ALMA observations of Serpens Main: protostellar evolution at the Class 0 stage

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Aso+ ’17a, ApJL, 850, L2; Aso+ ’18, ApJ, 863, 19A

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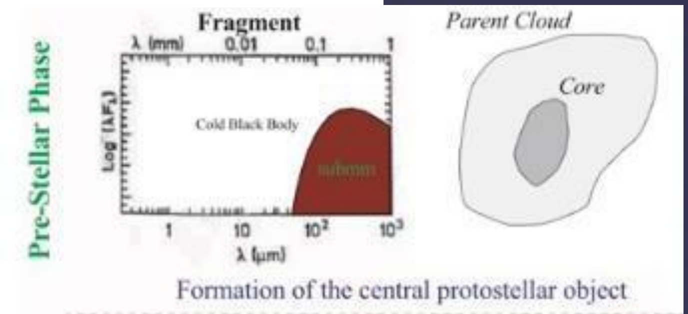
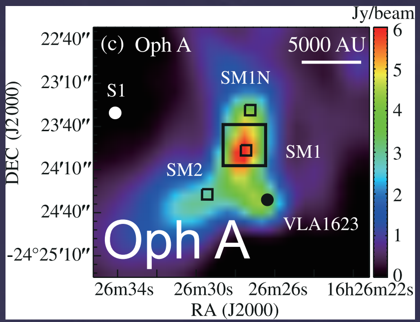
1. Introduction — Class 0 in star formation

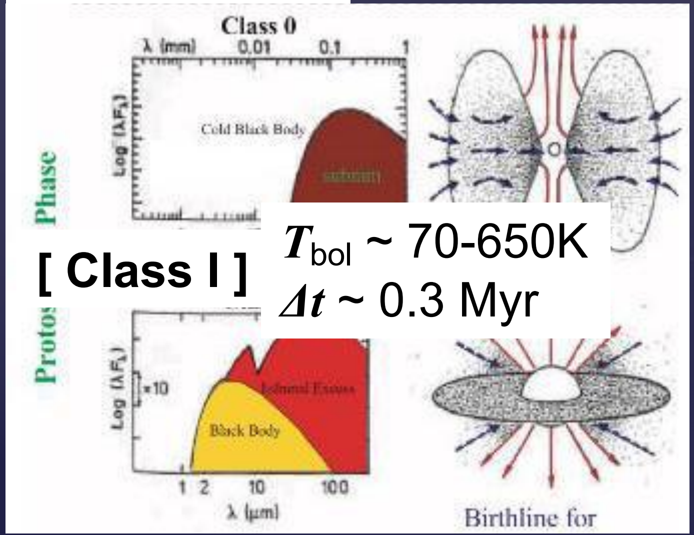
[Starless core] T_{bol} ~ 10-20 K Δt ~ 300 kyr



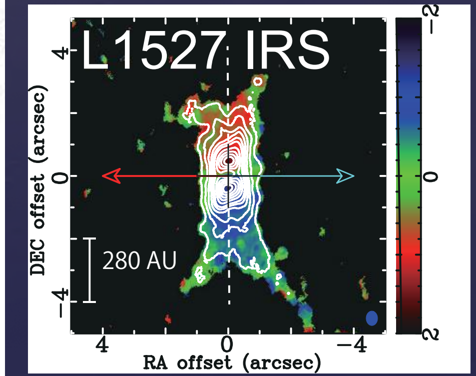


➢ Early phases (starless→Class 0) cannot be observed in optical/NIR/MIR.

[Class 0] T_{bol} < 70 K Δt ~ 0.2 Myr



[Class I] T_{bol} ~ 70-650K Δt ~ 0.3 Myr



Millimeter observations:

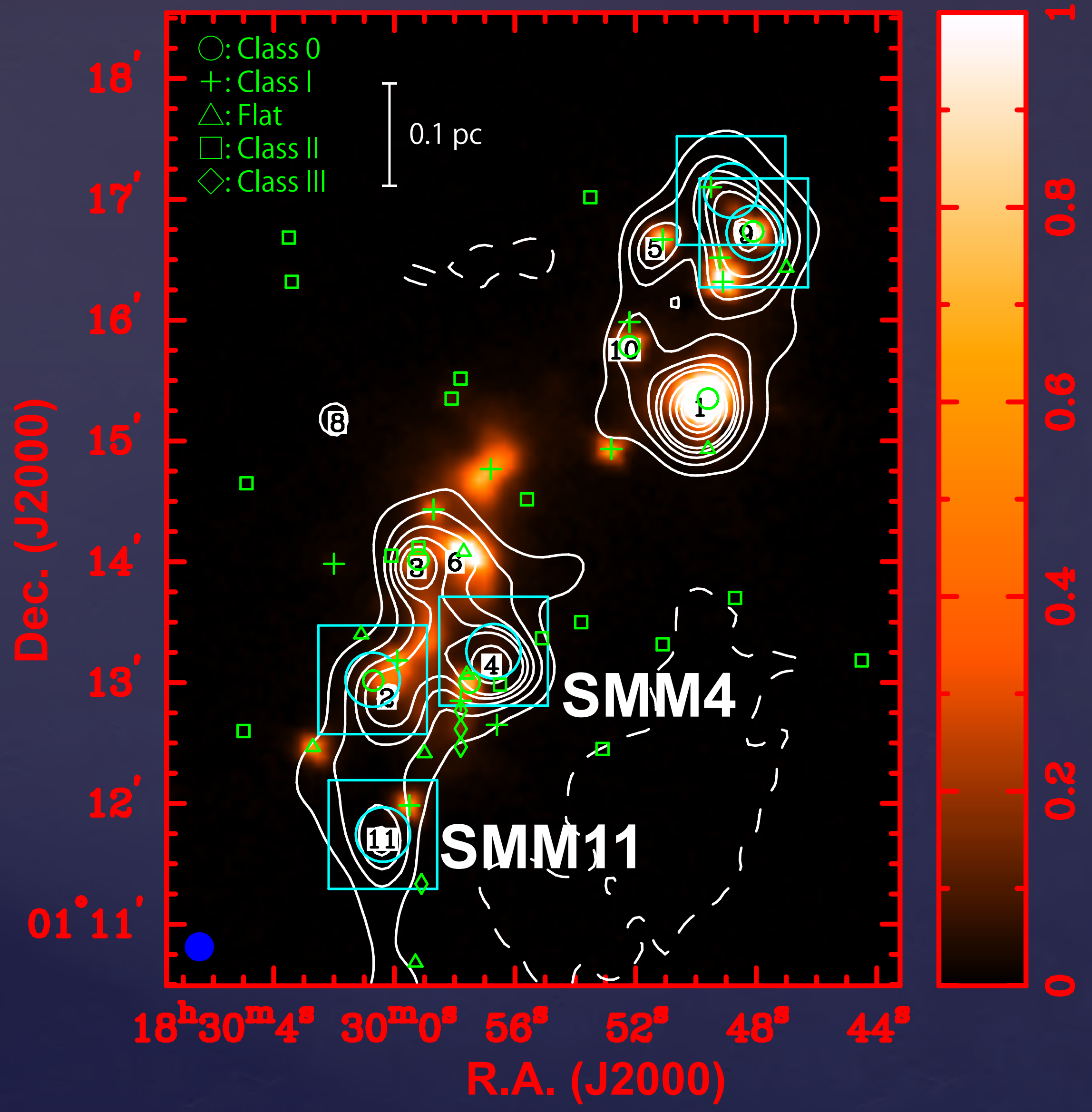
Continuum ——Column density. Structure e.g., spherical or disk-like.

