S E E D S

Polarimetric Imaging of Large Cavity Structures in the Transitional Disk around PDS 70

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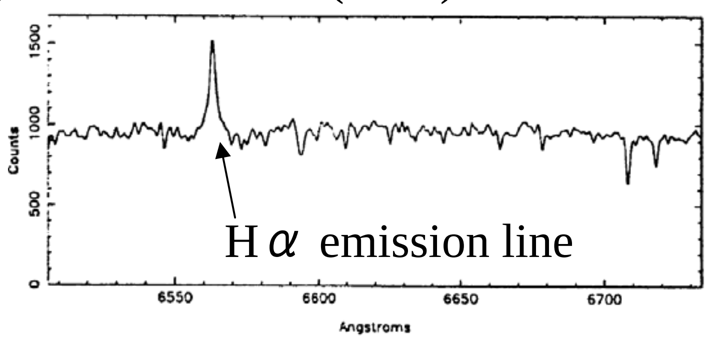
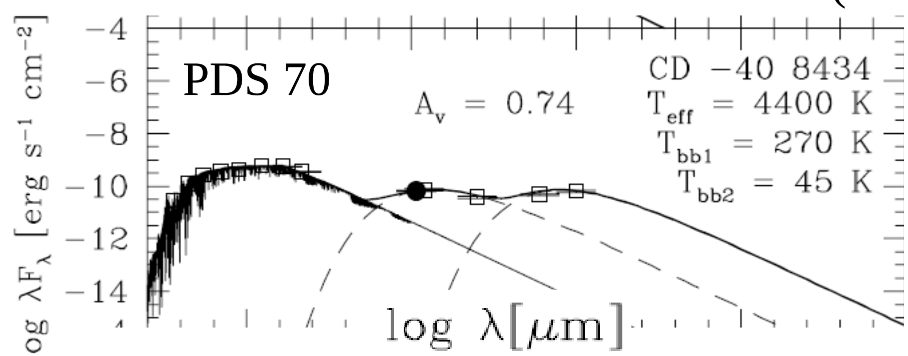
Protoplanetary disk around PDS 70

- K5 type, mass of 0.86 Mo, age of <10 Myr
- WTTS with 2Å of Hα equivalent width.
- Class II inferred by α(2.2-25μm) of -0.68

Gregorio-Heten et al. (1992)

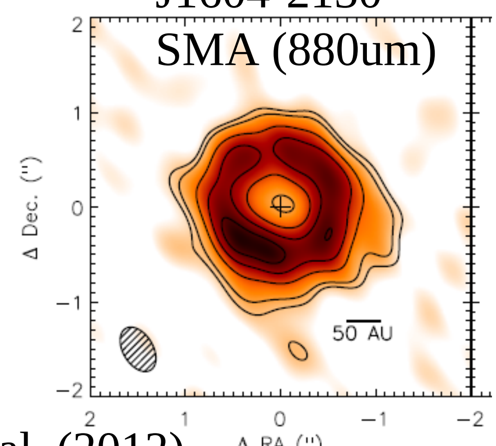


Metchev et al. (2004)



- PDS 70 could have inner hole(?)
  – Objects with WTTS and class II might be relatively rare
  – CoKu Tau 4, UX Tau A, J1604-2130 have inner holes

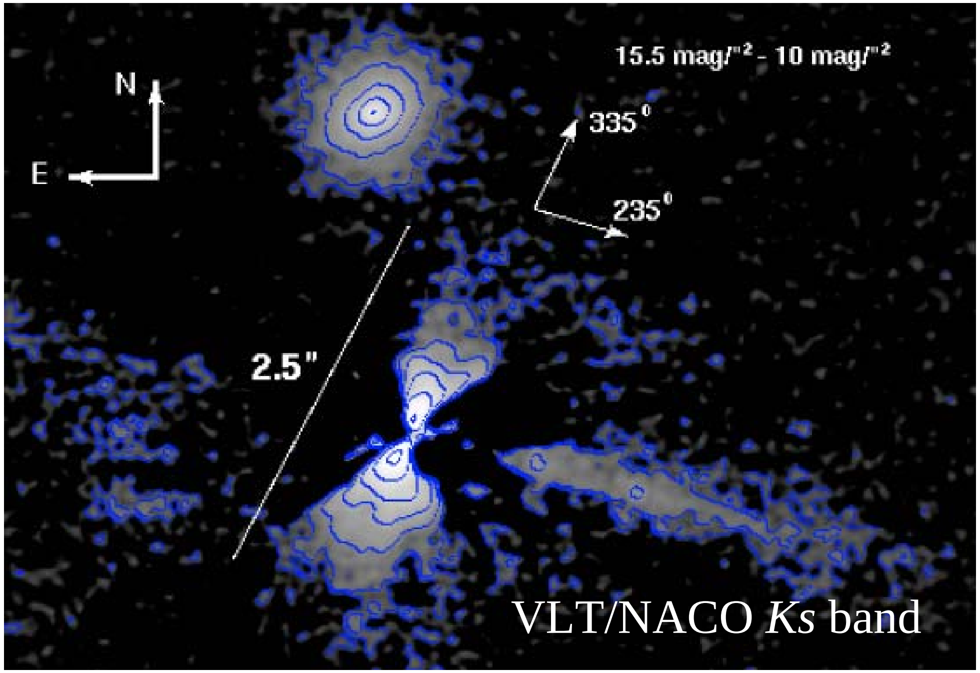
J1604-2130



Mathews et al. (2012)

Previous high resolution image of PDS 70

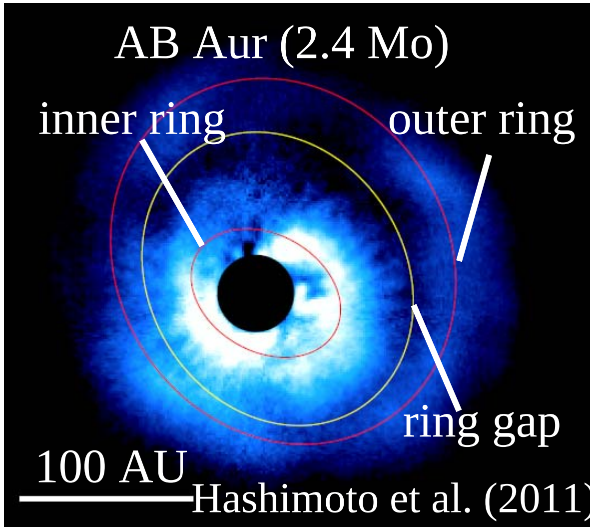
- Scattering disk with r ~ 200 AU, i~62°, PA~155°
- Companion candidate with 27-80 M_{Jup} at ~300 AU from PDS 70
- No gap has been reported.
- No radio observation has been performed.

