Characterizing Low-Mass Cores in Nearby Molecular Clouds

Scott Schnee (NRAO)

Australian ALMA
Community Workshop
February 7, 2012

Collaborators

- James Di Francesco
- Melissa Enoch
- Rachel Friesen
- Alyssa Goodman
- Doug Johnstone
- Stella Offner
- Sarah Sadavoy
- Lisa Wei

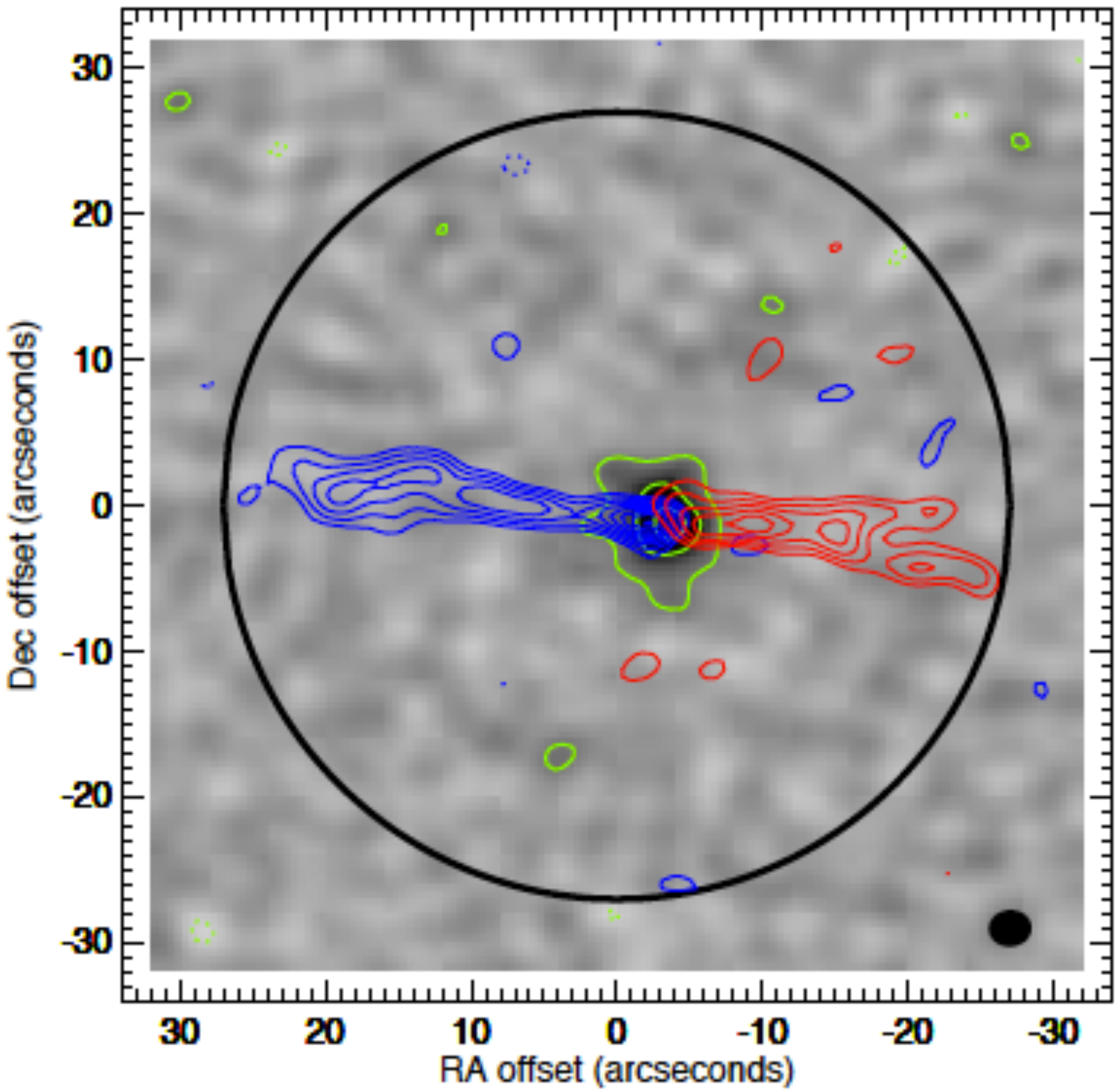
Related Questions

1. At what stage during star formation does fragmentation begin?
2. How smooth is the mass distribution within starless cores?
3. How can one find deeply embedded protostars?

Samples

1. 11 of the brightest (at 1mm) starless cores in Perseus molecular cloud
   – Starless status based on Spitzer NIR-MIR data
   – Chosen from Enoch et al. (2006; 2008) Bolocam 1.1mm survey of Perseus
   – Observed with CARMA D&E array + SZA
     - 3mm continuum
   – Follow-up observations with CARMA, SMA, Spitzer
     - Spectral line, 70 μm continuum, 1.3mm continuum

