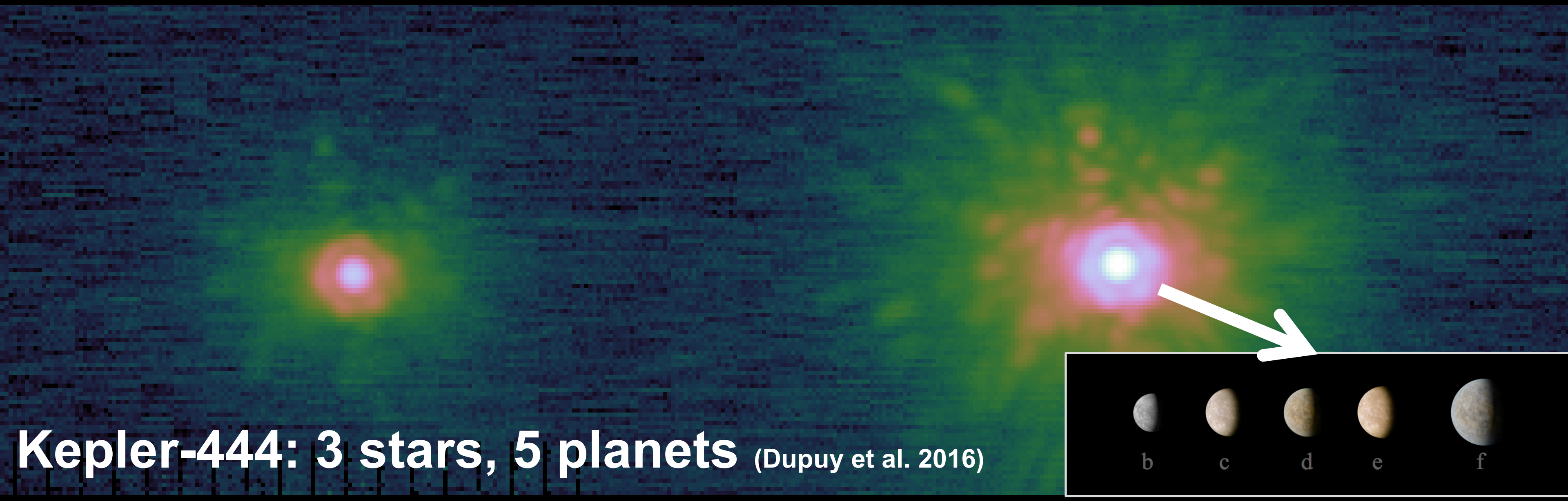
The Impact of Binary Stars on Protoplanetary Disks and Planet Formation

Adam Kraus
University of Texas at Austin



Kepler-444: 3 stars, 5 planets (Dupuy et al. 2016)

Outline

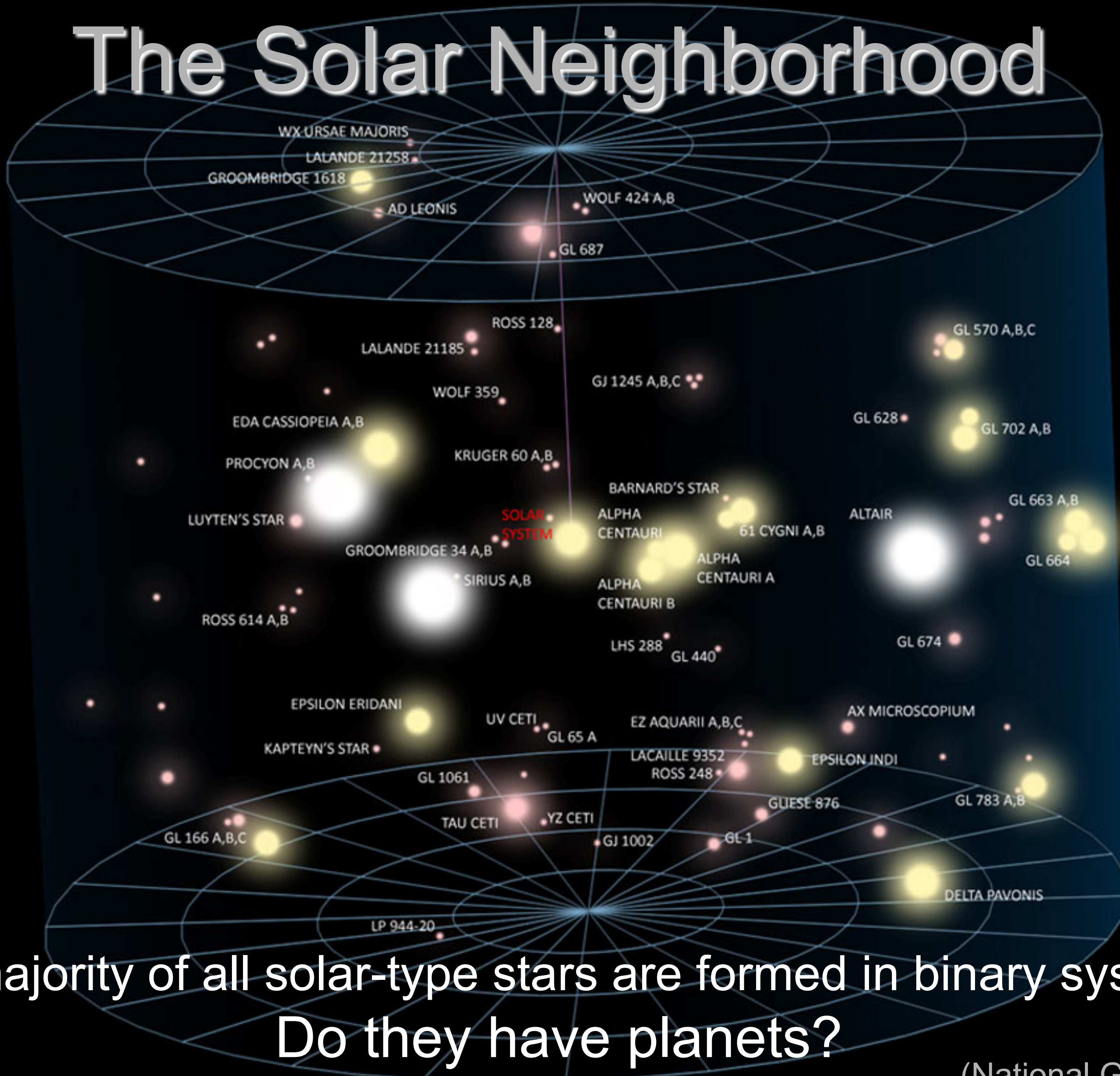
1. The Story of Planet Formation, and How Binary Systems Complicate the Picture

2. Disk Occurrence Rates and Lifetimes in Binary Star Systems

3. Dynamic Signatures of the Interaction Between Disks and Binaries

4. The Final Boundary Condition: Planetary Demographics in Binary Star Systems

The Solar Neighborhood



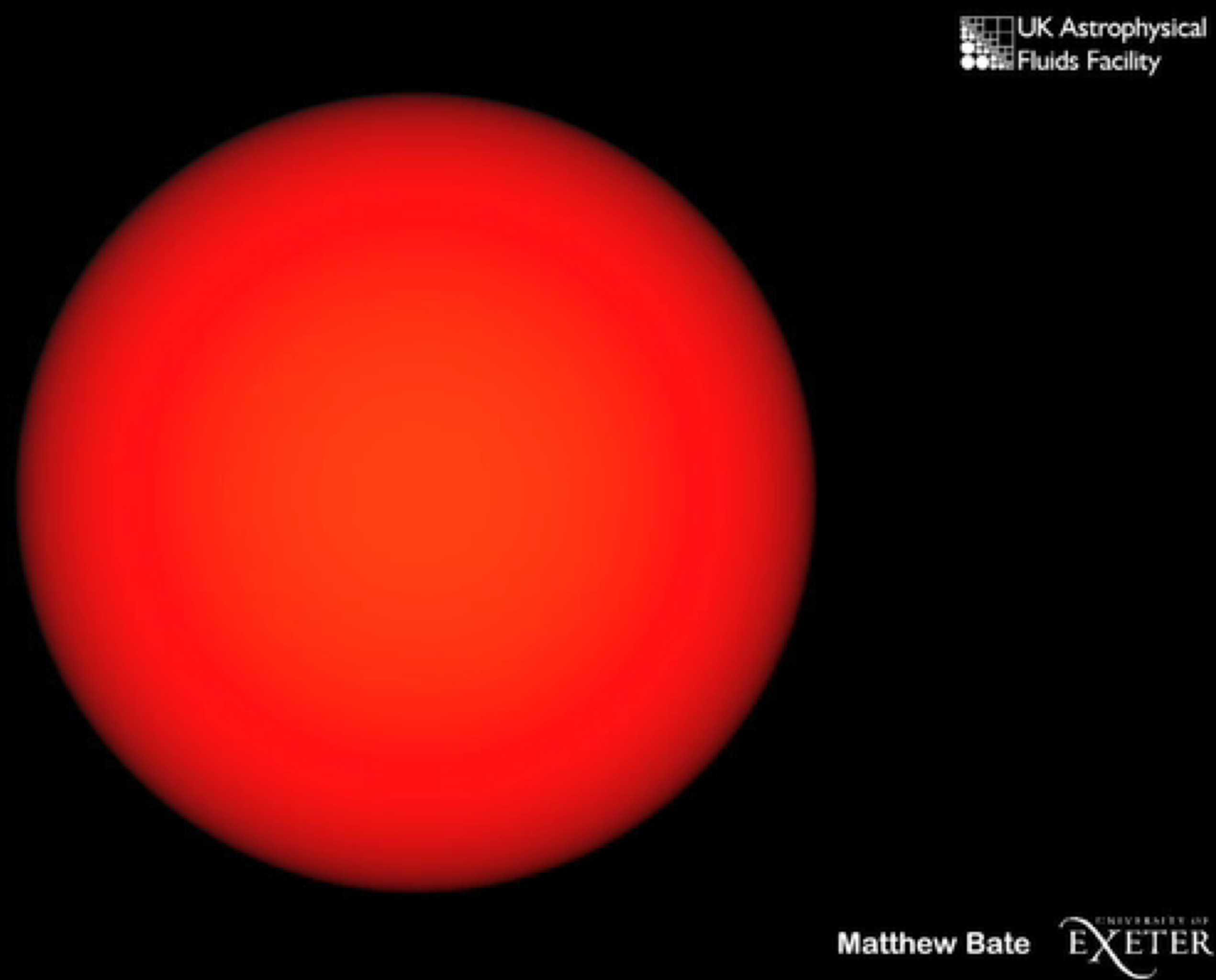
The majority of all solar-type stars are formed in binary systems!

Do they have planets?

(National Geographic)

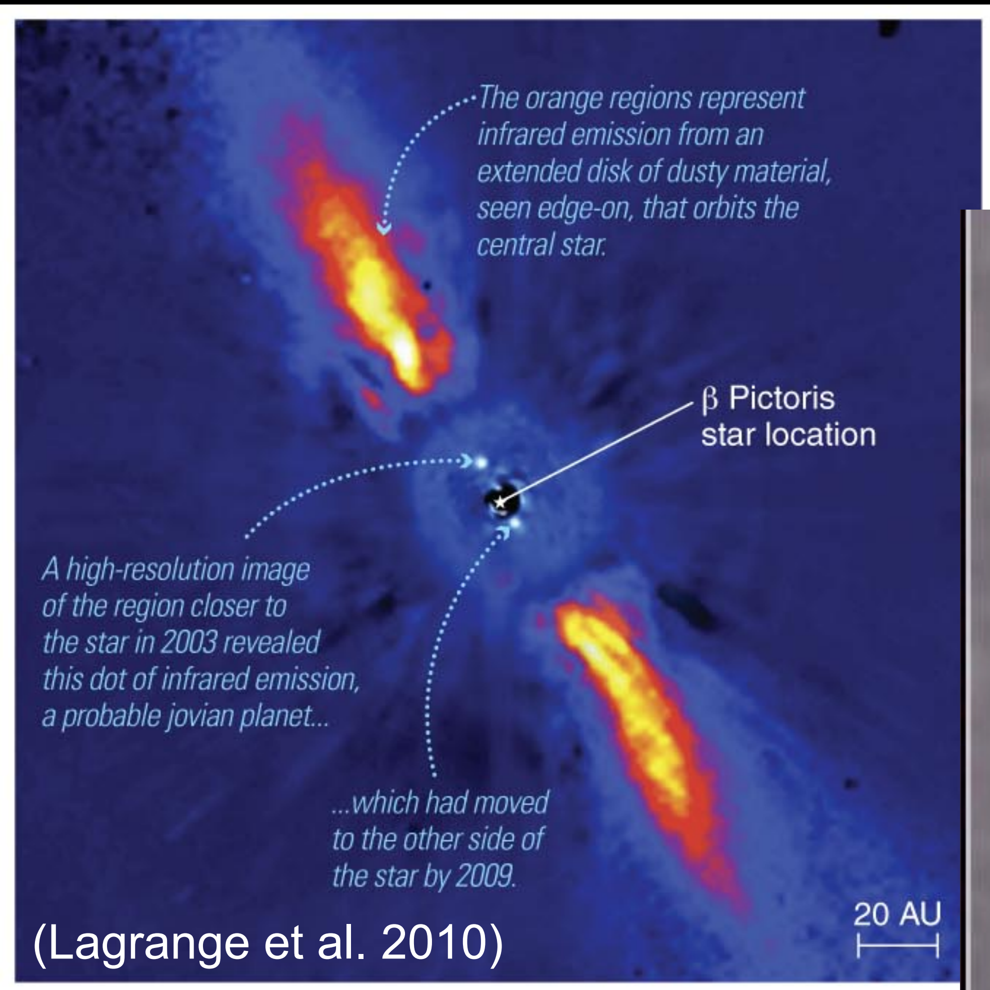
Part 1: Planet Formation & How Binaries Systems Complicate the Picture

Canonical Model of Star/Planet Formation



Step 1: Cloud collapses into protostars

Canonical Model of Star/Planet Formation



(Lagrange et al. 2010)

(M. McCaughrean, C. O'Dell, NASA)

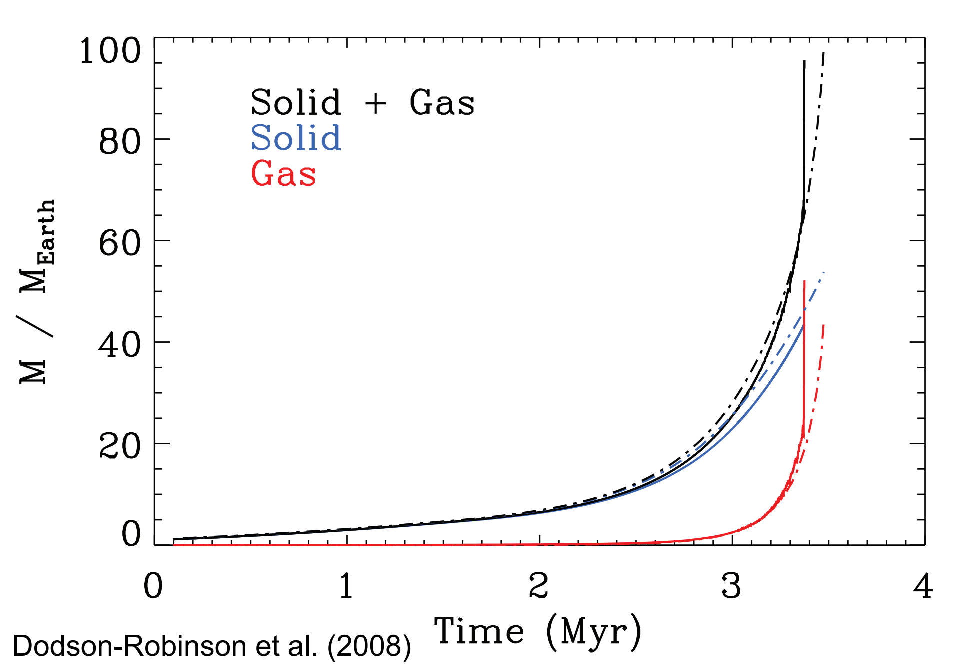
Step 2: Disks Form

Because Angular Momentum is Conserved

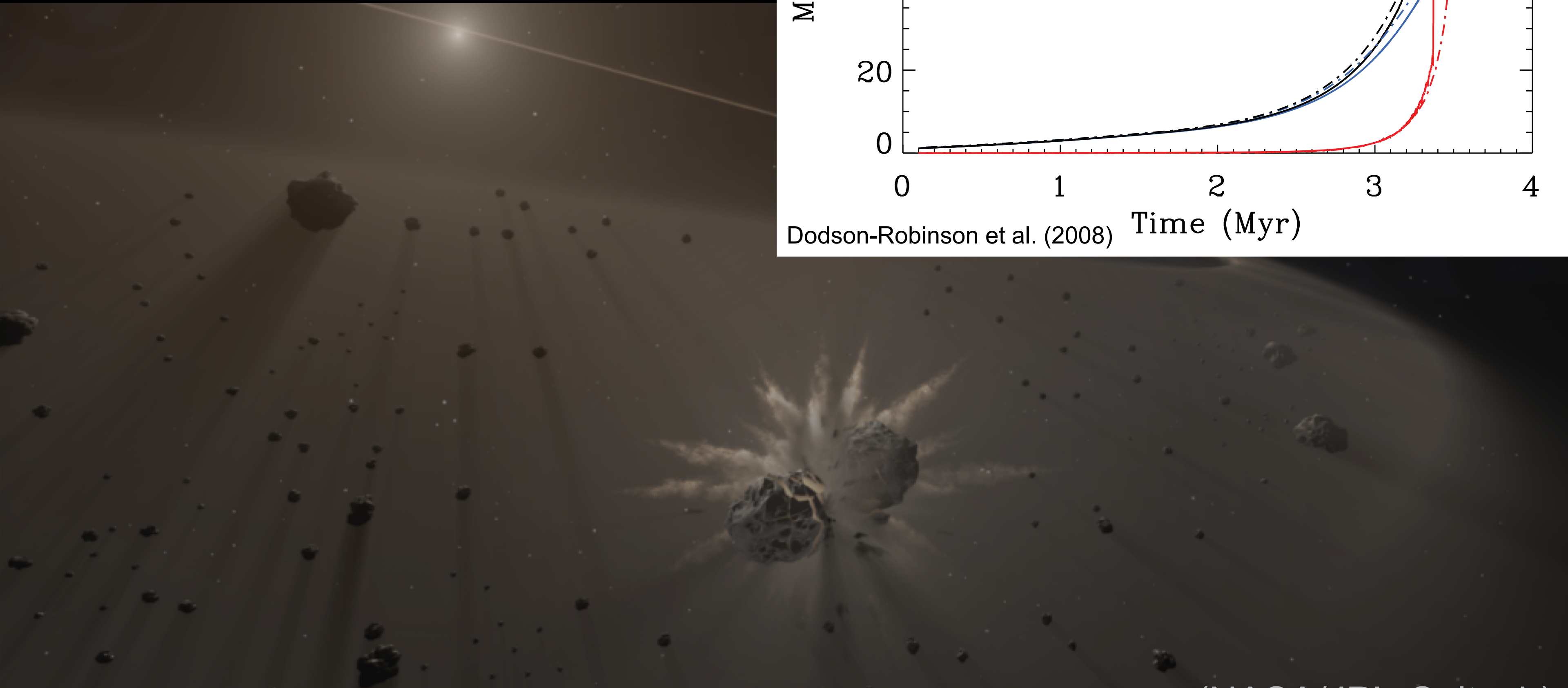
Planet Formation Via Core Accretion

Step 3: Planets form from "Bottom Up"

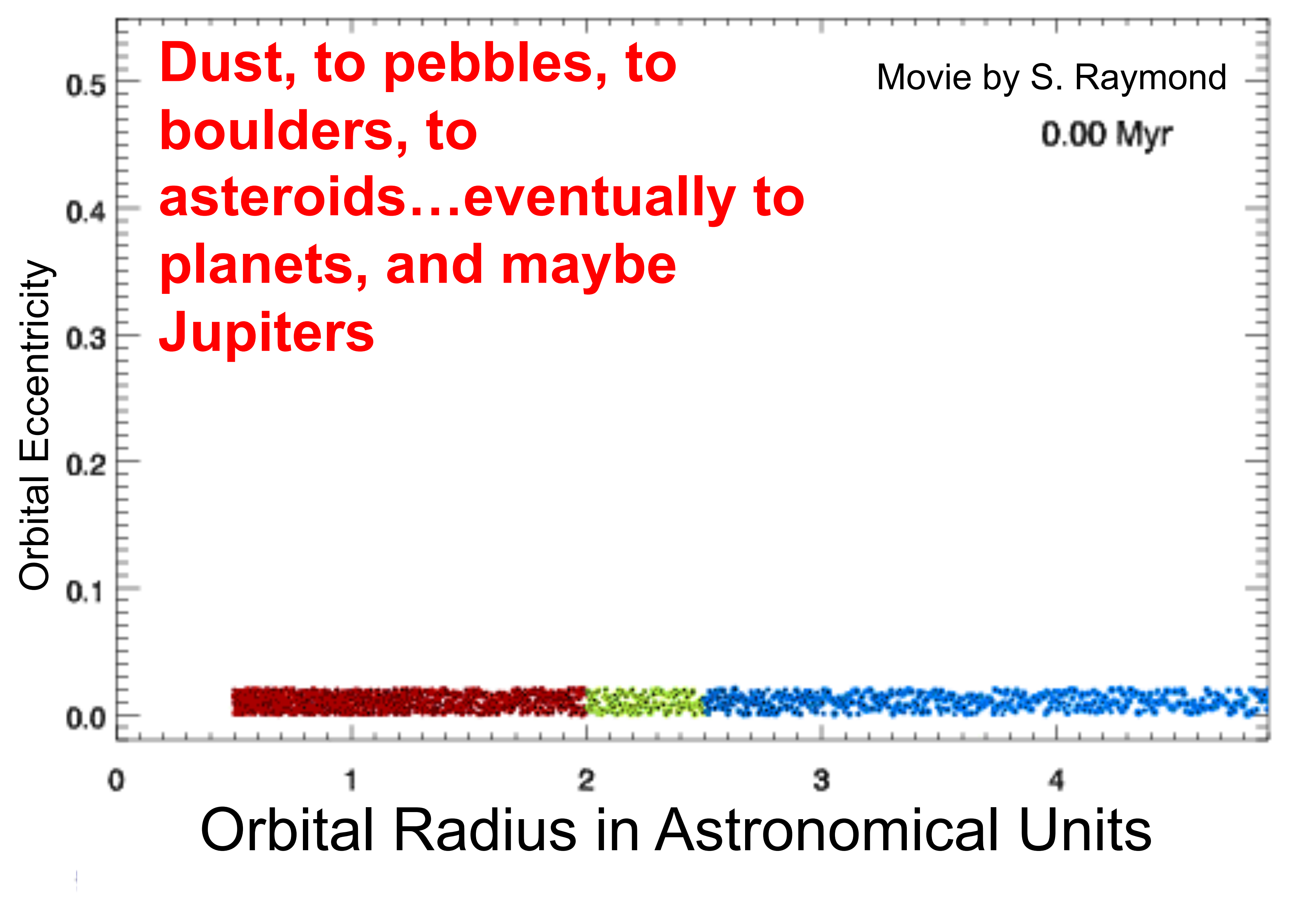
Dust => Pebbles => Boulders => Planetesimals => Planets => Gas Giants



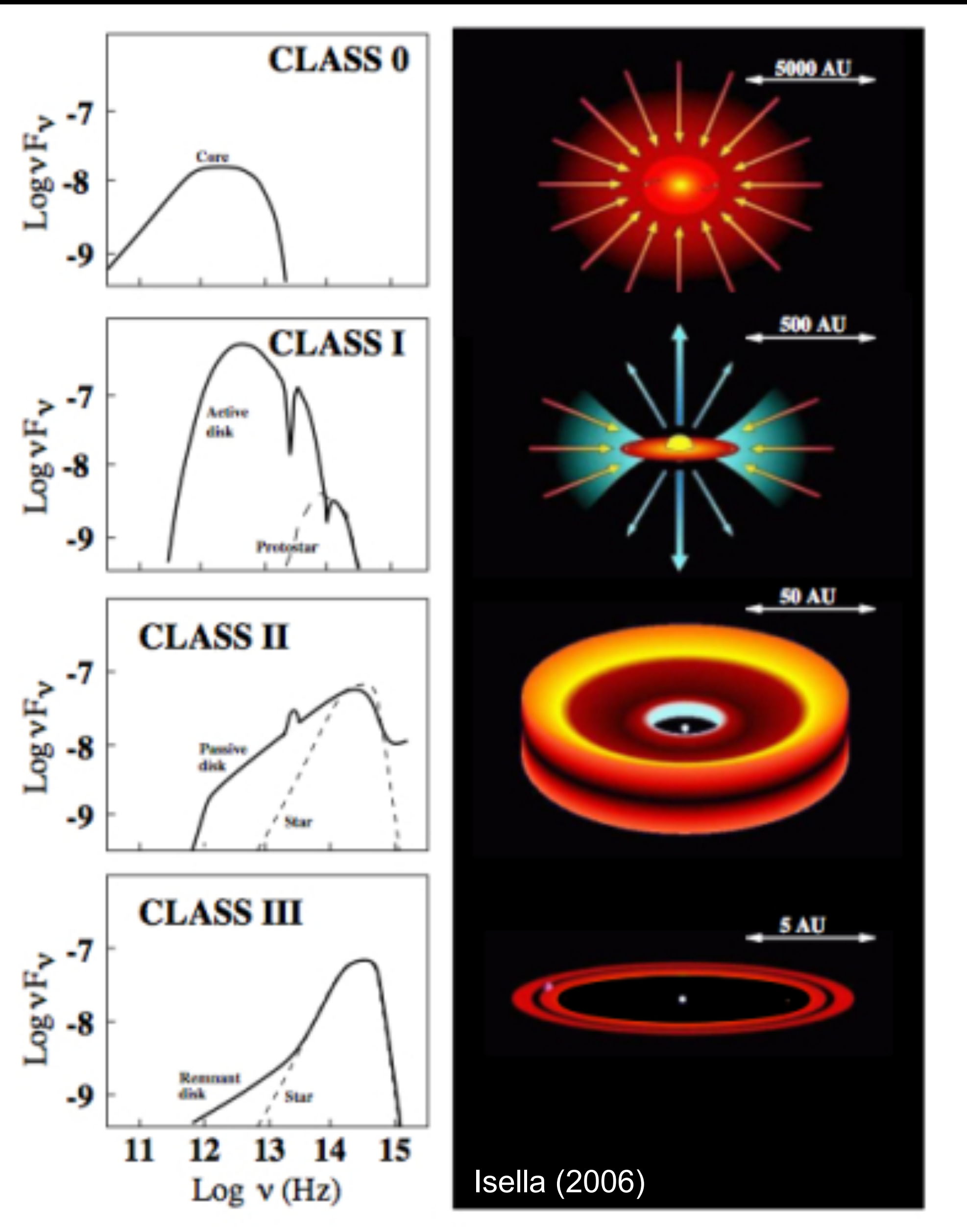
Dodson-Robinson et al. (2008)



