NAOJ研究集会「将来装置による地球型系外惑星直接検出および撮像」
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工学院大学
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Observability of Fine-Structures in Protoplanetary Disks

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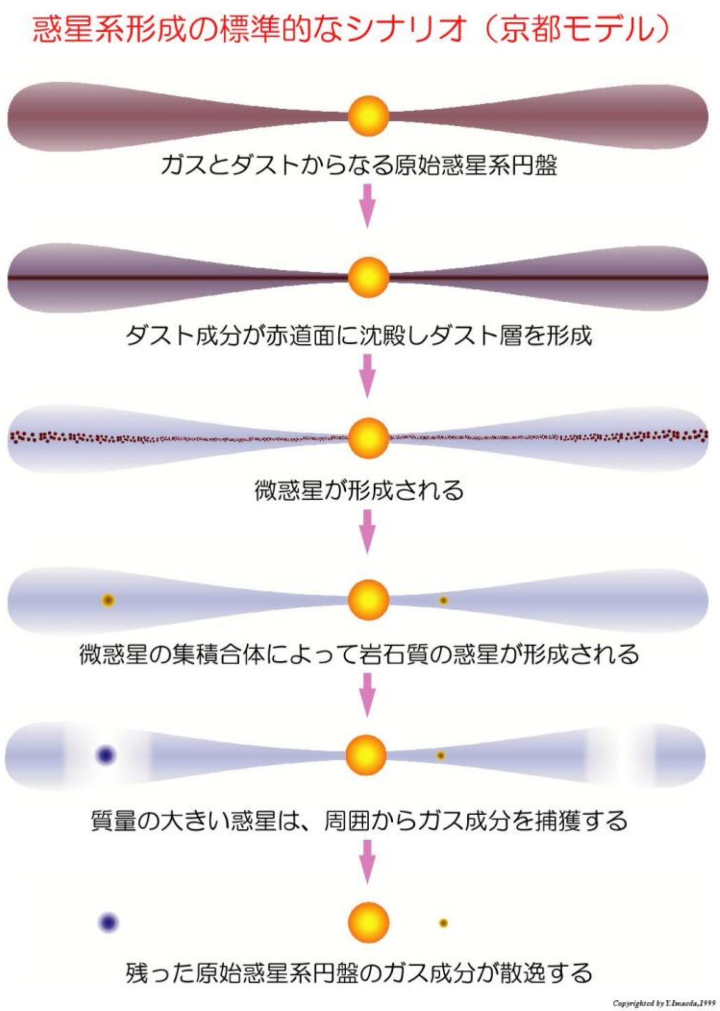
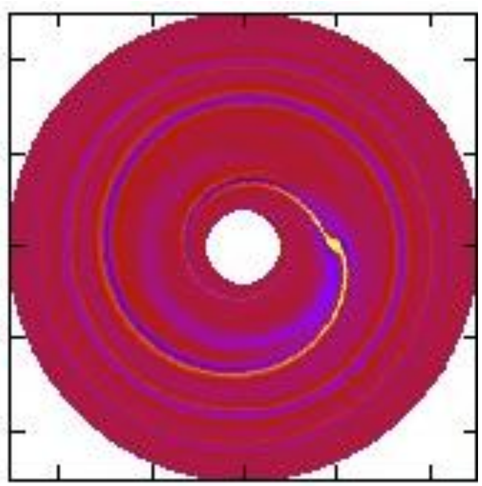
Protoplanetary Disk



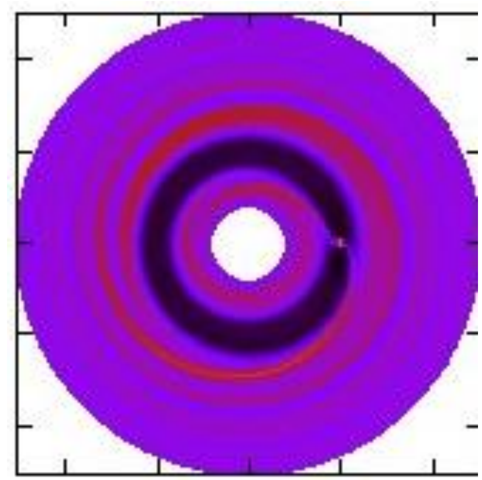
- A protoplanetary disk is a birthplace of planets
- Mixture of gas and dust
- Planet formation via coagulation of dust
- Gas dispersal
- Disk lifetime ~10^{6-7} yr
  - Constraint on the formation timescale of gas giants

