Maser bow shocks and non-linear proper motions near massive young stars

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Motivations

- Parallax -> source distance
- Use proper motions to study jets
- Low- vs High-mass star formation

Targets: AFGL 5142 MM1 -and- S255IR-SMA1

- > 1000 Lo
- 6.7 GHz maser
- Centimeter emission
- 22 GHz water masers

QSOs < 50 mJy
Inverse phase referencing

Observations: VERA

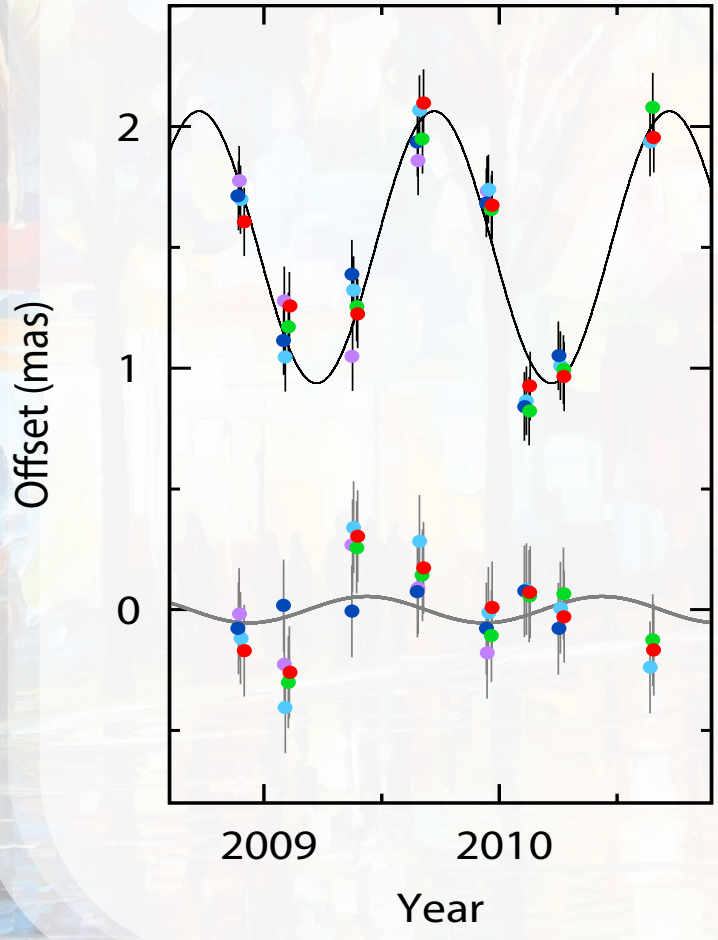
Observations: AFGL 5142 MM1

Epoch number	Observation date	Modified Julian date	Number of features
1	21 Apr 2014	56768	12
2	20 May 2014	56797	9
3	2 Oct 2014	56932	17
4	25 Nov 2014	56986	22
5	31 Jan 2015	57053	24
6	29 Mar 2015	57110	29
7	29 May 2015	57171	19

Observations: S255IR-SMA1

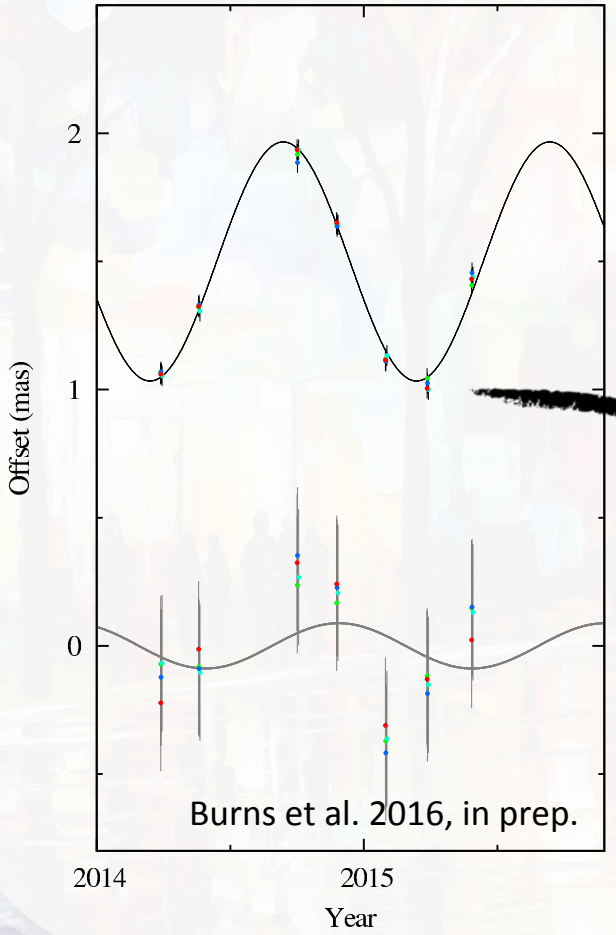
Epoch number	Observation date
1	23rd Nov 2008
2	1st Feb 2009
3	18th May 2009
4	28th Aug 2009
5	15th Sep 2009 †
6	27th Sep 2009 †
7	24th Oct 2009 †
8	13th Dec 2009
9	28th Jan 2010 †
10	10th Feb 2010
11	4th Apr 2010
12	11th Aug 2010

Results: Parallax S255IR-SMA1

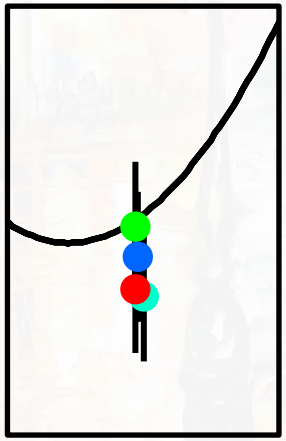


- D = 1.78 ± 0.12
- Consistetn with VLBA:
  D_{VLBA} = 1.59 ± 0.07 kpc
- Actually VERA is more reliable in this case (more epochs, higher v)

Results: Parallax AFGL 5142 MM1



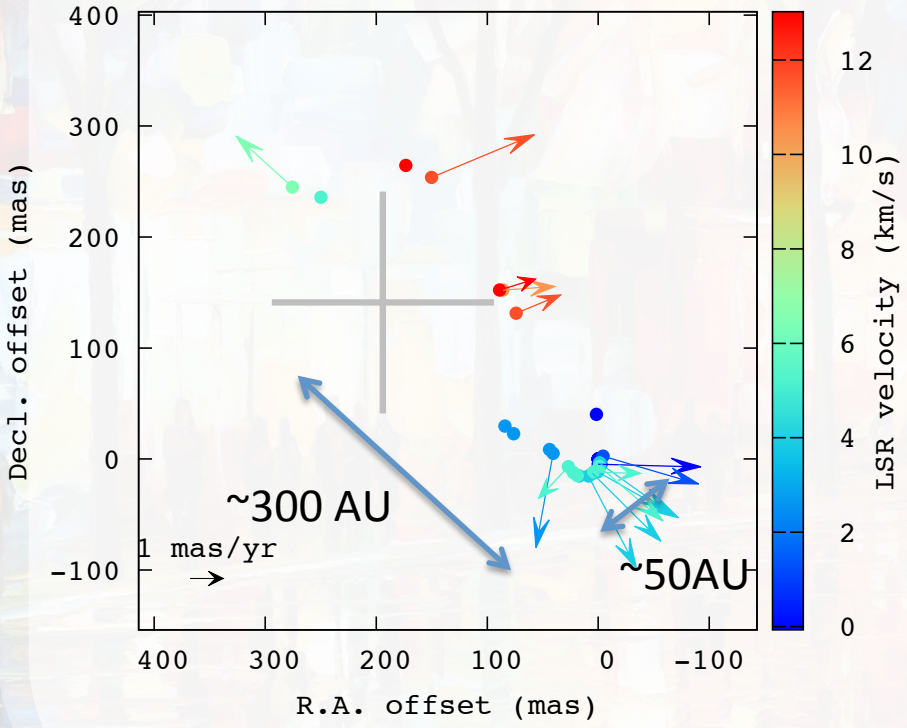
- D = 2.14 ± 0.05
- Using 4 maser features
- Reliable astrometry



S255IR-SMA1
Maser maps
Proper motions

Results

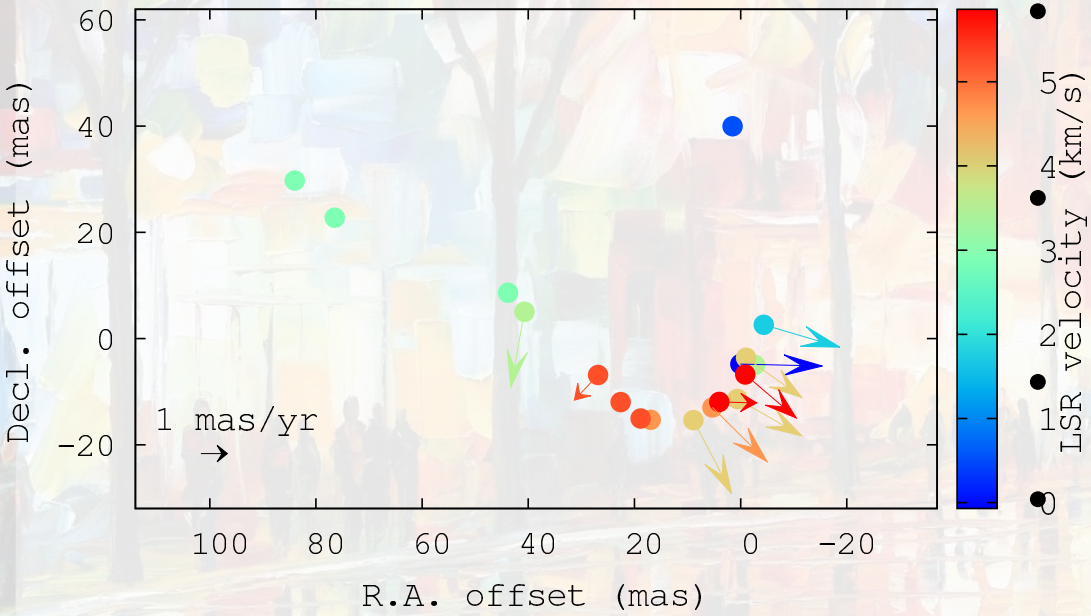
S255IR-SMA1



- Masers symmetric around the star (cross)
- Expanding motion
- Trace the bow shock
- Proper motions of 1-3 mas/yr 10-25 km/s

Results

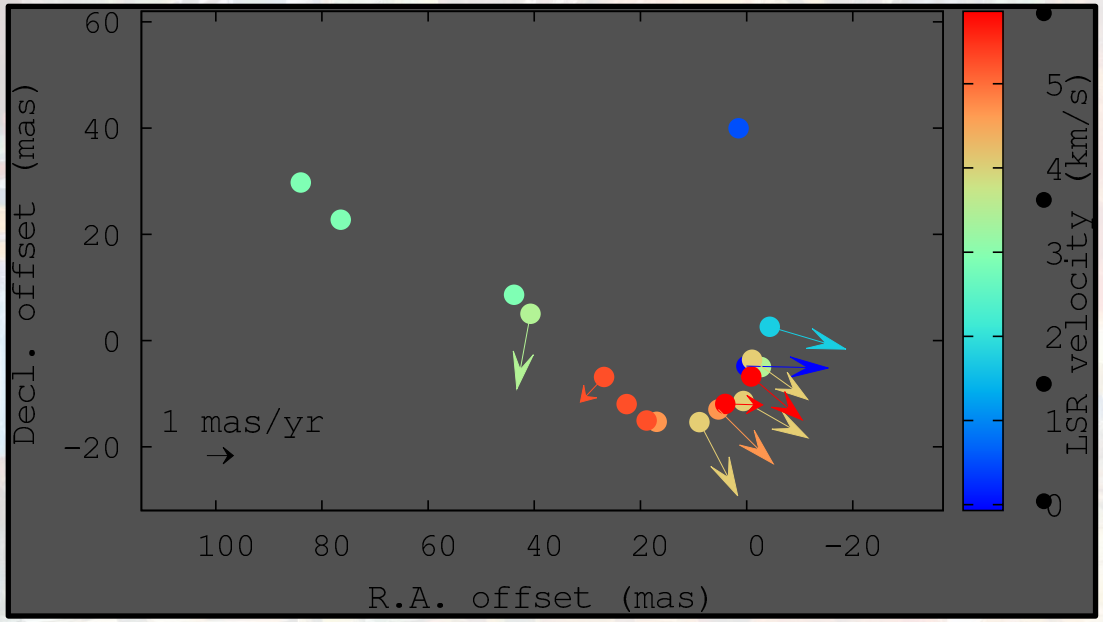
S255IR-SMA1



- U-shaped bow shock similar to S106
- Bow shock ejected from the MYSO
- Highly collimated
- Some velocity dispersion at the tip (Signature of jet)

