The Herbig Ae/Be Star Opportunity: Deciphering Planet Formation Around Intermediate Mass Stars With Empirical Data

Sascha P. Quanz (ETH Zurich)

"Herbig Ae/Be stars:
The missing link in star formation"

ESO, Santiago de Chile, April 7-11, 2014

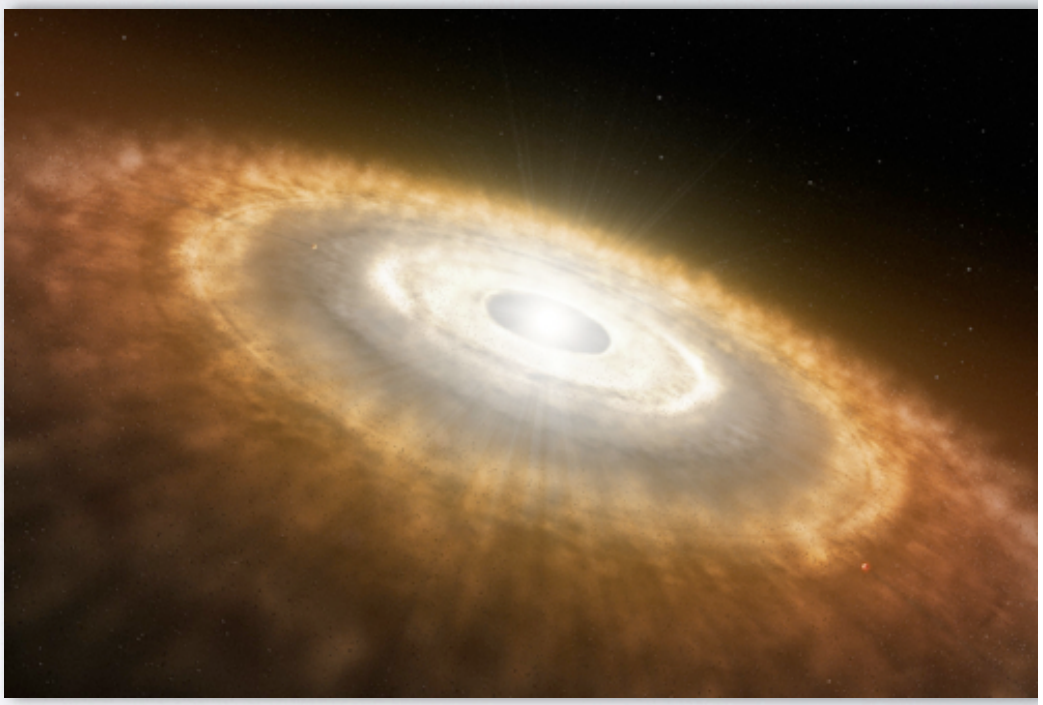

Image credit: ESO/L. Calçada

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Gas Giant

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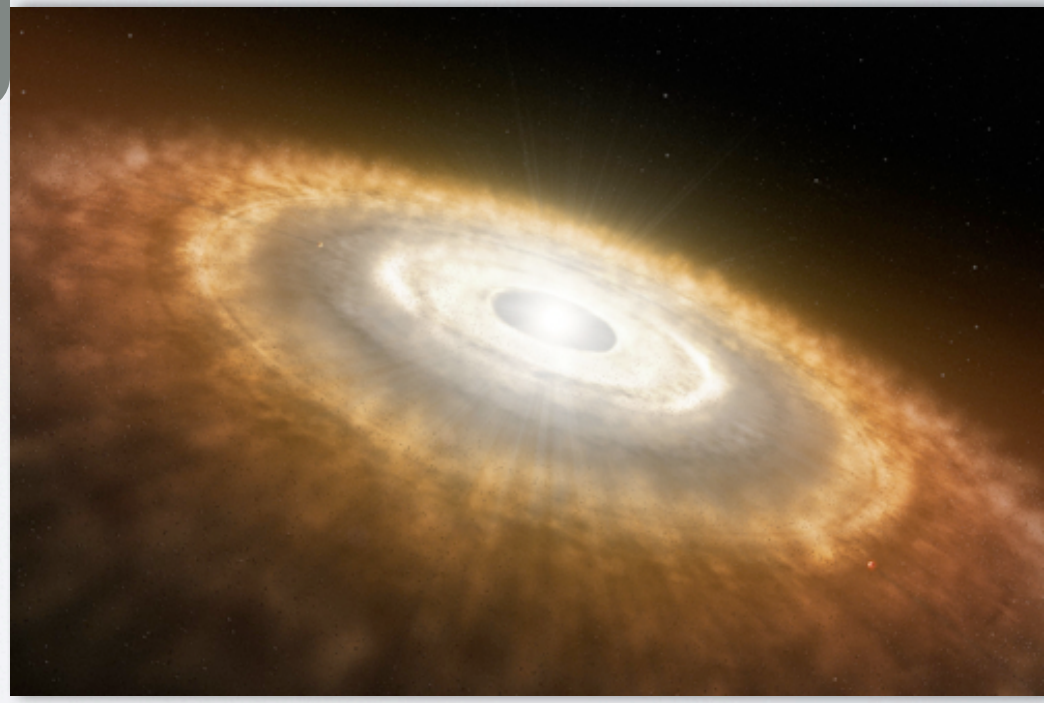


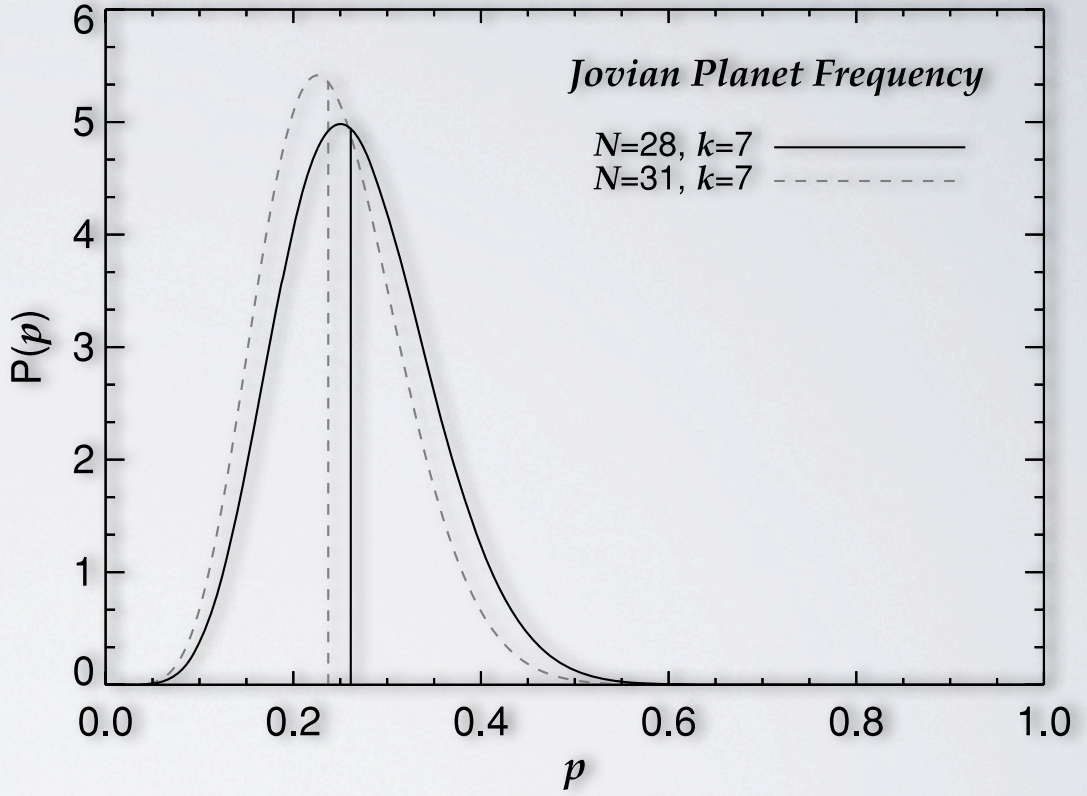
Image credit: ESO/L. Calçada

PLANETS AROUND INTERMEDIATE MASS STARS

From RV planet searches:

- Higher frequency of giant planets within 3 AU:
  $\sim 26^{+9}_{-8}$ % vs. ~10% for solar type stars

- Mass-period power-law distributions significantly different (4-sigma level) compared to solar-type stars

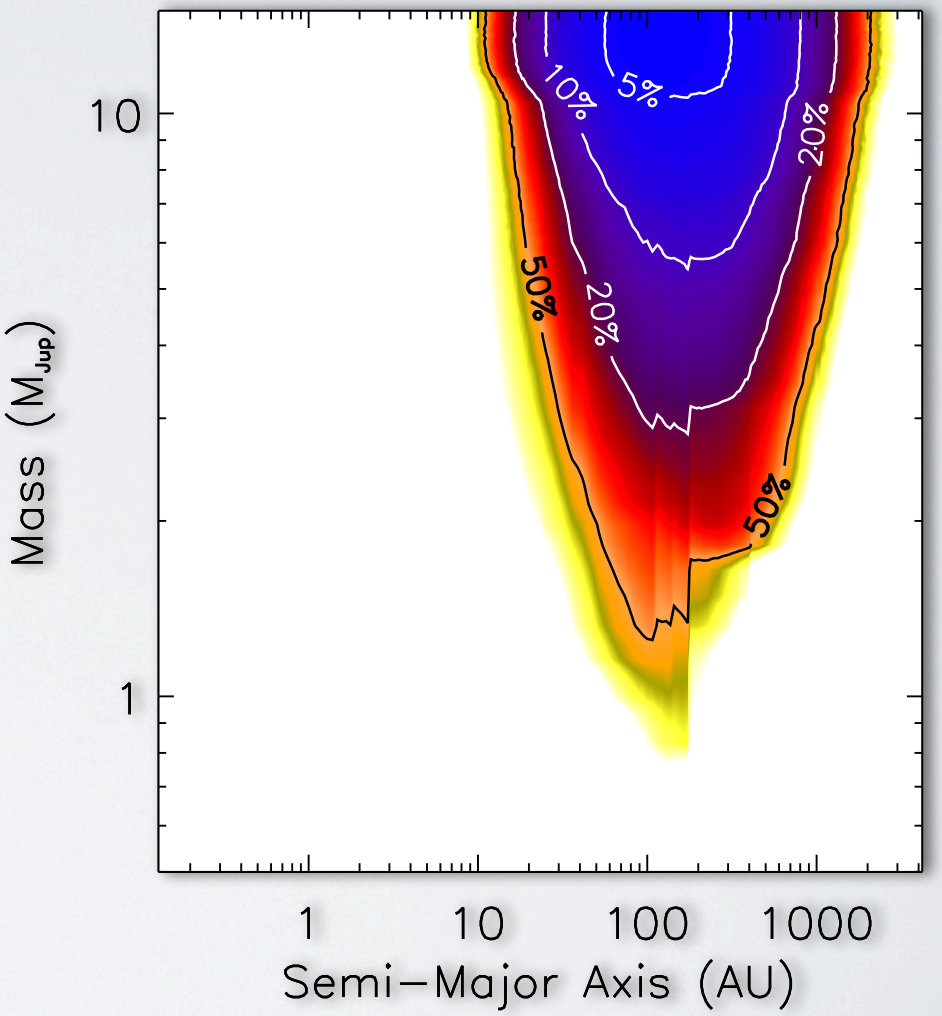


Bowler et al. 2010;
also Johnson et al. 2007a,b, 2010

PLANETS AROUND INTERMEDIATE MASS STARS

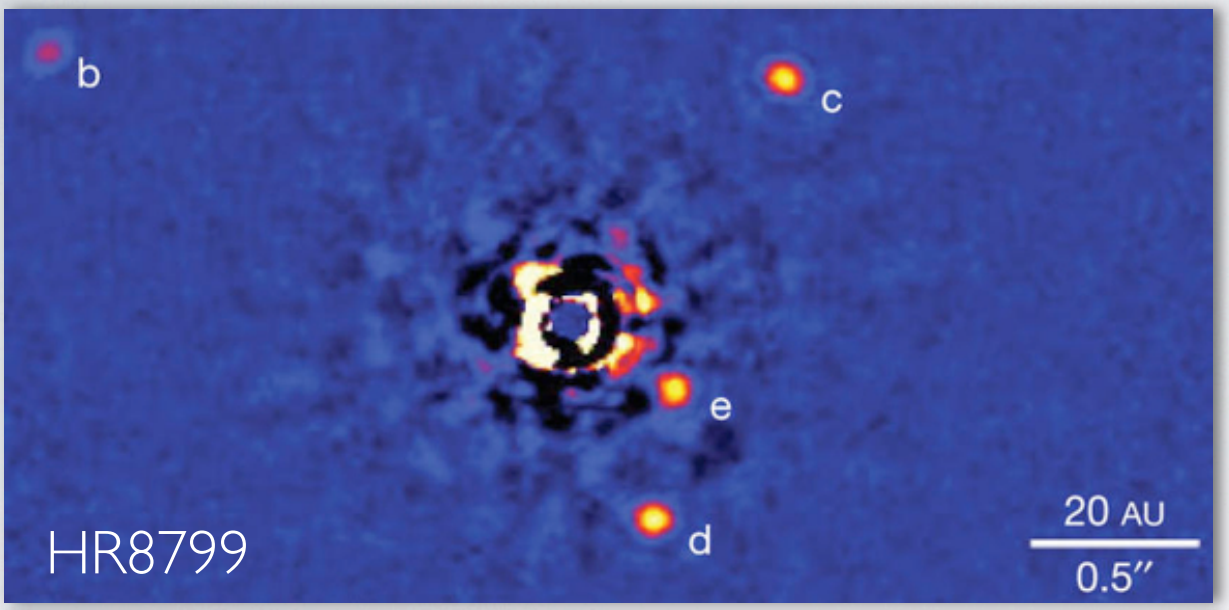
From direct imaging searches:

