DISK KINEMATICS & FRAGMENTATION IN HIGH-MASS STAR FORMATION

LINKING OBSERVATIONS AND SIMULATIONS

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Zooming in on Star Formation
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CORE: IRAM NOEMA LARGE PROGRAM

- Sample of 20 young high-luminosity regions: $L > 10^4 L_\odot$
- Dust continuum & line observations at 1.3 mm (220 GHz)
- NOEMA: Plateau de Bure + new antennae

x12
NOEMA
NOrthern Extended Millimeter Array

A, B, & D configurations in decreasing baseline length

Highest resolution ~ 0.3" => 600 AU at 2 kpc

- IRAM 30-m telescope data to cover the missing flux

CORE: MOTIVATION

- What are the fragmentation properties of high mass star forming regions during the early evolutionary stages of cluster formation?
  Beuther et al. 2018
- How is the gas accumulated into the central cores and what are the larger-scale gas accretion flow and infall properties?
  Mottram et al. subm.
- What are the chemical properties of distinct substructures within high-mass star-forming regions?
  Gieser et al. subm.
- Can we identify genuine high-mass accretion disks, and if yes, what are their properties?
  Ahmadi et al. 2018

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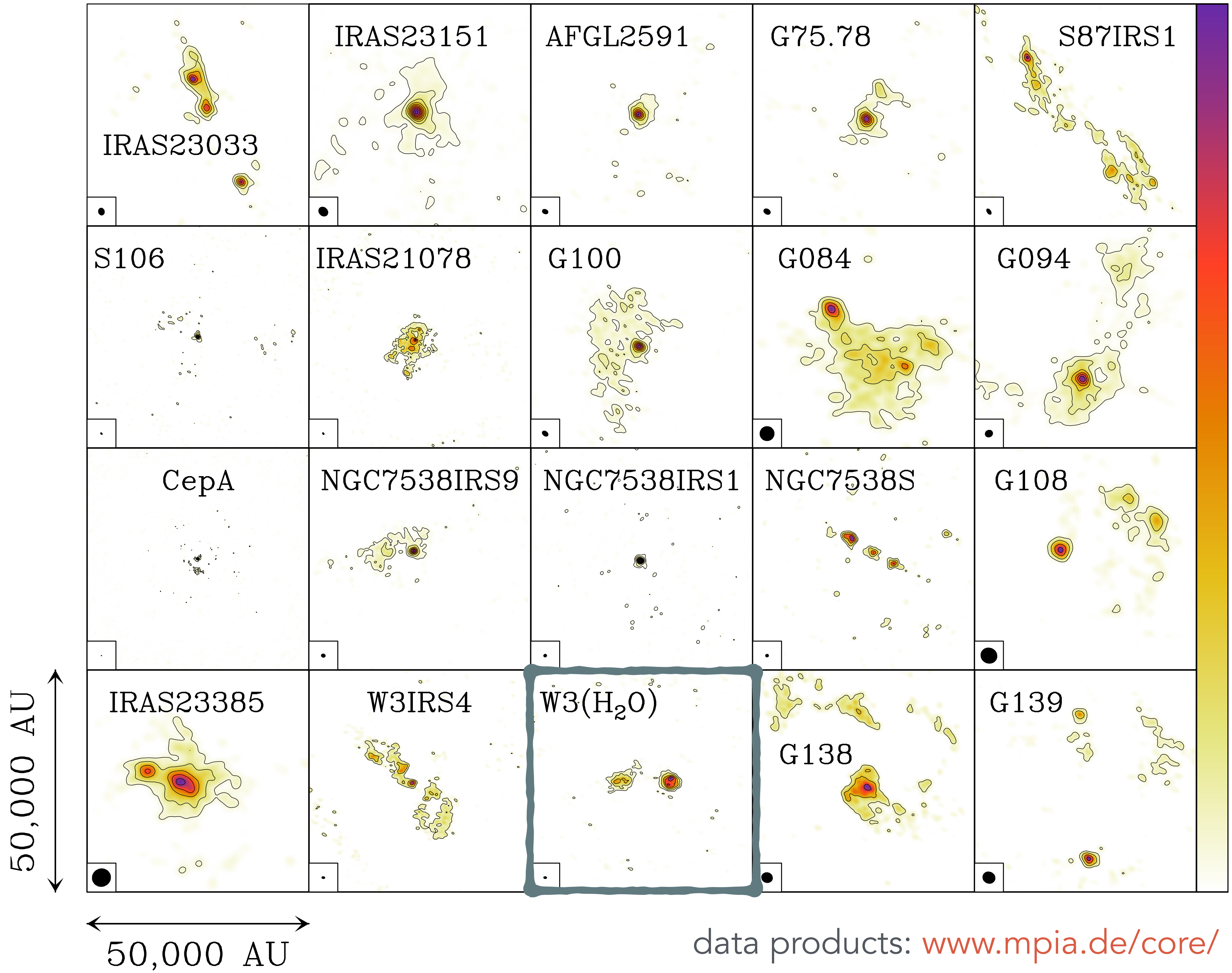
CORE: DUST CONTINUUM

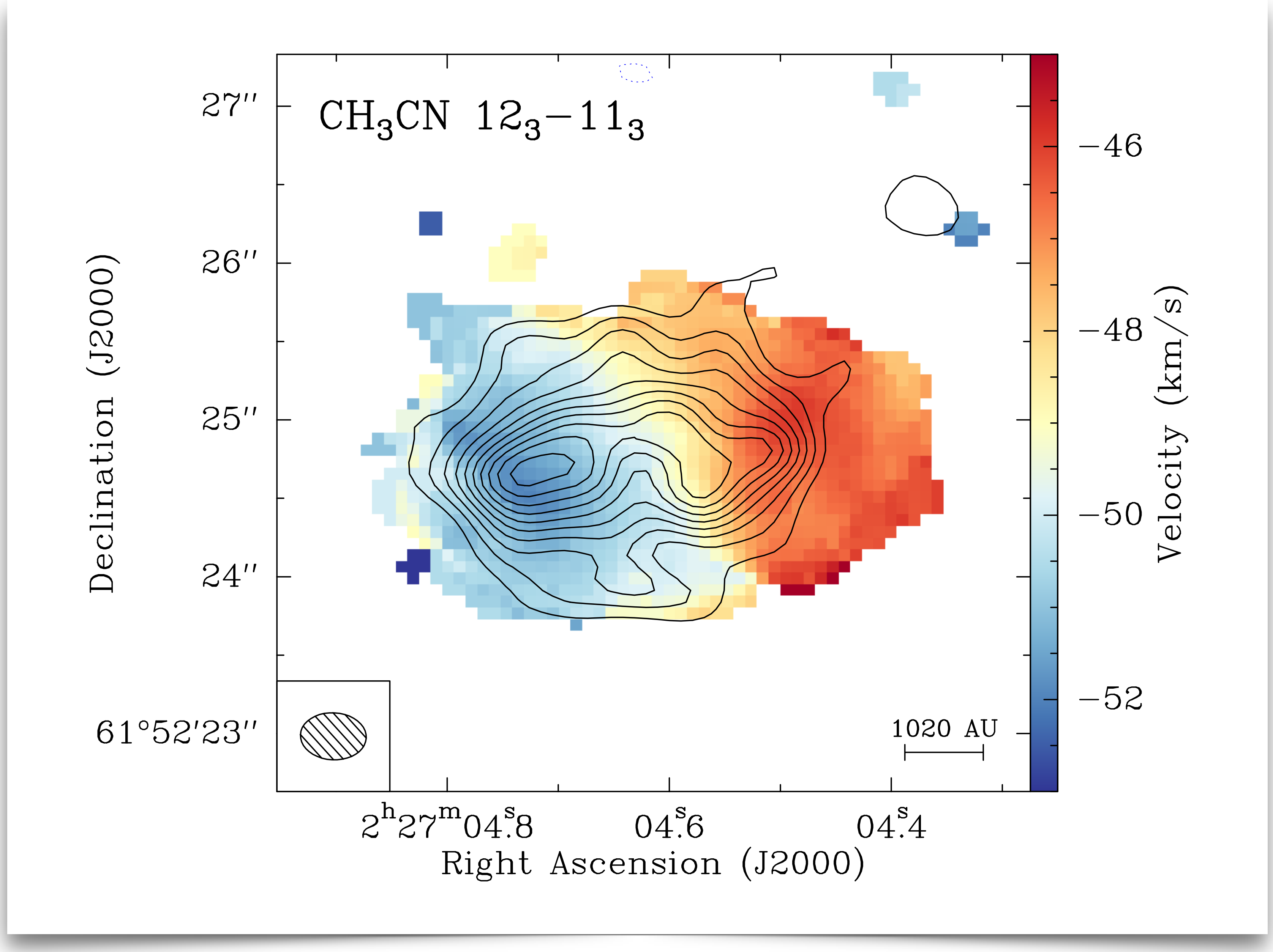
Beuther, Mottram, Ahmadi et al. 2018



data products: www.mpia.de/core/

CONTINUUM & VELOCITY STRUCTURE

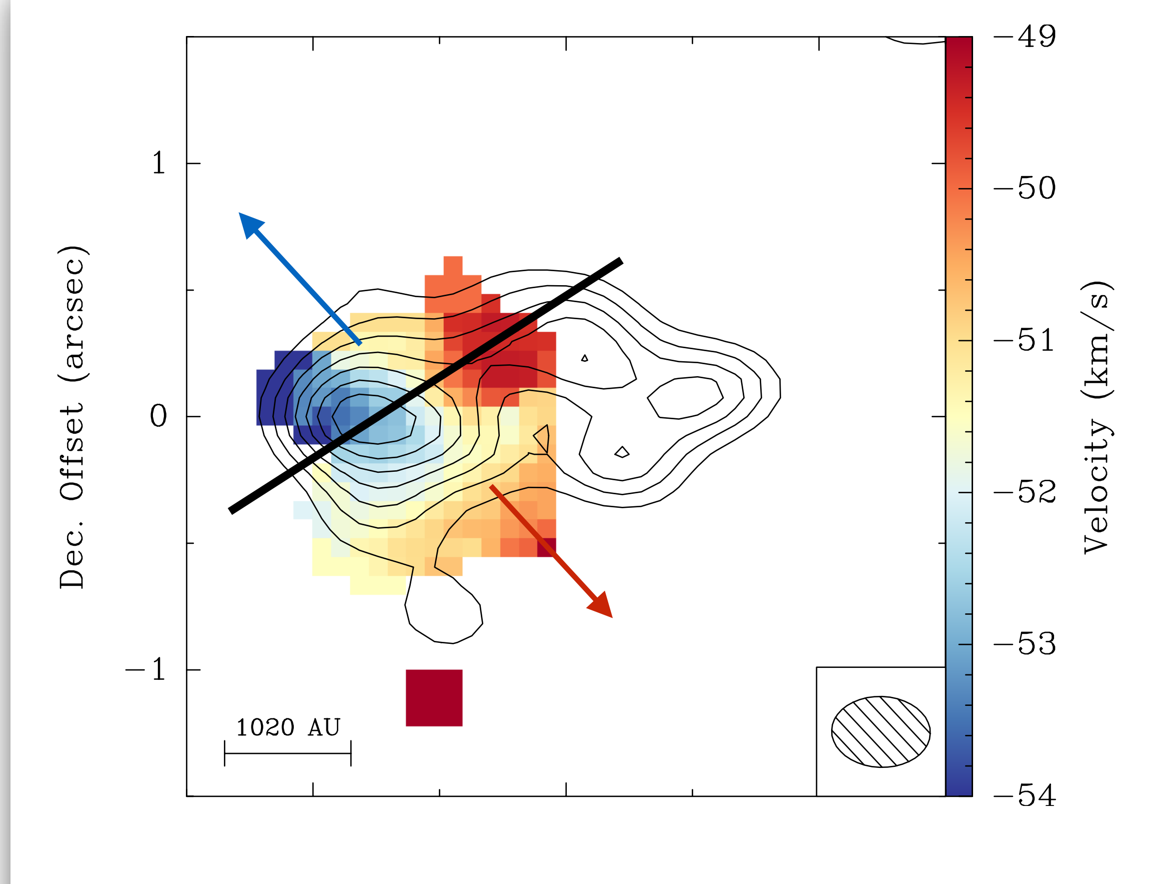
- Velocity map of the region in CH_3CN (12_3-11_3) shows clear gradient in the E-W direction



