Fine Structures of Giant Planet Forming Regions around a Young Star of AB Aur

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S. Inutsuka, E. Kokubo, G. Knapp, M. W. McElwain,
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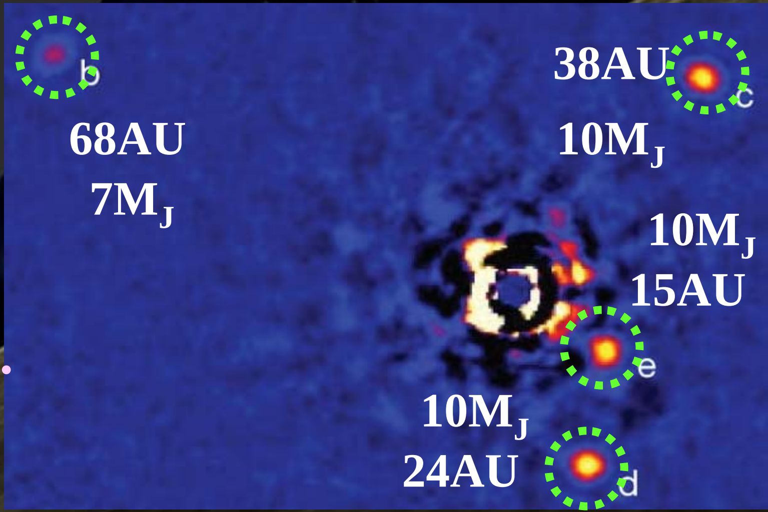
and HiCIAO/AO188/SEEDS members

Introduction

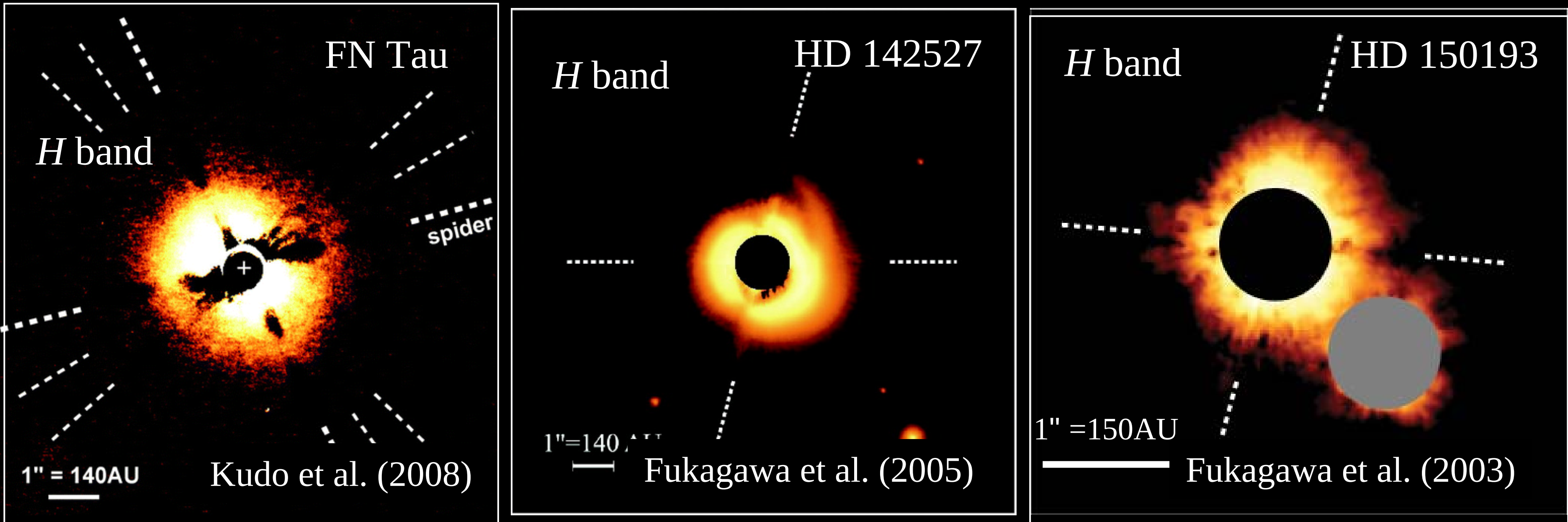
- One of the key issues in planetary science is to understand "how planets form in disks".
  - Core accretion model can successful explain giant planets at several AU (e.g., Pollack et al. 1996)
  - Recent direct detections of giant planets with ~10 M_J at beyond the planet forming zone (r >20 AU) (e.g., Marois et al. 2008)

HR8799
L' band (NIR) image



Marois et al. 2010

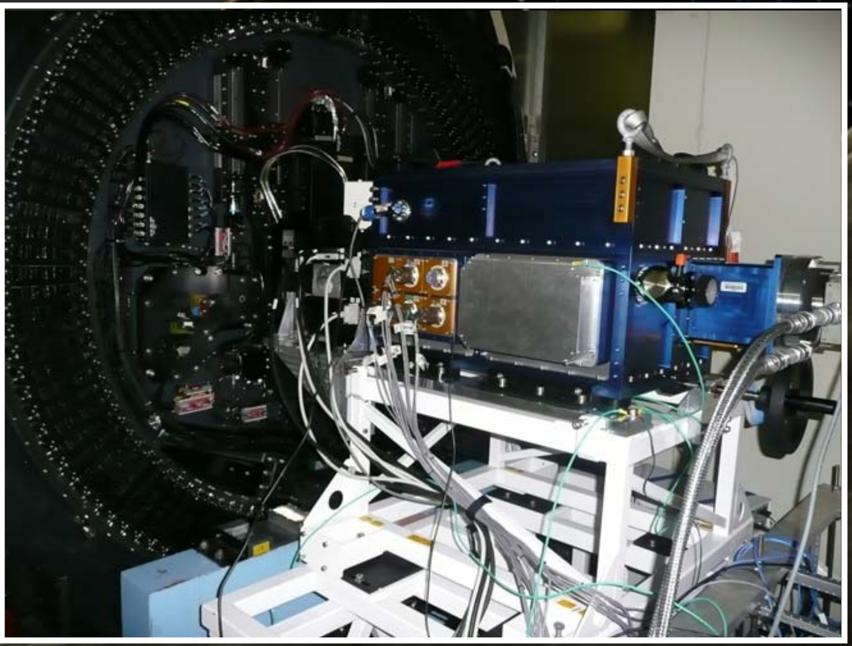
- Difficulty of inner regions (r <100AU) of circumstellar disks.
  - Typical star forming regions (e.g., Taurus) : ~100 pc
    - Need to access the disk within 1 arcsec.



