Mass Assembly of Stellar Systems and their Evolution with the SMA (MASSES)

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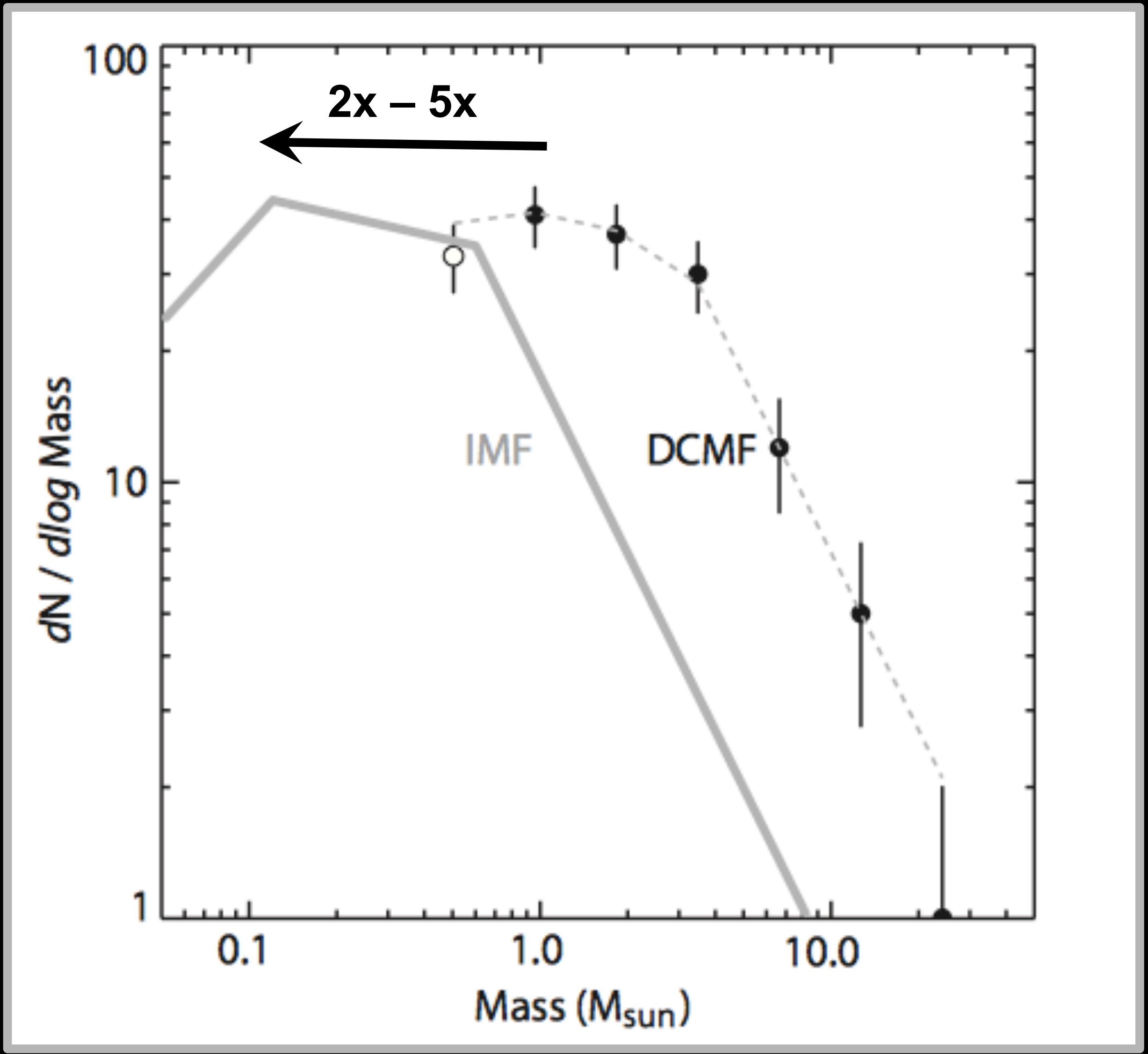
Presentation to the SMA Advisory Committee
Tuesday, July 17, 2018

Origins of Stellar Masses



Alves et al. 2007; Offner et al. 2014, PPVI

The origins of the stellar initial mass function (IMF) is one of the great unsolved problems in stellar astrophysics

The IMF and dense core mass function (CMF) are similar in shape, with the IMF shifted to about 3x lower masses

IMF set by CMF?