Planet Formation from the Bottom Up



The Stages of Star/Planet Formation



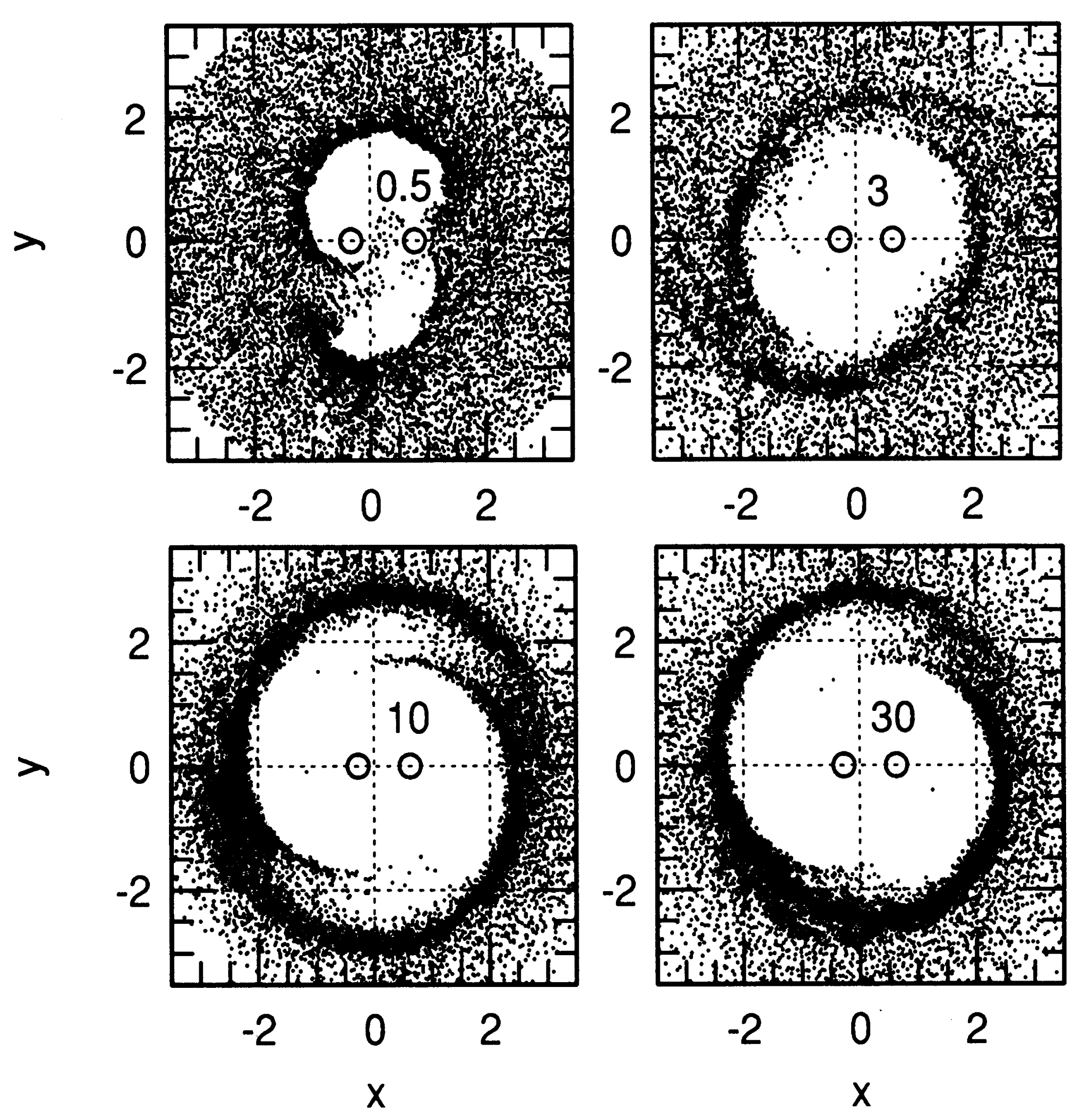
Age ~ 10^5 years

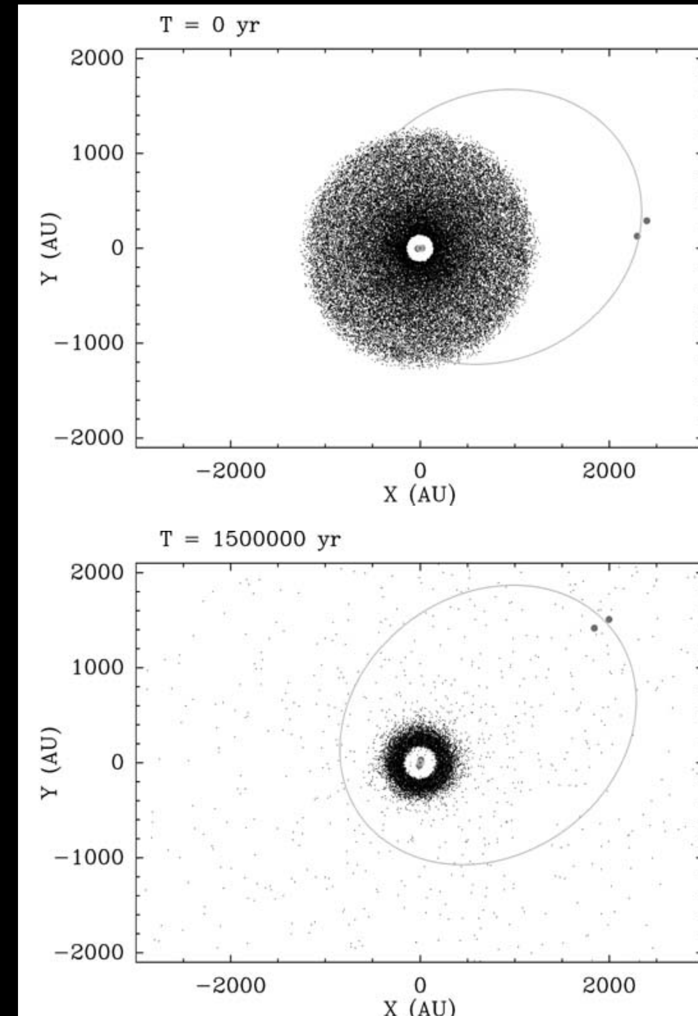
Age ~ 10^5-10^6 years

Age ~ 10^6-10^7 years

Age > 10^7 years

Obstacle #1: Disk Sculpting

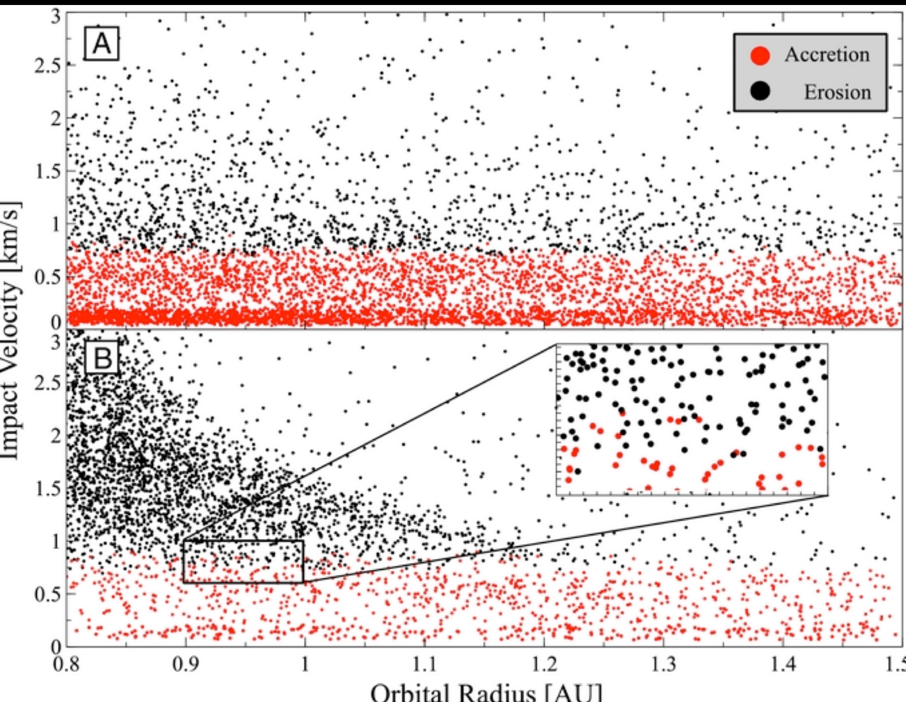


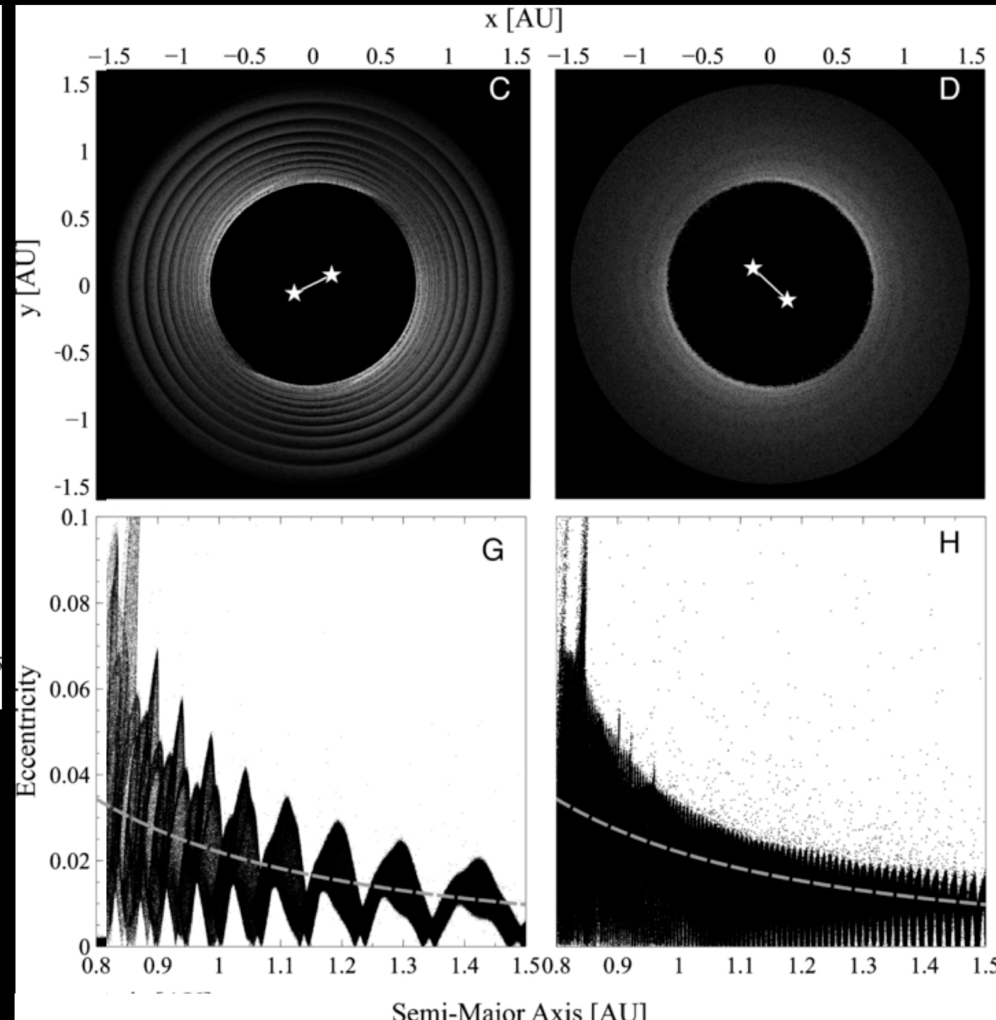


Above: Beust (2002)
Left: Artymowicz & Lubow (1994)

Gaps are typically opened to 1/3 and 3x the binary semimajor axis.

Obstacle #2: Planetesimal Stirring

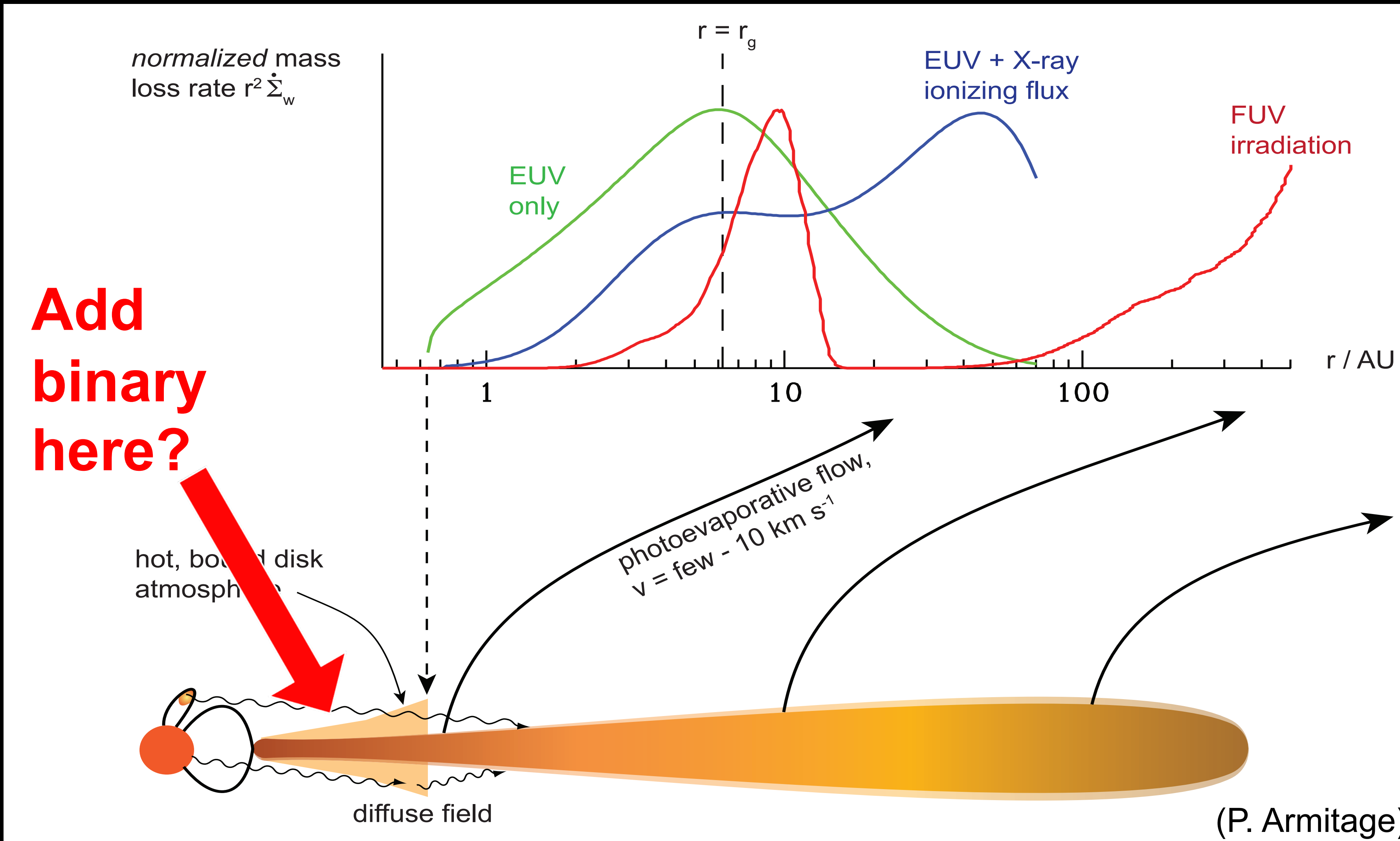




A case study for Kepler-34 AB+b, showing planetesimal eccentricity evolution (right) and accretion vs erosion (above). (Lines et al. 2014)

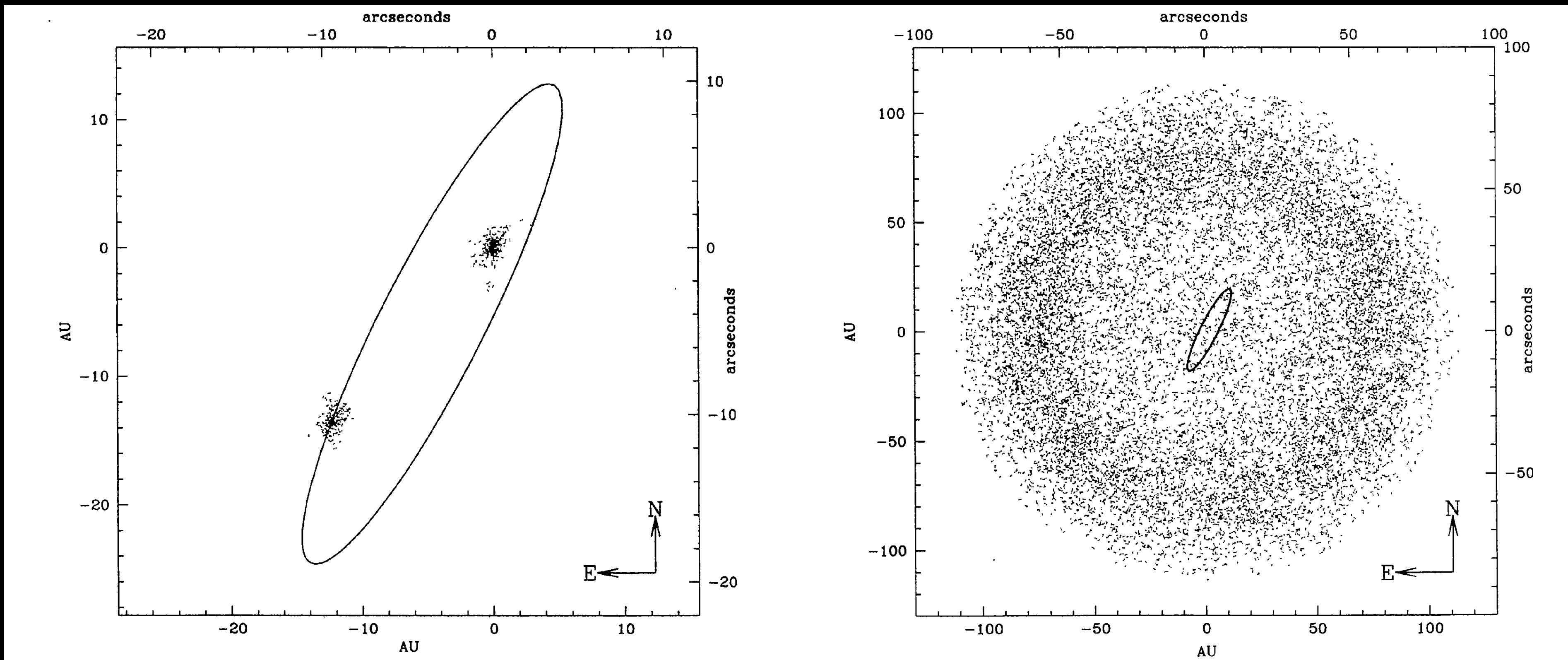
Planetesimal sizes rapidly begin grinding down instead of growing up.

Obstacle #3: Disk Dissipation



In binaries, the outer disk is directly exposed to erosion via photoevaporation and boils away. (e.g., Alexander 2012)

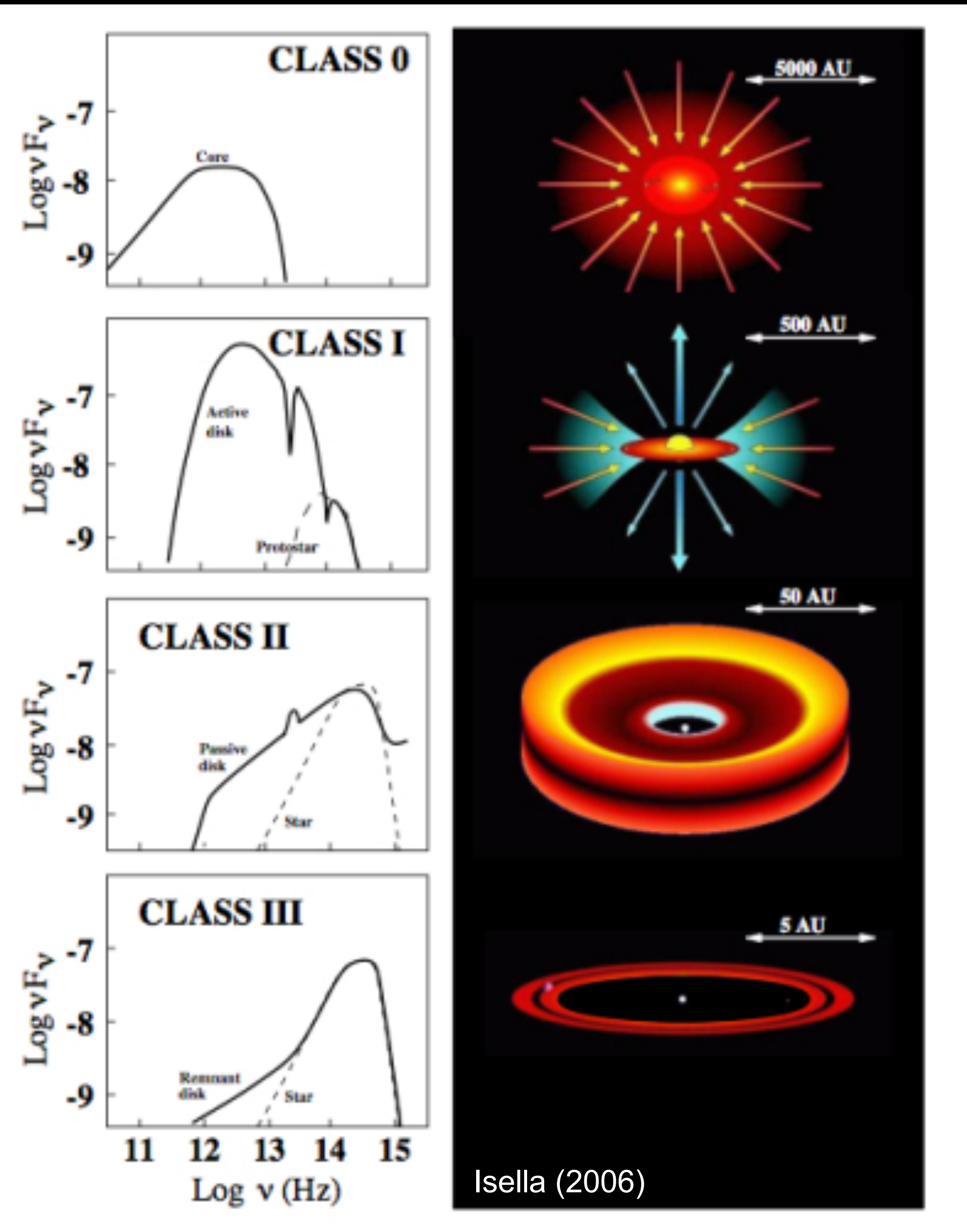
Obstacle #4: Orbital Stability



Stable orbital configurations in the Alpha Cen AB system, in circumstellar (left) and circumbinary (right) configurations. (Wiegert & Holman 1997)

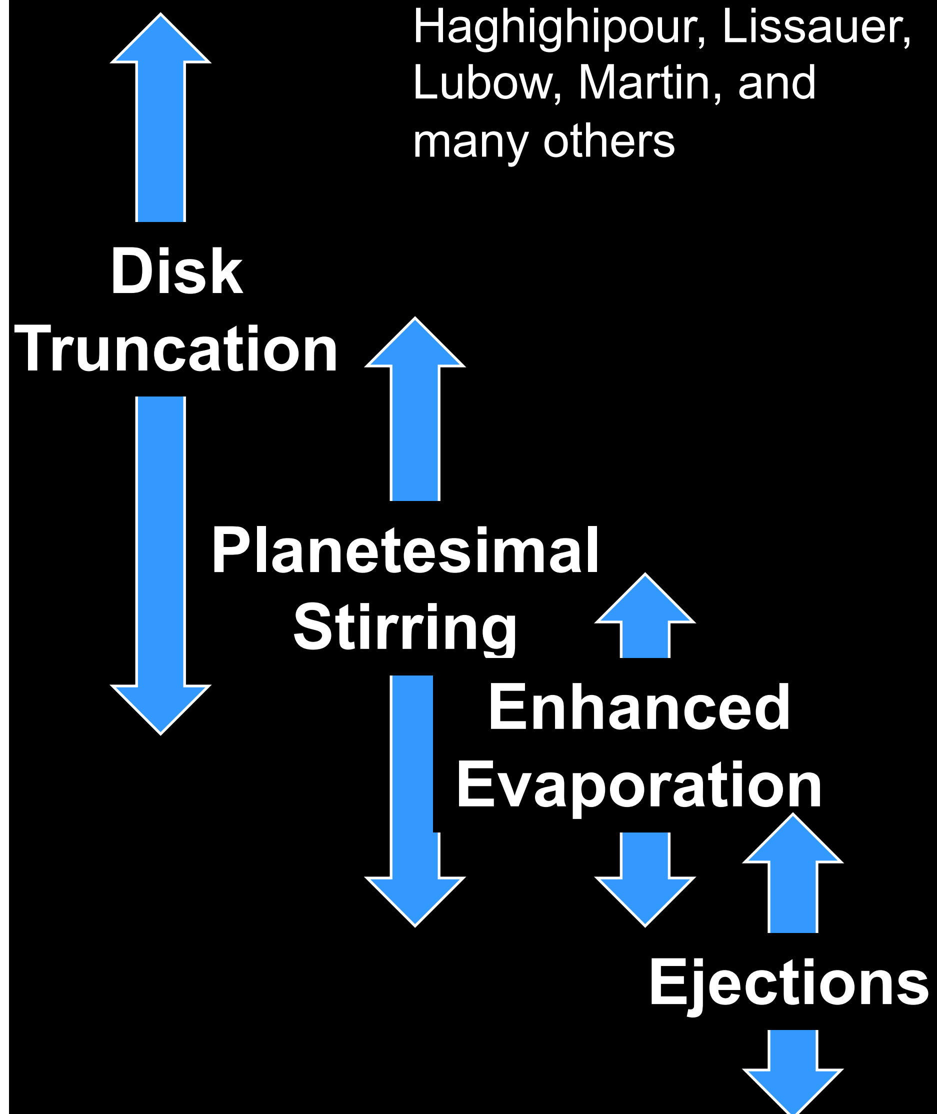
Even if planets form, only (a fraction of) those in restricted ranges of parameter space will remain on stable orbits across the MS lifetime.

