

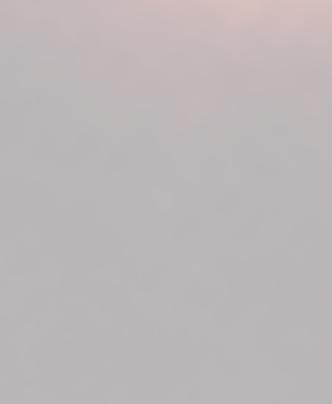
The physico-chemical connection between nascent planets and their birth environment

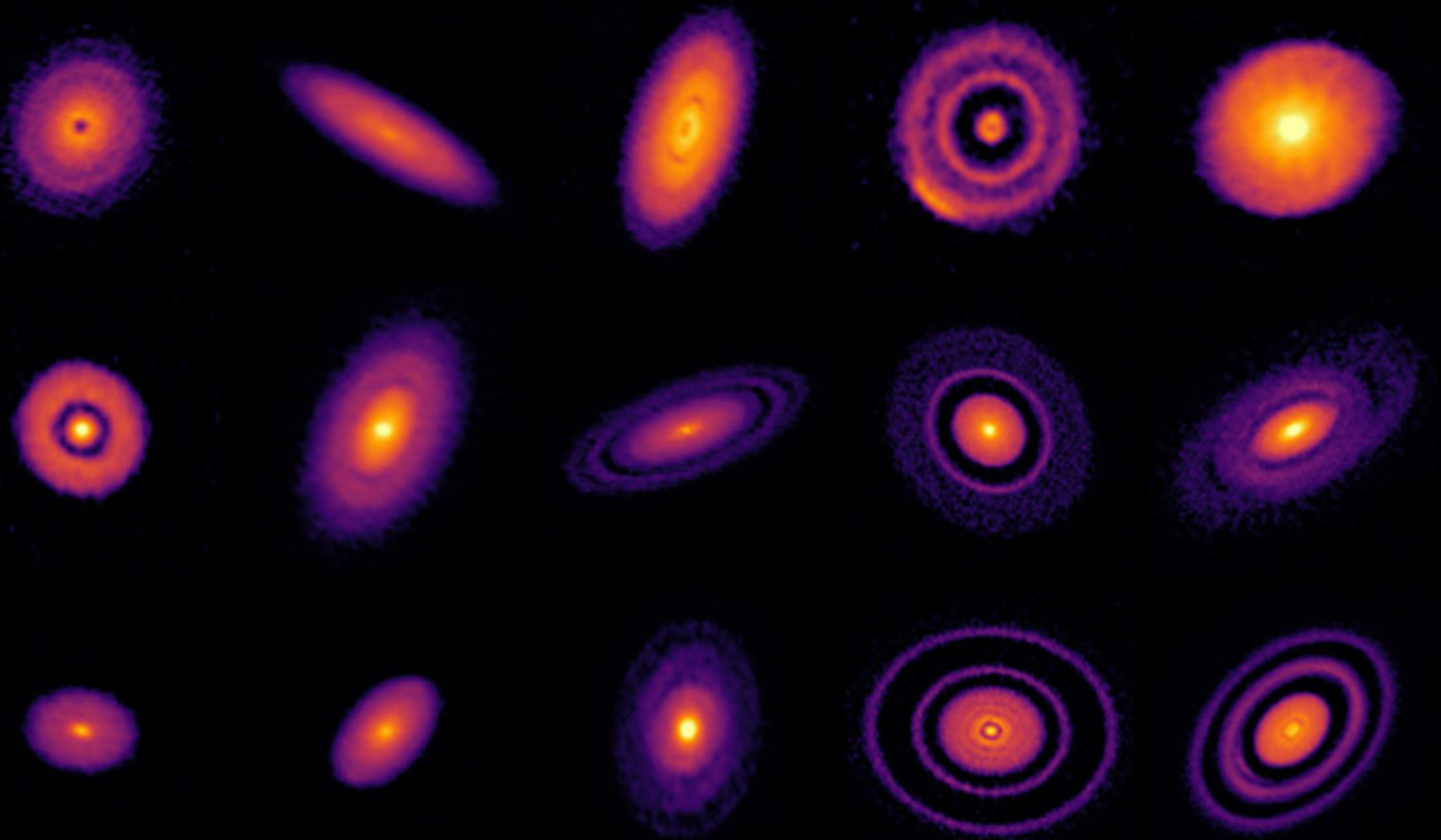
In collaboration with:

M. Benisty, M. Fukagawa, C. Pinte, R. Teague, and the exoALMA collaboration;

J. Bae, **P. Curone**, E. Humphreys, A. Isella, **A. Izquierdo**, **C. Law**, G. Lodato,

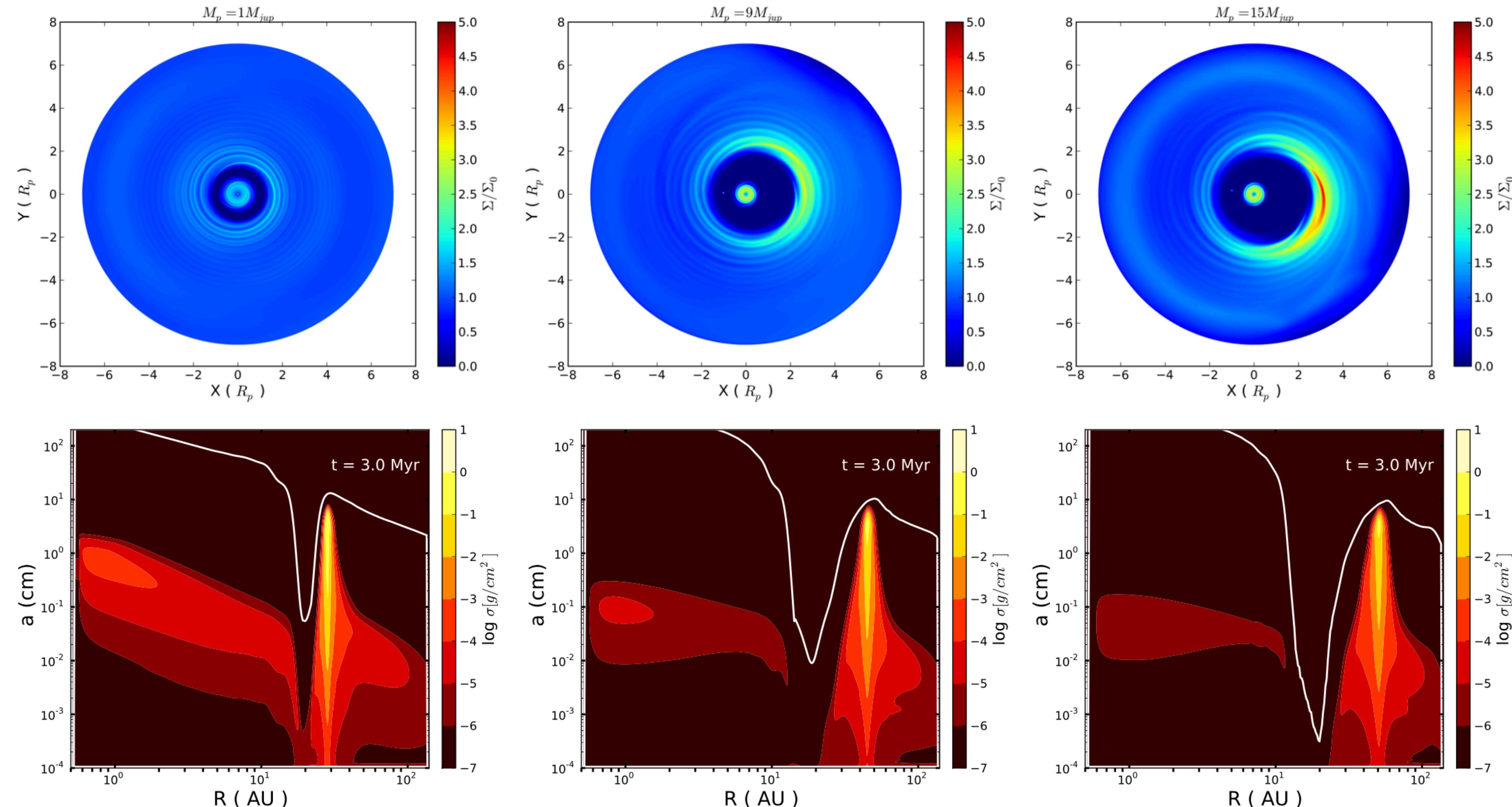
V. Pezzotta, L. Rampinelli, G. Rosotti, L. Testi, and many others





Andrews+2018

Massive planets are expected to create massive traps



Open questions

How do embedded planets affect the physico-chemical structure of their host environment?

What is the origin of substructures? Are they (all) due to planets?

How do hydrodynamics and chemistry promote planet formation?

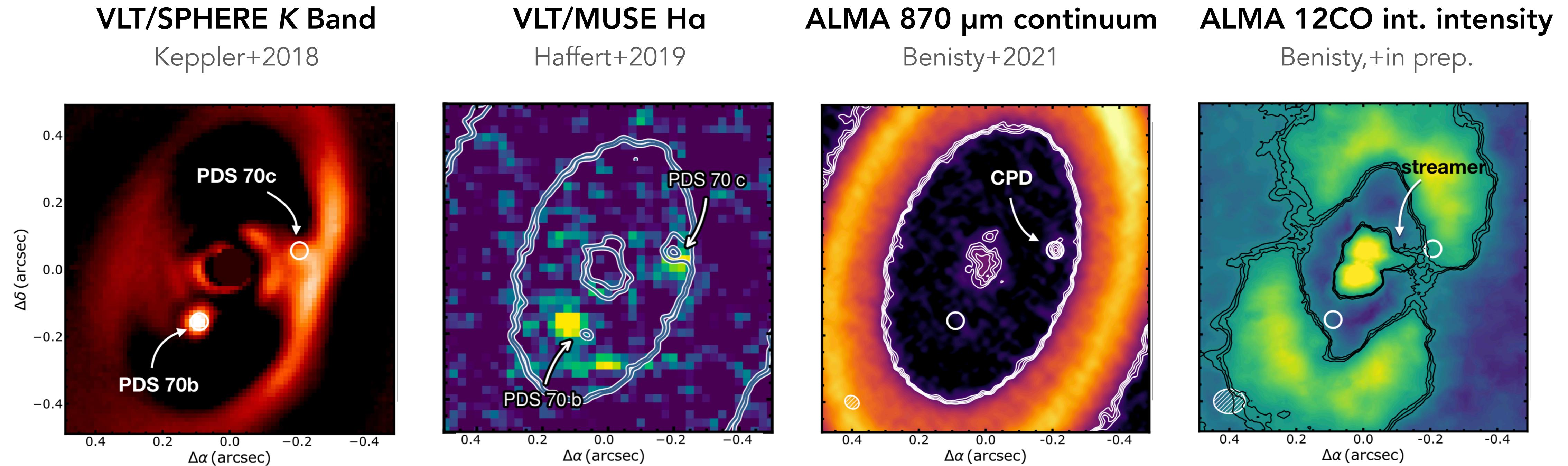
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A benchmark case: PDS 70



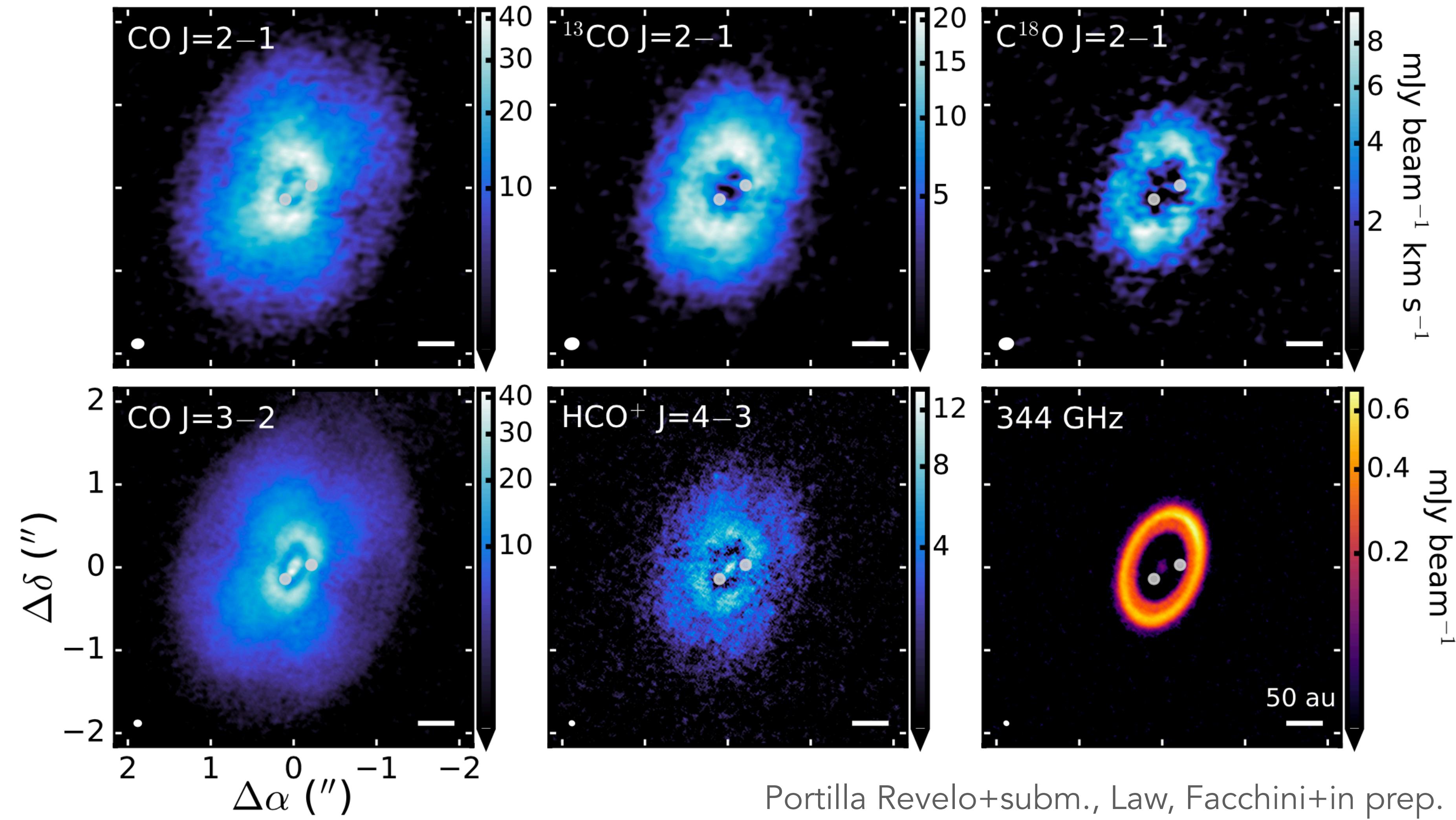
First (and only) accreting planets directly detected in a protoplanetary disk

A detection of a circumplanetary disk



Benisty, Bae, Facchini+2021

Effects on density



Portilla Revelo+subm., Law, Facchini+in prep.