Physical Processes Regulating Accretion

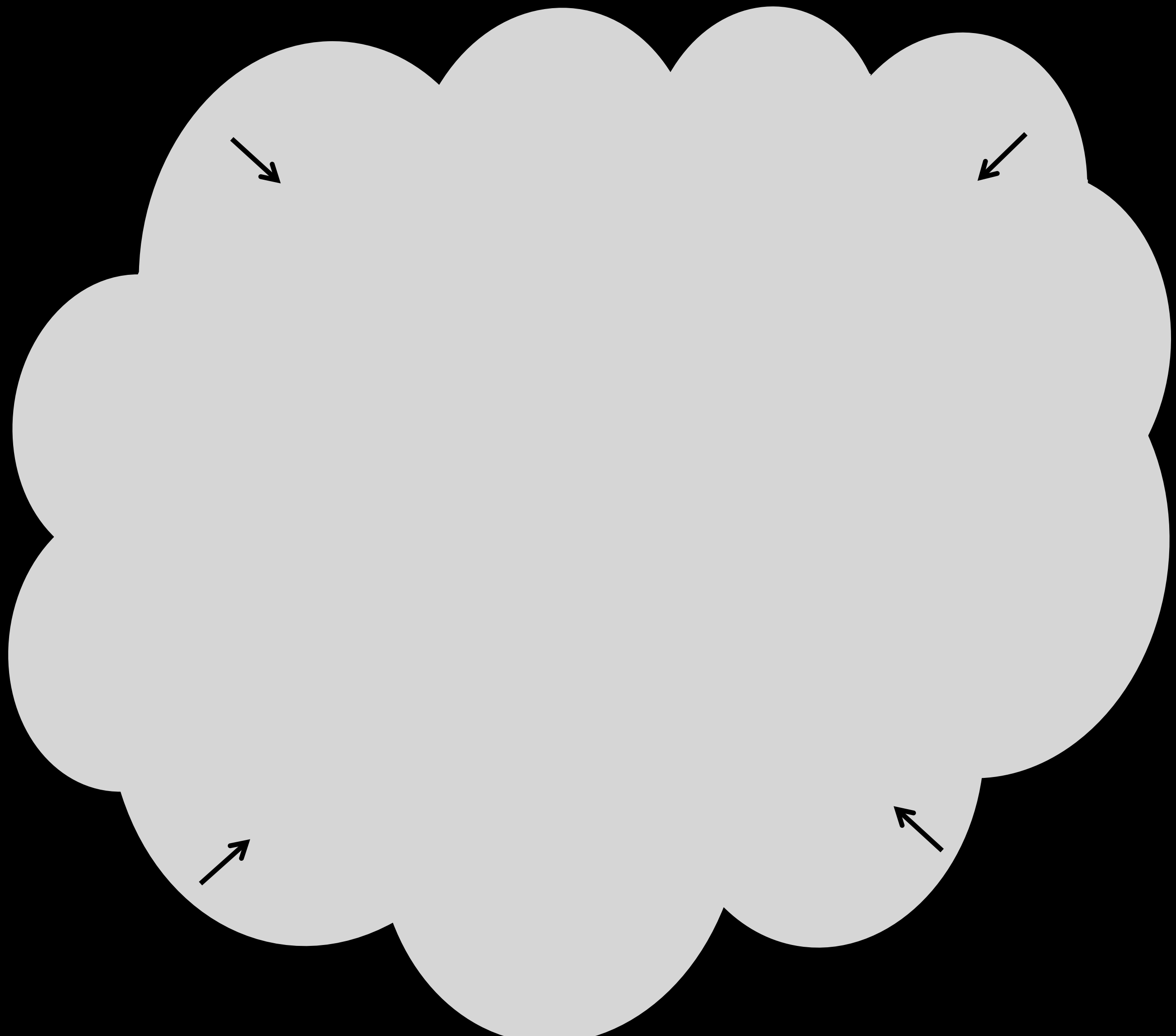


Diagram adapted from M. Persson

Physical Processes Regulating Accretion

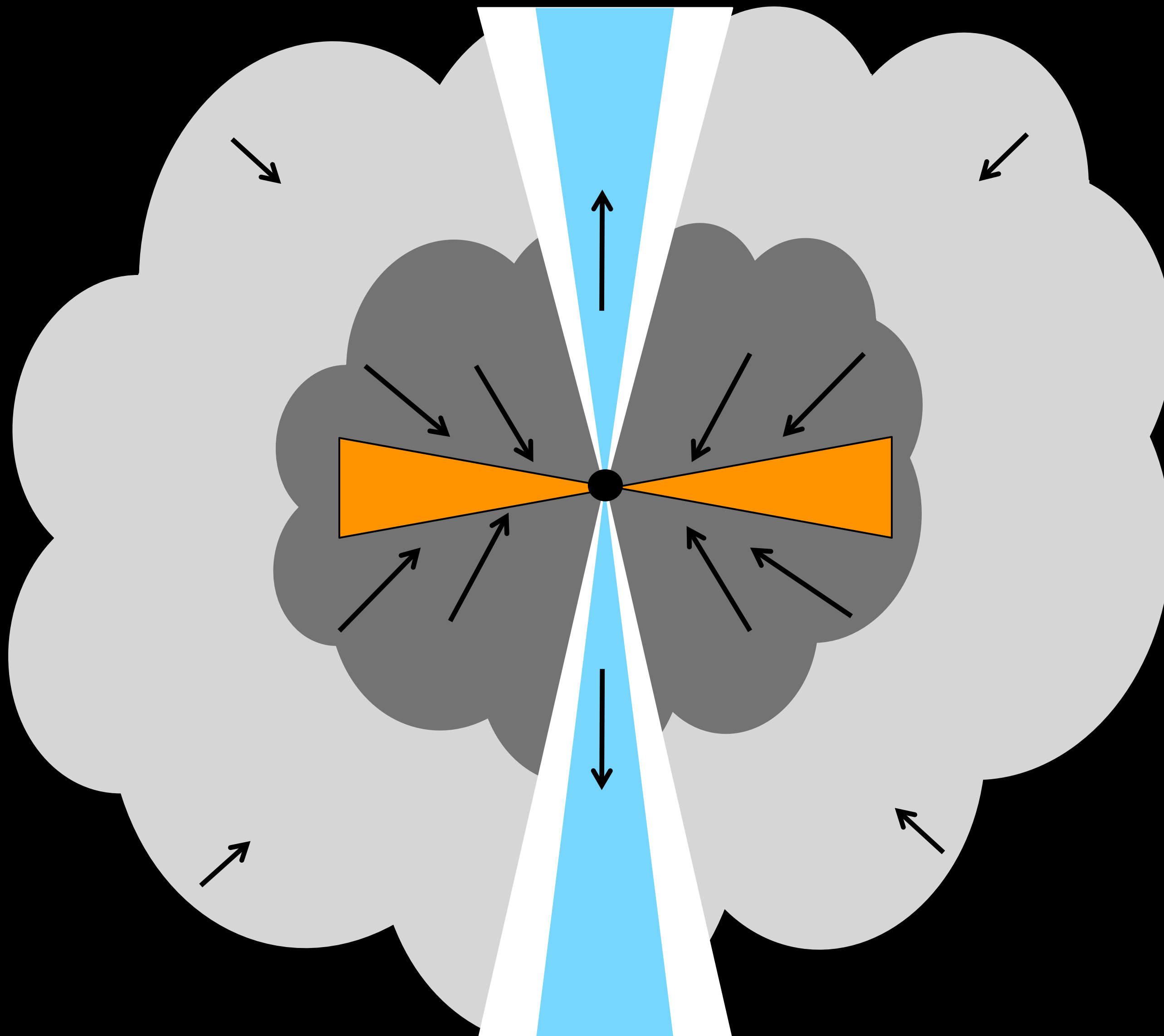