Results

S255IR-SMA1



U-shaped bow shock similar to S106

Bow shock ejected from the MYSO

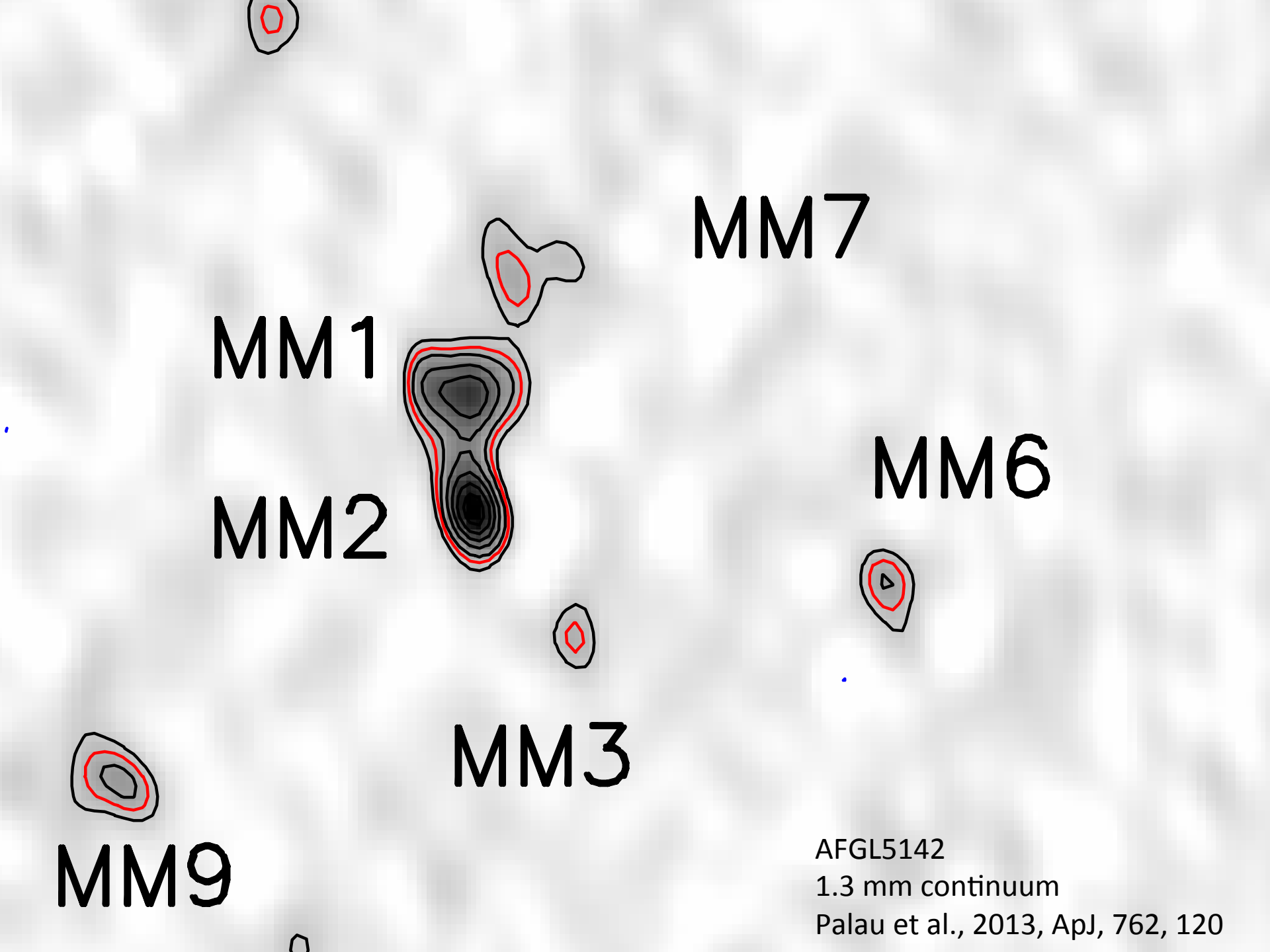
Highly collimated

Some velocity dispersion at the tip (Signature of jet)

AFGL 5142 MM1

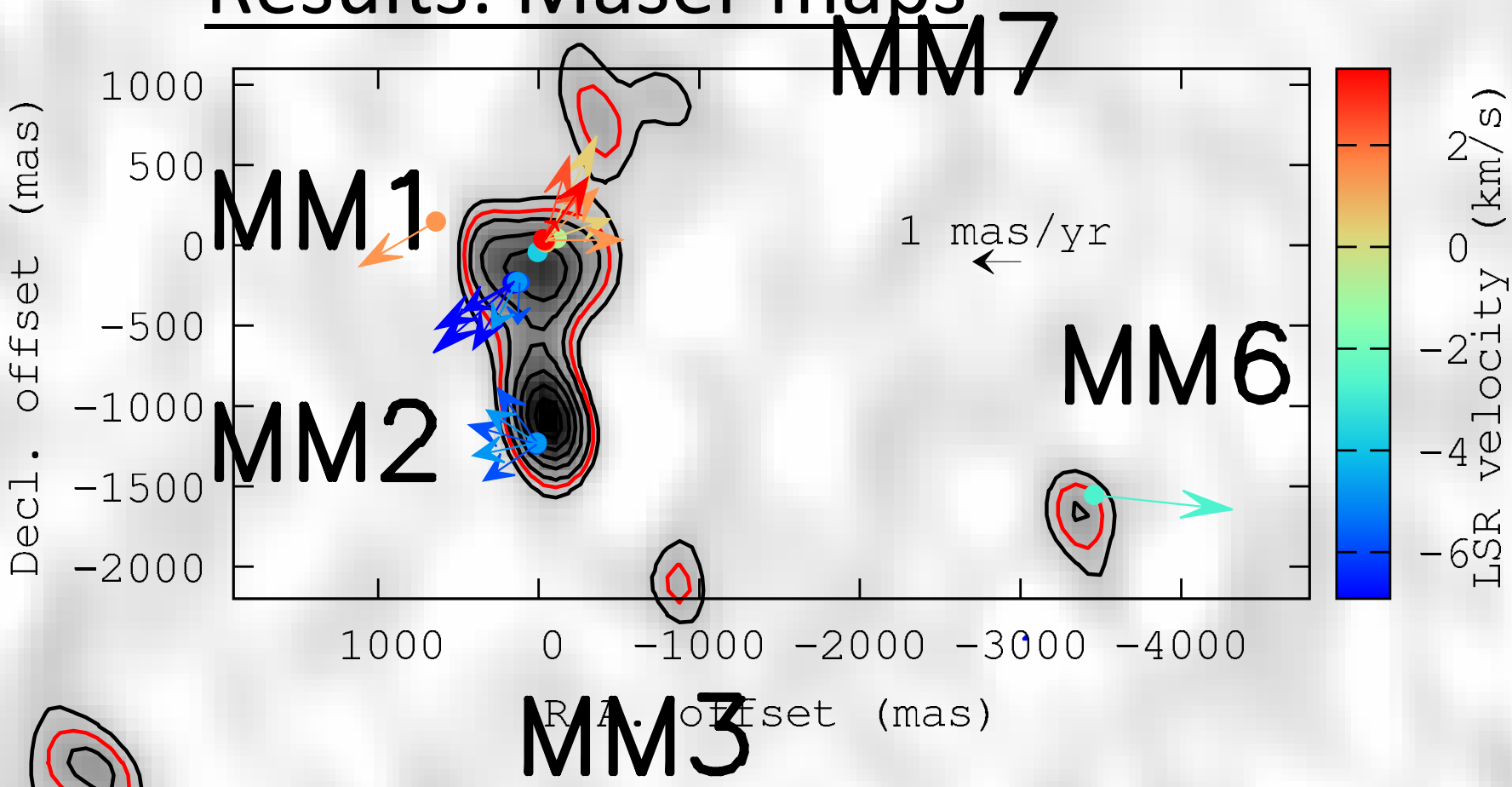
Maser maps

Proper motions



AFGL5142
1.3 mm continuum
Palau et al., 2013, ApJ, 762, 120

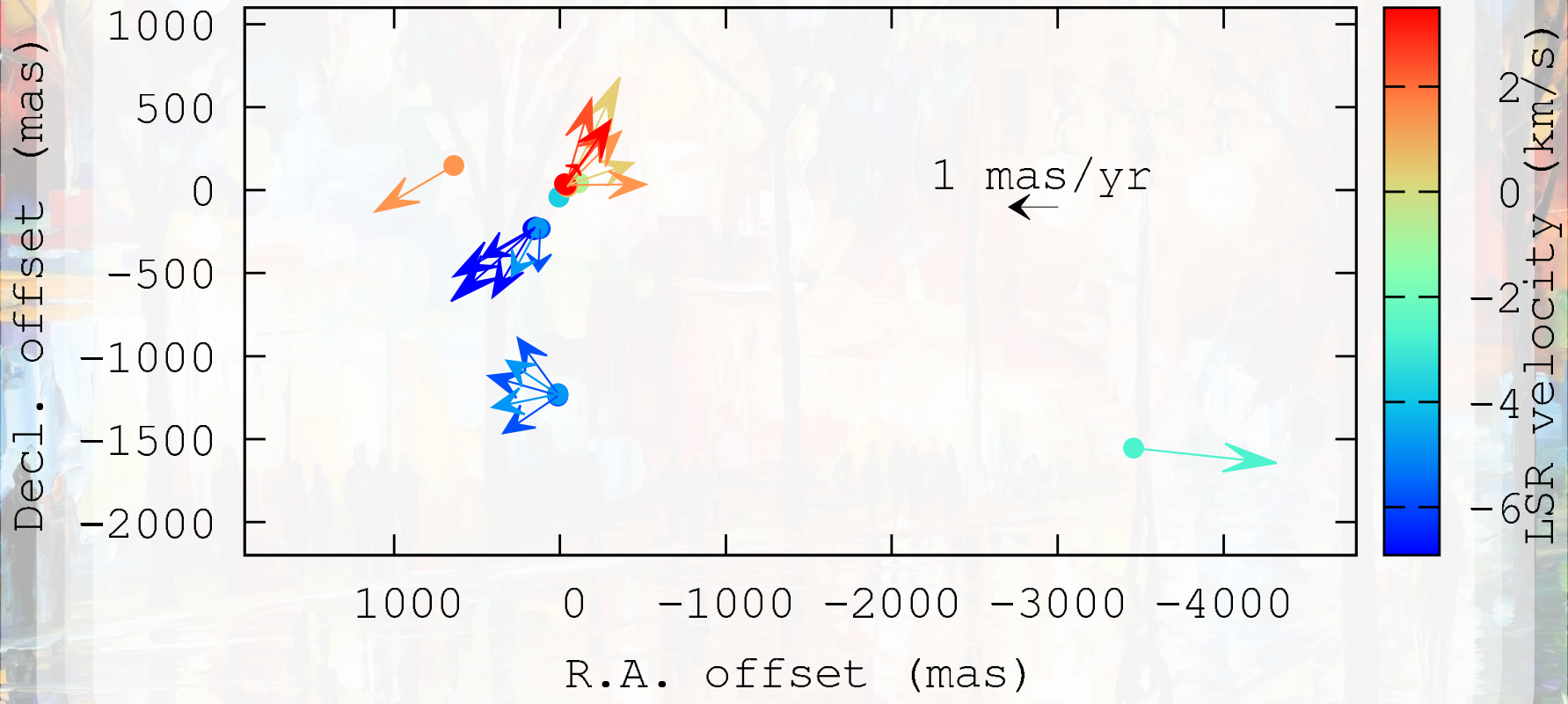
Results: Maser maps



Burns et al. 2016, in prep.

