Zoom In to the Heart of Massive Star Formation

Yichen Zhang

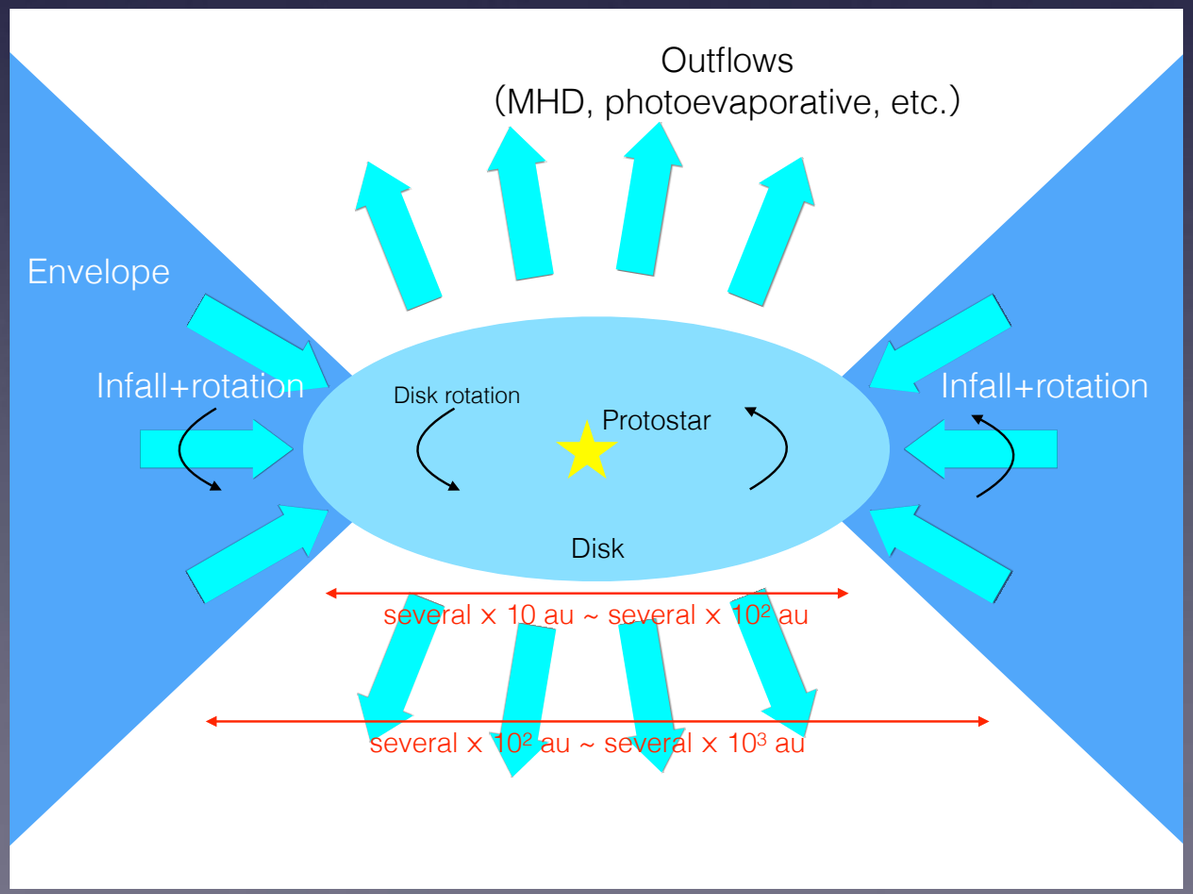
RIKEN

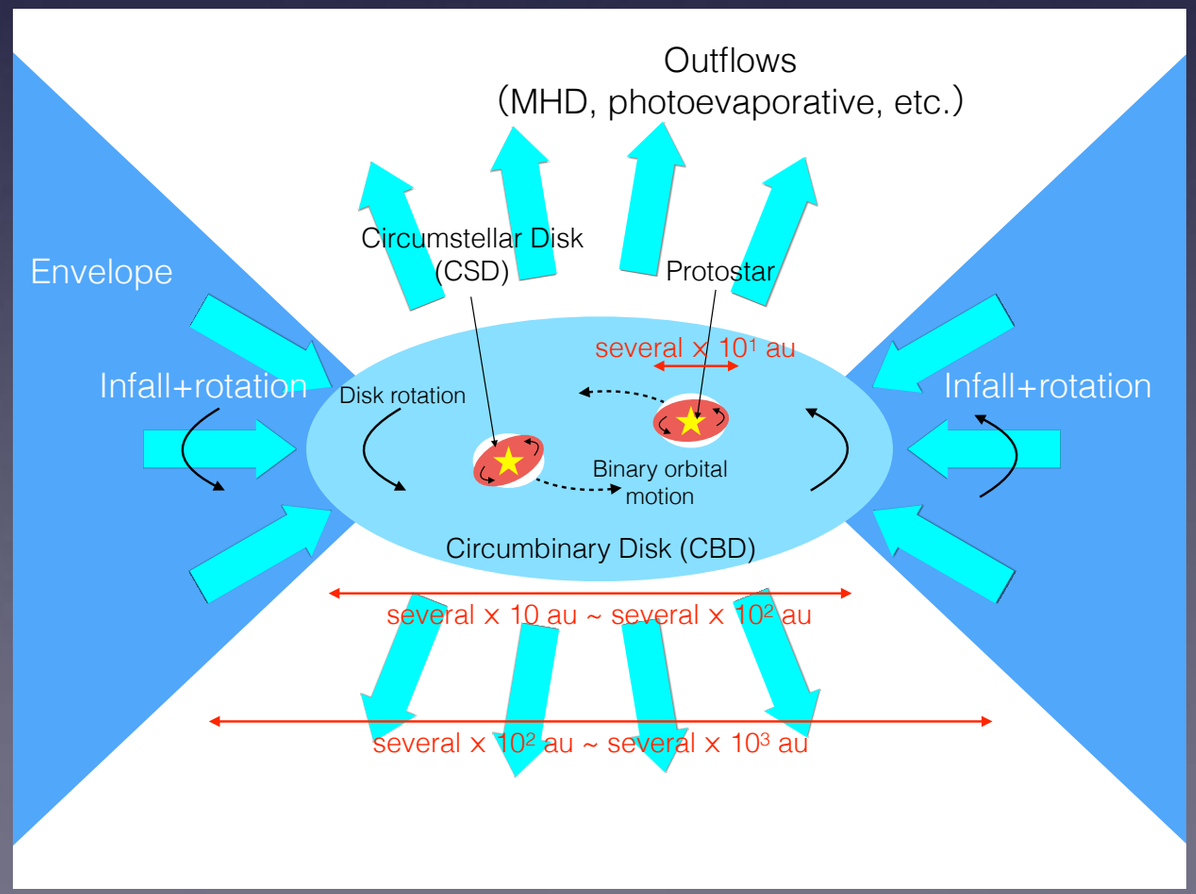
Collaborator:

Kei Tanaka (Osaka U.; NAOJ), **Jonathan Tan** (Chalmers; U. Virginia), **Nami Sakai** (RIKEN), **Viviana Rosero** (NRAO), **James De Buizer** (SOFIA/NASA), **Mengyao Liu** (U. Virginia), **Diego Mardones** (U. Chile), **Maria Beltrán** (INAF), **Kaitlin Kratter** (U. Arizona), **Diego Mardones** (U. Chile), **Guido Garay** (U. Chile)

Massive Star Formation

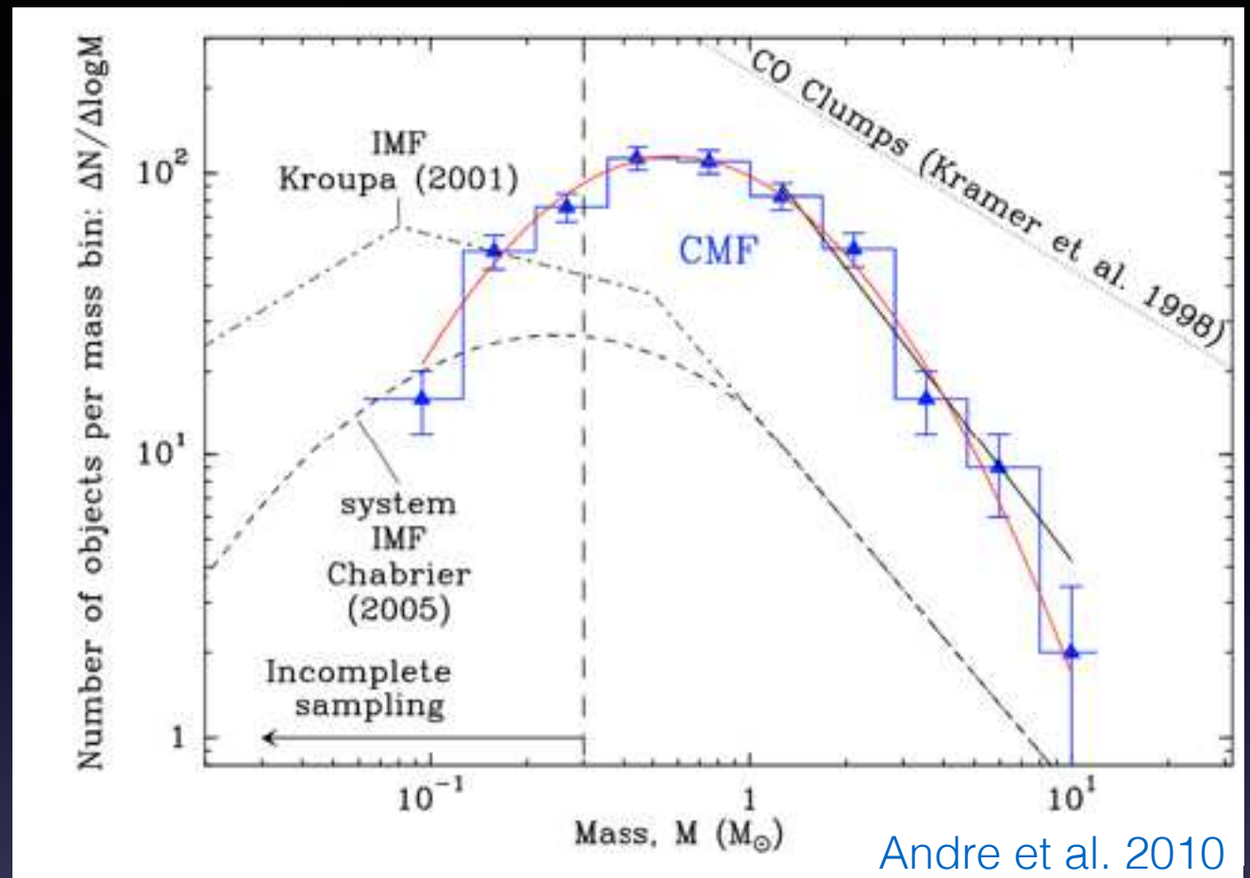
- Understanding massive star formation is important.
- How different from low-mass star formation? Is there a unified picture of star formation?
- Difficulties: highly embedded, distant (resolution, disk, binary), short-lived (smaller sample).
- Observing the innermost regions of massive star formation is crucial to understand accretion and feedback processes.
- Feedback, massive binary formation, searching for rotationally supported disk in massive star formation



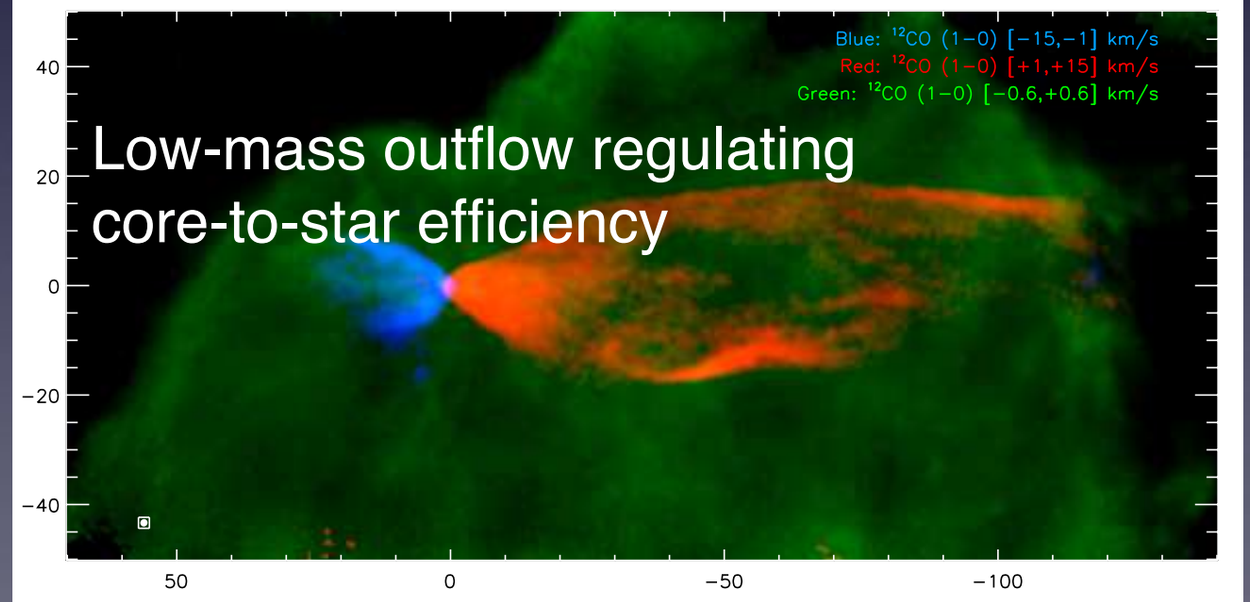


I. Feedback in Massive Star Formation

- What determine the mass of forming star? Initial mass reservoir, feedback regulations
- Feedback: MHD driven outflows (jet, molecular outflows) play a major role in regulating accretion in low-mass star formation.
- Additional feedback (radiation force, photoionization, stellar winds) becomes important in massive star formation.
- Which feedback is more important in regulating the accretion?



Andre et al. 2010



Zhang et al. 2016

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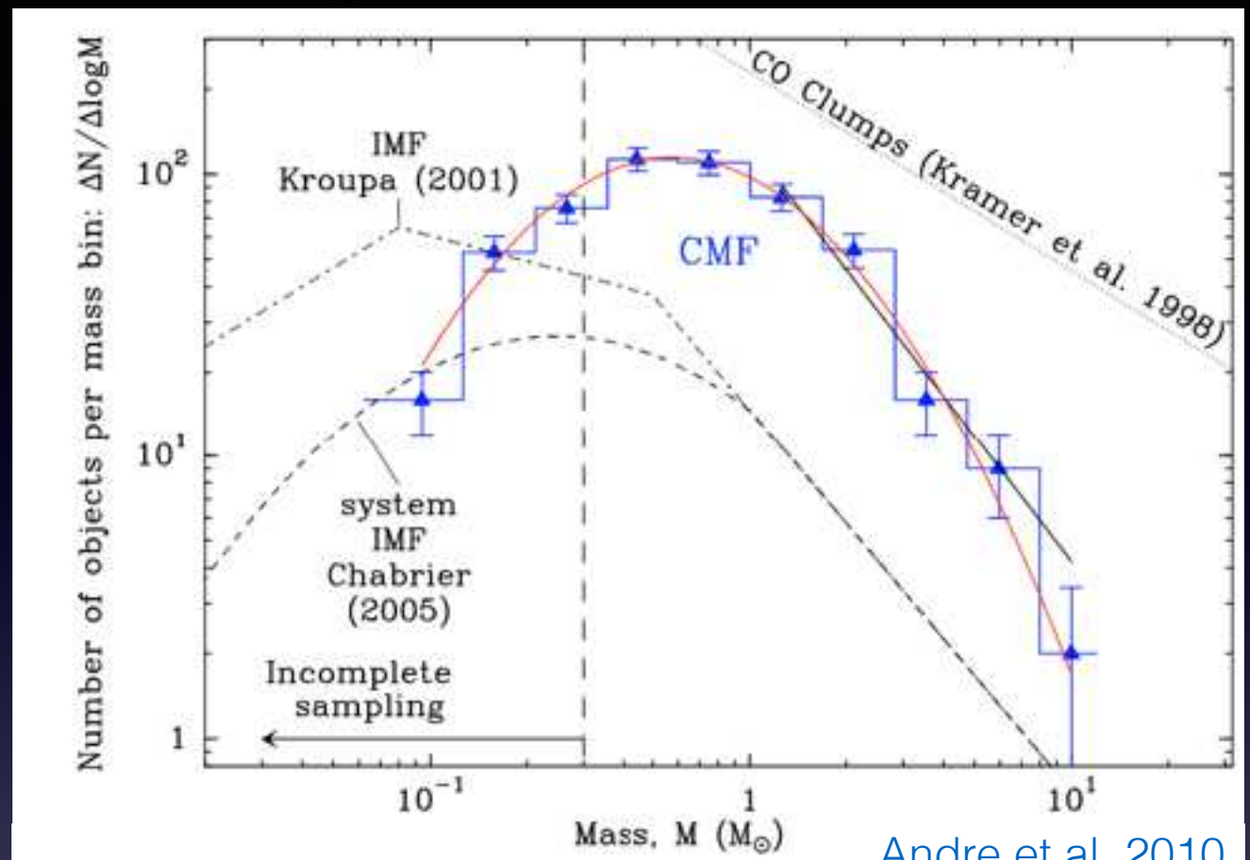
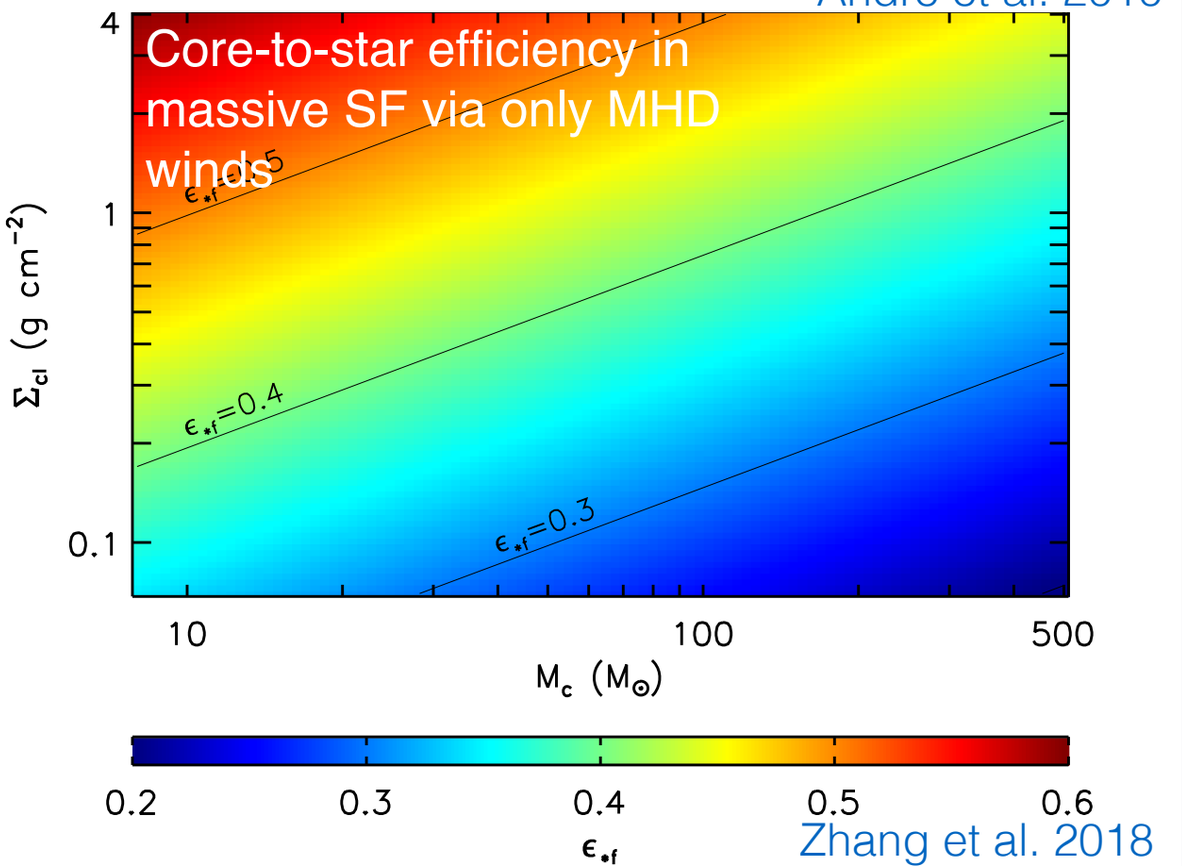


Andre et al. 2010



Zhang et al. 2018

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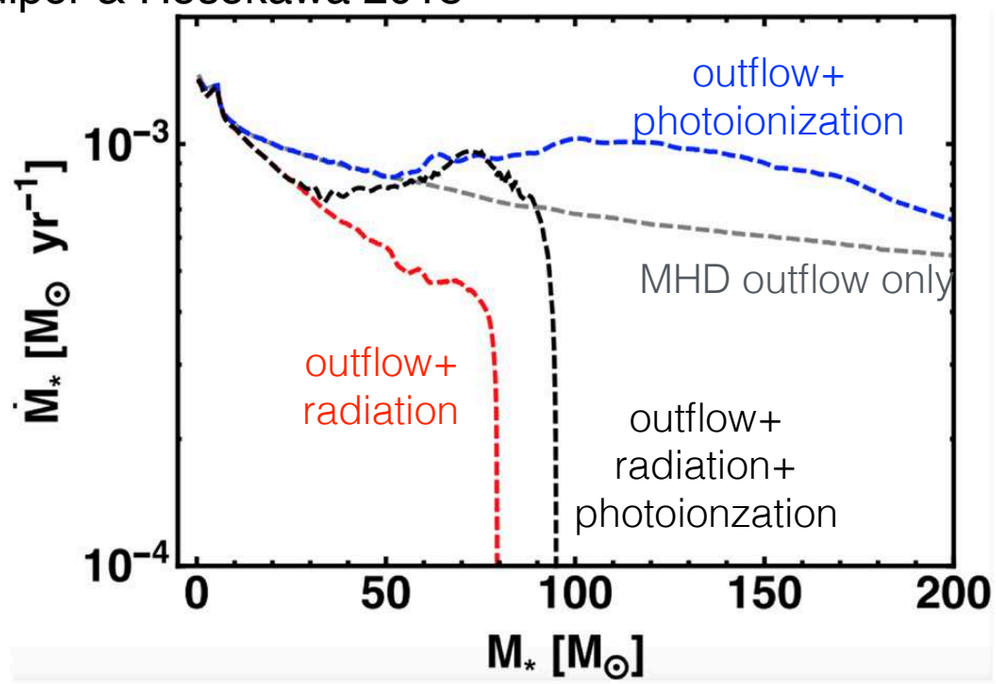
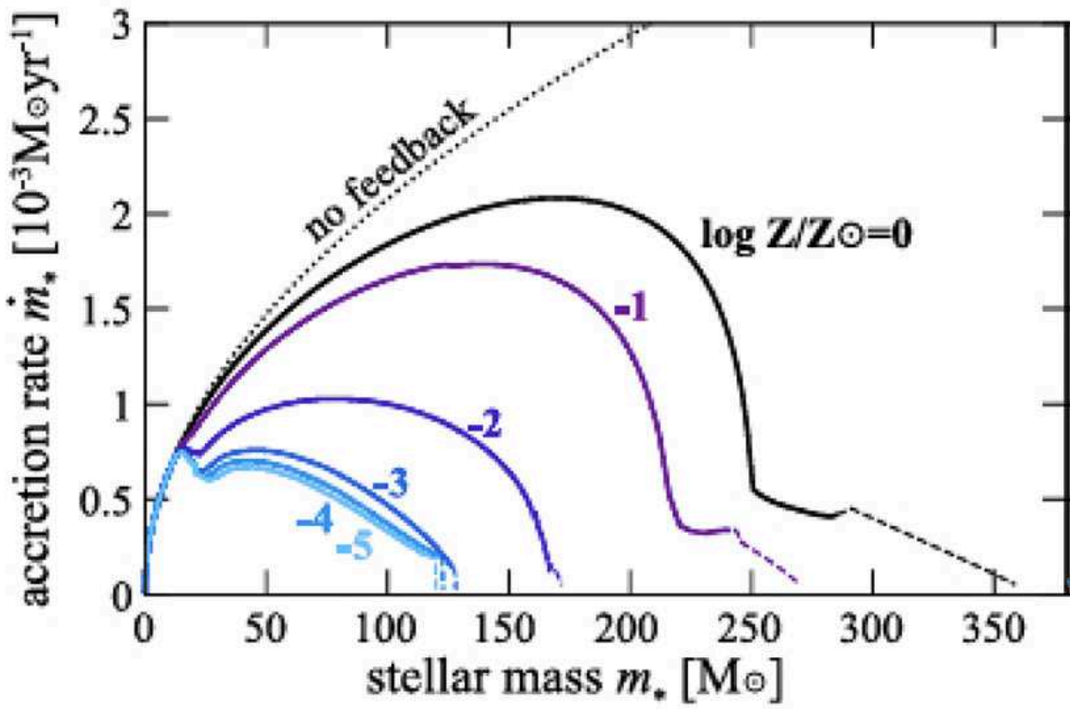
Kuiper & Hosokawa 2018