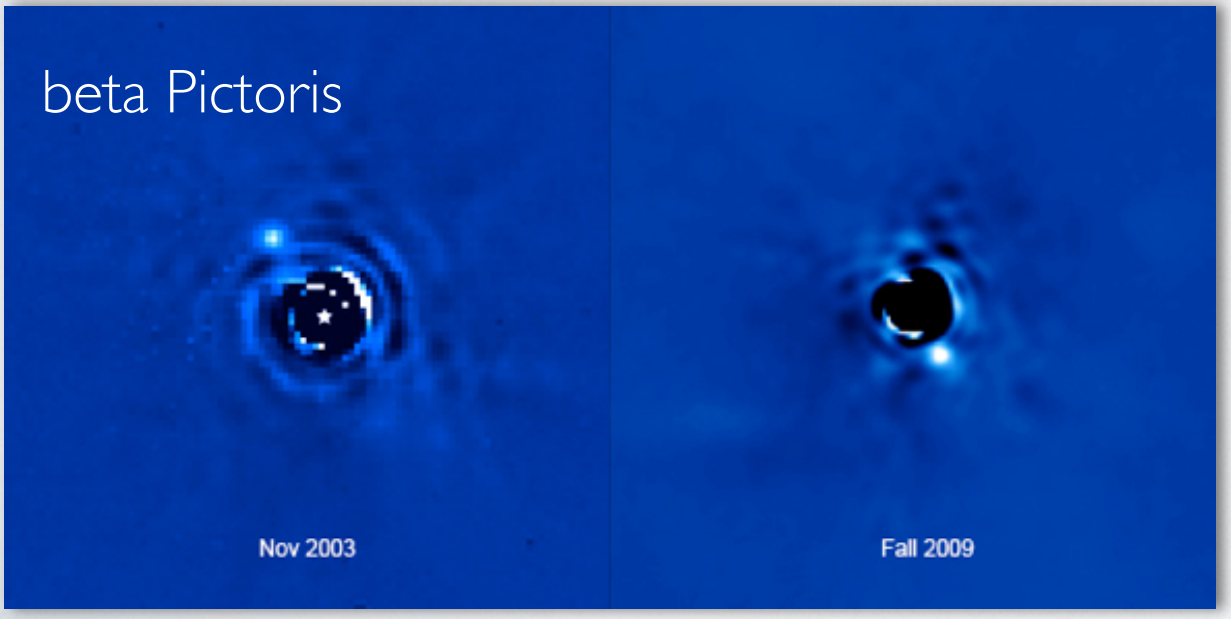
- Gas giant planets on wide orbits are rare
- <20% of 2-M_{Sun} stars have companions >4 $M_{Jupiter}$ in between 59 and 460 AU (95% confidence)



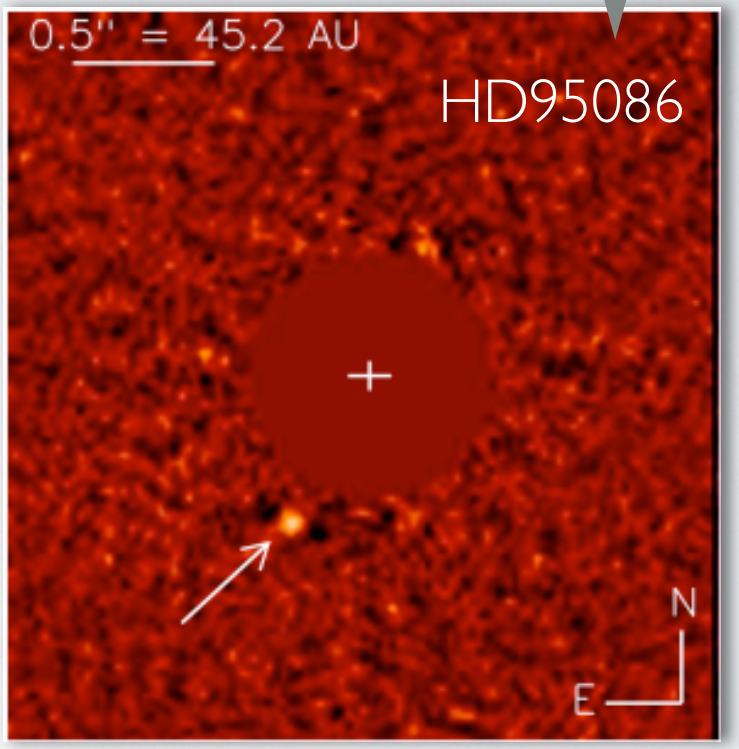
Nielsen et al. 2013;
also, e.g., Vigan et al. 2012; Rameau et al 2013; Janson et al. 2011

PLANETS AROUND INTERMEDIATE MASS STARS



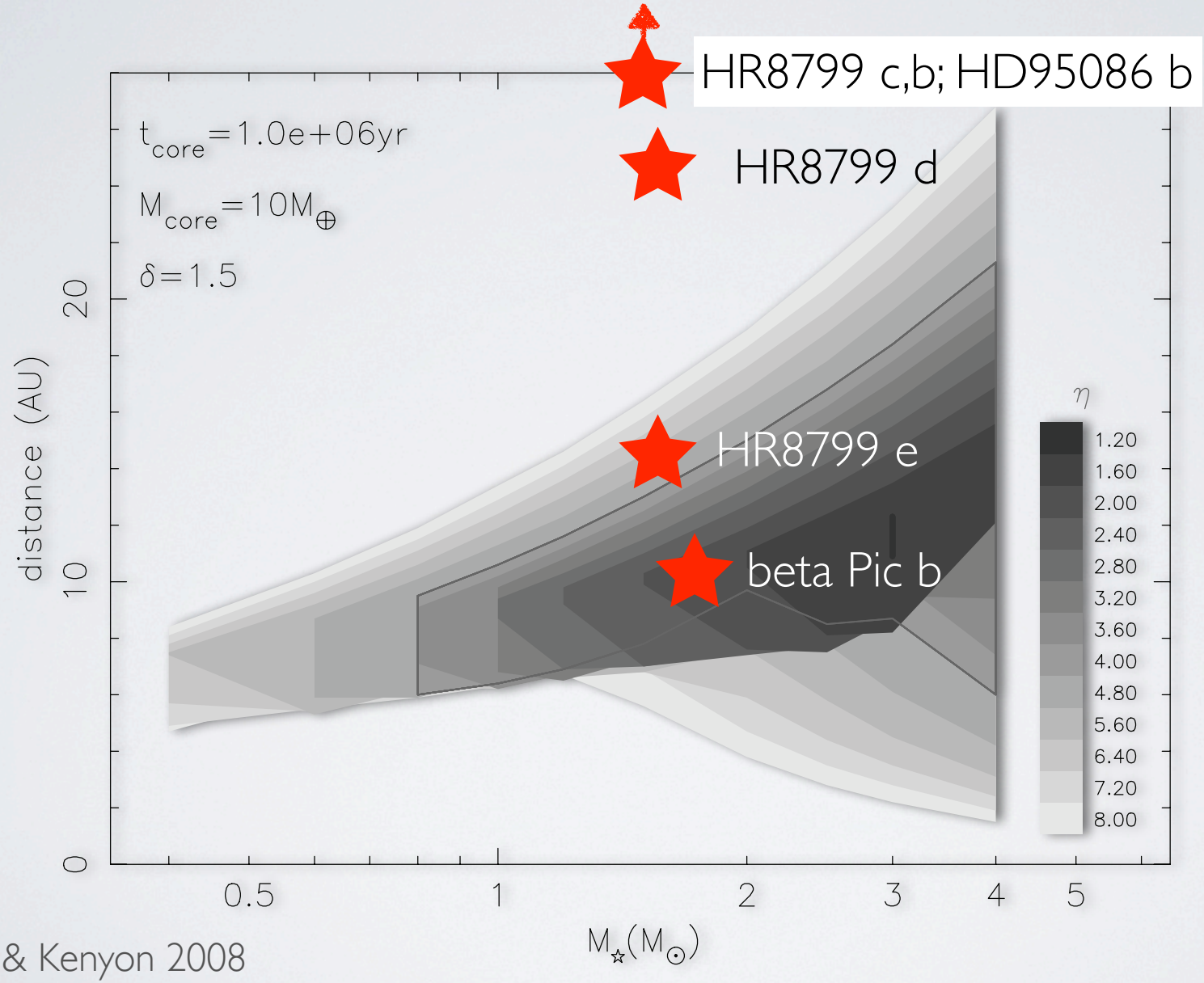


See poster by Agnes Kospal



Marois et al, 2008, 2010; Lagrange et al. 2010; Rameau et al. 2013

PLANET FORMATION AROUND INTERMEDIATE MASS STARS

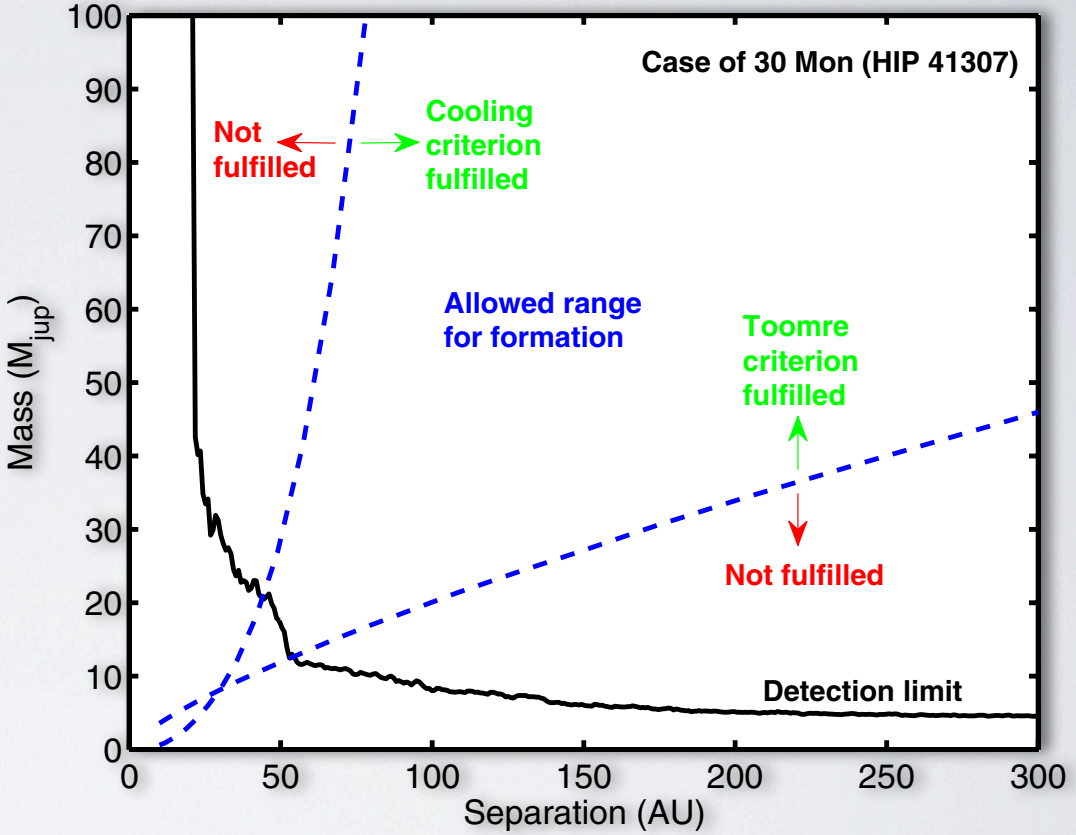


Kennedy & Kenyon 2008
(also, e.g., Ida & Lin 2004)

PLANET FORMATION AROUND INTERMEDIATE MASS STARS

Combing direct imaging surveys with planet formation models:

- Gravitational instability GI most likely not the main formation mechanism for gas giant planets
- <30% of stars retain low-mass companions from GI within 300 AU (99% confidence)



Janson et al. 2012
also Kratter et al. 2010 for HR8799 planets

PLANET FORMATION AROUND INTERMEDIATE MASS STARS

Gravitational instability

Core accretion

Pebble accretion (Lambrechts & Johansen 2012; Ormel & Klahr 2010)

PLANET FORMATION AROUND INTERMEDIATE MASS STARS

Let's get some observational data! Let's image disk regions where gas giant planets might form!

