Cerro Calán
Observatorio Astronómico Nacional

VORTEX

MAD

Spirals in protoplanetary disks

Valentin Christiaens

MAD meeting 12/01/2016

Universidad de Chile

Université de Liège

Plan

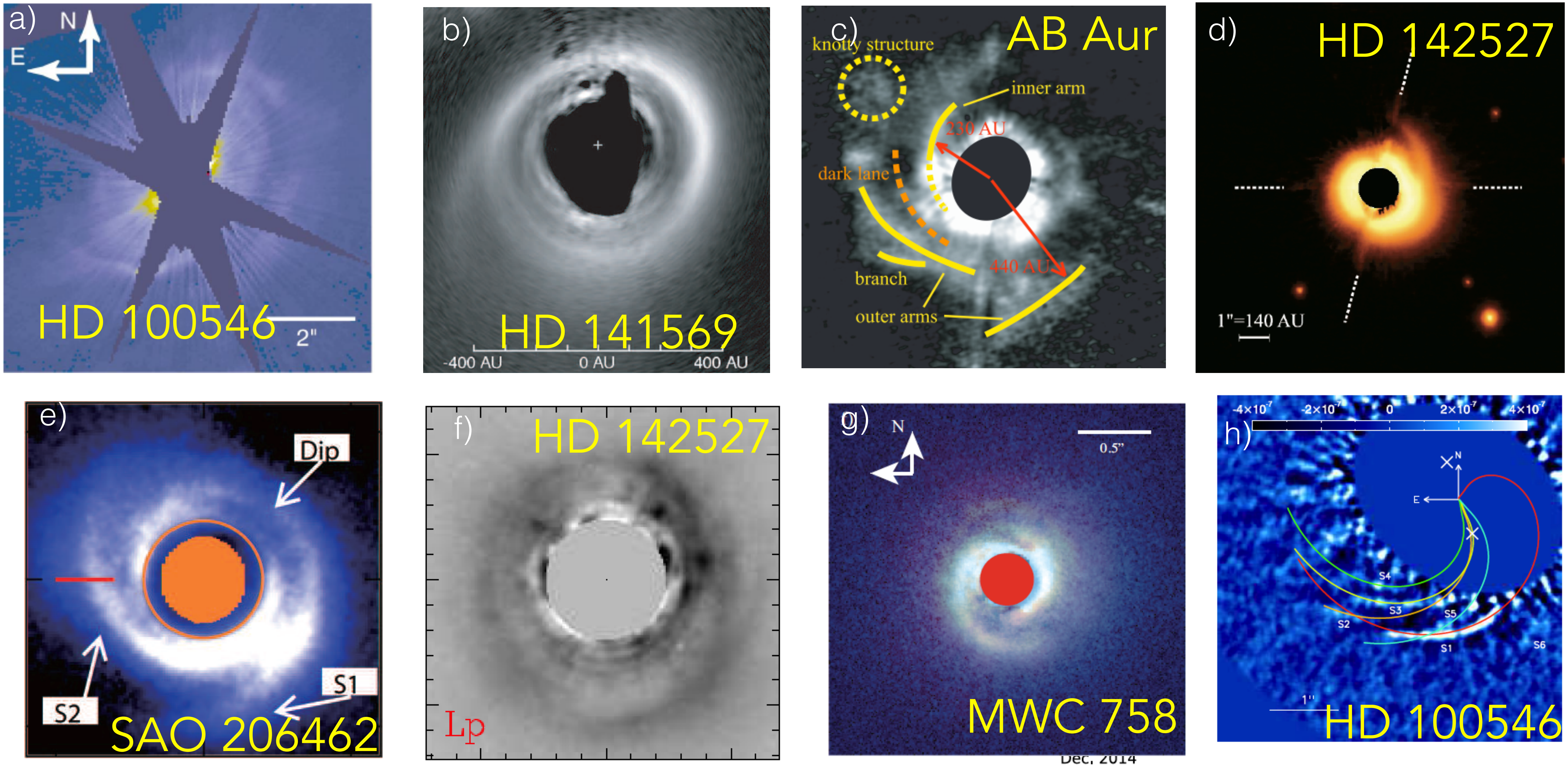
1. Overview of observed spirals in protoplanetary disks

2. Theory and simulations of spiral arms
    2.1. Gravitational Instability
    2.2. Planet-disk interaction
    2.3. GI + planet
    2.4. Shadows casted by the inner disk
    2.5. Stellar fly-by

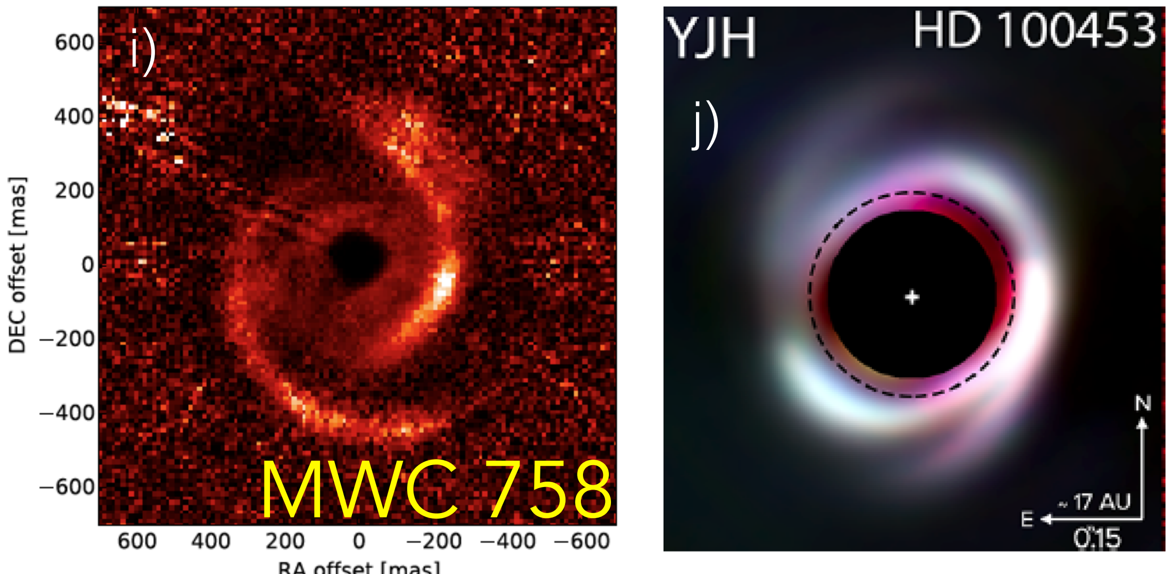
3. For a given spiral observation, how to untangle the origin?

4. Observational perspectives
    4.1. Re-observations of HD 142527 spirals with ALMA

Global picture of observed spirals in disks in Near-IR

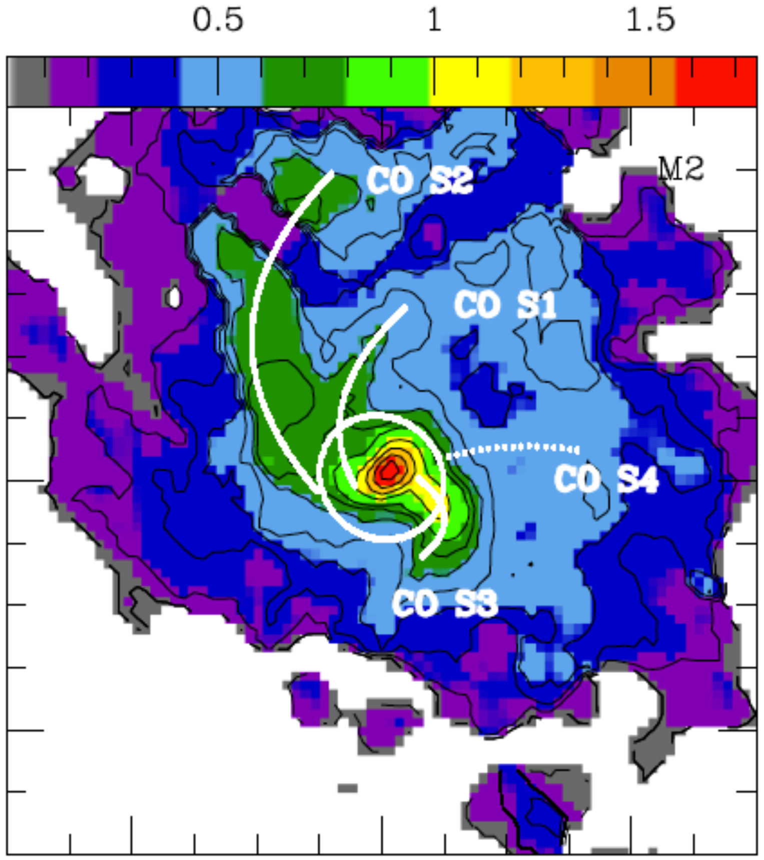


a) Grady+01 (HST); b) Clampin+03 (HST);
c) Fukagawa+04 (HiCiao); d) Fukagawa+06 (HiCiao);
e) Muto+08 (HiCiao); f) Casassus+12 (NICI);
g) Grady+13 (HiCiao); h) Boccaletti+13 (NICI);
i) Benisty+15 (SPHERE); j) Wagner+2015 (SPHERE)



