Probing high-mass star formation through different molecules

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High-mass → >8 $M_{\odot}$ → >10^3 $L_{\odot}$ → O-B star

1) The recipe of (OB) star formation: infall, outflow, rotation → the role of accretion disks
2) OB star formation: observational problems
3) The search for disks: tracing rotation and infall
4) Results: **disks** in B stars; for O stars **ALMA is needed**

The recipe of (OB) star formation: infall, outflow, rotation

Infall of circumstellar material onto protostar

Two relevant timescales:

accretion: $t_{acc} = M_{star}/(dM/dt)_{acc}$

contraction: $t_{KH} = GM_{star}/R_{star}L_{star}$

$M_{star} > 6\text{-}10\ M_{\odot}$ ➔ $t_{acc} > t_{KH}$ (Palla & Stahler 1993)

High-mass stars reach ZAMS still accreting!

Spherical symmetry ➔ $P_{radiation} > P_{ram}$ ➔

➔ stars > 6-10 $M_{\odot}$ should not form!??

Rotation and outflow may be the solution
(Yorke & Sonnhalter, Kruhmolz et al.):

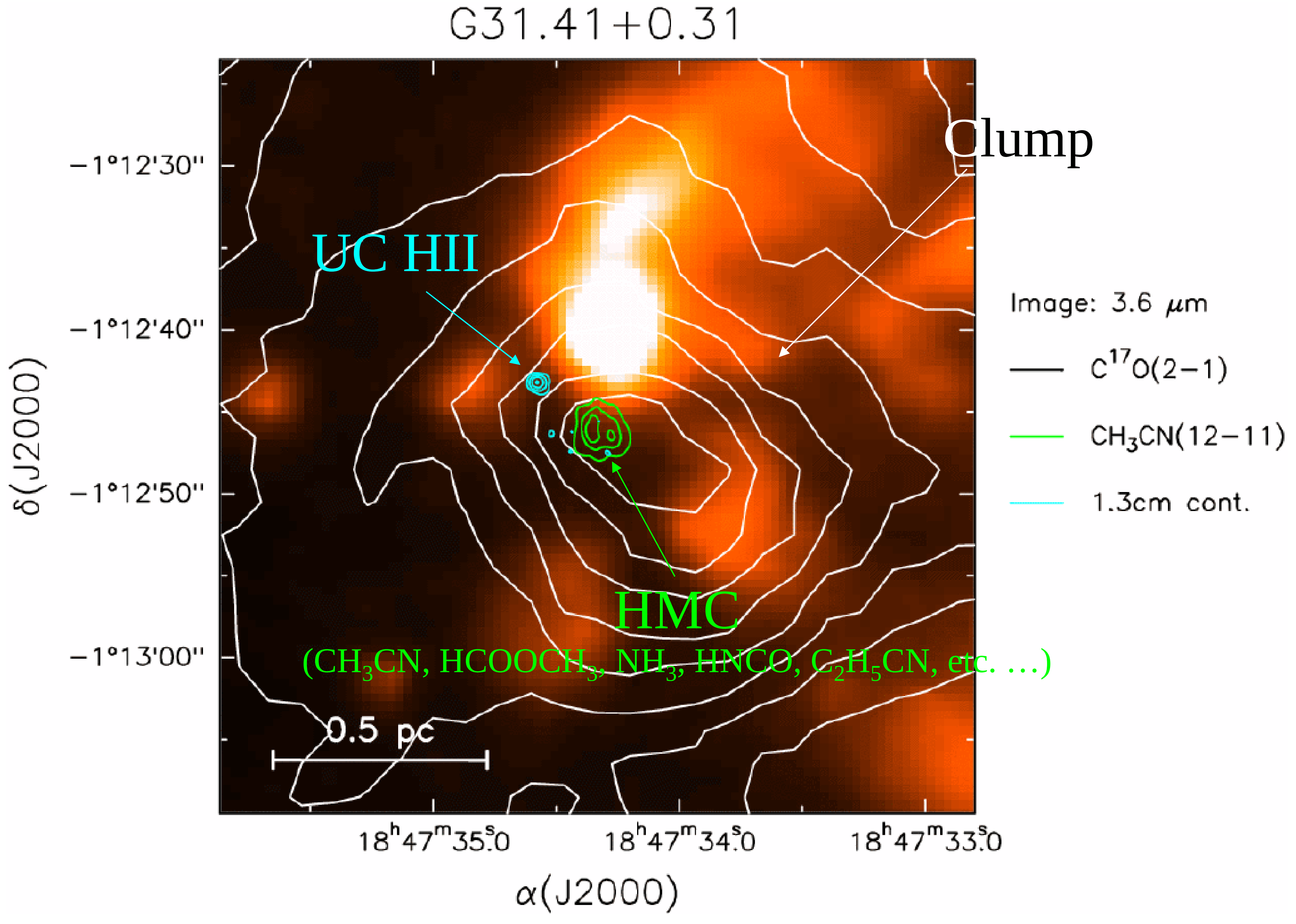
Rotation+ang.mom.conserv. → Disk →
→ focuses accretion →
→ boosts ram pressure

Outflow → channels stellar photons →
→ lowers radiation pressure

→Detection of accretion disks is crucial to understand O-B star formation

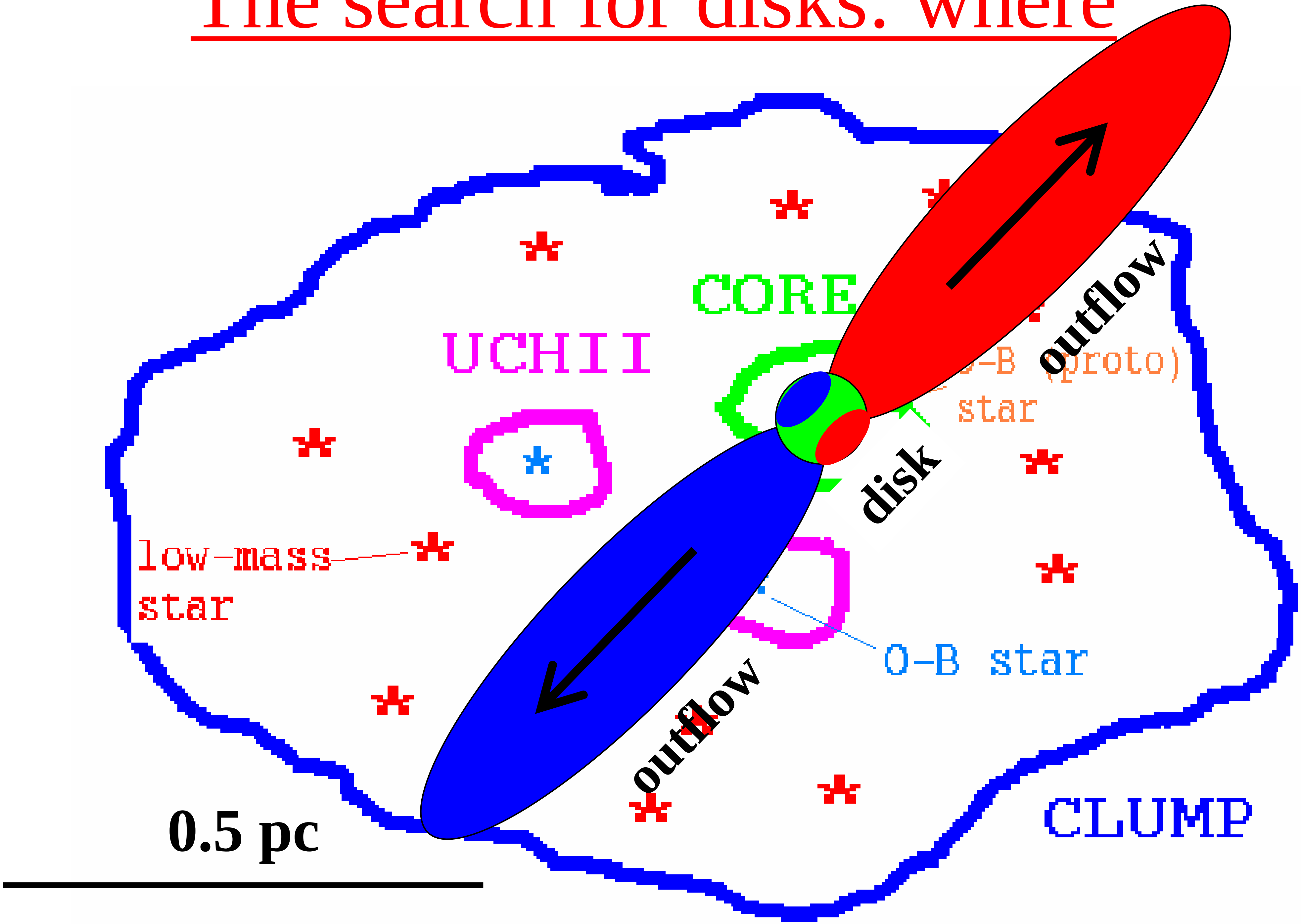
High-mass star observations

- Problems:
  - IMF → high-mass stars are rare
  - large distance: >450 pc → a few kpc ***ALMA** sensitivity!*
  - formation in clusters → confusion ***ALMA** resolution!*
  - rapid evolution: $t_{acc}=50\ M_\odot / 10^{-3} M_\odot yr^{-1} = 5\ 10^4 yr$
  - parental environment profoundly altered
- Advantage:
  - very luminous (cont. & ***line***) and rich (***molecules***)!
    ***ALMA** spectral coverage!*



G31.41+0.31
Clump
UC HII
HMC
(CH3CN, HCOOCH3, NH3, HNCO, C2H5CN, etc. ...)
Image: 3.6 μm
C17O(2−1)
CH3CN(12−11)
1.3cm cont.
−1°12'30"
−1°12'40"
−1°12'50"
−1°13'00"
δ(J2000)
0.5 pc
18h47m35.0s
18h47m34.0s
18h47m33.0s
α(J2000)

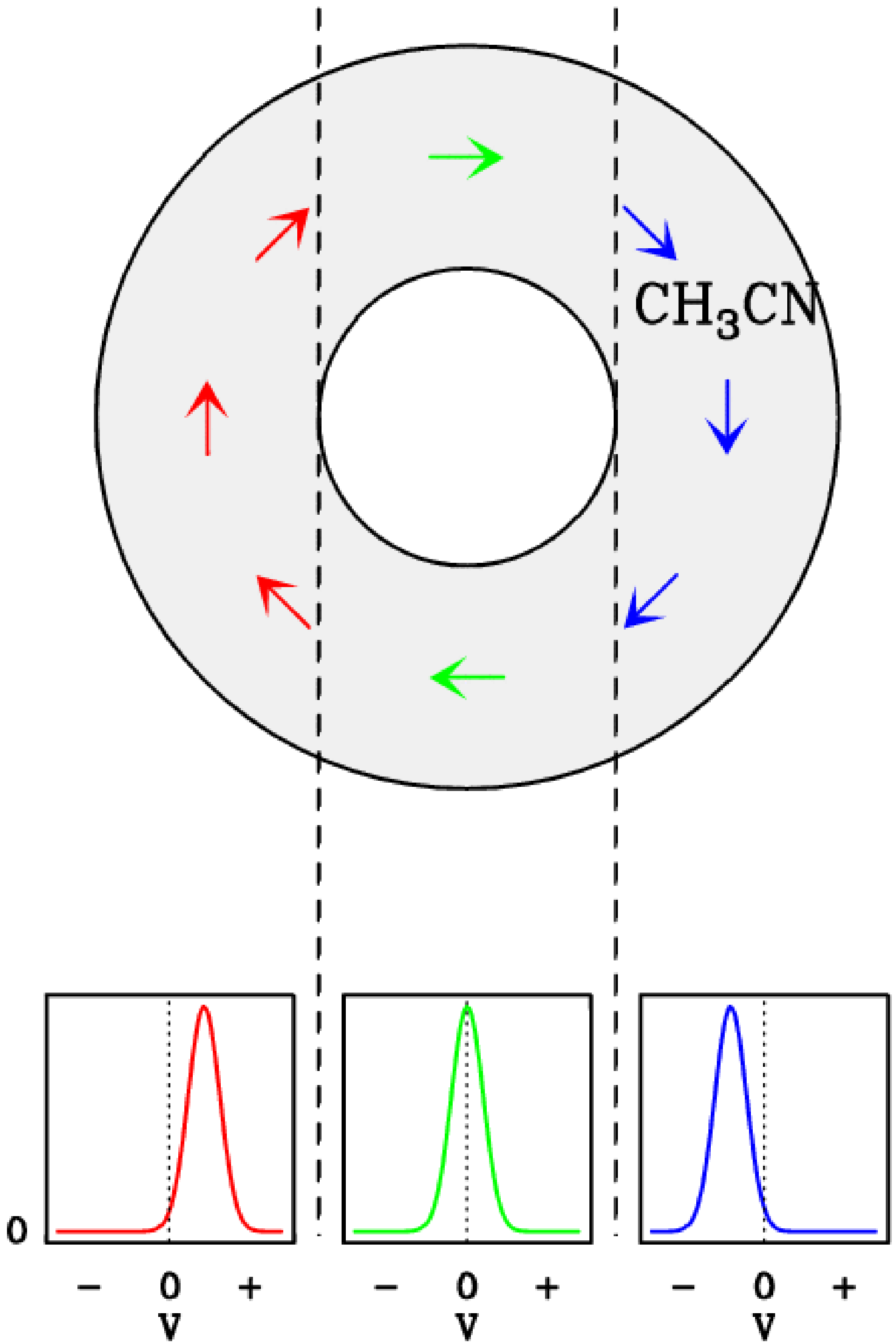
The search for disks: where



The search for disks: what

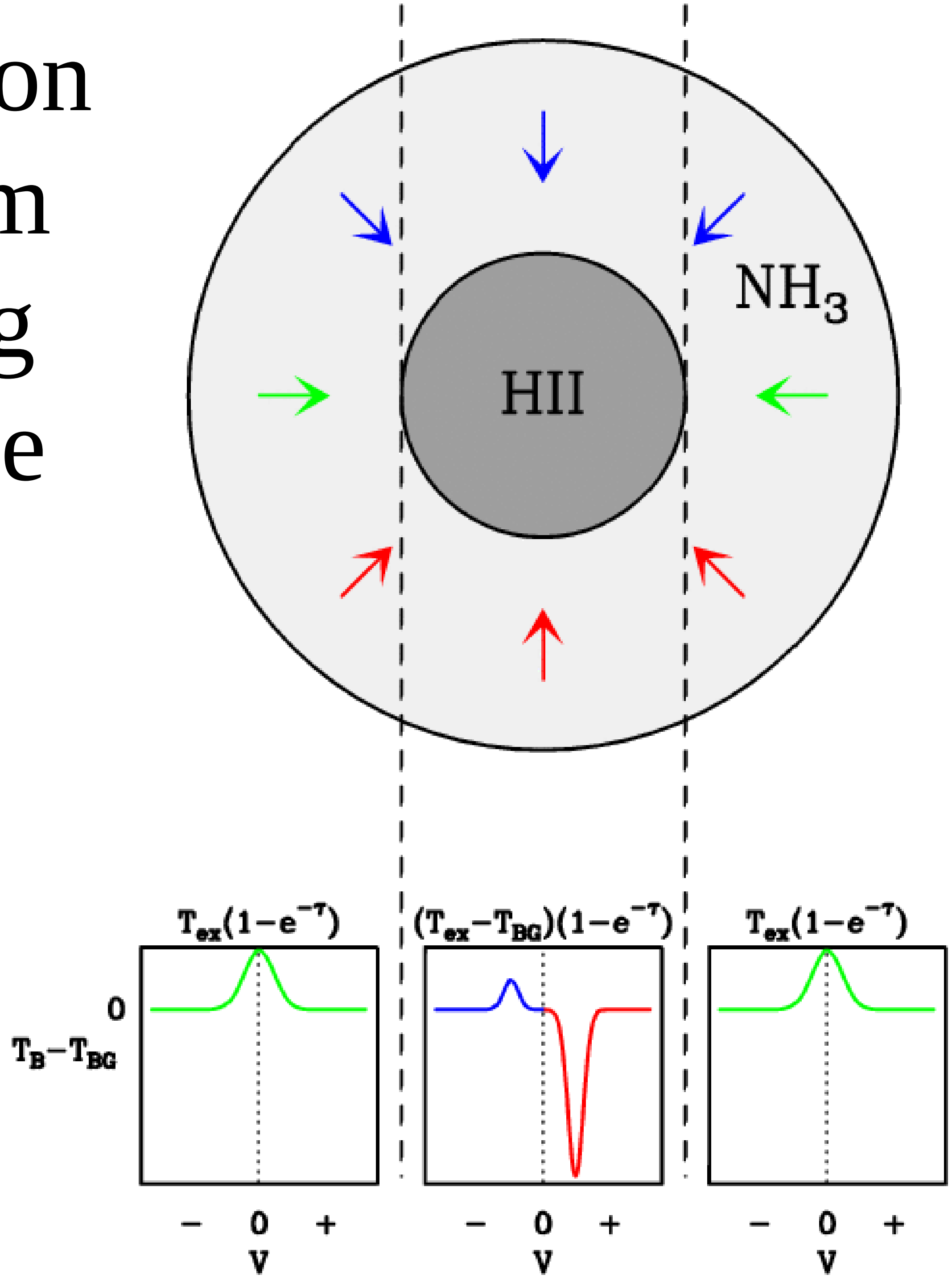
HMC LINE TRACER	PROs	CONTRAs
Emission e.g. CH_3CN, CH_3OH, HCO^+	Kinematics and geometry of outflow (expansion) and disk (rotation)	Limited angular resolution and sensitivity → **ALMA** needed
Absorption e.g. NH_3	Excellent tracers of infall	Bright, embedded continuum source needed → cm, submm (**ALMA**)?
Maser e.g. H_2O, CH_3OH	Very high angular resolution (1 mas); 3D velocity field	Unclear geometry & kinematics

