Origin of large cavities in protoplanetary disks

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http://madnucleus.com

Pierre Cox Symposium 2018

Outline

1. Transition disks
2. Lopsided rings
3. Warps
4. Hypotheses: tilted companions
5. Summary

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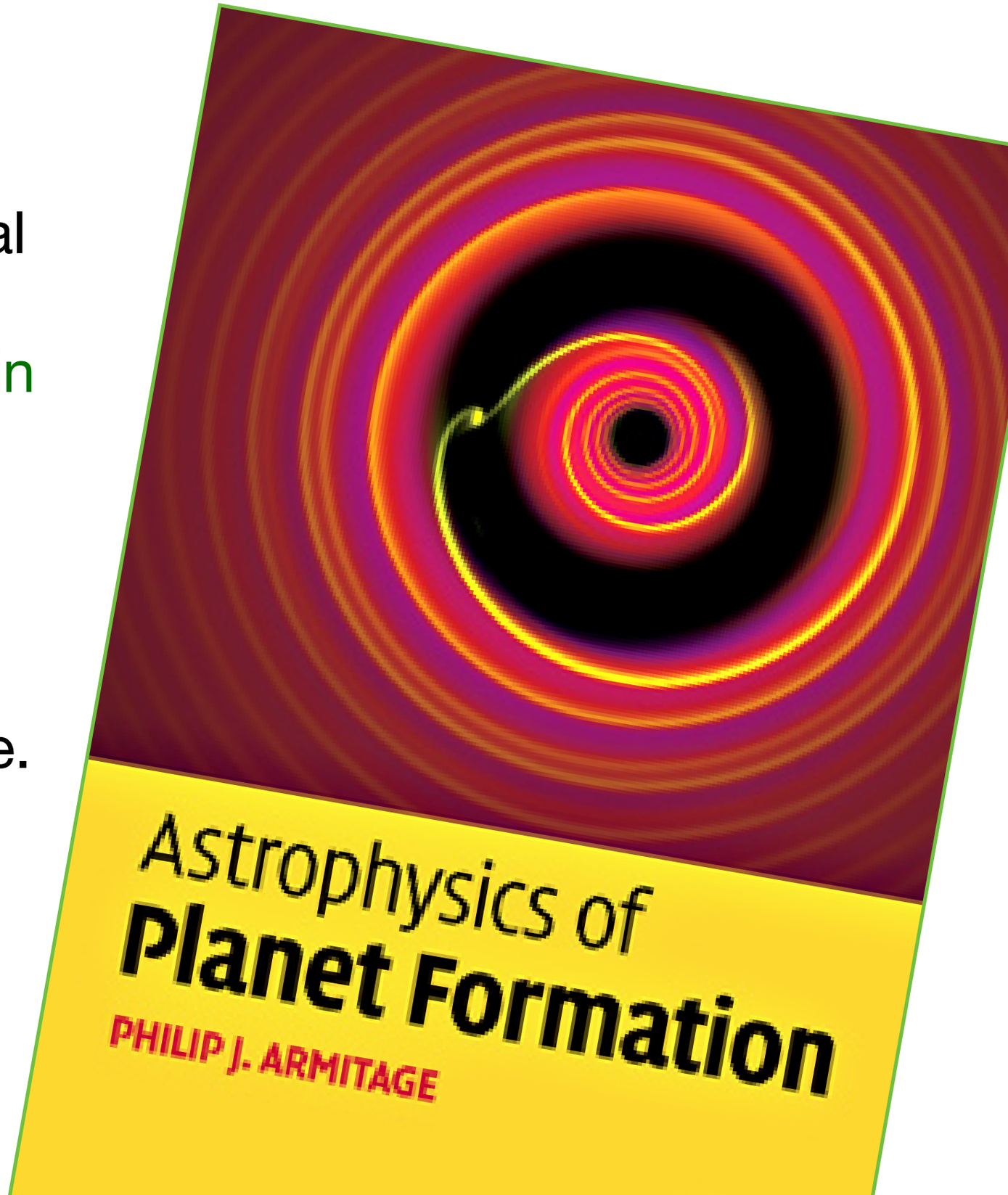
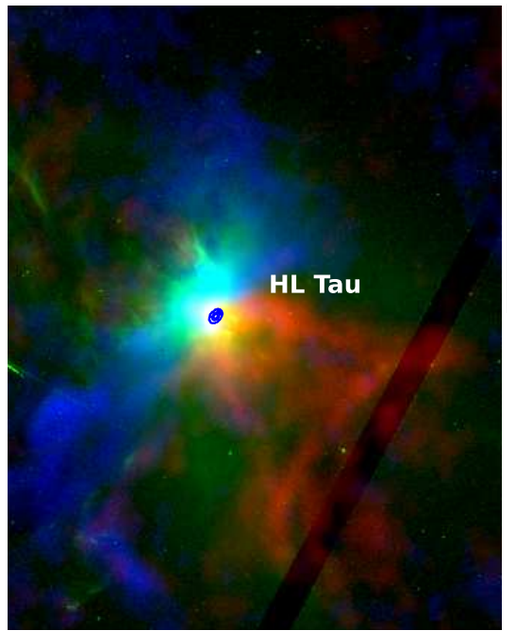
Cavities as planet formation signposts

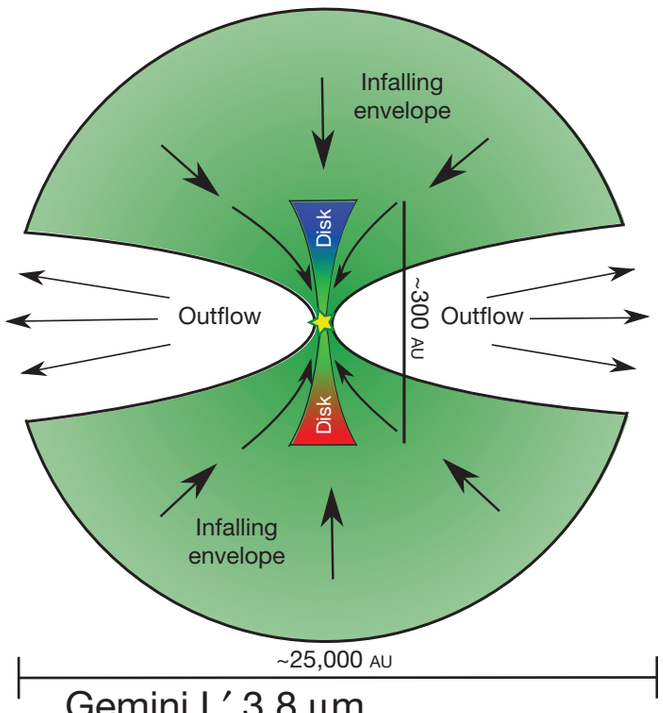
Giant planet formation is thought to clear gaps or central cavities since the 80s (Goldreich & Tremaine 1980, Lin & Papaloizou 1980)

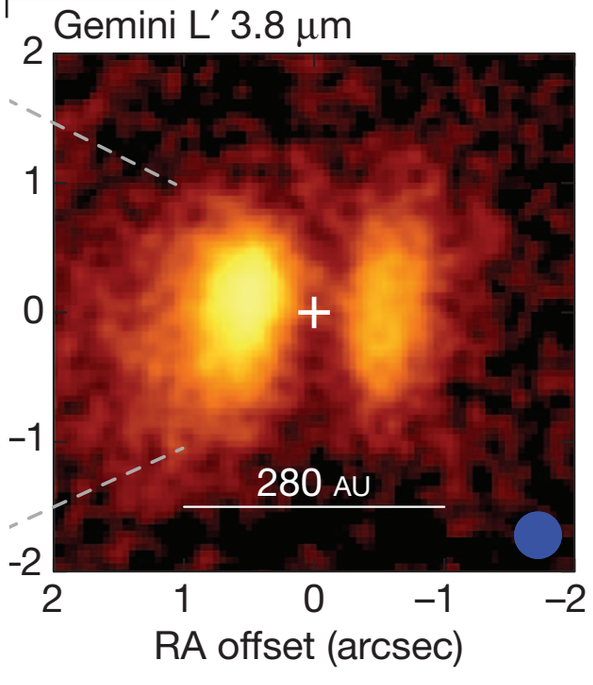
…. but definite observational evidence for the origin of resolved gaps remains elusive.

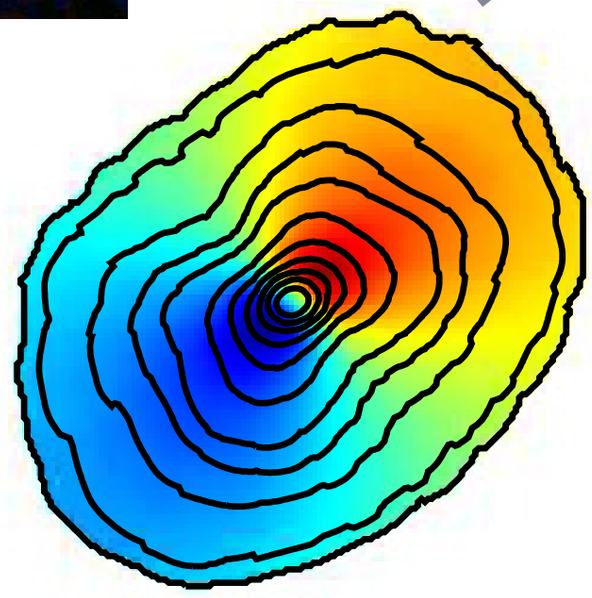


I, HLTau (ALMA)

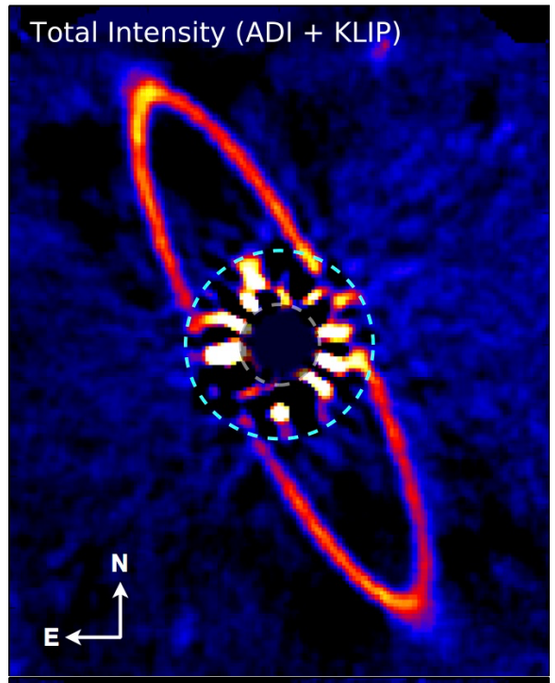


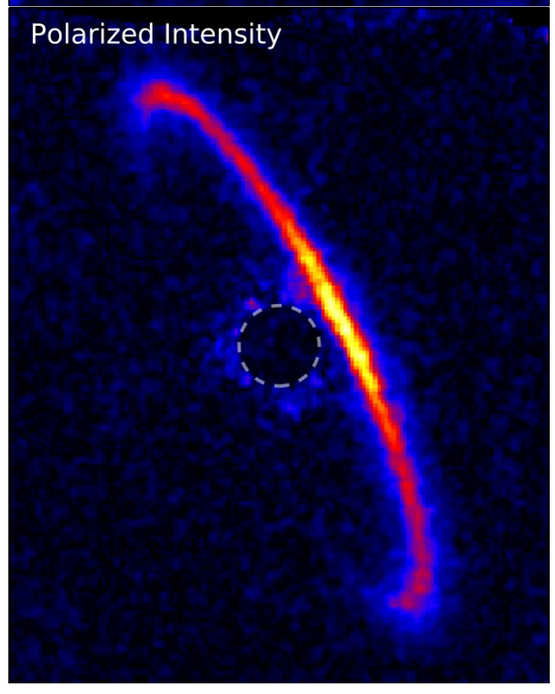






II, HD162396 (Rosenfeld+ 2013)

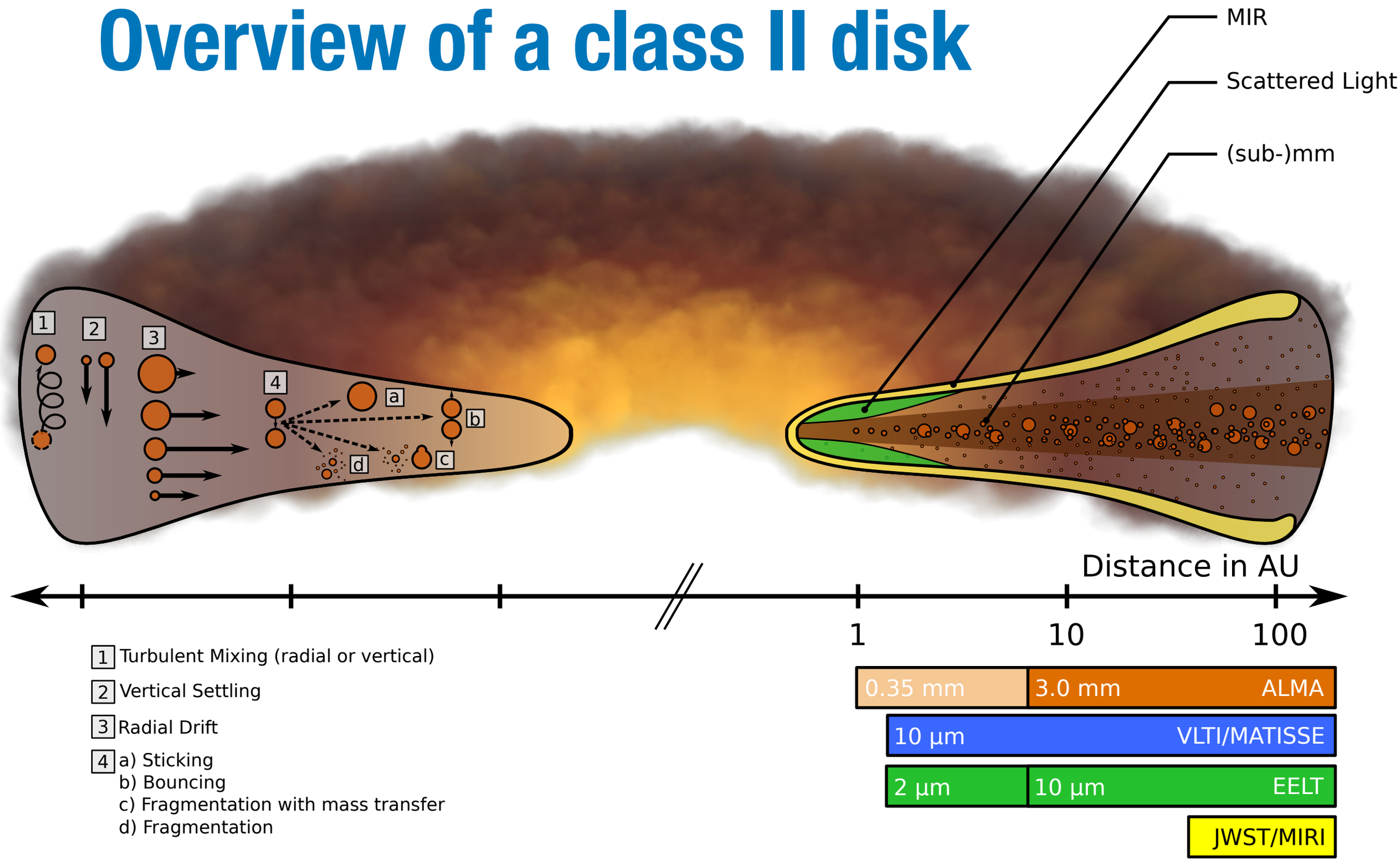




III, debris, HR4796A (GPI)

