Star & Planet Formation:
High angular resolution study of protoplanetary disks

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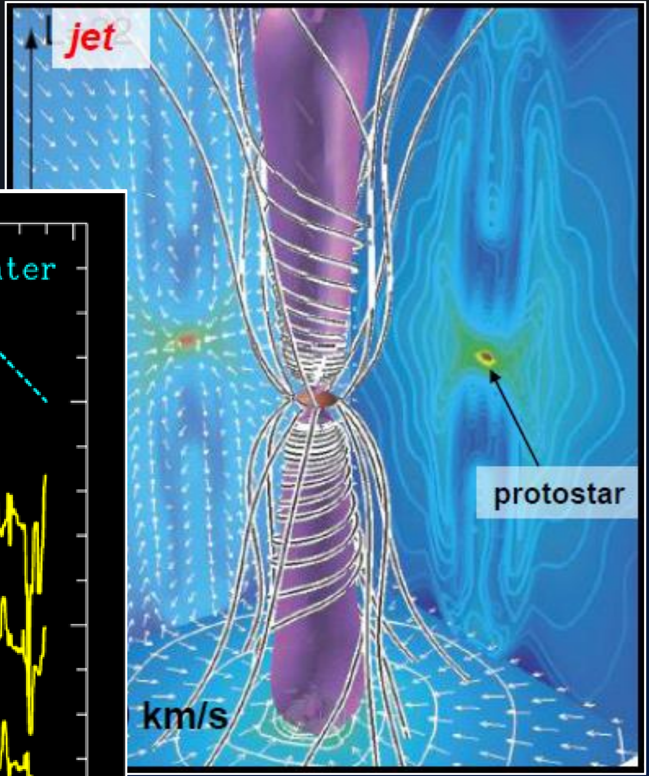
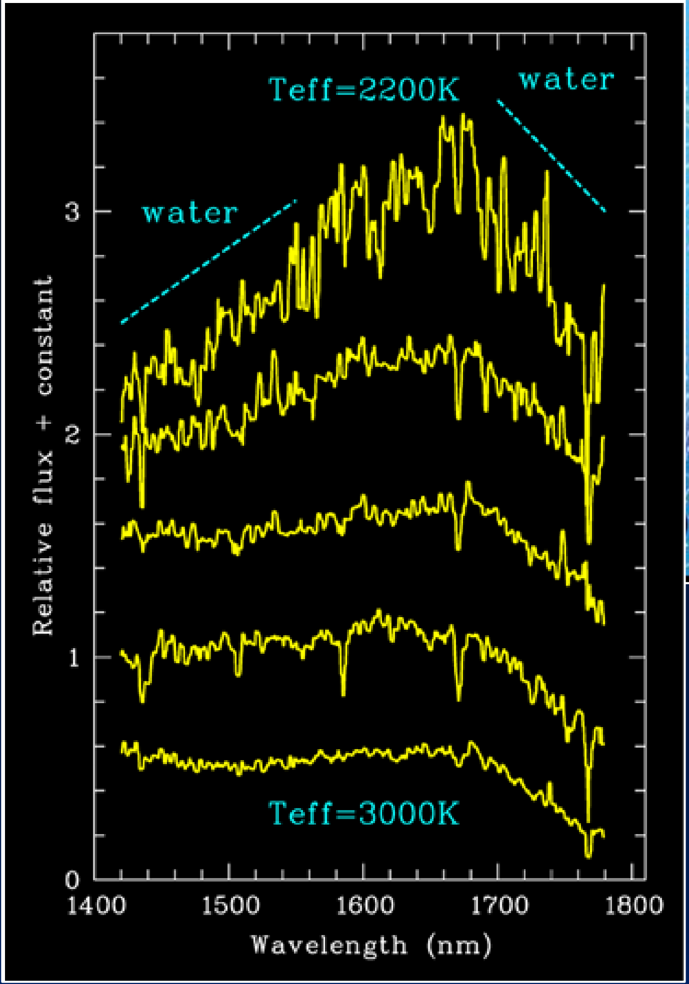
Science with TMT star/planet formation

- Launching mechanism of the young stellar outflows/jets.
  - Evolutional dependence of the characteristics of the outflows/jets
  - Difference of the outflows from massive stars to sub-stellar objects
- Massive star formation
- IMF in various star forming regions
  - Environmental effects
  - The bottom of IMF (free-floating planets)