Perbo58 as a Protostar



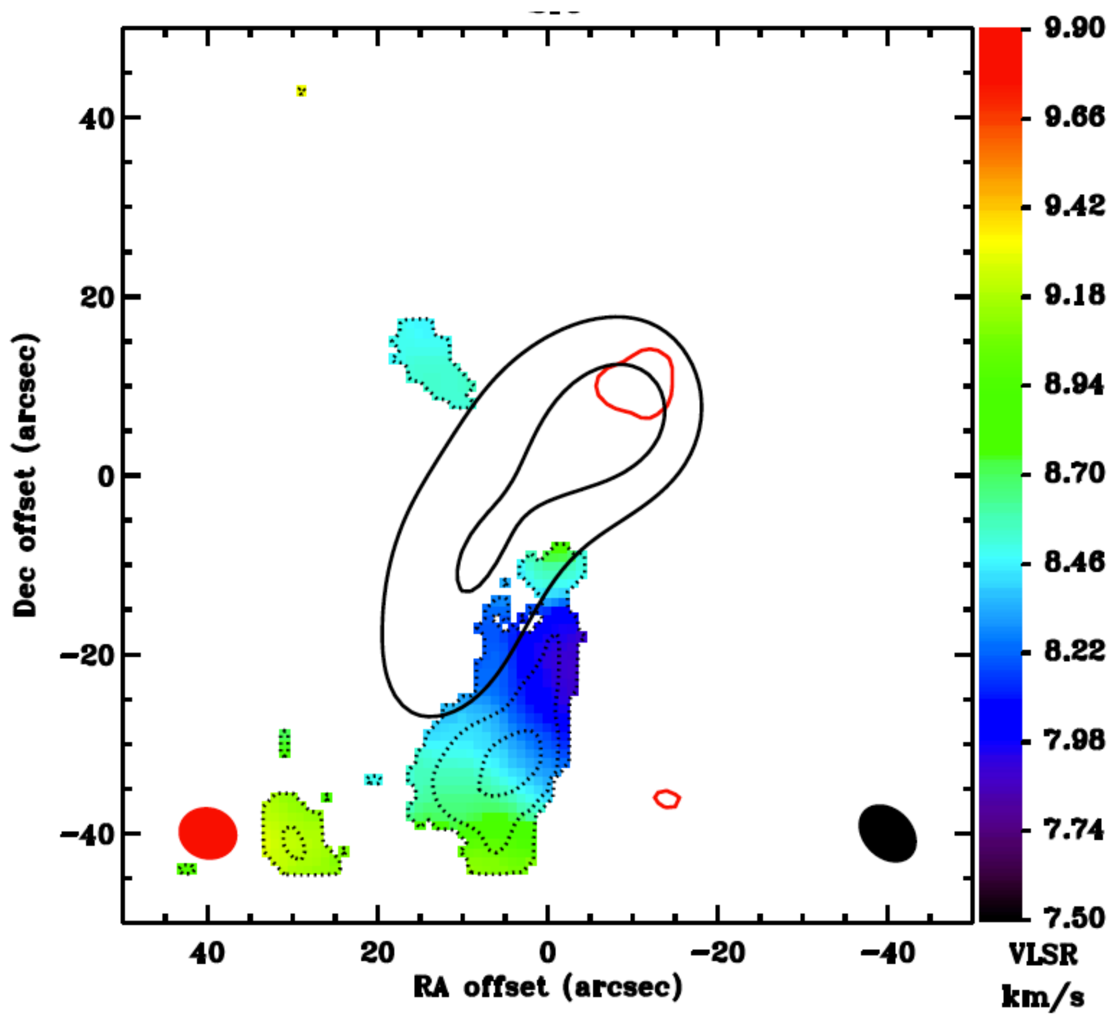
Greyscale and Green contours: 1.3mm continuum emission

Red and blue contours: Red and blue-shifted 12CO (2-1) emission

(0.3-7.3 & 7.3-14.3 km/s)

(Dunham, Chen, Arce, Bourke, Schnee, & Enoch 2011)

Perbo45 as a Protostar



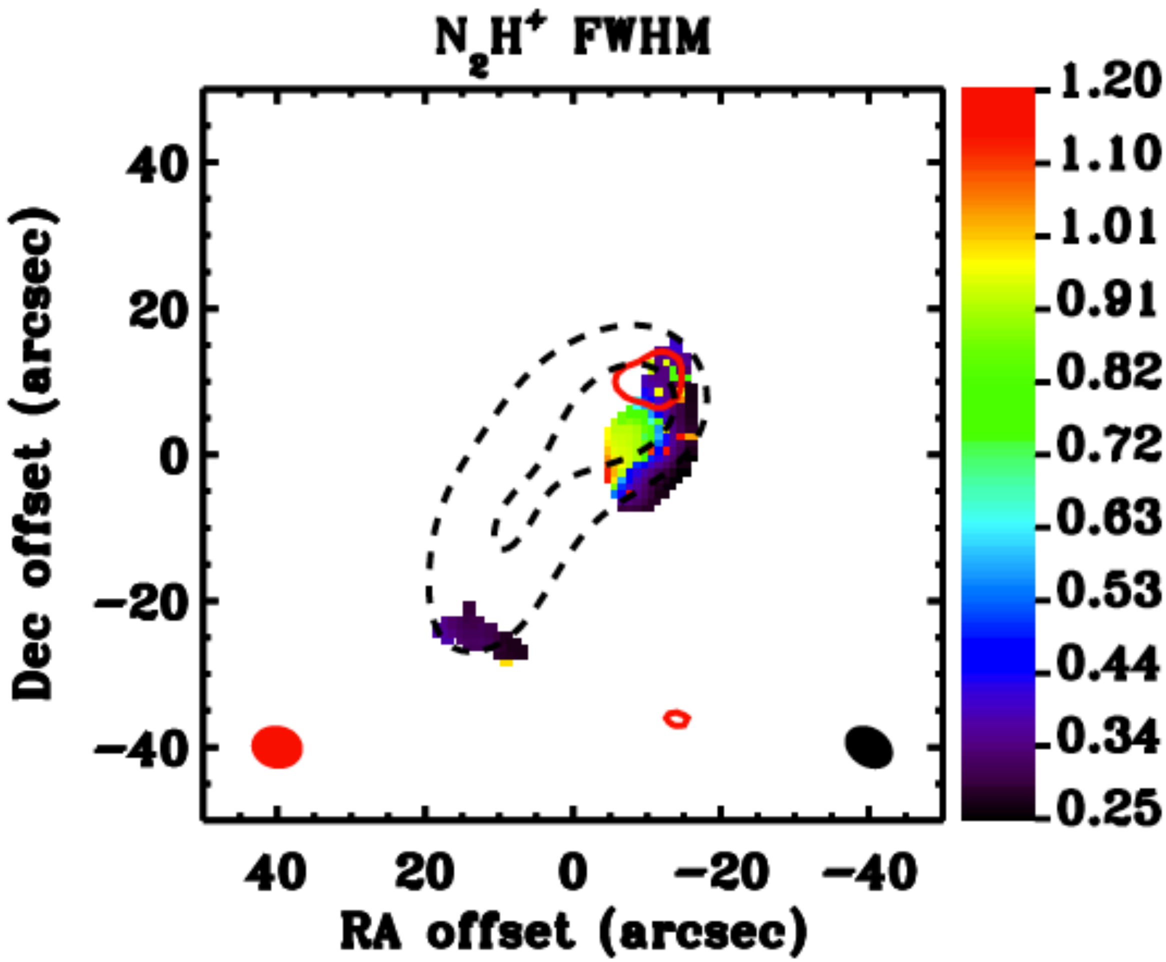
(Schnee et al. 2012)

