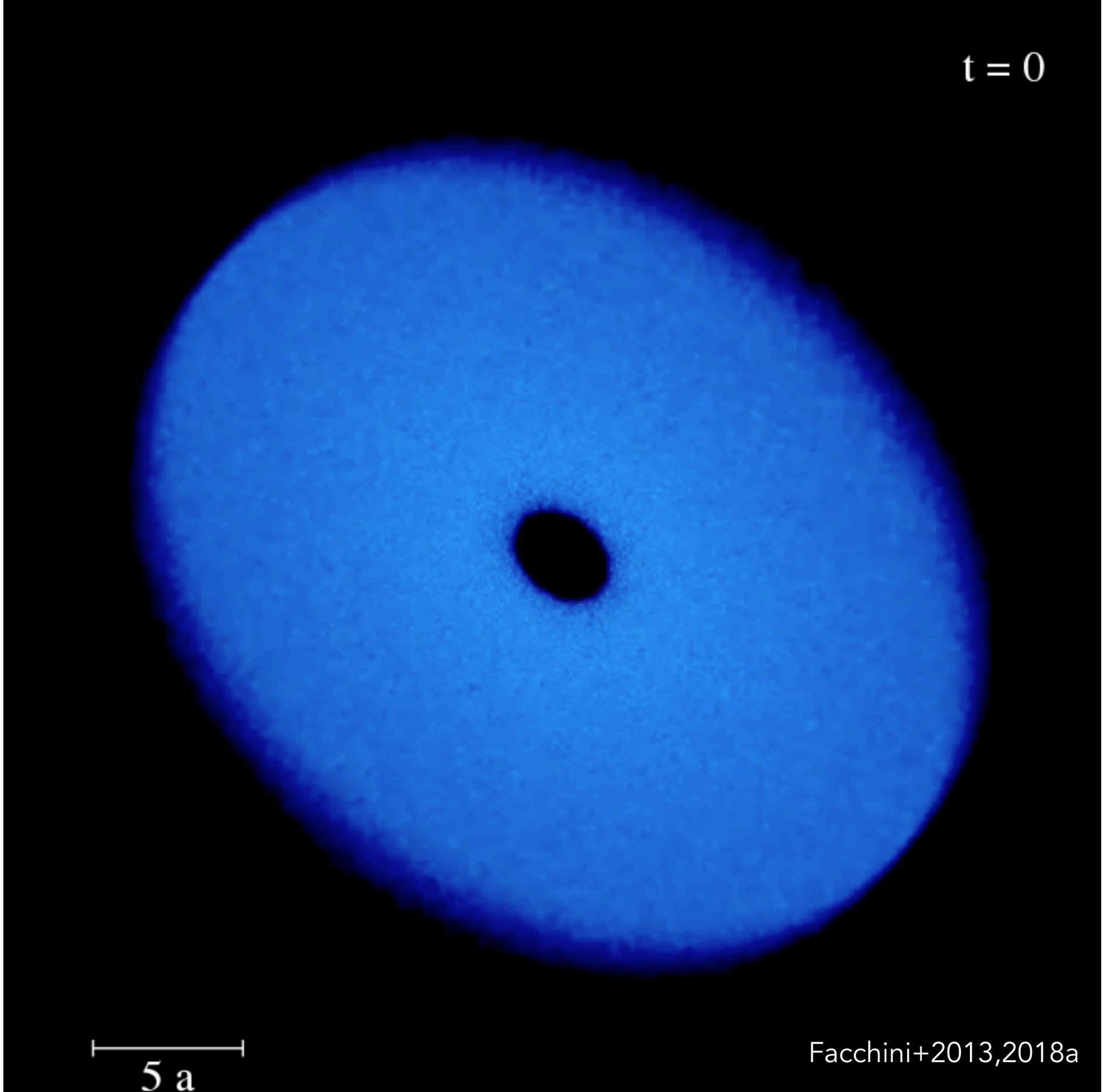
The interplay of inner and outer disks in misaligned systems

Stefano Facchini

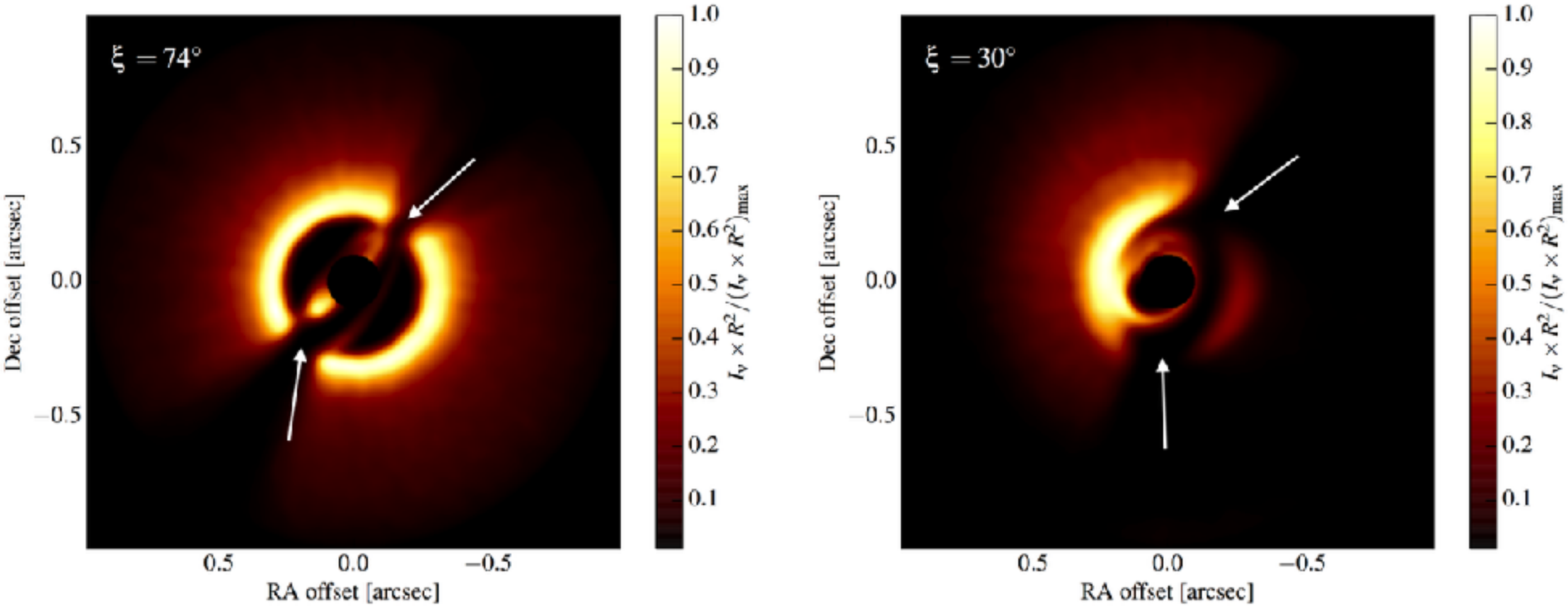
Collaborators: Myriam Benisty, Carlo Manara, Attila Juhàsz, Giuseppe Lodato, Maria Koutoulaki, Antonella Natta, Christian Schneider, and many others

Planet forming disks, Menaggio, 06/03/2019



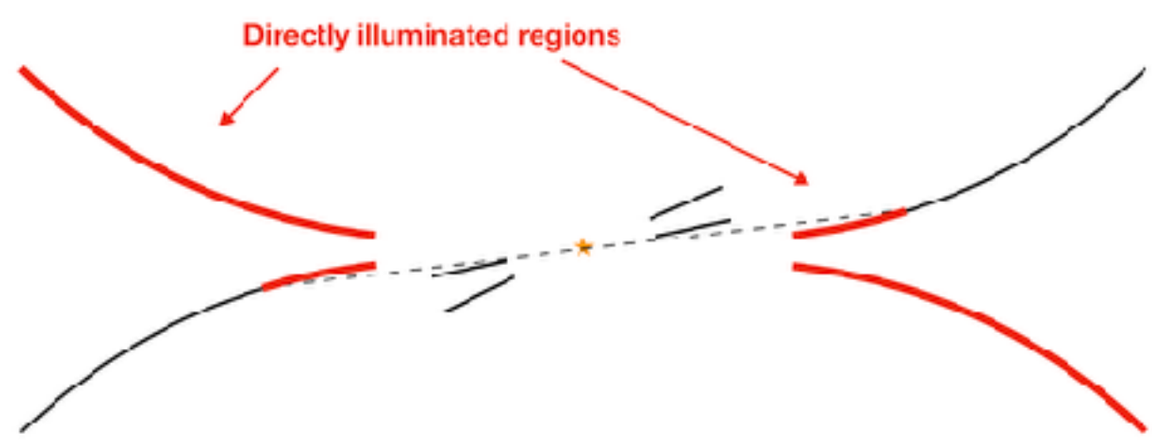
Facchini+2013,2018a

Post-processing of the hydro simulations



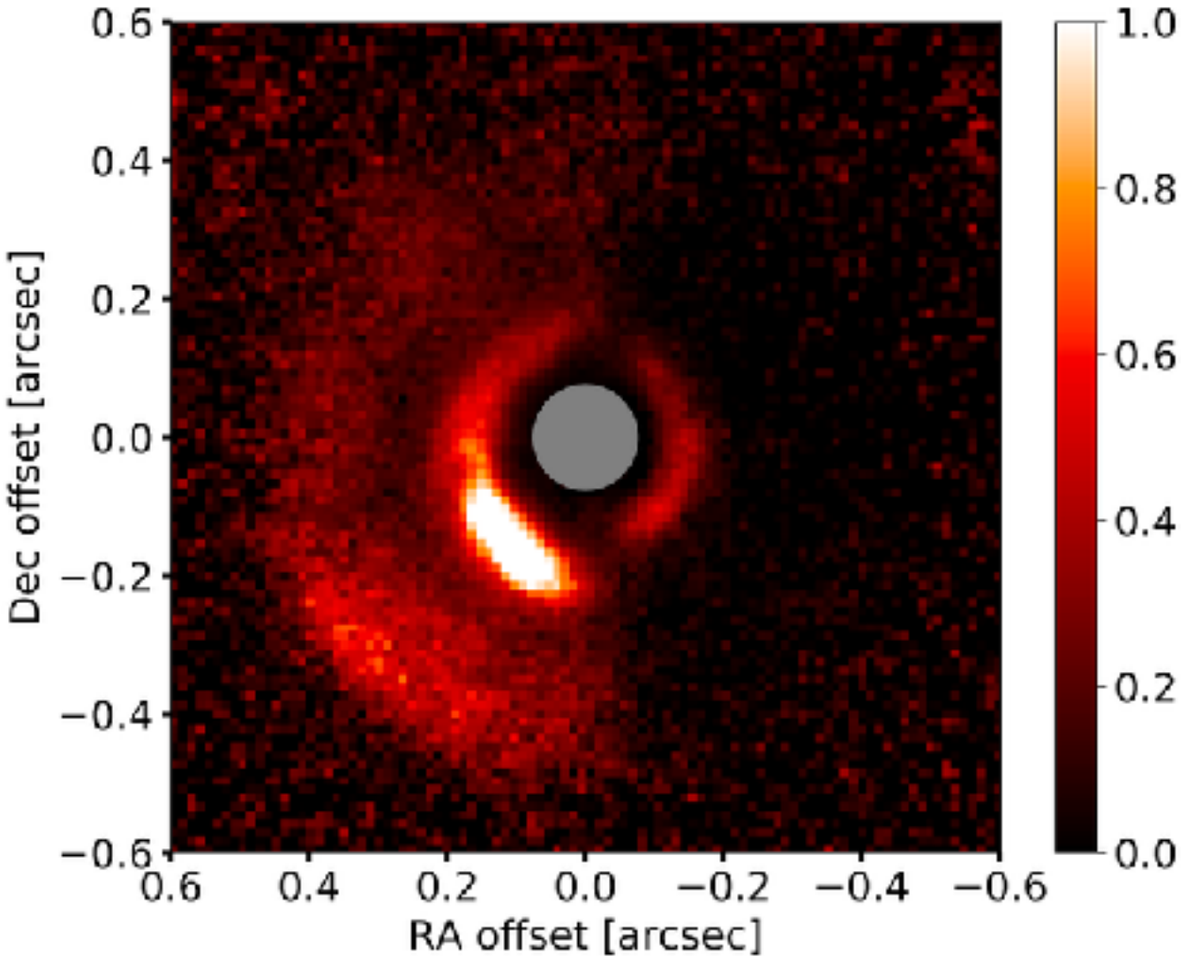
Facchini+2018a

Particular misalignment angles can shadow half of the disk when the disk is flared



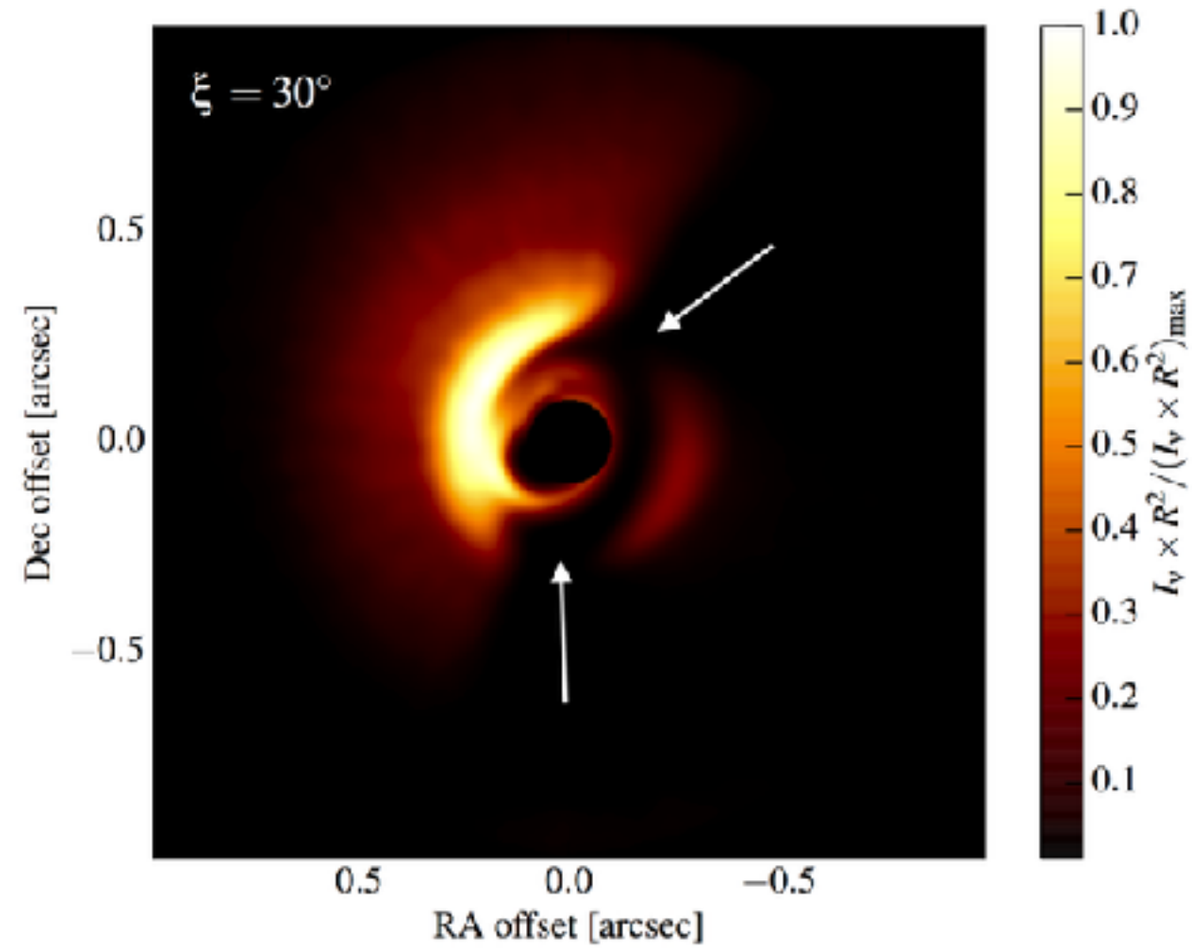
Post-processing of the hydro simulations

