Rings, gaps, asymmetries, warps and clumps:

Linking ALMA features to planet formation

Nienke van der Marel
NRC Herzberg/University of Victoria
Great Barriers in Planet formation
July 23rd 2019
@NienkeMarel

~~Rings, gaps~~, Asymmetries, warps and clumps:

Linking ALMA features to planet(?) formation

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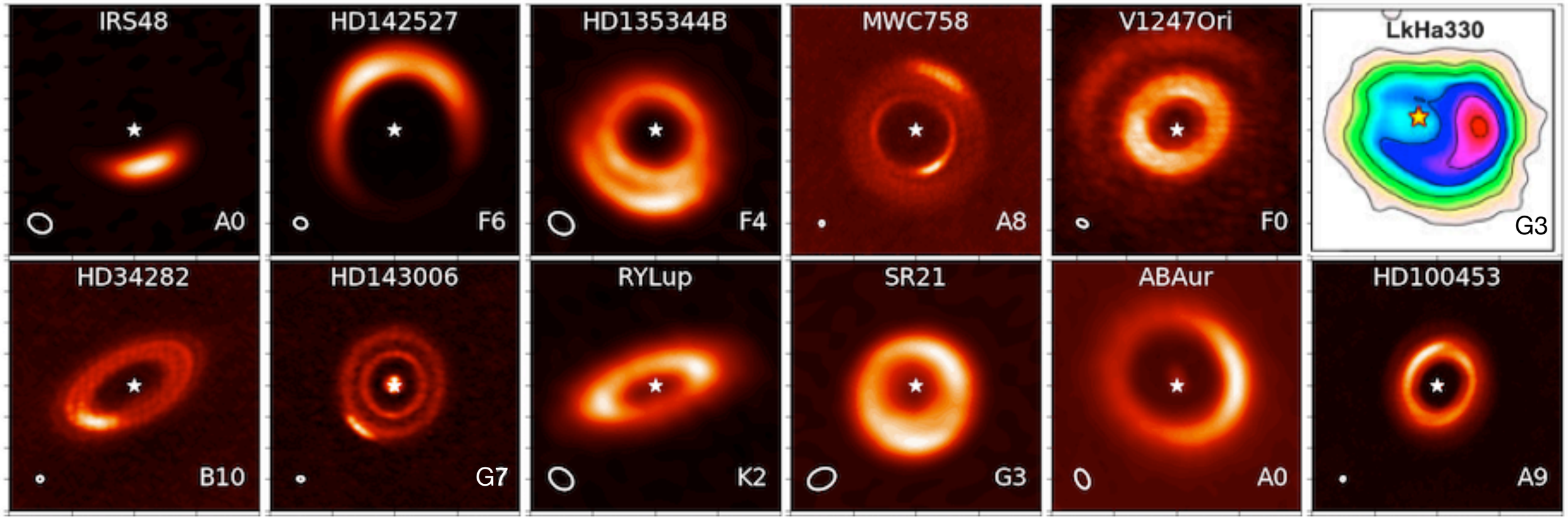
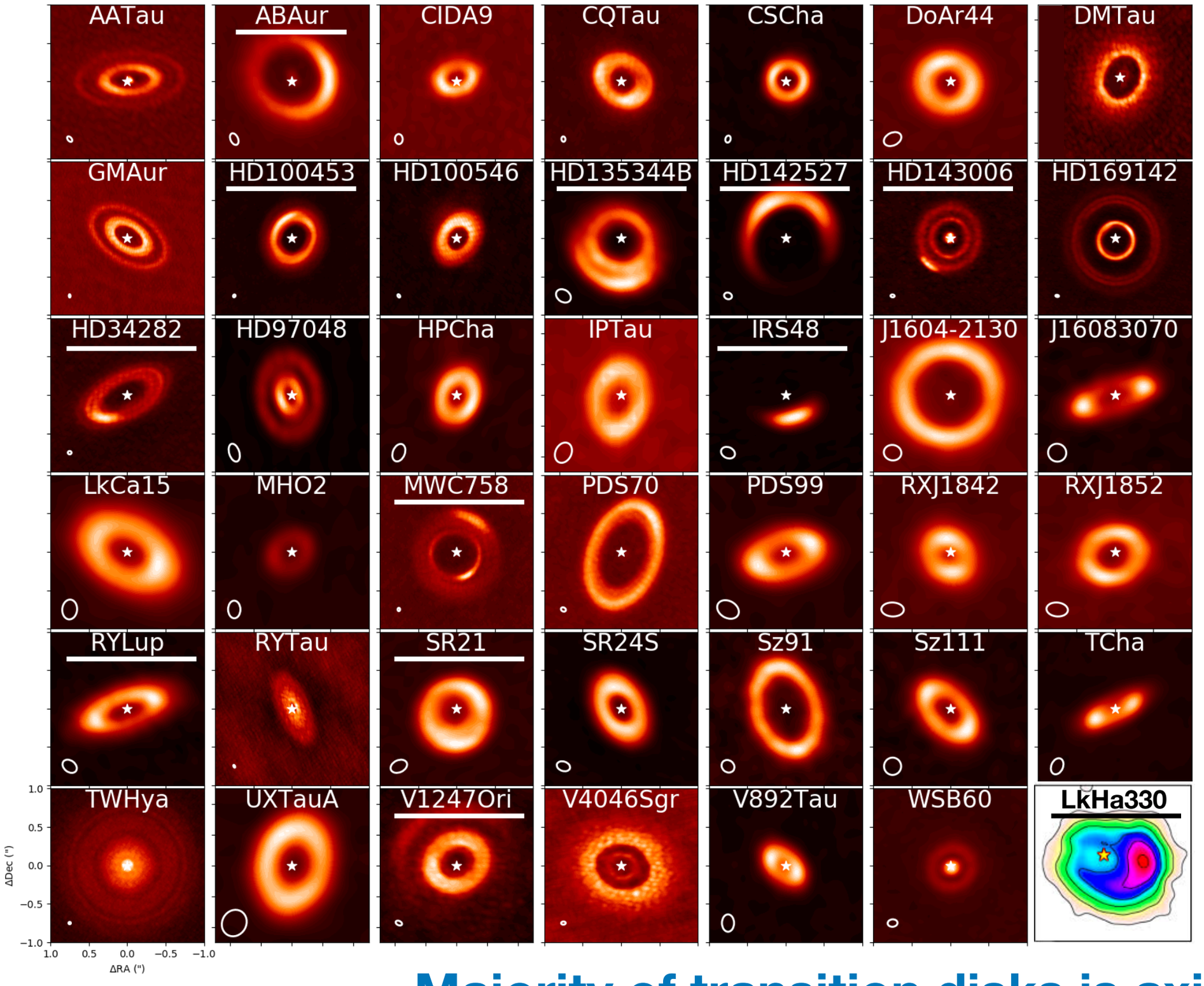
ALMA asymmetries



Large variety of asymmetric dust rings in protoplanetary disks

All asymmetries are intermediate-mass stars: 1.4-2.4 M_o,
but not all IM stars have asymmetries

ALMA transition disks

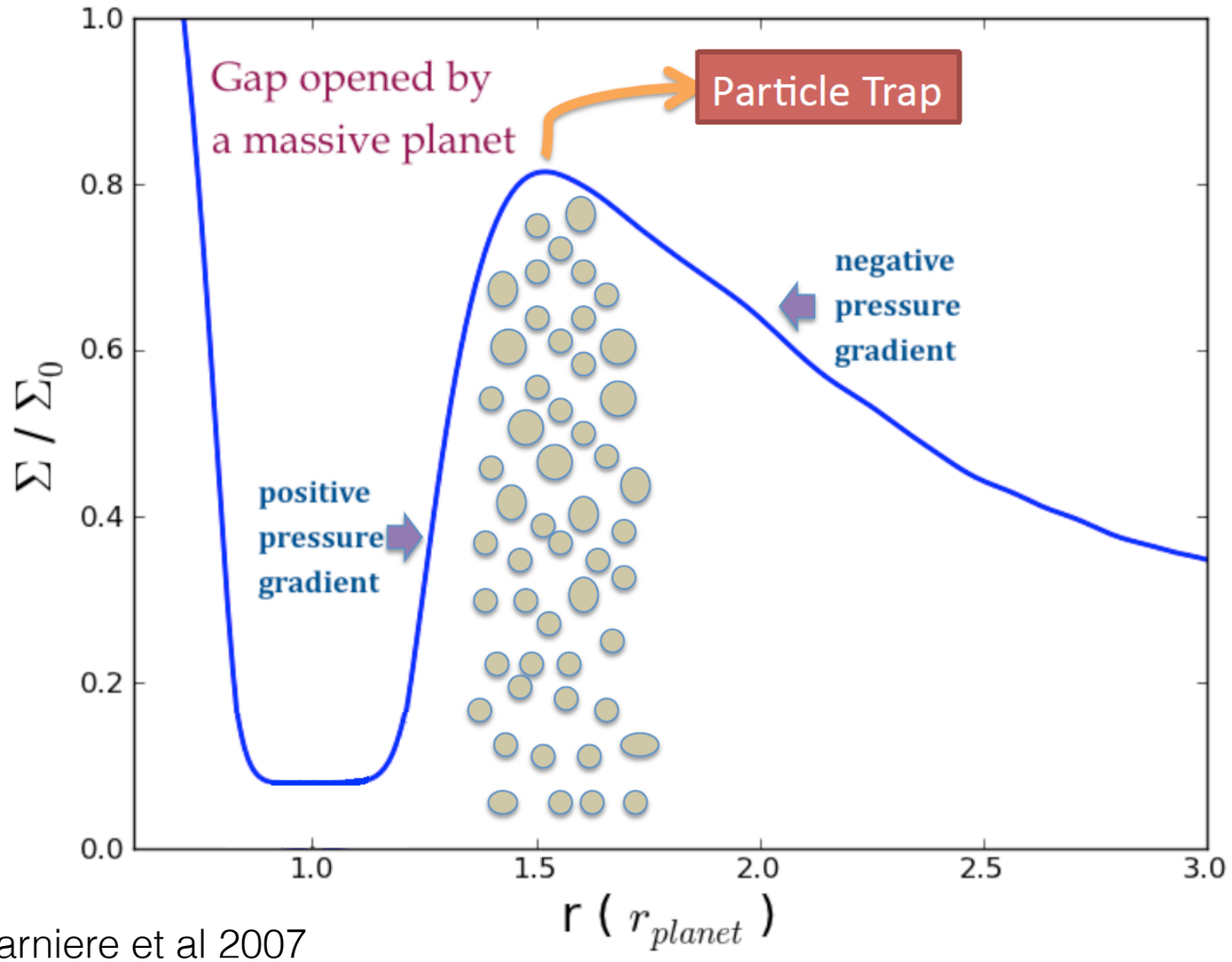


Majority of transition disks is axisymmetric

Dust trapping

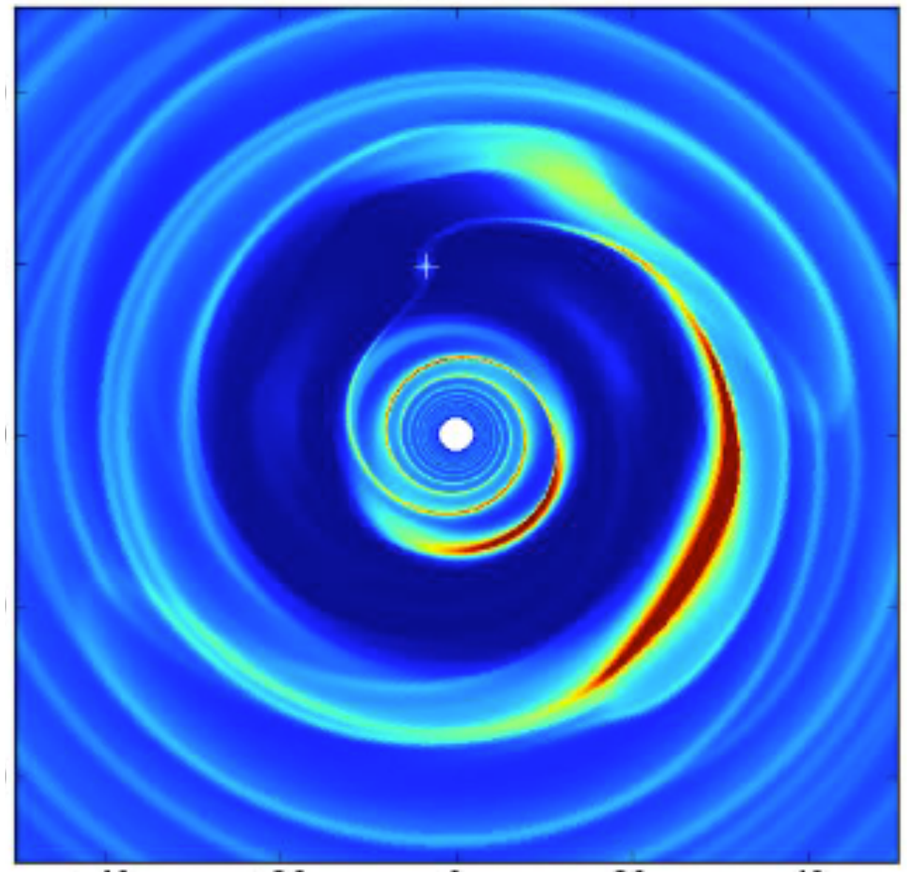
Due to gas-dust drag forces, larger dust particles move towards highest pressure

A pressure bump at the edge of a planet gap acts as dust trap



Varniere et al 2007
Pinilla et al. 2012
Zhu et al. 2012

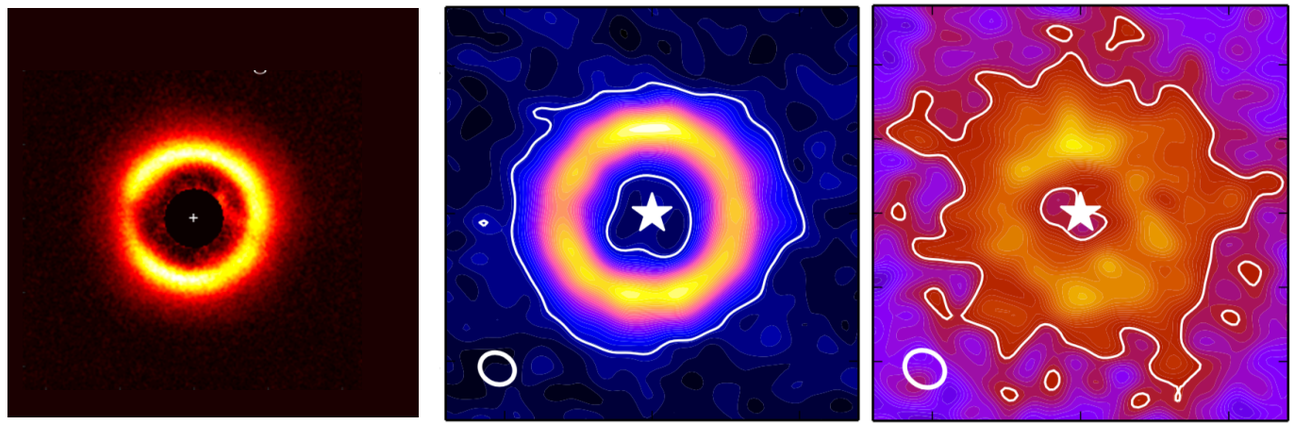
A radial pressure bump can become unstable under Rossby Wave Instability and form vortices



