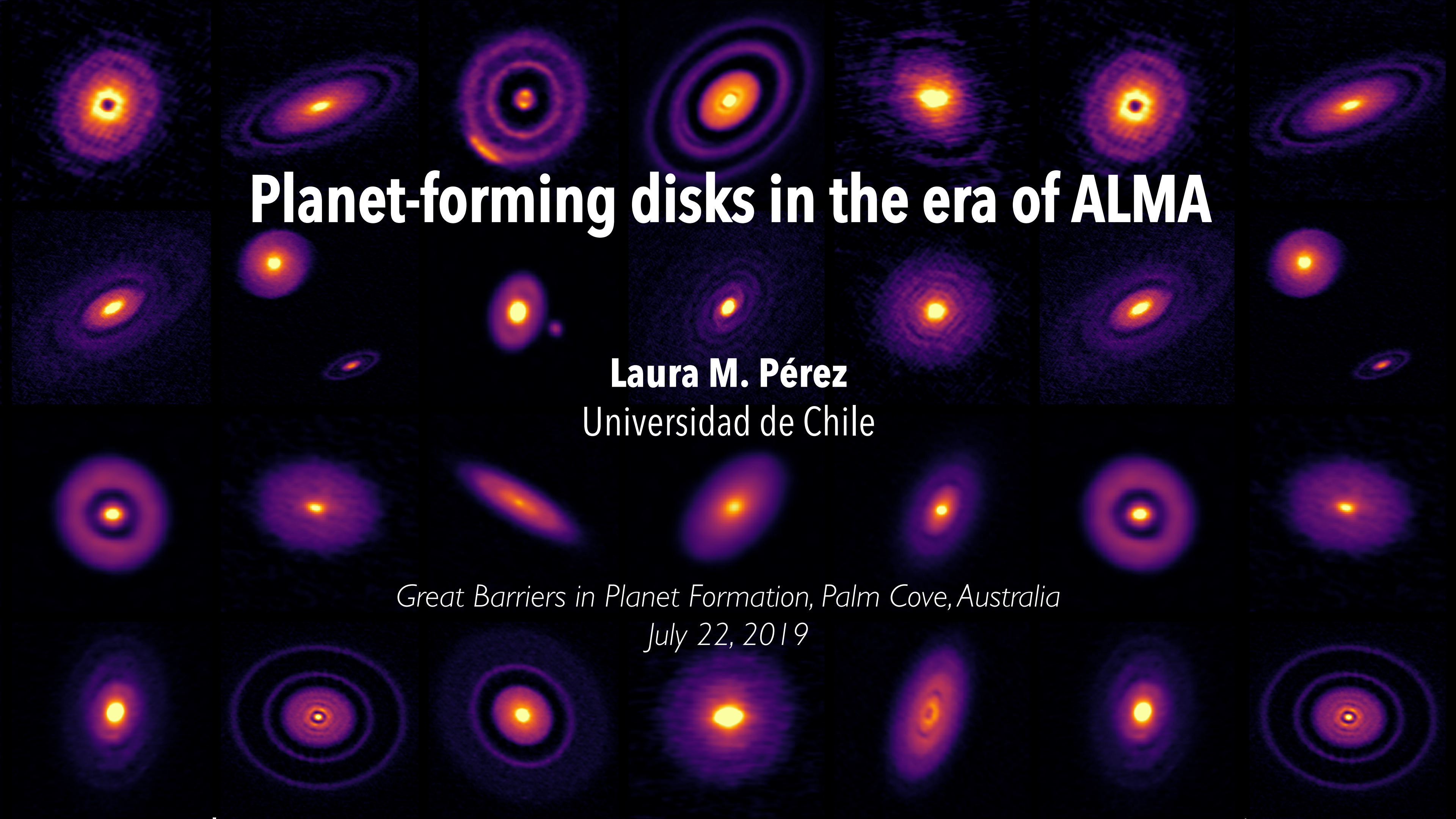


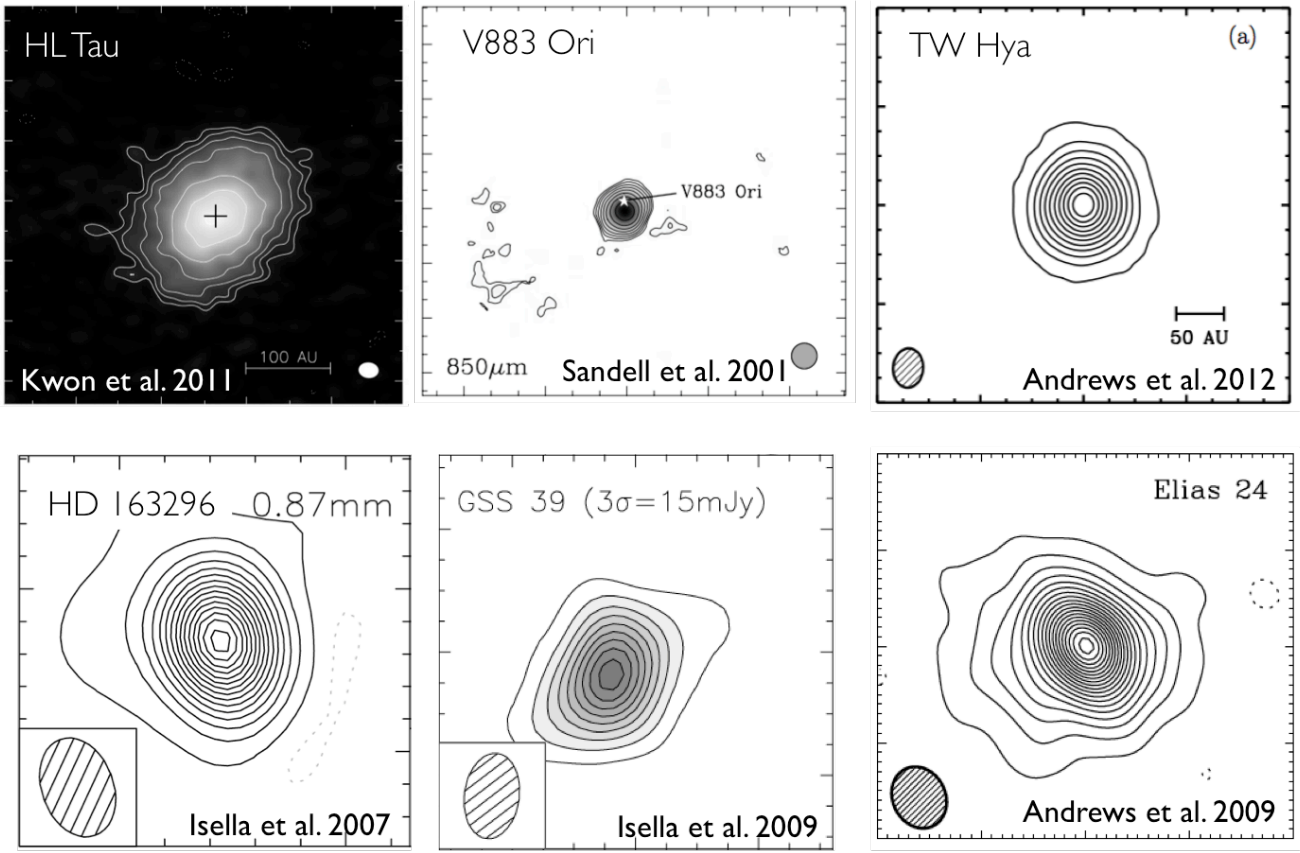
# Planet-forming disks in the era of ALMA

**Laura M. Pérez**
Universidad de Chile

*Great Barriers in Planet Formation, Palm Cove, Australia*
*July 22, 2019*

# A *former* great barrier to our understanding: lack of sensitivity and spatial resolution

## particularly at longer wavelengths sensitive to disk emission



# A *former* great barrier to our understanding: lack of sensitivity and spatial resolution

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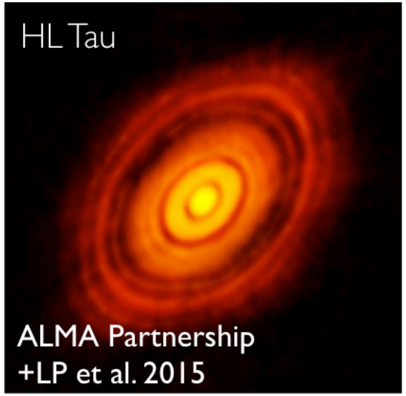
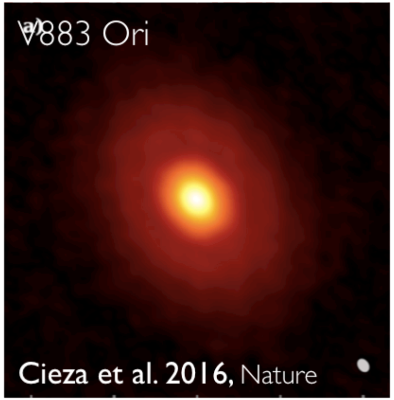
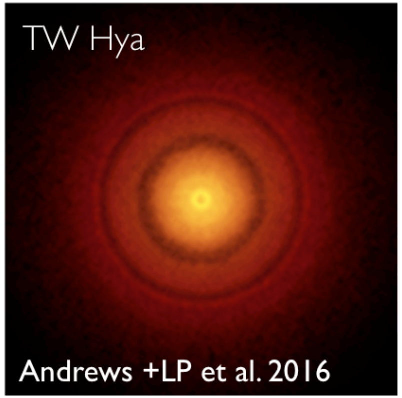
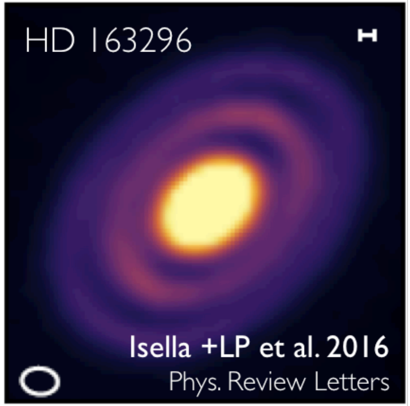
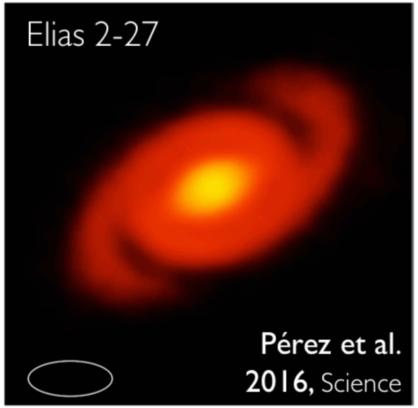
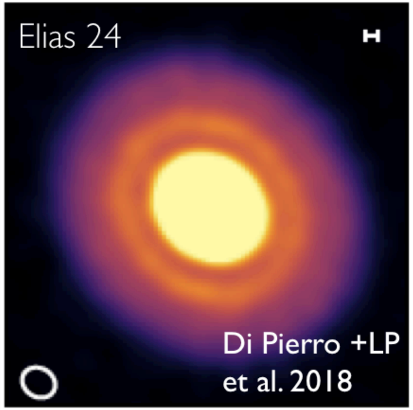


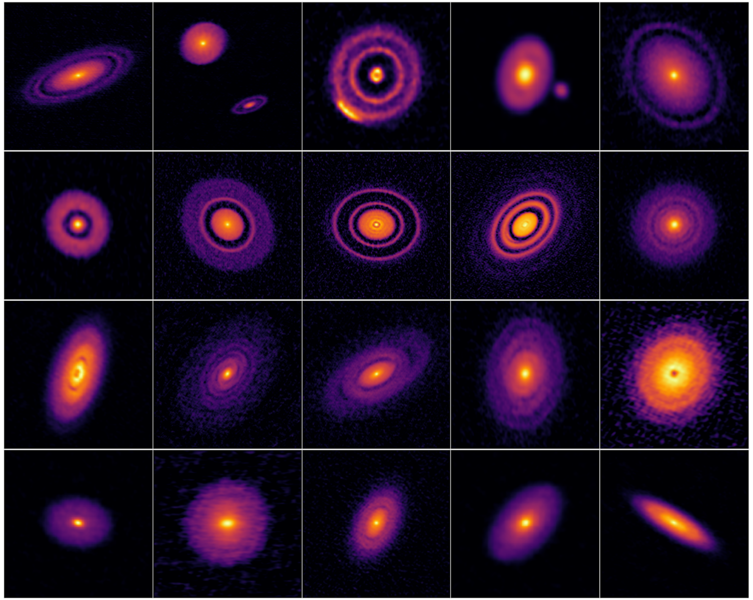



# A *former* great barrier to our understanding: lack of sensitivity and spatial resolution

## particularly at longer wavelengths sensitive to disk emission

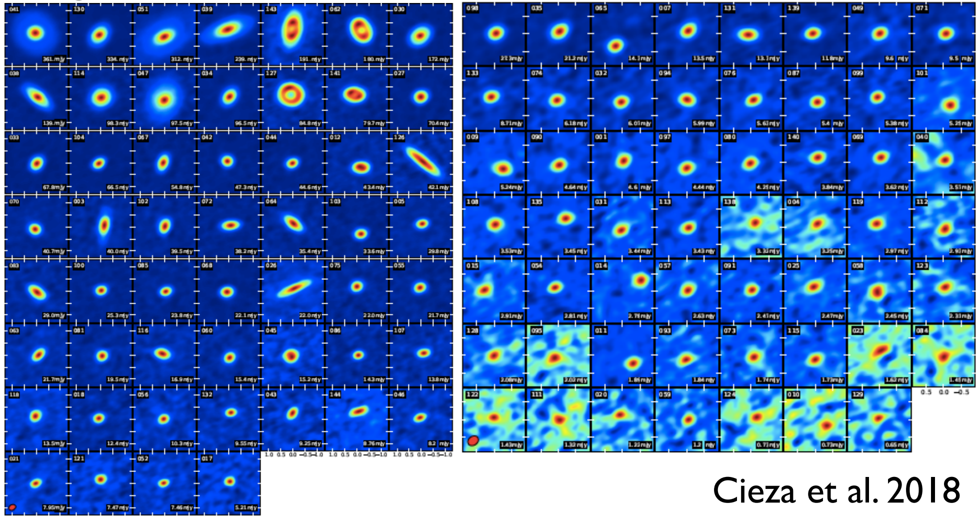
These developments motivated large surveys to characterize what is there…

e.g. DSHARP



Andrews et al. 2018

e.g. ODISEA



Cieza et al. 2018

Over 20 talks from ALMA results in both survey mode and high resolution imaging!

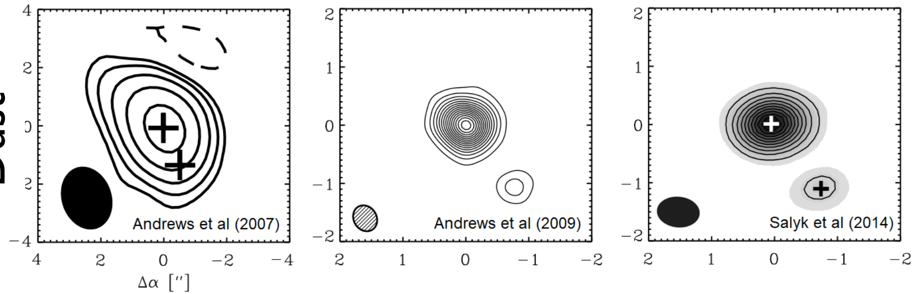
# An example of this: substructures in disks aroung *Multiple* young stellar systems

## Excellent laboratories to study dynamical interactions

## AS 205

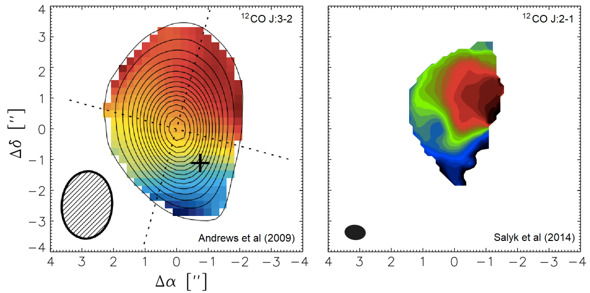
d = 127 pc
SpT K5 (AS205 N)
K7 and M0 (AS205 S)

Dust



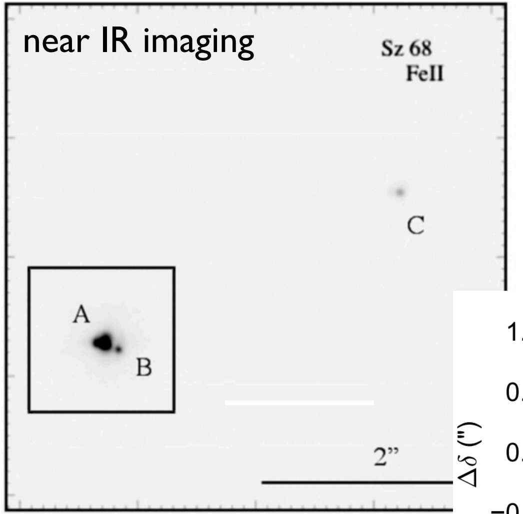

Andrews et al. 2007, 2009
Salyk et al 2014

Gas



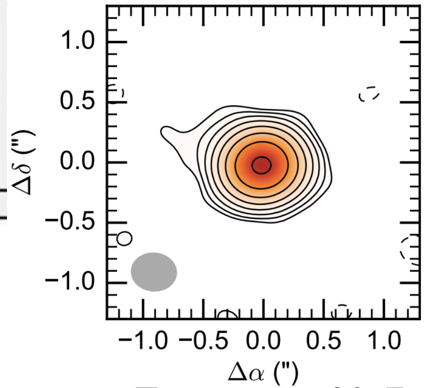

## HT Lup

d = 154 pc
SpT K2 (HT Lup A)
unknown (HT Lup C)




