Evolutional phases of three Class 0 protostars in Serpens Main

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Aso+’17b, ApJL, 850, L2; Aso+’18 in prep.

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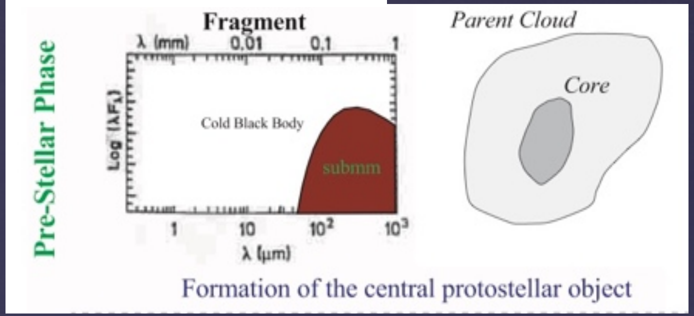
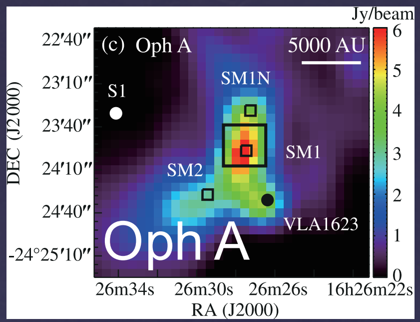
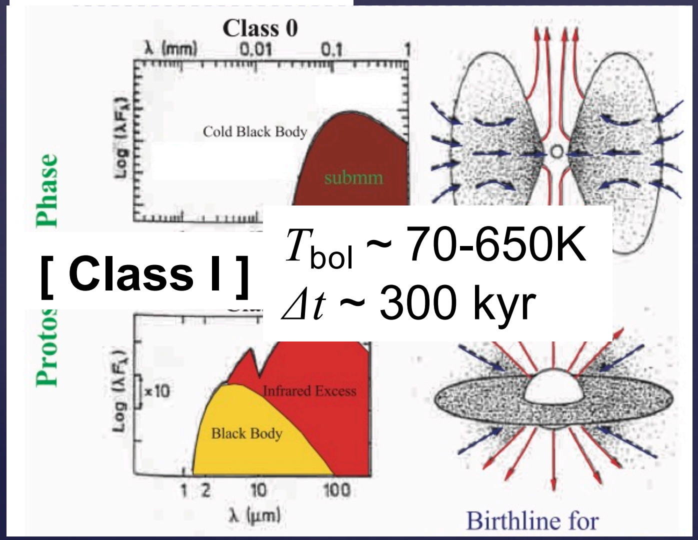
1. Introduction — evolution in star formation

[Starless core] $T_{\rm bol}$ ~ 10-20 K Δt ~ 300 kyr

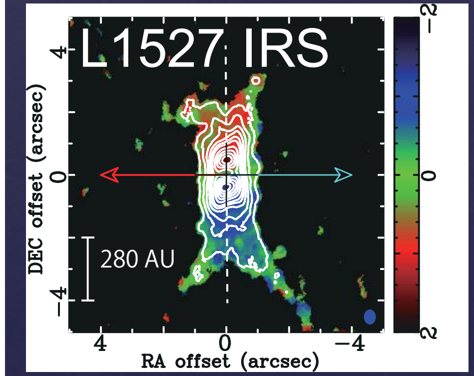




[Class 0] $T_{\rm bol}$ < 70 K Δt ~ 30 kyr



[Class I] $T_{\rm bol}$ ~ 70-650K
Δt ~ 300 kyr



➢ Early phases (starless→Class 0) cannot be observed in optical/NIR/MIR.

⬇

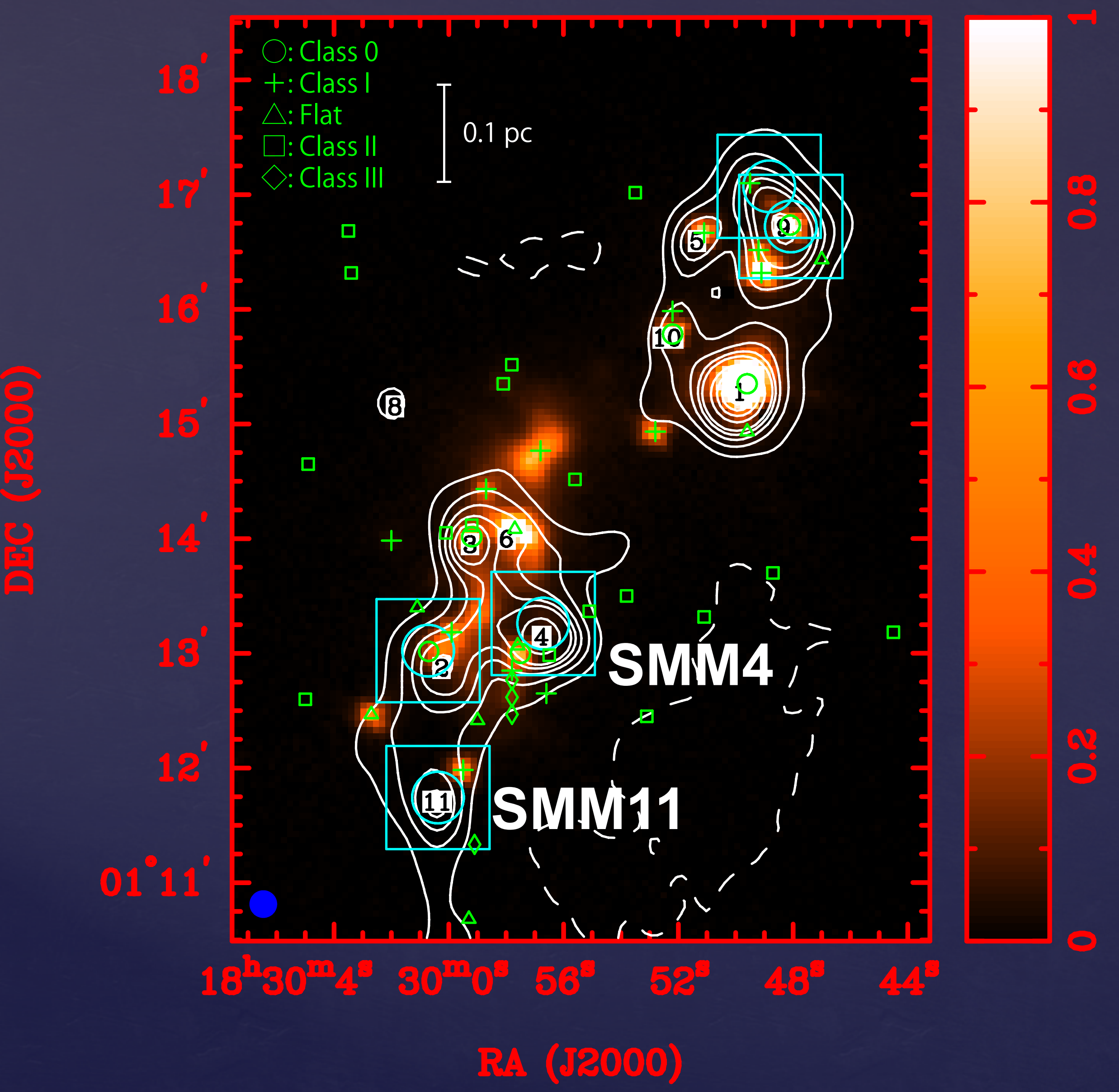
Millimeter observations:
Continuum ——Column density. Structure e.g., spherical or disk-like.

