Large Scale Disk Asymmetry in Protoplanetary Disks

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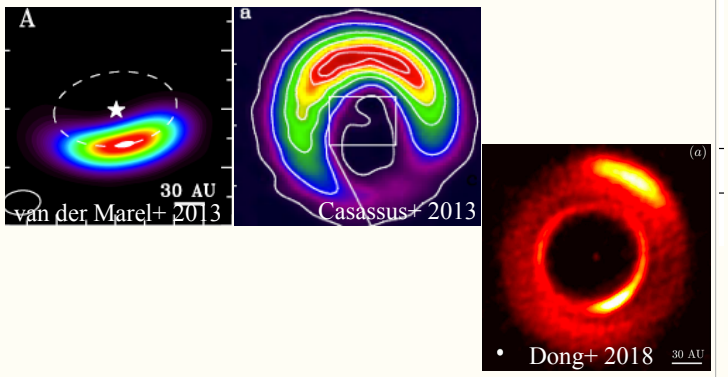
Large Scale Disk Asymmetry

	Optical/Near-IR	Radio (dust continuum)	Radio (polarization)
Asymmetry m=1			
Others			

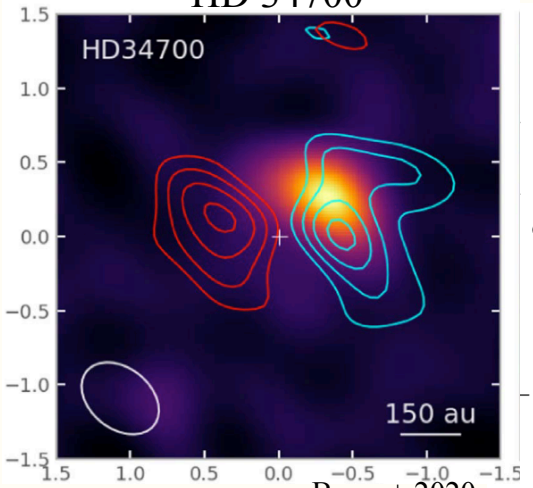
Not discussing spirals
(See Jaehan's talk)

polarization due to dust scattering
(dust properties, phase function, disk geometry)

due to illumination

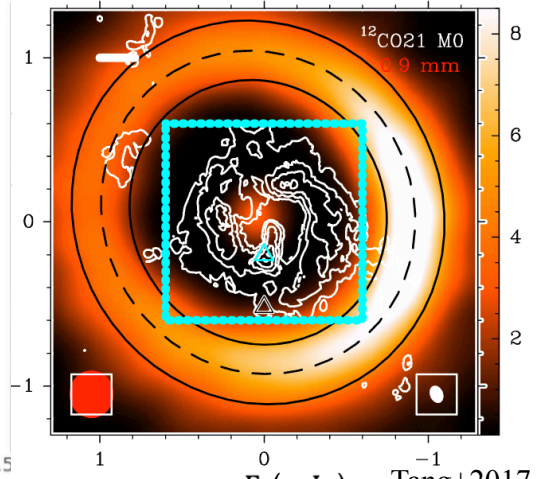
Focus on intrinsic mass asymmetric distribution

HD 34700



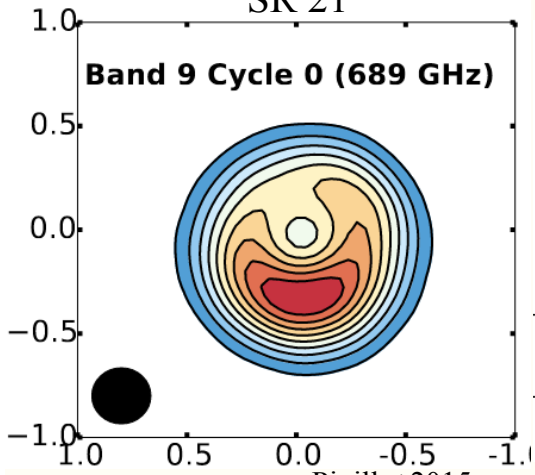
Benac+ 2020

AB Aur



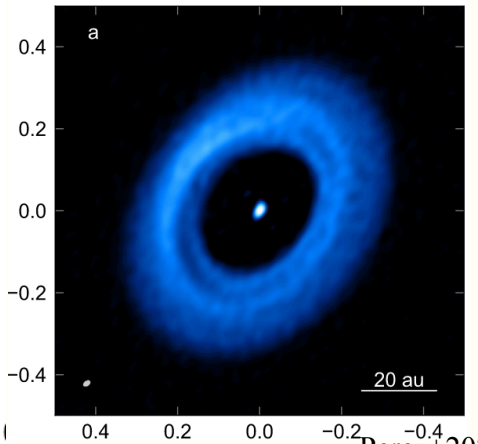
Tang+2017

SR 21



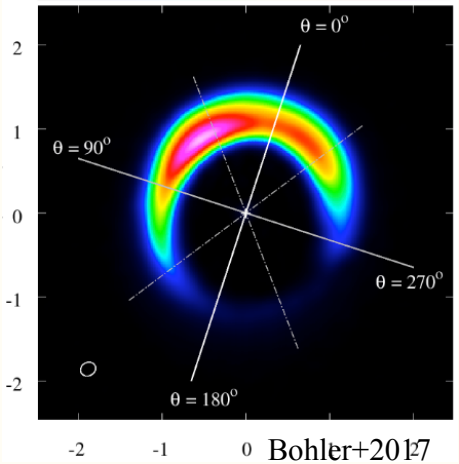
Pinilla+2015

HD 100546



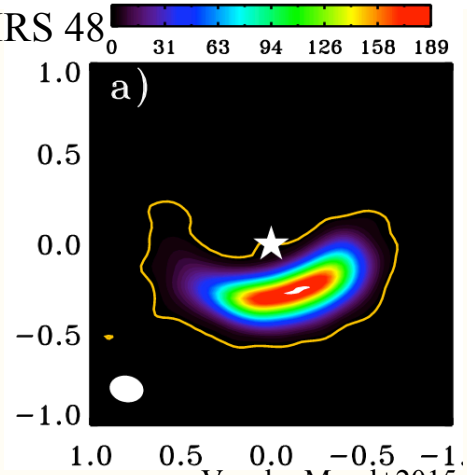
Perez+2020

HD 142527



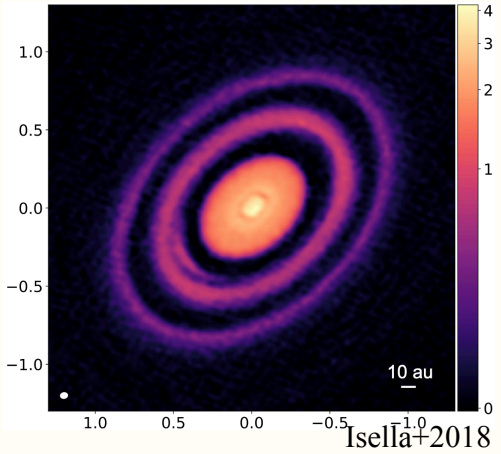
Bohler+2017

IRS 48



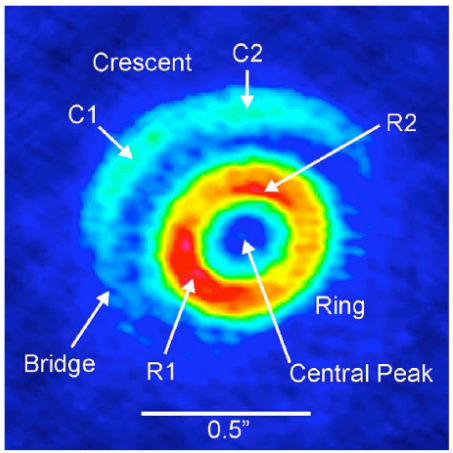
Van der Marel+2015

HD 163296



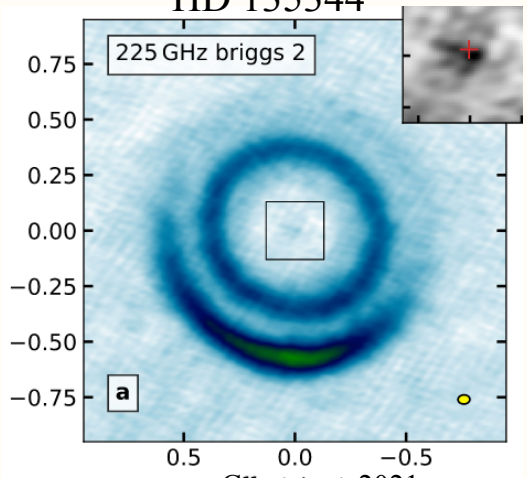
Isella+2018

V1247 Ori



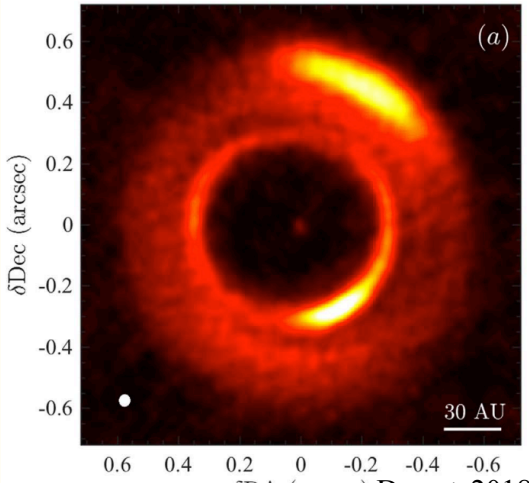
Kraus+ 2017

HD 135344



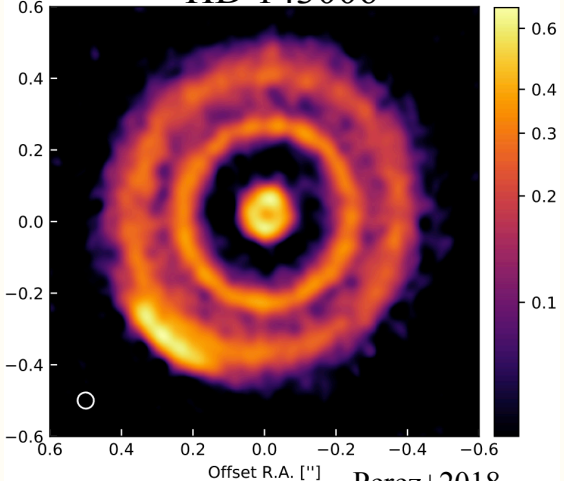
Cãsassus+ 2021

MWC 758



Dong+ 2018

HD 143006



Perez+2018

Bea, Isella, Martin, Okuzumi, Suriano, Zhu
PPVII chapter

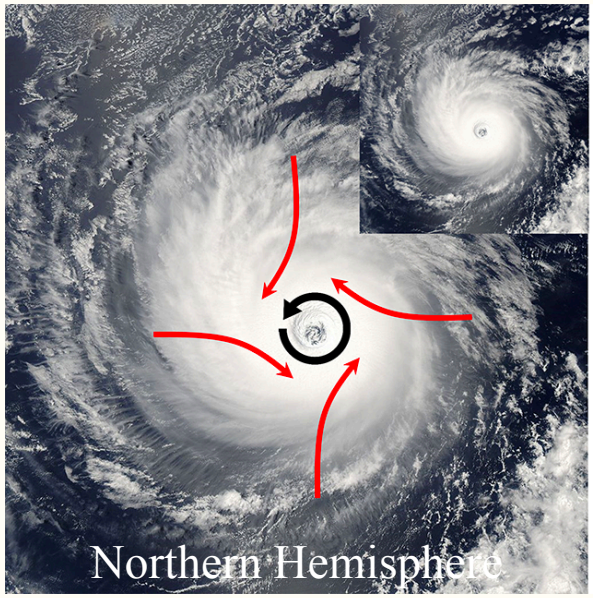
Outline

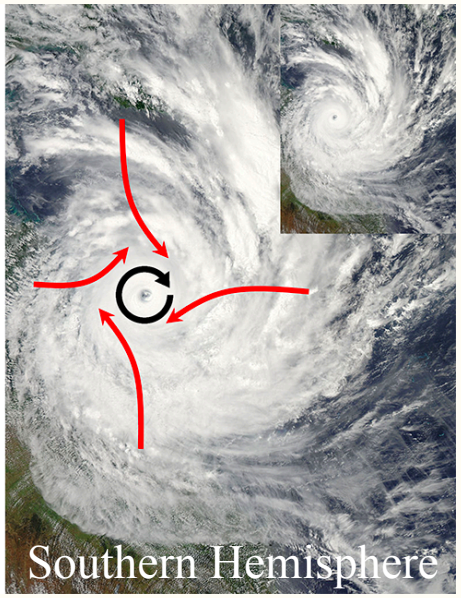
- Vortices
  - Basic properties of vortices
  - Excitation mechanisms
  - Spirals, particle trapping, self-gravity of vortices, MRI turbulence
- Lumps in circumbinary disks
  - Coplanar disks
  - Polar disks
- Observations

Vortices at various scales on earth

sink vortex: gravity, pressure

Conservation of angular momentum
(Kelvin's circulation Theorem)





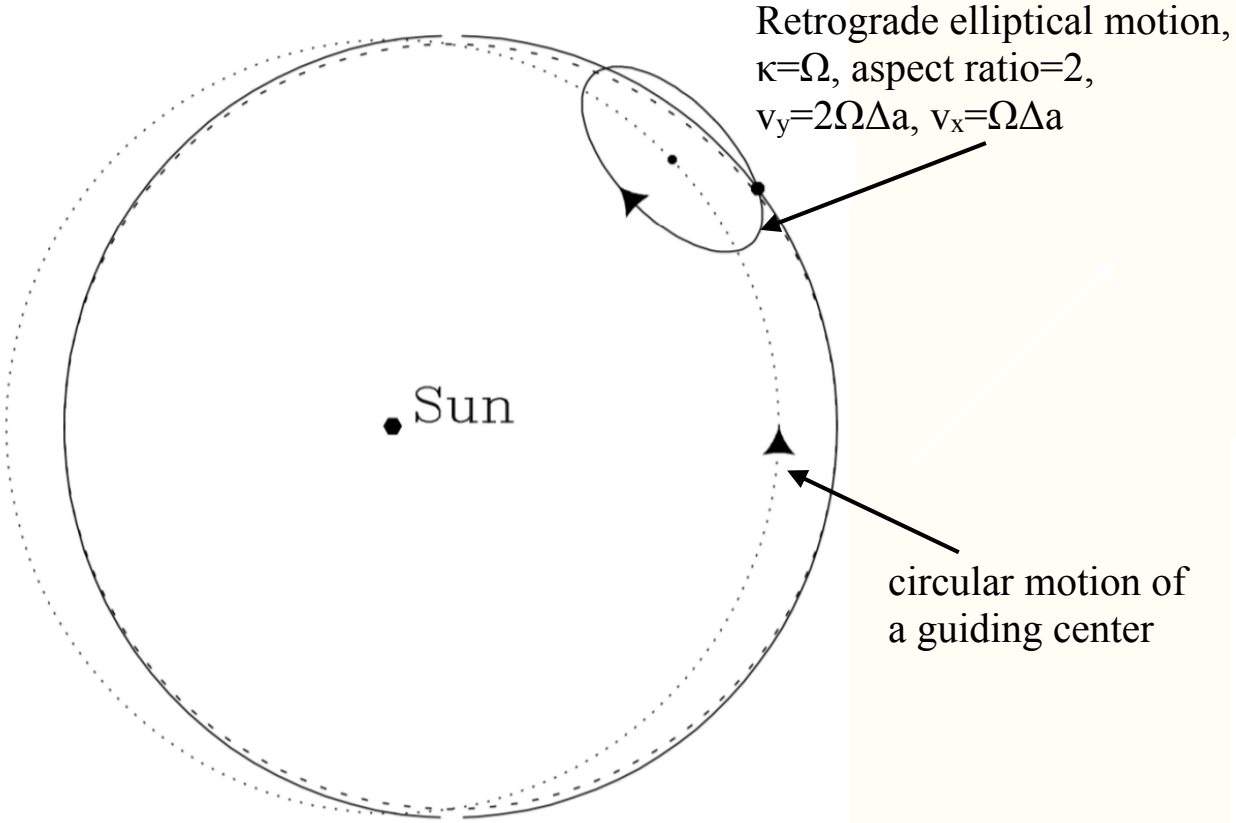
Hurricane: buoyancy force, latent heat

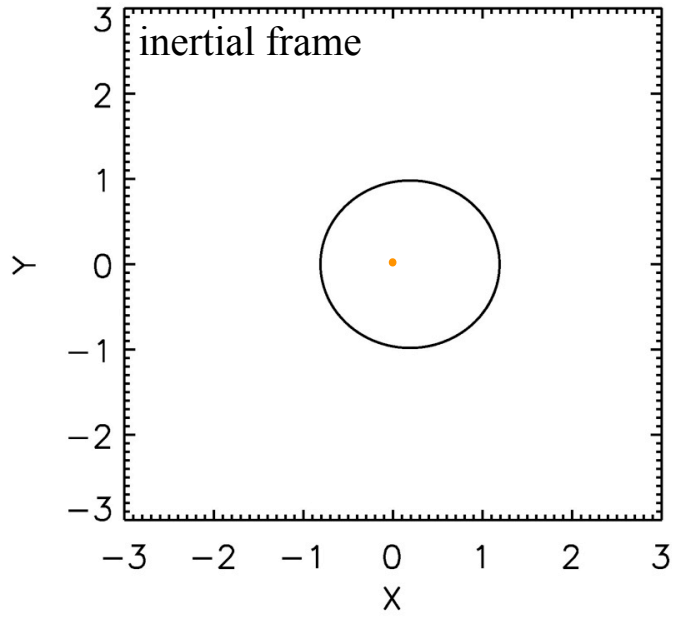
Coriolis force rotates the vortex

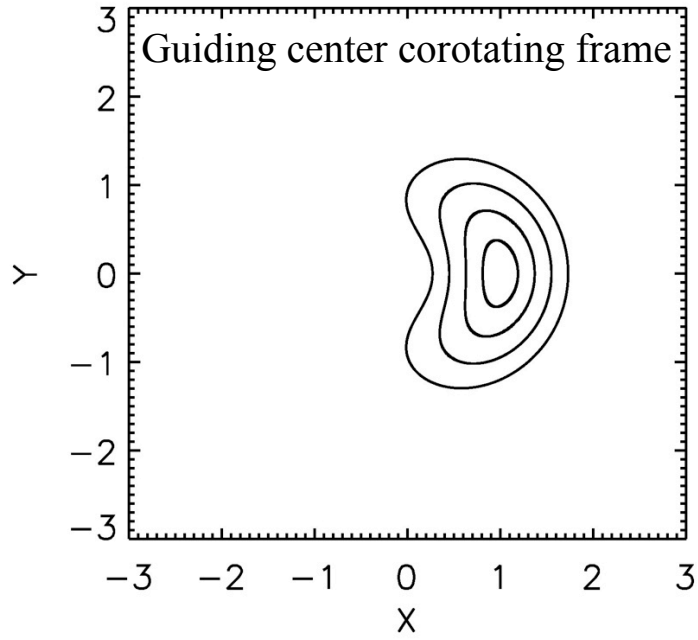
Vortices in protoplanetary disks

The simplest vortex: pressureless vortex

A particle in an eccentric orbit: epicyclic approx







When particles are arranged properly,
they can form a vortex structure.

- Circulation time for every particle: 1 orbit
- Aspect ratio: 2, $v_y/v_x=2$

Vortices in protoplanetary disks

Gas vortex with pressure: aspect ratio $\chi \geq 2$

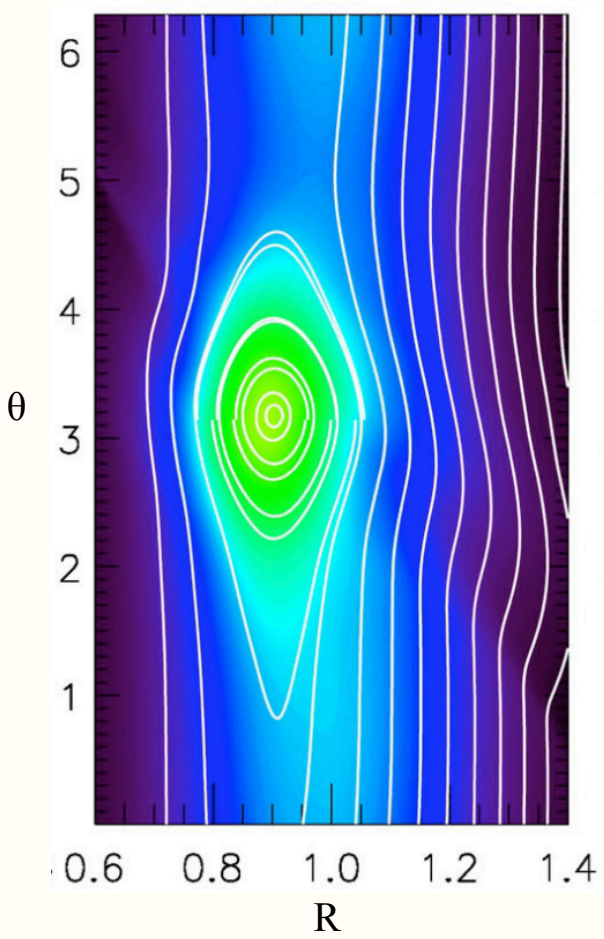
$$u_x = \Omega_V y/\chi$$

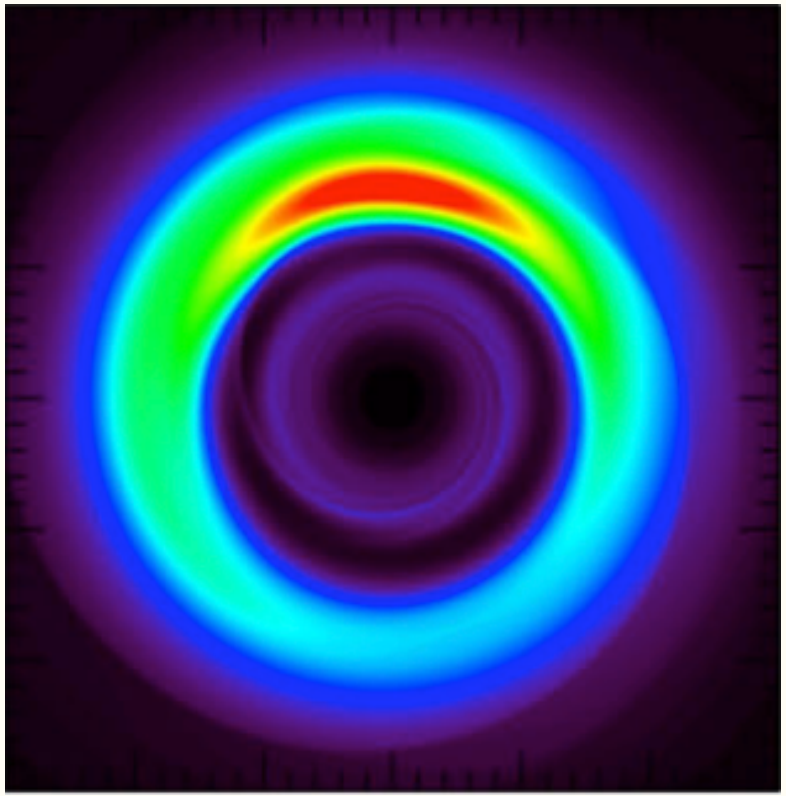
$$u_y = -\Omega_V x \chi$$

$$\Omega_V = \Omega\sqrt{3/(\chi^2 - 1)}$$

When χ=2, it returns the pressureless solution
When χ>2, it needs more pressure for the balance; high center density