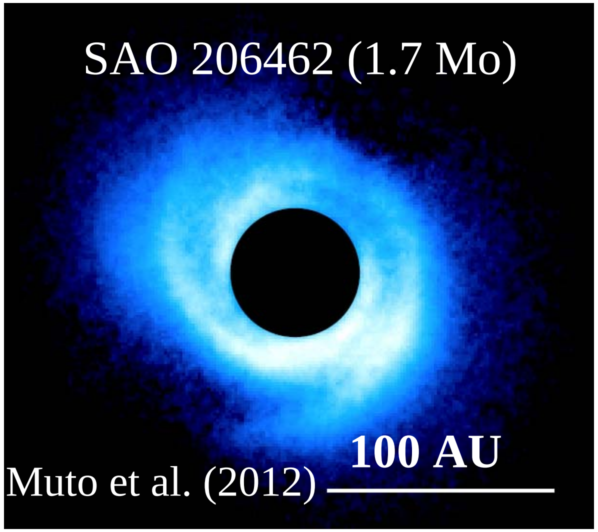


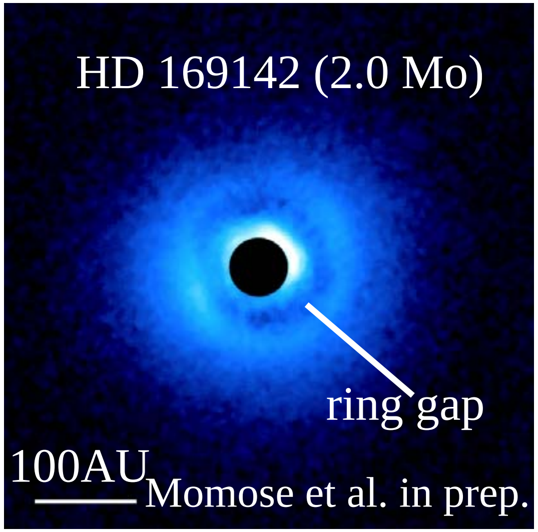
Riaud et al. (2006)

Our High Contrast Observations

- A part of SEEDS (talked by Grady)
- *H*-band Polarimetric imaging with Subaru/HiCIAO for the disk detection
- *L'*-band imaging Genimi S/NICI for the companion detection