Emission line from rotating disk



HMC LINE TRACER	PROs	CONTRAs
Emission e.g. CH_3CN, CH_3OH, HCO^+	Kinematics and geometry of outflow and disk	Limited angular resolution and sensitivity → **ALMA** needed
Absorption e.g. NH_3	Excellent tracers of infall	Bright, embedded continuum source needed → cm, submm (**ALMA**)?
Maser e.g. H_2O, CH_3OH	Very high angular resolution (1 mas); 3D velocity field	Unclear geometry & kinematics

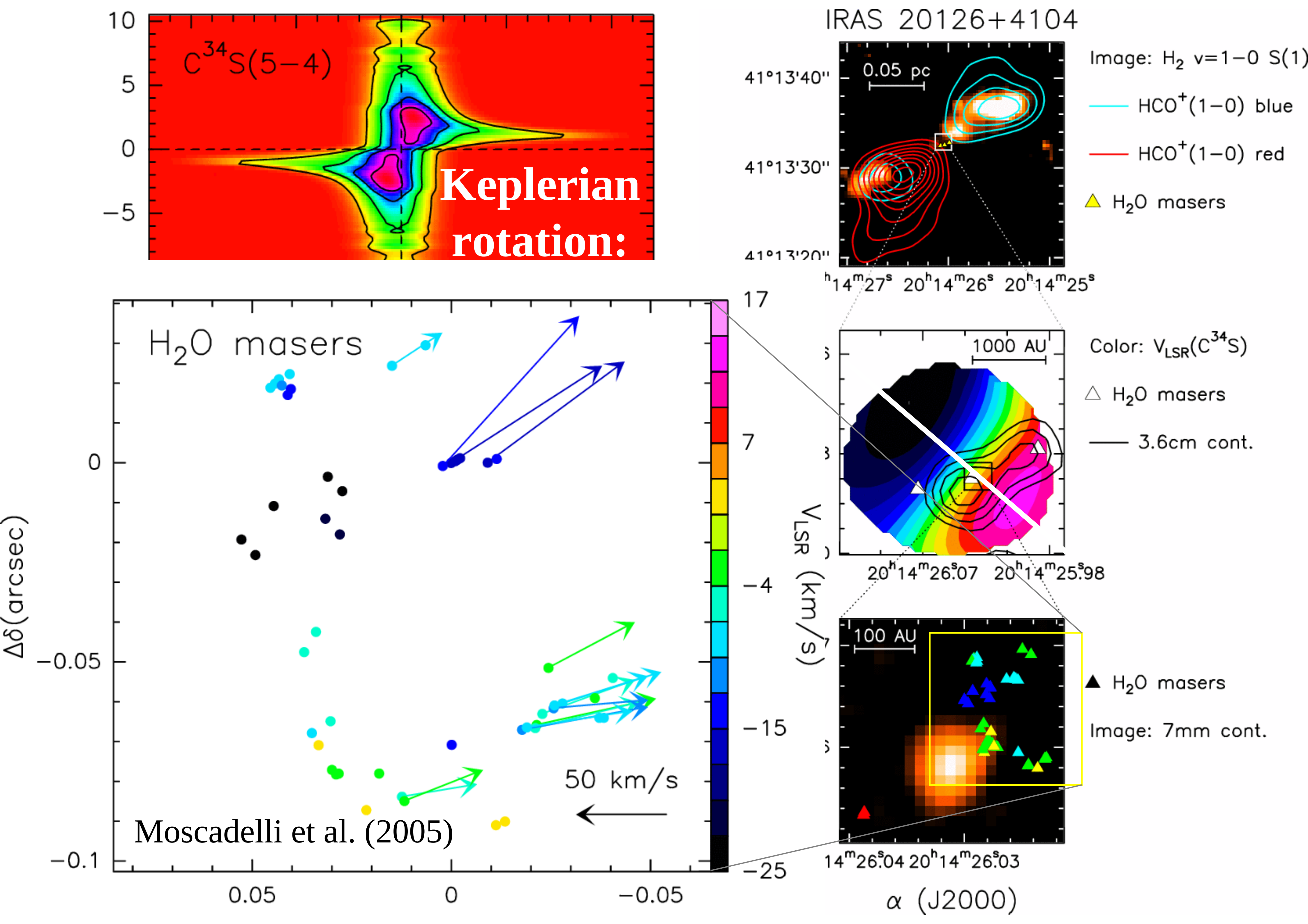
Absorption line from infalling envelope



HMC LINE TRACER	**PROs**	**CONTRAs**
Emission e.g. CH_3CN, CH_3OH, HCO^+	Kinematics and geometry of outflow and disk	Limited angular resolution and sensitivity → **ALMA** needed
Absorption e.g. NH_3	Excellent tracers of infall	Bright, embedded continuum source needed → cm, submm (**ALMA**)?
Maser e.g. H_2O, CH_3OH	Very high angular resolution (1 mas); 3D velocity field	Global picture unclear

Results of disk search in B and late-O (proto)stars: 2 examples

	L_* (L_O)	M_{disk} (M_O)	D_{disk} (AU)	M_* (M_O)	Spec. Type
IRAS20126	10^4	4	1600	7	B0.5
G24.78 A1	$5\ 10^4$	130	5000	20	O9.5

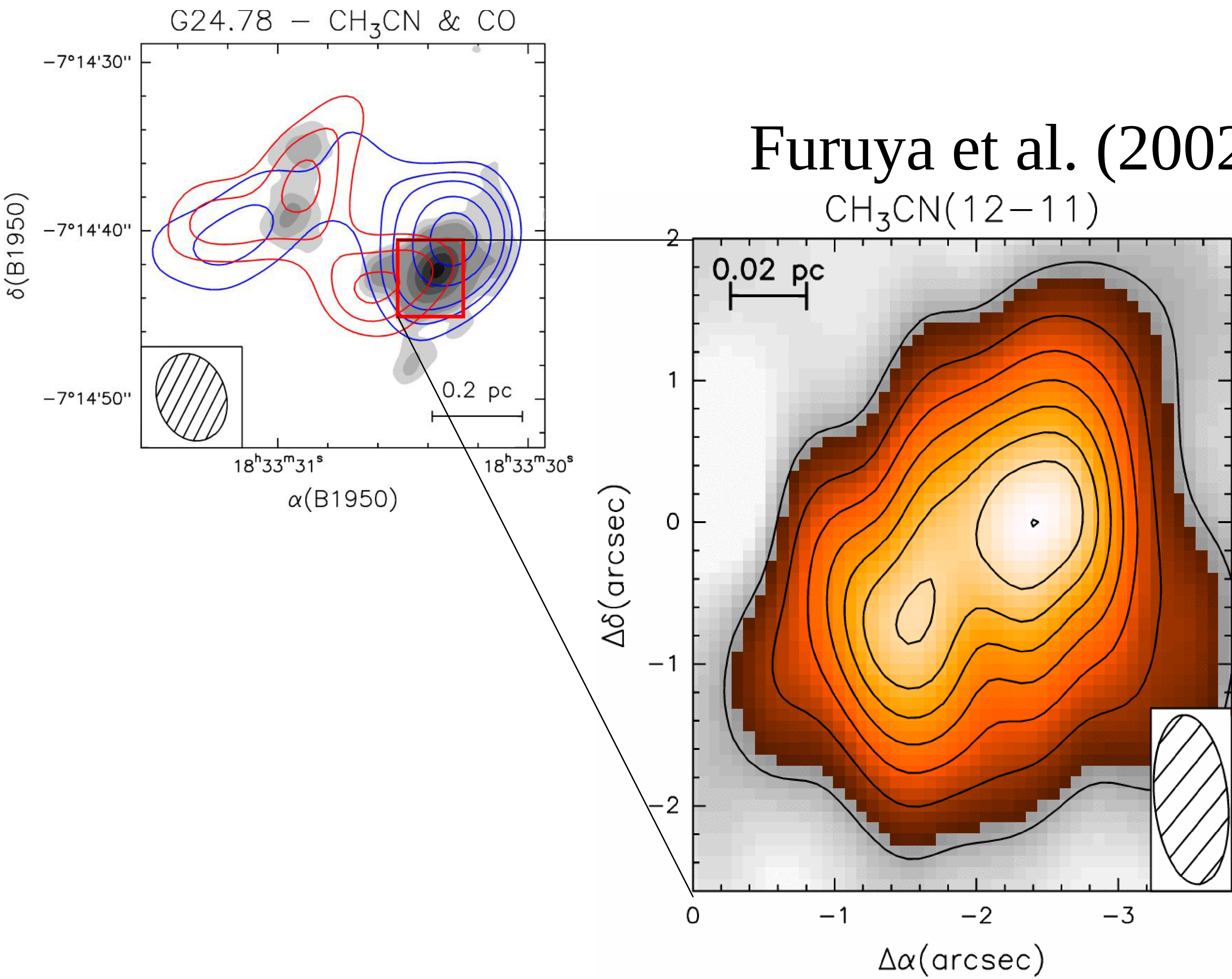


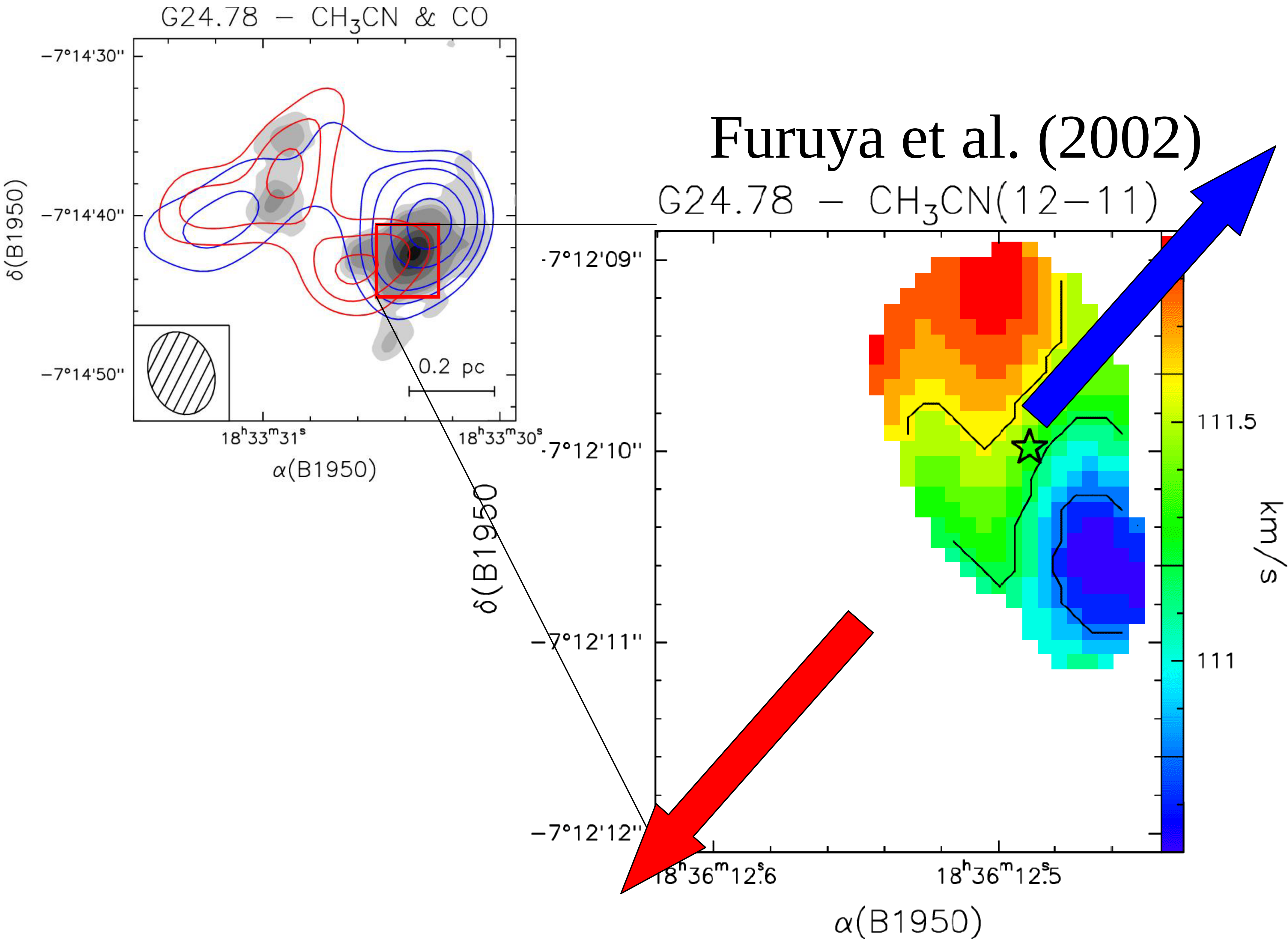
C34S(5−4)
Keplerian rotation:
IRAS 20126+4104
0.05 pc
41°13'40"
41°13'30"
41°13'20"
Image: H2 v=1−0 S(1)
HCO+(1−0) blue
HCO+(1−0) red
H2O masers
H2O masers
50 km/s
Moscadelli et al. (2005)
Δδ(arcsec)
VLSR (km/s)
17
7
−4
−15
−25
1000 AU
Color: VLSR(C34S)
H2O masers
3.6cm cont.
20h14m26.07
20h14m25.98
100 AU
H2O masers
Image: 7mm cont.
14m26.04
20h14m26.03
α (J2000)

Furuya et al. (2002)