Outflows ——Evidence of mass accretion. Gravitational potential.

Chemistry ——Abundance reflecting thermal history.

Andre’02, Nakamura+’12, Aso+’17a

1. Introduction — Serpens Main



Serpens Main:

- Cluster forming region.
- Two episodes of star formation, 2 Myr and 0.5 Myr ago.

- D=429 pc, M=30 $M_\odot$ (each subcluster).
- Sub-mm sources (SMM) by JCMT.
- YSOs by Spitzer.
- 1.3 mm sources without counterparts in 70 μm (SMA archival data).
- Cyan boxes were observed this time.

Contours: JCMT 850 μm
Color: Herschel 70 μm

Dzib +'11, Duarte-Cabral +'10

2. ALMA observations

- Atacama Large Millimeter/submilleleter Array (Cycle 3, May 19, 21 2016, PI: Y. Aso)
- Calibrators:
  J1751-0939 (Bandpass), Titan (Flux),
  J1830+0619 (470 mJy; Gain),
  J1824+0119 (79 mJy; Gain)
- Data reduction : CASA, MIRIAD

	ν (GHz)	$\Delta\nu$	Beam Size	σ (mJy/beam)
Continuum	225	4 GHz	0.57"×0.46" (–85°)	~0.1
^{12}CO J=2–1	230.5380000	1.27 km s^{-1}	0.61"×0.50" (–83°)	~3.7
C^{18}O J=2–1	219.5603541	0.083 km s^{-1}	0.64"×0.52" (–83°)	~12

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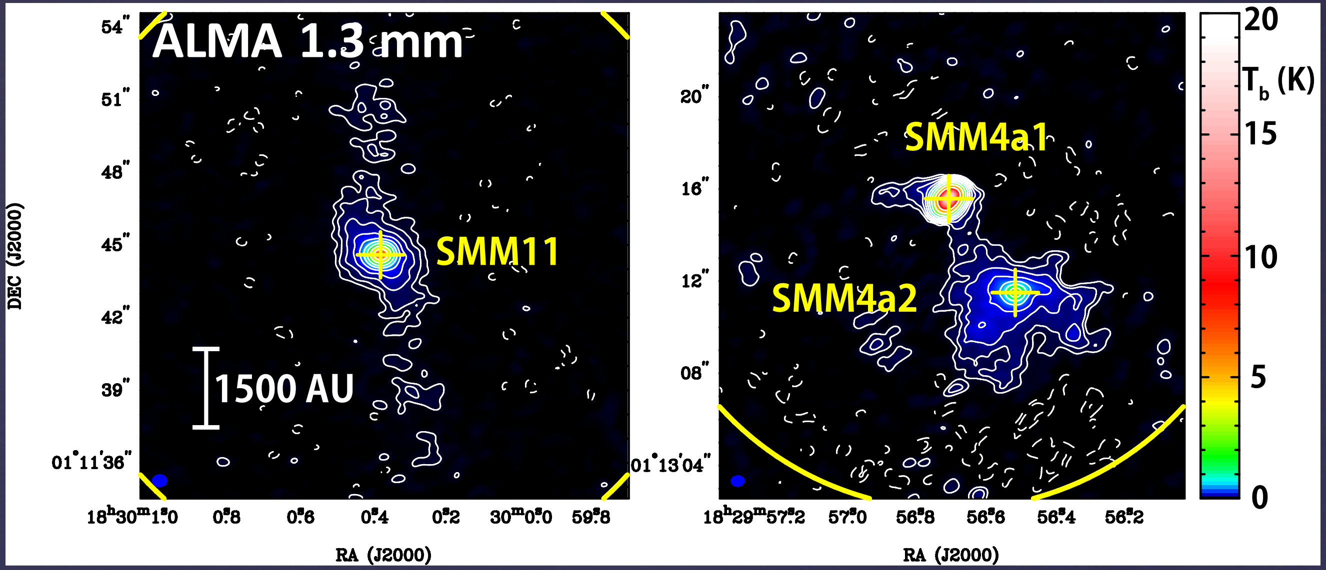
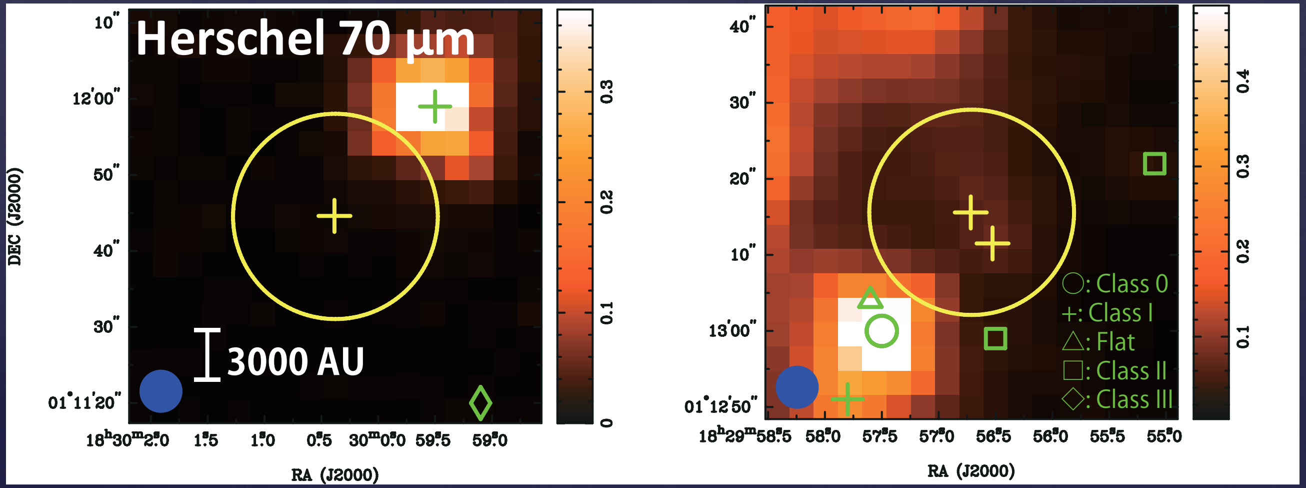
3. Results — 1.3 mm & 70 μm





