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Planets in Protoplanetary Disks: Dynamical Processes and Observational Prospects

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Outline

- Introduction: Planet Formation and Disk-Planet Interaction
- Spiral Density Wave Theory and Type I Planet Migration
- Direct Imaging Observations of Disk Non-axisymmaetric Structures

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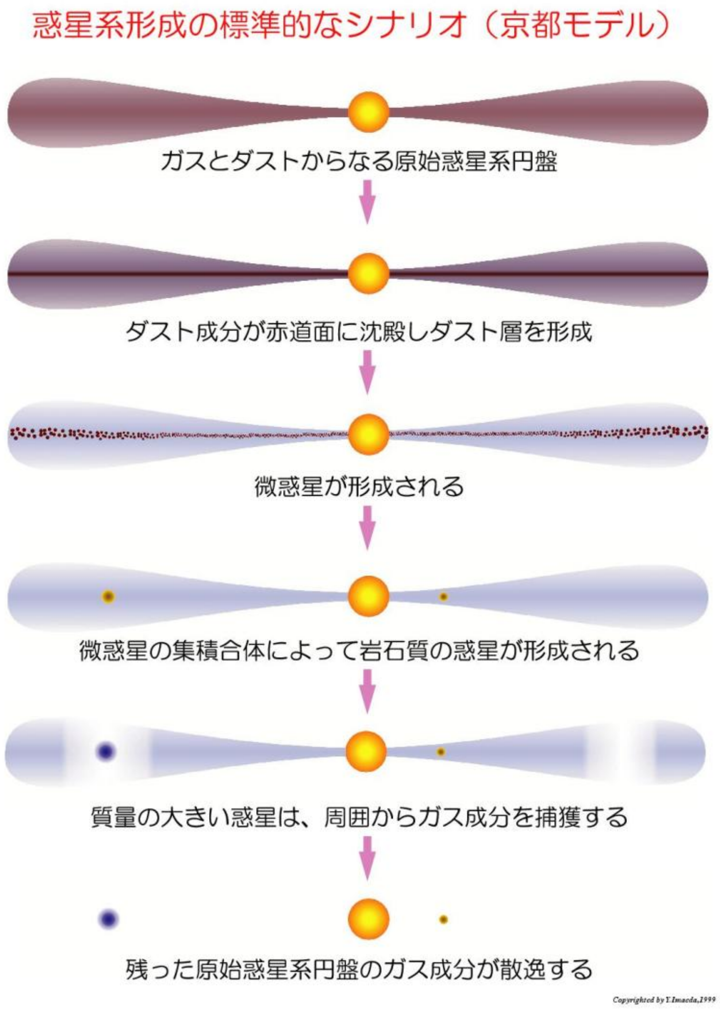
Planet Formation Scenario

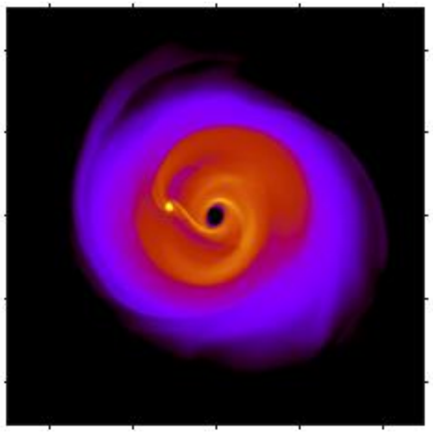


- Initial condition:
  - Protoplanetary disk
  - Mixture of gas and dust particles (~1um)
- Coagulation of dust particles in the disk
  - Planetesimals (~1km)
  - Protoplanets (~1000km)
- Disk gas dispersal
- Disk lifetime ~10^{6-7} yr
  - Timescale constraint on (gaseous) planet formation

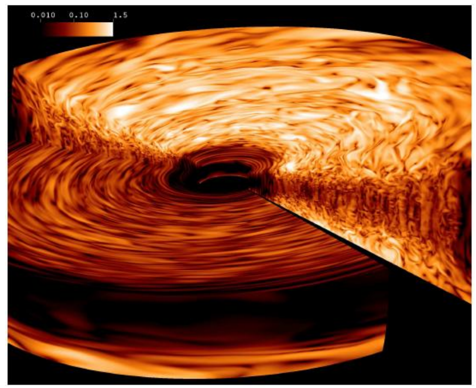
Dynamical Processes in Protoplanetary Disks

Turbulence:

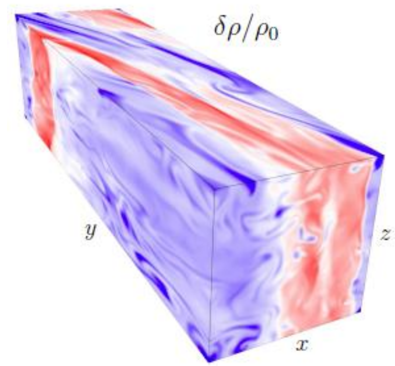
gravitational instability / magnetorotational instability / others…



Boley 2009

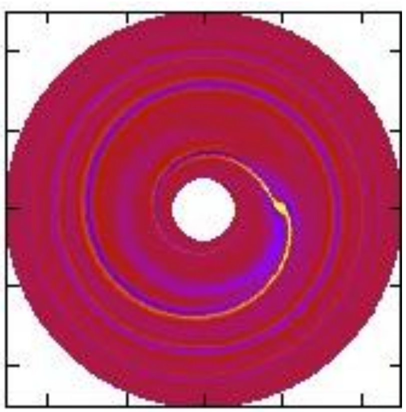


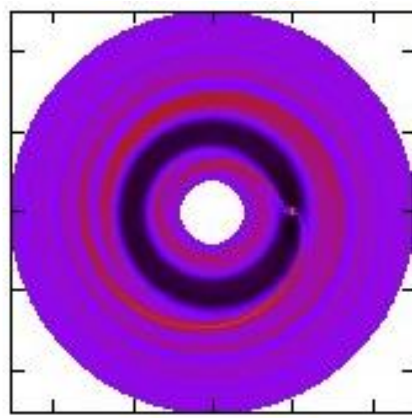
Flock et al. 2011



Heinemann and Papaloizou 2009

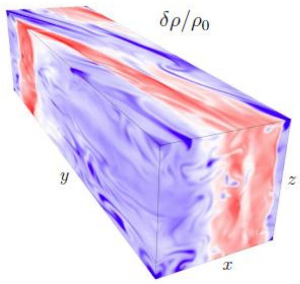
Disk-planet interaction: spiral wave, gap-opening…



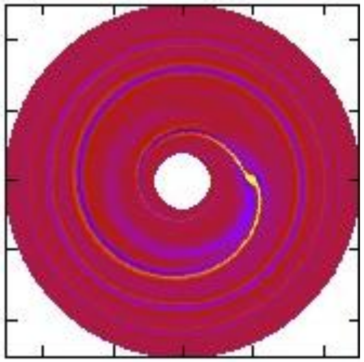


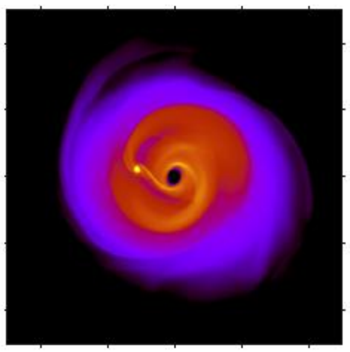
FARGO simulation

Spiral Wave as an Indicator of Dynamical Activity in a Disk



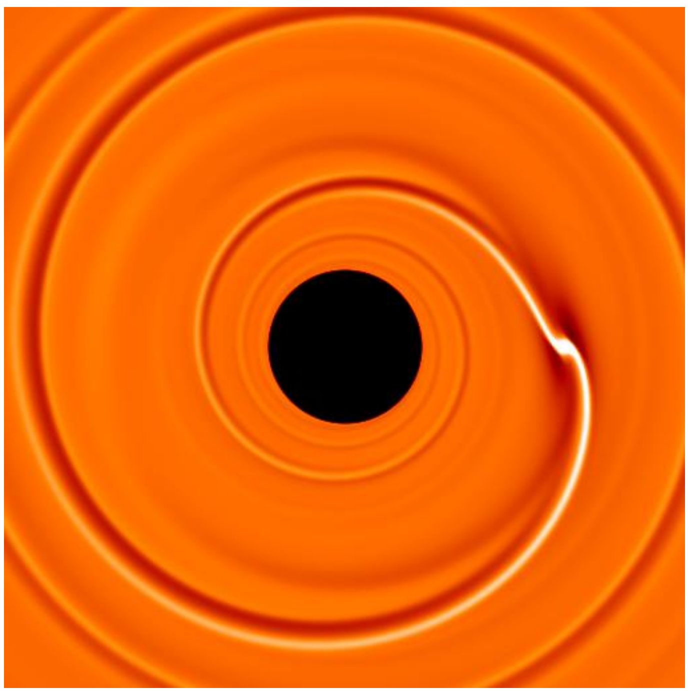
- Spiral structures are expected quite generally in dynamically active disks
- Spiral density wave
  - (non-axisymmetric) sound wave excited in a disk
  - Any perturbation can cause non-axisymmetric structures

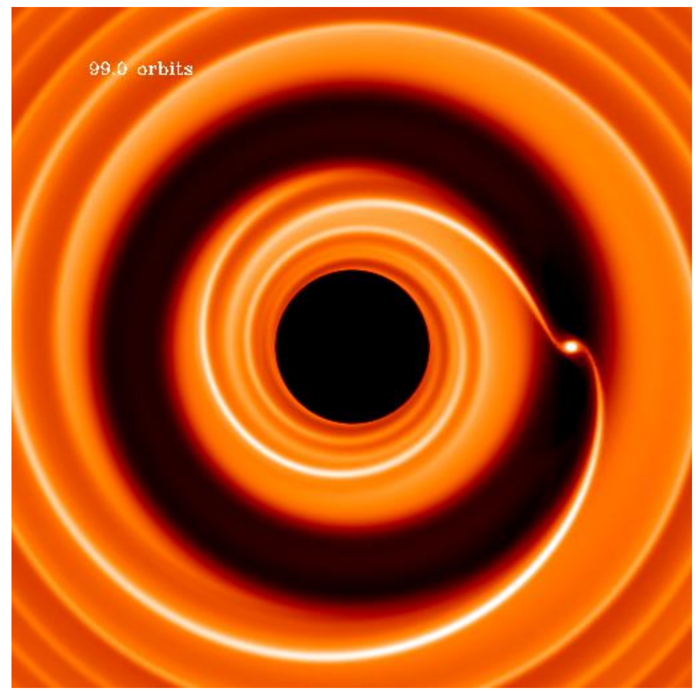




Disk-Planet Interaction

- Gravitational Interaction between a Planet and a Disk
  - And nothing more…





http://www.maths.qmul.ac.uk/~masset/moviesmpegs.html

Why Disk-Planet Interaction?

