A Class 0 proto-brown dwarf

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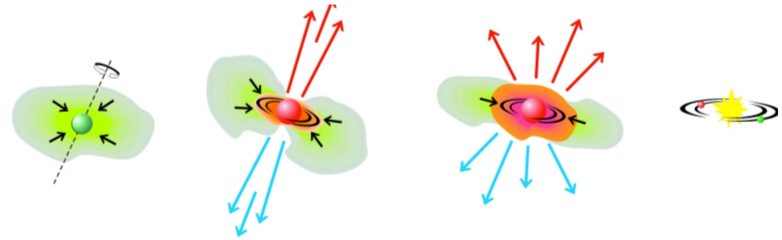
Brown dwarf (BD) formation

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



Possible formation scenarios for brown dwarfs (BDs):

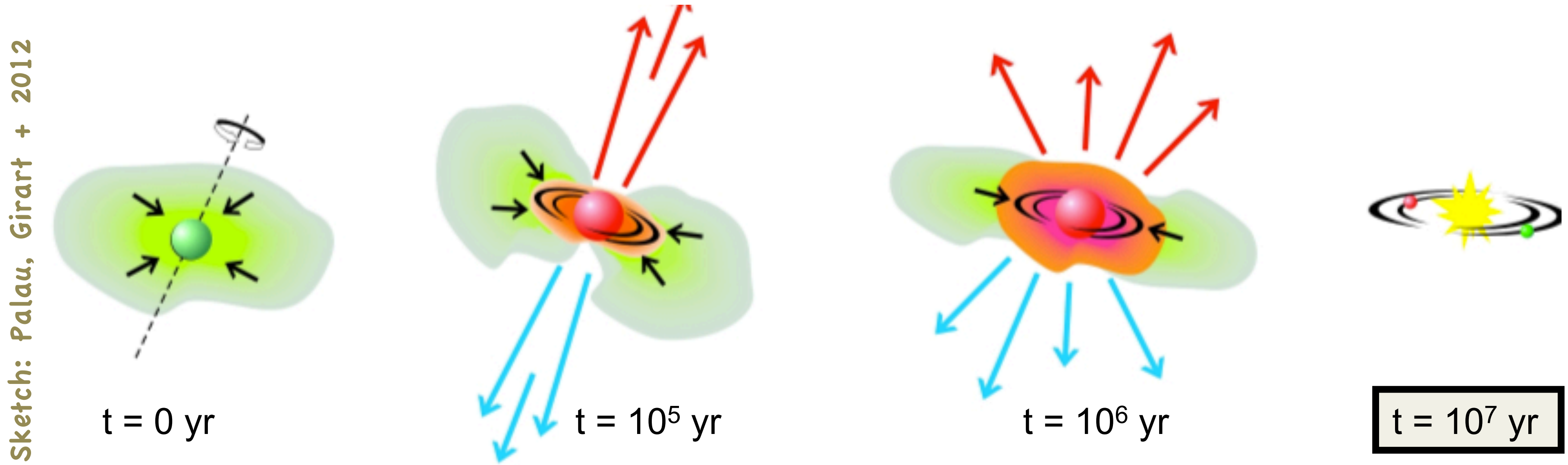
-photo-erosion (eg, Hester+96, Whitworth & Zinnecker'04)

-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**

Classical view of low-mass star formation:

$0.075\ M_{sun} < M_* < 3\ M_{sun}$



1. Rotating Pre-stellar Core
Isothermal collapse

~10 K
~10^4 cm^{-3}

2. **Class 0/I:**
adiabatic collapse
hydrostatic core

rotation + infall:
disk accretion
+ outflow

~1000 K ~10^{10} cm^{-3}

3. **Class I/II:**
Envelope Disruption

Quasi-static contraction

~10^5 K
~10^{23} cm^{-3}

4. **Class III:**
Proto-planetary disk

~10^6 K
~10^{24} cm^{-3}

~10^7 K
~10^{25} cm^{-3}

Brown dwarf formation

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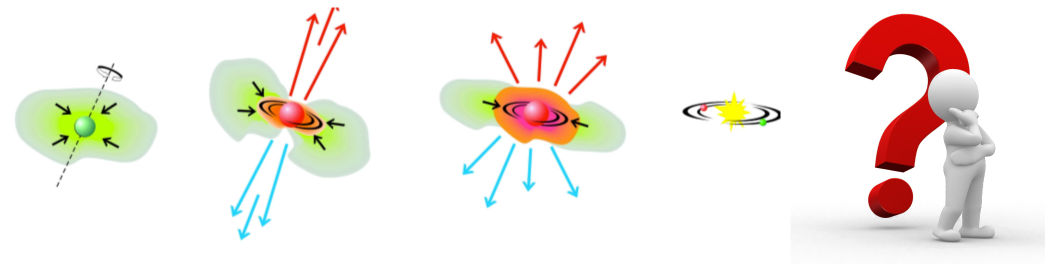
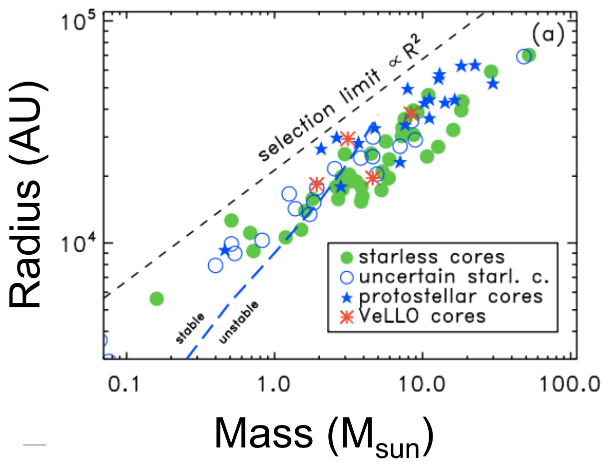
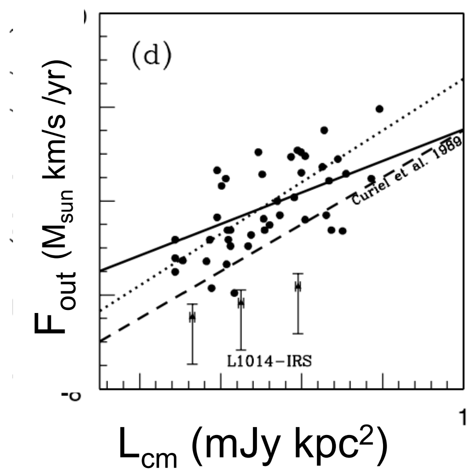


If scaled-down version: **substantial disks, envelopes, and outflows**, similar to **Class 0/I** protostellar objects:

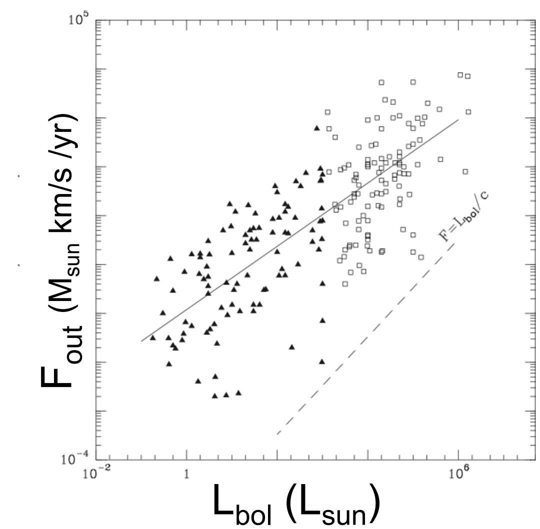
Proto-BDs



eg, Kauffmann+08…

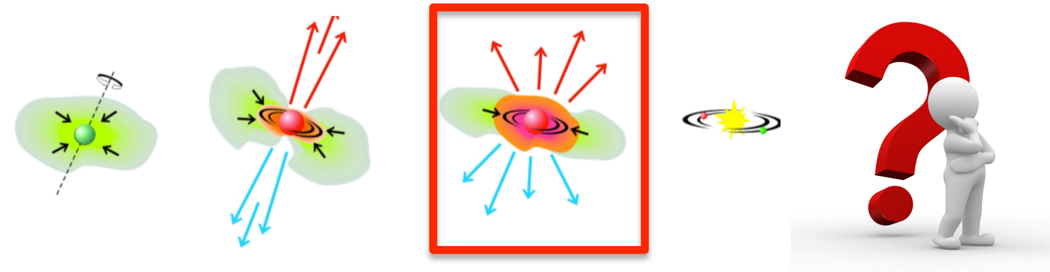


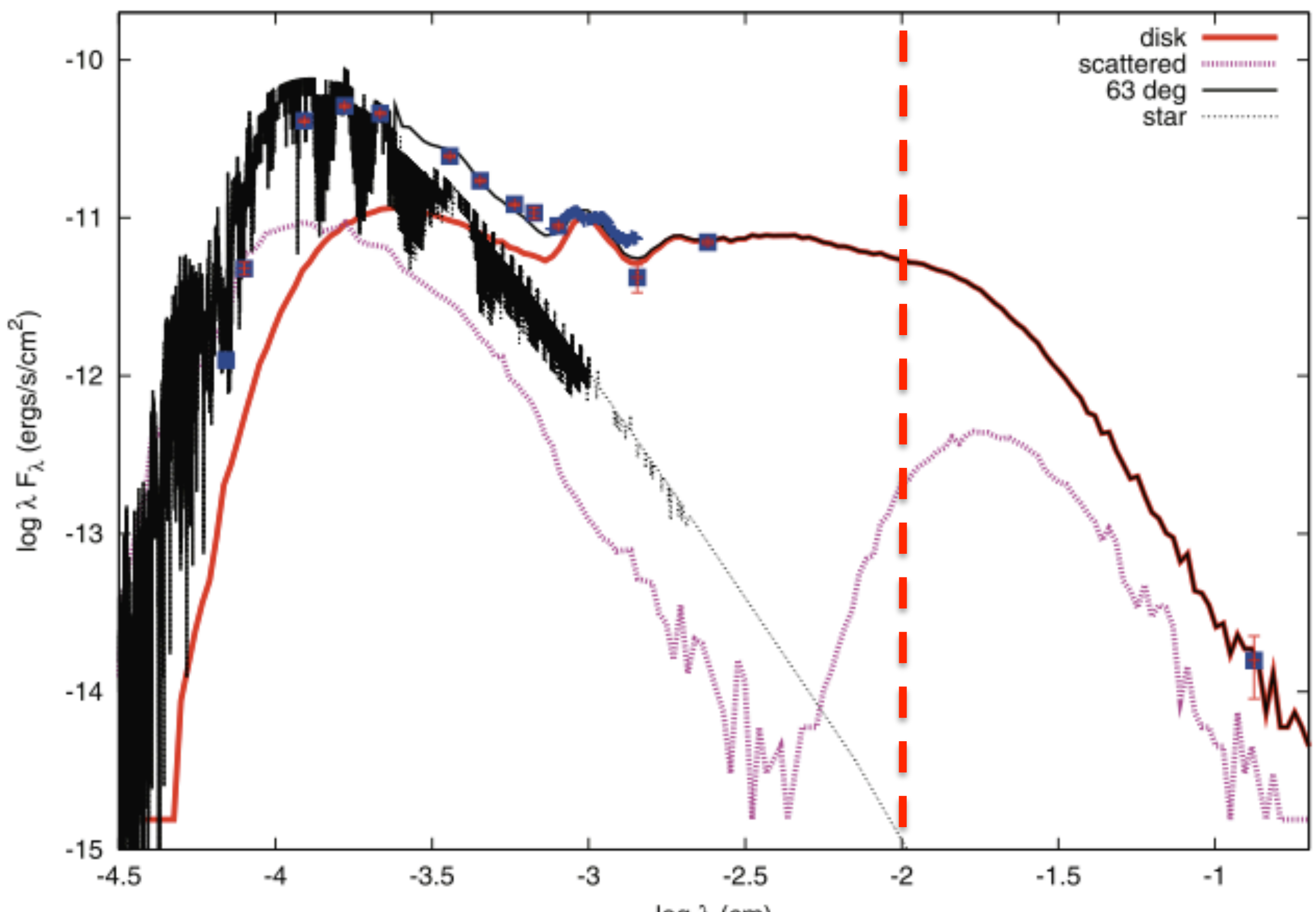
eg, Anglada95, Shirley+07…



eg, Wu+04…

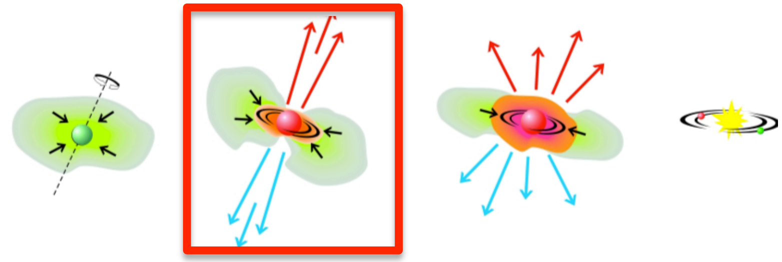
Confirmed BDs in the Class II phases...

