A Keplerian disk with a four-arm spiral birthing an episodically accreting high-mass protostar

Ross A. Burns and M2O team
RIKEN

国立天文台
NAOJ
National Astronomical Observatory of Japan

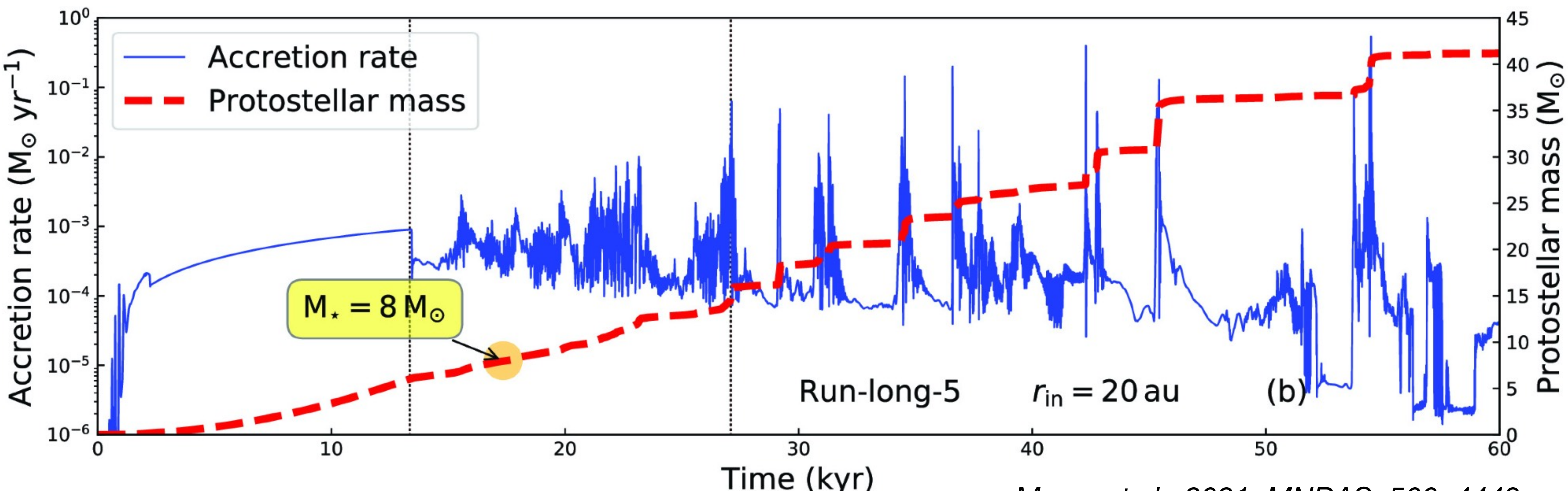
RIKEN

GERA Foundation

Background: High-mass star formation

Simulations predict:

- **More than half of a high-mass star's mass is gained through accretion bursts.**
- **Accretion bursts in high-mass protostars are infrequent (~ 10^3-4 yrs) with a short duration (months/yrs).**
- **Accretion bursts associated with GI disks**



Meyer et al., 2021, MNRAS, 500, 4448

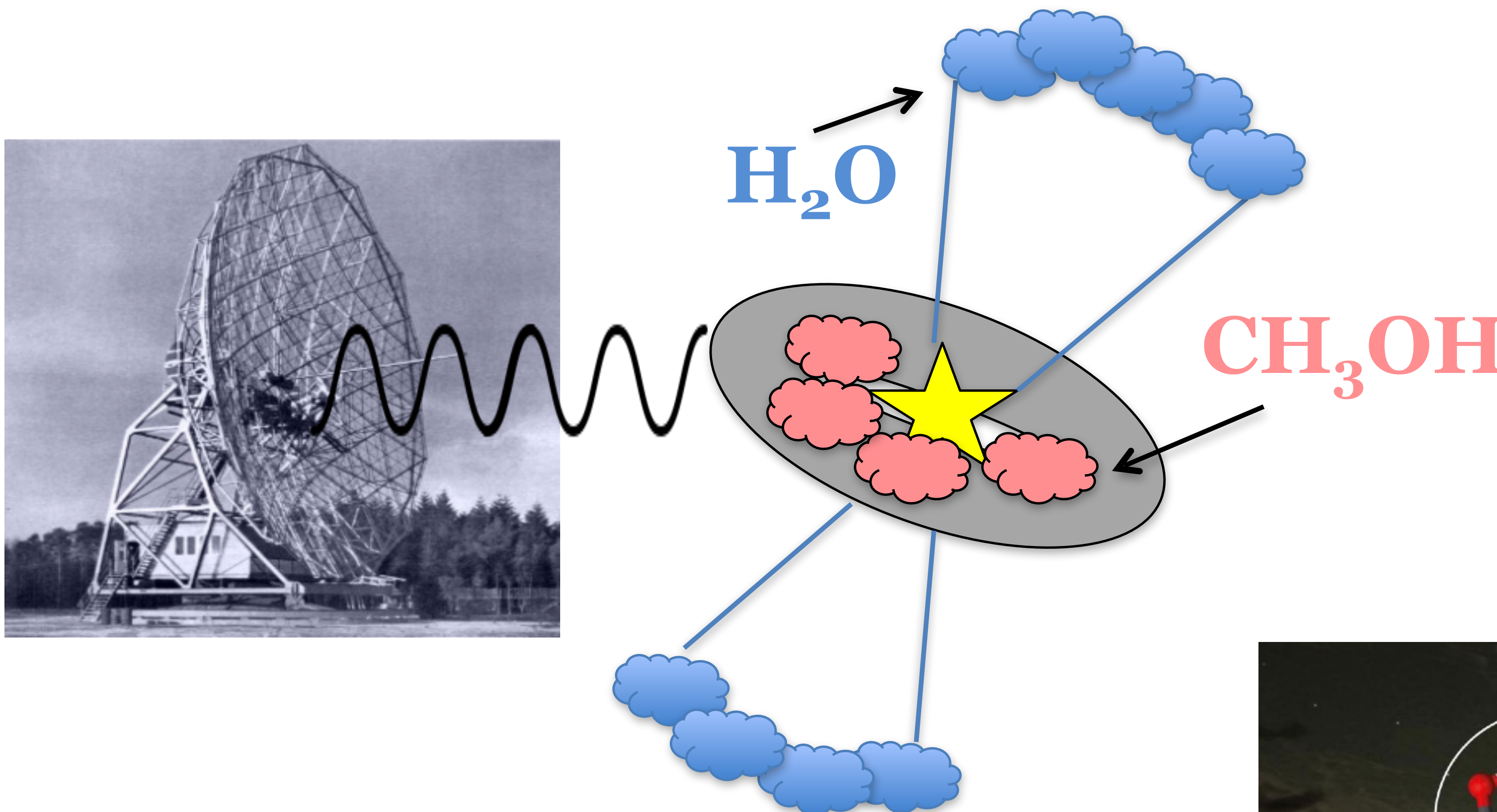
Lacking observational evidence

- **Deeply embedded + large distances + infrequent —> difficult to observe at high spatial resolution.**
- **3 published observationally confirmed accretion bursts in high-mass protostars, S255IR, NGC6334, G358.**

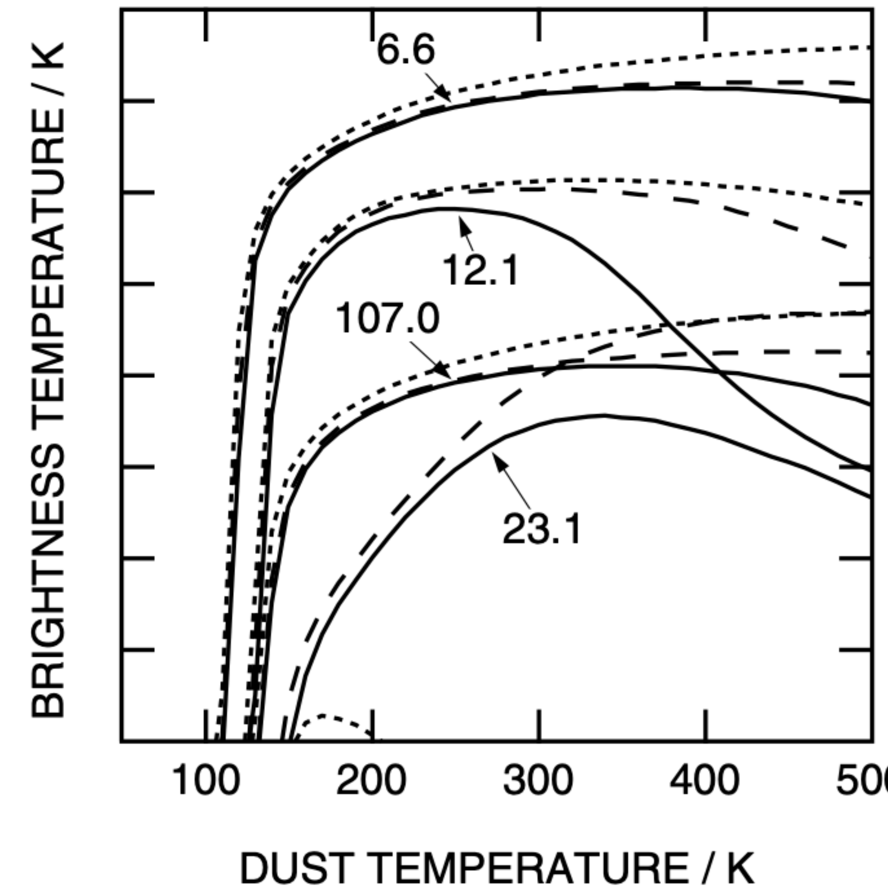
We are searching for the association of disk GI and accretion bursts in high-mass protostars

Maser VLBI is a suitable tool…

Use masers?



Cragg et al., 2005, MNRAS, 360, 533

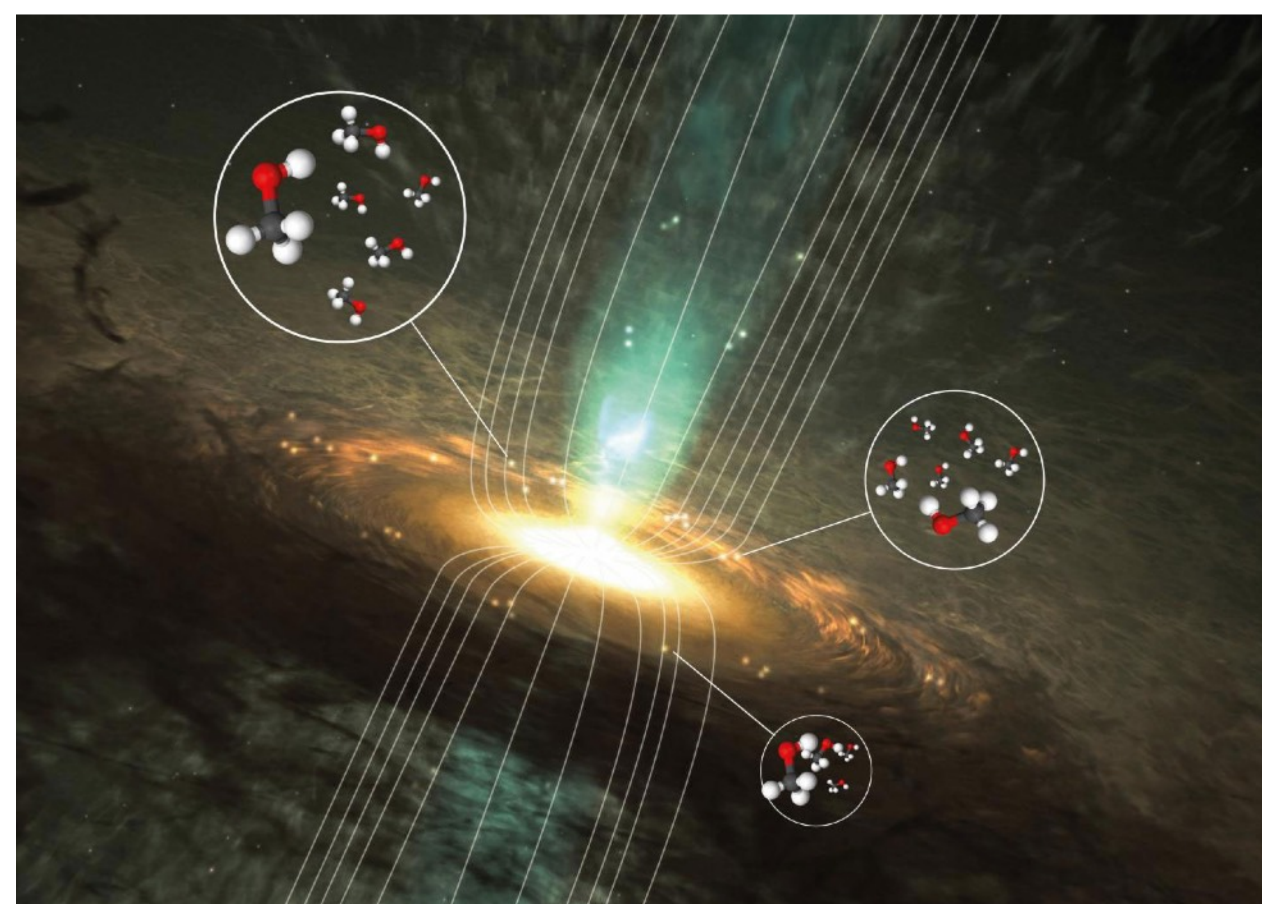


Methanol maser at 6.7 GHz often located in disks around high-mass protostars.

Brightness of 6.7 GHz methanol maser is highly sensitive to temperature and density.

Changes in maser flux reveal changes in the disk radiation field.

Monitoring 6.7 GHz masers is effective at locating HMPO accretion bursts.



Credit: Wolfgang Steffen /Chalmers/Boy Lankhaar

The Maser Monitoring Organisation (M2O)

Communications platform to bring together maser monitoring stations, theorists and follow-up campaigns

M2O source sky coverage

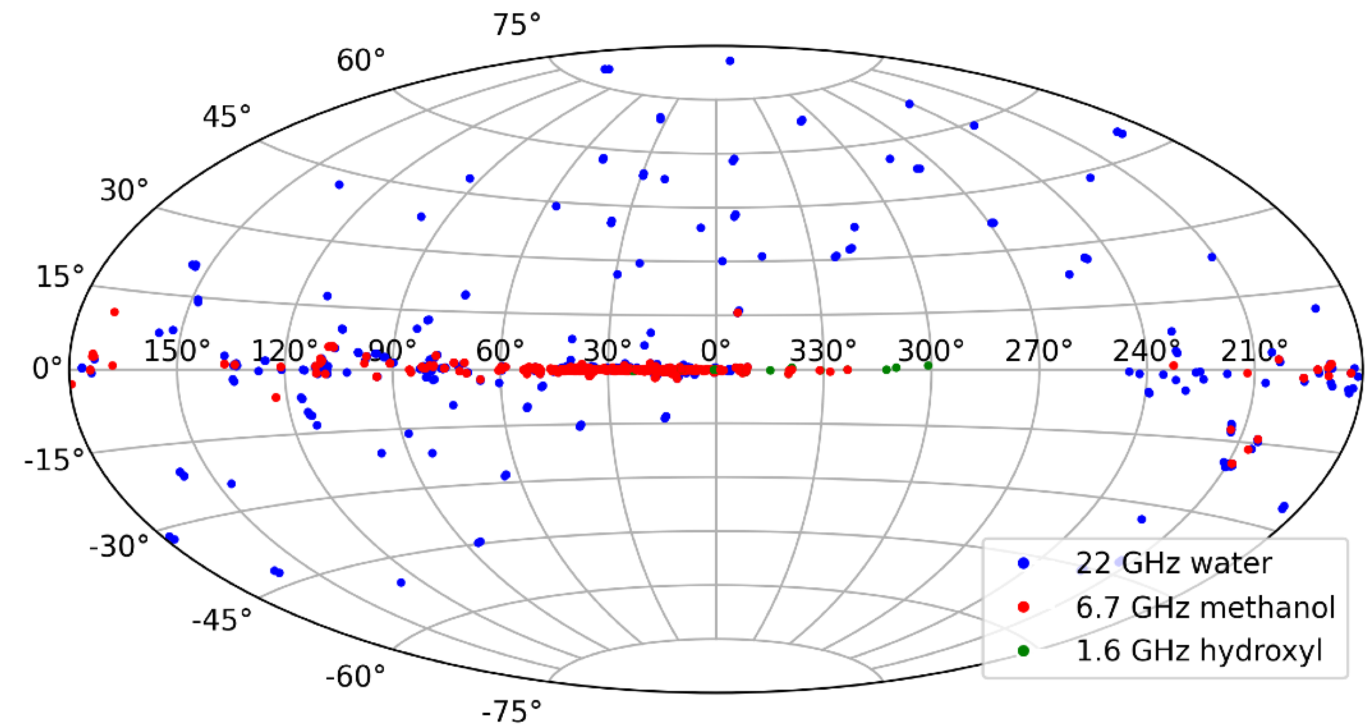
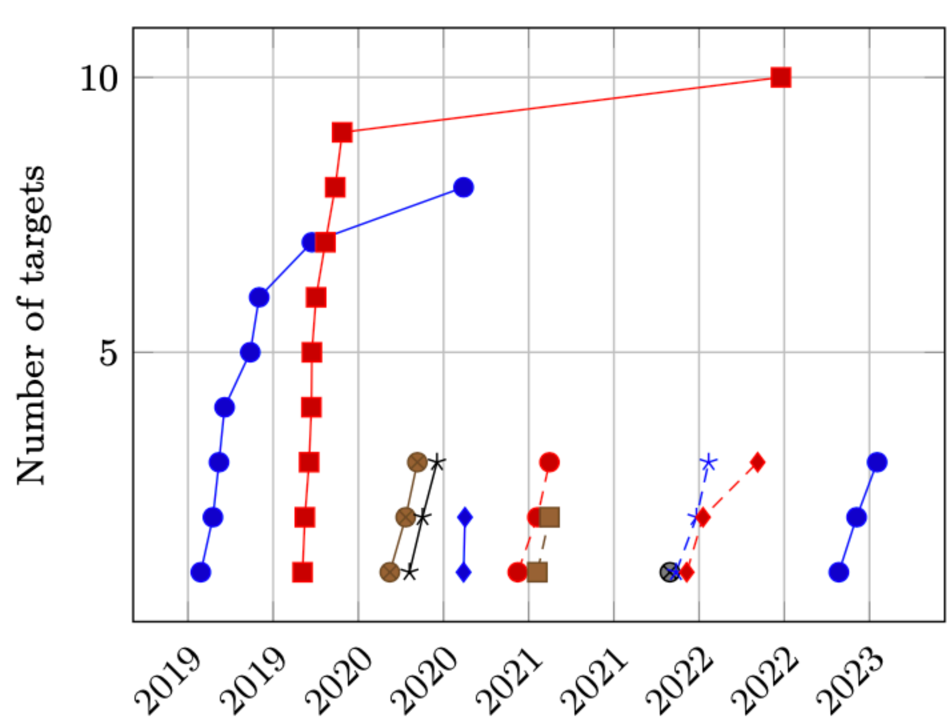
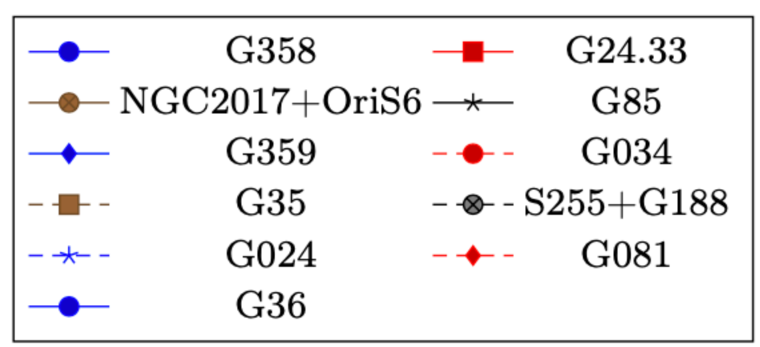


Fig 2. VLBI data aquisition.





