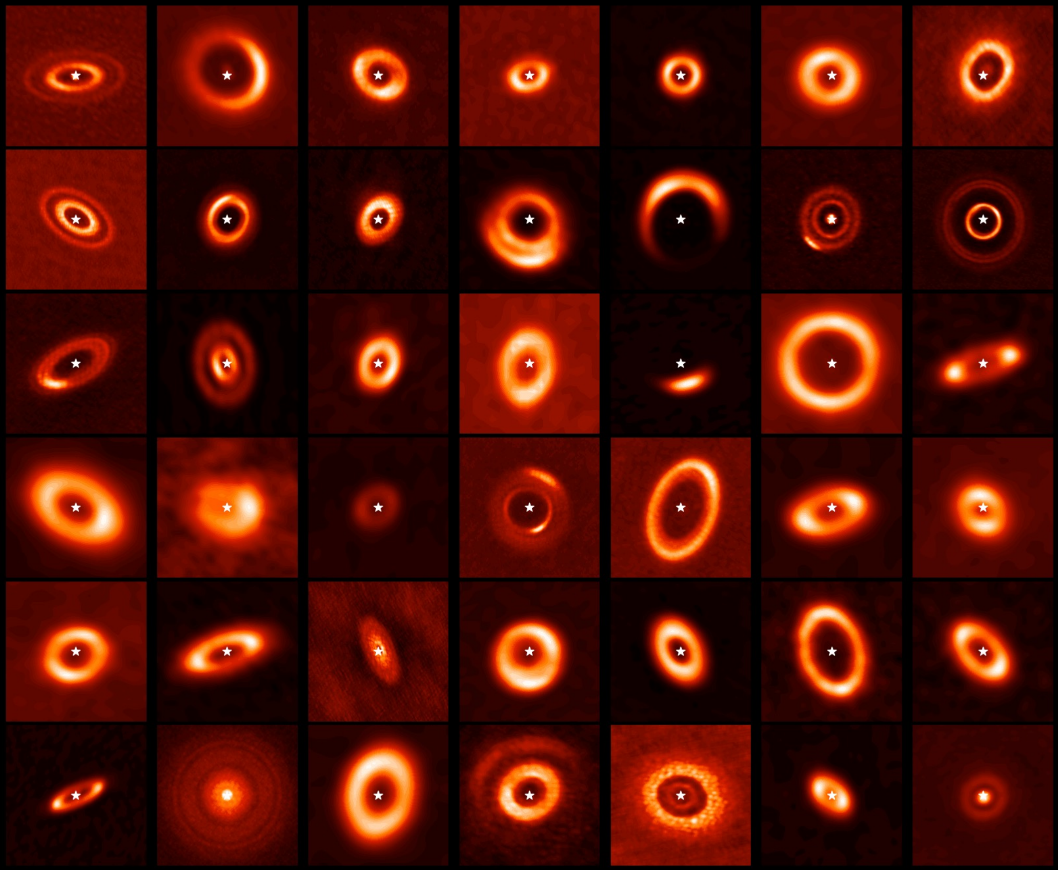
Should ***vortices*** be more ubiquitous in protoplanetary disk observations?



Credit:
Nienke van der Marel
(nienkevandermarel.com/)

Michael Hammer

(No institution, …but ASIAA soon!! :-)

Collaborators: Min-Kai Lin (ASIAA), Paola Pinilla (MPIA), Kaitlin Kratter (Arizona)

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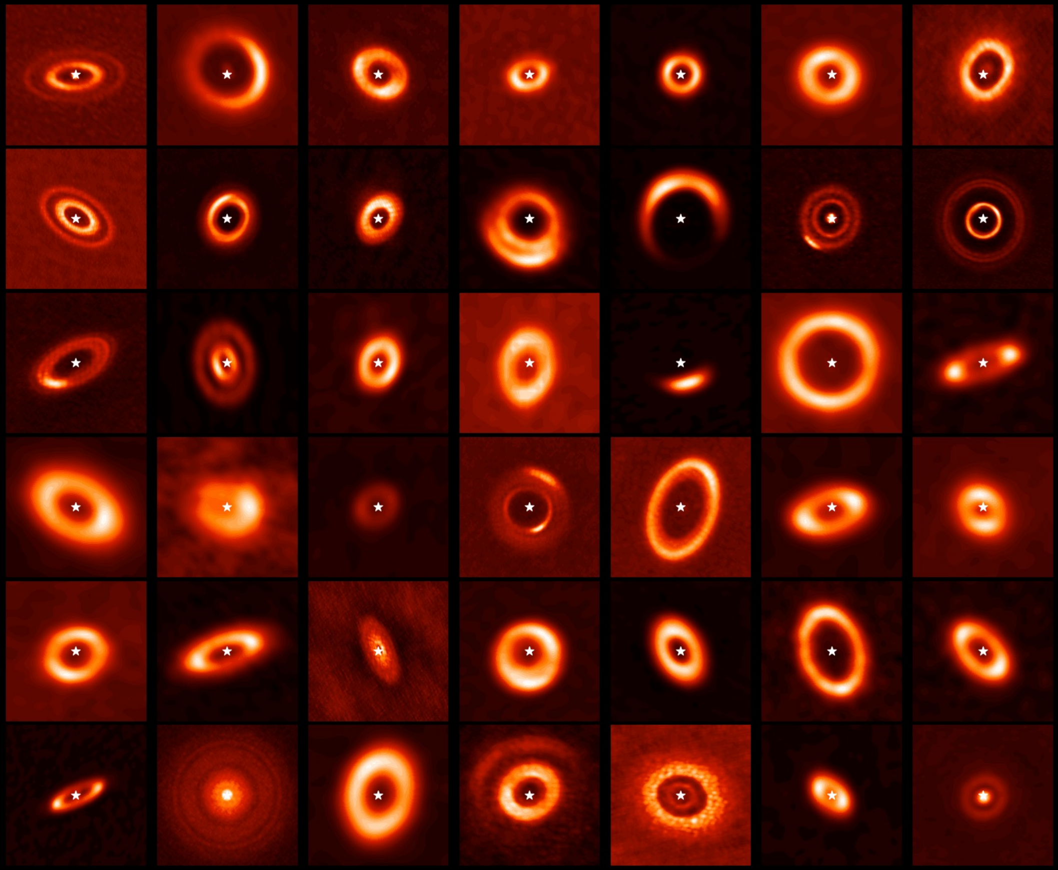

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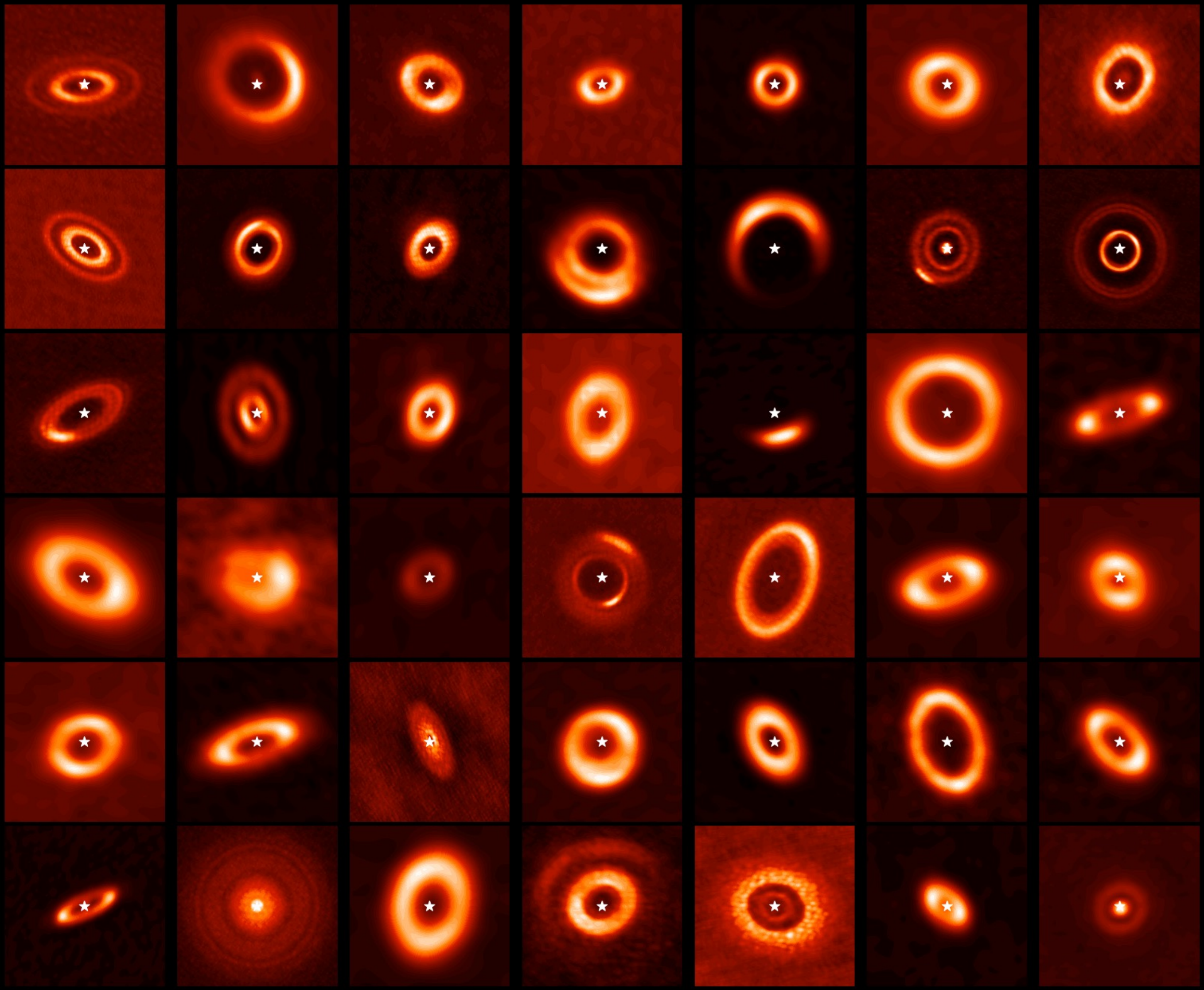
Do protoplanetary disks ***typically*** contain vortices?

ALMA suggests ***no***!

Question #1

How common are ***large-scale asymmetries****?

* (vortex candidates)

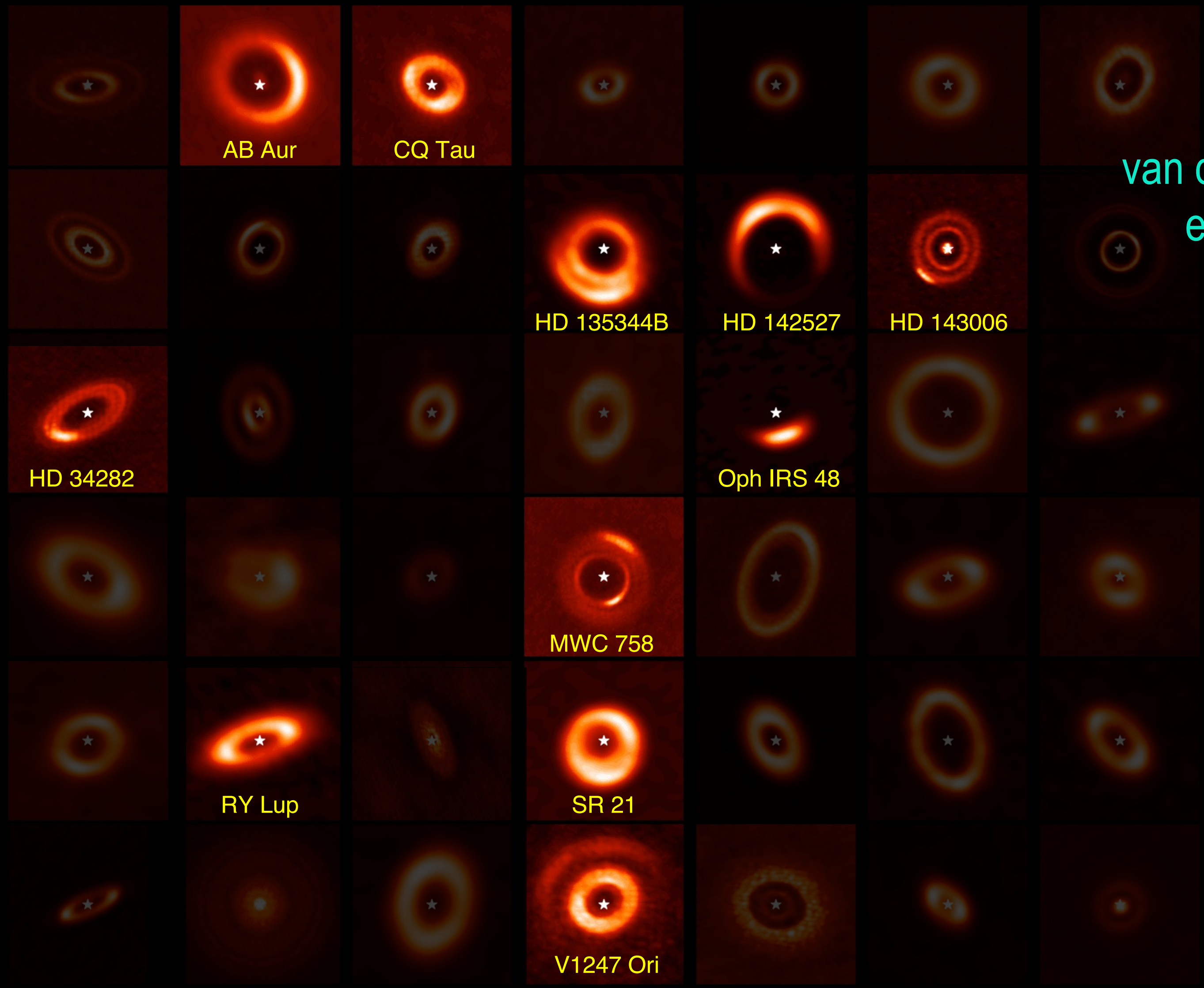


ALMA observations of mm dust

Credit: Nienke van der Marel
(nienkevandermarel.com/)

Only about ***25% of disks**** contain ***asymmetries***!