Gas intensity (density structure) affected by planets carving gaps

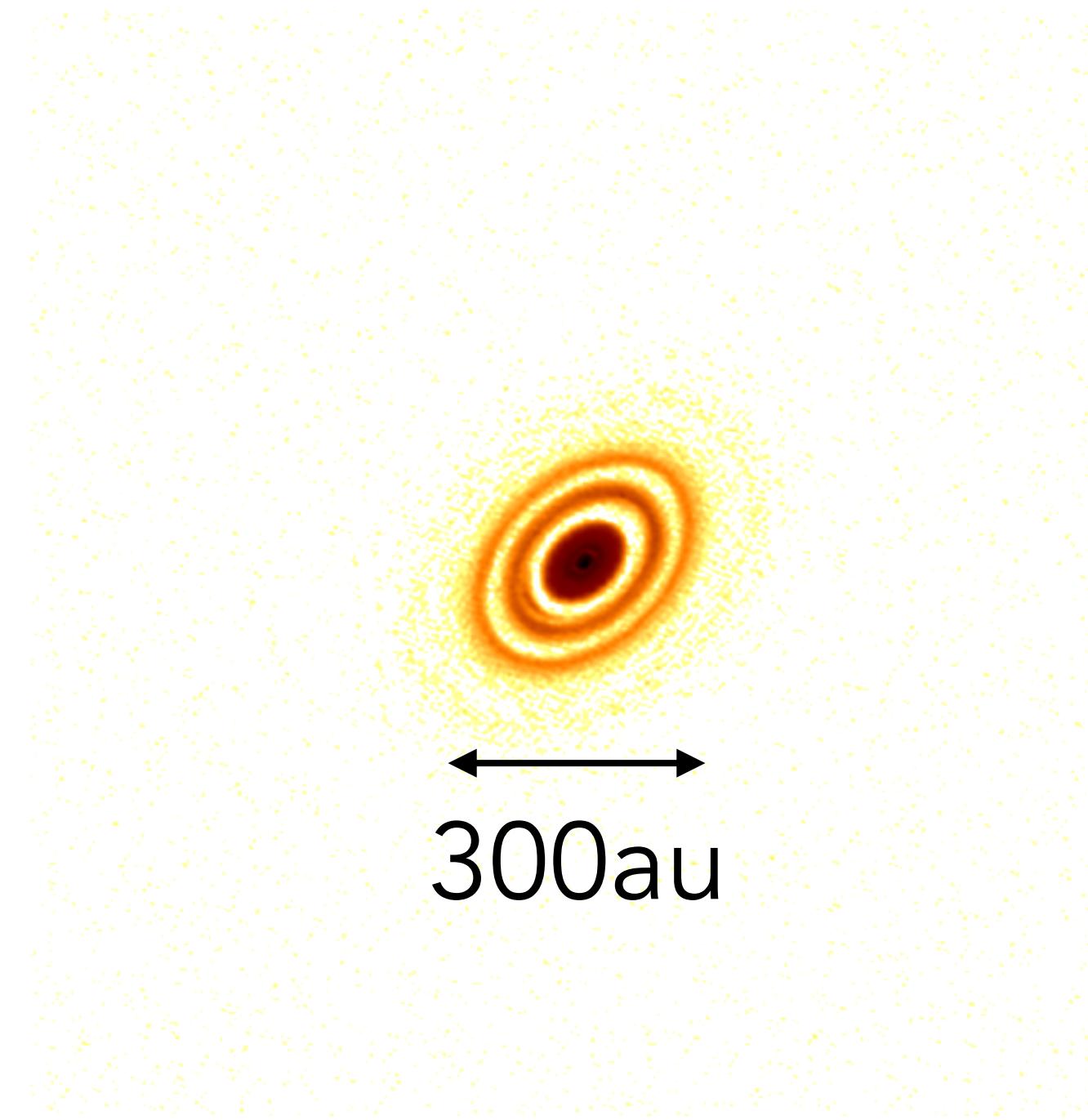
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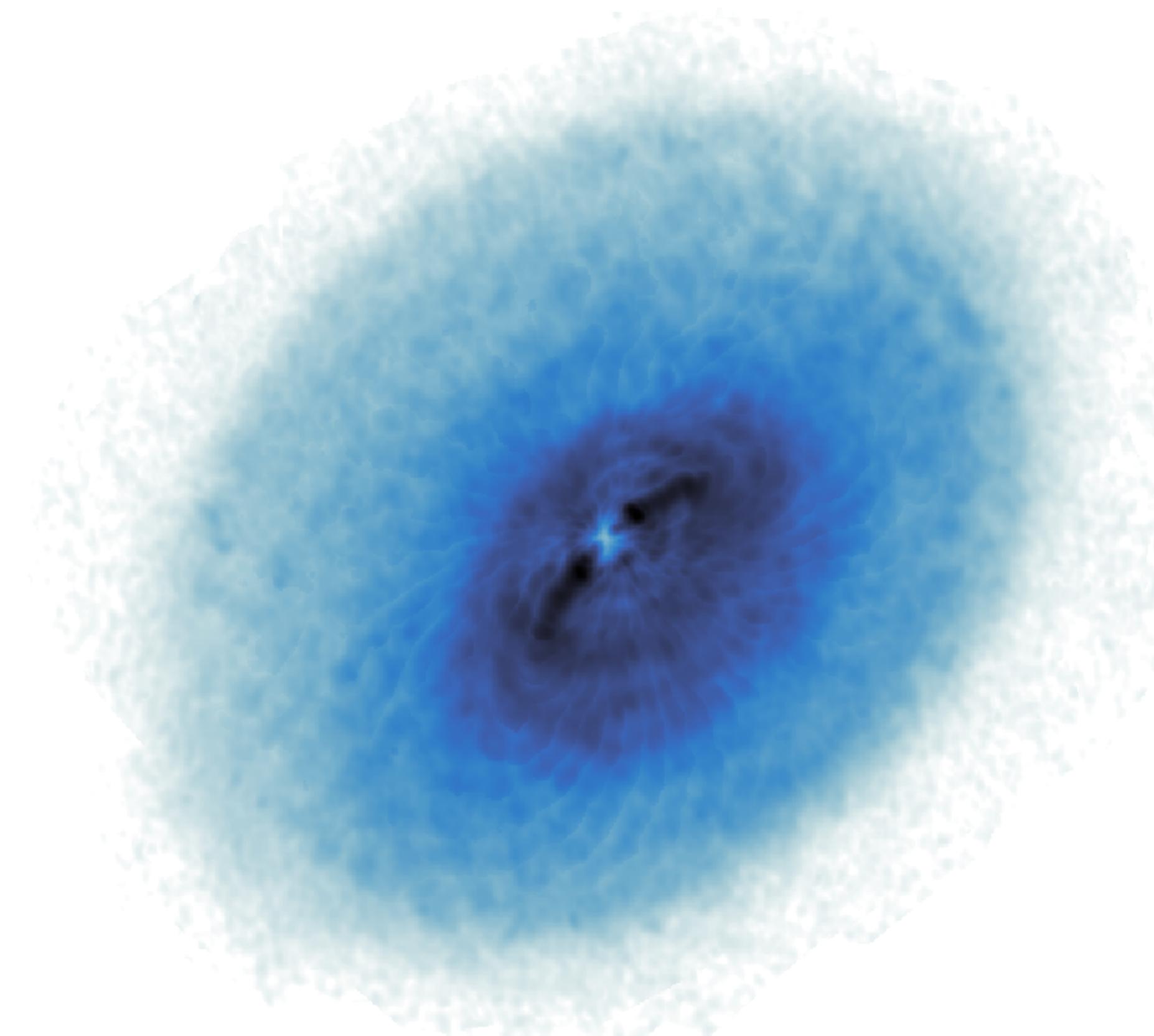
How do hydrodynamics and chemistry promote planet formation?

Typical maps of protoplanetary disks



Data from Andrews+2018, Huang+2018, Isella+2018

Typical maps of protoplanetary disks

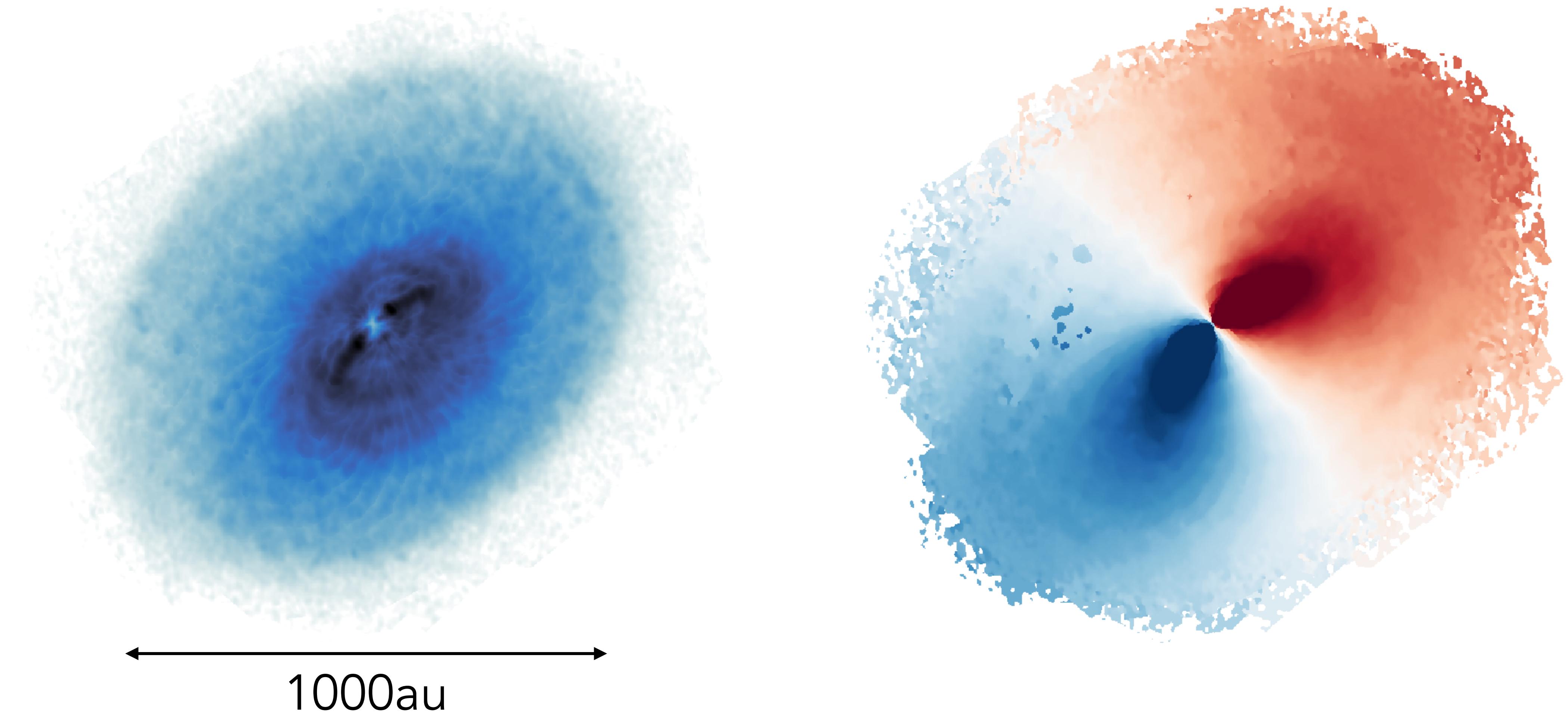


1000au

Gaseous disks significantly larger than mm continuum disks

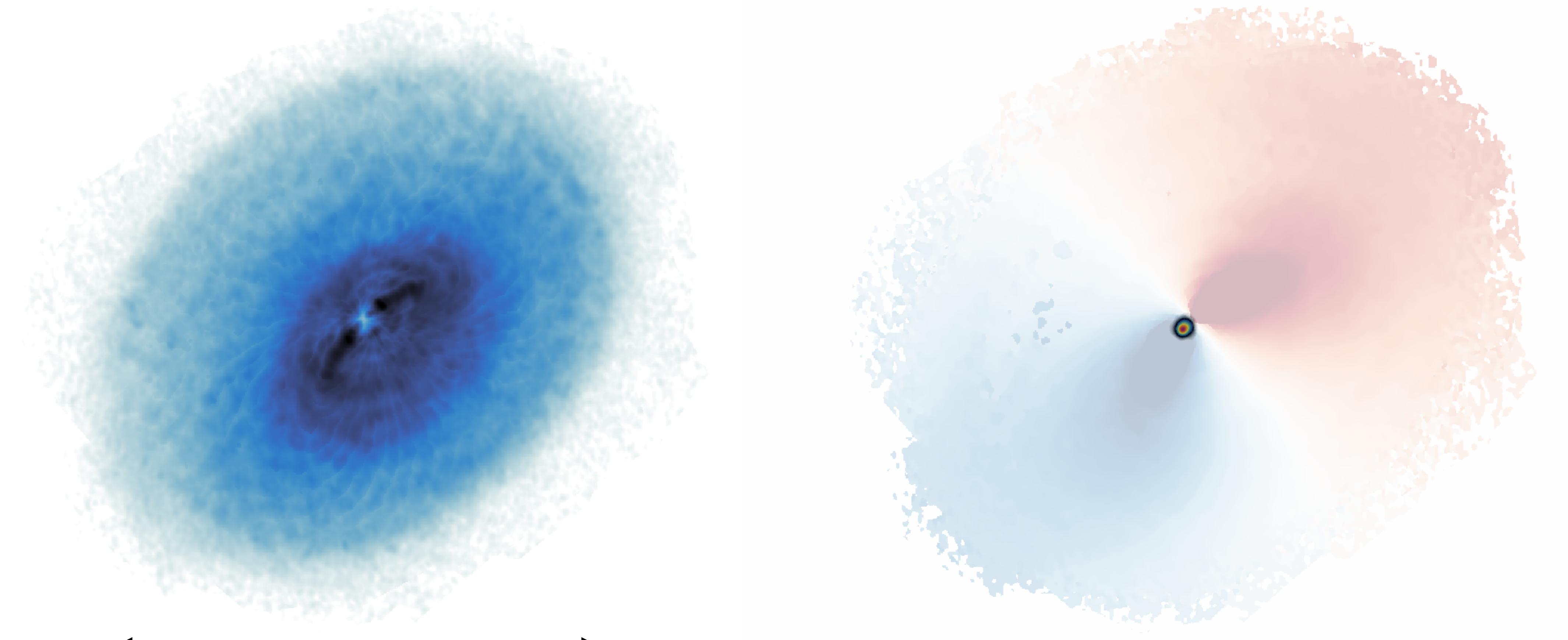
Data from Öberg+2021, Czekala+2021, Law+2021, Teague+2021

Typical maps of protoplanetary disks



It is possible to extract a velocity field for the whole disk

Typical maps of protoplanetary disks

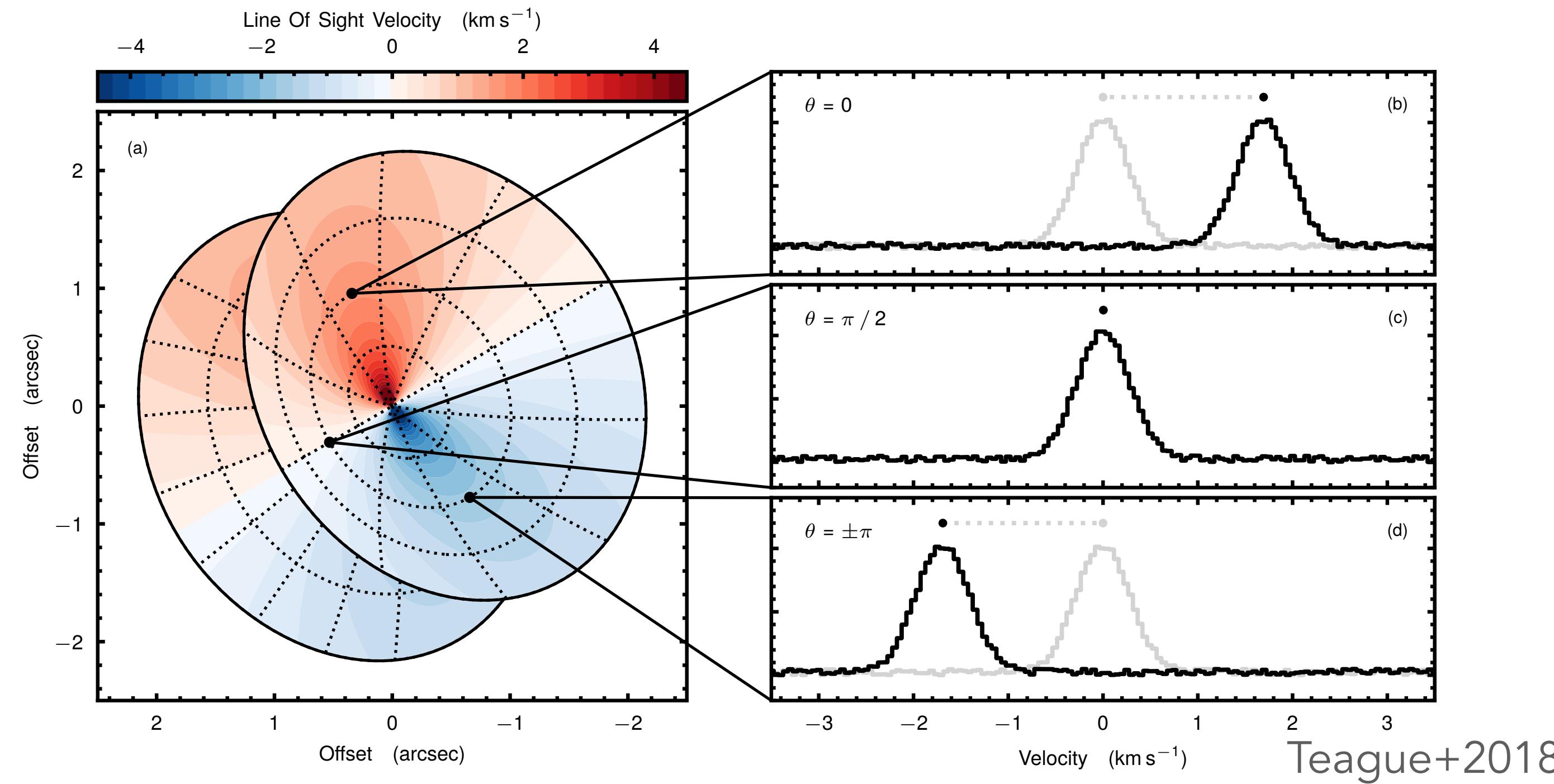


Channel maps trace isovelocity contours

Data from Öberg+2021, Czekala+2021, Law+2021, Teague+2021

Velocity decomposition

We can decompose the velocity in three orthogonal components
(with ~ 10 m/s precision assuming azimuthal symmetry)



$$v_0 = \underbrace{v_\phi \cos(\phi) \sin(|i|)}_{\text{rotational}} + \underbrace{v_r \sin(\phi) \sin(i)}_{\text{radial}} - \underbrace{v_z \cos(i)}_{\text{vertical}} + v_{\text{LSR}}$$