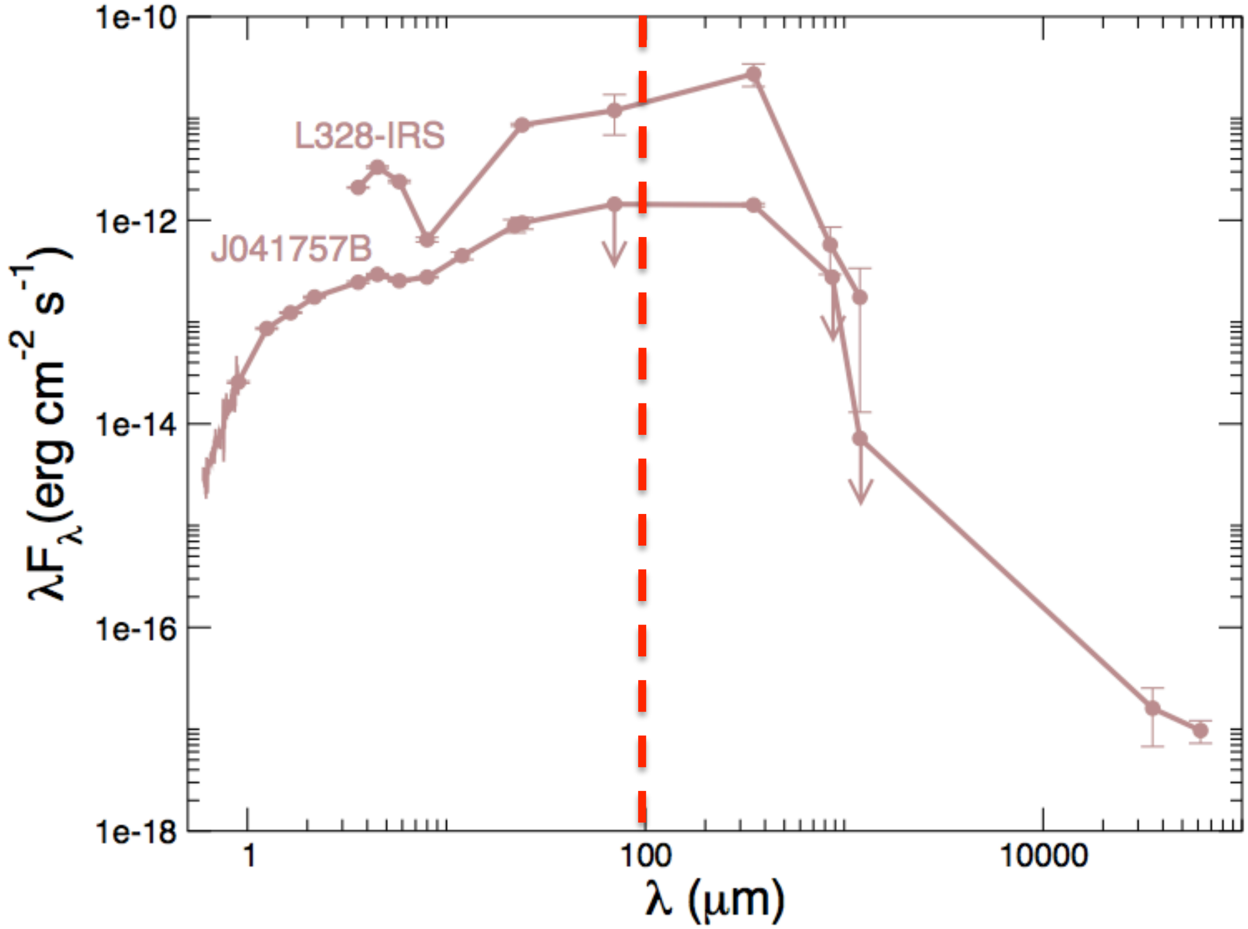




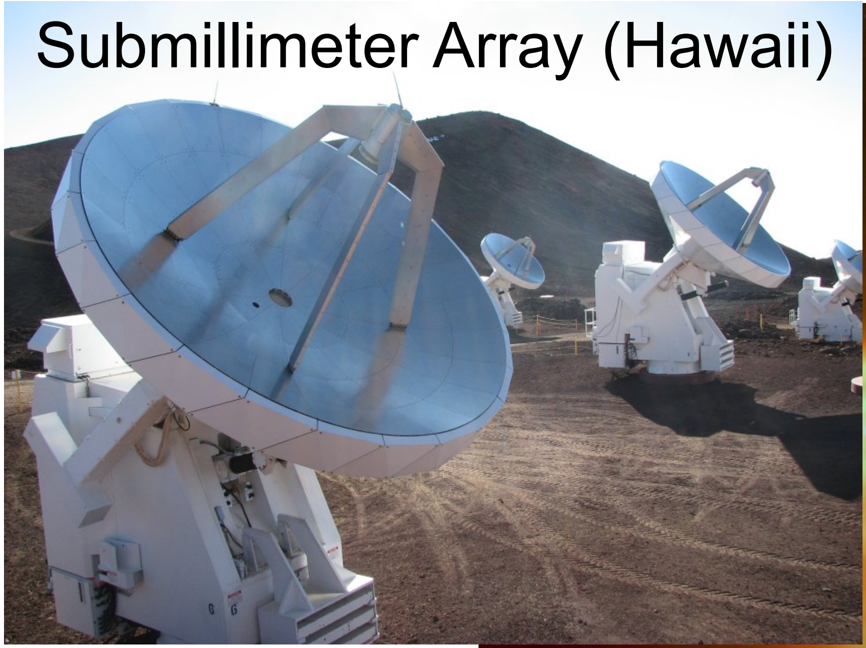
ρ-Oph 102: Phan-Bao+08; 2M0444: Ricci+14

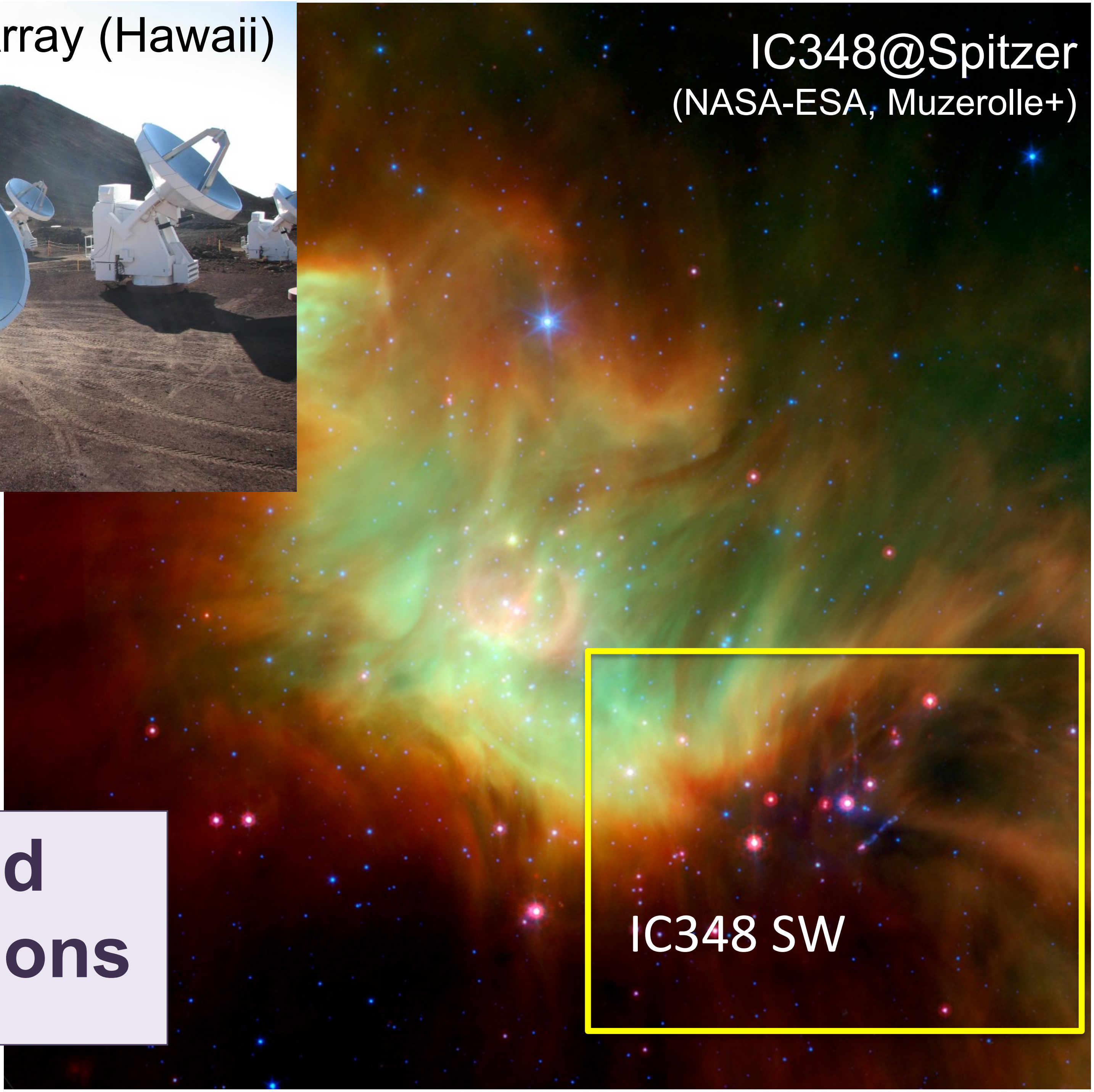
Very few BDs in the Class 0/I phases!