Circle：ALMA Primary Beam　Contours: 3,6,12,24,…σ

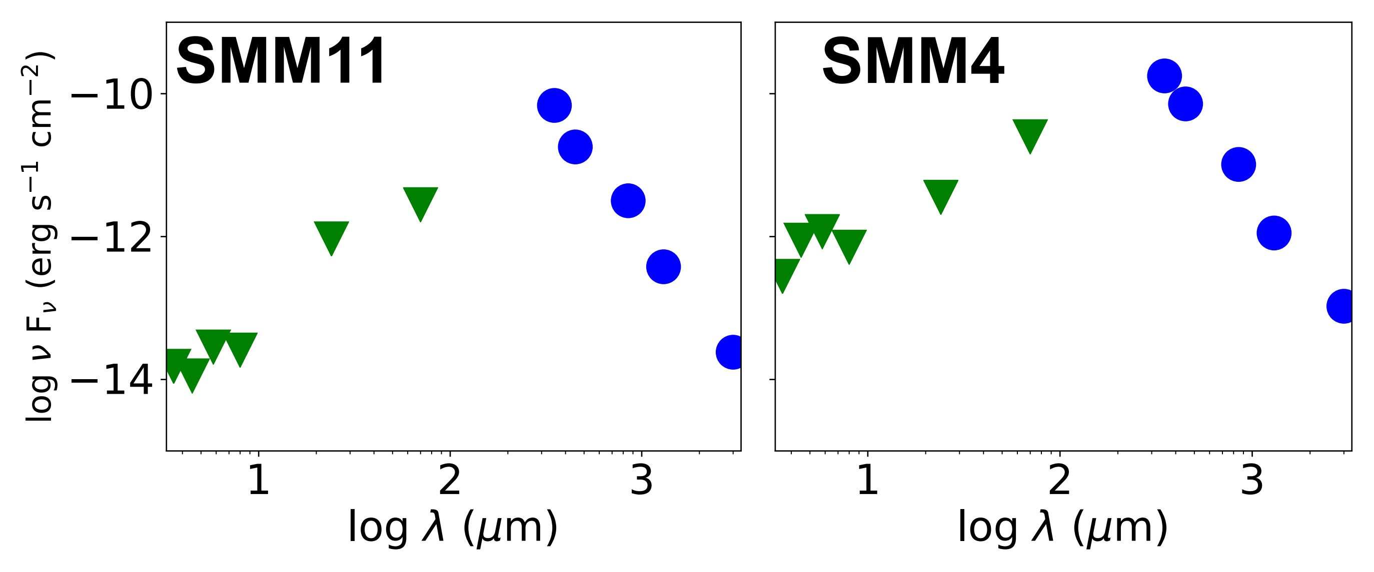
- 1.3 mm sources without 70 μm counterparts.

	SMM11	SMM4a1	SMM4a2
Deconvolved size (AU)	160x130 (80°)	320x200 (145°)	300x230 (94°)
M_{gas} ($M_\odot$)†	0.16	0.49	0.14

- SMM11 → circular shape.
- SMM4a1 → high T_b~20 K.
- SMM4a2 → compact+extended.

† κ(870 μm)=0.035 cm^{2}g^{-1}, β=1, T=30 K

3. Results — SED



	SMM11	SMM4a1	SMM4a2
$T_{\rm bol}$ (K)	~26	~30	
$L_{\rm bol}$ ($L_\odot$)	< 0.91	< 2.6	
$L_{\rm int}$ ($L_\odot$) †	< 0.04	< 0.3	
$L_{\rm submm}$ ($L_\odot$) ††	~0.095	~0.31	

† From 70 μm flux (Dunham+'08), †† From >350 μm fluxes.

- Aperture photometry using Spitzer & Herschel. +FIR/sub-mm/mm from literature. → All the three are Class 0 ($T_{\rm bol}$<70 K).
- SMM11 has one order fainter $L_{\rm bol}$ and $L_{\rm int}$ than SMM4.
- The difference of $L_{\rm bol}$ and $L_{\rm int}$ is mainly due to contamination from nearby YSOs in this region.

350 μm CSO SHARC-II (Suresh+'16), 450, 850 μm JCMT SCUBA (Davis+'99)
1.3 mm ALMA (this work), 3 mm CARMA (K. Lee+'14)

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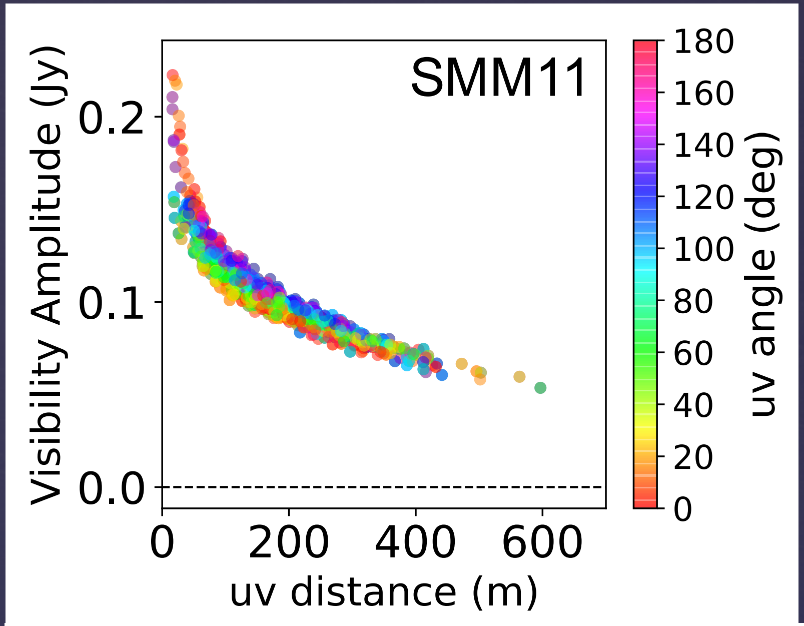
3. Results — Continuum Visibility