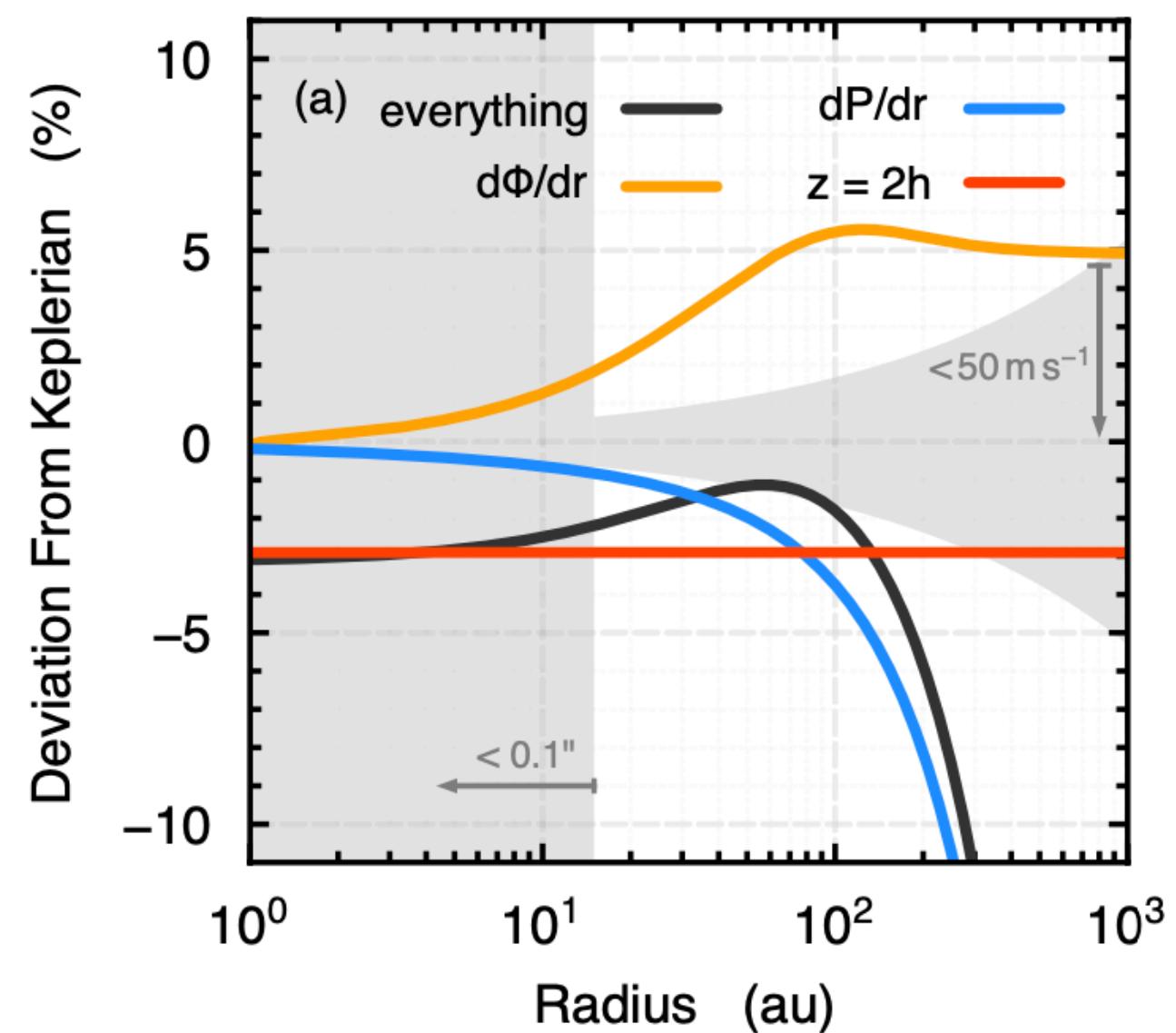
systemic

See conerot (Cassassus+2021), eddy (Teague 2019), discminer (Izquierdo+2021,2023)

Azimuthal component (rotation)

$$\frac{v^2}{r} = \frac{GM_*r}{(r^2 + z^2)^{3/2}} + \frac{1}{\rho_{\text{gas}}} \frac{\partial P_{\text{gas}}}{\partial r} + \frac{\partial \phi_{\text{gas}}}{\partial r}$$

————— stellar gravity ————— pressure support ————— self-gravity

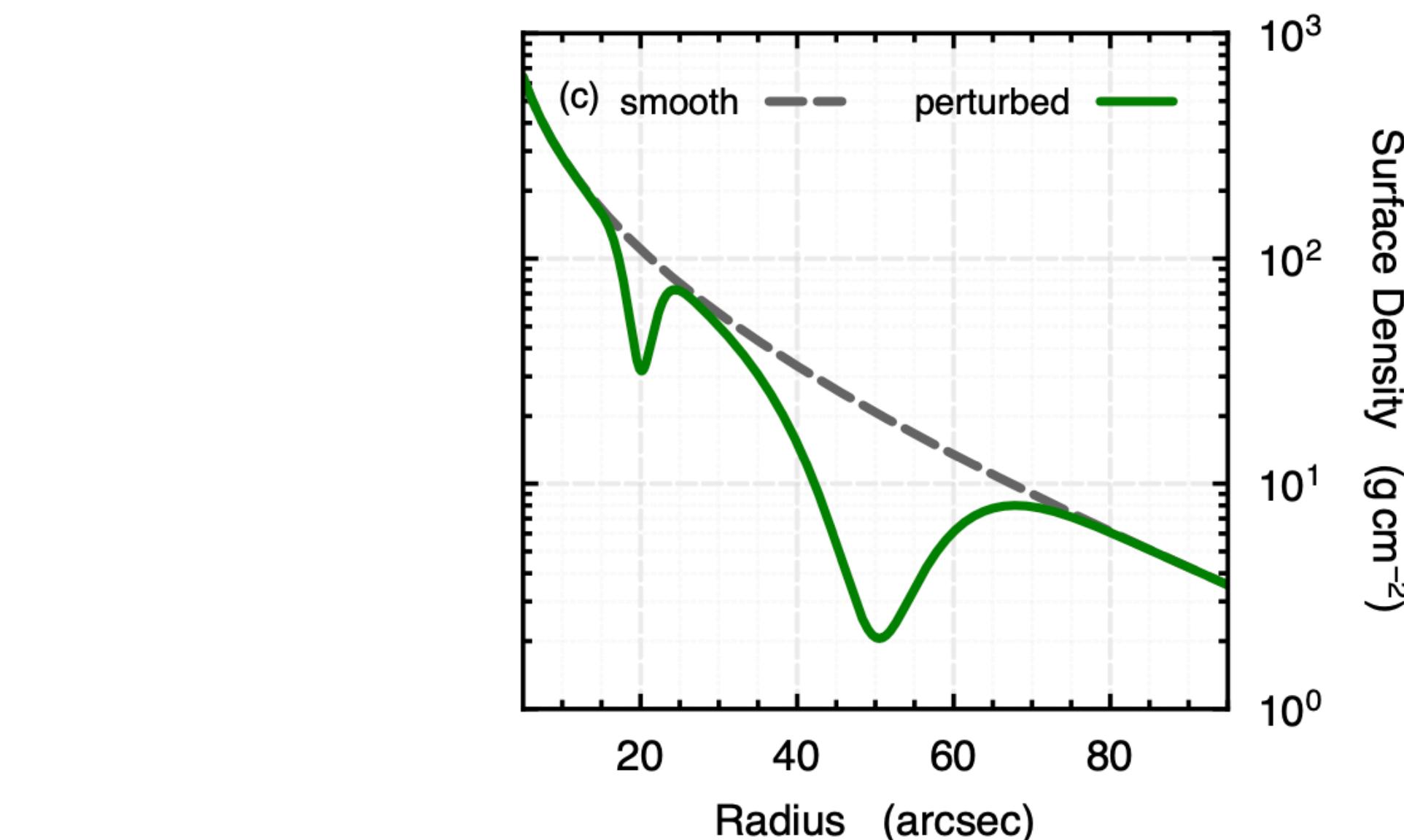
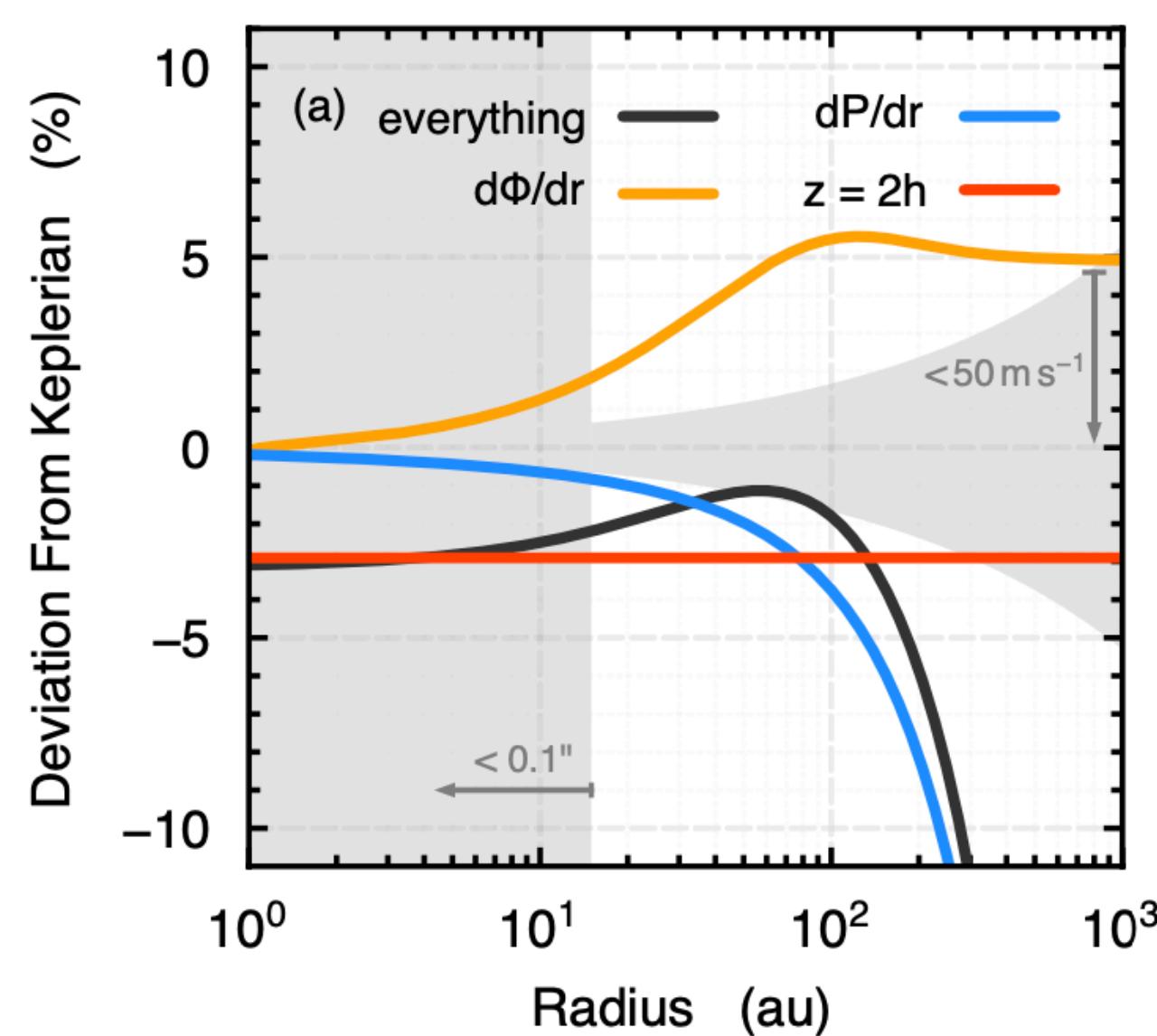


While stellar gravity dominates, we have the precision to measure pressure gradients and self-gravity in a few cases

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stellar gravity pressure support self-gravity

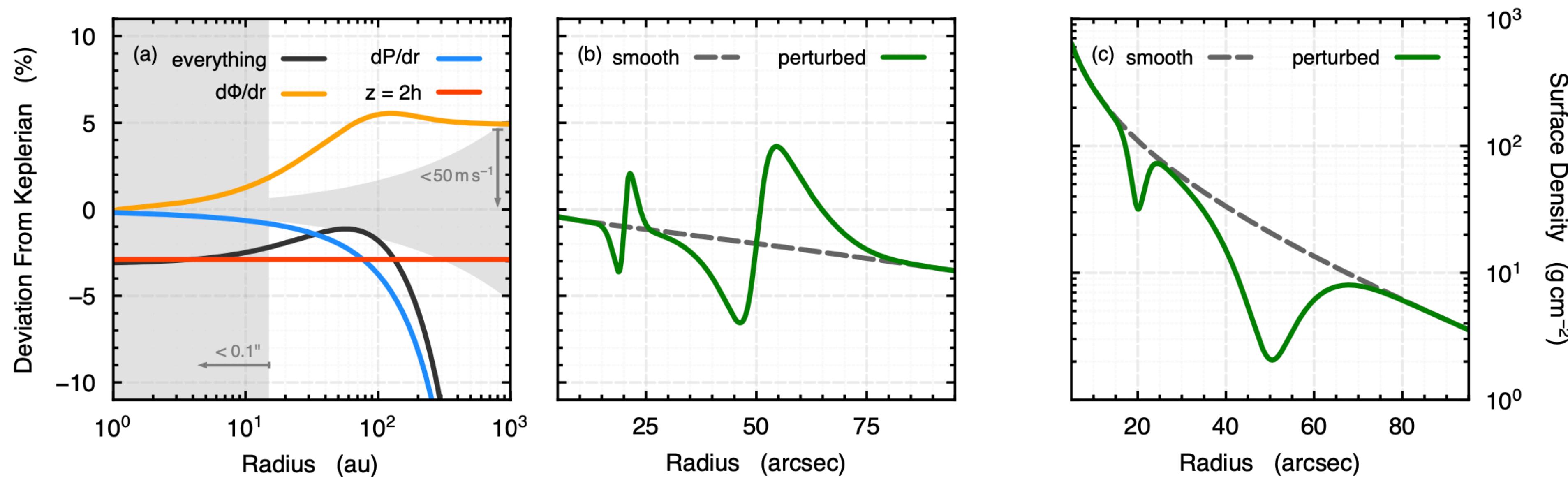


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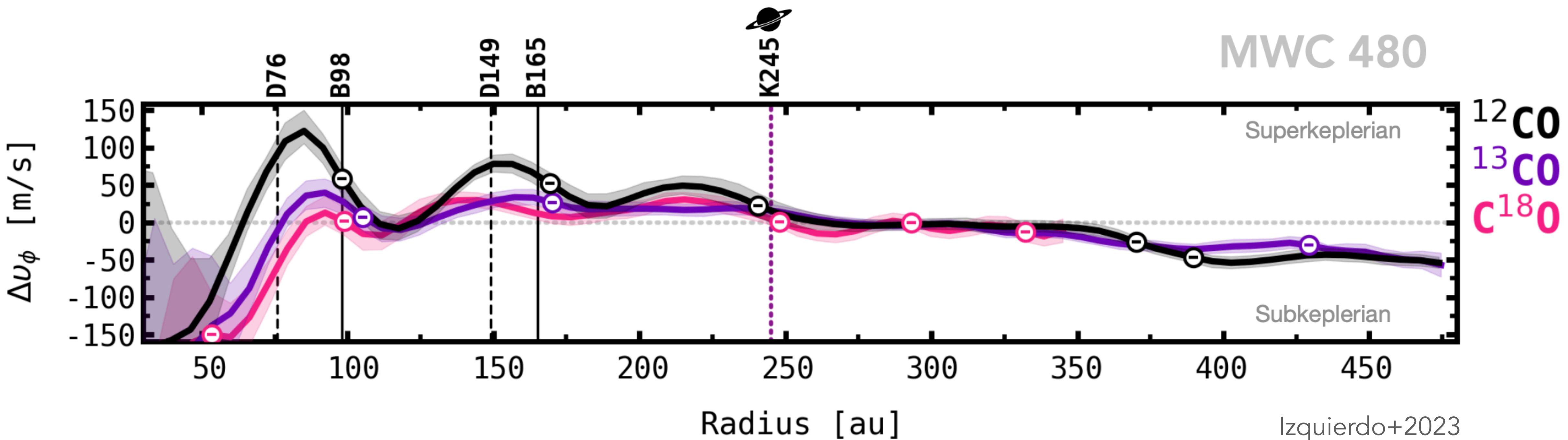
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Pressure substructure