Dust trapping in transition disks

J1604-2130

Small dust | **Large trapped dust** | **Gas**

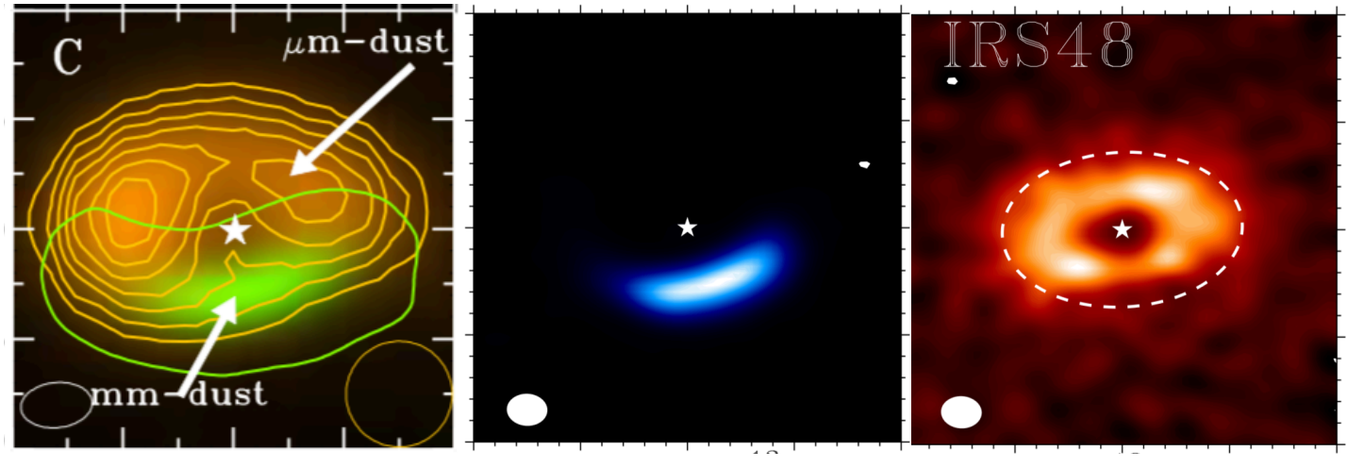


NIR (Subaru) | 1.3mm (ALMA) | ^{13}CO (ALMA)

Radial trapping

Distinct distribution of mm-dust and gas/small grains shows trapping!

IRS48



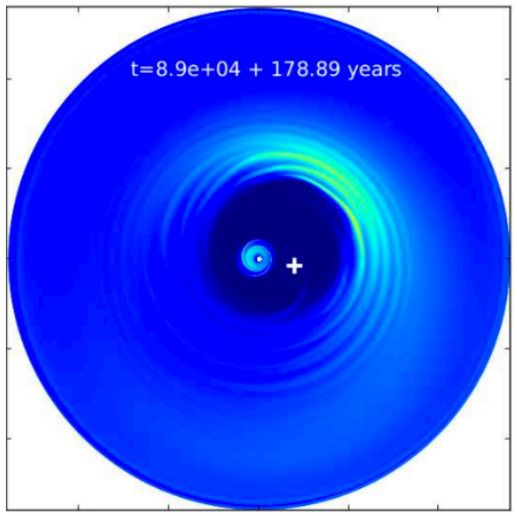
MIR (VISIR) | 0.5mm (ALMA) | ^{13}CO (ALMA)

Azimuthal trapping

Van der Marel et al. 2013, 2016
Dong et al. 2017

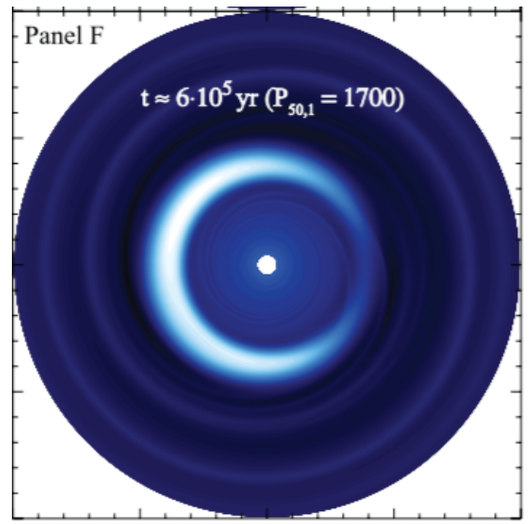
Mechanisms asymmetry

1. Jupiter planet: eccentric cavity



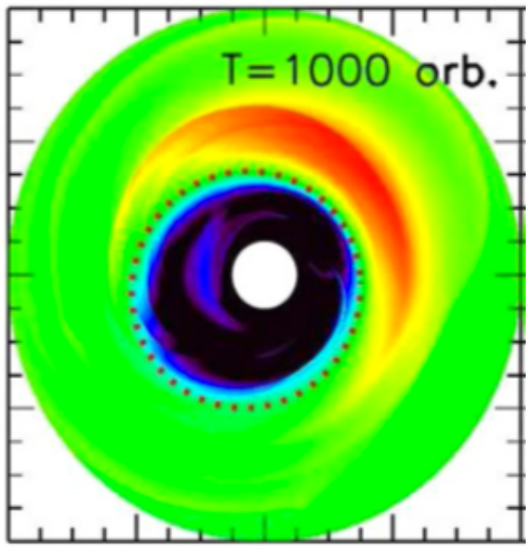
e.g. Ataiee et al. 2013, Pinilla et al. 2016

2. Dead zone: RWI vortex (ionization gradient)



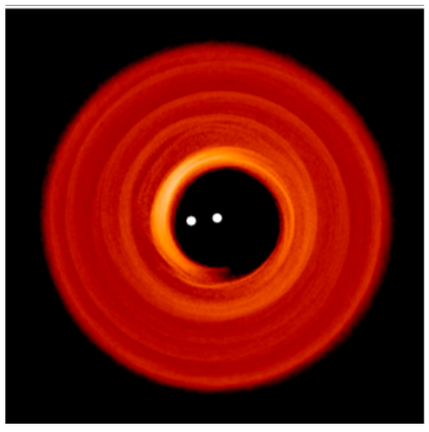
e.g. Regaly et al. 2012

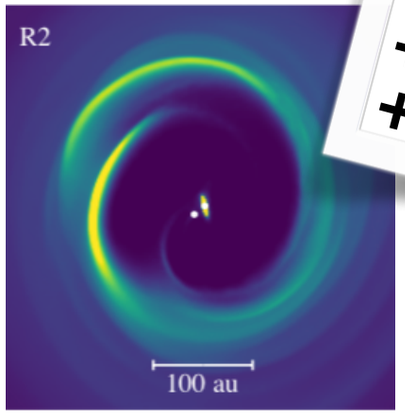
3. Jupiter planet: RWI vortex (density gradient)



e.g. Barge & Sommeria 1995, Lyra & Lin 2013,
Zhu & Stone 2014

4. Stellar companion at misaligned/coplanar orbit: eccentric cavity with gas overdensity





See talk Ragusa
+ poster Hirsh
+ T-shirt Calcino

e.g. Ragusa et al. 2017, Price et al. 2018

Mechanisms signatures

1. Jupiter planet: eccentric cavity

- ✓ Gas cavity
- ● Dust asymmetry
- ✗ Trapping
- ✗ Orbital motion
- ● Companion

2. Dead zone: RWI vortex (ionization gradient)

- ✗ Gas cavity
- ✓ Dust asymmetry
- ✓ Trapping
- ✓ Orbital motion
- ✗ Companion

3. Jupiter planet: RWI vortex (density gradient)

- ✓ Gas cavity
- ✓ Dust asymmetry
- ✓ Trapping
- ✓ Orbital motion
- ● Companion
  - + Low viscosity ($\alpha \sim 10^{-4}$)
  - + Vortex kinematics

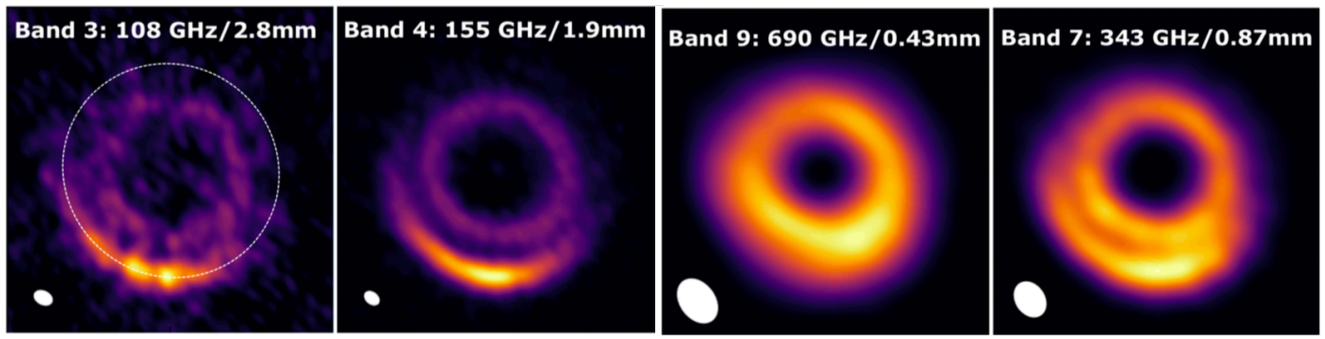
4. Stellar companion: eccentric cavity

- ✓ Gas cavity
- ✓ Dust asymmetry
- ✓ Trapping
- ✓ Orbital motion
- ✓ Companion
  - + Eccentric cavity

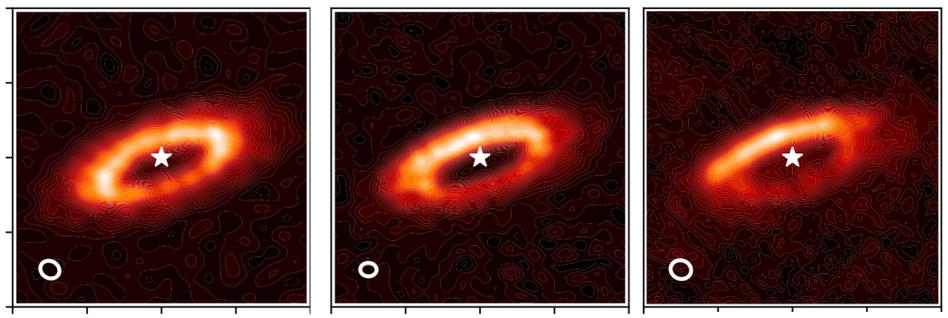
1. Eccentric cavity?