- Very little is known about inner regions (r <100AU) of circumstellar disks.
  - Direct imaging at near-infrared has explored beyond r > 100AU.
  - Inner regions have not been easily accessible due to speckle noise.
- Dual-beam polarimetry allows us to investigate the inner regions of the disk.
  - Non-polarized speckle noise is automatically suppressed.
  - Only polarized light scattered at disks is detected.

Observations

- Date: Oct. 29th, 2009 at the beginning of SEEDS
  - SEEDS: Strategic observation of Subaru Telescope
- Instrument: 8m Subaru/HiCIAO
- Target: AB Aurigae (144 pc)
- Mode: Dual-beam polarimetry
- Wavelength: H band (1.6 μ m)
- Resolution: 0.06" (9 AU)
- Occulting mask: 0.3" diameter
- Exposure time: 189.6 seconds
- PSF reference star: HD282411
- Accuracy:
  degree of polarization $\delta P < \sim 0.3\%$,
  polarization angle $\delta \theta < \sim 5^{\circ}$

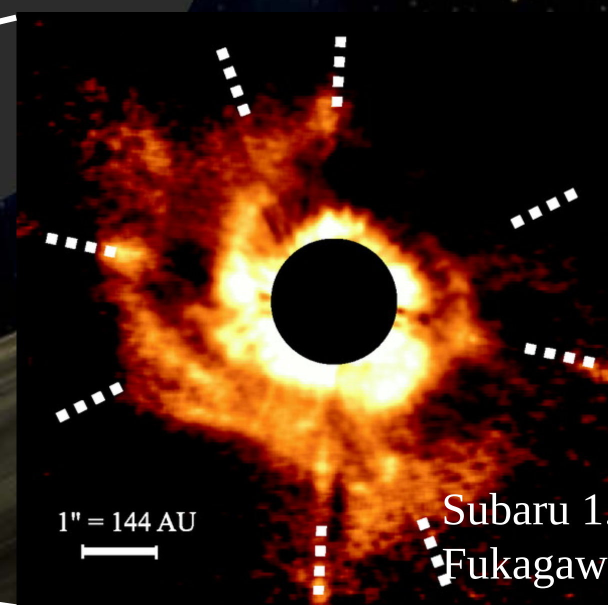


HiCIAO at Subaru Telescope

AB Aurigae

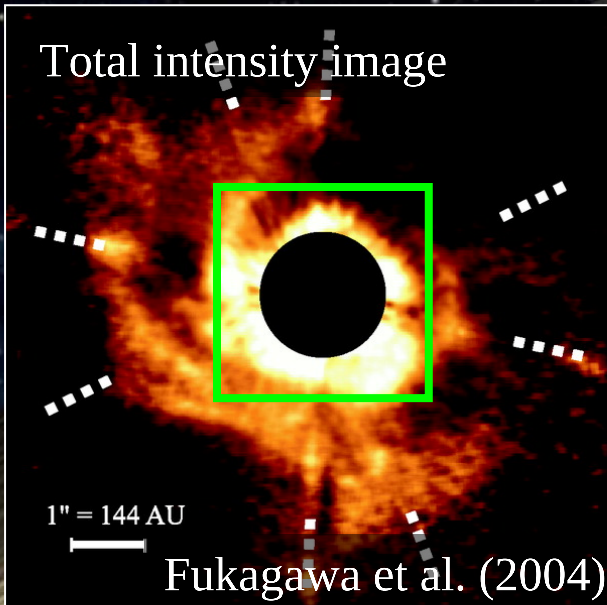
- Well studied Herbig Ae star
  - distance 144 pc, age 3-5Myr, mass 2.4Mo (van der Ancker et al. 1997; deWarf et al. 2003)
- Rotating CO disk (r ~450AU) with mass of ~20M_J (Henning et al. 1998).
- Large nebula with r >1000 AU (Grady et al. 1999)
- Spiral structures in the outer part (r >130 AU) of the disk (Fukagawa et al. 2004)

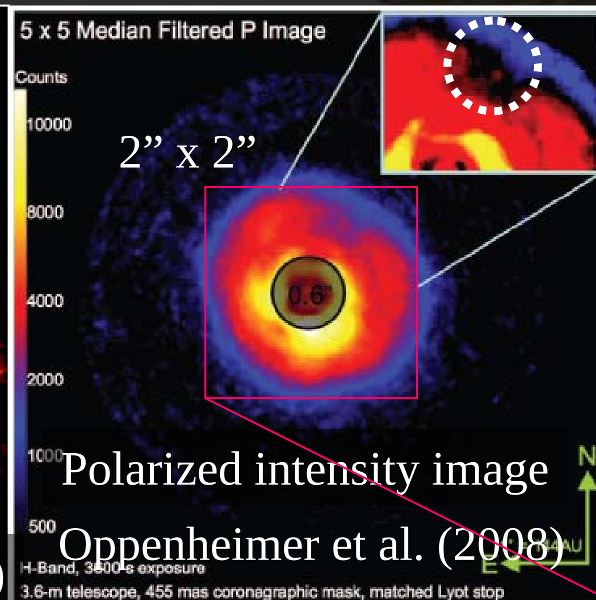
HST 0.57 μ m
Grady et al. (1999)

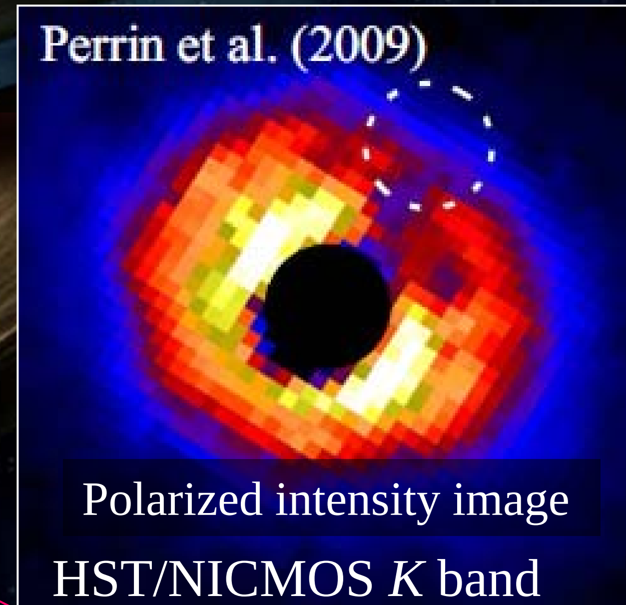


Subaru 1.65 μ m
Fukagawa et al. (2004)