Correia et al. 2006

Dust (ALMA)



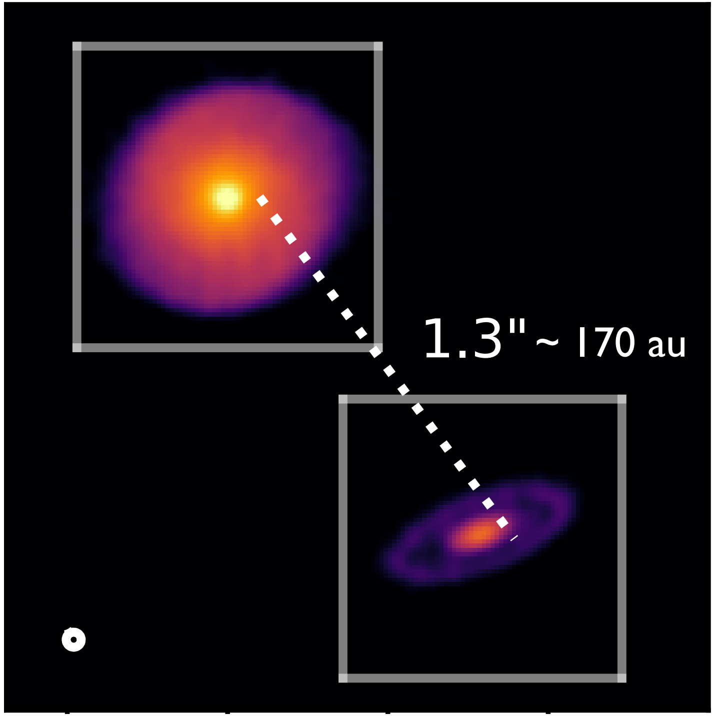

Tazzari et al. 2017

# Substructures in the disks aroung *Multiple* young stellar systems

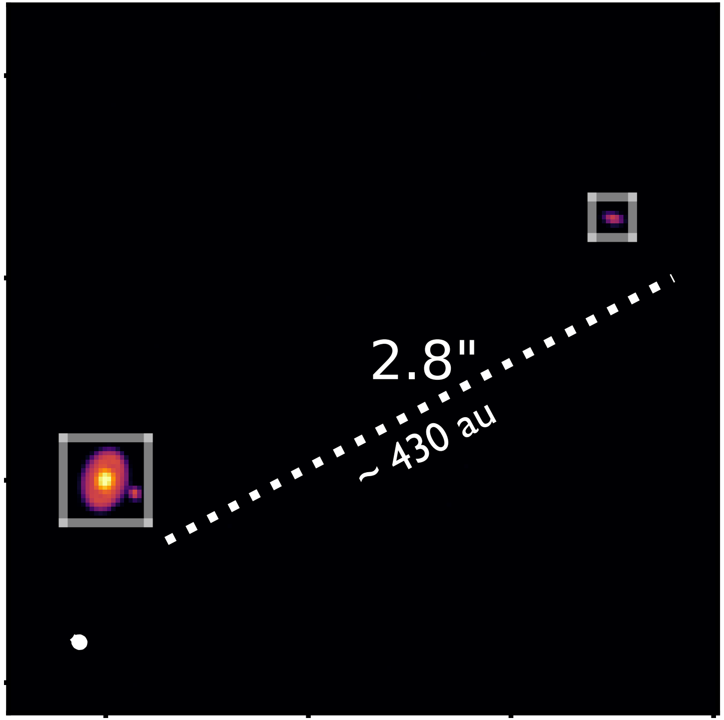
## Excellent laboratories to study dynamical interactions

Kurtovic et al. 2018
DSHARP IV

AS 205




HT Lup

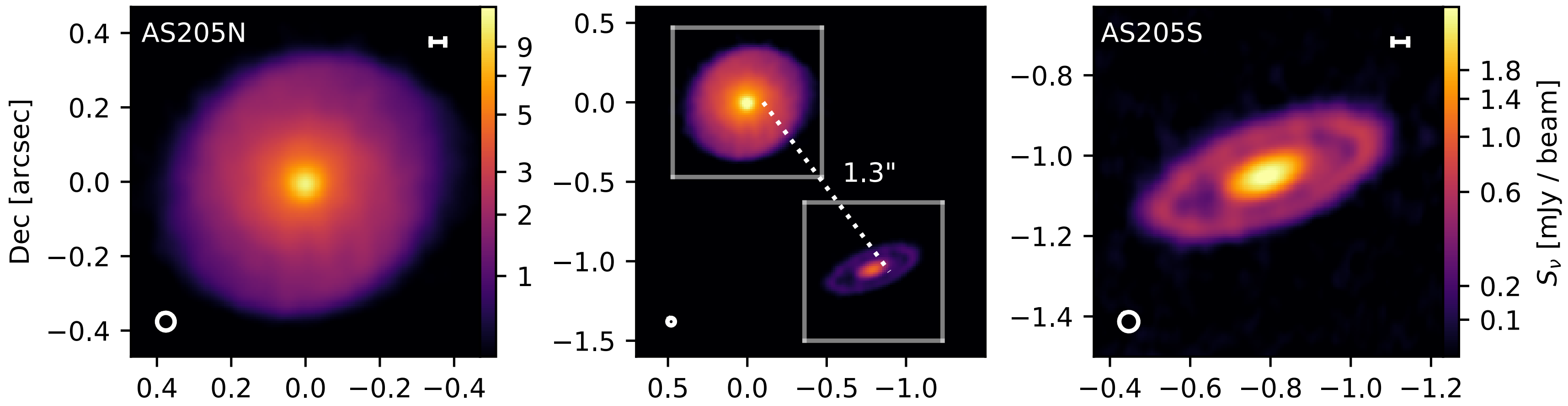


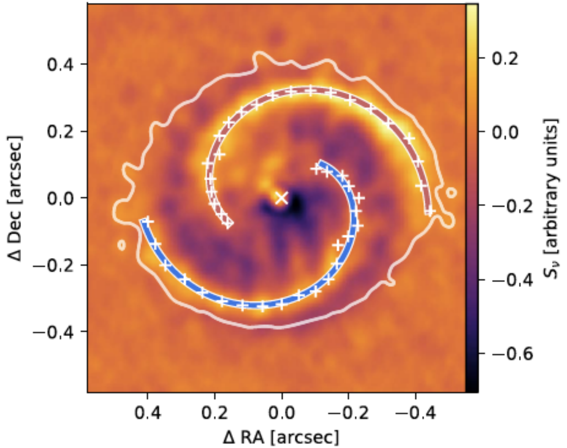

Nicolas T. Kurtovic
MSc Student, U. de Chile

AS 205

# Substructures in the disks aroung *Multiple* young stellar systems

**Rings and Spirals** are present in disks around AS205 components



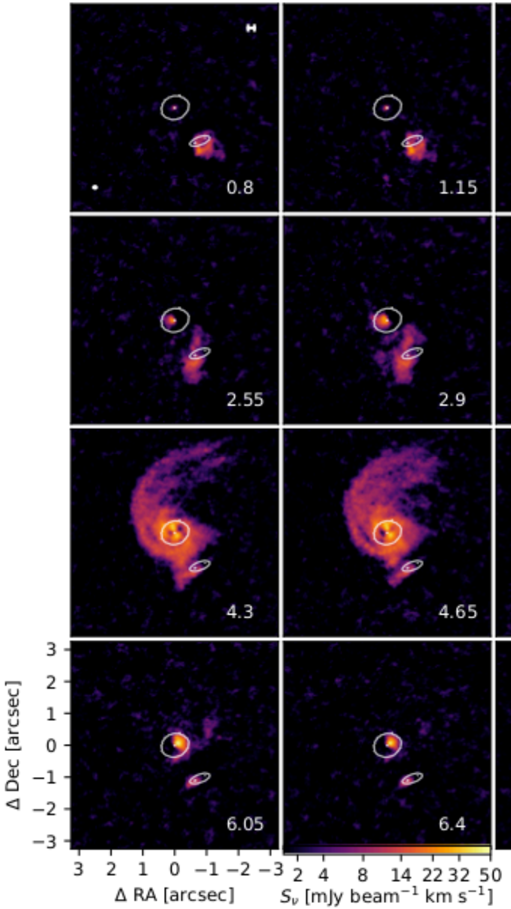

- ✧ Triple stellar system (AS 205 S is spectroscopic binary)
- ✧ Grand-design spiral in N, ring/gap in S, inner cavity too

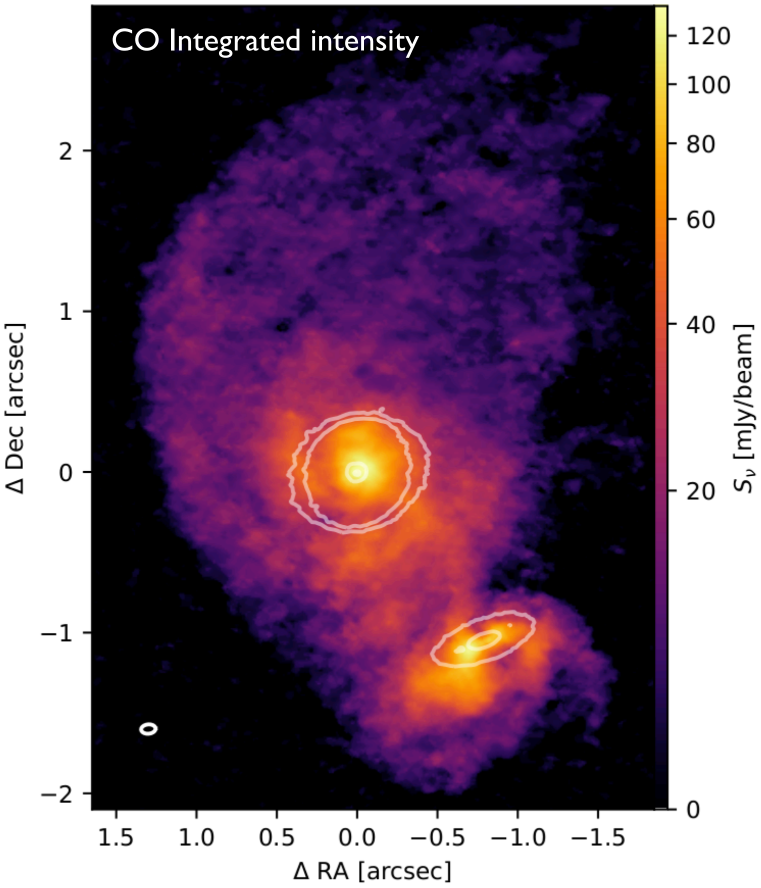
- ✧ Pitch angle ~ 15°
- ✧ (Variable pitch angle is better fit than constant)

# AS 205 Substructures in the disks aroung *Multiple* young stellar systems

CO (J = 2-1)

Multiplicity also reflected in kinematics, possible fly-by evidence?

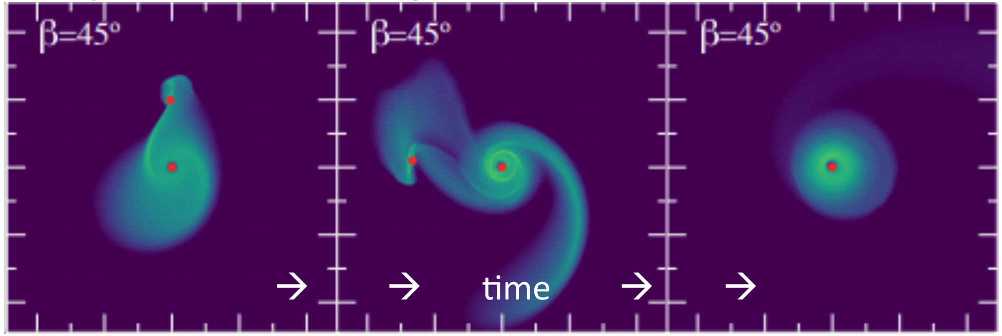


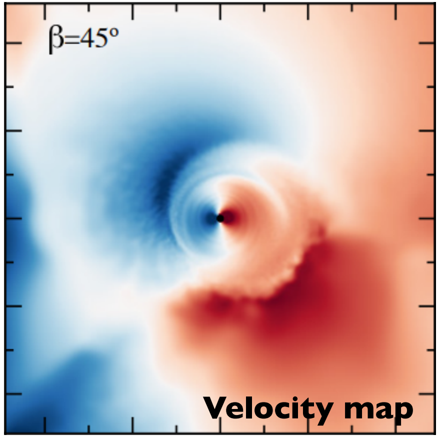



# AS 205 Substructures in the disks aroung *Multiple* young stellar systems

CO (J = 2-1) Multiplicity also reflected in kinematics, possible fly-by evidence?

Prograde interaction by Cuello et al. 2019

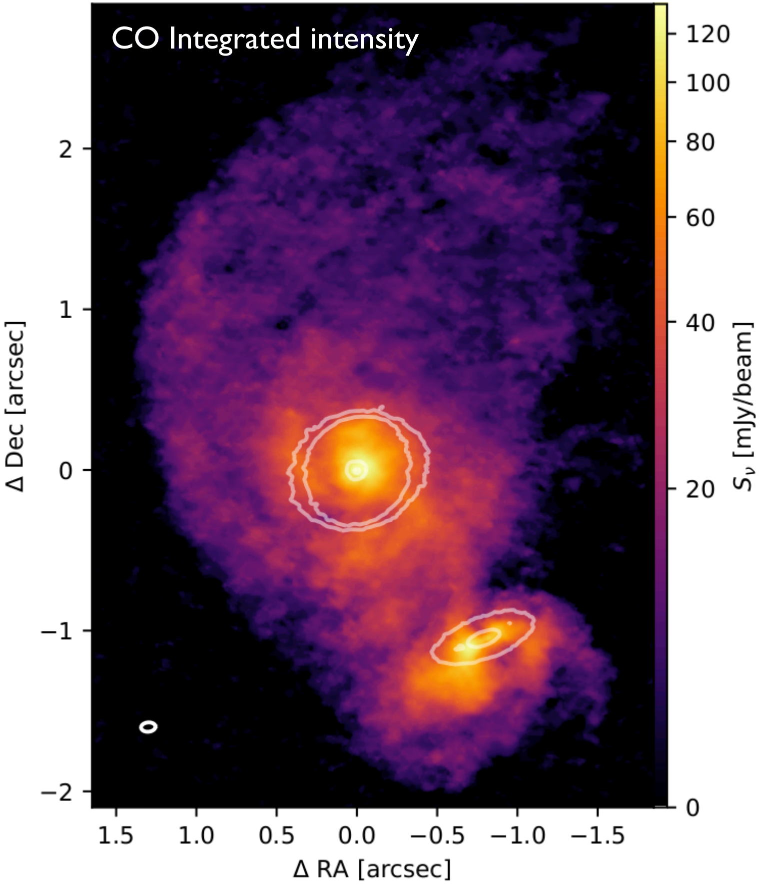



Hydrodynamic simulations of fly-bys show:

- Arc structures in gas
- Spirals in dust
- Interesting kinematics

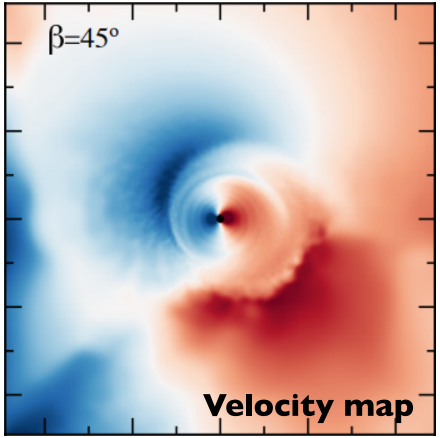
more on N. Cuello's talk



# AS 205 Substructures in the disks aroung *Multiple* young stellar systems

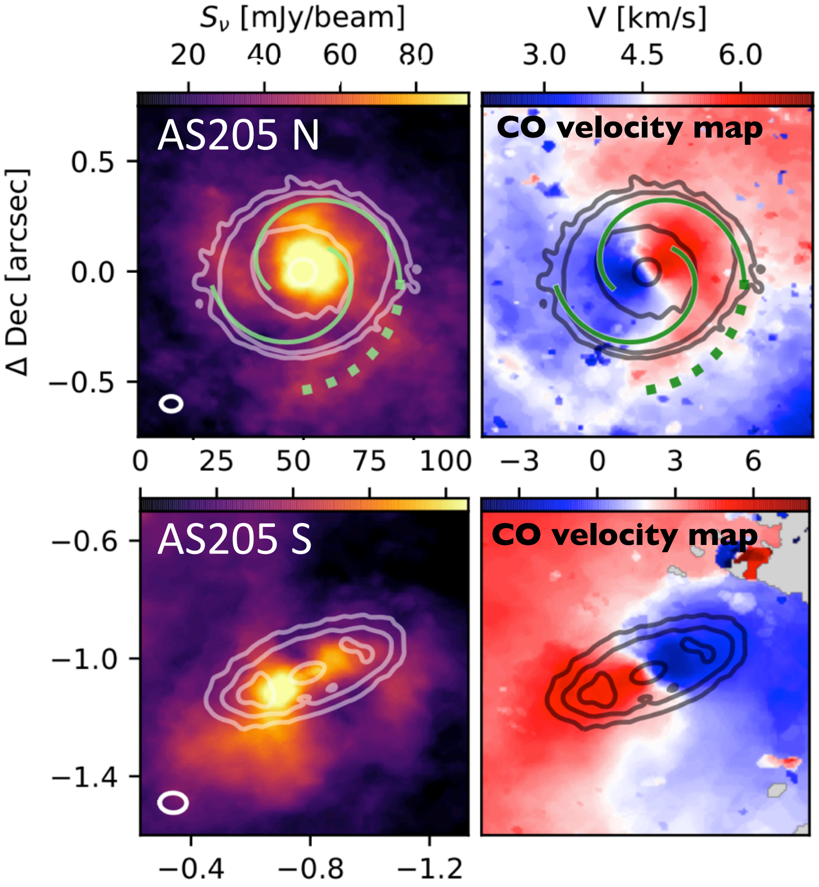
## CO (J = 2-1) Multiplicity also reflected in kinematics, possible fly-by evidence?

