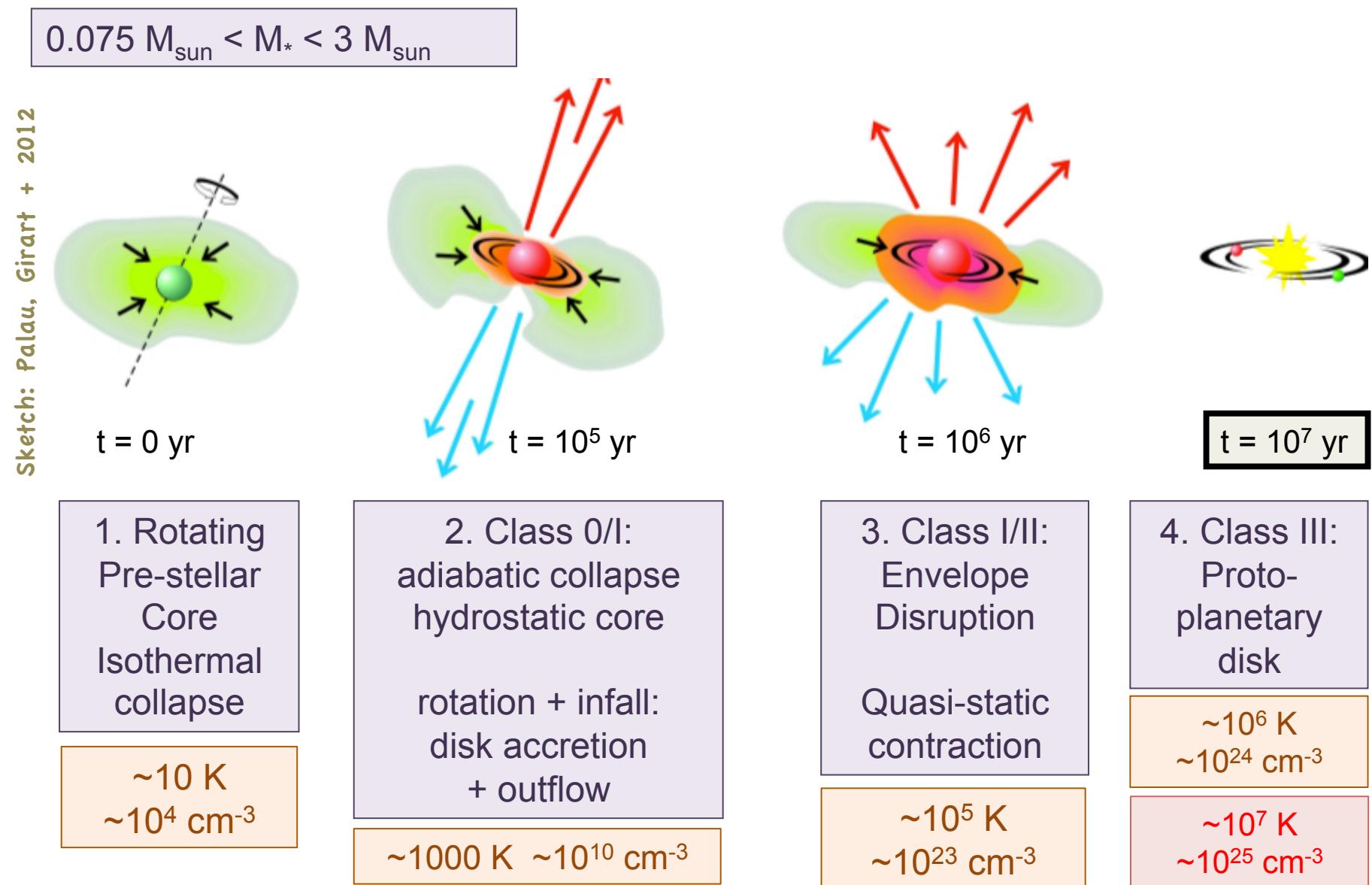


# A Class 0 Proto-Brown Dwarf Candidate Driving a Compact Molecular Outflow

Aina Palau  
(CRyA-UNAM)

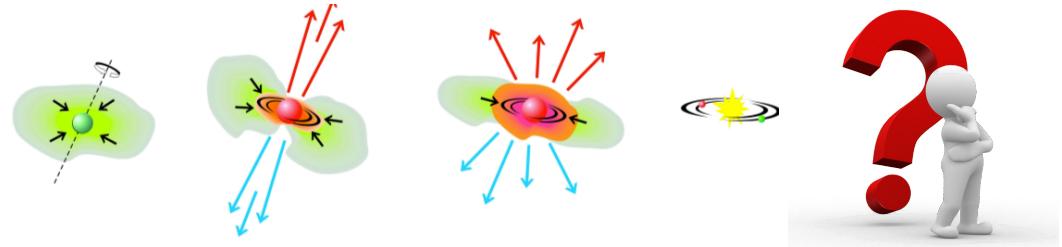
Luis A. Zapata, Luis F. Rodríguez, Hervé Bouy, David Barrado,  
María Morales-Calderón, Philip C. Myers, Nicholas Chapman, Carmen Juárez, Di Li

# Classical view of low-mass star formation:



# Brown dwarf (BD) formation

$$0.013 \text{ M}_{\text{sun}} < M_* < 0.075 \text{ M}_{\text{sun}}$$



## PROBLEM:

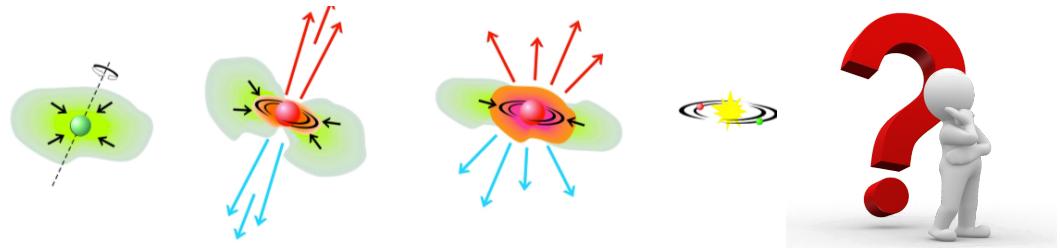
Jeans mass for  $T \sim 10\text{K}$ ,  $n \sim 10^4 \text{ cm}^{-3}$ :  $\sim 2 \text{ M}_{\text{sun}} \gg 0.05 \text{ M}_{\text{sun}}$

Possible formation scenarios for brown dwarfs (BDs):

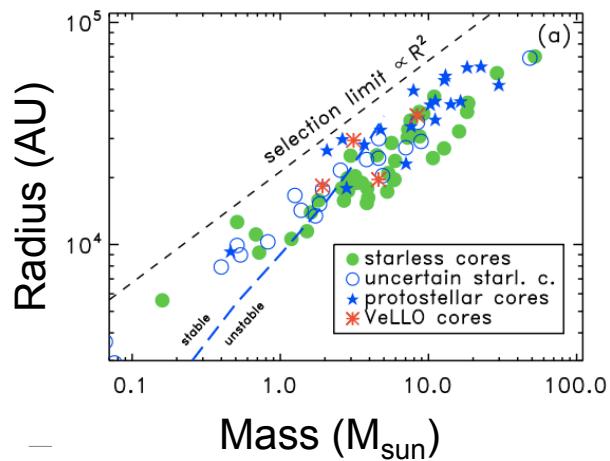
- photo-erosion (eg, Hester+96, Whitworth & Zinnecker'04)
- ejection of fragments from multiple protostellar system/disk (eg, Reipurth & Clarke'01, Stamatellos & Whitworth'09)
- gravoturbulent fragmentation (eg, Padoan & Nordlund'04, Hennebelle & Chabrier'08) → Scaled-down version

# Brown dwarf formation

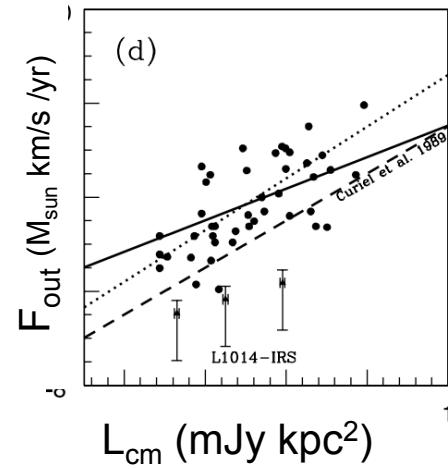
$0.013 M_{\text{sun}} < M_* < 0.075 M_{\text{sun}}$



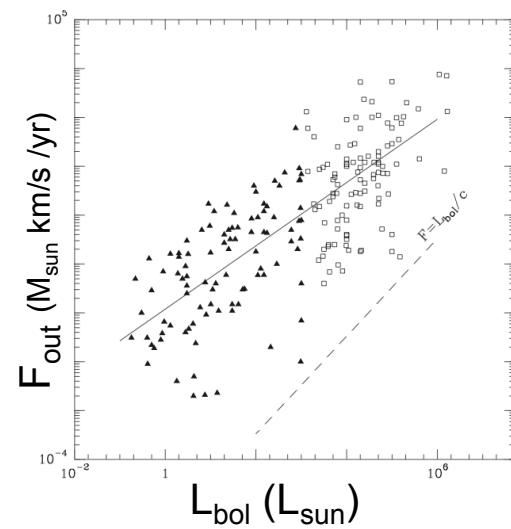
If scaled-down version: **substantial disks, envelopes, and outflows**, similar to **Class 0/I protostellar objects: Proto-BDs**



eg, Kauffmann+08...



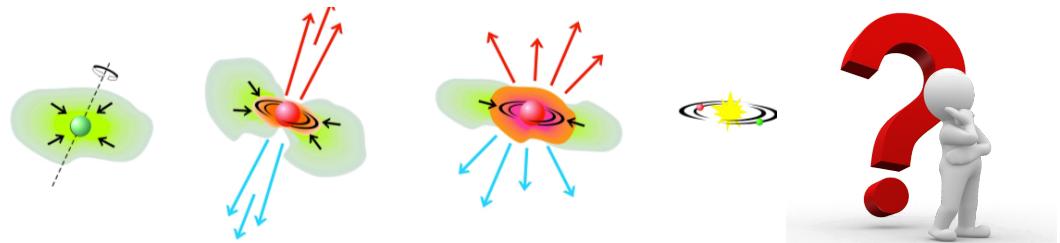
eg, Anglada95,  
Shirley+07...



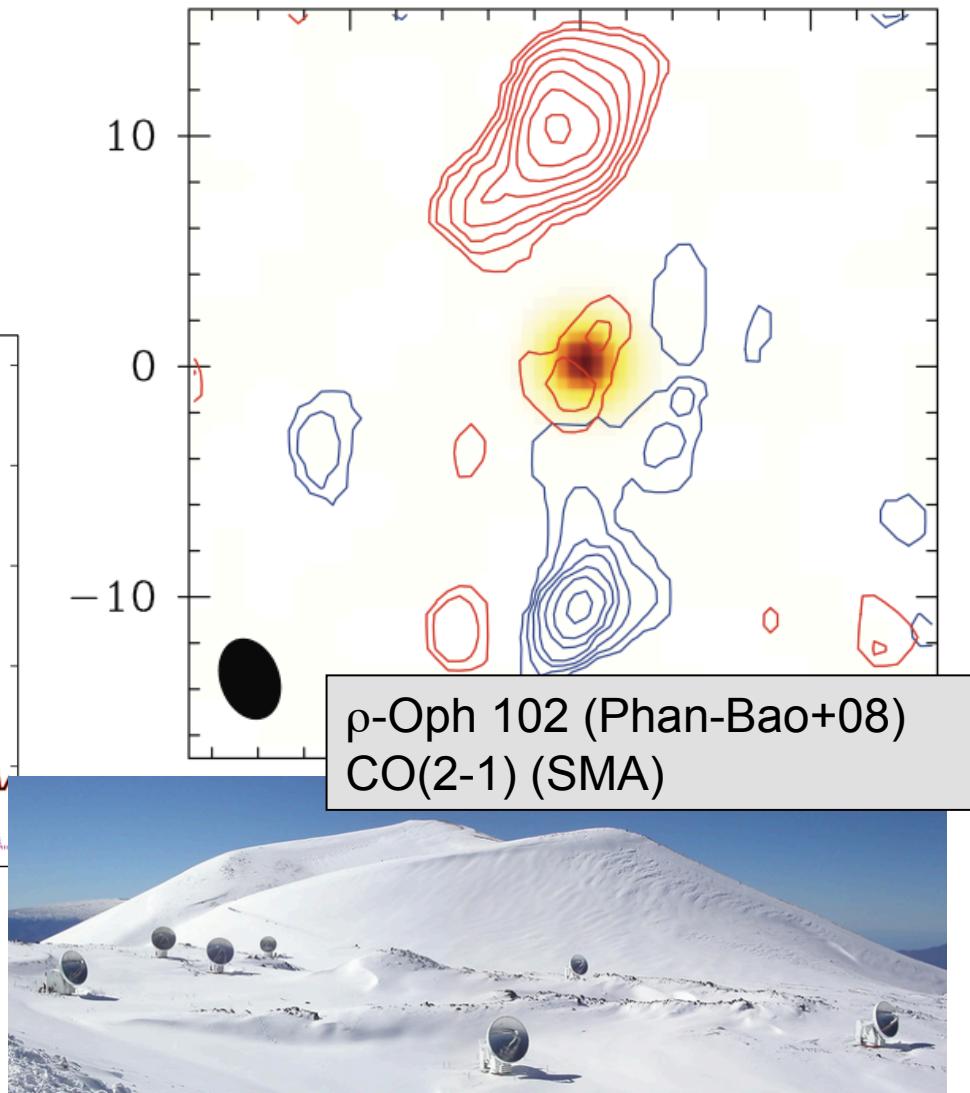
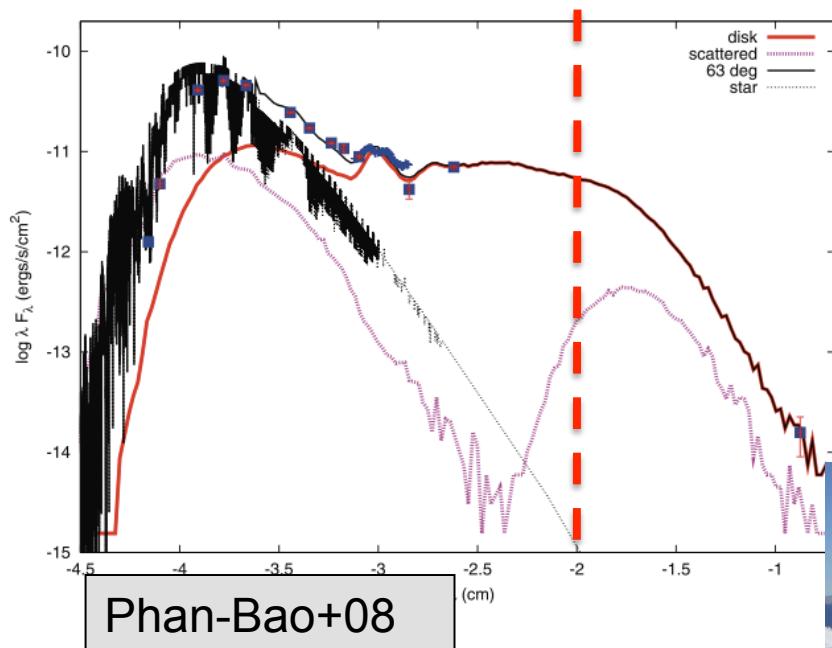
eg, Wu+04...