POLARIMETRIC DIFFERENTIAL IMAGING (PDI): BASICS

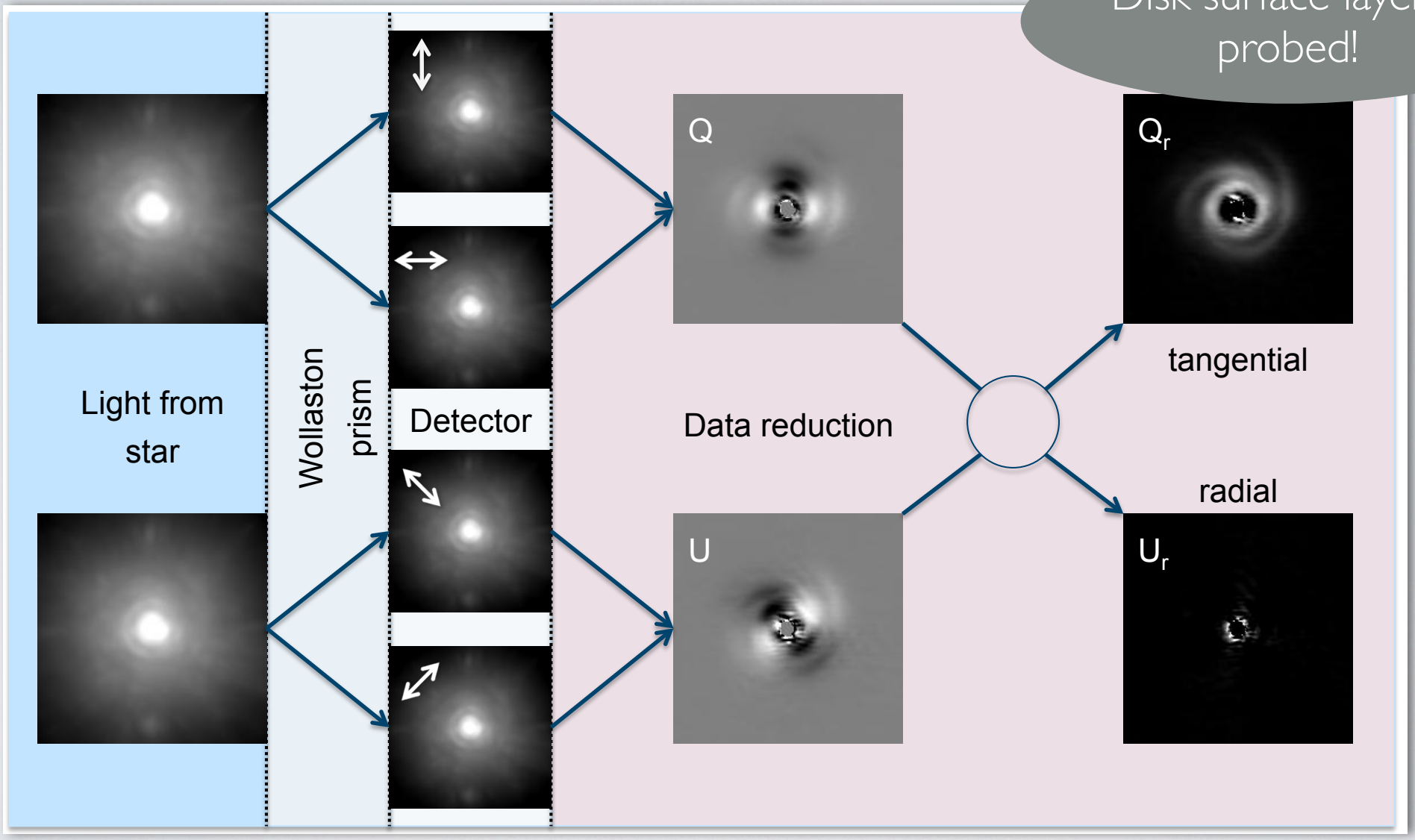
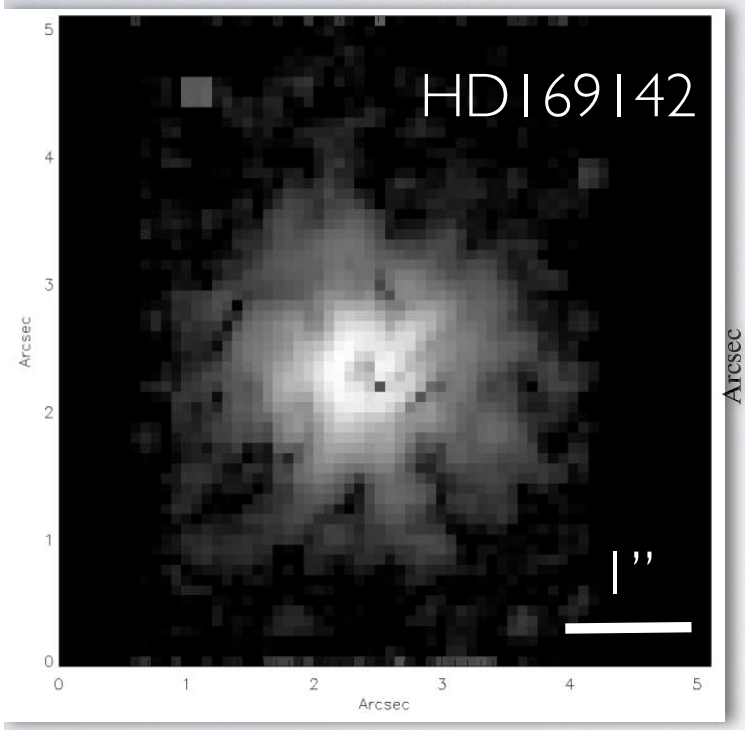
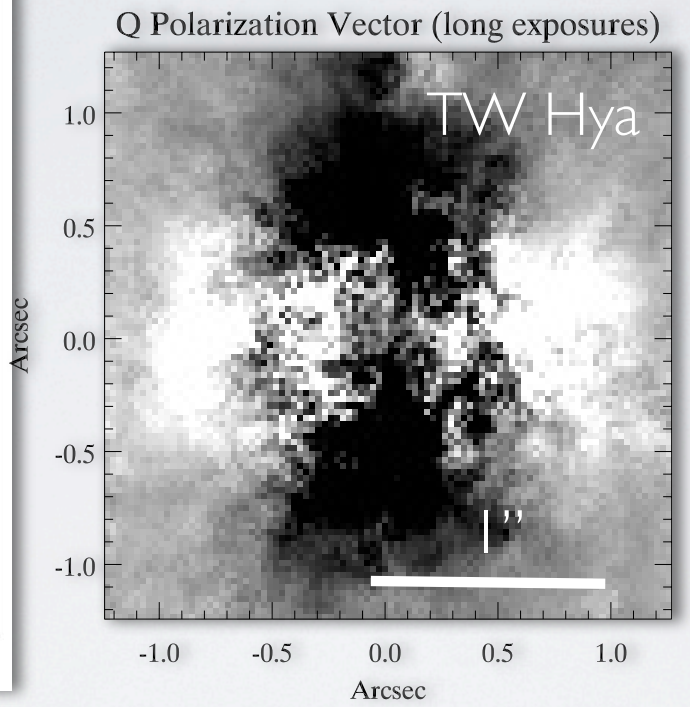
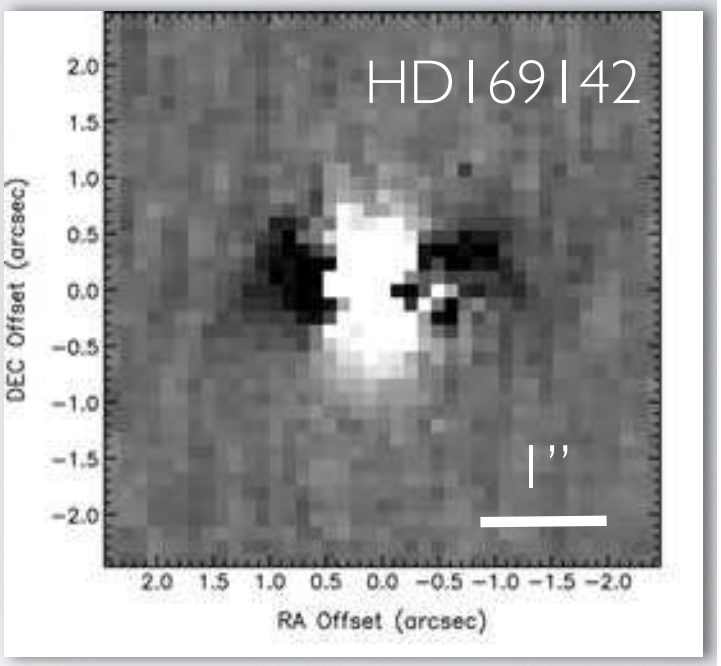


Image credit: H. Avenhaus

PDI: SOME HISTORY

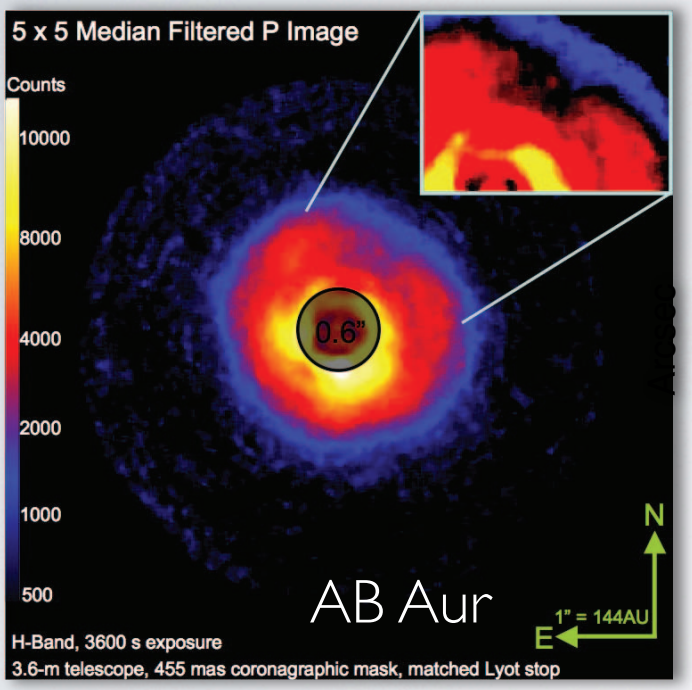


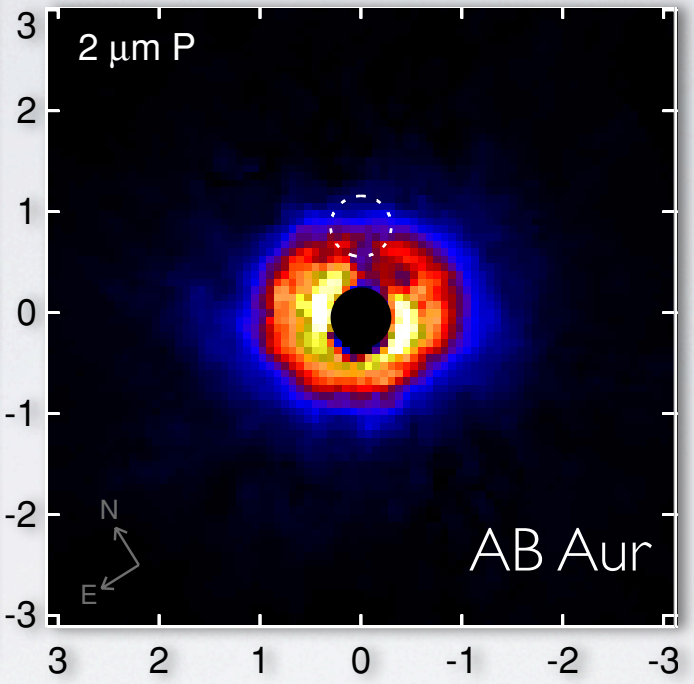


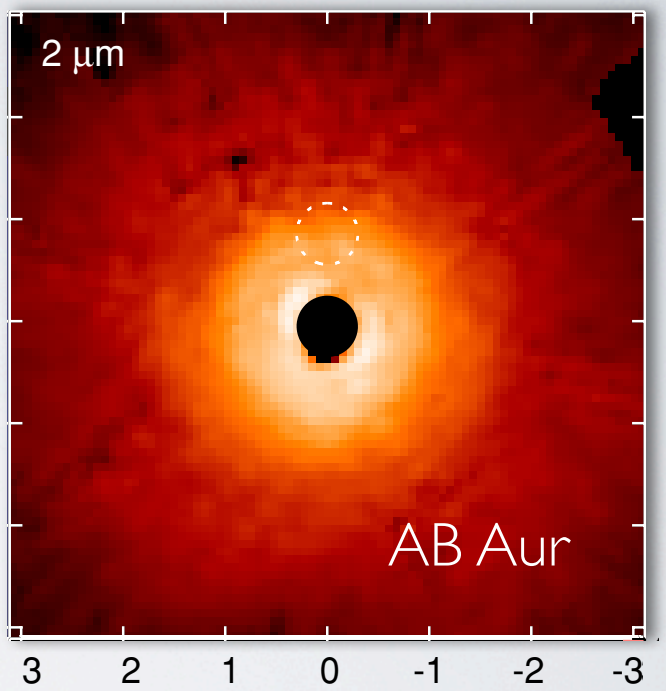


Kuhn et al. 2001; Apai et al. 2004; Hales et al. 2006

PDI: SOME (MORE RECENT) HISTORY

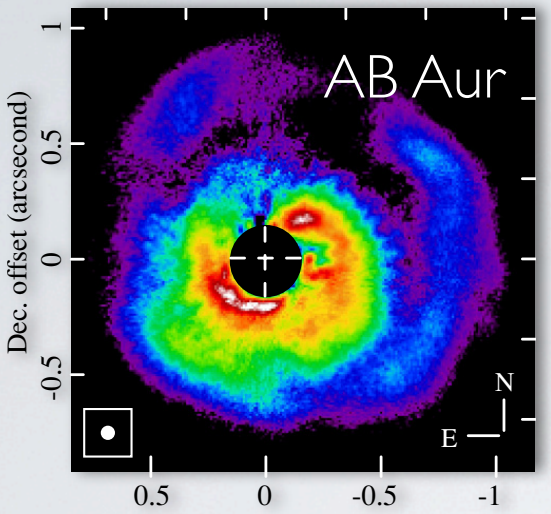


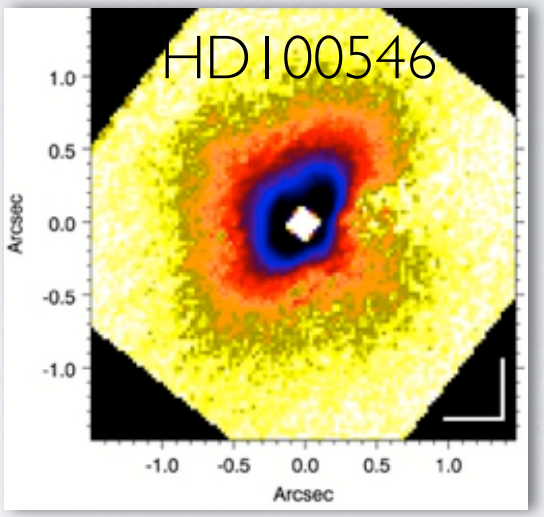


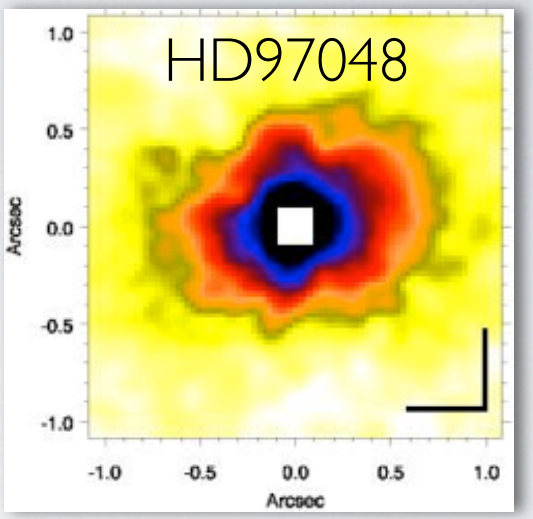


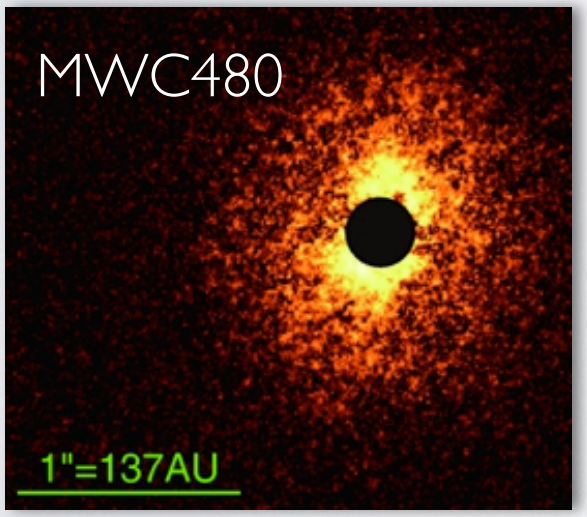
Oppenheimer et al. 2008; Perrin et al. 2009