- Radial migration of the planet
  - Planets can migrate significantly before the dispersal of the gas disk
  - Impact on planet formation theory
- Redistribution of the gas in the disk
  - Planets can form a spiral density wave, gap, possibly inner hole…
  - Observational predictions

- Introduction: Planet Formation and Disk-Planet Interaction
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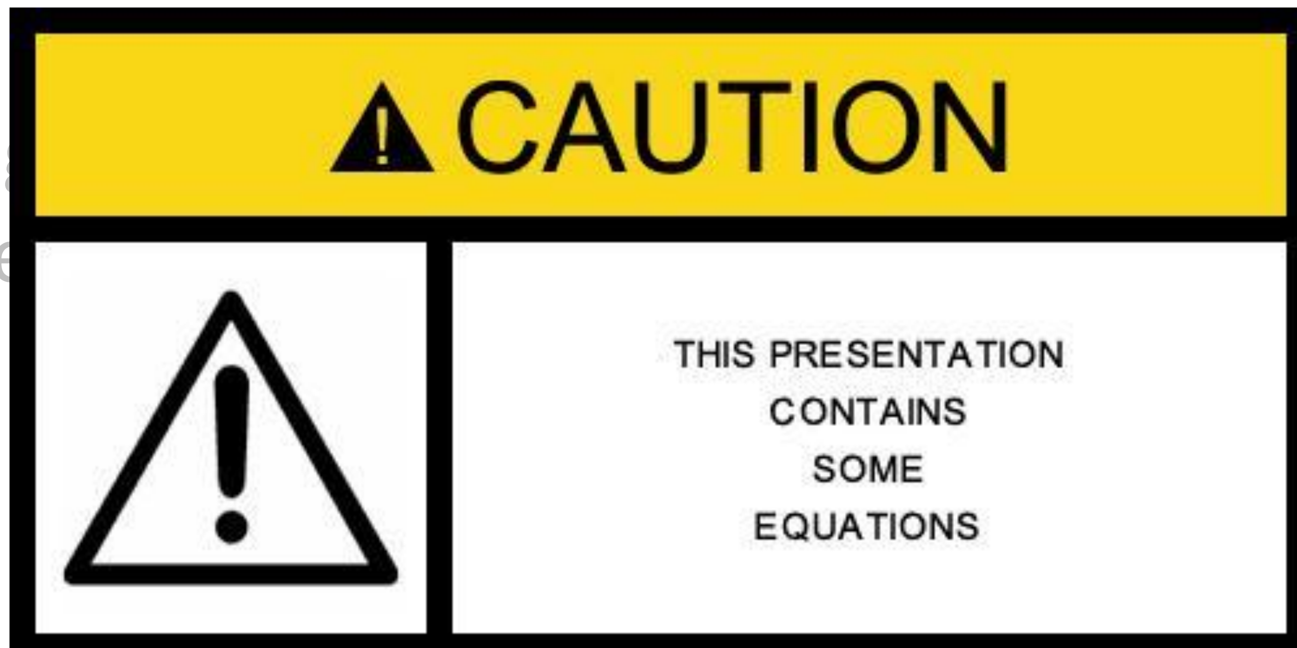
- Direct Ima
axisymmae

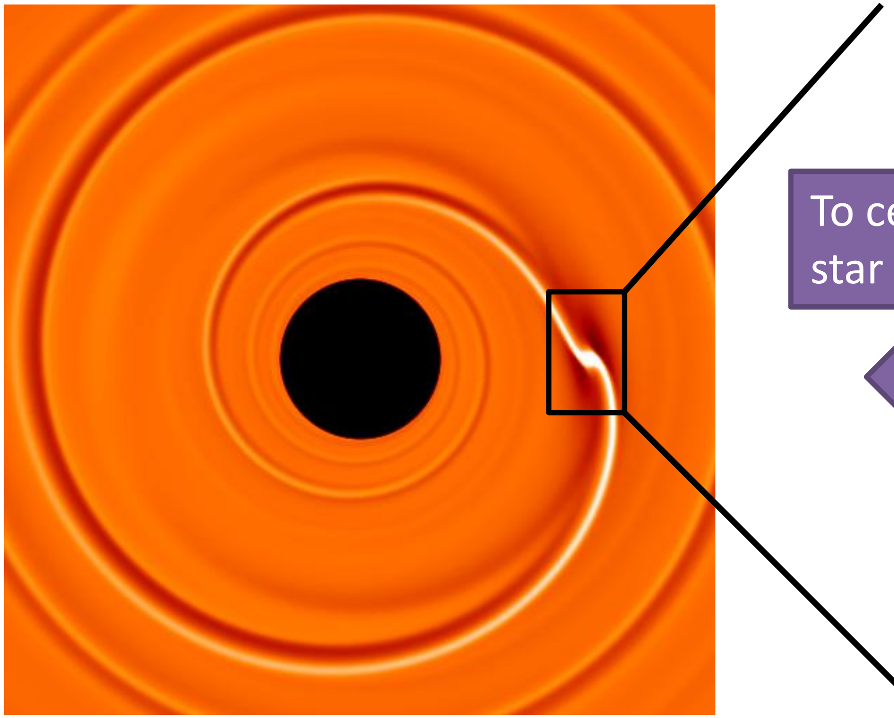


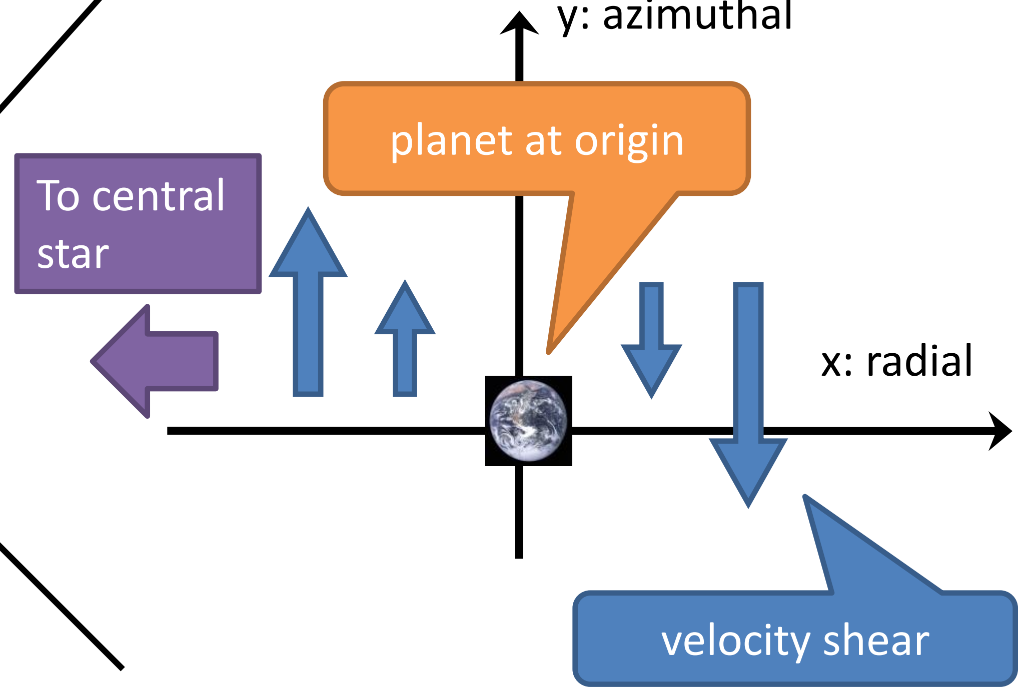
http://www.warninglabelgenerator.com/

Problem Setup

- Consider the simplest case
  - A planet in a circular orbit in a circular disk
- We expect a steady state ***in a rotating frame with the planet***

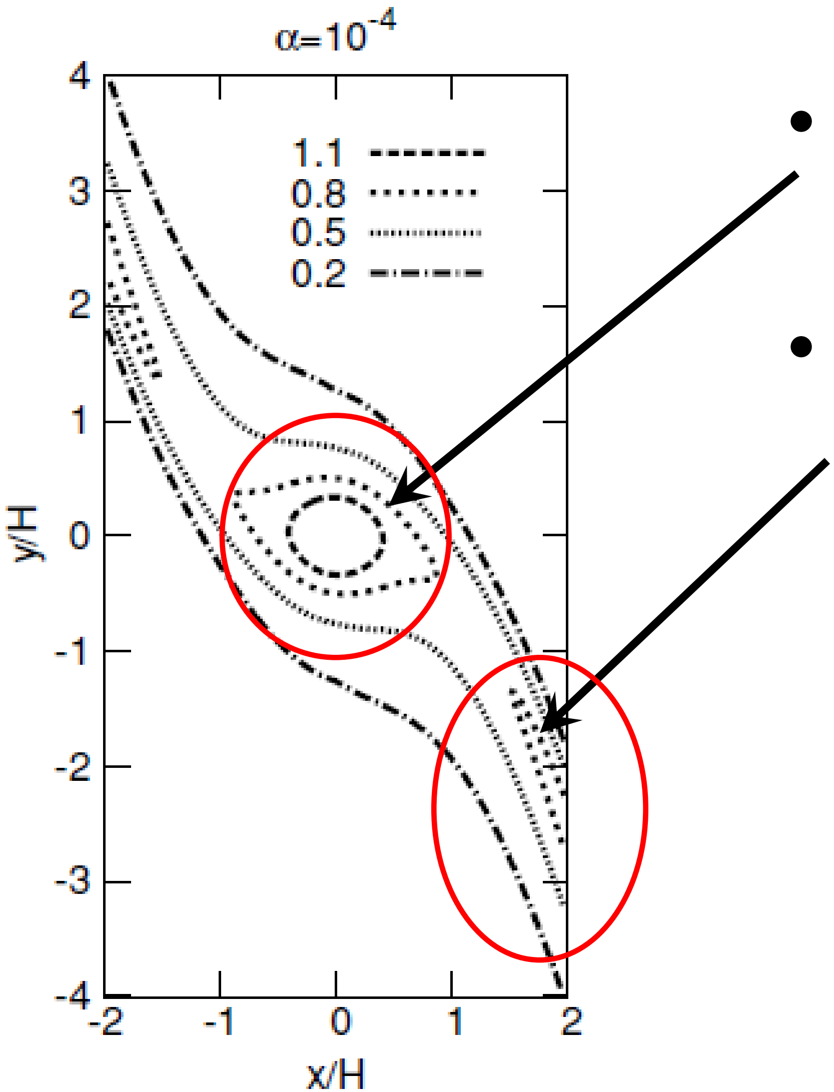
Shearing-sheet
close-up view around the planet