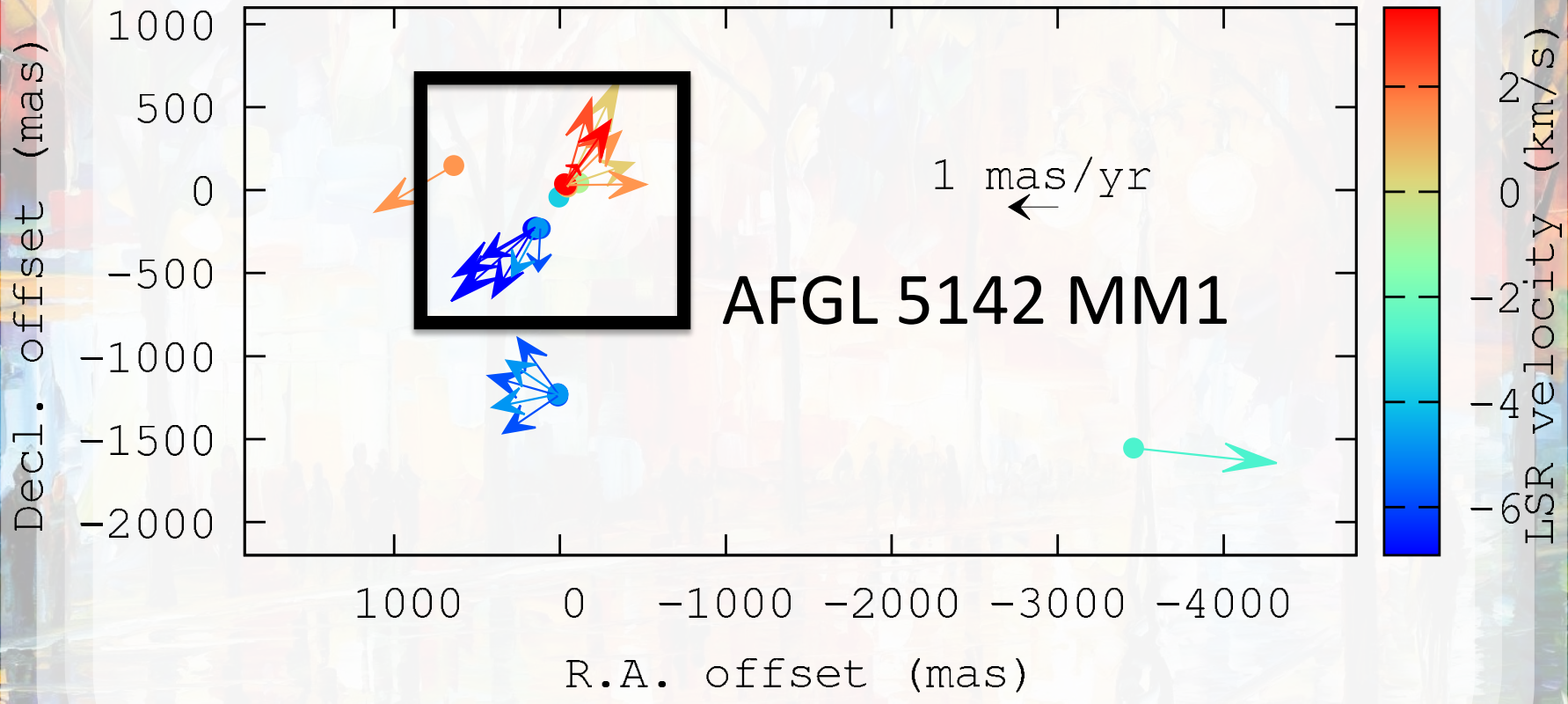
Palau et al., 2013, ApJ, 762, 120

Results: Maser maps



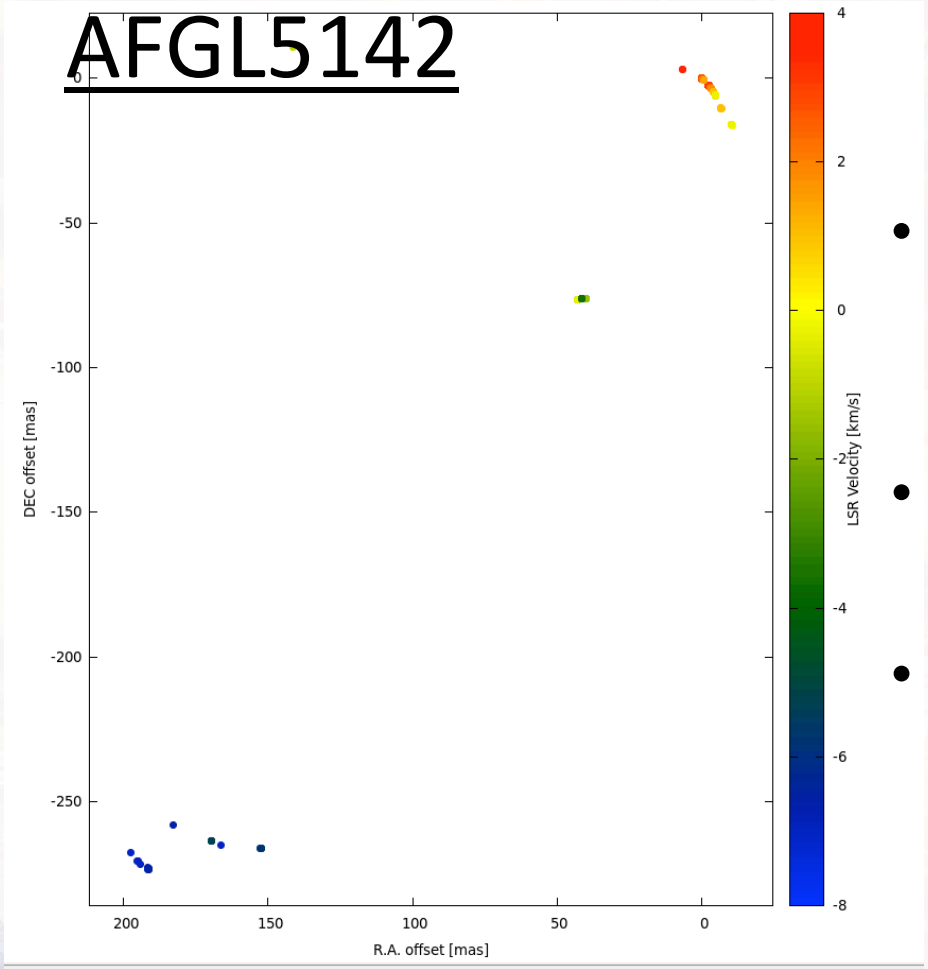
Burns et al. 2016, in prep.

Results: Maser maps



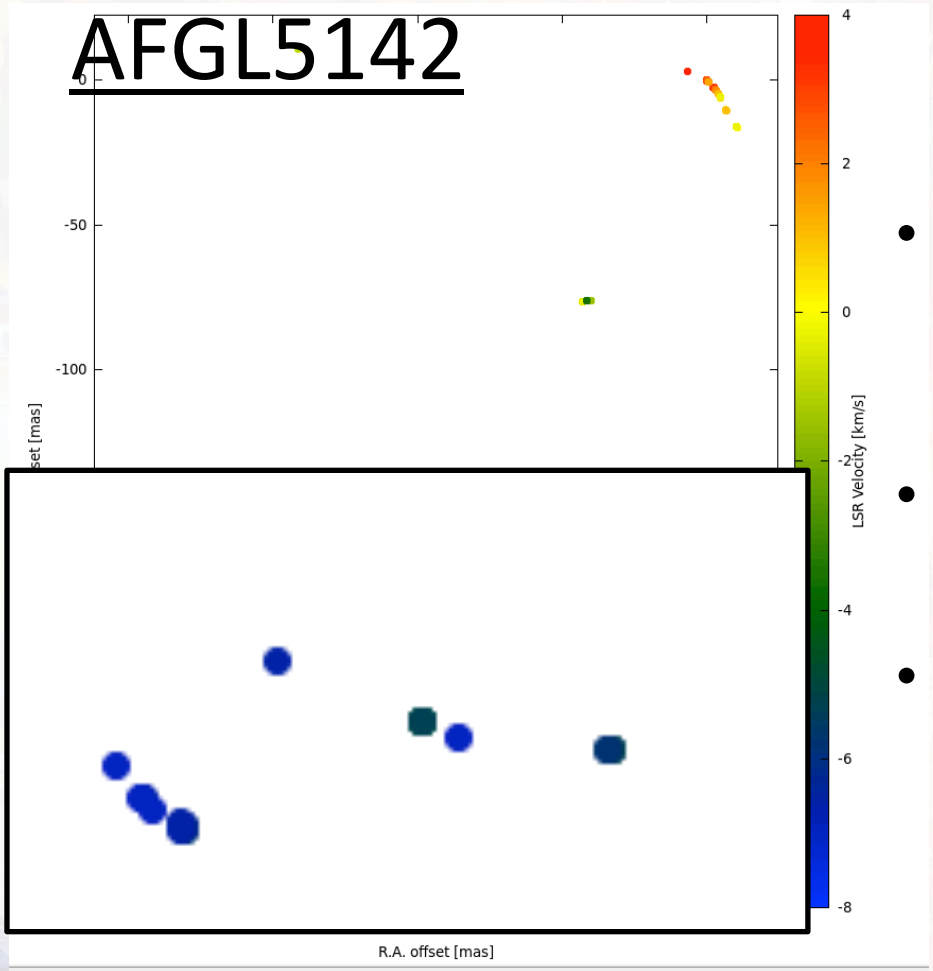
Burns et al. 2016, in prep.

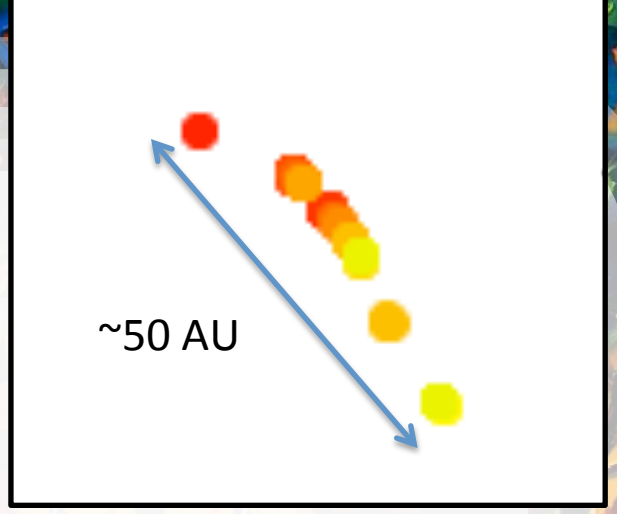
Results



- Masers symmetric around the star
- Trace the bow shock
- Double bow shock in the SE direction

