Kinematics of Circumbinary Disks around the Prototypical Protostellar Binary Systems L1551 IRS 5 and NE

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1. Introduction: Binary Star Formation

Previous observational and theoretical studies have established a standard scenario of single star formation (Myers et al. 2000, Andre et al. 2000).

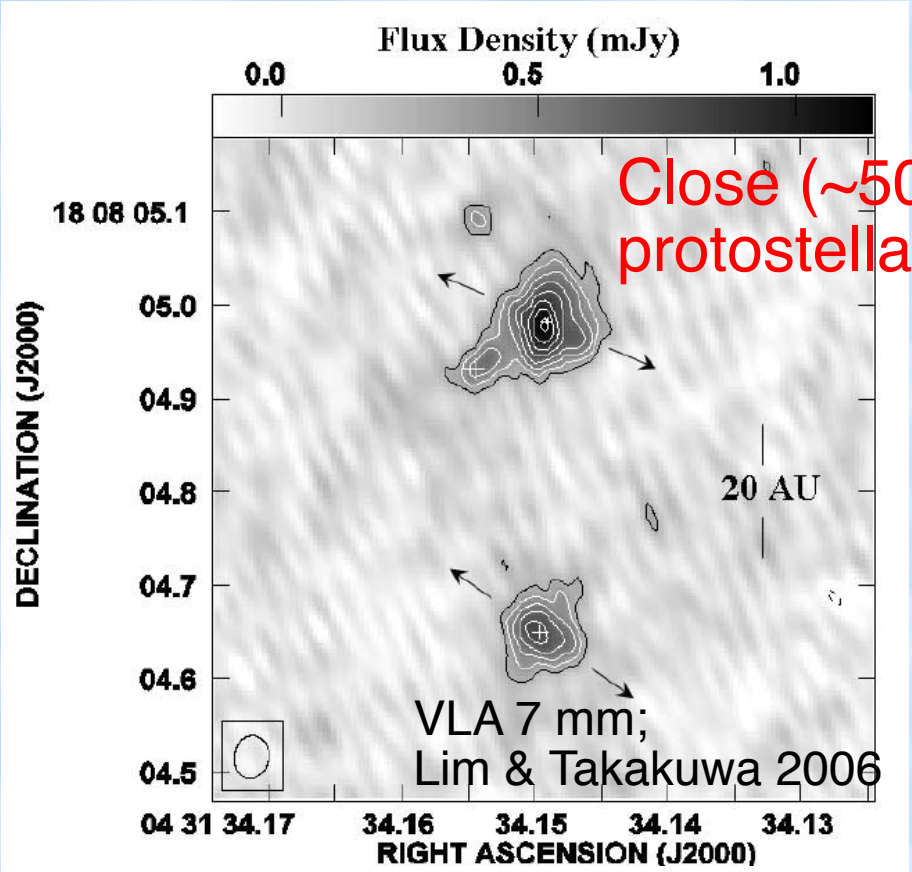
However, stars often form as members of binary or multiple systems (Dunquennoy & Mayor ‘91, Mathieu ‘94).

``Circumbinary Disks'' fragment into binaries (see Lim & Takakuwa 2006), thus possess information of the binary orbit, masses, the mass ratio…..

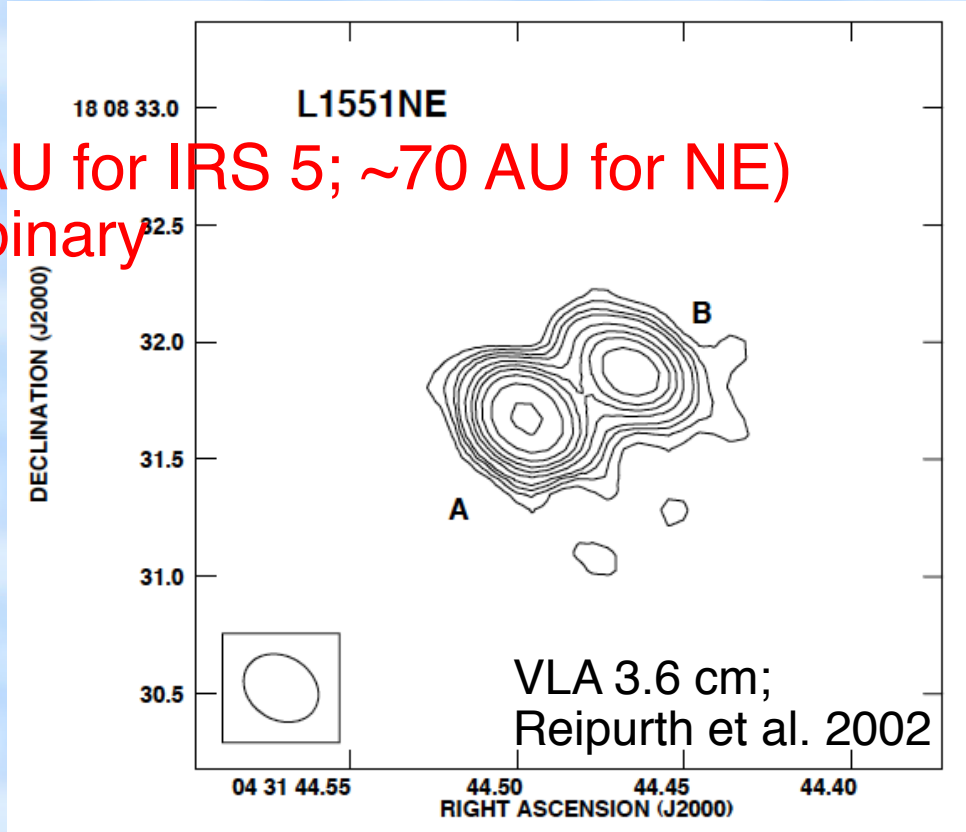
Observational understanding of structure and kinematics of circumbinary disks around the forming binary protostars is essential.

