High-Contrast Imaging Of Protoplanetary Disks: Probing The Formation Sites Of (some) Gas Giant Planets

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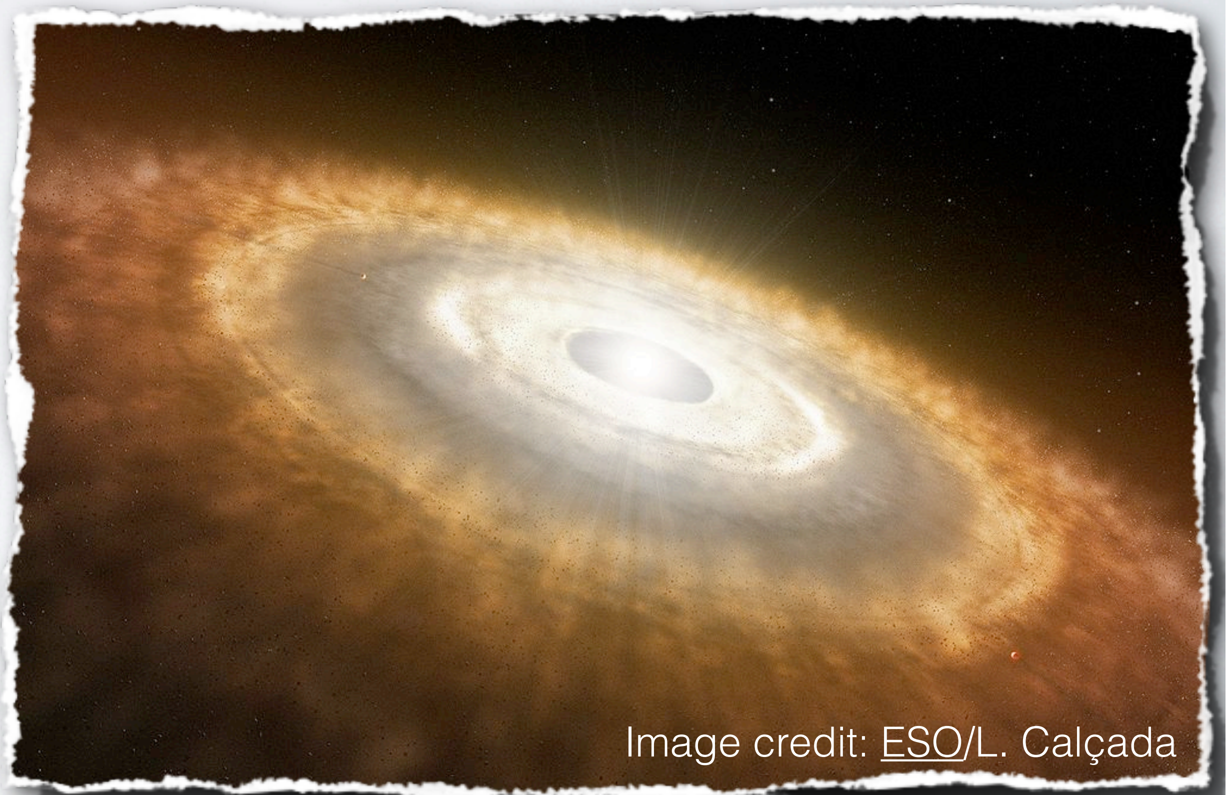
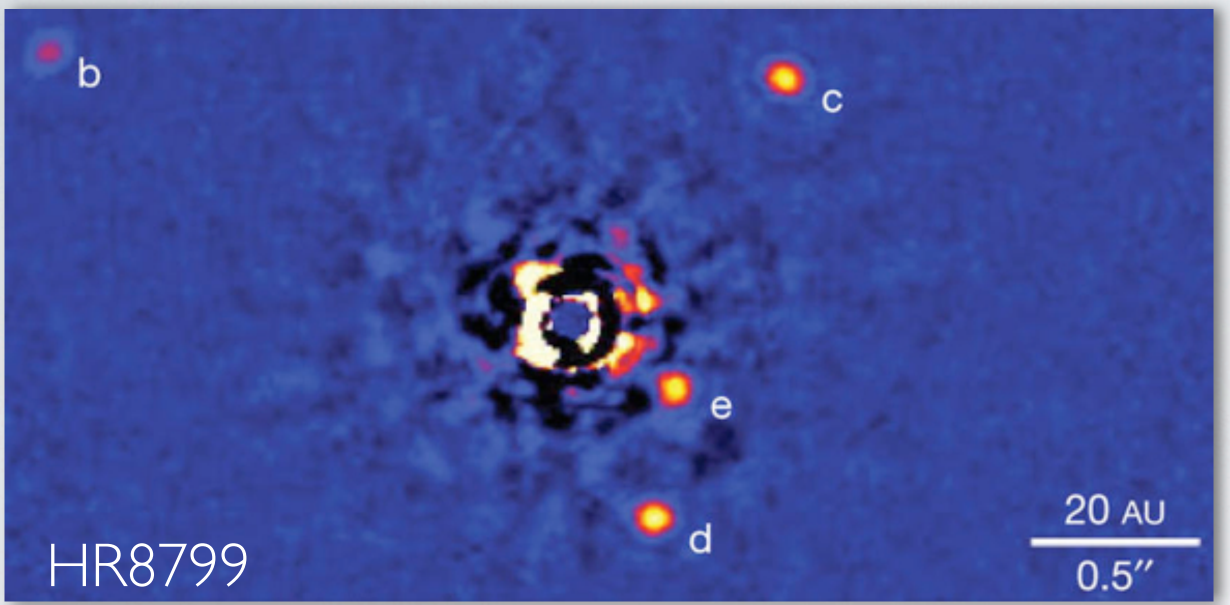
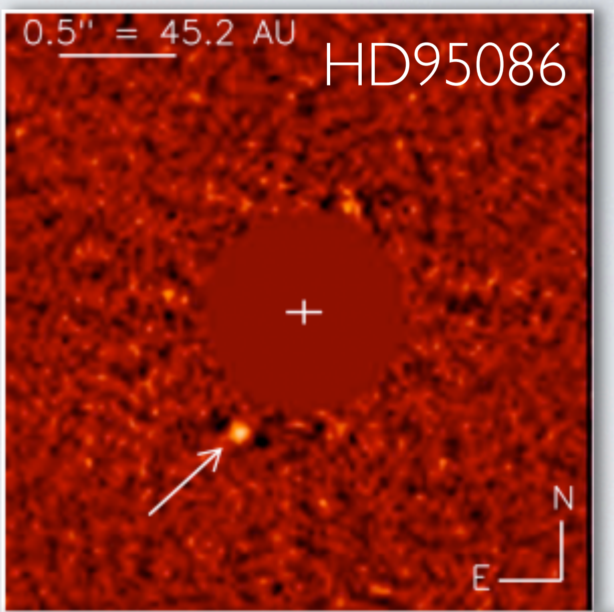
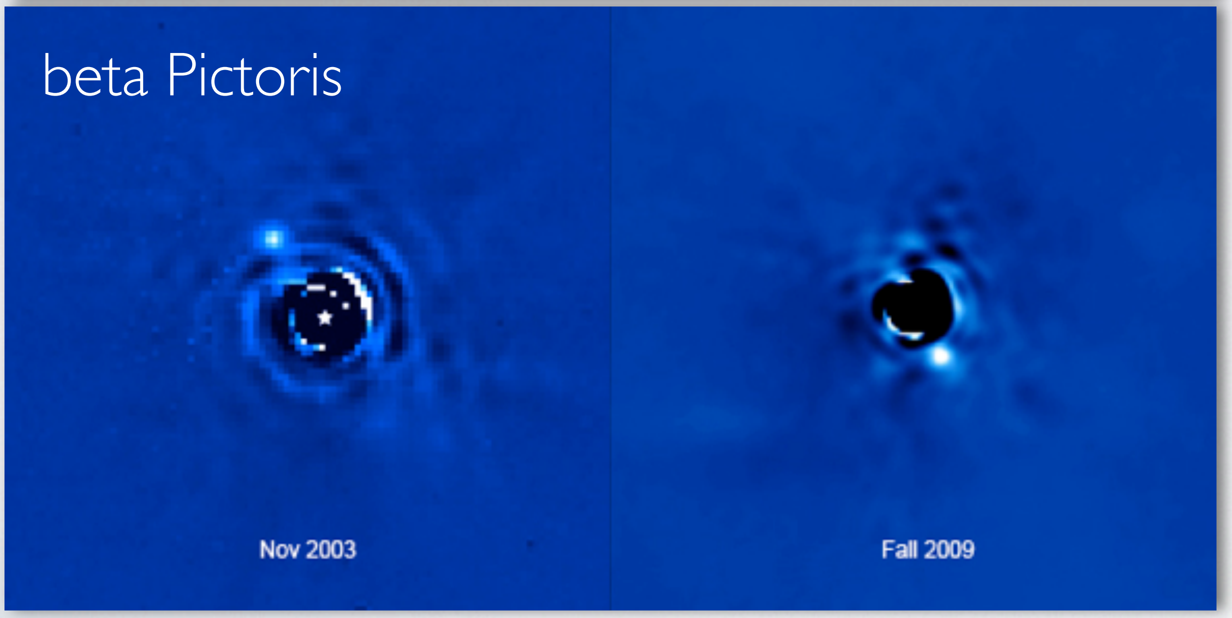
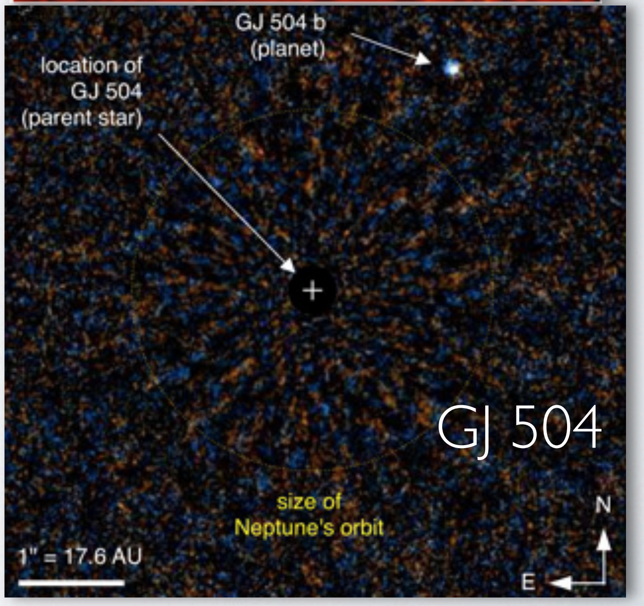


Gas giant planets do exist at wide orbital separations...