* (resolved transition disks)



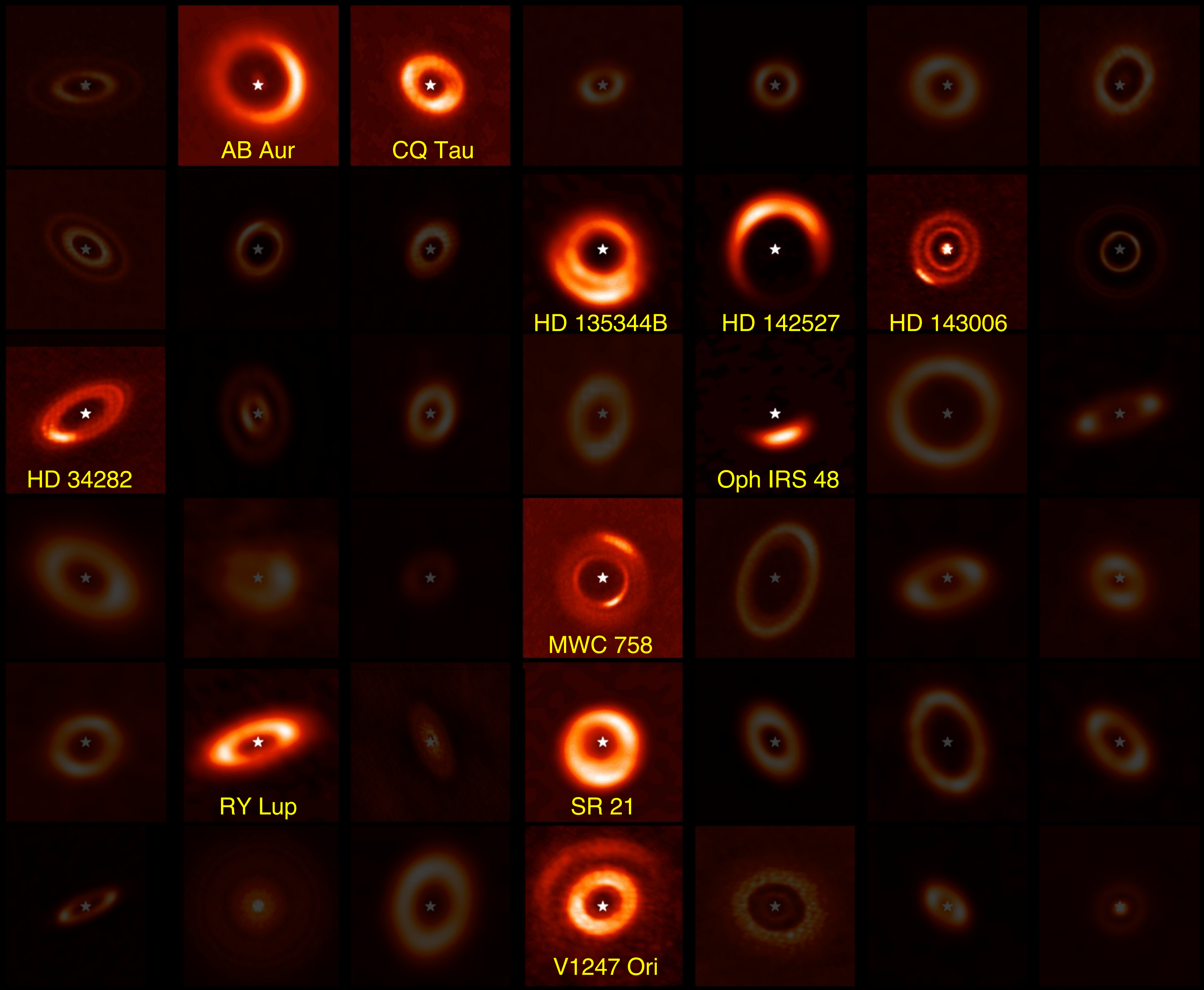
van der Marel, N., et al. 2021

ALMA observations of mm dust

Credit: Nienke van der Marel (*nienkevandermarel.com/*)

Only 2 *disks* have *two-sided gaps** with an* asymmetry!

* (one or more)



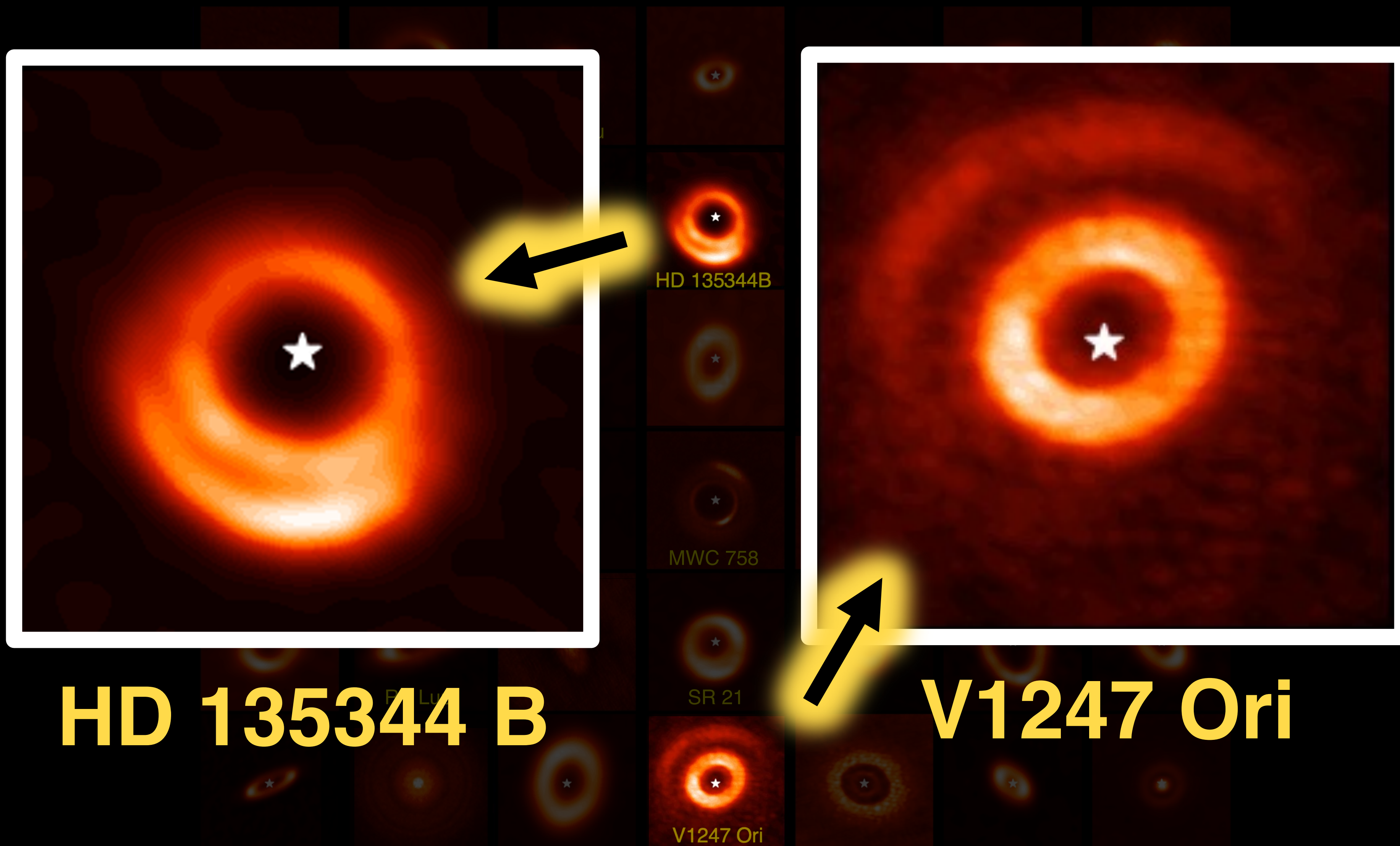
ALMA observations of mm dust

Credit: Nienke van der Marel
(nienkevandermarel.com/)

Only 2 *disks* have *two-sided gaps** with an* asymmetry!

* (with a planet??)

* (one or more)



Cazzoletti, P., et al. 2018

Kraus, S., et al. 2017

Can planets generate these large-scale asymmetries?

Yes, but…

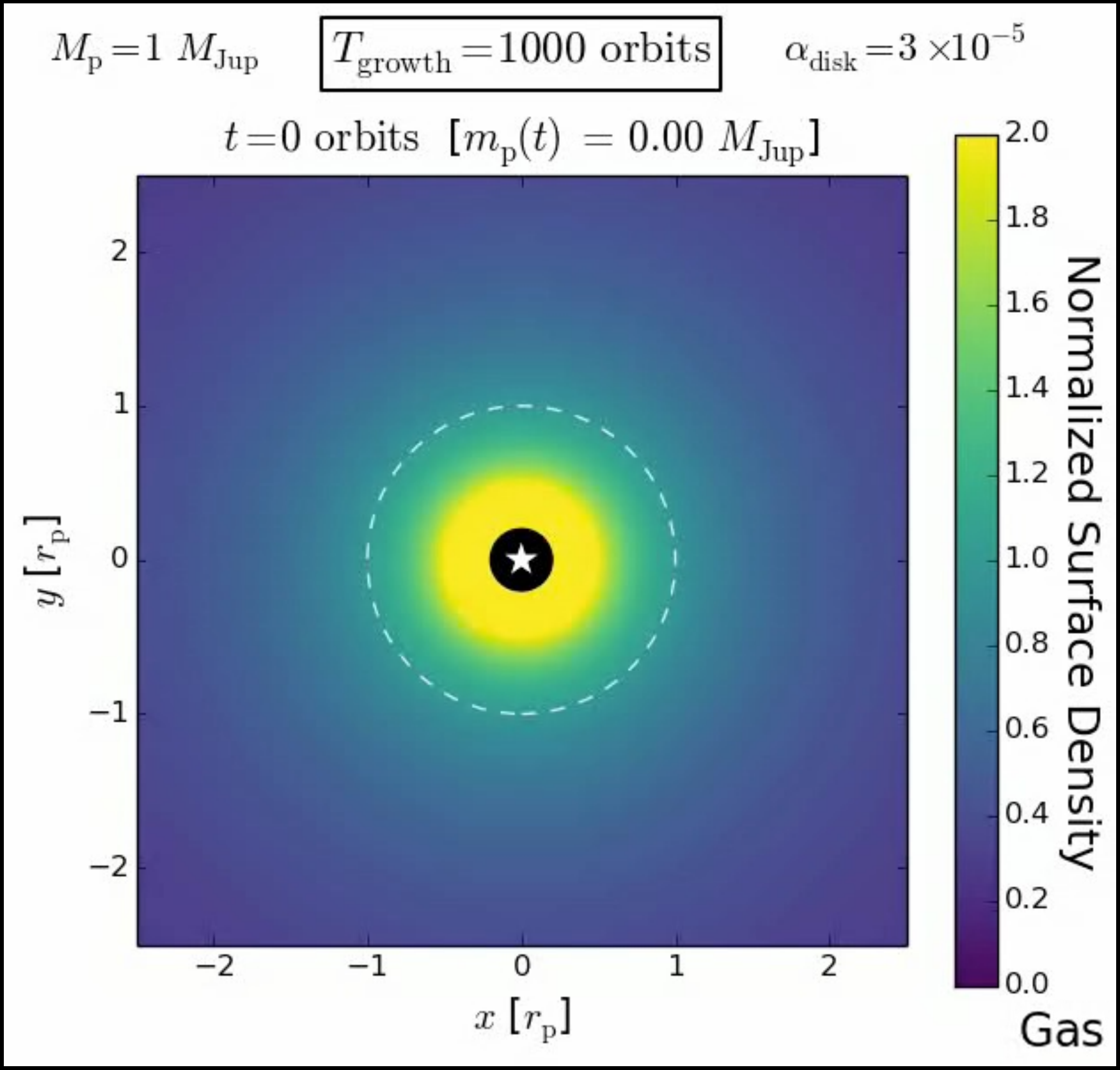
…only if they just formed

AND

you may need to consider the planet's growth time.

Question #2

Vortex Evolution (with ***Slow*** Planet Growth)



Notice:

Extent

>180 degrees.

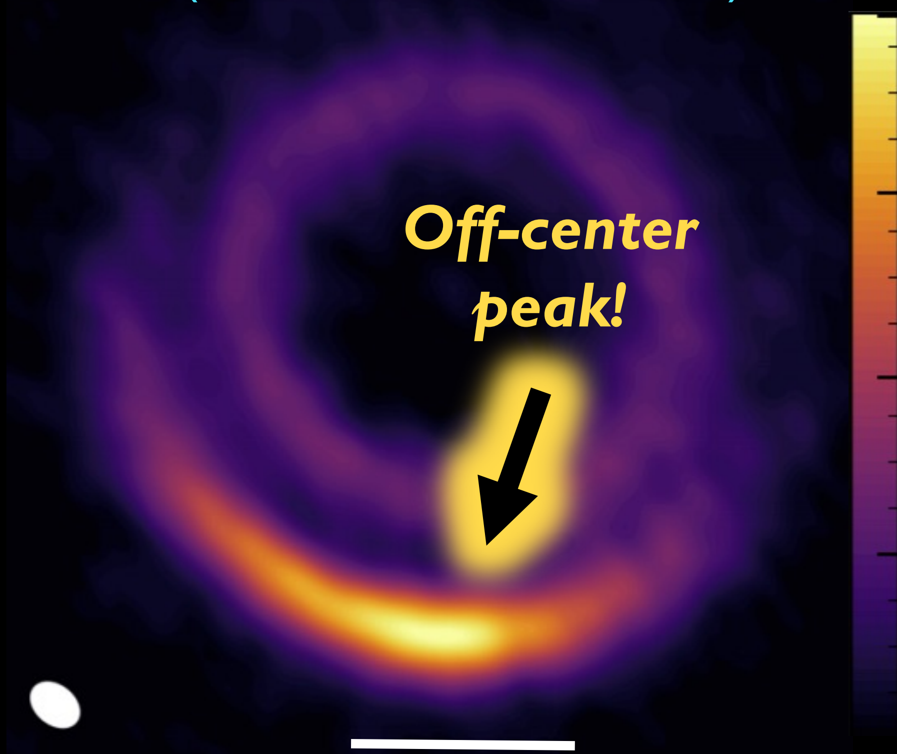
Lifetime

Lasts ~1500 orbits. (~5x shorter than instant growth case!)