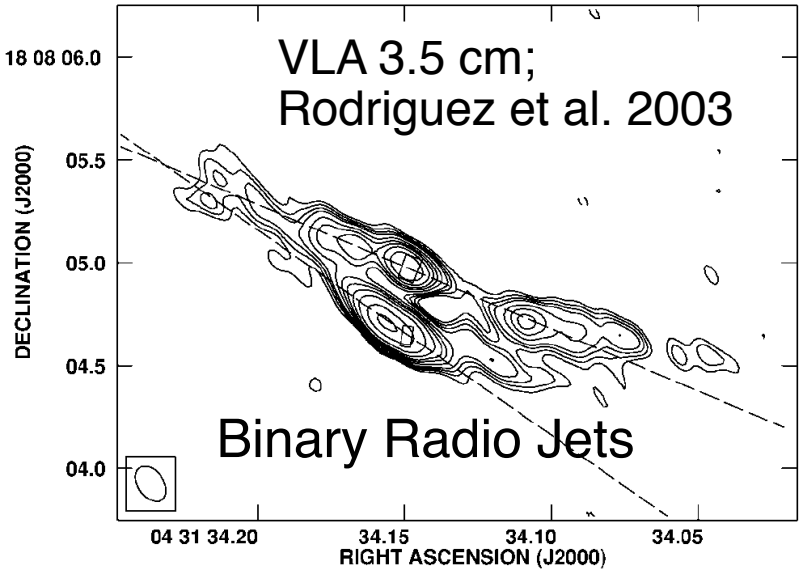
L1551 IRS 5

L1551 NE



Close (~50 AU for IRS 5; ~70 AU for NE) protostellar binary





L1551 IRS 5

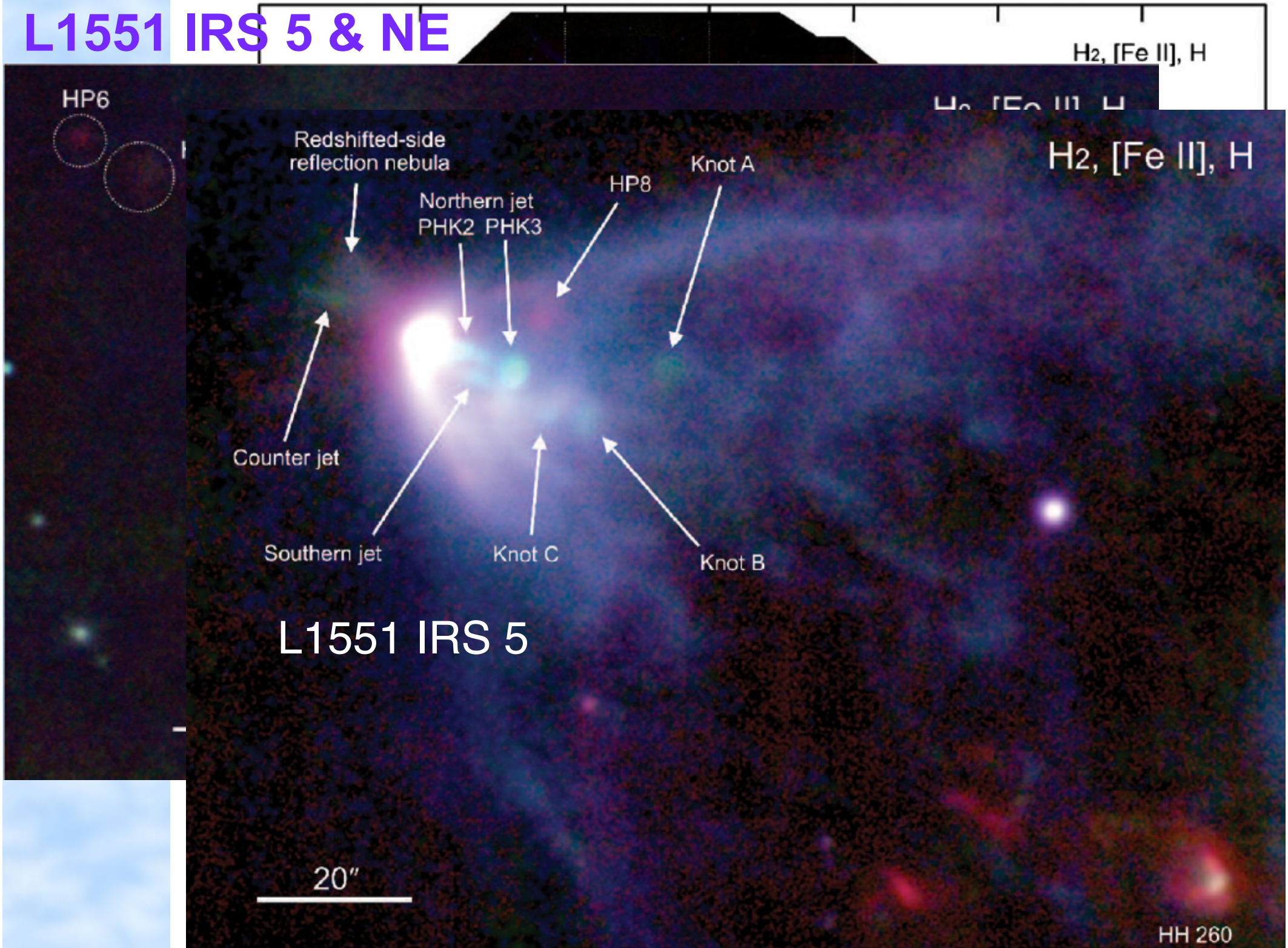
L_{bol}=22 L_{sun}, T_{bol}=92 K, 0.9 M_{sun}

L1551 NE

L_{bol}=4.2 L_{sun}, T_{bol}=91 K, 0.8 M_{sun}

Similar Class I Binary Protostars

L1551 IRS 5 & NE



2. SubMillimeter Array (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”

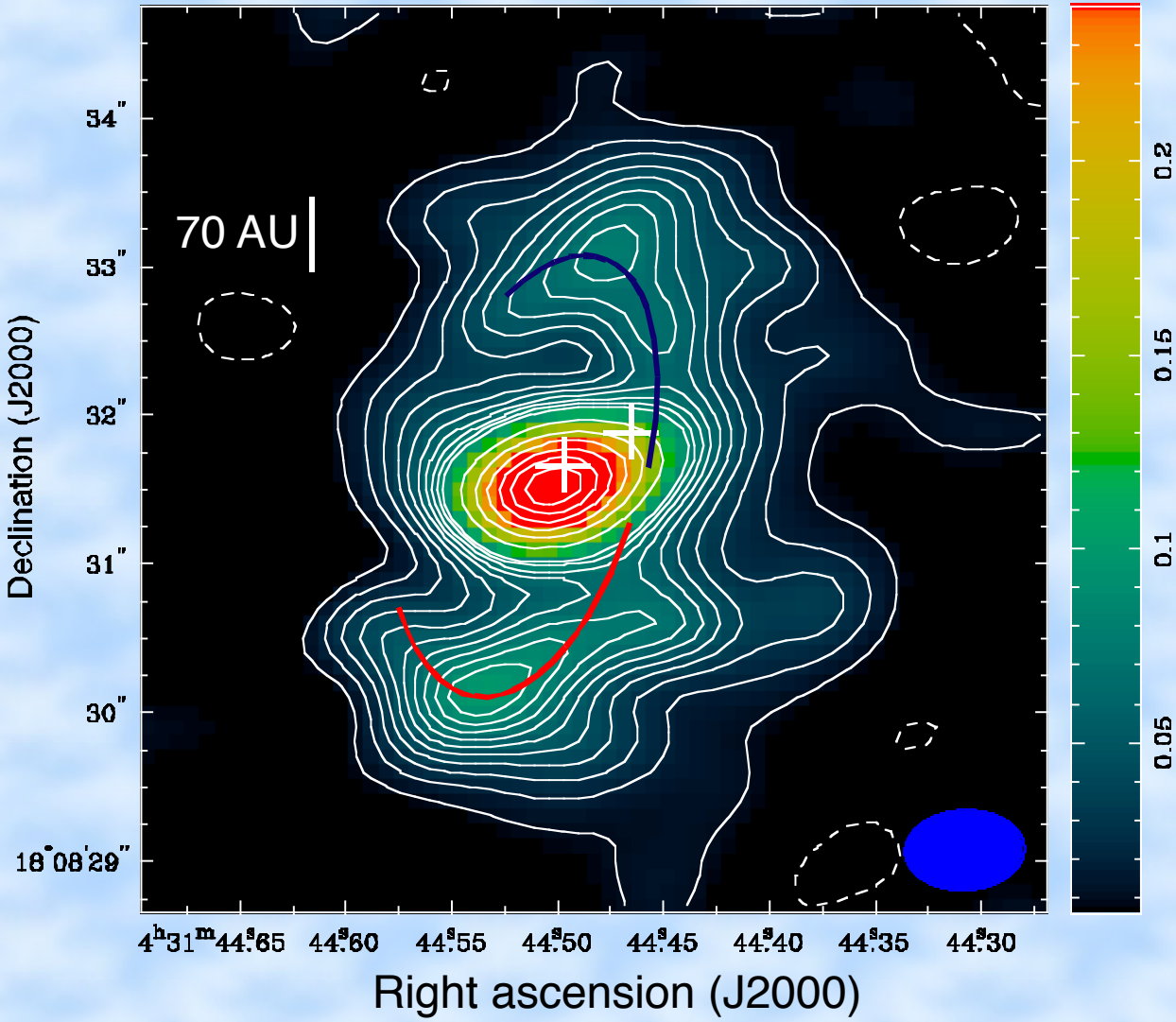
Resolution: 0.80” × 0.54” (cont.), 0.95” × 0.66” (line)