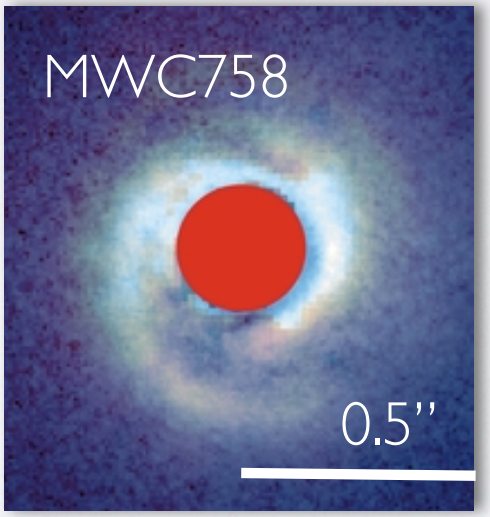
PDI TODAY: SUBARU (SEEDS) + VLT/NACO

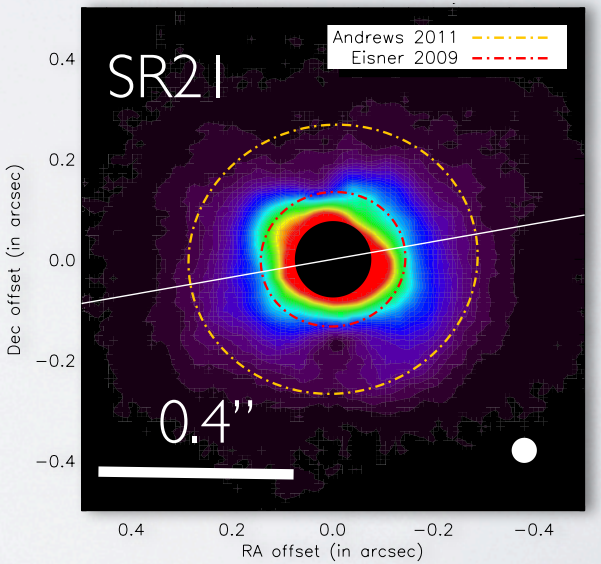






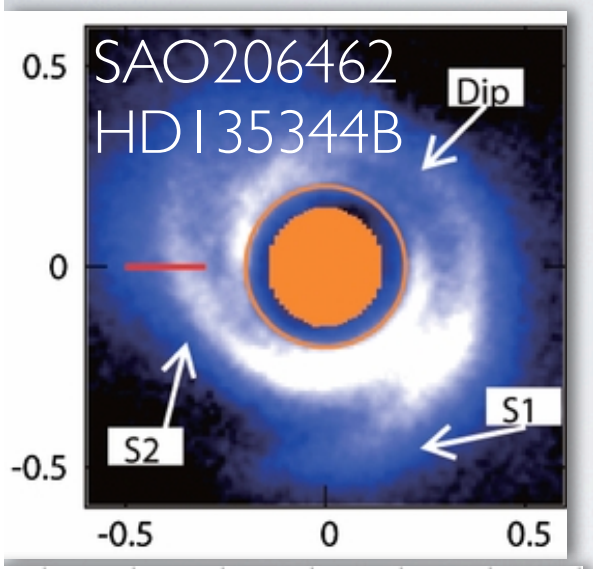


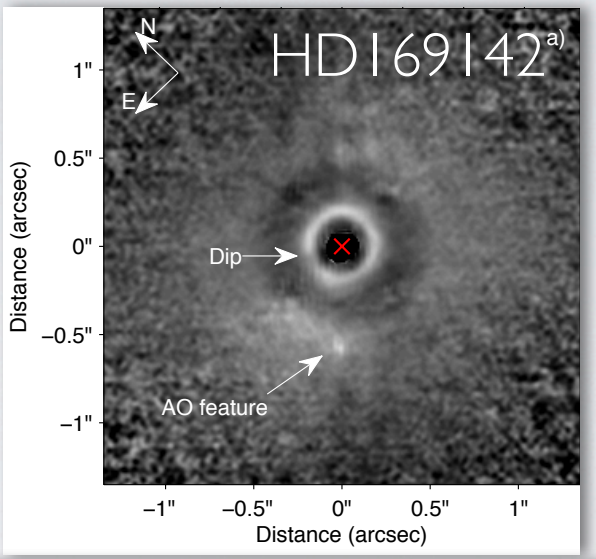


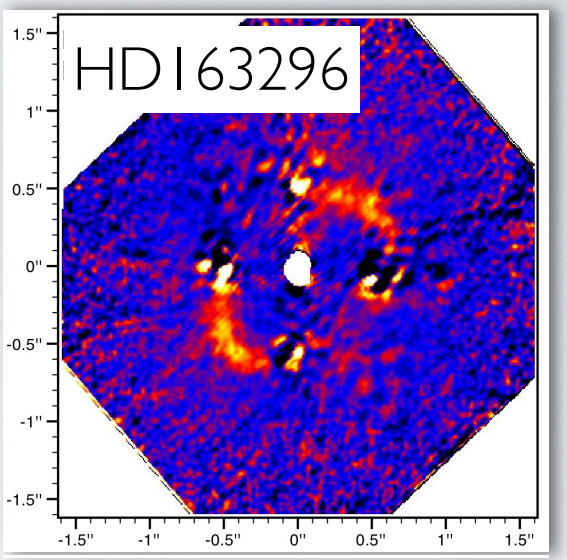


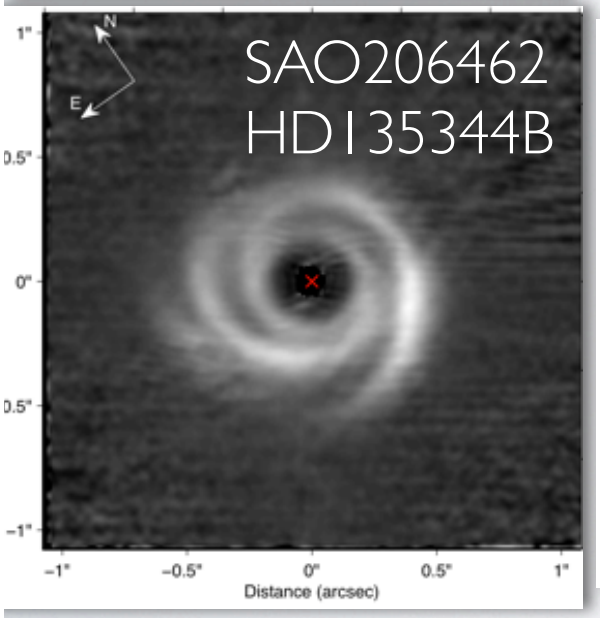
Hashimoto et al. 2011; Quanz et al. 2011,2012; Kusakabe et al, 2012; Grady et al. 2013; Folette et al. 2013

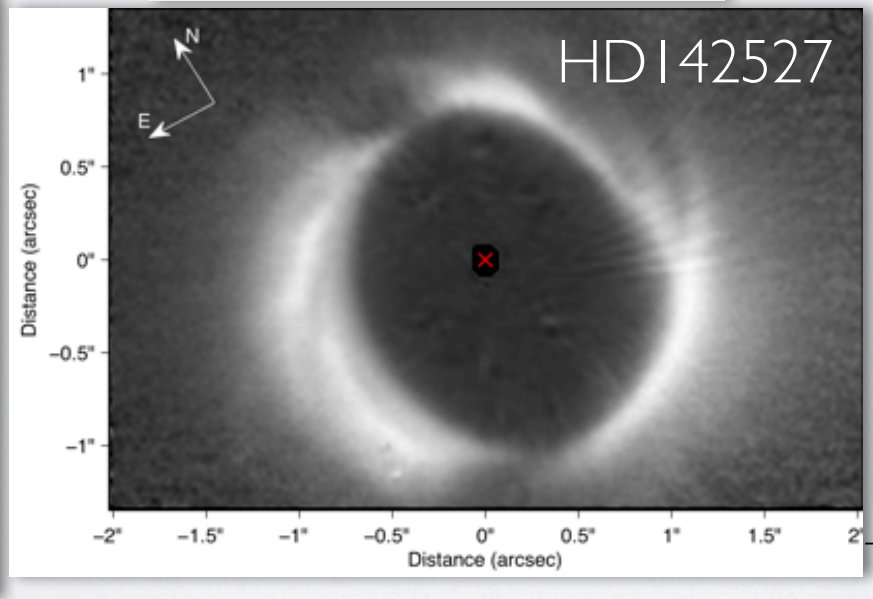
PDI TODAY: SUBARU (SEEDS) + VLT/NACO

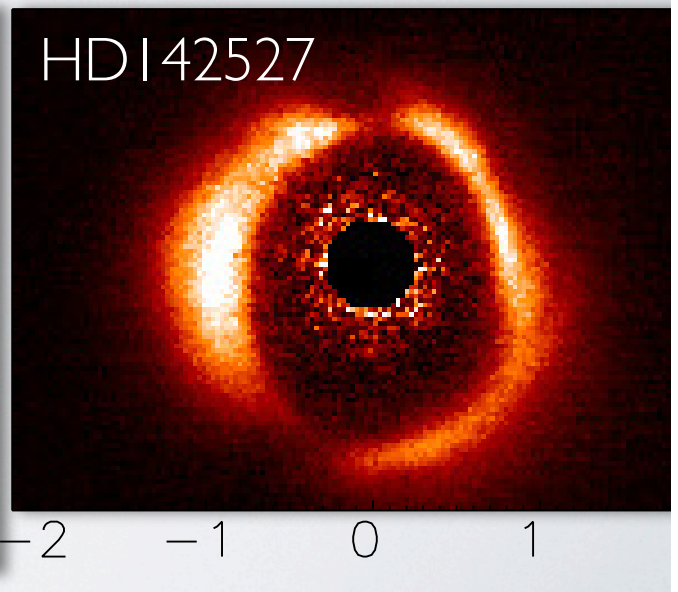








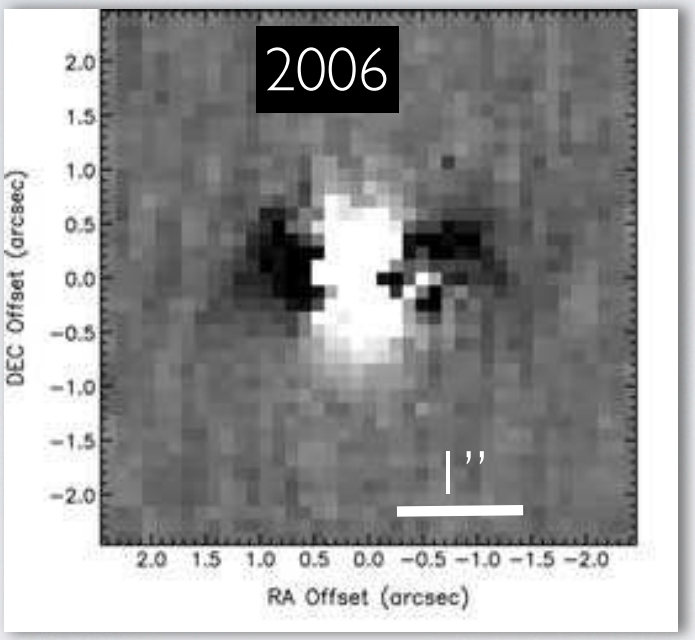


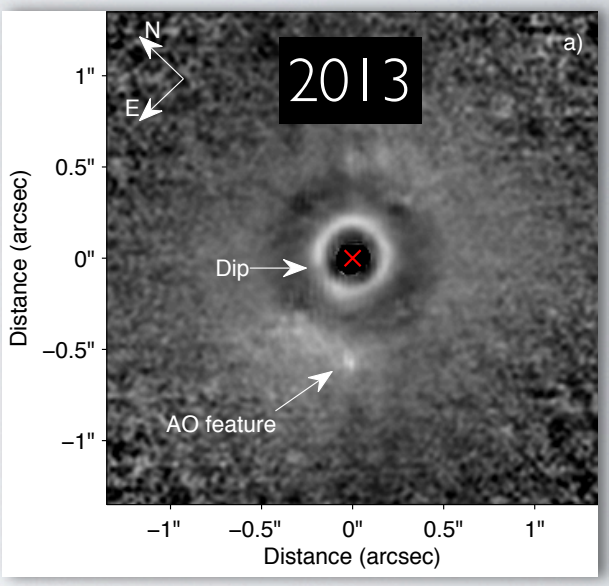


Muto et al. 2013; Quanz et al. 2013; Garufi, Quanz et al. (in prep.); Garufi, Quanz et al. 2013; Avenhaus, Quanz et al. 2014; Canovas et al. 2013