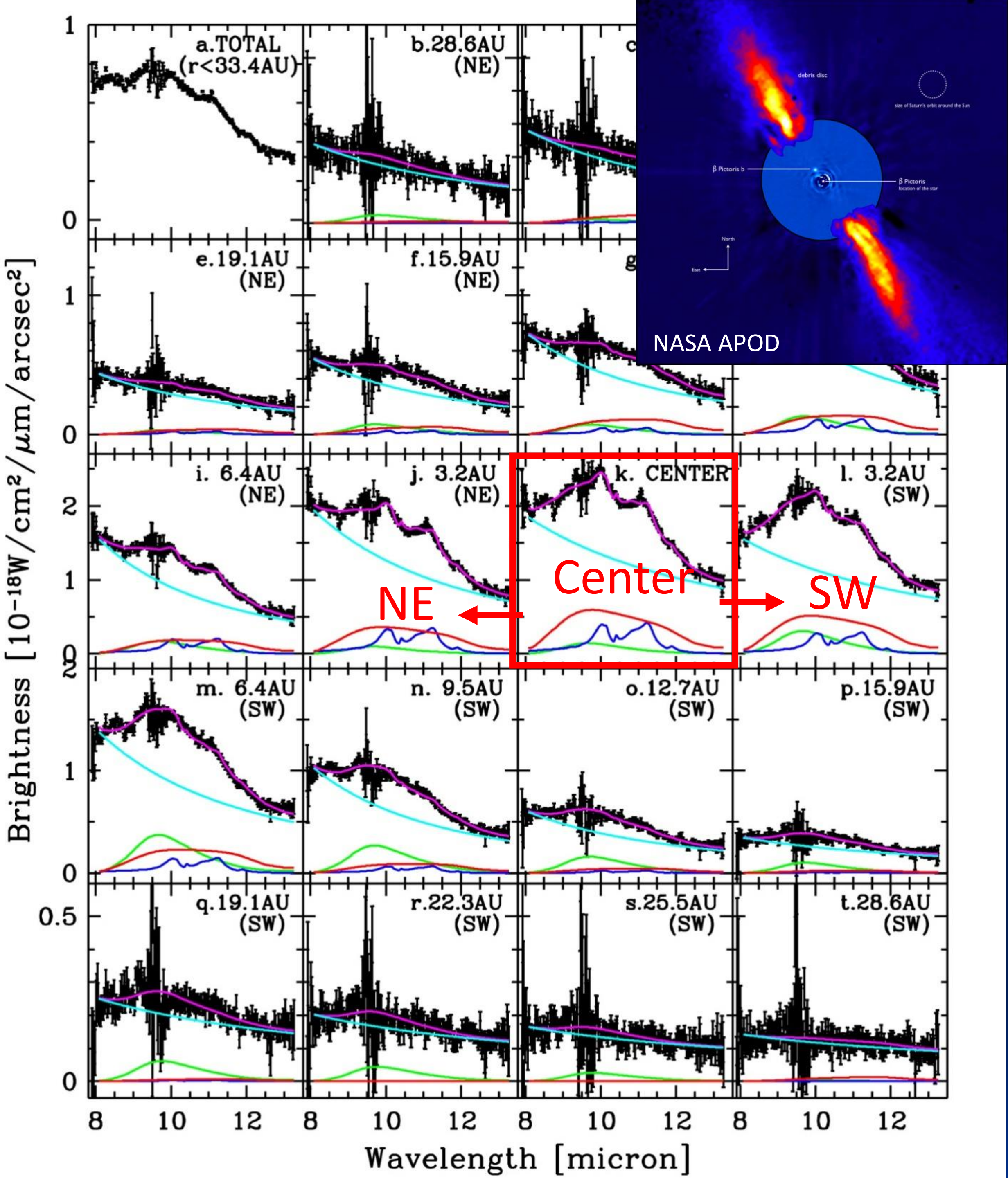
Simulation of early phase of a protostar Machida et al. (2006 – 2009)



Spectra of brown dwarfs in NGC1333 (Scholz et al. 2012) Credit: NAOJ

Science with TMT

- Young circumstellar (protoplanetary and debris) disks
  - Detailed structure
  - Mechanism of gas dispersal (H_2 gas)
  - Spatial distribution of various kinds of dust, icy grains, organic molecules
  - Magnetic field
  - Forming planets embedded in disks
  - …



Subaru MIR spectroscopy for β Pictoris (Okamoto et al. 2004)

High angular resolution study of protoplanetary disks: Results from Subaru & ALMA

Protoplanetary disks

- Natural outcome of star formation
- Stellar age : 1~10 Myr
- Optically thick
- Gas-rich
    - Gas-to-dust = 100:1 in the interstellar
    - Formation of gas giant planets
- R ~ 100 AU
    - ~1 arcsec in the nearest star-forming regions

Disks at ~1 million years of age

1. Planet formation will occur, or is ongoing
   - Initial condition
2. Planet formation has recently finished
   - Interaction between planets and disks, evolution of planetary orbits, triggered formation of more planets?
   - Forming planets in disks

$\rho(r, z)$, $T(r, z)$...

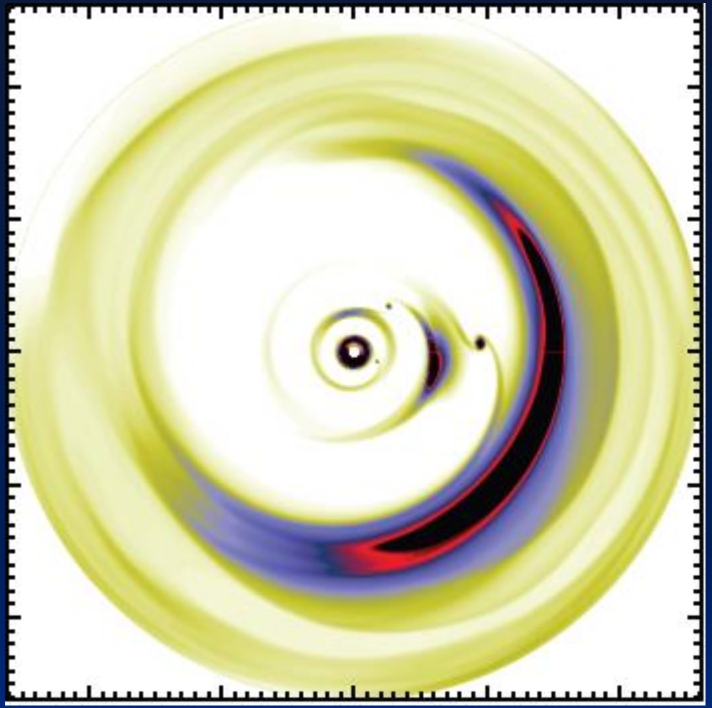
- Transformation of interstellar dust & gas
- Transport of material

Planet footprint?