Obstacles to Planet Formation

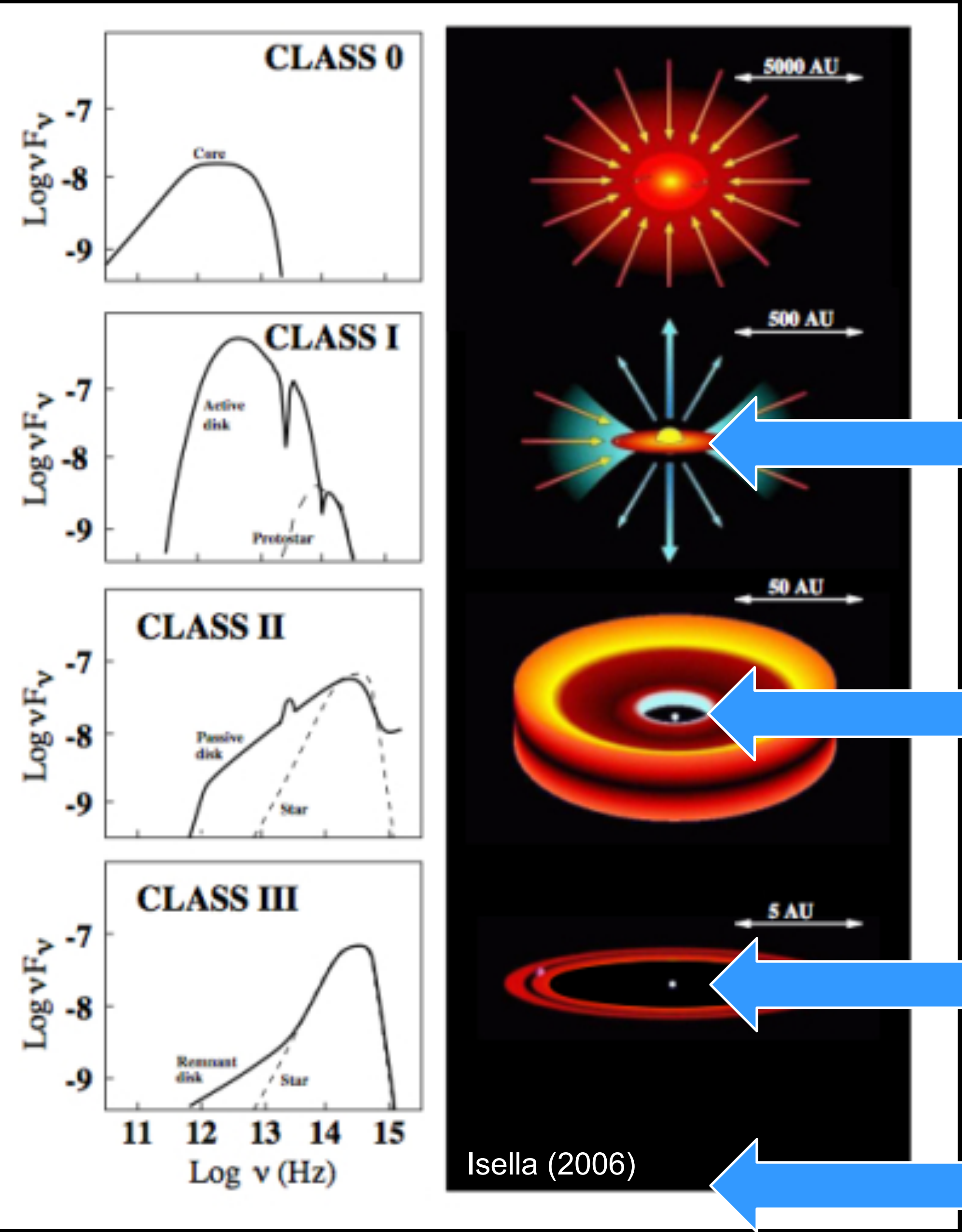


Isella (2006)

See papers by: Alexander, Beust, Haghighipour, Lissauer, Lubow, Martin, and many others



Observational Tests



Protostellar Disks

Protoplanetary Disks

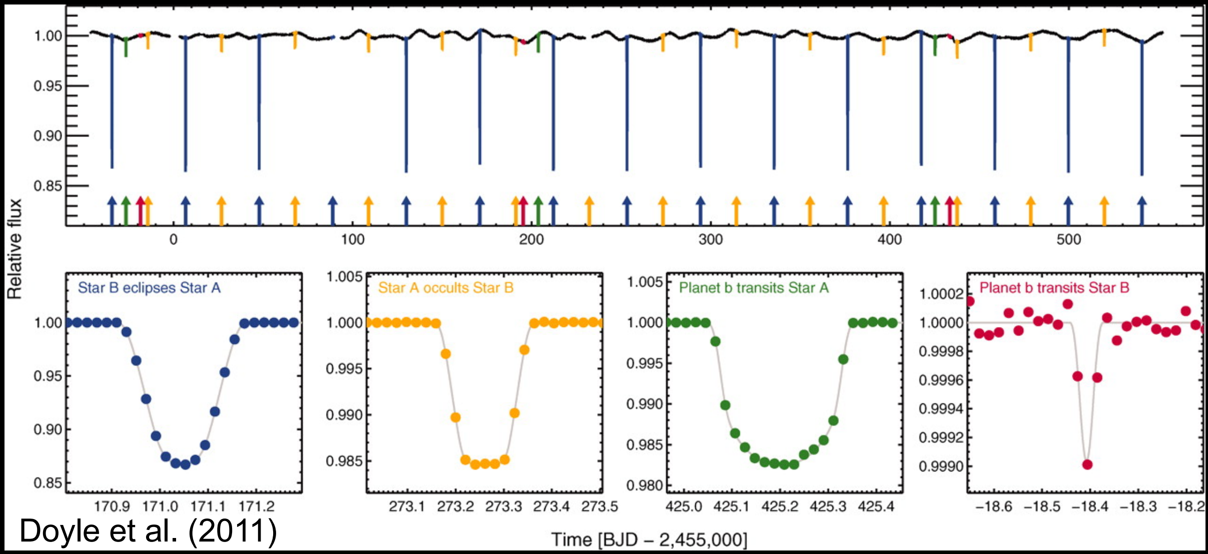
Debris Disks

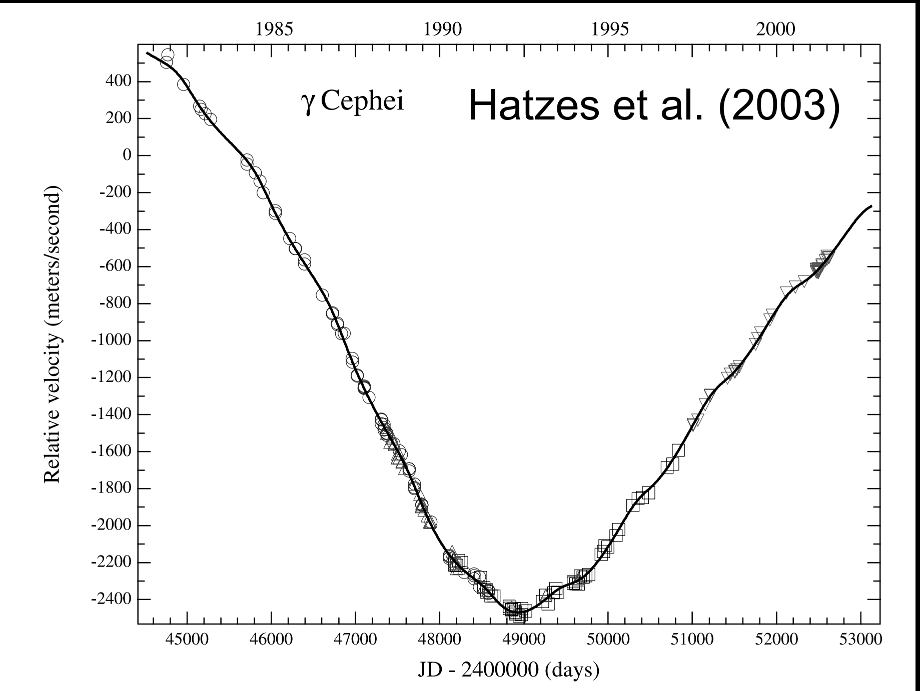
Old Planetary Systems

Despite These Obstacles…

Planets are being found:

- Gamma Cep
- GJ 86
- HD 196885
- Kepler-16



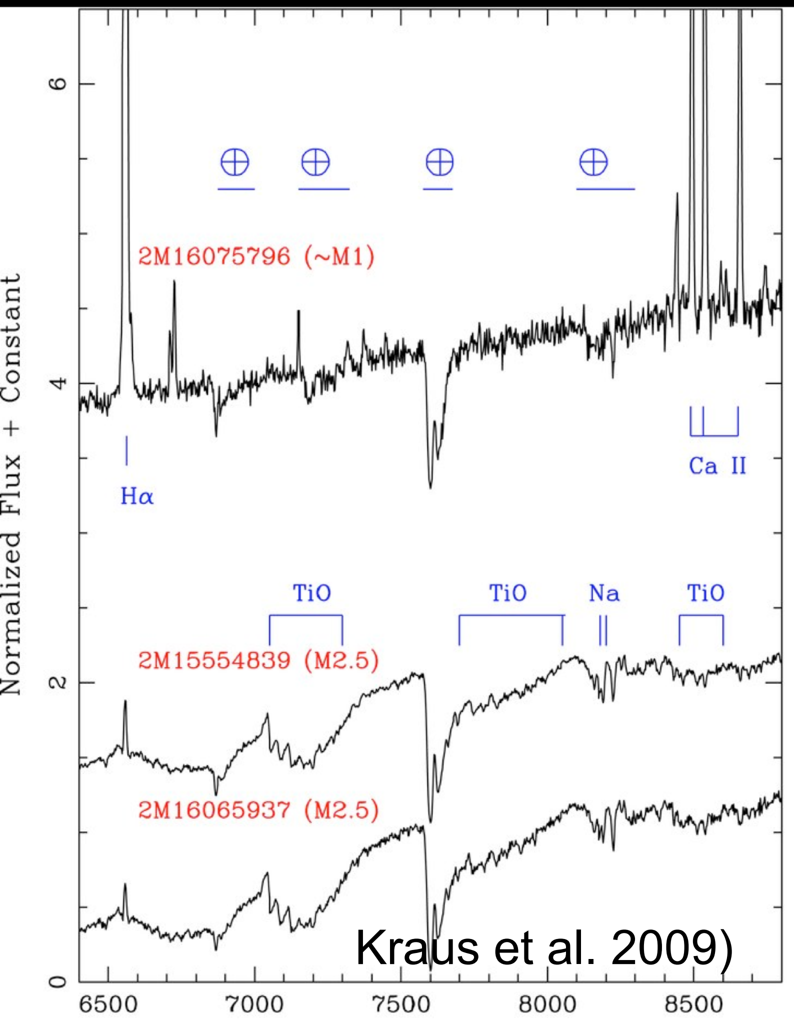


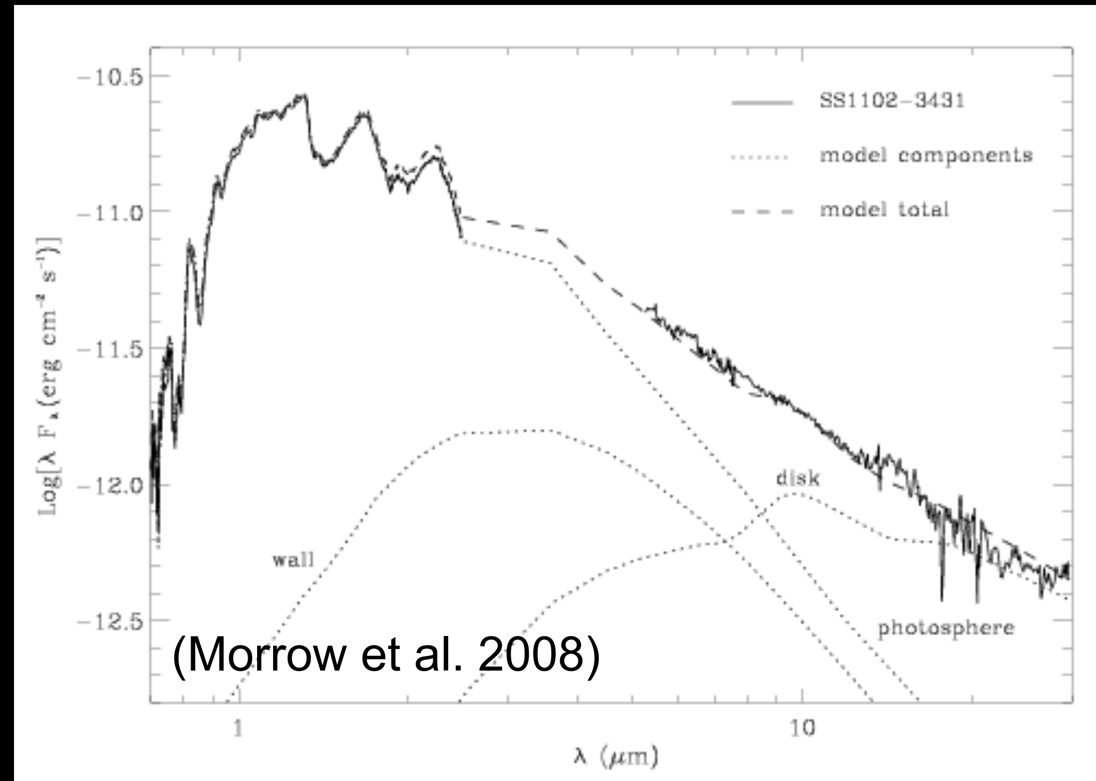
So why do some planetary systems successfully navigate this series of obstacles? And which ones don't?

Part 2: The Impact of Multiplicity on Protoplanetary Disk Existence & Lifetime

We Know How to Find Disks

Two Main Signatures:

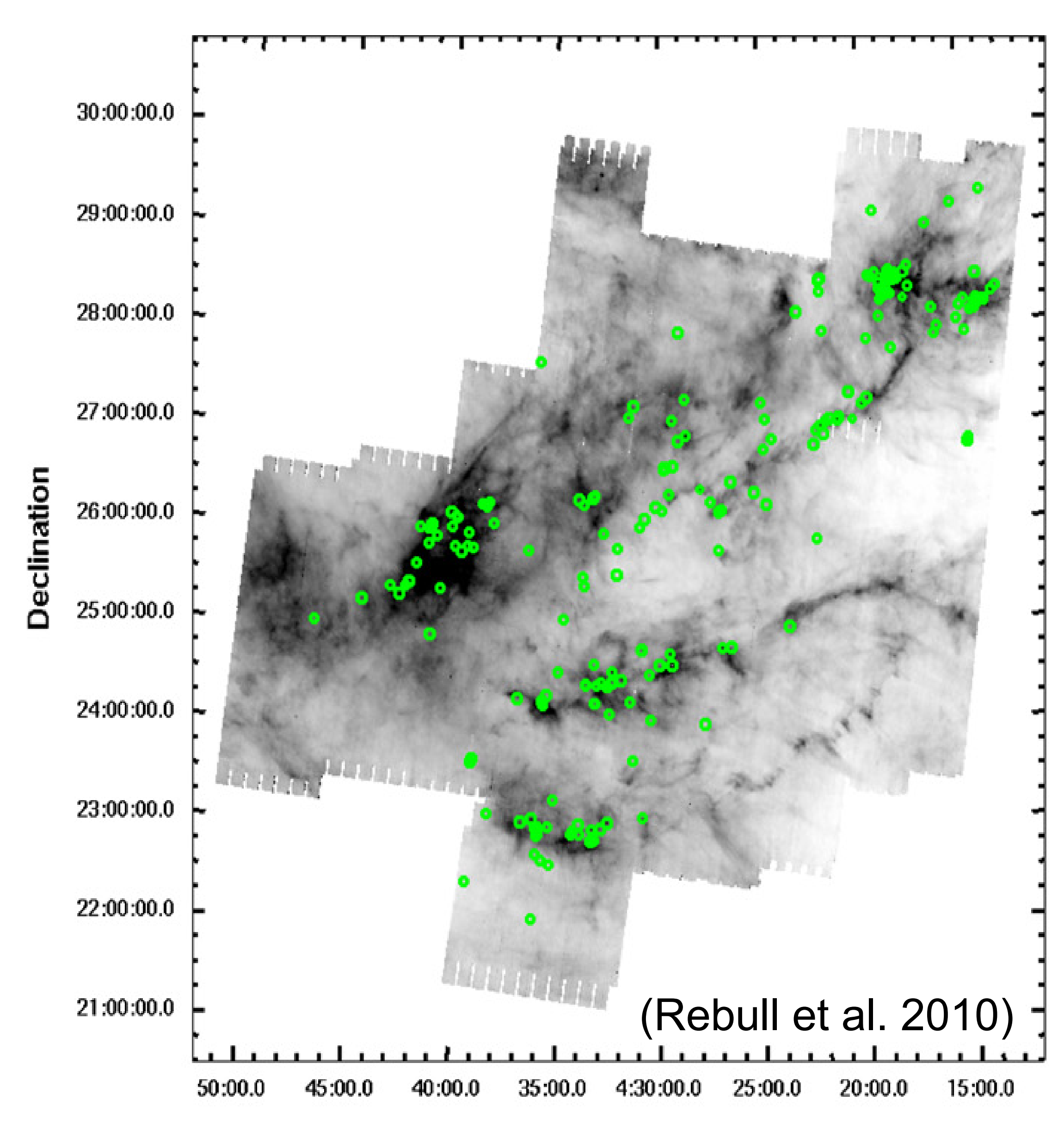




Accretion (left): Matter falling onto the star(s)

Disk Excess (above): Cool blackbody radiation from dust heated by stellar radiation

The Disk (and Disk-Free) Sample

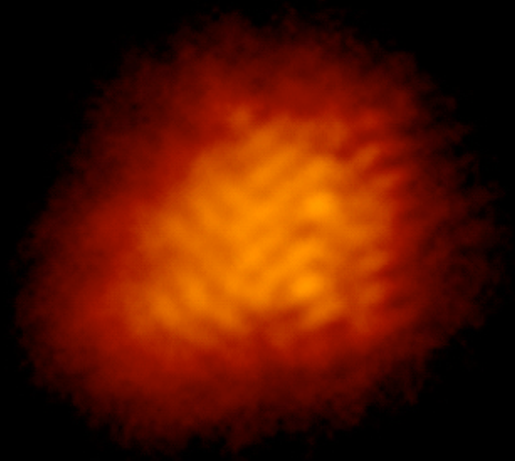


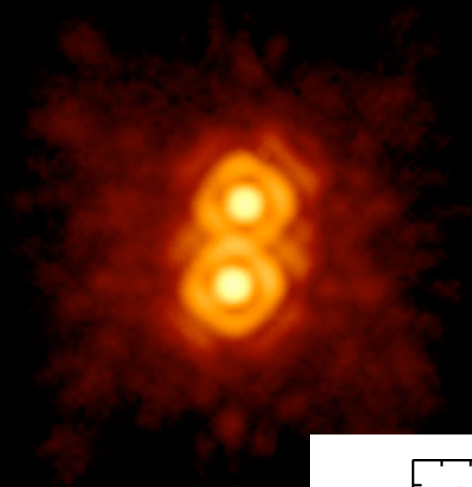
Over the past decade, Spitzer has yielded a complete census of disks within all the nearest star-forming regions.

(Cue uncomfortable silence on completeness for disk-free stars. Gaia is helping a lot on this front!)

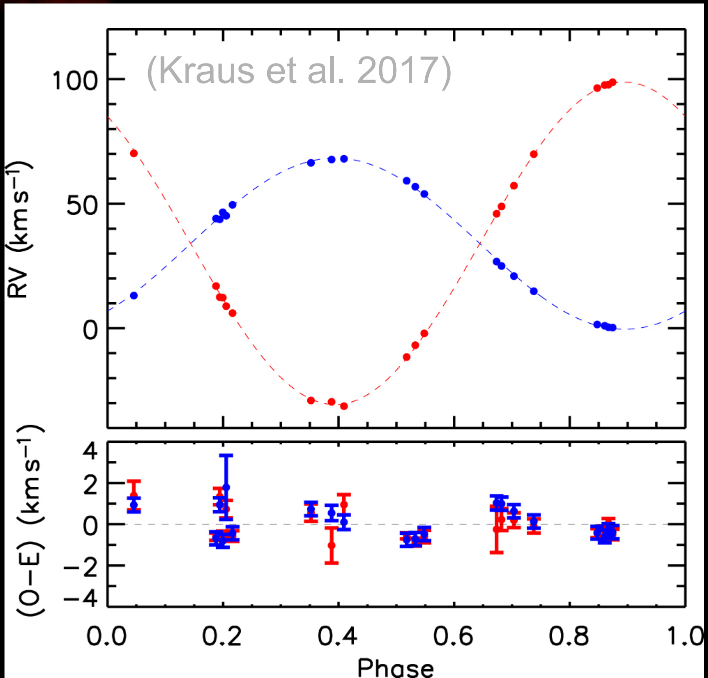
How do we identify binary systems?