$$v_y = -\frac{3}{2}\Omega_{\rm p} x$$

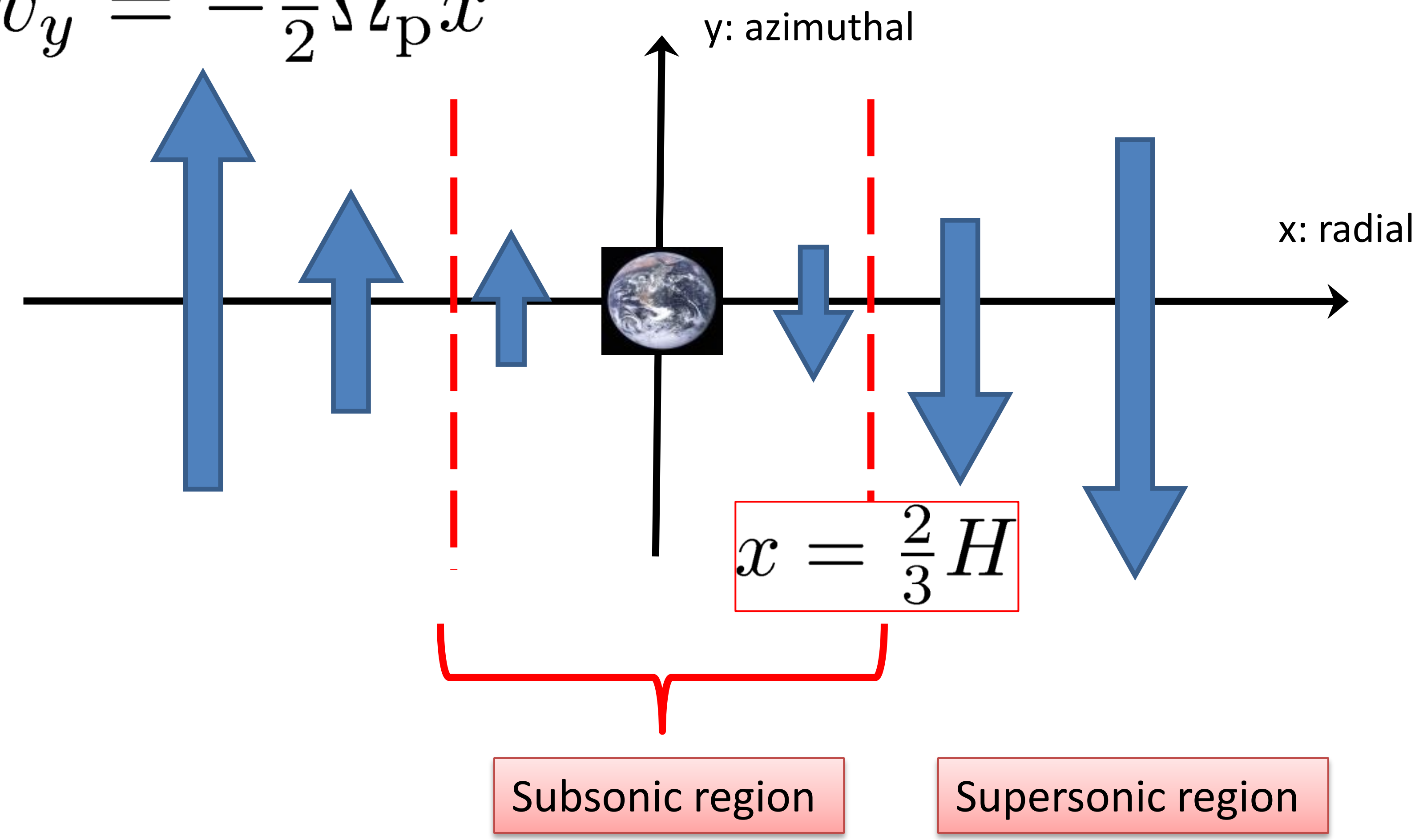
Surface Density Perturbation



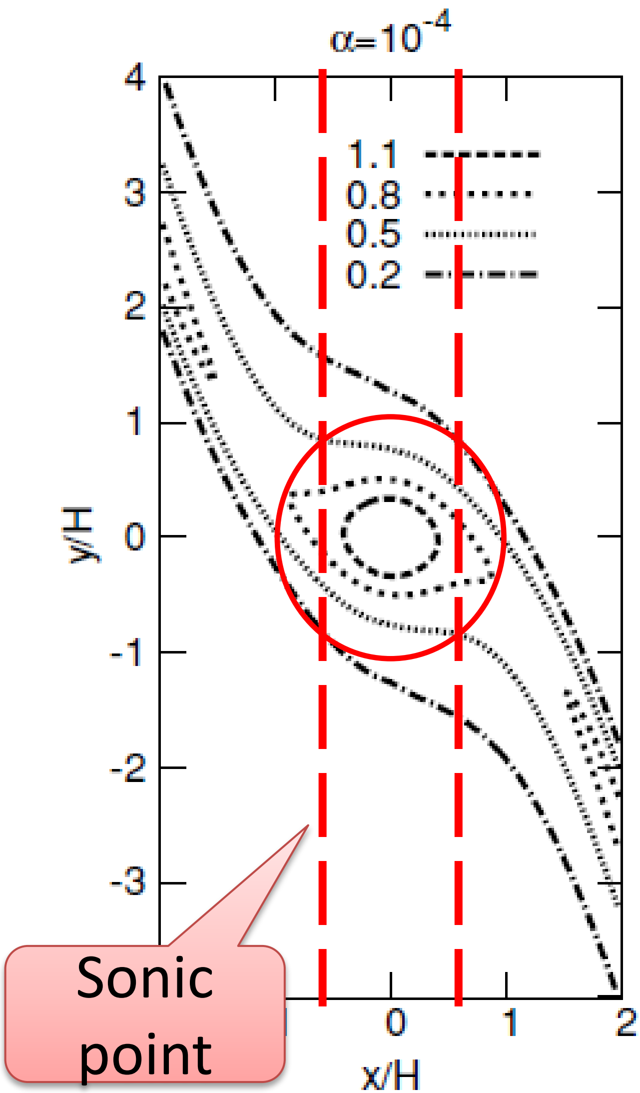
- Spherical structure around the planet
- Spiral density wave launched a little far away from the planet

Background Velocity Field

$$v_y = -\frac{3}{2}\Omega_{\rm p} x$$



Response of Gas in Subsonic Region



- Hydrostatic equilibrium
- A little tilted due to shear, viscosity…

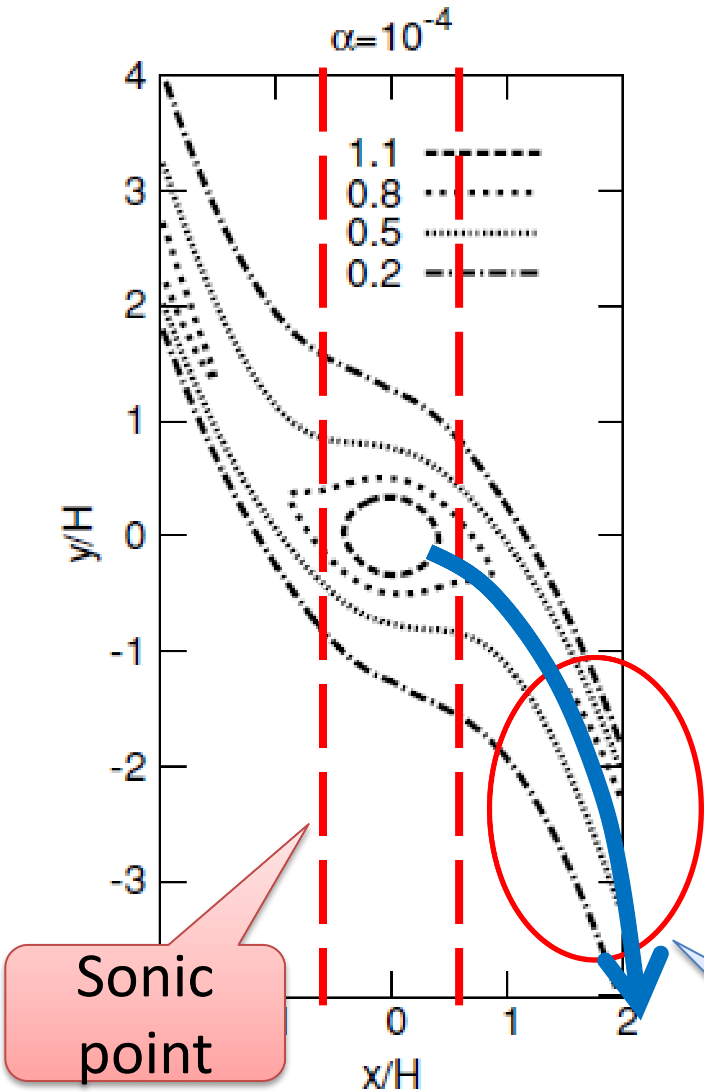
$$\frac{GM_{\rm p}}{d} \sim c^2 \frac{\delta\Sigma}{\Sigma}$$