Disk-Planet Interaction

- (A) planet(s) embedded in a disk perturbs the disk through gravitational interaction
  - Planets excite spiral density wave, gap, and possibly turbulence



A low-mass planet:
spiral waves



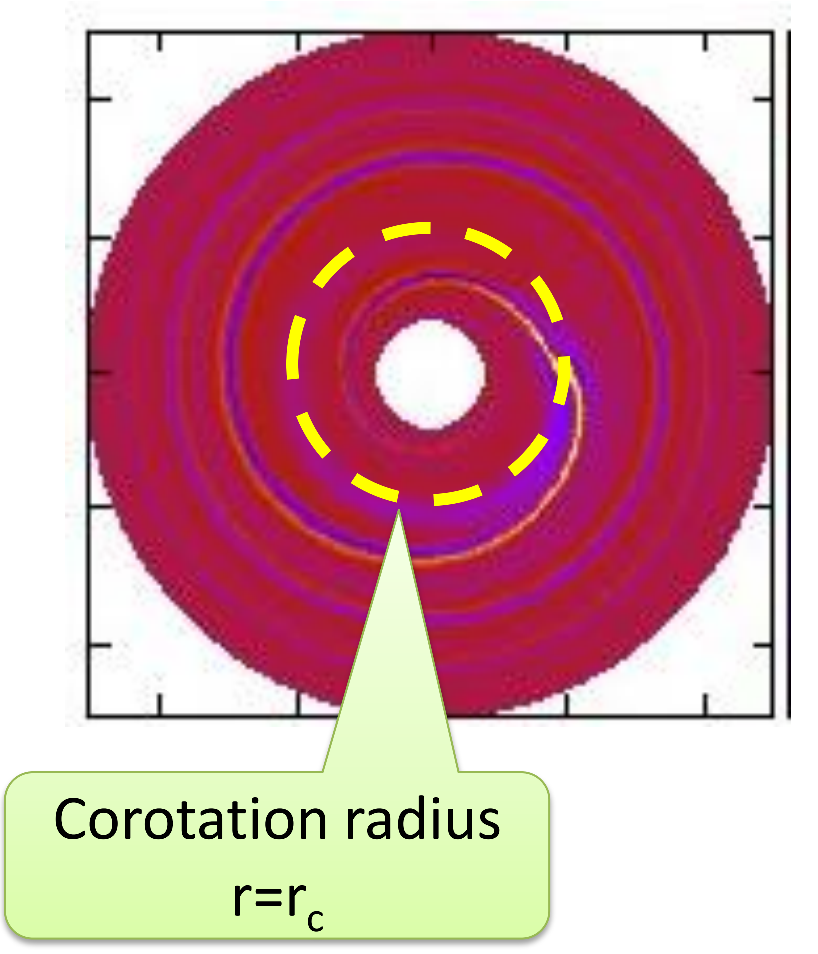
A high-mass planet:
spiral waves and a gap

Why Disk-Planet Interaction?

- **Direct evidence of planet formation within a disk if we can detect BOTH the spiral and the planet**
- **Theory of spiral waves is relatively well-understood**
  - Possible to construct a simple model (under many assumptions!)
- **Planet Migration timescale is (generally) faster than the disk lifetime**
  - A planet may fall into the central star?
  - A planet may go to outer radii?
  - ***Migration direction depends on the details of disk structure***
  - We basically do not know how planets behave in a disk
- **Need observational evidences**
  - Physical parameters of protoplanetary disks
  - Any disk that harbors (a) planet(s) at any age?

Spiral Density Wave

- Density wave
  - Is a **sound wave** in a differentially rotating disk
  - **Looks stationary** if we are in a **corotating frame**, which ***rigidly* rotates** at the rotation frequency of the corotation radius
  - Is excited by any perturbation in a disk: turbulence, a planet…



Density Wave: Dispersion Relation

$$f(r, \phi) = f_0 \exp\left[ik_r r + im\phi\right]$$

$$m^2(\Omega(r) - \Omega_p)^2 = \kappa^2 + c^2 k_r^2$$

Ω_p: pattern speed

← equals the Kepler frequency at the corotation radius

The dispersion relation gives the shape of the spiral density wave

What determines the shape of the density wave?

