Precessing Protostellar Outflows from a Potential Proto-Brown Dwarf System IRAS 16253-2429

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Introduction

- Brown dwarf (BD)
  - $M < 0.08\ M_\odot$
- The BD formation mechanism is still unclear (Padoan & Nordlund 2004, Bate et al. 2002, Whitworth & Zinnecker 2004, Stamatellos 2013)

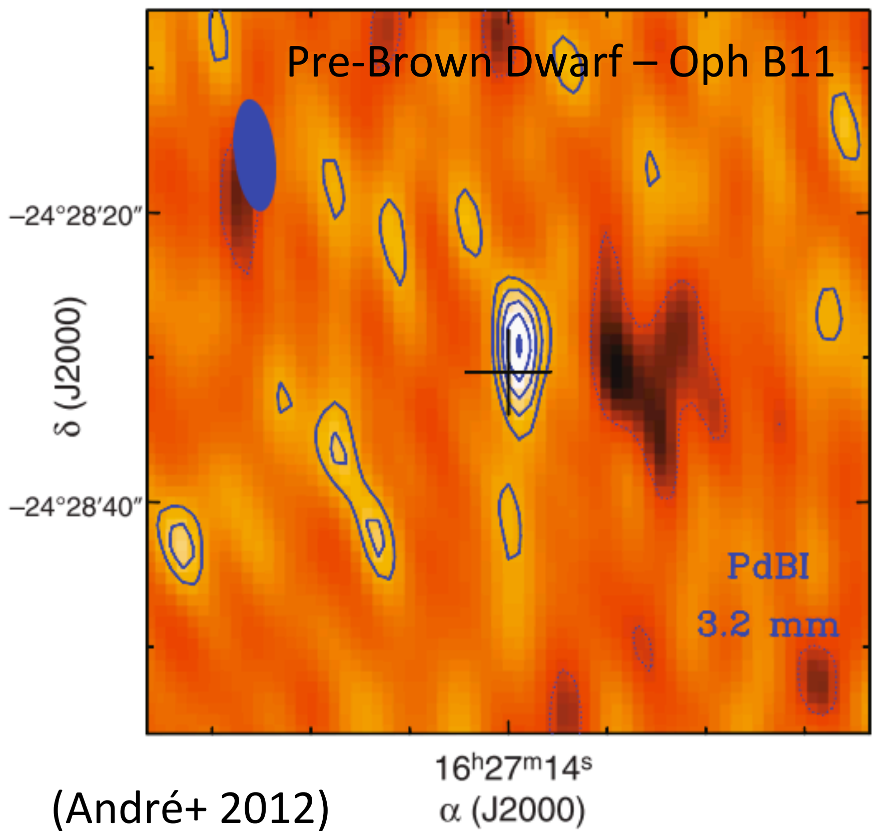
$$M_{\mathrm{JEANS}} = \frac{4\pi^{5/2}}{24} \frac{c_s^3}{(G^3\rho)^{1/2}}$$

- To form a BD, $M_{JEANS} < 0.08\ M_\odot$

$$\rho > 10^{-16} \mathrm{g\ cm^{-3}}$$

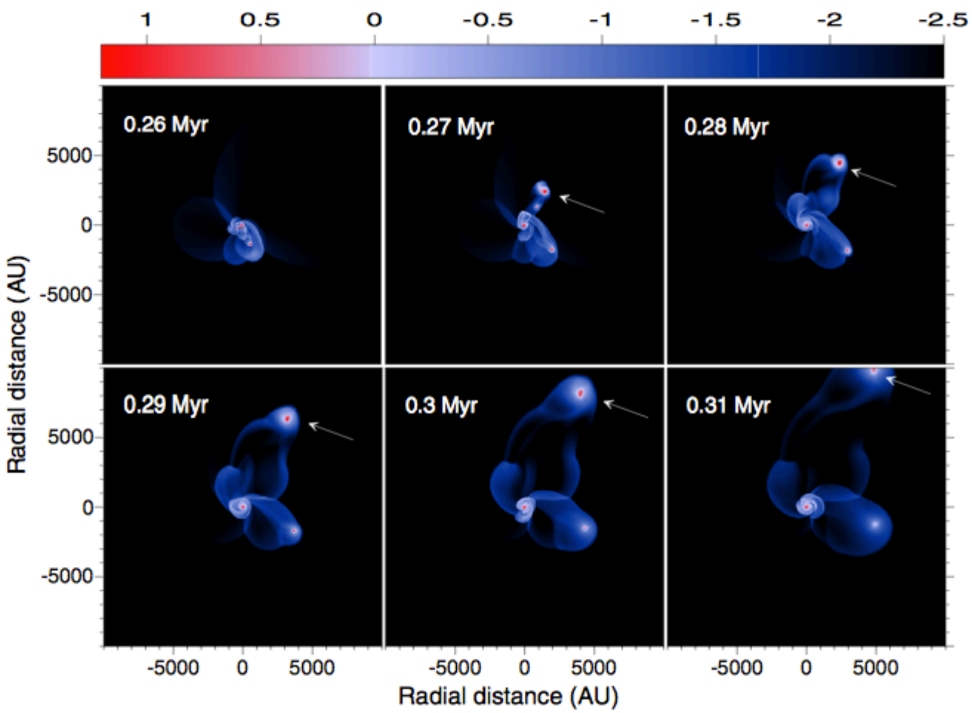
Brown dwarf formation

1. Form through gravitational collapse



(André+ 2012)

2. Form like planet and be ejected later



(Basu & Vorobyov 2012)

Brown dwarf formation

1. Form through gravitational collapse

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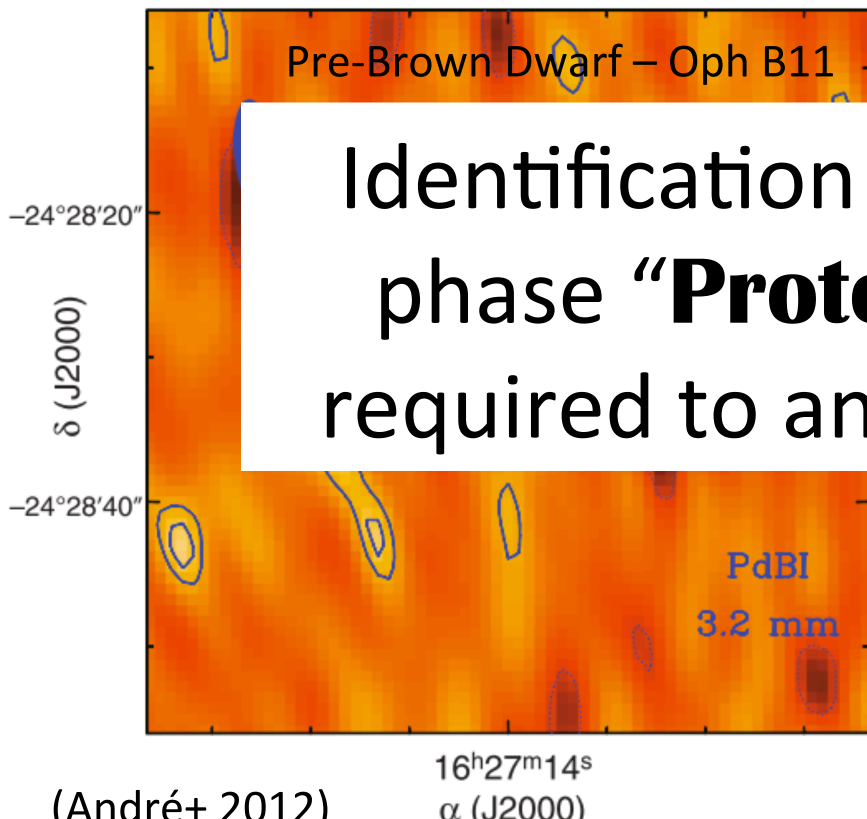
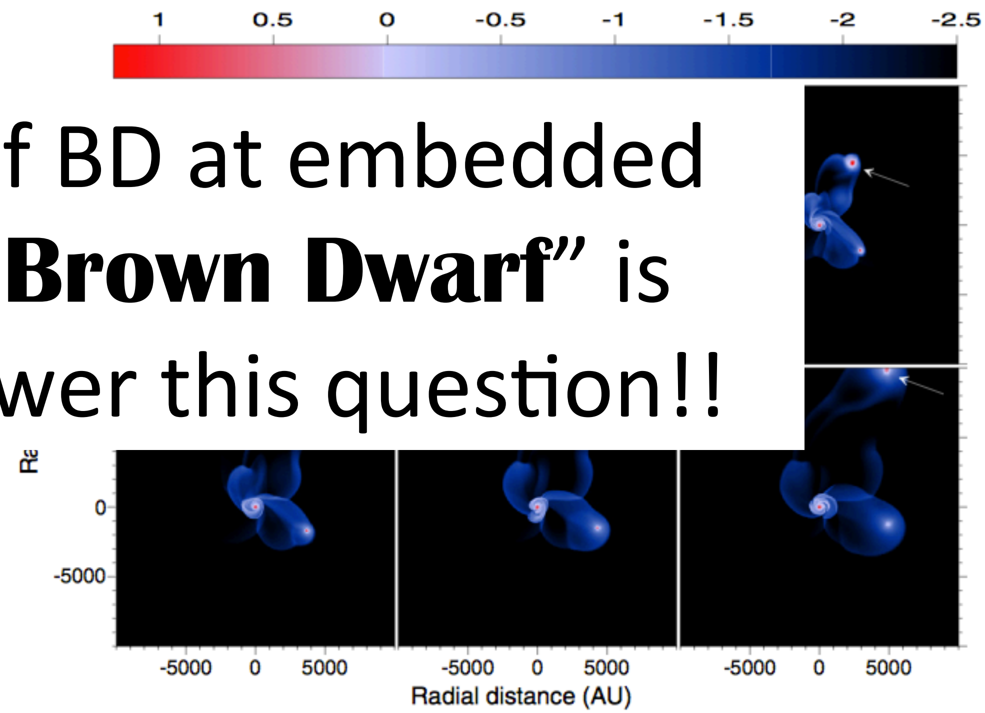