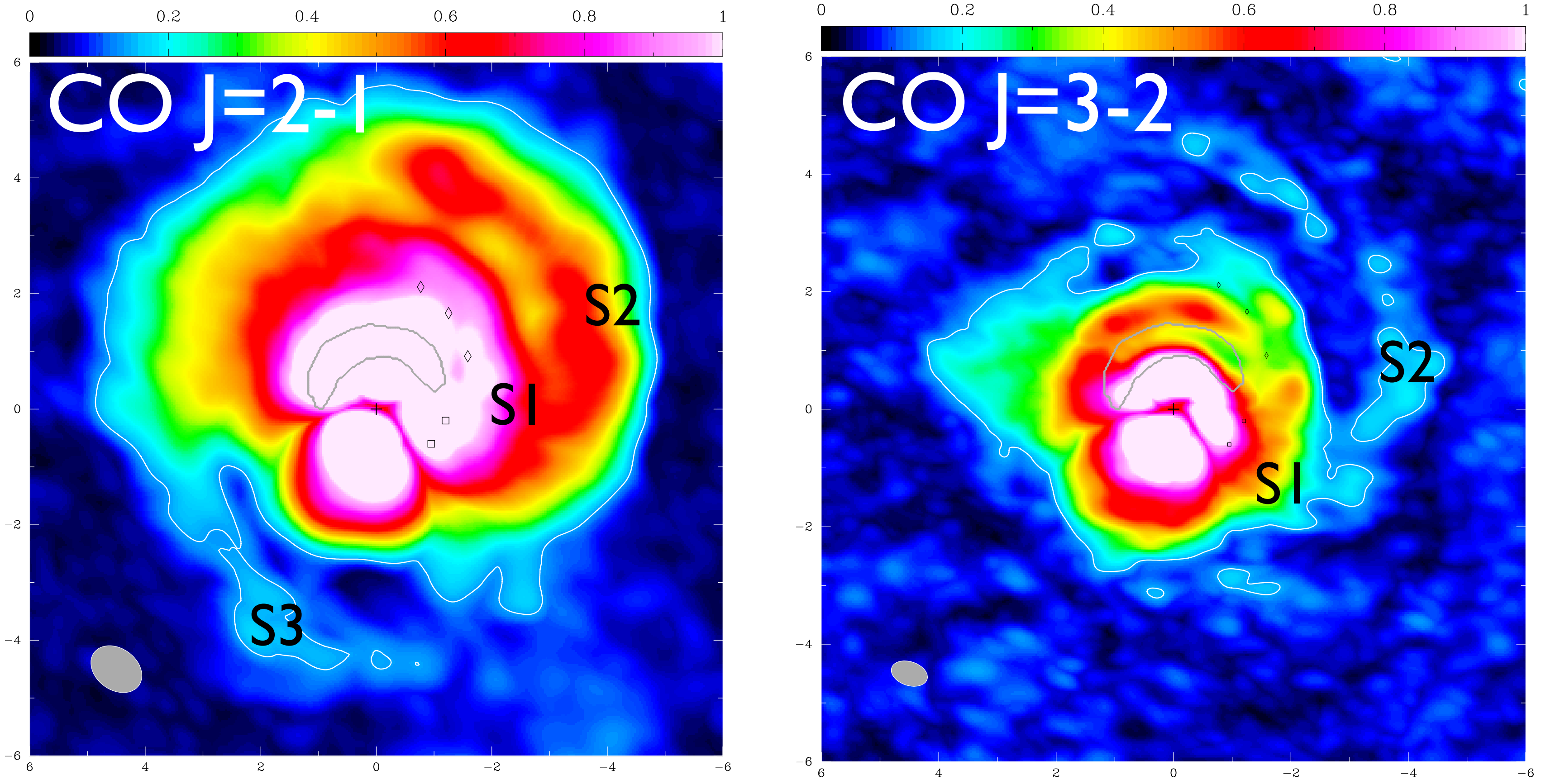
Global picture of observed spirals in disks in sub-mm

AB Aur



Tang+13

HD 142527



Christiaens+14

- In view of the diversity of spirals in protoplanetary disks, there must be different ways to launch them. What are these processes?
- What are the implications on disk evolution?

Gravitational Instability

If the disk is massive enough, the influence of its own gravity is non-negligible compared to the star's gravity alone

Toomre parameter: $Q = \frac{c_s \Omega}{\pi G \Sigma} \approx \frac{M_\star}{M_\mathrm{d}} h$

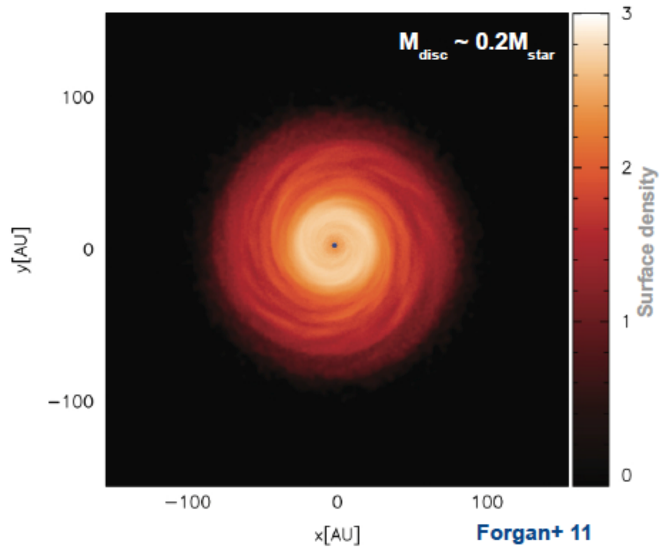
$Q > 2$: grav. stable

$Q \lesssim 2$: grav. unstable

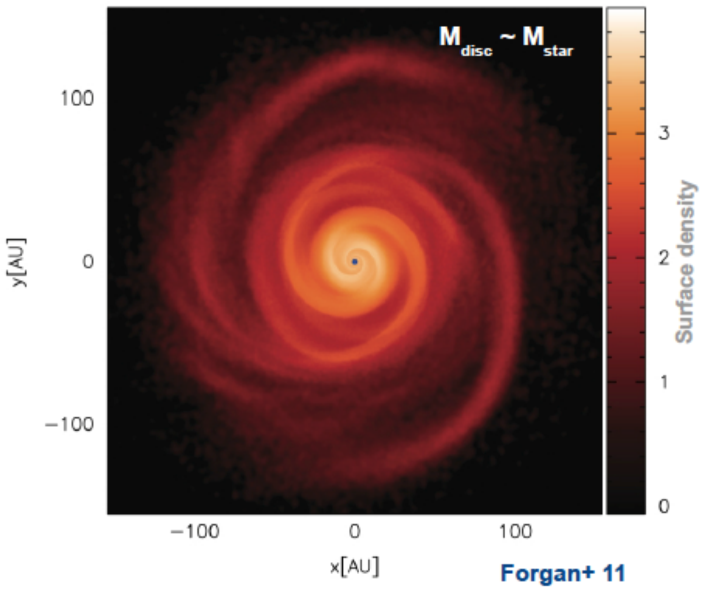
The evolution of a GI disk depends on its cooling timescale:

a/ $\tau_\mathrm{cool}\Omega \leq 3 - 5$ => disk **fragmentation** and possible inward clump migration (e.g. Paardekooper+11); typically outer part of large primordial disks

b/ $\tau_\mathrm{cool}\Omega > 3 - 5$ => no fragmentation, but creation of **spirals**, whose pattern depends on the disk mass and elapsed time:

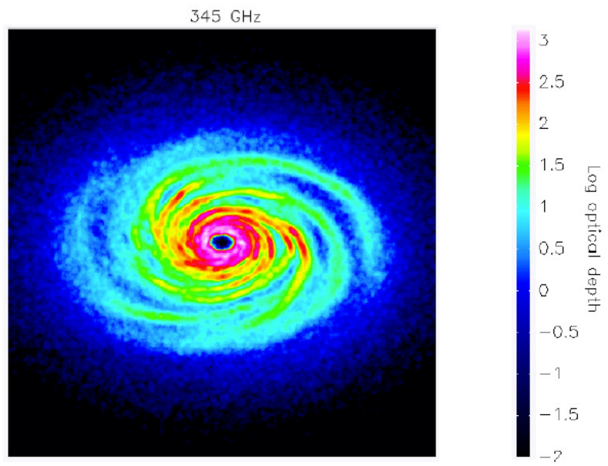


or

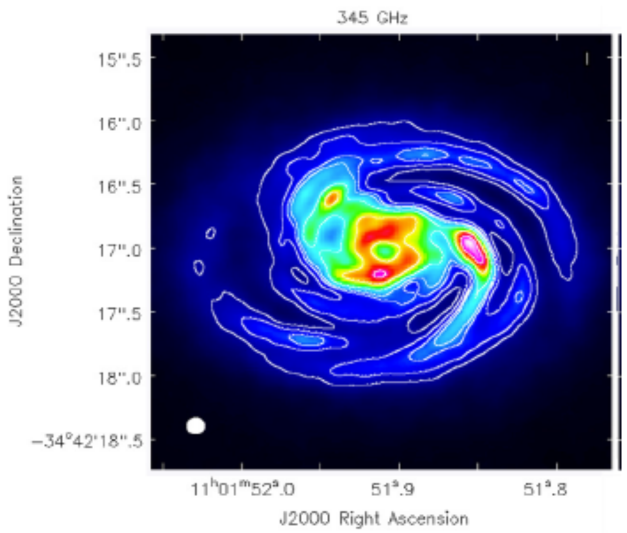


(Forgan+ 11)