Outflows ——Evidence of mass accretion. Gravitational potential.

Chemistry ——Abundance reflecting thermal history.

Andre ’02, Nakamura+ ’12, Aso+ ’17b

1. Introduction — Serpens Main



Serpens Main:

- Star forming cluster.
- Two episodes of star formation, 2 and 0.5 Myr ago.

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

Contours: JCMT 850 μm
Color: Herschel 70 μm

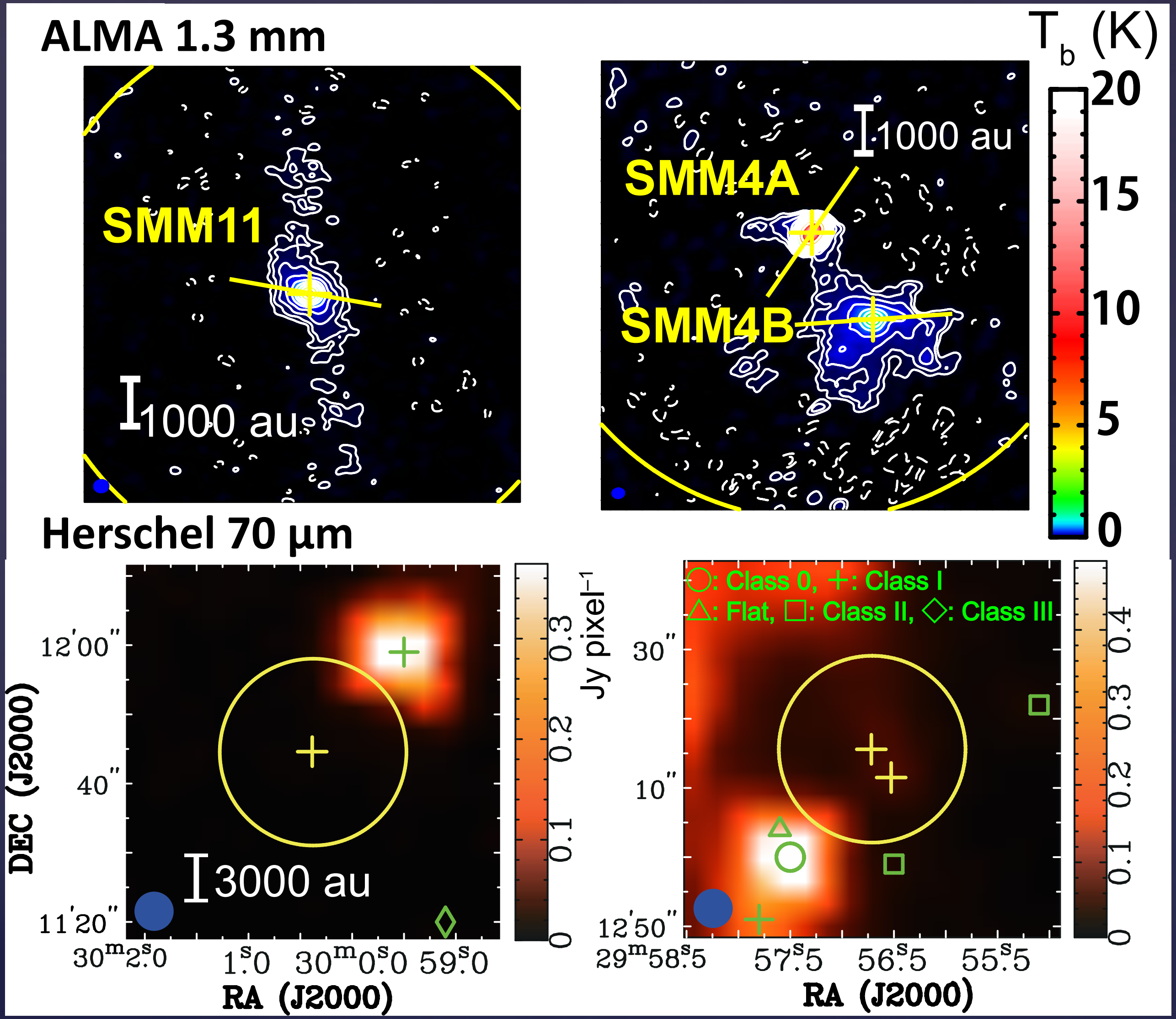
Dzib +'11, Duarte-Cabral +'10, K. Lee +'14