# Brown dwarf (BD) formation

$$0.013 M_{\text{sun}} < M_* < 0.075 M_{\text{sun}}$$



Confirmed BDs in the  
Class II/III phases  
eg,  $\rho$ -Oph 102 (Phan-Bao+08)



# Brown dwarf (BD) formation

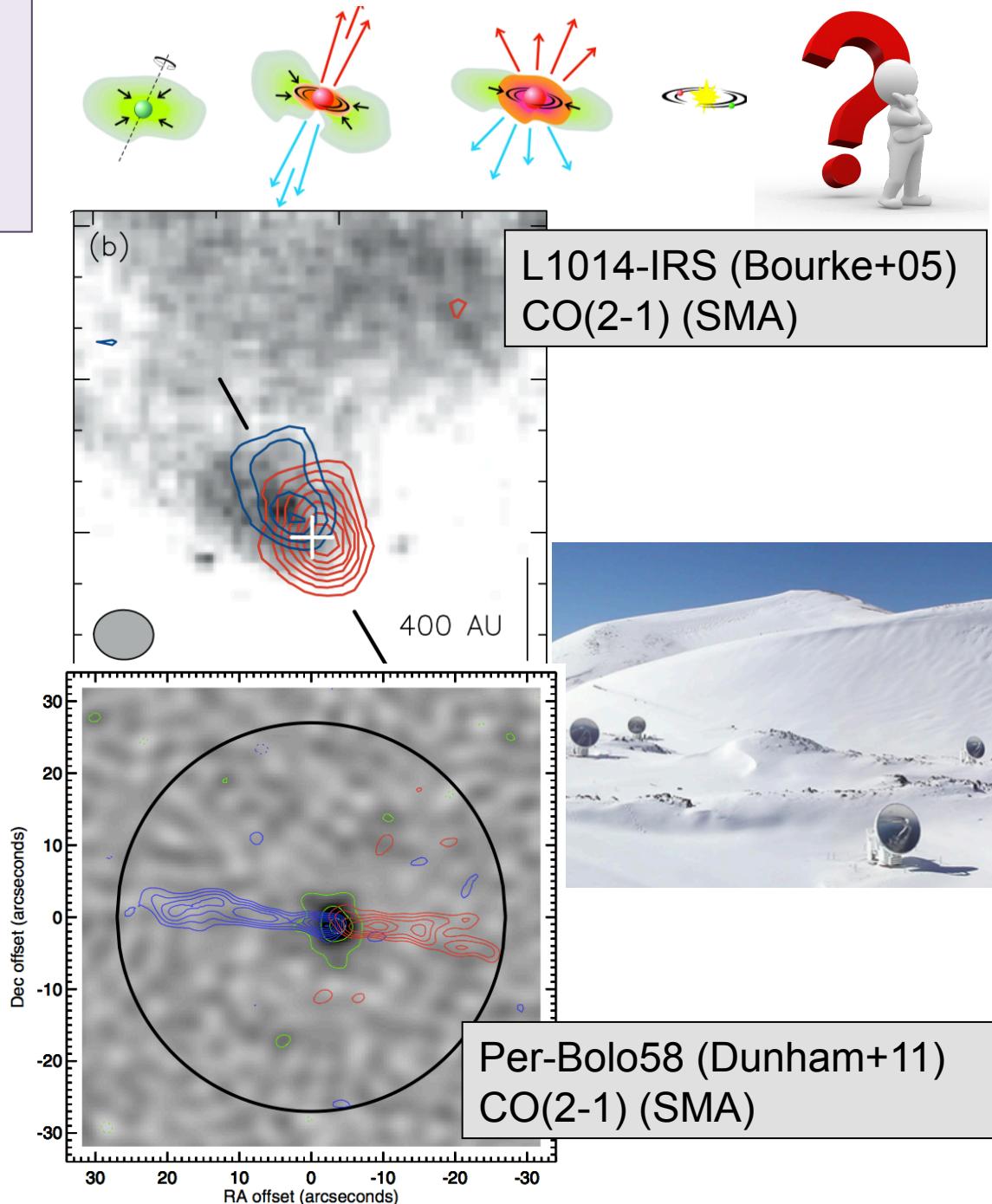
$$0.013 M_{\text{sun}} < M_* < 0.075 M_{\text{sun}}$$

**Very Low Luminosity Objects (VeLLOs):**  $L_{\text{int}} < 0.1 L_{\text{sun}}$

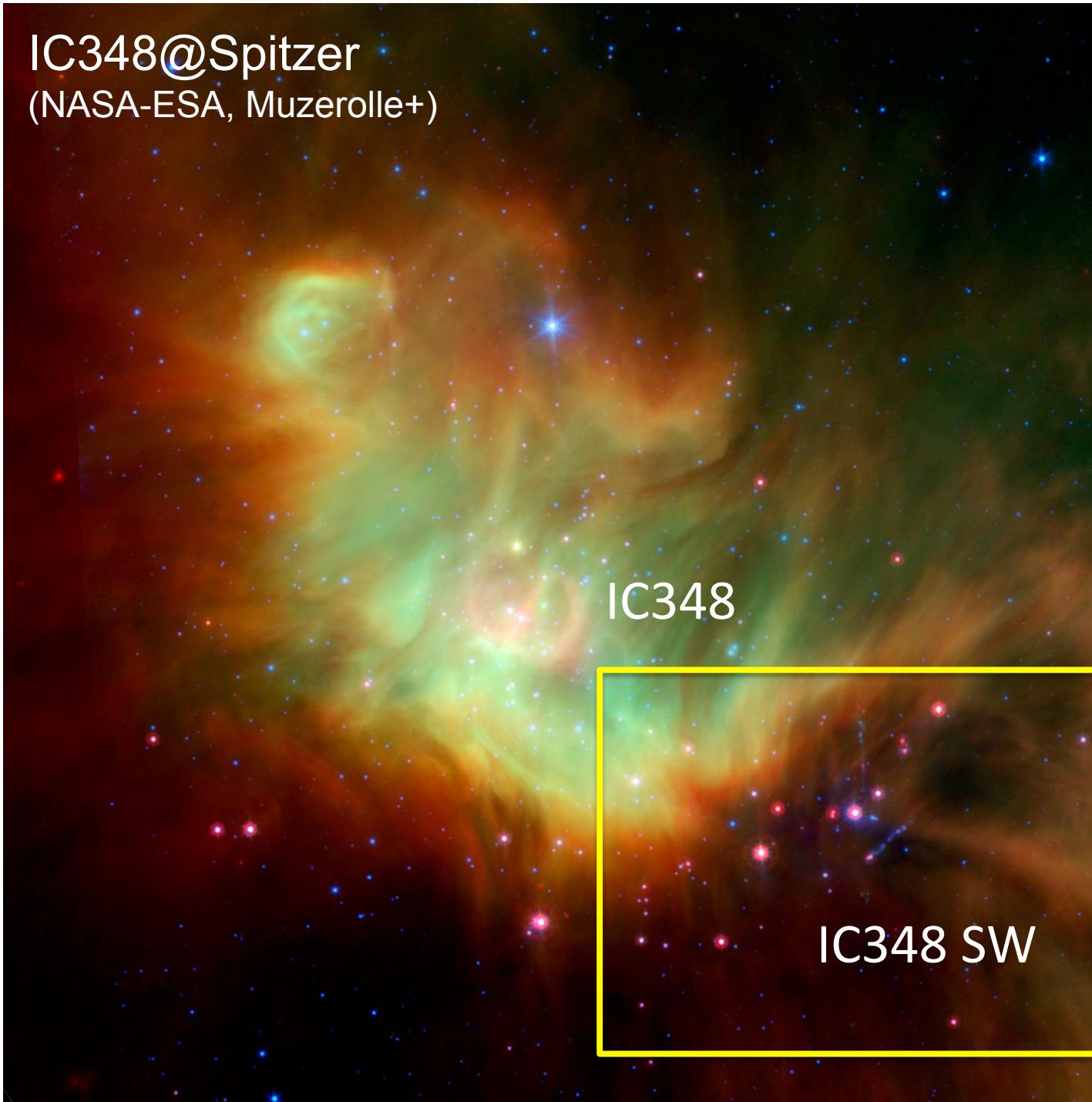
Class 0 proto-BD: L328-IRS  
(eg, Young+04, Dunham+08, Lee+13...)

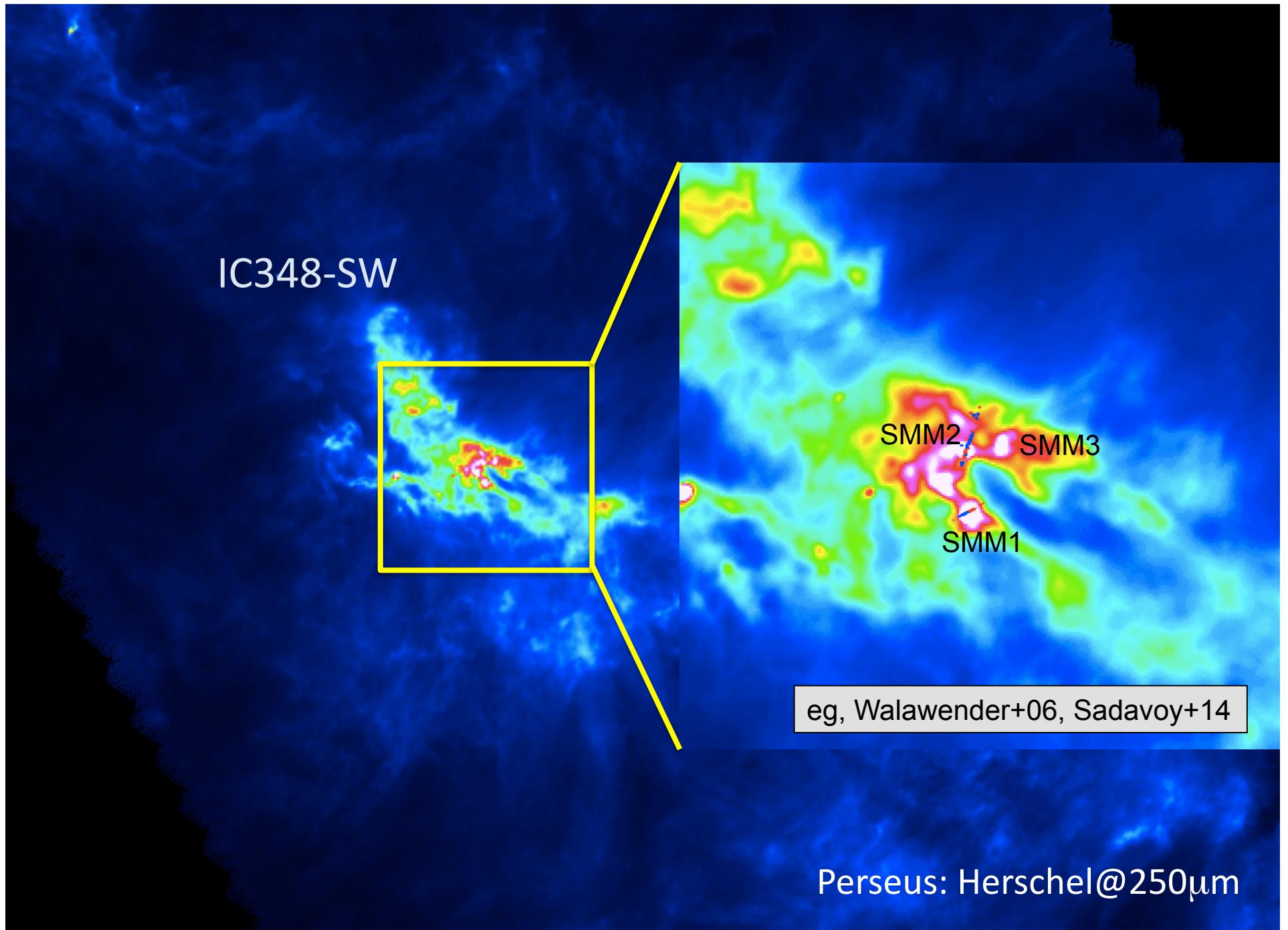
**First Hydrostatic Cores (FHCs):** density high enough to turn collapse from isothermal to adiabatic (eg, Dunham+11, Chen+10, 12)

**Clue property:**  
 $M_{\text{env}} \sim M_{\text{substellar-limit}}$



IC348@Spitzer  
(NASA-ESA, Muzerolle+)