(Palomar Observatory/NASA-JPL)





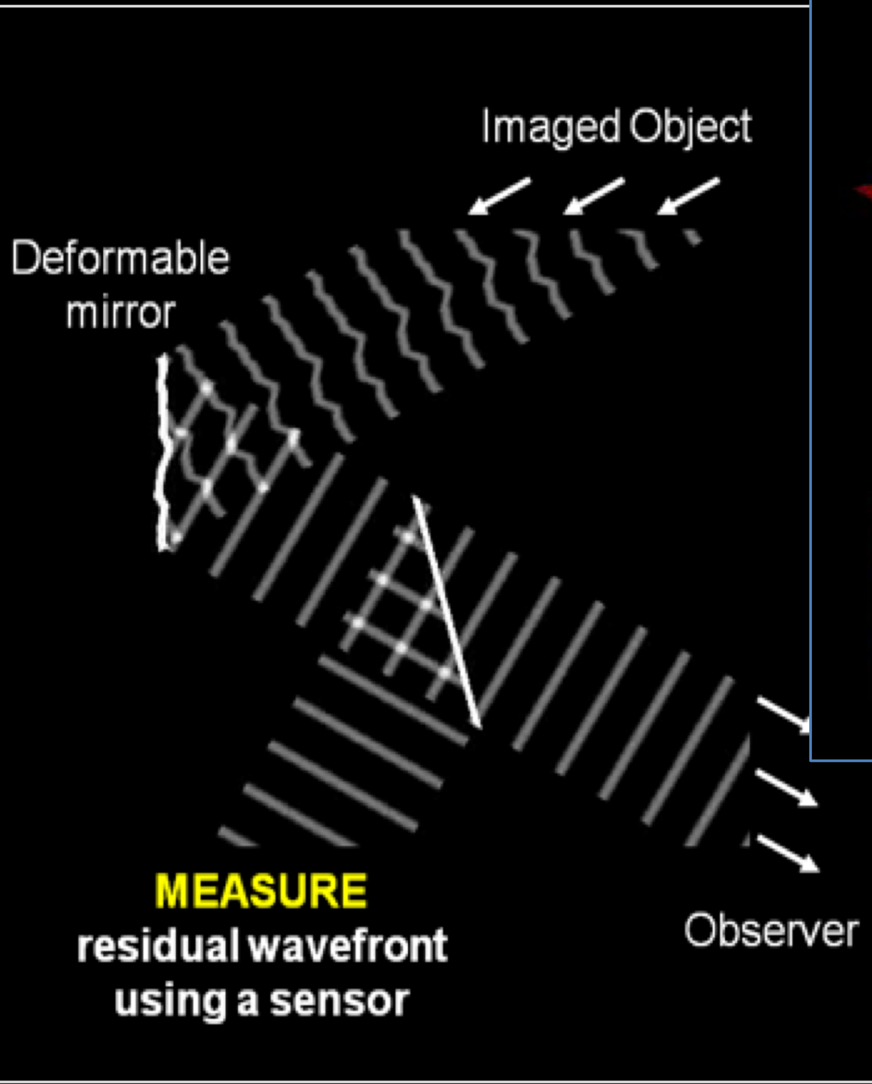
RV Monitoring

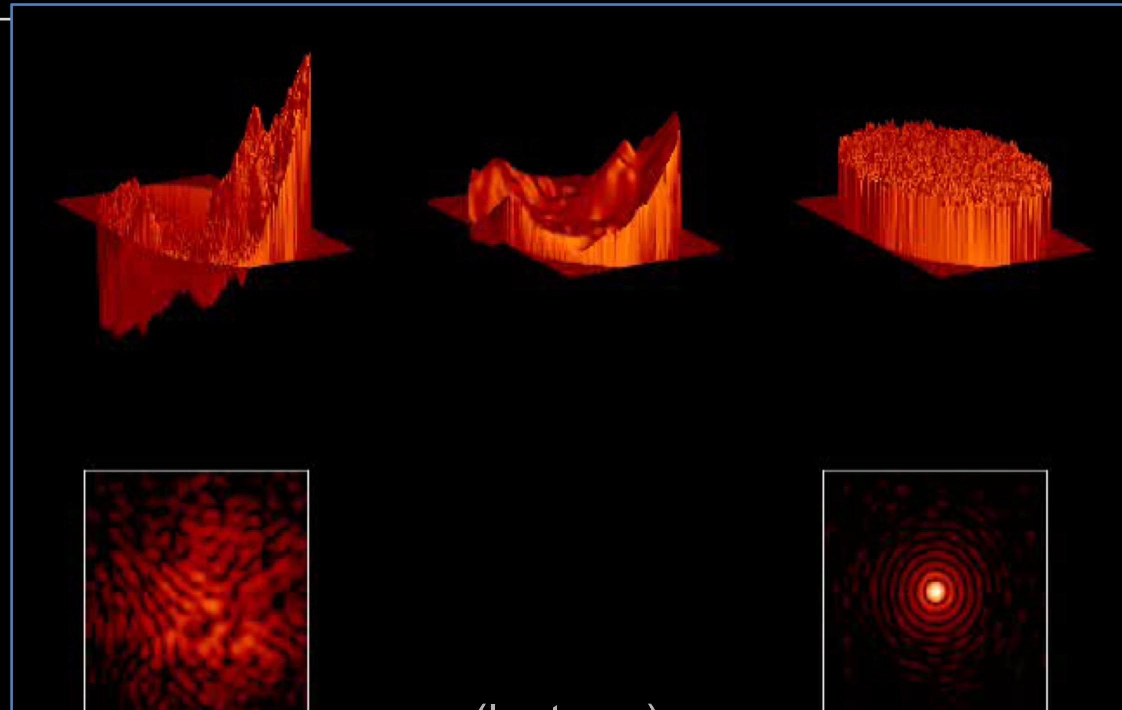


Adaptive Optics Imaging
Speckle Imaging
Space Observatories

Soon: Gaia Astrometry?

Finding Binaries: Adaptive Optics



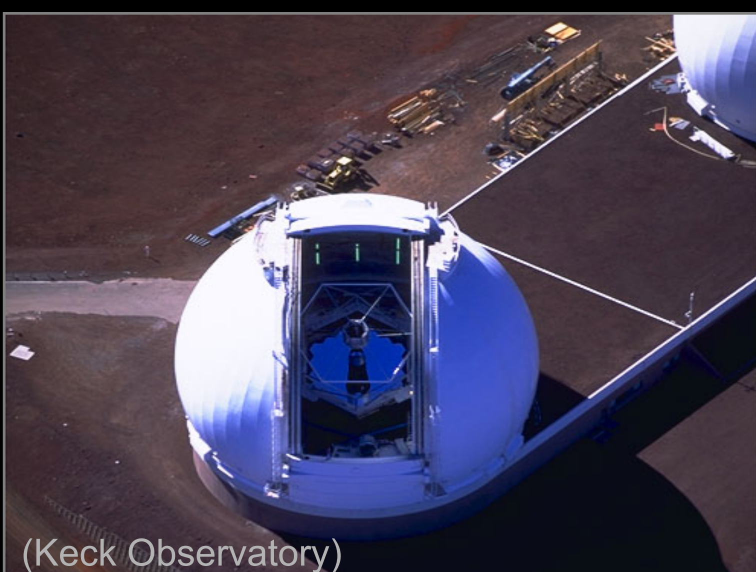


(lyot.org)

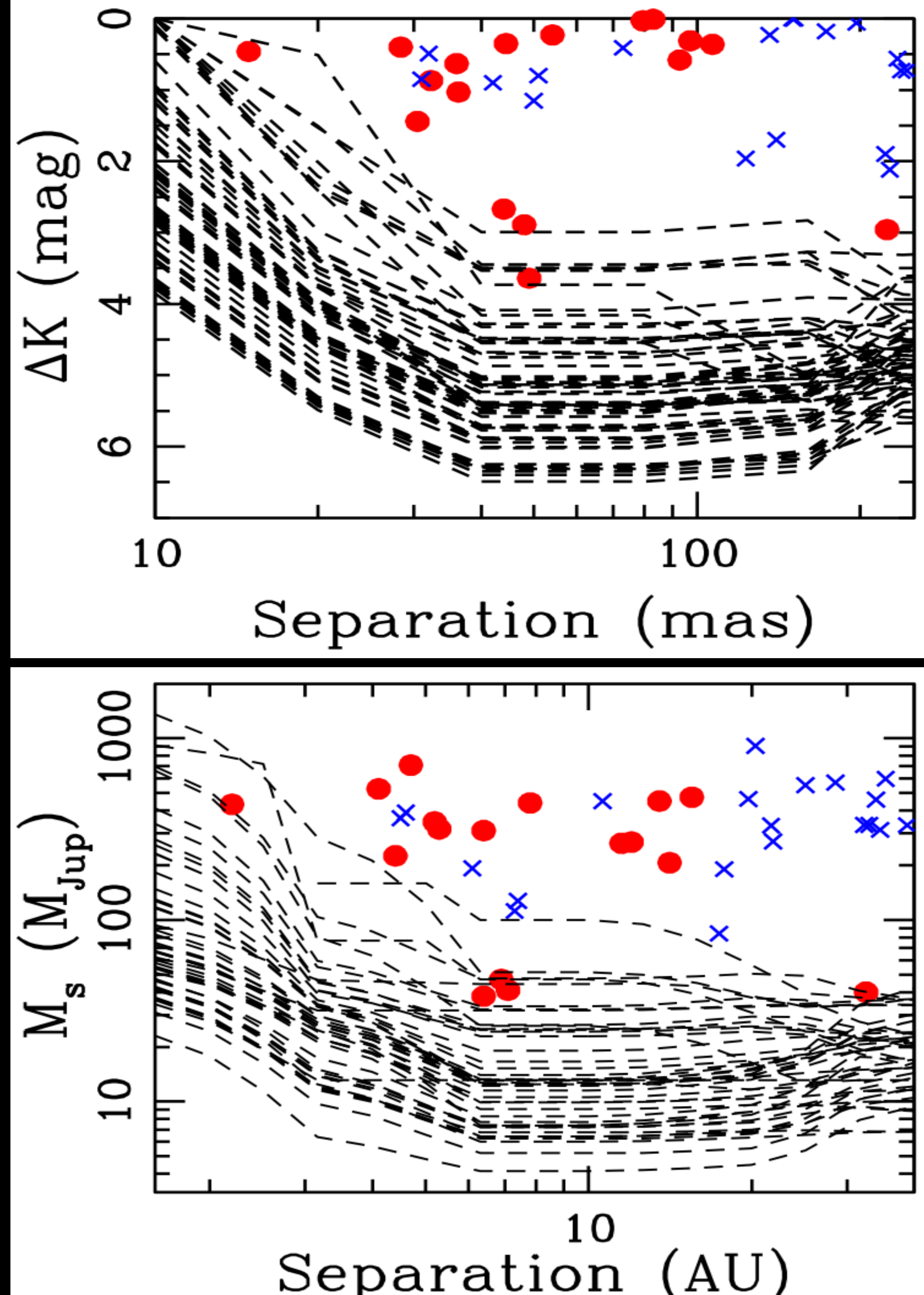
Correct the turbulence introduced by the atmosphere, and you can concentrate the light of the primary star away from any companion stars (or planets).

Binary Surveys of Young Stars

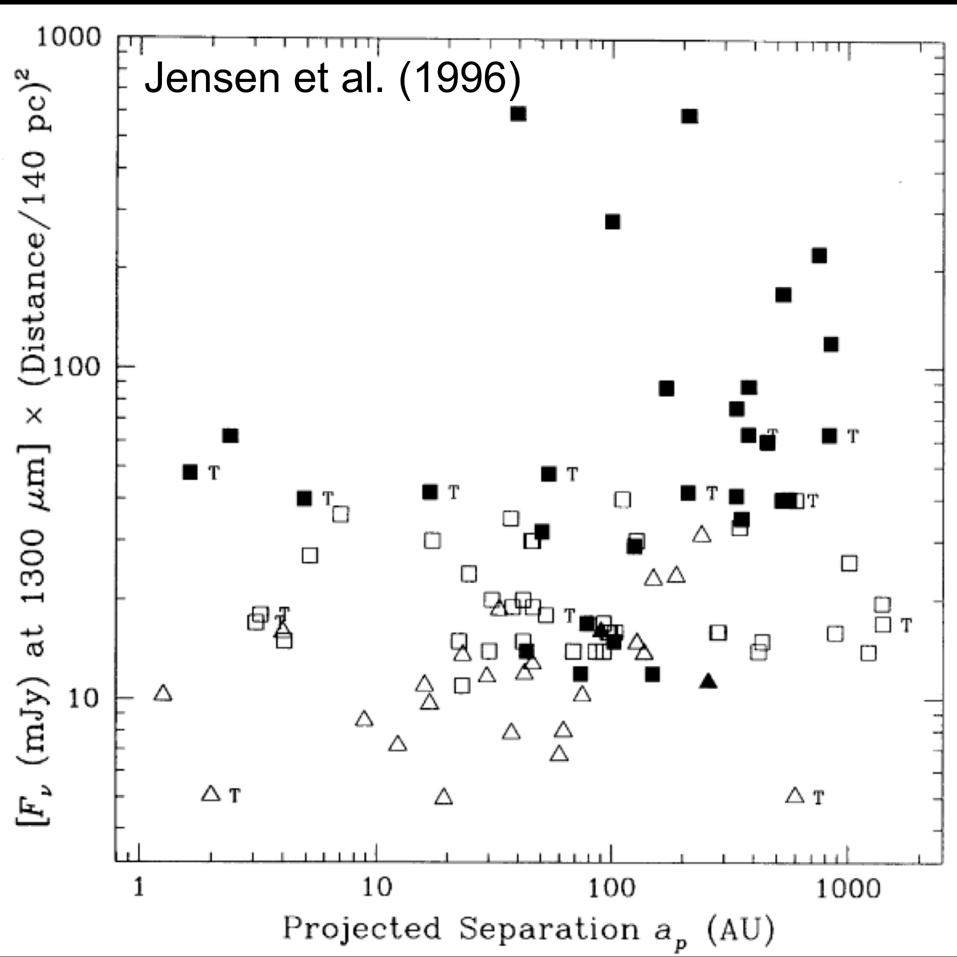
To pick one example, my collaboration has observed >400 young stars in many nearby SFRs. (Kraus et al. 2008, 2011; Ireland et al. 2011; Cheetham et al. 2015)



(Keck Observatory)

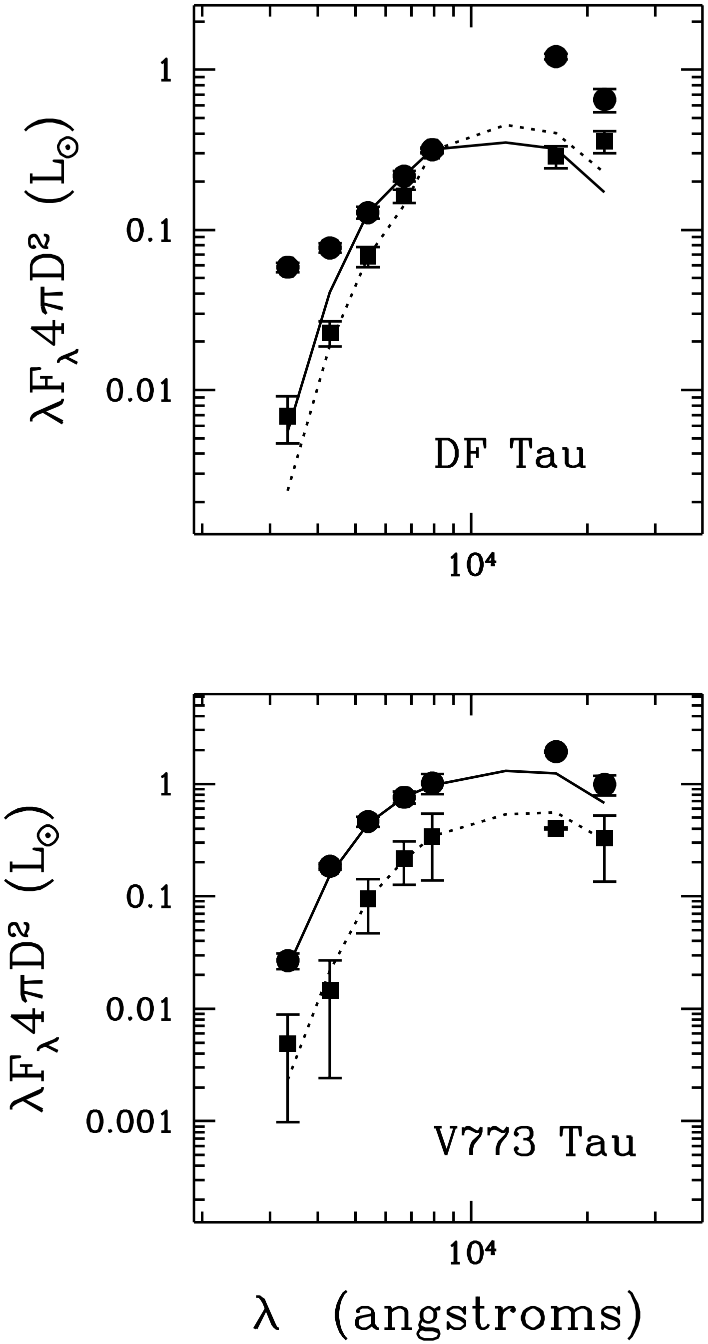


Jensen et al. (1996)



Filled: Detections
Open: Upper Limits

- First large study of disks in binary systems, using millimeter flux to indicate disk existence+mass
- Found that the most luminous objects were all among the wider binaries; maybe fewer (or less massive?) disks among tighter binaries?

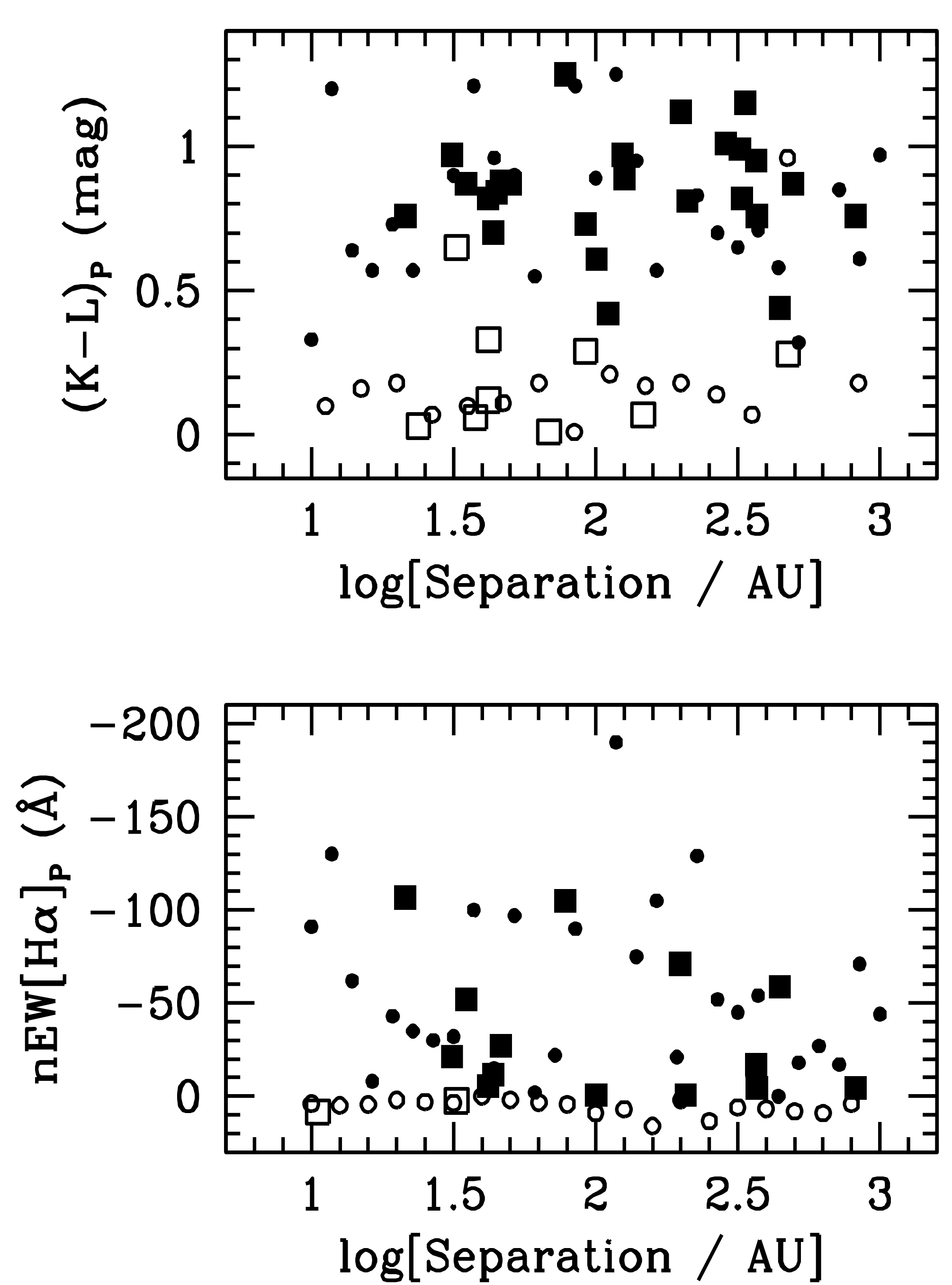


Ghez et al. (1997)

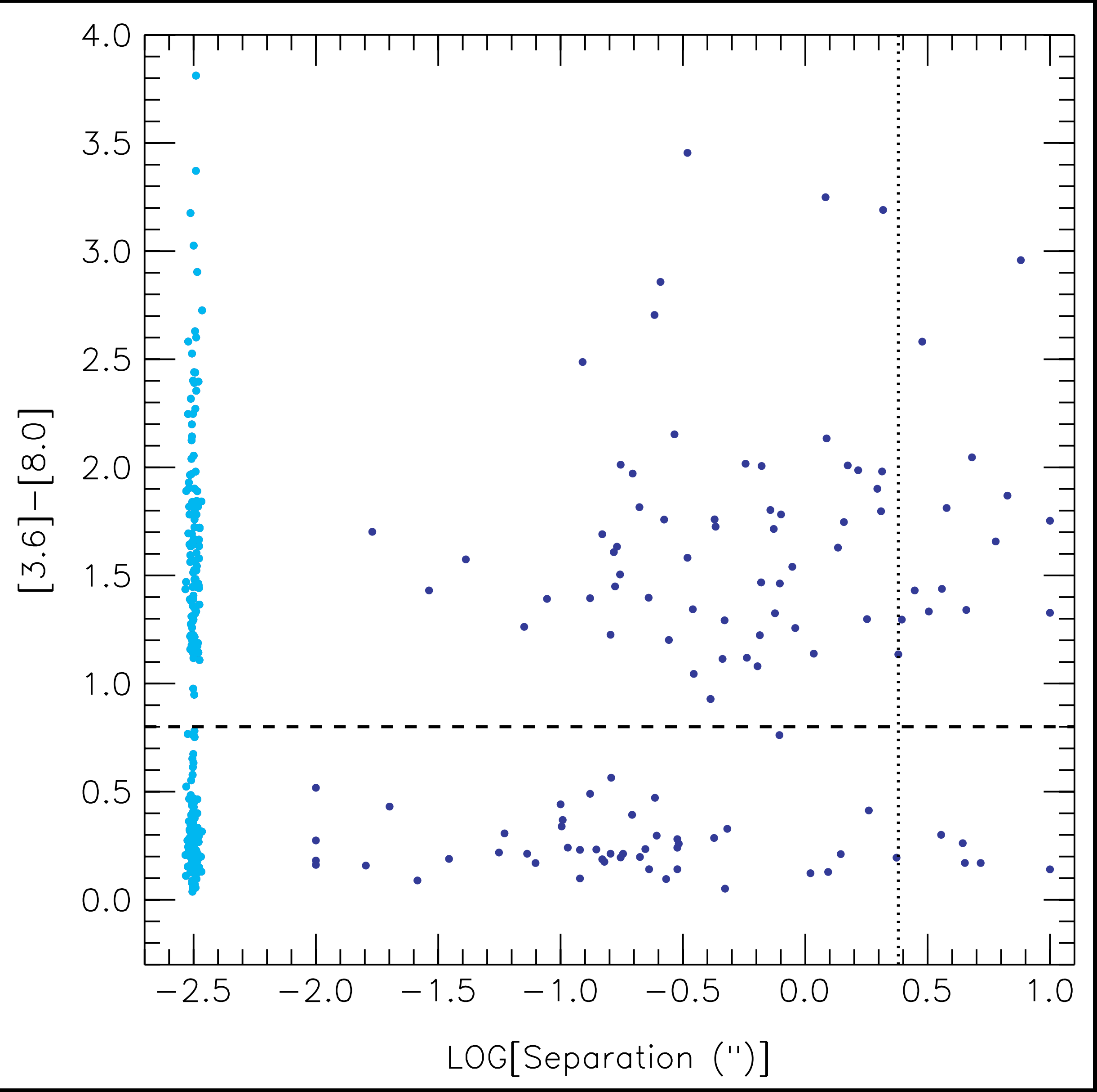
- Constructed detailed infrared SEDs for stars that were known to be close binary systems
- Observed 8 close binaries and found that several hosted stable protoplanetary disks

White & Ghez (2001)

- For a large sample, measured disk and accretion diagnostics vs binary separation
- Still mostly limited to >30 AU



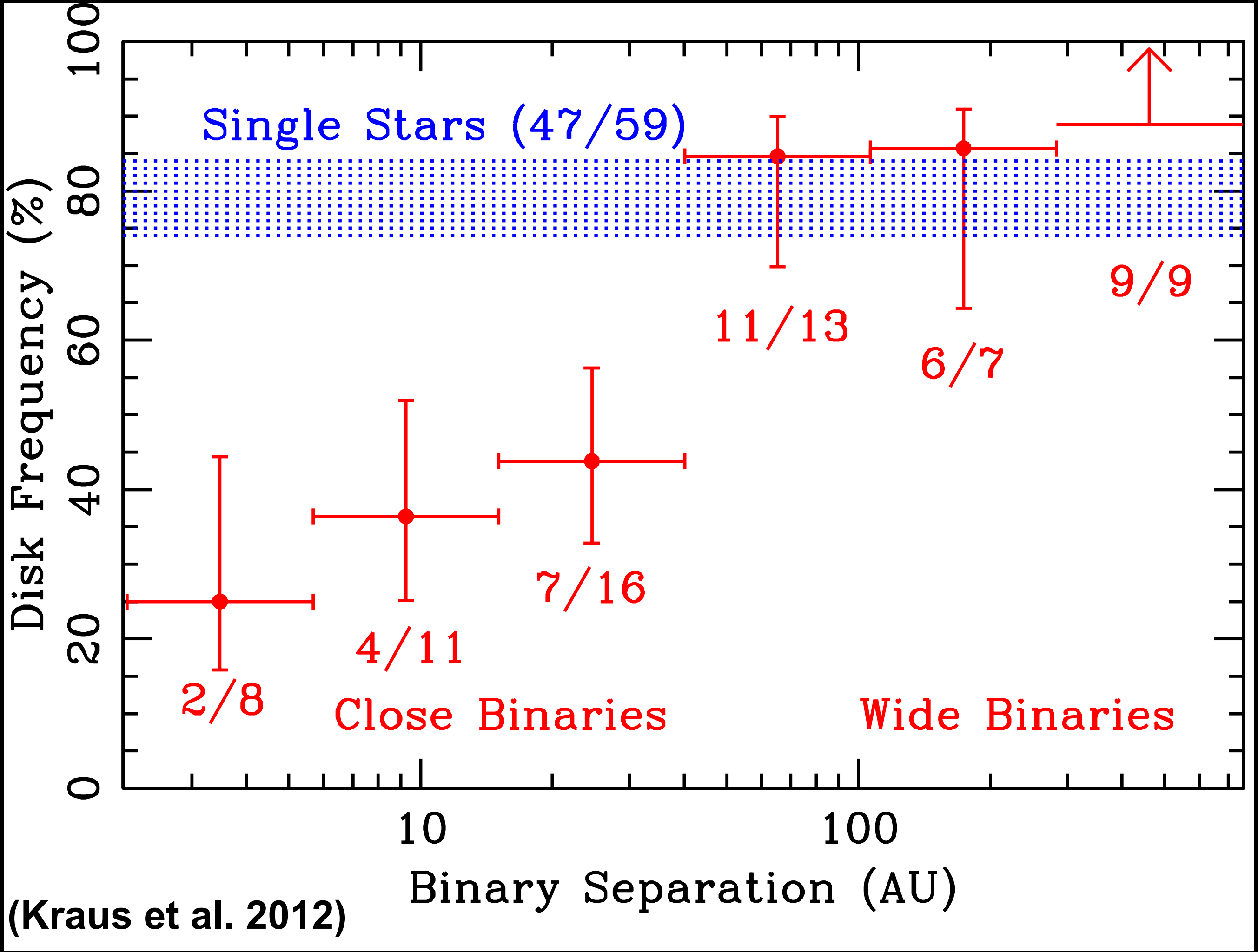
Cieza et al. (2009)



Sample has a lot going on– many input binary surveys, and a number of correlated systematic effects.