If eccentric, no trapping occurs:
no wavelength dependence expected for width

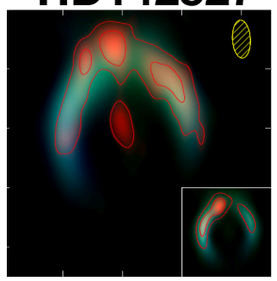
HD135344B



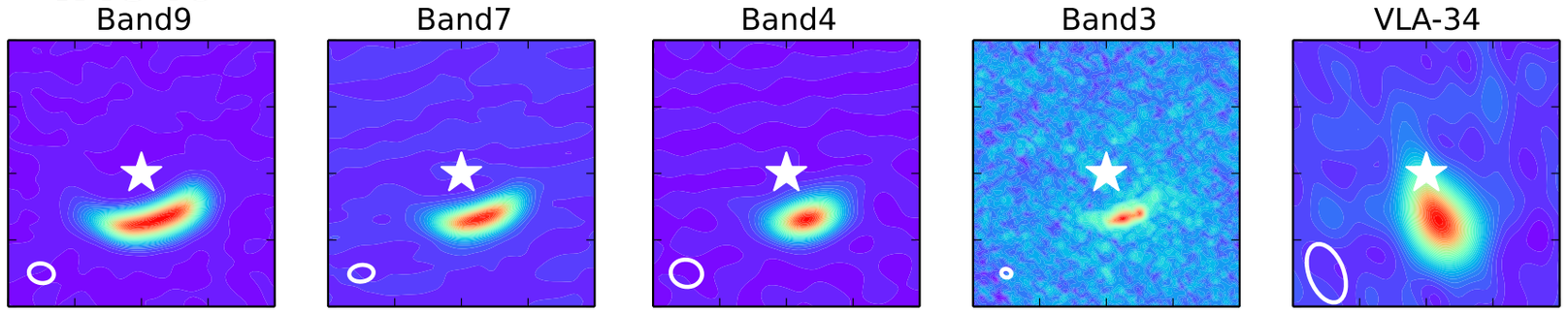
RY Lup



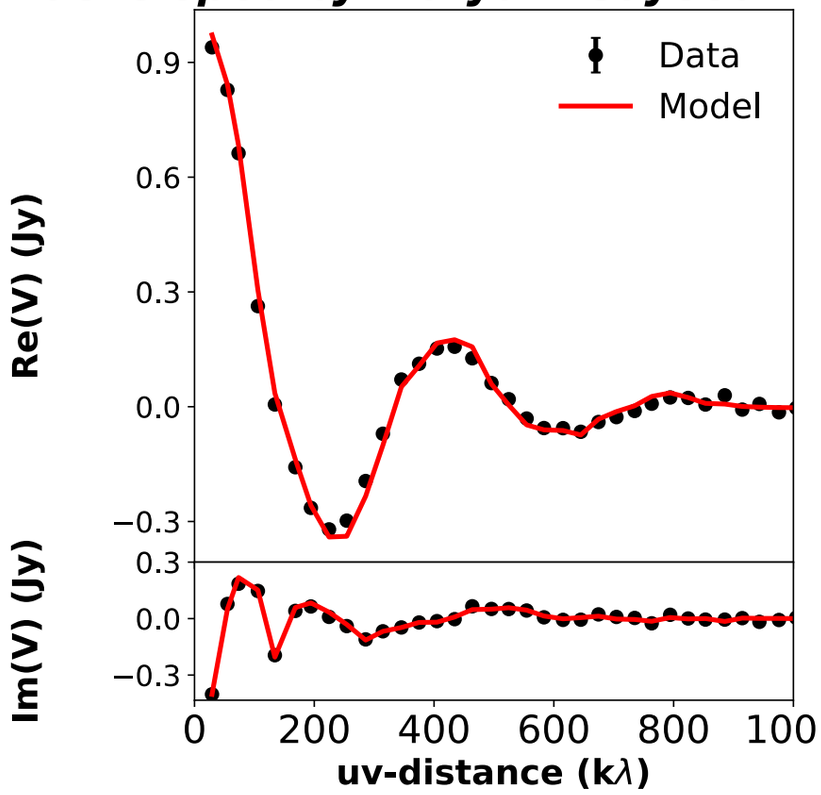
HD142527



IRS48



Modeling asymmetries with GALARIO (Tazzari+2018) developed by Maryum Sayeed

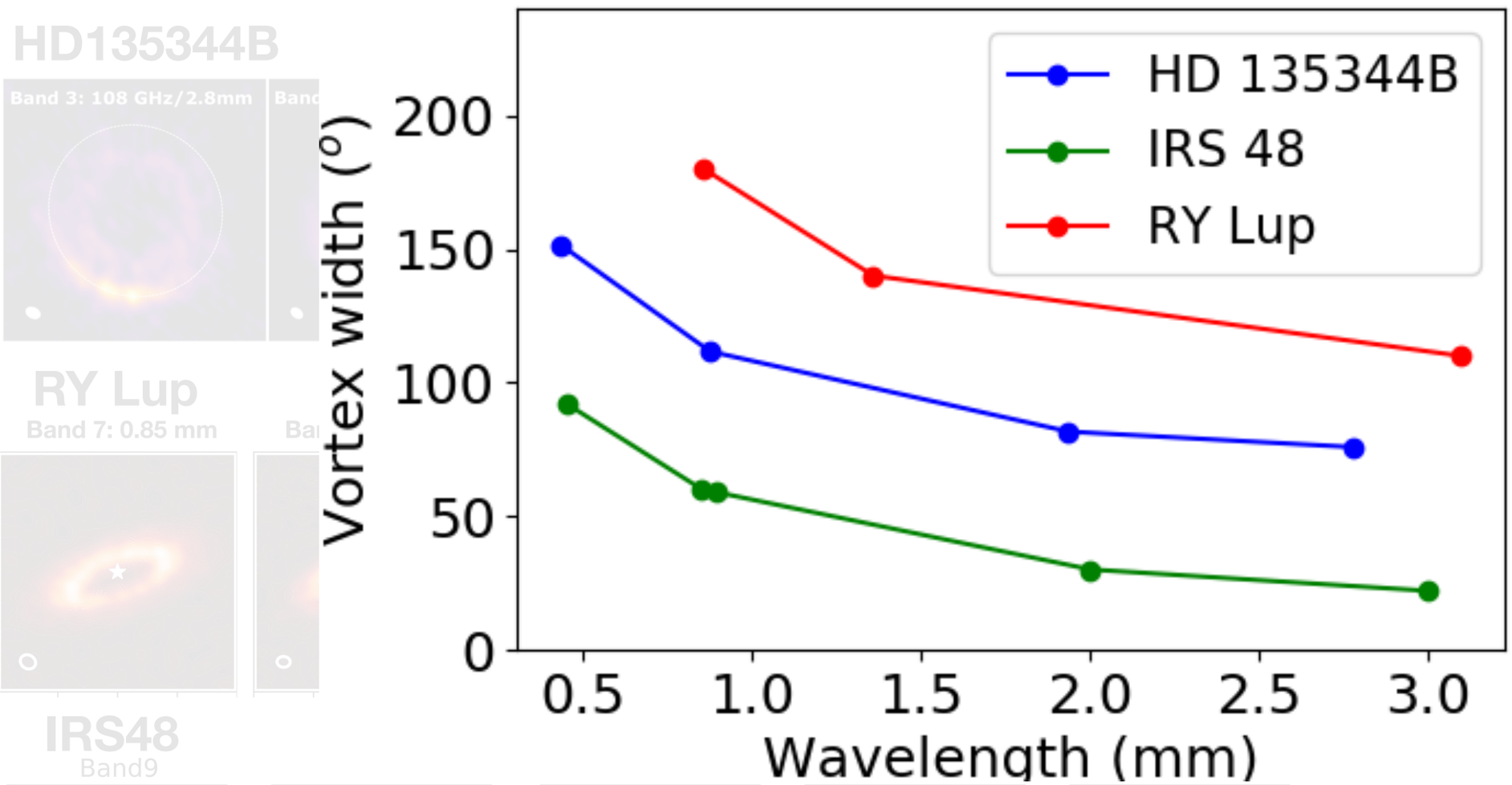


HD100453: see talk Laura Perez

Cazzoletti et al. 2018
Van der Marel et al. 2015 & in prep.

1. Eccentric cavity?

If eccentric, no trapping occurs:
no wavelength dependence expected for width

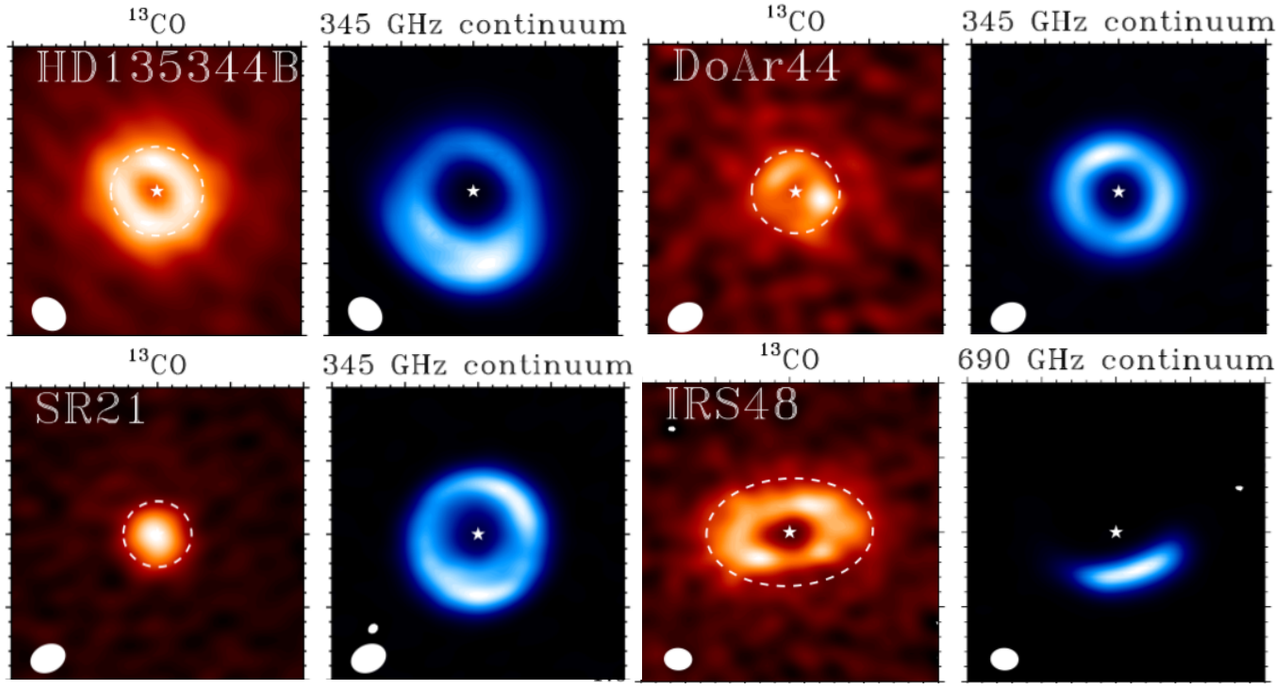


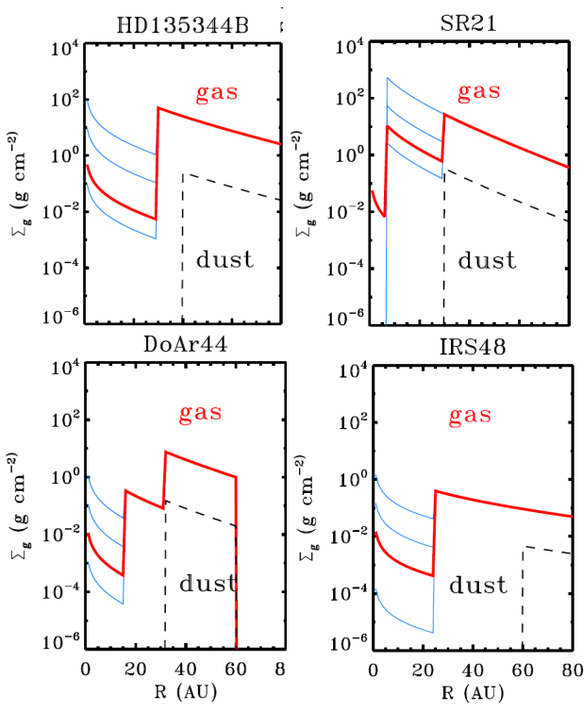
Multi-wavelength observations are consistent with trapping, not eccentricity

Cazzoletti et al. 2018
Van der Marel et al. 2015 & in prep.

2. Dead zone?

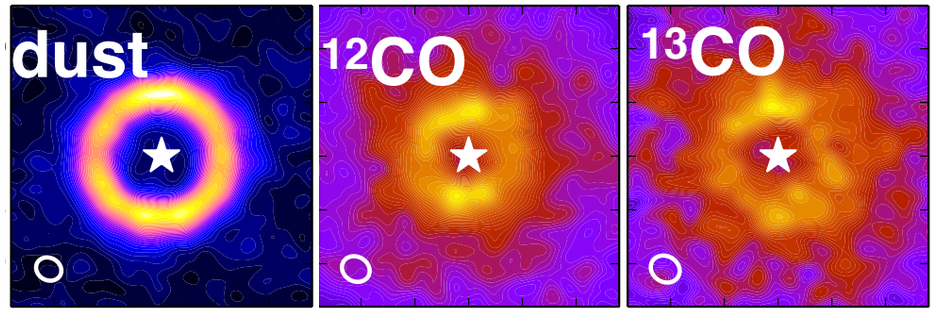
If dead zone, no deep gap expected in the gas



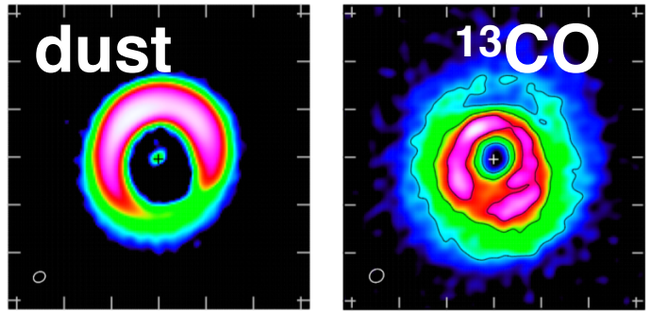


All (a)symmetric transition disks observed to date have deep gas cavities < dust cavities

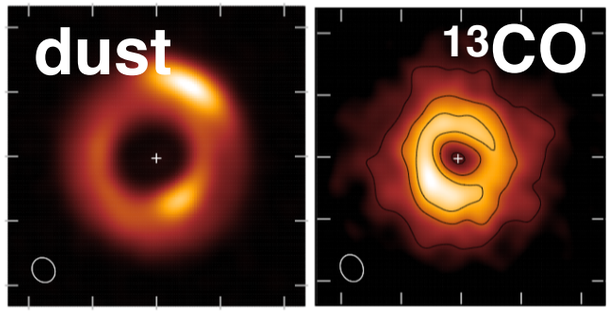
J1604-2130



HD142527



MWC758



Van der Marel et al. 2016
Dong et al. 2017
Boehler et al. 2017, 2018

Mechanisms signatures

1. Jupiter planet: eccentric cavity

- ✓ V…
- ● D… …etry
- ✗ T…
- ✗ …
- ✗ …mpan…

2. Dea… …e: RWI v… …onization gradient)

- ✓ C…
- ✓ …nmetry
- ✓ …
- ✗ …
- ✗ …on
- ✗ Comp…

Not mutually exclusive

3. Jupiter planet: RWI vortex (density gradient)

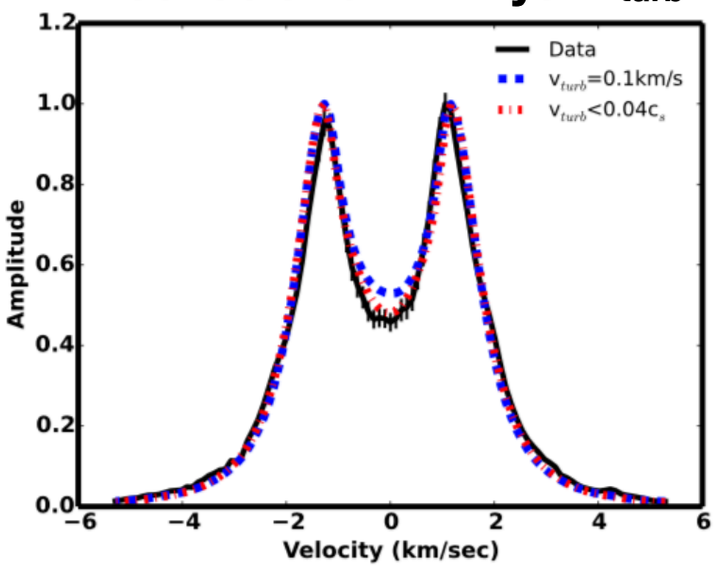
- ✓ Gas cavity
- ✓ Dust asymmetry
- ✓ Trapping
- ✓ Orbital motion
- ● Companion
  - + Low viscosity ($\alpha \sim 10^{-4}$)
  - + Vortex kinematics

4. Stellar companion: eccentric cavity

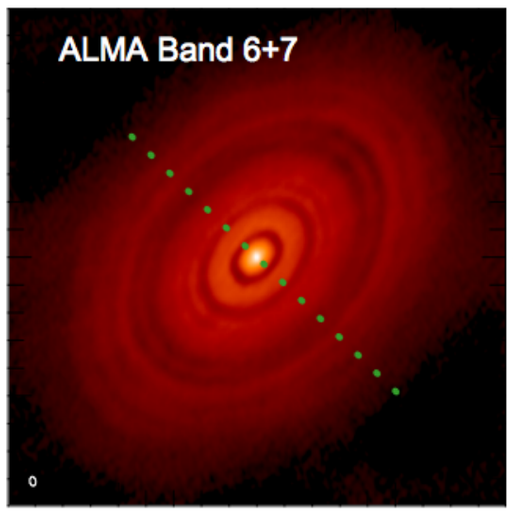
- ✓ Gas cavity
- ✓ Dust asymmetry
- ✓ Trapping
- ✓ Orbital motion
- ✓ Companion
  - + Eccentric cavity (hard to measure)

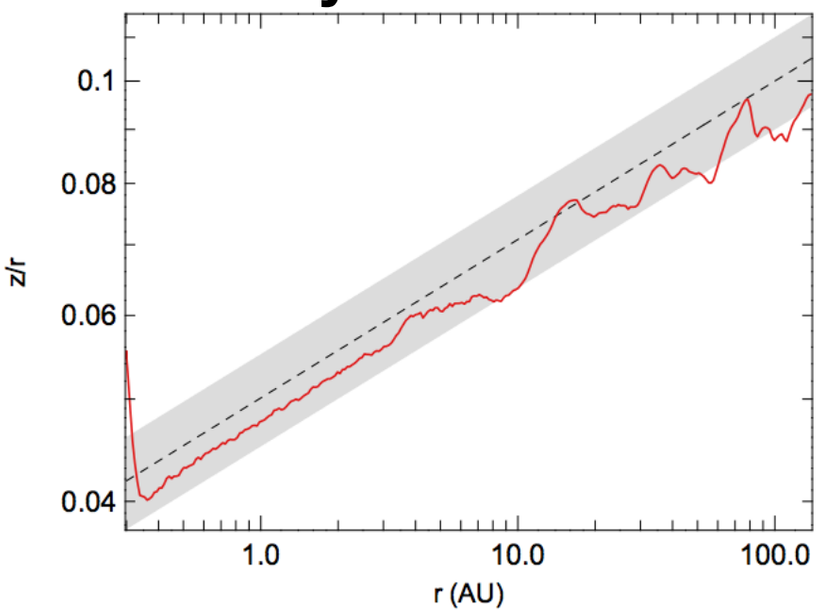
Viscosity?

