Gas and Dust Properties in Protoplanetary Disks at mm/sub-mm wavelengths

Nguyen Thi Phuong

Thanks to my collaborators:

Dutrey, S. Guilloteau, E. Di Folco - LAB/CNRS
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N. T. Thang - SAG & VNSC
And ….

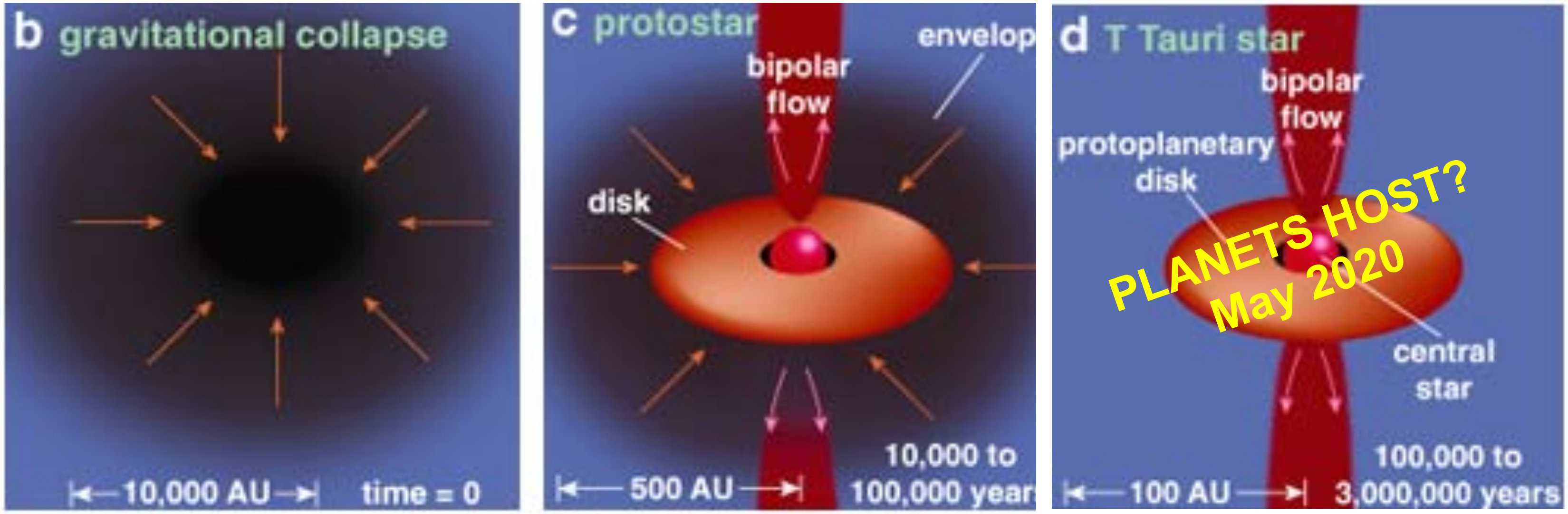
SAGI seminars – Nov 2024

Outline

1. Protoplanetary disk
2. Gas and dust morphology and kinematics
    1. Young single disk – a case study of IRAS 04166 + 2706
    2. Binary systems – case studies of AS 205 and GG Tau A
3. On-going projects

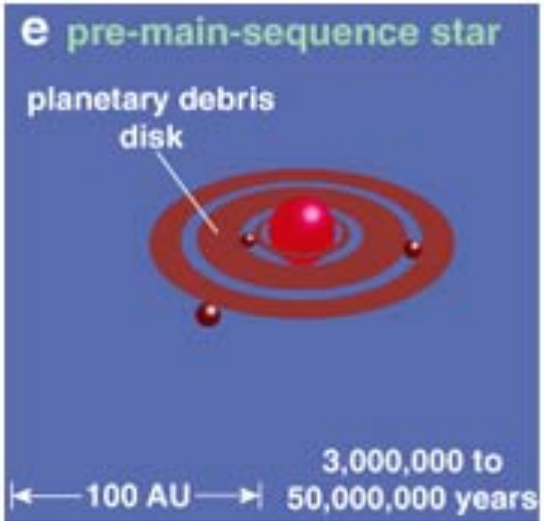
Protoplanetary disks

- Stars form from small fractions (dense cores) of the **dust and gas** contained in relatively dense and cold molecular clouds.



PLANETS HOST? May 2020

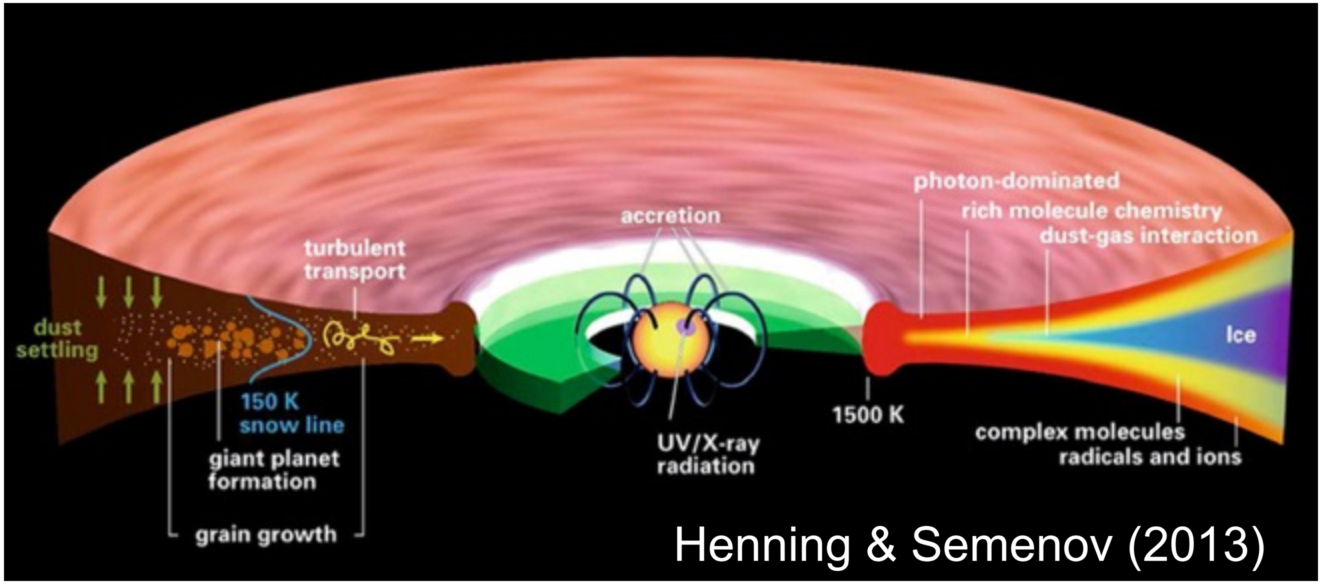
- Disks form around protostars as a consequence of angular momentum conservation.
- A small quantity of material remains in the disk for few million years, allowing planets to form (hence the name “**protoplanetary” disks – PPD**).



Greene (2001)

The disk structure of young star similar to the Sun at 1Myr (TTauri)

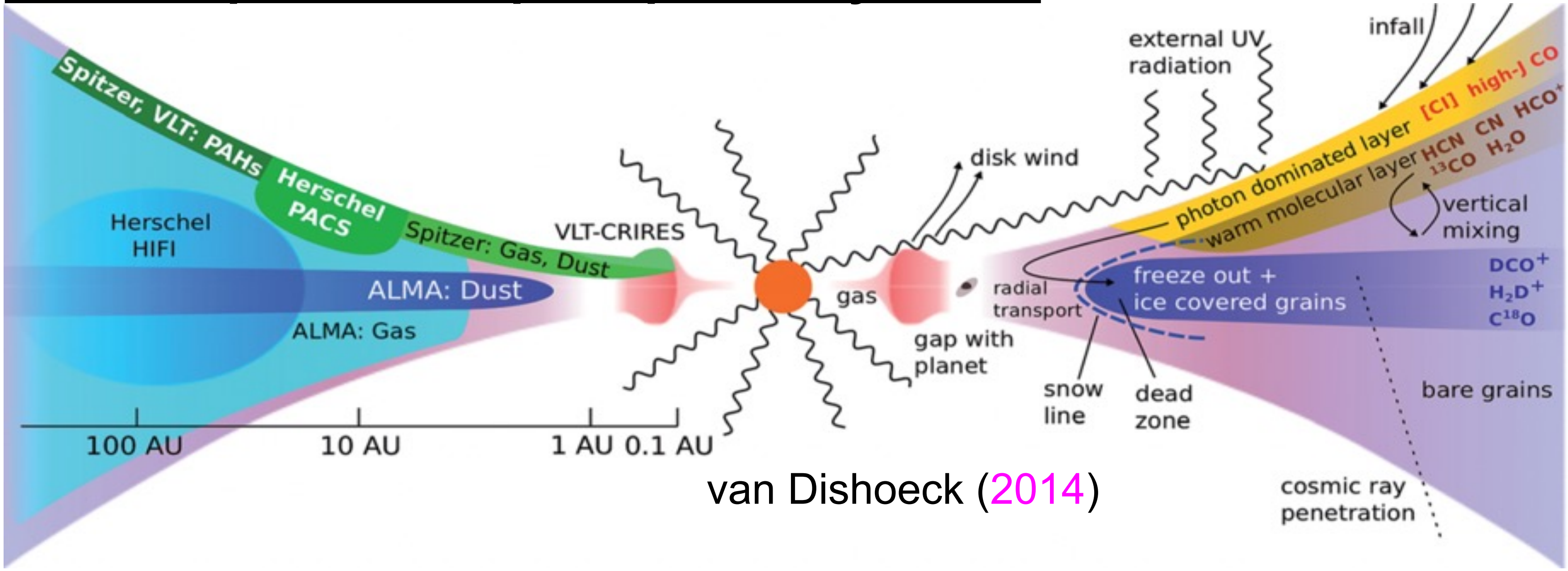
- 99% of gas (mostly H_2, …) and 1% of dust
- Temperature is governed by dust, which is directly heated by radiation from the central star and accretion shocks.



Henning & Semenov (2013)

- Disks are flared and display important vertical and radial density and temperature gradients:
  i. external layer – photodissociation reactions
  ii. molecular layer – rich molecular reactions
  iii. Mid-plane – molecules stick to dust grains (e.g. CO snow-line ~17–20K)

Gas composition of protoplanetary disks



van Dishoeck (2014)

Inner region (R<30 au):

Directly illuminated by the stellar radiation

Continuum is resolved in IR and (sub)mm

Line emission is unresolved in (sub)mm

H_2 is very hard to observe

→ studies of gas disk rely on trace molecules

Outer disk (R>30 ~300 au):

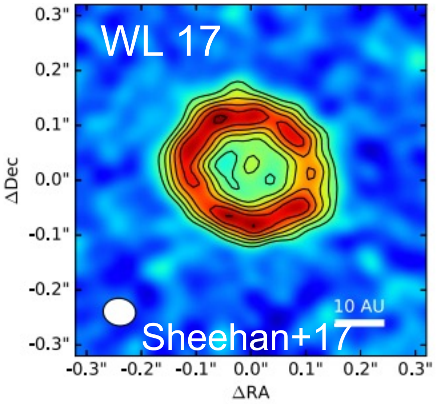
Different chemical reactions in different physical conditions taking place in different layers resulting in different chemical compositions

Resolved in IR and (sub)mm domains

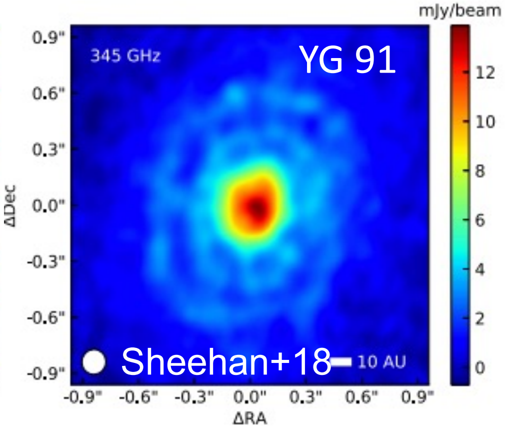
ALMA traces outer region (continuum, lines and kinematics): CO, ^{13}CO, $C^{18}O$, CN, HCN, HCO^+, DCO^+,….

My studies: gas and dust physical conditions, kinematics, and chemistry favorable to the formation of planets, either in circumstellar or circumbinary orbits.

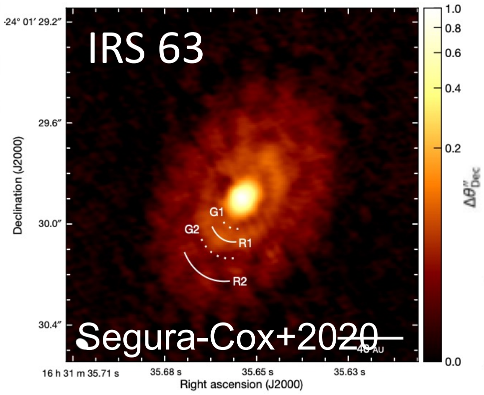
Is a protoplanetary disk the disk where planet(s) form or a planet(s)-host disk?