Color scale – VLSR of SiO (2-1) emission

Red contour: 3mm continuum

Black contours:
850 micron SCUBA map

Perbo45 as a Protostar



Color scale – FWHM of N_2H^+ (1-0)

Red contour: 3mm continuum

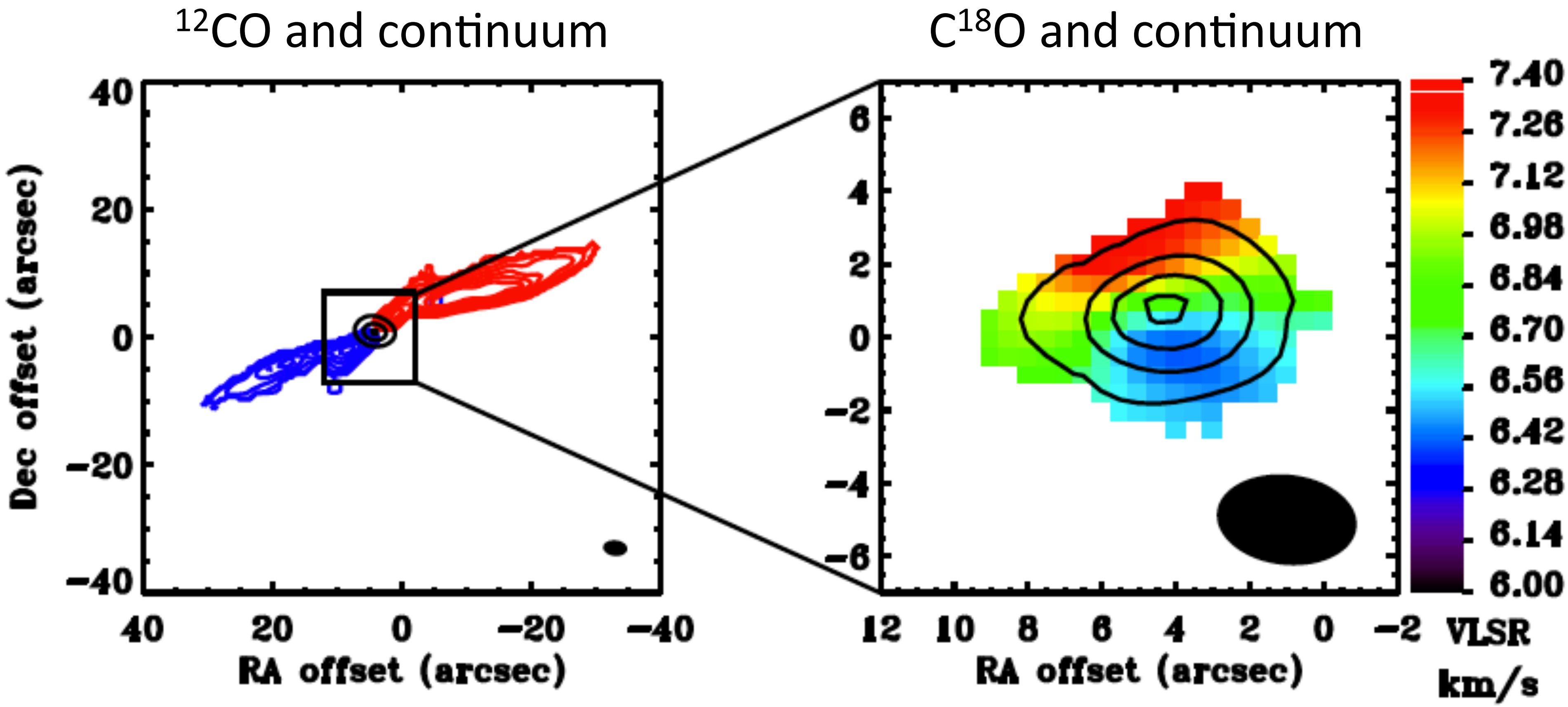
Black contours: 850 micron SCUBA map

(Schnee et al. 2012)

Samples

2. 5 most Jeans unstable starless cores in Perseus and Ophiuchus
   - Starless status based on Spitzer NIR-MIR data
   - 1.3mm continuum, ^{12}CO (2-1), ^{13}CO (2-1), $C^{18}O$ (2-1), N_2D^+ (3-2)
   - SMA subcompact observations
   - Chosen from Sadavoy et al. (2010)

J033217 as a Protostar



Black: 1.3mm continuum (0.1 – 0.5 mJy/beam)
Red: ^{12}CO (2-1) T_{int} 9 km/s ≤ v ≤ 18 km/s
Blue: ^{12}CO (2-1) T_{int} -2 km/s ≤ v ≤ 5 km/s
Color contours at 3, 6, …, 21 K km/s

Black: C^{18}O T_{int} in intervals of 2 K km/s
Color: C^{18}O VLSR

(Schnee et al. in prep)