Prograde interaction
(Cuello et al. 2019)




***Prograde*** encounter in AS 205 favored by observations:

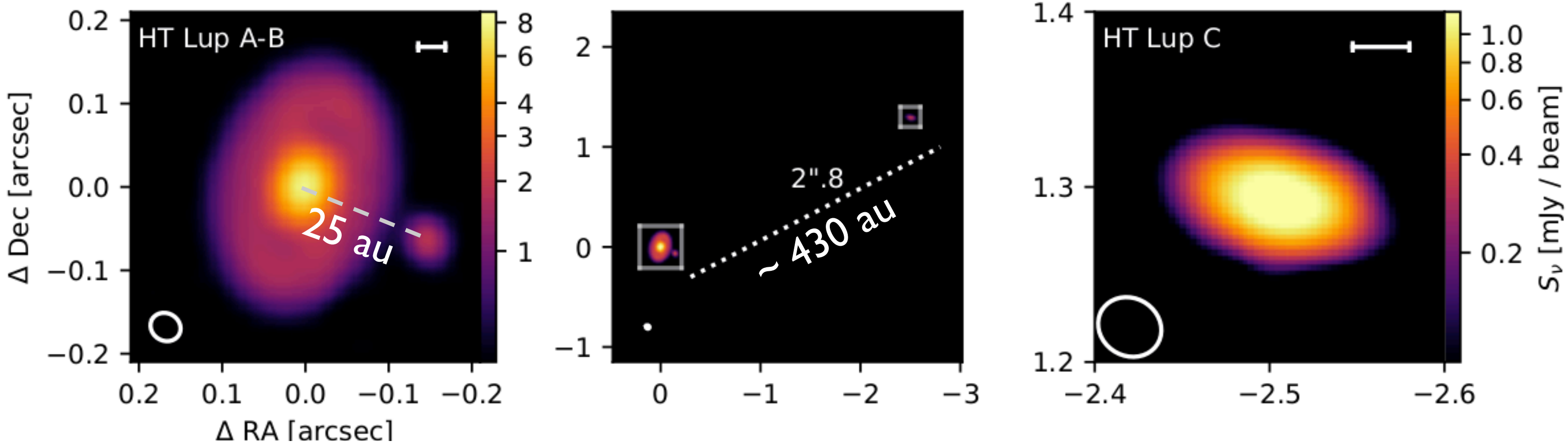
- ***Large*** arc structures in gas
- ***High contrast, large pitch angle*** spirals in dust
- ***Warped*** kinematics

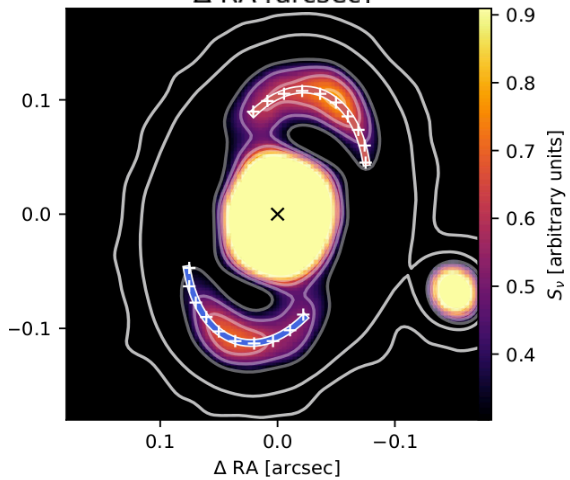


# HT Lup

# Substructures in the disks aroung *Multiple* young stellar systems

## **Spirals** and **tiny disks** around HT Lup components




- ✧ Triple stellar system
- ✧ Spiral in A, resolve tiny disks in B and C

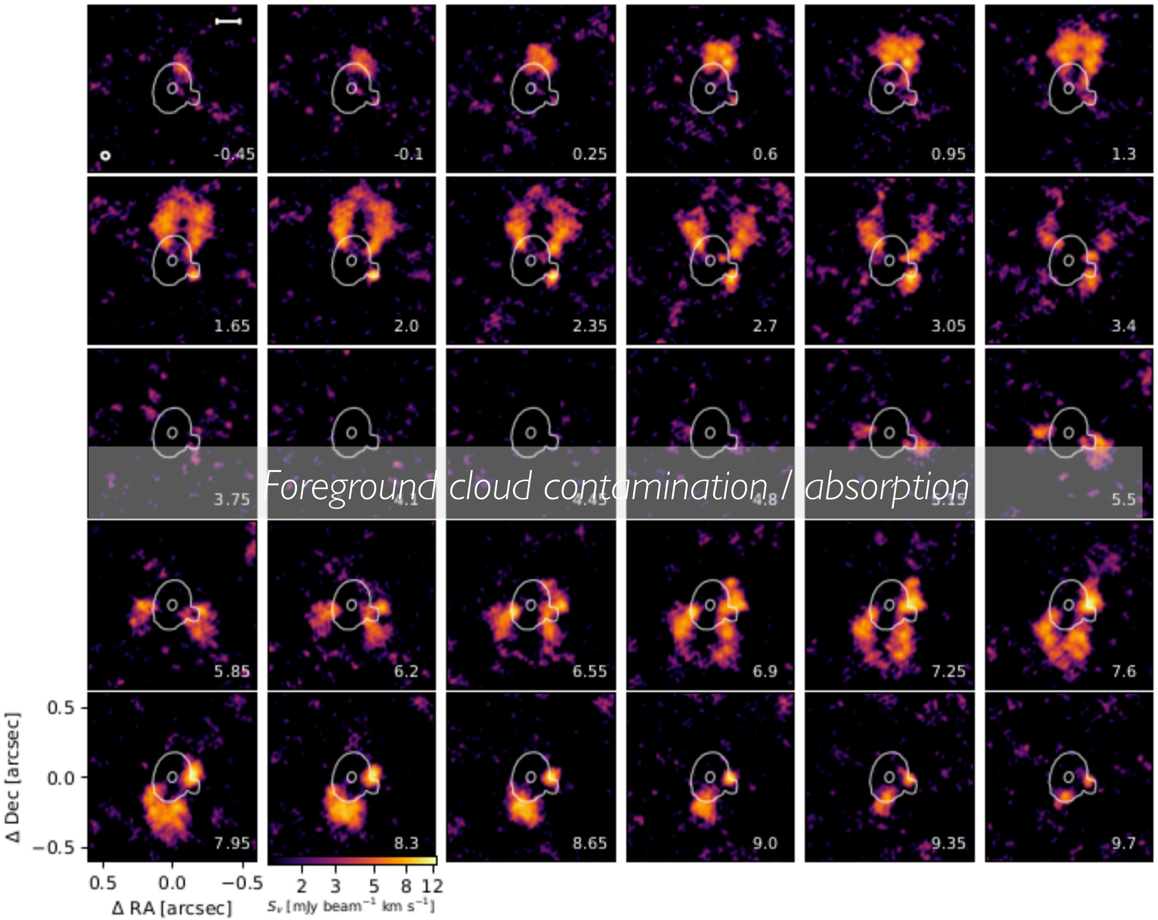
- ✧ Lower contrast spirals, pitch angle ~ 4°
- ✧ B and C are the smallest disks of the whole sample

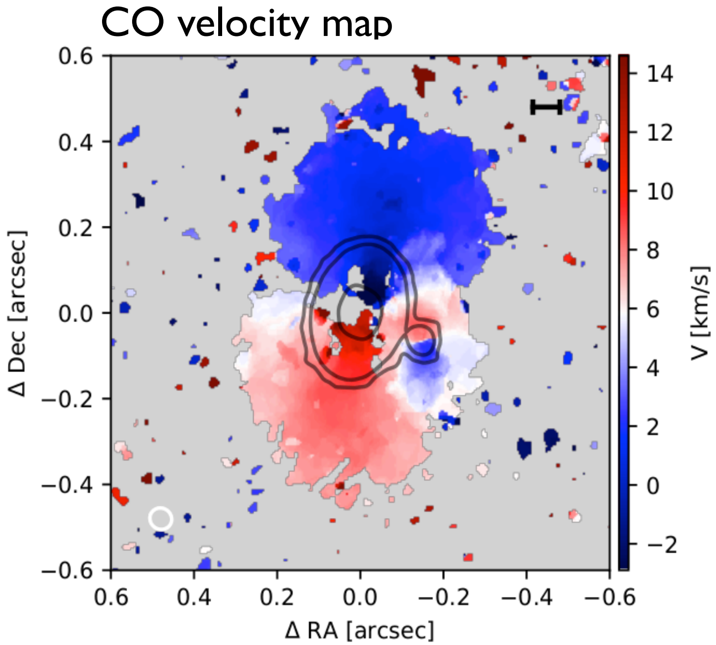
# HT Lup

# Substructures in the disks aroung *Multiple* young stellar systems

## CO (J = 2-1)

## Kinematics show apparent disk counterotation



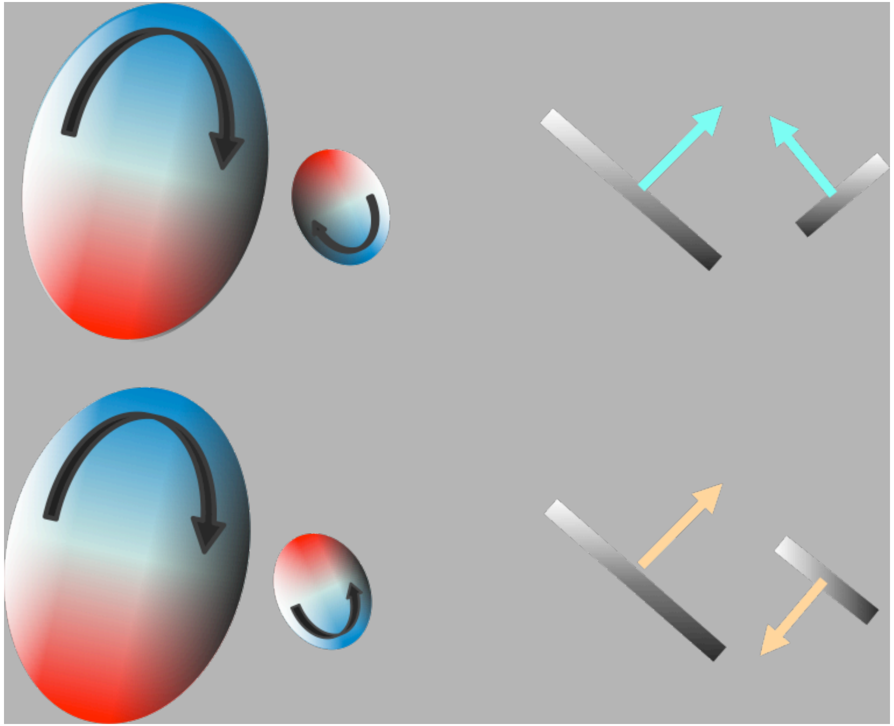
# HT Lup

# Substructures in the disks aroung *Multiple* young stellar systems

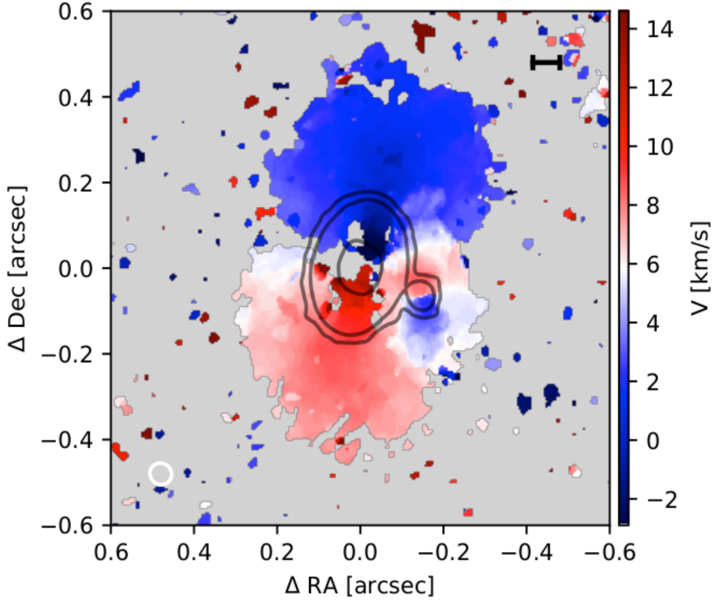
CO (J = 2-1)

Kinematics show apparent disk counterotation

**Misalignment** between angular momentum vectors could be ~ **90°** or **164°**



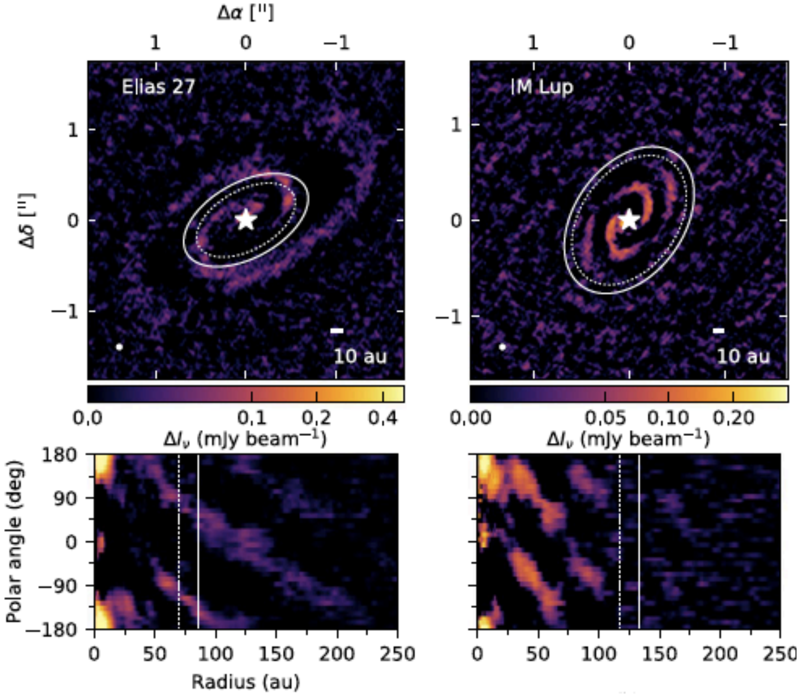
CO velocity map



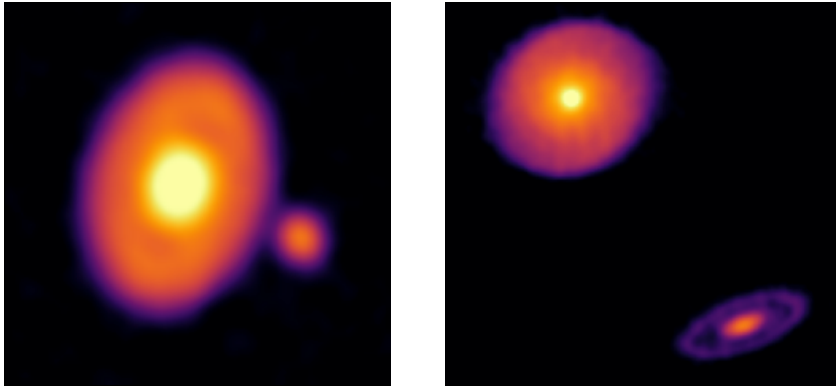
# Substructures in the disks aroung *Multiple* young stellar systems

## Excellent laboratories to study dynamical interactions

Spirals and rings around ***single*** systems (Huang et al. 2018b)
→ very large disks (more than 100au)




Only spirals in ***multiple*** systems (Kurtovic et al. 2018b)
→ Truncated disks !
→ ~ 40 au in HT Lup, 60au in AS 205

