The SEEDS of Planet Formation: Indirect Signatures of Giant Planets in Transitional Disks

C. Grady
and the SEEDS
consortium

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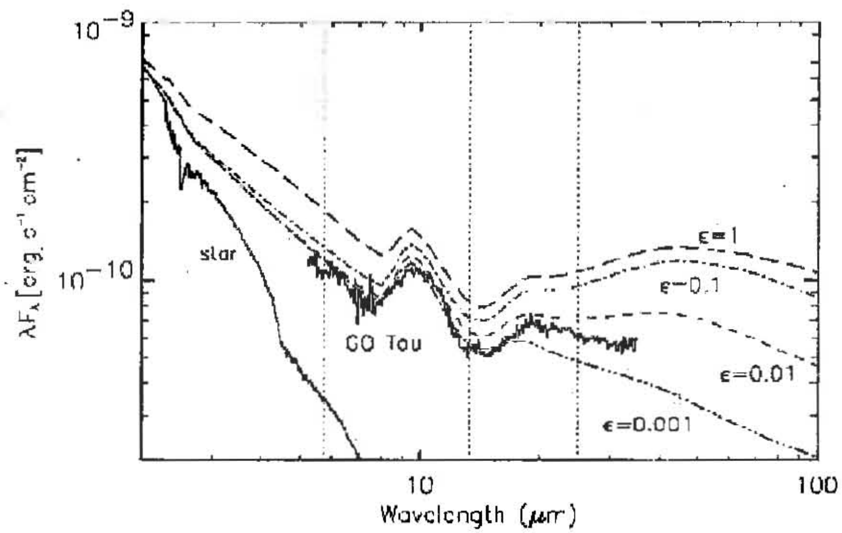
1. Background

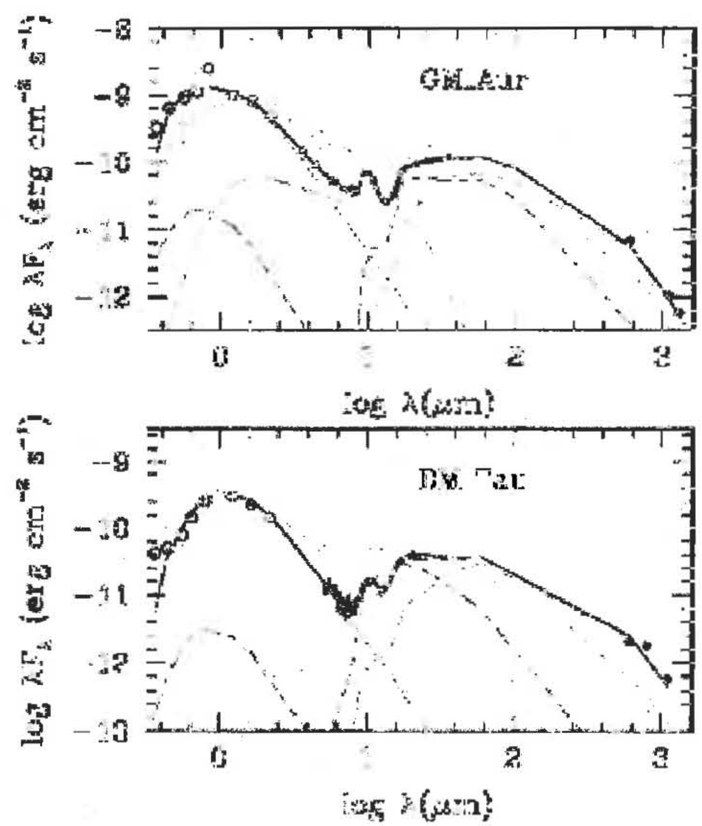
* We live in a planetary system with 2 gas giant planets, and as a result of RV, transit, microlensing, and transit timing studies have identified hundreds of giant planet candidates in the past 15 years.

* Such studies have preferentially concentrated on older, low activity Solar analogs, and thus tell us little about when, where, and how giant planets form in their disks, or how frequently they form in disks associated with intermediate-mass stars.