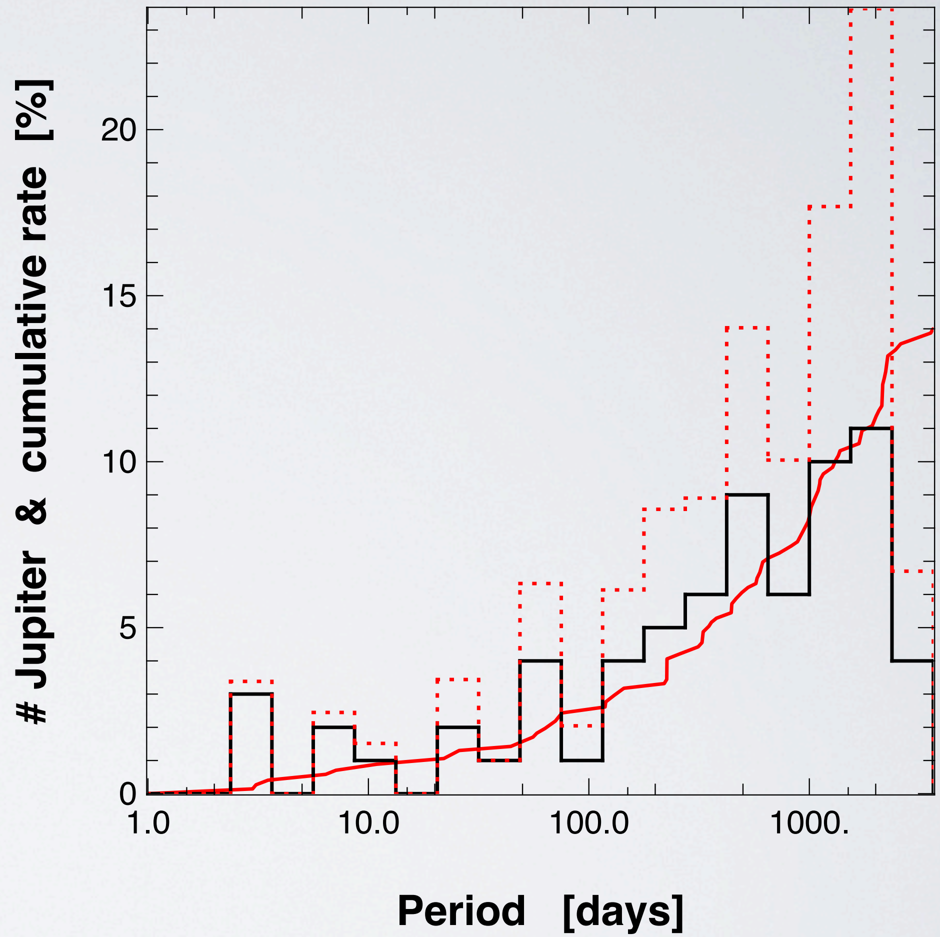


Marois et al, 2008, 2010; Lagrange et al. 2010; Rameau et al. 2013a,b; Kuzuhara et al. 2013

...and their peak occurrence rate is somewhere >4 AU

From RV planet searches:

- # of gas giant planets strongly increases with period
- Early-type stars have higher frequency of giant planets within 3 AU (~26^{+9}_{-8} % vs. ~10% for solar-type stars) and also increasing for longer periods



Mayor et al. 2011 (arxiv:1109.2497); Bowler et al. 2010; also Johnson et al. 2007a,b, 2010

Polarimetric Differential Imaging (PDI) probes relevant disk regions

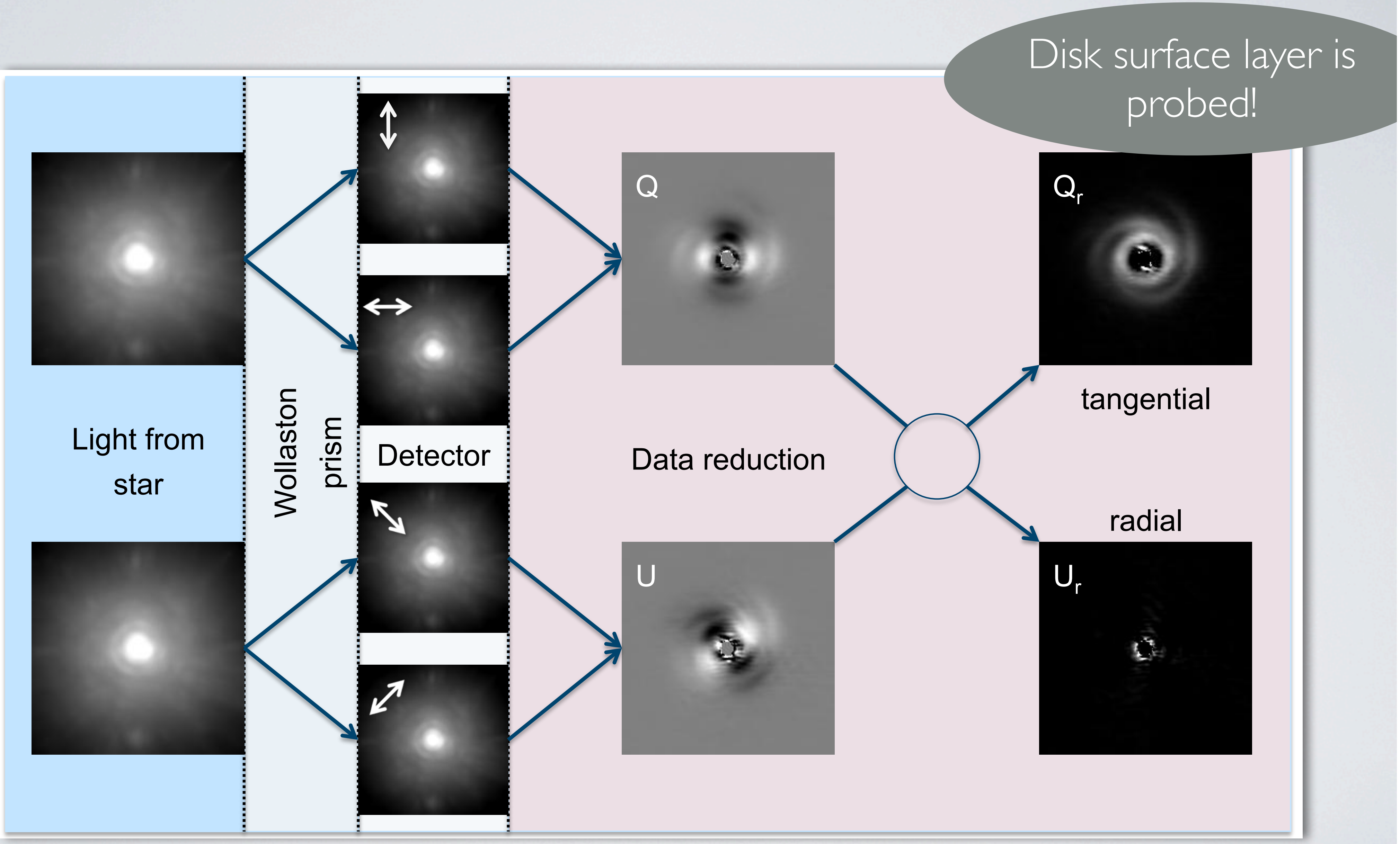
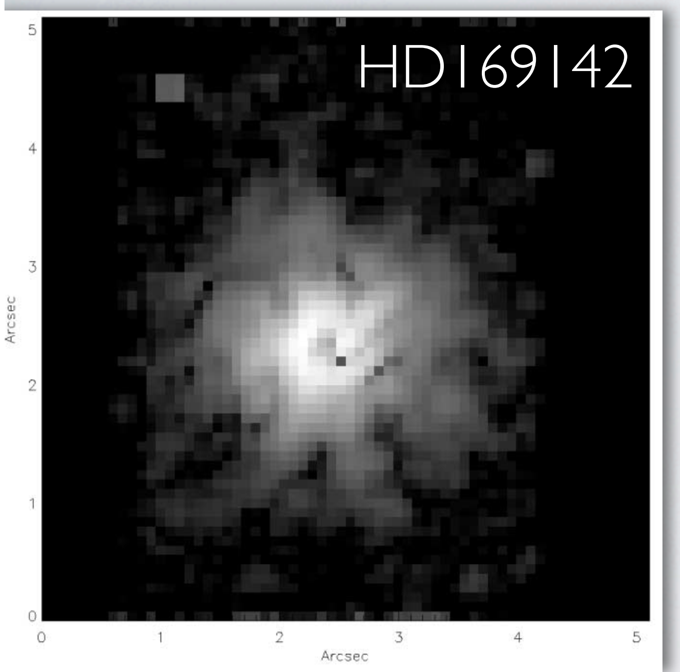
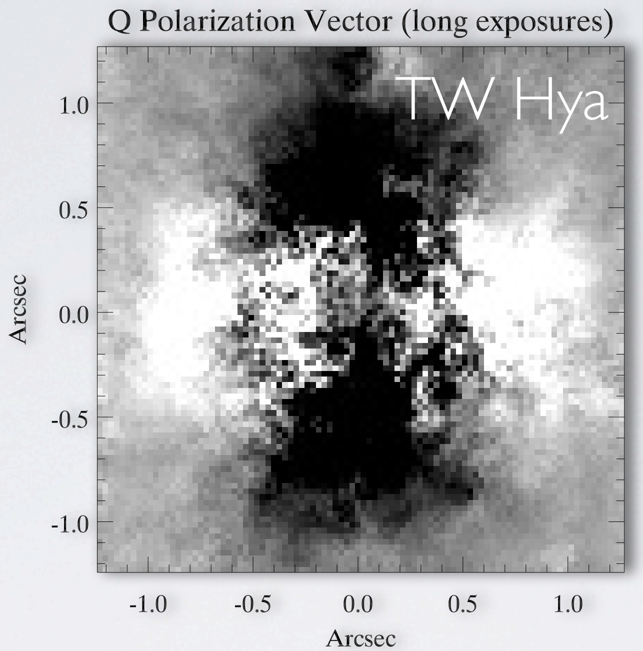
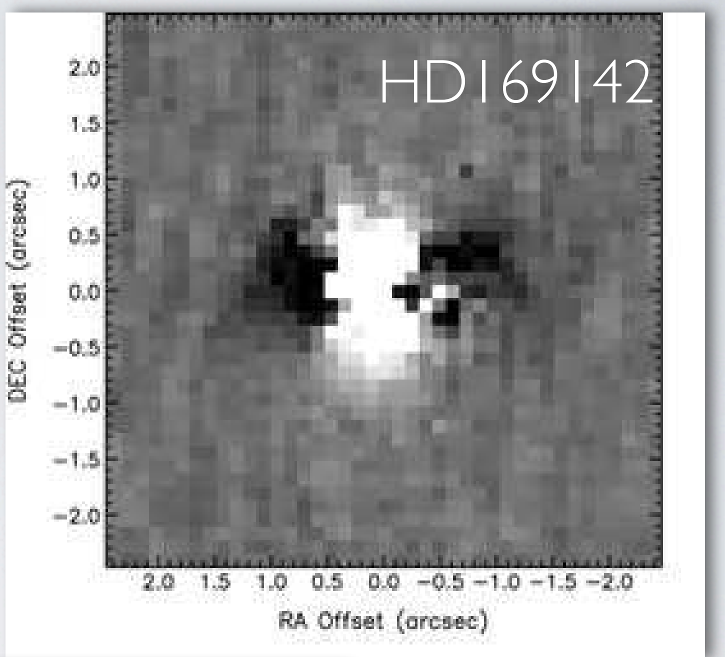