Goodman et al. 1987

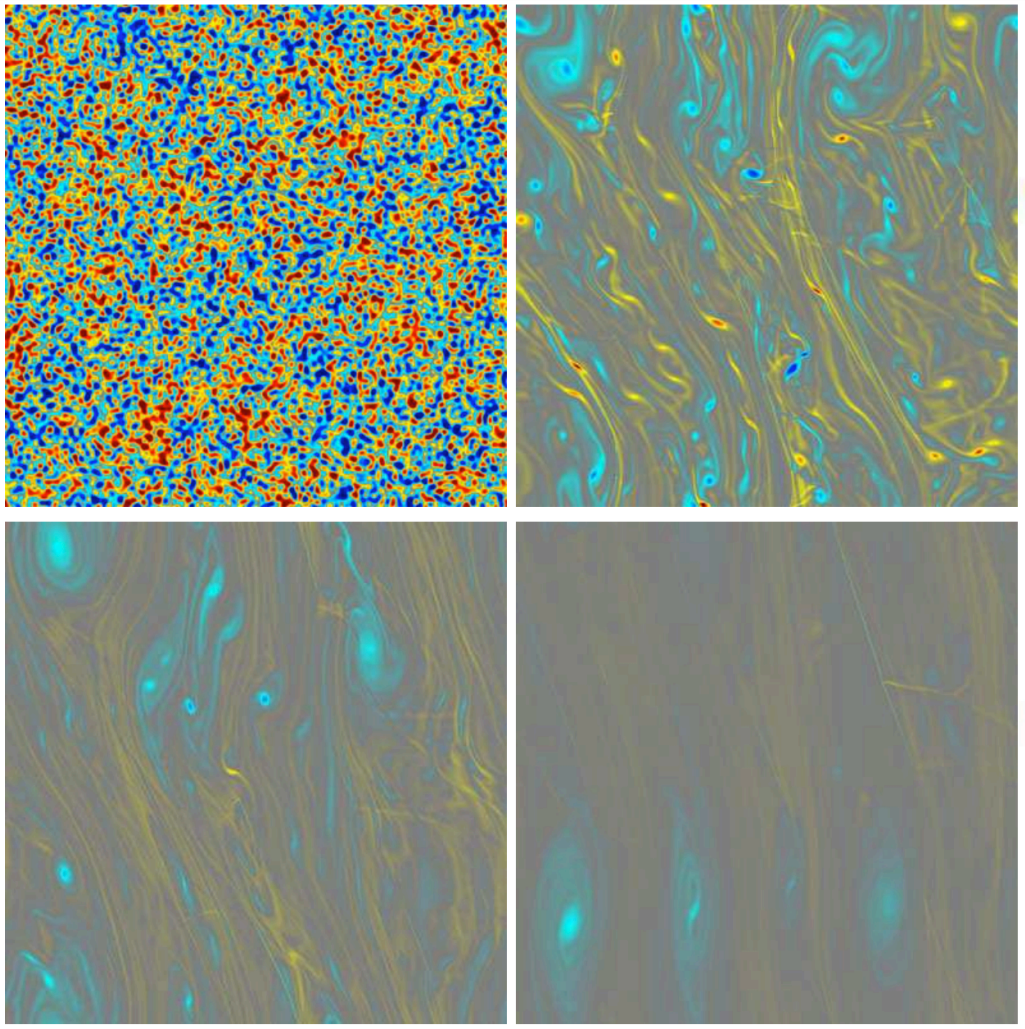


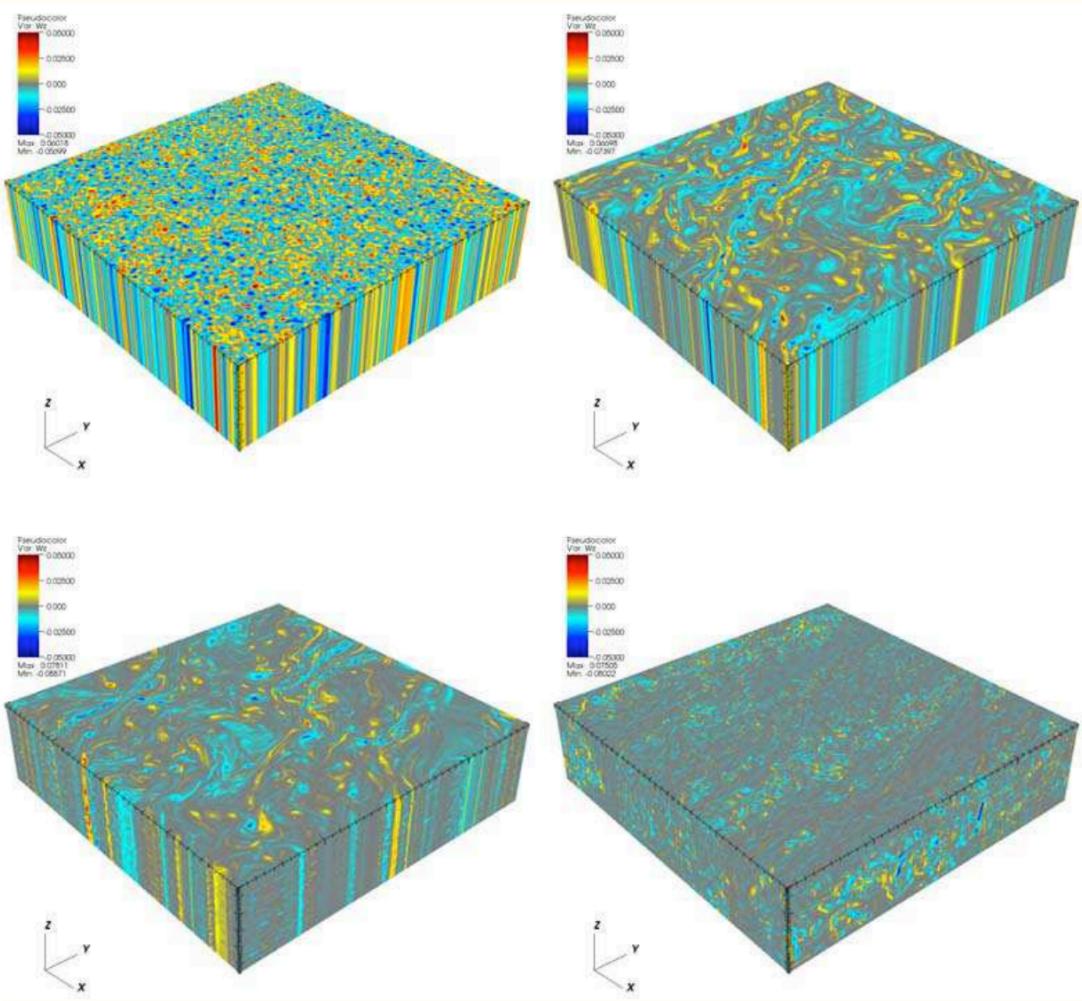


Vortex Evolution and Instability

2-D vortices: inverse energy cascade

tall small 3-D vortices: turbulence

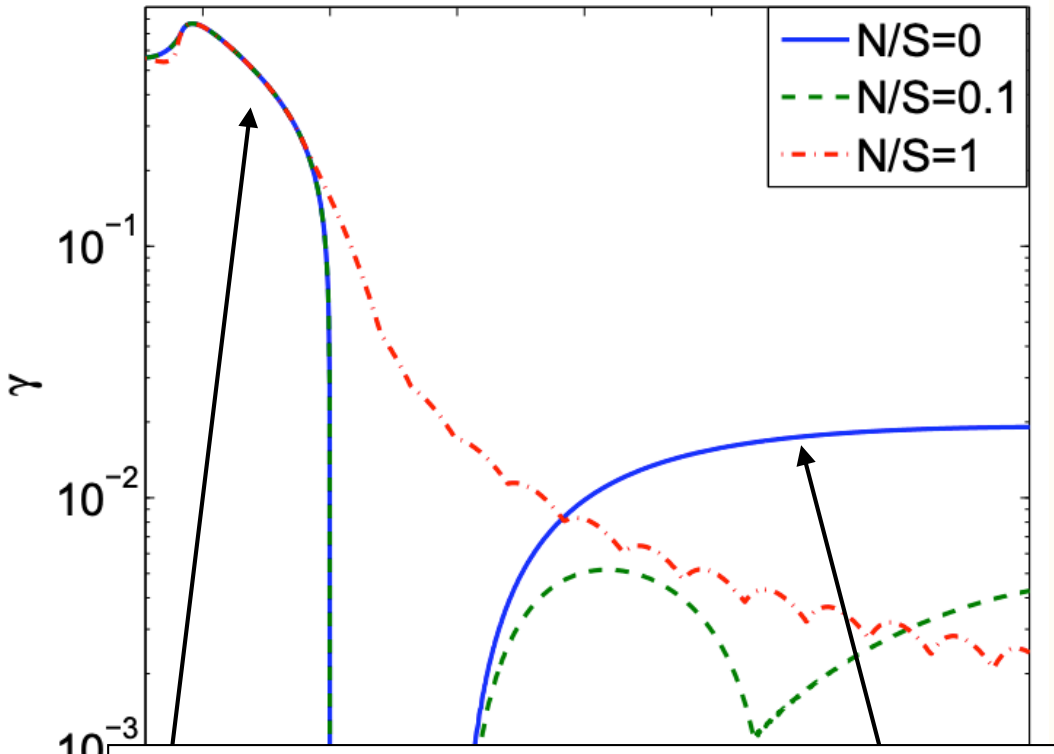




Enstrophy (vorticity variance) conservation

Shen et al. 2006

Vortex Evolution and Instability



Future: compressible vortices with 3-D flow structure

A large vortex (maybe ~H radially) with a large aspect ratio ($\chi \gtrsim 3$) is easier to survive.

Strong horizontal instability

Weaker elliptical instability

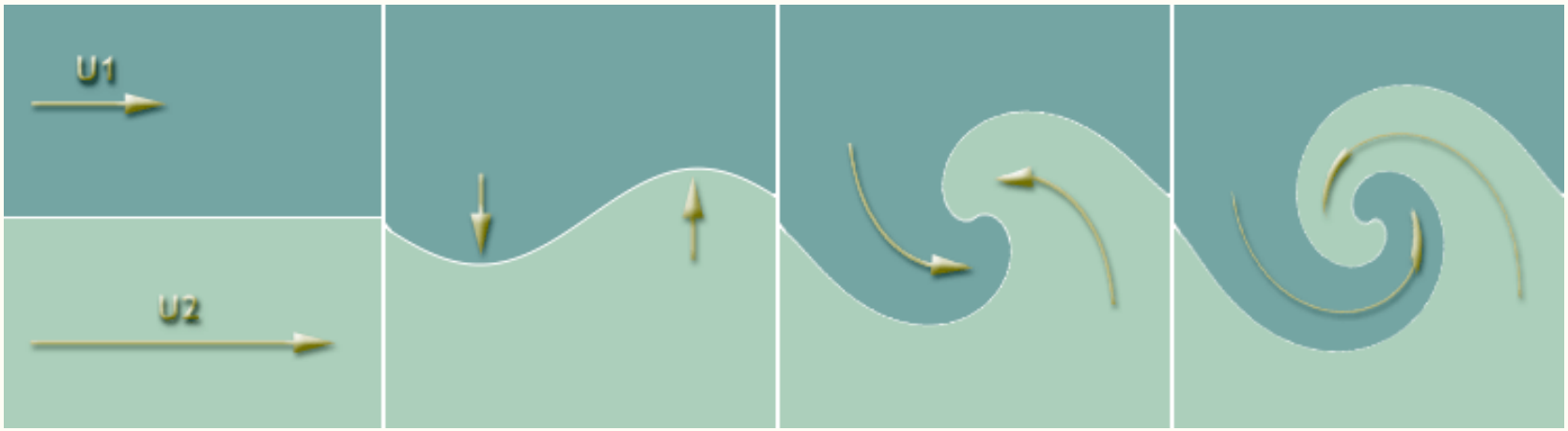
Large scale asymmetry

- Vortices
  - Basic properties of vortices

    (circulation motion, large scale~H, aspect ratio$\gtrsim$3)
  - Excitation mechanisms
  - Spirals, particle trapping, self-gravity of vortices, MRI turbulence
- Lumps in circumbinary disks
  - Coplanar disks
  - Polar disks
- Observations

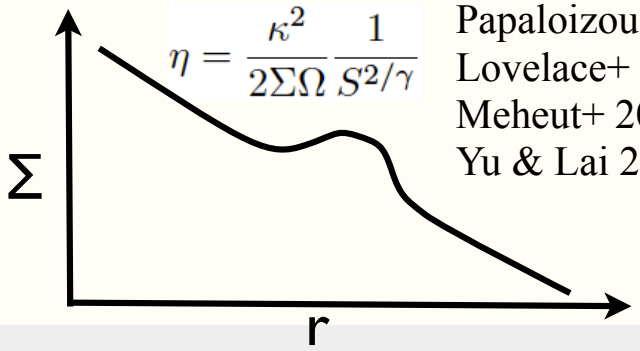
Excitation mechanisms: starting from a shear

Kelvin Helmholtz Instability (shear flow)

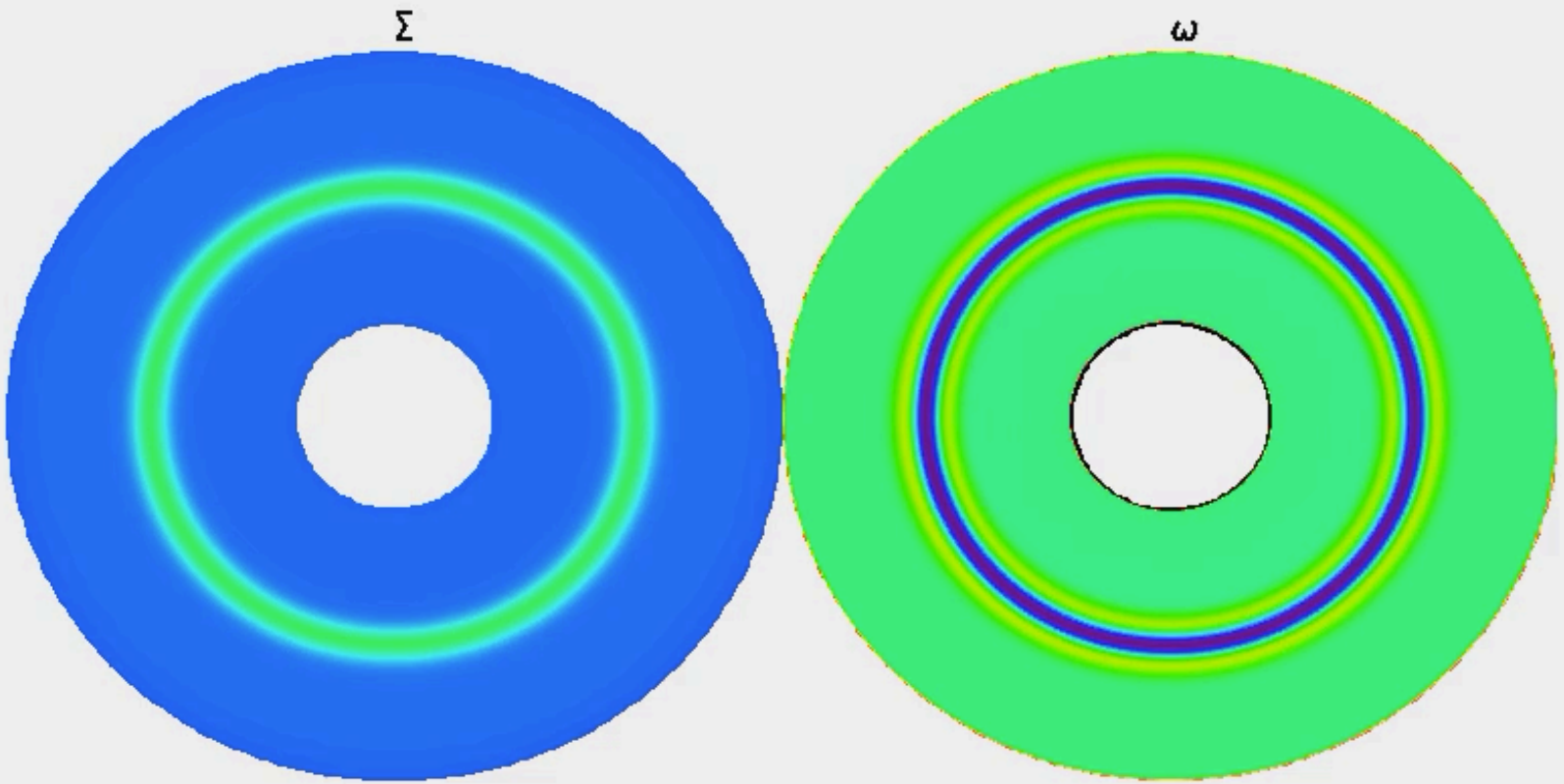


Wiki

Rossby Wave Instability



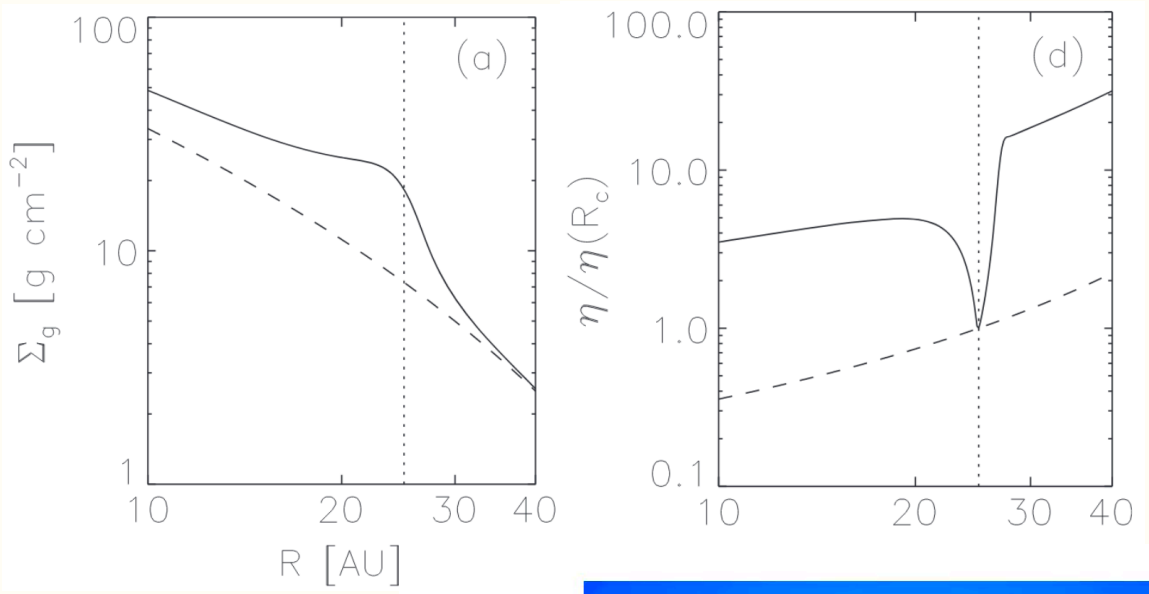
Papaloizou & Pringle 1984,1985
Lovelace+ 1999, Li+ 2000, 2001
Meheut+ 2010, 2012, Lin+ 2012,
Yu & Lai 2013, Ono+ 2016



Rossby Wave Instability with density bumps

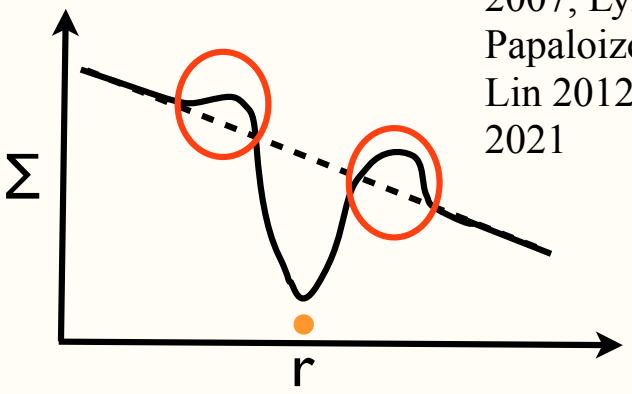
Any density bump can trigger RWI:

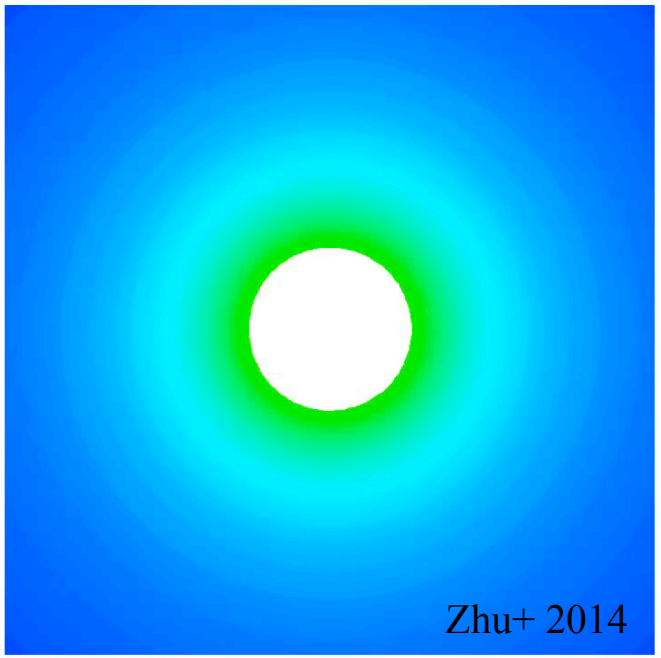
1. Infall (Bae et al. 2015)



2. Planet induced gap

Li+ 2005, de Val-Borro 2007, Lyra+ 2009, Lin & Papaloizou 2010, Lin 2012, Hammer+ 2019, 2021