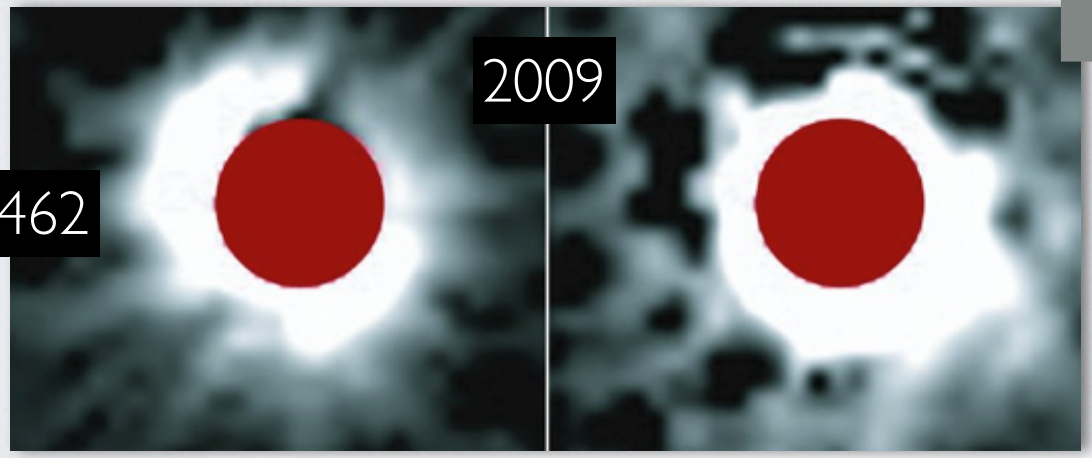
PDI: EVOLUTION OF DATA QUALITY

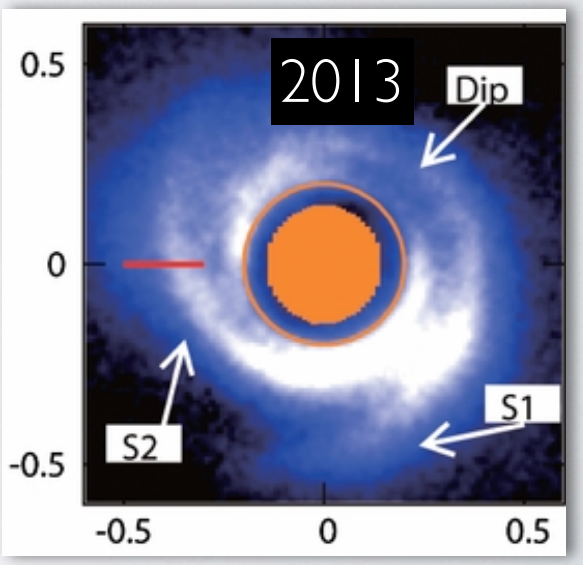
HD169142





SAO206462





Hales et al. 2006; Quanz et al. 2013; Grady et al. 2009; Muto et al. 2013

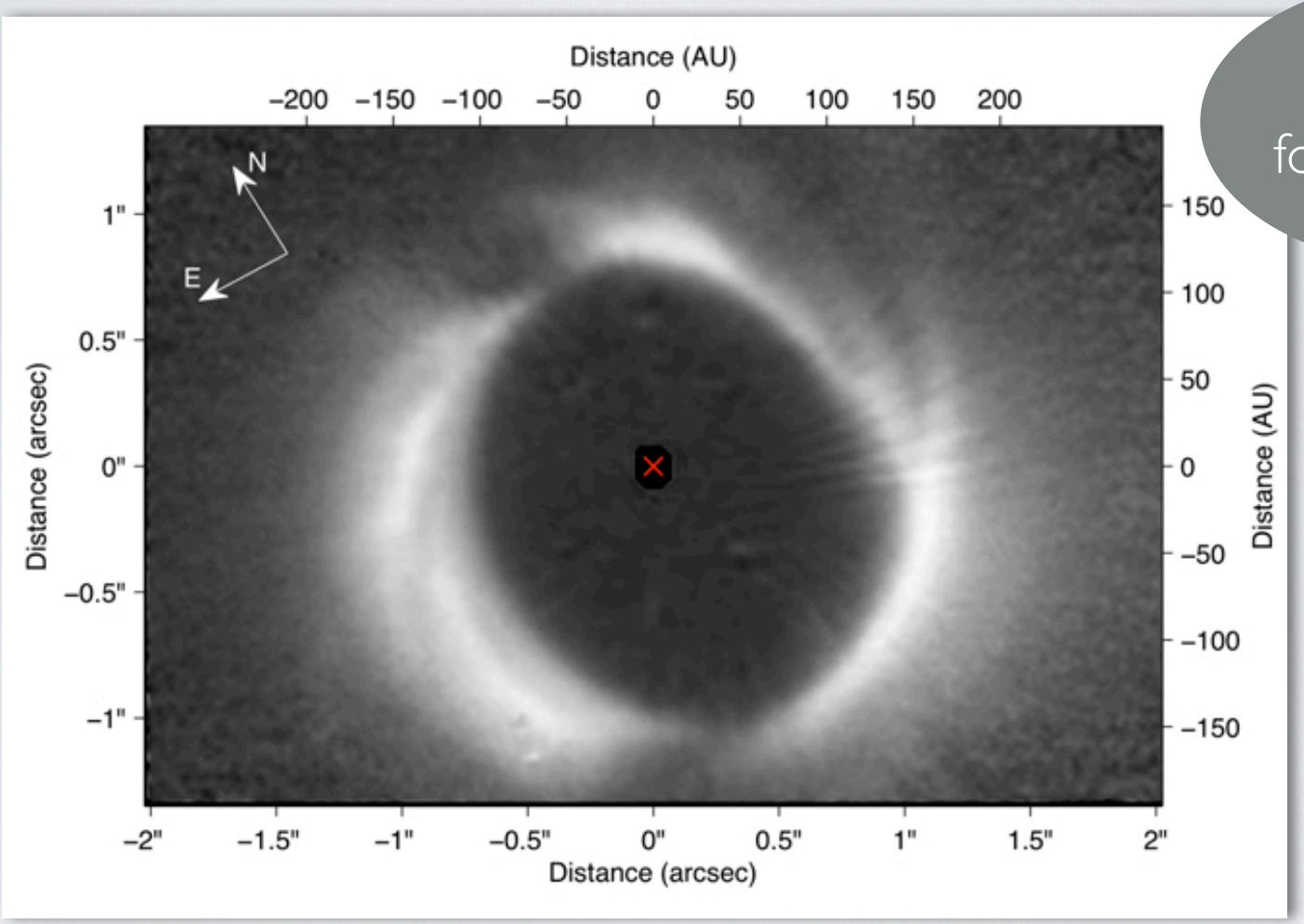
PLANET FORMING DISKS?

4 OBJECTS, 4 MORPHOLOGIES

- SAME CAUSE?

See also poster by Claudio Cáceres for an object in Lupus

PLANET FORMING DISKS?- HD142527

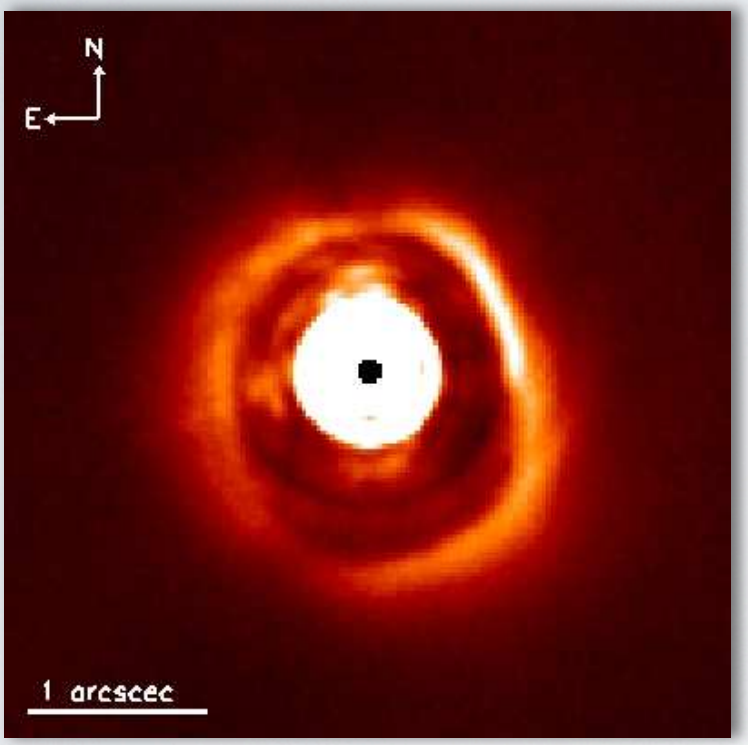


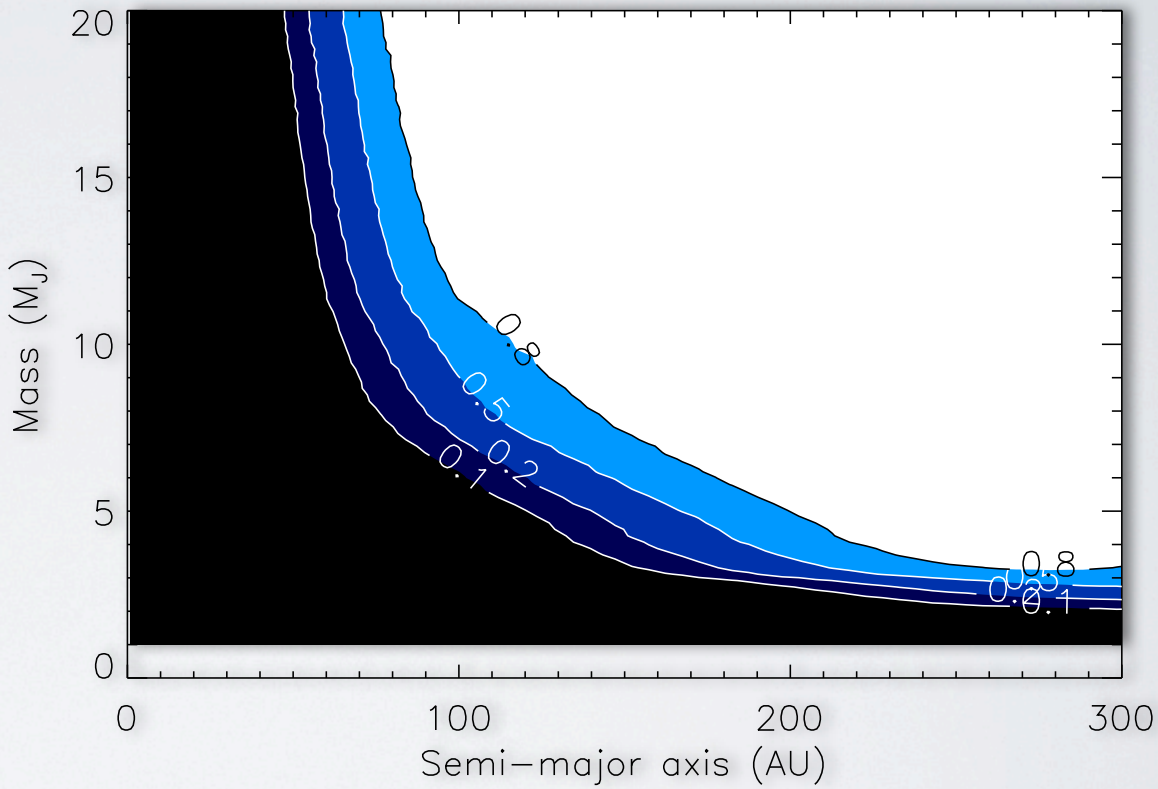
See also following talks!

Avenhaus, Quanz et al. 2014; also, Canovas et al. 2013

PLANET FORMING DISKS?- HD142527

High-contrast L band imaging constrains the existence of massive planets >50 AU

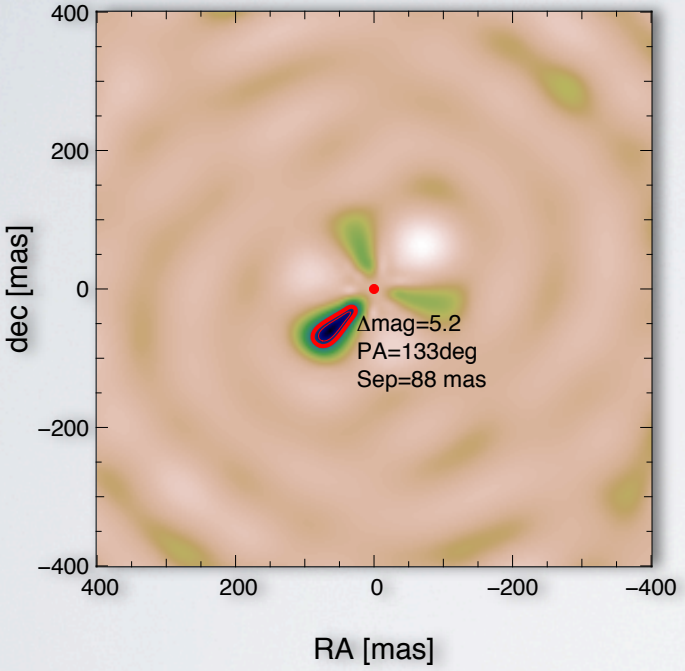


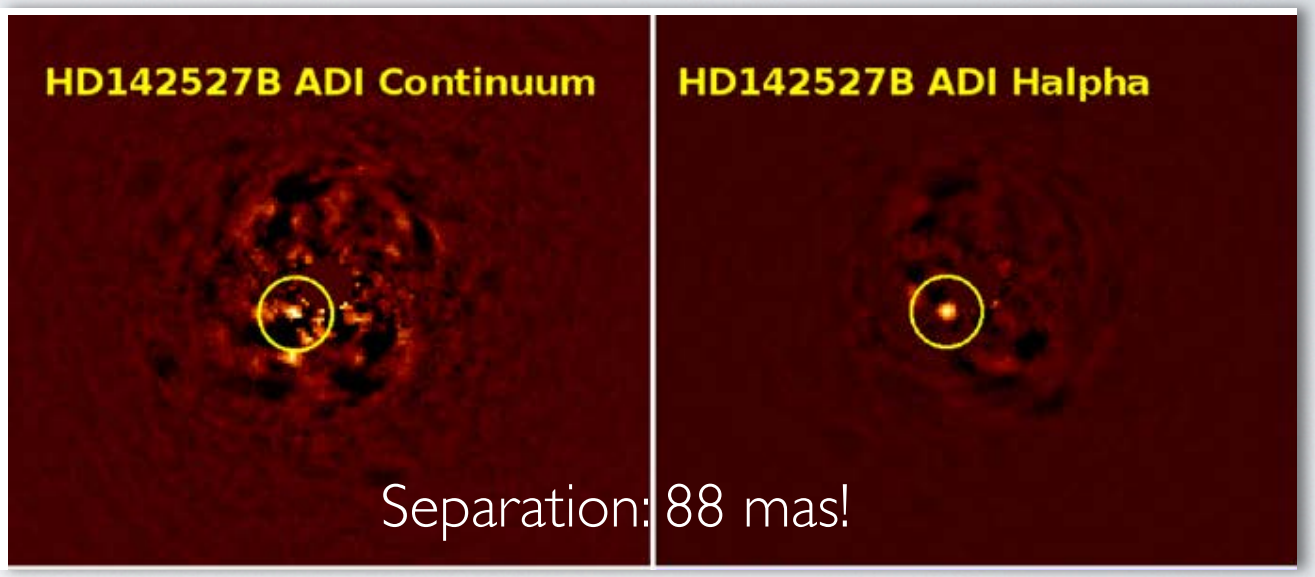


Rameau et al. 2012; cf. Casassus et al. 2013

PLANET FORMING DISKS?- HD142527

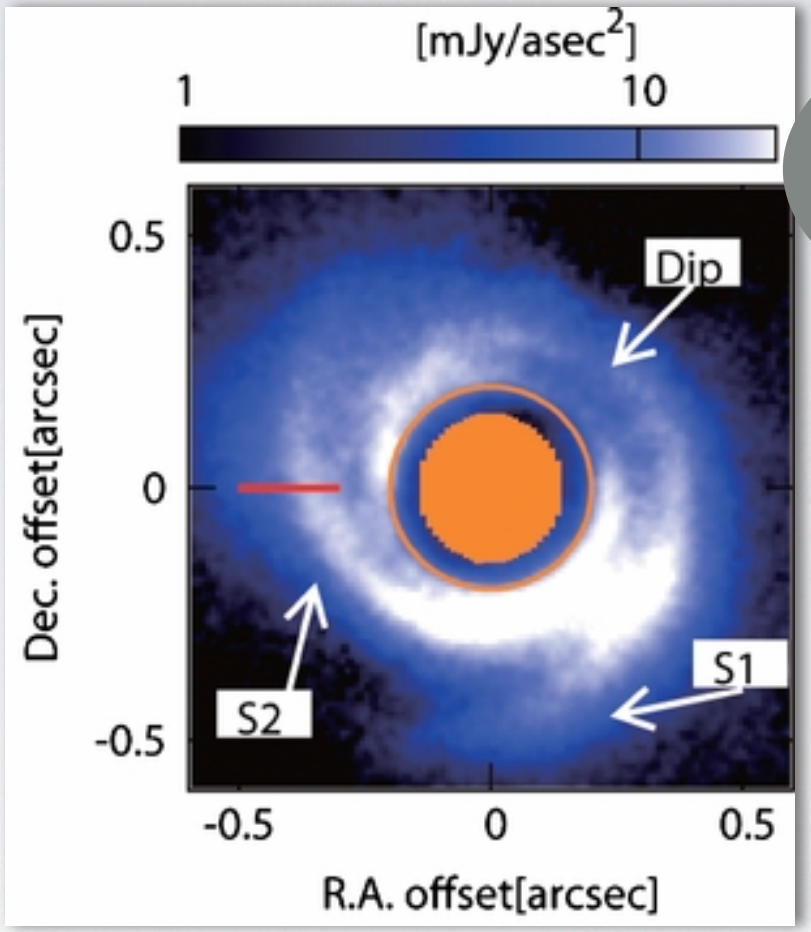
Sparse aperture masking (L band) and high-contrast optical(!) imaging reveal the existence of close-in stellar companion