SPHERE observation of HD143006



Benisty, Juhasz, Facchini+2018

Model *before* seeing the data



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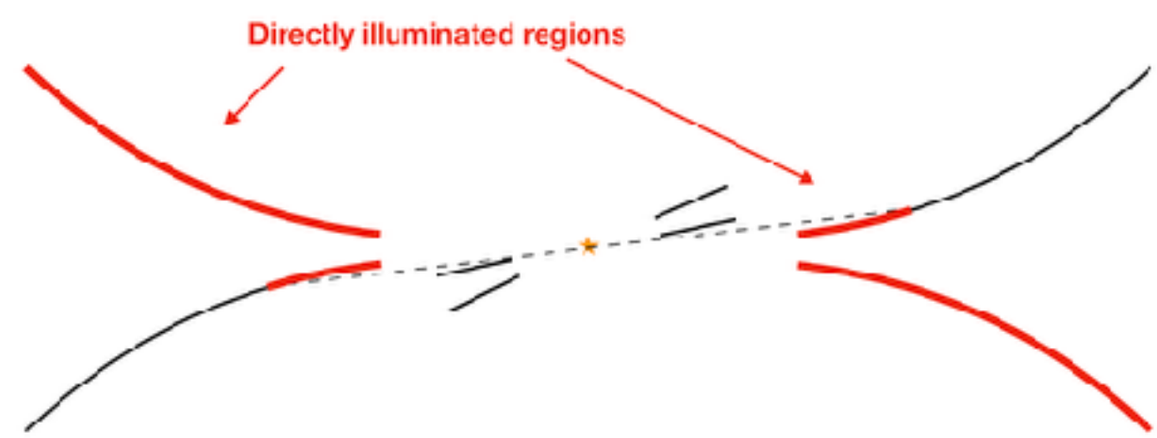
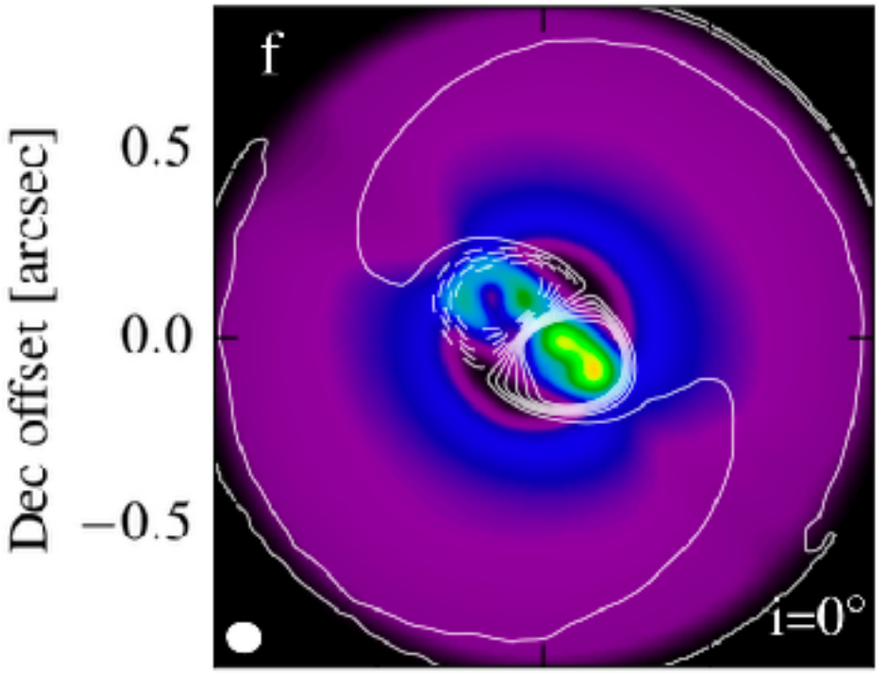
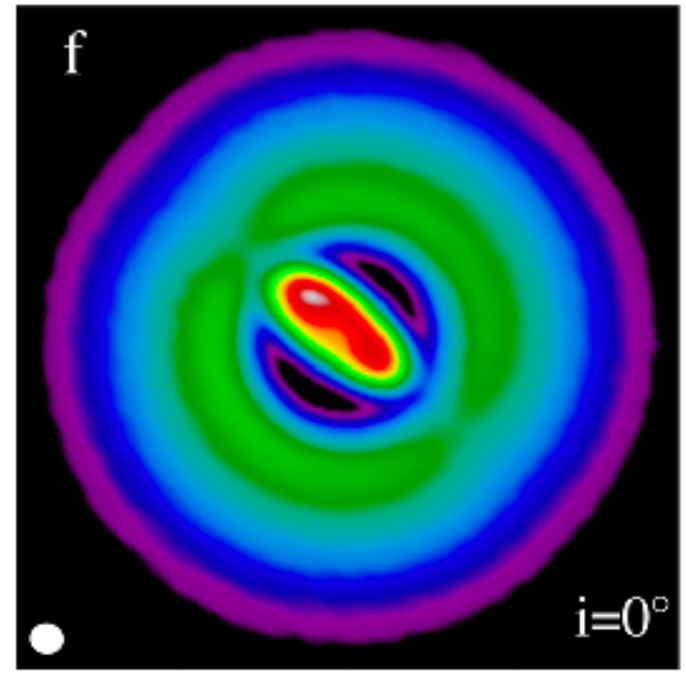


Other predictions

CO 3-2 mom0

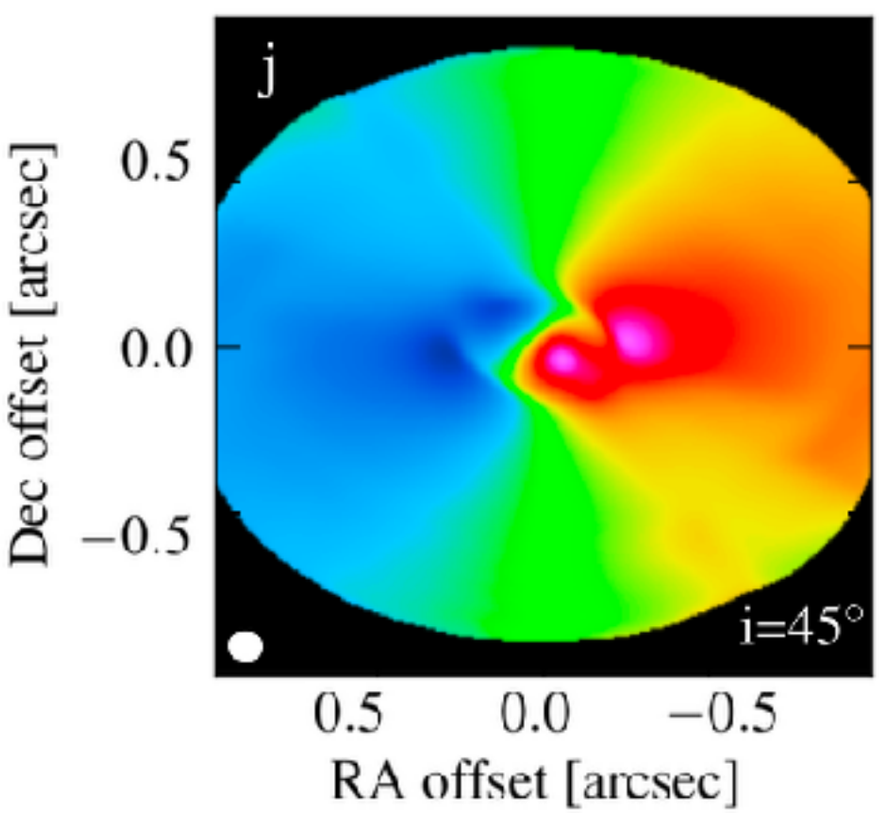


0.87 mm continuum

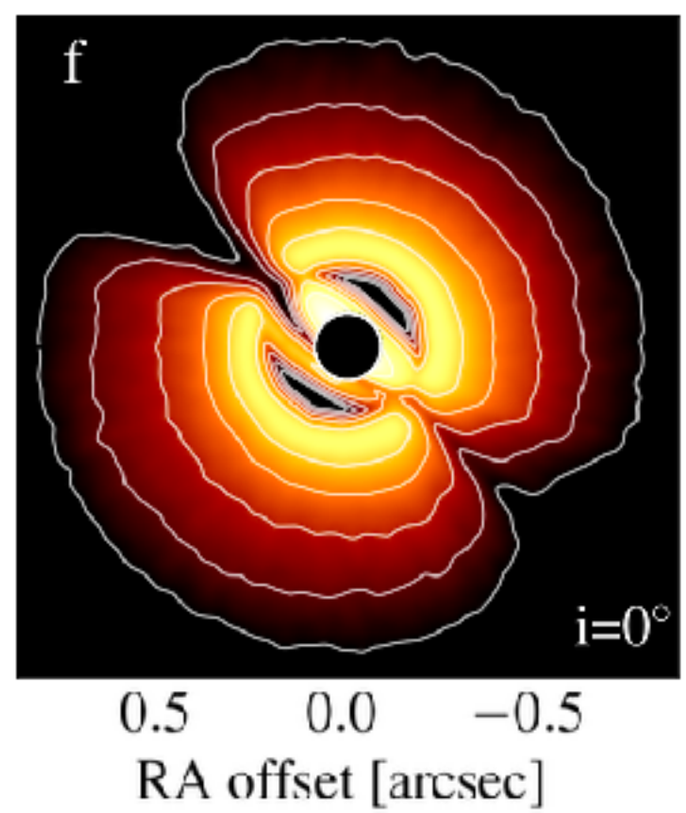


1) Azimuthal asymmetries in temperature profile

CO 3-2 mom1



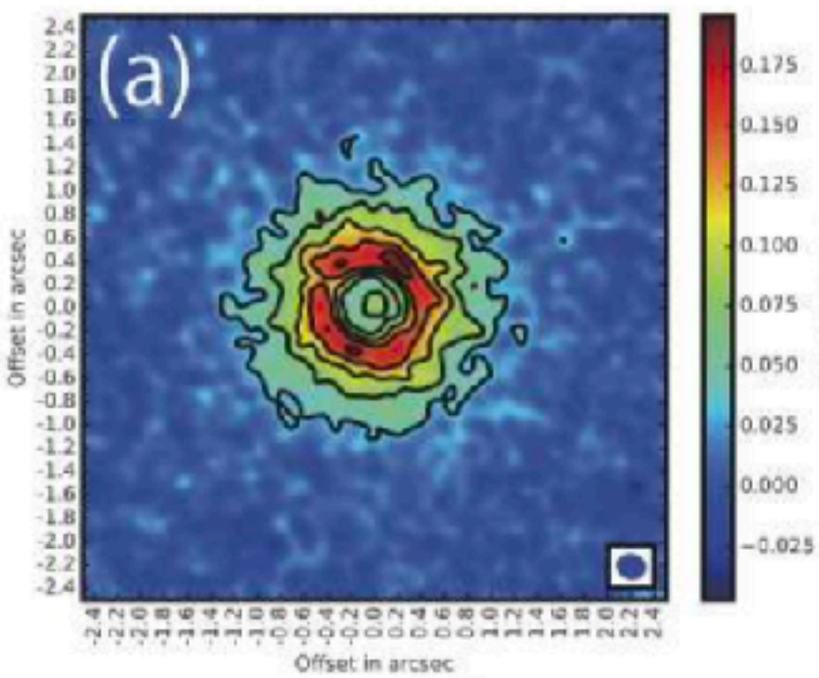
SPHERE J-band



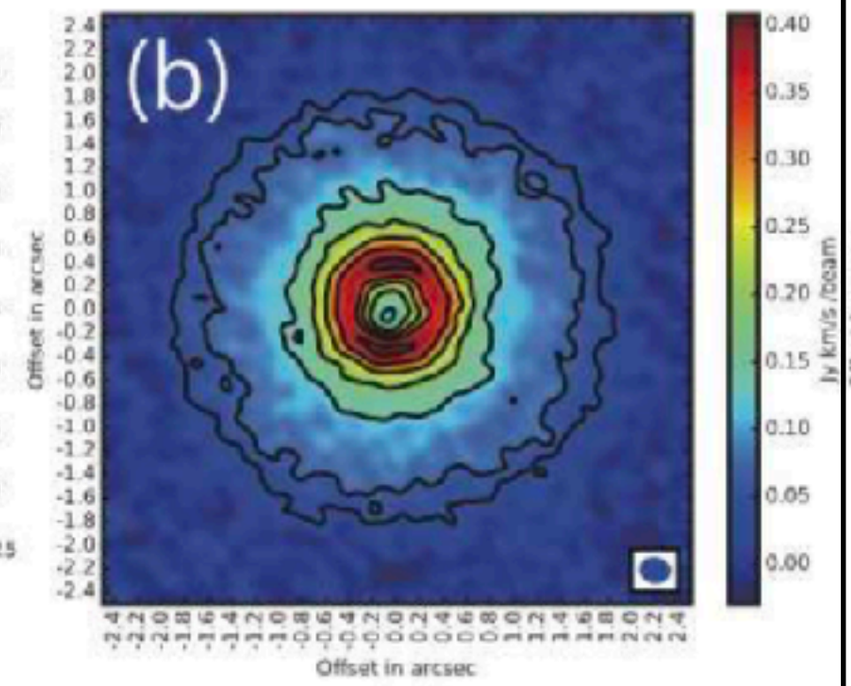
2) Twisted kinematics

Observations of J1604

HCO+ 4-3 mom0



CO 3-2 mom0



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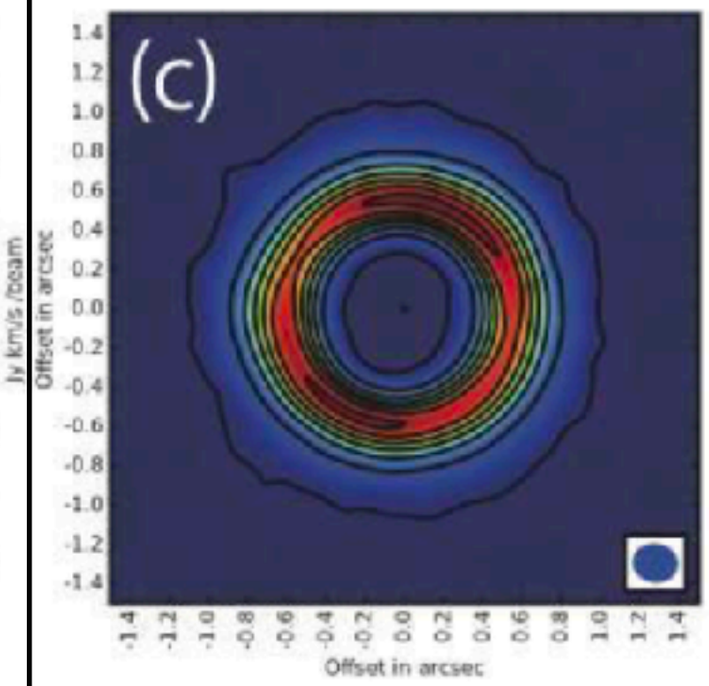

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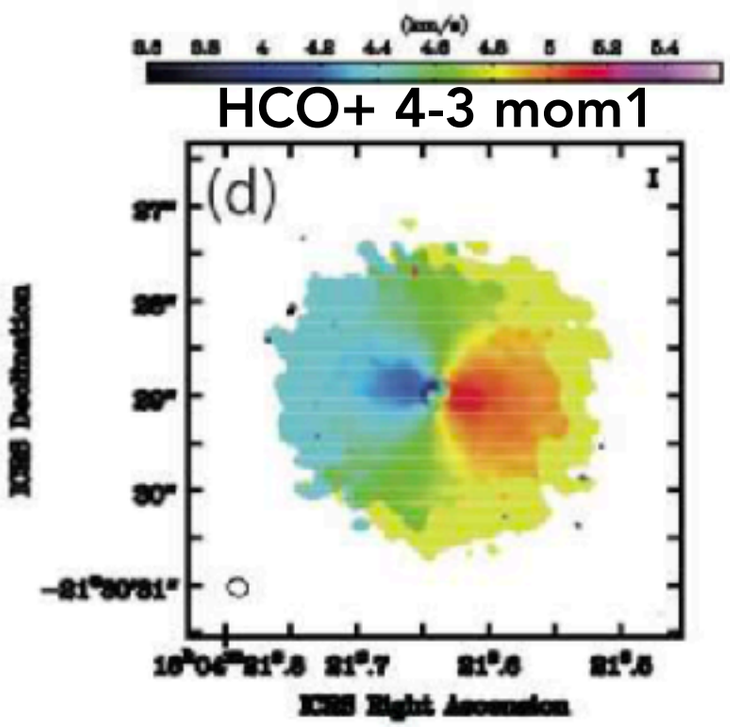