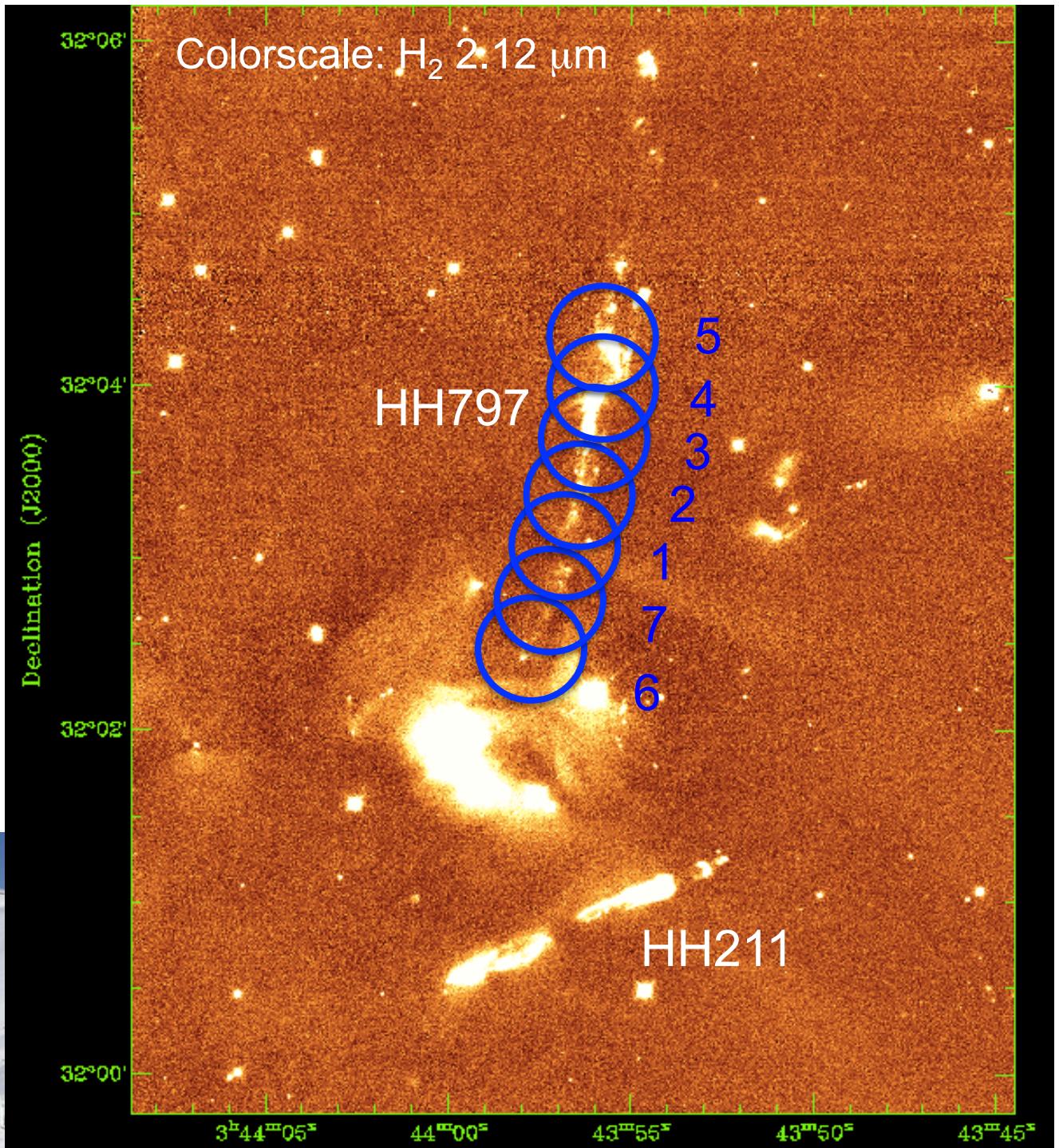




SMA  
observations:

345 GHz

7 pointings  
separated 17''  
PB~37''