Biller et al. 2012; Close et al. 2014

PLANET FORMING DISKS? SAO206462 (HD135344B)

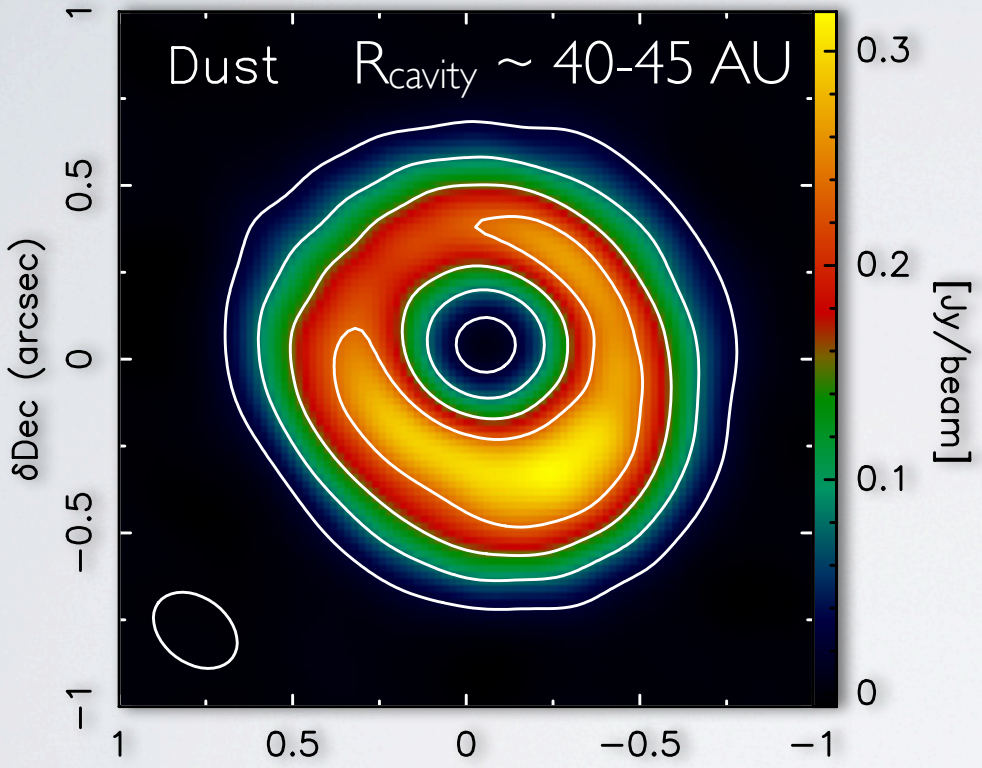


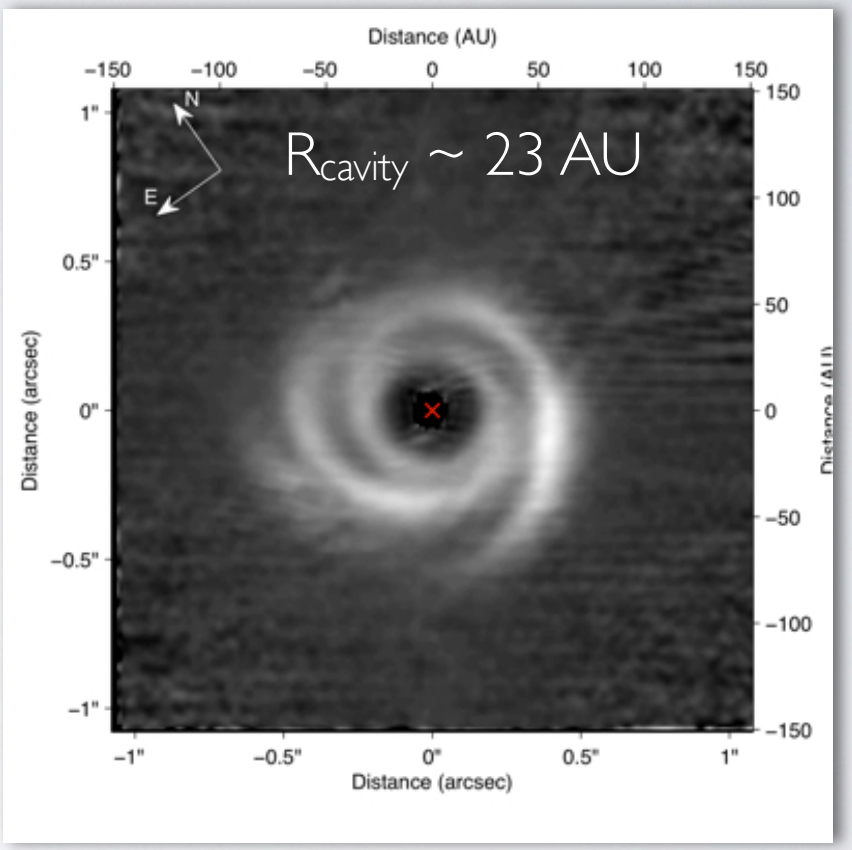
See also talk by Christophe Pinte

Muto et al. 2012

PLANET FORMING DISKS? SAO206462 (HD135344B)

Different cavity sizes for different observing wavelengths (i.e., grain sizes)

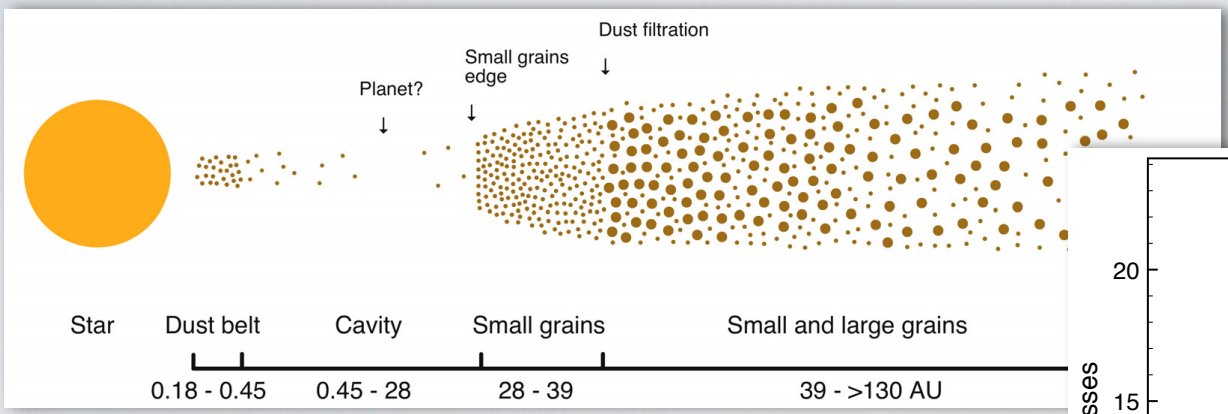


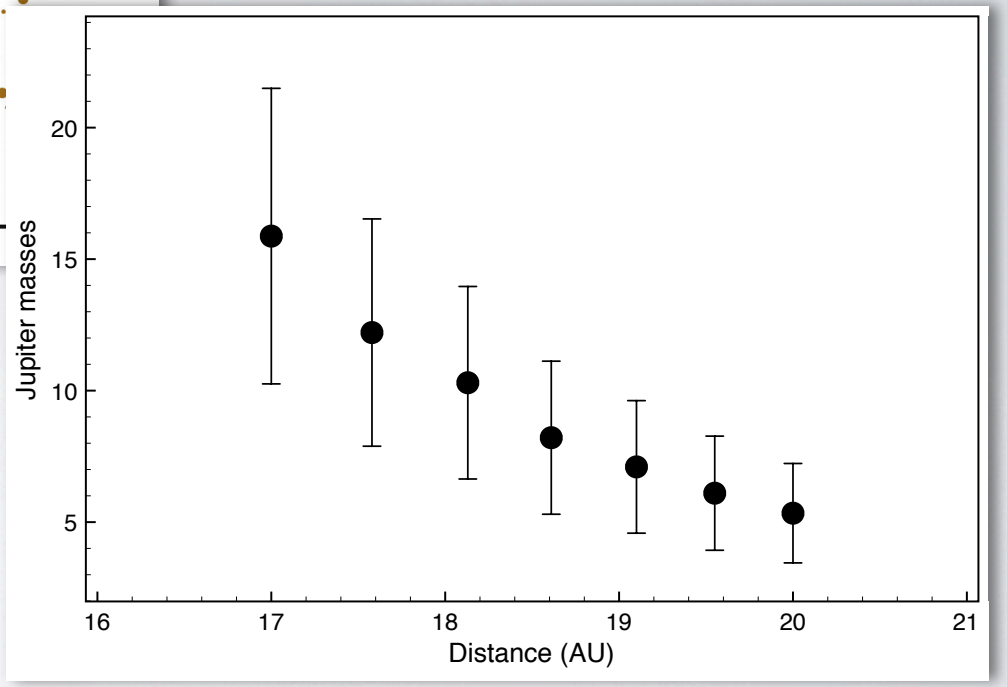


Perez et al. 2014; Garufi, Quanz et al. 2013;
also, Brown et al. 2009

PLANET FORMING DISKS? SAO206462 (HD135344B)

Dust filtration due to the presence of a planet might explain different cavity sizes

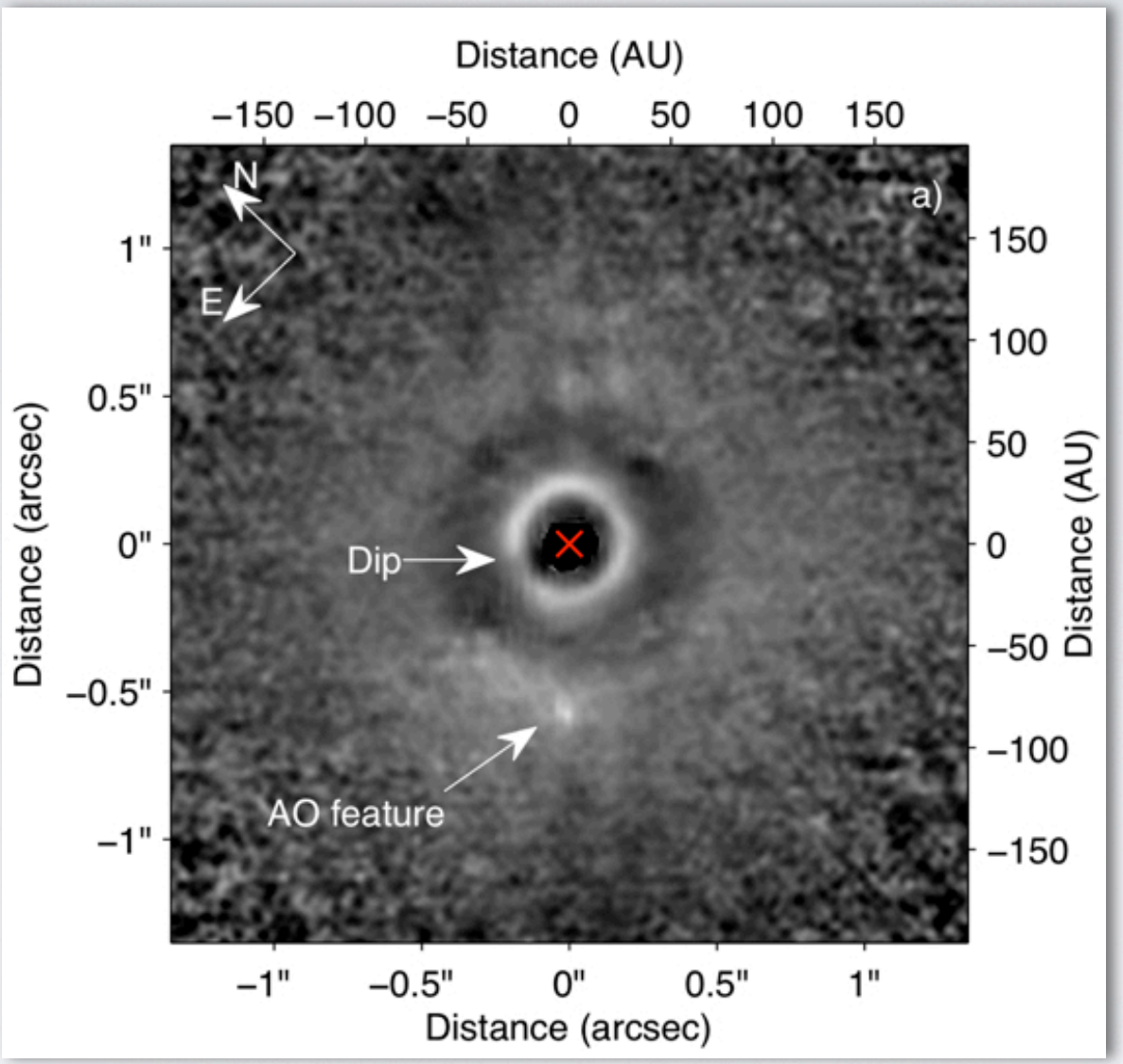




Garufi, Quanz et al. 2013; Pinilla et al. 2012; de Juan Ovelar et al. 2013

Most work in preparation or just submitted!