Line width measurements in HD163296 and TW Hya: v_{turb} <0.1 c_s



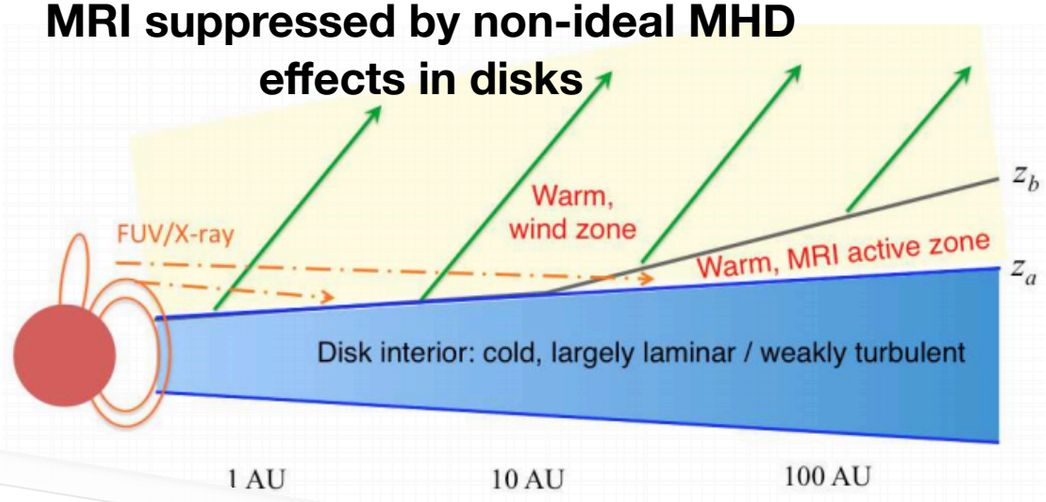
HL Tau geometrically thin: α ~ 10^{-4}



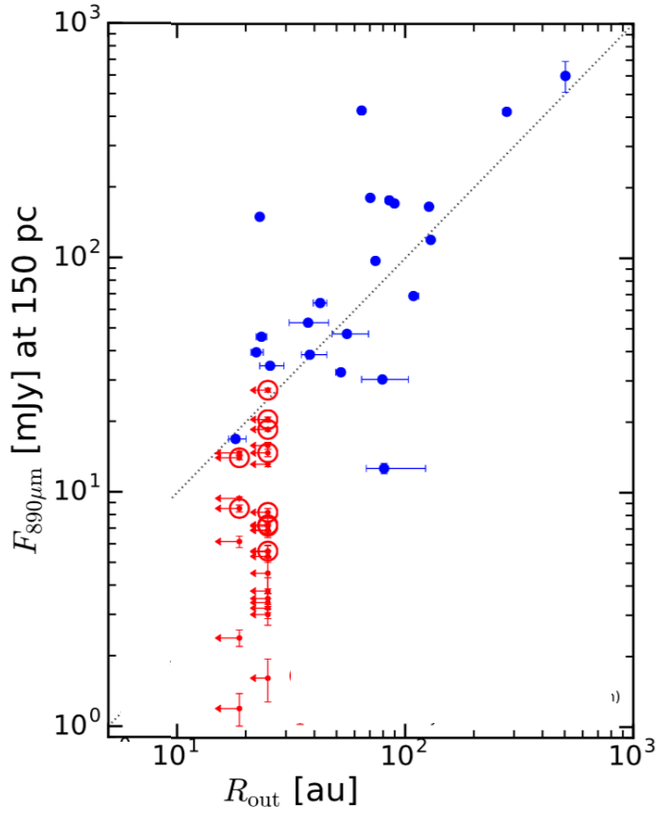


Disk turbulence is low!

MRI suppressed by non-ideal MHD effects in disks



See talk Bai



Many disks in surveys are small (<25 au)…

Flaherty et al. 2015
Pinte et al. 2016
Ansdell et al. 2018
Bai & Stone 2013, 2016

Vortex kinematics

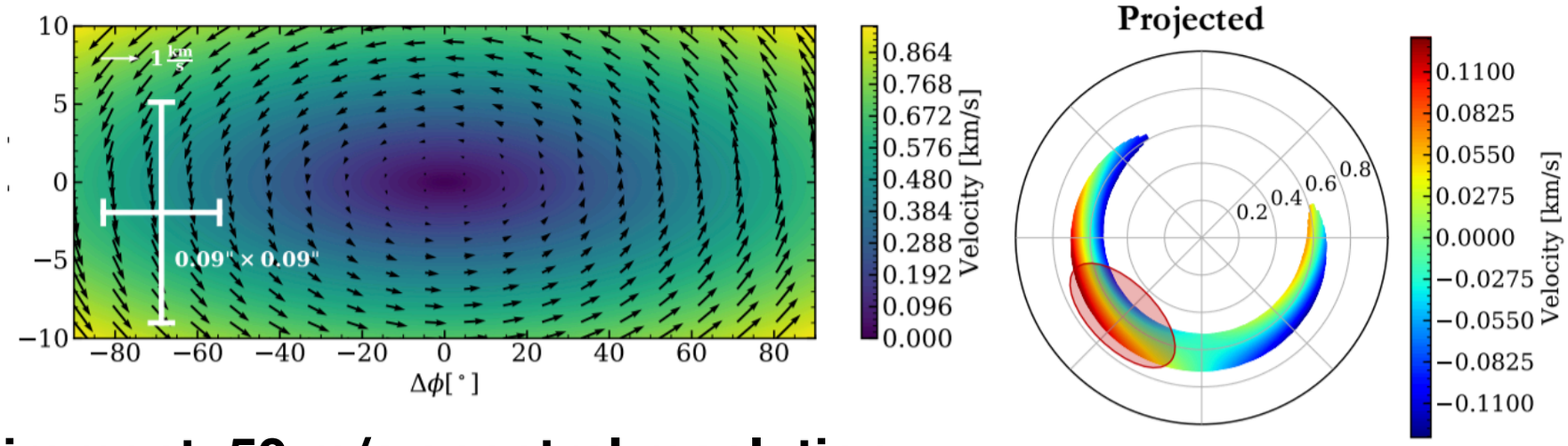
Vortex kinematics: Kida solution

$$v_\phi = \Omega_{\rm Vortex} \Delta r \Gamma$$

$$v_r = -\Omega_{\rm Vortex} \frac{r \Delta \phi}{\Gamma}$$

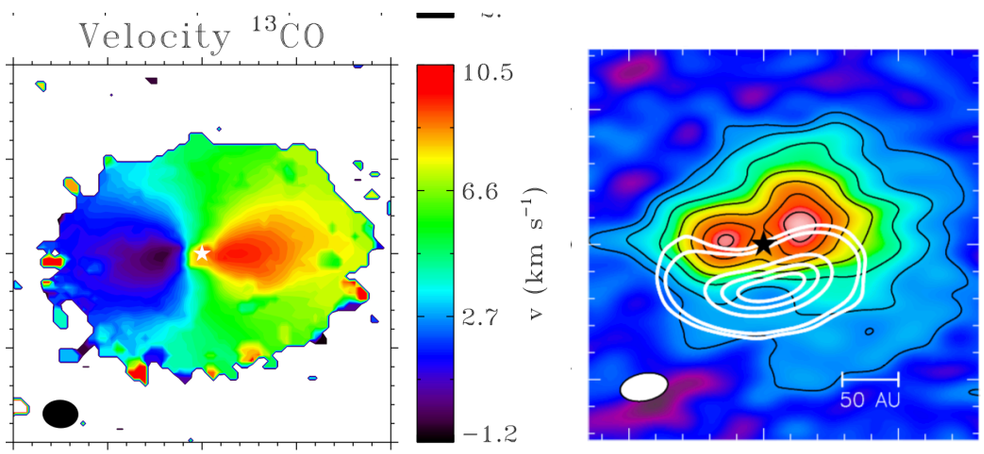
$$\Omega_{\rm Vortex} = -\frac{3}{2\,(\Gamma - 1)} \Omega_{\rm Kepler}$$

Predictions for HD135344B



Requirement: 50 m/s spectral resolution (current ALMA observations ~0.2 km/s)

Oph IRS 48: complicated due to continuum and line absorption



But see talk Boehler?

Kida 1981
Bruderer et al. 2014
Van der Marel et al. 2016
Cazzoletti et al. priv.

Planet or stellar companion?

1. Direct imaging constraints on companion mass

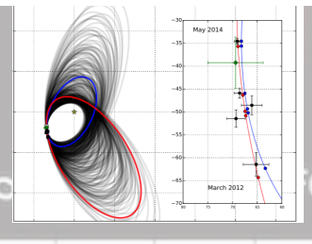
Lacour+2016 | Maire+2017 | Reggiani+2017 | Willson+2019 | Willson+2016

IRS48

Not possible due to extinction

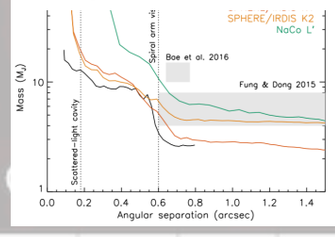
HD142527

Substellar companion ~0.3 $M_\odot$! 😊



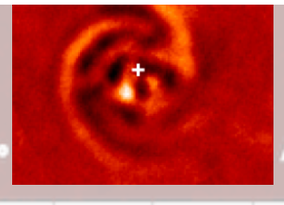
HD135344B

No planets ~10 M_{Jup} > 25 au



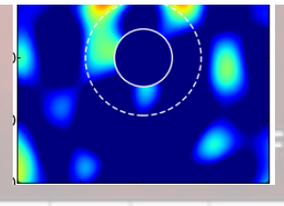
MWC758

Substellar or planetary+CPD companion at 20 au



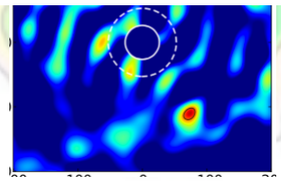
V1247Ori

High mass/high accretion object at 6 au (SAM)

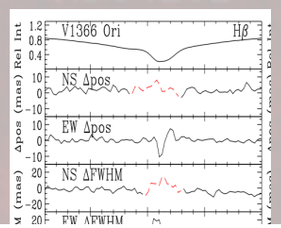


TkHa330

High mass/high accretion object at 37 au (SAM)



HD34282



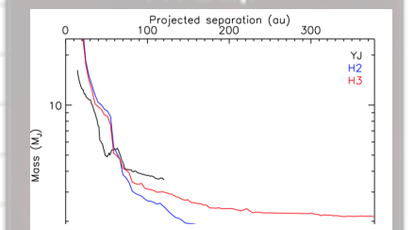
Spectroastrometry: binary <30 au

Wheelwright+2010

HD143006

No candidate study?

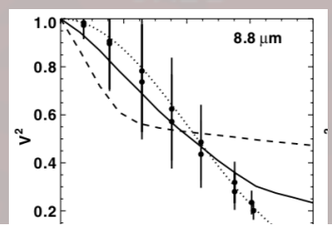
RYLup



No planets ~10 M_{Jup} > 32 au

Langlois+2018

SR21



Potential companion at 6-10 au

Eisner+2009
Sallum+subm.

ABAur

No candidate study?

HD100453

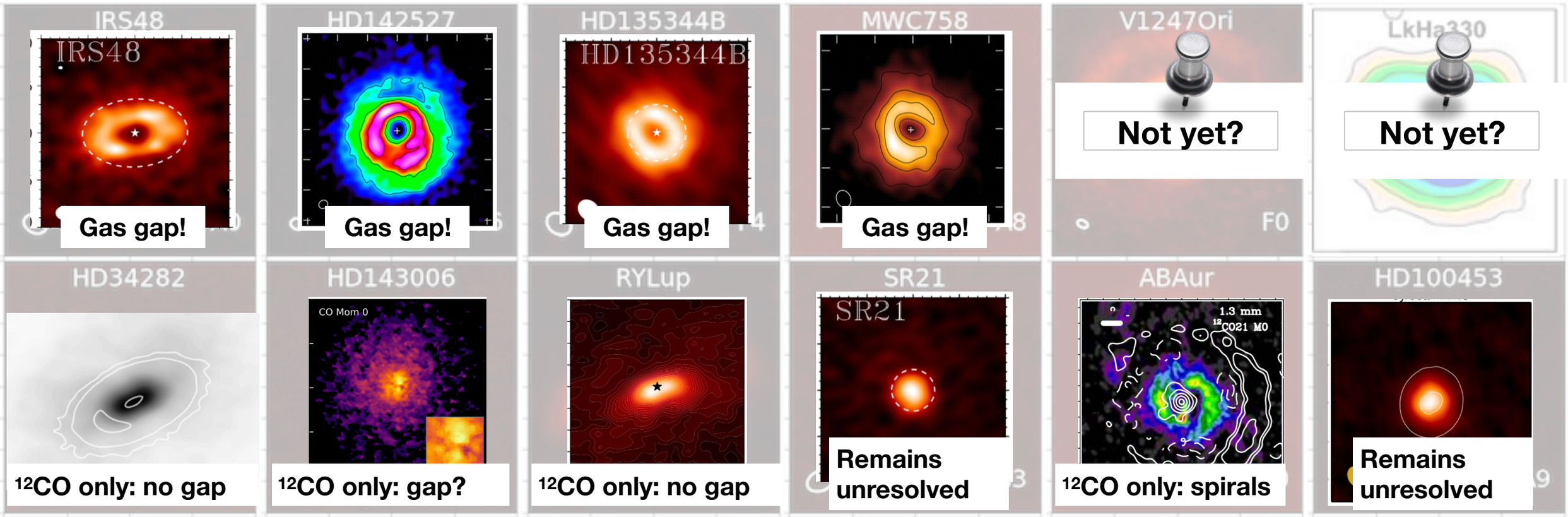
No candidate study?

Most disks may have a companion: mass remains unclear

Note that misaligned ‘semi-polar’ companion (like HD142527B) even harder to see

Planet or stellar companion?