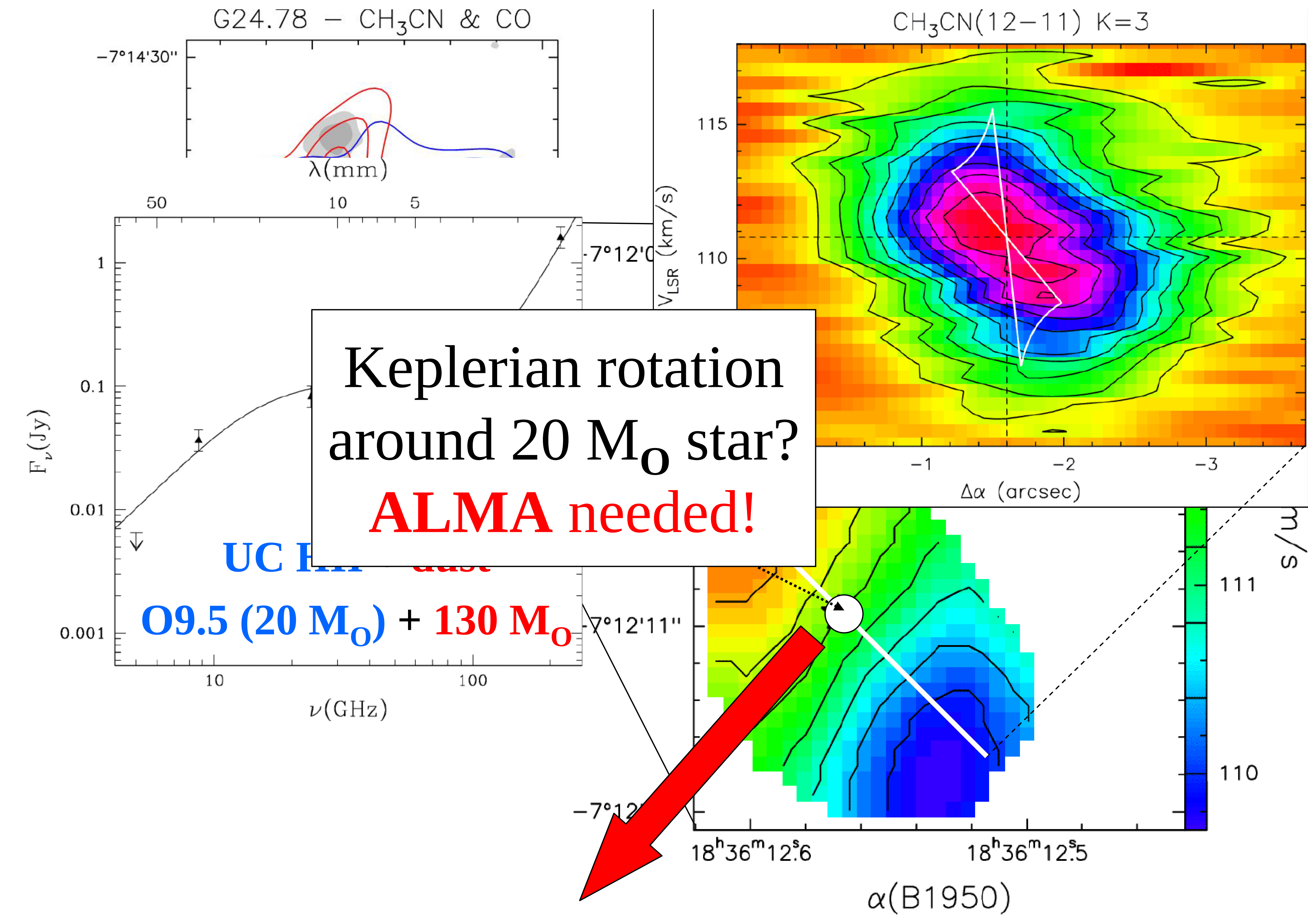
4)

5)

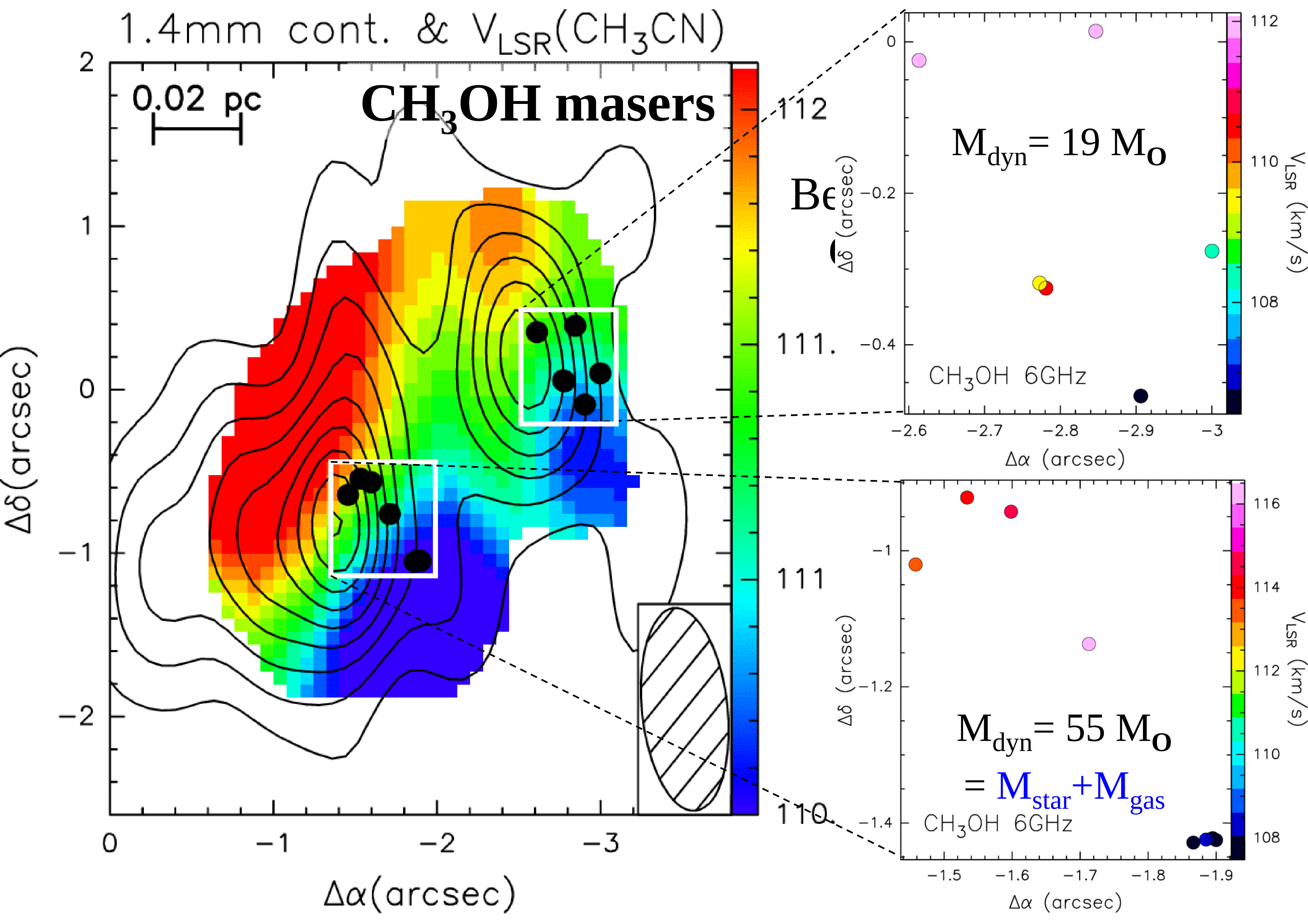




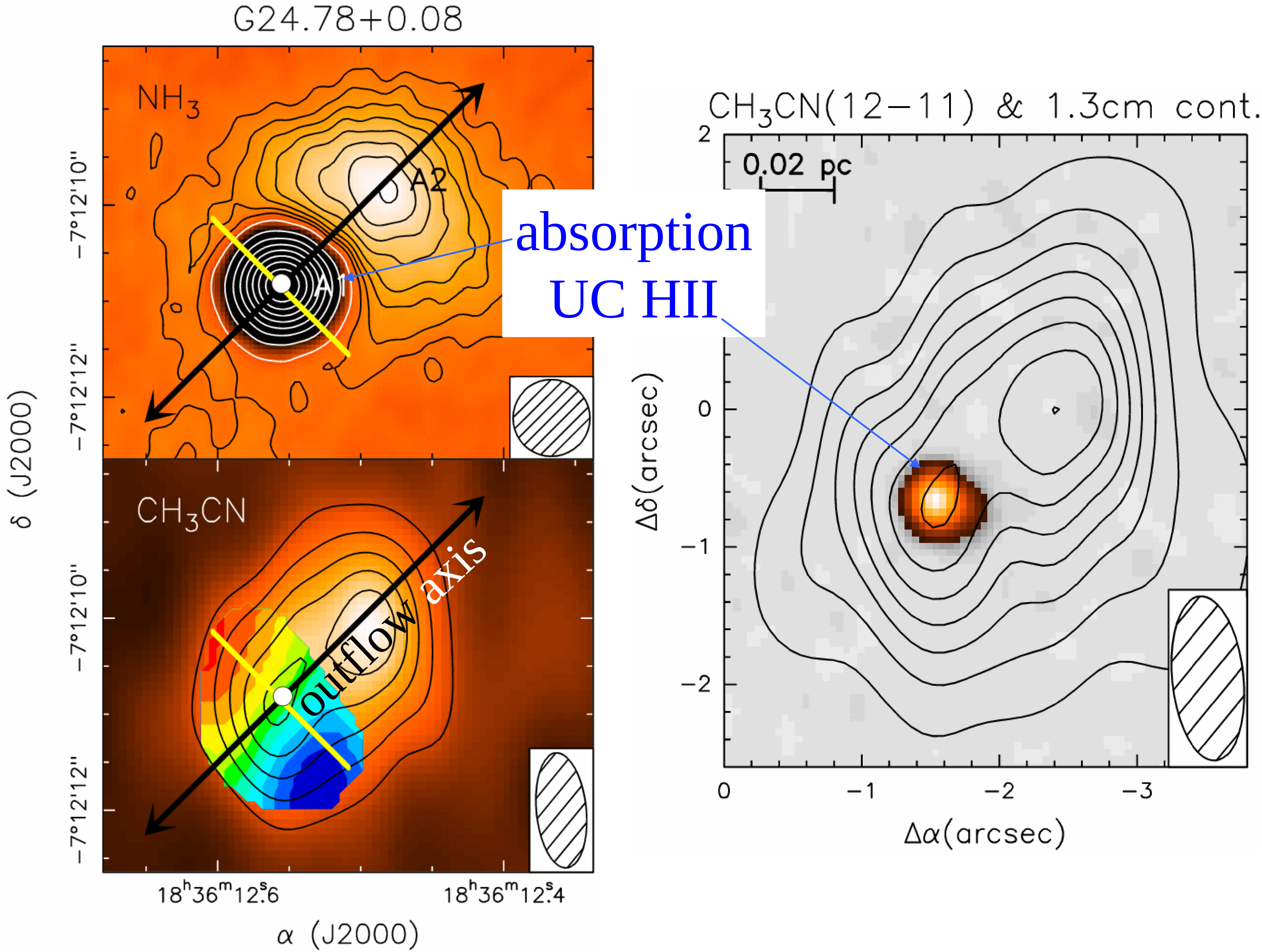
G24.78 – CH3CN & CO
−7°14'30"
−7°14'40"
−7°14'50"
δ(B1950)
0.2 pc
18h33m31s
18h33m30s
α(B1950)
Furuya et al. (2002)
G24.78 – CH3CN(12–11)
-7°12'09"
-7°12'10"
-7°12'11"
−7°12'12"
δ(B1950)
18h36m12.6s
18h36m12.5s
α(B1950)
111.5
111
km/s



G24.78 – CH_3CN & CO
−7°14'30"
λ(mm)
50
10
5
1
0.1
0.01
0.001
F_ν(Jy)
10
100
ν(GHz)
O9.5 (20 M_O) + 130 M_O
Keplerian rotation
around 20 M_o star?
ALMA needed!
CH_3CN(12−11) K=3
115
110
V_{LSR} (km/s)
−1
−2
−3
Δα (arcsec)
-7°12'11"
111
110
$18^h36^m12\overset{s}{.}6$
$18^h36^m12\overset{s}{.}5$
α(B1950)



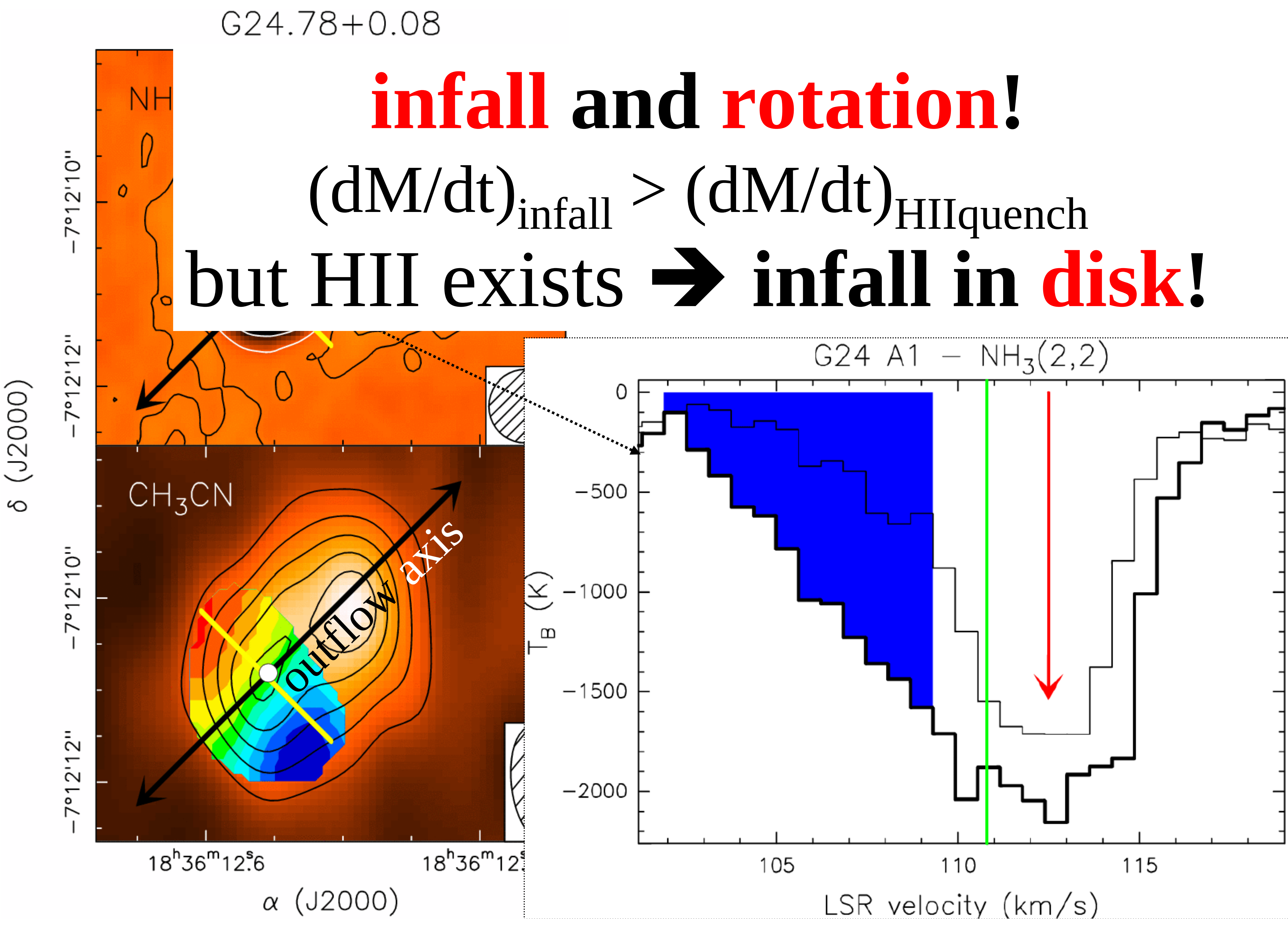
1.4mm cont. & VLSR(CH3CN)
0.02 pc
CH3OH masers
Mdyn= 19 MO
Mdyn= 55 MO
= Mstar+Mgas
CH3OH 6GHz
CH3OH 6GHz
Δα(arcsec)
Δδ(arcsec)
Δα (arcsec)
Δδ (arcsec)
VLSR (km/s)


G24.78+0.08
NH3
A2
A1
absorption
UC HII
CH3CN
outflow axis
−7°12'10"
−7°12'12"
δ (J2000)
18h36m12.6s
18h36m12.4s
α (J2000)
CH3CN(12−11) & 1.3cm cont.
0.02 pc
Δδ(arcsec)
Δα(arcsec)
2
0
−1
−2
−3