2. ALMA observations

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

3. Results — 1.3 mm & 70 μm



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

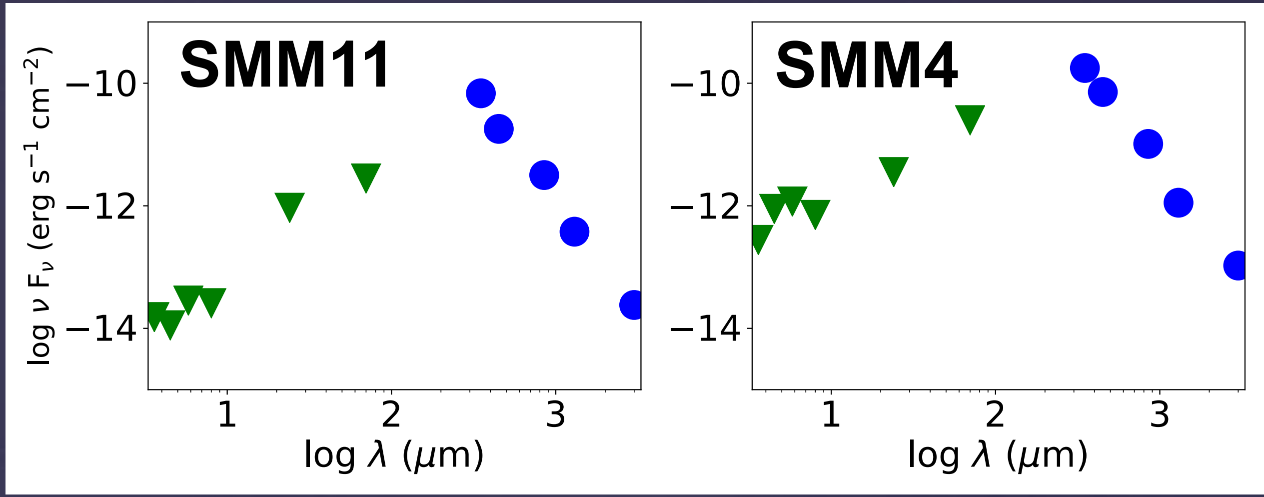
- 1.3 mm sources faint at 70 μm.

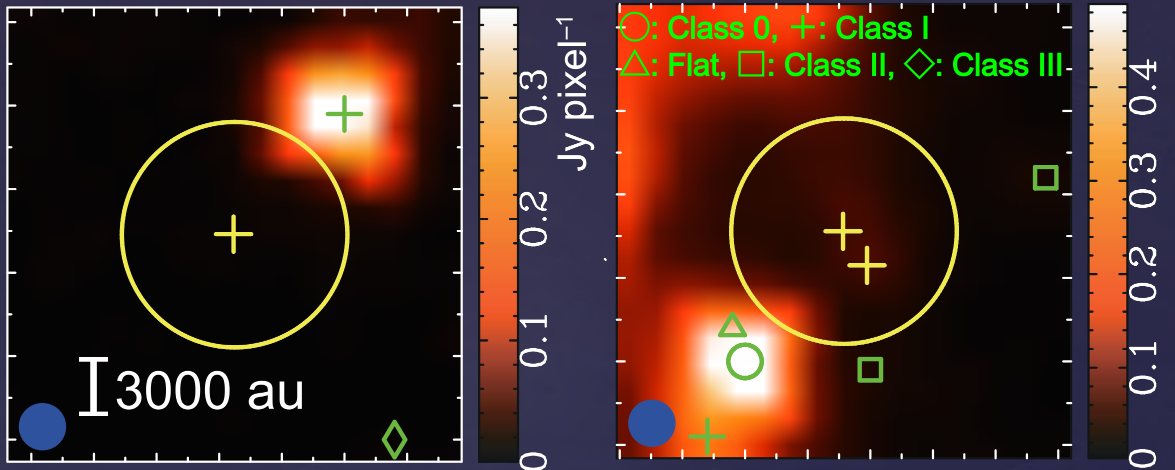
	SMM11	SMM4A	SMM4B
Deconvolved size (AU)	160x130 (80°)	320x200 (145°)	300x230 (94°)
M_{gas} ($M_\odot$)†	0.27	> 0.83	0.29

- SMM11 → circular shape.
- SMM4A → high T_b~18 K, high τ.
- SMM4B → extended.

† κ(870 μm)=0.035 cm^2 g^{-1}, β=1, T=20 K

3. Results — SED





- All the three are Class 0 (T_{bol} < 70 K, L_{bol} / L_{submm} < 200).
- SMM11 is fainter at 70 μm → Lower L_{int}.

(Upper limits include contamination from nearby YSOs.)

