Chemical and physical structure of planet hosting disks

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Collaborators:
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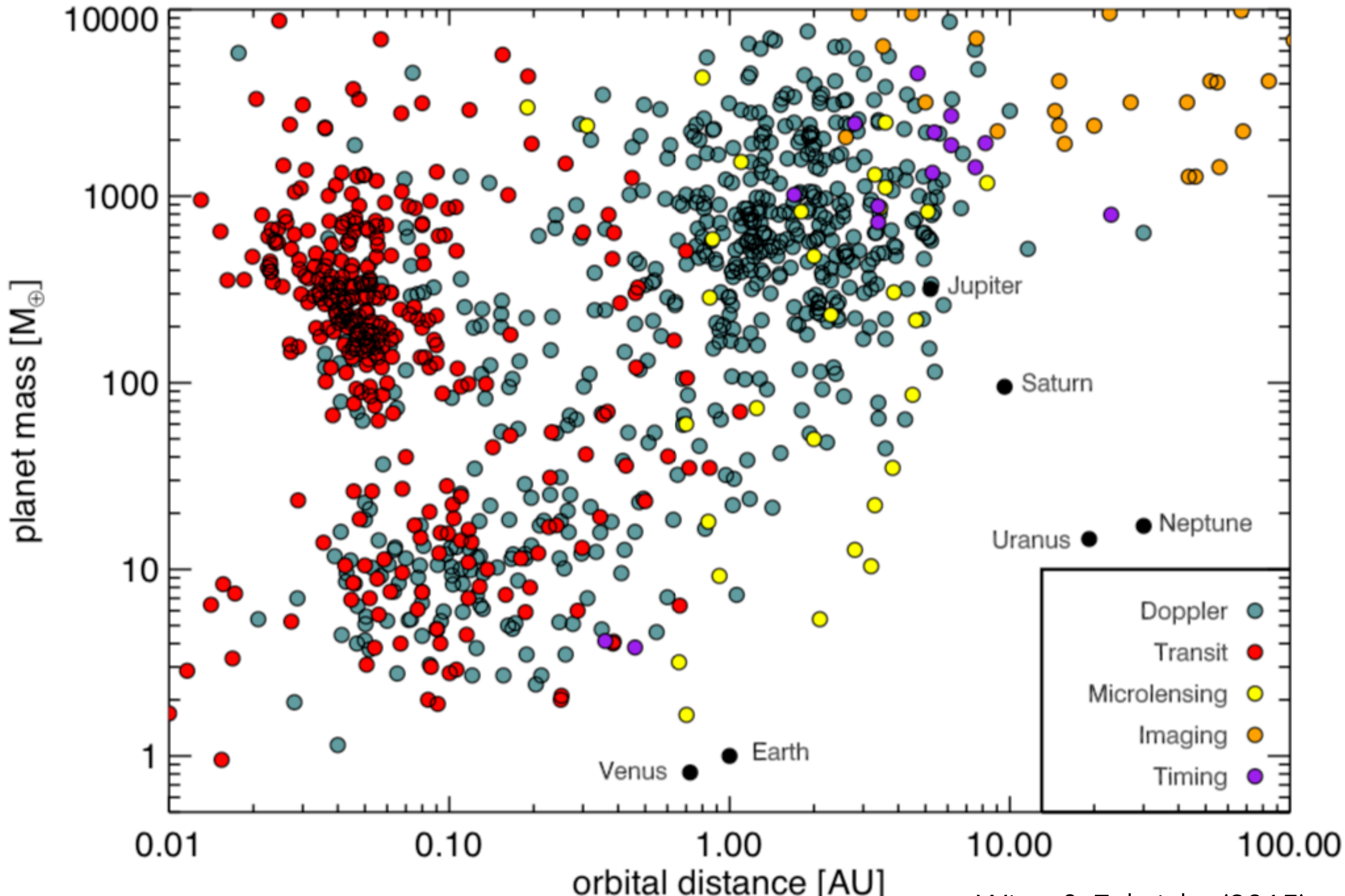
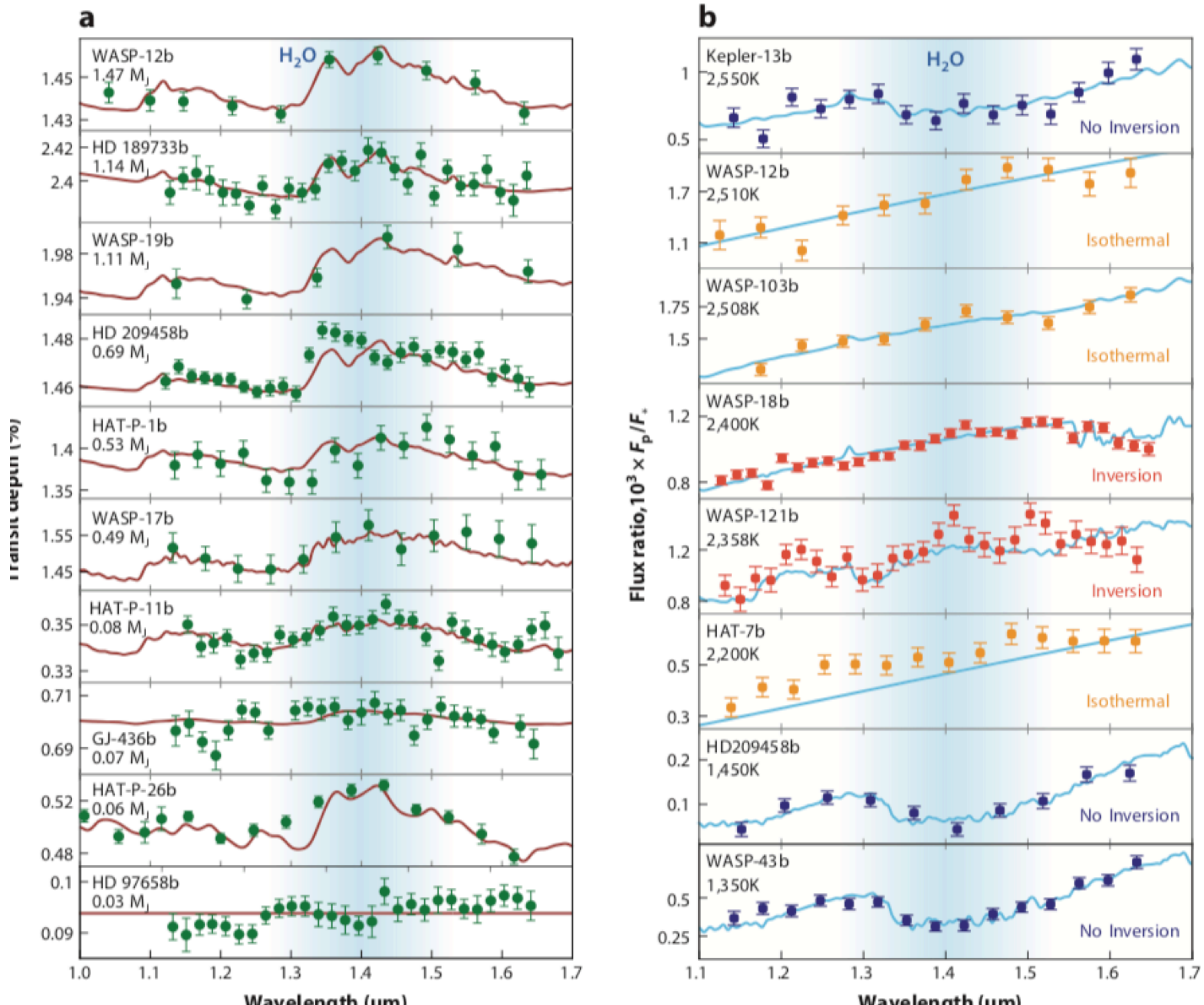
Miriam Keppler, Ryan Loomis, Richard Teague, Leonardo
Testi, Ewine van Dishoeck, Lisa Wölfer and others

Huge leap forward in exoplanet demographics



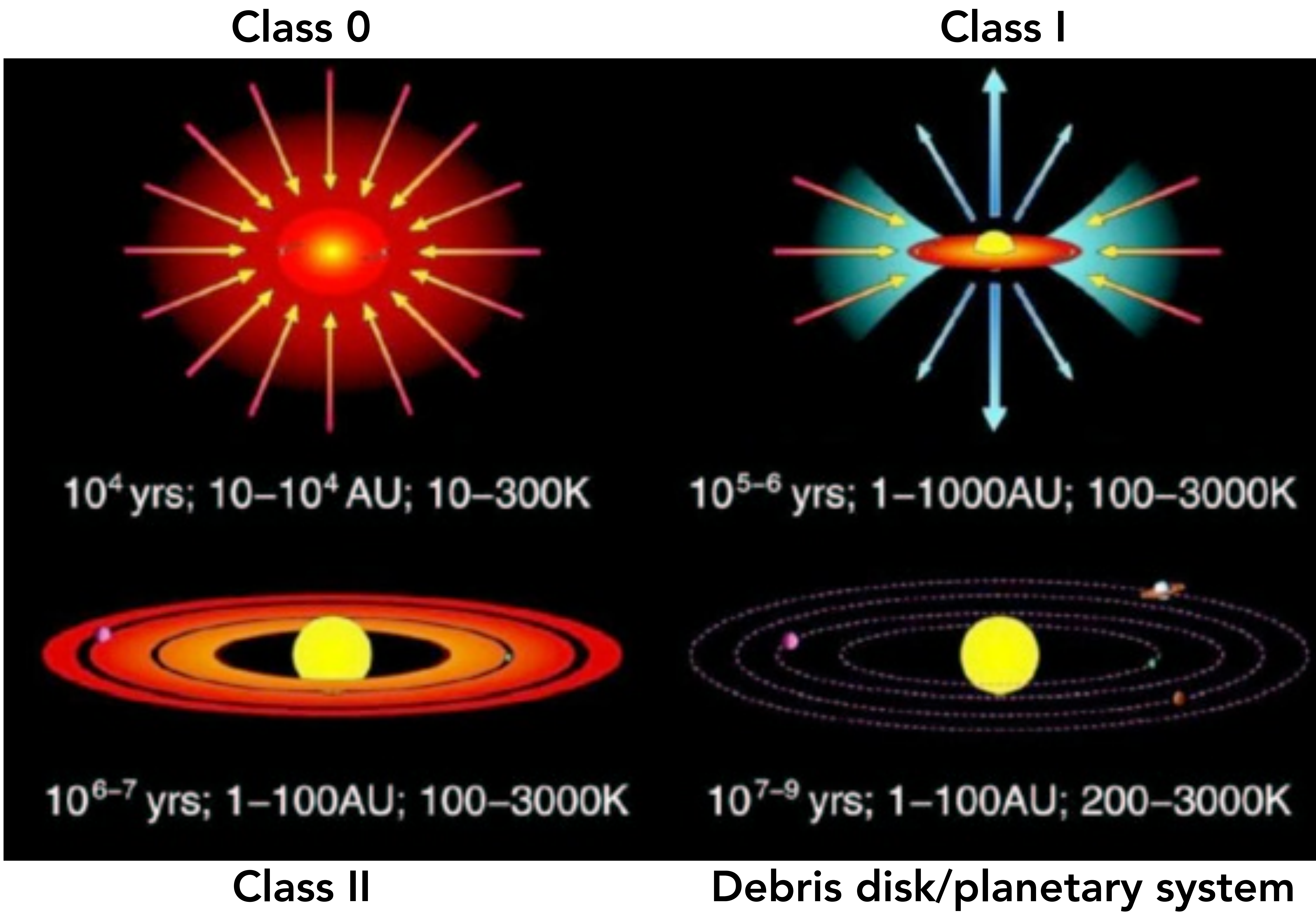
Winn & Fabricky (2015)

Huge leap forward in exoplanet characterization

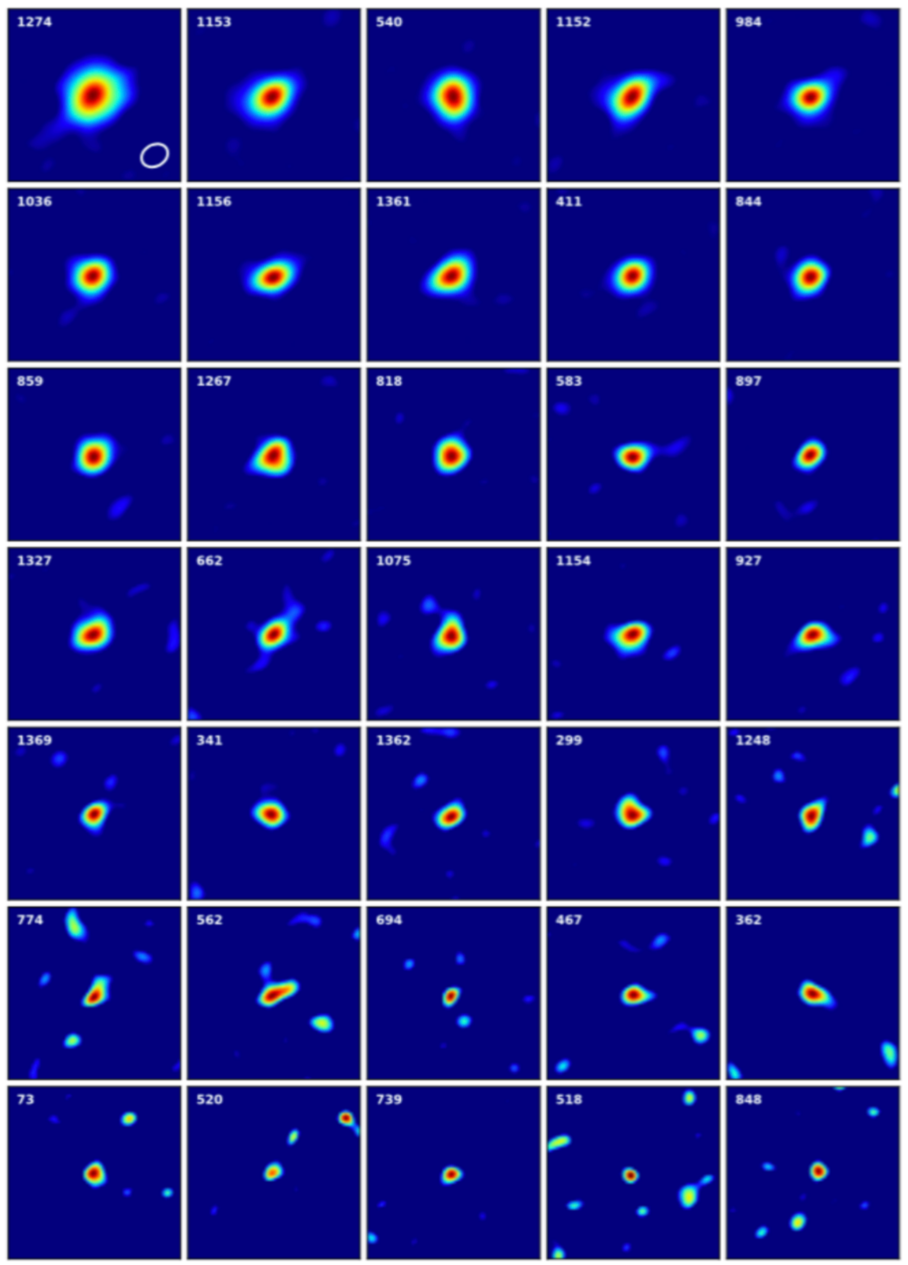


Madhusudhan (2019)

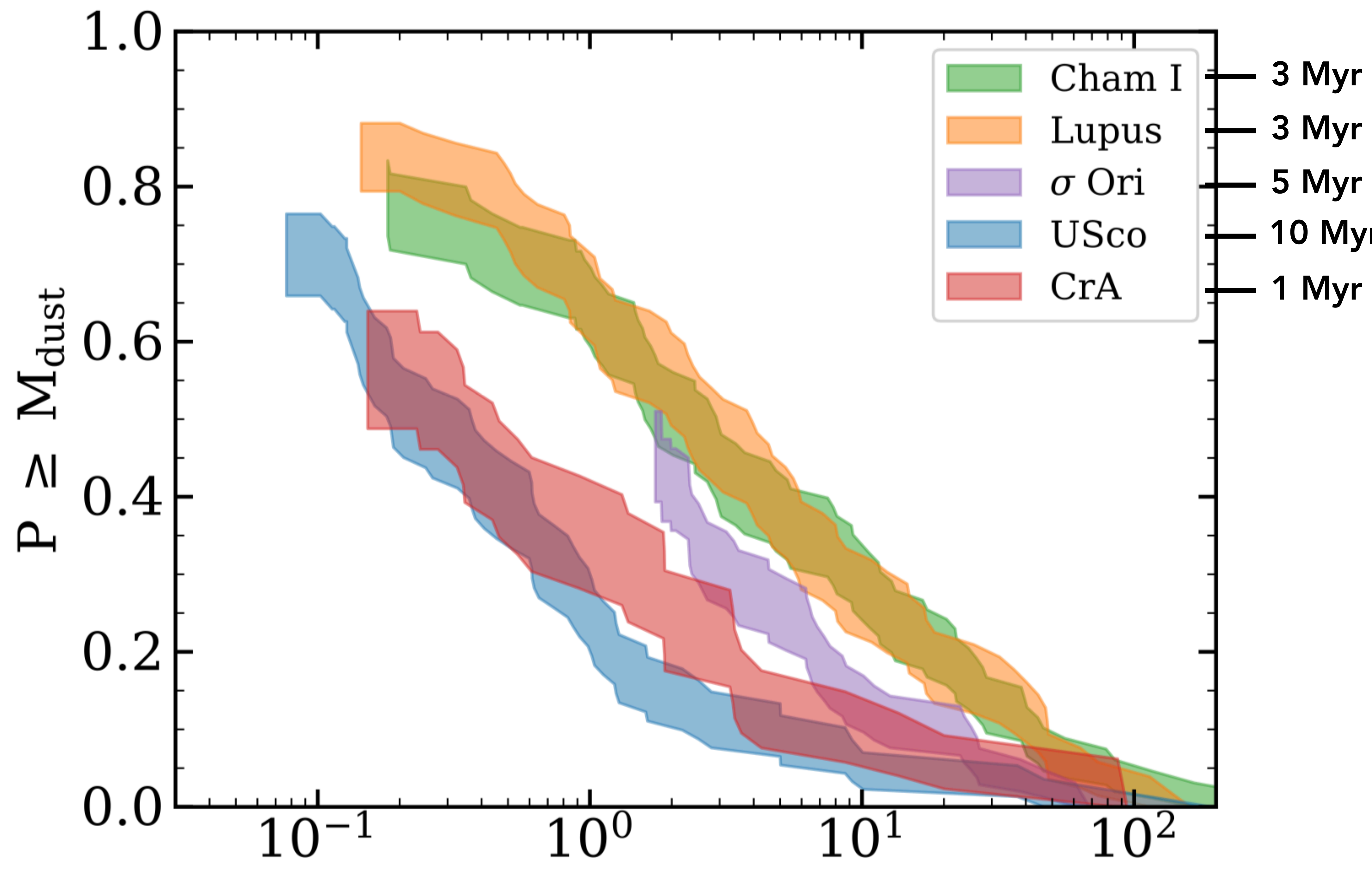
Evolutionary stages of protoplanetary disks



Disk surveys



Ansdell, …, SF+2017



Cazzoletti, …, SF+2019

Surveys of close by star forming regions provide statistical properties of planet forming (hosting?) disks