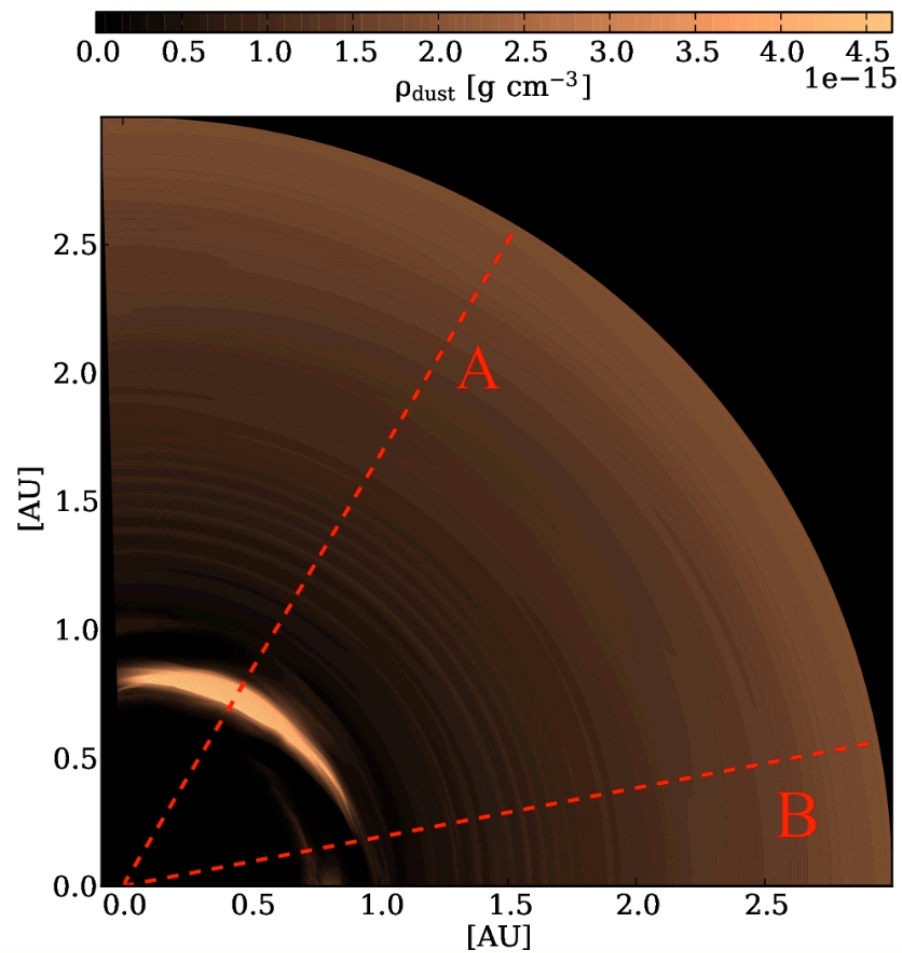




Rossby Wave Instability with density bumps

3. Any accretion mechanism transition (tends to be long lived)

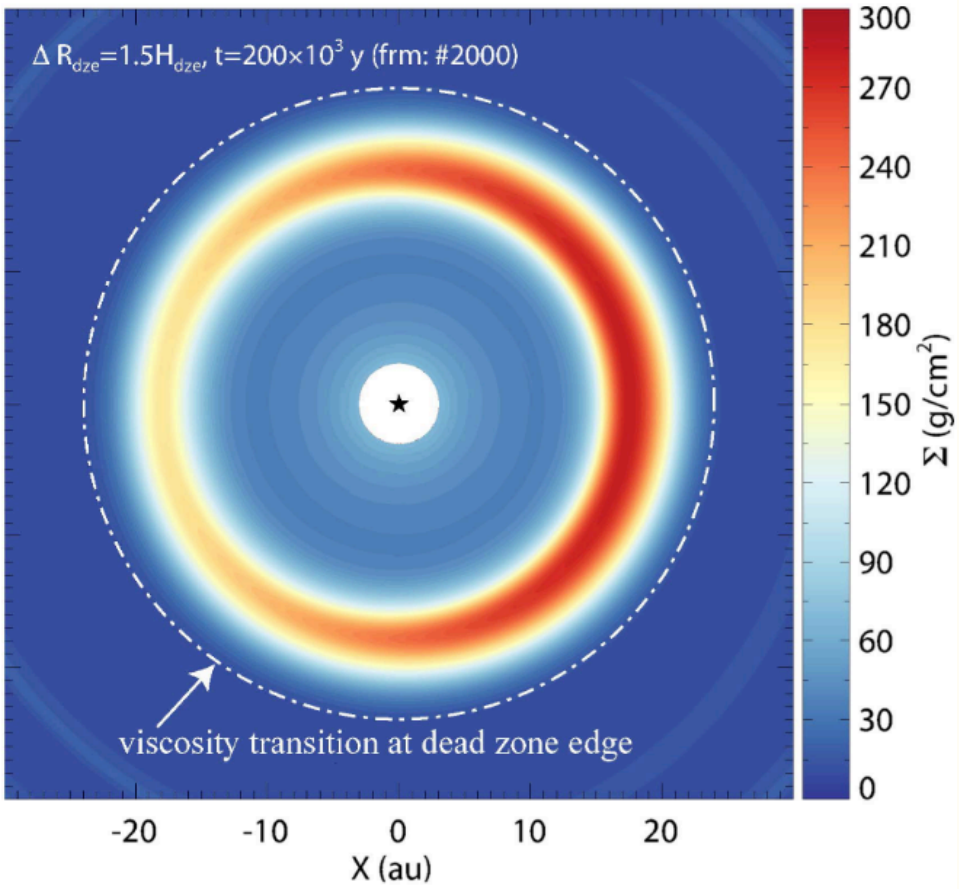
Deadzone inner edge



Flock et al. 2017

Deadzone outer edge

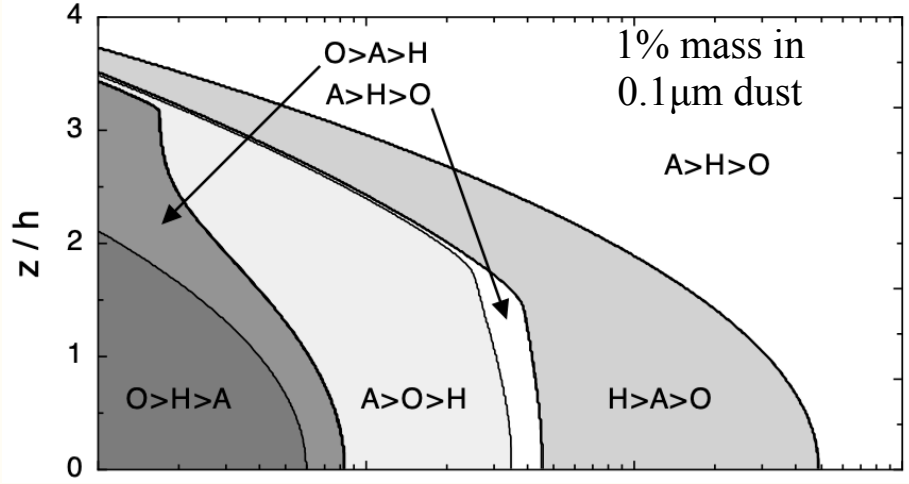
Varniere & Tagger 2006, Lyra+ 2009, 2014, Regaly+ 2012, Miranda+ 2017, Tarczay-Nehez+ 2021

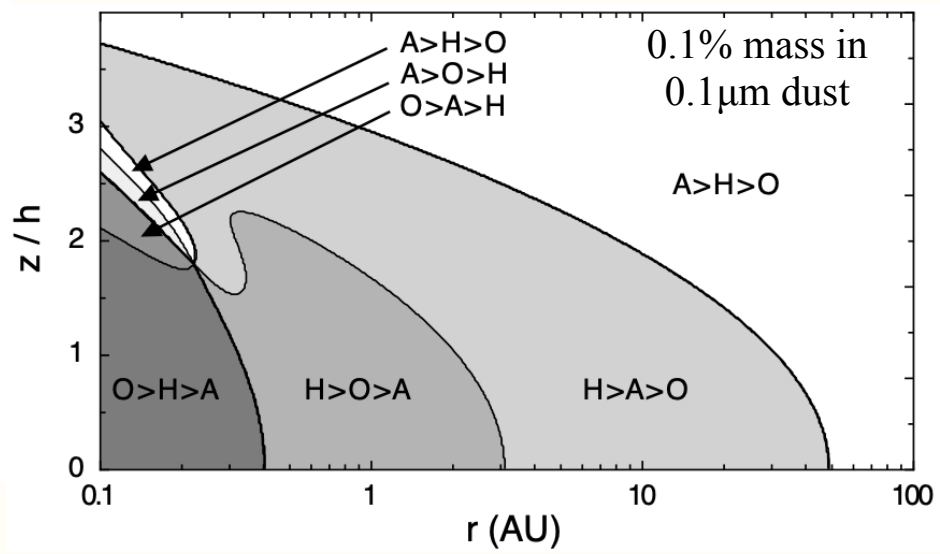


Regaly et al. 2017

Rossby Wave Instability

Magnetized disk

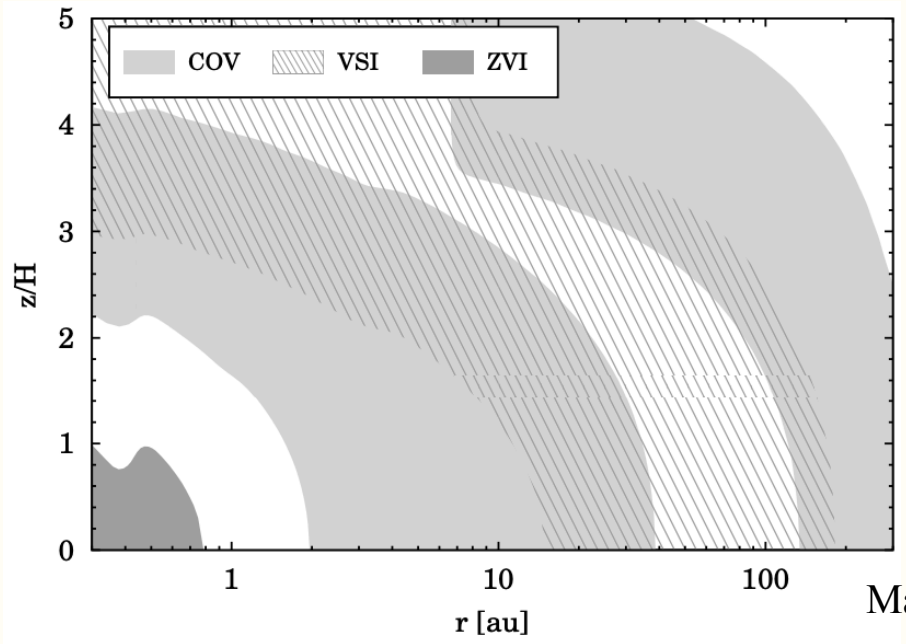




Turner et al. 2014

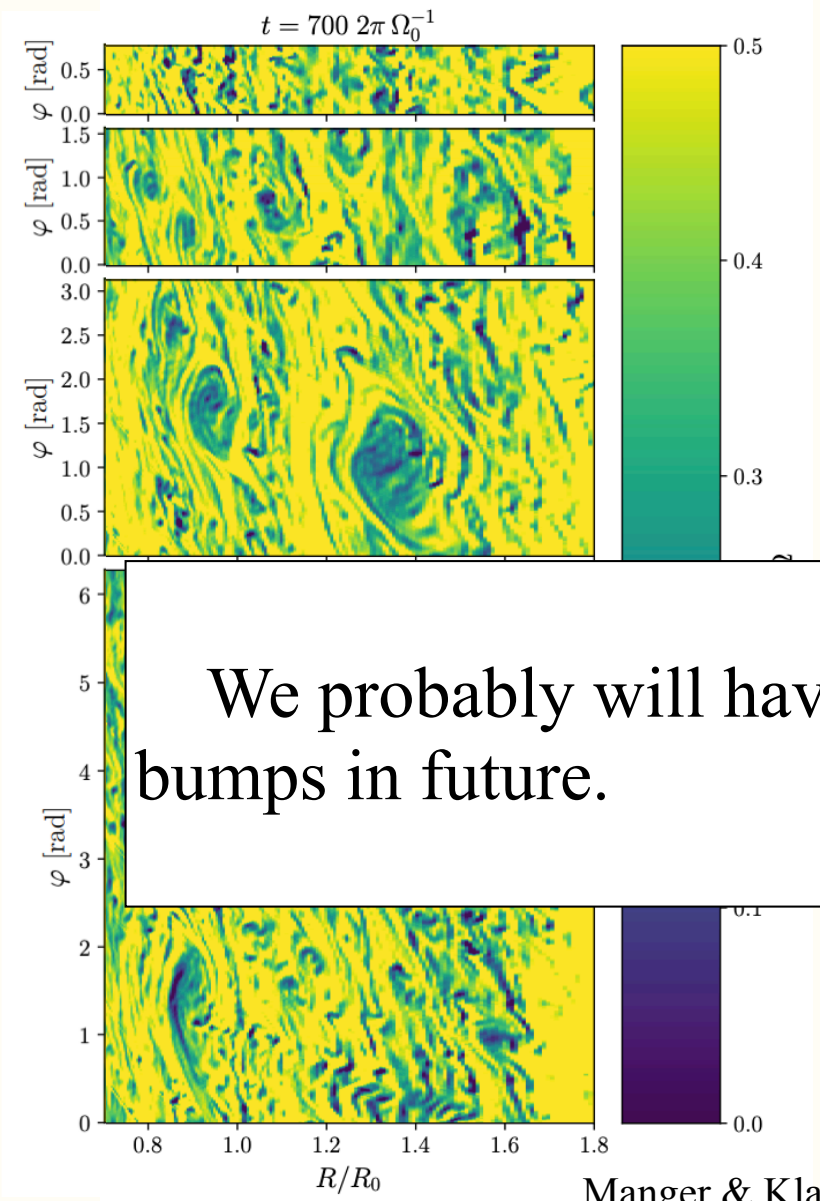
Hydrodynamic Instability

Vertical shear instability
(fast cooling)
Convective overstability
(thermal structure transition)
Zombie vortex instability
(slow cooling)

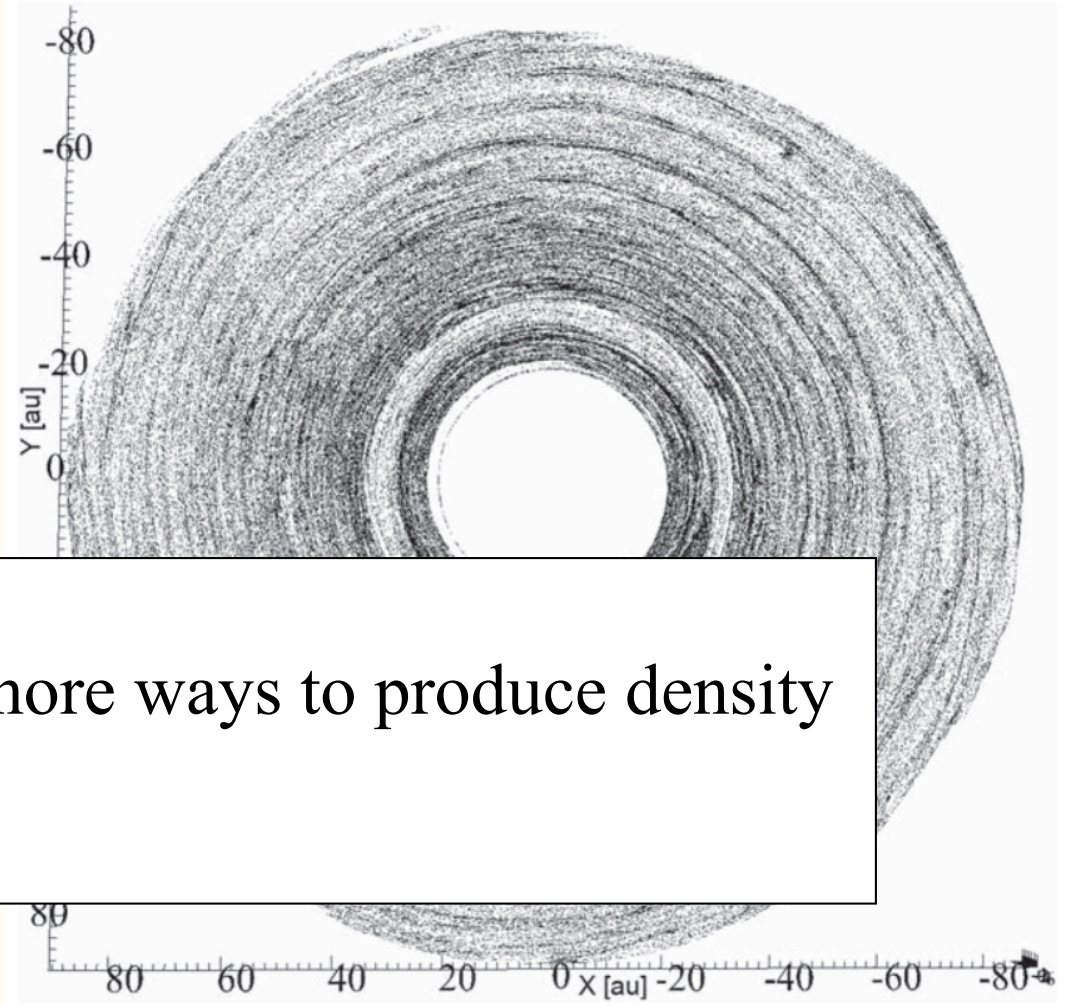


Malygin et al. 2017

Vertical Shear Instability + RWI



Manger & Klahr 2018
Manger et al. 2020



Flock et al. 2020

We probably will have more ways to produce density bumps in future.

$t_{relax} > 0.1\ \Omega^{-1}$ within 20 au

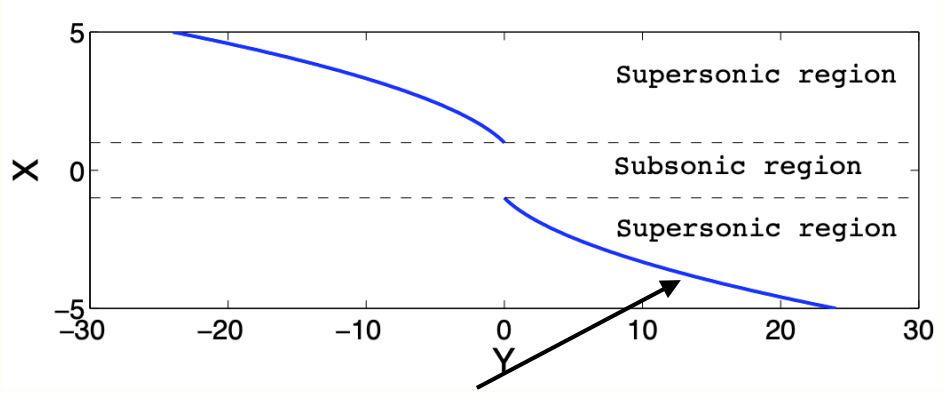
Large scale asymmetry

- Vortices
  - Basic properties of vortices

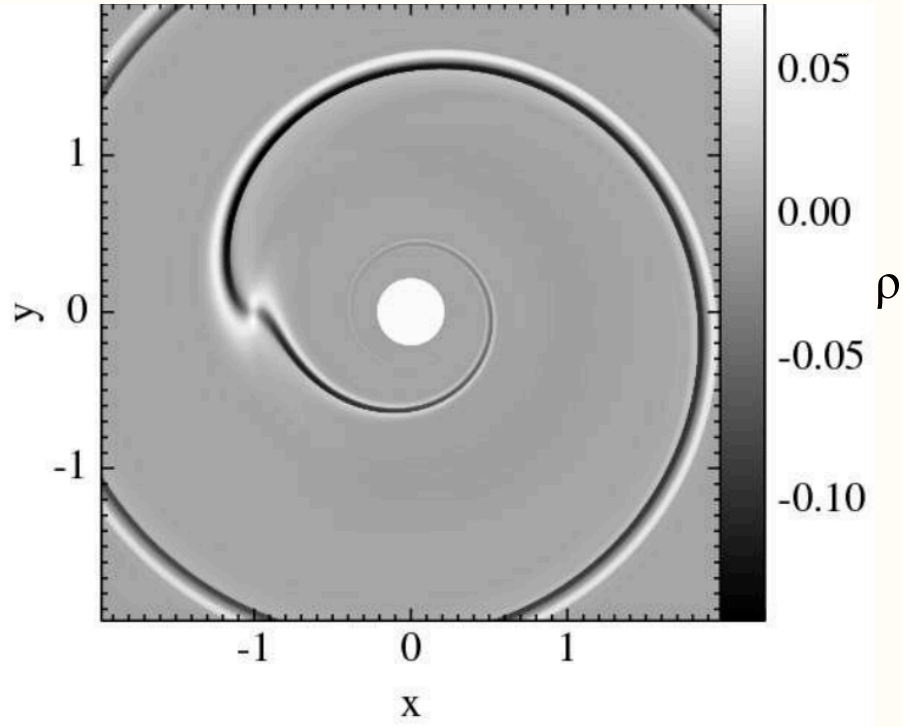
    (circulation motion, large scale~H, aspect ratio$\gtrsim$3)
  - Excitation mechanisms

    (density bumps, special location/transition)
  - Spirals, particle trapping, self-gravity of vortices, MRI turbulence
- Lumps in circumbinary disks
  - Coplanar disks
  - Polar disks
- Observations