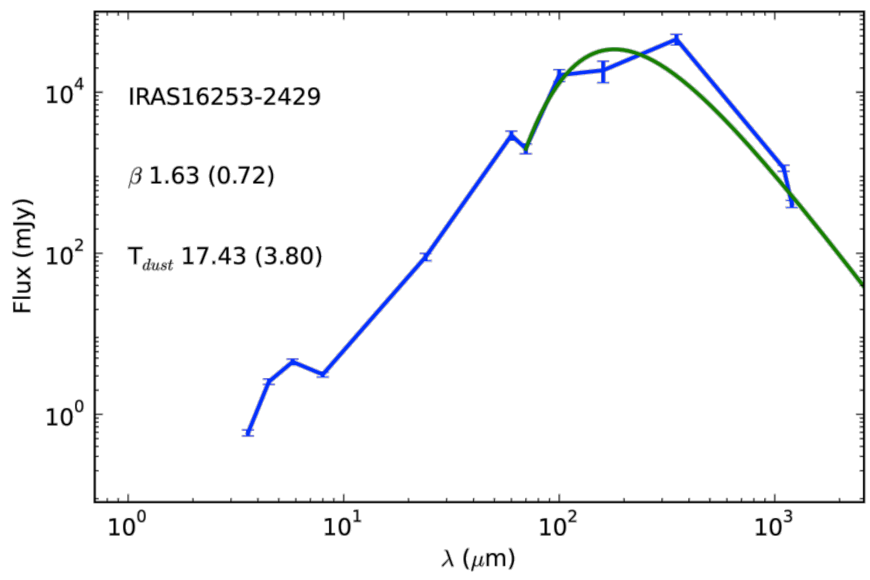
Identification of BD at embedded phase "**Proto Brown Dwarf**" is required to answer this question!!

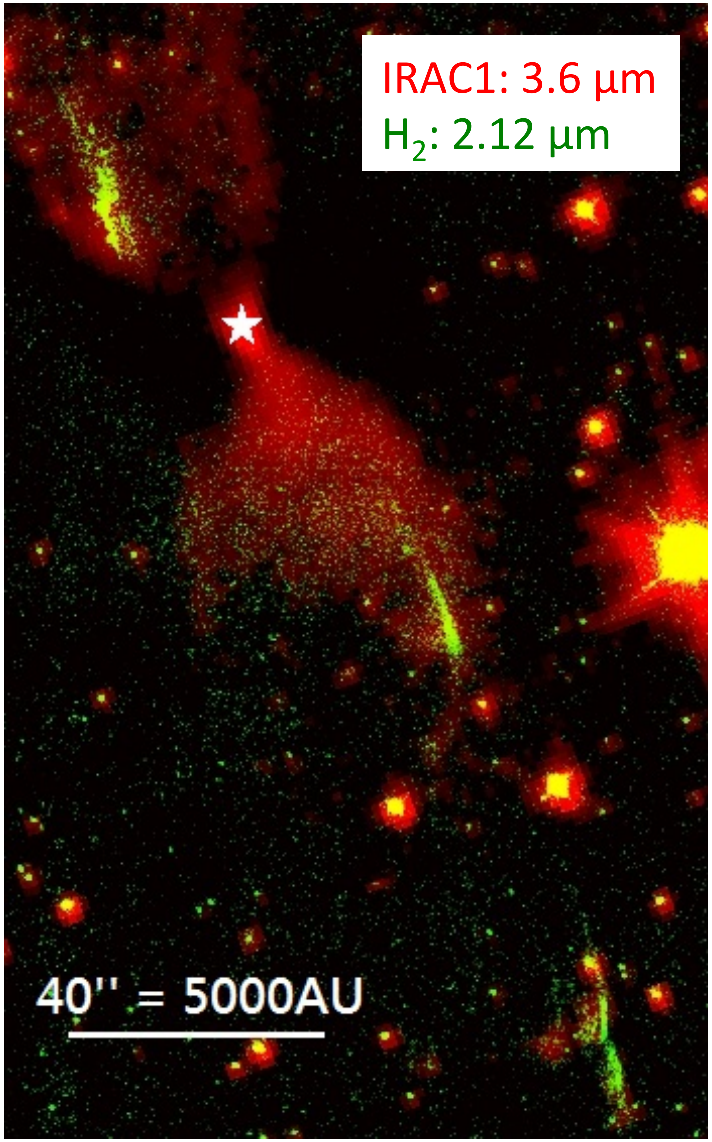
(André+ 2012)

(Basu & Vorobyov 2012)

Introduction - IRAS 16253-2429

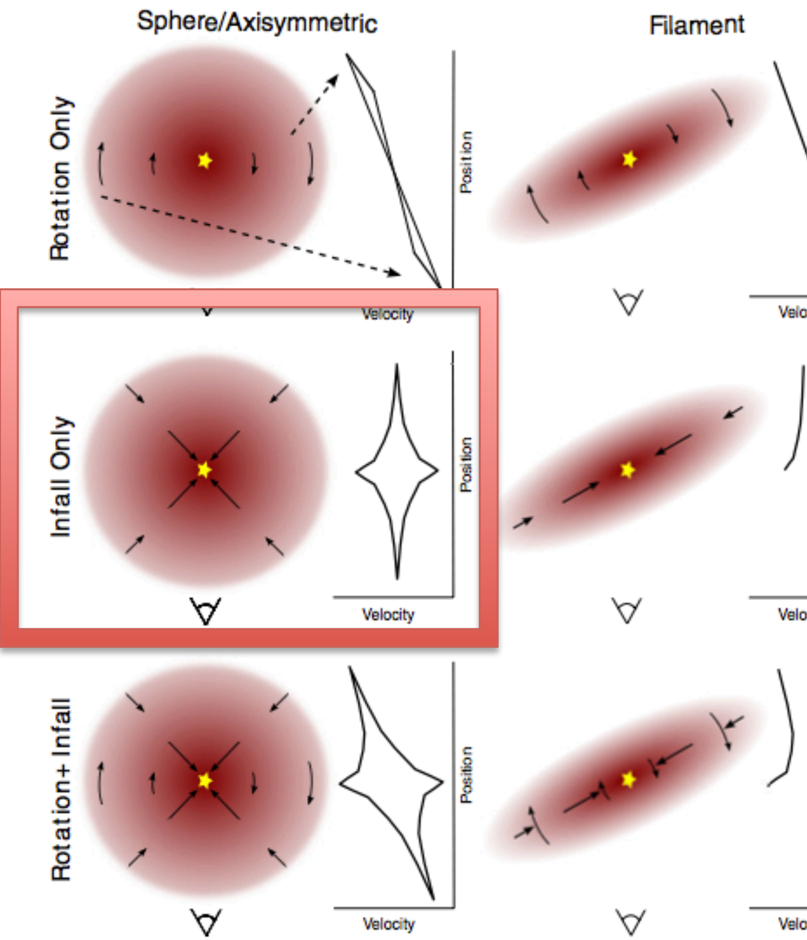
- $L_{int} = 0.09\ L_\odot$
  $L_{Bol} = 0.45 \pm 0.08\ L_\odot$ (Dunham+ 2008)
  $T_{bol} = 30 \pm 2$ K
- $T_{dust} = 17 \pm 4$ K
  $N_2D^+/N_2H^+ = 0.064 \pm 0.005$ (Hsieh+ 2015)
- $M_{env} = 0.46\ M_\odot$ (Stanke+ 2006, Tobin+ 2012)