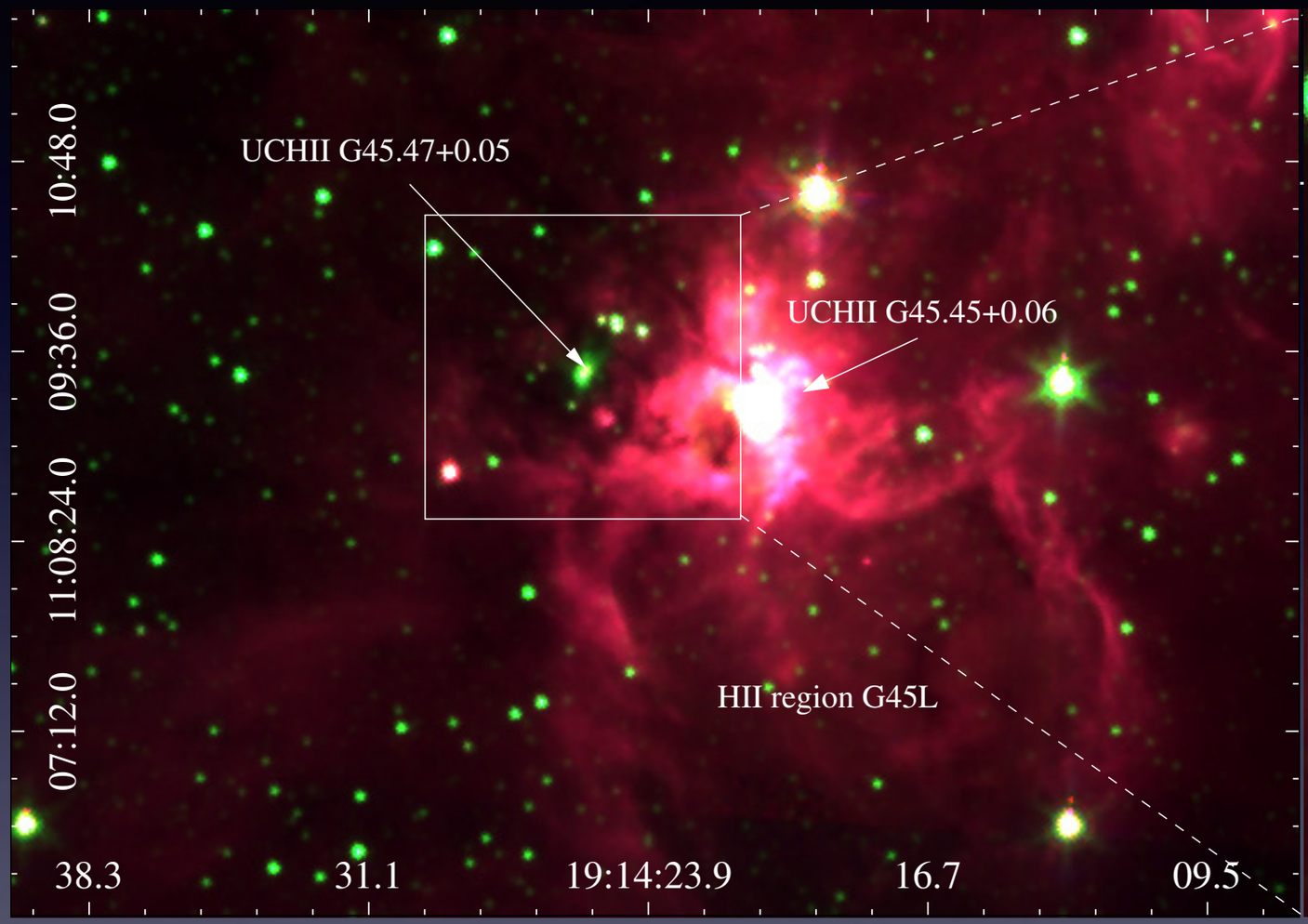


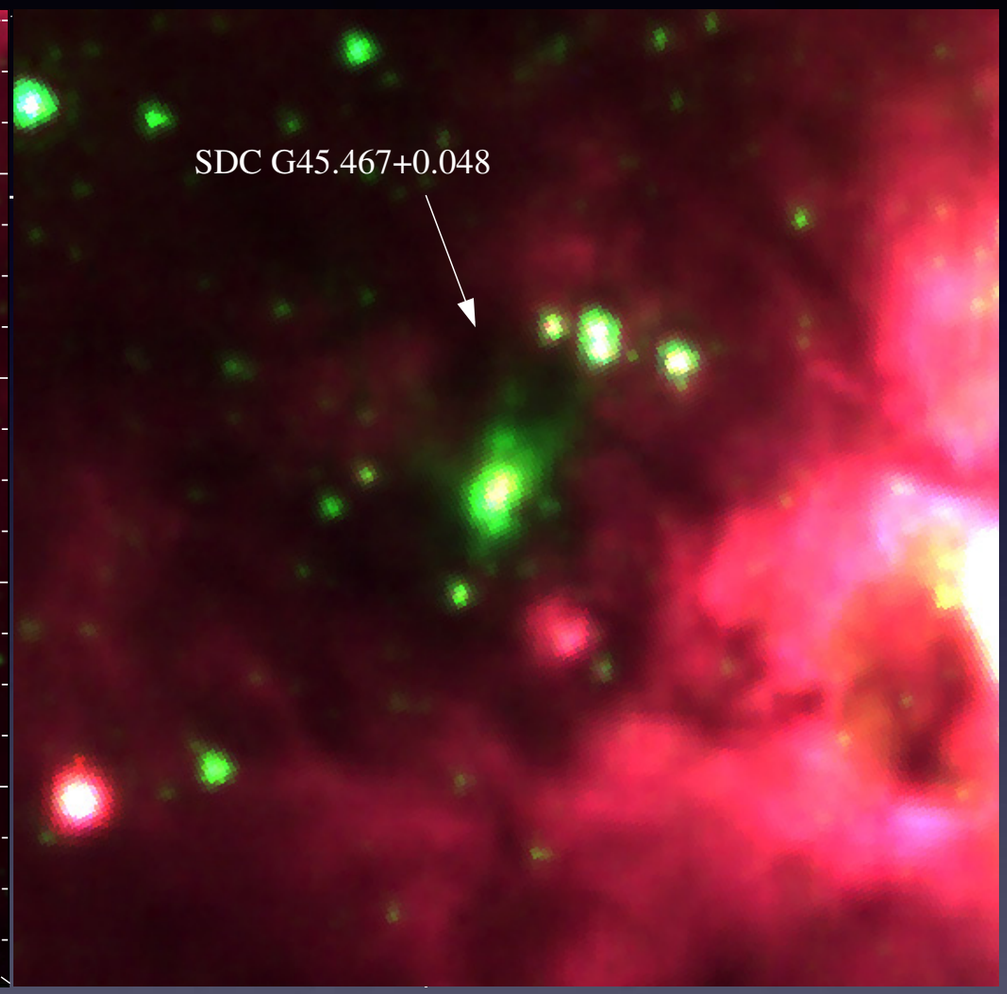
Tanaka et al. 2018



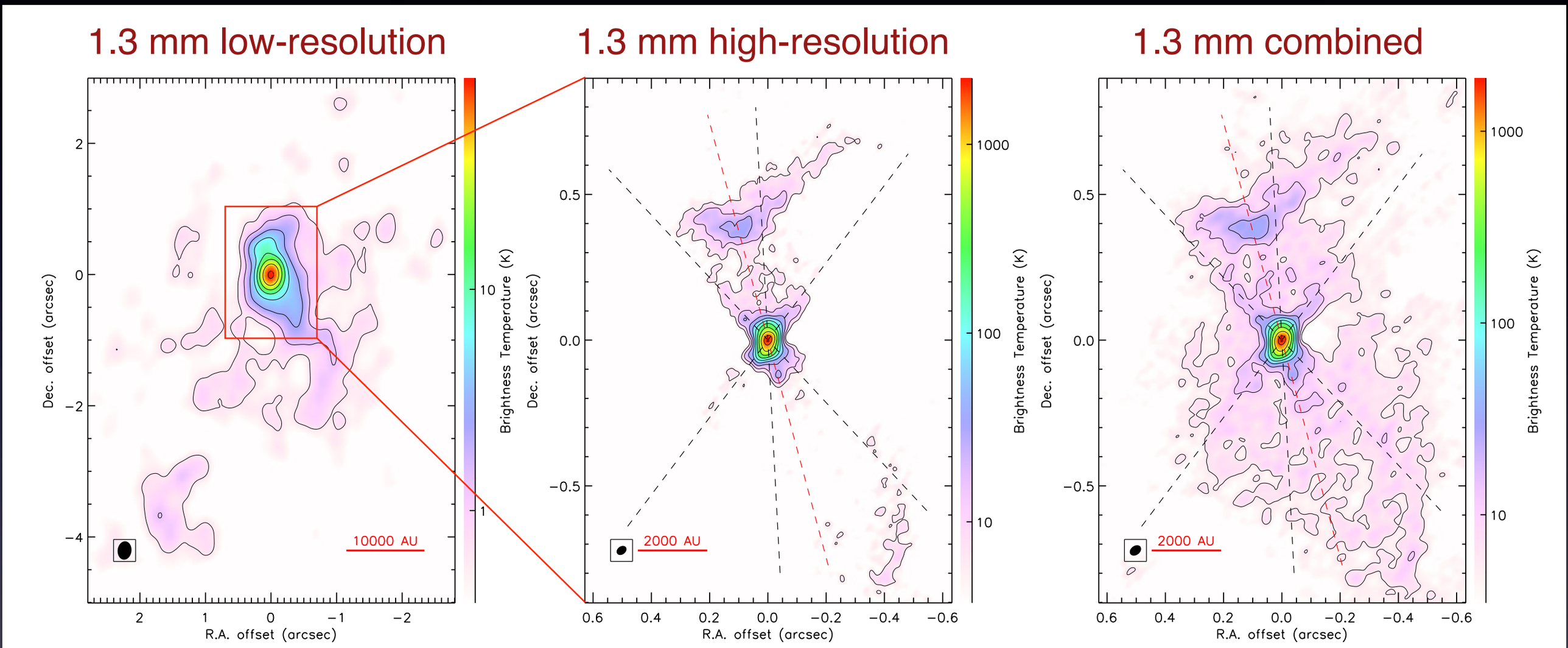
Target: G45.47+0.05

d=8.4 kpc





Continuum emission



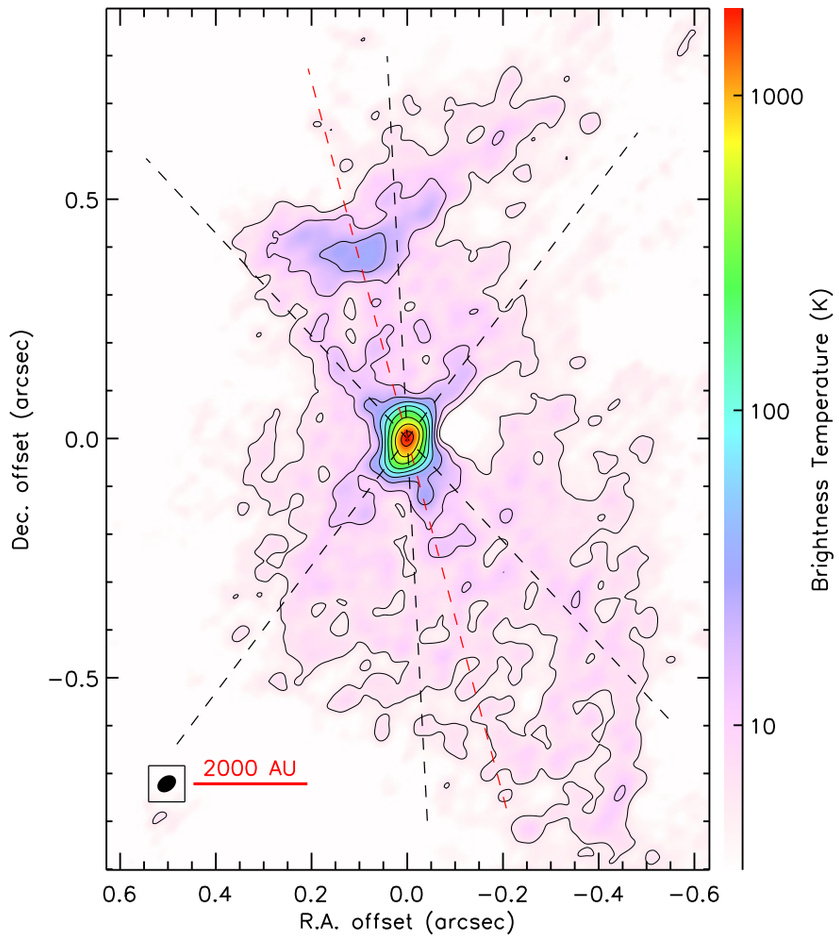
Large-scale dust emission
several ×100 $M_\odot$ in the gas cloud

Compact free-free emission

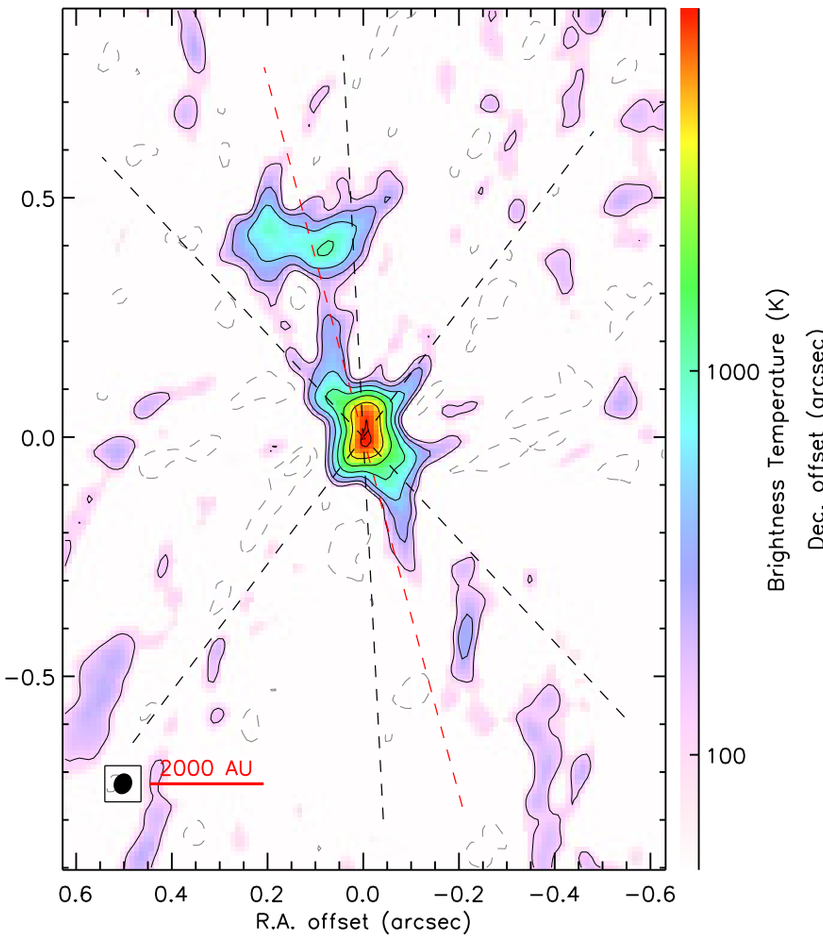
Zhang, Tanaka, Rosero et al. 2019, ApJL, 886, L4

Continuum emission

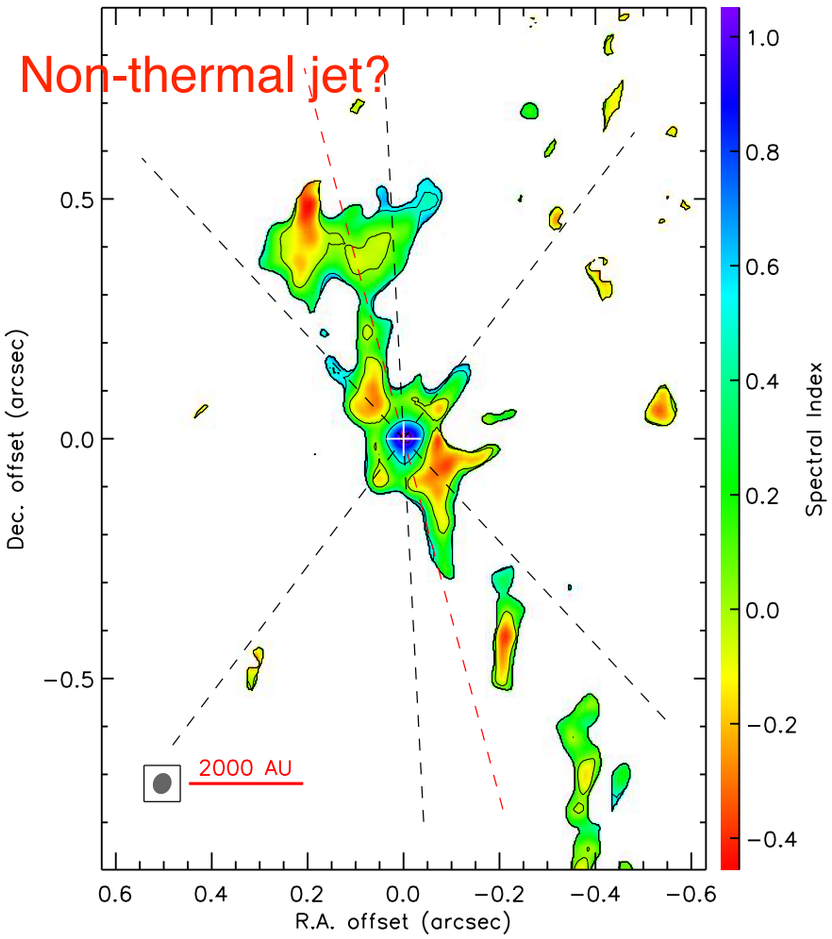
1.3 mm combined



7 mm continuum



Spectral index map



α>2: dust
0<α<2: partially optically thick free-free
α~0: optically thin free-free
α<0: non-thermal synchrotron emission

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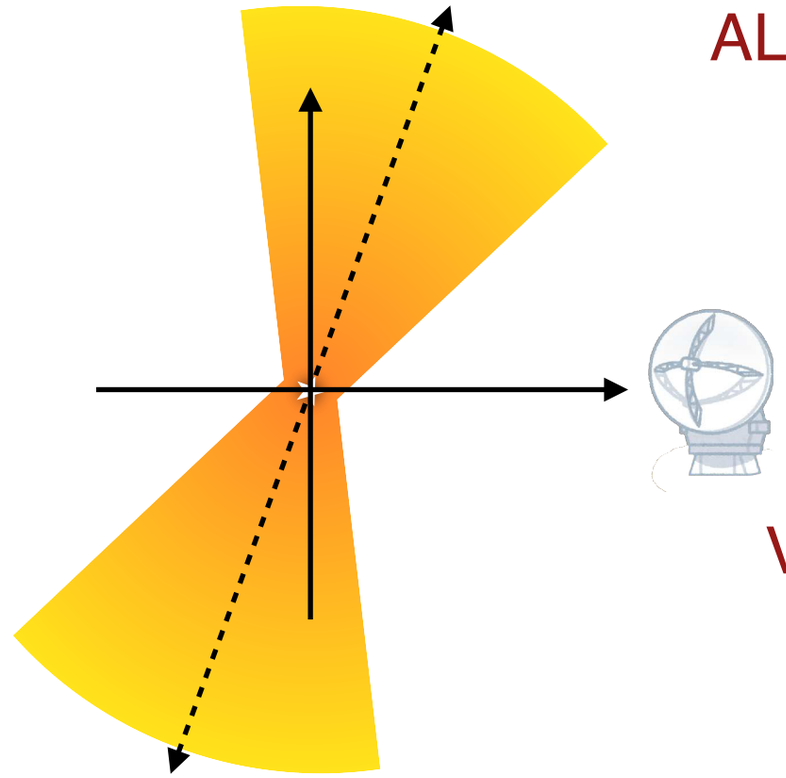
Continuum model

Free-free Model



EUV photon rate ~ 2×10^{49} s^{-1}
→ M*~ 50 $M_\odot$ (ZAMS) or 30~50 $M_\odot$ (protostars)

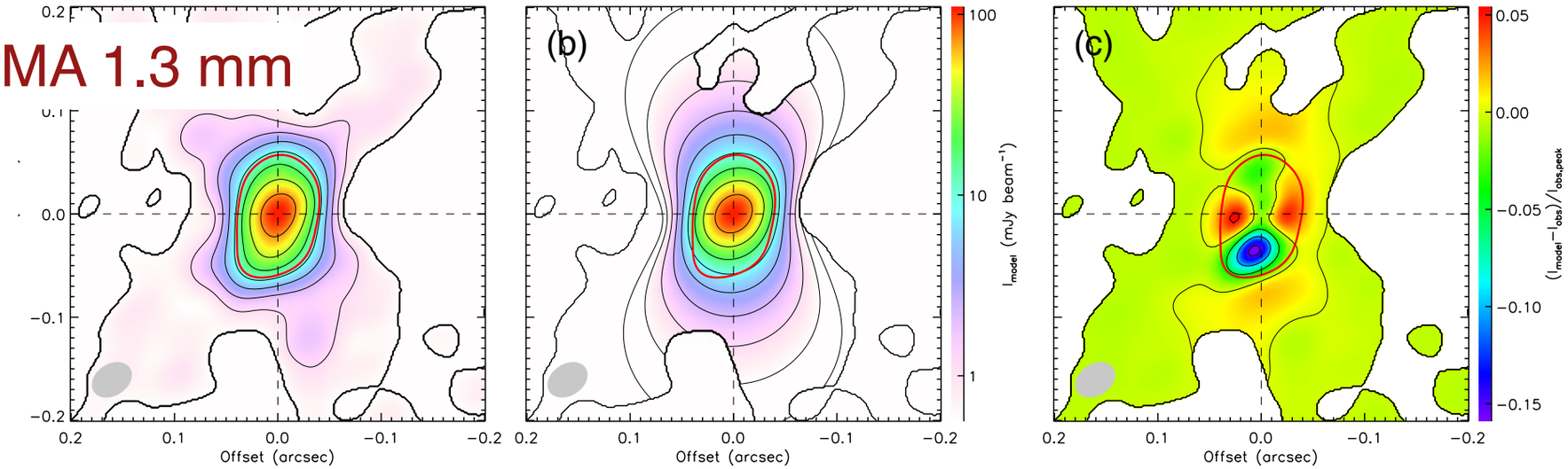
Flow rate ~ 2×10^{-5} $M_\odot$ yr^{-1}
→ consistent with photoevaparative outflow
→ strong ionizing feedback from the massive forming star

Observation

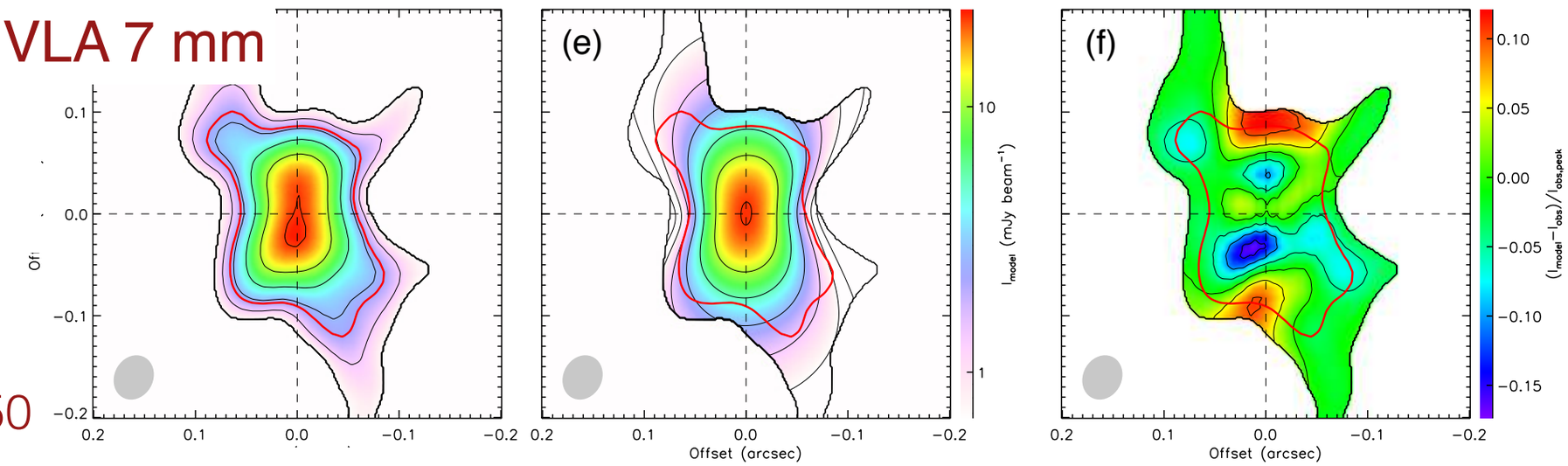
Model

Residual

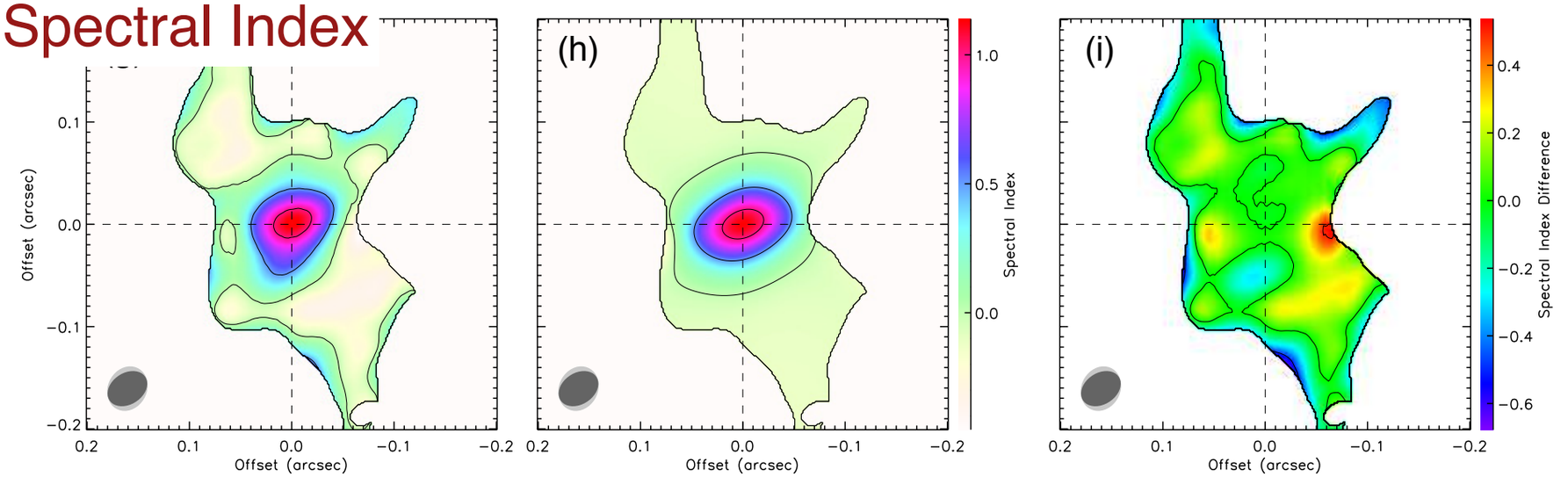
ALMA 1.3 mm



VLA 7 mm

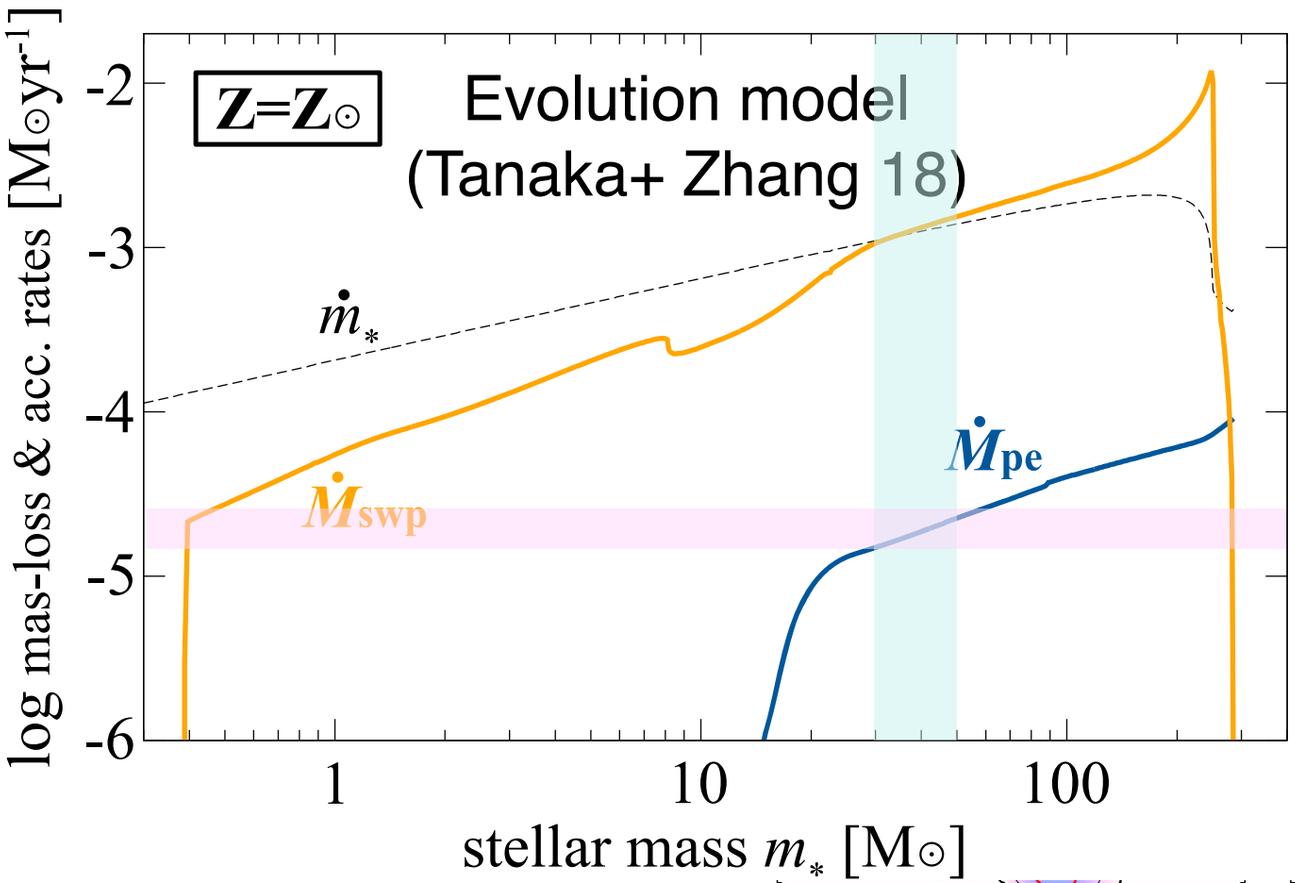


Spectral Index



Continuum model

Free-free Model



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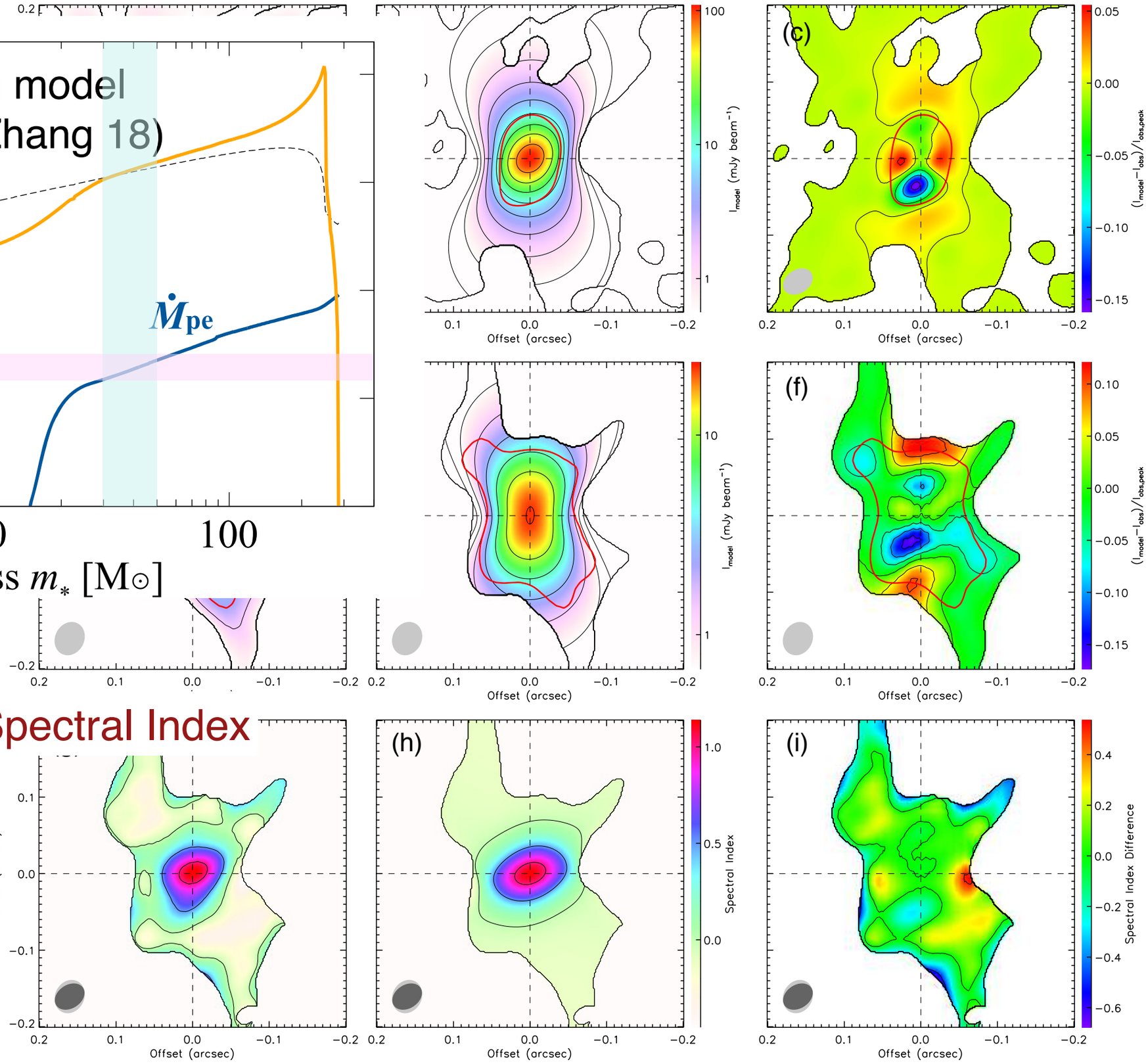