Results

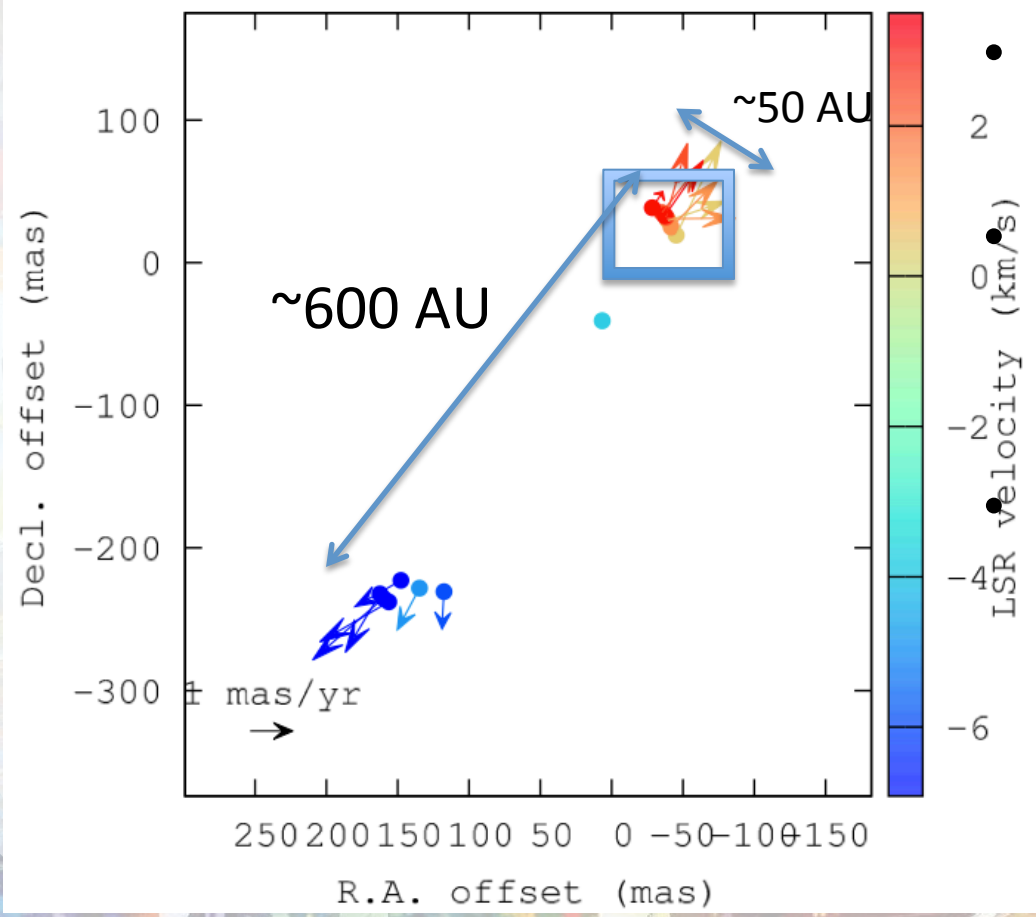




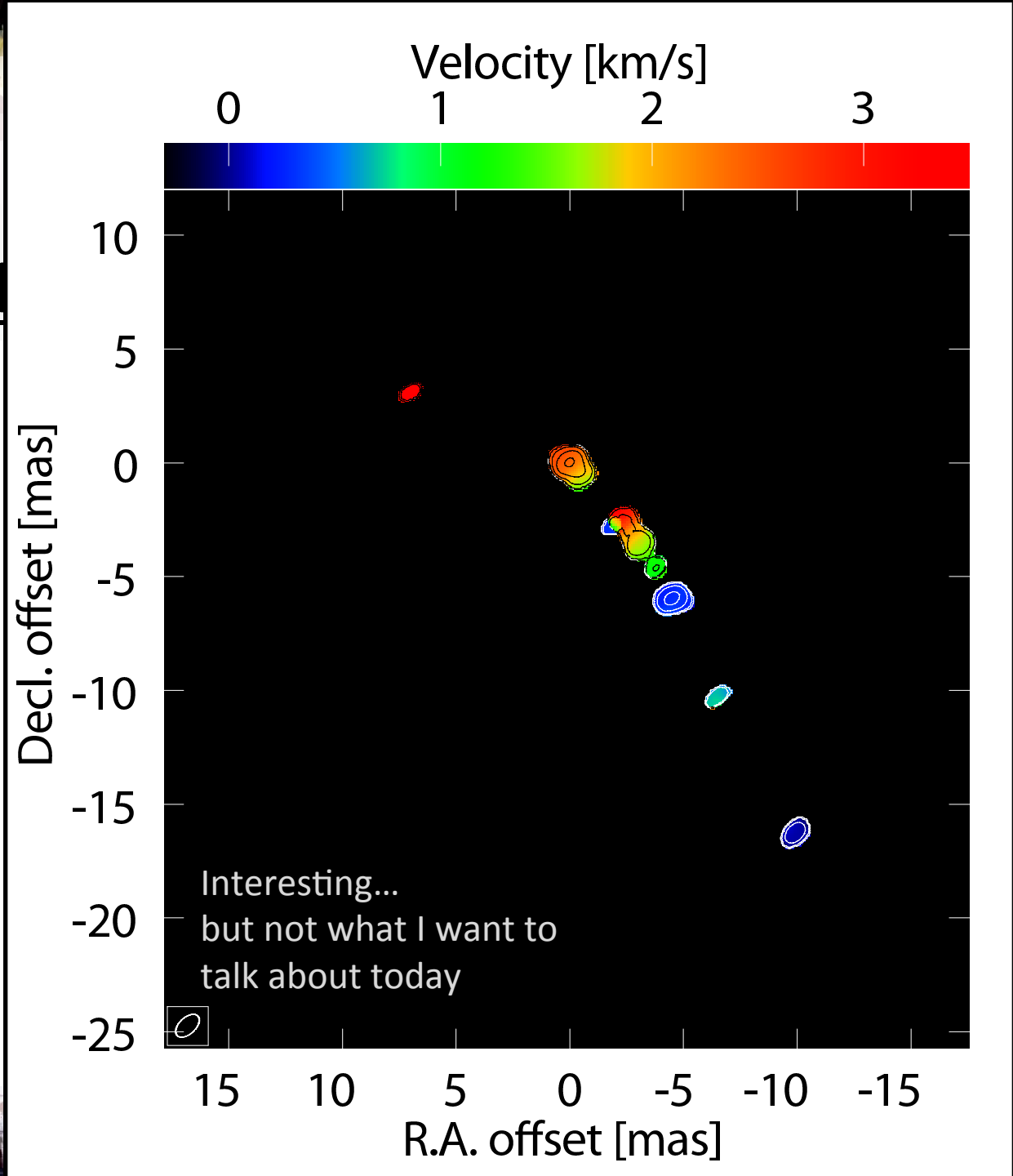
- Masers symmetric around the star
- Trace the bow shock
- Double bow shock in the SE direction

Results

AFGL5142



- Bow shocks ejected from the MYSO
- Proper motions of 1-2 mas/yr 10-20 km/s
- Some velocity dispersion at the tip

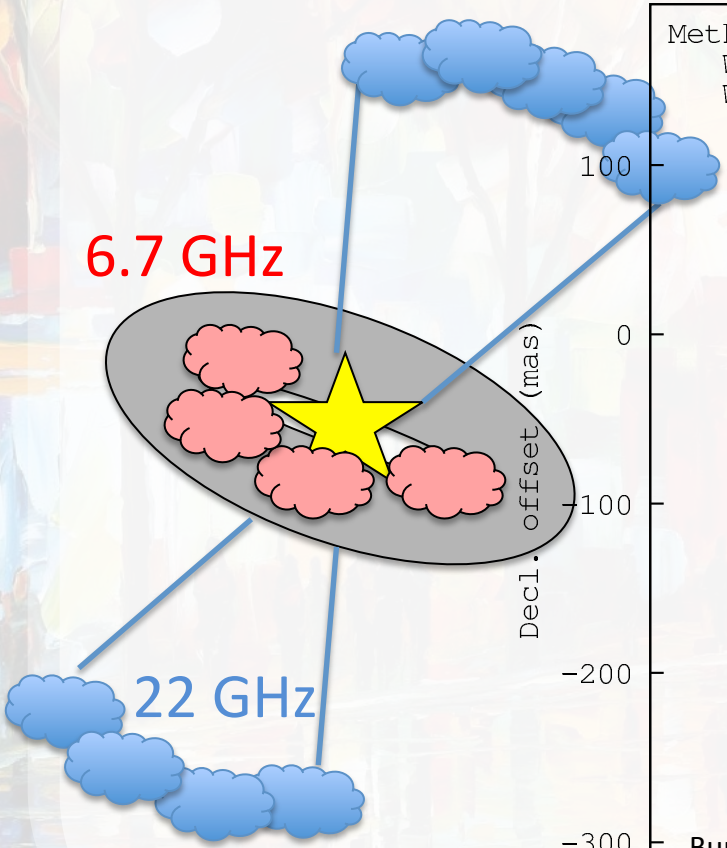

Velocity [km/s]
0
1
2
3
10
5
0
-5
-10
-15
-20
-25
Decl. offset [mas]
15
10
5
0
-5
-10
-15
R.A. offset [mas]
Interesting...
but not what I want to
talk about today

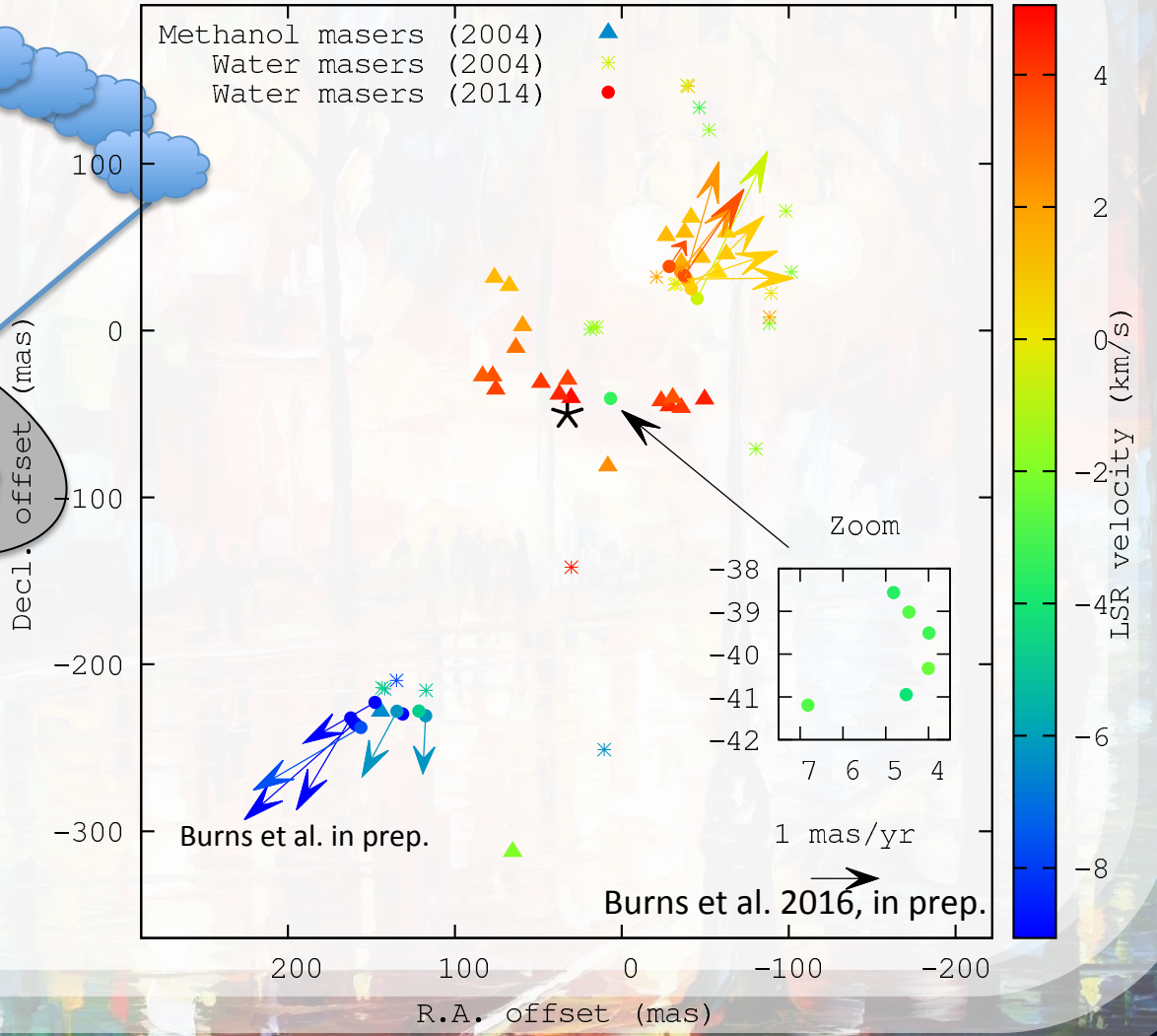
Results: Maser maps

Combine with previous VLBI data

- EVN – 6.7 GHz CH_3OH 2004
  Goddi C., Moscadelli L., 2006, A&A, 447, 577
- VLBA – 22 GHz H_2O 2004
  Goddi C. et al., 2007, A&A, 461, 1027
- VERA – 22 GHz H_2O 2014
  Burns et al. 2016, in prep.