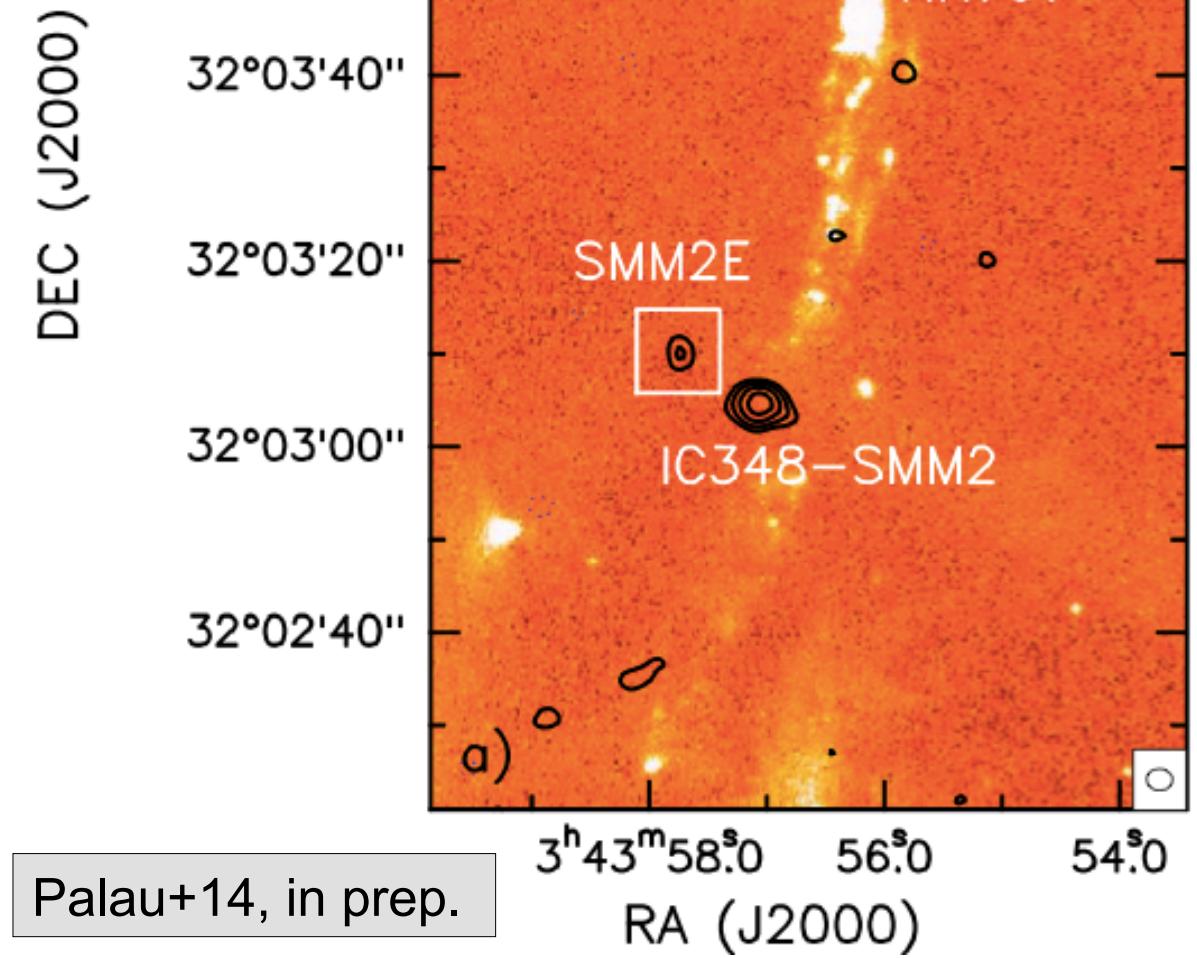


Results: continuum @ 870  $\mu$ m

SMM2: 250  $M_{Jup}$

SMM2E: 30  $M_{Jup}$

Assuming  $T_d=24K$  and dust opac OH94

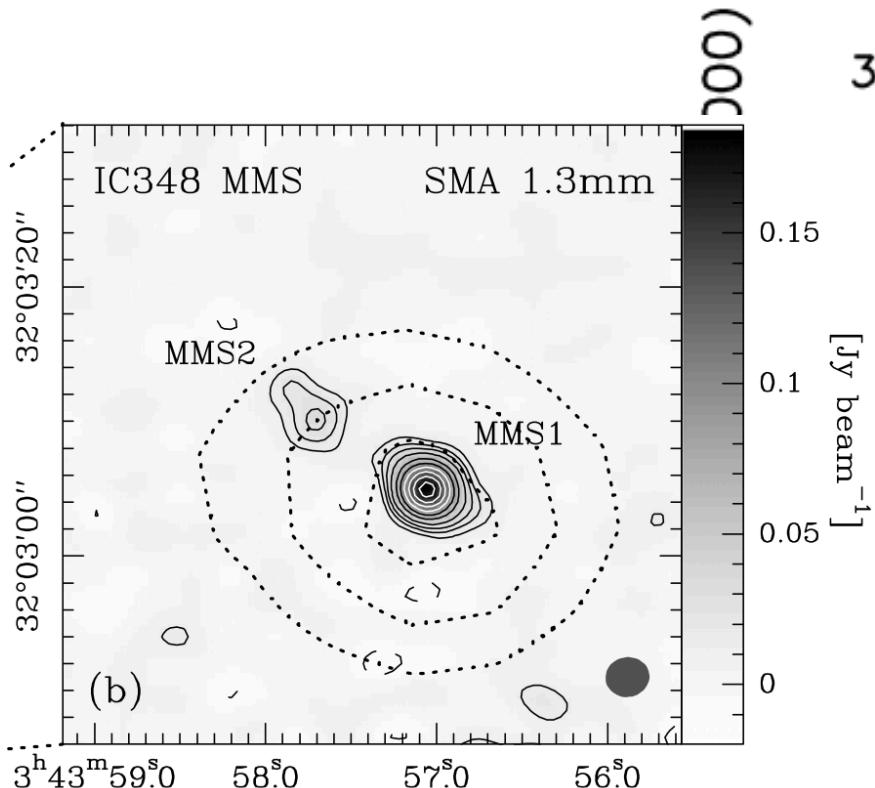


Results: continuum @ 870  $\mu$ m

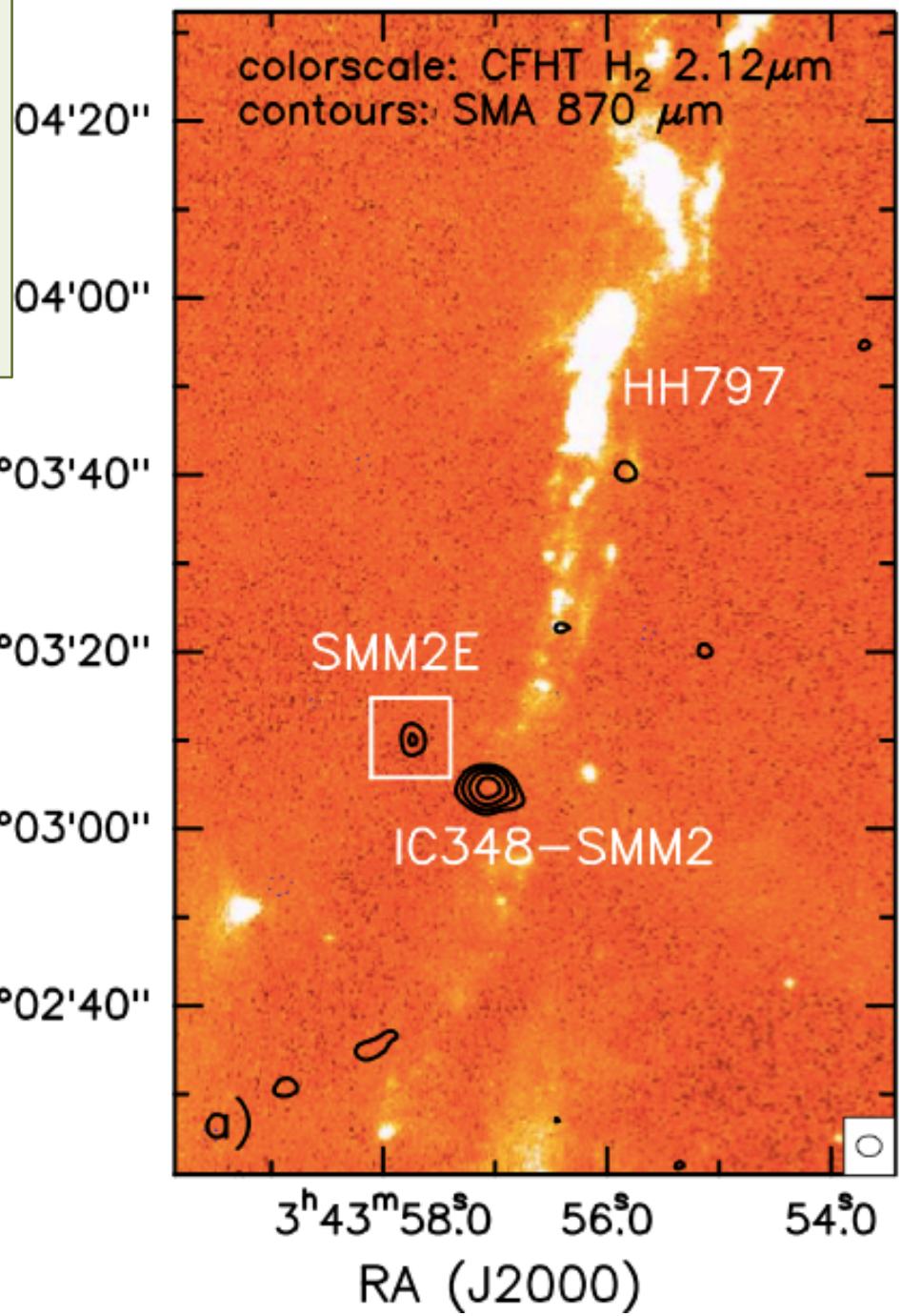
SMM2: 250 M<sub>Jup</sub>

SMM2E: 30 M<sub>Jup</sub>

Assuming T<sub>d</sub>=24K and dust opac OH94



Chen+13

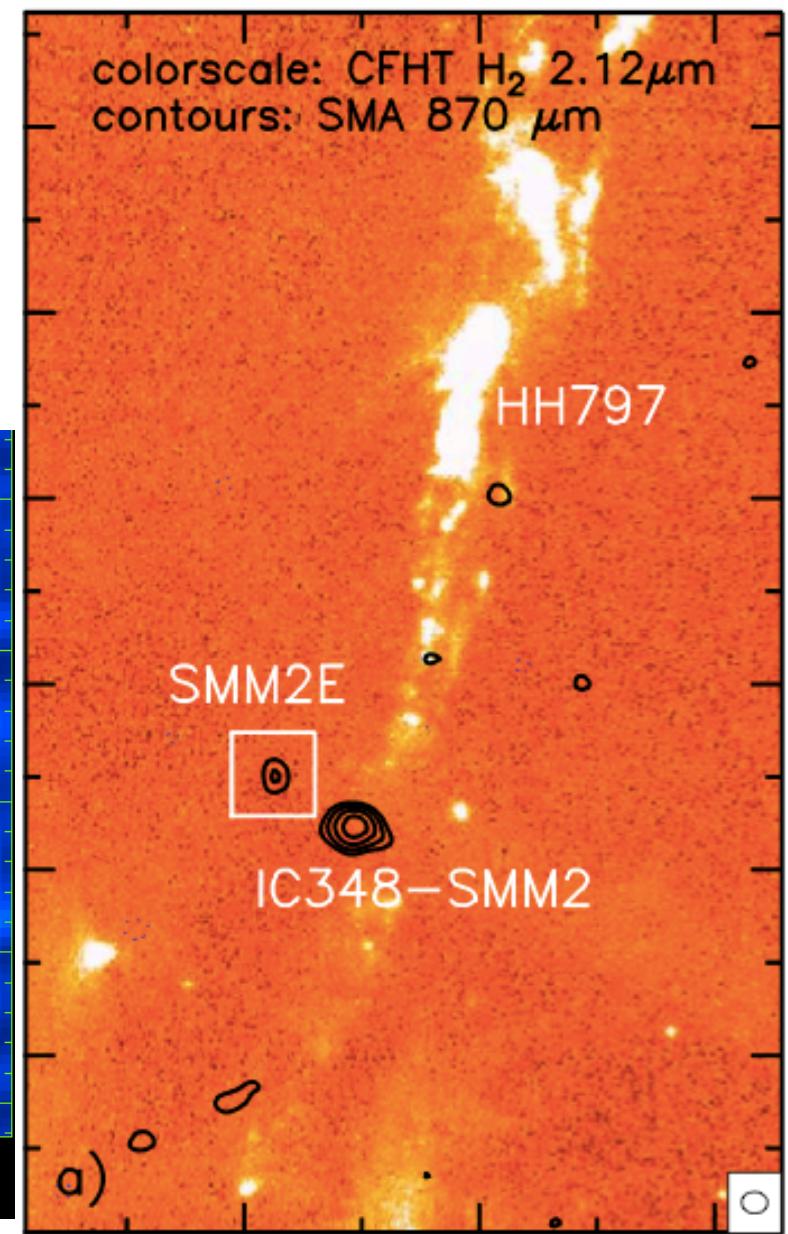
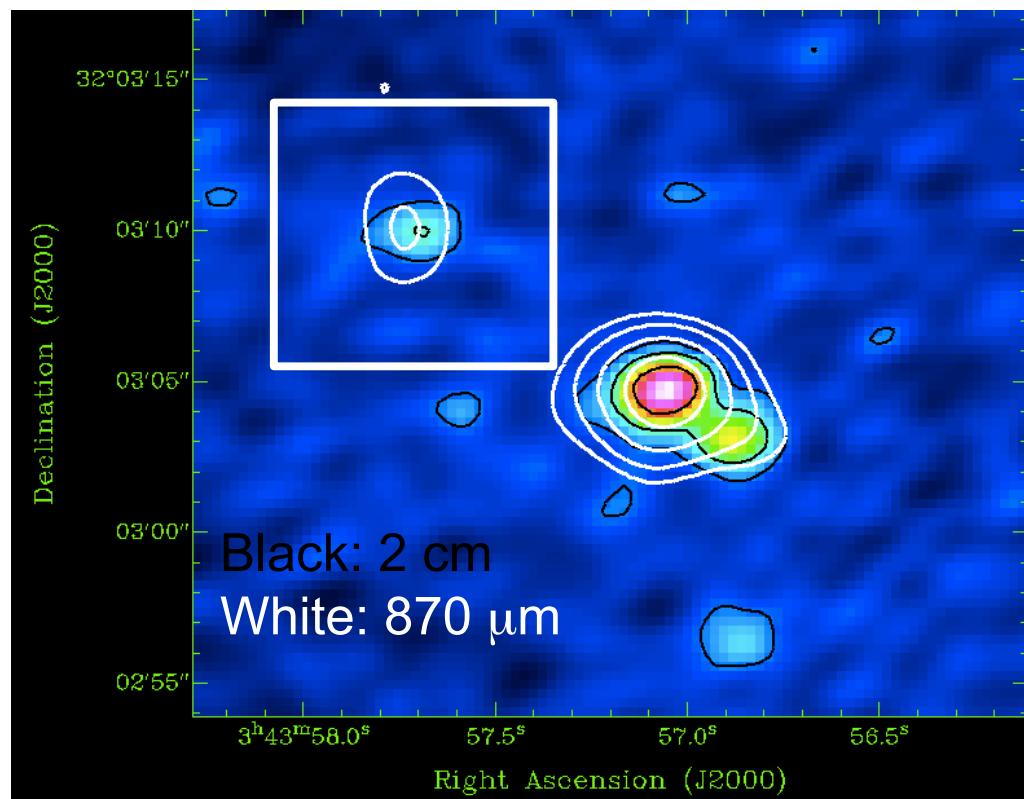


Results: continuum @ 870  $\mu$ m

SMM2: 250 M<sub>Jup</sub>

SMM2E: 30 M<sub>Jup</sub>

Assuming T<sub>d</sub>=24K and dust opac OH94



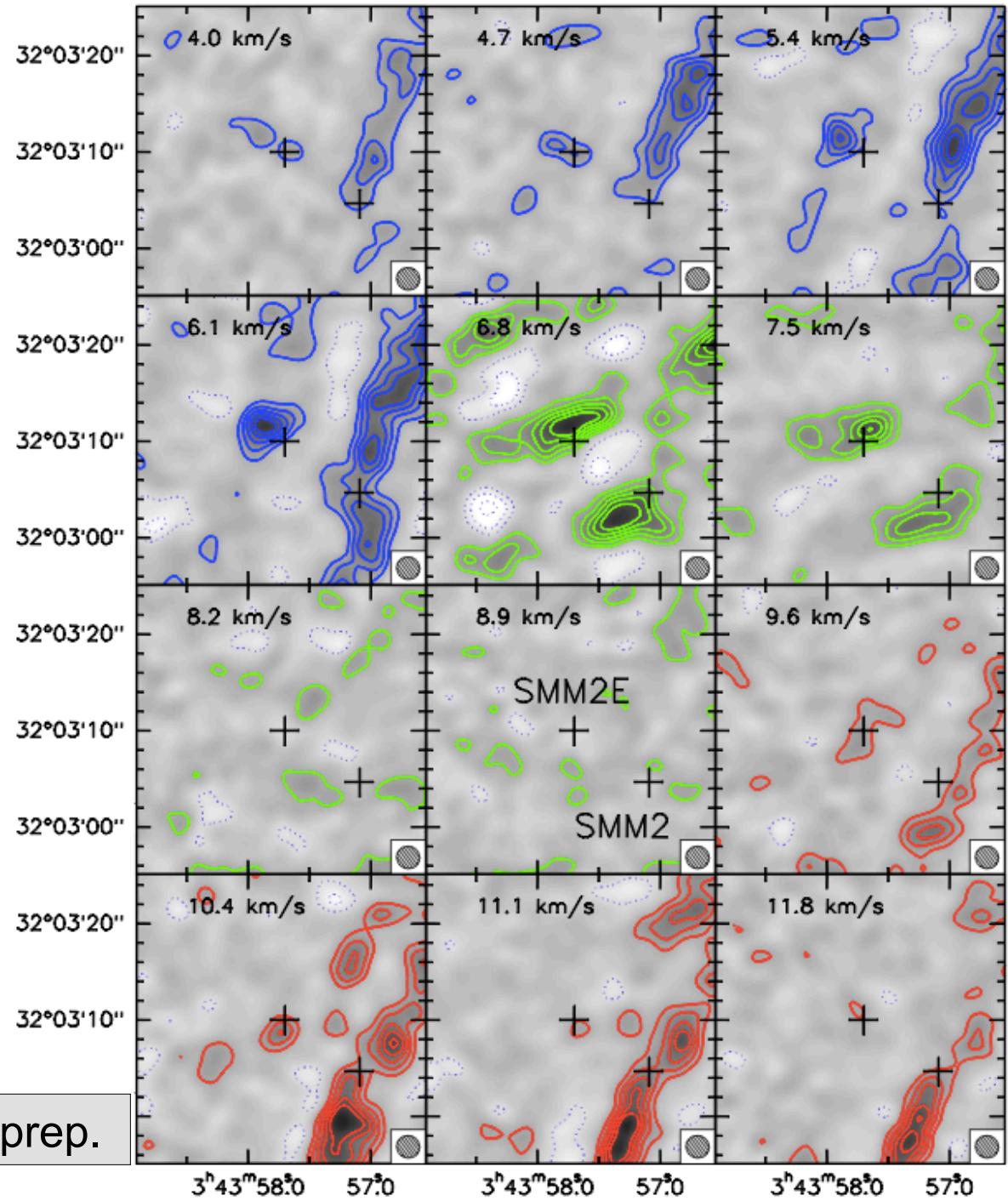
Colorscale + black contours: 2.1 cm (Rodríguez+14, accepted)

## Results: CO(3-2) channel map

Blue-shifted lobe  
up to  $\sim 4$  km/s  
with respect to  
systemic velocity

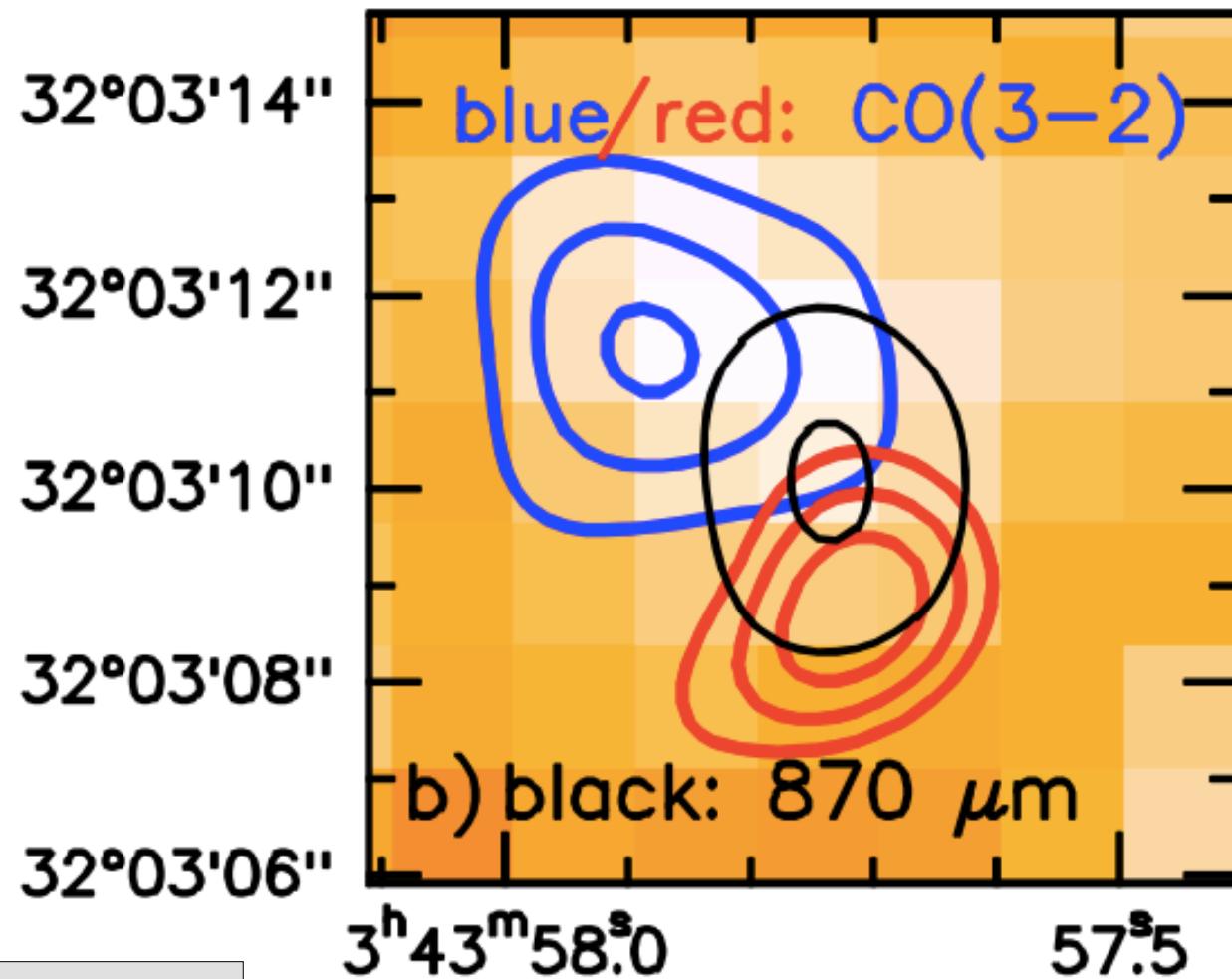
Very faint red-  
shifted lobe

Palau+14, in prep.



Results: moment zero

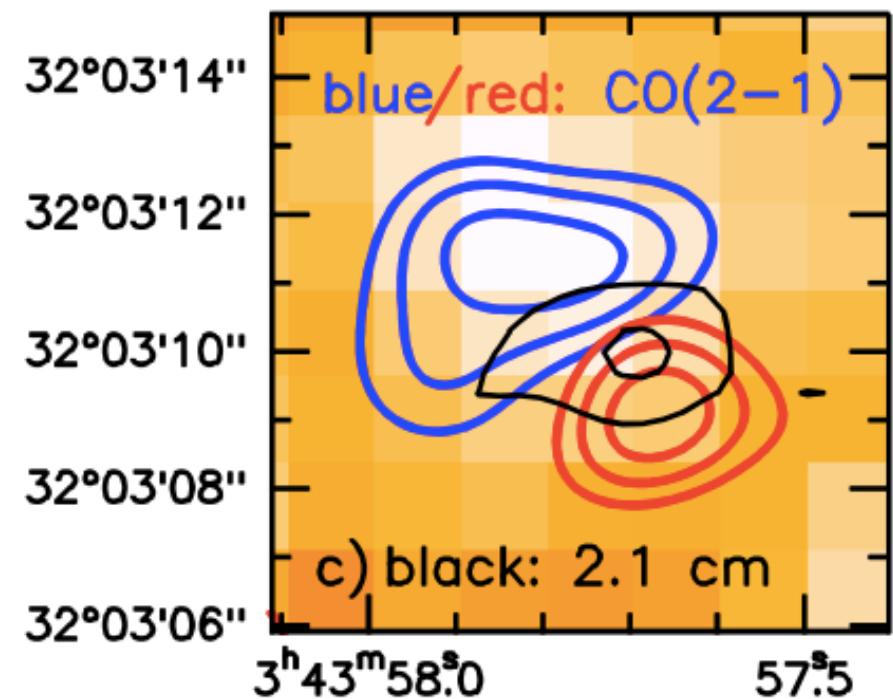
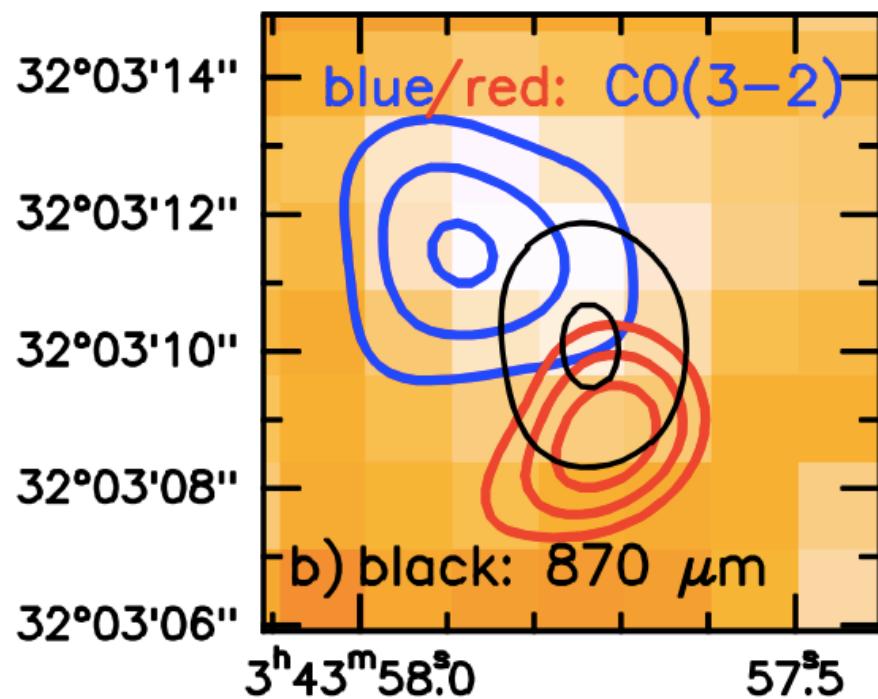
CO(3-2): 4.0–6.1 km/s, 9.7–11.1 km/s