2. Width gas cavities

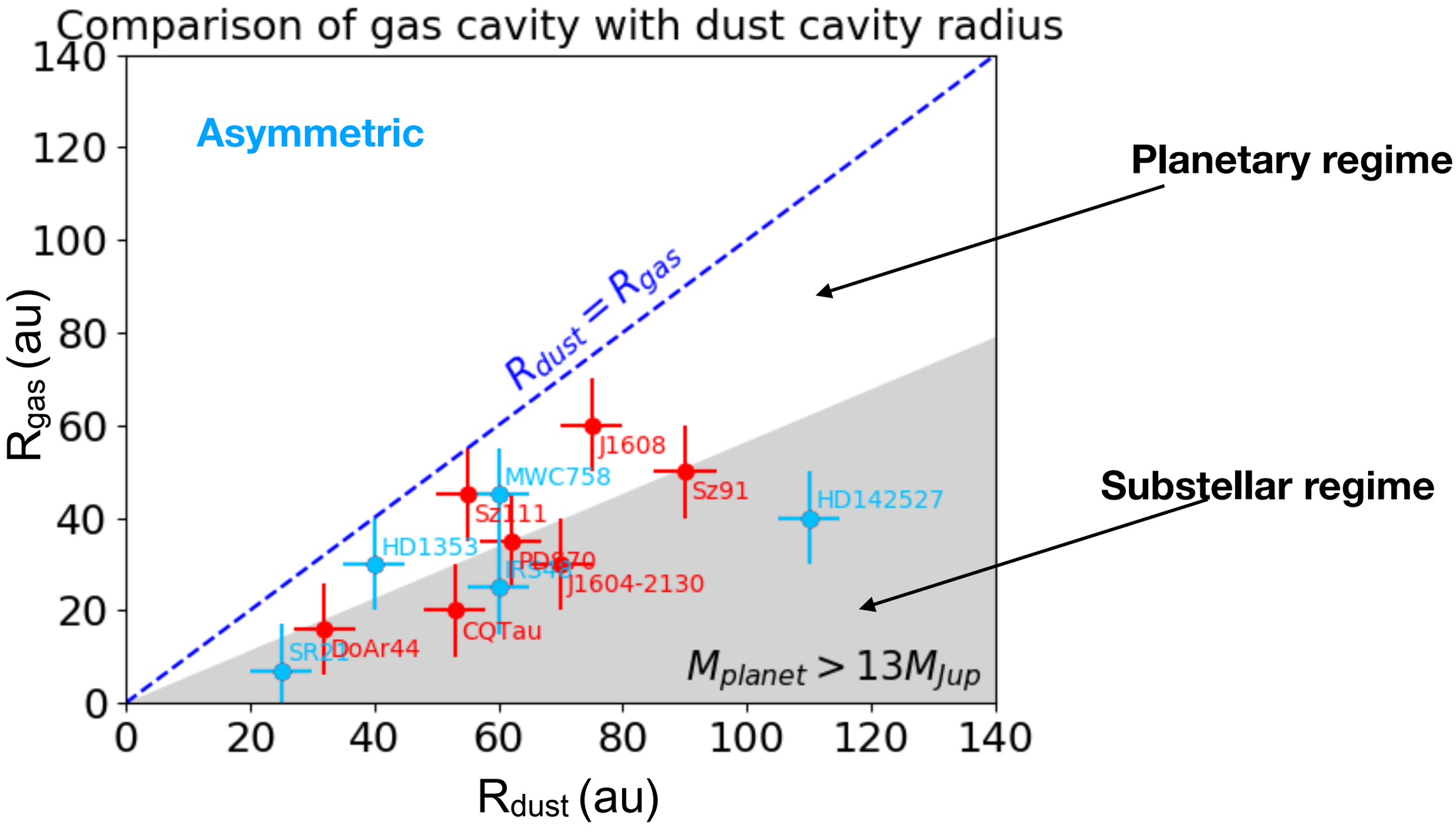


About half of the disks have a deep gas gap, consistent with companion masses > 5 M_{Jup}

Van der Marel et al. 2016 & in prep.
Boehler et al. 2017, 2018
Van der Plas et al. 2017, 2018
Tang et al. 2014

Planet or stellar companion?

2. Width gas cavities



(but note Muley+2019: accreting PDS70b can induce large gap)

Van der Marel et al. in prep.

Planet or stellar companion?

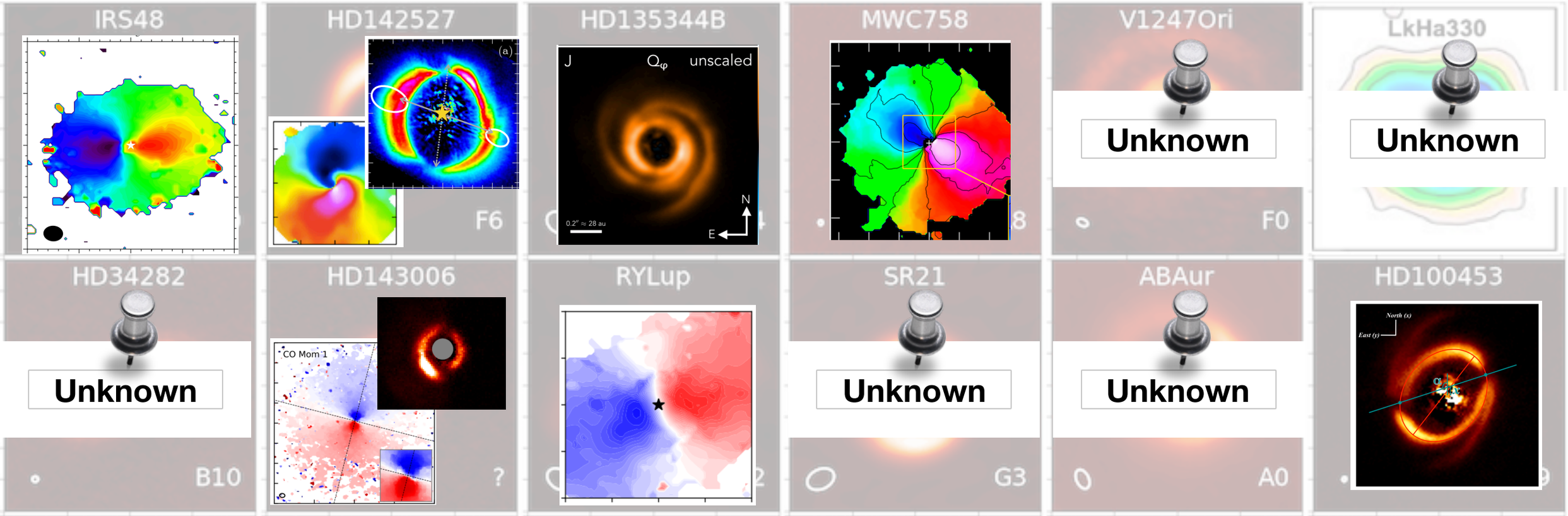
3. Warps and misalignment

vdMarel+2016

Marino+2015
Casassus+2015

Stolker+2016

Boehler+2018



Benisty+2018
Perez+2018

vdMarel+in prep.

Min+2017

At least half of the disks have indicators of a warp
but axisymmetric disks with warps exist too!

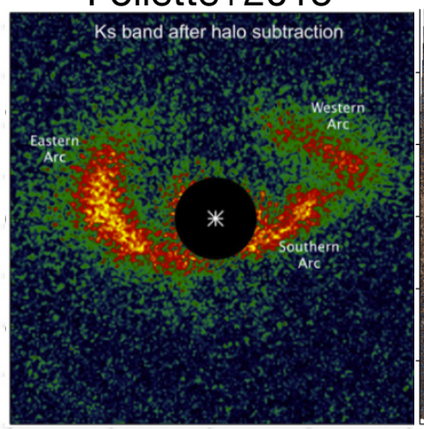
Relation warp and companion mass?

See talk Facchini

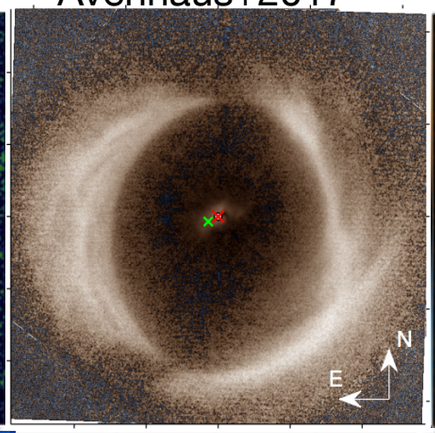
Planet or stellar companion?

4. Spiral arms

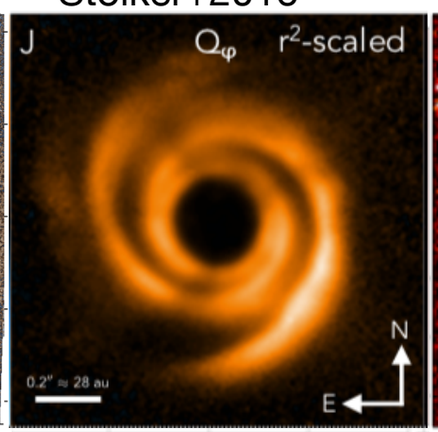
Follette+2015



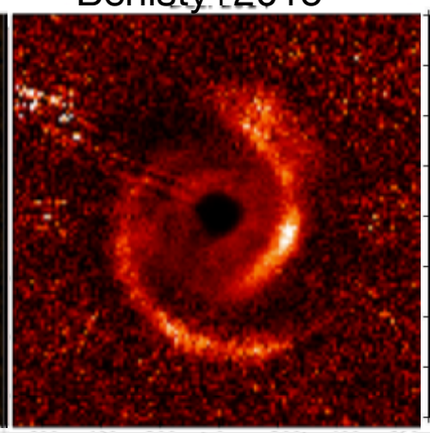
Avenhaus+2017



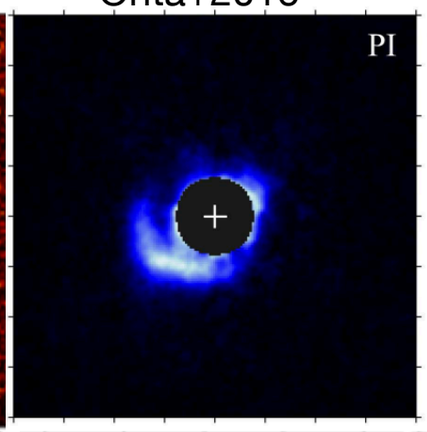
Stolker+2016



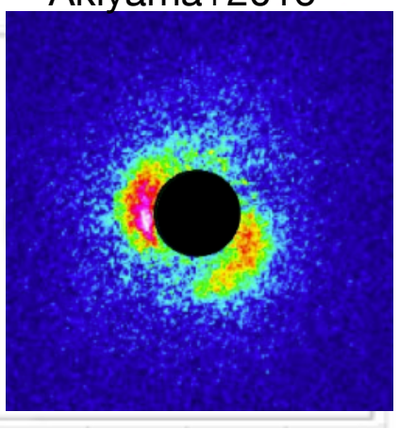
Benisty+2015

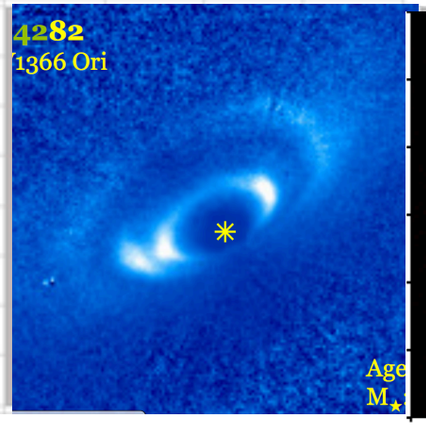


Ohta+2016

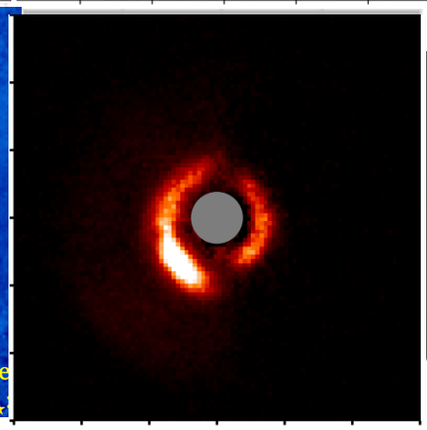


Akiyama+2016

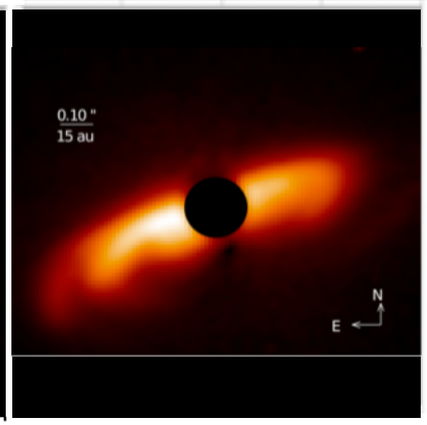




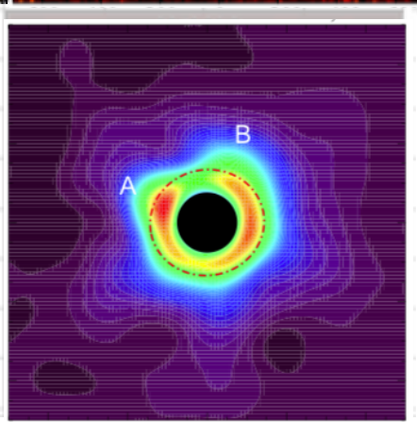
De Boer+ in prep.



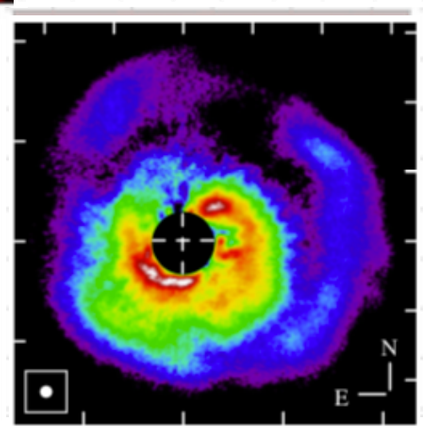
Benisty+2018



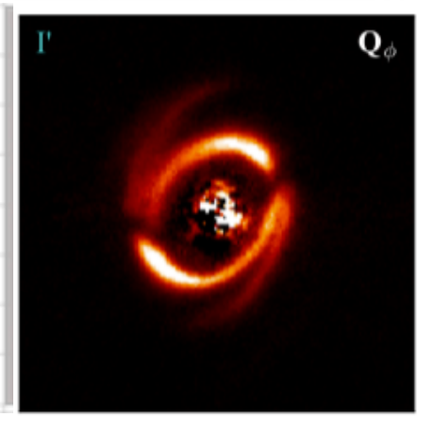
Langlois+2018



Follette+2013



Hashimoto+2011



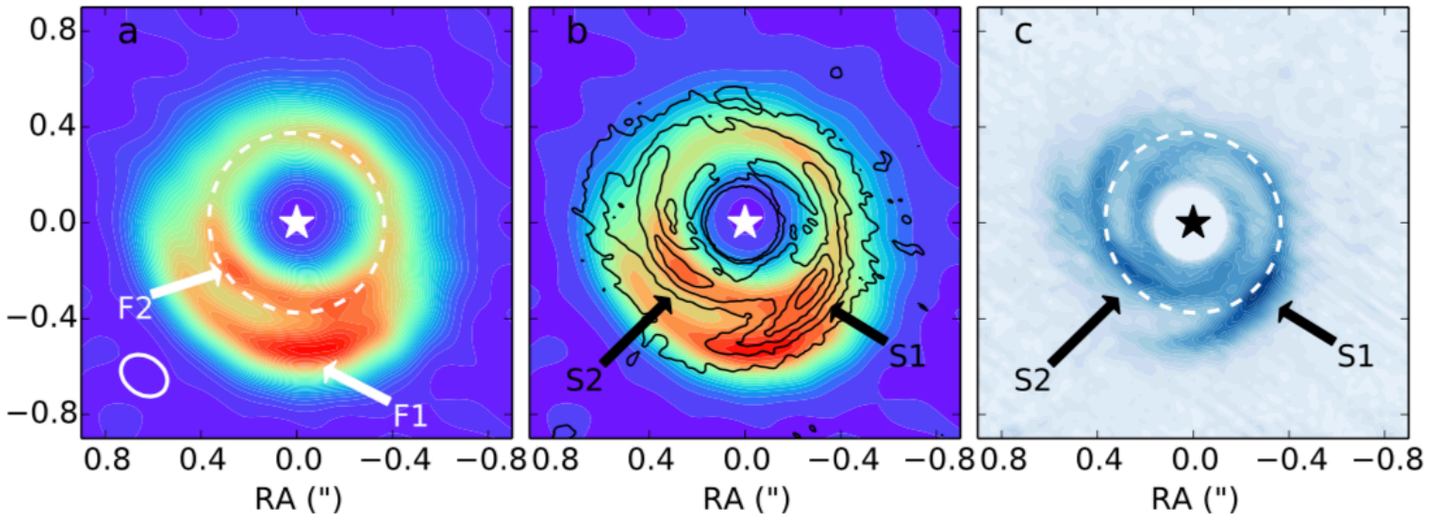
Min+2017

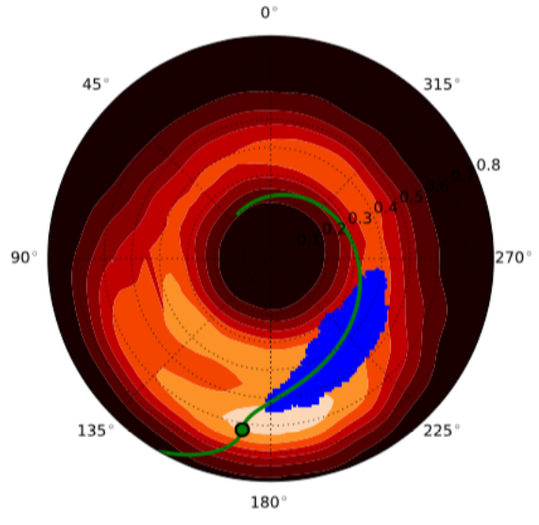
Most disks have evidence spiral arms (axisymmetric disks don't!)