Some flares are not followed up…

<u>Most flare targets have ~3 VLBI follow ups:</u>

- Identify flaring component
- Get proper motions
- ‘Movie’ of flux changes
- Establish if its worth pursuing further

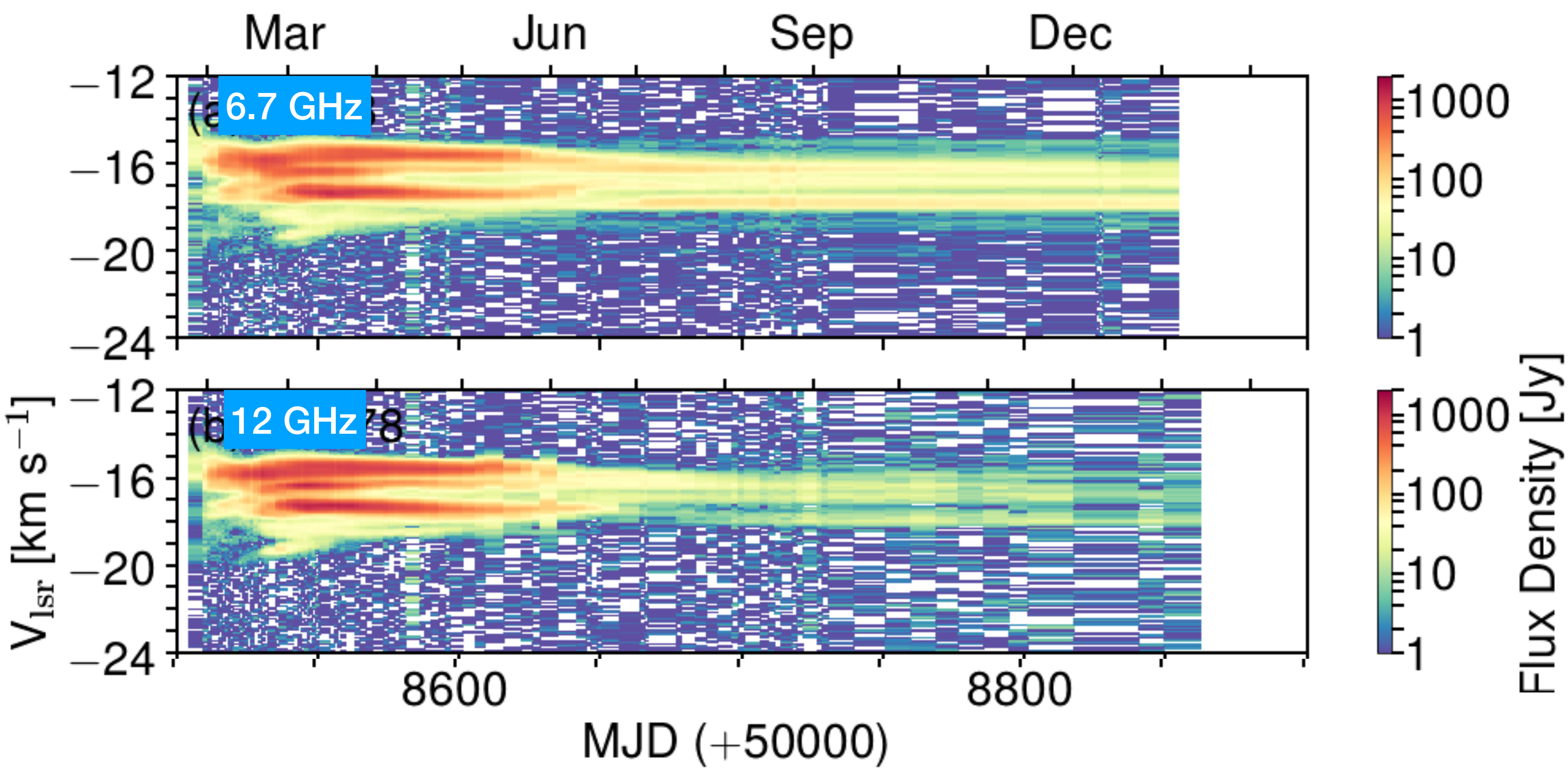
Maser flare: G358.93-0.03

First flare of the 6.7 GHz methanol maser reported to the M2O

- **Main phase ~4 months**
- **Prolonged elevated flux (decreasing toward ~10Jy)**
- **Flares seen in a large number of maser transitions**

K. Sugiyama alerted the M2O in mid January 2019

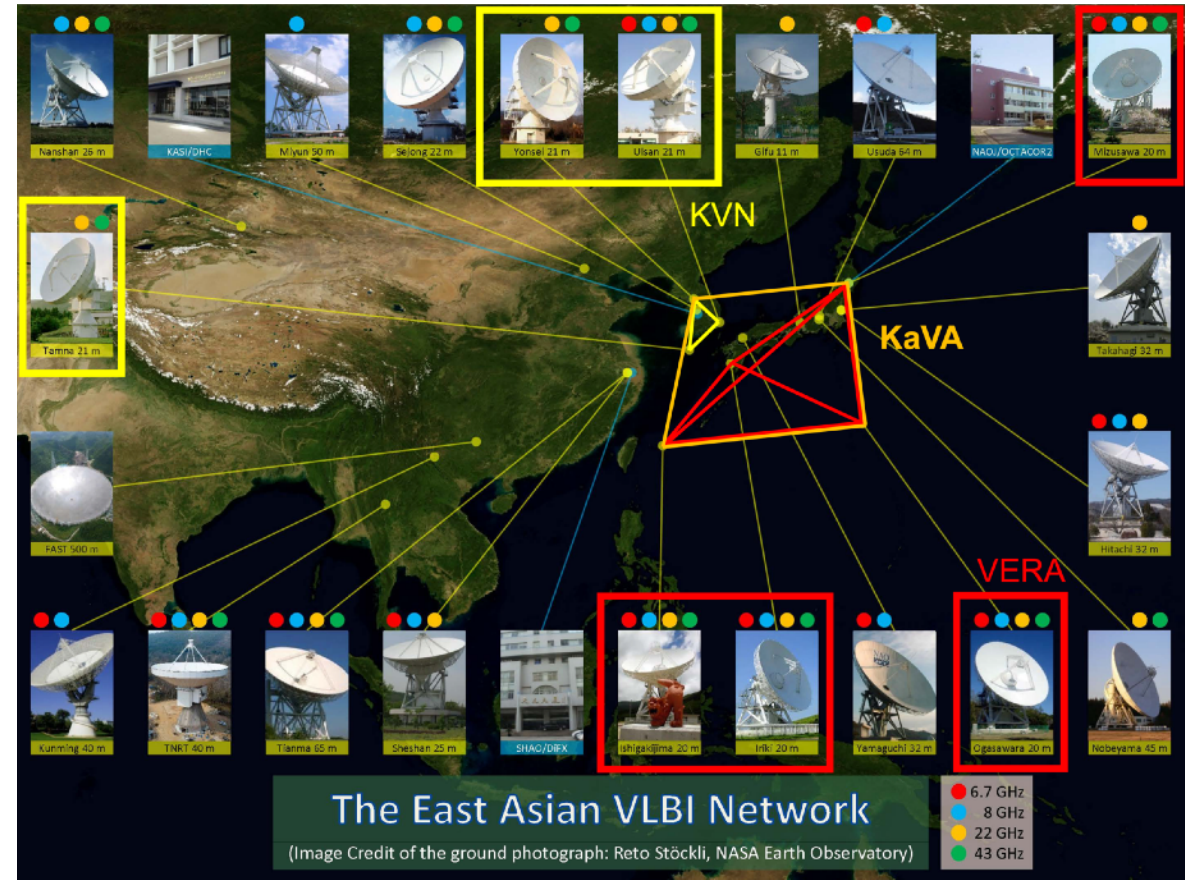
KS, Y. Yonekura, et al. (2019), ATel

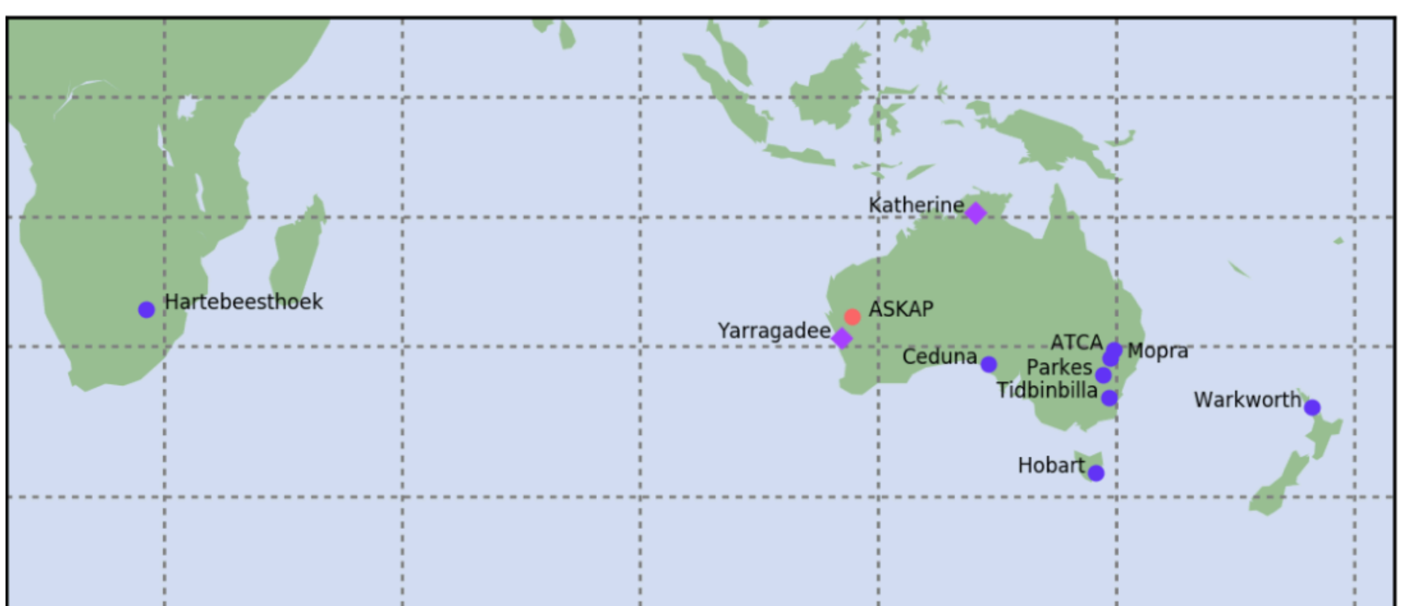


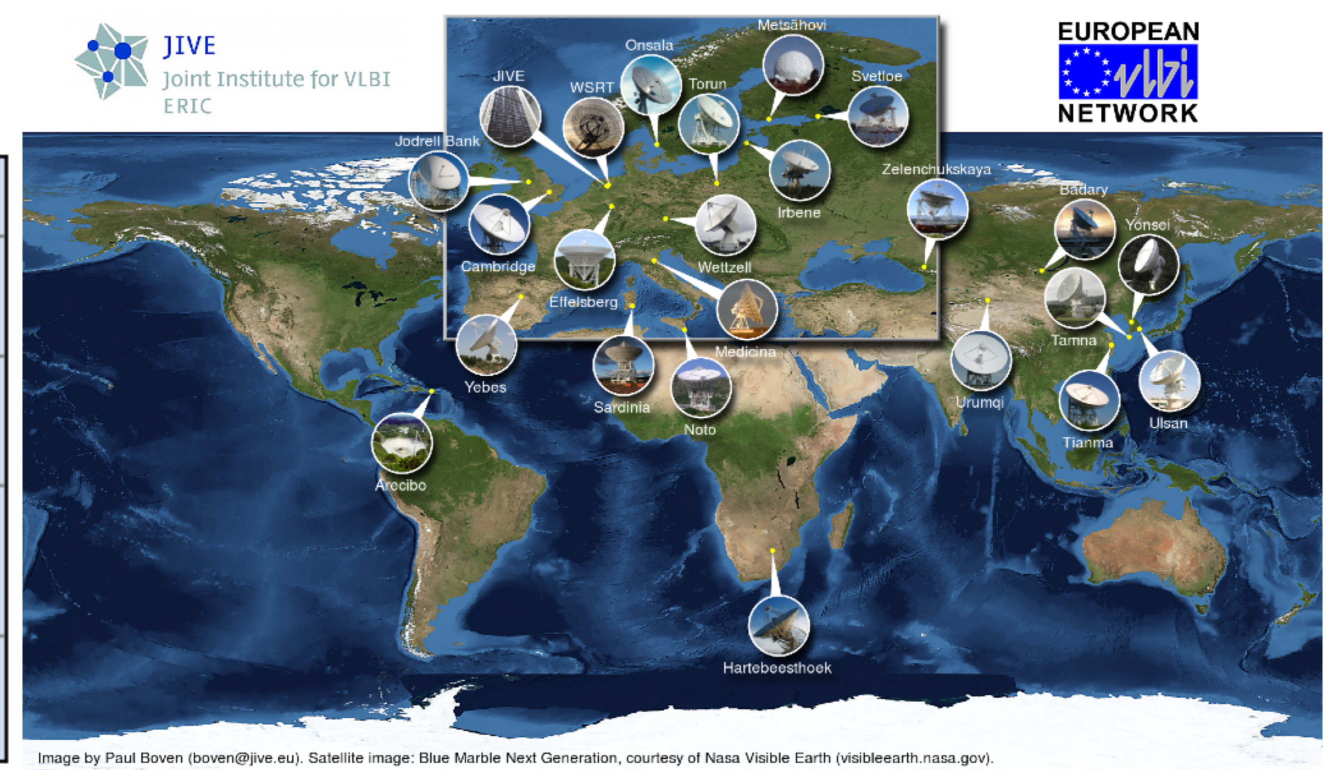
Monitoring results from Hart (courtesy of G. Macleod and F. v.d. Heever)