Gravitational Instability

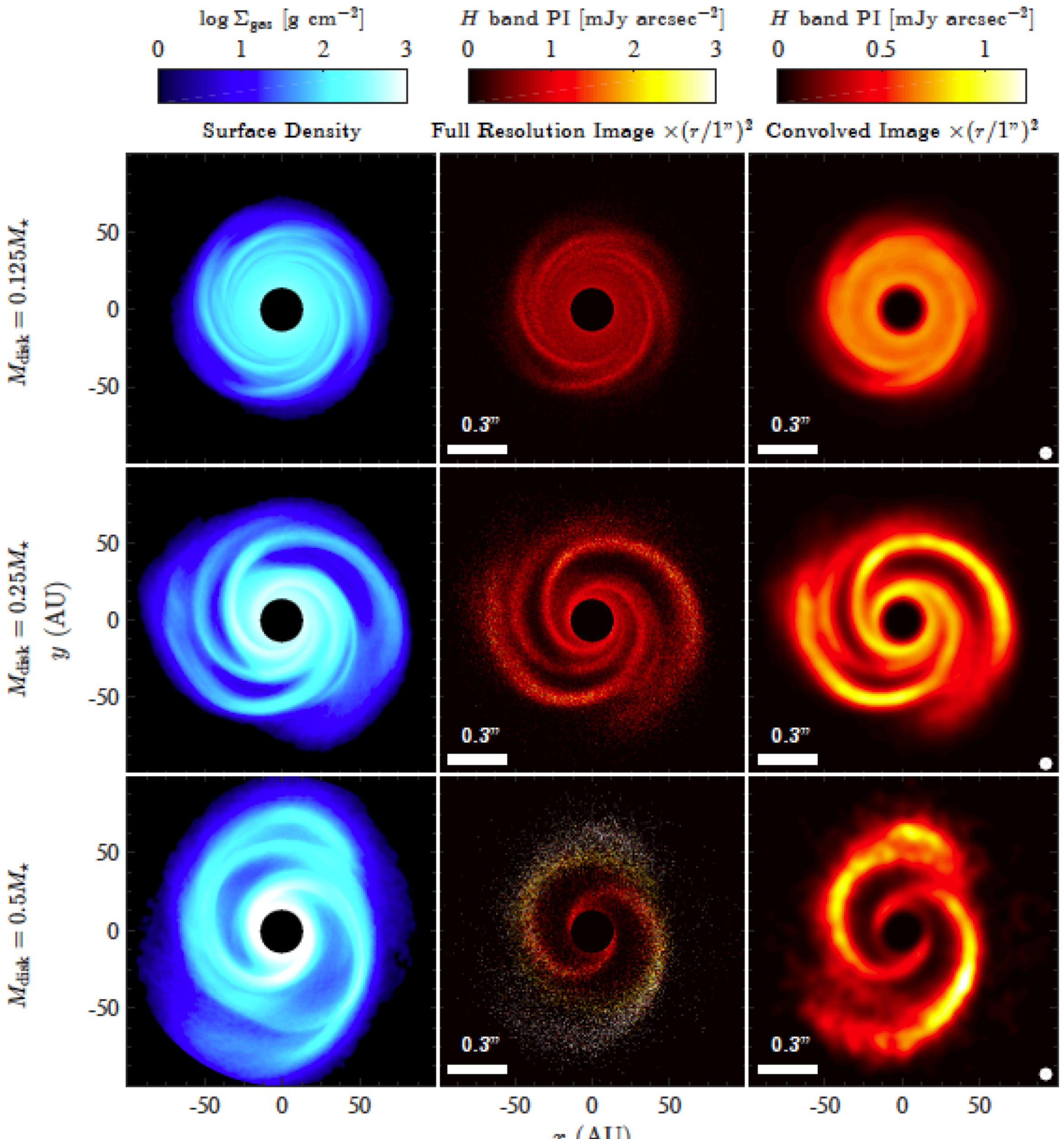


seen as:



(Di Pierro+ 15)

$$q = \frac{M_d}{M_\star}$$



q = 0.125

q = 0.25

q = 0.5

=> m ~ 8

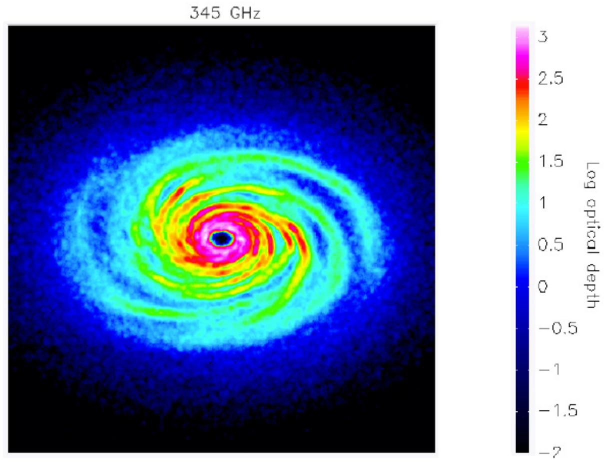
=> m ~ 4

=> m ~ 2

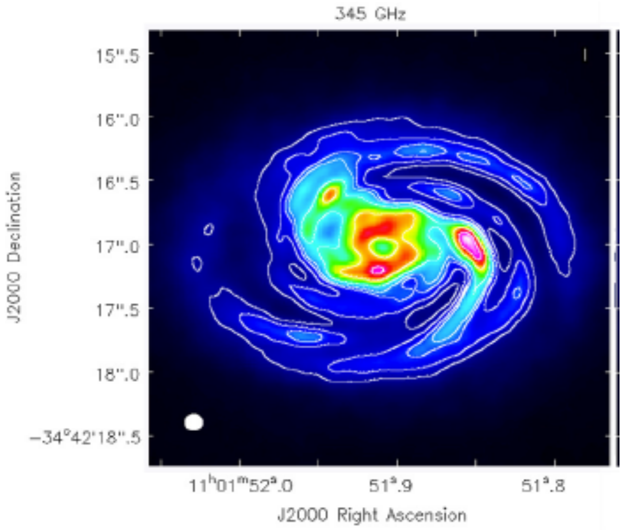
m ~ 1/q

(Dong+ 15)

Gravitational Instability

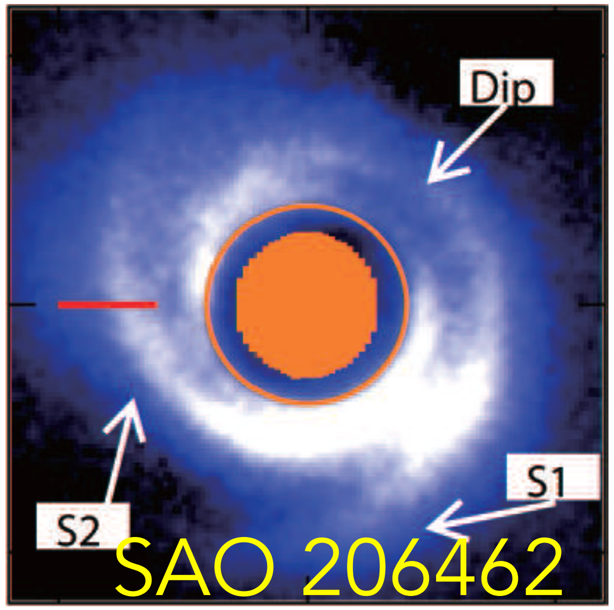


seen as:



(Di Pierro+ 15)

