The Structure of Class I Protostellar Disks

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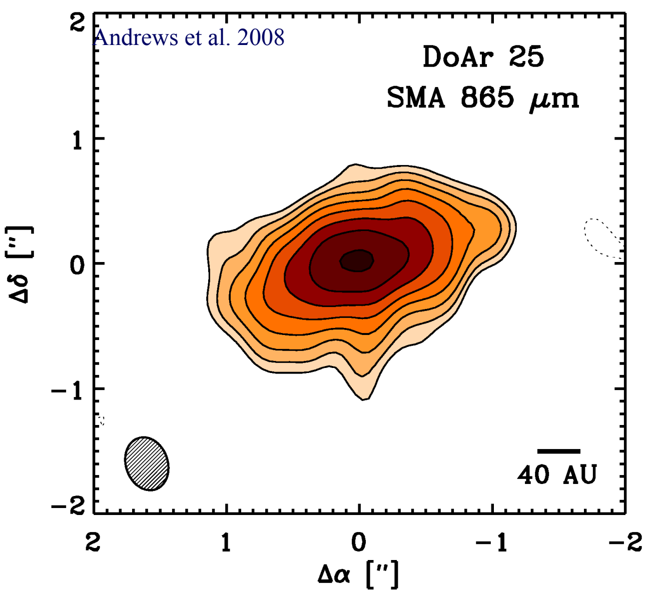
Mike Dunham (Yale), Kevin Covey (Lowell Obs.), and thanks to
Christian Brinch

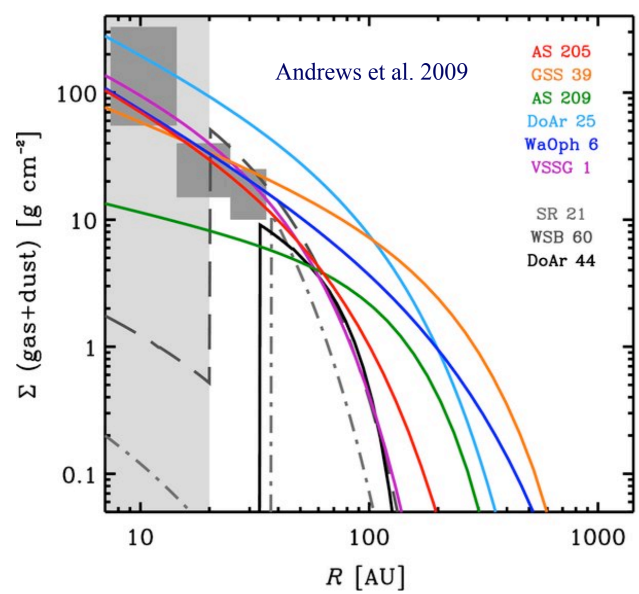
How do proto-planetary disks evolve?

When do stars form gravitationally supported (Keplerian) Disks?

How does disk mass and size evolve? Disk structure?

When do disks become massive enough to form planetary systems?





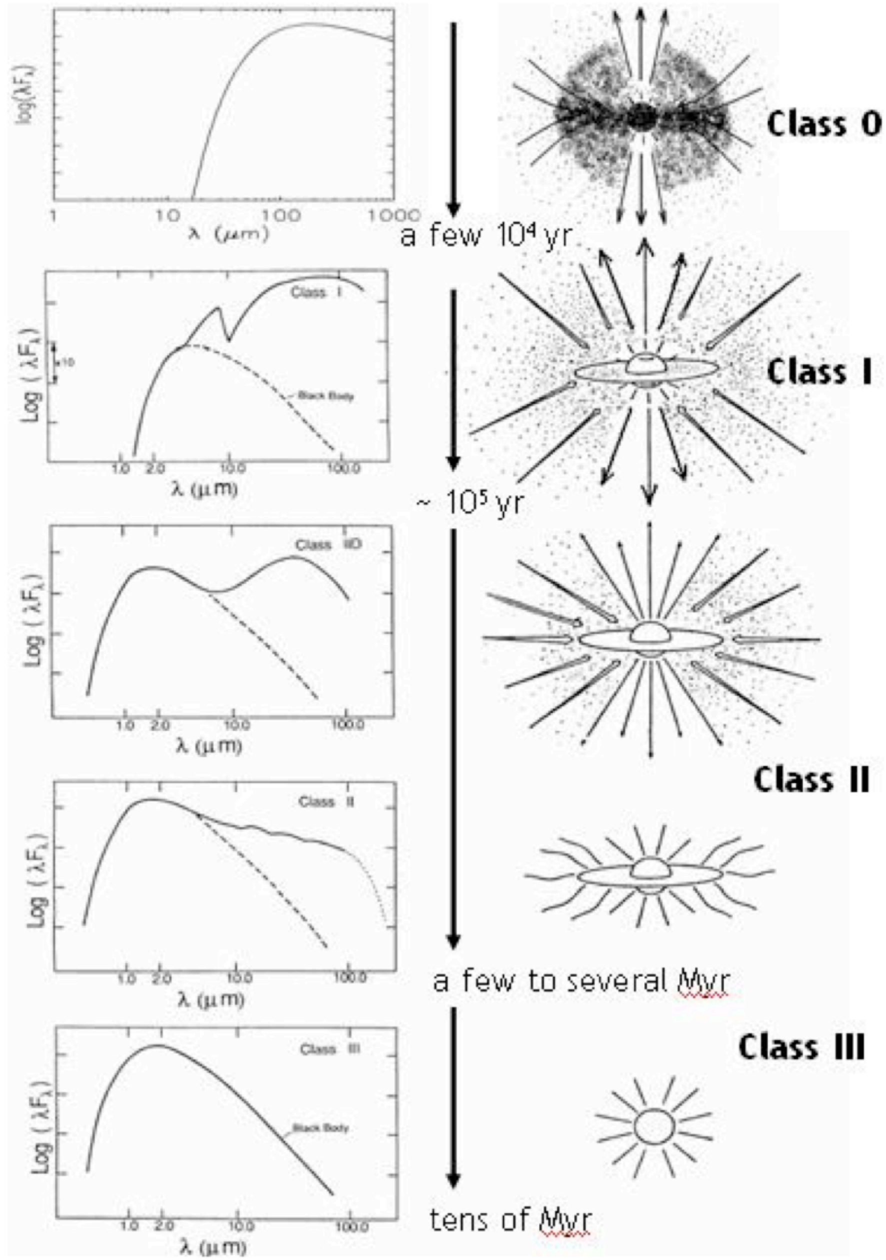
Difficulties

Star formation occurs inside dusty cores

- high column density
- difficult to separate disk emission from envelope (cf. T Tauri stars, no problem)

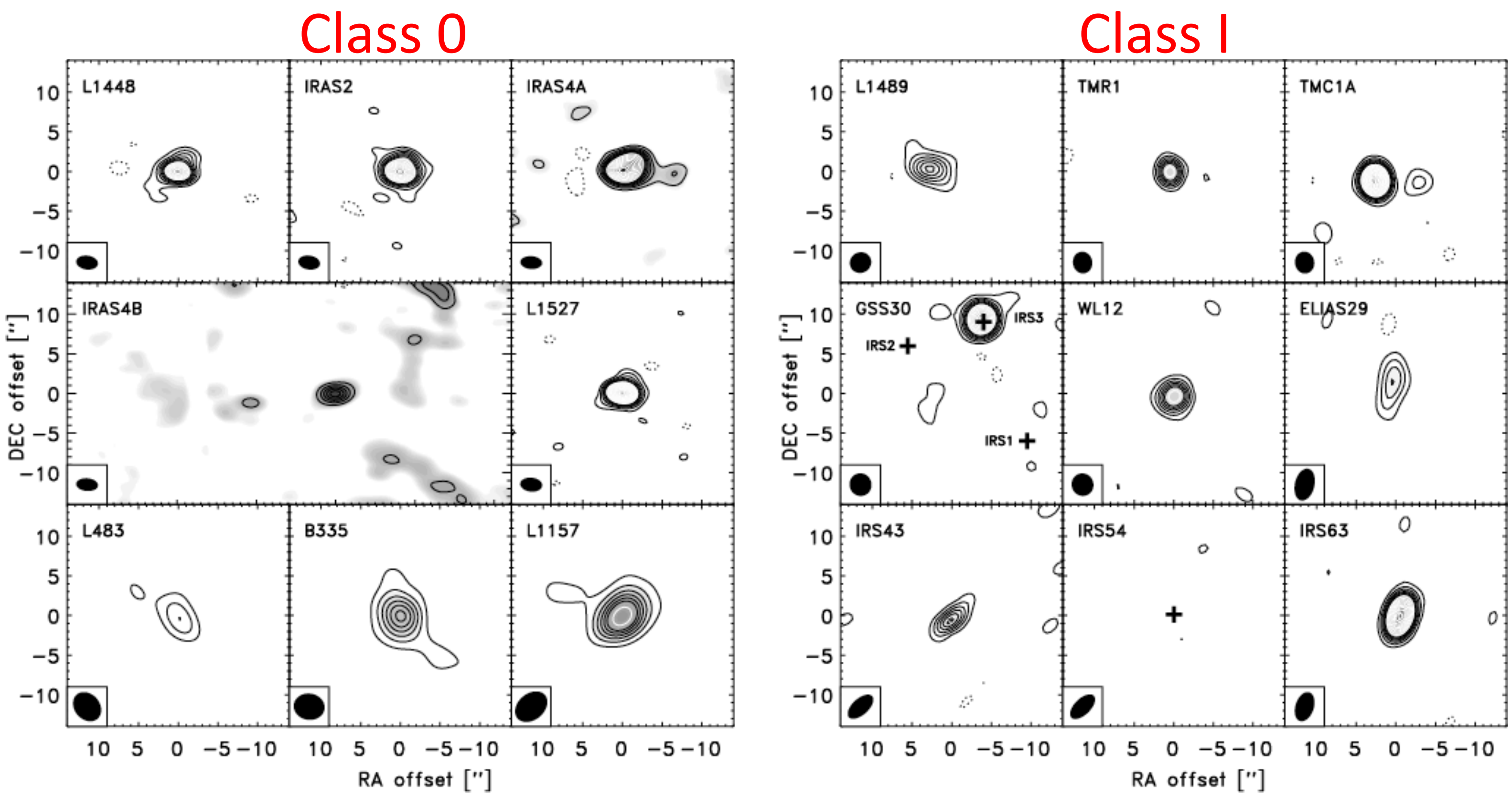
Protostars not optically visible

- unknown mass (star/disk mass – GI?)