Recent direct imaging of AB Aur

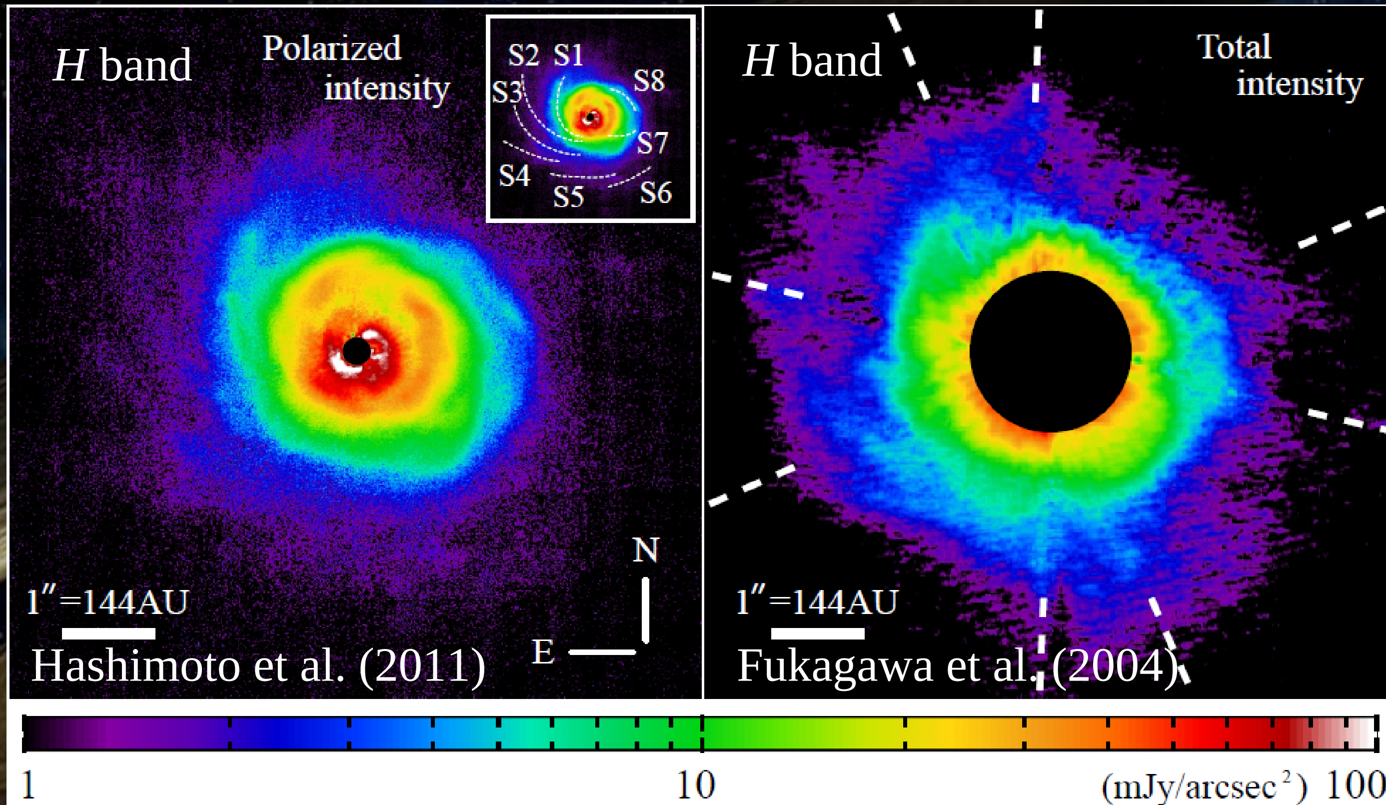






- Revealed inner disk structures (r <130 AU) by polarimetry
  - The disk at r <40 AU has not been accessible.
- Planet candidate with $5 < M < 37\ M_J$ was found in a gap region at r ~100 AU (Oppenheimer et al. 2008)
- No point source was found in a gap (Perrin et al. 2009)

Results of the outer structure



- Spiral arms (S1-8) are detected in Polarized Intensity (*PI*) image.
  - The morphology of the outer part in those images are consistent.
- Structures near the midplane of the disk
  - These images of scattering light trace surface of the disk due to optically thick.
  - Sub-millimeter observations reveal the some of spiral arms (Lin et al. 2006)
  - Our *PI* image also reflects the structures of the midplane of the disk

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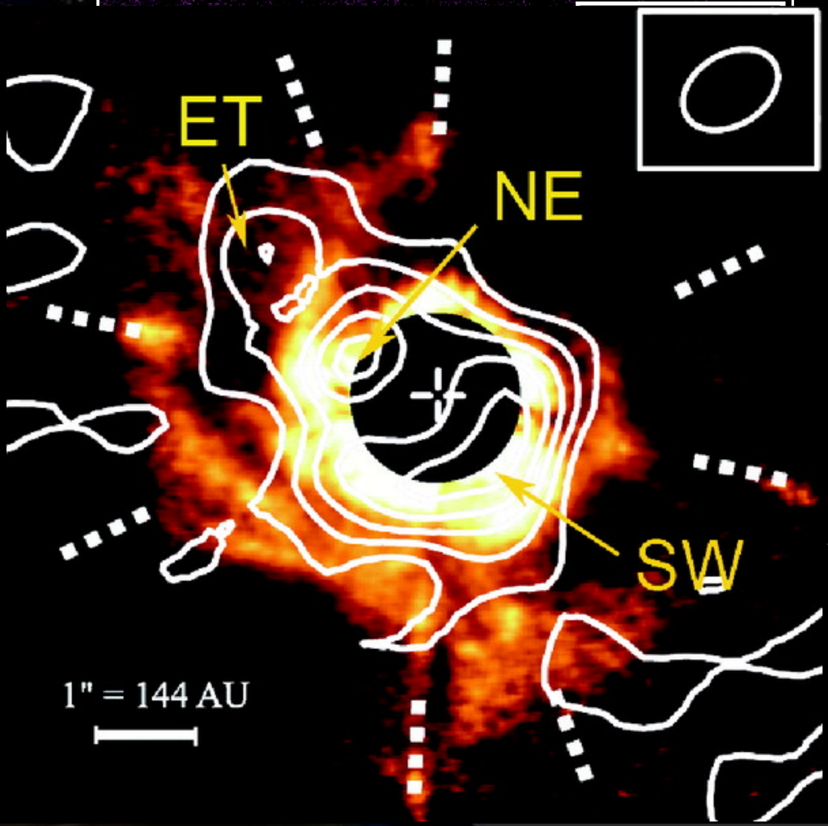

Dust continuum of Lin et al. (2006) superposed on the near-infrared total intensity image of Fukagawa et al. (2004).