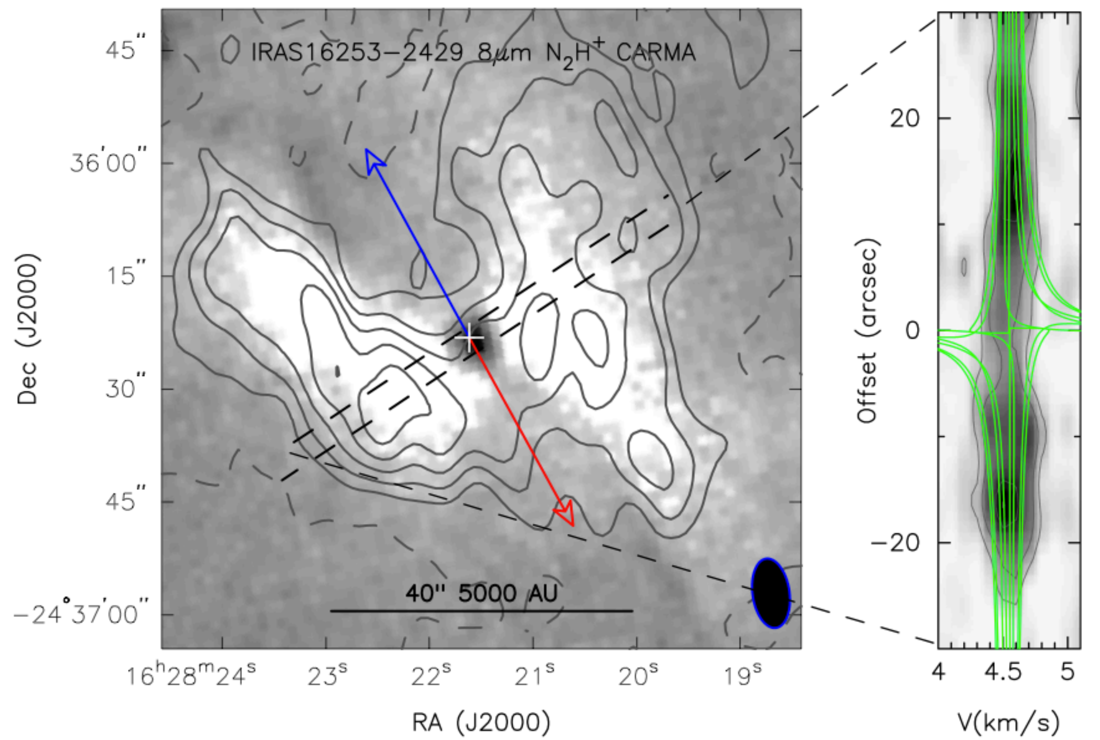




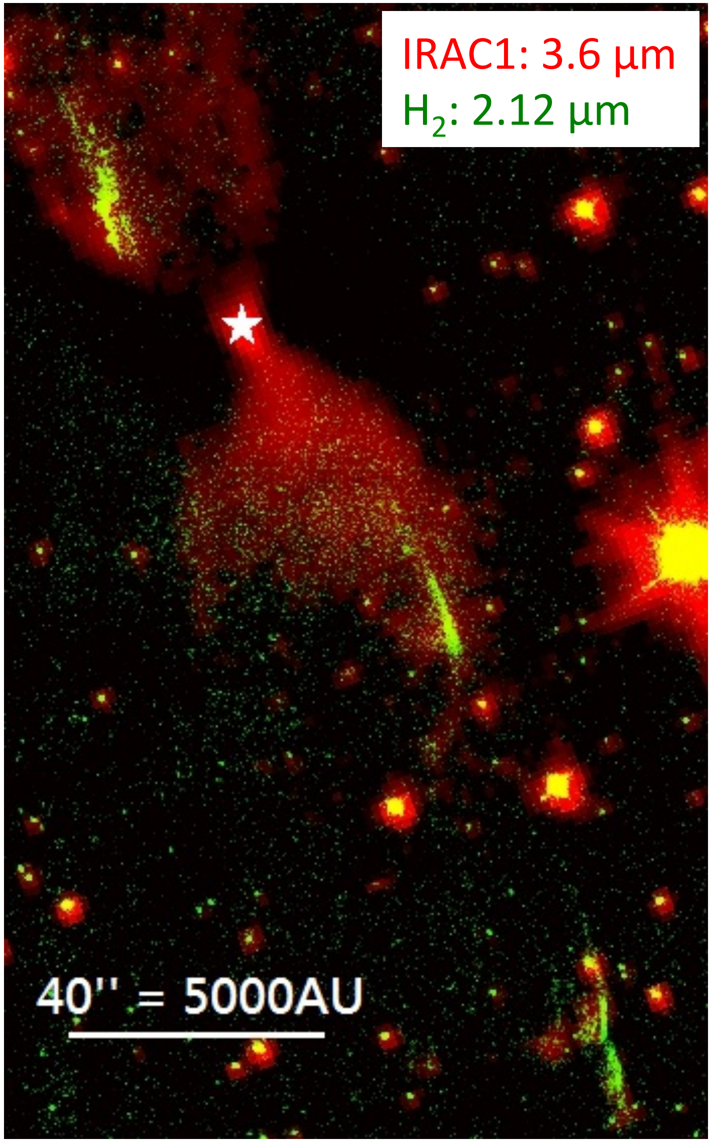
Central mass of IRAS 16253-2429

- $M_{cent} \lesssim 0.1\ M_{\odot}$ is implied by the very narrow N_2H^+ line (Tobin+ 2012)





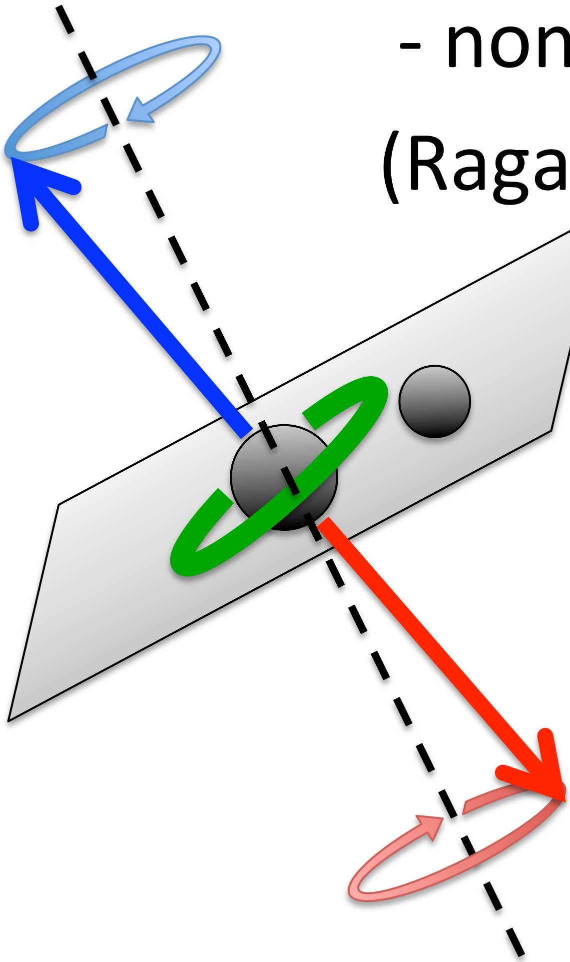
Existence of binary system?



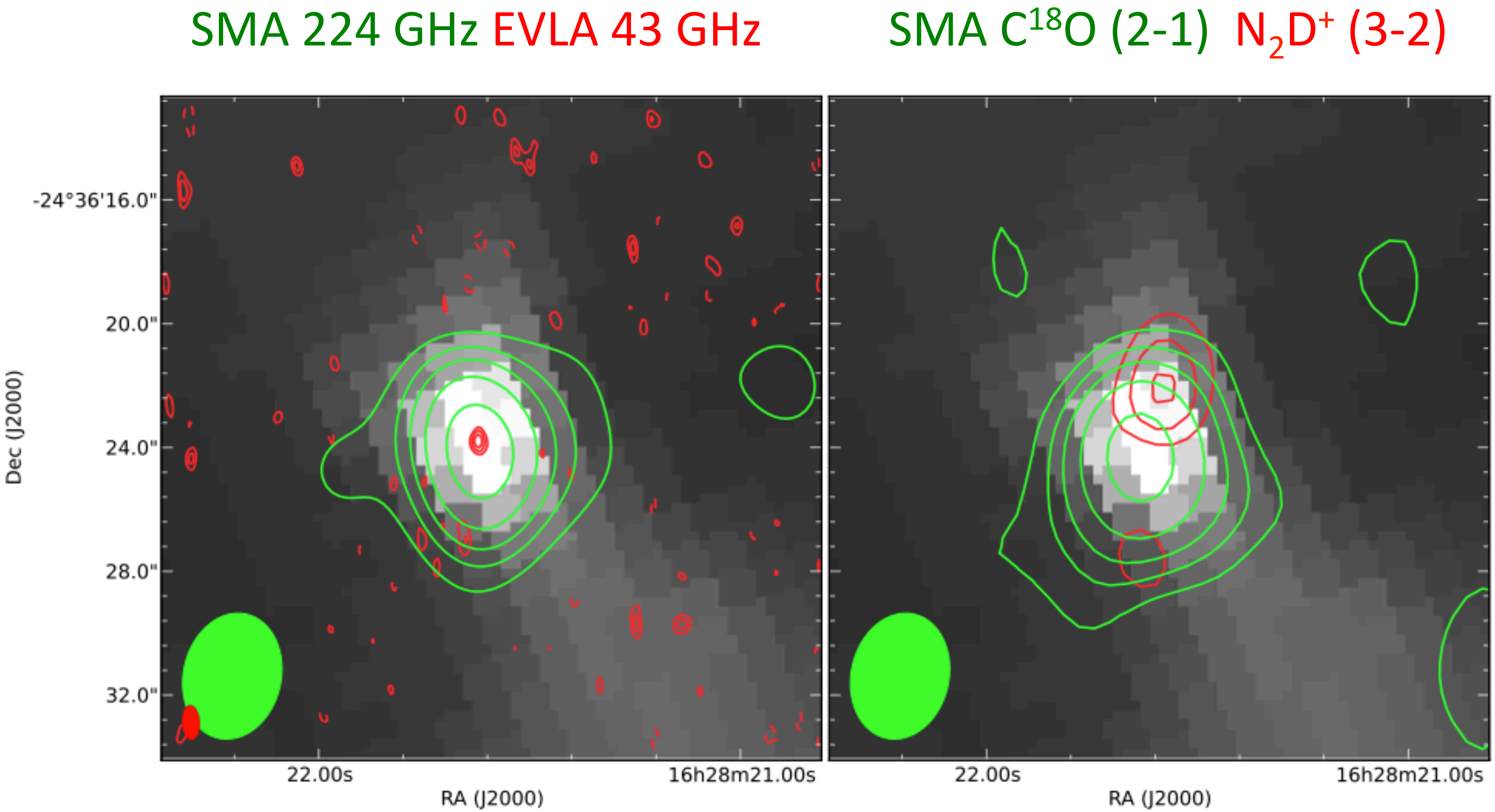
The precessing outflow (i.e. S shape)

- non-coplanar disk

(Raga+ 2009)