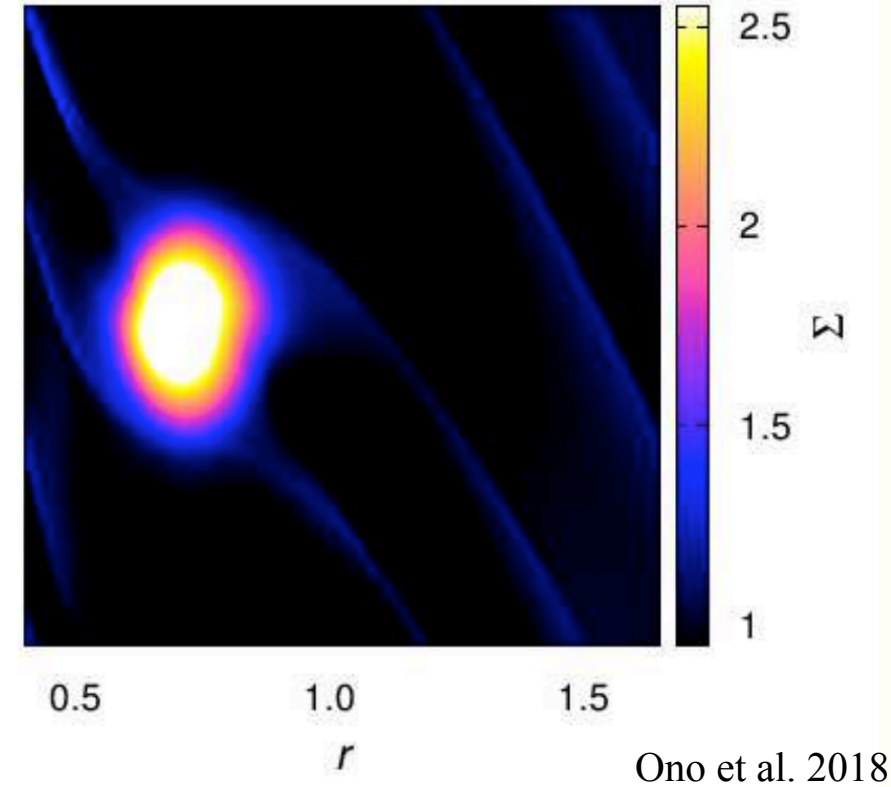
Spirals excited by Vortices



Same as planetary spirals



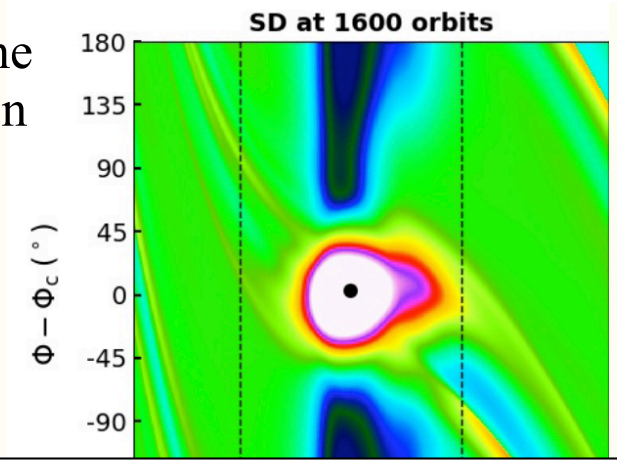
Paardekooper et al. 2010



Ono et al. 2018

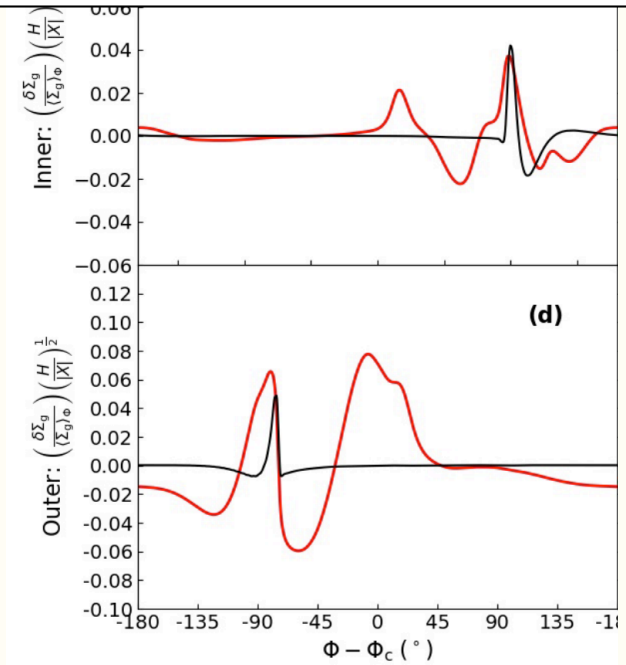
Spirals excited by Vortices

Deadzone transition

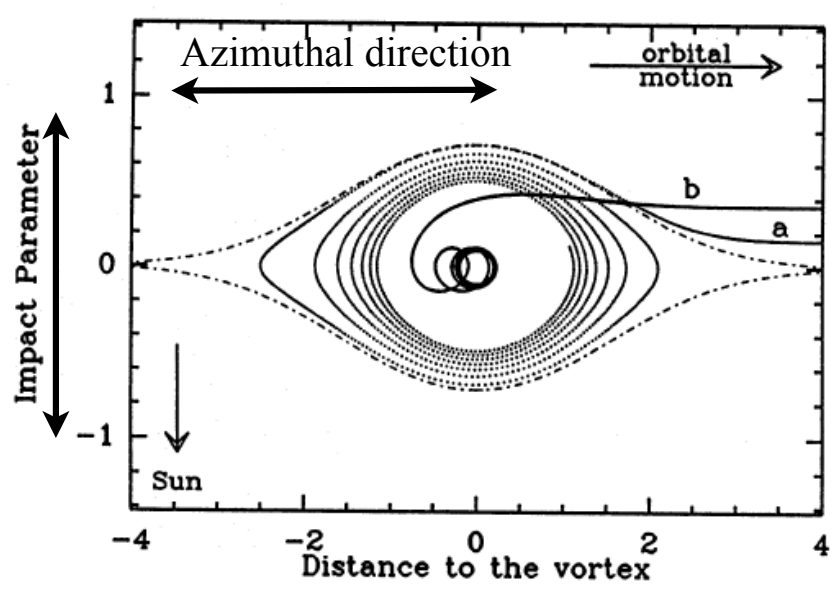


Huan

Spirals excited by vortices are too weak to be observed.

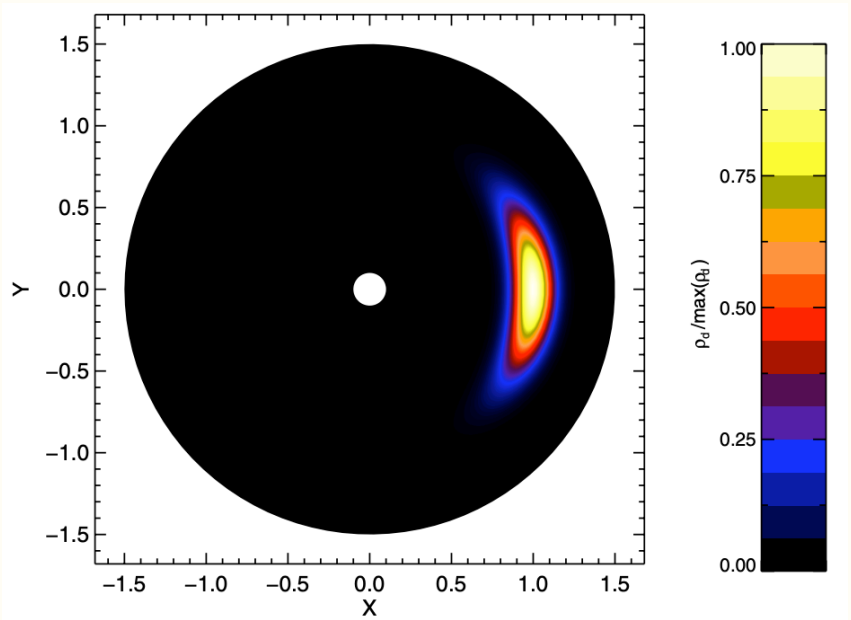


Trapping particles by vortices



Barge & Sommeria 1995

With turbulence



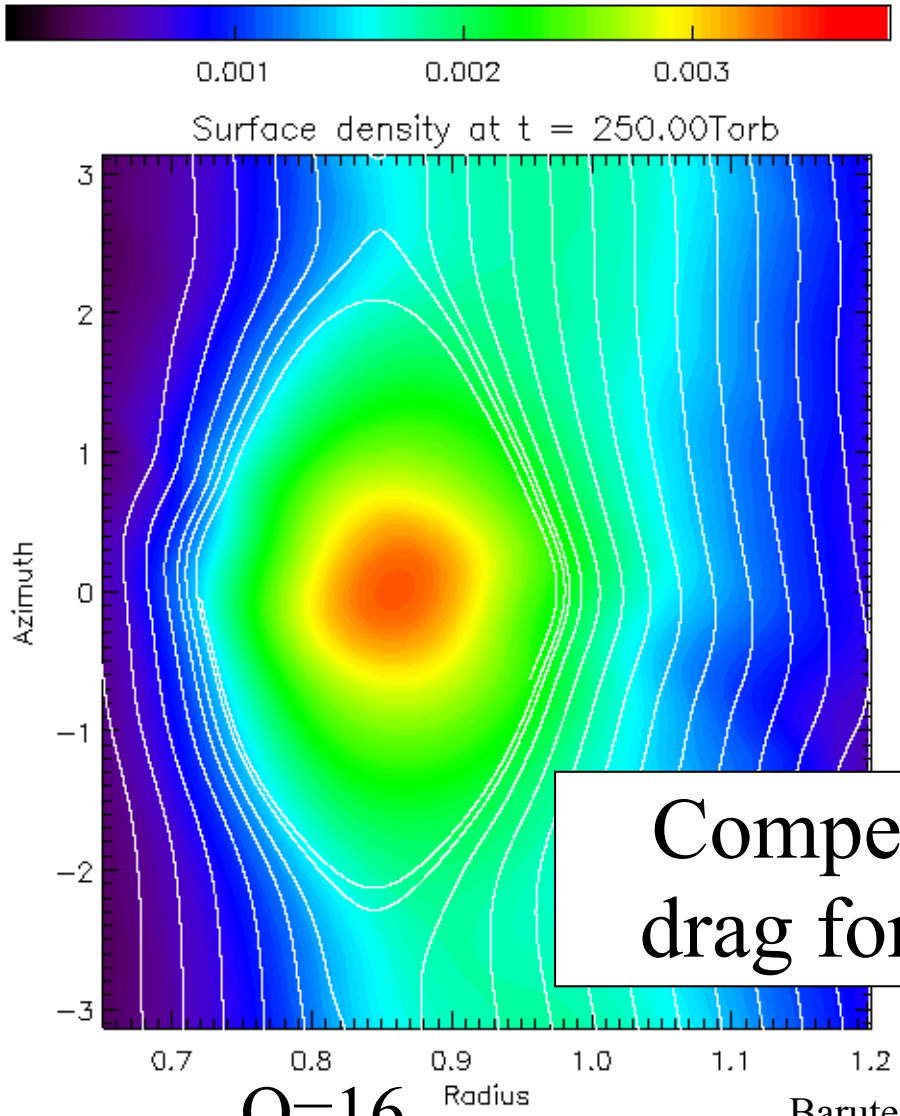
Important parameter:
St/α

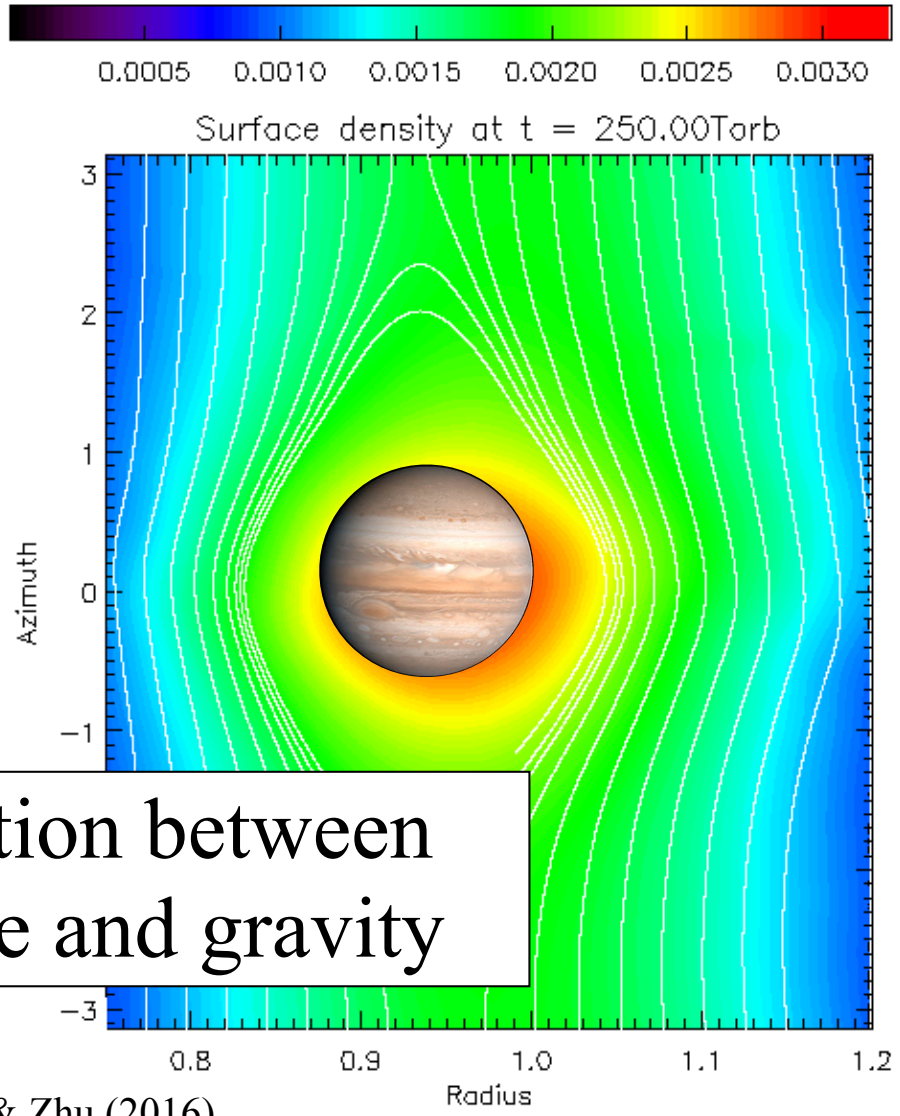
Lyra & Lin 2013, Birnstiel et al. 2013

Particles are not always at the center (gas gravity)

No gravity from gas to dust

Considering gravity from gas to dust



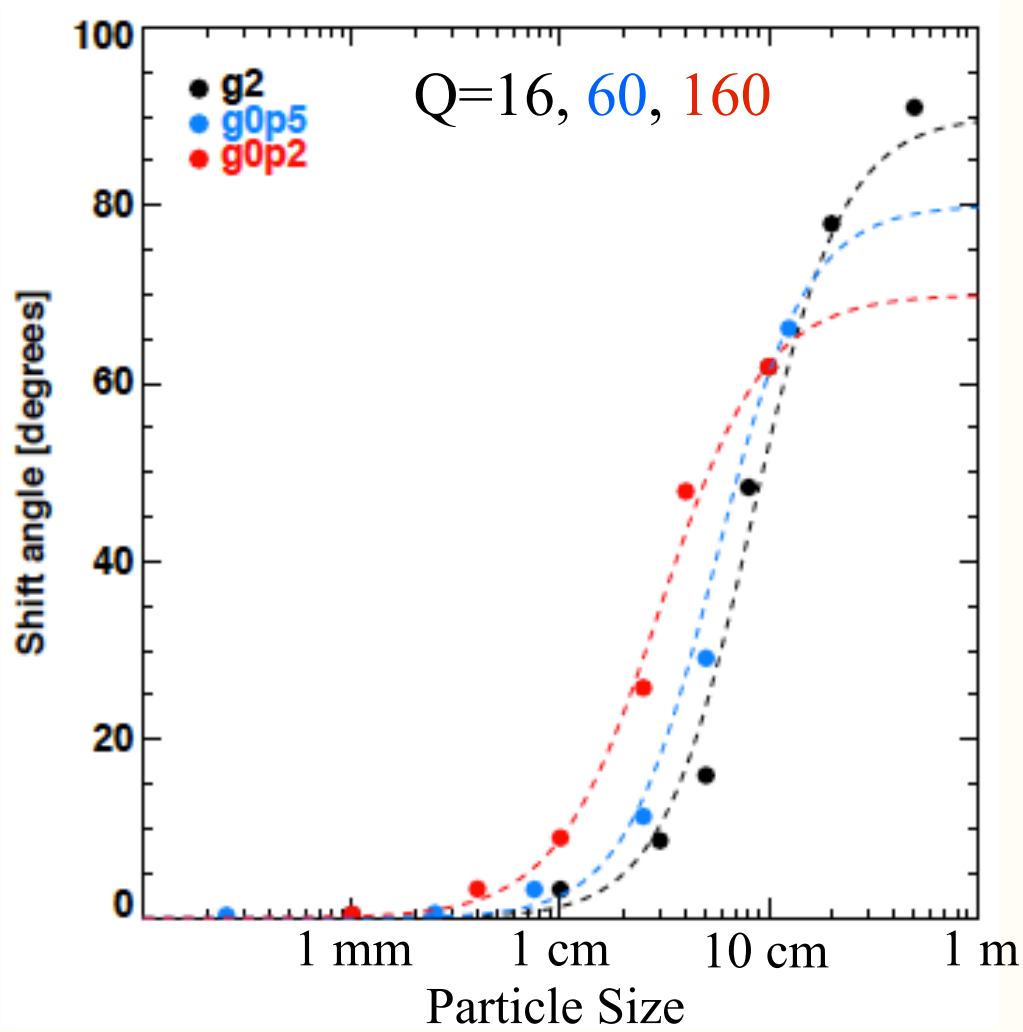


Competition between drag force and gravity

Q=16

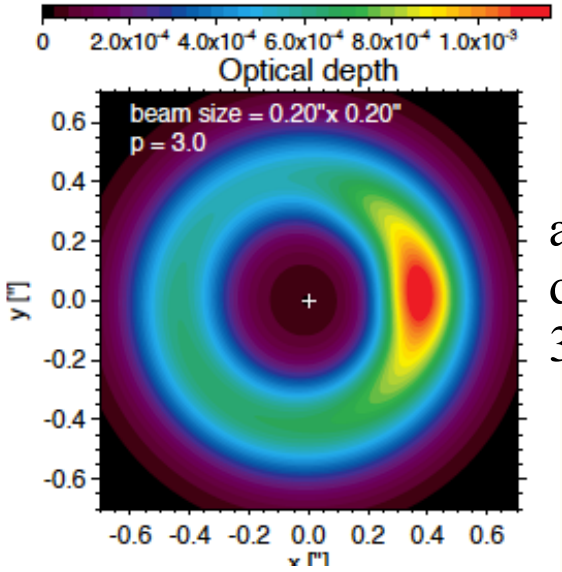
Baruteau & Zhu (2016)

Dust Peak Shift Angle



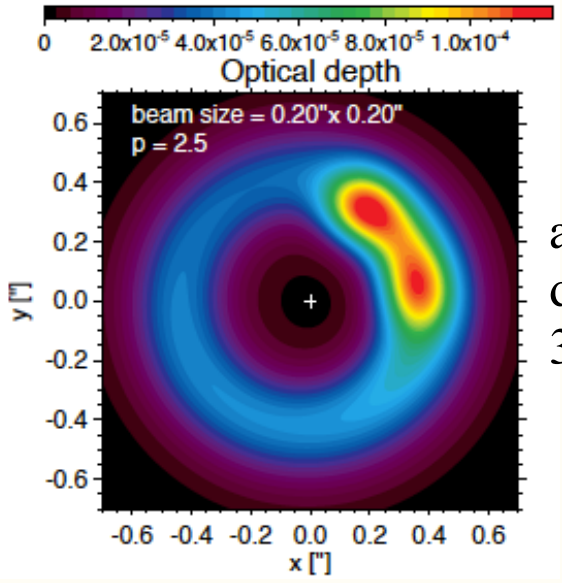
Baruteau & Zhu (2016)

Synthetic VLT Observation



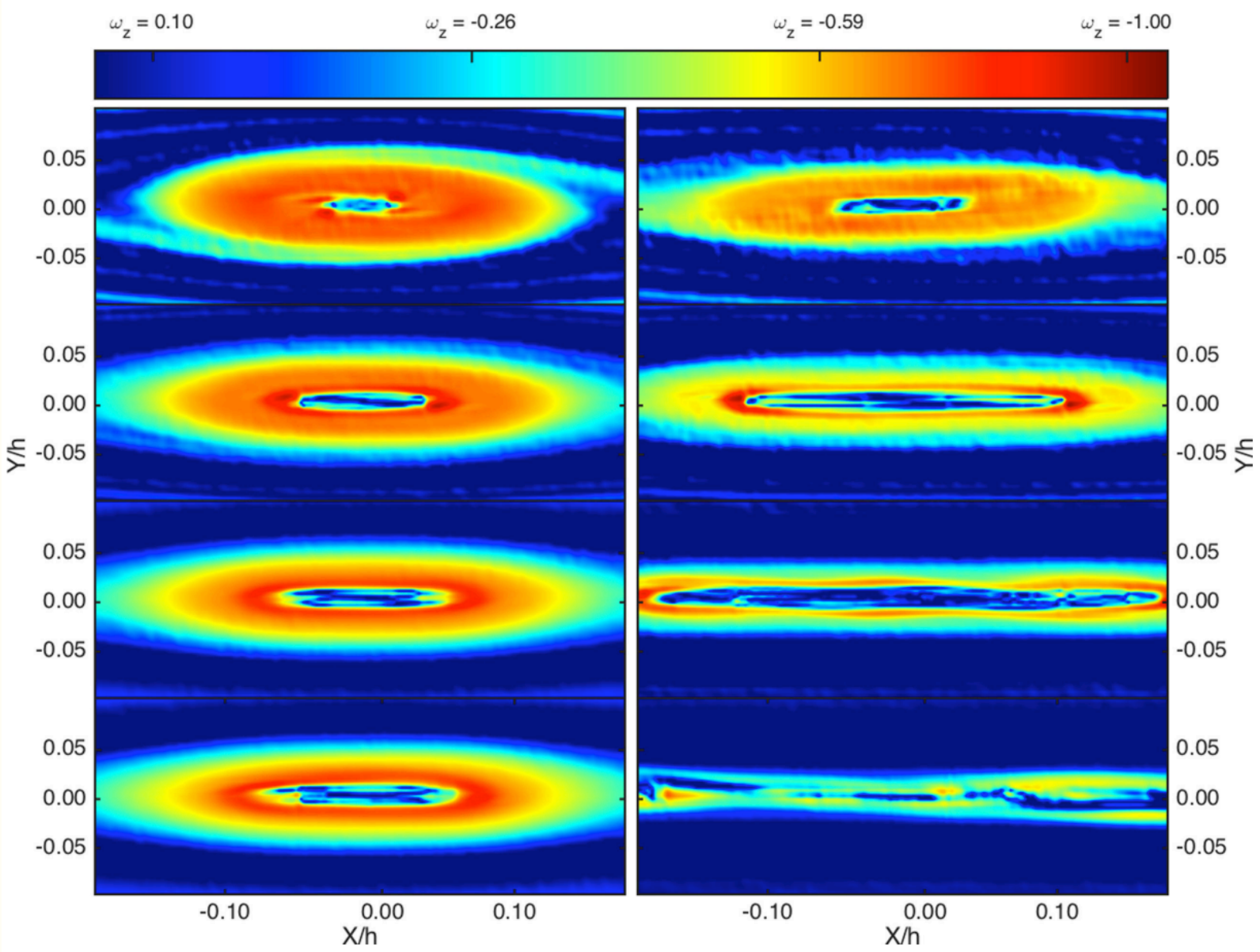
8 mm

assume
d n(s)/d s~s^{-3}
30 μm to 20 cm



assume
d n(s)/d s~$s^{-2.5}$
30 μm to 20 cm

Dust feedback weakens the vortex



The vortex is unstable when dust-to-gas mass ratio within the vortex reaches 0.3-0.5 (for t_s: 10^{-2}-10^{2})