2. IR SEDS and Transitional Disks

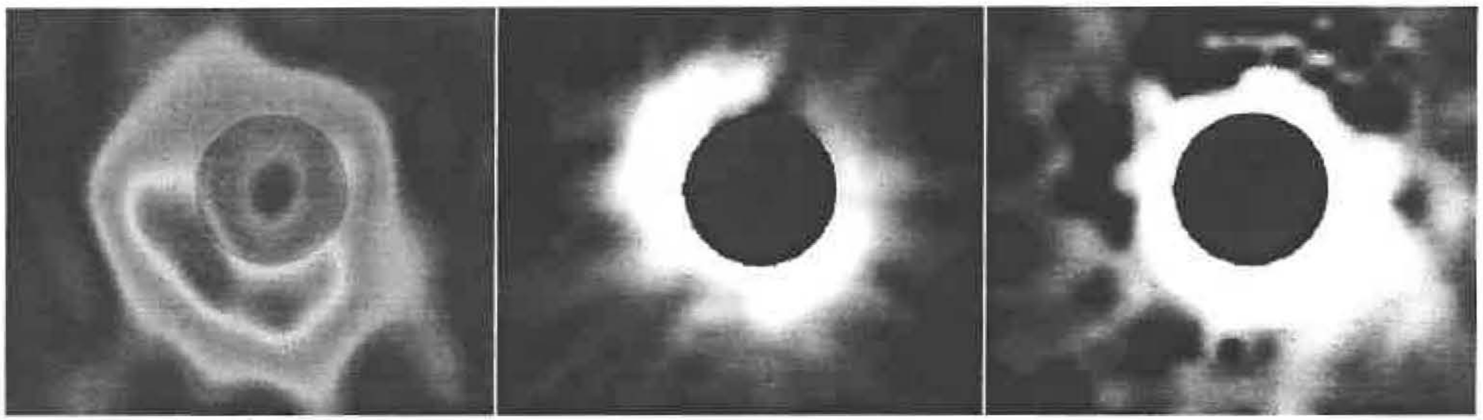


Average SED for Taurus T Tauri Stars - Furlan et al. 2005



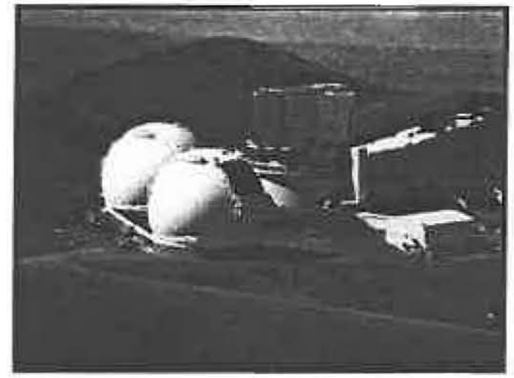
Calvet et al. 2005

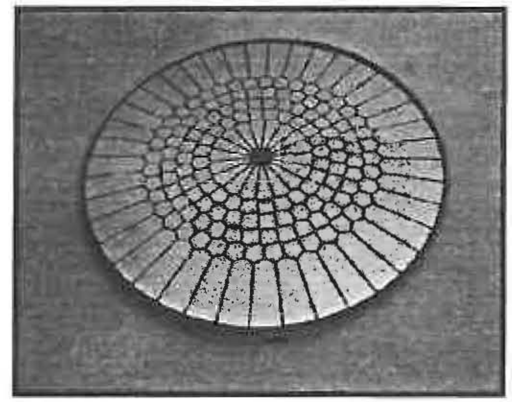
3. (sub)mm interferometry (con't)

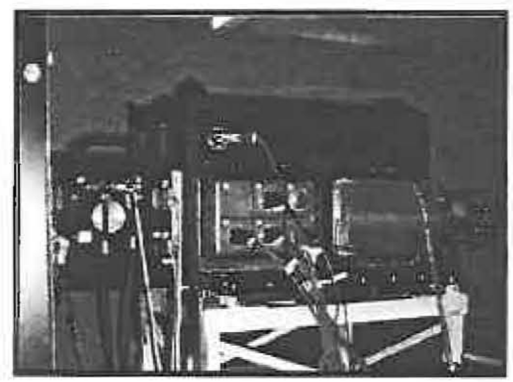


(sub)mm continuum image can also show gapped rings (Pontoppidan et al. 2008), with some differences from the disk appearance in scattere light (Grady et al. 2009)