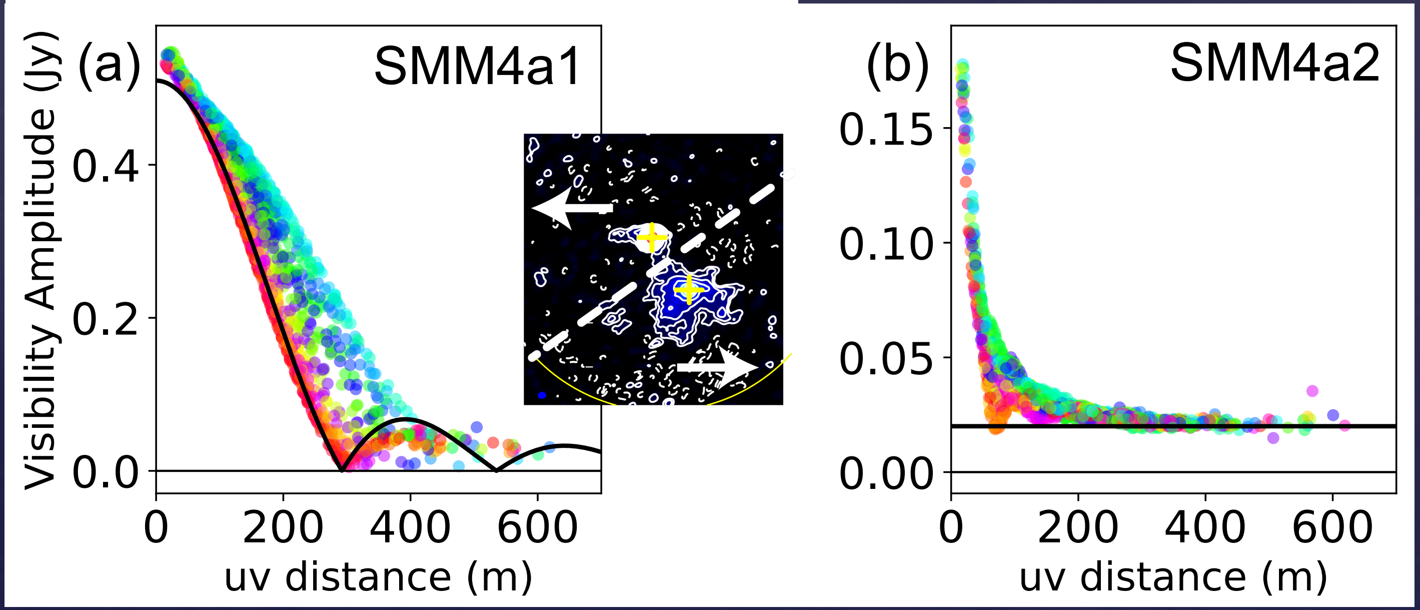


Major

Minor

Major

➢ SMM11:
Similar profiles at different uv-angles.
→Spherical envelope (or face-on disk).

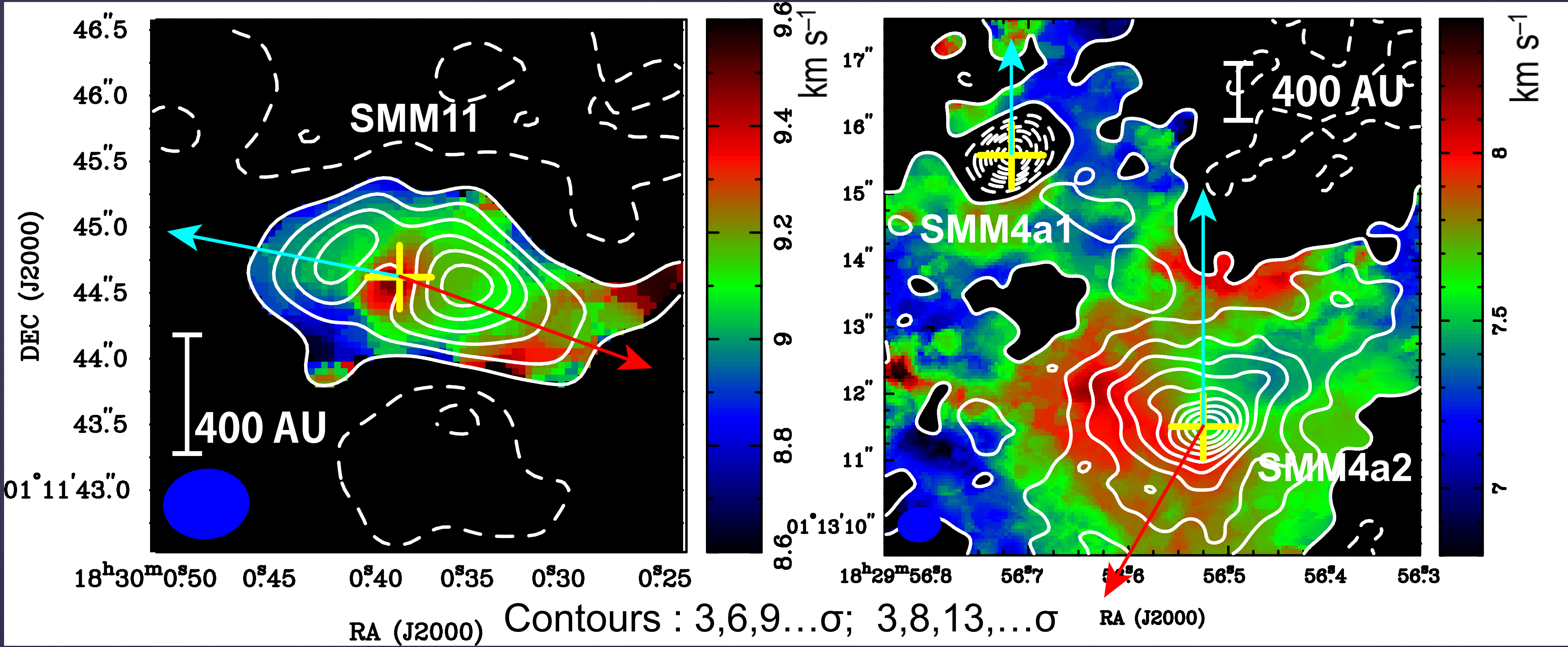


Synthetic observations of CLEAN components of SMM4a1 and 4a2 divided in the image domain.

➢ SMM4a1:
Null point at ~290 m (major axis).
→If boxcar disk then r ~ 240 AU.

➢ SMM4a2:
Point source at 200-600 m.
→unresolved disk, r < 30 AU.