Conclusions from Continuum Survey

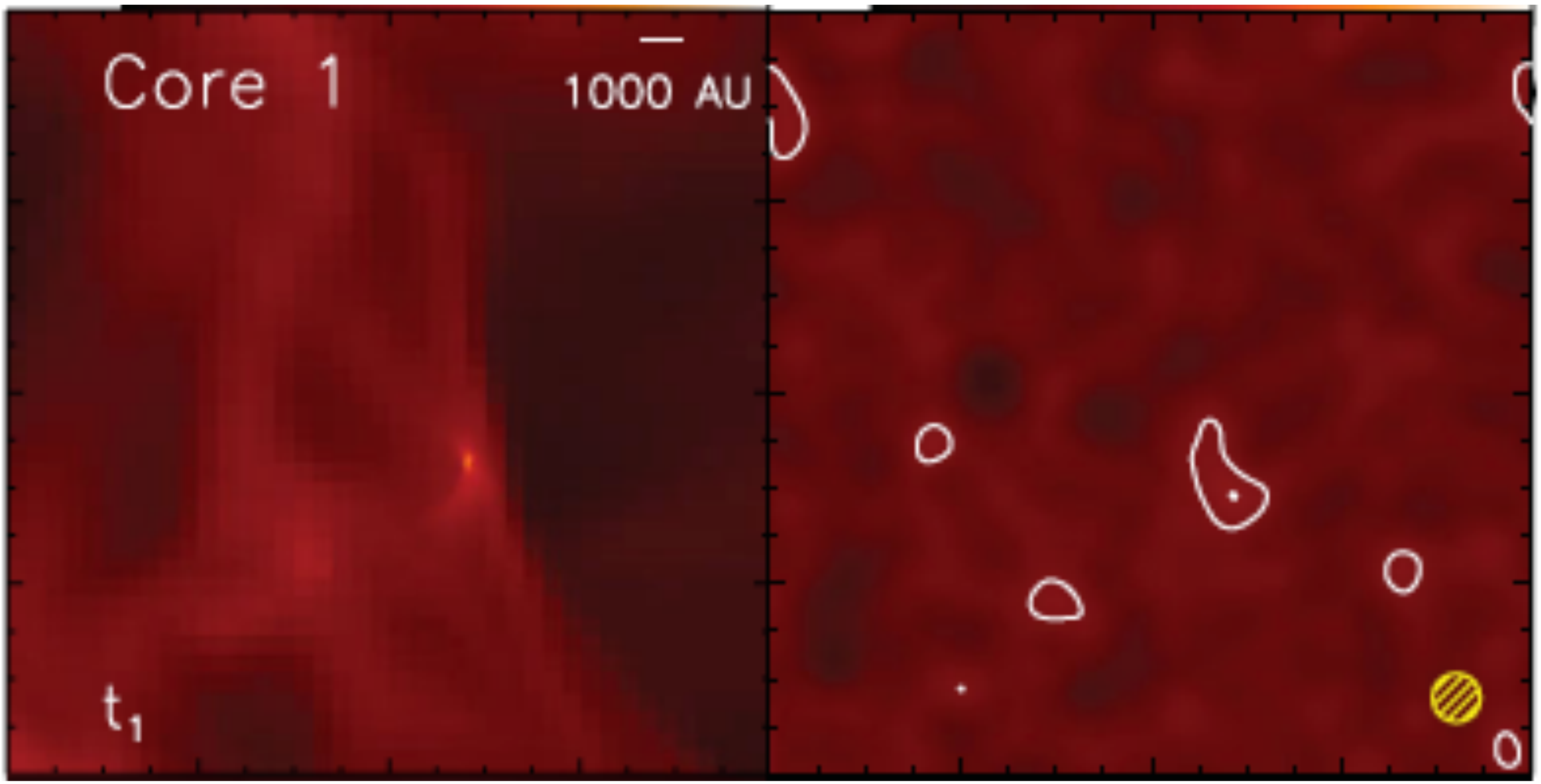
- Of the 11 brightest “starless” cores in Perseus
  - 2/11 single-peak continuum detections
  - Both detections are protostellar
- Of 5 most Jeans unstable “starless” cores in Ophiuchus and Perseus
  - 1/5 detection rate
  - Protostellar source

Conclusions from Continuum Survey

- The majority of starless cores have no observational evidence of sub-structure or fragmentation
- Estimate that 5-20% of "starless" cores in Perseus are actually protostars
  - ~100 starless cores and 50 protostars in Perseus
- *Spitzer* observations alone are not enough to determine if a core is starless

Simulations of Turbulent Fragmentation in Starless Cores

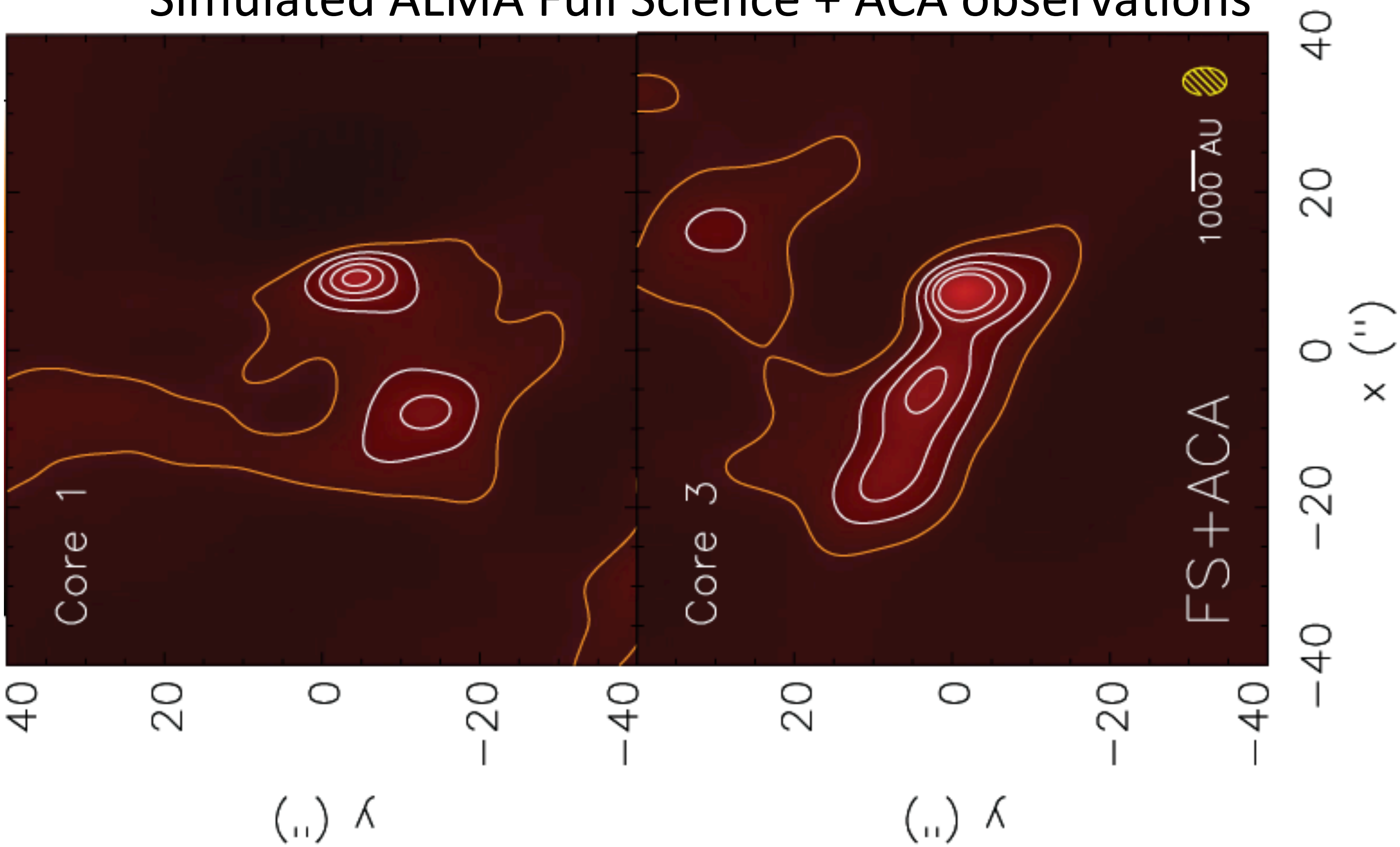
Simulated CARMA D-array observations



(Offner, Capodilupo, Schnee, & Goodman 2011)

