SMA and ALMA Observations of a Prototypical Binary Protostellar System L1551 NE

Infall, Keplerian Circumbinary Disk, and Accretion Streams

Takakuwa Shigehisa (ASIAA),
Masao Saito (NAOJ / JAO),
Jeremy Lim (HKU),
Kazuya Saigo (NAOJ ALMA),
Tomoyuki Hanawa (Chiba Univ.) et al.

1. Introduction: Binary Protostellar Formation

A substantial fraction of low-mass stars form as binary systems (Dunquennoy & Mayor '91, Mathieu '94).

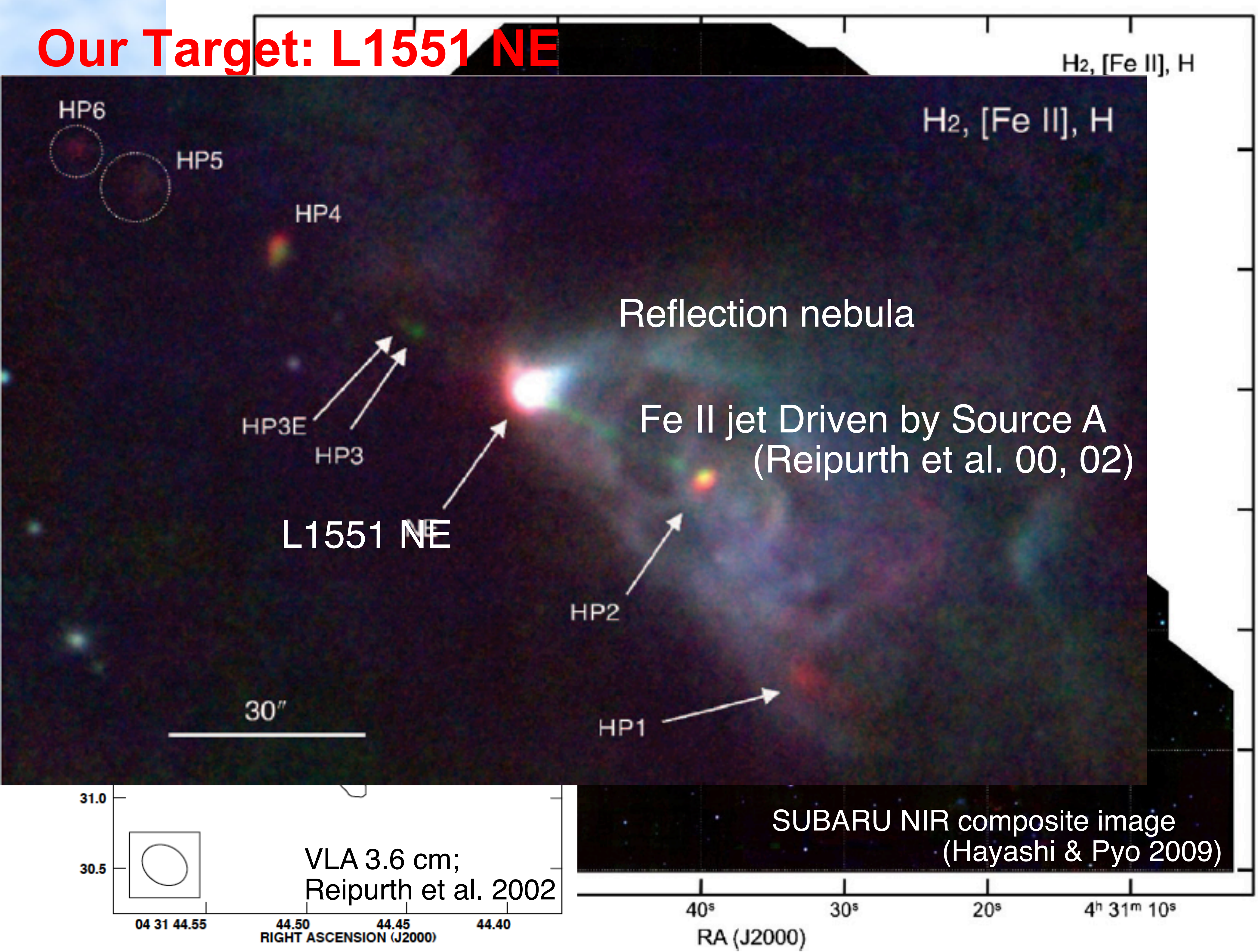
Compared to single star formation,

binary formation is little understood.

High-dynamic Range Observations of Protostellar Binaries are essential.

- Protostellar Envelope (Infall ?)
- Circumbinary Disk (Rotation ?)
- Connecting Gas Stream
from Circumbinary to Circumstellar Disks ?

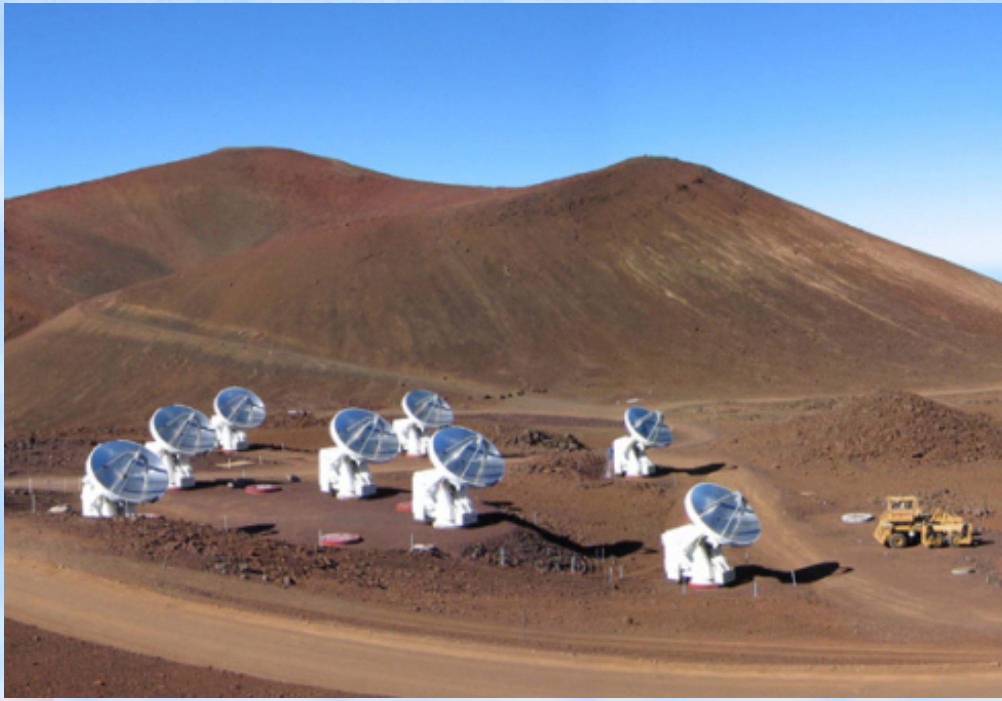
Our Target: L1551 NE

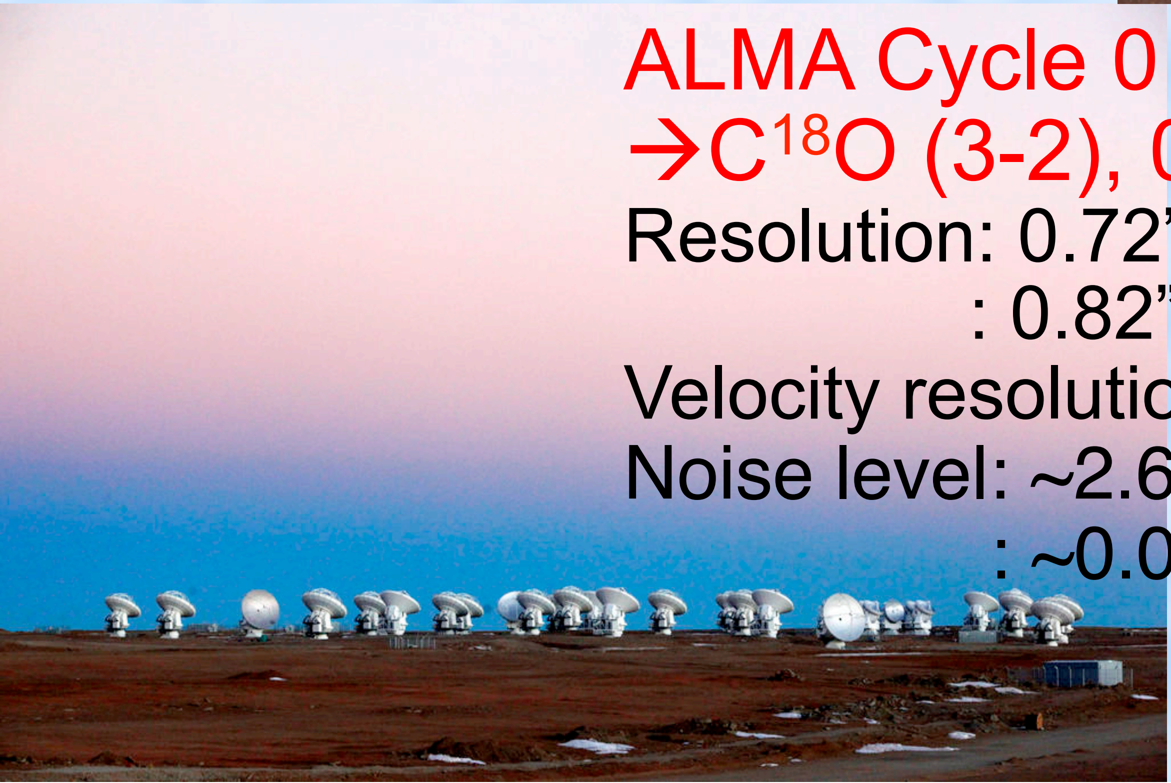


2. SMA & ALMA Observations of L1551 NE

SMA
→$C^{18}O$ (3-2; 329.331 GHz)

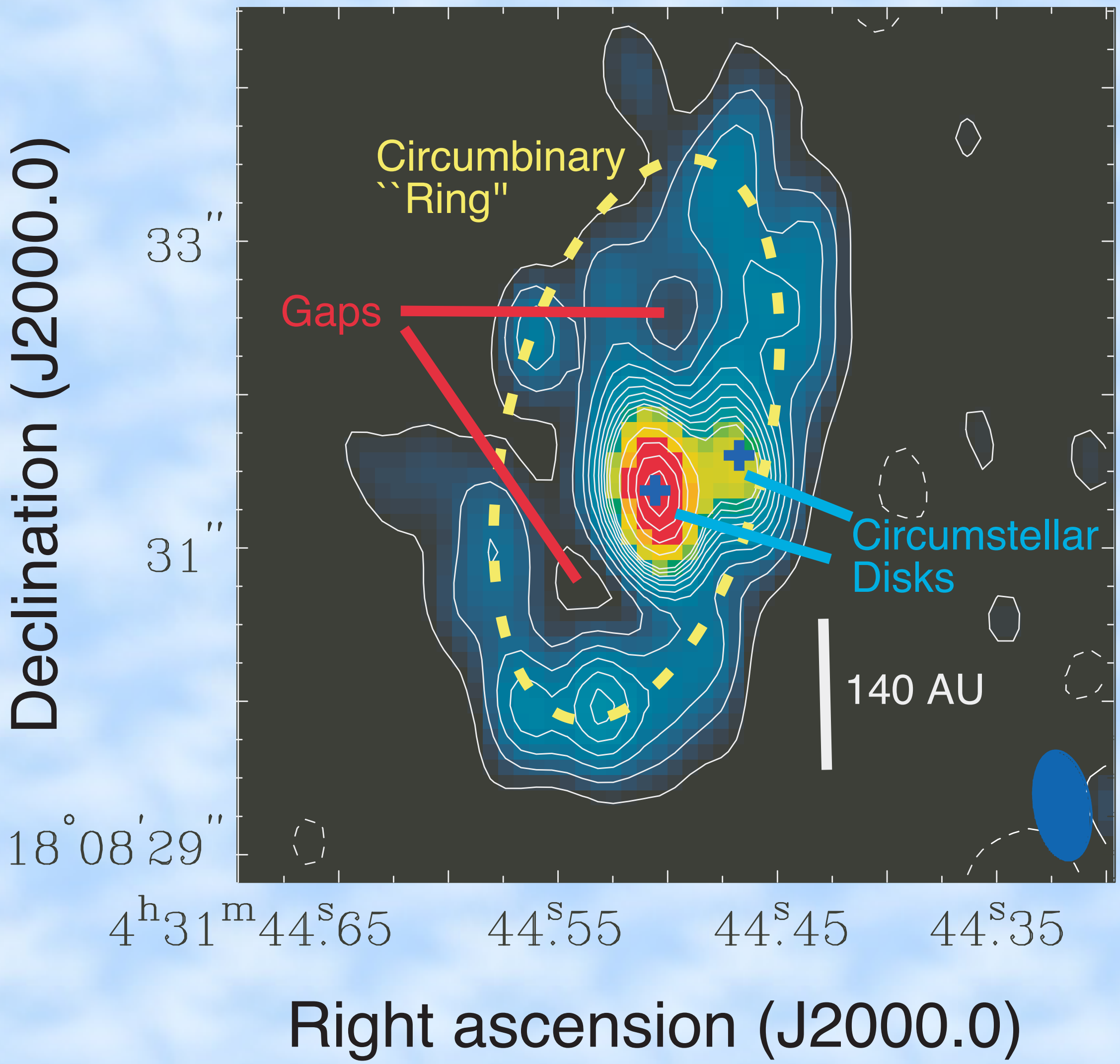
Resolution: 1.36” × 1.06”
Velocity resolution: 0.37 km s^{-1}
Noise level: ~0.078 Jy $beam^{-1}$





ALMA Cycle 0 (Filler Project)
→$C^{18}O$ (3-2), 0.9-mm Continuum
Resolution: 0.72” × 0.36” (Cont. > 80 kl)
: 0.82” x 0.49” (Line)
Velocity resolution: 0.22 km s^{-1}
Noise level: ~2.6 mJy $beam^{-1}$ (Cont. > 80 kl)
: ~0.016 Jy $beam^{-1}$ (Line)

3. Results: ALMA 0.9-mm Continuum



Compact Components associated with Sources A & B

Southern U-shaped Feature + Western Shell-like Feature

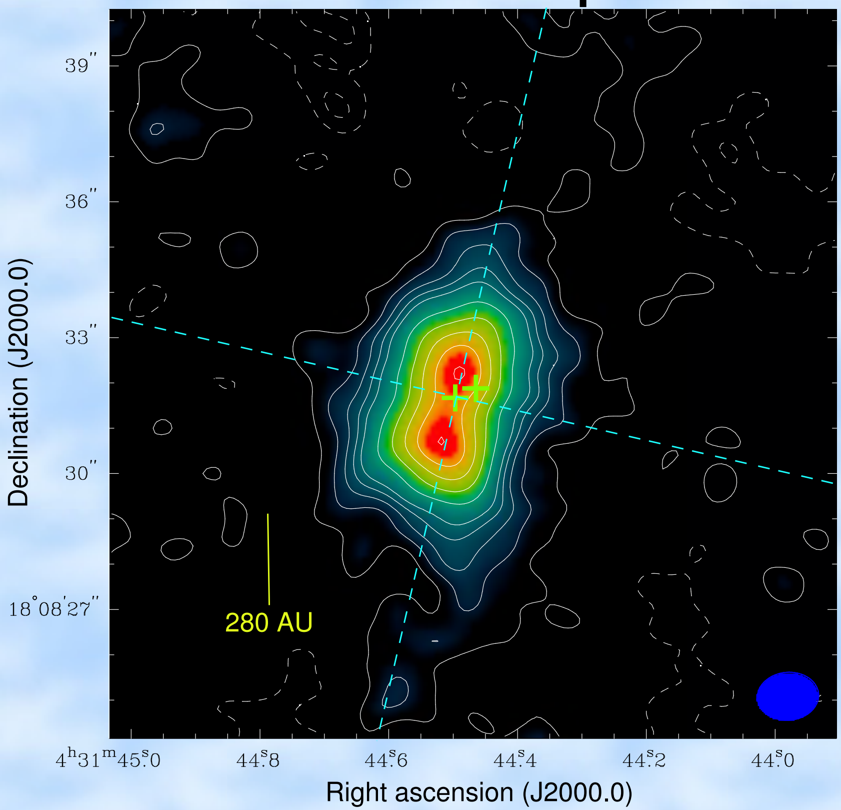
Local Emission Minima

→ Circumstellar Disks + Circumbinary ``Ring" with ``Gaps"

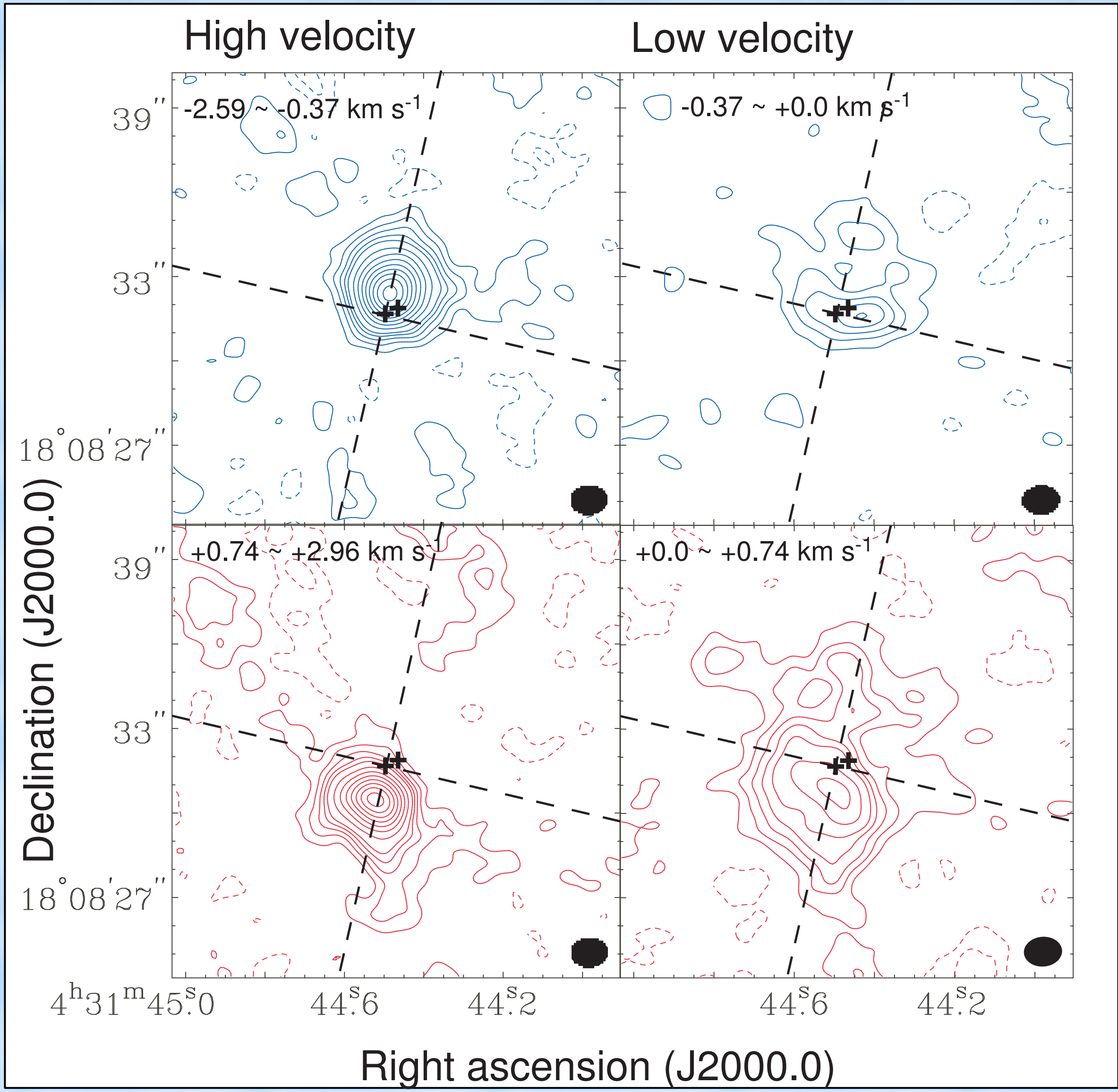
Total Mass ~0.046 M_{solar}

SMA $C^{18}O$ (3-2)