Subaru High Contrast Instrumentation







- ∗ Subaru – 8.2 m telescope
- ∗ AO 188 (+ SCExAO – 1st light 2/5/2011)
- ∗ Classical Lyot Coronagraph
- ∗ HiCIAO – NIR Science camera
  - ∗ Direct Imaging
  - ∗ Simultaneous Differential Imaging
  - ∗ Polarization Differential Imaging
  - ∗ Modes can be combined

The Strategic Exploration of Exoplanets and Disks with Subaru - YSO Survey

* 5-year Subaru strategic programs (Tamura et al. 2006)

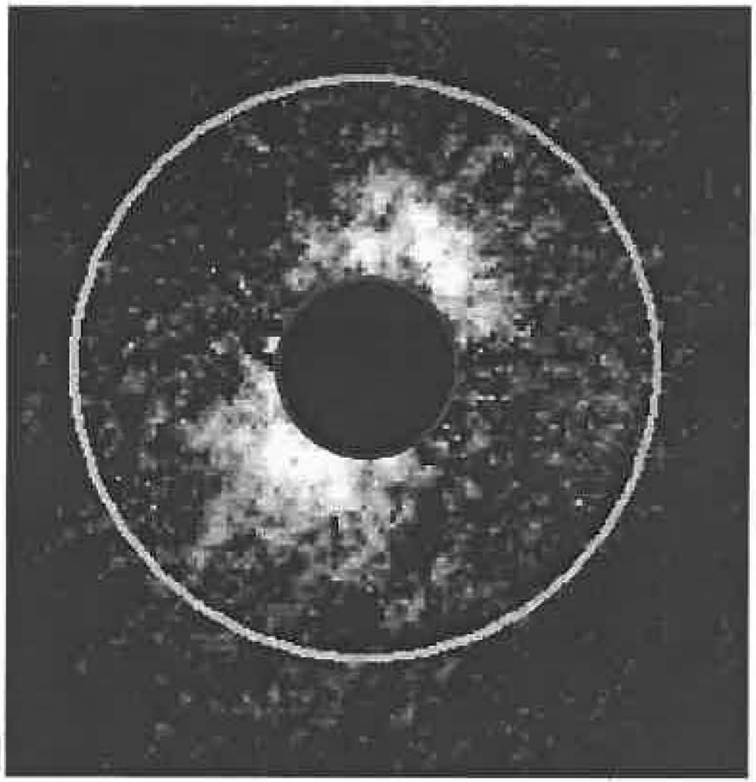
* YSO survey of 210, 1-10 Myr old objects, both single and binary/multiple stars

* Bulk of objects will be studied at H-band using Polarimetric Differential Imaging (Hinkley et al. 2009) + Angular Differential Imaging (Thalmann et al. 2010).

* ~30 transitional disks in hand

* 85% of the objects in Andrews et al. (2011) have been observed, as well as more recently identified systems.

What Protoplanetary Disks Look Like in PDI



M
Kusakabe et al. 2012

- Disk is brightest along semi-major axis

- PI concentrates toward disk semi-major axis – progression with inclination.

- Depolarization due to scattering angle
along the system semi-minor axis

- Short integration times for PDI+ADI limit region where the disk can be imaged to r<1″ unless the disk is bright.

Expectations from the (sub)mm for transitional disks

* With an inner working angle of ~0.15" (21 AU at 140 pc), would expect to image the outer portions of the wide gaps or central cavities seen in the mm data.

* Large depletions of grains in these cavities are required to fit the SED and the (sub)mm data.

* Had expected to see holes – inner dust belts detected in NIR interferometry would be indirectly detected only if they shadow the outer disk.

* Expected little diversity among transitional disks with wide gaps.