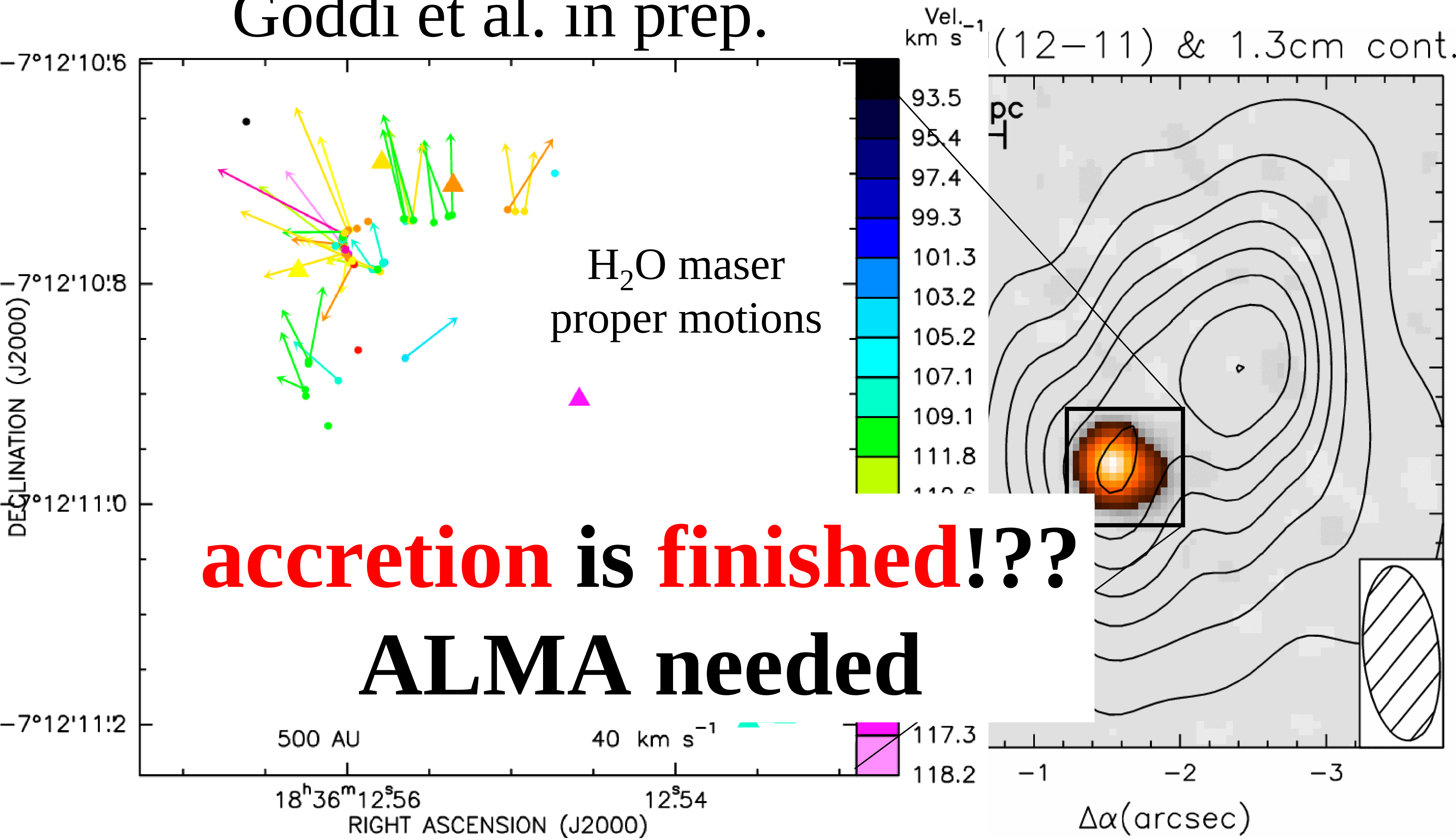
infall and rotation!

$(dM/dt)_{infall} > (dM/dt)_{HIIquench}$

but HII exists ➔ **infall in disk!**



Goddi et al. in prep.



accretion is finished!??

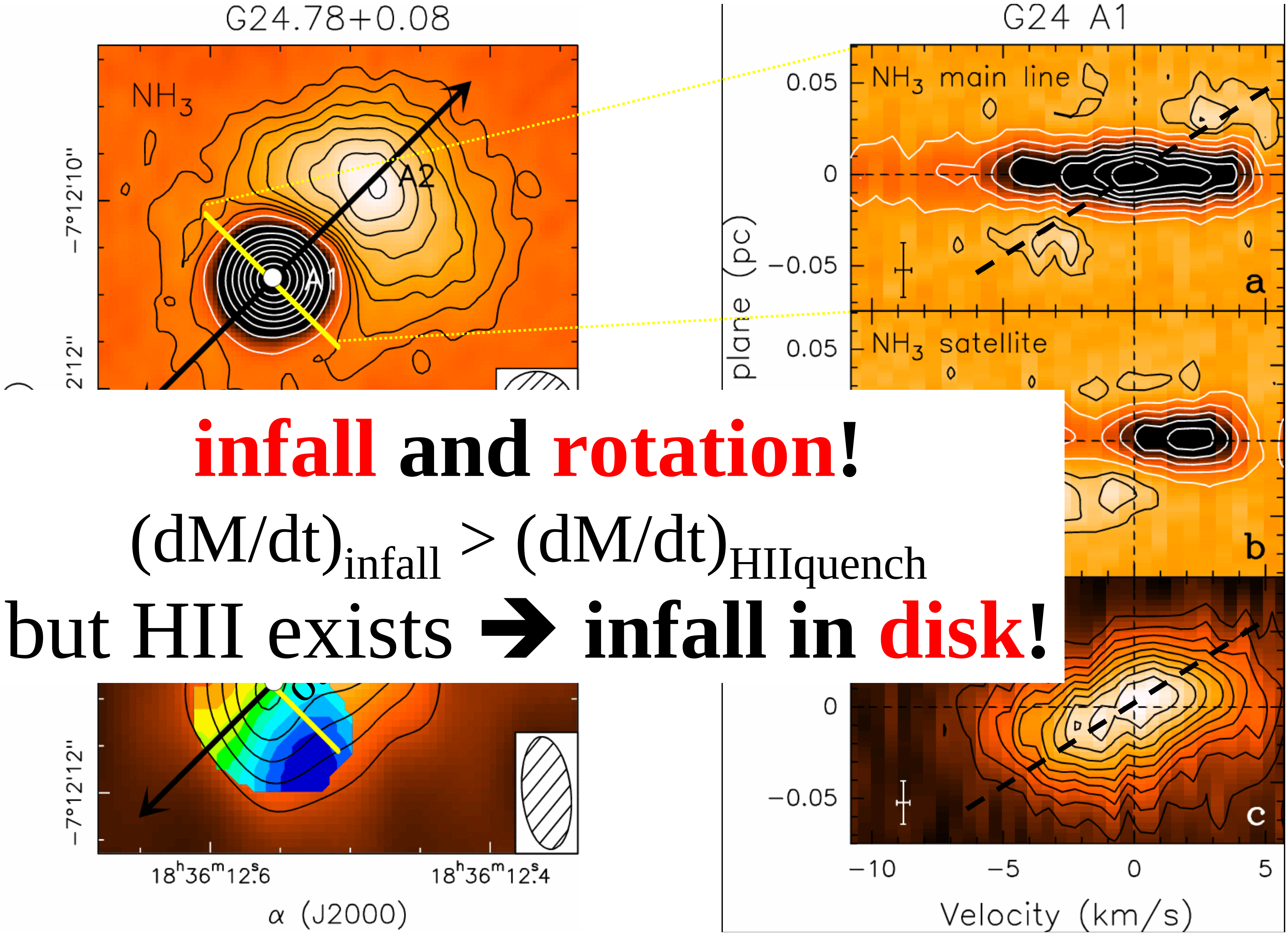
ALMA needed

Conclusions

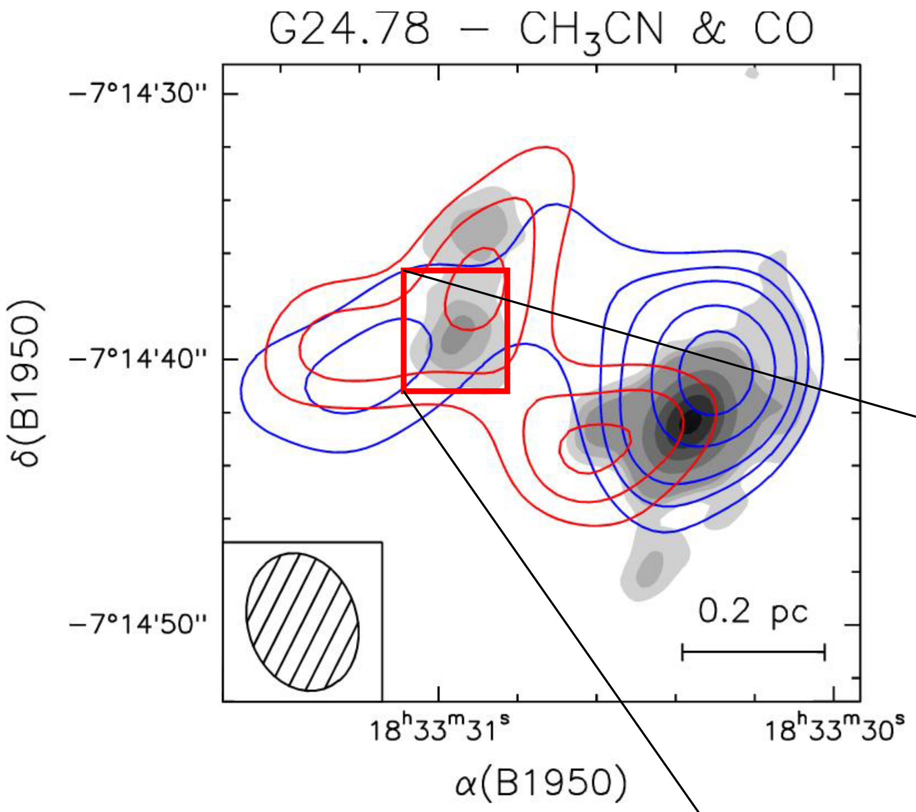
- Robust evidence of **disks** in B (proto)stars and perhaps in late O (proto)stars → star formation by **accretion** as in low-mass stars
- **No disk** found ***yet*** in *early* O (proto)stars → perhaps **observational bias**? perhaps **other star formation mechanisms** possible?

Only ALMA will tell:

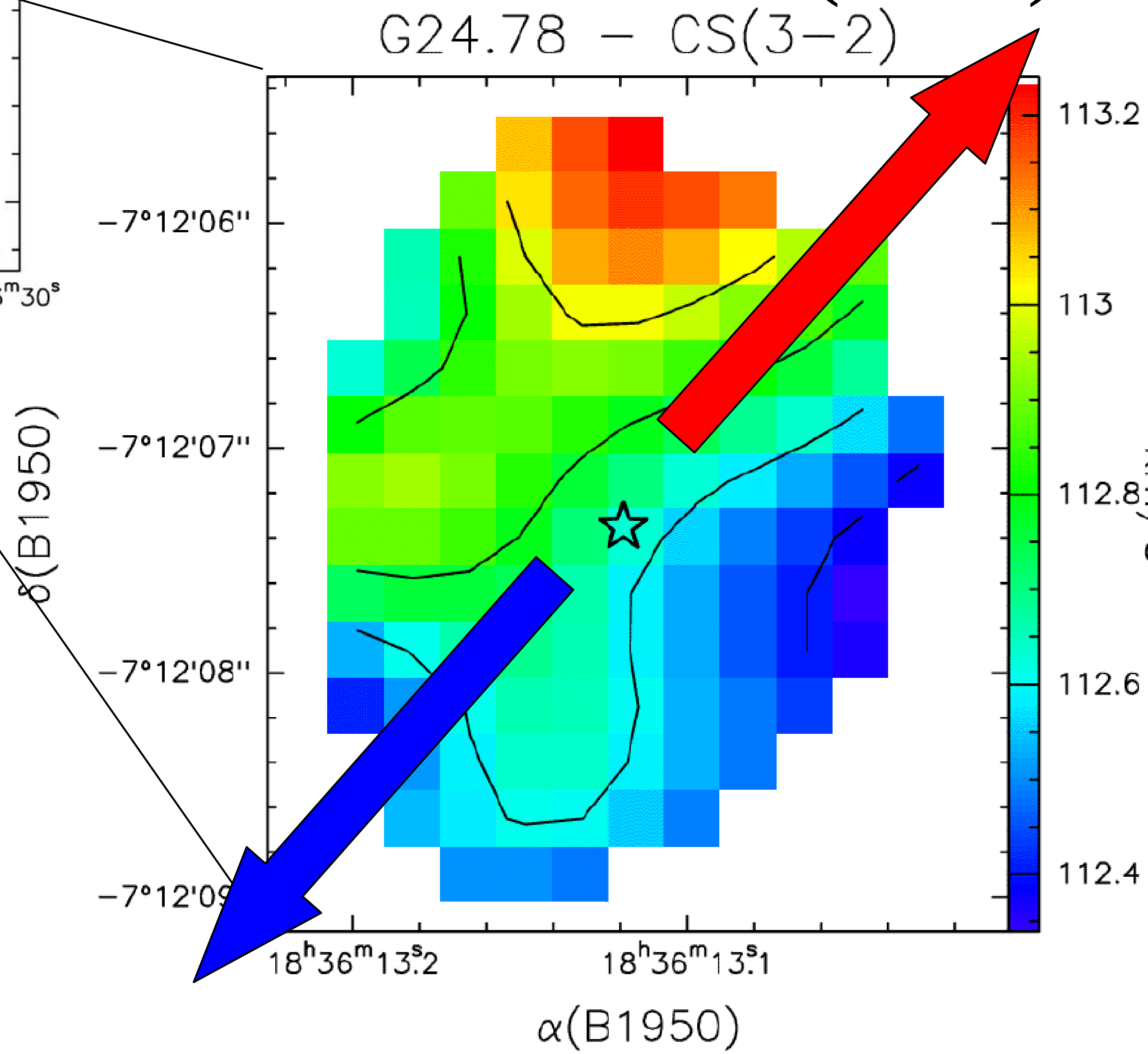
- High **sensitivity** & **resolution** → large **distances**
- **Sub-mm** lines → high-T tracers → **100 AU** region
- Wide **bandwidth** → **outflow**, **infall**, and **rotation** tracers *simultaneously*



G24.78+0.08
NH3
A2
A1
−7°12'10"
−7°12'12"
18h36m12.6s
18h36m12.4s
α (J2000)
G24 A1
NH3 main line
a
NH3 satellite
b
c
0.05
0
−0.05
plane (pc)
−10
−5
0
5
Velocity (km/s)
infall and rotation!
(dM/dt)infall > (dM/dt)HIIquench
but HII exists ➔ infall in disk!



Furuya et al. (2002)
Beltran et al. (2004)



Results of disk search

Two types of objects found:

Disks in B stars

- $M < 10\ M_{\odot}$
- $R \sim 1000$ AU
- **$L \sim 10^4\ L_{\odot}$**
- $(dM/dt)_{star} \sim 10^{-4}\ M_{\odot}/yr$
- $t_{rot} \sim 10^4$ yr
- $t_{acc} \sim M/(dM/dt)_{star} \sim 10^5$ yr

→ **$t_{acc} >> t_{rot}$**

➔ equilibrium, circum*stellar* structures

Toroids in O stars

- $M > 100\ M_{\odot}$
- $R \sim 10000$ AU
- **$L >> 10^4\ L_{\odot}$**
- $(dM/dt)_{star} > 10^{-3}\ M_{\odot}/yr$
- $t_{rot} \sim 10^5$ yr
- $t_{acc} \sim M/(dM/dt)_{star} \sim 10^4$ yr

→ **$t_{acc} << t_{rot}$**

➔ non-equilibrium, circum-*cluster* structures

The elusive disks in early O (proto)stars

Observational bias? For $M_{disk} = M_{star}/2$, a Keplerian disk in a 50 $M_{\odot}$ star can be detected up to:

- continuum sensitivity:

  $d < 1.7\,[M_{star}(M_{\odot})]^{0.5} \sim$ 12 kpc

- line sensitivity:

  $d < 6.2\,M_{star}(M_{\odot})\,\sin^2 i/W^2(\mathrm{km/s}) \sim$ 8 kpc

- spectral + angular resolution:

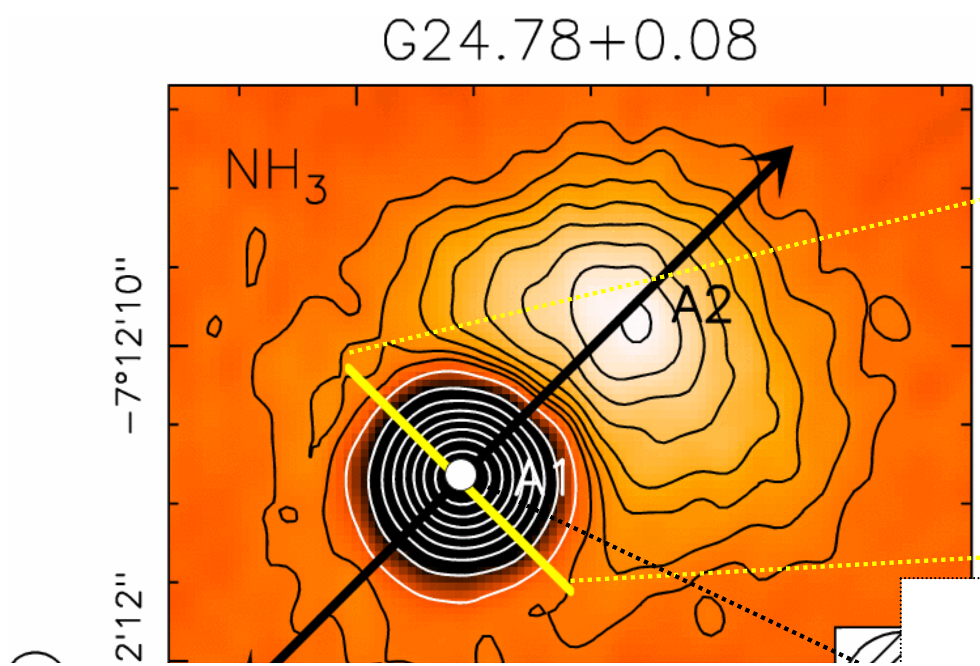
  $d < 14\,M_{star}(M_{\odot})\,\sin^2 i/[D('')W^2(\mathrm{km/s})] \sim$ 19 kpc