0, L1527IRS (Tobin+ 2012)

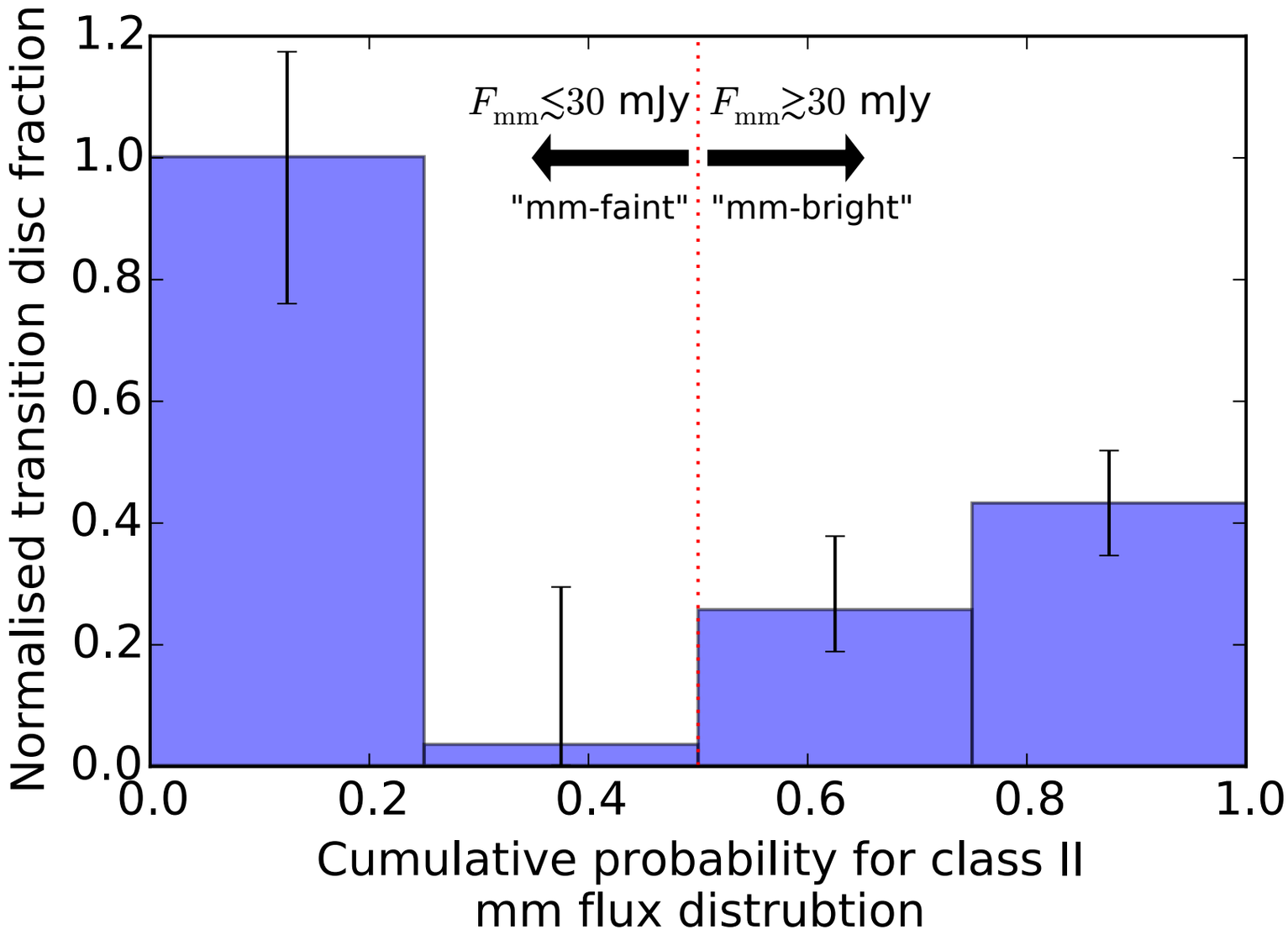
Overview of a class II disk



- Schematics of disk structure and dust growth (Testi+ 2014, PPVI)

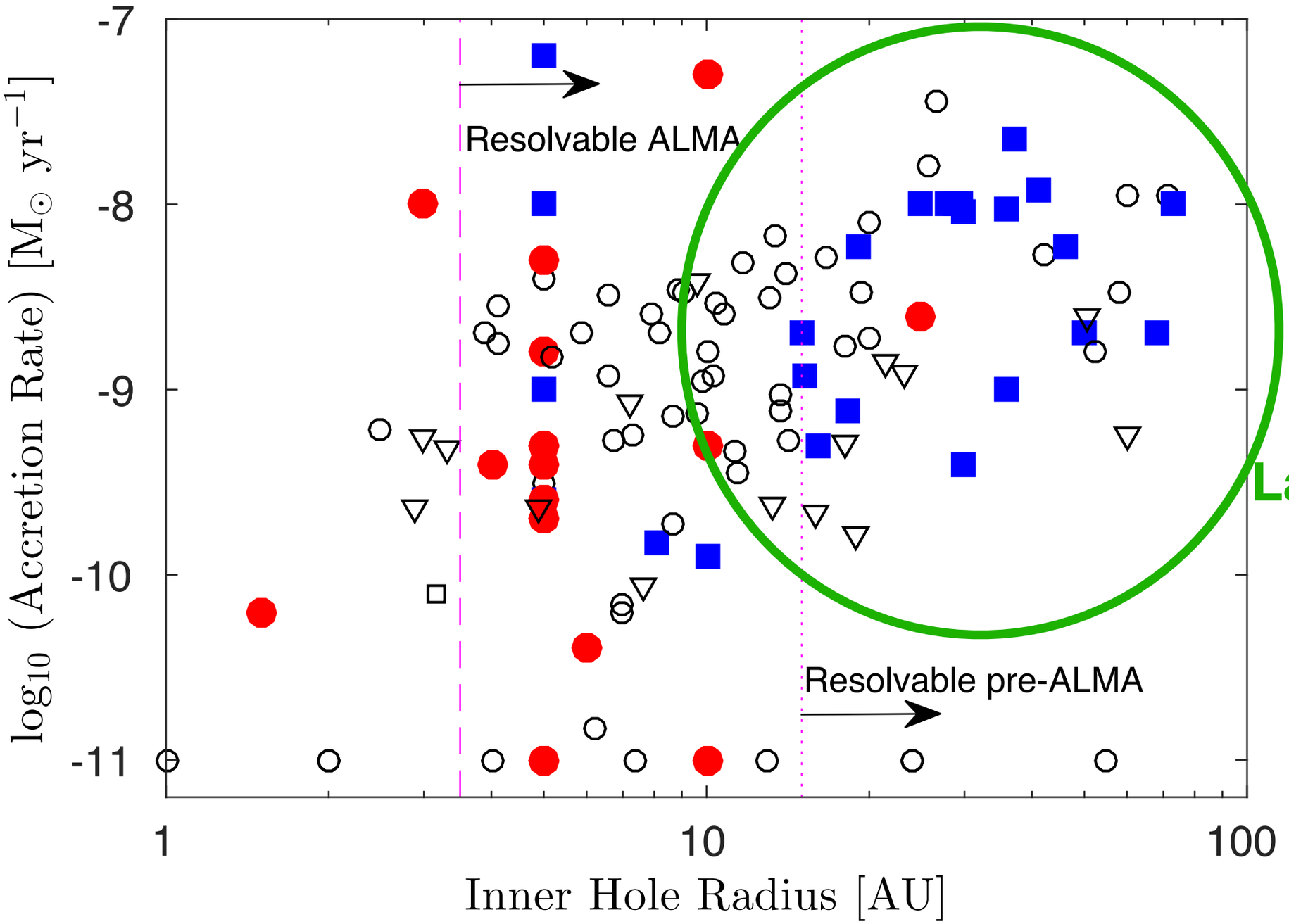
Scope: large transition disks

- Axisymmetric SED modelling ⇒ radial gaps or central cavities in **transition disks**, in transition from Class II to Class III.
- Class of SED-selected TDs is heterogeneous: bimodal distribution in dust mass



Owen 2016

Scope: large transition disks



mm-bright

mm-faint

Large cavities

Owen 2016

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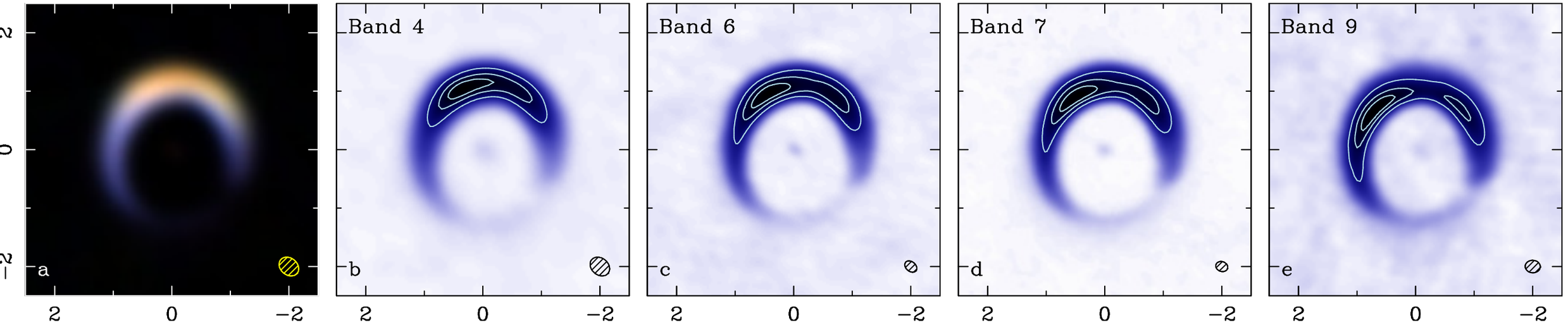
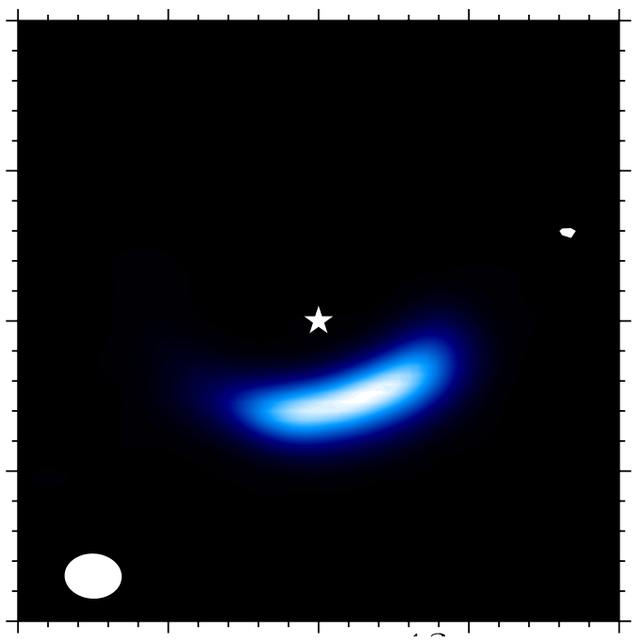
Narrow and lopsided rings



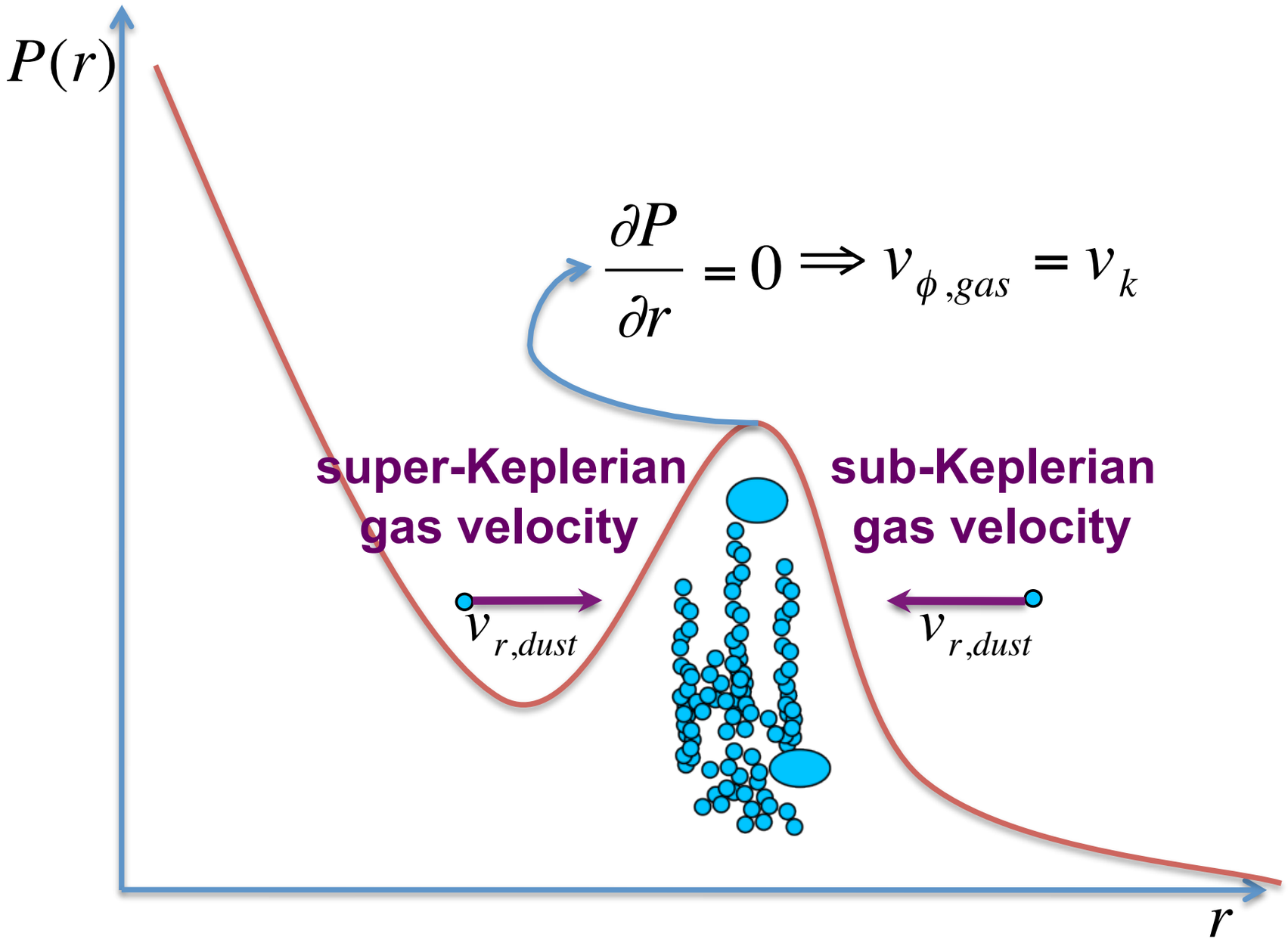
- HD142527: Factor of 30 asymmetry along ~140AU ring (Ohashi 2008, Casassus+ 2013 **JAO PR**, Muto+ 2015, Boehler+ 2017)