MH, Kratter, K., Lin, M.-K. 2017, MNRAS, 466, 3533

Matching ALMA Observations

HD 135344 B
(Dust at λ = 1.9 mm)

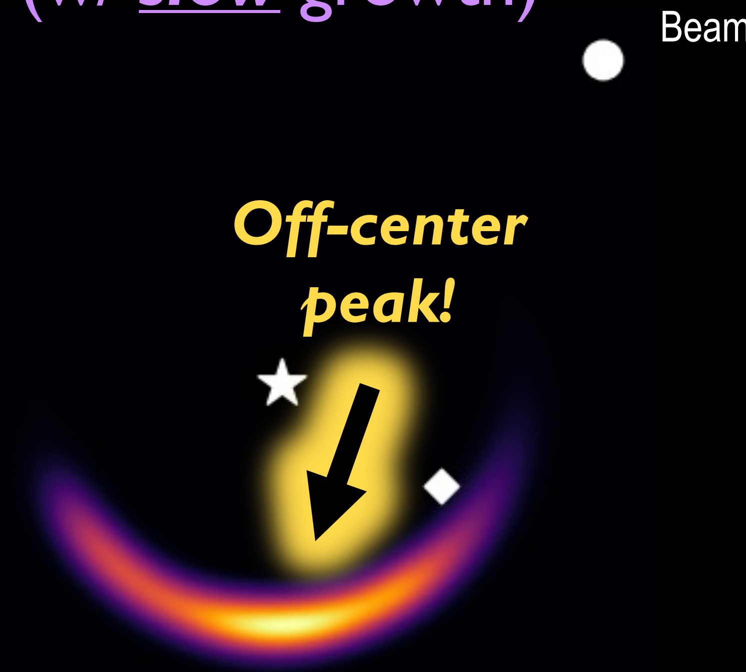


~50 AU

Cazzoletti, P., et al. 2018

ALMA Observation

Elongated Vortex
(w/ ***slow*** growth)

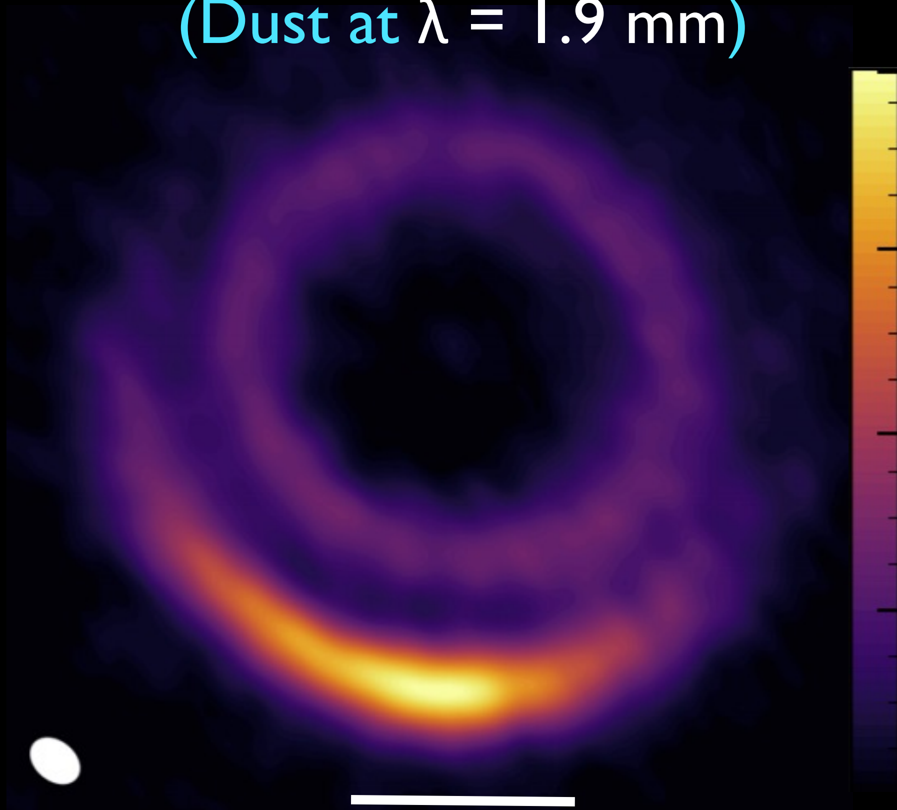


MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Synthetic Image

(Not) Matching ALMA Observations

HD 135344 B
(Dust at λ = 1.9 mm)



~50 AU

Cazzoletti, P., et al. 2018

ALMA Observation

Compact Vortex
(w/ ***instant*** growth)

Too compact!!

Peak not off-center!!

MH, Pinilla, P., Kratter, K., Lin, M.-K. 2019, MNRAS, 482, 3609

Synthetic Image

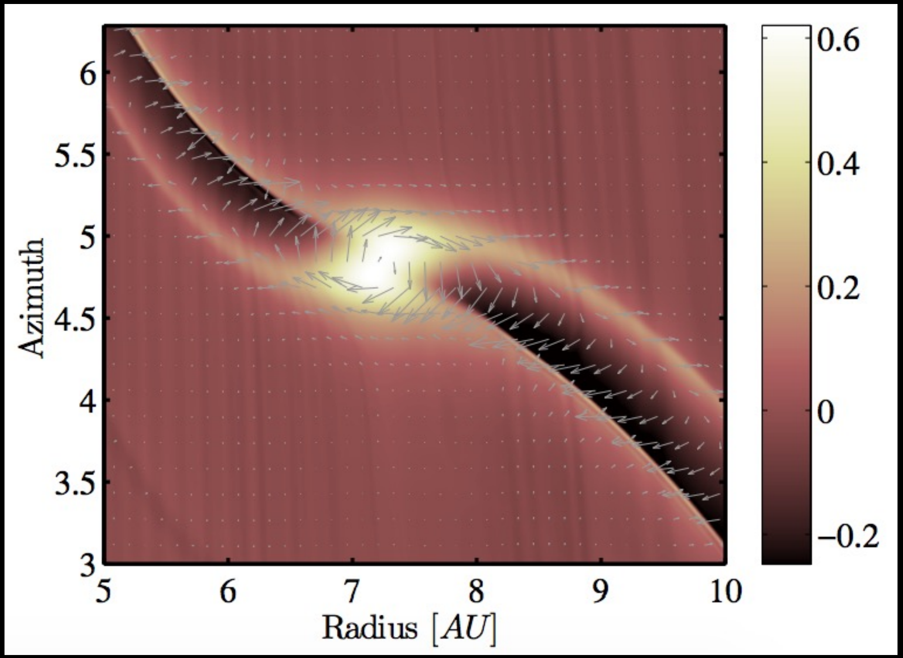
Why do these vortices look different?

There are ***two types*** of vortices!!

Question #3

Two types of vortices!!

Compact

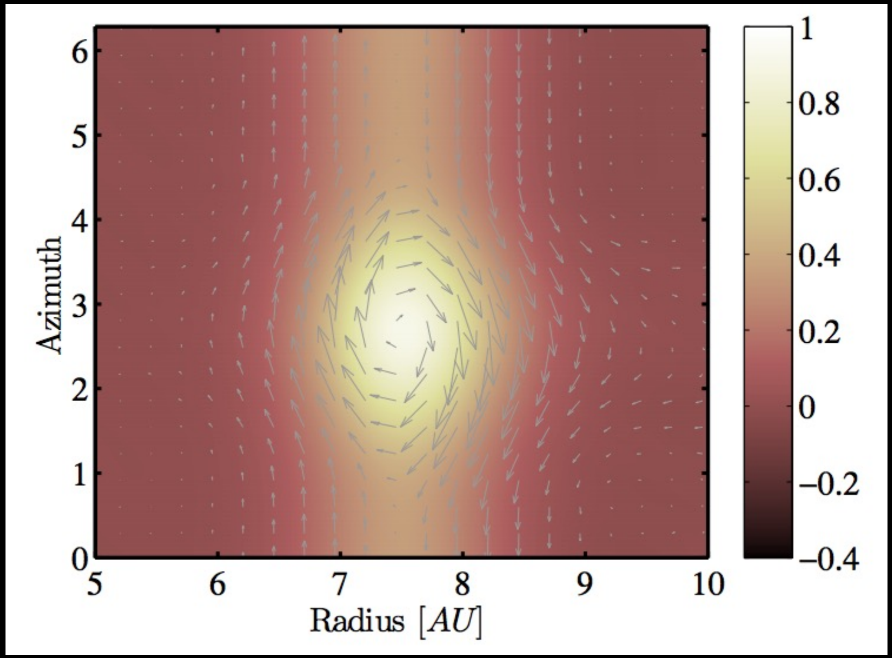


Gaussian model (Surville + Barge 2015)

Rossby number: ***Ro < -0.15***

INSTANT *growth!!*

Elongated

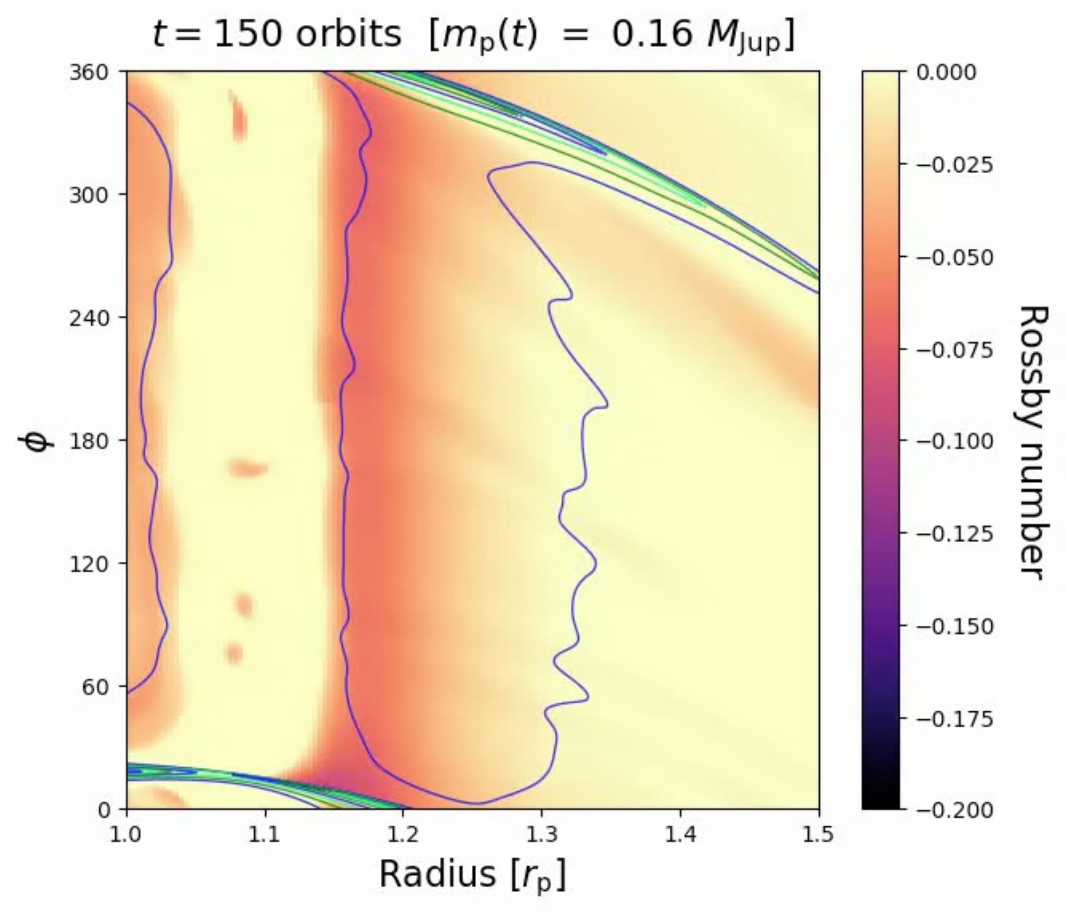


GNG model (Goodman et al. 1987)

Rossby number: ***Ro > -0.15***

SLOWER *(realistic) growth!!*

Why is the *final* vortex elongated?



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

The ***initial*** set of vortices are elongated!
(***Ro > -0.15***)

The final vortex has ***no clear vorticity minimum*** at the center!

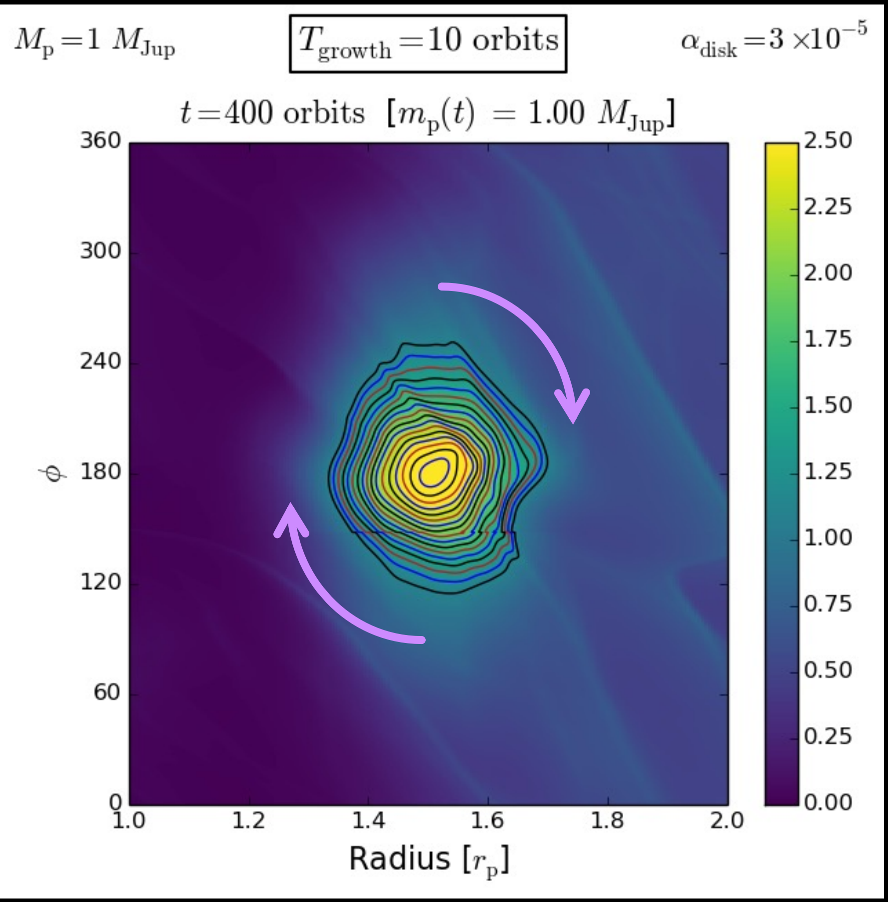
The Rossby number never drops to ***compact***!