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Continuum model

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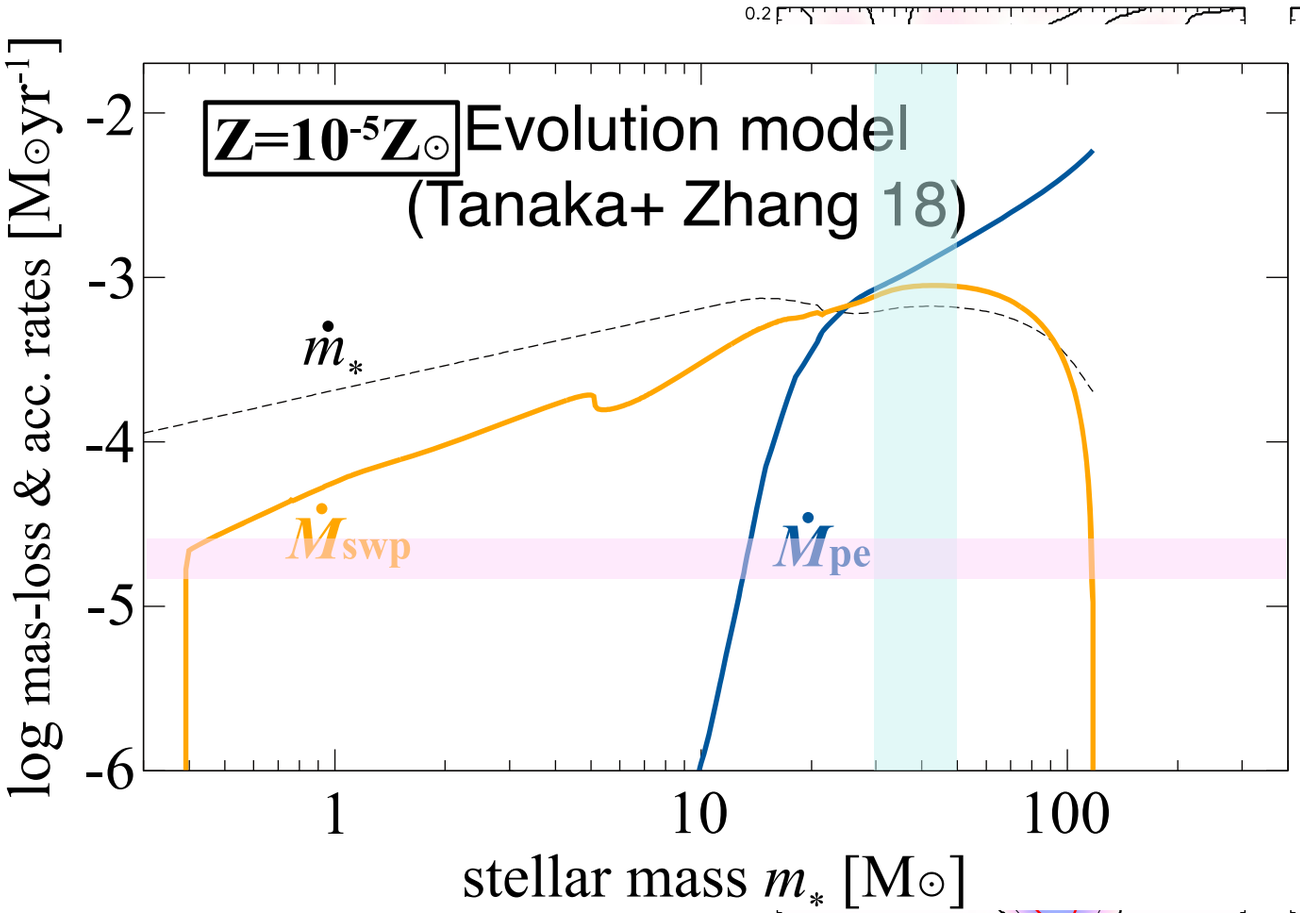

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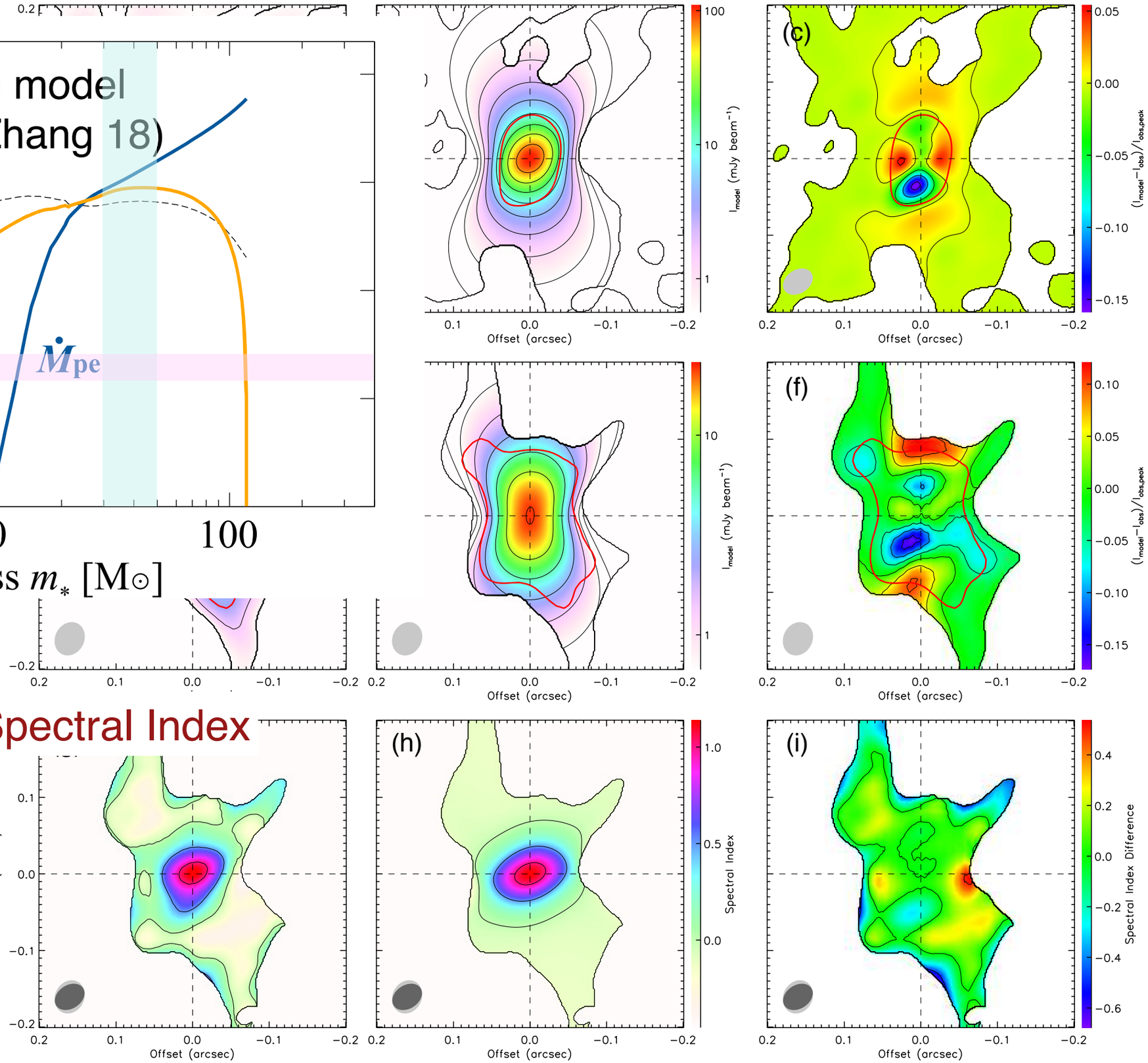
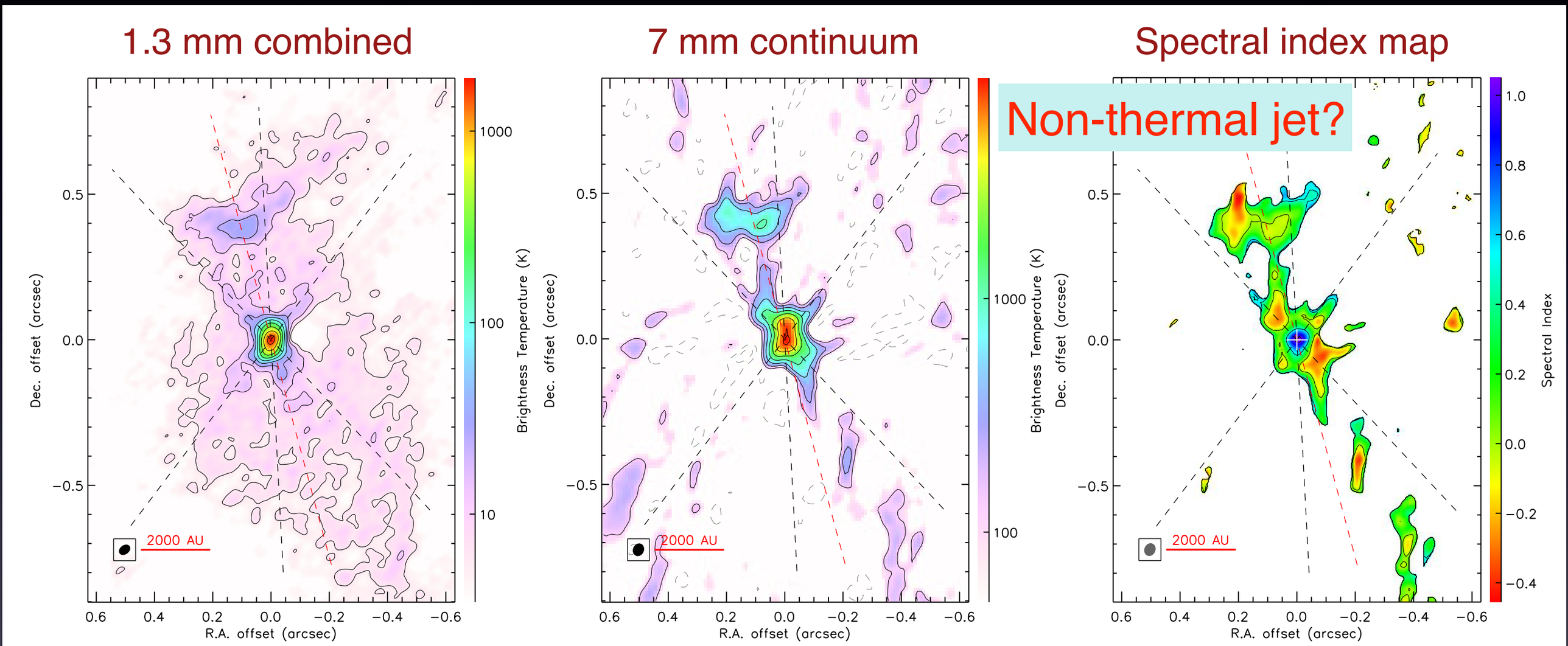


Still accreting despite strong ionization feedback?



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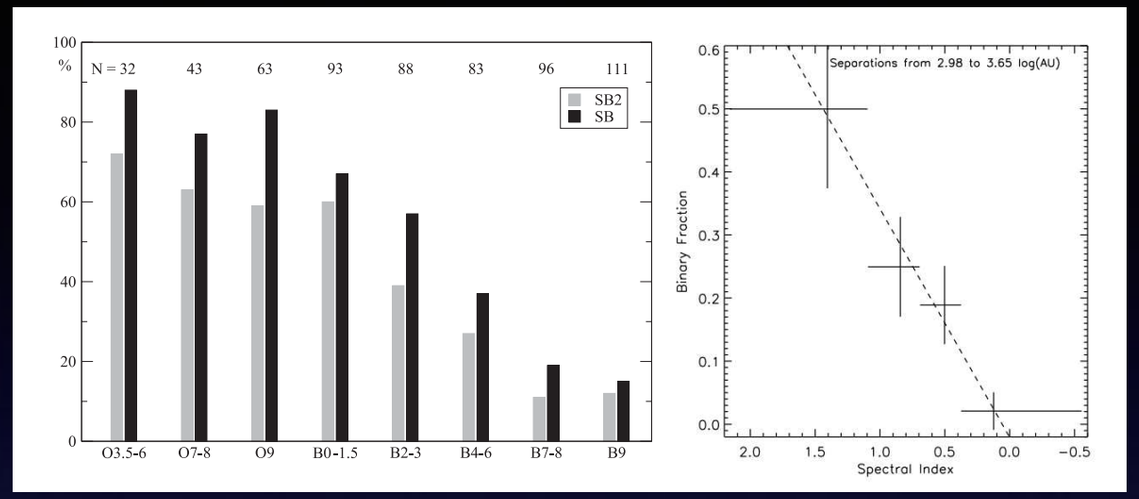
Zhang, Tanaka, Rosero et al. 2019, ApJL, 886, L4

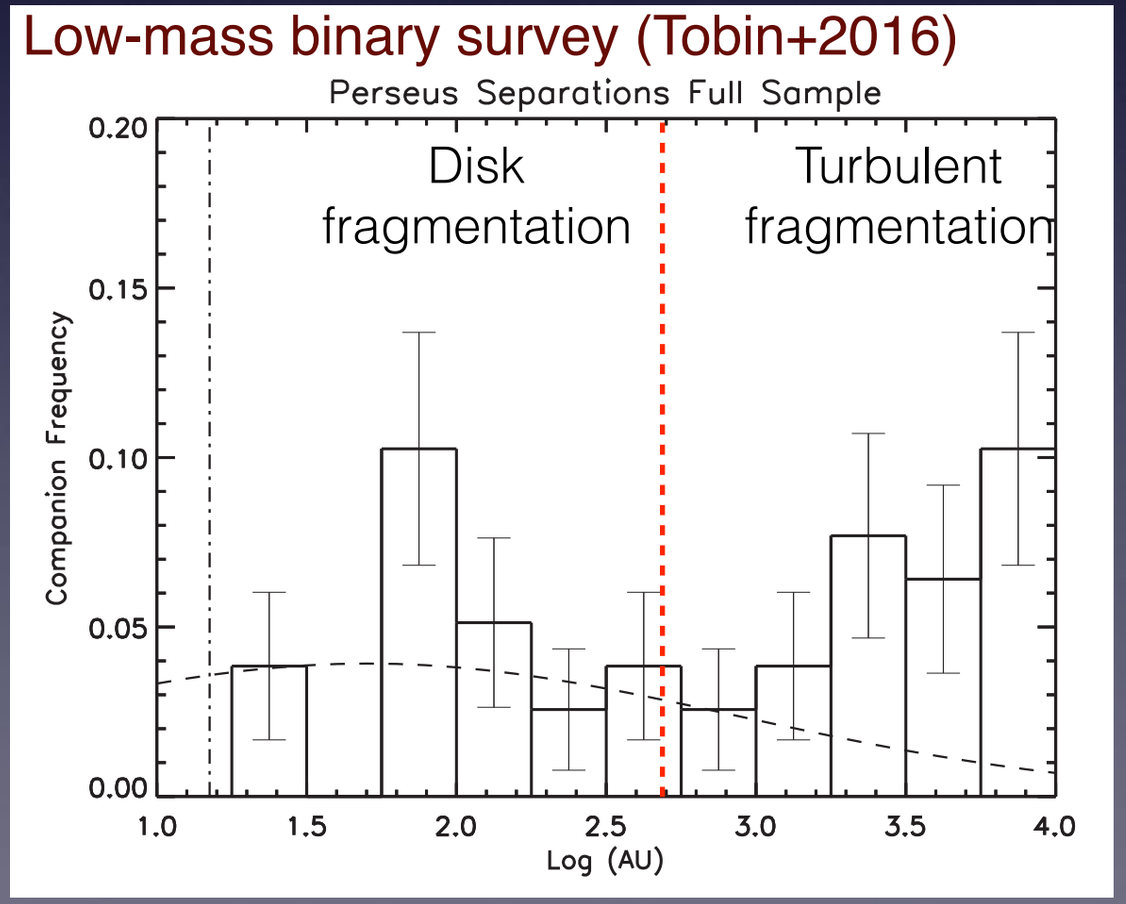
II. Massive Binary Formation

- Binary formation is the primary mode of (massive) star formation.

- Disk fragmentation (e.g. Bonnell & Bate 1994; Kratter et al. 2010)
  - Fragmentation of a disk around the primary protostar
  - Form close binaries (<500 au)
  - Massive disks are expected in Core Accretion scenario of massive star formation (scaled-up version of low-mass star formation)

- Turbulent fragmentation (e.g. Padoan & Nordlund 2002; Offner et al. 2010)
  - Fragmentation of the star-forming core/clumps
  - Form wide (<500 au) and close binaries
  - Naturally expected in the Competitive Accretion scenario of





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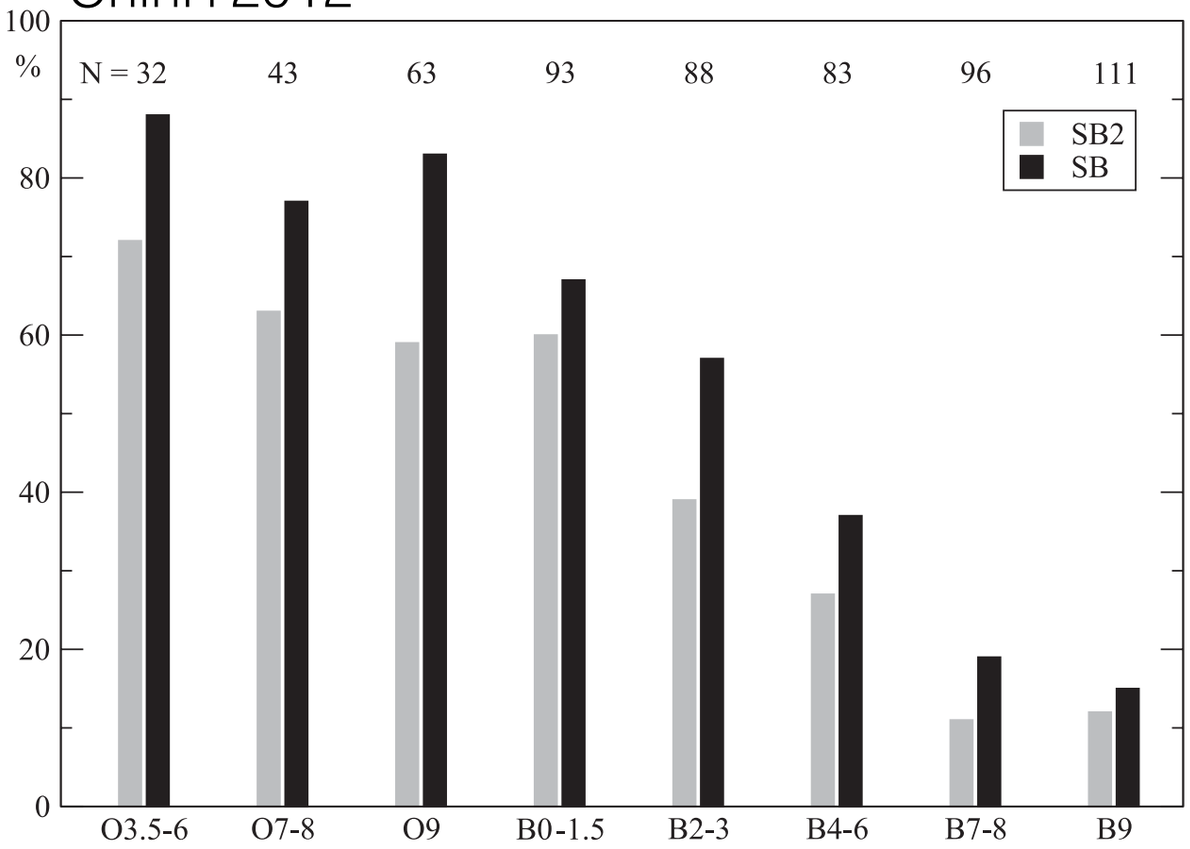
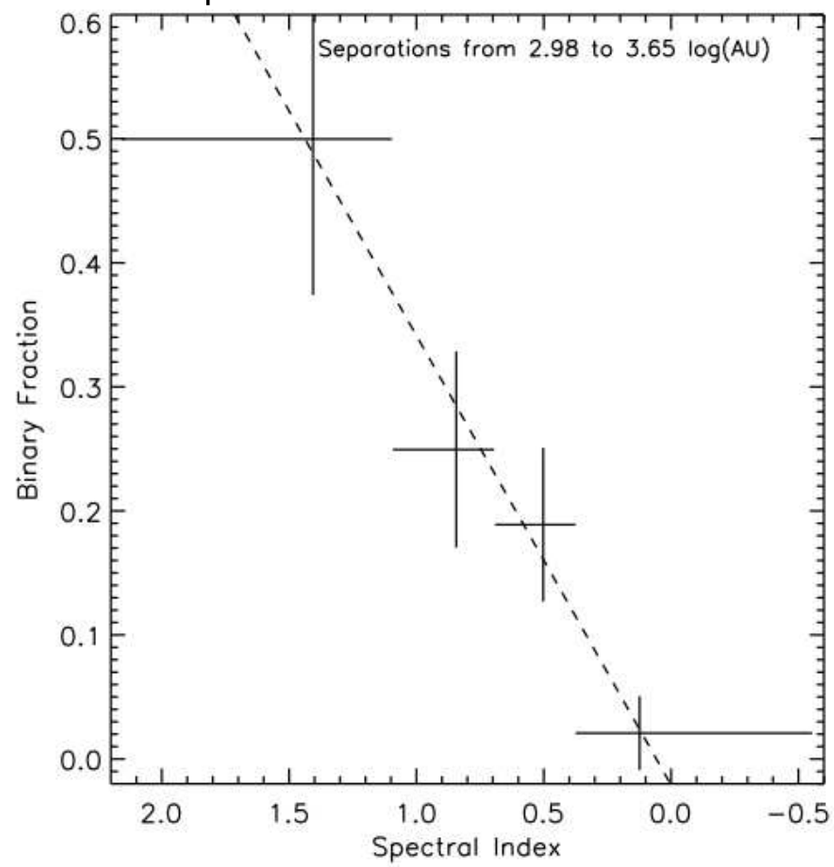
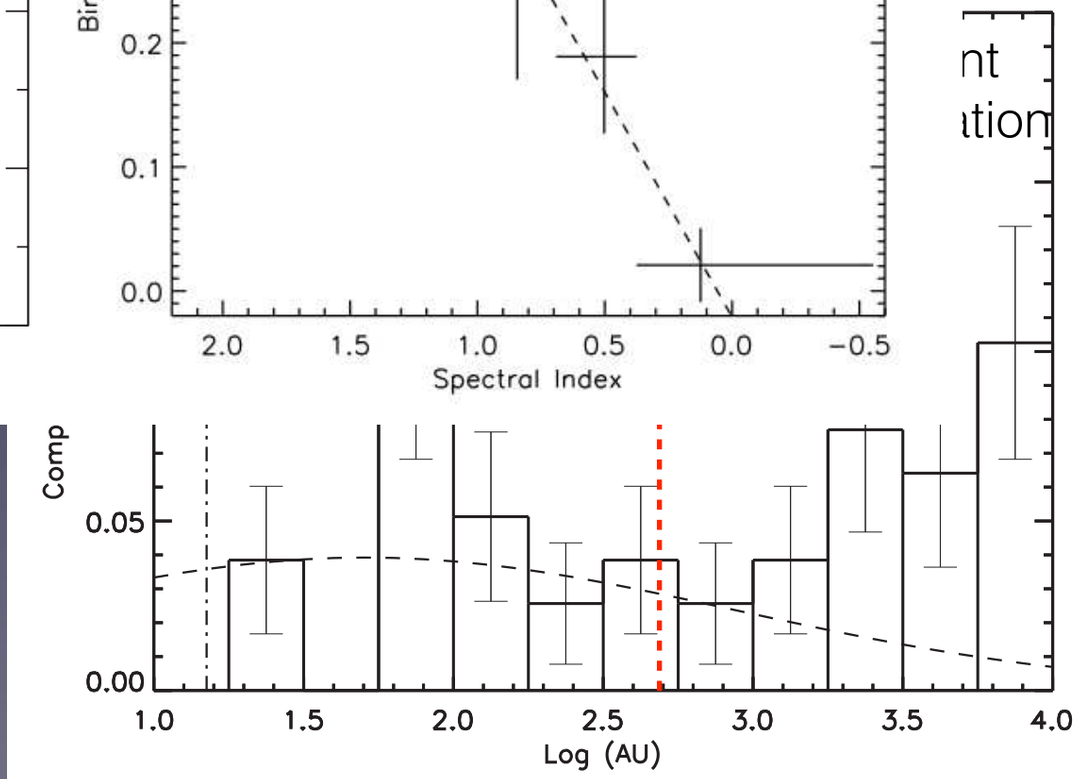
Chini+2012