Planet's gravitational energy
d: distance to the planet

Gas thermal energy perturbation

Figure adopted from Muto and Inutsuka 2009

Response of Gas in Supersonic Region



- Density perturbation "carried away" by shear

Characteristic curve (steady state in a supersonic flow):

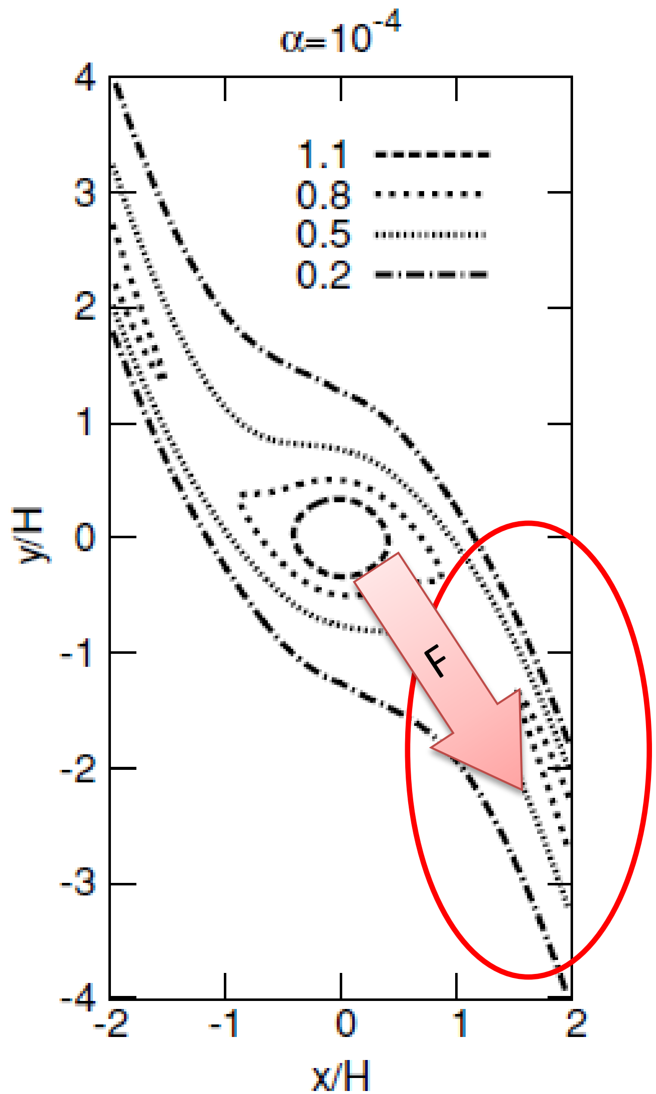
$$\left(\frac{dy}{dx}\right)_{\pm} = \frac{v_x v_y \pm c\sqrt{v^2 - c^2}}{v_x^2 - c^2}$$

Landau & Lishitz

Gives the shape of the spiral:

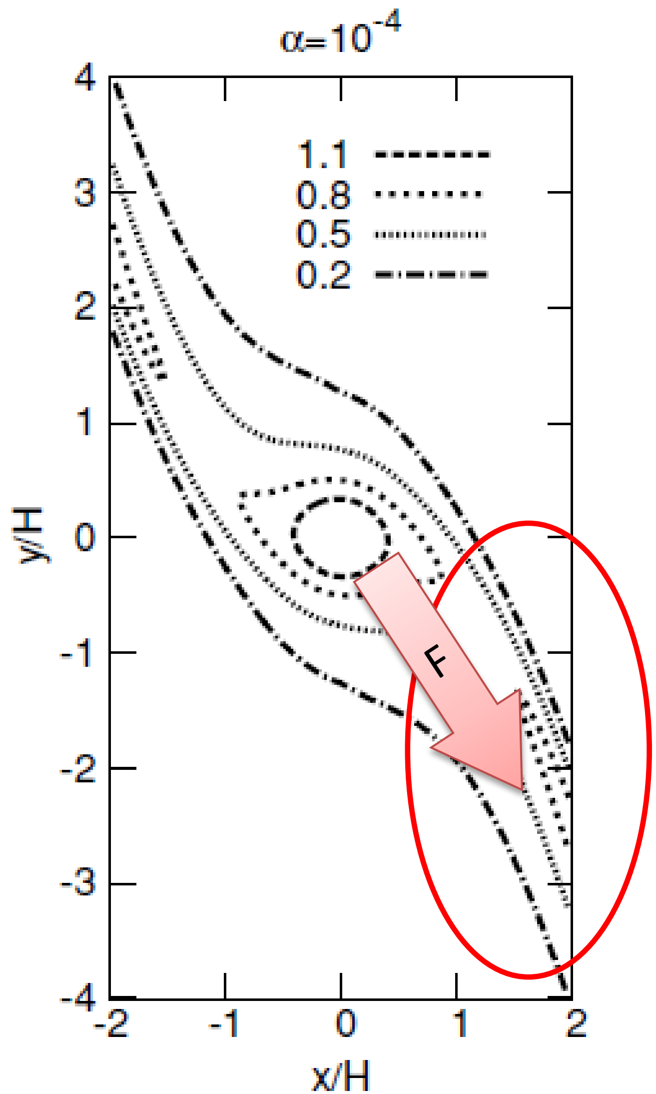
$$y \sim -\frac{3}{4}\frac{x^2}{H} + y_0$$

Backreaction onto the Planet



- Type I migration
- Perturbed surface density exerts gravitational force to the planet

Order-of-Magnitude of type I rate (1)

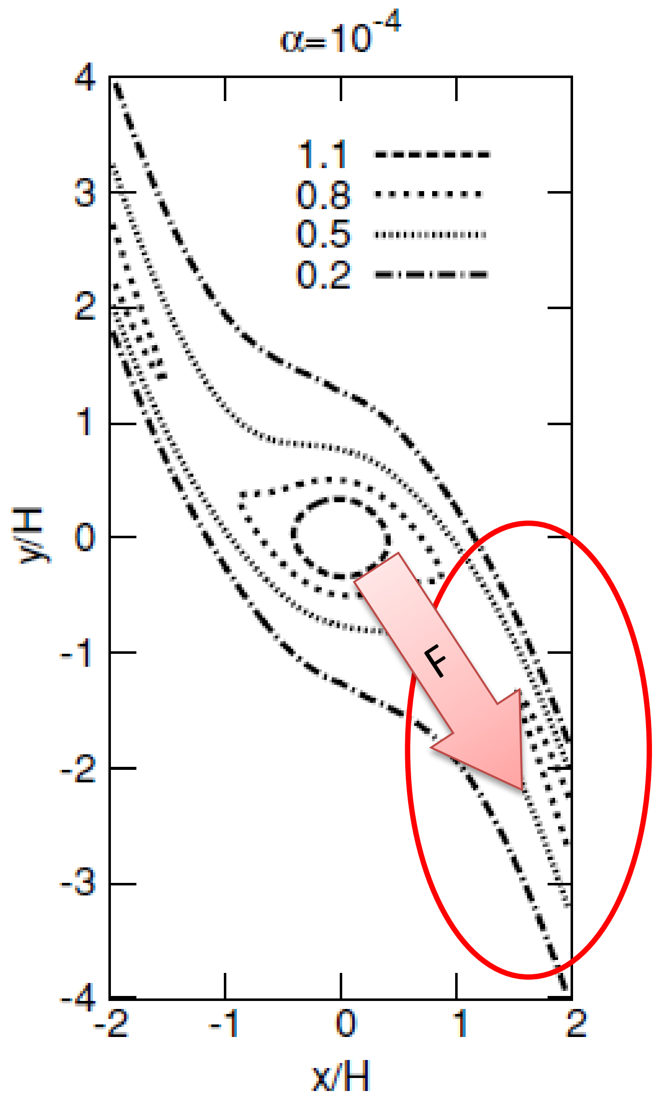


Significant asymmetry in the y-direction at the sonic point: distance ~H away from the planet

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

Gives you the estimate of surface density perturbation

Order-of-Magnitude of type I rate (2)



Calculate force from the surface density perturbation

$$F \sim \frac{GM_{\rm p}(\delta\Sigma H^2)}{H^2}$$

NOTE: this force is from one side of the planet

Differential Force:

$$F \sim \frac{GM_{\rm p}(\delta\Sigma H^2)}{H^2} \times \frac{H}{r}$$

Order-of-Magnitude of type I rate (3)

Now you know the force, you can calculate the torque and migration rate

$$T \sim r_p F \sim \frac{dL}{dt} \sim M_p r_p \Omega_p \frac{dr_p}{dt}$$

Migration rate is then given by:

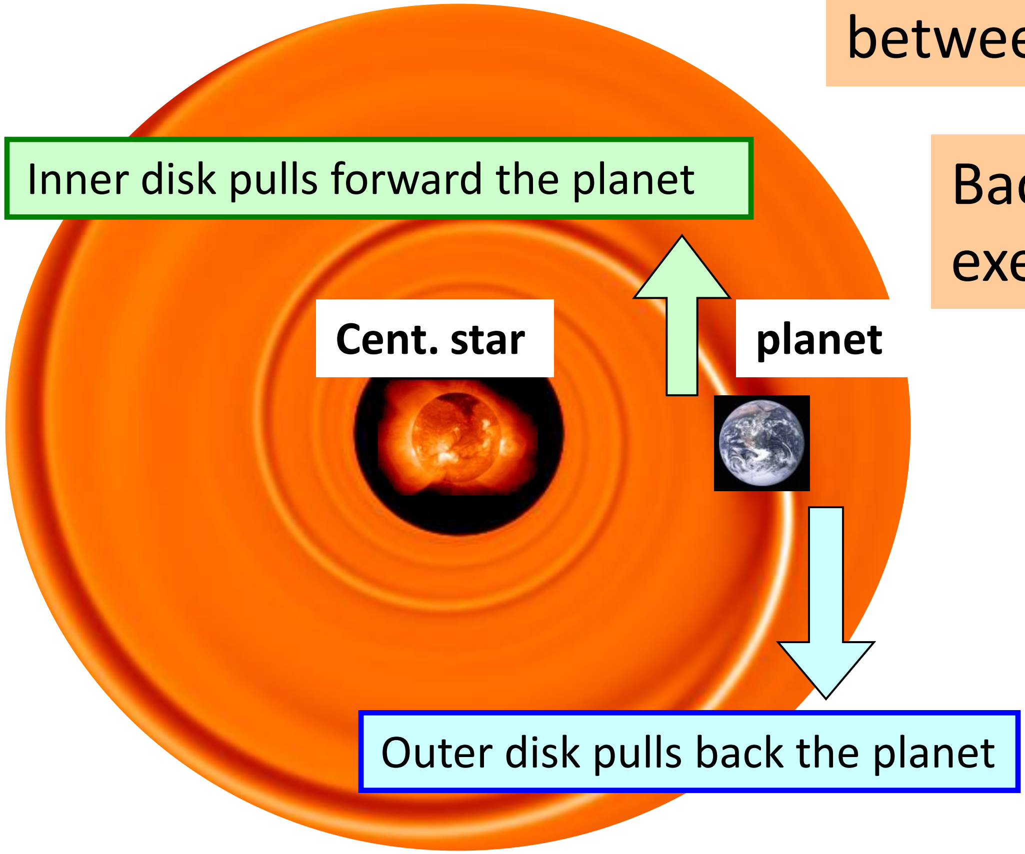
$$\frac{1}{r_\mathrm{p}} \frac{dr_\mathrm{p}}{dt} \sim \left(\frac{M_\mathrm{p}}{M_*} \right) \left(\frac{\Sigma r_\mathrm{p}^2}{M_*} \right) \left(\frac{r_\mathrm{p}}{H} \right)^2 \Omega_\mathrm{p}$$

Typically, 10^5 yrs for $10M_E$ at 5AU
Much shorter than disk lifetime!

Tanaka et al. 2002

Disk-Planet Interaction: Brief Summary

Spiral density wave formation due to ***gravitational interaction*** between the disk and the planet



Back reaction of the wave exerts torque on the planet

After some complicated calculations…

Protoplanets seems to fall into the central star

Some Recent Studies on Migration

- Modification to migration rate and direction due to various physical processes in the disk
  - Viscosity
    - Masset (2001, 2002), Paardekooper and Papaloizou (2009), Muto and Inutsuka (2009)…
  - Self-gravity
    - Baruteau and Masset (2008)…
  - Thermal physics
    - Paardekooper and Mellema (2006), Baruteau and Masset (2008), Paardekooper and Paploizou (2008), Kley and Crida (2008), Bitsch and Kley(2010), Paardekooper et al. (2010)…
  - Turbulence
    - Nelson and Papaloizou (2004), Oishi et al. (2007), Baruteau and Lin (2010), Baruteau et al. (2011)…
  - Ordered (stable) magnetic field
    - Terquem (2003), Fromang et al. (2005), Muto et al. (2008)…
  - Planet Eccentricity and Inclination
    - Papaloizou and Larwood (2000), Tanaka and Ward (2004), Cresswell and Nelson (2006), Cresswell et al. (2007), Bitsch and Kley (2010), Muto et al. (2011), Rein (2011)…

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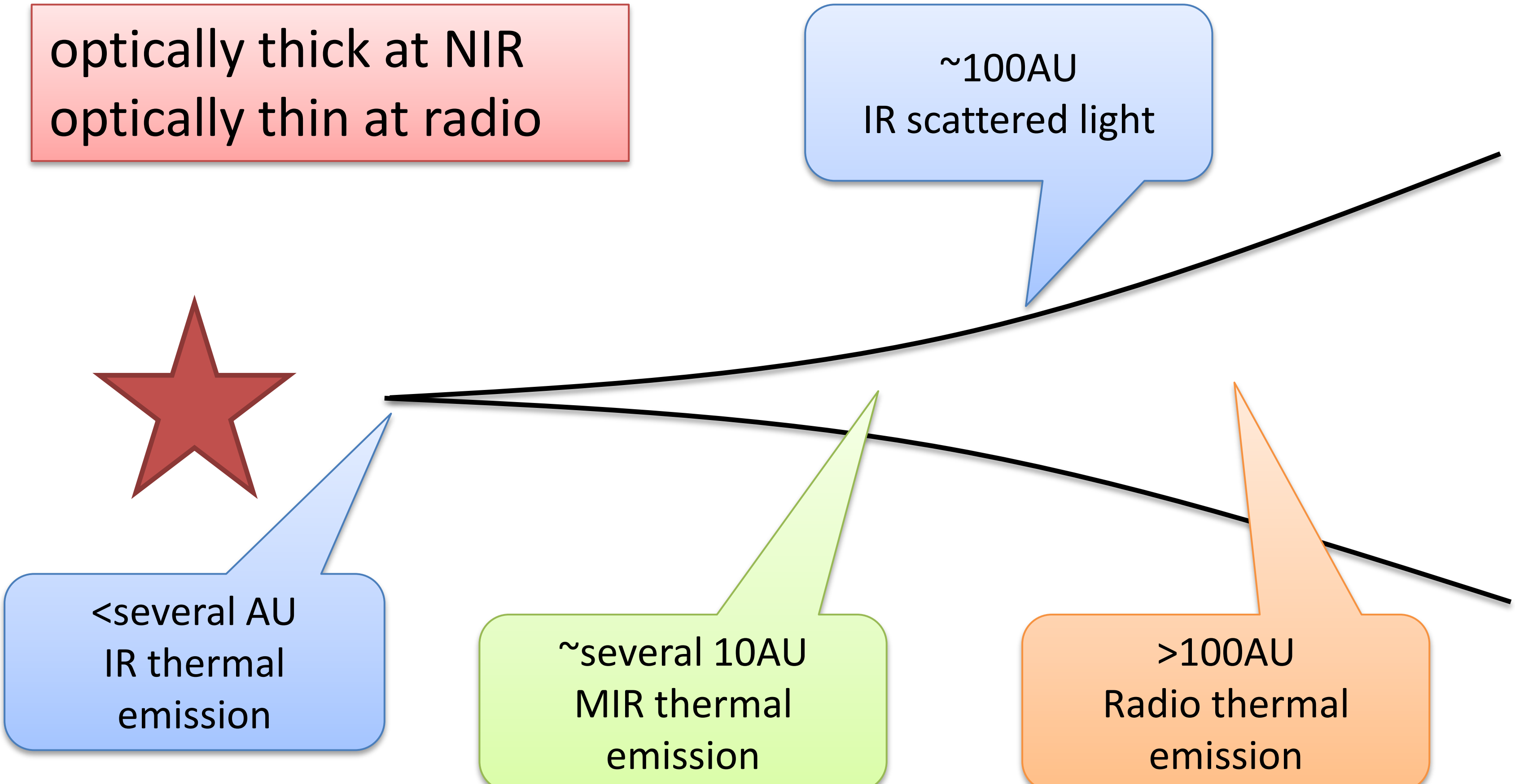
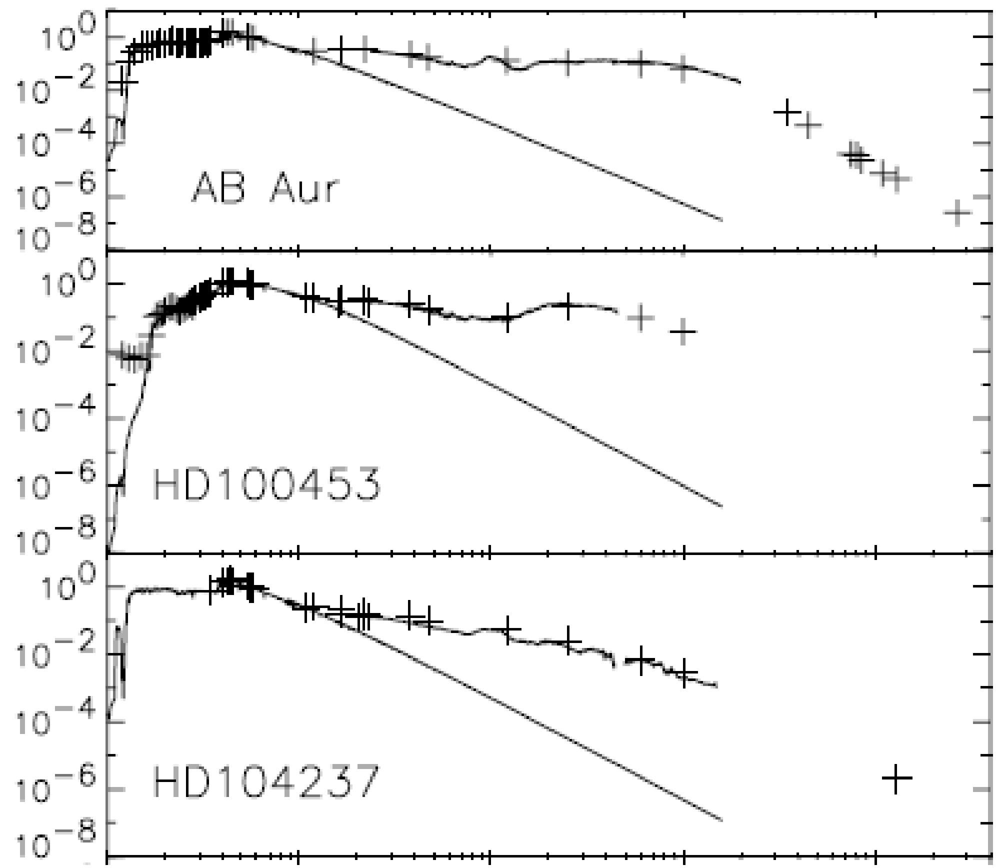
Disk Observation Overview

optically thick at NIR
optically thin at radio



SED

- Stellar blackbody + excess and longer wavelengths
  - Excess from disk emission
- SED tells us:
  - The existence of the disk
  - The overall structure of the disk