At a place away from the corotation:

Inner disk: $r \ll r_c \rightarrow \Omega(r) \gg \Omega_p$

$$f(r,\phi) \propto \exp\left[im\left(\phi \pm r\Omega(r)/c(r)\right)\right]$$

Spiral shape

Outer disk: $r \gg r_c \rightarrow \Omega(r) \ll \Omega_p$

$$f(r,\phi) \propto \exp\left[im\left(\phi \pm r\Omega_p/c(r)\right)\right]$$

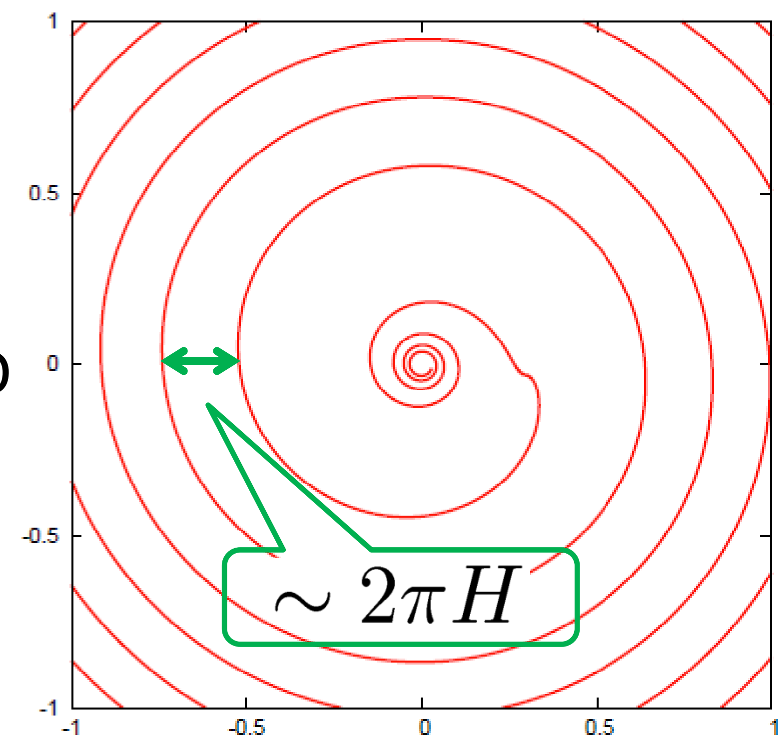
Spiral shape

The form of the spiral: $\phi(r) \sim \pm \frac{r}{H}$

- **The spiral shape does not depend on mode number in WKB regime**
- **The opening angle of the spiral indicates the disk thickness (temperature)**

Detectablity of Spiral Structures

- Spirals are just the perturbation to the background disk
  - The overall disk structure is not affected
  - Difficult to find “spirals” in SED
- We need good spatial resolution
  - Spirals are “tightly-wound”
  - Need to distinguish spirals from a ring



Need to resolve structure with scale ~H

Spiral Wave Amplitude

- So far, we have only looked at the "shape" of the spiral.
- Another measurable quantity of the wave – amplitude
- Spiral amplitude is related to:
  - Angular momentum that is carried by the wave
  - The planet mass if the spiral is excited by a planet