Reipurth+2014





core/clumps

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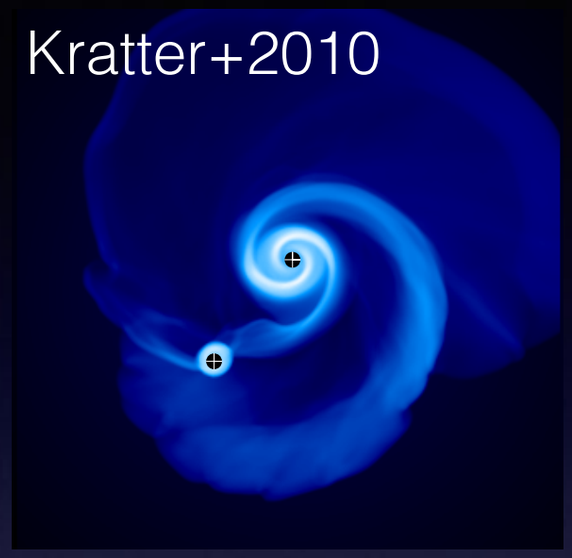
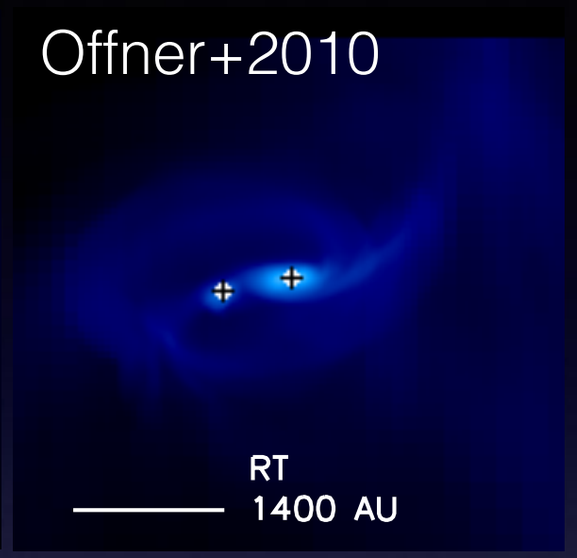
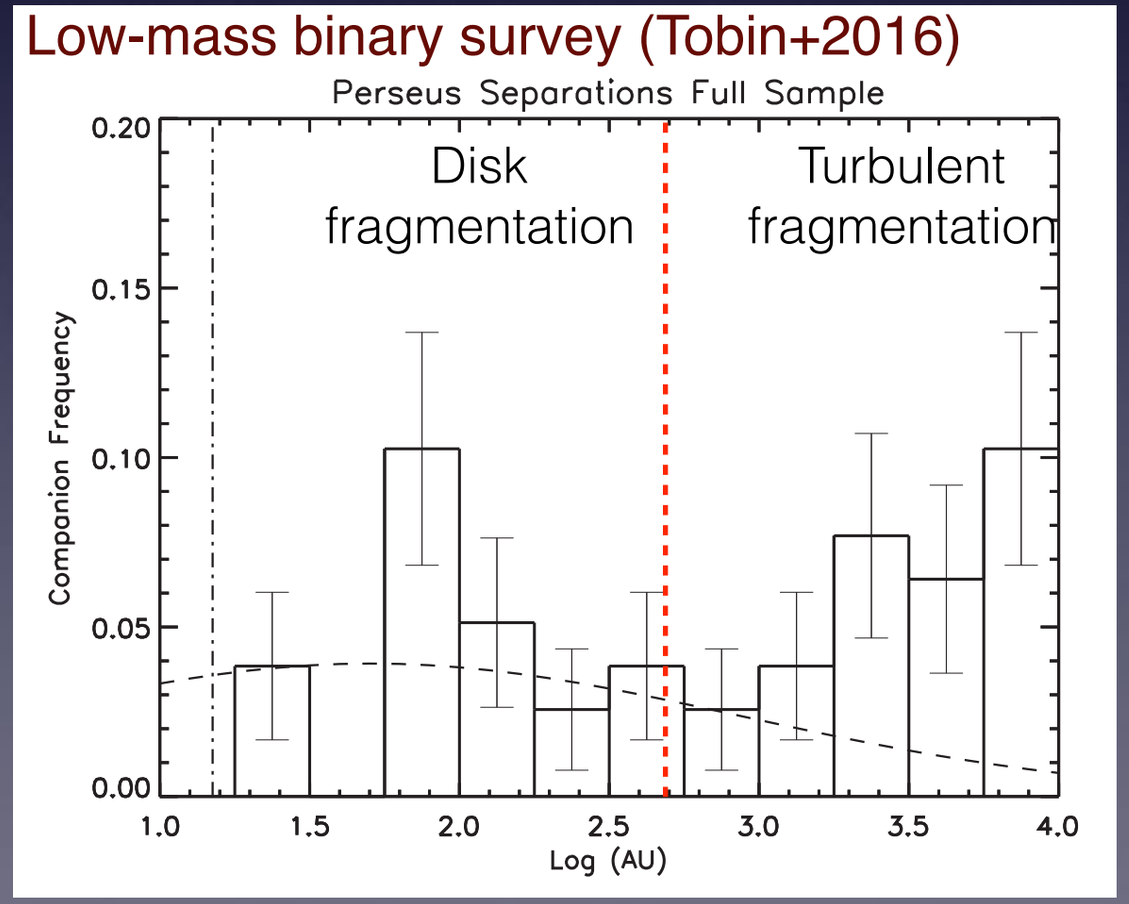
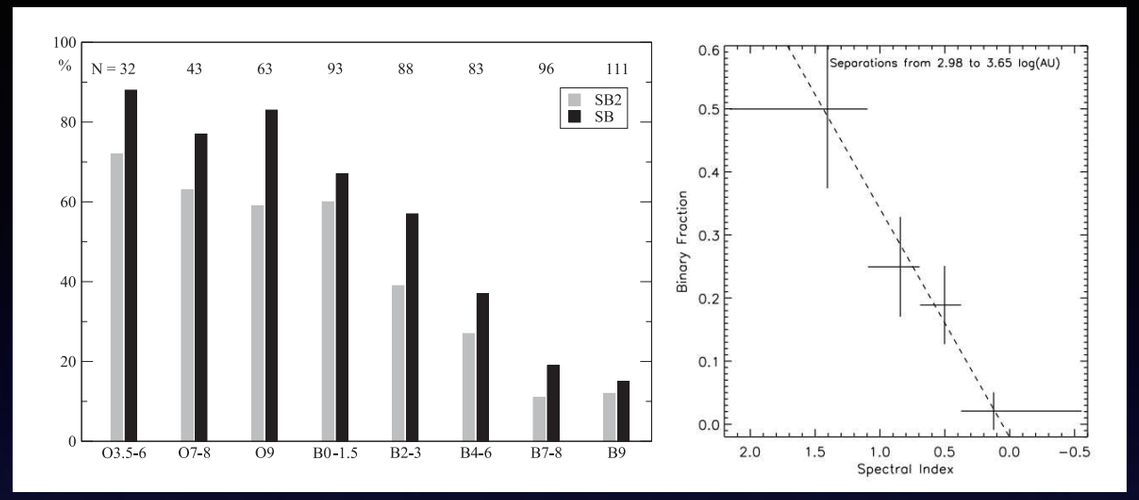




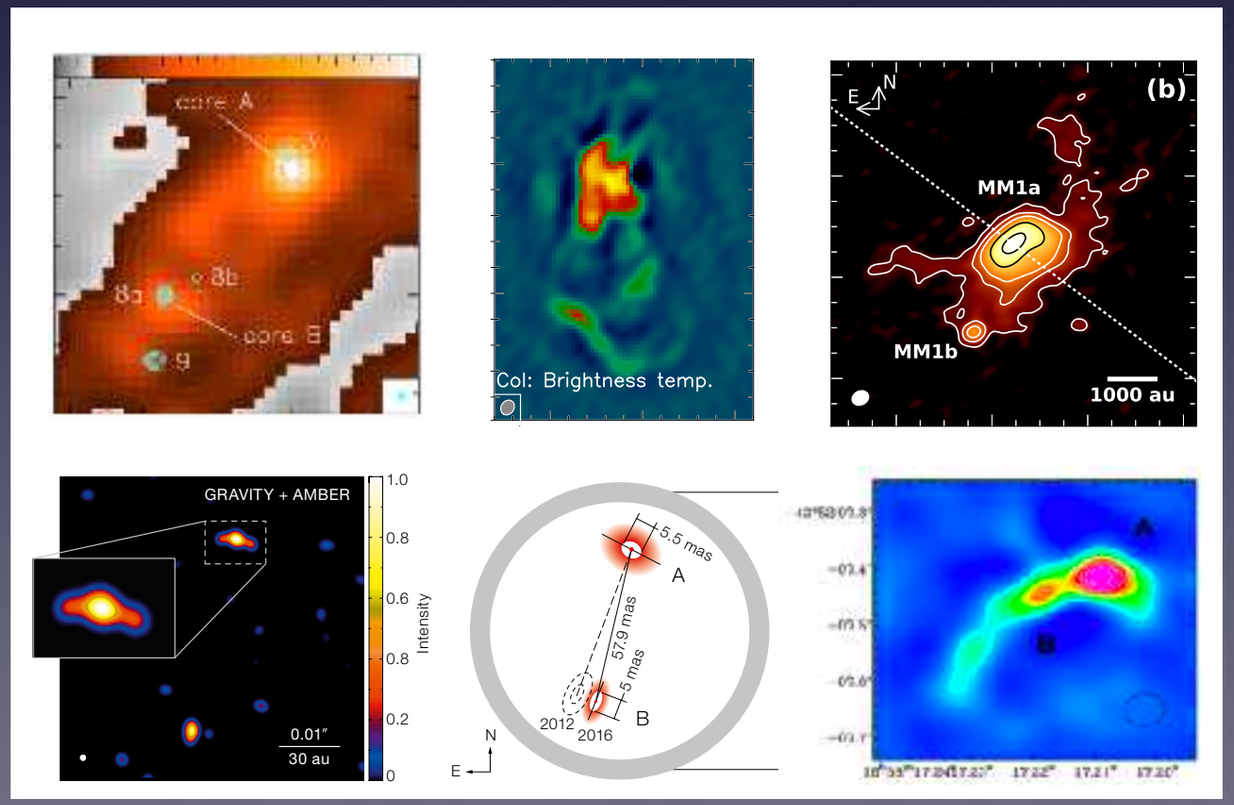


II. Massive Binary Formation

- Most knowledge about massive binaries are from formed stars. Their orbital properties may have changed since their birth. To understand formation of binaries, we need study binaries still in formation.



- So far, massive protobinary systems are still rare, and only the position information is obtained (no binary kinematics for systems still in formation).



II. Massive Binary Formation

- Mo
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- So
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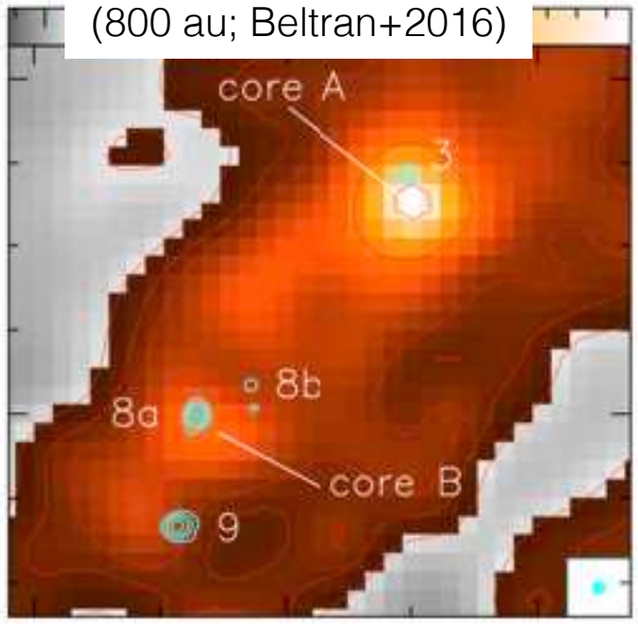
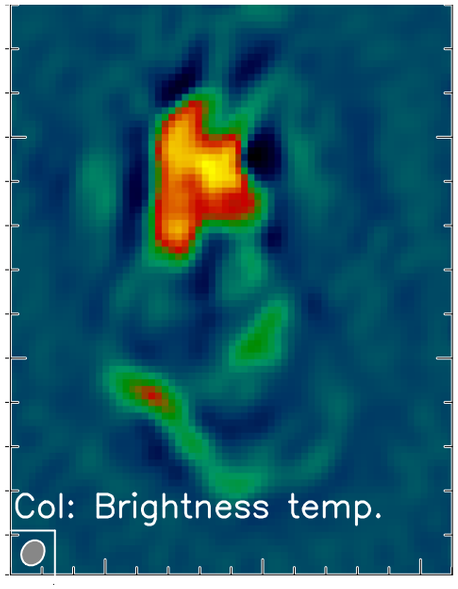
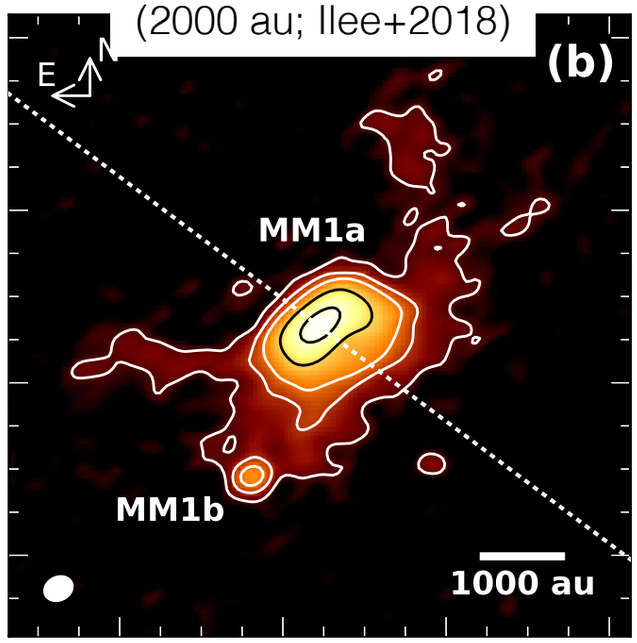
G35.2-0.74
(800 au; Beltran+2016)

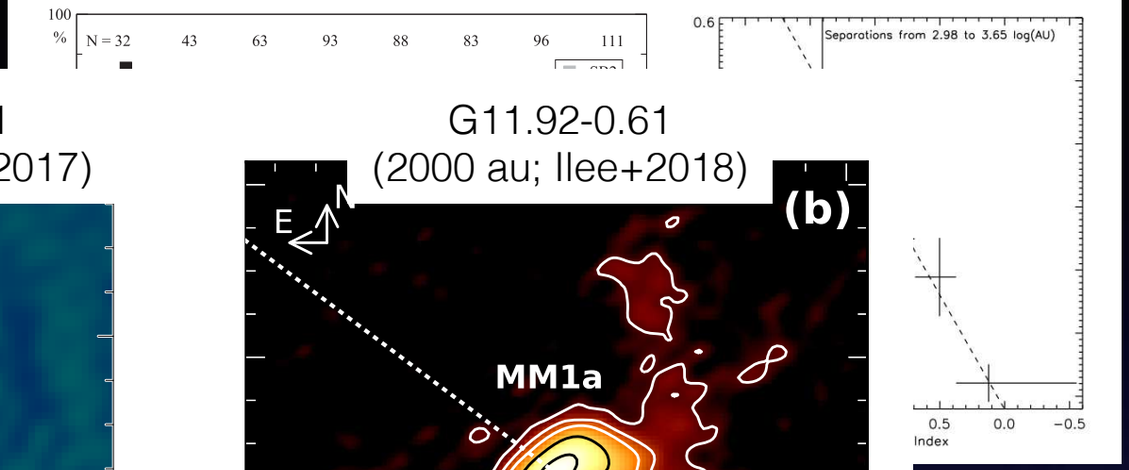


NGC7538IRS1
(430 au; Beuther+2017)

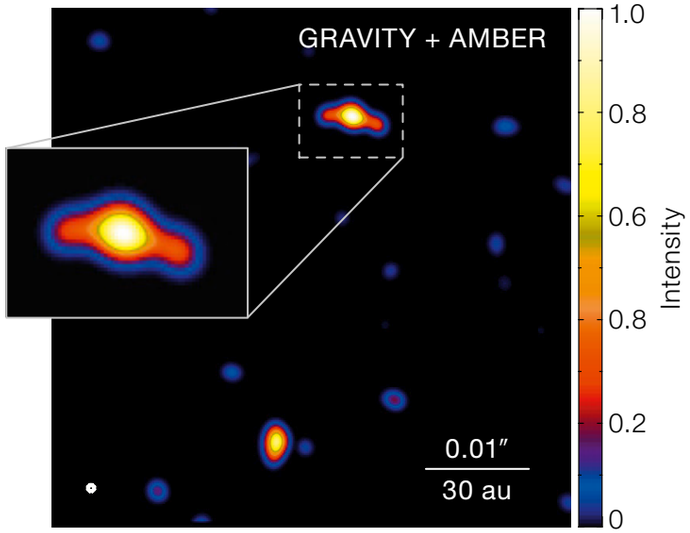


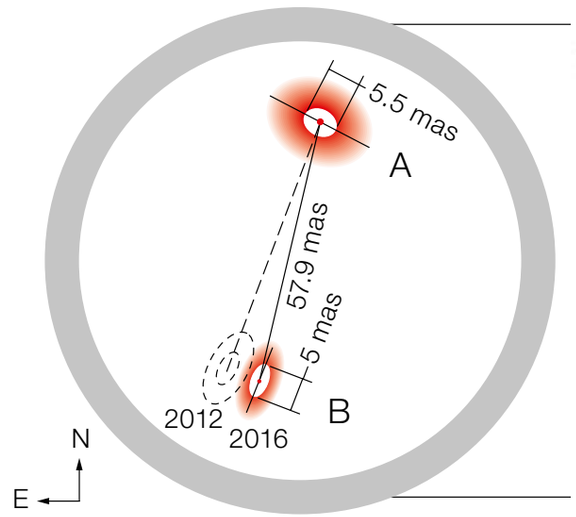
G11.92-0.61
(2000 au; Ilee+2018)



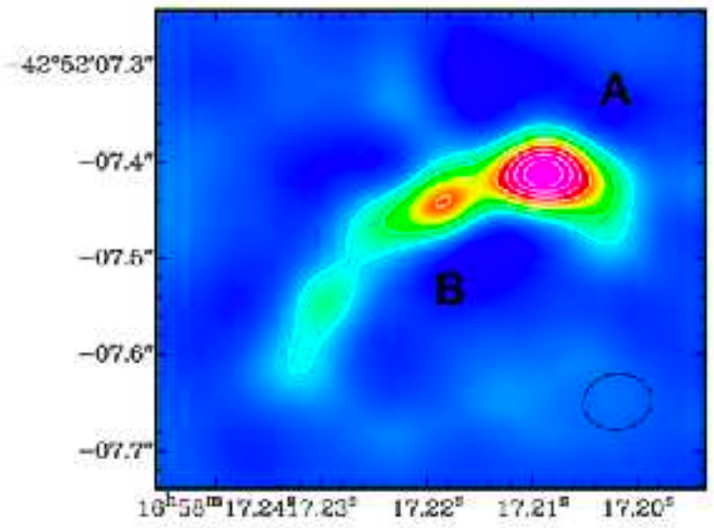


IRAS 17216-3801 (170 au; Kraus+2017)



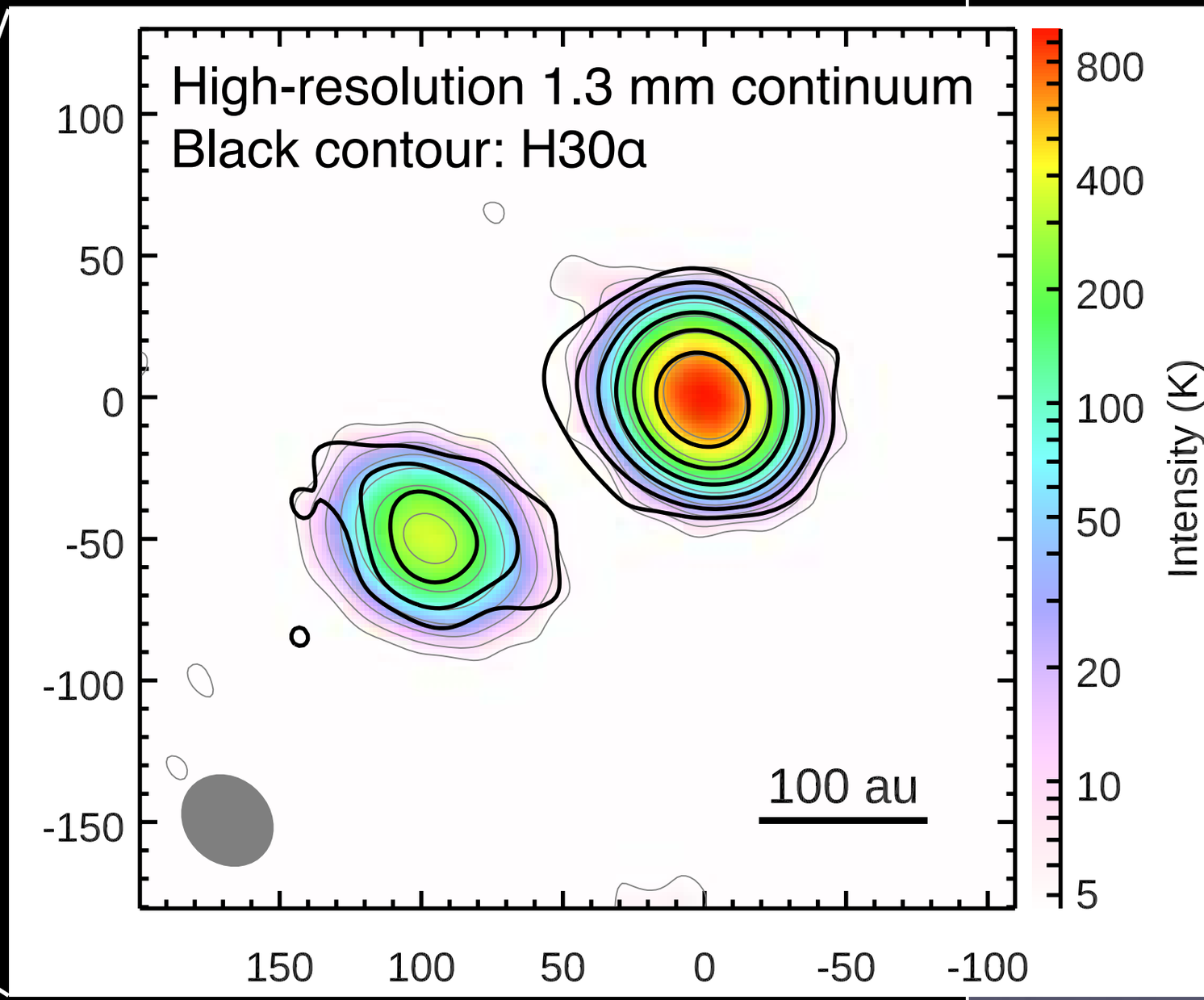


IRAS16547-4247 (300 au; Zapata+2019)



ALMA View of IRAS 07299-1651 d=1.68 kpc

Low-resolution
1.3 mm continuum



2,000 au

0 2 4 6 8
Intensity (K)

Zhang, Tan, Tanaka et al. 2019, Nature Astronomy, 3, 517

ALMA View of IRAS 07299-1651

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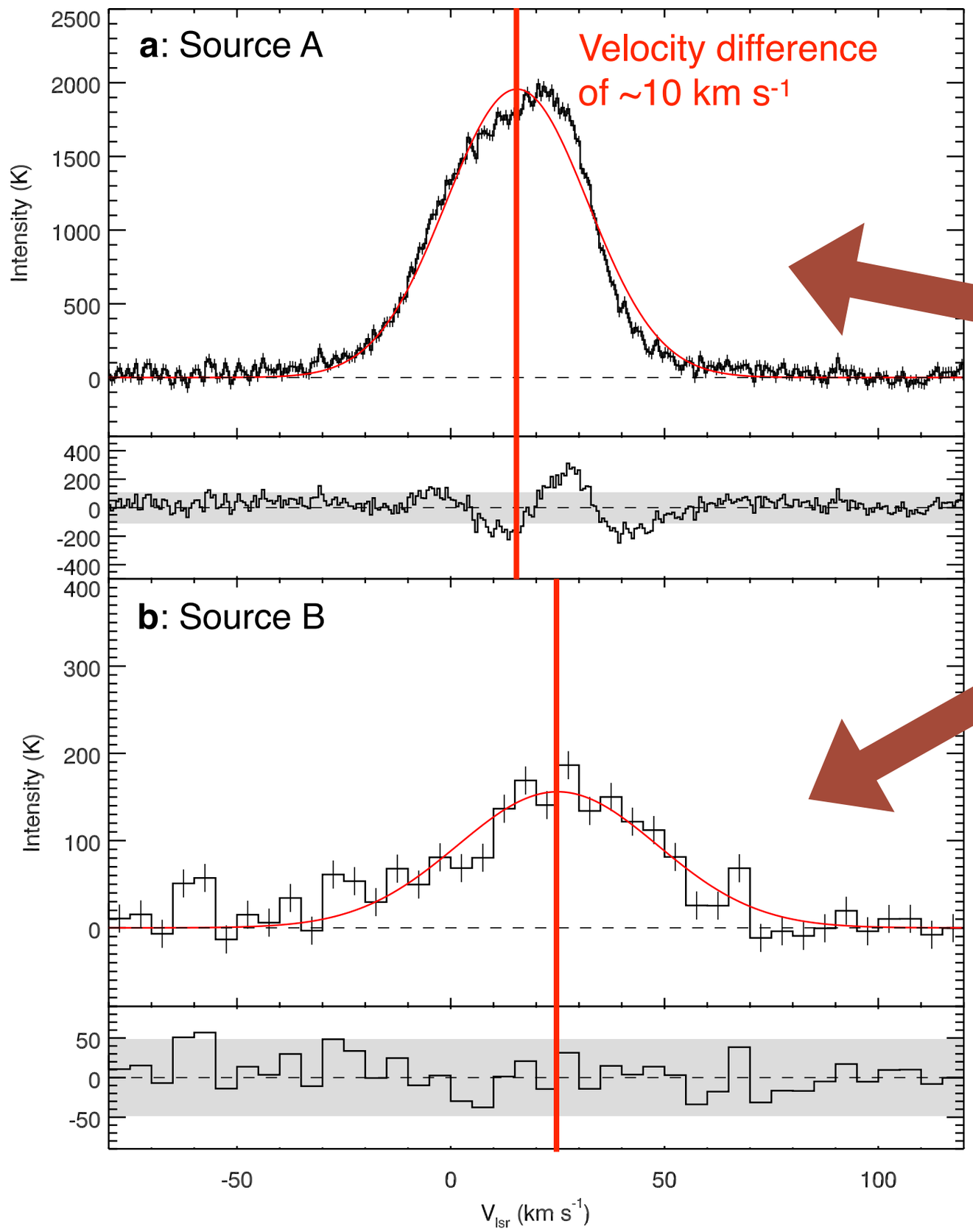
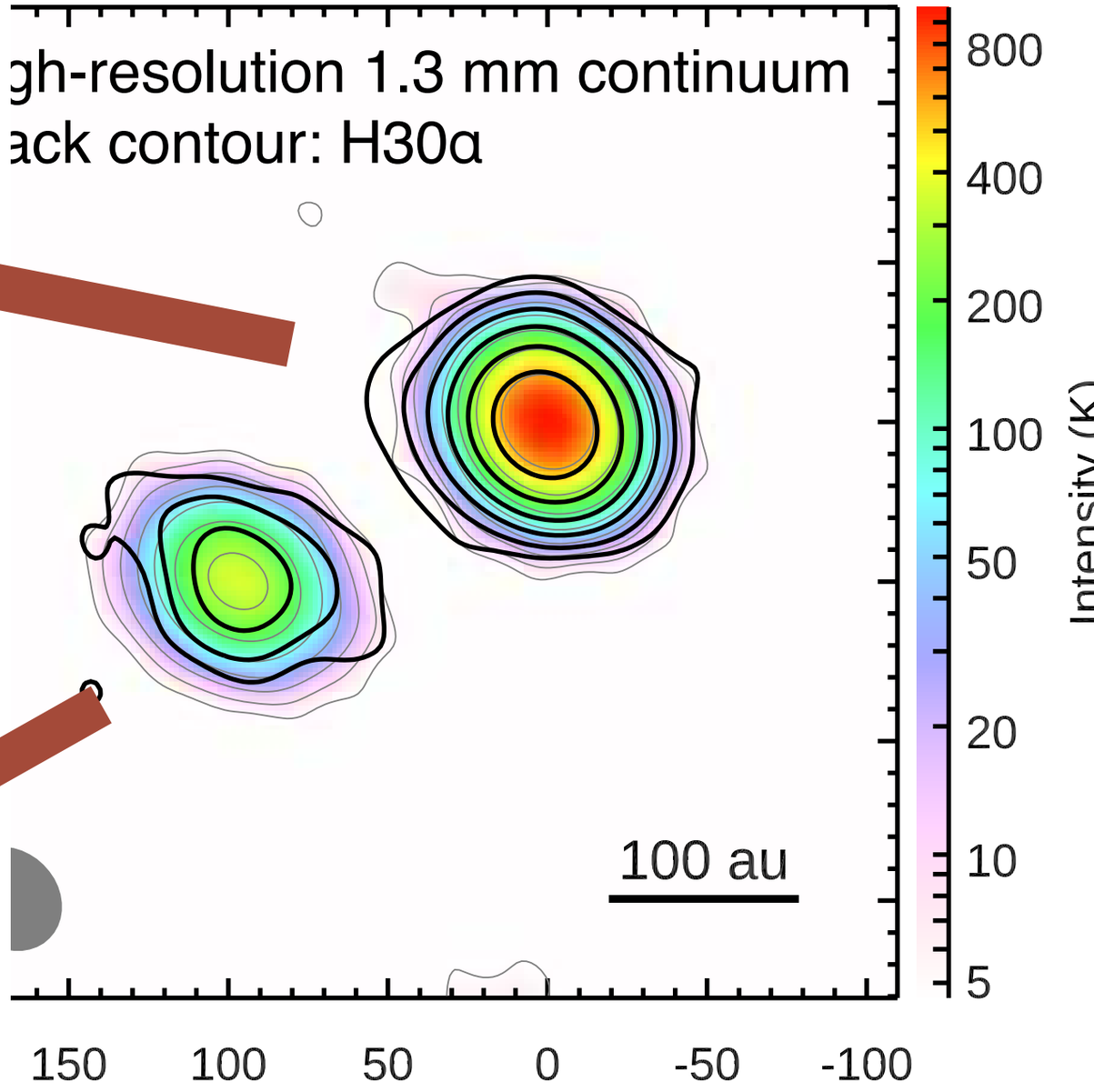