	SMM11	SMM4A	SMM4B
T_{bol} (K)	~26	~30	
L_{bol} ($L_\odot$)	< 0.91	< 2.6	
L_{int} ($L_\odot$) †	< 0.04	< 0.3	
L_{submm} ($L_\odot$) ††	~0.095	~0.31	

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

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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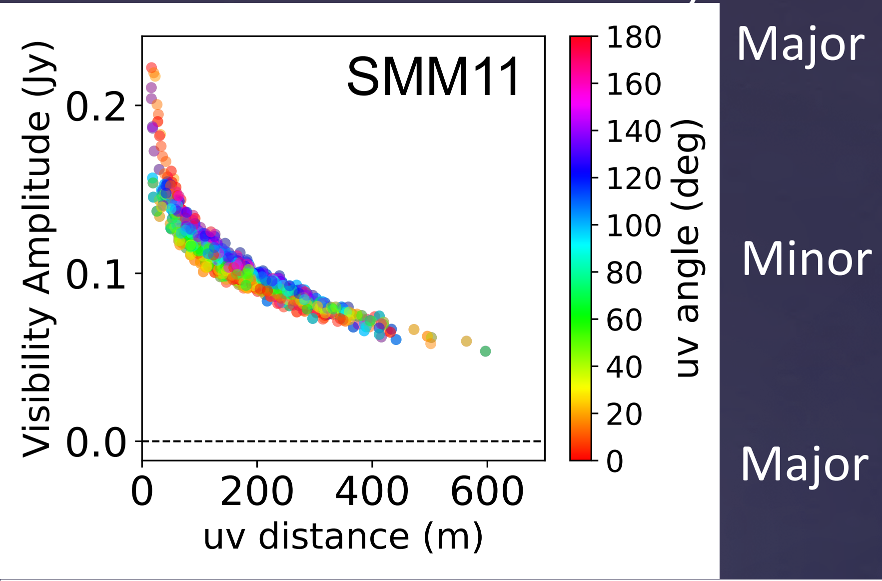
4. Analysis — Continuum visibility



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

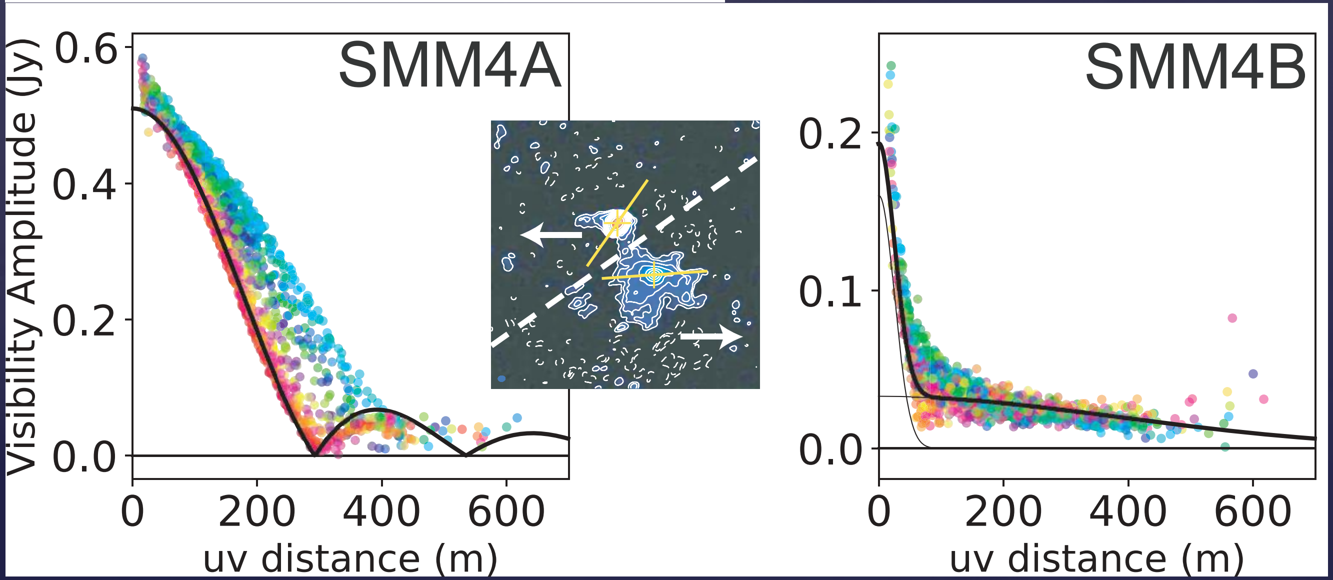
Dividing CLEAN components.

- SMM4A: Null point at ~290 m.
  →If boxcar disk then r ~ 240 AU.
- SMM4B:
  Extended envelope, r ~ 590 au &
  unresolved disk, r ~ 56 AU.