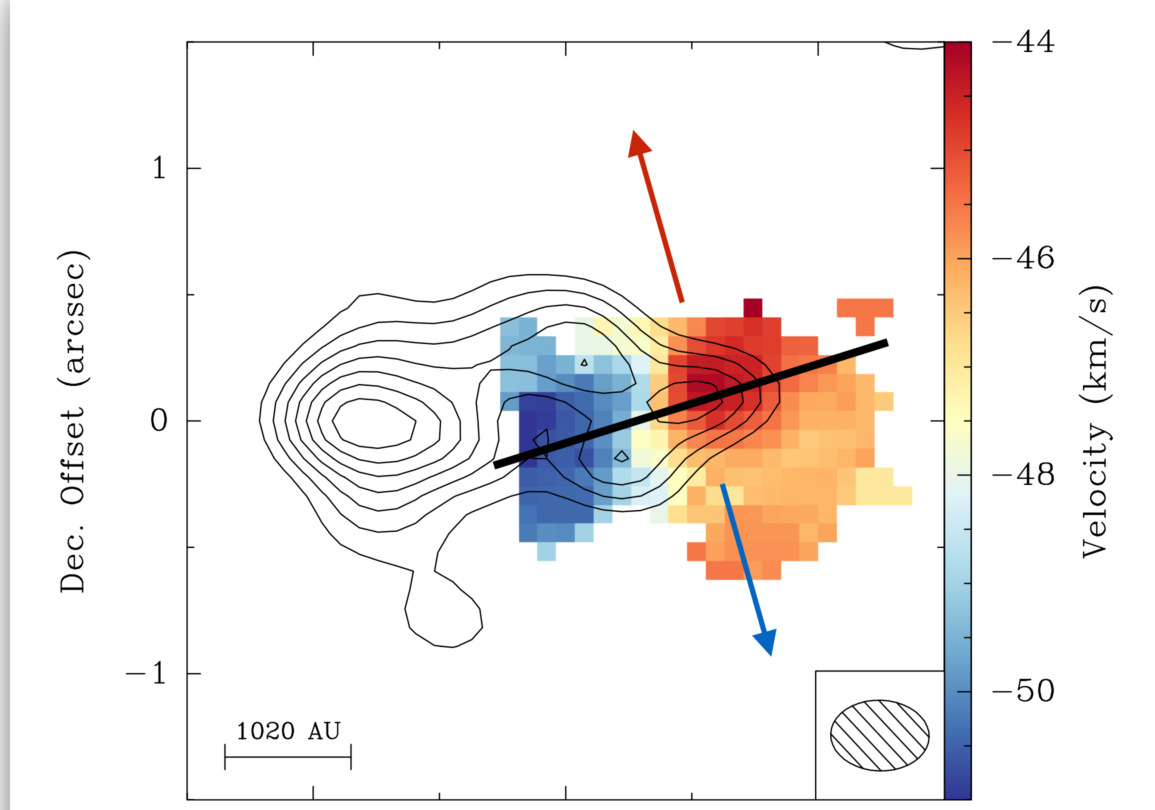
KINEMATICS OF FRAGMENTS

- Velocity gradient observed for each fragment consistent with molecular outflows

left fragment



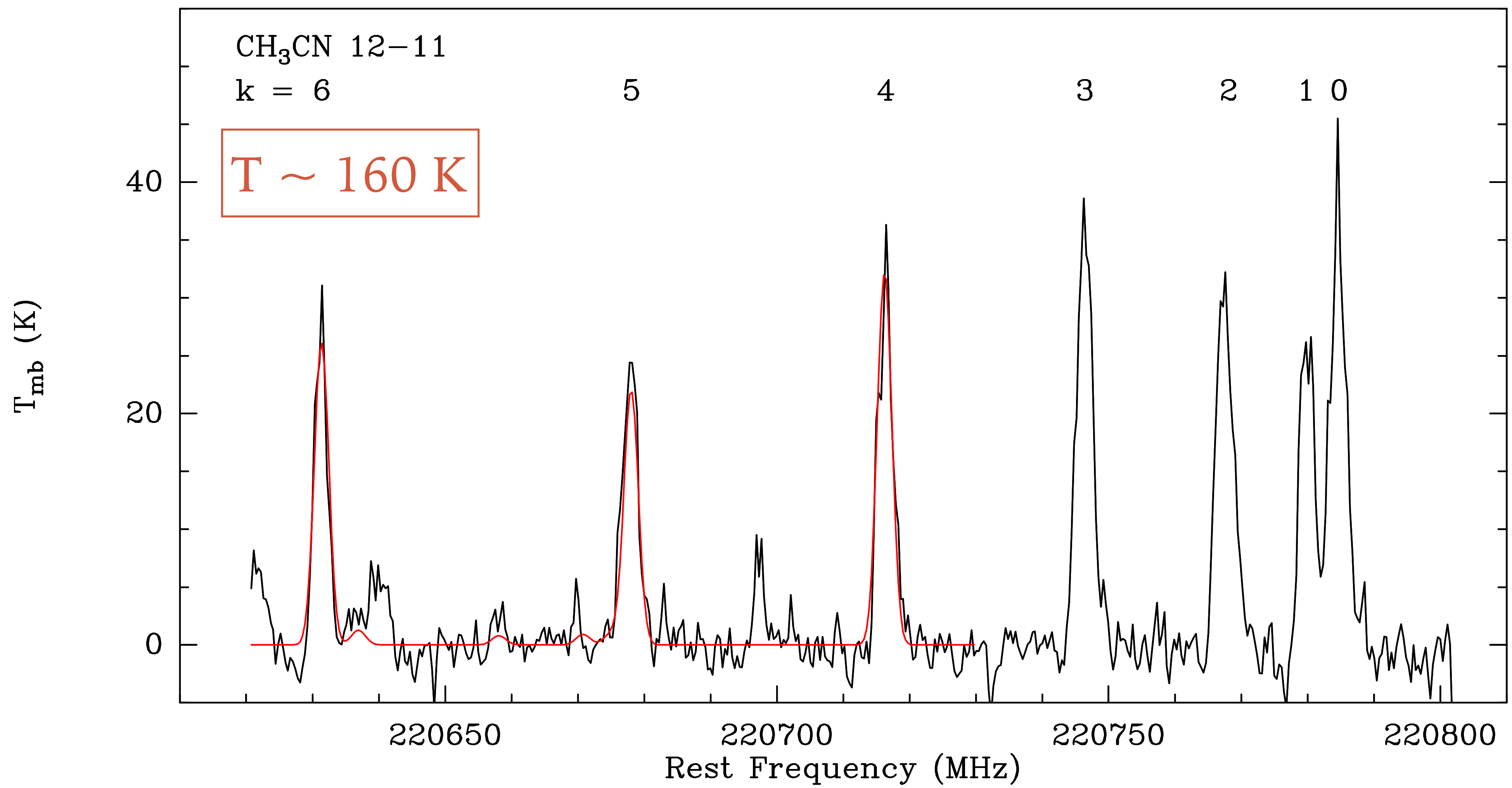
right fragment



Ahmadi et al. 2018

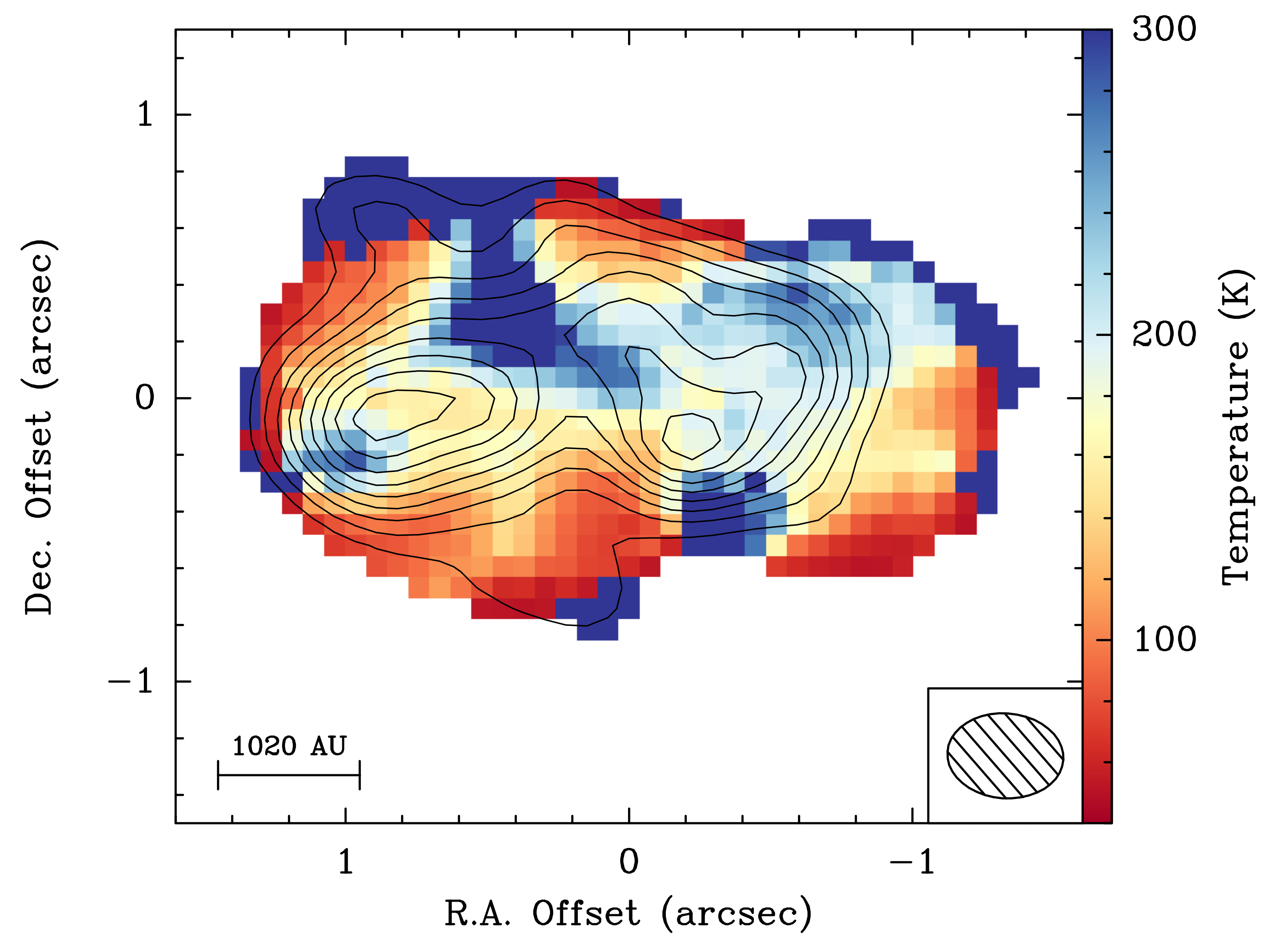
MODELLING WITH XCLASS

- XCLASS: solves the radiative transfer equation under LTE and generates synthetic spectra that can be compared to the real spectra
- Fitting **CH_3CN (12-11) k=4 to k =6** lines simultaneously along with their $CH_3{}^{13}CN$ isotopologues