High resolution images

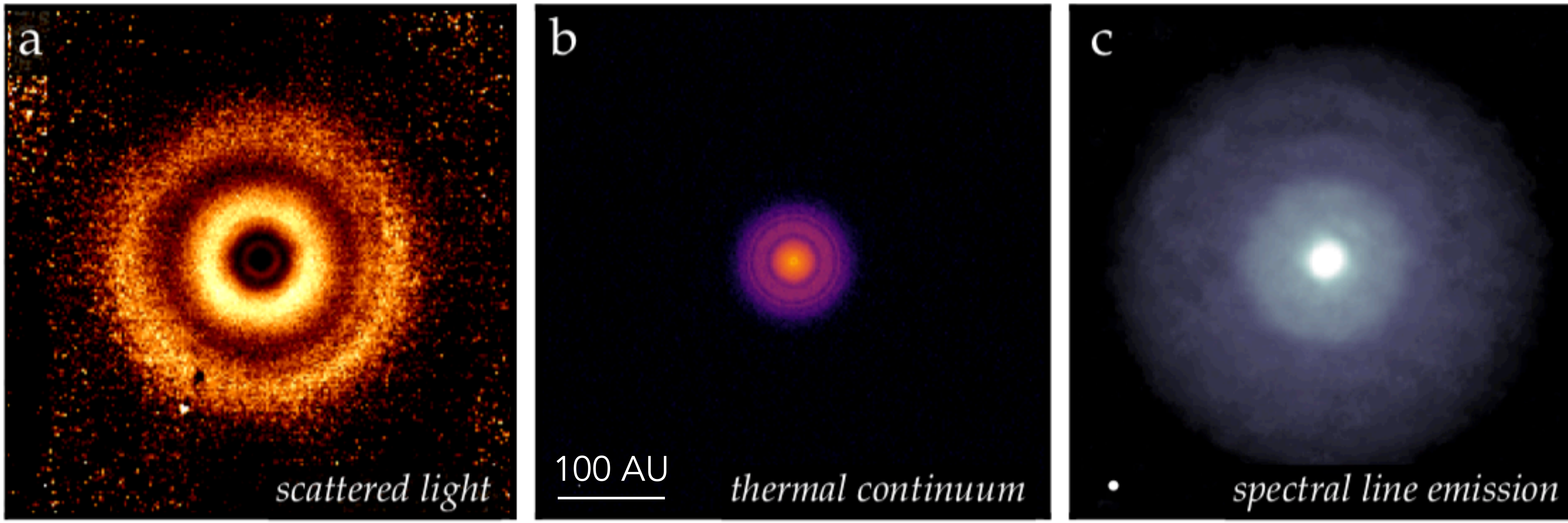
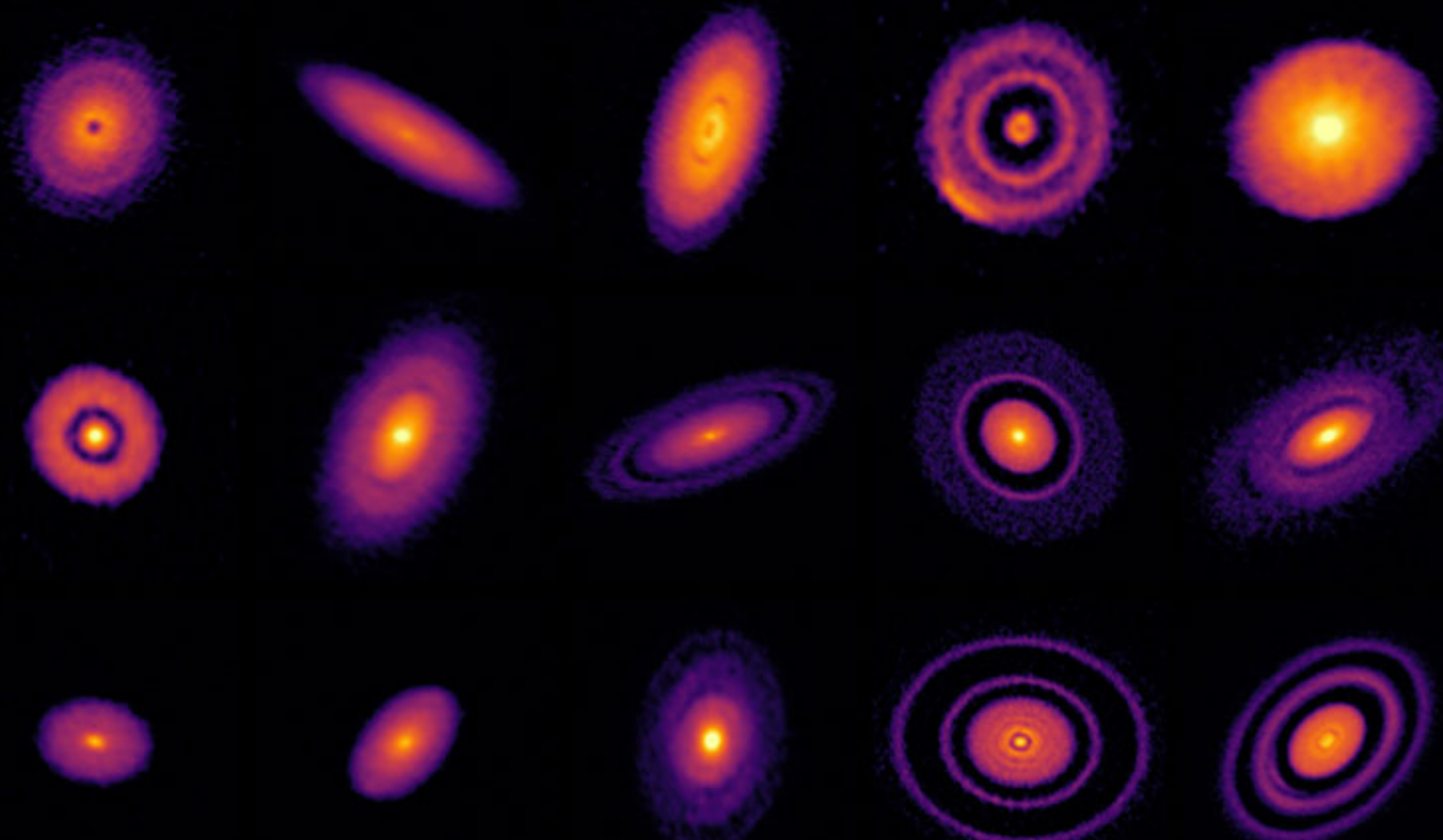


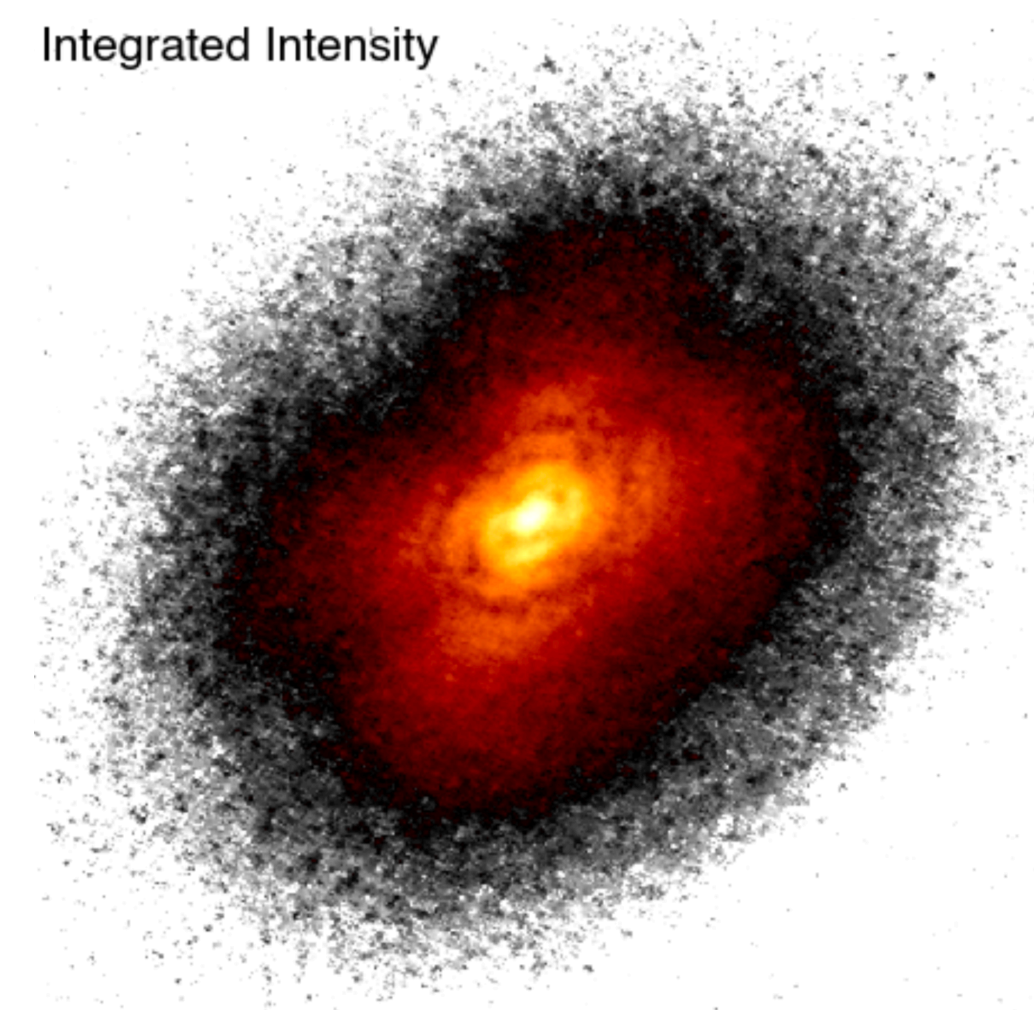
Image from Andrews 2020, data from Andrews+2016, van Boeckel+2017, Huang+2018

View of planet forming regions down to ~ few AU scales, ~10-15 AU in gas



Andrews+2018

Disks and protoplanets co-evolve

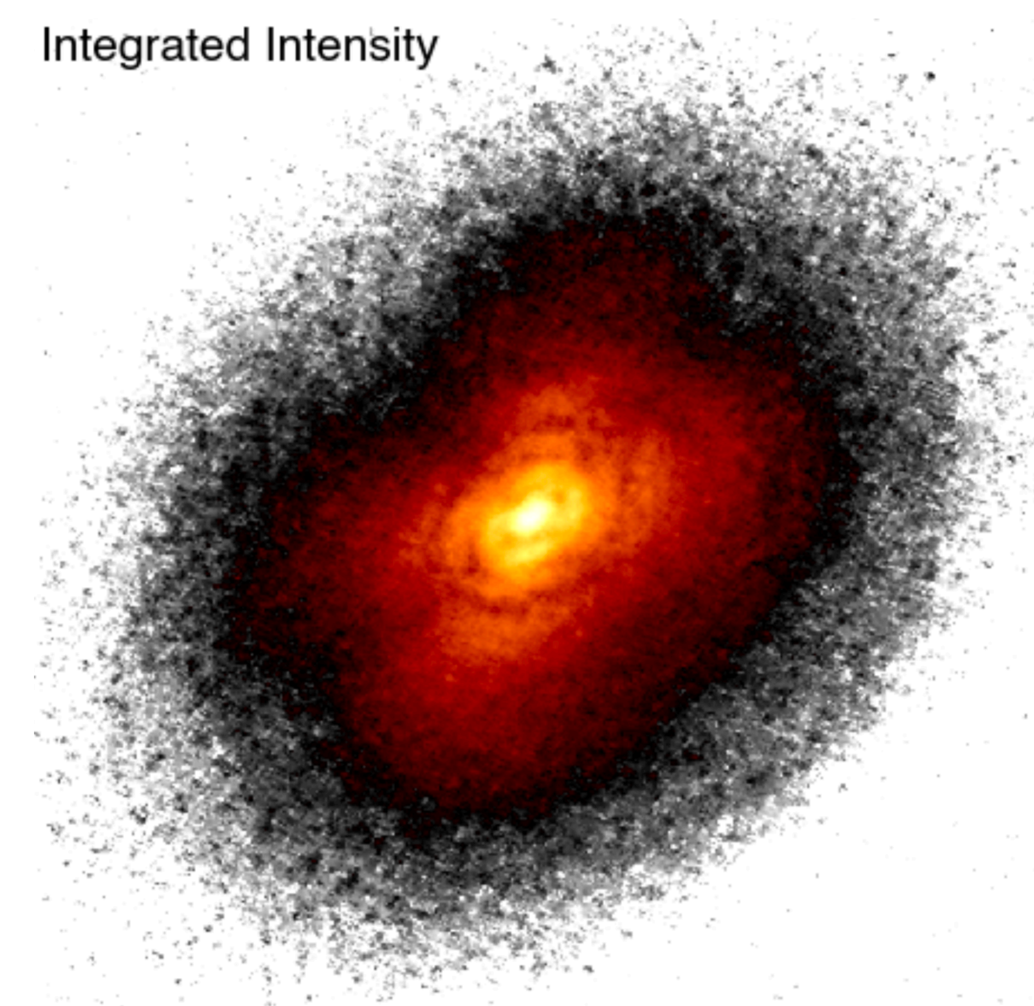


Disk Dynamics Collaboration+2020

Data from Isella+2018

Disks and protoplanets co-evolve

Structure
Ionisation
Dynamics
Accretion



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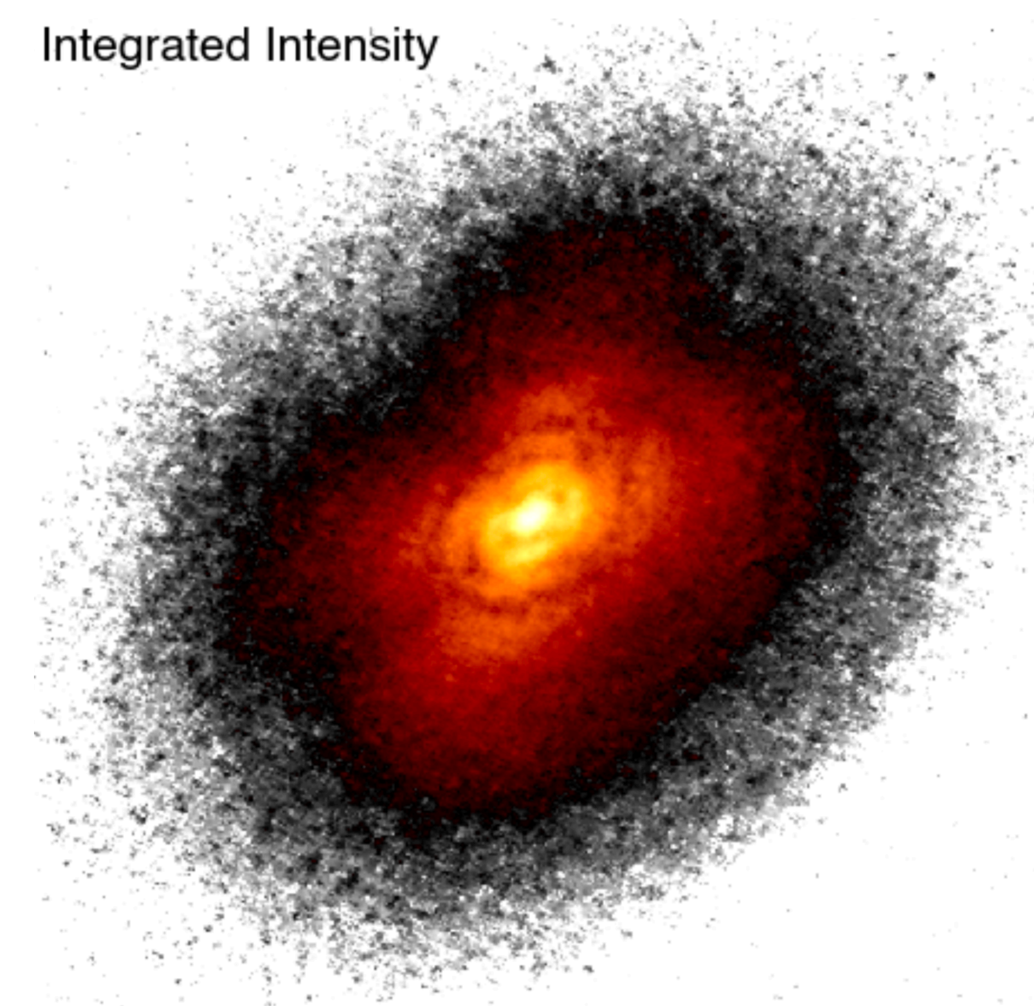

Disk Dynamics Collaboration+2020
Data from Isella+2018

Mass
Orbital radius
Chemical composition
Multiplicity

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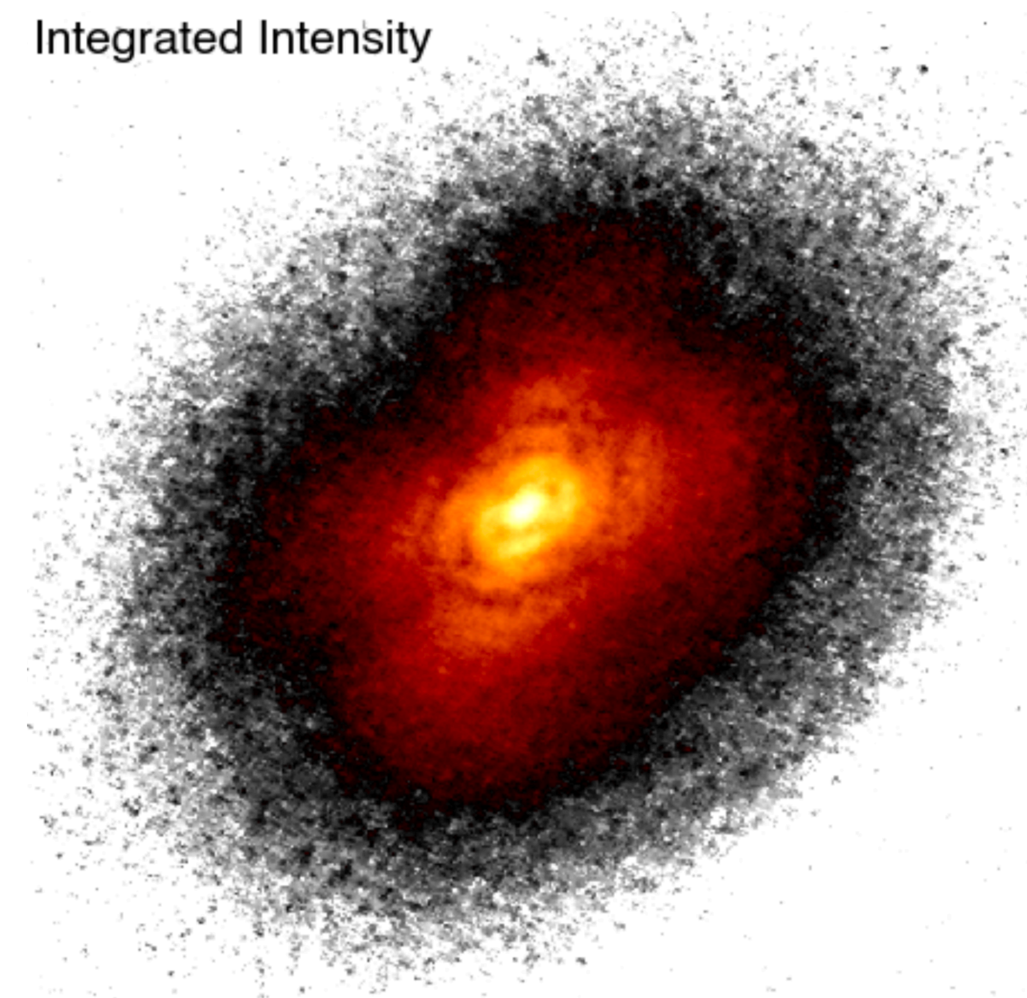
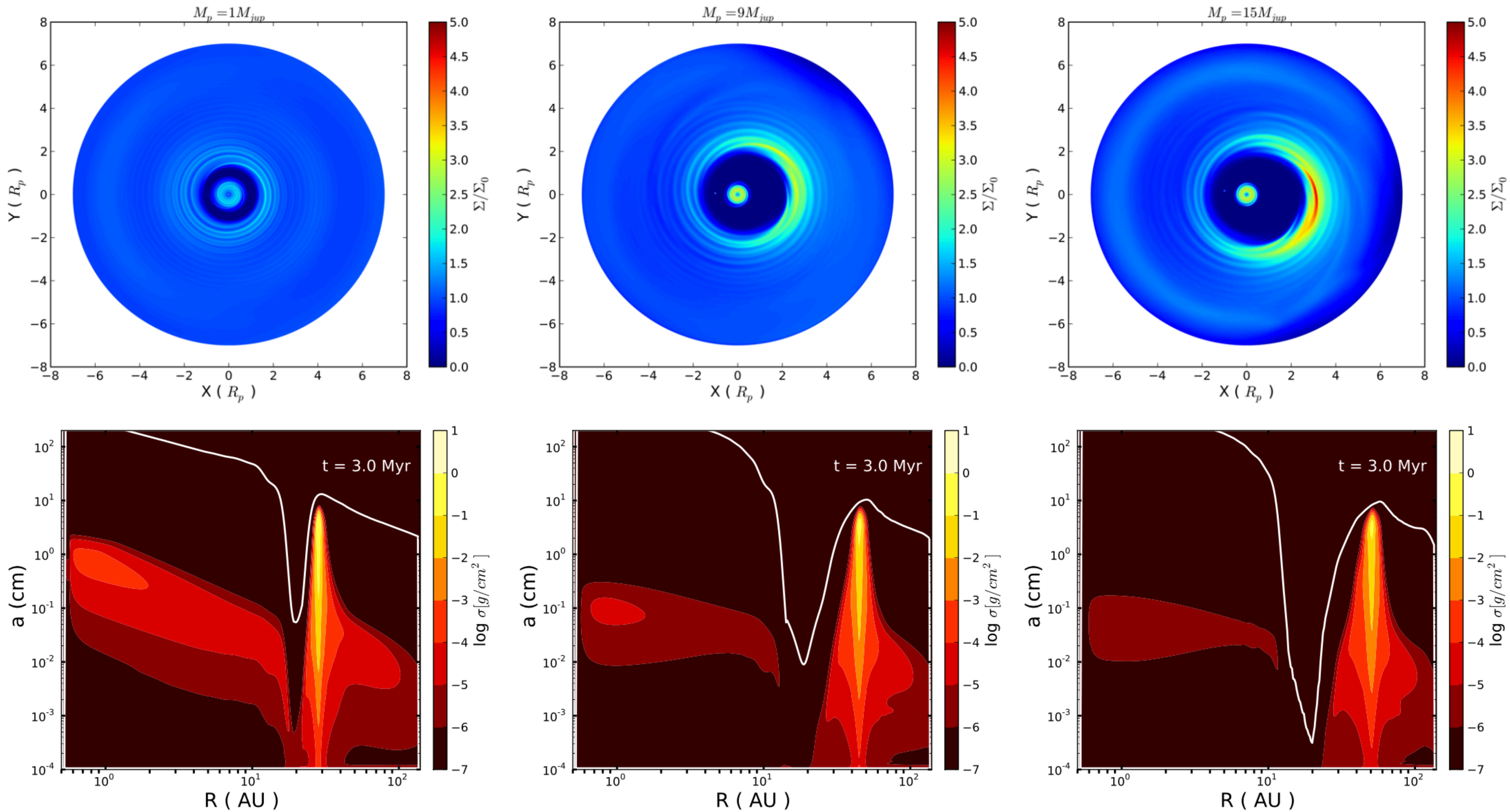