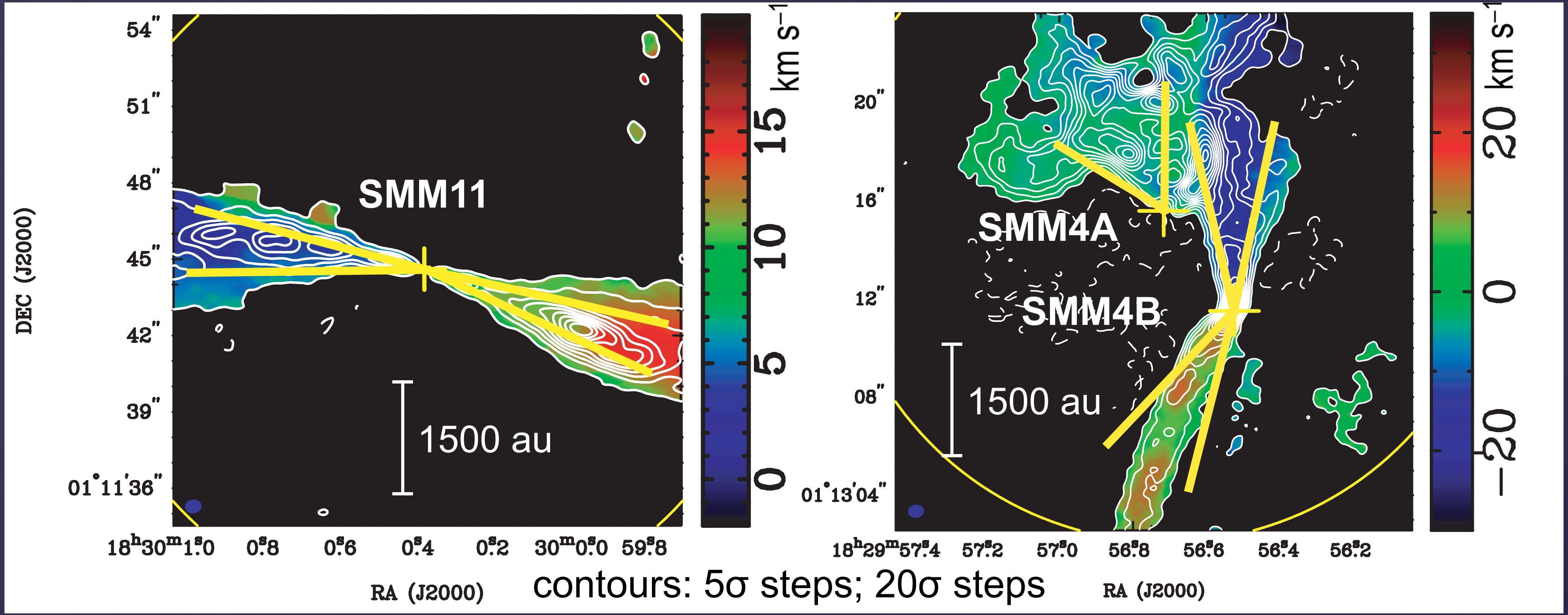
⇩

Disk growth?

SMM11 → SMM4B → SMM4A



5. Discussion —^{12}CO J=2–1 outflows



Contour: moment 0
Color: moment 1

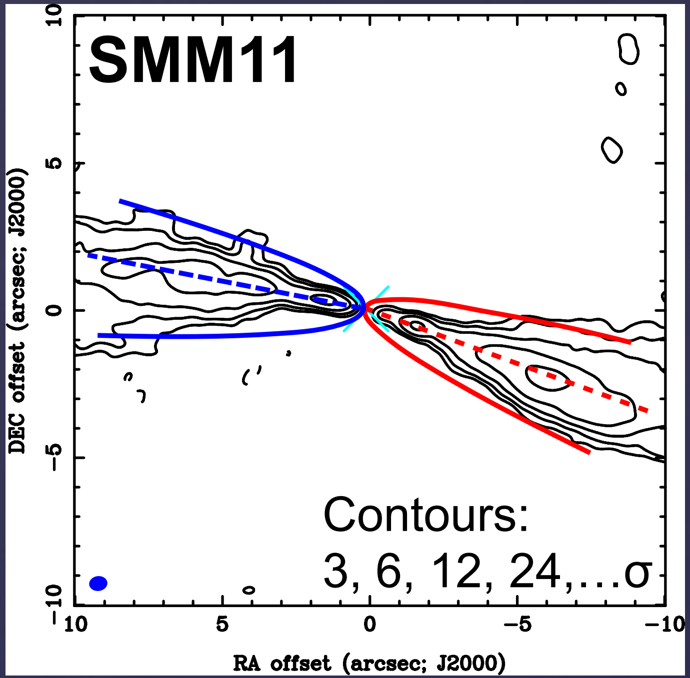
—— : Intensity weighted R & θ.

- SMM11: Collimated bipolar outflow. $\theta \sim 12° - 16°$.
- SMM4A: Fan-shaped unipolar outflow. $\theta \sim 59°$.
- SMM4B: Collimated bipolar outflow. $\theta \sim 25° - 29°$.

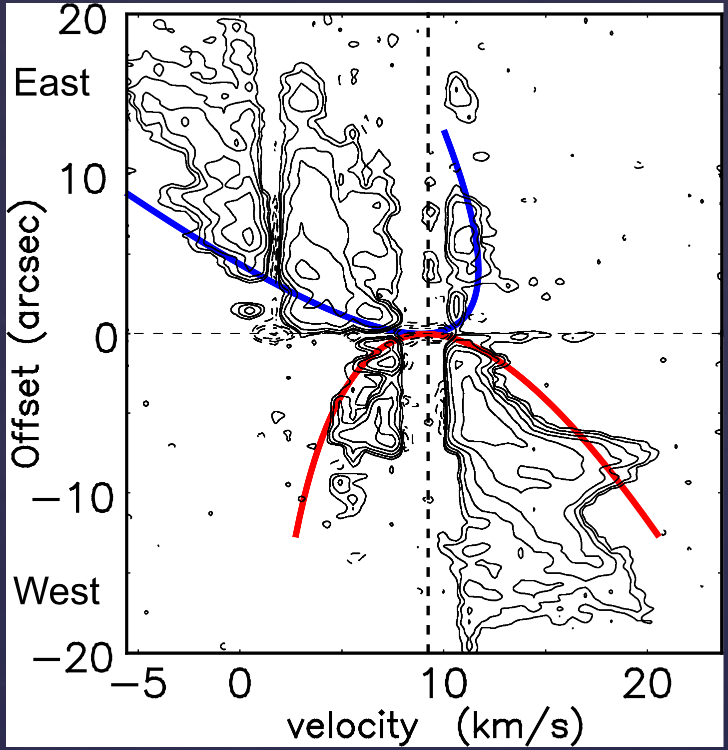
→ Widening of opening angles (Arce & Sargent '06, Machida & Hosokawa '13).