- IRS48: Factor of 100 asymmetry along ~140AU ring (van der Marel+ 2013 **JAO PR**, van der Marel+ 2016)

- Interestingly, both cavities in HD142527 and IRS48 are filled with residual 12CO emission

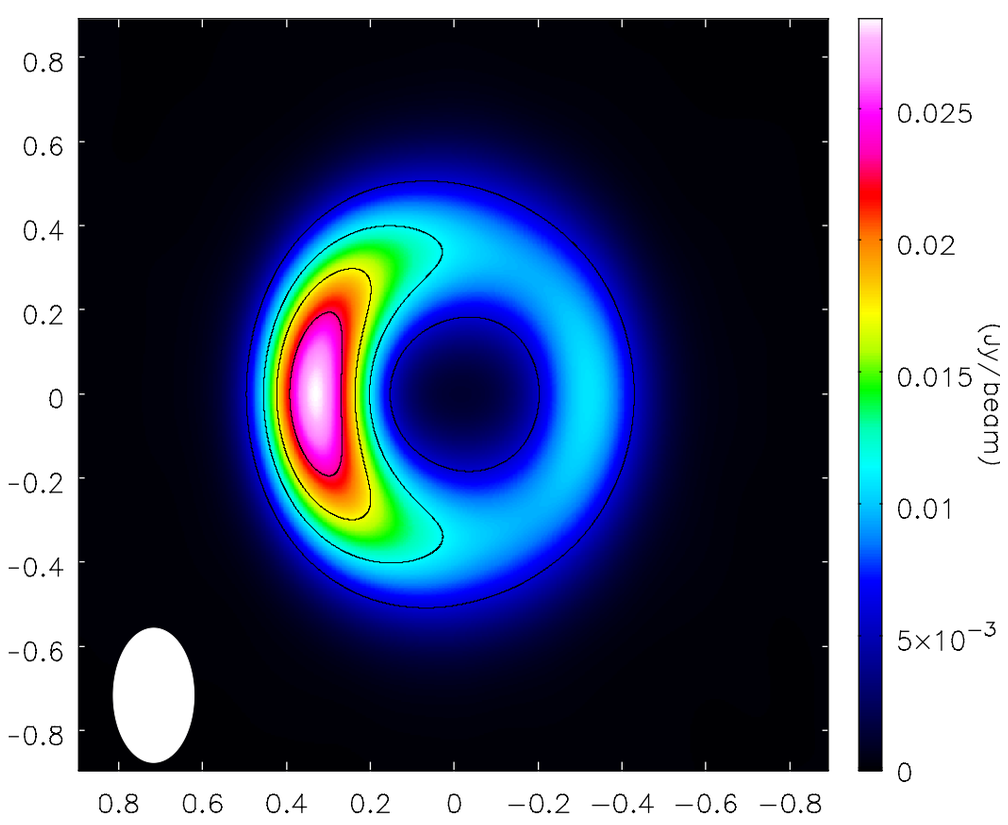
Radial dust trapping

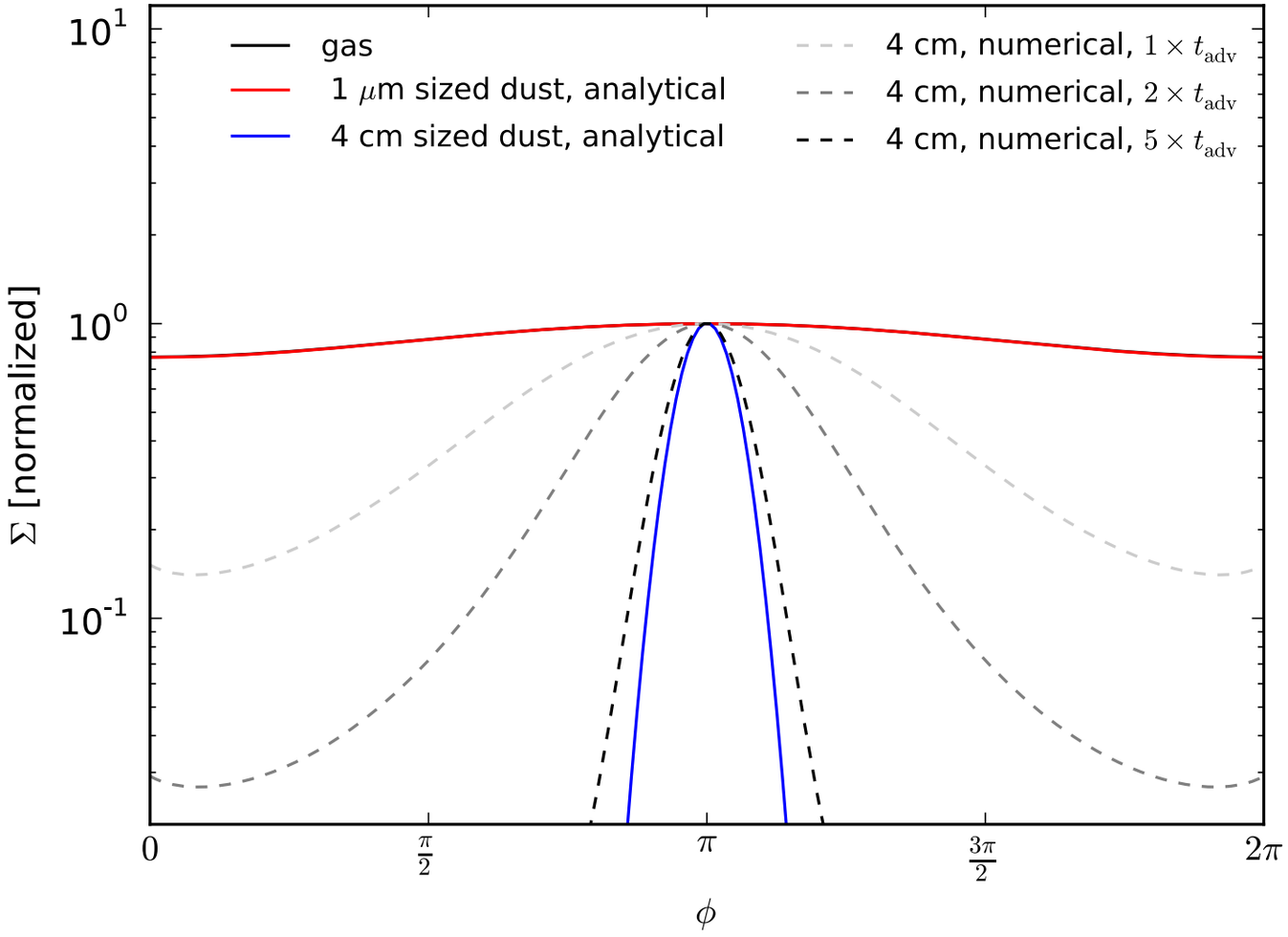


- Pinilla, Youdin 2017

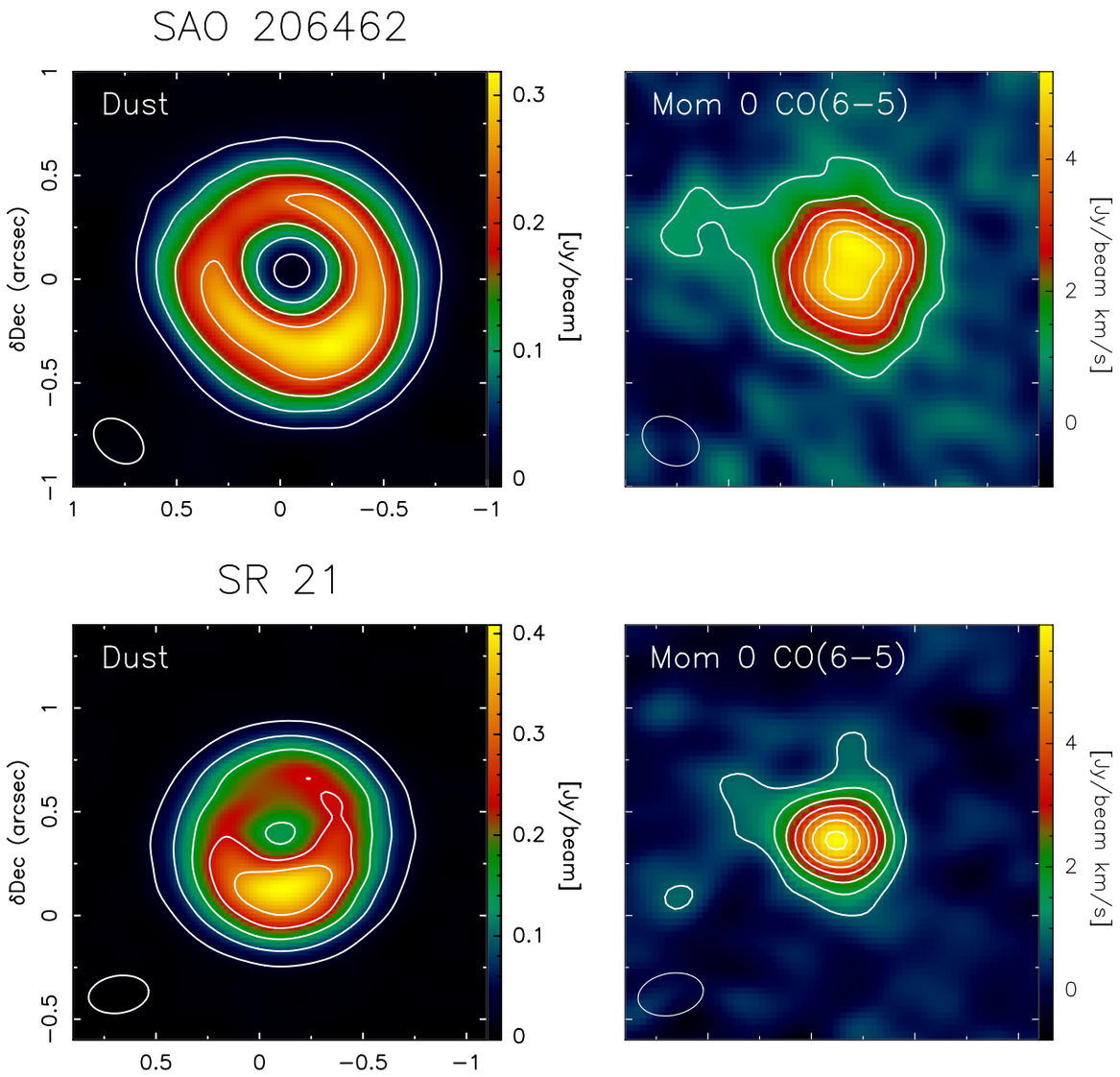
Azimuthal dust trapping

- Azimuthal dust trapping in anticyclonic vortices proposed in the 90s as a pathway for efficient core accretion (Barge & Sommeira 1995)
- The extreme lopsidedness of HD142527 and IRS48 are suggestive of dust trapping in a mild pressure maximum. However, the predicted grain size segregation is not yet observed.
- Trapping in a generic gas background (Birnstiel+ 2013):

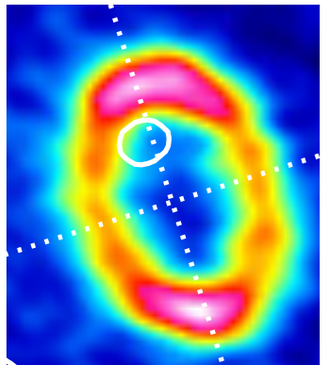




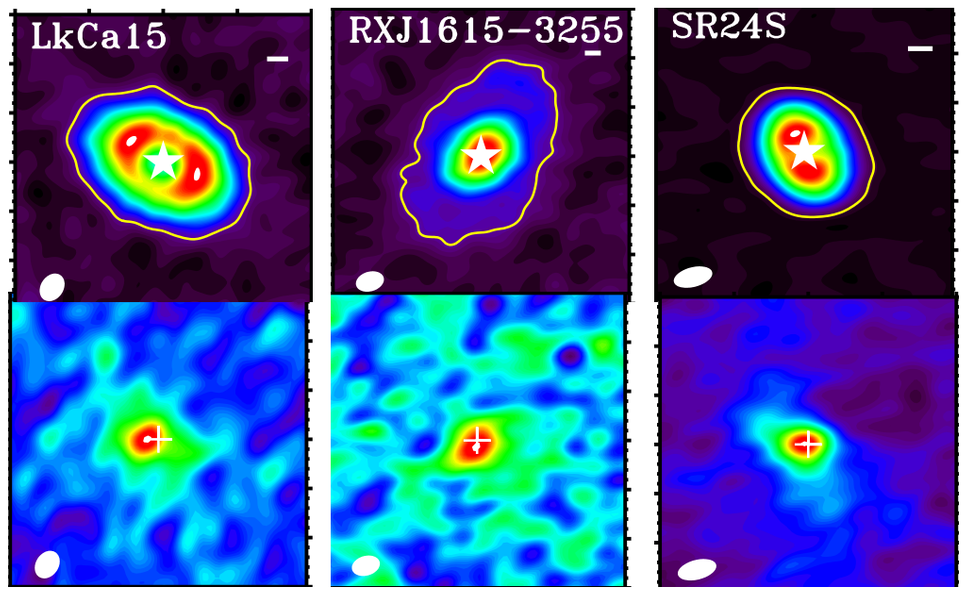
Examples of dust rings with gas-filled cavities.