Chang & Oishi 2010
Fu et al. 2014
Railton & Papaloizou 2014

Stable vortex

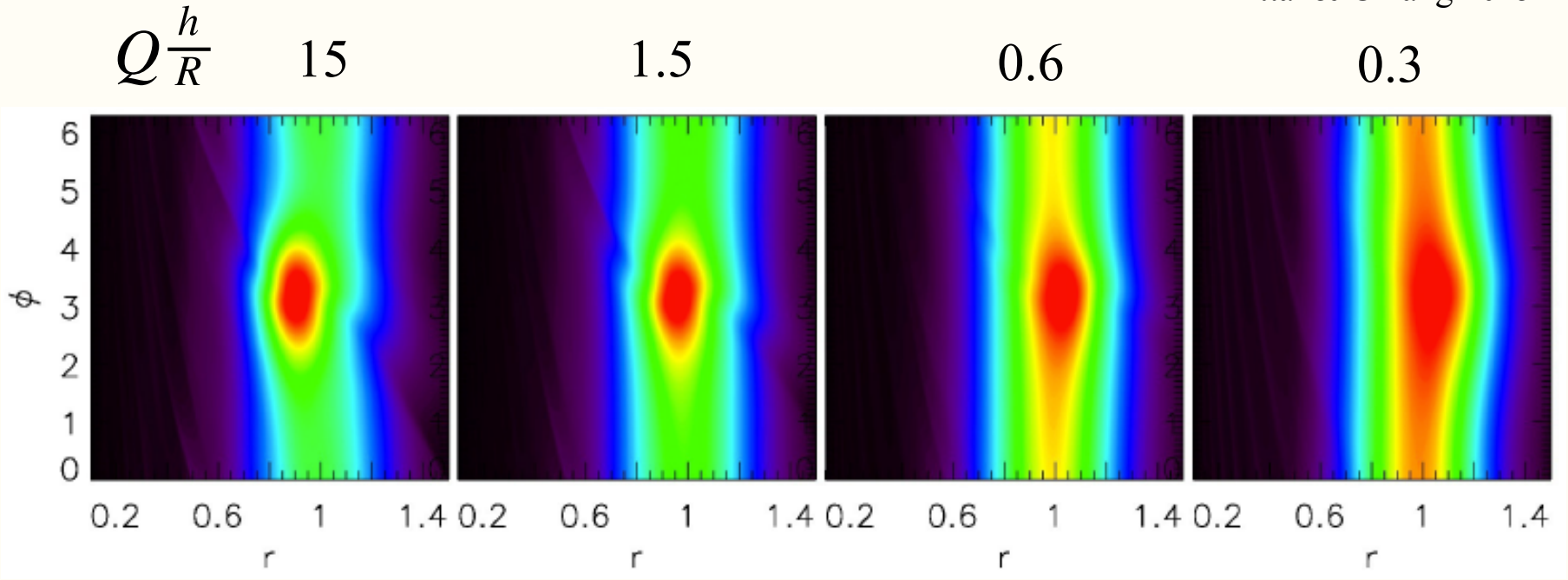
unstable vortex

Crnkovic-Rubsamen et al. 2015

Self-gravity weakens the vortex

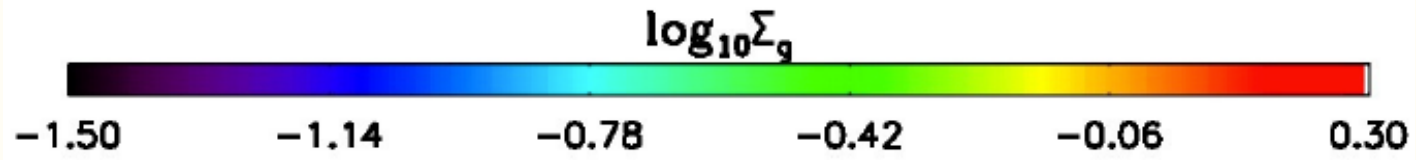
Disk self-gravity can suppress RWI when $Q\frac{h}{R}<1$

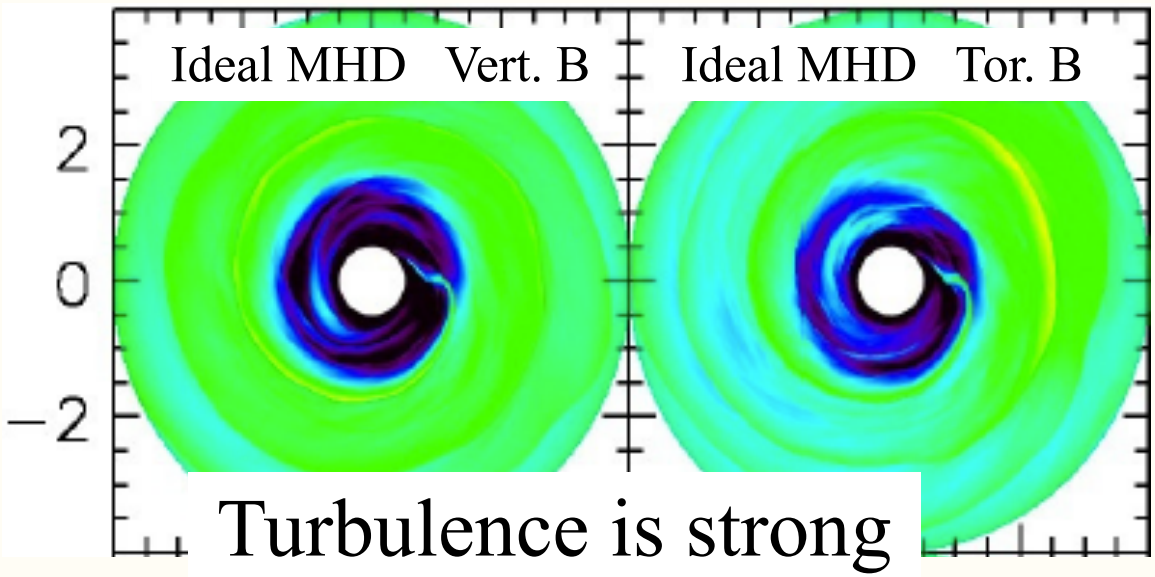
Lovelace & Hohfeld 2013
Lin & Papaloizou 2011
Mittal & Chiang 2015



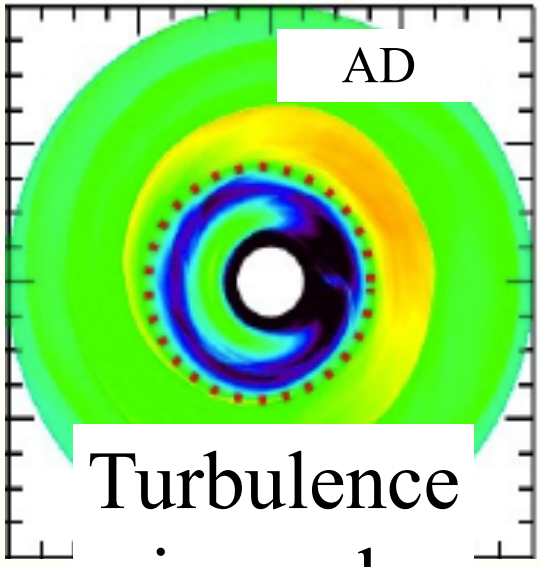
Zhu & Baruteau (2016)

MHD turbulence weakens the vortex



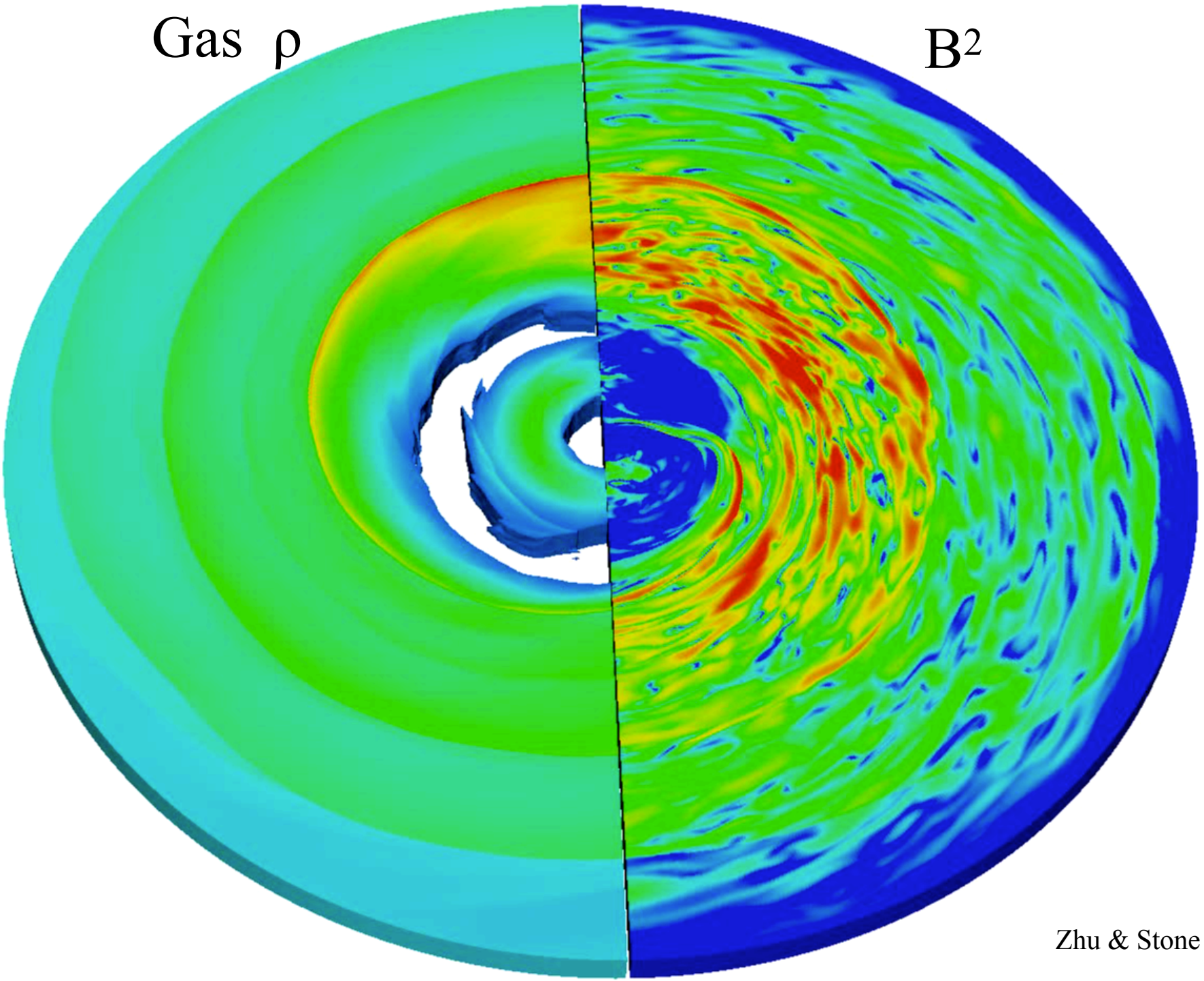


Turbulence is strong
α~0.01



Turbulence is weak
α~0.001

Zhu & Stone 2014



Zhu & Stone 2014

Large scale asymmetry

- Vortices
  - Basic properties of vortices

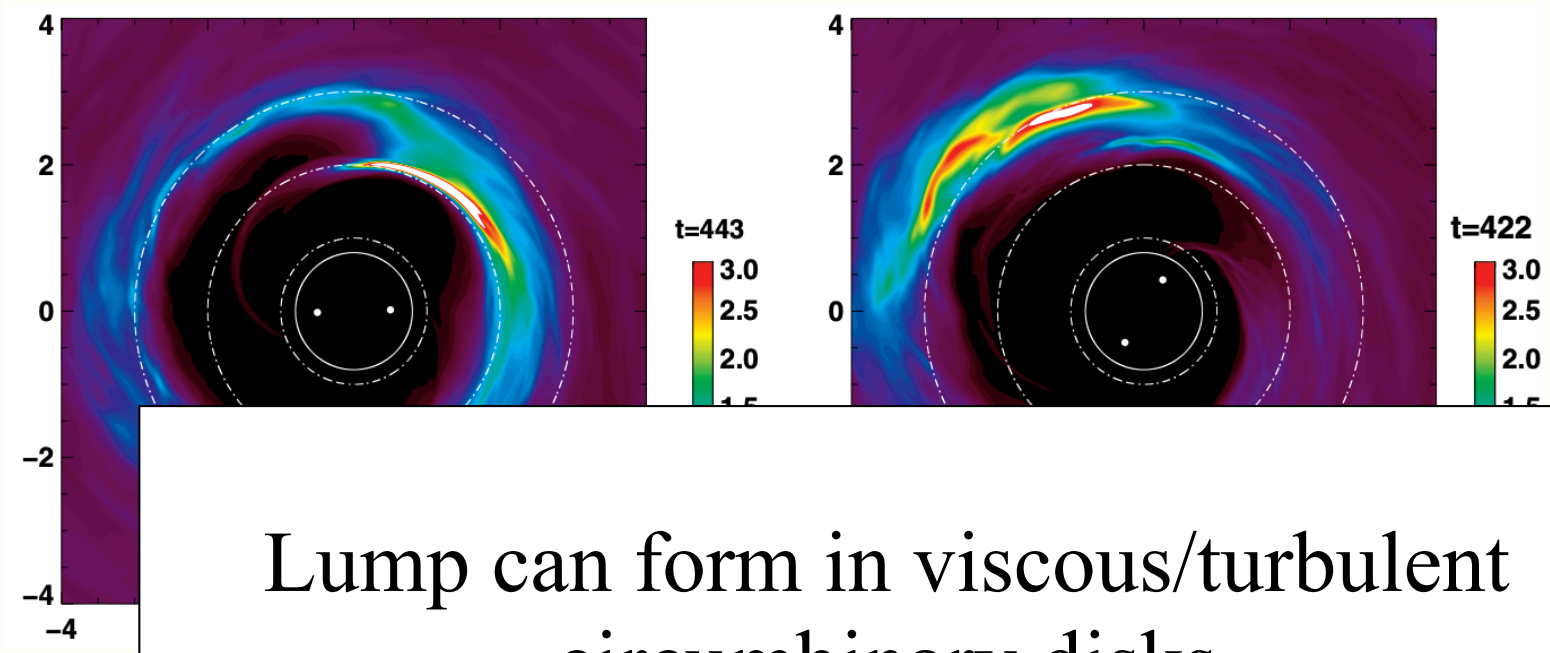
    (circulation motion, large scale~H, aspect ratio$\gtrsim$3)
  - Excitation mechanisms

    (density bumps, special location/transition)
  - Spirals, particle trapping, self-gravity of vortices, MRI turbulence

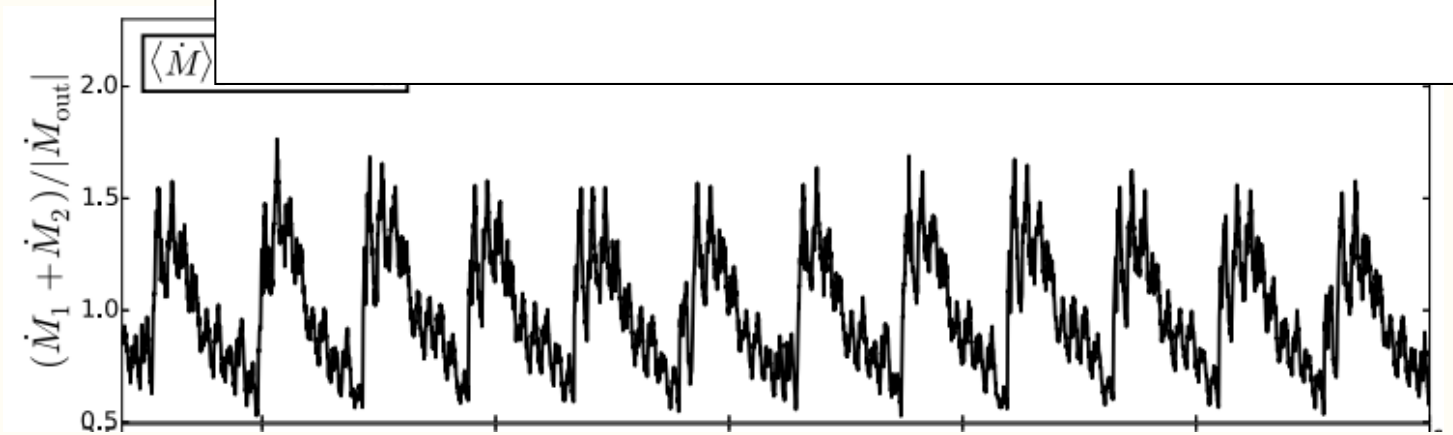
    (Weak spirals, St/α, peak shift, dust-to-gas ratio/massive disks/ turbulence weaken the vortex)
- Lumps in circumbinary disks
  - Coplanar disks
  - Polar disks
- Observations

Lump formation

MRI simulation for the equal mass binary, α~0.1

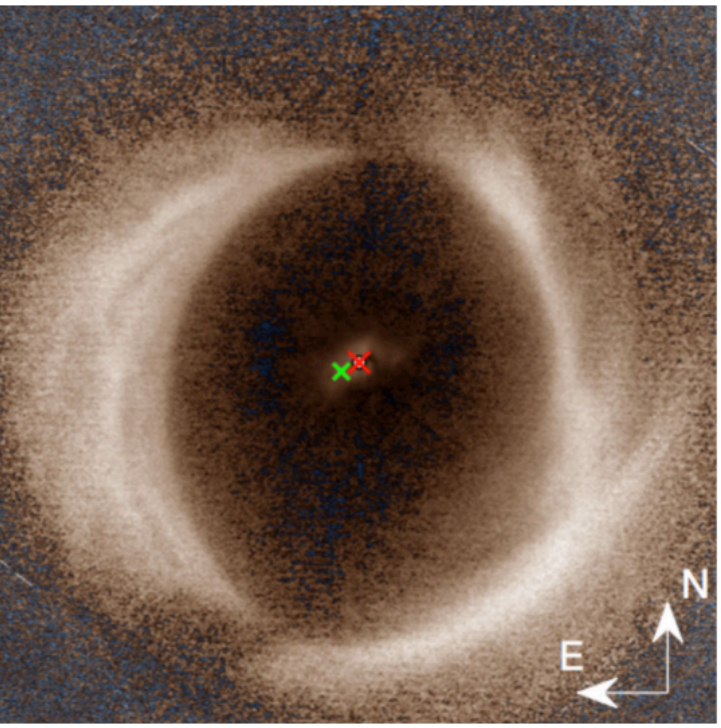


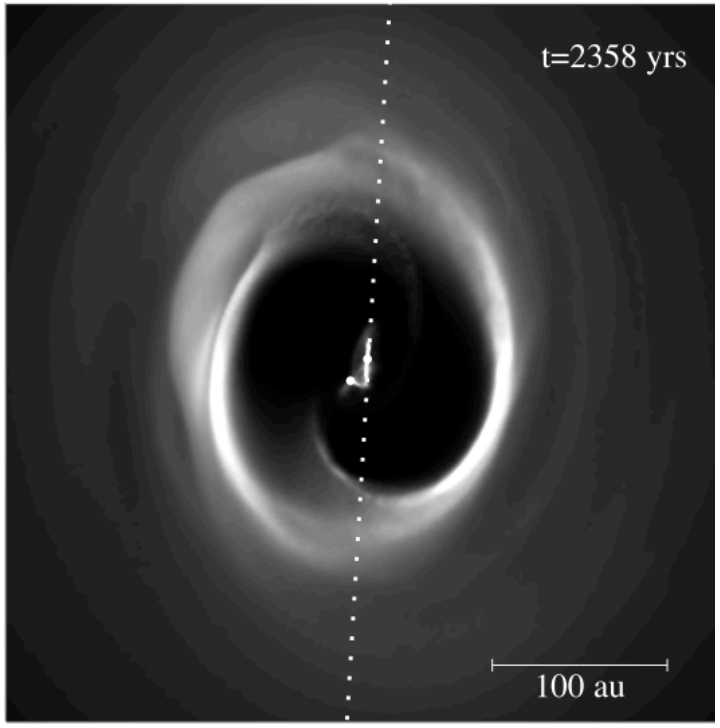
Lump can form in viscous/turbulent circumbinary disks

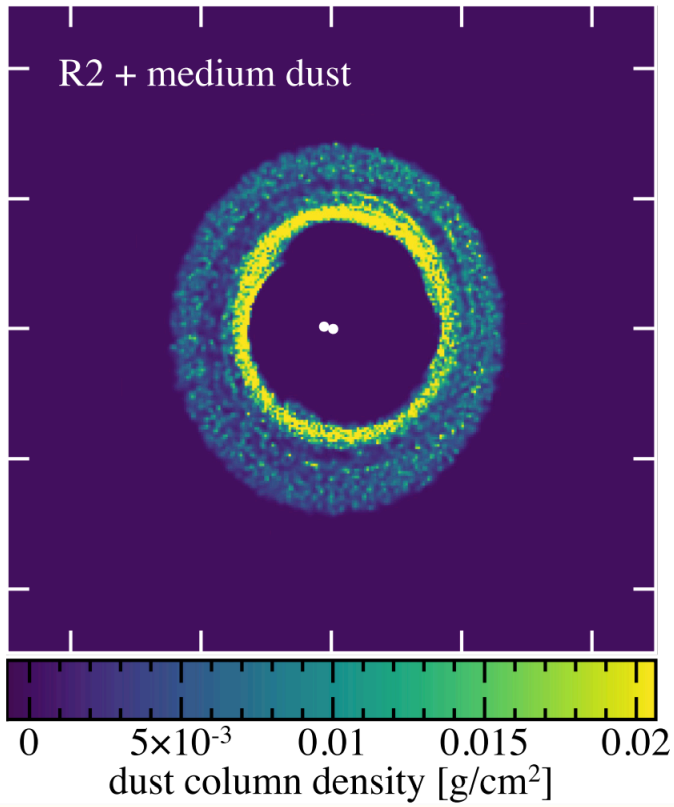


Munoz & Lai 2016

Lump around young binaries







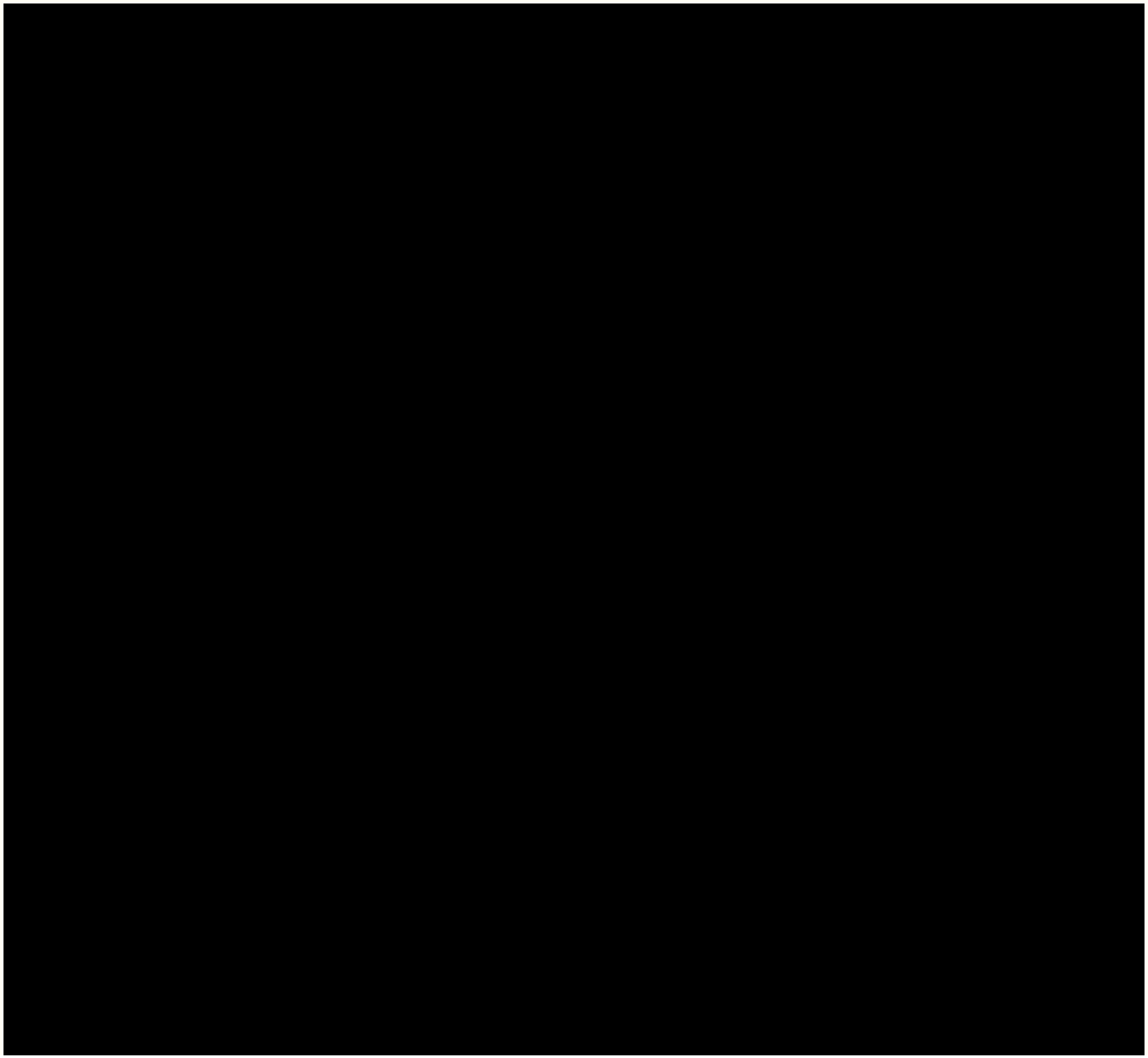
Ragusa et al. 2017, Price et al. 2018

Vortex in polar circumbinary disks

Another disk configuration around eccentric binaries:

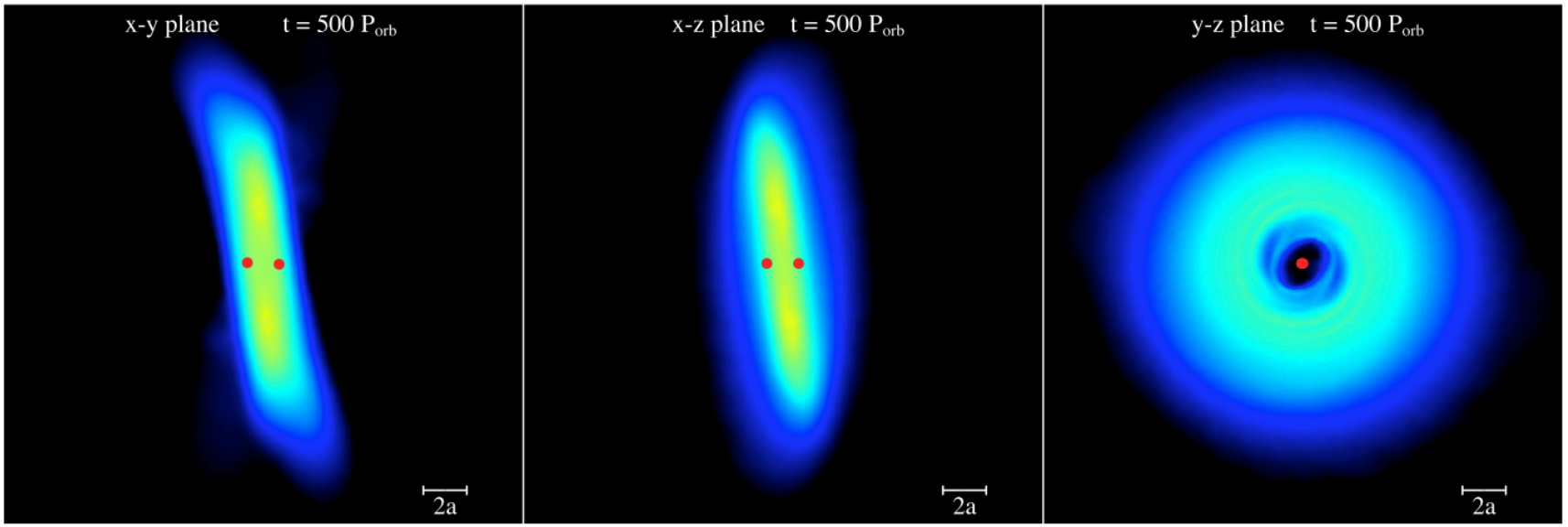
polar disk

A single particle's orbit

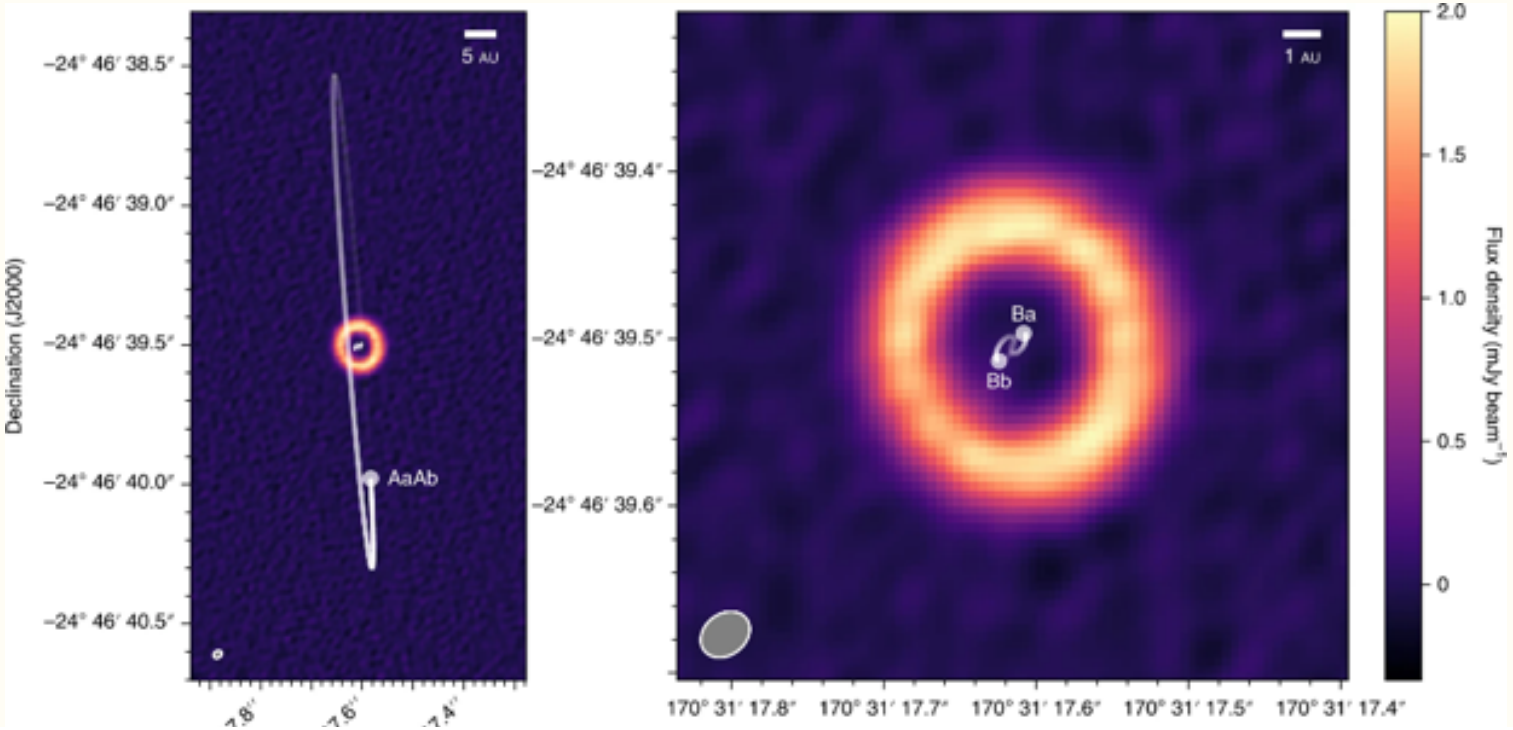


Credit: Ian Rabago

Vortex in polar circumbinary disks

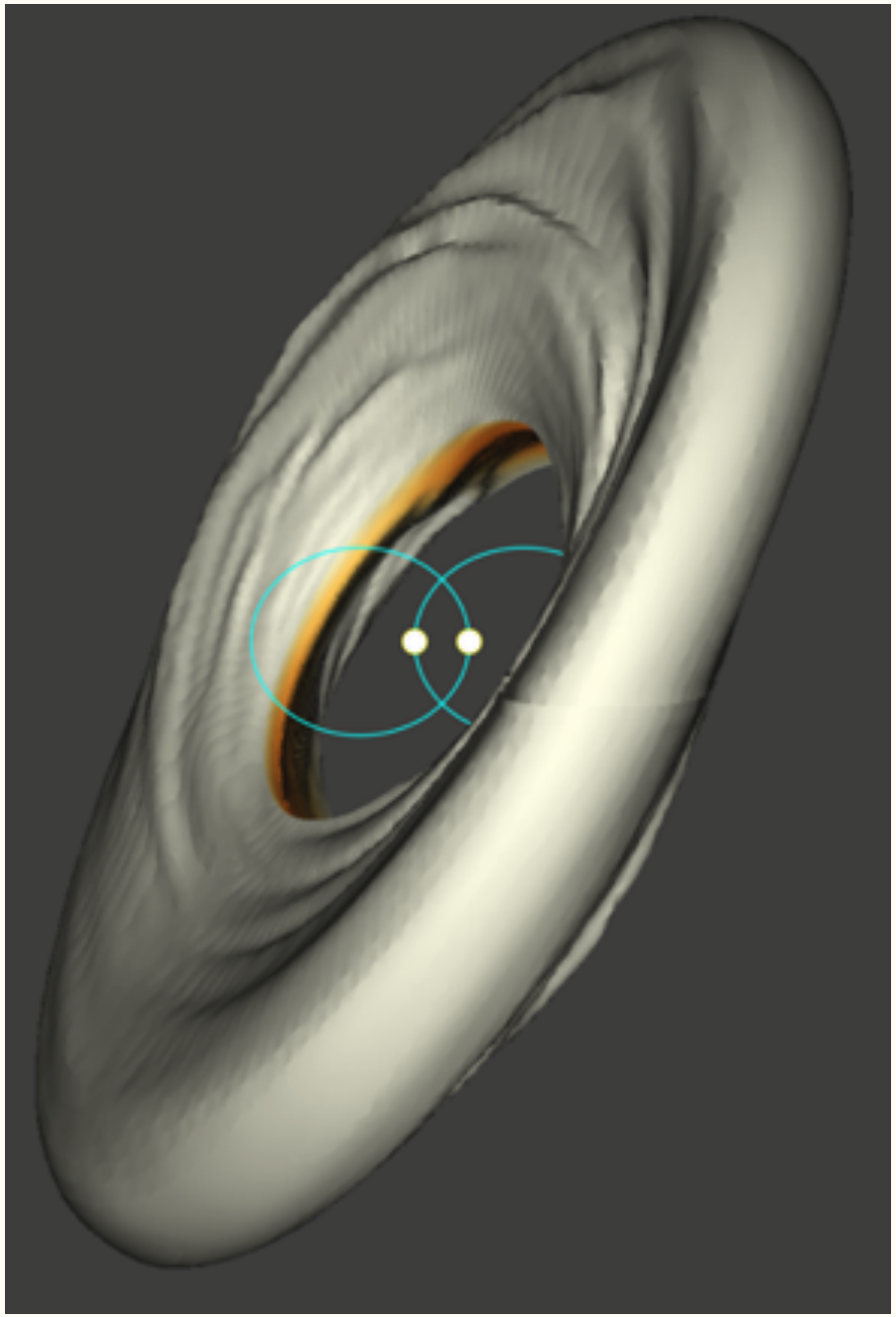


Martin & Lubow 2017



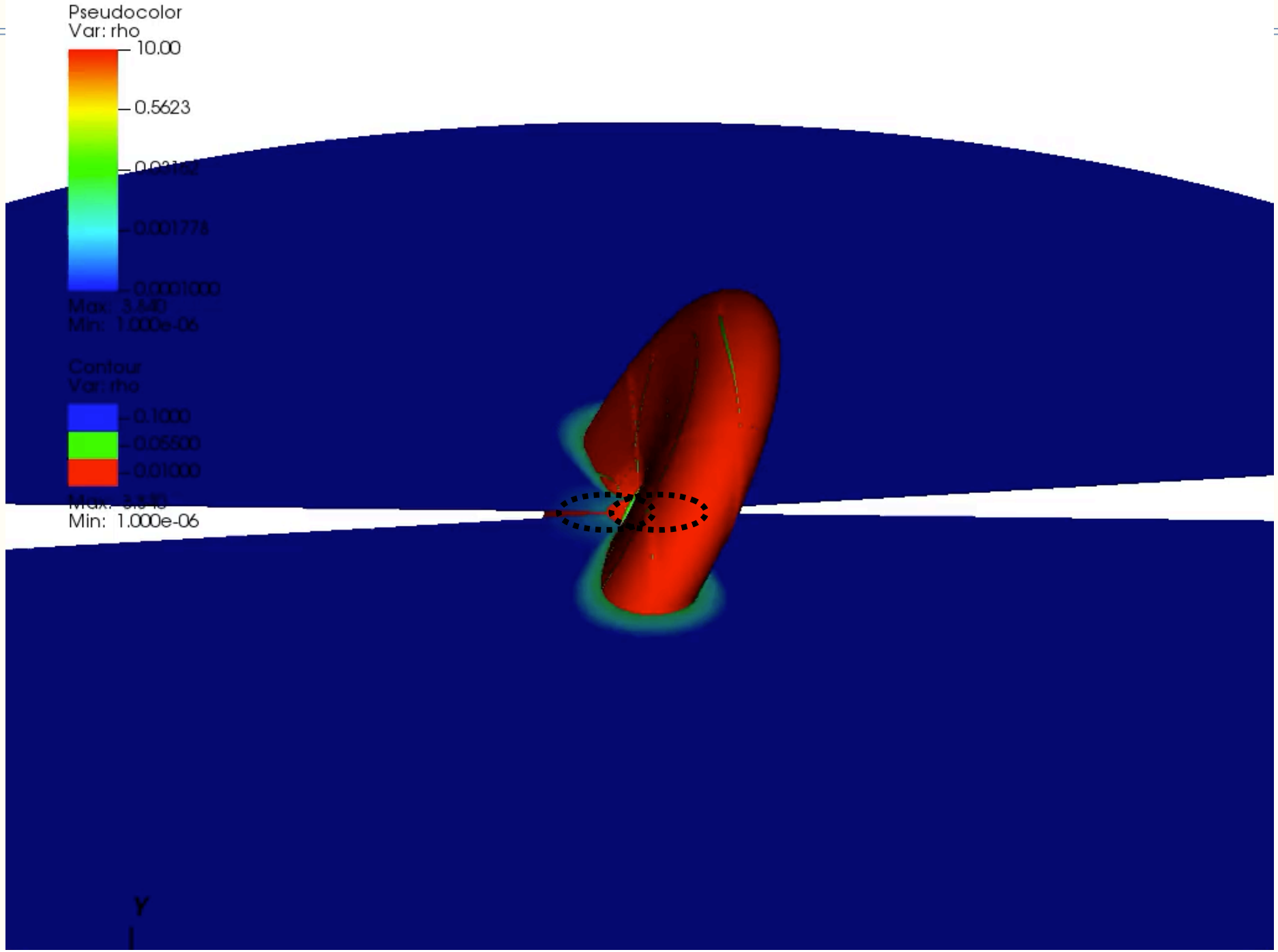
HD 98800
Kennedy et al. 2019

Athena++ simulation

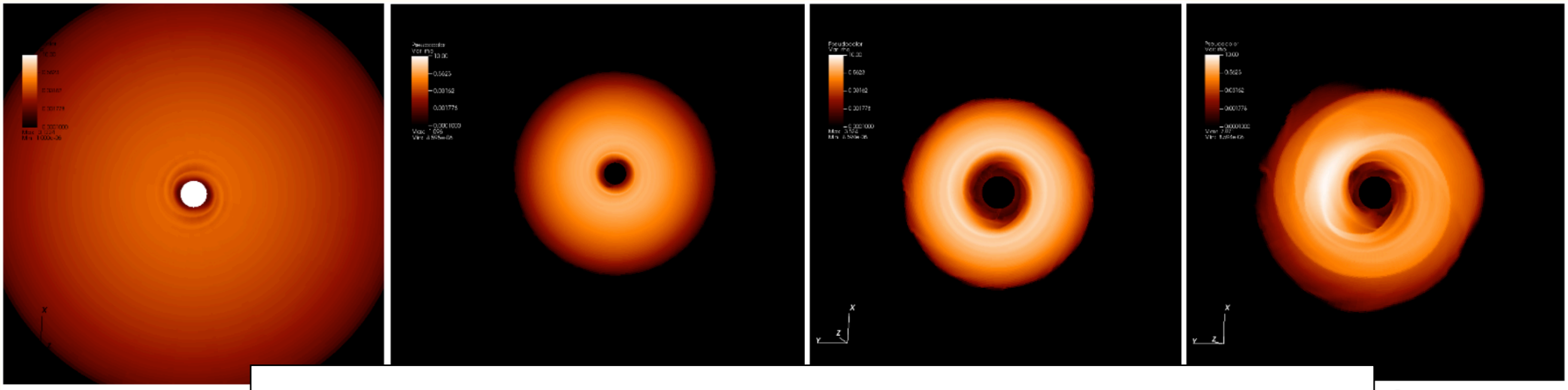


Rabago et al., in preparation

Athena++ simulation

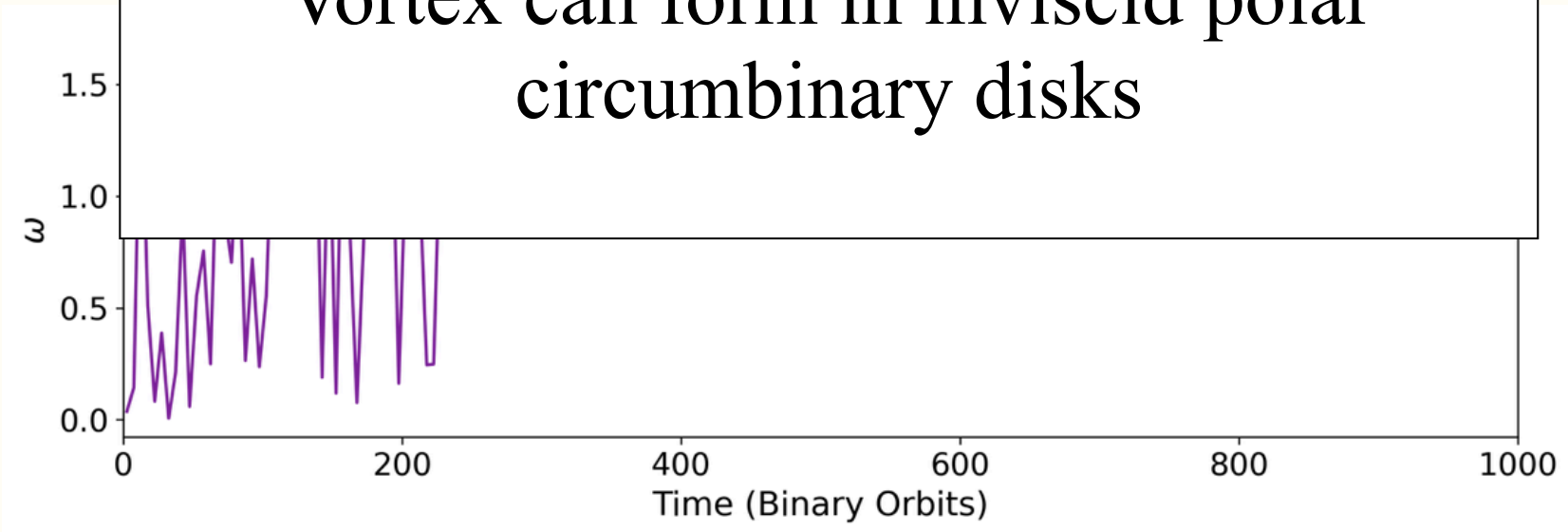


Vortex in polar circumbinary disks



$\alpha = 0.1$ 10^{-5}

Vortex can form in inviscid polar circumbinary disks



Large scale asymmetry

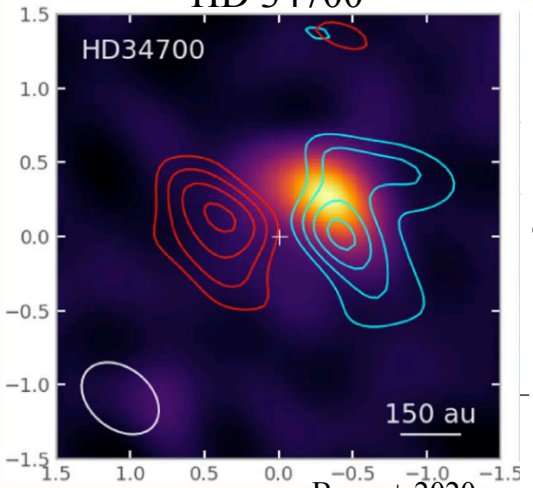
- Vortices
  - Basic properties of vortices

    (circulation motion, large scale~H, aspect ratio$\gtrsim$3)
  - Excitation mechanisms

    (density bumps, special location/transition)
  - Spirals, particle trapping, self-gravity of vortices, MRI turbulence