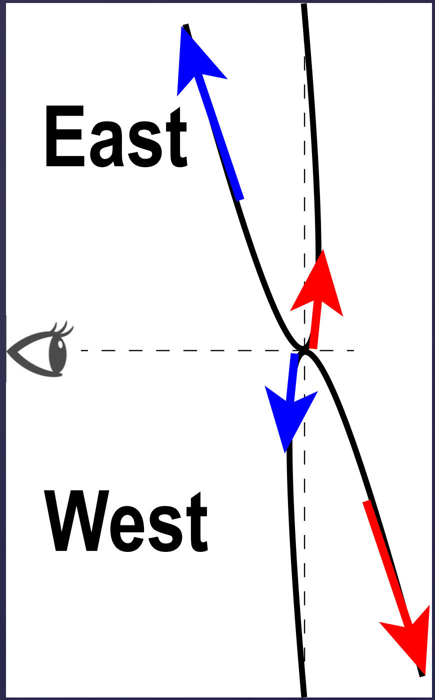
5. Discussion —— Outflow inclination (SMM11)

^{12}CO moment 0



^{12}CO Position-Velocity diagrams





- The SMM11 outflow is almost // to 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}

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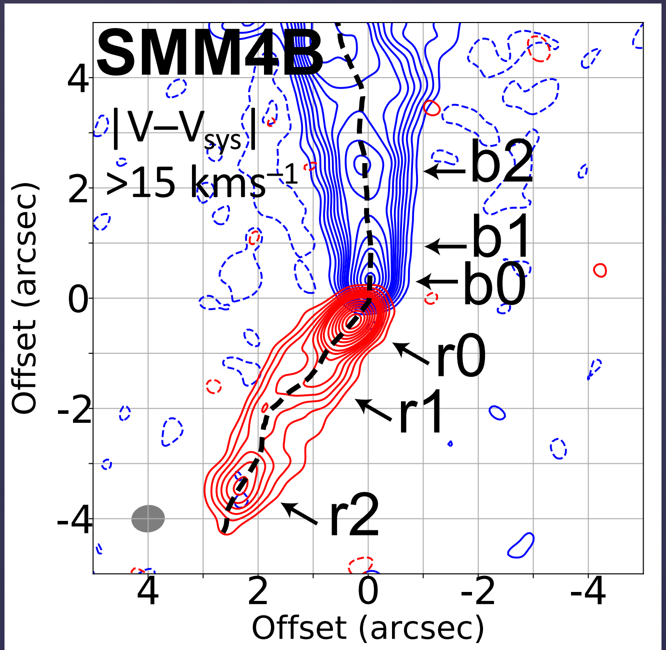
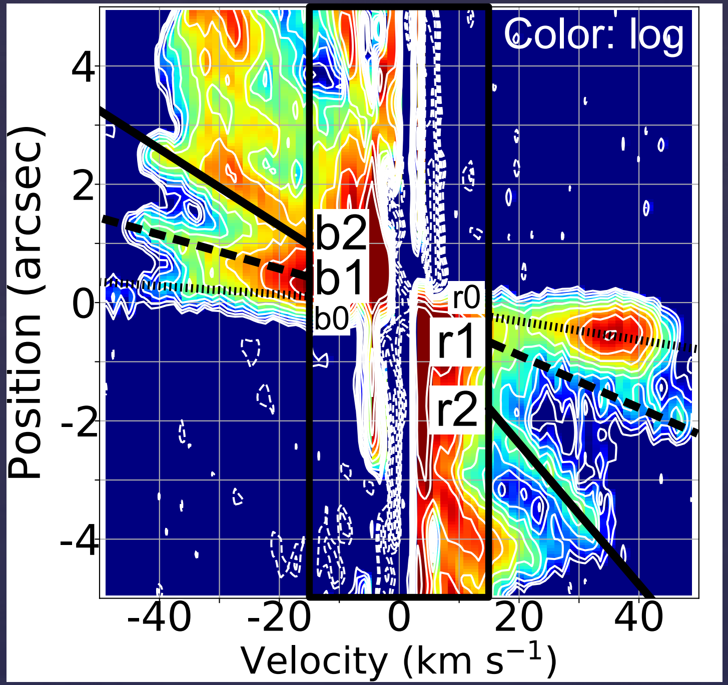
5. Discussion —— Outflow inclination (SMM4B)

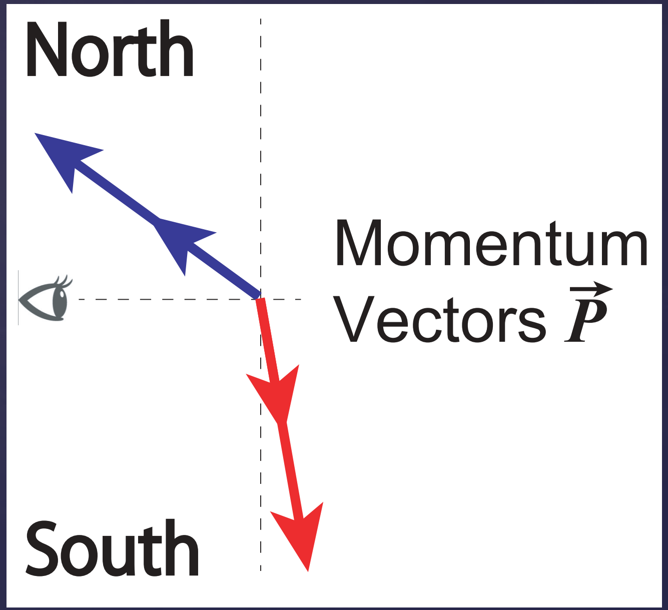
^{12}CO moment 0



Cut

^{12}CO Position-Velocity diagrams





- The SMM4B outflow ejects mass episodically.
- If blue and red lobes have different i but common P at common distances,
  →inclination angles i_{blue}~36°, i_{red}~70°, where $P \propto I_\nu * V$ is assumed.

5. Discussion —— Outflow dynamical time

- i = 50° for SMM4A from major/minor axes ratio of continuum.

	R (au)	M ($1e{-}3M_\odot$)	P ($1e{-}3M_\odot$ km s^{-1})
SMM11	4300	1.1	2.6
SMM4A	2900	1.6	3.8
SMM4B	4800	1.6	1.2

V (km s^{-1})	τ_{dyn} (yr)
29	700
6.1	2300
19	1200

- Optically thin and T = 30 K are assumed.
  $M \propto$ mom 0, $P \propto$ mom0 * mom1 / cos i, while $V = P / M$, $\tau_{dyn} = R / V$.
- R and V are intensity-weighted and inclination-corrected.