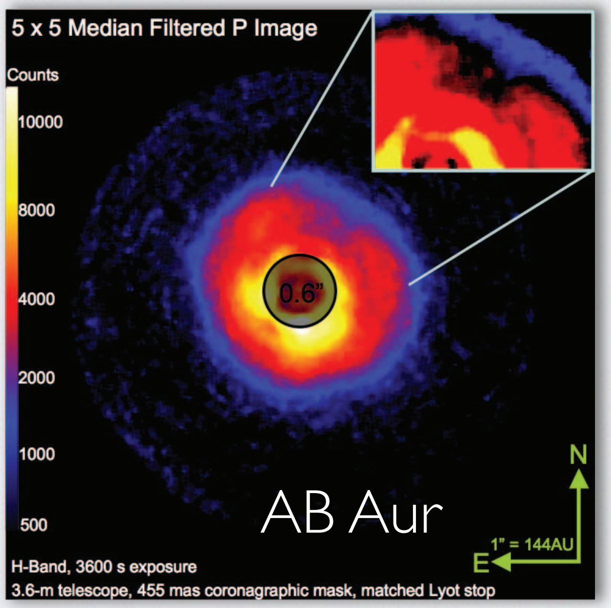
Image credit: H. Avenhaus

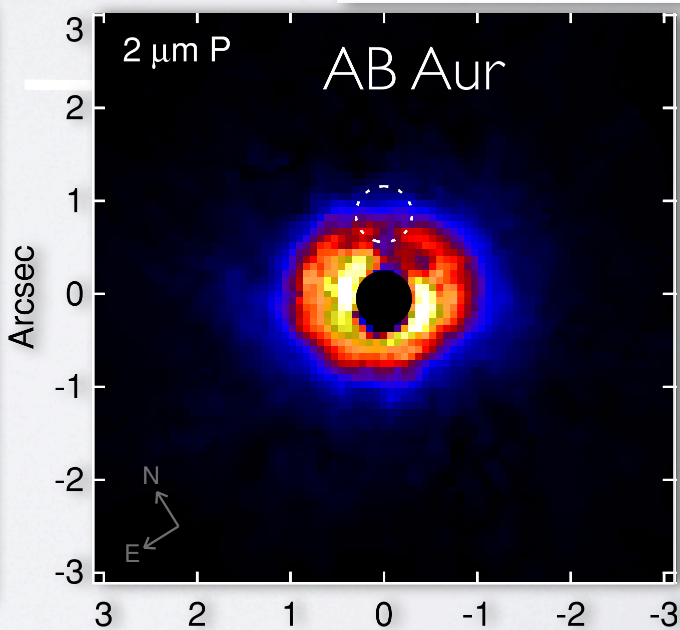
PDI is not a new technique...





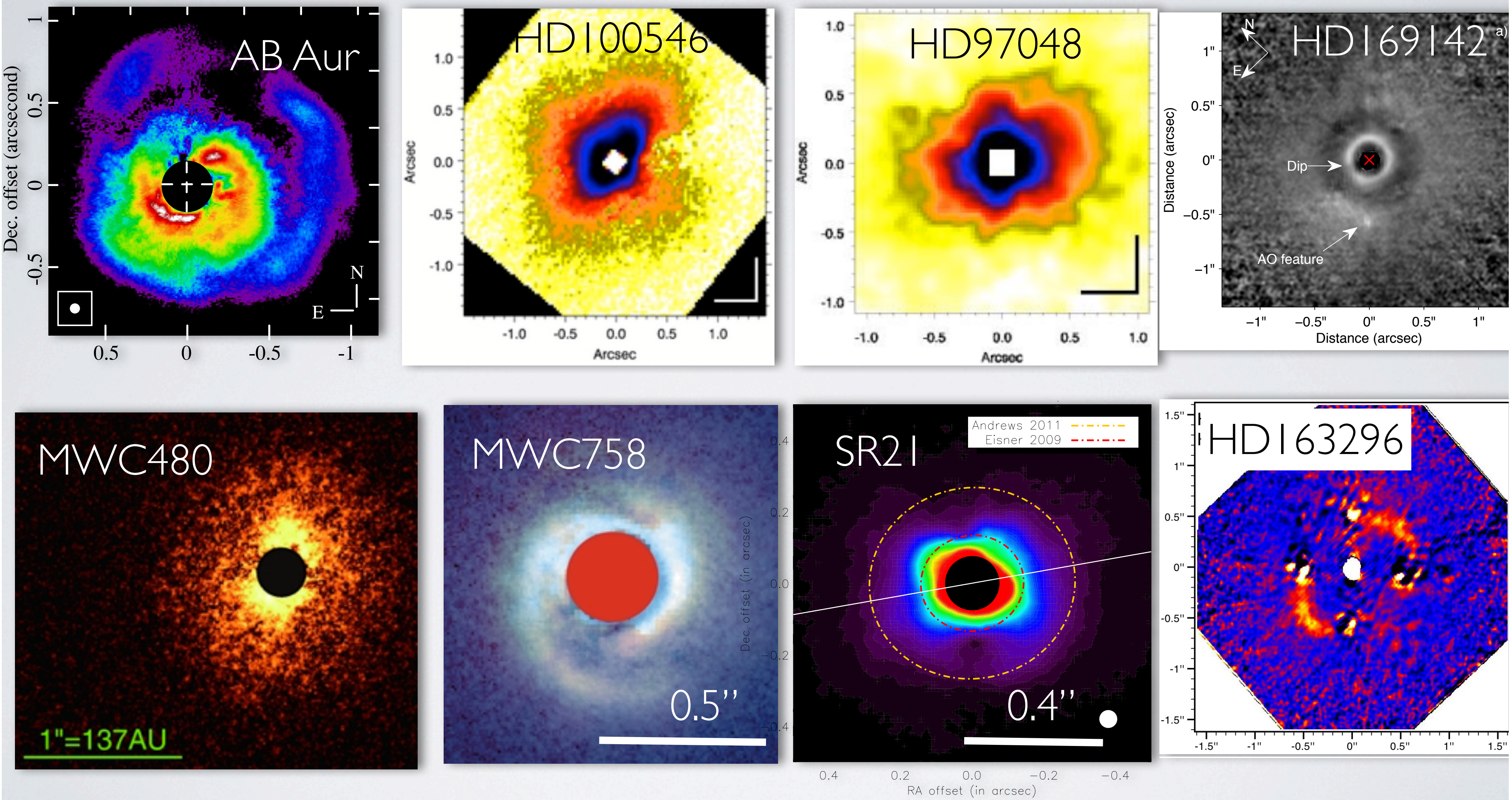






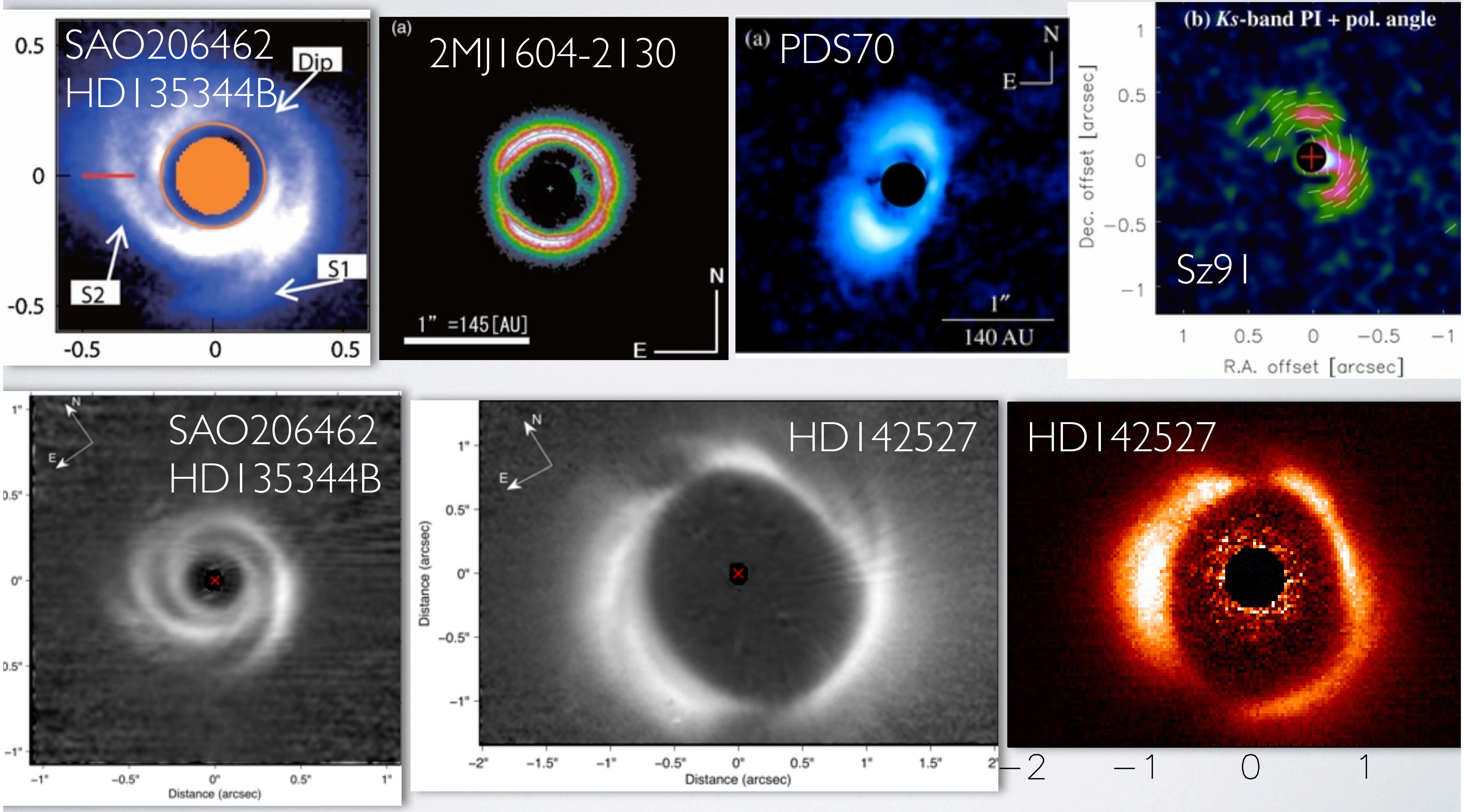
Kuhn et al. 2001; Apai et al. 2004; Hales et al. 2006; Oppenheimer et al. 2008; Perrin et al. 2009

...but in the last 3 years a lot of new results came out



Hashimoto et al. 2011; Quanz et al. 2011,2012; Kusakabe et al, 2012; Grady et al. 2013; Folette et al. 2013; Garufi et al. 2014