3. Results — $C^{18}O$ abundance

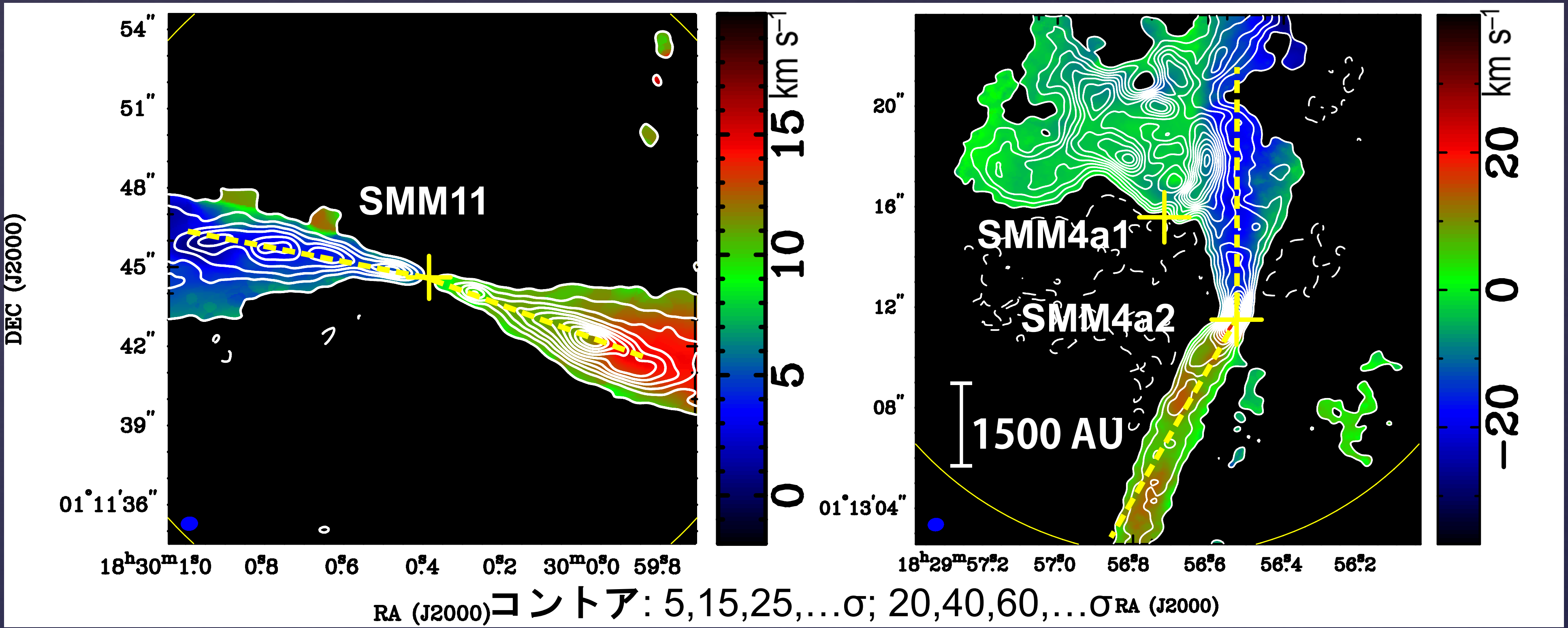


$C^{18}O$ J=2–1
Contour: moment 0
Color: moment 1
Arrows: outflows

Inter stellar medium:
$X(C^{18}O)$~5×10^{-7}
(Lacy+'94,
Wilson & Rood '94)

- SMM11: Double peak. $X(C^{18}O)$~$2\text{-}3\times10^{-10}$ at the center. Frozen-out due to low T.
  East-west extension is due to heating by the outflow (shock, cavity).
- SMM4a1: Negative intensity due to continuum subtraction (T_b~ –9 K).
- SMM4a2: Single peak. $X(C^{18}O)$~$0.7\text{-}1\times10^{-8}$ at the center. Possibly frozen-out.