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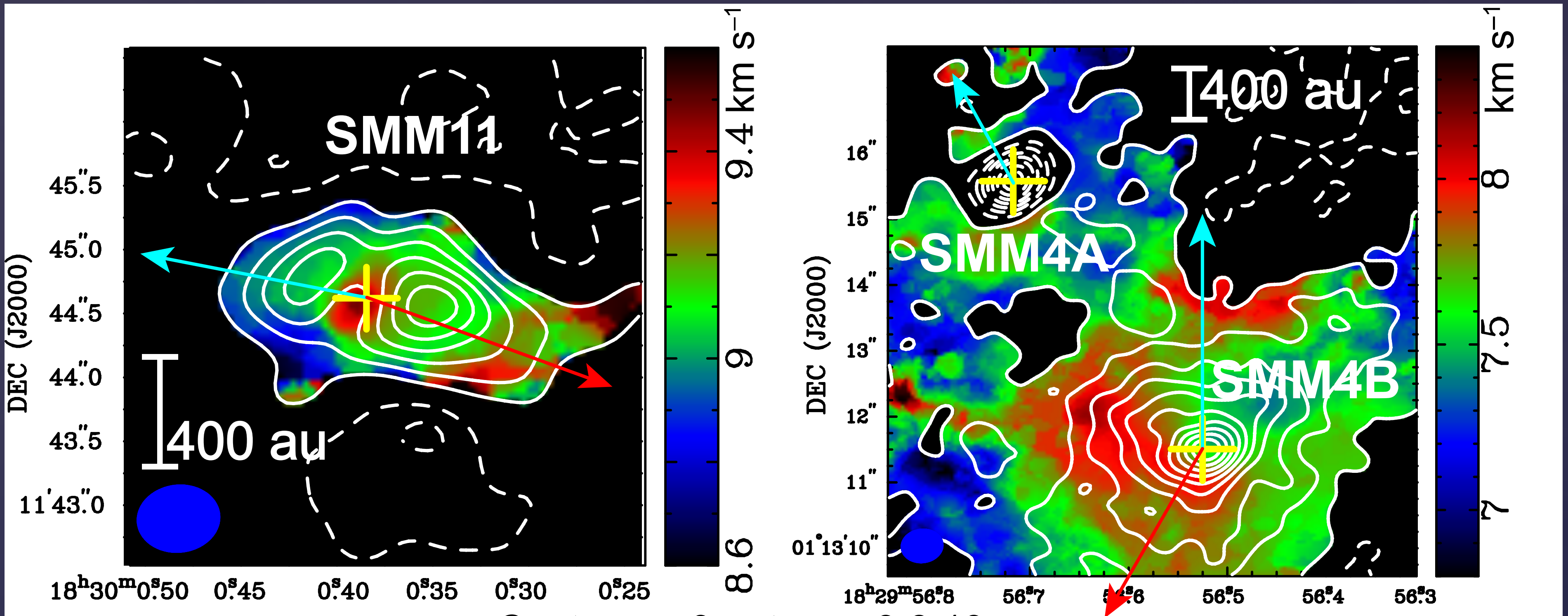
5. Discussion — $C^{18}O$ abundance



Contours : 3σ steps; 3,8,13,…σ

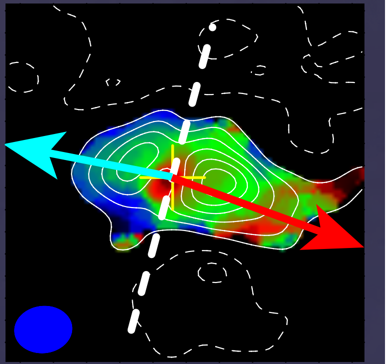
$C^{18}O$ J=2–1
Contour: moment 0
Color: moment 1
Arrows: outflows

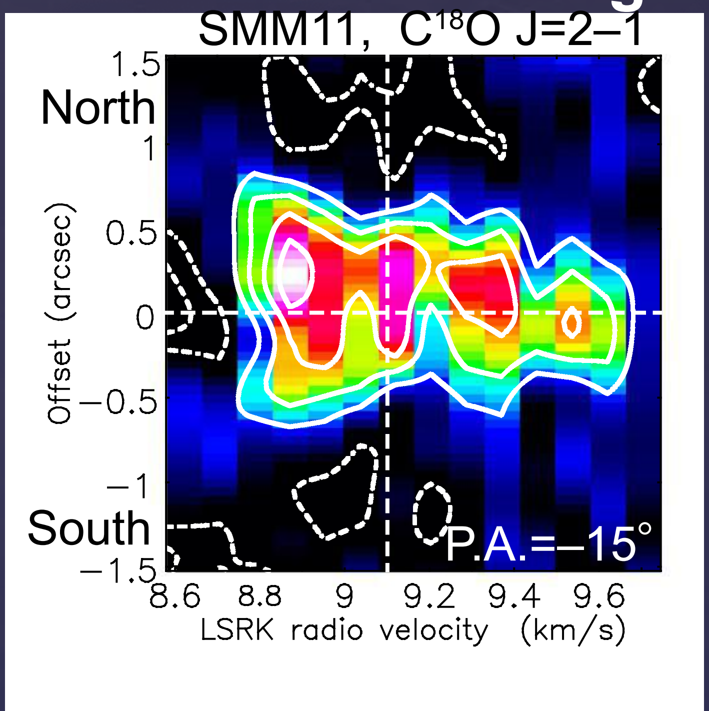
Inter stellar medium:
$X(C^{18}O) \sim 5\times10^{-7}$
(Lacy+'94,
Wilson & Rood '94)