Zhang, Tan, Tanaka et al. 2019, Nature Astronomy, 3, 517

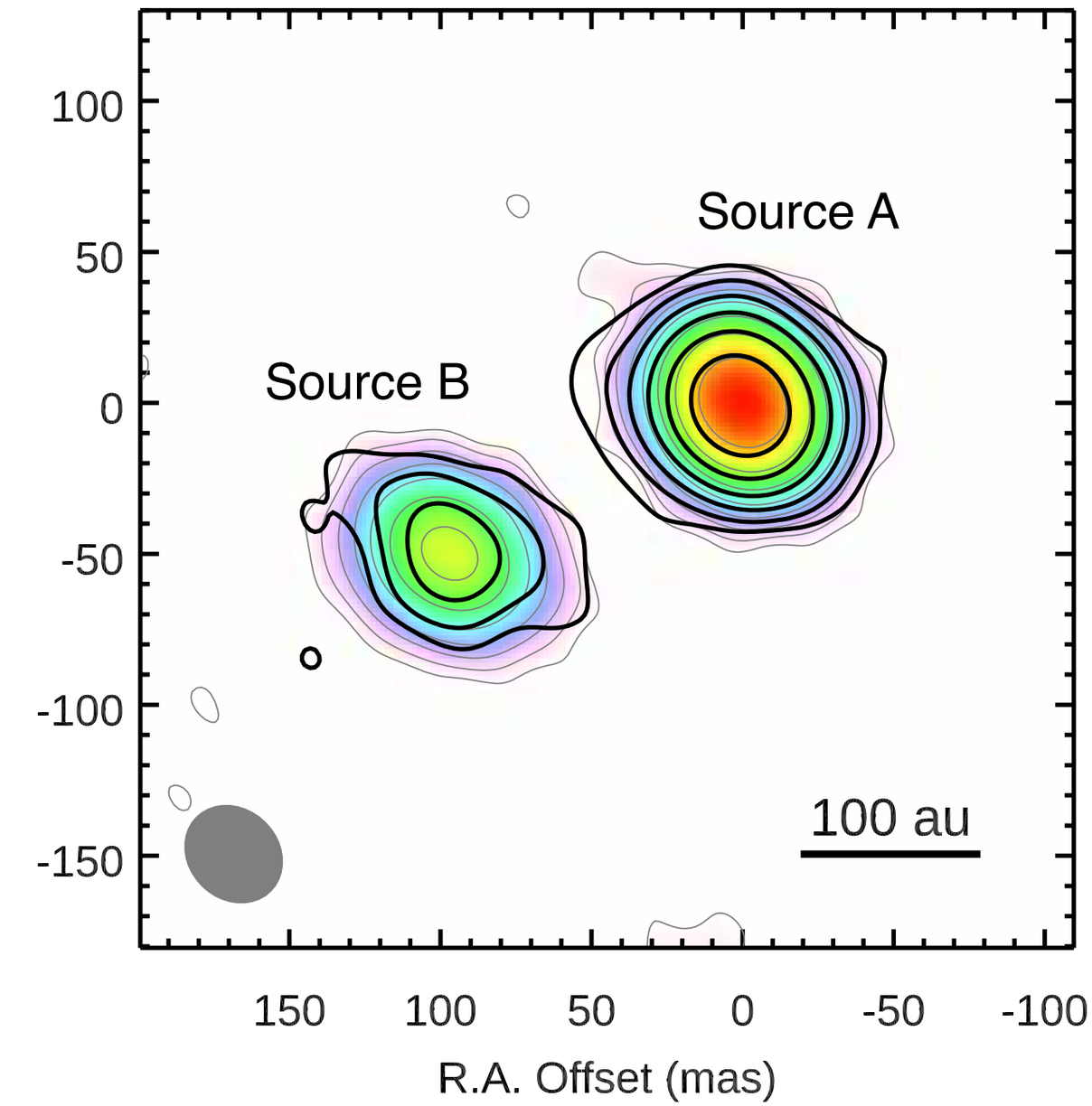
Constraining Binary Orbital Properties

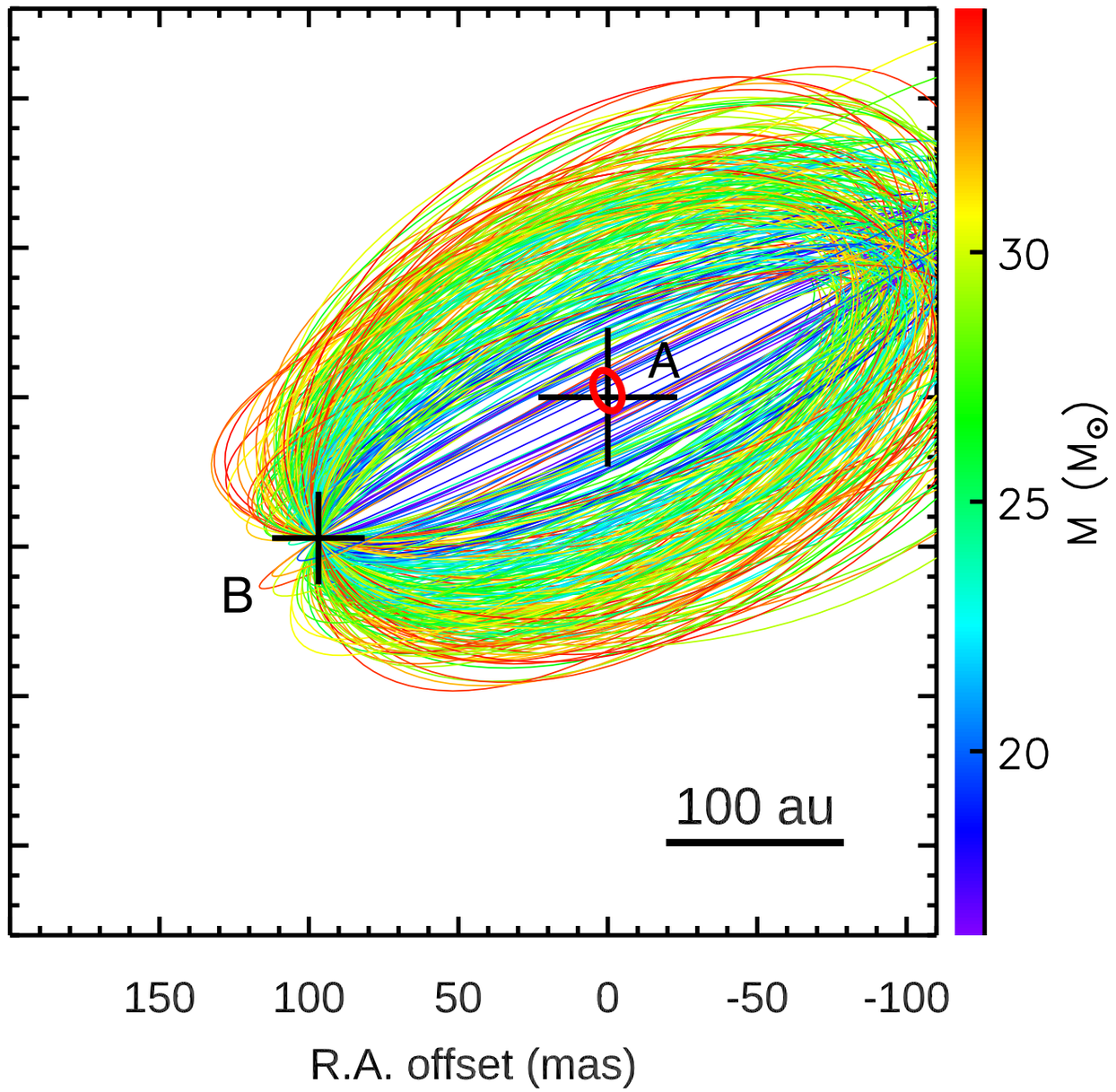
Apparent separation: ~180 au
Line-of-sight velocity difference: ~10 km/s

⇒ $M_{binary} > 18\ M_\odot$

$M_{binary} = 23\ M_\odot$ from free-free + ZAMS model (12.5 $M_\odot$ + 10 $M_\odot$)
$M_{binary} = 14 – 35\ M_\odot$ from free-free + protostellar model

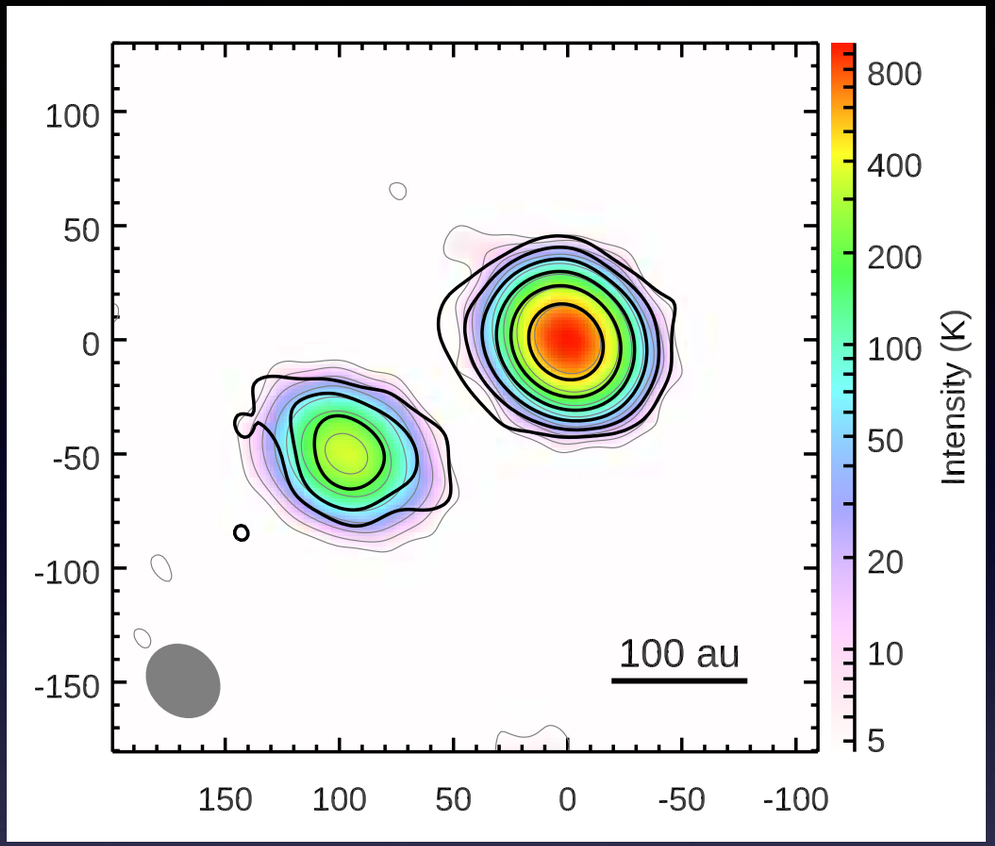
a < ~400 au, P< 2000 yr, near-edge-on inclination (for reasonable mass range and relatively low e)





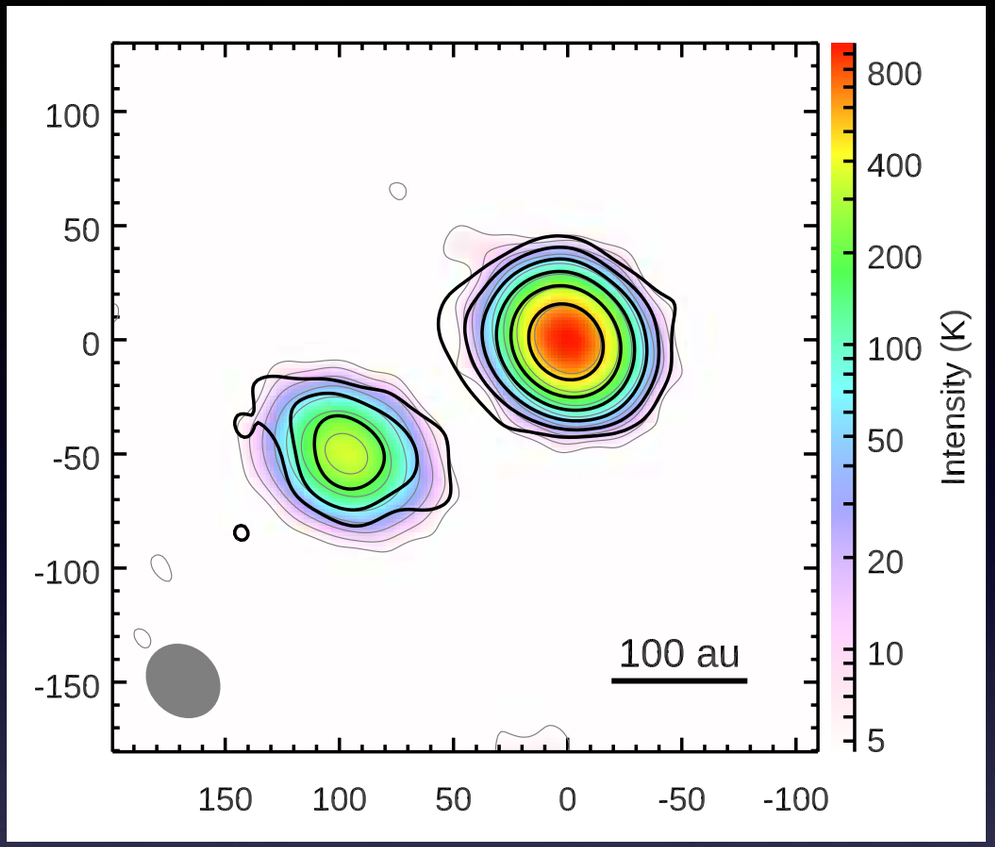
Circumstellar Disk

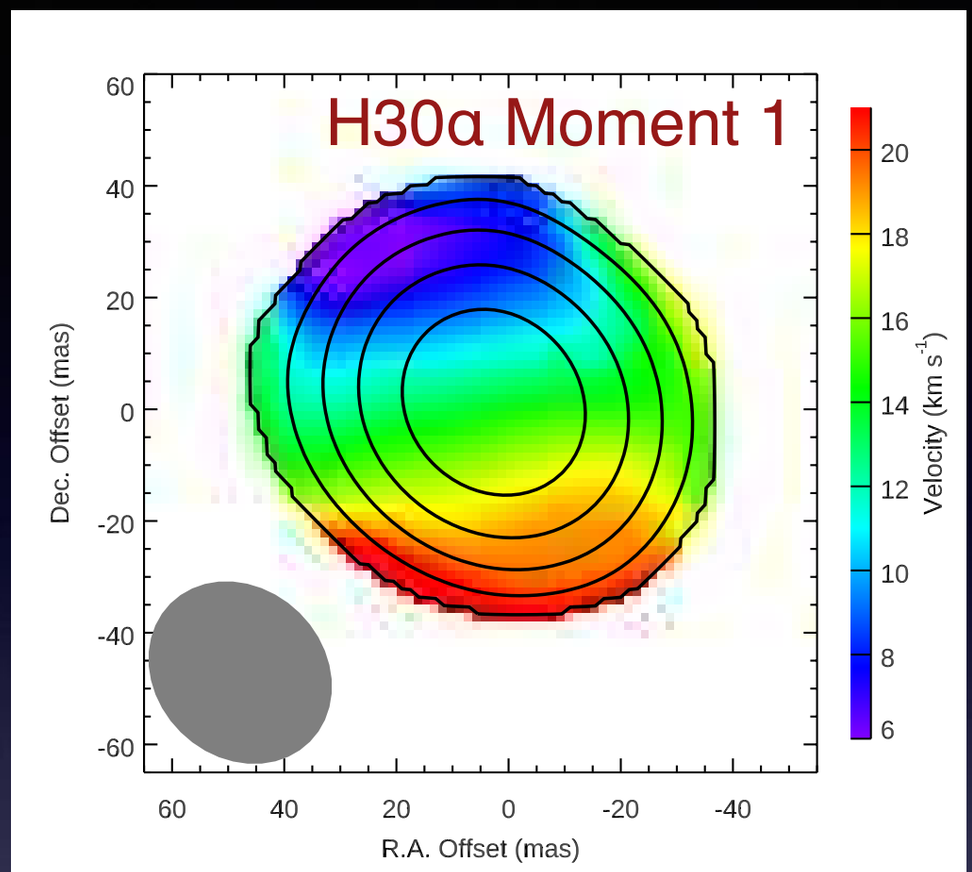
12 au radius rotating ring around the primary



Circumstellar Disk

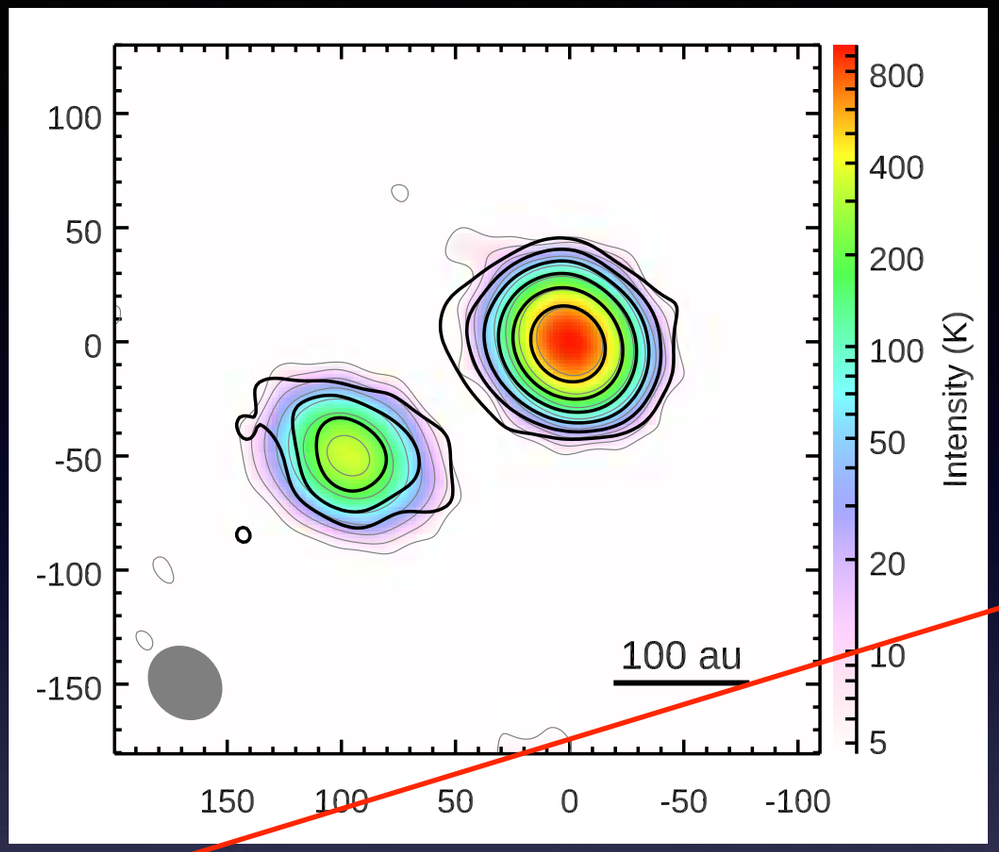
12 au radius rotating ring around the primary

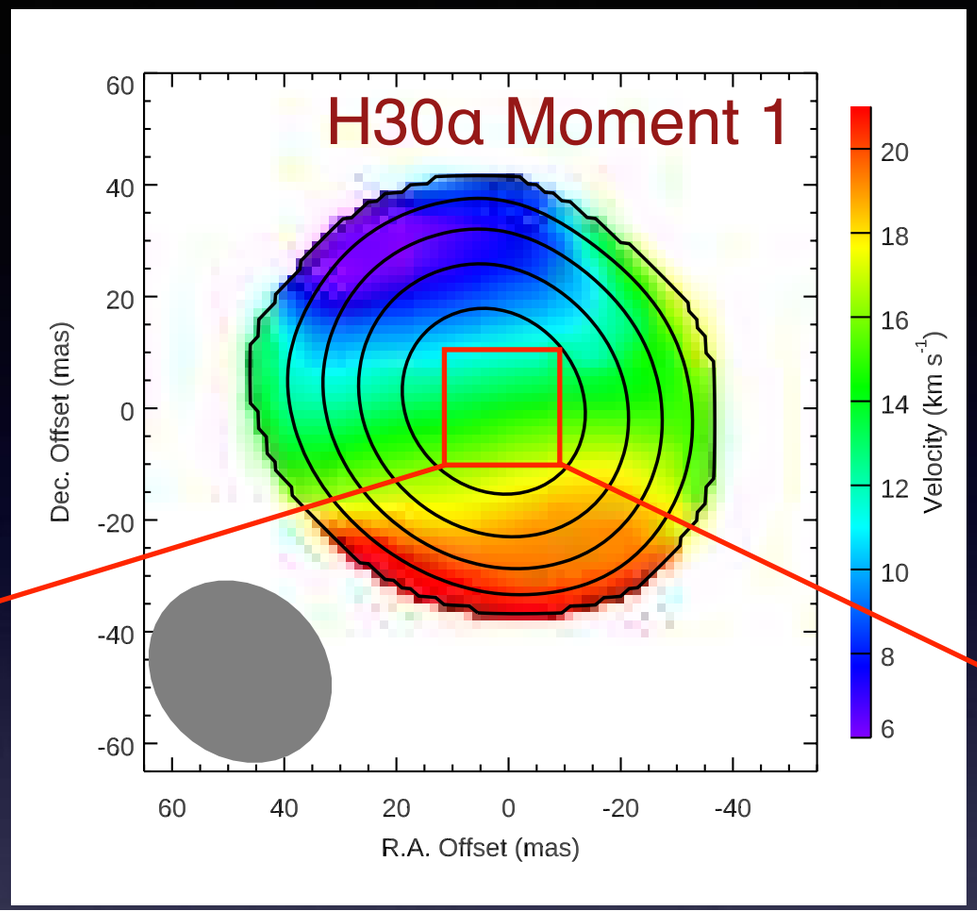


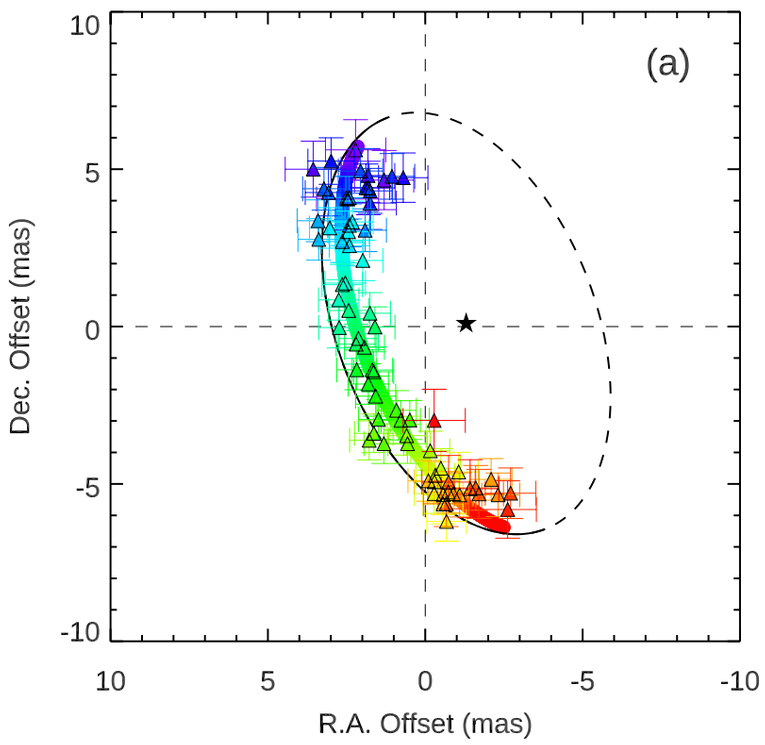


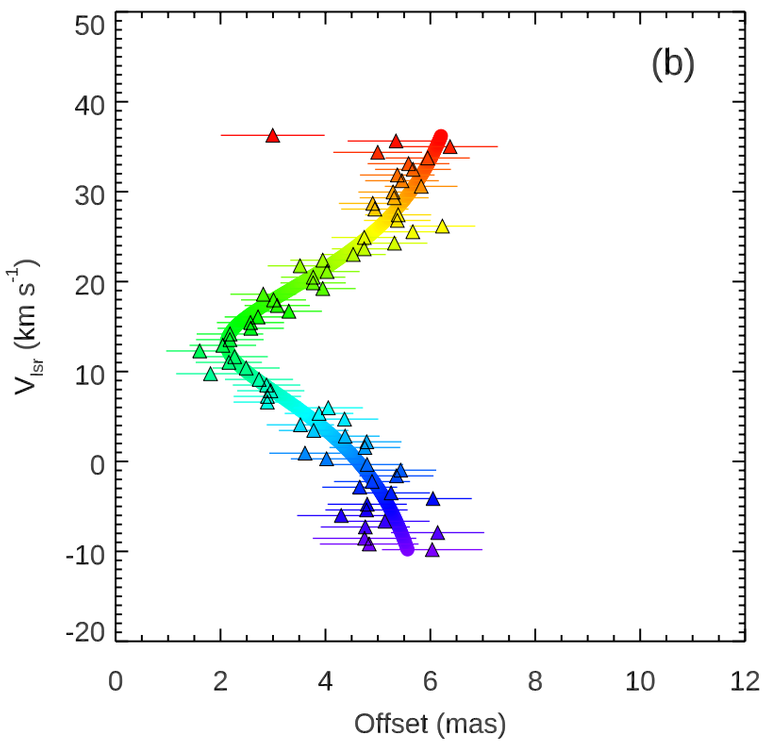
Circumstellar Disk

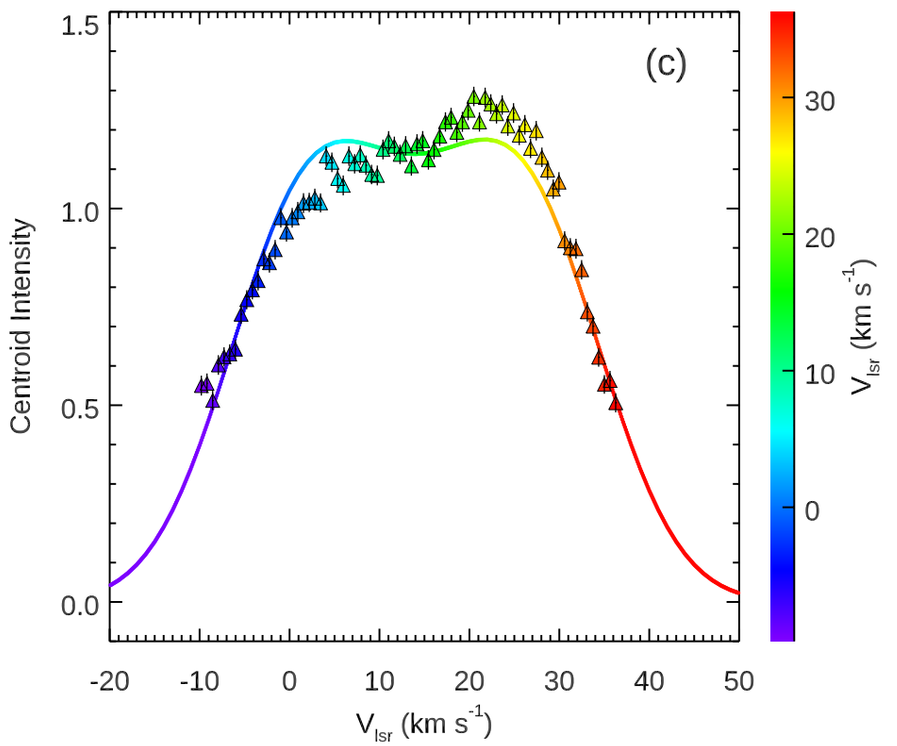
12 au radius rotating ring around the primary