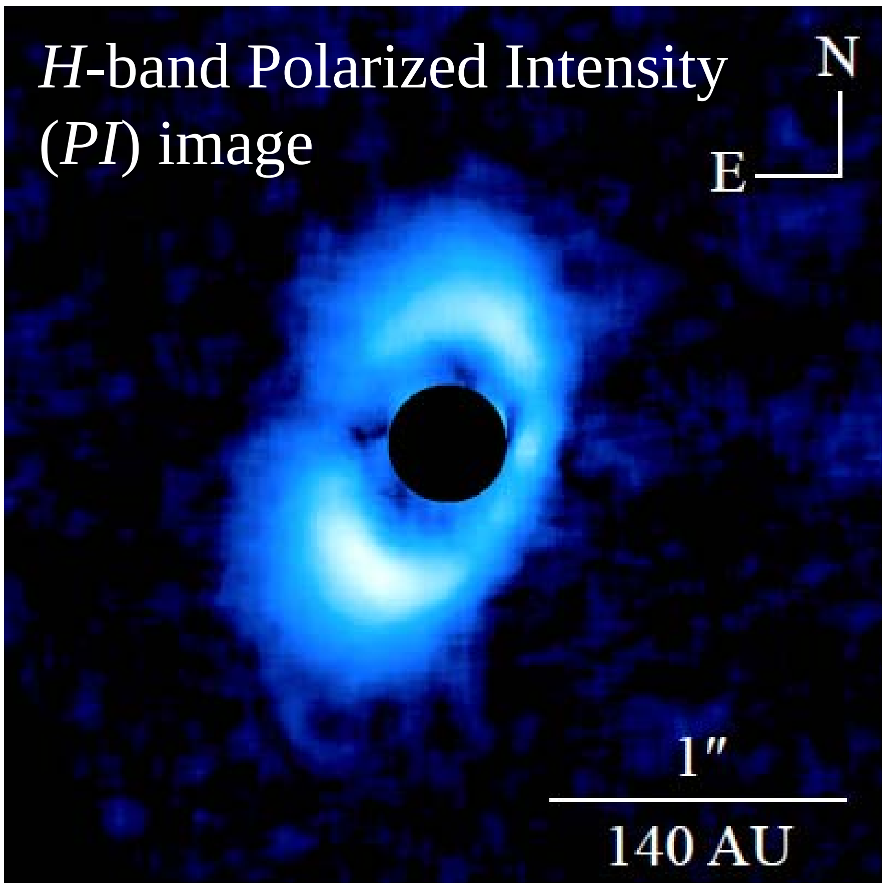




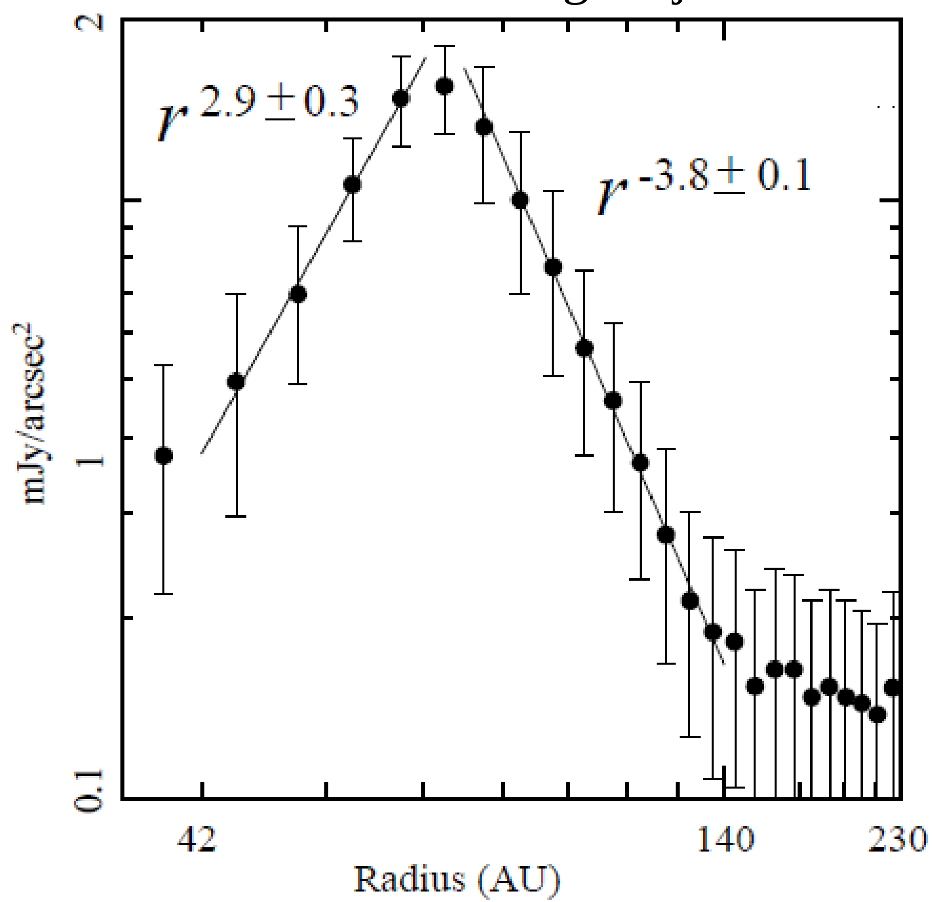
HiCIAO has revealed fine structures of disks at tens AU with high-resolution (~10AU)!!

Results of PDS 70 with HiCIAO (1)

- Stellar FWHM is ~0.1″ (14 AU)
- Giant and sharp gap with ~70AU.
- Outer disk radius with ~140 AU.