W3(H_2O) TEMPERATURE MAP

- Average temperature is **warm: ~180 K**



TOOMRE STABILITY

- For a differentially rotating disk, the shear force can provide added stability against collapse
- Quantified by Toomre (1964) via

sound speed

epicyclic frequency of the disk
= angular velocity for Keplerian rotation

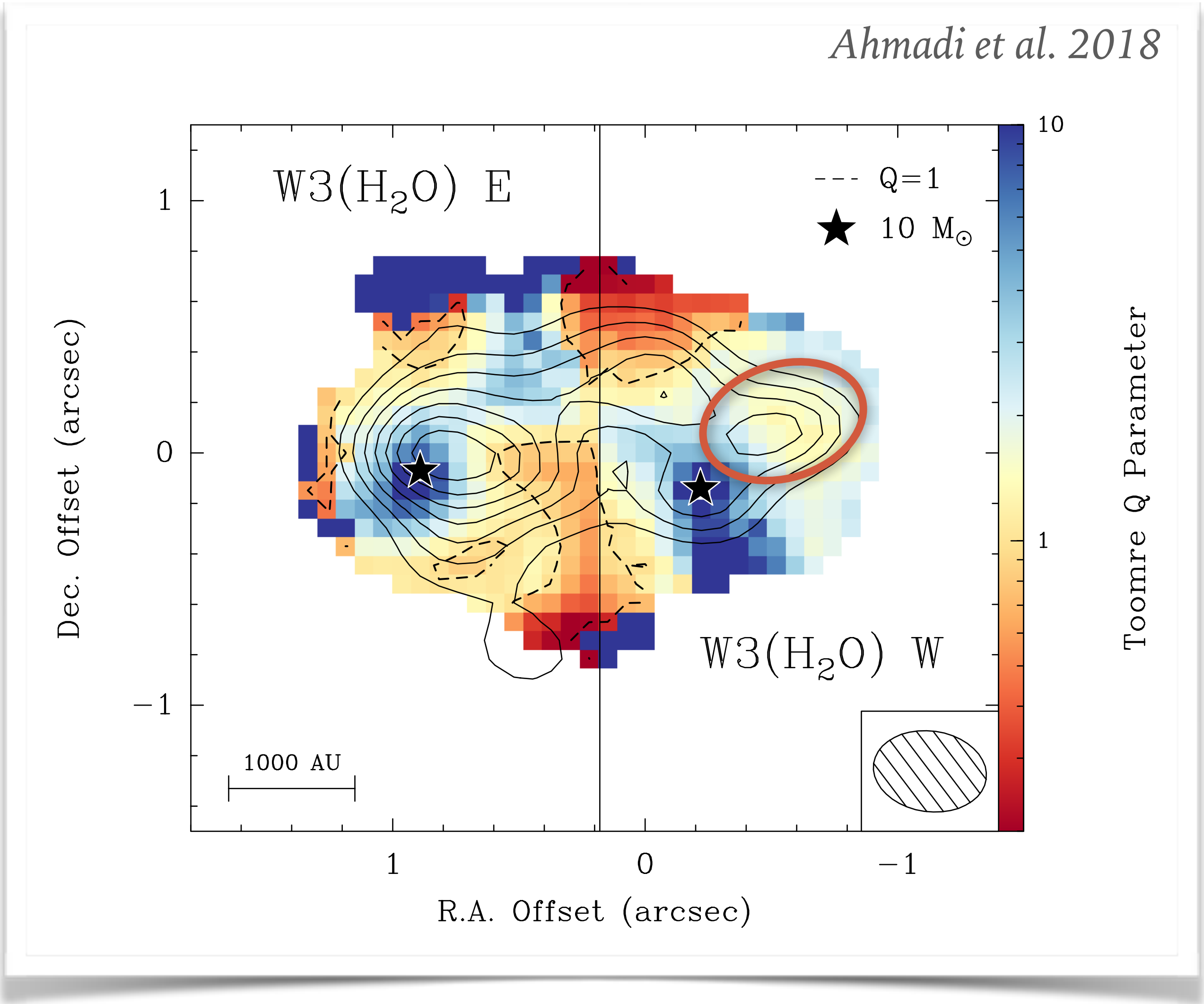
$$Q = \frac{c_s \Omega}{\pi G \Sigma}$$

surface density of the disk

- A thin disk becomes **unstable** against axisymmetric gravitational instabilities if **Q < 1**

TOOMRE STABILITY

- Outer rotating structure is Toomre-unstable in parts
  - Further **disk fragmentation** possible



UNCERTAINTIES

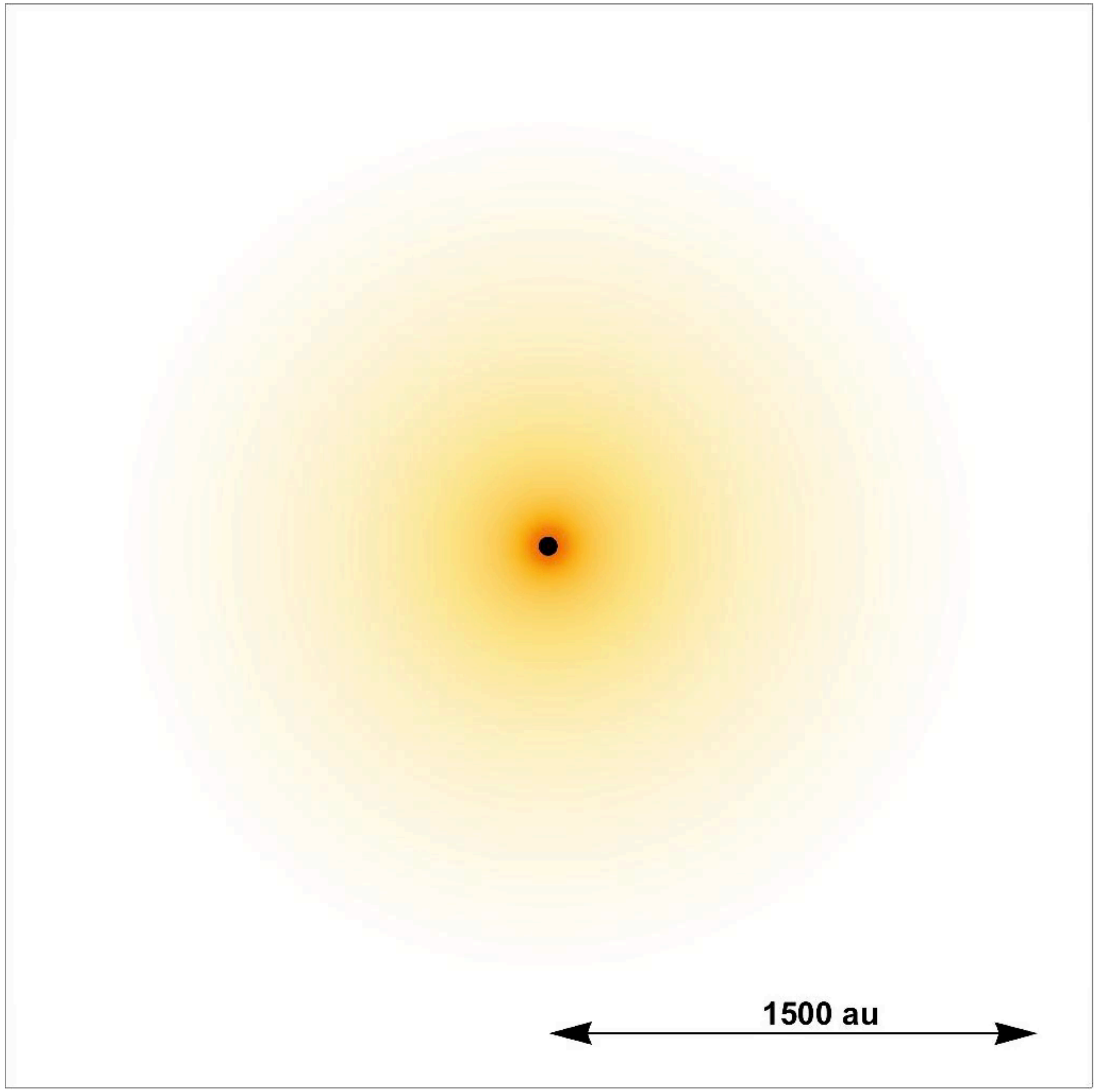
- Inclination angle
- Mass of disk & central object

RADIATION HYDRO SIMULATIONS

- Global collapse of a cloud of gas + dust with 200 $M_\odot$ in 0.1 pc

DETAILS

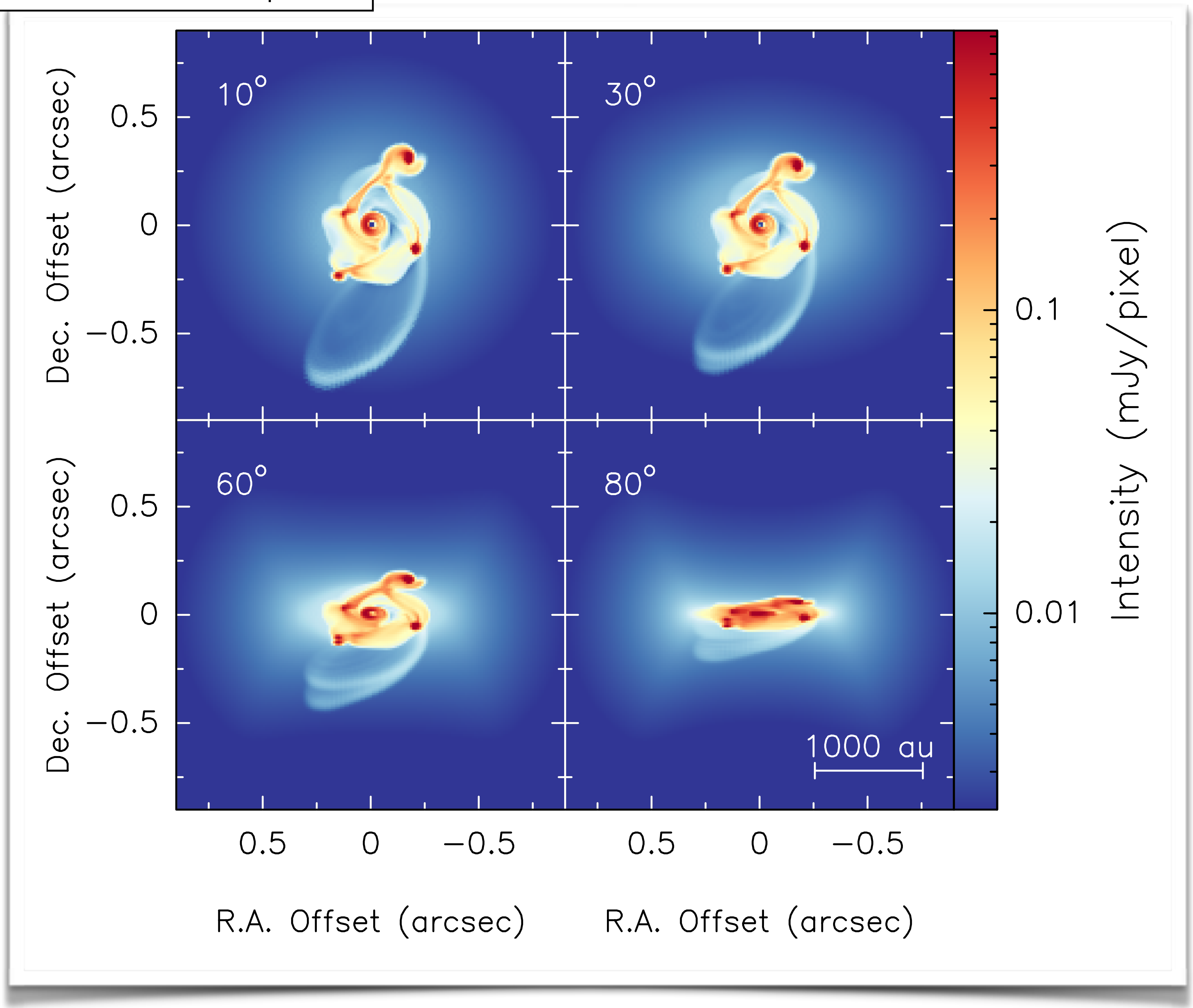
- PLUTO code
- Initial mass density profile: $\rho \propto r^{-1.5}$
- Spherical grid
- Outer edge of disk resolved down to 25 au
- Inner part resolved down to 0.75 au
- ✓ Jeans length resolved!