Disk Structure:

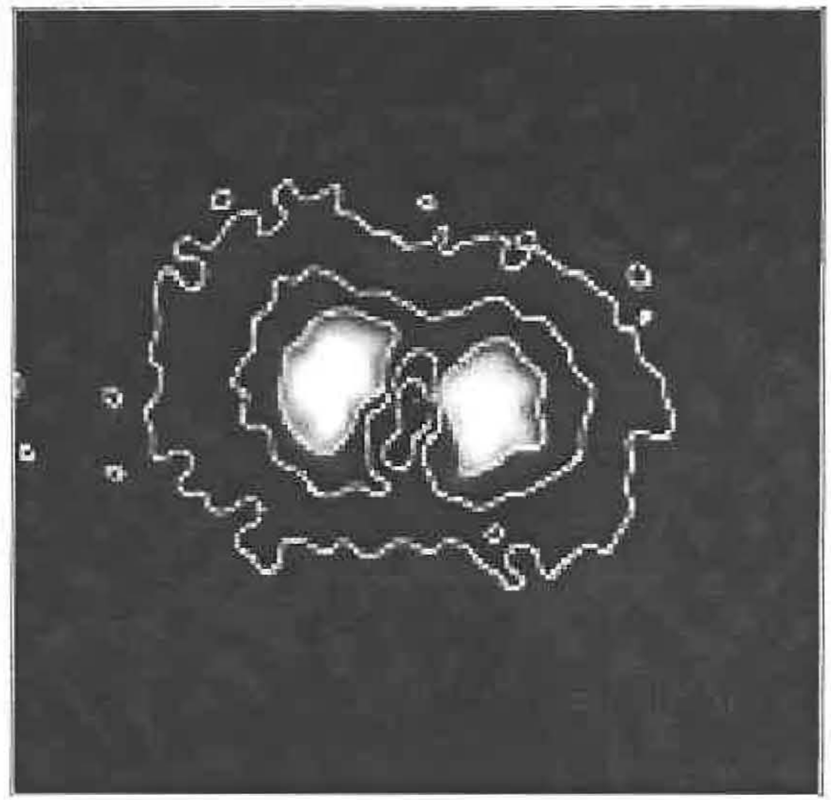
* If PDI is combined with angular differential imaging can use variants of LOCI to retrieve portions of disks with sharp edges at expense of suppression of smooth features.

* If field rotation is sufficiently large, can use the ADI+LOCI processed data to detect planets.