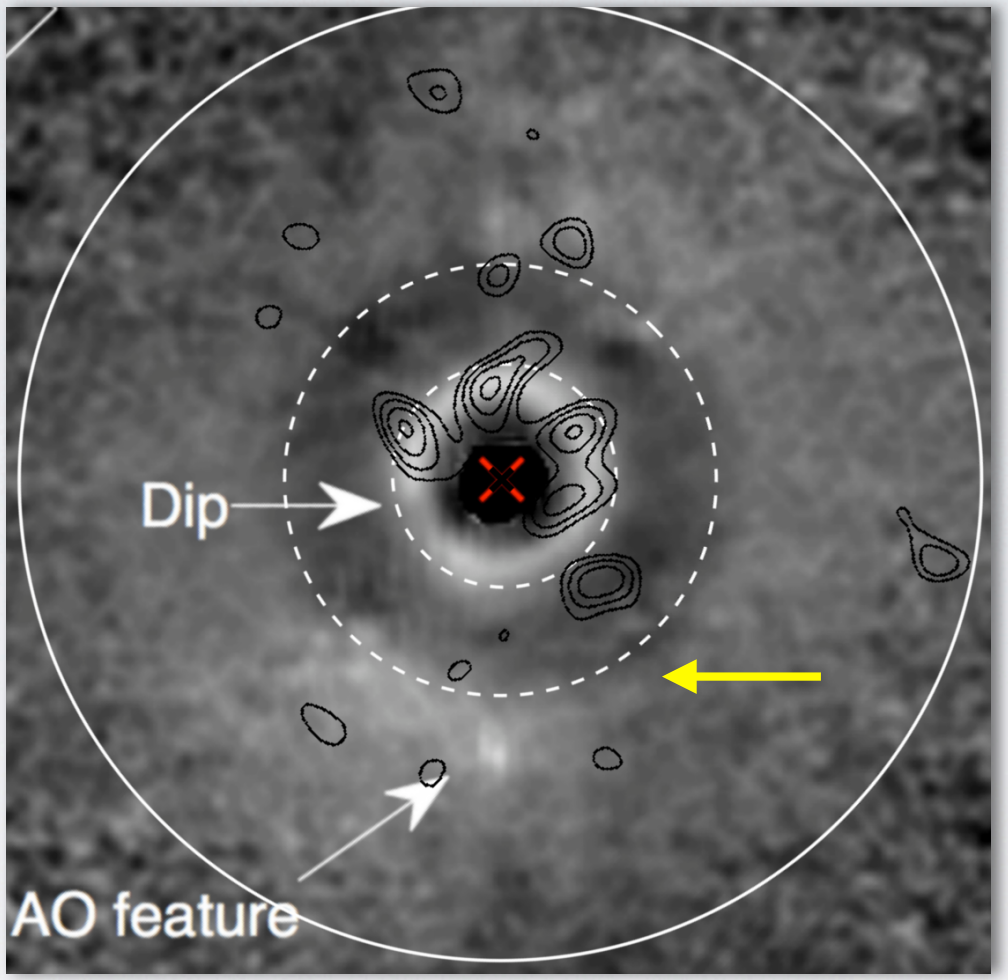
PLANET FORMING DISKS? HD169142



Quanz et al. 2013

PLANET FORMING DISKS? HD169142

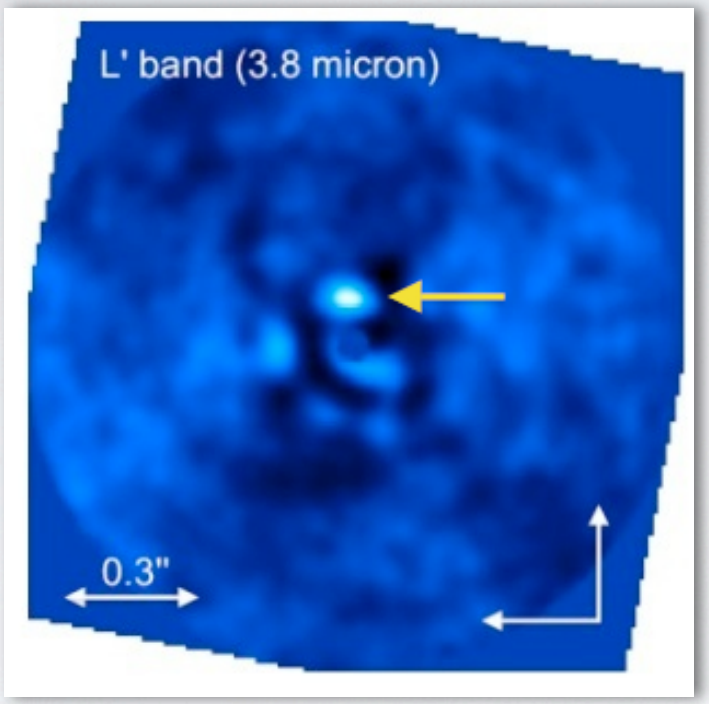
An overdensity in 7mm flux (EVLA) in the annular gap?

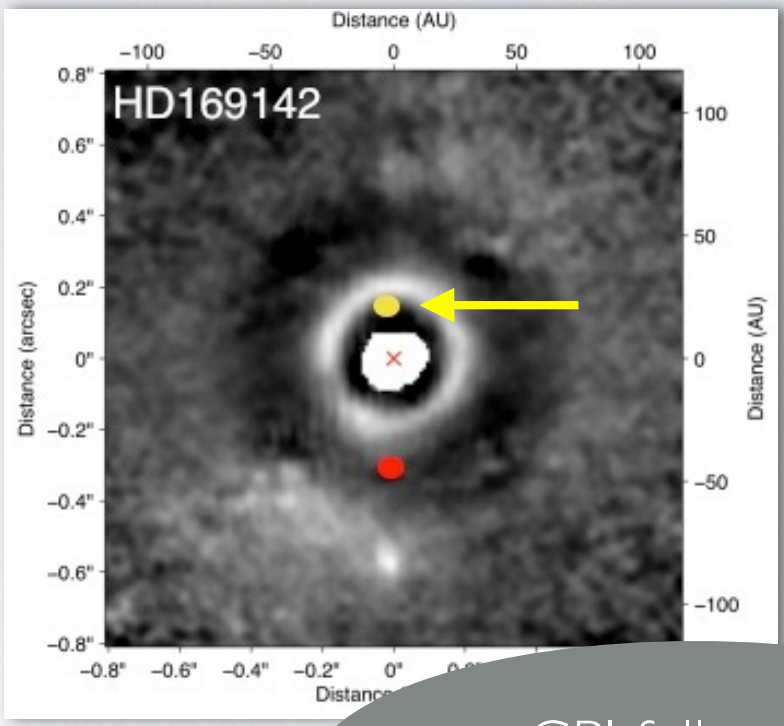


Osorio et al, (in prep.)

PLANET FORMING DISKS? HD169142

A companion in the inner cavity? L' high-contrast imaging with NACO/AGPM



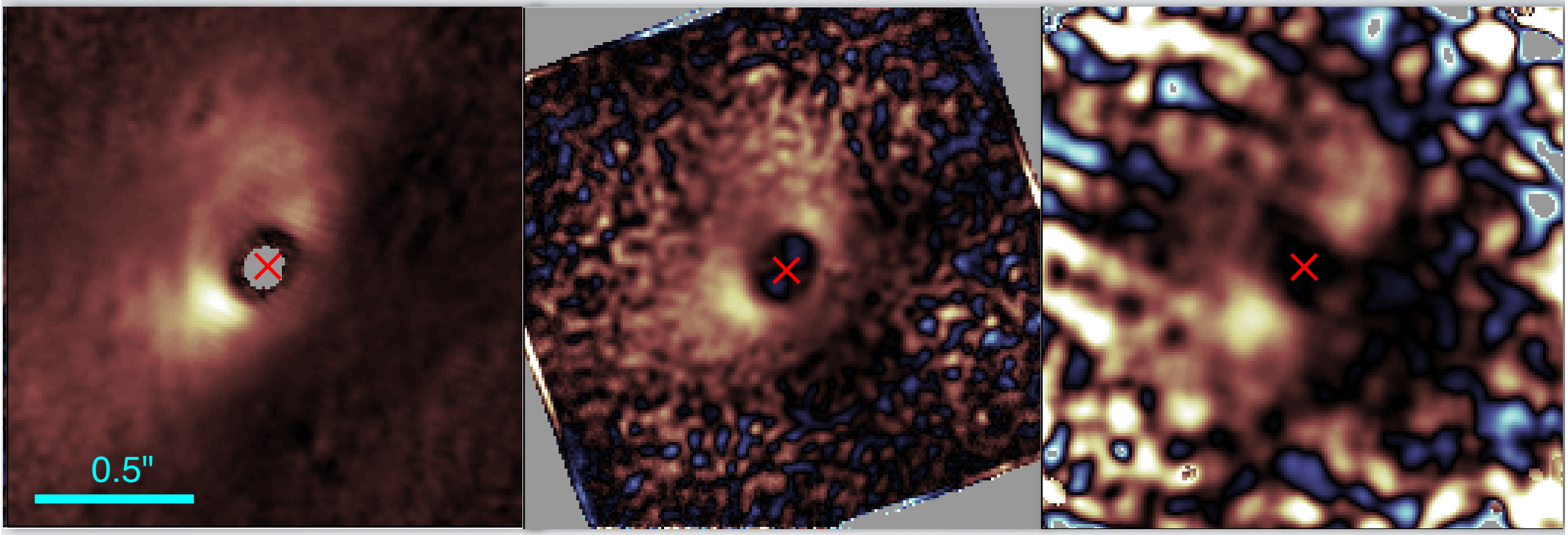


GPI follow-up observations in 2 weeks!

Reggiani, Quanz et al. (in prep.)

PLANET FORMING DISKS? HD100546

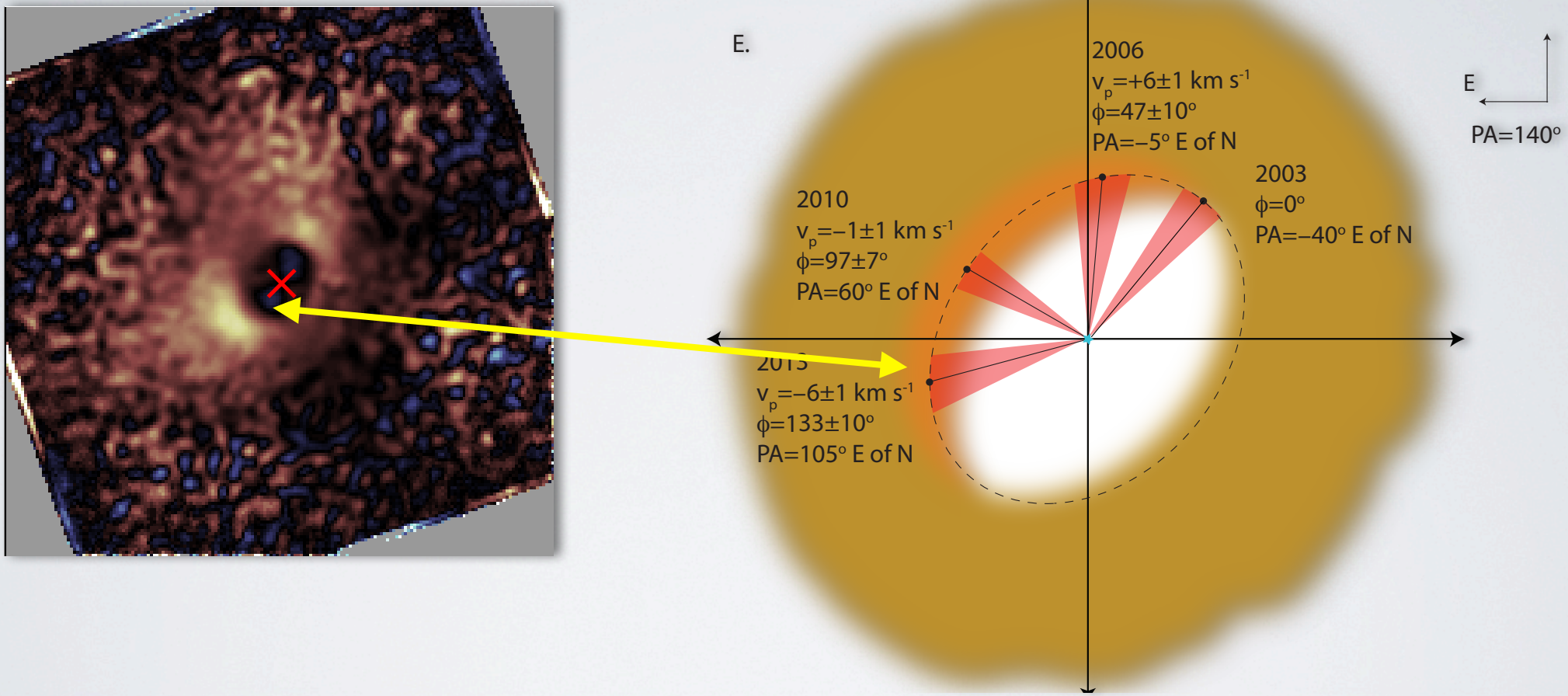
New NACO/PDI images: Brightness asymmetries, inner cavity, L-band PDI



Avenhaus, Quanz et al. submitted

PLANET FORMING DISKS? HD100546

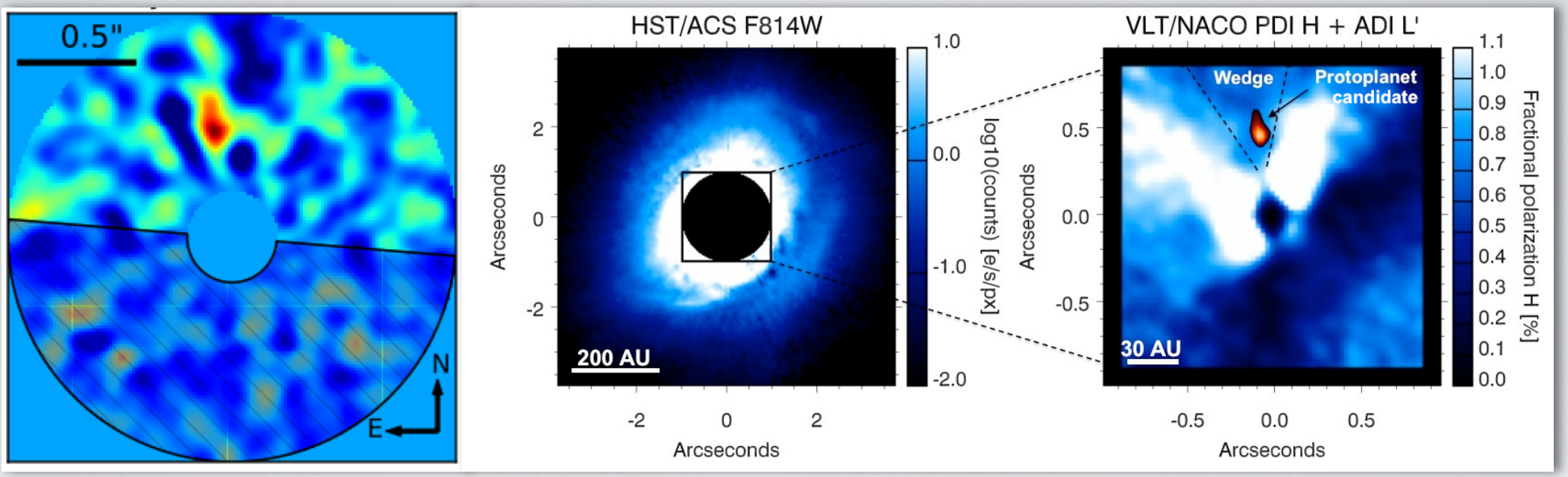
A companion candidate in the cavity; see talk by S. Brittain on Monday



Avenhaus, Quanz et al. (subm.); Brittain et al. (subm.);
also, Bouwman et al. 2003, Acke & van den Ancker 2006; Tatulli et al. 2011; Mulders at al. 2013