Diagram adapted from M. Persson

Physical Processes Regulating Accretion

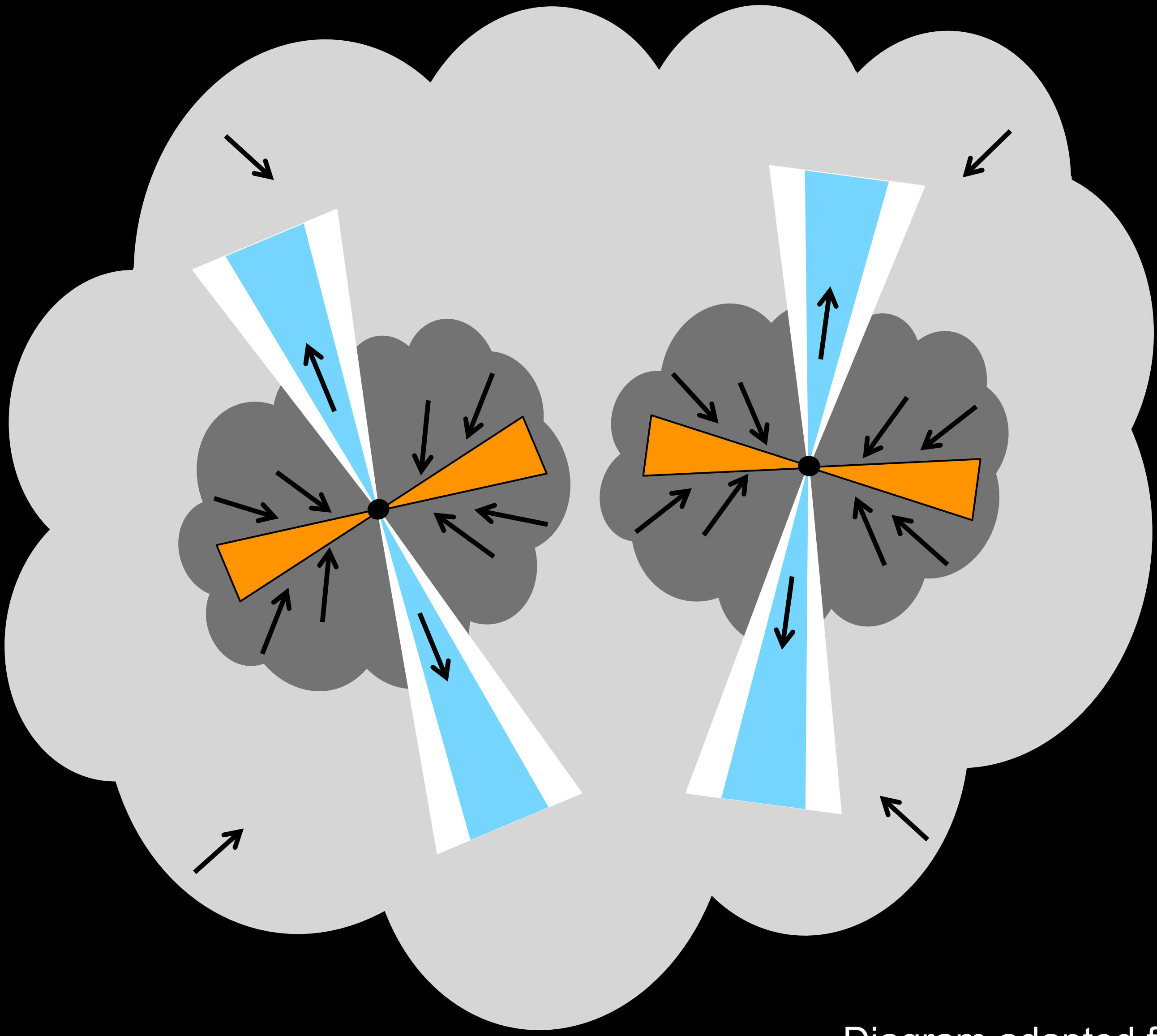


Diagram adapted from M. Persson