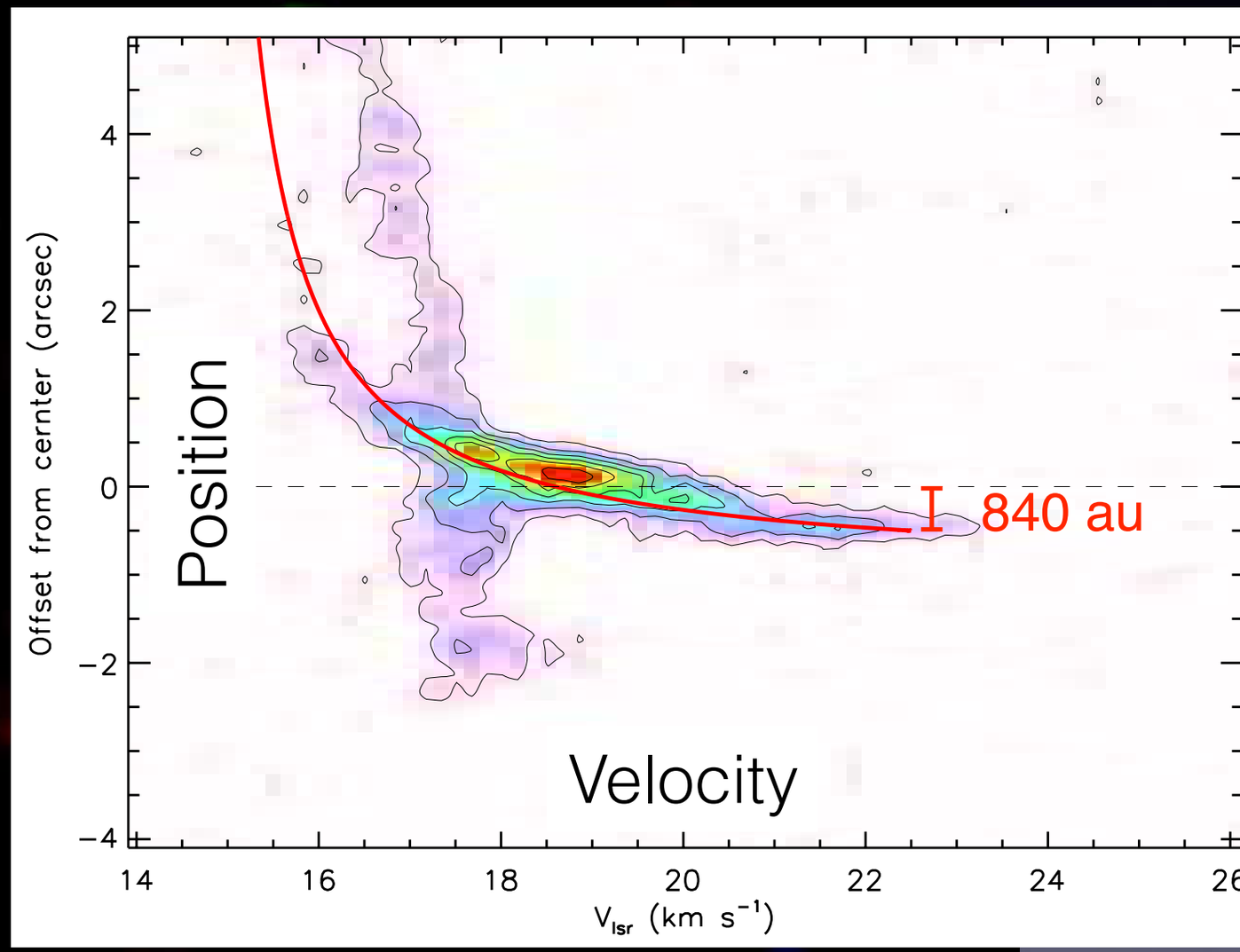




Blue/red: CH_3OH blue and red-shifted
Green: Continuum

Large scale structures

Infalling-rotating streams
down to ~1000 au.

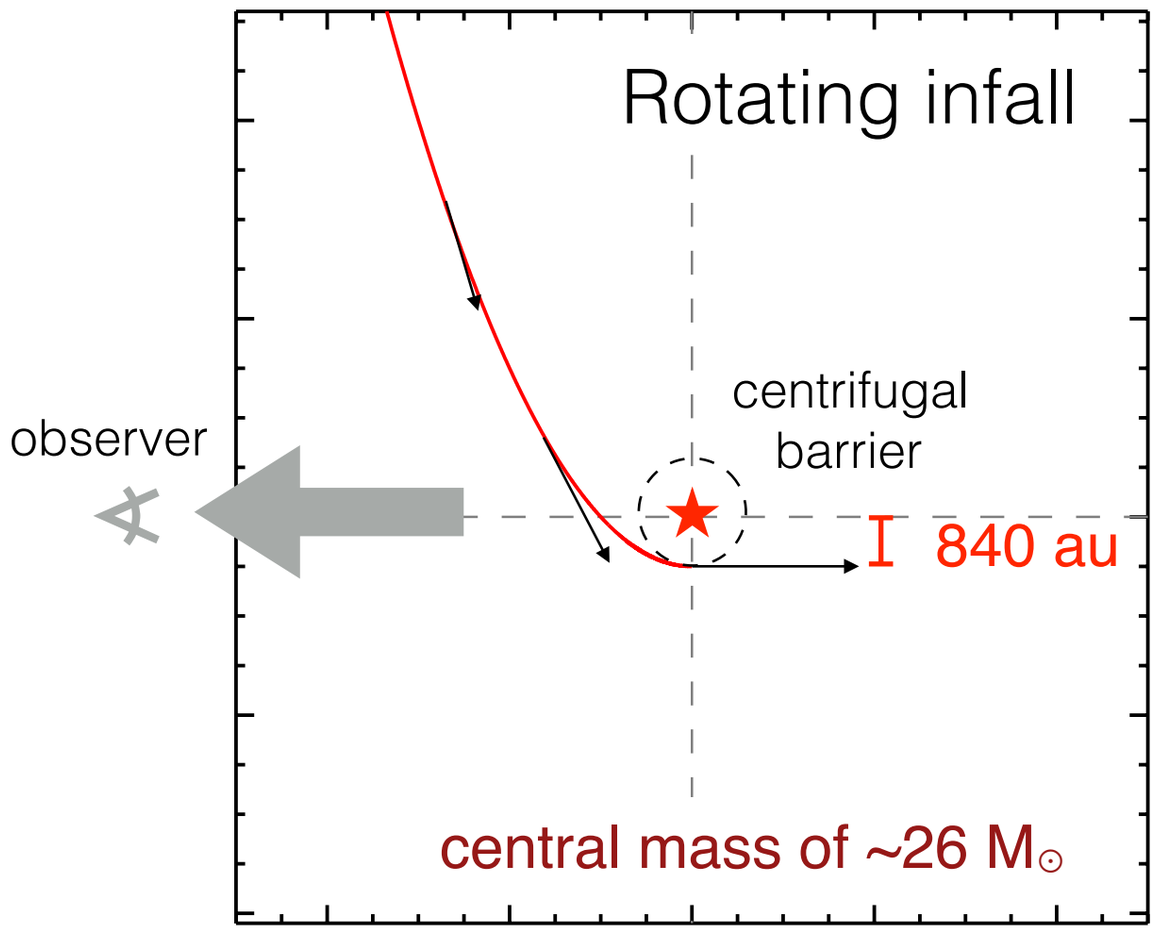


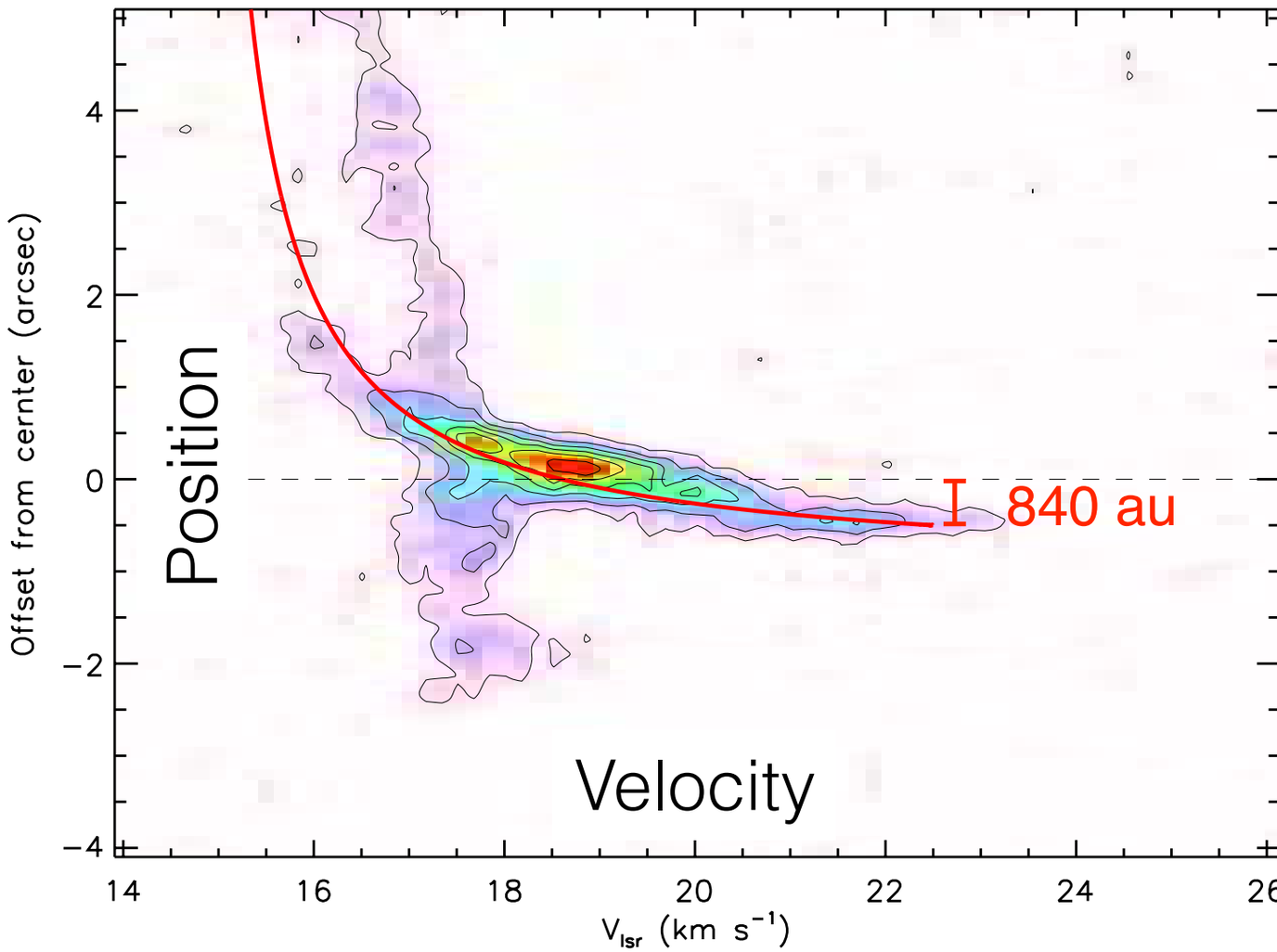
5,000 au

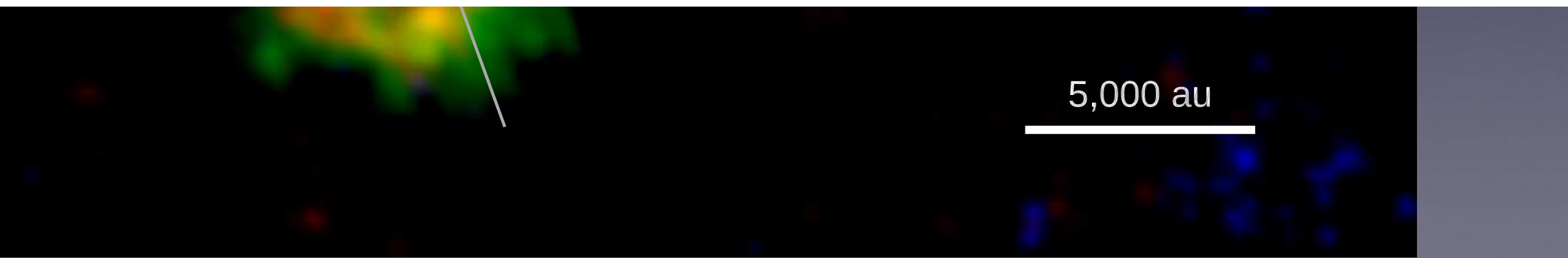
Blue/red: CH_3OH blue and red-shifted
Green: Continuum

Large scale structures

Infalling-rotating streams
down to ~1000 au.







General picture

Infalling-rotating streams from ~10,000 au to ~1000 au.

Binary formation in ~100 au scale.

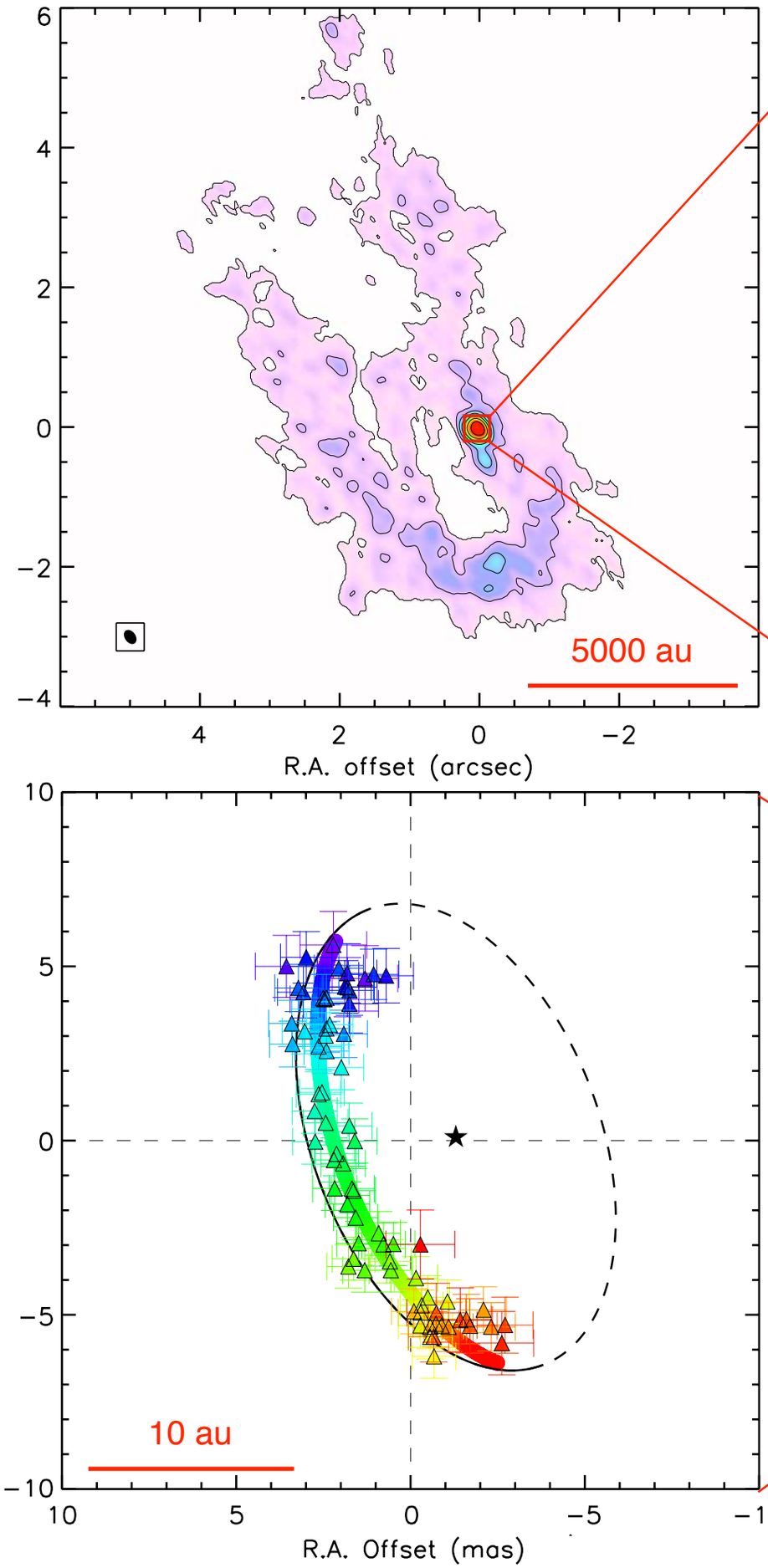
Individual circumstellar disk in 10 au scale.

How did it form?

Disk fragmentation formation:
Consistent with large and small scale structures; Near-equal-mass massive protostars

Misalignments:
Misalignments among the circumstellar disk, binary orbits, and large-scale streams

Zhang et al. 2019, Nature Astronomy, 3, 517

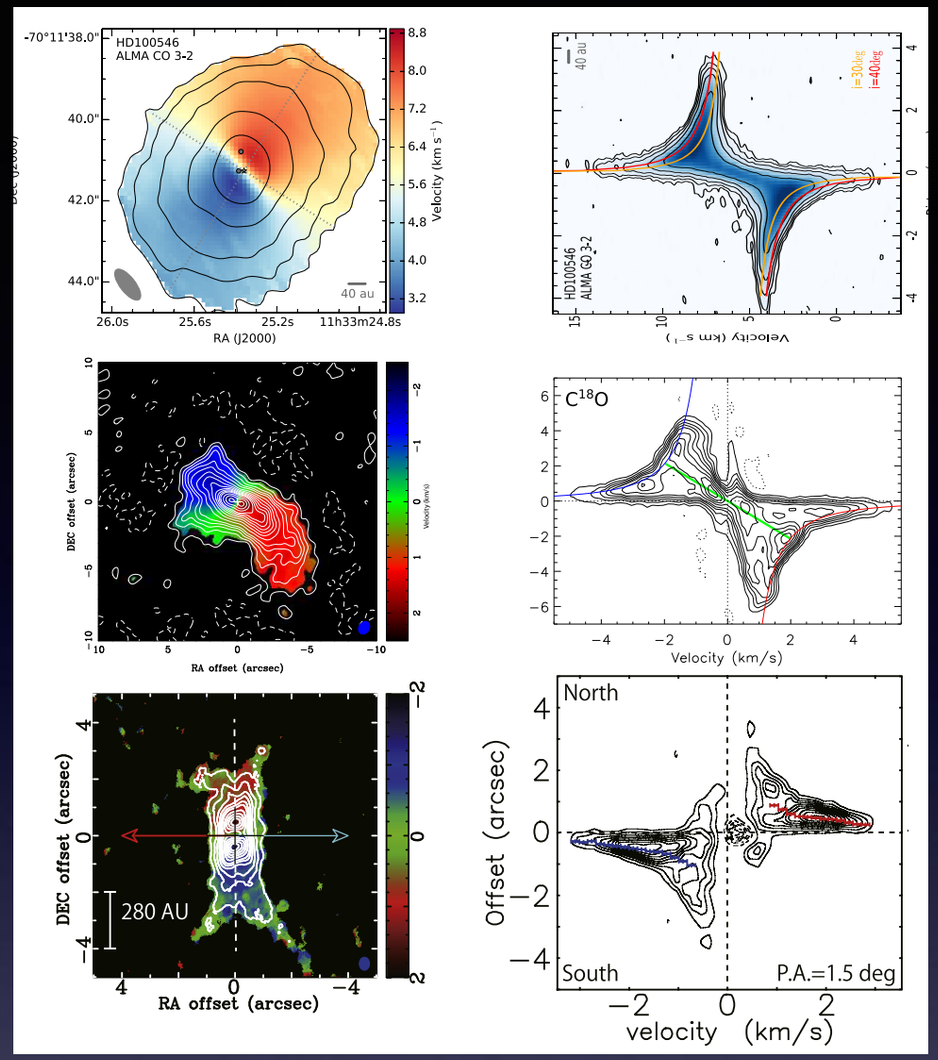


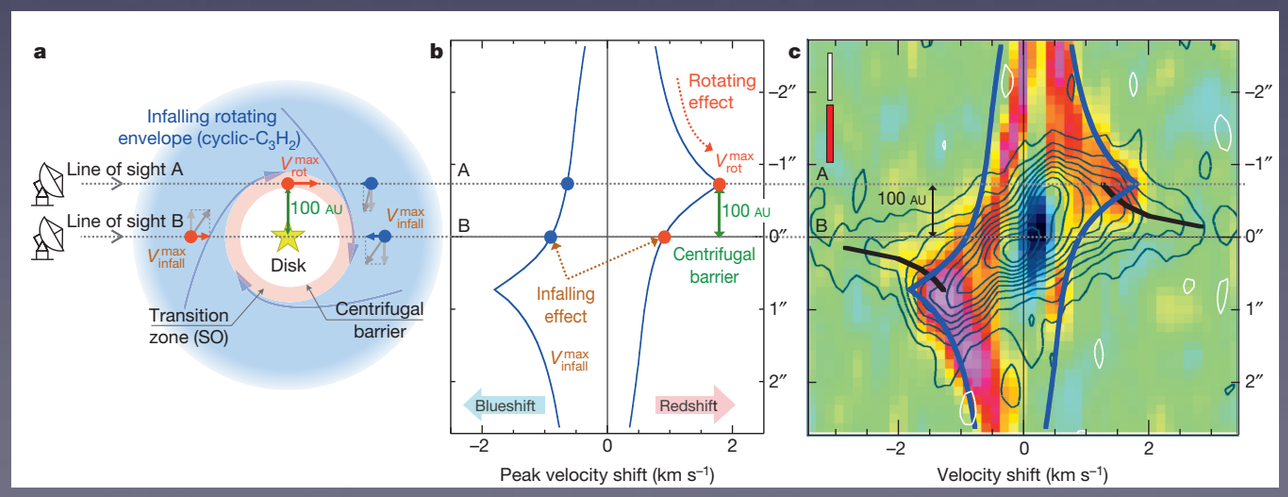
III. Disks in Massive Star Formation

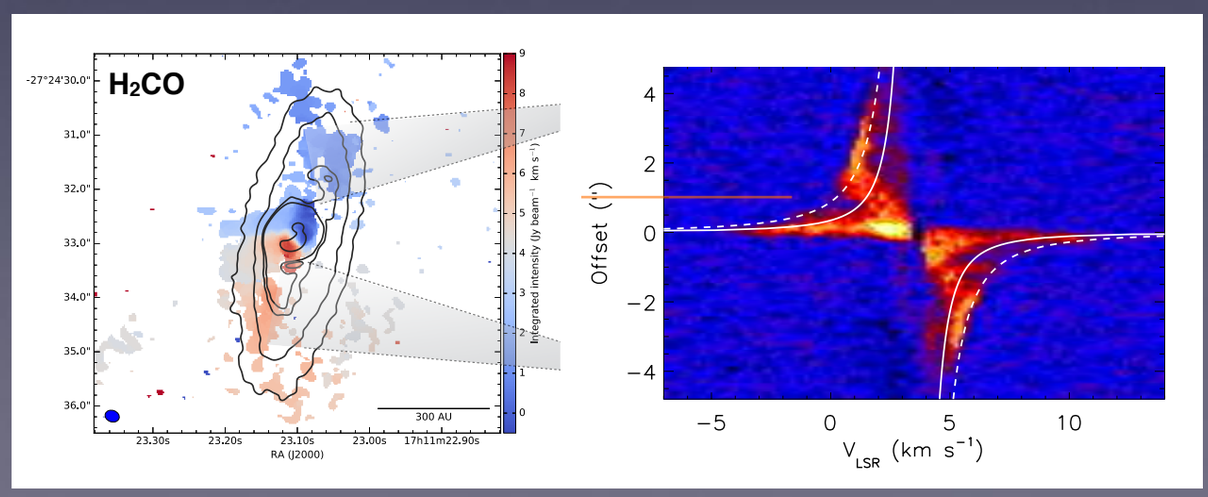
- Keplerian (rotationally supported) disks can form in early stage (Class 0) of low-mass star formation.

- Common molecules such as CO and isotopologues can trace both disk and rotating envelope.

- Envelope-disk transition (centrifugal barrier) can be distinguished in kinematics and chemical changes.