Velocity resolution: 0.37 km s^{-1}

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

SMA at the summit of Mauna Kea, Hawaii

0.9-mm Continuum



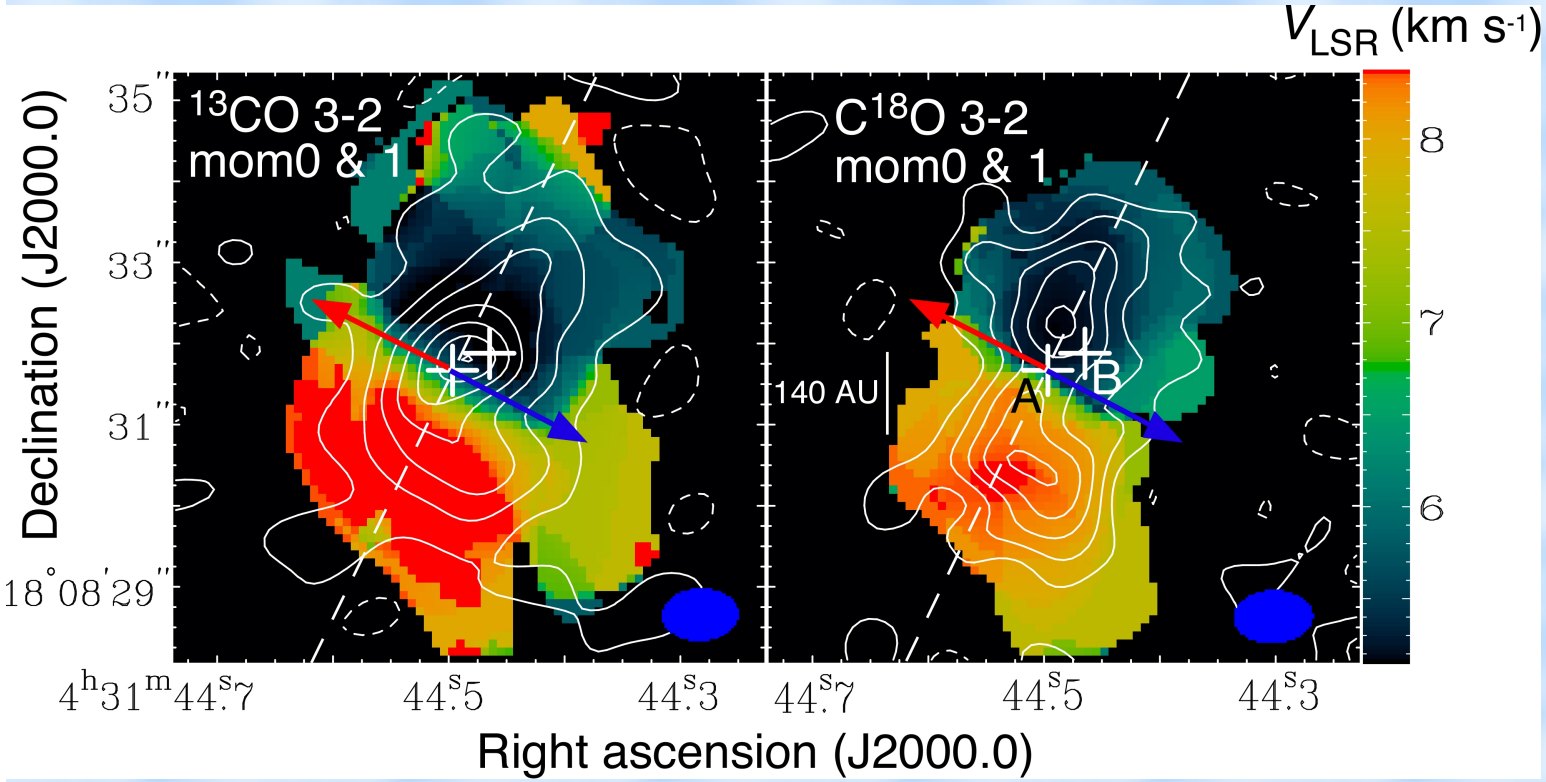
Compact Component associated with Source A (0.9" x 0.5", 0.7 Jy)
+ Extension to Source B

+ North and South Comp.

Rim-Brightening Circumbinary Disk + Circumstellar Disks ?

Total Mass ~ 0.046 M_{solar}

Kinematics of the Circumbinary Disk traced in ^{13}CO (3-2) and $C^{18}O$ (3-2)



Color: Mom 1
Contour: Mom 0

SE - NW Elongated, circumbinary disk seen

Clear Velocity Gradient along the major axis,
No clear Velocity Gradient along the minor axis ?