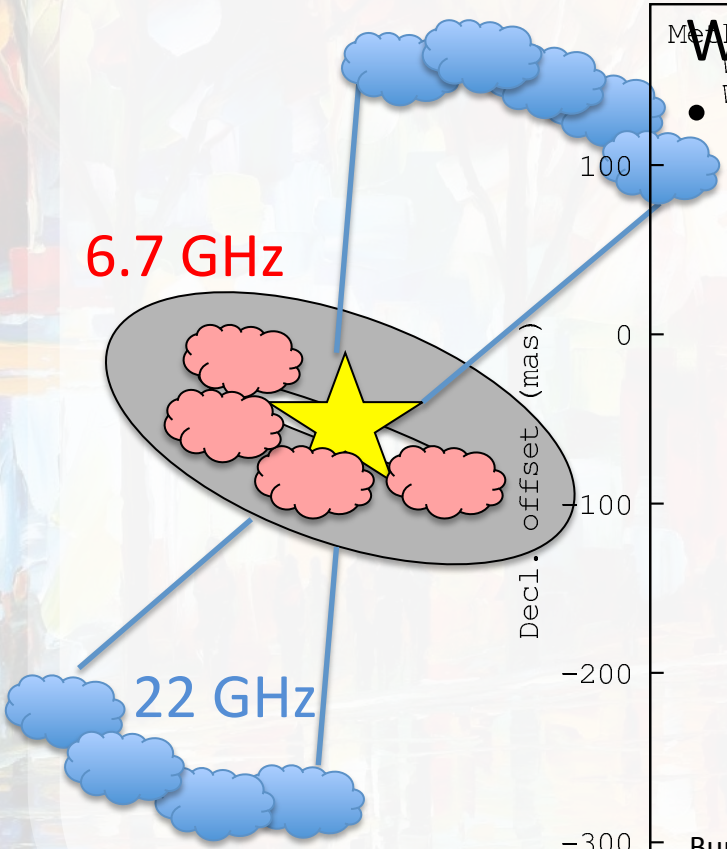
Results: Maser maps

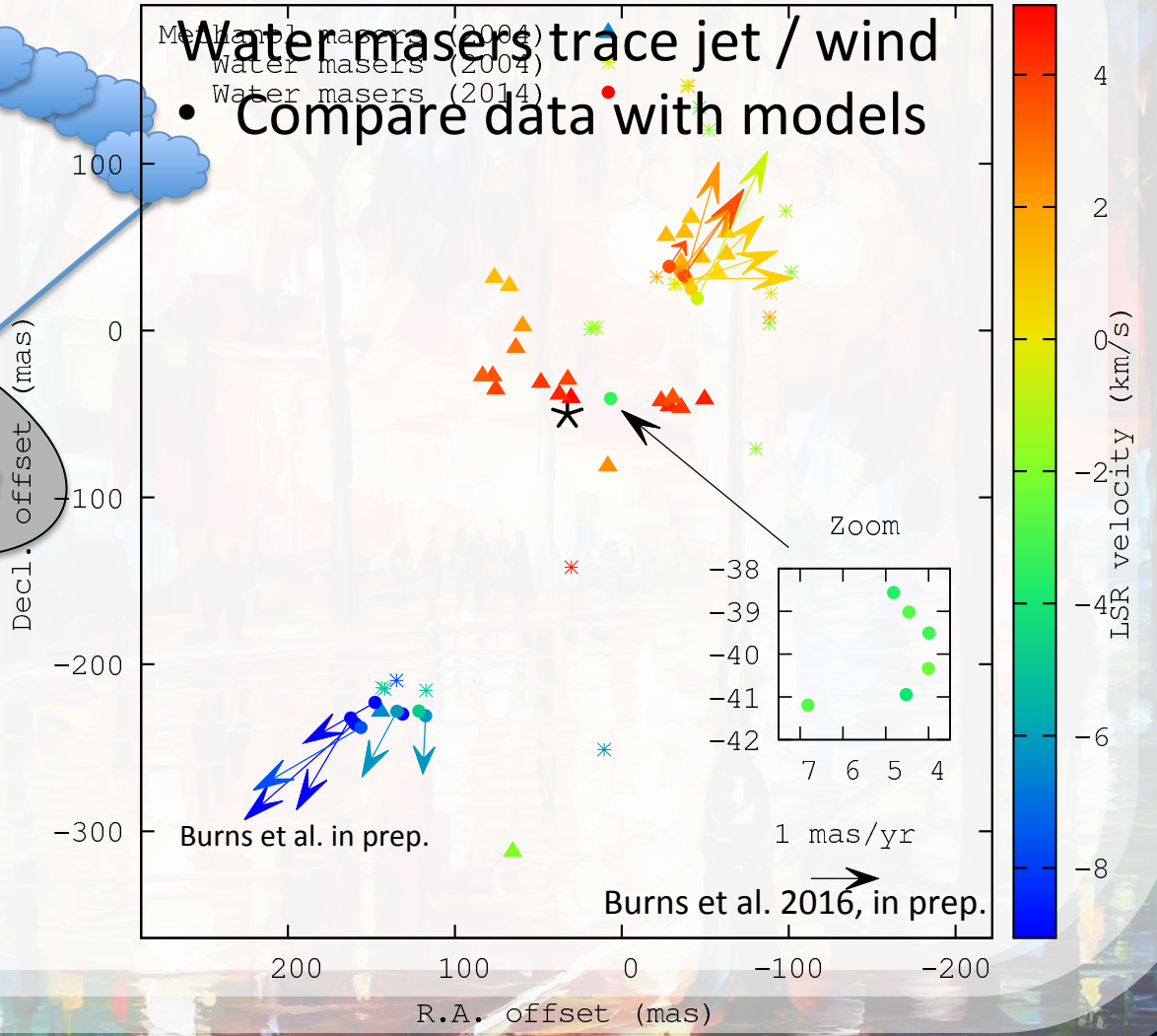




Results: Maser maps

- Water masers trace jet / wind
- Compare data with models

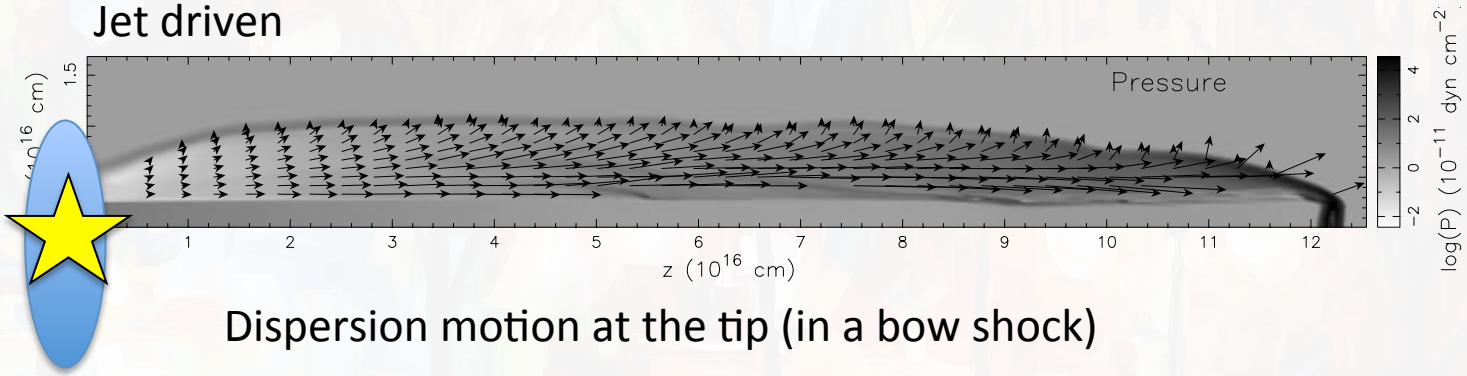




VLBI Proper motions
vs
Outflow models

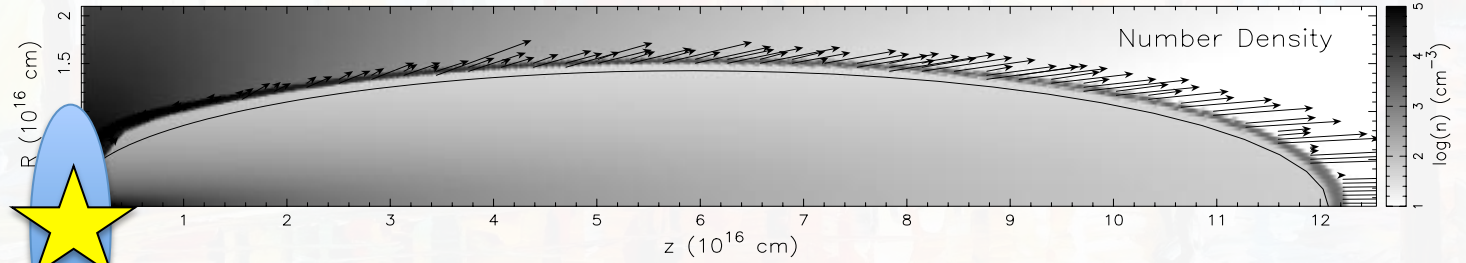
Model: Lee & Ostriker

Jet driven



Dispersion motion at the tip (in a bow shock)

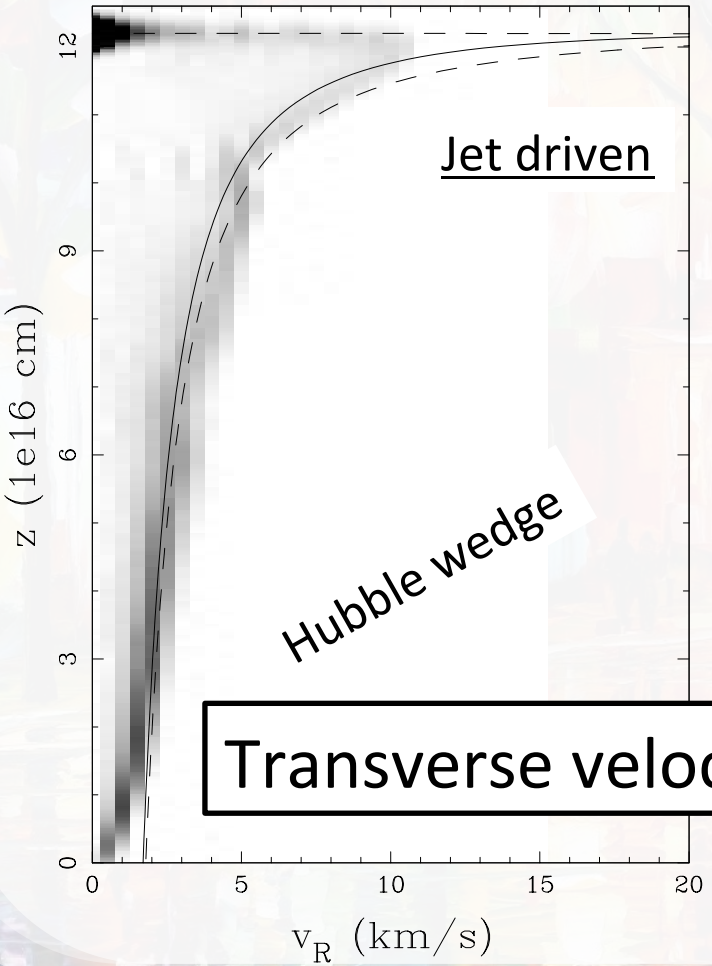
Wind driven



Motions all interpolate back to source (momentum driven)

Lee et al., 2001, ApJ, 557, 429

Model: Lee & Ostriker



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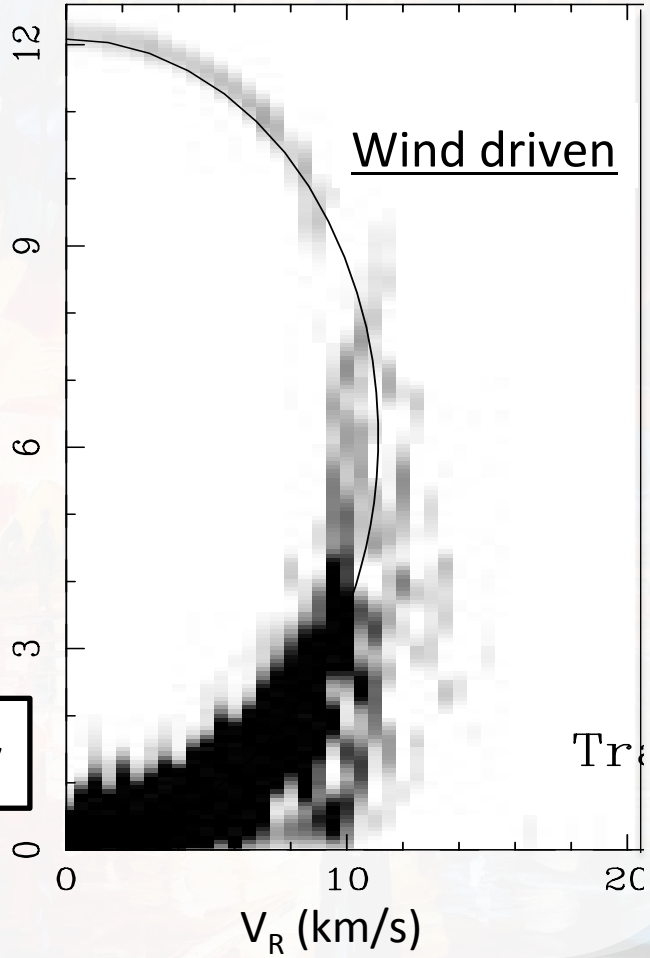
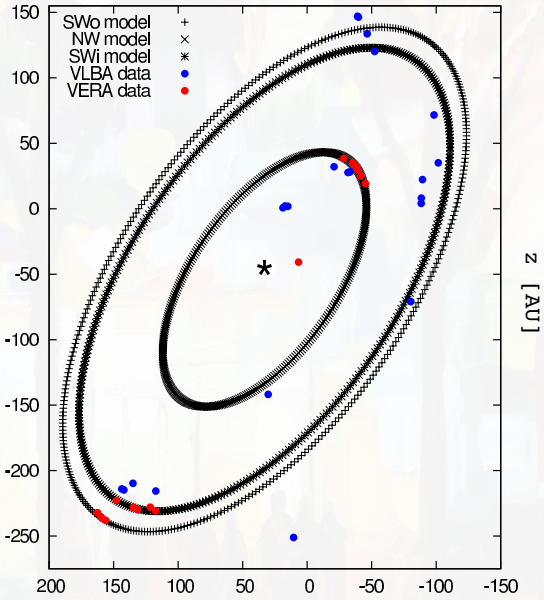
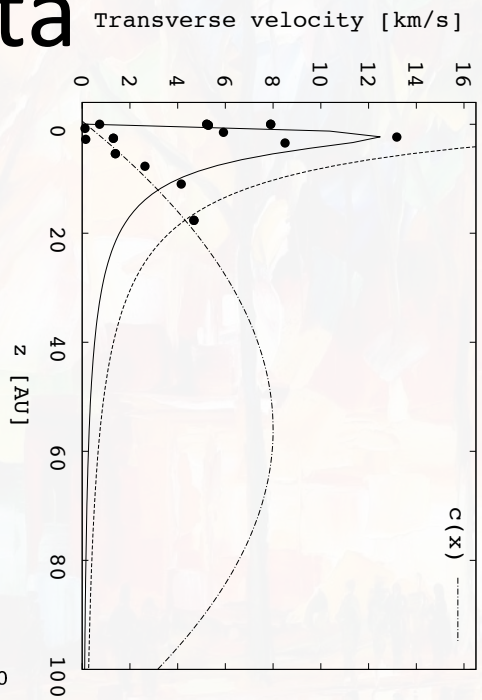
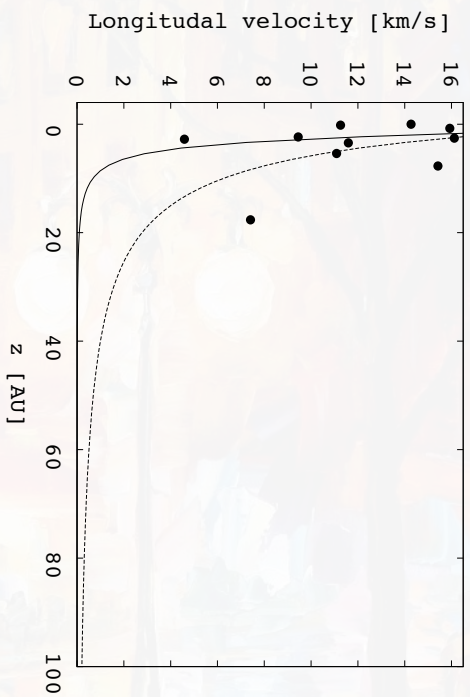