- J160421-2130 (Zhang+ 2014).
- PDS70 (Hashimoto+ 2015)

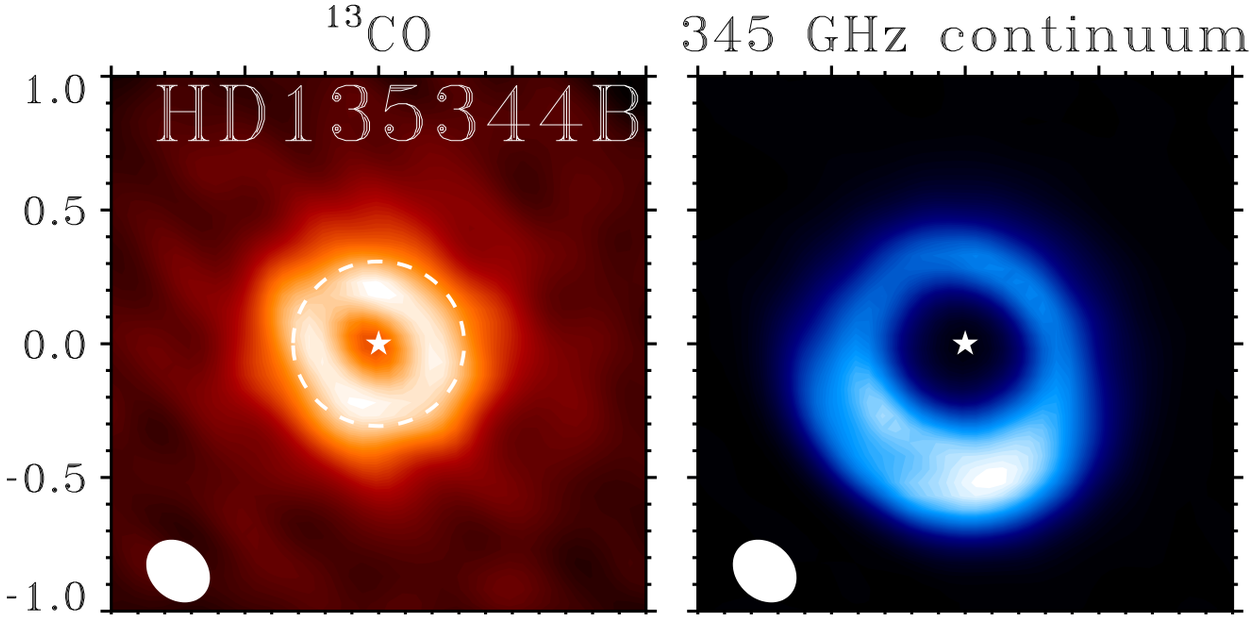


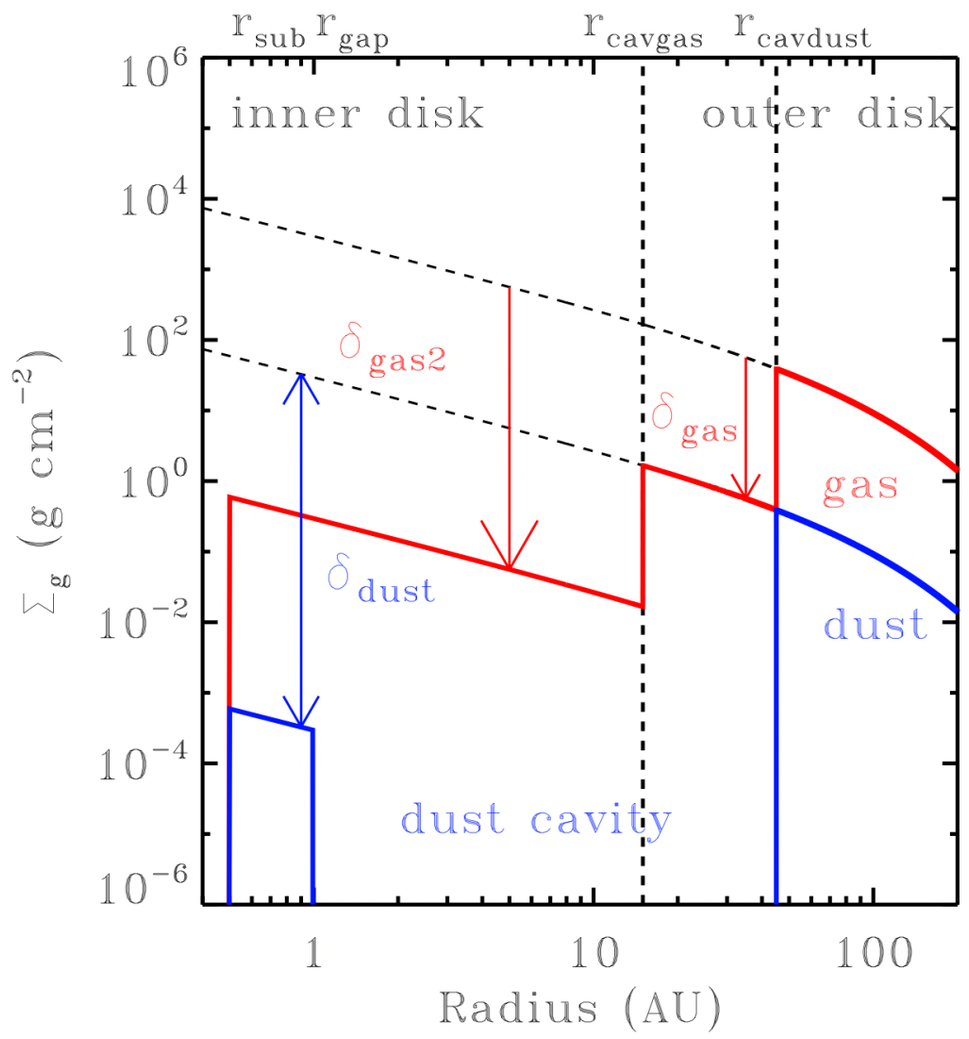
- SZ91 (Canovas+ 2015)
- HD135344 + SR21 (Perez L.+ 2014)
- LkCa15, RXJ1615, SR24S (van der Marel+ 2015)

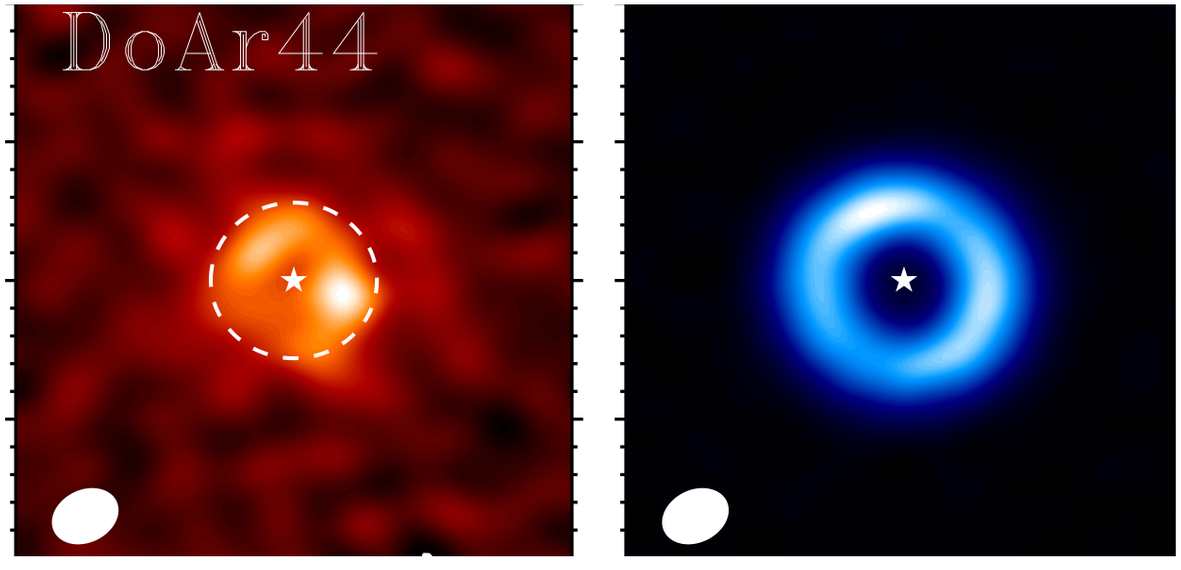


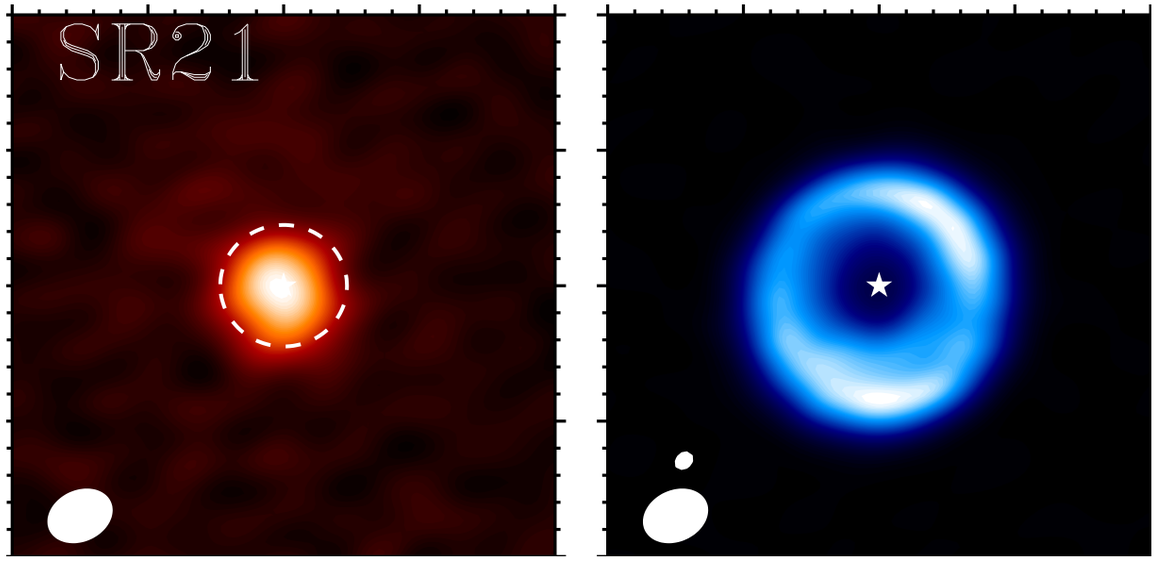
… more ring examples

- Examples from van der Marel+ 2016

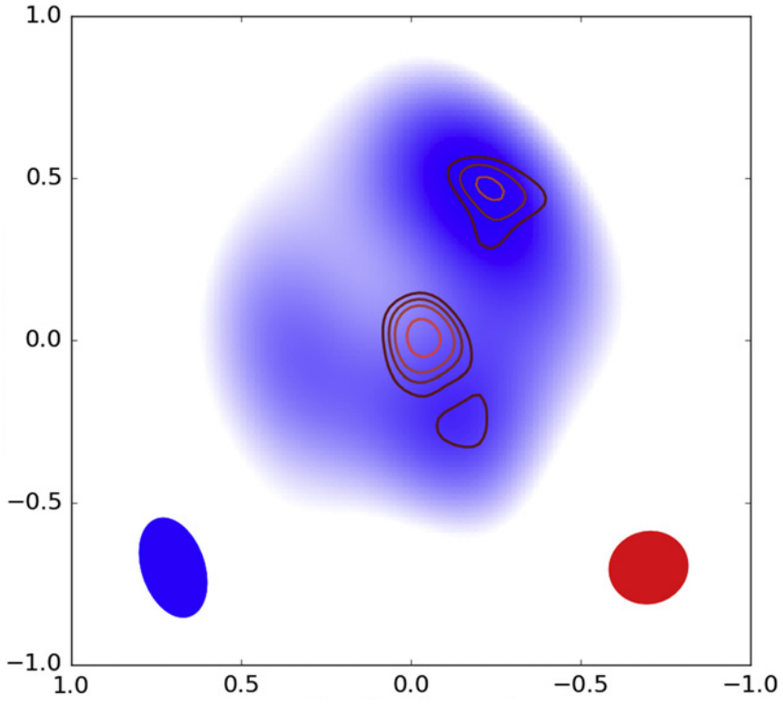




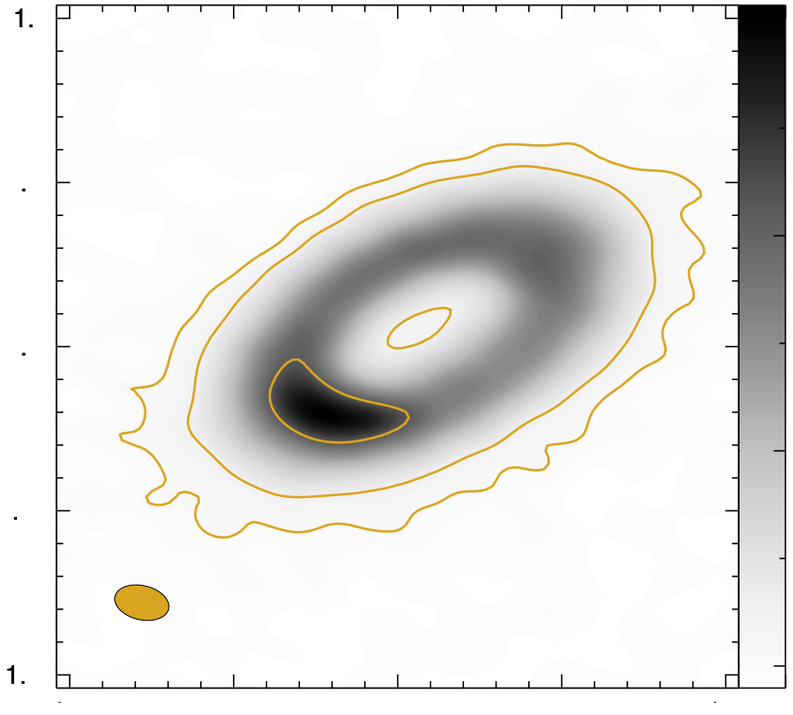




Compact clumps in rings: MWC758 and HD34282

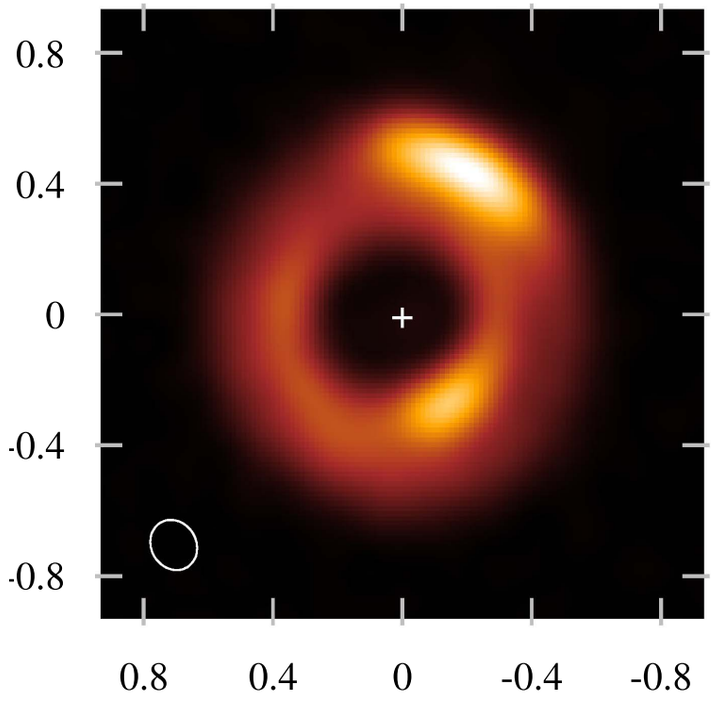


- MWC758 (ALMA blue, VLA red Marino+ 2015)