Results from VLBI

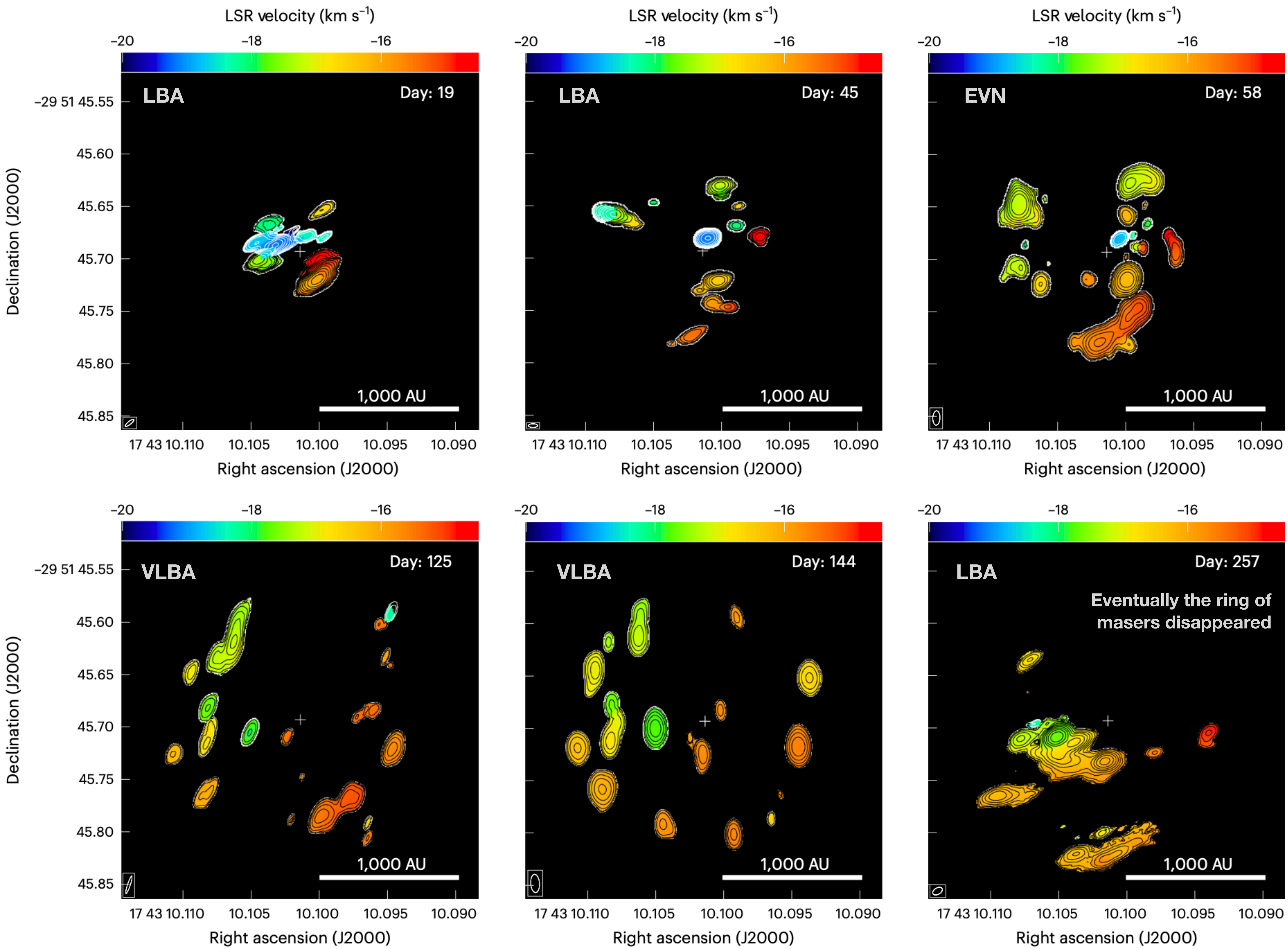
© 2020- The EAVN Collaboration



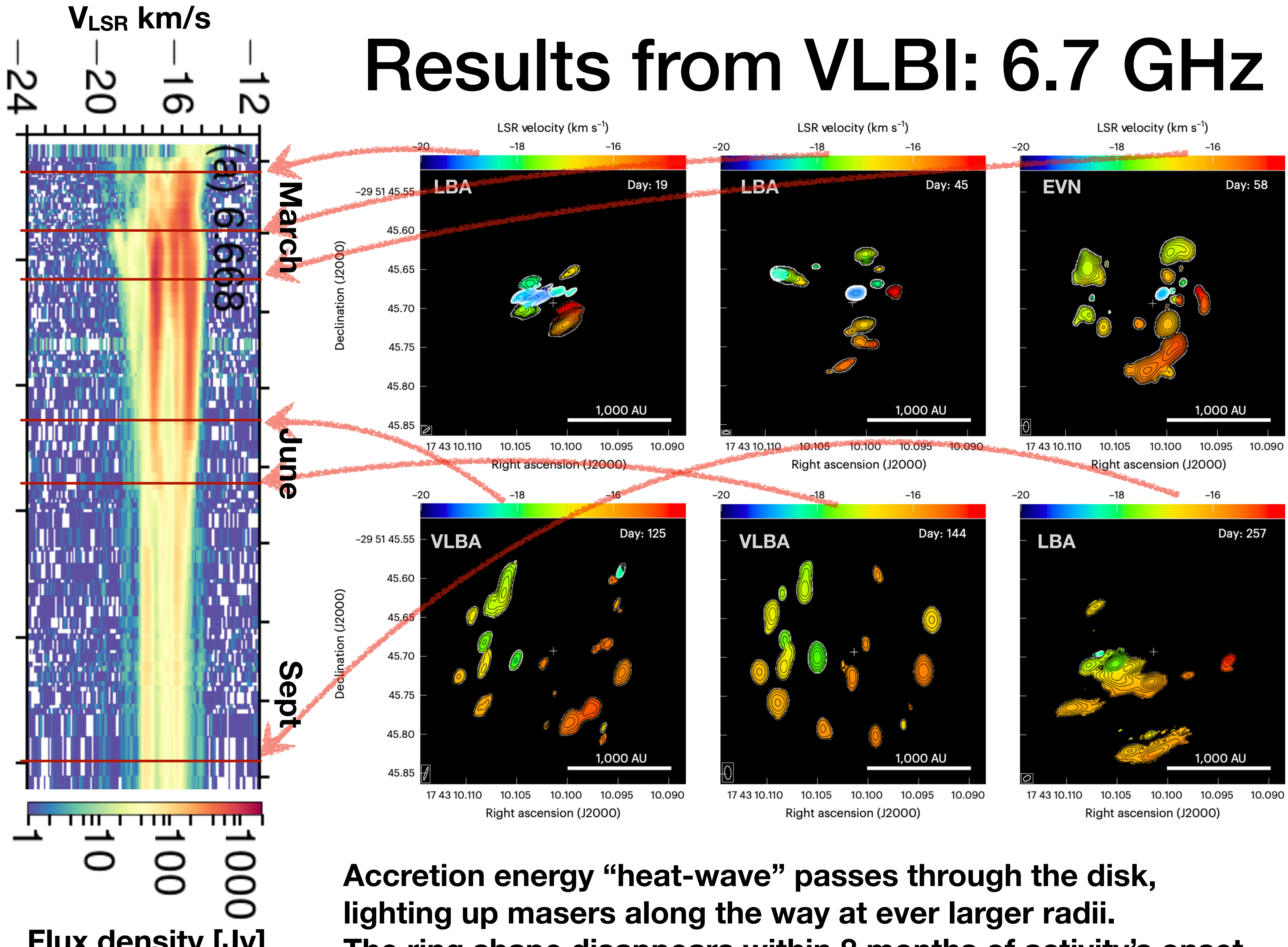




Results from VLBI: 6.7 GHz



Results from VLBI: 6.7 GHz



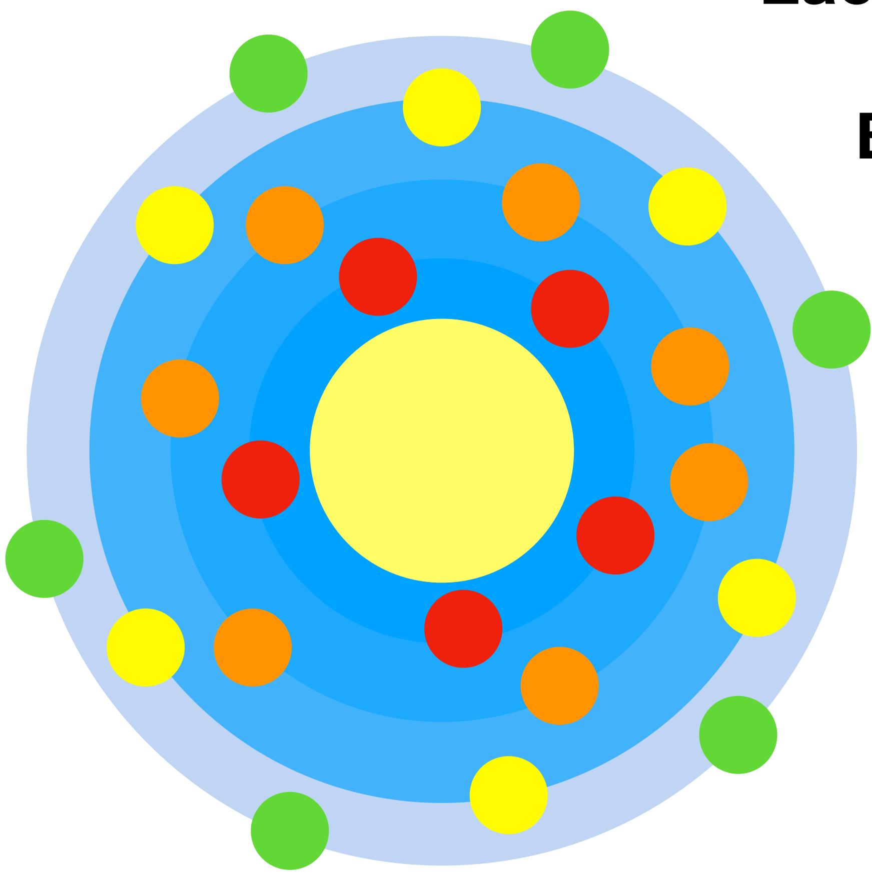
MacLeod et al. in prep

Accretion energy “heat-wave” passes through the disk, lighting up masers along the way at ever larger radii.
The ring shape disappears within 8 months of activity’s onset.

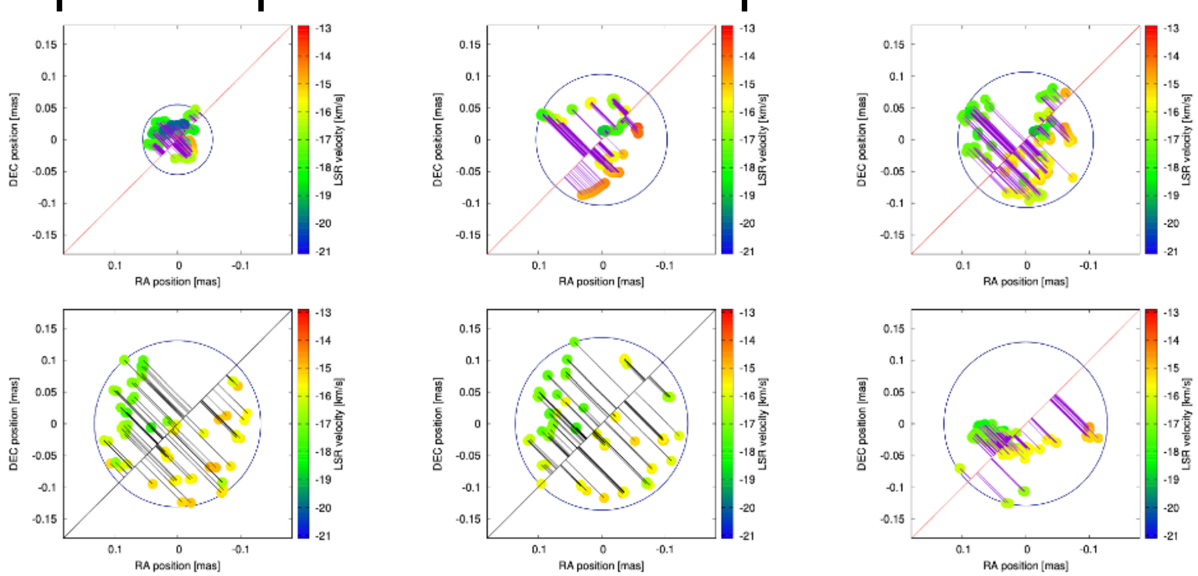
‘Heat-wave mapping’ of the disk

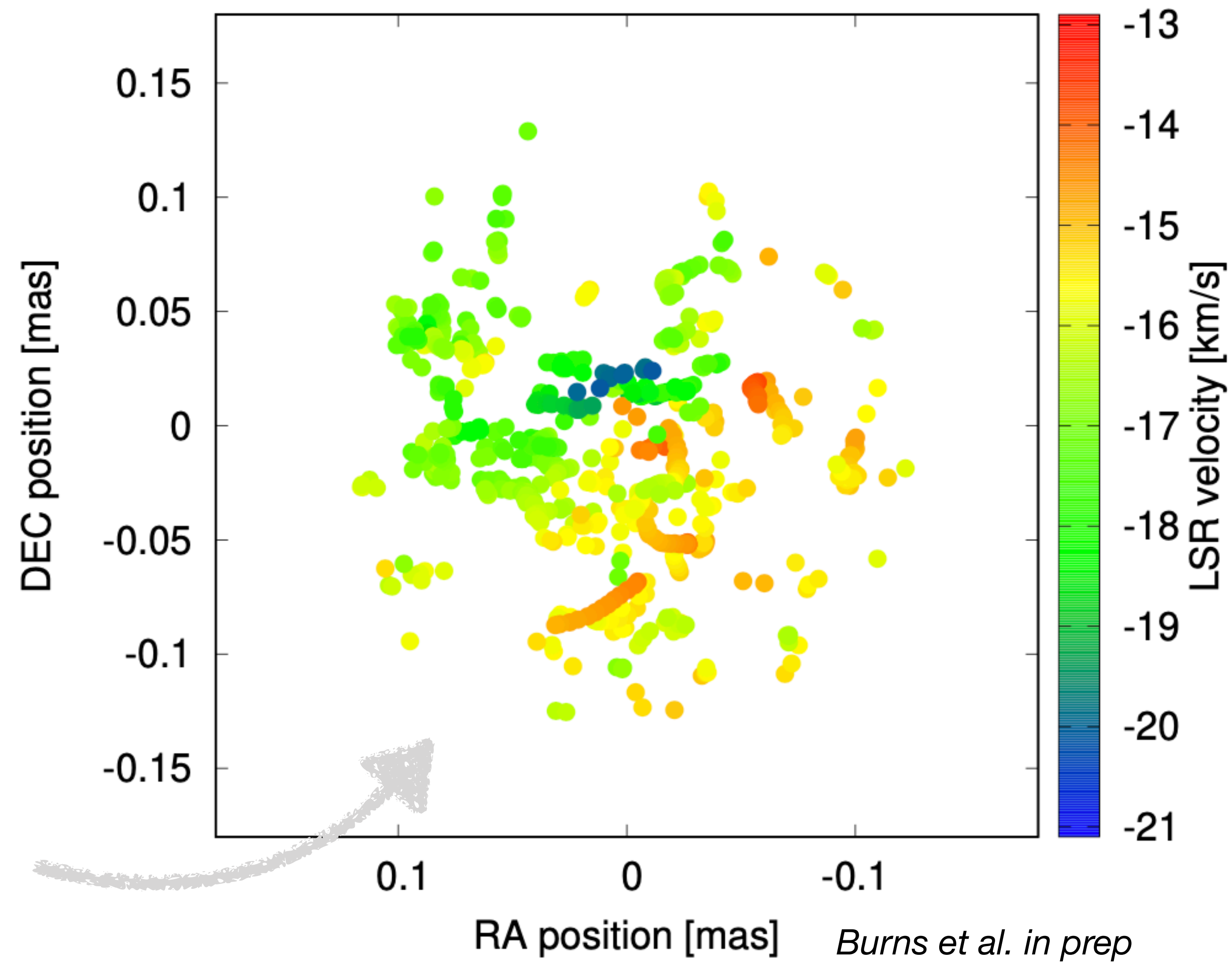
Each VLBI epoch traces one radius of the disk

By compiling all VLBI epochs we can fully trace the disk



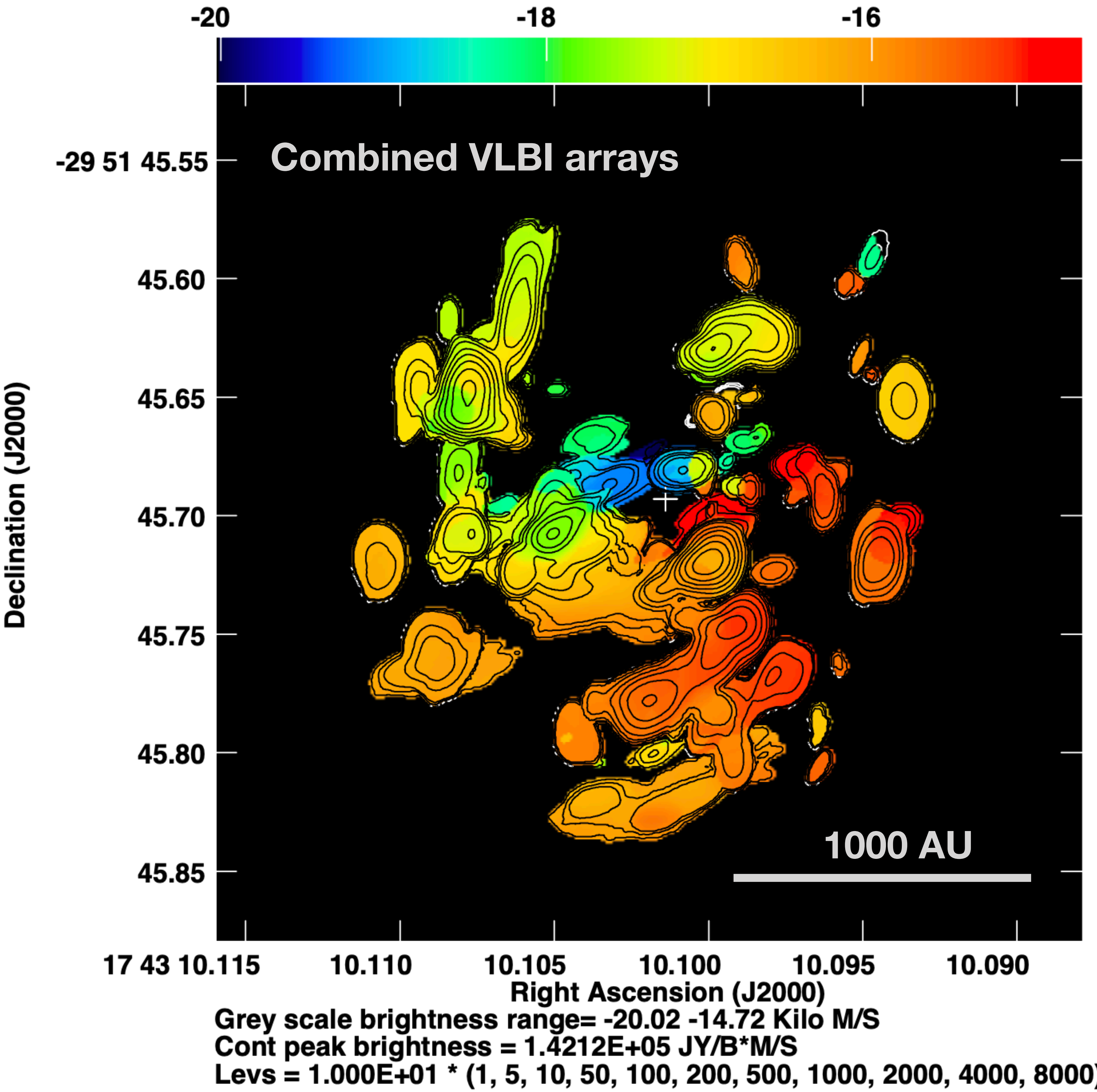
Spot maps of individual epochs





Burns et al. in prep

Tentative sub-structures in the disk?