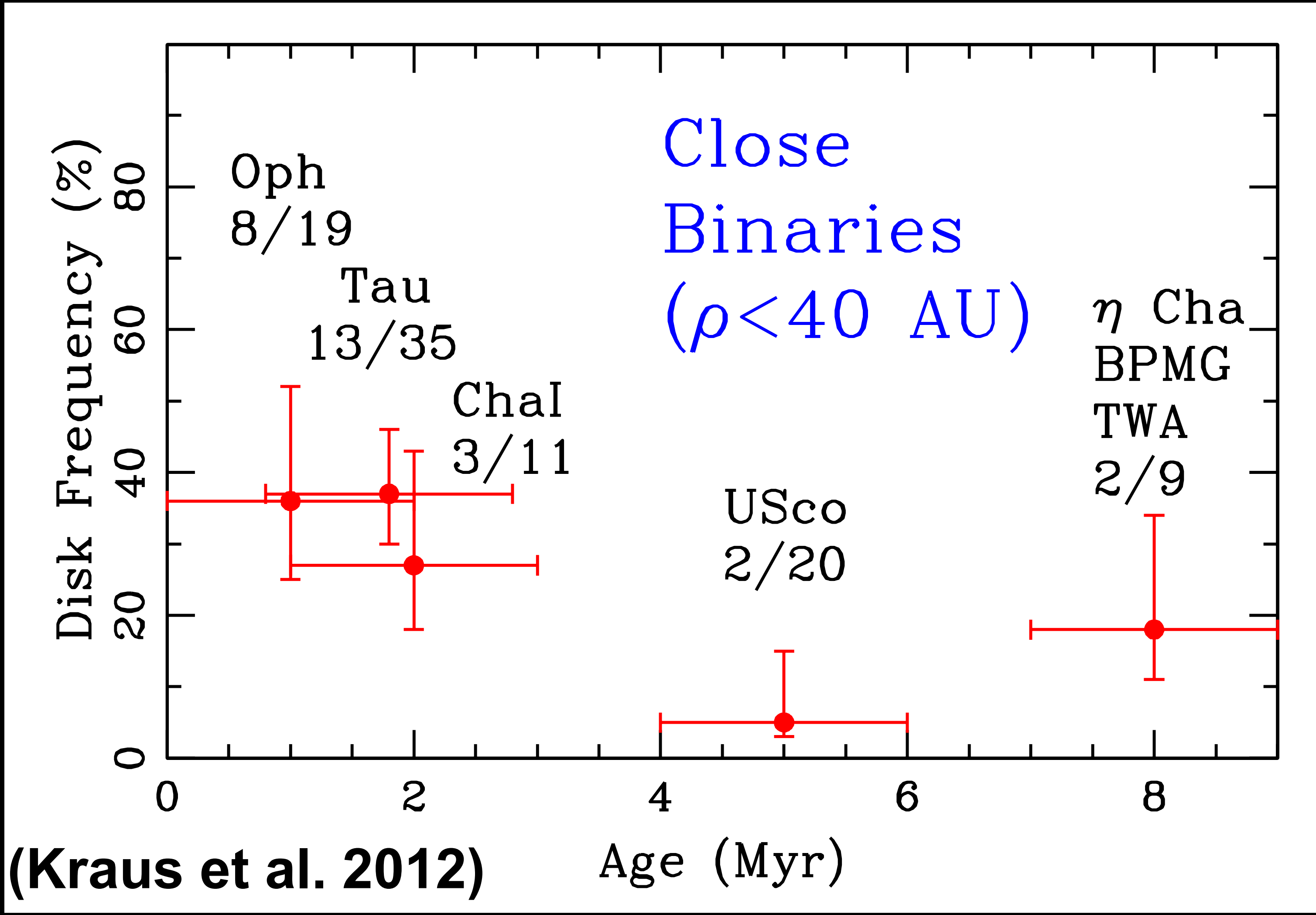
But, it shows a trend that close binaries might lack disks.

Kraus et al. (2012)



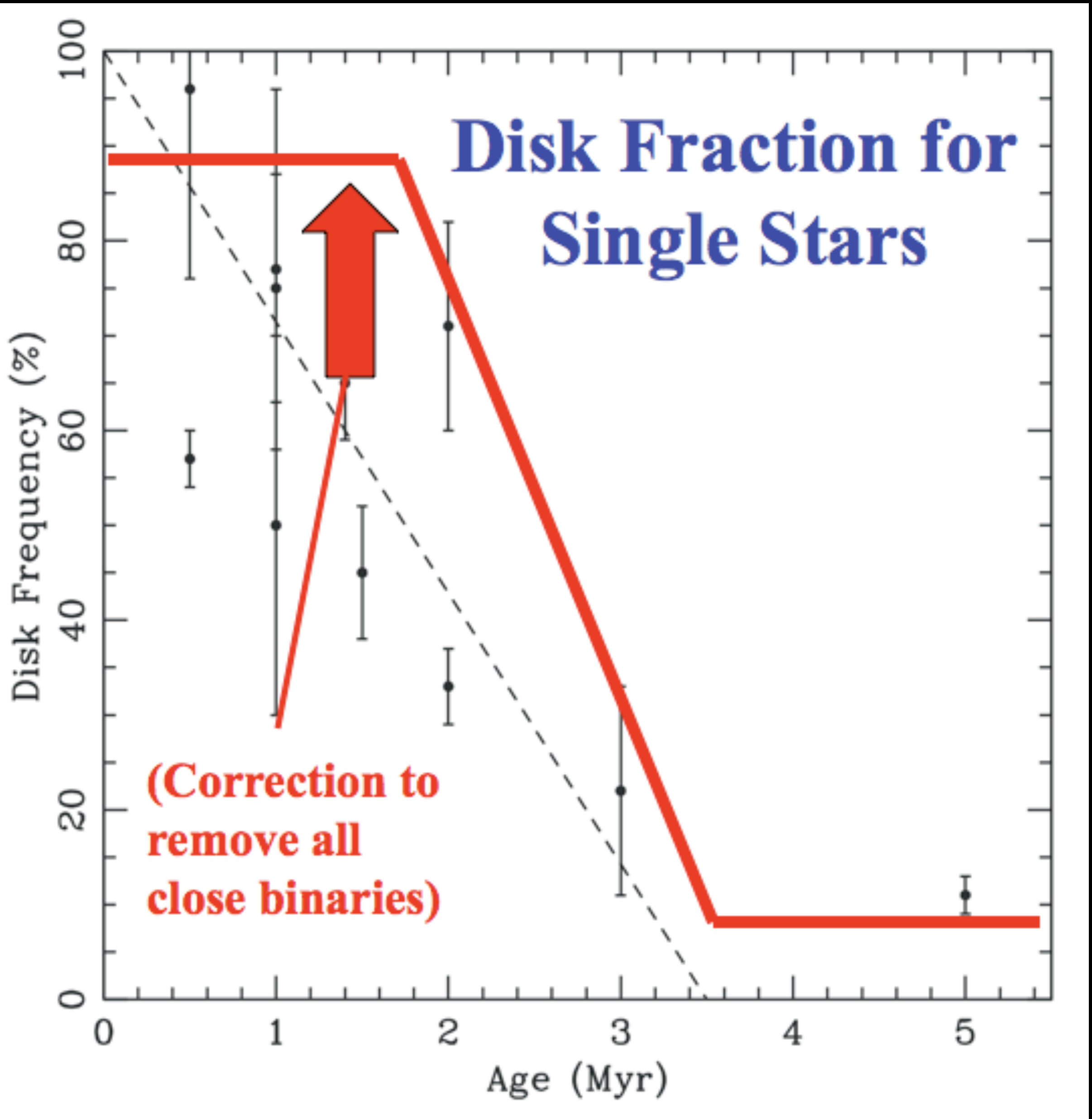
In Taurus-Auriga (~2 Myr), the disk fraction is high for single stars and wide binaries, but suppressed by a factor of 3 for <40 AU binaries. ***The majority of close binaries don't host disks, even when singles + wide pairs do.***

Binaries Disperse Their Disks Fast



This pattern is established within <1 Myr. Also see Cheetham et al. (2015) for an update confirming the frequency in Oph, the youngest nearby SFR.

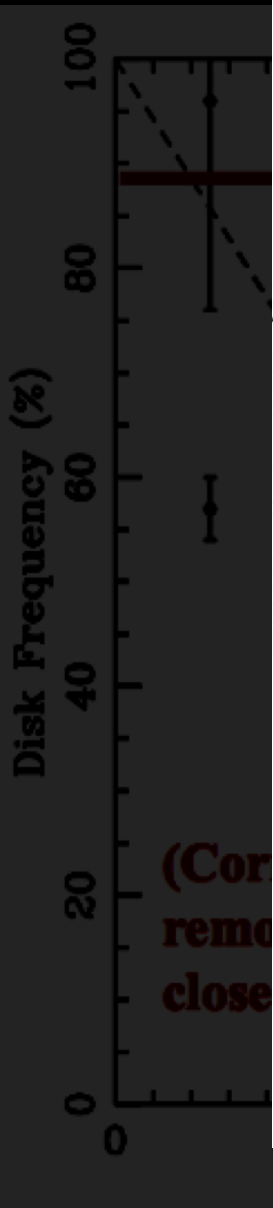
The Multiplicity Correction for Singles

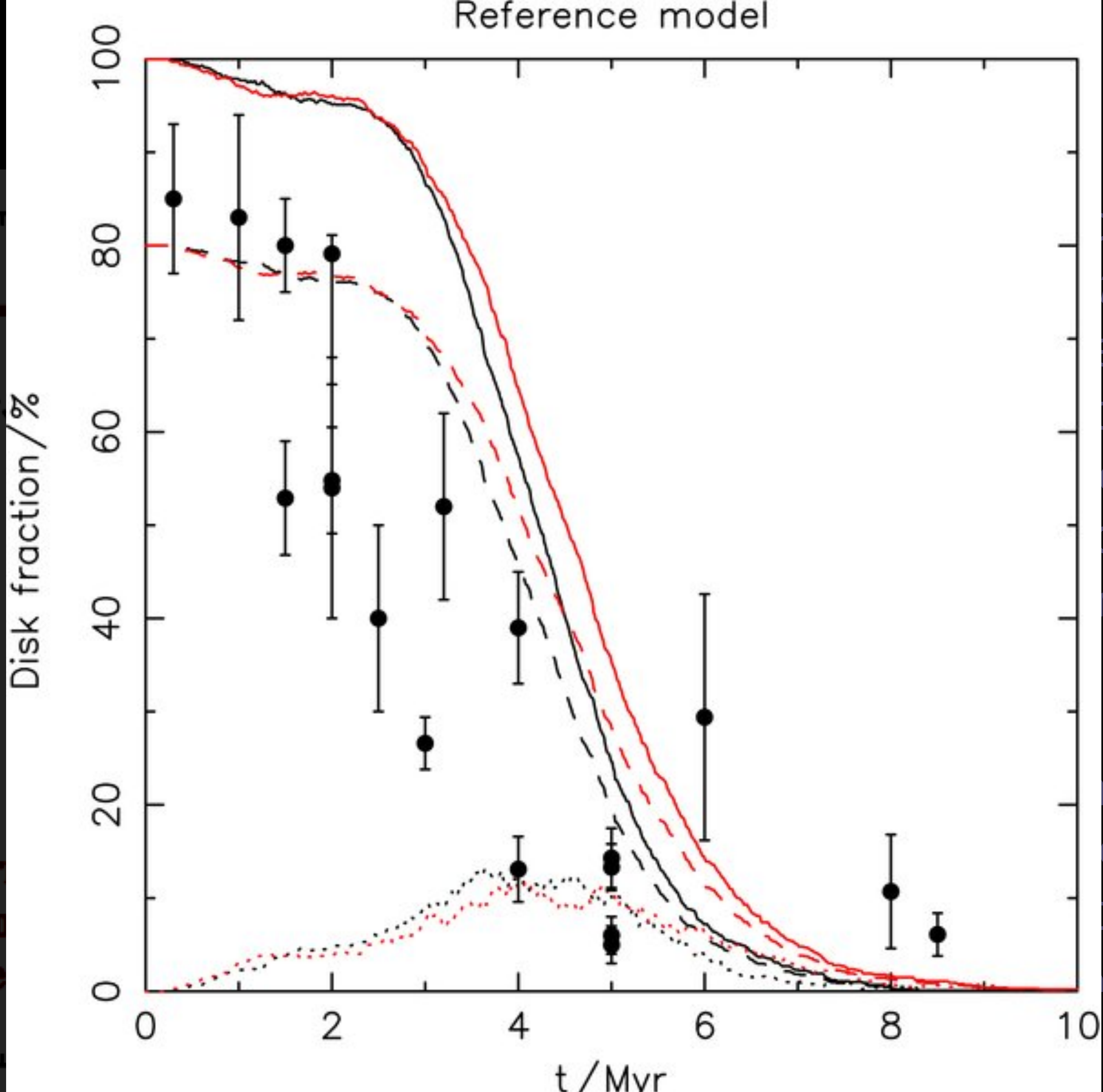


It seems that many of the disk-free stars in these 1-2 Myr associations are binaries; if we remove them, the disk fraction of genuinely single stars goes up by ~10-20%.

Open question: What happens inside a few AU?

(Disk fractions from Hillenbrand 2005).





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ter et al. 2006)

(Figure from Alexander & Armitage 2009)

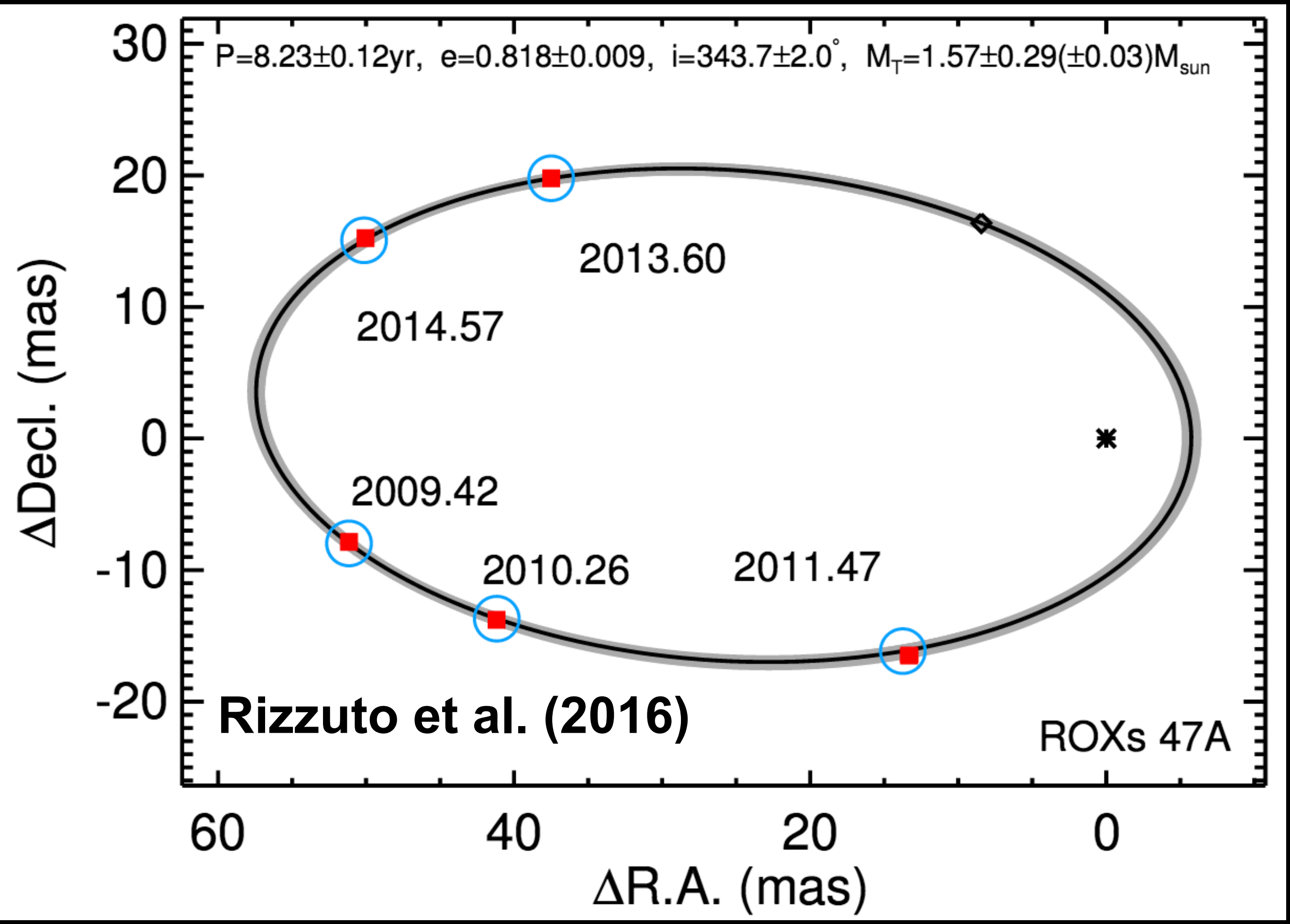
Punchlines from Disk Existence

1. Many young binary systems host disks; for those wider than solar-system scales (50 AU), binarity might not even matter
2. On solar-system scales, disks still exist, but ~2/3 of close binaries do not host disks even when almost all singles and wide binaries do
3. This pattern is established early; even the youngest populations (<1 Myr) have a low disk frequency among close binaries

Open question: Why do ~1/3 of disks survive?

Part 2: Dynamical Signatures of Disk/Binary Interactions

Disks Survive in Extreme Binaries



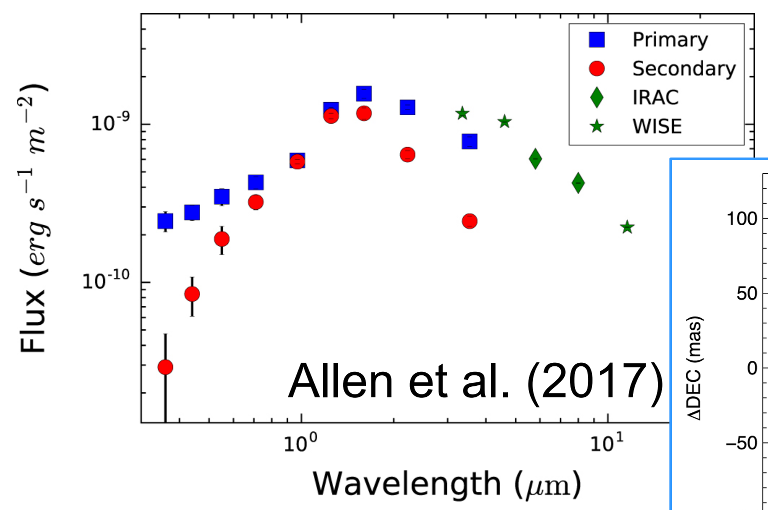
ROXs 47 Aab

a=5 AU
e=0.82
R_{peri} ~ 1 AU

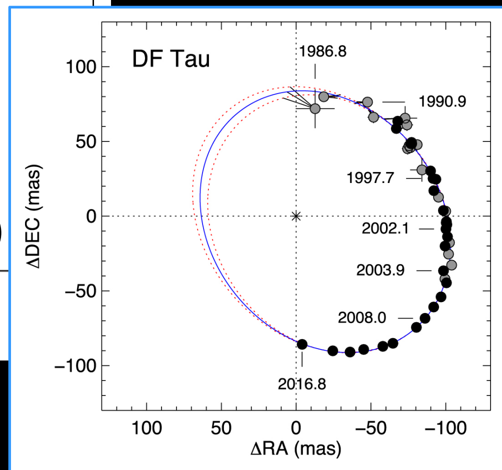
Orbit is very eccentric, and yet the disk has survived (so far). Why?

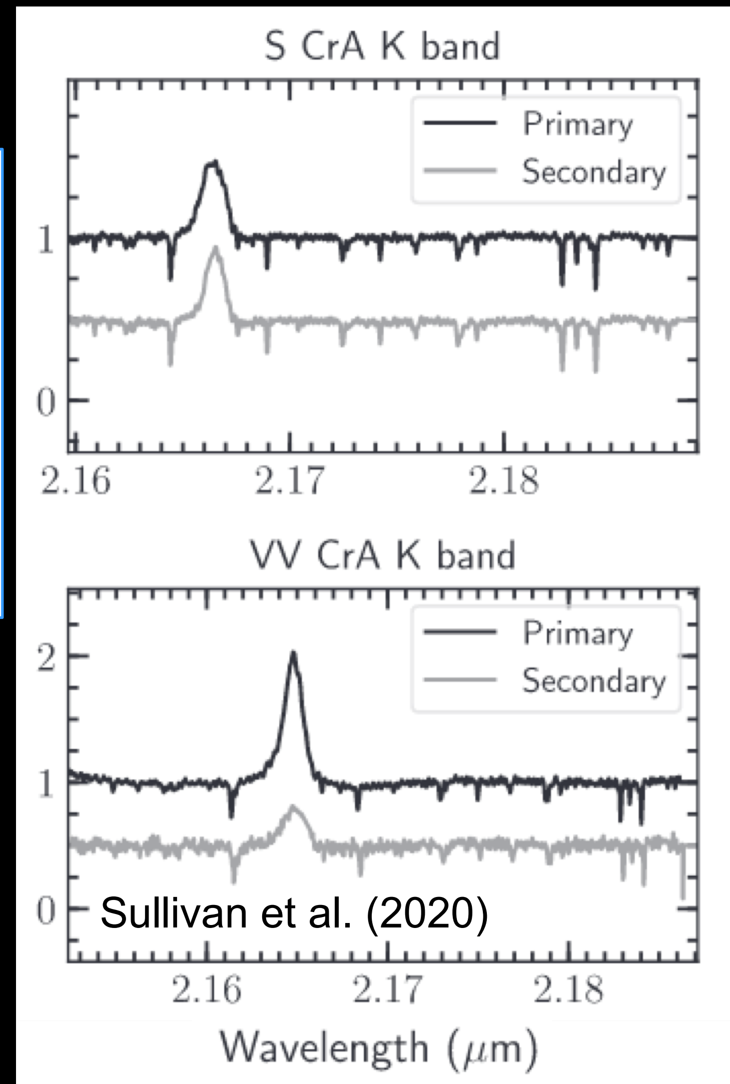
Many more orbits coming or recently arrived; Schaefer et al. (2014, 2018); Rizzuto et al (2020)

Accretion & Disks for Each Star in Binaries



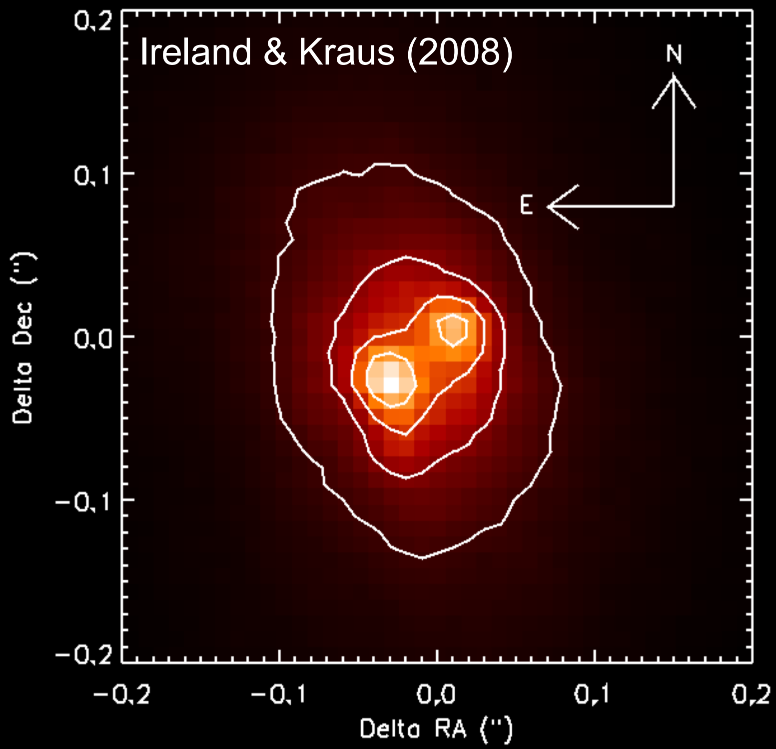
Lisa Prato can tell you more about these results on Tuesday!