Disk Dynamics Collaboration+2020
Data from Isella+2018

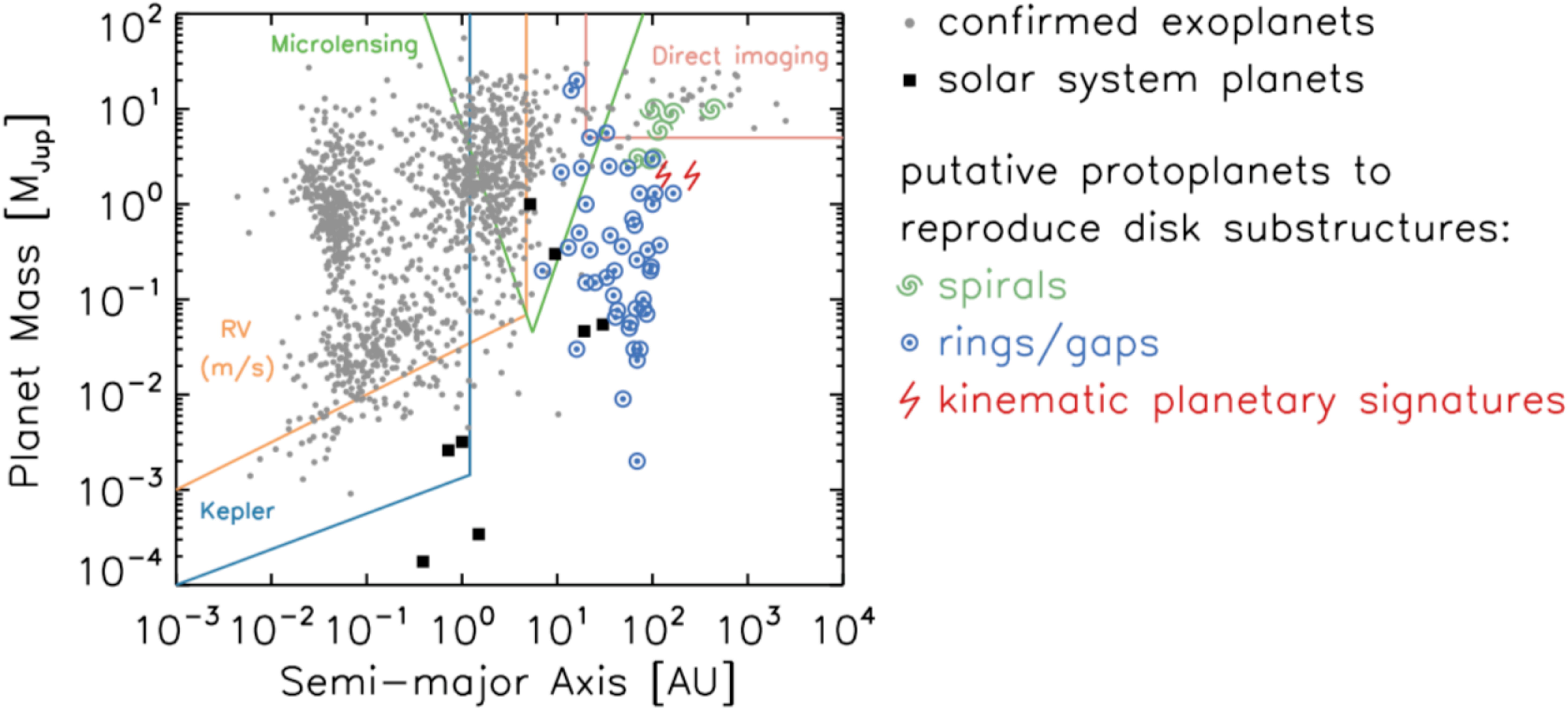
Mass
Orbital radius
Chemical composition
Multiplicity

Massive planets are expected to create massive traps



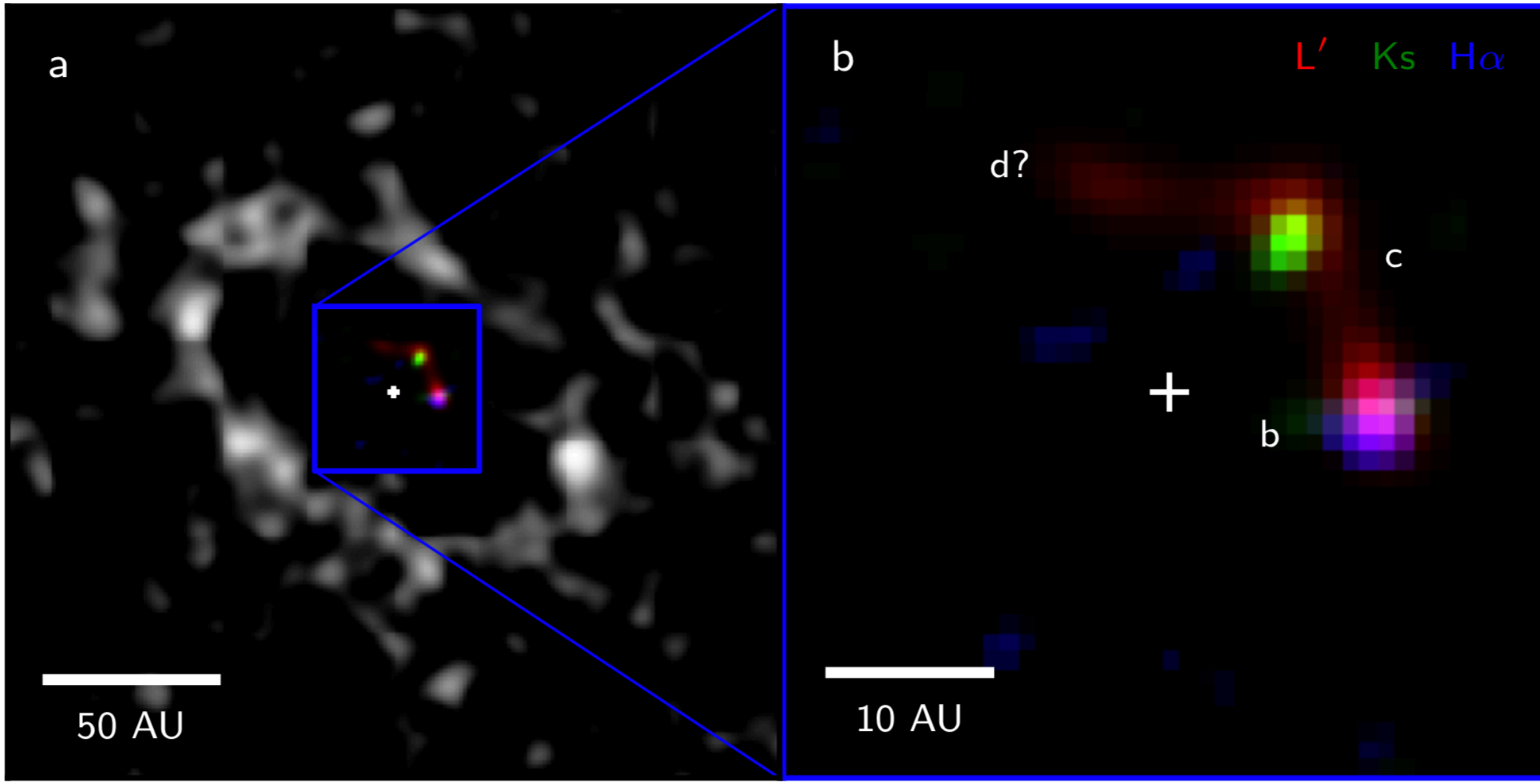
De Juan Ovelar+2013

Within this assumption, growing planet population can be derived



Disk Dynamics Collaboration+2020, Bae+2019

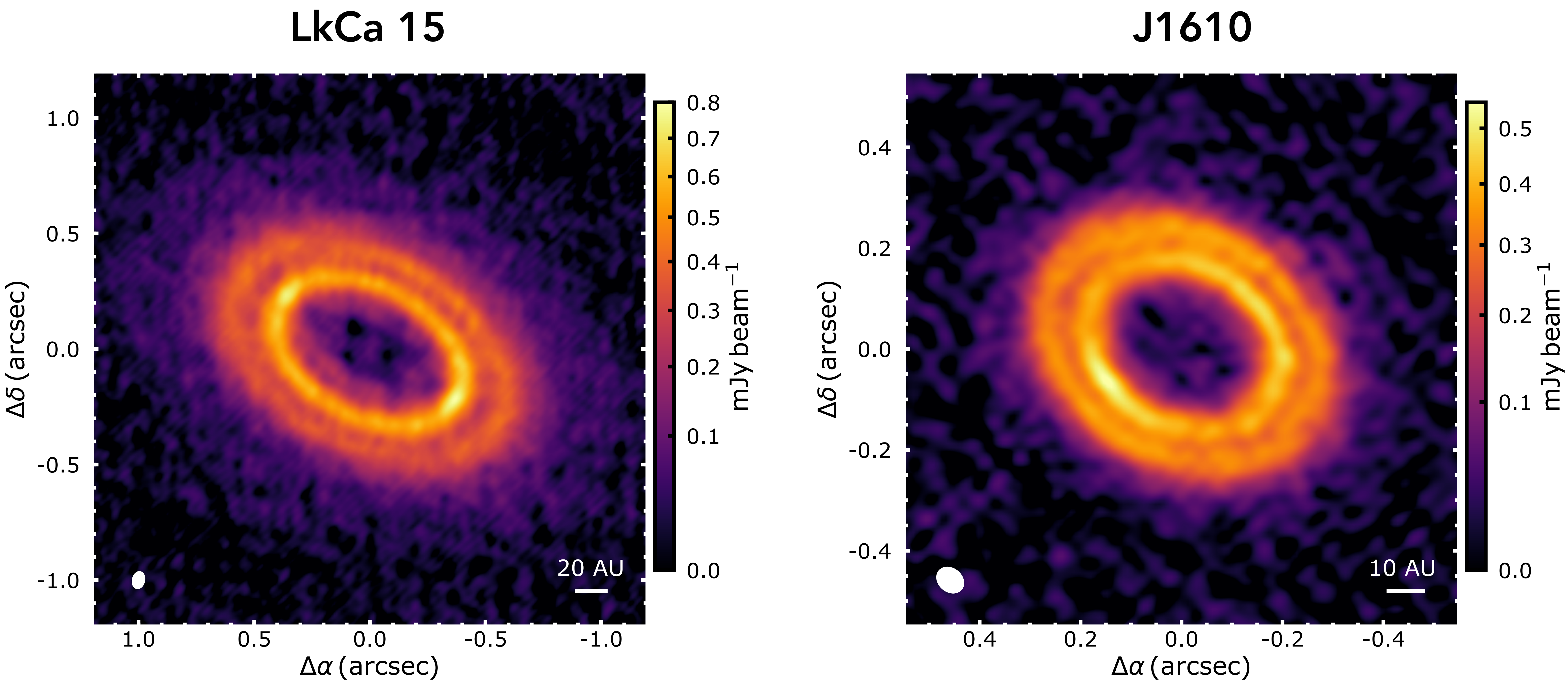
LkCa 15



Sallum+2015

LBT observations claimed presence of embedded planets.
Now evidence that these are disk features
(Mendigutia+2018, Currie+2019)

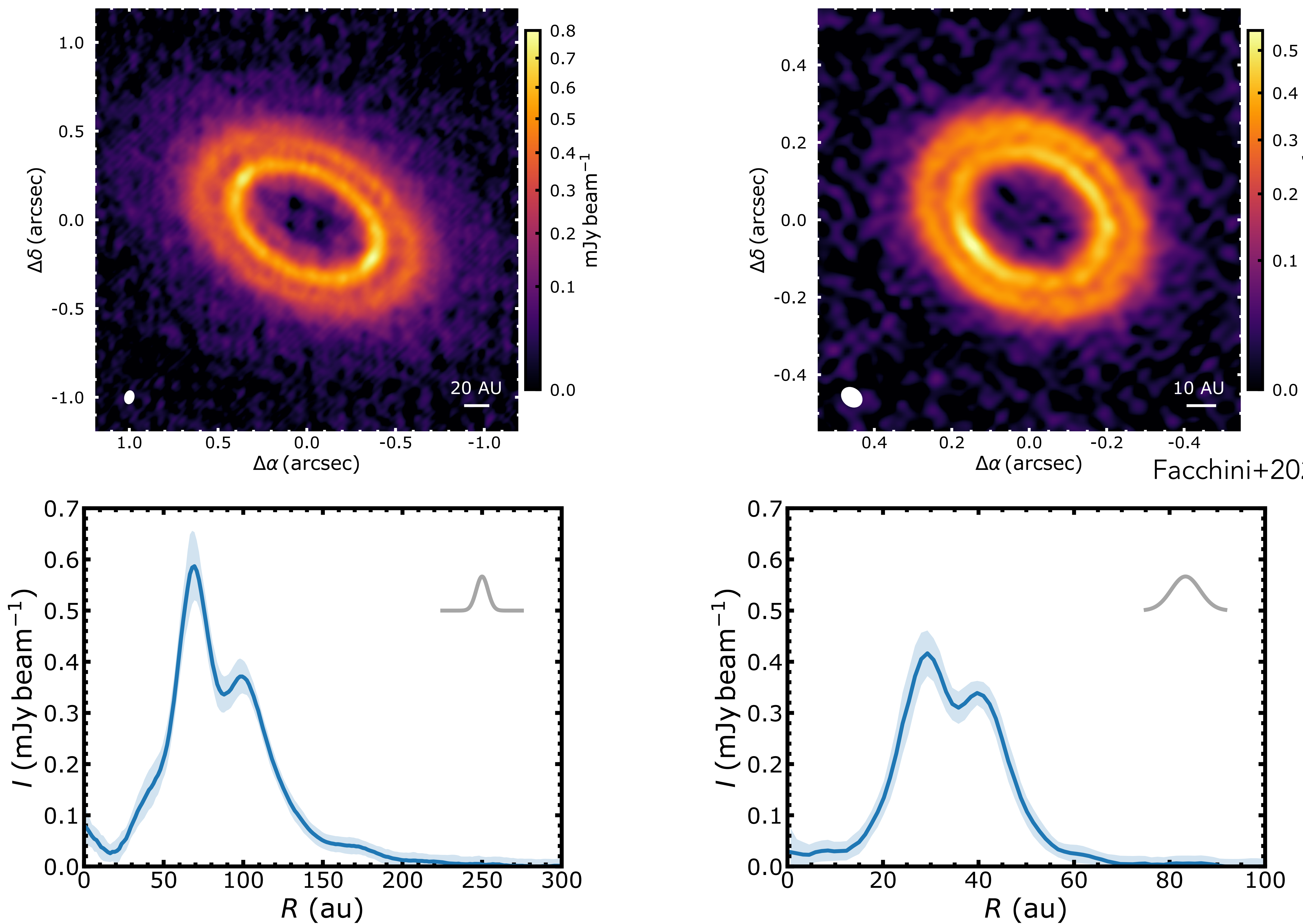
Substructured rings in transition disks



Facchini+2020a

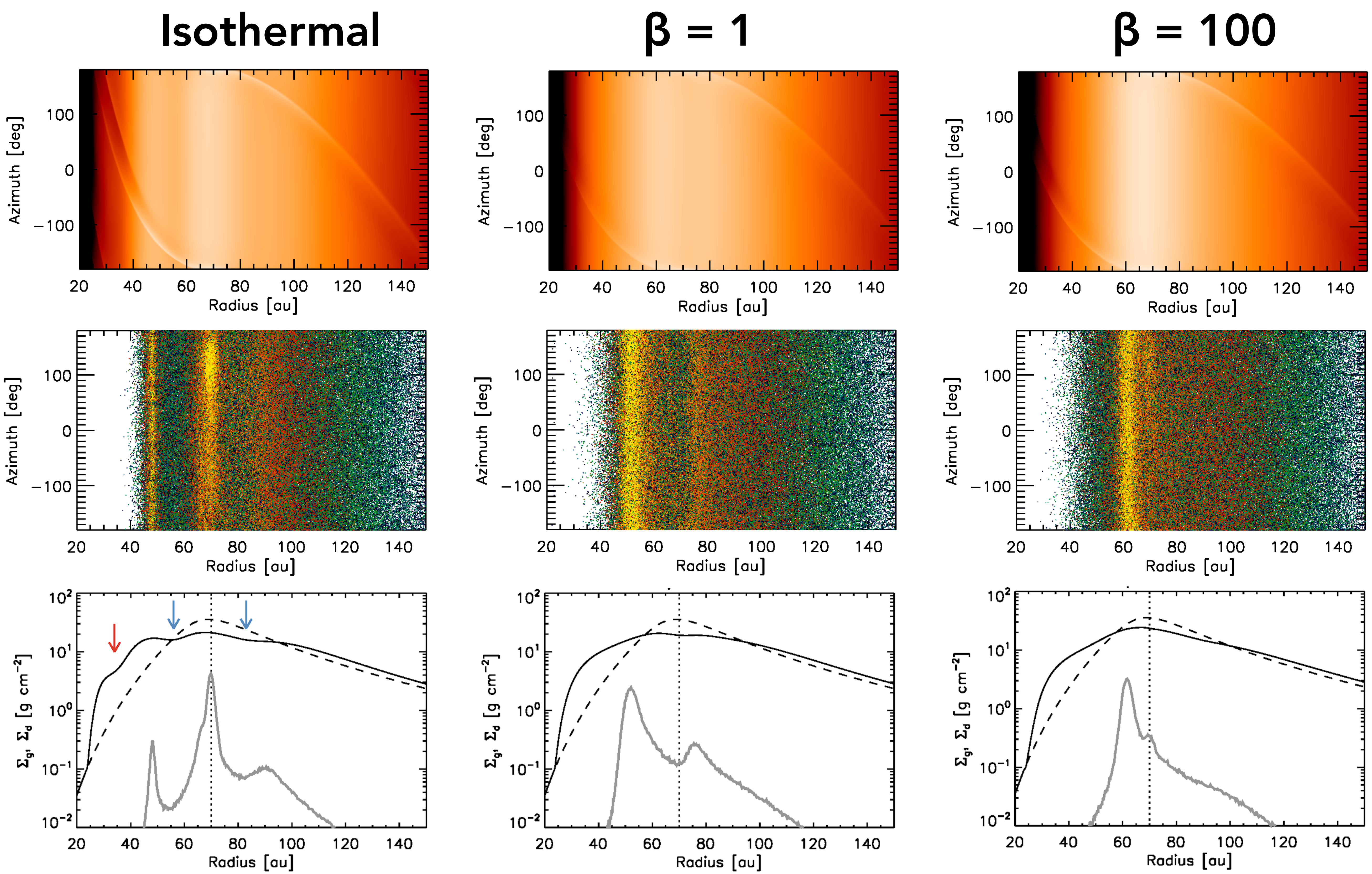
Substructured rings in transition disks

LkCa 15 | J1610

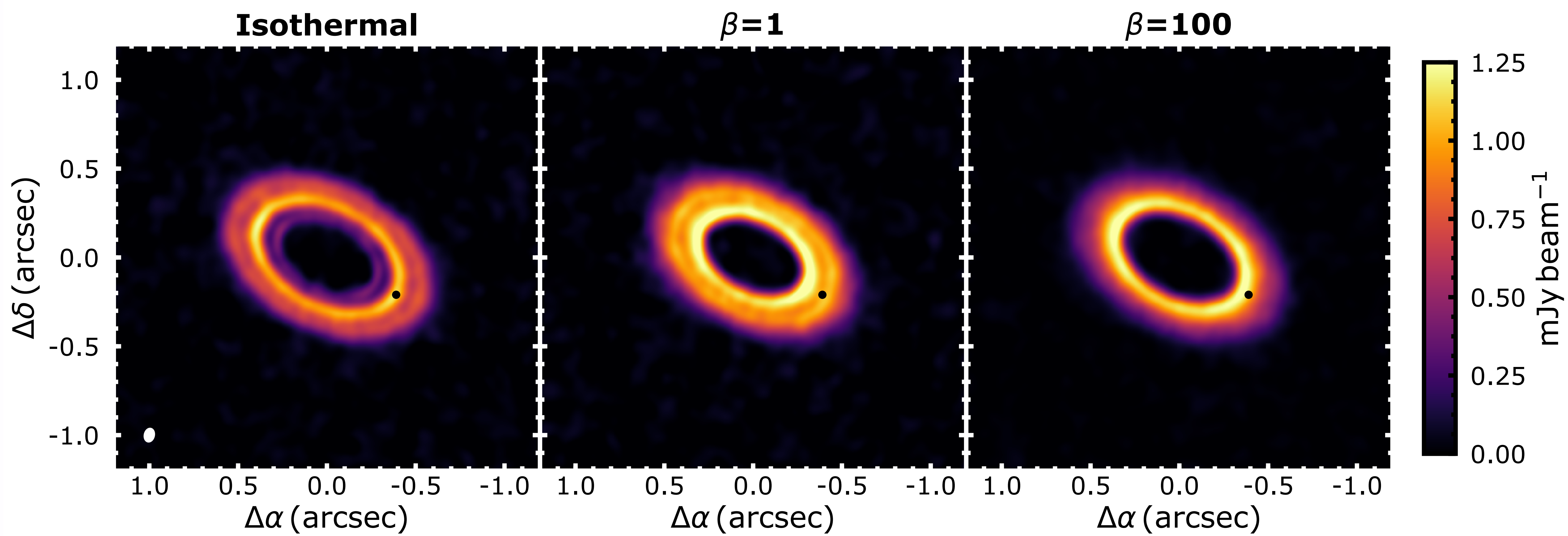


Facchini+2020a

Secondary formation of “low” mass planets?



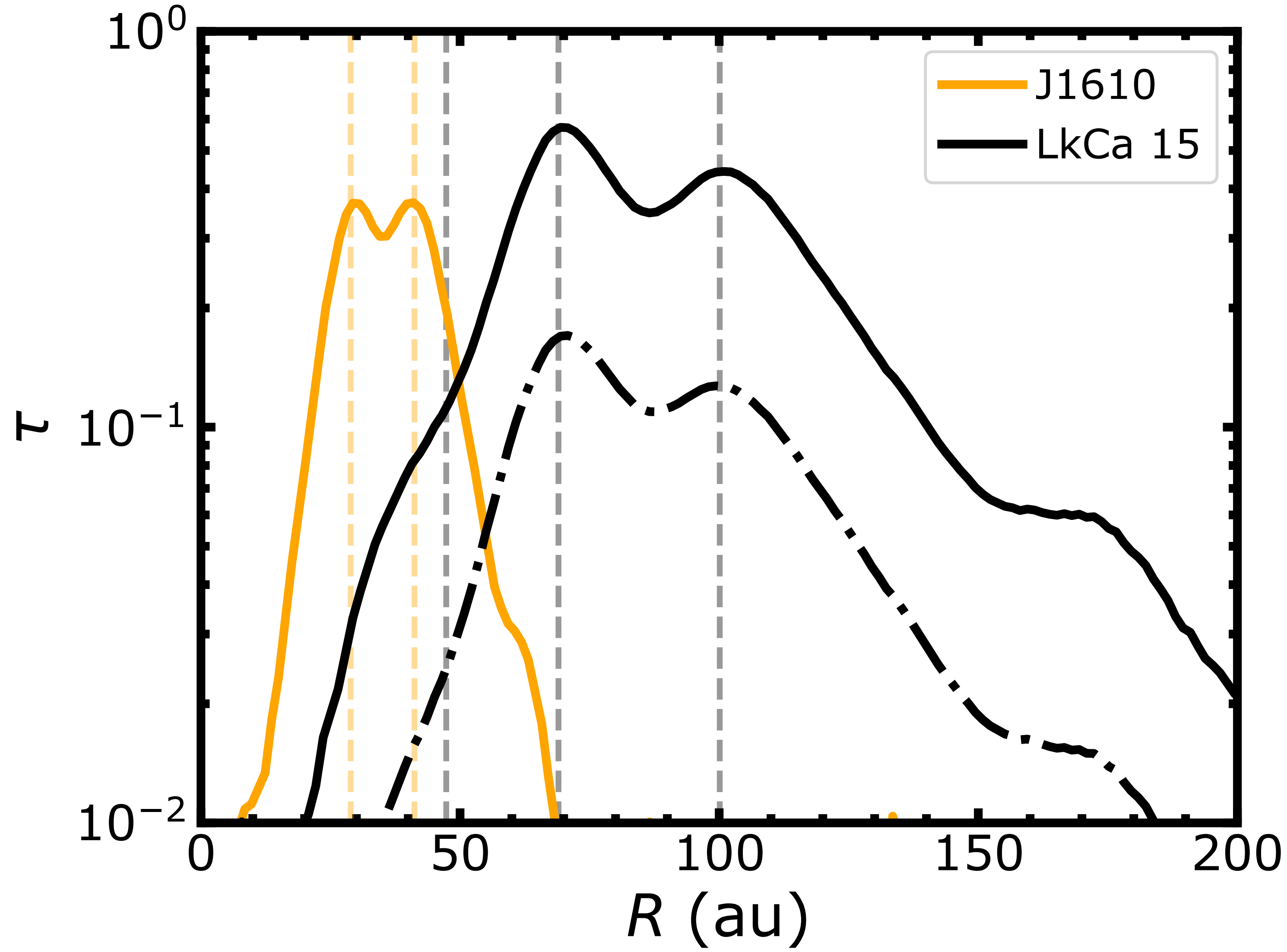
High degeneracy



3 rings **2 rings** **1 ring**

Thermodynamics (disk cooling) can play an important role in shaping the resulting dust structure at fixed turbulence and planet mass (Miranda & Rafikov 2019,2020, Perez et al. 2019).