Spiral Wave Excited by a Planet

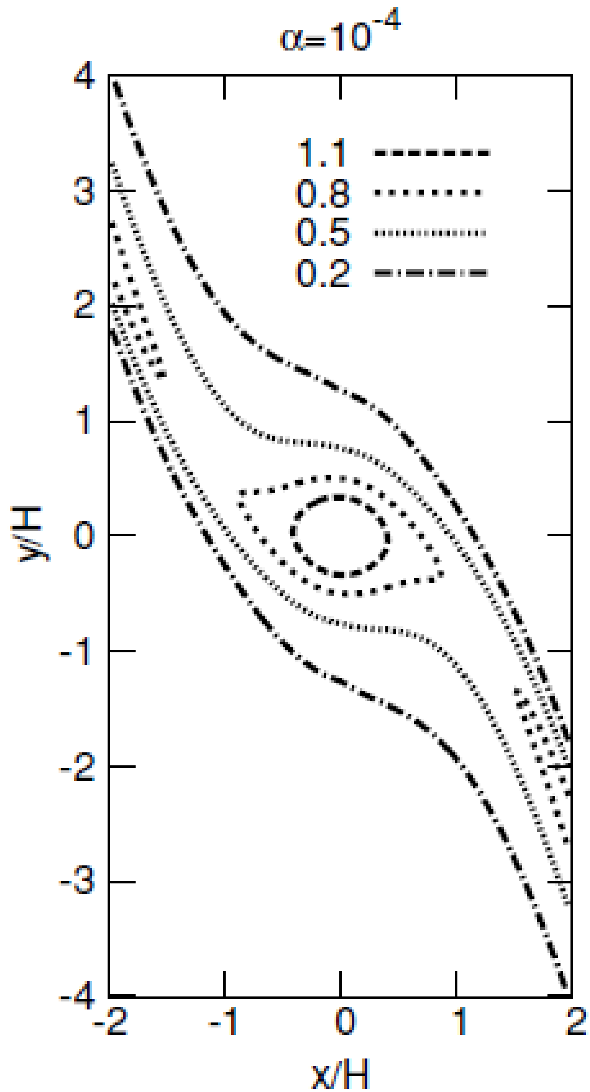
Typical scale length for the spiral ~H

Planet's gravitational energy
~ perturbation of the thermal energy

$$\frac{GM_{\rm p}}{H} \sim c^2 \frac{\delta\Sigma}{\Sigma}$$

This reduces to:

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



Protoplanetary Disk @ 100AU

- Surface density (MMSN model)

$$\Sigma_{\rm gas} = 1.7{\rm g/cm^2} \left(\frac{r}{100{\rm AU}}\right)^{-3/2}$$

- Disk thickness (scale height)

$$H = 15{\rm AU} \left(\frac{r}{100{\rm AU}}\right)^{5/4}$$

- Disk aspect ratio

$$\frac{H}{r} = 0.15 \left(\frac{r}{100{\rm AU}}\right)^{1/4}$$

14 AU = 0.1” @ 140 pc

→ Subaru

Protoplanetary Disk @ 10AU

- Surface density (MMSN model)

$$\Sigma = 50\mathrm{g}/\mathrm{cm}^2 \left(\frac{r}{10\mathrm{AU}}\right)^{-3/2}$$

- Disk thickness (scale height)

$$H = 0.8\mathrm{AU} \left(\frac{r}{10\mathrm{AU}}\right)^{5/4}$$

- Disk aspect ratio

$$\frac{H}{r} = 0.08 \left(\frac{r}{10\mathrm{AU}}\right)^{1/4}$$

1.4 AU = 0.01” @ 140 pc

➔ TMT, full ALMA

Protoplanetary Disk @ 1AU

- Surface density (MMSN model)

$$\Sigma = 1600\mathrm{g/cm^2}\left(\frac{r}{1\mathrm{AU}}\right)^{-3/2}$$

- Disk thickness (scale height)