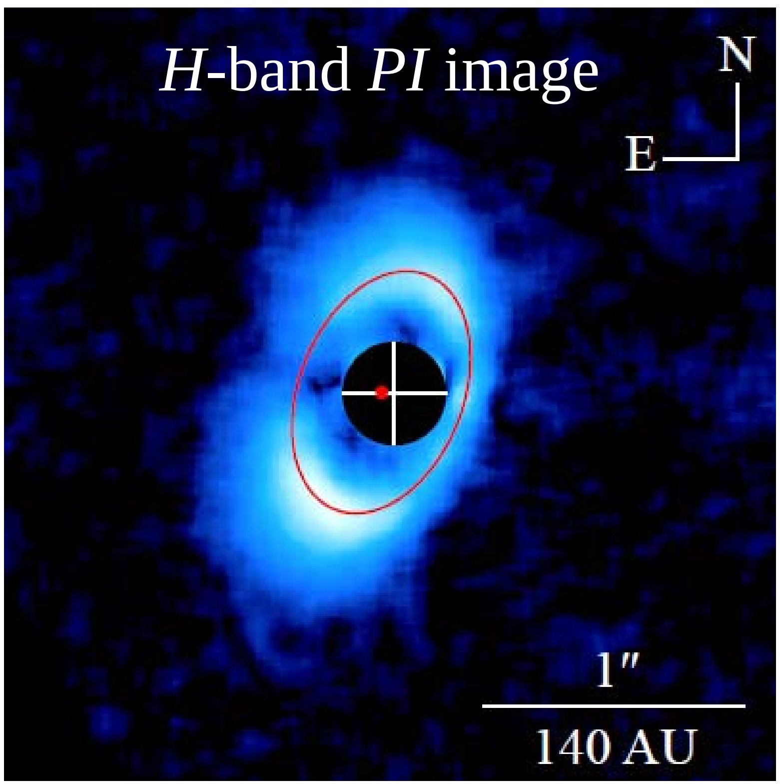
Radial Profile along Major Axis

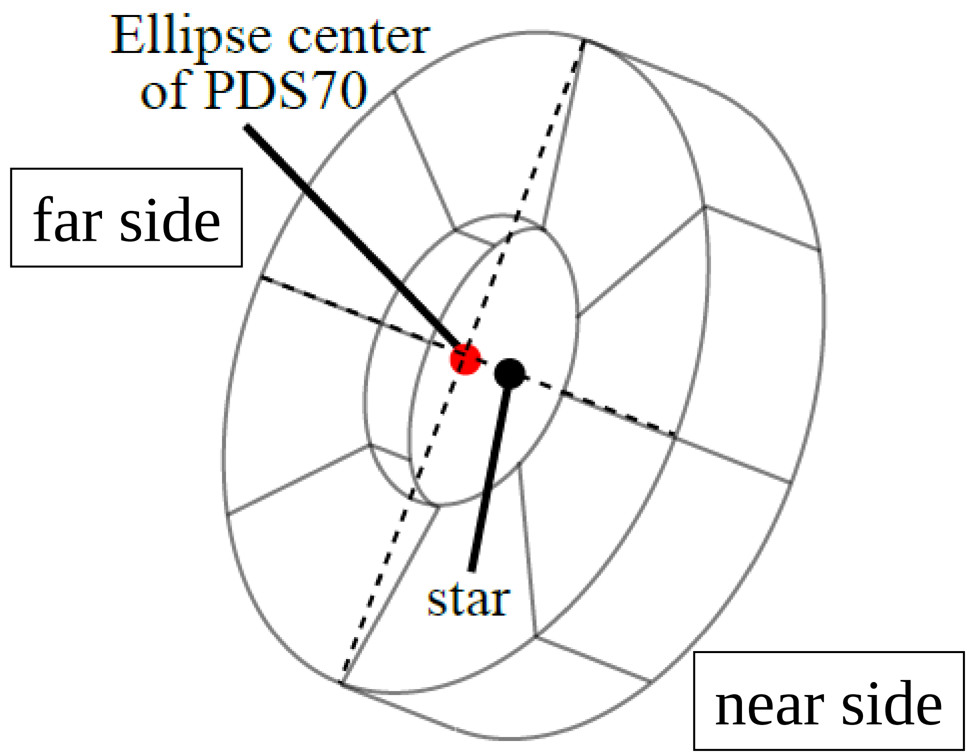


Results of PDS 70 with HiCIAO (2)

- Geometric center (filled red circle) of the disk is shifted to east with ~6AU
- Tend to shift to far side

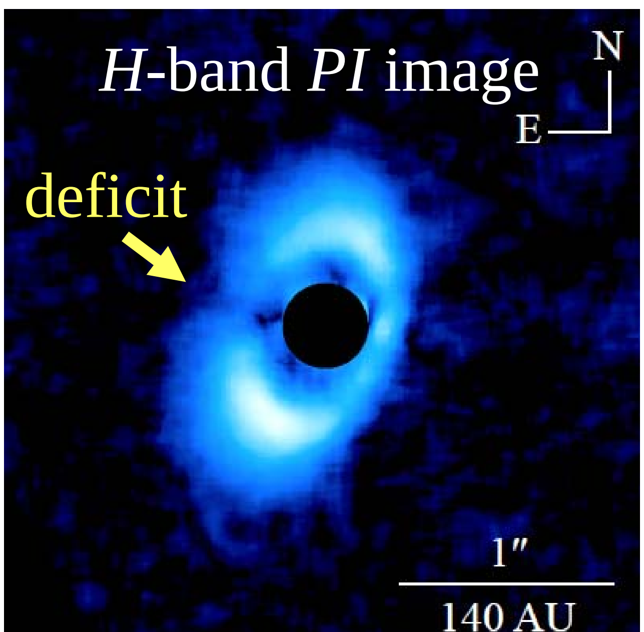
→ Due to an inclination effect.



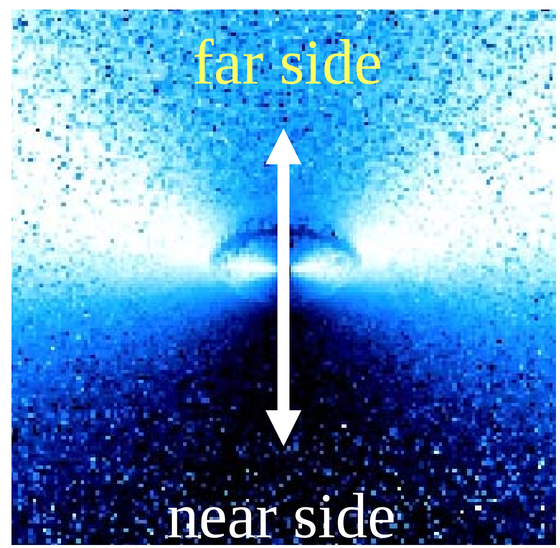


Results of PDS 70 with HiCIAO (3)

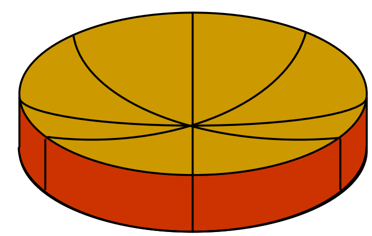
- Deficit of polarized intensity in the north-east
  - Scattering angle along the major axis is ~90° , but along the minor axis is not 90° .
  - Polarized faction is lower along minor axis.
- "NO real dip structure", due to inclination effect.



Simulated polarized fraction (*i*=50deg)



far side



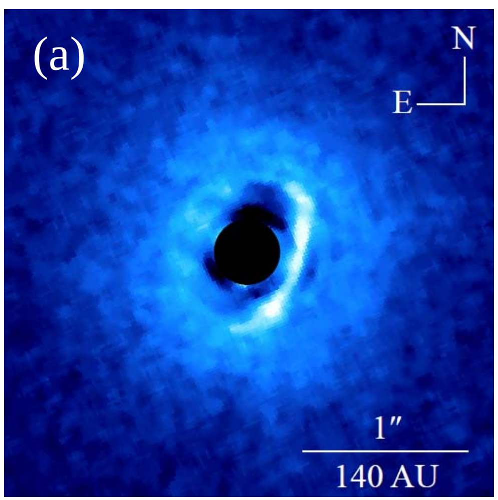
near side

Results of PDS 70 with NICI

- Stellar FWHM is ~0.11″ (15 AU)
- Partial ring disk by LOCI due to self subtraction
  - Similar structure with LkCa 15 (Thalmann et al. 2010)
- No point-like source *r*< 230 AU
- Detectable companion mass within cavity is ~30M_{Jup}

<u>*L’* imaging</u>

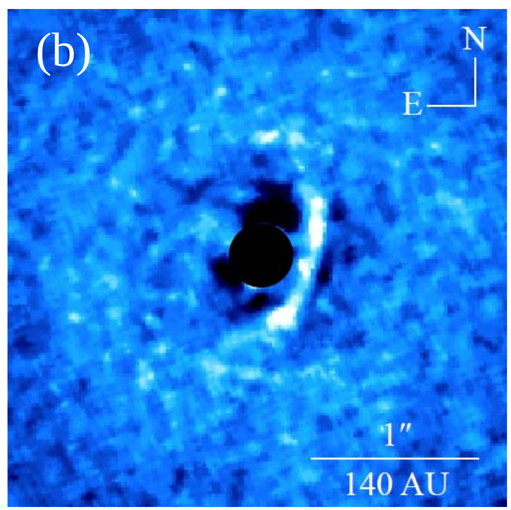
LOCI with large (N_A=1000) optimization area