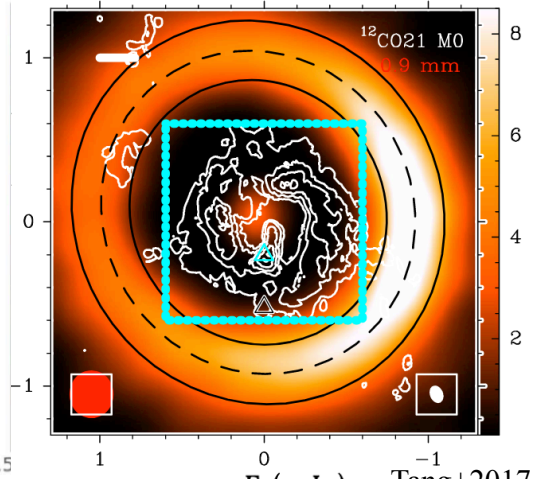
    (Weak spirals, St/α, peak shift, dust-to-gas ratio/massive disks/ turbulence weaken the vortex)
- Lumps in circumbinary disks
  - Lumps even in highly turbulent disks
  - For polar circumbinary disks, only forms in low viscous disks
- Observations

HD 34700



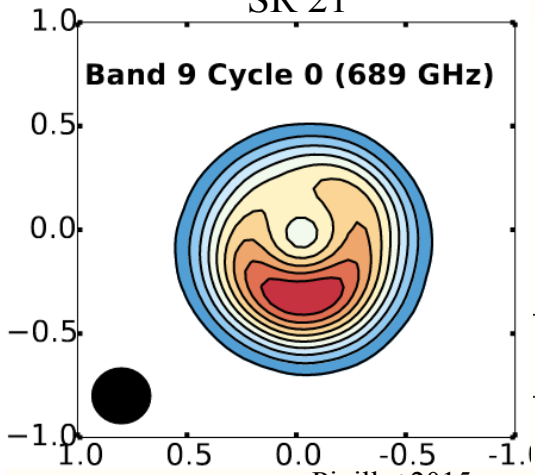
Benac+ 2020

AB Aur



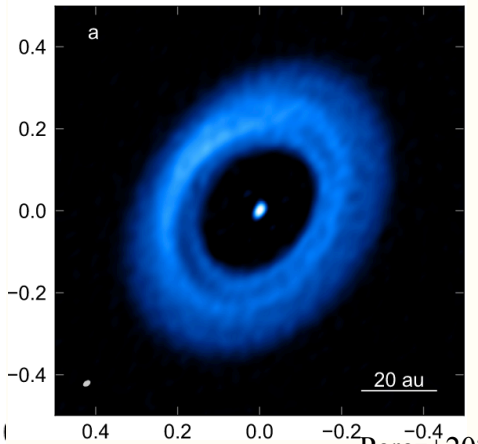
Tang+2017

SR 21



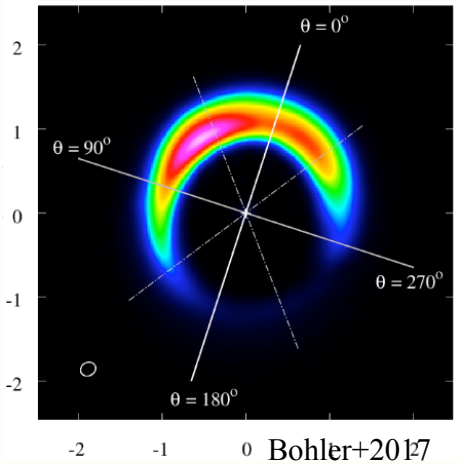
Pinilla+2015

HD 100546



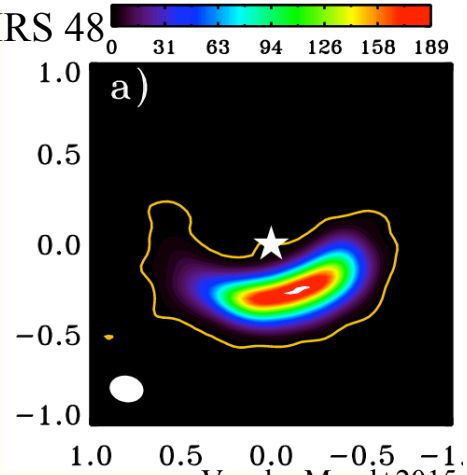
Perez+2020

HD 142527



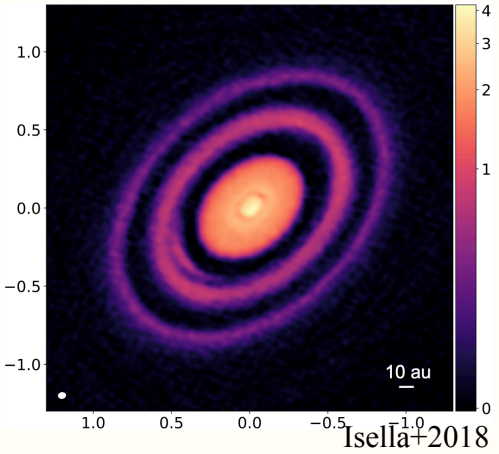
Bohler+2017

IRS 48



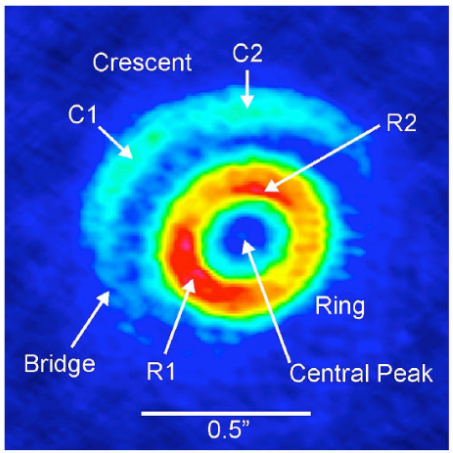
Van der Marel+2015

HD 163296



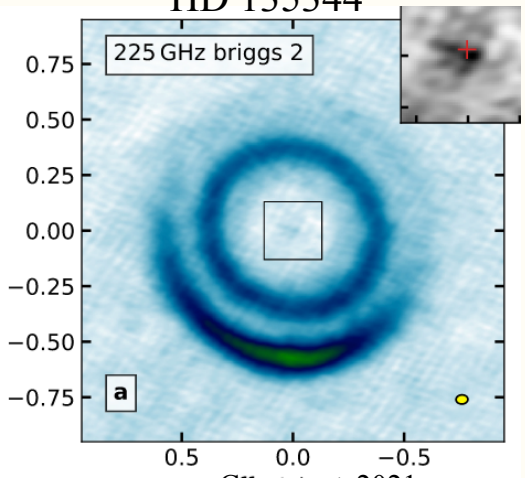
Isella+2018

V1247 Ori



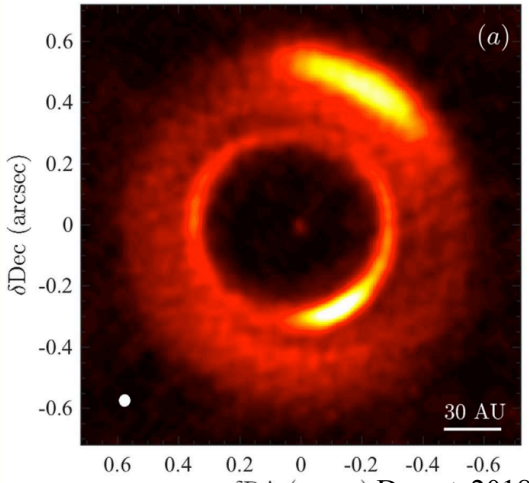
Kraus+ 2017

HD 135344



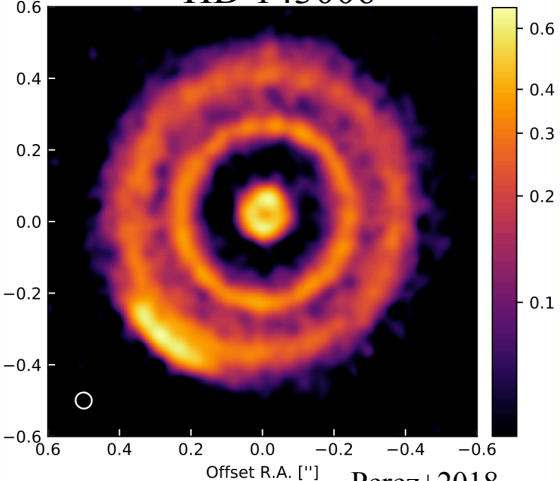
Cãsassus+ 2021

MWC 758



Dong+ 2018

HD 143006



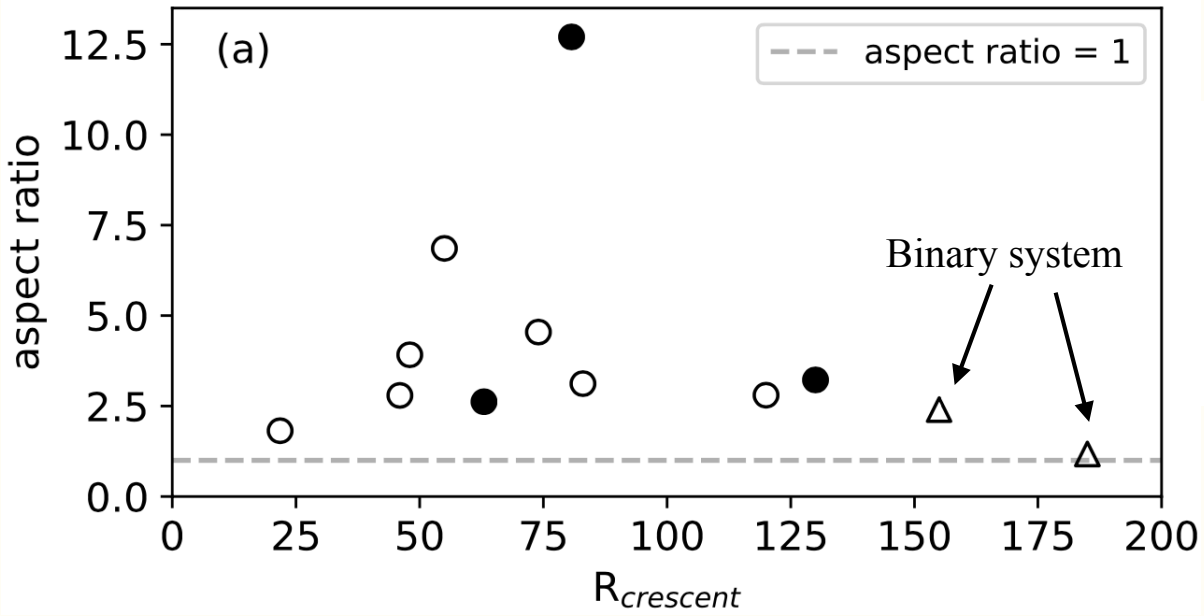
Perez+2018

Vortex observations

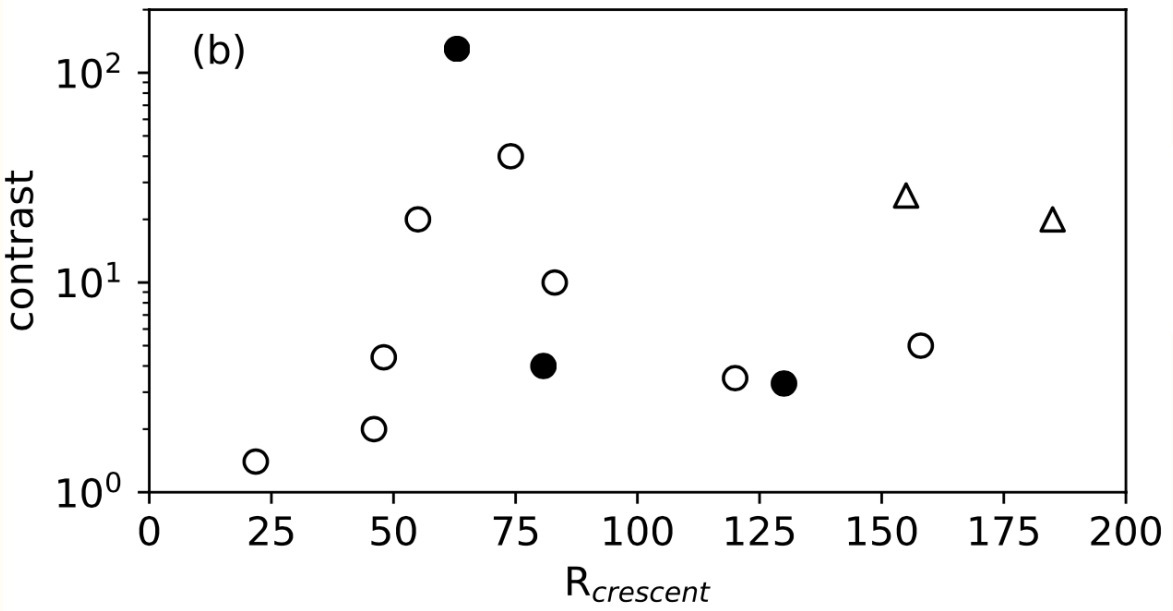
Alt. Name	d (pc)	$M_\star$ ($M_\odot$)	$L_\star$ ($L_\odot$)	Class	M_d ($0.01 M_\odot$)	λ	n	rad (au)	FWHM$_r$ (au)	FWHM$_\theta$ (au)	Δ	FWHM (au)
LkHa330	309	2.95	22.91	II	16.97	mm	1	130	< 36	116	3.3	93
ABAur	163	3.17	123.03	II	2.12	mm	1	120	< 50	140	3-4	23
MWC758/HD36112	156	1.5	10.96	II	1.16	mm	2	48,83	12,25	47,78	4.4,10	6
V1247Ori	398	1.9	15.81	PTD	7.72	mm	1	158	20	-	5	16
HD34700A	356	4.0[a]	25.12	II	0.8	mm	1	155	72	173	>26	18
IRS48/WLY2-48	121	2	14.29	TD	0.65	mm	1	63	42	110	>130	60
SR21	138	2.5	12.59	II	2.93	mm	1	46	34	95	~ 2	14
HD163296	101	2	16.98	II	6.23	mm	1	55	~ 7	~ 48	>20	4
HD100546	110	2.2	25.12	TD	4.34	mm	1	21.8	22	40	1.4	6
HD142527	157	2.1	16.22	II/TD	24.85	mm	1	185	80	94	20-40	31
HD139614	135	1.6	9.23	-	3.02	ir	4	-	-	-	-	68
SAO206462/HD135344B	135	1.6	9.77	TD	10.79	mm	1	80.7	14.8	188	>4	24
HD143006	166	1.4	3.89	II	4.12	mm	1	74	11	50	>40	7
HD143006	166	1.4	3.89	II	4.12	ir	2	40,74	-,-	-,-	-,-	6

Bea, Isella, Martin, Okuzumi, Suriano, Zhu
PPVII chapter

Vortex statistics



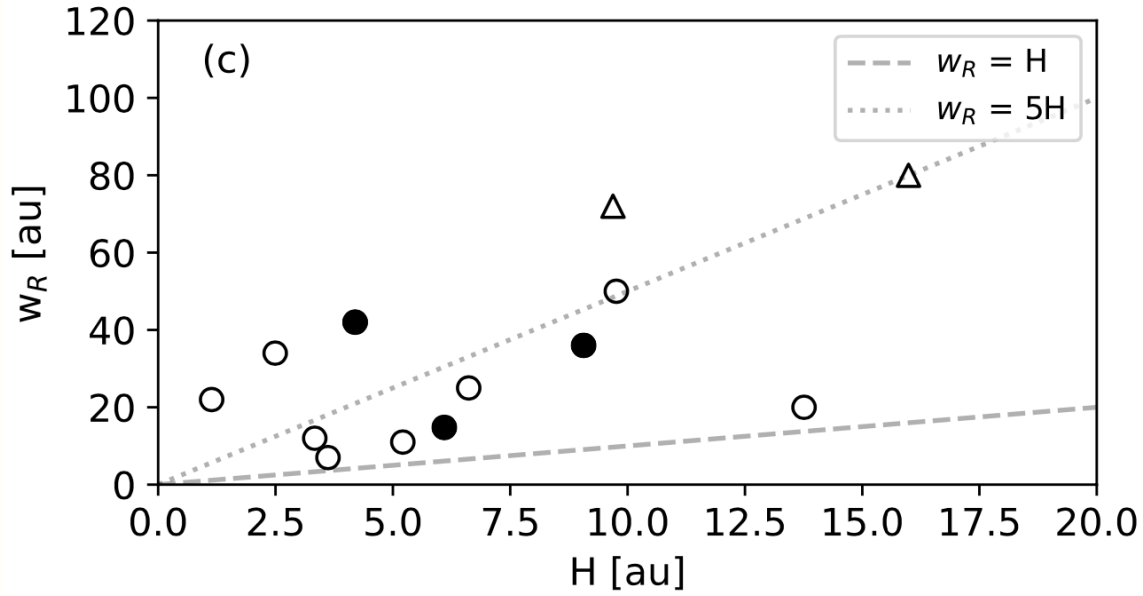
- Asymmetry can occur everywhere (low number statistics)
- Asymmetry is at the largest distance in circumbinary disks
- Aspect ratio ≳ 3



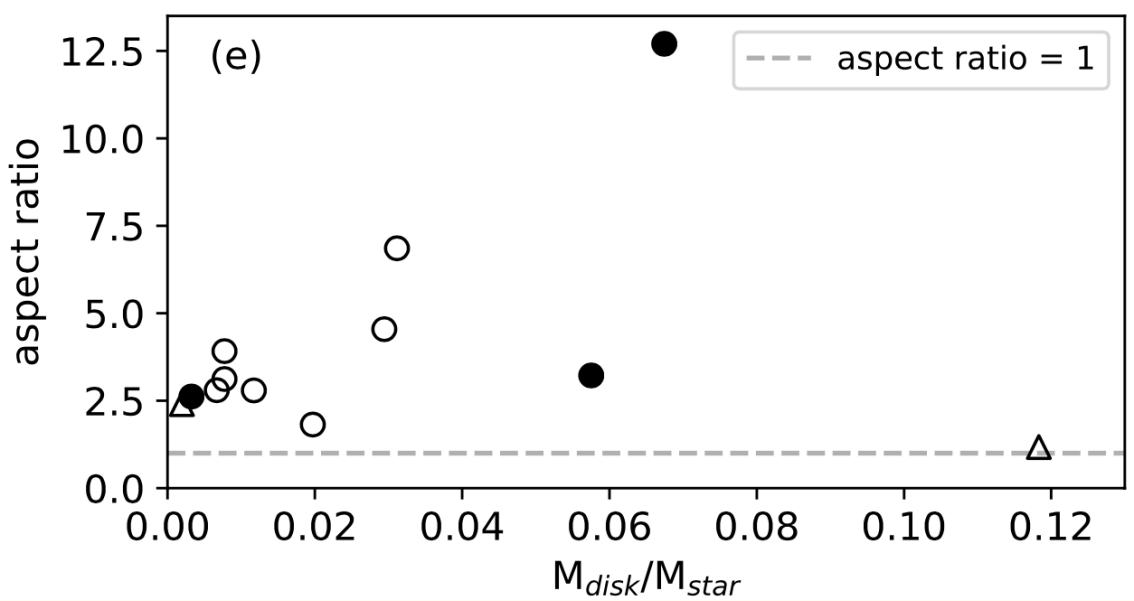
- Contrast can be larger than 10, particle trapping probably is happening