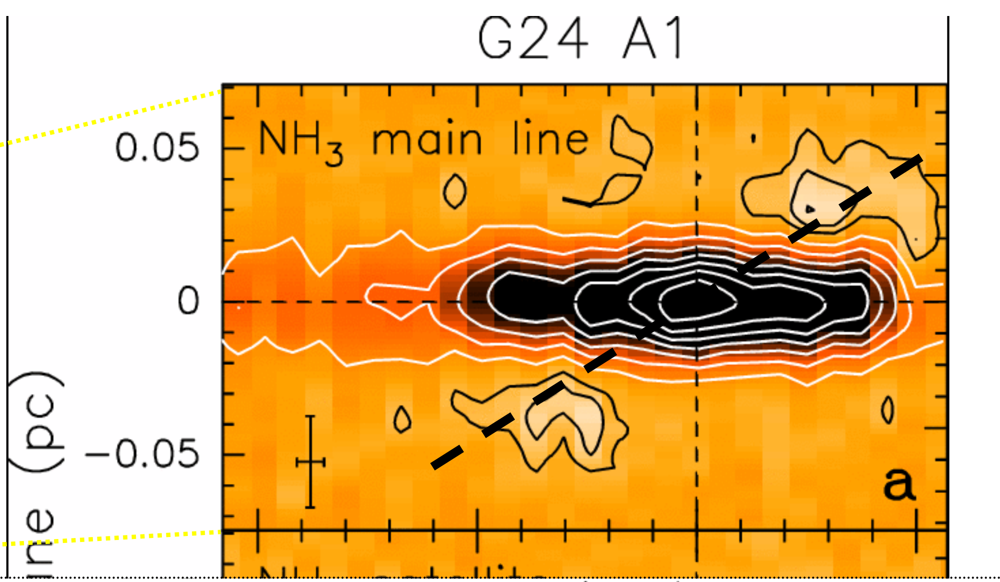
➔ disks in all O stars should be detectable up to the galactic center

Caveats!!!

One should consider also:

- rarity of O stars → ALMA sensitivity
- confusion with envelope → ALMA resolution
- Chemistry → ALMA spectral coverage
- confusion with outflow/infall → ALMA resol.
- non-keplerian rotation
- disk flaring
- inclination angle
- …

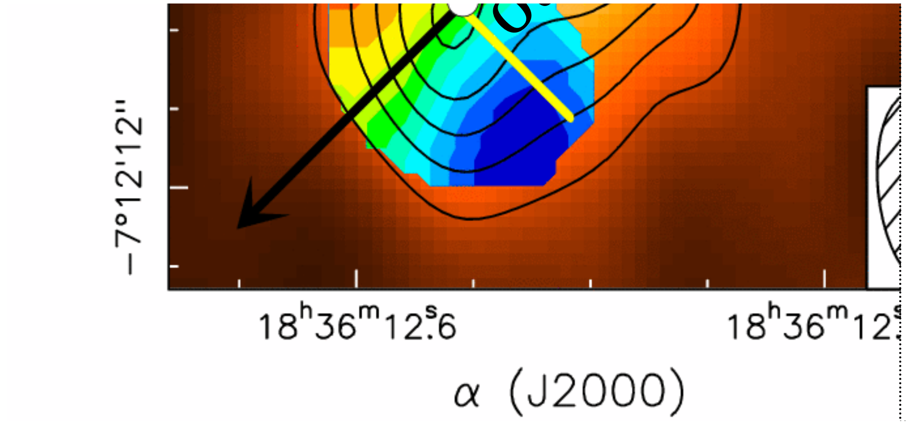


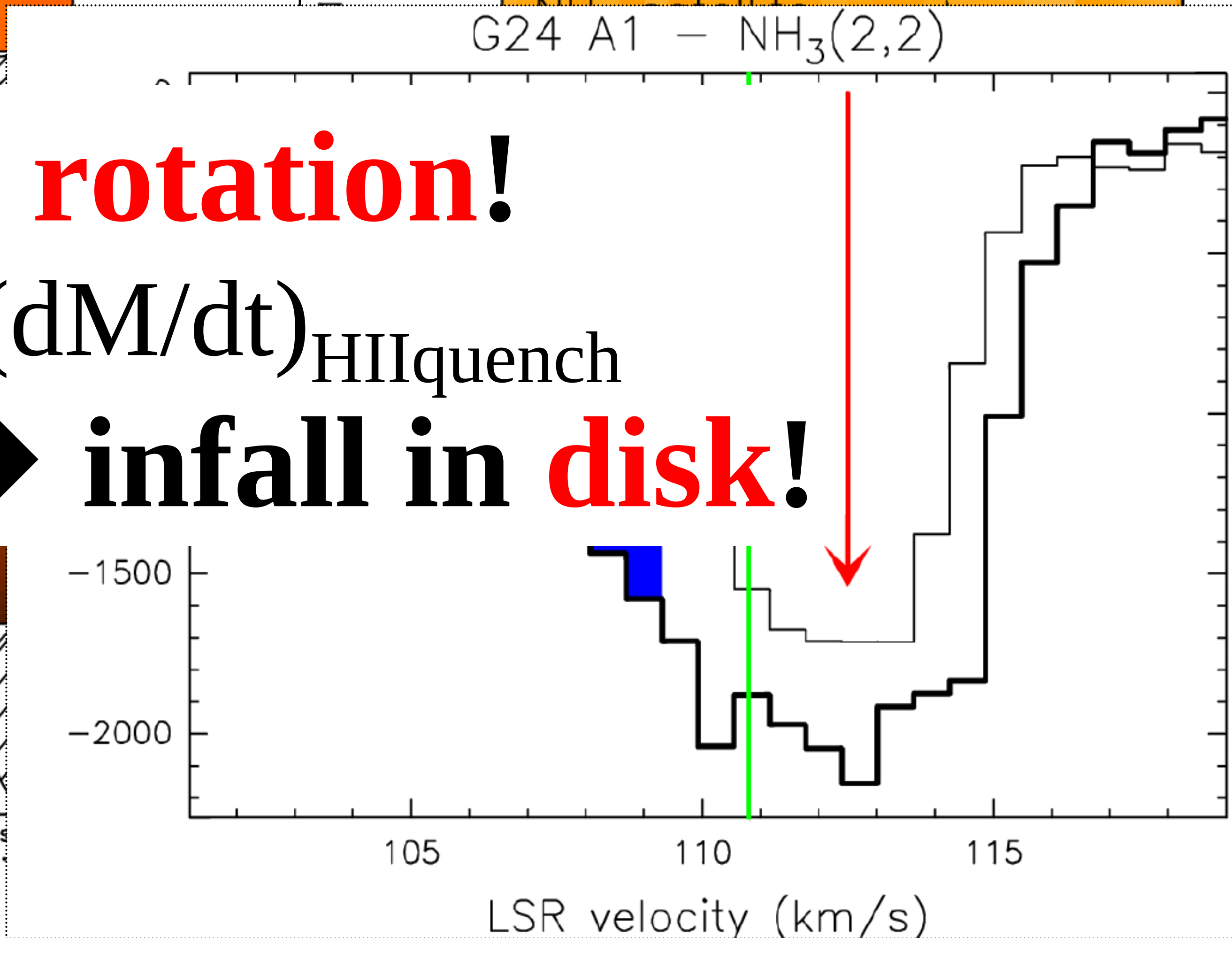


infall and rotation!

$(dM/dt)_{infall} > (dM/dt)_{HIIquench}$

but HII exists ➔ **infall in disk!**





$L_{star} = 10^3\text{-}10^5\ L_{\odot}$ →

→ $T_{dust} = 65\ K\ (L_{star}/10^5 L_{\odot})^{0.2}\ (R/0.1pc)^{0.4}$

→ $T_{dust} > 100\ K$ for $R < 0.1$ pc

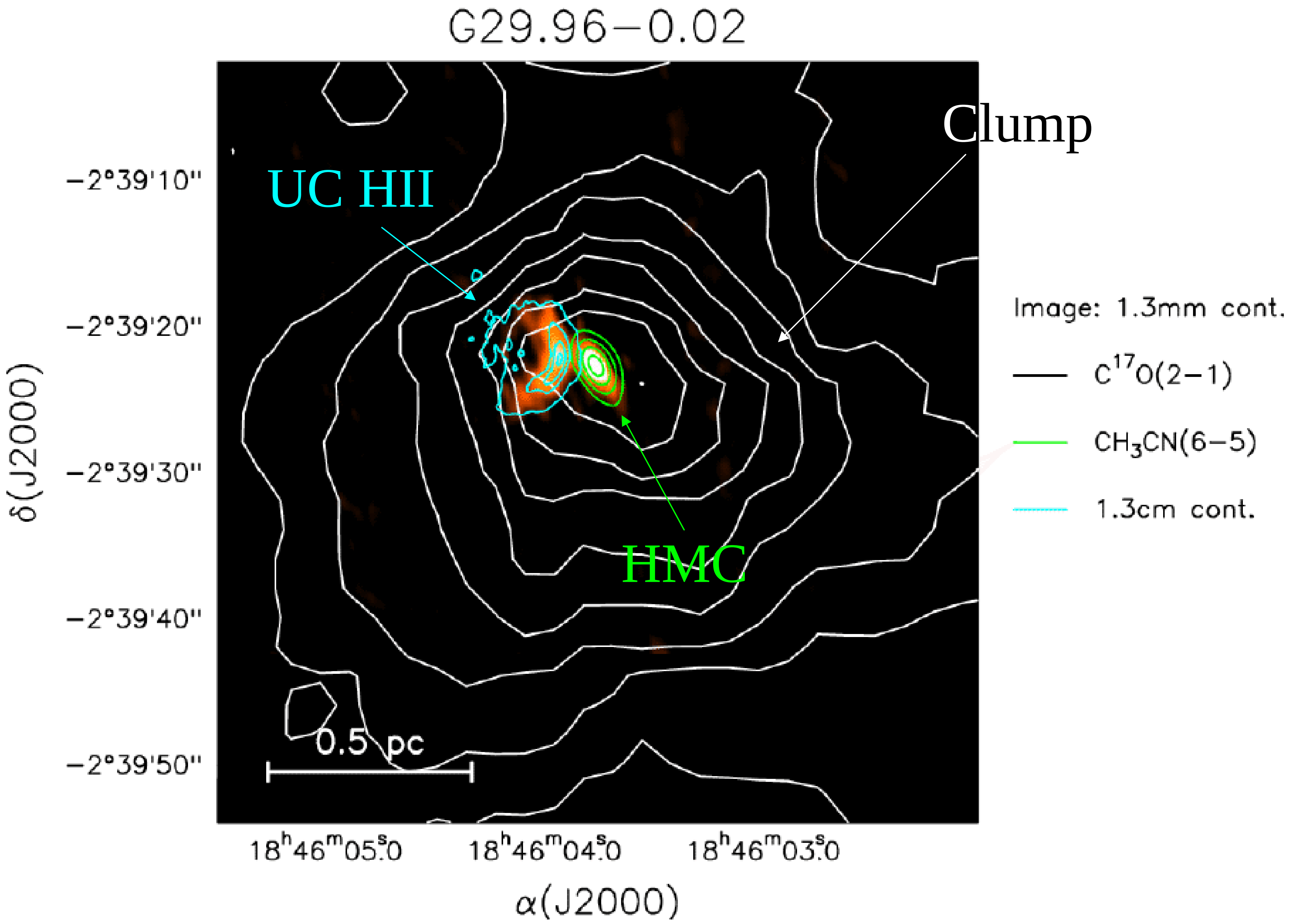
→ Grain mantles evaporated

→ chemical enrichment of gas phase: hot cores

→ wide choice of molecular probes: CH_3OH, CH_3CN, $HCOOCH_3$, etc. …

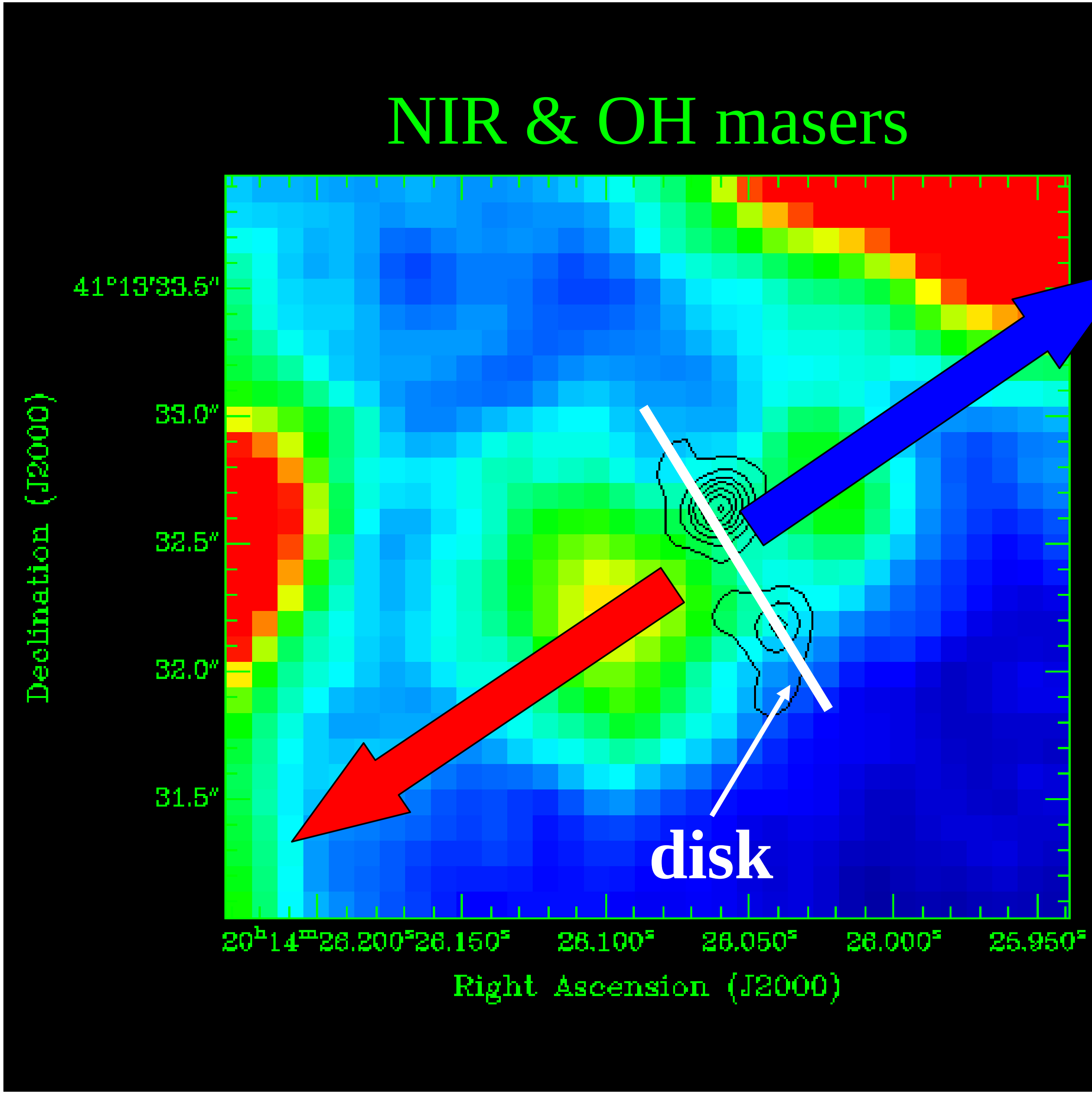
Jets/outflows →

→ shocks: H_2O, SiO, HCO^+, etc. …


G29.96−0.02
Clump
UC HII
HMC
0.5 pc
−2°39'10"
−2°39'20"
−2°39'30"
−2°39'40"
−2°39'50"
δ(J2000)
18h46m05.0s
18h46m04.0s
18h46m03.0s
α(J2000)
Image: 1.3mm cont.
C17O(2−1)
CH3CN(6−5)
1.3cm cont.