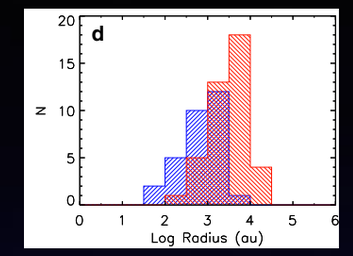


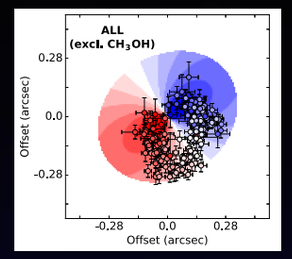


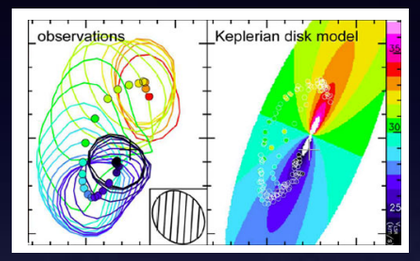


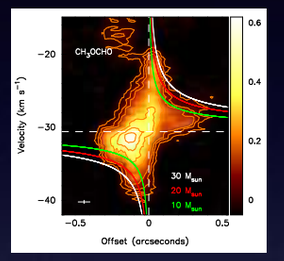
III. Disks in Massive Star Formation

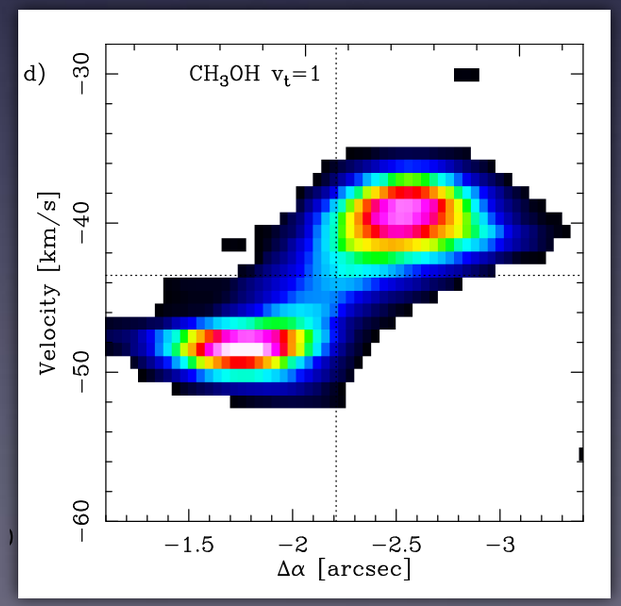
- Is high-mass star formation a scaled-up version of low-mass star formation? (core accretion vs. competitive accretion)
- Searching for Keplerian disks around massive protostars are important (Sánchez-Monge+ 2013; Beltrán+ 2014; Ginsburg+ 2018; Johnston+ 2015; Zapata+ 2015; Ilee+ 2016; Cesaroni+ 2017; Maud+ 2018)
- Confirmation of Keplerian disks around massive protostars are difficult (resolution, mixing of envelope rotation and Keplerian rotation)
- Hint of low-mass star formation: envelope-disk transition (centrifugal barrier) seen in chemical changes (e.g Sakai et al. 2014a,b; Oya et al. 2015, 2016, 2017)
- Can we use similar method to search Keplerian disks around massive protostars? — Envelope/disk transition in both kinematics and chemistry (Csengeri+ 2018)



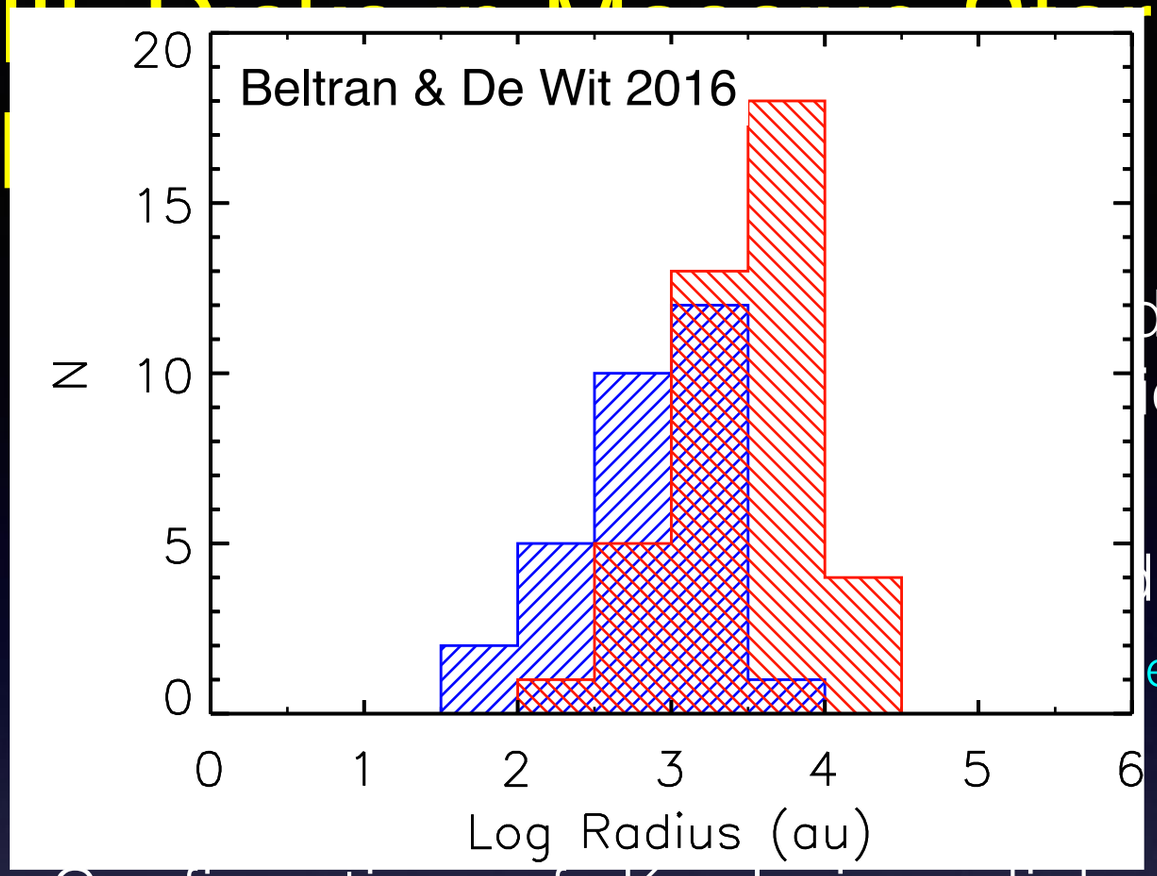








III. Disks in Massive Star



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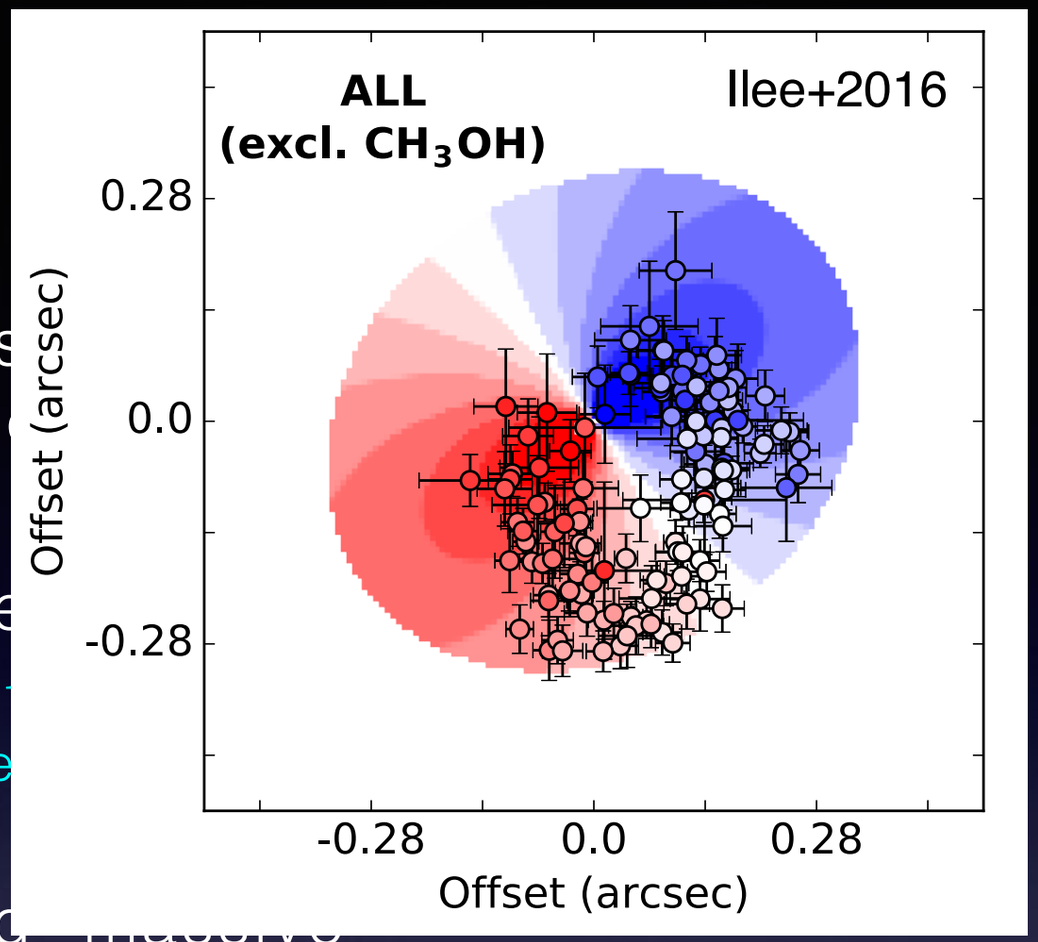
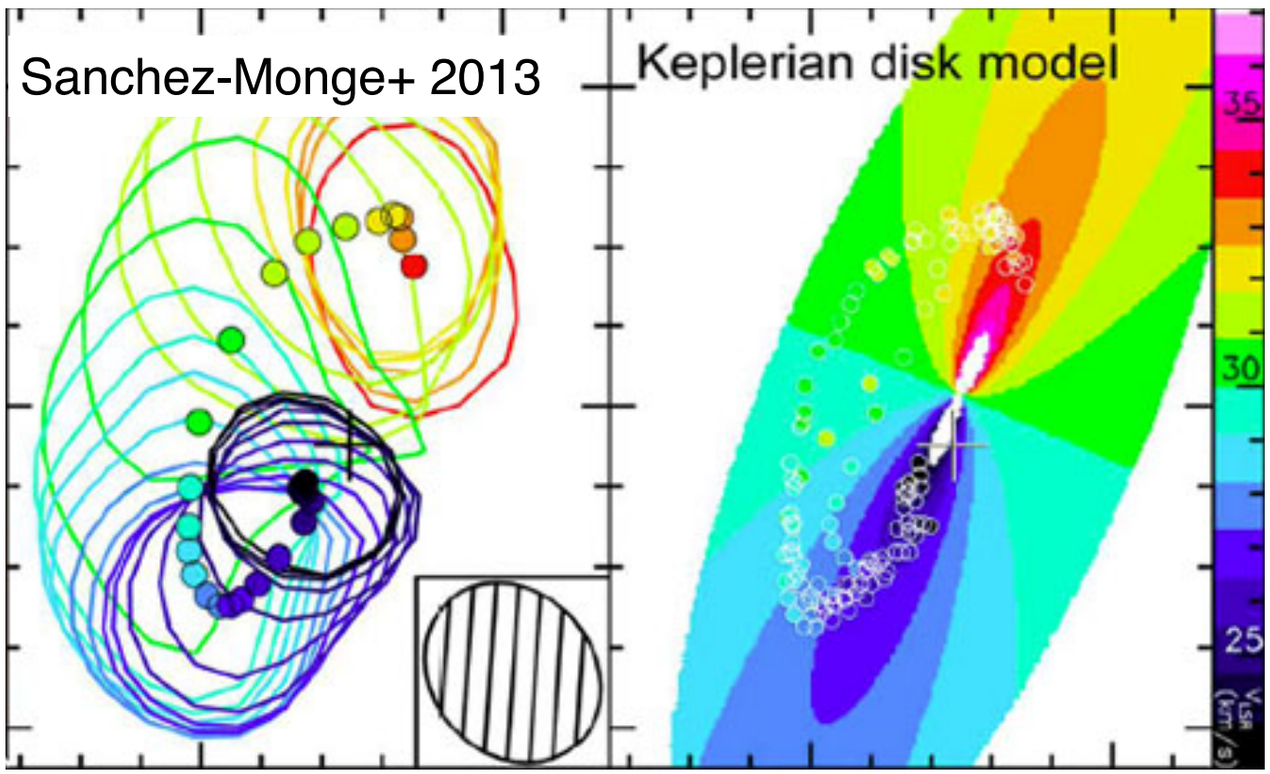
- ion vs.
- massive
- eltrán+ 201
- 2016; Ce



- Confirmation of Keplerian disks around massive
- of envelope



- disk trans
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- eplerian d
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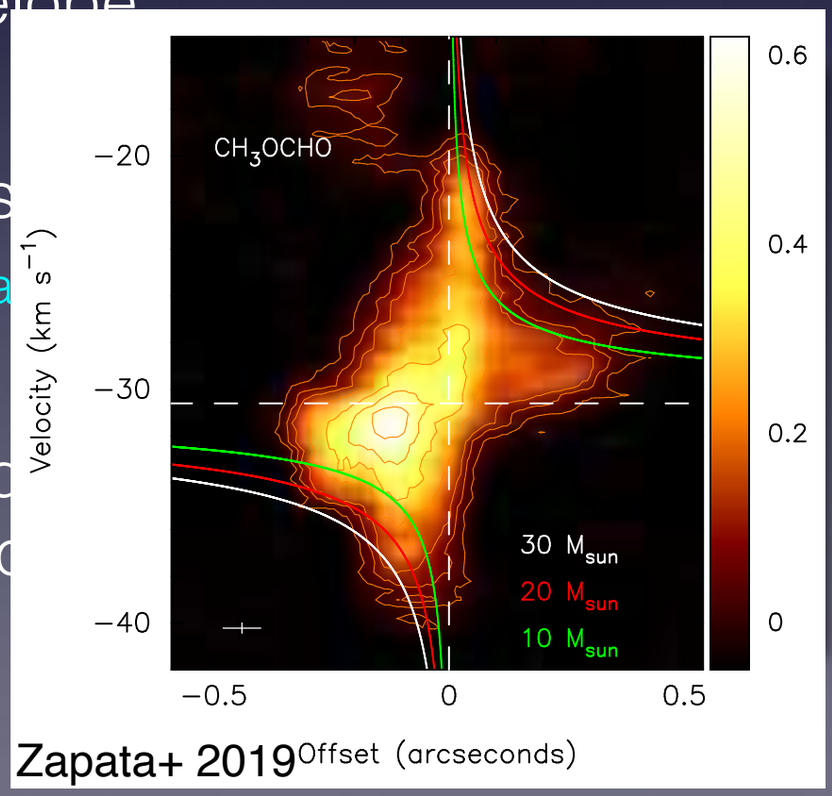


G339.88-1.26

d = 2.1 kpc

$L_{bol} \sim 5 \times 10^4\ L_\odot$

$M_\star \sim 12 - 16\ M_\odot$

Green: 1.3 mm Continuum

Red/Blue color: ^{12}CO

Zhang, Tan, Sakai et al. 2019, ApJ, 873, 73

10000 AU

Green: 1.3 mm Continuum

Red/Blue color: ^{12}CO

White: SiO

SiO jet

SiO also peaked at continuum center

5000 AU

Zhang, Tan, Sakai et al. 2019, ApJ, 873, 73

Zhang, Tan, Sakai et al. 2019, ApJ, 873, 73

SiO

CH_3OH

H_2CO

SO_2

H_2S

Offset (arcsec)

V_{lsr} (km s^{-1})

0.8”, 1600 au

0.25”, 530 au

Infalling-rotating envelope

~~Keplerian disk~~

Infalling-rotating envelope

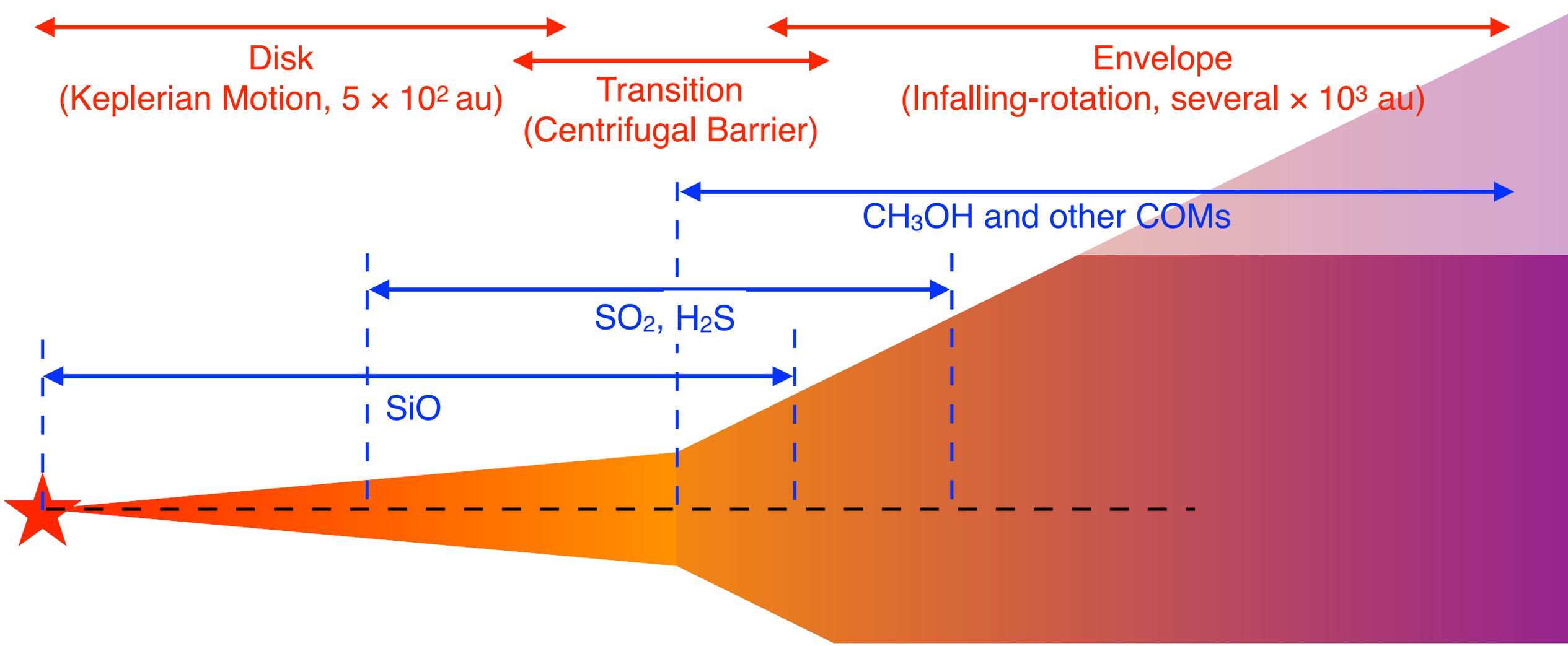
Infalling-rotating envelope

Outer part of Keplerian disk

SiO: High rotation velocities; trace the disk and the inner envelope

CH_3OH and H_2CO: low rotation velocities; trace the infalling-rotating envelope outside of the centrifugal barrier, and enhanced at the centrifugal barrier

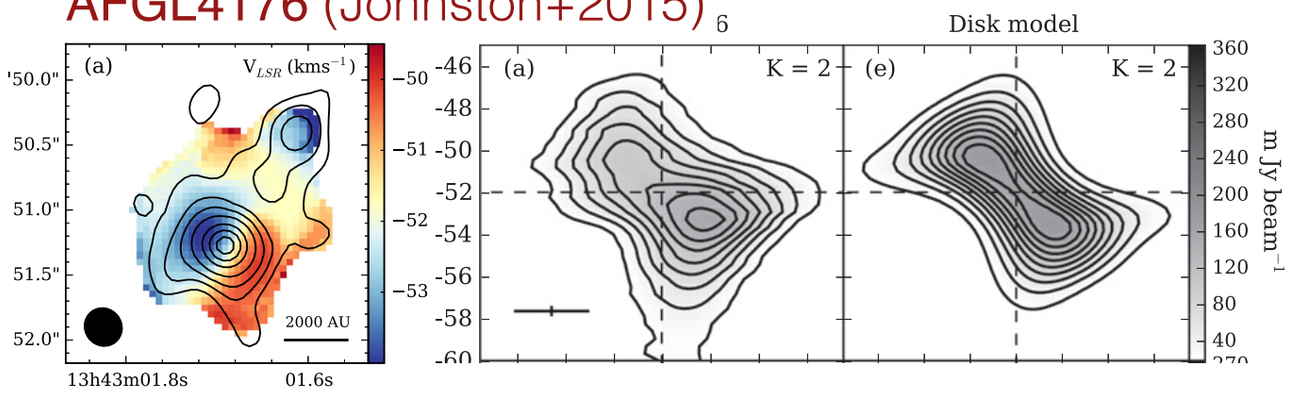
SO_2 and H_2S: intermediate rotation velocities; enhanced at the centrifugal barrier; trace the disk inside, but not reaching the inner part of the disk.



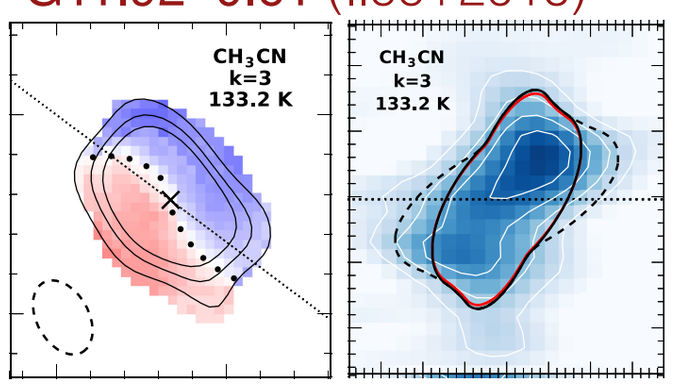
How common?

CH_3CN: real disk tracer?

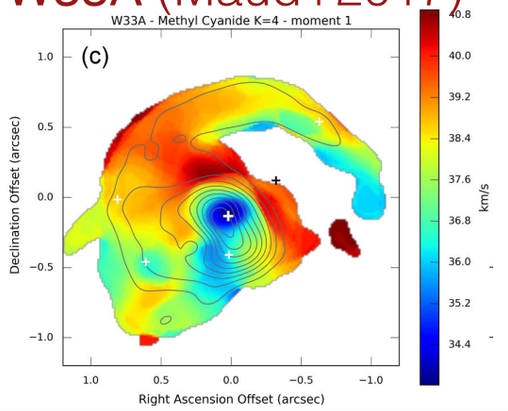
AFGL4176 (Johnston+2015)



G11.92–0.61 (Ilee+2016)

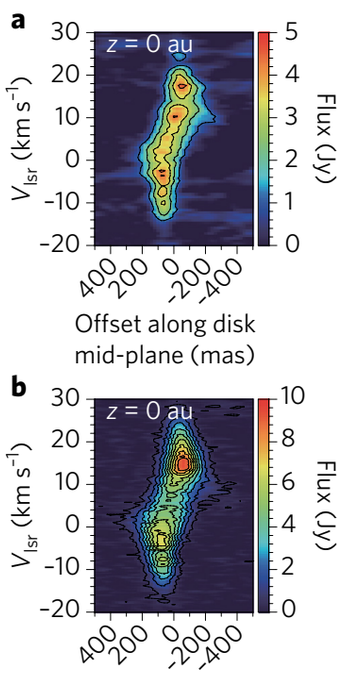


W33A (Maud+2017)

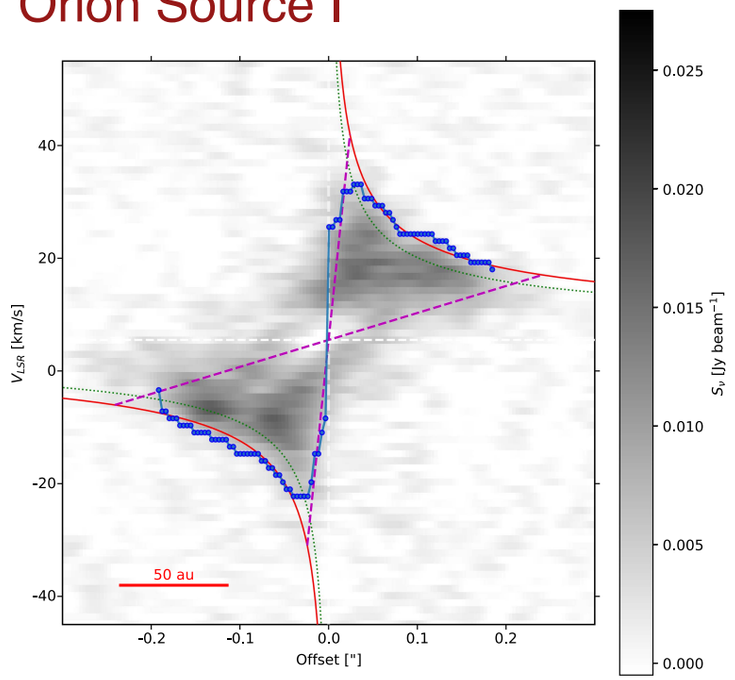


SiO: maybe better disk tracer? But how common?