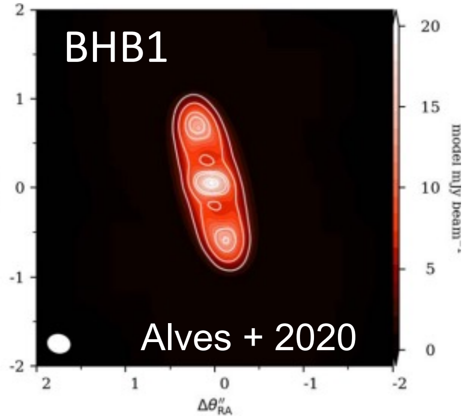
Sheehan+17



Sheehan+18

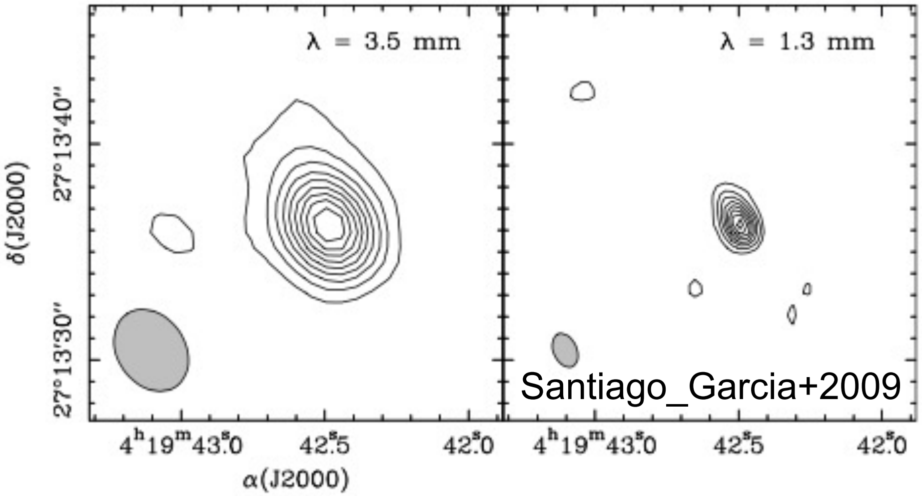


Segura-Cox+2020

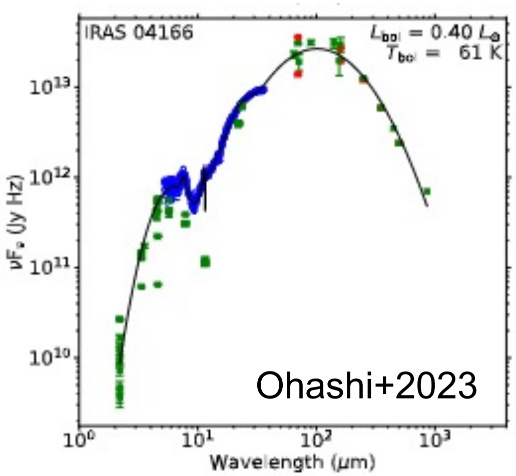


Alves + 2020

IRAS 04166+2706



Santiago_Garcia+2009



Ohashi+2023

$T_{\rm bol}$ = 54 K

$L_{\rm bol}$=0.41 $L_{\rm sun}$

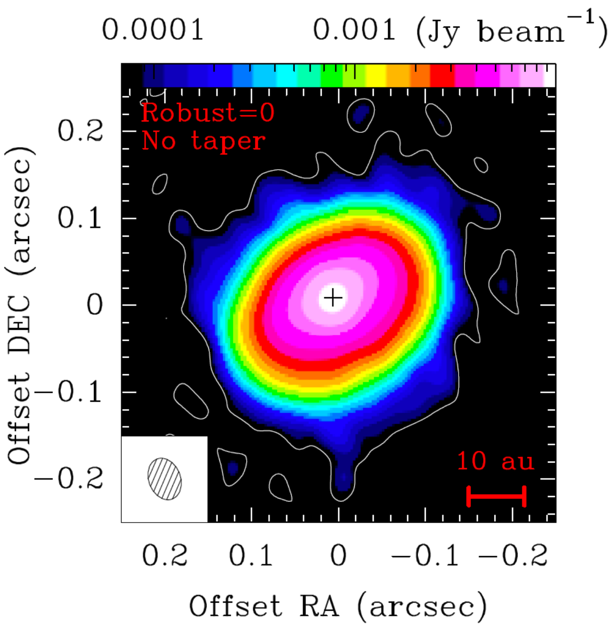
Class 0

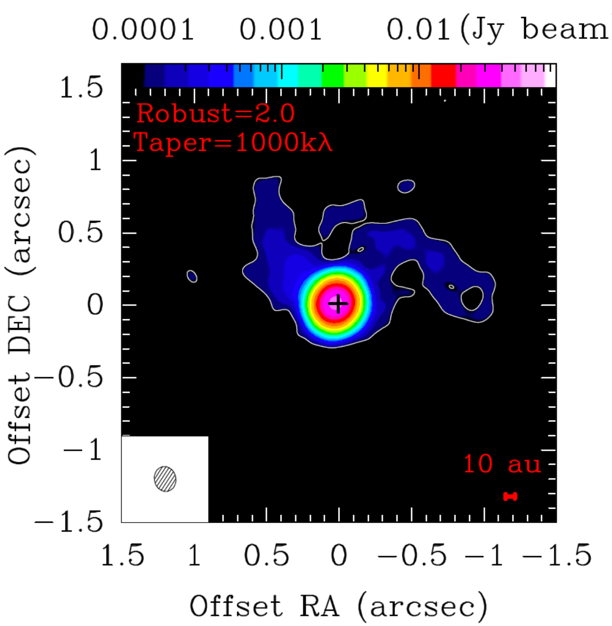
Located in the B213 cloud, which belongs to the Taurus star-forming region, at a distance of 156 pc (Gaia EDR3, Krolikowski + 2023)

$M_{\rm core}$ = 0.179±0.02 $M_{\rm sun}$ (Marsh + 2016) & $M_{\rm disk}$= 0.02 $M_{\rm sun}$ (Santiago_Garcia+2009)

1.3 mm continuum

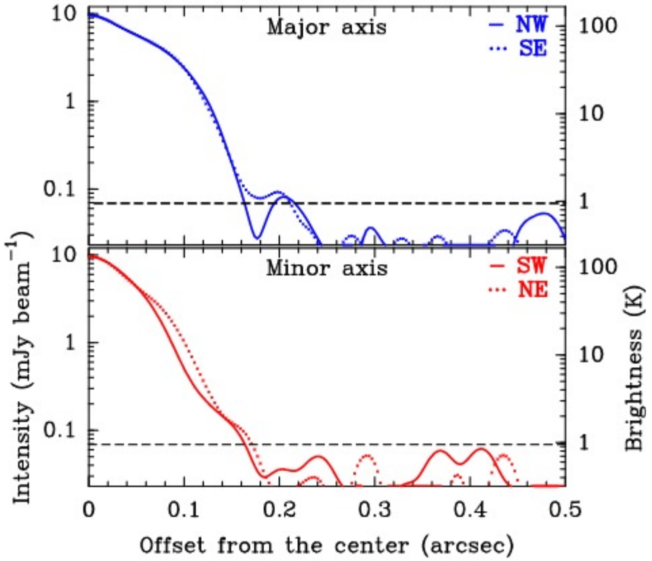
ALMA observations – eDisk collaboration





Asymmetry at the outer edge in high angular resolution image (robust=0)

Extended emission is shown in the low angular resolution image (robust=2.0)



2D Gaussian fit (imfit – CASA):

The deconvolution size of 22 au ×15 au

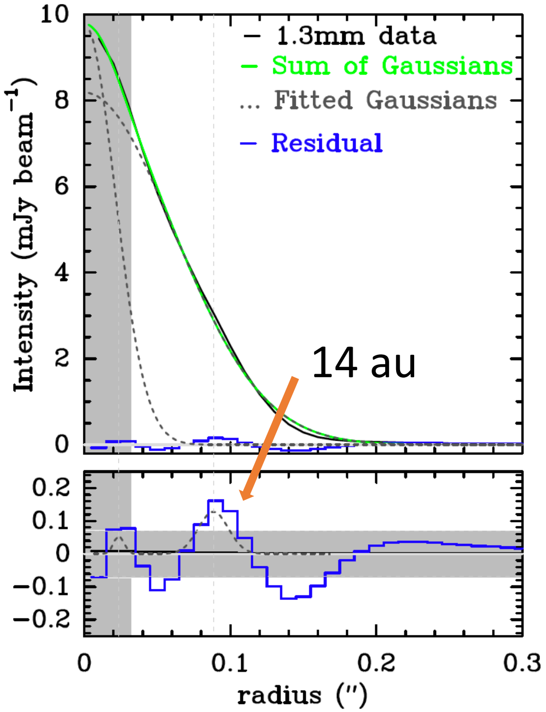
→ inclination = 47°

T_d=20 K → M_{disk} = 0.015 M_{sun}

T_d = 43 $(L_{bol}/L_{sun})^{0.25}$ ~ 34 K (L_{bol}=0.41L_{sun})

→ M_{disk} = 0.008 M_{sun}

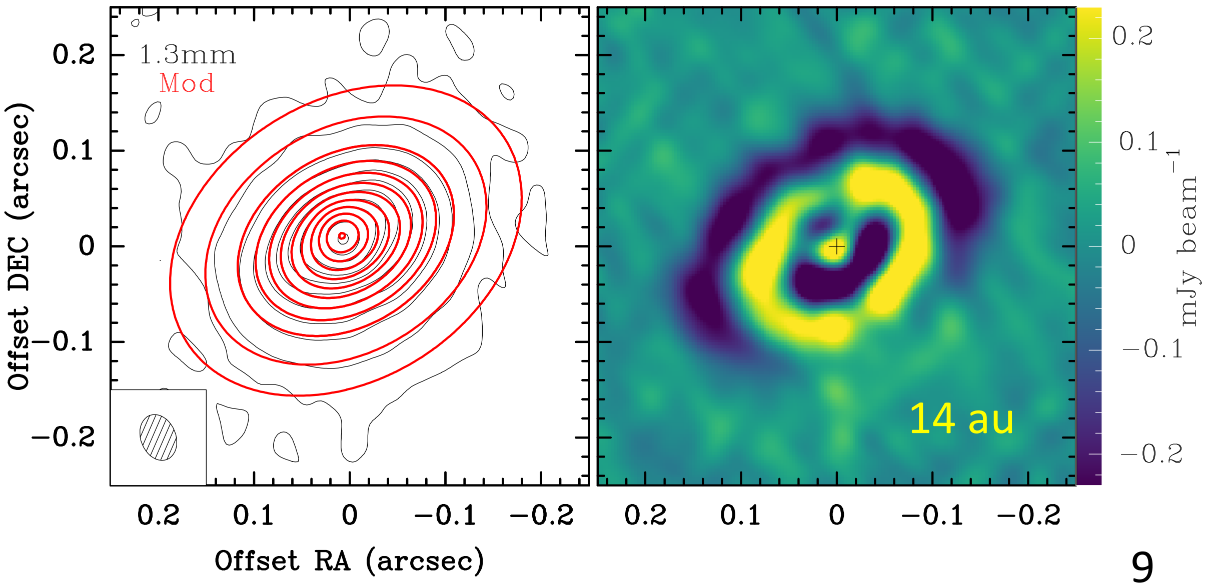
Identifying a possible substructure in the continuum disk



Fit a function of 2 Gaussian components to the radial profile (in the disk plane).

→ Residual shows the excess emission (> 3σ) at 14 au, and the width is about the beam size.

2D Gaussian fitting and also identify the same features



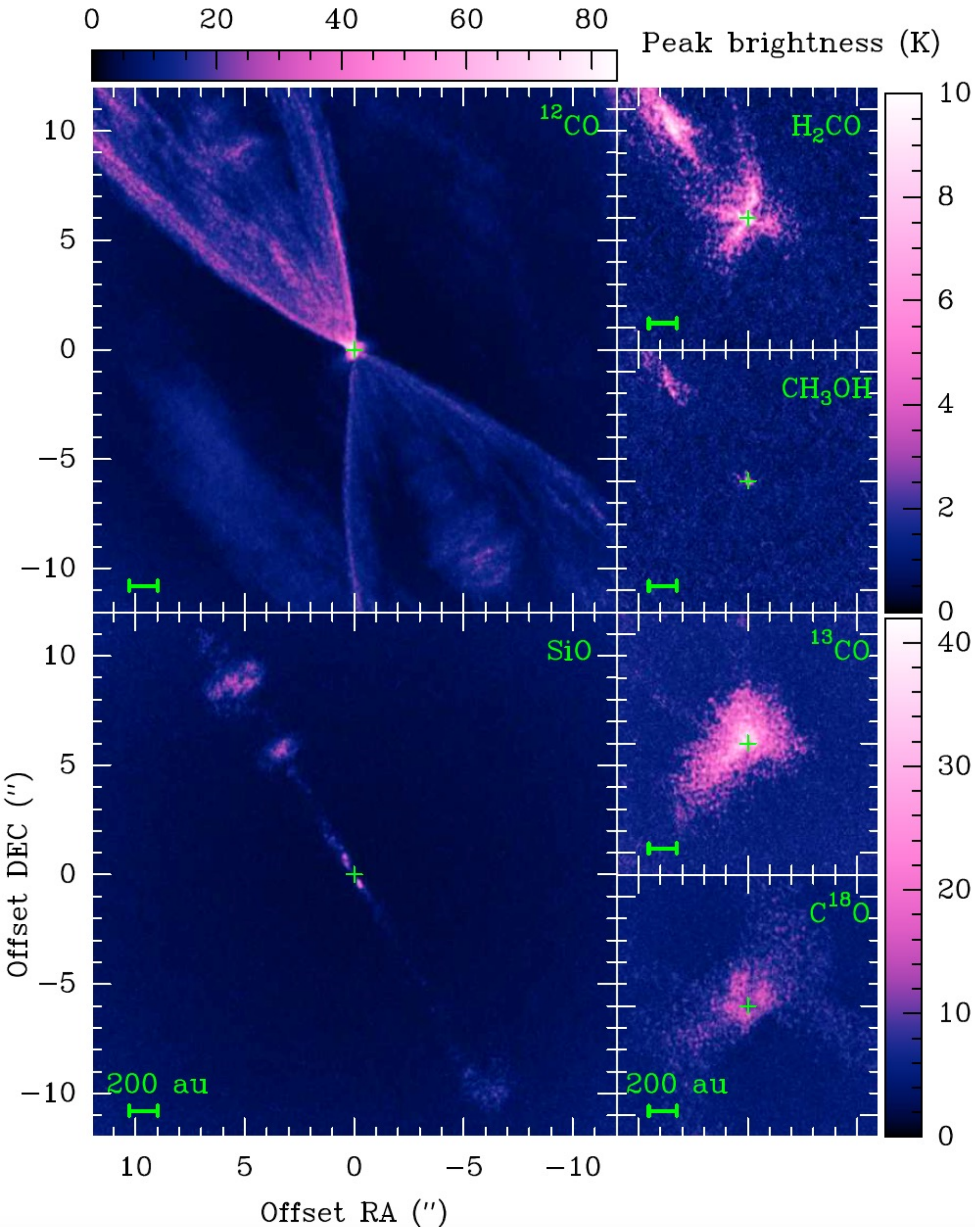
Line emission

^{12}CO: Outflows, Jets

SiO: Jets

^{13}CO, $C^{18}O$, H_2CO: disk + envelope

CH_3OH: Rotation gas disk.