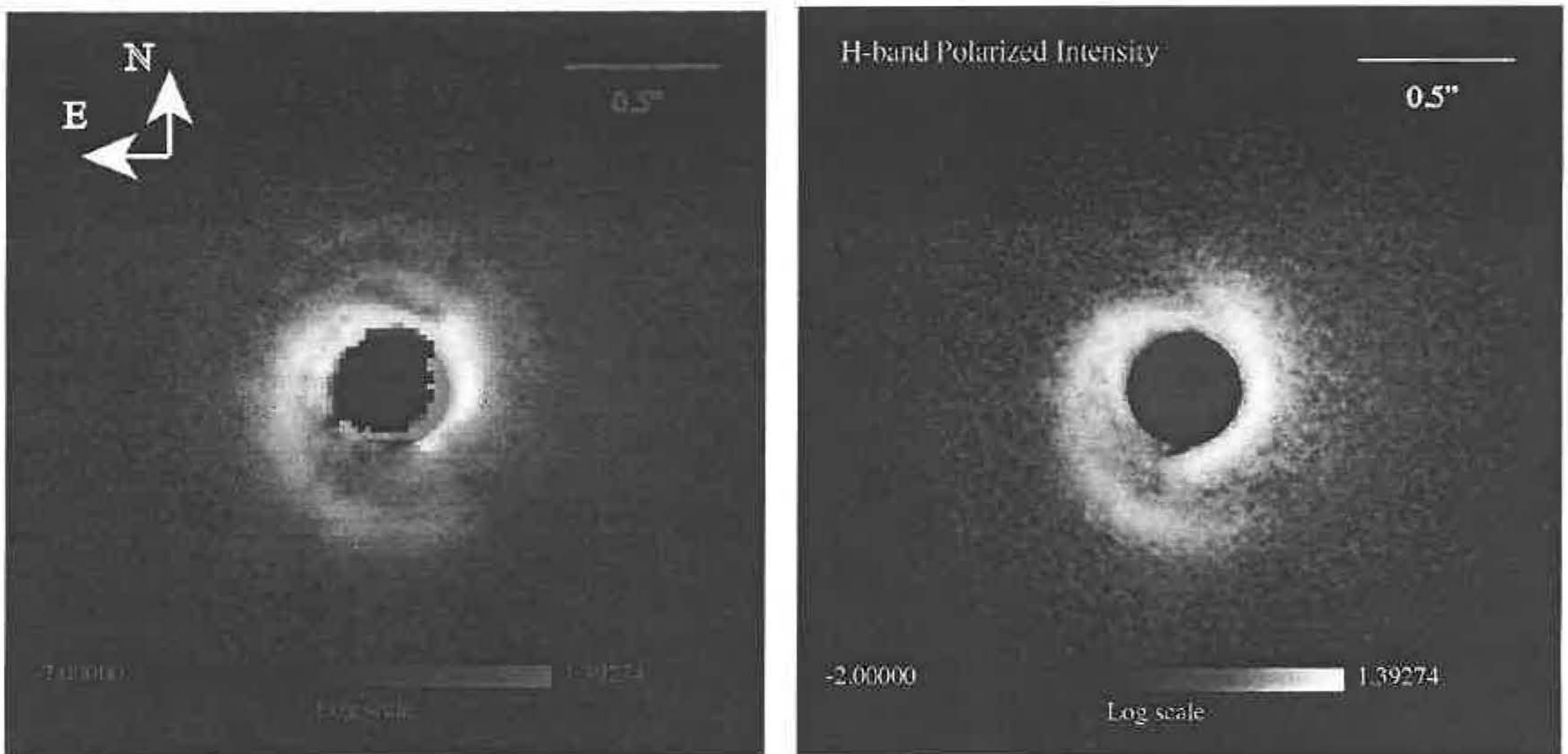
* PI for this disk has material in the gap region (Wisniewski et al. 2012 in prep), but did not detect the outer disk – function of short integration times. HST saw the outer disk.

LkCa 15: Thalmann et al. (2010)

Spiral Arcs – from same region as bright mid-IR emission

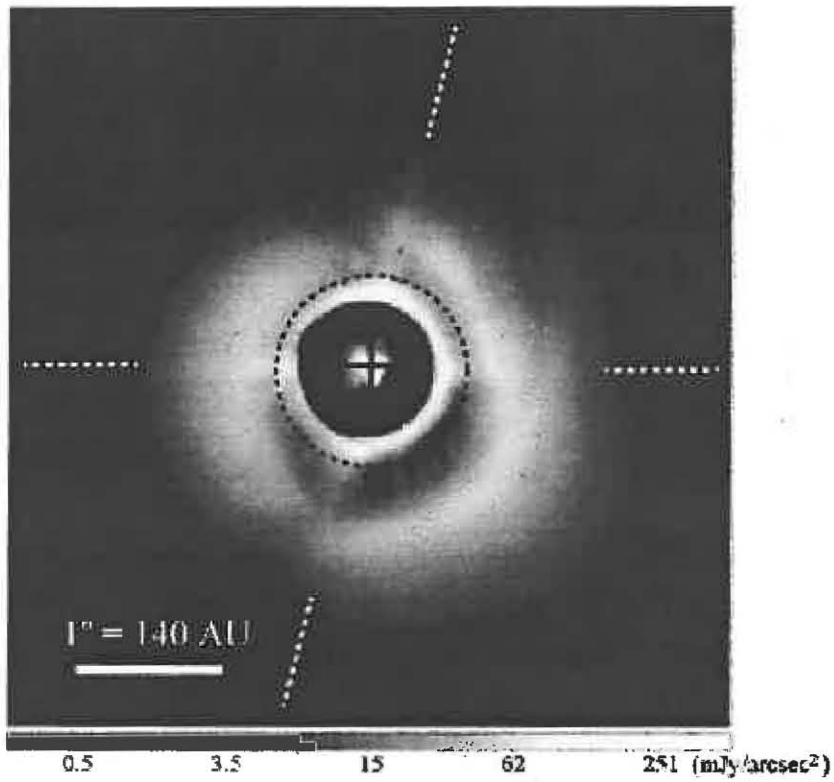


IS SAO 206462 UNIQUE? - No



Grady et al. 2012, (in prep).