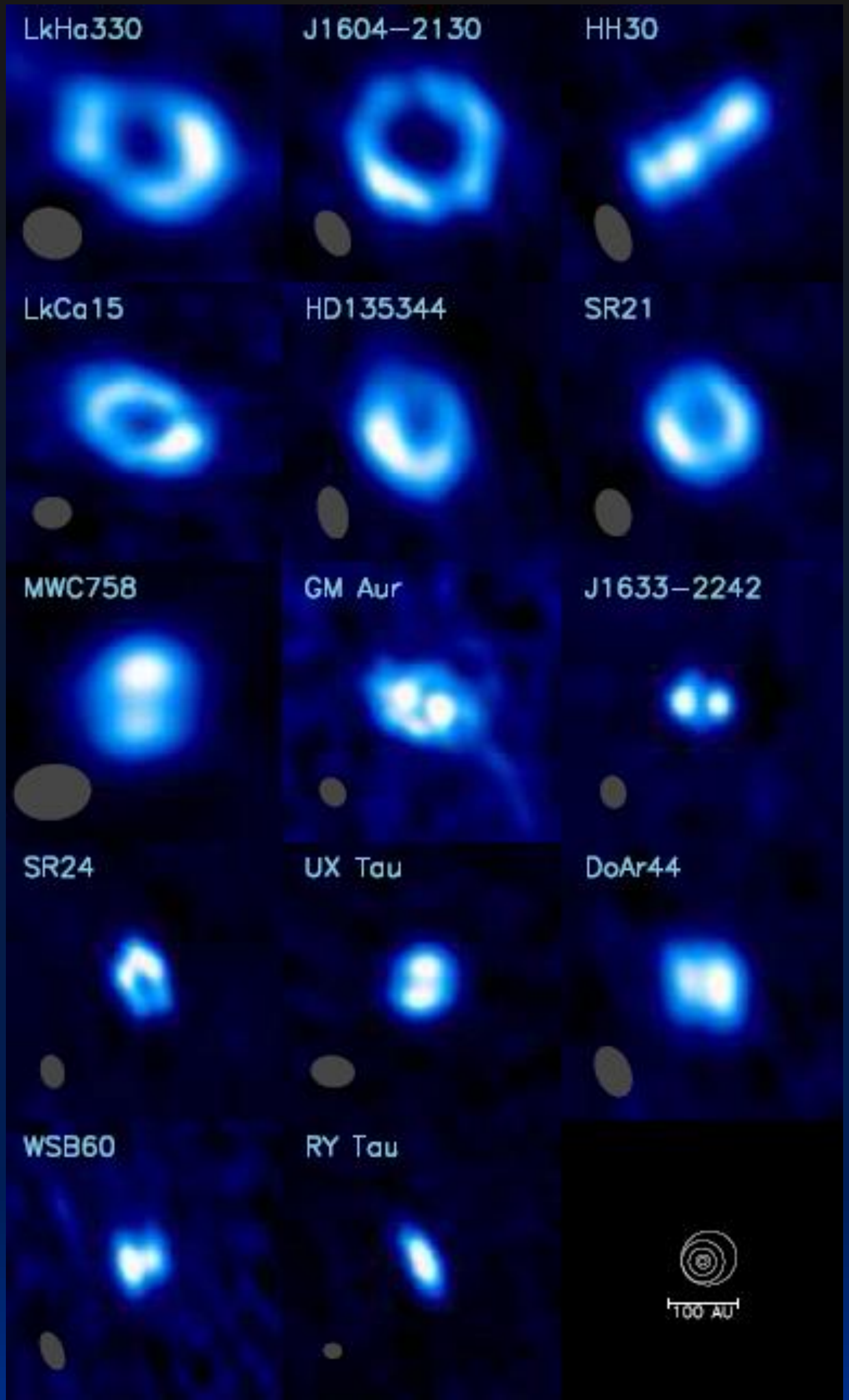
Disks with holes or radial gaps

- Cavity size > 20 AU
- Carved by multiple planets, or by other mechanisms?

Simulation of a wide gap with 3 planets (Dodson-Robinson et al. 2011)

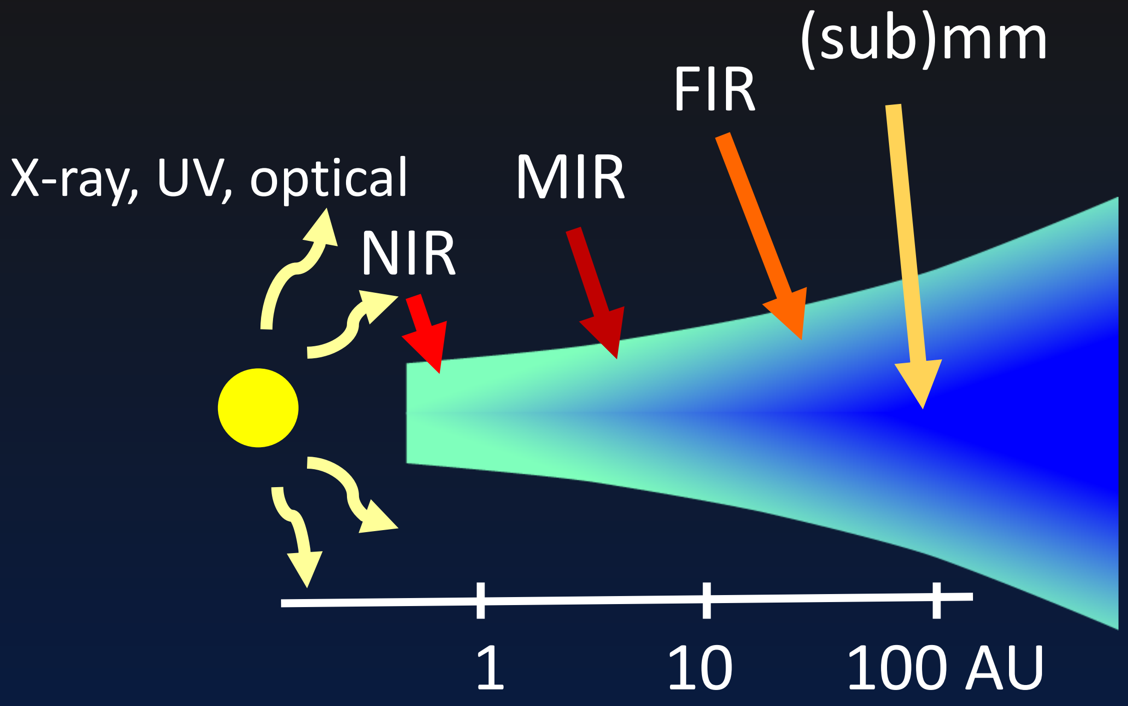


submmm dust cont. (Williams & Cieza 2011)