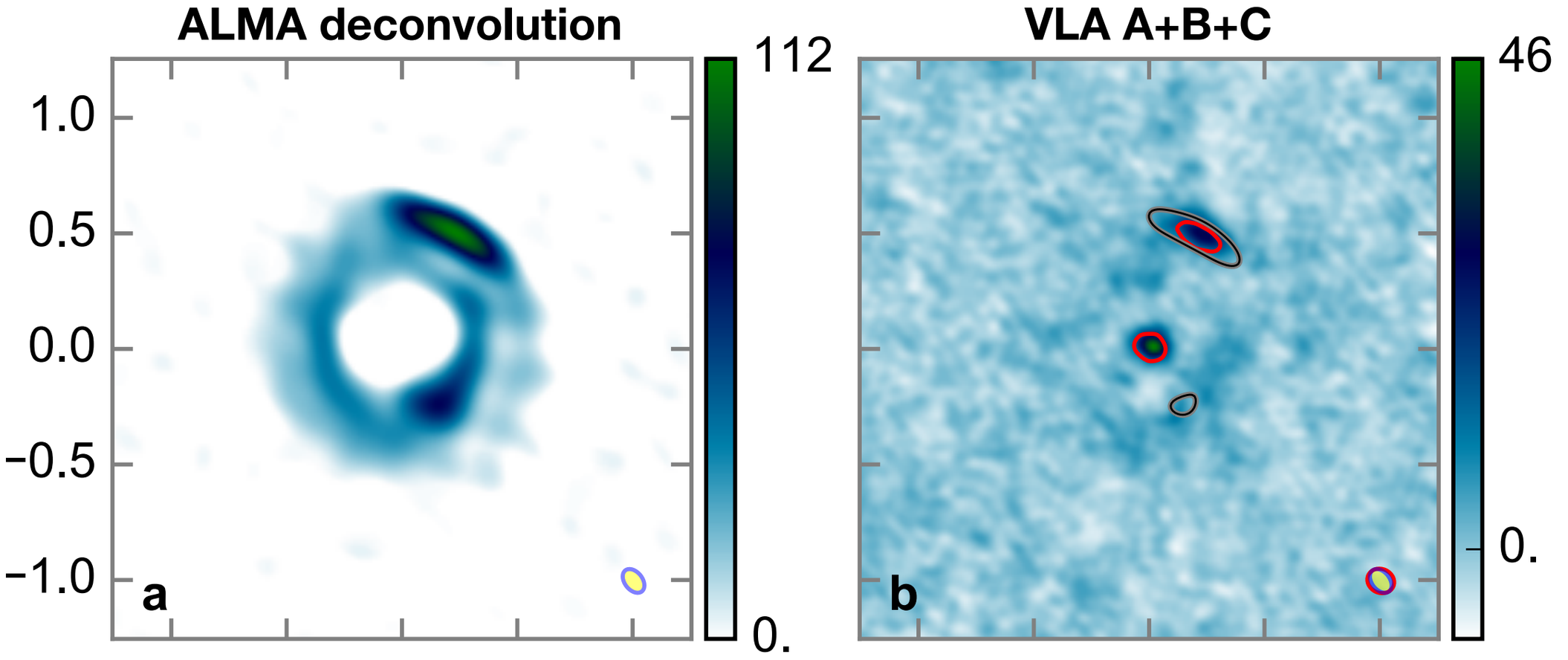
- HD 34282 (van der Plas+ 2017)

- MWC758 (Boehler+ 2018)

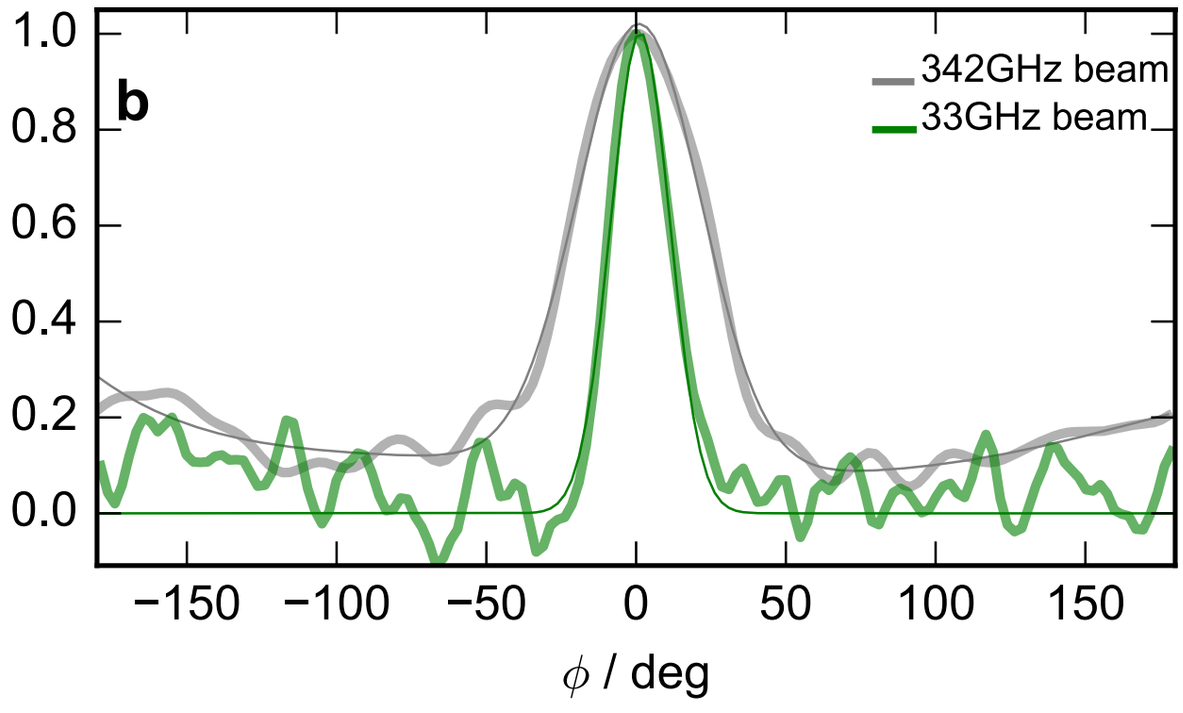


Are MWC758 and HD34282 examples of anticyclonic vortices?

New VLA observations of MWC758

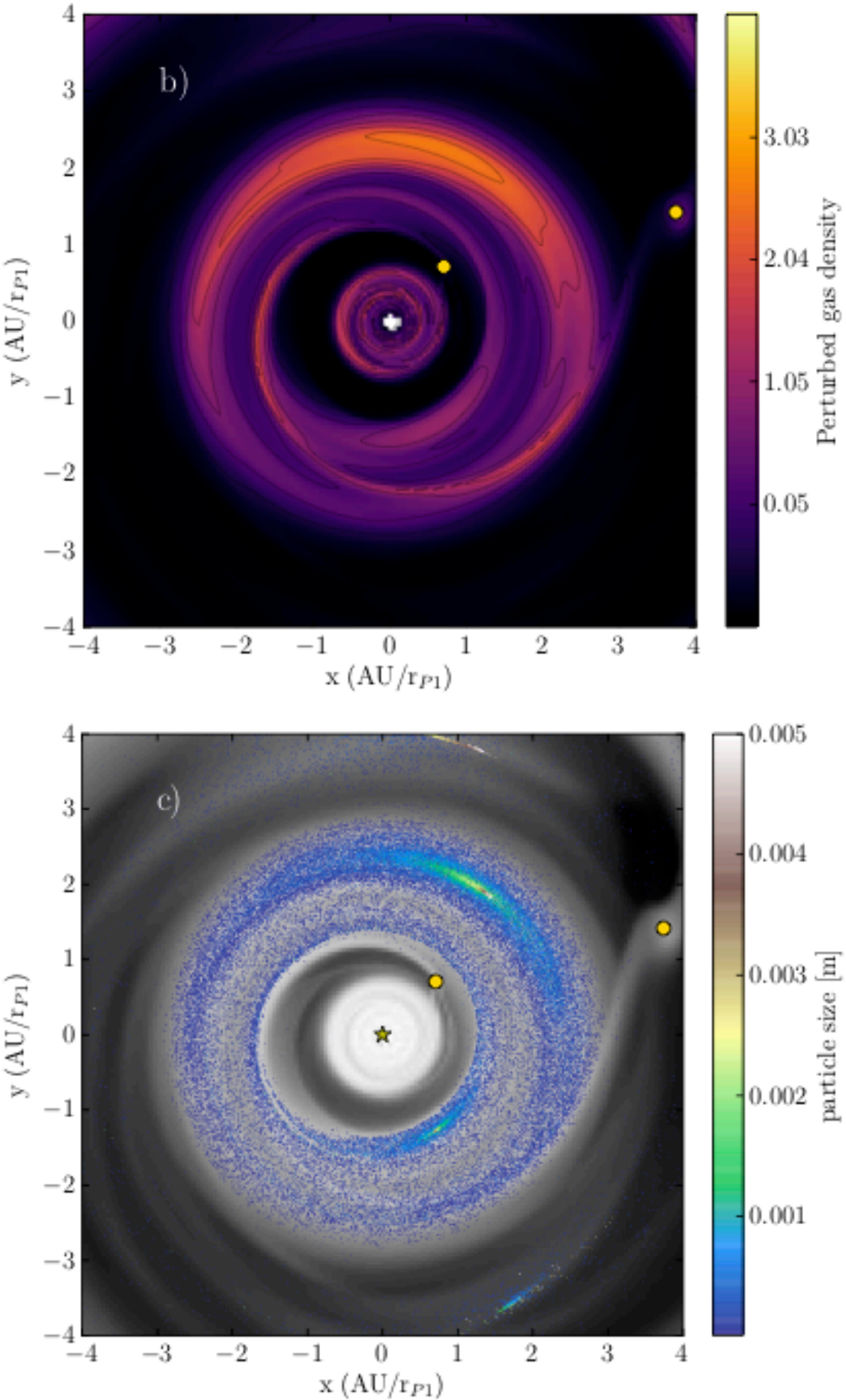


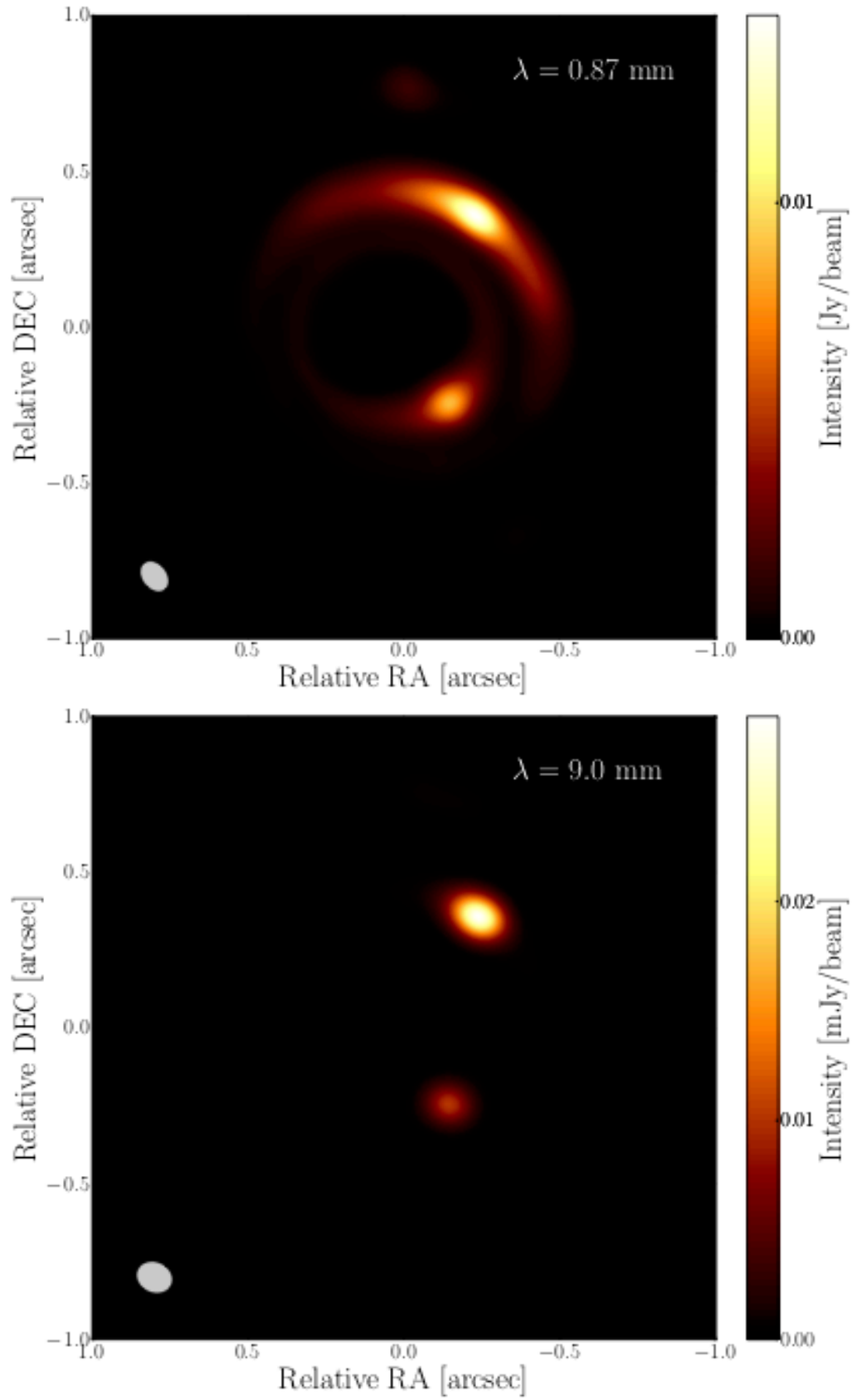
Observations match vortex predictions from Lyra & Lin 2013, provided with gas densities x10 higher than inferred from CO (Casassus+ 2018)