Simulations of Turbulent Fragmentation in Starless Cores

Simulated ALMA Full Science + ACA observations



(Offner, Capodilupo, Schnee, & Goodman 2011)

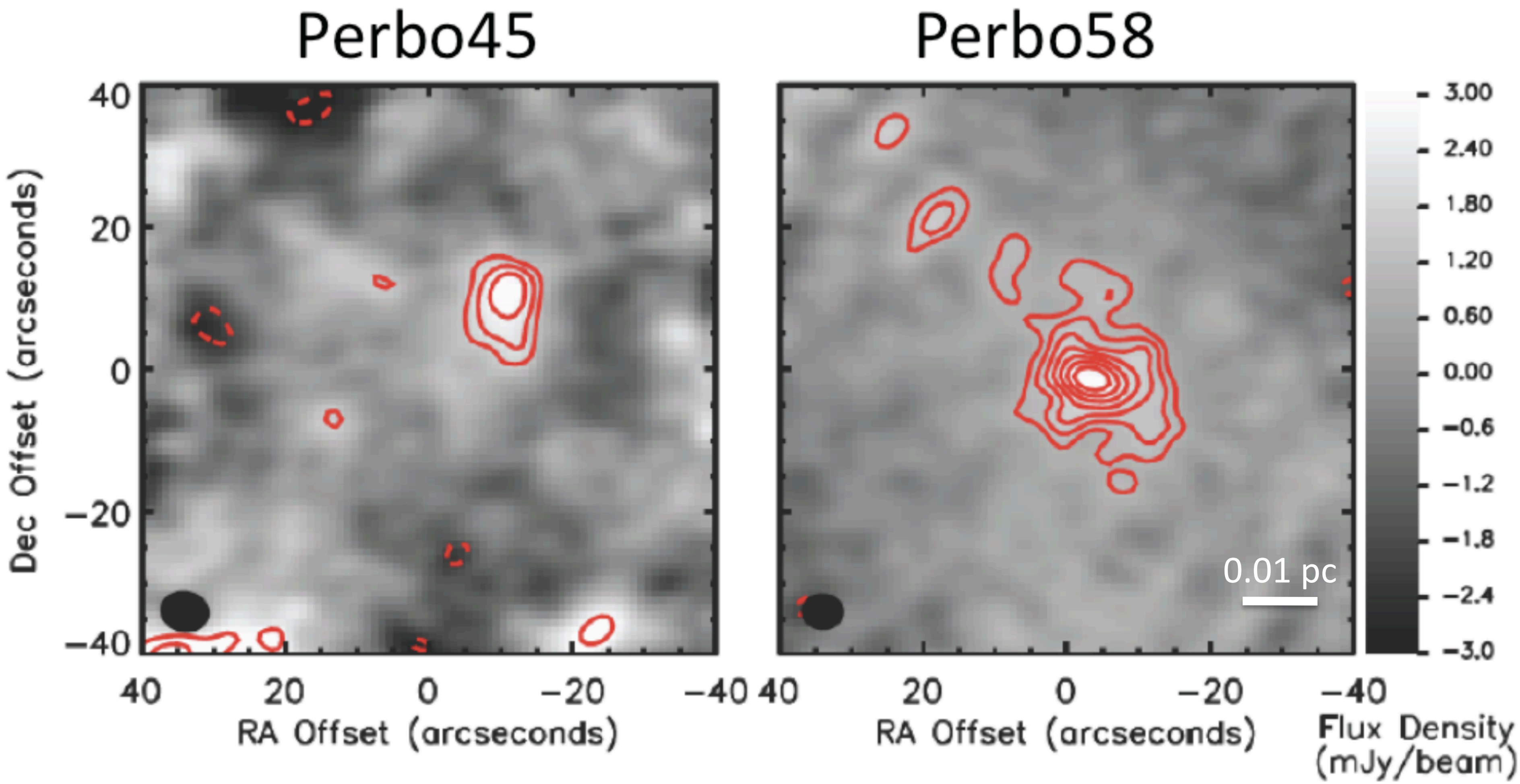
Final Thoughts

- The observational data do not yet support the theory that fragmentation begins in the starless stage
- Turbulent fragmentation theory suggests that ALMA, combining the main (12m) array with the ACA (7m & total power), can detect fragmentation in starless cores
- ALMA will surely find many low-luminosity protostars in the process

The End

Thank you for your time!

CARMA & SZA 3mm Continuum



(Schnee et al. 2010)

3mm-derived Properties of Starless Cores

Name	RA offset[1] ($''$)	Dec offset[1] ($''$)	Peak Flux[2] (mJy/beam)	Total Flux[2] (mJy)	Axes[3] ($''$)	θ_{PA}[3] (degrees)	Mass[4] ($M_\odot$)	density (cm^{-3})
Perbo11							<0.11	
Perbo13							<0.29	
Perbo14							<0.20	
Perbo44							<0.14	
Perbo45[5]	-10.3 ± 0.5	8.8 ± 0.7	2.4 ± 0.3	11 ± 0.5	14×9	-14	0.8	1.1×10^7
Perbo50							<0.16	
Perbo51							<0.62	
Perbo58	-4.3 ± 0.8	-1.1 ± 0.9	2.0 ± 0.3	33 ± 1	26×18	35	2.4	4.5×10^6
Perbo74							<0.07	
Perbo105							<0.20	
Perbo107							<0.24	

1. Offset from (0,0) position given in Enoch et al. (2006)
2. Derived from Gaussian fit to flux distribution
3. Deconvolved using the synthesized beam
4. For non-detections, 3σ upper limits to a point source are given
5. Does not include SZA data, so some 3mm emission is resolved out

(Schnee et al. 2010)

Perbo58 as a FHSC?