Phenomenon not limited to disks around single stars?



- HD 142527

H band total intensity
Fukagawa et al. (2006)

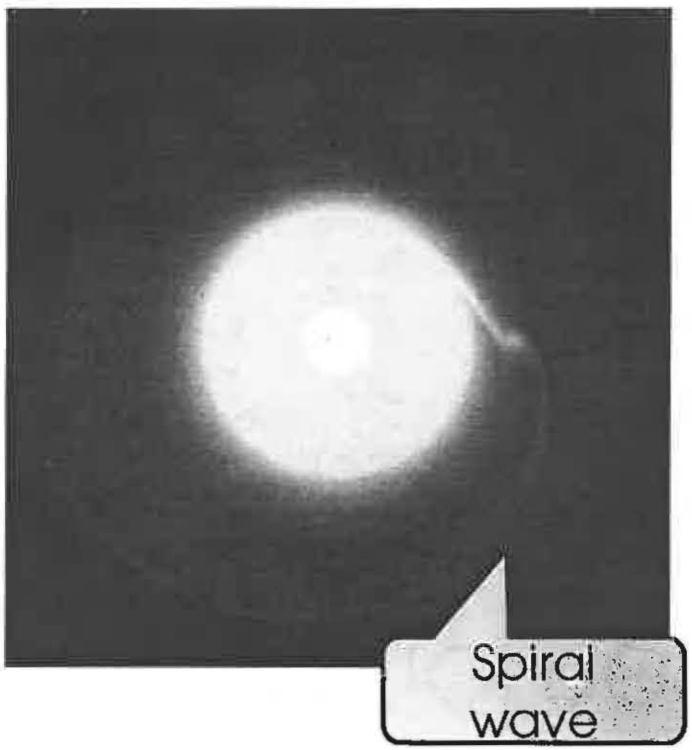
- recently claimed as an 88 mas-separation binary star (Biller et al. 2012).

- wall features are all spirals at higher angular resolution

Spiral Density Wave

The approximate form of the spiral density wave:

$$\theta(r) = \theta_0 - \frac{\mathrm{sgn}(r-r_p)}{h_p}\left[\left(\frac{r}{r_p}\right)^{1+\beta}\left\{\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta}\left(\frac{r}{r_p}\right)^{-\alpha}\right\} - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta}\right)\right]$$



(r_p, θ_0): the location of the launching point

h_p: disk aspect ratio at the launching point

α: power-law index of the rotation angular frequency

β: power-law index of the sound speed

[redacted]

Some Notes on Spiral Density Wave

* The shape of the spiral density wave
  * Depends only on the corotation point and the disk temperature (i.e. sound speed)
  * The theory is robust

* IF the spiral density wave is caused by an embedded planet, the amplitude of the perturbation gives you a rough estimate of the mass of the planet.

$$\frac{\delta\Sigma}{\Sigma} \sim \frac{M_{\rm p}}{M_*}\left(\frac{H}{r}\right)^3$$

Prediction for Future Observations

* Spiral pattern rotates at the Keplerian velocity at the corotation point ($r=r_p$)

$$\omega = 0.8\left(\frac{r_p}{70\mathrm{AU}}\right)^{-3/2}\left(\frac{M}{1.7M_\odot}\right)^{1/2}\ [\mathrm{deg/yr}]$$

- The spiral patterns in SAO 206462 will move ~10° (corresponding to the movement of 0.1″ at r=0.5″) over ~10 years if the corotation point is at r_p=70 AU (0.5″) – faster rotation for closer-in r_p.
- Absence of rotation over a time period then indicates that the perturber is distant from the star.