Observations in opt/IR

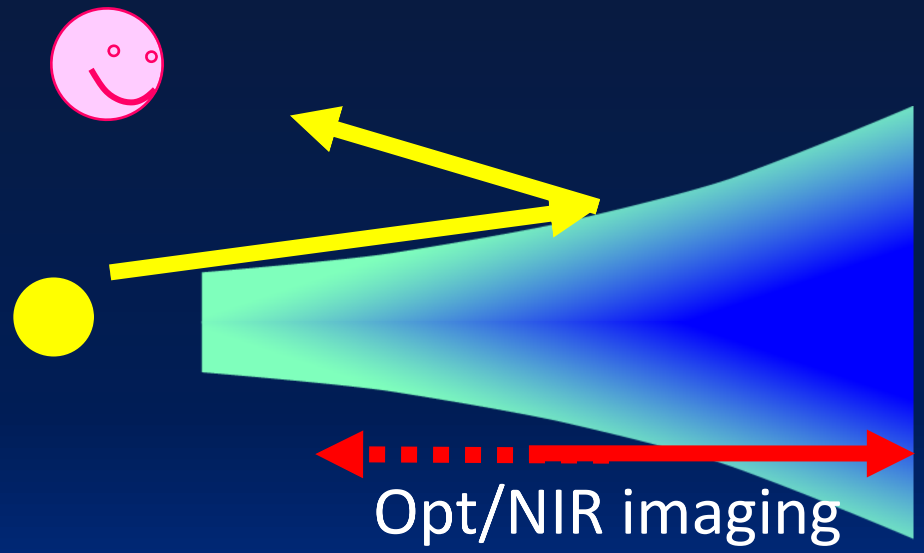
- Observing dust
  - Thermal IR emission from the hot, inner region
  - Scattered light from the outer disk



- Scat. light

  Sensitive to (sub)micron-sized grains in the upper surface of an optically thick disk

  ↔ millimeter-sized grains near the disk mid-plane efficiently detected in mm thermal observations



To observe…

1. Detailed structure (higher angular resolution)

   Res. < 0.”1 (~10 AU) is required

   - Typical size of a disk ~ 100 AU
   - Nearest star-forming regions: d = 140 pc

   - Atmospheric blurring ~0.”6
   - Diffraction limit: ~λ/D < 0.1 arcsec with a 8-m telescope at NIR

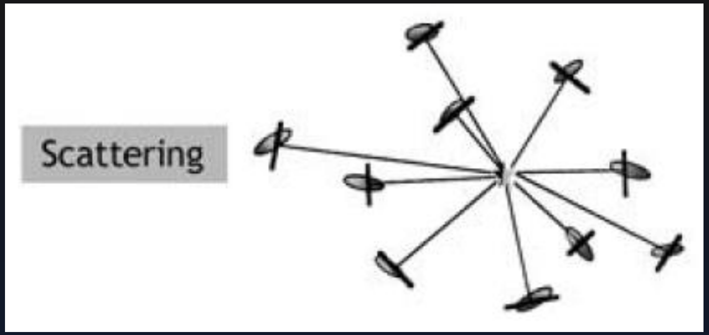
   $\rightarrow$ Solution: Use of adaptive optics from the ground

2. Inner region (higher contrast)

   Need to eliminate stellar light

   - Adaptive optics (high angular resolution)
   - Polarization differential imaging

Polarization differential imaging (PDI) with Subaru



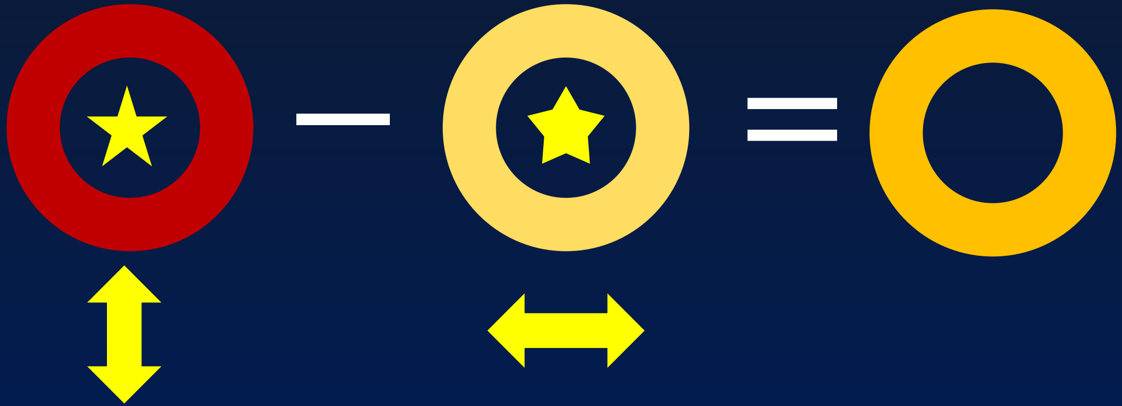
(Weintraub et al. 2000, PPVI)

- Subaru/HiCIAO + AO188
- *H* band (1.64 μm)
- FWHM = 0.06” = 8 AU at 140 pc (typical)
- PDI: Powerful to remove the stellar light

→Inner working angle

r ~ 0.2” = 30 AU at 140 pc (typical)

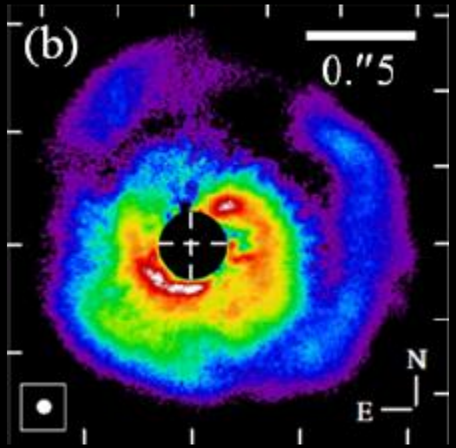
Scattered light is polarized, while starlight is unpolarized.



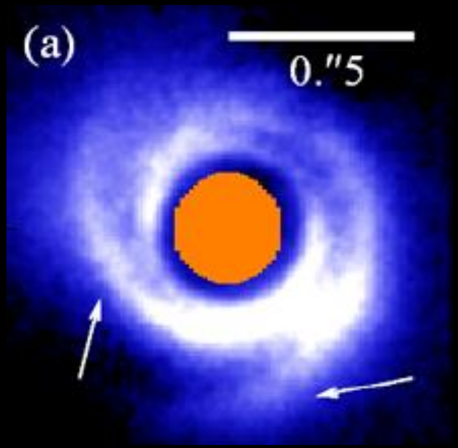
Star + Disk Star + Disk Disk

Observable: Polarized intensity (PI)
= (Intensity) × (Pol. degree)