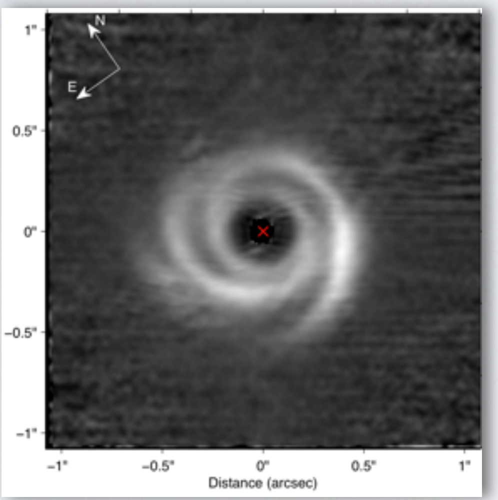
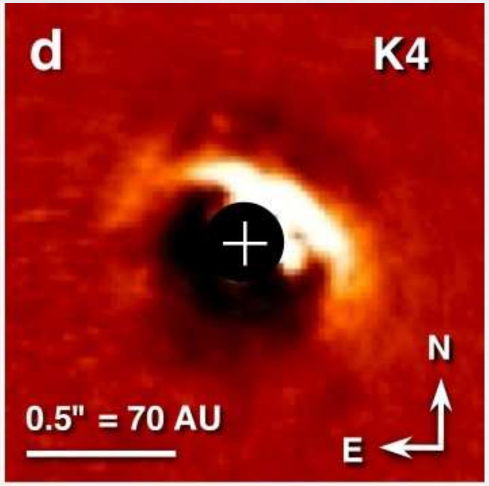
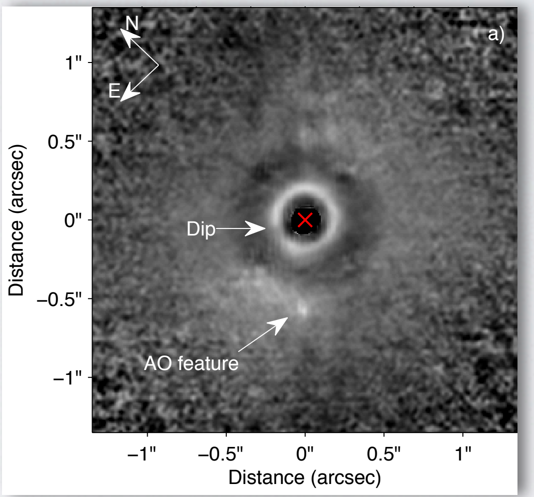
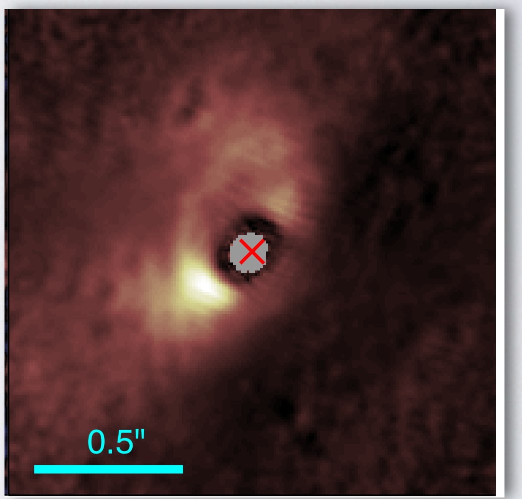
...but in the last 3 years a lot of new results came out



Muto et al. 2013; Garufi et al. 2013; Avenhaus et al. 2014; Canovas et al. 2013; Tsukagoshi et al. 2014; Mayama et al 2012; Hashimoto et a;. 2012

Have learned anything about planet formation?

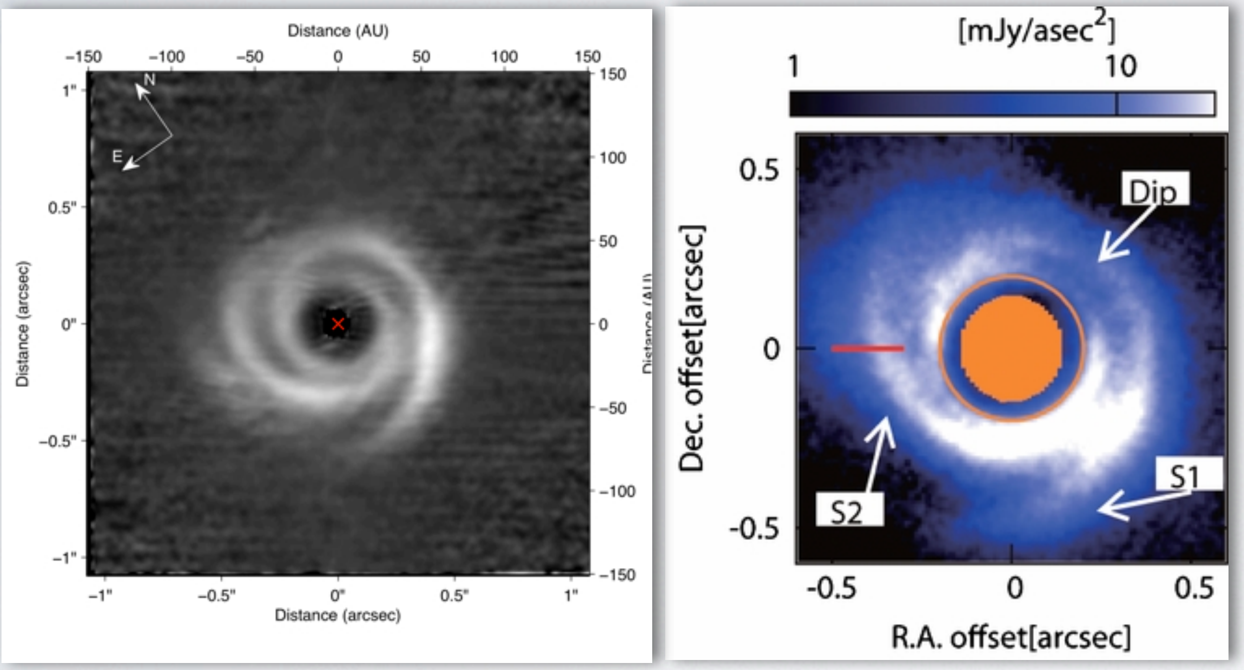
4 case studies:

SAO206462	LkCa 15	HD169142	HD100546
			
0 planets (yet)	**1 planet**	**2(?) planets**	**2(?) planets**

Is there a planet hiding in the disk of SAO206462?

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

PDI images in the NIR



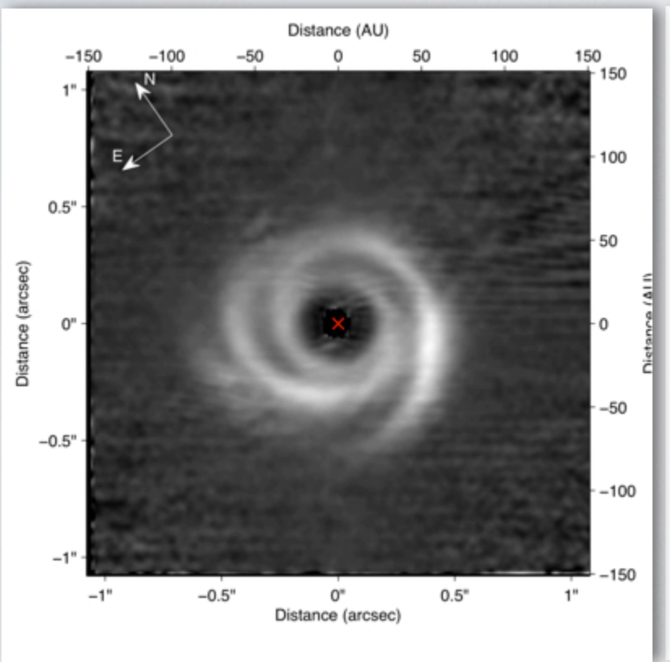
- Inner cavity <28 AU
- Strong spiral arm structure

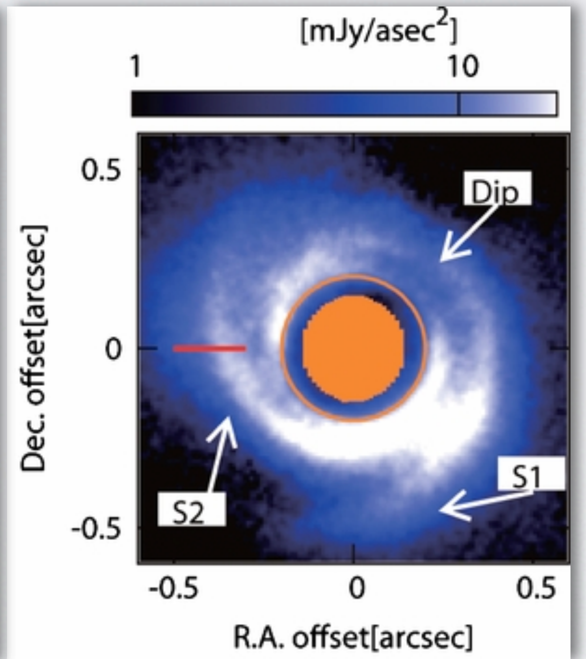
Muto et al. 2013; Garufi et al. 2013

Is there a planet hiding in the disk of SAO206462?

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

PDI images in the NIR





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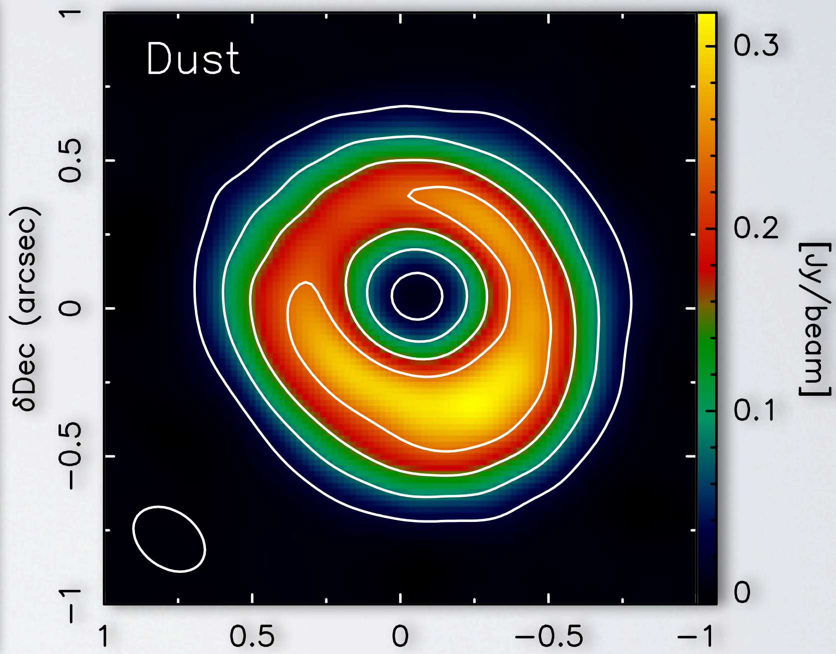
- Strong spiral arm structure