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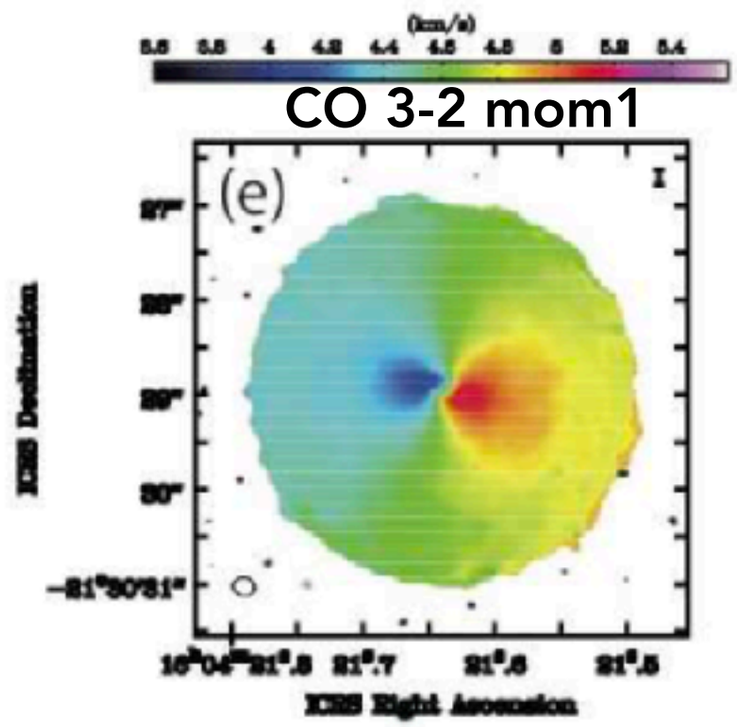
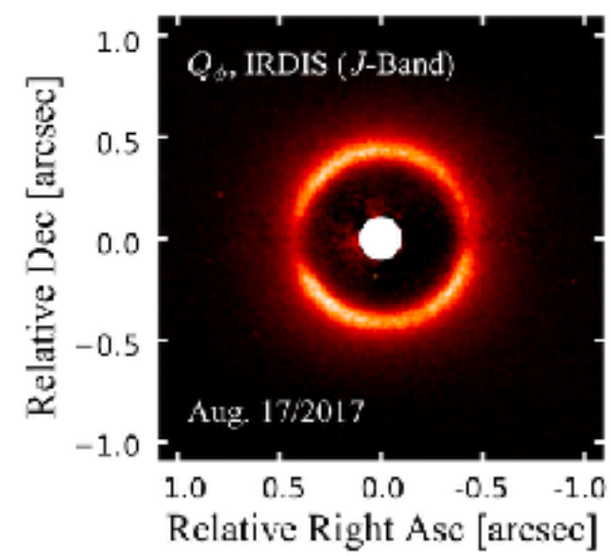
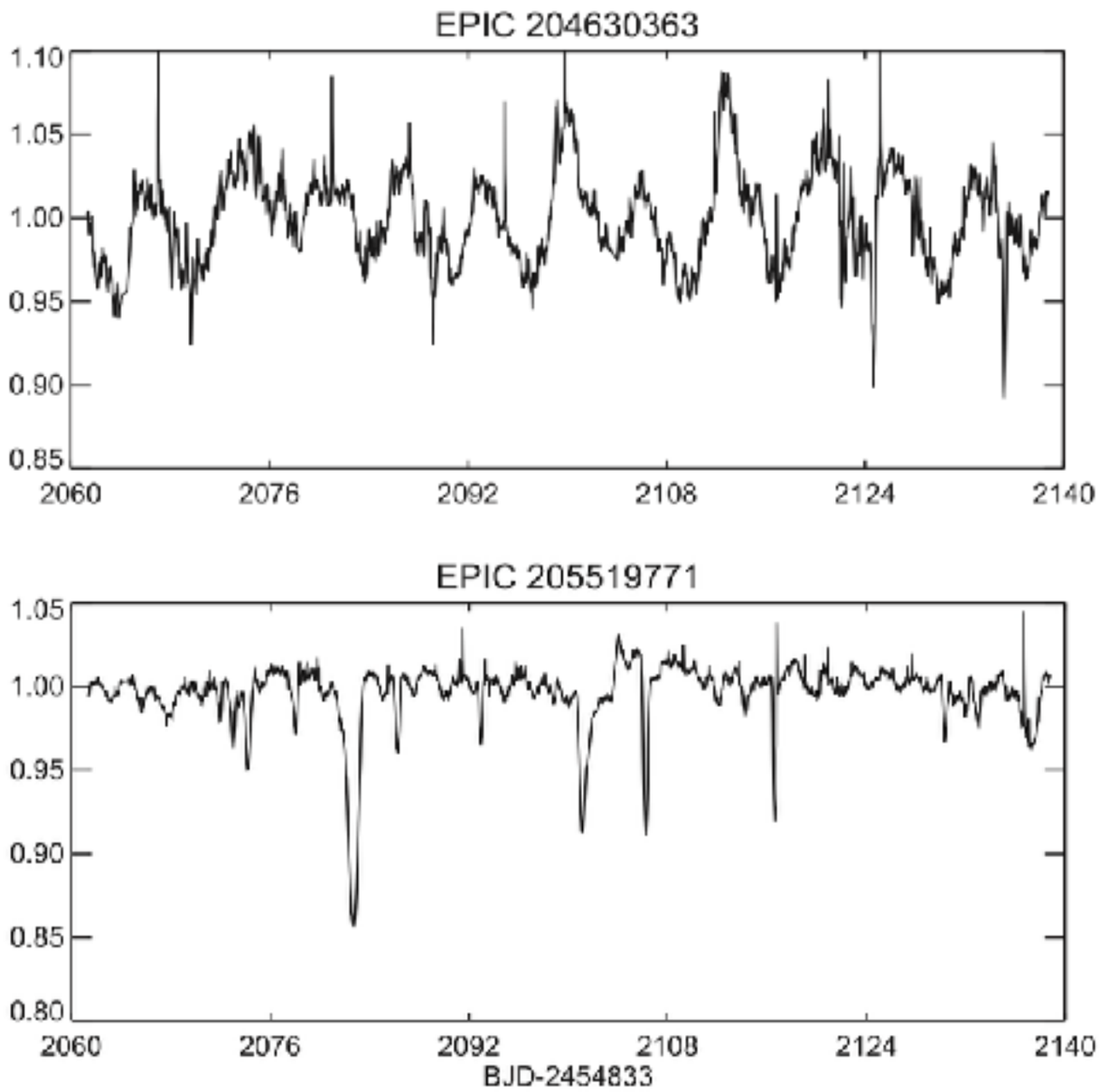




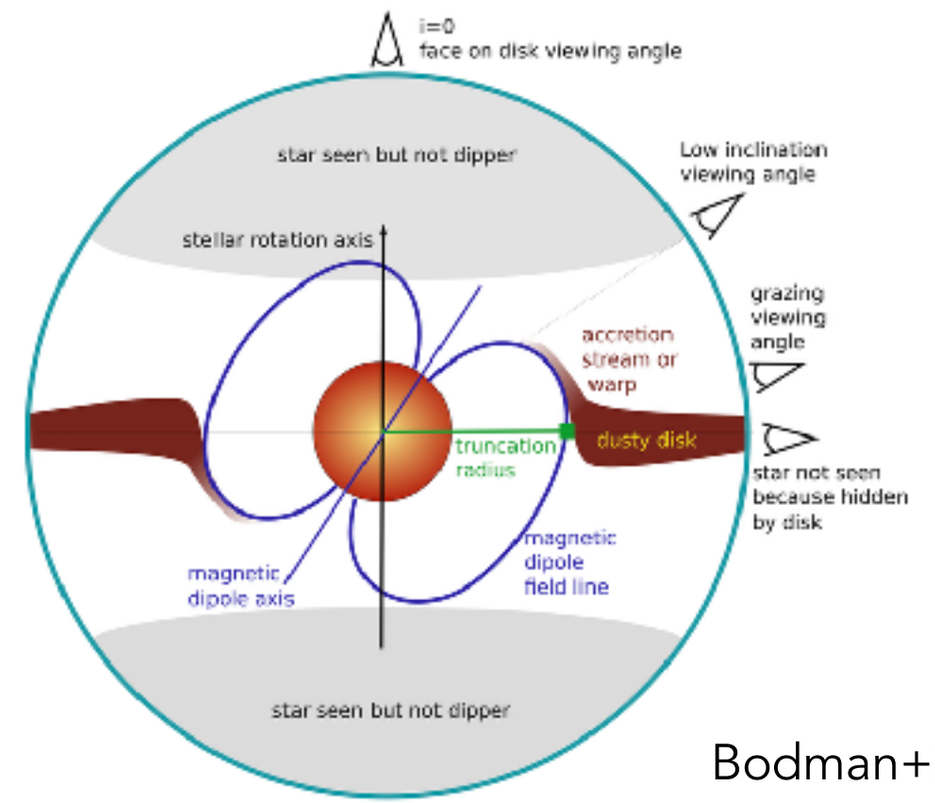
Mayama+2018

Pinilla+2018

Could it be frequent around low mass stars? Dippers



Ansdell+2016

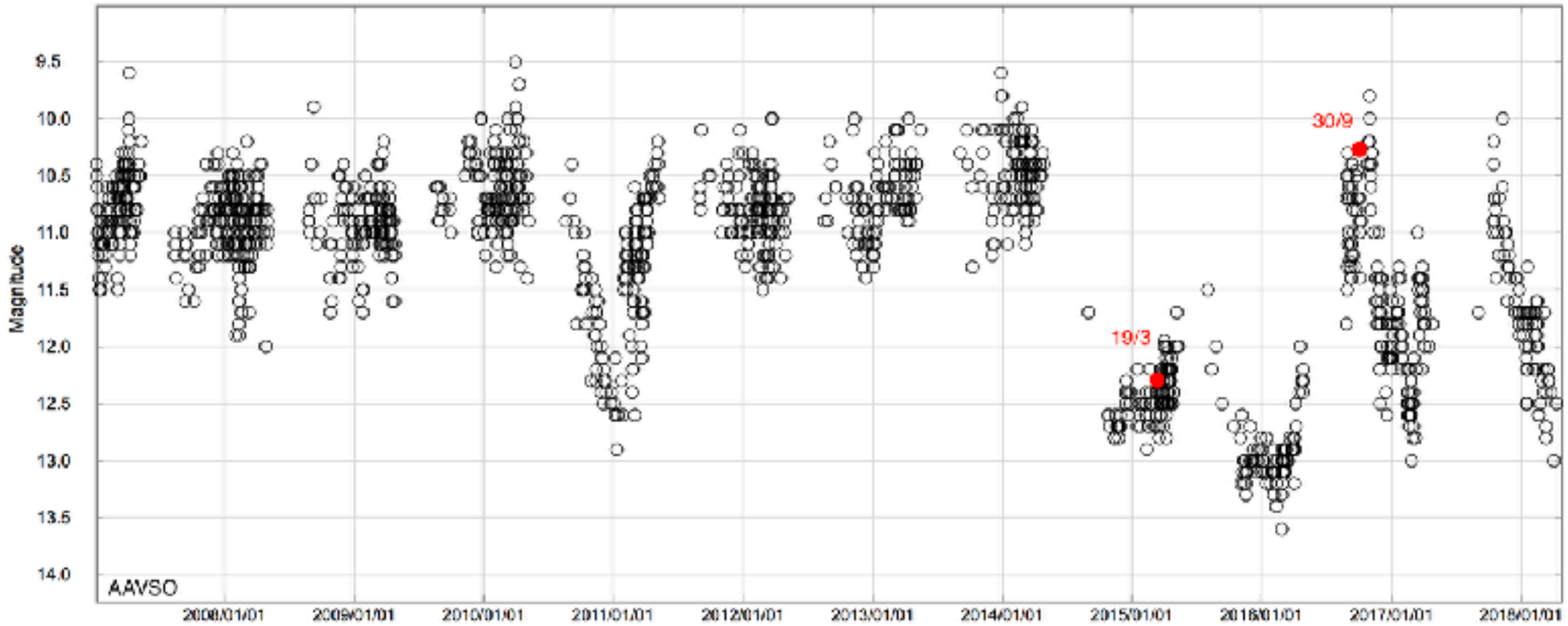


Bodman+2017

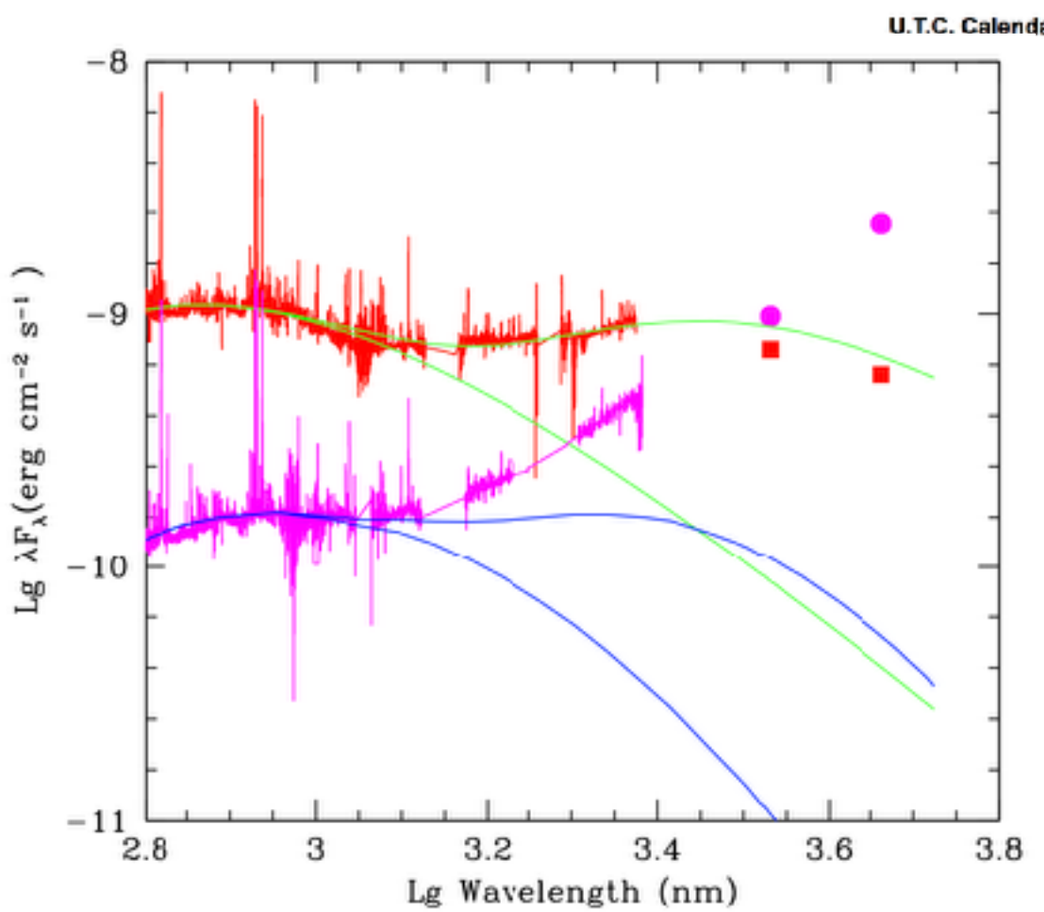
20% of young stars (K and M) with a disk are dippers

Dippers could be caused by warps, or magnetospheric accretion if $R_{mag} > R_{subl}$ (e.g. McGinnis+2015, Bodman+2017)

More extreme cases: UX Ori like objects

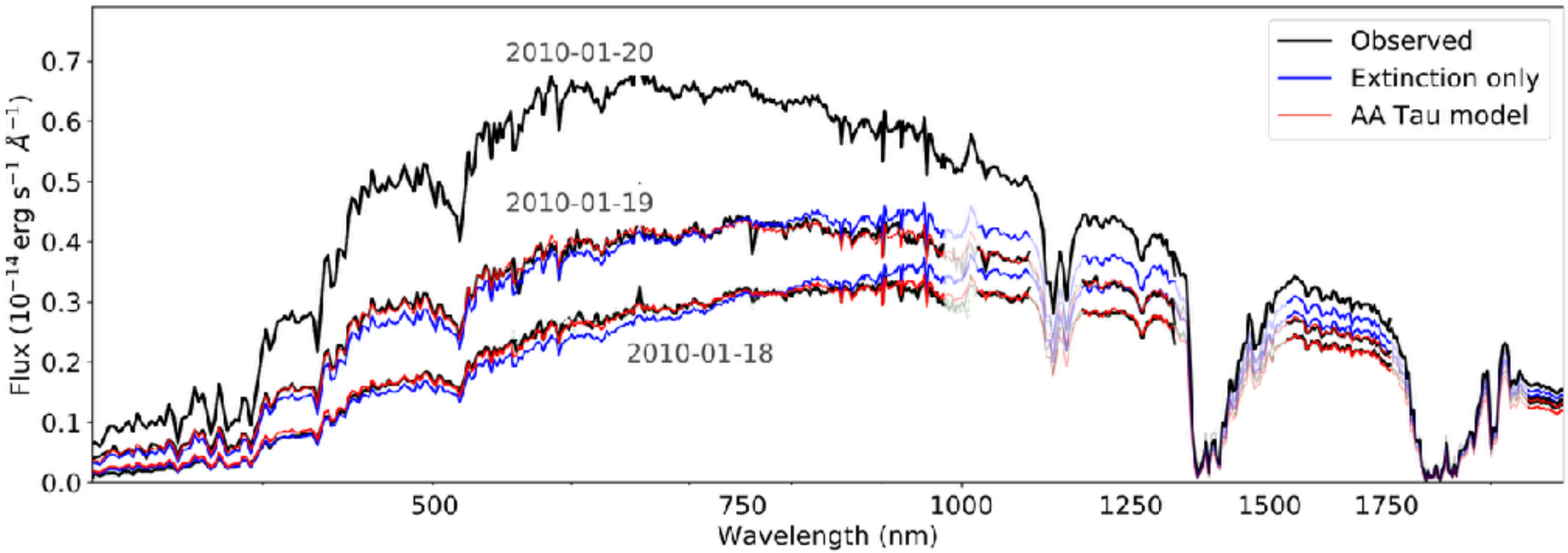


Koutoulaki, Facchini+submitted

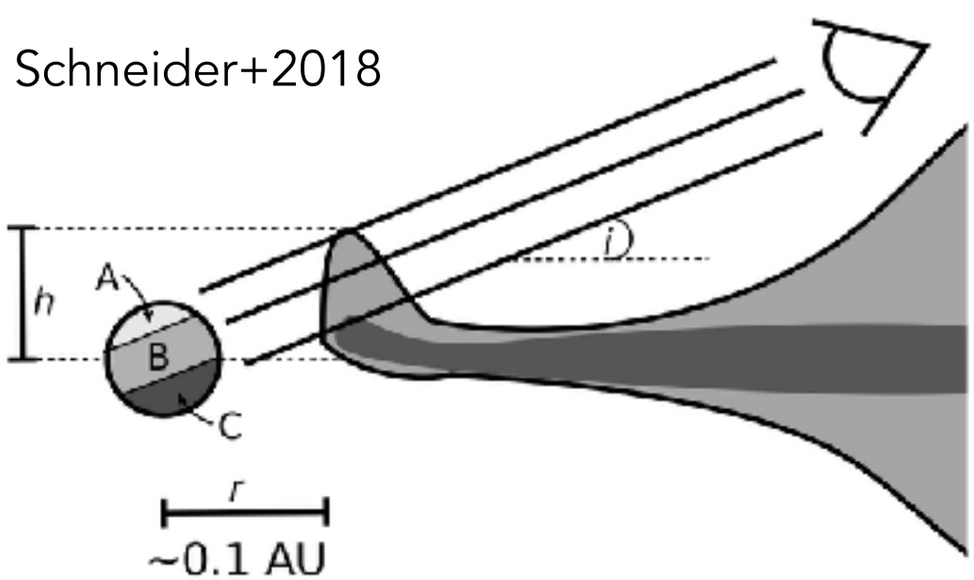


X-Shooter spectra of RW Aur A with WISE photometry (Bozhinova+2016)
The morphology of the inner disk is changing drastically