Orion Source I

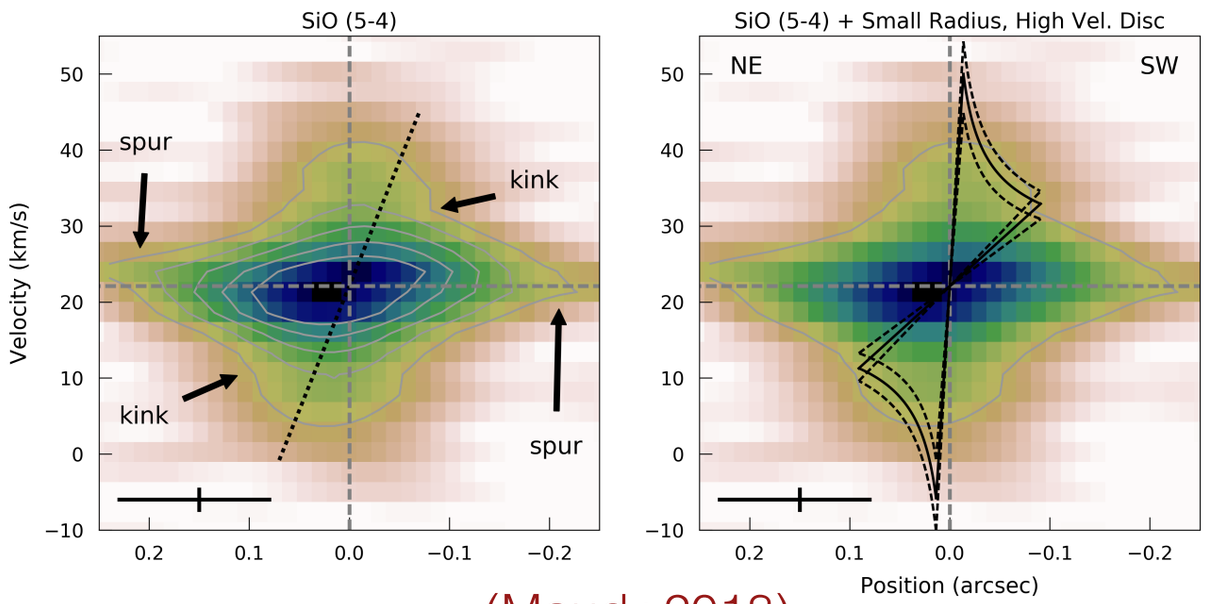


(Hirota+2017)



(Ginsburg+2018)

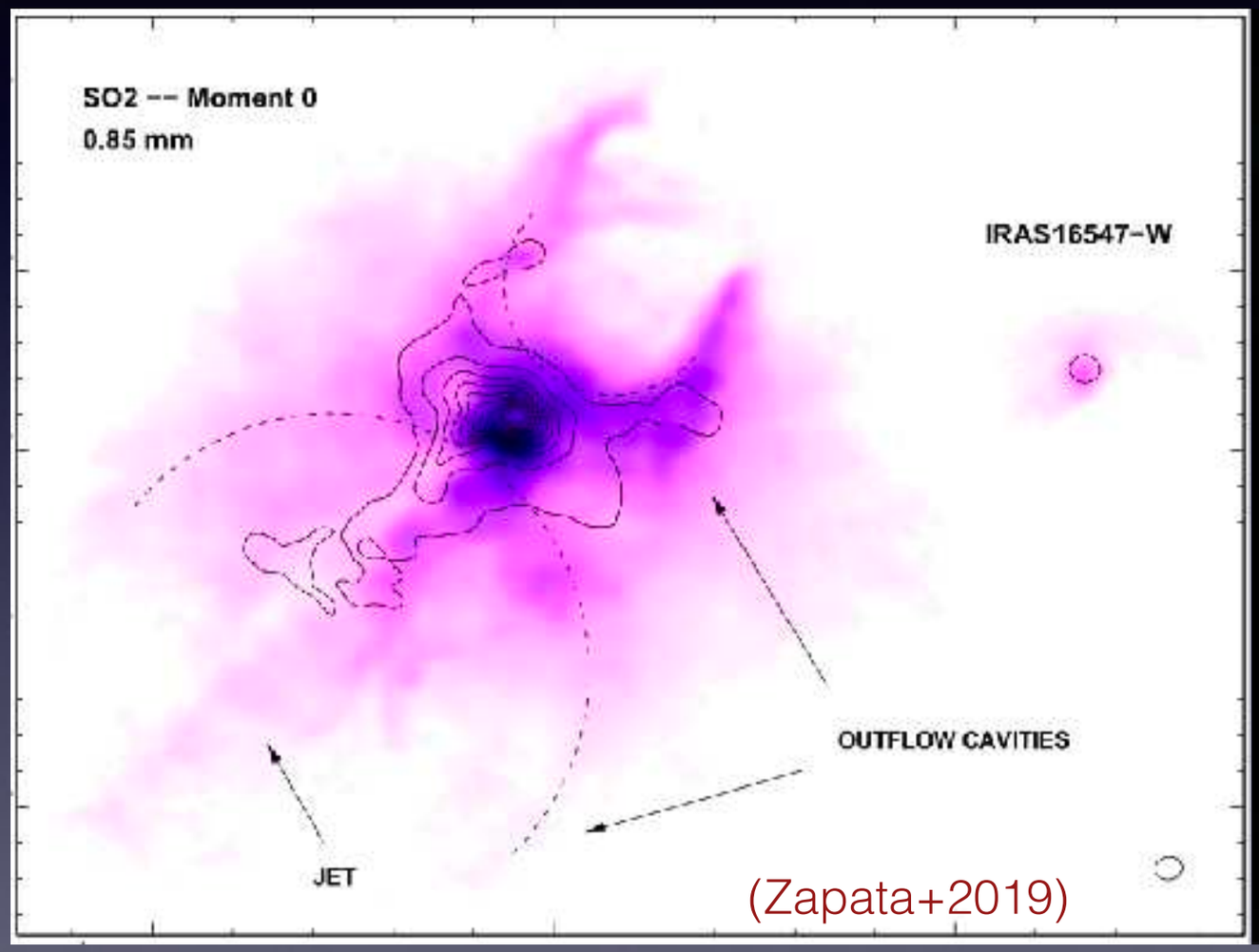
G17.64+0.16



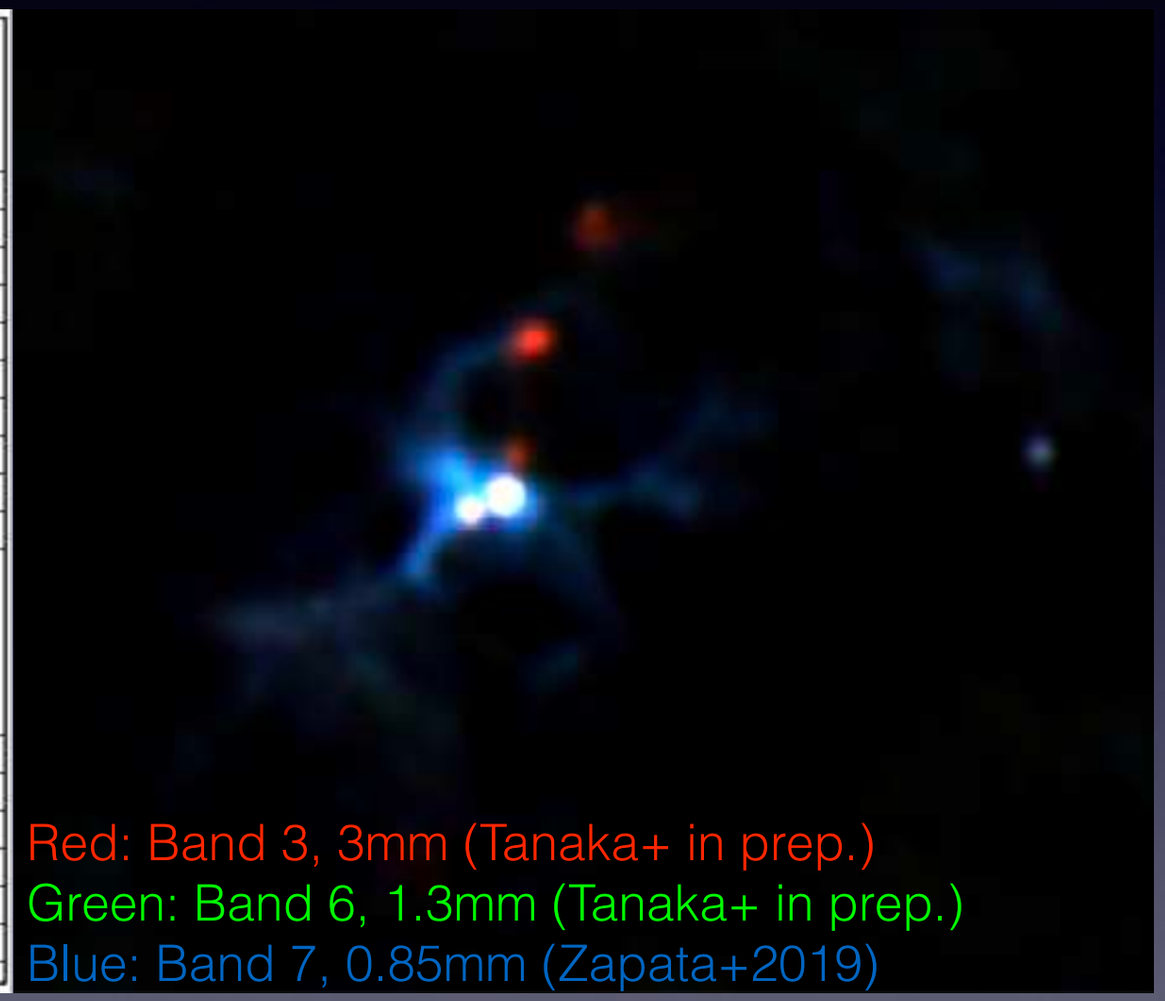
(Maud+2018)

Another example: IRAS16547-4247

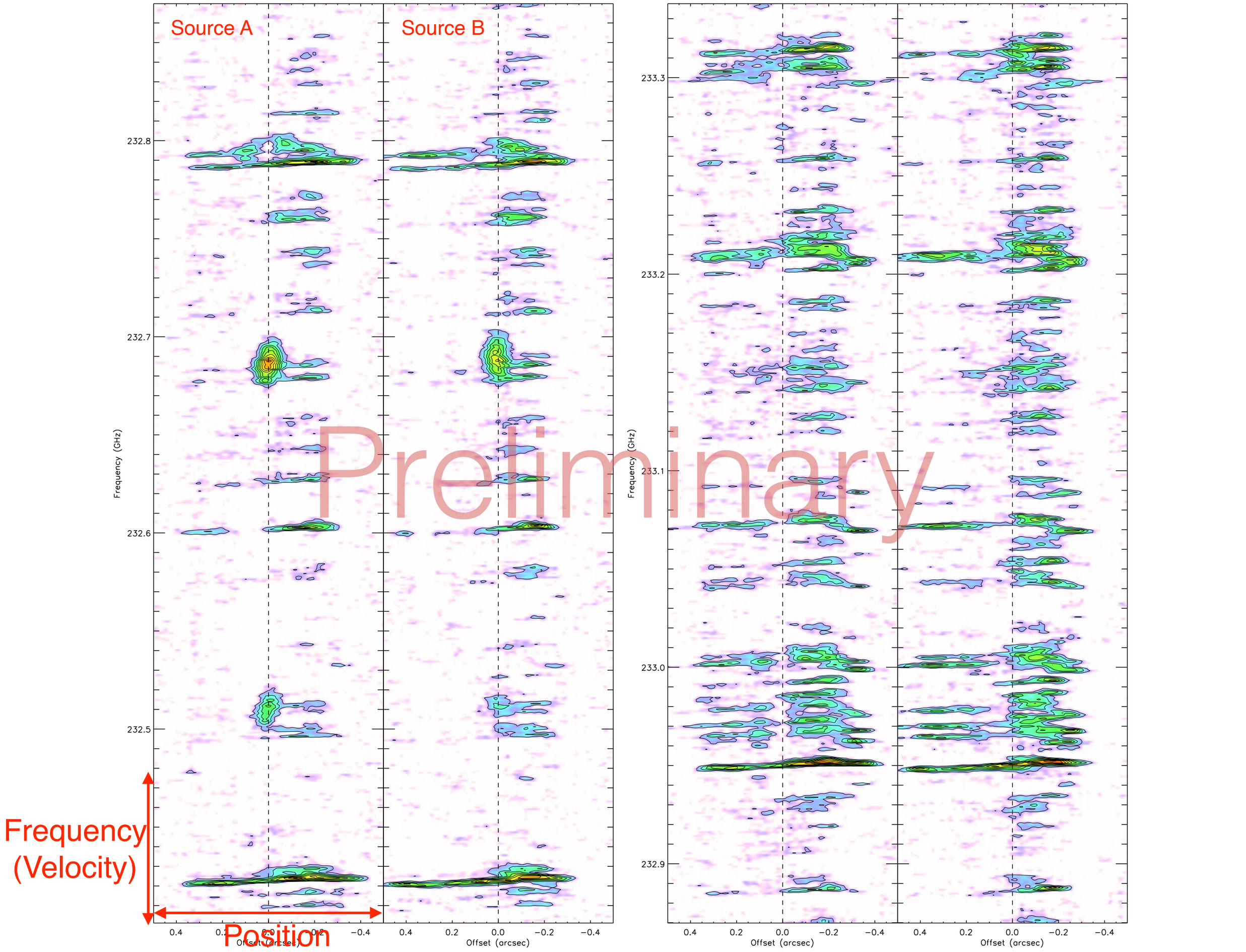
d=2.9 kpc



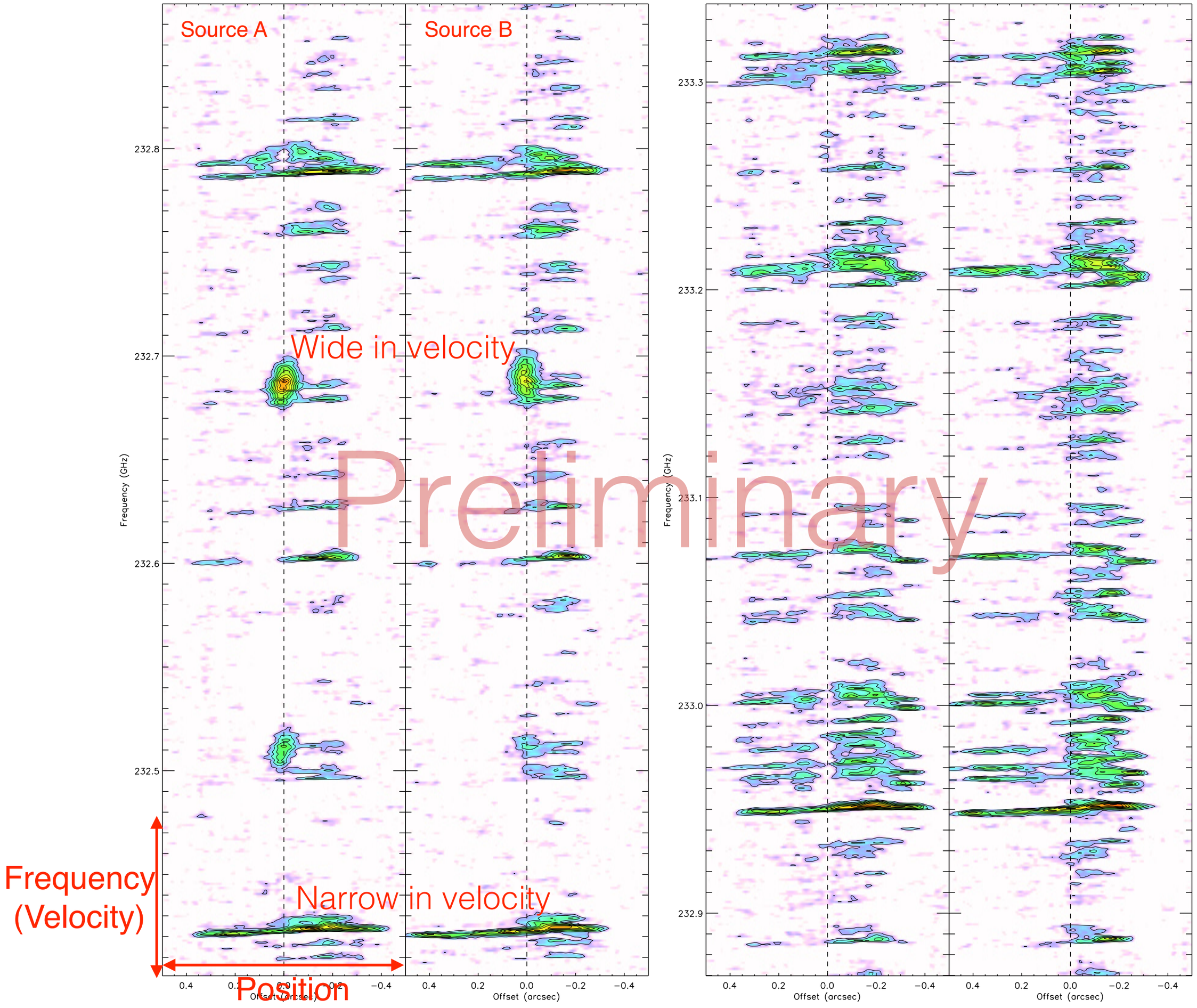
(Zapata+2019)



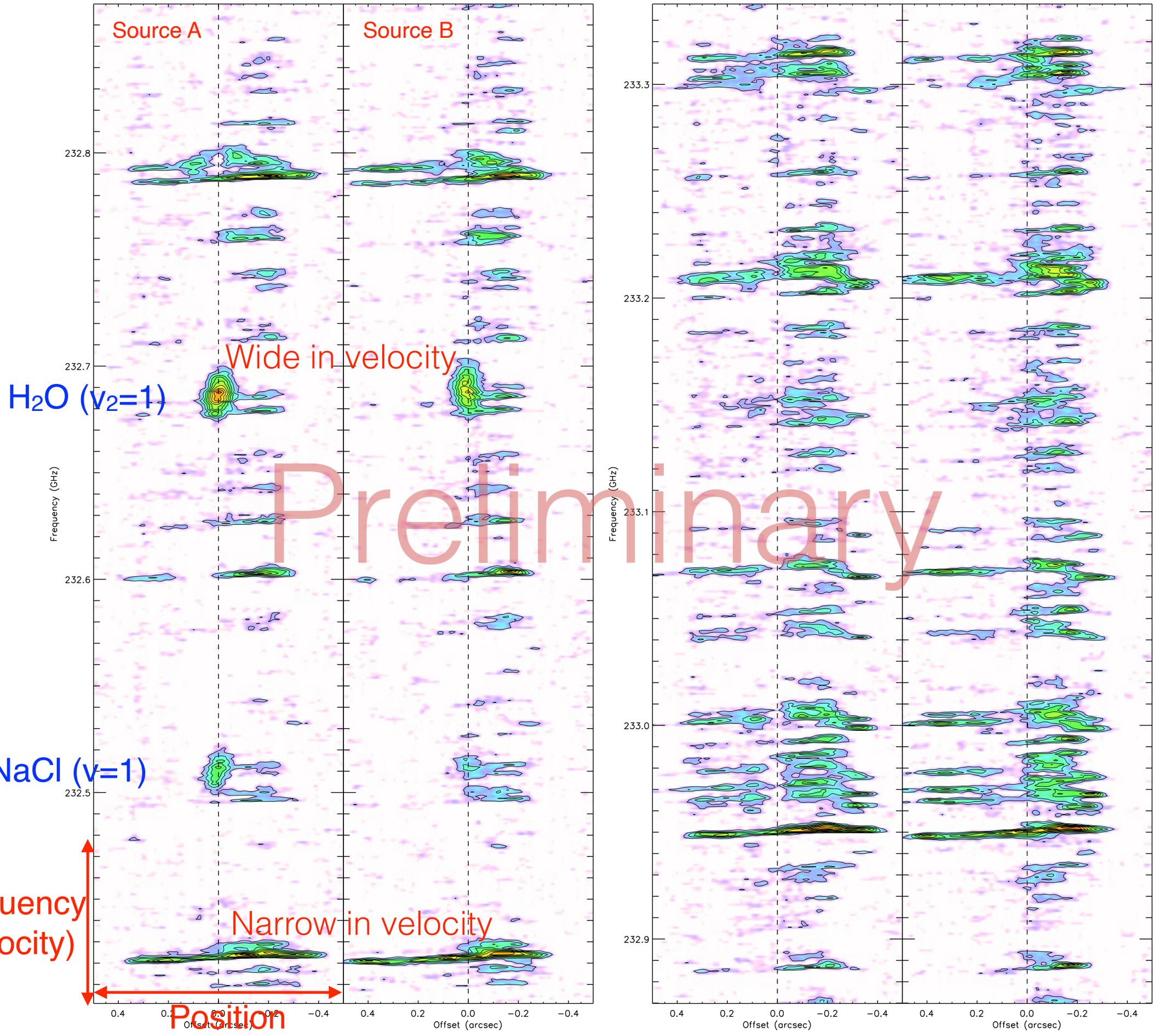
Red: Band 3, 3mm (Tanaka+ in prep.)
Green: Band 6, 1.3mm (Tanaka+ in prep.)
Blue: Band 7, 0.85mm (Zapata+2019)



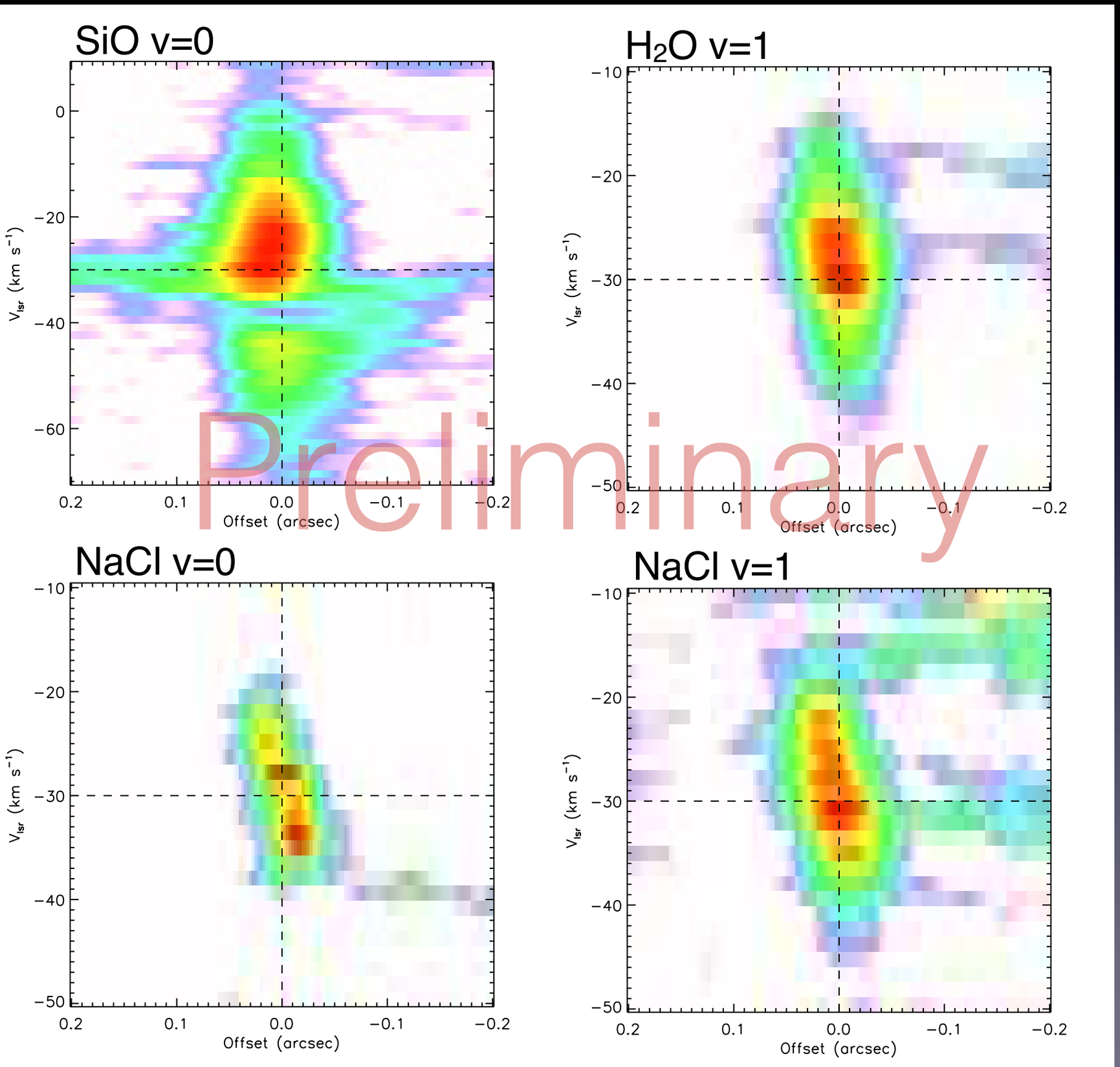
Preliminary



Preliminary


Source A
Source B
Wide in velocity
H2O (v2=1)
NaCl (v=1)
Narrow in velocity
Frequency
(Velocity)
Position
Preliminary
Frequency (GHz)
232.8
232.7
232.6
232.5
233.3
233.2
233.1
233.0
232.9
Offset (arcsec)
0.4
0.2
0.0
−0.2
−0.4

IRAS16547-4247 d=2.9 kpc



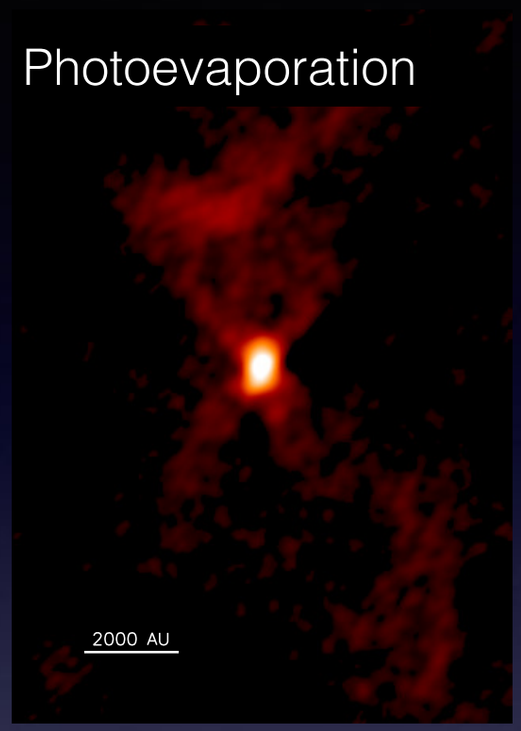
These are likely to be the real disk tracer.

Do they exist in all the massive sources? What are the conditions for them to exist in disk?

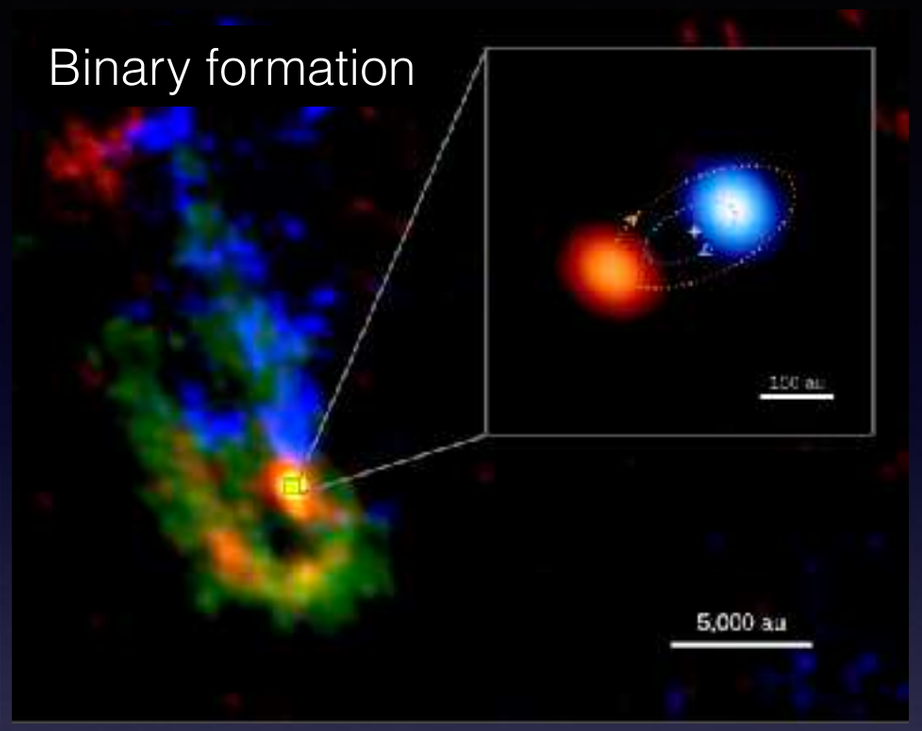
Summary

- We studied wide ranges of phenomenon in the innermost regions of massive star formation including photoionization feedback for early O-type star, binary formation, and disk formation.
- Feedback may not be the limiting process for the mass of the formed massive star around solar metallicity.
- Constraining massive binary formation mechanism: probing massive protobinary kinematics with recombination lines tracing confined ionized regions around forming massive stars
- Massive stars accrete via disks similar to low-mass stars. Chemical signatures, combined with kinematics signatures can be useful for searching such disks.
- In general, dynamics appears to be quite ordered in the innermost regions (qualitatively similar to low-mass star formation).

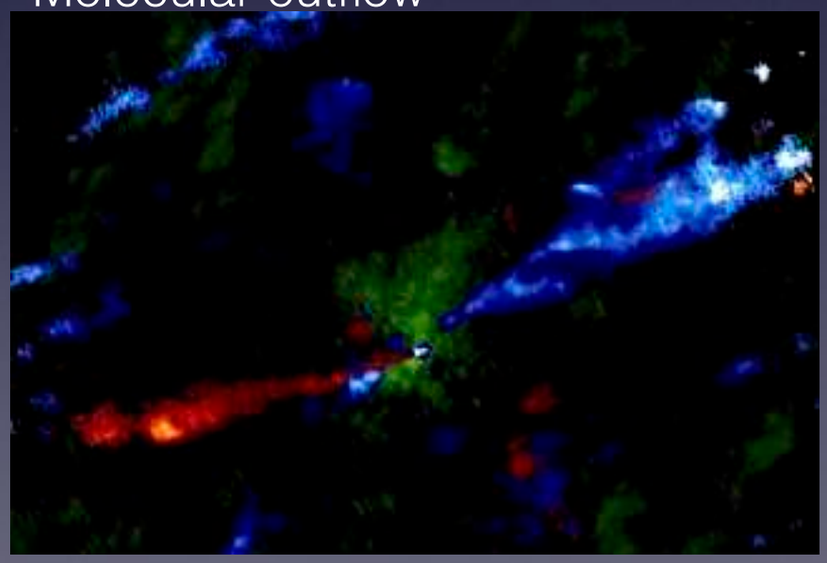
Photoevaporation



Binary formation



Molecular outflow



Disk formation