ALMA / SMA image

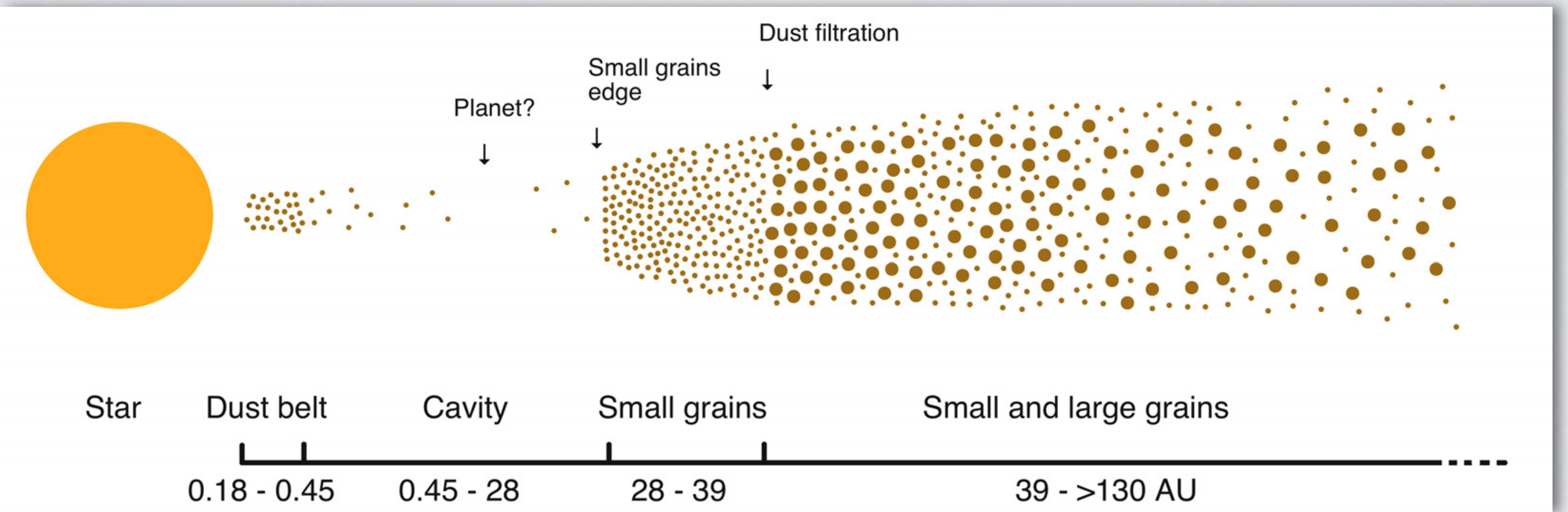


- Inner cavity ~40-45 AU
- Some brightness asymmetry

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

Is there a planet hiding in the disk of SAO206462?

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

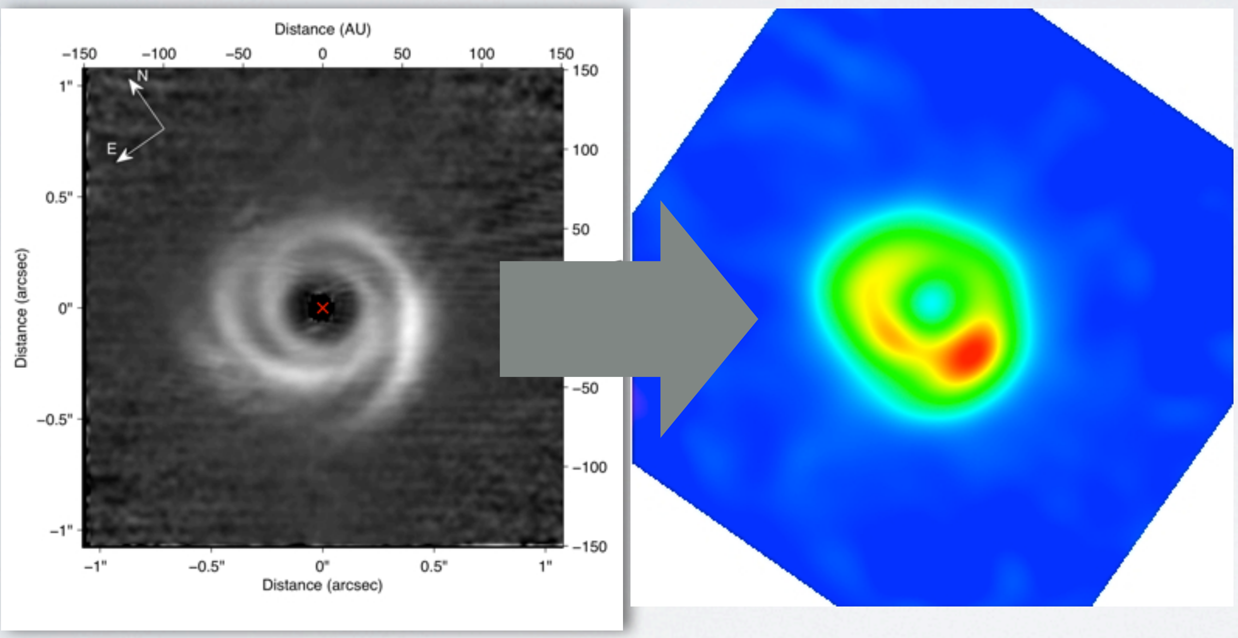


See also poster from Ke Zhang

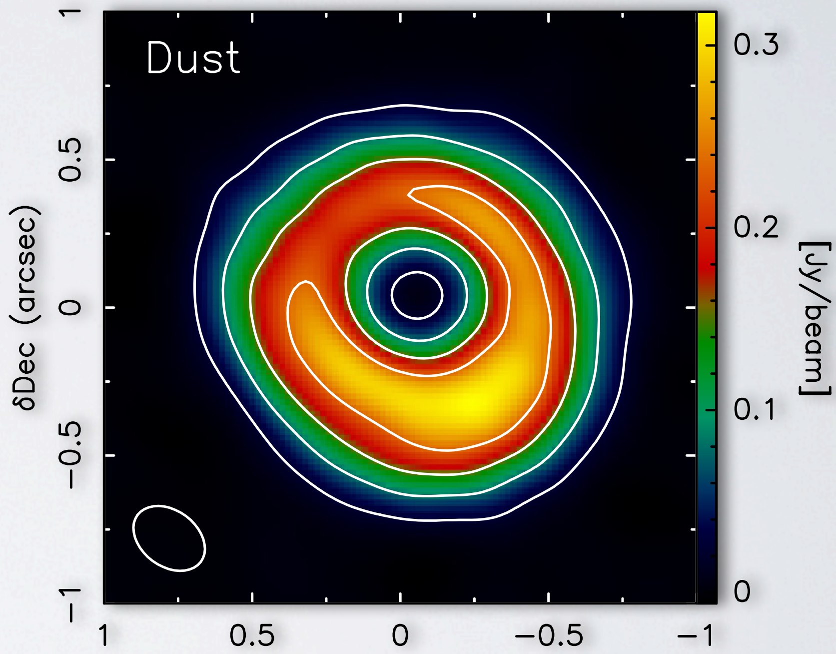
Garufi et al. 2013; e.g., Pinilla et al. 2012; Zhu et al. 2012; de Juan Ovelar et al. 2013

Is there a planet hiding in the disk of SAO206462?

NACO PDI image scaled to ALMA resolution



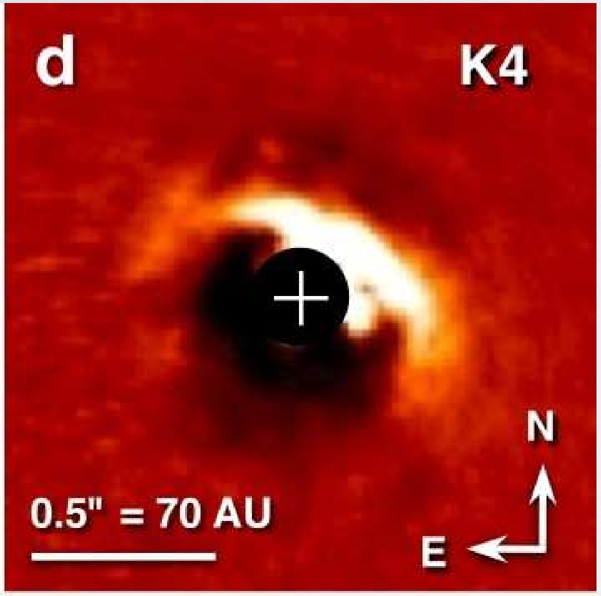
ALMA / SMA image



The planet candidate in the LkCa 15 disk

Not PDI!

Scattered light Subaru Ks



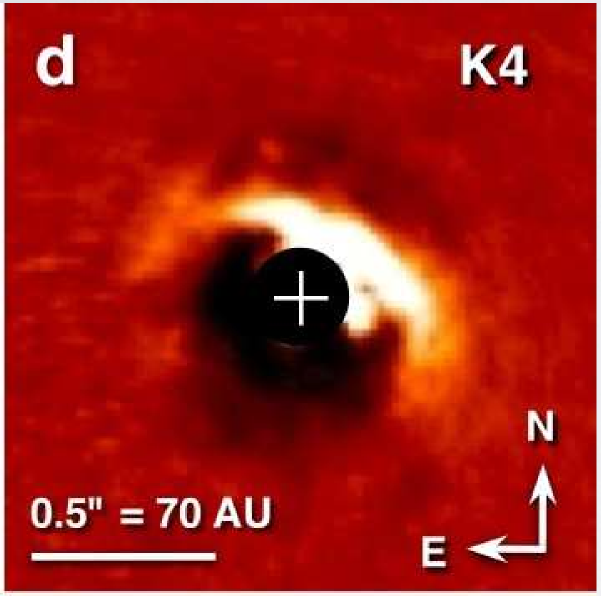
- Inner cavity <40-50 AU
- Eccentric cavity?
- Strong forward scattering

Thalmann et al. 2011,2014

The planet candidate in the LkCa 15 disk

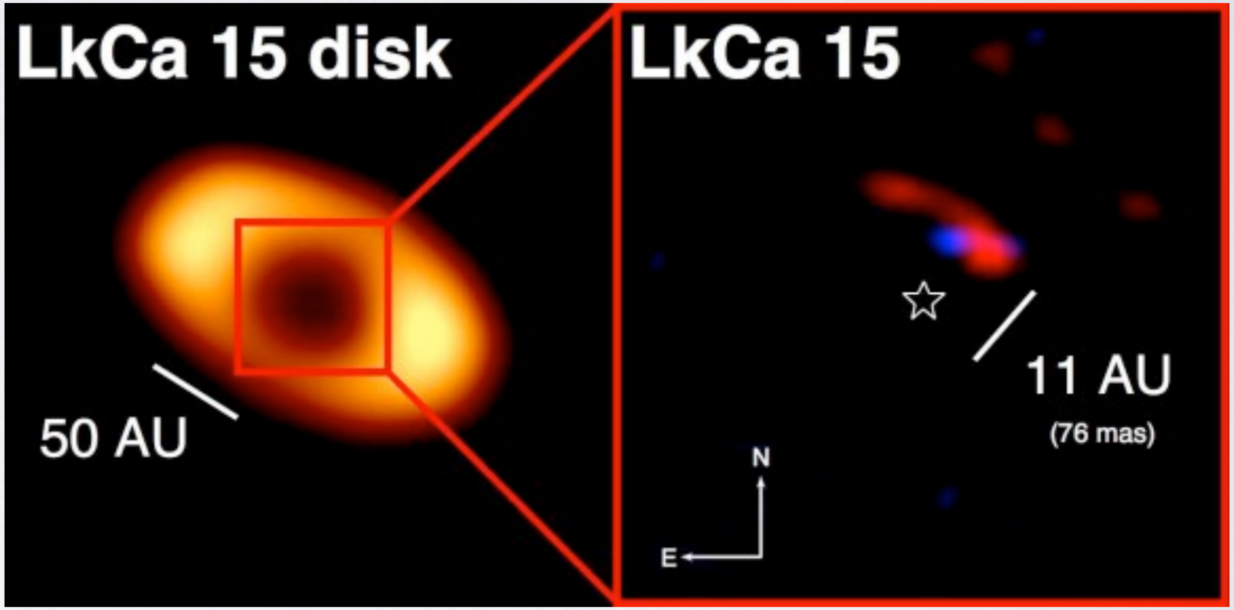
Not PDI!