Moment 0 map



~800 AU scale, elongated circumbinary feature



@High-Velocity → North-South Vel. Grad., along the major axis

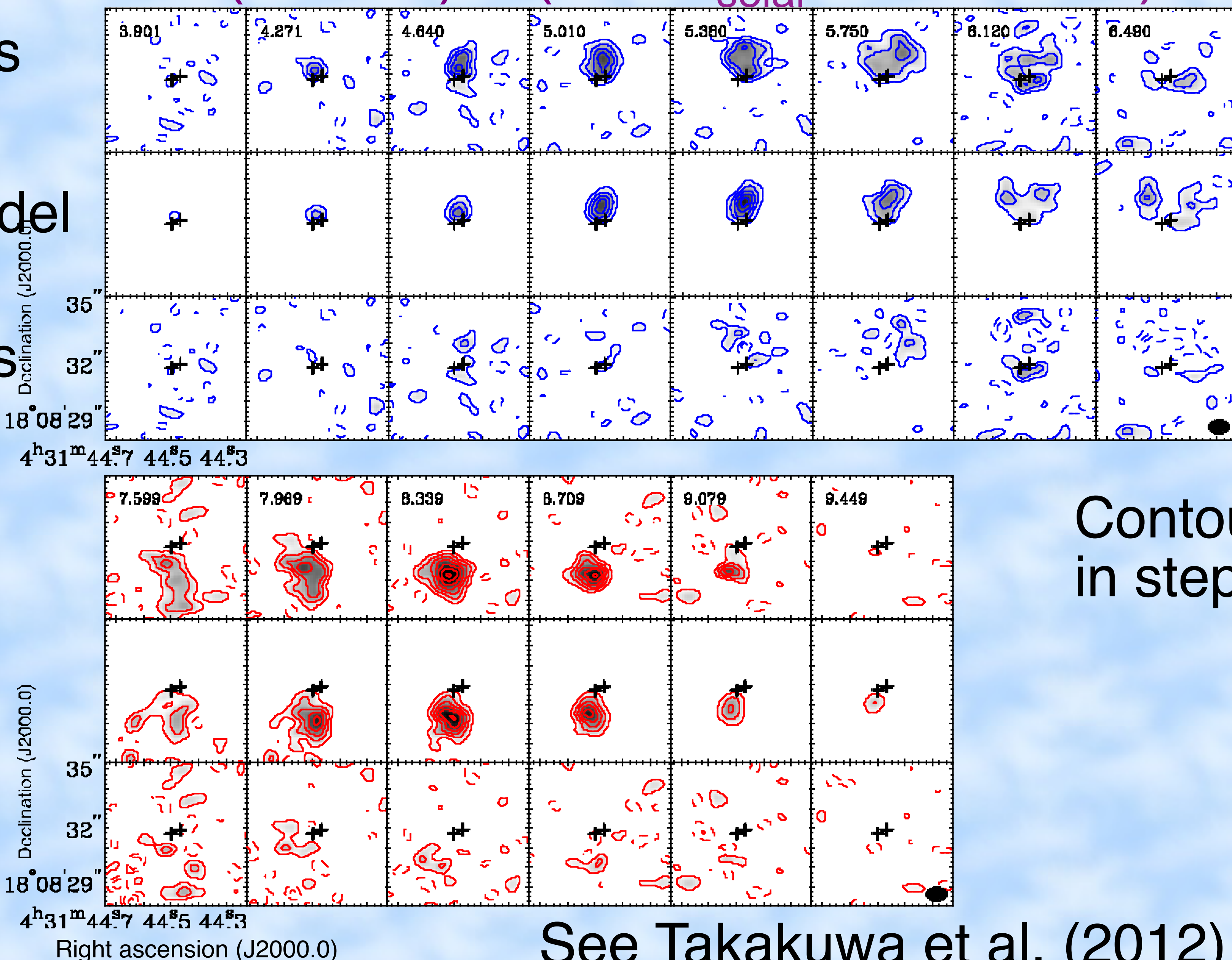
@Low-Velocity → West-East Vel. Grad., along the minor axis

χ^2 model fitting to the High-Velocity Components
→ Keplerian Circumbinary Disk with (M_*, i, θ) = (0.8 M_{solar}, -62°, 167°)

Obs

Model

Res

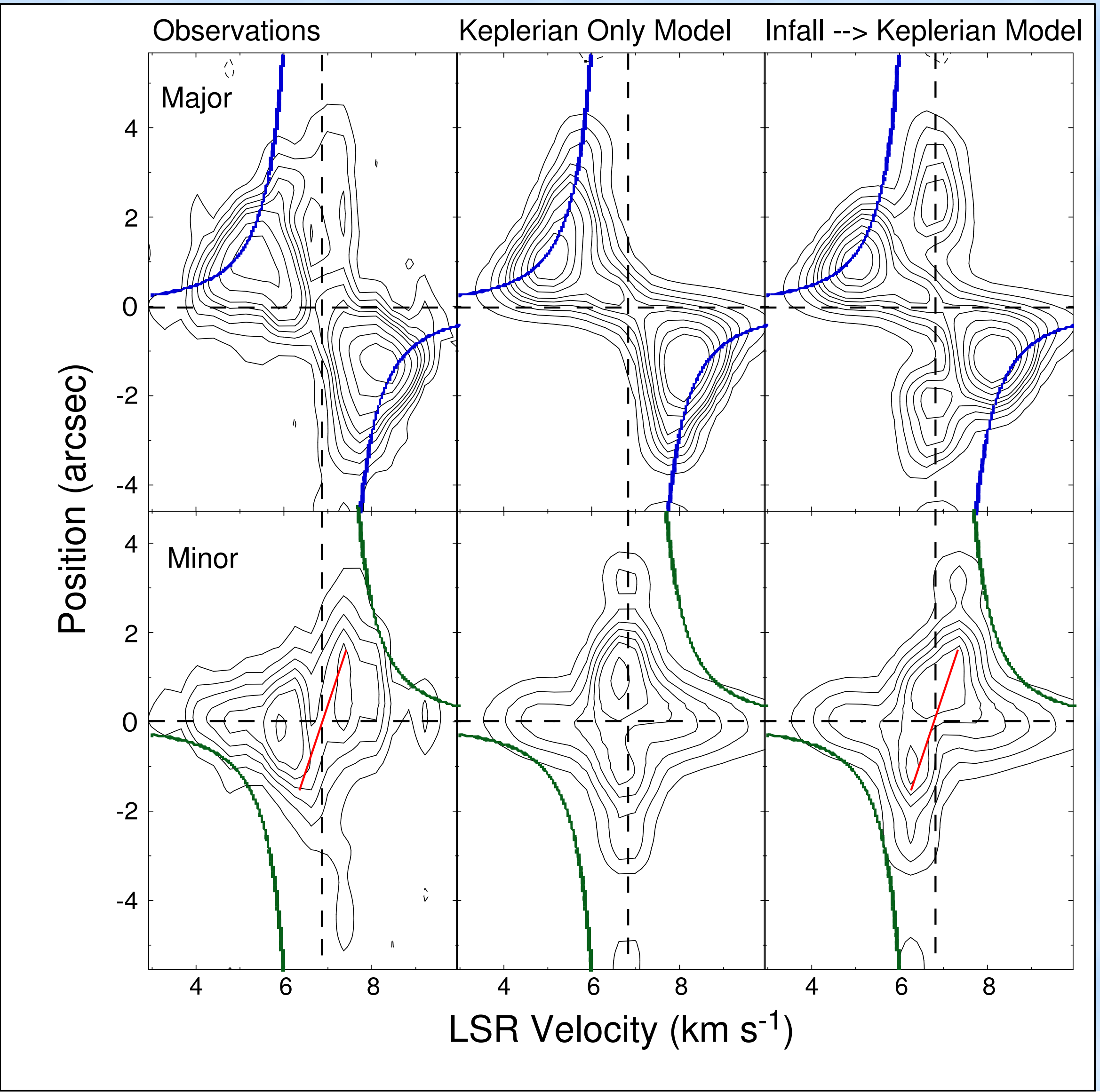


Contours
in steps of 2σ

See Takakuwa et al. (2012) for details.

Low-Velocity Components
→ Infalling Gas toward the Keplerian Circumbinary disk ??

Observed & Model P-Vs along the major and minor axes



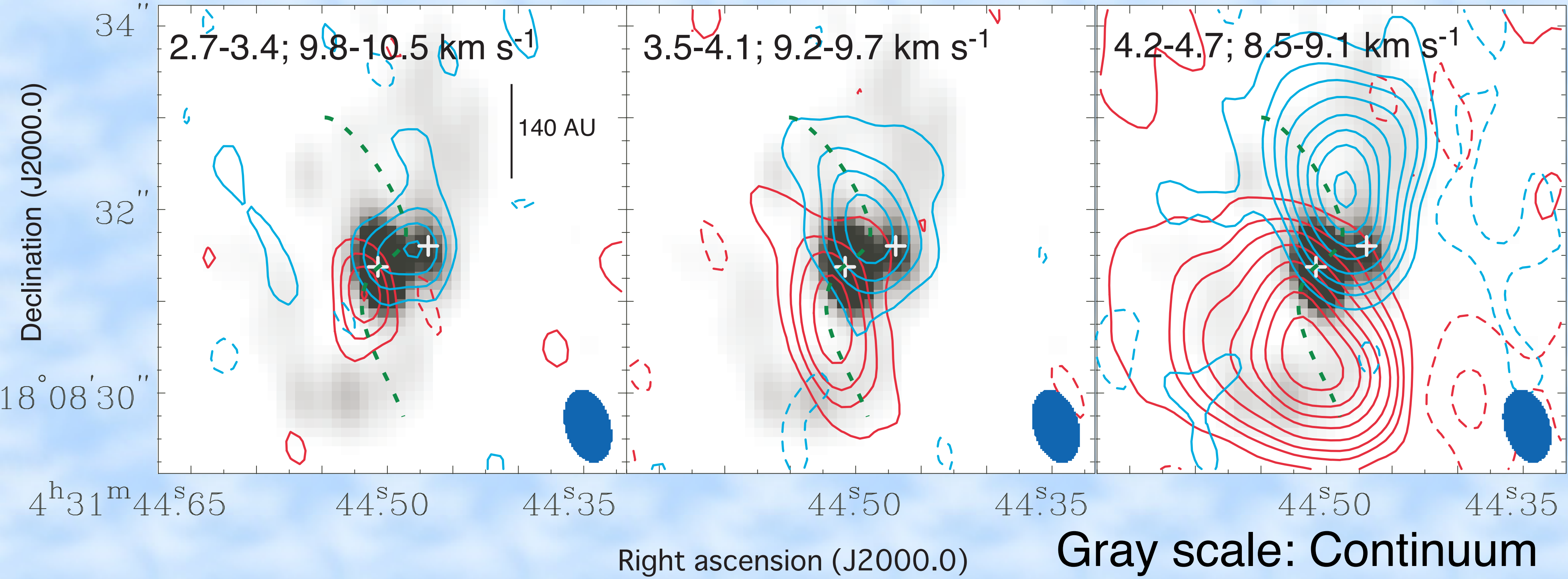
Keplerian-only model cannot explain the vel. grad. along the minor axis, nor the northern redshifted component.

Outer Infalling component,
r_{kep} ~300 AU
v_{inf}~0.6 km s^{-1}
No rotation

Note: $v_{inf} < v_{free\text{-}fall}$
@$M_* = 0.8\ M_{solar}$

ALMA $C^{18}O$ (3-2)

→ Even High-Vel. Emission closer to the protobinary

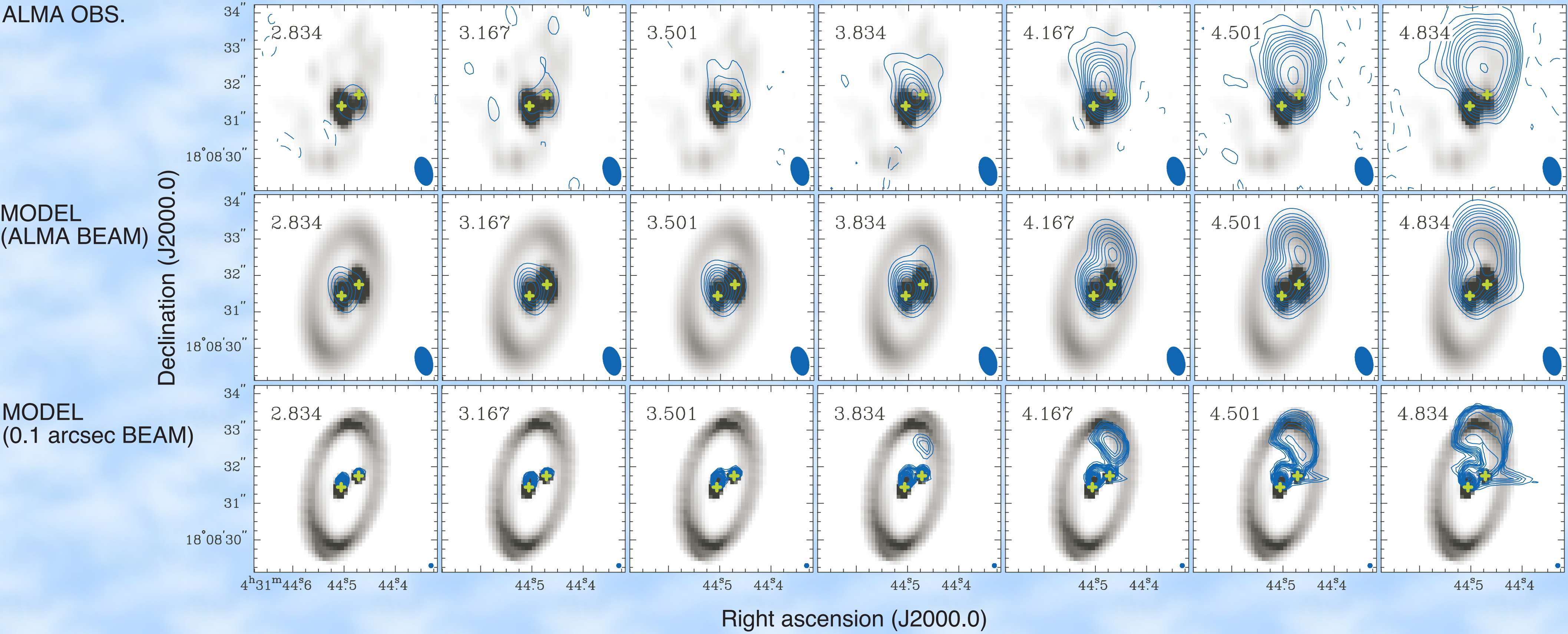


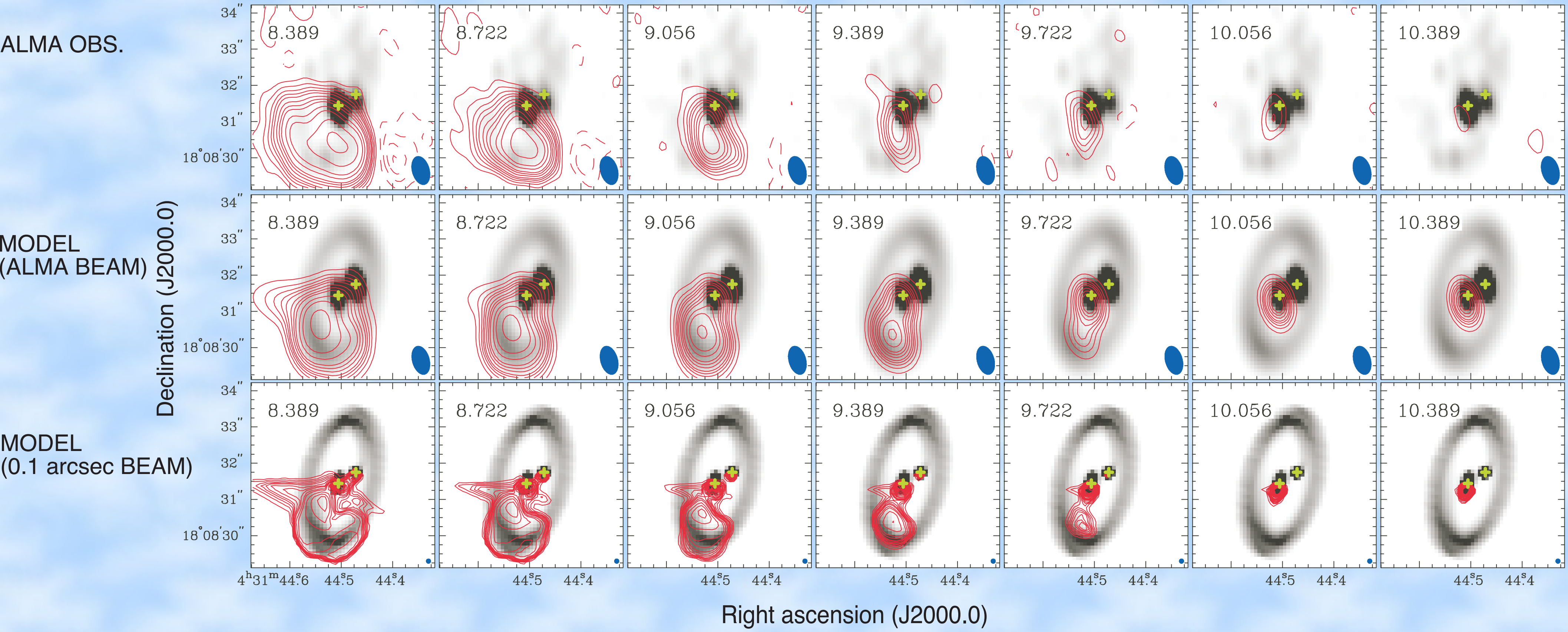
Gray scale: Continuum

S-shaped features, from the Circumbinary Ring to Source A, passing through Source B

→ Accretion Stream ?!

Comparison with theoretical simulation of binary accretion (Ochi et al. 2005; Hanawa et al. 2010)





The ALMA results are consistent with our theoretical model of binary accretion.

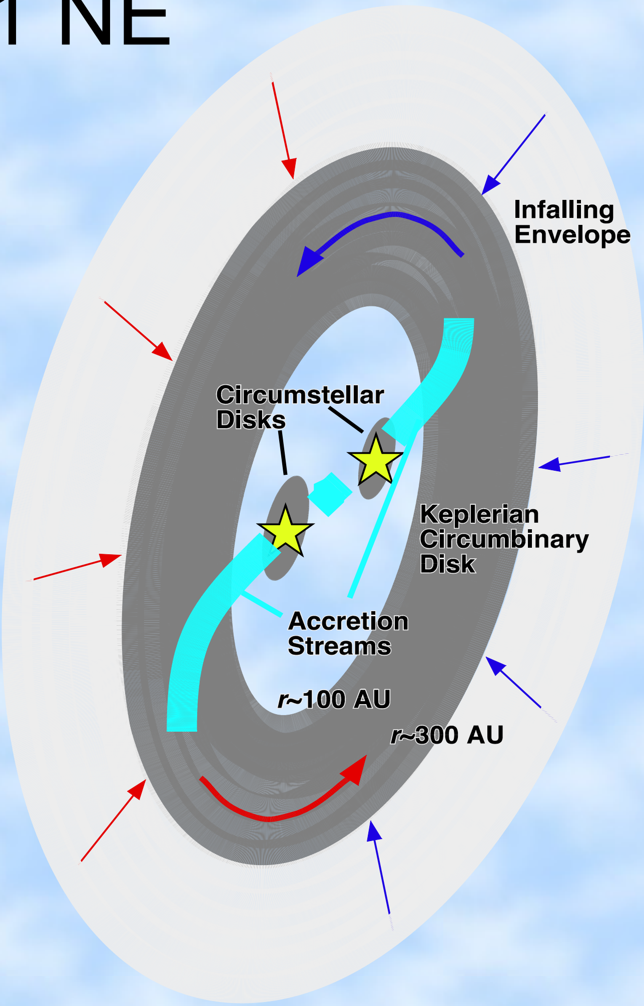
4. Summary: Hierarchical Structure of the Binary-Forming Region L1551 NE

Outer ($r > 300$ AU) Infalling Envelope

Keplerian Circumbinary Disk
(~100 AU < r < 300 AU)

Circumstellar Disks

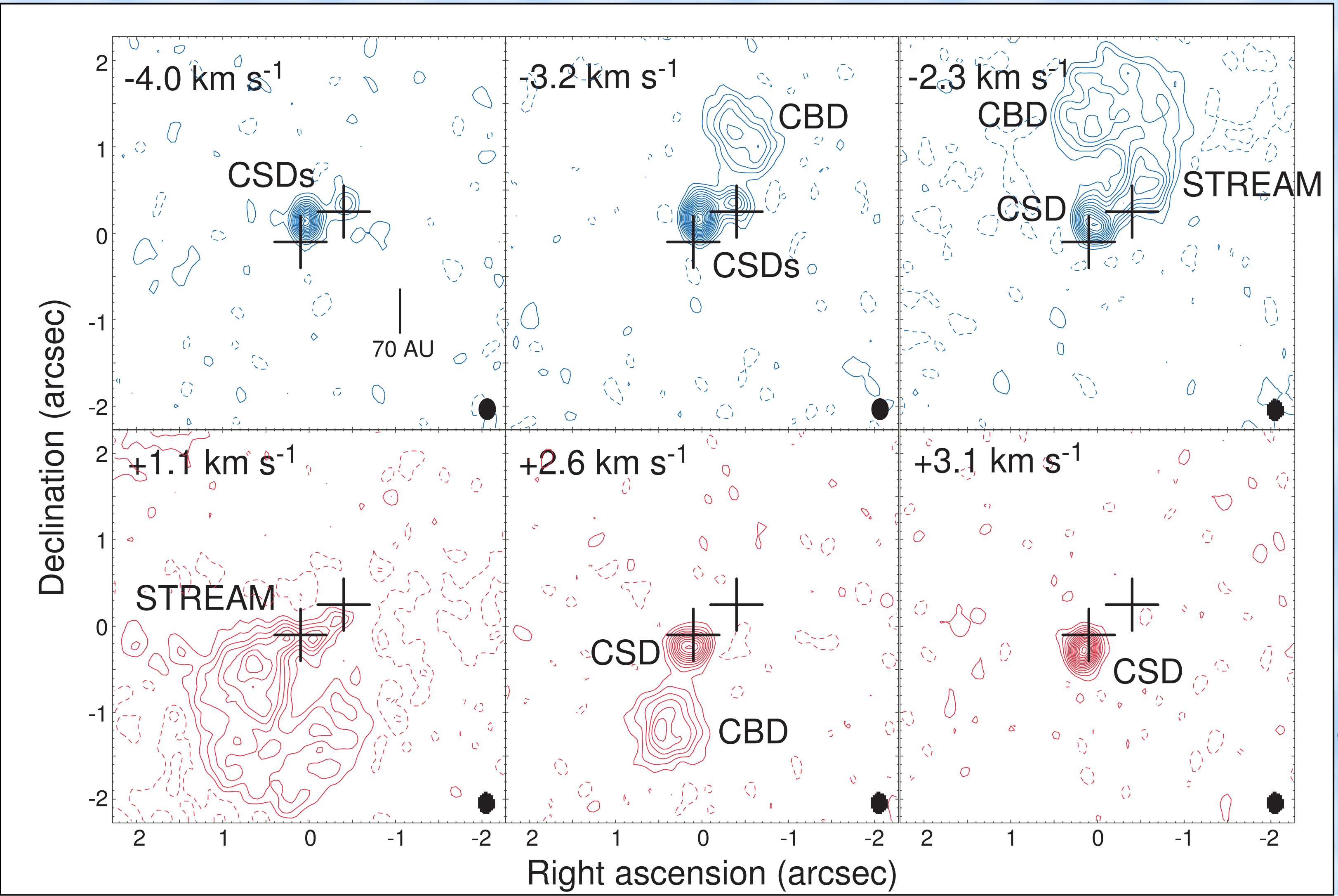
Accretion Streams from the Circumbinary Disk
to the Circumstellar Disks