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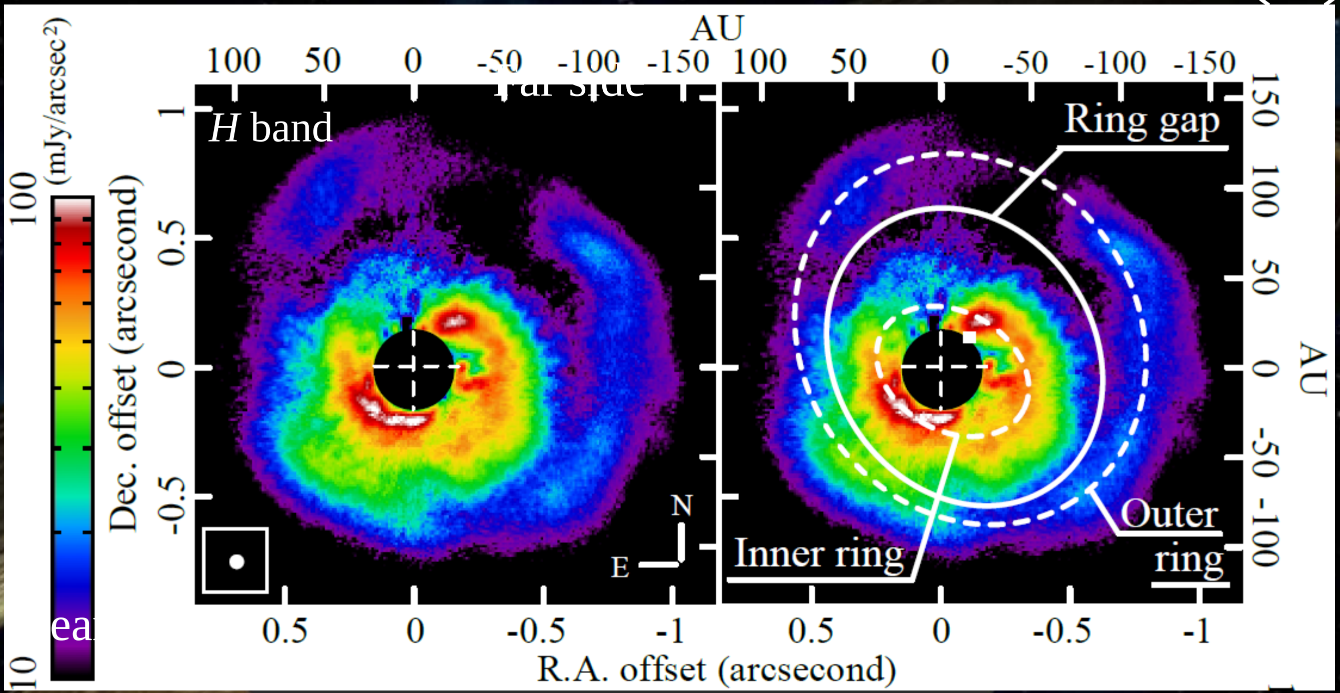

Inclination

inner ring: 43.1° ±6.8°

outer ring: 26.8° ±1.9°

- The inner working distance (r ~20 AU) with the high resolution (9 AU)
- Double ring (dashed lines) and ring-like gap (solid line)
  - Ellipse shape due to the inclination
  - The inner ring (i ~43°) might be warped relative to the outer ring (i ~27°).

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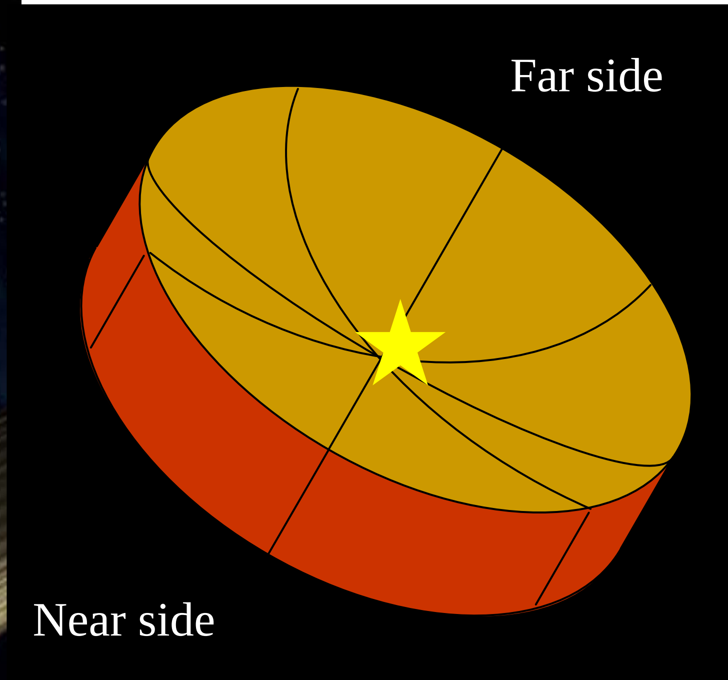