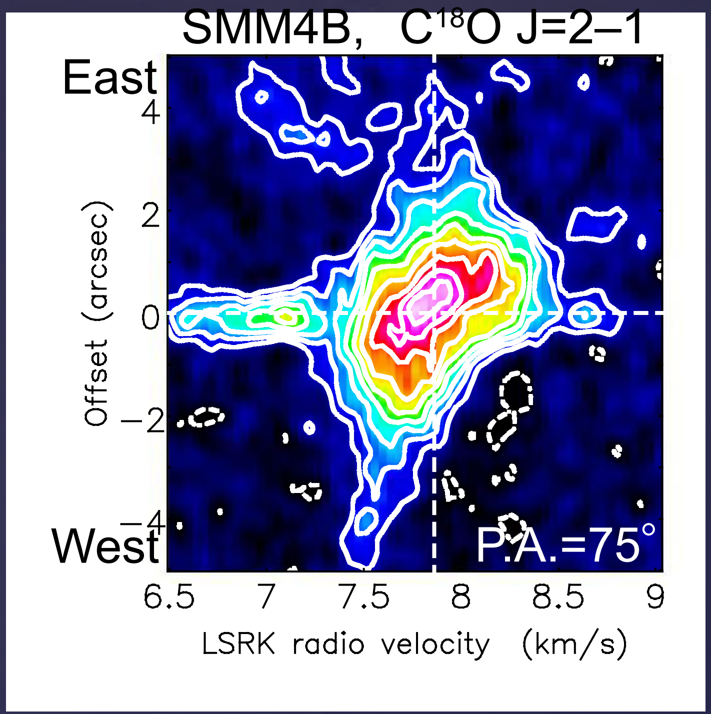
- SMM11: $X(C^{18}O)$ ~ 1 / 2000 × ISM. Frozen-out (simulation by Aikawa+ '12). E-W extension is due to heating by the outflow.
- SMM4A: Absorption against continuum (T_b ~ –9 K).
- SMM4B: $X(C^{18}O)$ ~ 1 / 50 × ISM. Possibly frozen-out.

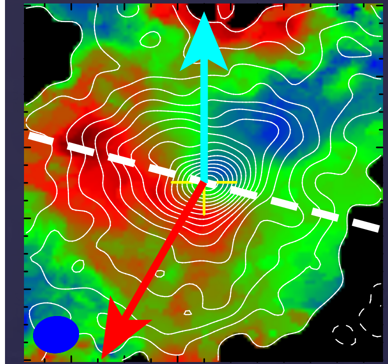
5. Discussion — $C^{18}O$ Rotational velocity

$C^{18}O$ PV diagrams across outflow









- SMM11: No significant velocity gradient ← freeze-out
- SMM4B: blueshfited component

  \+ Main body, no spinning up ← freeze-out at high vel.?

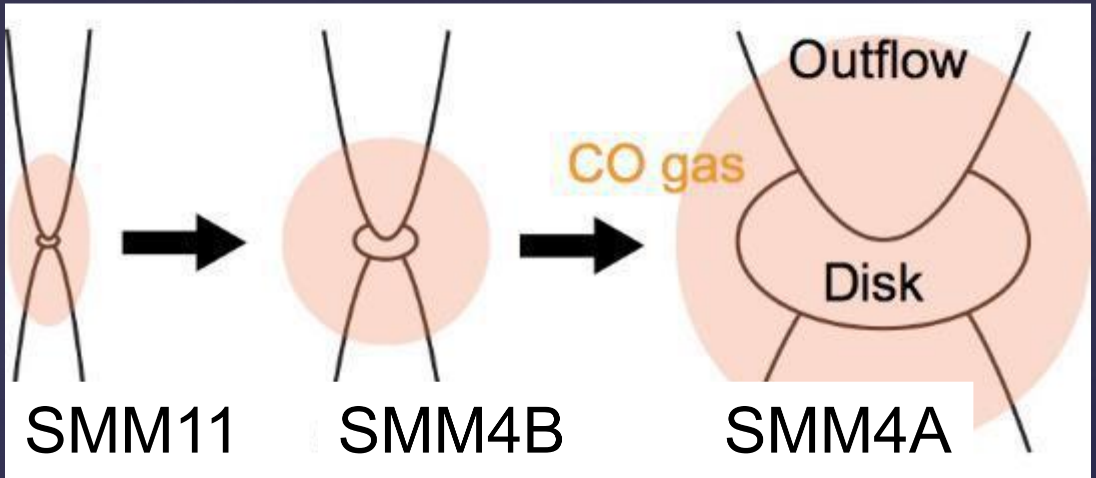
  → a new disk tracer is necessary…

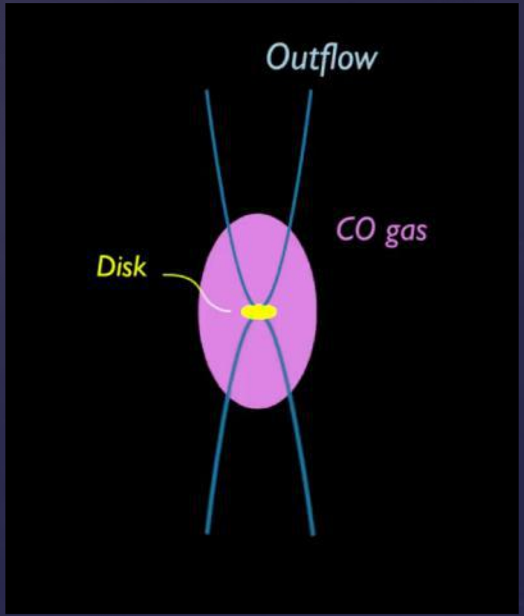
6. Summary

Summary:

Millimeter observations can differentiate evolution even in the Class 0 stage.

- Disk growth.
- Widening of outflow.
- Dynamical time.
- CO freeze out.





See also press release from ASIAA!

Future plan:

- To observe molecules not frozen-out in SMM11, such as N_2H^+.
- Dynamics of the possible disks around SMM4A and 4B.