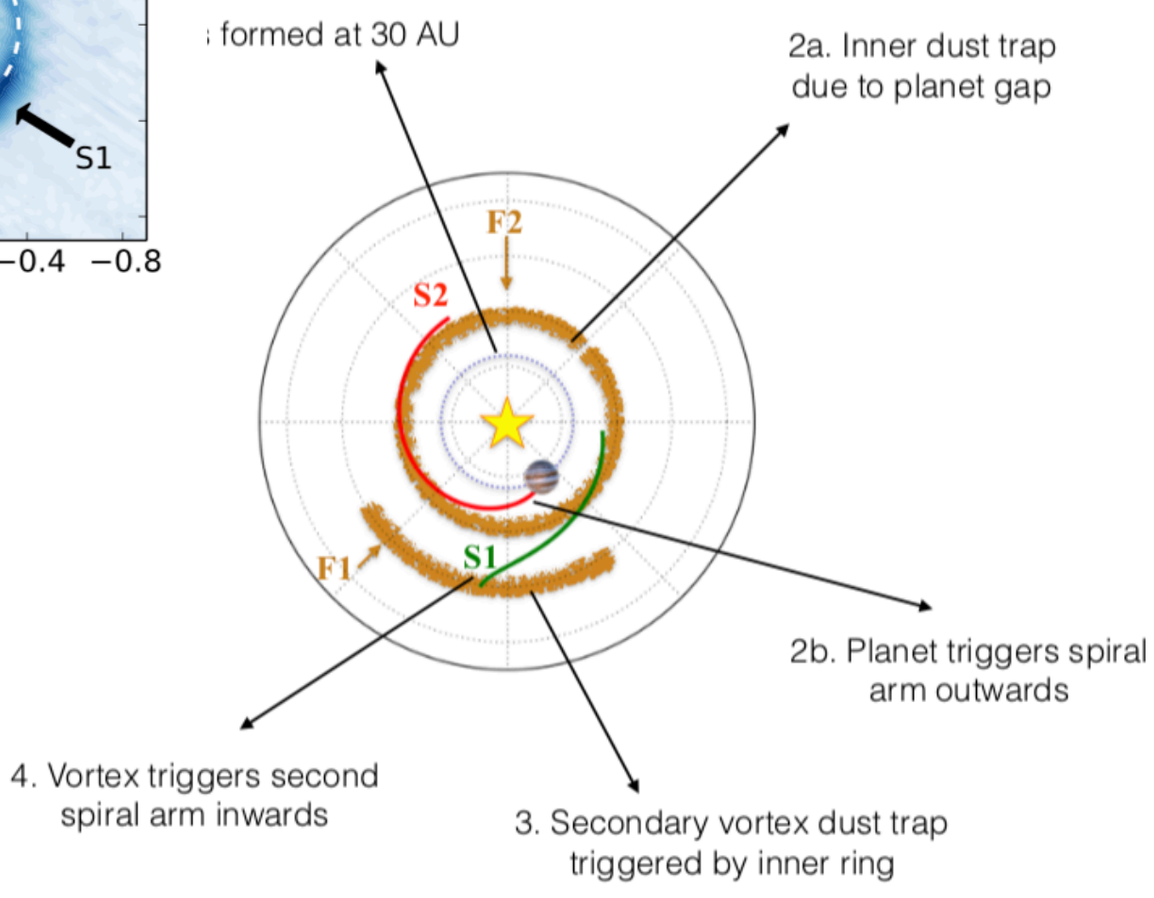
Relation spiral arms and companion mass?

Link with spiral arms

HD135344B has an interesting connection between spiral arm and vortex: origin?





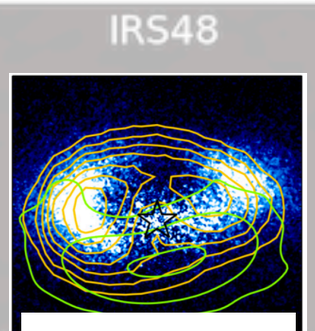


Van der Marel et al. in 2016
Cazzoletti et al. 2018

Link with spiral arms

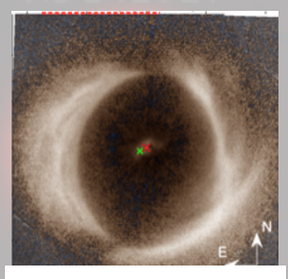
All asymmetric disks show spiral arms in NIR

Follette+2015



From cavity

Price+2018

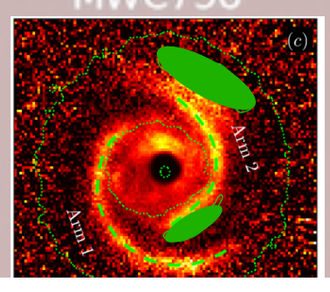


From binary

Cazzoletti+2018

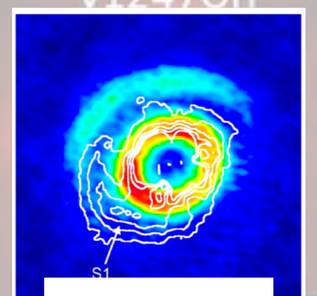
From asymmetry

Dong+2018



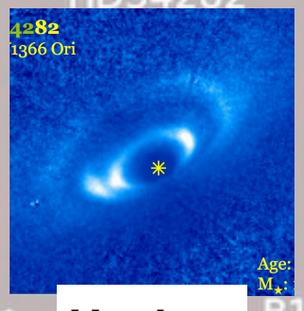
Alongside asymm.

Kraus+2017

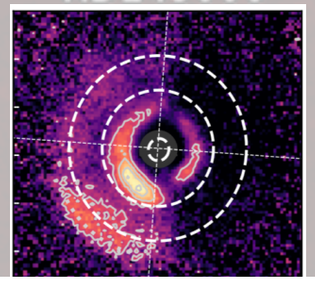


From gap

Unclear

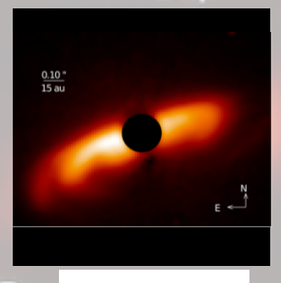


Unclear

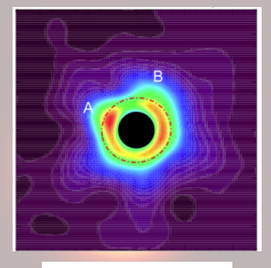


Alongside asymm.

Perez+2018



Unclear



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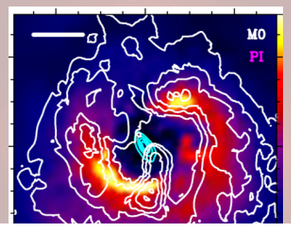
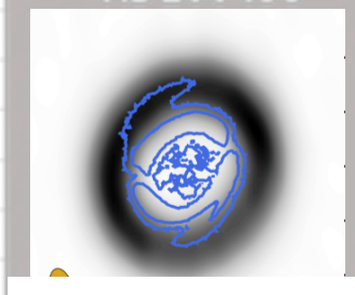


Following CO: inside cavity

Tang+2017



From asymmetry

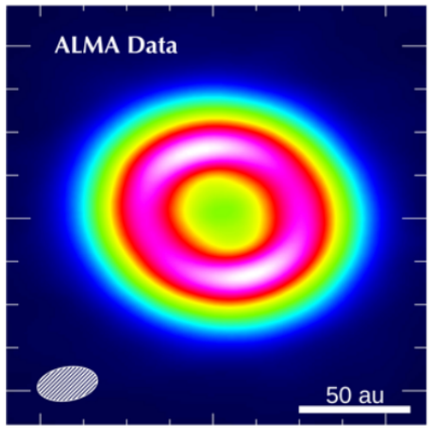
Van der Plas+2018

Exact origin spiral arms remains unclear
but likely a link between asymmetries and companions

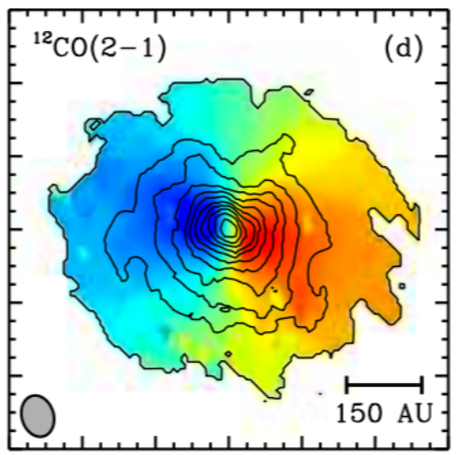
Symmetric disks with known companions

Why are these not asymmetric?

V4046 Sgr:
0.05 au q~1 binary

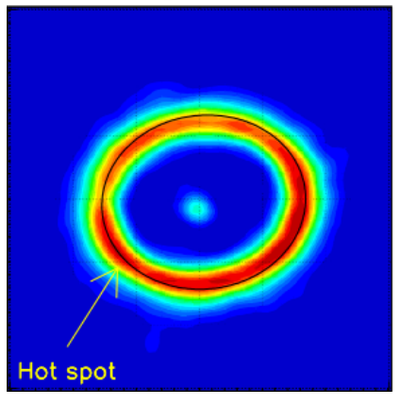


Ruiz-Rodrigez+2019

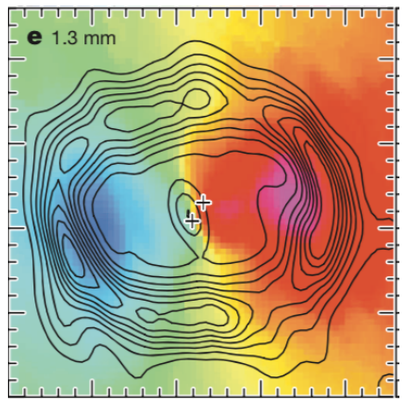


Rosenfeld+2013

GG Tau:
35 au q~1 binary

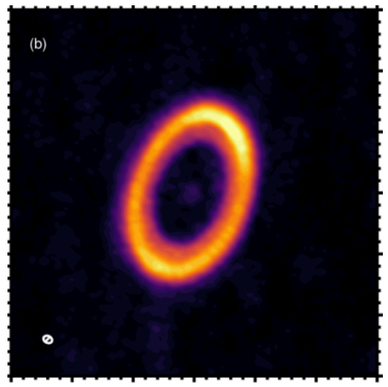


Phuong+2019

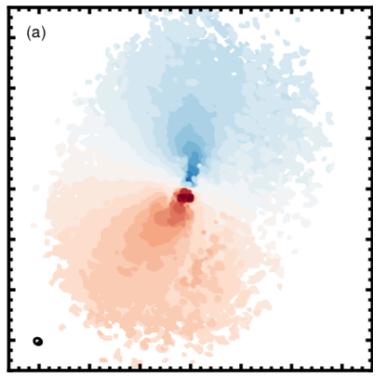


Dutrey+2015

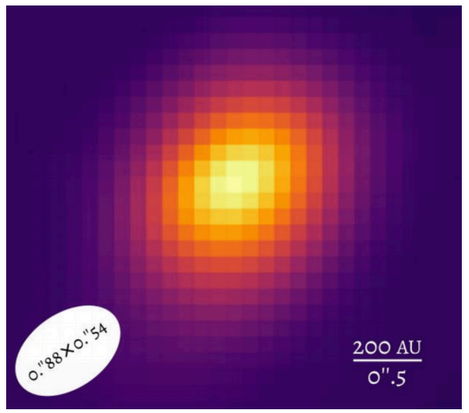
PDS70:
22 au q~0.01 “binary"



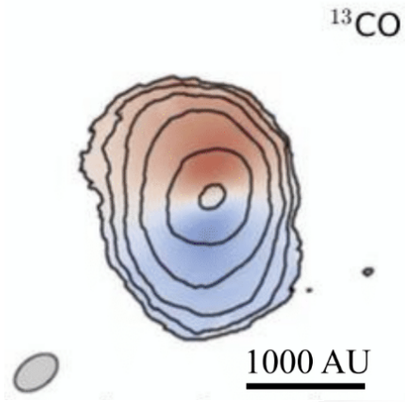
Keppler+2019



GW Ori:
8 au q~0.25 triple



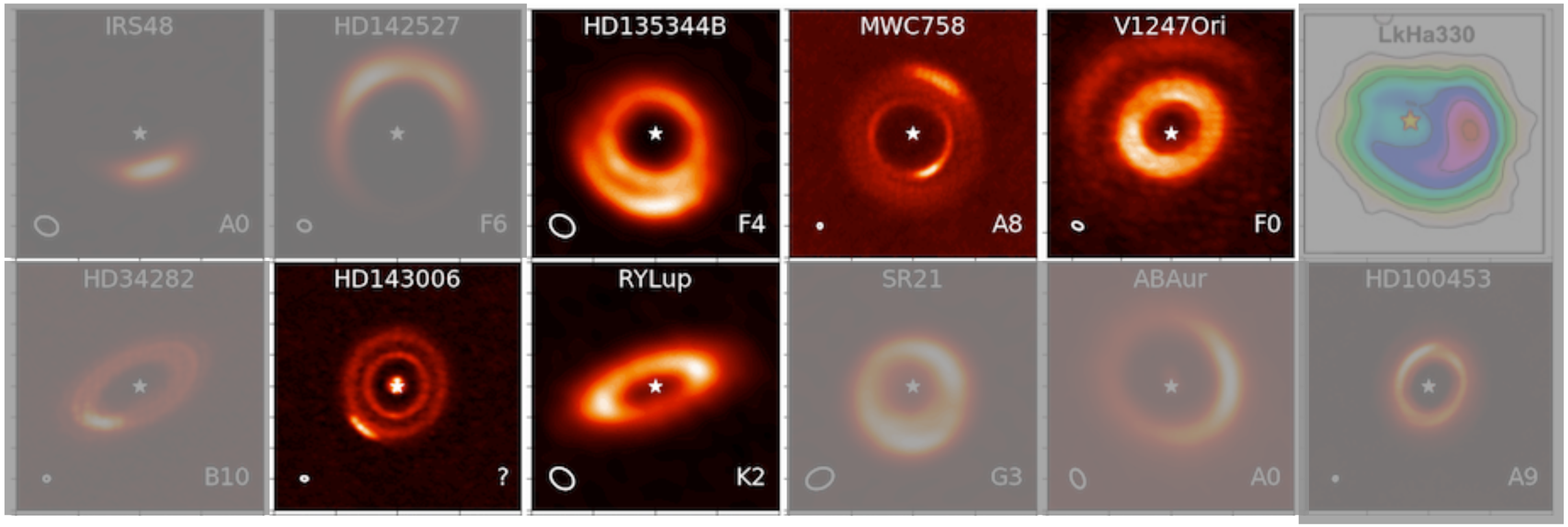
Czekala+2017

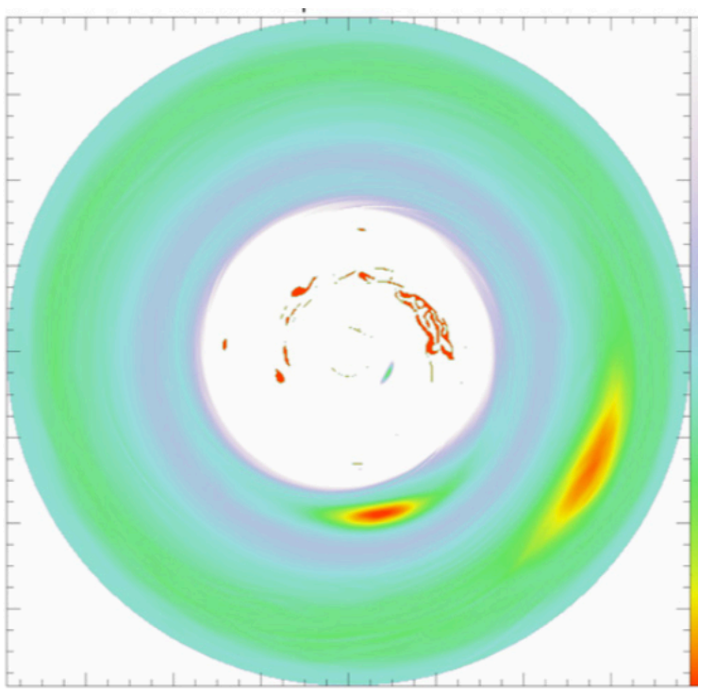


But see talk Dong

Warp exists: but only specific mass ratios generate asymmetries?