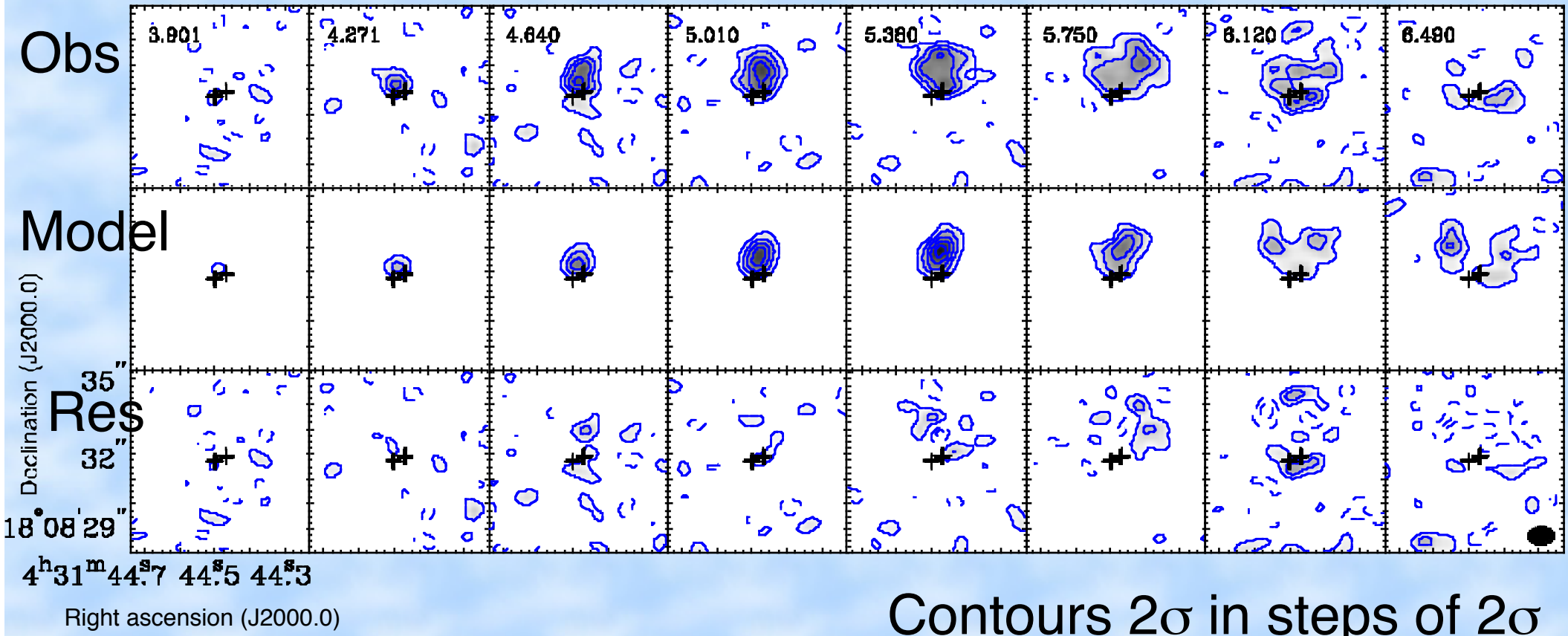
The position of Source A appears to be the ``center'' (V_{sys} ~ 7 km s^{-1})

Keplerian Disk Model Fitting

Best Fit Result of $C^{18}O$ 3-2

--> (M_*, i, θ) = (0.8 M_{solar}, -62°, 167°)

$C^{18}O$ Blue



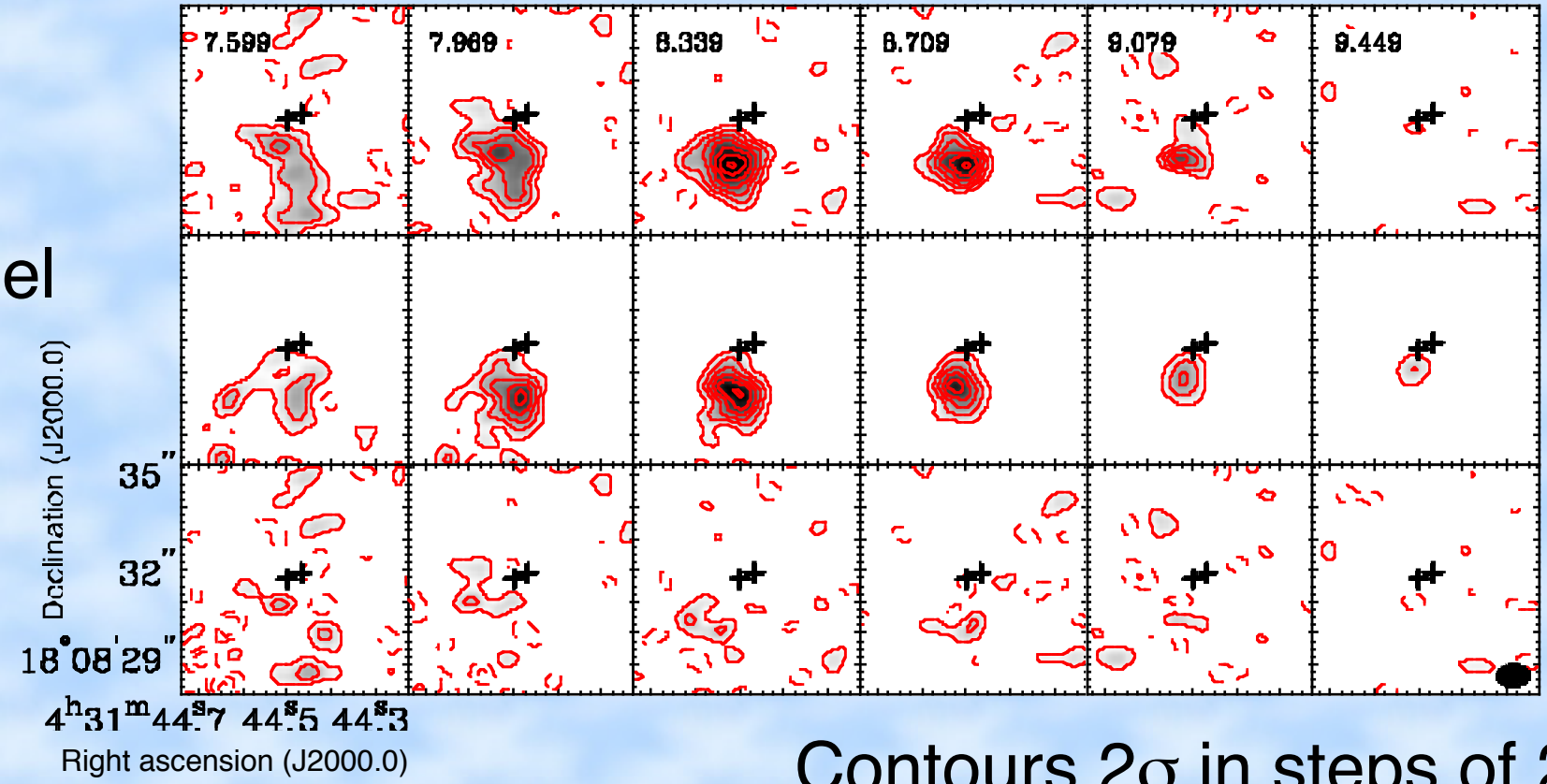
Contours 2σ in steps of 2σ

$C^{18}O$ Red

Obs

Model

Res



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.