4. Future ALMA Observation

→ Direct Imaging of the ``Accretion Streams'' connecting between the Circumbinary Disk (CBD) and the Circumstellar Disks (CSDs)

Simulated ALMA Image of L1551 NE in the $C^{18}O$ 3-2 Emission



Based on the theoretical model by Ochi et al.('05)

2. SubMillimeter Array (SMA) Observations of L1551 NE

$C^{18}O$ (3-2; 329.331 GHz) and 0.9-mm continuum

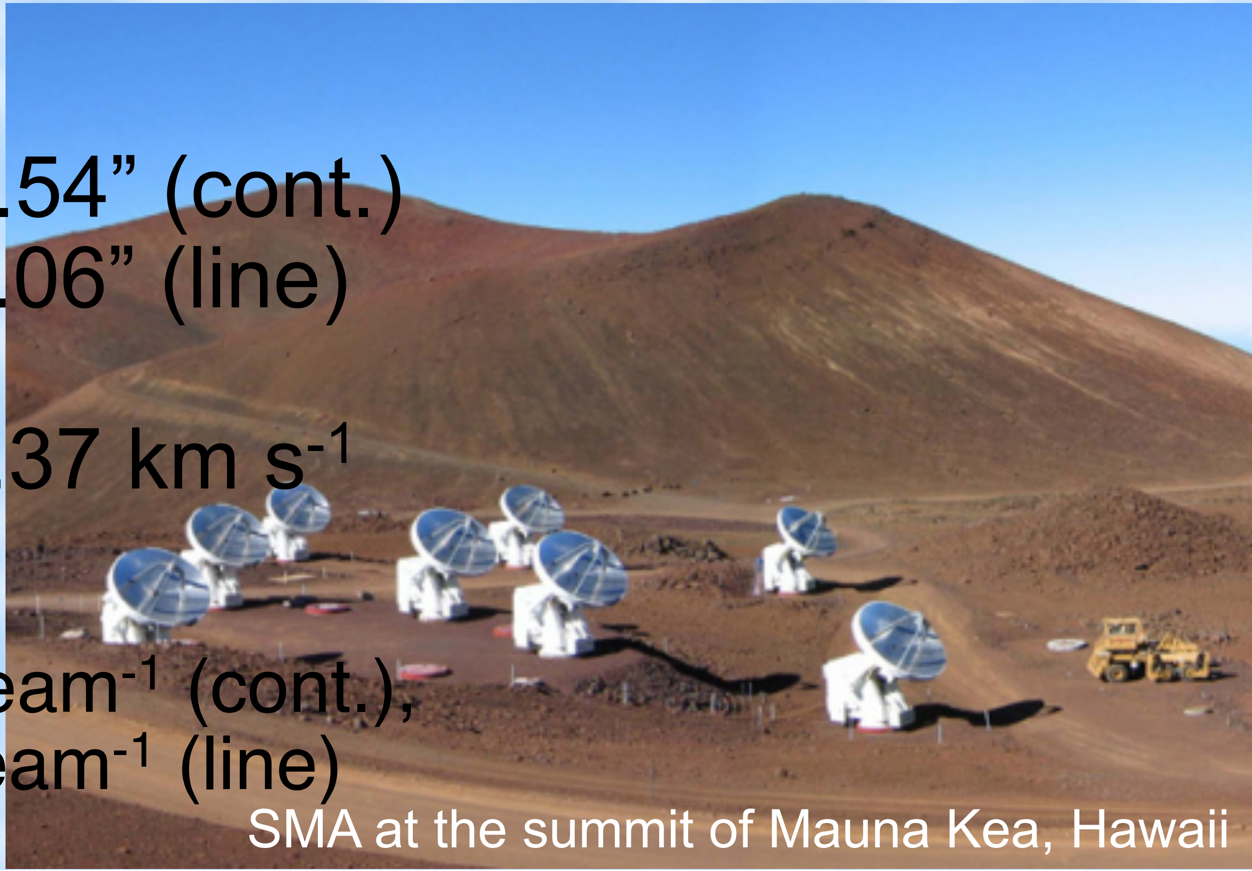
Extended Configuration (2010) → Circumbinary Disk
(Sub-)Compact Config. (2011, 2012) → Envelope

Primary beam: ~37”

Resolution: 0.80” × 0.54” (cont.)
: 1.36” × 1.06” (line)

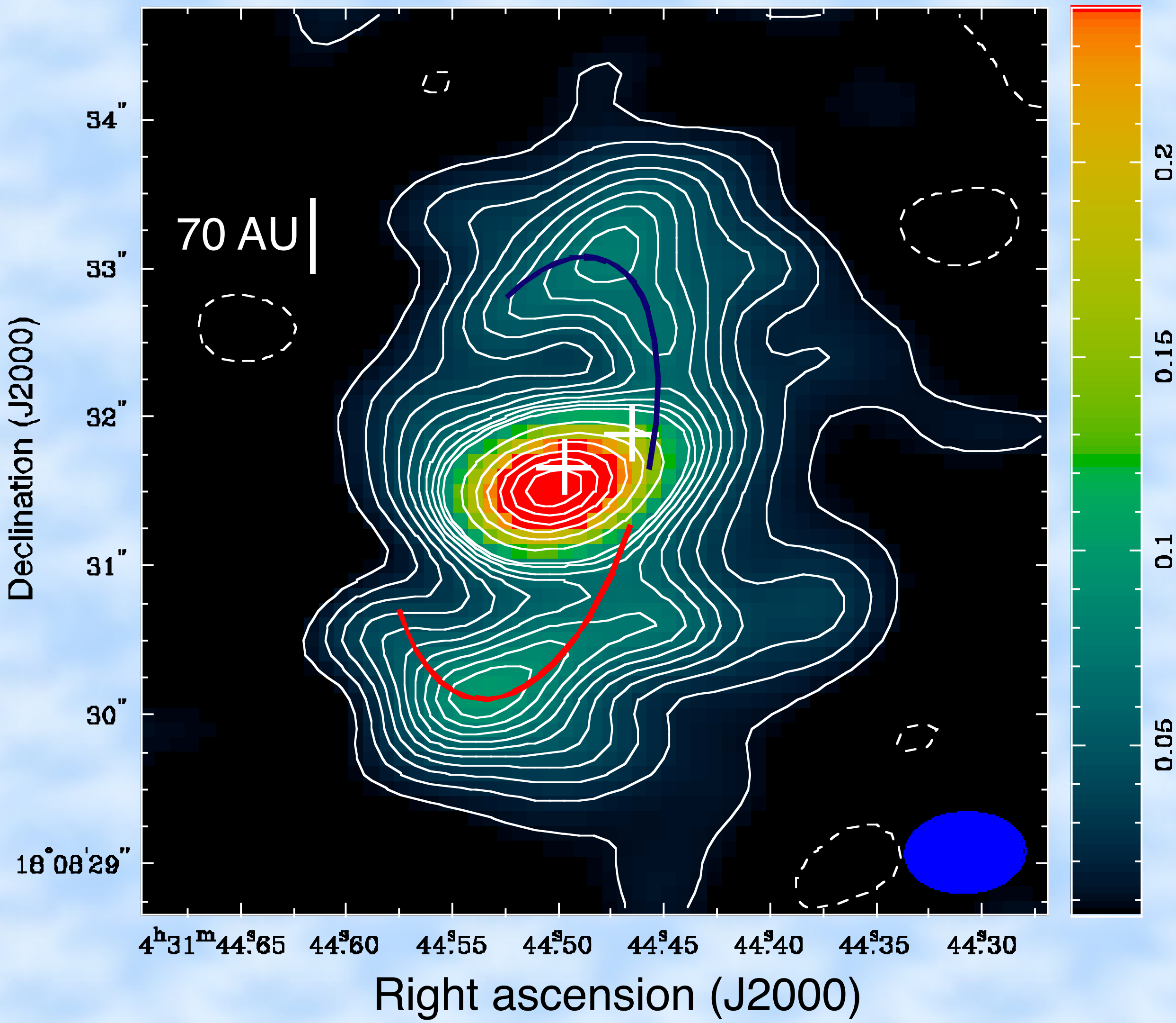
Velocity resolution: 0.37 km s^{-1}

Noise level: ~3.6 mJy $beam^{-1}$ (cont.),
~0.078 Jy $beam^{-1}$ (line)



SMA at the summit of Mauna Kea, Hawaii

3. Results: 0.9-mm Continuum



Compact Component associated with Source A (0.9” x 0.5”, 0.7 Jy) + Protrusion to Source B

+ North and South Comp.

Rim-Brightening Circumbinary Disk + Circumstellar Disks ?

Total Mass ~ 0.046 M_{solar}

4. Discussion

4. Discussion

- Compact (~100 AU) dusty condensation at Source A, B
  → Circumstellar Disks
- Northern + Southern components

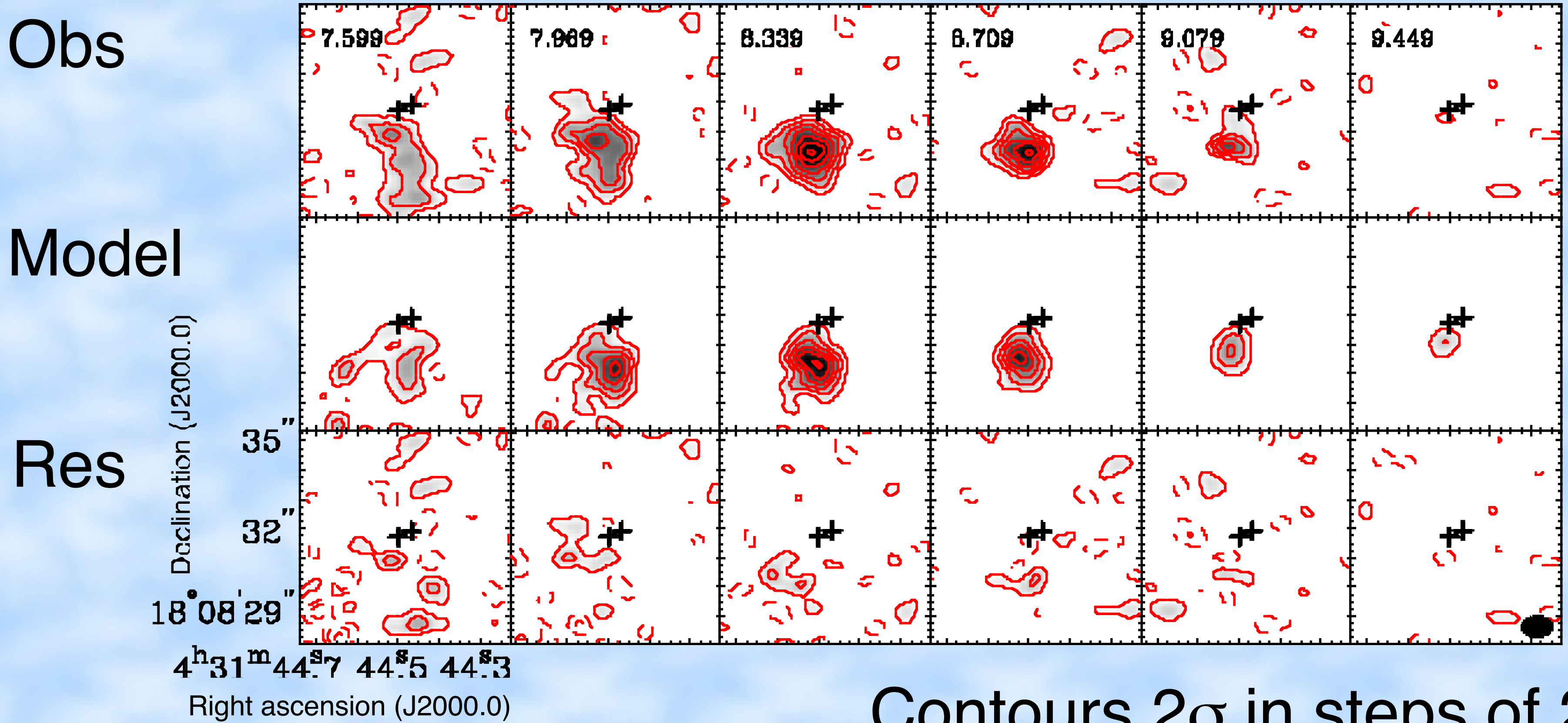
→ r_{kep}~300 AU Circumbinary Disk

- The Circumbinary Disk exhibits Keplerian Rotation seen in the $C^{18}O$ line.

- Outside of the Disk (r_{kep}~300 AU), there is a

- ^{13}CO (3-2) & $C^{18}O$ (3-2) line show clear velocity gradient along the major axis (SE - NW), centered on Source A

$C^{18}O$ Red

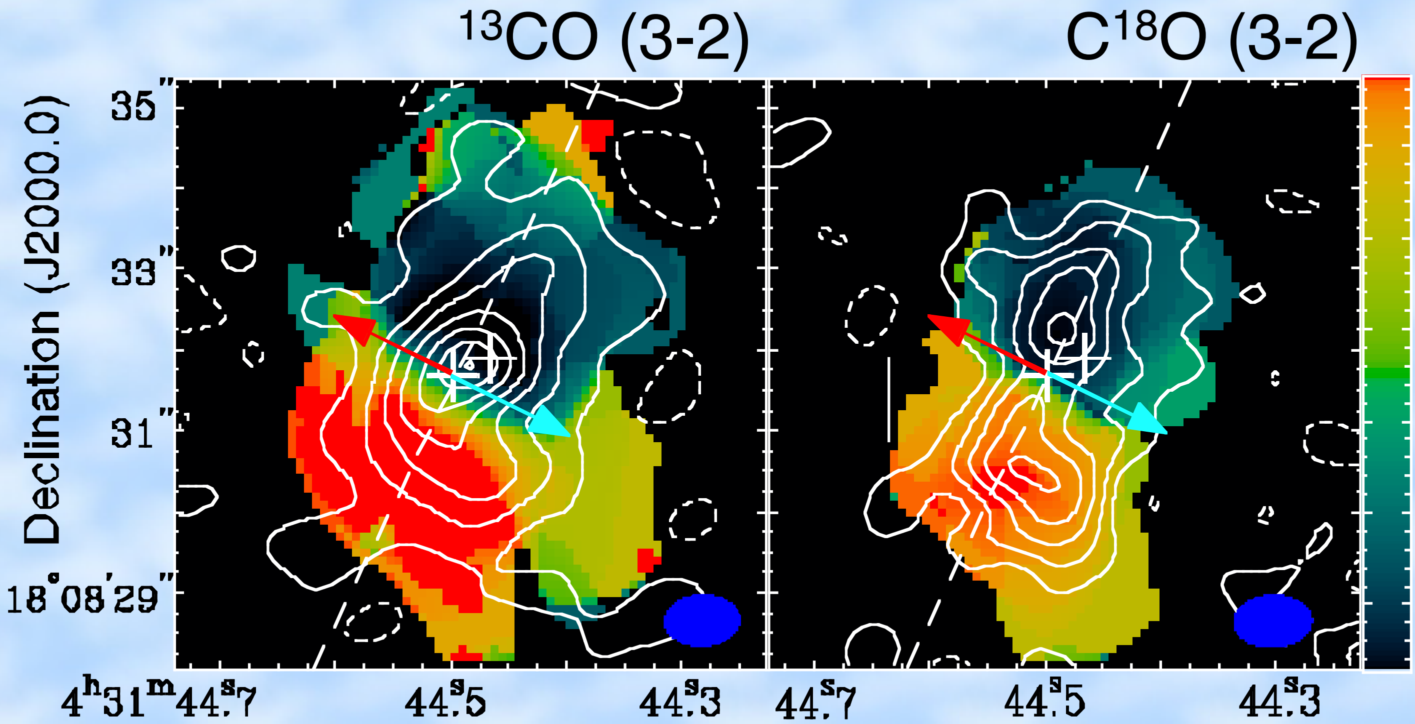


Contours 2σ in steps of 2σ

Fitting rms ~0.14 Jy $beam^{-1}$ >~ Obs rms 0.12 Jy $beam^{-1}$

For this simple, thin disk model with only three parameters, the $C^{18}O$ fitting result is good.

Moment 0 & 1 Maps



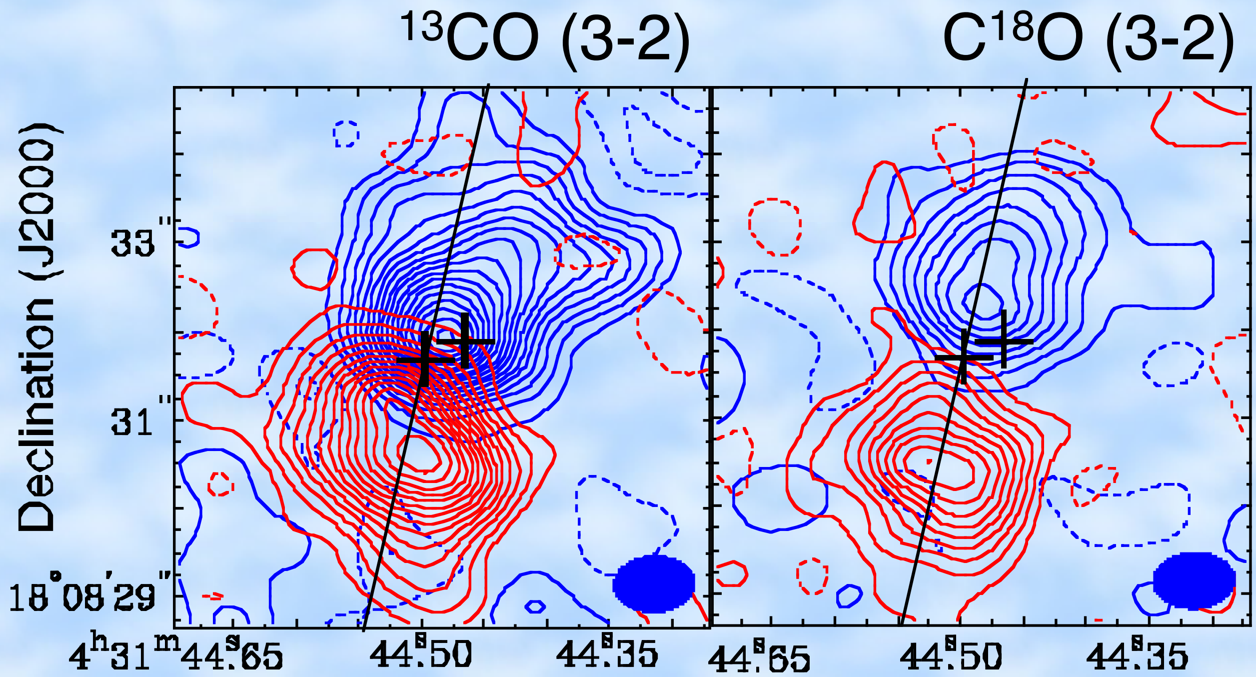
Color: Mom 1
Contour: Mom 0

Clear Velocity Gradient along SE - NW, approximately along the major axis

No clear Velocity Gradient along the minor axis ?

The position of Source A appears to be the ``center" (V_{sys} ~ 7 km s^{-1})

Blue- and Redshifted Components



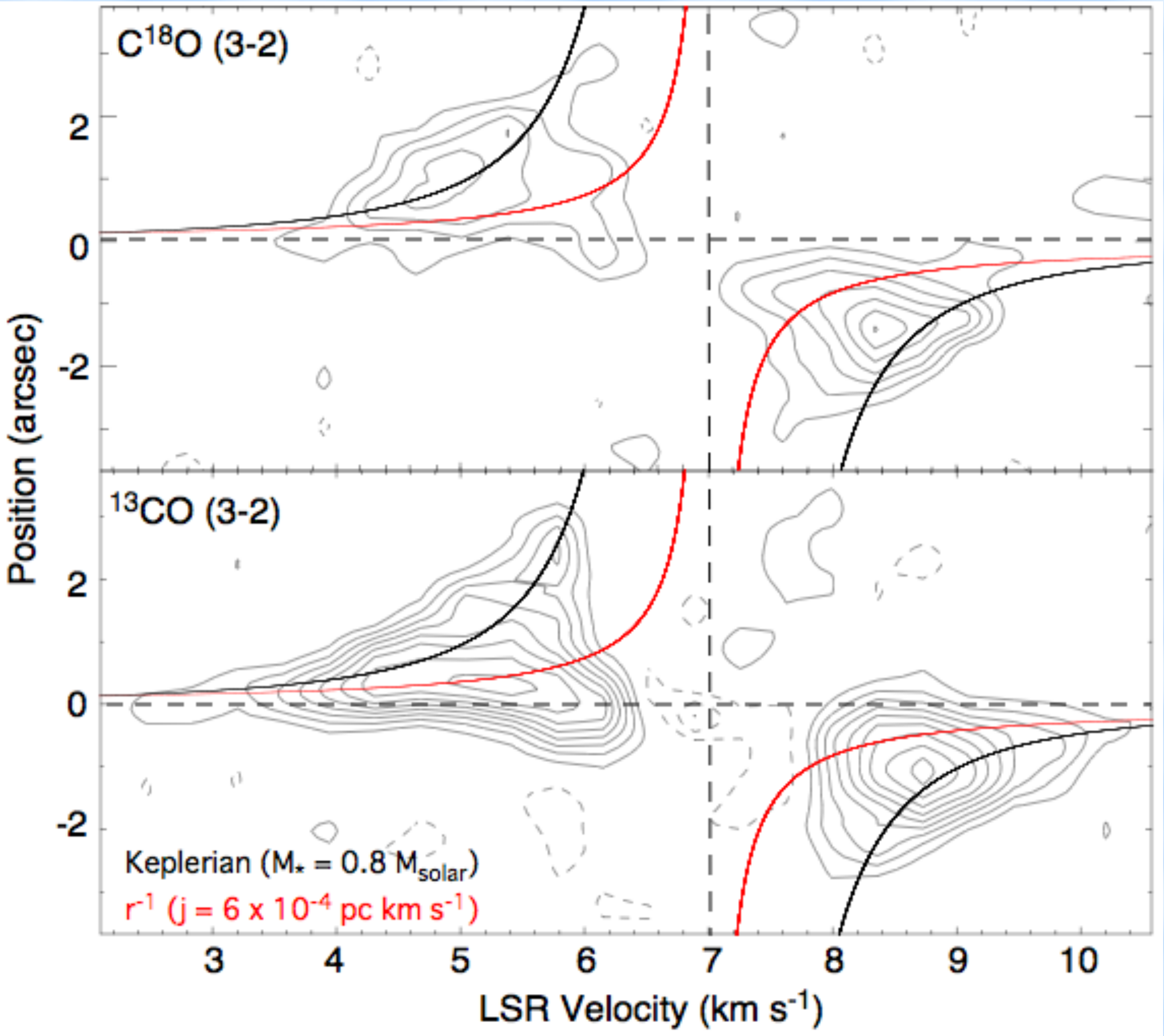
Blue: 4.1 - 6.0 km s^{-1}

Red: 7.8 - 9.7 km s^{-1}

Blue- and Redshifted Emission at the NW and SE of Source A, Aligned along the major axis

Source A is likely the kinematical Center of the Gas Motion.