## Results: moment zero

CO(3-2): 4.0–6.1 km/s, 9.7–11.1 km/s

CO(2-1): 5.4–7.5 km/s, 10.4–12.5 km/s (Pech+12)



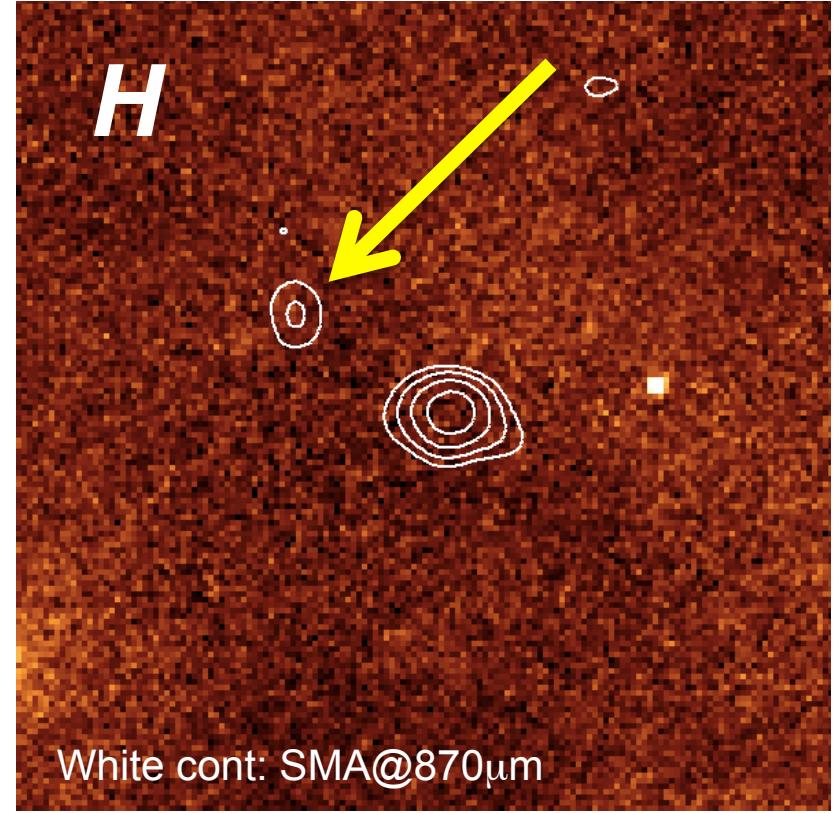
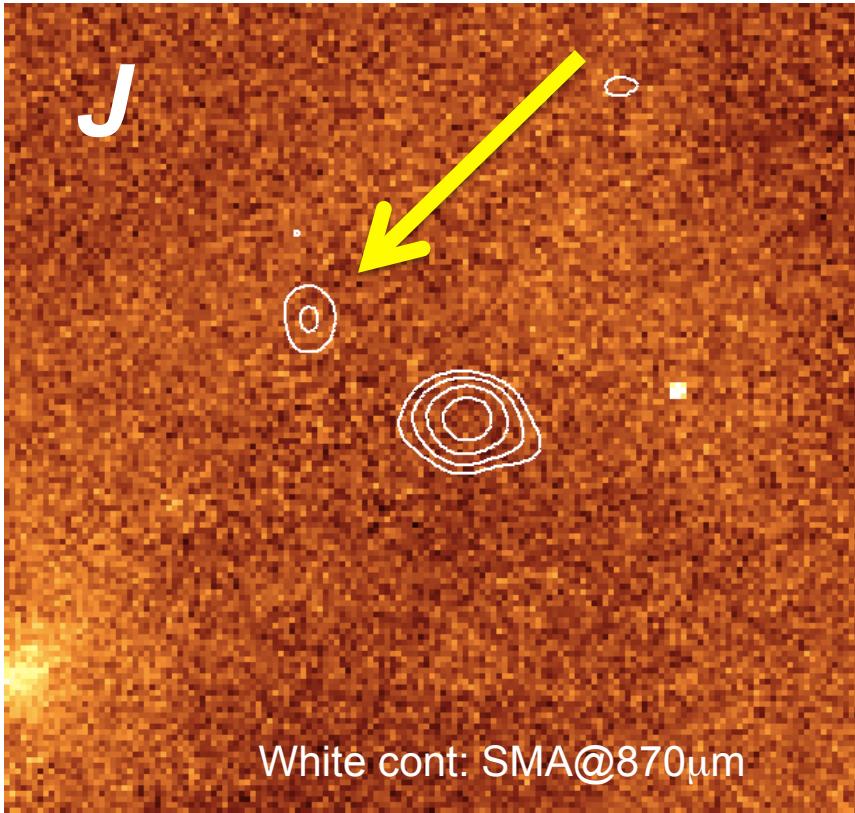
## Outflow parameters

	CO(2-1)	CO(3-2)
size (AU)	<b>480</b>	<b>390</b>
$t_{\text{dyn}}$ (yr)	<b>390</b>	<b>380</b>
$M_{\text{out}}$ ( $M_{\text{sun}}$ )	<b><math>5.4 \times 10^{-6}</math></b>	<b><math>5.1 \times 10^{-6}</math></b>
$M_{\dot{\text{out}}}$ ( $M_{\text{sun}} \text{ yr}^{-1}$ )	<b><math>1.4 \times 10^{-8}</math></b>	<b><math>1.4 \times 10^{-8}</math></b>
$P$ ( $M_{\text{sun}} \text{ km s}^{-1}$ )	<b><math>3.0 \times 10^{-5}</math></b>	<b><math>1.8 \times 10^{-5}</math></b>
$P_{\dot{\text{out}}}$ ( $M_{\text{sun}} \text{ km s}^{-1} \text{ yr}^{-1}$ )	<b><math>7.8 \times 10^{-8}</math></b>	<b><math>4.9 \times 10^{-8}</math></b>
$E_{\text{kin}}$ (erg)	<b><math>1.7 \times 10^{38}</math></b>	<b><math>6.6 \times 10^{38}</math></b>
$L_{\text{mech}}$ ( $L_{\text{sun}}$ )	<b><math>2.0 \times 10^{-5}</math></b>	<b><math>7.2 \times 10^{-6}</math></b>

Ok and... any optical/NIR counterpart?



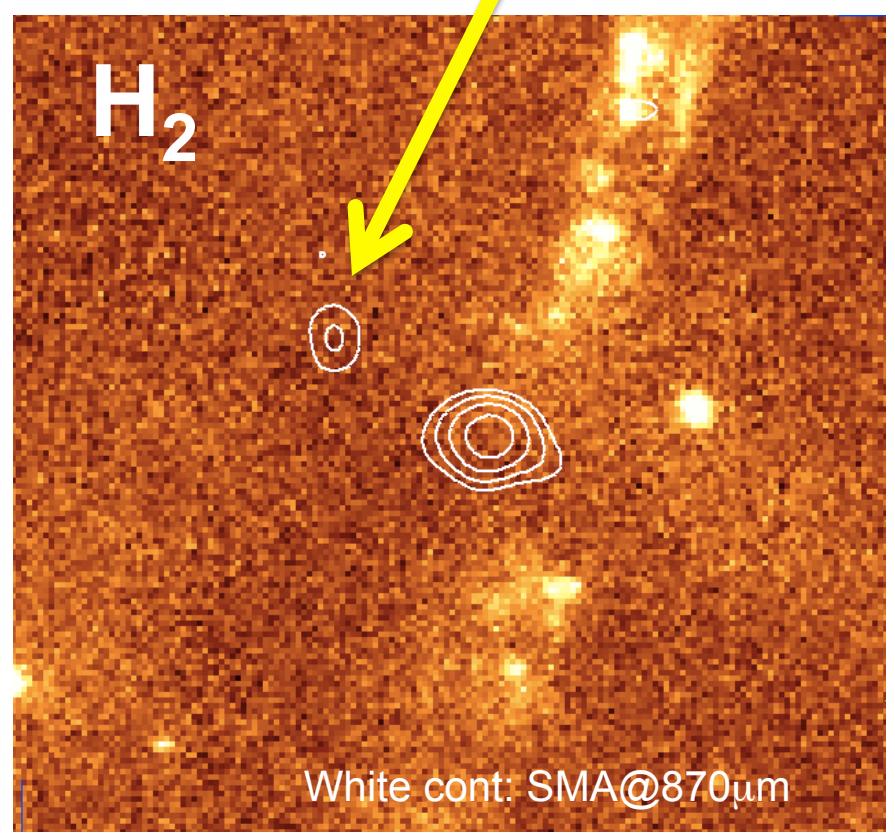
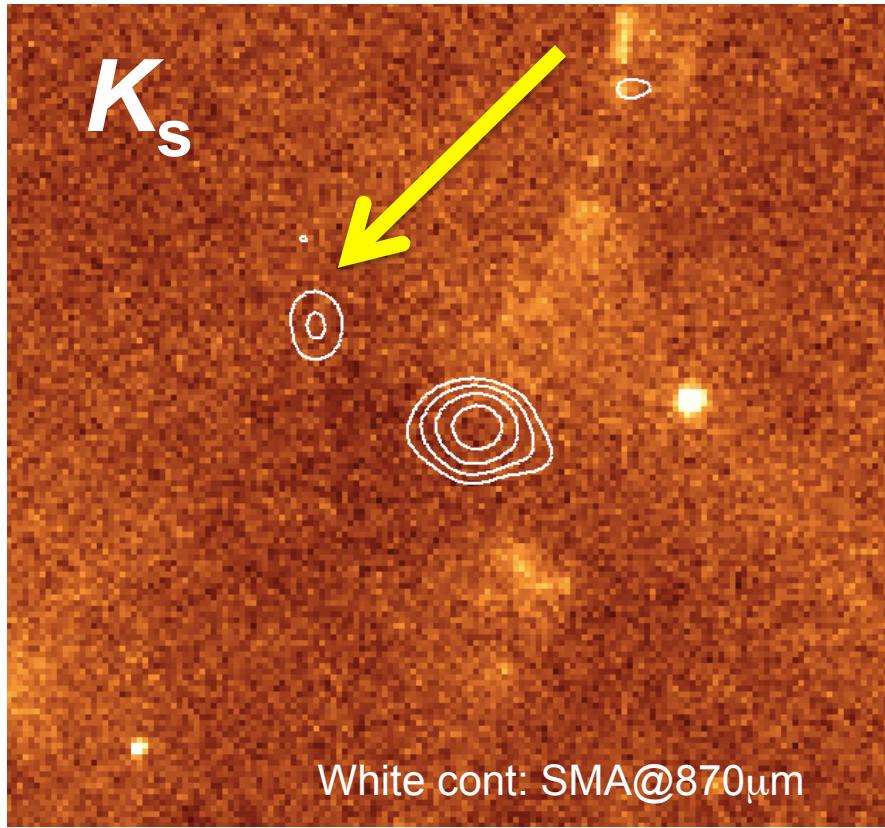
## A multiwavelength study: optical + NIR CFHT archive