L328-IRS: Lee+09,+13



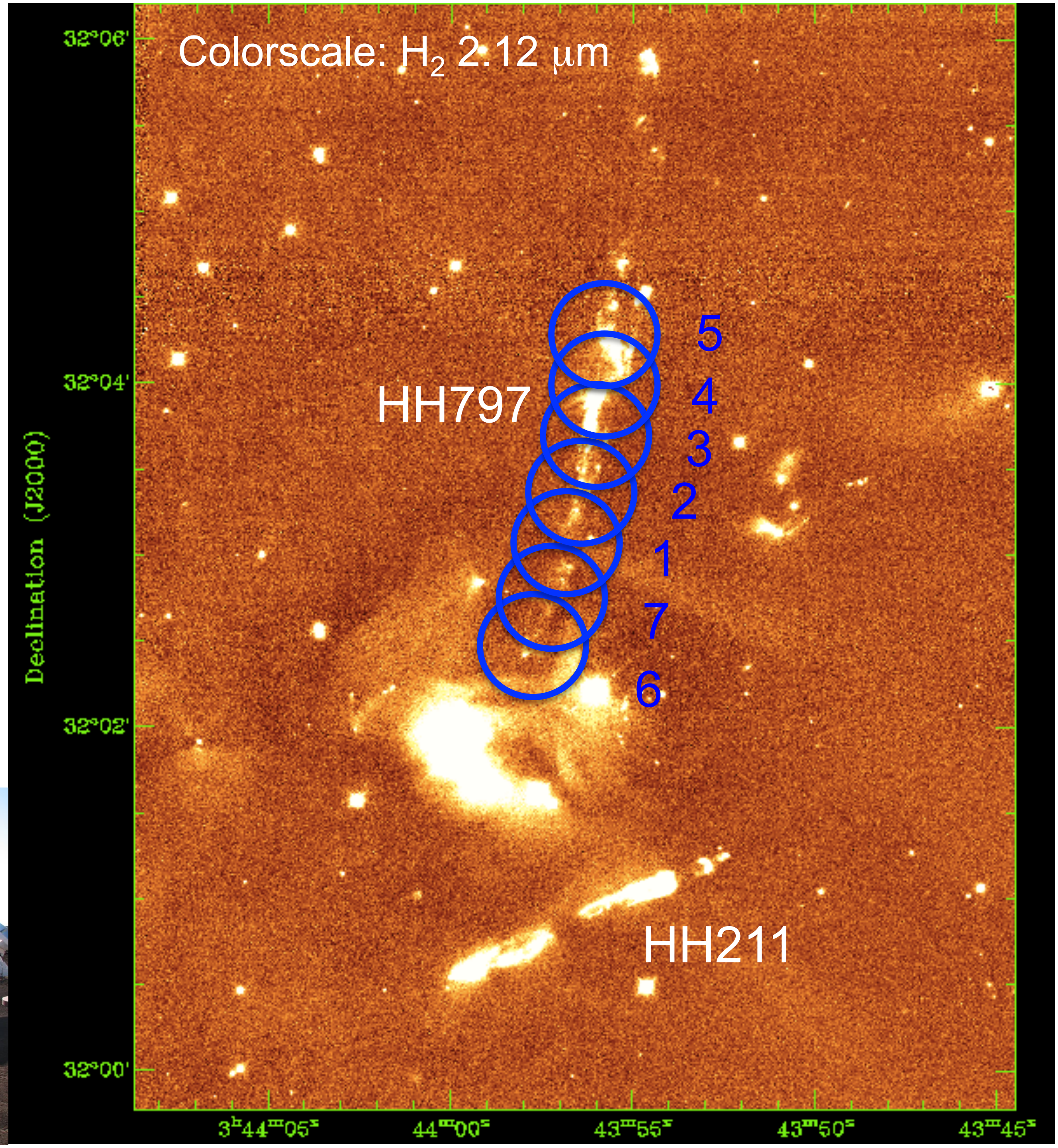


Target and observations

SMA observations:

345 GHz

7 pointings
separated 17’’
PB~37’’

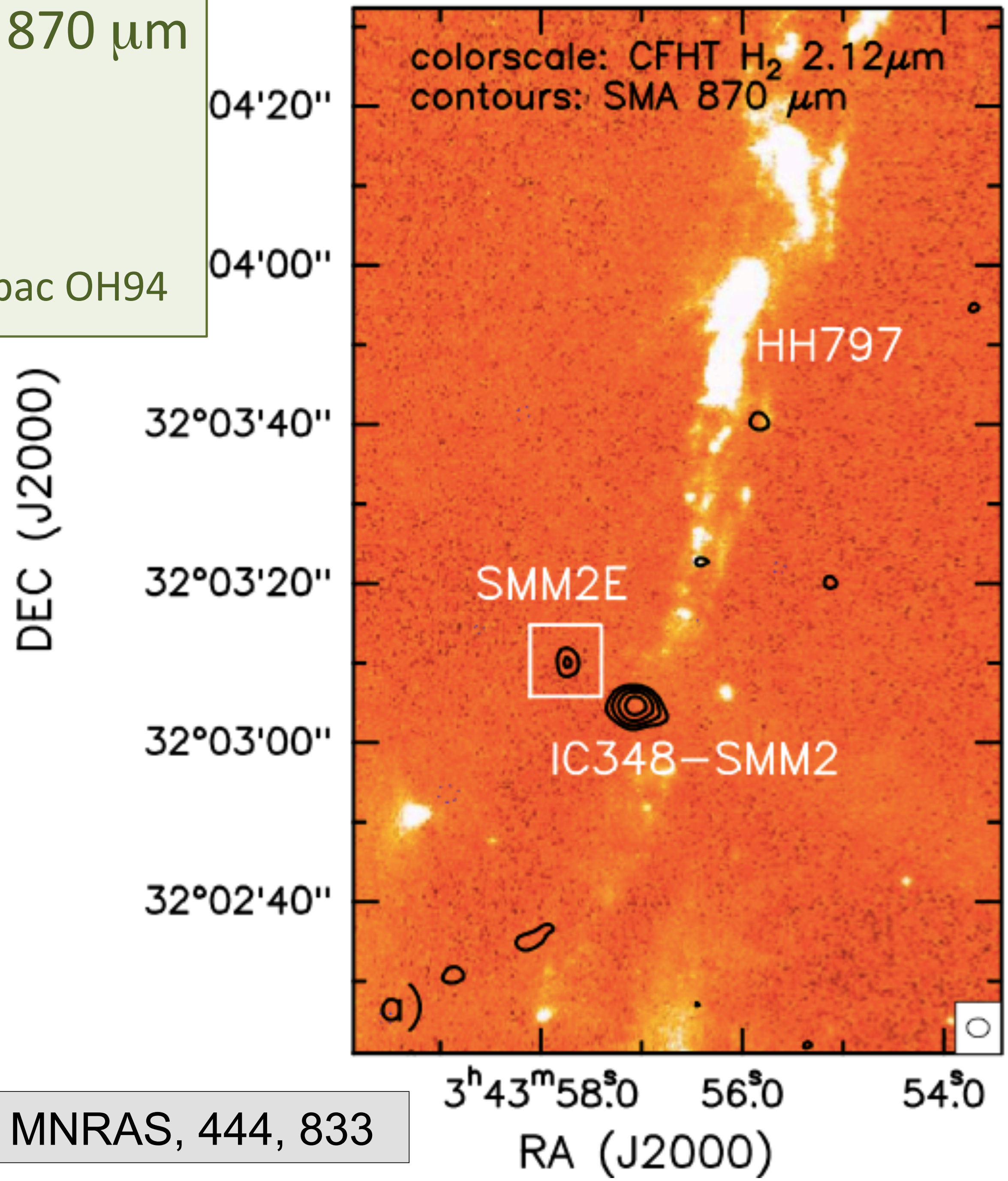


Results: continuum @ 870 μm

SMM2: 250 M_{Jup}

SMM2E: 30 M_{Jup}

Assuming T_d=24K and dust opac OH94



Palau+14, MNRAS, 444, 833

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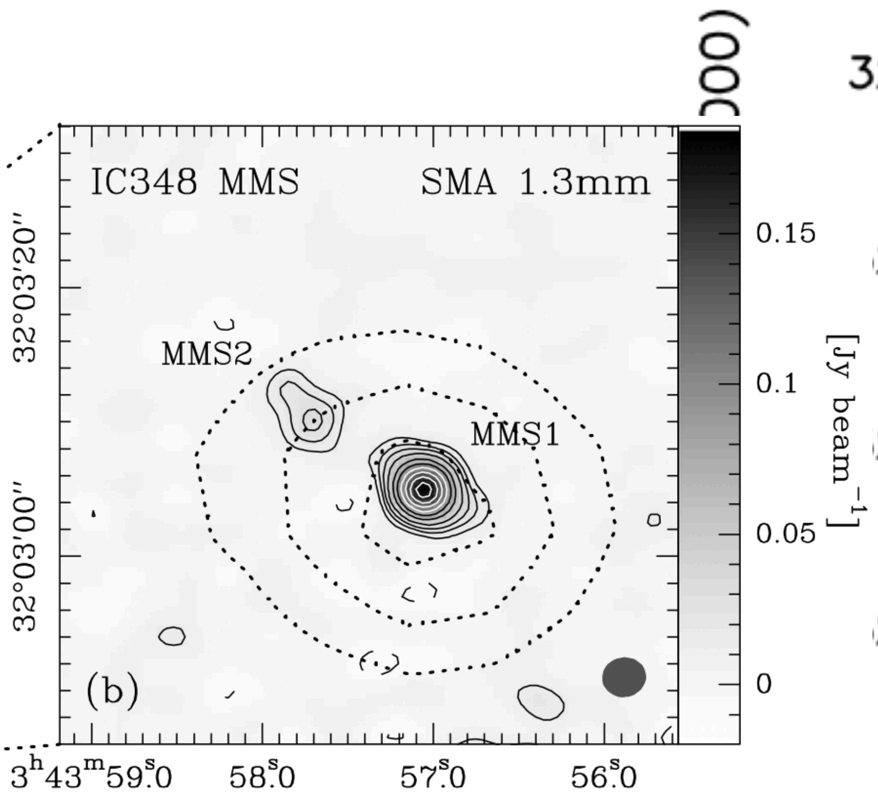
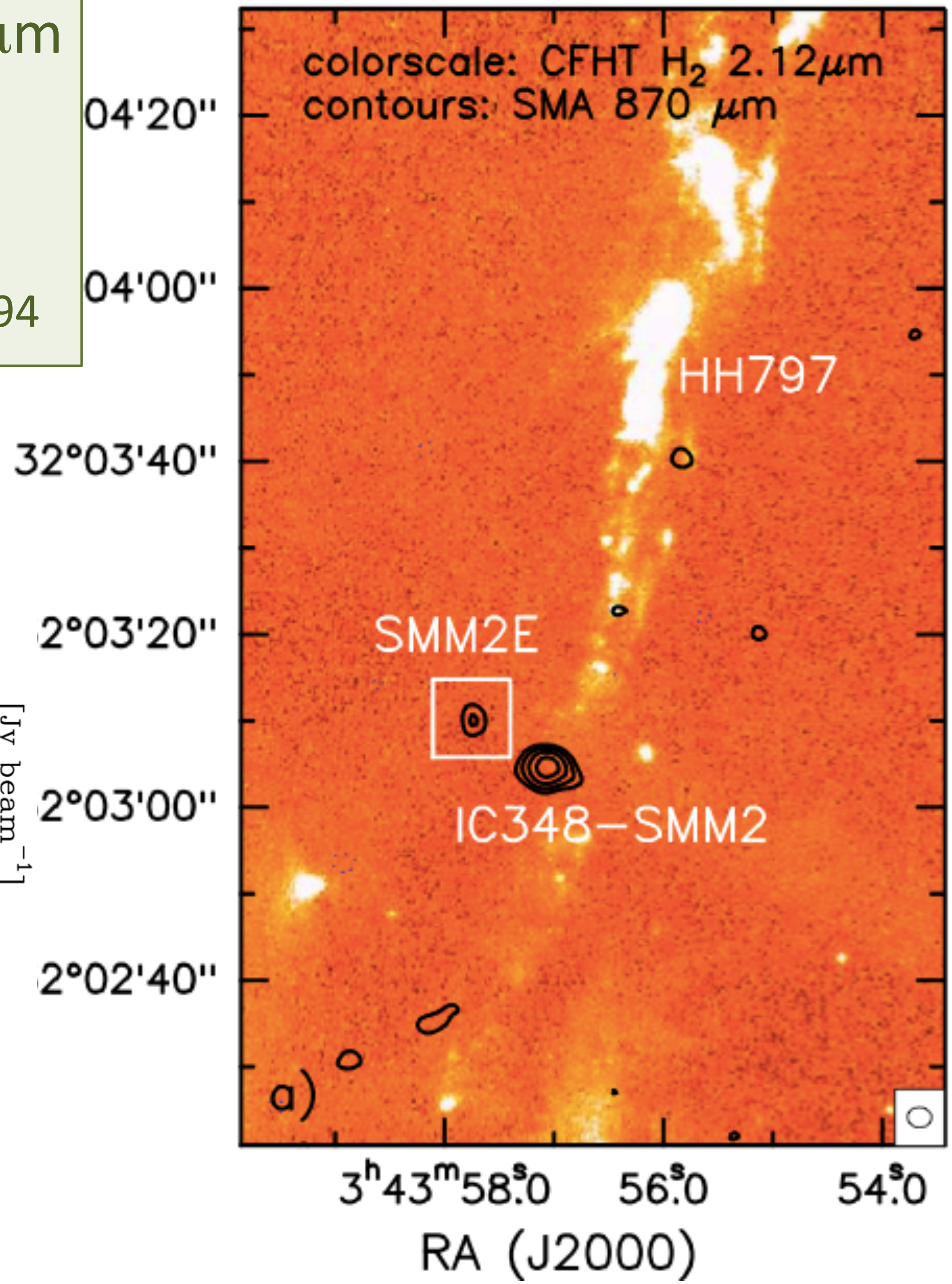