OBSERVATIONS

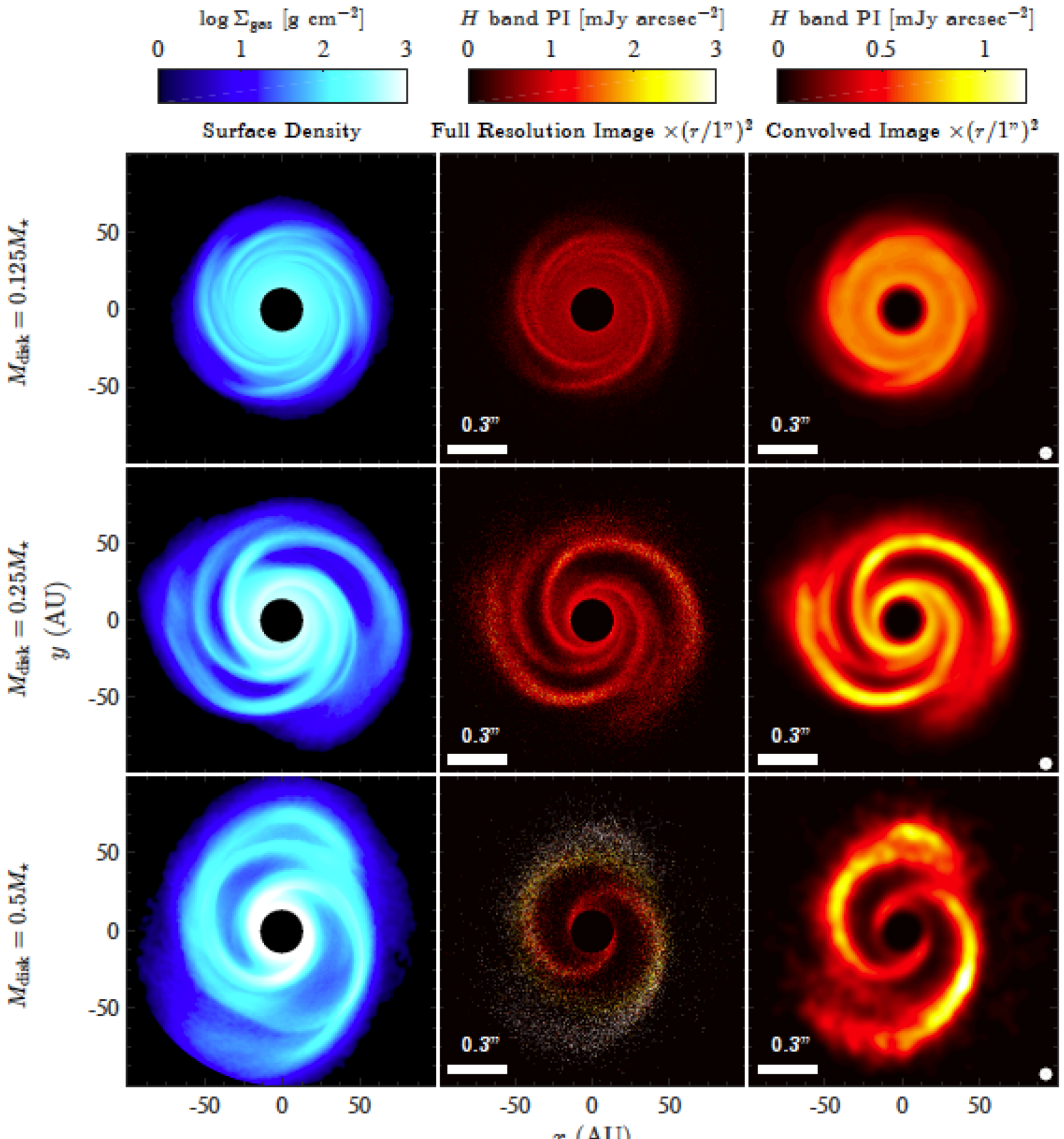


$$q = \frac{M_d}{M_\star}$$

q = 0.125

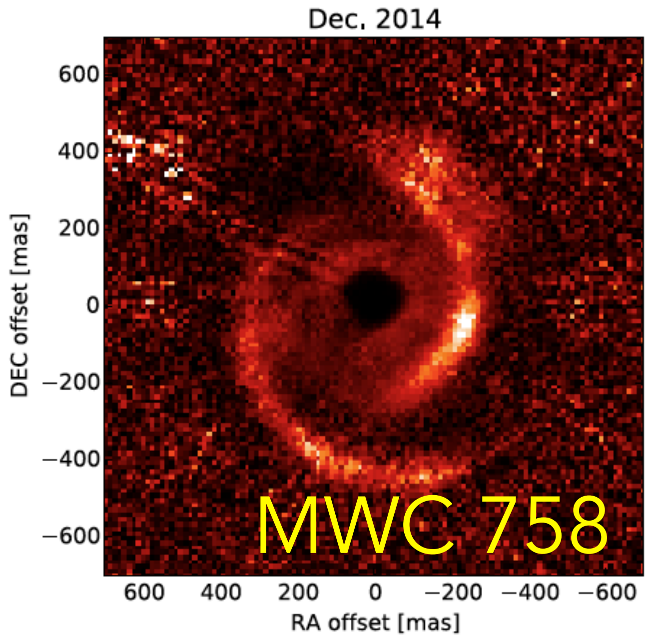
q = 0.25

q = 0.5



m ~ 1/q

(Dong+ 15)

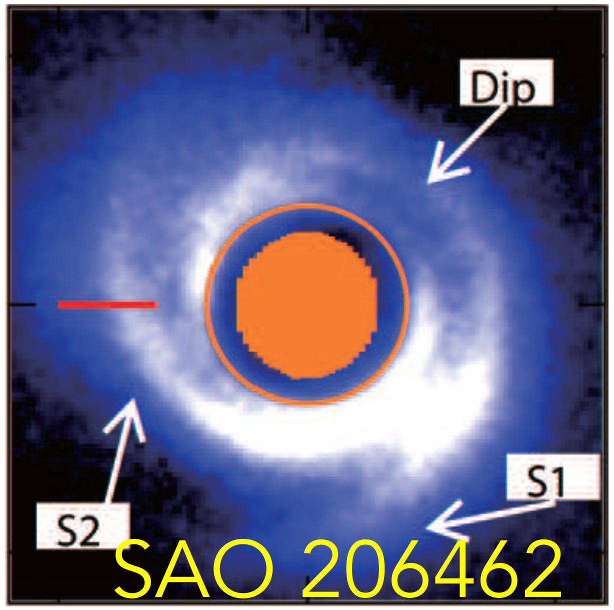


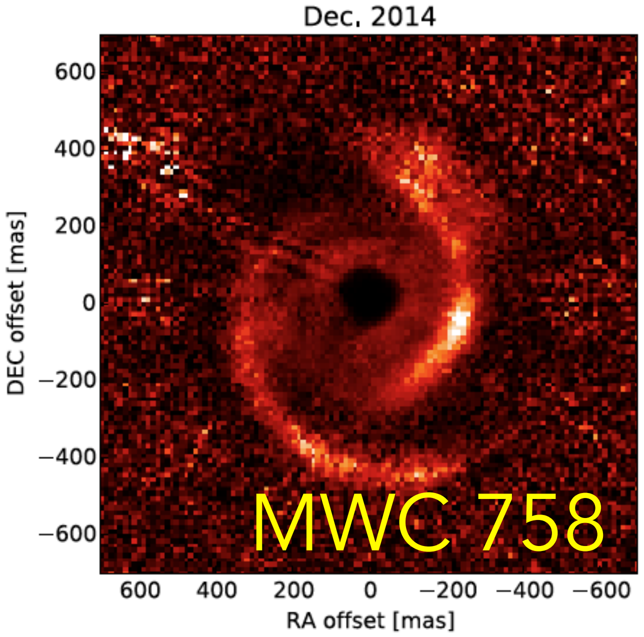
Gravitational Instability

Caveats of the theory:

- *q* has to be > 0.25 to be prominent in NIR scattered images, and q~0.5 to have m=2 spirals! This is contrary to most observations
- Requires high stellar accretion rates ($\sim 10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$)
- The disk fragments with GI beyond a certain radius (typically ~100au)

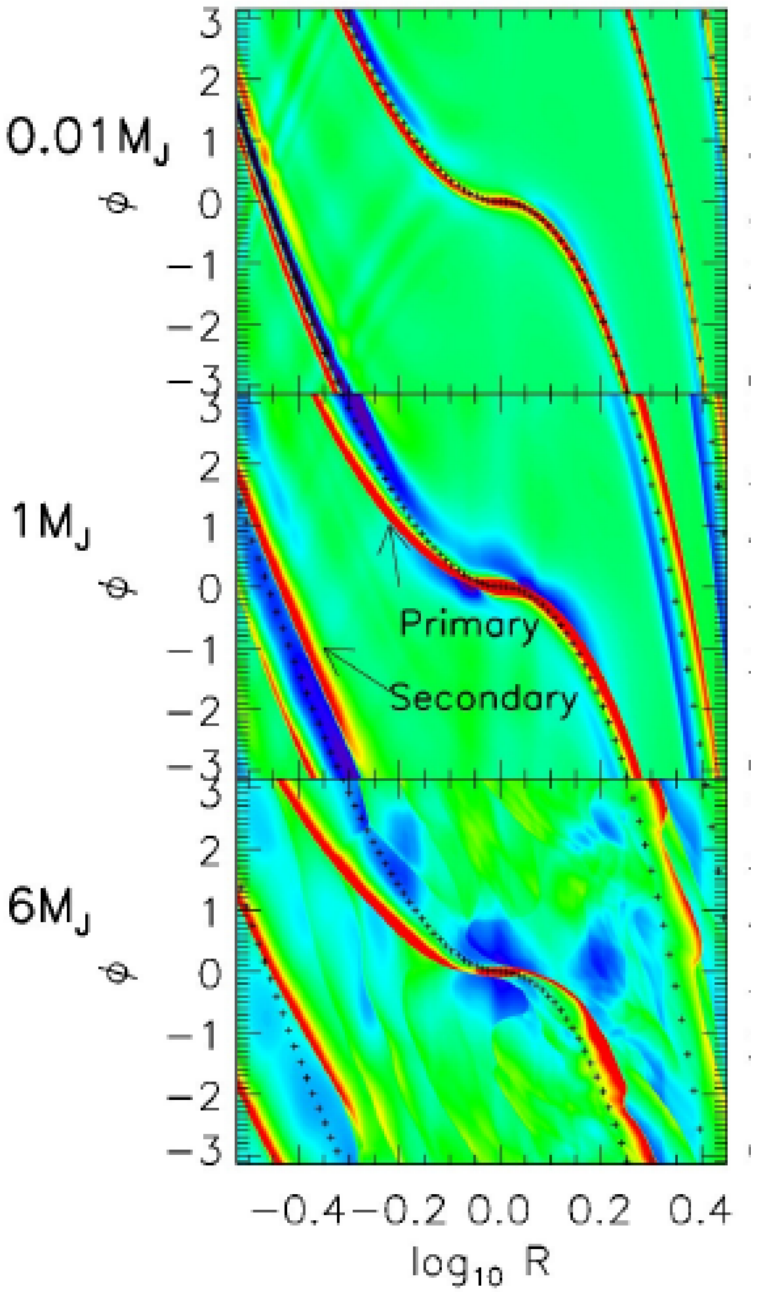
OBSERVATIONS



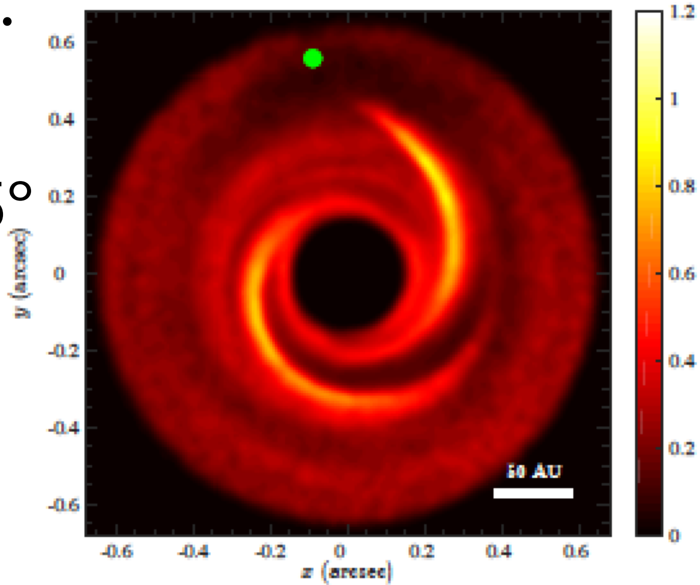


Planet-disk interaction

- Lessons from Zhu+15 (2D+3D hydro-simulations):
  - The more massive the planet, the larger the pitch angle.
  - A secondary spiral (or even tertiary) is excited. The more massive the planet, the larger the azimuthal separation between primary and secondary.
  - Using 3D hydro-simulations, one can re-create more proeminent spirals as can be observed in NIR, than with 2D hydro-simulations assuming hydrostatic equilibrium
  - Inner spirals (to the planet) usually appear more prominent than outer spirals, due to: 1/ enhanced vertical motion, 2/ sharper edges.