Summary of L1551 NE

Compact (~100 AU) dusty condensation at protobinary
→ Circumstellar disks

Northern + Southern dusty components
--> 600-AU circumbinary disk (total mass ~ 0.05 M_{solar})

^{13}CO (3-2) & $C^{18}O$ (3-2) lines show Keplerian Rotation in the Circumbinary Disk

3. SMA & ASTE Observations of L1551 IRS 5

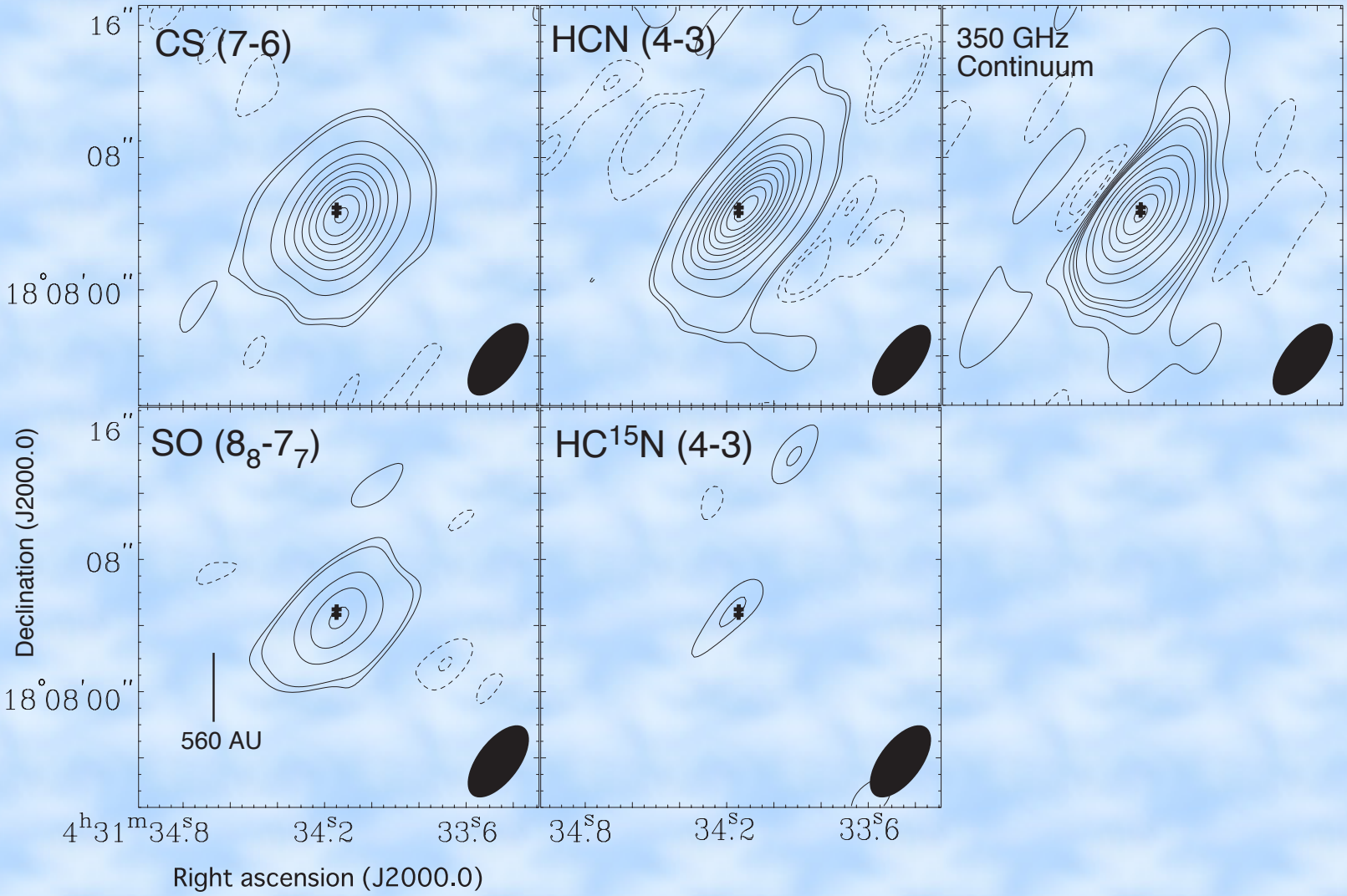
ASTE: CS (7-6; 342.9 GHz)
SMA: CS, HCN, SO, 0.9-mm continuum

<u>SMA + ASTE combined CS data</u>

- Primary beam: ~36”
- Resolution: ~5.2” × 2.4”
- Velocity resolution: 0.18 km s^{-1}
- rms noise ~0.3 K