Seven disks analysed to reconstruct pressure profiles from precise rotation curves



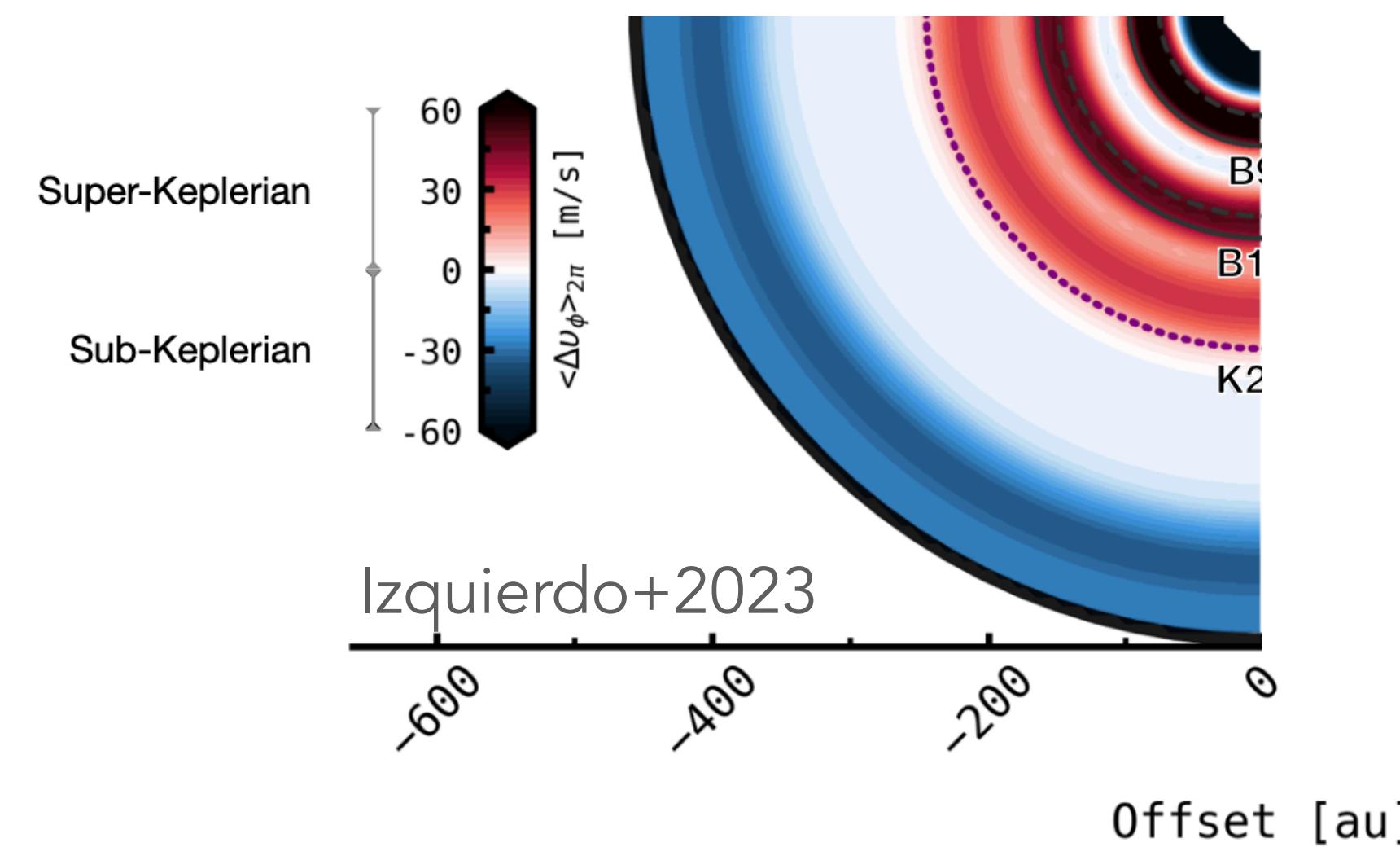
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Velocity

MWC 480

^{12}CO



Teague+2018b,c, Rosotti+2020, Yu+2021, Izquierdo+2022,2023

Pressure substructure

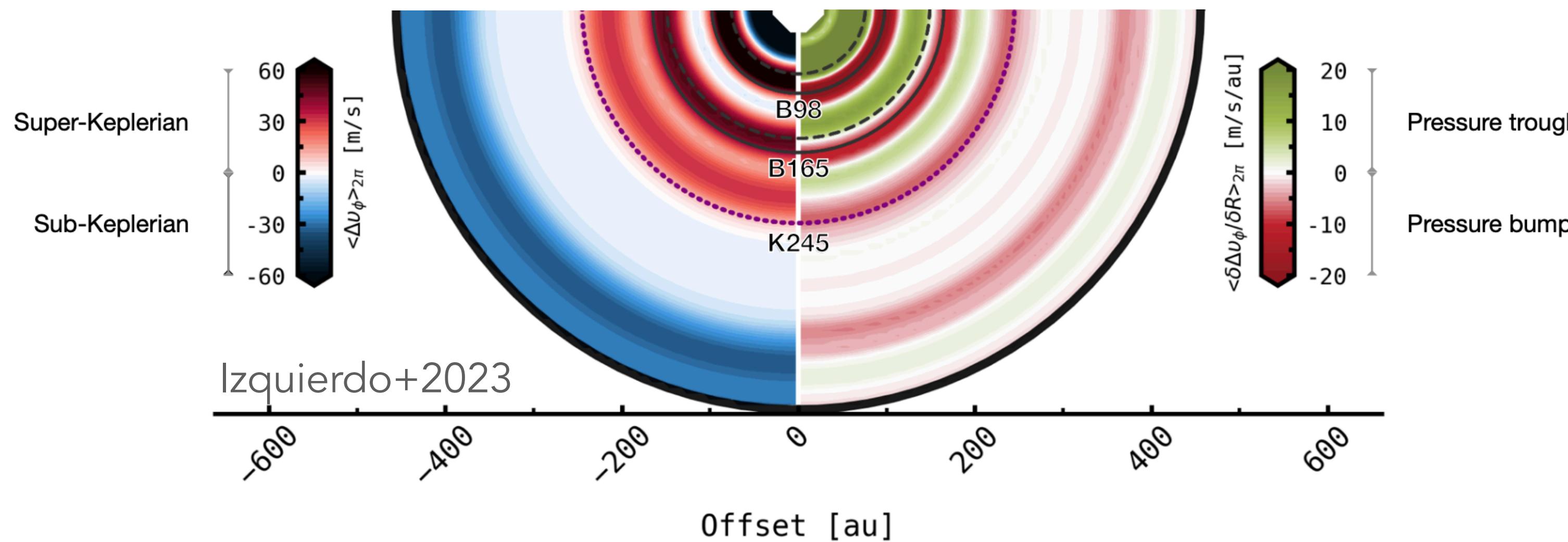
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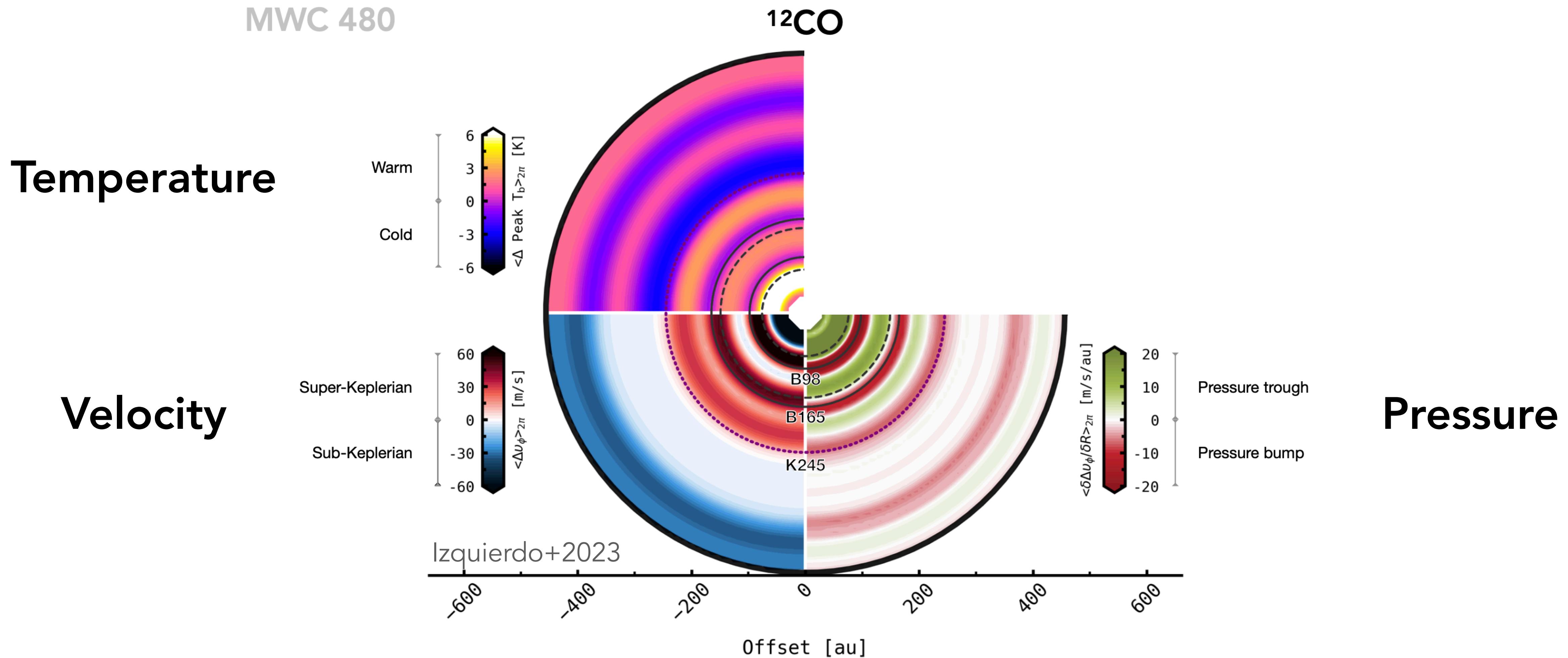
^{12}CO