Dust+gas hydro for MWC758

Simulations from Barraza+





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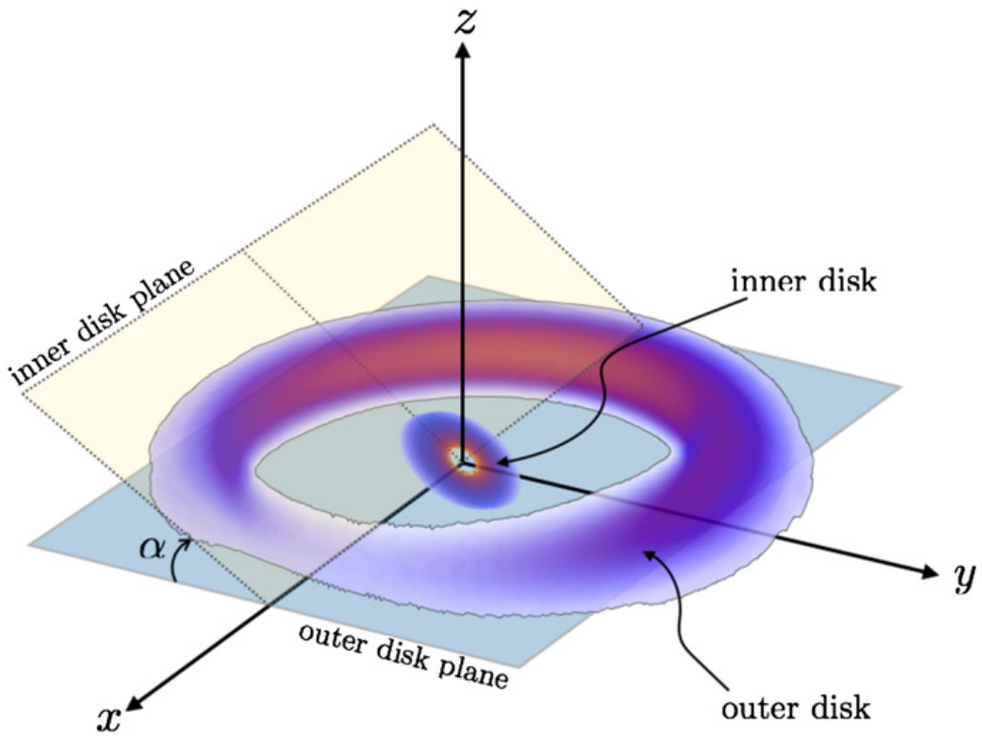
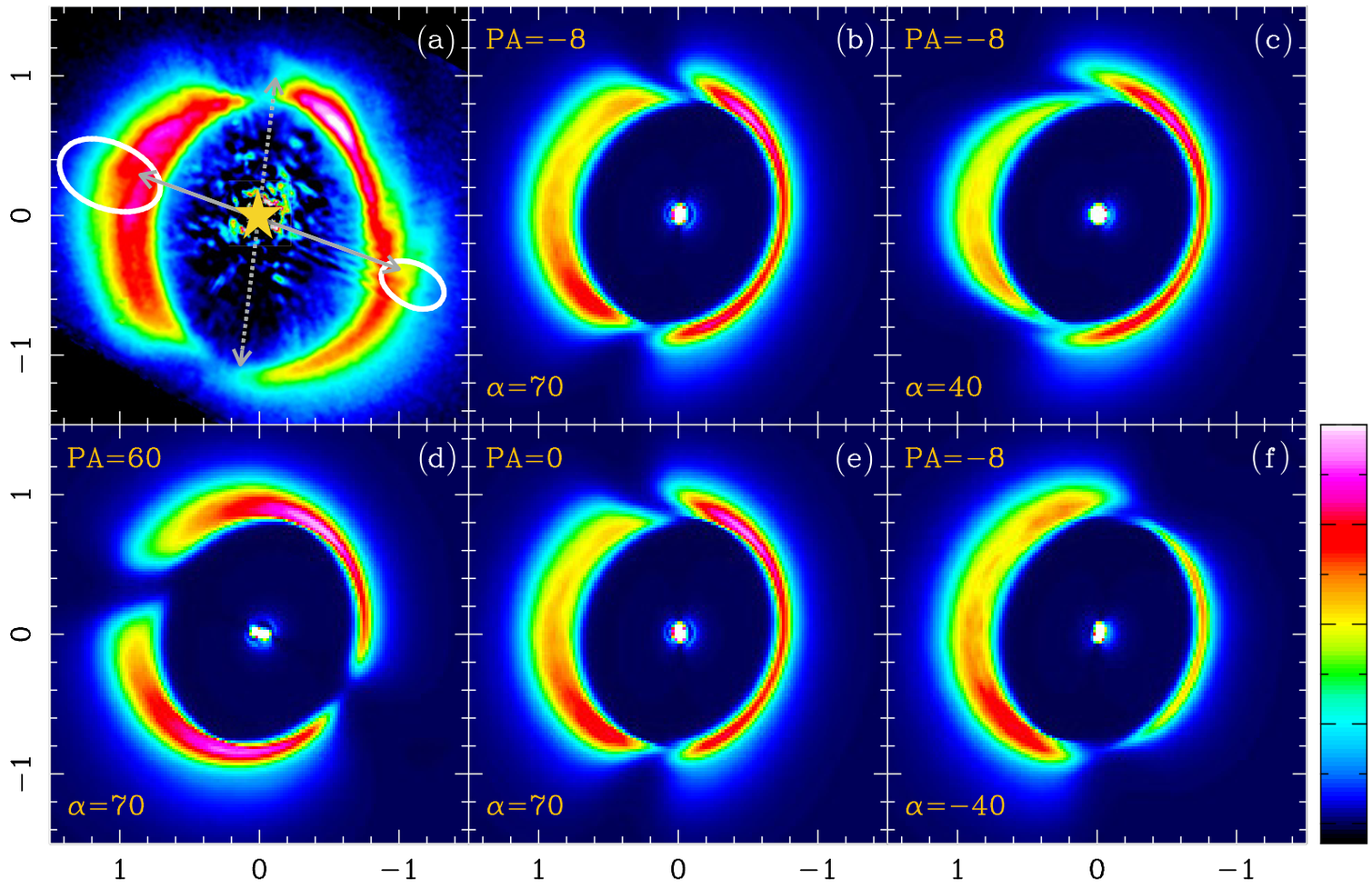
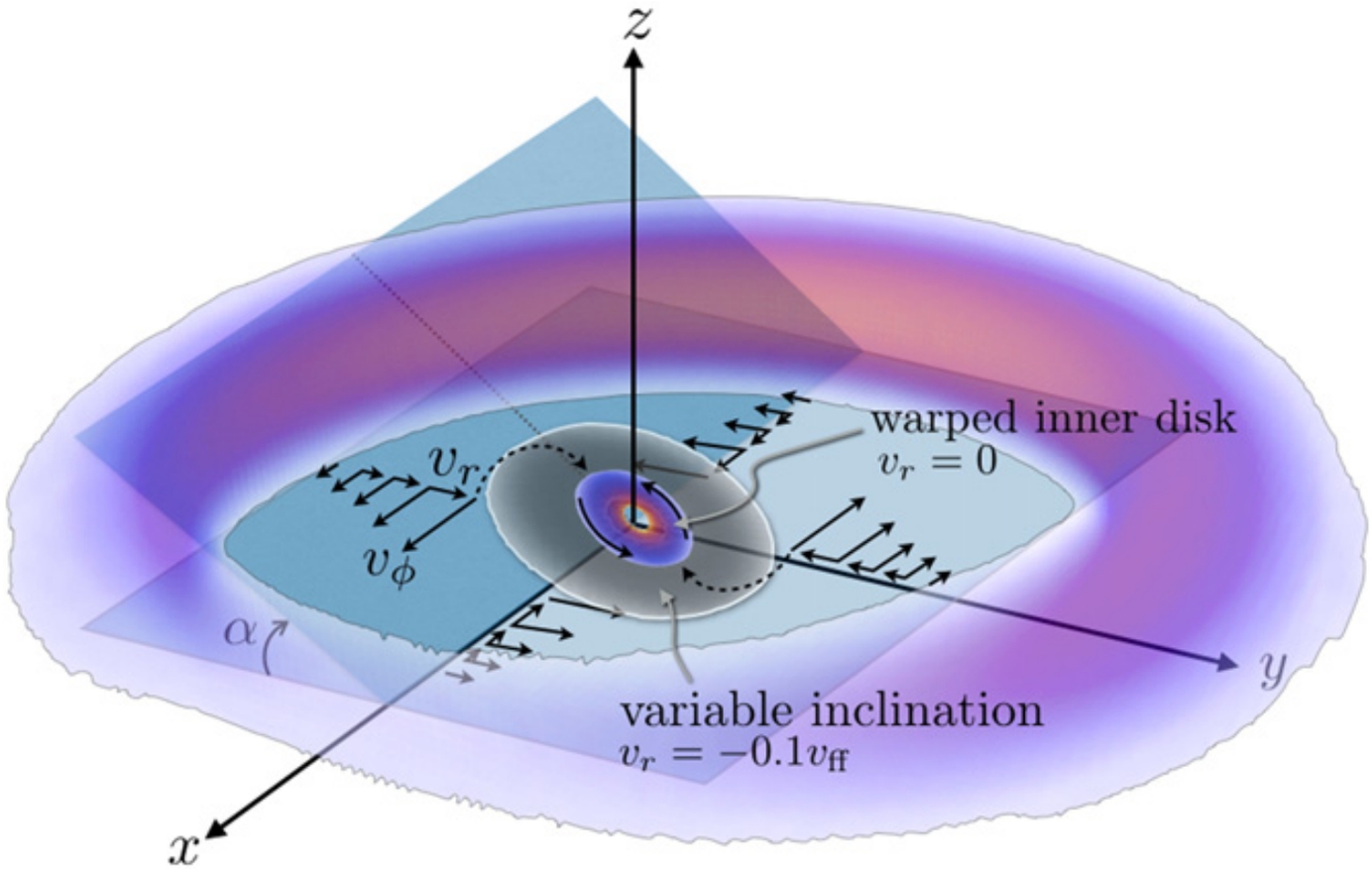
HD 142527: clear case for a 70deg warp

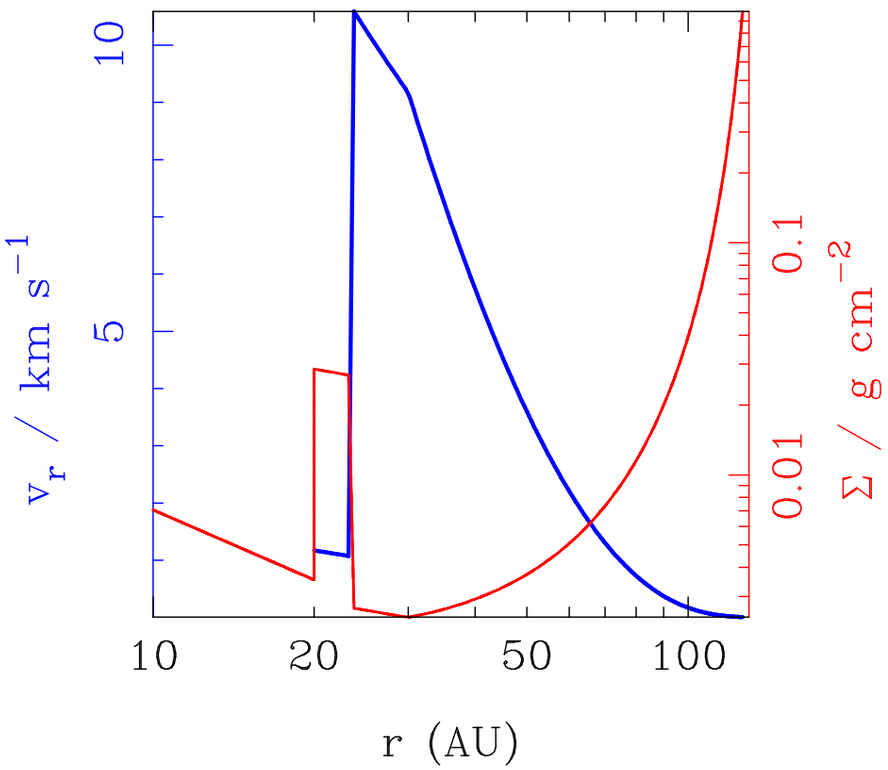


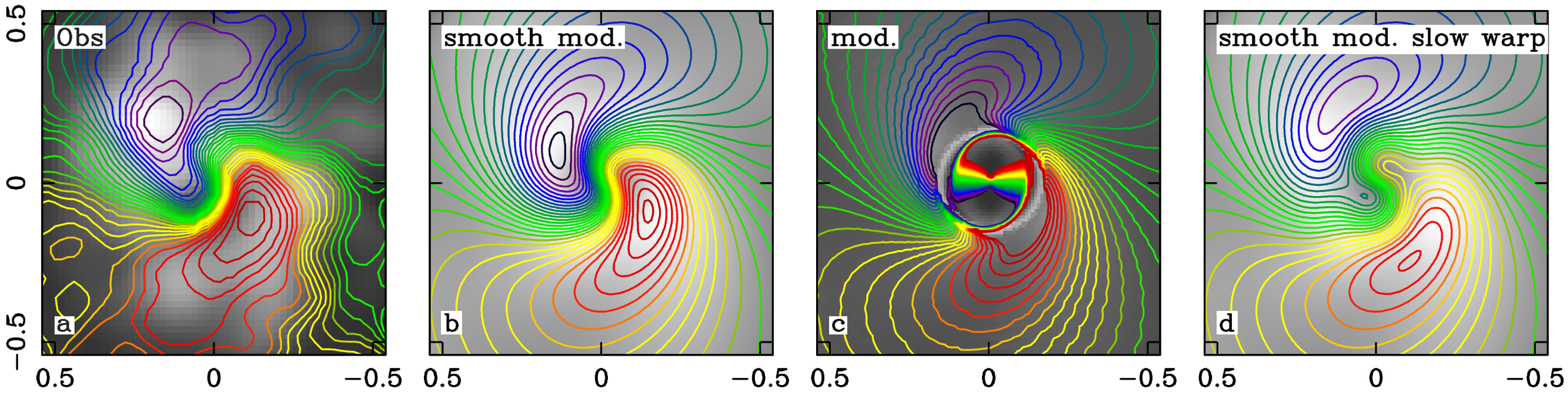


- Shape of the shadows unambiguously confirms a dramatic warp, with a 70deg inclination change(Marino+ 2015). Note clean shadow → regular, long lived inner disk.