Unique probe of inner disk properties



Schneider+2018

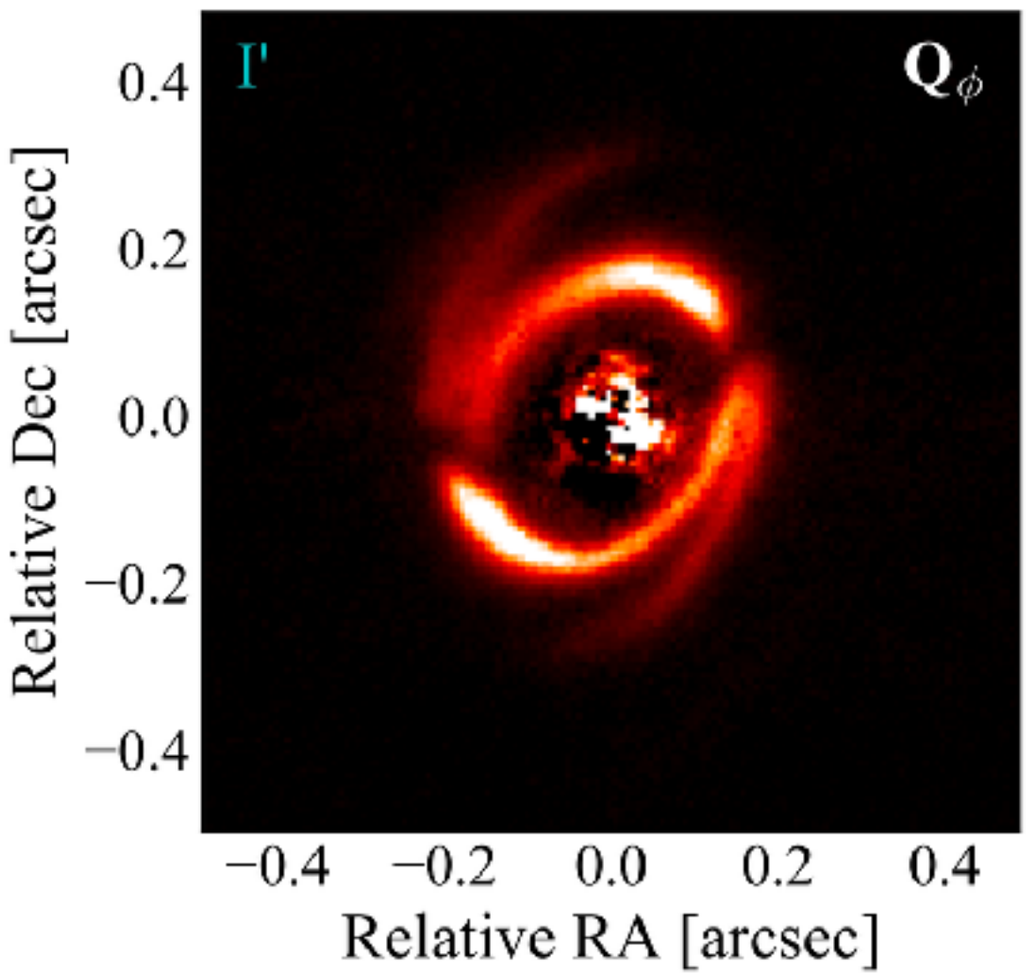


Schematics of AA Tau model (Bouvier+2007, 2013), with optically thick and thin extinction.

The dust properties of the inner disk can be inferred from the extinction curve (Schneider, Manara, Facchini+2018)

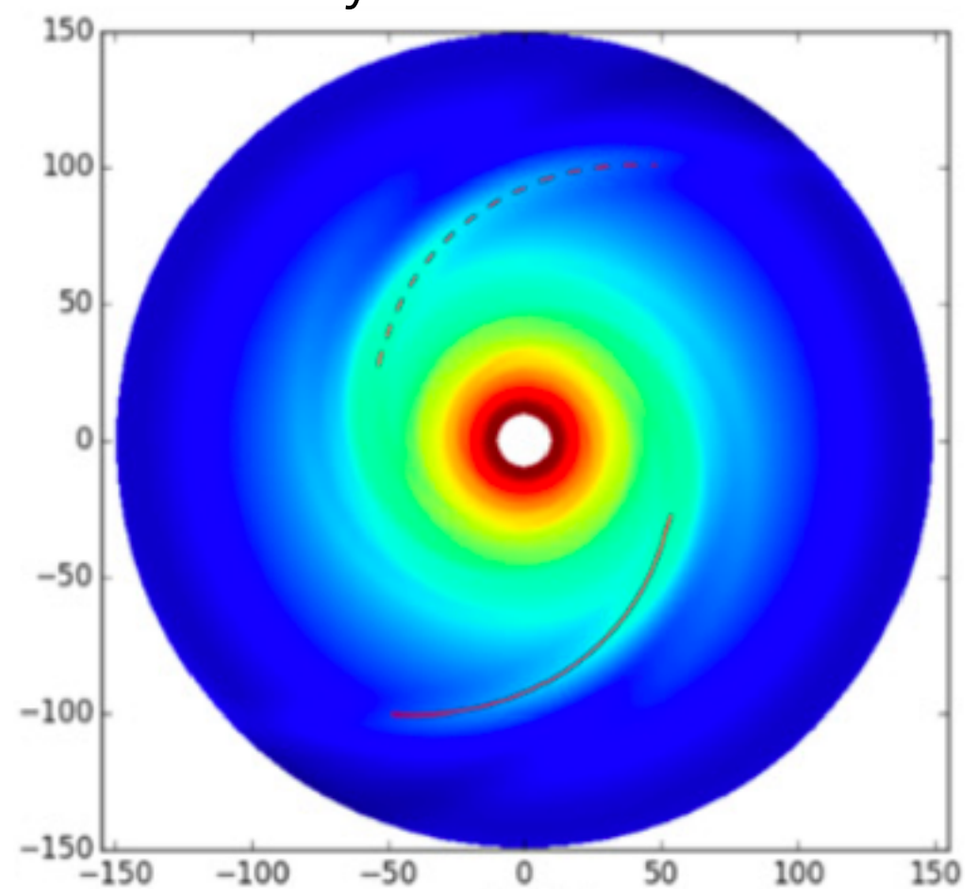
Outer disk affects inner disk
And viceversa!

SPHERE observation of HD100453



Benisty+2017

Hydro simulation

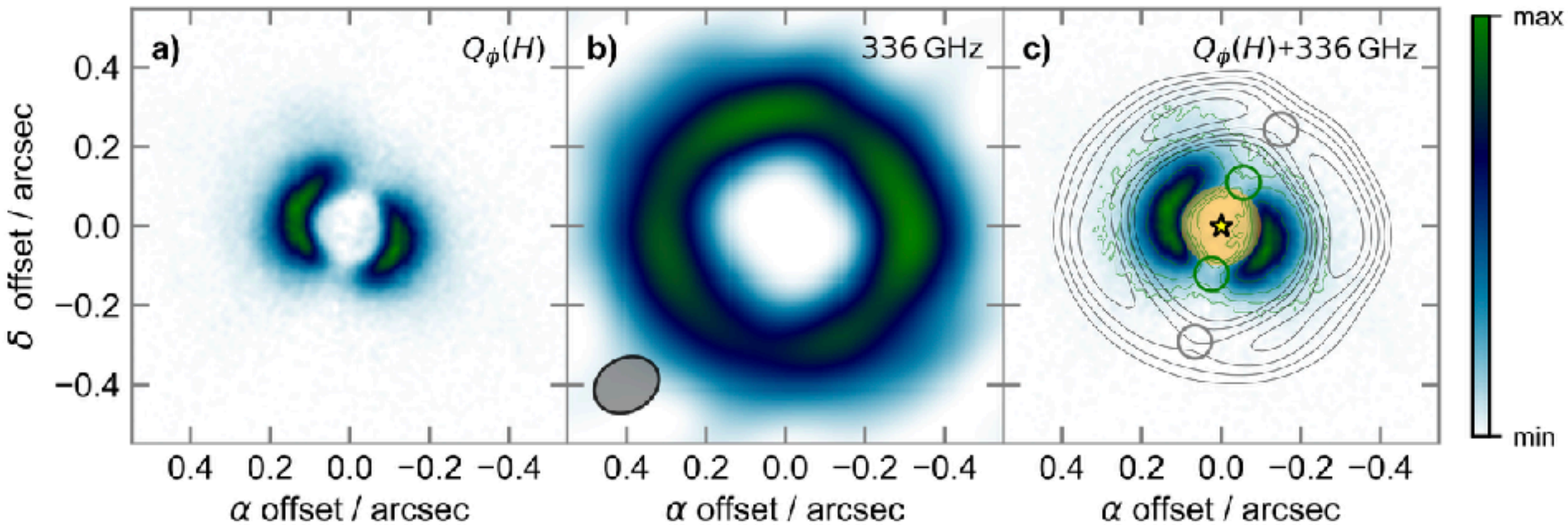


Montesinos+2016

Shadows can affect the azimuthal pressure profile,
and possibly launch spiral waves
(Montesinos+16, to be tested with more realistic cooling)

Inner disks can be tilted: other 3D effects

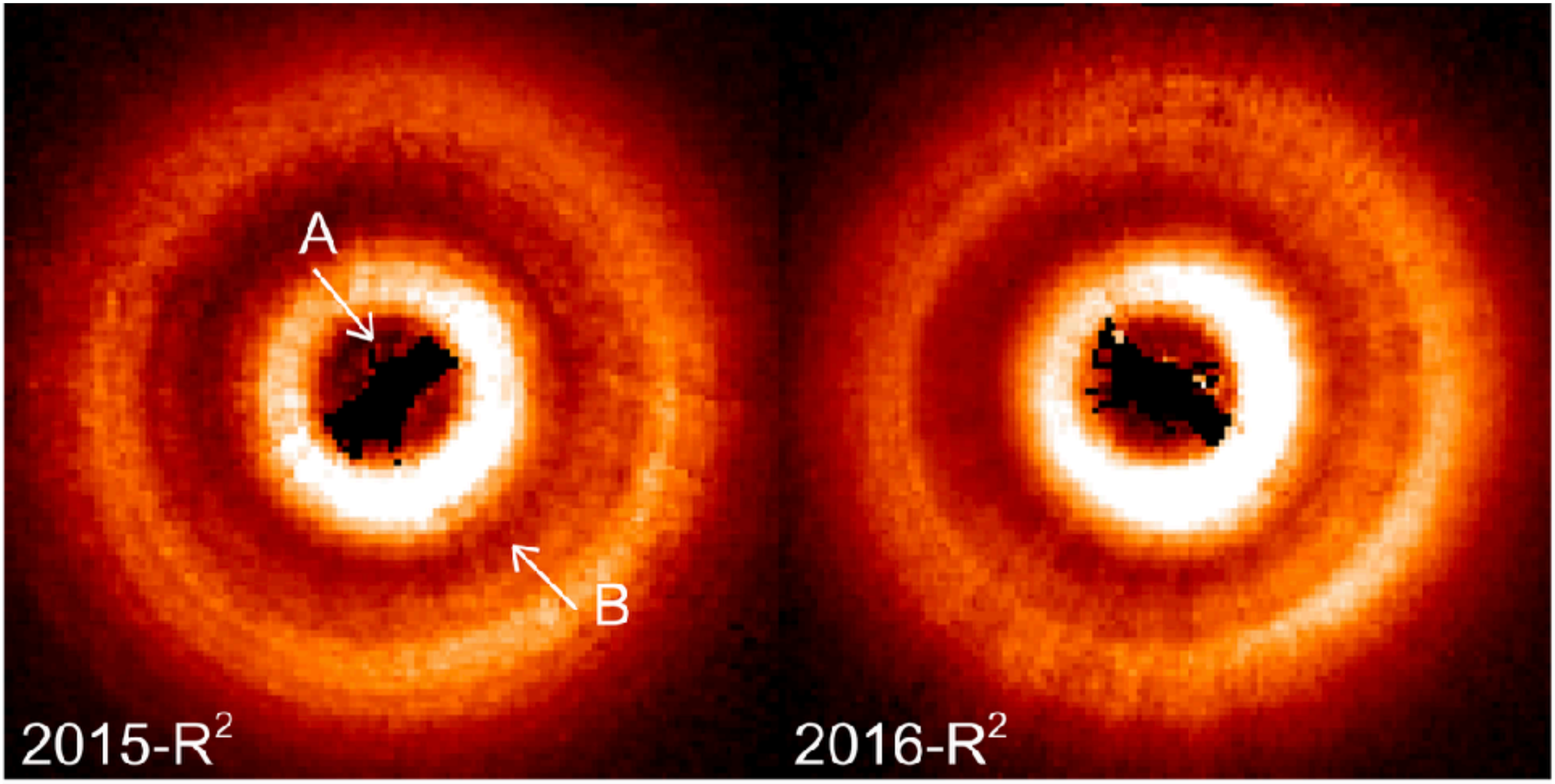
SPHERE and ALMA observations of DoAr 44



Casassus+2018

The ratio of the azimuthal widths of the asymmetry (scattered light/mm continuum) is informative on the thermal timescale in the disk midplane