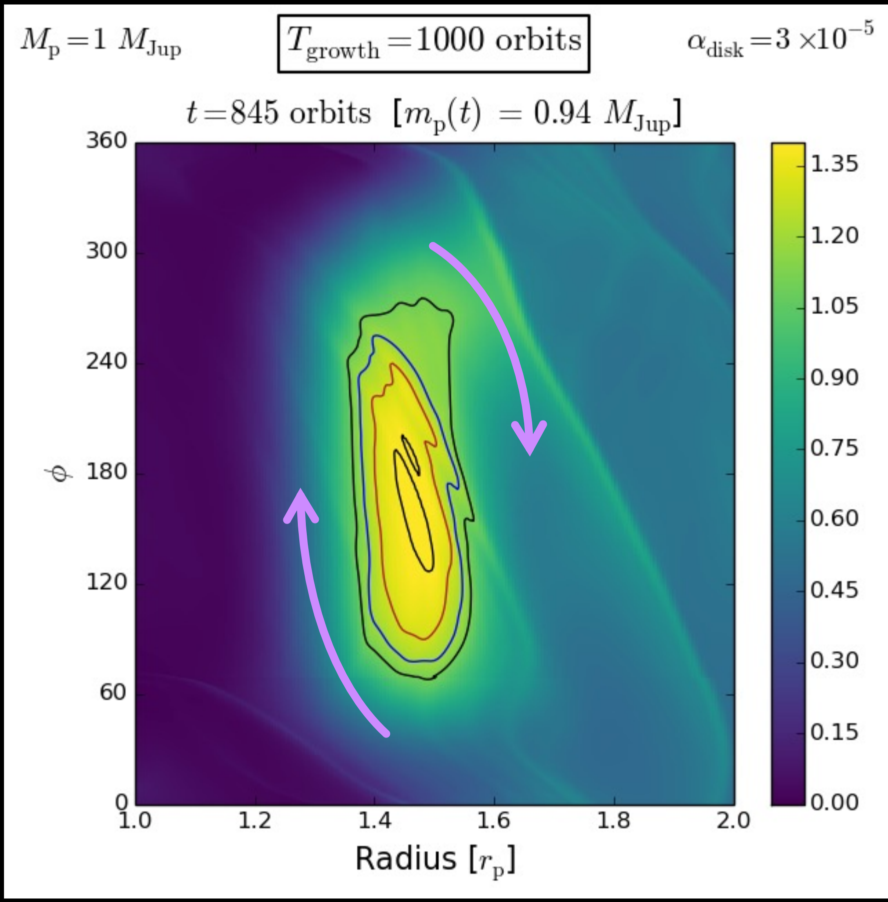
Why do elongated vortices have off-center peaks?

The dust circulates around the vortex.

Question #4

Different Vortex Structures





Compact Vortex

Gas

Elongated Vortex

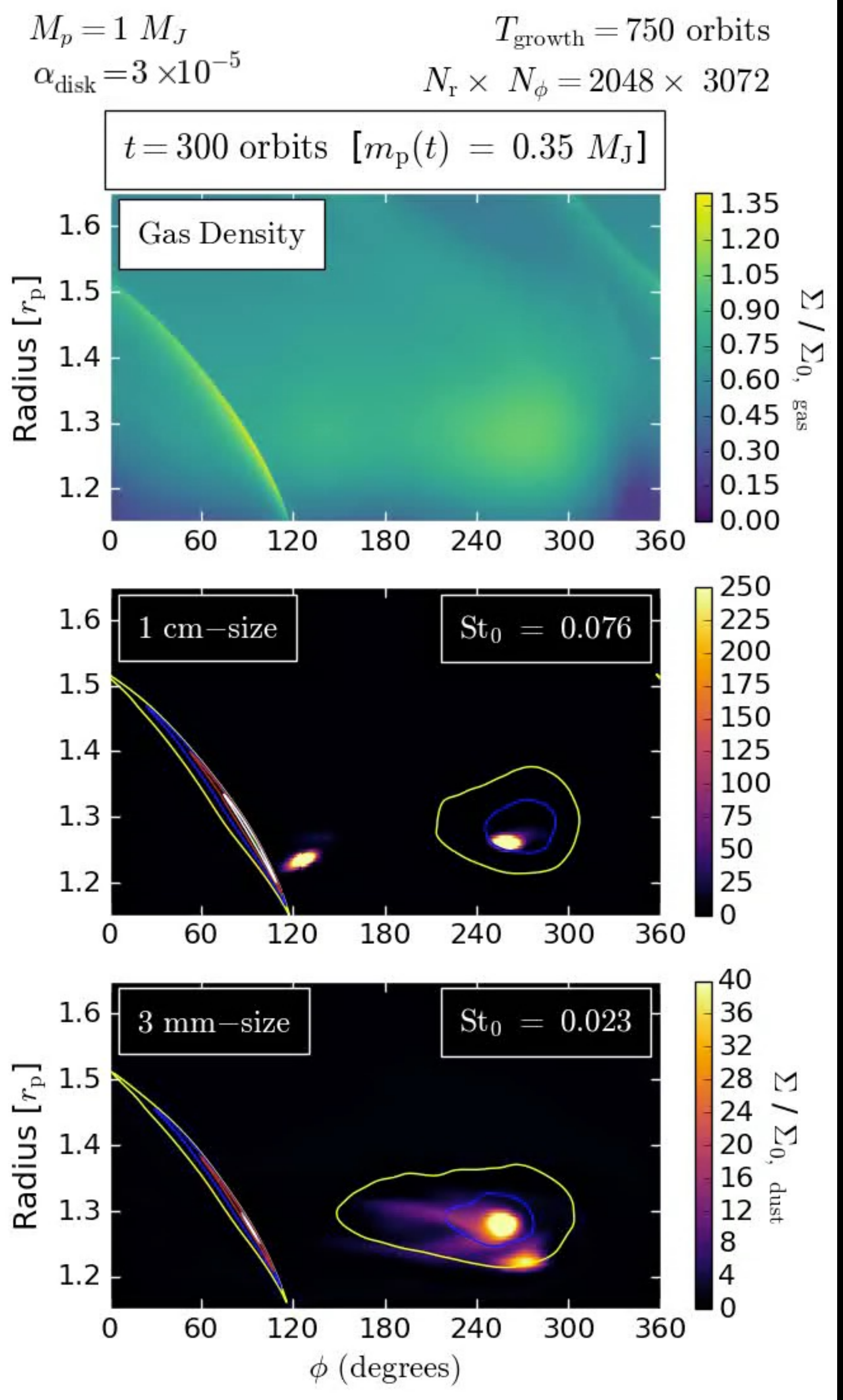
Contour Levels: 1.10, 1.20, 1.30, 1.40, ..., 2.70 $[\Sigma / \Sigma_0]$

The dust circulates around the vortex!

Vortex is also elongated in the dust.

The peak is usually off-center.

MH, Pinilla, P., Kratter, K., Lin, M.-K. 2019, MNRAS, 482, 3609



Does incorporating
the planet's growth time
always shorten vortex lifetimes?

Not for lower-mass planets!

Question #5

Growing the planet even more realistically

Our Past Work:

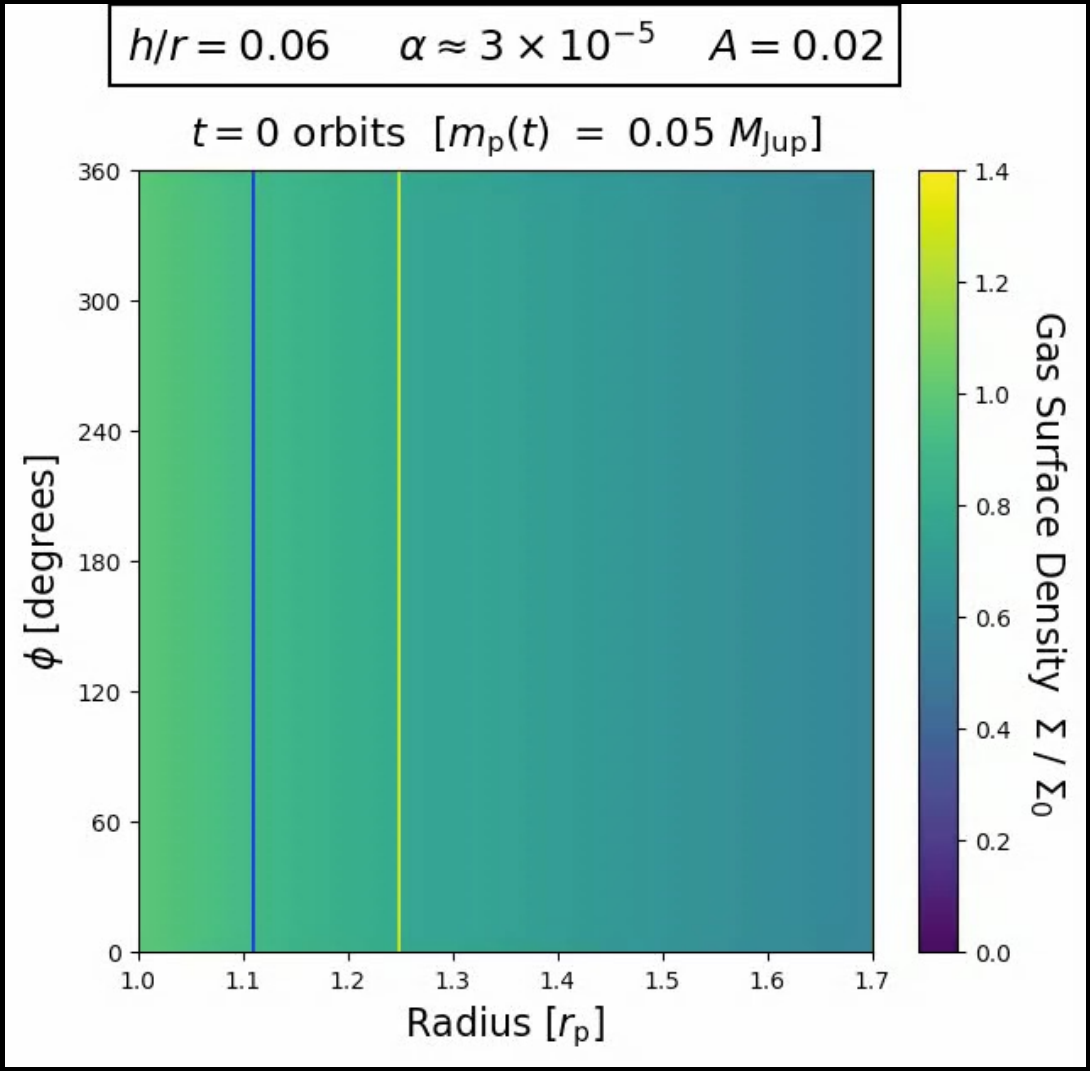
Prescribe the growth of the planet.

More Realistic Approach:

Have the planet accrete gas directly from the disk.

MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Vortex (with *H/R* = *0.06* and *0.20 M_{Jup}* planet)



Notice:

Vortex re-forms?

Yes, multiple times:

t* = *2610

t* = *3150

t* = *3660

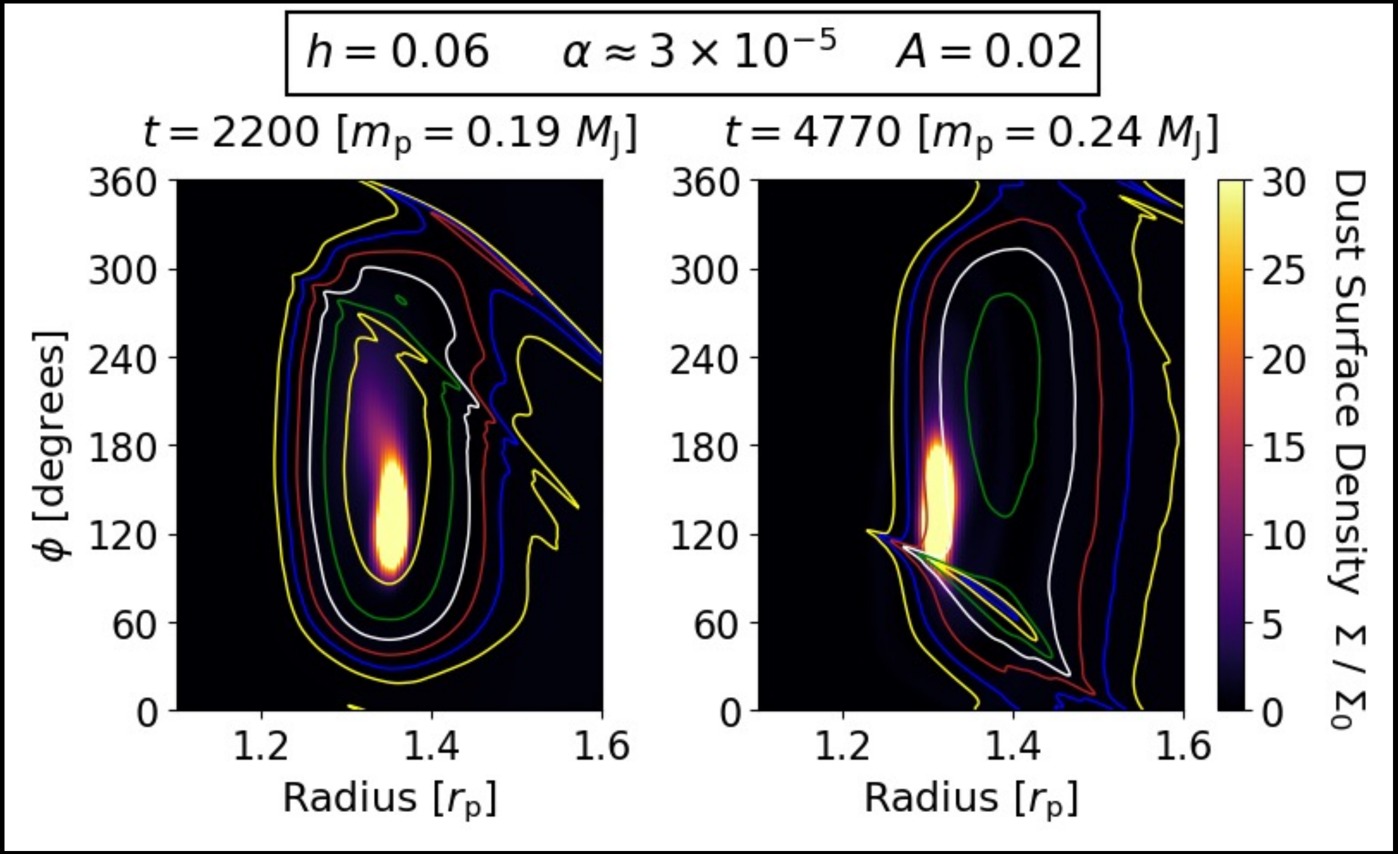
Lifetime

Vortex is still alive at the end of this movie:

t* = *6000

MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

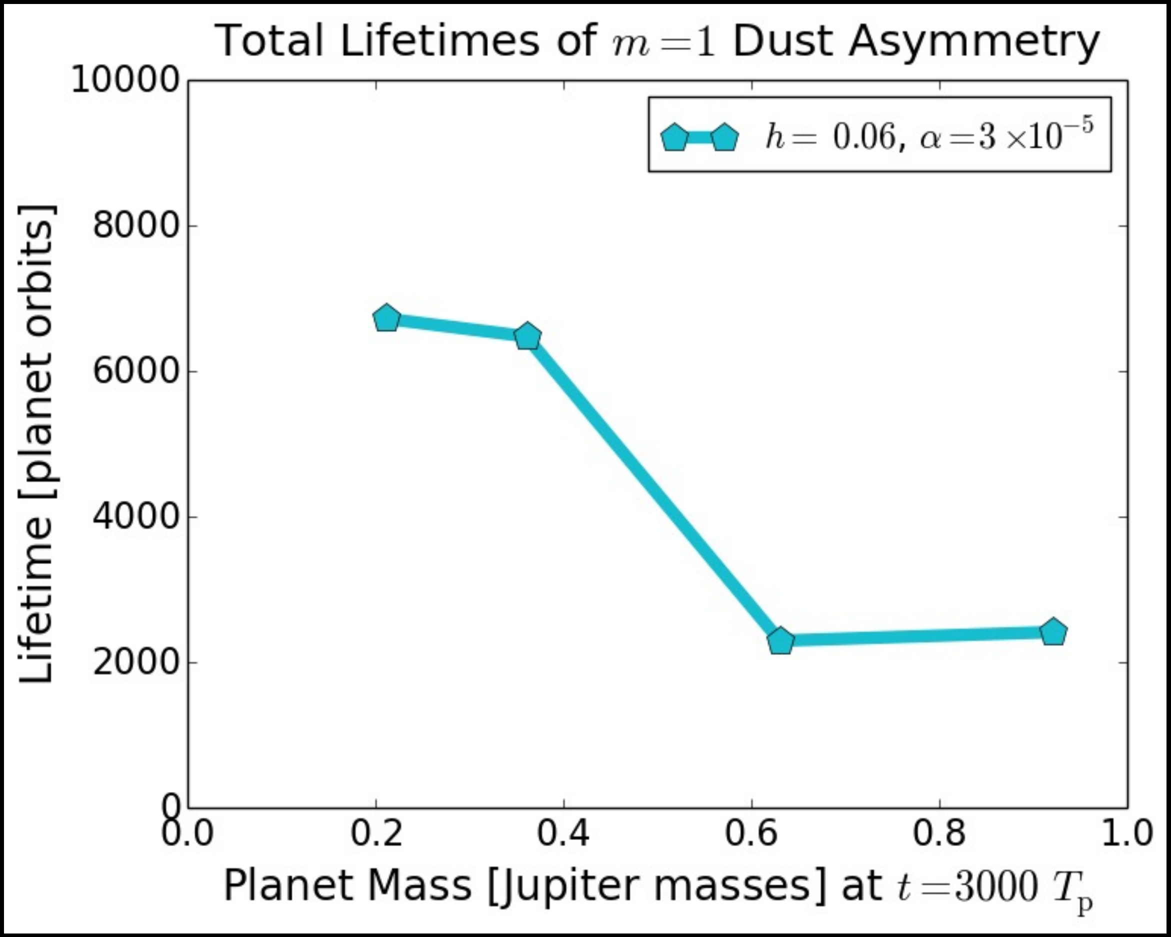
Dust snapshots (with ***0.2 M_{Jup}*** planet)



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021, MNRAS, 504, 3963

Note: Dust asymmetry survives in-between gas vortices.

Vortex Lifetimes



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Note:

Because of ***later-generation vortices,***

the ***low-mass planets*** produce longer vortex lifetimes.

How do you kill a vortex?

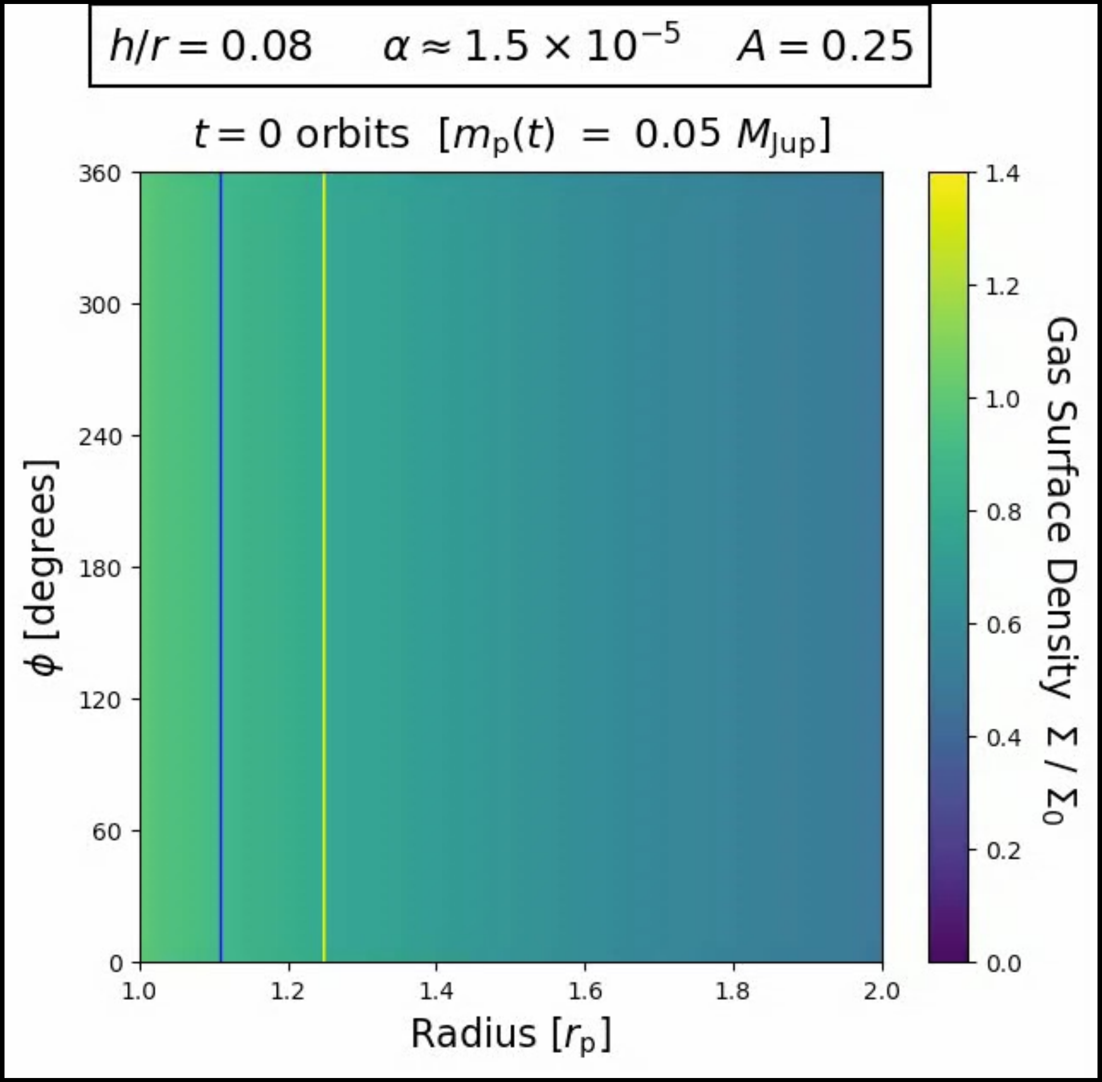
Viscosity! (but only if $\alpha > 10^{-4}$)

Shocks! but not always!

(from the planet's spiral waves)

Question #6

Vortex Evolution (with ***H/R = 0.08***)



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Notice:

Vortex Growth

After first 200 orbits, ***nothing happens!***

The ***shocks*** passing through the vortex are ***weaker!***

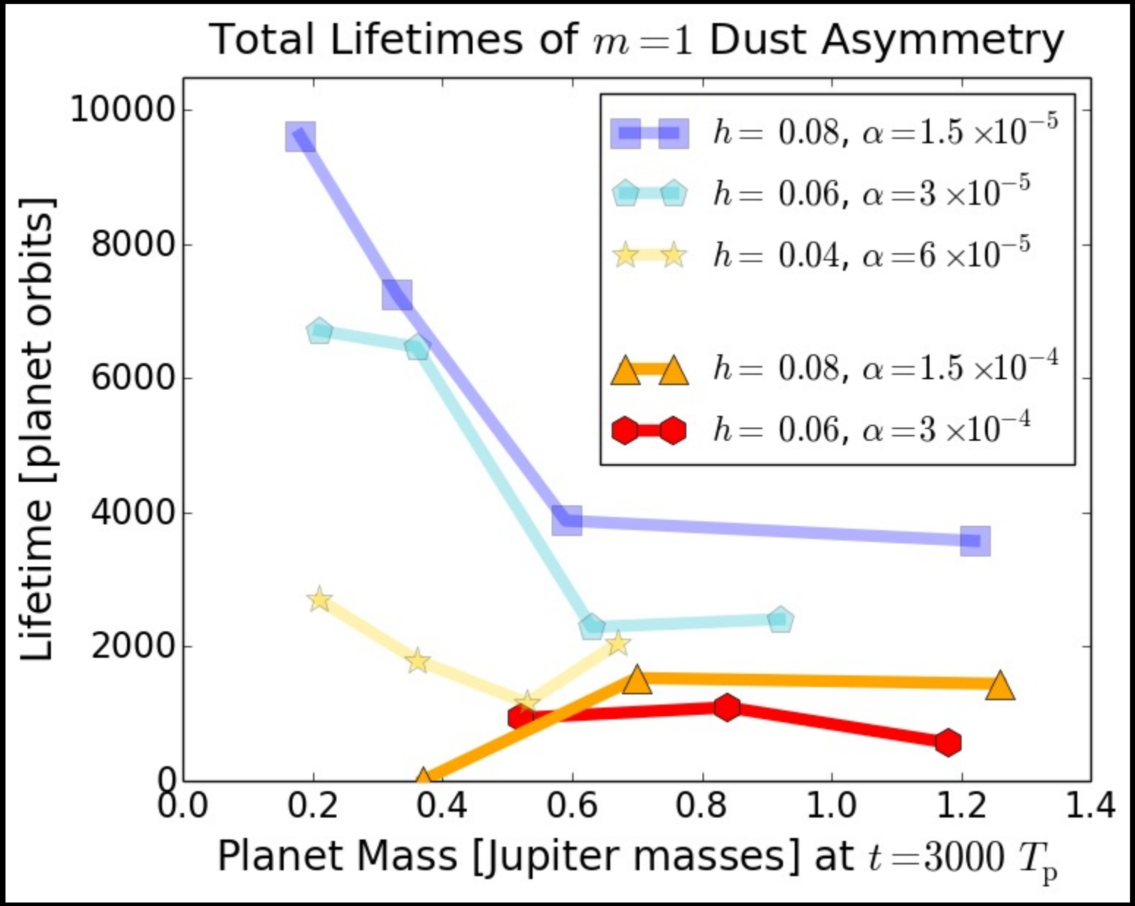
The vortex is still alive at the end.

Do these trends occur with higher viscosity?

No, viscosity still shortens vortex lifetimes.

Question #7

Vortex Lifetimes (at $\nu = 10^{-7}$ and $\nu = 10^{-6}$)



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Viscosity

} $\nu = 10^{-7}$

} $\nu = 10^{-6}$

With $\nu = 10^{-6}$, vortices are ***short-lived*** regardless of planet mass.

Should vortices be more ubiquitous in protoplanetary disc observations?

At least in some cases, yes!

AND

Figuring out why may constrain planet or disc properties.

Question #8

Chances of Observing Vortices in Taurus

Disc w/ Gap	Planet mass (per solar mass)	Gap location	(Cluster Age = 2 Myr) Chance (Lifetime = 1000 orbits)
FT Tau	0.44 M_{Jup}	25 AU	10%
DS Tau	9.65 M_{Jup}	33 AU	12%
CI Tau	0.40 M_{Jup}	48 AU	18%
MWC 480	0.40 M_{Jup}	73 AU	23%
DL Tau	0.34 M_{Jup}	89 AU	42%
CI Tau	0.42 M_{Jup}	120 AU	68%
Sample from Long, F., et al. 2018 **(NO asymmetries!)**	Mass estimates by Lodato, G., et al. 2019 (over-estimates assuming a low viscosity)	There should be at least ONE vortex! (but there are none)	

Why are there so few asymmetries?
(and what can we learn?)

Higher viscosity?

Viscosity may not be so low!

e.g. MH, et al. 2021

Sub-optimal cooling time?

$\beta \gtrsim 1.0\ \Omega^{-1}$ weakens vortices

Fung, J. + Ono, T. 2021; Rometsch, T., et al. 2021

May be realistic in outer disc?!!

Bae, J., et al. 2021; Malygin, M., et al. 2017

Planet migration?

Planet massive enough to create vortex, but not if it is migrating!

Kanagawa et al. 2021;
MH, et al. in prep. a

Strong disc self-gravity?

Planet formed early!

Relevant for $Q < (H/R)^{-1}$, but weaker for lower-mass discs

Vortex forms later?

Planet can't be too massive!

(more relevant for outer disc)

MH, et al. 2021

Strong dust feedback?

Dust-to-gas ratio must be high!

Not in 3-D?!!

Lyra, W., et al. 2018;
MH, et al. in prep. b

Summary

Have questions? Contact
mhammer@email.arizona.edu

Elongated planet-induced vortices are characterized by (1) *wider azimuthal extents* and (2) *off-center peaks*.