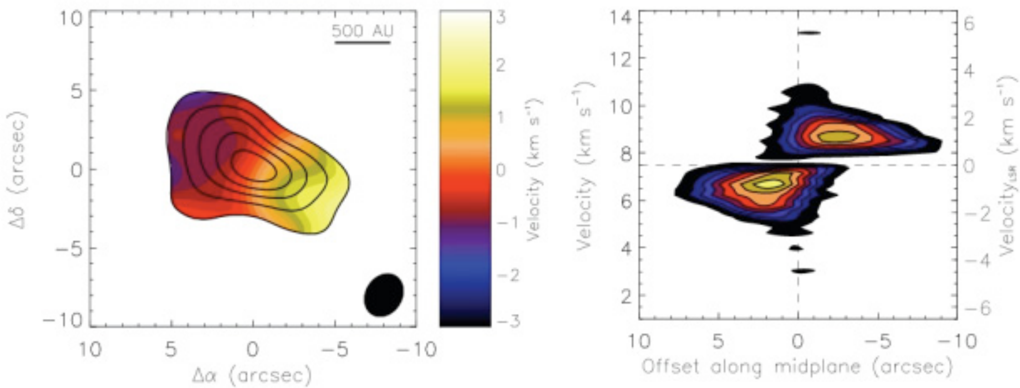
Compact Structures – are they disks?

modelling – envelope + disk (dust continuum)
– rotation + infall (line emission)
direct confirmation – Keplerian rotation on 100 AU scales

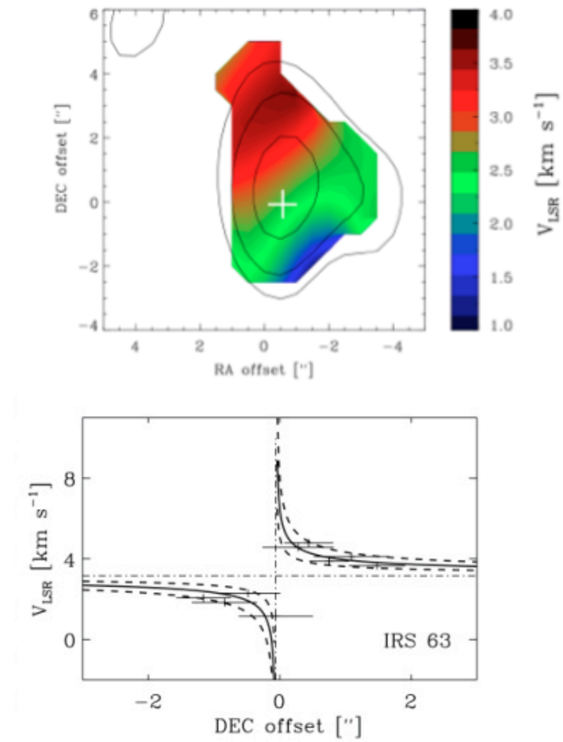


1-mm dust continuum (Jørgensen et al. 2009 – PROSAC II)

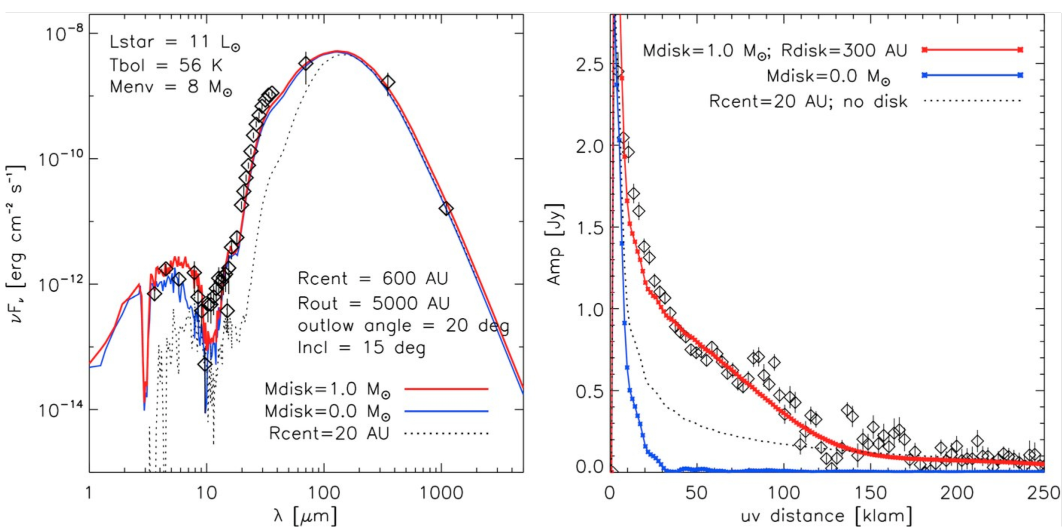
L1489 HCO^+ 3-2 (Brinch et al 2007)



IRS63 HCO^+ 3-2
(Lommen et al. 2008)



Serp SMM1 1-mm (Enoch et al 2010)



and Elias 29 (Lommen 08),
IRS43 (Jørgensen 09,
CB26 (Launhardt in prep)

Submillimeter Array Survey of Class I disks

(1) separate disks from envelopes
(2) model disk + envelope (SEDs, SMA, single-dish) – sizes, masses
(3) resolve the disks – structure
(4) identify Keplerian motions – protostar mass
(5) model line motions – infall, rotation
(6) mass ratios (star, disk, env) – evolutionary trends?

Source Selection and Observations

- Use T_{bol}, L_{submm}/L_{bol}, near-mid infrared spectral index to select candidates
- Association with a dense core to further separate edge-on Class II from I
- 8 sources, 4 each in Taurus and Ophiuchus (nearby regions)

[Doppmann et al 2005 (class I; Tau and Oph); Eisner et al 2005 (OVRO; Tau); Enoch et al 2009 (c2d+Bolocam; Oph); Evans et al 2009 (c2d; Oph); Furlan et al 2008 (Tau class I); Jørgensen et al 2008 (c2d+SCUBA; Oph); Luhman et al 2010 (Tau)]

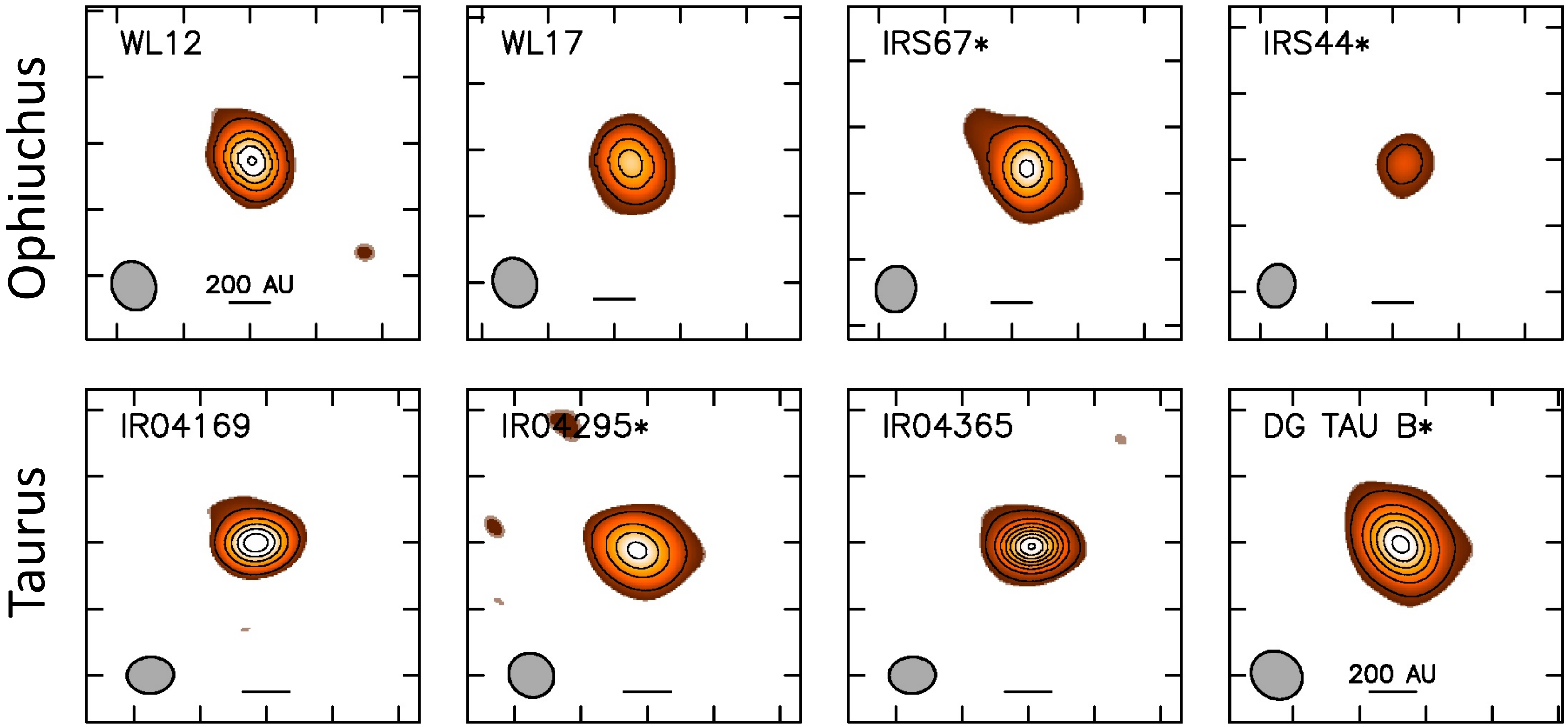
- overlap with Eisner (2012), 3 Taurus sources (CARMA 1.3 mm +)
- overlap with Guilloteau et al (2011), DG Tau B (PdBI 1.3 mm)
- overlap with Jørgensen et al (2009; PROSAC II), TMC1A, WL12