3. Results —^{12}CO J=2–1 outflows

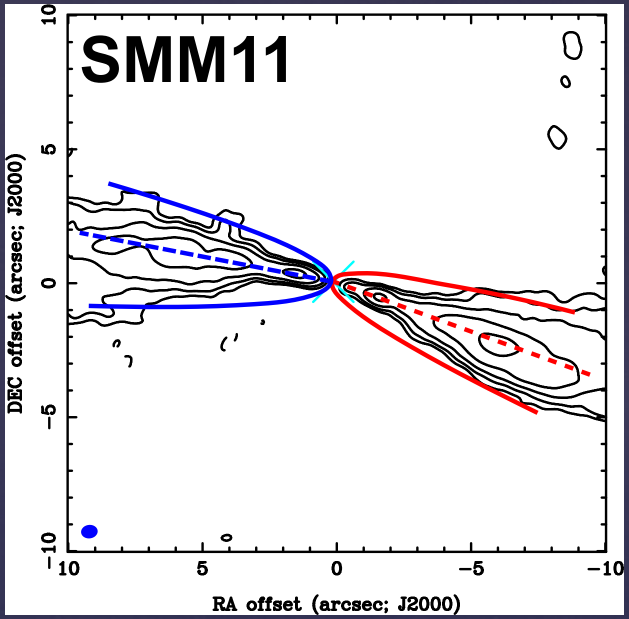


Contour: moment 0
Color: moment 1

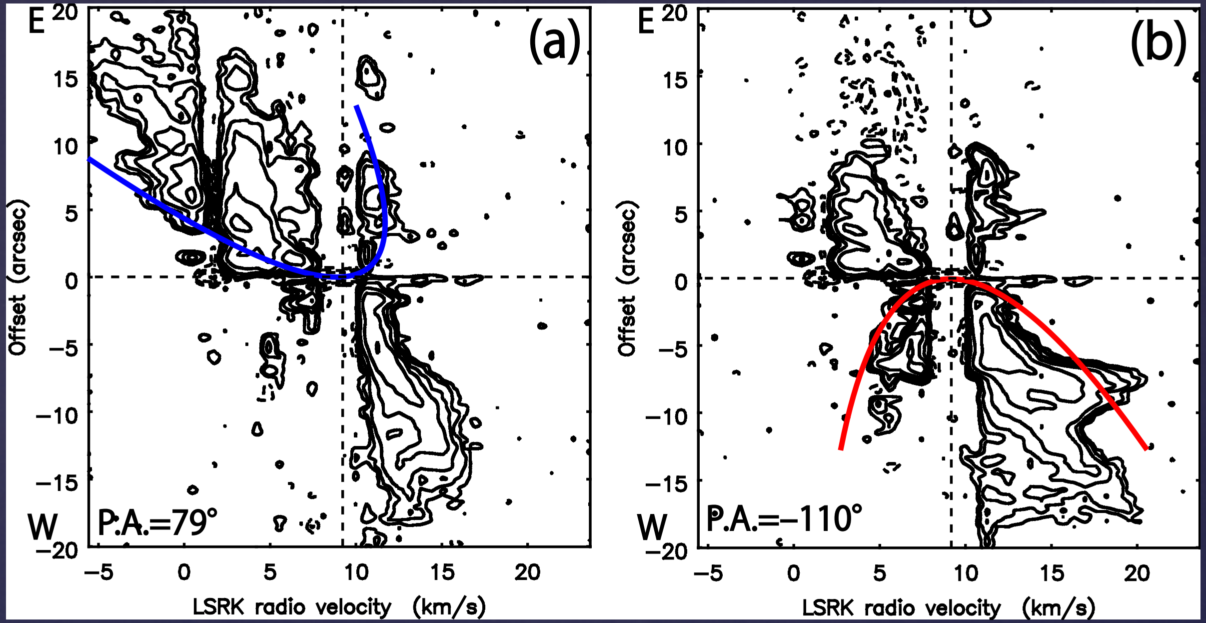
- SMM11: Bipolar outflow. Slower (l.o.s) velocity than SMM4a2.
- SMM4a1: Fan-shaped toward the north with low velocity.
- SMM4a2: Collimated bipolar outflow with high velocity.

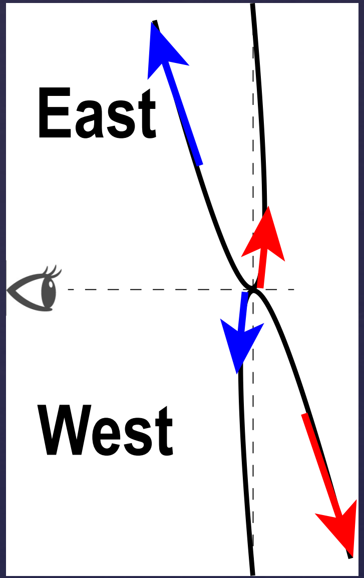
4. Discussion —— Outflow directions (SMM11)

^{12}CO moment 0



^{12}CO Position-Velocity diagrams



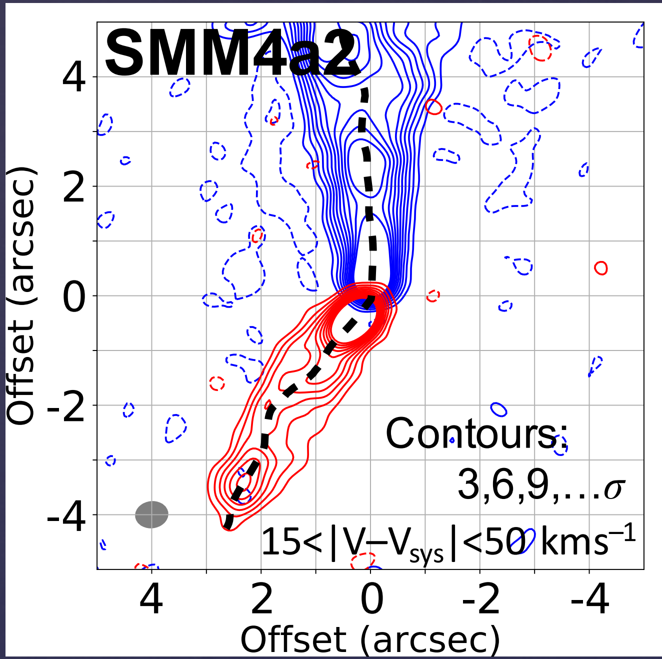


- The SMM11 outflow lies almost on the plane of the sky.
- Wind-driven shell (parabolic) model: $z = c_0 R^2, \ \vec{V} = v_0 \vec{R}$
  →inclination angle i~80°, c_0~4 kAU^{-1}, v_0~9 km s^{-1} kAU^{-1}

- ~30 km s^{-1} @ 3000 AU requires point mass, i.e., a protostar.

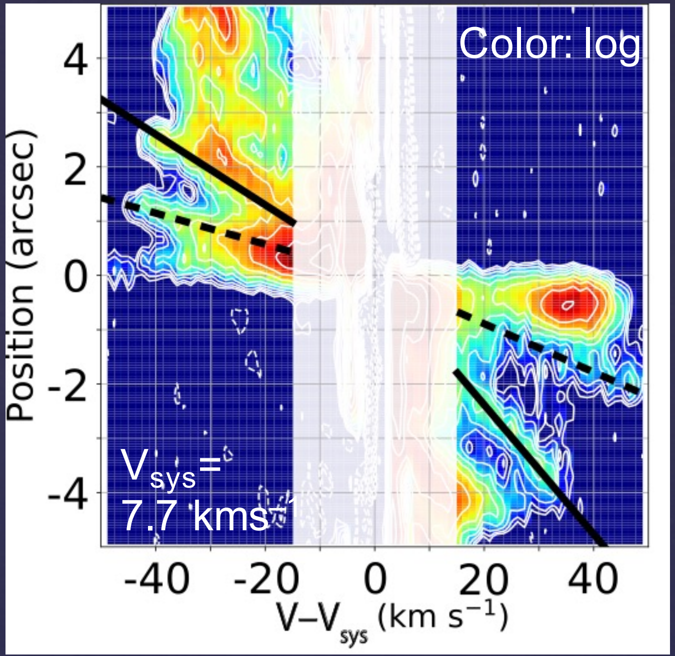
4. Discussion —— Outflow directions (SMM4a2)