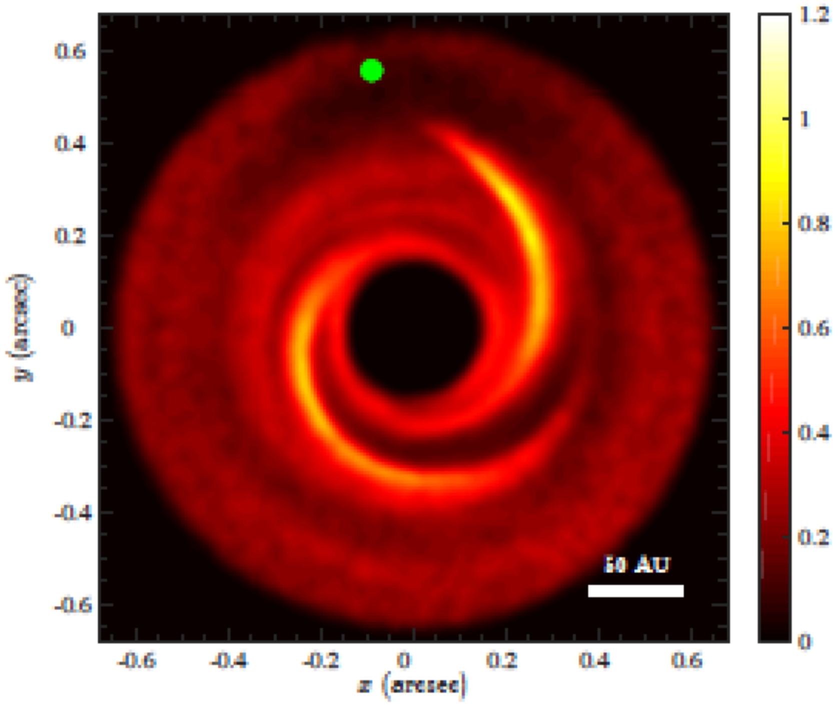
- Lessons from Dong+15 (radiative transfer of Zhu+15):
  - m = 2 symmetry
  - Inner spirals appear to have pitch angle between 10° and 15°
  - The spirals subtend 180° to 270°
  - ~ 150% brightness enhancement

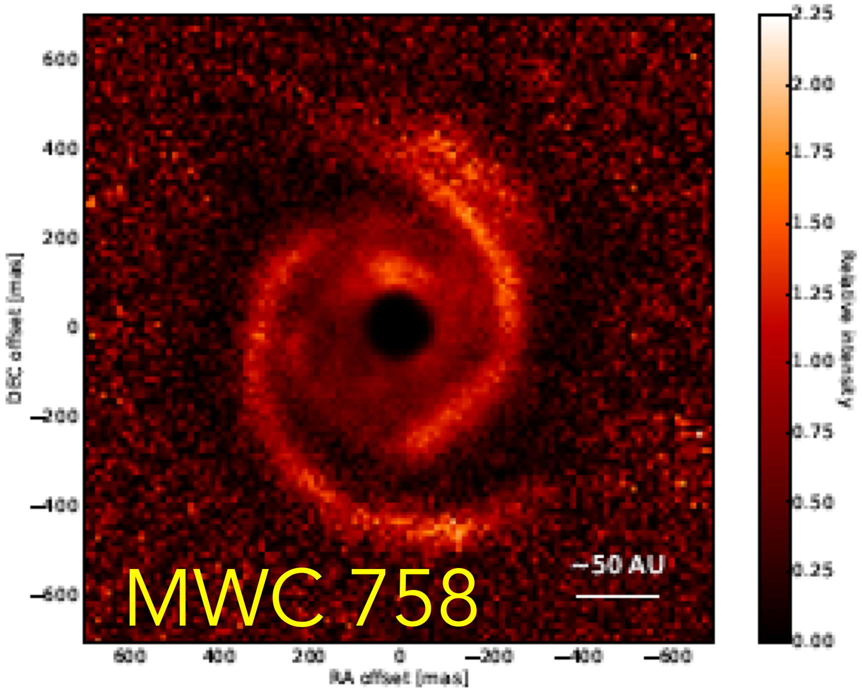


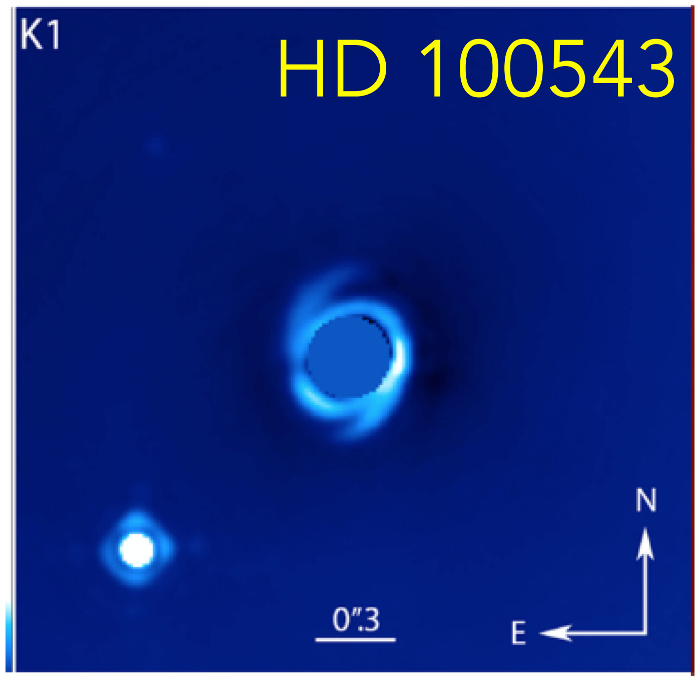
Planet-disk interaction

- Dong+15 (radiative transfer of Zhu+15):

=> VERY SIMILAR TO SOME OBSERVED SPIRALS:

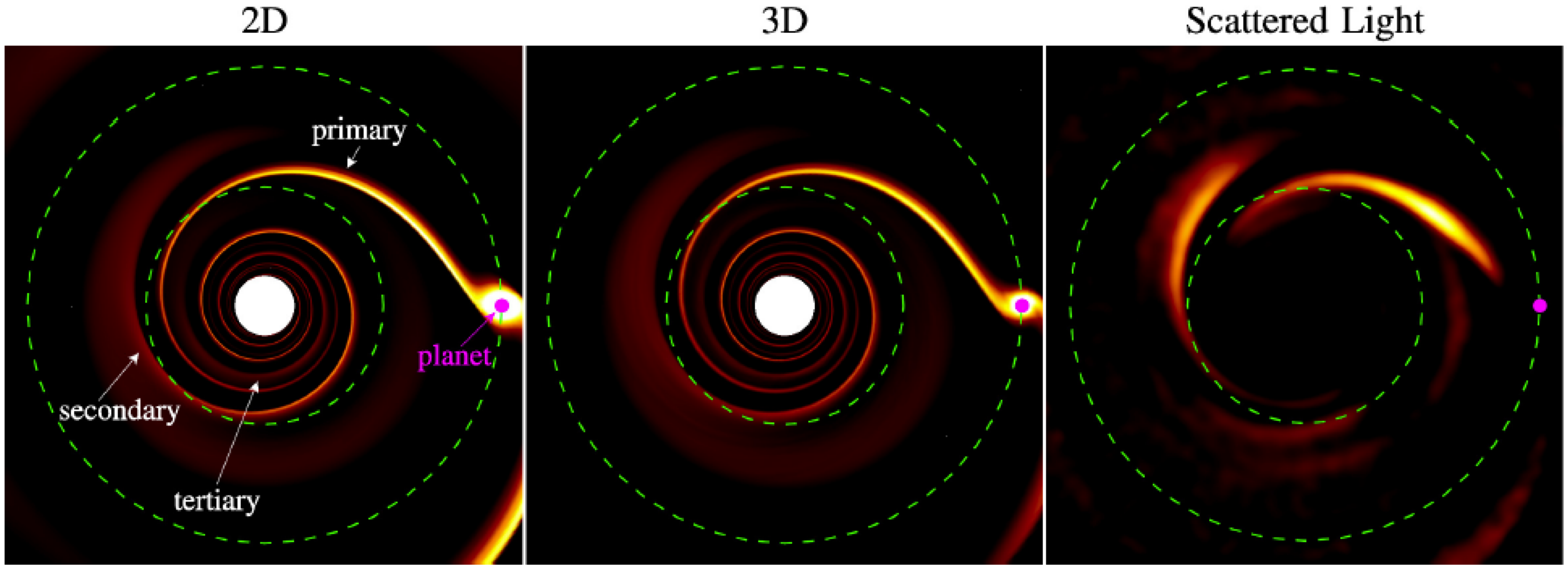






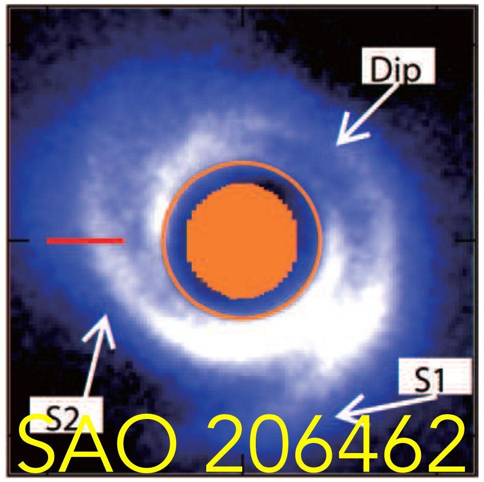
Planet-disk interaction

"The more massive the planet, the larger the azimuthal separation between primary and secondary."