○ SMA compact + extended array @ 230 GHz ($^{12/13}$CO 2-1)

○ 1 – 1.5” resolution; 0.25 km/s spectral resolution

○ aim to do 0.3” at 345 GHz in future, with HCO^+ 3-2 and/or 4-3

Initial Results



1.3 mm continuum @ 1" resolution

4 x Ophiuchus (top)

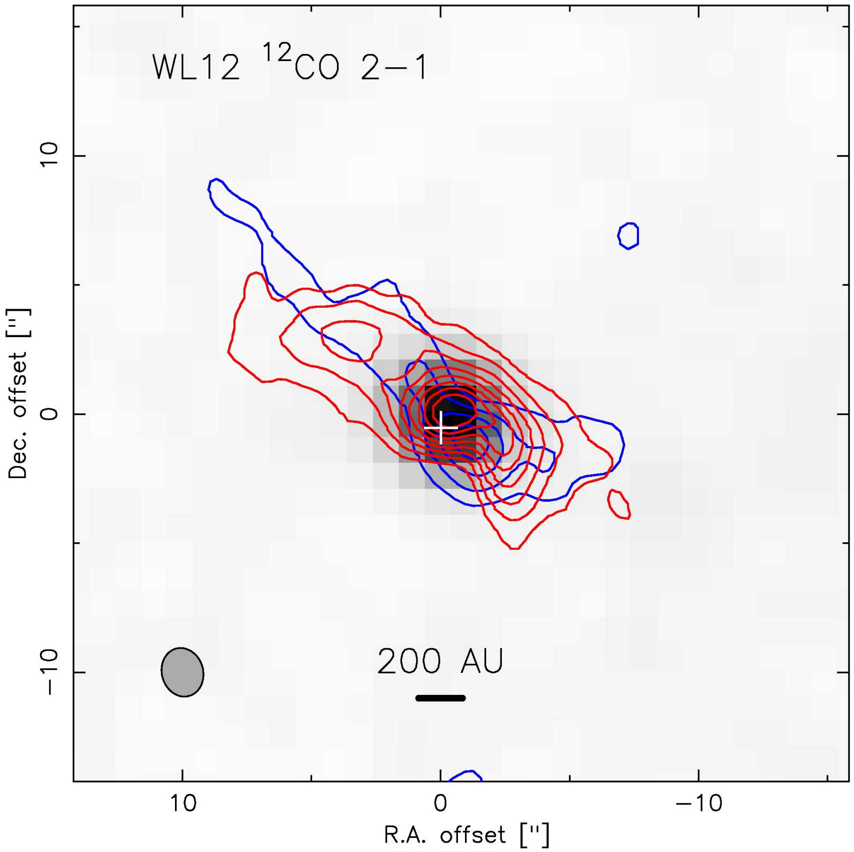
4 x Taurus (bottom)

* = resolved (Gaussian fitting)

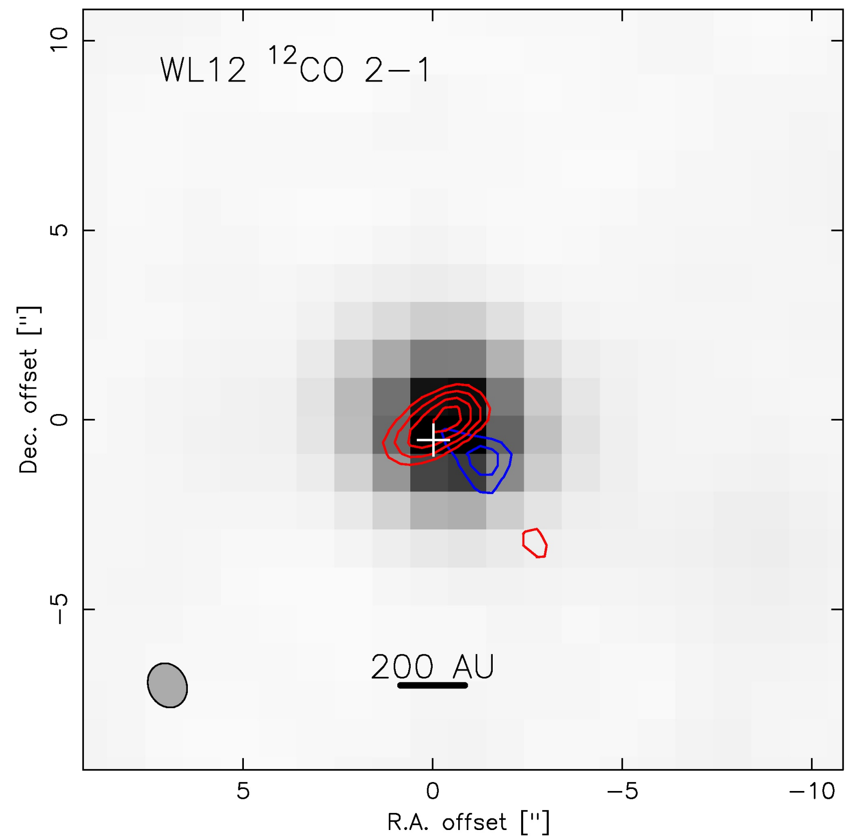
Masses

Source	Mass ($M_\odot$)
DG Tau B	0.110
IRAS 04196	0.023
IRAS 04295	0.025
IRAS 04365	0.050
Oph-IRS67	0.016
Oph-IRS44	0.004
WL12	0.014
WL17	0.010

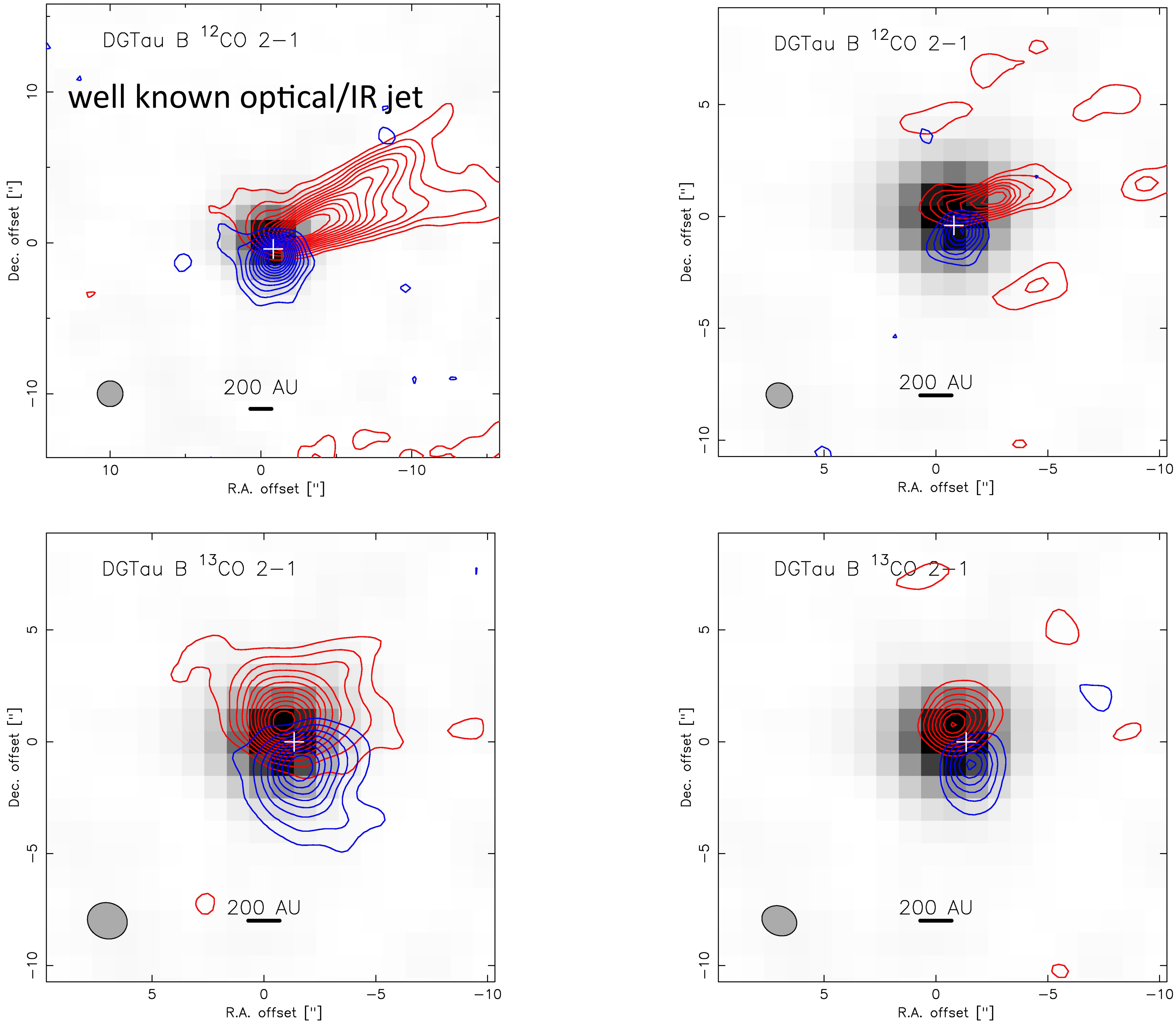
Assume OH5 dust, G/D = 100, T = 30 K
UV distance > 30 kλ