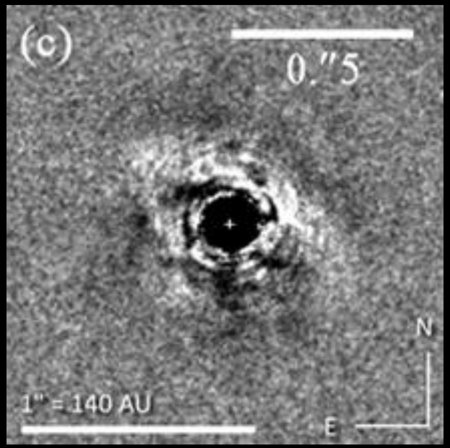
Scat. light imaging with <0.1” resolution



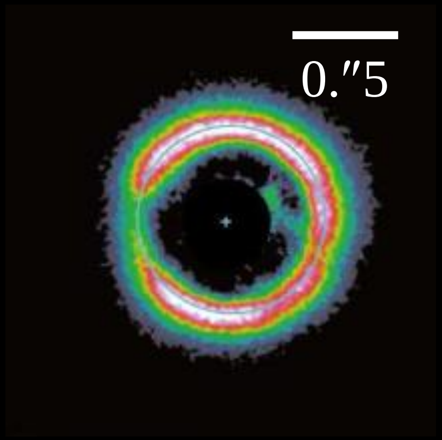
AB Aur
(Hashimoto+ 2011)



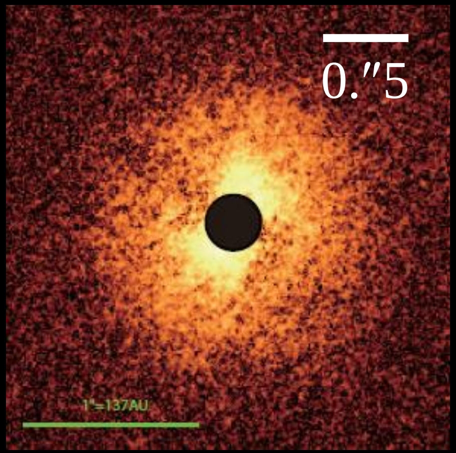
SAO 206462
(Muto+ 2012)



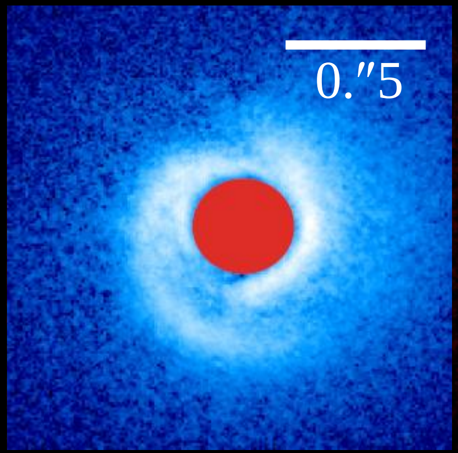
LkCa 15
Thalmann+ (2010)



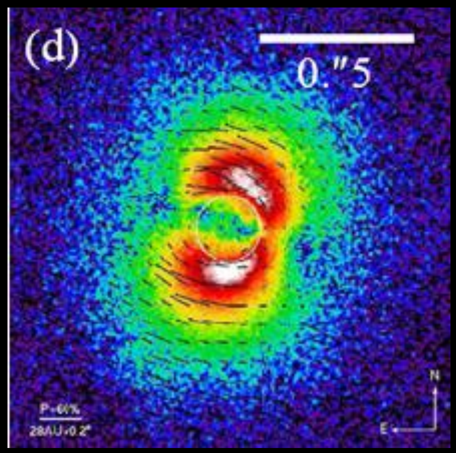
J1604-2130
(Mayama+ 2012)



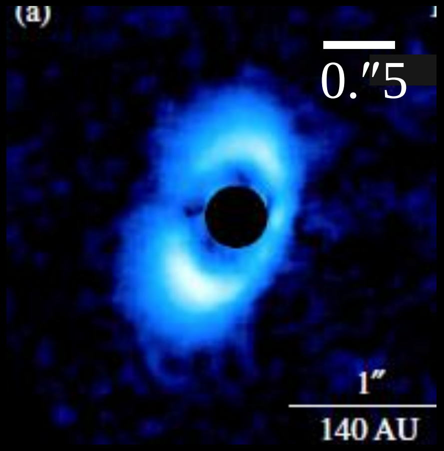
MWC 480
(Kusakabe+ 2012)



MWC 758
(Grady+ 2013)



UX Tau A
Tanii+ (2012)



PDS 70
(Hashimoto+ 2012)

Spirals

- Two systems with clear, compact spirals

  Spiral feature may not be unique
- Modeling based on the density-wave theory

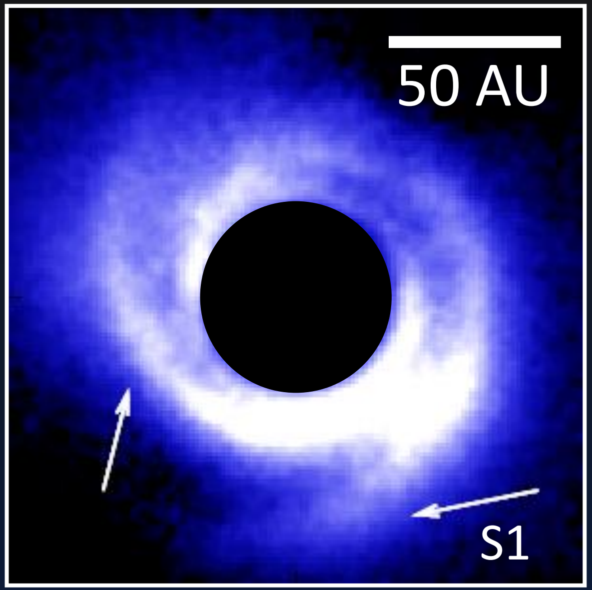
  → launching point, r_c

  → scale height (~ T distribution)
- Amplitude (if density fluctuation)