Physical Processes Regulating Accretion

Open Questions

1. When, where, and how do cores and disks fragment into multiple systems?

2. What role do disks play in the transfer of mass from cores to stars?

3. To what extent do outflows regulate the protostellar mass accretion process?

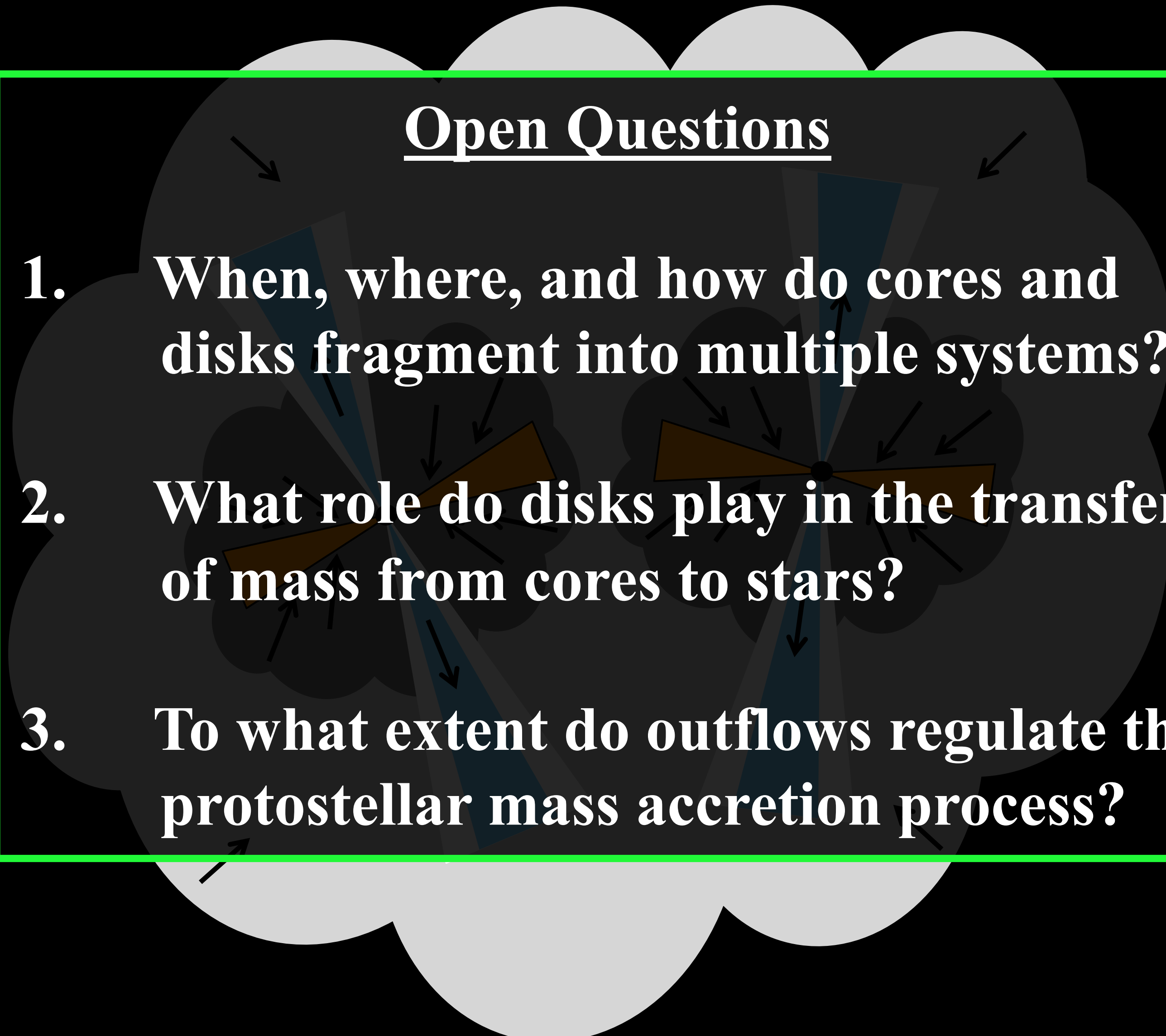
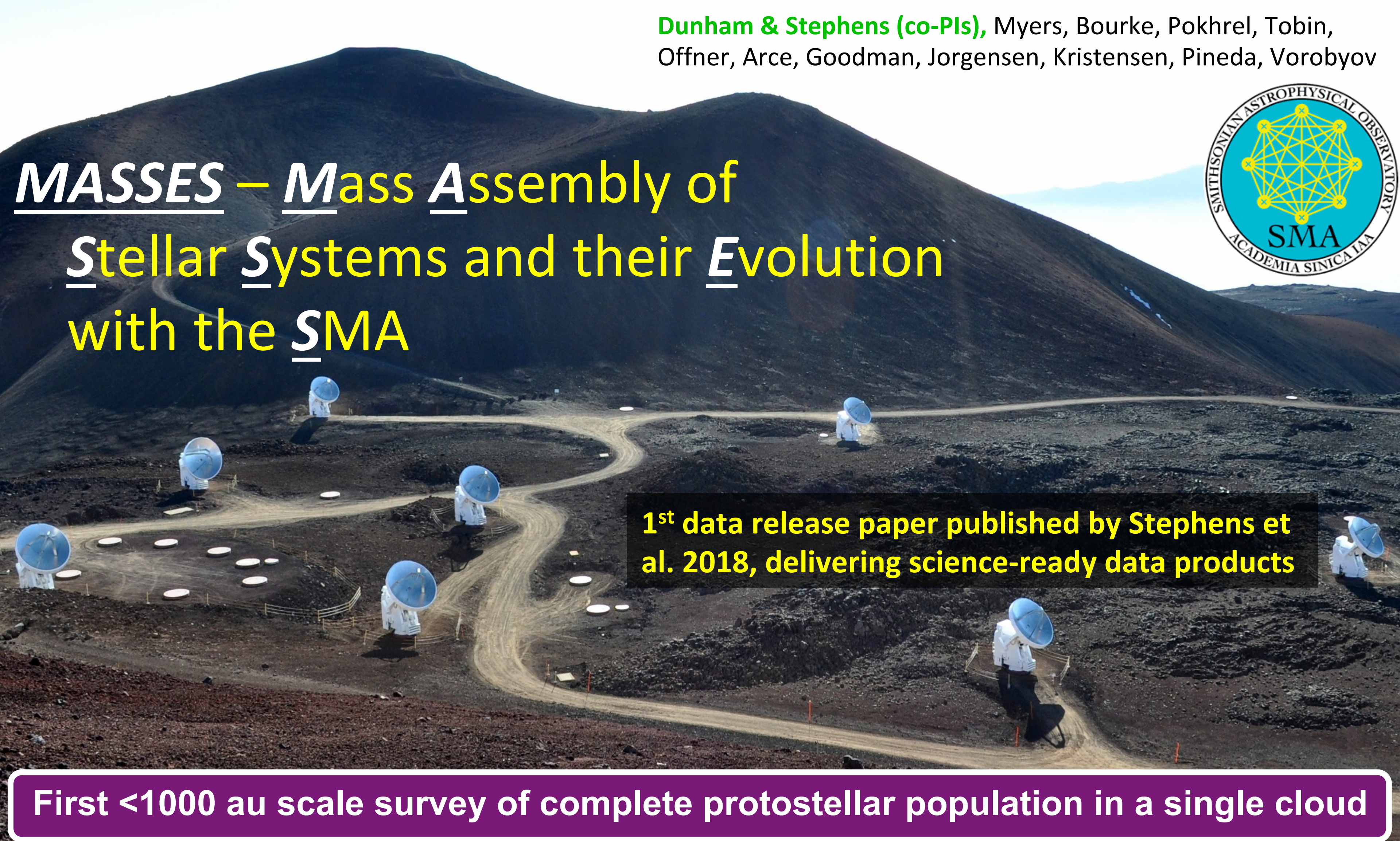