Multiple rings and asymmetries





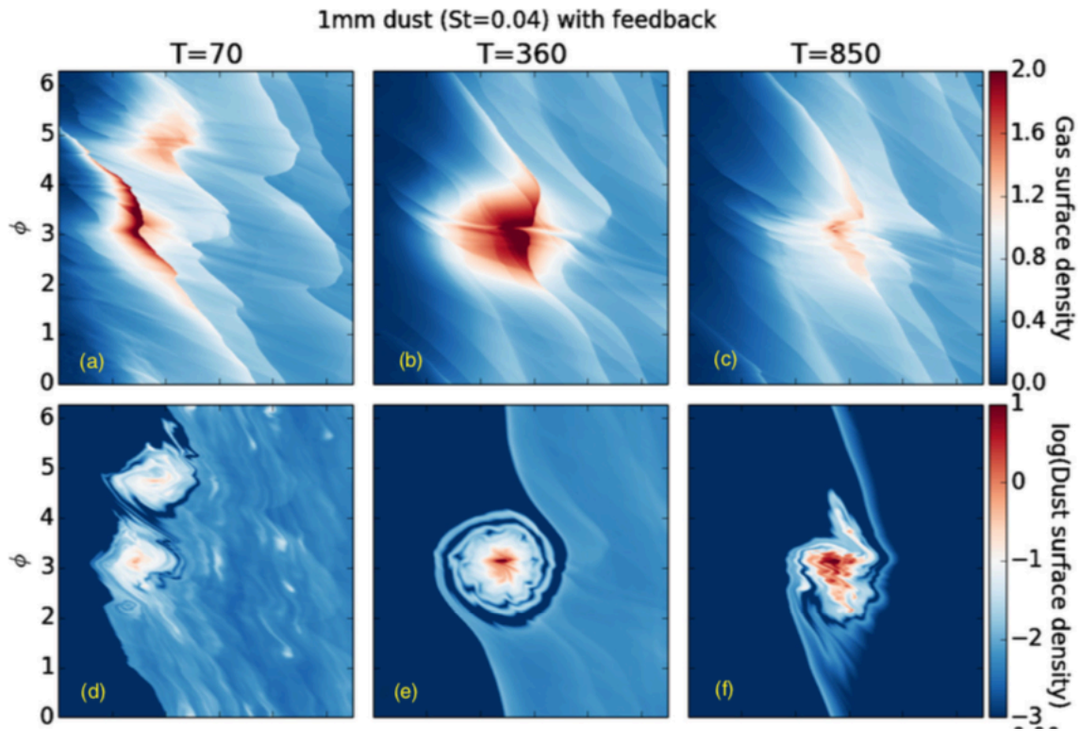
Possible scenarios:

1. **Secondary vortex generation**
2. **Multiple companions, one for each vortex**
3. **Inner and outer vortex**

Lobo Gomes et al . 2016
Hammer et al. 2017

Asymmetry lifetime

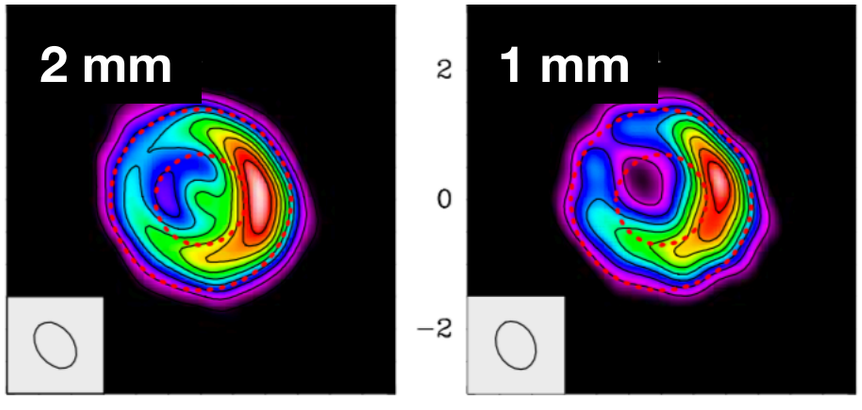
Vortices destroyed by dust feedback when GDR~1?



2D simulations (Fu+2014, Miranda+2017, Barge+2017)

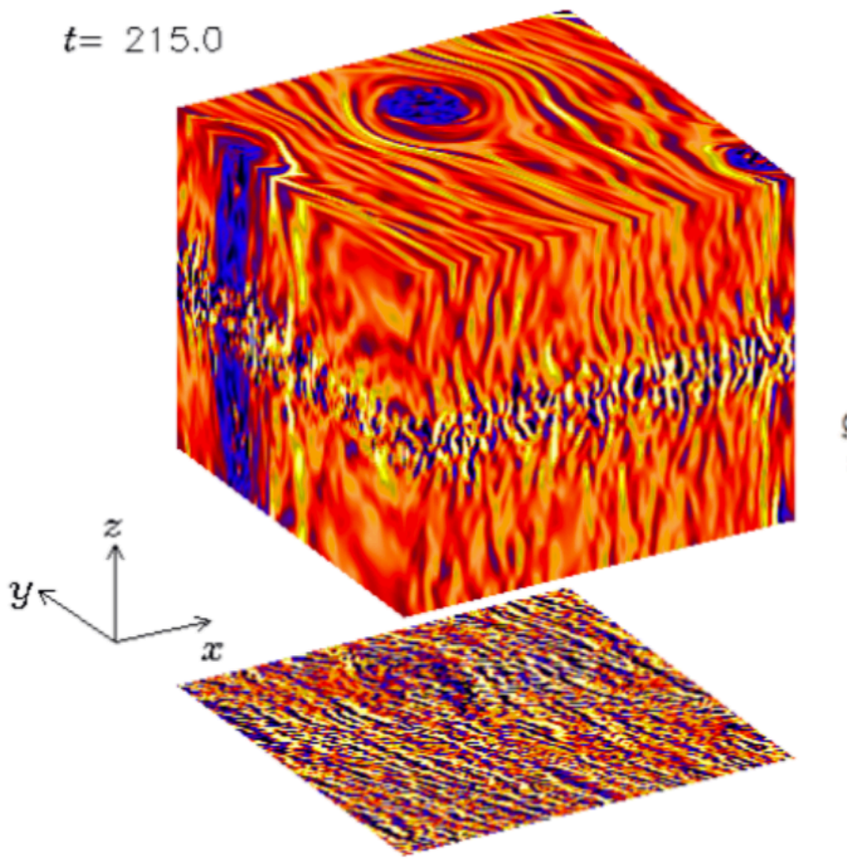
AB Aur (PdBI)

Several disks show trapping but AB Aur has tentative evidence dust dissipation?



Fuente+2017

CAREFUL! Not happening in 3D (maybe midplane?)