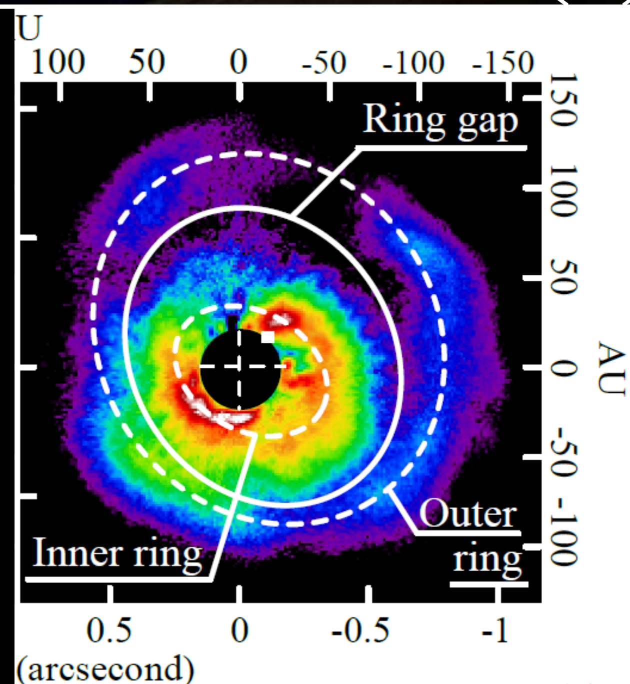

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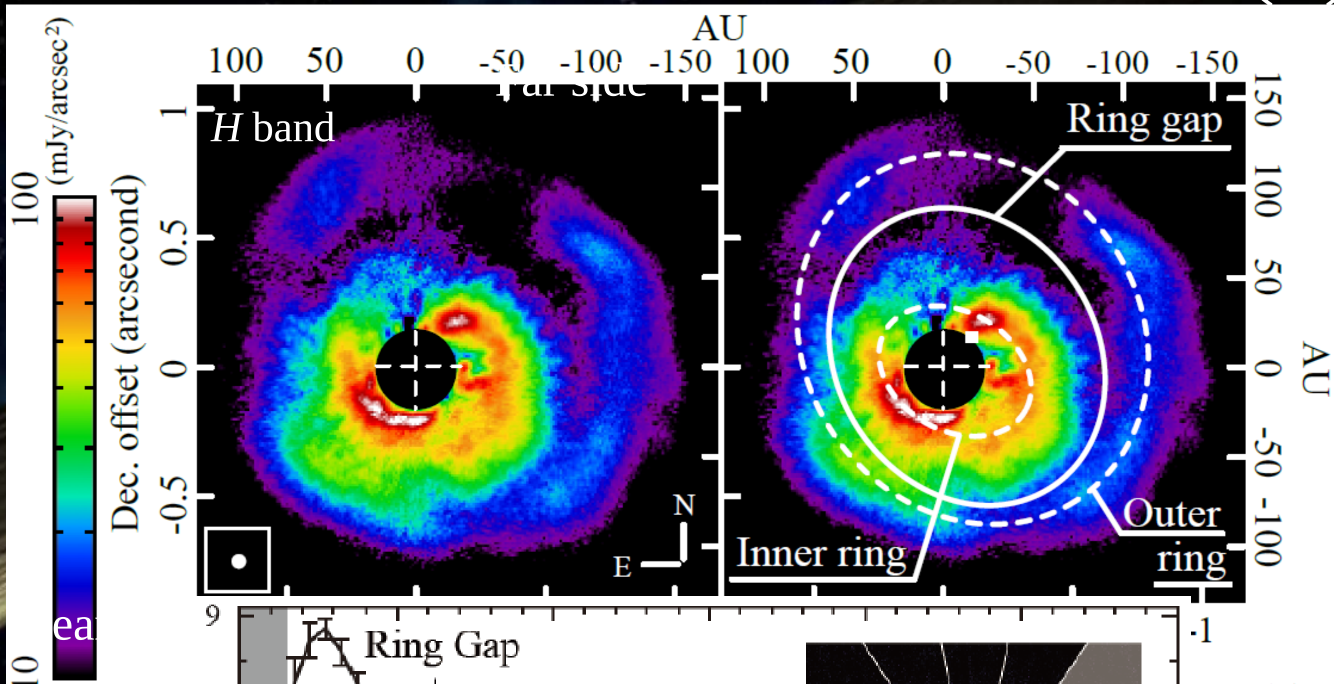

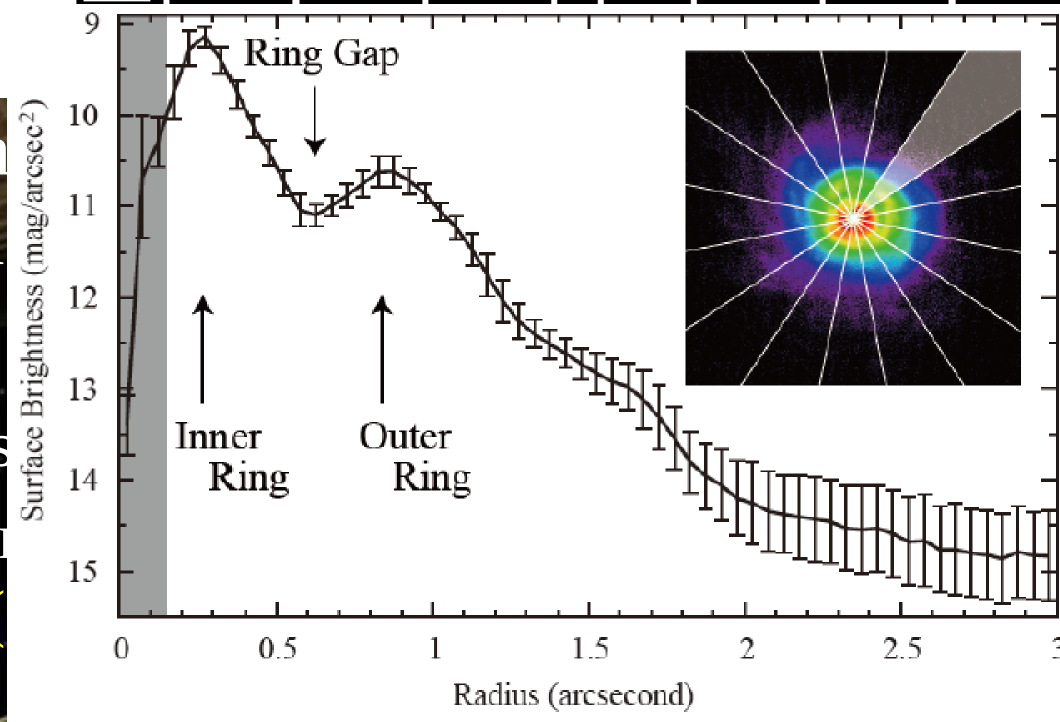

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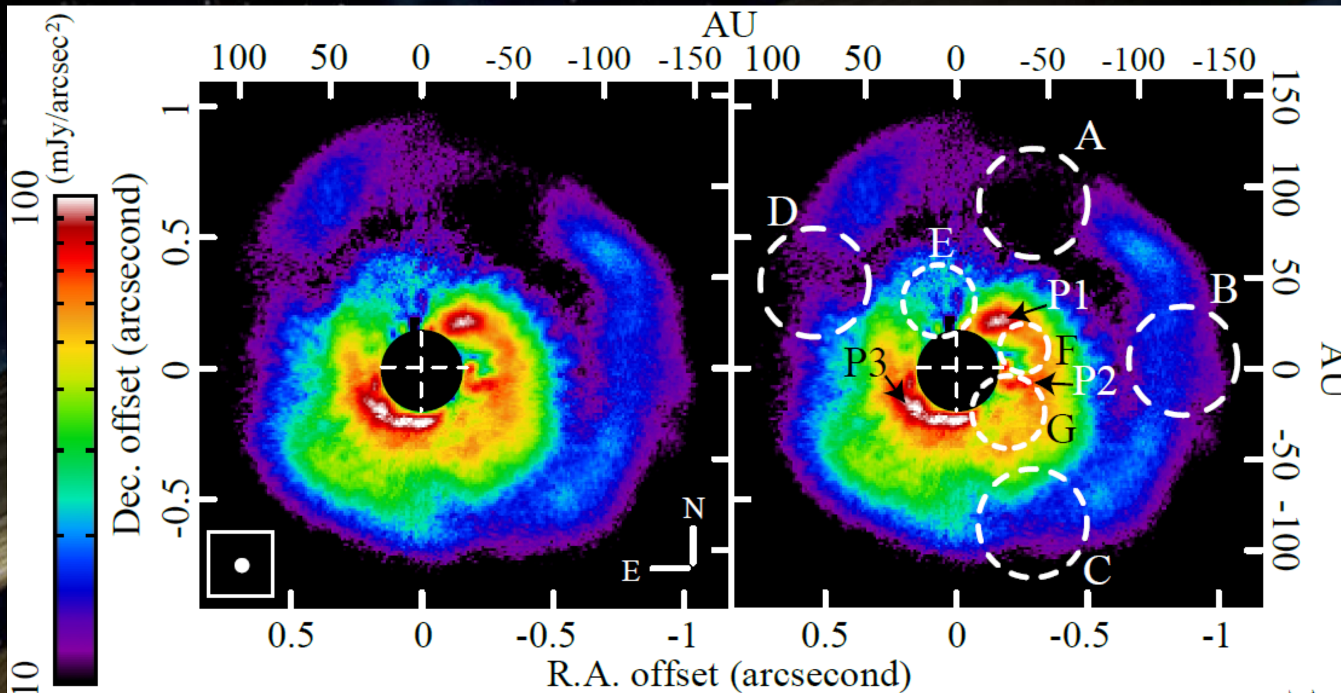
Results of the inner structure (2)