Meeus et al. 2001

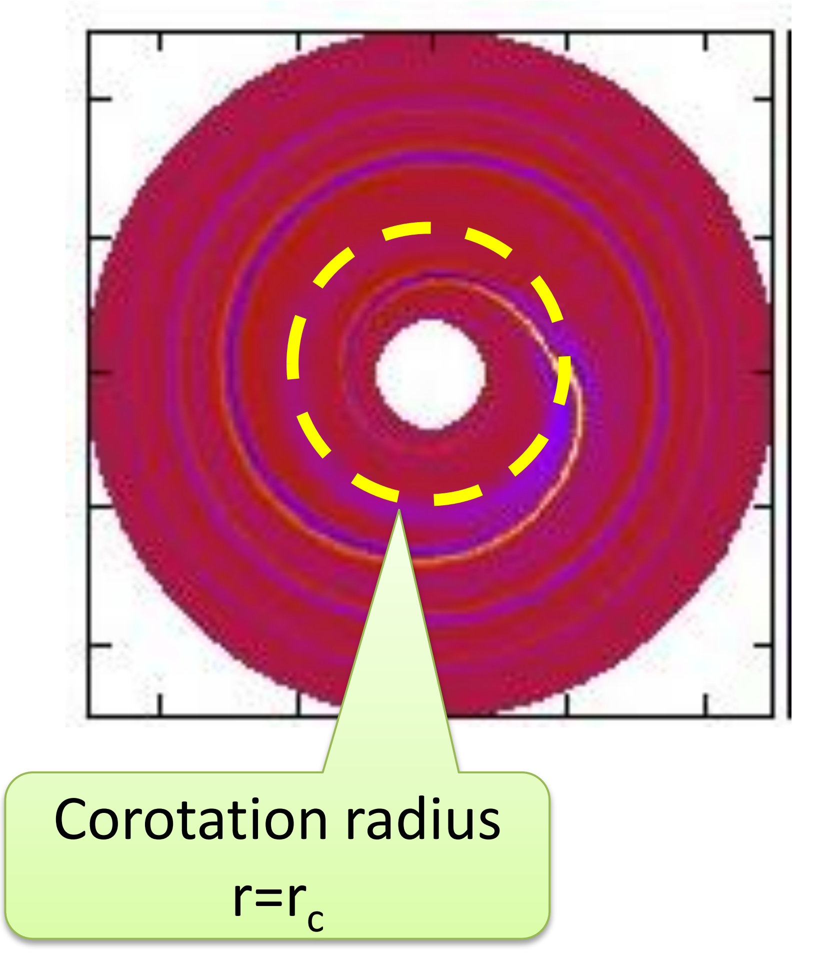
Need to go beyond SEDs if one wants to know more…

Detectablity of Spiral Structures

- **Spirals are the direct tracer of the dynamical activities in the disk**
- 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

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…



Spiral Shape Detectability: Spatial Resolution

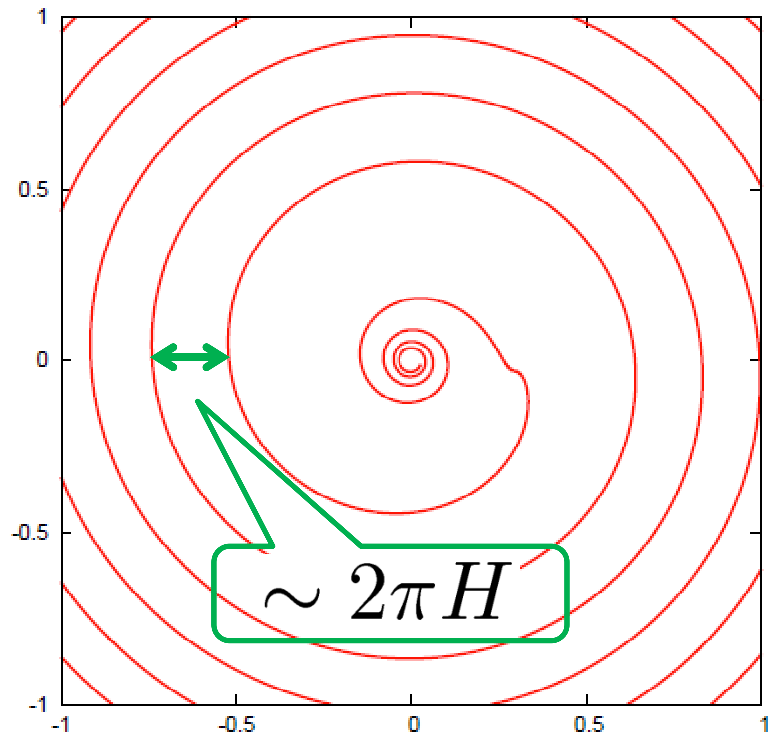
$$\phi(r) \sim \pm \frac{r}{H}$$

Need to resolve structure with scale ~H

$$d = 140\mathrm{pc}$$

$$R = 100\mathrm{AU}, H \sim 10\mathrm{AU}$$

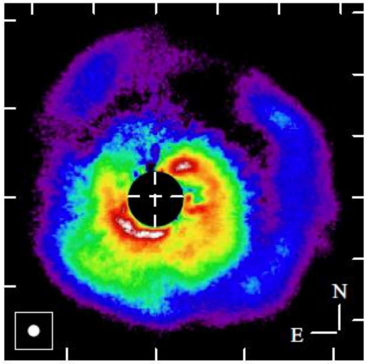
Need ~0.1asec resolution
➔ Subaru, ALMA…



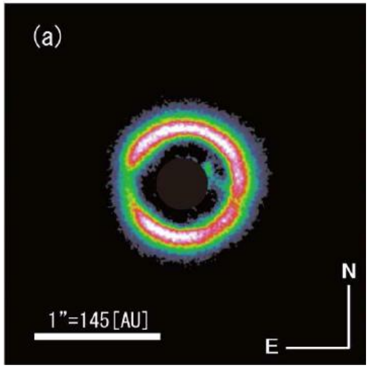
Strategic Exploration of Exoplanets and Disks with Subaru/HiCIAO

SEEDS

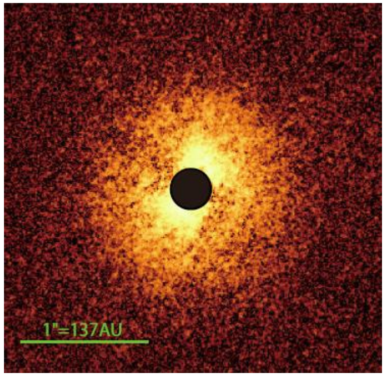
- Direct imaging observations of planets and disks using HiCIAO/AO188 mounted on Subaru
- 120 nights/5years
- Disk observations see polarized light that originates exclusively in the disk