(Fung & Dong 15)

- From $1M_{Nep}$ to $16M_{Jup}$ planetary companions: $$\phi_{sep} = 102^\circ (\frac{q}{0.001})^{0.2}$$
- For brown dwarf companions: $$\phi_{sep} = 180^\circ$$
- Application to SAO 206462 => $M_{pl} \sim 6\ M_{Jup}$



Planet in a marginally gravitationnally stable disk

- Lessons from Juhasz+15 (2D hydro-simulations+ rad. transfer):
  - A surface density relative change of a factor 3.5 is necessary to be detectable
  - A pressure scale height variation of only 0.2 is enough to be detectable

- Lessons from Pohl+15 (2D hydro-simulations+ rad. transfer):
  - Scale height perturbations due to either 1/ accretion heating of the planet or 2/ local heating by GI can create enough spiral contrast to be detectable
  - A large variety of planetary gap + spiral morphologies can be created depending on planet and disk mass
  - The disk is not GI itself, but the massive planet is working as a trigger for GI

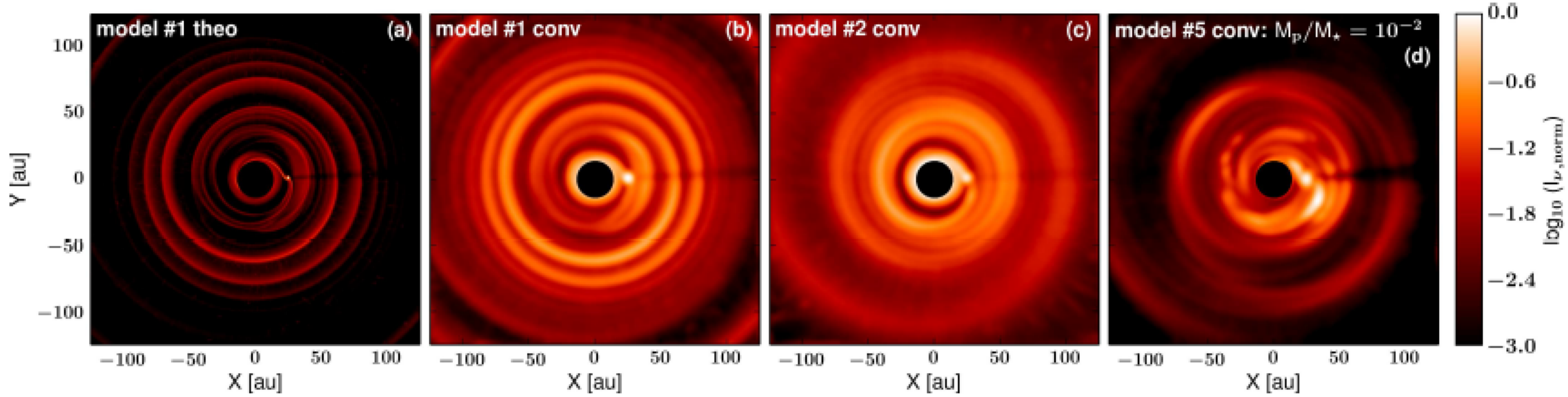
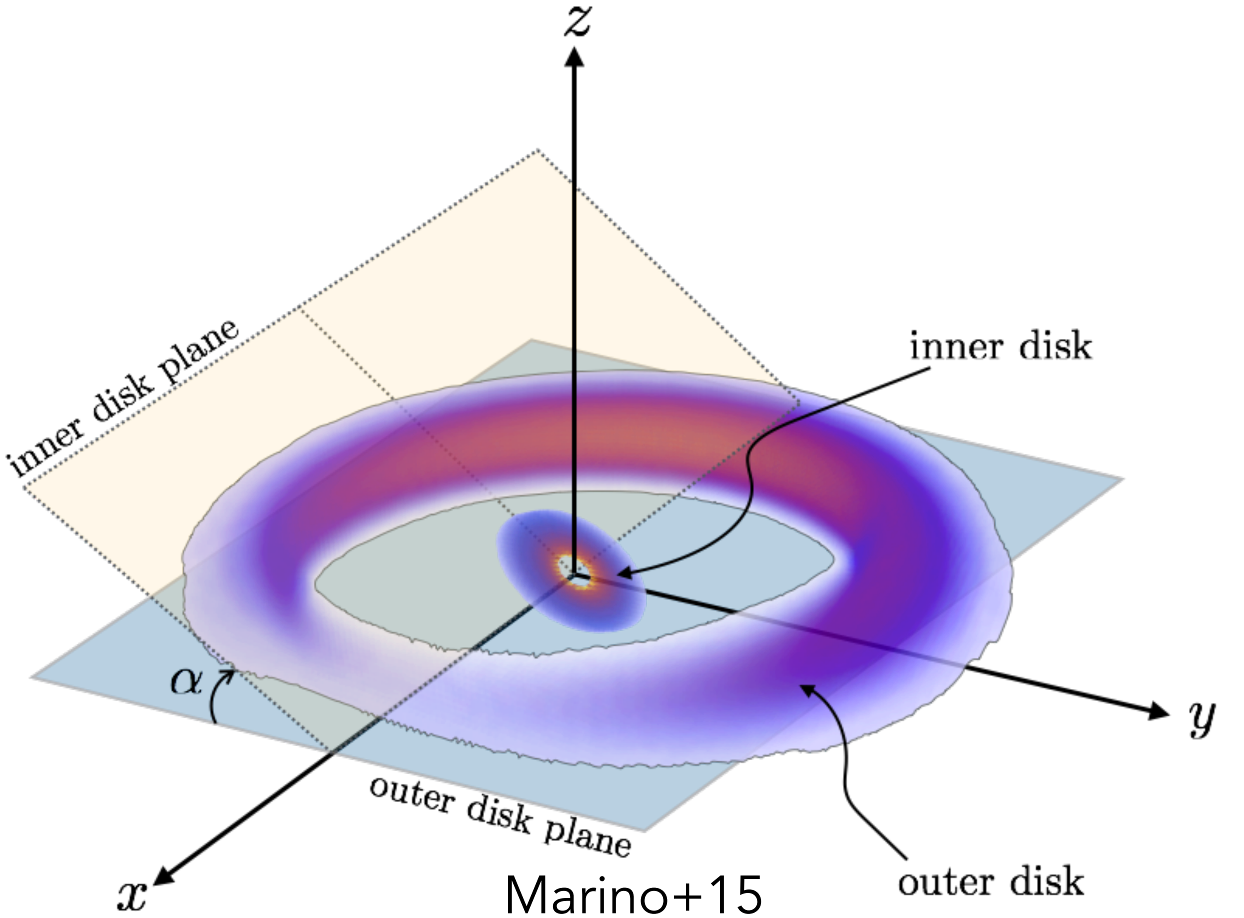


Figure 6. Simulated NIR scattered light images in *H*-band polarized intensity ($\lambda = 1.65\,\mu$m). All models consider a disc mass of $0.15\,M_\star$. (*a*) corresponds to the reference model *1* without self-gravity and shows the image at original resolution as calculated with the radiative transfer code RADMC-3D. All other images (*b*-*d*) are convolved with a Gaussian beam using a FWHM of $0.''04$ (at 140 pc distance), which is representative for observations with SPHERE/VLT in the *H*-band. The central $0.''1$ of the image were masked to mimic the effect of a coronagraph similar to real observations.

Inner disk casting shadows on the outer one

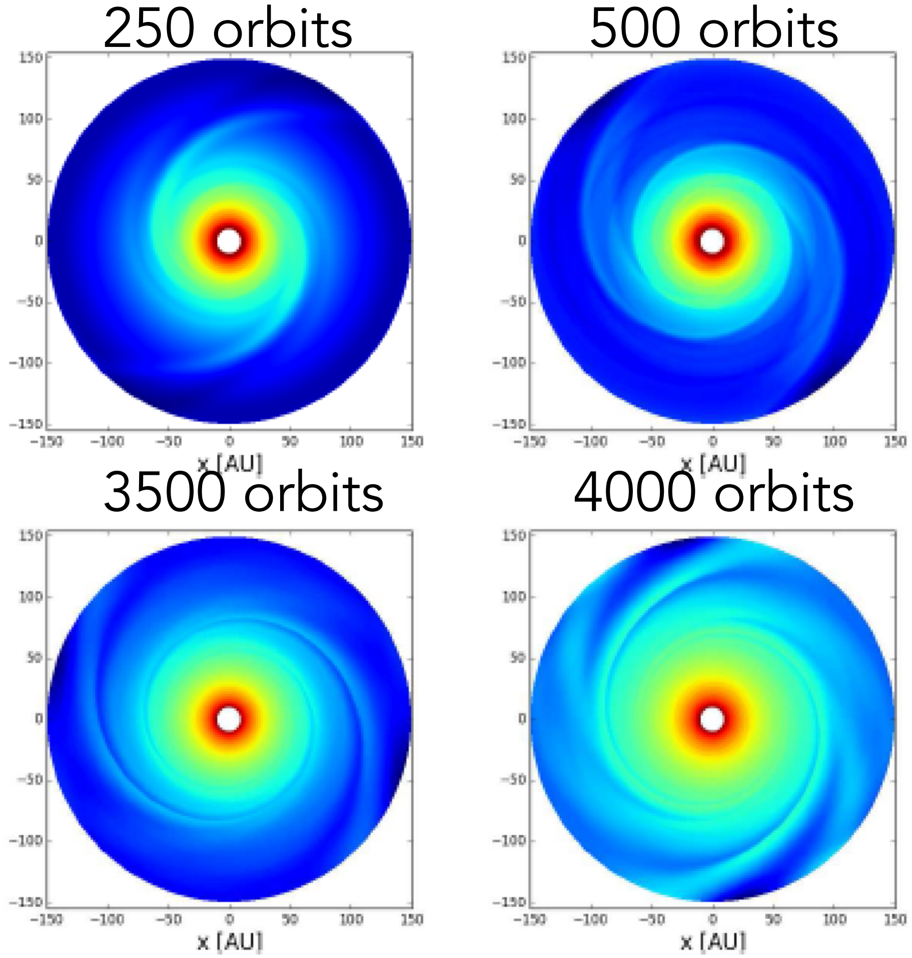
- Periodical density and temperature perturbations created by the shadows cast on the outer disk
- 2D hydrodynamical simulations show it can create spiral arms as well (Montesinos+ almost subm.):