Rings retain a lot of dust mass



Rings in LkCa 15 are locking >100 M_{Earth} of dust each, enough to form new planetary cores (Dullemond+2018, Andrews 2020)

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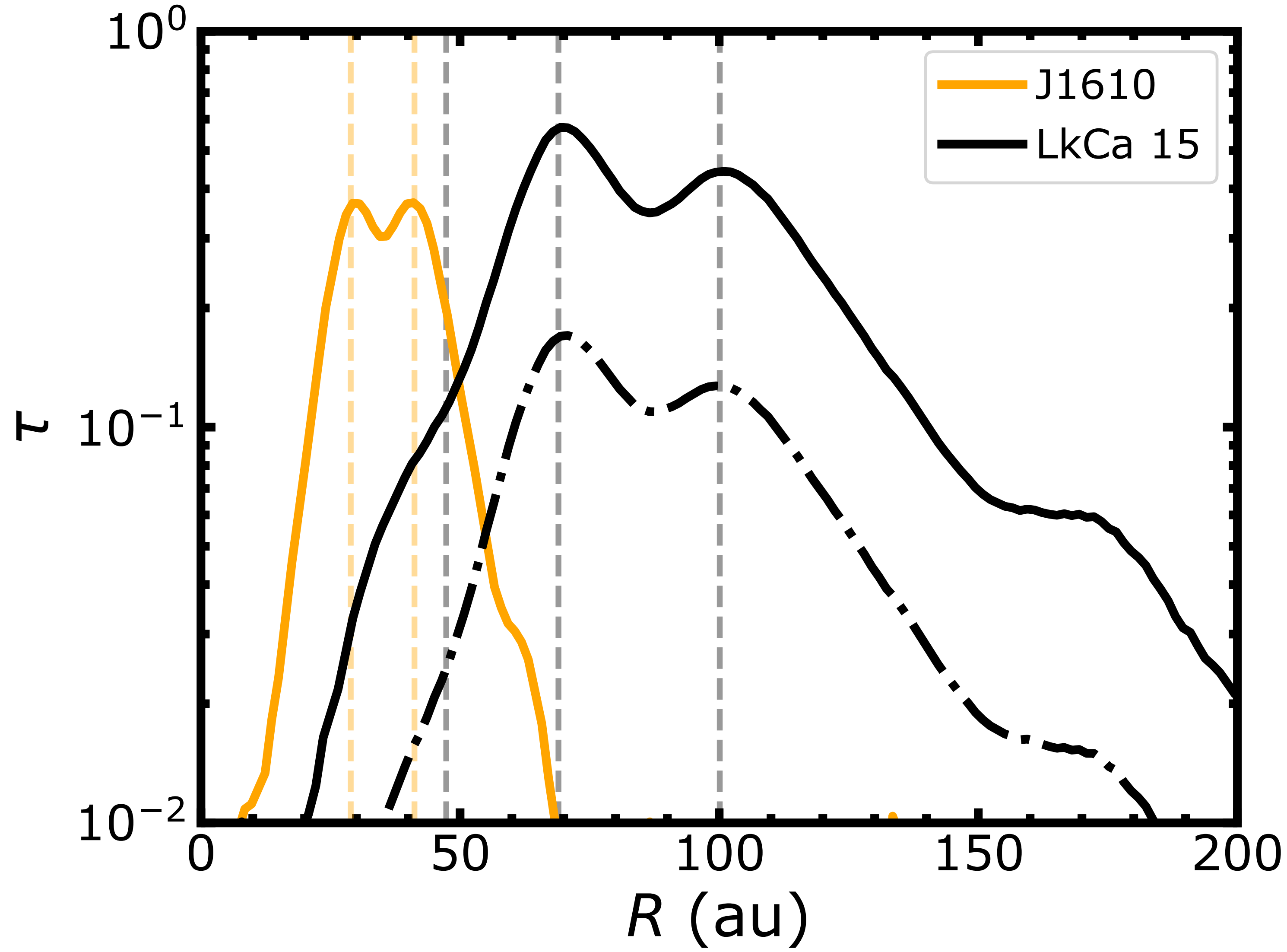
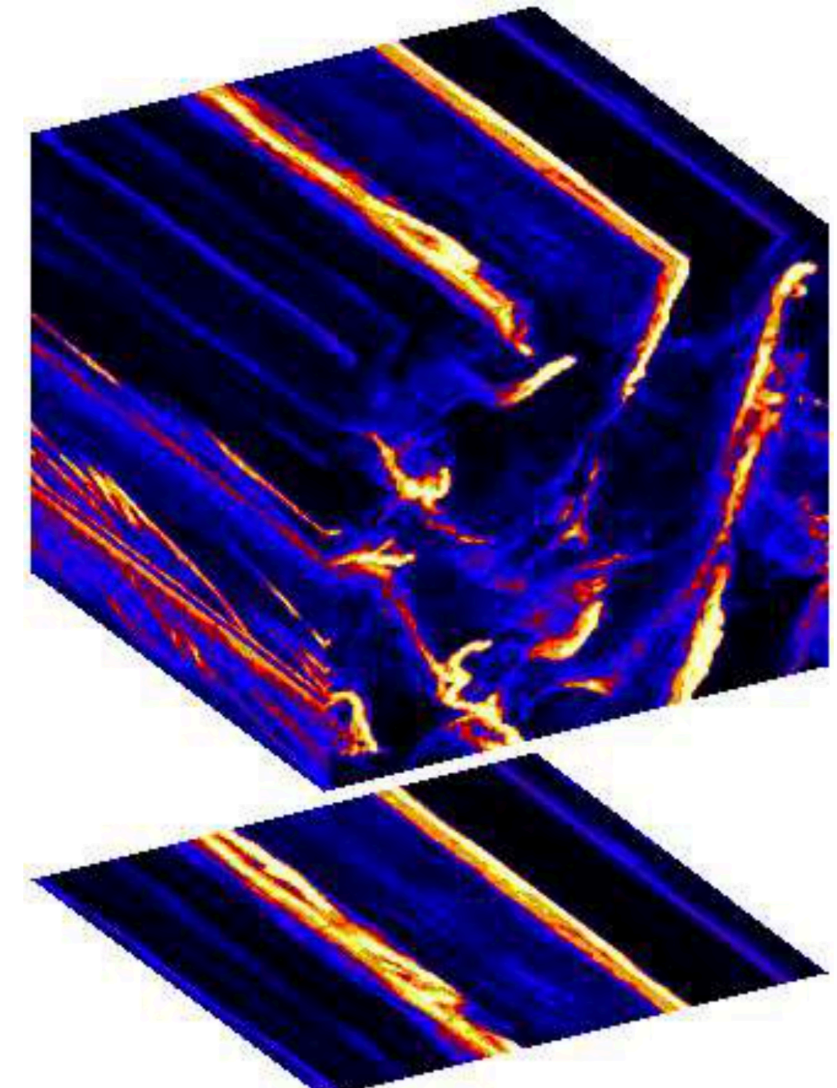


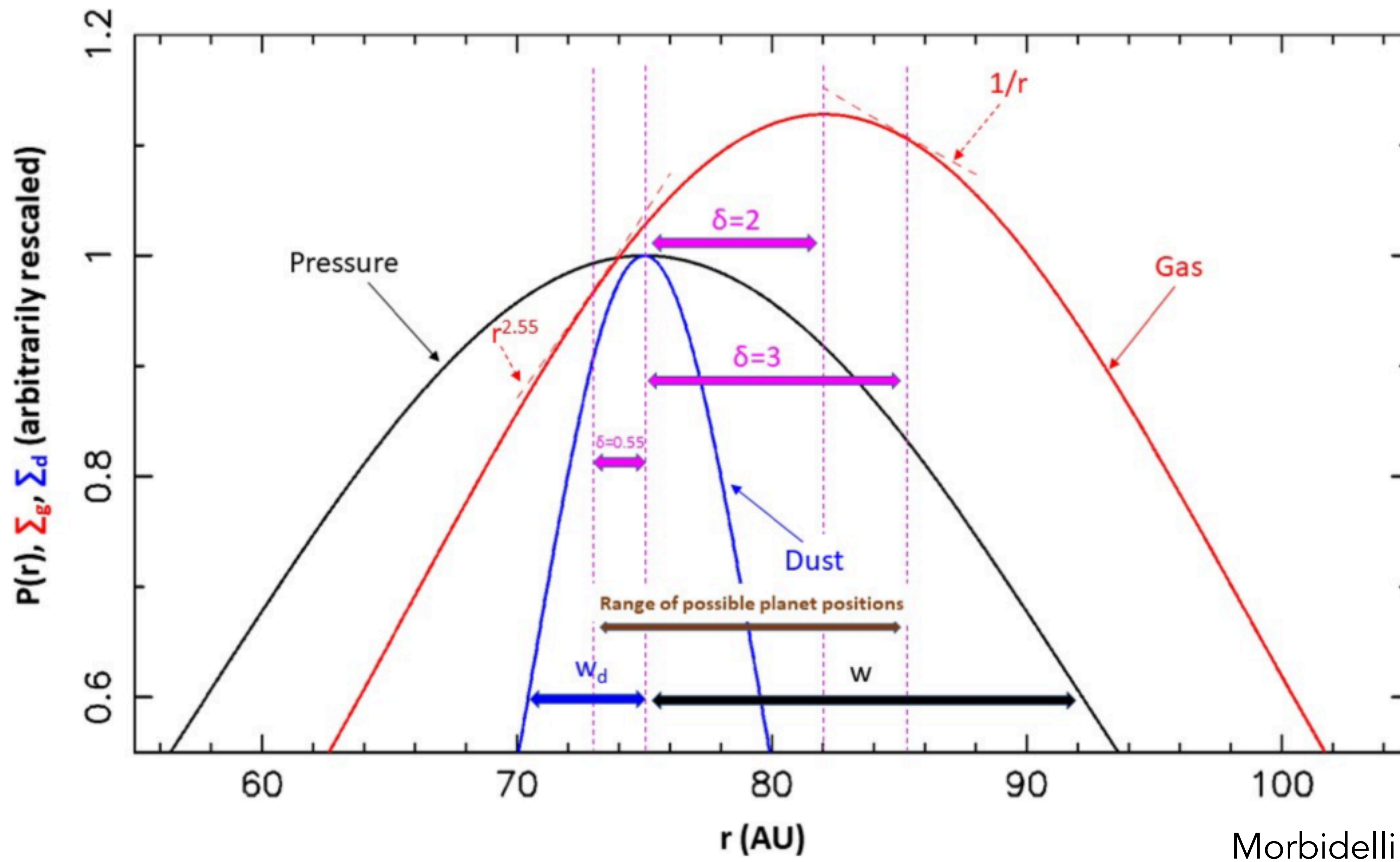


Johansen & Youdin 2007

Rings in LkCa 15 are locking >100 M_{Earth} of dust each, enough to form new planetary cores (Dullemond+2018, Andrews 2020)

Using upper limits from gravitational instability, **Σ_g/Σ_d < 70** in LkCa 15, where conditions for streaming instability to occur is **Σ_g/Σ_d < 50** (Youdin & Goodman 2005, Bai & Stone 2010). Rings in TDs could be the best place to look for planet formation in action (see Perez+2019)

A timescale problem for pebble accretion

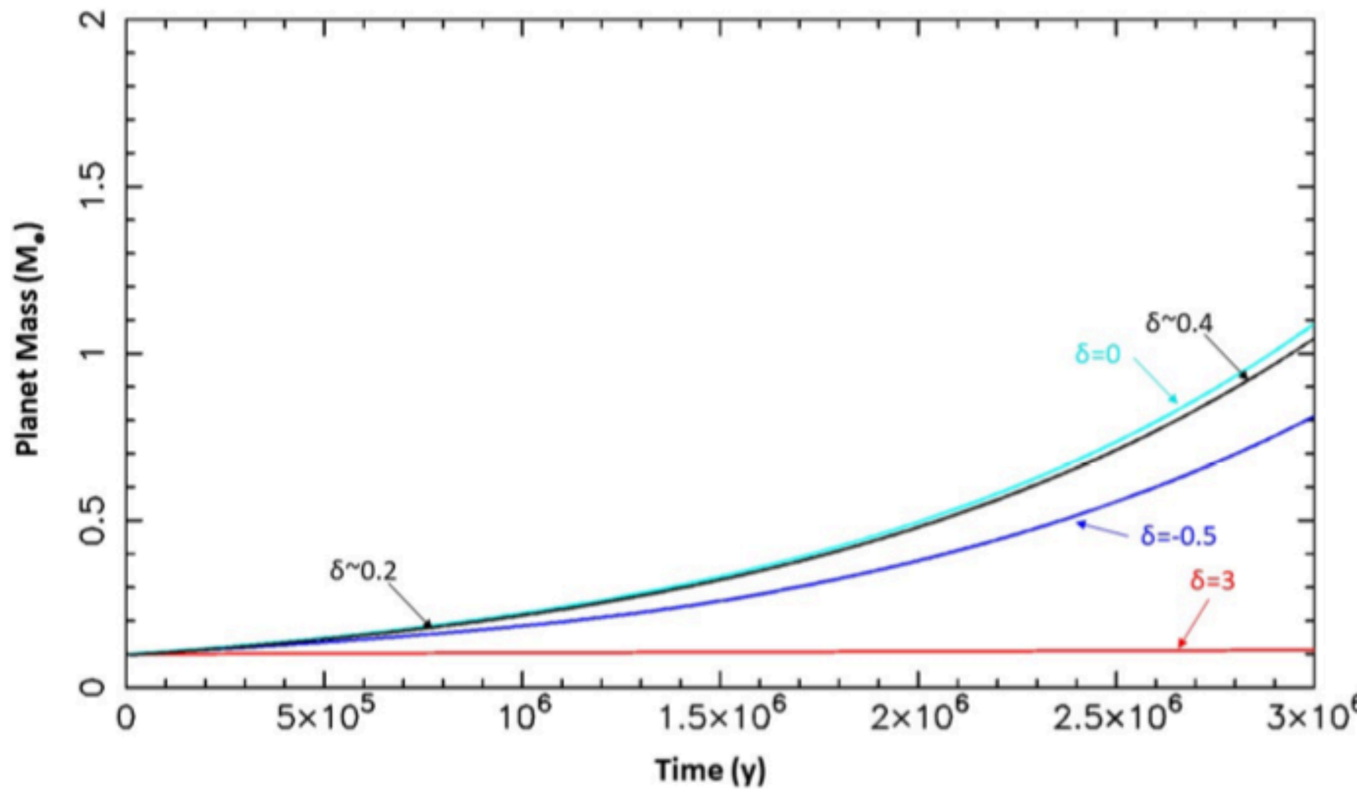


Morbidelli 2020

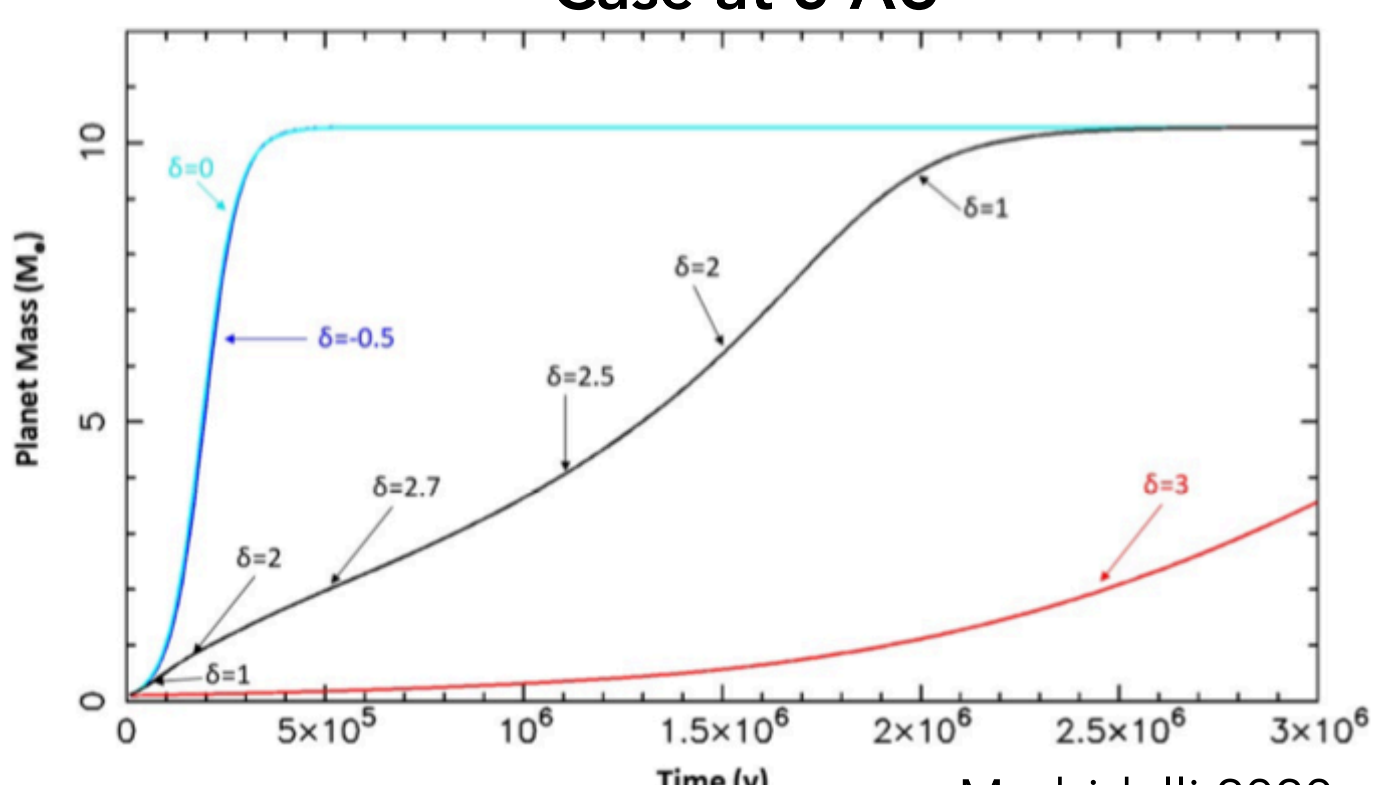
Type I migration of planet halting at different radii depending on thermodynamics

A timescale problem for pebble accretion

Case at 77 AU



Case at 5 AU



Morbidelli 2020

Pebble accretion inefficient at extracted dust surface densities at large distances, more efficient close to star

How to discriminate the origin of gaps?