PLANET FORMING DISKS? HD100546

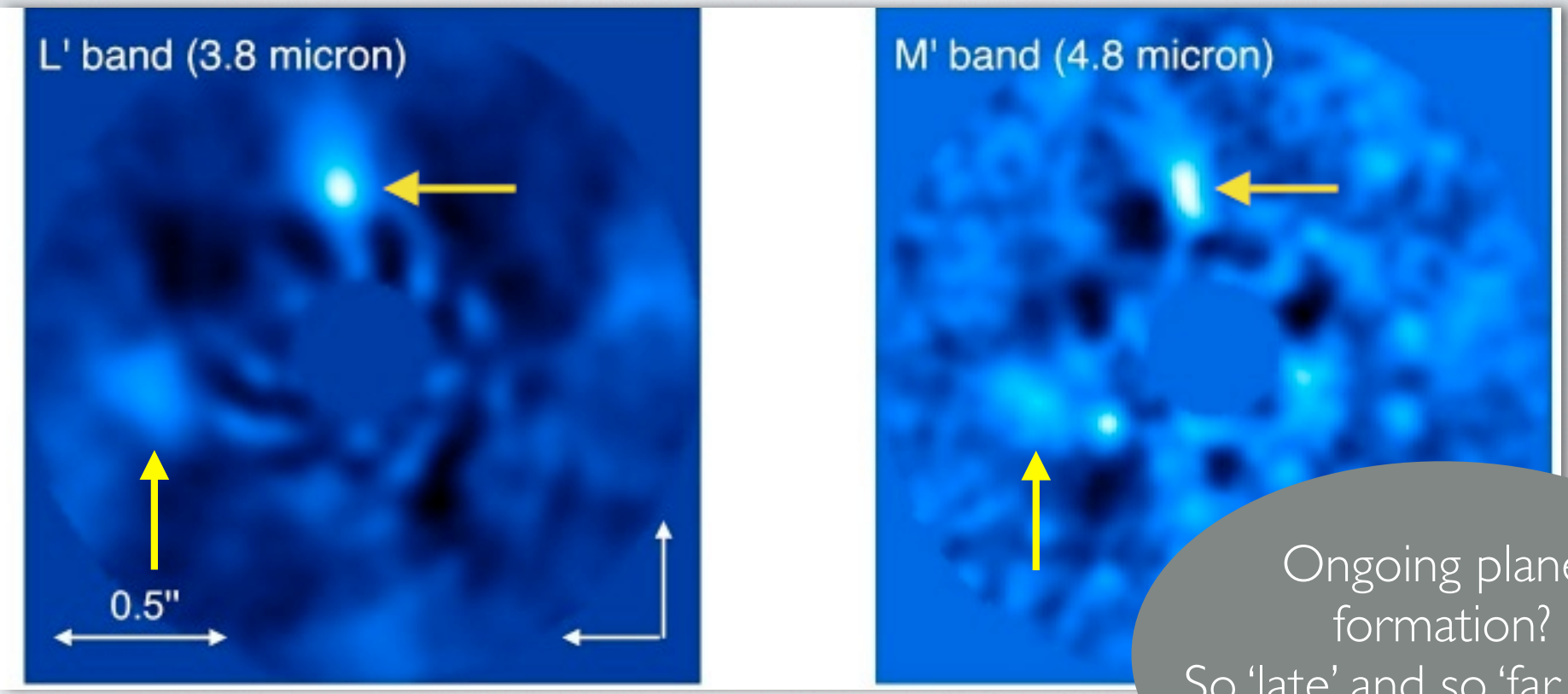
A companion candidate in the outer disk detected at L' (3.8 micron)



Quanz et al. 2013b

PLANET FORMING DISKS? HD100546

New data confirm results and provide additional insights

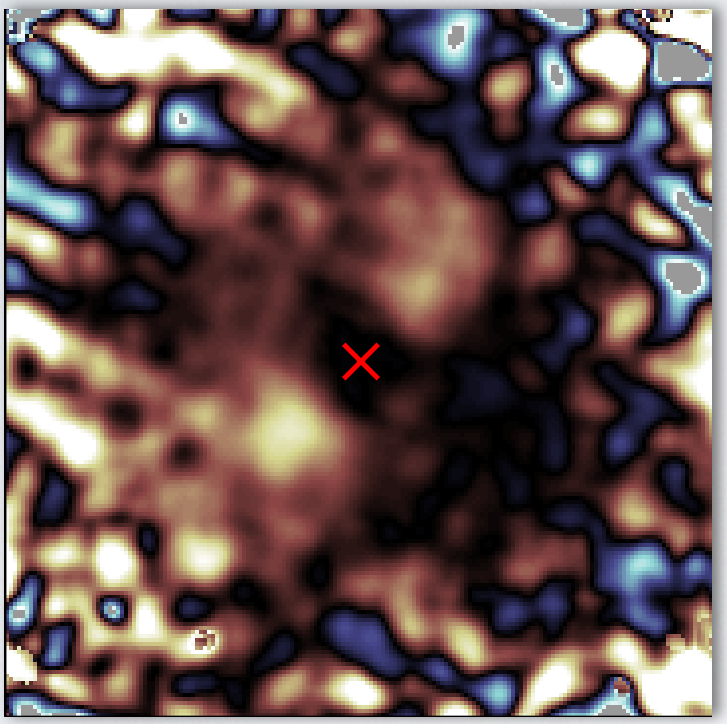


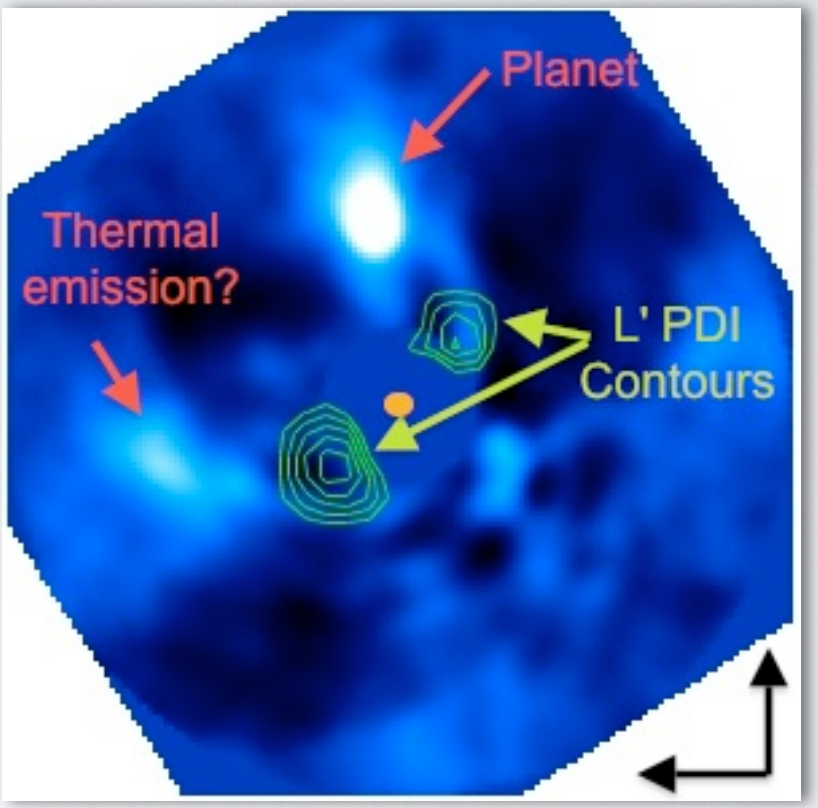
Ongoing planet formation?
So 'late' and so 'far out' in the disk?

Quanz et al. (in prep.)

PLANET FORMING DISKS? HD100546

Comparing 3.8 micron PDI data with 3.8 micron direct imaging data





Quanz et al. (in prep.)

TAKE HOME MESSAGES

- RV studies suggest that intermediate mass stars have more massive gas giant planets at larger orbital radii (compared to Sun-like stars)
- Direct imaging studies suggest that massive gas giant planets in orbits >60 AU around intermediate mass stars are rare
- Most directly imaged planets were detected around intermediate mass stars; formation process for some of these objects is unclear
- Polarimetric Differential Imaging (PDI) allows us to spatially resolved regions in HAEBE disks where (some of the) gas giant planets should form
- In a number of disks, PDI revealed structures (gaps, cavities, spiral arms) that could be immediately related to recent / ongoing planet formation
- In at least 2 HAEBEs (HD169142, HD100546) we have growing *direct* observational evidence that planets may (have) form(ed)

THE FUTURE IS BRIGHT...AS ALWAYS

- VLT/SPHERE and GEMINI/GPI planet surveys will further constrain statistics of gas giant exoplanets

- VLT/SPHERE and GEMINI/GPI might find additional planet embedded in HAEBE disks

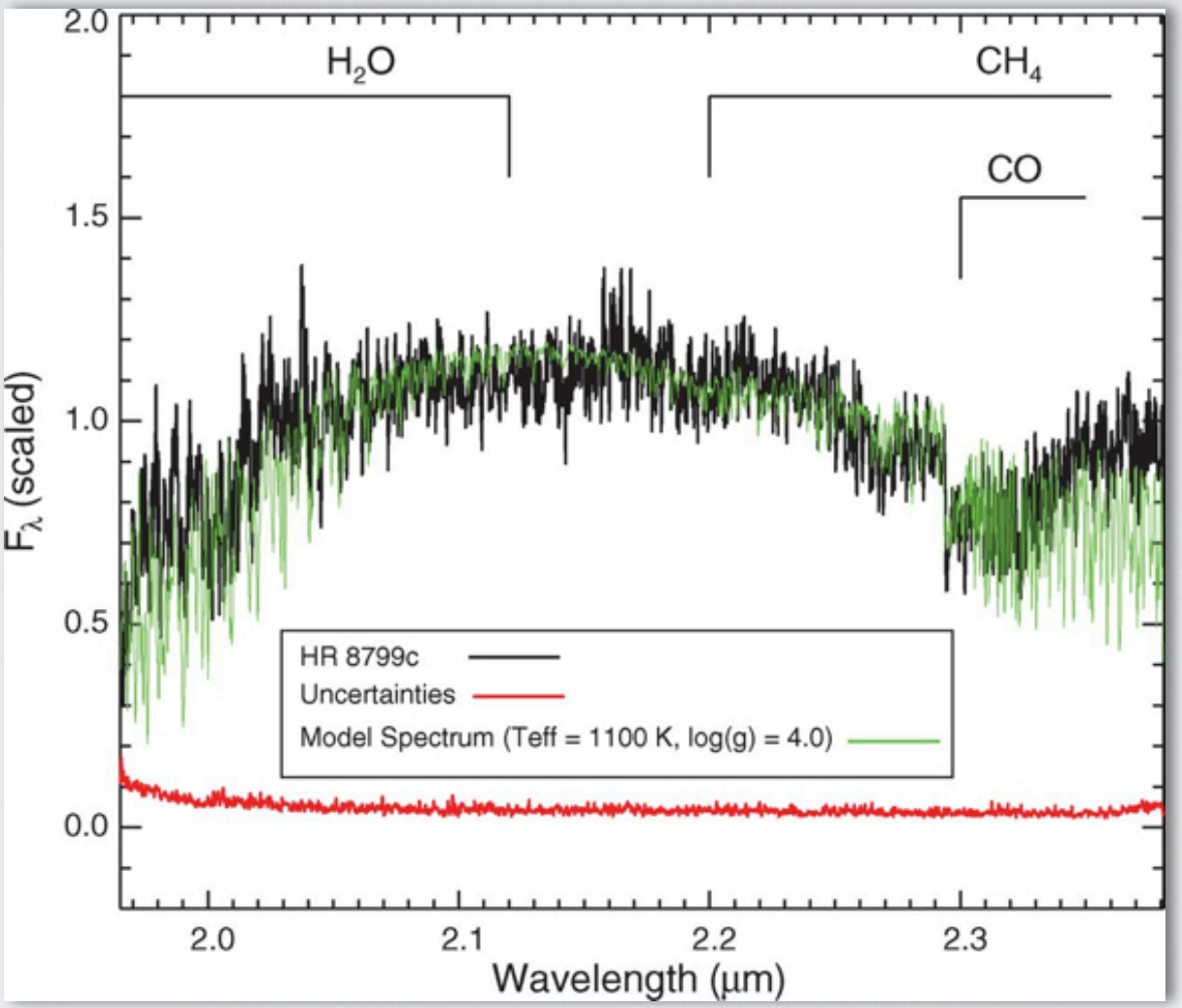
- VLT/SPHERE and GEMINI/GPI (and other instruments) will help us to characterize the composition of gas giant planet atmospheres

- VLT/SPHERE and GEMINI/GPI can both do PDI, allowing us to further study known HAEBE disks and - possibly - to image more

- ALMA now provides same spatial resolution as PDI studies, allowing us to study the 3-D disk structure from the disk surface to the mid-plane with unprecedented resolution and sensitivity

MORE OF THESE, PLEASE...

R ~ 4000 spectrum of HR8799 c



Konopacky et al. 2013

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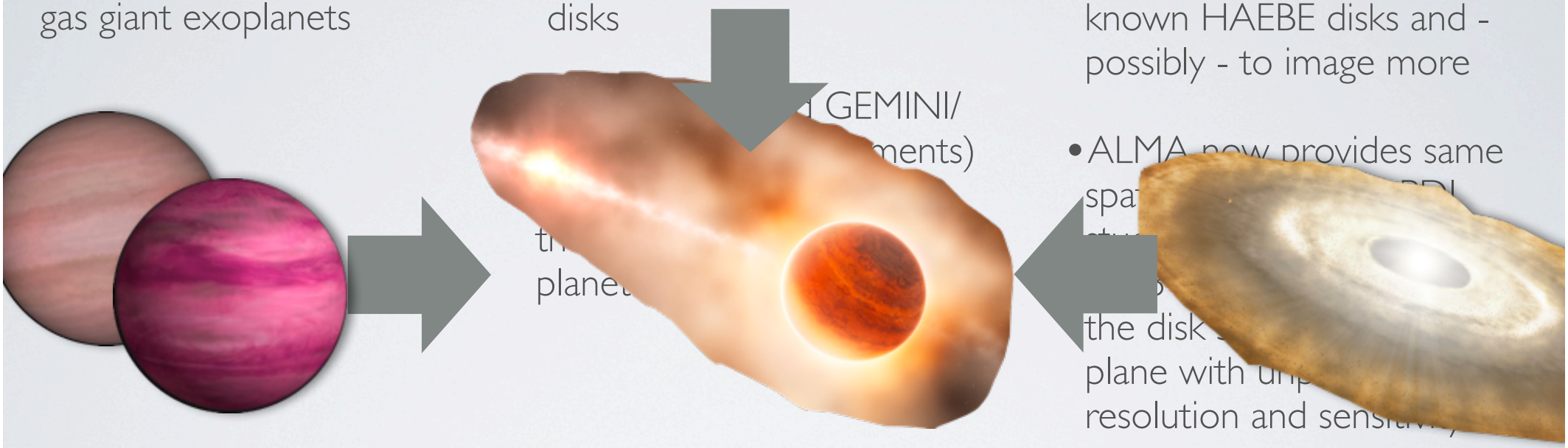

THANK YOU