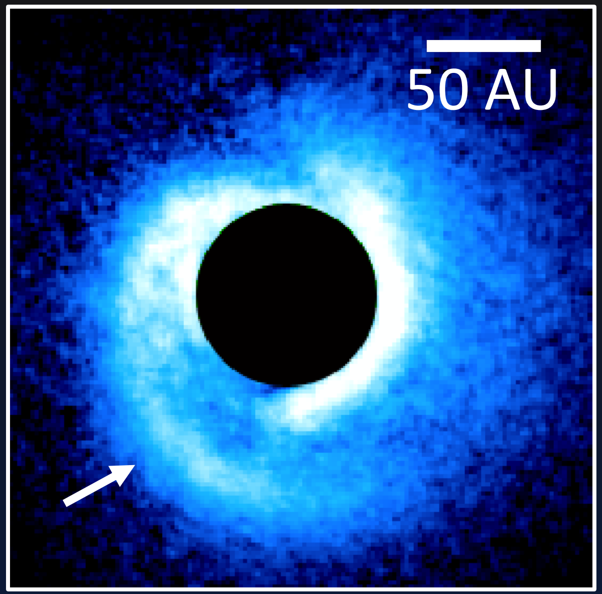
  → M_{planet} ~ 0.5 M_{Jup} for SAO 206462

  M_{planet} ~ 5 M_{Jup} for MWC 758
- Temporal variation?

  Rotation of the spiral pattern can be different from the local Keplerian speed.



SAO 206462
(Muto et al. 2012)



MWC 758
(Grady et al. 2012)

Best-fit external perturber

	SAO 206462 S1	**SAO 206462 S2**	**MWC 758 South**
r_c	0.39” (55 AU)	0.9” (130 AU)	1.55”
h_c	0.08	0.24	0.18

Subaru *vs.* TMT

Hydro-dynamical simulations for scattered light images at 1.6 μm

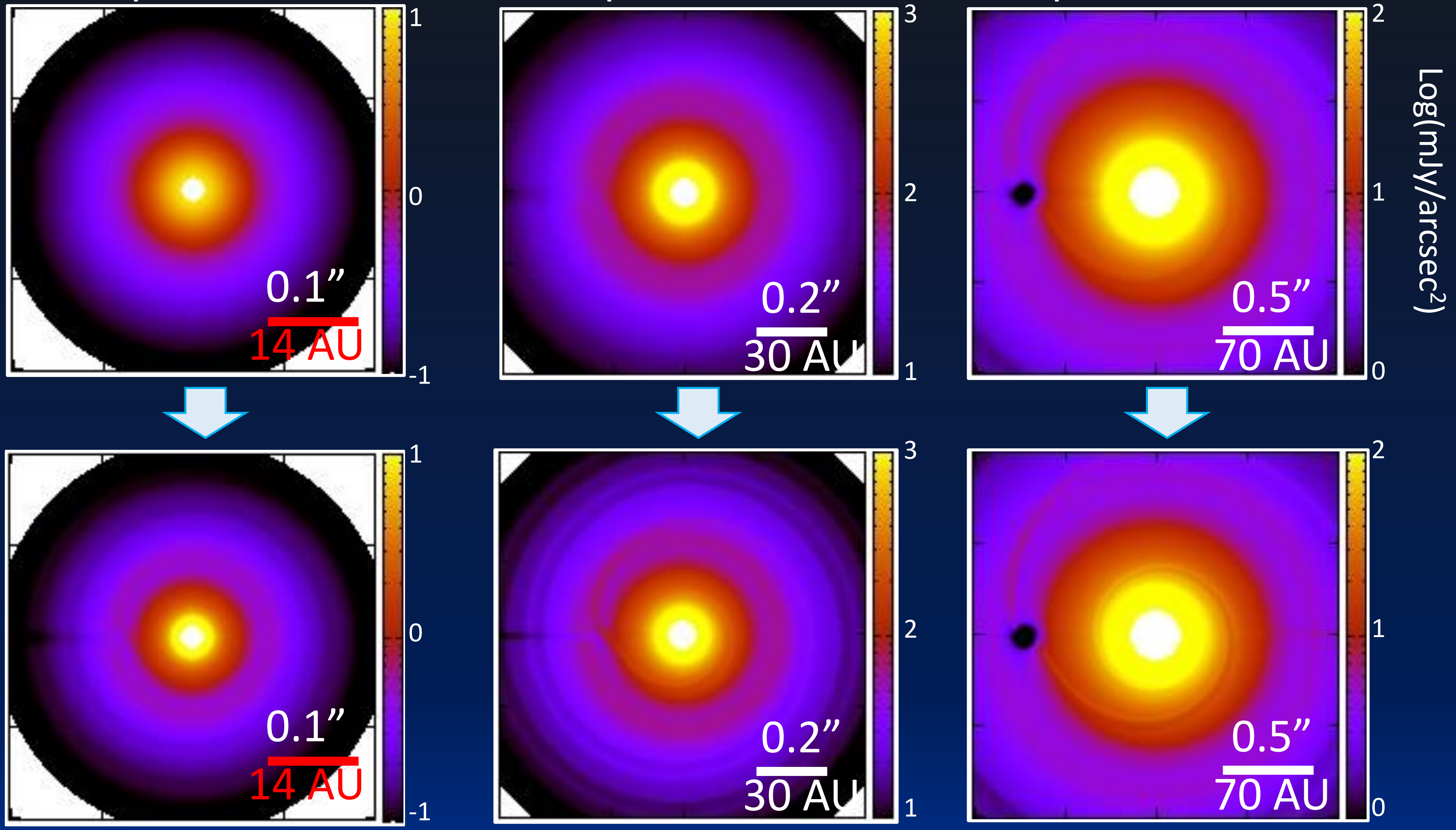
Calculations by T. Muto in the Japanese TMT science case book (2011)

$M_p \sim M_{Saturn}$

Rp = 10 AU | Rp = 30 AU | Rp = 100 AU

D = 8 m
IWA > 0.2”