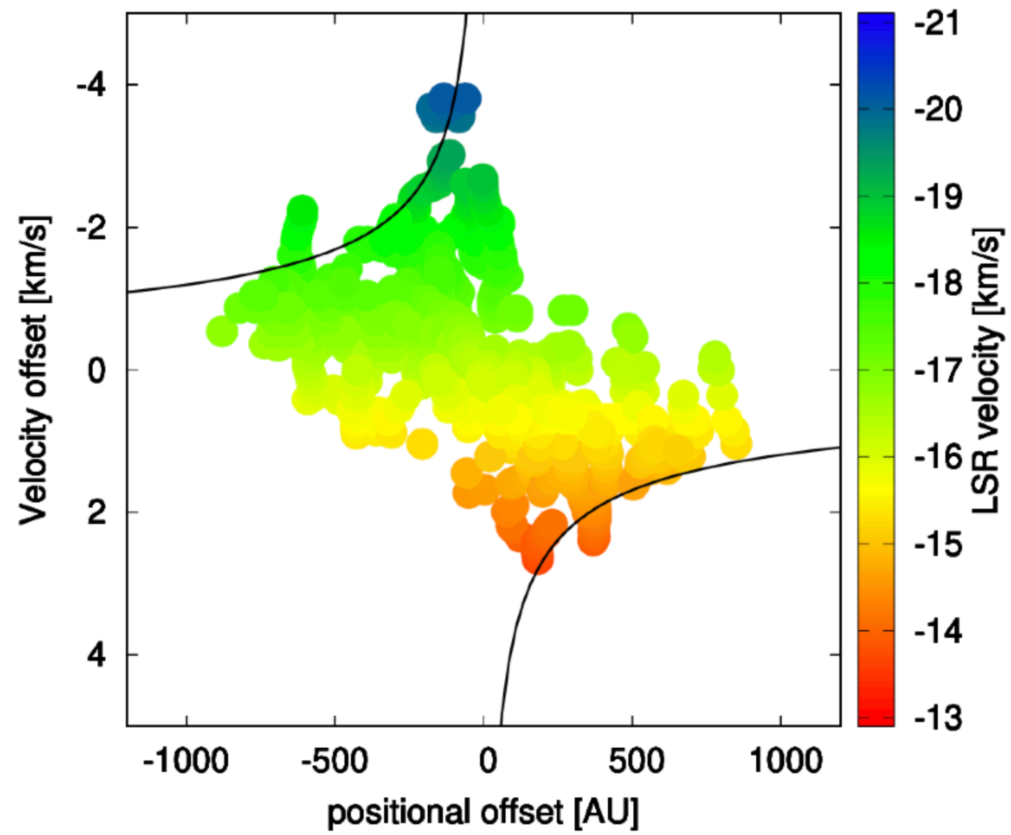
Combined FITS images revealed:

Disk radius:
920 AU

Velocity dispersion:
within +- 5 km/s

PA:
45 degrees

Inclination:
Near face-on

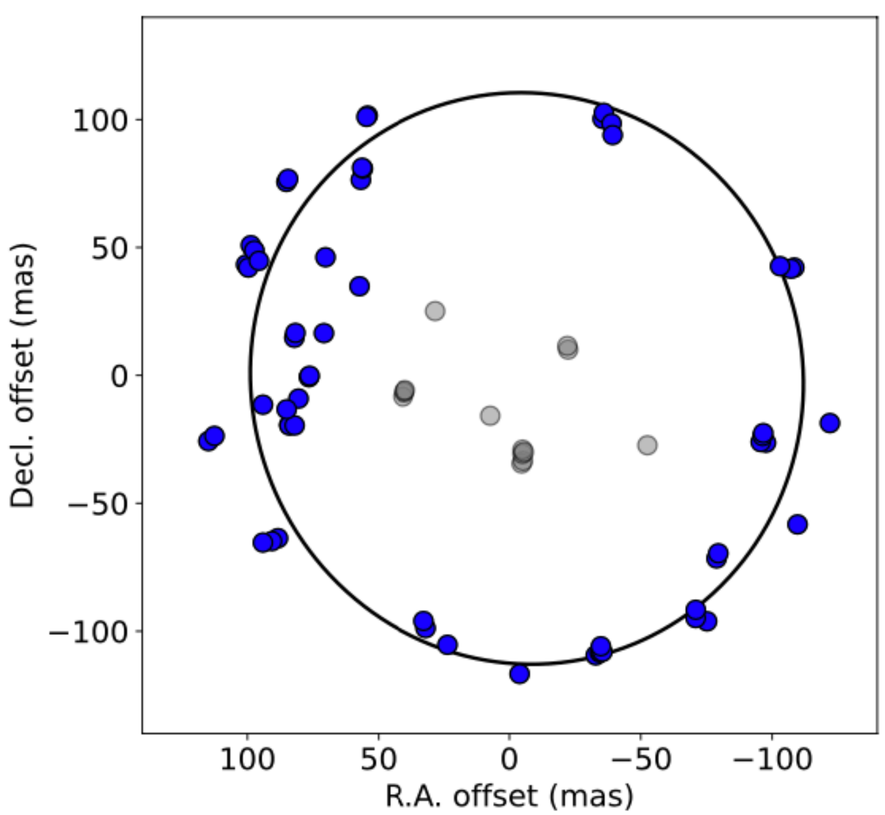


What is the enclosed mass?

(corrected for inclination)

Enclosed mass of M × sin i^2 =1.205±0.118 Mo
Must determine the disk inclination to break the degeneracy with 'i'

Inclination determined by fitting an ellipse to the 5th epoch data

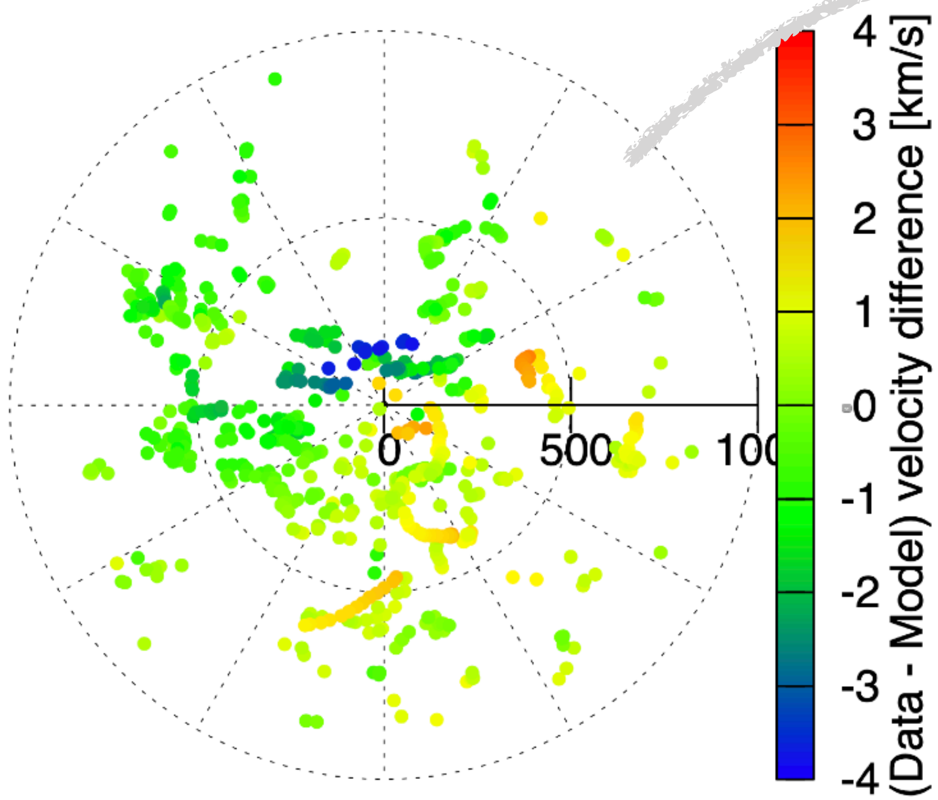


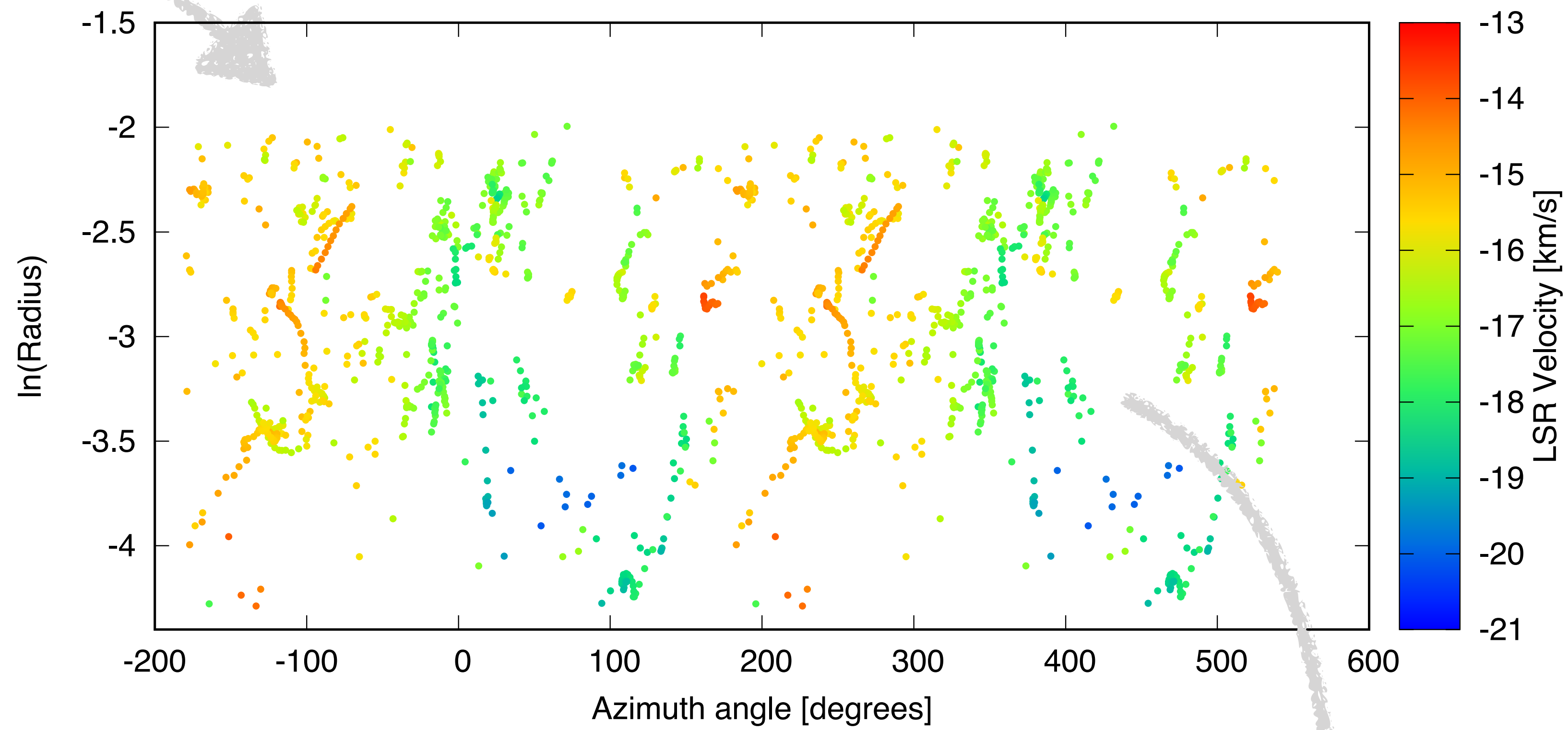
Results of least squares fitting:
I = 21 ± 5 degrees

This work: $M_* = 10.7 \pm 6.8\ \mathrm{M}_\odot$

SED analyses: $M_* = 9.7^{+0.3}_{-0.6}\ \mathrm{M}_\odot$

Are the Spiral arms real?



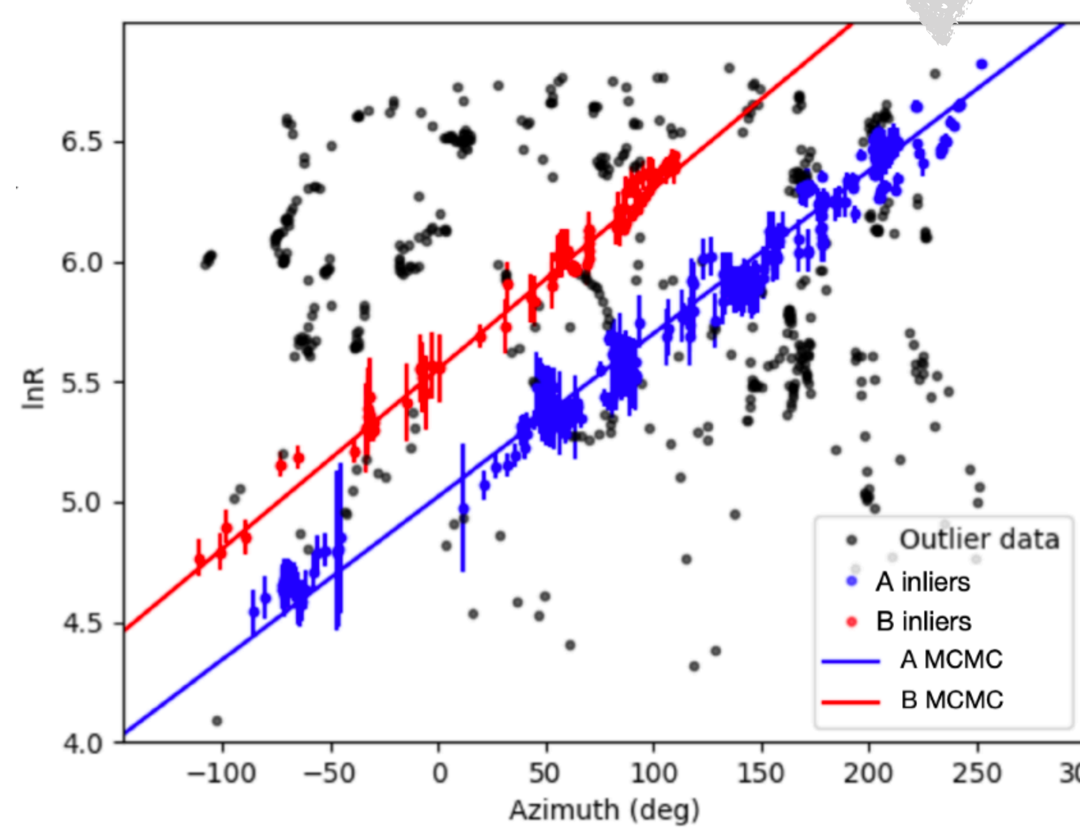


GI Spiral arms in disks are logarithmic wrt Radius

‘Unwrapping’ the spiral by plotting the spotmap with log-R vs R

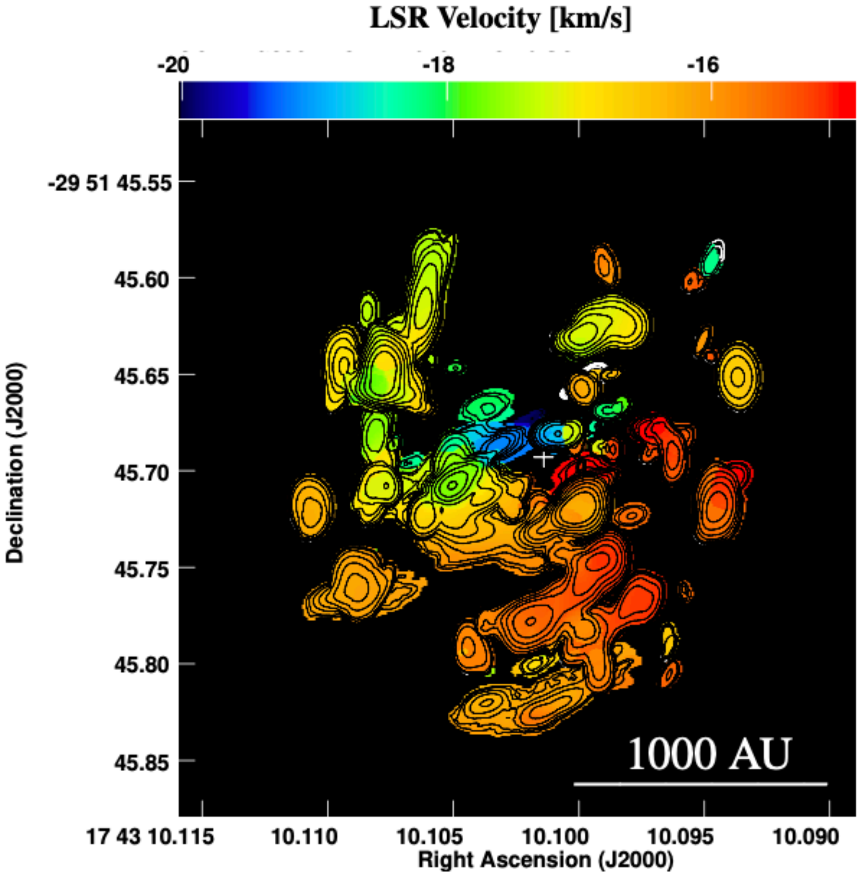
Then, Spiral arms appear as straight lines