Diagram adapted from M. Persson

Dunham & Stephens (co-PIs), Myers, Bourke, Pokhrel, Tobin, Offner, Arce, Goodman, Jorgensen, Kristensen, Pineda, Vorobyov

MASSES – ***M***ass ***A***ssembly of ***S***tellar ***S***ystems and their ***E***volution with the ***S***MA

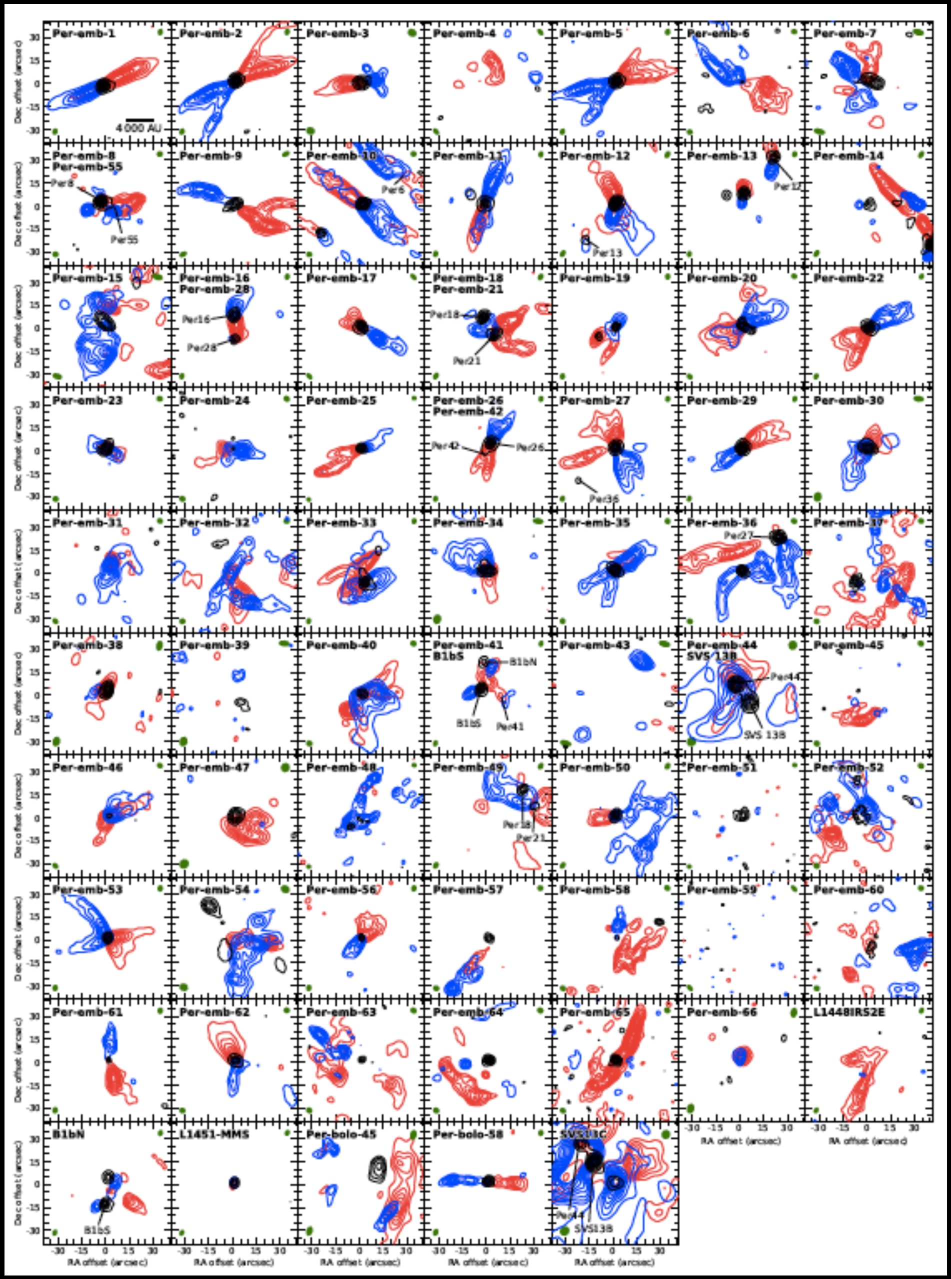


1st data release paper published by Stephens et al. 2018, delivering science-ready data products

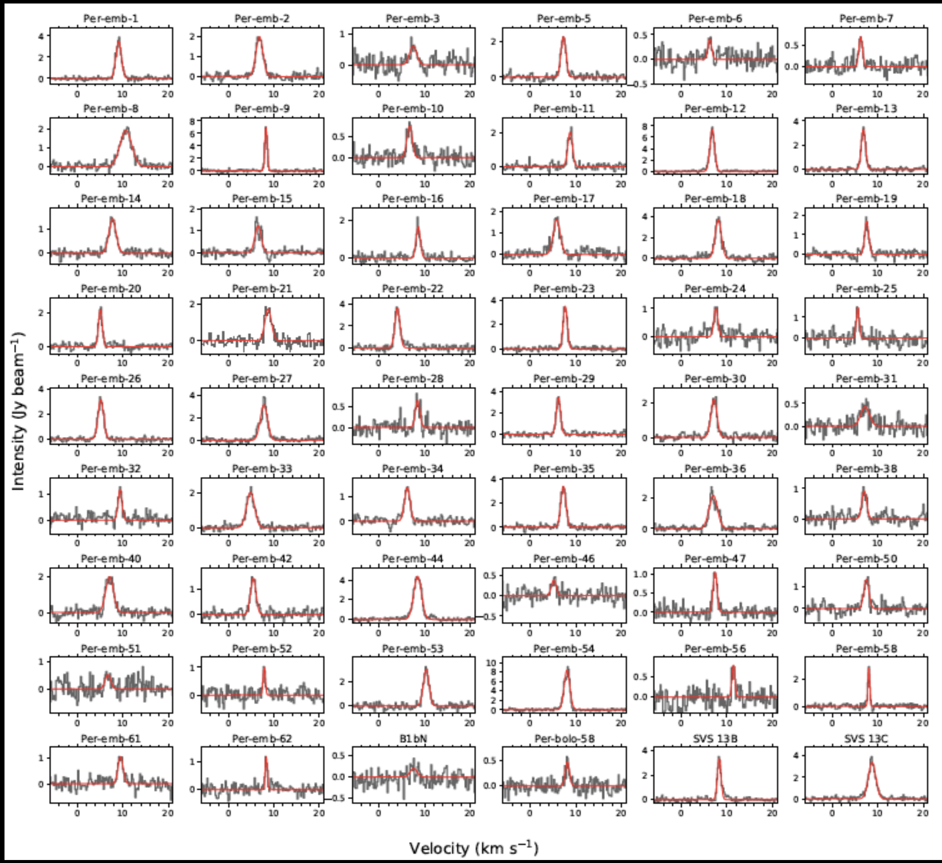
First <1000 au scale survey of complete protostellar population in a single cloud