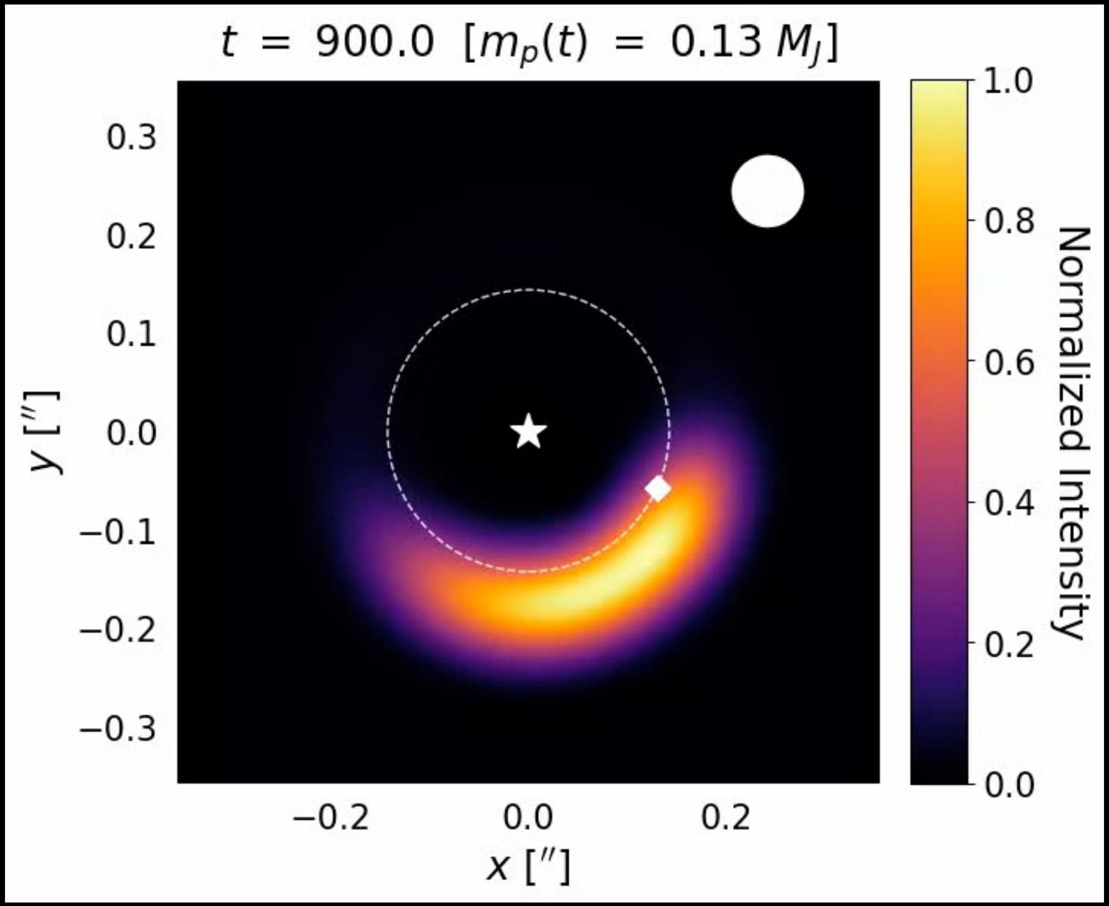
With ***H* / *R* ≤ 0.06,** lower-mass planets create longer-lived asymmetries because of the vortex re-forming.

With ***H* / *R* ≥ 0.08,** vortices are long-lived because of weaker shocks from the planet.

Test vortex-killing mechanisms w/ large ***H* / *R*** values!

It's still problematic that so few systems have large-scale asymmetries that could be vortices.

Other Signatures of Elongated Vortices

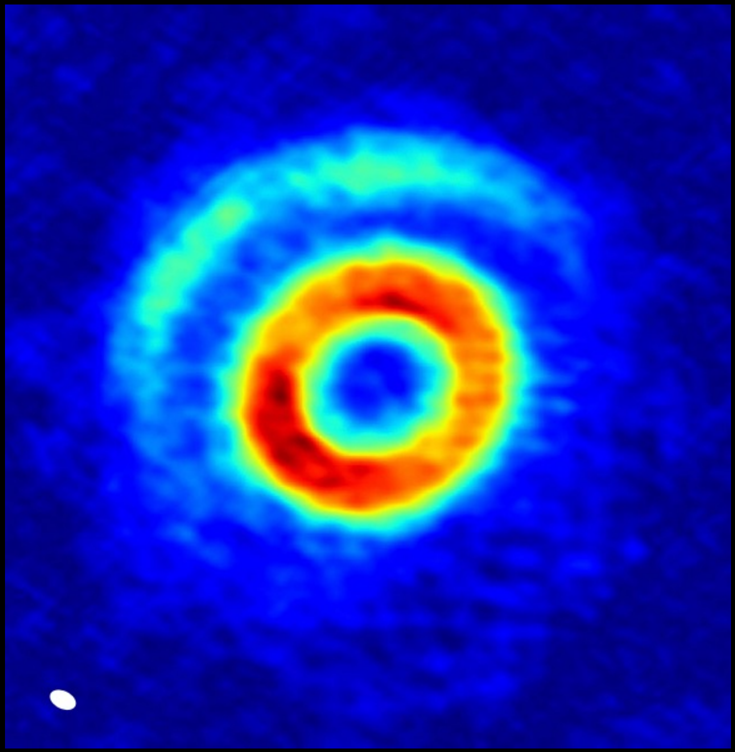


(1) Dust extent not always as wide as gas extent!

(2) Double peak also possible!!

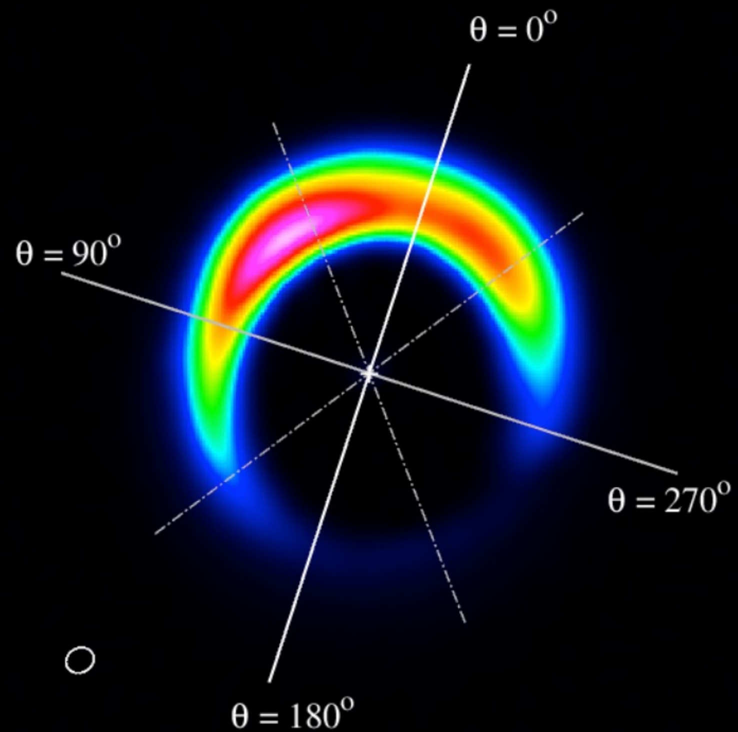
Dust supply is ***cut off!***

Double Peak Signature in Real Discs



V1247 Orionis

Kraus, S. et al. 2017



HD 142527

Boehler, Y. et al. 2021

What does it take to re-form a vortex?

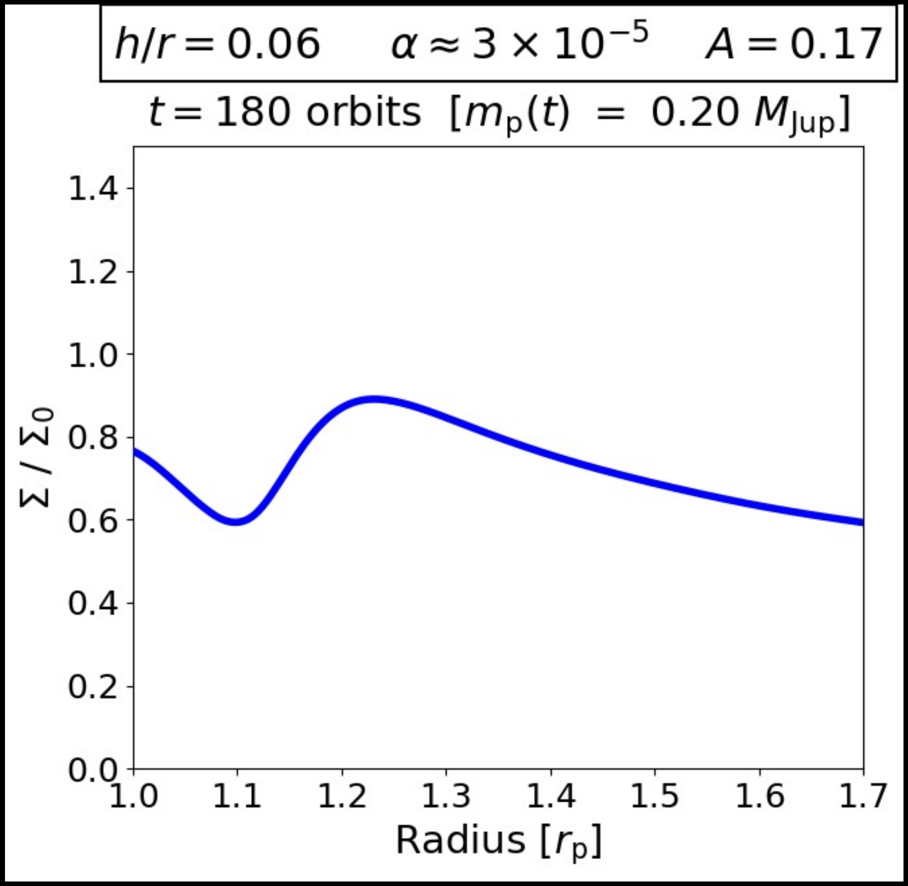
A new sharp pressure bump?

A sharp spike in $\Sigma / (\nabla \times \vec{v})$

Question #7

Pressure Bumps (with $0.6\ M_{Jup}$ planet)

Initial Vortex

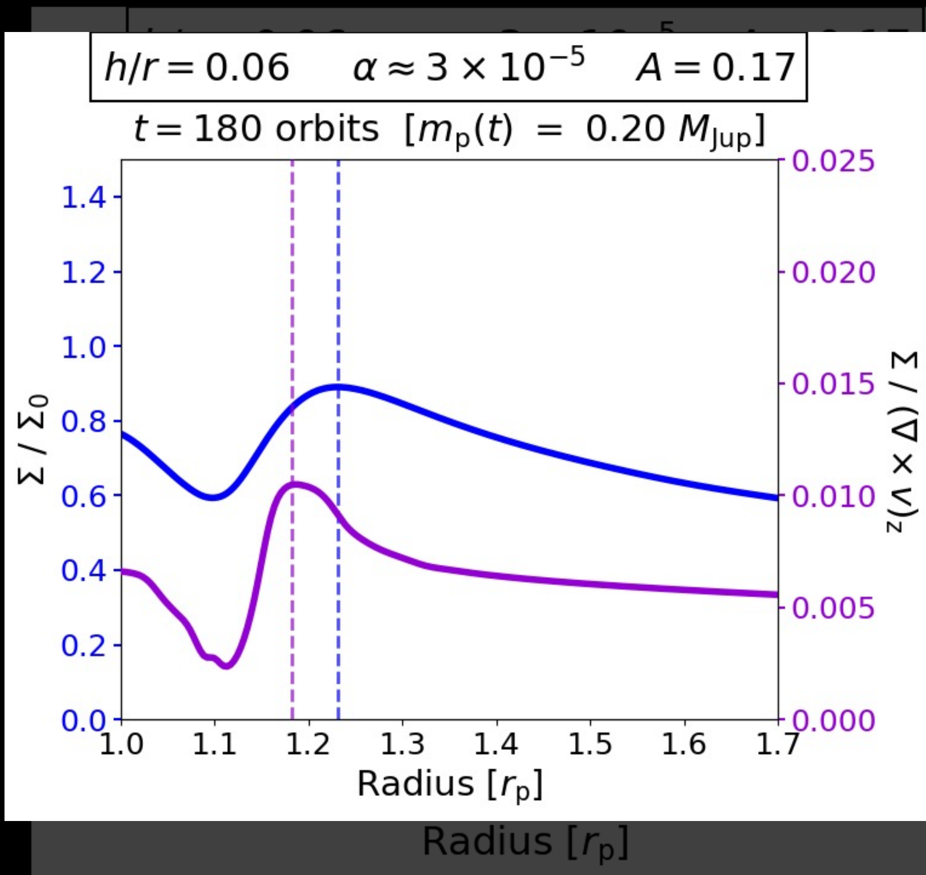


End State

MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

$\Sigma / (\nabla \times \vec{v})$ (with ***0.6 M_{Jup}*** planet)