Chen+13



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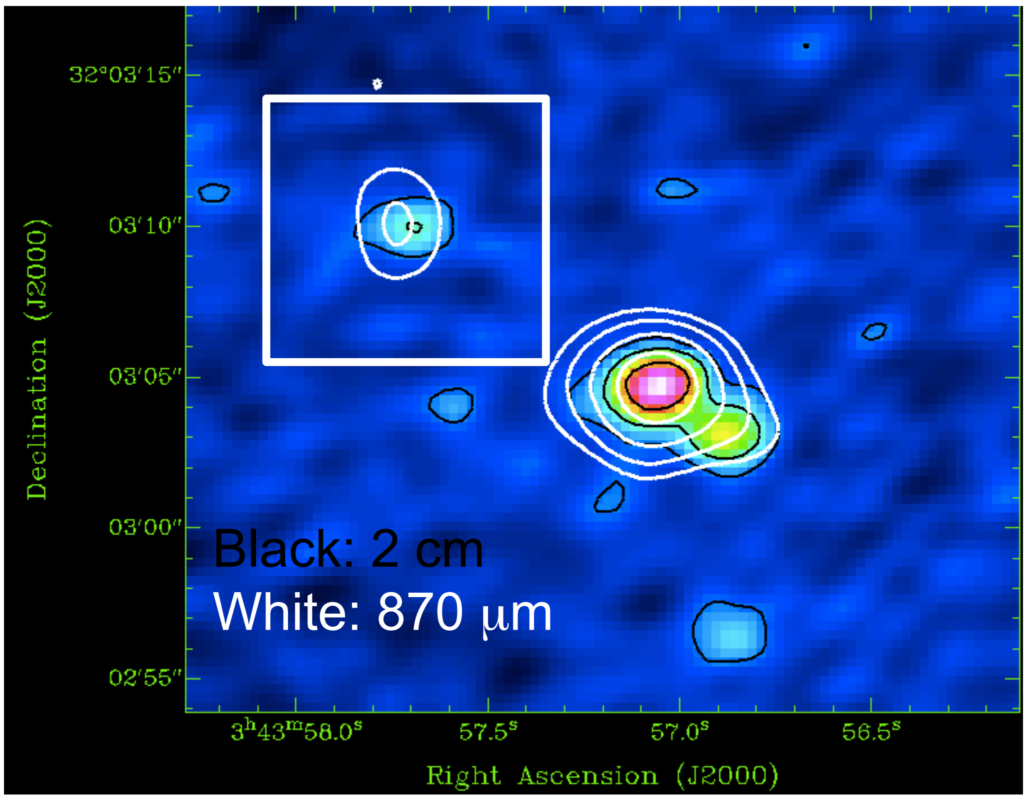
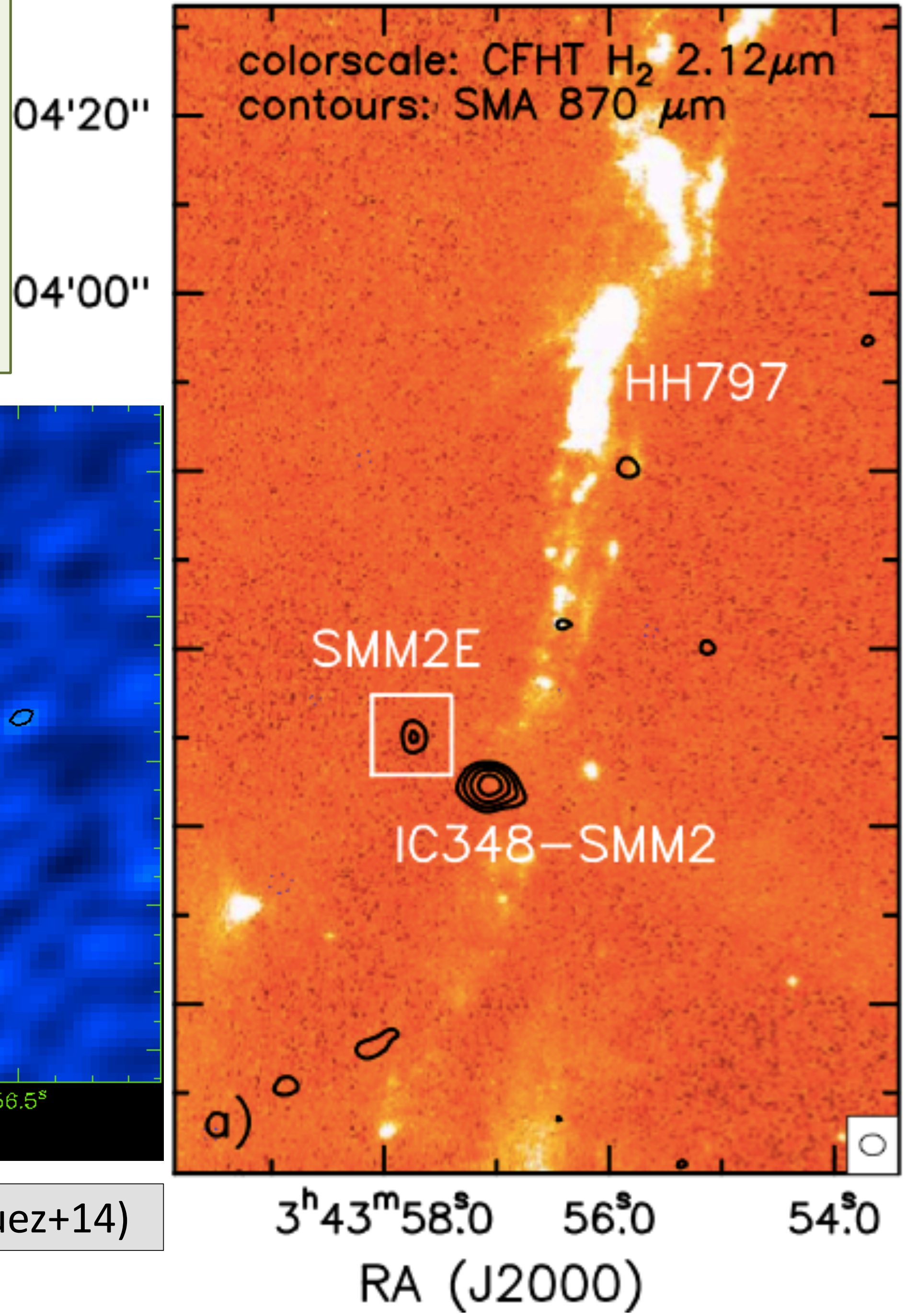


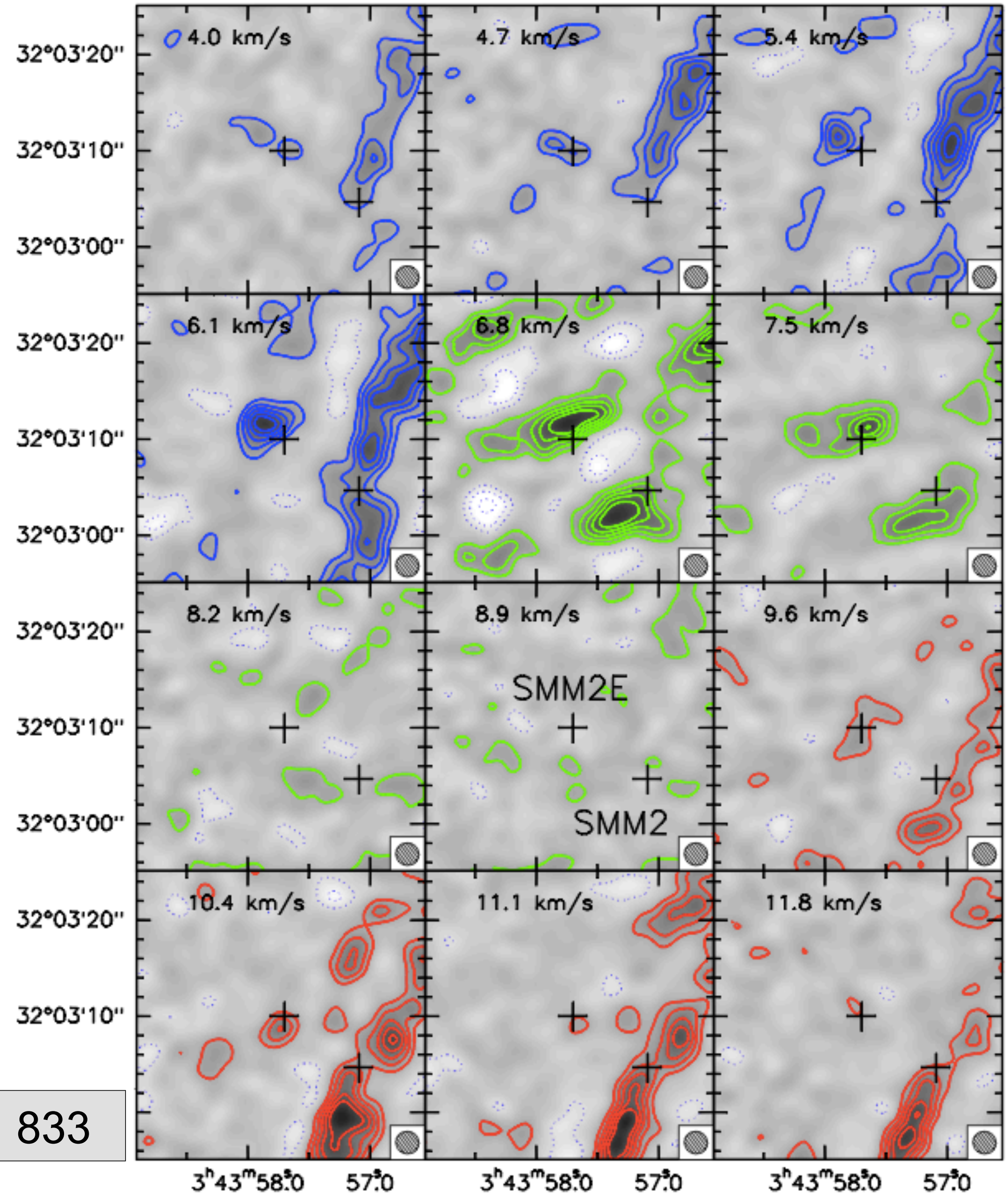
Colorscale + black contours: 2.1 cm (Rodríguez+14)