Pressure



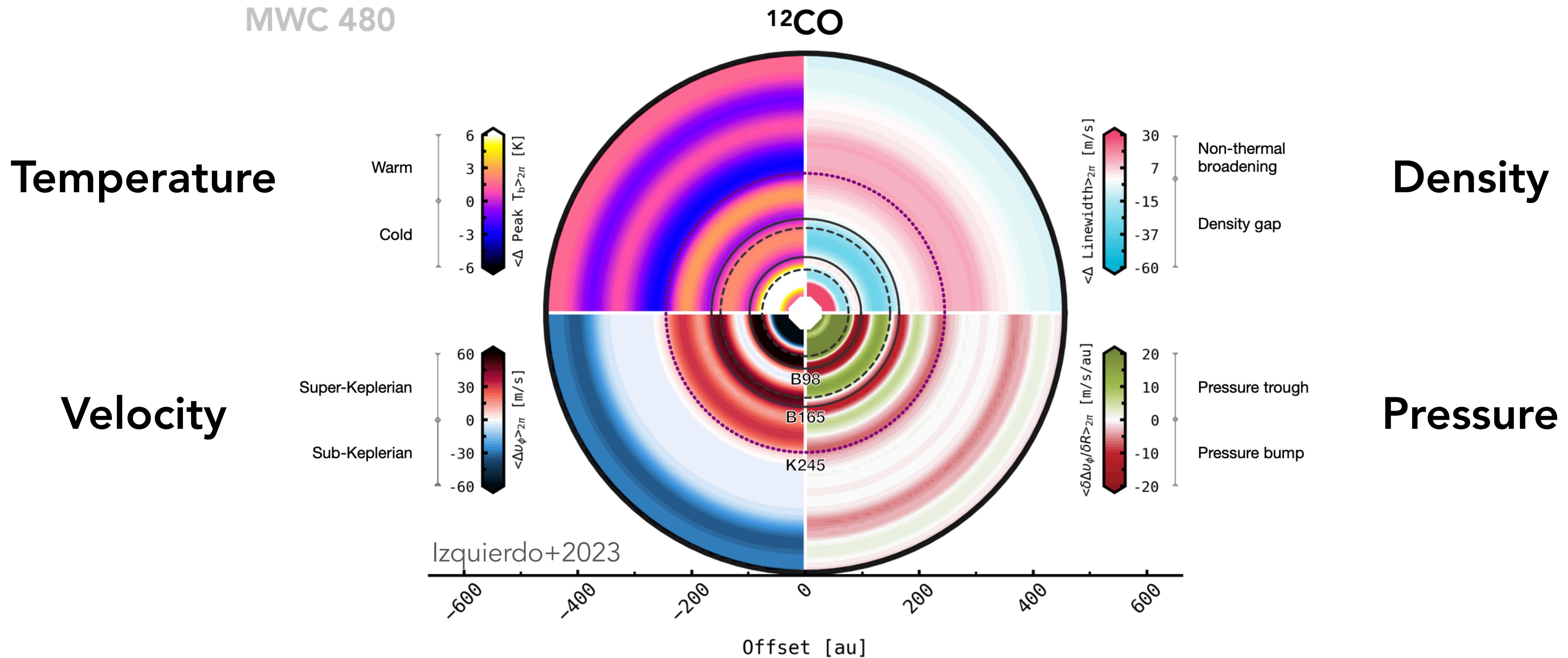
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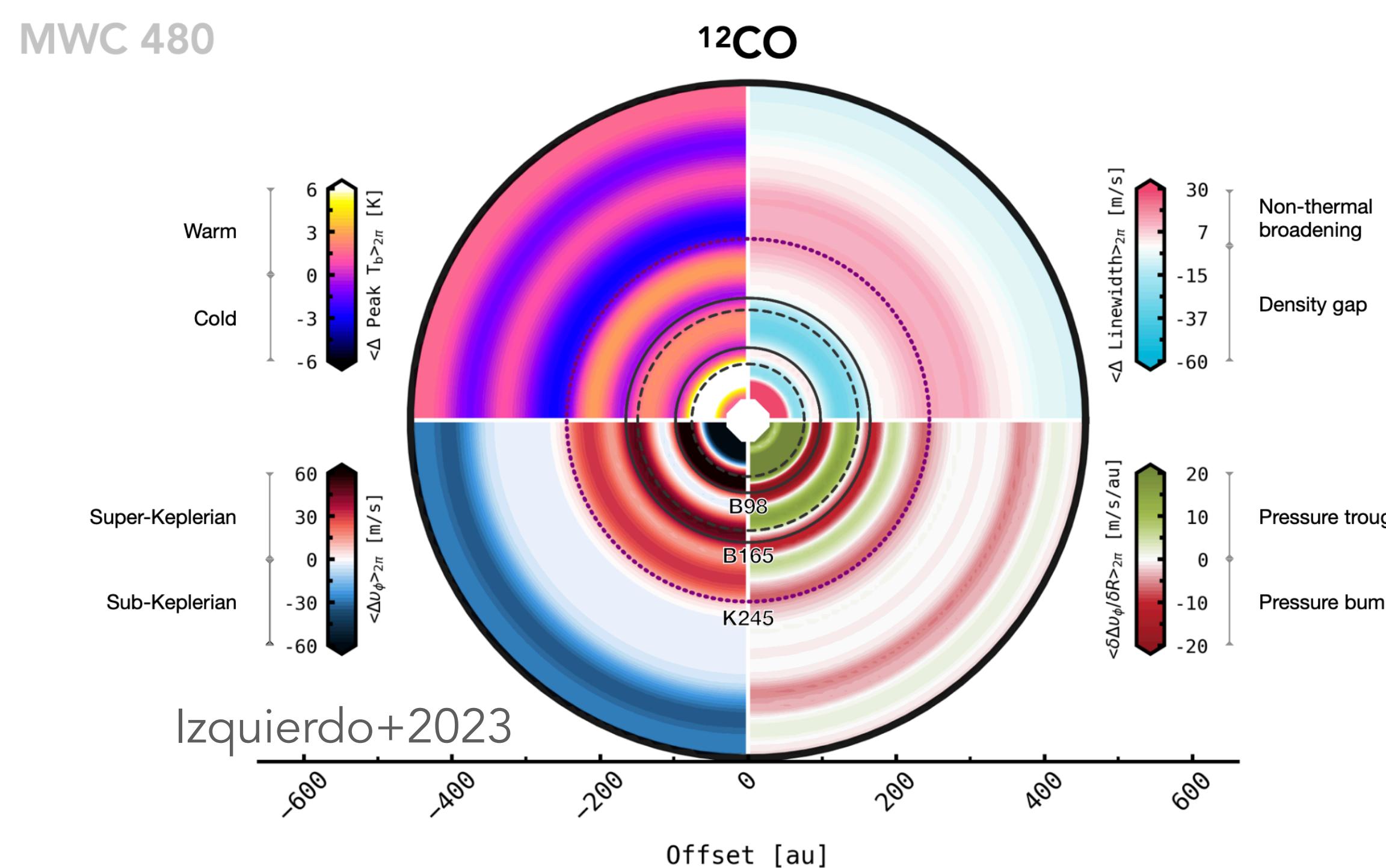
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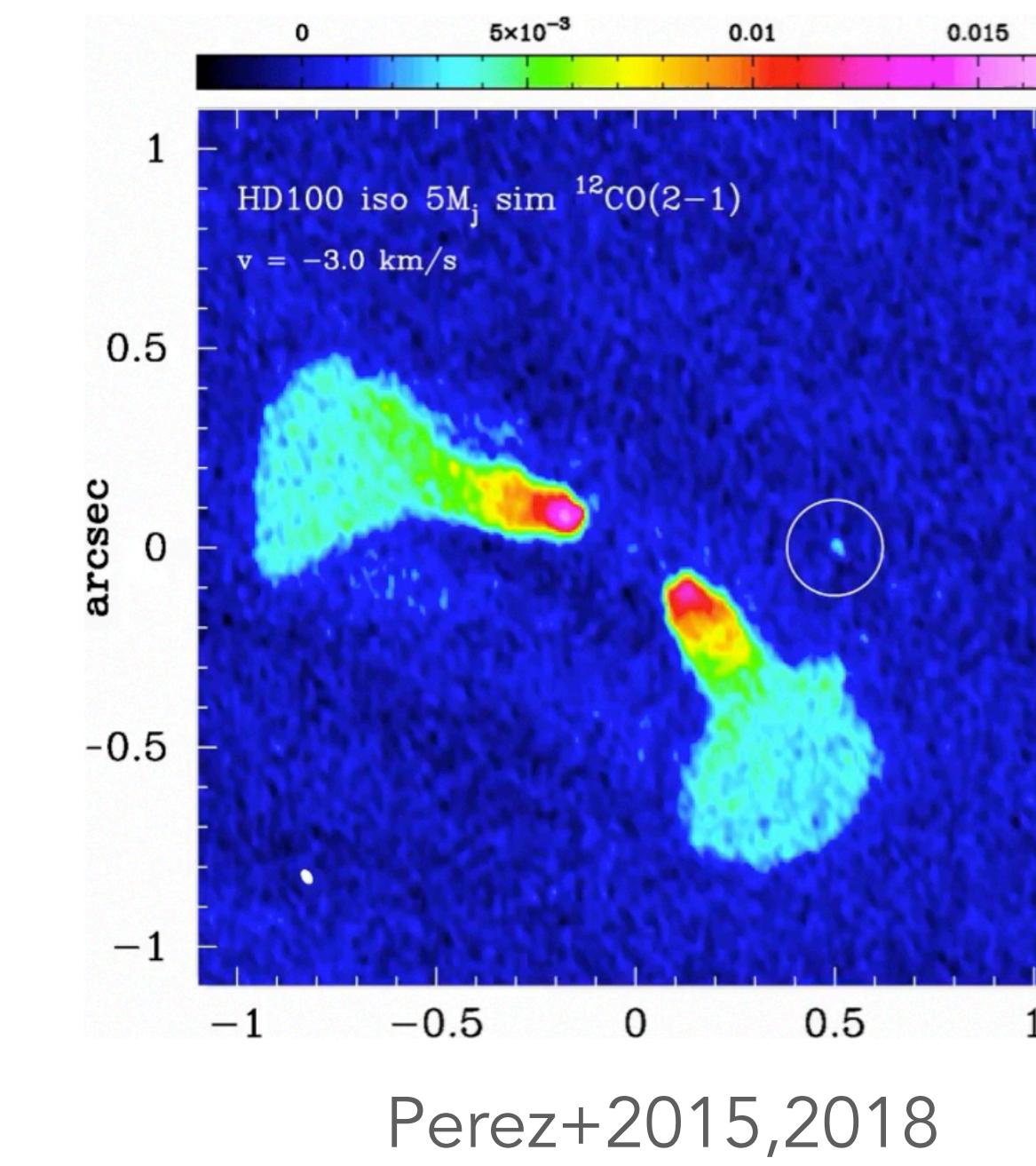
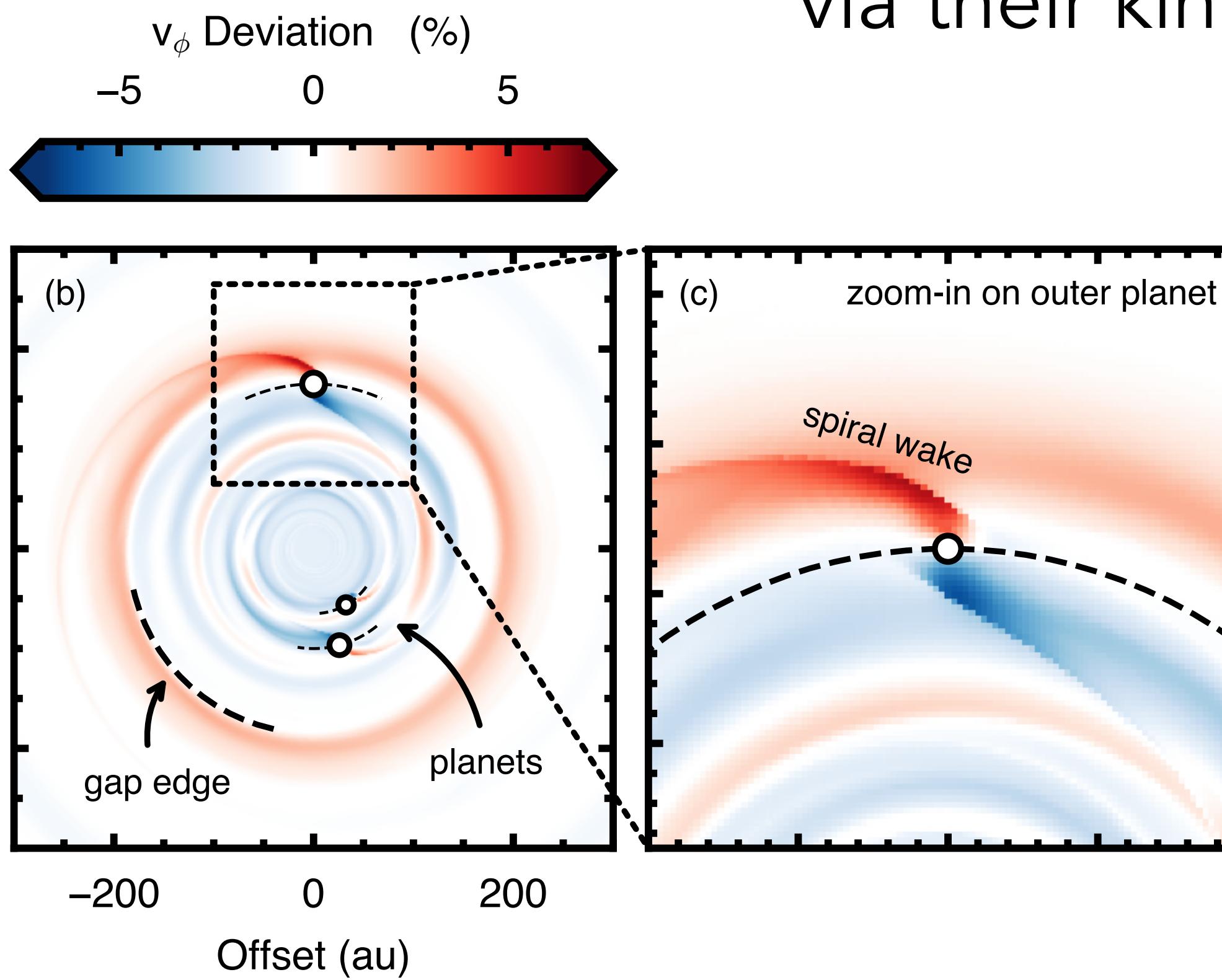
At least 11/13 continuum rings in MAPS sample + HD169142 coincide with pressure bumps extracted from kinematic analysis (Izquierdo+2023)

See Teague+2018b, Rosotti+2020, Yu+2021

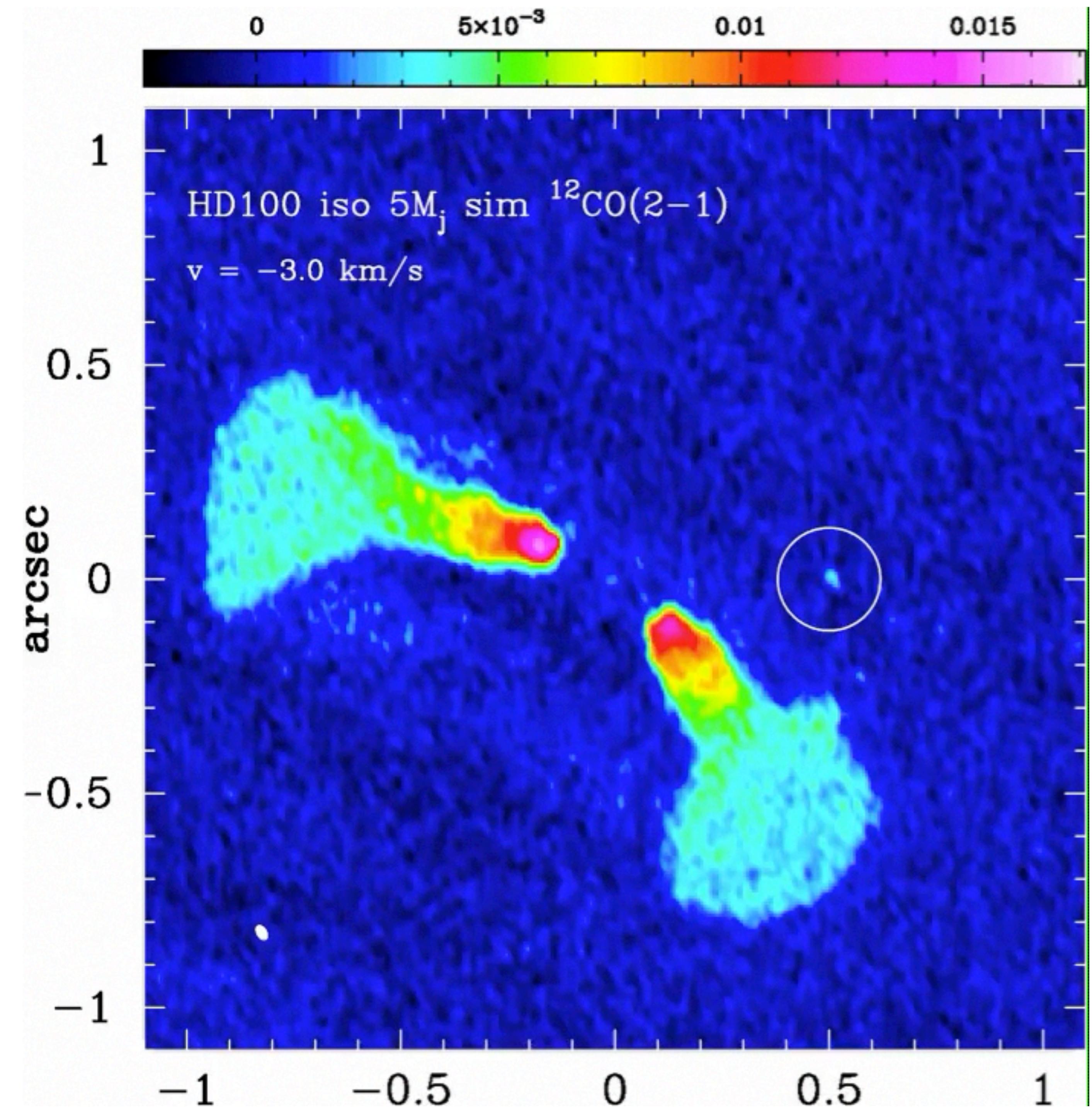
Pressure confinement of dust particles is a robust phenomenon

Planet disk interactions

Kinematics are a new exciting avenue to detect young planets via their kinematical imprint

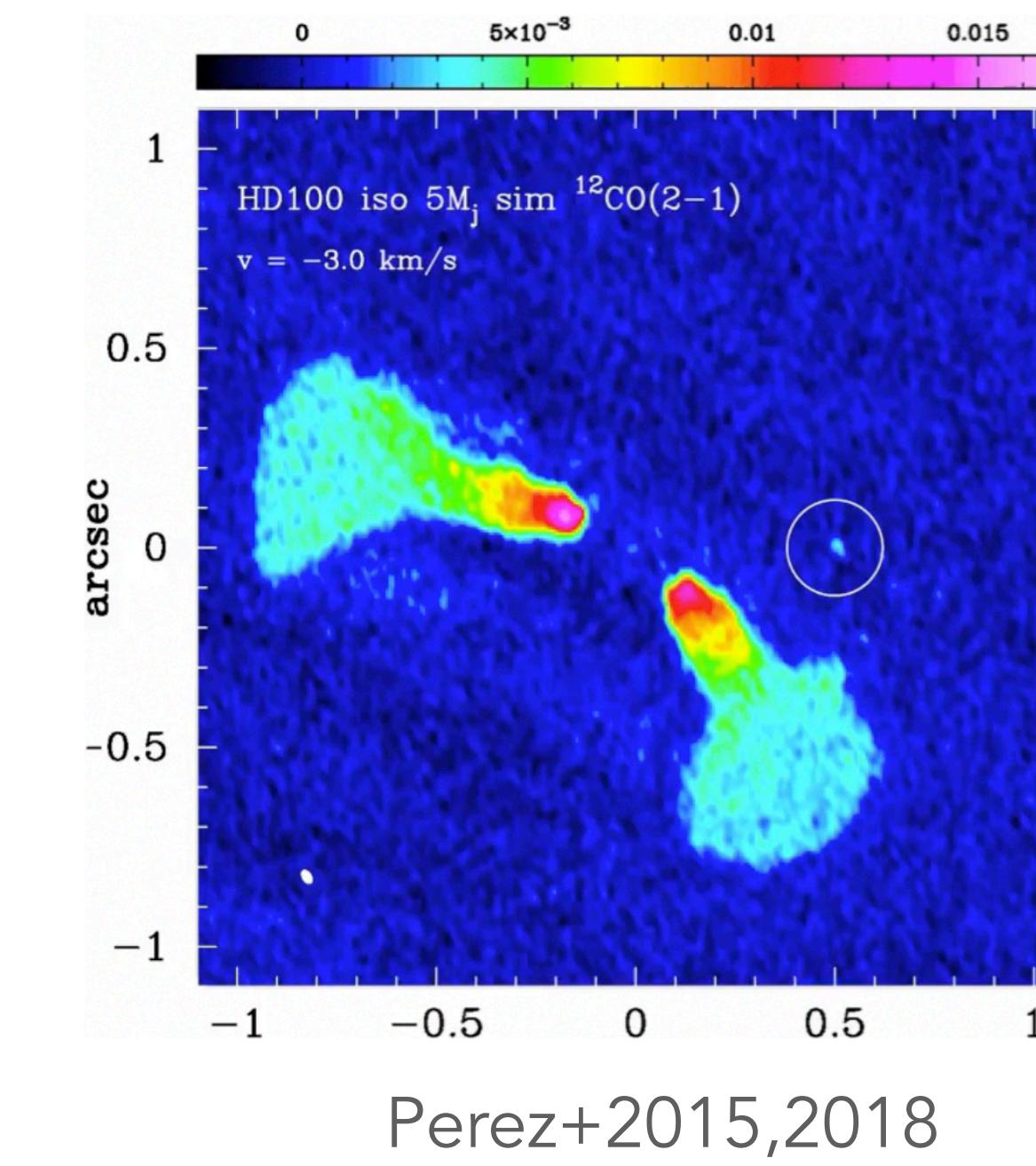
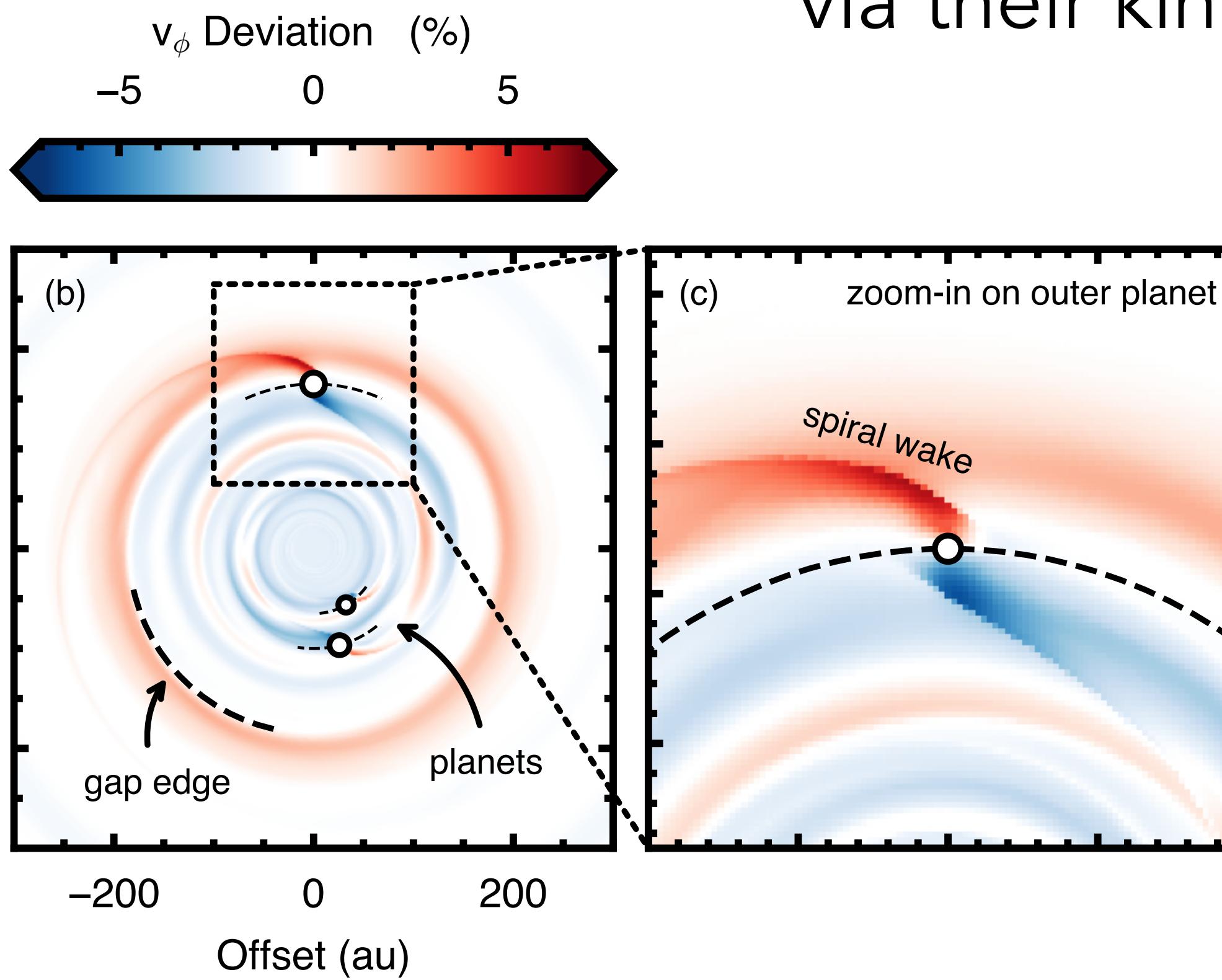