Table 1
Observed SED of Per-Bolo 58

Wavelength (μm)	Flux (mJy)	σ(Flux) (mJy)	Aperture Diameter ($''$)	Notes
4.5	0.024	0.07	2.2	Upper limit; *Spitzer* (c2d)
24	0.88	0.24	7	*Spitzer* (c2d)
70	65	6	17	*Spitzer*; this work
160	2870	1600	40	*Spitzer* (c2d)
350	6100	1200	40	SHARC II; M. M. Dunham et al. 2010, in preparation
850	920	200	18	SCUBA; Hatchell et al. (2005)
1100	330	30	40	Bolocam; Enoch et al. (2006)
2930	13	6	15	CARMA; Schnee et al. (2010)

(Enoch et al. 2010)

1mm-derived Properties of Starless Cores

Table 1
Core Properties from Bolocam 1 mm Data

Name	R.A. (J2000)	Decl. (J2000)	Peak Flux (mJy beam^{-1})	Total Flux (Jy)	Total Mass ($M_\odot$)	FWHM[a] ($''$)	Density[b] (10^5 cm^{-3})
Perbo11	03:25:46.0	+30:44:10	241	0.90	2.18	72.5	2.2
Perbo13	03:25:48.8	+30:42:24	407	0.47	1.14	38.2	3.9
Perbo14	03:25:50.6	+30:42:01	342	0.41	1.00	38.7	3.5
Perbo44	03:29:04.5	+31:18:42	274	0.72	1.73	47.0	2.7
Perbo45	03:29:07.7	+31:17:17	455	1.35	3.25	52.9	4.8
Perbo50	03:29:14.5	+31:20:30	313	1.31	3.15	68.0	3.2
Perbo51	03:29:17.0	+31:12:26	423	0.62	1.49	34.7	3.6
Perbo58	03:29:25.7	+31:28:16	273	0.33	0.78	25.9	1.8
Perbo74	03:33:01.9	+31:04:32	255	0.38	0.91	44.5	2.6
Perbo105	03:43:57.8	+32:04:06	283	0.61	1.47	46.6	2.8
Perbo107	03:44:02.1	+32:02:34	388	0.48	1.17	46.0	4.1

Notes.
[a] Derived from an elliptical Gaussian fit, deconvolved by the 31$''$ beam.
[b] Mean density calculated in a fixed linear aperture of diameter 10^4 AU.

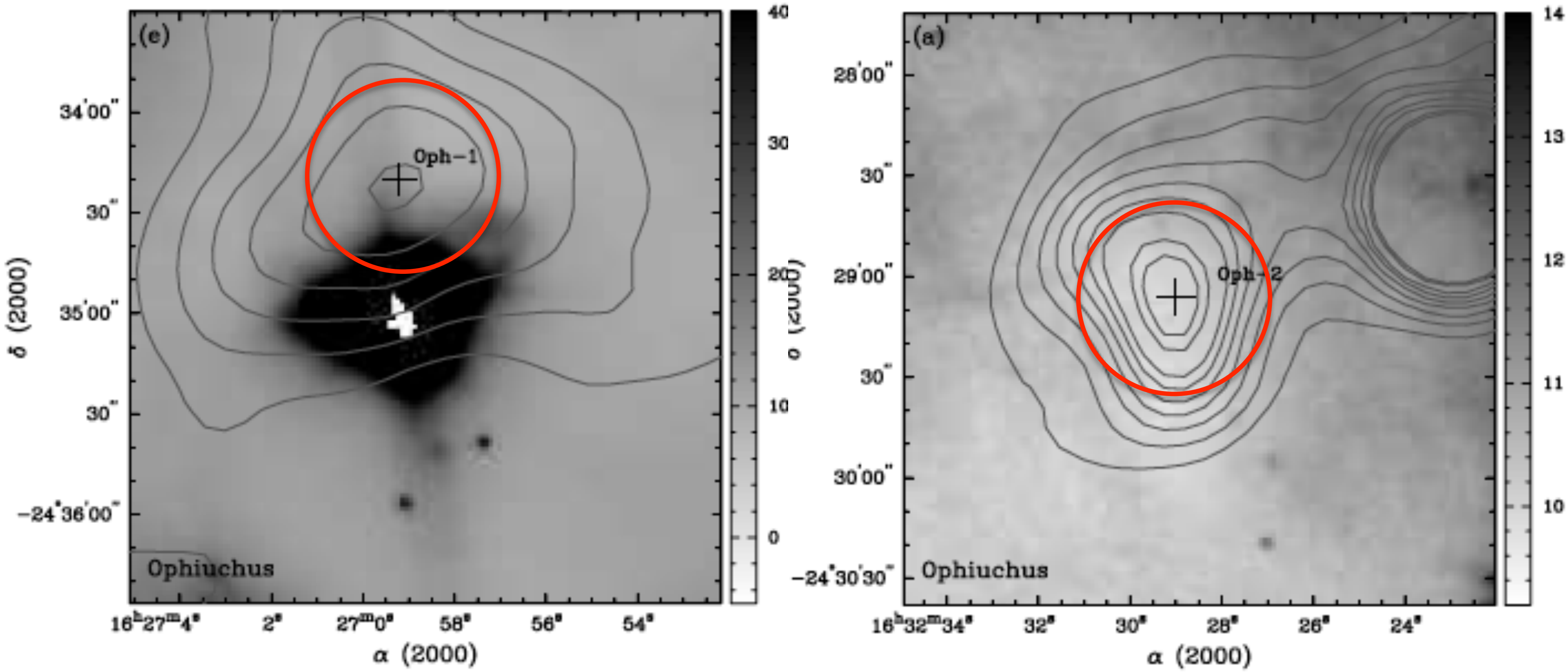
(Schnee et al. 2010)