MCMC identified two arms with pitch angle of ~21 degrees

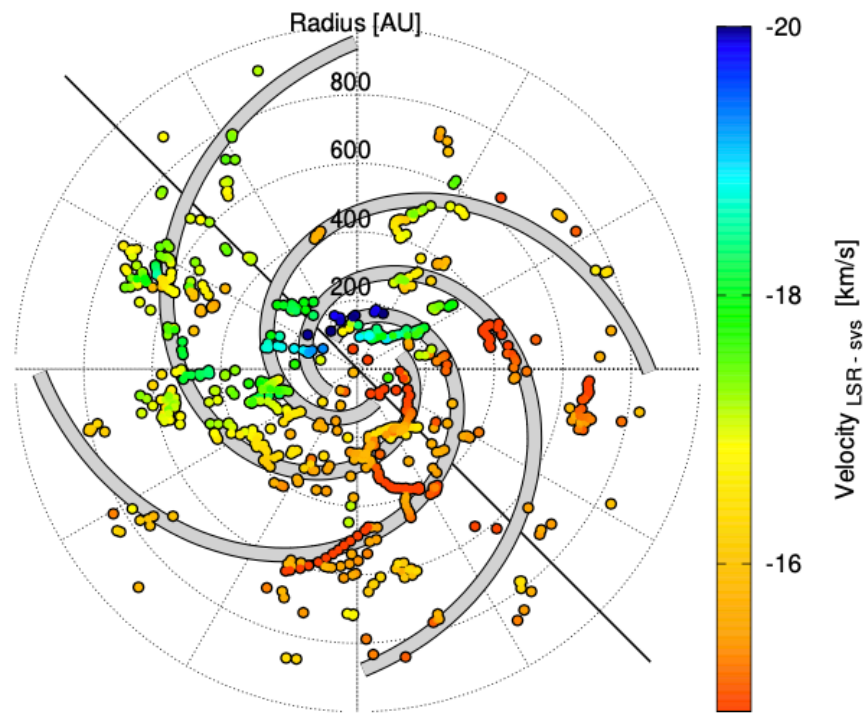


Heat-wave mapping of G358-MM1

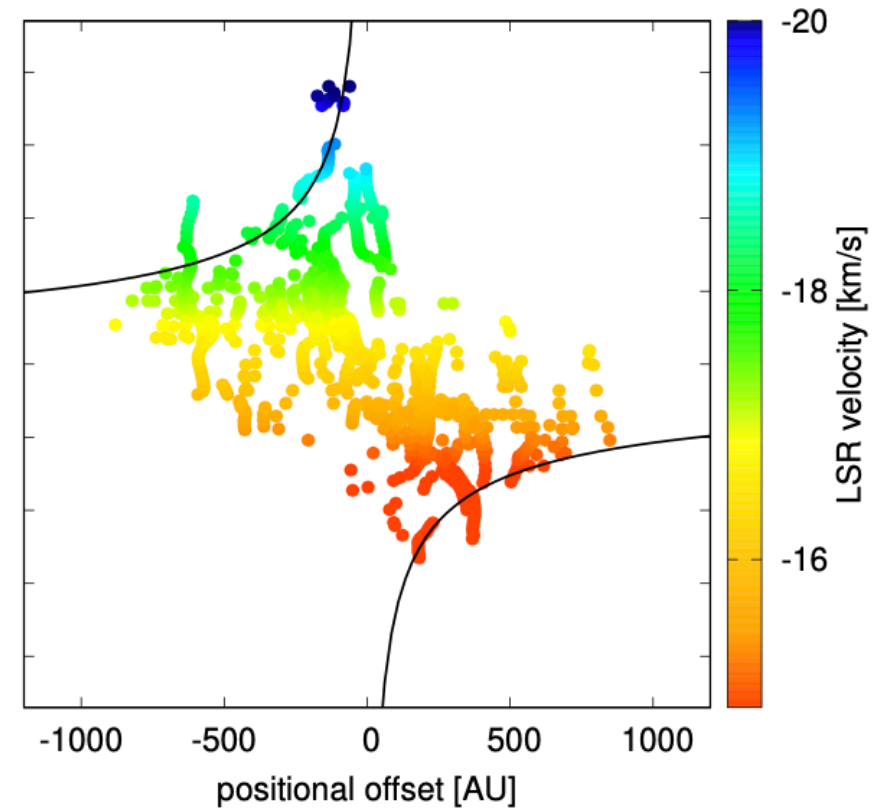
Combined FITS images



Spot map + model



Position-Velocity



Disk size:
920 AU

Inclination:
21 ± 5 degrees

Enclosed mass:
11 ± 7 Mo

Useful new observational approach for high-resolution imaging of accretion disks

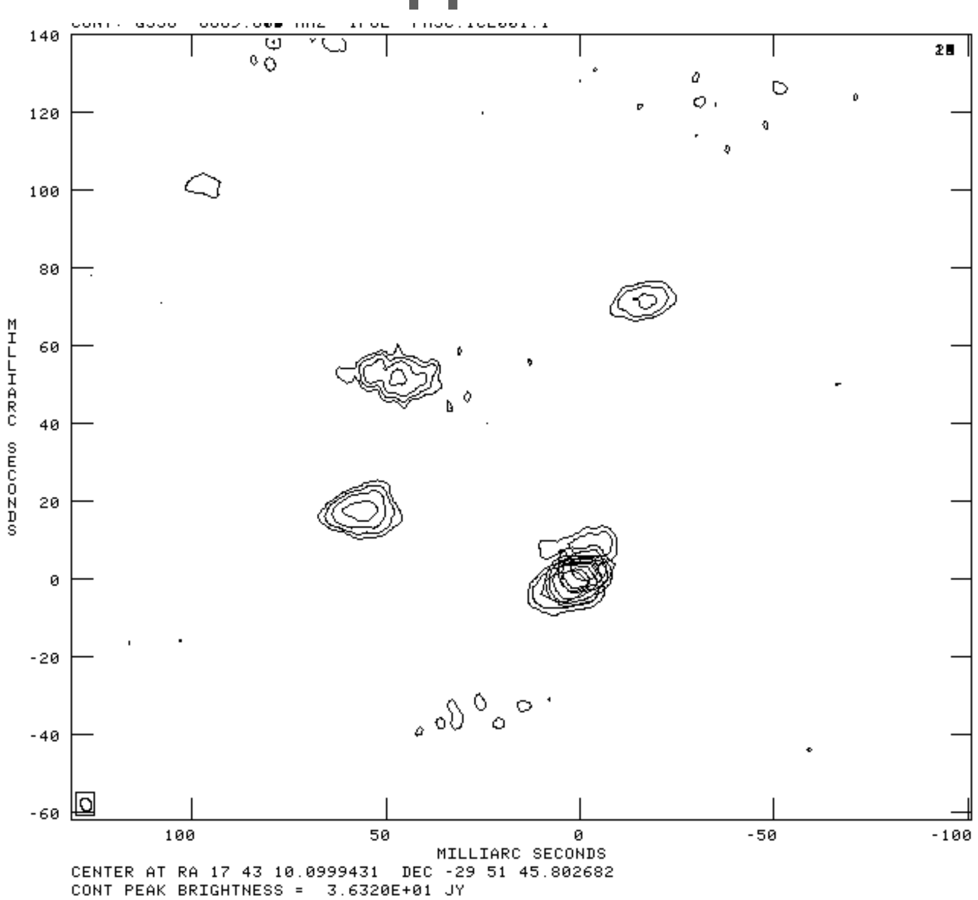
Data reduction

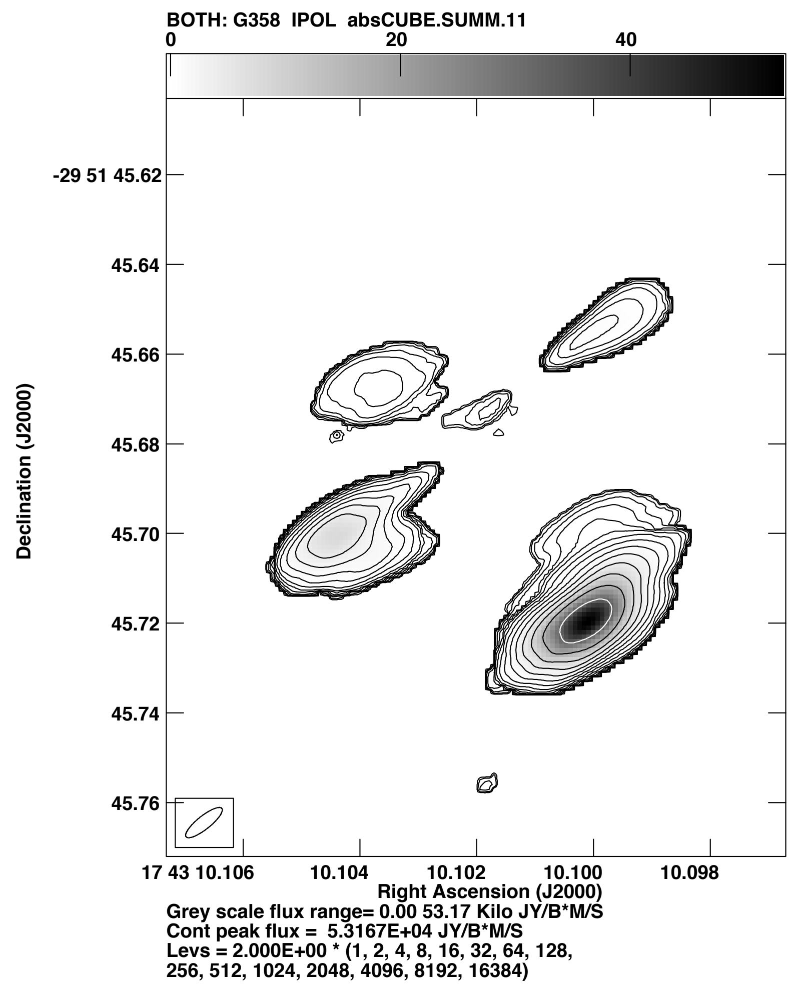
Data reduction

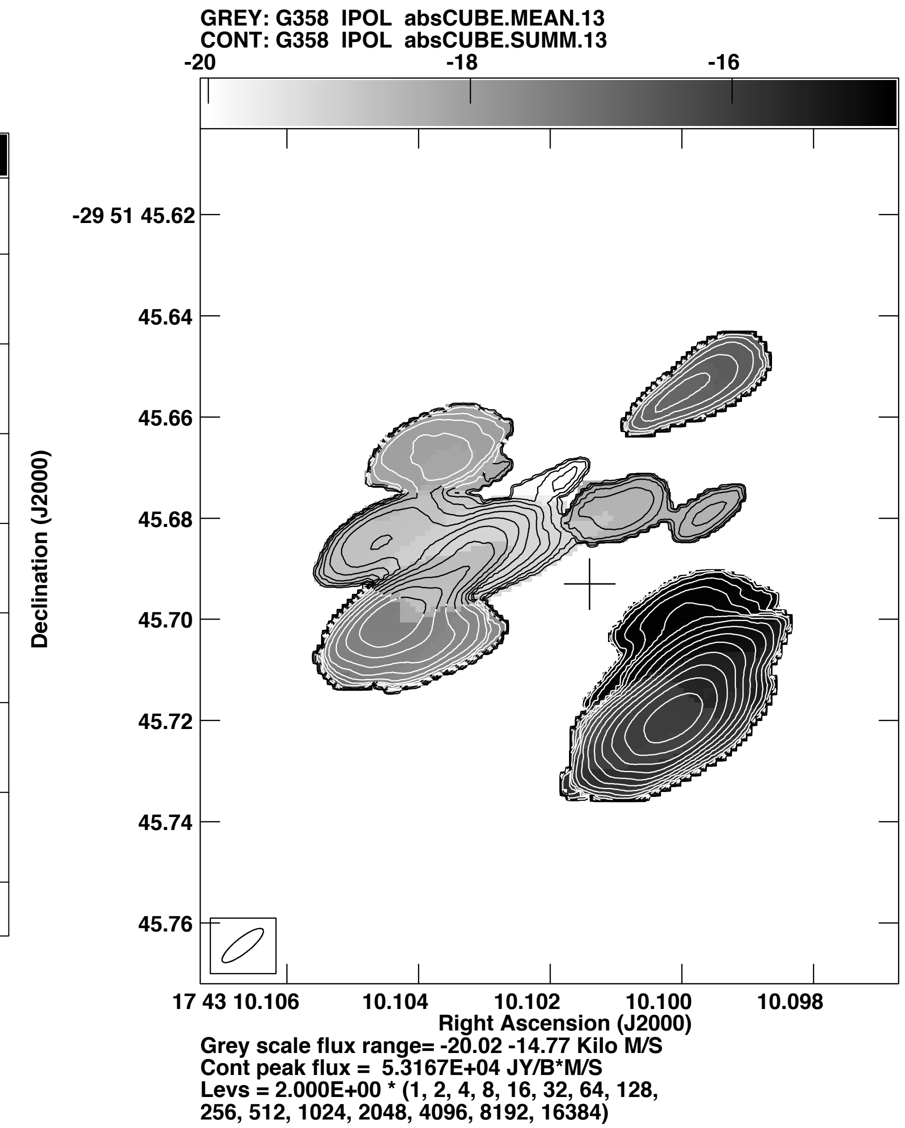
Ideal FRING settings ->
Shifting maser coords

Amp self-cal (DiffMap) ->

'Standard approach'



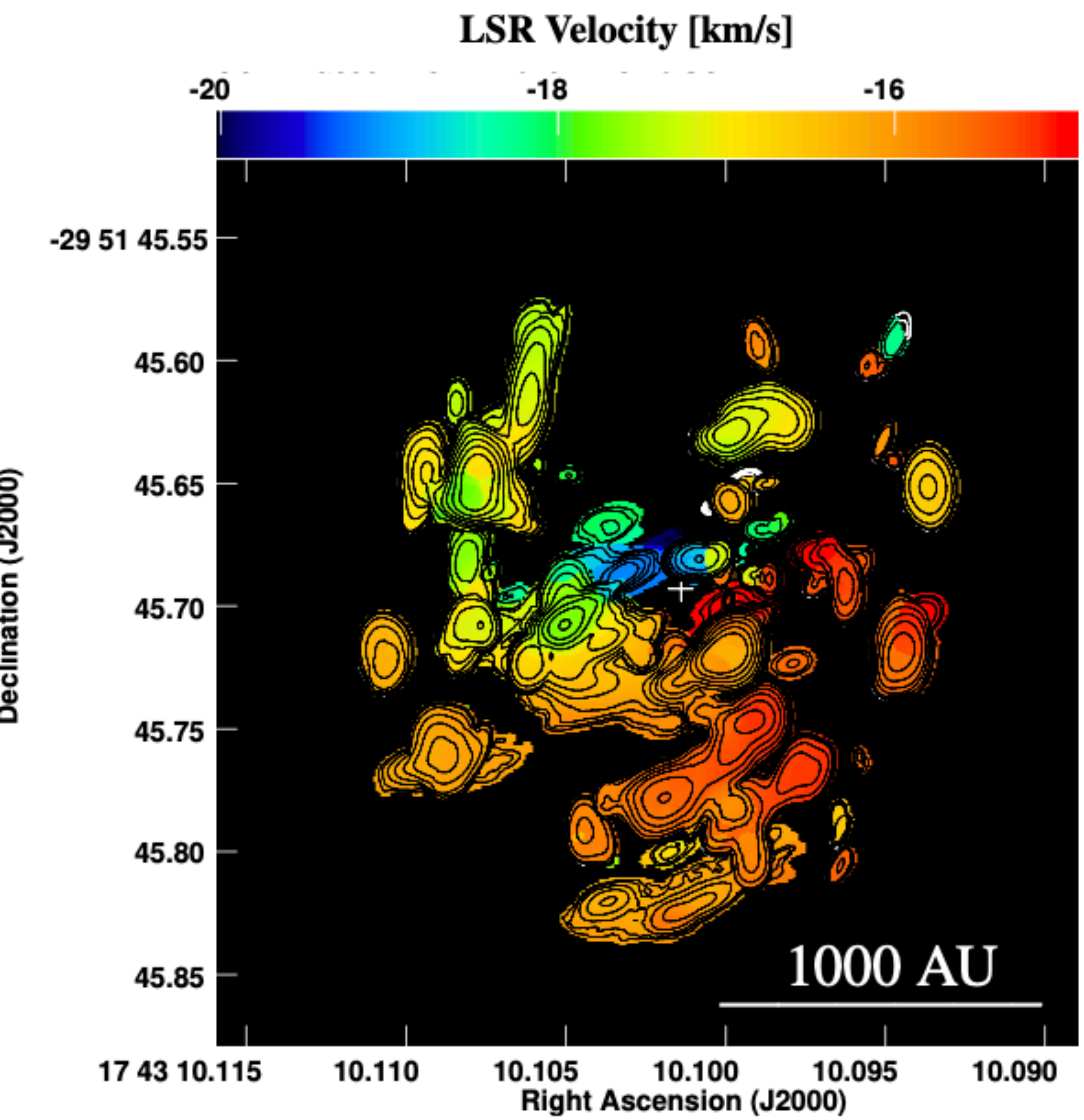


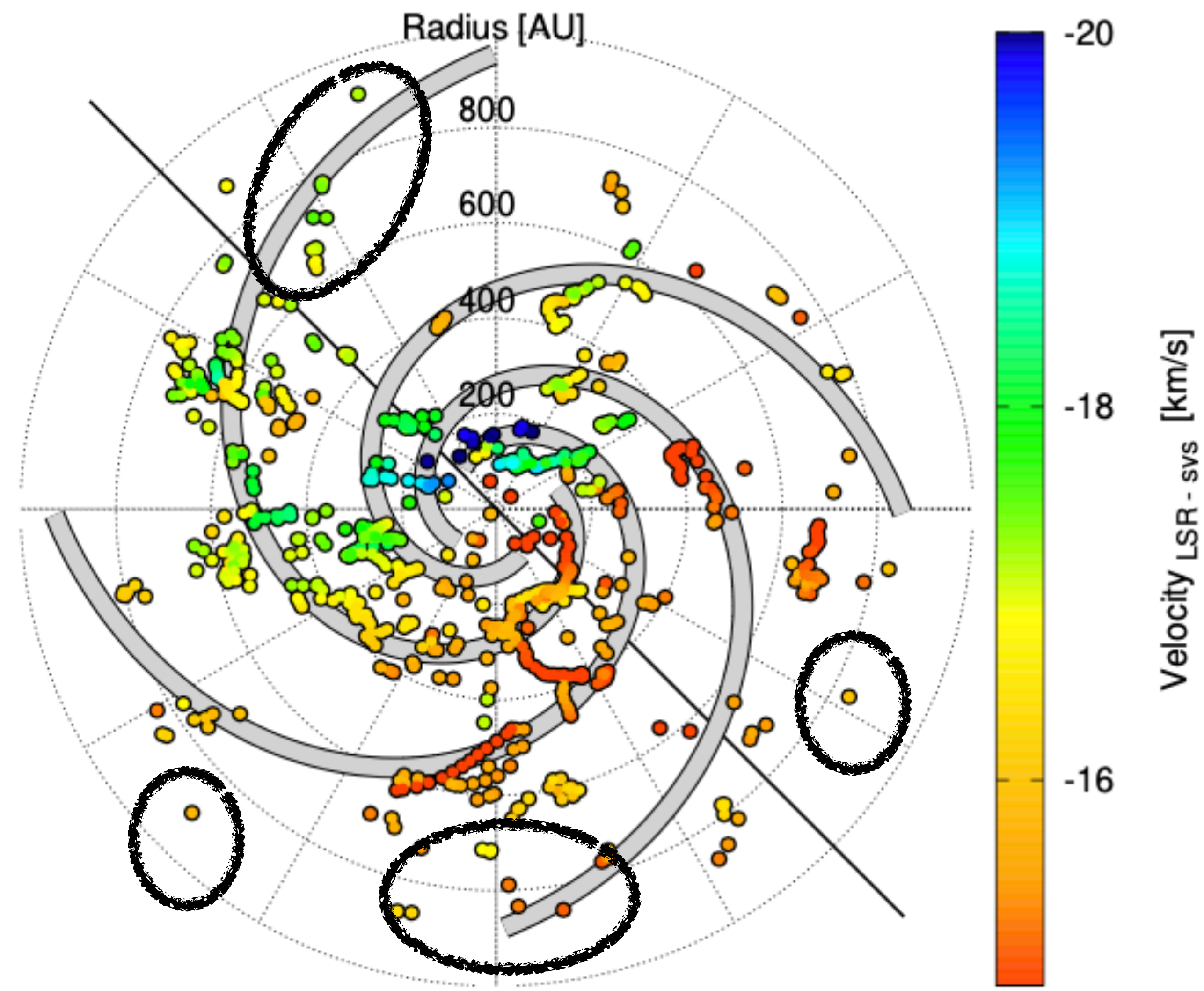


Proper data reduction is super important~!