Position - Velocity Diagrams along the major axis



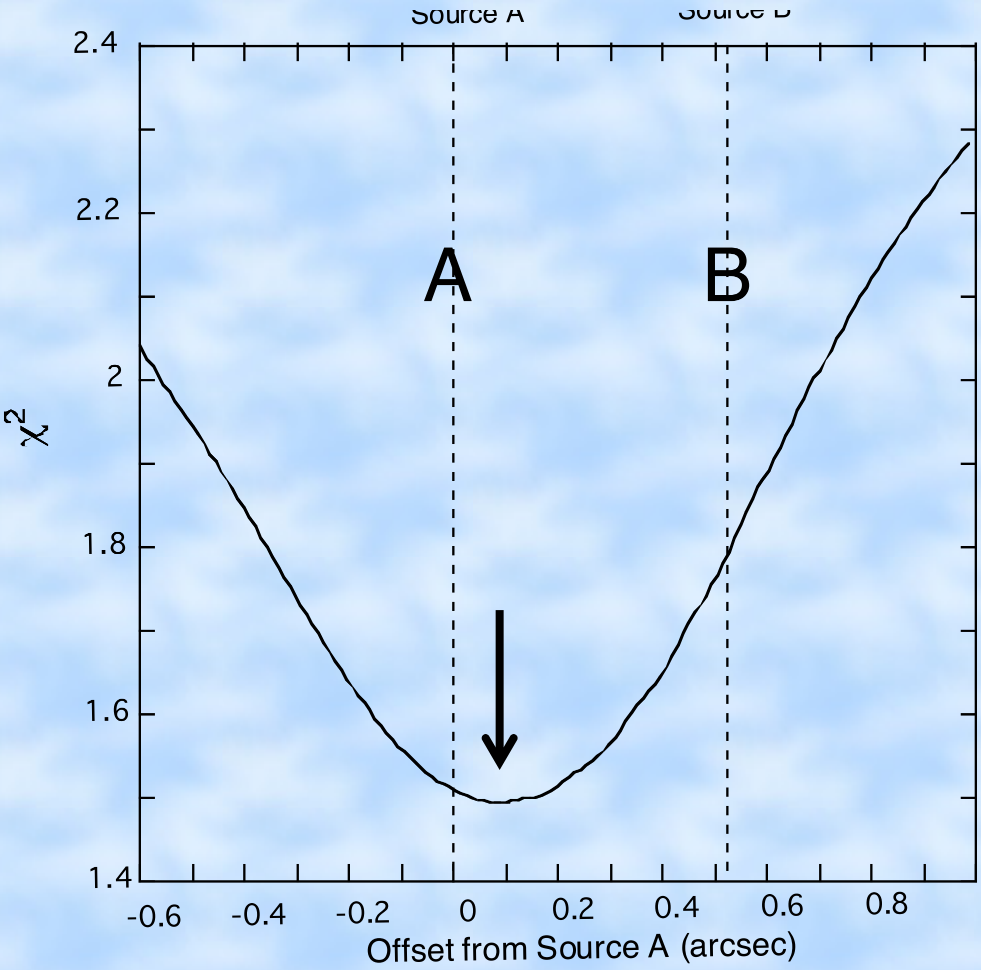
High-Velocity Comp. Closer to Source A

Keplerian Rotation better than r^{-1} rotation?

--> See Next

Discussion

The presence of the Keplerian-rotating circumbinary disk
→Direct method to measure the mass and the ratio of the protobinary.



Rotational Center

The location of the Keplerian Rotation Center between Source A and B provides the mass ratio.

Mimimum χ2 location
---> 0.08" offset from Source A over the binary separation of 0.52"

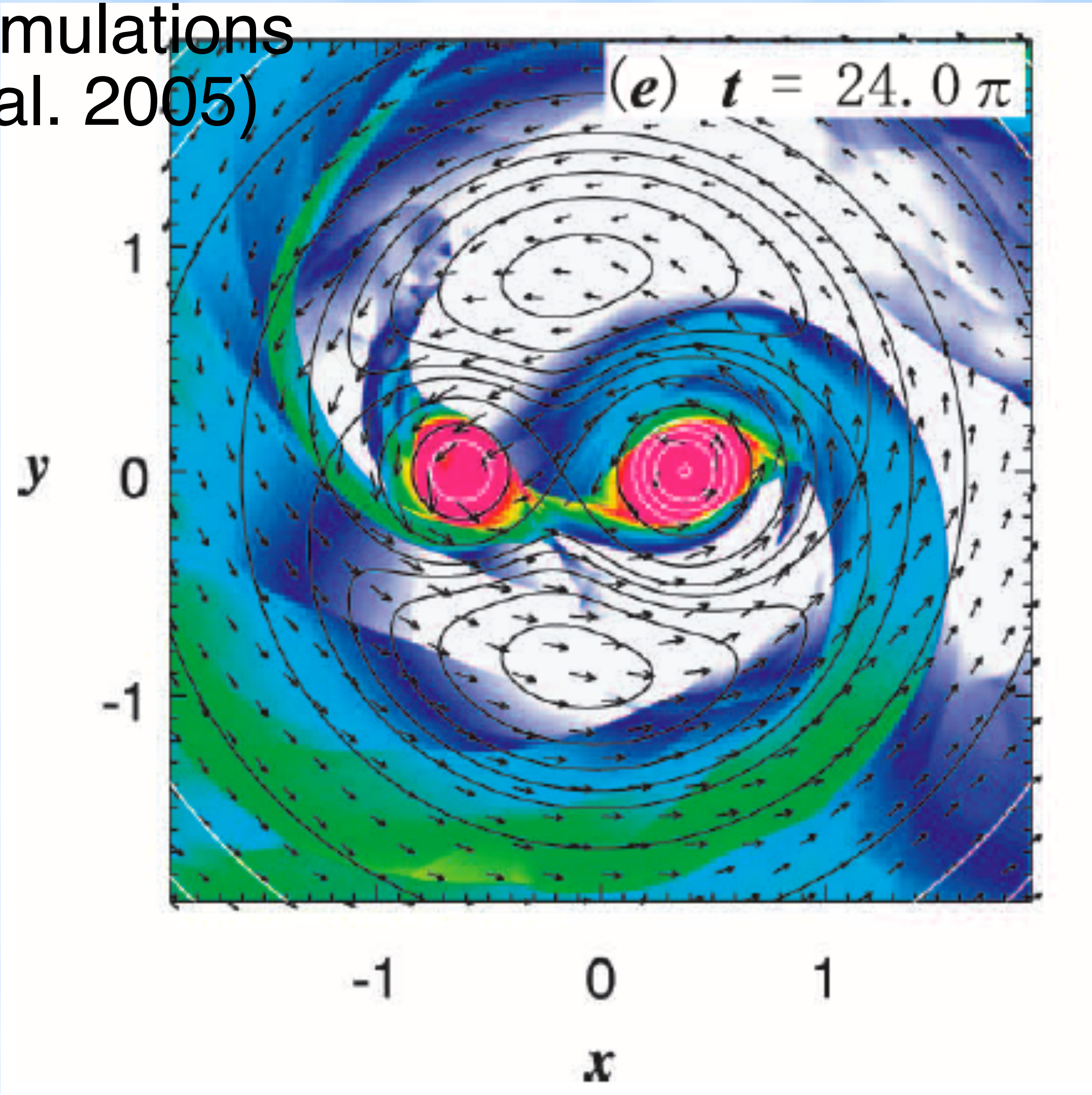
→Mass Ratio ~5.4
(Source A = 0.68 Msolar,
Source B = 0.13 Msolar)

Different Mass of the Protobinary companions ?

Put stringent constraint on the theory of binary formation

High-resolution numerical simulations of binary accretion (Ochi et al. 2005)

→The primary accretes more than the secondary, regardless of the specific angular momentum of the initial infalling envelope.



Our obs. consistent ??

5. Discussion

The presence of the Keplerian rotating circumbinary disk
--> Direct method to measure the mass of the protobinary.

Furthermore, the rotation center is close to Source A, not B
→*Source A is more massive than Source B ??*
→*(or, Source B is not a protostar ??)*

We could measure both the mass and mass ratio
of the protobinary.

In L1551 NE, the central mass ~ 0.8 Msolar

2. Sub-arcsecond SMA Observations of L1551 NE

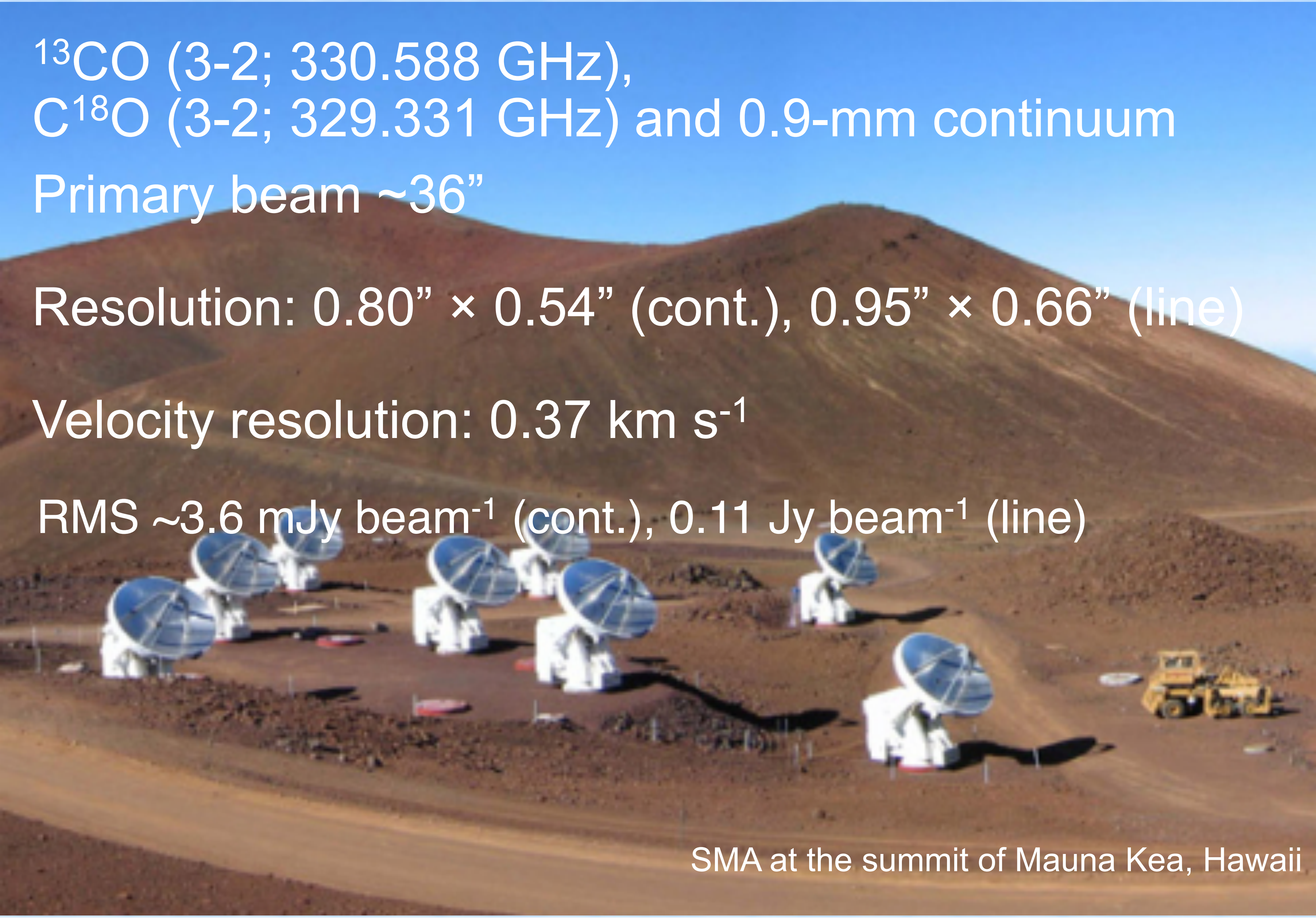
^{13}CO (3-2; 330.588 GHz),
$C^{18}O$ (3-2; 329.331 GHz) and 0.9-mm continuum

Primary beam ~36”

Resolution: 0.80” × 0.54” (cont.), 0.95” × 0.66” (line)

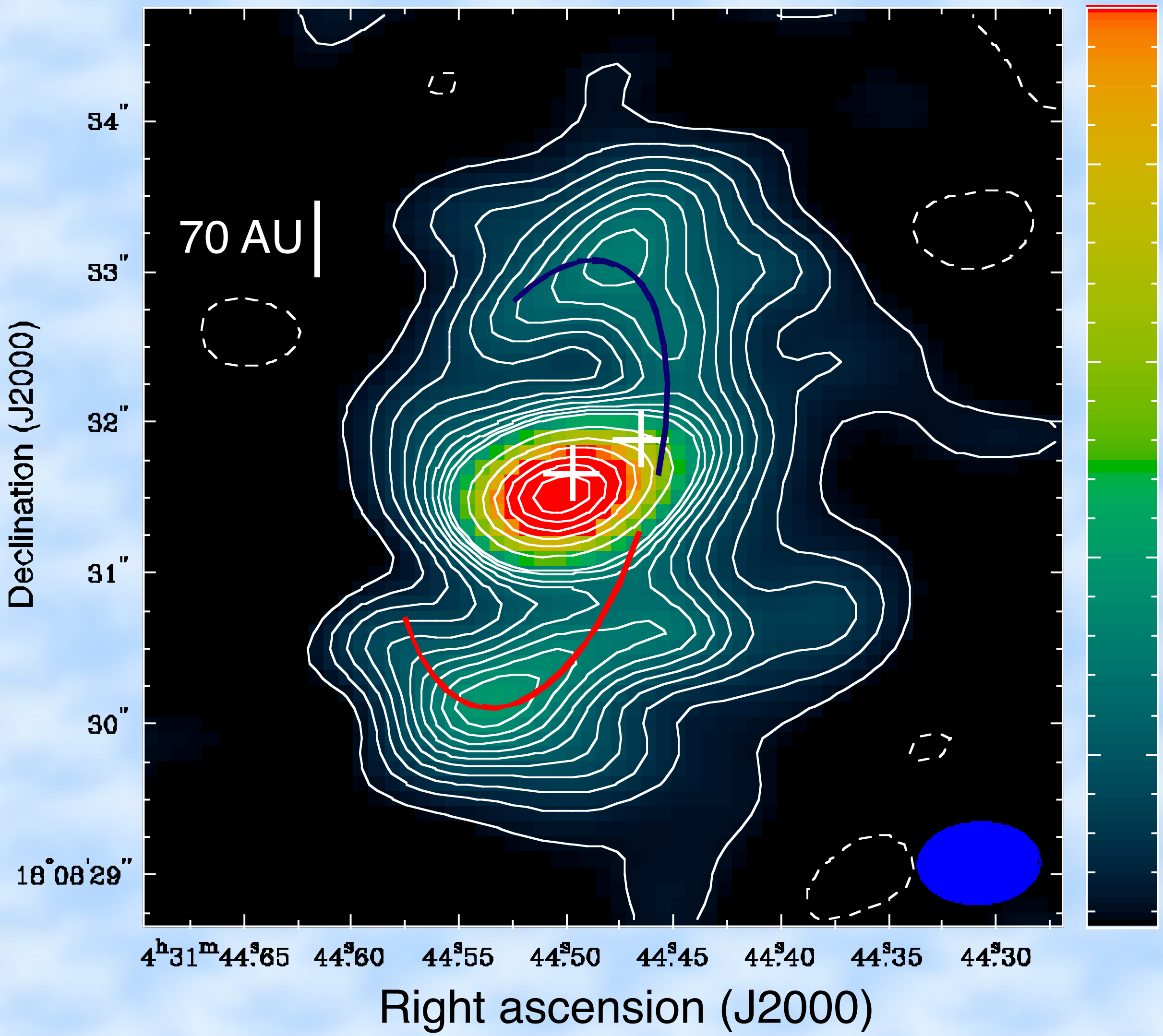
Velocity resolution: 0.37 km s^{-1}

RMS ~3.6 mJy $beam^{-1}$ (cont.), 0.11 Jy $beam^{-1}$ (line)



SMA at the summit of Mauna Kea, Hawaii

3. Results: 0.9-mm Continuum



Compact Component associated with Source A (0.9" x 0.5", 0.7 Jy)

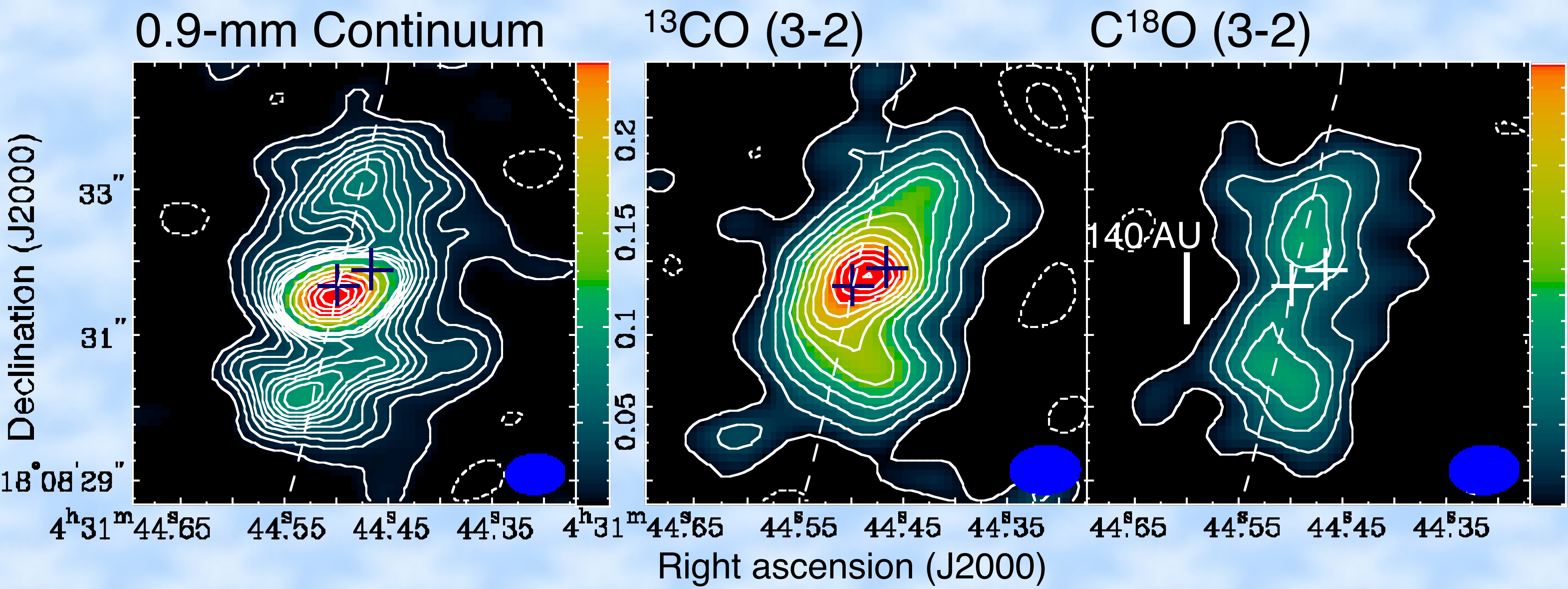
+ North and South Comp.

Rim-Brightening Circumbinary Disk + Circumstellar Disk at A ?

Total Mass ~ 0.046 M_{solar}

No compact component associated with Source B ?
--> Different Properties between Source A and B, Evolution ??

Moment 0 Maps



~500 AU Scale Elongated Features along the NW to SE Direction (P.A. ~ 167 deg: Dashed Lines), approximately centered on Source A

Molecular-Line Distributions Different from the Continuum
--> Abundance Variation, Background Dust-cont. Emission ?

4. Analysis

In order to quantitatively understand the Gas Motion in the Circumbinary Disk, we performed Model Disk Fitting to the observed Image Cubes.

Model: Geometrically-thin, Keplerian Rotating Disk

↓ χ^2 Fitting

Obs: $C^{18}O$ (3-2), ^{13}CO (3-2) Image Cube
(excluding the two channels around V_{sys} = 7 km s^{-1}, where the bulk of the emission ``resolved out")

Model Parameters

<u>Fitting Parameters</u>

Central Mass: M_*, Disk Inclination: i, Disk Position Angle: θ

<u>Fixed, Assumed Parameters</u>

Model Disk Mom 0 Image = Observed Mom 0 Image
(We do not ``model'' the 2-D emission Distribution)

Dynamical Center = Position of Source A

Vsys = 7 km s^{-1}

Internal Gas Dispersion: σ = 0.4 km s^{-1}

Distance = 140 pc

Fitting Procedure

1. At a given (M_*, i, θ) --> Central velocity in each position v_{cen} (α, δ) of the geometrically-thin disk, with the observed mom 0 emission $I_{obs}(\alpha, \delta)$.