compact + extended emission
^{13}CO 2-1 also messy

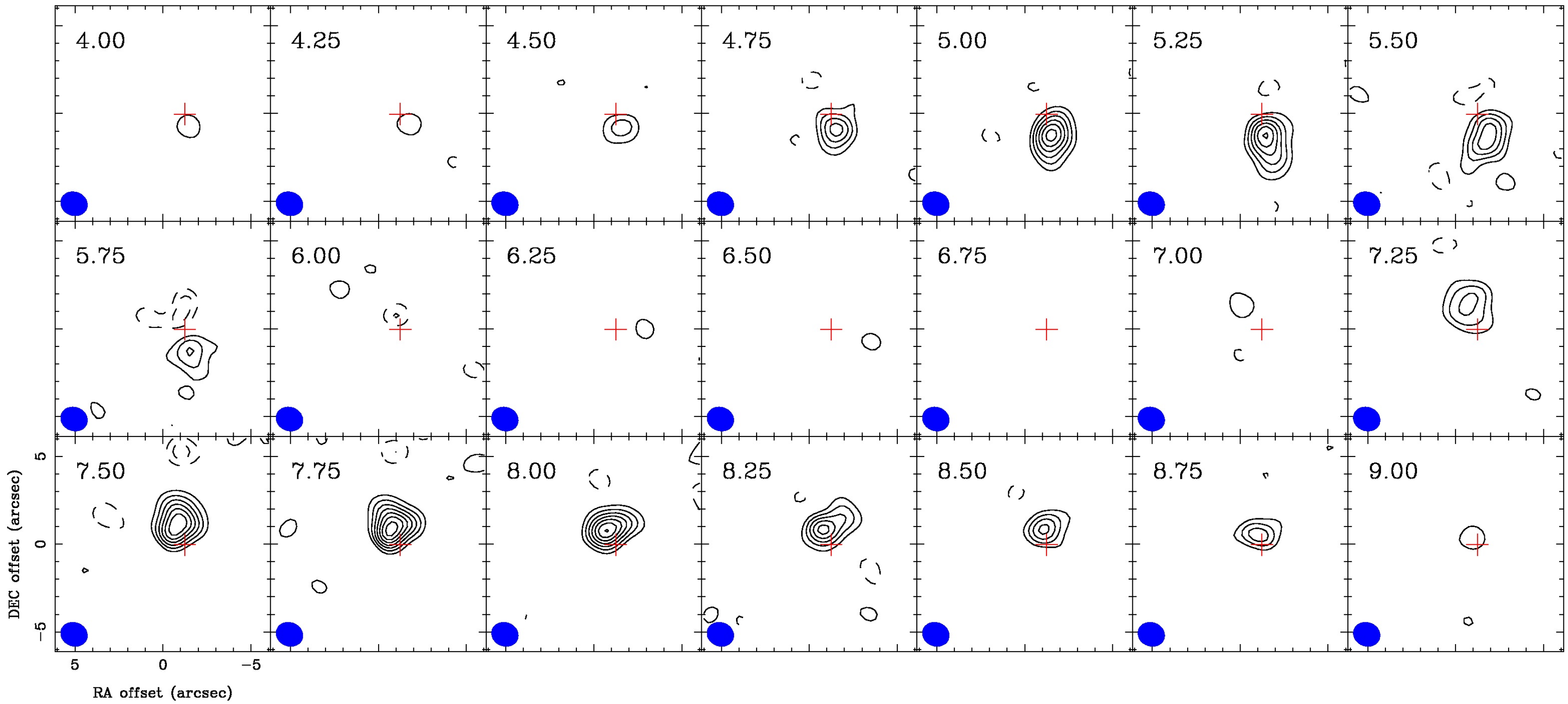


compact emission, hint of rotation?
pattern not clearly Keplerian
^{13}CO 2-1 too faint to help



DGTau B ^{12}CO 2−1
well known optical/IR jet
200 AU
Dec. offset ["]
R.A. offset ["]
DGTau B ^{12}CO 2−1
200 AU
DGTau B ^{13}CO 2−1
200 AU
DGTau B ^{13}CO 2−1
200 AU

DG Tau B ^{13}CO 2-1



Modelling Approach

1. Fit simple Keplerian curves to ^{13}CO 2-1 (assumes no envelope) – inclination needs constraints
2. Fit continuum data with disk model (assumes no envelope) – e.g., RADMC-3d
3. Fit continuum and SED with disk+envelope model
4. Results from 1 and 2, input into line radiative transfer – disk only (LIME)
5. Results from 1-4, input into LIME (disk+envelope)
6. If data available for envelope in same tracer, use it

Pure Infall

Pure Keplerian rotation

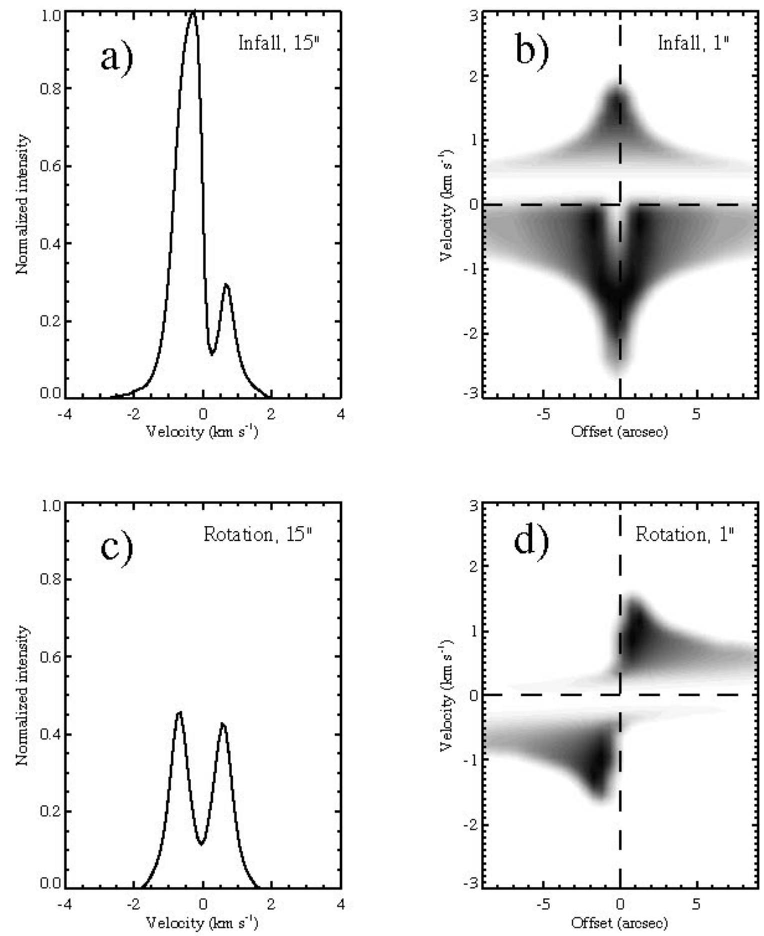
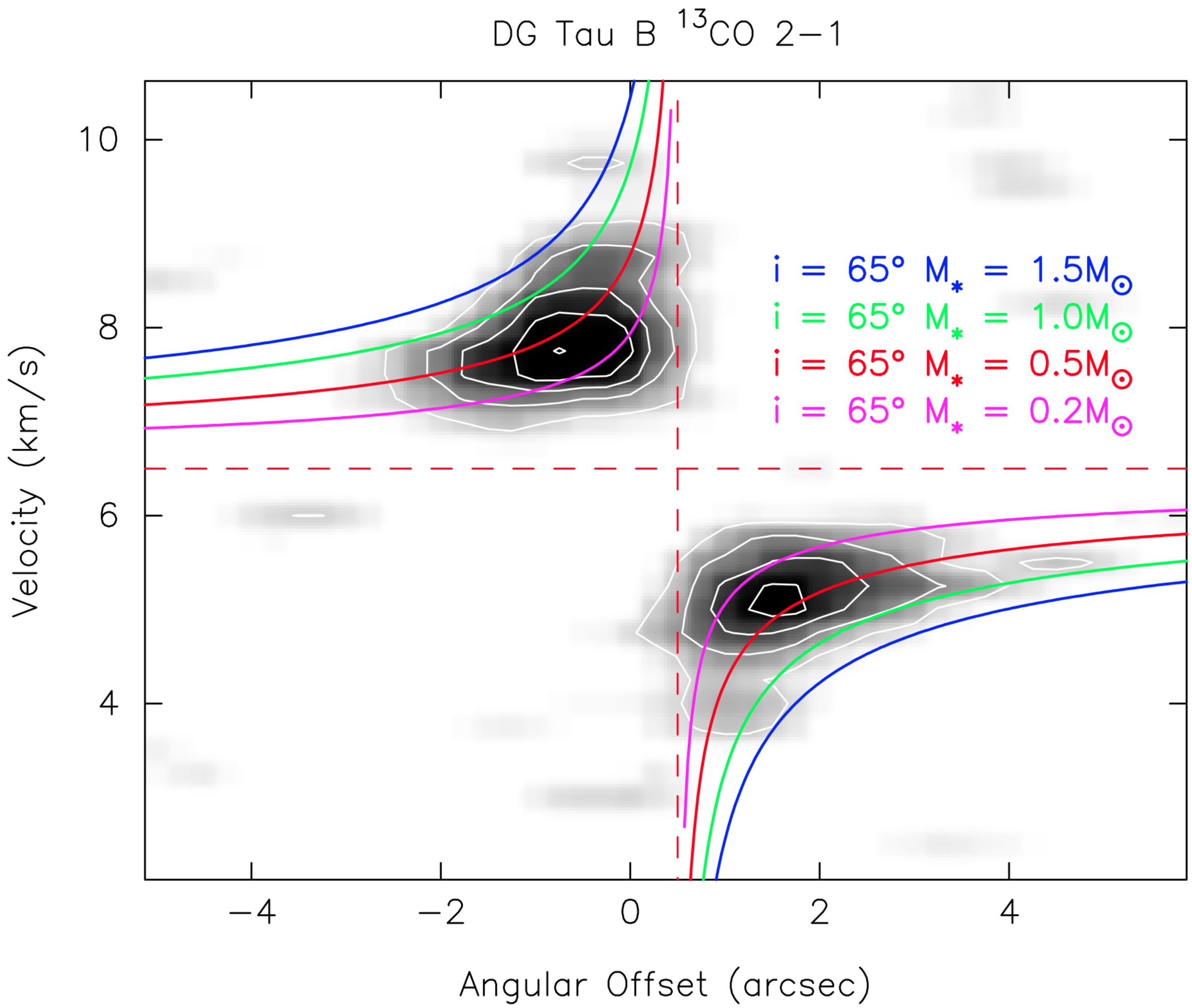
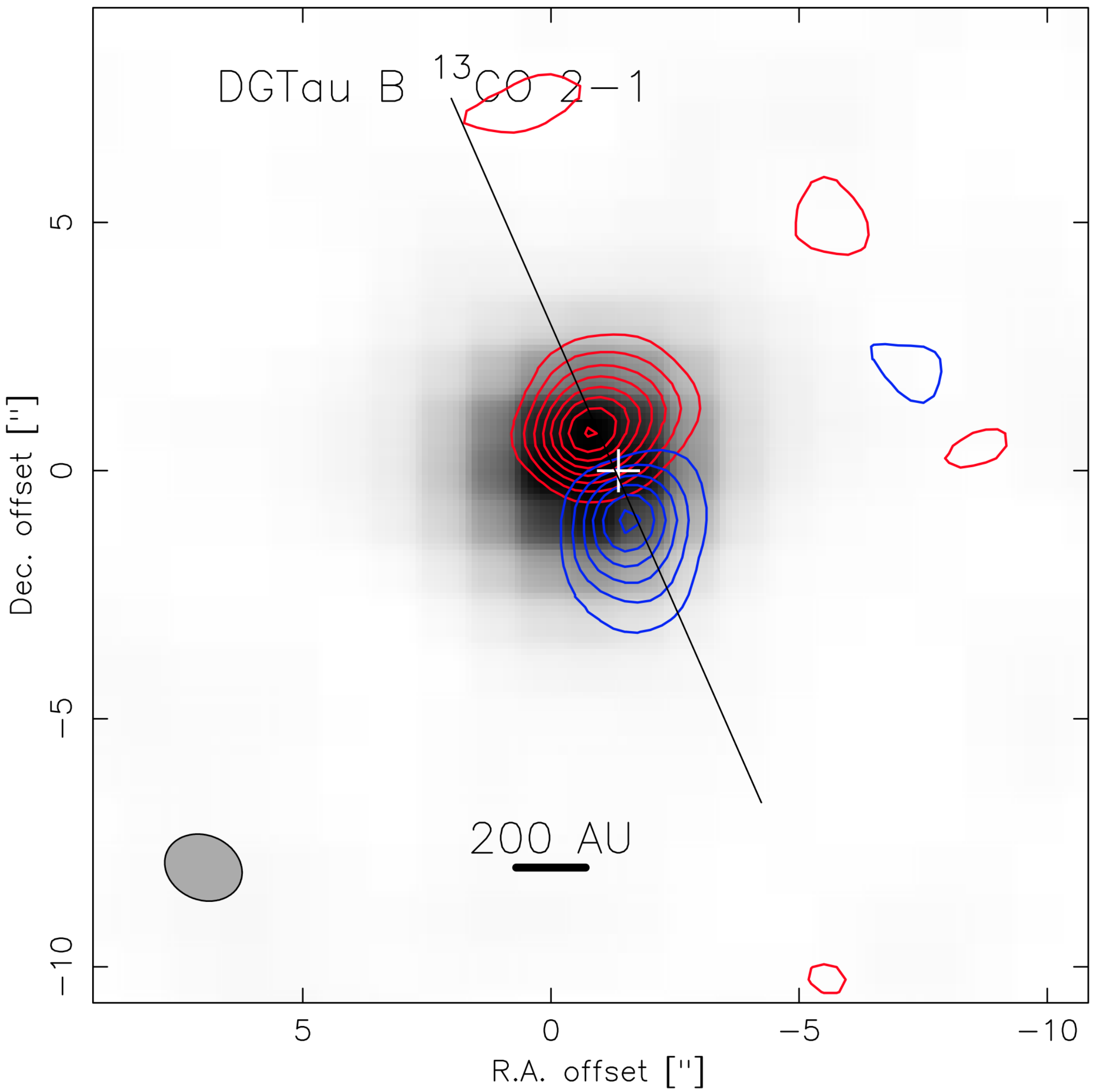