$$H = 0.05\mathrm{AU}\left(\frac{r}{1\mathrm{AU}}\right)^{5/4}$$

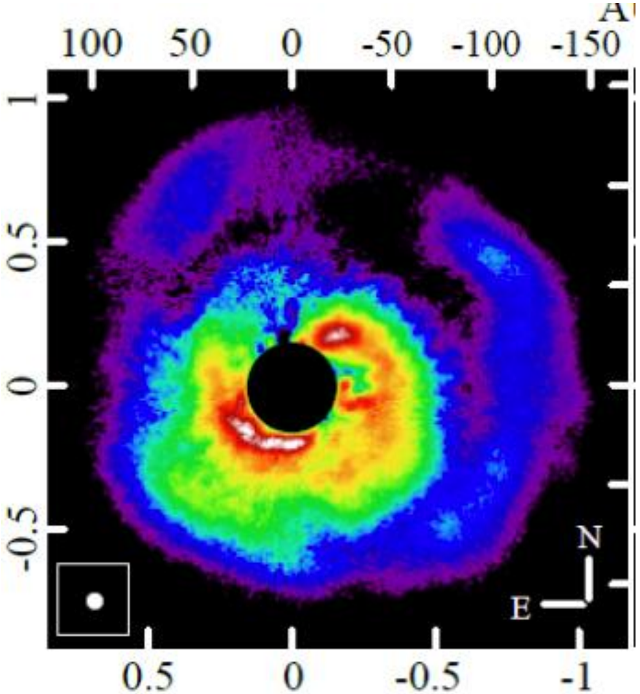
- Disk aspect ratio

$$\frac{H}{r} = 0.05\left(\frac{r}{1\mathrm{AU}}\right)^{1/4}$$

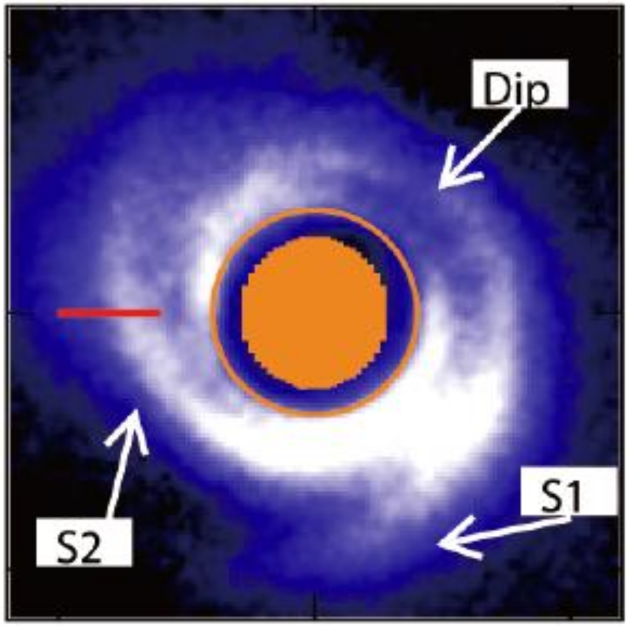
0.1 AU = 0.001” @ 140 pc
➔ ???

Direct Imaging Observations of Protoplanetary Disks

- NIR observations
  - SEEDS project with Subaru
  - A number of high resolution disk observations



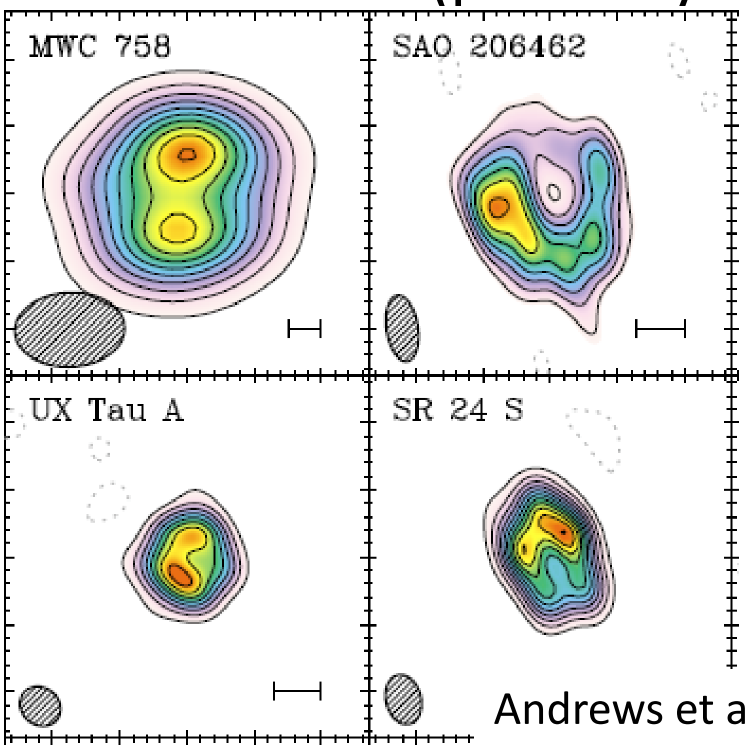
Hashimoto et al. (2010)