Results: CO(3-2) channel map

Blue-shifted lobe up to ~4 km/s with respect to systemic velocity

Very faint red-shifted lobe



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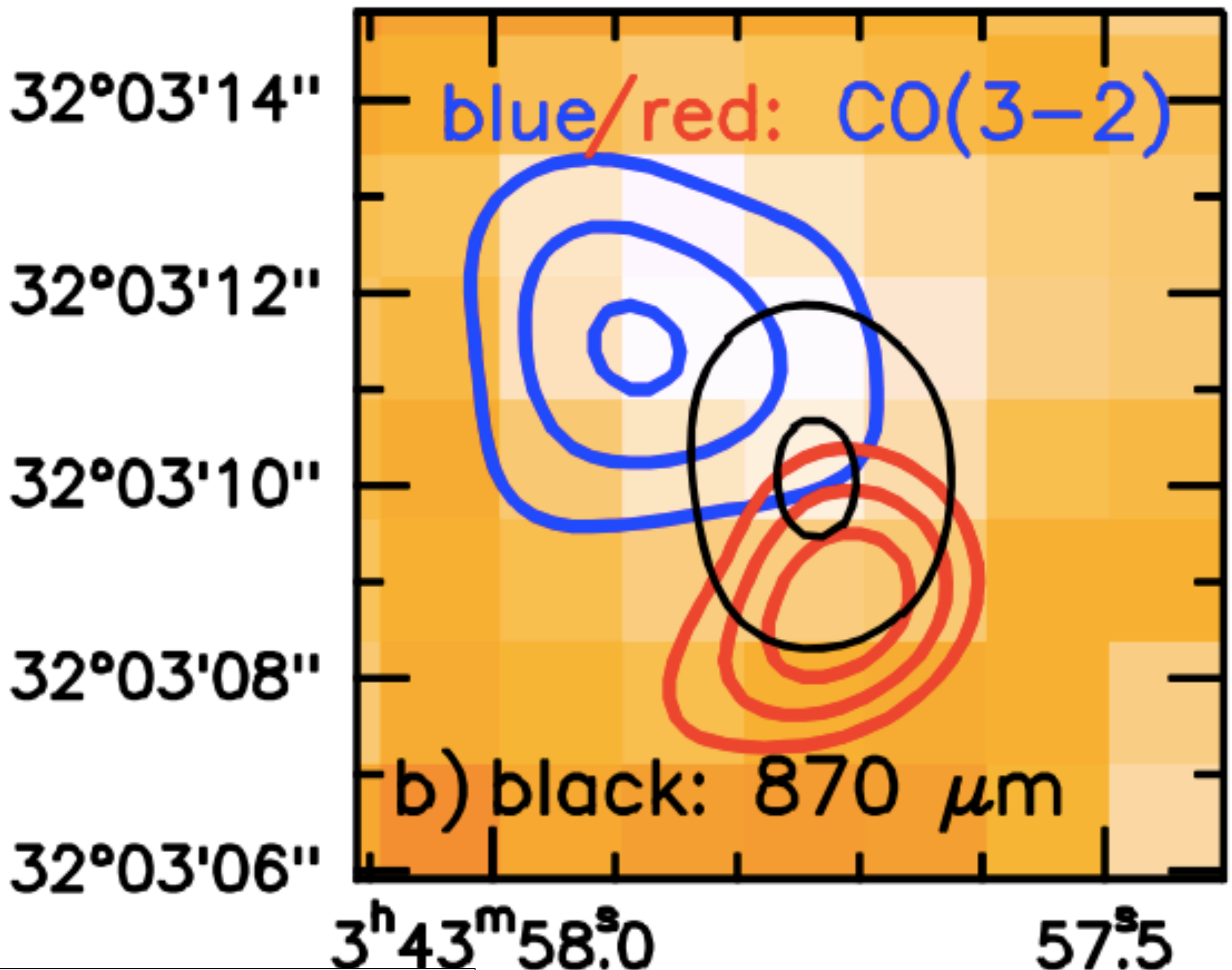
Results: moment zero

CO(3-2): 4.0—6.1 km/s, 9.7—11.1 km/s



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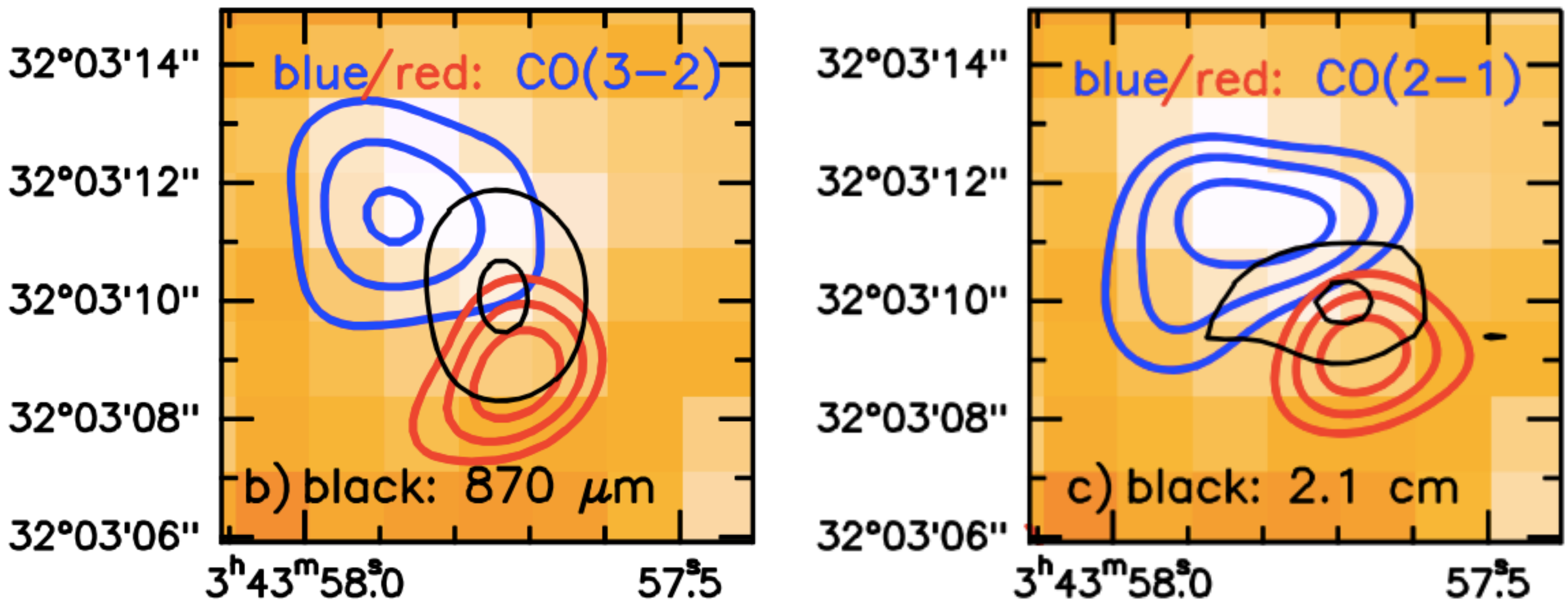
Results: moment zero

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)



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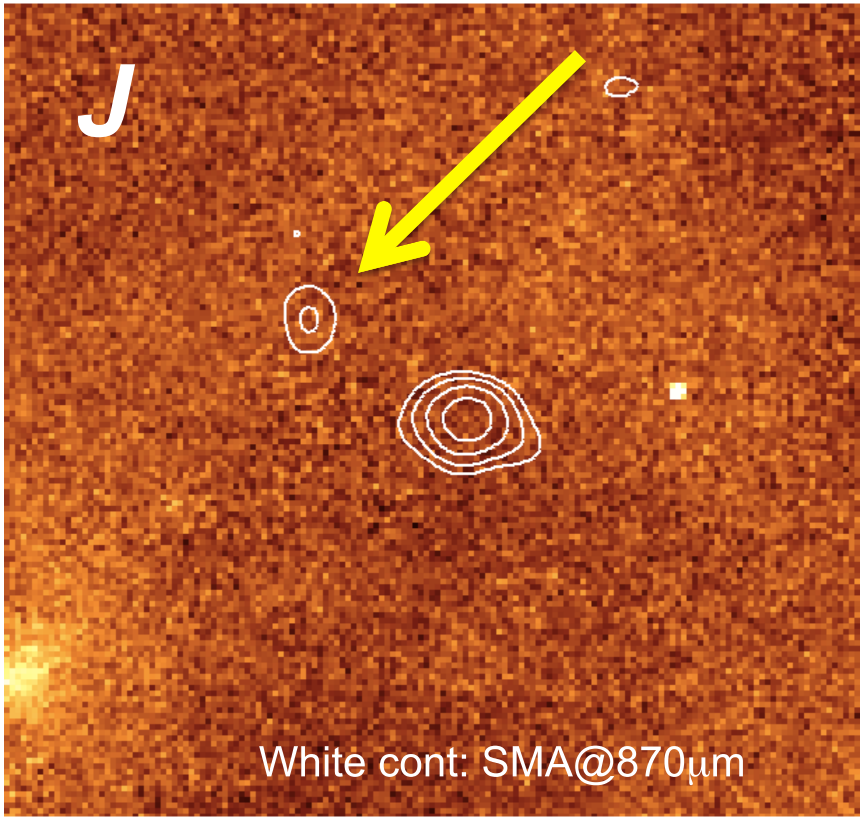
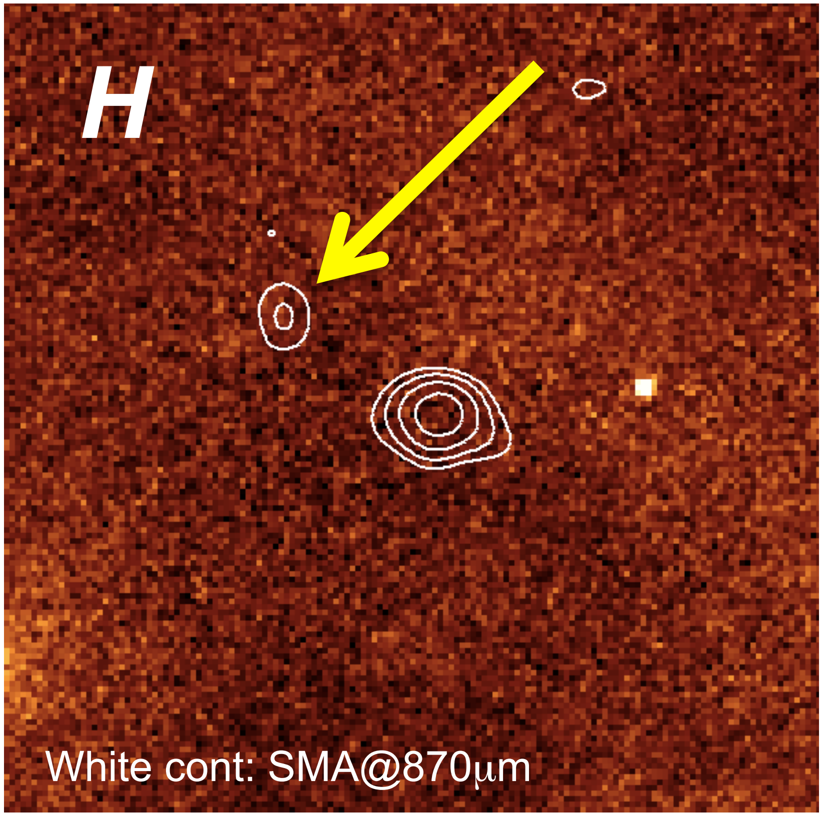
Outflow parameters

	CO(3-2)
size (AU)	**390**
t_{dyn} (yr)	**380**
M_{out} (M_{sun})	**5.1×10^{-6}**
M_{dot} (M_{sun} yr^{-1})	**1.4×10^{-8}**
P (M_{sun} km s^{-1})	**1.8×10^{-5}**
P_{dot} (M_{sun} km s^{-1} yr^{-1})	**4.9×10^{-8}**
E_{kin} (erg)	**6.6×10^{38}**
L_{mech} (L_{sun})	**7.2×10^{-6}**

Ok and… any optical/NIR counterpart?