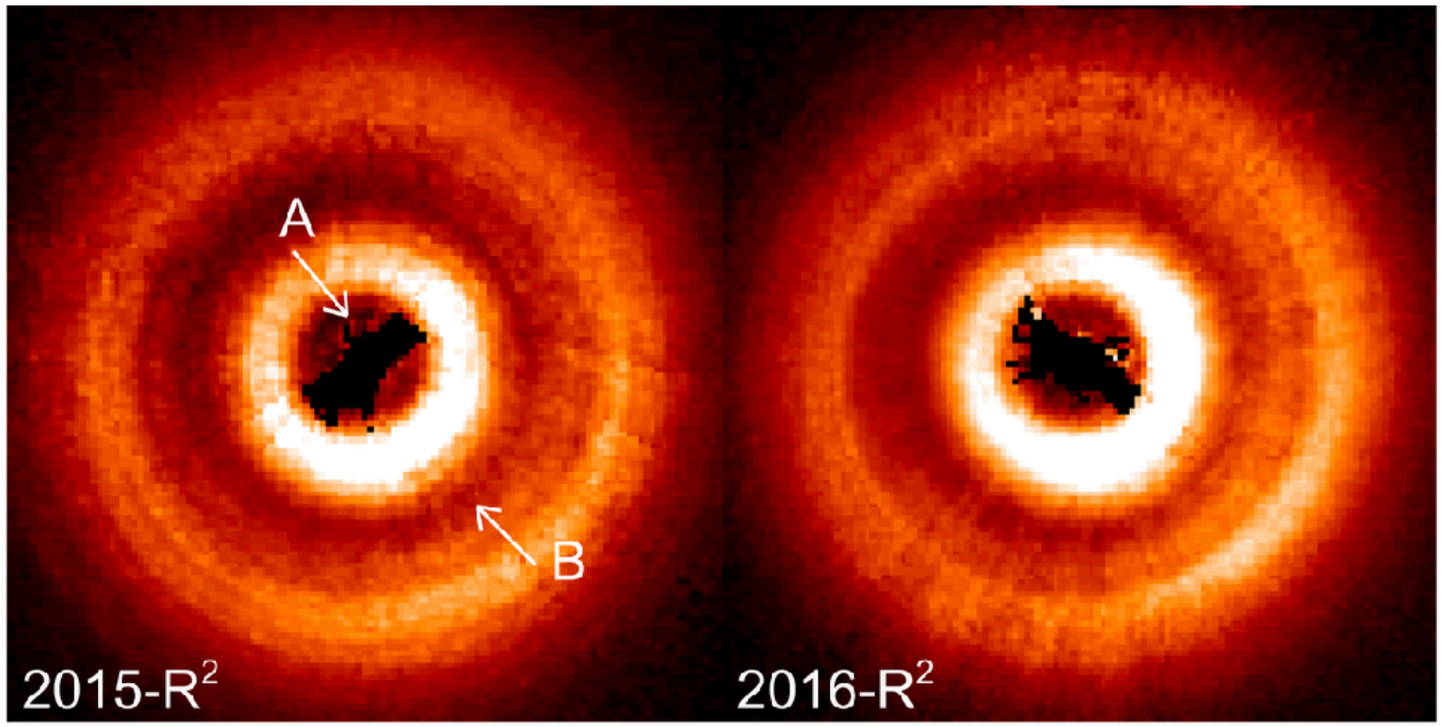
Shadows tracing dynamics of inner disk

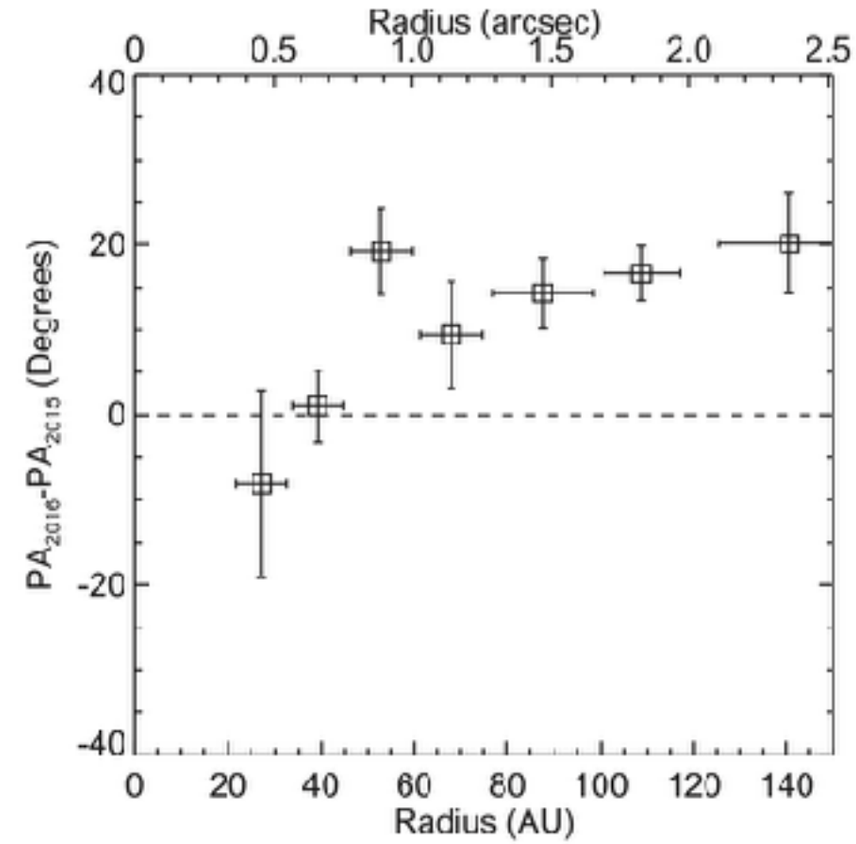


Total intensity map of TW Hya from HST

Debes+2017

Shadows tracing dynamics of inner disk





The asymmetry has moved by ~17° in 10 months. Debes+2017

See also Pinilla+18 for J1604 (timescale of *days*)

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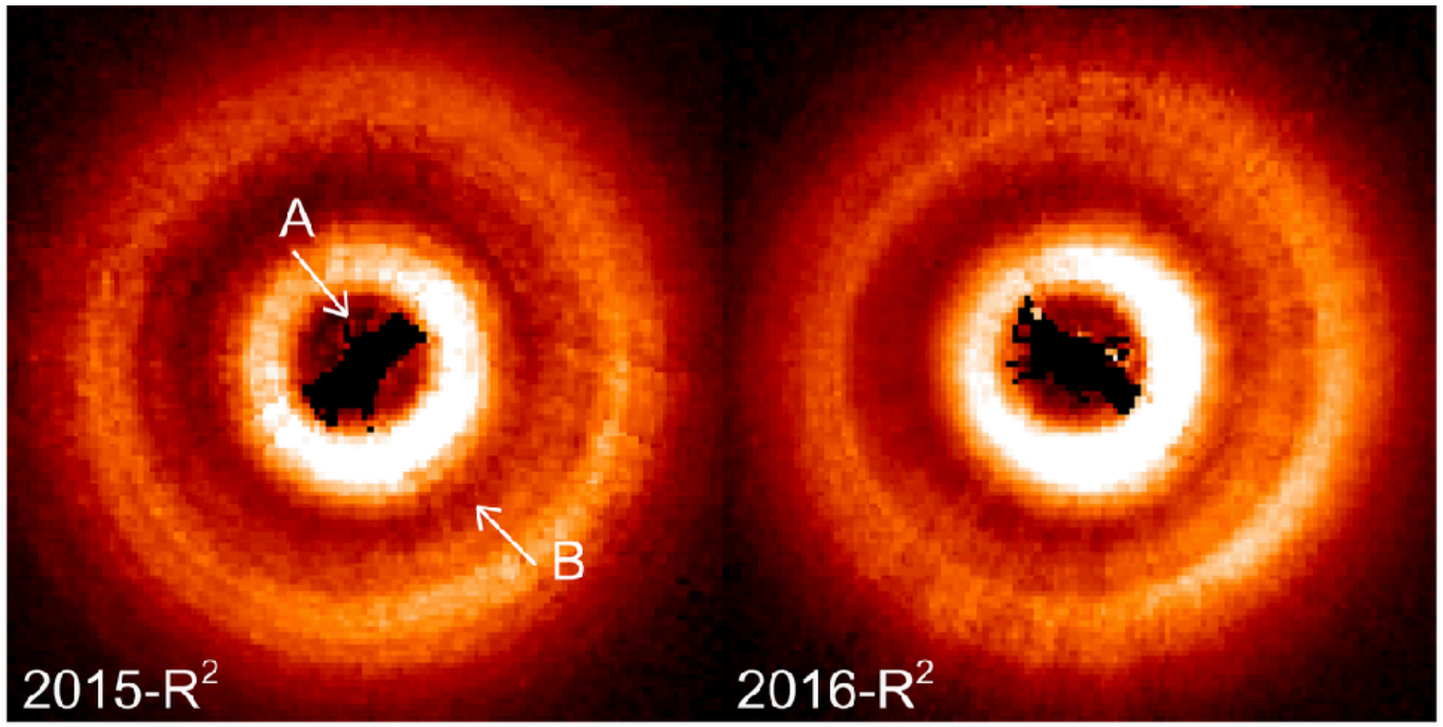

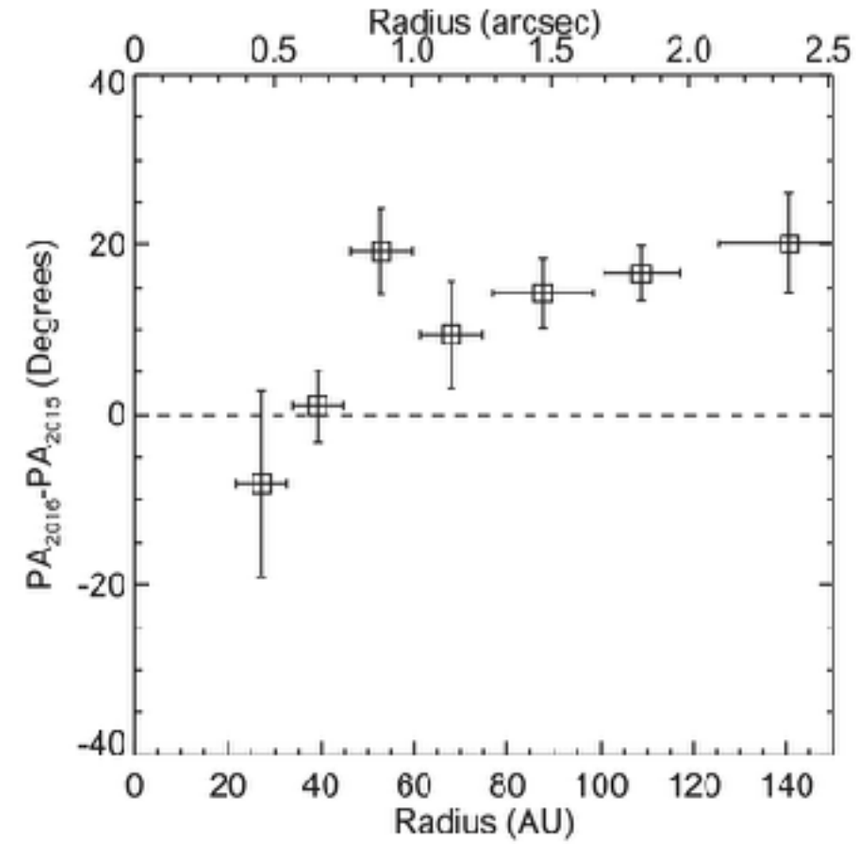

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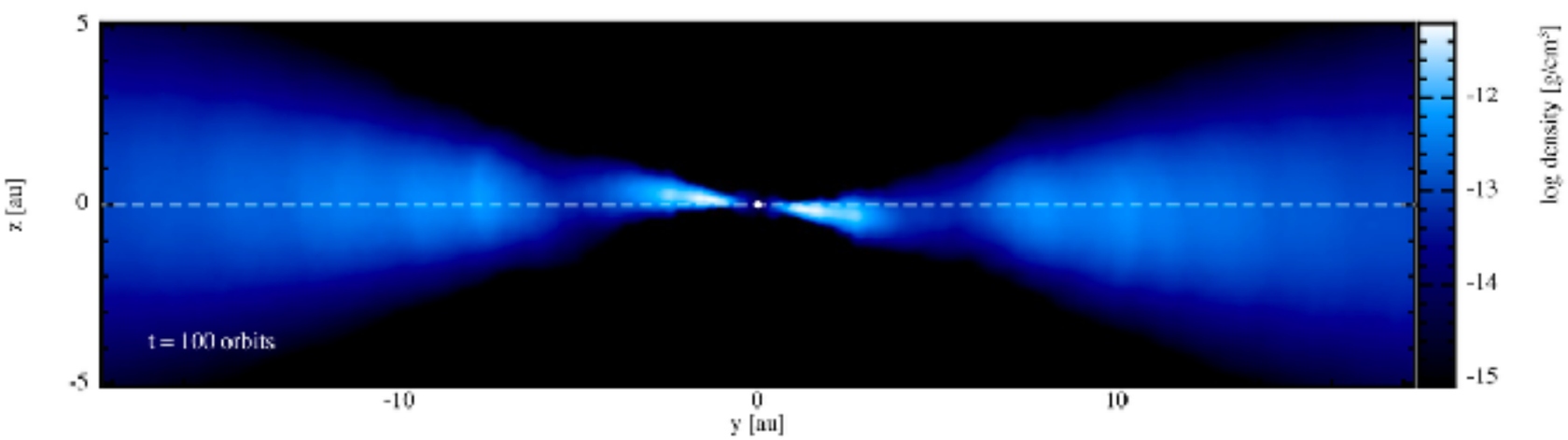


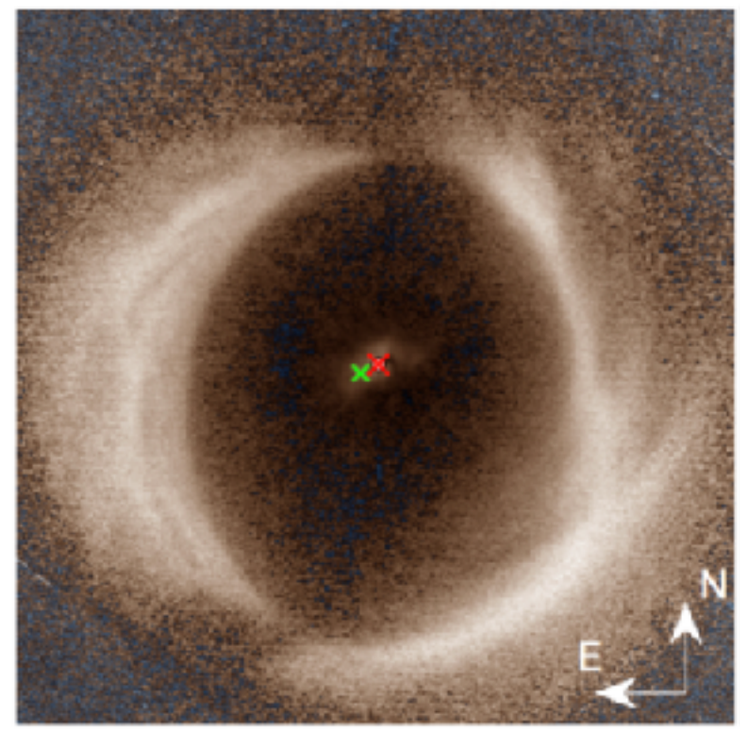
Nealon+2019 are able to explain the warping in the outer disk with a massive planet, but friction with precessing timescale.

What is driving the misalignment?

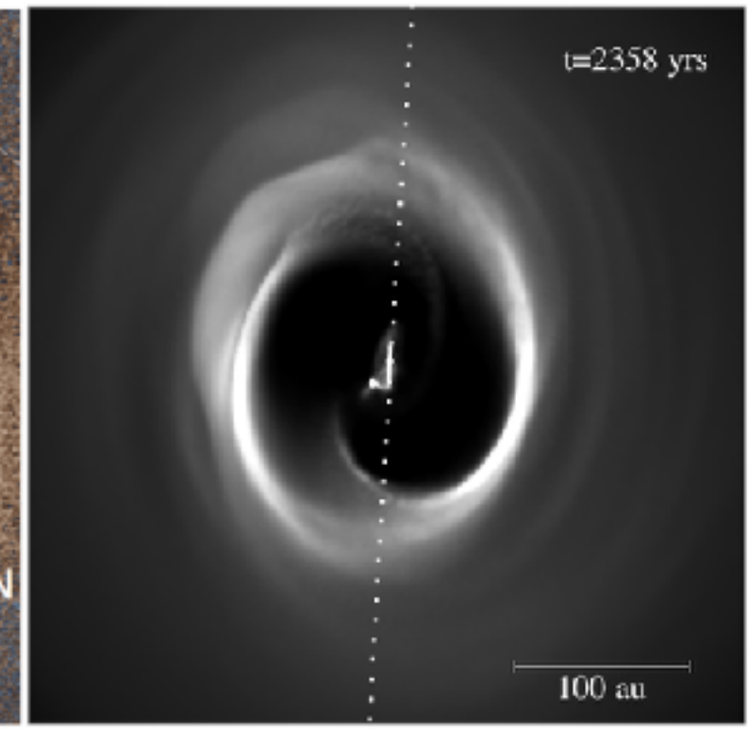
HD142527

1) (Sub)stellar companion

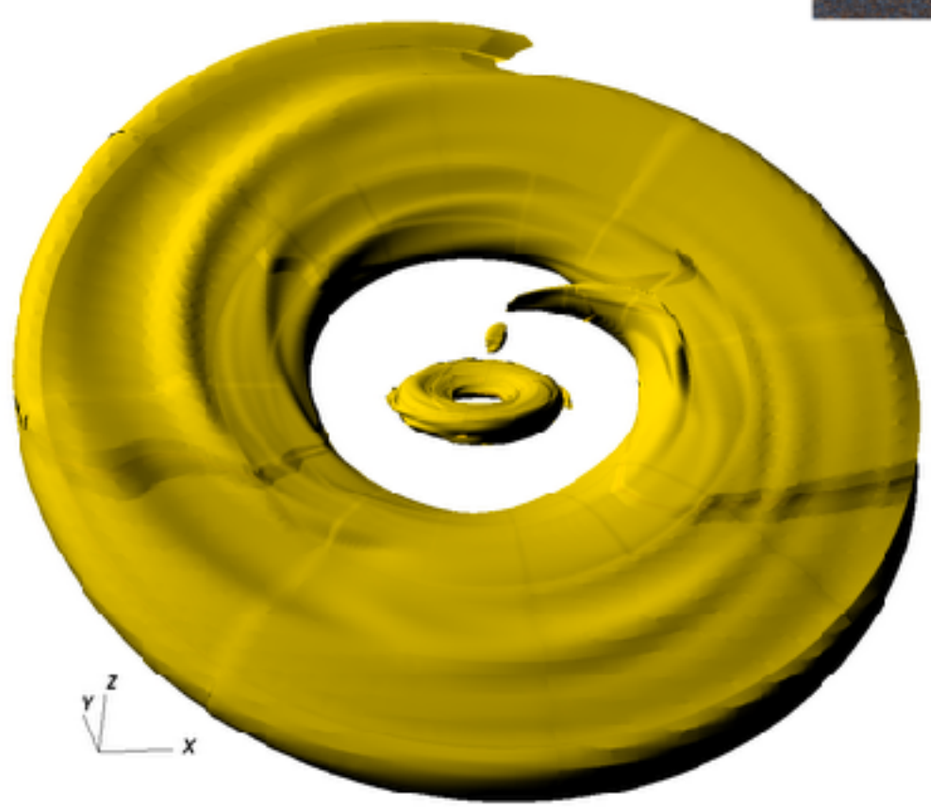
(e.g. Facchini+2013,2018, Price+2018)