1. Grain properties within rings?
   VERY degenerate
2. Probing gas surface density variations through molecular line intensity?
   VERY difficult
3. Gas kinematics

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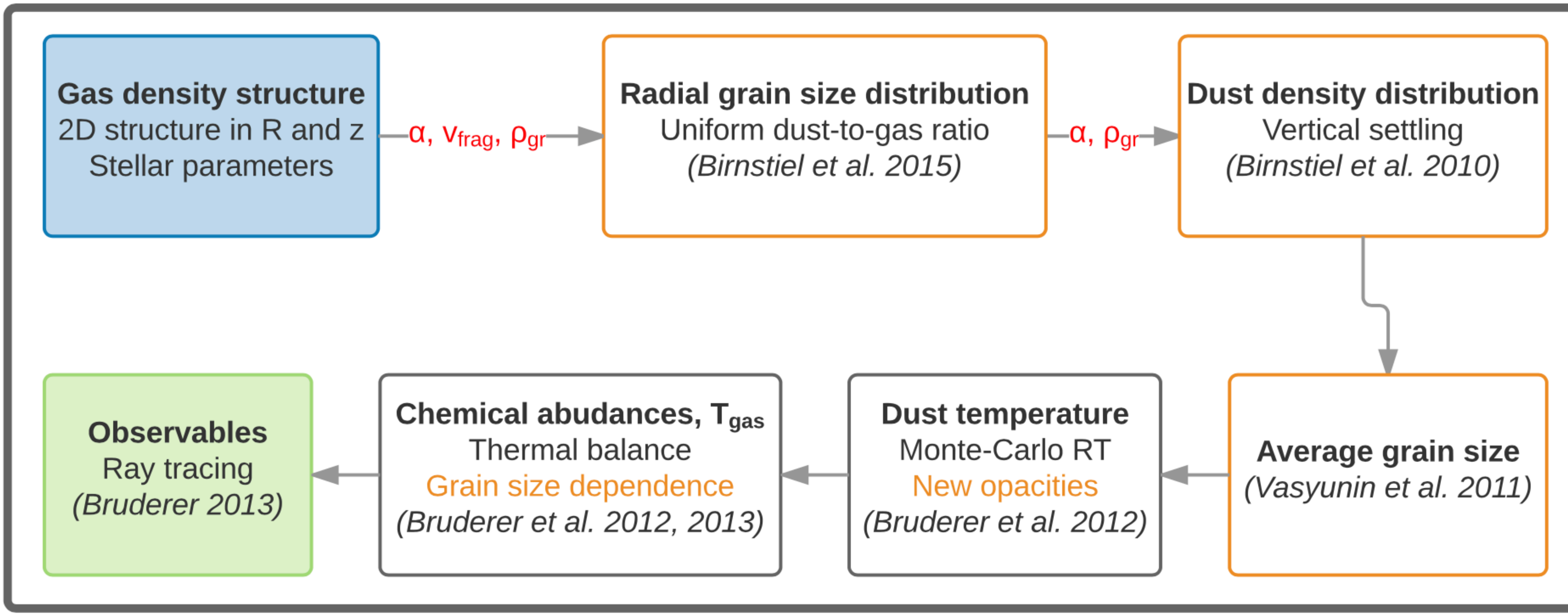
DALI : thermo-chemical code



Bruderer+2012, Bruderer 2013, Facchini+2017, 2018a

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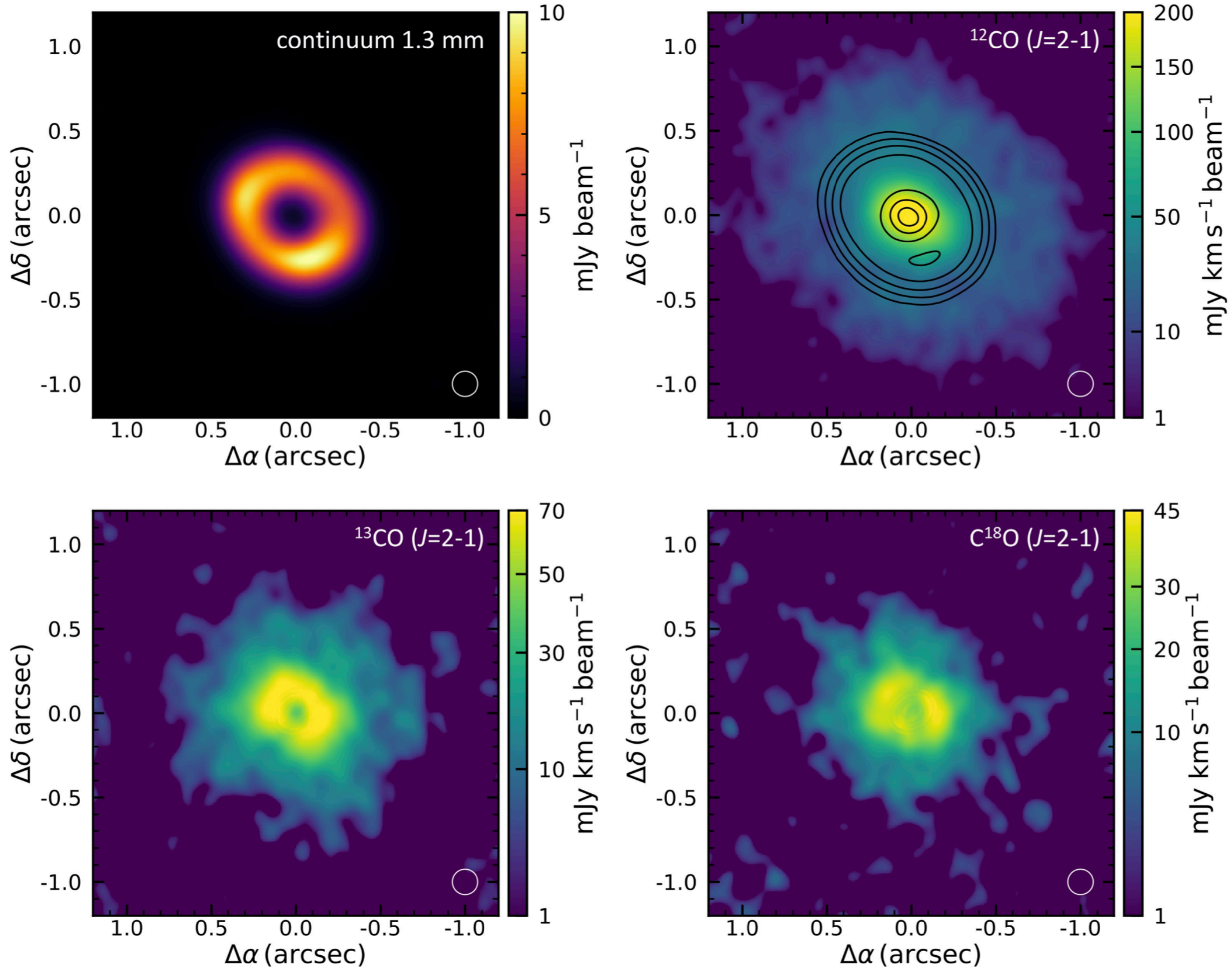
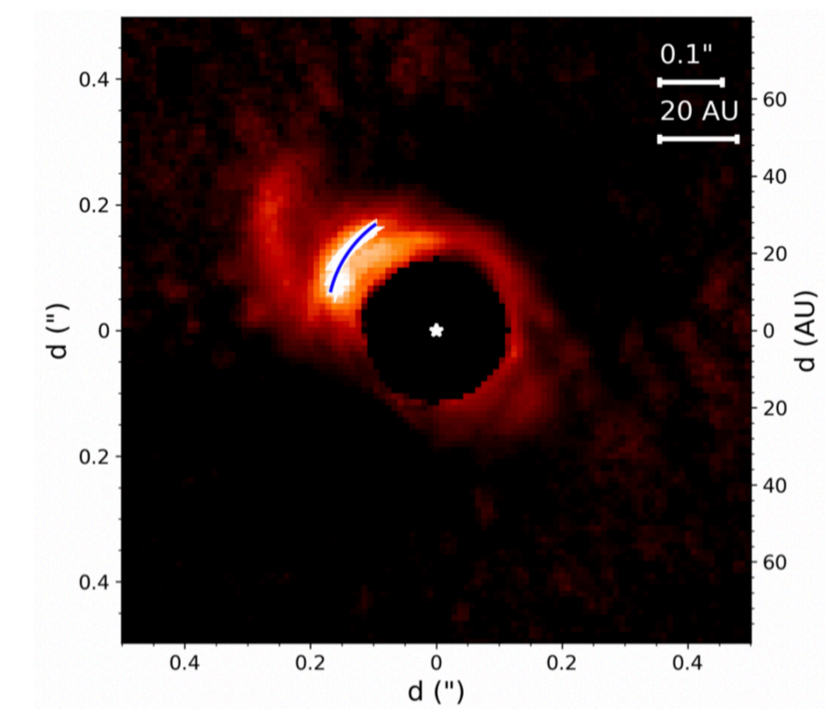
CQ Tauri

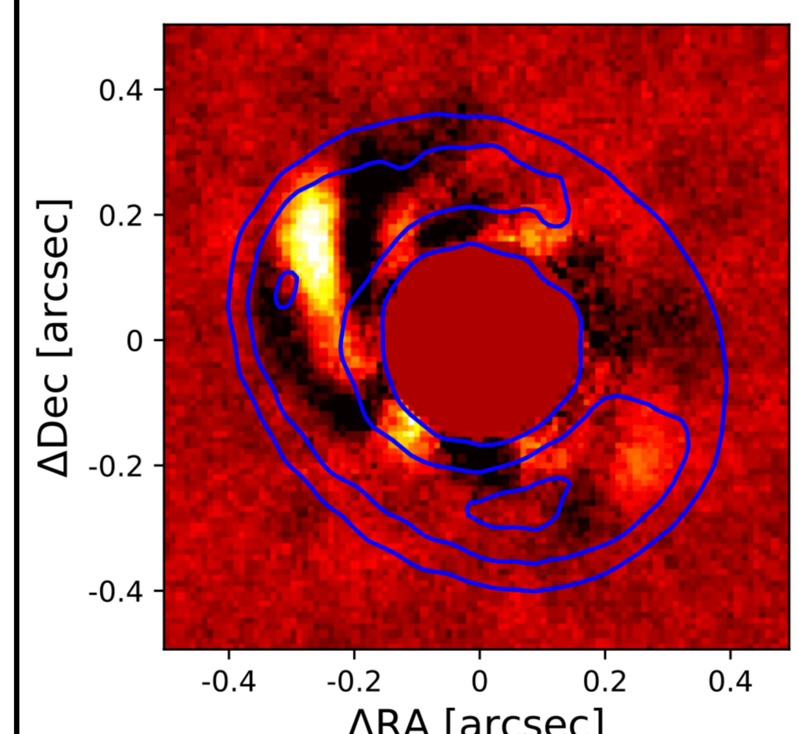
ALMA view



Ubeira Gabellini,…,**SF**+2019

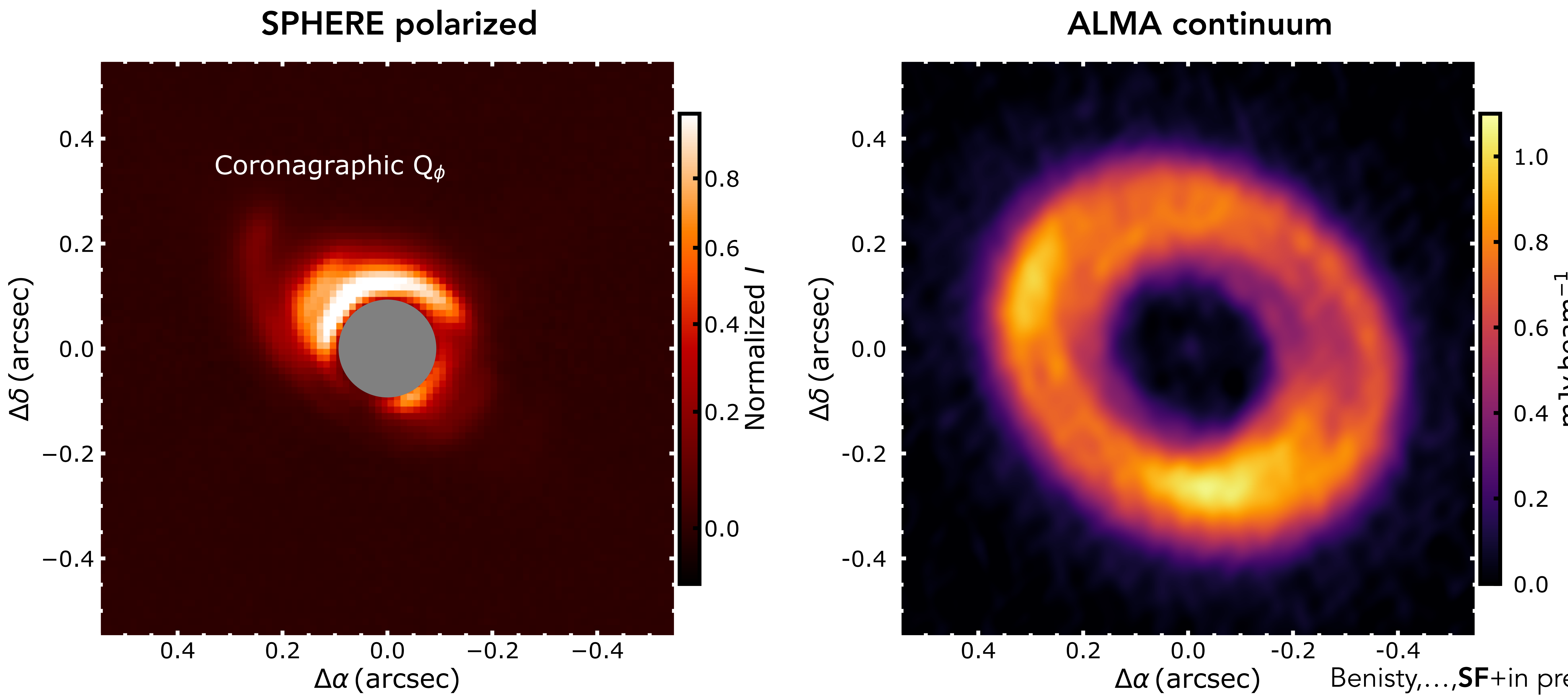
SUBARU view





Uyama+2019

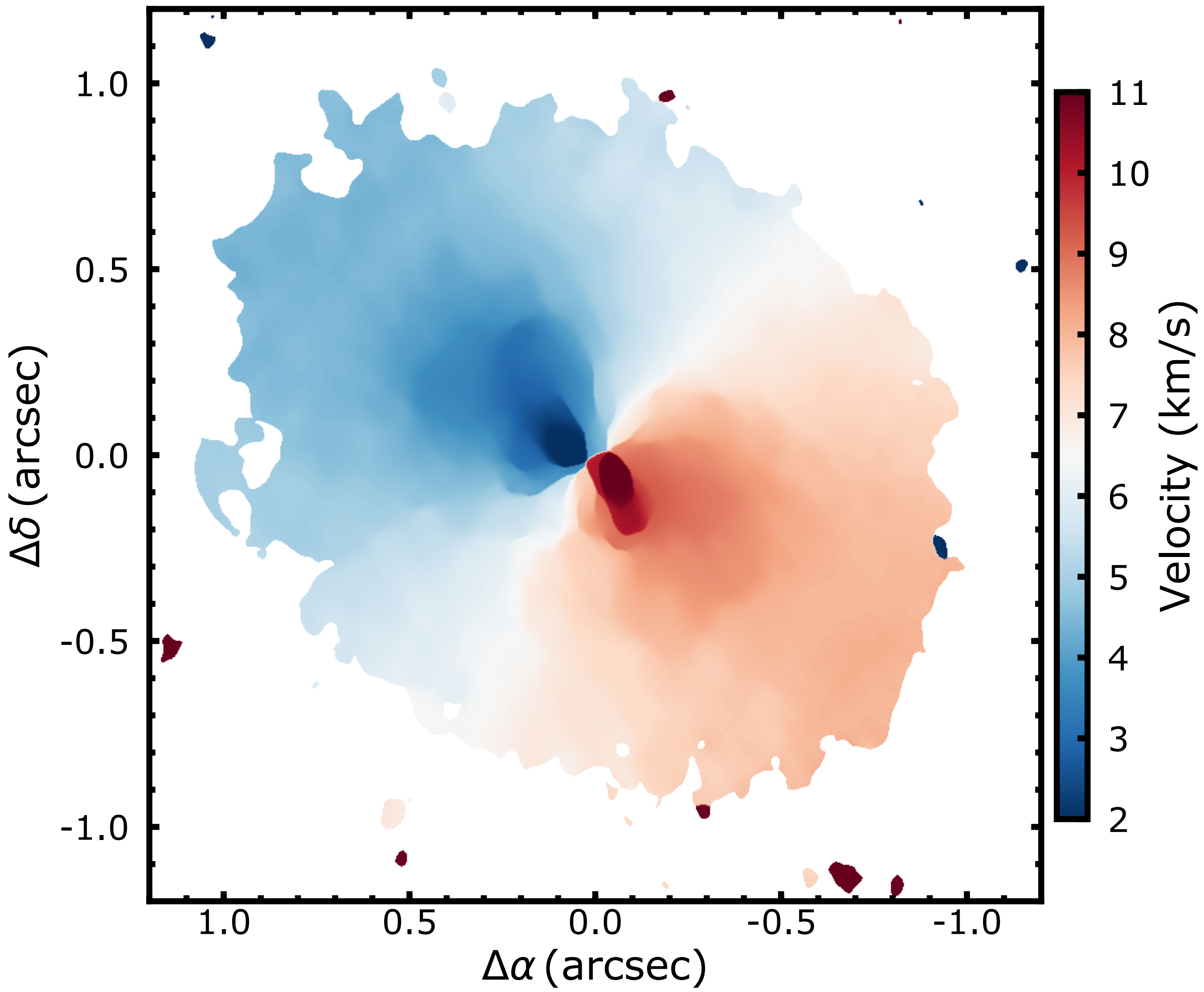
CQ Tauri

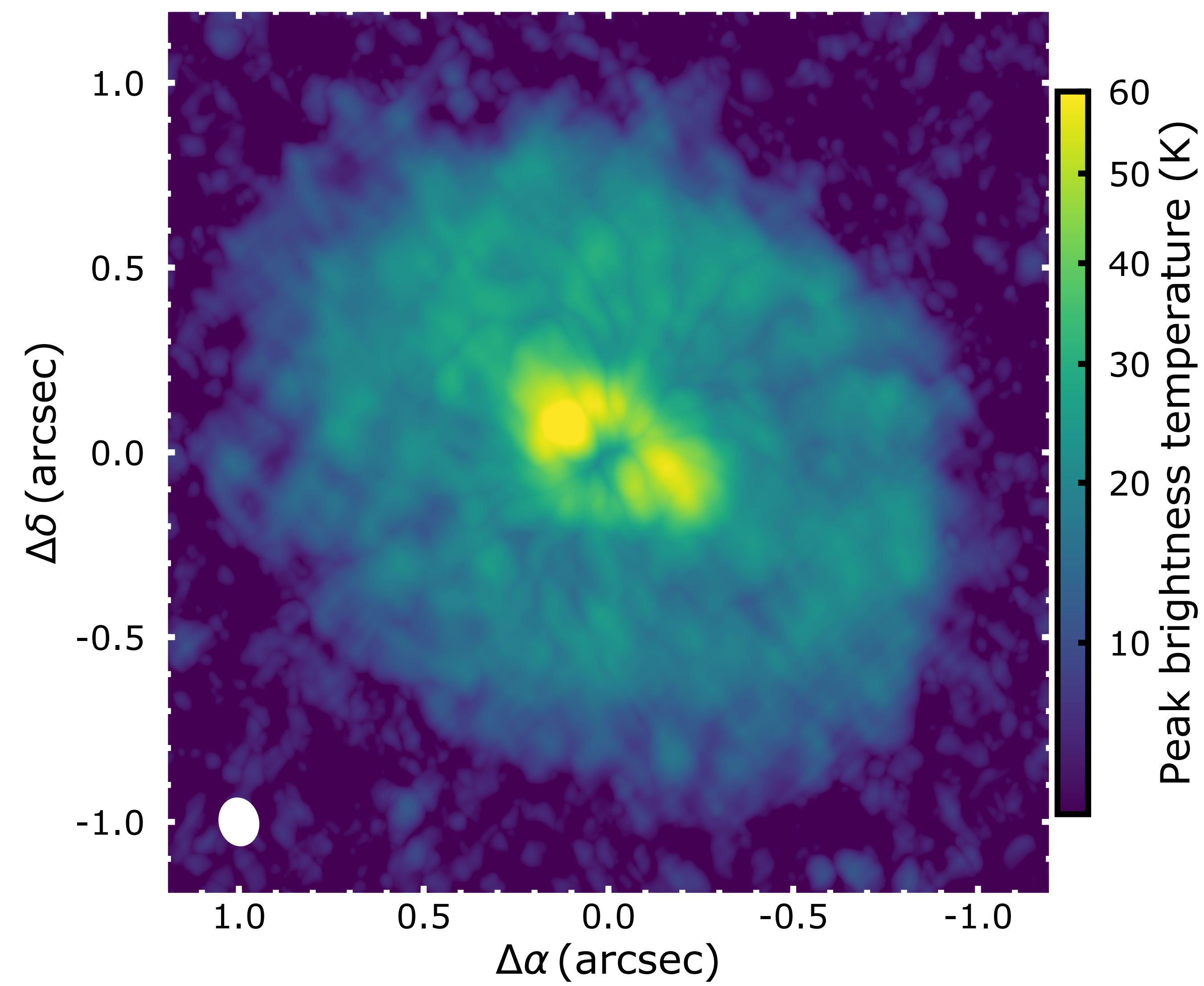


Benisty,…,**SF**+in prep.