Azimuthally localised kinks (thunderbolt shape in channel map) can trace the spiral wake of the planet (and CPD if present). Blue-red Doppler flip expected in v residuals



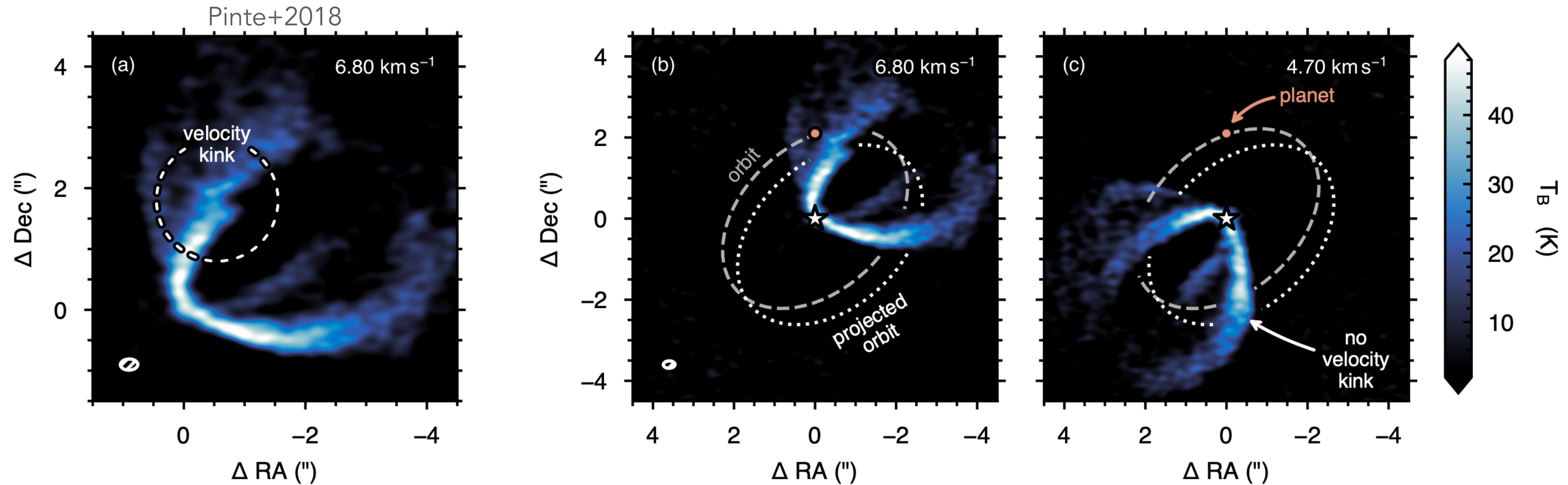
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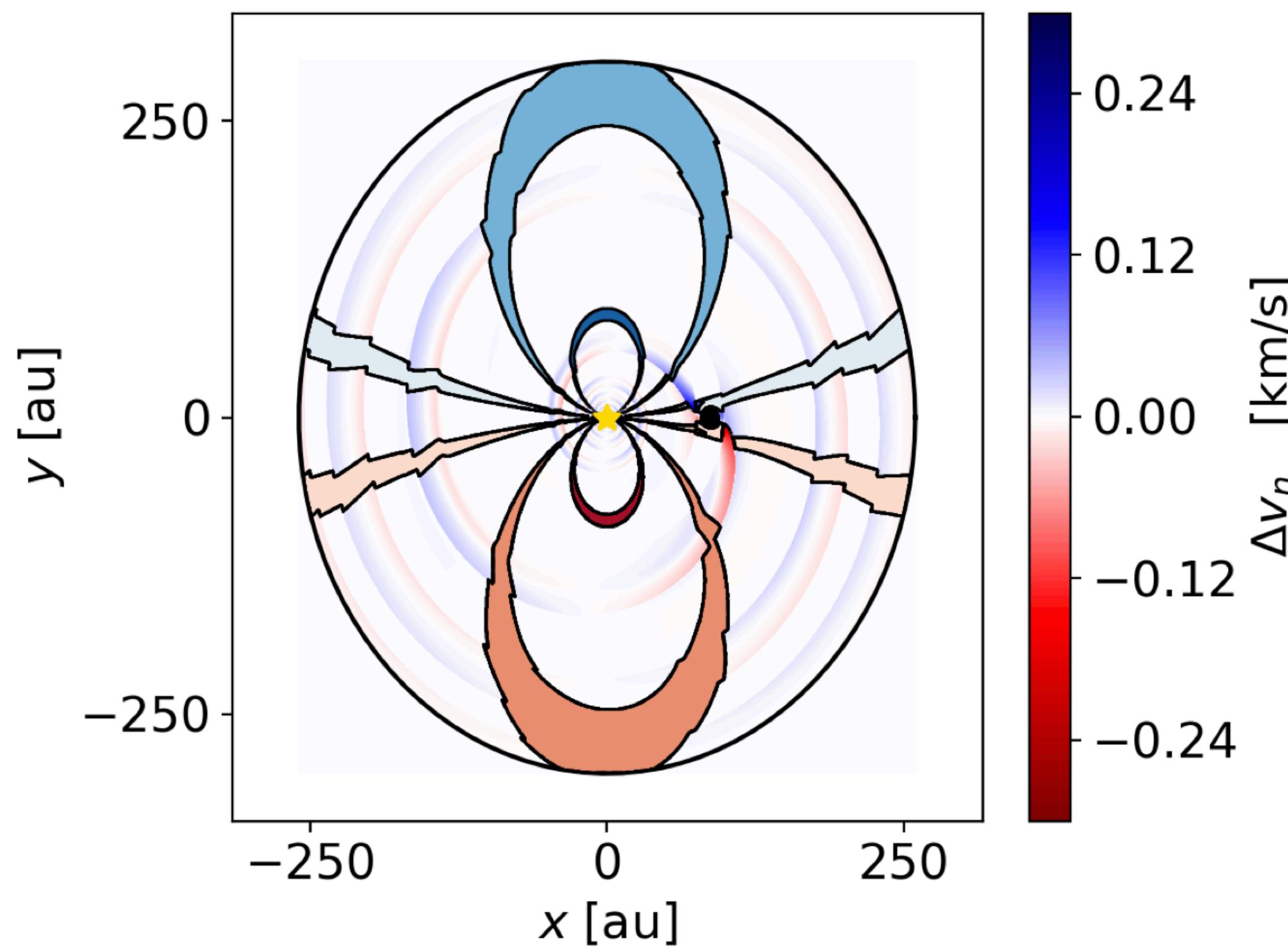
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‘Kinks’ detection: localised in azimuth and velocity

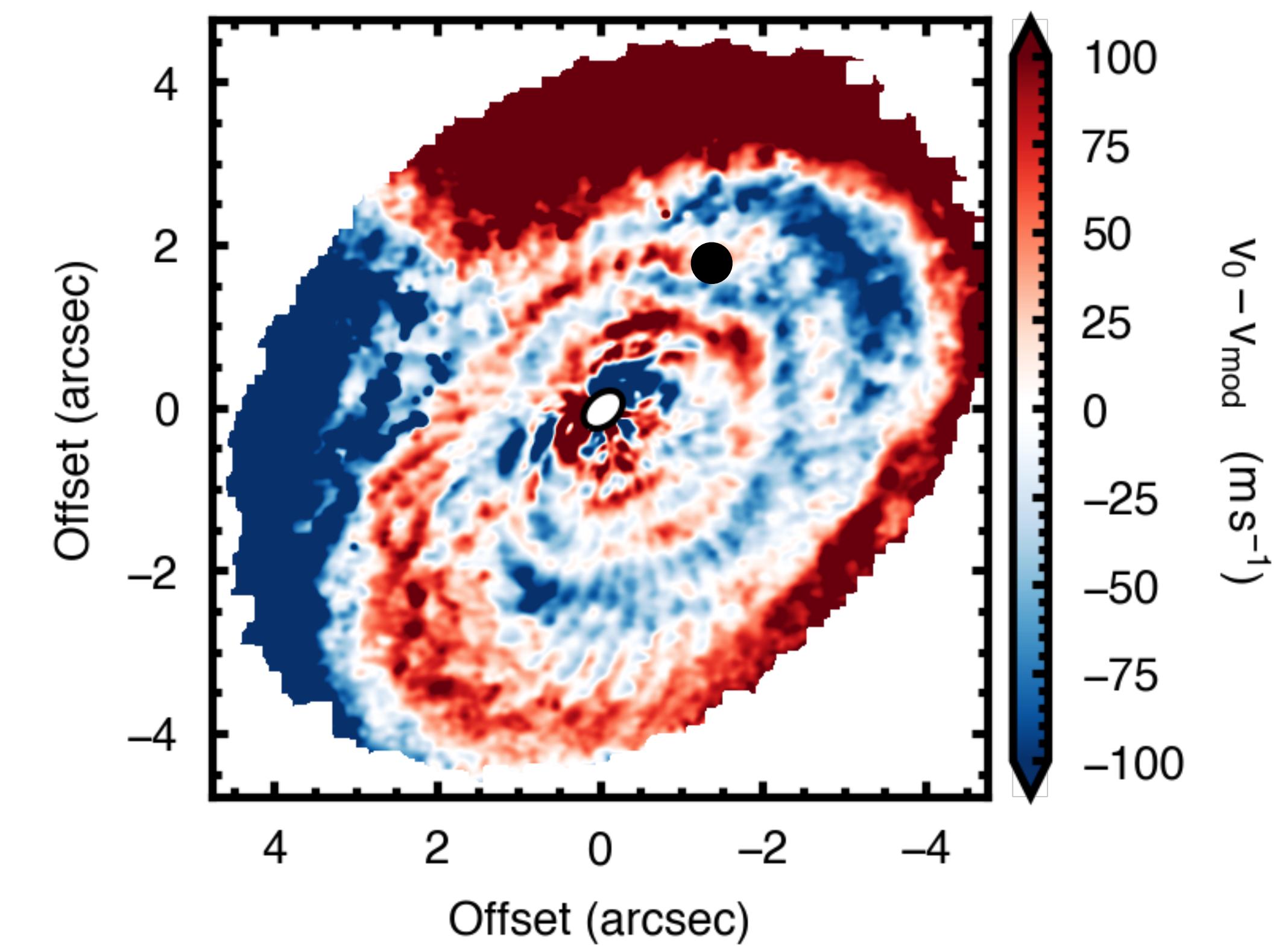


Several azimuthally localised kinks detected in different sources.
With data quality at hand, many are being found, but only few are robust.