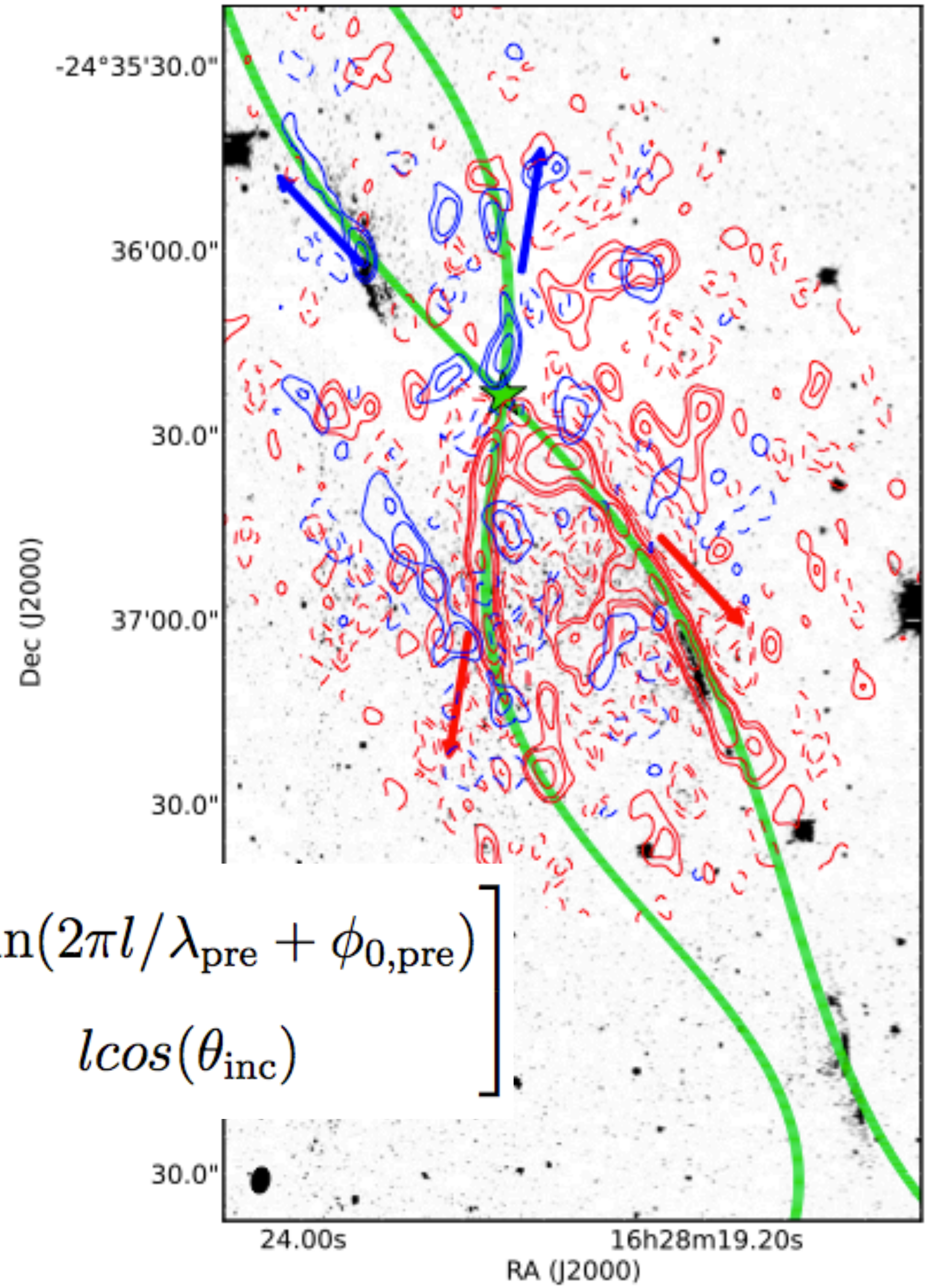


SMA + EVLA observations



Binary system: Two outflows?

SMA CO (2—1)
$+H_2$ emision

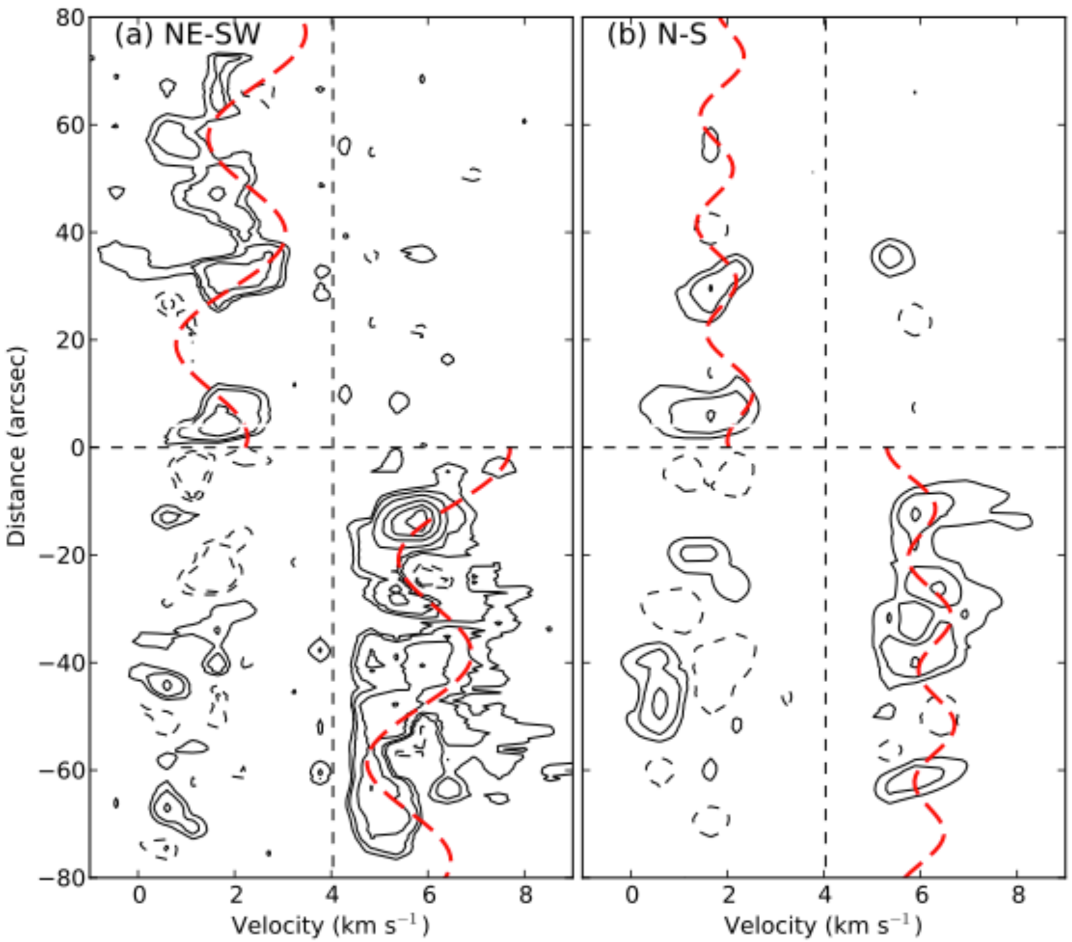


$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \alpha l \sin(2\pi l/\lambda_{\rm pre} + \phi_{0,\rm pre}) \\ l cos(\theta_{\rm inc}) \end{bmatrix}$$

(Eislöffel+ 1996; Wu+ 2009)