Oliva, Kuiper et al. (in prep.)

1.3 MM DUST CONTINUUM

distance: 2 kpc



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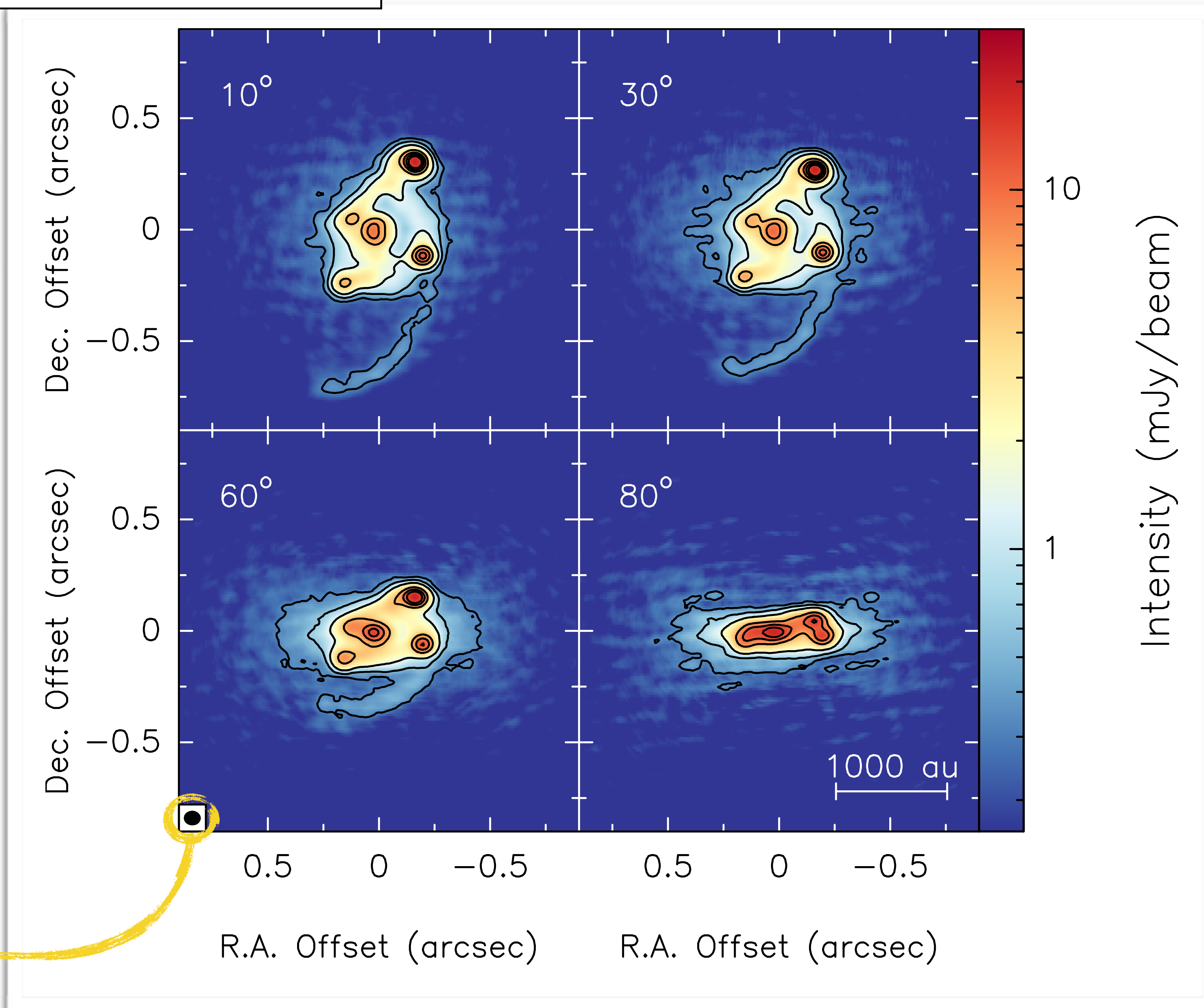
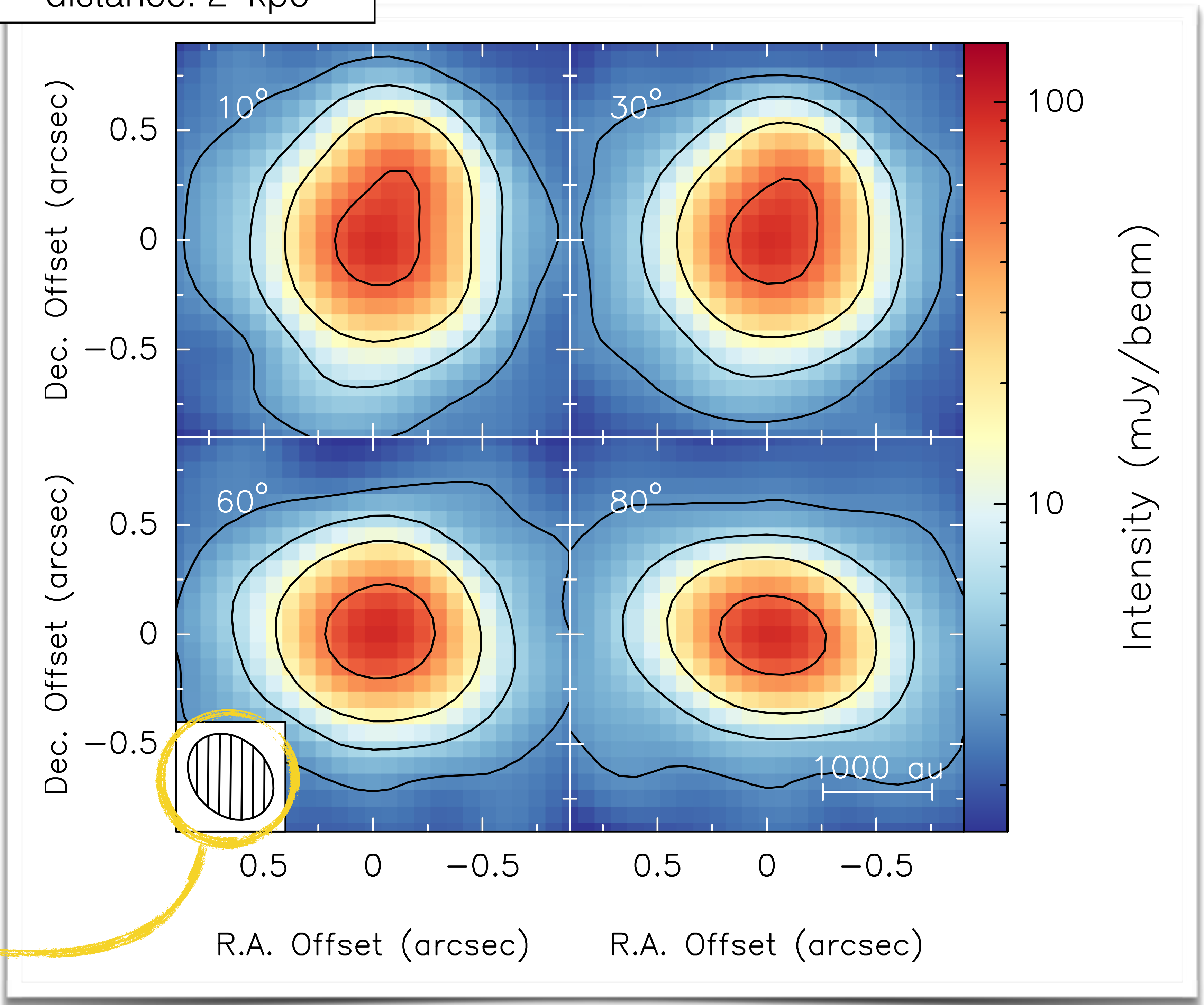


0.07″ (140 au)