Be careful…

Be careful with spot maps





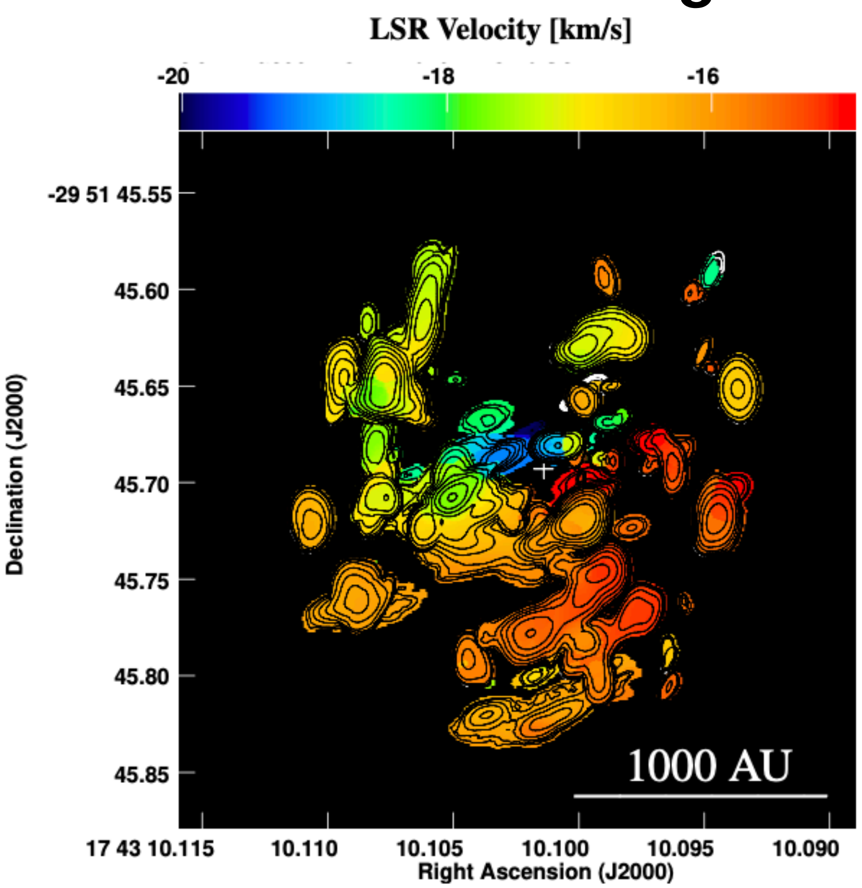
Some structures are not well represented by spot maps

Moment maps are sometimes better

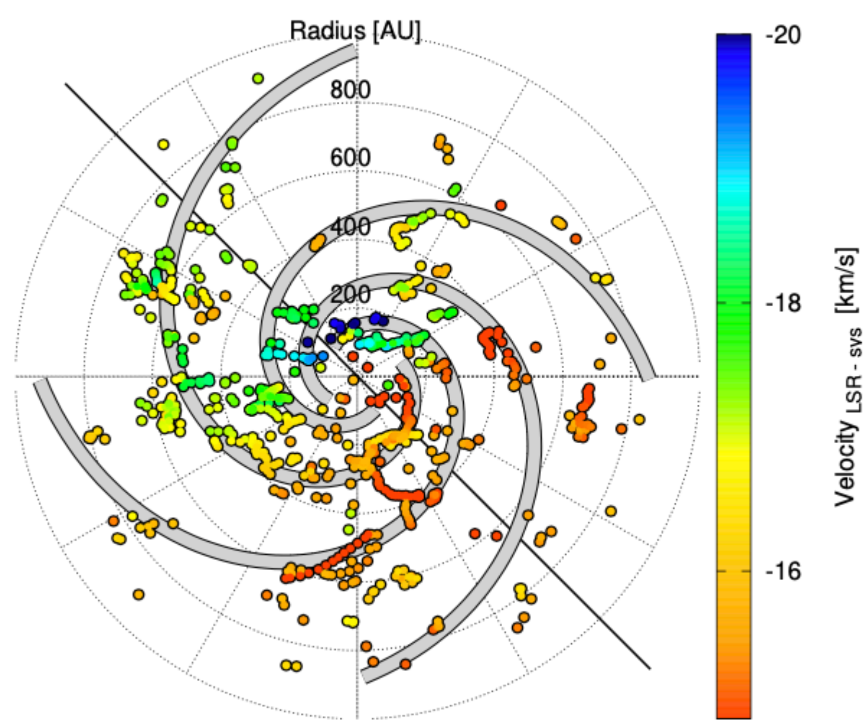
~Thank you for your attention~

Full details can be found in the published paper:
Burns et al. 2023, “A Keplerian disk with a four-arm spiral birthing an episodically accreting high-mass protostar” Nature Astronomy, (Feb. 2023)

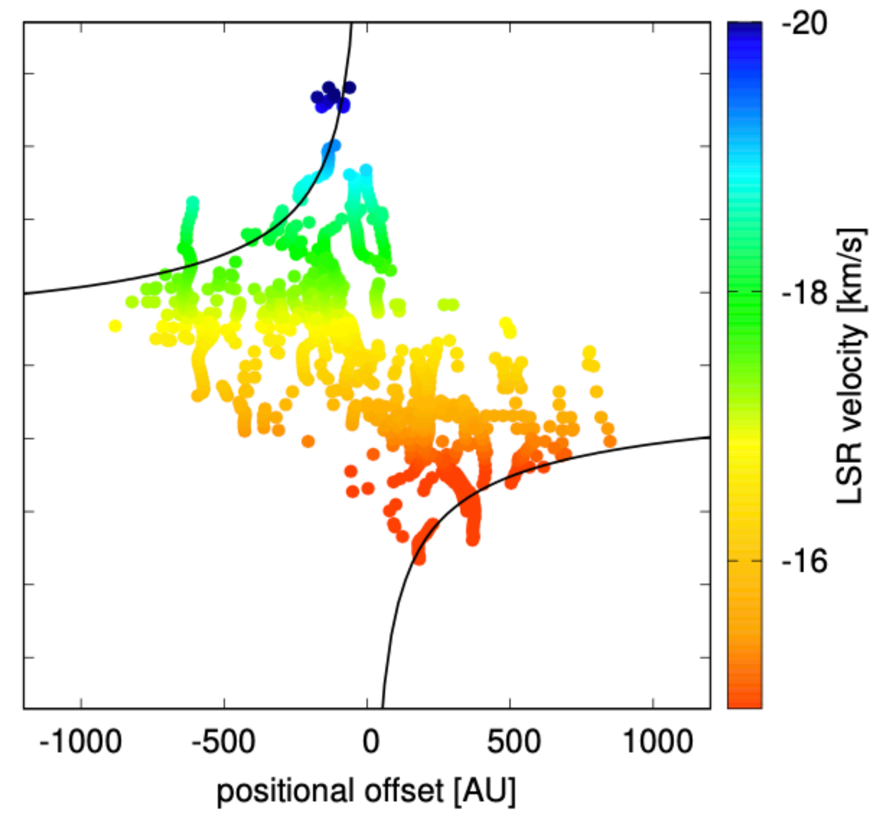
Combined FITS images



Spot map + model



Position-Velocity



Closing:

Using multiple high-cadence VLBI observations of masers can provide **milliarcsecond resolution** imaging of Keplerian disks in accreting high-mass protostars

Additional slides

For answering questions etc

Alternatives to GI: companion

Forgan et al. 2018 ApJ 860 L5

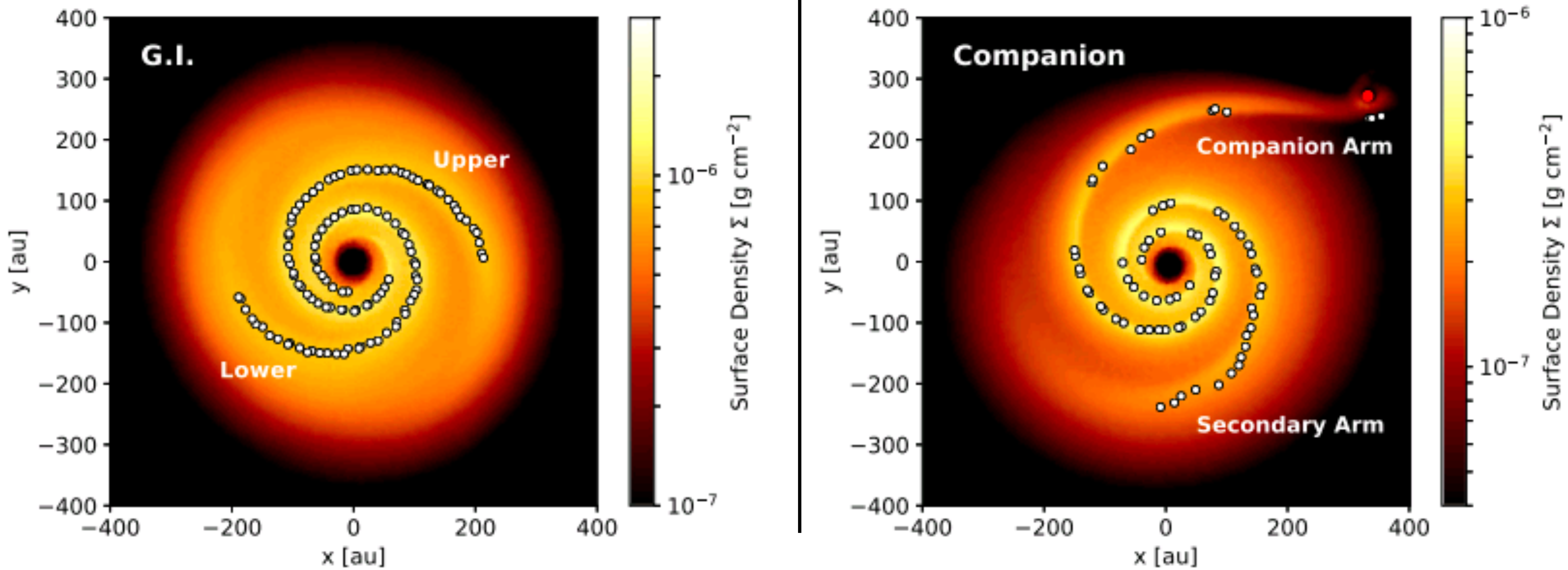


Figure 1. Surface density of the gravitationally unstable disk (left) and the companion encounter disk (right) overlaid with the results of the TACHE spiral identification algorithm (black crosses). Individual arms are identified as either "upper" or "lower" in each case.

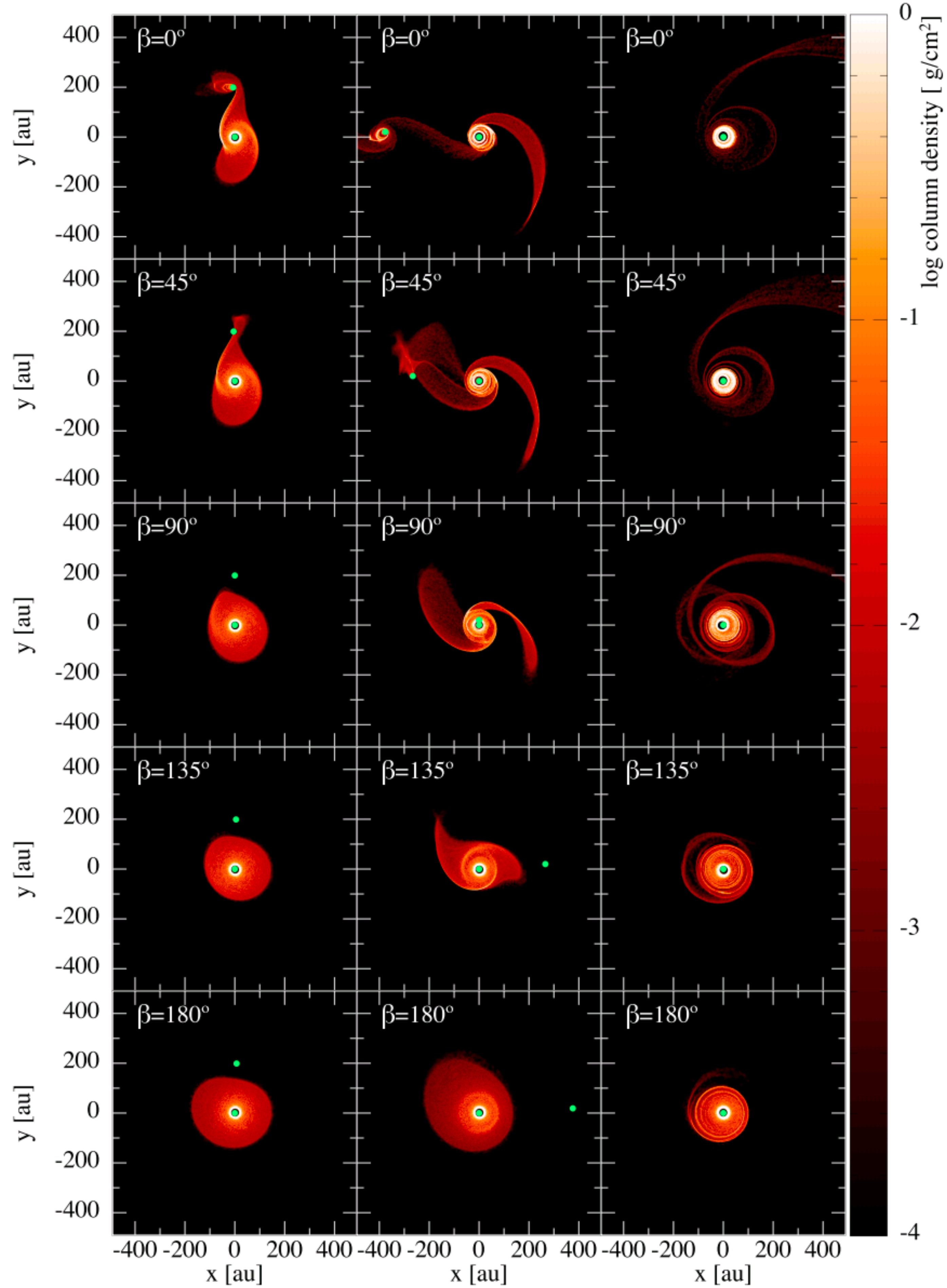
- **Logarithmic spiral function**
- **Constant pitch angle w.r.t radius**
- **Symmetric across the disk**

- **Deviates from Logarithmic spiral**
- **Pitch angle varies w.r.t radius**
- **Asymmetric (stretched by companion)**

Alternatives to GI: Fly-by

Fly-bys are when a non-bound encounter occurs.

- **m=2 spirals form.**
- **Each of the arms has a different shape due to different origin**
- **High likelihood of disk warping…**

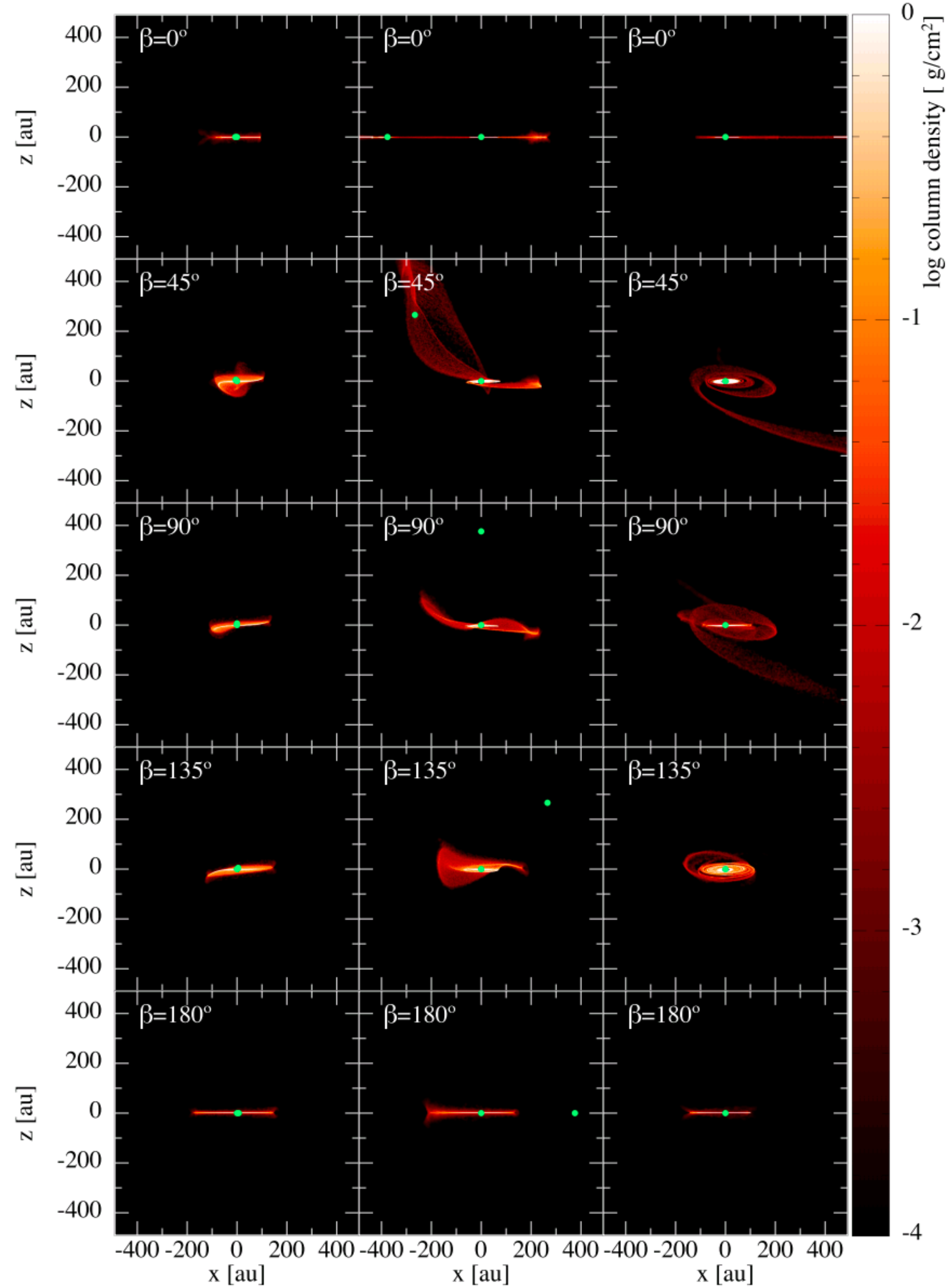


Cuello et al. 2019 MNRAS 483 4114

Alternatives to GI: Fly-by

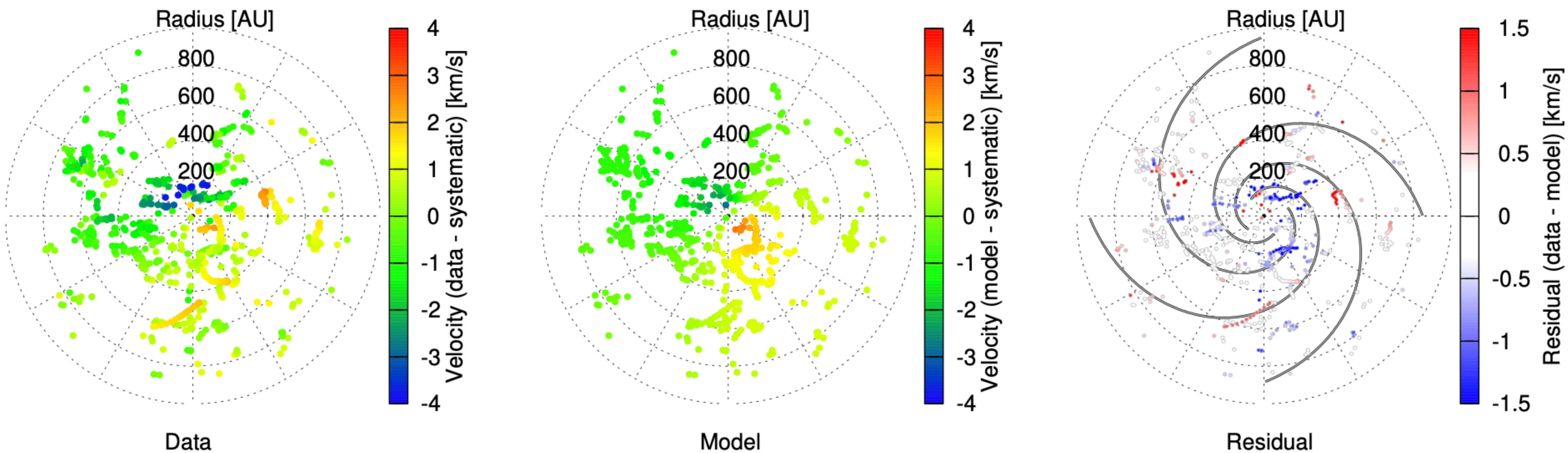
Warping of the disk

- **Fly-bys induce warping unless the encounter is in the disk plane**
- **Such warping would produce a clear signal in the velocity structure**



Cuello et al. 2019 MNRAS 483 4114

Absence of disk warping



Encounters cause disk warping which can be seen in the velocity field.