- Seven dips (Dip A to G) and three *PI* peak (P1 to 3)
  - Newly found except Dip A
  - No point-like source in Dip A, which is consistent with HST/NICMOS polarimetry (Perrin et al. 2009).
  - The upper limit of companion masses at 5 σ of the photon noise in Dip A are 5 and 6 M_J for an age of 3 and 5 Myr, respectively (COND model; Baraffe et al. 2003).
  - Dip A is confirmed in the total intensity image (~3 σ).

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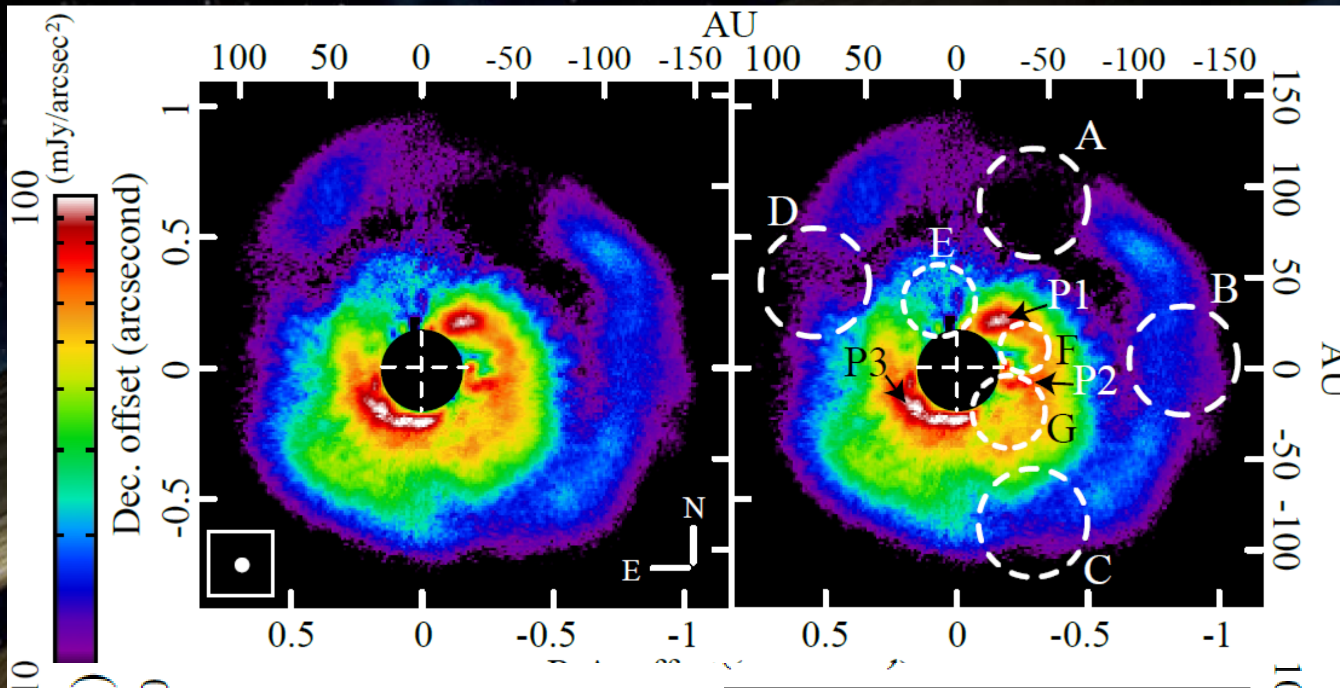