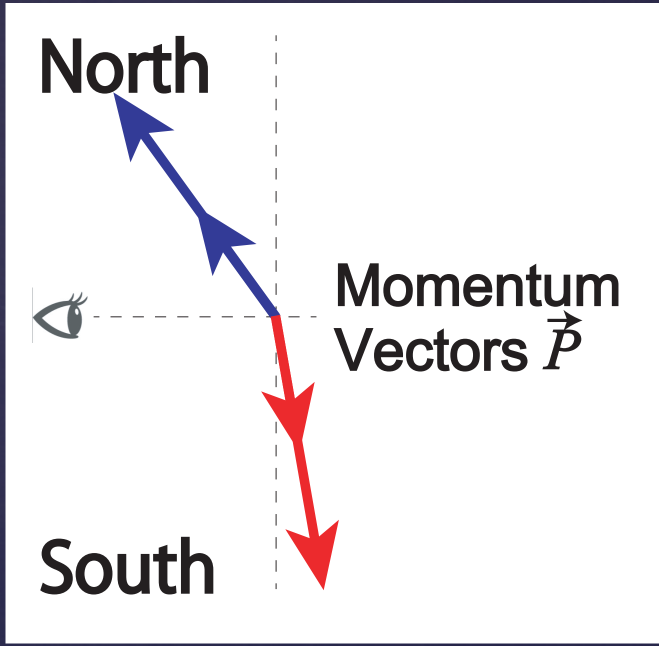
^{12}CO moment 0



^{12}CO Position-Velocity diagrams

Cut ➡





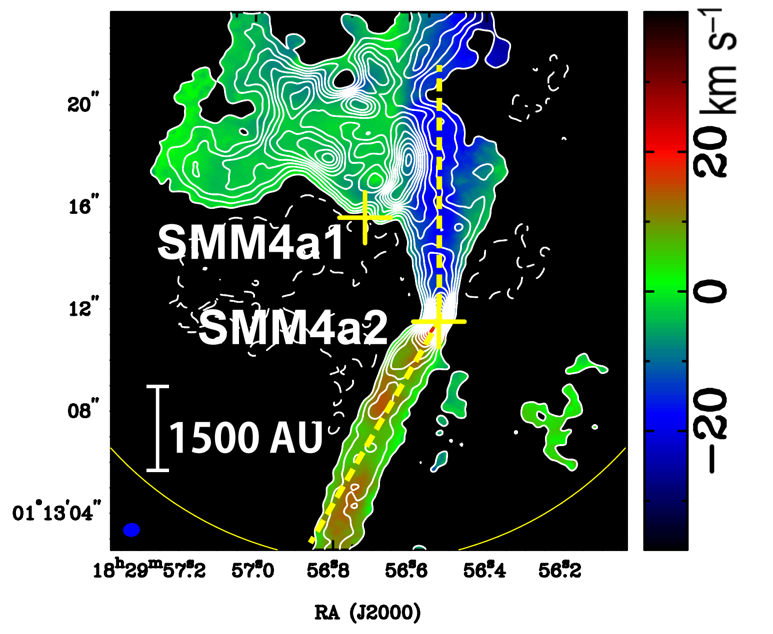
- The SMM4a2 outflow ejects mass periodically.
- If only inclination angles are different with common momenta and positions,

  →inclination angles $i_{\rm blue}$~36°, $i_{\rm red}$~70°; Bending angle α~40°,

  lengths L~1000 AU (dashed), 2000 AU (solid), velocity V~60 km s^{-1},

  where $P \propto I_v \times V$ assumed.

4. Discussion —— Possible origin of bending



SMM4a2 outflow is bending by α~40°.

- Binary orbital motion?
  Separation ~2000 AU, too slow.

- Dynamical interaction?
  Apparently pulled by SMM4a1 outflow.
  While, pc-scale outflows can push (Davis+'99).

- Electro-magnetic interaction?
  Required $B \propto \tan\alpha\ V/L$ with normalization about current (Ching+'16, Fendt&Zinnecker'98) → order of mG, which could occur around protostars.

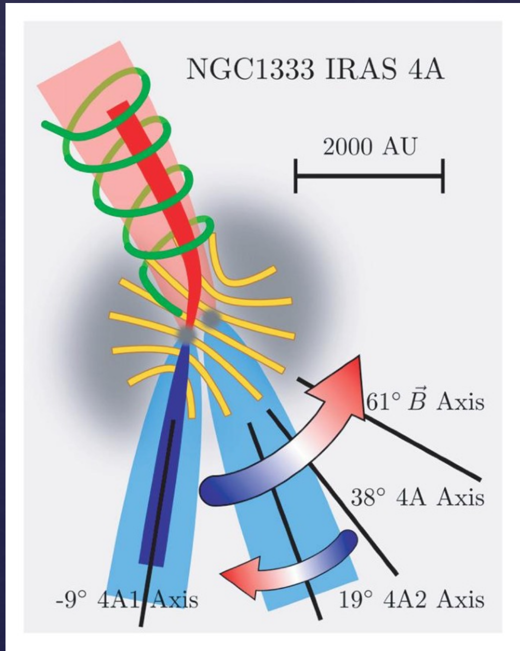


Figure 9 in Ching+'16

5. Summary

Summary:

Millimeter observations have revealed evolutionary phases in more detail than Class 0. ←*Naomi Hirano's talk tomorrow*

- Youngest SMM11: L_{int}=0.04 $L_{\odot}$, CO frozen out (~1000x), spherical envelope.
- Intermediate SMM4a2: collimated fast outflow, point source (r < 30 AU).
- Oldest SMM4a1: T_{b}(1.3 mm)~20 K, fan-shaped slow outflow, disk-like structure (r ~200 AU).

Inclination angles of the outflows were also constrained.

Future plan:

- To observe molecules not frozen-out in SMM11.
- Dynamics of the possible disks around SMM4a1 and 4a2.