Model vs Data





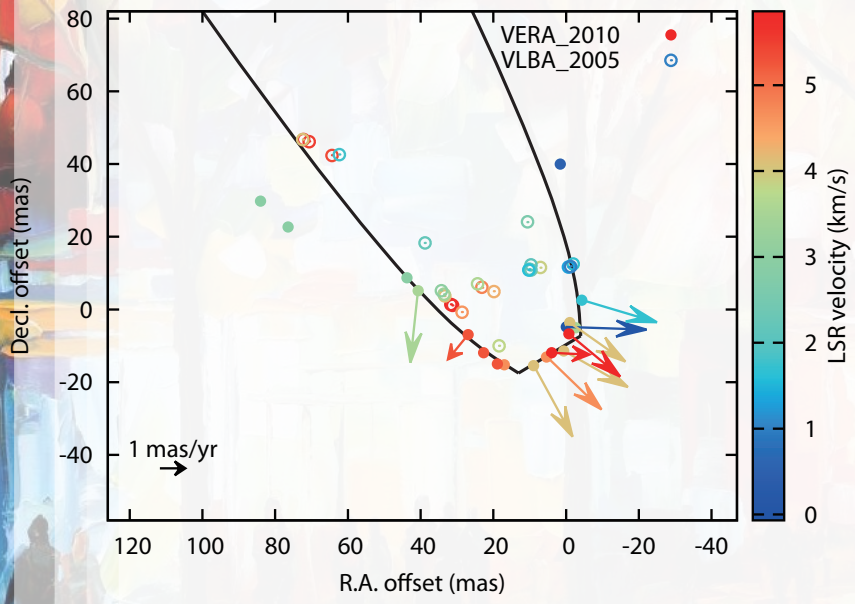


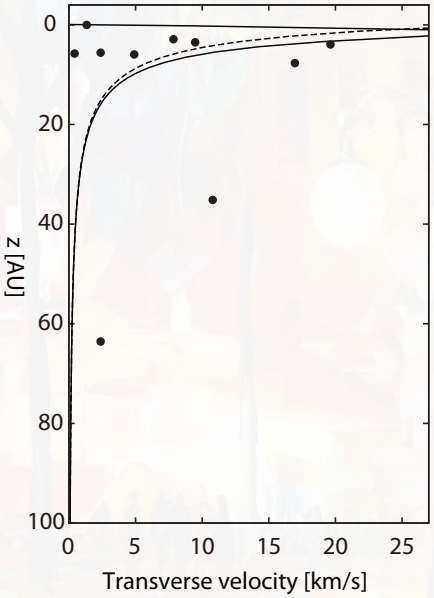
Transverse velocity profile

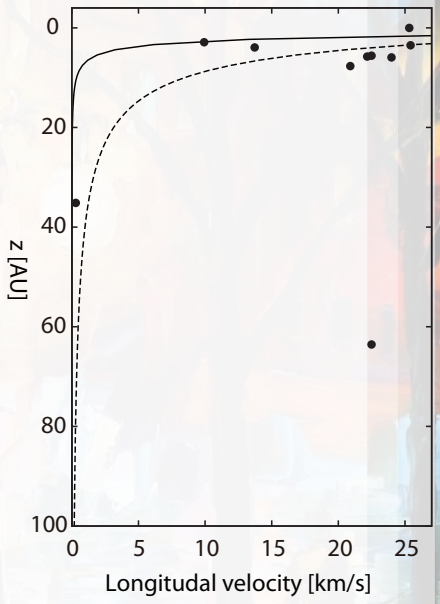
$$u_R = \frac{\beta c_s v_s R_j^2 (R^2 - R_j^2)}{(\beta c_s R_j^2)^2 + v_s^2 (R^2 - R_j^2)^2}\, v_s \,.$$

Lee et al., 2001, ApJ, 557, 429

Model vs Data







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Lee et al., 2001, ApJ, 557, 429

Conclusions #1

MYSO outflows driven by collimated jets w/ bowshock (Similar to low mass YSOs)

Small contribution from disk wind?

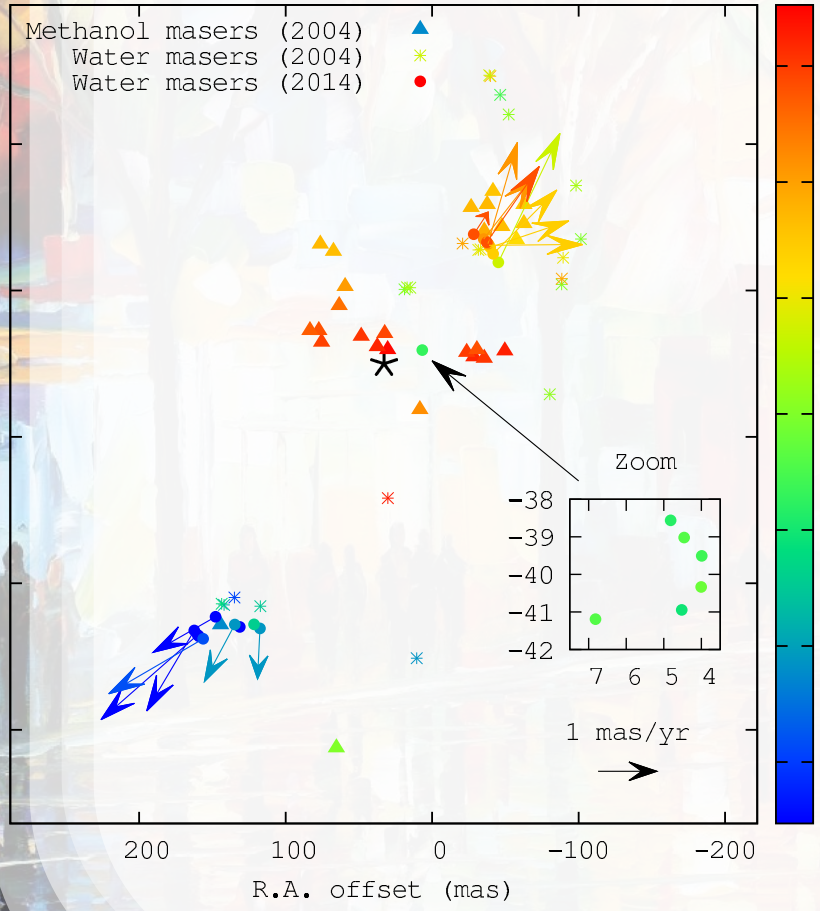
Bowshock physical parameters:

Jet width: 5-10 AU

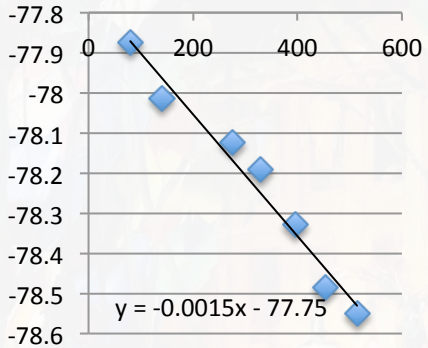
Jet velocity ≈ 50 km/s

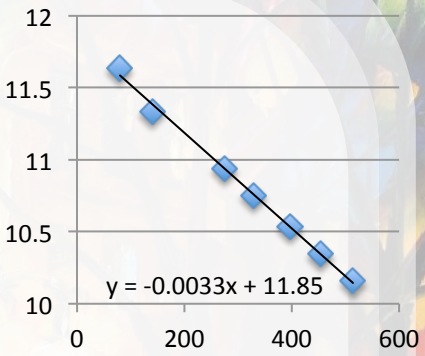
Momentum rate ≈

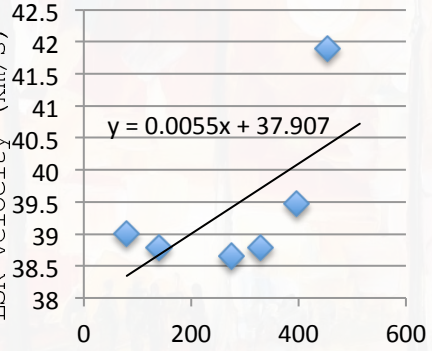
Non-linear proper motion
H_2O maser

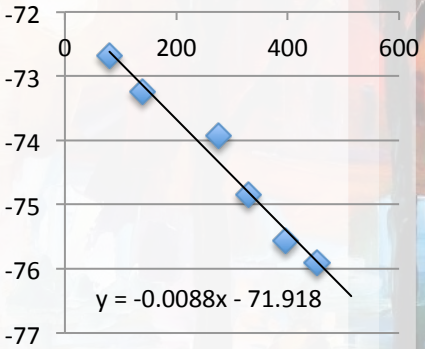


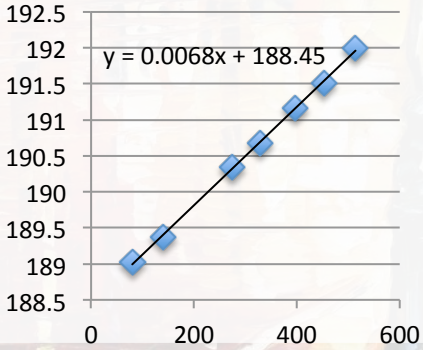
Burns et al. 2016, in prep.