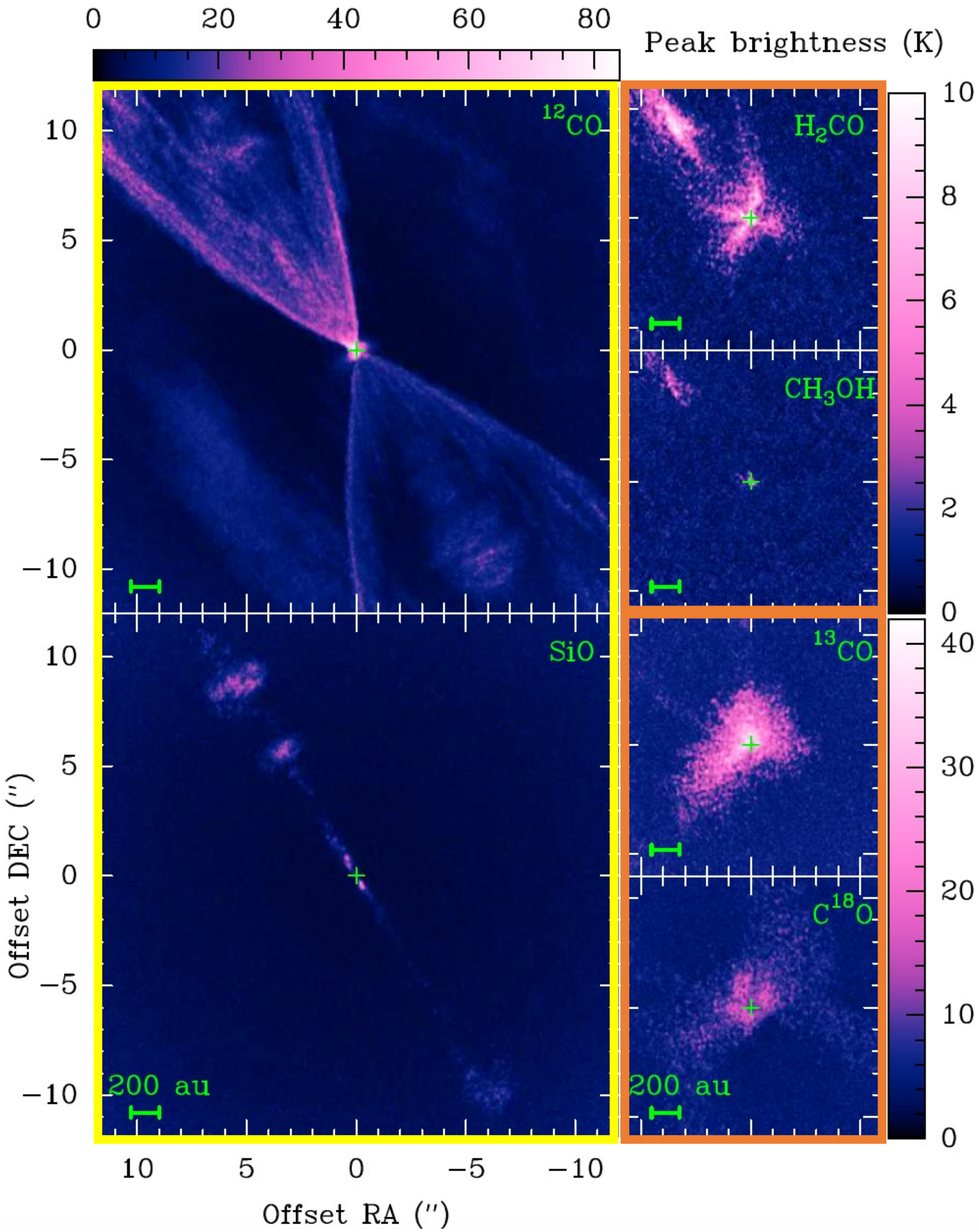
Line emission

^{12}CO: Outflows, Jets, outflows wall

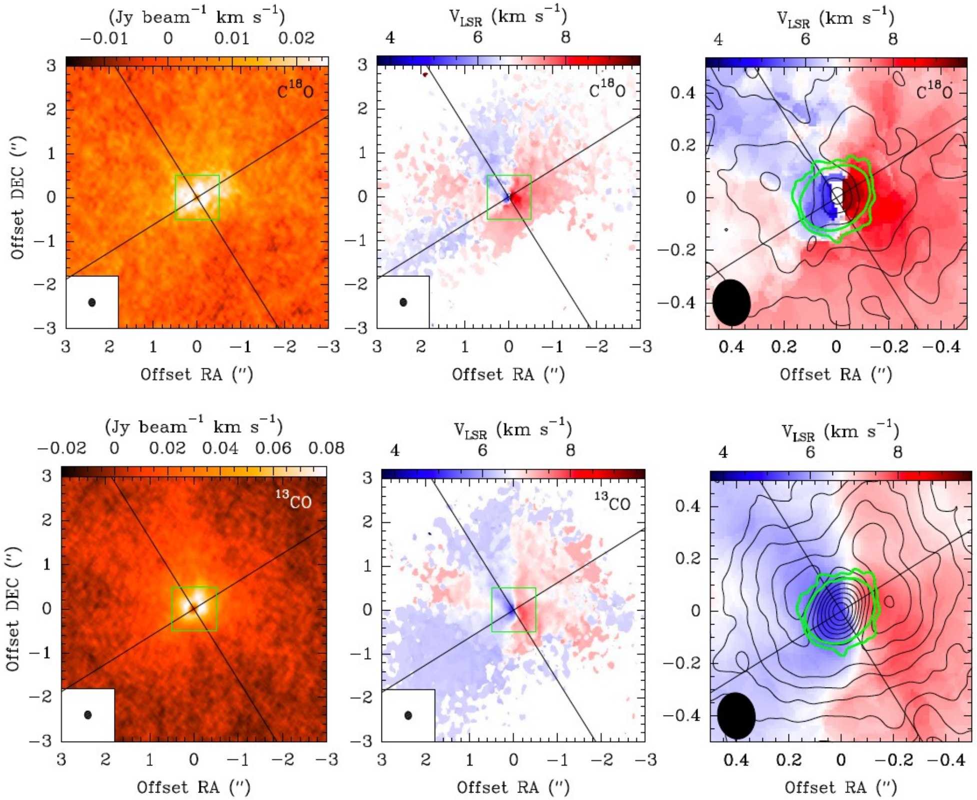
SiO: Jets

^{13}CO, $C^{18}O$, H_2CO: disk + envelope

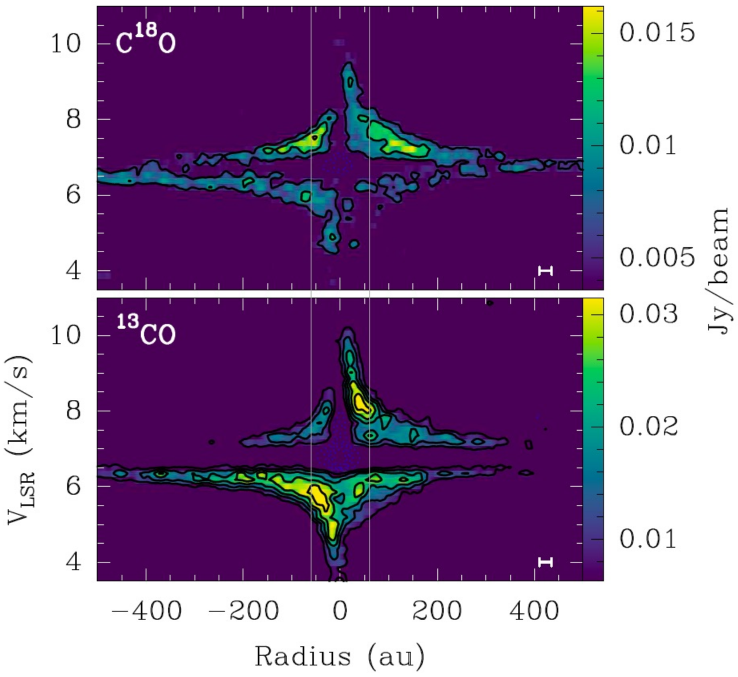
CH_3OH: Rotation gas disk.



^{13}CO(2 – 1) and C^{18}O (2 – 1) trace rotation gas disk → derive the dynamic mass of the star



PV diagram along the major axis

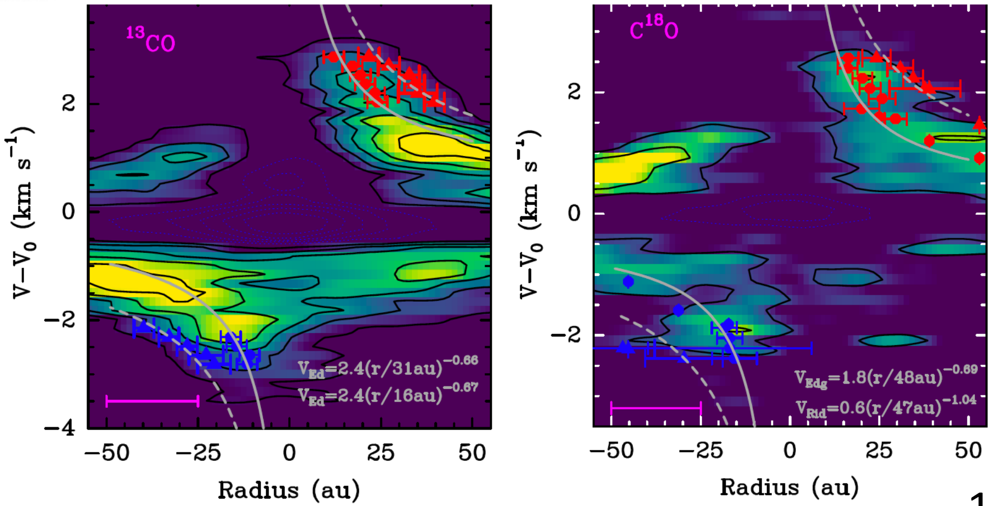


Large scale: Mixing red- and blue-shifted emissions --> Disk + envelope/outflows

Smaller scale: Velocity gradient misaligned with the minor axis of the dust structure

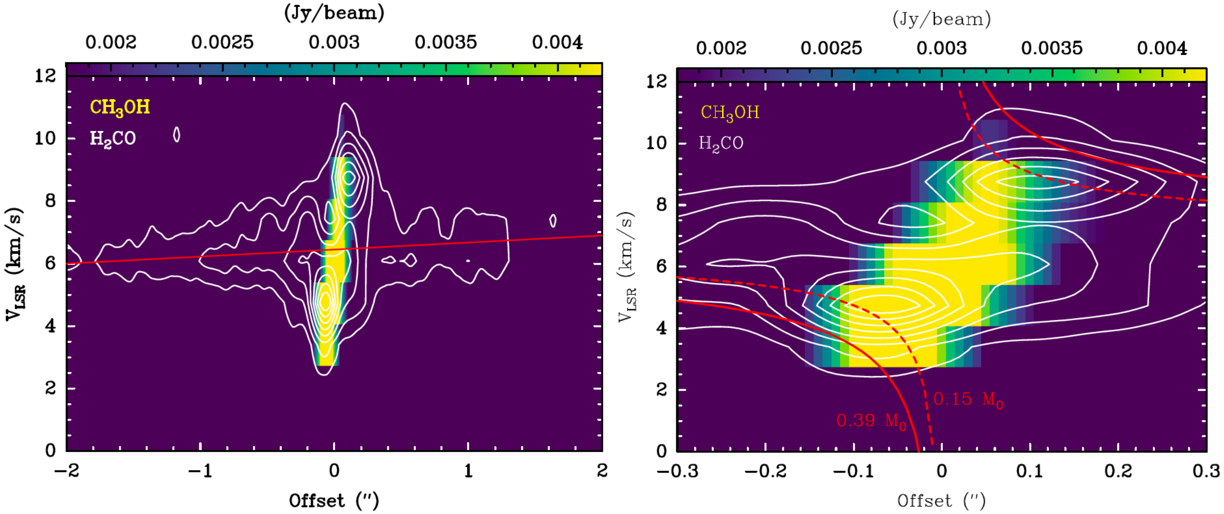
-> Infalling and rotation

$M_\star$ = 0.15 – 0.39 M_{sun}



H_2CO traces the rotation disk and the outflow, CH_3OH traces the rotation disk

Position – Velocity diagrams along major axis

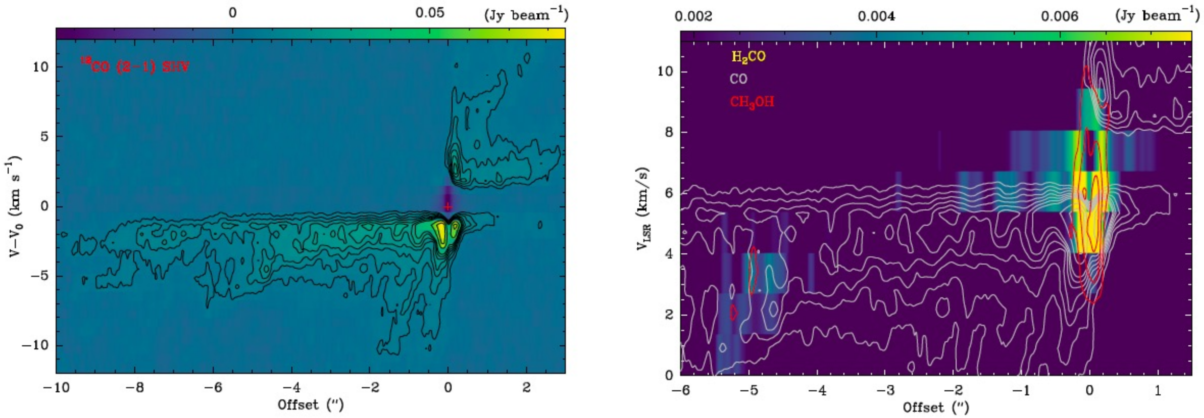


At the large scale, the H_2CO shows the east-west velocity gradient, while at smaller scale, it shows the signature of Keplerian motion

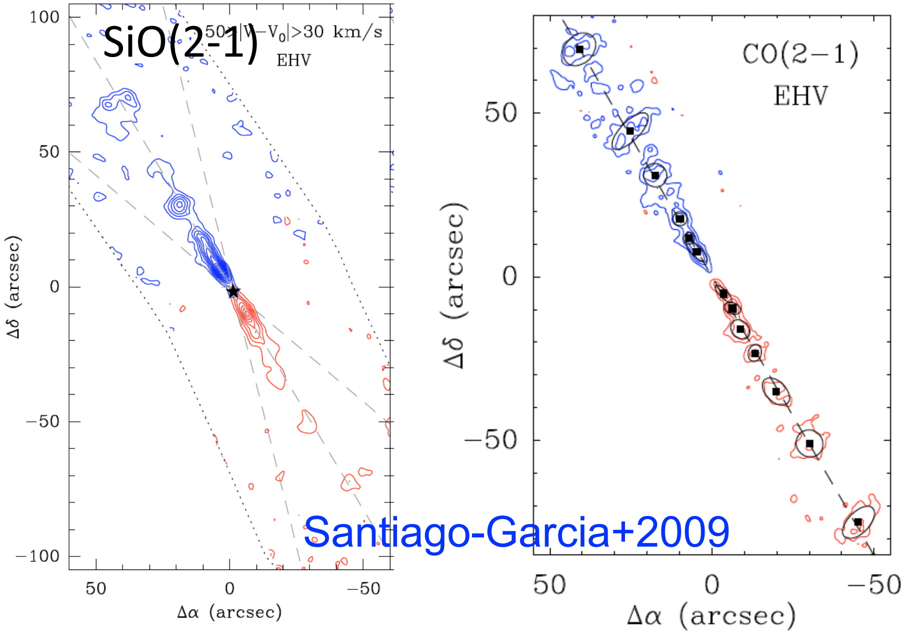
→ Keplerian motion at ~ 45 au

Position – Velocity diagrams along minor axis

Along the minor axis, H_2CO and CH_3OH show the signature of outflows at smaller scales than the ^{12}CO outflows.

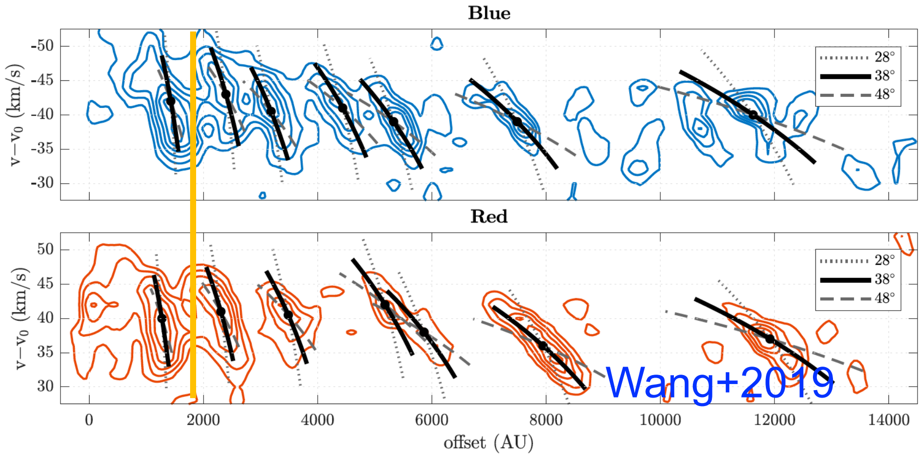


SiO (2-1) and CO (2-1) trace jets and outflows



Santiago-Garcia+2009

Saw-tooth like pattern in the PV diagram



Wang+2019

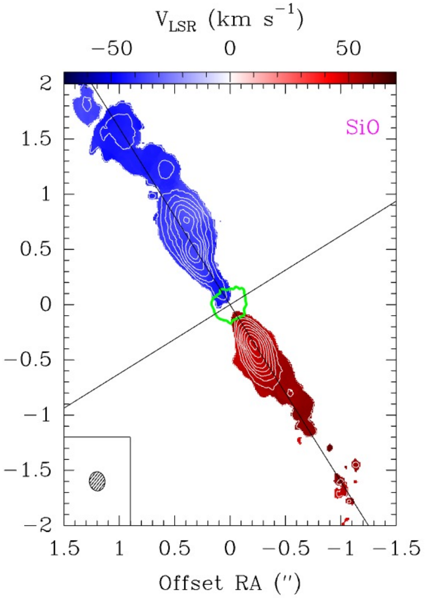
unified wind model

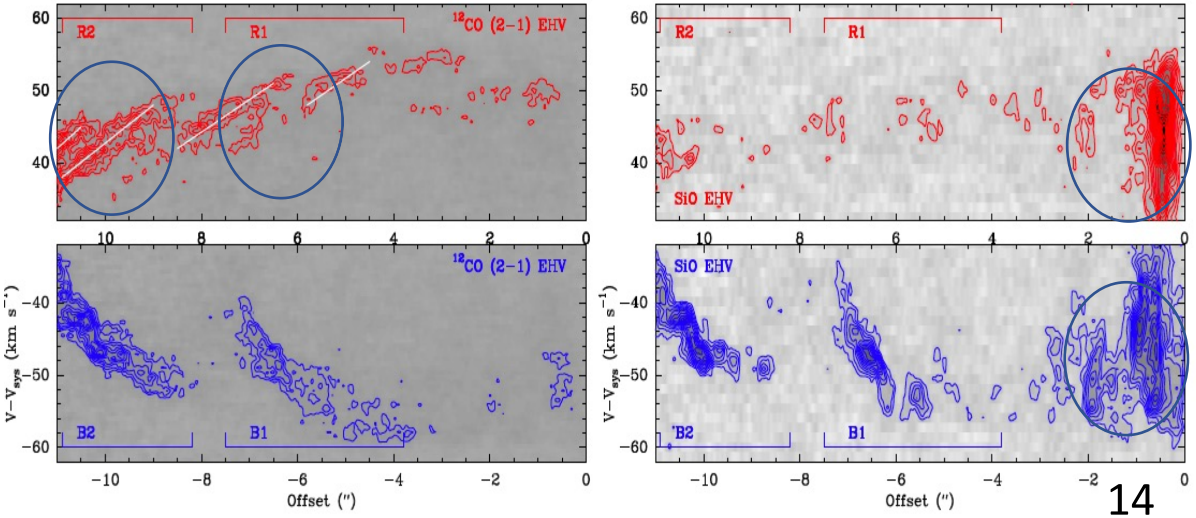
+ Outflow is a spherically directed wide-angle wind