IRAS 20126+4104

Edris et al. (2005)
Sridharan et al. (2005)



IRAS 20126+4104

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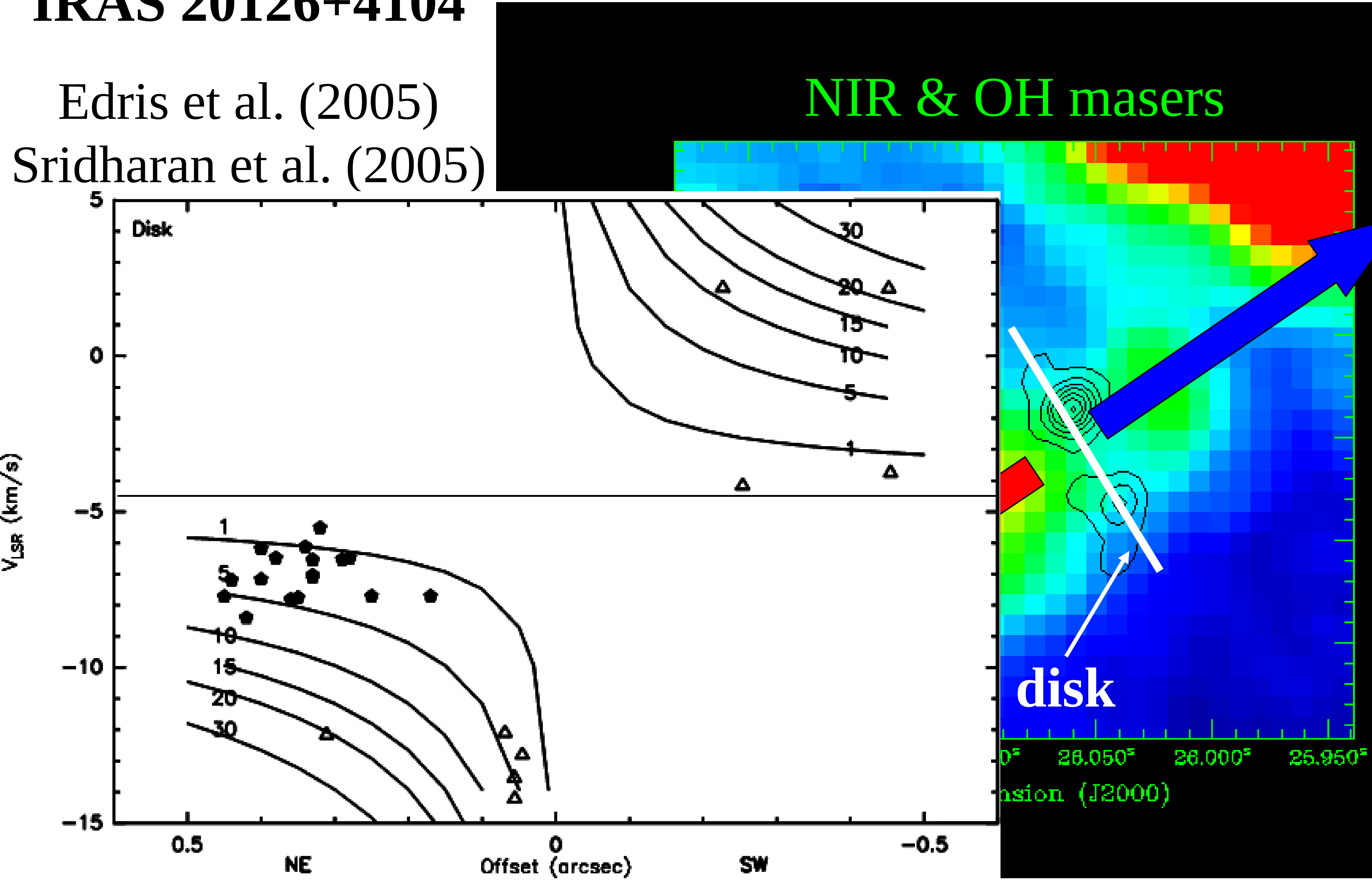
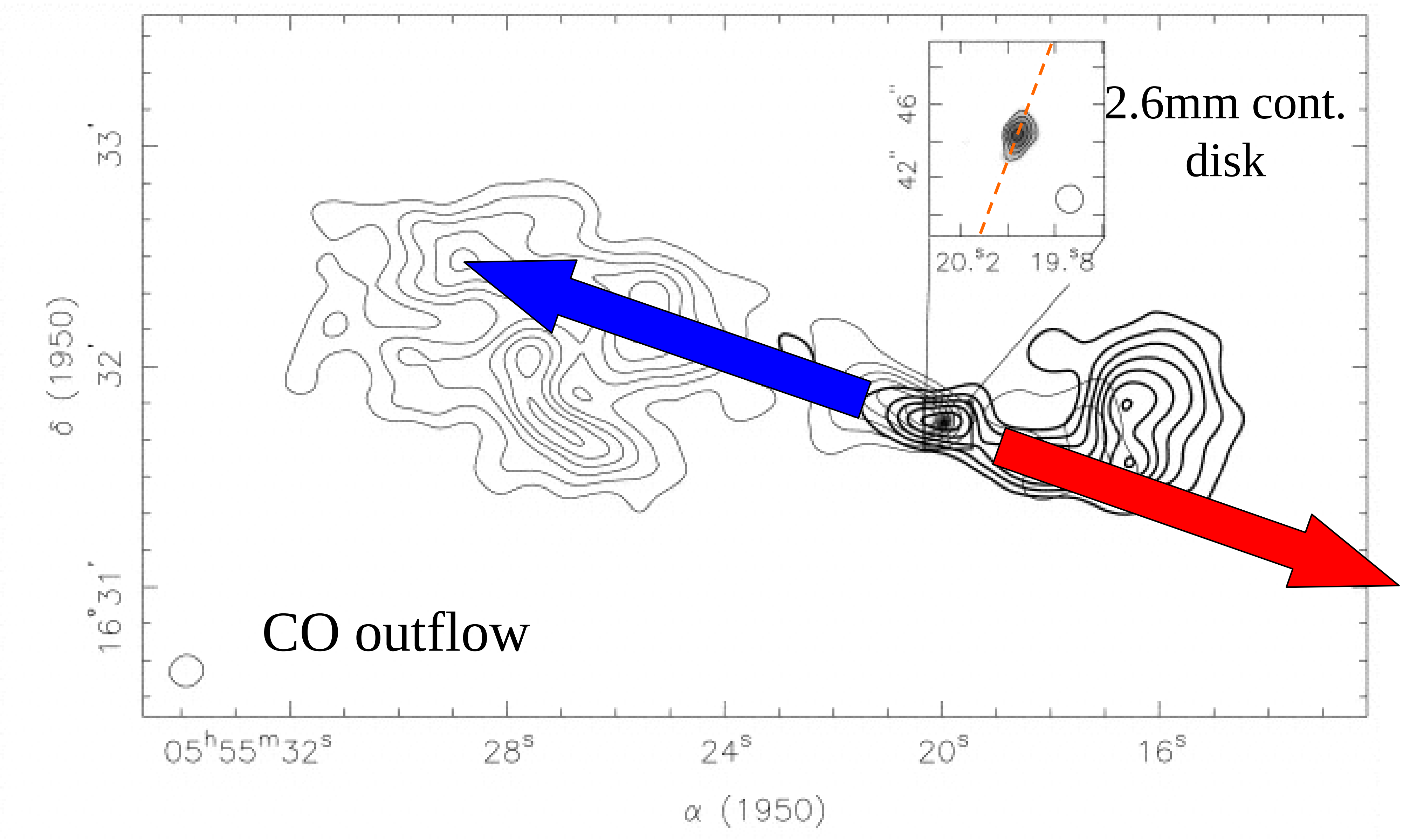


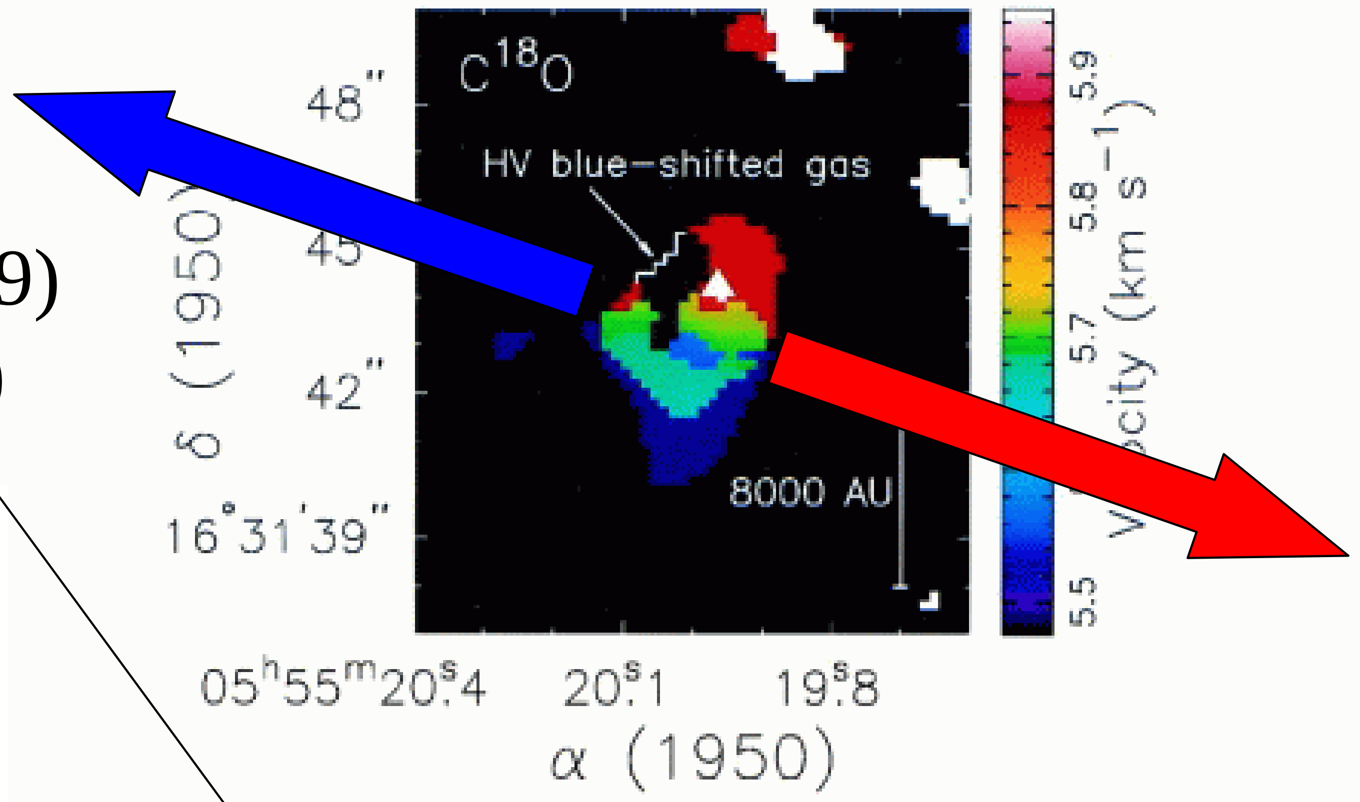
G192.16-3.82

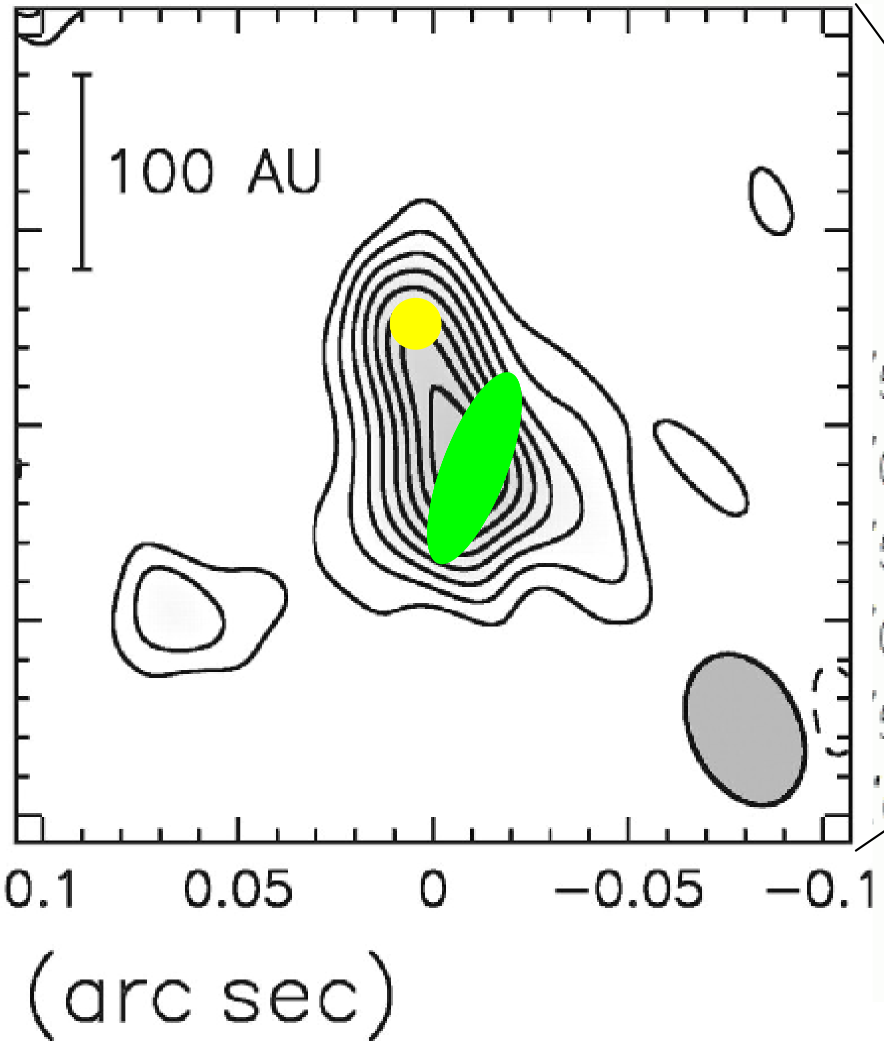
Shepherd & Kurtz (1999)

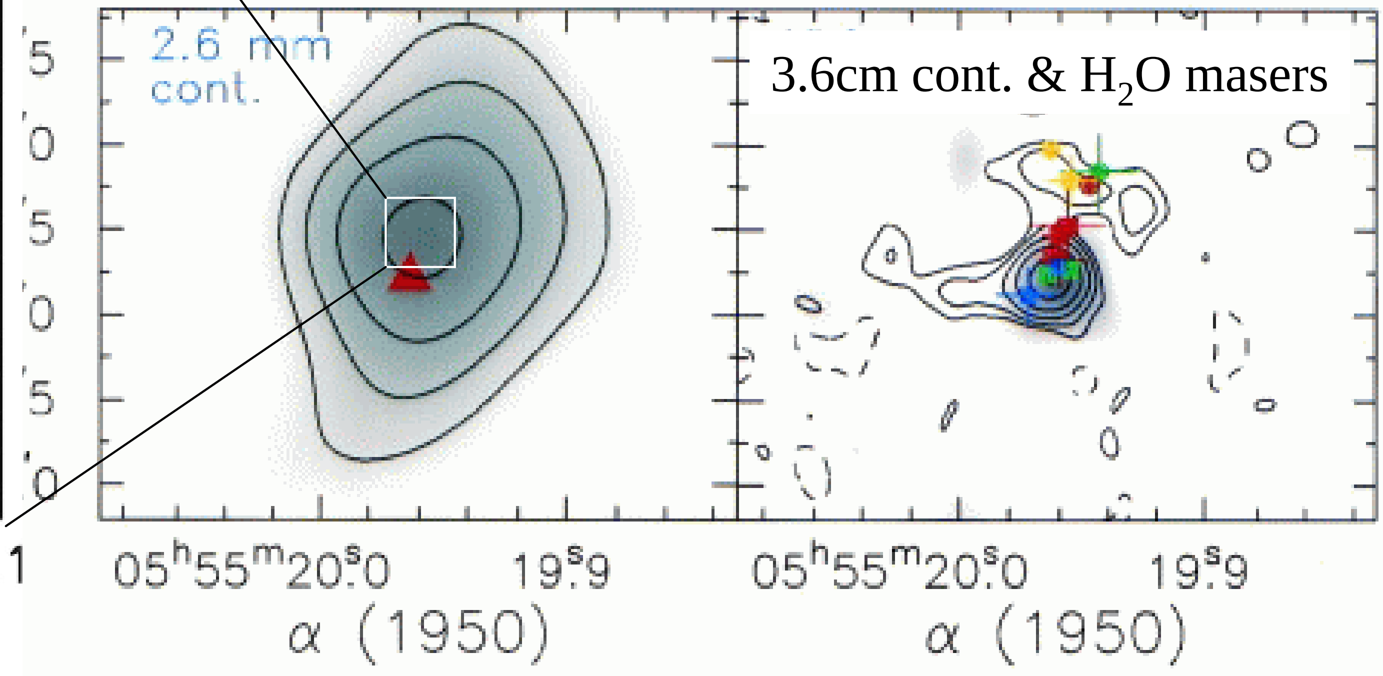


G192.16-3.82

Shepherd & Kurtz (1999)
Shepherd et al. (2001)