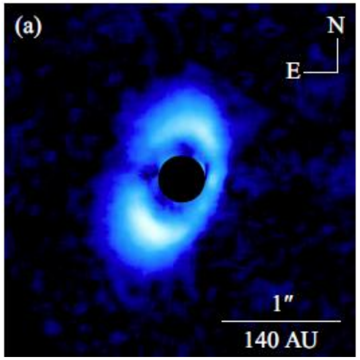
Hashimoto et al. 2011



Mayama et al. 2012



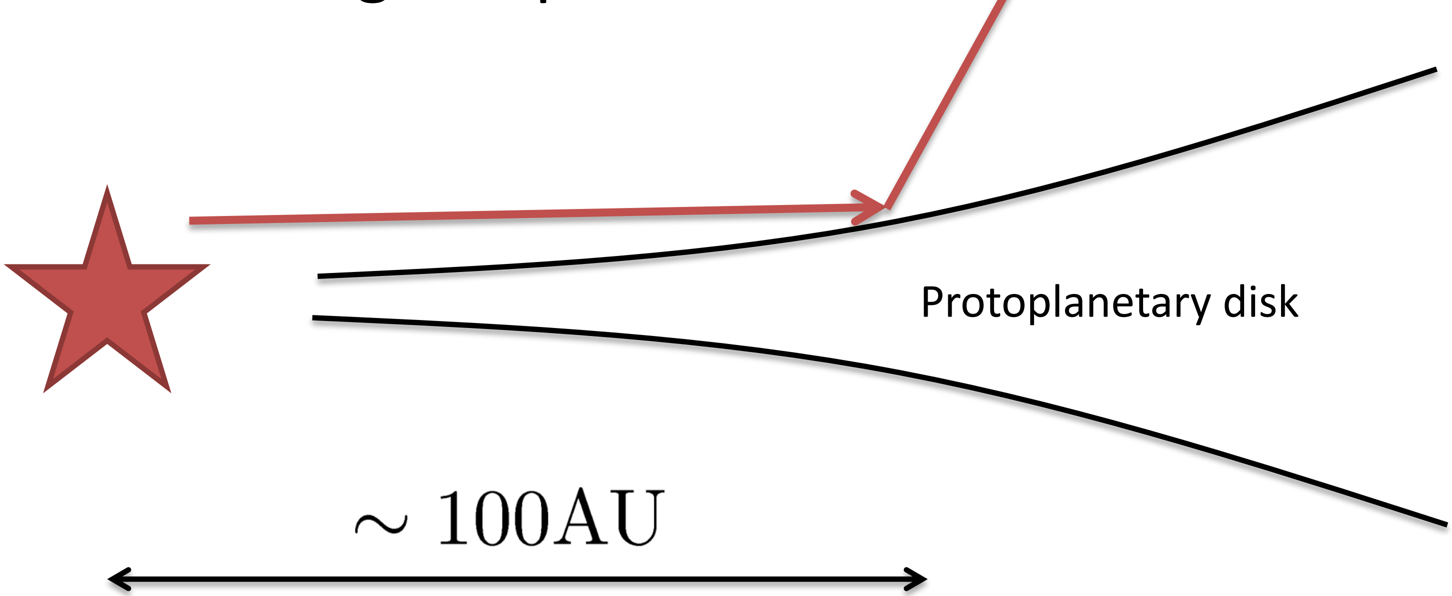
Kusakabe et al. 2012



Hashimoto et al. 2012

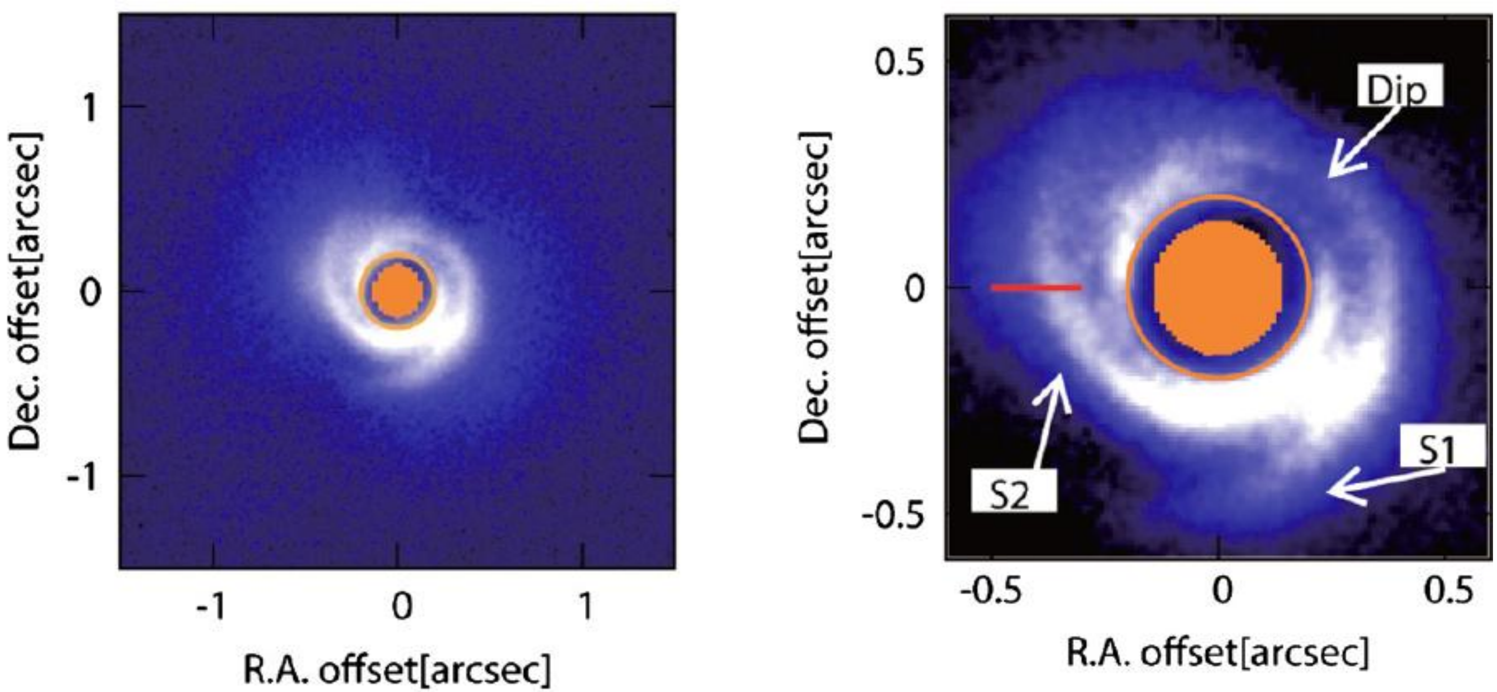
Direct observation of disks at NIR

- The scattered light from the disk surface is oserved
  - Protoplanetary disks are optically thick at NIR
  - Scattered light is polarized



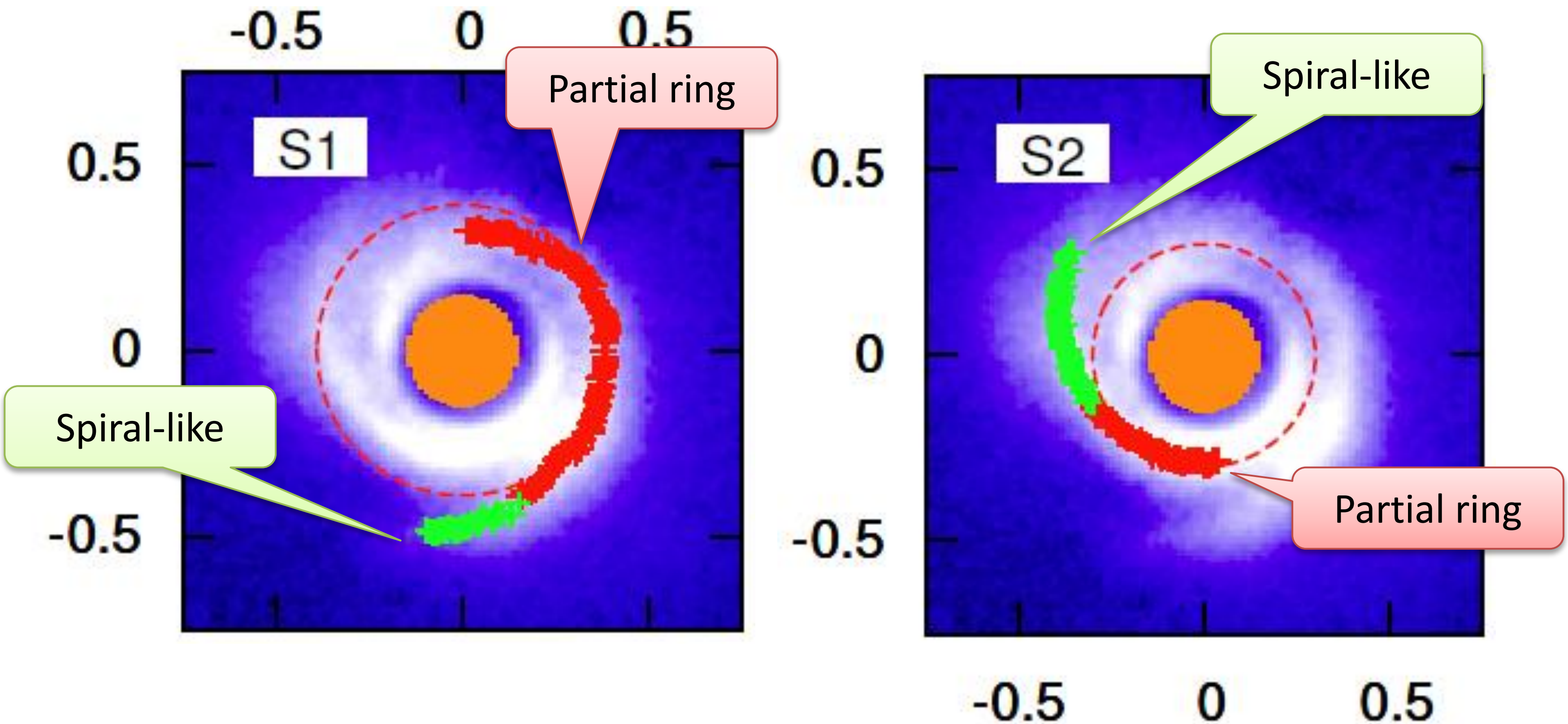
HD 135344B/SAO 206462 Image

- ~1.7Msun star at d~140pc
- Polarized intensity image at H-band
- Scattered light is detected even at the “cavity” zone
- Small-scale spiral structure is clearly visible



Muto, Grady, Hashimoto, Fukagawa et al. 2012

Non-Axisymmetric Structures



Density wave theory is used to fit the spiral-like structure

Model using Density Wave Theory

Spiral shape by density wave theory

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

Disk parameters: $\Omega(r) \propto r^{-\alpha}$ $c(r) \propto r^{-\beta}$

Fixed (Kepler)

Fixed (almost const. opening-angle)

$$h_c = \frac{H(r_c)}{r_c}$$

Disk thickness (temperature)

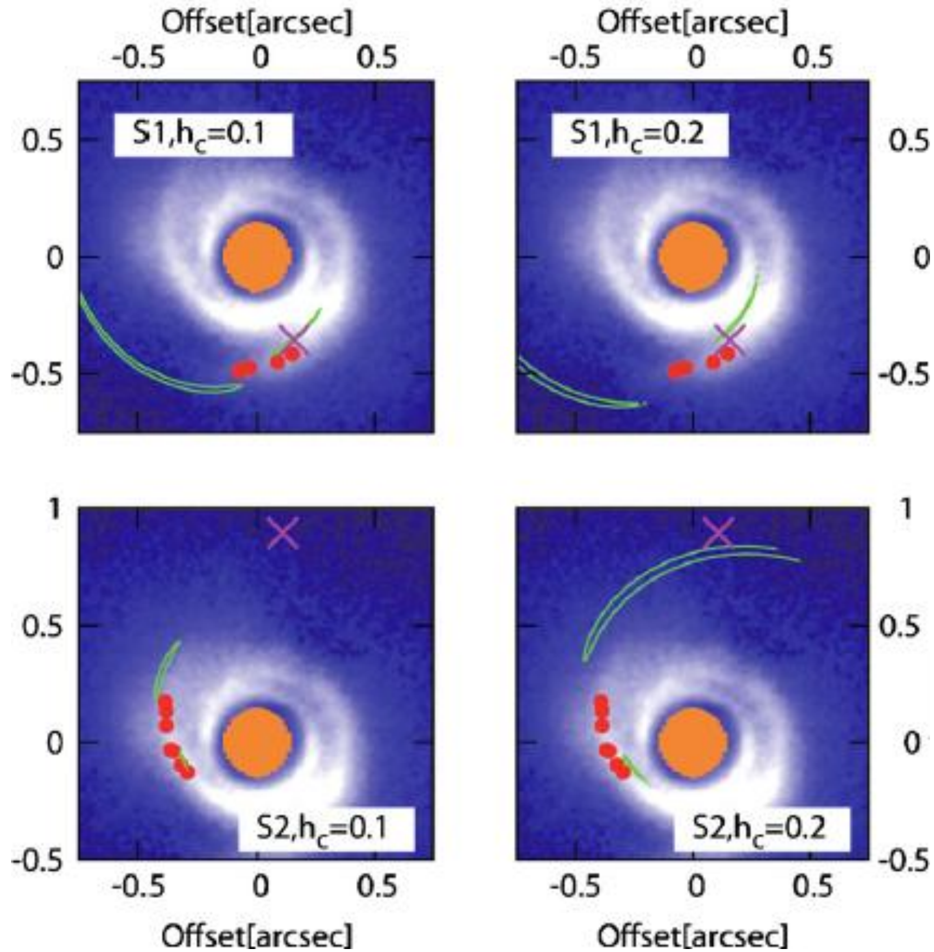
Parameters for spiral location: r_c : corotation radius