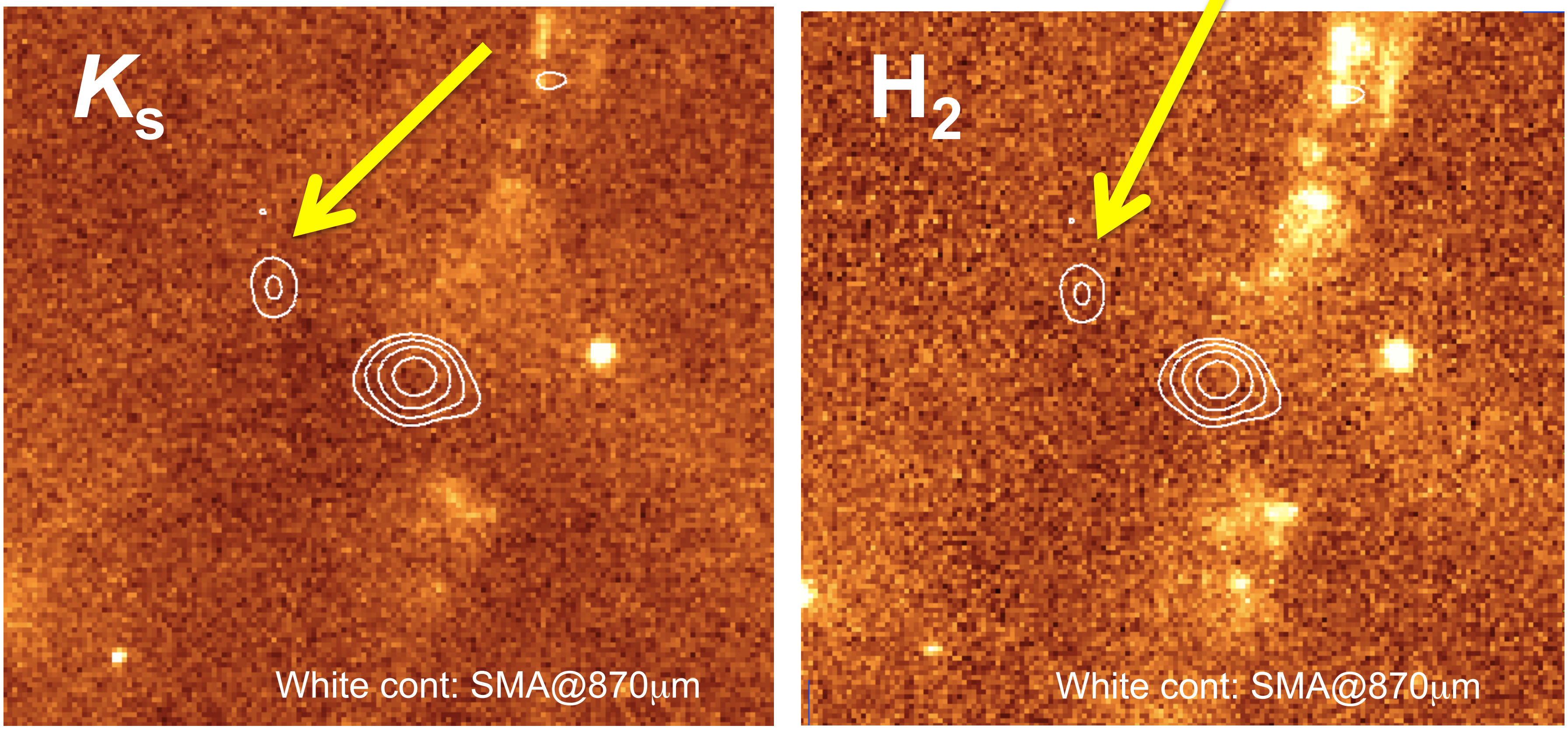
A multiwavelength study: optical + NIR CFHT archive



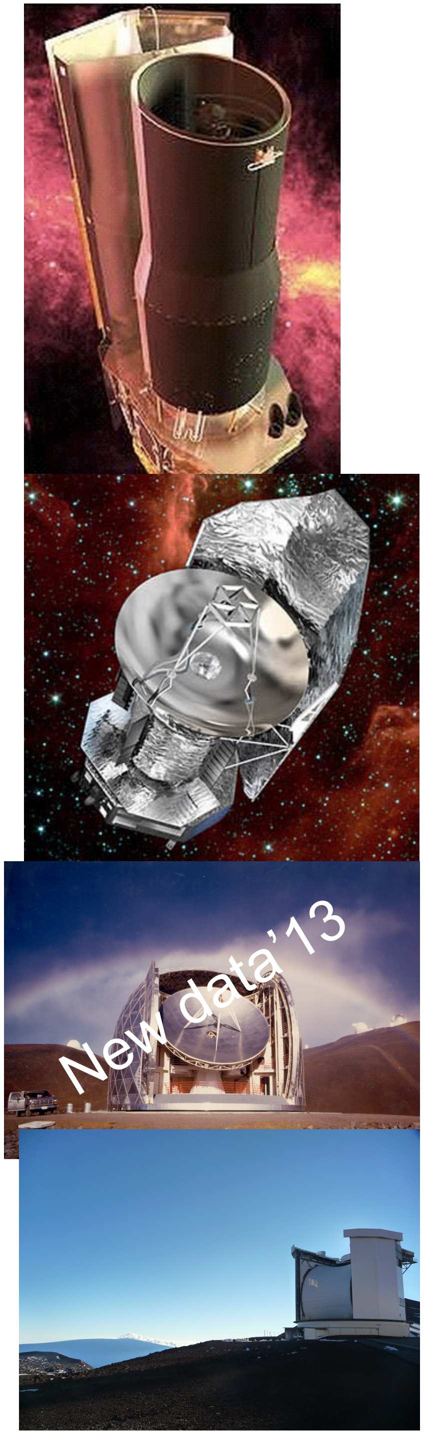


Colorscale: CFHT/WIRcam *J*, *H* (1.25, 1.65 μm):
NO DETECTIONS!

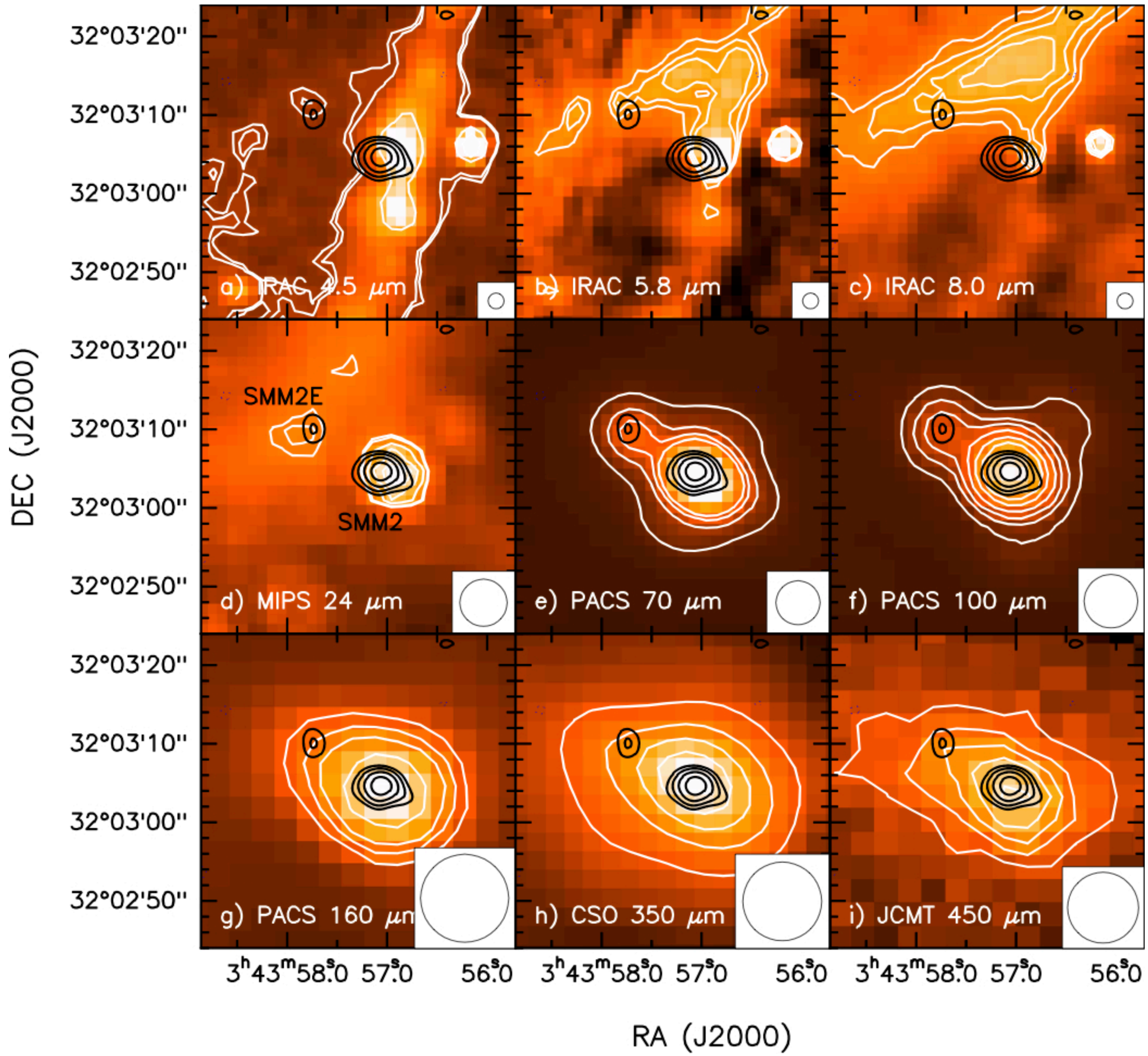
A multiwavelength study: optical + NIR CFHT archive



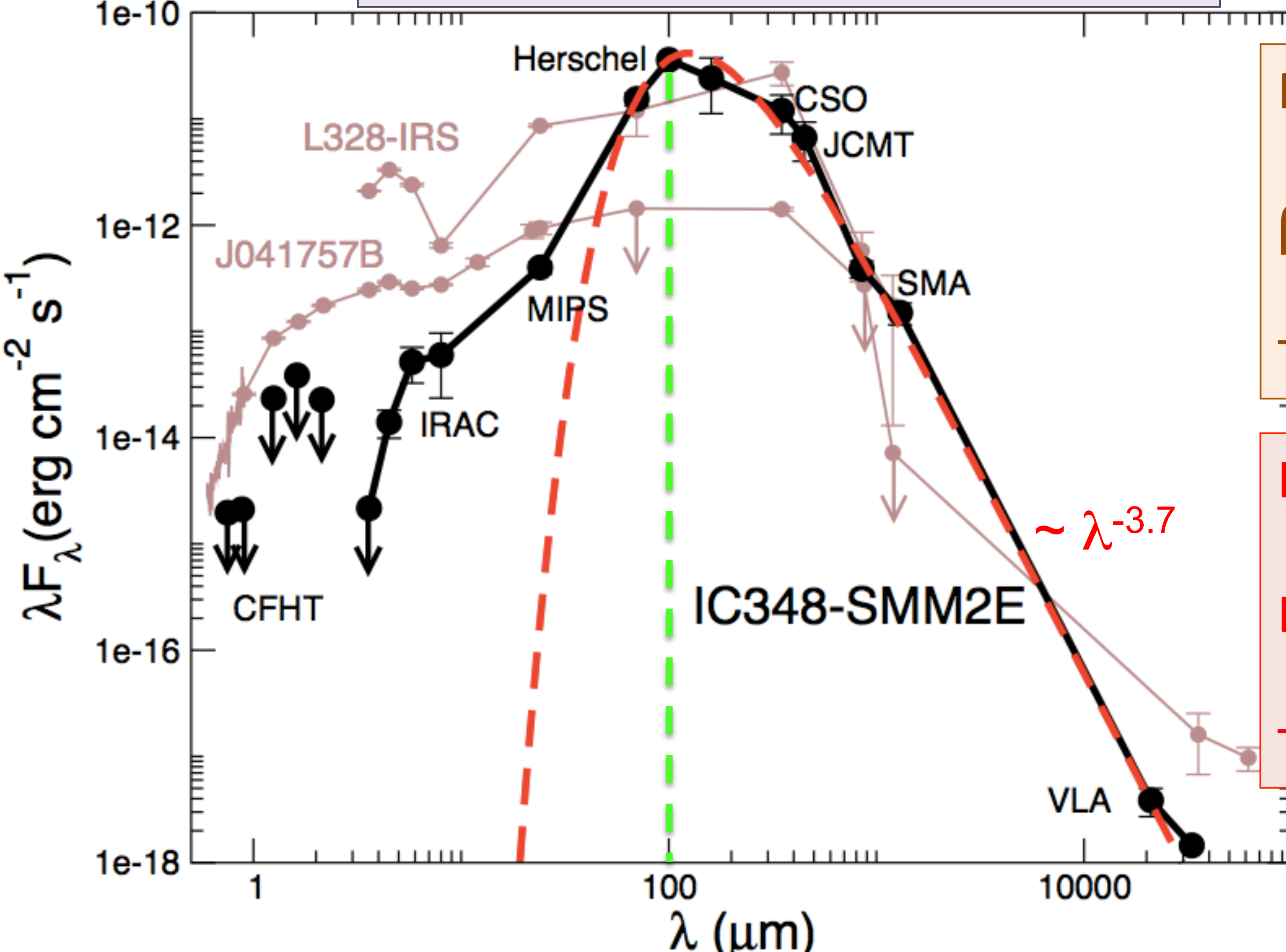
Colorscale: CFHT/WIRcam K_s, H_2 **(2.17, 2.12 μm):**
NO DETECTIONS!