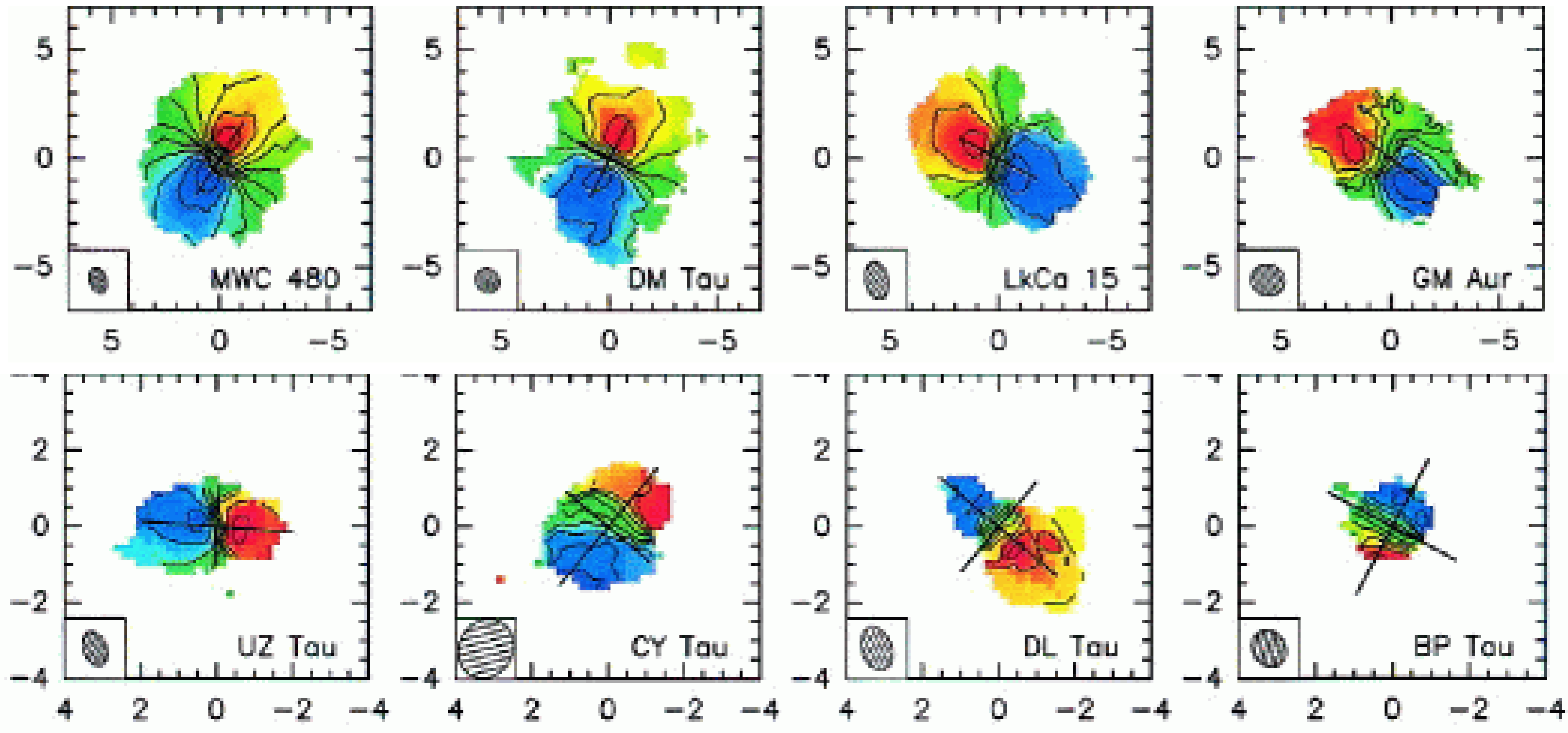


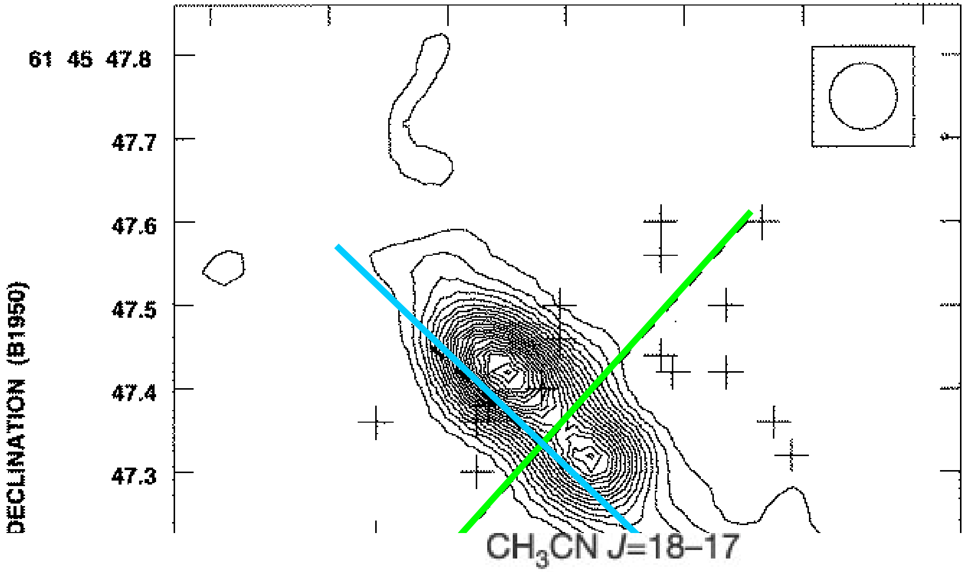


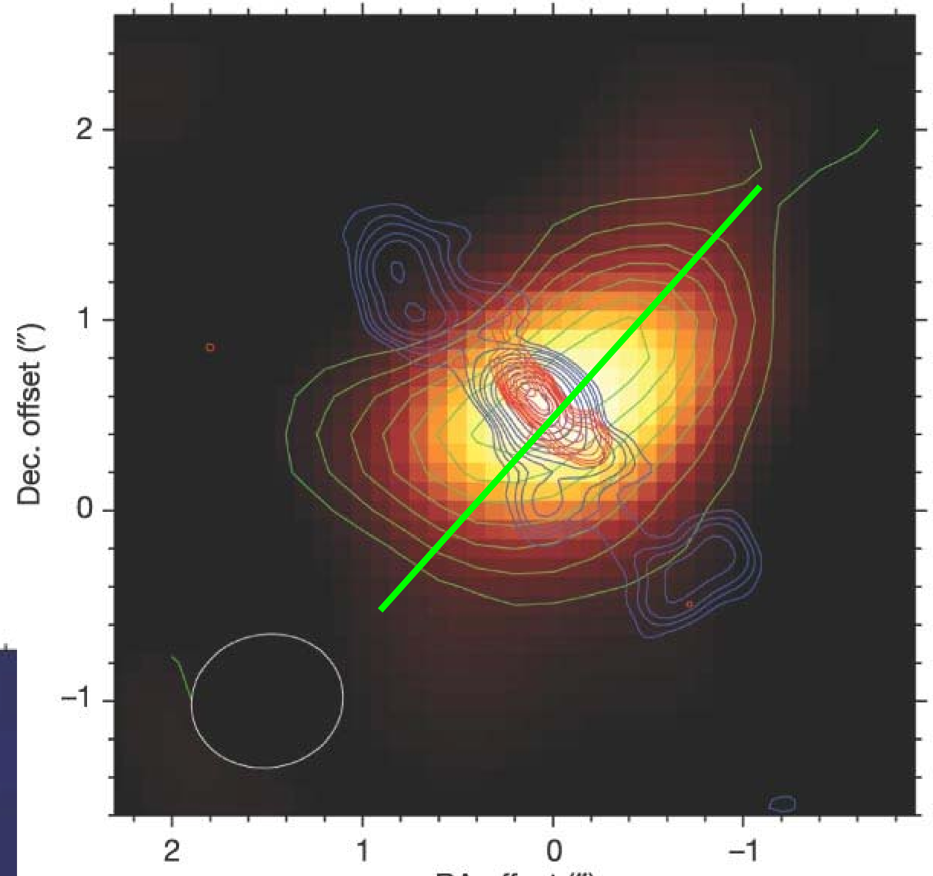


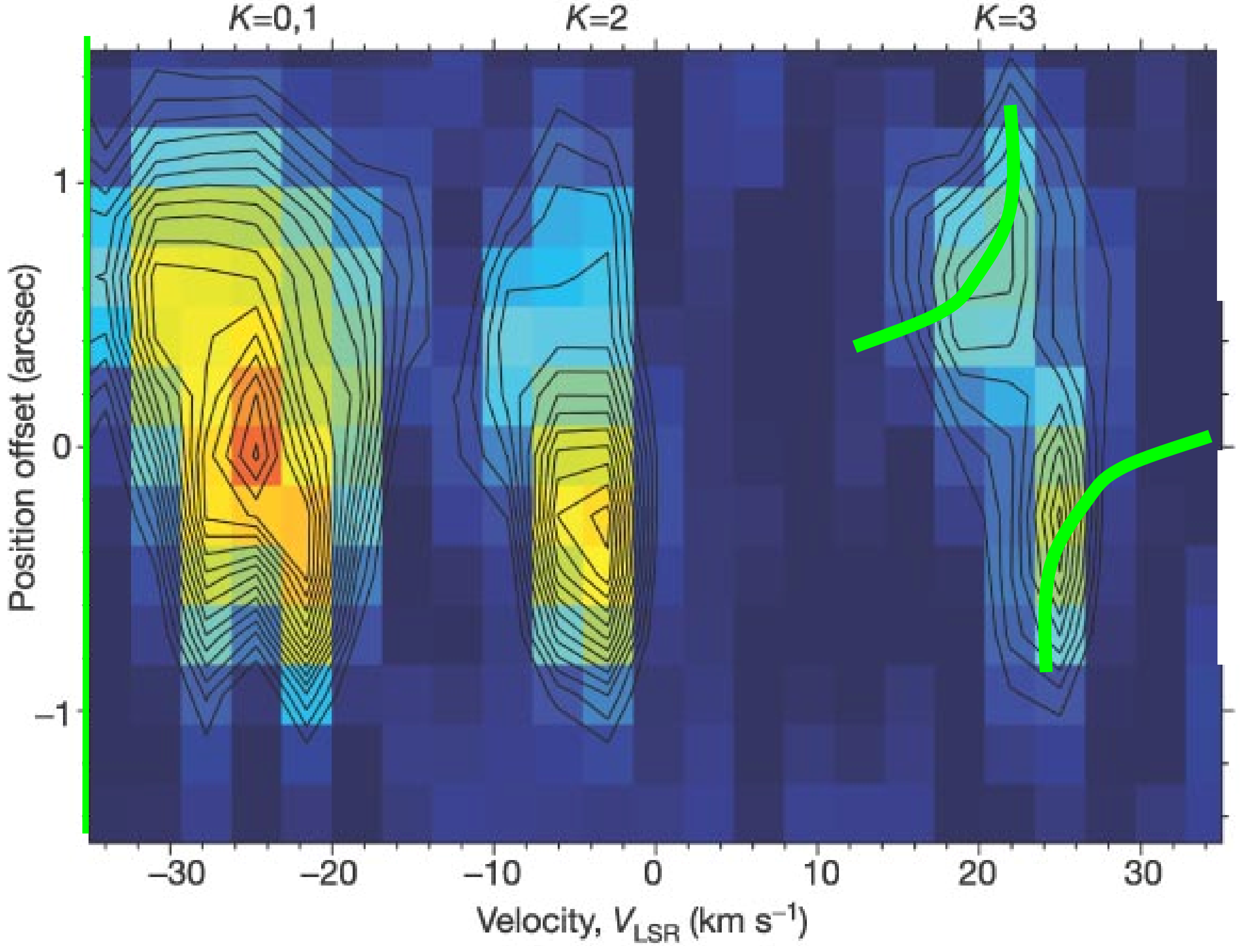
Simon et al. (2000): TTau stars

Velocity maps (CO J=2→1)



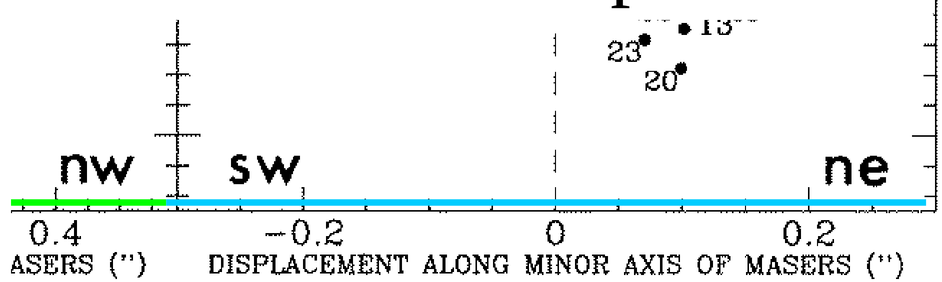




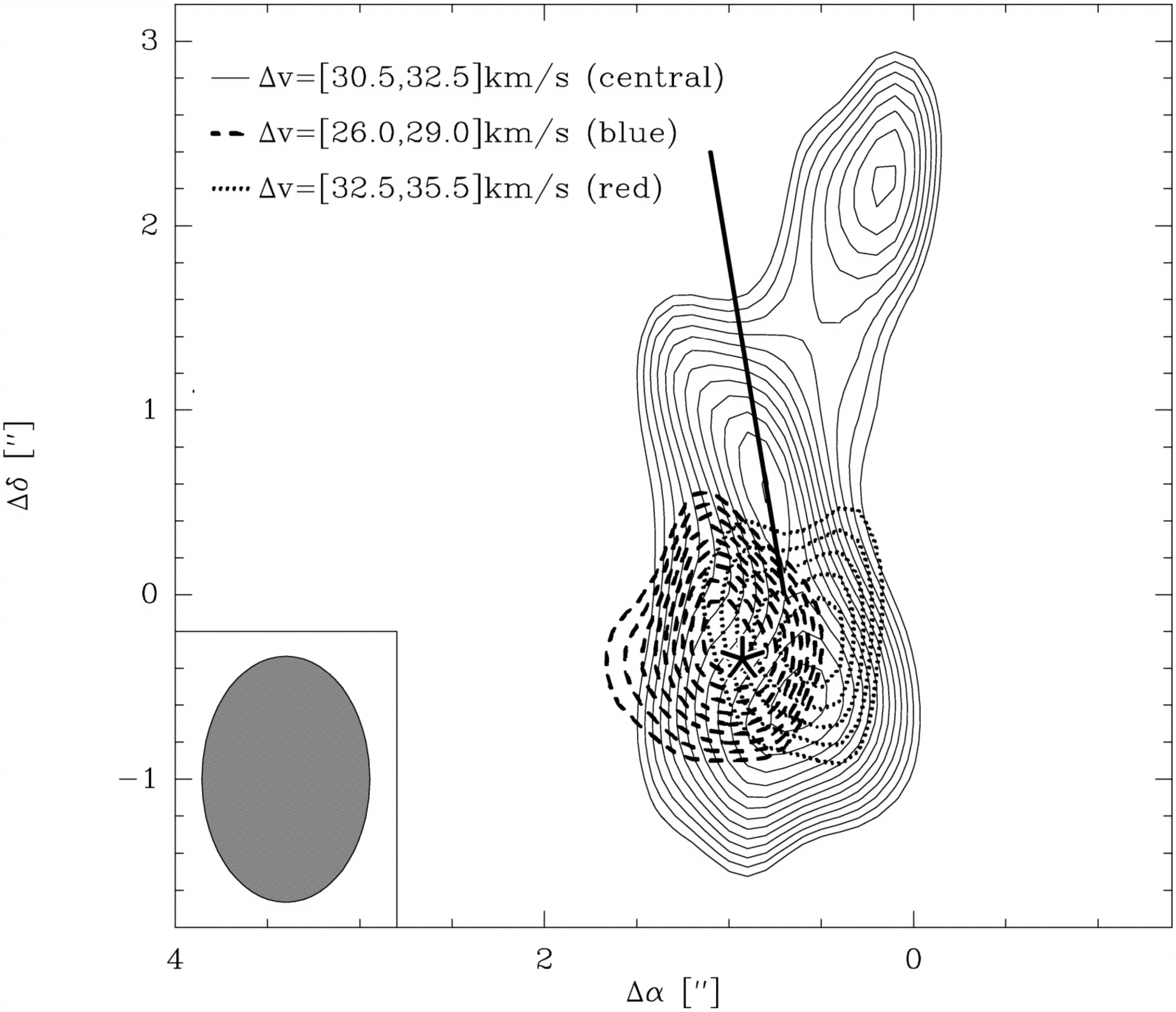


Patel et al. (2005)