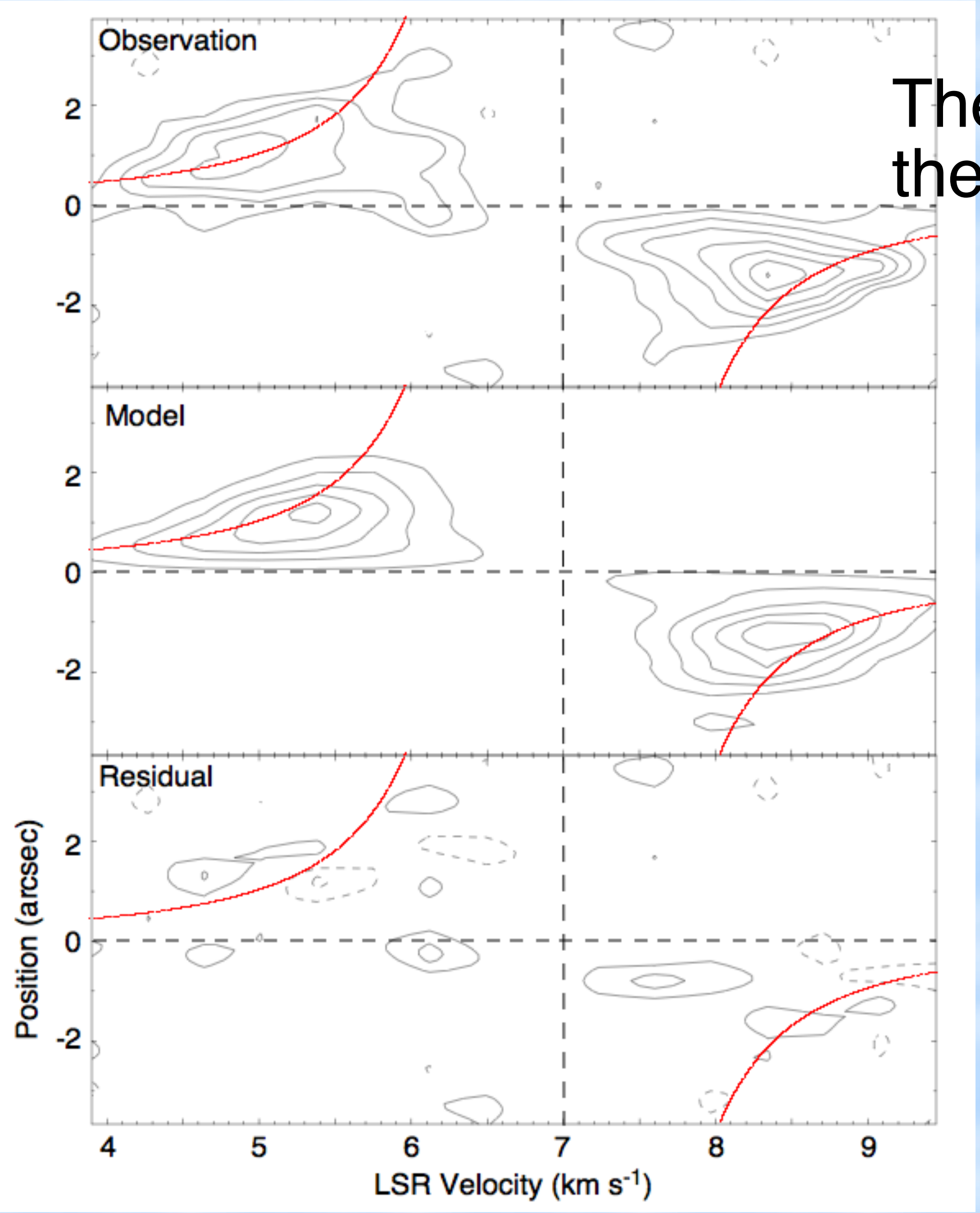
Loop

2. Calculate Model Image Cube as,
S_{model} (α, δ, v) = $I_{obs}(\alpha, \delta)$ * exp (-(v-$v_{cen}(\alpha, \delta))^2$ / 2 σ^2)

3. Calculate $\chi 2$ between S_{model} (α, δ, v) and S_{obs} (α, δ, v)

4. Store (M_*, i, θ) with the least $\chi 2$

$C^{18}O$ 3-2 P-V Fitting

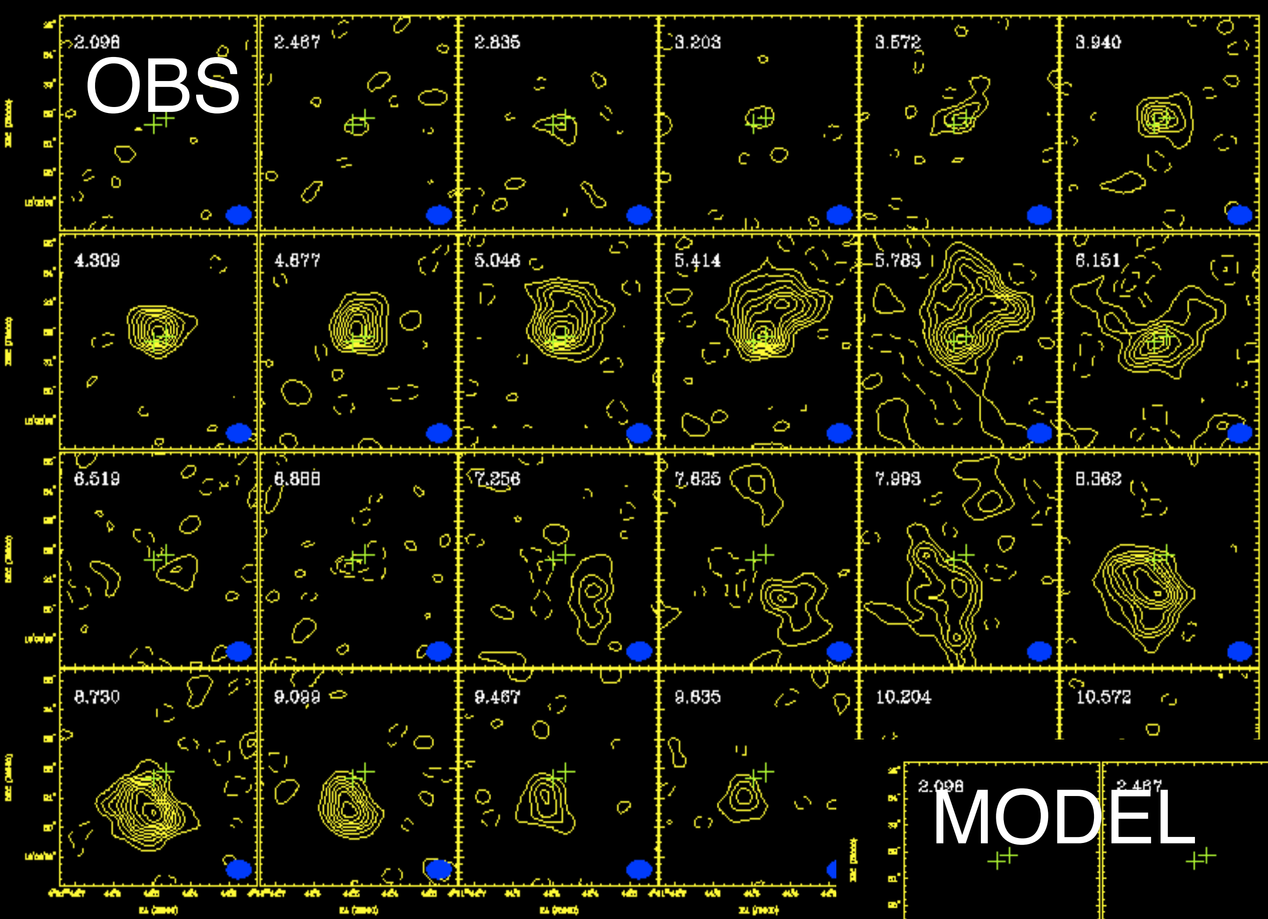


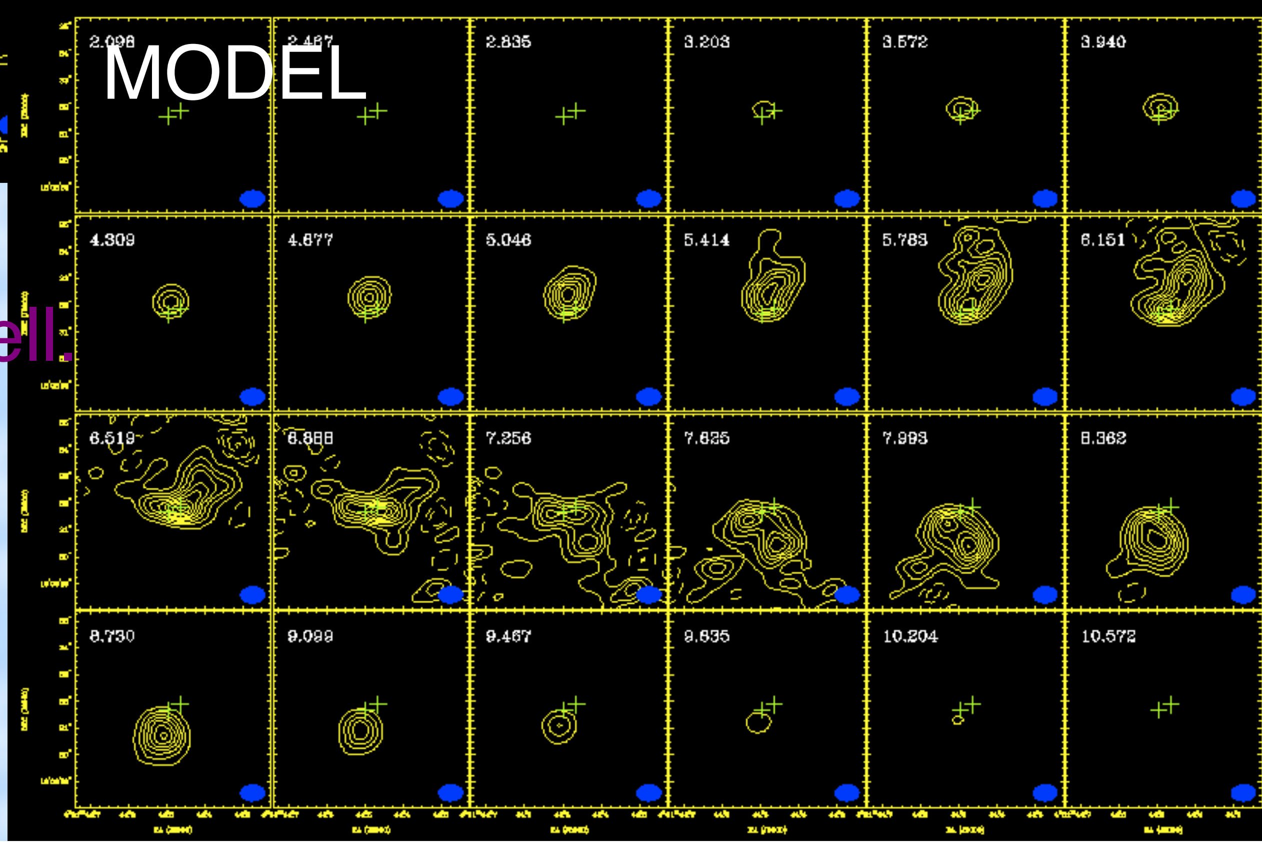
The same model can reproduce the observed P-V.

^{13}CO Fitting

The parameters from $C^{18}O$ reproduce the overall velocity feature, but significant residuals.

Independent fitting
--> still significant res.





^{13}CO cannot be fitted with the thin Kep disk well.

Effect of Outflow ?
Thickness of the disk ?
More missing Flux ?

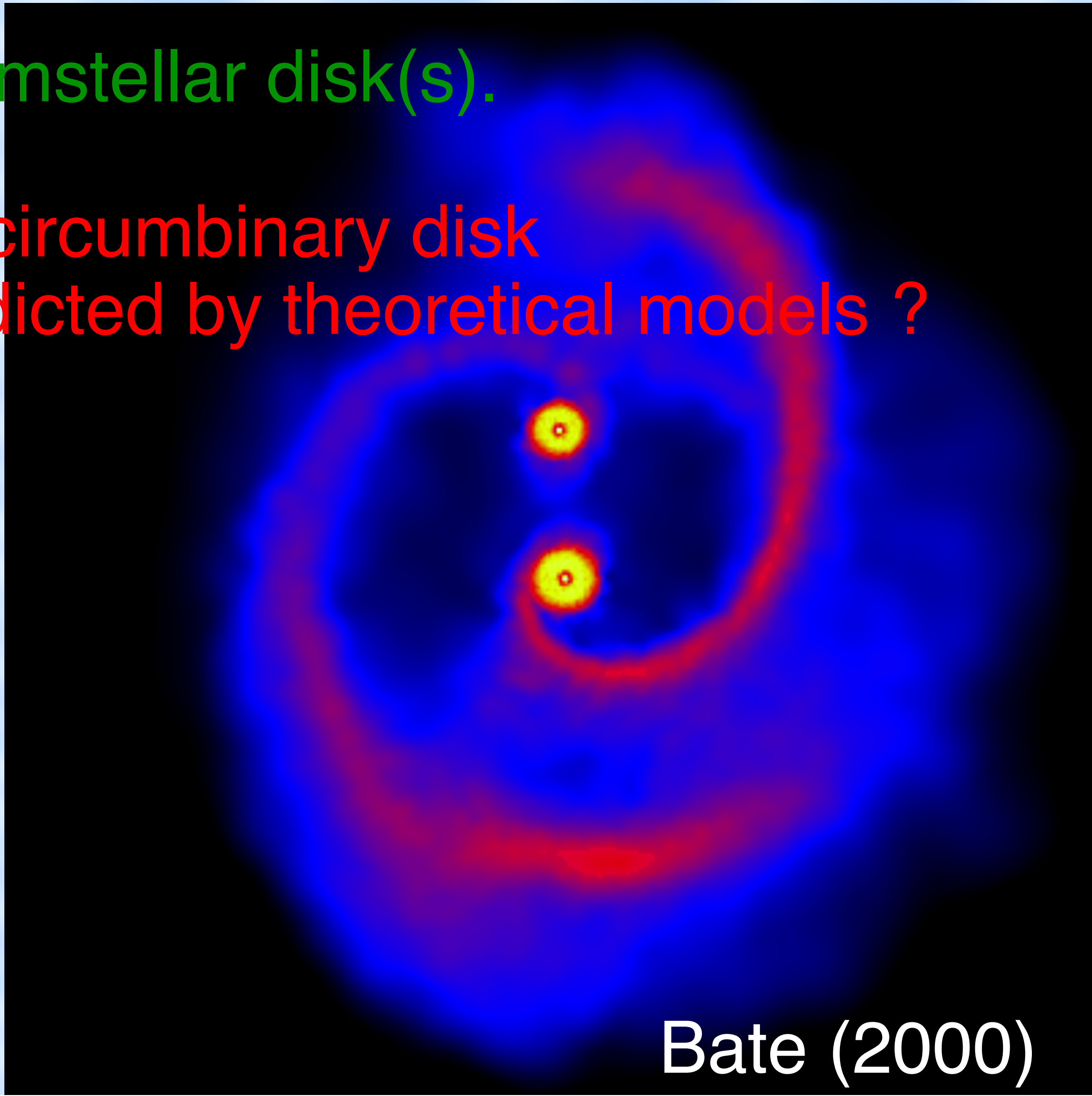
What about the inner part ?

The presence of the Kep. Circumbinary Disk hinders infall ??
<--> collimated jet, outflow

There may be accreting circumstellar disk(s).

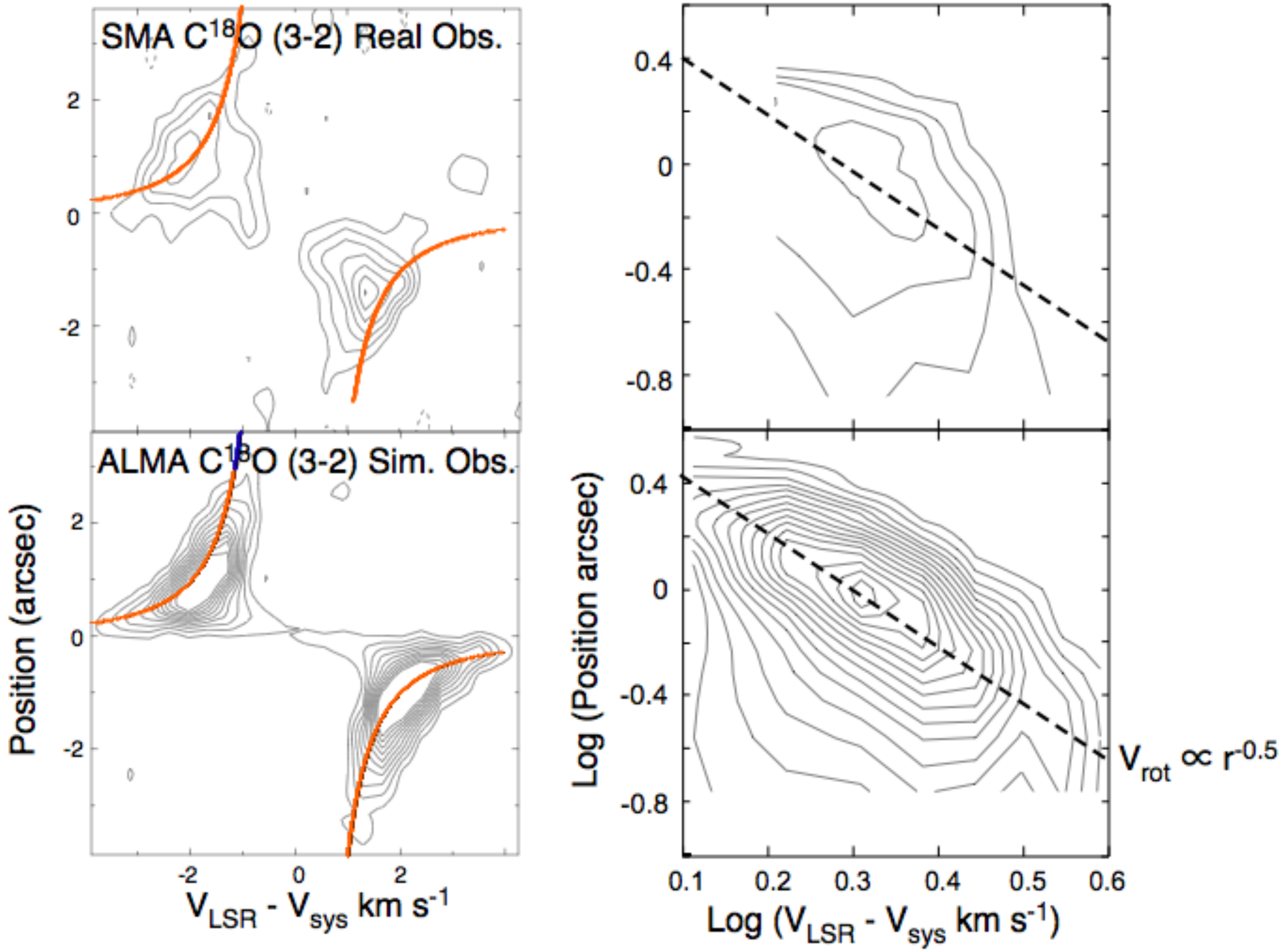
Any gas trail streaming from circumbinary disk
to circumstellar disks, as predicted by theoretical models ?

High-resolution ALMA
(not cycle 0) obs.



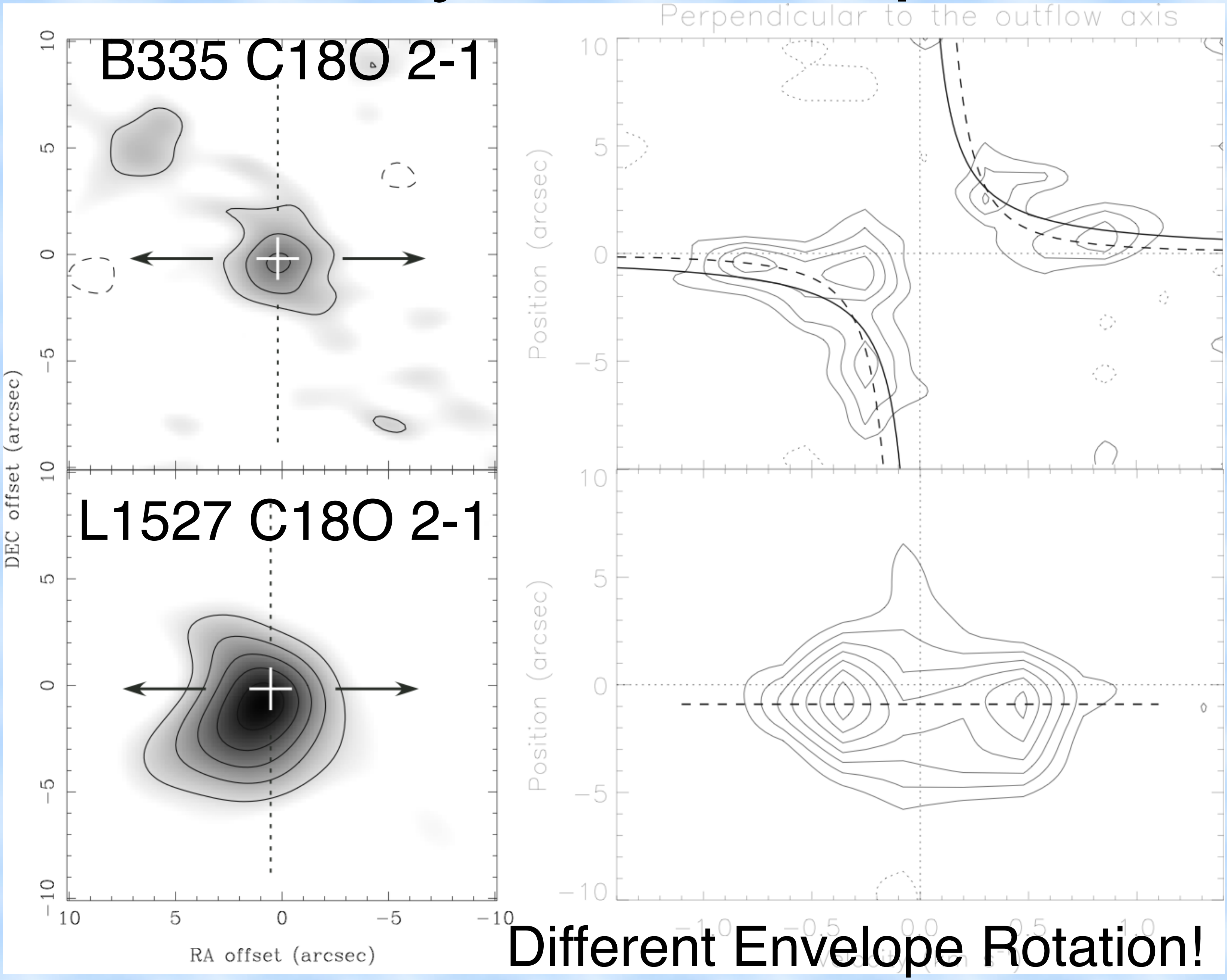
Bate (2000)

ALMA Observations



ALMA Observations should identify the Keplerian Disk Unambiguously!