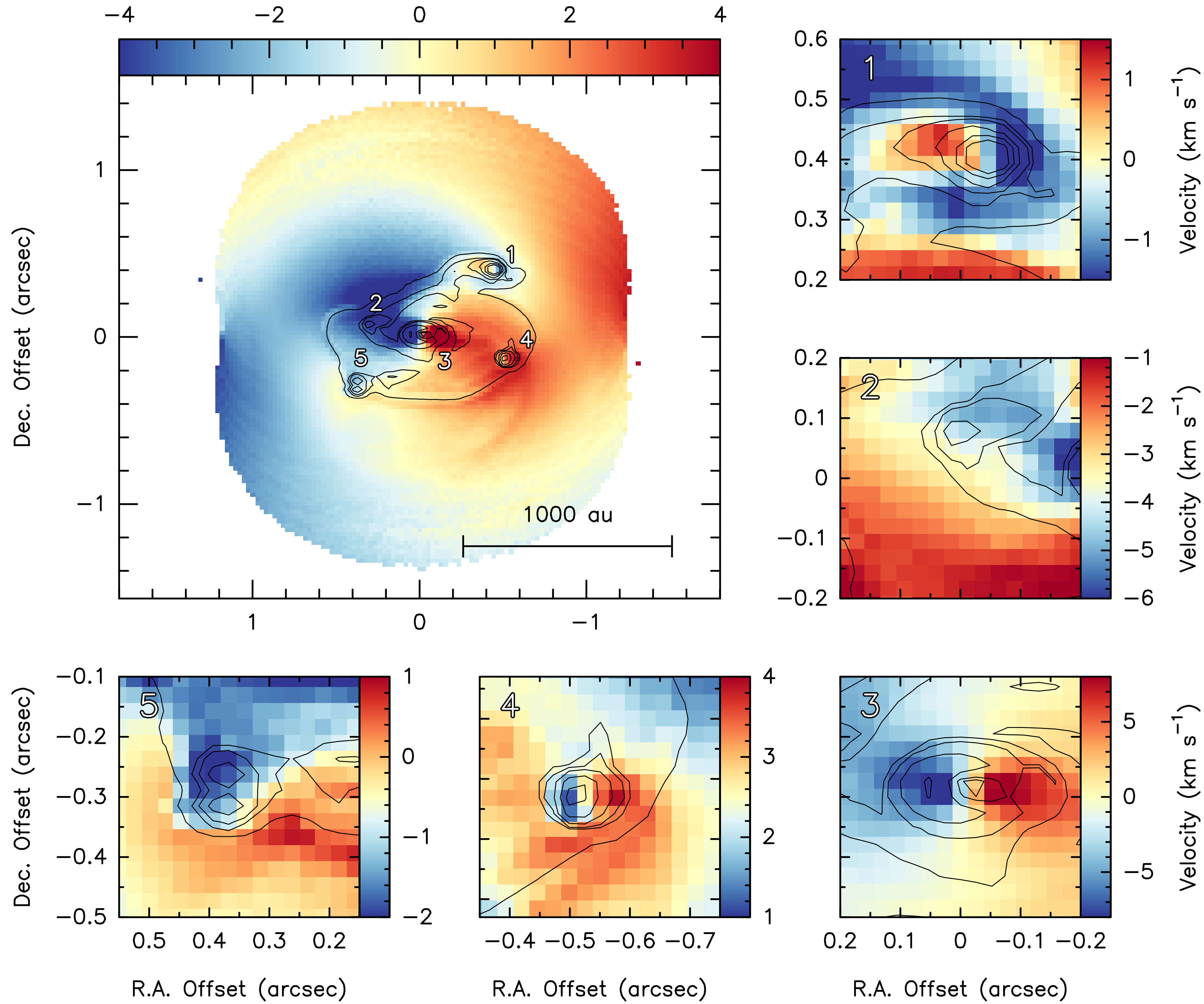
1.3 MM DUST CONTINUUM

distance: 2 kpc

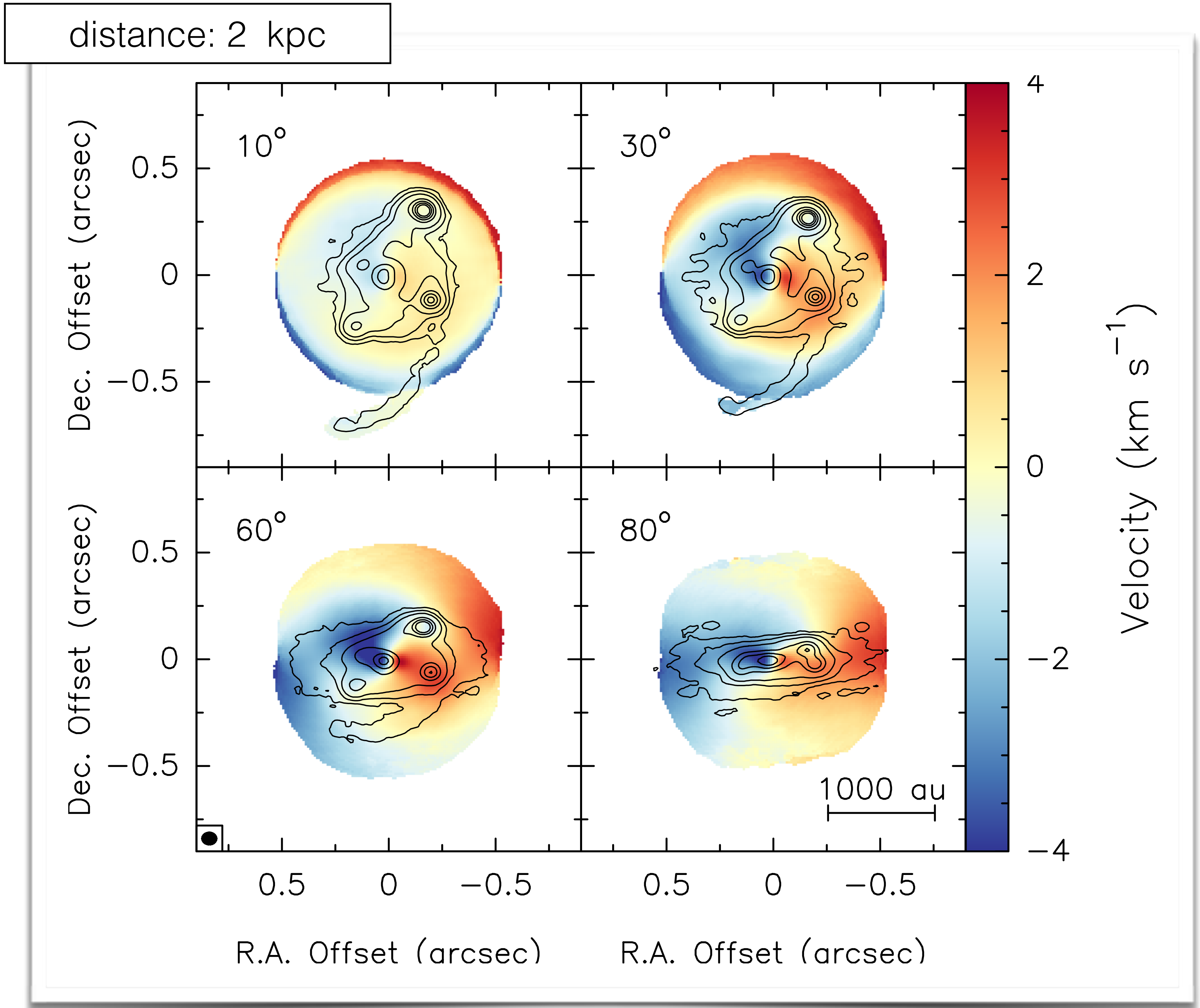


0.4″ (800 au)

KINEMATICS: CH_3CN (12_4-11_4)

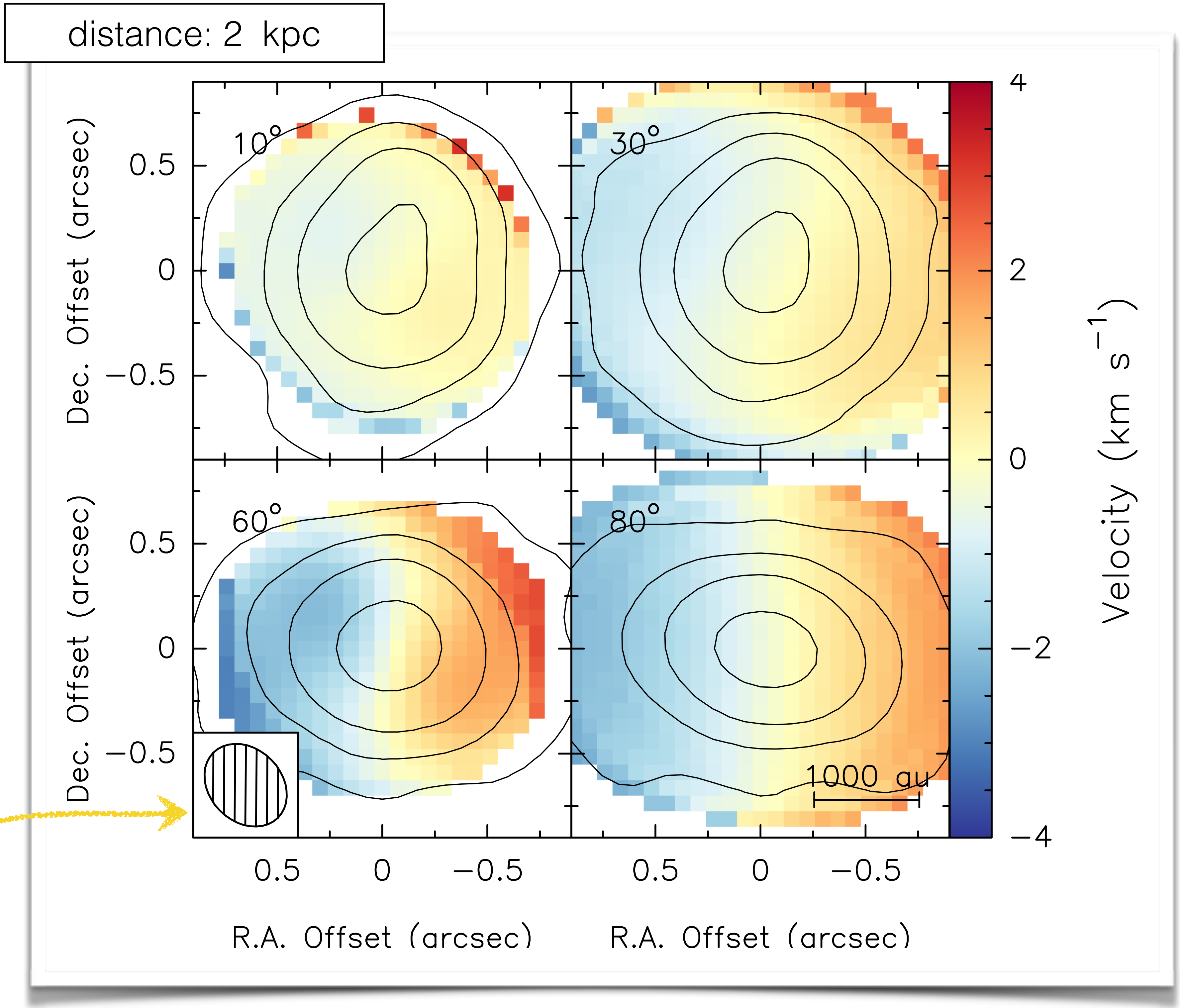


KINEMATICS: CH_3CN (12_4-11_4)