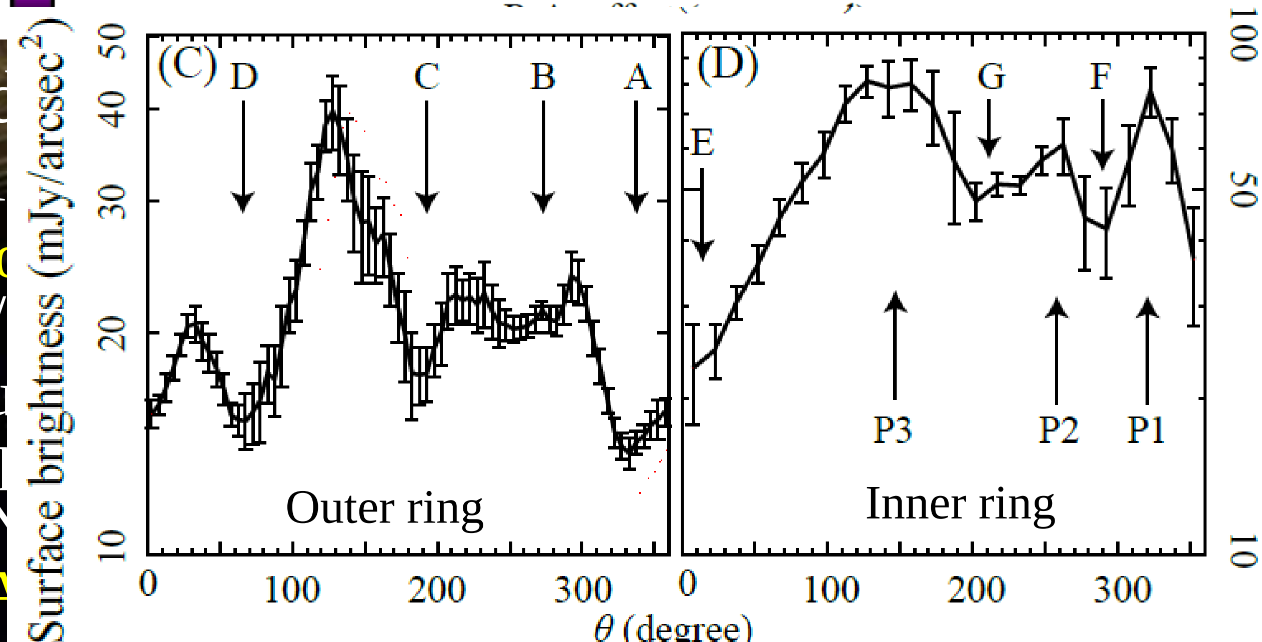

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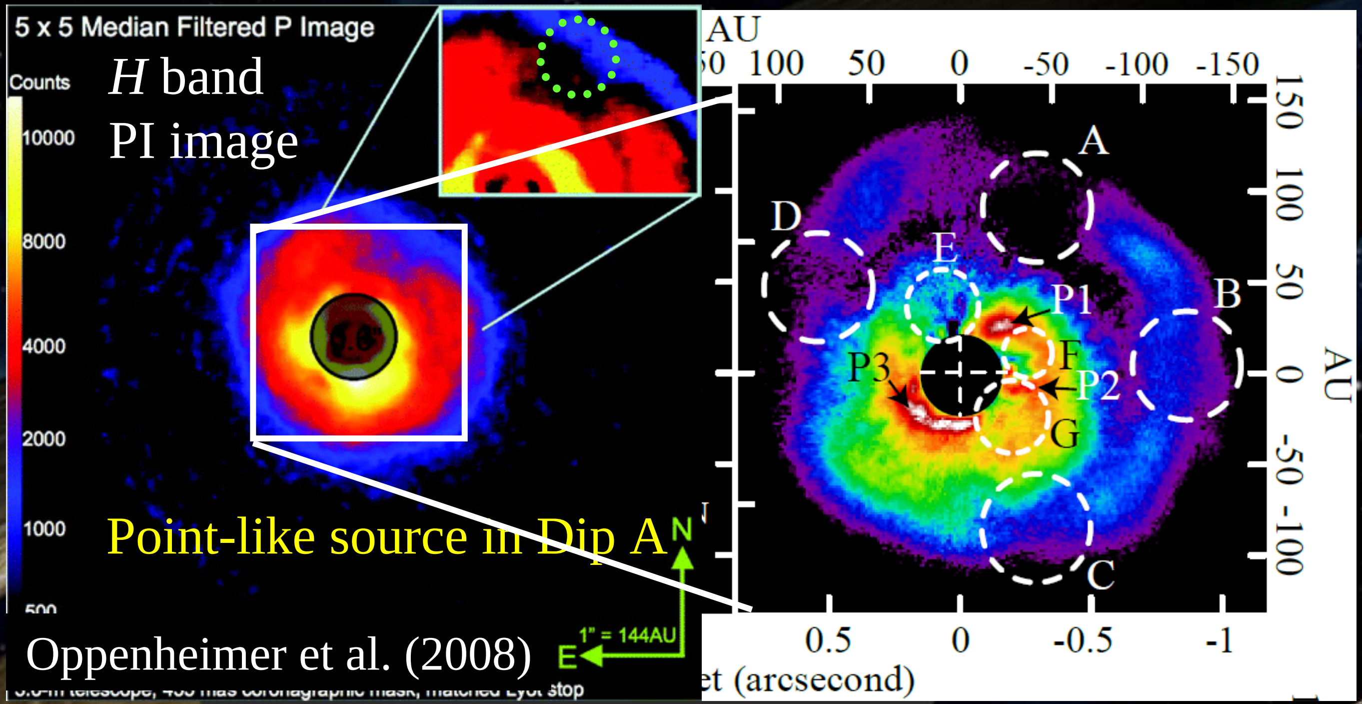

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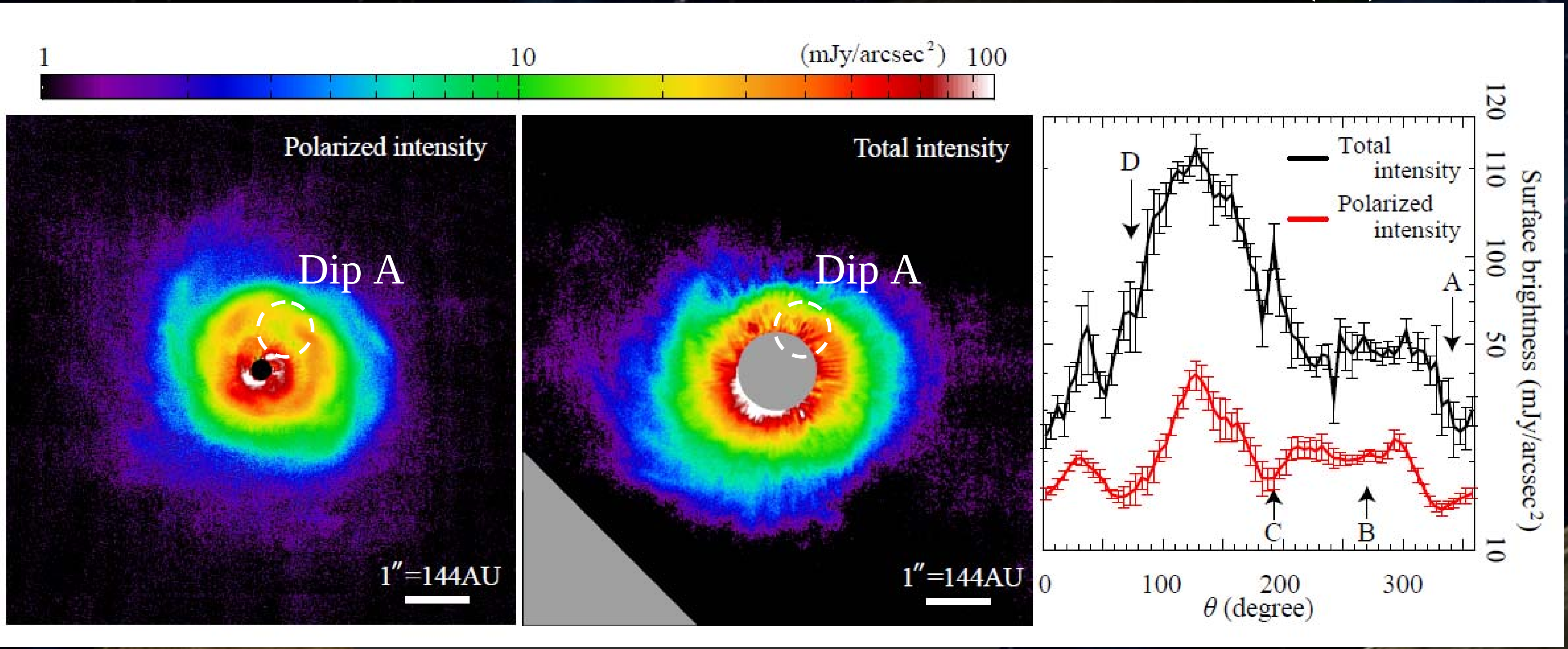