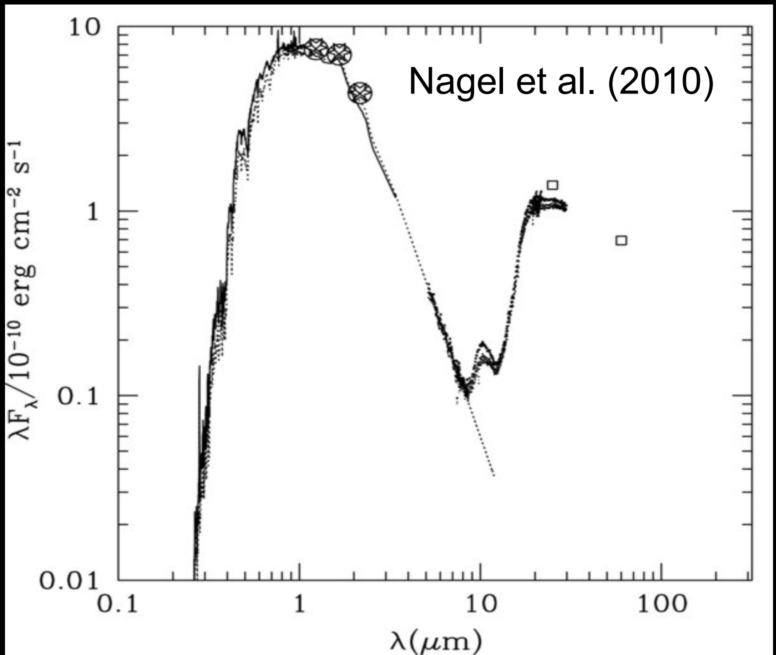




Individual SEDs and binary orbit of DF Tau AB (above), and individual K-band spectra for S CrA AB and VV CrA AB (right). Individual SEDs show that DF Tau has a disk around its primary, but apparently none around its secondary. The individual spectra reveal accretion (shown by Brackett-γ emission), indicating there are disks around both components of S CrA and VV CrA.

A unified story has not yet emerged as to why, even if there is a disk, it might be around primary, or secondary, or both. Samples are growing, though! (e.g., Akeson et al. 2019)





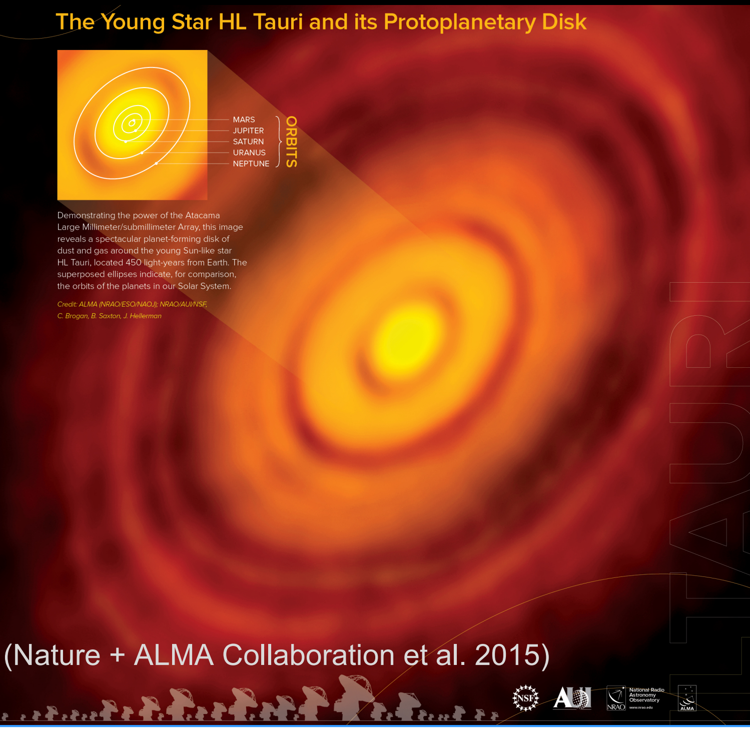
Circumbinary Disks

As first seen in the 1990s (e.g., Jensen & Mathieu 1996), disk-hosting binary systems often lack excess emission at short wavelengths, indicating an inner gap cleared in a circumbinary disk.

A more recent example is CoKu Tau/4, where modeling suggests the inner 10-15 AU of the disk have been cleared; this had been attributed to active planet formation. (Quillen et al. 2004)

It turns out that CoKu Tau/4 is an ~8 AU binary (Ireland & Kraus 2008); the disk truncation can be explained by binary tidal truncation (e.g., Nagel et al. 2010).

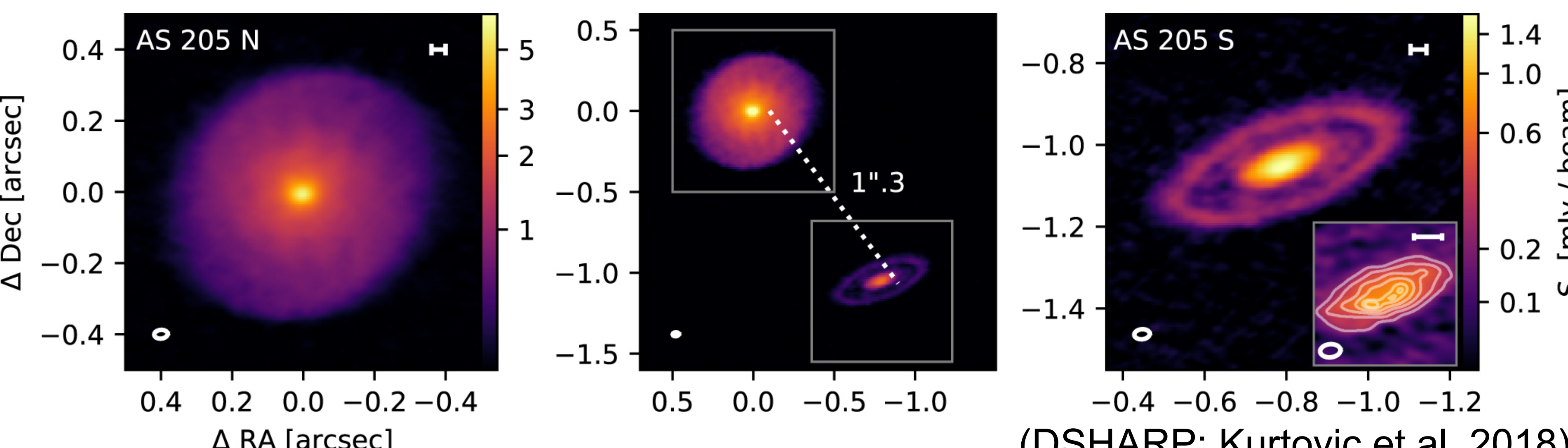
Disks & Binaries at Millimeter Wavelengths



(Nature + ALMA Collaboration et al. 2015)

With first the SMA and later ALMA, disks can now be directly imaged in the emission from their dust and gas. These observations yield masses, orientations, and a detailed view of their structure.

HL Tau started a revolution, and now there is a flood of results (such as from the DSHARP survey).



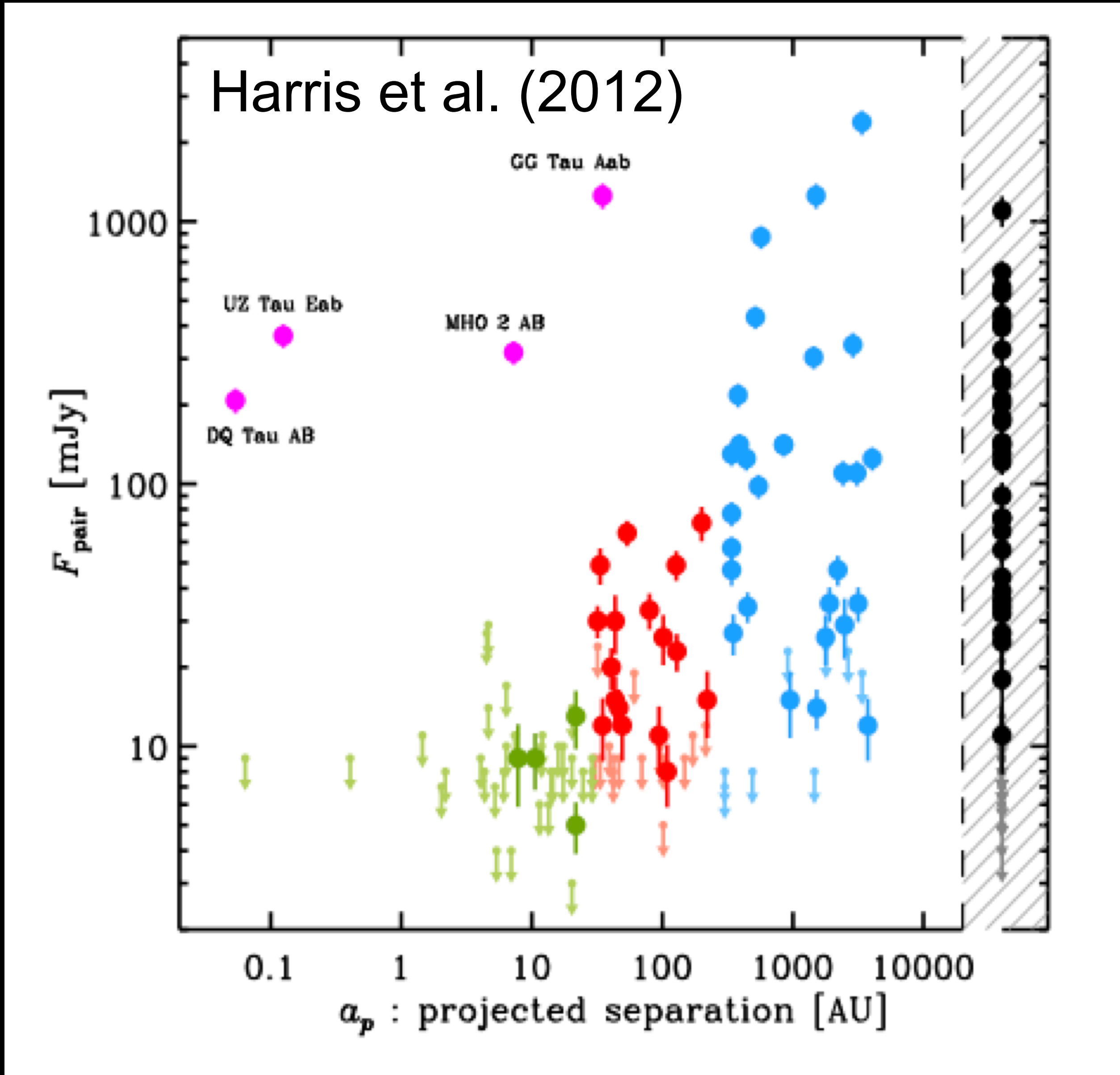
(DSHARP; Kurtovic et al. 2018)

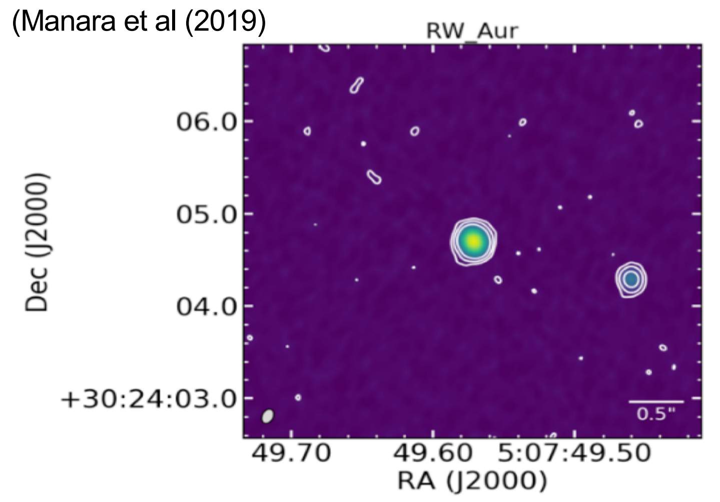
Disk Masses/Sizes in Binaries

Jensen et al. (1997) and later Harris et al. (2012) measured the submm flux (a proxy for disk mass) as a function of binary separation.

Compared to single stars and wide binaries, even 40-400 AU binaries have disk fluxes suppressed by a factor of 5, while 4-40 AU binaries are suppressed by another factor of 5.

Maybe disk mass varies with semimajor axis?

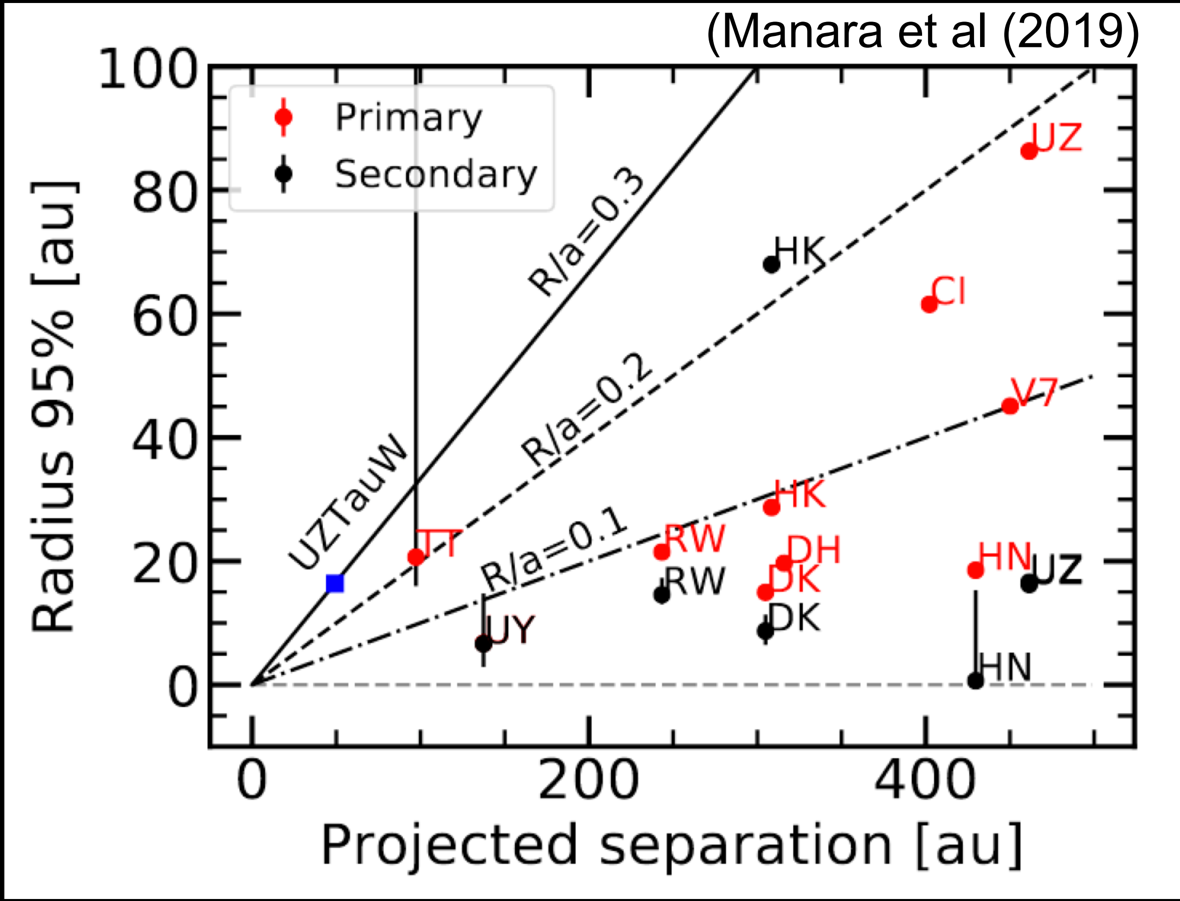




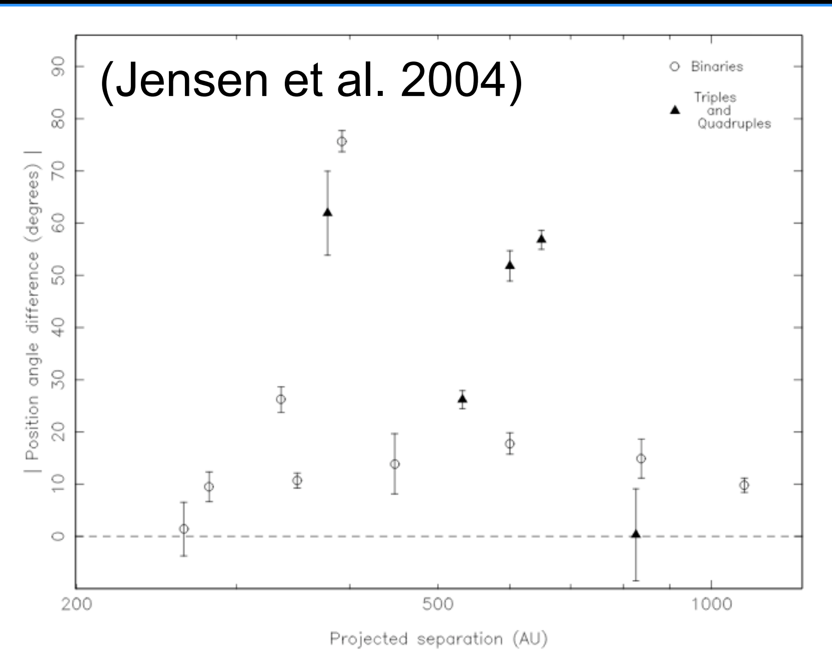
Or Possibly Disk Truncation + Inward Migration of Solids

Manara et al. (2019) resolved disks in binaries with ALMA, and they're typically smaller than the truncation radius. Maybe fluxes are low because they're small + optically thick?

Consistent with surveys of older regions (Barenfeld et al. 2019), where the connection between disk flux and binary separation disappears, perhaps because the solids migrated inward and made all dust disks small.



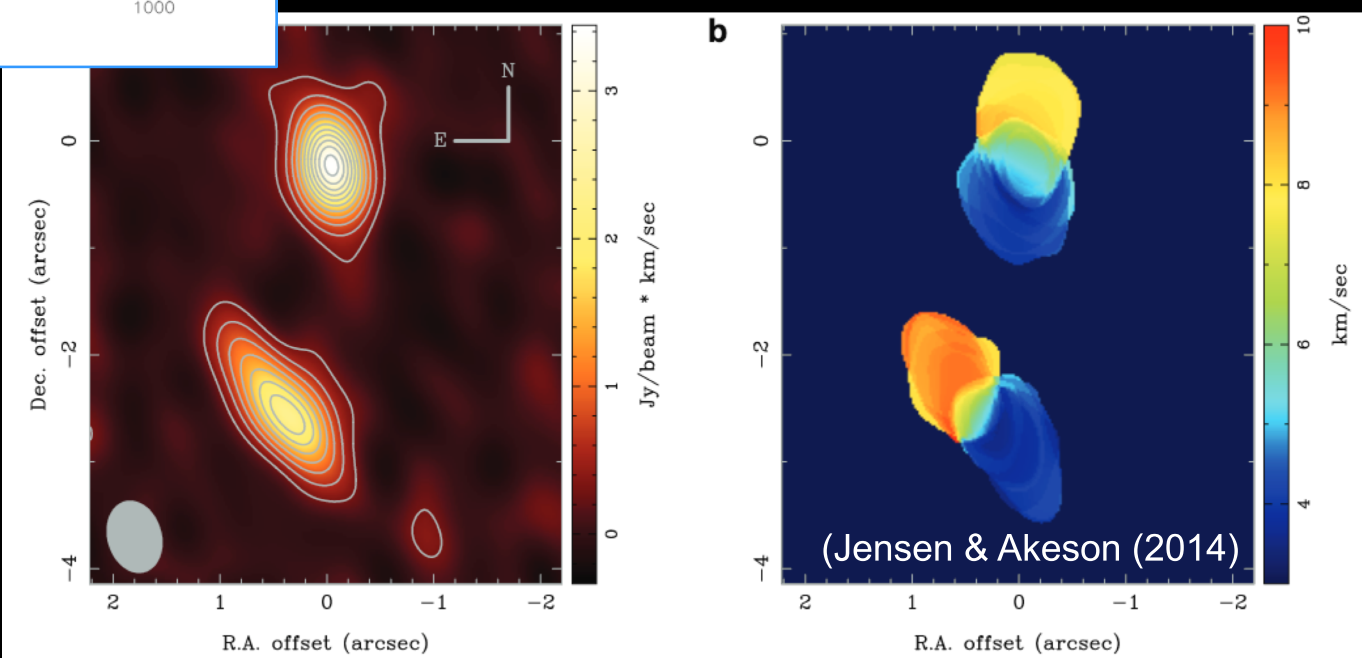
Disk Alignment in Wide Binaries



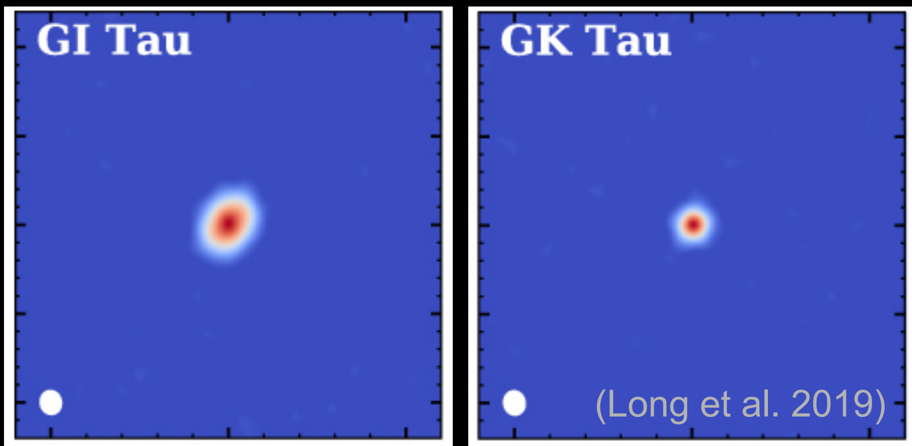
How dynamically active is the binary + planet formation process? Do the stars move around, scatter off each other, etc?

The degree of such interactions, reflected in randomization of spin or orbit vectors, might tell us why some disks survived.

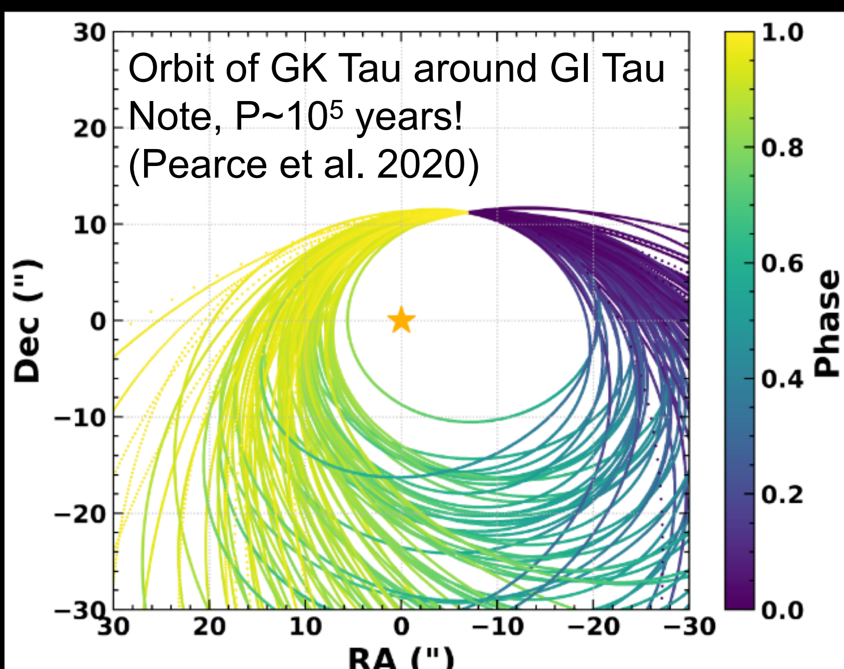
This said, wider binaries (1000s to 1000s of AU) appear to have some scatter in the orientations between the two disks. Often agree within ~10-20 degrees, but not zero.