New VLT/SPHERE and ALMA images show remarkable complexity in both small and large grains distribution (see Perez+2019 for HD100546)

CQ Tauri - CO maps





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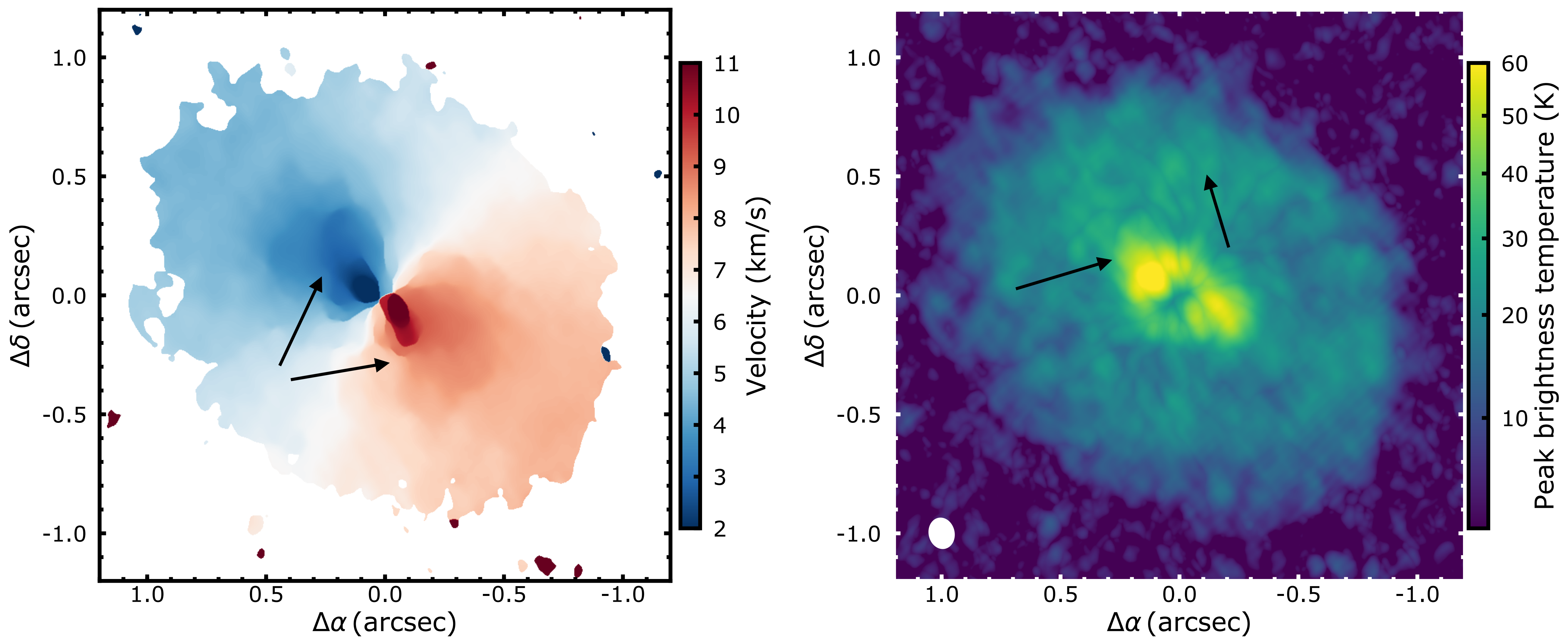
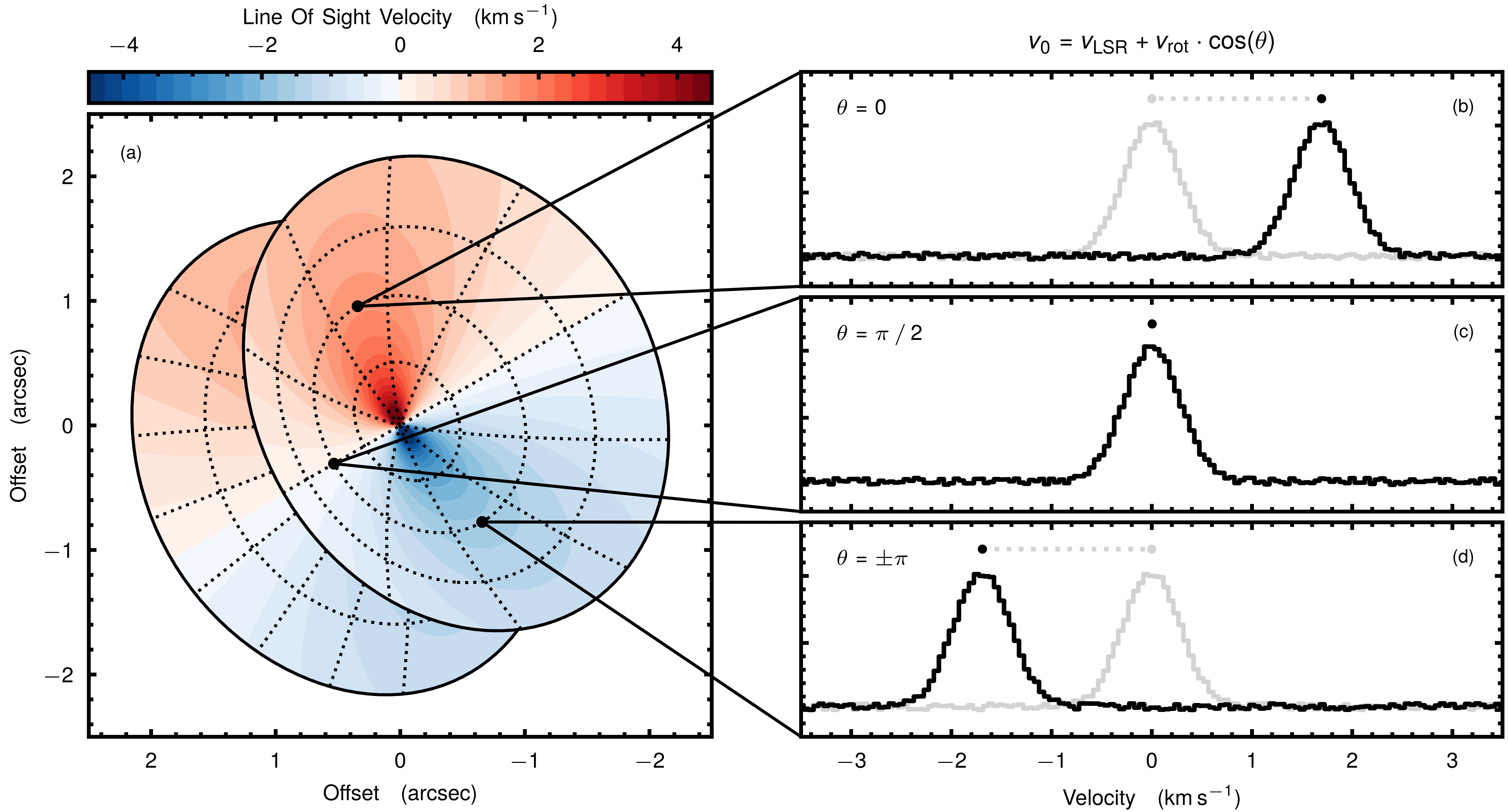


Kinematics and brightness temperature show azimuthal structure

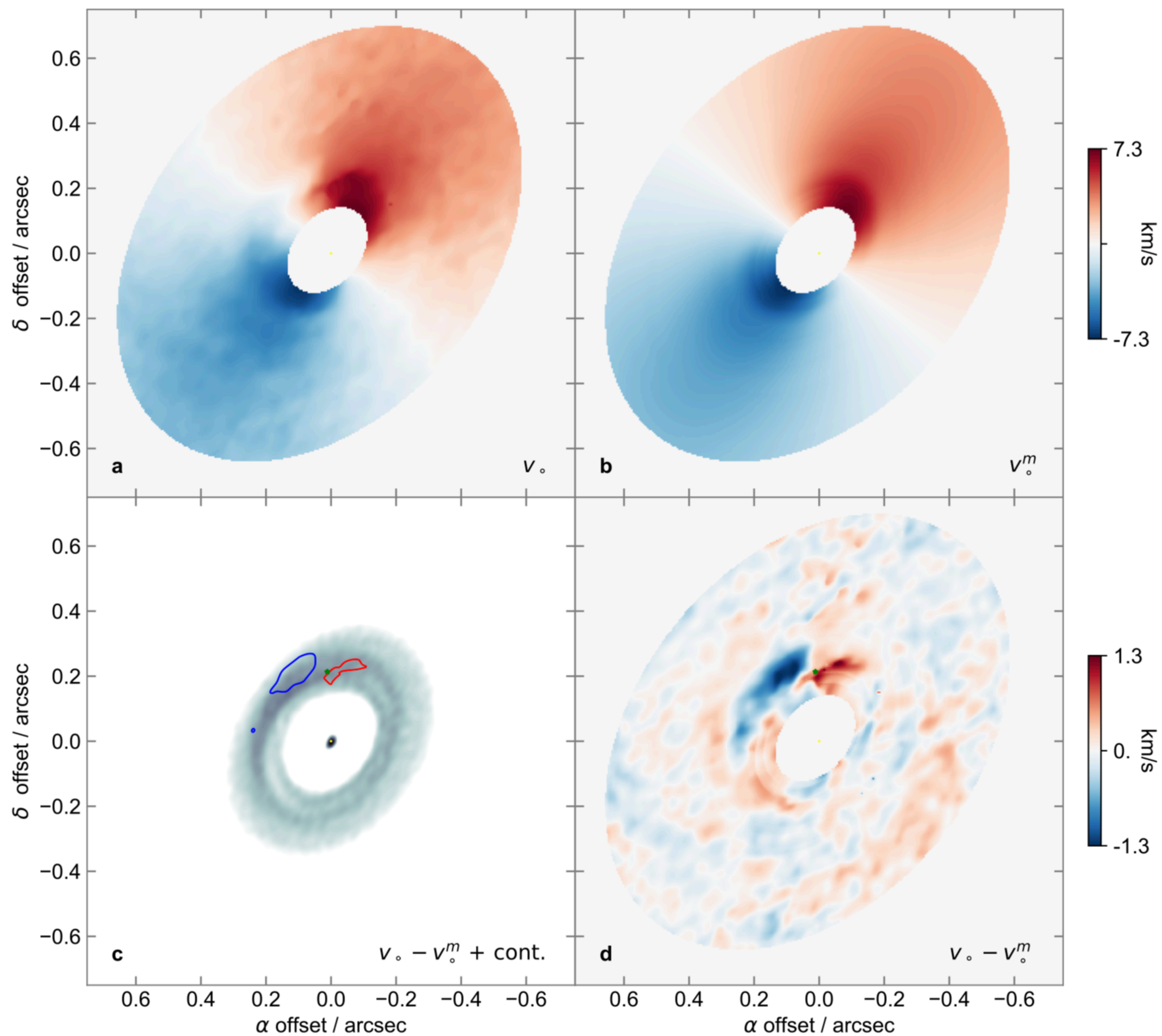
Fitting a keplerian rotation curve



Teague+2018 (see Casassus & Perez 2019, Disk Dynamics Collaboration+2020)

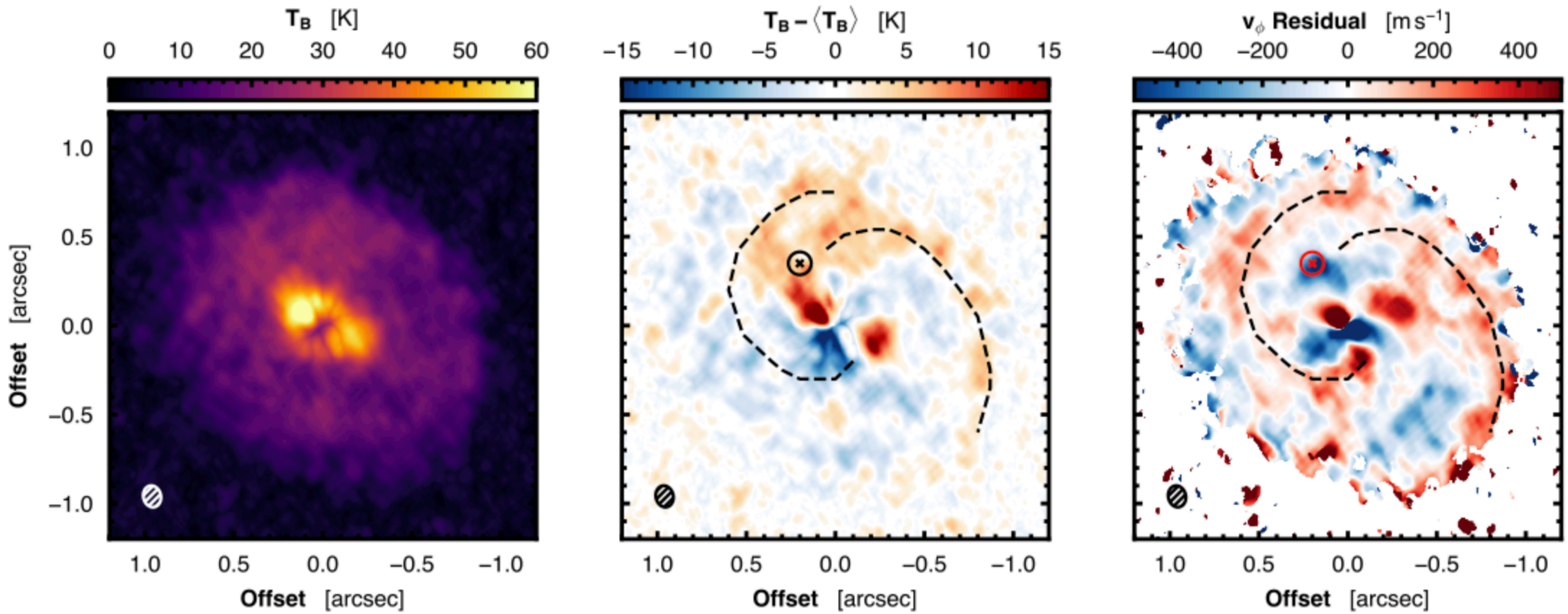
Fitting a keplerian rotation curve

HD 100546



Casassus & Perez (2019)

CQ Tauri - CO maps

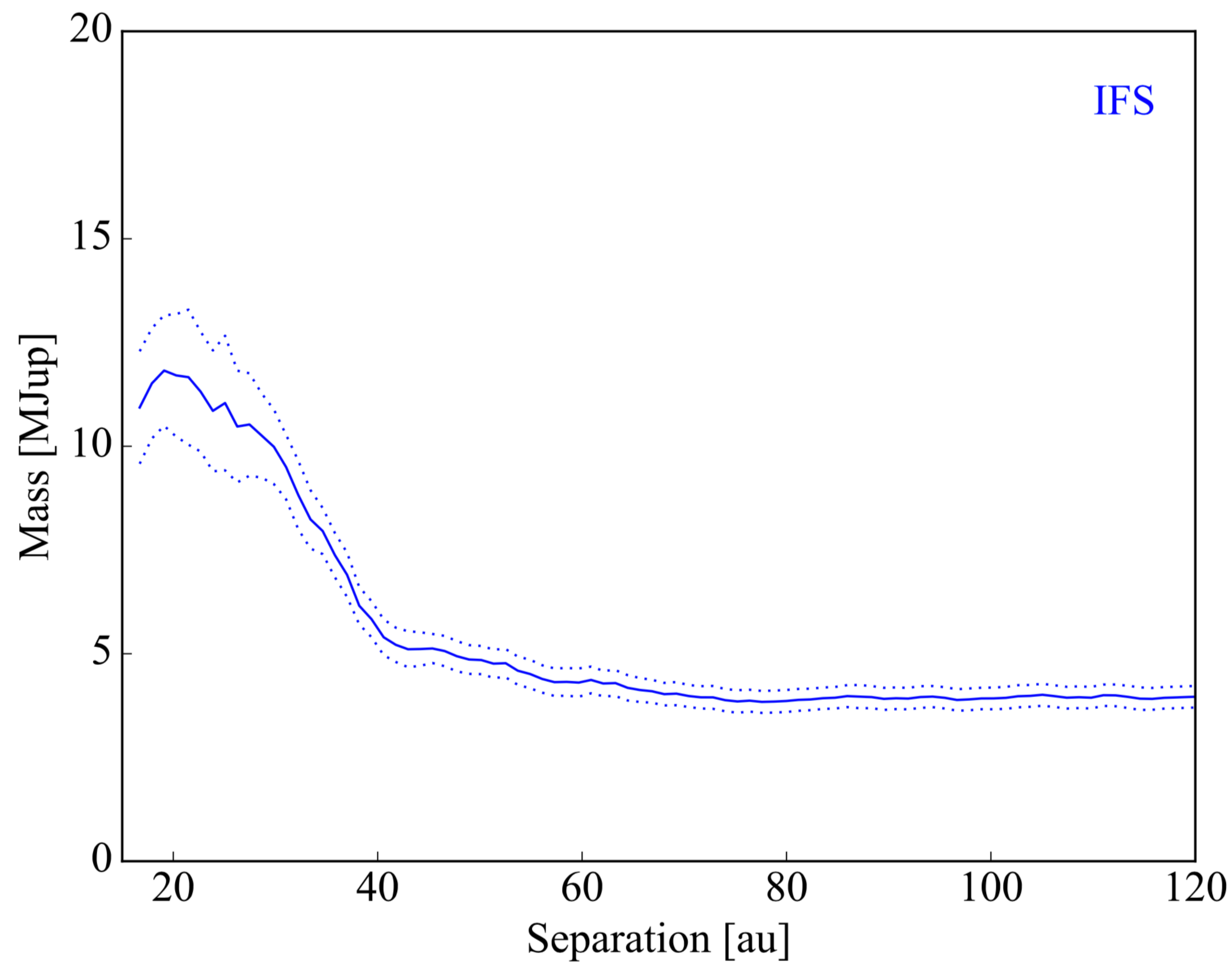


Subtraction of azimuthal averaged brightness temperature profile reveals spiral pattern, similarly to residuals in kinematics

Kinematical residuals suggest vertical motions (buoyancy waves, e.g. Zhu+2012)

Wölfer, Facchini+subm.

Upper limits on perturbing body

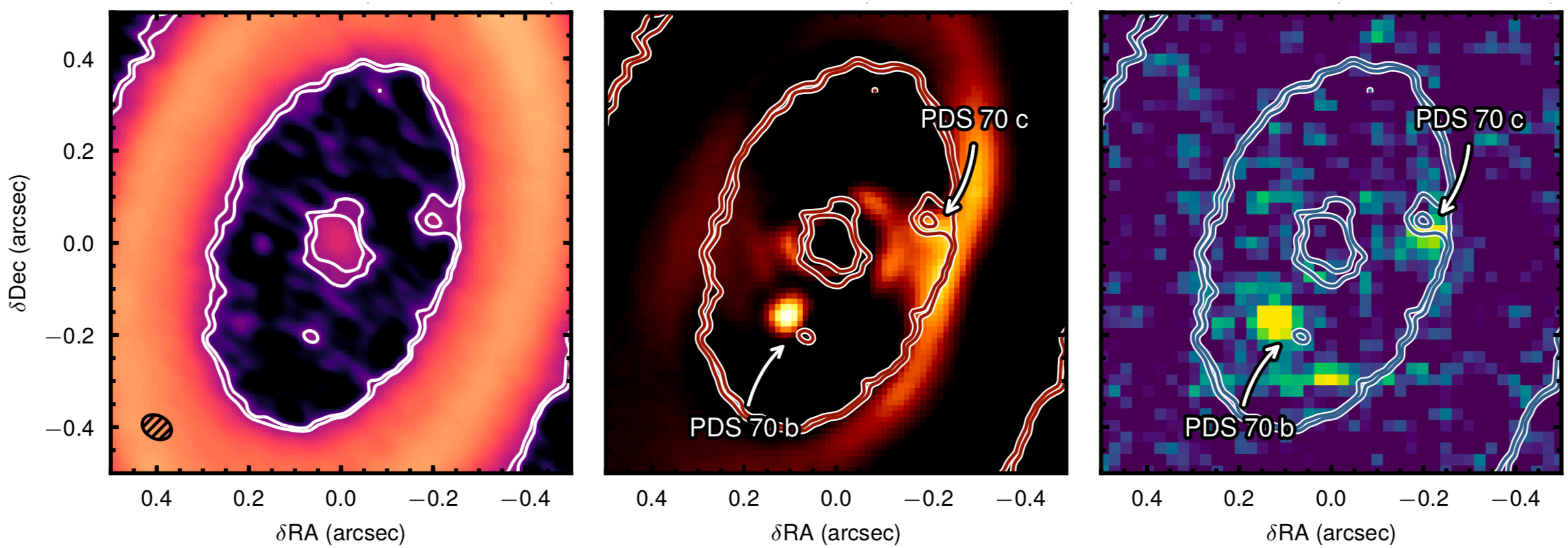


Benisty,…,**SF**+in prep.

Detailed hydrodynamical simulations needed to compare upper limits from SPHERE IFS to observed gas and dust structures