Accretion kinematics in the HD142527 warp

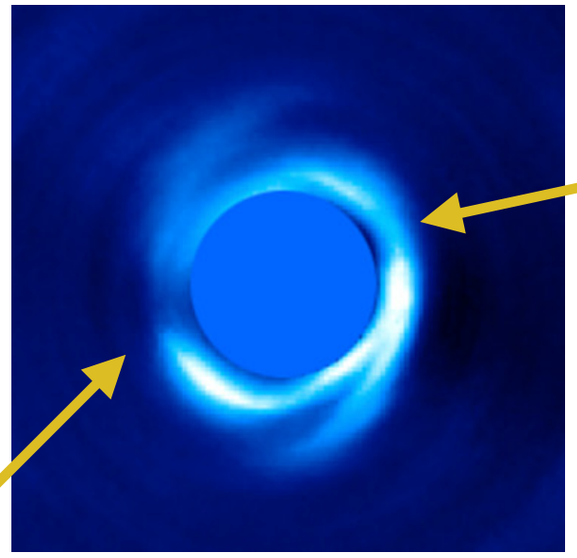




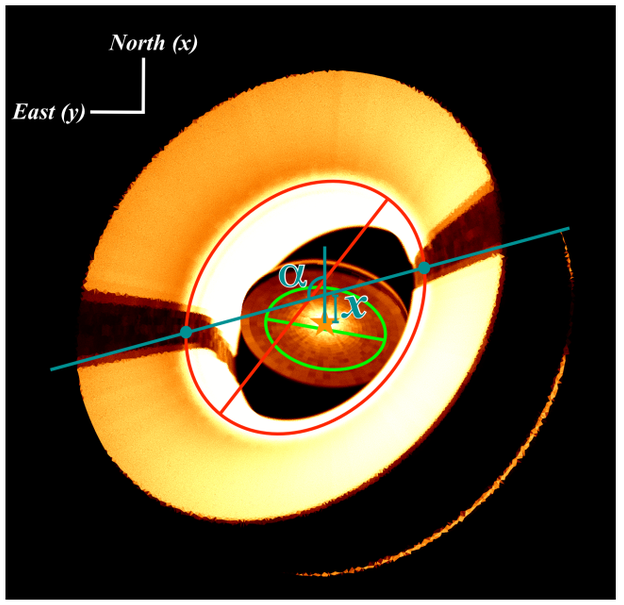


- Resolved gas-rich cavities ➪ interesting kinematics (Casassus+ 2015b).

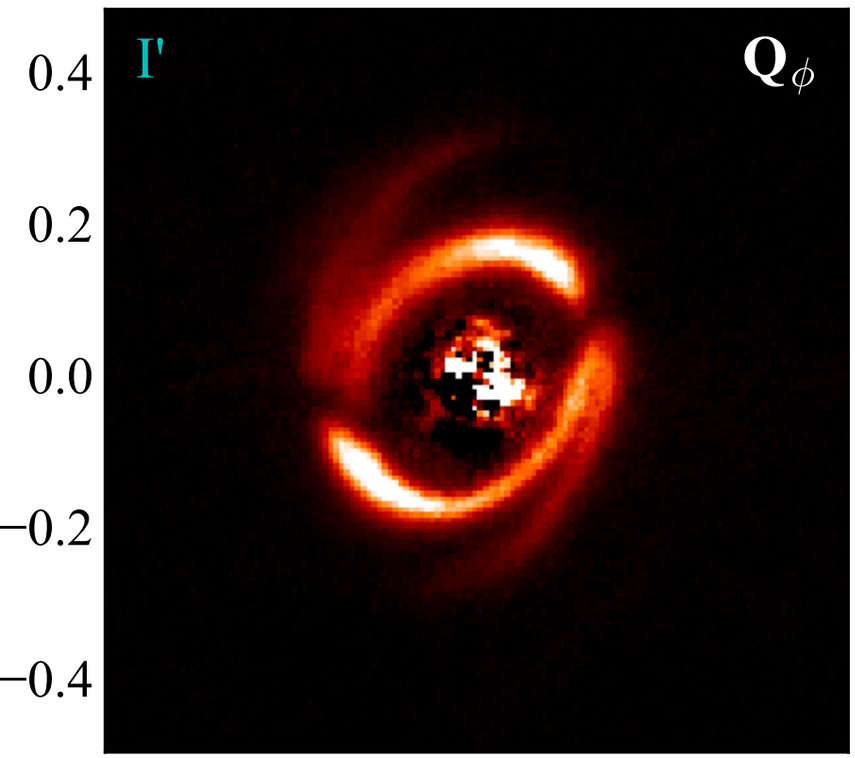
Another 70deg warp: HD 100453



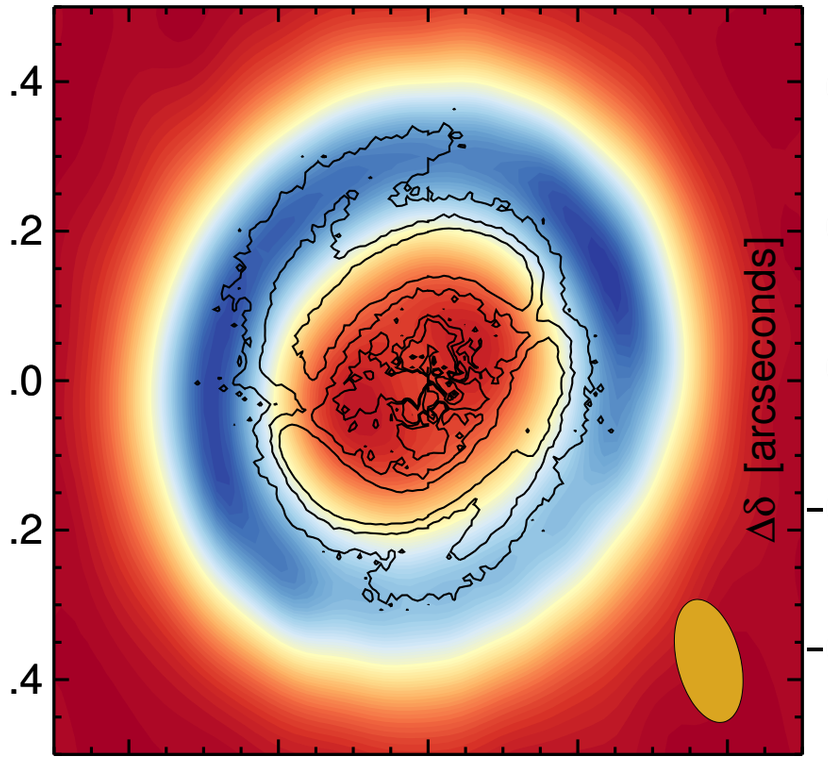
Illumination effects in HD100453
(SPHERE 1.04um, Wagner+ 2015, Casassus 2016)



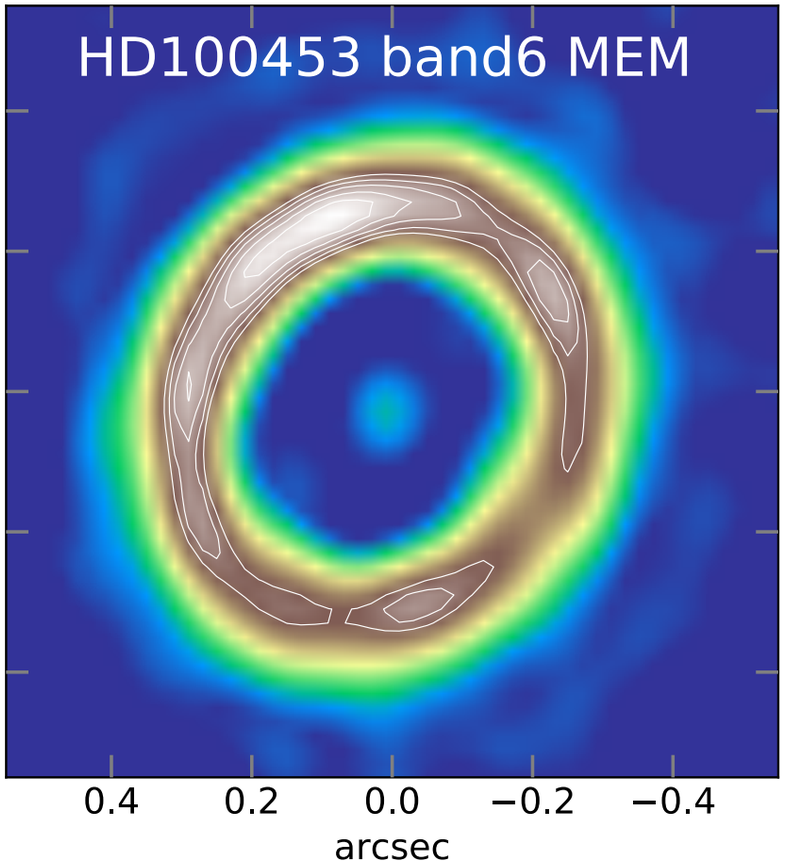
Min+ 2017



VLT+SPHERE PDI
(Benisty+ 2017)

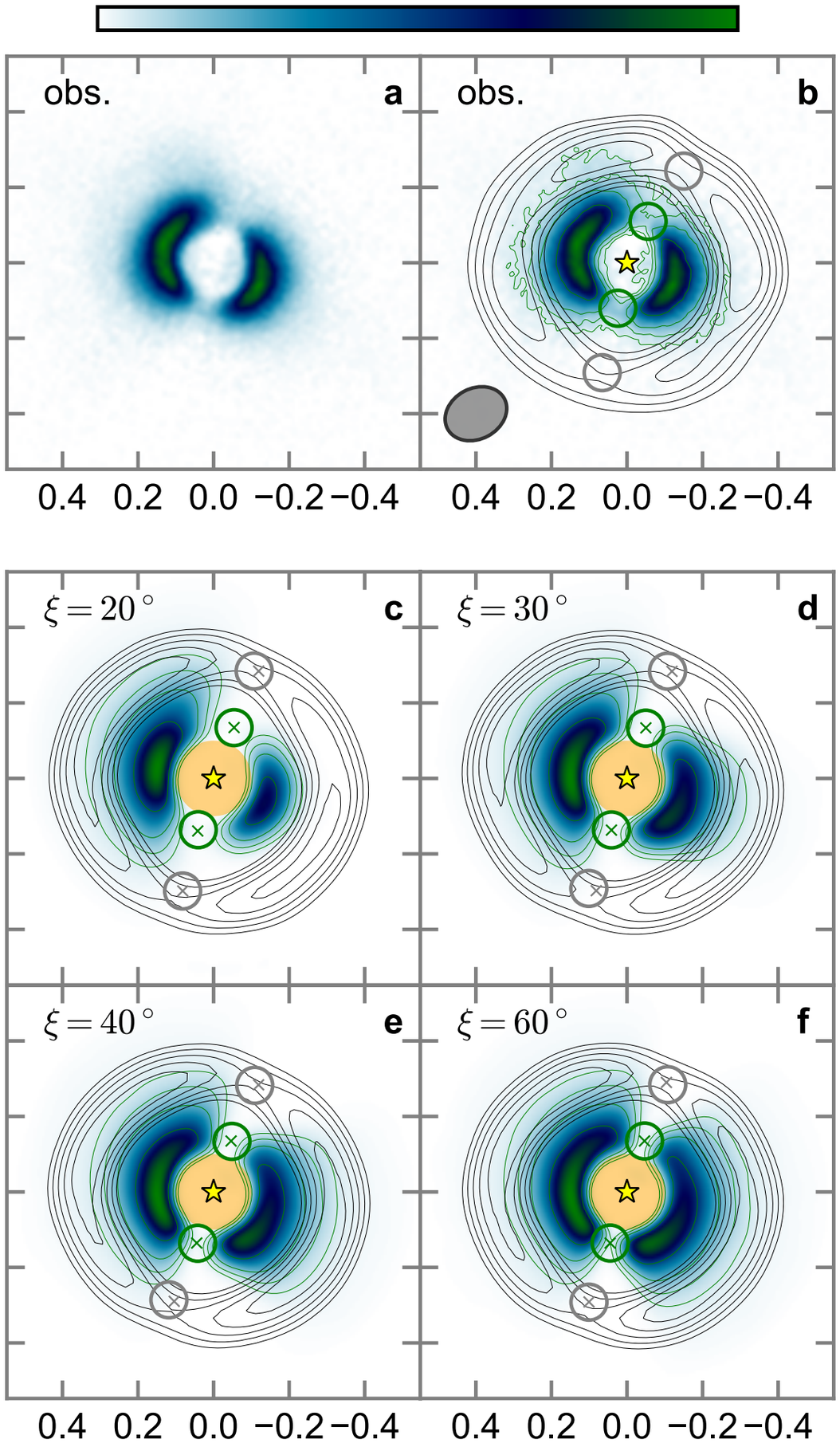


ALMA CLEAN
(van der Plas+ 2018)

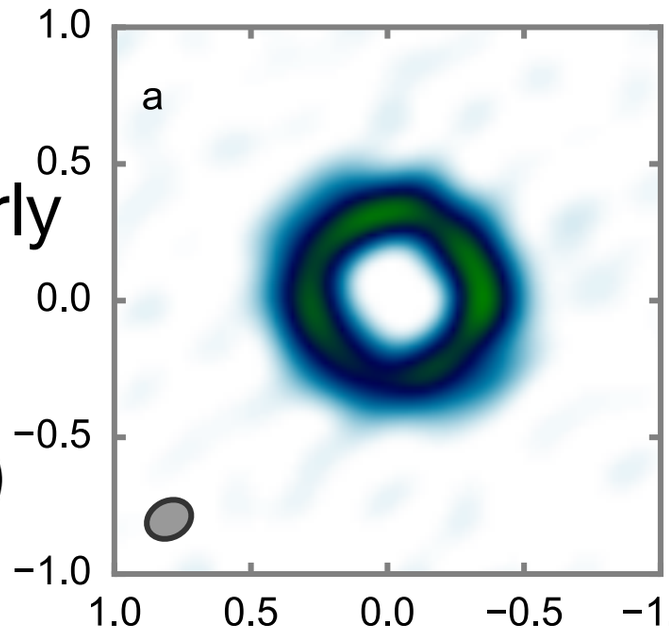


ALMA GPU UVMEM
Cárcamo+

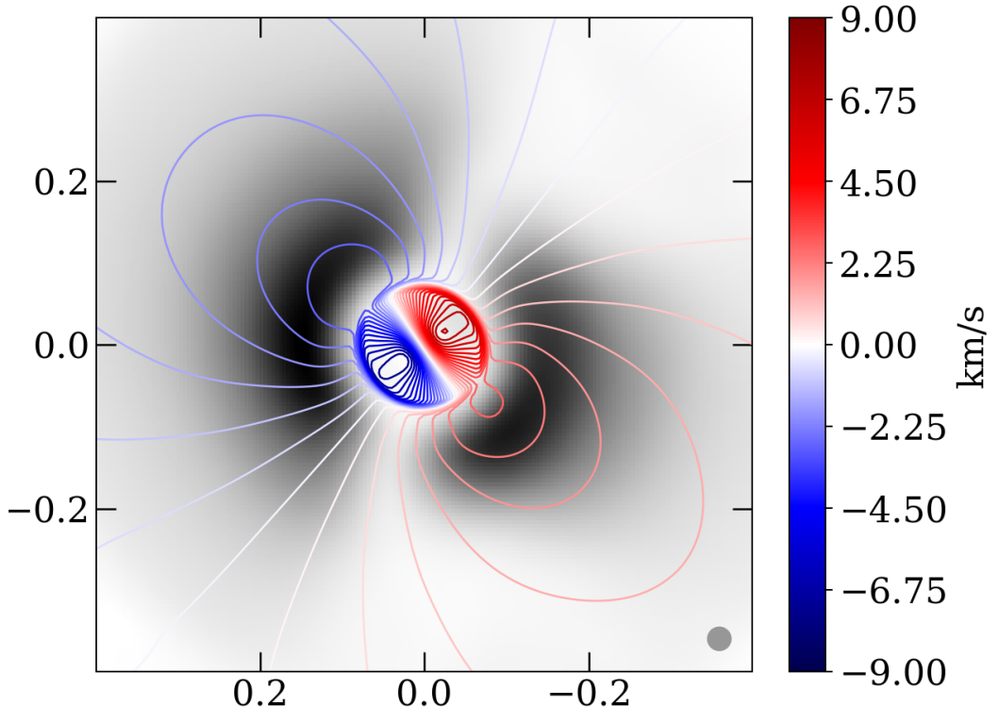
DoAr 44: a TTauri warp at 30deg



Deep near-IR decrements in a fairly smooth and face continuum ring (Casassus+ 2018)