850μm-derived Properties of Starless Cores

No.	SCUBA Core (J2000.0)	Nearby Sources[b]	Mass ($M_\odot$)	R_{eff} (pc)	M/M_J	New Classification[c]
Oph-1	J162659.2−243420	Oph C-MM3	5.3	0.060	2.2	Undetermined
Oph-2	J163229.0−242906	IRAS 16293-2422E	3.2	0.038	2.1	Starless
Tau-1	J043134.1+180802	LDN 1551 IRS 5	7.3	0.057	3.6	Protostellar
Tau-2	J043144.6+180832	LDN 1551NE	3.8	0.047	2.3	Protostellar
Per-1	J032855.2+311437	IRAS 2A	12	0.062	6.7	Undetermined
Per-2	J032859.5+312131	···	7.6	0.053	4.8	Starless
Per-3	J032901.3+312031	IRAS 6	15	0.059	8.6	Undetermined
Per-4	J032903.1+311555	NGC 1333 13A	18	0.047	13	Undetermined
Per-5	J032906.4+311537	HH 8	6.5	0.040	5.5	Undetermined
Per-6	J032908.7+311513	···	8.1	0.055	4.9	Starless
Per-7	J032910.1+311331	IRAS 4A	25	0.045	18	Protostellar
Per-8	J033217.6+304947	IRAS 03292+3039	7.2	0.055	4.4	Undetermined
Ori-1	J053514.4−052232	SMA 1	1200	0.17	130	Undetermined
Ori-2	J053514.4−052608	COUP 617	150	0.19	15	Undetermined
Ori-3	J053516.8−051926	OMC-N4	160	0.16	19	Undetermined
Ori-4	J053522.0−052508	COUP 1194	80	0.13	11	Undetermined
Ori-5	J053524.8−052220	COUP 1314	35	0.13	5.0	Undetermined

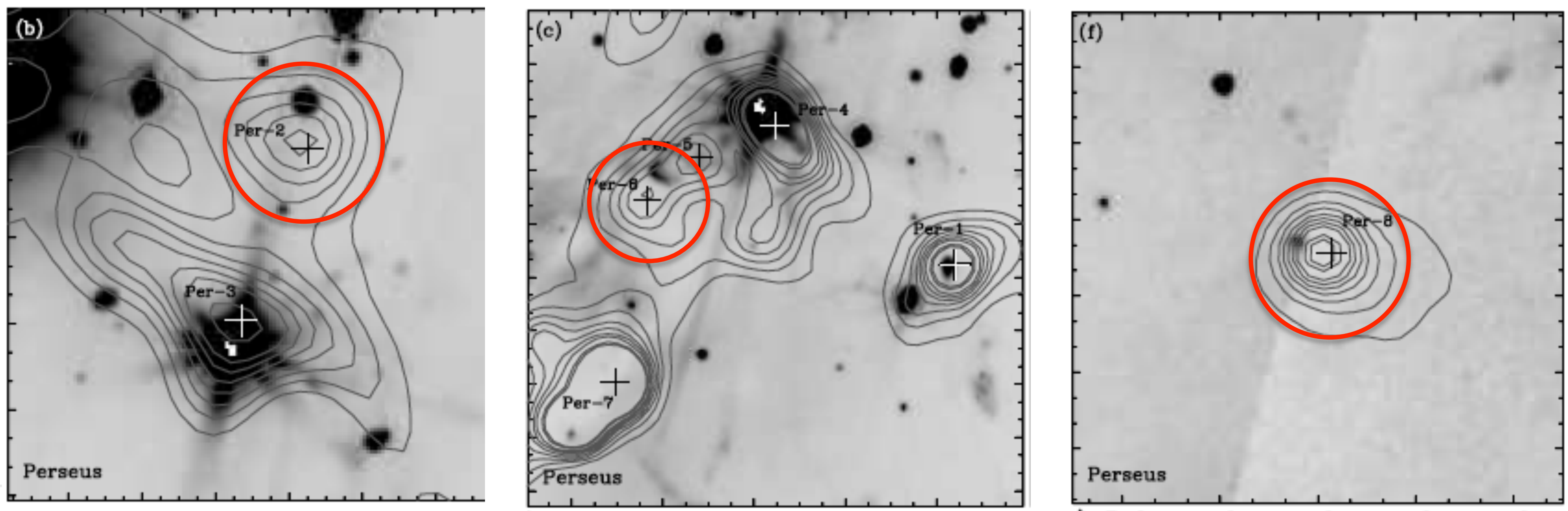
(Sadavoy et al. 2010)