Initial Vortex

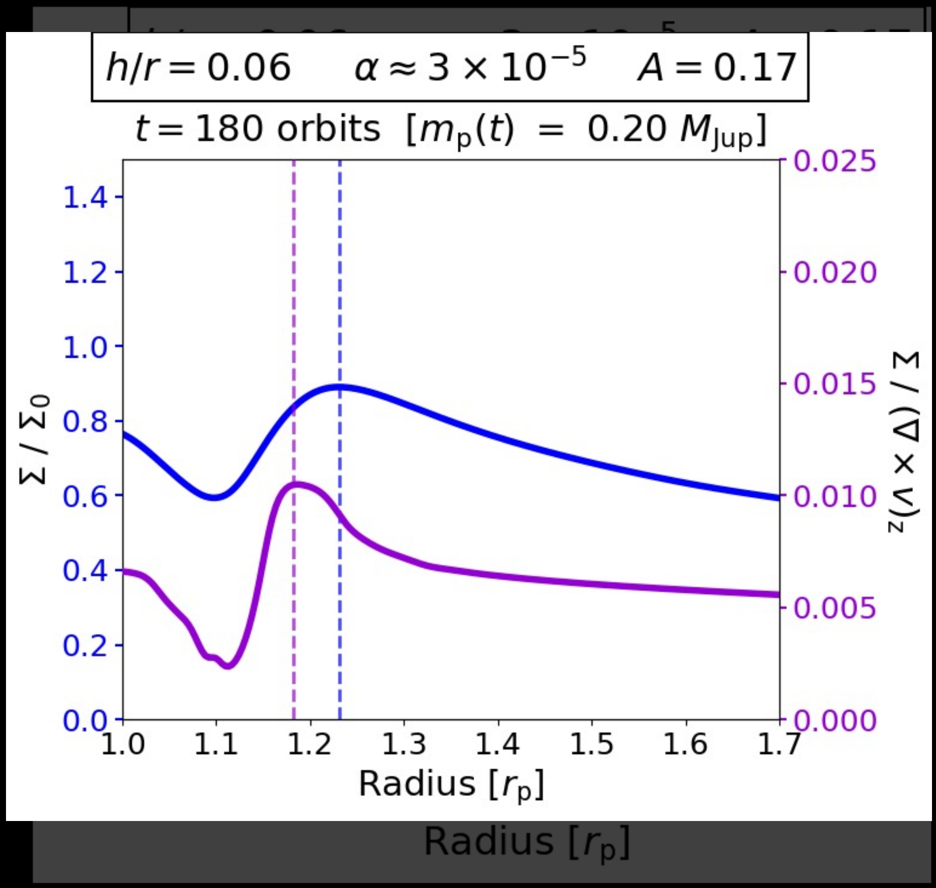


End State

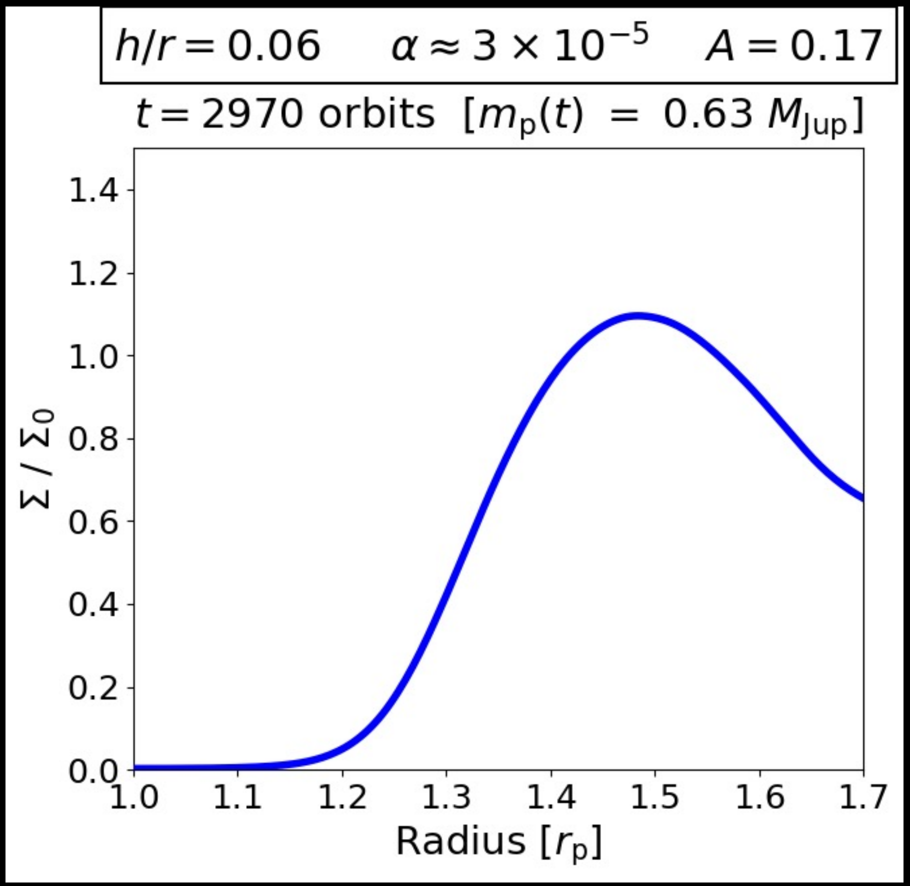
MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Pressure Bumps (with 0.6 M_{Jup} planet)

Initial Vortex



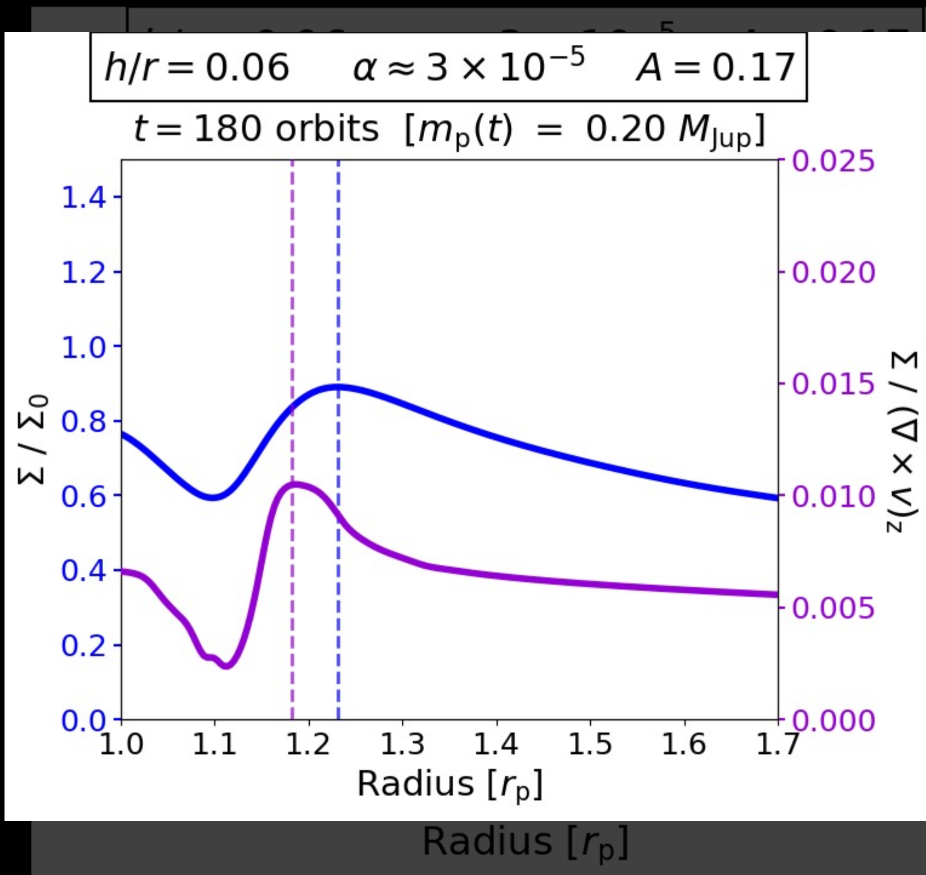
End State



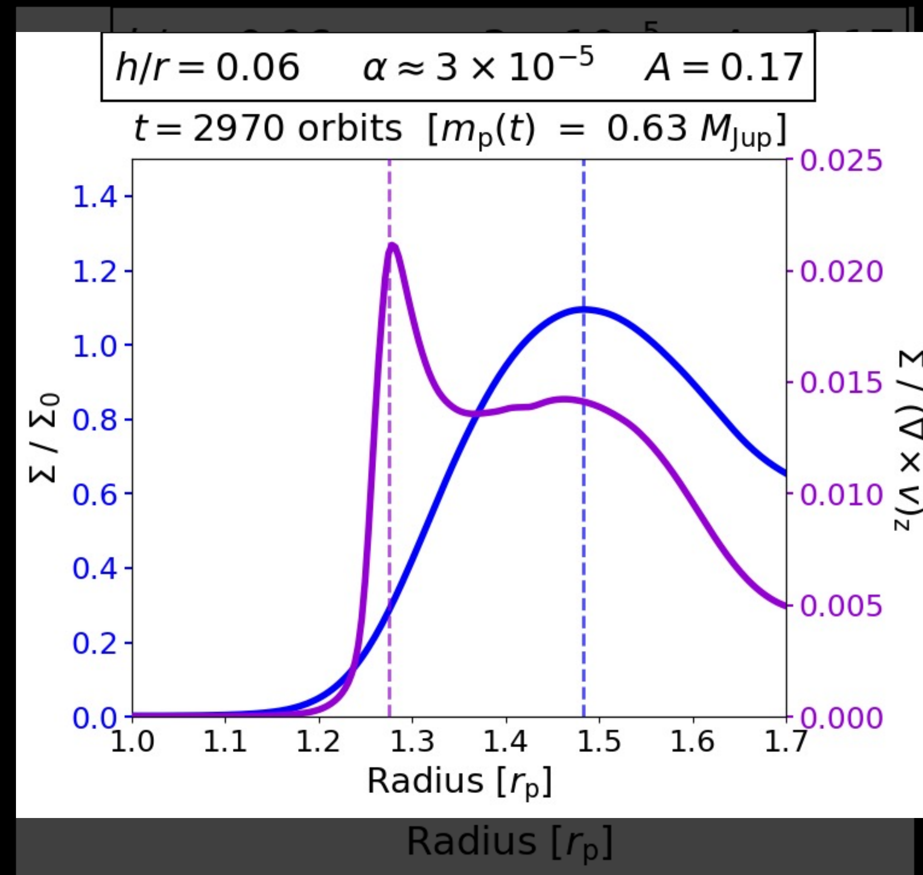
MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

$\Sigma / (\nabla \times \vec{v})$ (with ***0.6 M_{Jup}*** planet)

Initial Vortex

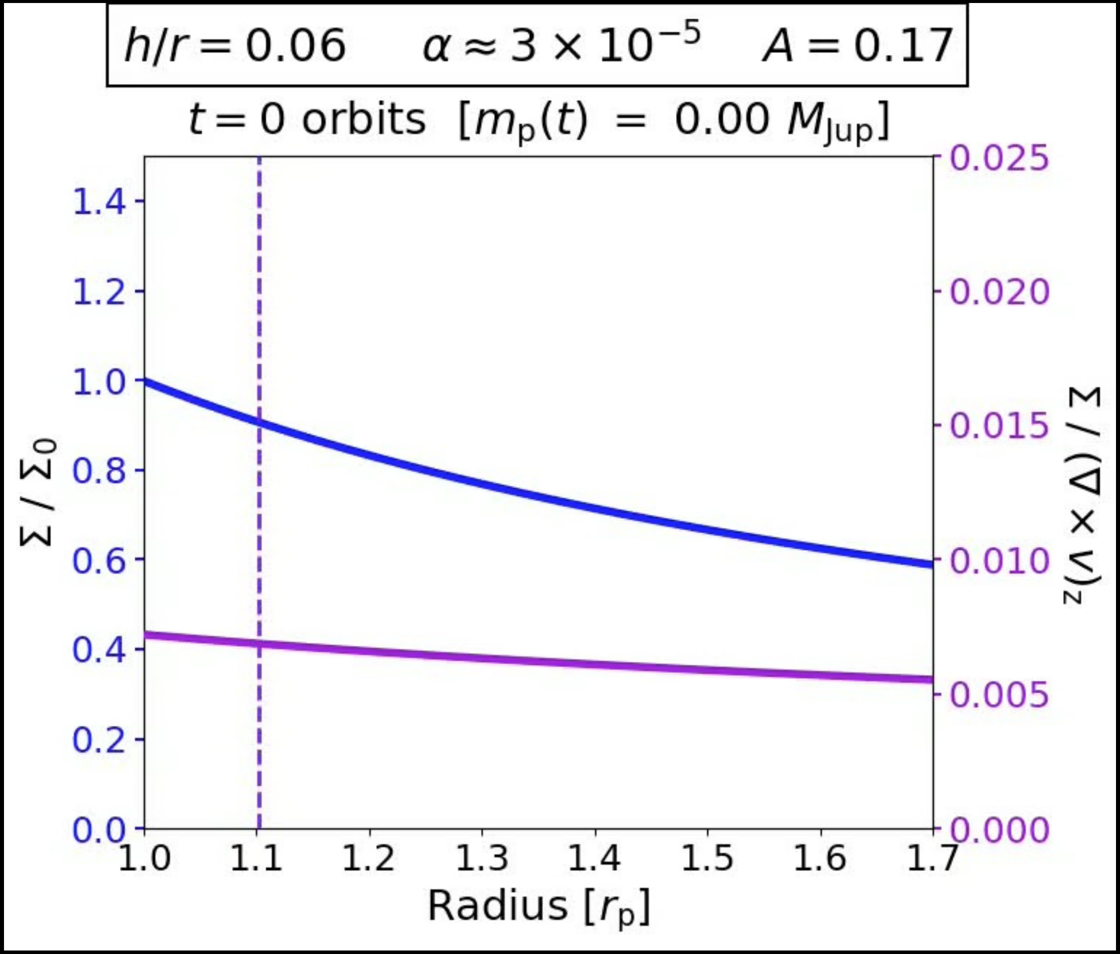


End State



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

$\Sigma \,/\, (\nabla \times \vec{v})$ Evolution (with ***0.6 M_{Jup}*** planet)



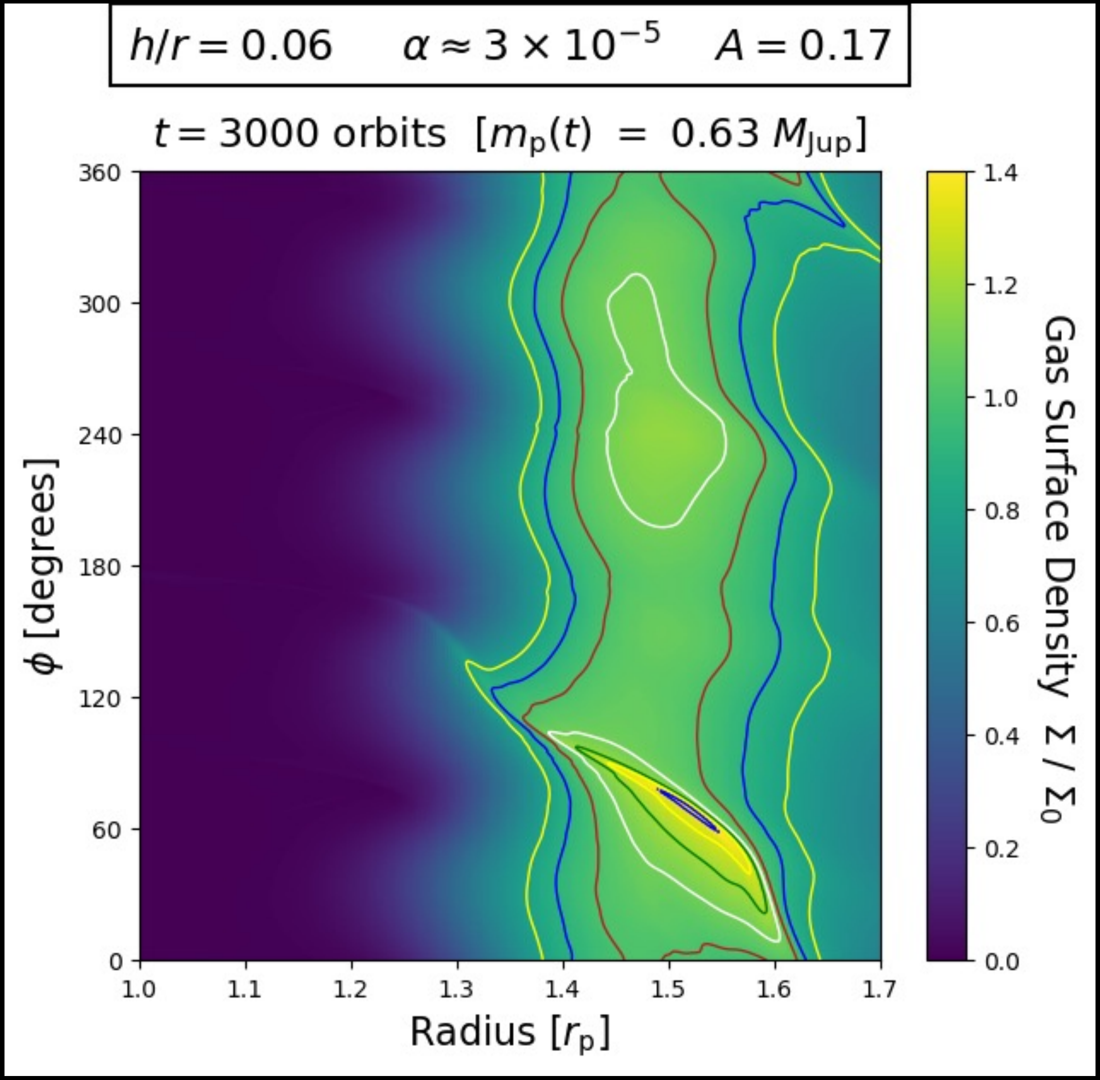
Notice:

A ***spike*** appears after the initial vortex dies (*t > 1350 orbits*).