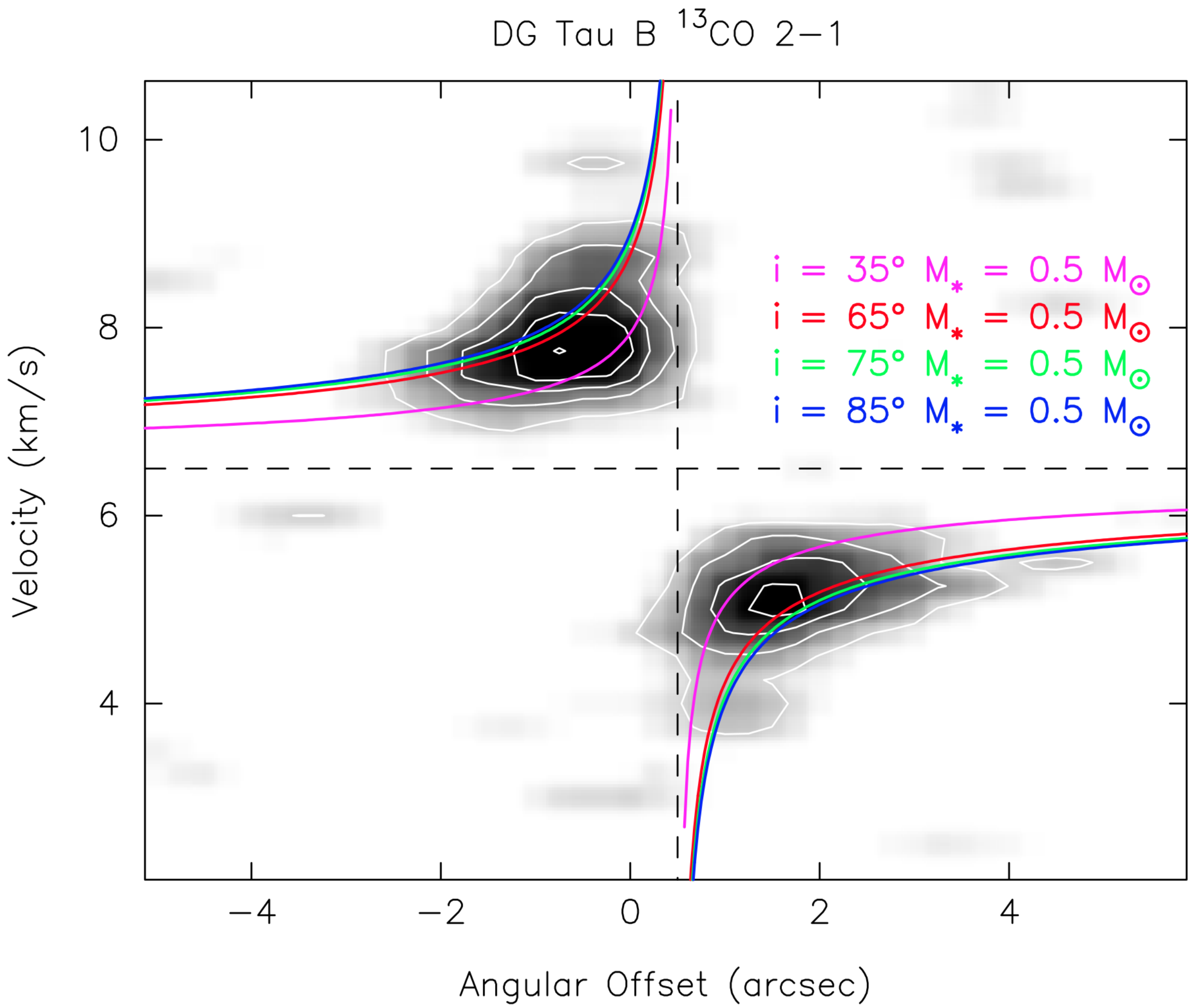
Figure 3.5: Low-resolution spectra and high-resolution position-velocity diagrams of a purely (free) infalling model and a purely (Keplerian) rotating model.

C. Brinch, PhD thesis



Inclination from PdBI 1-mm higher resolution (Guilloteau)


DGTau B ^{13}CO 2−1
200 AU
Dec. offset ['']
R.A. offset ['']
5
0
−5
−10
5
0
−5
−10



Suggests $M \sim 0.5\ M_\odot$, with $i \geq 65°$

LIME model, using disk parameters from fitting PdBI 1-mm data (Guilloteau et al. 2011)

Input:

$M = 0.5\ M_{\odot}$, with $i = 65°$

$T \propto r^{-q}$

(22K @ 40AU, q=0.3

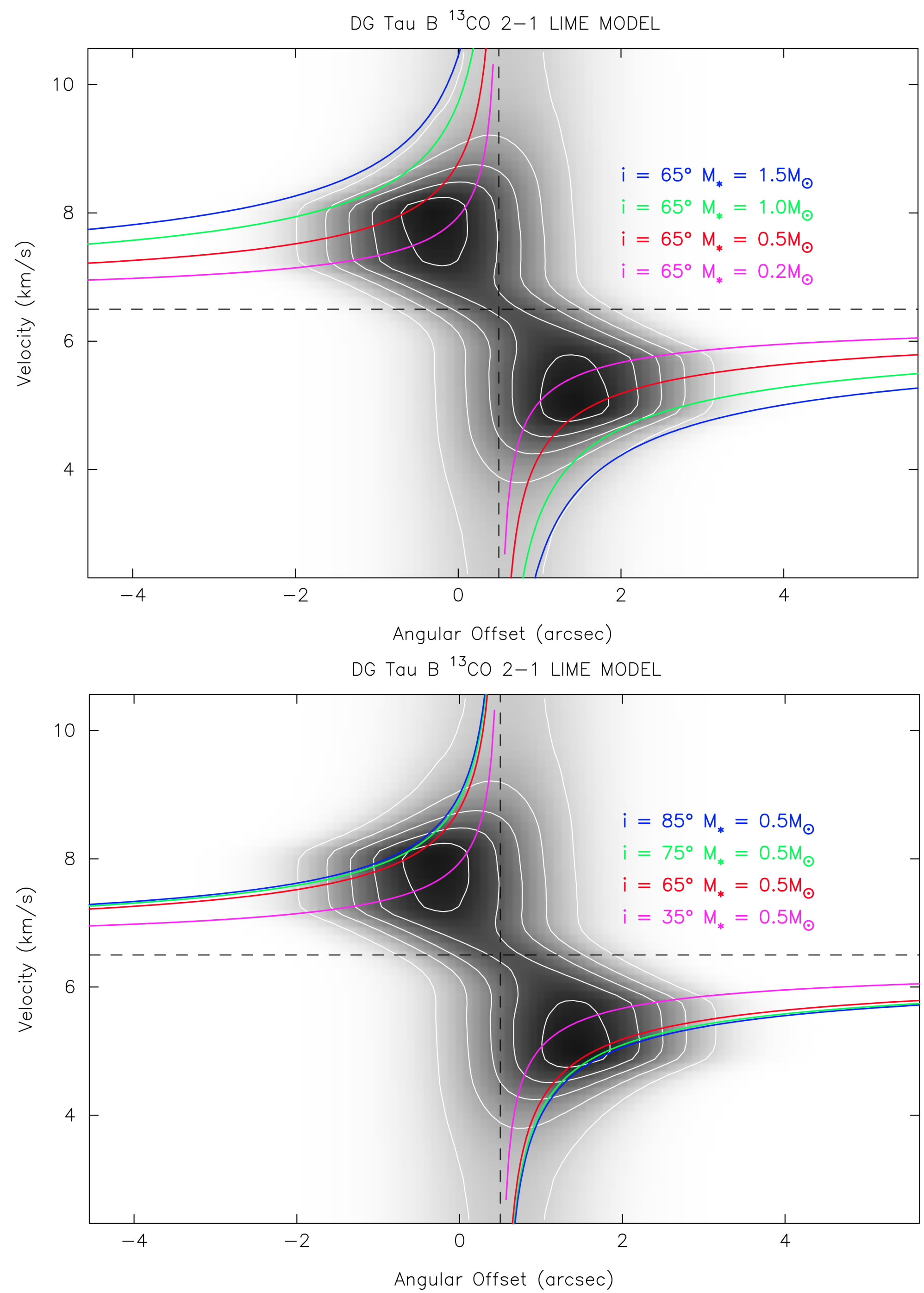
$\Sigma \propto r^{-p}$

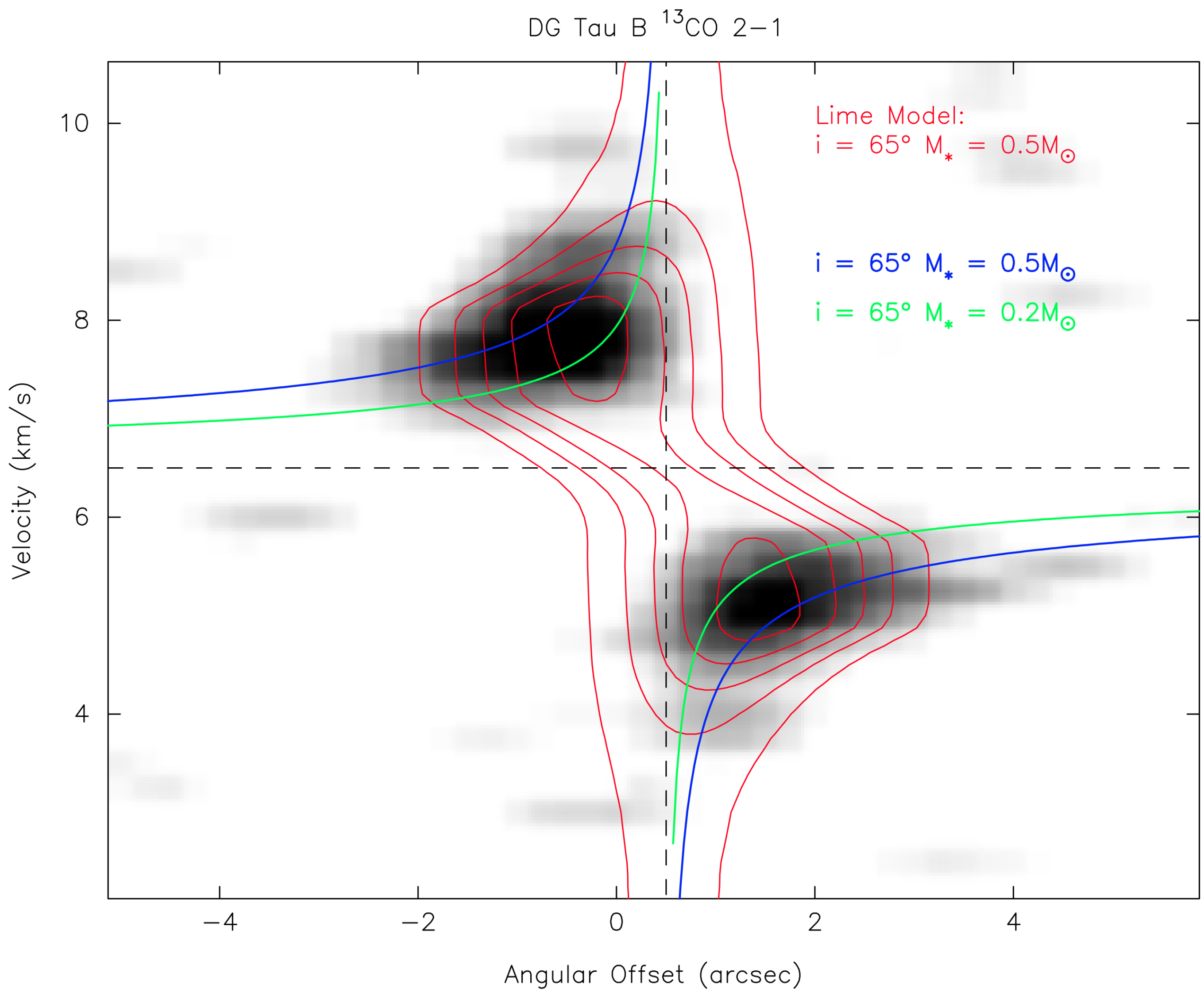
(Σ_{100} = 5.7, R_{out} = 300AU

p = 1.95)