**Colorscale: CFHT/WIRcam  $J, H$  (1.25, 1.65  $\mu$ m):  
NO DETECTIONS!**

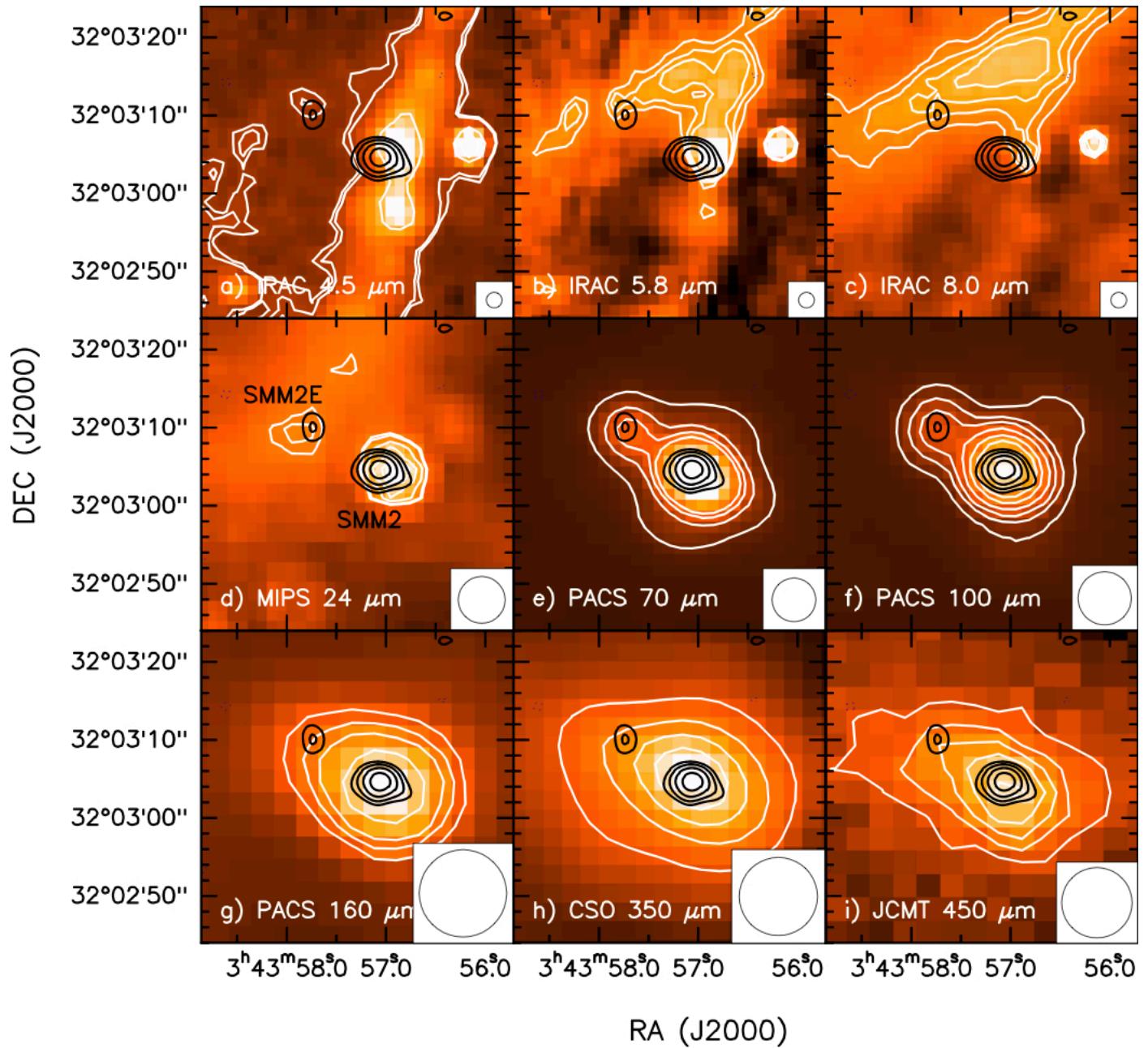


## A multiwavelength study: optical + NIR CFHT archive

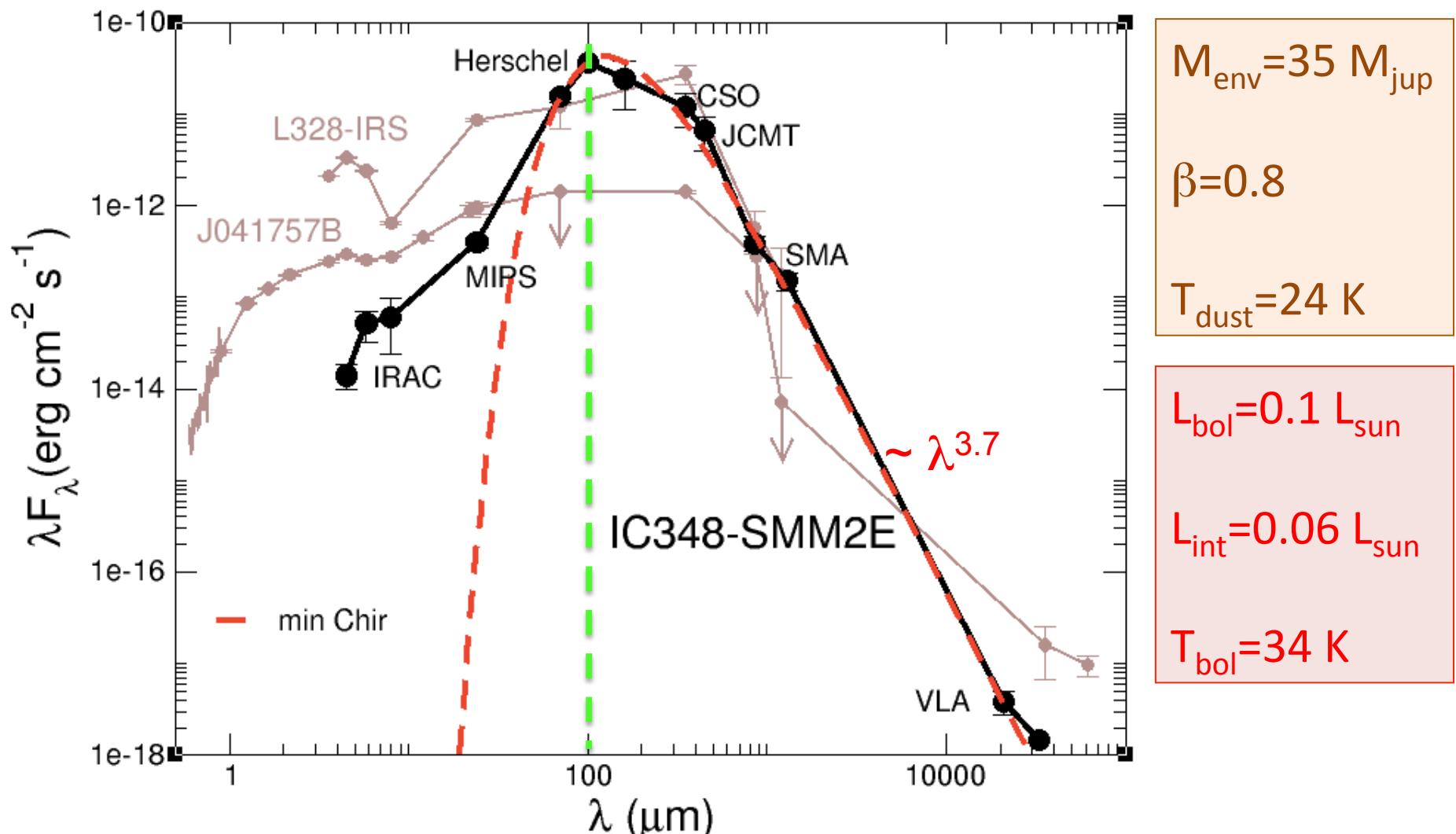


**Colorscale: CFHT/WIRcam  $K_s$ ,  $H_2$  (2.17, 2.12 μm):  
NO DETECTIONS!**

# A multiwavelength study: MIR + FIR

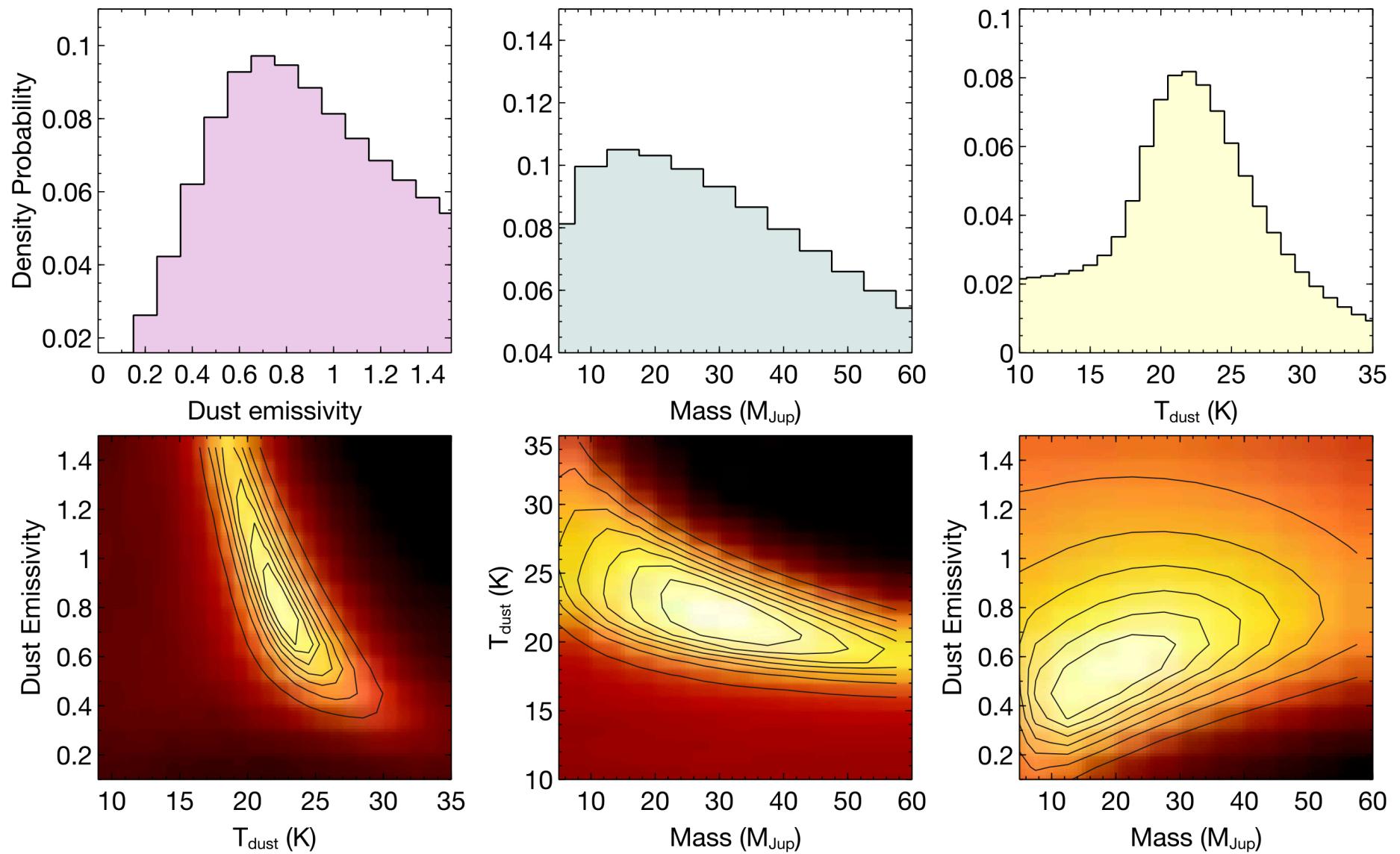


## SED and modified black body



One modified BB fits SED in the range  $70 \mu\text{m} - 2.1 \text{ cm}$   
cm emission produced by thermal dust

# SED and modified black body: Bayesian analysis



$\beta=0.7$  (0.6-1)

$M_{\text{env}}=15$  (10-30)  $M_{\text{Jup}}$

$T_{\text{dust}}=22$  (20-24) K

## Will IC348-SMM2E remain substellar?

$$L_{acc} = \eta_L \frac{G m_* \dot{M}_{acc}}{R_*}$$

Adopt:

$L_{acc} \sim L_{int} \sim 0.06 L_{\text{sun}}$

$R_* \sim 0.1 - 1 R_{\text{sun}}$

$\eta_L \sim 0.5$  (Hartmann98)

Total mass = accreted mass + reservoir of mass

Accreted mass:

$$m_* = \frac{R_* L_{acc}}{\eta_L G \dot{M}_{acc}}$$

T~10K

$$1) \dot{M}_{acc} = \eta_{\dot{M}} \frac{c_s^3}{G} \rightarrow \dot{M}_{acc} = \frac{\eta_{\dot{M}}}{G} \left( \frac{kT}{\mu m_H} \right)^{3/2}$$

$\dot{M}_{acc} \sim 5 \times 10^{-7} M_{\text{sun}} \text{ yr}^{-1}$

$m_* \sim 2 - 24 M_{\text{Jup}}$

$$2) \dot{M}_{acc} = \frac{1}{f_{\text{ent}}} \frac{\dot{M}_{acc}}{\dot{M}_W} \frac{1}{V_W} F_{\text{outflow}}$$