The disk warp signature is absent in G358-MM1

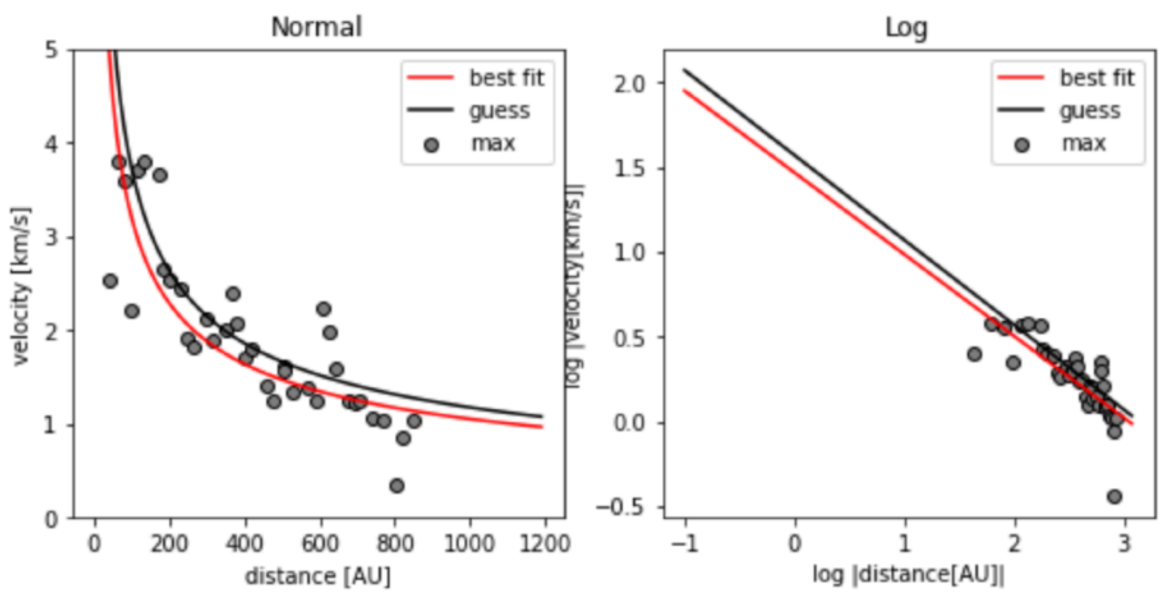
Furthermore there is an interesting mass argument relating to the 6.7 GHz methanol maser

Is the disk Keplerian?

1st fit attempt: varying the slope and intercept

```
****************************************
best parameters by Least squares method
Mass_i: 2.13+-4.424, Power: 0.48+-0.065

****************************************
```

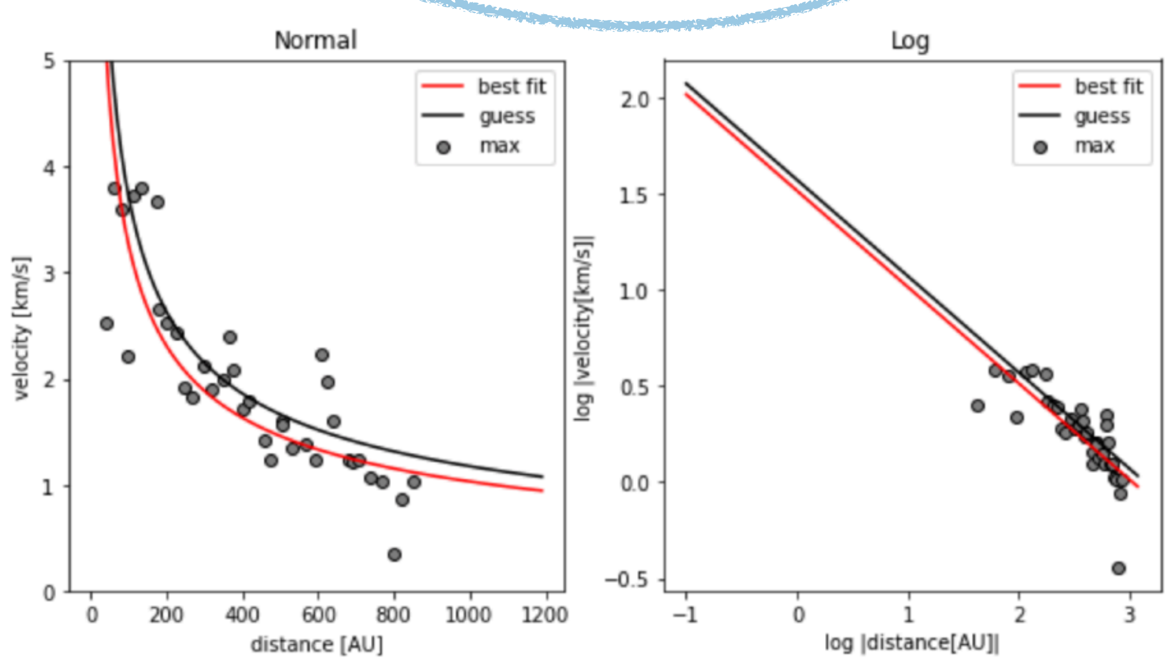
Results:
Power law 0.48 +- 0.065
Consistent with Kelperian



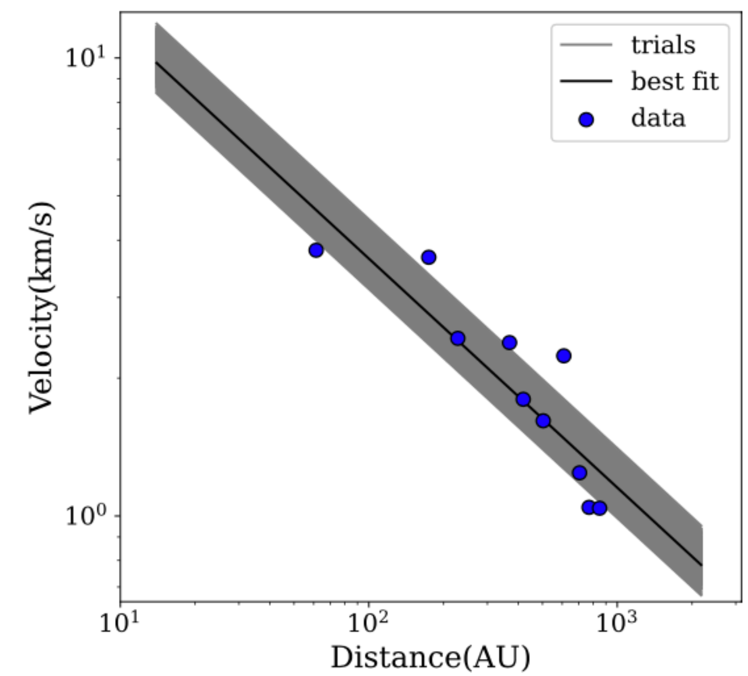
2nd fit attempt

Returns enclosed mass

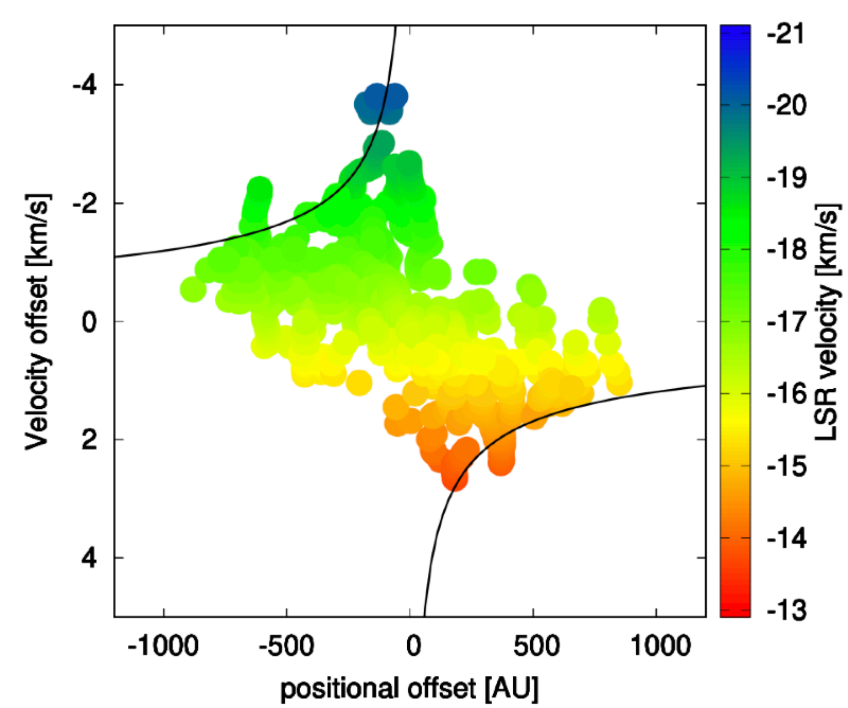
```
****************************************
best parameters by Least squares method
Mass_i: 1.205+-0.1182

****************************************
```



PV data in log space (zoomed)