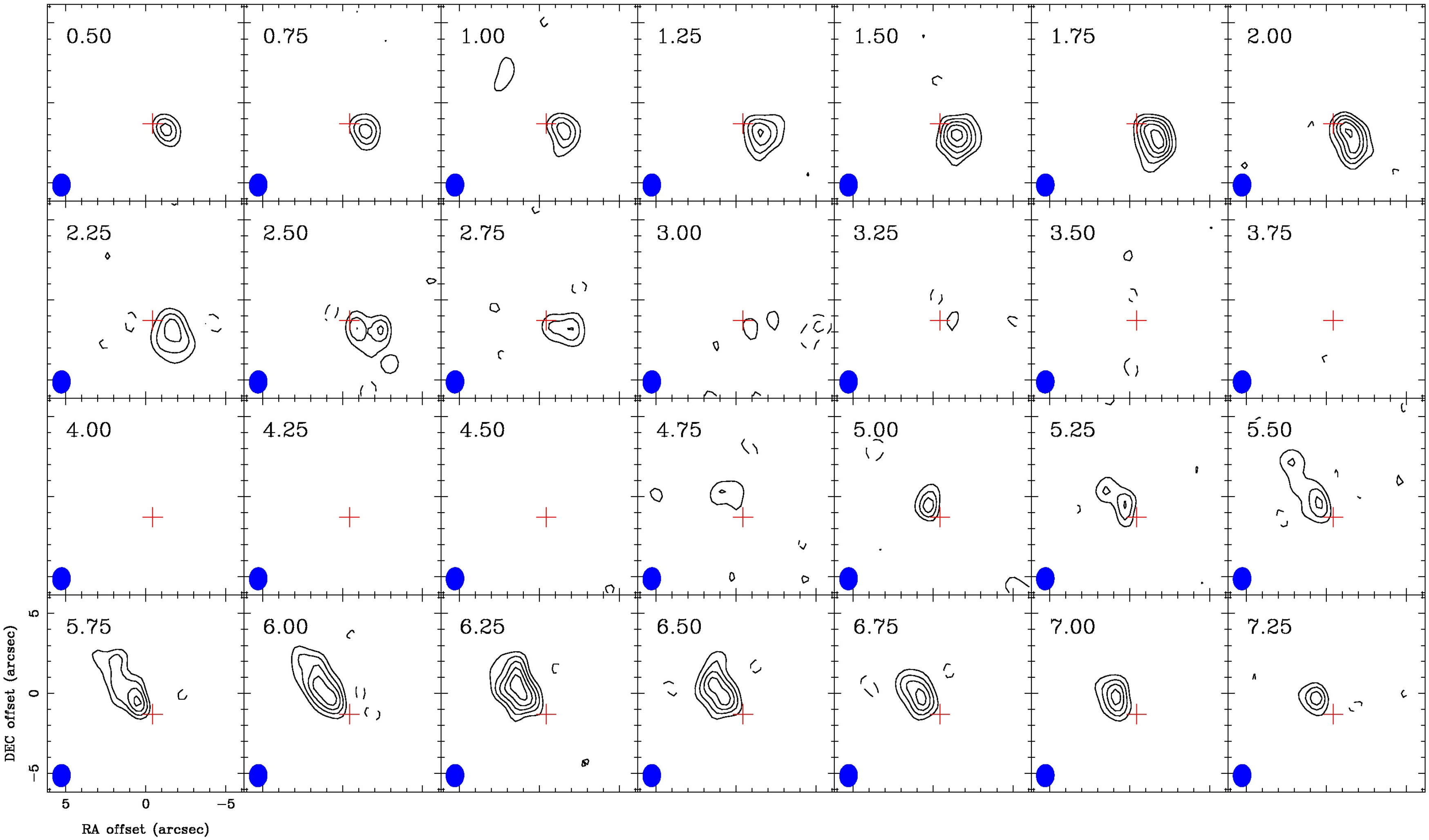
$H \propto r^{-h}$

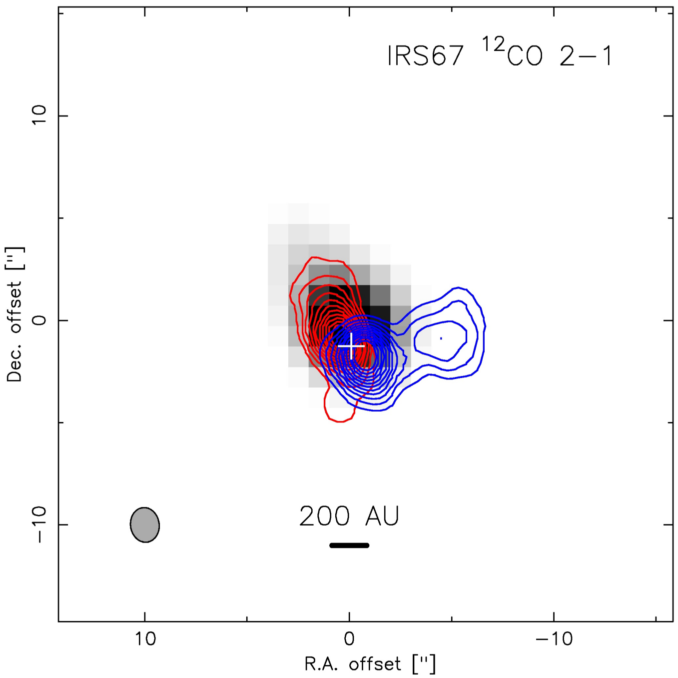
(H_{100} = 27, h = 1.35



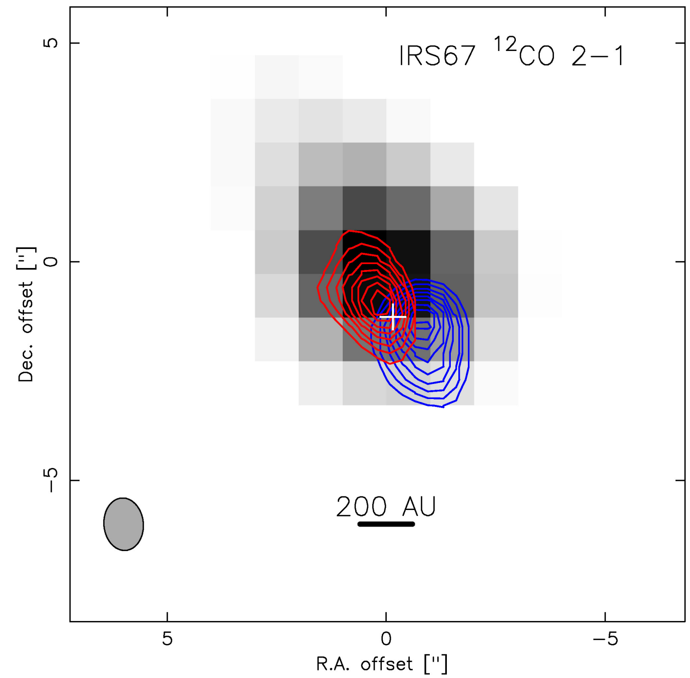

DG Tau B ^{13}CO 2−1
Lime Model:
i = 65° M_* = 0.5$M_\odot$
i = 65° M_* = 0.5$M_\odot$
i = 65° M_* = 0.2$M_\odot$
Velocity (km/s)
Angular Offset (arcsec)
10
8
6
4
−4
−2
0
2
4

IRS 67 ^{13}CO 2-1



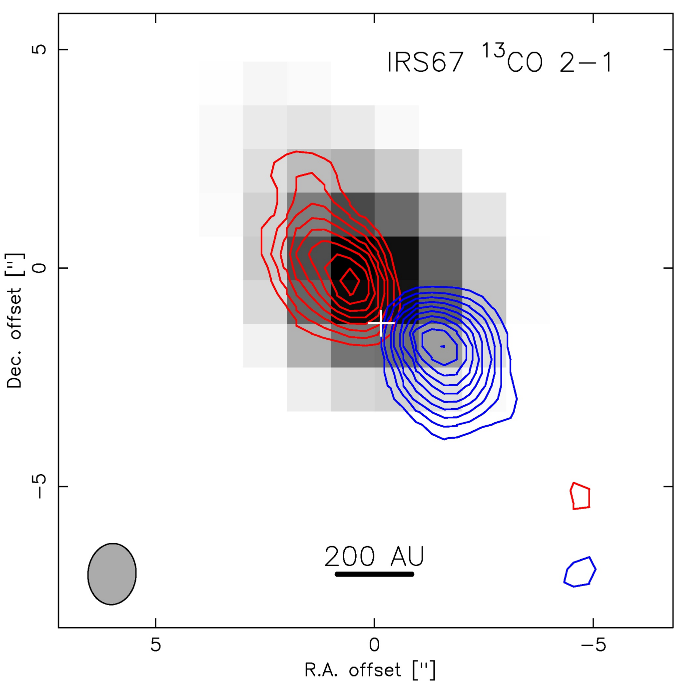


IRS67 12CO 2−1
200 AU
Dec. offset ["]
R.A. offset ["]

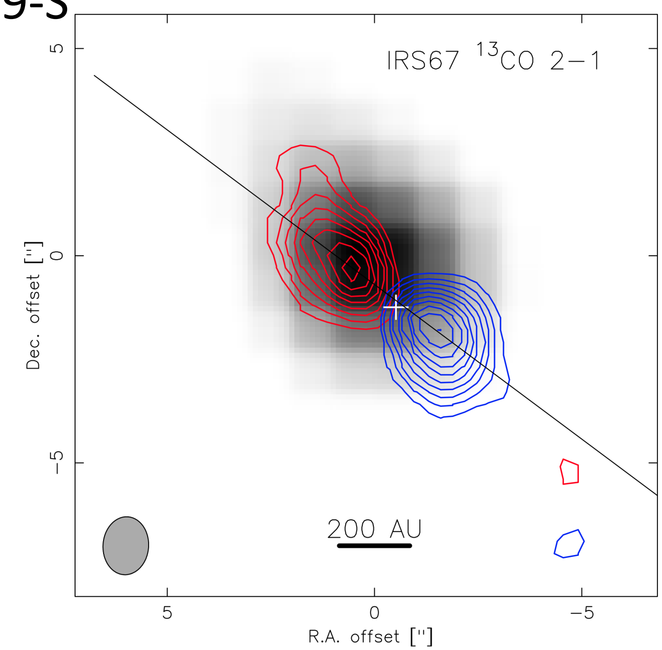


IRS67 12CO 2−1
200 AU
Dec. offset ["]
R.A. offset ["]