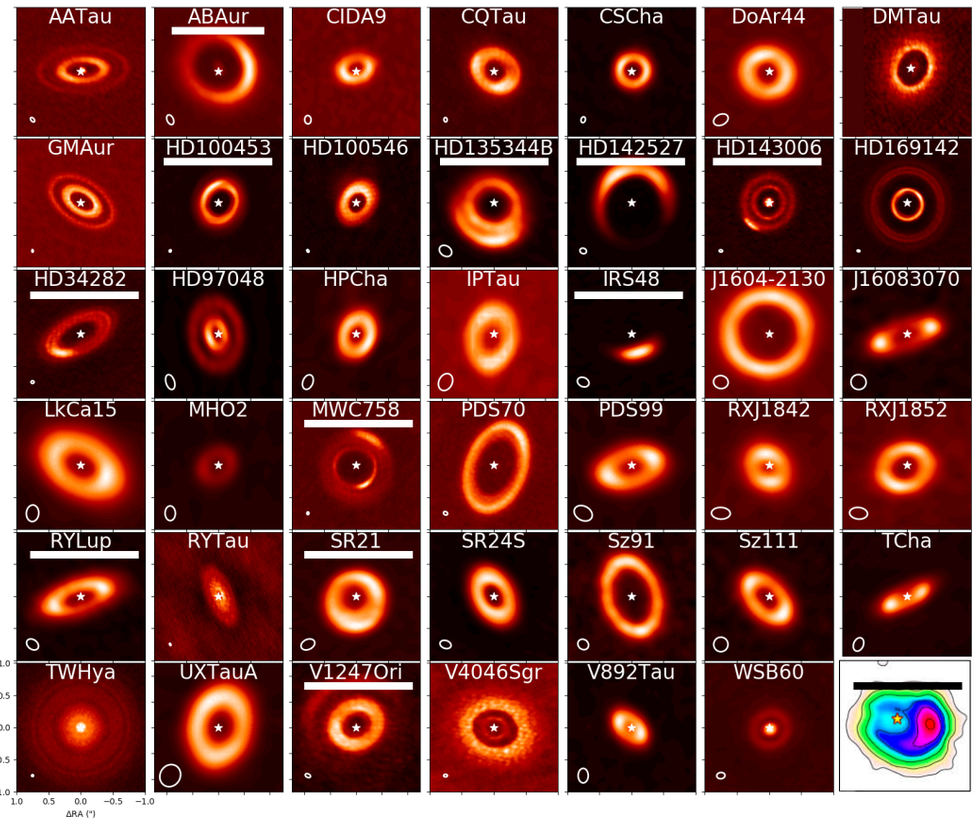
Lyra+2018

<u>(Unknown whether this happens in binary case)</u>

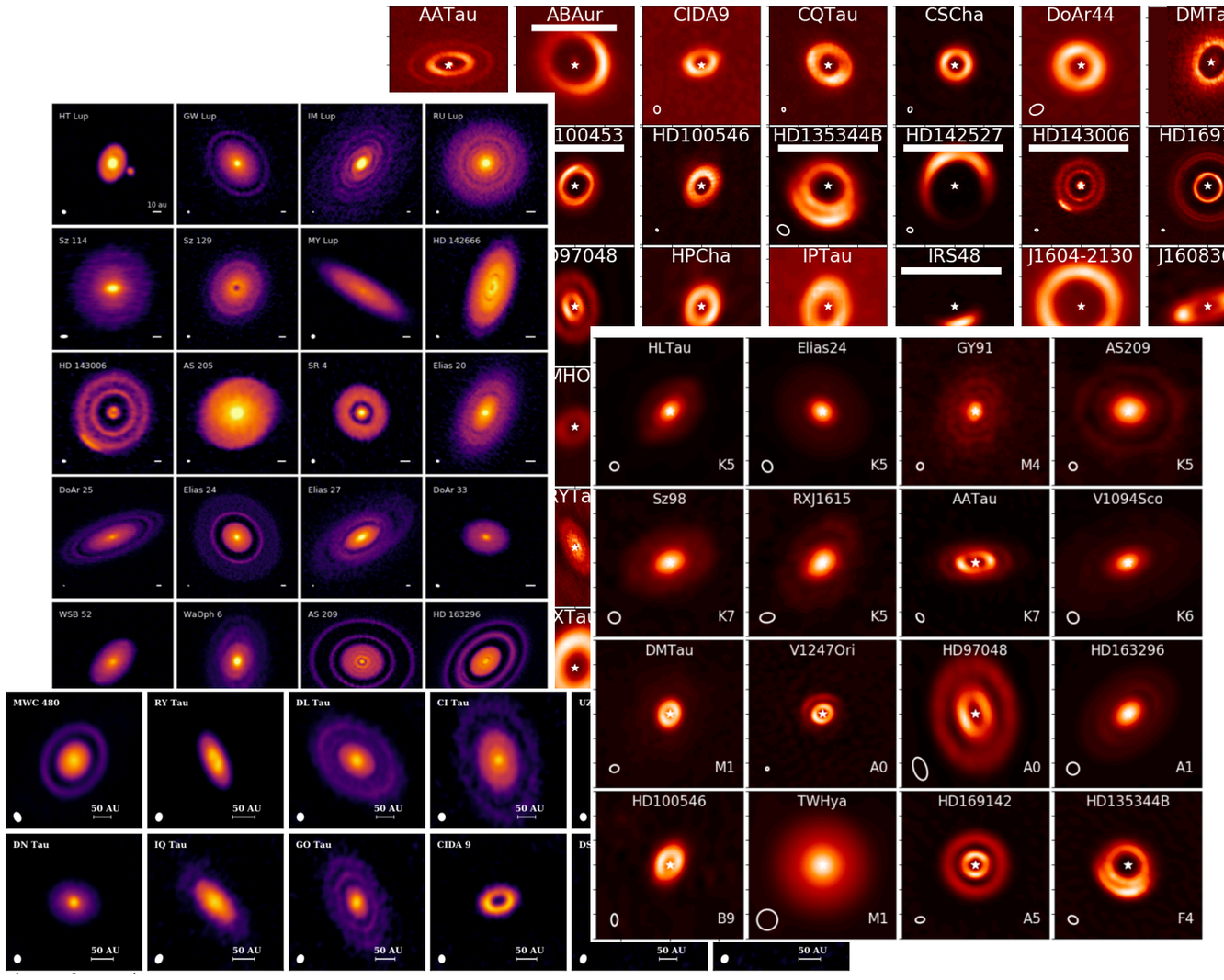
So let's take a look at morphologies…

Occurrence rate

Within transition disks with >20 au cavities (12/48): ~25%



Within population bright disks (12/91): ~13%

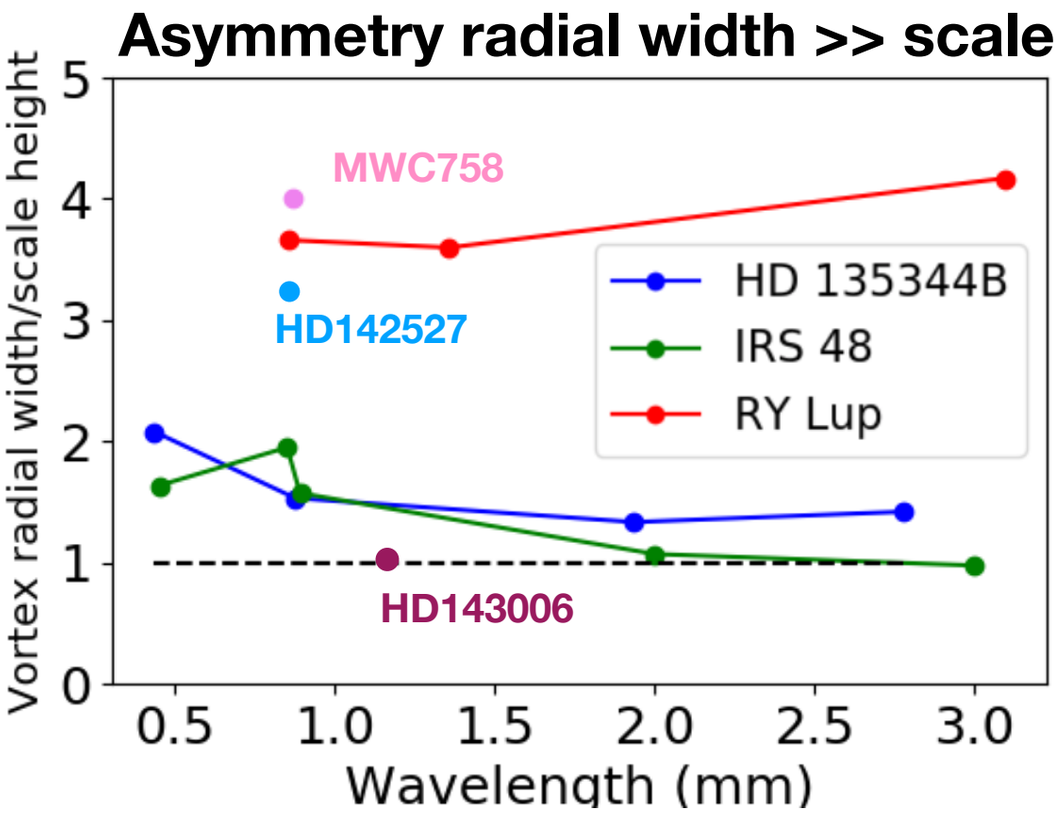


"Everybody's favourite targets which managed to get past the ALMA-TAC"

Is the low occurrence rate related to expected lifetime?

Long et al. 2018
Andrews et al. 2018
Cieza et al. 2019
Van der Marel et al. in 2019

Radial width



In most radially resolved asymmetries, the radial width is (much) larger than the scale height

Is this evidence against vortex scenario?

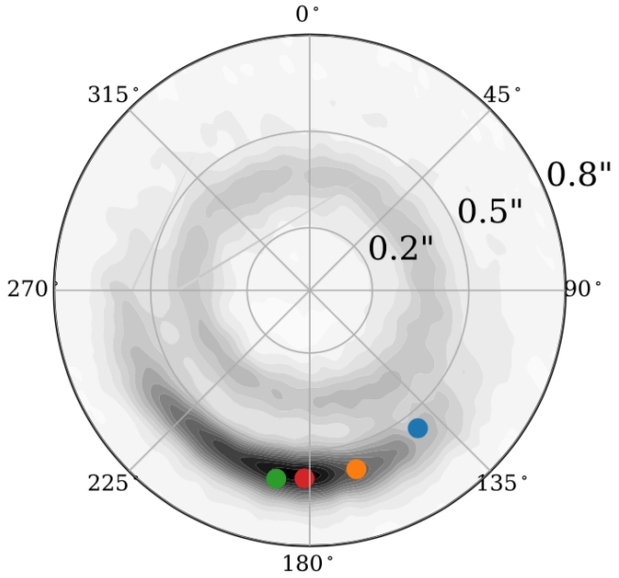
Is dust representative of real vortex morphology?

Is dust diffusing out of the vortex?

Cazzoletti et al. 2018
Dong et al. 2018
Perez et al. 2018
Boehler et al. 2017
Van der Marel et al. in prep.

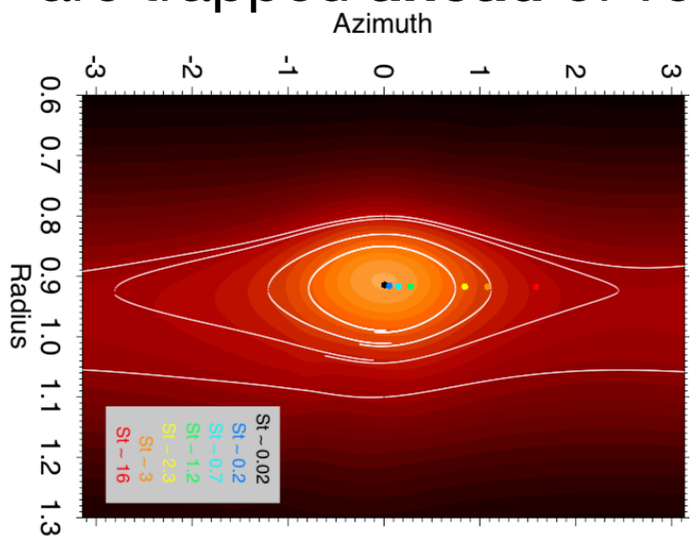
Peak shift

HD135344B



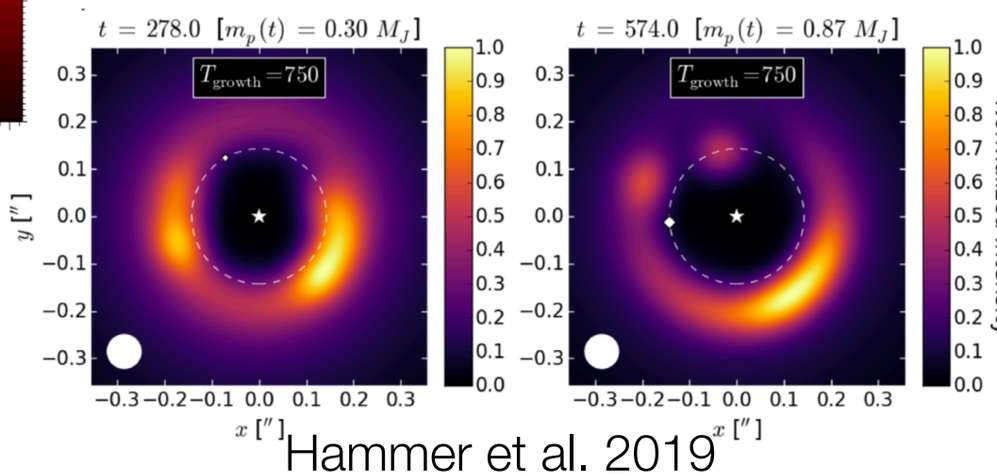
Peak shifts with wavelength opposite to Keplerian motion (**behind** vortex), Cazzoletti+2018

Due to self-gravity, larger grains are trapped **ahead** of vortex

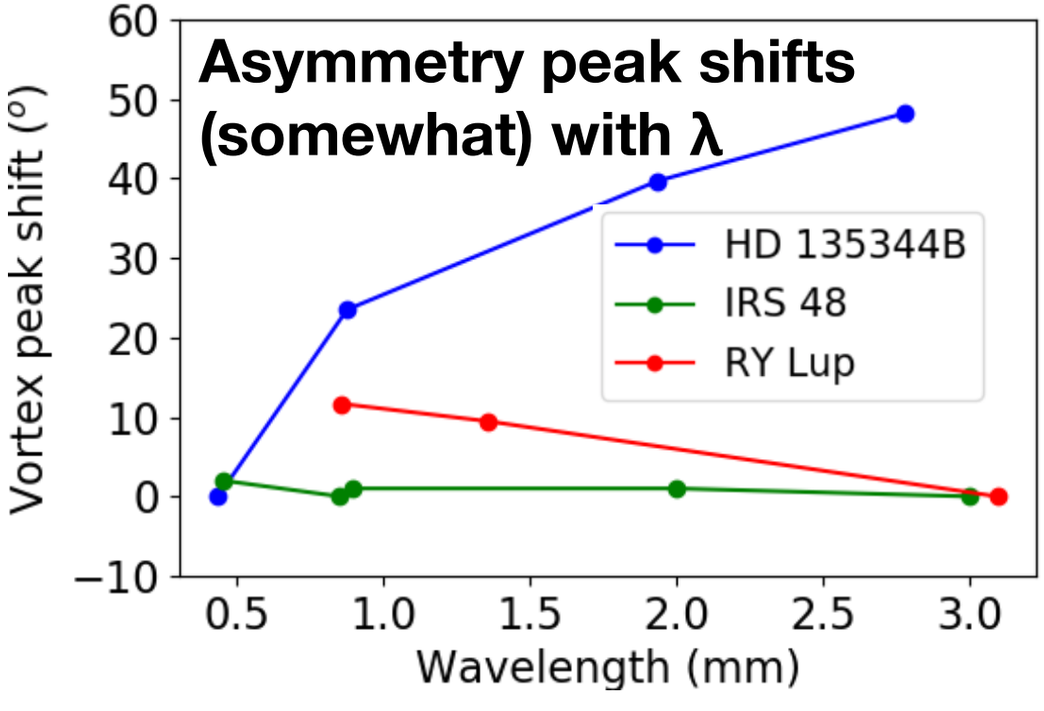


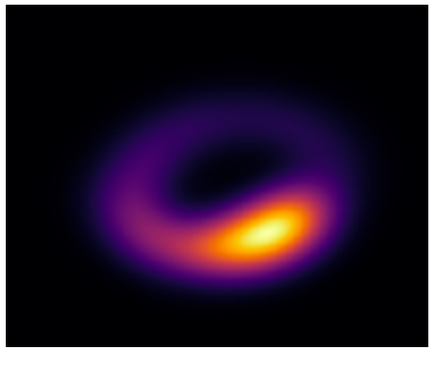
Baruteau & Zhu 2016

If vortex-generating planet continues to grow, grains spread out and create double-peaks



Hammer et al. 2019





Simulation IRS 48 (Calcino+)

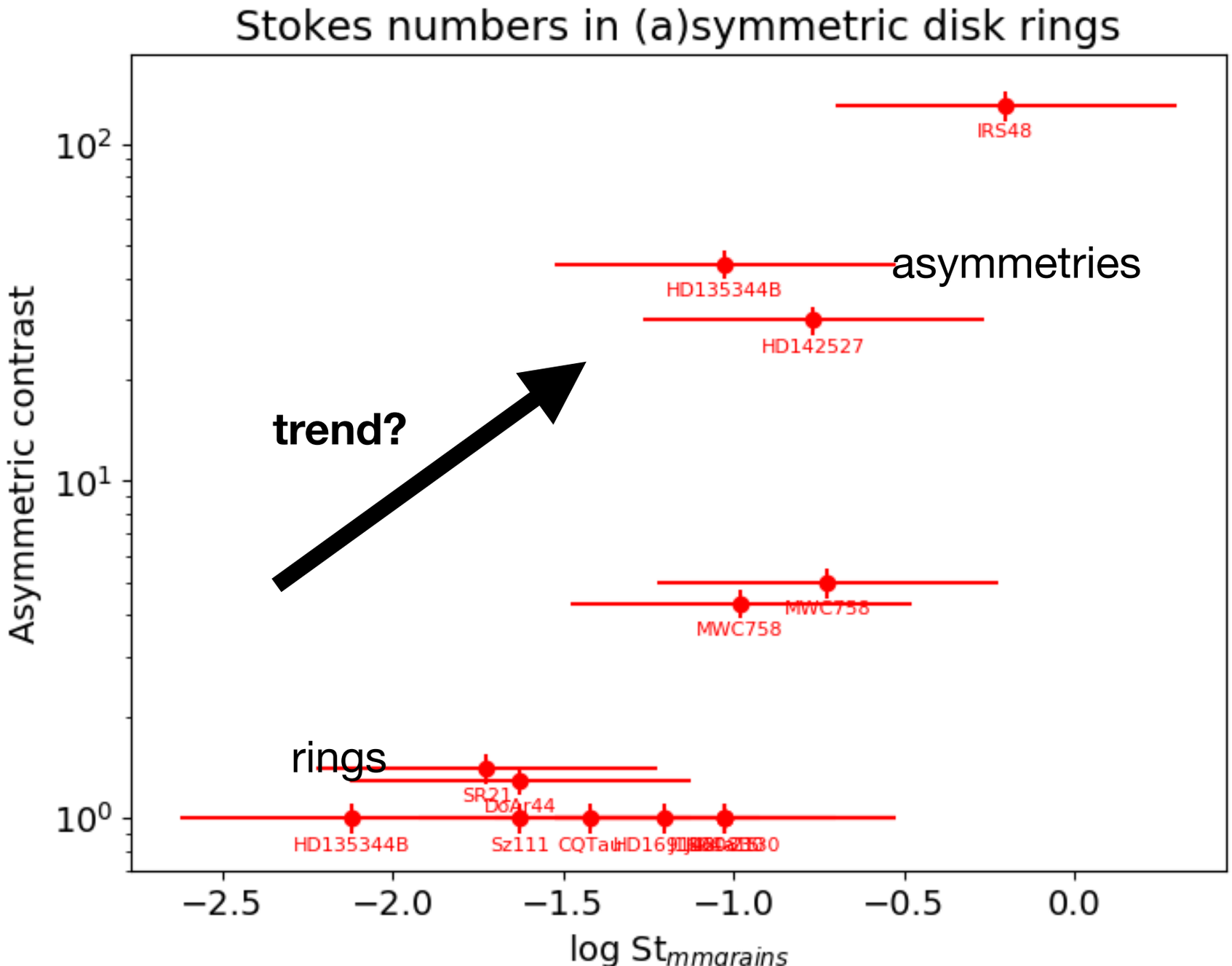
Binary scenario predicts tail of gas overdensity

Degree dust asymmetry

$$St = \frac{\pi}{2}\frac{s\rho_{\rm pc}}{\Sigma_{\rm gas}}$$

Use gas surface density at *radial location* asymmetry/ ring (so ***not*** *disk mass*) for Stokes number mm-grains (Band 6/7)

Is the variety in asymmetric degree in dust just due to the local radial gas surface density or also lifetime related?



All TDs contain companions (warps, spirals, gaps) but asymmetry only if Stokes number is right

Van der Marel et al. in prep.

Summary

- Properties of observed dust asymmetries are consistent with either RWI vortices at planet gaps or eccentric gaps due to stellar binaries
- Many (indirect) indicators for companions, but inconclusive about mass
- Asymmetric disks all have spiral arms in NIR, but with different origin locations: origin or correlation?
- Dust trapping lifetime may be limited: constraints from multi-wavelength morphology
- Appearance of asymmetry may just be Stokes number related?
- Need systematic parameter study of eccentric companions with observable predictions on morphology and mass