+ Jet arises from the high-density concentration near the axis

Each knot consists of two mass ejection events with a period of 73 years

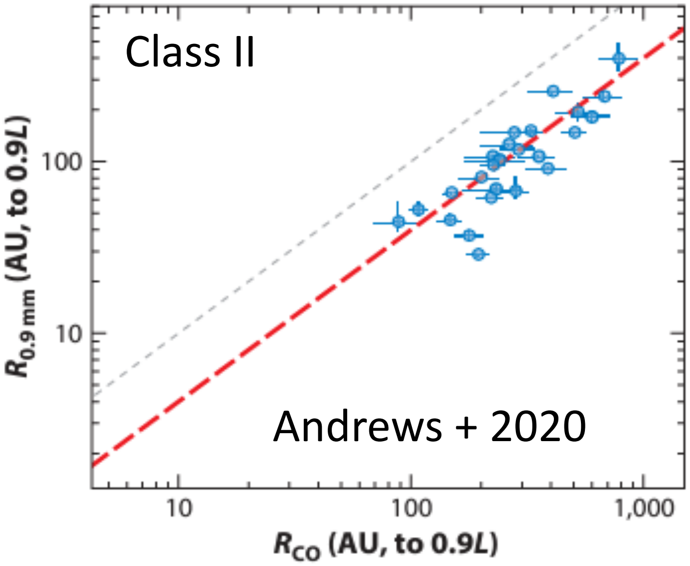
S-shape morphology on the blue-shifted side, suggesting wiggling or precession motions in the jet.





Gas and dust disk

$R_{gas} = 2.5\ R_{dust}$



In the case of IRAS 04166 + 2706 (Class 0):
+ R_{dust} = 22 au and R_{gas} = 45 au
→ $R_{gas}/R_{dust} \sim 2.0$

+ Optical depth effects, i.e., the ^{13}CO and C^{18}O lines are optically thicker than the dust emission.
+ Dust grains grow in the disk and then decouple from the gas, resulting in their radial drift to the inner parts of the disk → The larger grains can then be halted in the maximal pressure region, and a sub-structure (i.e. ring) can form in that region.

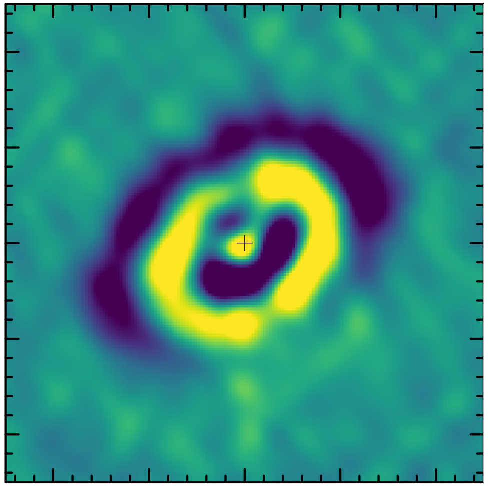
$$R_c = 56\, au \times (\frac{M_\star}{M_\odot})^{1/3}(\frac{\zeta_d}{0.01})^{2/3}(\frac{t_{disk}}{0.1Myr})^{2/3} = 6 - 26 \text{ au}$$

Disk stability ?

$$Q = 2 \times \frac{M_\star}{M_{\rm disk}} \frac{H}{R} = 2 - 7$$

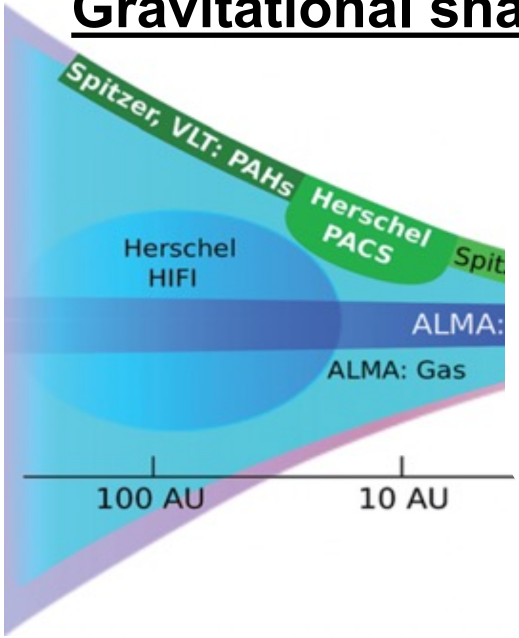
H = c_s/Ω with c_s is sound speed and $\Omega = \sqrt{GM_\star/R^3}$

→ **The disk is instability**



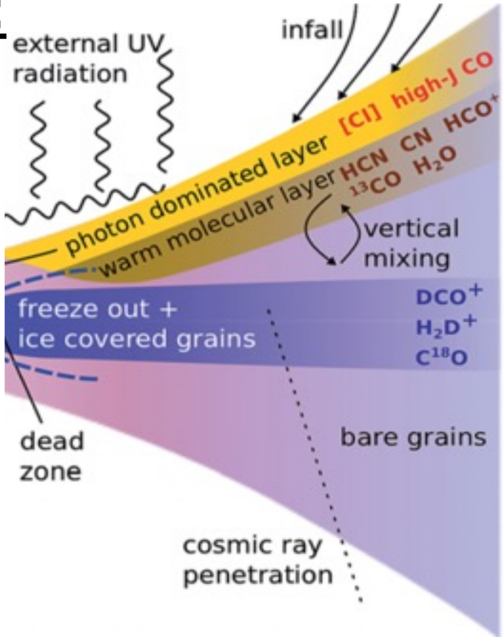
Phuong et al (in prep)

Gravitational shape in a binary environment:



Tidally truncated cavity
(gravitational disturbance)

Adapted from van Dishoeck (2014)



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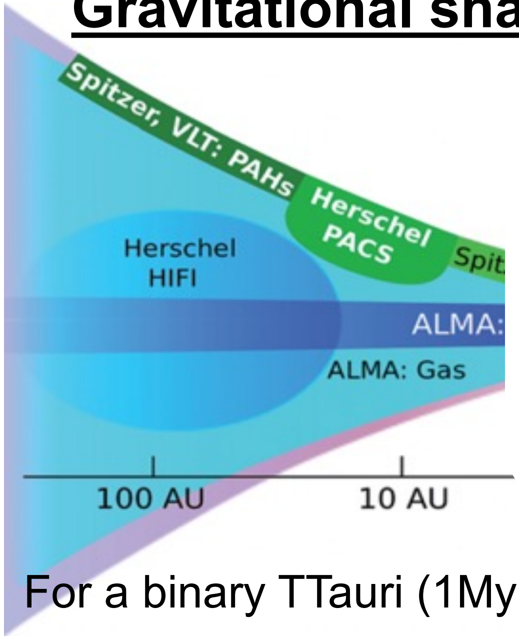

Tidally truncated cavity
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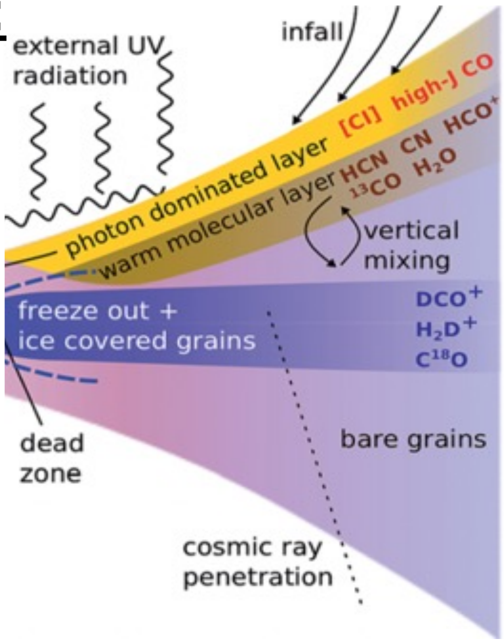
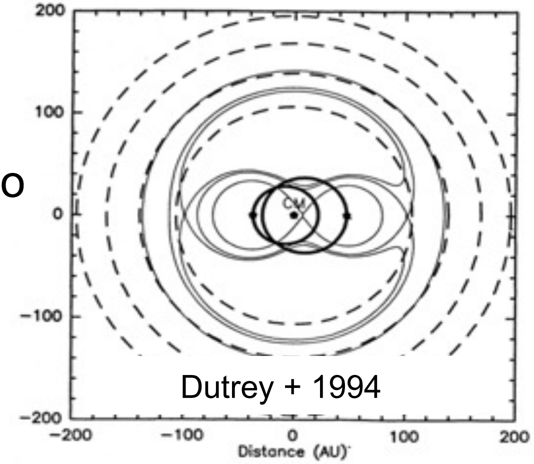


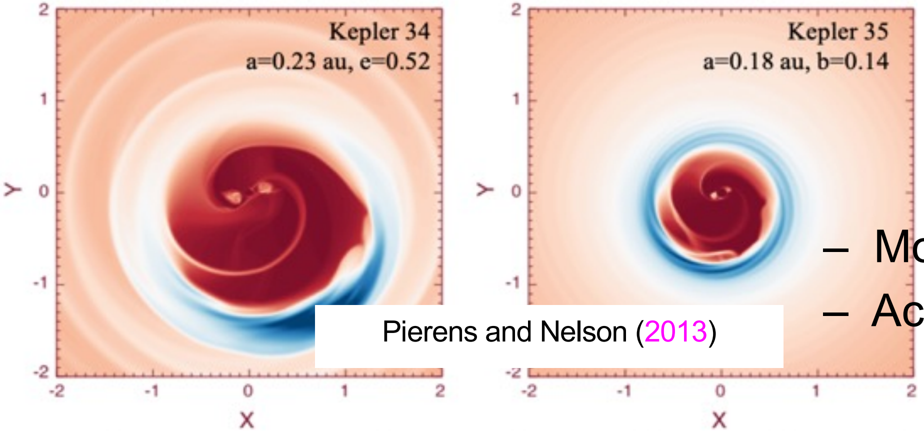
For a binary TTauri (1Myr):

- Two inner **circumstellar (CS) disks** (inside Roche Lobe)
- An outer **circumbinary (CB) disk** in Keplerian rotation
- Large cavity of size ~ 2 major-axes of the binary orbit

→ Unstable gas and dust falling down from the CB disk onto the stars through the inner disks: **«streamers»**



Dutrey + 1994



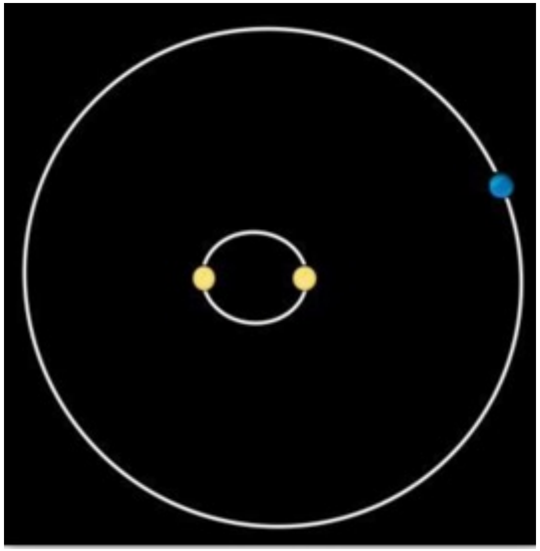
Pierens and Nelson (2013)

- More eccentric systems exhibits larger cavities
- Accretion rate changes with time ~ binary period

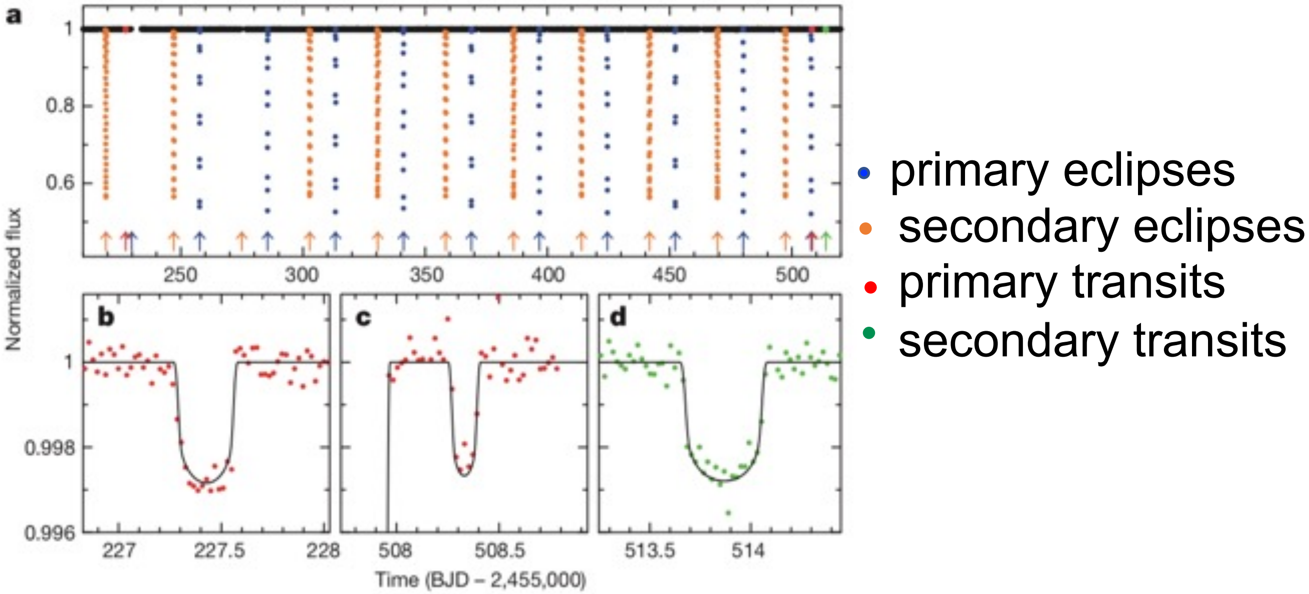
Planets formation in binary systems

- 50% of stars are in binary/multiple systems (possible reservoir of planets?)
- Planets can form either in circumbinary (CB) or circumstellar (CS) disks

Kepler 34: one of the first CB planets



Credit: Rahul Sharma

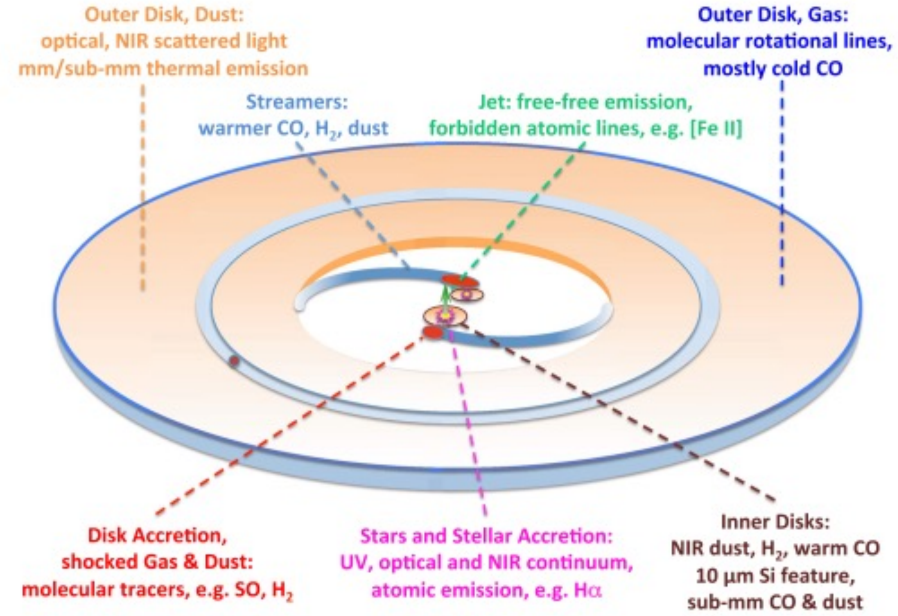


Welsh et al. (2012)

- Studying the gas and dust properties in these environments is a necessary step to understand the formation of planets in binary/multiple systems and unveil the variety of planetary systems.