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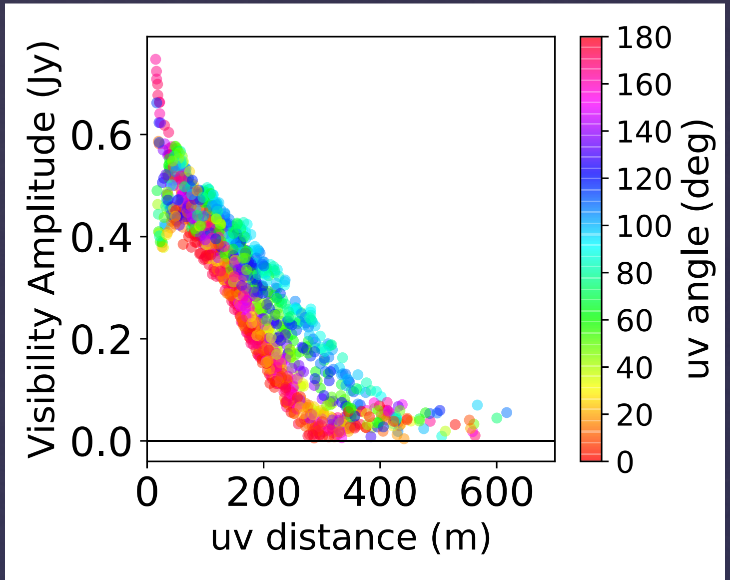
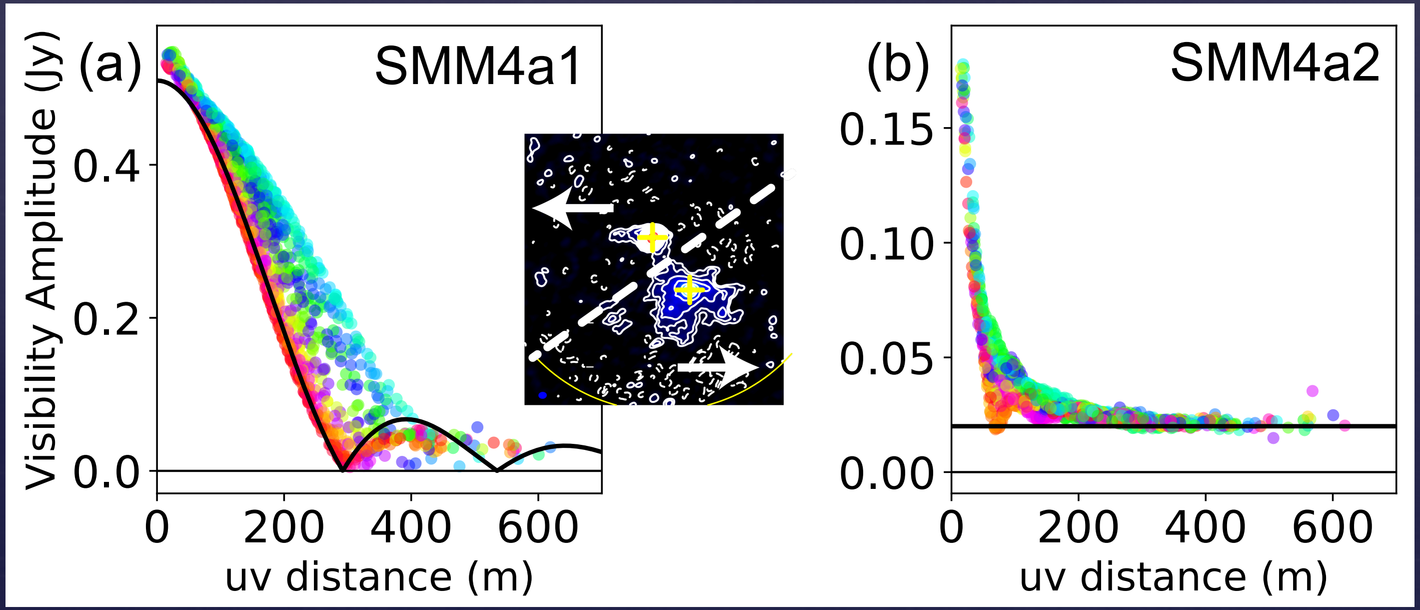
3. Results — Continuum Visibility



Before divided.



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  →unresolved disk, r < 30 AU.

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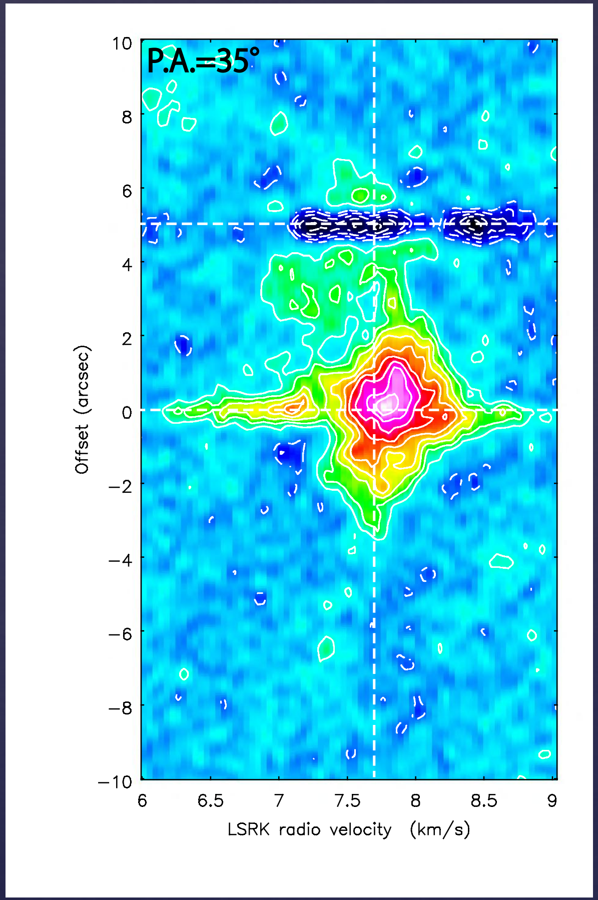
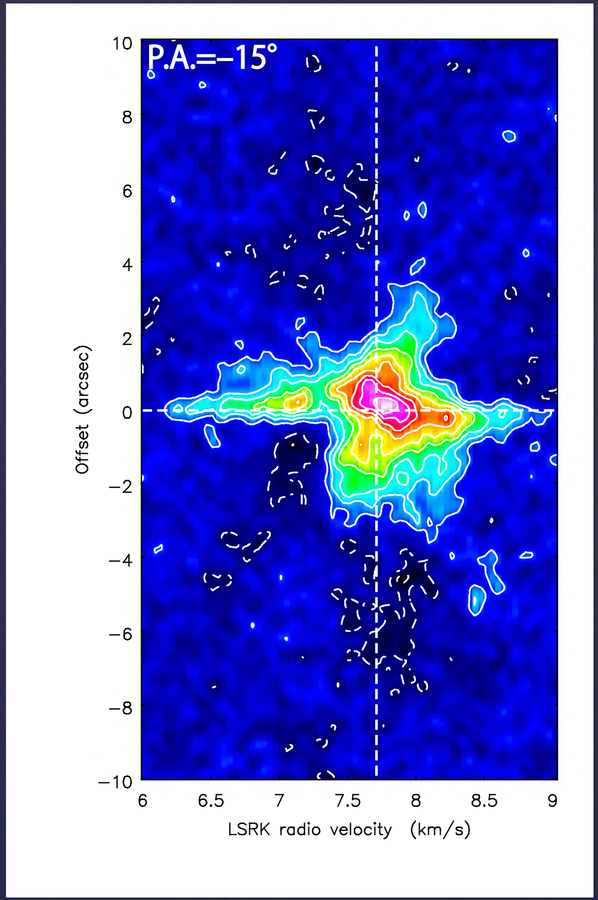
3. Results — Position-Velocity diagram

Passing 4a1 and 4a2



Along 4a2 outflow



Across 4a2 outflow