Avenhaus+2017



Price+2018

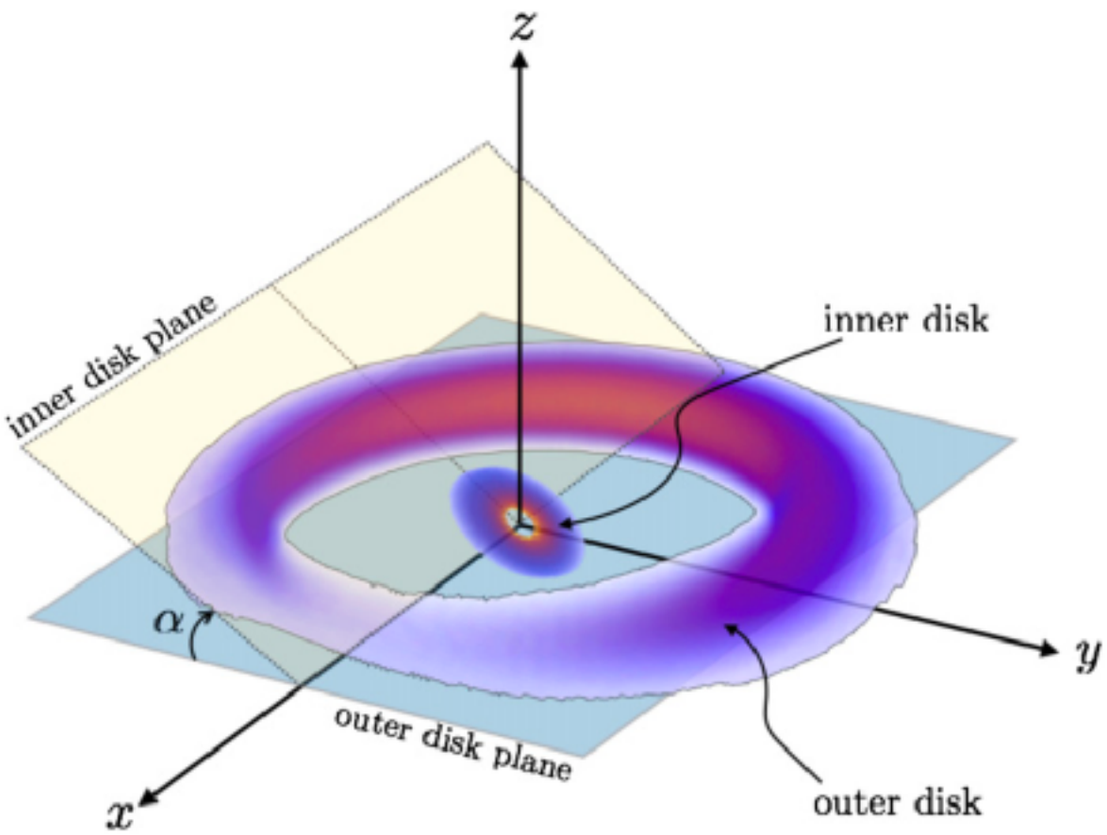


Zhu 2019

2) Misaligned planet

(e.g. Facchini+2014, Nealon+2018,2019, Zhu 2019)

Can we infer the mass and orbital radius of the putative companion?



From radially integrated angolar momentum/radially integrated torque we get precession period of inner disk

$$\omega_{\rm prec} \approx \Omega_{\rm pl} \frac{3}{8} \cos i_{\rm pl} \frac{M_{\rm pl}}{M_*}$$

Larwood+1996, Bate+2002, … Zhu 2019

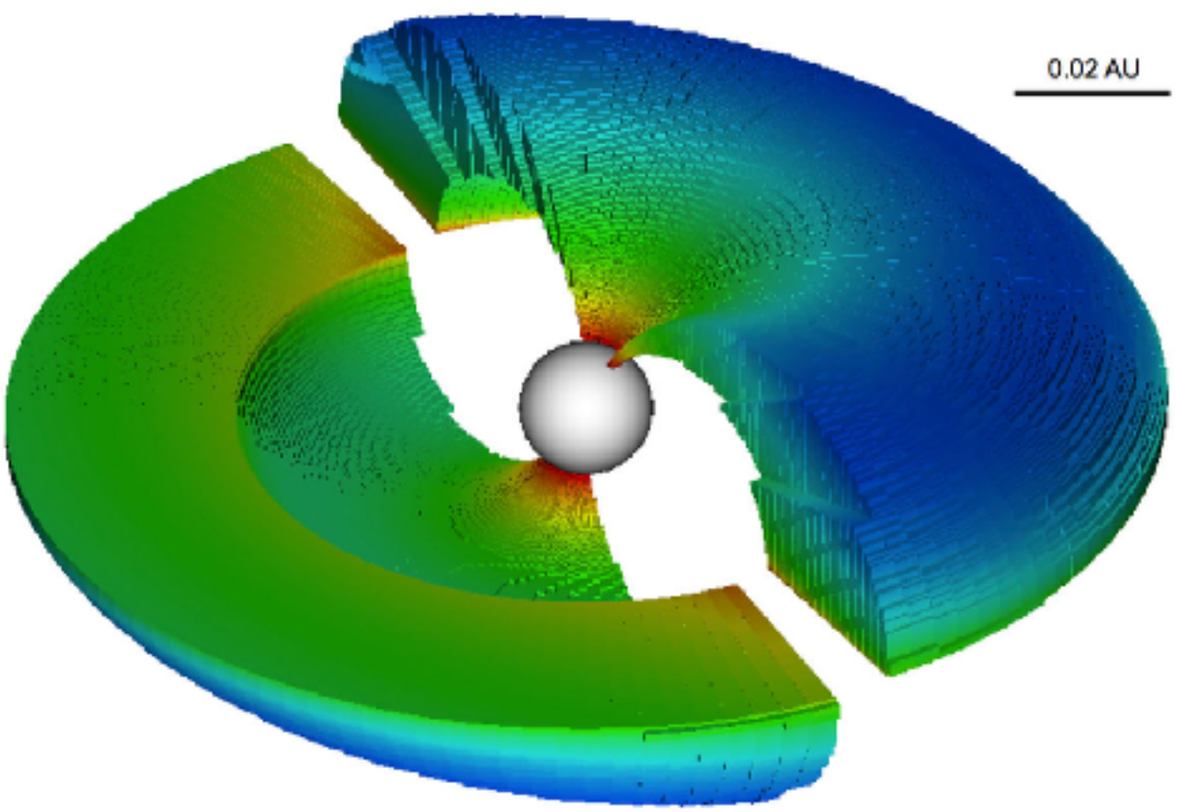
With a few approximation, precession timescale scales simply with planet mass: a different way to constrain masses?

What is driving the misalignment?

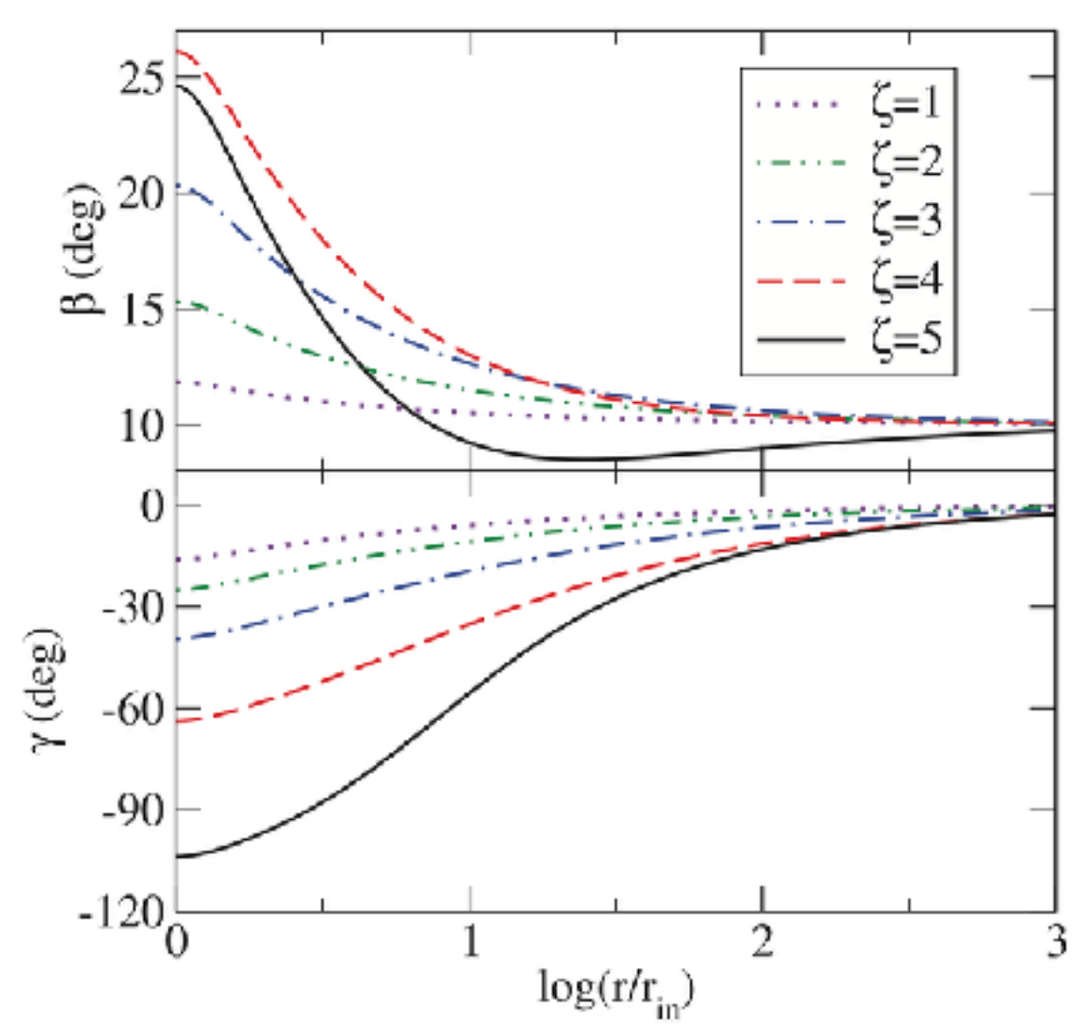
3) Misaligned stellar magnetic field

(e.g. Romanova+2002, 2003, 2005, Foucart & Lai 2011, Esau+2014)

While companions are the most likely explanation for Herbig stars, TTauri stars can have a strong magnetic dipole that can warp the disk



Esau+2014



Foucart & Lai 2011

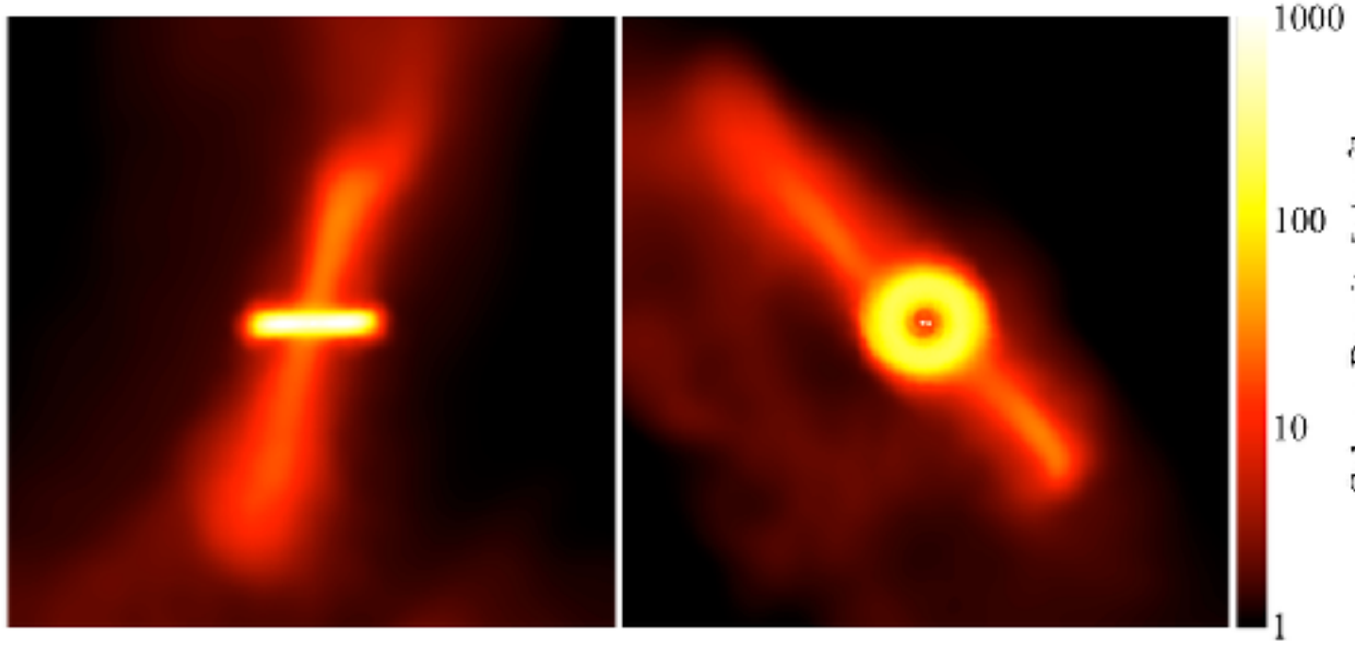
How do planets get misaligned?

1) Planet-planet scattering (possible when there is a gaseous disk around?)

2) Change of angular momentum direction during disk lifetime

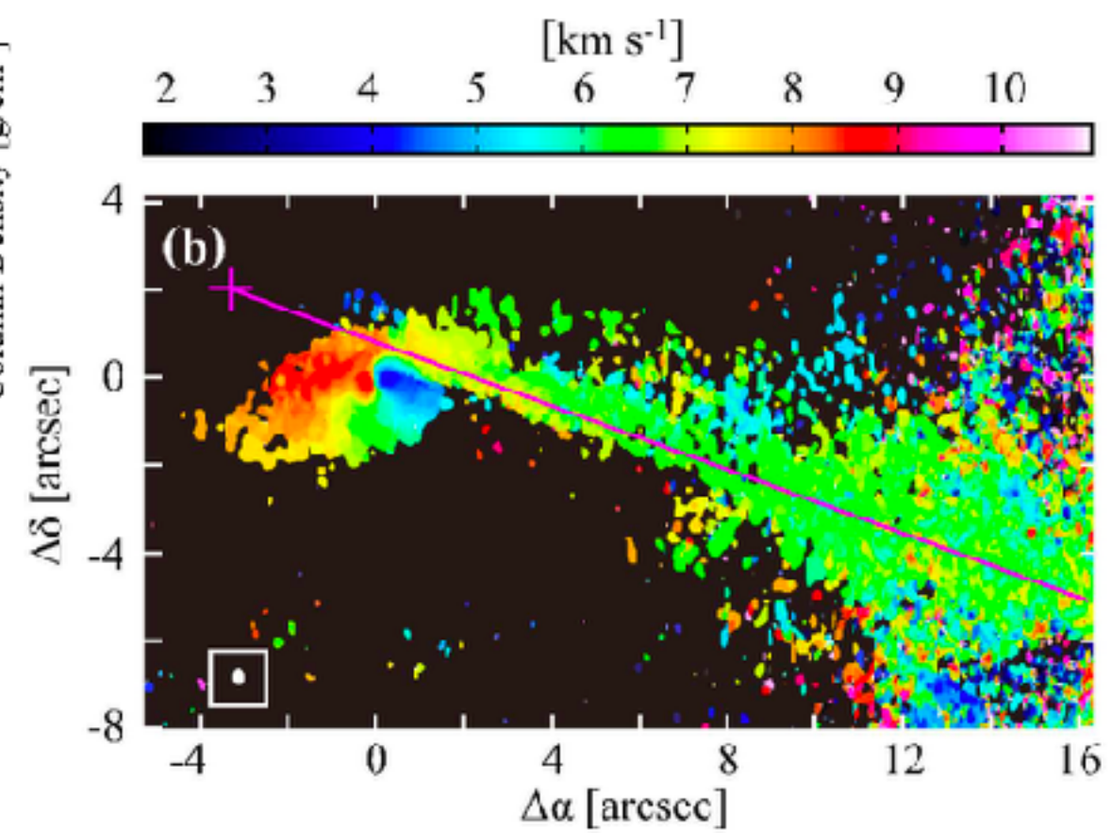
3) ????????

