does core accretion work at large radii? Migration?**



- This whole system is really luminous! **Accretion? What about the resolved material?**
- When surveying transition disks, the companion detection rate is **1 out of ~~2~~ 5.** (but see Huelamo et al. 2011…)

Open questions



1. **How did this system form?** Nominally too distant for core accretion, too close for disk instability.
2. **Why is the gap large?** (R_{planet}~20 AU, R_{gap}~50 AU)
3. **How is the extended material heated?** Not direct radiation – shock heating from accretion, maybe?