SMA Survey for Envelope Rotation



Different Envelope Rotation!

Analyses 1: CO Depletion ?

^{13}CO, C^{18}O (3-2) Distribution do not follow Dust Distribution.
---> Molecular Abundance Variation ? Optical Depth ?

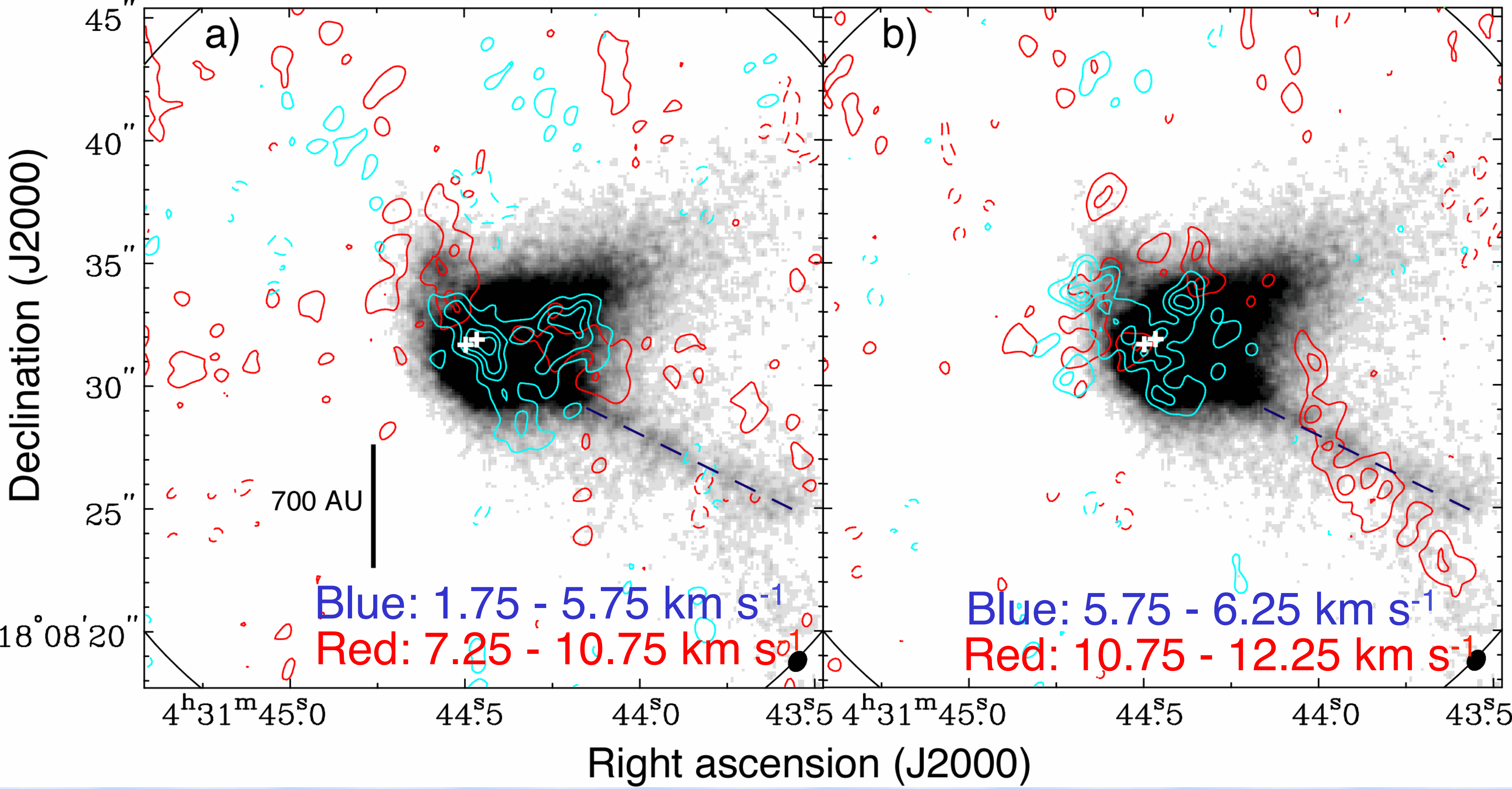
$$T_B^{13CO} = (J_{\nu 13CO} (T_{ex}) - J_{\nu 13CO} (T_{bg})) (1 - \exp(-X_{13CO} / X_{C18O} \tau_{C18O}))$$

$$T_B^{C18O} = (J_{\nu C18O} (T_{ex}) - J_{\nu C18O} (T_{bg})) (1 - \exp(-\tau_{C18O}))$$

--> Dust Emission TB !!

Isotopic lines Tex, tau, column

CO (3-2) images on SUBARU FeII + cont.



``Fan-shaped" blueshifted CO emission centered on Source B + weak red counterpart

``Collimated" blueshifted outflow centered on Source A + red counterpart

Different blue, red direction, and morphology between Source A and B

4. Discussion

Source A

Compact 0.8-mm continuum, ``collimated'' outflow, & FeII jet

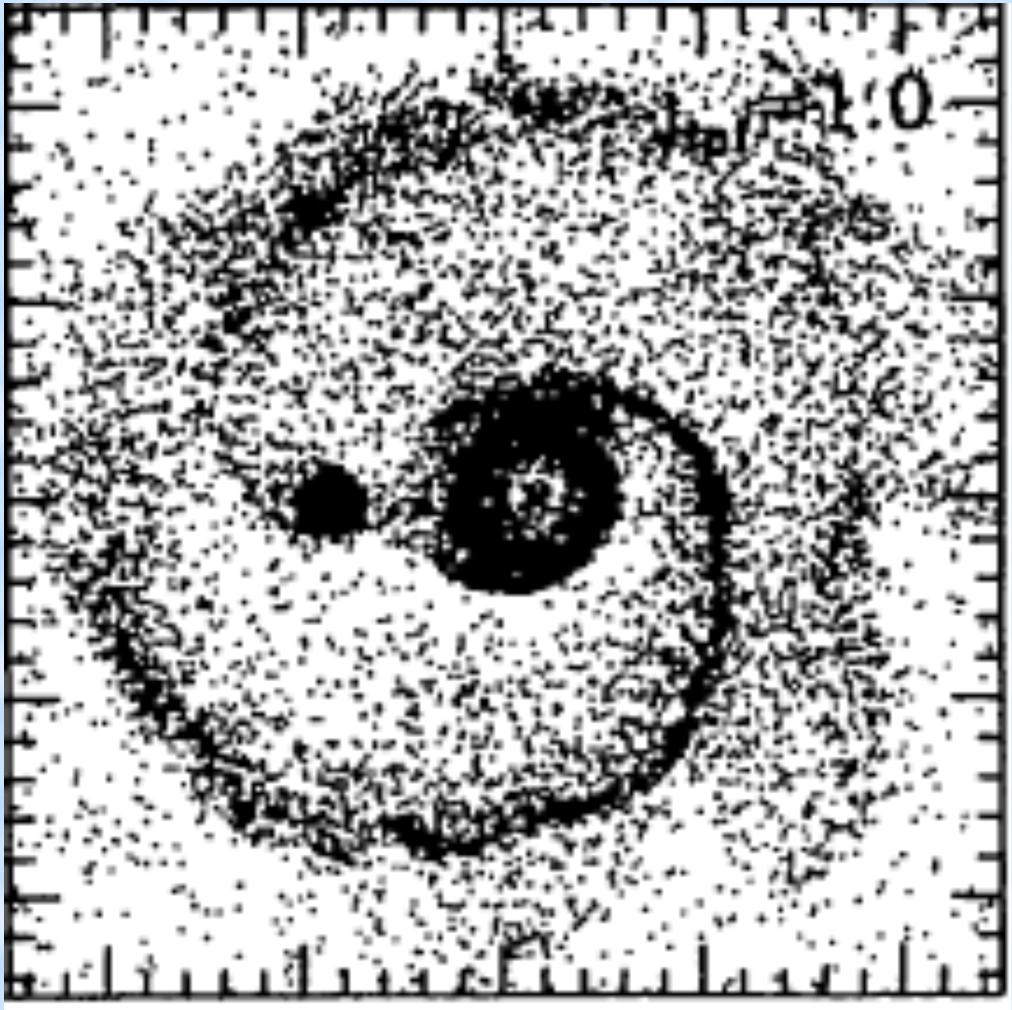
Source B

No compact continuum but extended envelope,

``fan-shaped'' outflow, & Reflection Nebula

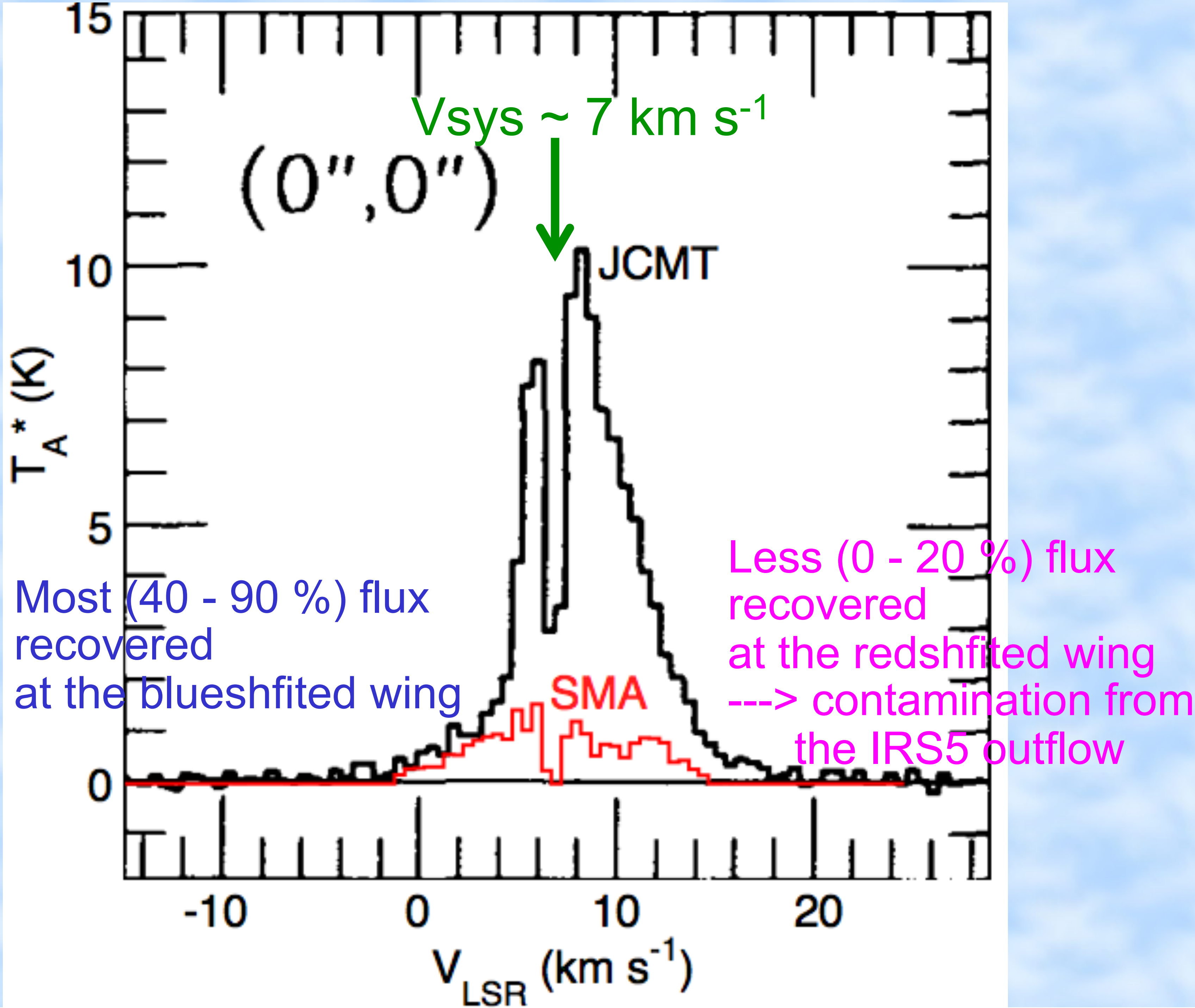
Source A is younger than Source B ??
Different evolutionary stages in the close (~ 70 AU)
binary system ??

Models of Binary Formation
--> Primary accretes more than secondary ?
(Bate & Bonnell 1997, Ochi et al. 2005)



ALMA + SUBARU can reveal the binary formation!

CO (3-2) spectrum



Estimated Outflow Properties

Outflow	Extent (AU)	Maximum Velocity (km s^{-1})	Dynamical Time (year)	Mass (10^{-5} $M_\odot$)	Momentum (10^{-4} $M_\odot$ km s^{-1})	Momentum Flux (10^{-7} $M_\odot$ km s^{-1} yr^{-1})
Outflow B (blue)	800	9.3	1400	9.6	5.4	8.7
Outflow B (red)	1100	8.4	5500	11.7	4.0	4.1
Jet A (blue)	700	1.9	1800	1.8	0.3	0.2
Jet A (red)	2700	10.2	2000	4.7	4.3	3.0

2. Sub-arcsecond SMA Observations of L1551 NE

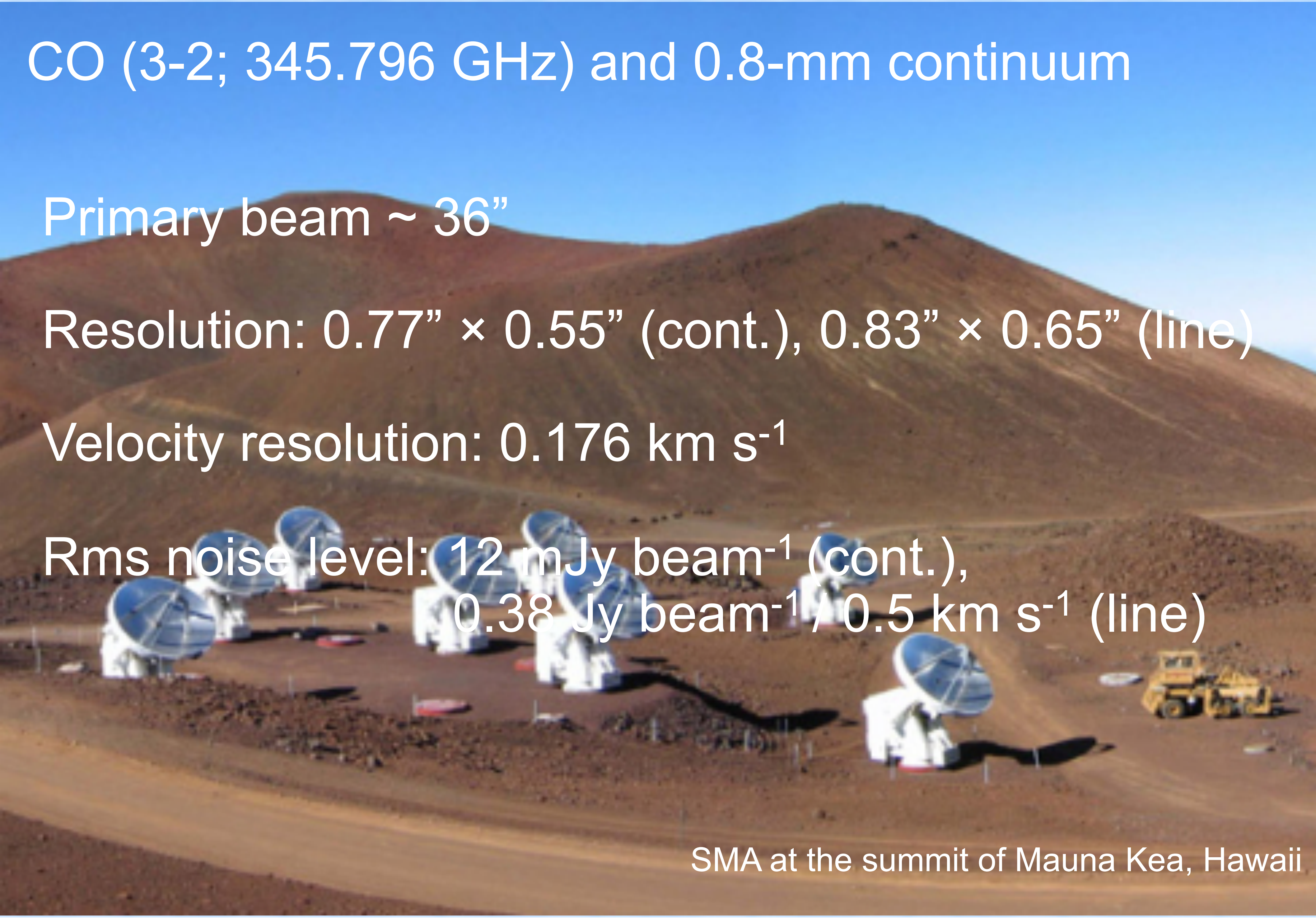
CO (3-2; 345.796 GHz) and 0.8-mm continuum

Primary beam ~ 36”

Resolution: 0.77” × 0.55” (cont.), 0.83” × 0.65” (line)

Velocity resolution: 0.176 km s^{-1}

Rms noise level: 12 mJy $beam^{-1}$ (cont.),
0.38 Jy $beam^{-1}$ / 0.5 km s^{-1} (line)



SMA at the summit of Mauna Kea, Hawaii

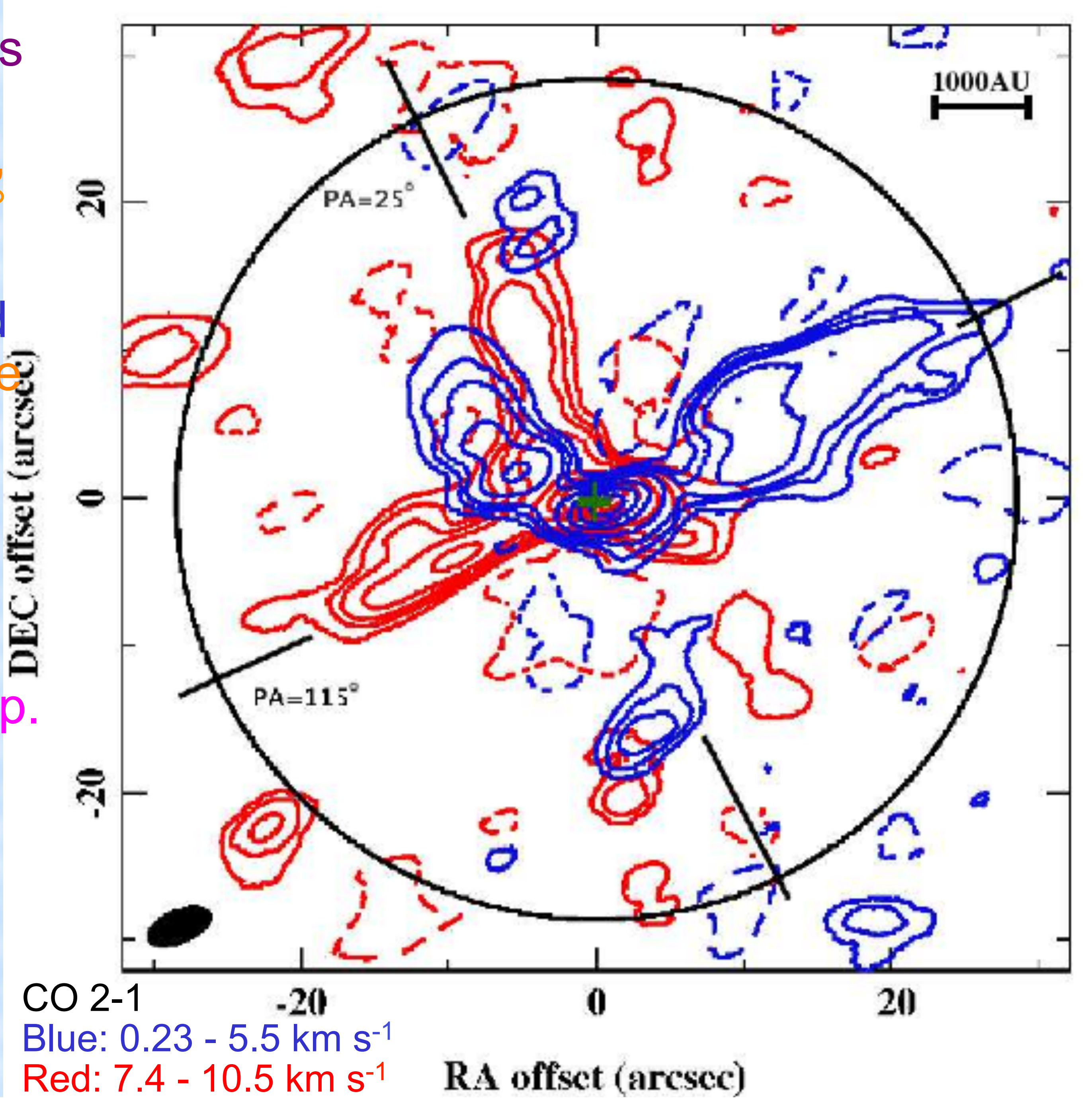
3. Results & Discussion: Mom 0 Map

Three outflow components

1. X-shaped outflow shell, Symmetric axis P.A. ~ 70°
   Eastern part Redshifted,
   Western part Blueshifted
   --> Base of the large-scale outflow