D = 30 m



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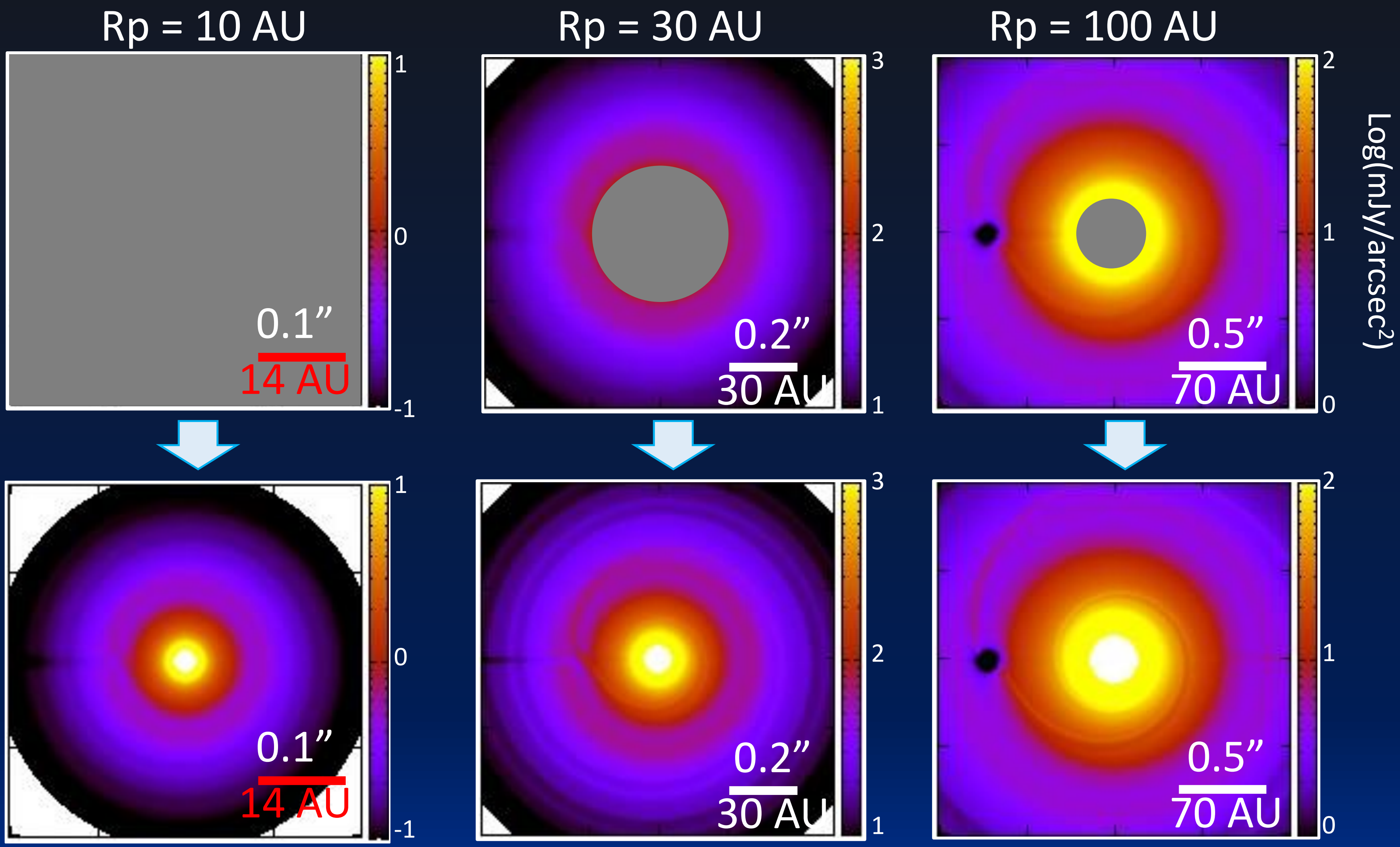
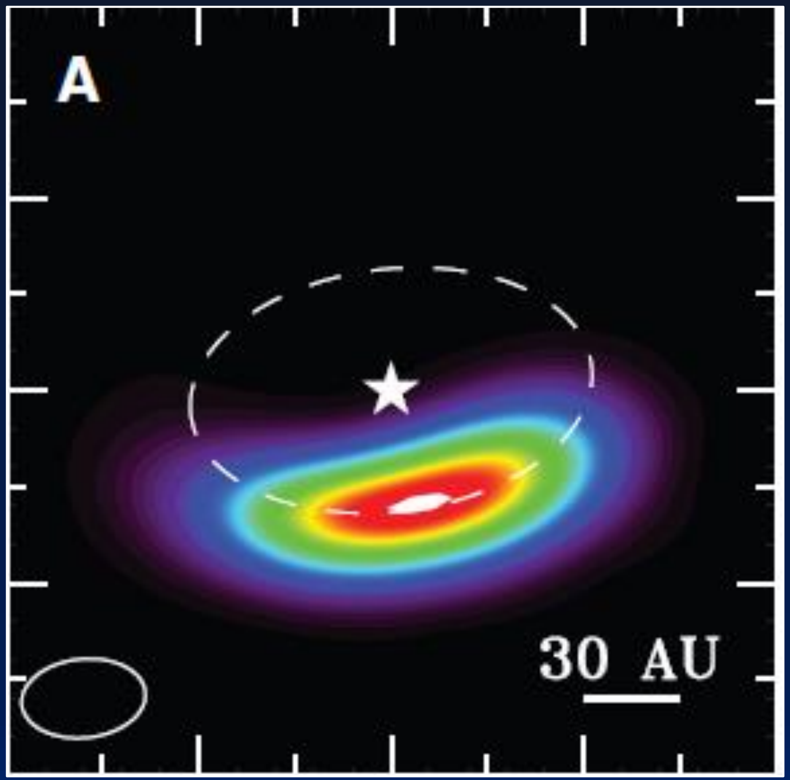
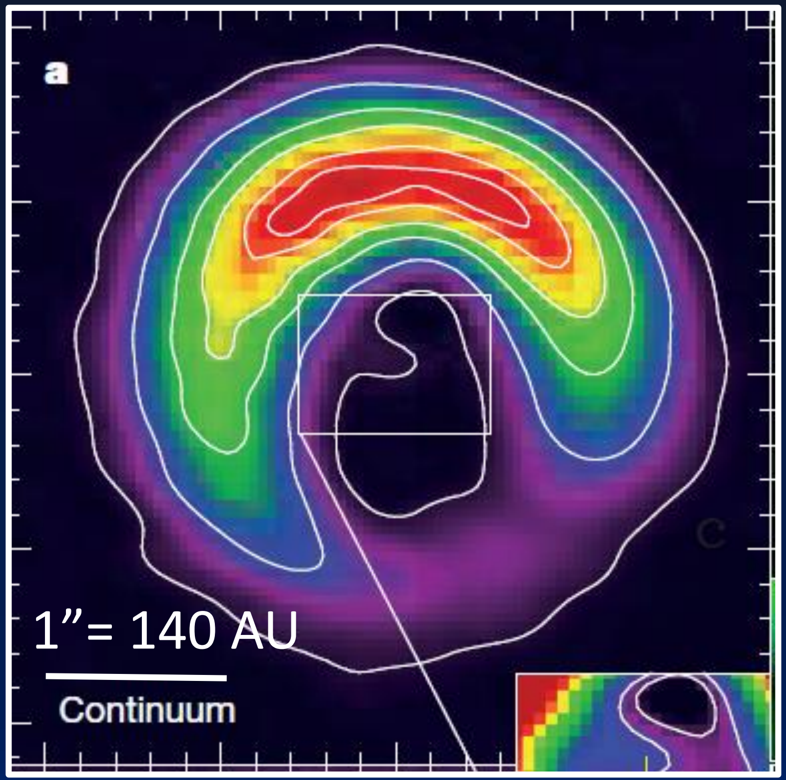