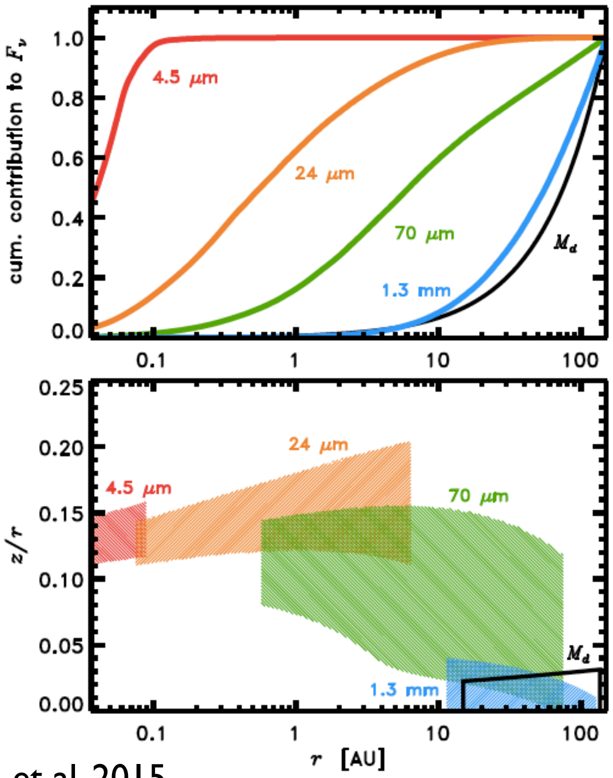


✧ Are we observing inhibited planet formation due to stellar encounters and close binary companions?
  ✧ Remember: lower exoplanet rates around binaries

# A *current* great barrier: Not clear if optical depths are really low, even at ALMA wavelengths

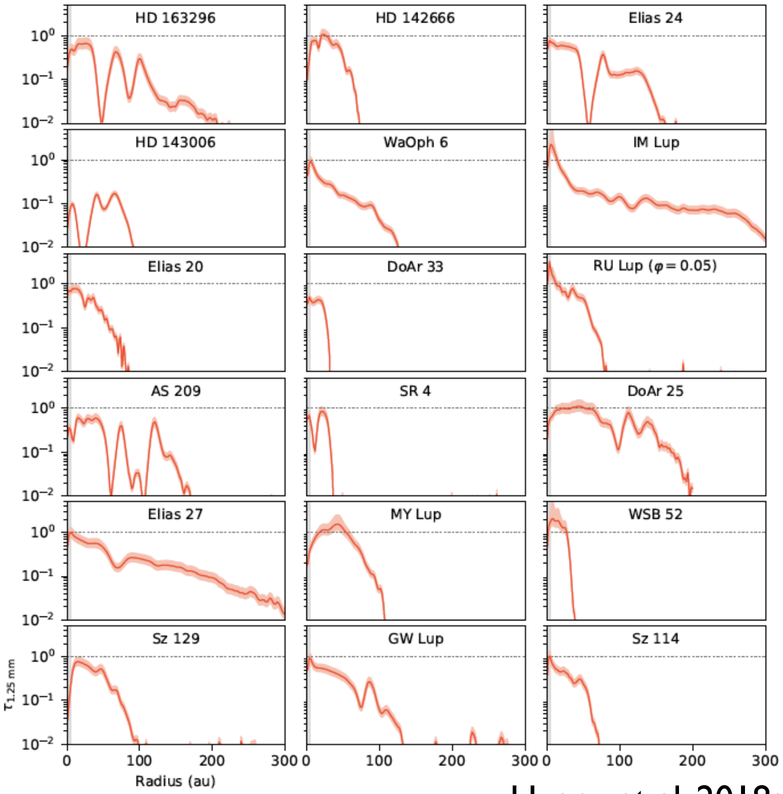
## (both the presence of substructure and the effect of dust scattering were generally ignored)

Longer wavelengths better trace mass distribution




Andrews et al. 2015

But mass distribution is not necessarily smooth…



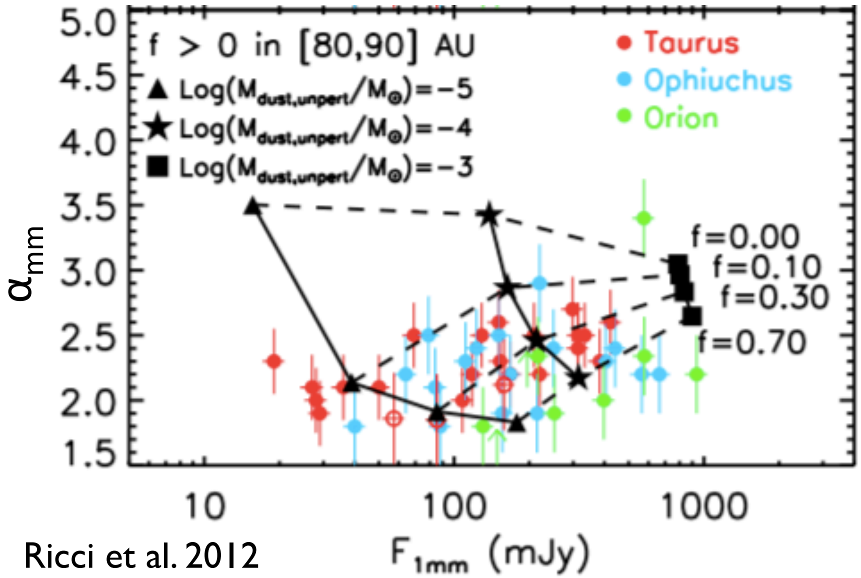

Huang et al. 2018a

# A *current* great barrier: Not clear if optical depths are really low, even at ALMA wavelengths

## (both the presence of substructure and the effect of dust scattering were generally ignored)

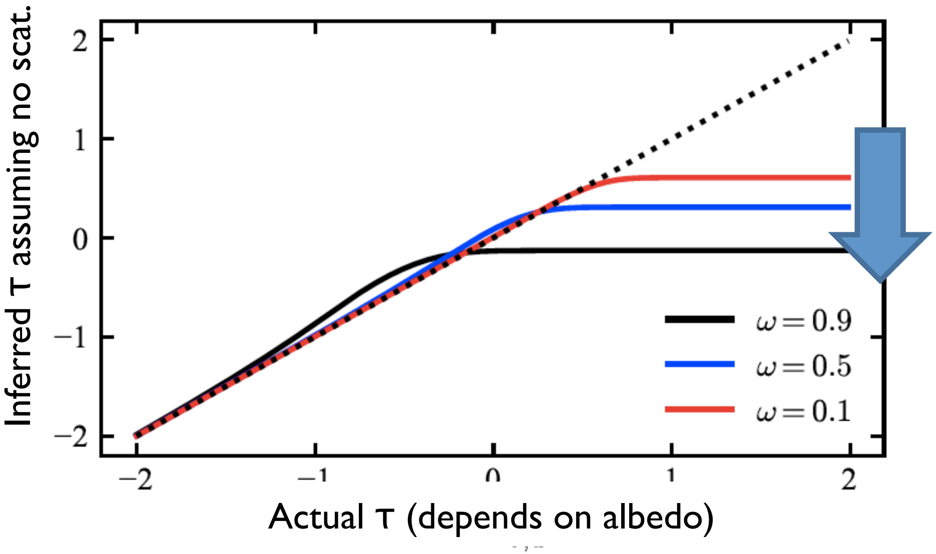
… the presence of susbtructures had already come up as an idea to explain low spectral indices

*No need to include large pebbles, just ~0.3 filling factors in an unperturbed disk*




Ricci et al. 2012

… combined with dust scattering effects, it makes for further trouble

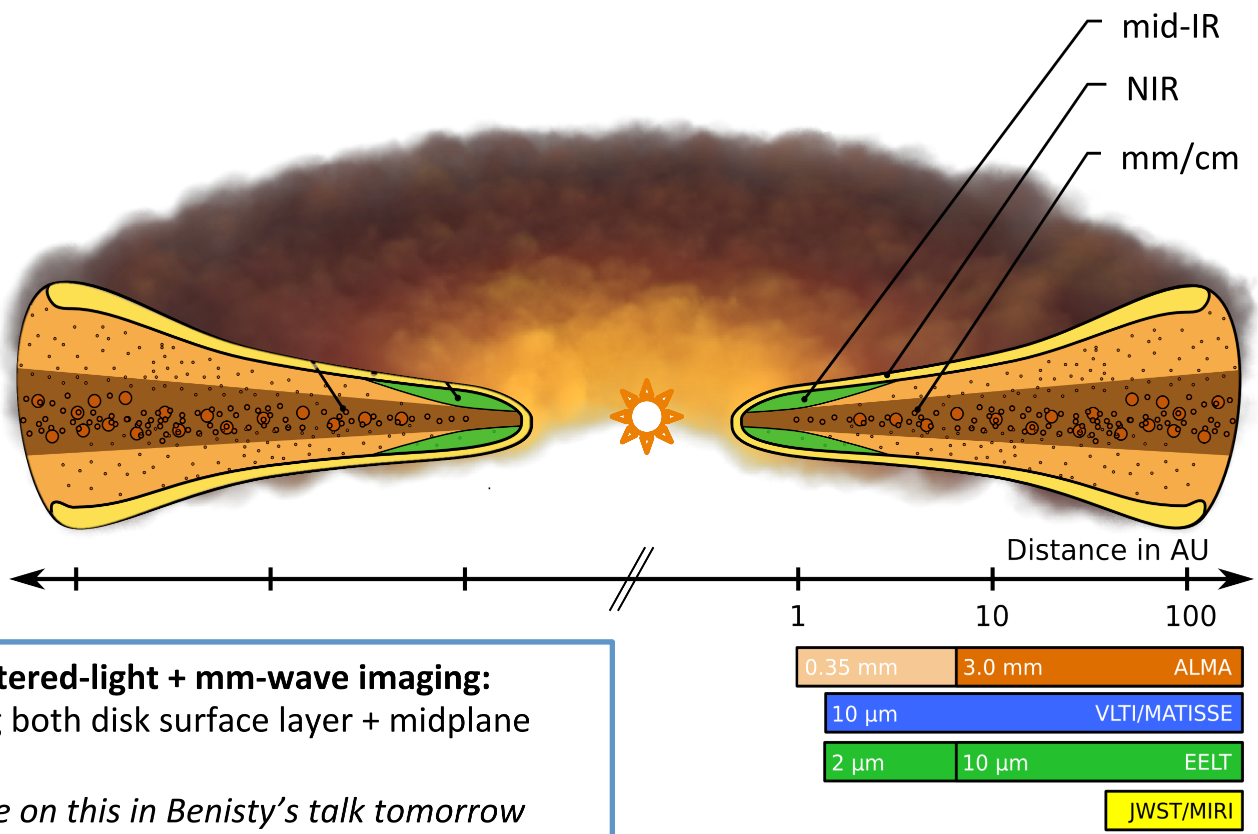



Zhu et al. 2019

… more on this issue in Z. Zhu's talk tomorrow

# A *former* great barrier to our understanding: lack of multiwavelength high-res observations

## from optical/near-IR scattered light to millimeter wavelenghts



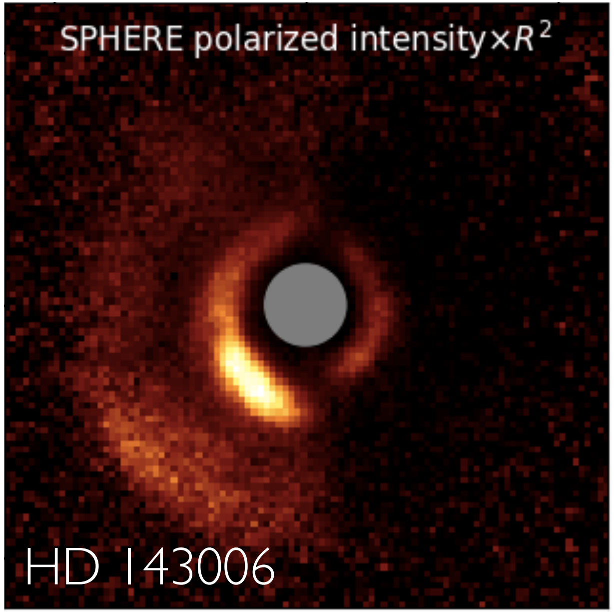

adapted from
Testi et al. (2014)

**Scattered-light + mm-wave imaging:**
Tracing both disk surface layer + midplane

*… more on this in Benisty's talk tomorrow*

# Substructures at multiple wavelengths

## What can we learn from studying the same object at multiple wavelengths?



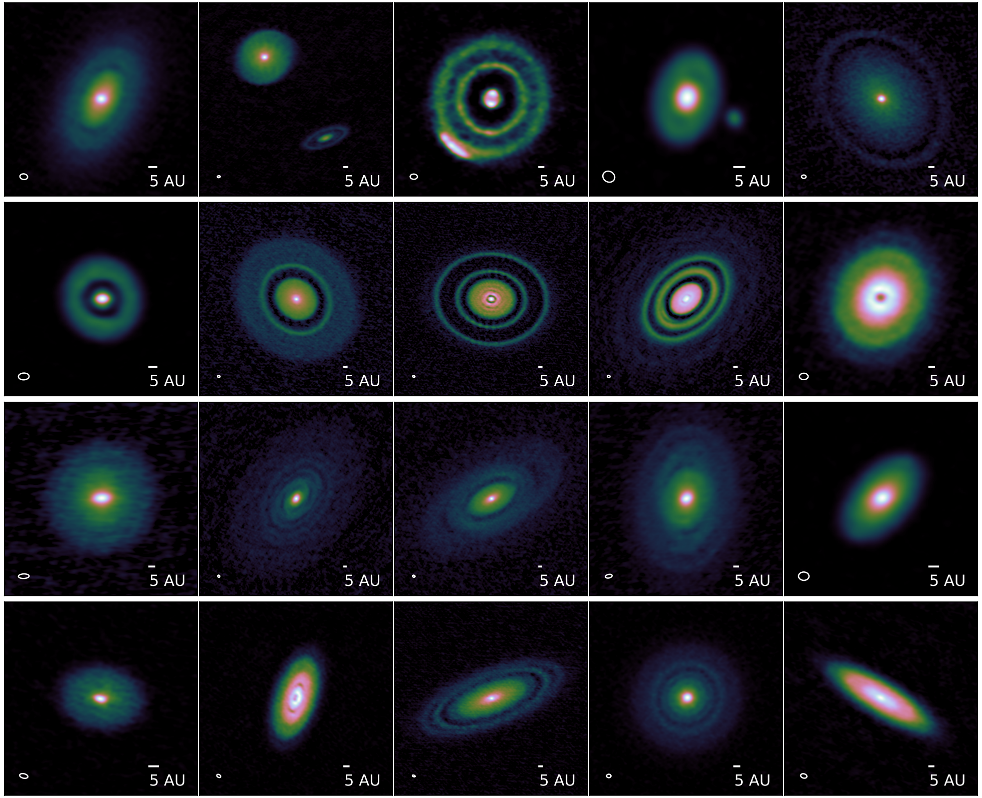

SPHERE J-band (40mas)

d = 165 pc

Benisty et al. 2018

G-type star, 1.8 Msun

Age ~ 4-12Myr



# Substructures at multiple wavelengths

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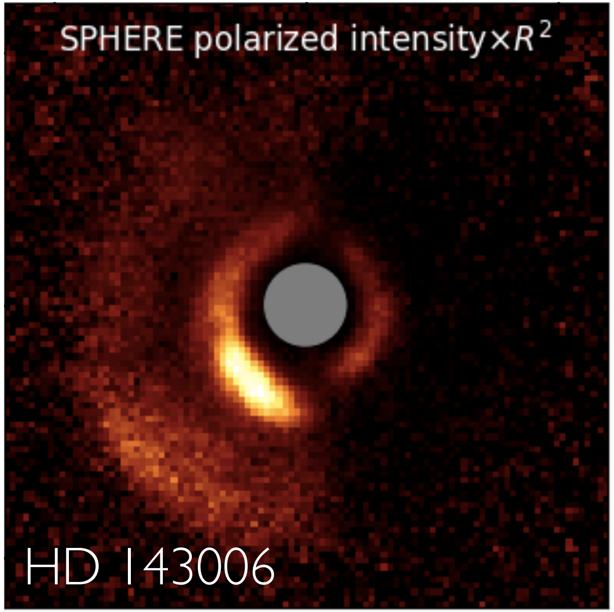