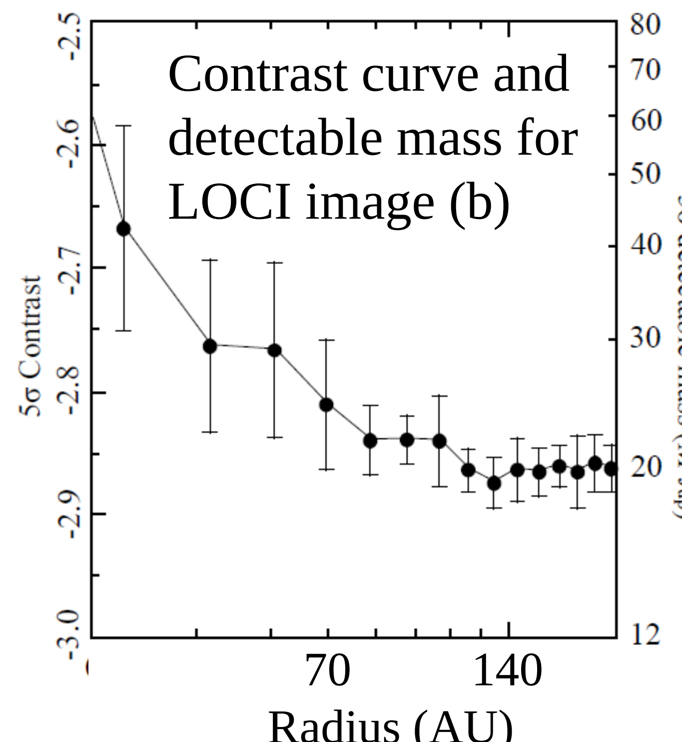
Optimized for disk detection

<u>*L’* imaging</u>

LOCI with small (N_A=250) optimization area



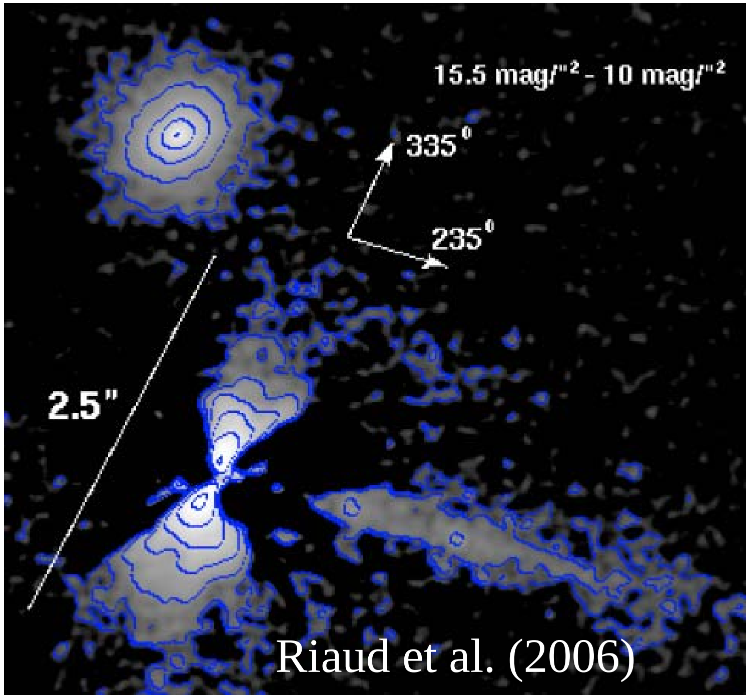
Optimized for companion detection



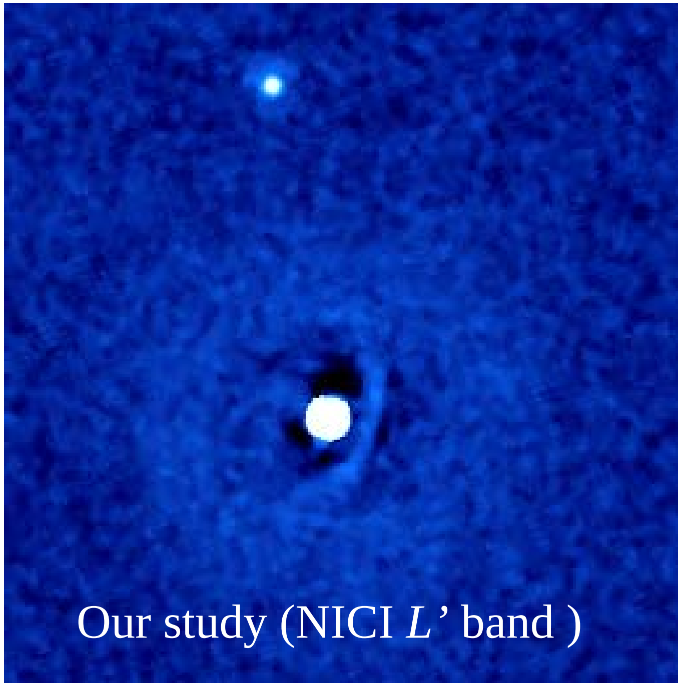
Companion analysis of PDS 70

- Proper motion of PDS 70: $(\mu_\alpha \cos\ \delta, \mu_\delta) = (-24.7 \pm 11.4, -13.3 \pm 11.4)$ mas/yr
  (Roeser et al 2010)
- Separation in Riaud et al. (2006) at 22/07/2005 UT: 301.75±0.06AU
- Our study at 31/03/2012 UT: 324.44±0.10AU

→ Background star



Riaud et al. (2006)


Our study (NICI *L*' band)