What we have learned so far

* Spiral arms in ~33% of the SEEDS transitional disks – numbers range from 2-8 per star – systems are not "transitional", but already are young planetary systems
* ~12% have cavities visible at H or K
* Some objects have both cavities and arms
* Detections are preferentially for low inclination disks (11-21°) where foreshortening is not an issue.
* Detections are for warmer disks (h~0.1 and higher). This is dictated by the Strehl ratios of the imagery.
* Perturbers come in sub-Jovian and few Jovian masses (at least) – work in progress.

Conclusions

* Transitional and pre-transitional disks show a wide range of NIR structure compared either to primordial or debris disks. - poor correlation with deficit of material required to fit (sub)mm, or with depth of dip in SED.

* Better correlation with mid-IR (12, 18 micron imagery)

* Thus far cannot predict what the structure will be for a particular disk – except that wide spirals are found in disks after a few Myr.

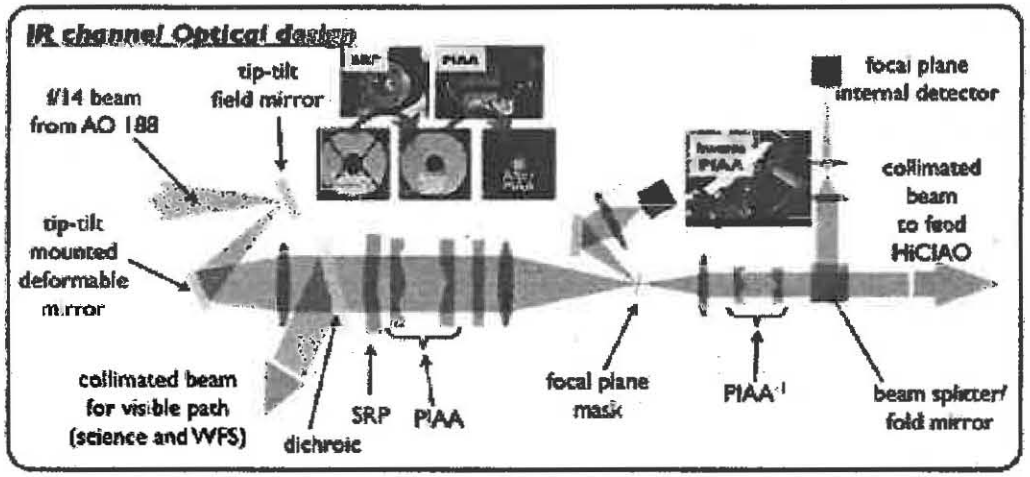
* Spiral arm data, and pericenter offsets for some gaps can be used to constrain the mass and location of the perturbing planet independent of its luminosity.

* Expect to have preliminary mass estimates within a year. Searches for the planets are in progress.

LkCa 15 Image Credit: Sky & Telescope, Casey Reed

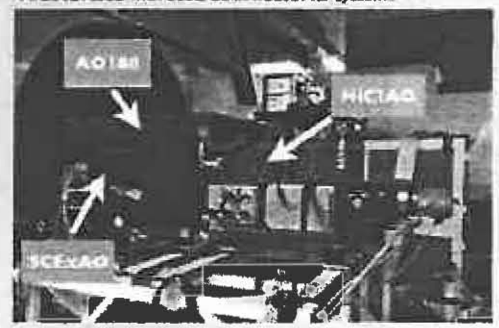
Extreme AO at Subaru: SCExAO

- **First light Feb. 2011**
- **Two telescope engineering runs completed**



SCExAO engineering observations

SCExAO is an upgrade to the existing coronagraphic imager HiCIAO used with Subaru's in house AO system.



SCExAO on the Subaru IR Nasmyth platform, before craning behind AO. On September 11, 2011, SCExAO had its first engineering observing night with acceptable observing conditions

First on-sky demonstration of small IWA coronagraphy by PIAA

Images acquired on the binary star HIP101769 (separation: 0.238" i.e. ~6 λ/D in H-band) in four different optical configurations of SCExAO. Compare the apparent change of size of the focal plane mask in panels **b** (4.75 λ/D Lyot-type coronagraph), and **d** (1.5 λ/D PIAA-coronagraph):

The inclusion of PIAA and PIAA^{-1} successfully boosts the IWA by a factor of 3!

See Martinache & Guyon 2009 SPIE