i~32.7deg

$\dot{M}_{acc} \sim 4 \times 10^{-8} M_{\text{sun}} \text{ yr}^{-1}$

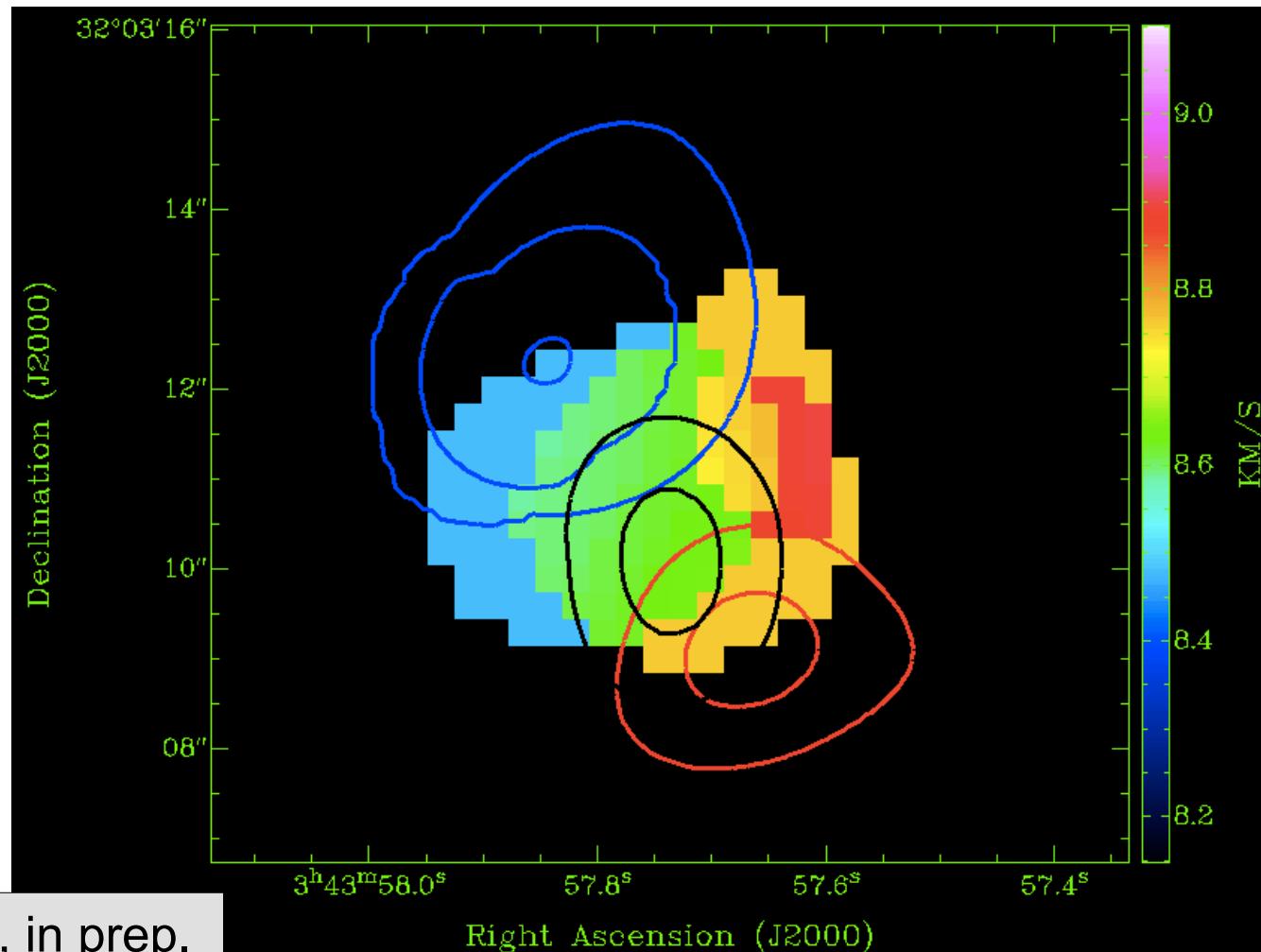
$m_* \sim 9 - 89 M_{\text{Jup}}$

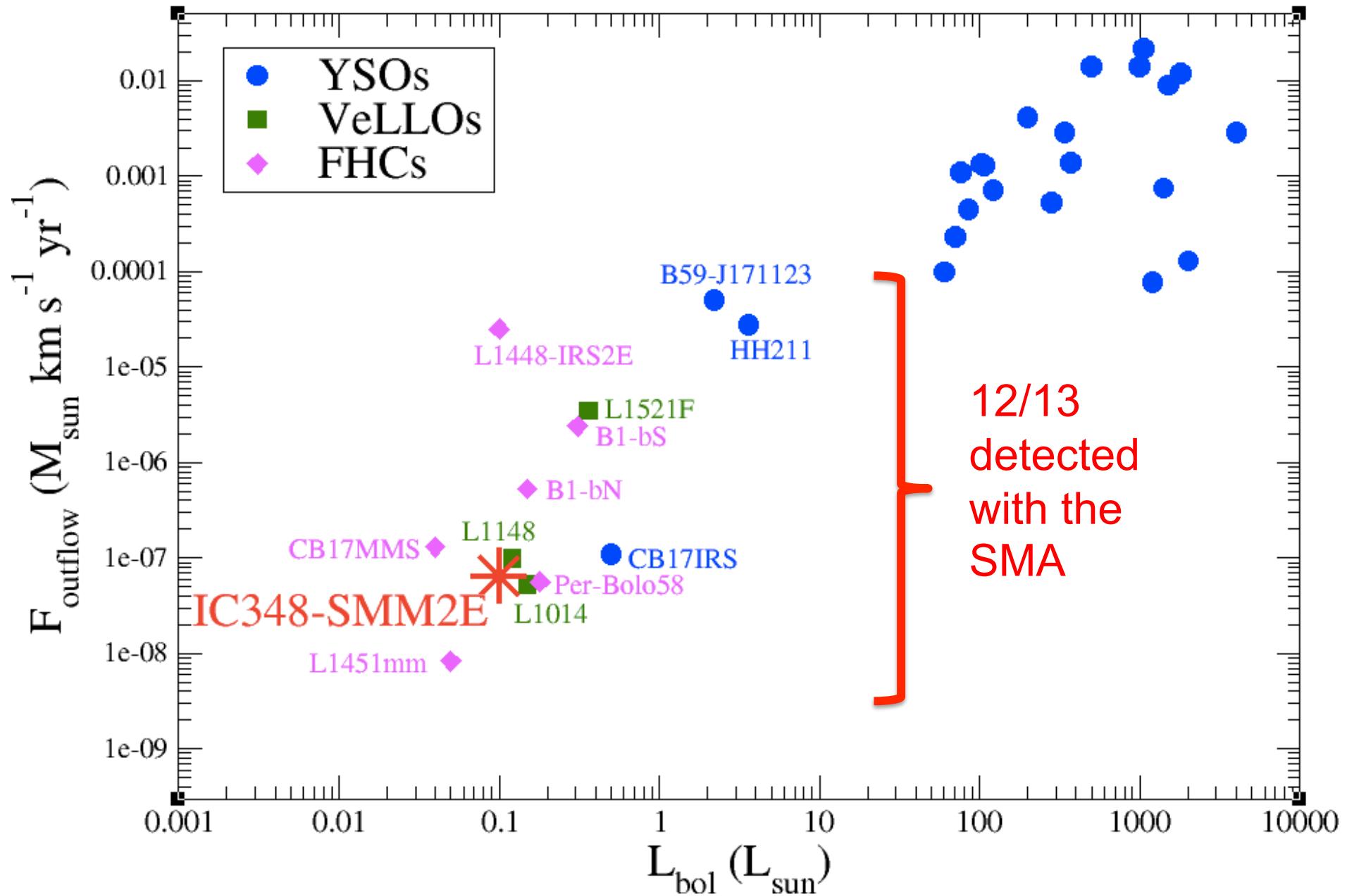
Reservoir of mass which could still be accreted:

$M_{\text{env}} < 30 M_{\text{Jup}}$

$M_{\text{tot}} < 119 M_{\text{Jup}}$

SMA correlator setup included other lines in sidebands  
 $\text{C}^{18}\text{O}(2-1)$ : peaks around 8.5 km/s,  
velocity gradient perp to outflow,  $M_{\text{dyn}} \sim 16 M_{\text{Jup}}$

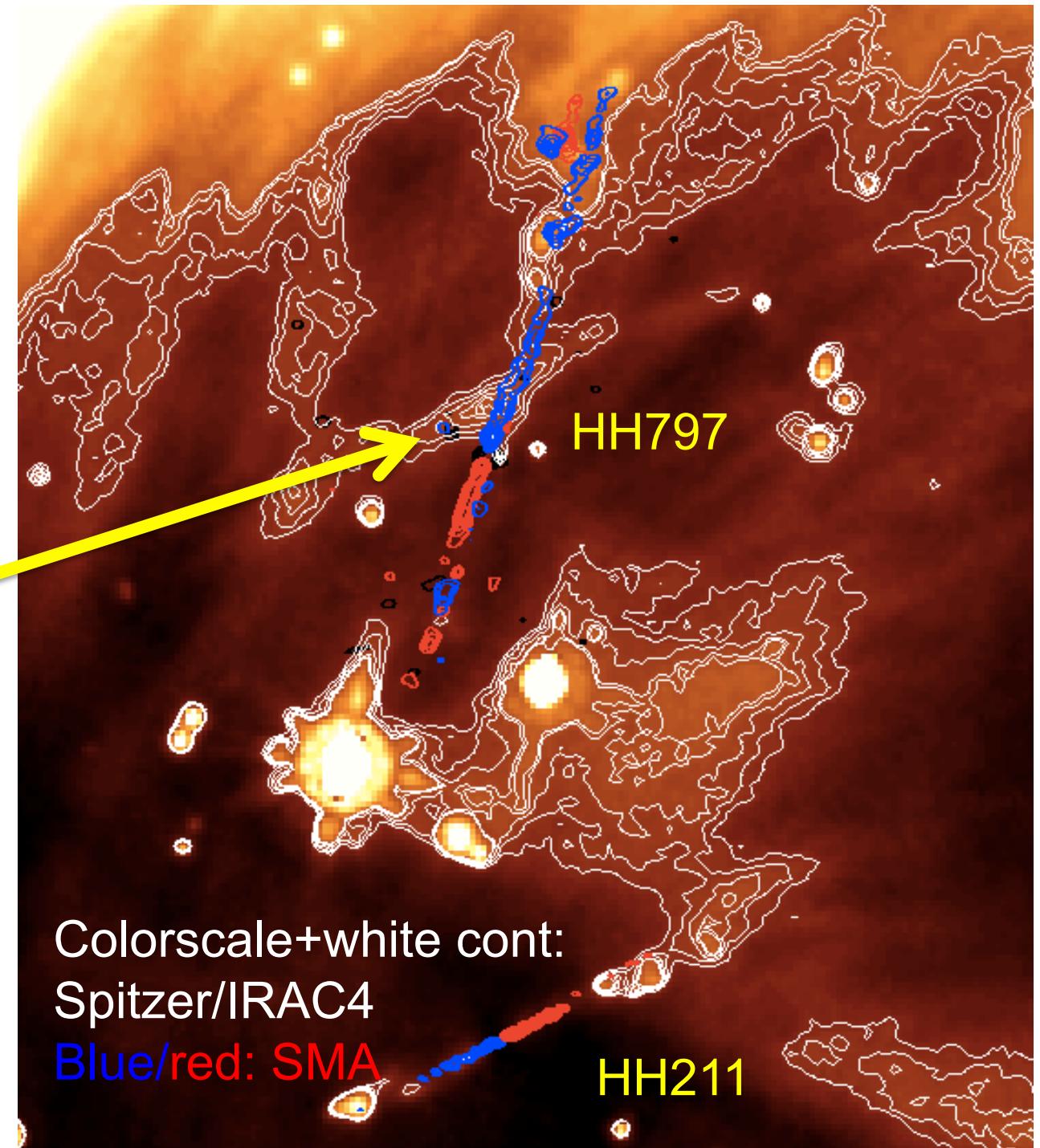




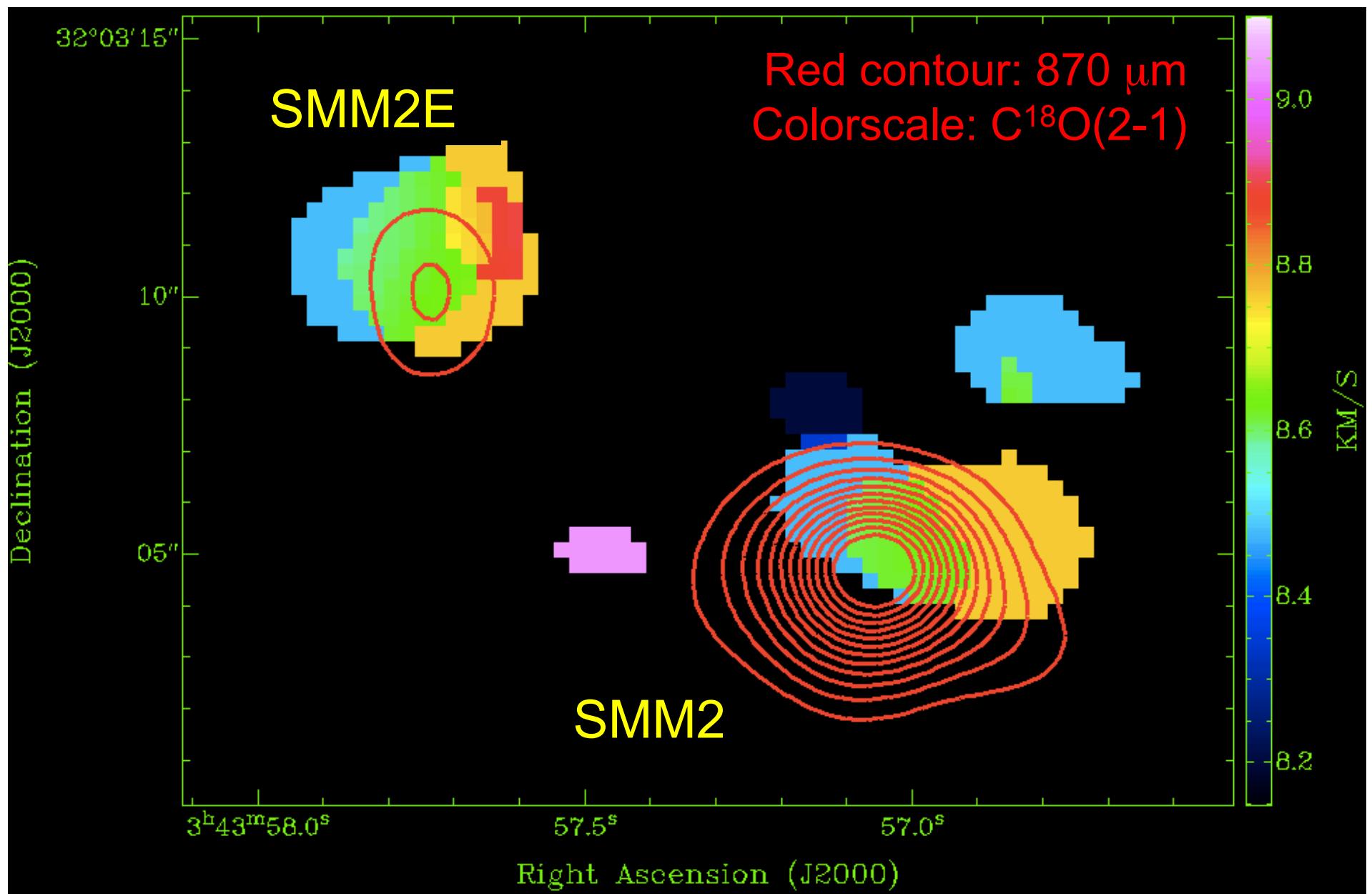
Are SMM2E  
and SMM2  
gravitationally  
bound?

Large-scale  
environment...

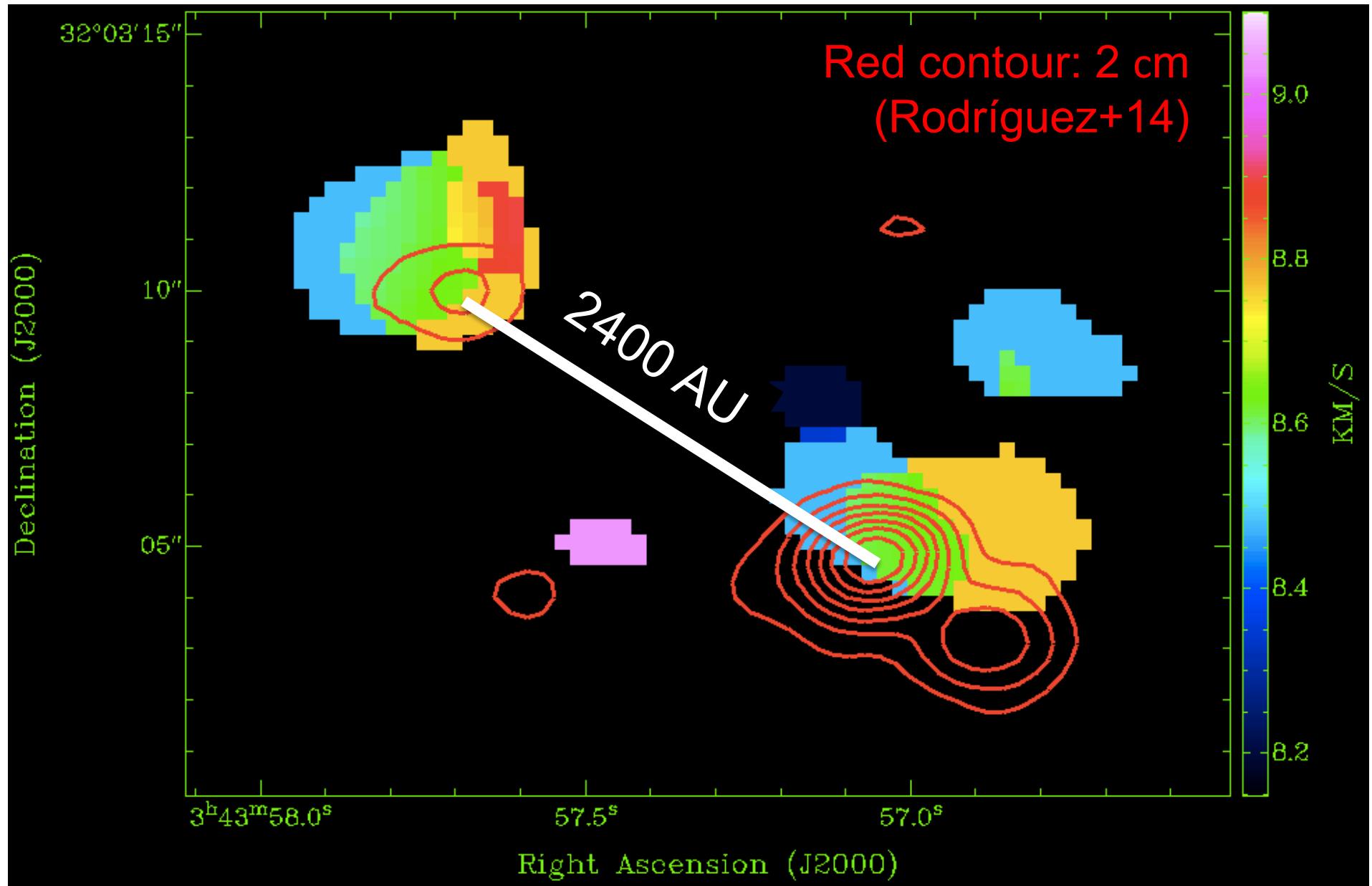
SMM2E



SMM2E and SMM2 could be a binary system...