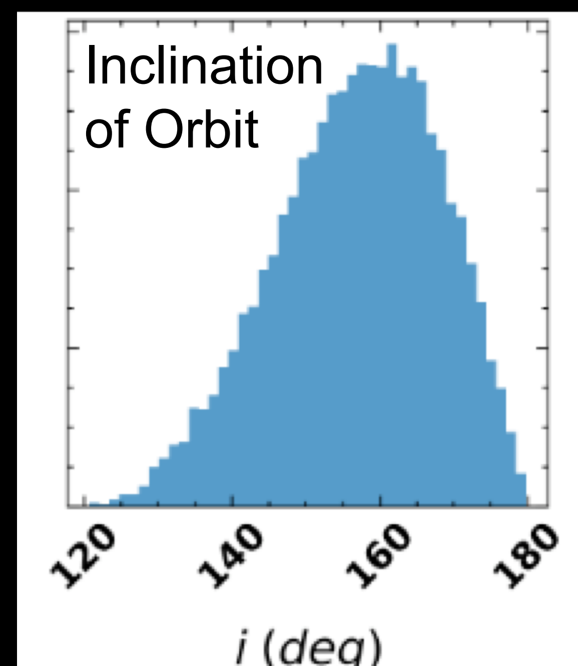


Disk-Orbit Alignment

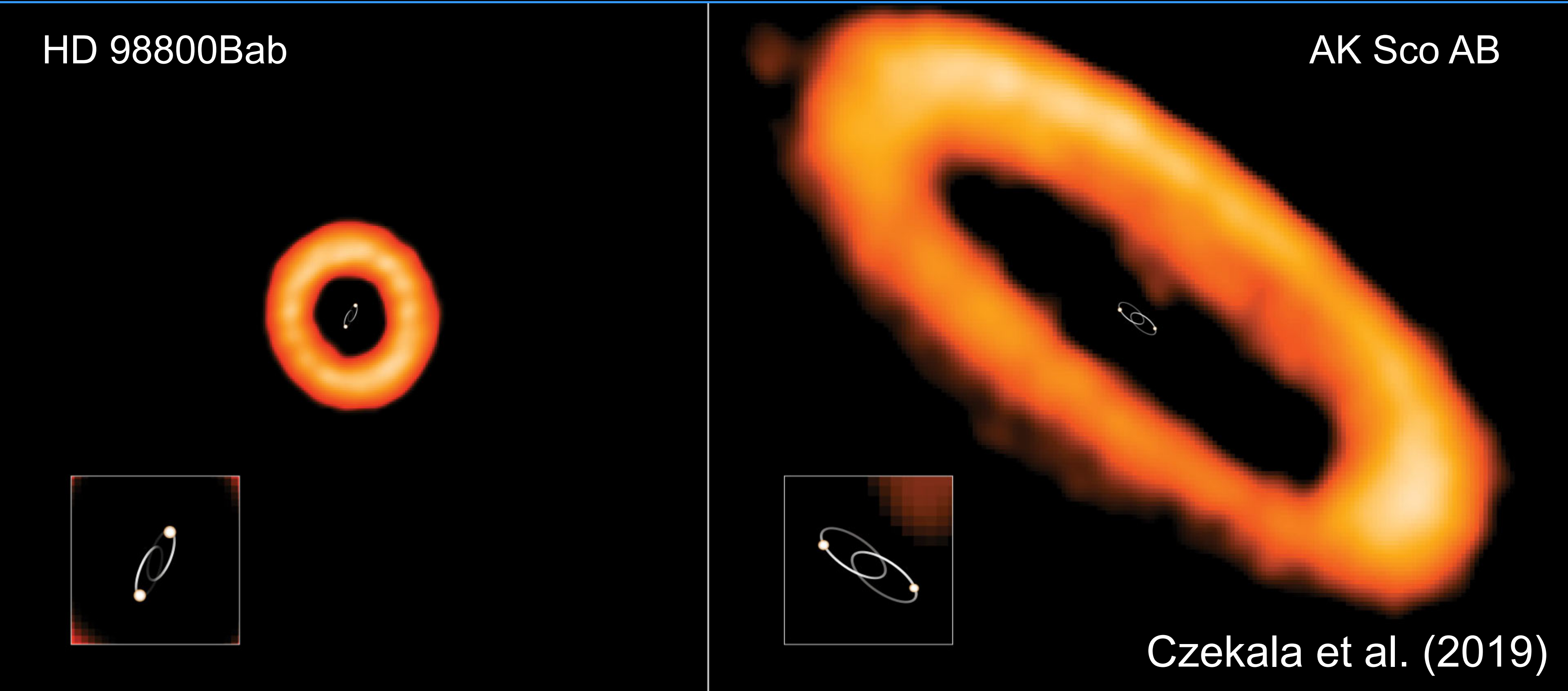


Long et al. (2019) found disk inclinations of ~140 deg. The orbit's orientation is consistent with the orientations of both disks, suggesting this may have been a pretty calm system so far.





Circumbinary Disk Gaps & Alignment



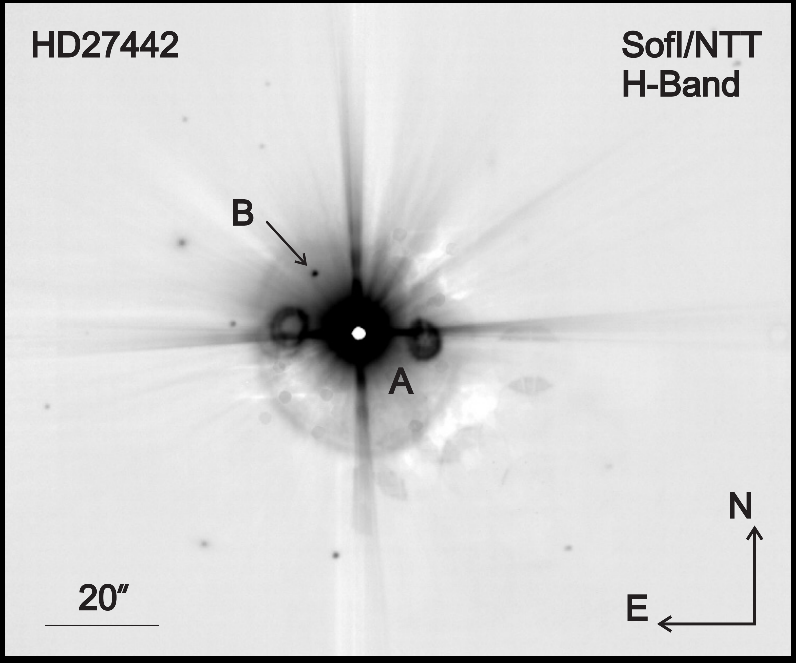
For circumbinary disks around the short-period binaries (P < 1 month), alignment seems to be common (as for AK Sco). For wider orbits, the disk orientation becomes less correlated, with even some polar configurations seen (as for HD 98800B). This might be consistent with what's seen for Kepler's circumbinary planets. (Czekala et al. 2019)

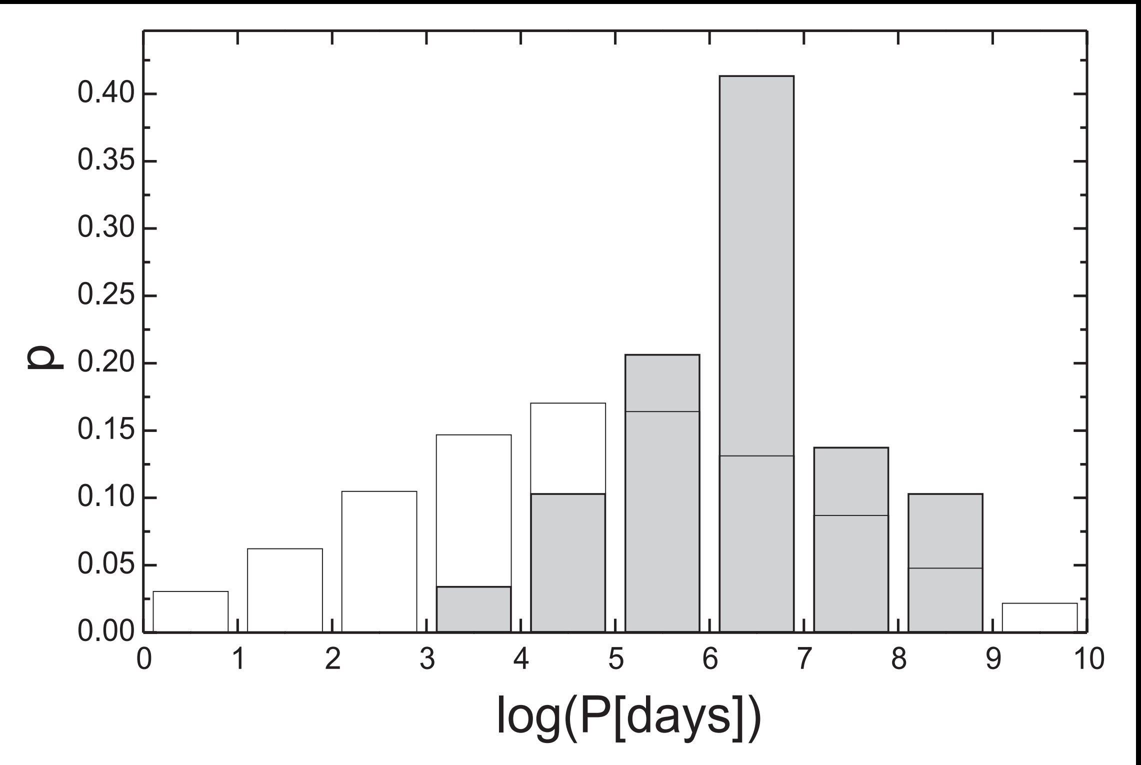
Punchlines from Disk Properties

- Binaries sculpt disks in observable ways, carving openings both internal (circumbinary gaps) and external (truncation)
- Disks survive in extreme configurations, such as very high eccentricity
- Alignment certainly isn’t universal, but tests at solar-system scales have been challenging

Part 4: Final Boundary Condition: Planets in Binary Systems

Imaging for Wide Binaries Among RV Planet Hosts





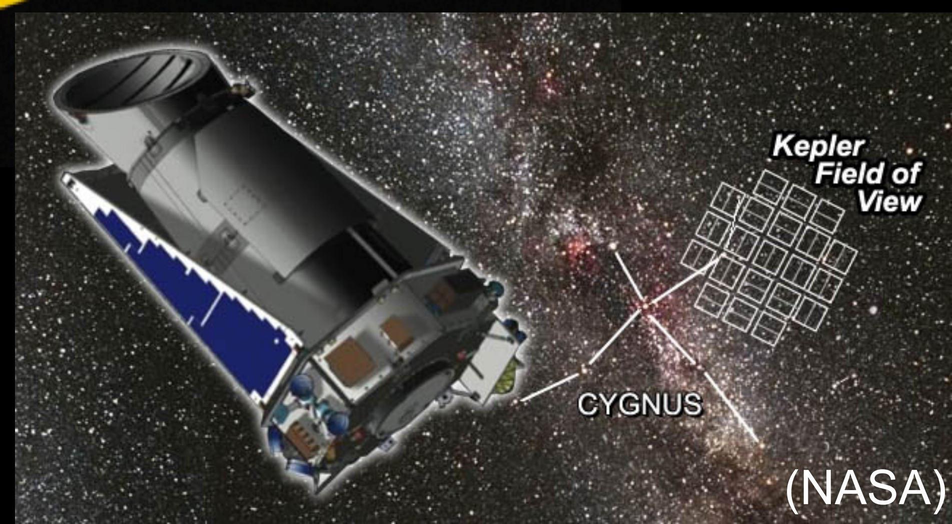
Magrauer et al. (2007) showed that RV planets might have a shortage of close binary companions, but there’s a heavy selection bias in planet discovery that could be affecting the results. Also see Desidera & Barbieri (2009) and Duchene (2010).

Binarity in the Kepler Sample

Some nearby binaries do host planets (e.g. Gamma Cep). Most searches are forced to anti-select against close binaries though.

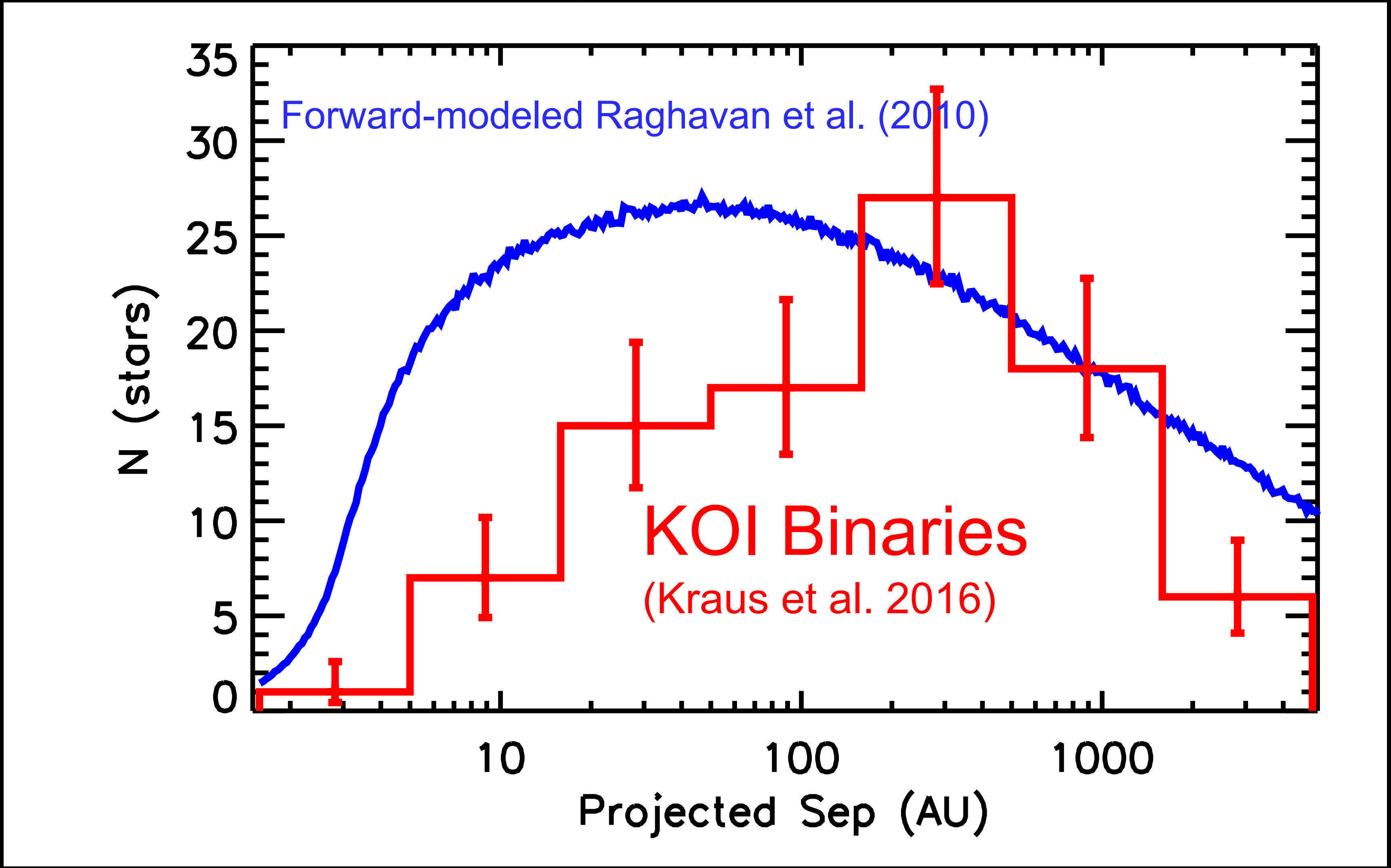
(https://en.wikipedia.org/wiki/File:Astronomical_Transit.gif)

Due to low spatial resolution, Kepler is (mostly) indifferent to multiplicity status – though we can discuss caveats.



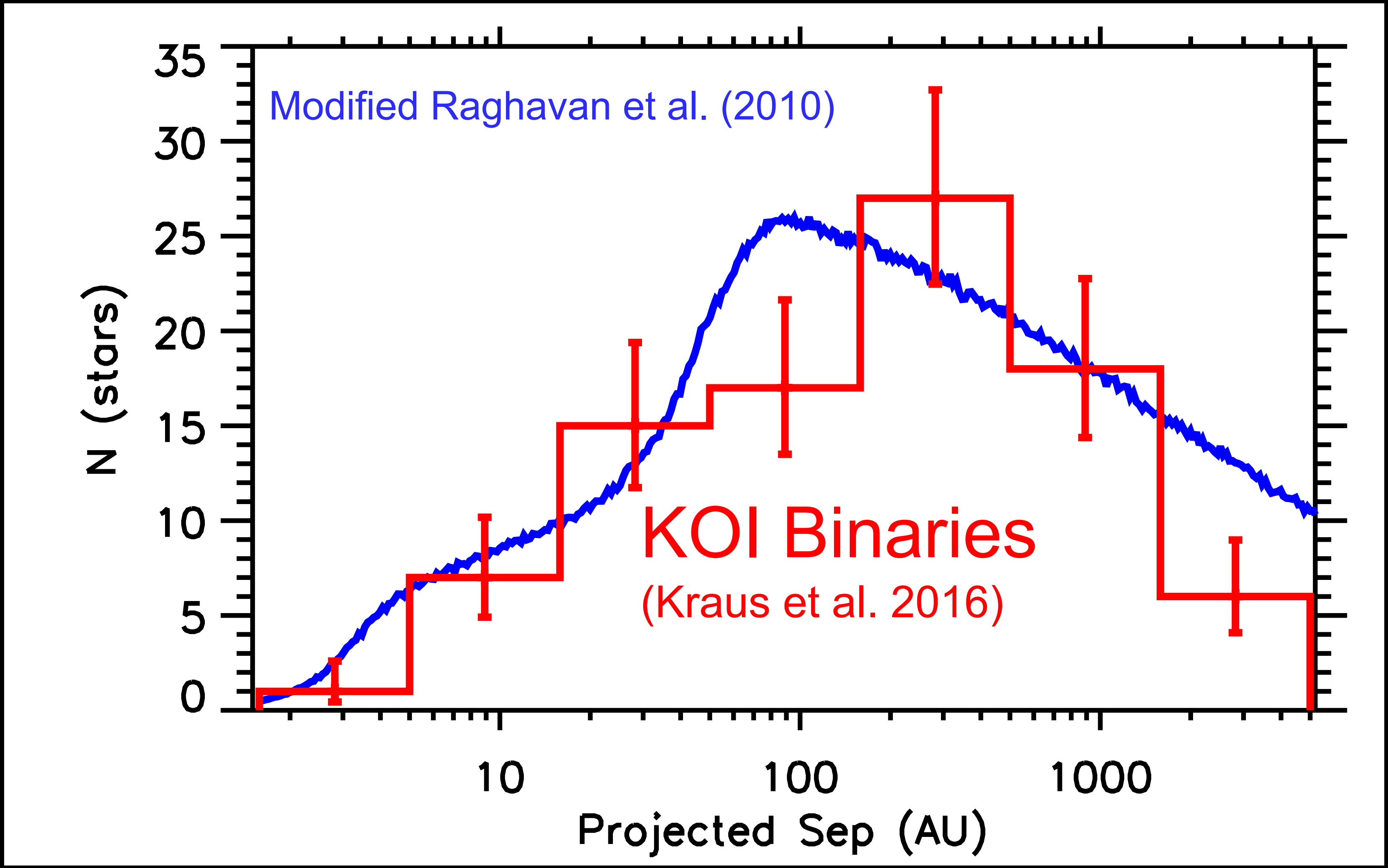
(NASA)

Planet Demographics in Binaries



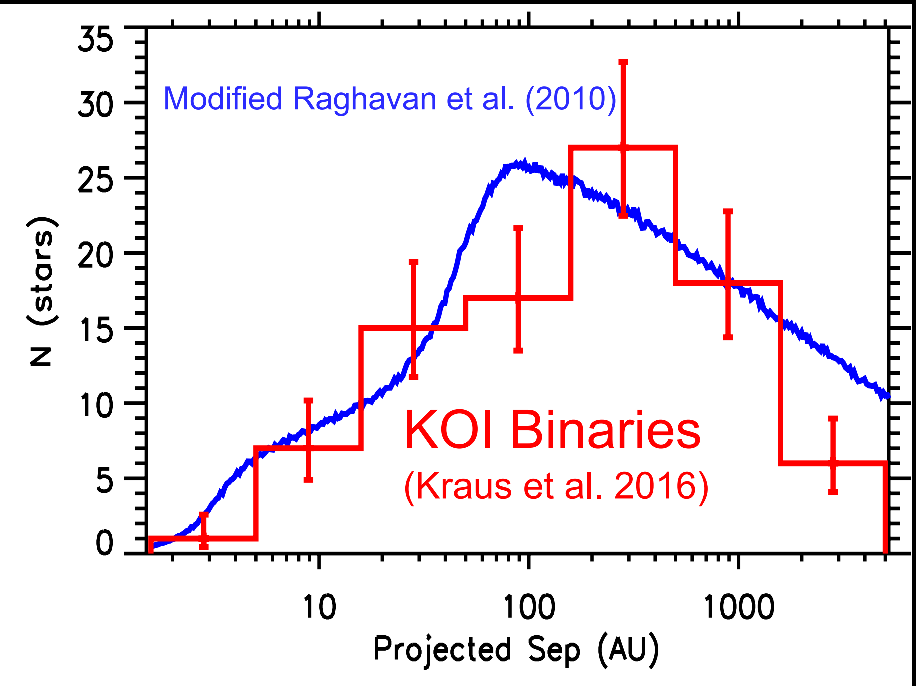
Red = Observed, Blue = Simulation of known binary occurrence rate with Malmquist bias + detection limits included

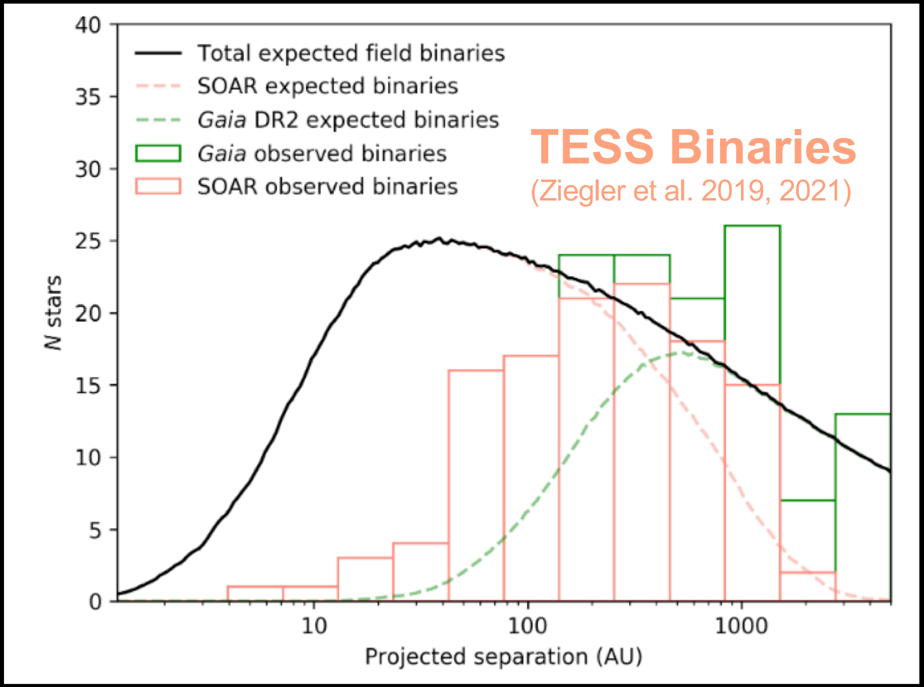
Planets are Suppressed in Close Binaries



Model: Suppress close binaries inside a < 50 AU by a suppression factor of 2/3.