Estimation of central mass

PV diagrams of the two jets



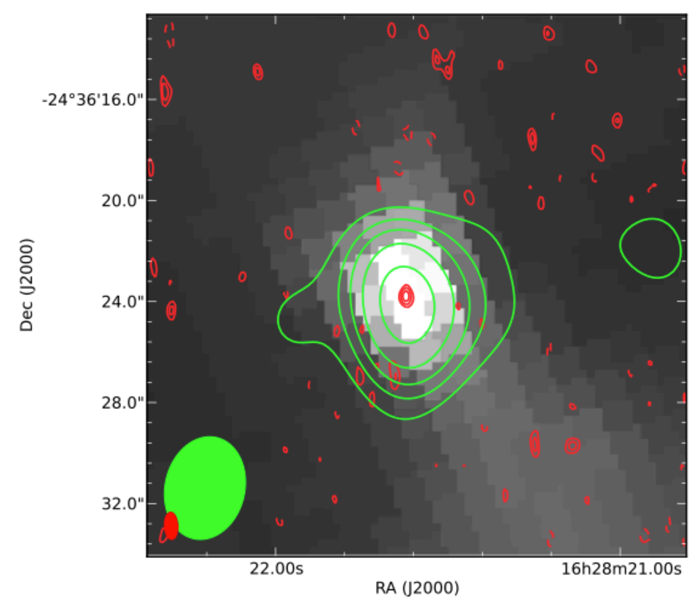
$P_{orb} \sim 3000$ yr

$$P^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)}$$

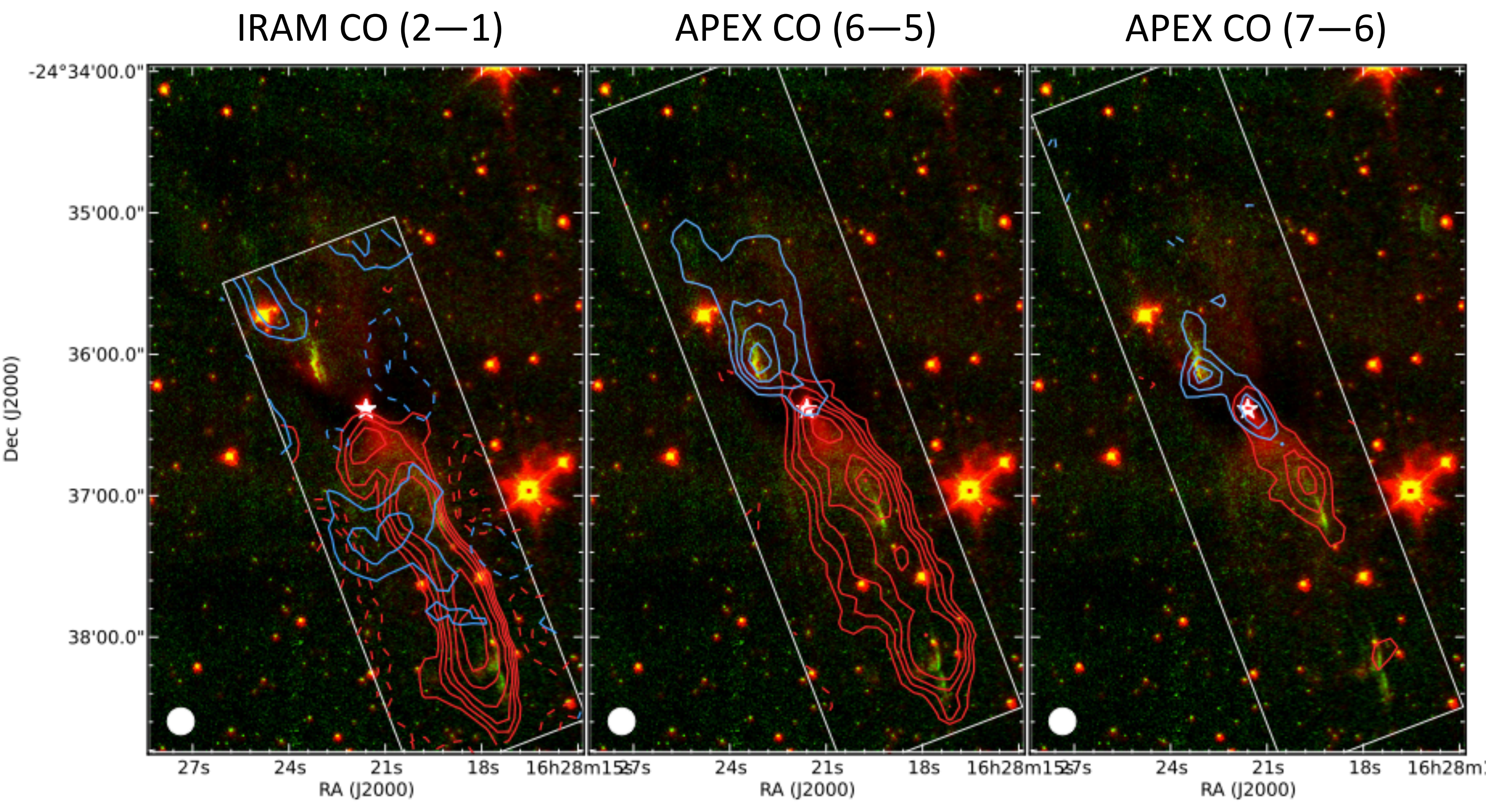
If a < 90 AU (0.72″)

$M_{central}$ $(M_1+M_2) < 0.08\ M_\odot$

Proto BD candiate?



IRAM 30m + APEX Champ^{+} observations



Outflow mass comparison

	Barsony+ 2010 H_2 lines	CO (6-5) and (2-1)	CO (6-5)
T_{gas} (K)	~1000 K (derived)	~20-60 K (derived)	120 K (assumed)
Red shifted	$7.95 \times 10^{-7}\ M_{\odot}$	$13.0 \times 10^{-4}\ M_{\odot}$	$3.8 \times 10^{-4}\ M_{\odot}$
Blue shifted	$5.78 \times 10^{-7}\ M_{\odot}$	$1.8 \times 10^{-4}\ M_{\odot}$	$0.4 \times 10^{-4}\ M_{\odot}$
Total	$13.7 \times 10^{-7}\ M_{\odot}$	$14.8 \times 10^{-4}\ M_{\odot}$	$4.2 \times 10^{-4}\ M_{\odot}$

If we assume $\dot{M}_{outflow} \sim (0.1 — 0.5)\dot{M}_{acc}$ (Hartigan et al. 1995)

$M_{star\ (A)}$	$3\text{-}14 \times 10^{-6}\ M_{\odot}$	$0.004\text{-}0.015\ M_{\odot}$	$0.001\text{-}0.004\ M_{\odot}$

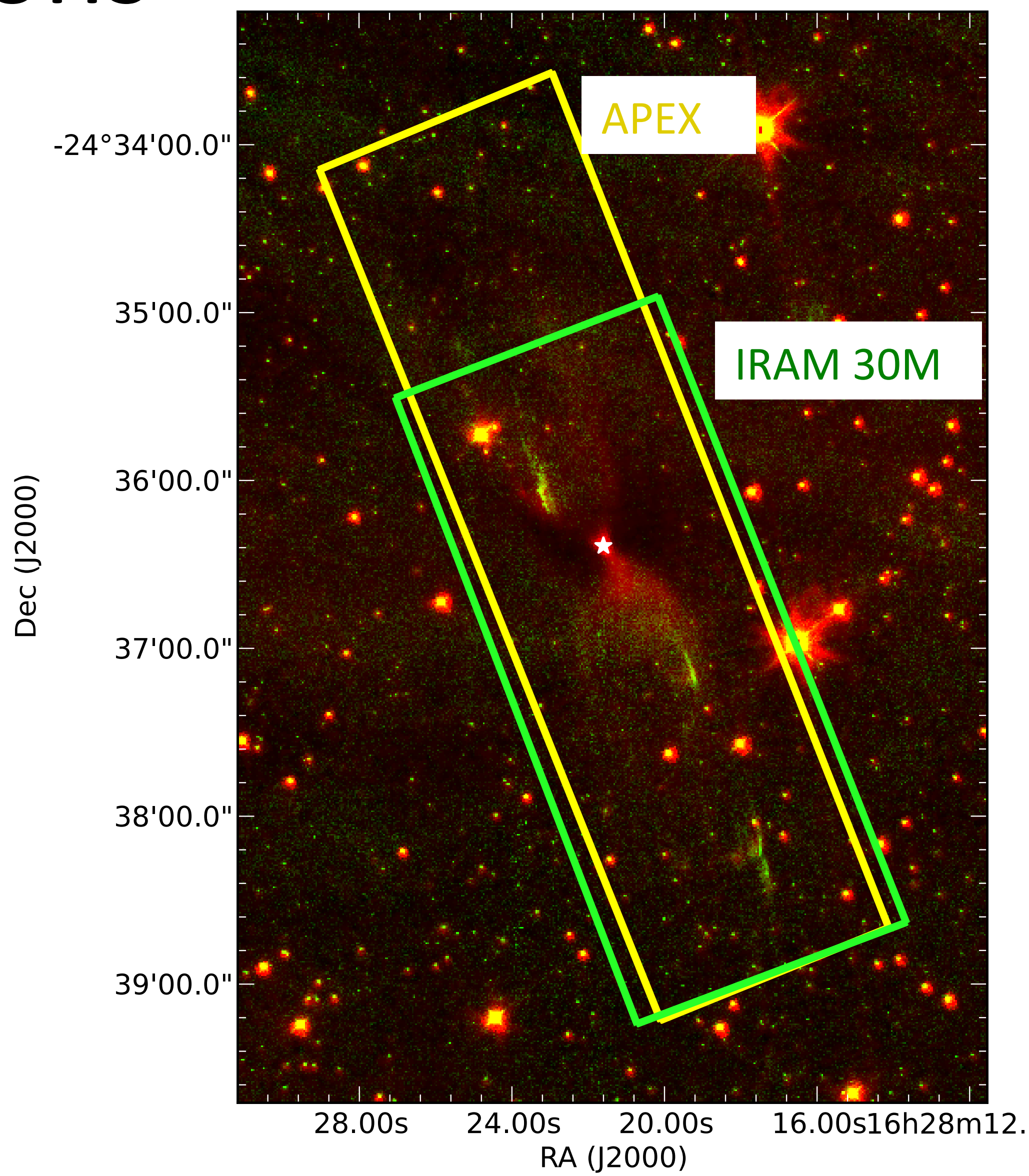
Summary

1. A proto brown dwarf candidate - IRAS 16253-2429:
   M_{env} = 0.46 $M_\odot$ (Stanke+ 2006; Tobin+ 2012)
   $M_{cen,dyn} \sim 0.08\,(a/90\ \mathrm{AU})^3\,M_\odot$
   $M_{cen,\ jet} \sim$ 0.004-0.015 $M_\odot$
2. Outflow morphology
   CO (2-1): low-J transition traces outflow cavity
   CO (6-5): mid-J transition traces more excited gas (H_2 jet)
3. Mass of outflows:

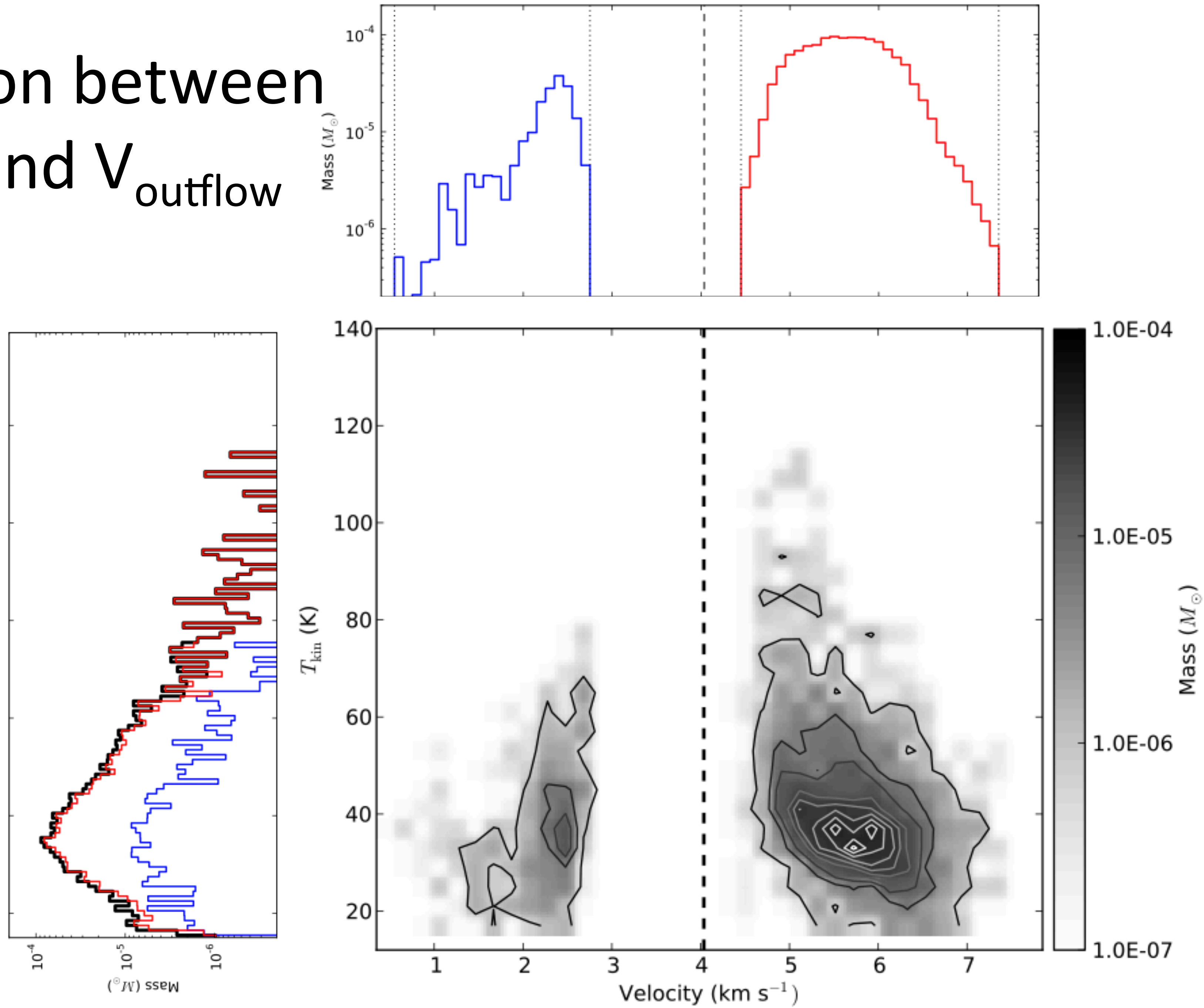
   - hot gas (1000K): $1.4 \times 10^{-6}\,M_\odot$ (Barsony+ 2010)
     warm gas (120 K): $4.2 \times 10^{-4}\,M_\odot$
     cold gas (20-60 K): $14.8 \times 10^{-4}\,M_\odot$

Outflow observations

- IRAM 30M
  CO (2—1)
  σ = 0.46 K at 0.1 km s^{-1}
- APEX Champ+
  CO (6—5)
  σ = 0.49 K at 0.1 km s^{-1}



Relation between T_{kin} and $V_{outflow}$



The outflows in large scale

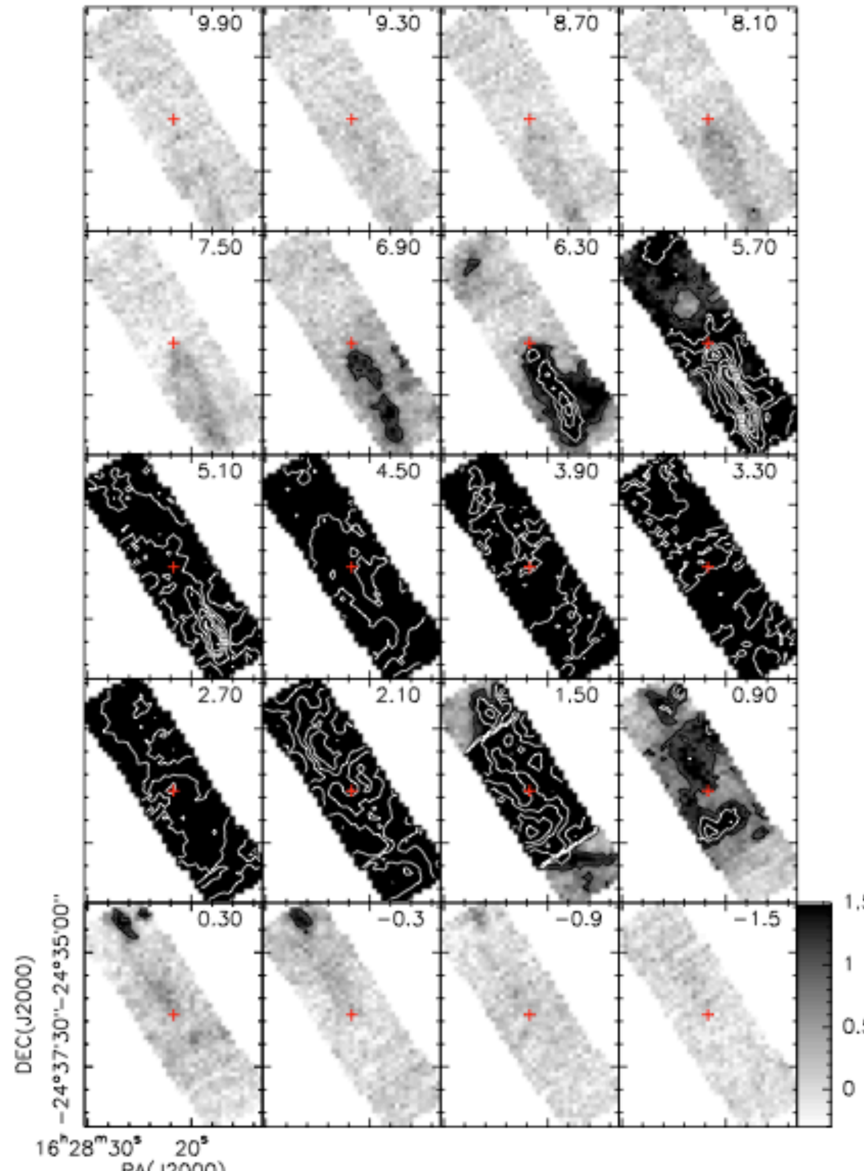
JCMT CO (3—2) obs.

Stanke et al. (2006)

$M_{outflow} = 3.37 \times 10^{-3} M_{\odot}$

(assuming

$\tau_{CO}/(1-e^{-\tau CO}) = 3.5$)