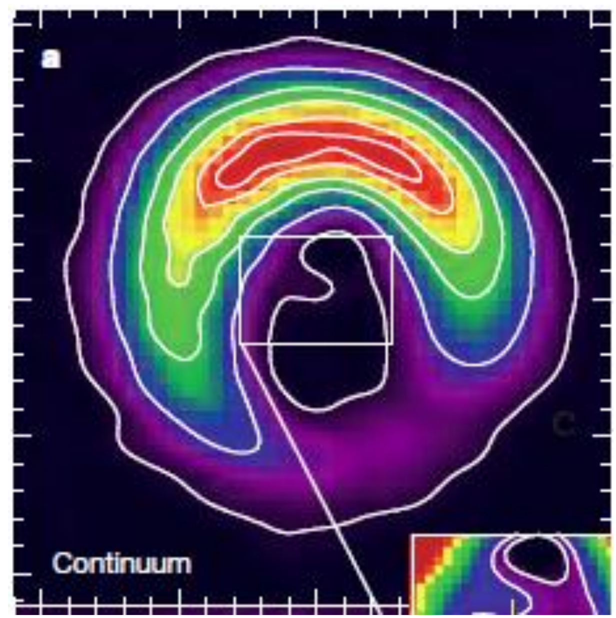
Muto et al. (2012)

Direct Imaging Observations of Protoplanetary Disks

- Sub-mm observations
  - With SMA, ALMA. Mainly with dust continuum
  - Not yet reached to the resolution comparable with NIR (probably in ALMA Cycle 2)