Wider Binaries Look Like Single Stars

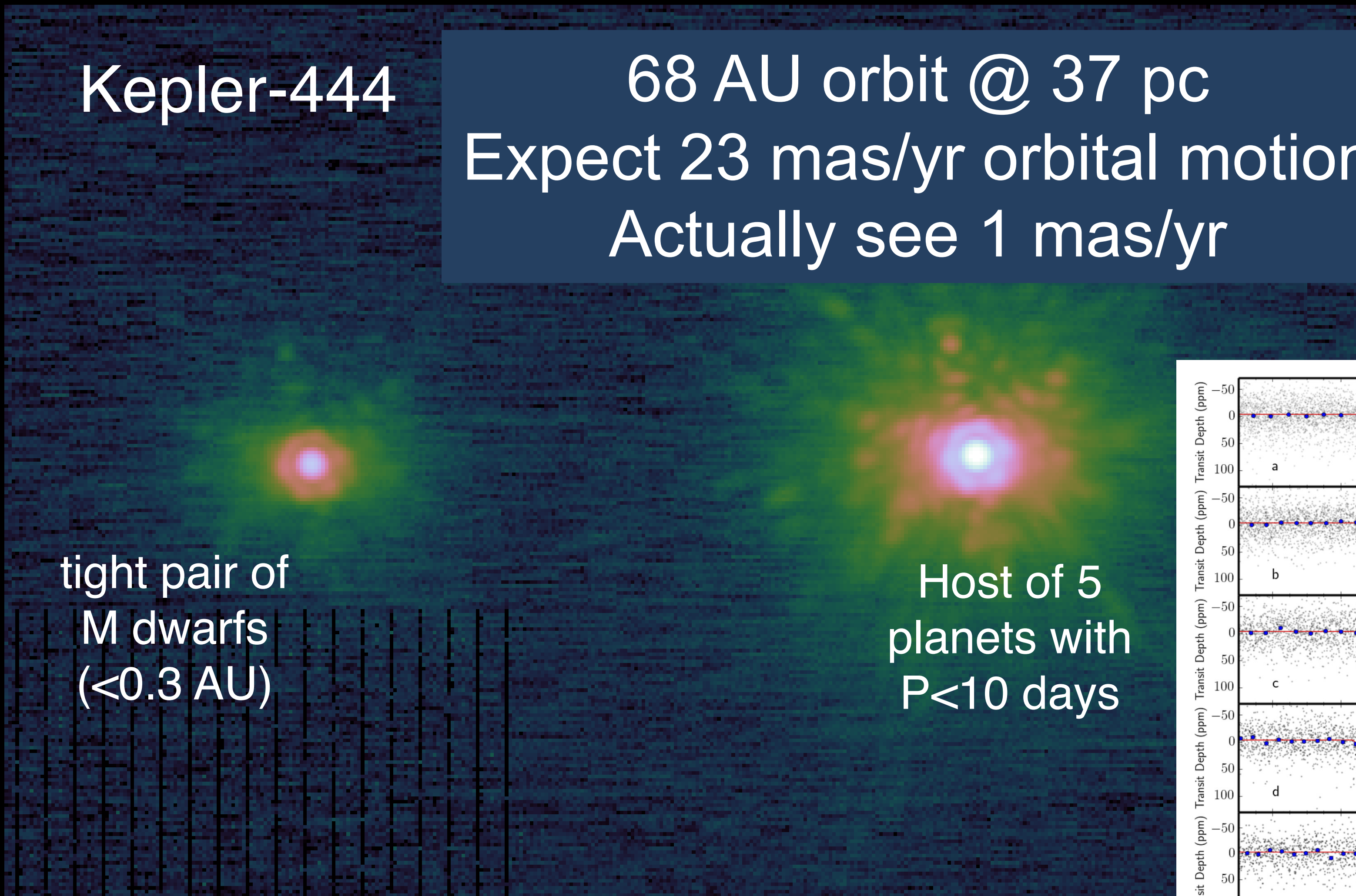




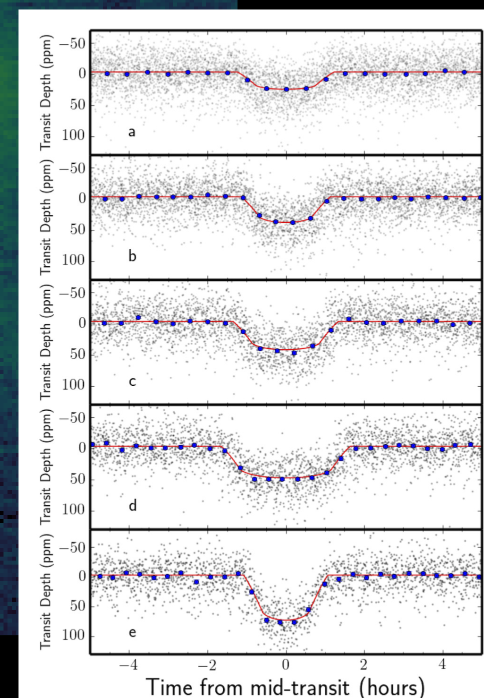
Now common to observe candidate planet hosts with high-resolution imaging to screen for identify binaries, in case they might cause spurious signals (Ziegler et al. 2017, 2021; Furlan et al. 2017). These are supporting sample sizes in the thousands at moderate spatial resolution and in the hundreds at the highest spatial resolution.

Now multiply confirmed the deficit of planets in close binaries, but also finding that the planets in wider binaries are indistinguishable from single stars (e.g., Lester et al. 2021).

Stars & Planets Might be Aligned



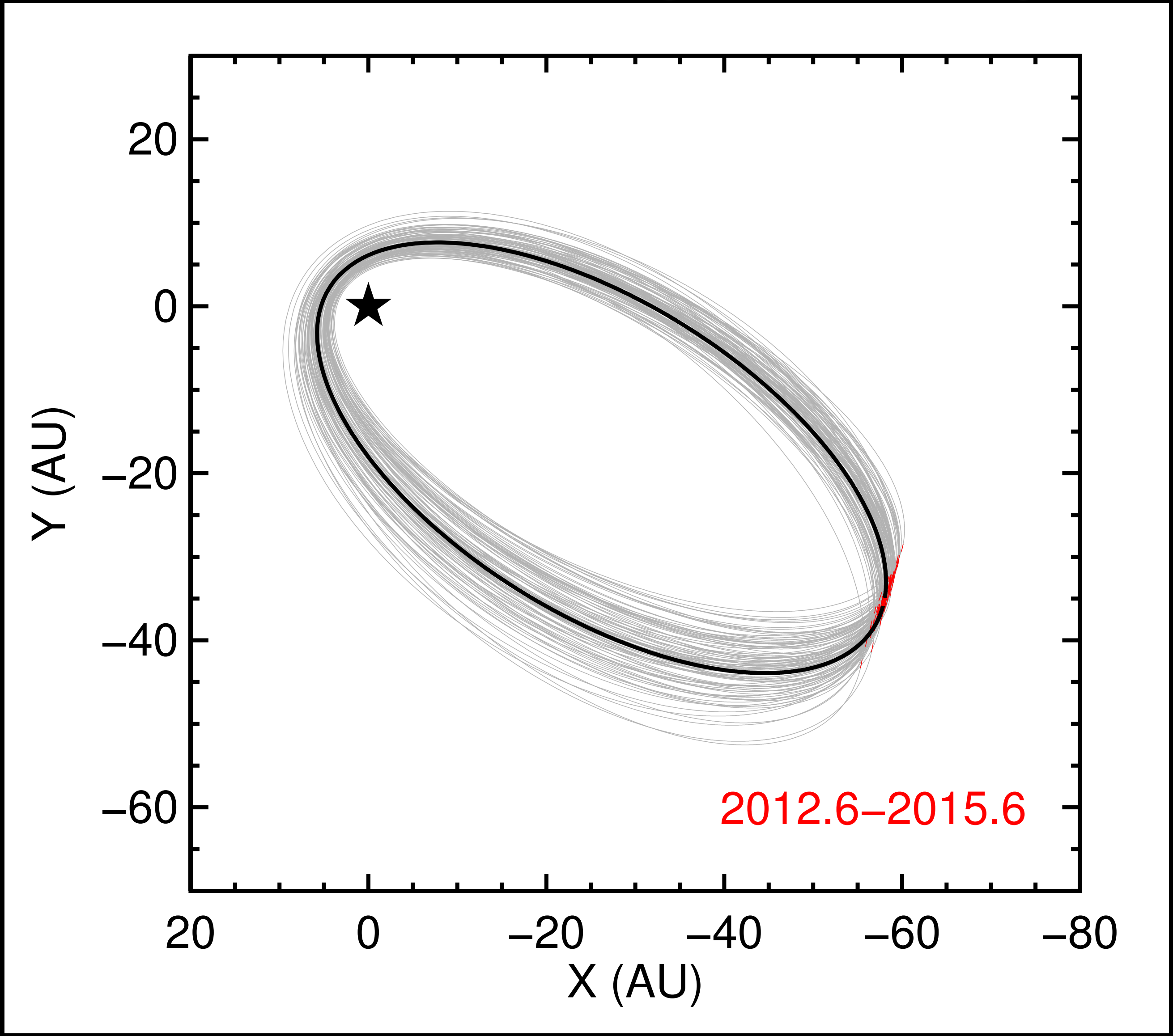
68 AU orbit @ 37 pc
Expect 23 mas/yr orbital motion
Actually see 1 mas/yr



Campante et al. (2015)

Results from Dupuy et al. (2016)

Dupuy et al. (2016)



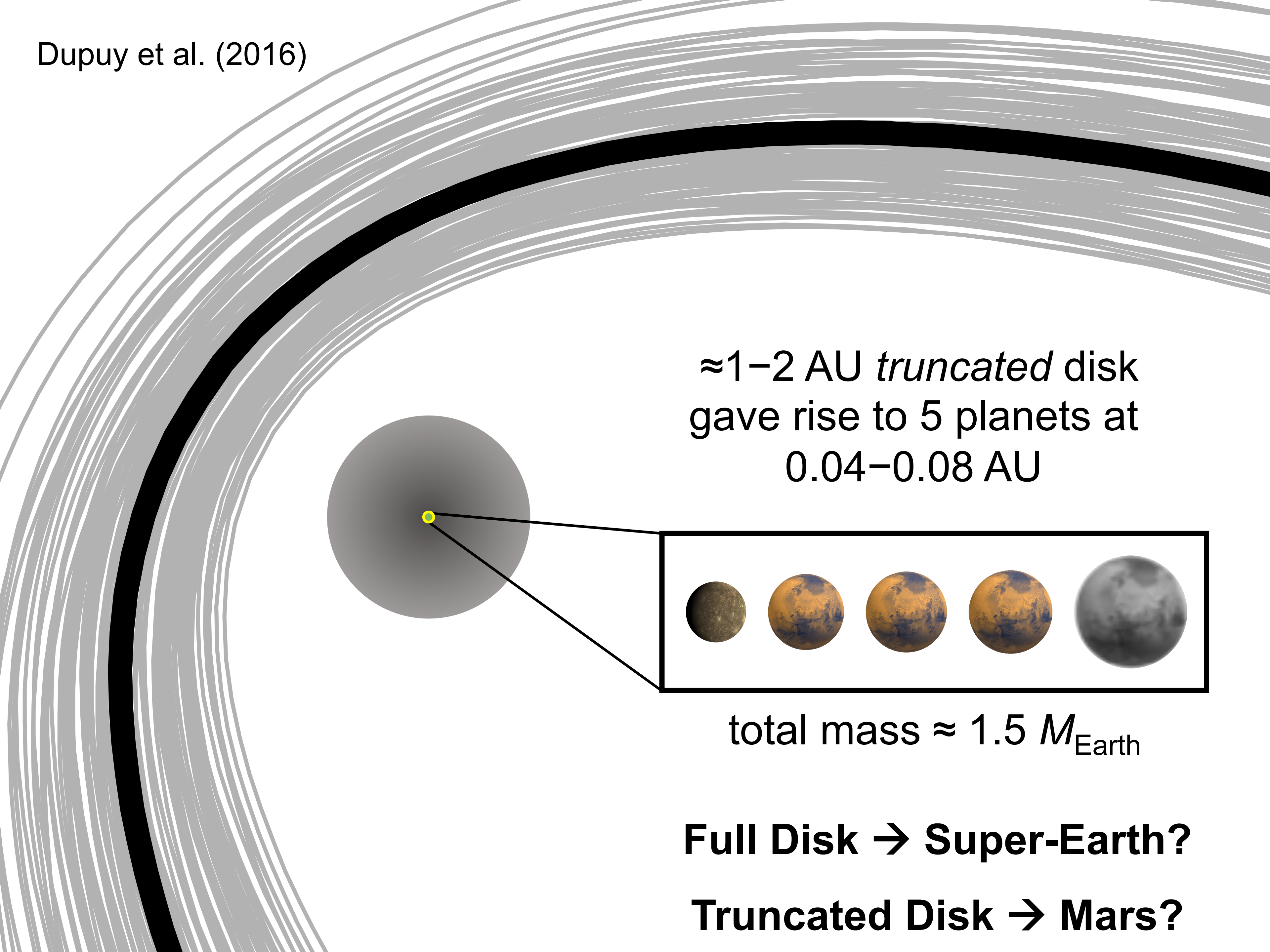
a = 36.6 ± 0.8 AU

e = 0.864 ± 0.023

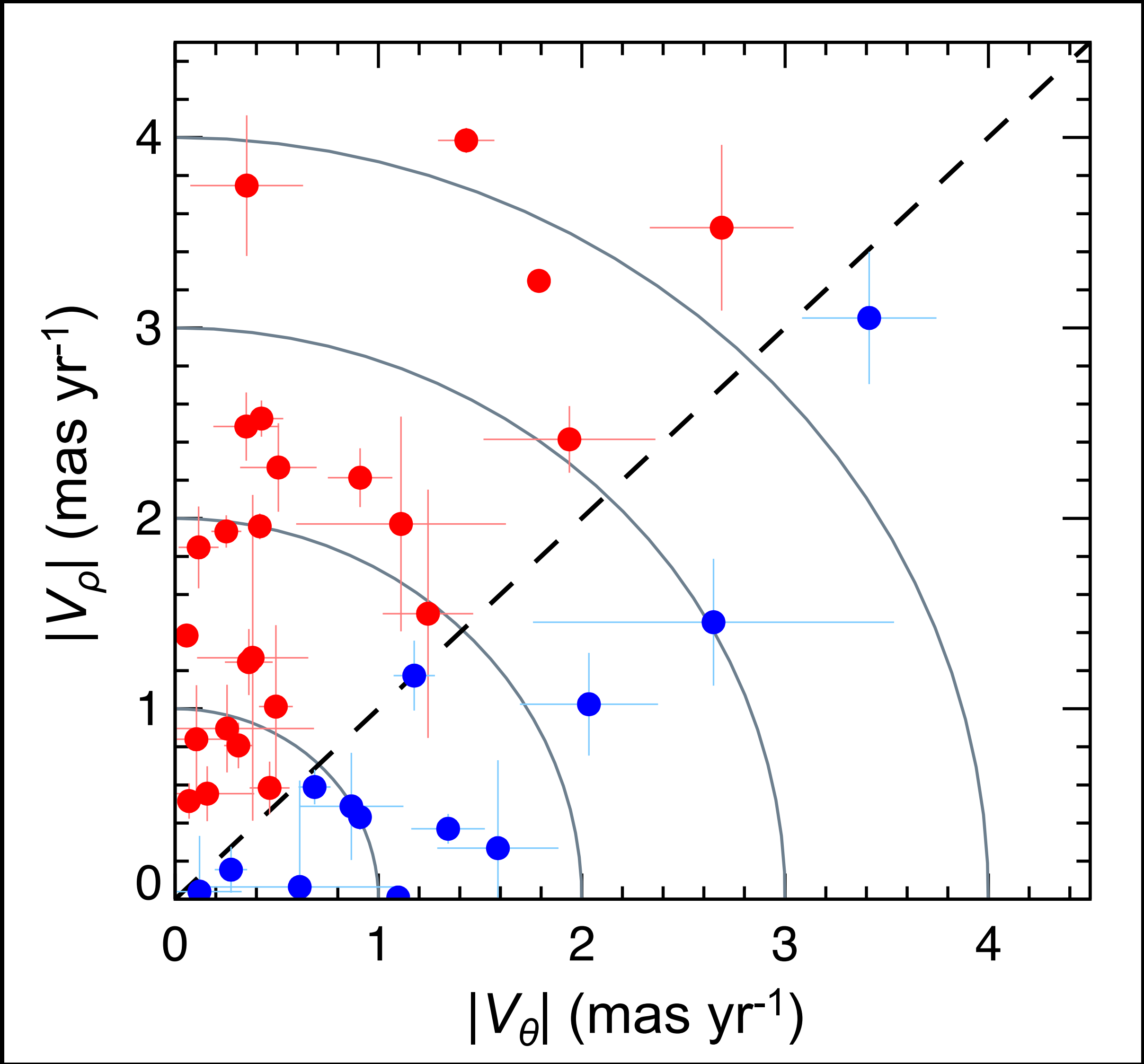
closest approach

5.0 ± 1.0 AU

How in the world (x5) do you make this?


Dupuy et al. (2016)
≈1−2 AU *truncated* disk
gave rise to 5 planets at
0.04−0.08 AU
total mass ≈ 1.5 M_{Earth}
Full Disk → Super-Earth?
Truncated Disk → Mars?

Not Always Aligned, but Frequently!



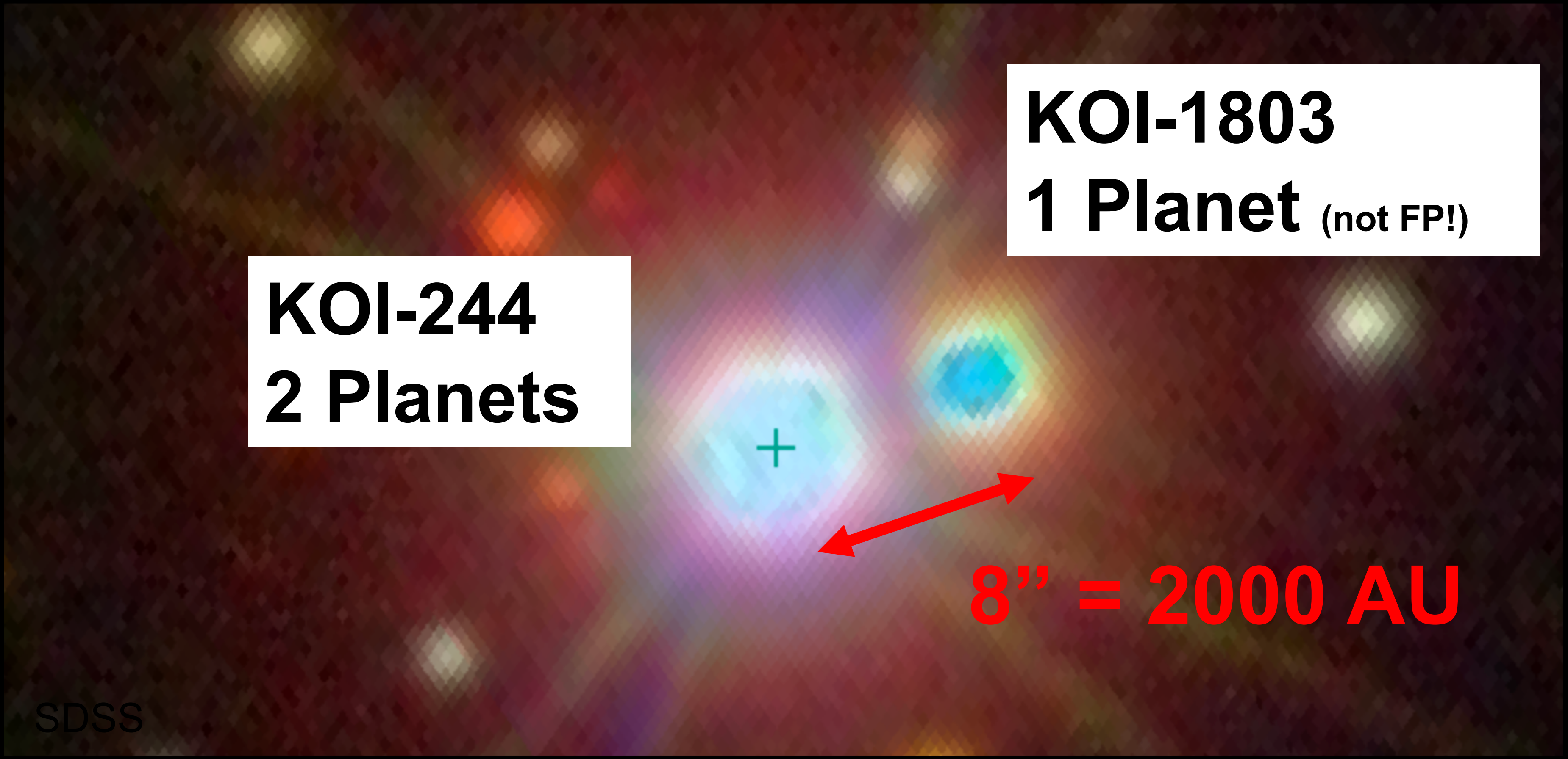
64% of sample has $V_\rho > V_\theta$

For Isotropic,
$p_{K\text{-}S} = 0.003$

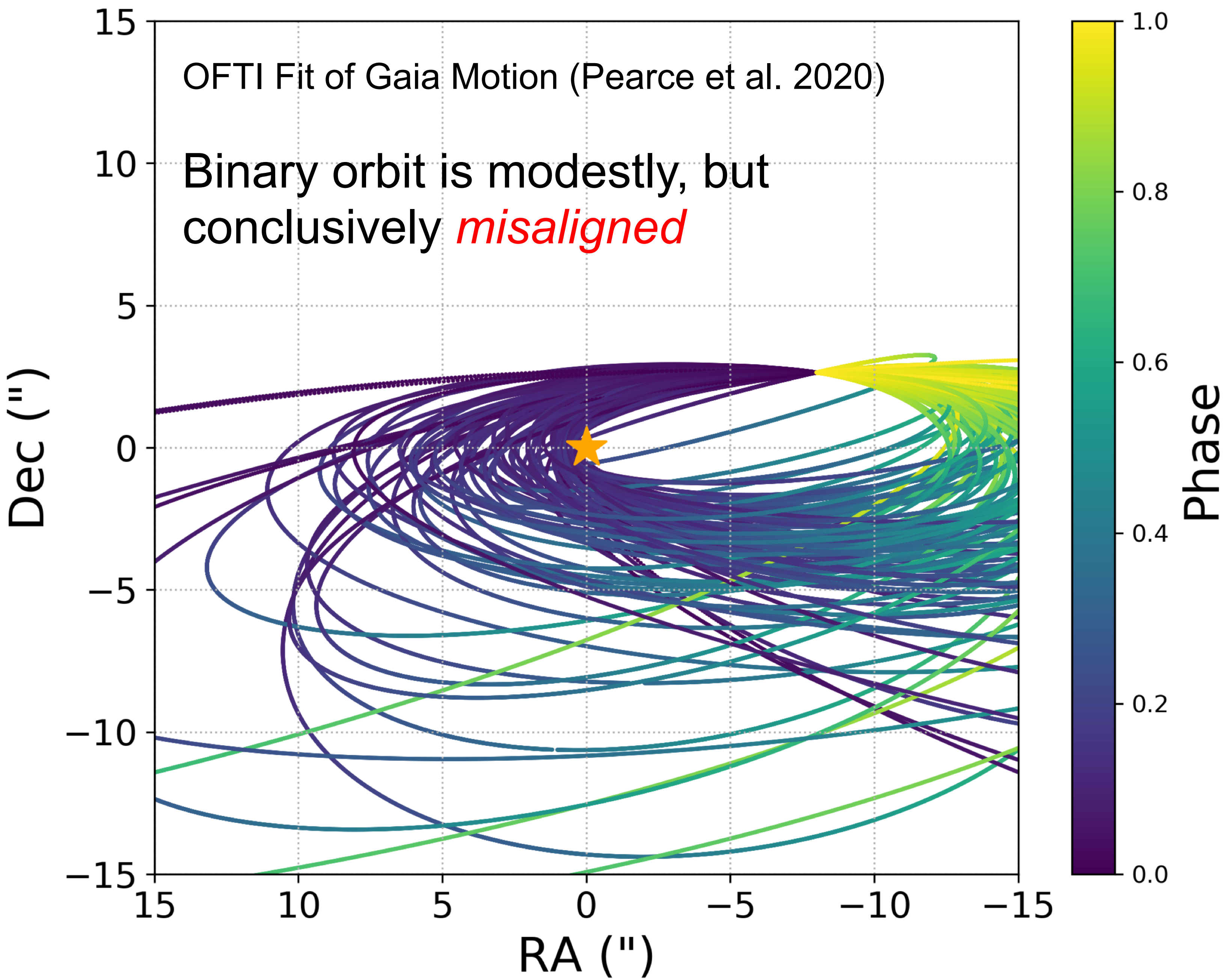
Planets + Stars are dynamically connected

(Dupuy et al. in prep)

Are Wide Binaries Aligned?



Both planetary systems are edge-on (transiting).
Is the whole system aligned? (Pearce et al. 2020)



OFTI Fit of Gaia Motion (Pearce et al. 2020)
Binary orbit is modestly, but
conclusively *misaligned*
15
10
5
0
−5
−10
−15
Dec (")
15
10
5
0
−5
−10
−15
RA (")
1.0
0.8
0.6
0.4
0.2
0.0
Phase

Punchlines from Planetary Systems

1. The “suppression” effect for planets in close binaries is a good match to the effect for disks – inside 50 AU, a factor of ~3.
2. Outside 50 AU, occurrence rates might be similar between wide binaries and singles
3. Relative-orientation distributions look similar to disk-hosting young binaries, at least thus far.
4. Planets are found even in some very eccentric binaries. Interesting opportunity to “test” the impact of disk size on planet properties?

Lessons for Planet Formation

- When there is a binary companion on solar-system scales, it suppresses planet formation by a large factor (not 100%, but >50%)
- Something like 2/3 of close binaries (i.e., 20% of all stars) fail one of these steps. This means all the planets are orbiting the other 80% of stars.
- The impact of binarity is early and fast. Disk effects are locked in by ~1 Myr, and planetary populations at 5 Gyr look similar to disk populations at 1-5 Myr.
- **Open question: What key features establish which close binaries keep their disks and form planets?**