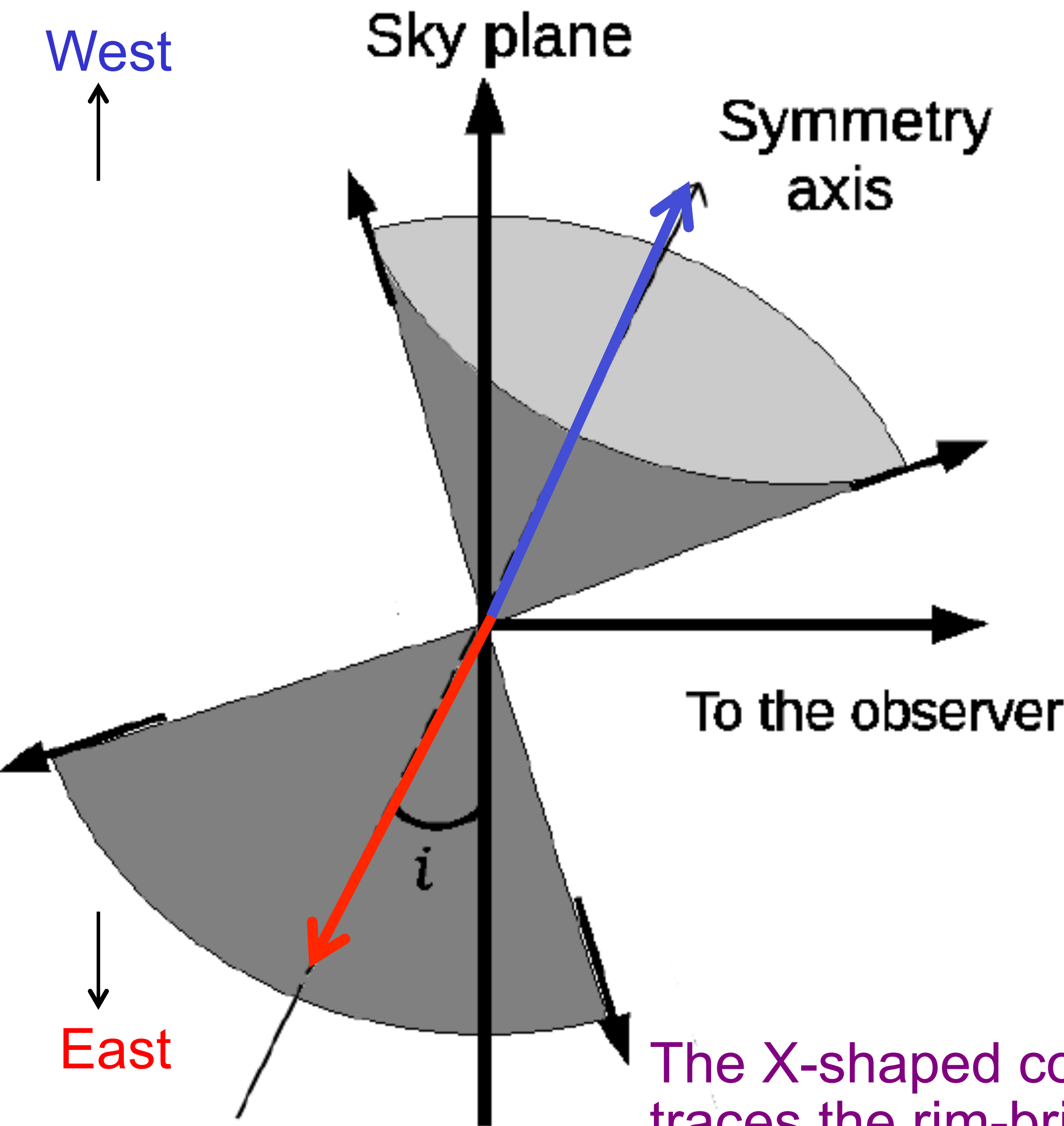
2. Collimated, winding Component,
   Opposite blue-red to that of the X-shaped comp.

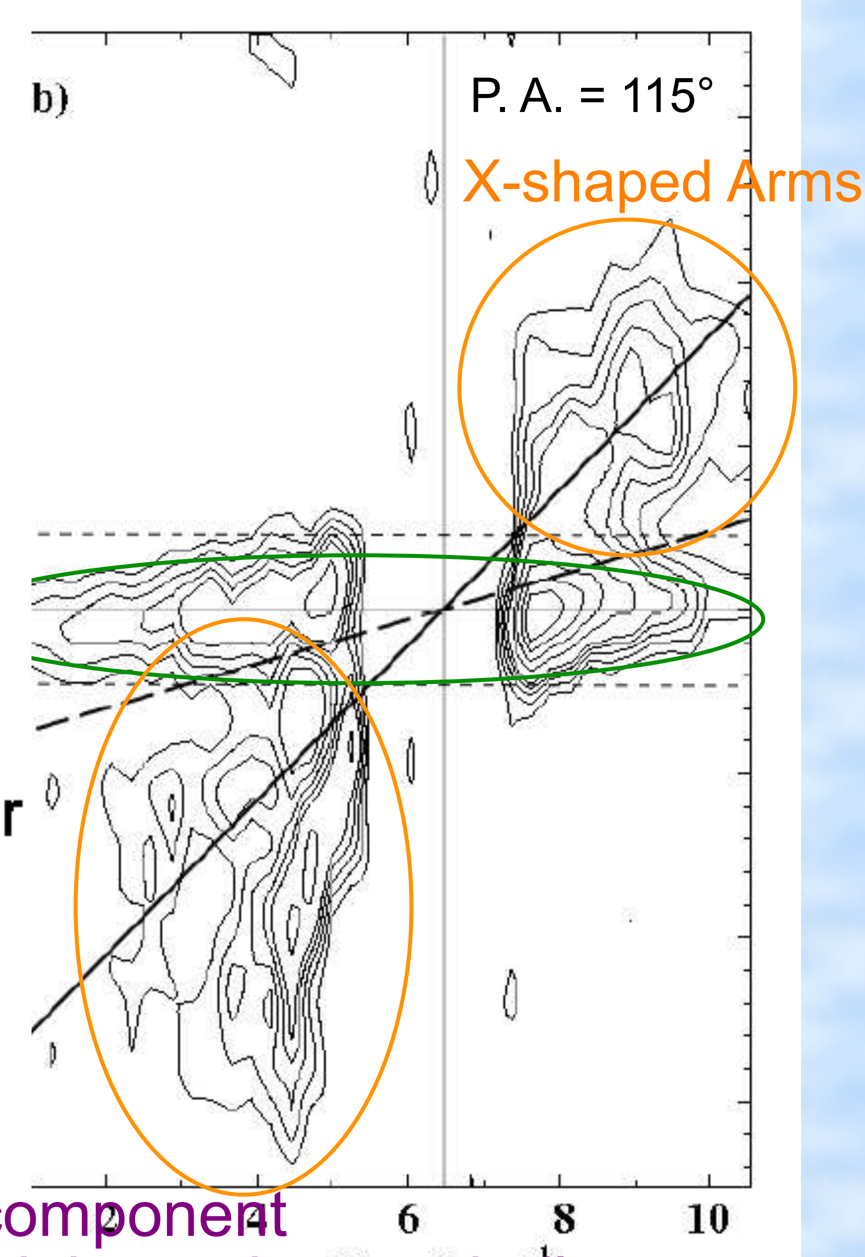
3. Central compact Component, high-vel.



CO 2-1
Blue: 0.23 - 5.5 km s^{-1}
Red: 7.4 - 10.5 km s^{-1}

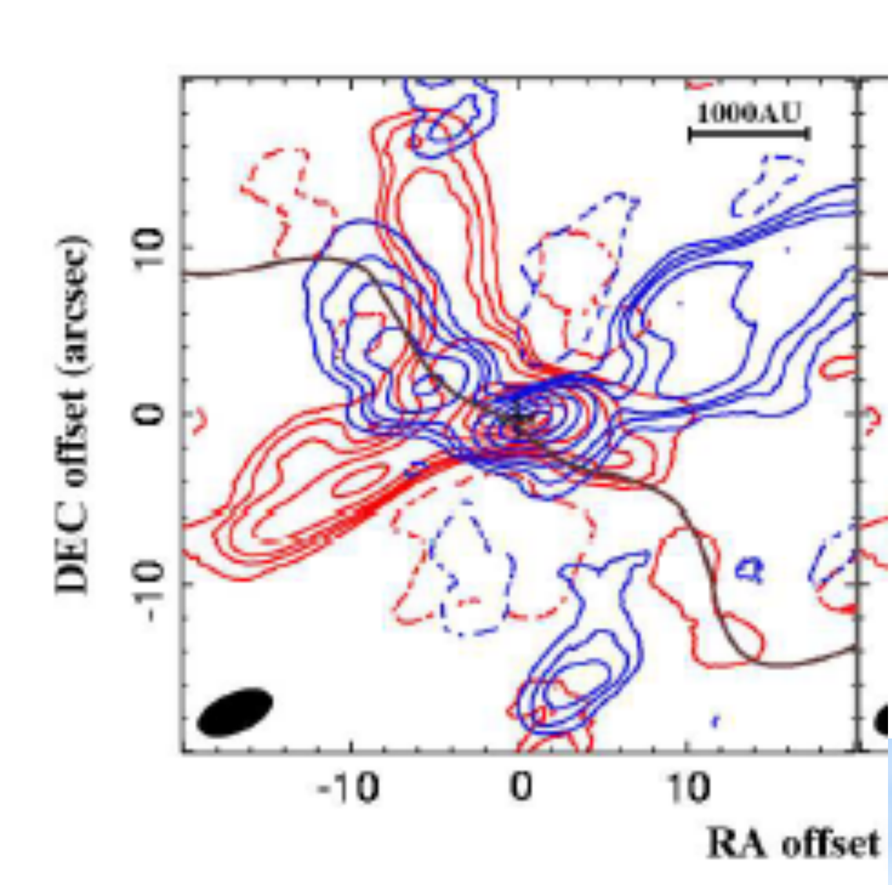
Position - Velocity diagrams along the X-shaped arms

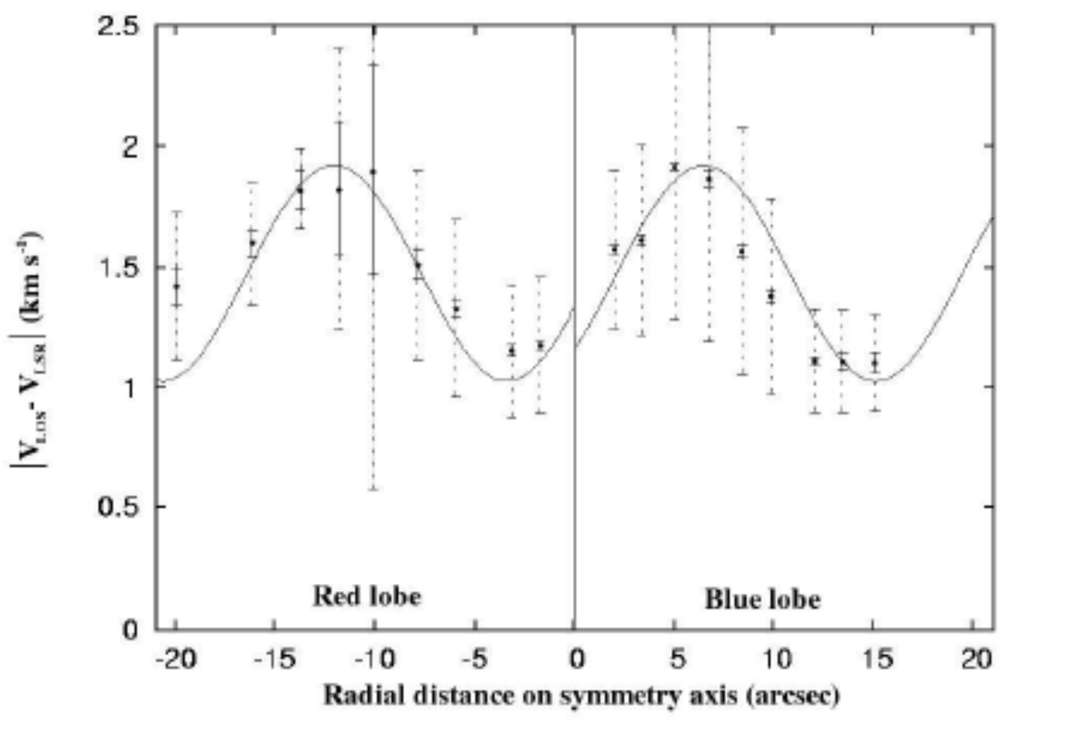


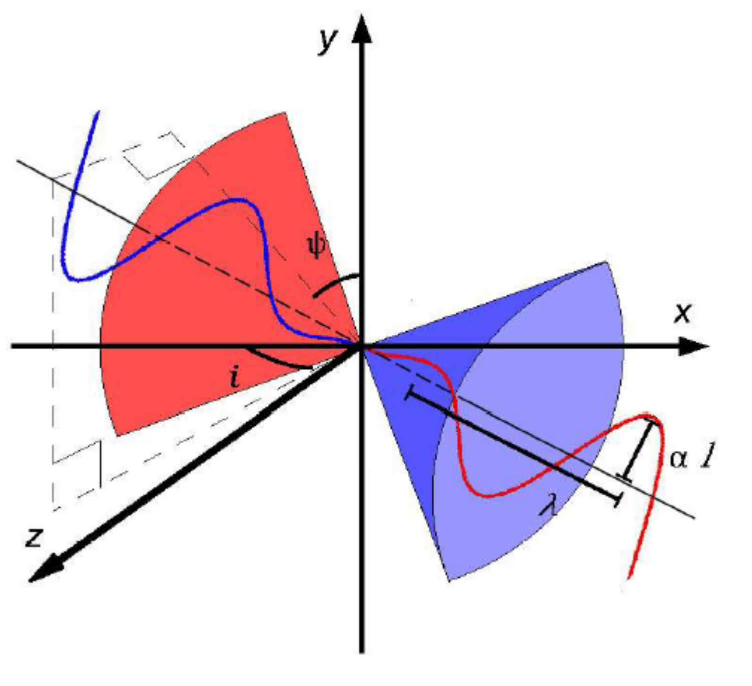


The X-shaped component traces the rim-brightened cone shell

Model of the winding outflow component







Precessing jet model

Precessing period ~ 135 year
Precessing angle ~ 10°
Jet velocity ~ 100 km s^{-1}
Inclination angle 30°
Position angle 57°

The Origin of the winding outflow ?

--> It could be the third protostellar component.

The winding component has different blue-red sense
--> consistent with the different disk orientation of the third component

Tidal interaction between the two main protostars and the third component can cause the precession of the third disk.
Main northern component 0.45 M, third one 0.1 M, separation 13 AU
---> orbital period ~ 63 year
c.f. the observed precession period of the winding outflow is ~ 135 year
(consistent with the model by Bate et al. 2000)

Summary

Three distinct outflow components were found in L1551 IRS5:

1) X-shaped outflow cavity ---> Base of the large-scale outflow, driven by the main protostellar binary of L1551 IRS5

2) winding outflow
---> The third protostar could be the driving source.

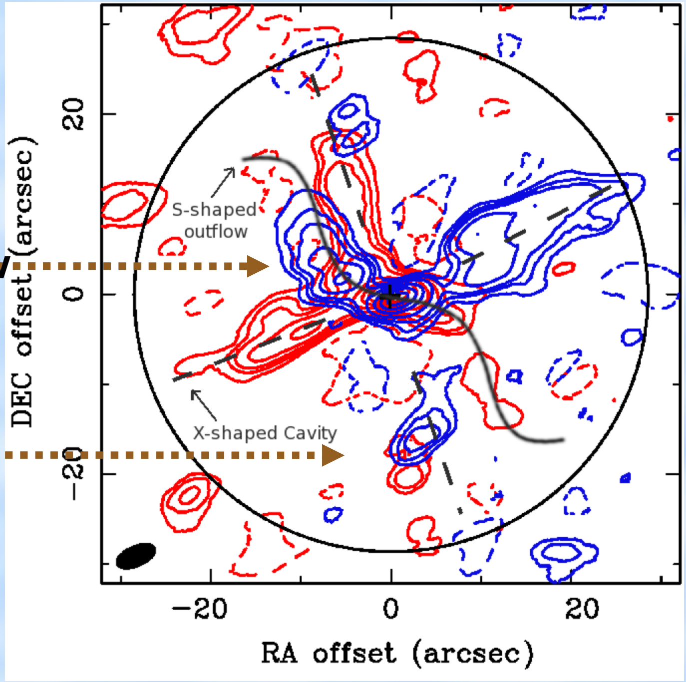
3) central high-velocity compact component.

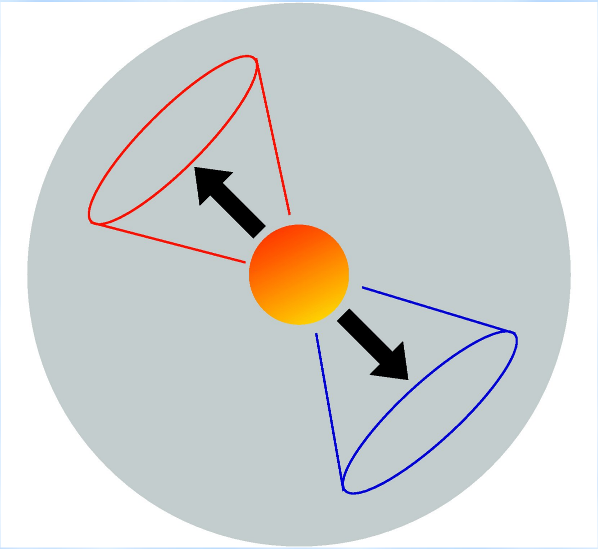
New Outflow in L1551 IRS5

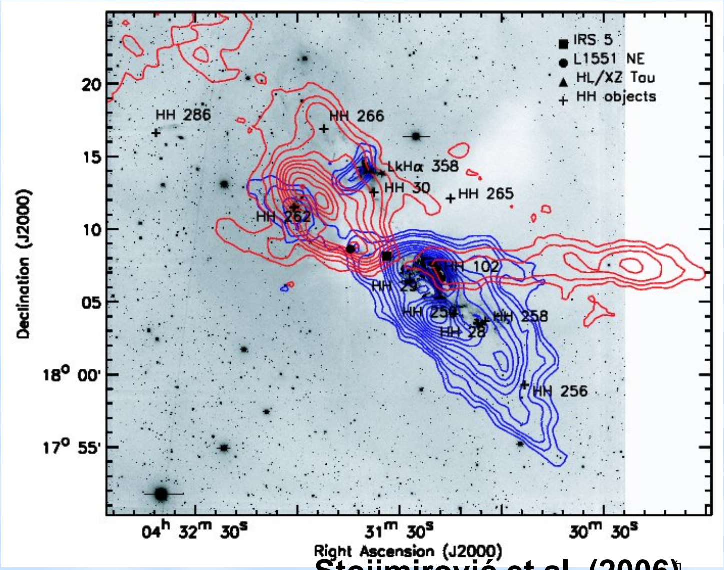
- The big opening-angle cavity suggest a wide angle wind.
- The collimated component may be driven by the 3rd component.
- The red and blue lobes are not aligned with each other
- The possible 3rd disk may be affect by the tidal force form the N disk, causing the collimated outflow precesses.