+ Combined

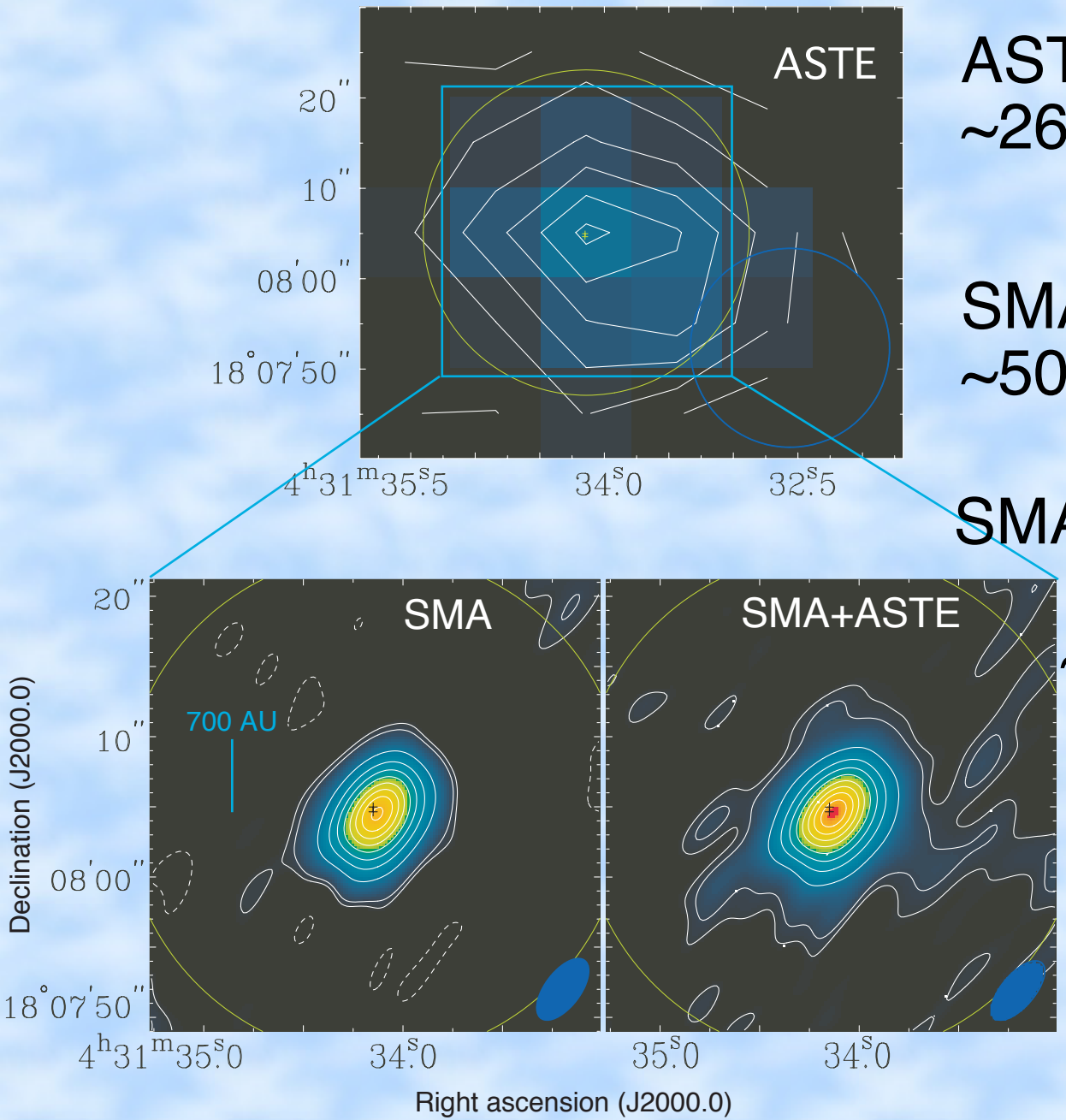
SMA ``Gallery'' of L1551 IRS 5



NW-SE elongated feature both in submm molecular lines and continuum (~500 AU; P.A.= -32 deg)

→ Circumbinary Disk

Combined SMA + ASTE CS (7-6) image of L1551 IRS 5



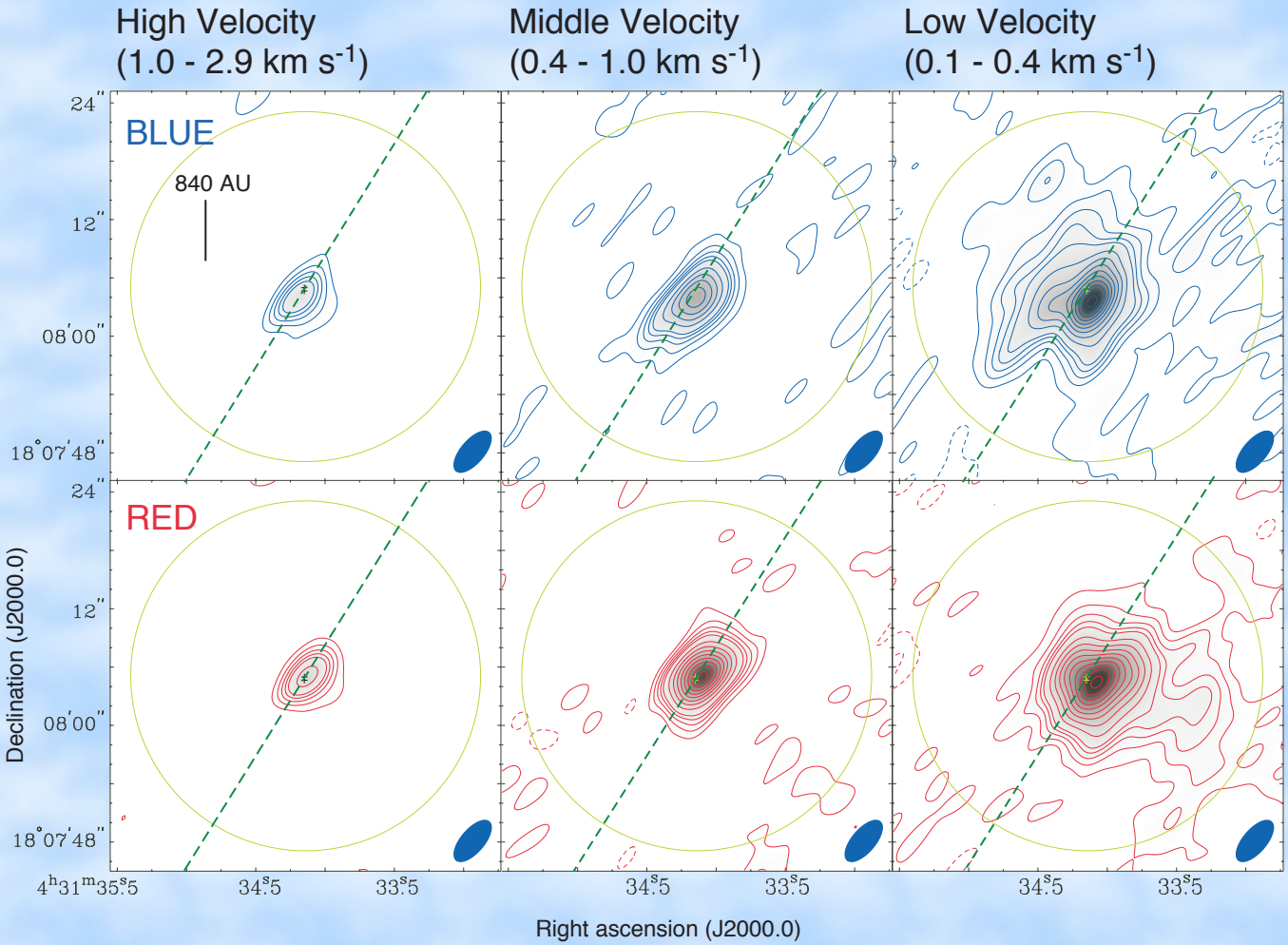
ASTE →
~2600 AU extended comp.

SMA →
~500 AU circumbinary disk

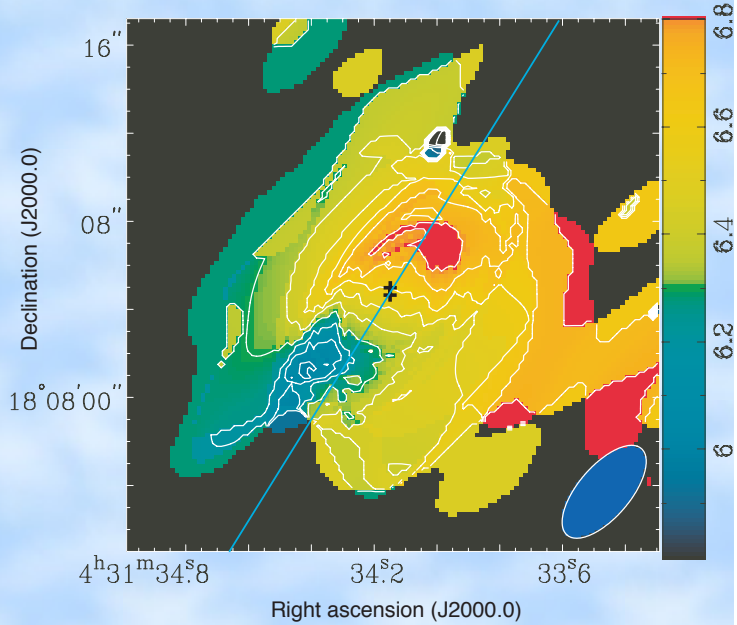
SMA + ASTE → ~500 AU circumbinary disk + ~2600 AU extended comp.