Bea+, PPVII chapter

Vortex statistics



- Quite wide, wider than H. Maybe too wide?
- Lumps seem to be the widest

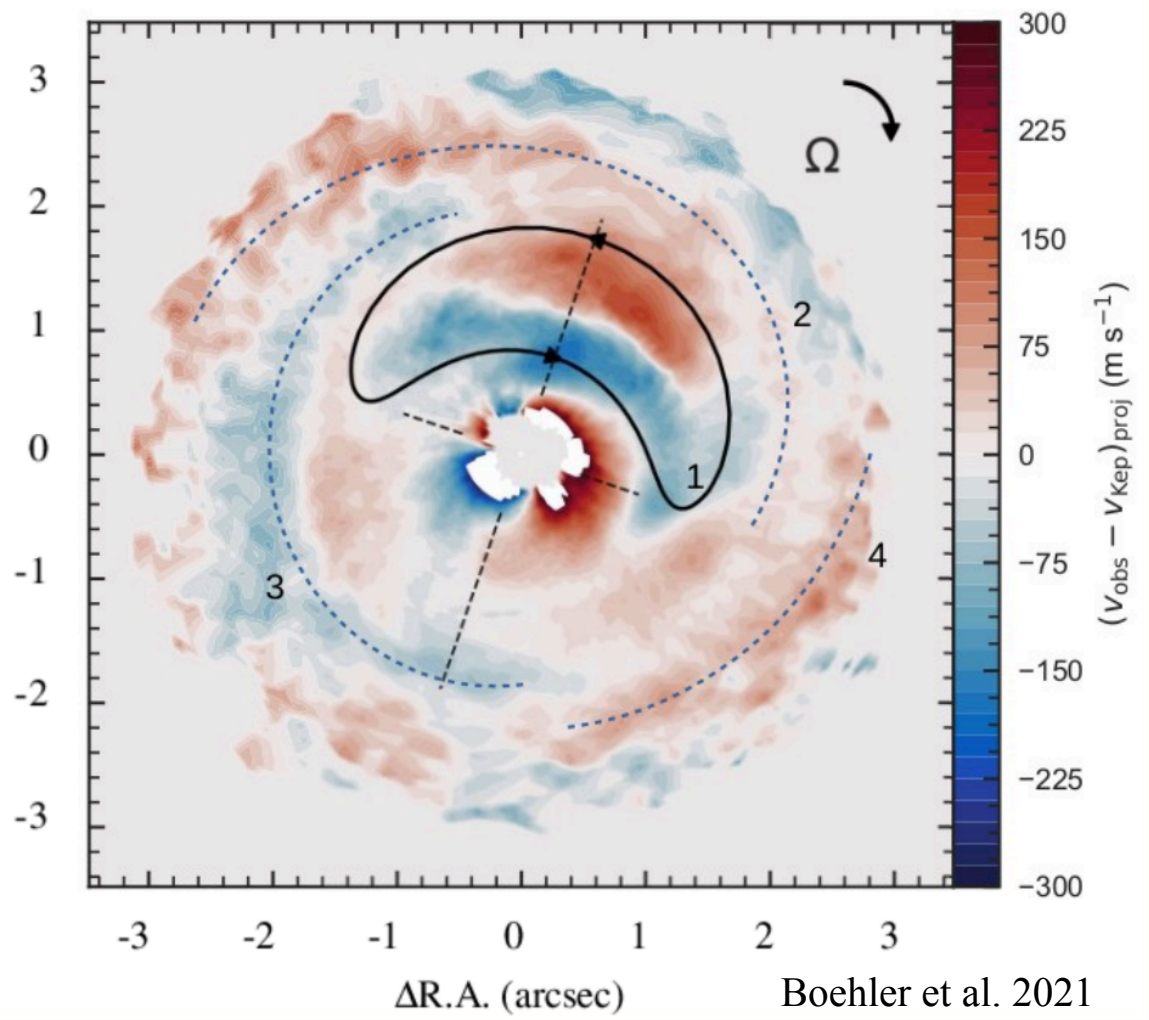


- Larger aspect ratio (weaker disk) in more massive disks

Bea+, PPVII chapter

Vortex kinematic

HD 142527

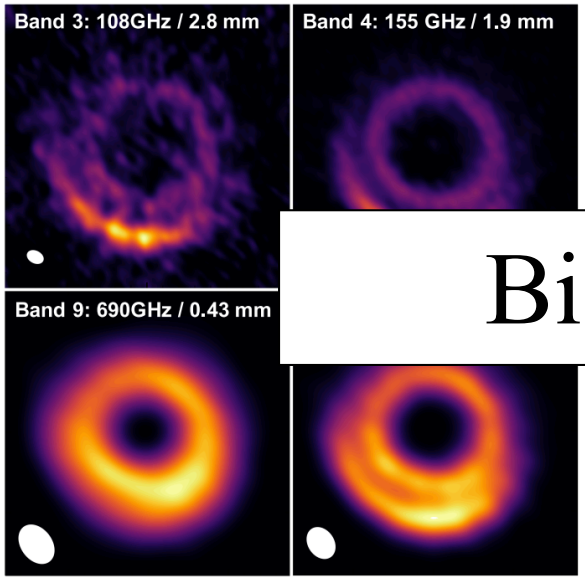


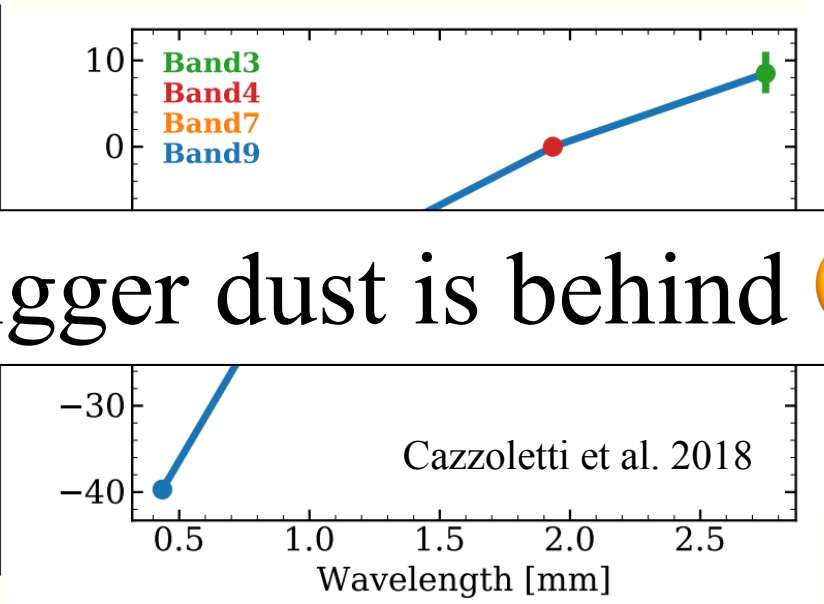
Boehler et al. 2021

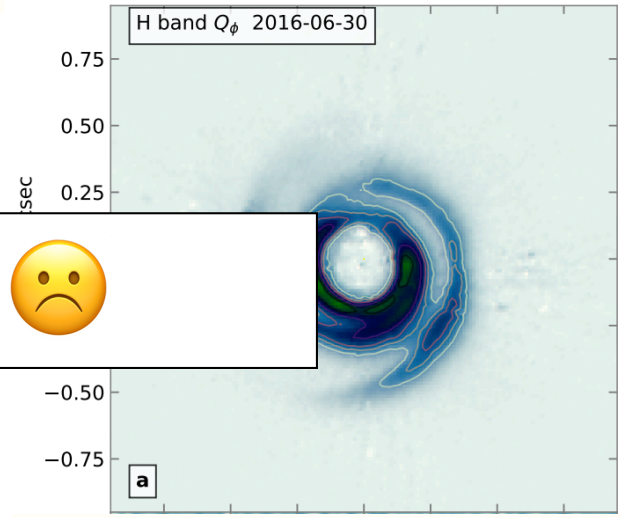
Vortex or beam smearing?

Vortex observations: multi-wavelength

HD 135344



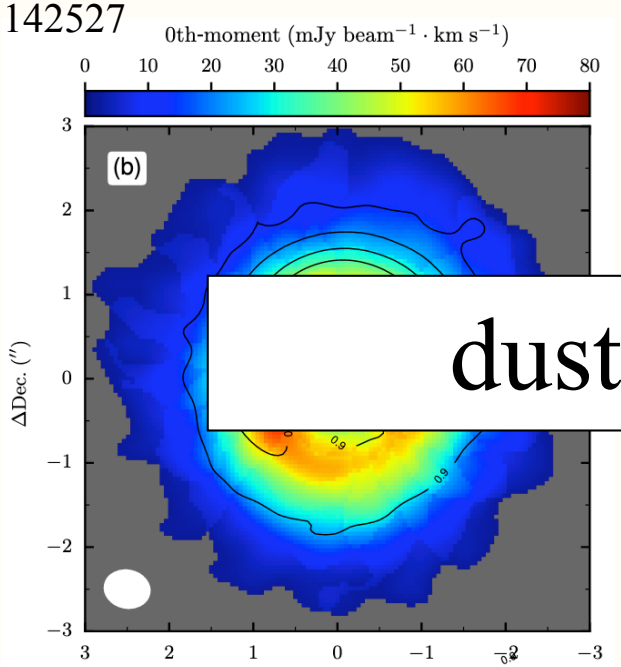




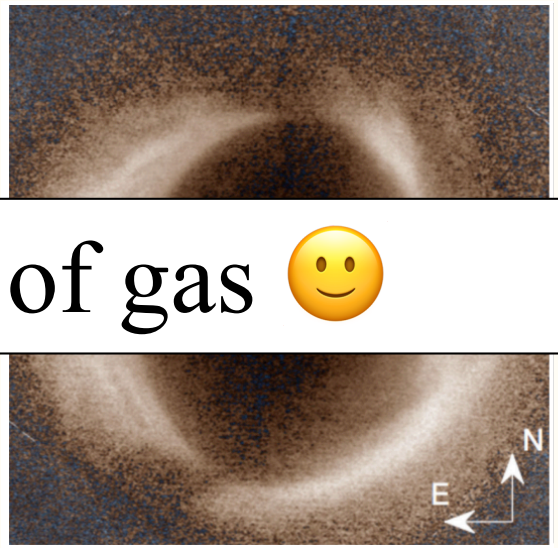
Stolker et al. 2017

Bigger dust is behind ☹️

HD 142527



Soon et al. 2019

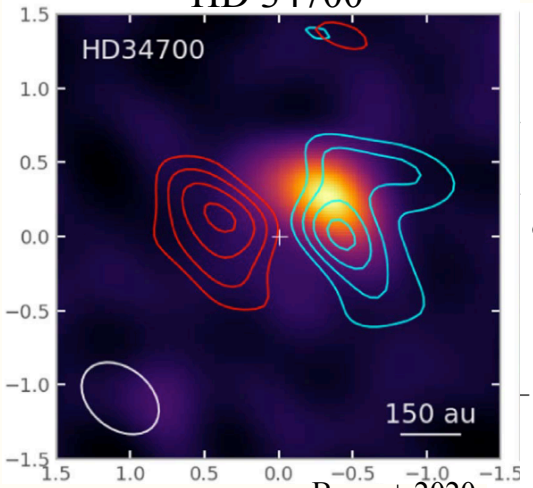


Avenhaus et al. 2014

dust is ahead of gas 🙂

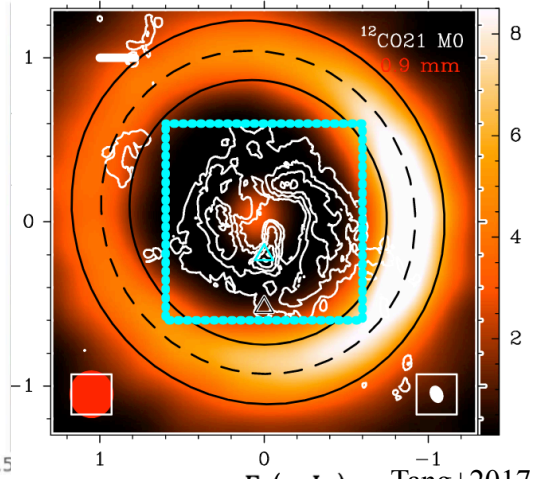
Connection between vortex and spiral?

HD 34700



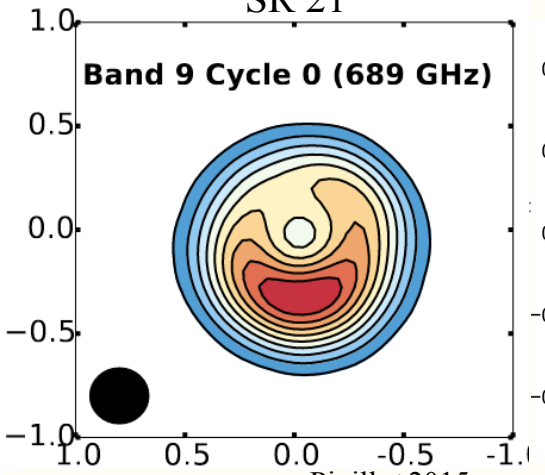
Benac+ 2020

AB Aur



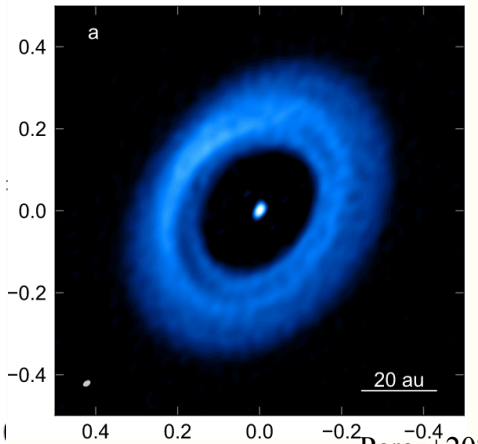
Tang+2017

SR 21



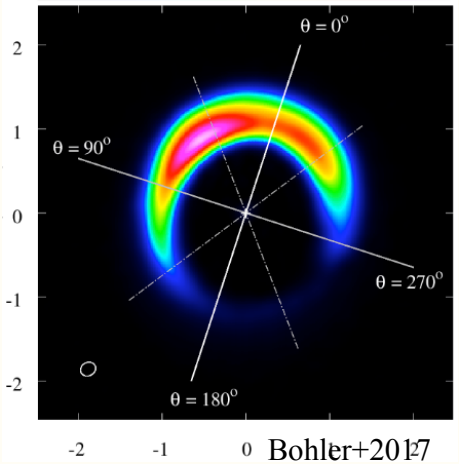
Pinilla+2015

HD 100546



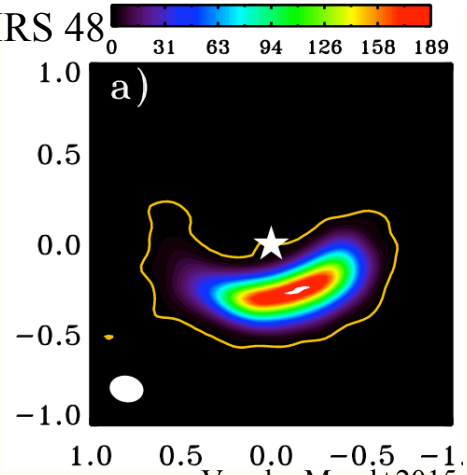
Perez+2020

HD 142527



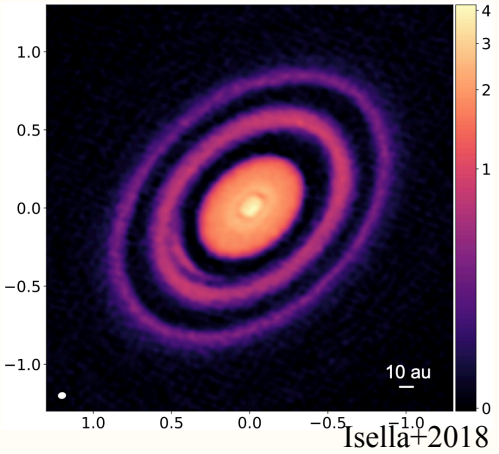
Bohler+2017

IRS 48



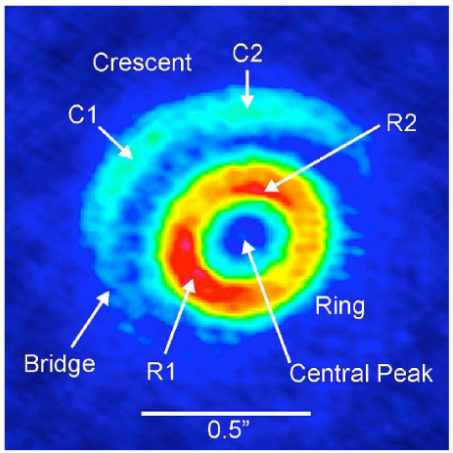
Van der Marel+2015

HD 163296



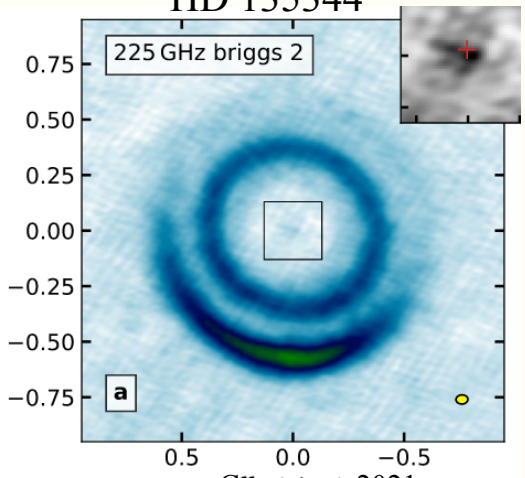
Isella+2018

V1247 Ori



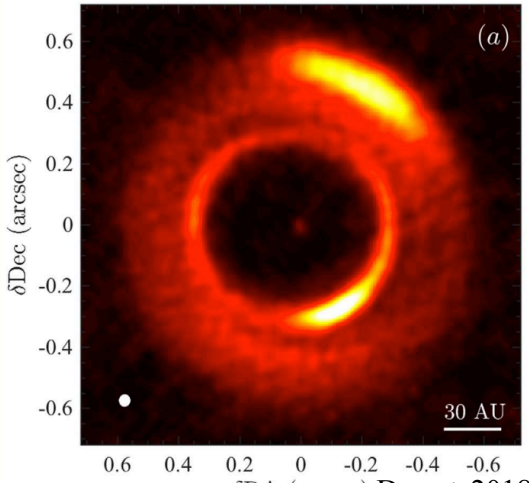
Kraus+ 2017

HD 135344



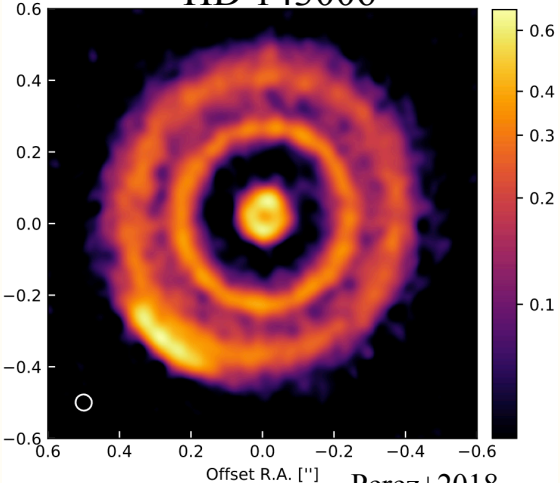
Cãsassus+ 2021

MWC 758



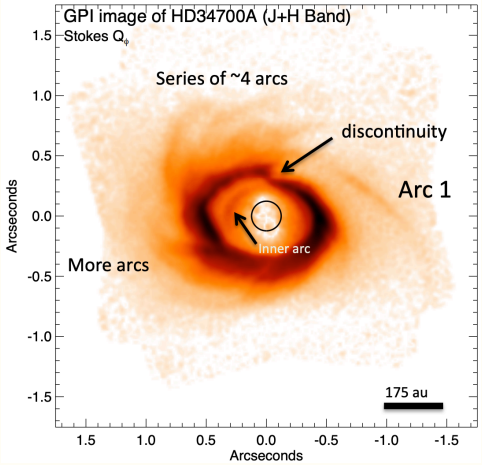
Dong+ 2018

HD 143006



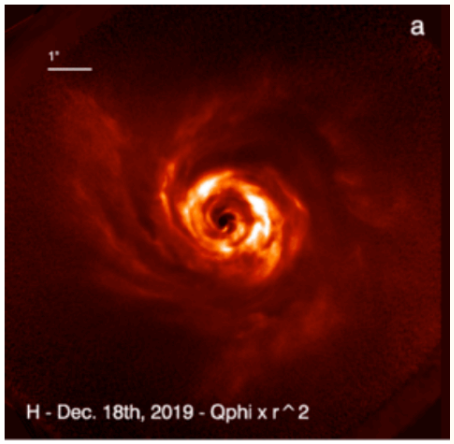
Perez+2018

HD 34700



Monnier+ 2019

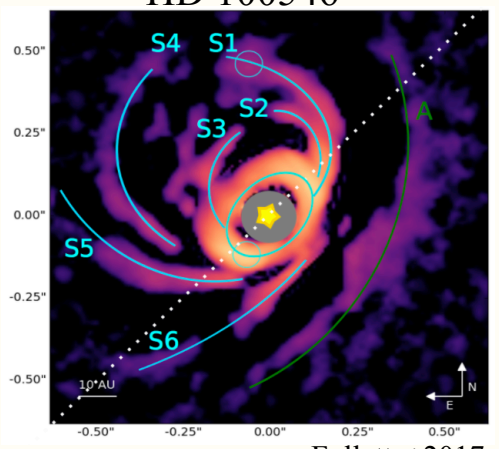
AB Aur



Boccaletti+2020

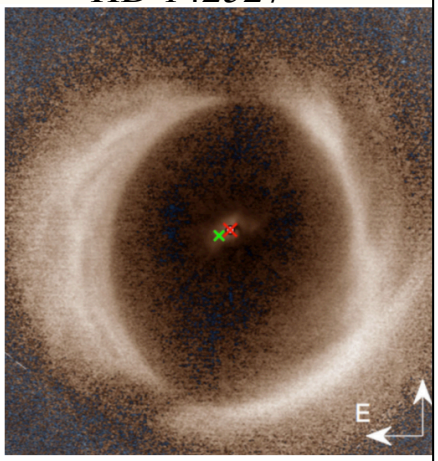
SR 21

HD 100546



Follette+2017

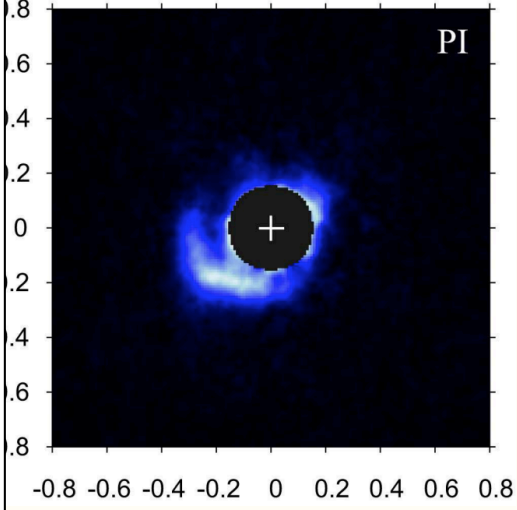
HD 142527



Avenhaus et al. 20

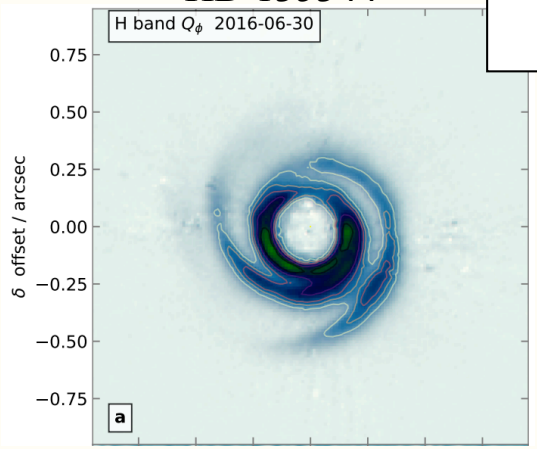
Some connections between vortex and spiral???

V1247 Ori

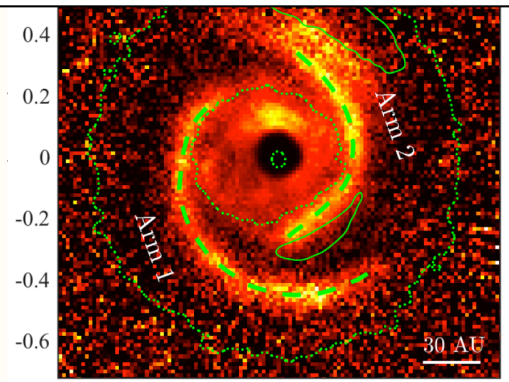


Ohta+ 2016

HD 135344



Stolker+ 2017



Benisty+ 2014

- Vortices
  - Basic properties of vortices

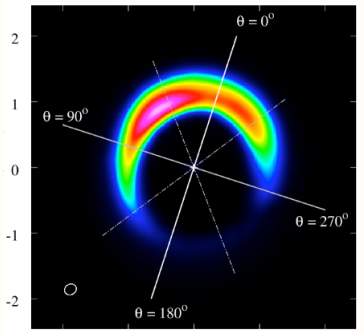
    Maybe Maybe OK

    (circulation motion, large scale~H, aspect ratio≳3)
  - Excitation mechanisms ?

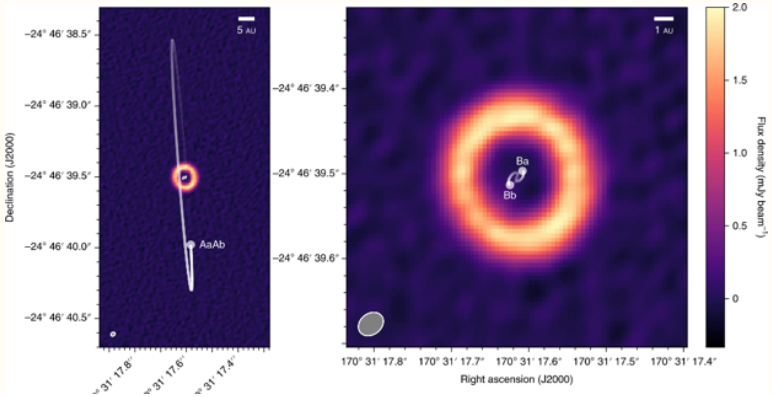
    (density bumps, special location/transition)
  - Spirals, particle trapping, self-gravity of vortices, MRI turbulence

    opposite ? Maybe ? Maybe

    (Weak spirals, St/α, peak shift, dust-to-gas ratio, weaker vortices in massive disks, cannot exist in strongly turbulent disks) ?



- Lumps in circumbinary disks
  - Lumps even in highly turbulent disks
  - For polar circumbinary disks, only forms in low viscous disks



- Observations