Ophiuchus Cores



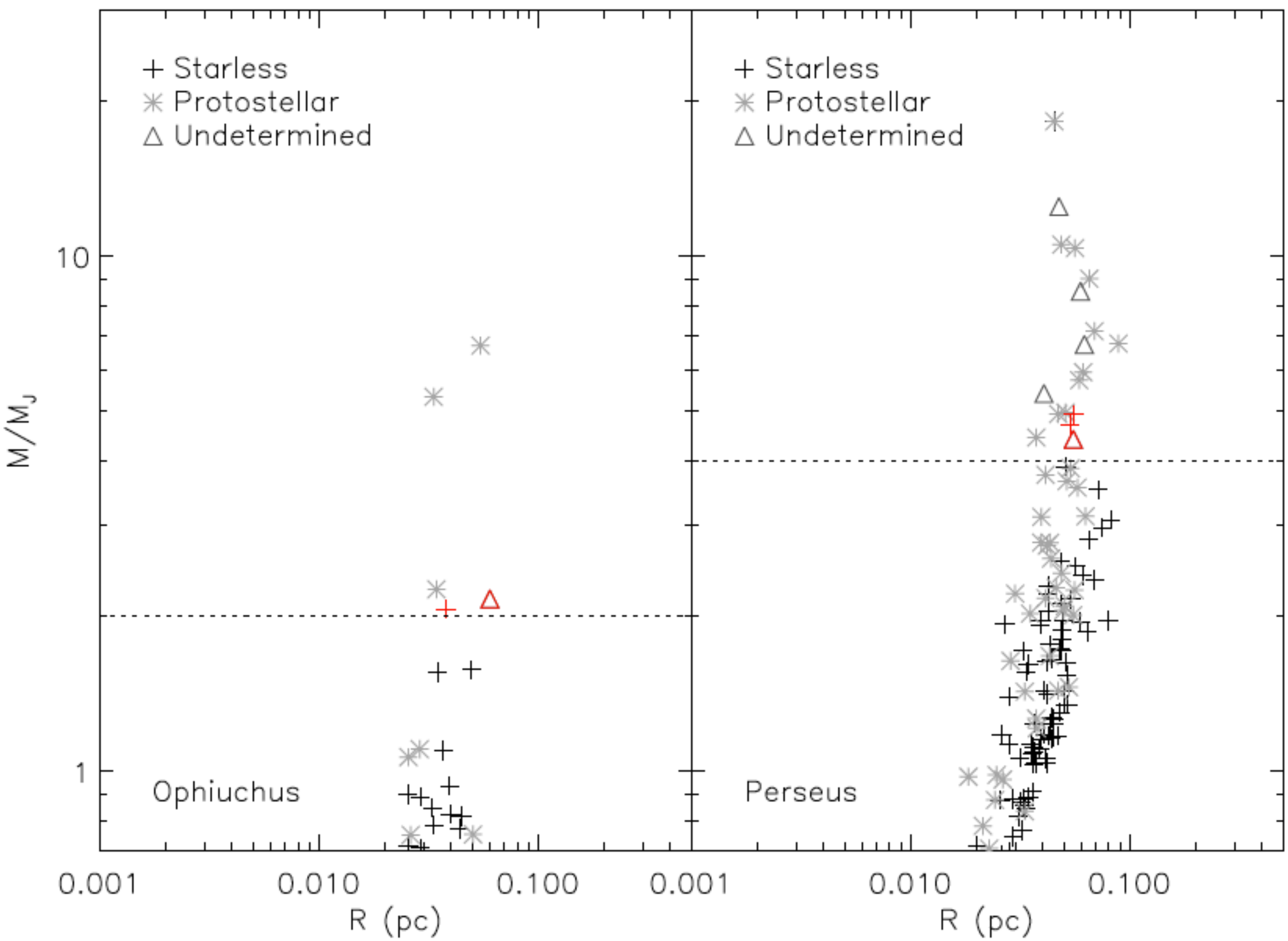
Grey scale: Spitzer 8μm map
Contours SCUBA 850μm map in steps of 0.2 Jy/beam
(Sadavoy et al. 2010)

Perseus Cores



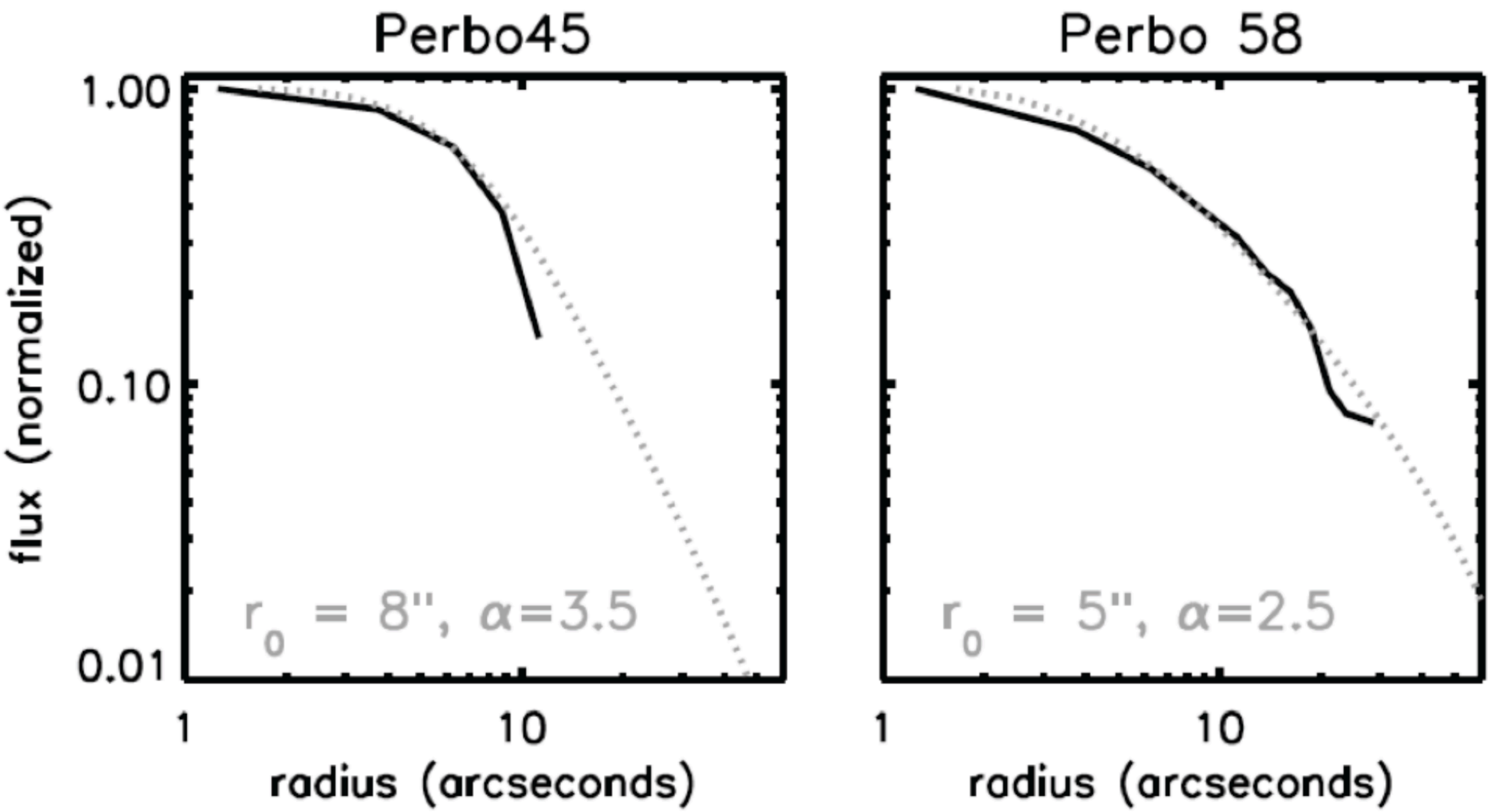
Grey scale: Spitzer 8μm map
Contours SCUBA 850μm map in steps of 0.2 Jy/beam
(Sadavoy et al. 2010)

Jeans Instability of Cores



3mm Continuum Flux Profiles

$$n(r) = n_0/[1 + (r/r_0)^\alpha]$$



(Schnee et al. 2010)