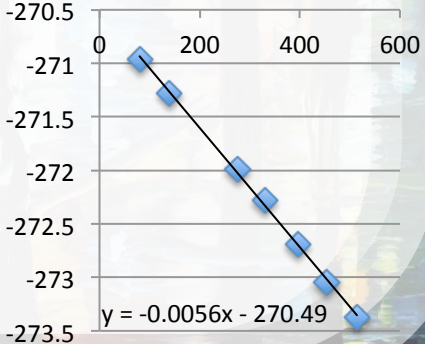


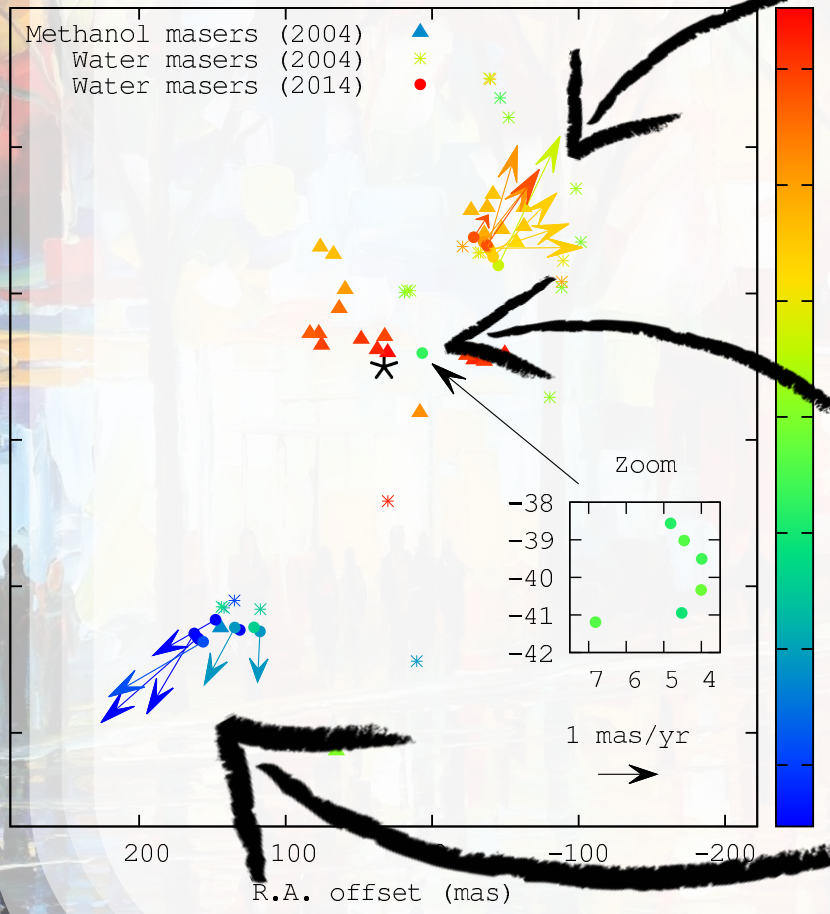


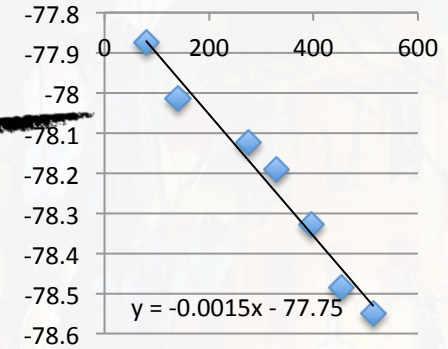


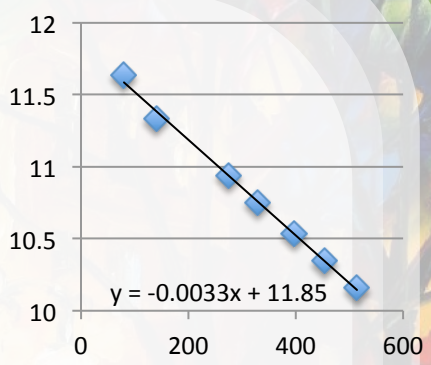


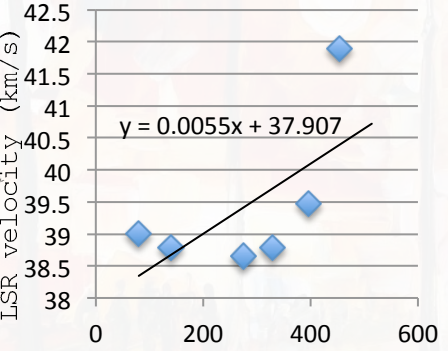


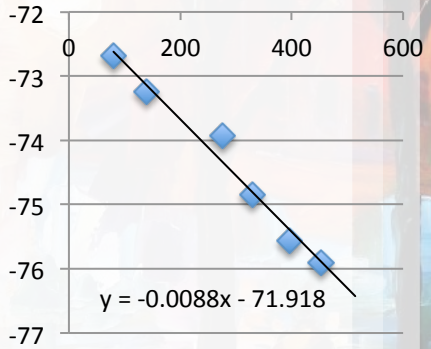


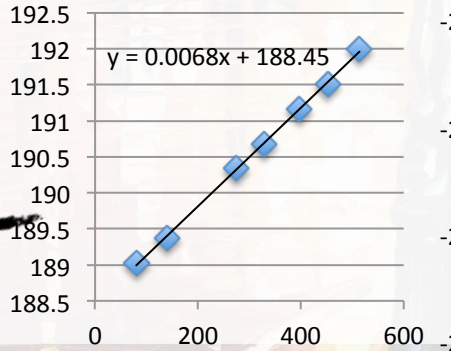


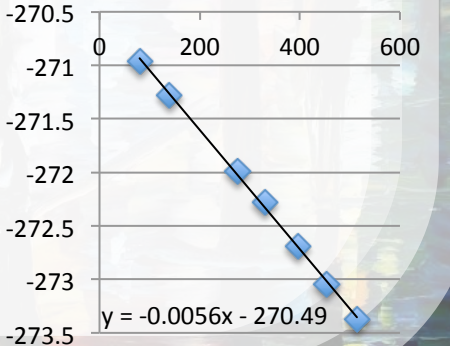




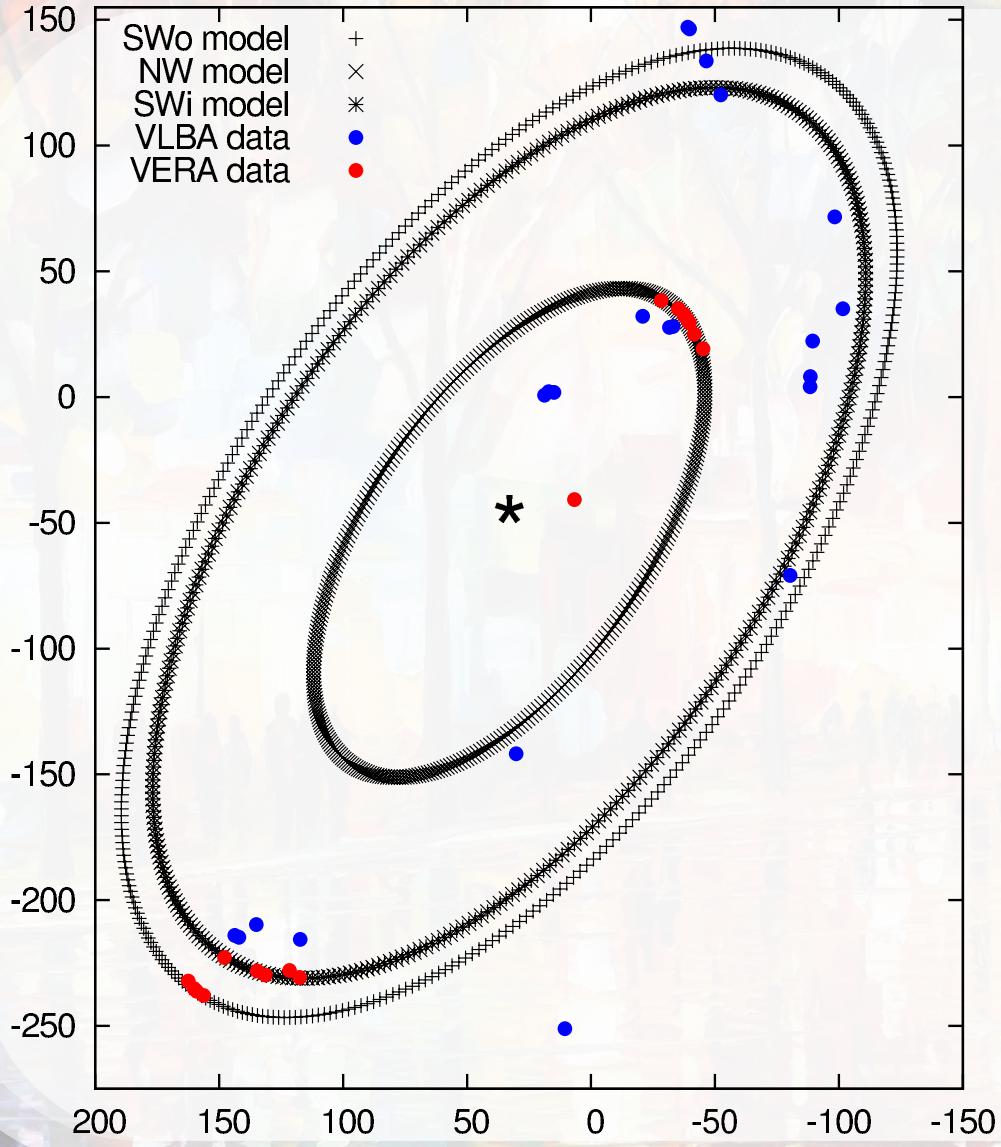




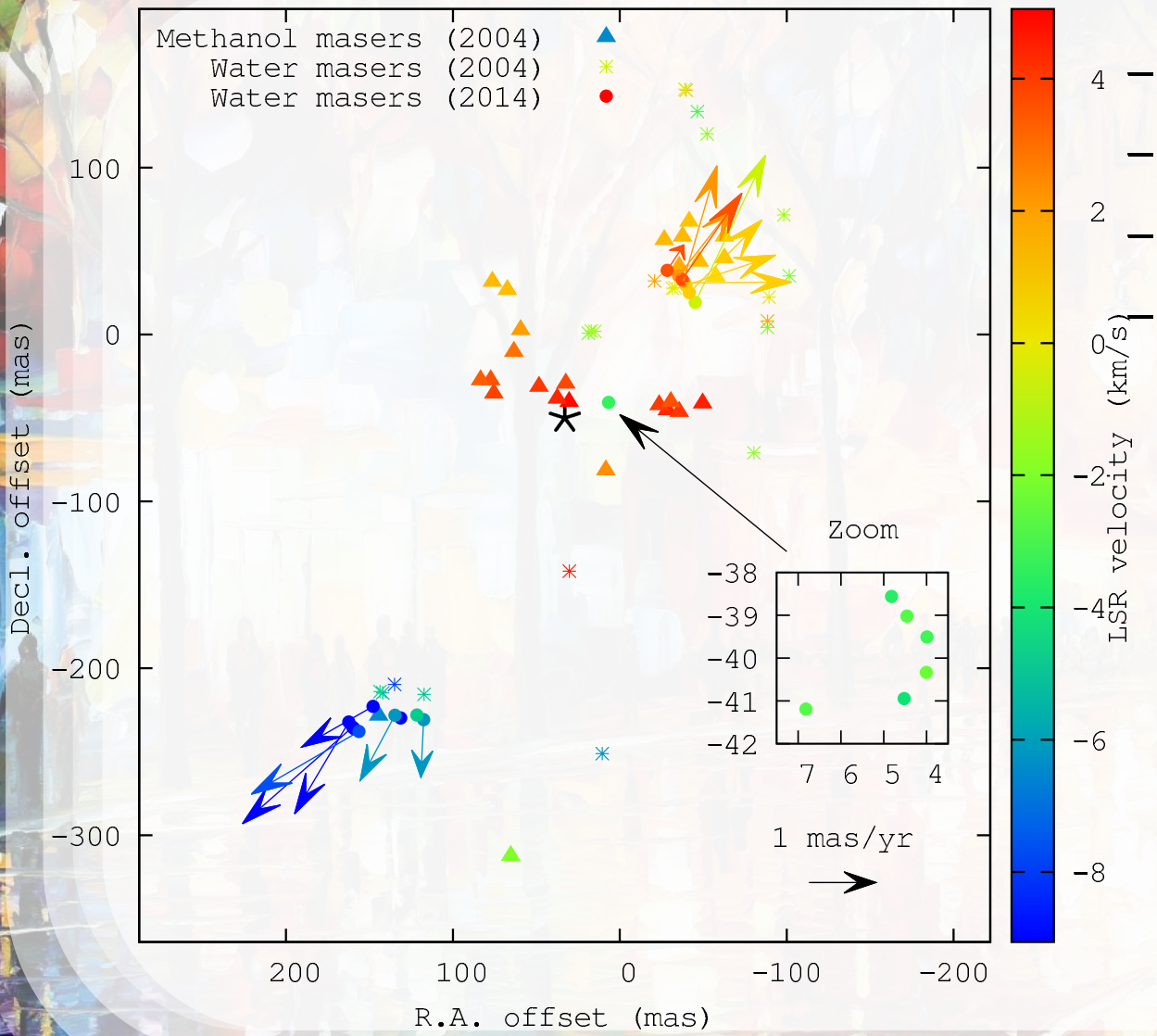


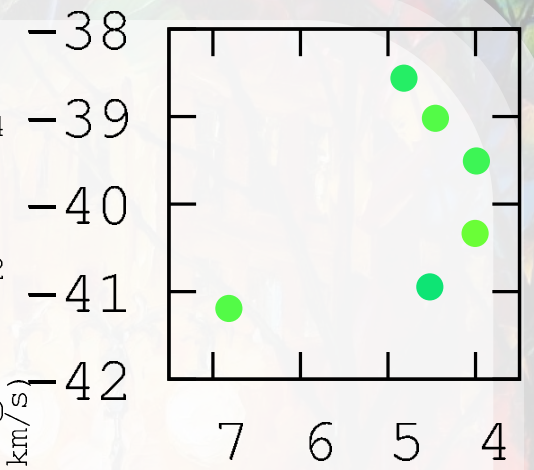


Burns et al. 2016, in prep.