What can be observed in a binary TTauri system?

i) the circumstellar disks
ii) the cavity and the "streamers"
iii) the circumbinary ring or disk



Outer Disk, Dust:
optical, NIR scattered light
mm/sub-mm thermal emission

Outer Disk, Gas:
molecular rotational lines,
mostly cold CO

Streamers:
warmer CO, H_2, dust

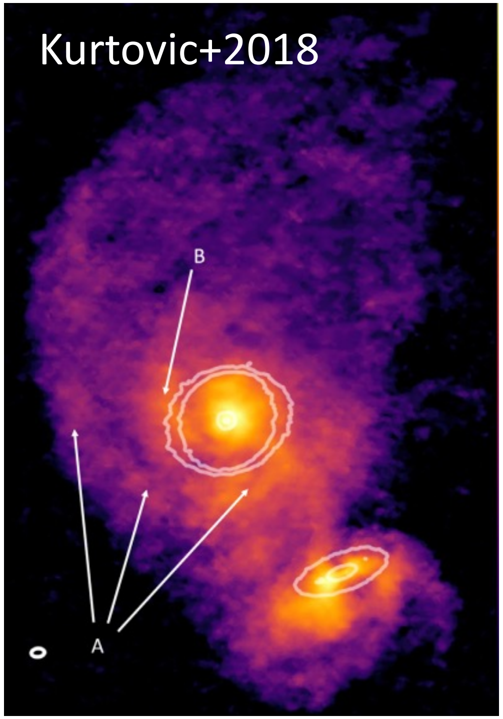
Jet: free-free emission,
forbidden atomic lines, e.g. [Fe II]

Disk Accretion,
shocked Gas & Dust:
molecular tracers, e.g. SO, H_2

Stars and Stellar Accretion:
UV, optical and NIR continuum,
atomic emission, e.g. Hα

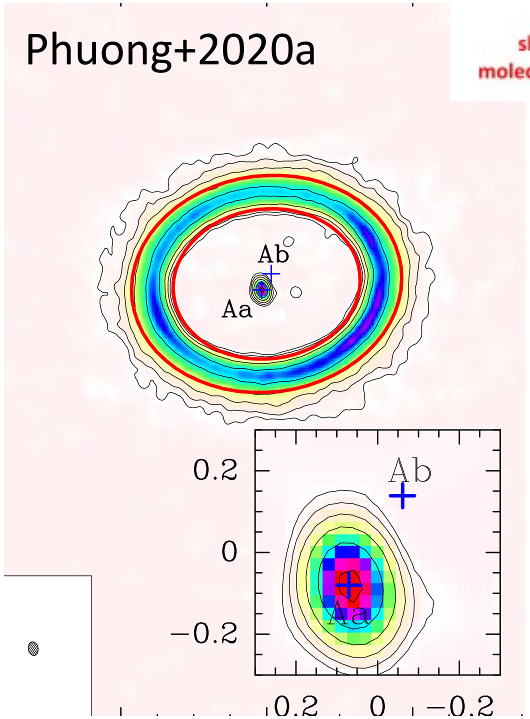
Inner Disks:
NIR dust, H_2, warm CO
10 μm Si feature,
sub-mm CO & dust

AS 205



Kurtovic+2018

GG Tau A

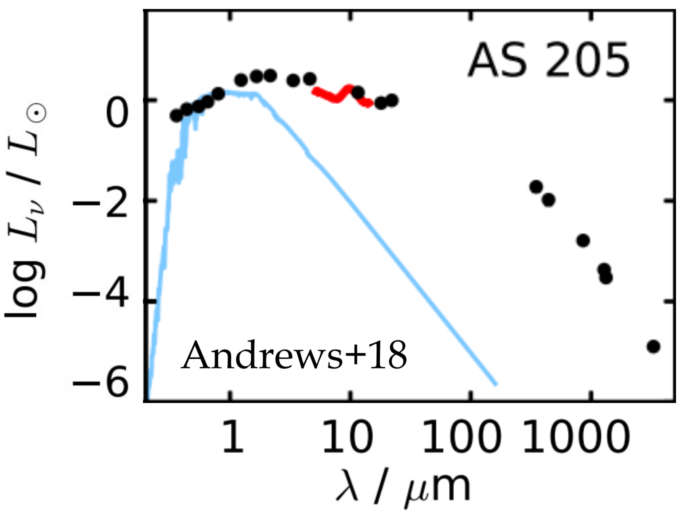


Phuong+2020a

Formation of circumstellar disk (and stars) in the gravitationally perturbed environment ?

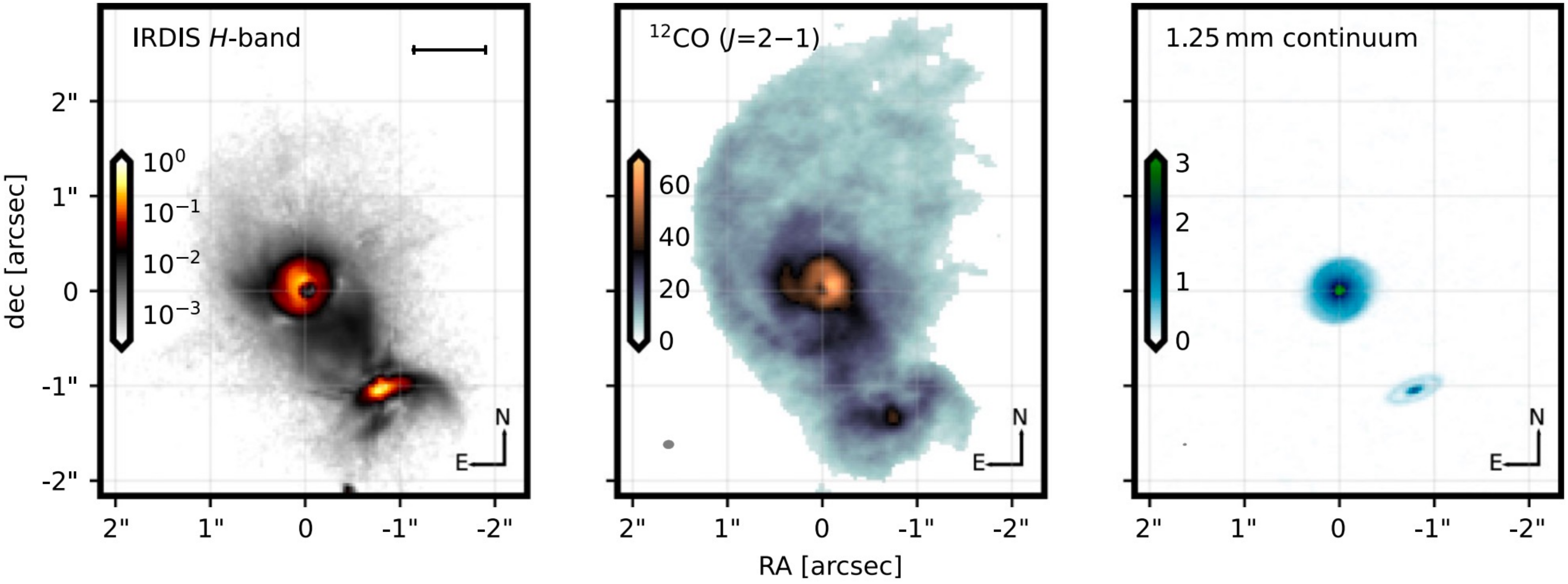
Amount of material transiting from circumbinary disk (CB) to circumstellar disk (CS) ?

AS 205/ V866 Sco



SED

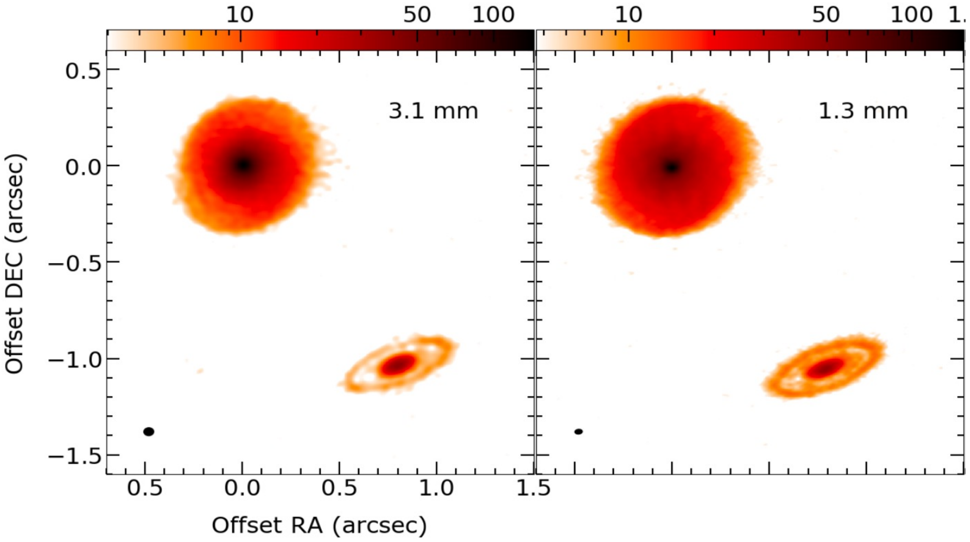
- Class II, 0.6 Myr
- Located between the Upper Sco and ρ-Ophiushi star-forming regions, at a distance of 132 pc (Gaia Collaboration et al . 2021)
- A star AS 205 N and a spectroscopic binary AS 205 S with a separation of 1.3”



Webb+ 2023

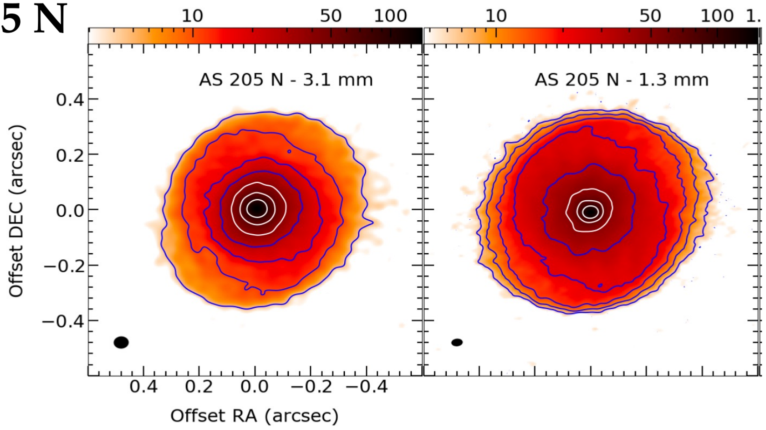
Continuum emission

AS 205

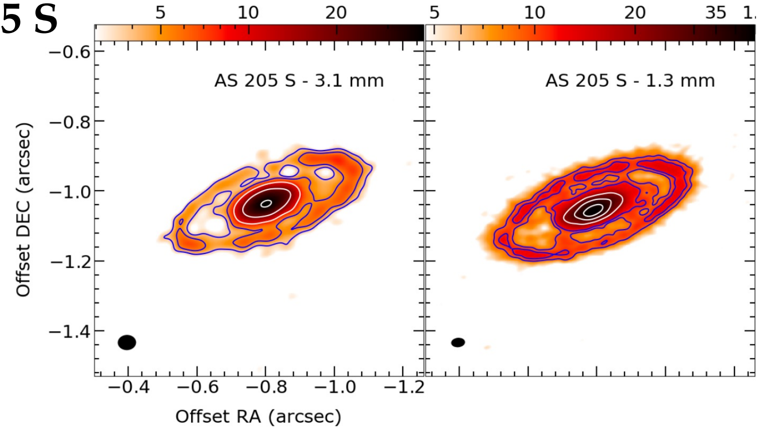


- Two components AS 205 N and AS 205 S
- Separation of ~ 1.3″
- AS 205 N is much brighter than AS 205 S
- Substructures are visible in both components

AS 205 N



AS 205 S



- Exhibits warped features in the outer region

→ **Estimate spectral index map**

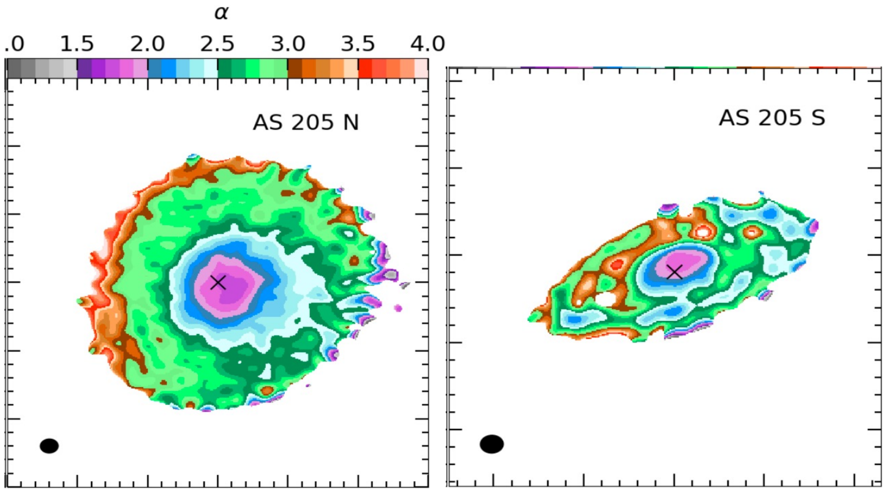
- Unresolved binary
- Displays ring and gap structures with bridges connecting the outer ring to its inner central region