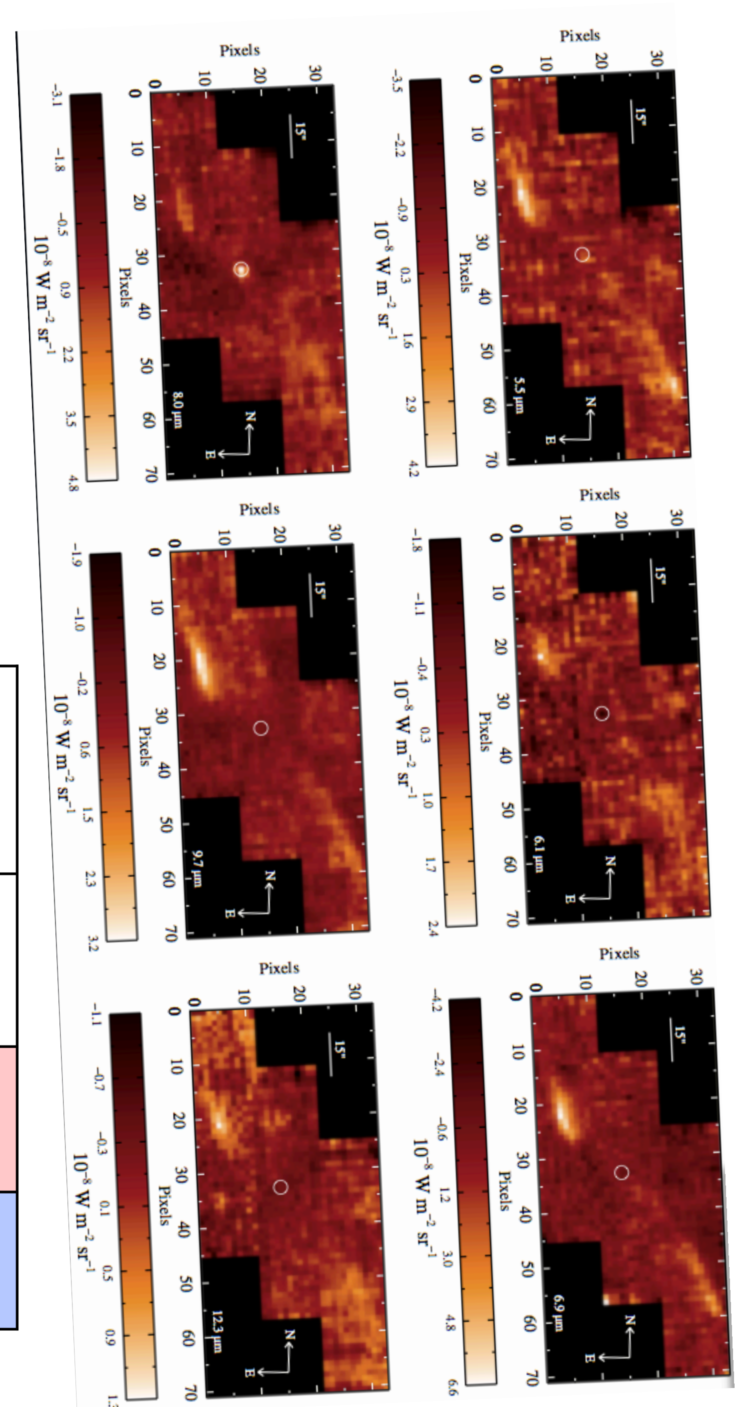


$M_{hot}/M_{cold} \sim 10^{-3}$

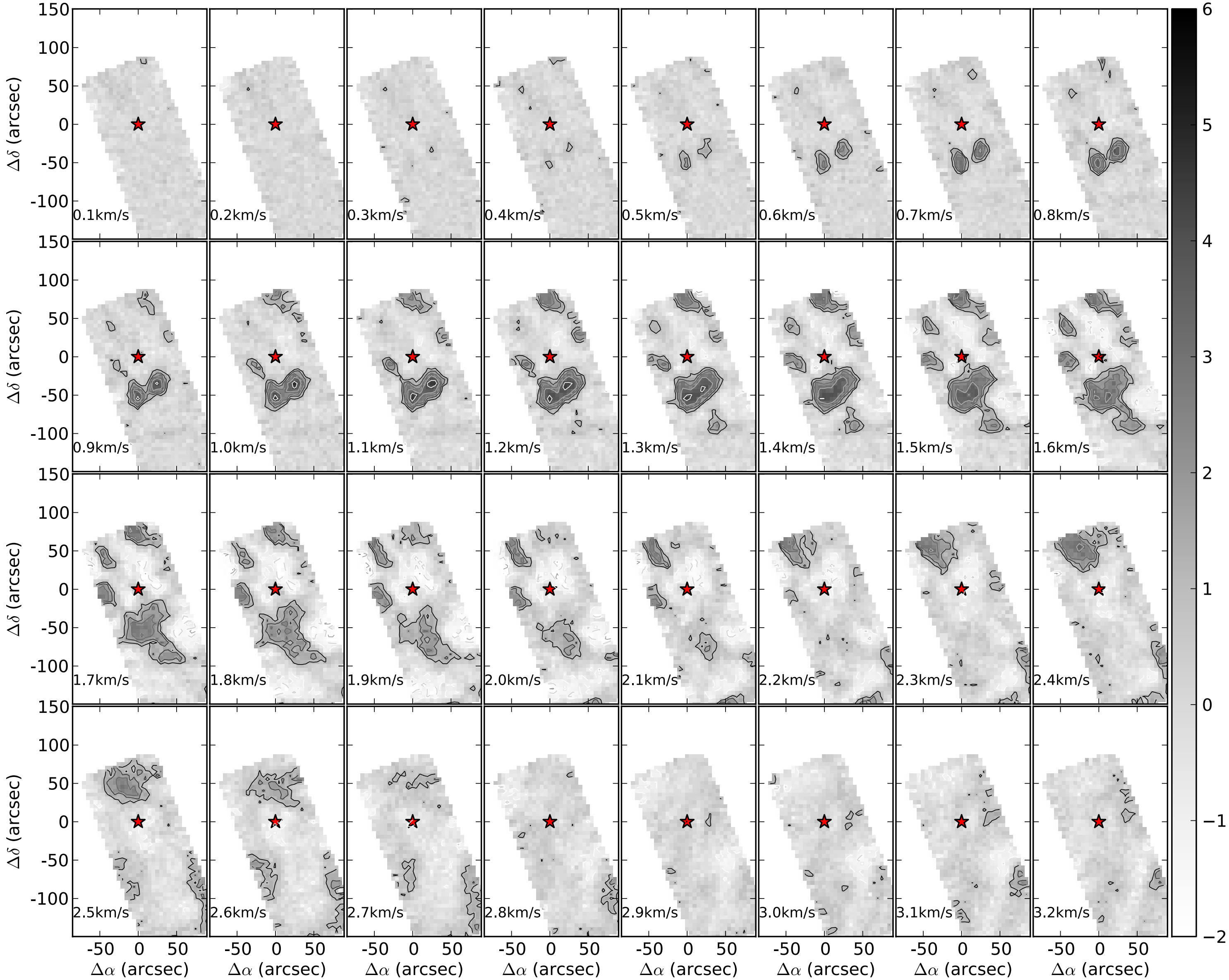
Spitzer IRS H_2 obs.

(Barsony et al. 2010)

$M_{outflow}$	Barsony+ 2010 H_2 line obs.	Stanke+ 2006 CO (3—2) obs.
T_{gas} (K)	1000 K (derived)	30 K (assumed)
Red shifted	$7.95 \times 10^{-7}\ M_\odot$	$28.2 \times 10^{-4}\ M_\odot$
Blue shifted	$5.78 \times 10^{-7}\ M_\odot$	$5.5 \times 10^{-4}\ M_\odot$



Channel maps of CO (2—1)



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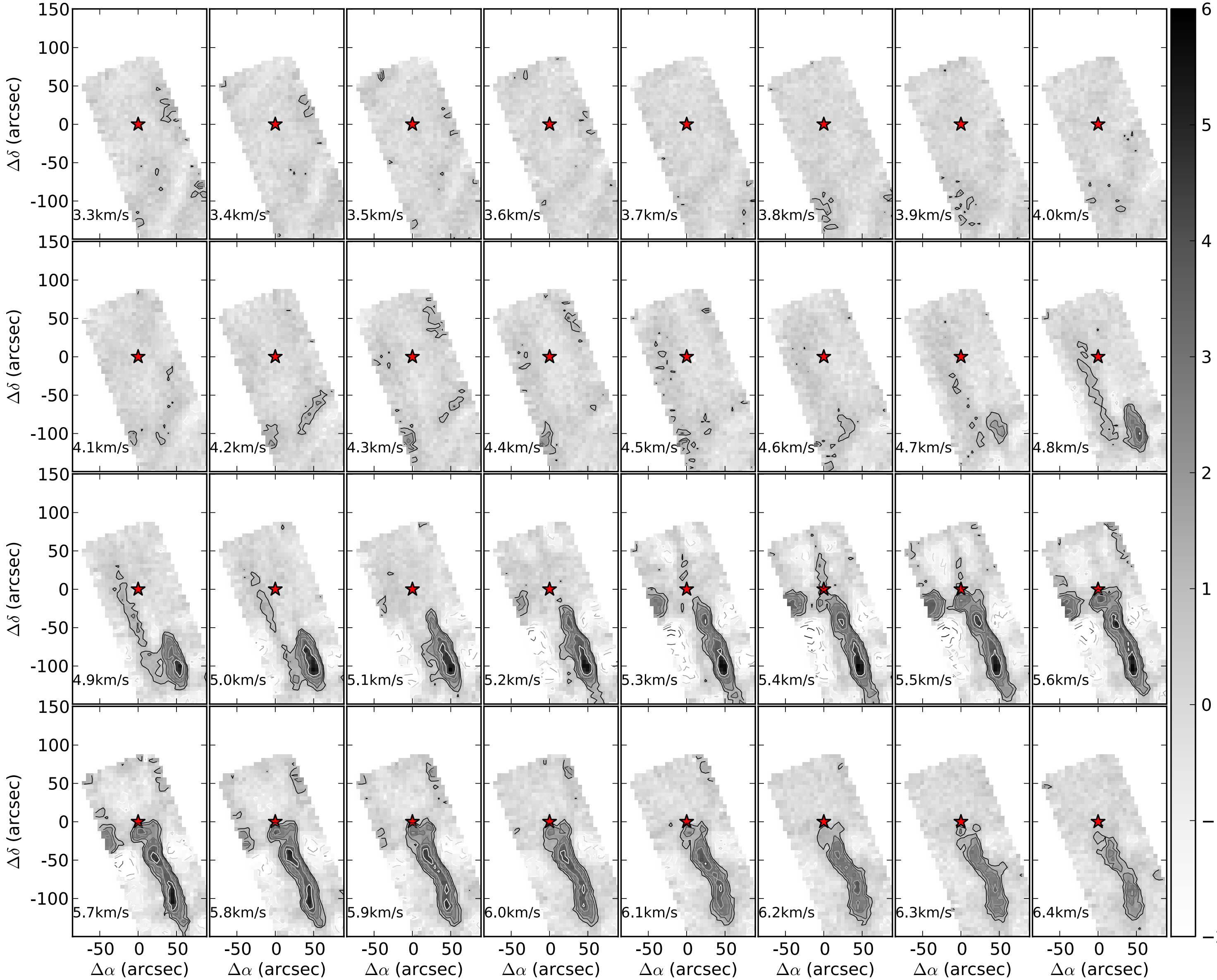