PDS 70

344 GHz continuum (Isella,…,**SF**+2019) NIR with VLT/SPHERE (Müller+2019) Hα with VLT/MUSE (Haffert+2019)



PDS 70b

$M_p \sim$ 5-9 M_{Jup}

a ~ 20.6 au

$M_{acc} > 5 \times 10^{-7}\ M_{Jup}\ yr^{-1}$

PDS 70c

$M_p \sim$ 4 M_{Jup}

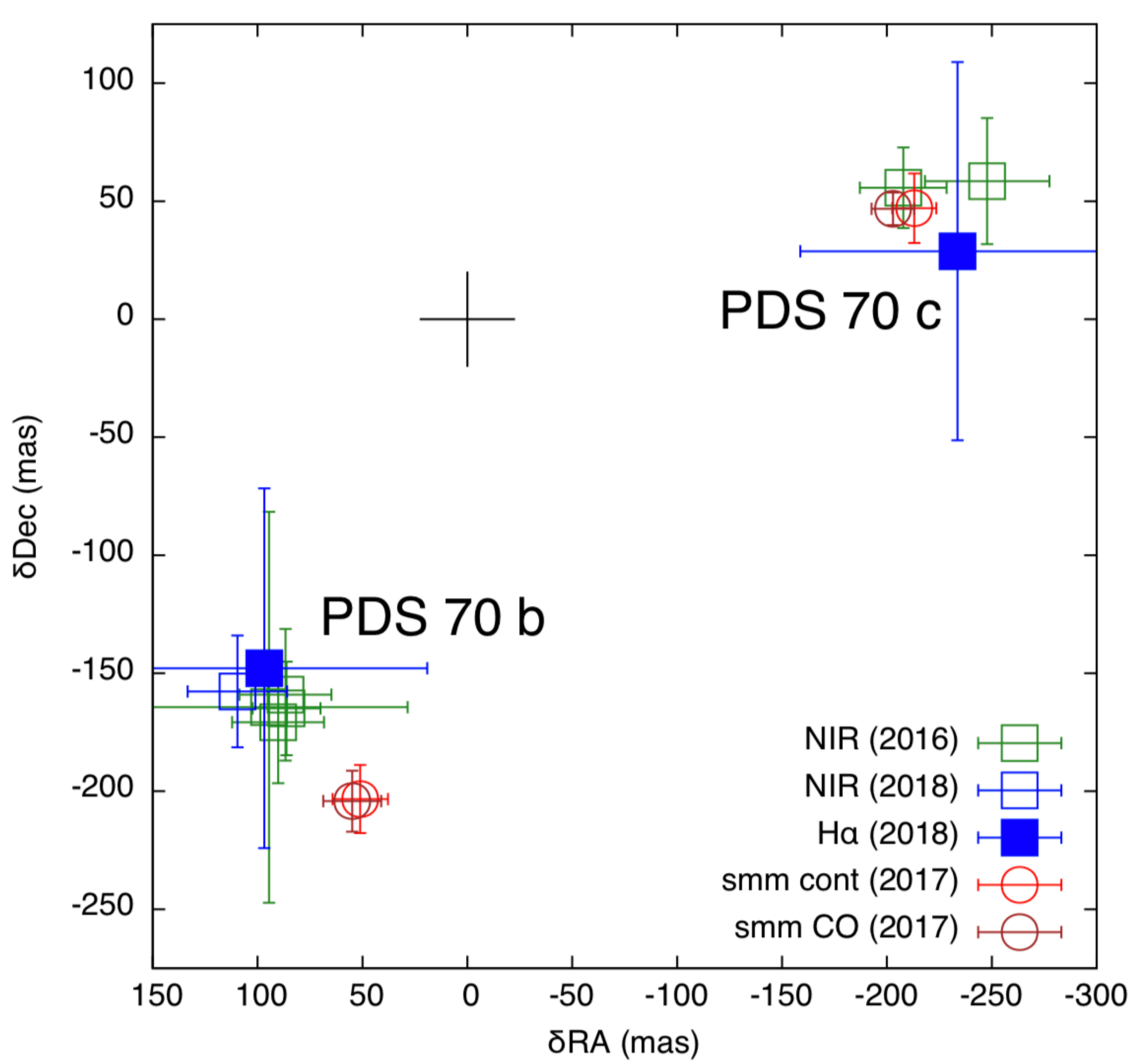
a ~ 34.5 au

$M_{acc} \sim 1 \times 10^{-8}\ M_{Jup}\ yr^{-1}$

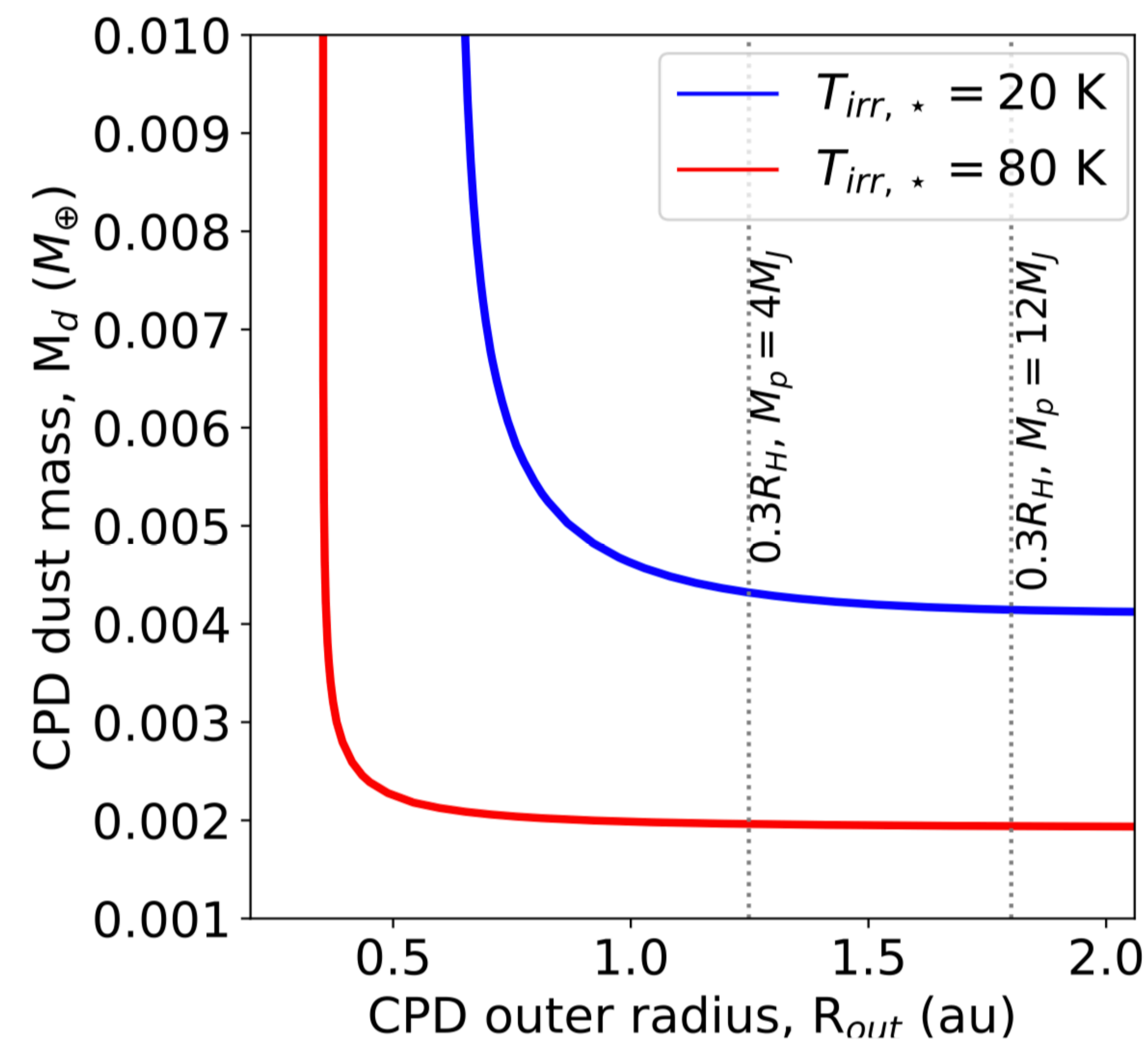
References: Keppler+2018, Haffert+2019, Christiaens+2019, Mesa+2019, Aoyama+2019, Thanathibodee+2019, Hashimoto+2020, Stolker+2020, Toci+2020

mm close to b shows astrometry not consistent with IR data

Astrometry

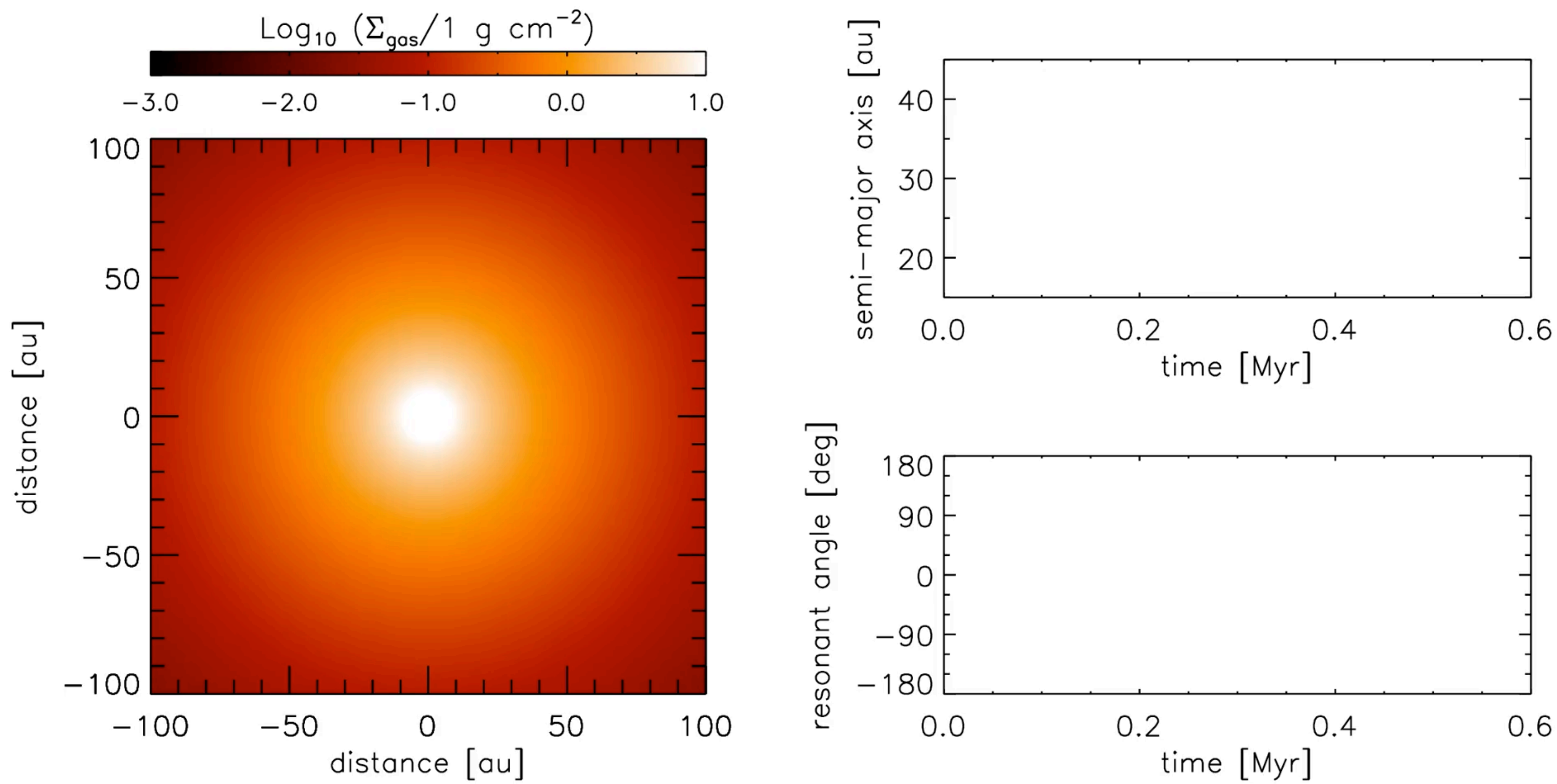


CPD-c mass/radius



Isella,…,SF+2019

Hydrodynamical simulations of PDS 70



Bae,...,**SF**+2019

2D simulations (FARGO) with 0.1 μm -1 mm dust included (Baruteau+2019).

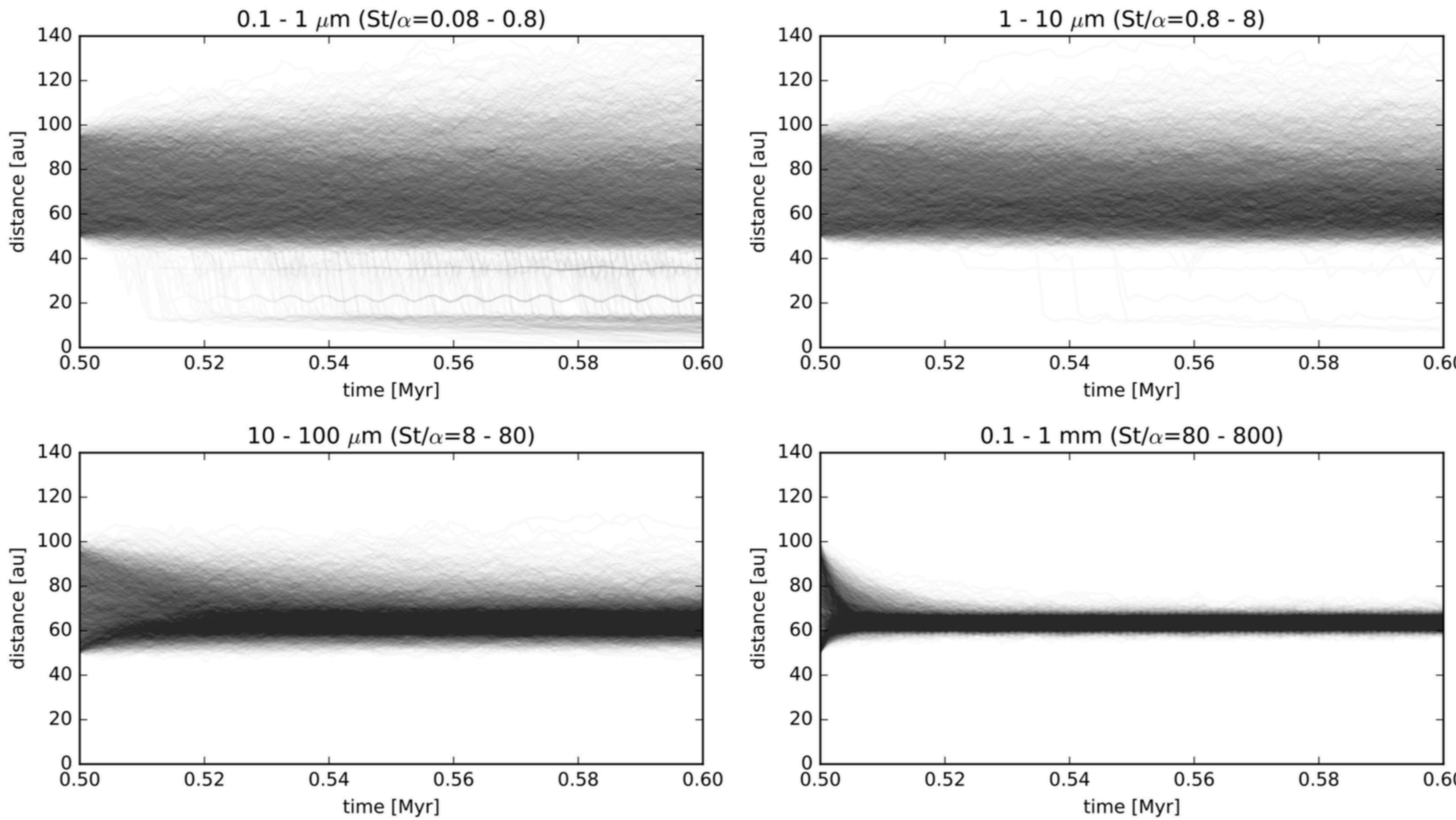
Mass of b: **5** M_{Jup}; Mass of c: **2.5** M_{Jup}

Simulations show that planet c is less massive than b, otherwise disk would be too eccentric.

Planets enter 2:1 resonance, with outside migration: **Jupiter-Saturn analogue**

Dust segregation and filtration

Trajectories of dust particles



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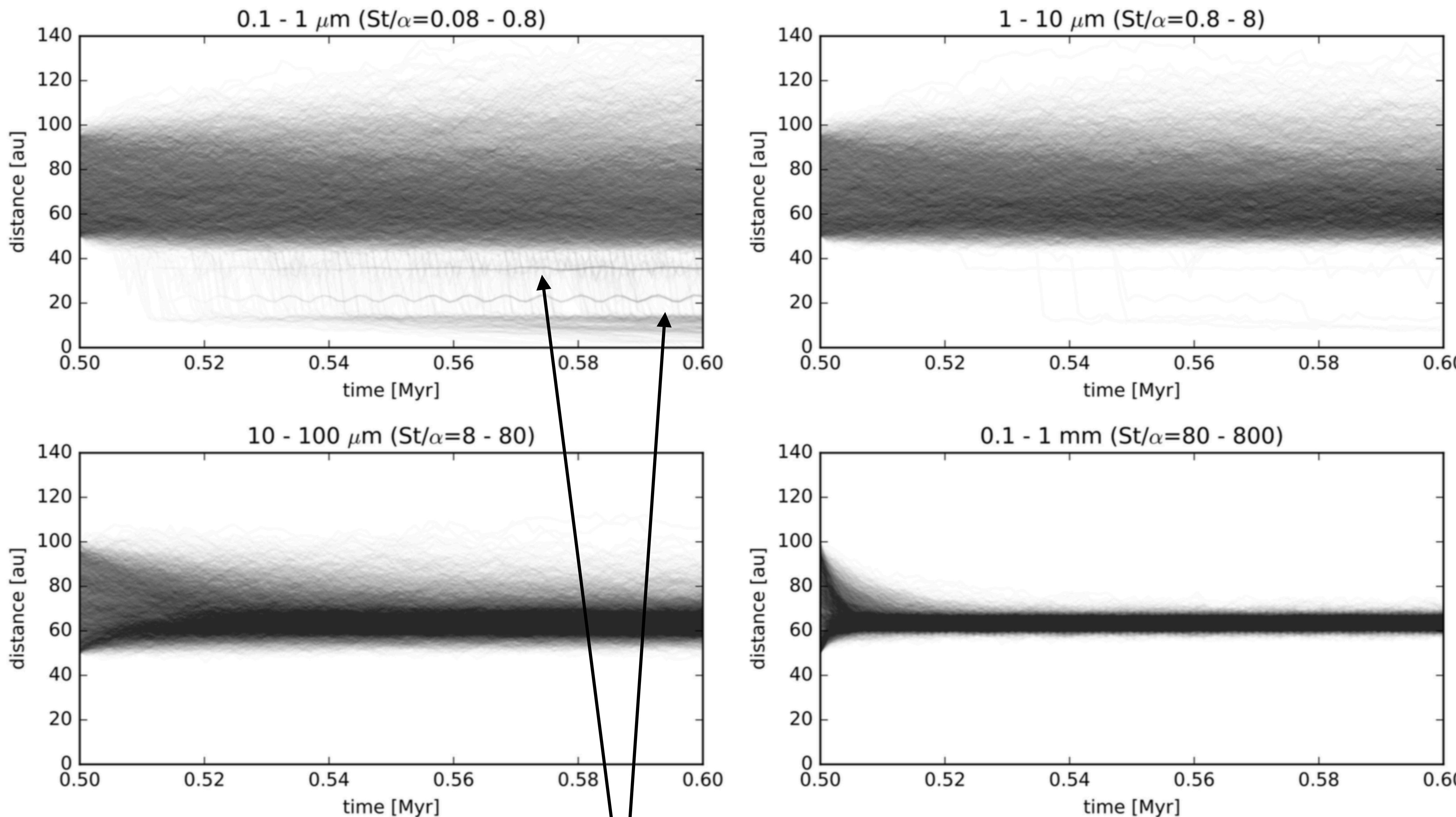
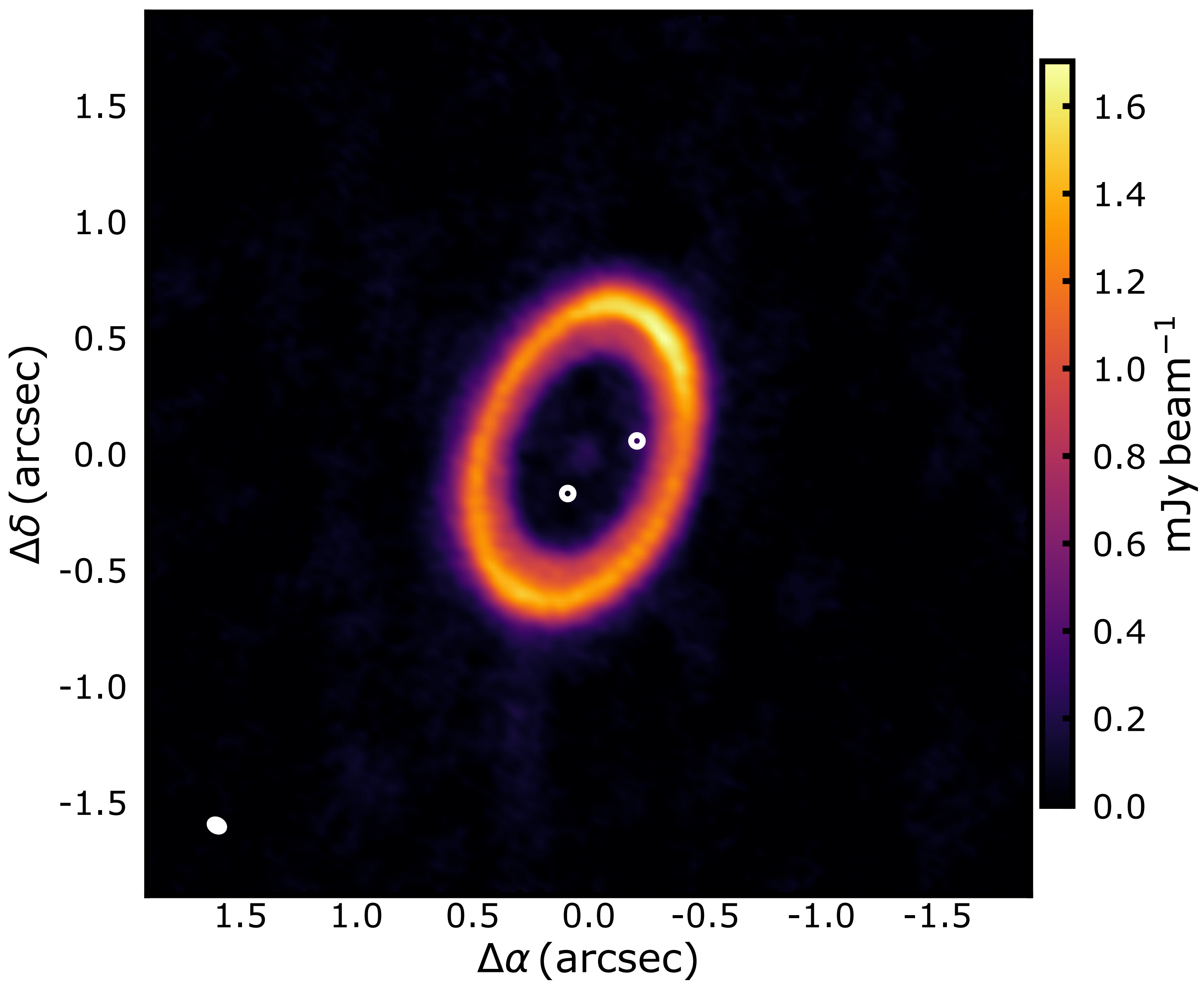


Small particles trapped in CPDs; to explain the observed flux grain growth is not sufficient; we need either dust trapping, or $\alpha_{CPD} < 10^{-5}$, or dust stalling in decretion disk scenario (Batygin & Morbidelli 2020)

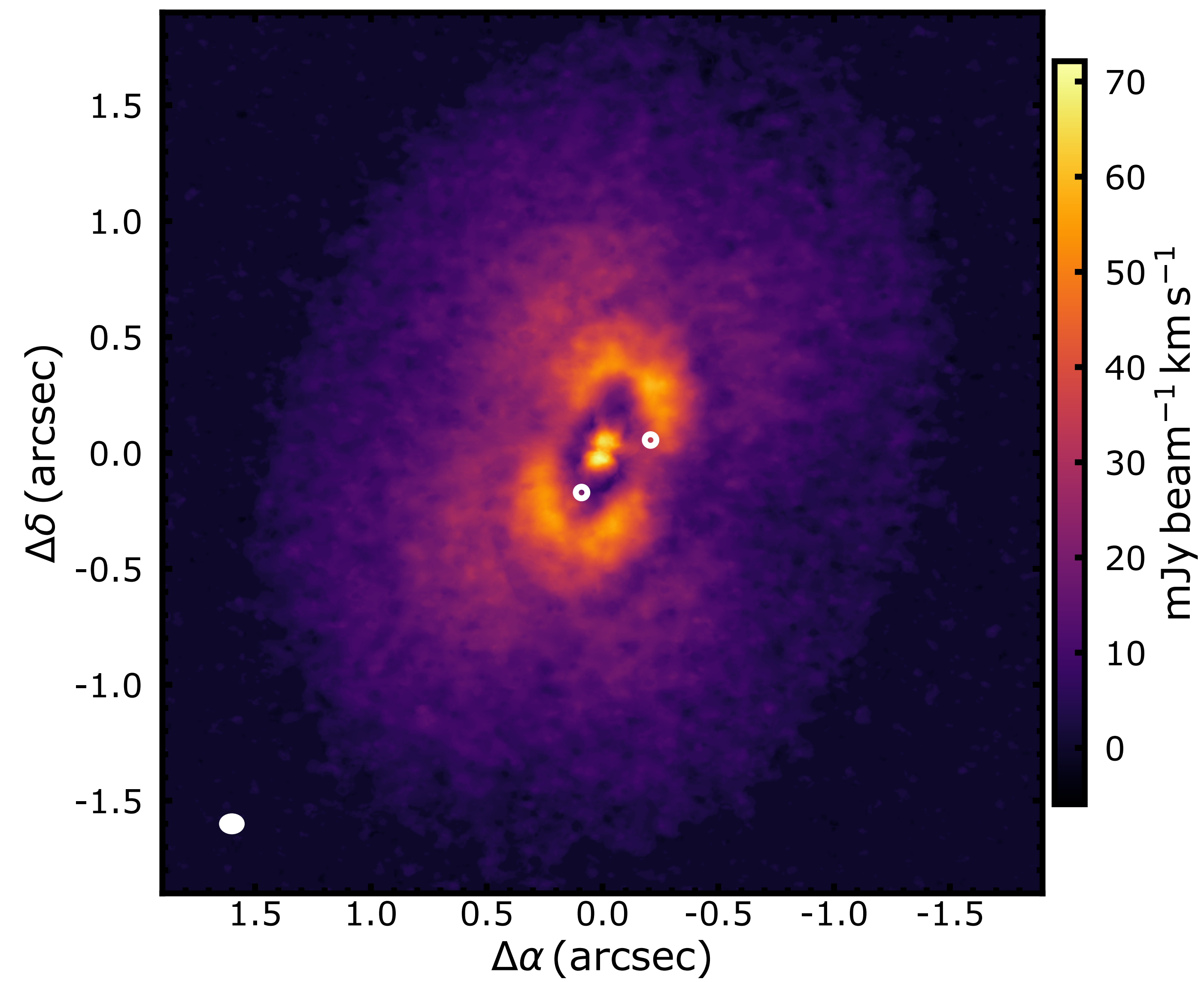
3D structure of PDS 70

Band 7 ALMA continuum



Data from Keppler,…,**SF**+2019

CO 3-2 moment 0



Data from Keppler,…,**SF**+in prep.