θ_0 : azimuthal phase

Rafikov 2002, Muto et al. 2012

Fitting Results

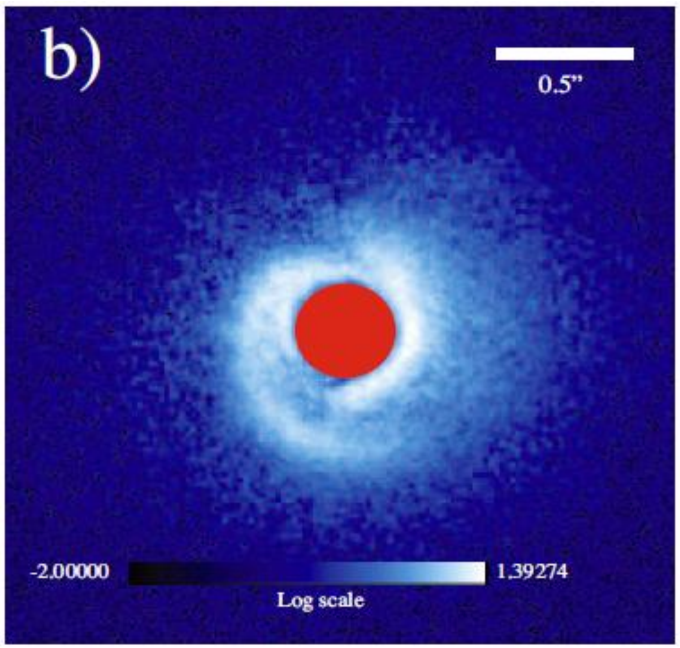
- Significant parameter degeneracy, but…
  - **H/R ~ 0.1-0.2** is consistent with the spiral structure
  - Also consistent with sub-mm estimate
- Prediction for the "launching point" of the spiral
  - Prediction for the corotation radius
  - Prediction for the **time evolution of the spiral structure**

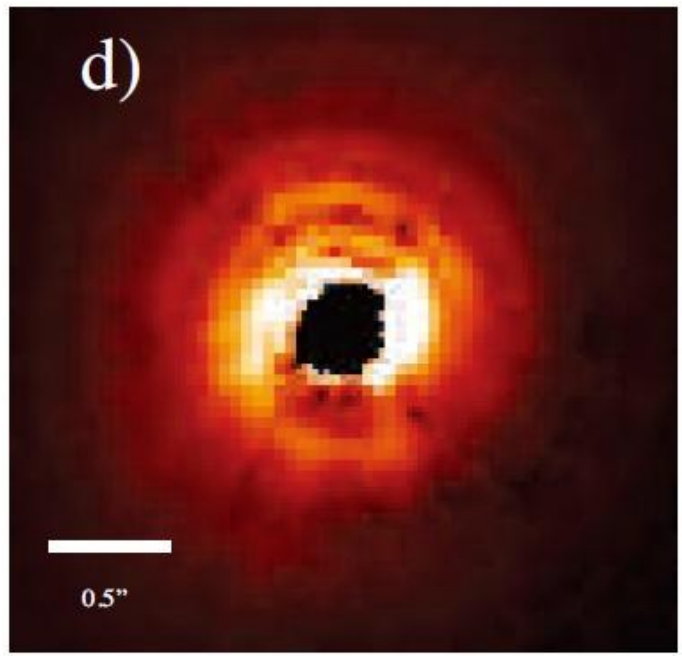


$$\Omega_{\rm pattern} = 0.8 \left(\frac{r_{\rm c}}{70{\rm AU}}\right)^{-3/2} \left(\frac{M_*}{1.7M_\odot}\right)^{1/2} [{\rm deg/yr}]$$

MWC 758/HD 36112 Image

- ~2Msun star at d~200-300pc
- Polarized intensity image at H-band, Intensity at K-band
- (A) spiral structure(s) is/are visible in both bands



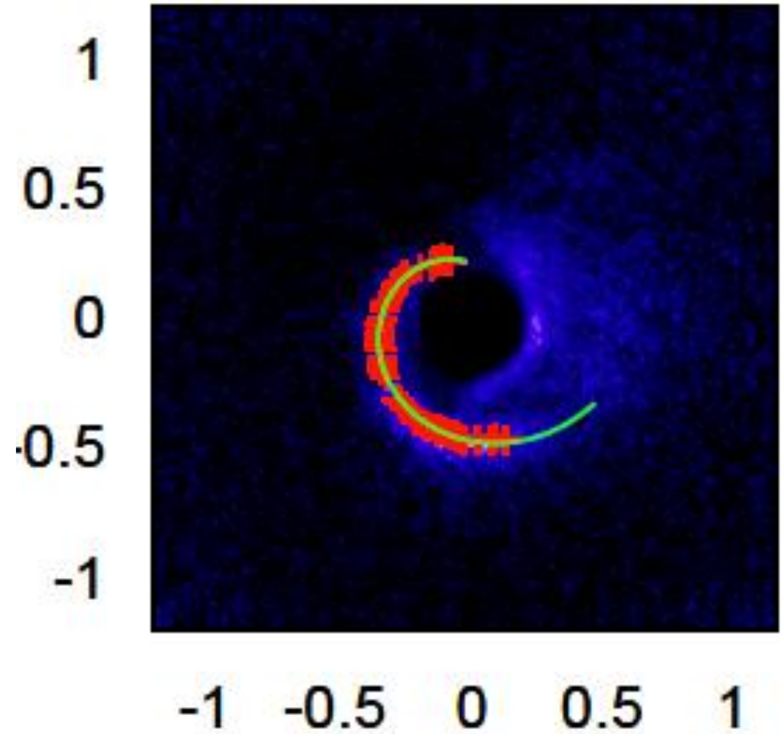


Grady, Muto, Hashimoto, Fukagawa, Currie et al. 2013

Spiral fitting for MWC 758

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

- Corotation radius is likely at outer radii
  – Rc ~ 1.55asec
- Rather hot (~ thick) disk
  – H/R~0.18



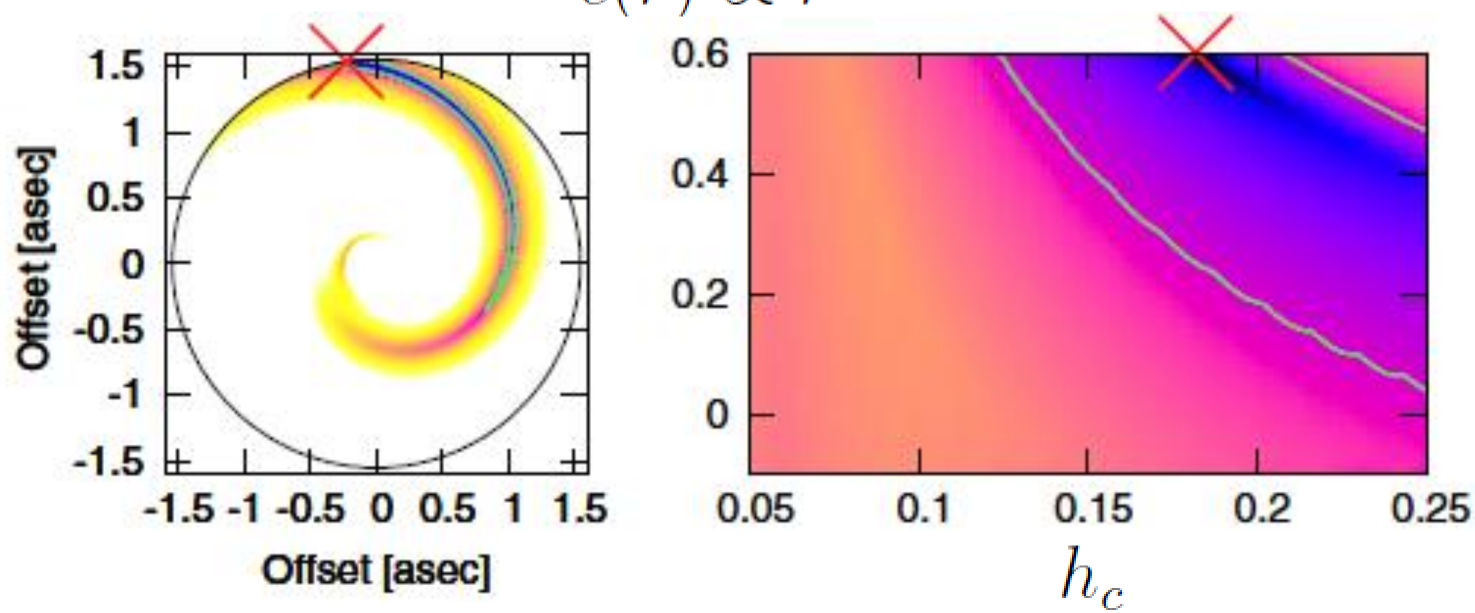
Parameter Degeneracy

Launching point

Sound velocity distribution

パラメータ: $(r_c, \theta_0, h_c, \cancel{\alpha}, \beta)$

$$c(r) \propto r^{-\beta}$$



- Corotation at outer radii?
- H/R>0.1, the disk can be both flat or flared

What is the Origin of the Spiral?

I don't know.

But let's assume it is a planet, then:

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

This yields:

- ~0.5 Jupiter Mass for SAO 206462
- ~5 Jupiter Mass for MWC 758

and its location can be predicted by the spiral fitting

Disk structure as a probe of *indirect signature* of an embedded planet (signposts of planets)

http://giveupinternet.com/2009/03/30/i-dont-know-who-this-is-but-my-friends-say-hies-cool-reddit-alien-pic/

Summary

- Disk-planet interaction is one of important dynamical processes in protoplanetary disks
- Disk-Planet interaction:
  - Excites spiral waves and opens up a gap
  - Causes radial migration of a planet
- It is now possible to observe spiral structures in the disk with Subaru
  - A relatively simple model for spirals is given
- ALMA will definitely reveal spiral structures in the near future

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