Early chaotic accretion



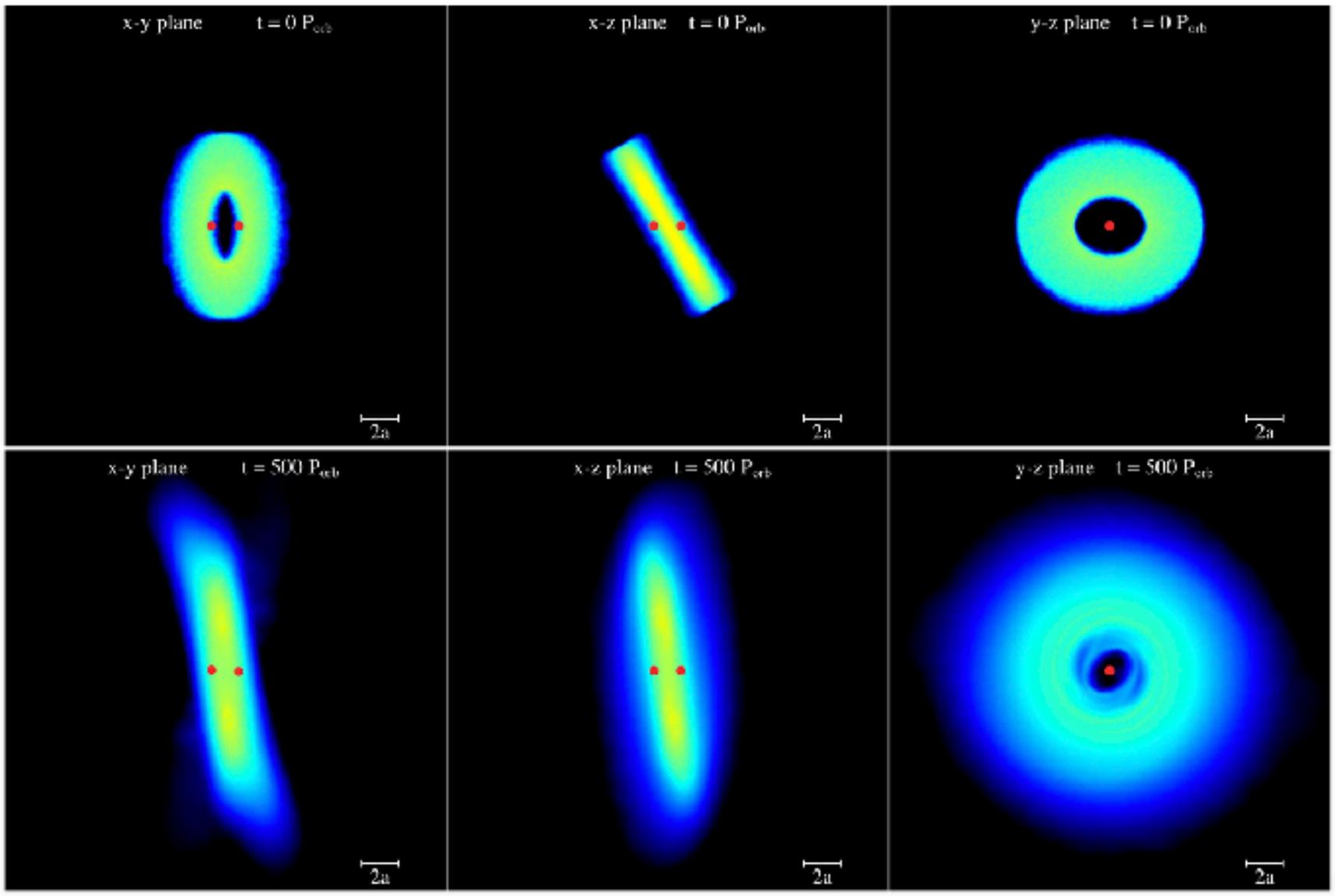
Bate 2018 (hydro simulations)

Late accretion or interactions



Akiyama+2019

An extreme case: polar circumbinary disks

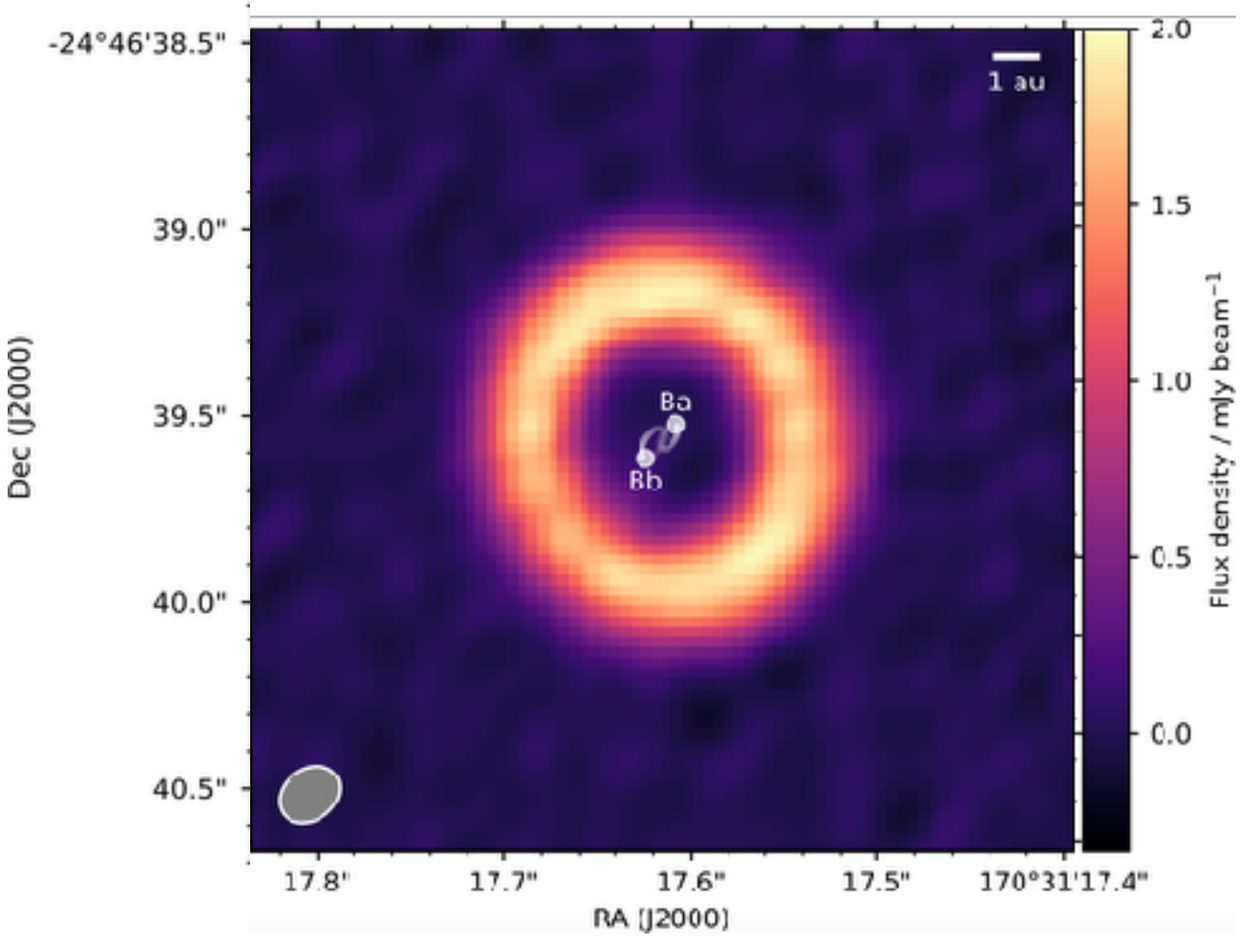


Martin & Lubow 2017

When the binary is eccentric, the disk can align along the eccentric vector (90° to angular momentum vector) to angular momentum vector (e.g. Aly+2015, Martin & Lubow 2017, Zanazzi & Lai 2017)

When theory predictions come true...

The case of HD 98800



Kennedy, Matrà, Facchini+2019

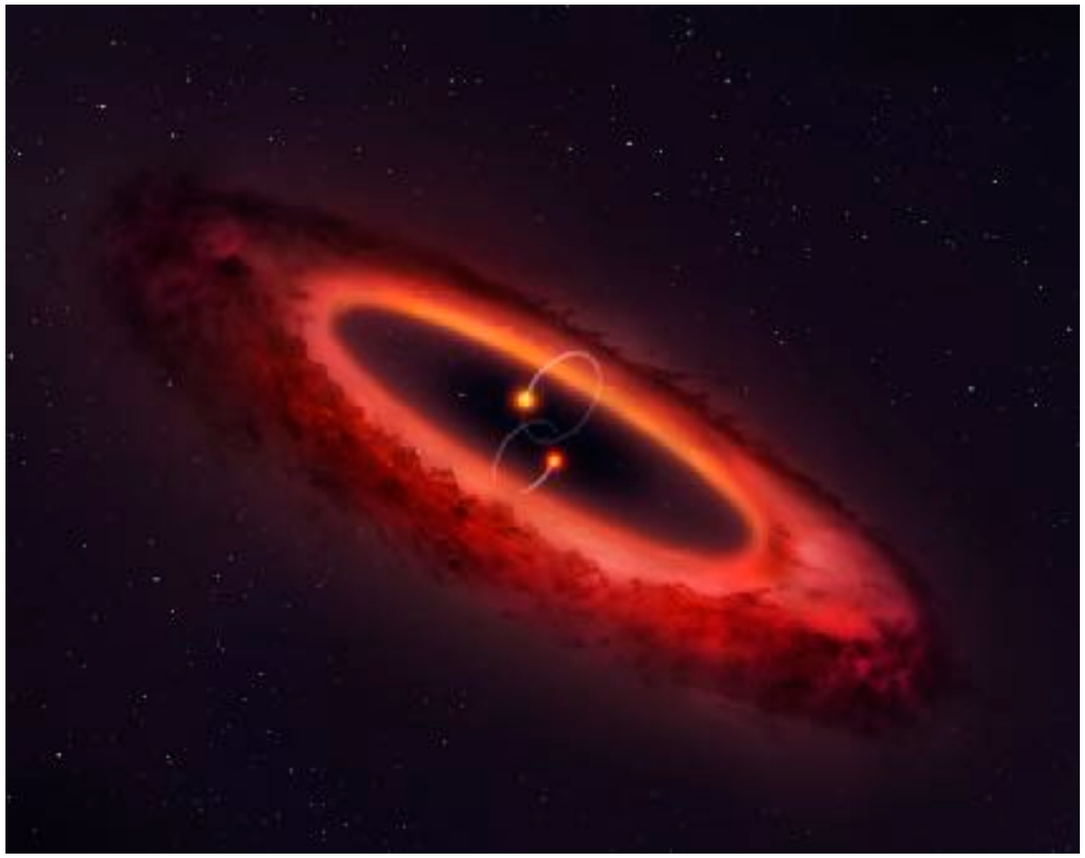
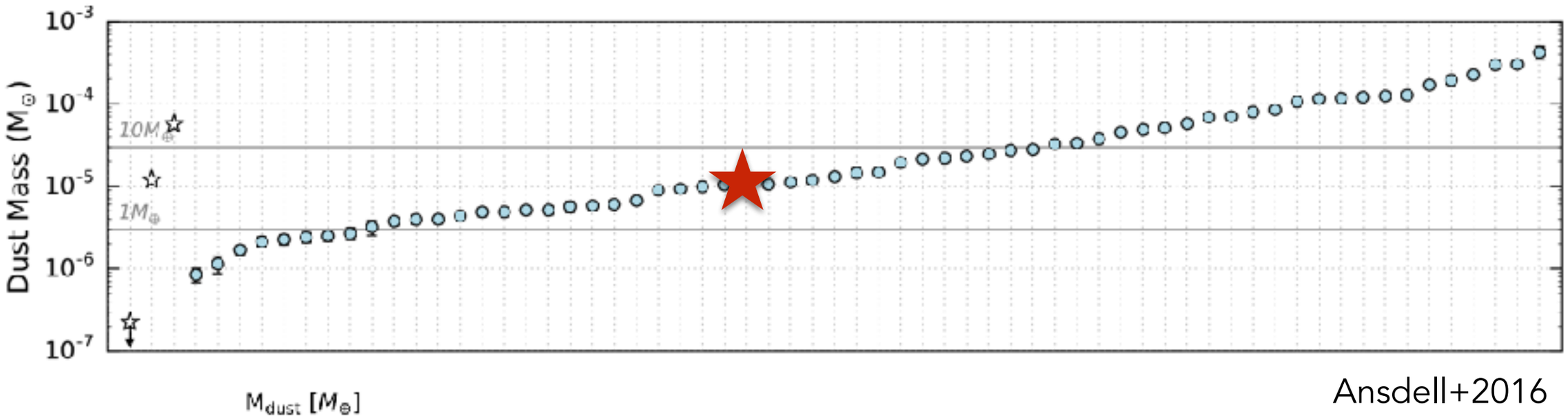


Image credit: University of Warwick/Mark Garlick

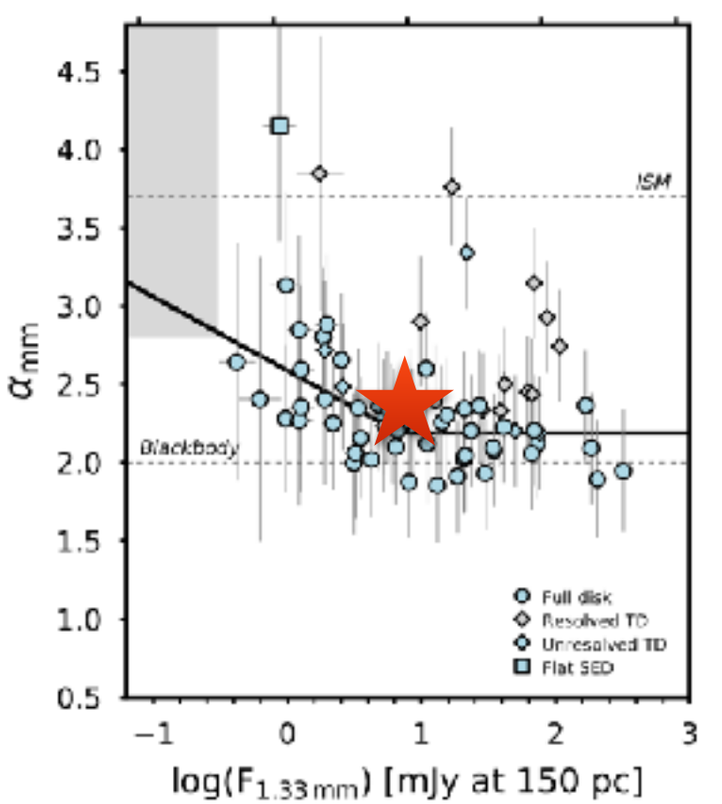
The dust ring seems optically thick, and is misaligned by 90 degrees wrt binary angular momentum. A path to polar circumbinary planets?

CX Tau

a "boring" disk?



Ansdell+2016



Ansdell+2018

CX Tau properties

Star: 0.26 Msun (dynamically estimated, Simon+2017)

Disk: ~10 mJy (1.3 mm), spectral index α ~2.2 (Ricci+2010), classified as transition disk from NIR (Furlan+2011)

New Band 6 ALMA observations

Compact and extended configurations (C43-5, C43-8)

Continuum sensitivity of 20 μJy/bm

Angular resolution continuum of 30 x 50 mas

CX Tau

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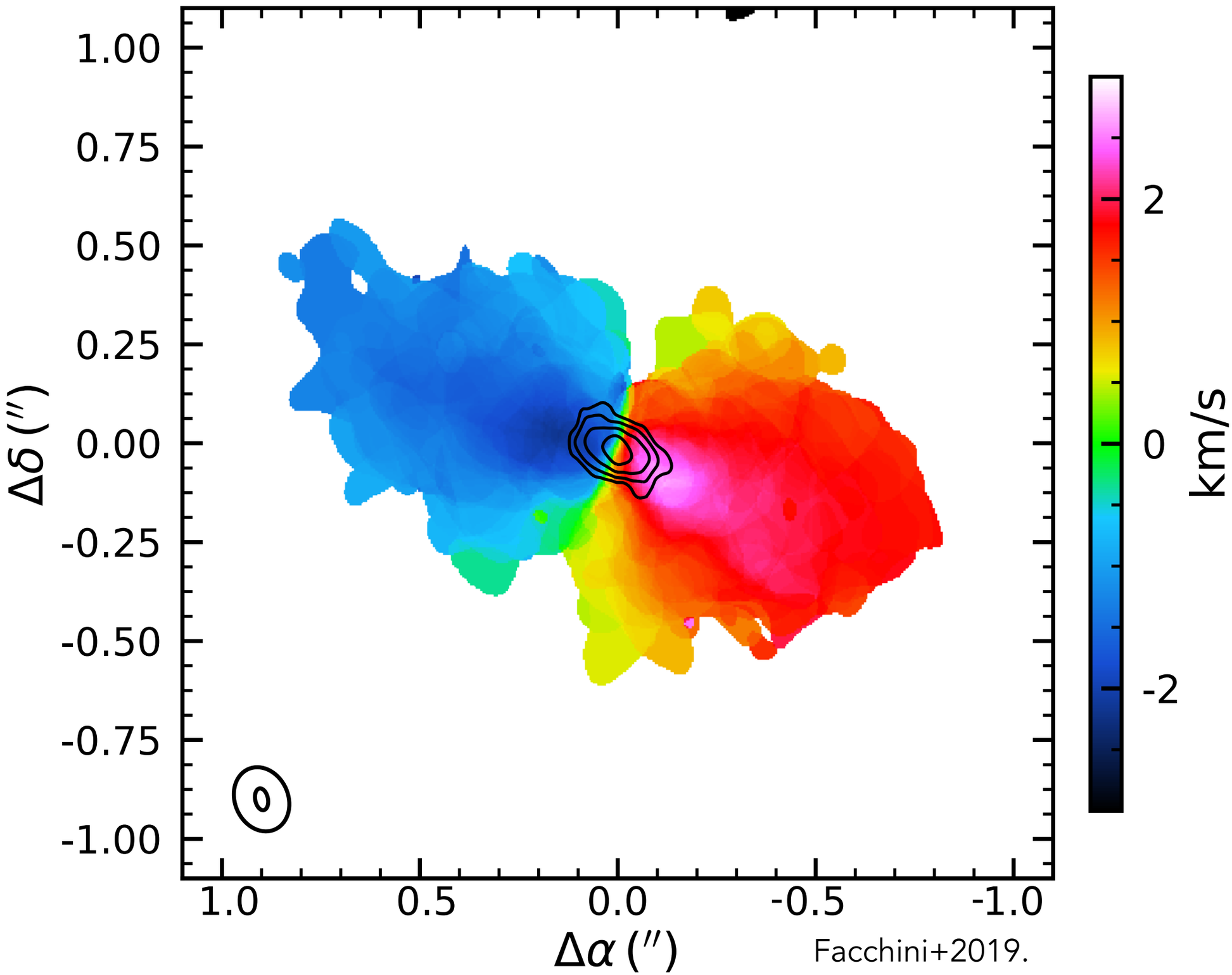

Facchini+2019.