(Some) Kinks are tracing the spiral wake



Bollati+2021

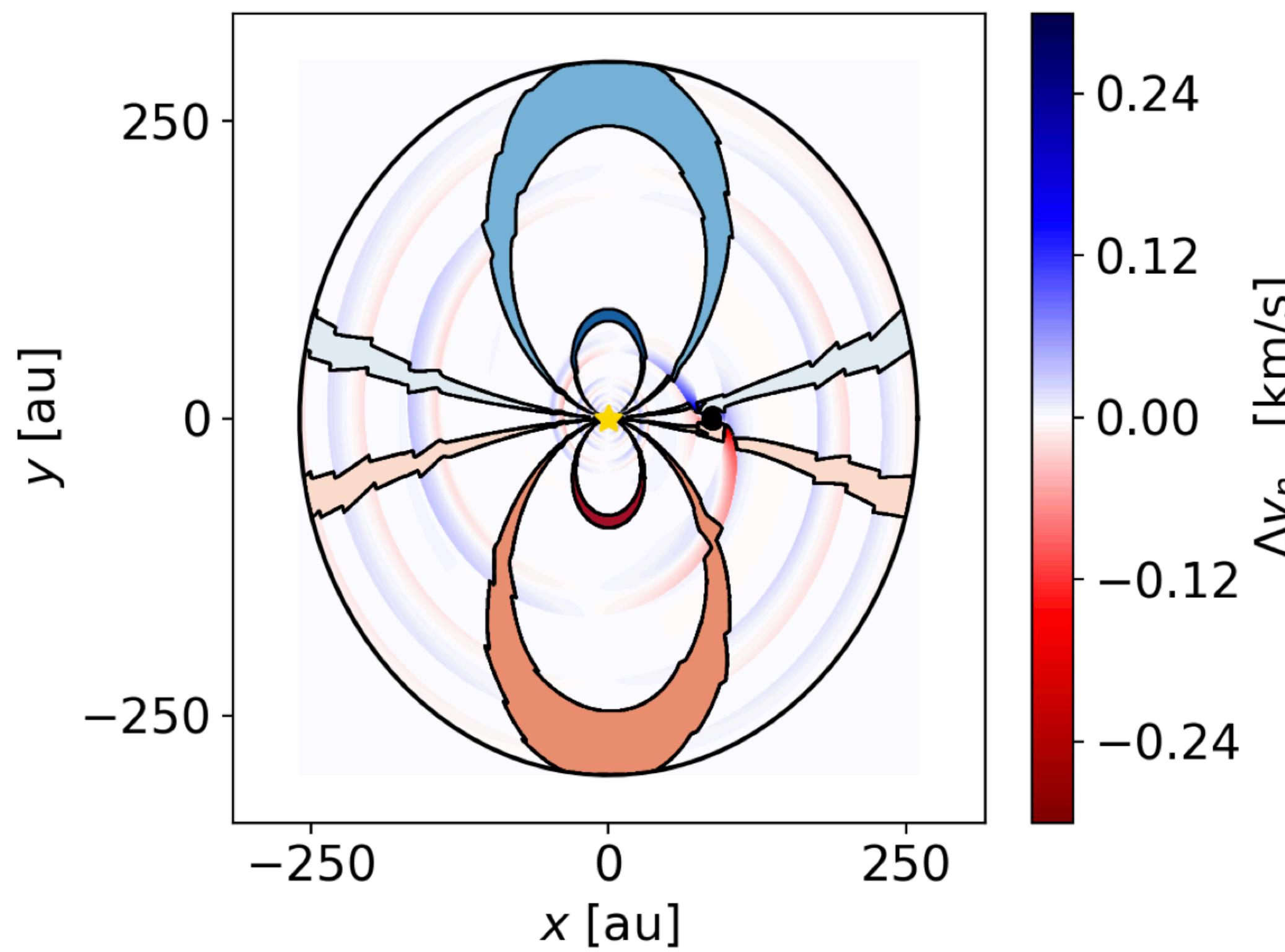


Calcino+2022, image credit: R. Teague

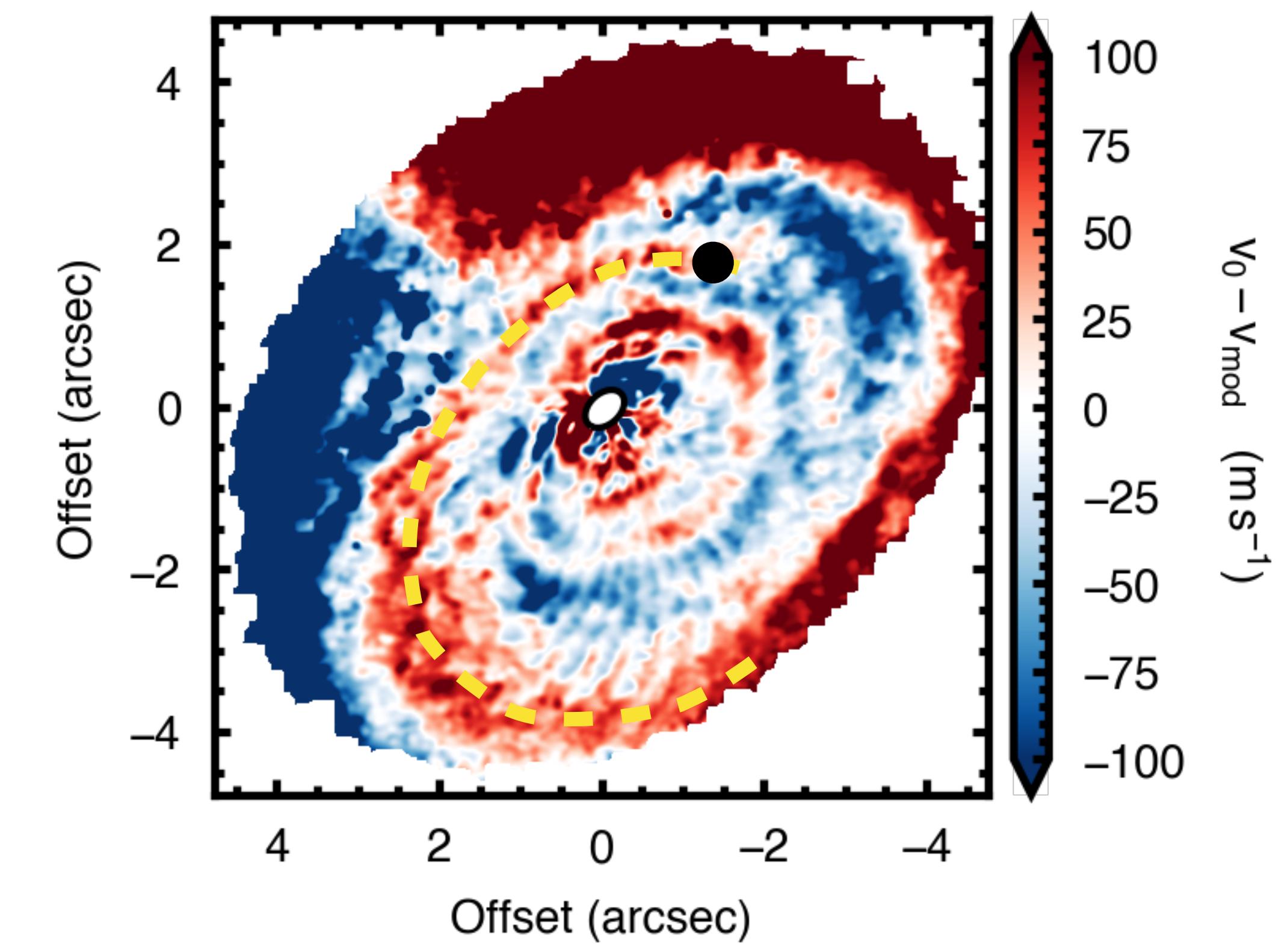
In HD 163296, kinks trace a spiral wake across a large azimuth (Calcino+2022). Note however that any kinematic disturbance (not just planets) can generate kinks

Calcino+2022, Izquierdo+2022, Verrios+2022

(Some) Kinks are tracing the spiral wake



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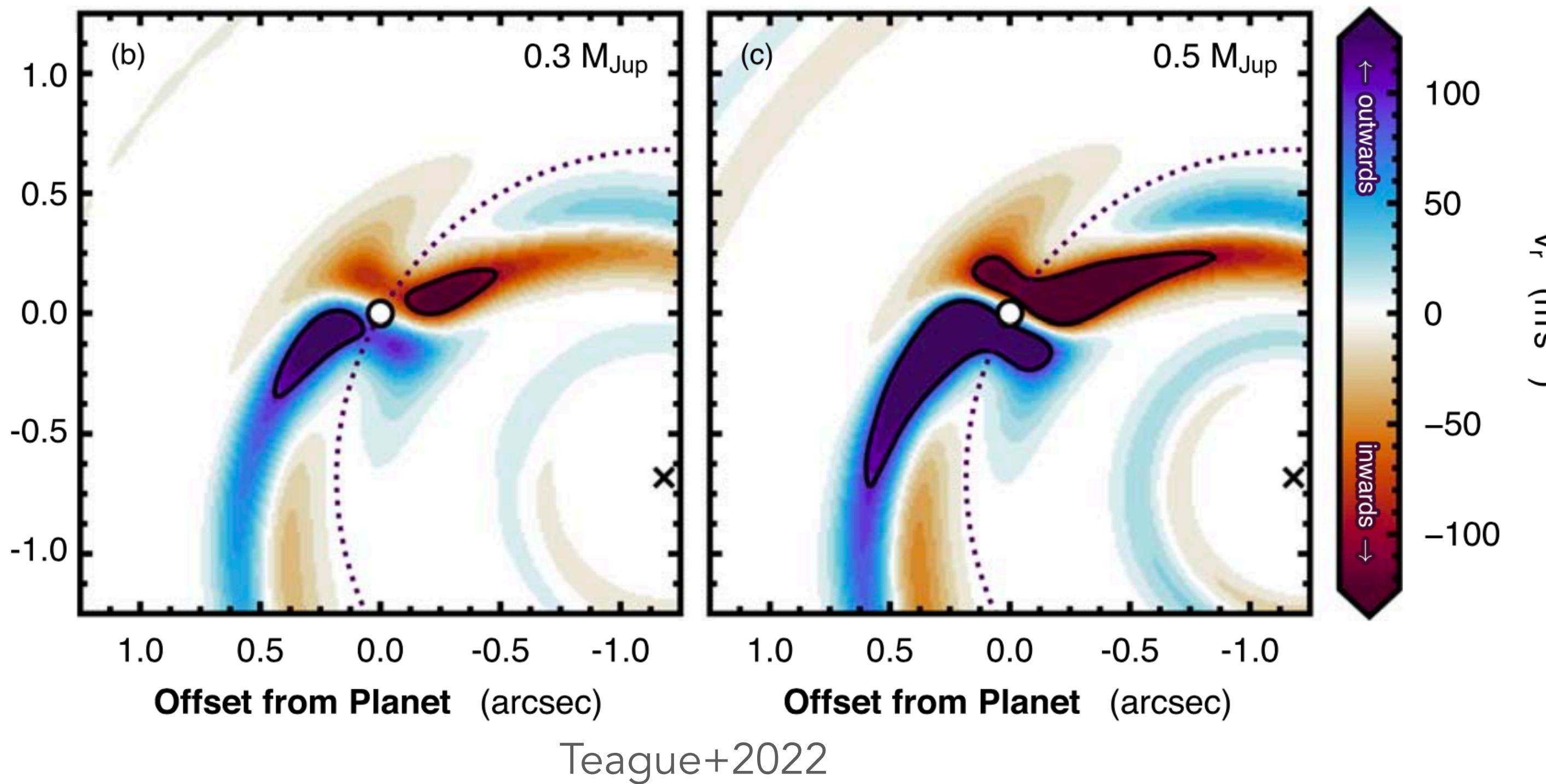
Calcino+2022, image credit: R. Teague

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Amplitude of perturbations depends on mass

In the limit of planet masses below the thermal mass:



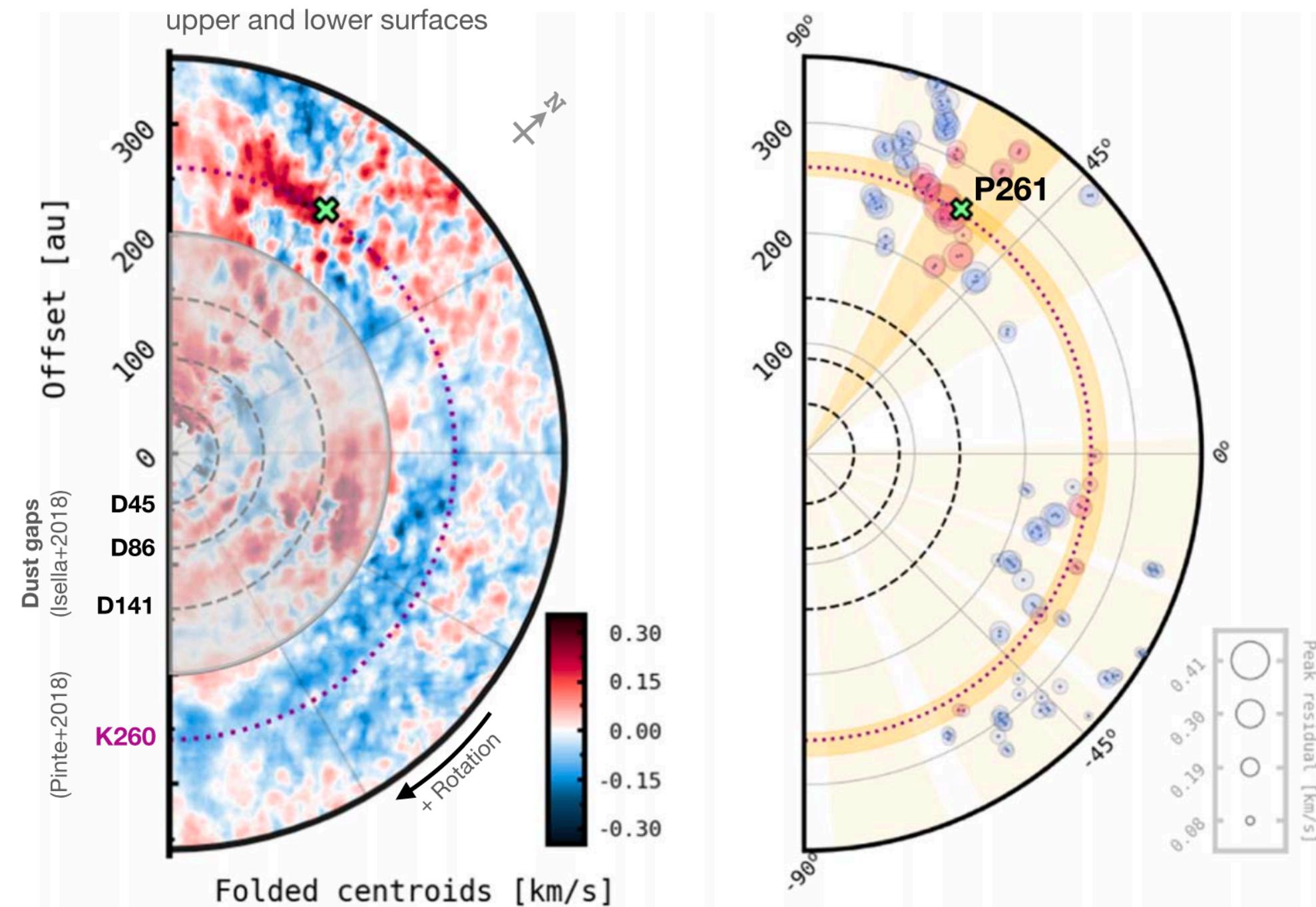
$$\Delta v_p \propto \frac{m_p}{m_{\text{th}}} = \frac{m_p}{M_*} \left(\frac{h_p}{r_p} \right)^{-3}$$

When disk density/temperature structure is well known, velocity perturbations can be used to infer planet masses.

Caveat: locally isothermal models

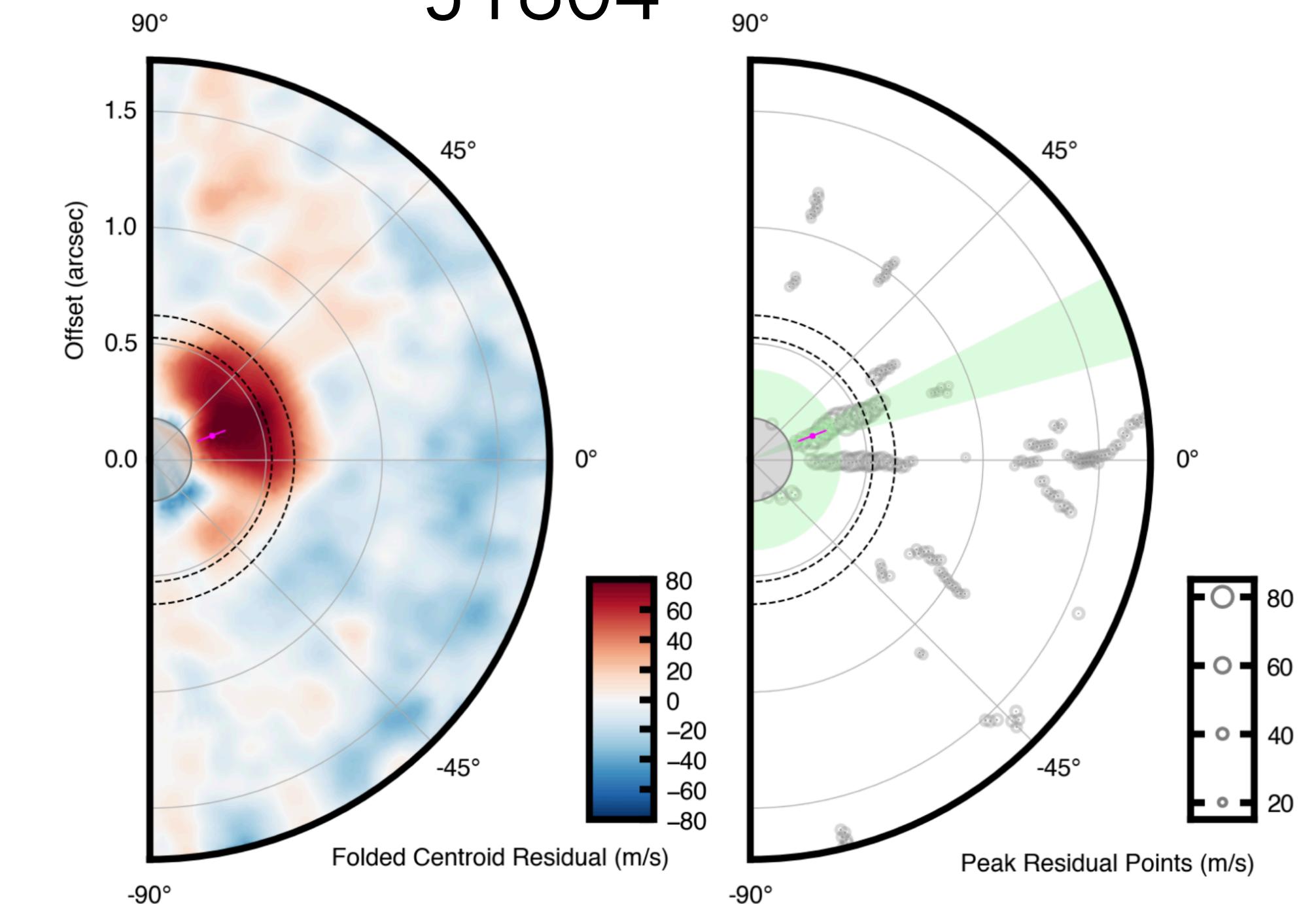
Search algorithms and statistical inference