Fit ellipses to find kinematic center

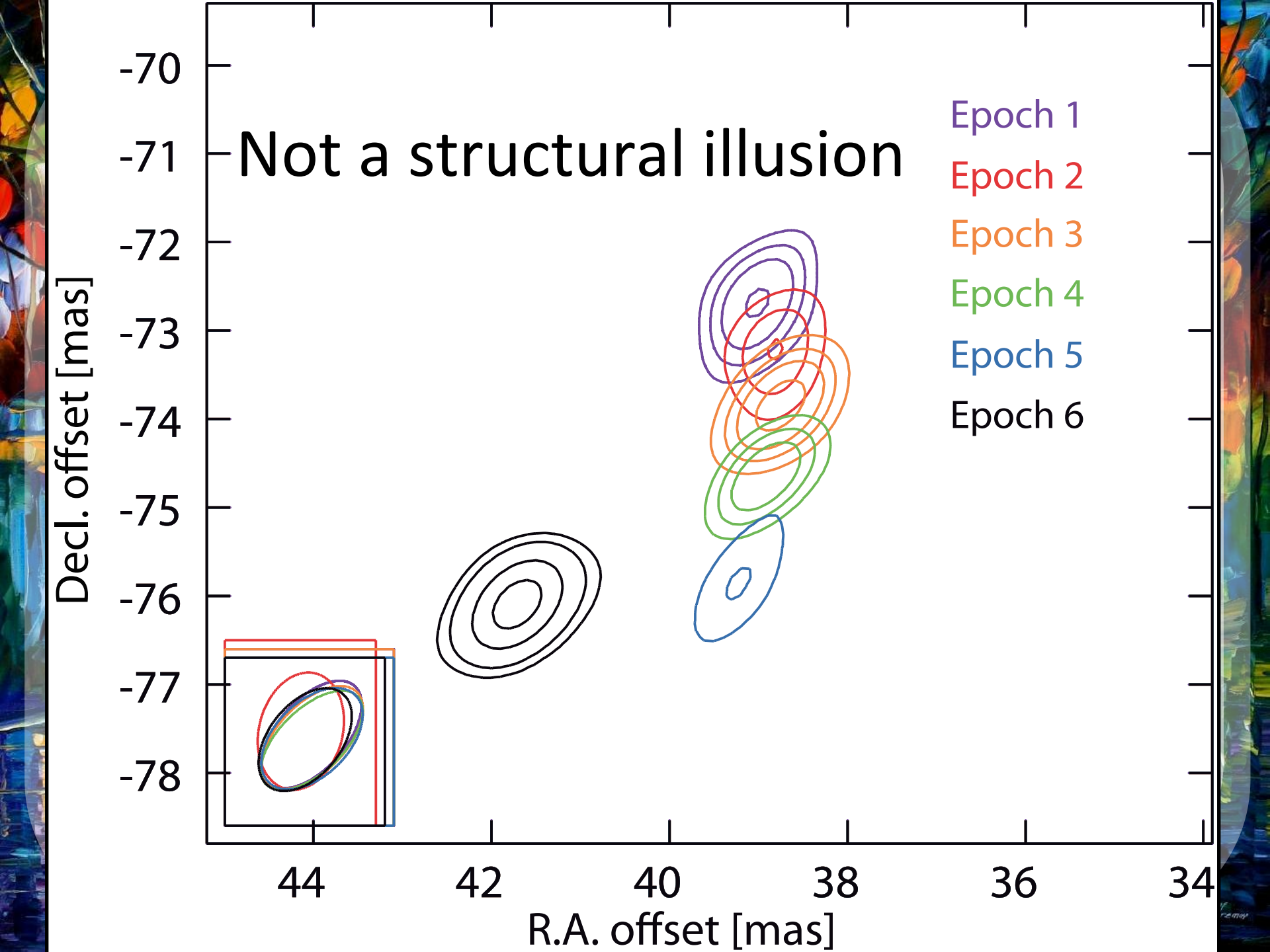




Near:
Kinematic center
6.7 GHz maser disk

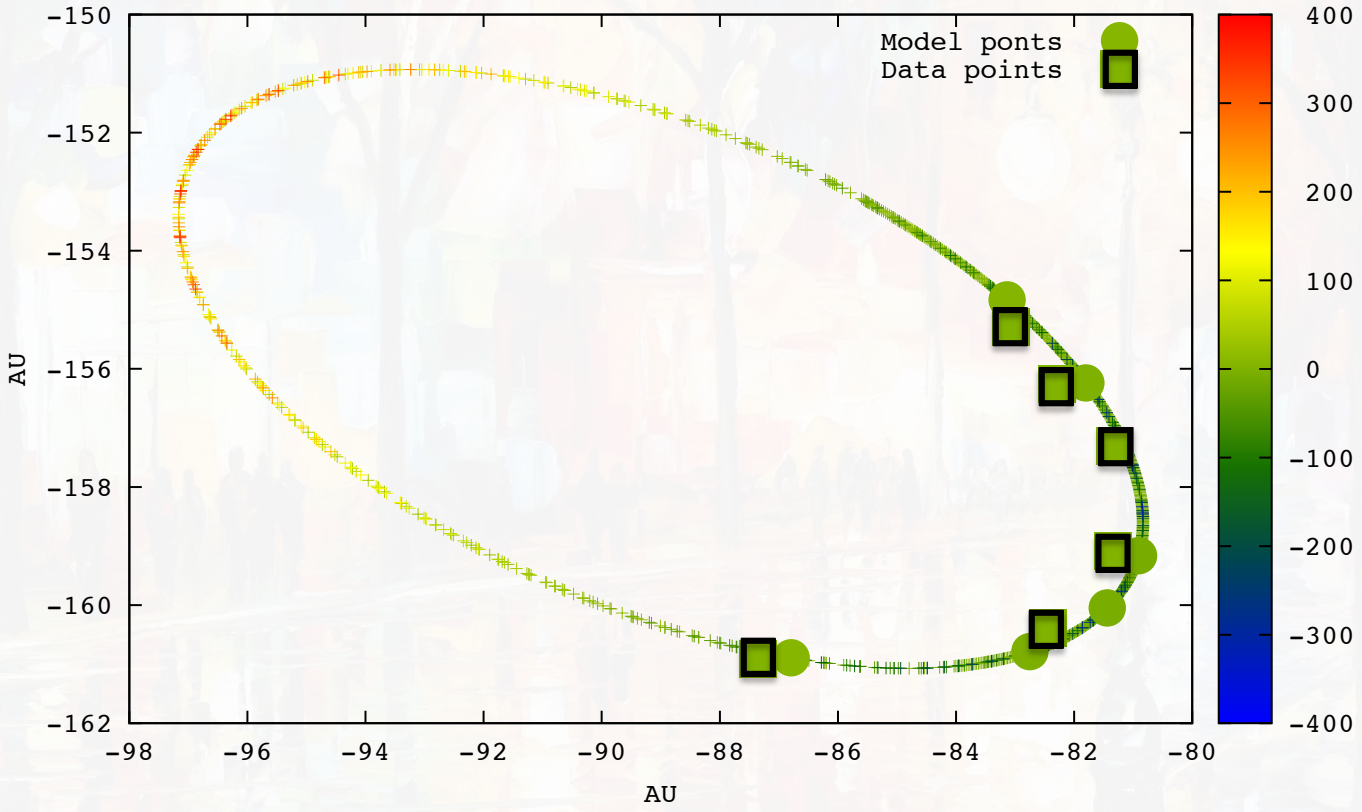
Non-linear motions

Related to
accretion disk???


Not a structural illusion
Epoch 1
Epoch 2
Epoch 3
Epoch 4
Epoch 5
Epoch 6
Decl. offset [mas]
-70
-71
-72
-73
-74
-75
-76
-77
-78
R.A. offset [mas]
44
42
40
38
36
34

Best fit: accelerating orbit

I’m not sure how to interpret this, physically



Conclusions #2

AFGL 5142-MM1:

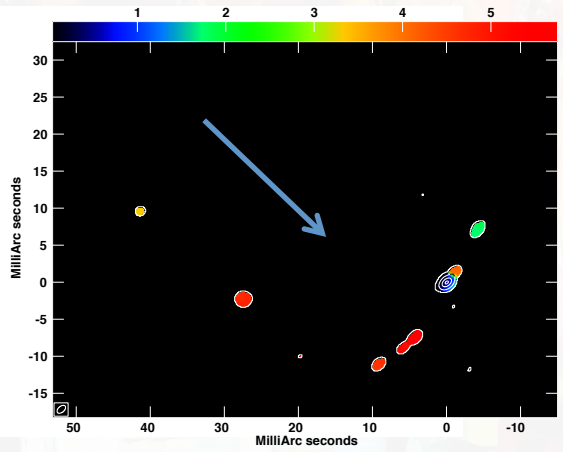
Unusual (non-linear) proper motion in one water maser feature near the MYSO.

Interpretation not yet conclusive.
Further observations needed to explain it.

JIVE

Joint Institute for VLBI ERIC

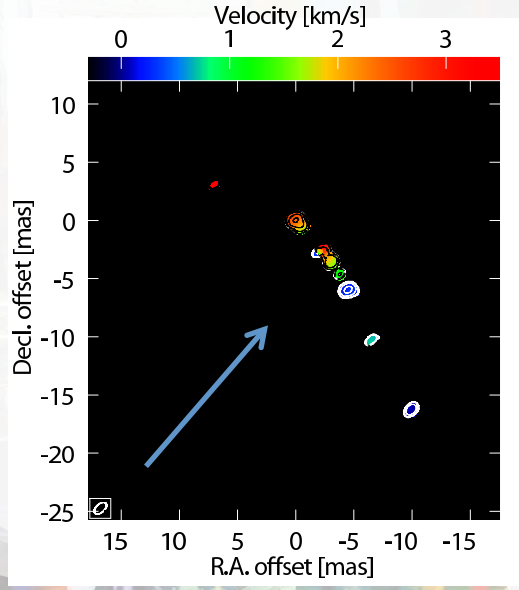
Bonus slide (woooh!)



Burns et al., 2016, MNRAS, 460, 283

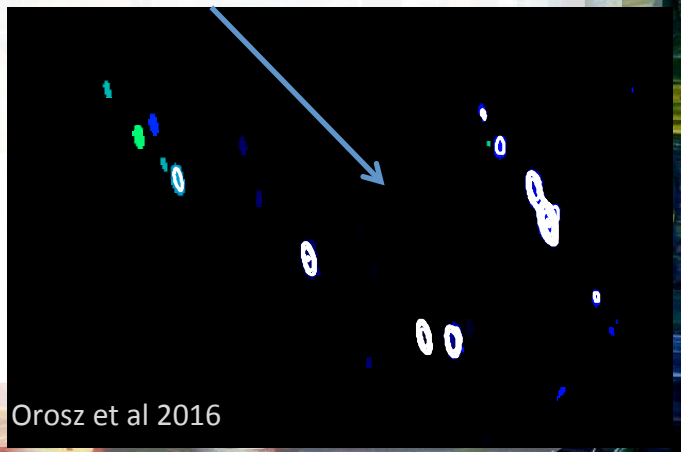
U-shaped
(cubic)

- Density of jet-ambient gas
- Source/launching energetics
- Obs. test of models/theory

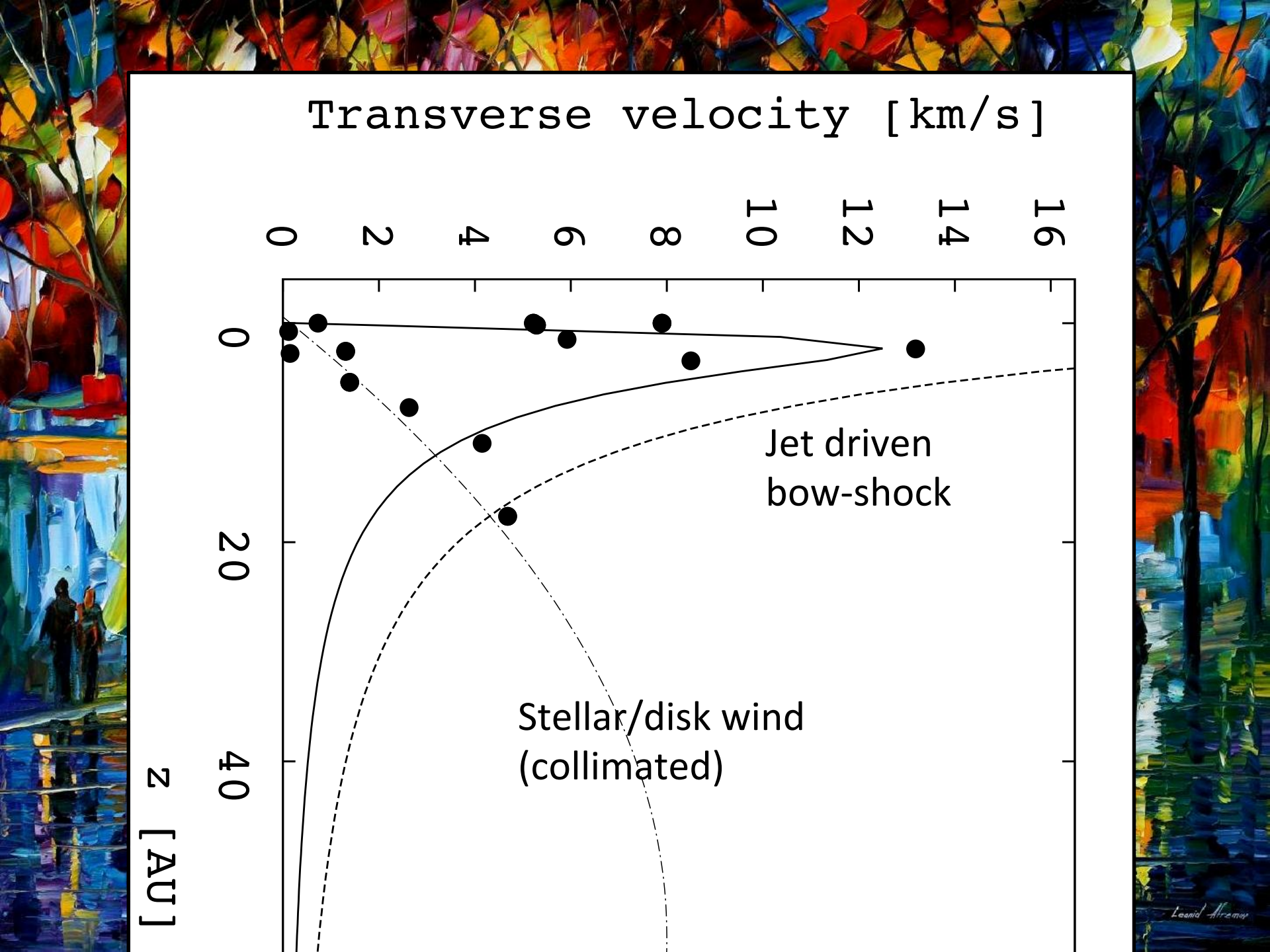


Burns et al. 2016, in prep.

Arc-shaped
parabolid



Orosz et al 2016


Transverse velocity [km/s]
0
2
4
6
8
10
12
14
16
0
20
40
z [AU]
Jet driven
bow-shock
Stellar/disk wind
(collimated)