Free from ``missing flux''
--> Kinematical study of the circumbinary disk

SMA + ASTE CS (7-6) Blueshifted and Redshifted Emission



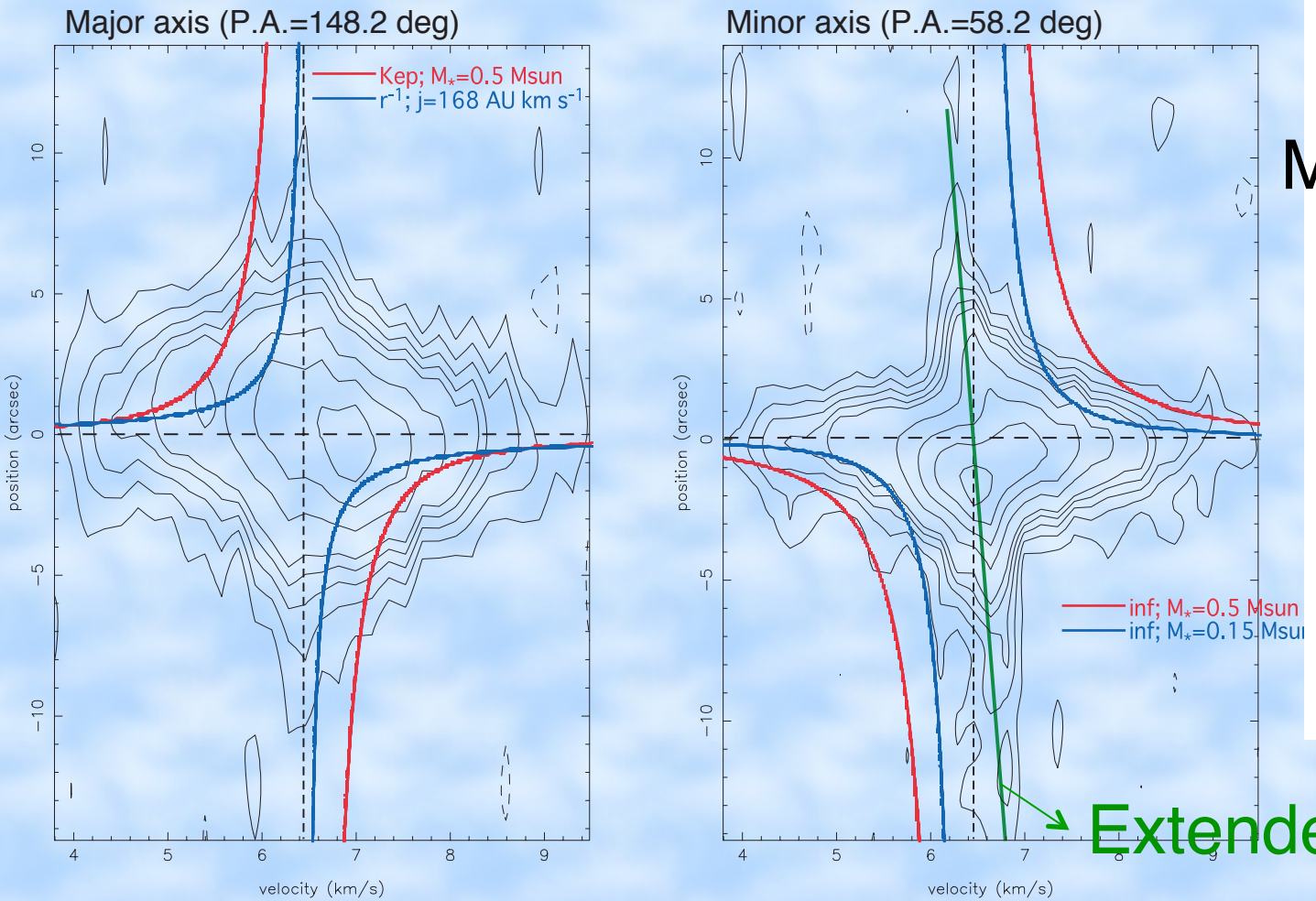
Mean Velocity Map

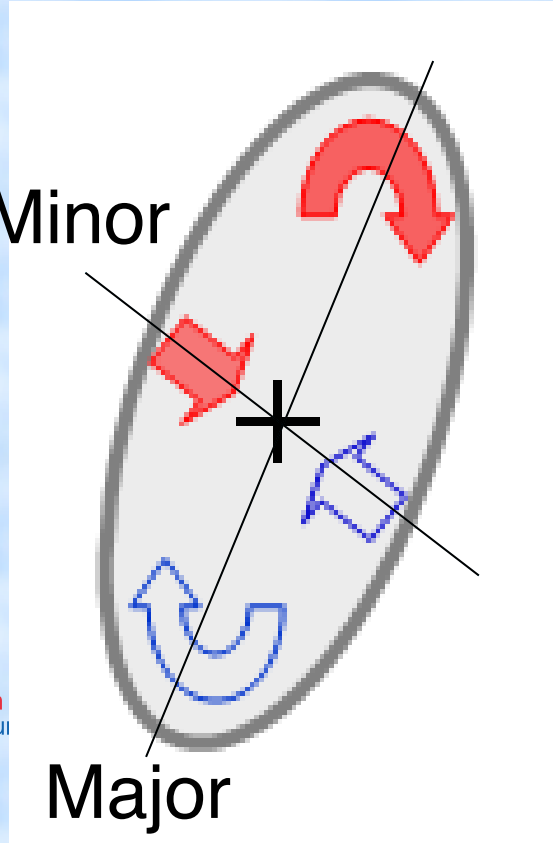


SE Blue, NW Red, exactly along the disk major axis.
No velocity gradient along the minor axis in the disk.