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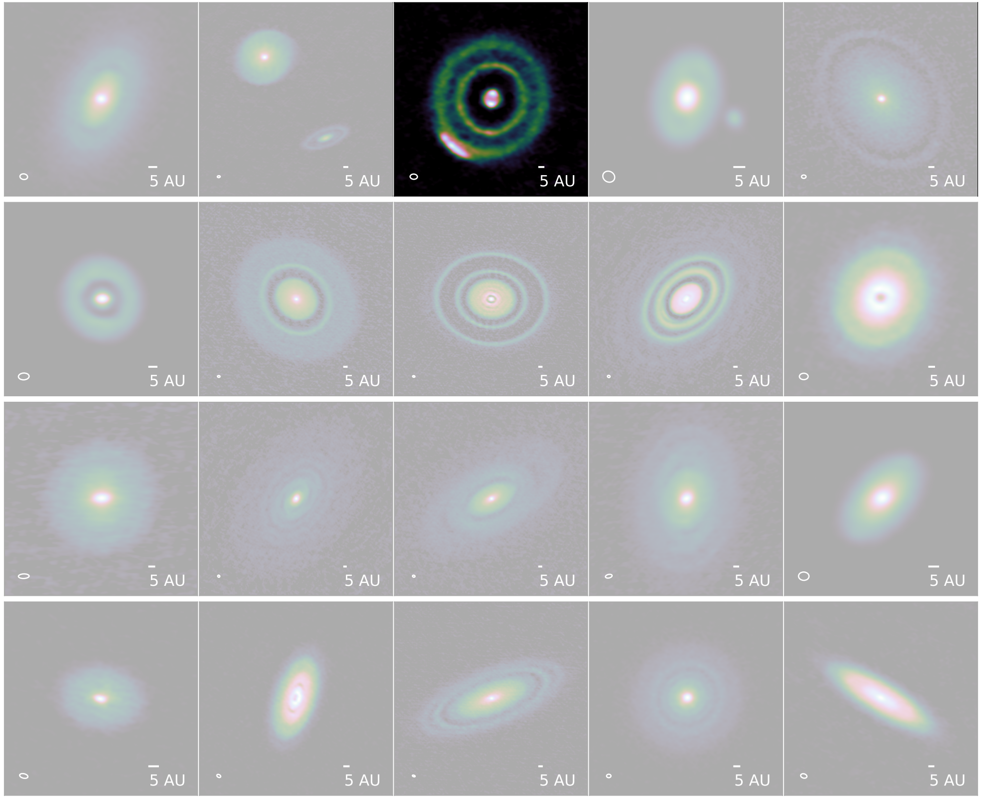
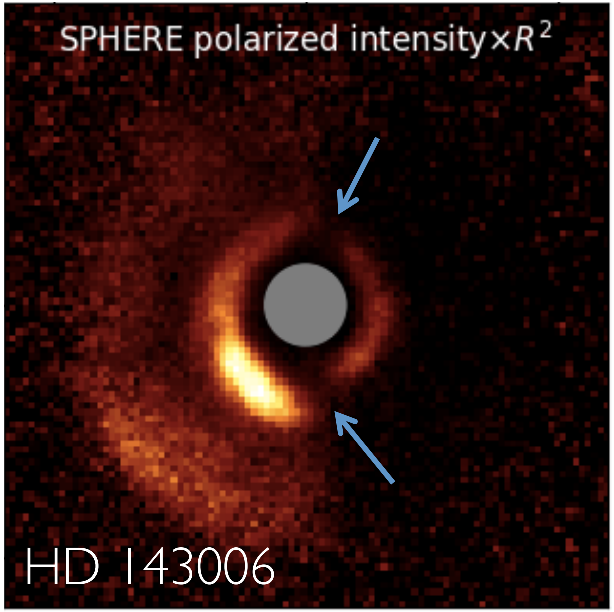


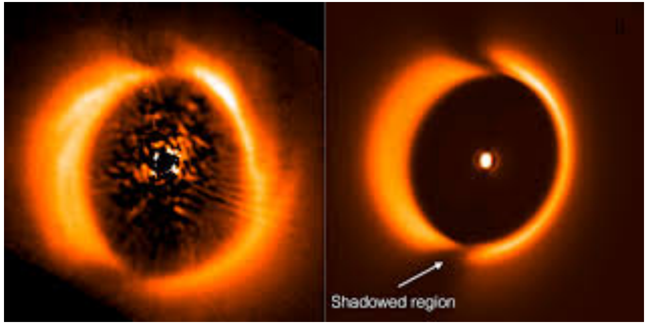
# Shadows in scattered light: a different probe of disk substructure

Scattered light observations are very sensitive to the illumination pattern

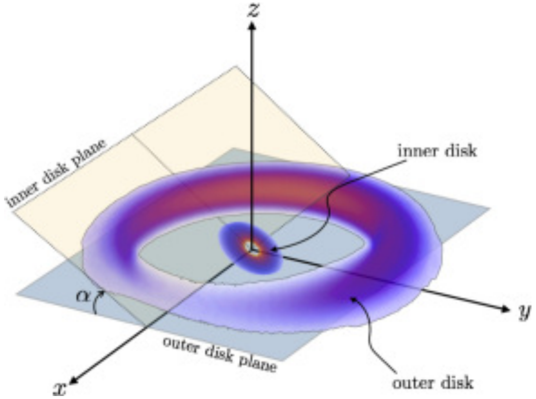



SPHERE J-band (40mas)
Benisty et al. 2018

Observations | Model




**HD 142527**
Marino et al. 2015



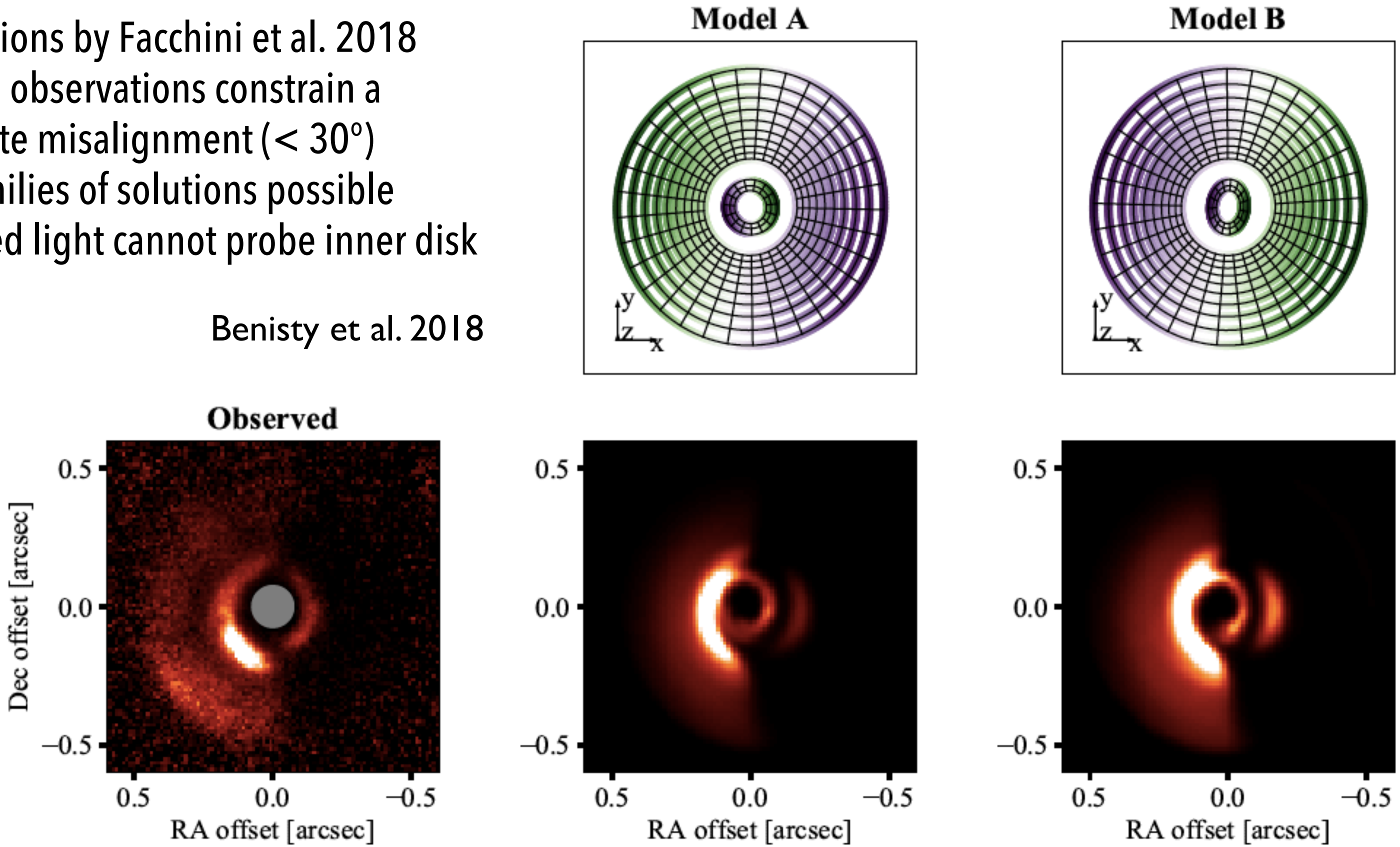

Highly misaligned inner disk cast <u>narrow</u> shadows on the outer disk

# Shadows in scattered light: a different probe of disk substructure

## A less pronounced misalignment can produce broad shadows in scattered light

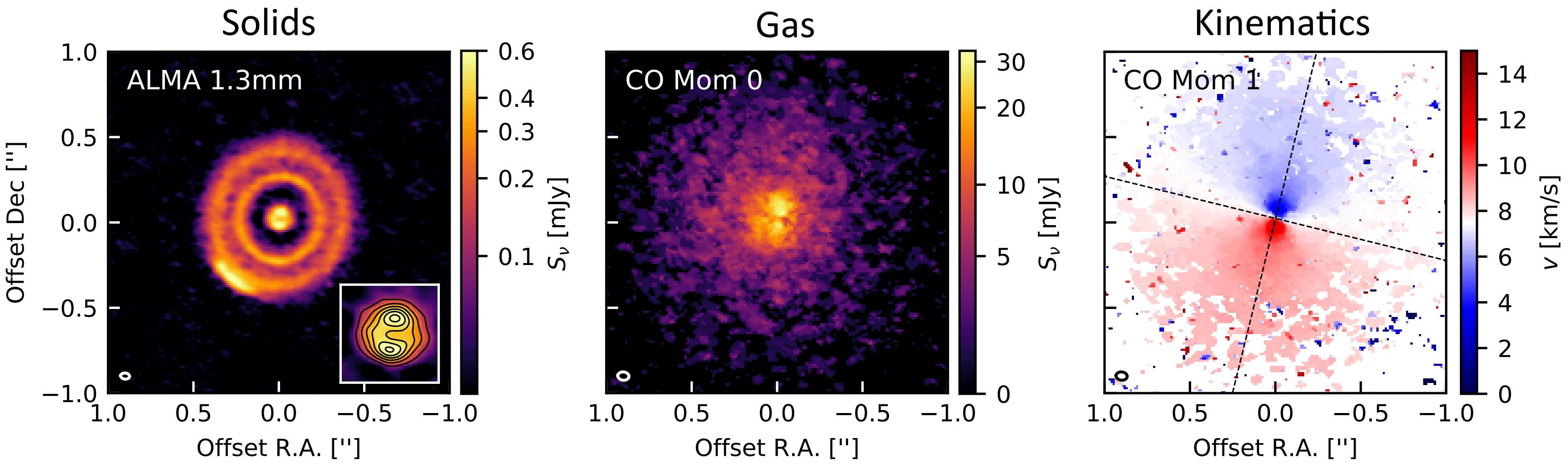
- Simulations by Facchini et al. 2018
- SPHERE observations constrain a moderate misalignment (< 30°)
- Two families of solutions possible
- Scattered light cannot probe inner disk

Benisty et al. 2018



# What do the new DSHARP observations of HD 143006 tell us?

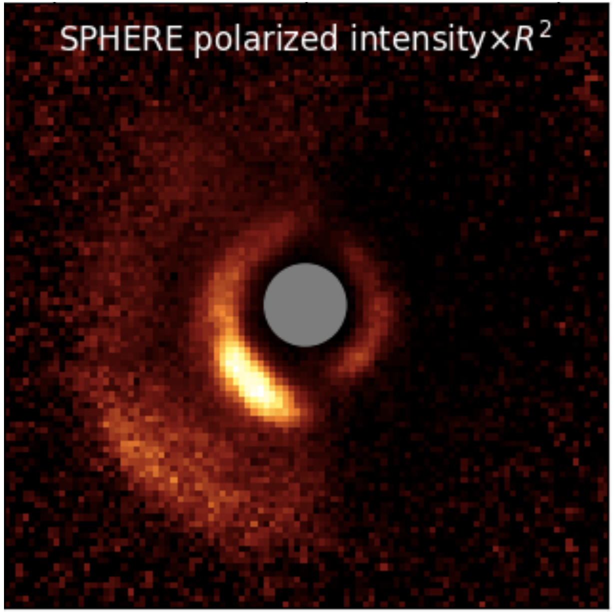
## New information about kinematics, gas emission, and dust continuum emission



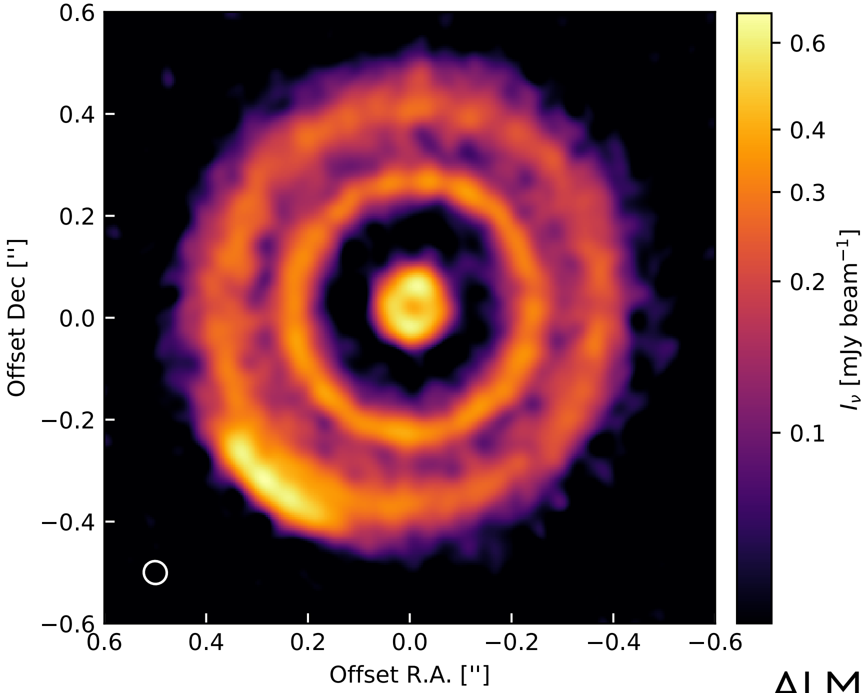

ALMA (45mas)
Pérez et al. 2018

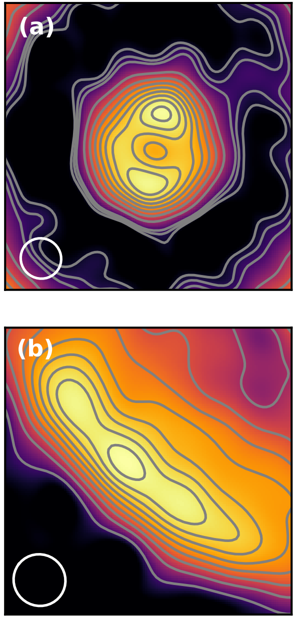
# What do the new DSHARP observations of HD 143006 tell us?

Dust emission resolves into multiple rings and gaps + a "bridge" + an "arc"




SPHERE J-band (40mas)
Benisty et al. 2018

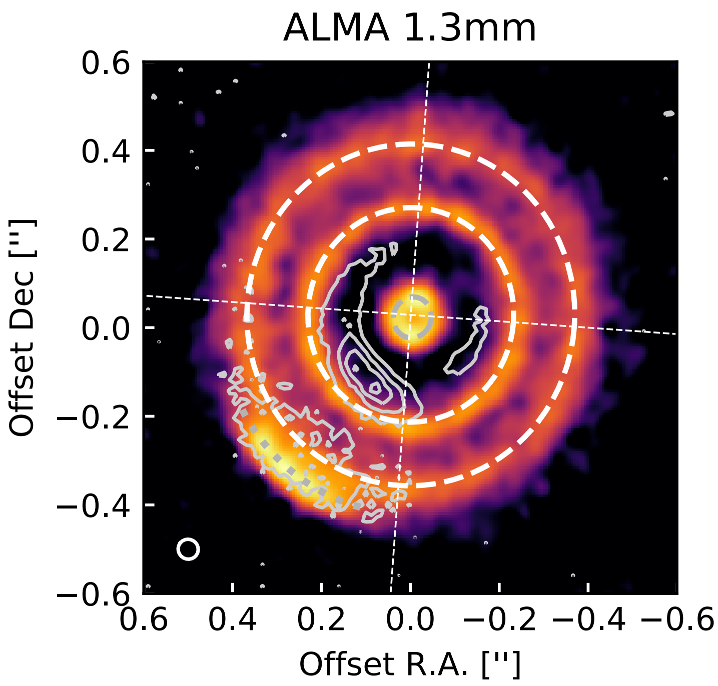



ALMA 1.3mm (45mas)
Pérez et al. 2018

# What do the new DSHARP observations of HD 143006 tell us?

## Substructures observed at multiple wavelenghts/tracers not necessarily co-located



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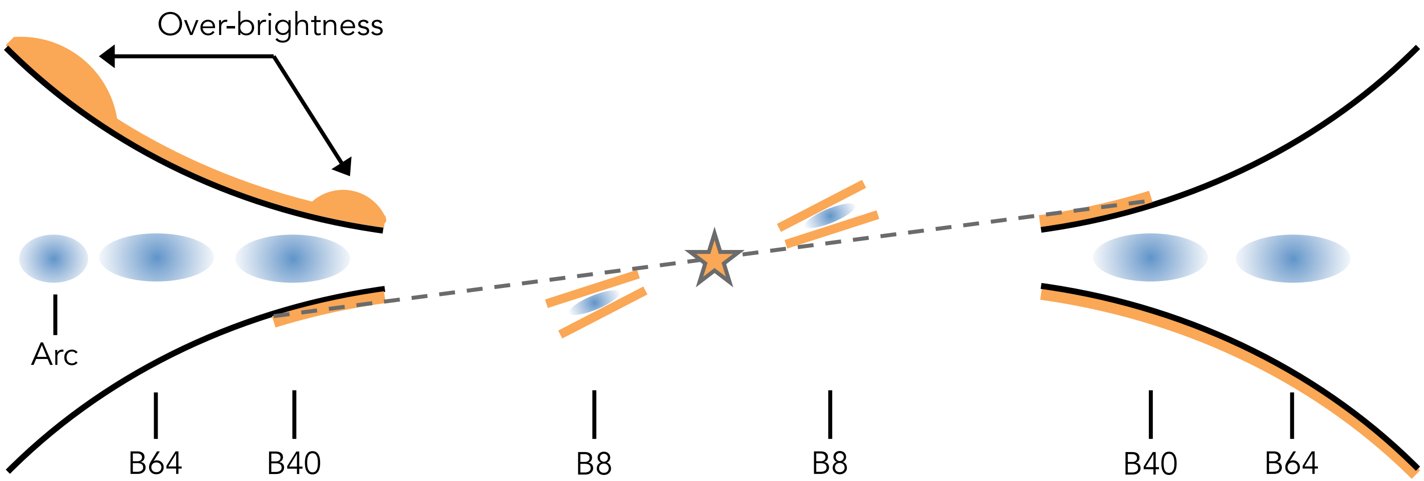
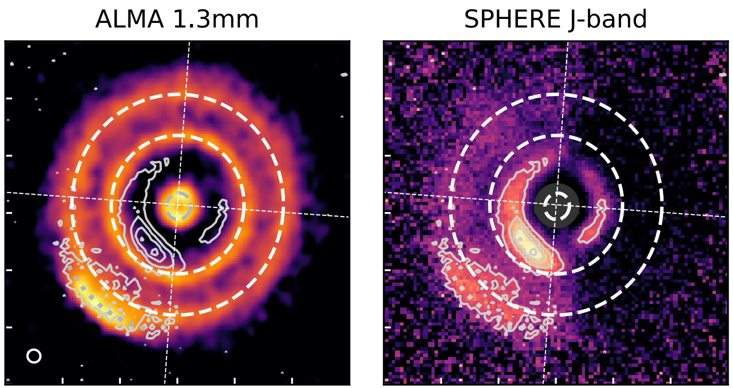