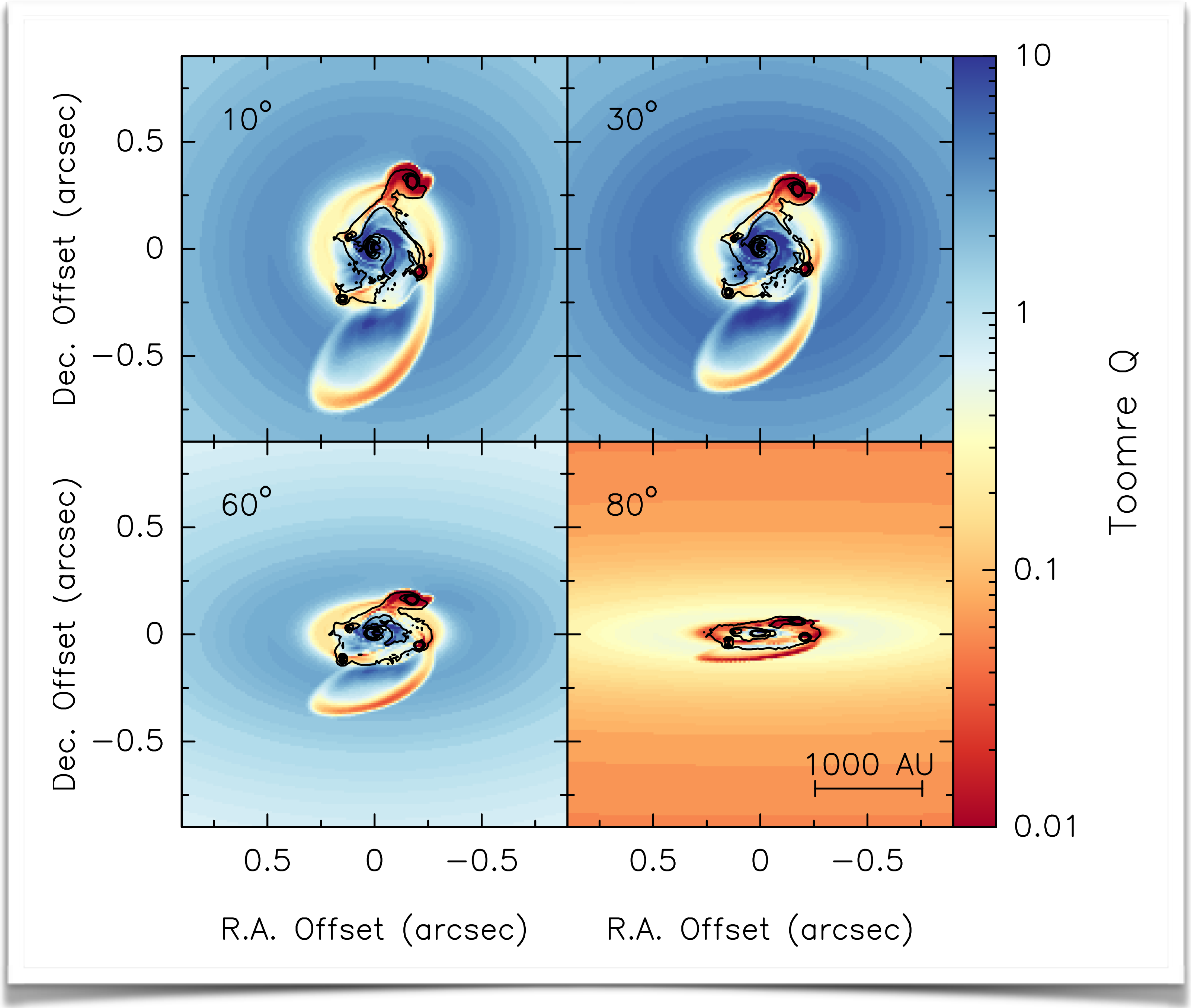
ALMA resolves the velocity structure well

KINEMATICS: CH_3CN (12_4-11_4)



In NOEMA observations, the emission is smeared out over a larger region

TOOMRE STABILITY: INCLINATIONS



'true' Toomre Q maps at different inclinations

Q < 1 at the positions of fragments

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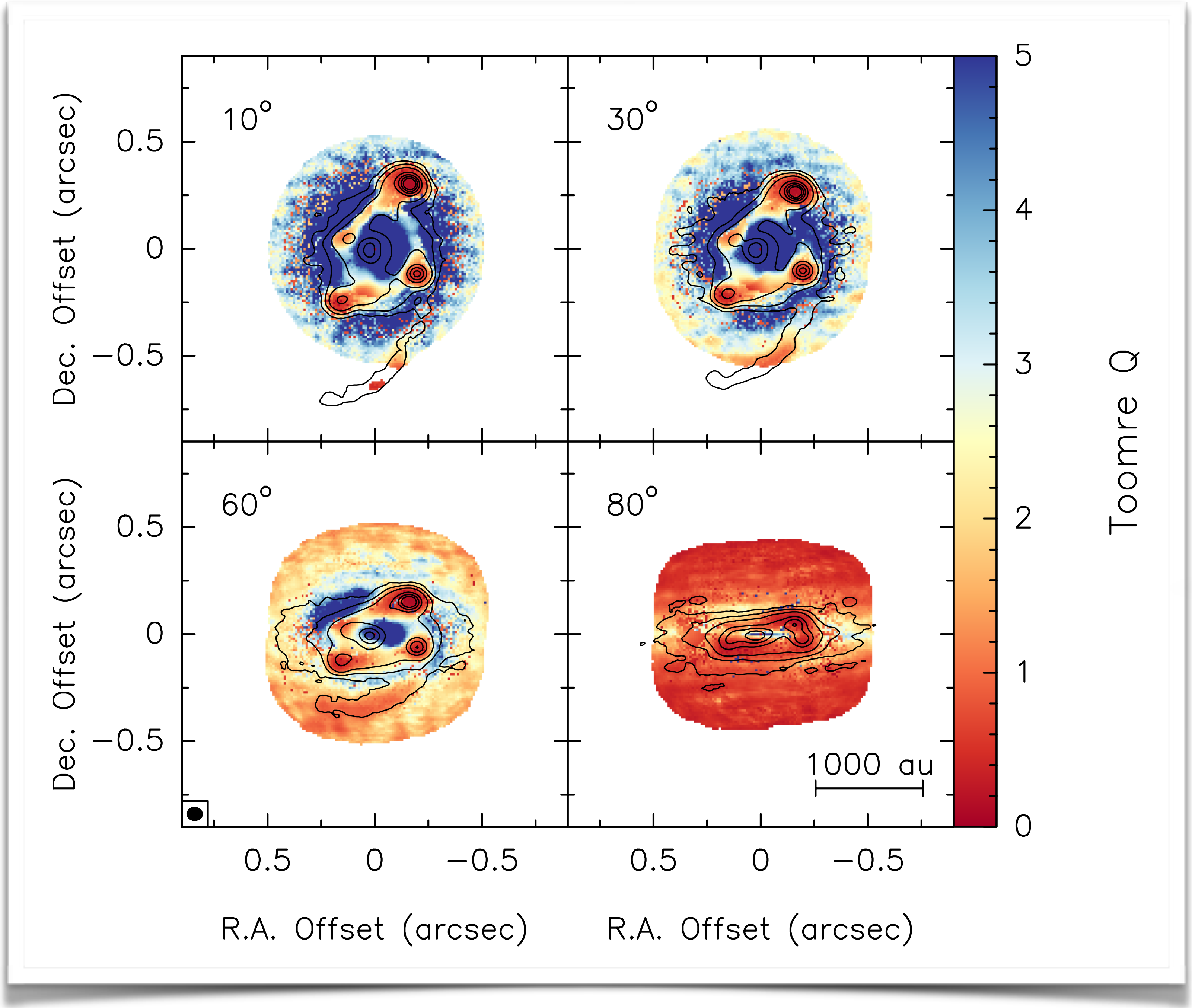


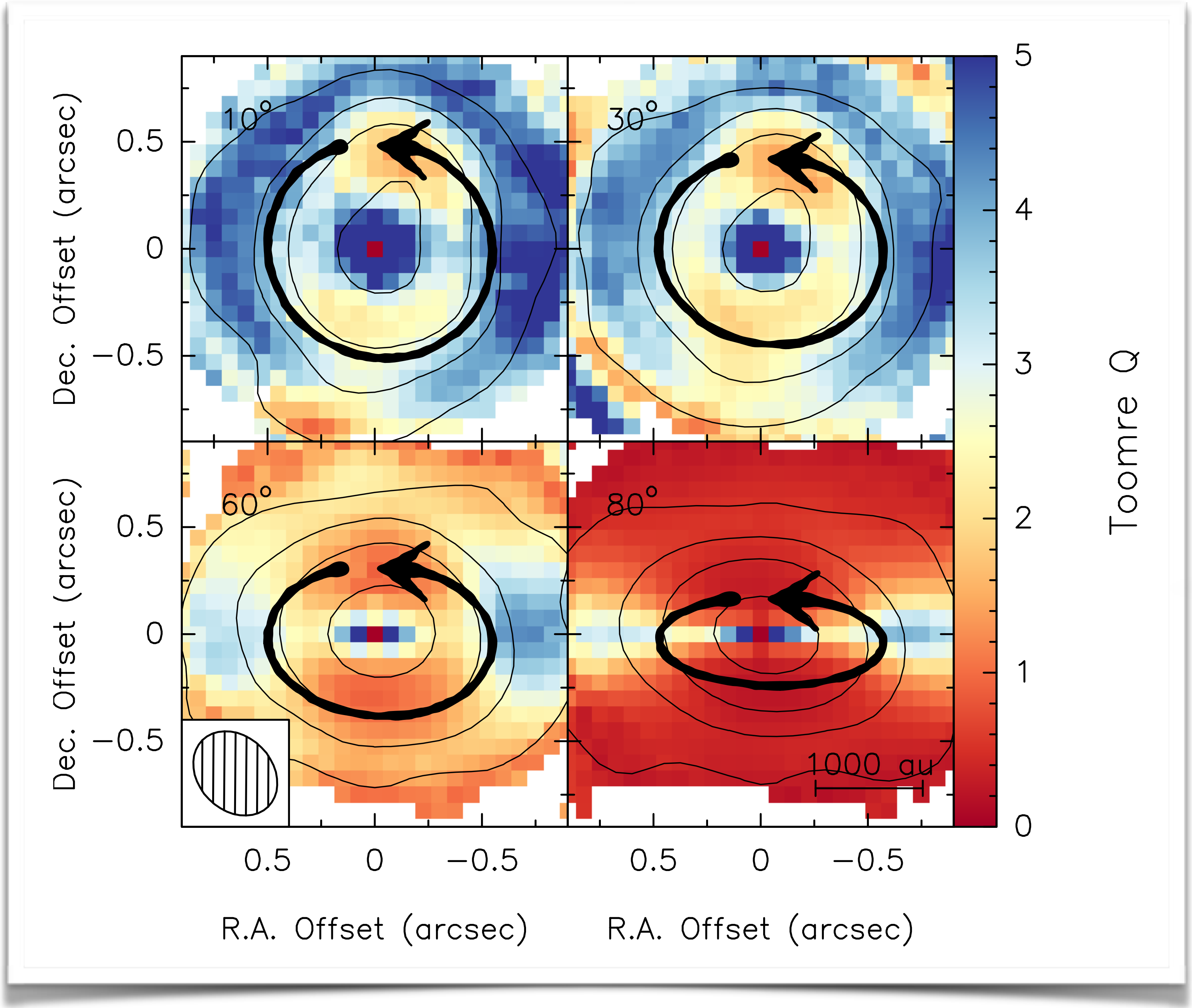
$$Q = \frac{c_s \Omega}{\pi G \Sigma}$$

$$\Omega(r) = \sqrt{\frac{G(M_* + M_{\rm disk}(r))}{r^3}}$$

Q < 1 at the positions of **fragments**

Ahmadi, Kuiper & Beuther (submitted to A&A)