CX Tau

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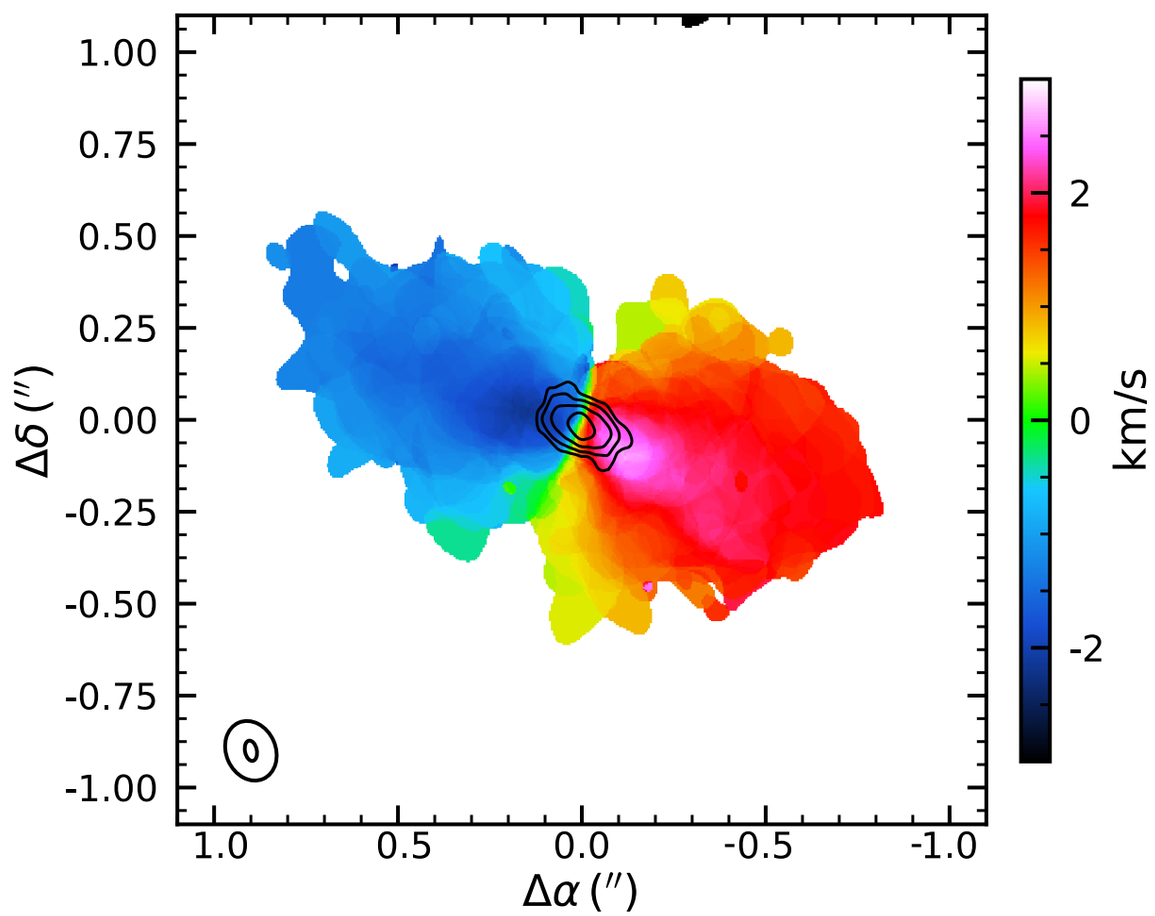
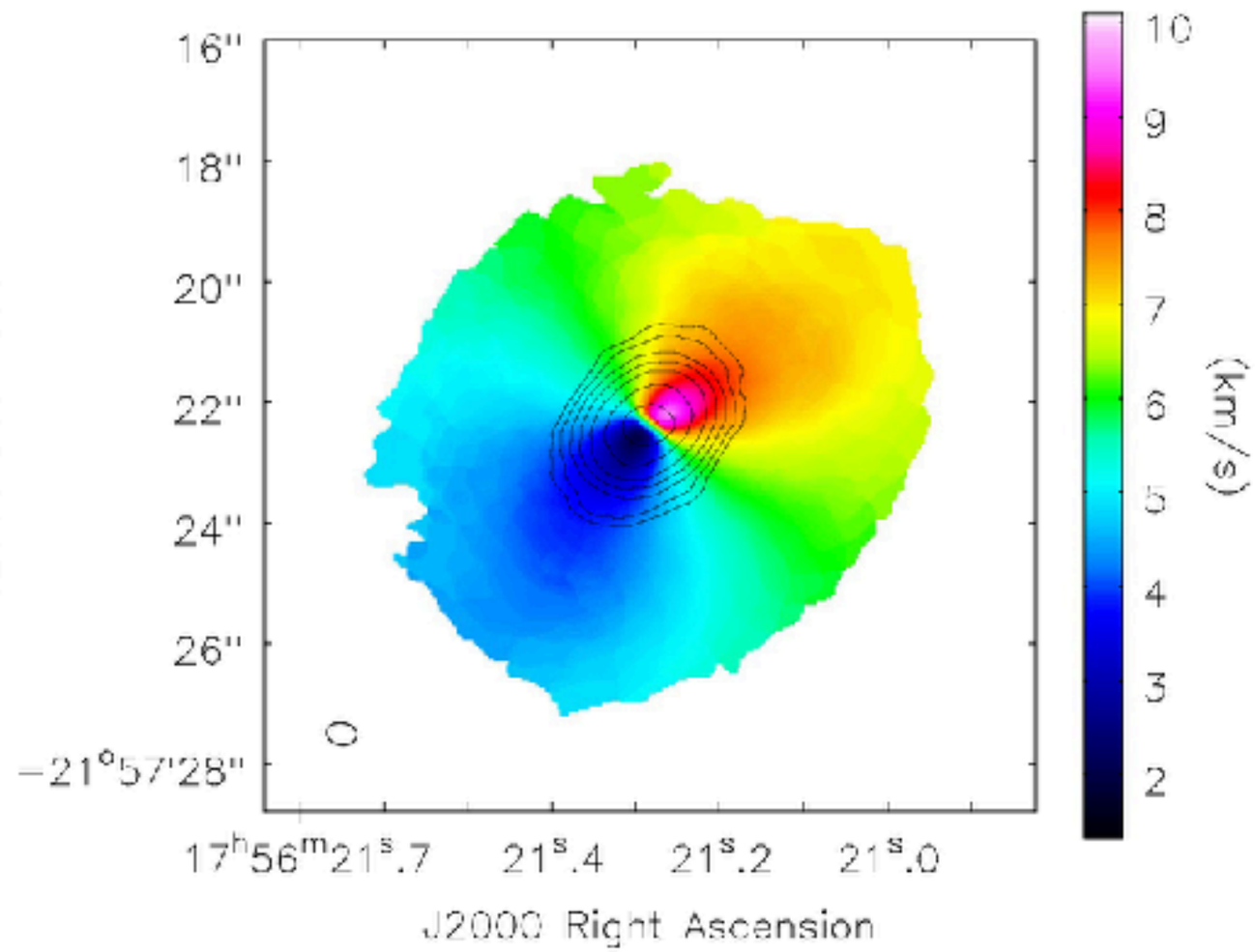
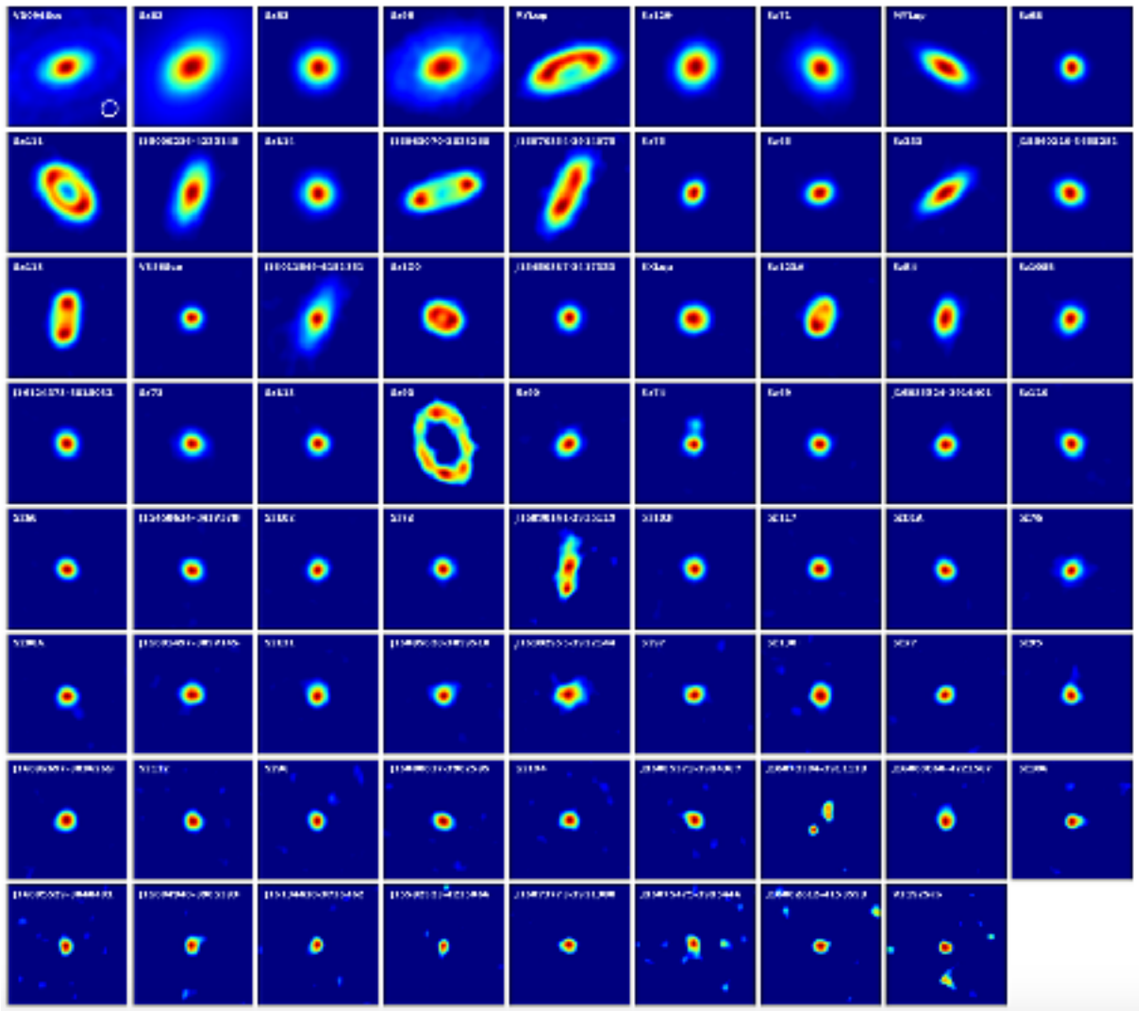


Facchini+2019

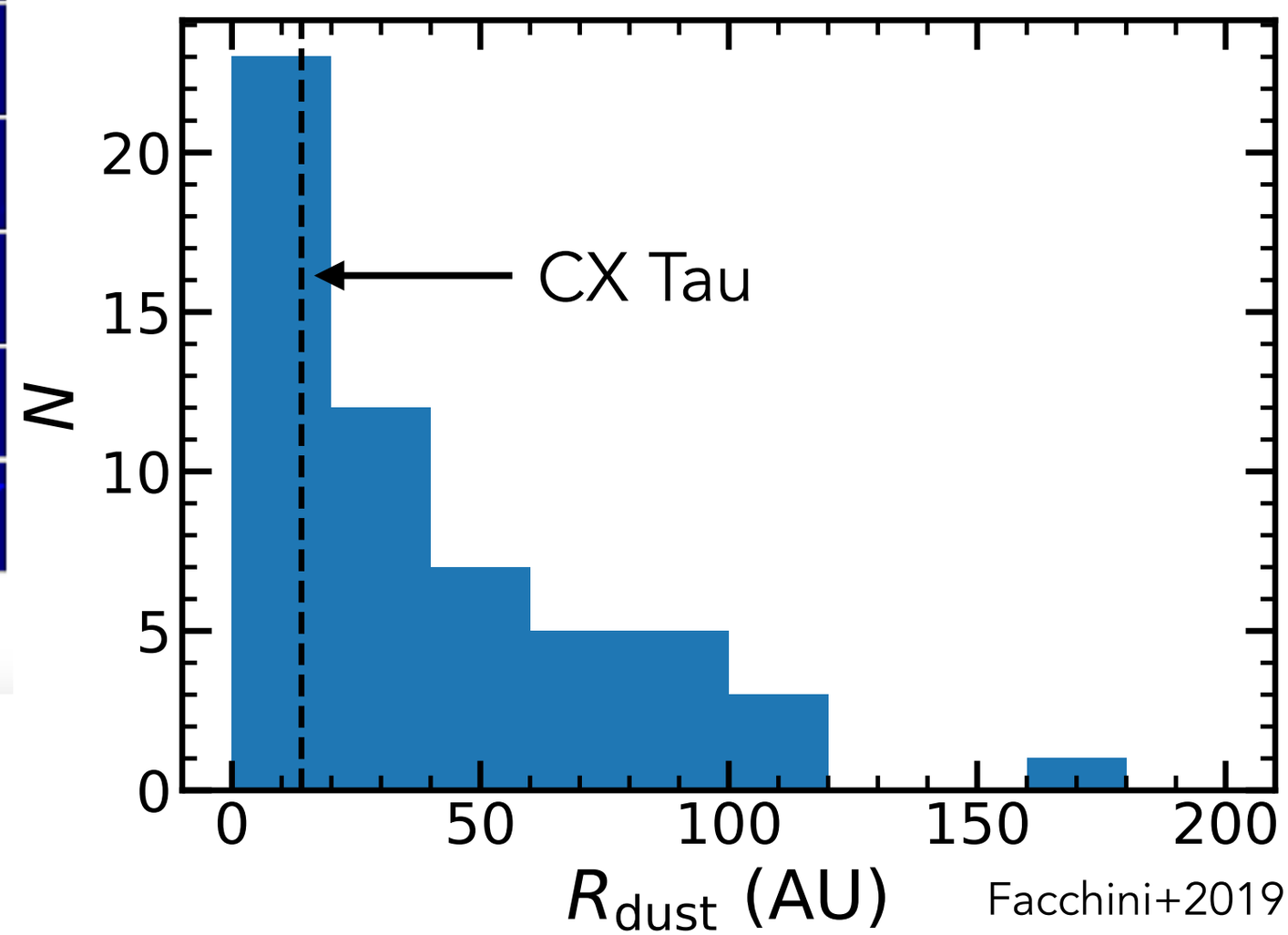


De Gregorio Monsalvo+2013

A typical object



Ansdell+2018



Facchini+2019

What are the properties of these low flux objects,
which are the **bulk** of the disk population?
What is their gas extent?

OPEN QUESTIONS

- Are many Herbig stars hiding a misaligned low mass (stellar) companion?
- What is the impact of misaligning torques on planet formation?
- What are the varying shadows tracing?
- Can a massive planet become misaligned?
- What is the origin of dippers?

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- What sets the dust disk size, and what is the relation with radial substructure?
- What are the *gas* properties of these compact objects? Is the gas setting the dust size and level of substructures (probably yes…)?