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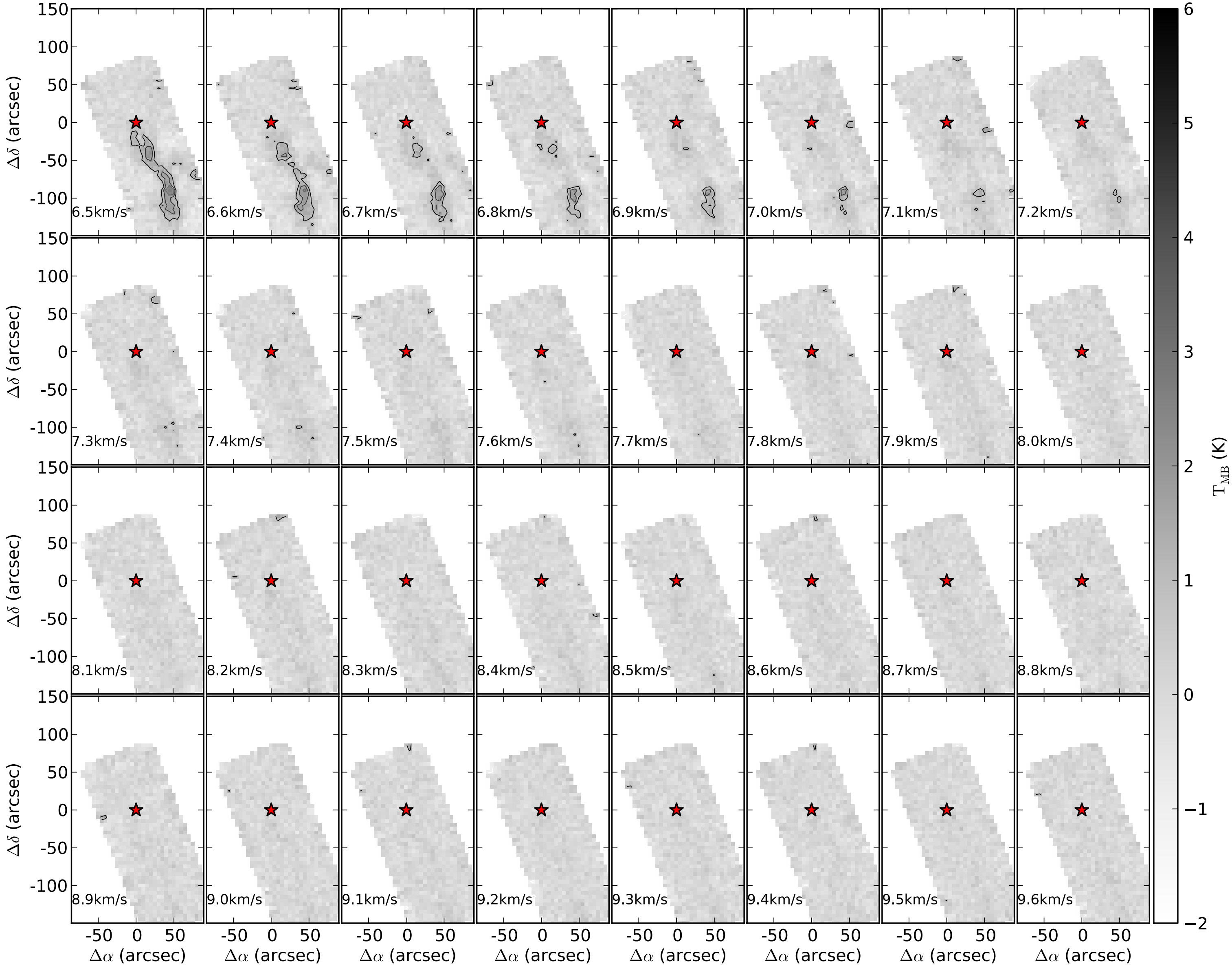
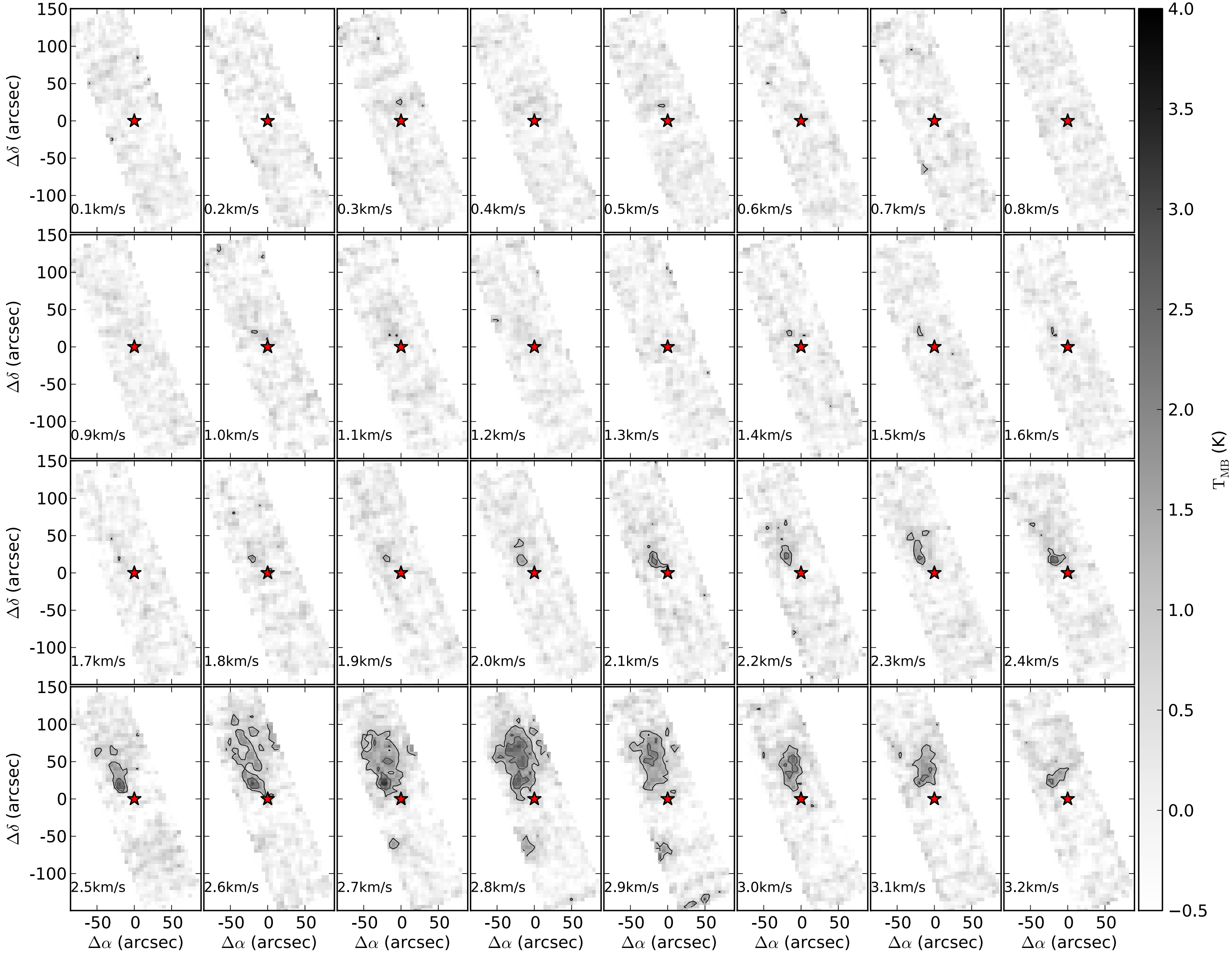
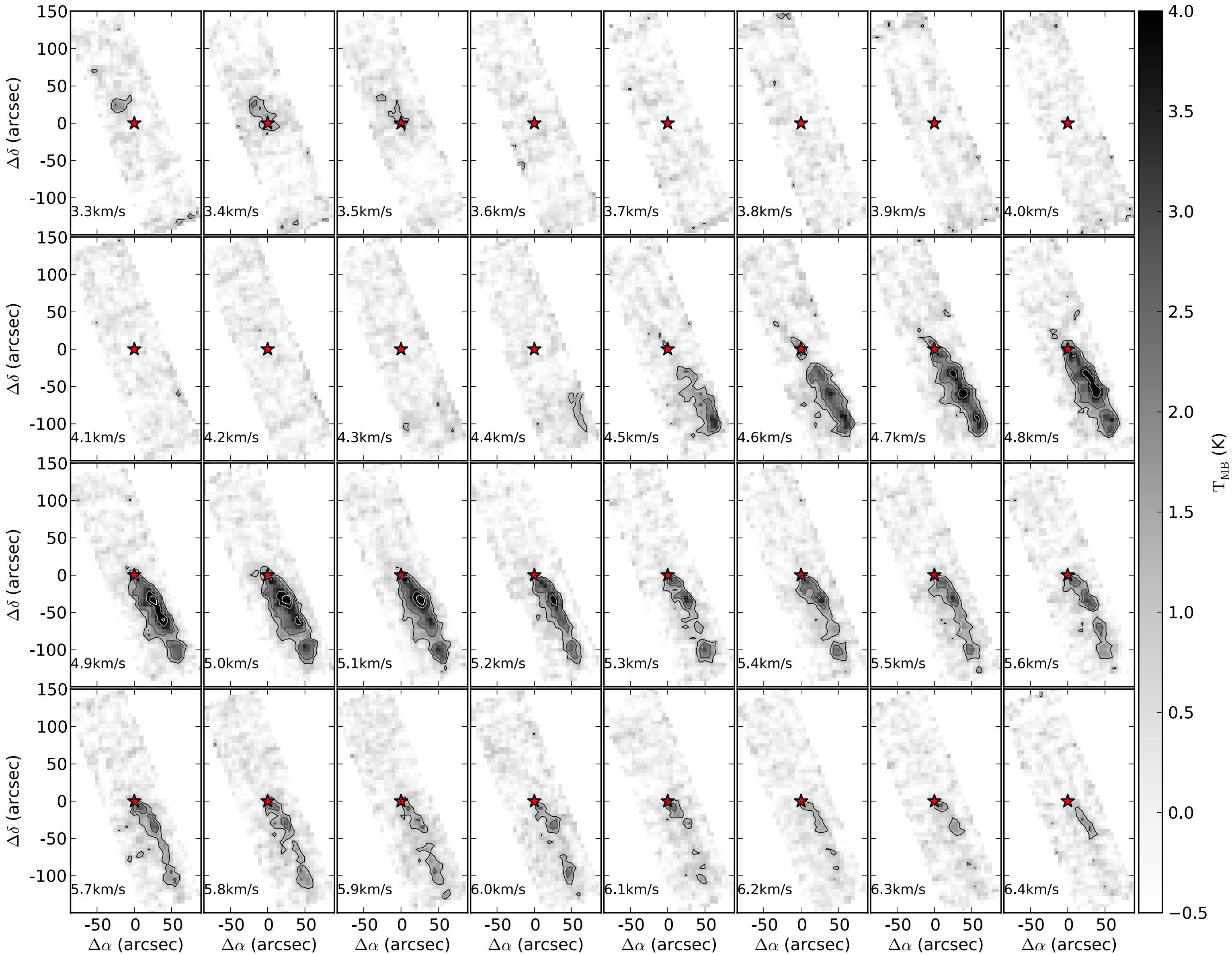


Channel maps of CO (6—5)



Channel maps of CO (6—5)



Channel maps of CO (6—5)