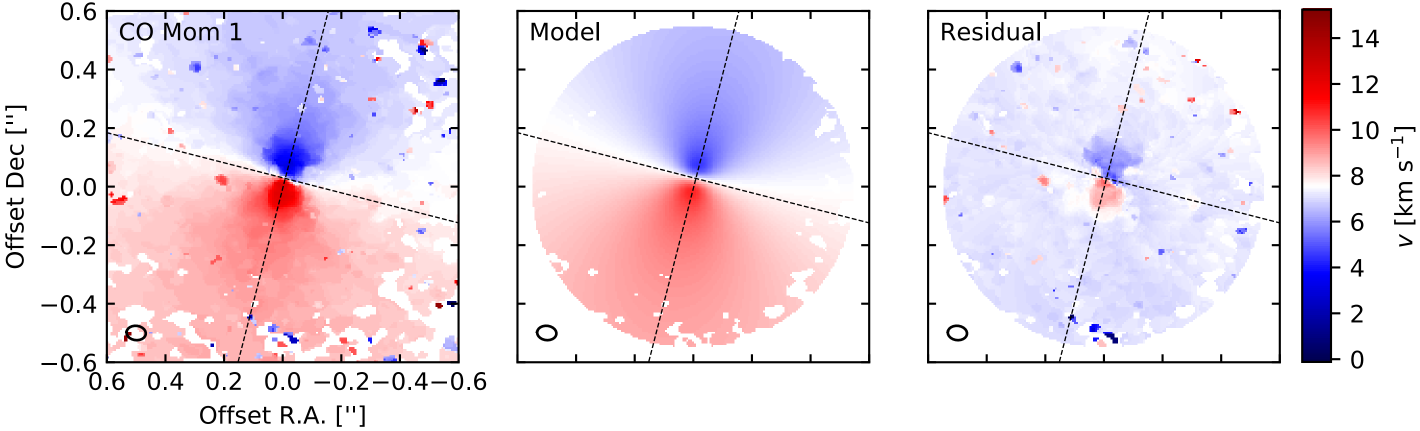




- ✧ Strong depletion of small and large grains in the main gap
- ✧ Radial segregation by particle size in the outer edge of gap; but no gap in gas → dust filtering w/gas can flow in
- ✧ Arc extent changes with wavelength → also consistent with a dust trapping

# What do the new DSHARP observations of HD 143006 tell us?

## Constraints on misaligned inner disk, inaccesible to scattered-light observations

<u>Kinematics</u>: assuming no misalignment, significant residuals remain

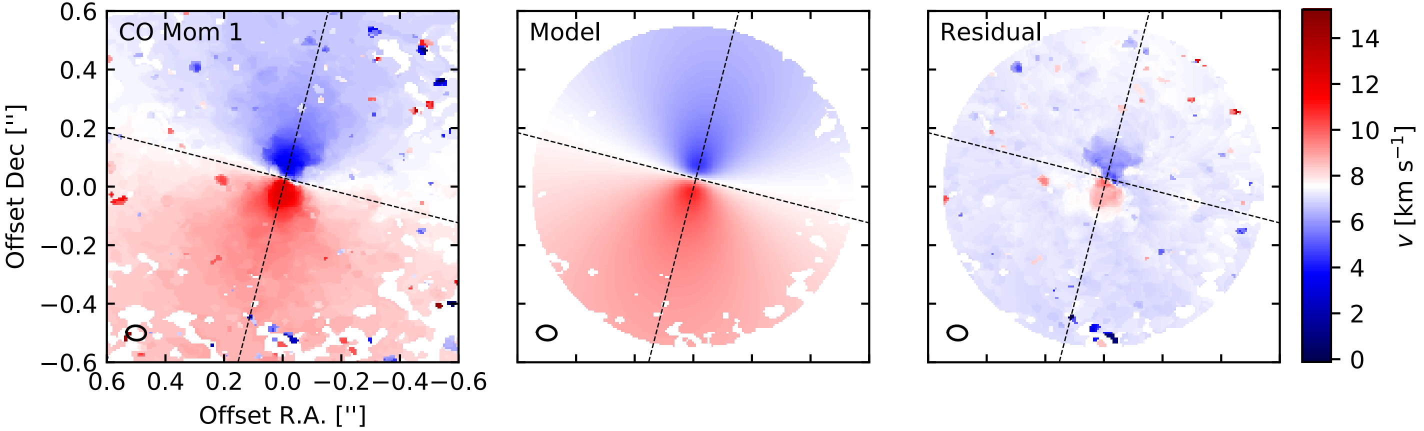



also seen in other disks where kinematics inner disk ≠ outer disk
e.g. Rosenfeld et al. 2012, Casassus et al. 2015, Walsh et al. 2017

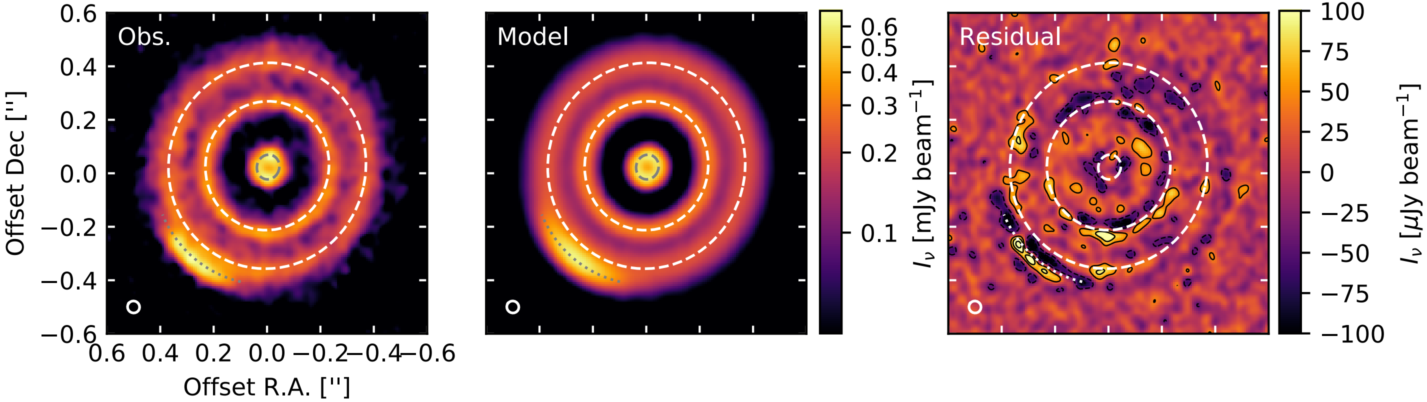
# What do the new DSHARP observations of HD 143006 tell us?

## Constraints on misaligned inner disk, inaccesible to scattered-light observations

**Kinematics**: assuming no misalignment, significant residuals remain

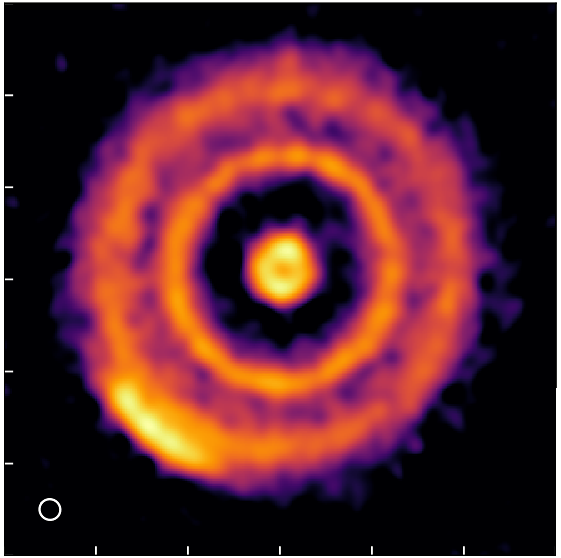


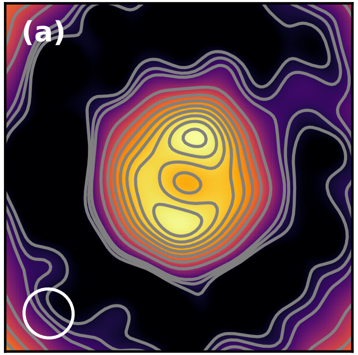

**Solids**: inner disk is misaligned w.r.t. the outer disk (small ~8° or moderate ~41°)

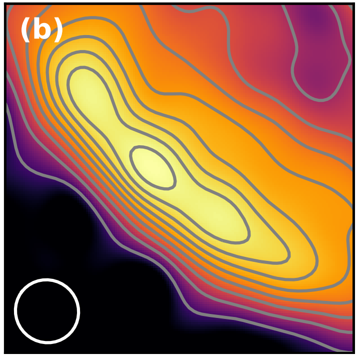


# What do the new DSHARP observations of HD 143006 tell us?

## New information about kinematics and distribution of solids






### Conclusions for HD 143006

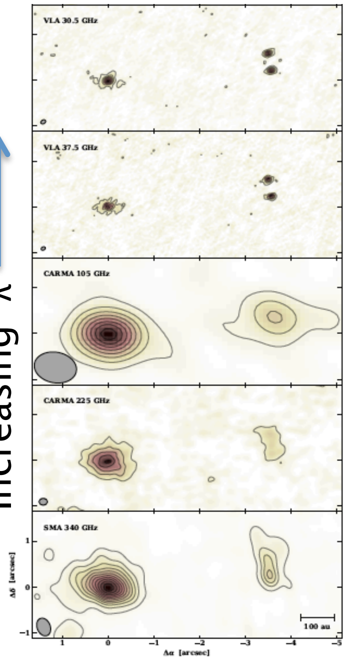
- Inner disk geometry different from outer disk
- Arc-like structure consistent with dust-trapping vortex predictions and has further substructure
- Either small (8°) or moderate (41°) misalignment
- Scattering surface height from shadows in SPHERE image + pressure scale height estimates agree with the 41° misalignment → predictions for inner disk to appear counterotating w.r.t. outer disk at high enough resolution

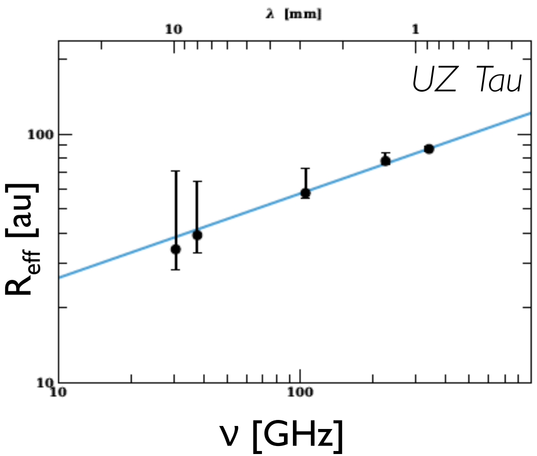
# A current great barrier: some disagreement persist between grain growth tracers

## e.g. dust continuum results vs. polarization results

### Disks get "smaller" with increasing $\lambda$

Increasing $\lambda$

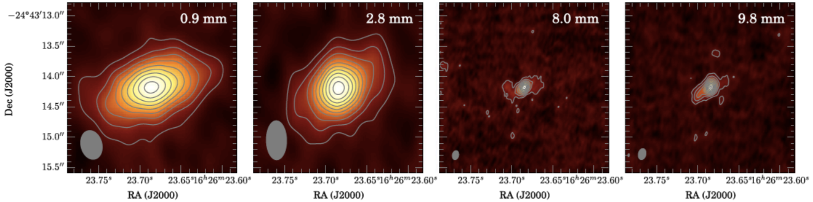


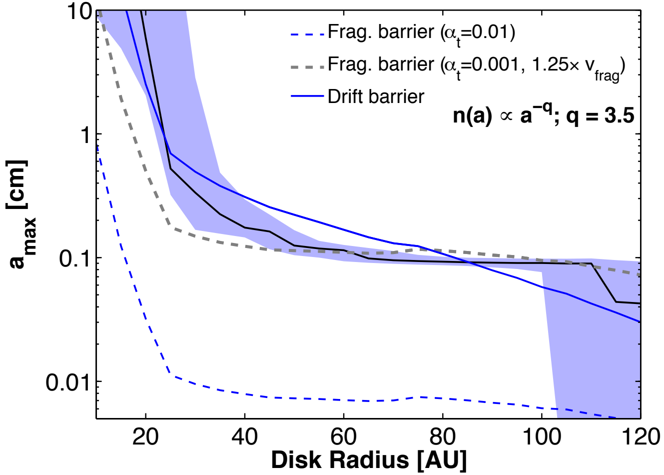




e.g. Tripathi et al. 2018
(see also Powell et al. 2019)