SED fitting

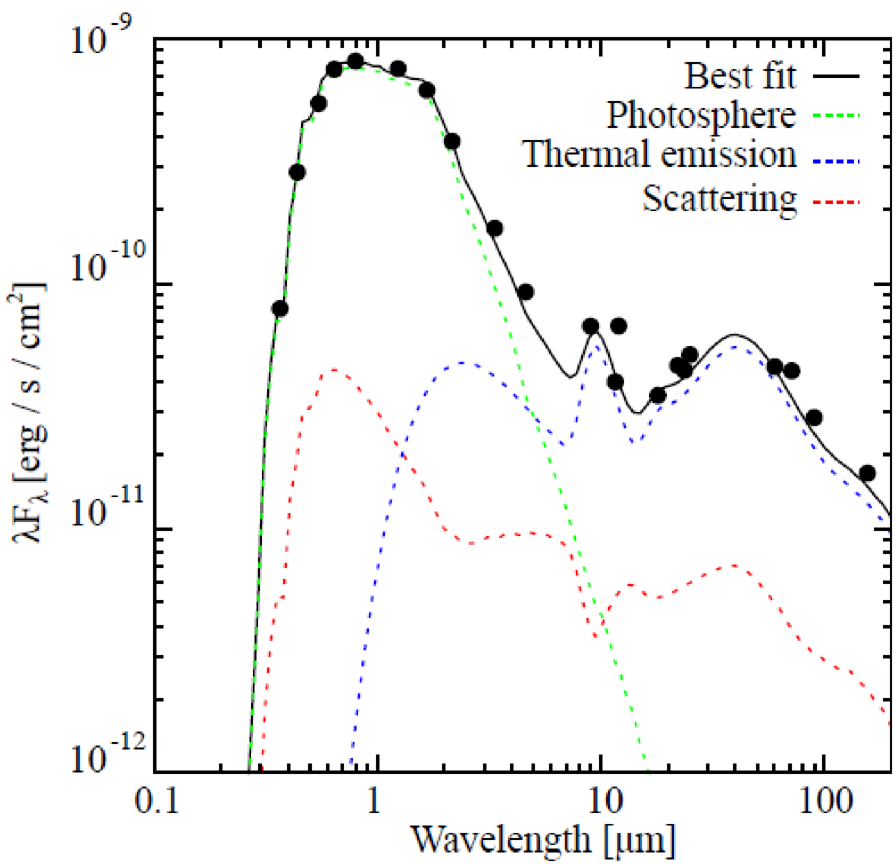
- SED fitting has been already done by Metchev et al. (2004) and Riaud et al. (2006)
- New photometric data are available
  - WISE, AKARI, MIPS
  - IRS spectra was not used due to misalignment
- Monte Carlo radiative tranfer (MCRT) modeling (Whitney et al. in prep) to infer the inner disk structure.

Wavelength	F_ν (mJy)	Note
$U^{a,b}$	9.7	Gregorio-Hetem et al. (1992)
$B^{a,b}$	41.8	Gregorio-Hetem et al. (1992)
$V^{a,b}$	99.2	Gregorio-Hetem et al. (1992)
$R^{a,b}$	160.9	Gregorio-Hetem et al. (1992)
$I^{a,b}$	216.3	Gregorio-Hetem et al. (1992)
2MASS $(J)^{a,b}$	311.9 ± 6.9	Cutri et al. (2003)
2MASS $(H)^{a,b}$	342.7 ± 12.6	Cutri et al. (2003)
2MASS $(Ks)^{a,b}$	275.6 ± 5.8	Cutri et al. (2003)
WISE (3.4 μm)[b]	188.1 ± 4.0	Cutri et al. (2012)
WISE (4.6 μm)[b]	142.0 ± 2.6	Cutri et al. (2012)
WISE (12 μm)[b]	153.9 ± 2.3	Cutri et al. (2012)
WISE (22 μm)[b]	341.8 ± 0.7	Cutri et al. (2012)
AKARI (9 μm)	201.2 ± 25.8	VizieR II/297
AKARI (18 μm)	209.8 ± 13.4	VizieR II/297
AKARI (90 μm)	851.1 ± 62.6	VizieR II/298
IRAS (12 μm)	251 ± 25.1	Moshir (1989)
IRAS (25 μm)	348 ± 27.8	Moshir (1989)
IRAS (60 μm)	884 ± 61.9	Moshir (1989)
MIPS (24 μm)	349.7[c] ± 7.0	Spitzer Heritage Archive[e]
MIPS (70 μm)	1049.9[c] ± 19.9	Spitzer Heritage Archive[e]
MIPS (160 μm)	873.0[c,d] ± 36.2	Spitzer Heritage Archive[e]

Results of SED fitting

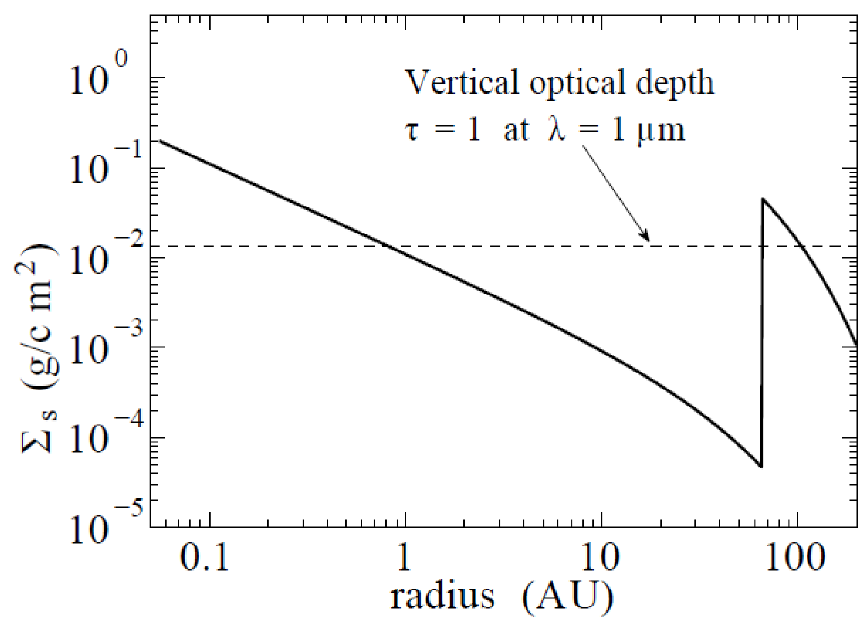
- The detailed discussions including SED fitting and reproduction of *PI* image can be found in Paper II (Dong et al. submitted to ApJ)
- Optically thick inner disk inferred by the reproduction of both of SED and *PI* image