...of  $\sim$ 2400 AU of separation, and mass ratio  $\sim$ 0.2: fragile! (Chen+13)



Whatever its formation scenario is...

It is forming as a scaled-down version of low-mass stars



Thanks!

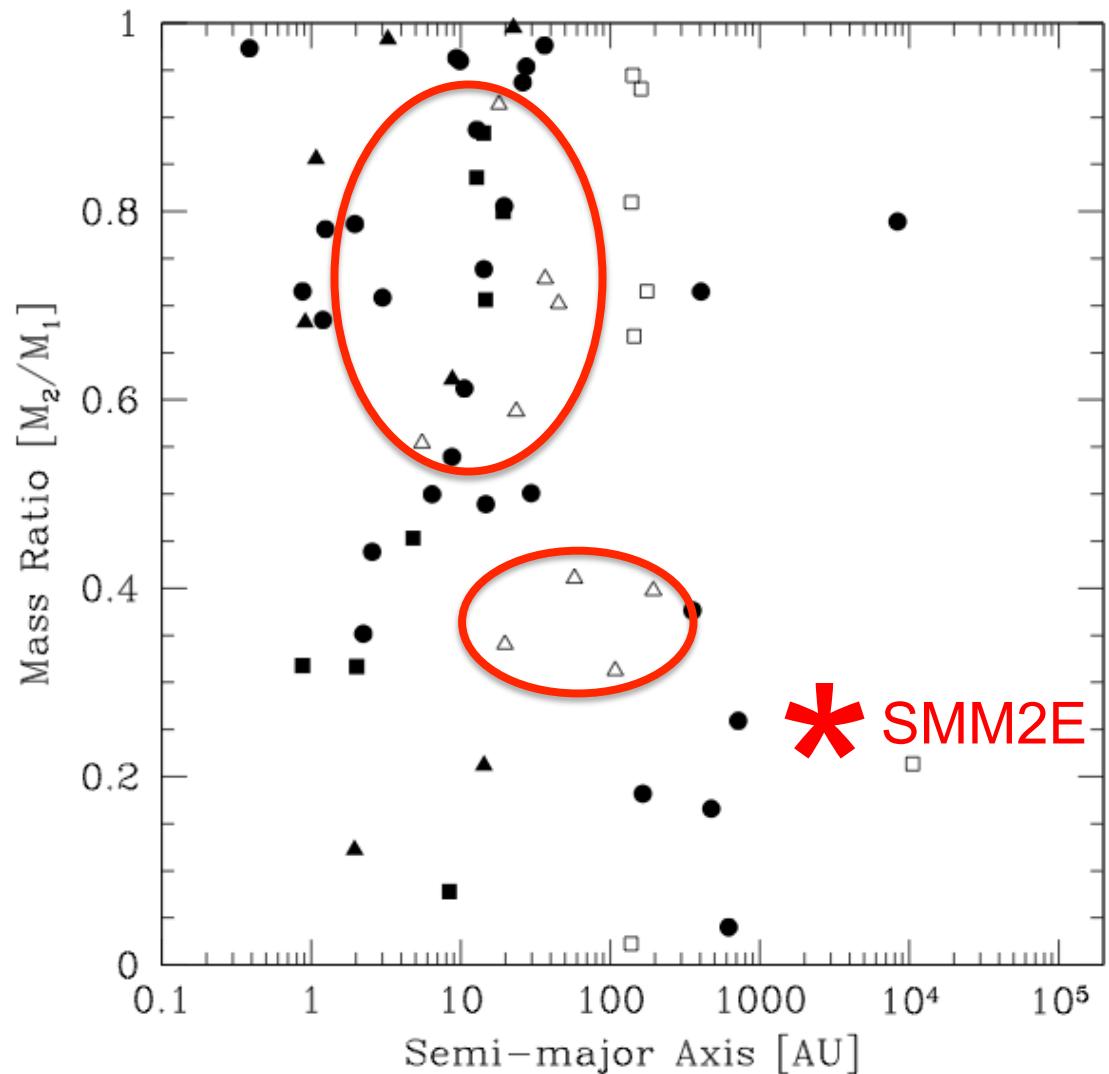


...Not likely disk fragmentation, neither ejection from cluster

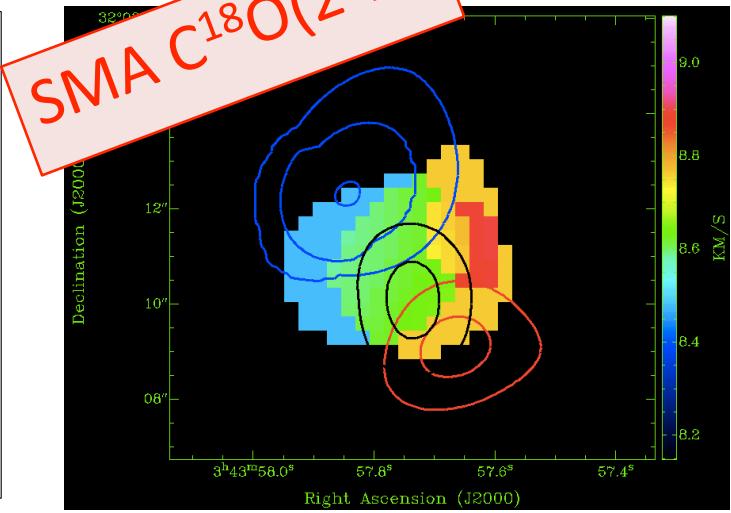
Bate 2012:

Open triangles:  
wide triples

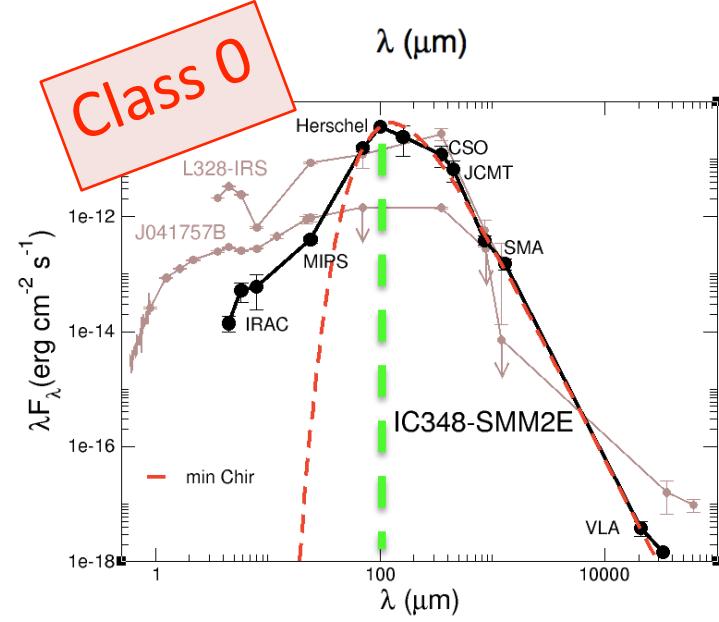
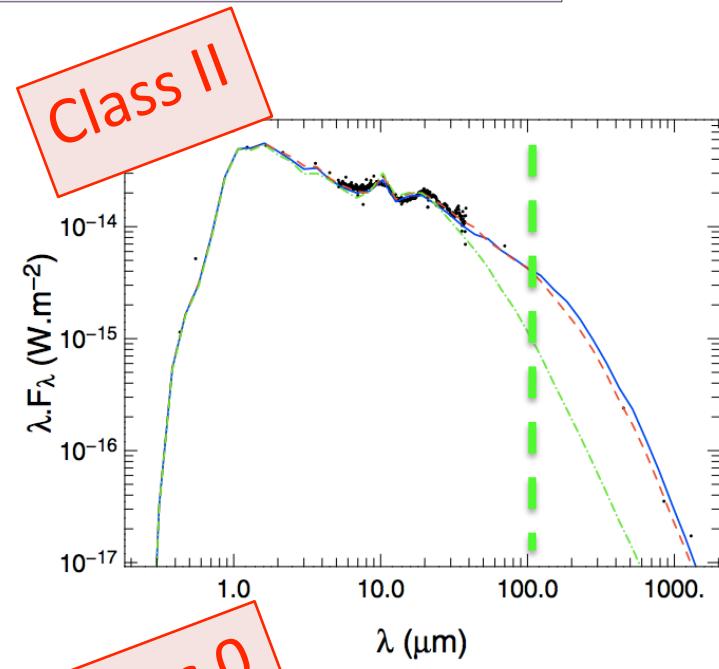
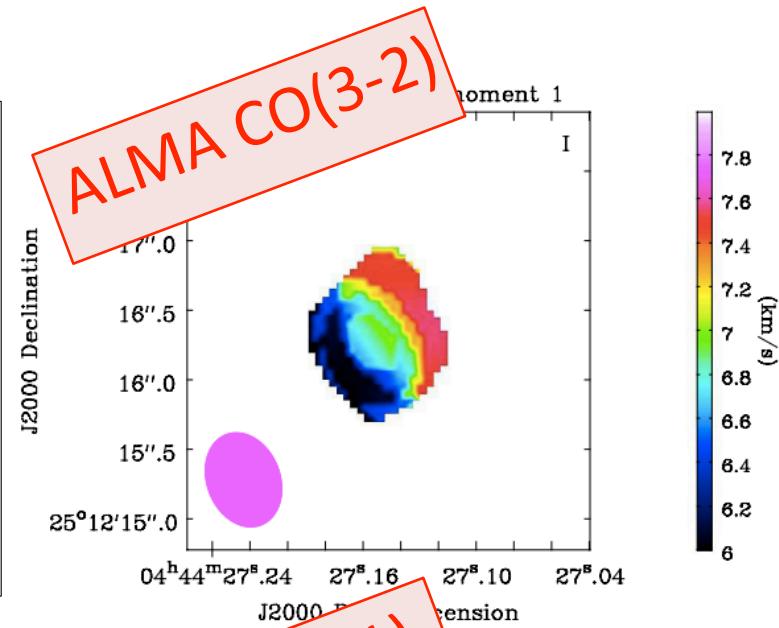
But too small  
numbers...



**IC348-SMM2E**  
(Palau+14, submit'd)



**2M0444+2512**  
(Ricci+14)



**Disks in other BDs: ALMA CO(3-2) (Ricci+14)**

**Table 4. Summary properties of VeLLOs and FHCs**

Source	$T_{\text{bol}}$ (K)	$L_{\text{bol}}$ ( $L_{\odot}$ )	$L_{\text{int}}$ ( $L_{\odot}$ )	$M_{\text{env}}^{\text{a}}$ ( $M_{\odot}$ )	$F_{\text{out}}^{\text{SD}}{}^{\text{b}}$ ( $M_{\odot}$ km s $^{-1}$ yr $^{-1}$ )	$F_{\text{out}}^{\text{interf}}{}^{\text{b}}$ ( $M_{\odot}$ km s $^{-1}$ yr $^{-1}$ )	Refs. <sup>c</sup>
<b>VeLLOs</b>							
IRAM04191	18	0.15	0.07	0.60	$1.5 \times 10^{-5}$	—	1
L1521F-IRS	25	0.36	0.04	0.87	—	$3.5 \times 10^{-6}$	2, 3
L1148-IRS	110	0.12	0.10	0.14	—	$1.0 \times 10^{-7}$	4
L673-7-IRS	16	0.18	0.04	0.39	$1.0 \times 10^{-6}$	—	5, 6
L1014-IRS	154	0.15	0.09	0.36	—	$5.3 \times 10^{-8}$	7, 8
L328-IRS	44	0.14	0.05	0.09	$2.0 \times 10^{-7}$	—	9, 10
GF9-2	20	0.30	< 0.3	—	$6.1 \times 10^{-8}$	—	11, 12
J041757B	155	0.003	< 0.003	0.01	—	—	13, 14
IC348-SMM2E	34	0.10	0.06	0.03	—	$1.4 \times 10^{-8}$	15
<b>FHCs</b>							
Cha-MMS1	20	0.45	0.15	0.80	—	—	16, 17
Per-Bolo58	19	0.18	0.012	1.00	—	$5.6 \times 10^{-8}$	18, 19
L1448-IRS2E	—	< 0.1	< 0.1	0.50	—	$2.5 \times 10^{-5}$	20
L1451-mm	30	0.05	< 0.03	0.15	—	$8.3 \times 10^{-9}$	21
CB17-MMS	< 16	< 0.04	< 0.04	4.0	—	$1.3 \times 10^{-7}$	22, 23
B1-bS	22	0.31	0.1–0.2	7.3	—	$2.4 \times 10^{-6}$	24, 25, 26
B1-bN	17	0.15	< 0.03	9.4	—	$5.3 \times 10^{-7}$	24, 25, 26

<sup>a</sup> Envelope masses taken from Kauffmann et al. (2011) when available (being thus the mass measured with a single-dish within a radius of 4200 AU). For objects not included in the compilation of Kauffmann et al. (2011) the envelope masses are those measured with single-dish as reported in the literature.

<sup>b</sup>  $F_{\text{out}}^{\text{SD}}$  and  $F_{\text{out}}^{\text{interf}}$  refer to the outflow force as observed with a single-dish telescope and an interferometer, respectively.