Large dust grains are well trapped in pressure maximum.

CO exhibits a deep gap co-located with orbital radius of planet b

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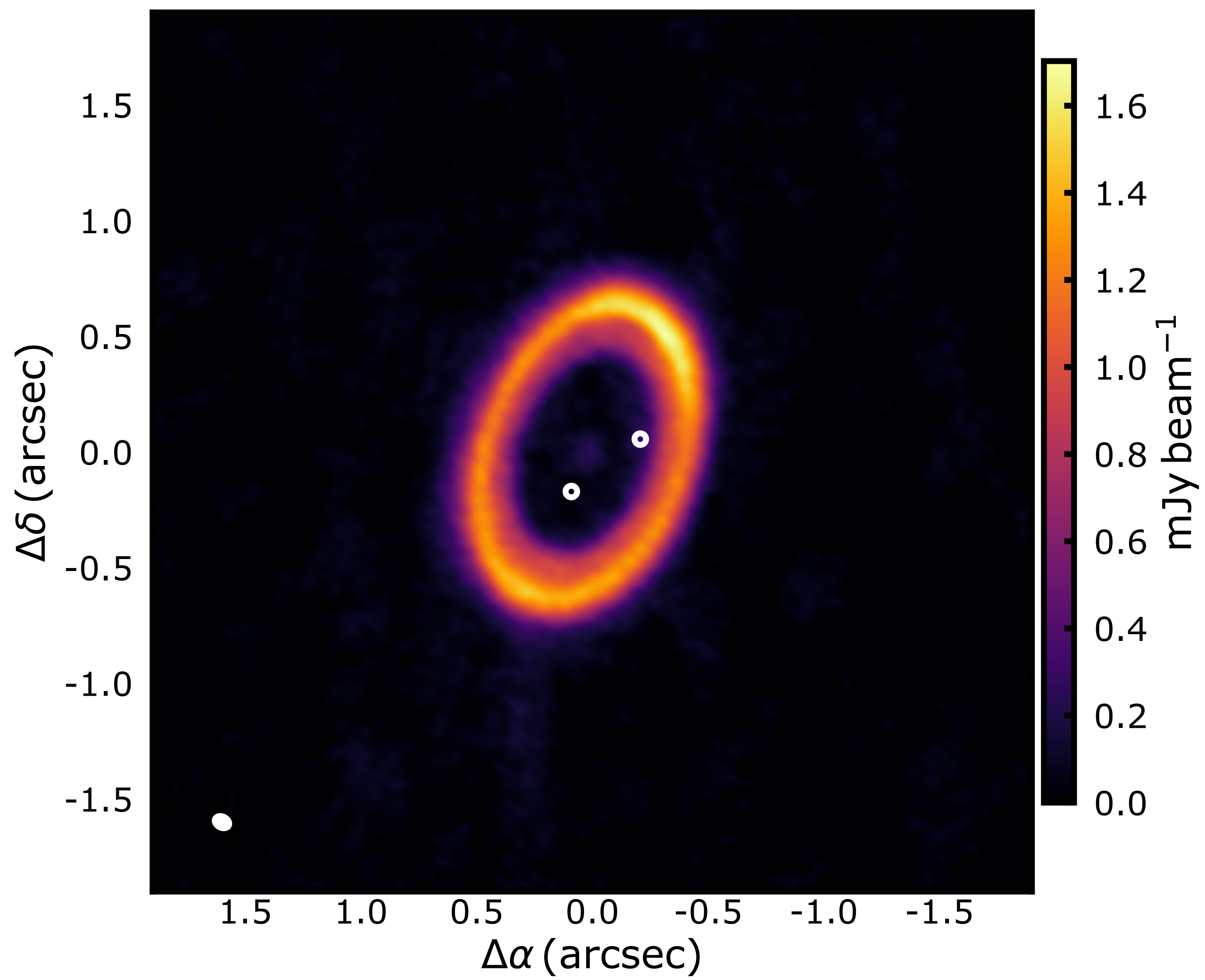

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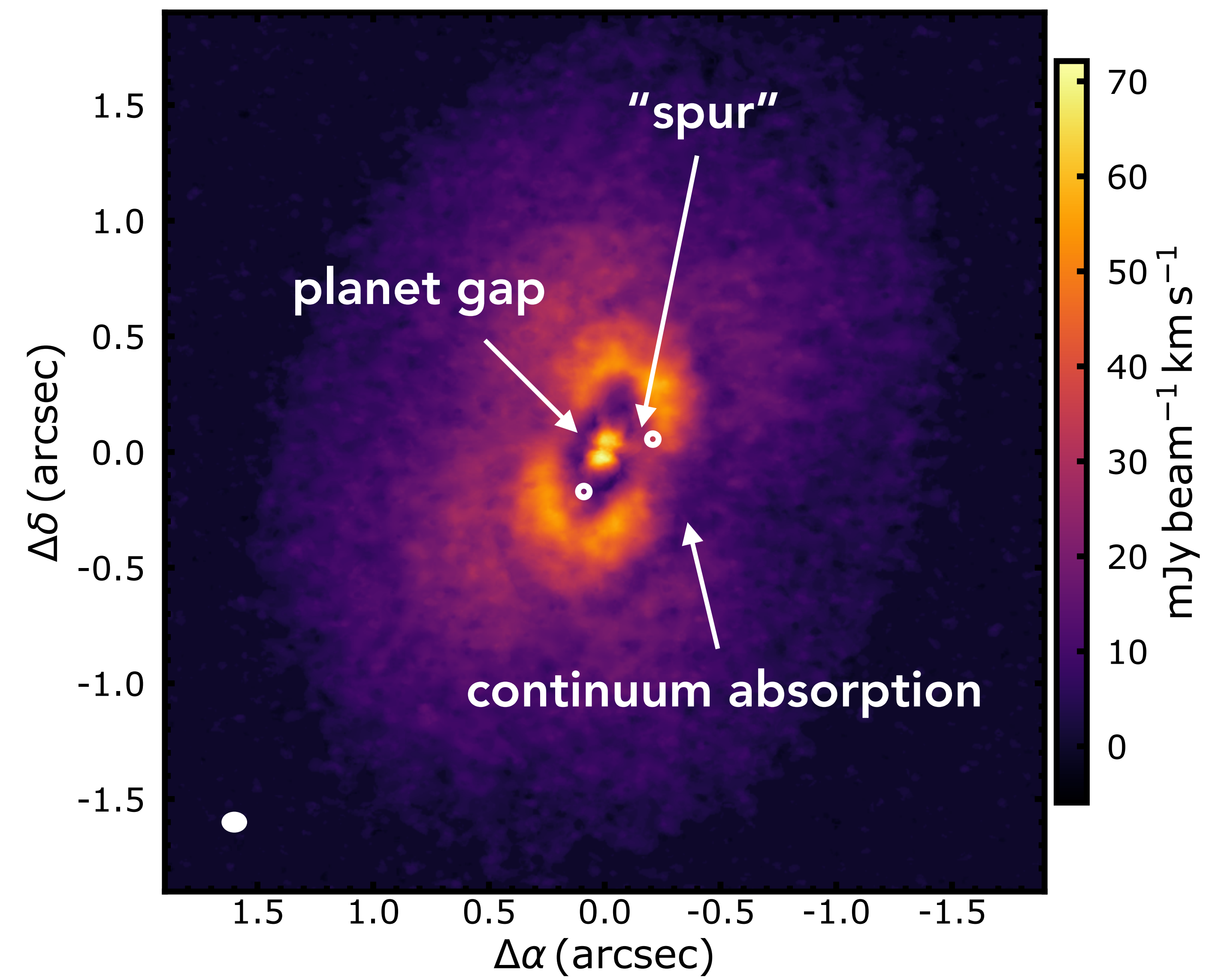

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Chemical program

ALMA Band 6 observations to image PDS 70
with 230 and 260 GHz spectral setups at ~0.1″ resolution

Compact configuration (~0.4-0.5″ resolution) observed
at ~ 1.3 - 2 K sensitivity on 0.5 km/s channel

Most relevant molecules covered:

^{12}CO, ^{13}CO, $C^{18}O$

$H^{13}CO^+$

C_2H, c-C_3H_2

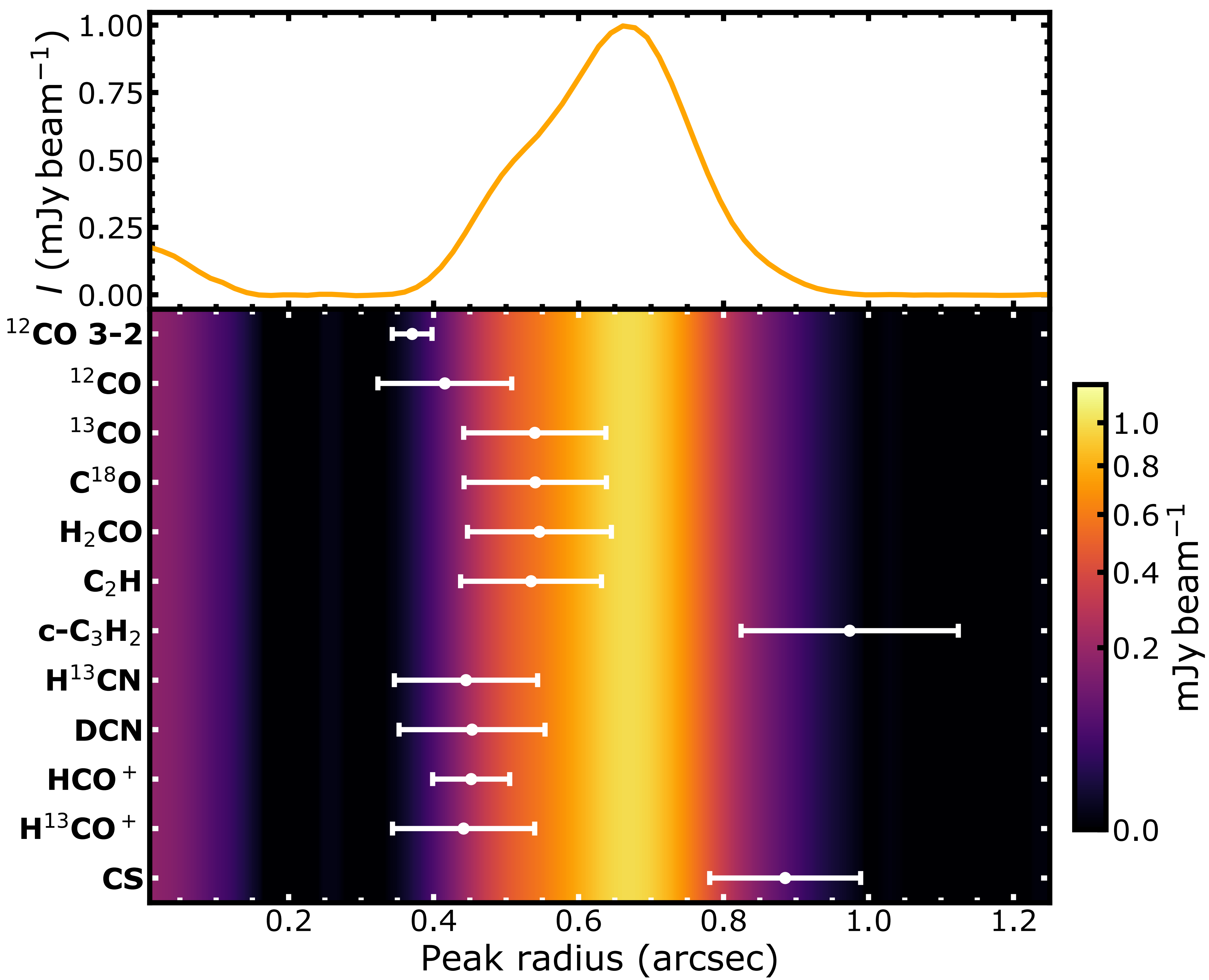
CS, SO

$H^{13}CN$, $HC^{15}N$, DCN

CH_3OH, H_2CO

Ancillary data (Band 7) on ^{12}CO 3-2, HCO^+ 4-3

Peak of radial profiles



^{12}CO: gas cavity wall

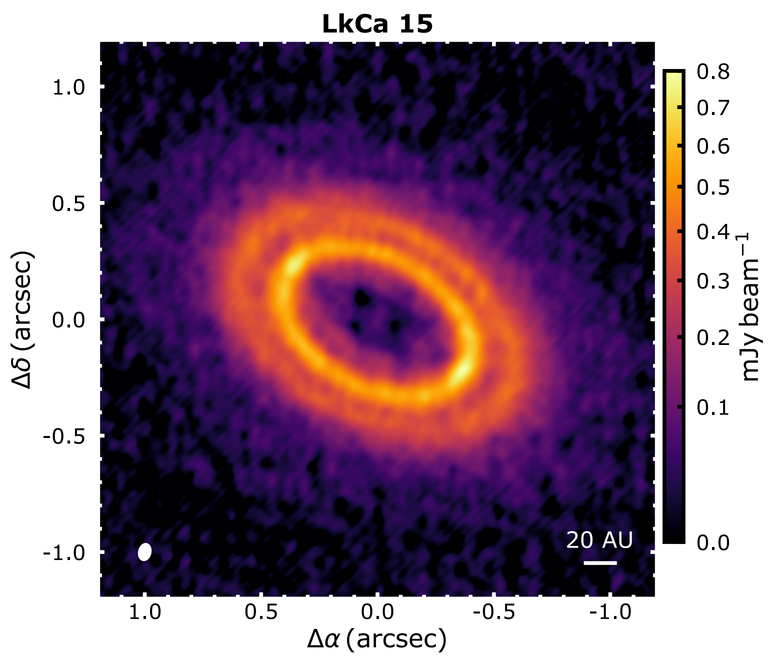
^{13}CO/C^{18}O: between density peak and cavity wall

Cyanides/H^{13}CO^{+}: dust cavity wall

C_2H/H_2CO: between density peak and cavity wall

CS: outside continuum ring

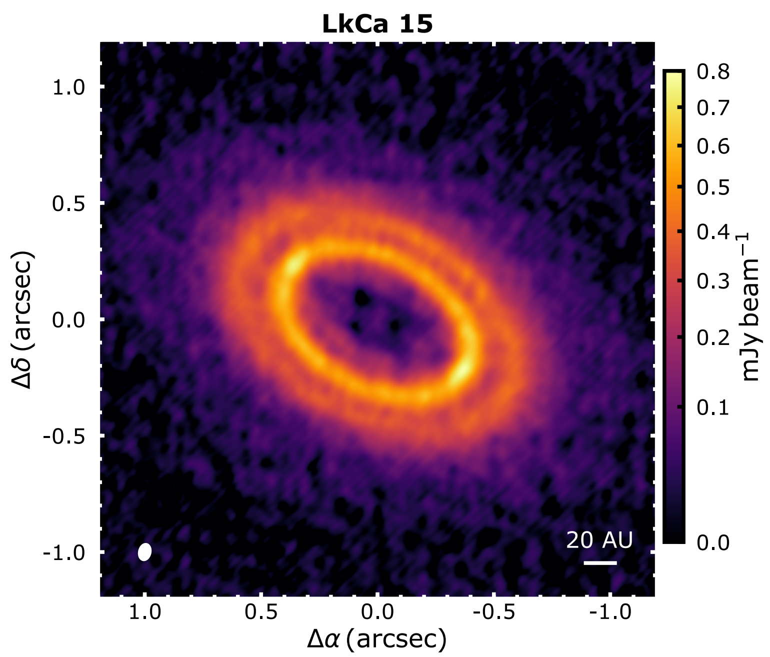
Conclusion



Gaps and rings observed in a few transition disks around TTauri stars in the bright dust ring enclosing the inner cavity

Annular substructure in TDs may be showing sequential planet formation, but friction with pebble accretion theory

Conclusion



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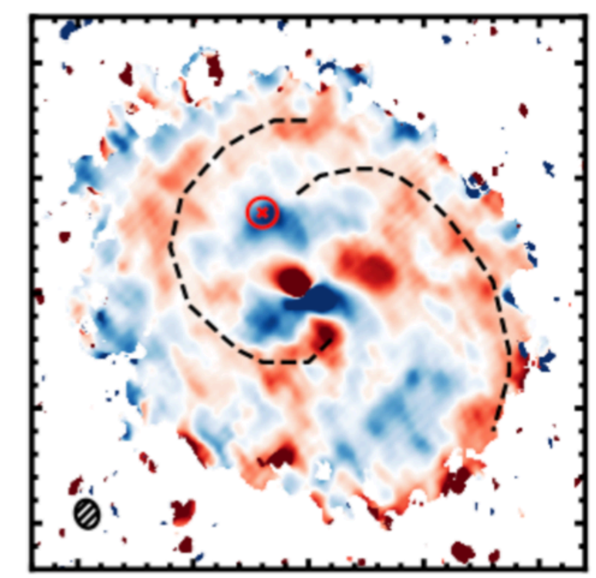
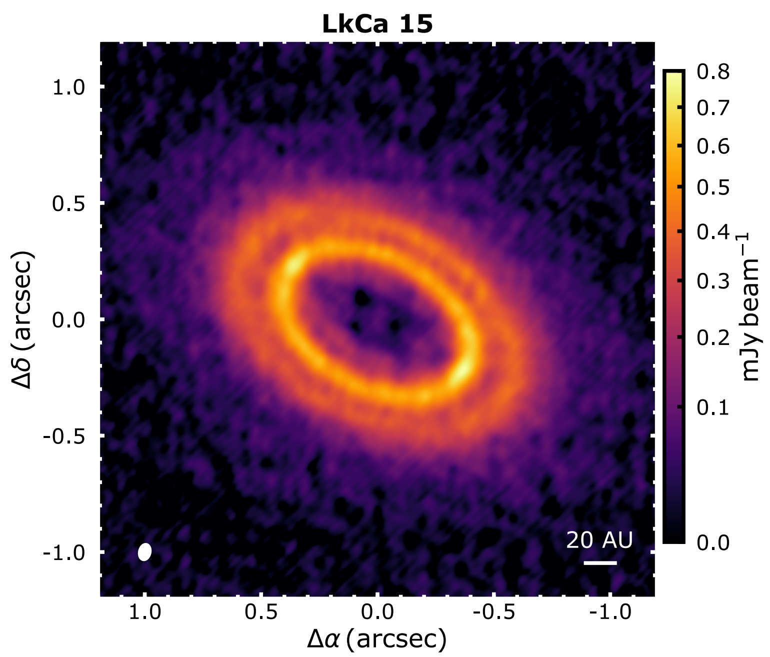


Kinematical pattern can show indication of dynamical perturbation caused by an embedded planet

Conclusion



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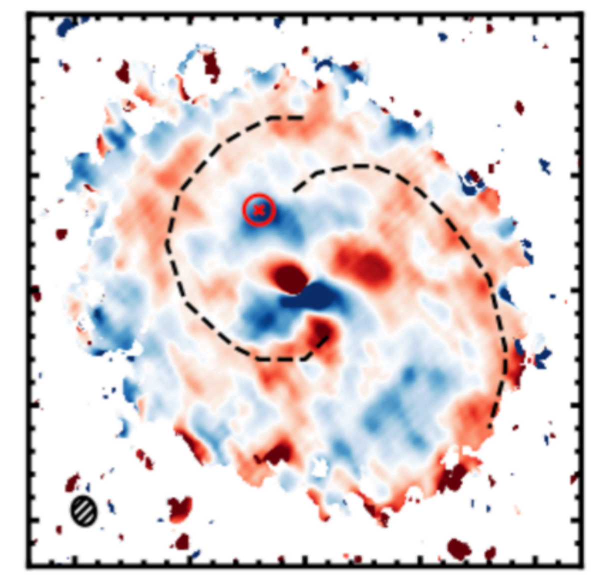

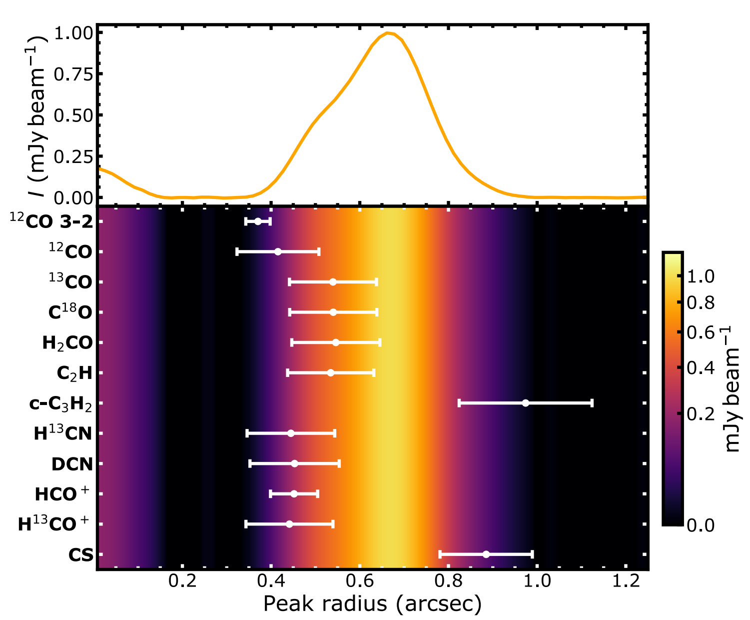

We can probe the chemical inventory of planet hosting disks, seeing elemental ratios of gas material being advected towards the planets

Edge of the cavity (close to planet c) is the best location where to characterize chemical abundances, directly accessing properties of accreting gas