In the extended component, NE Blue, SW Red

SMA + ASTE CS (7-6) Position-Velocity Diagrams



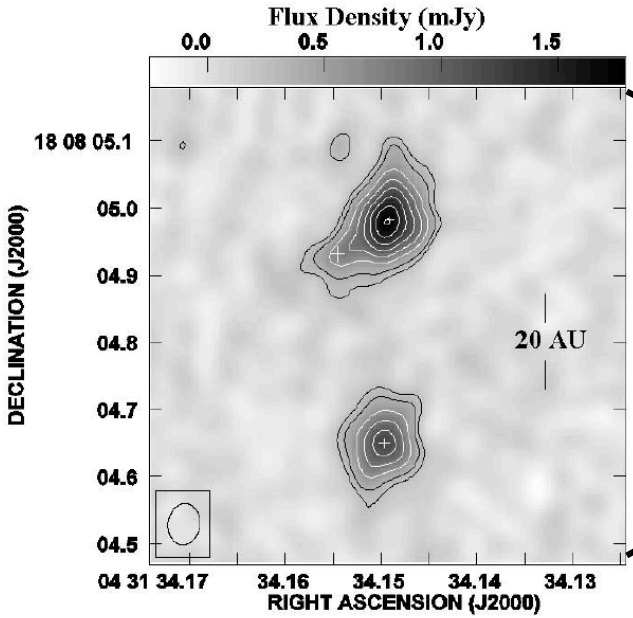


The velocity gradient along the disk major axis can be fitted with the $v_{rot} \sim r^{-1}$ rotation, better than the Keplerian rotation

No infalling motion in the disk, which should be observed as a velocity gradient along the minor axis

Hierarchical Spatial and Dynamical Structures

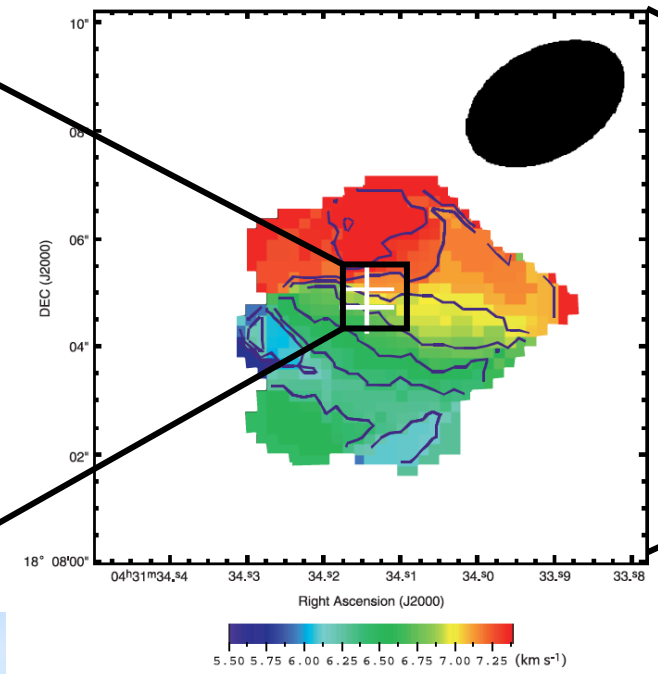
Circumstellar Disks (~20 AU)



VLA 7-mm
(Lim & Takakuwa 2006)

Proper motion
→ Coplanar rotation
to the disk ?

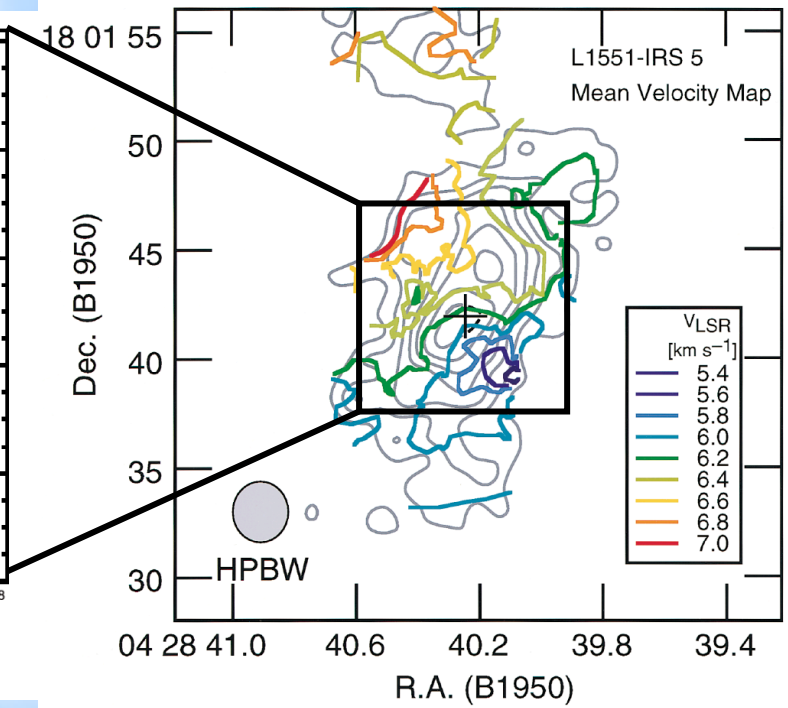
Circumbinary Disk (~500 AU)



SMA CS (7-6)
(Takakuwa+ 2004, 2012)

$v_{rot} \sim r^{-1}$ rotation,
but no infall ?

Protostellar Envelope (~2000 AU)



NMA $C^{18}O$ (1-0)
(Momose et al. 1998)

$v_{rot} \sim r^{-1}$ rotation
+ infall

Summary of L1551 IRS 5

500 AU-scale Circumbinary Disk
in 0.9-mm continuum and CS (7-6)

Velocity Gradient primarily along the major axis
of the circumbinary disk → r^{-1} rotation

Contrary to the ~2000-AU scale mm $C^{18}O$ envelope,
no infall in the 500-AU scale Circumbinary Disk

4. Discussion: Different Rotation in the Circumbinary Disks ?

L1551 NE → Keplerian rotation

$$v_{rot}(r) = \sin i \sqrt{\frac{GM_\star}{r}}$$

L1551 IRS 5 → $v_{rot} \propto r^{-1}$ rotation

$$v_{rot}(r) = \sin i \frac{j}{r}$$

In L1551 IRS 5, the expected Radius of Keplerian Rotation is ~35 AU.
However, this is comparable to the binary separation,
Thus no Keplerian circumbiary disk in L1551 IRS 5

Theory of Binary Formation

The rotation of the circumbinary disk is a ``free'' parameter.

Bate & Bonnel 1997, Bate 2000, Ochi et al. 2005
r^{-1} rotating and infalling circumbinary disk assumed

Gunther & Kley 2002
Keplerian Disk assumed → stable accretion flow

No detailed binary formation model can explain the different rotation in circumbinary disks around the protobinary systems.

Possible explanation ?

Tidal interaction of the binary orbital motion could pile up the angular momentum at the inner edge of the circumbinary disk, thus, forming a Keplerian disk ?

Then, the different rotations between IRS 5 and NE may be due to the evolutionary difference ?

L1551 IRS 5 → The circumbinary disk just formed from the infalling, $v_{rot} \sim r^{-1}$ envelope

L1551 NE → The binary tidal interaction has piled up the enough angular momentum in the circumbinary disk, thus shows Keplerian rotation.