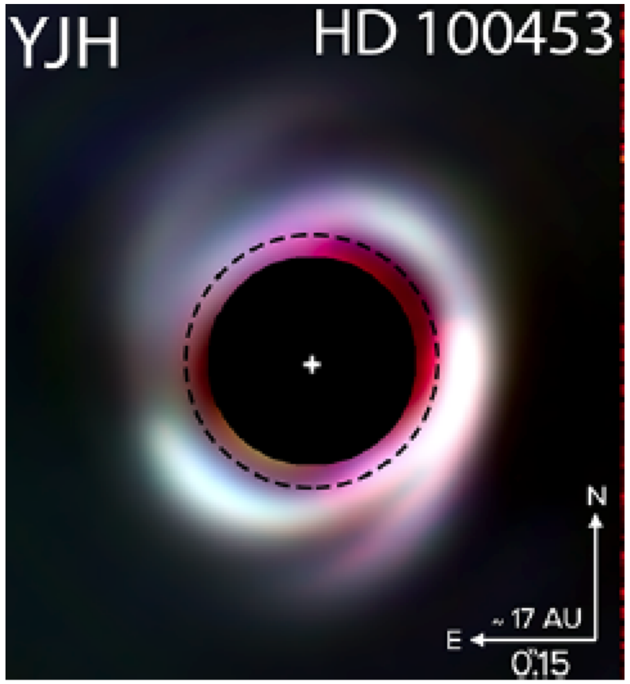


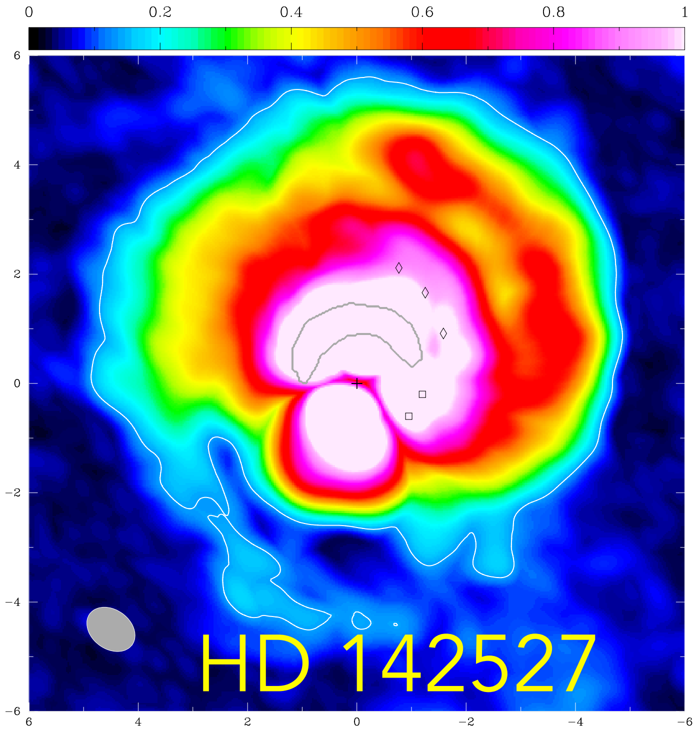
Marino+15

$L = 100L_{Sun}$

$L = L_{Sun}$

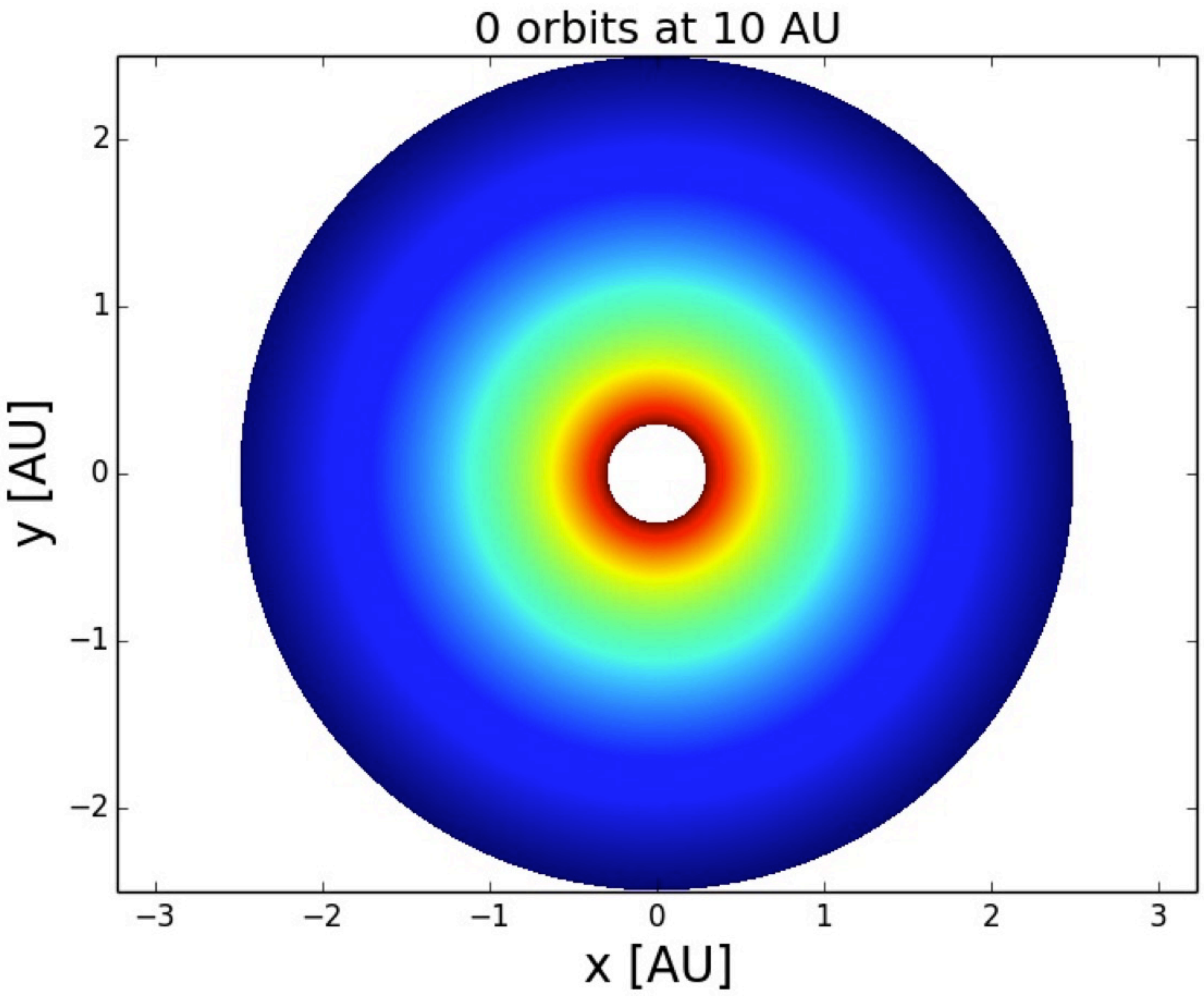






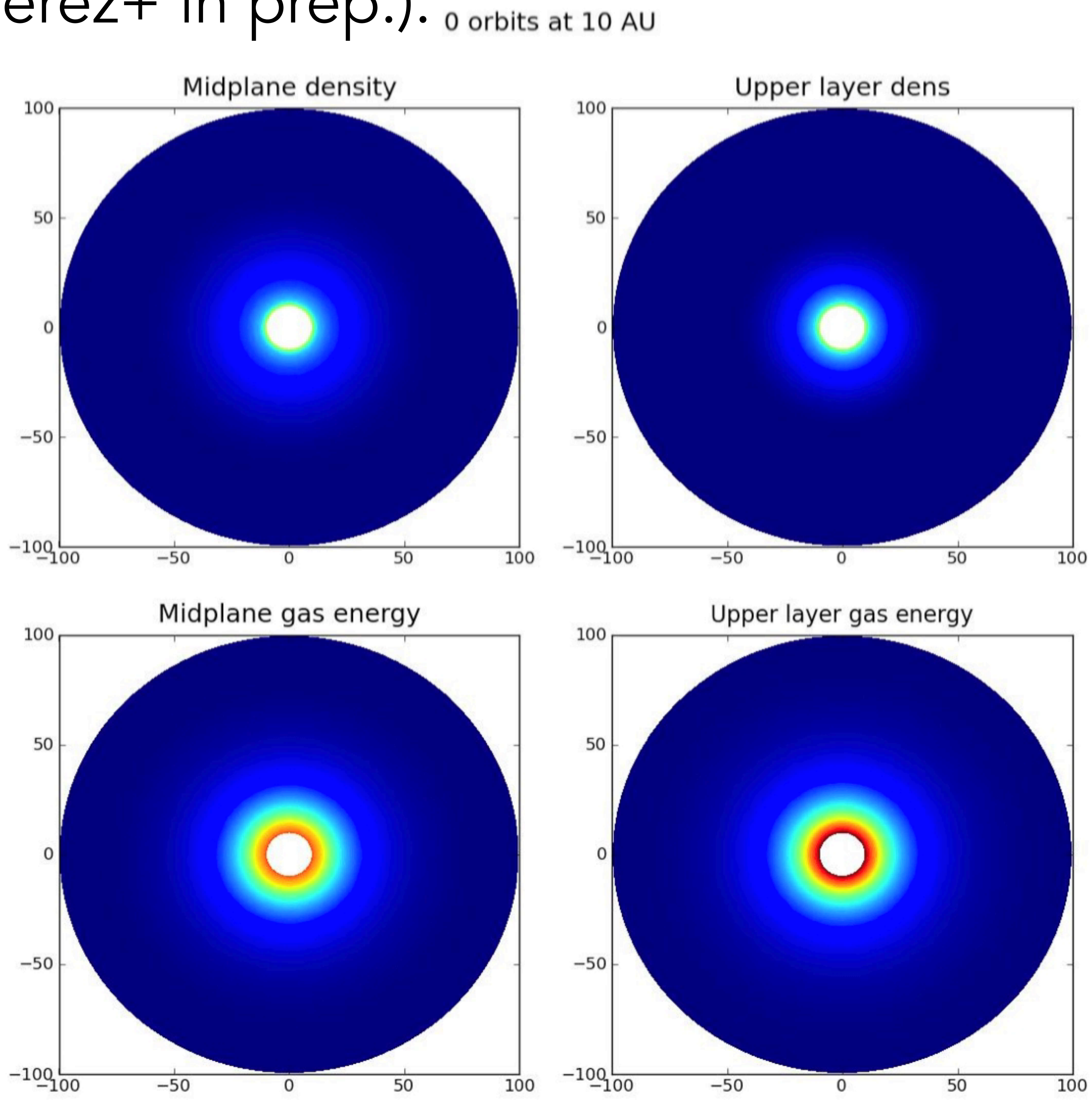
Inner disk casting shadows on the outer one