### Particles get "bigger" with decreasing R

Increasing λ



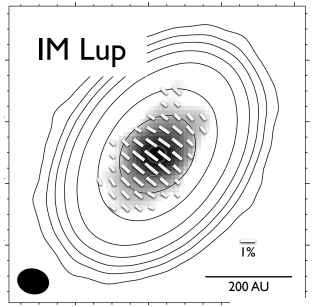



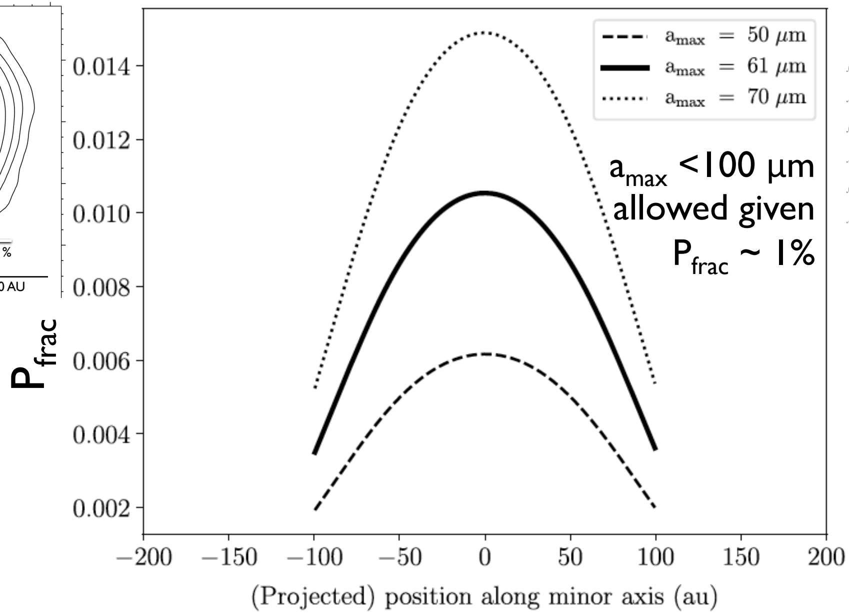

e.g. Pérez et al. 2015

# A current great barrier: some disagreement persist between grain growth tracers

## e.g. dust continuum results vs. polarization results

### But polarization results appear preclude larger particles



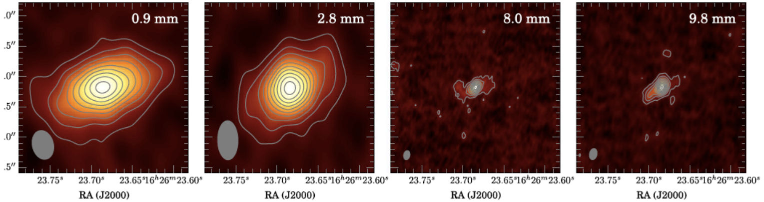



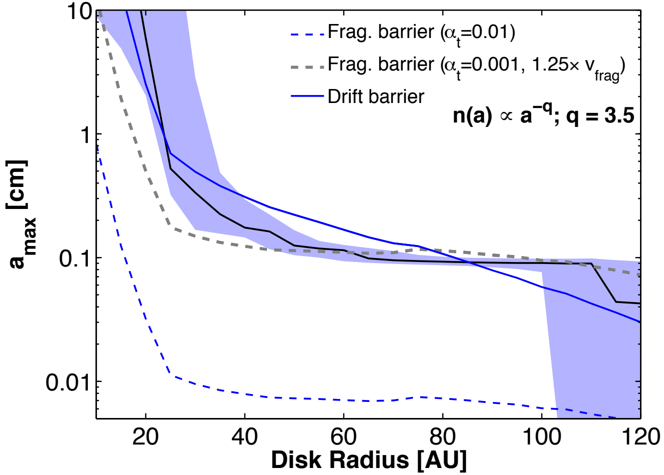

Hull et al. 2018

... more on this issue in Ohashi and Kataoka's talk

### Particles get "bigger" with decreasing R

Increasing λ



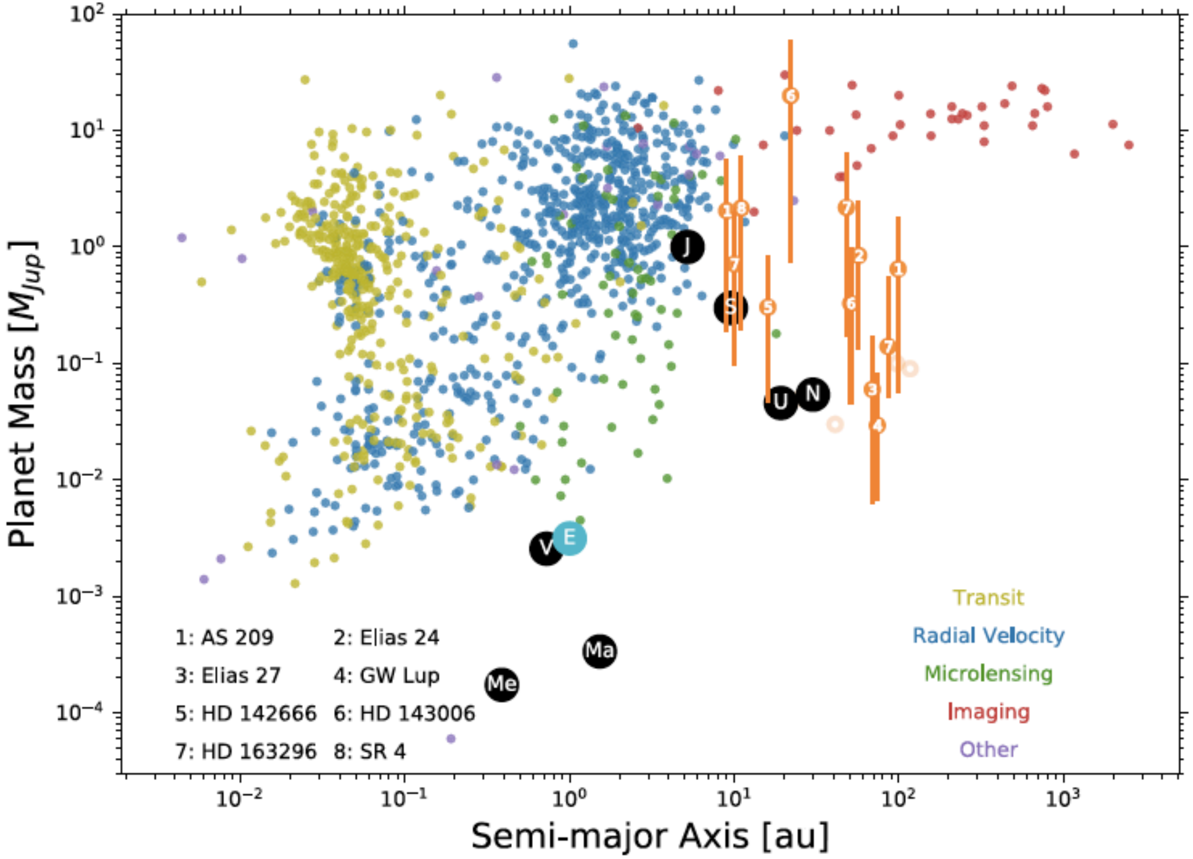




e.g. Pérez et al. 2015

# Overcoming some barriers: figure out what is the origin of the observed substructure

Both theoretical + observational studies will be critical

Hydro simulations compared to well-resolved gaps → infer perturber mass

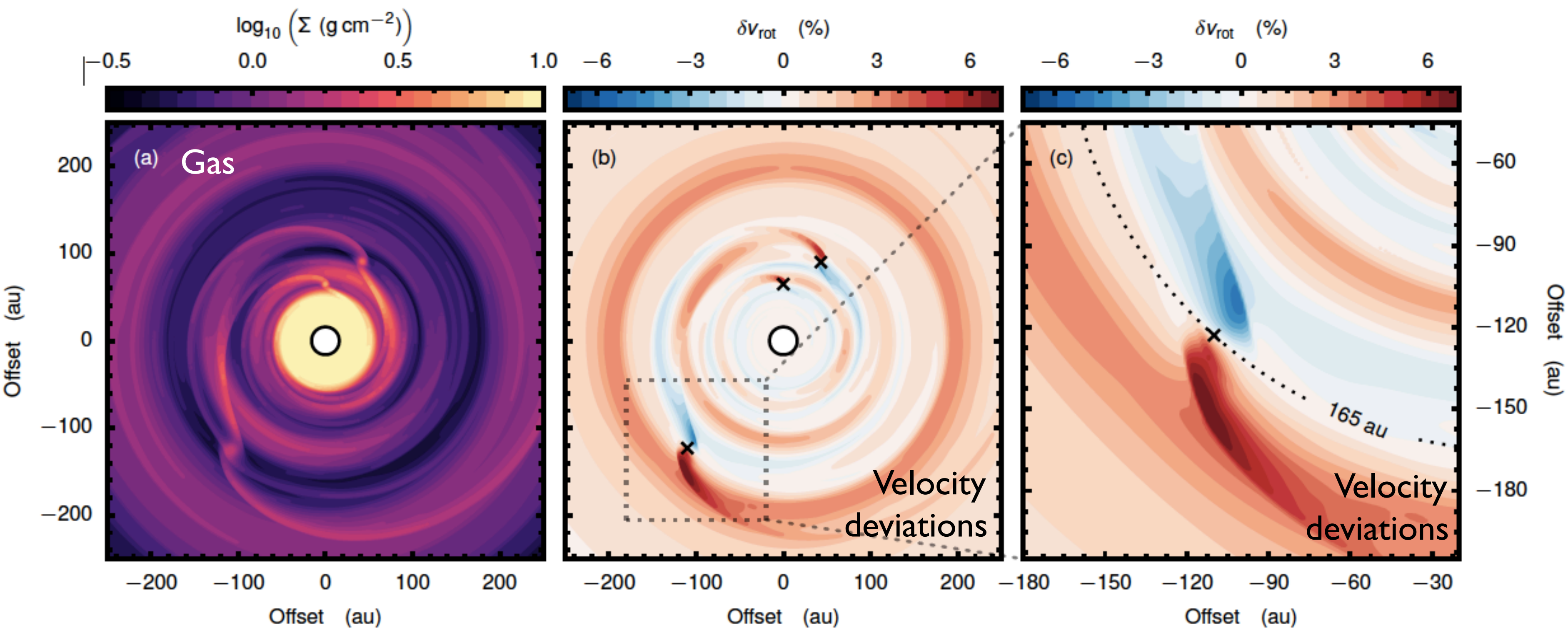



Zhang et al. 2018
see also:
Lodato et al. 2019

# Overcoming some barriers: figure out what is the origin of the observed substructure

## If substructure is caused by planets, we better search for them

Detections of deviations from Keplerian motion → infer perturber mass

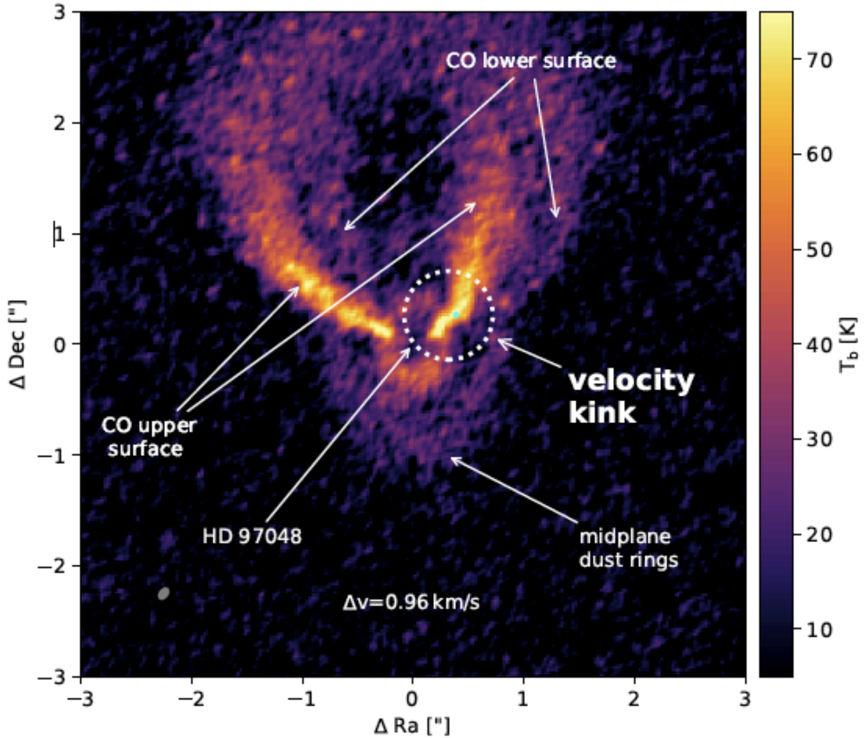



Teague et al. 2018 (see also S. Perez et al. 2015)

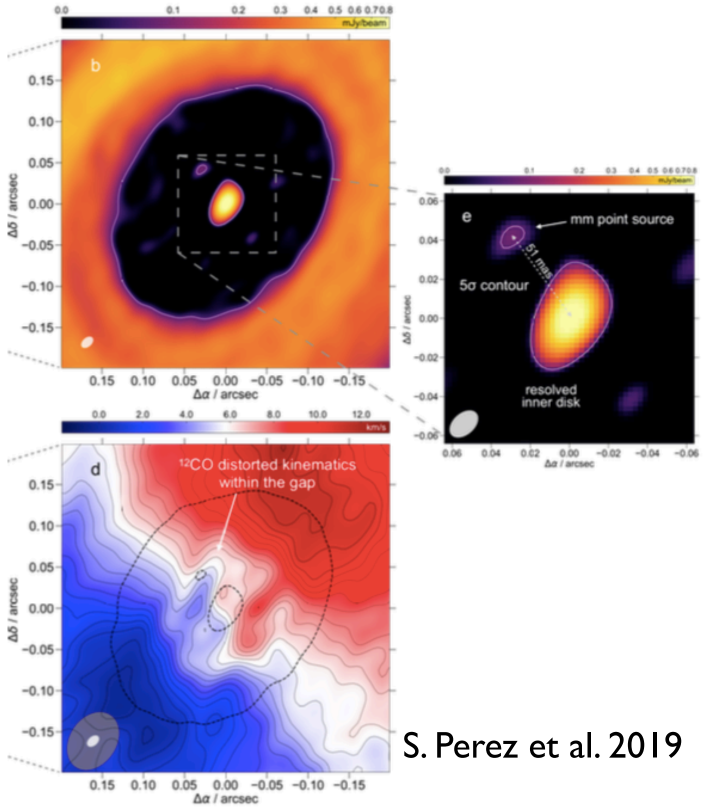
# Overcoming some barriers: figure out what is the origin of the observed substructure

## If substructure is caused by planets, we better search for them

Detections of deviations from Keplerian motion → infer perturber mass




Pinte et al. 2019

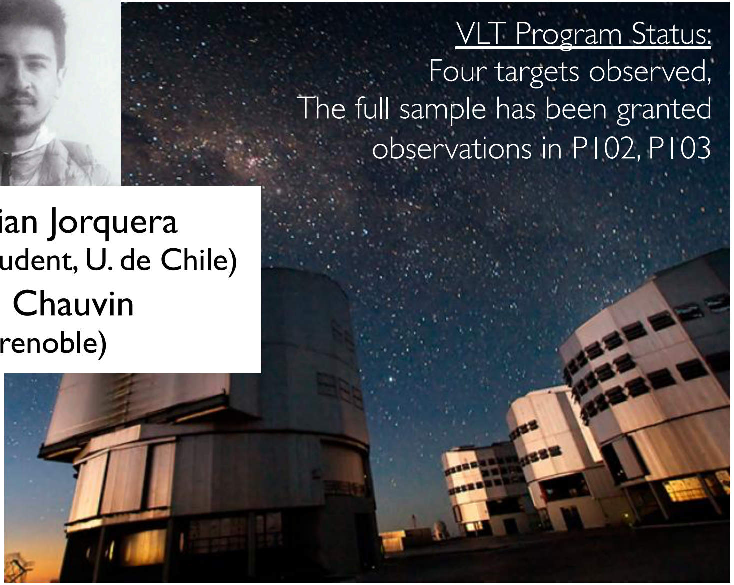



S. Perez et al. 2019

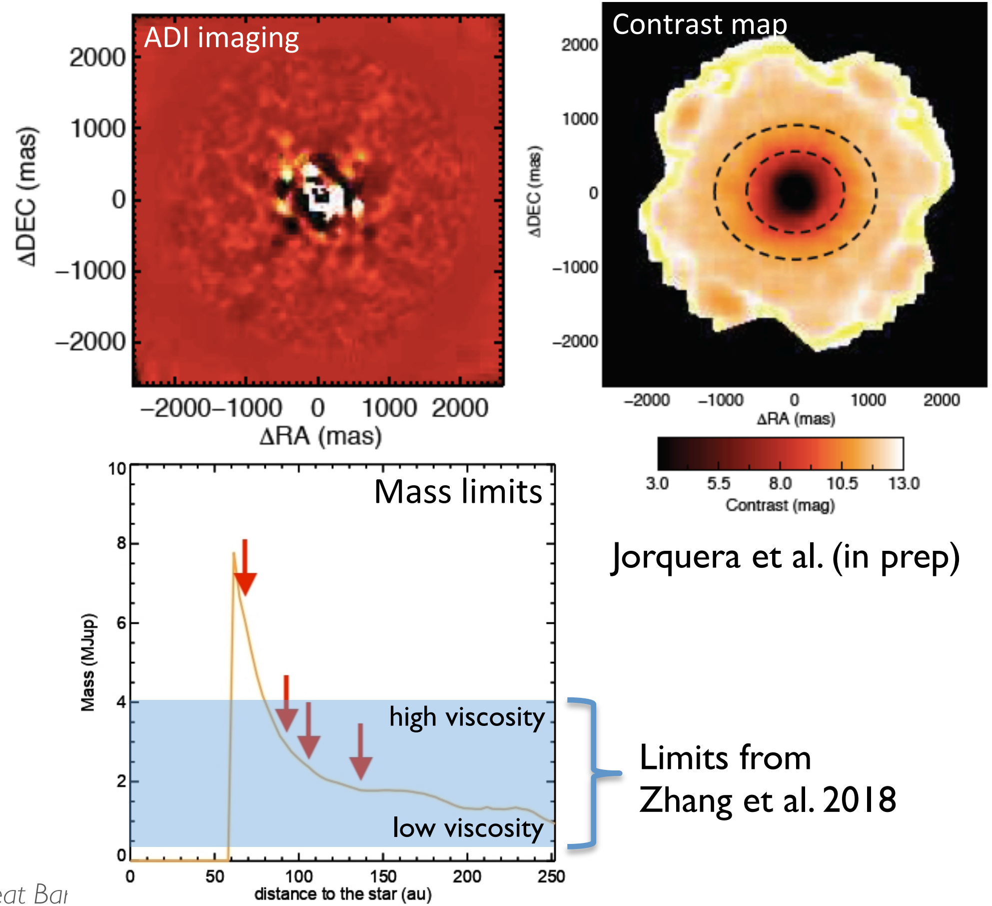
# Overcoming some barriers: figure out what is the origin of the observed substructure

If substructure is caused by planets, we better search for them

Sebastian Jorquera
(MSc Student, U. de Chile)
+ Gael Chauvin
(UMI/Grenoble)




NACO L' observations to check for companions creating substructure
(PI: L. Pérez)




Jorquera et al. (in prep)

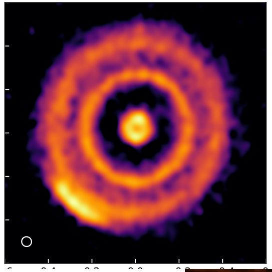
Limits from Zhang et al. 2018

# Overcoming some barriers: figure out what is the origin of the observed substructure

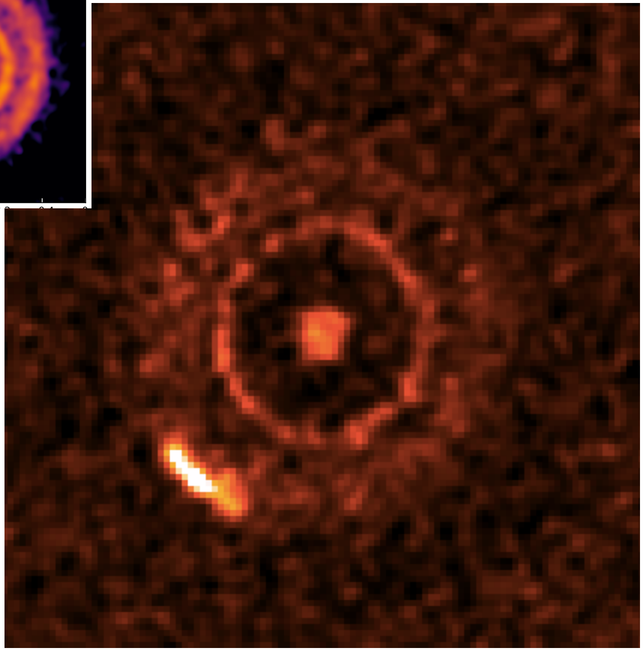
If substructure is caused by planets, we better search for their trapping …


Cycle 5-6 ALMA observations at 3mm to check for dust trapping in substructure
(PI: L. Pérez)

1.3mm



3mm



(ALMA delivery images, not final!)