  → optically thick inner and outer disk with ring-gap structure



$\Sigma \propto \frac{R_c}{R} e^{-R/R_c}$, where $R_c = 50$ AU

Uniform depletion factor of 1000 inside of the cavity

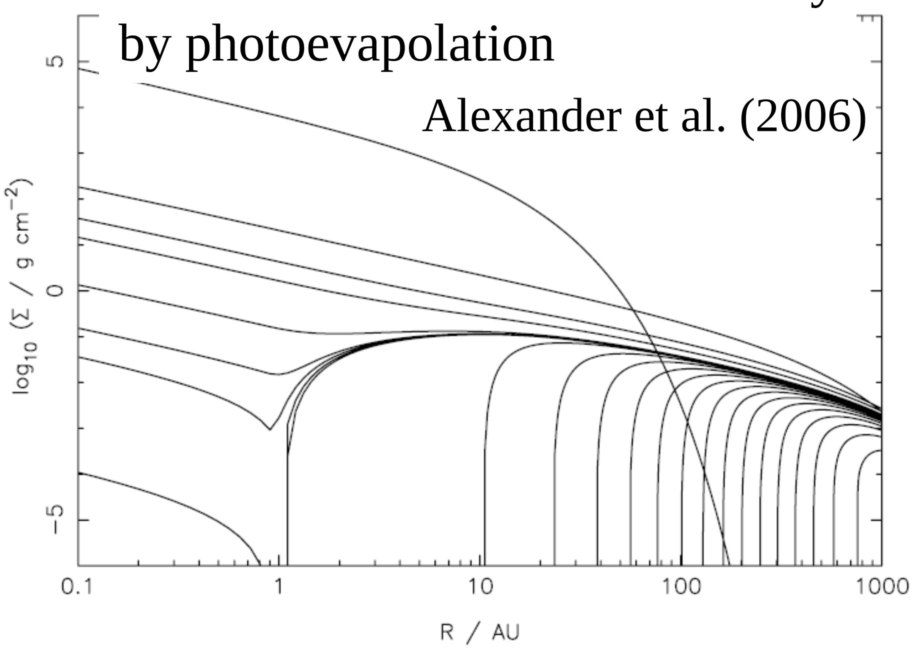


Gap formation mechanism (1)

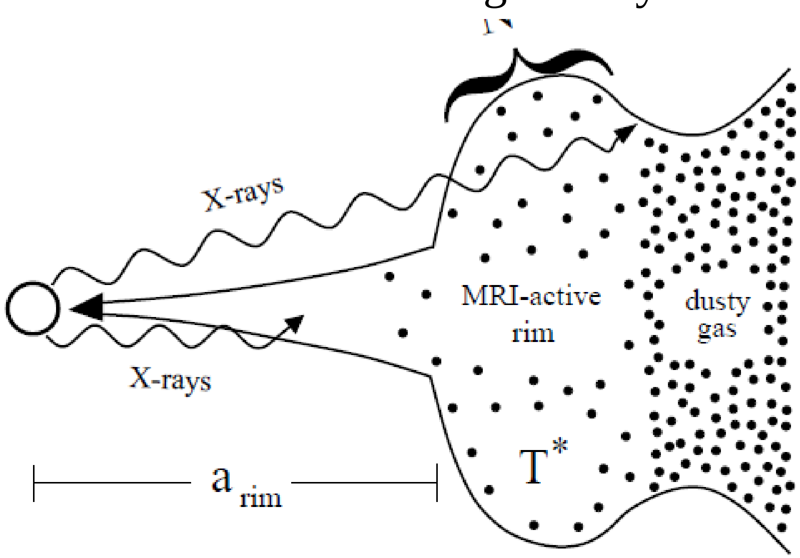
- Photoevapolation, Magnetro-rotational instability (MRI)
  - These work inside-out
  - Could be difficult to explain the existence of optically thick inner disk inferred by SED (e.g., Alexander et al. 2006; Chiang et al. 2007).

Time evolution of surface density by photoevapolation

Alexander et al. (2006)