TOOMRE STABILITY: INCLINATIONS



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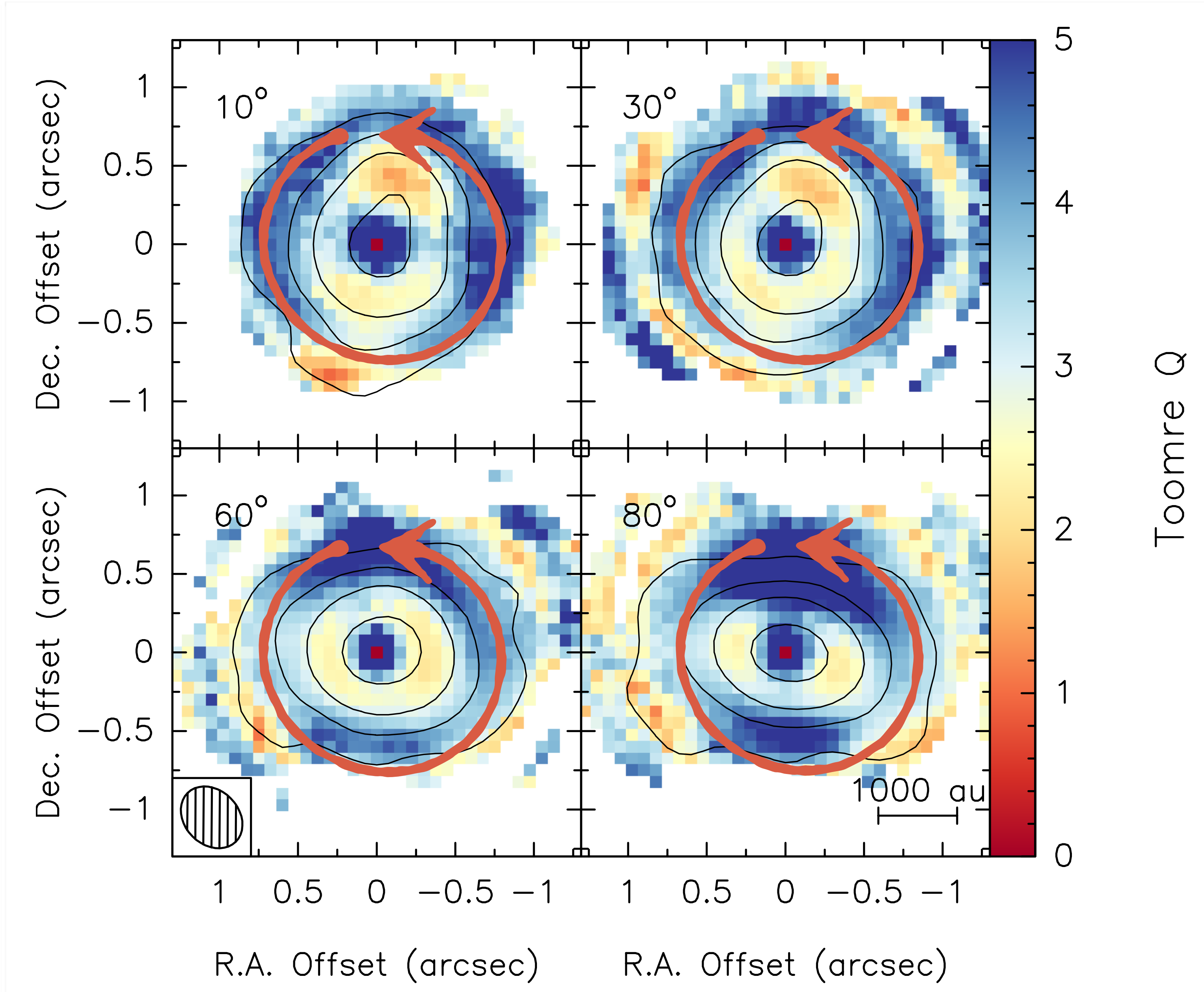
Although NOEMA wouldn't resolve fragments at 2 kpc, the disk is asymmetrically unstable and **fragmentation is predicted** nonetheless

TOOMRE STABILITY: INCLINATIONS



$$Q = \frac{c_s \Omega}{\pi G \Sigma}$$

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Method is robust in predicting **disk fragmentation** regardless of inclination uncertainties

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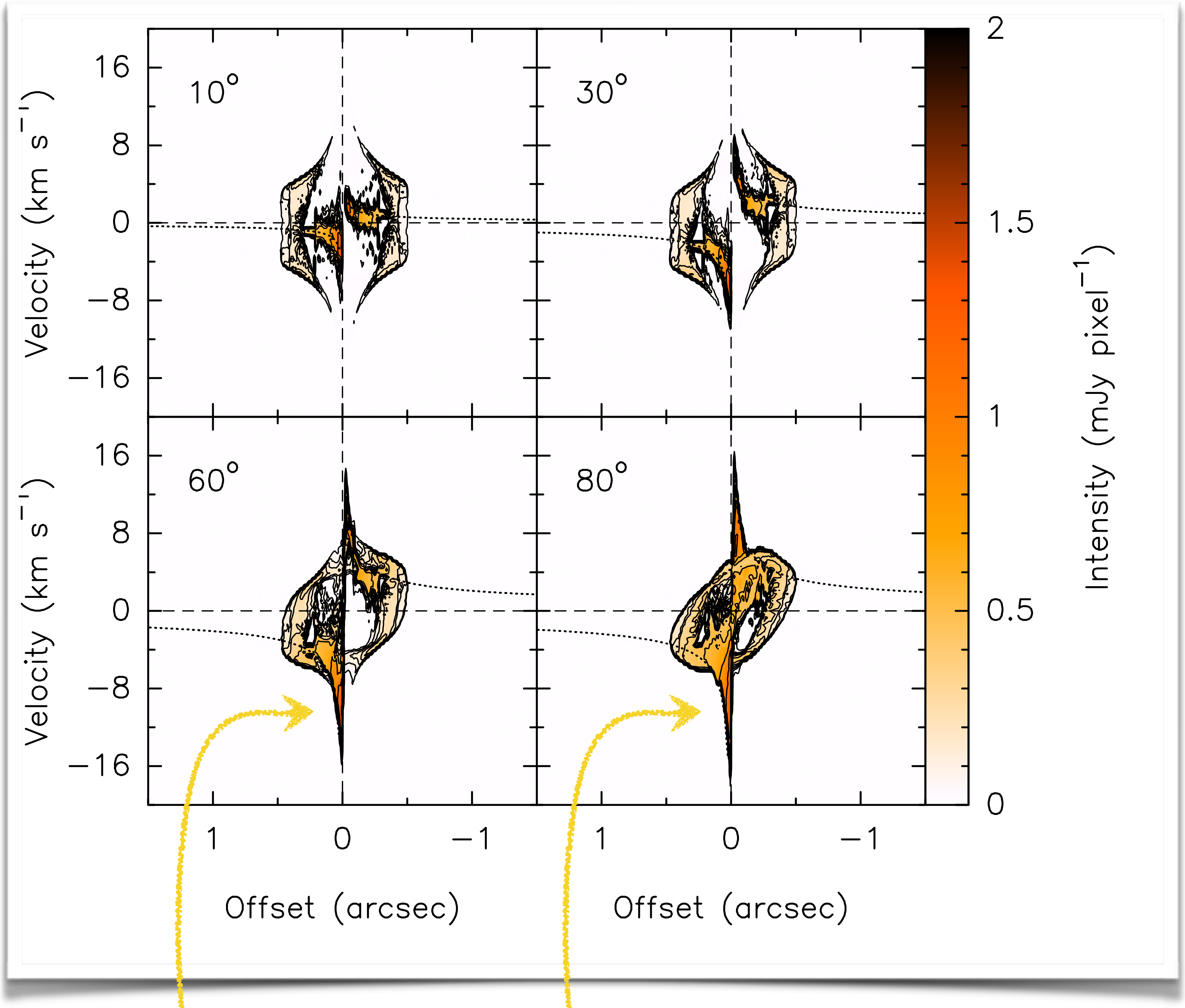
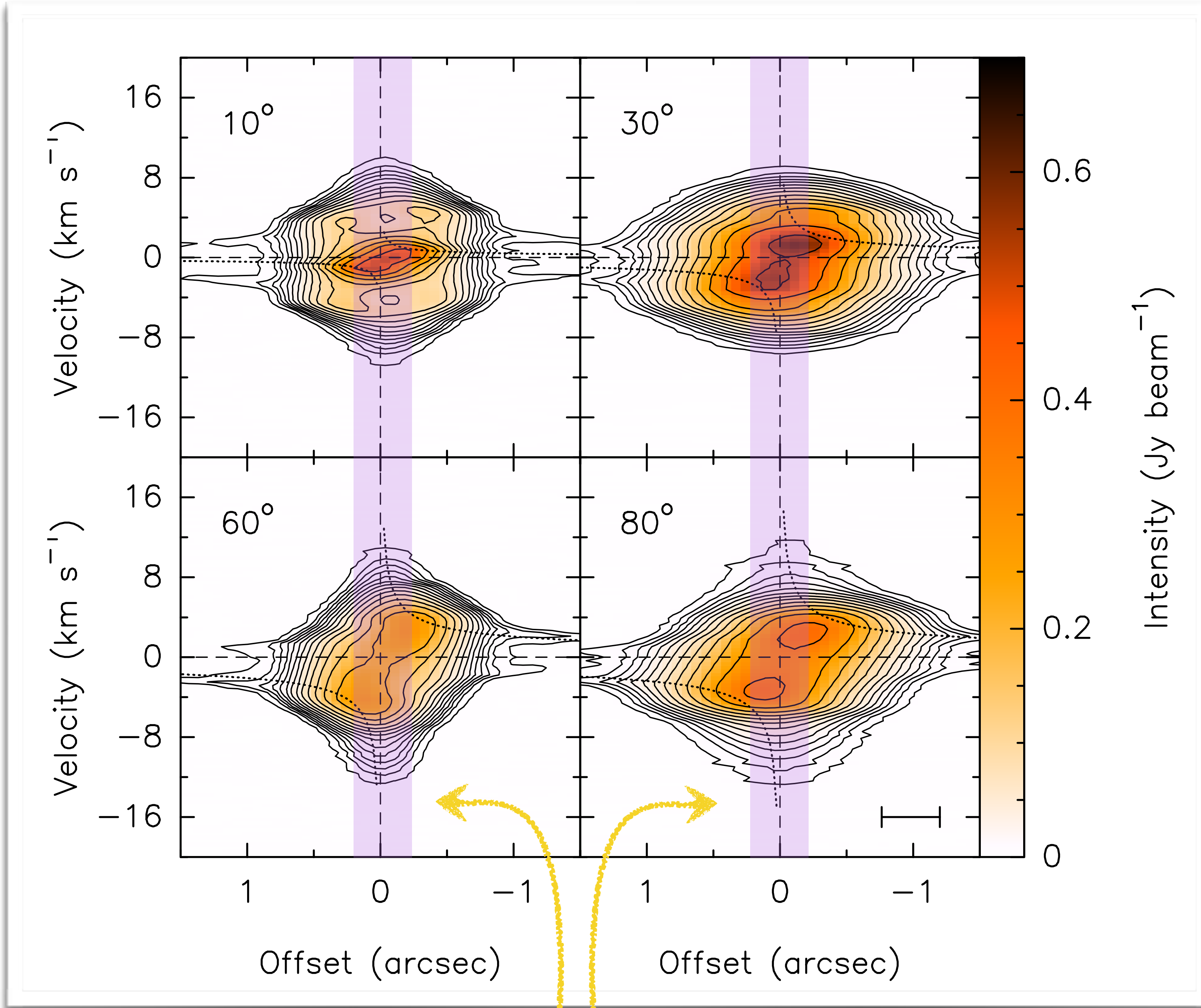
KINEMATICS: PV MAPS