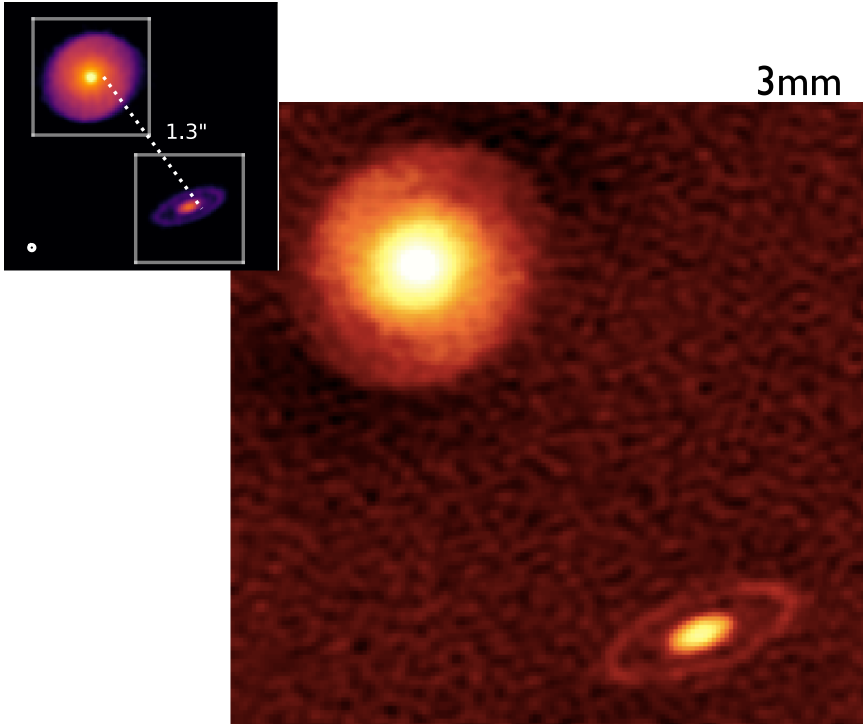
# Overcoming some barriers: figure out what is the origin of the observed substructure

## If substructure is caused by planets, we better search for their trapping …


Cycle 5-6 ALMA observations at 3mm to check for dust trapping in substructure (PI: L. Pérez)

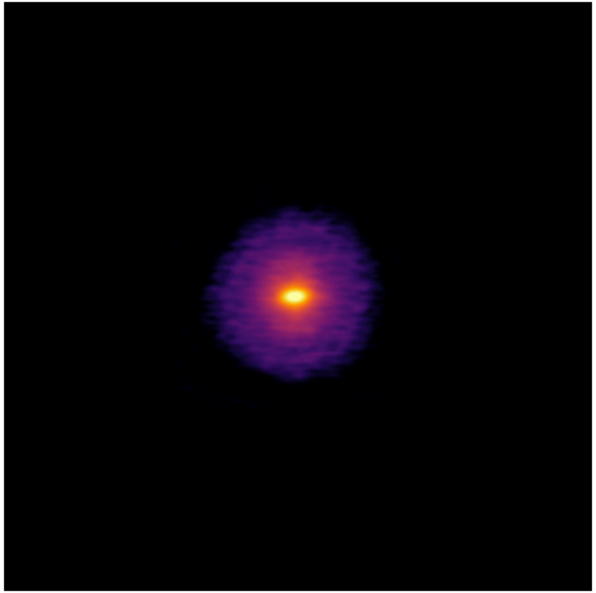
1.3mm

3mm




(ALMA delivery images, not final!)

# Some final thoughts and questions…



*Disks on the same physical scale*

*DSHARP disks. Credit: ALMA (ESO/NAOJ/ NRAO), Andrews et al.; N. Lira.*

One of the *great barriers* to our understanding of the process of planet formation has been (*roughly*) overcome:

→ Resolution and sensitivity at multiple wavelengths is within reach with ALMA & latest near IR instruments:

- ✧ but what about substructure in the gas?
- ✧ or substructure in fainter disks?
- ✧ or substructure in smaller disks?
- ✧ or substructure in younger disks?
- ✧ or substructure in transitional disks?

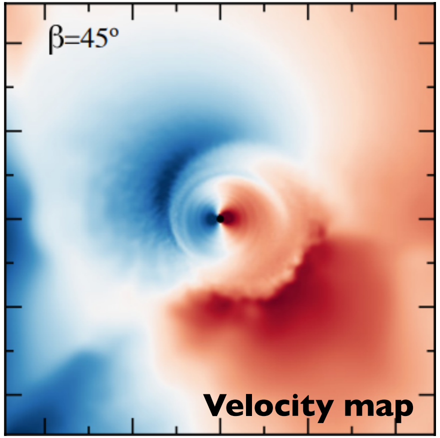
While other *great barriers* to our understanding of the process of planet formation remain:

→ what is the real optical depth in these objects?
→ how far does grain growth has proceeded?
→ what causes the observed substructure?

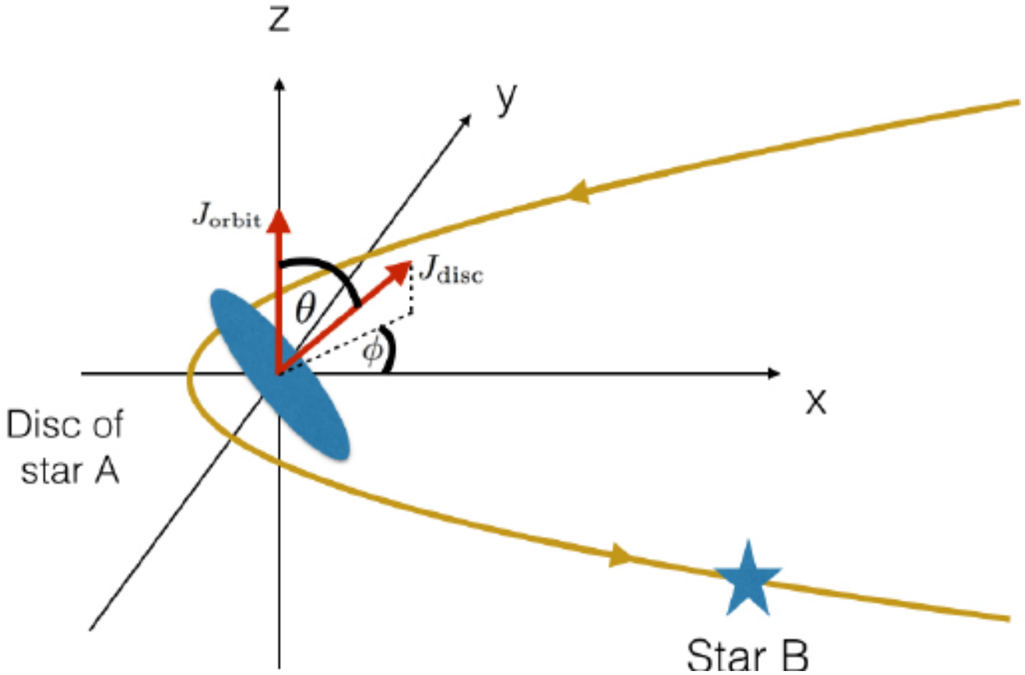
# AS 205 Substructures in the disks aroung *Multiple* young stellar systems

CO (J = 2-1) Multiplicity also reflected in kinematics, possible fly-by evidence?

Prograde interaction
(Cuello et al. 2019)

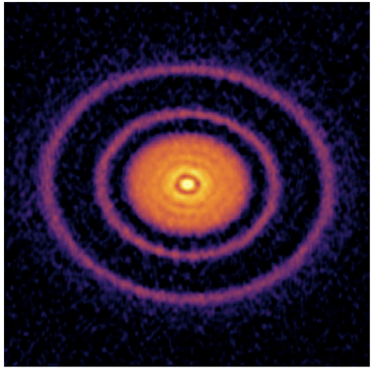


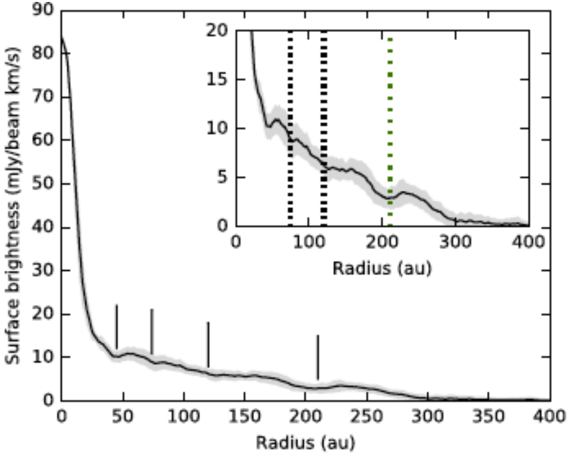

***Prograde*** encounter



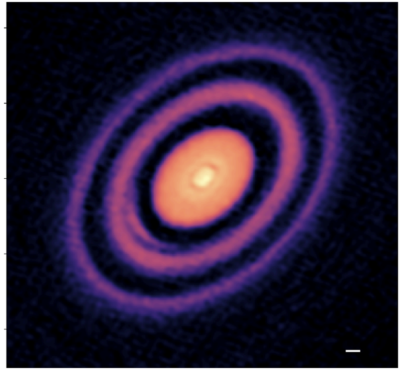
# Detailed studies on interesting targets show different degrees of complexity

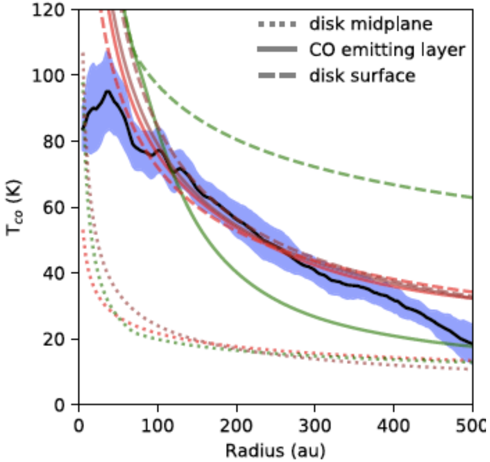
AS 209: Guzmán et al. 2018



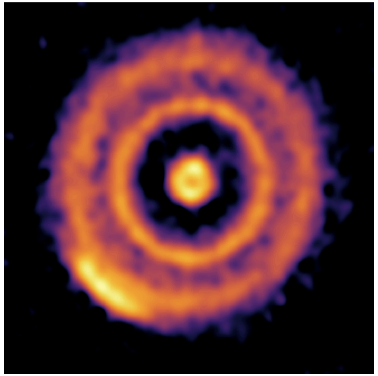


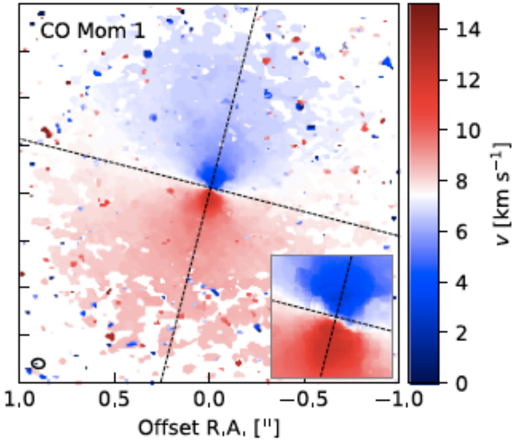

HD 163296: Isella et al. 2018

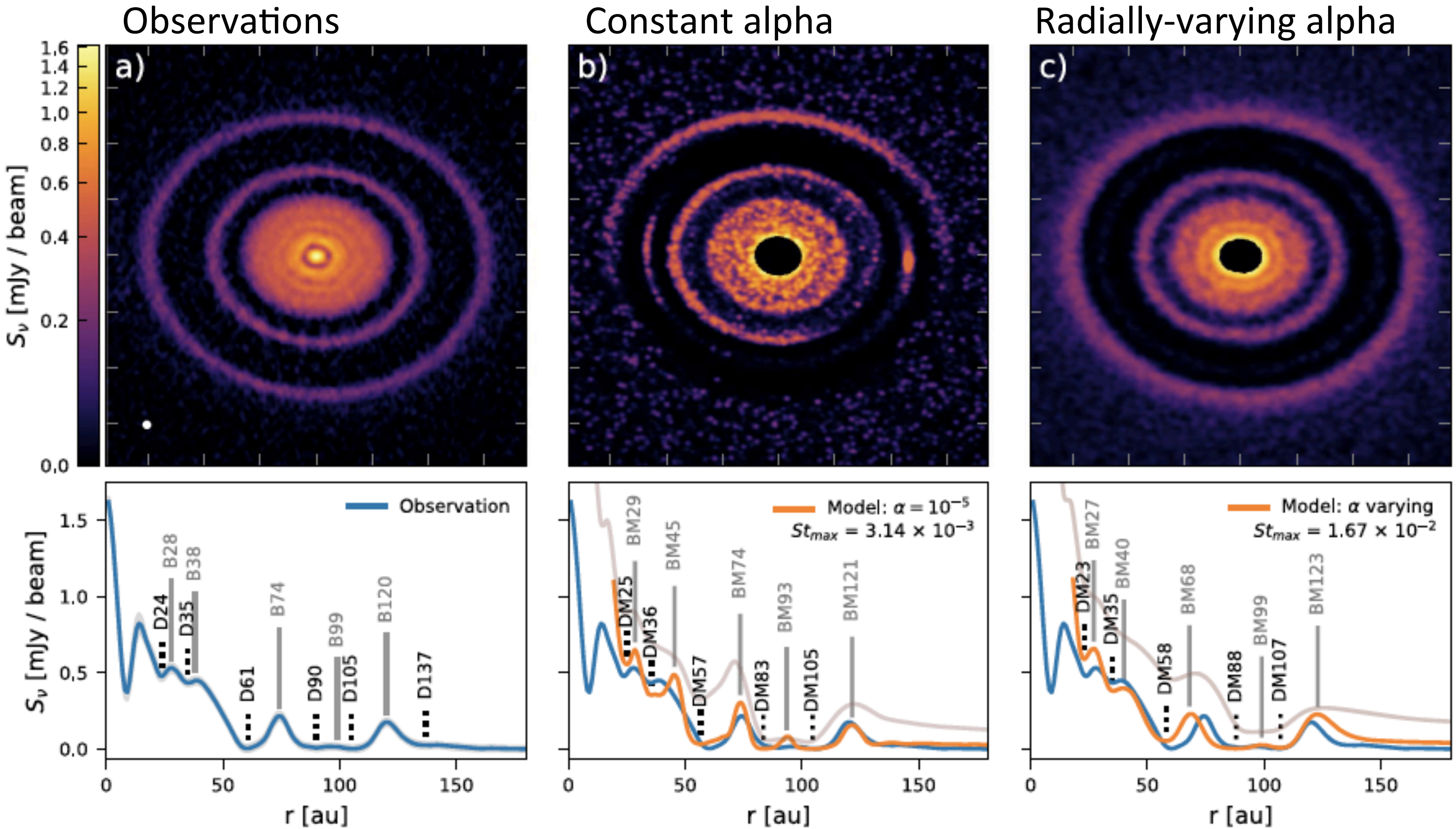





HD 143006: Pérez et al. 2018







Observations
Constant alpha
Radially-varying alpha
a)
b)
c)
$S_\nu$ [mJy / beam]
Observation
Model: $\alpha = 10^{-5}$
$St_{max}$ = 3.14 × $10^{-3}$
Model: $\alpha$ varying
$St_{max}$ = 1.67 × $10^{-2}$
D24
B28
D35
B38
D61
B74
D90
B99
D105
B120
D137
DM25
BM29
DM36
BM45
DM57
BM74
DM83
BM93
DM105
BM121
DM23
BM27
DM35
BM40
DM58
BM68
DM88
BM99
DM107
BM123
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