Prediction for CO(6-5):



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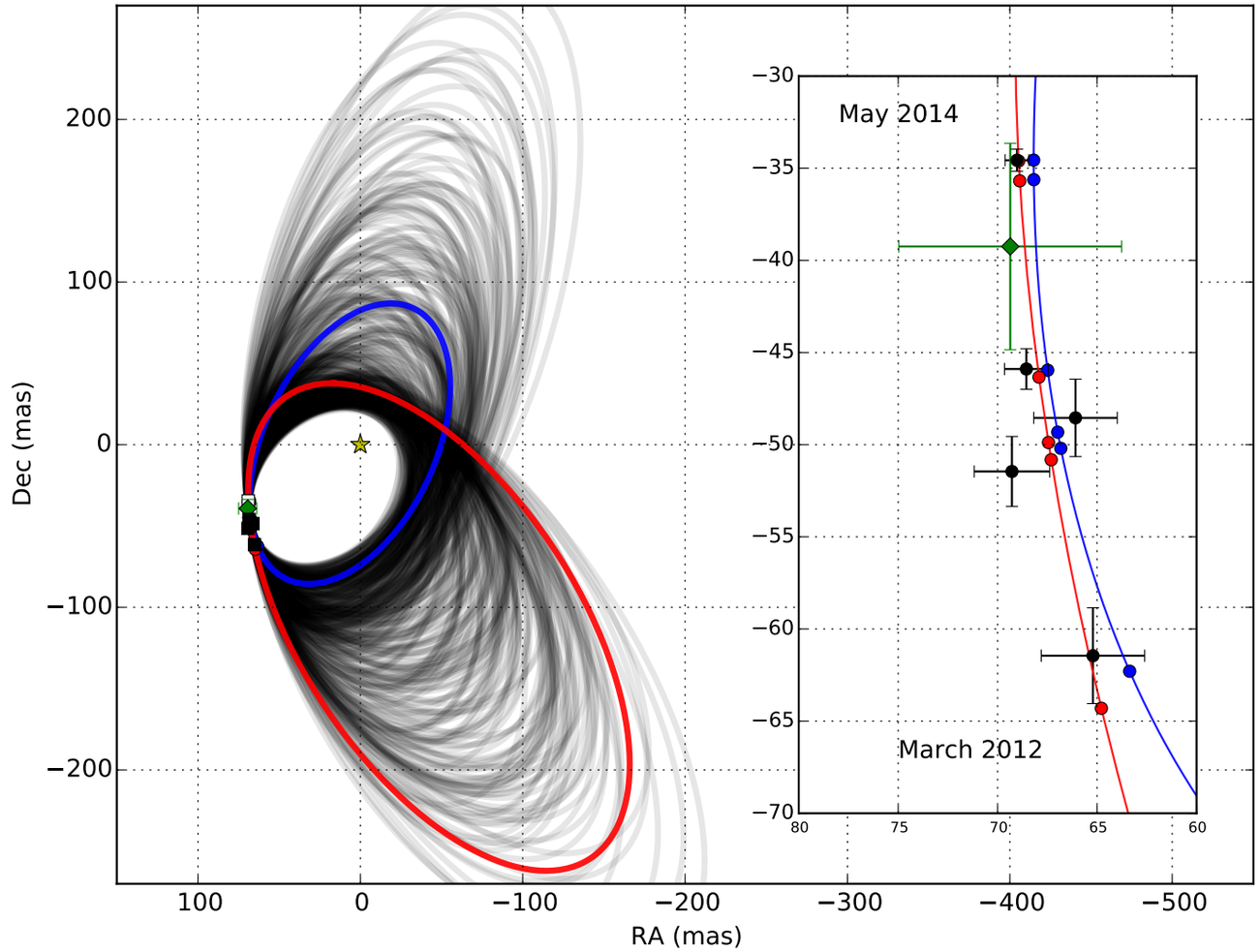
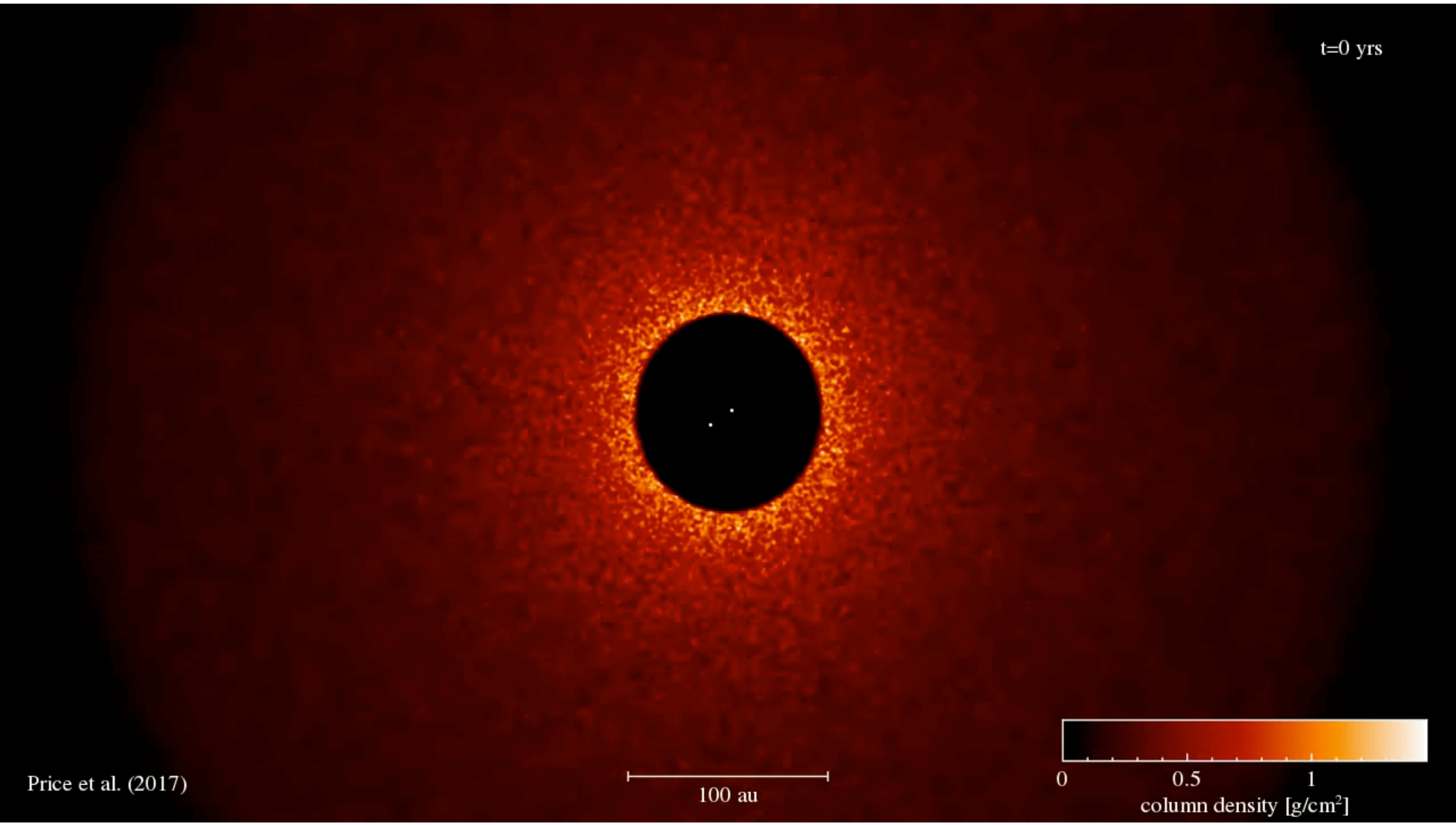
Disk breaking in HD142527?

- Only 1 case of resolved cavity kinematics: HD142527 ➪ clear case for fast accretion (at free-fall) through an abrupt warp.
- Disk breaking by a tilted companion?
- HD142527B: mass ratio ~0.1 (Close+ 2014, Christiaens+ 2018)

HD142527B orbit
Lacour+ 2016



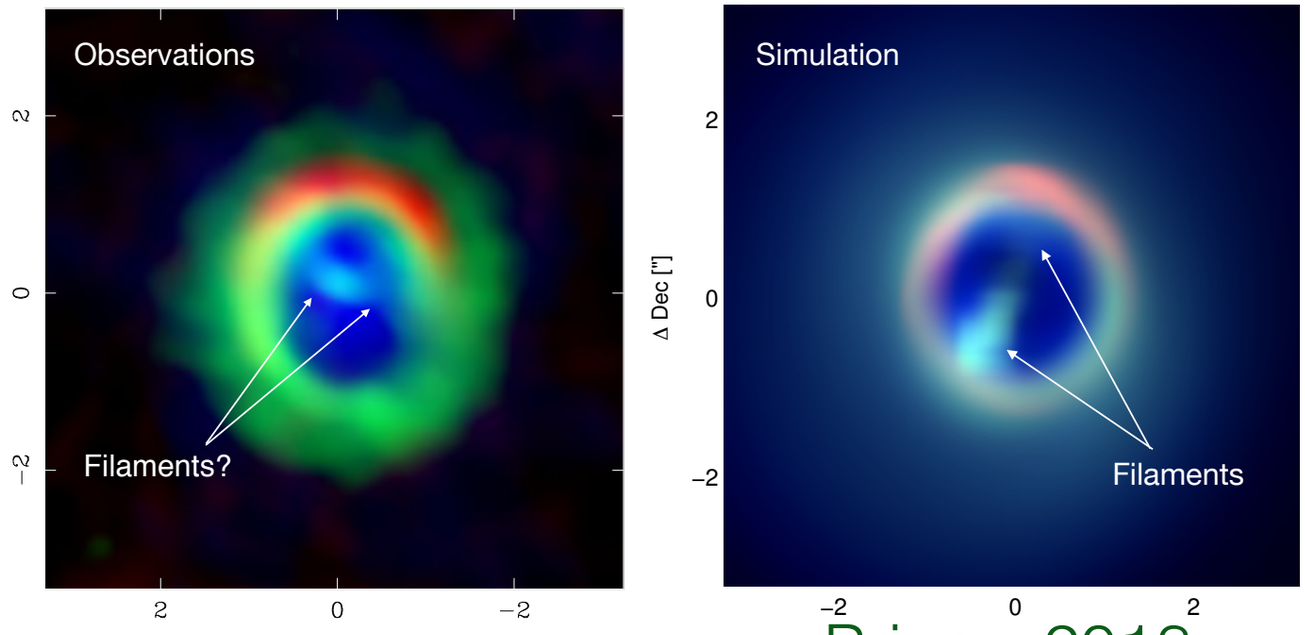


PHANTOM simulation (Price+ 2018)

Summary: large cavities as circumbinary disks?

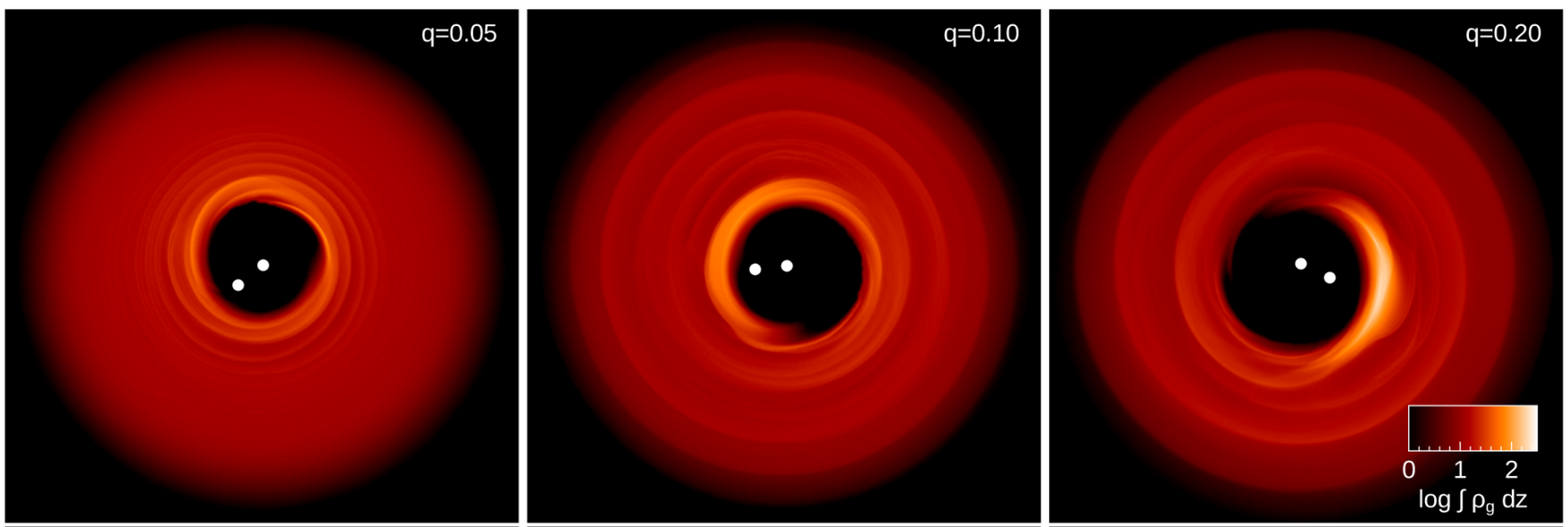
- HD142527, with q~0.1, could be an extreme which informs on other cavities with q~0.01-0.05

- Intermediate separation binaries (~1-10au) are poorly constrained (Duchêne & Kraus 2013)



Price+ 2018

- Wide range of cavity radii, lopsidedness and inner disk tilts, could reflect wide variety of binary orbits.



PHANTOM simulations
Ragusa+ 2017

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Summary

- ALMA has revealed transition disks with large cavities **as narrow continuum rings filled with residual gas**.
- These rings are lopsided at different levels, with spectral trends indicative of **high optical depth at ALMA frequencies**.
- **cm-wavelengths** (i.e. ALMA band1) allow observing the **segregation of grains sizes** expected from anticyclonic vortices, as in MWC758.
- AO-assisted **polarization imaging** has revealed that rings are affected by a wide range of **warps**.
- **Ring lopsidedness and warps are reproduced** by simulations of binary-disk interactions on inclined orbits at low mass ratios, **q~0.1**.
- The **convergence of theory and observations** promises to soon allow quantitative comparisons, also in the q~0.001 regime.