HD 163296



Izquierdo+2022

J1604

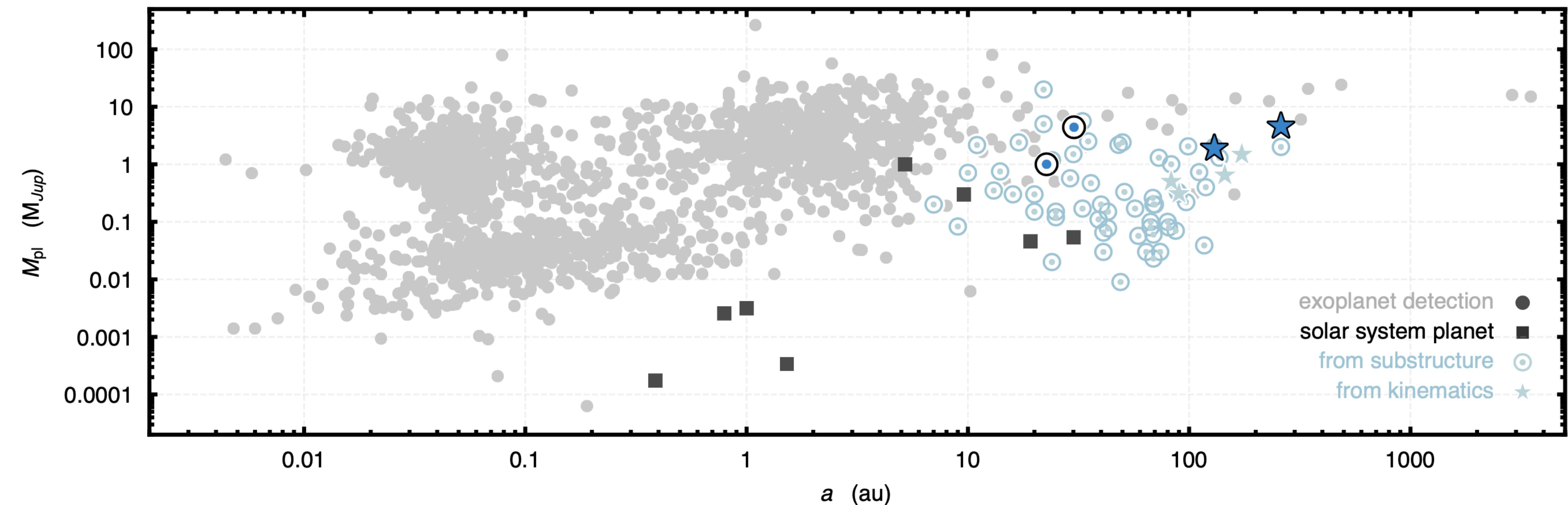


Stadler+2023

Clustering algorithms or ML tools to assess significance of localised kinematical deviation. Current limits on exquisite datasets are $> M_{\text{Sat}}$, whenever other dynamical effects are not dominating kinematics.

Izquierdo+2021,2022,2023, Terry+2022

Exoplanet demographics + kinematic candidates



Current robust detections of planetary candidates are $> 1 M_{Jup}$ in mass

The next steps (ALMA)

- Increase the statistics of kinematically-characterised disks to:
 - A. Identify common fundamental dynamical properties of disks
 - B. Search for planet-disk interactions
 - C. Quantify the insurgence of (M)HD instabilities promoting planet formation
- Use different tracers (ions, atomic carbon, ...) to map the full 3D kinematic of disks in a range of conditions (ALMA WSU will help, line sensitivity will be the main limiting factor)
- Kinematic studies on earlier sources, whenever possible



A 180h ALMA Large Program to characterize disk dynamics

PIs: R. Teague, M. Benisty, S. Facchini, C. Pinte, M. Fukagawa



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Protoplanets
(M-)hydrodynamical flows/instabilities (zonal flows, GI, VSI, etc.)

Disk turbulence
Disk masses from rotation curves
3D tomography of disks

Accretion layers (velocities can be probed!)

Level of dust trapping (radial and vertical)

Properties of disk outer edges

Winds

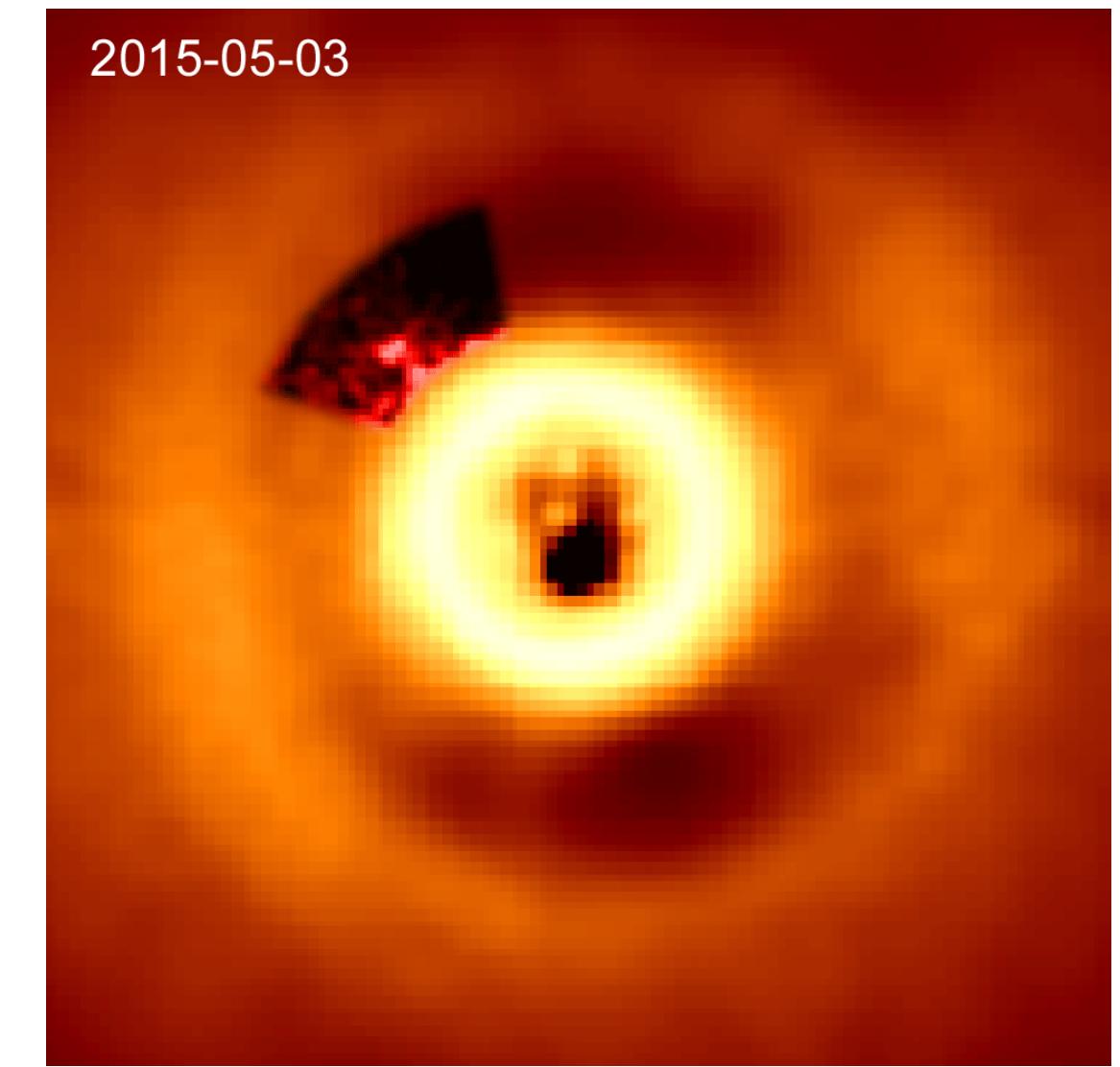
Radial inflows

Warps

Next steps (synergies with other instruments)

Combine kinematic results from ALMA with NIR/MIR
HCl campaigns by new/ng instruments.

**Huge potential to benchmark
the mass-luminosity relation of protoplanets**

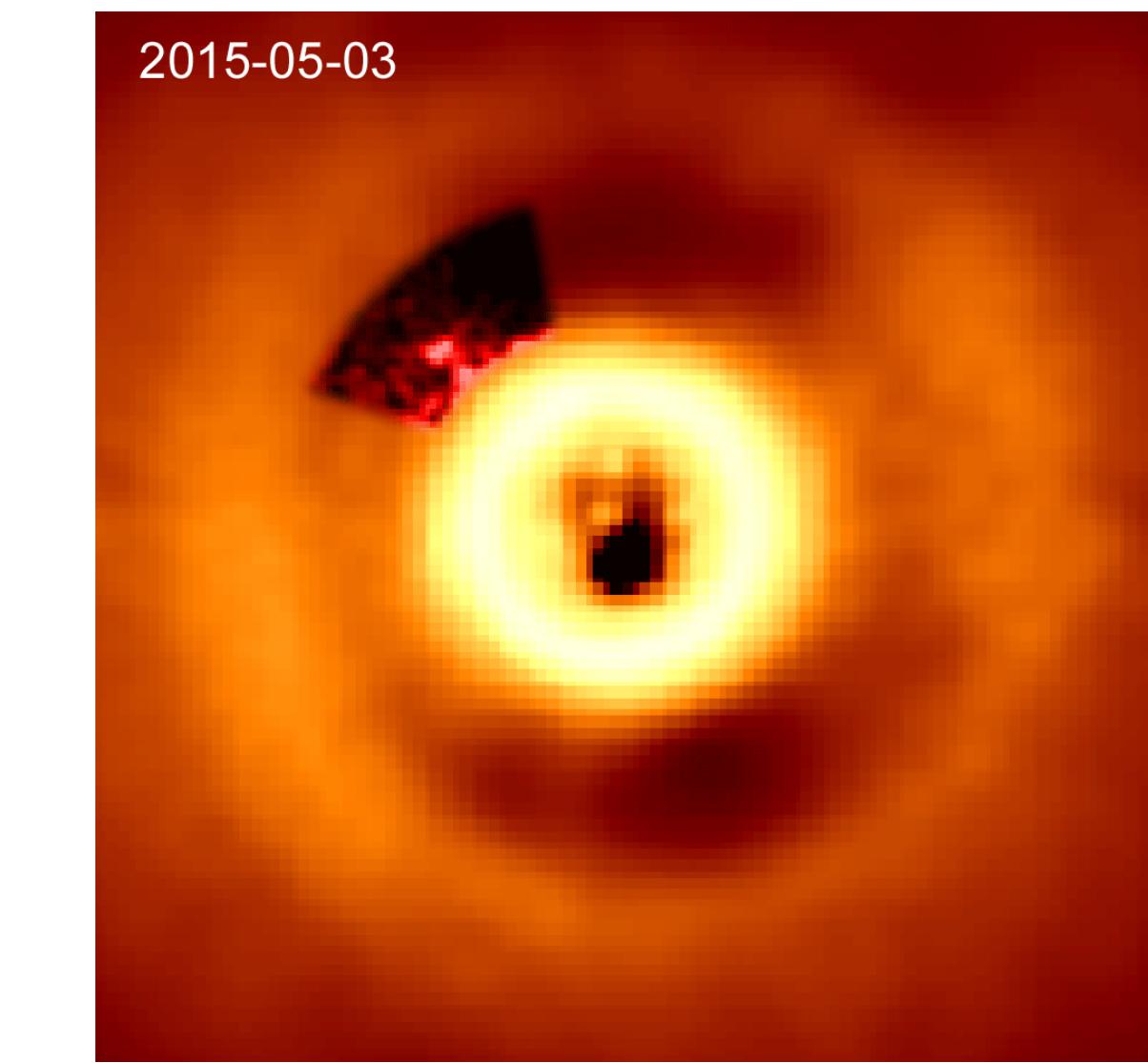
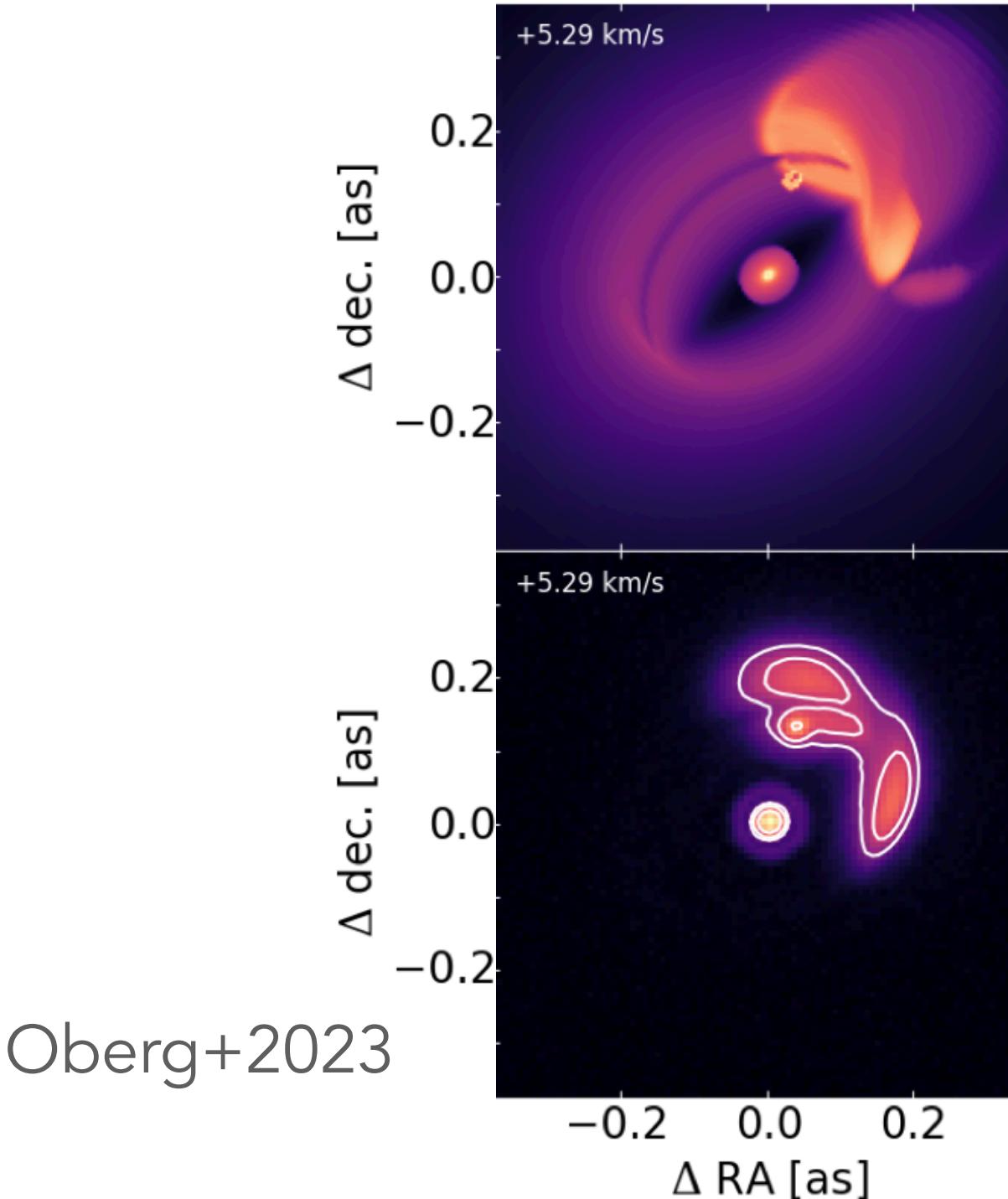


Hammond+2023 (see Yu+2021, Garg+2022)

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Going to inner disk regions with e.g., ELT/METIS to characterize kinematics with NIR/MIR lines.

Potential to do kinematical studies on proto-Solar System analogues.

Towards a panchromatic and multidisciplinary view of massive planetary assembly

- Planets are observed to sculpt their hosting disks in their physical, thermal and chemical properties
- Kinematics is new exciting avenue to detect protoplanets, determine their masses, benchmark mass-luminosity relationship of protoplanets
- Gas dynamics can offer new clues into planet formation mechanisms
- A new window into determination of water snowline is opening