Scattered light Subaru Ks



- Inner cavity <40-50 AU
- Eccentric cavity?
- Strong forward scattering

SMA 850 micron + Keck aperture masking



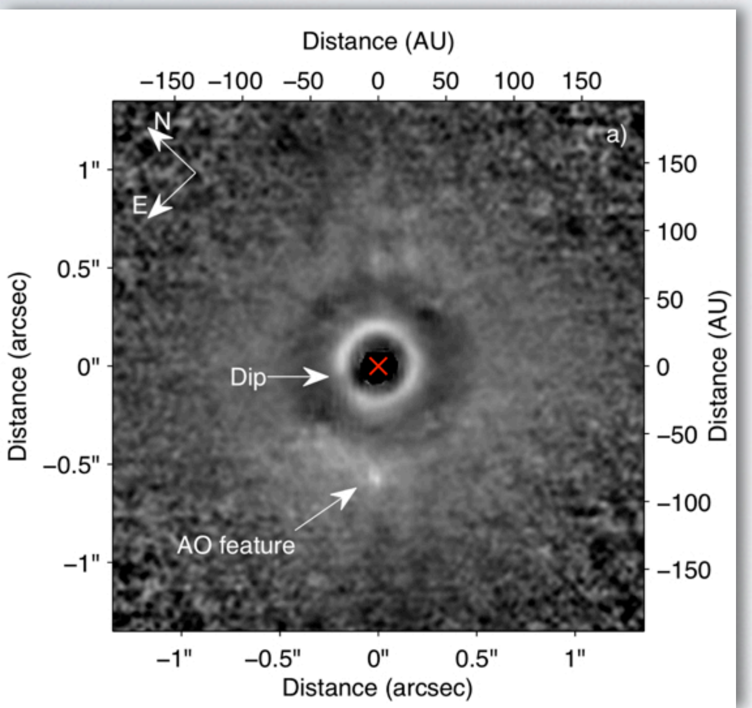
- Cavity with comparable radius
- Companion candidate in the cavity

See also poster from Andrea Isella

Thalmann et al. 2011,2014; Kraus & Ireland 2012; Andrews et al. 2011

HD169142 - sequential planet formation?

H band PDI image

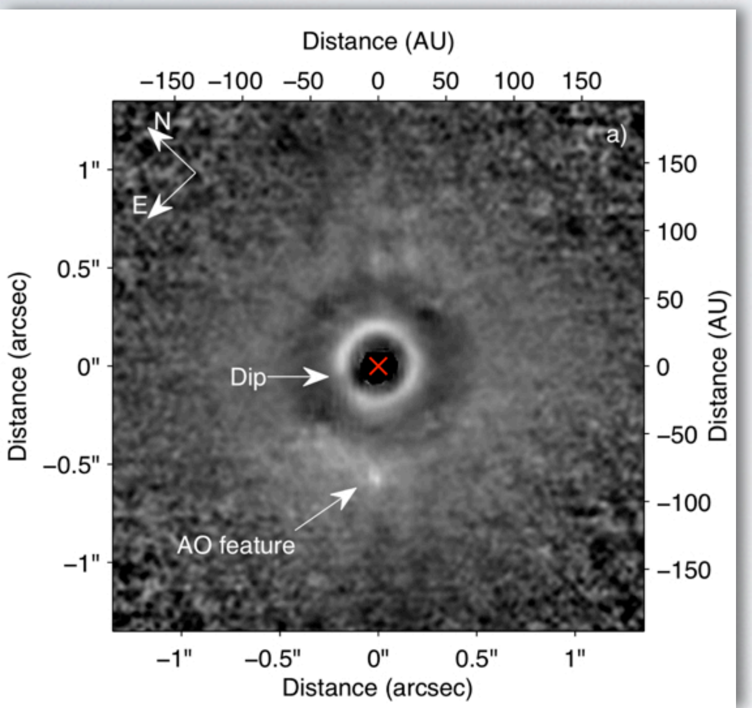


- Inner cavity <25 AU
- Annular gap ~40-70 AU

Quanz et al. 2013

HD169142 - sequential planet formation?

H band PDI image



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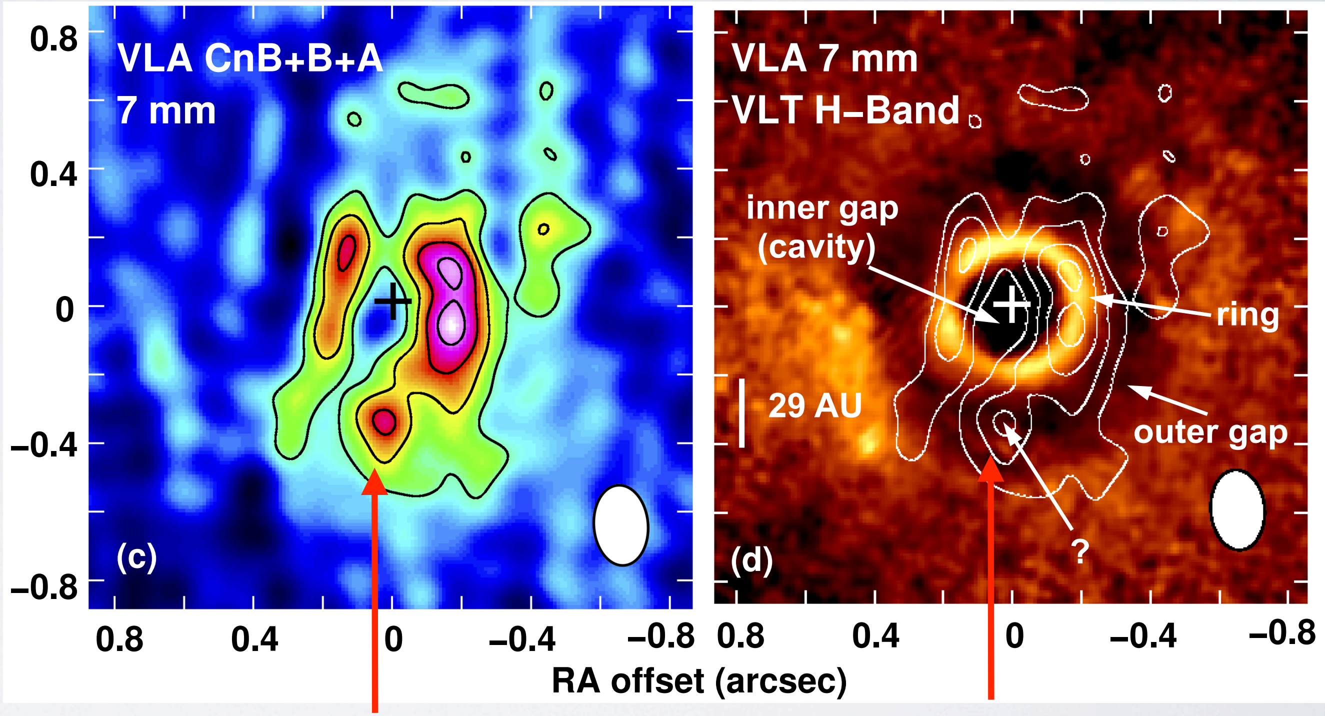
7 mm VLA

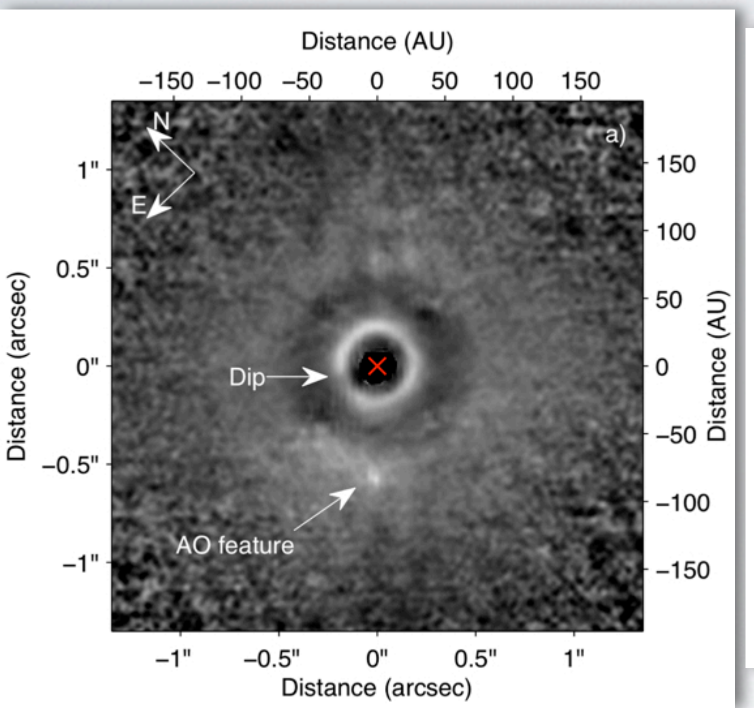


- ~5 sigma 'overdensity' - planet?

Quanz et al. 2013; Osorio et al. 2014

HD169142 - sequential planet formation?

H band PDI image



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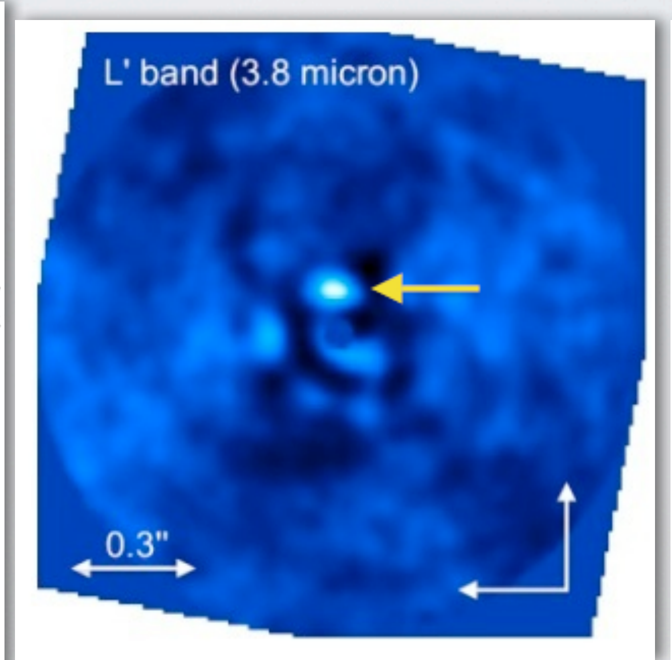
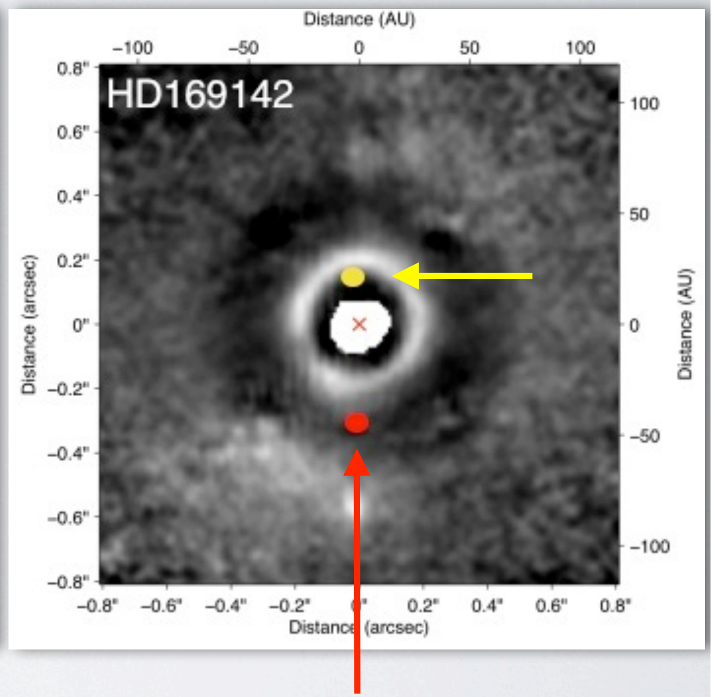
L band high-contrast image