Continuum emission

Spectral index

$$\alpha = \frac{\log(I_{\nu_{1.3\mathrm{mm}}}/I_{\nu_{3.1\mathrm{mm}}})}{\log(\nu_{1.3\mathrm{mm}}/\nu_{3.1\mathrm{mm}})}$$

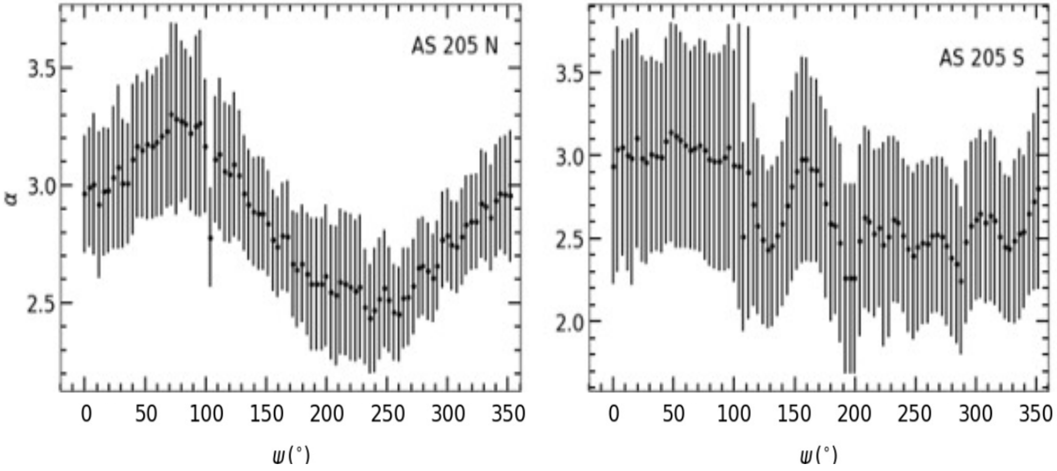
$\alpha < 2.0$ in the center regions
$\alpha = 3 – 4$ in the outer edge
southeast – northwest asymmetry



α smaller towards the AS 205 S side

high spectral index in the gap

Azimuthal dependence of α in r=0.2″- 0.4″

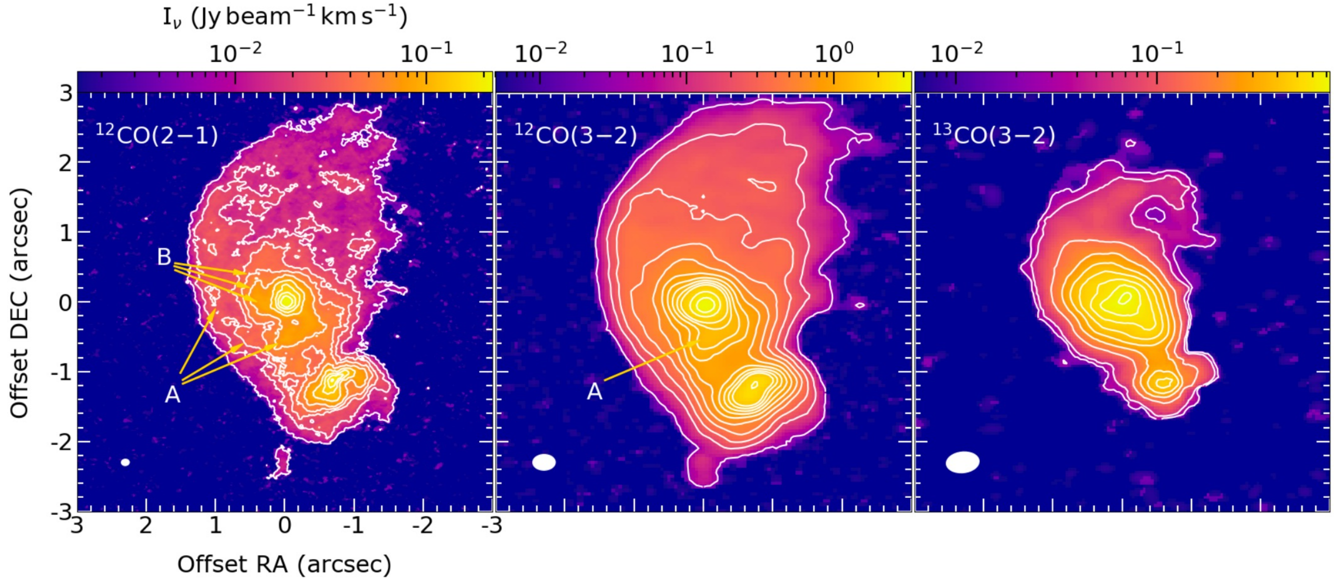


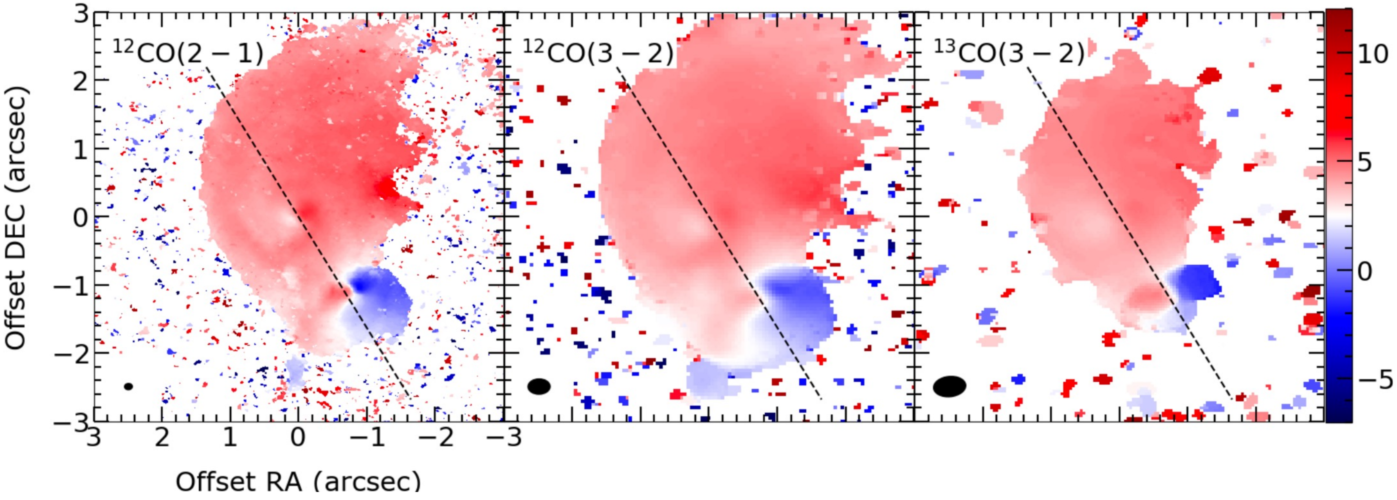
- The asymmetry in spectral index distribution suggests the presence of asymmetric grain size distribution within the disk, where larger grains are concentrated in the southwest and smaller grains in the northeast directions.

Origin of the asymmetry

+ Tidal effect: the azimuthal variation of dust radial migration in the presence of gravitational pulls from their host star and that of the companion disk.

Line emissions





- More extended than dust emission
- Strong connection between the N and S components
- N- S asymmetry, more extended in the north
- Spirals are seen in the highest-resolution obs
- The velocity gradient is close to the protostar's center and likely shares a common axis
- Spirals also shown in the kinematics maps

→ Derive the gas density, temperature distribution, and dynamics mass of the center protostars

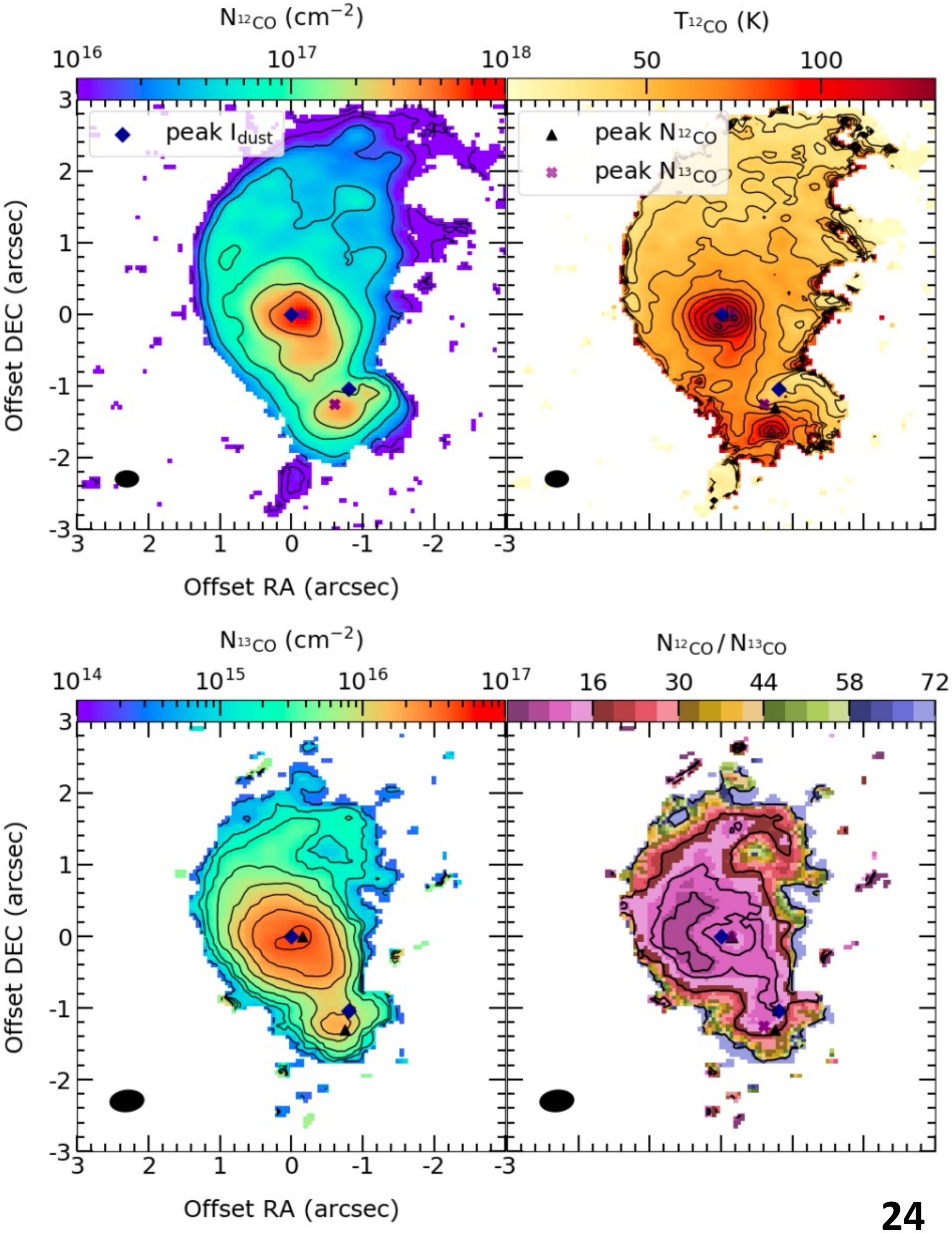
Line emissions

Assume:

- Dust opacity has negligible effects on the molecular line emission
- Beam filling factor = 1
- ^{12}CO and ^{13}CO arise in the same layer, namely the same temperature

$$I_g = B_\nu(T_g)[1 - \exp(-\tau_g)]$$

$$N_{\rm tot} = \frac{3h}{8\pi^3\mu^2 J_{\rm u}} \left(\frac{kT_{\rm ex}}{hB_0} + \frac{1}{3}\right) \exp\left(\frac{E_{\rm J_u}}{kT_{\rm ex}}\right) \times \left[\exp\left(\frac{h\nu}{kT_{\rm ex}}\right) - 1\right]^{-1} \Sigma[\tau_g(v)\Delta v]\ {\rm cm}^{-2}$$



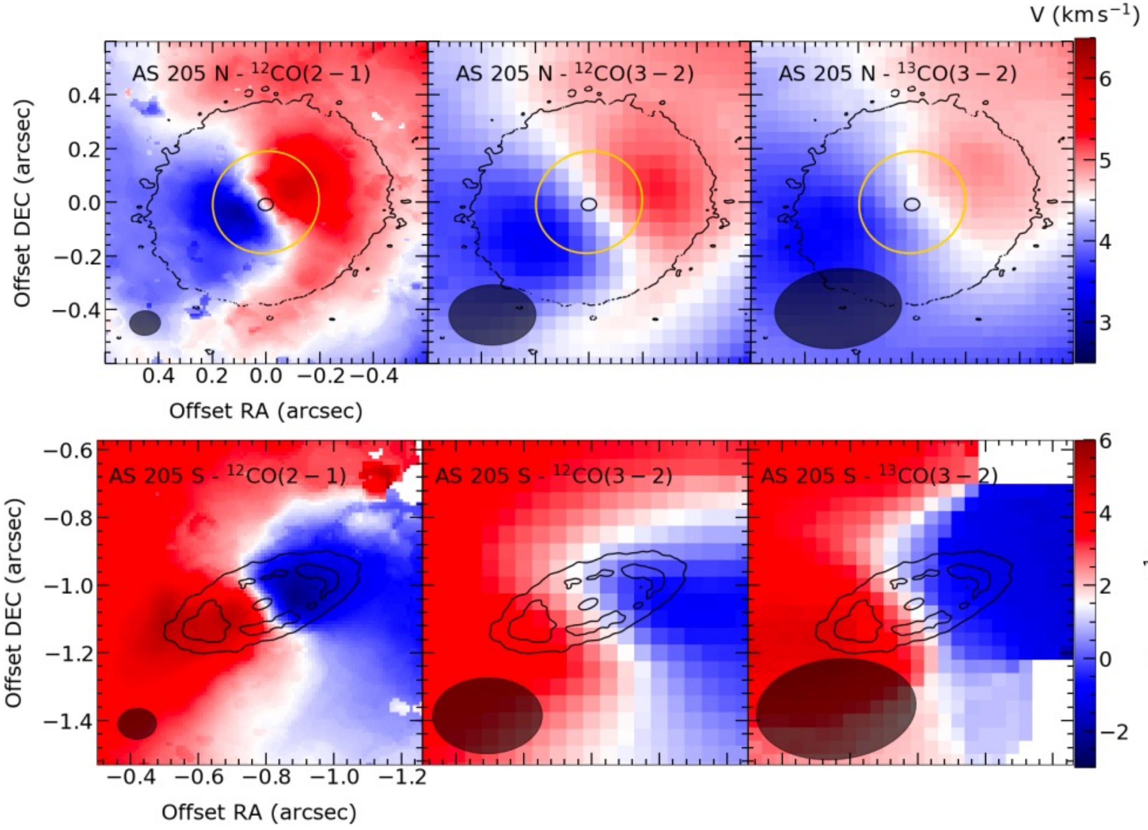
- ^{12}CO and ^{13}CO column density is at 10^{18} cm^{-2} and 10^{16} cm^{-2}, similar to many other disks.
- Standard ^{12}CO/^{13}CO ratio in ISM (~65) is found in the outer region.
- Standard ^{12}CO/^{13}CO ratio in disk (~25) in the smaller inner region.
- Lower values along the spirals and close to the stars.
- Particularly low in a small arc close to AS 205 N.