aka L1689-S

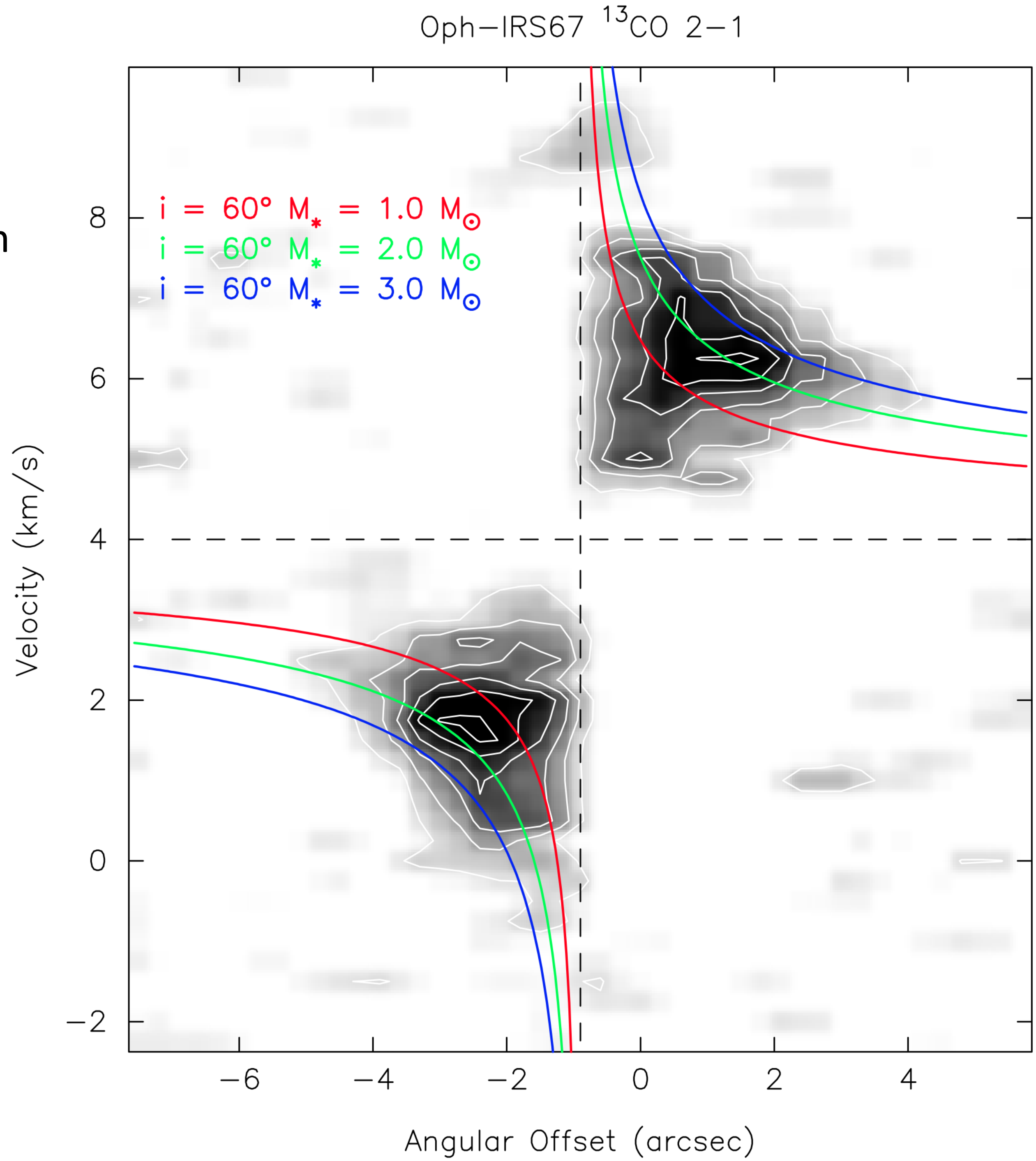


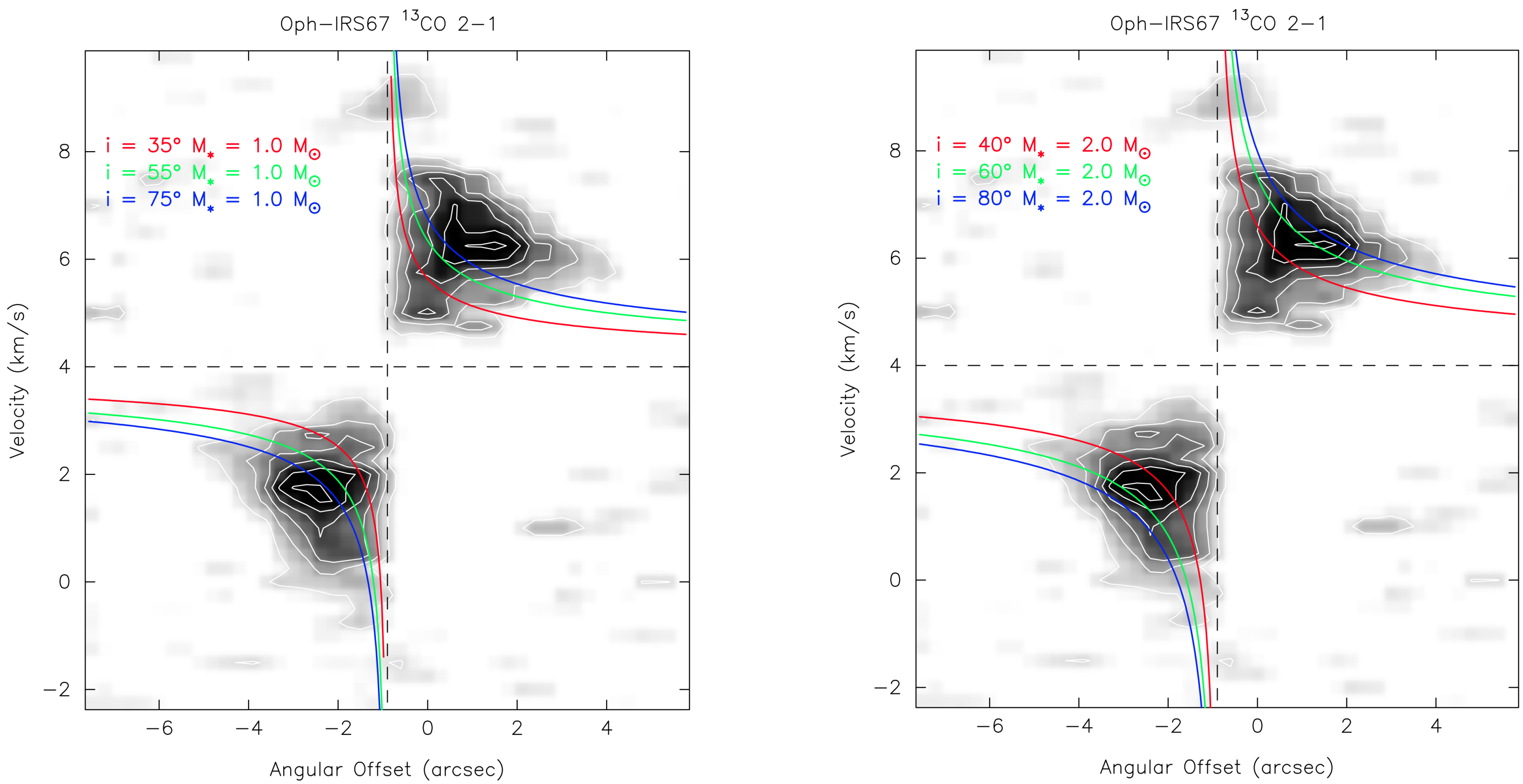
IRS67 13CO 2−1
200 AU
Dec. offset ["]
R.A. offset ["]



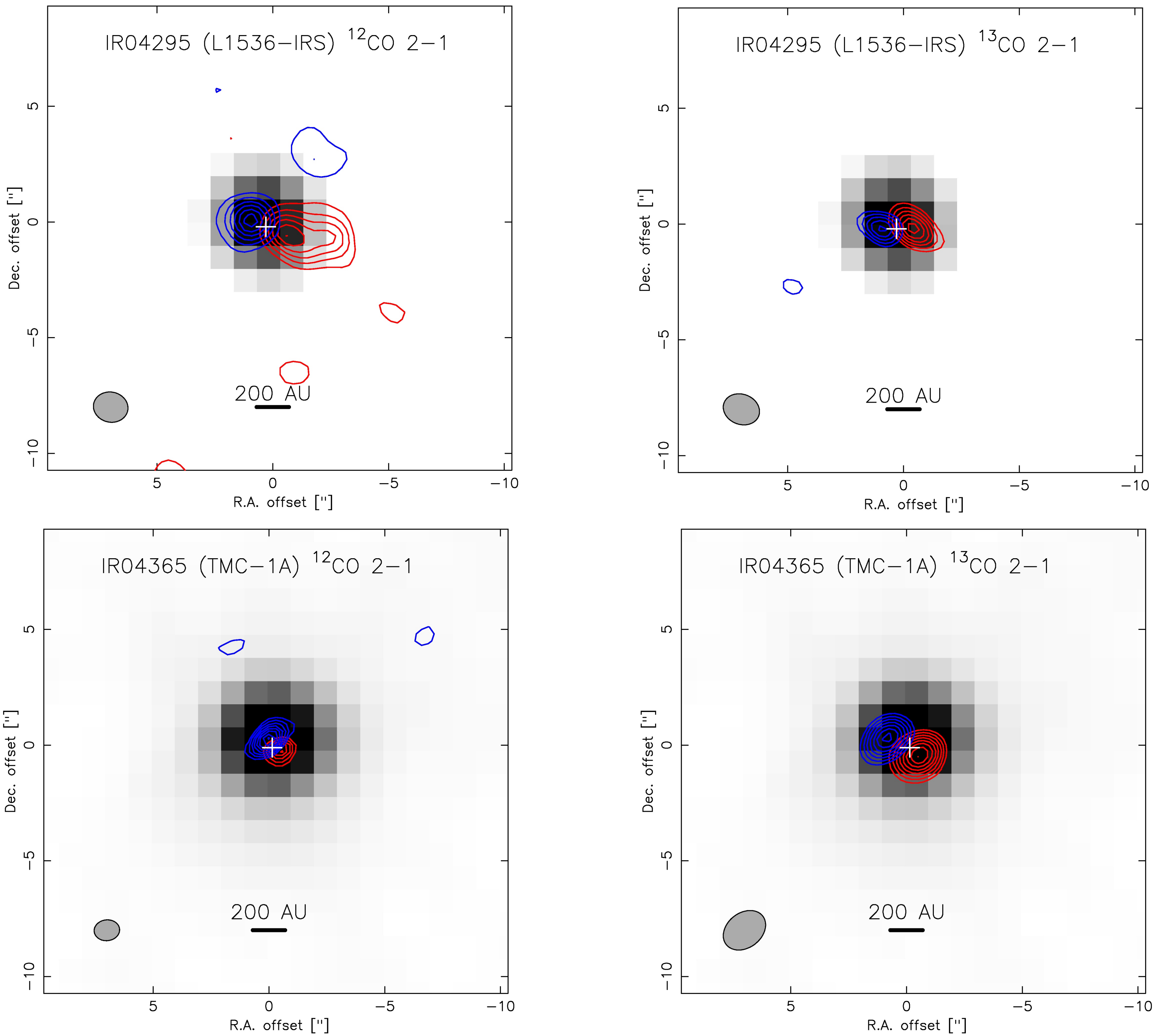
IRS67 13CO 2−1
200 AU
Dec. offset ["]
R.A. offset ["]

Inclination constraint from 1-mm continuum





Oph−IRS67 13CO 2−1
i = 35° M* = 1.0 M⊙
i = 55° M* = 1.0 M⊙
i = 75° M* = 1.0 M⊙
Velocity (km/s)
Angular Offset (arcsec)
Oph−IRS67 13CO 2−1
i = 40° M* = 2.0 M⊙
i = 60° M* = 2.0 M⊙
i = 80° M* = 2.0 M⊙
Velocity (km/s)
Angular Offset (arcsec)



IR04295 (L1536−IRS) ^{12}CO 2−1
IR04295 (L1536−IRS) ^{13}CO 2−1
IR04365 (TMC−1A) ^{12}CO 2−1
IR04365 (TMC−1A) ^{13}CO 2−1
200 AU
Dec. offset ["]
R.A. offset ["]

Summary

8 Class Is imaged with 1" resolution @ 1.3 mm

4/8 clearly resolved (disk > 100 AU)

5/8 show rotation on compact scales

2 clearly Keplerian, others very suggestive

(surprising lack of confusion in CO)

significant increase in Class I sources showing Keplerian disk motions (~5 previously known ...)

When added to PROSAC sample (8 Class 0/I) ...

- Disk size and mass as function of evolution (e.g., bolometric temperature)
- Disk/Envelope mass ratio (mass evolution)
- Protostar/Disk mass ratio (disk stability, evolution)

Future

Need observations that actually resolve the disk structure e.g.,

- **DG Tau B** 1-mm continuum (Guilloteau et al 2011)

    ... but no envelope

- **CB 26** 1-mm continuum (Sauter et al 2009; Akimkin et al 2012)

    ... but distance uncertain

- sample of Class Is with Keplerian-dominated motions on disk scales are the best targets for high-resolution observations

    - 0.3” at 345 GHz (dust continuum) with SMA (also provides for direct comparison with similar studies of Class IIs, e.g. Andrews et al)
    - Line emission with less envelope confusion, e.g., HCO^+ 3-2 and 4-3, HCN?, CS?
    - ALMA (of course)

END