- Periodical density and temperature perturbations created by the shadows cast on the outer disk
- 2D hydrodynamical simulations show it can create spiral arms as well (Montesinos+ almost subm.):



Inner disk casting shadows on the outer one

- Periodical density and temperature perturbations created by the shadows cast on the outer disk
- 3D RT hydrodynamical simulations ALSO show it can create spiral arms as well (Perez+ in prep.):

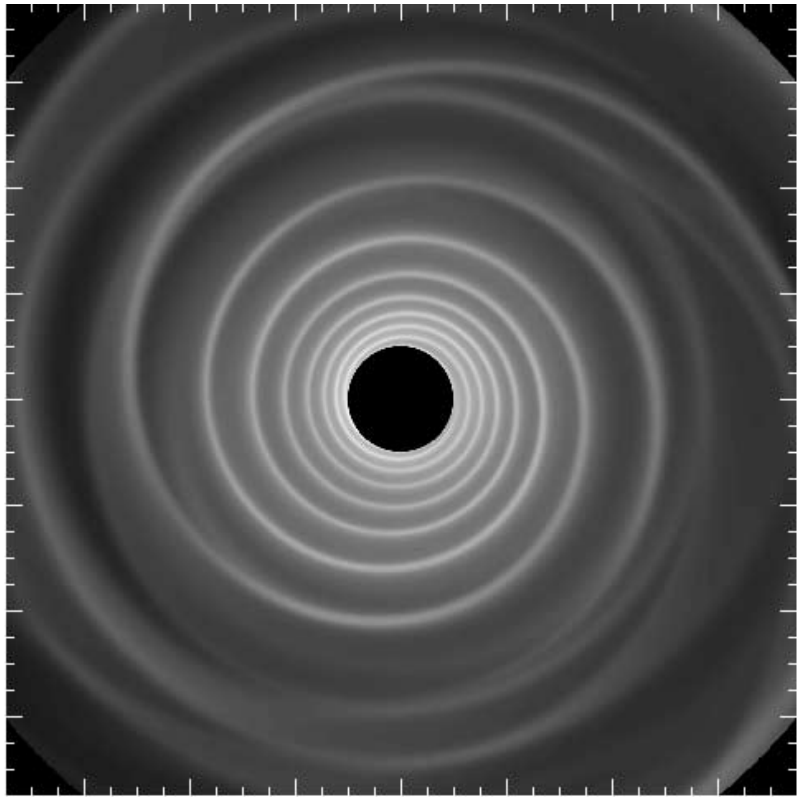


Stellar fly-by

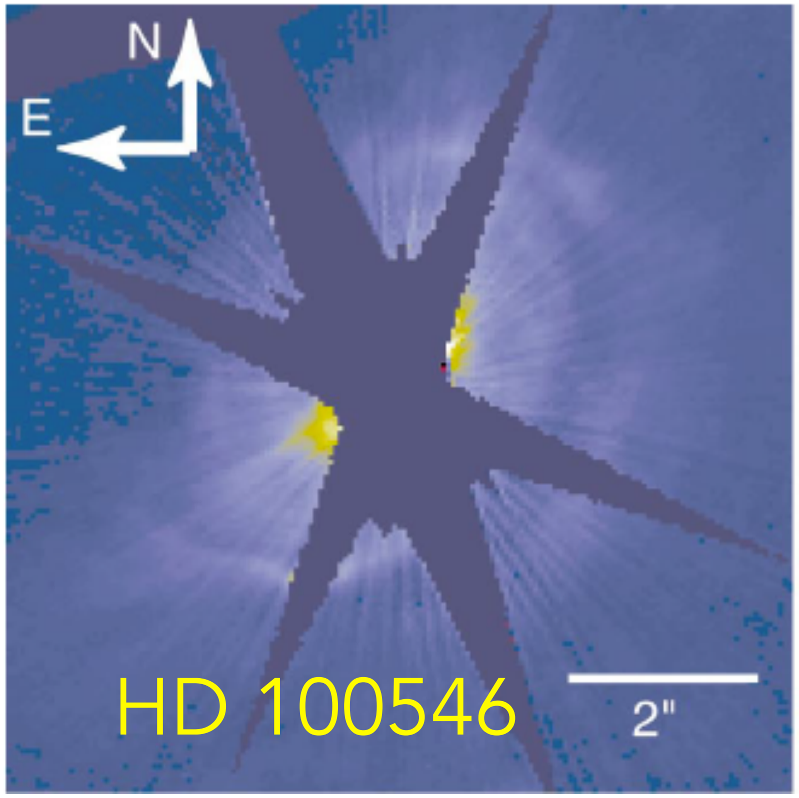
- Tidal interaction by a past stellar encounter?

(e.g. Larwood+ 01, Augereau+ 04, Quillen+ 05)

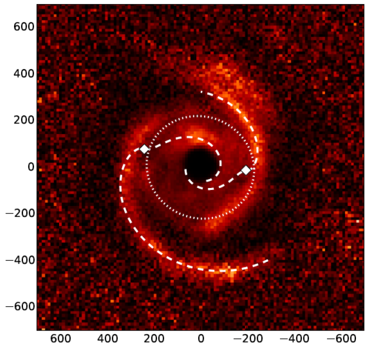
> Transient spirals (a few dynamical timescales ~ 10^3 years)
> Requires the perturber star to still be found in the neighbourhood
> Can excite very large scale spirals



Quillen+ 05



What is the effect of spirals on the disk itself?



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

Rafikov 02, Muto+12

- Linear theory of spiral waves have trouble to match observations:
  - Predicted disks are too hot
  - They require too large *h*

- Non-linear propagation of tidal waves: (Goodman & Rafikov 01, Rafikov 02)
  - Tidal interactions between planet and disk generate density waves.
  - Density waves carry angular momentum (AM)

    =>1/ Planet migration or clump migration

    2/ Evolution of the disk itself, but how is the AM transferred to the disk?
      - Linearly? Viscosity does not seem efficient enough
      - Non-linear dissipation (shock formation) seems inevitable
  - Consequences on the evolution of the disk (Rafikov 16)
    - Spirals drive significant mass accretion (> than the one due to viscous stress)
    - Shock AM transport drives significant and quick surface density evolution
    - It could proceed in an inside-out fashion, first clearing the inside cavity

    => naturally explain the transition morphology of many spiral-bearing systems

For a given spiral observation, how to untangle the origin?

Diagnostics:

1. Estimate either the global Q (e.g. with rad. transfer modelling to get M_d) or local Q under the spirals (with sub-mm continuum or line observations for the surf. density)
   - $Q \lesssim 2$: strong indicator of GI
   - Q ~ 2: could still be the case of marginal stability+massive planet
2. Small or large scale?
   - < 100au: GI or planet
   - > 100au: Stellar fly-by, external companion, late envelope infall
3. Get kinematics/dynamics of the disk (e.g. velocity map/dispersion of line observations):
   - Non-keplerian speeds under the spirals: late-envelope infall
4. Number of spirals and their symmetry:
   - m = 1: single low-mass sub-stellar companion
   - m = 2: stellar fly-by, (sub-)stellar companion within or external to the disk, GI, or shadows
     - Apply Fung&Dong15 empirical relation to estimate the mass of the possible companion
   - m > 2: GI or shadows
5. Pitch angle of the spirals:
   - Pitch angle ~ 10-15°: compatible with GI, planets or shadows
   - Pitch angle ~ 15°-30°: compatible with external companions or fly-by
6. Check surroundings:
   - Within a few arcsec: low-mass bound companion external to the disk?
   - Within a few arcmin: star with similar proper motion?

Observational perspectives

- Waiting for ALMA cycle 3 data on the spirals of HD 142527:
  - Confirm the temperature of 10-15K under S2 (below freeze-out)
  - Observe at better continuum sensitivity to confirm the lack of dust under S2 that could explain T below freeze-out.
  - More stringent constraints on the origin of these spirals; test of the shadows theory.