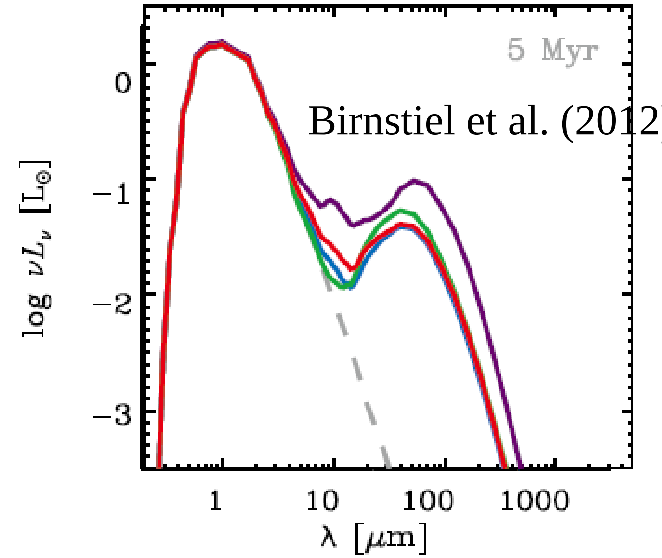
Schematic of a accreting disk by MRI

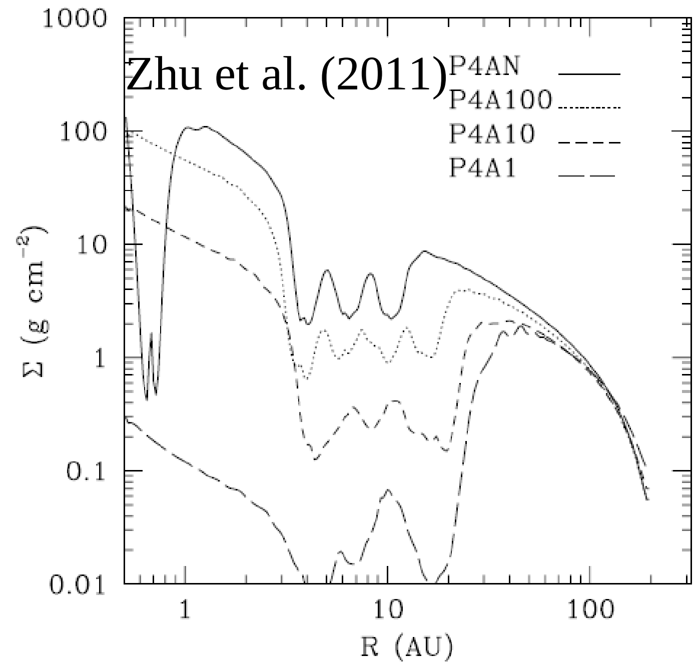


Chiang et al. (2007)

Gap formation mechanism (2)

- Grain growth
  - Reproduce of the SED (Birnstiel et al. 2012)
  - Infer the smooth surface density as a function of radial distance
  - May not explain sharp cavity of PDS 70
- Disk-planet interaction
  - multiple planets open wide gap (Zhu et al. 2011)
  - Optically thick inner disk exists.
  - May account for the gap of PDS 70.

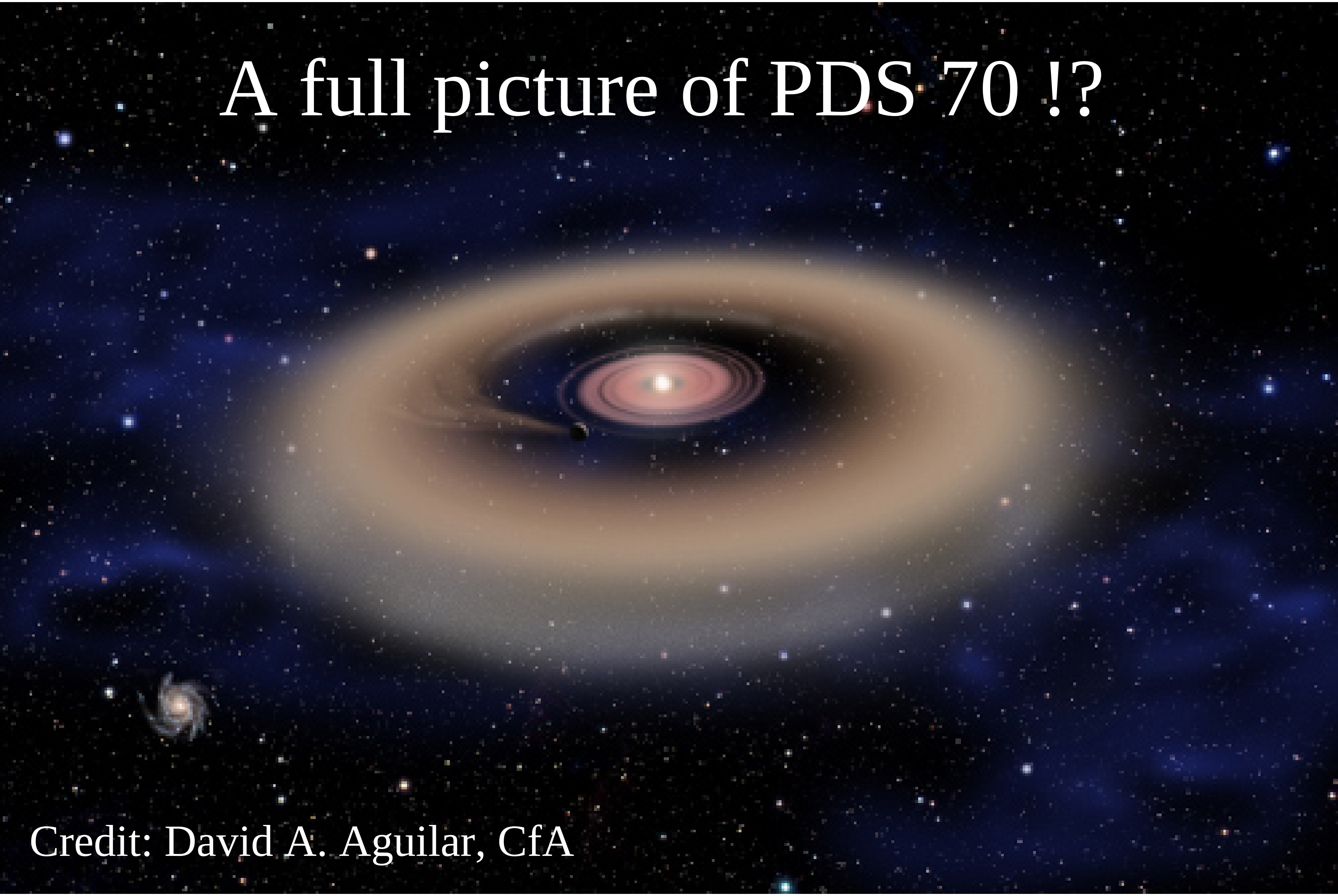




Future plan and summary

- Future plan
  - Aperture masking observations to further constraint the companion mass in the gap.
  - Radio observations, e.g., ALMA, to detect gas and big (millimeter size) dust.
- Summary
  - High contrast *H*-band polarimetric imaging and *L'*-band imaging of protoplanetary disk around PDS 70.
  - A giant and sharp cavity with ~70AU.
  - Brown dwarf companion candidate is a background star.
  - Detectable companion mass in the gap is ~$30M_{Jup}$.
  - Pre-transitional disk based on SED fitting
  - Cavity could be formed by dynamical interactions with sub-stellar companions or multiple planets based on the presence of sharp and large cavity.

A full picture of PDS 70 !?



Credit: David A. Aguilar, CfA