- L band point source
- Not (yet) detected in J with GPI
- Not detected with MagAO

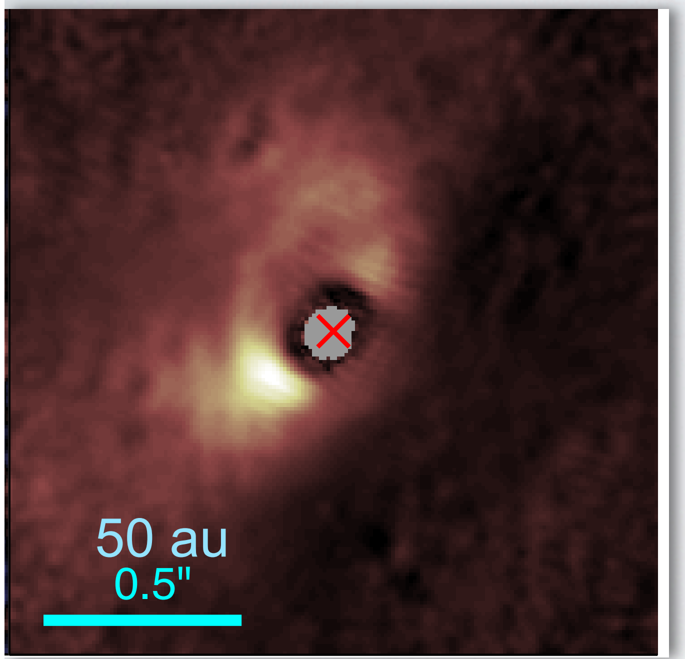


- 7mm source not detected in L'

Quanz et al. 2013; Reggiani et al. 2014; also Biller et al. 2014

HD100546 - sequential planet formation again?

H band PDI image

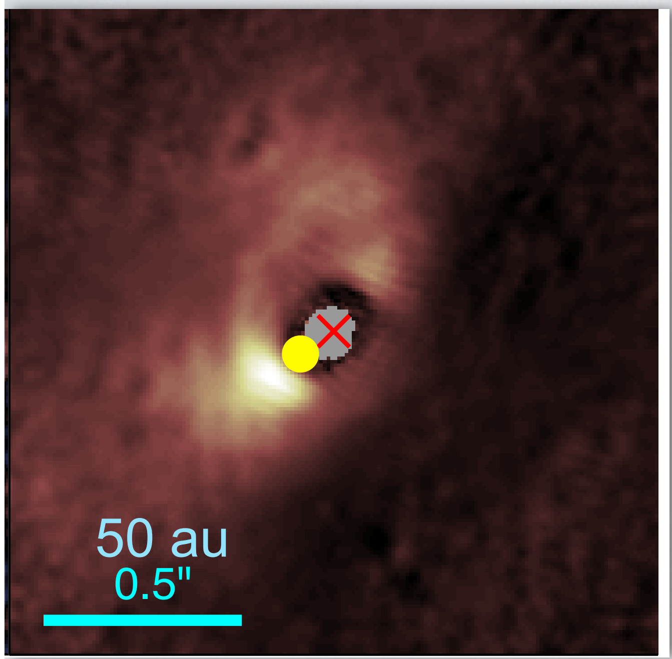


- Inner cavity <14 AU
- Brightness asymmetry

Avenhaus et al. 2014; Quanz et al. 2011

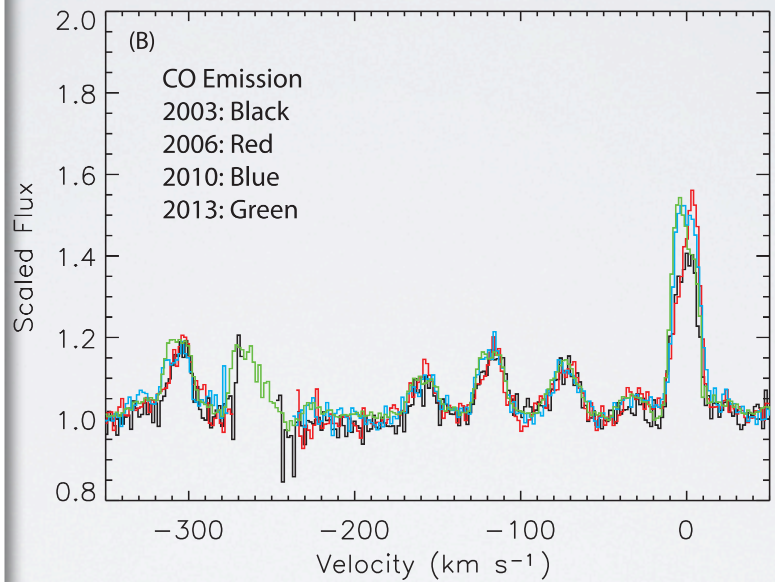
HD100546 - sequential planet formation again?

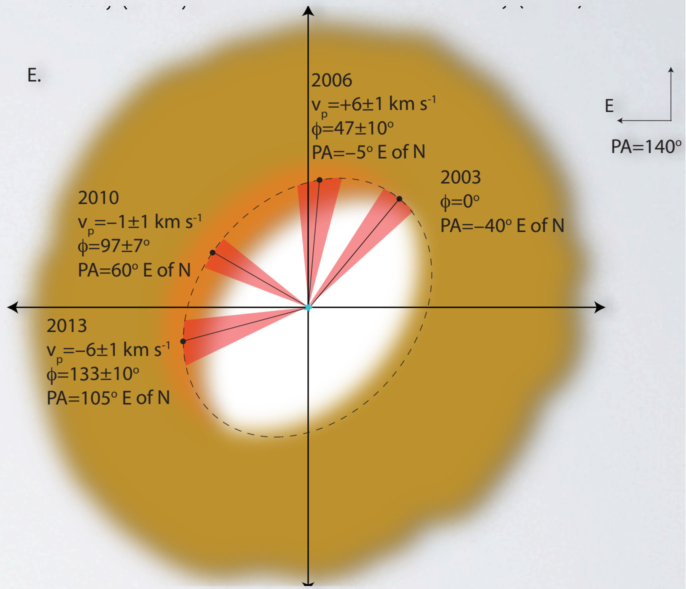
H band PDI image



- Inner cavity <14 AU
- Brightness asymmetry

High dispersed M band spectroscopy





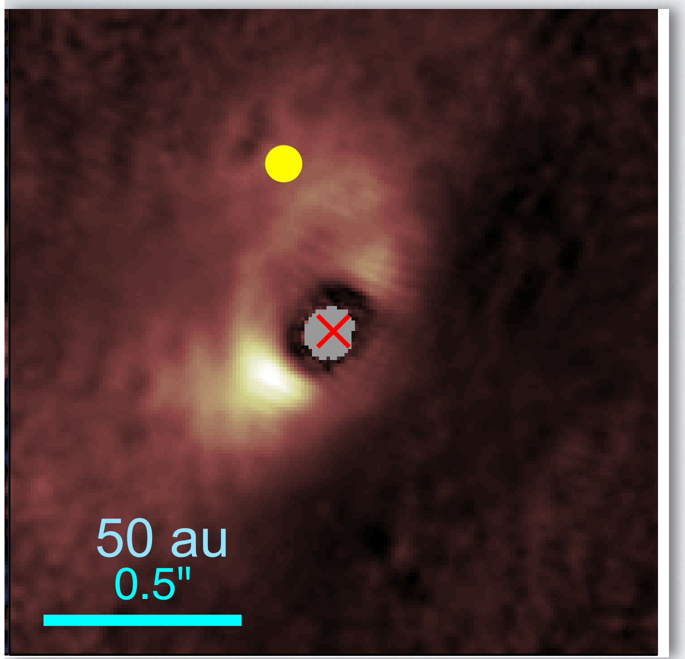
- Fundamental CO ro-vibrational lines
- Hot-band lines static
- v=1-0 P26 line varies

- Spectro-astrometric signal consistent with orbiting body

Avenhaus et al. 2014; Quanz et al. 2011; Brittain et al. 2013,2014

HD100546 - sequential planet formation again?

H band PDI image



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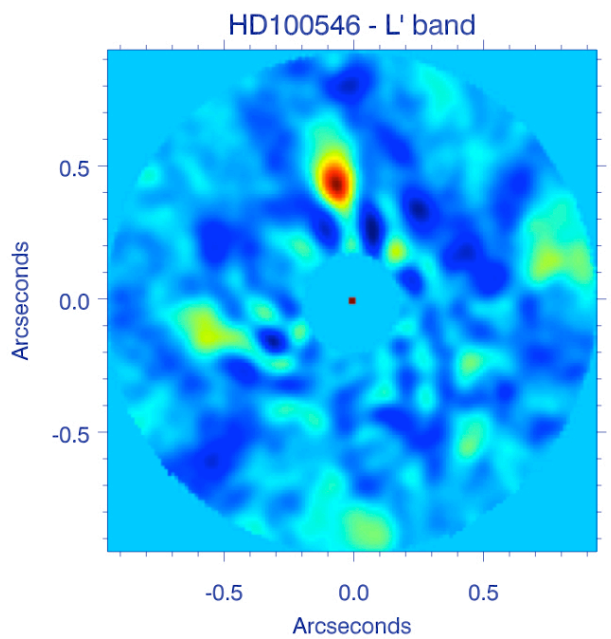
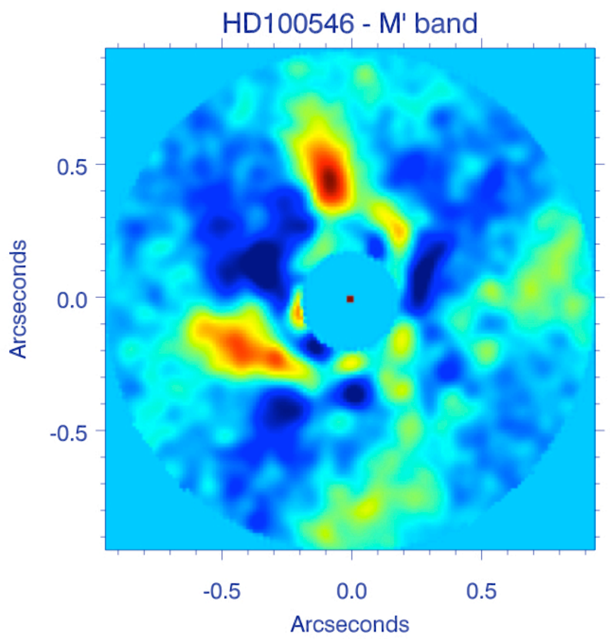
L and M band high contrast images