New outflow

Outflow cavity







Stojimirović et al. (2006)

Model of Precessing Jet

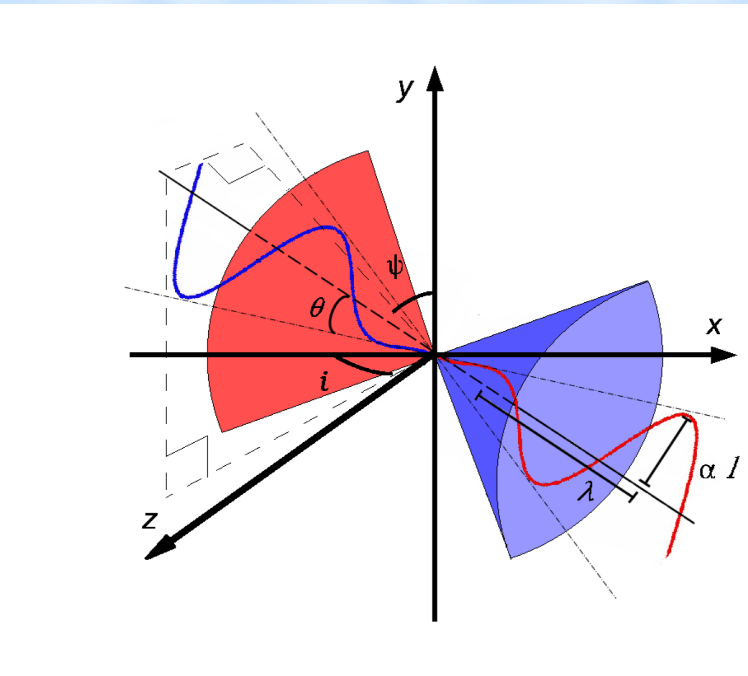
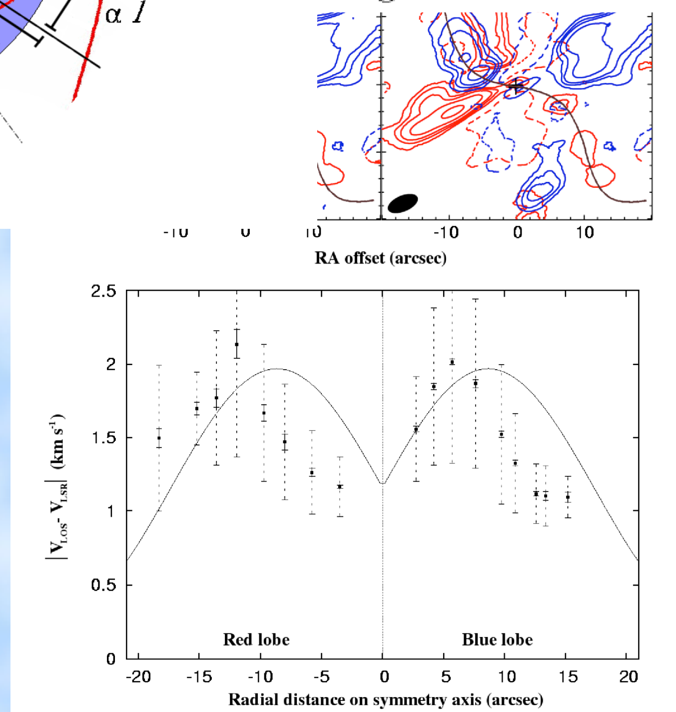


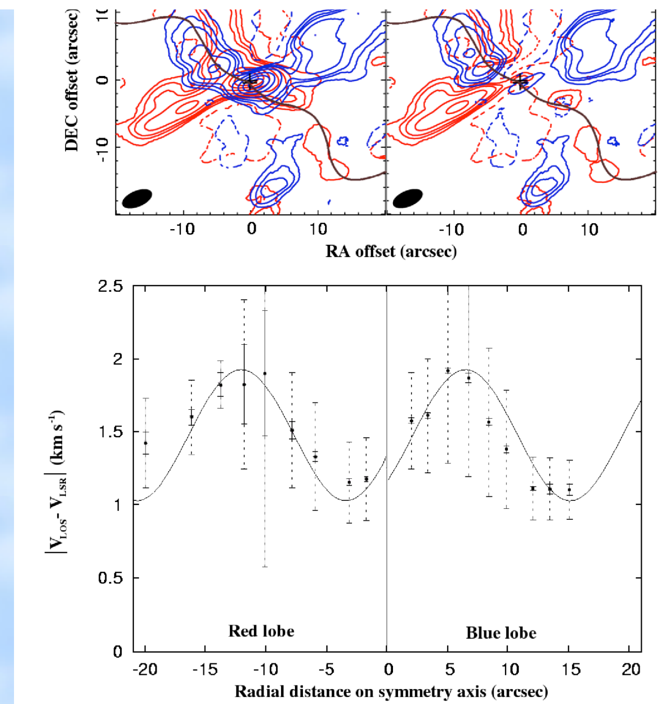
Table 1: Parameters for precessing jet[a]

	Precessing Angle	Period(yrs)[b]	Position Angle
Straight Jet	22°	270	57°
Bent Jet	10°	135	57°

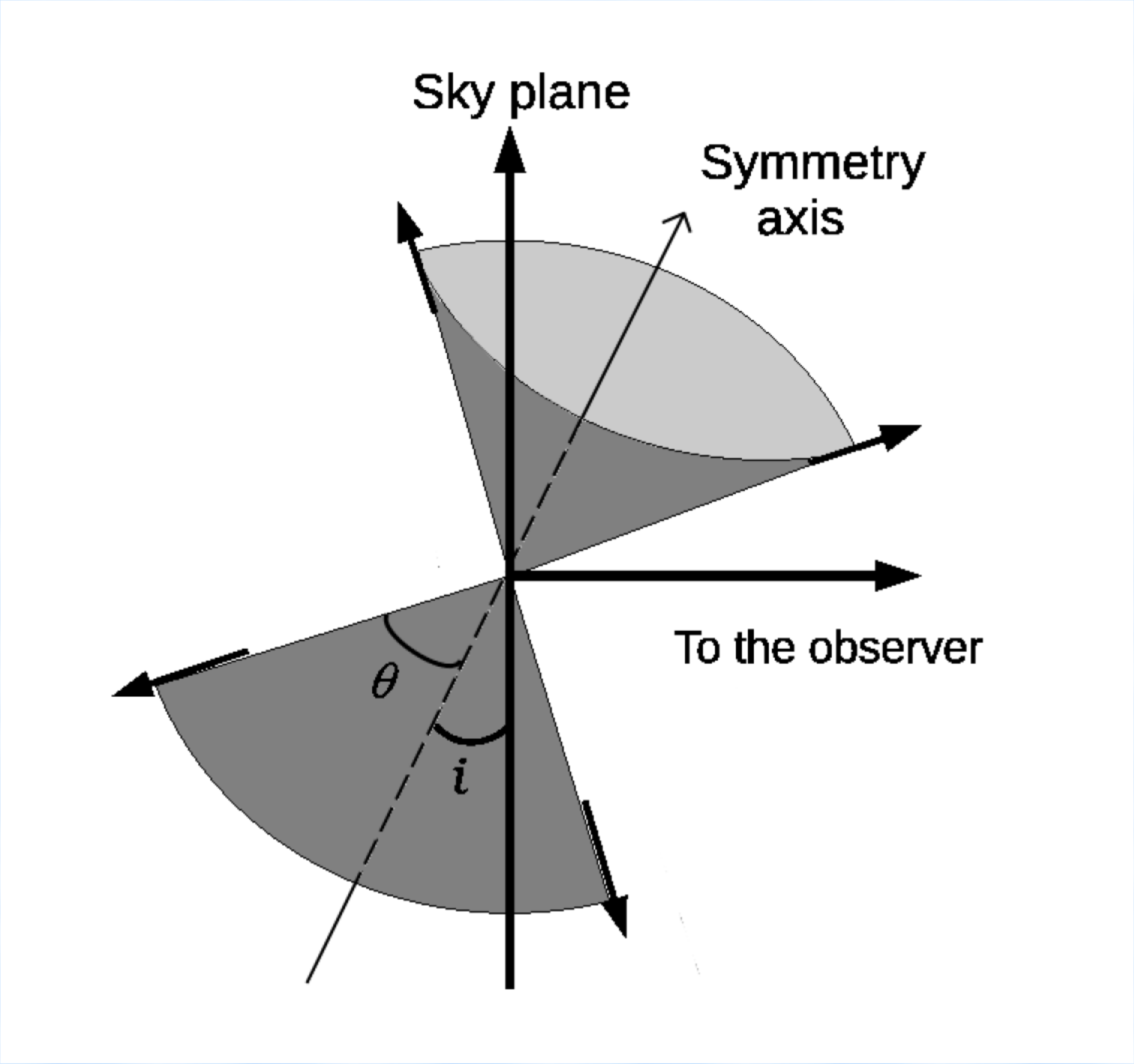
[b] Assuming a jet velocity of 100 km s^{-1}

[a] Assuming an inclination angle of 30°

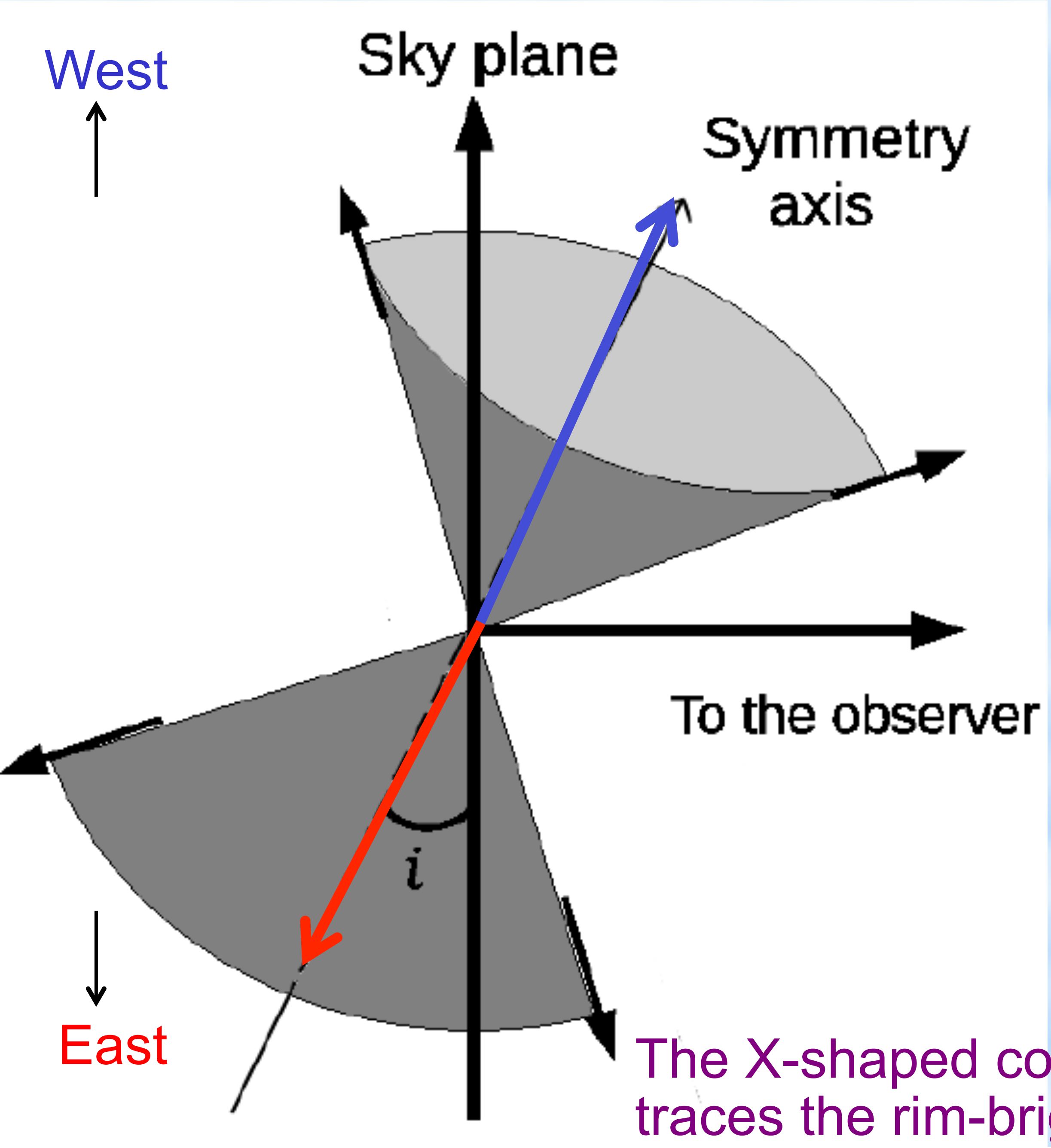




Thanks For Your Attention

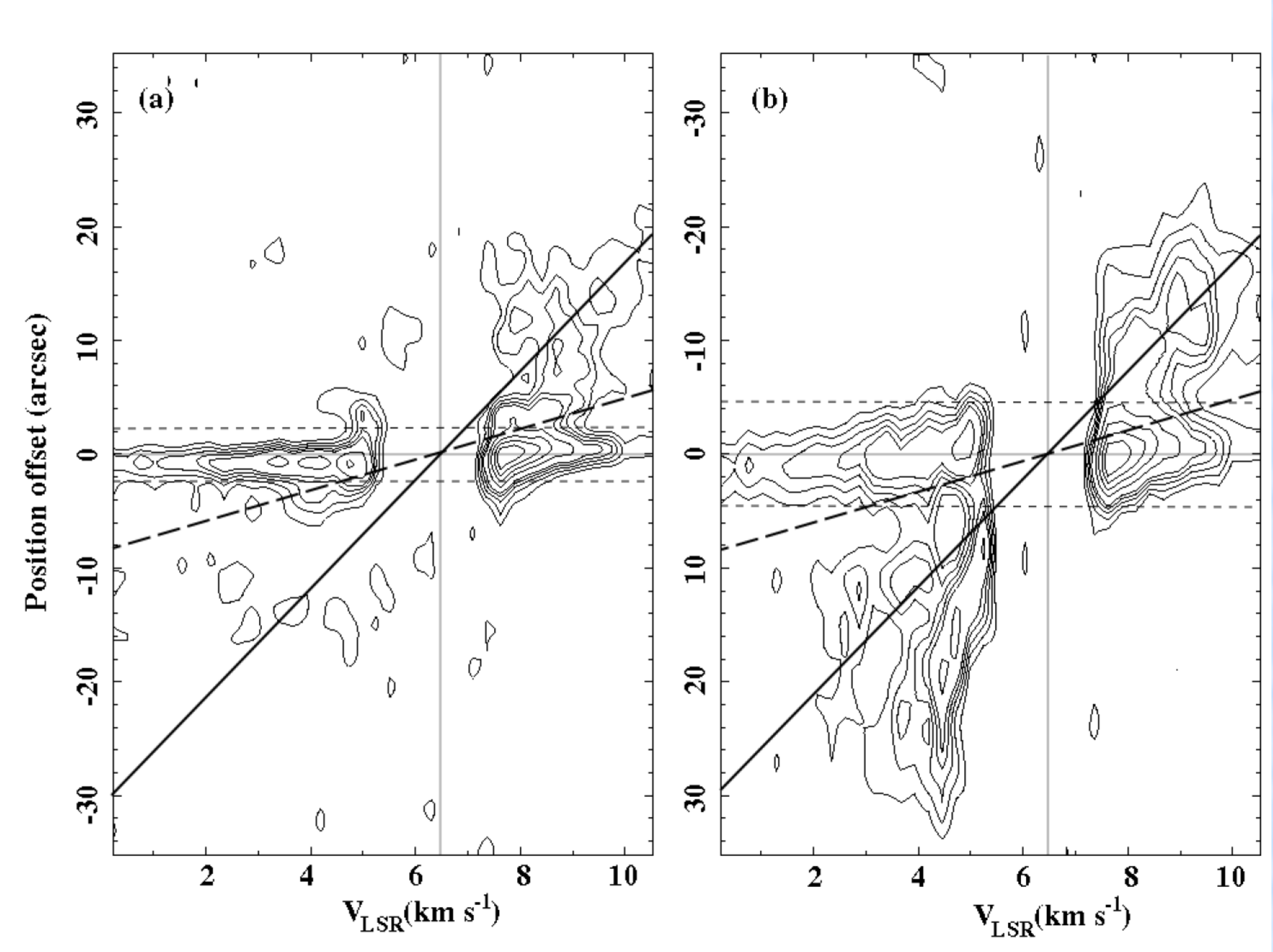

Sky plane
Symmetry
axis
To the observer
θ
i

Model Parameters of the X-shaped Component

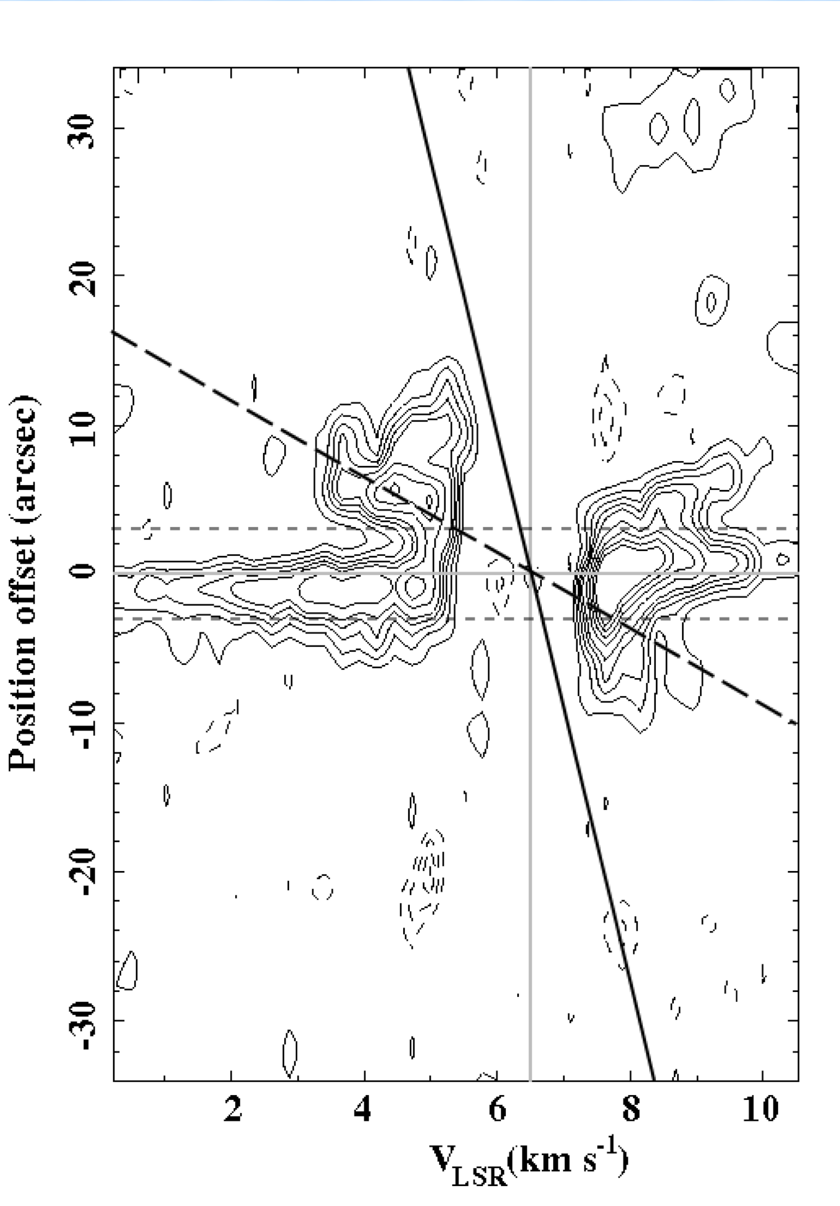


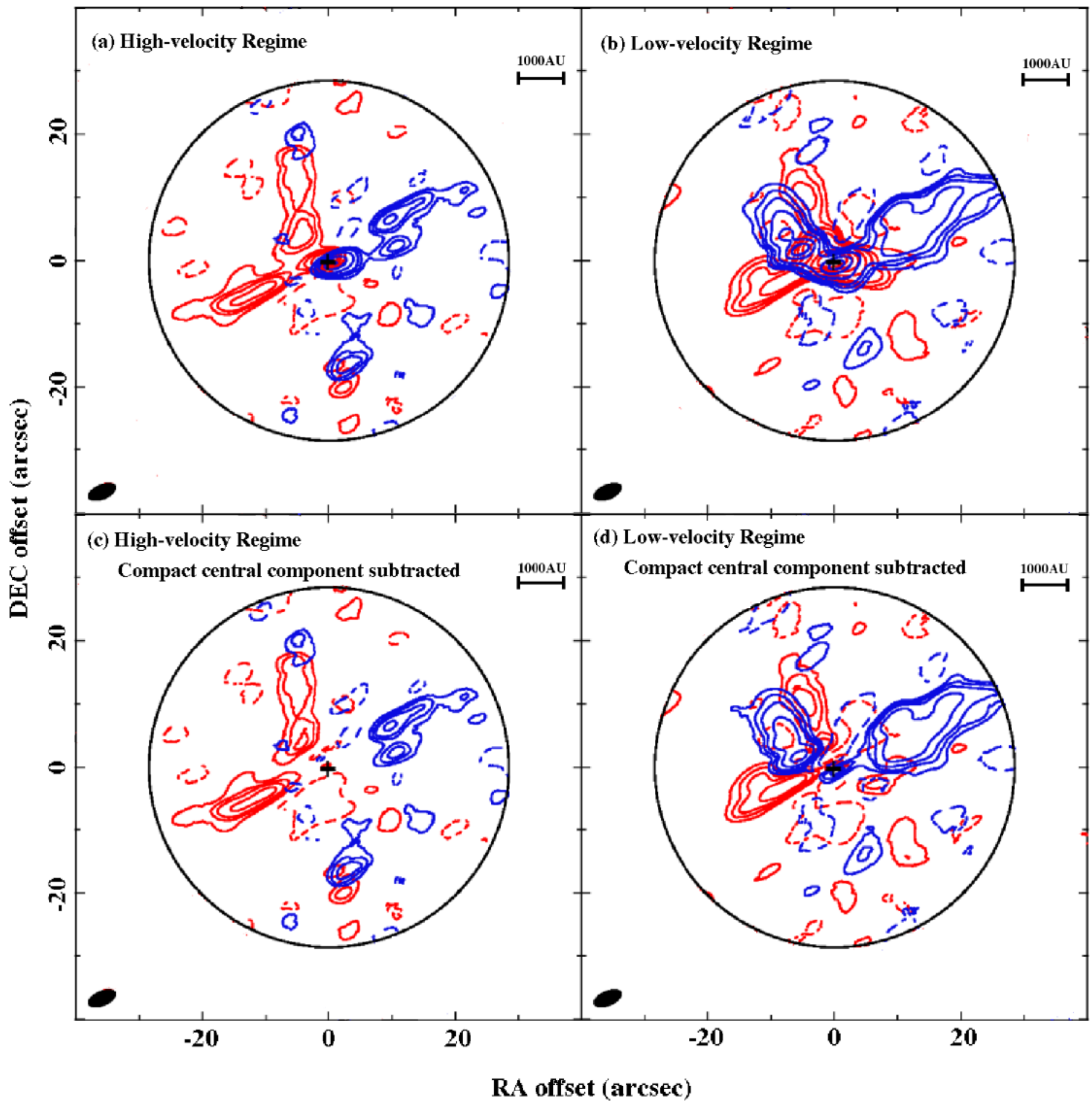
The X-shaped component traces the rim-brightened cone shell

pv along 25 and 115 degree (arms)



pv along 70 degree (S-shaped comp.)





(a) High-velocity Regime
1000AU
(b) Low-velocity Regime
1000AU
(c) High-velocity Regime
Compact central component subtracted
1000AU
(d) Low-velocity Regime
Compact central component subtracted
1000AU
DEC offset (arcsec)
RA offset (arcsec)
20
0
-20

Model parameters for precessing jet

	ψ	α	λ	ϕ_0 (red, blue)	i
Straight Jet	57°	0.40	40	-90°, -90°	30°
Bent Jet	57°	0.18	20	110°, -135°	30°