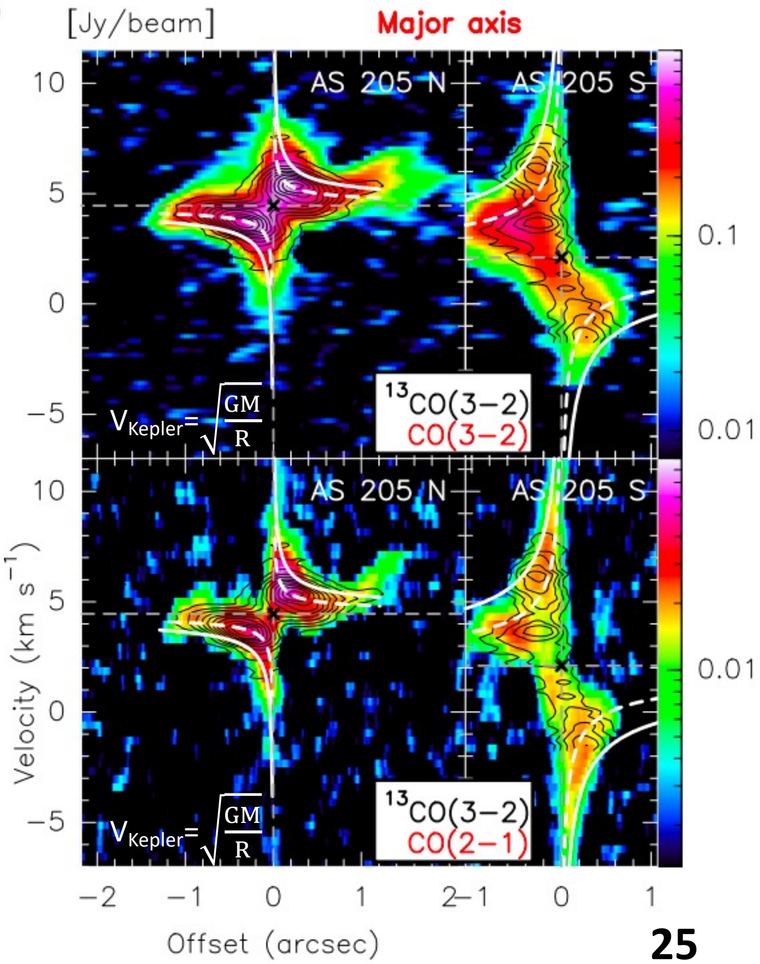
Gas kinematics

The gas rotation axis is not perfectly aligned with the dust minor axis. The gas in the outer region is strongly contaminated by other motions.

We fitted the azimuthal profile of the observed Doppler velocity with a sinusoidal function of $\langle V_z \rangle = V_0 - \Delta V \sin(\psi - \psi_0')$ to derive the gas rotation axis.

The PV diagrams were then performed using the derived gas rotation axis.

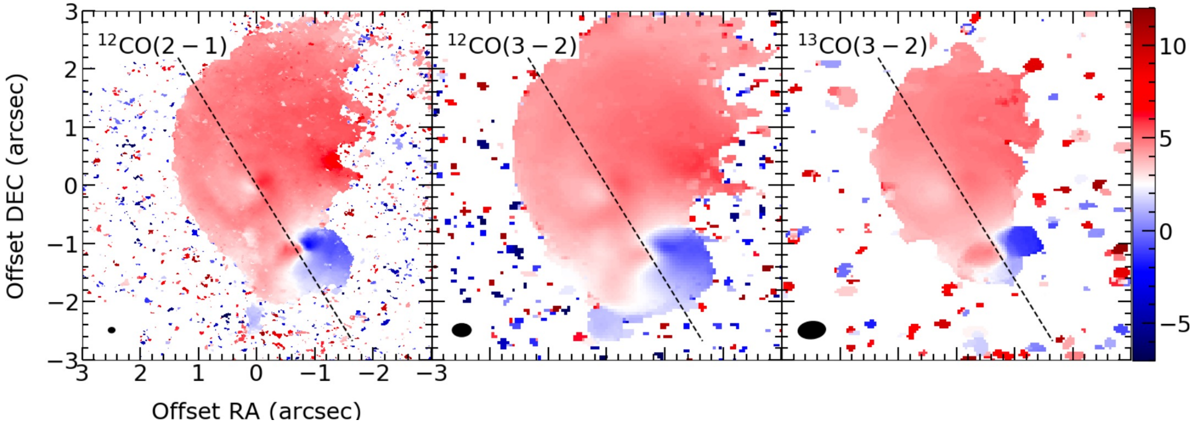




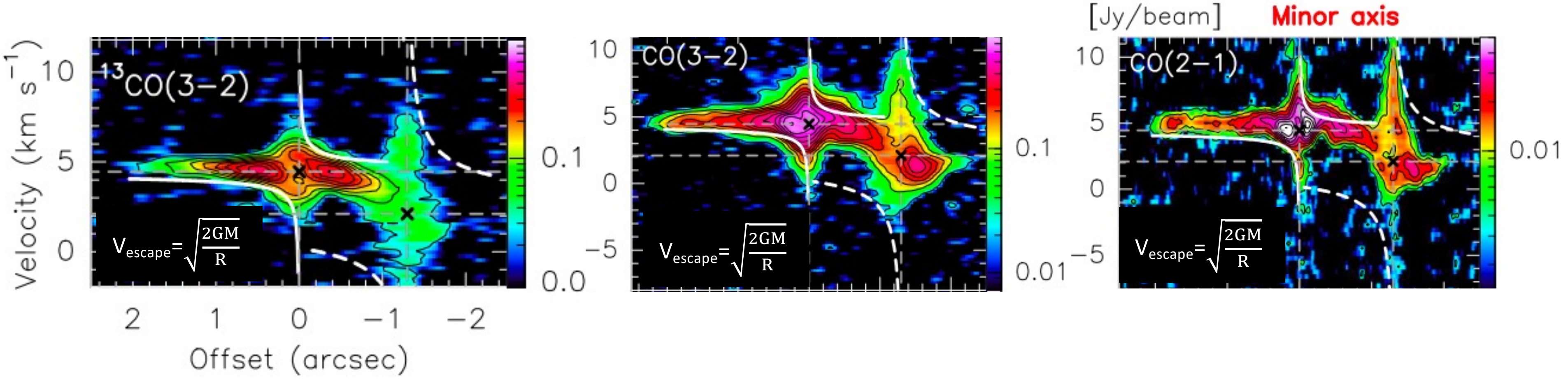
$M_{\mathrm{AS\ 205\ N}} = 0.26\ M_\odot - 0.43\ M_\odot$

$M_{\mathrm{AS\ 205\ S}} = 0.55\ M_\odot - 0.64\ M_\odot$

Gas kinematics



The velocity gradient along the minor axis of a disk can be formed either by radial motions in the disk plane (*i.e. infalling or expansion*) or by motion perpendicular to the disk plane (*i.e. jets/outflows*).

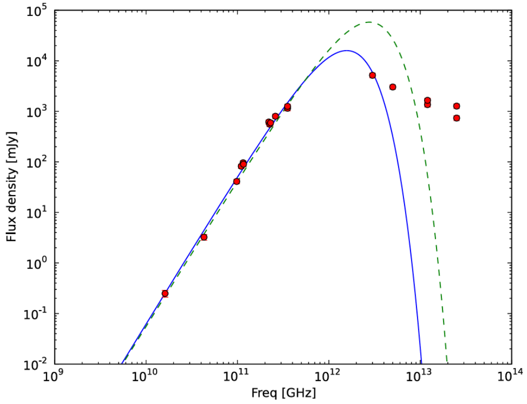


Not the outflow motions.

→ Either from infalling, expansion, or a combination thereof. It could involve material rotating and infalling from the inner envelope to fuel the central protostars while some of them are being pulled out due to hyperbolic fly-by interaction.

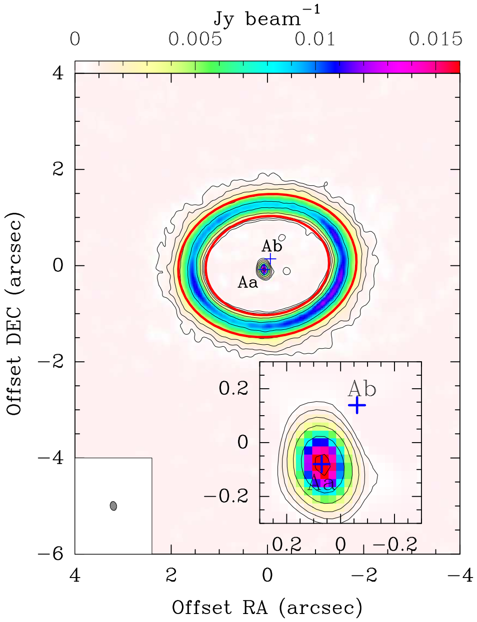
Phuong and Thang (submitted)

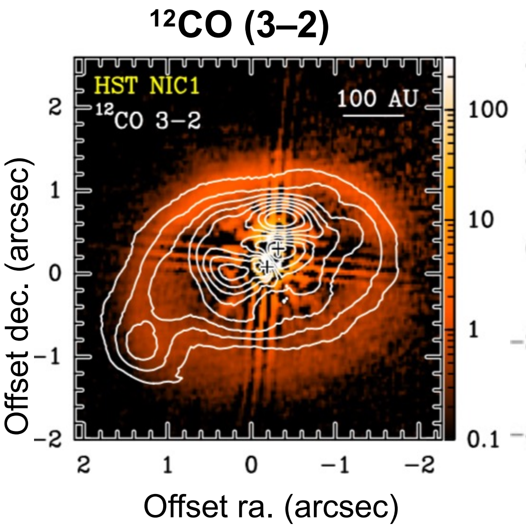
GG Tau A – a prototype of triple stellar system

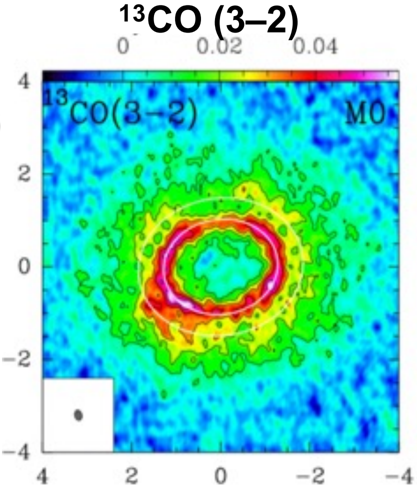


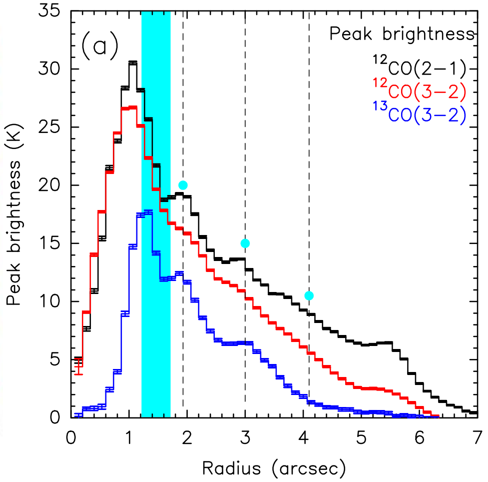
- – Class II, 3 Myr
- - Located in Tarus- Auriga star-forming region at a distance of 150 pc
- – A single star Aa (d=35 au) and a close binary Ab1/Ab2 (d=4.5 au)
- – Cavity <= 180 au: 2 times larger than theoretical studies)
- – Circumbinary disk:
  - + disk (gas): out to 800 au
  - + ring (gas+dust): 180 – 260 au

Narrow dense ring host 70% of total circumbinary disk mass





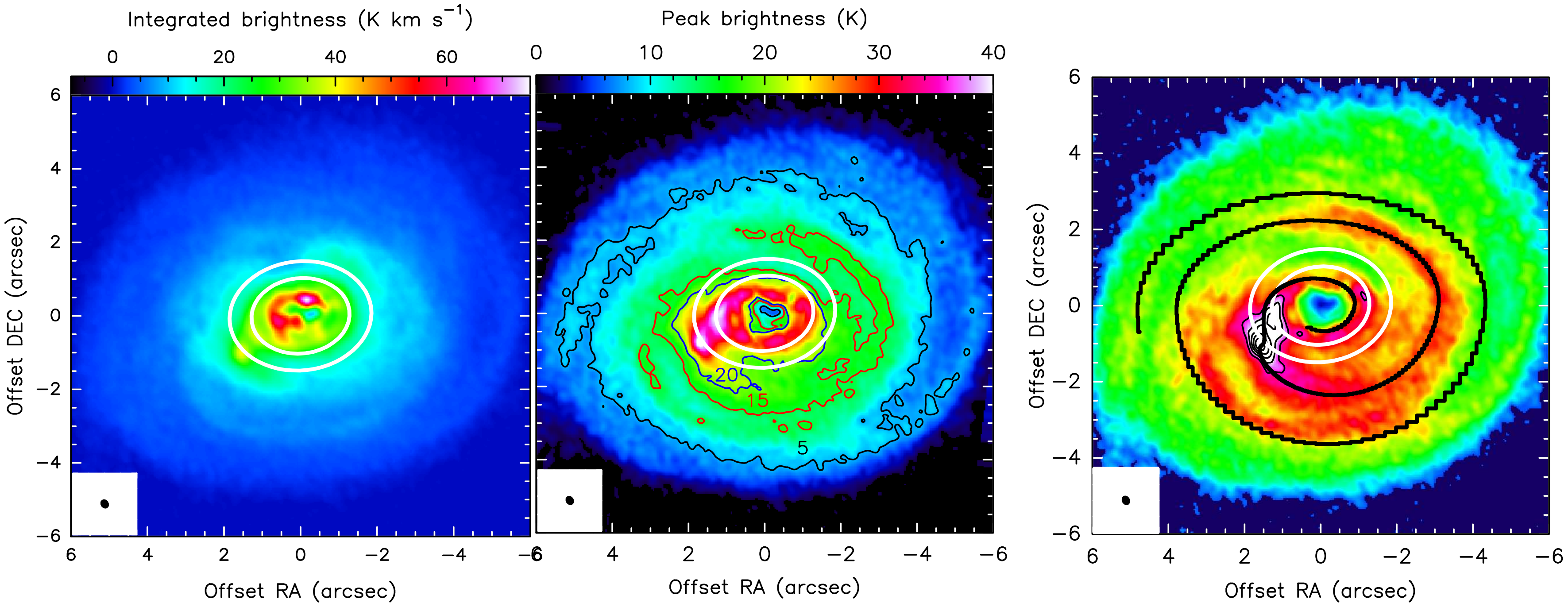




Hotspot in CO observations + unsmooth radial profile

Planet(s) formation in the CB of GG Tau A

An answer for the puzzle of the existence of a narrow and dense in the CB of GG Tau A



North-West: r ~ 1.7″–2.7″ (255 – 400 au)
$T_{b,peak}$ = 16 − 18 K
contrast of ~ 50% w.r.t the interarm

South-East: r~ 2.7″ –3.5″ (530 au)
$T_{b,peak}$ = 14 − 16 K
contrast of ~ 35%

Lower level spirals at r> 5.4″, $T_{b,peak}$=8−9K.