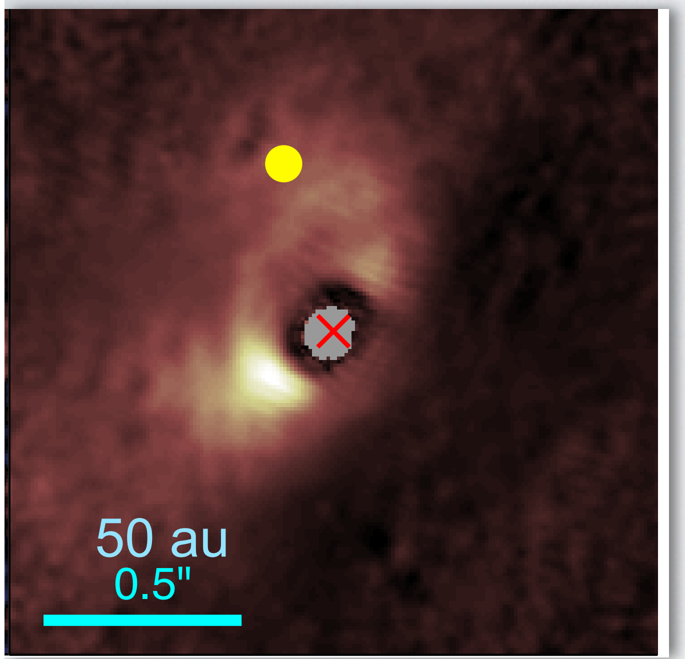


- Point source + plus extended emission at 0.48"
- Very red: L=13.9 mag; M=13.3 mag; K>15.4 mag
- $T_{eff} \sim$ 1030 K; R = 6 $R_{Jupiter}$; L = 2.3*10^{-4} L_{Sun}

Avenhaus et al. 2014; Quanz et al. 2011, 2013, under review

HD100546 - sequential planet formation again?

H band PDI image



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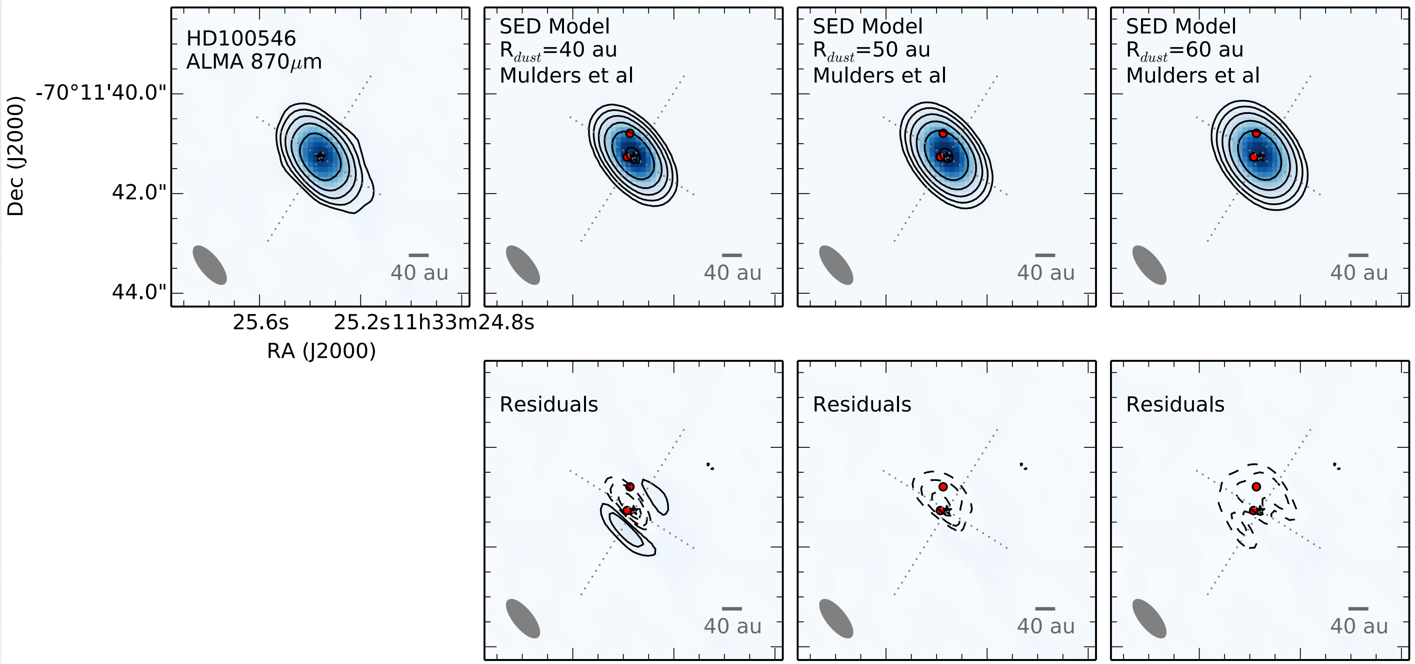
- Brightness asymmetry

ALMA dust continuum data for HD100546

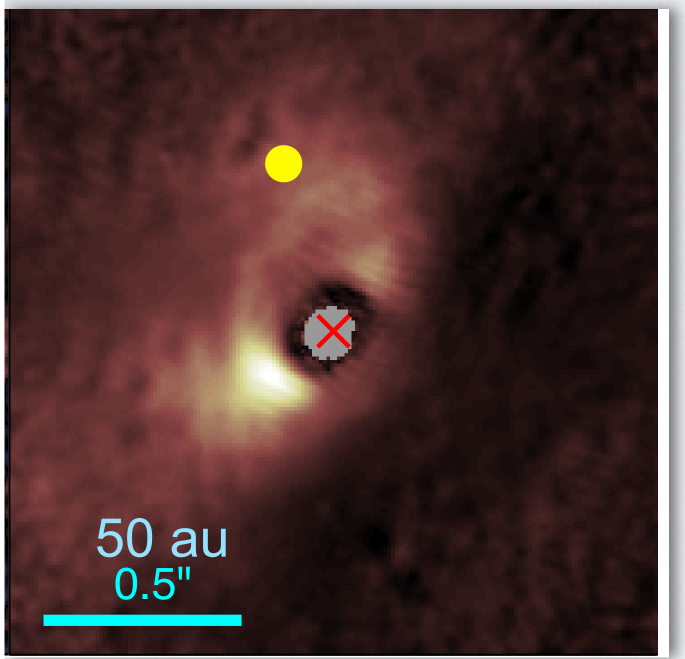


- Large grains are confined to within 50-60 au
- Gas extends out to >350 au

Avenhaus et al. 2014; Quanz et al. 2011; Pineda et al. 2014

HD100546 - sequential planet formation again?

H band PDI image



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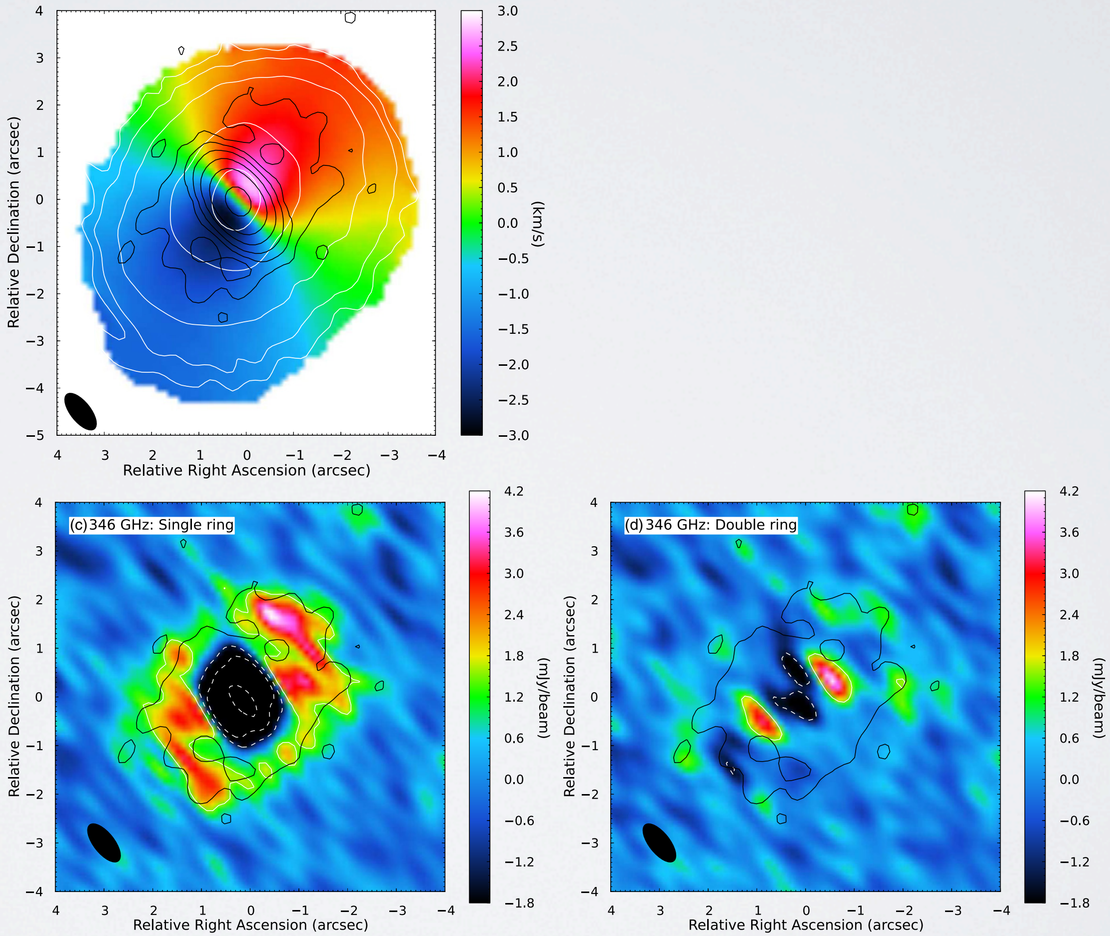

- Double-ring model fits data best

Avenhaus et al. 2014; Quanz et al. 2011; Walsh et al. 2014

Take home messages

- Polarimetric Differential Imaging (PDI) allows us to spatially resolve regions in protoplanetary disks as close as 0.1'' (~10 au) and with a resolution of 10 au; ideal to study potential formation sites of gas giant planets

- In a number of disks, PDI revealed unexpected variety of disk structures (gaps, cavities, spiral arms) part of which could be immediately related to recent / ongoing planet formation

- In a few targets we have growing observational evidence that planet(s) may (have) form(ed) in particular where various datasets (e.g., PDI, (sub-)mm imaging, high-contrast imaging) are combined

What's next?

- Increase the sample of resolved disks with PDI using Gemini/GPI and VLT/SPHERE
- Combine PDI images with ALMA data with same spatial resolution to get 3D picture of protoplanetary disks
- Derive the "big picture" messages from PDI results; a lot of in depth studies of individual objects so far, but more overarching results need to be synthesized
- Use spatially resolved information at multiple wavelengths to determine dust properties on disk surface as a function of wavelength

Thank you