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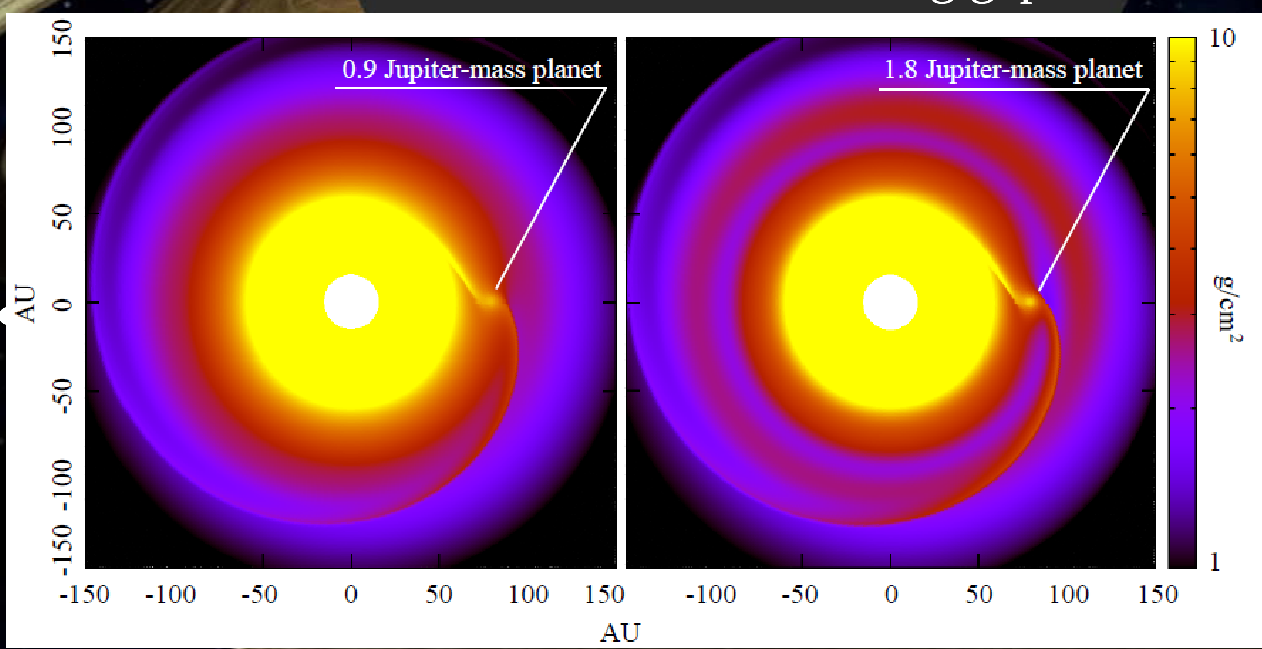
The origin of fine structures of the disk

- Gravitational Instavility
  - Toomre Q parameter of ~10 (Lin et al. 2006) is not favored
- Disk-planet interactions
  - Planet in the disk excites the spiral density wave (e.g., Papaloizou et al. 2007)
    - High-mass planet can open the gap.
    - Resemble structures with our ring gap.



Simulation with the FARGO code (Masset 2000) by T. Muto.

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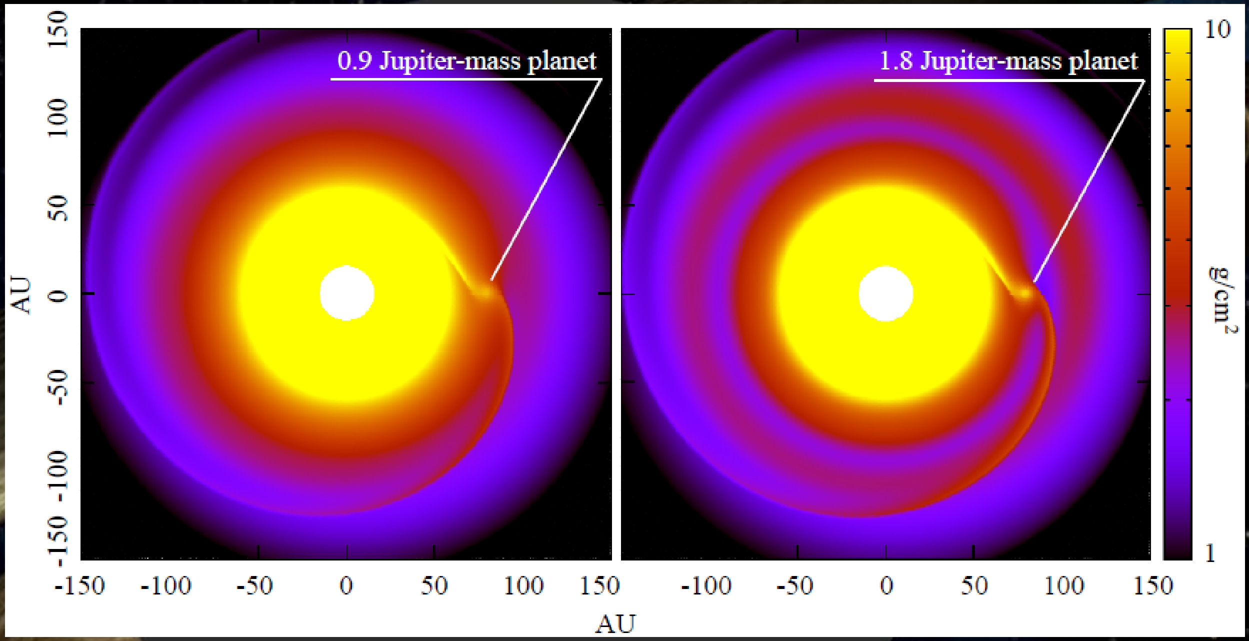
  - Observed warp in the inner ring can be explained by gravitational perturbation from unseen planets (Mouillet et al. 1997)
- Fine structures of disk including a double ring, a warp, and a ring gap are most likely due to planetary perturbation.

How to confirm ?



- The pattern caused by a planet co-rotates with a planet.

$$\omega = 0.78 \left(\frac{\mathrm{M}}{2.4\, M_\odot} \right)^{\frac{1}{2}} \left(\frac{r_\mathrm{p}}{80\,\mathrm{AU}} \right)^{-\frac{3}{2}} \ (\mathrm{deg\,yr}^{-1})$$

  – M is a mass of central star, r_p is an orbital radius of a planet

- We can observe this variability in the next seveal years

Summary

- We have conducted the dual-beam polarimetry of the prototype young star AB Aur.
  - Both the inner working distance (r ~ 20 AU) and the resolution (9 AU) are better than previously achieved.
  - A double ring, a ring gap, and a warp structures discovered in the disk.
  - These fine structures of the disk suggest giant-planet formation in the disk.
- We demonstrate that we are able to investigate the planet forming regions of wide-orbit planets (r >20 AU)

Future Work

- Revealing fine structures of more disks at r > 20 AU.
- Understanding the formation mechanisms of the wide-orbit planets