CO (2–1) emission is optically thick, the peak brightness is representative of the **gas temperature.**

→ spirals correspond to warmer gas located well above the mid-plane (2–3 scale heights)

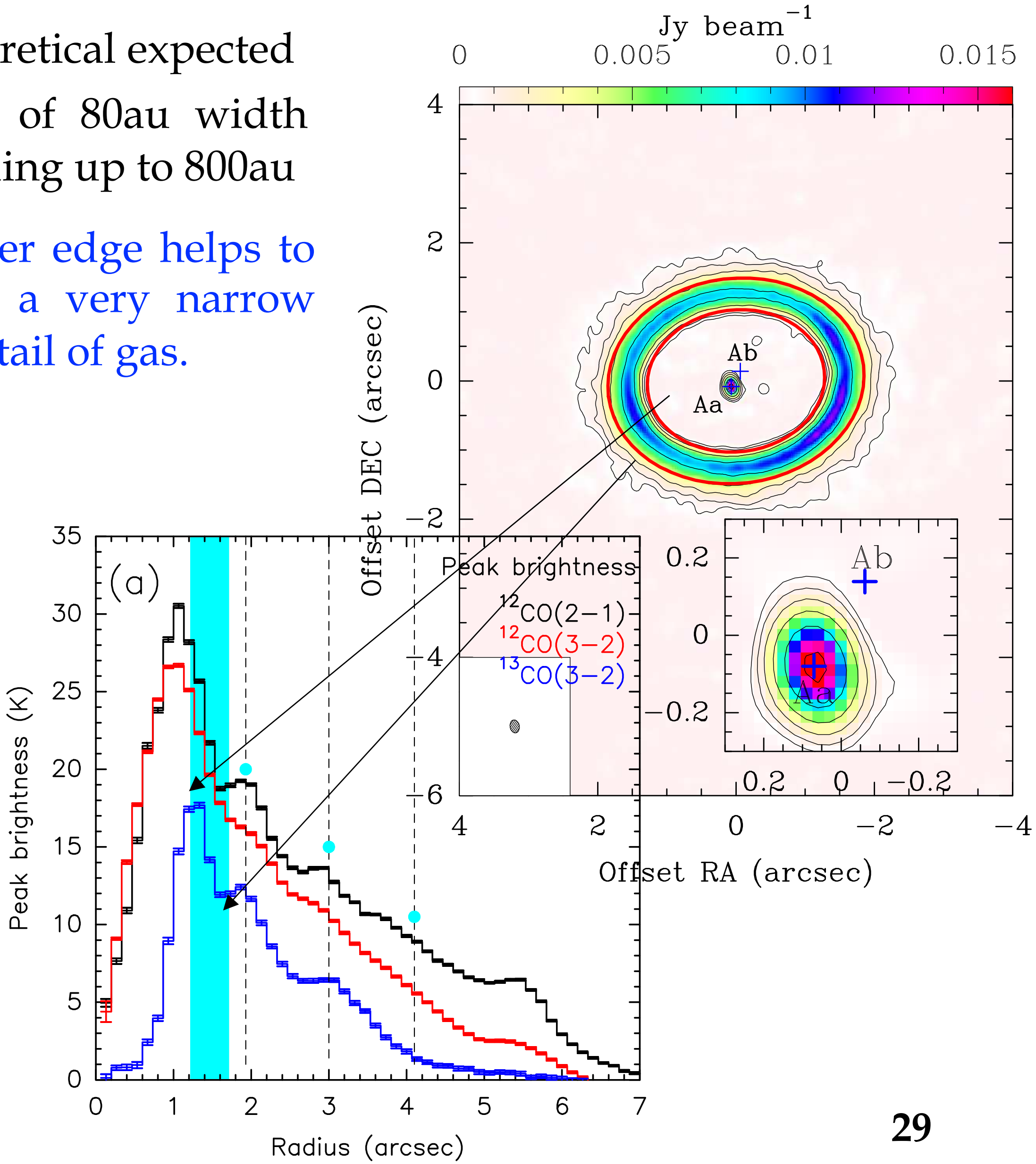
Even though, the object has been studied in decades, there are two major questions remain unexplained in GG Tau A

Wide cavity: 2 times wider than theoretical expected

Narrow and massive ring: a ring of 80au width contains 80% mass of the disk extending up to 800au

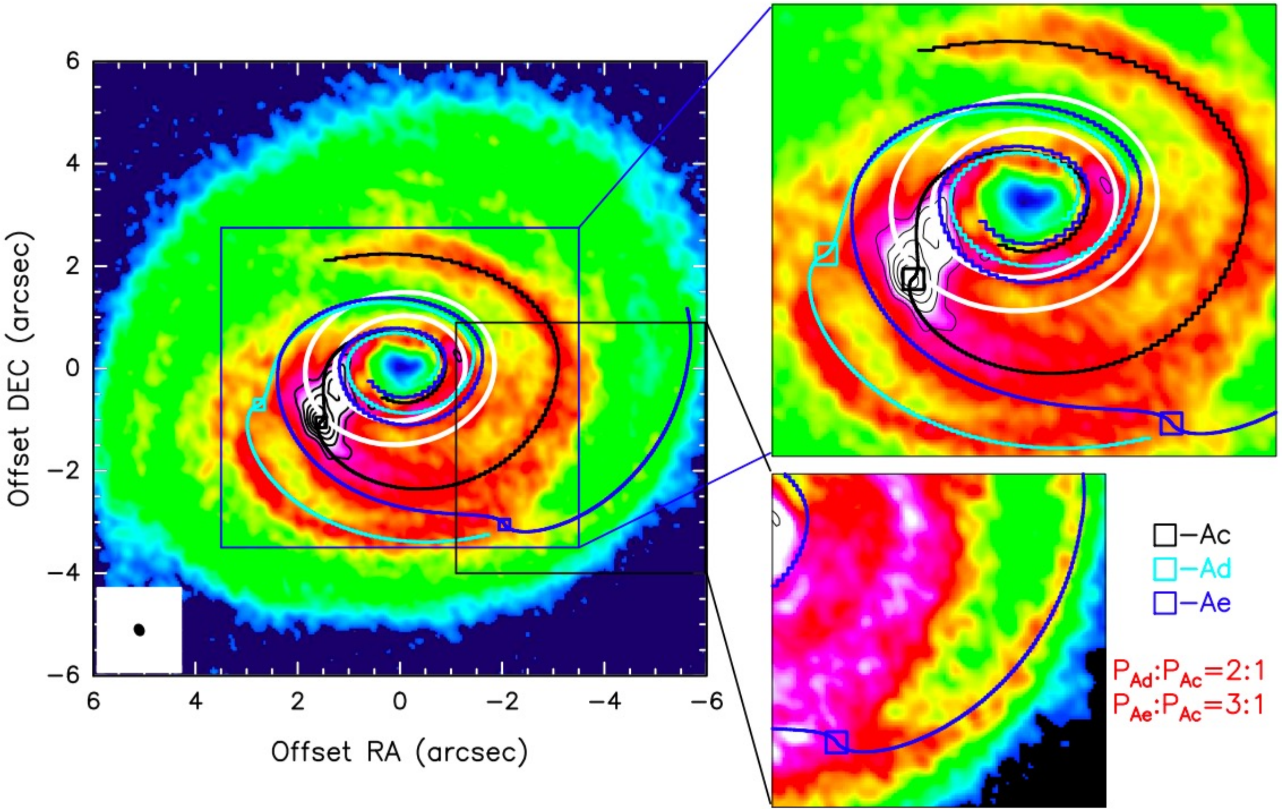
The presence of a planet in the outer edge helps to explain the structure of the disk: a very narrow dense ring followed by an extended tail of gas.

A disk with a constant aspect ratio, and **a viscous parameter** α~0.001:
→ inward migration halted due to the formation of a narrow ring located in between the edge of the central cavity and the planet orbit
(Pierens & Nelson 2008)



Planetary system in formation ?

Other spiral patterns can be explained by the other 2 putative planets located nearly 3:2:1 mean-motion resonance with the "hot-spot" planet. This resonance is by far the most frequent resonant configuration observed among Kepler multiple exoplanet systems.

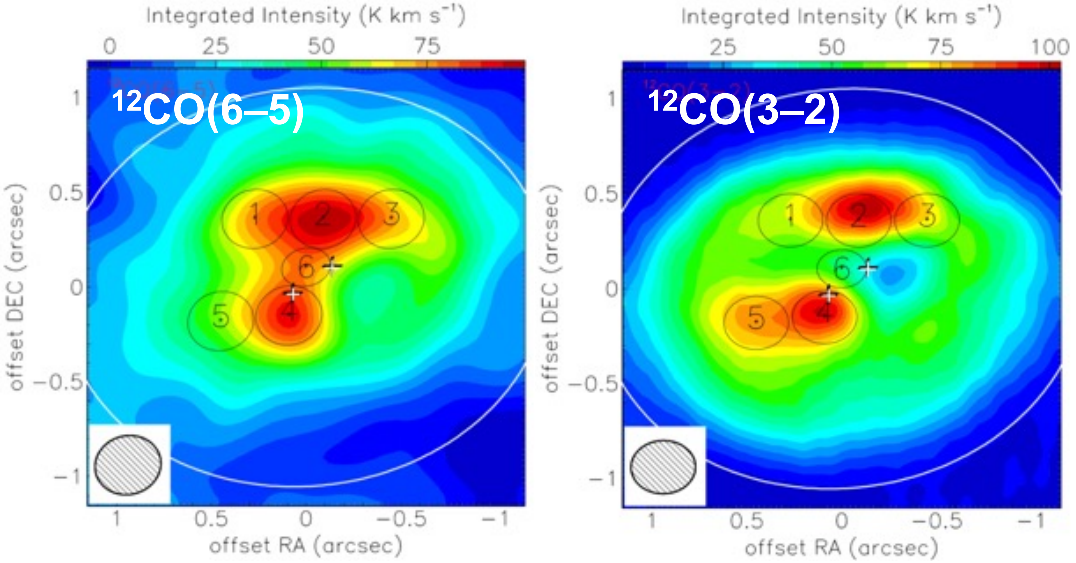


Phuong et al, 2020a, A&A, 635L,9P

CNRS highlight: https://www.insu.cnrs.fr/fr/cnrsinfo/une-meilleure-comprehension-de-la-formation-des-planetes-dans-les-systemes-stellaires?fbclid=IwAR0sE3mgZNTj99YMiDv4jnuig6pO-wjRLmTfdog39d2_q5PcTGsFMJvhoyw

Gas properties inside the cavity

- Amount of material transiting from circumbinary disk to circumstellar disk
- S-type planets



Non-LTE analysis results:

Temperature: **T_k=20–80 K**

Column density: **$N_{CO}=(1–10)10^{16}$ cm^{-2}**

H_2 density: **$n_{H2} > 10^5$ cm^{-3}**

H_2 density is derived from the N_{CO}, blob geometrical thickness and CO abundance (w.r.t H_2)

→ **n_{H2} ~10^7 cm^{-3}**

LTE analysis results:

Integrated flux (^{13}CO and C^{18}O) + kinetic temperature (nLTE results) → Mass

Mass inside the cavity (T_k=40K everywhere): **M_{cavity}~ 1.6 10^{-4} M_{sun}**

Cumulative mass of 6 brighter blobs: **M_{blobs} ~1.2 10^{-5} M_{sun}**

M_{cavity} ~10 **ΣM_{blobs}** → gas in the cavity resides mostly in diffuse.

Accretion rate:

This mass will dissipate/accrete onto the GG Tau Aa disk in ~2500 years (V_{fall}=0.4 km/s)

→ giving the **accretion rate** of **~6.4 10^{-8} M_{sun}/year.**

Consistence with the stellar accretion rate observed by Hartigan & Kenyon (2003) using H_α line.

Phuong et al 2020b

Take home messages

- Grain growth and possible planetesimal can form in young and active protostars.

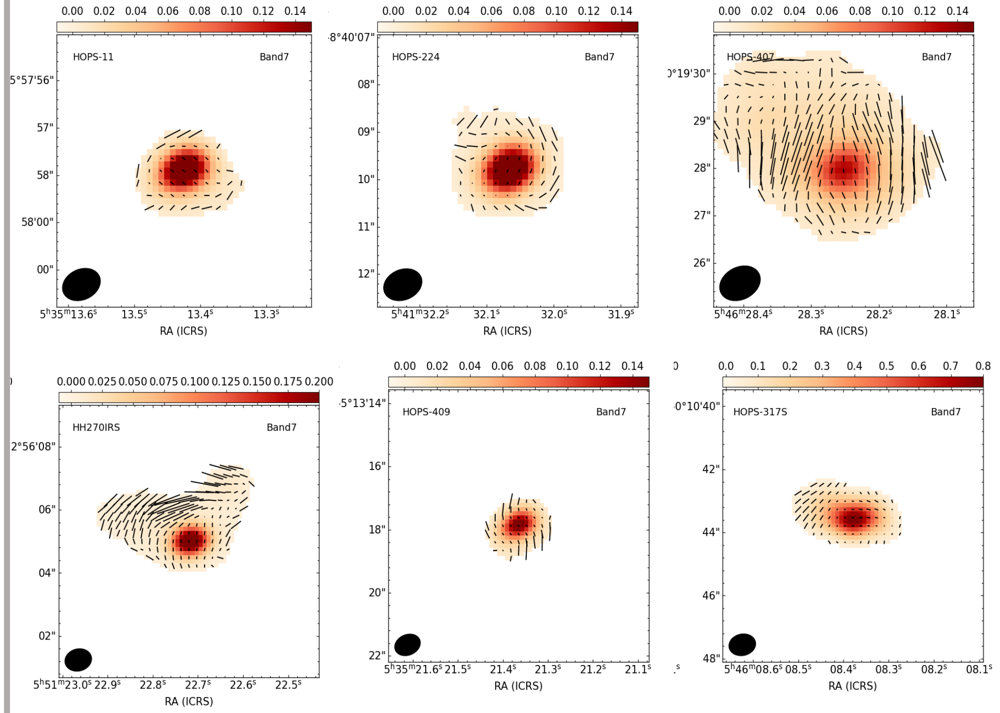
- In the binary system, the gravitational interaction between companions can affect the grain size distribution in the circumstellar disk.

- Planets can form and survive both in circumstellar and circumbinary disks. Once it forms in the circumbinary disk, it shapes the special form of a circumbinary ring due to the confining mechanism.

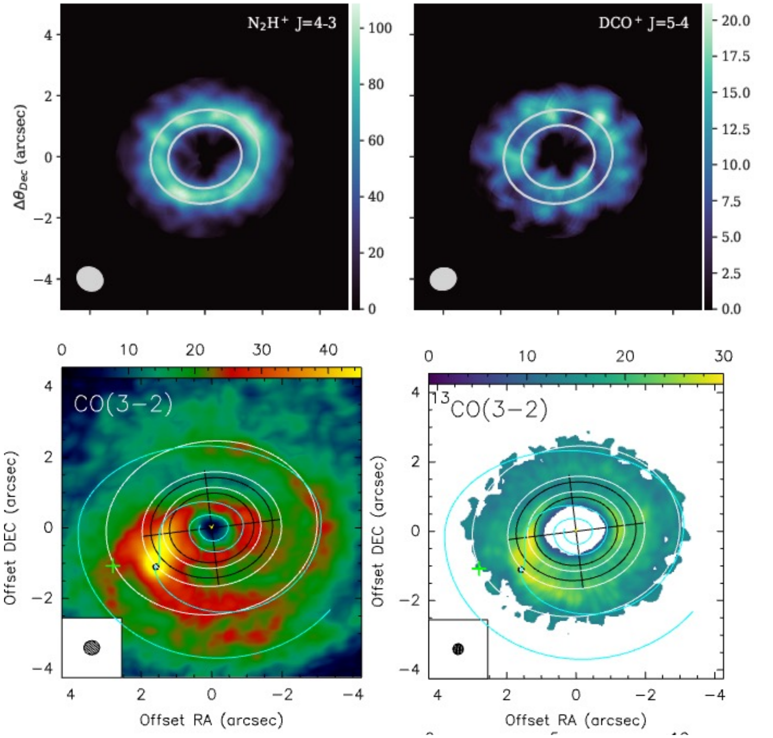
- The accretion rate from the circumbinary disk onto the circumstellar disks is at the levels of the accretion rate from the parent cloud to the single protostar.

Thank you for your attention!

Studying dust properties and B-field in protostars using dust polarization observation (with SAGI members)



Chemical content and kinematics inside the cavity of GG Tau A → condition of S-type planet formation



Numerical simulation for the morphology/kinematics of wide-separation young binary protostar in the scenario of fly-by interaction (*using public code*).

Any students interested in any of these topics are welcome to join!