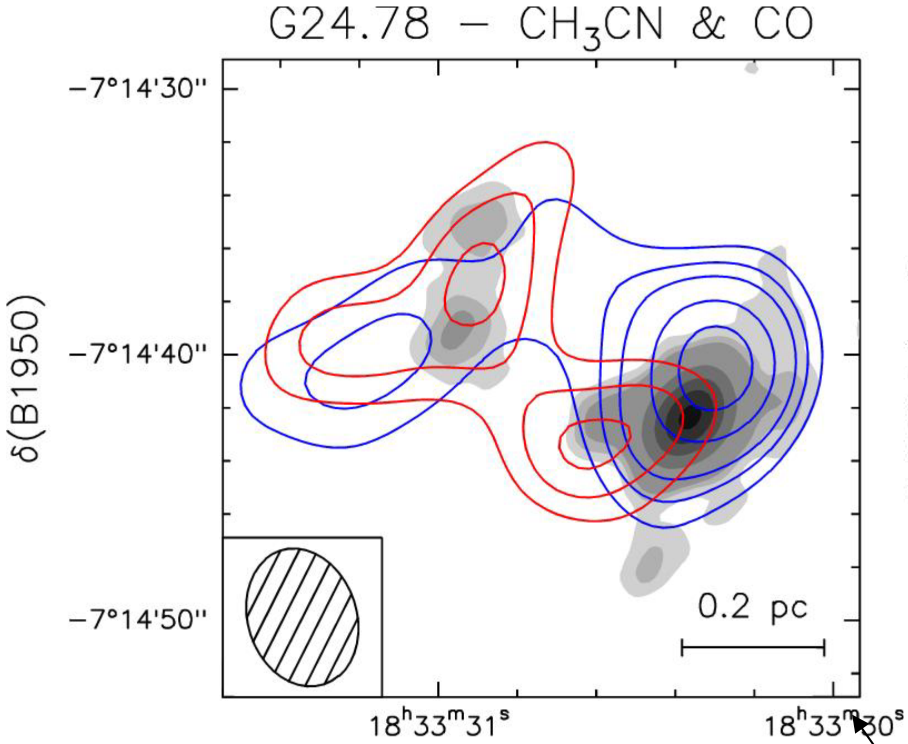
… but see Comito & Schilke for a different interpretation

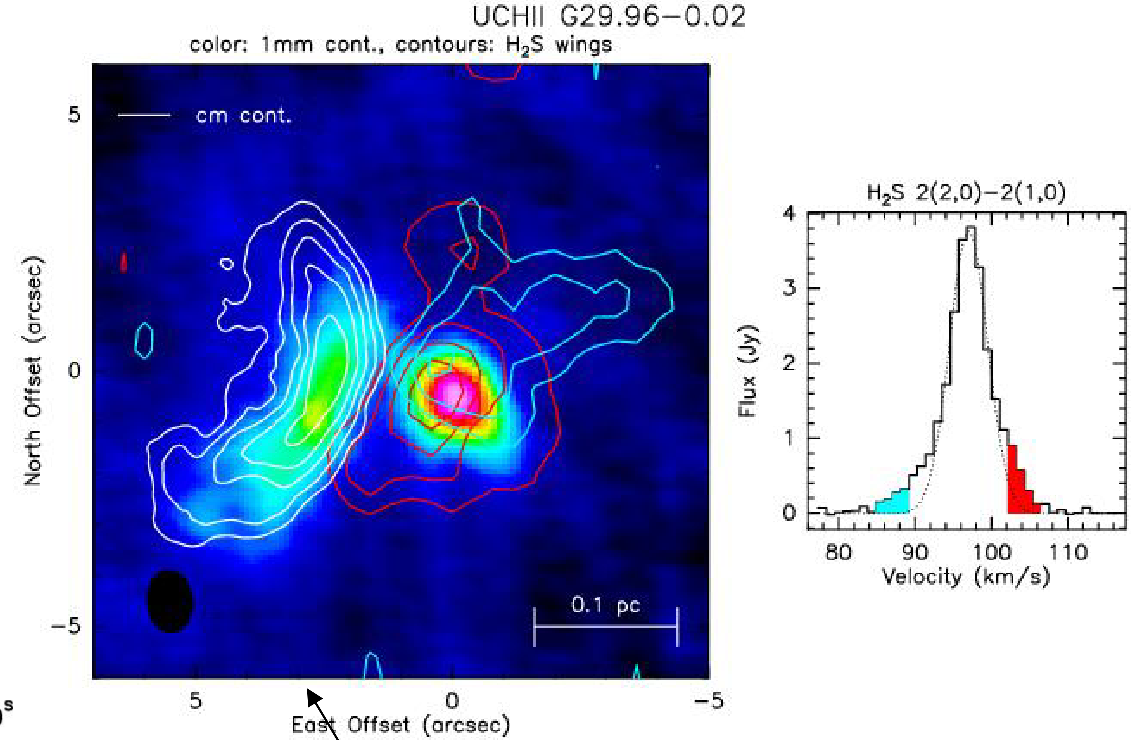


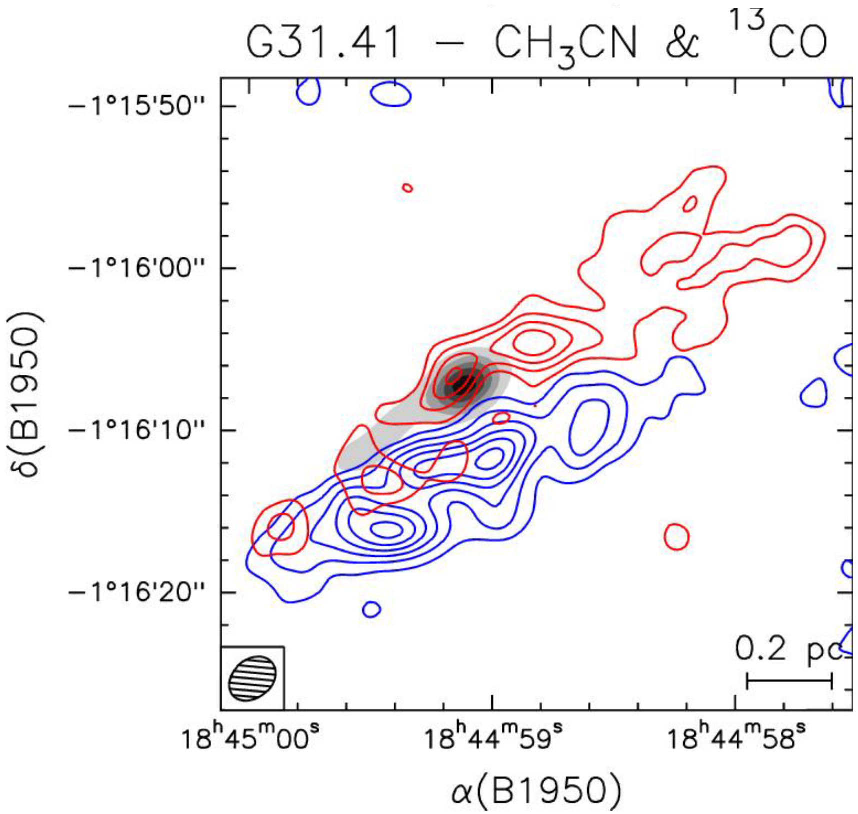
IRAS 18089-1732



Beuther et al. (2004, 2005)







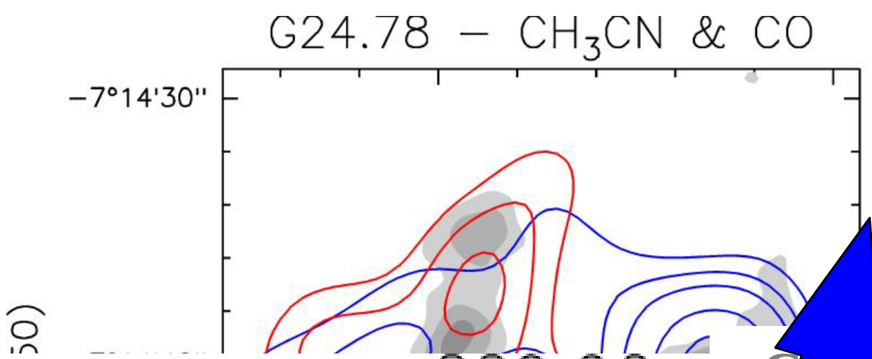
Gibb et al. (2002)

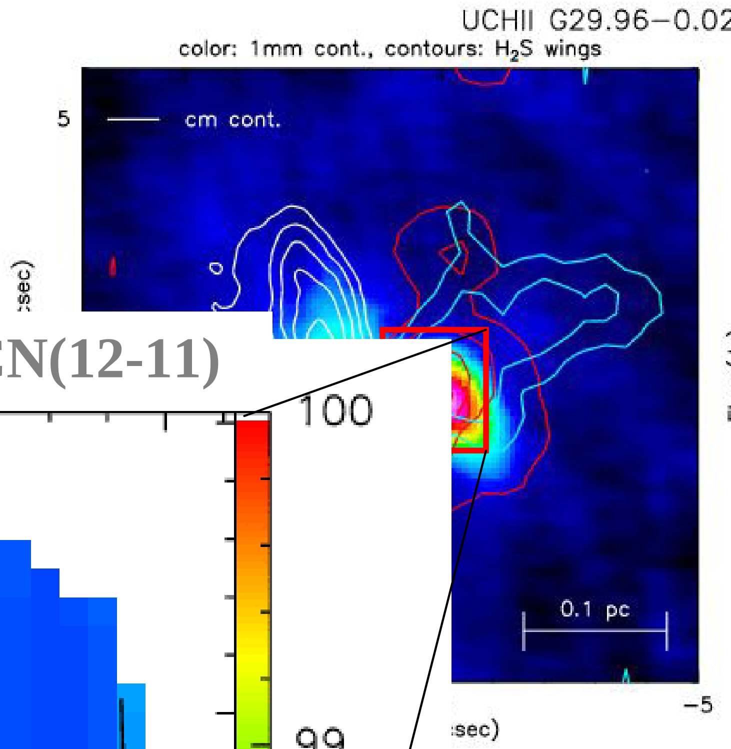
Olmi et al. (2003)

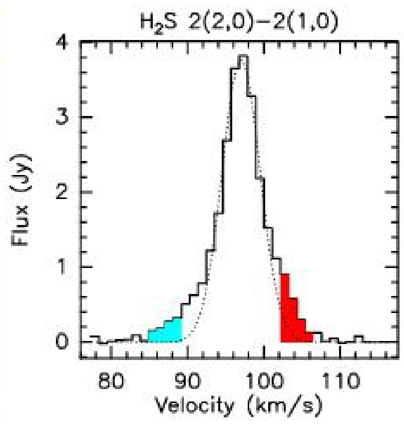
Olmi et al. (1996)

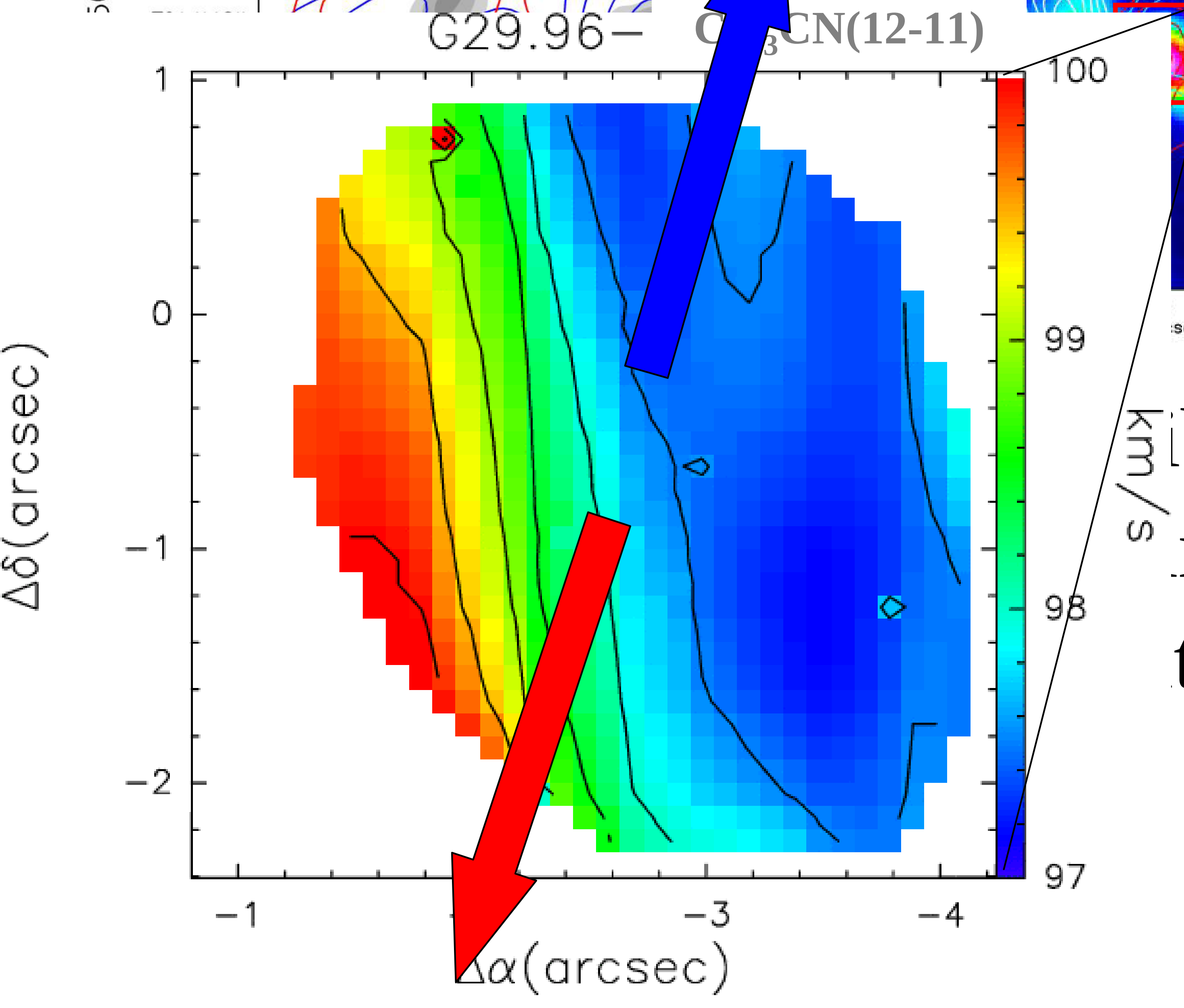
Furuya et al. (2002)

Beltran et al. (2004)









ibb et al. (2002)

mi et al. (2003)

tran et al. (2005)

Disks & Toroids

	L (L_O)	M_{disk} (M_O)	D_{disk} (AU)	M_* (M_O)
IRAS20126	10^4	4	1600	7
G192.16	$3\ 10^3$	15	1000	6-10
M17	?	>110	20000	15-20
NGC7538S	10^4	100-400	30000	40
G24.78 (3)	$7\ 10^5$	80-250	4000-8000	20…
G29.96	$9\ 10^4$	300	14000	-
G31.41	$3\ 10^5$	490	16000	-

B stars

O stars