Andrews et al. 2011

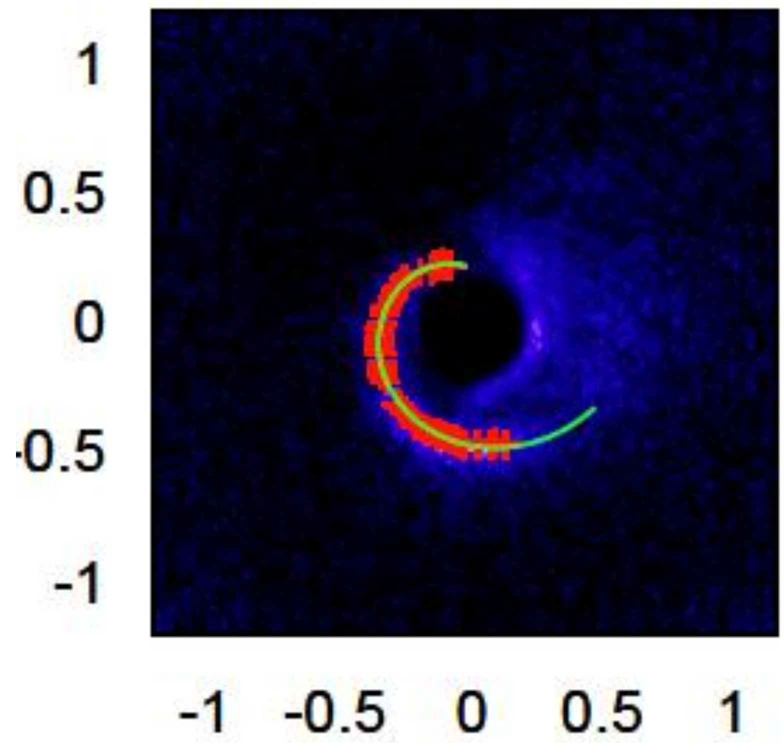


Casassus et al. 2013

Spiral Fitting

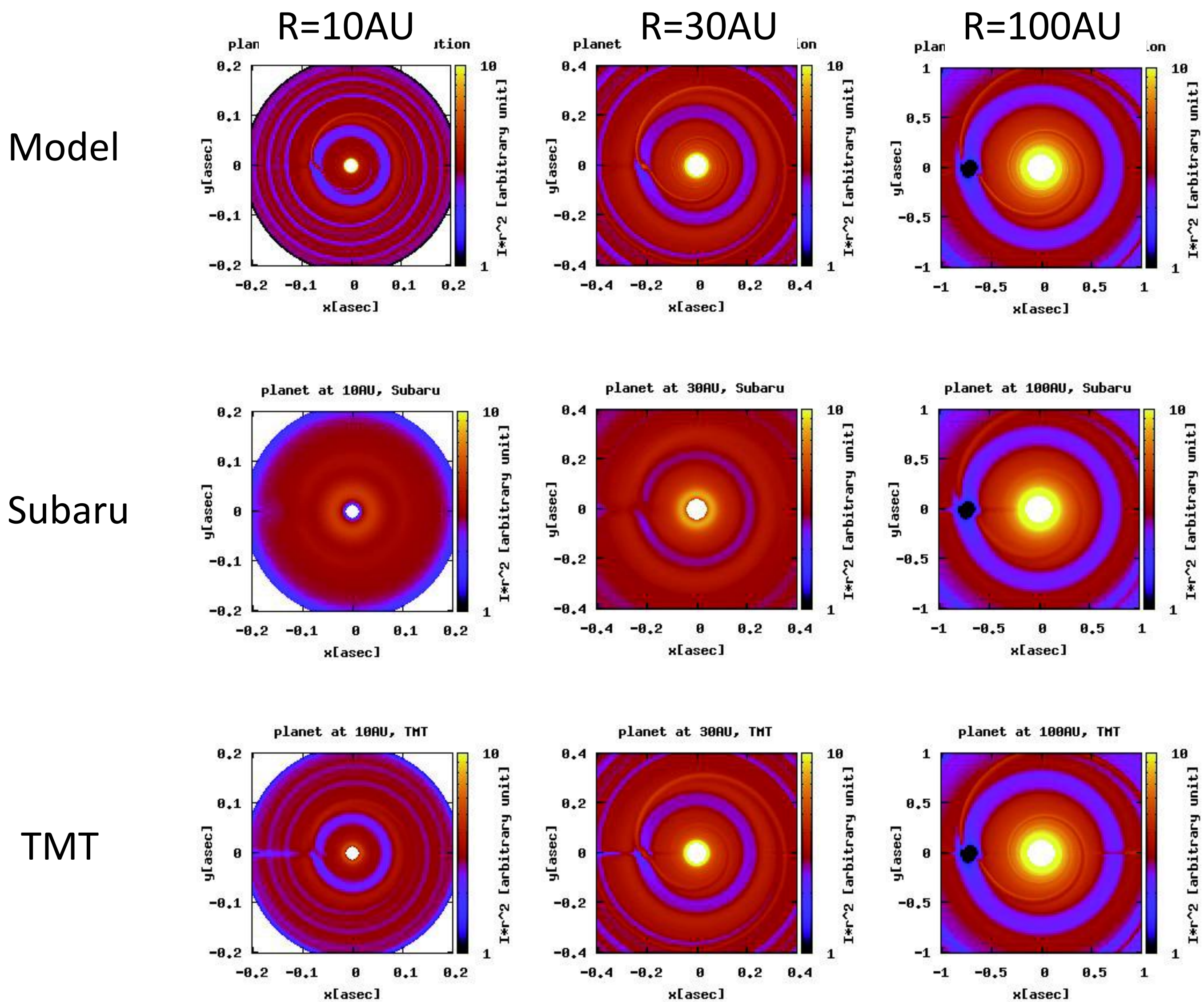
Parameter	Search Range	Best Fit External Perturber
r_c	$0''.05 \le r_c \le 1''.55$	$r_c = 1''.55$
θ	$0 \le \theta_0 \le 2\pi$	$\theta_0 = 1.72[\mathrm{rad}]^{a}$
h_c	$0.05 \le h_c \le 0.25$	$h_c = 0.182$
δ	$-0.1 \le \delta \le 0.6$	$\delta = 0.06$

- We can derive:
  - Disk thickness (~temperature)
  - Where the "launching point of the spiral" is
    - "Planet location", if it is launched by a planet



MWC 758 with Subaru, Grady, Muto et al. (2012)

TMT Simulation



Multiband Observation

- NIR scattered light observes upper layer of the disk
- Sub-mm continuum observes disk mid-plane
  - Laminar disk if both show similar spiral feature

- Planets are directly imaged at NIR
- Inflow of gas to the planet at sub-mm

Summary Figure