Disk structure in submm

- ALMA observations in Cycle 0 (~0.3”—0.5”)
  Strong azimuthal asymmetry (x10—100 in flux density)
  Forming site of rocky objects?

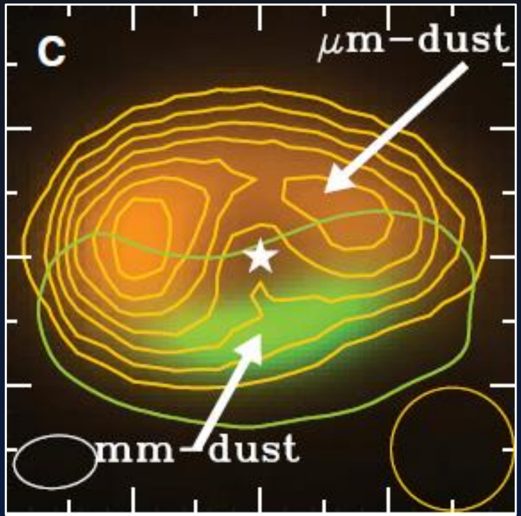


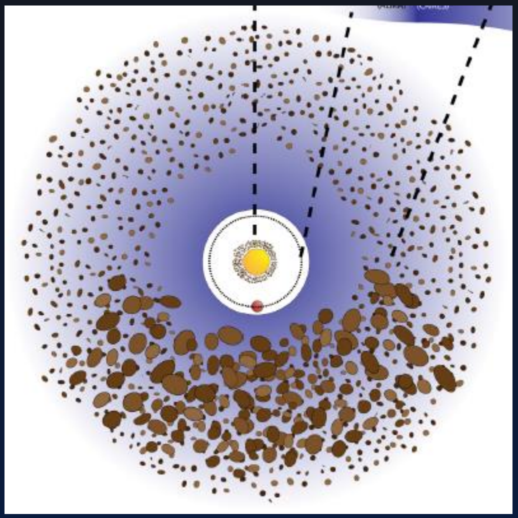
(van der Marel+ 2013)



(Casassus et al. 2013)

Multi-wavelength data



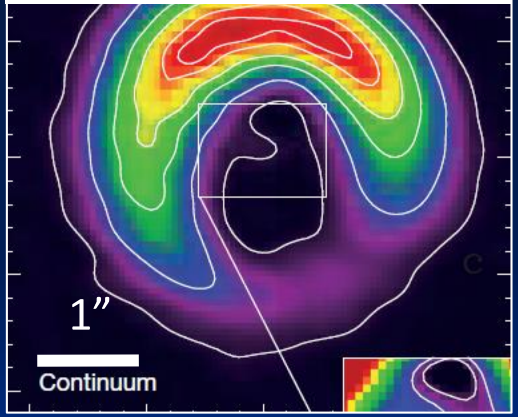


(van der Marel+ 2013)

- Larger grains in the mm-brighter region.

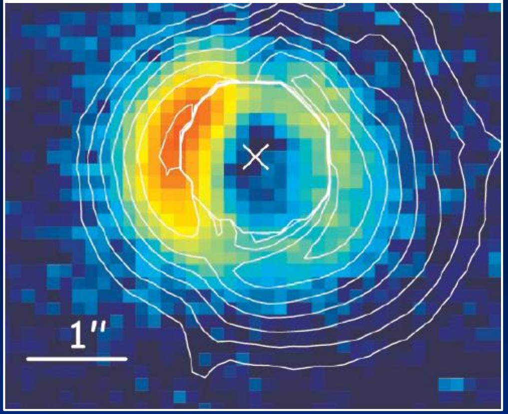
Segregation of dust particle size is also confirmed radially for some disks using VLA at ~1 cm (Perez et al. 2012)

Submm thermal



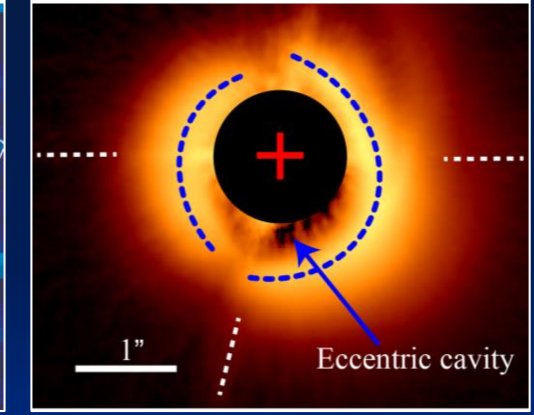
(Casassus+ 2013)

MIR thermal



(Fujiwara+ 2006)

NIR scat. light



(Fukagawa+ 2006)

- Better constraint on disk spatial structure
- λ-dependence of opacity

Summary

- High angular resolution of TMT will uncover
  - Detailed structure caused by an interaction with a planet less massive than the Jupiter
  - Inner planet-forming regions (< 30 AU)
  - Temporal change (rotation) of the structure
- Multi-wavelength study is essential to understand disks. ALMA will provide us stimulating sample for TMT.
- We do not forget gas (H_2, organic molecules…).
  - Constraints on formation of gas-giant planets, orbital evolution of planets
  - Inner disks can be kinetically resolved
  - Astrobiological interests