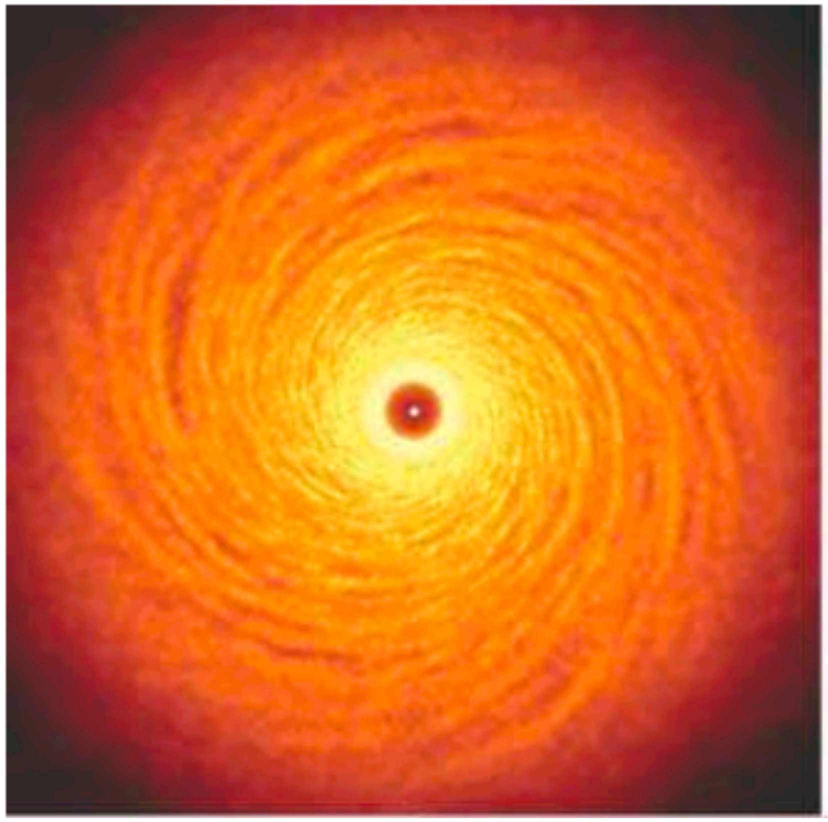


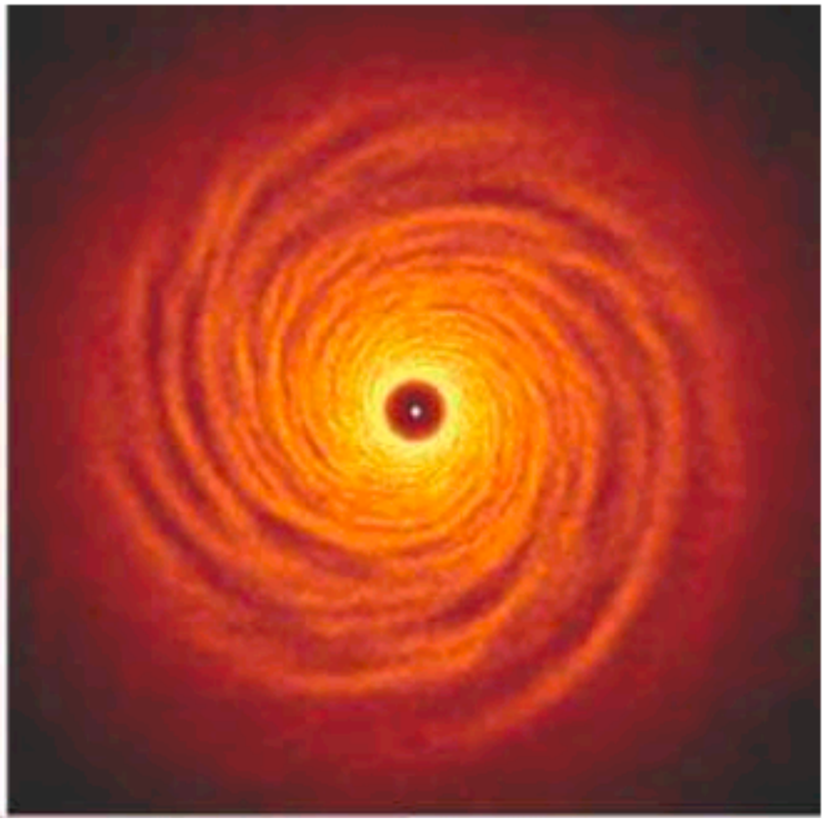
PV data on original maser data



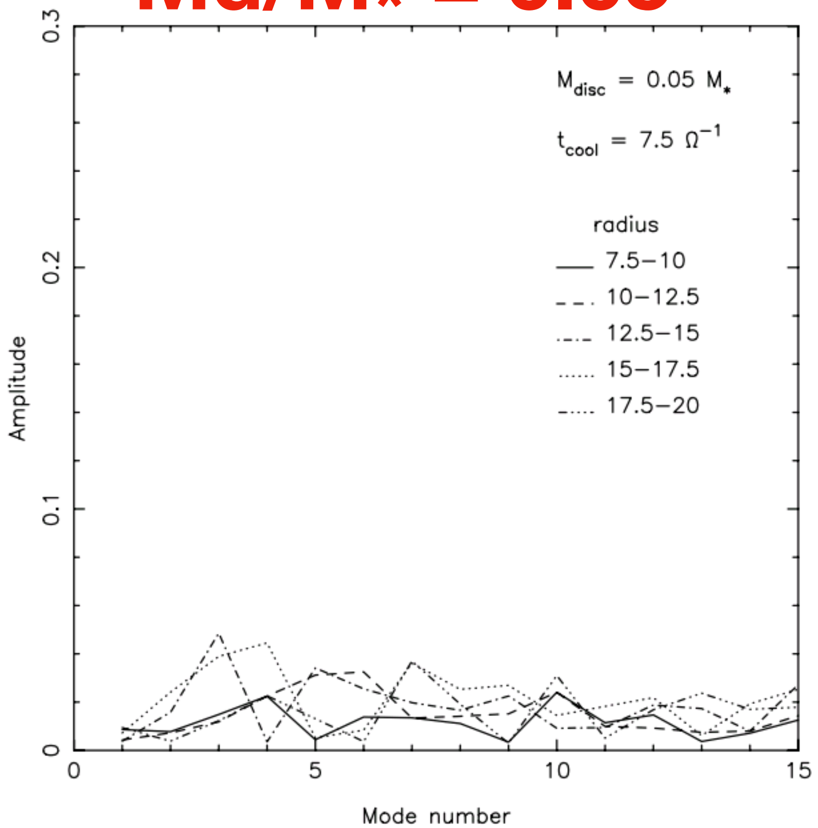
Evolving GI spirals

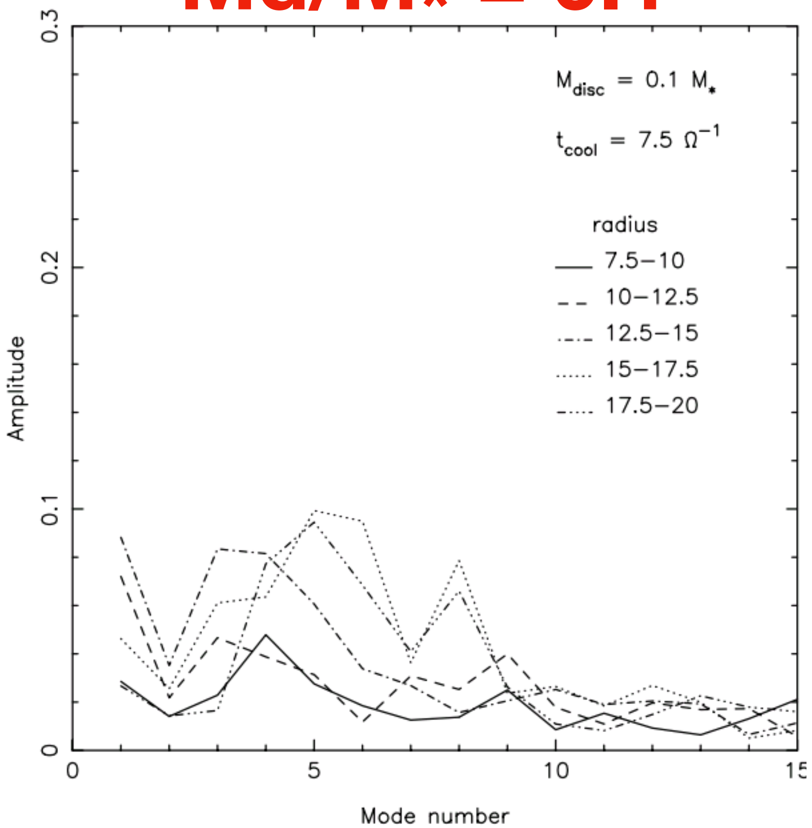
$M_d/M_* \sim 1/m$

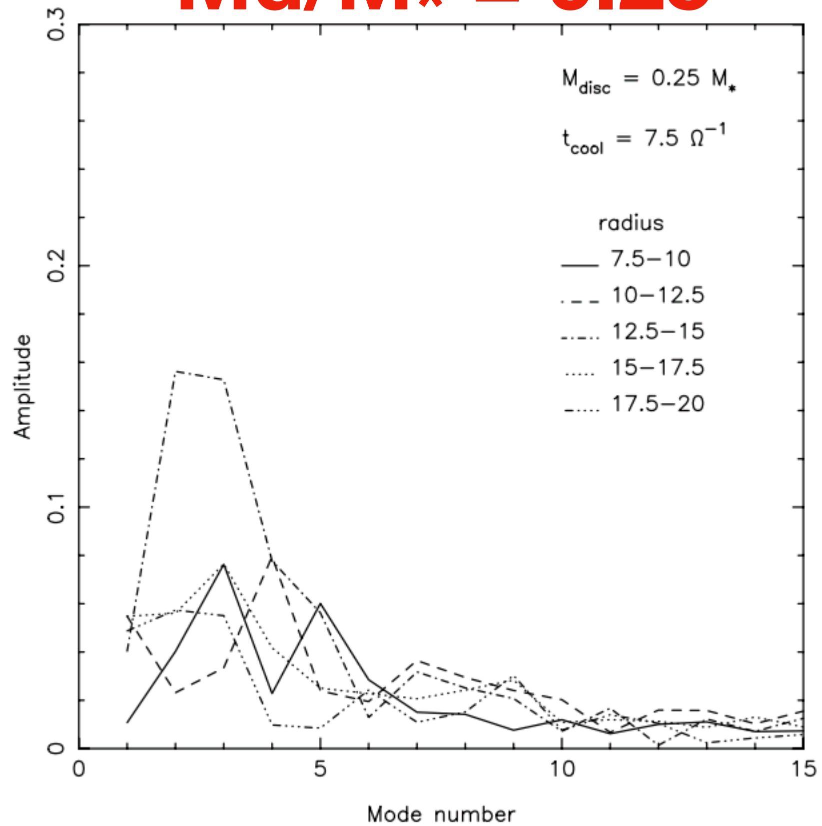




$M_d/M_* = 0.05$ **$M_d/M_* = 0.1$** **$M_d/M_* = 0.25$**







Lodato & Rice 2005 MNRAS 351 630

A note about spiral modes

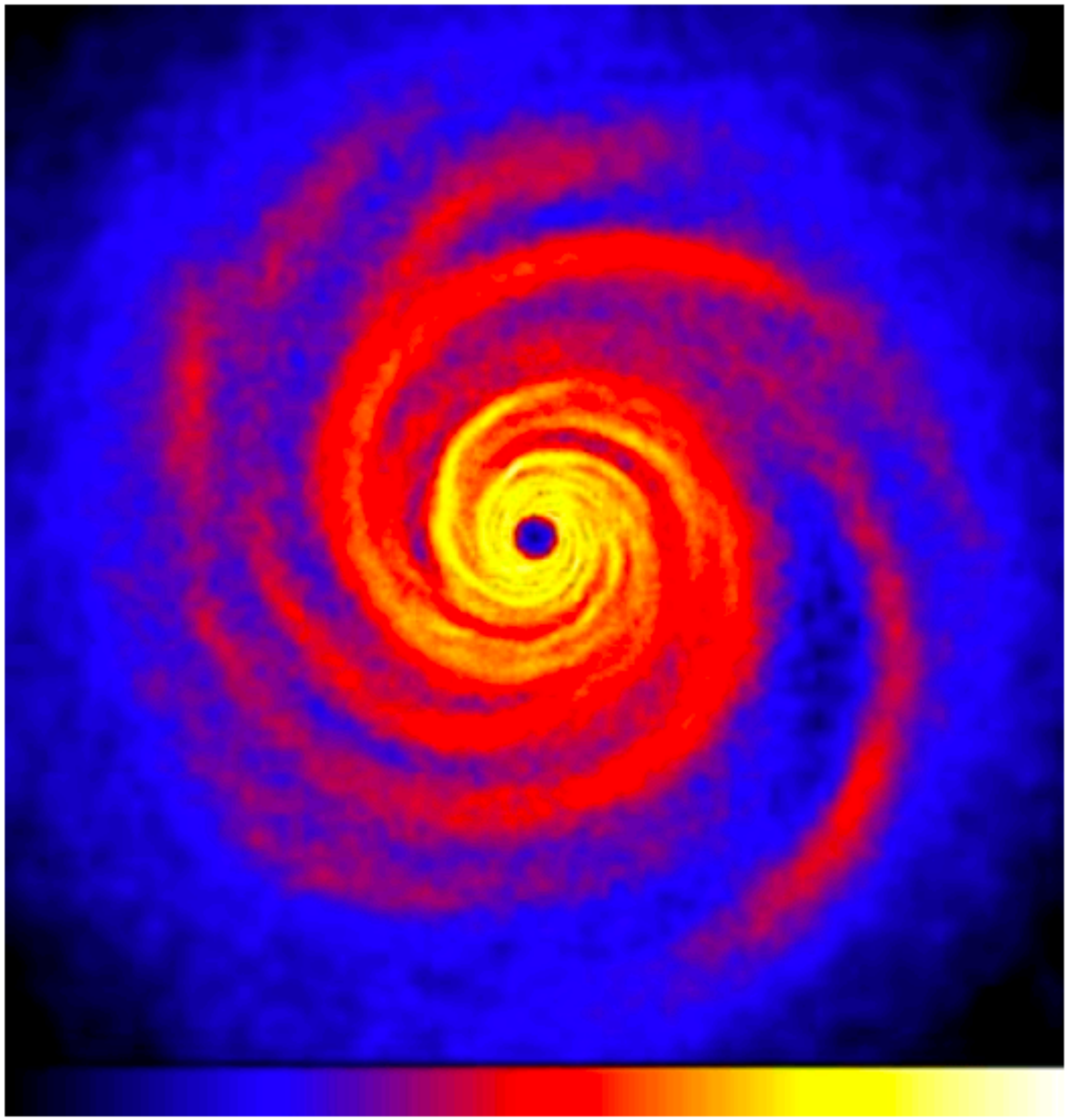


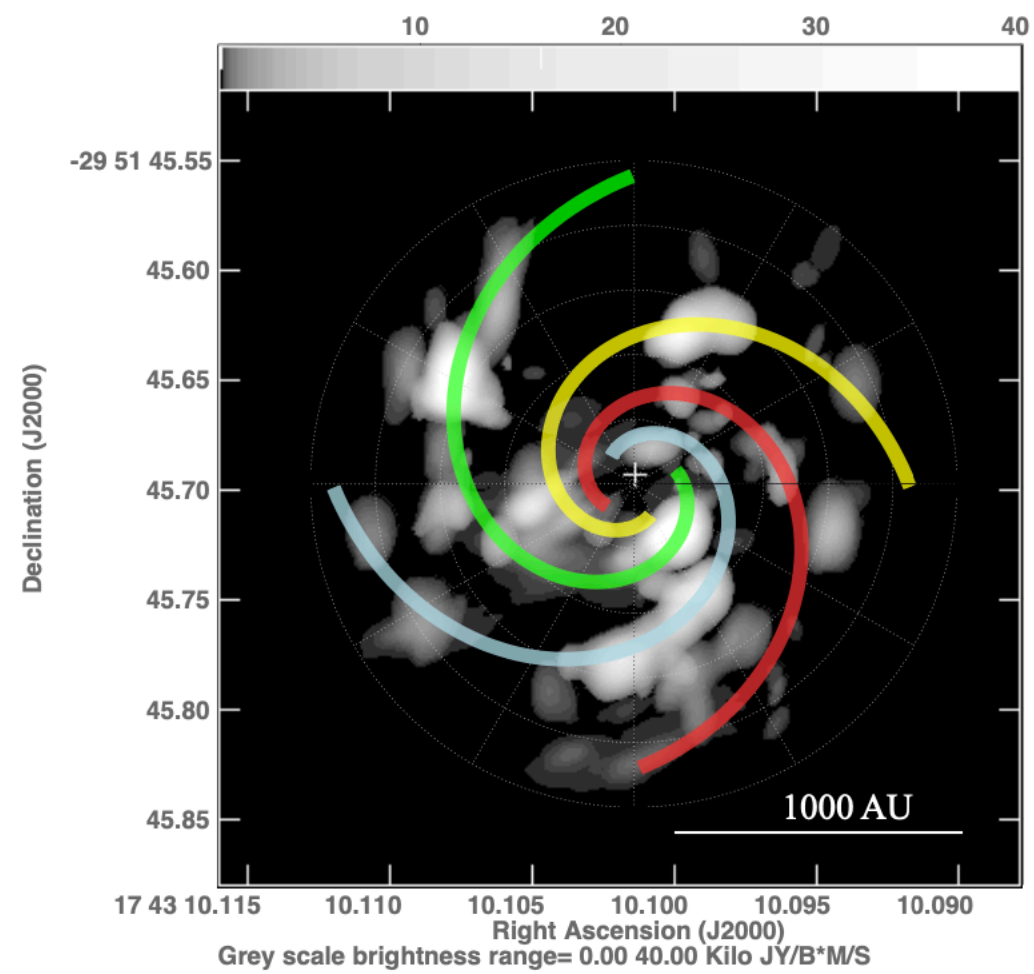
Figure 5. Surface density in the $M_{\rm disc} = 0.5\, M_\star$ case, at the end of the simulation. The scales are the same as in Fig. 1.

Lodato & Rice 2005 MNRAS 358 1489

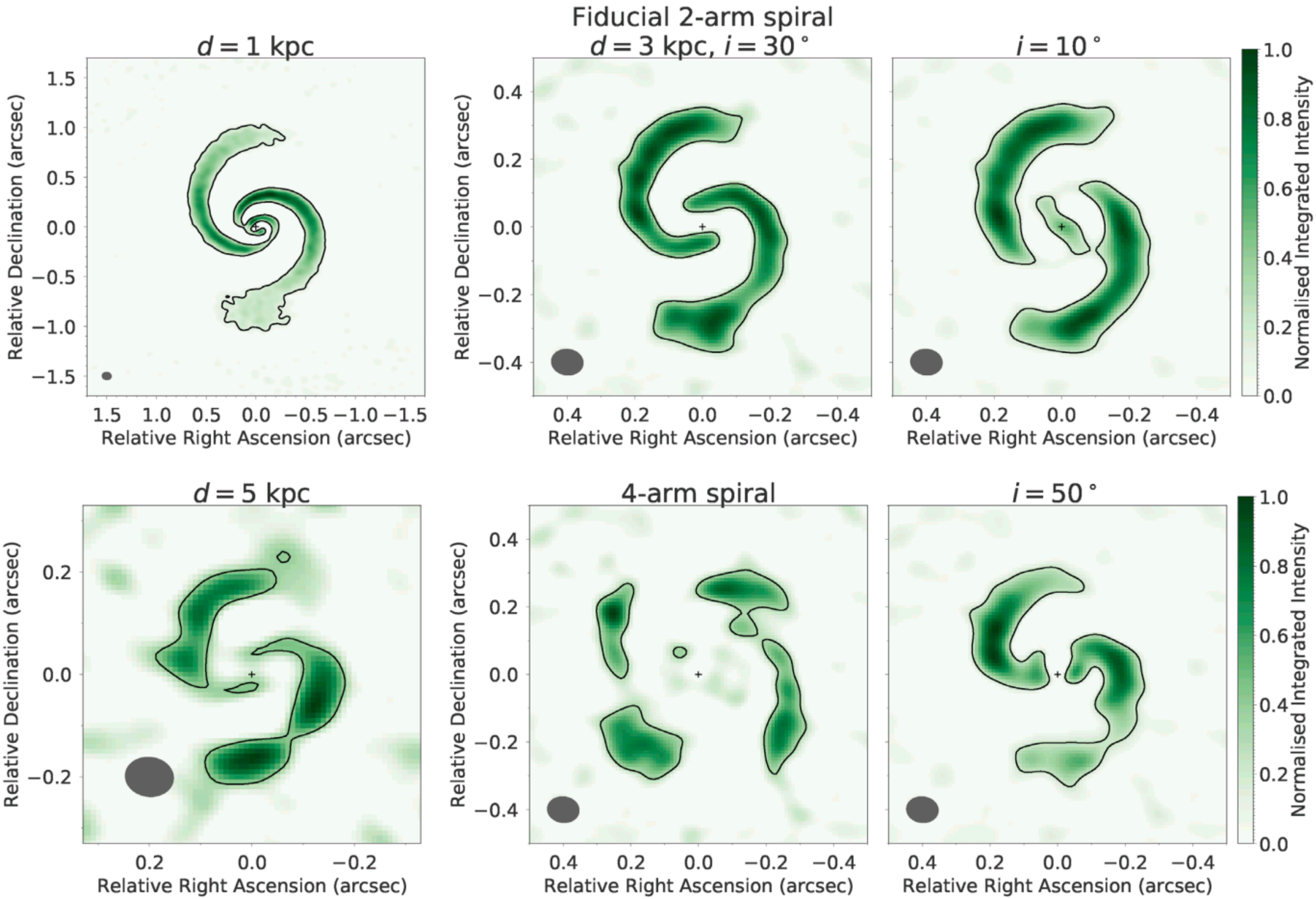
A spiral pattern is typically a mixture of modes: m1,m2,m3,m4,…

The Dominant mode is determined by *q*

But other modes can coexist.



Observing GI spirals



Jankovic et al. 2019 MNRAS 482 4673

Showed that as *m* increases the observability quickly deteriorates

Spirals become harder to observe

Kratter et al. 2016 ARAA 54 271

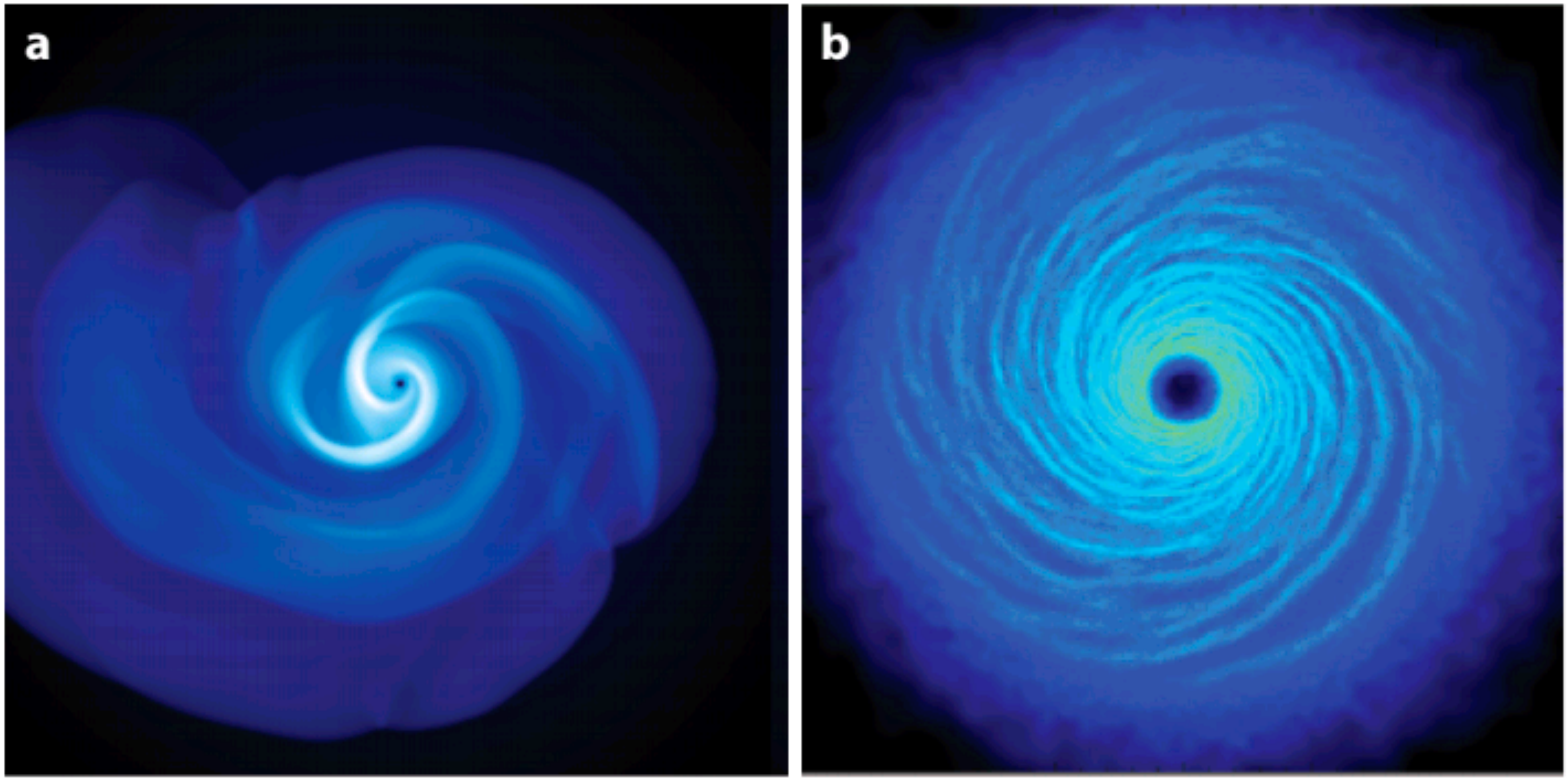


Figure 1

(*a*) A 3D isothermal simulation from the parameter studies of Kratter et al. (2010a), where $M_d/M_* \approx 0.5$. The strong left-right asymmetry is evidence of a dominant $m = 1$ mode. (*b*) A 3D simulation from Cossins et al. (2009) with slow cooling, where $M_d/M_* \approx 0.1$. Note the dominance of high m spiral structure. Reproduced by permission of the AAS.

As the star becomes more massive the value of *m* increases too