high-velocity components of Keplerian disk best seen at higher inclinations

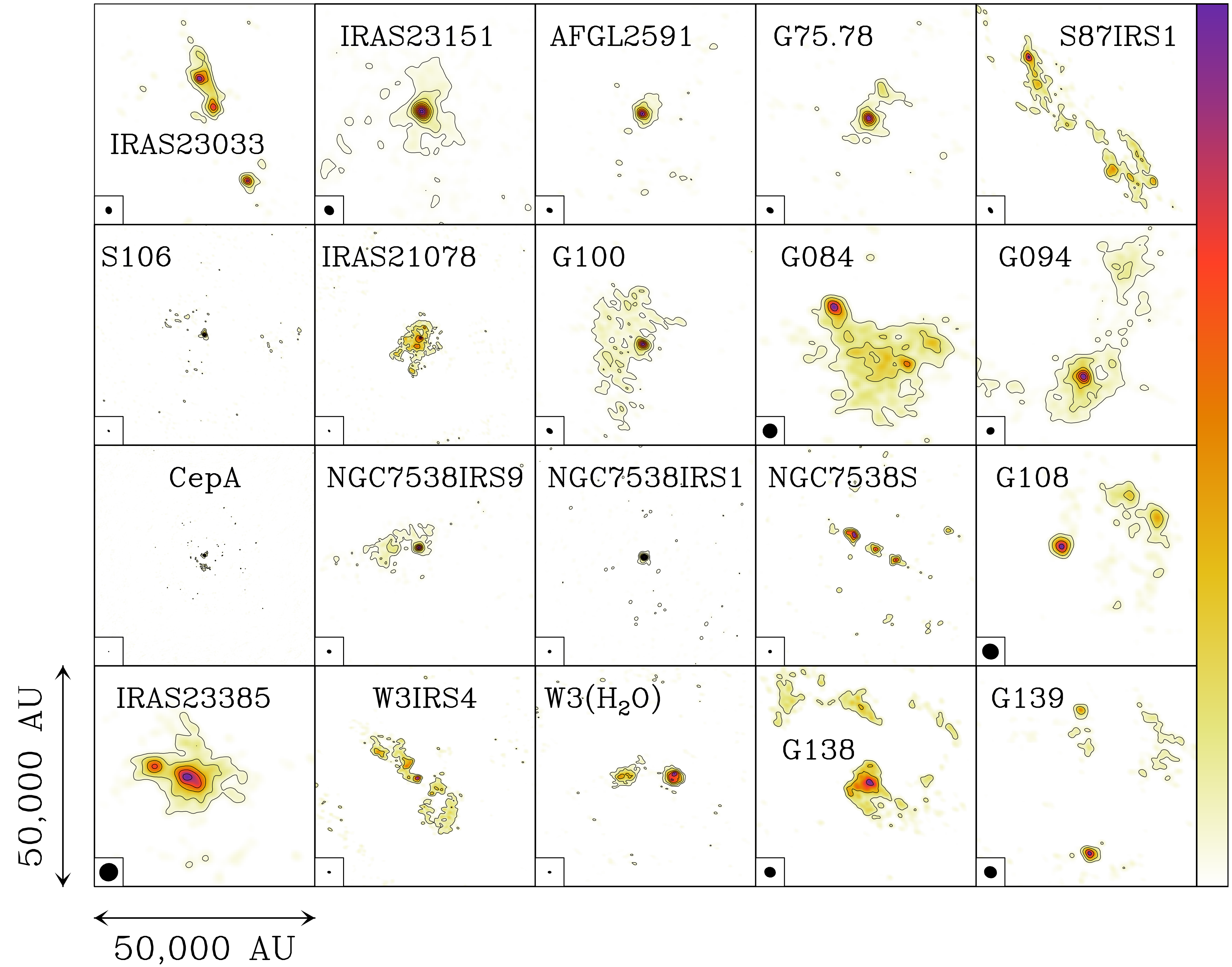
KINEMATICS: PV MAPS



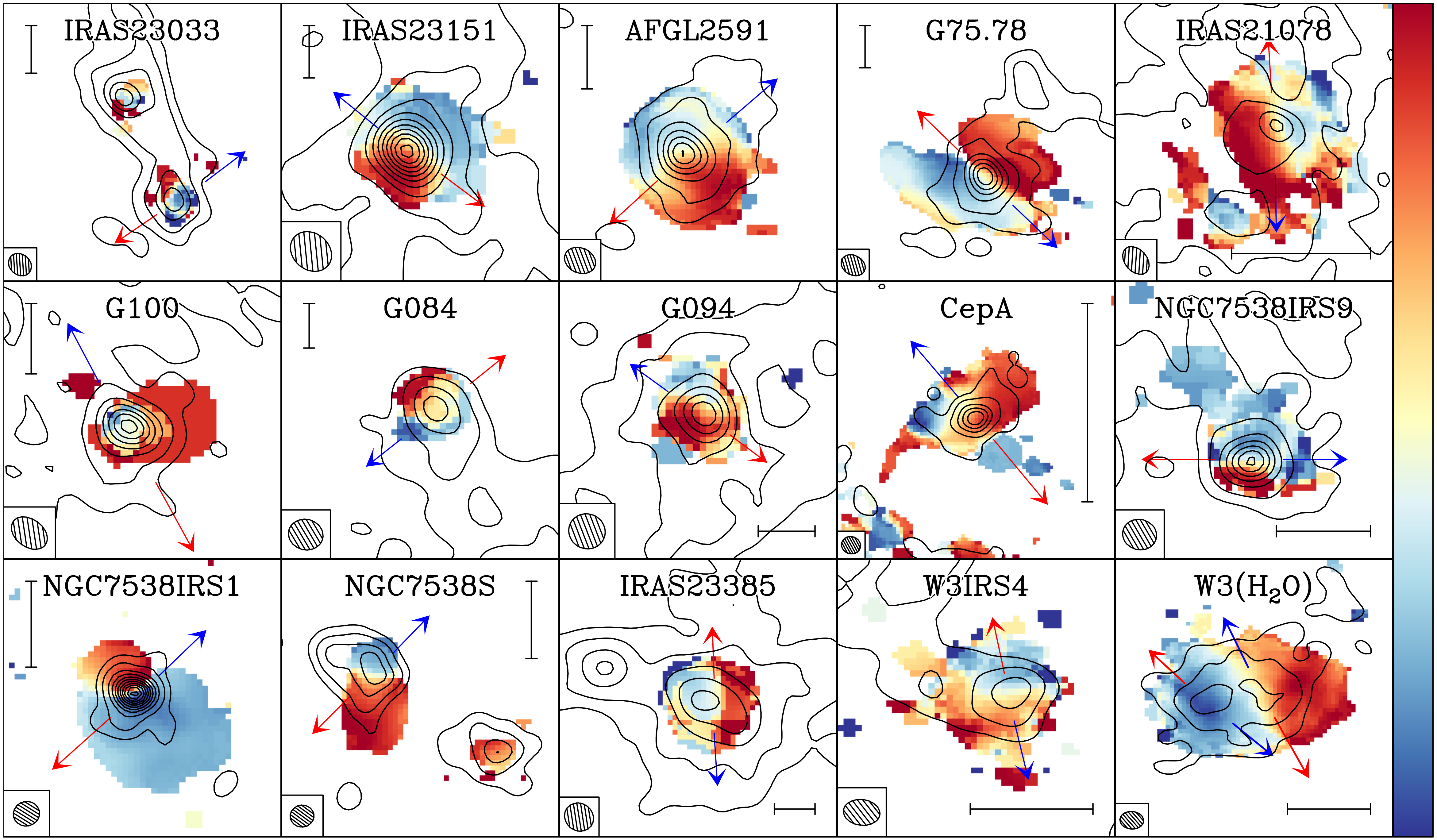
High-velocity components smeared out

CORE: DUST CONTINUUM

Beuther, Mottram, Ahmadi et al. 2018

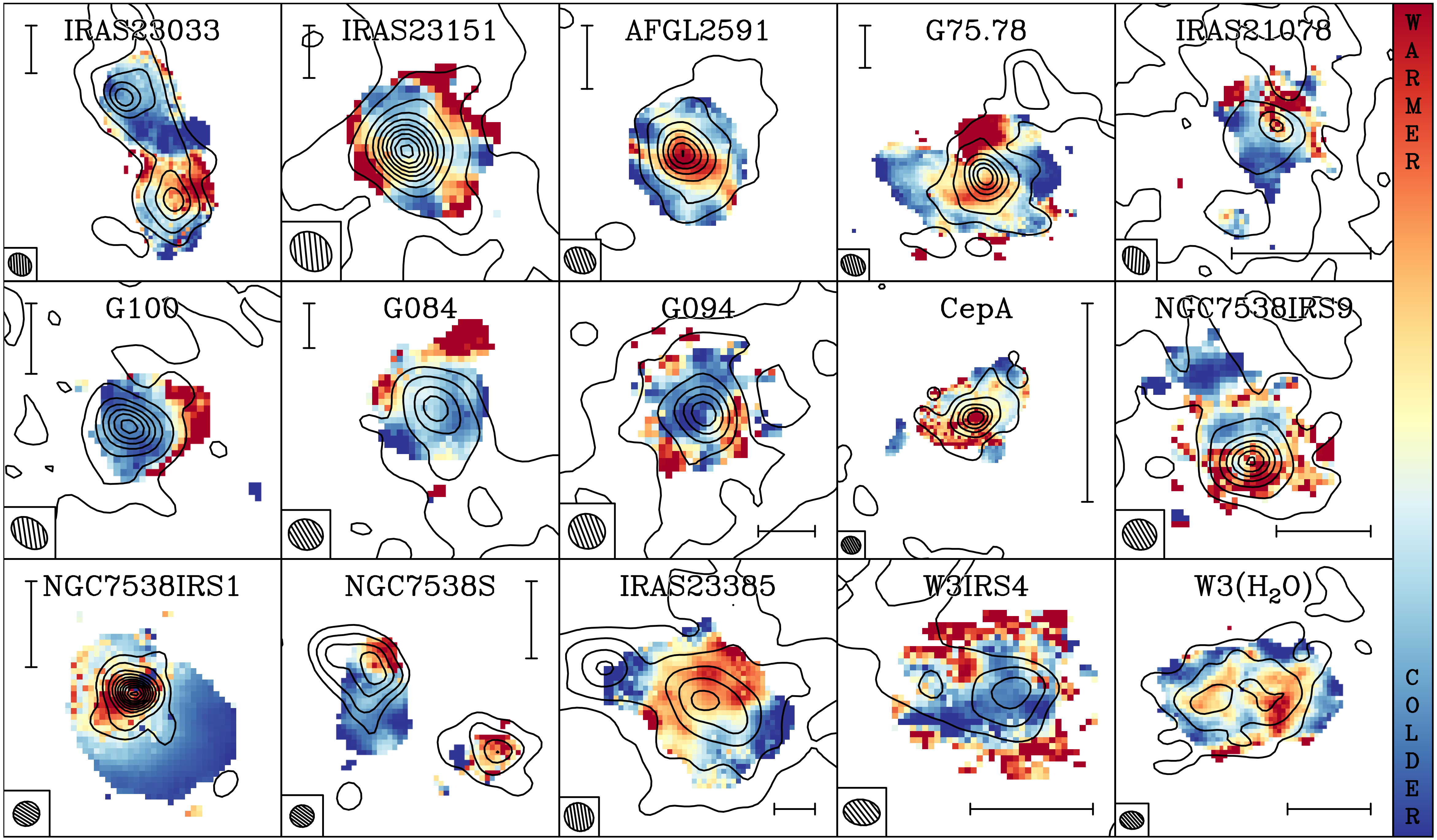


CORE : KINEMATICS



Ahmadi et al. in prep.

CORE: TEMPERATURES



CONCLUSIONS

- High resolution observations needed to study early phase of high-mass star formation -> CORE survey
- Different modes of fragmentation
  - Isolated cores vs. highly fragmented clumps
  - Core fragmentation on large scales & disk fragmentation on small scales
- Rotating structures detected around most objects
- Benchmarked method to study disk stability

OUTLOOK

- Apply similar analyses to all other sources and study fragmentation and disk kinematics in a statistical way

credit: Andre Rambaud