A multiwavelength study: MIR + FIR



SED and modified black body



M_{env}=35 M_{jup}

β=0.8

T_{dust}=24 K

L_{bol}=0.1 L_{sun}

L_{int}=0.06 L_{sun}

T_{bol}=34 K

One modified BB fits SED in the range 70 μm – 2.1 cm
cm emission produced by thermal dust

Will IC348-SMM2E remain substellar?

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

Adopt:

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

$R_* \sim 0.1$—$1\ R_{sun}$

$\eta_L \sim 0.5$ (Hartmann98)

Total mass = accreted mass + reservoir of mass

Accreted mass:

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

T~10K

$$\dot{M}_{acc} = \eta_{\dot{M}} \frac{c_s^3}{G} \longrightarrow \dot{M}_{acc} = \frac{\eta_{\dot{M}}}{G}\left(\frac{kT}{\mu m_{\mathrm{H}}}\right)^{3/2}$$

$M_{acc} \sim 1.6 \times 10^{-7}\ M_{sun}\ yr^{-1}$

$m_* \sim 2$—$24\ M_{Jup}$

Reservoir of mass which could still be accreted:

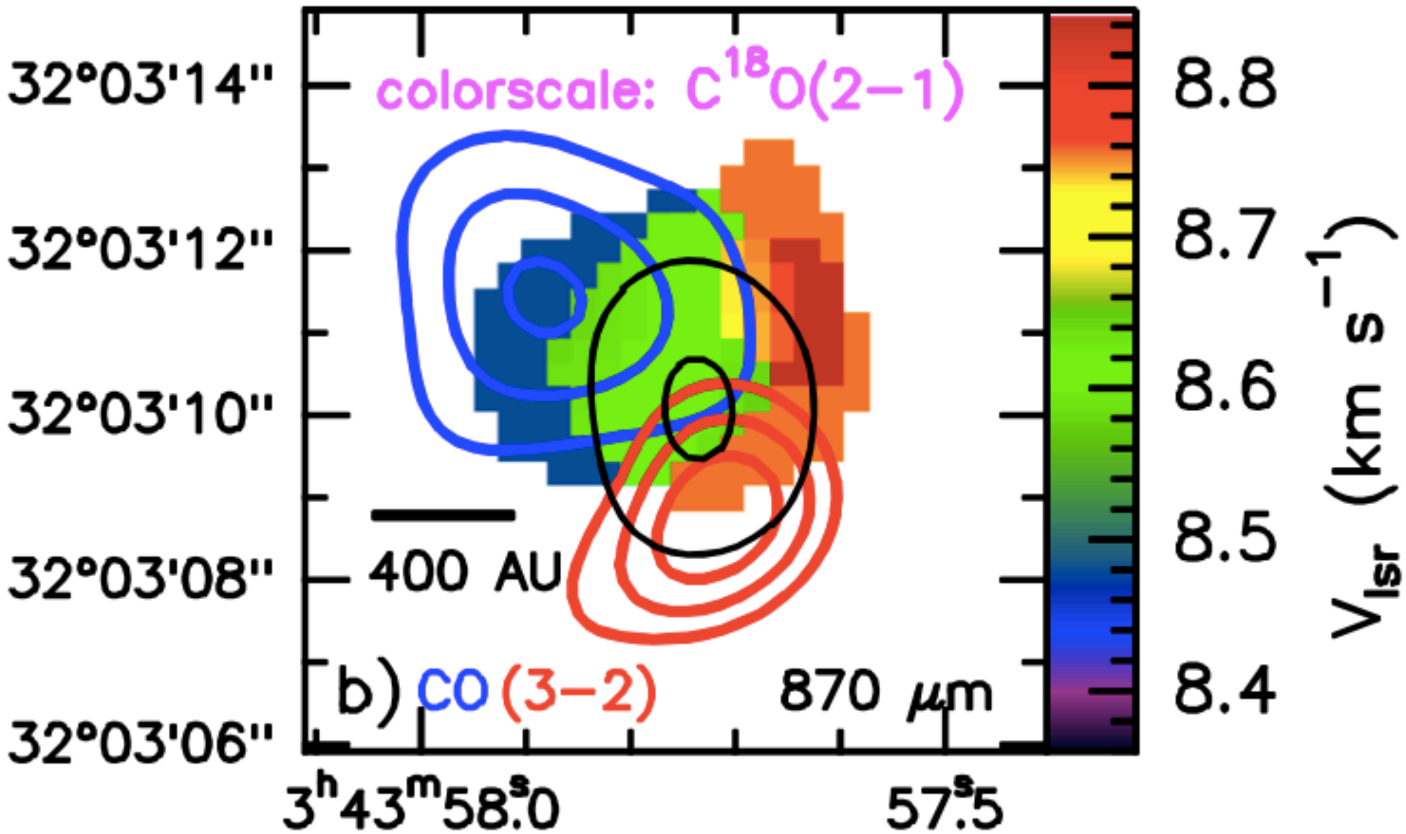
$M_{env} < 35\ M_{Jup}$

$M_{tot} < 59\ M_{Jup}$

SMA correlator setup included other lines in sidebands

$C^{18}O(2\text{-}1)$: peaks around 8.5 km/s,

velocity gradient perp to outflow, $\mathbf{M_{dyn} \sim 16\ M_{Jup}}$



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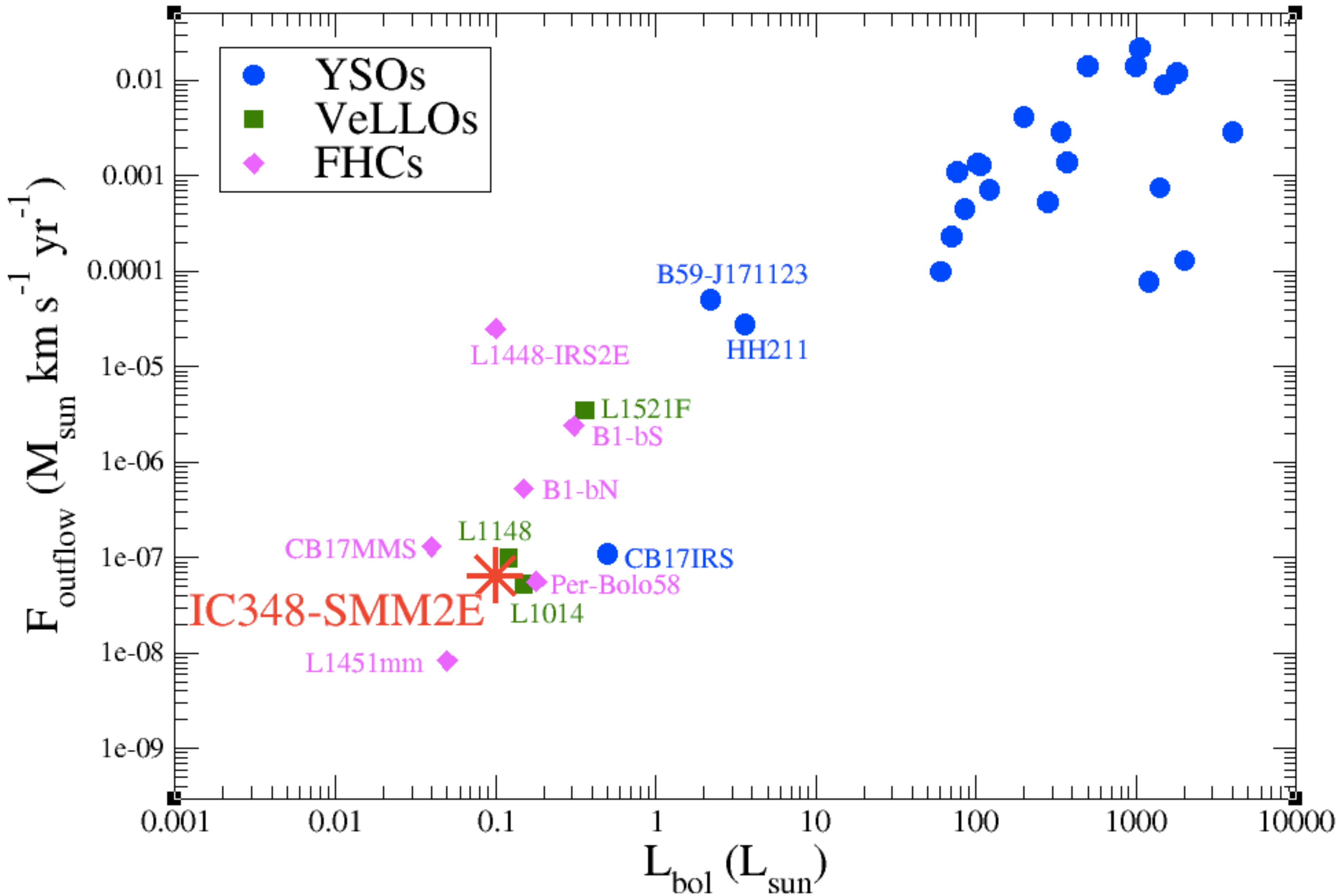