But it doesn't affect the pressure bump!

MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Vortex Evolution (with ***0.6 M_{Jup}*** planet)



Notice:

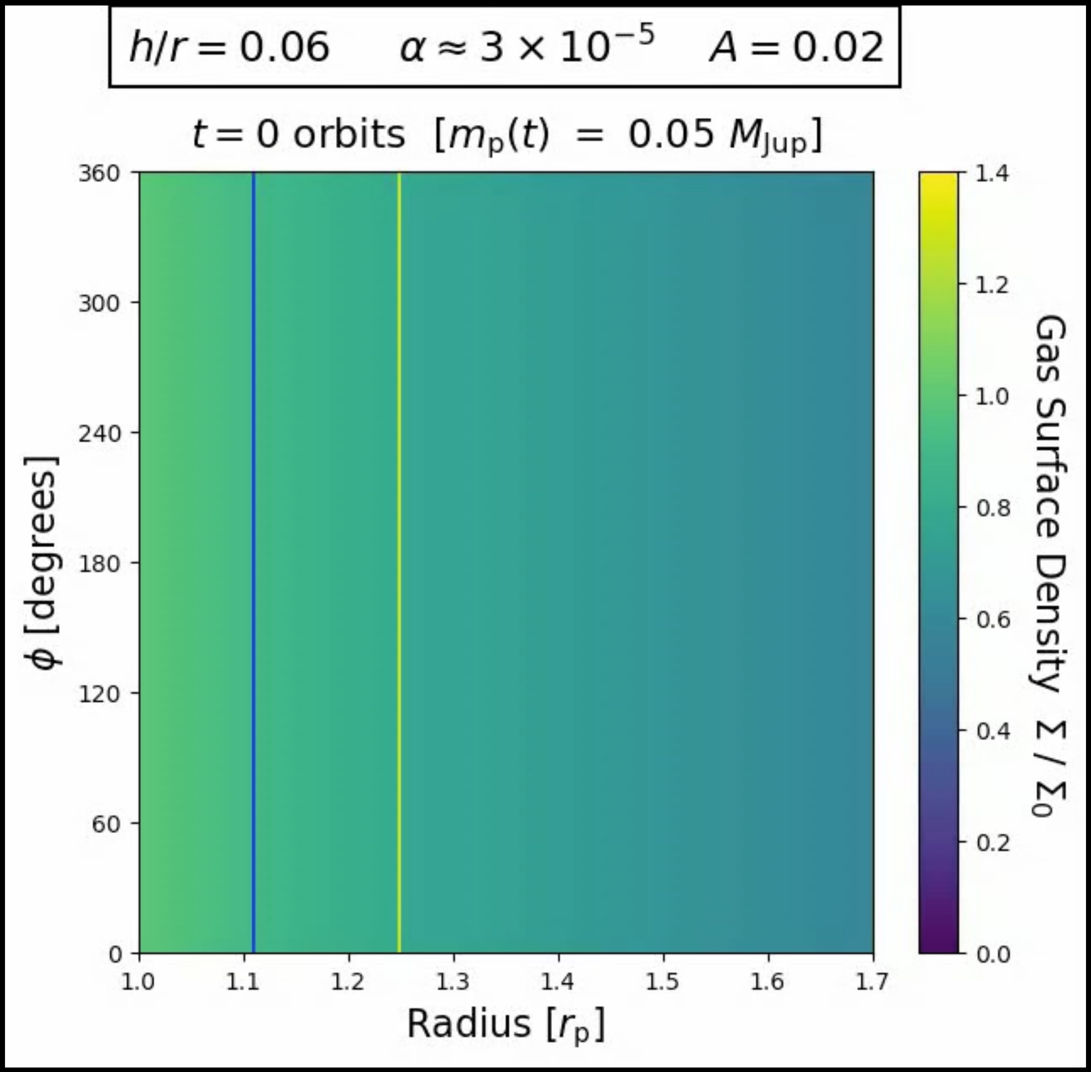
Vortex re-forms?

No, not at the pressure bump.

But vortices do re-form inside the pressure bump!

MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Vortex Evolution (with ***0.2 M_Jup*** planet)



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Notice:

Vortex re-forms?

Yes, multiple times:

t = 2610

t = 3150

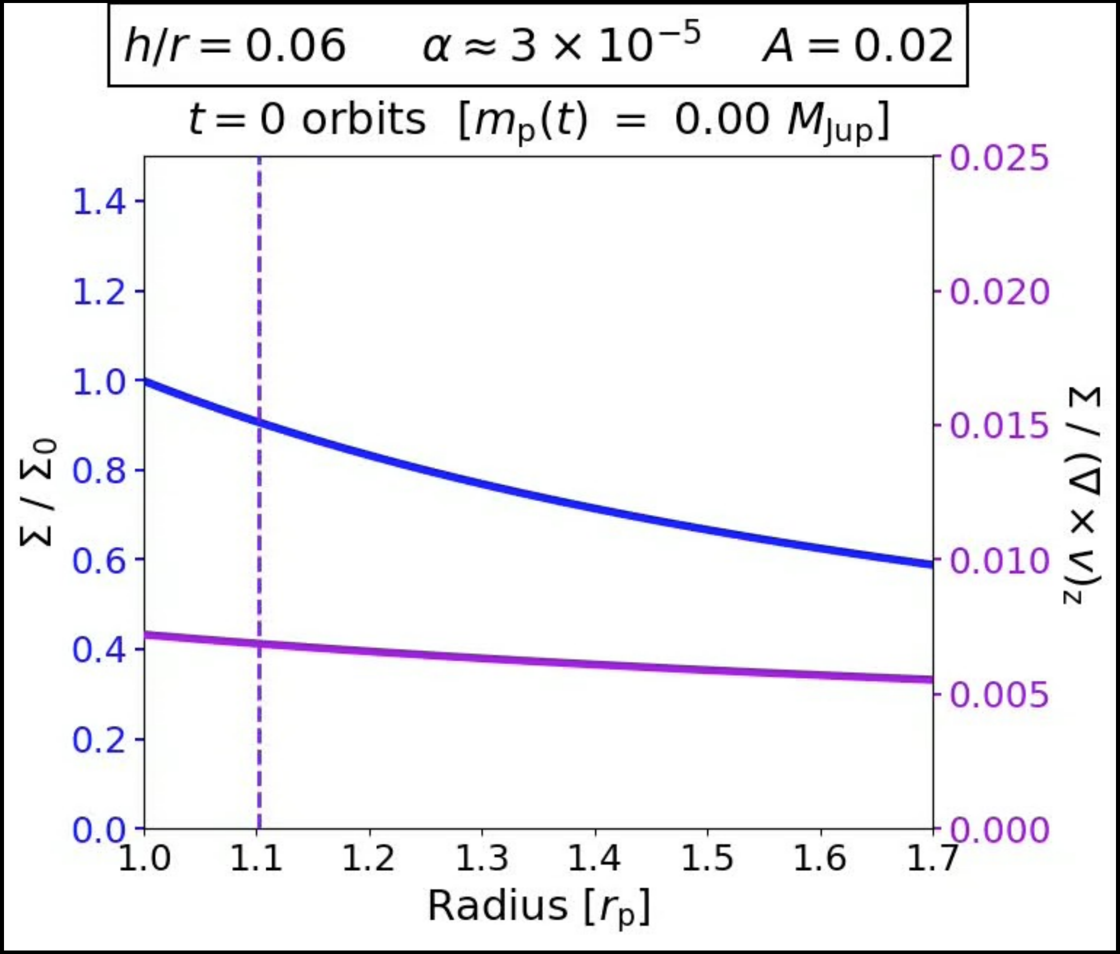
t = 3660

Lifetime

Vortex is still alive at the end of this movie:

t = 6000

$\Sigma / (\nabla \times \vec{v})$ Evolution (with ***0.2 M_{Jup}*** planet)



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2021
MNRAS, 504, 3963

Notice:

Tiny spikes appears after the initial vortex dies (t = *2350 orbits*).

They affect the whole pressure bump!

Separation must be less than 3 scale heights!

Early Vortex Evolution

...with Instant Growth:

(1) Planet grows to full size.

(2) Disk becomes unstable.

(3) A *compact* vortex forms.
(Ro < -0.15)

(4) Vortex smooths gap edge.

...with Slower Growth:

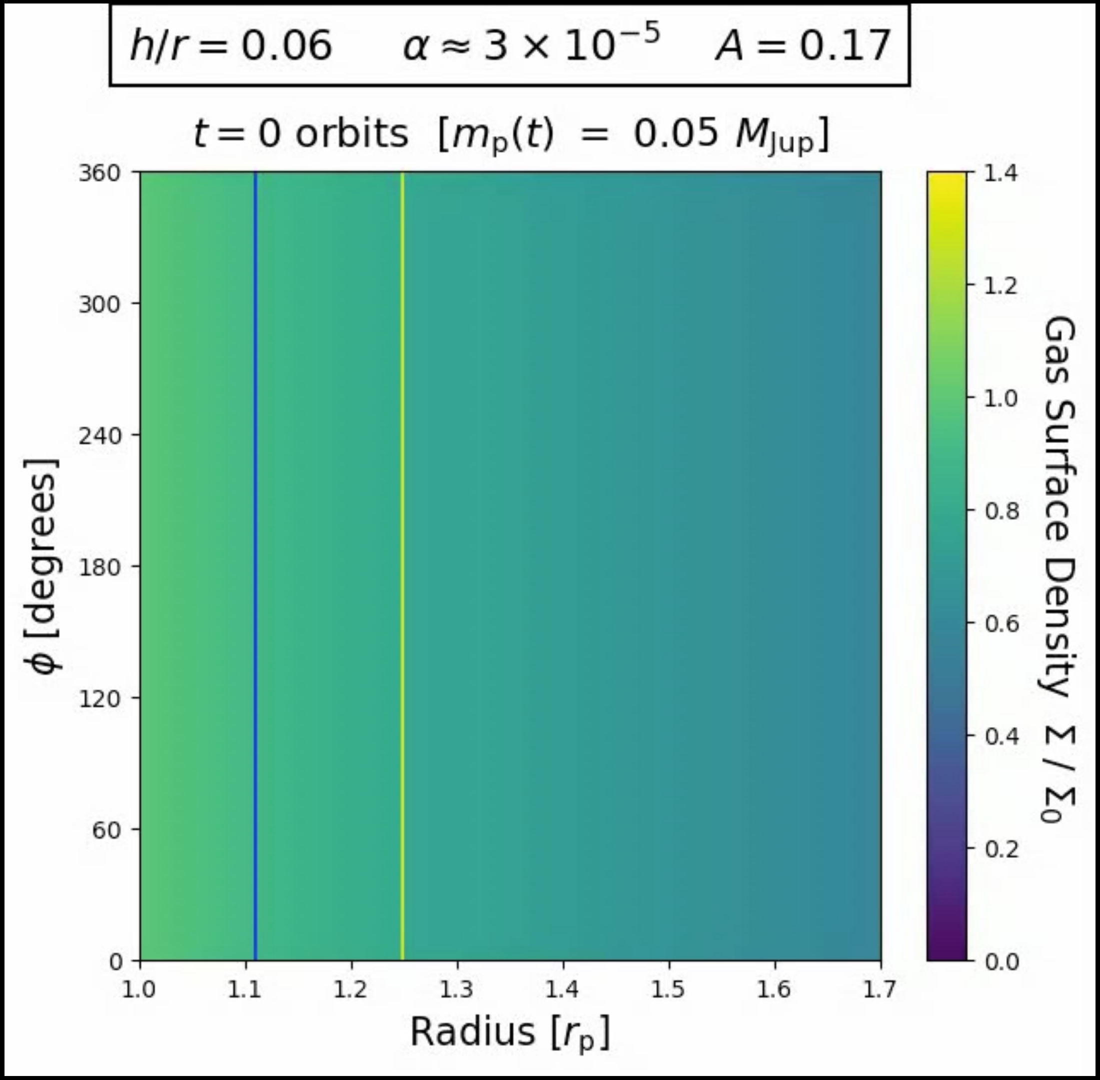
(1) Disk becomes unstable.

(2) An *elongated* vortex forms.
(Ro > -0.15)

(3) Vortex smooths gap edge.

(4) Planet grows to full size.

Vortex (with *H/R* = *0.06* and $0.6\ M_{Jup}$ planet)



MH, Lin, M.-K., Kratter, K., Pinilla, P., 2020
to be submitted

Notice:

Extent

Still very elongated!

Lifetime

Lasts ~1200 orbits.

(similar to the prescribed slow growth case)

Vortex re-forms?

No.