Only interferometric data

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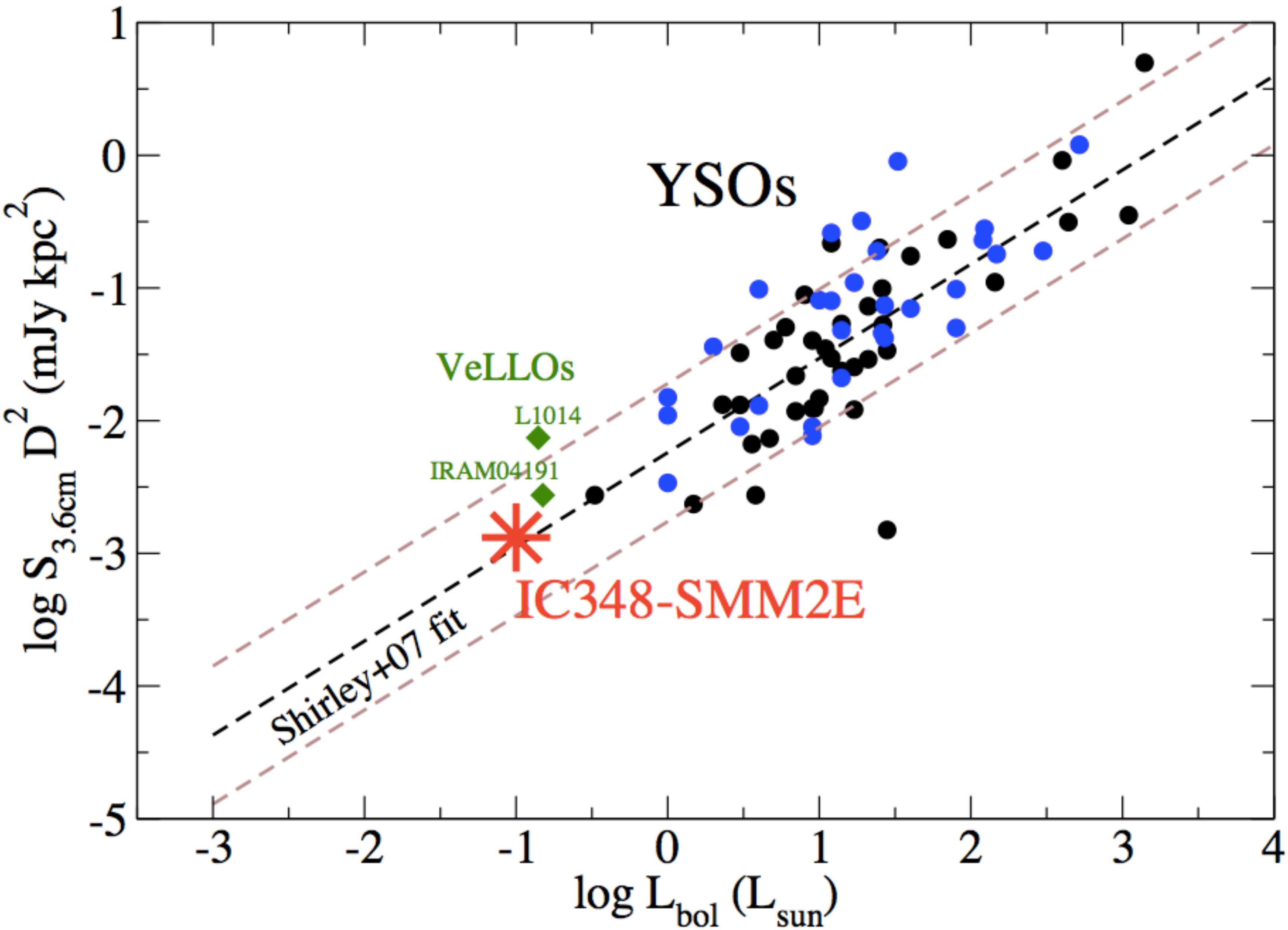
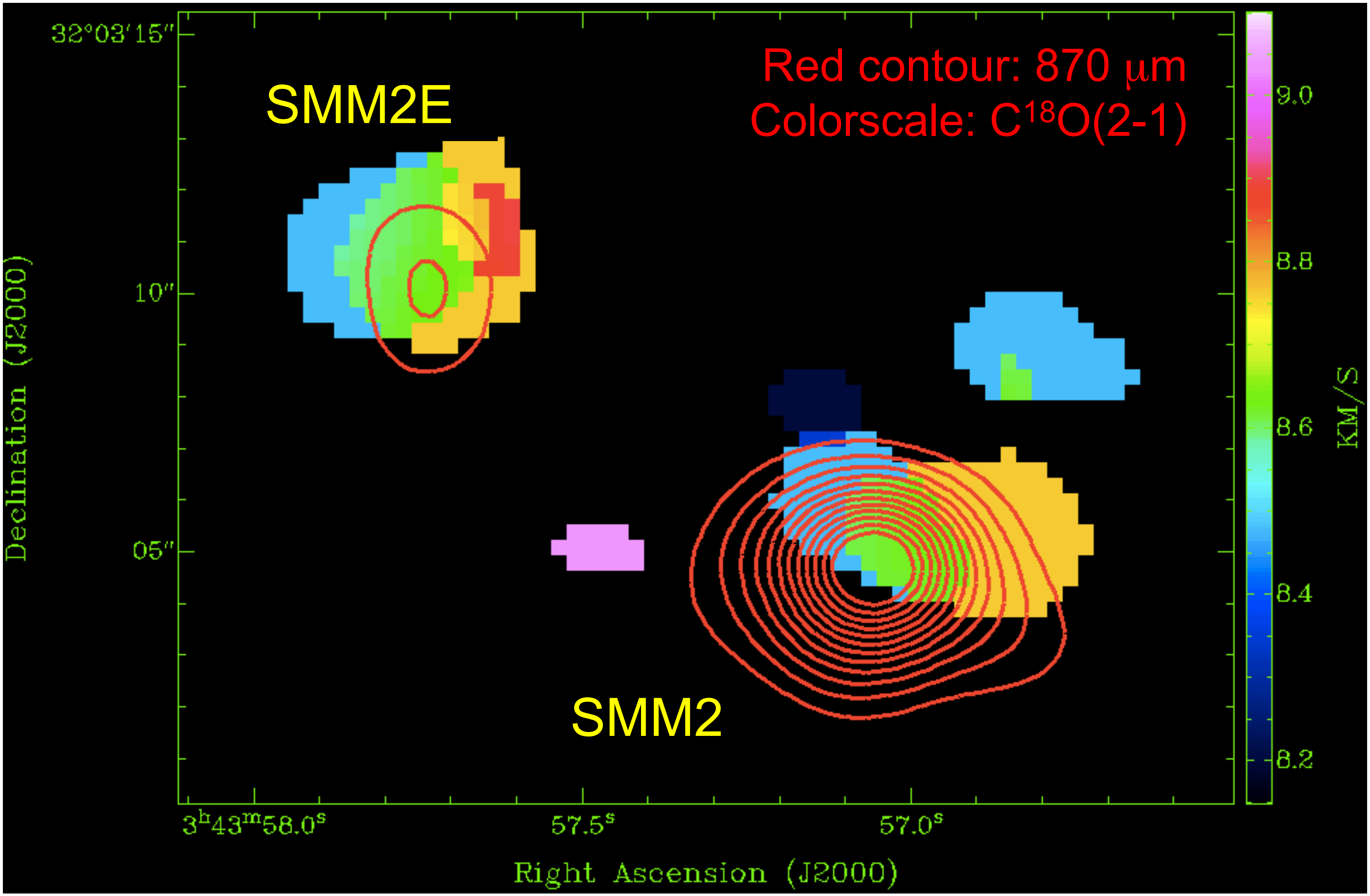
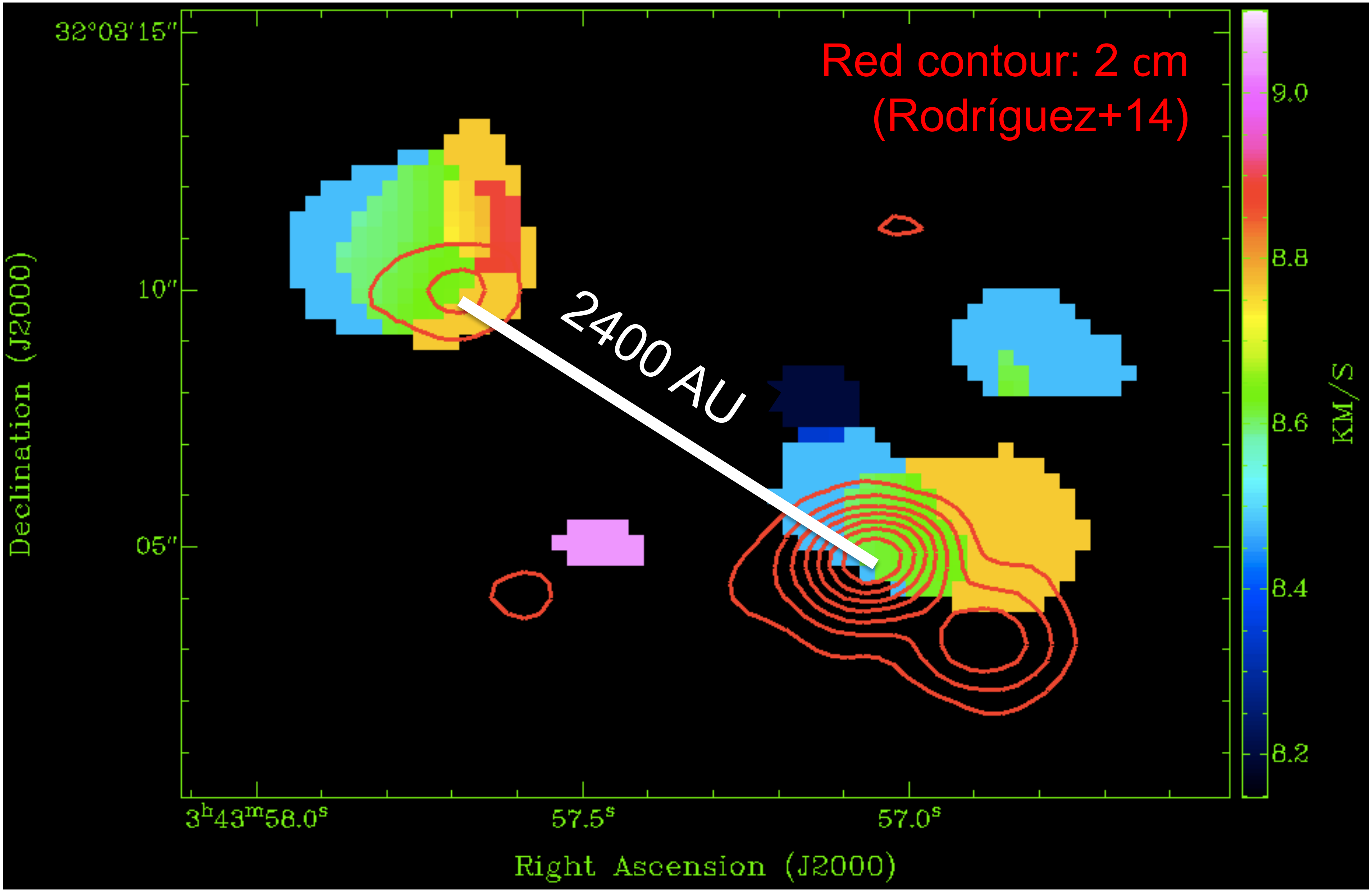


YSOs
VeLLOs
L1014
IRAM04191
IC348-SMM2E
Shirley+07 fit
log $S_{3.6cm}$ D^2 (mJy kpc^2)
log L_{bol} (L_{sun})
1
0
-1
-2
-3
-4
-5
-3
-2
-1
0
1
2
3
4

SMM2E and SMM2 could be a binary system...



…of ~2400 AU of separation, and mass ratio ~0.2: fragile! (Chen+13)



Whatever its formation scenario is... it is forming as a scaled-down version of low-mass stars

Thanks!

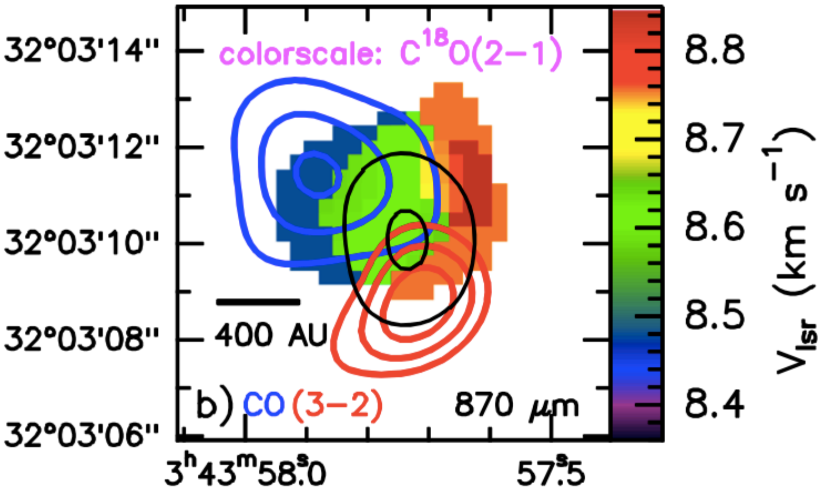


Table 4. Summary properties of VeLLOs and FHCs

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

[a] 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.

[b] F_{out}^{SD} and F_{out}^{interf} refer to the outflow force as observed with a single-dish telescope and an interferometer, respectively.

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