- (sub)millimeter survey of all (~70) protostars in Perseus (*d* = 230 pc)
- Approx. 600 hr over 3 years (Fall 2014 – Spring 2017), spans ASIC → SWARM upgrade
- Targets multiple dense gas & outflow tracers at 230 & 345 GHz, plus the continuum
- Two SMA configurations (SUB+EXT) – 200 AU resolution, >4000 AU max. scale

The Statistical Power of MASSES

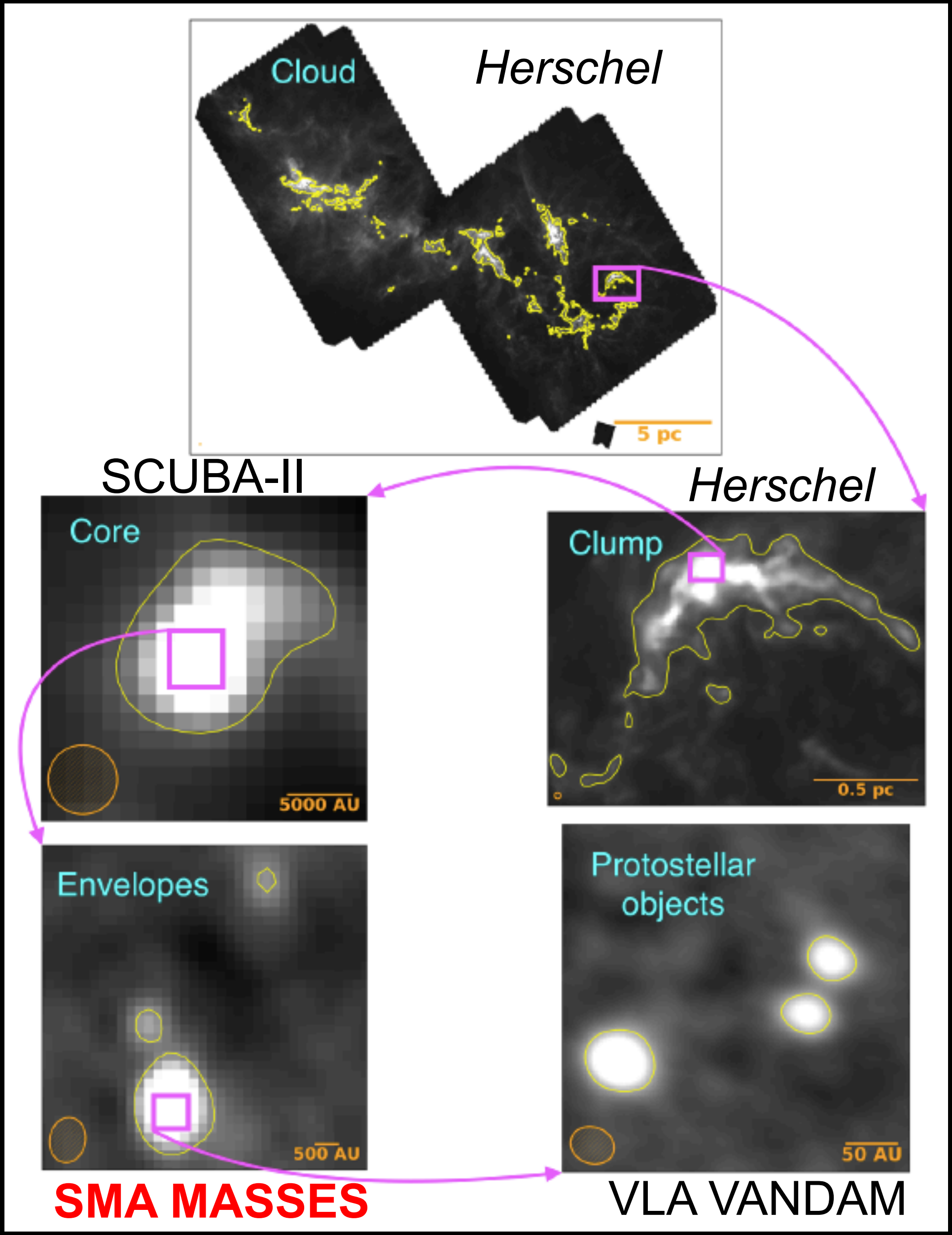


Stephens, Dunham, et al. (2018)



Hierarchical Fragmentation of a Molecular Cloud

Pokhrel, Myers, Dunham, et al. (2018)

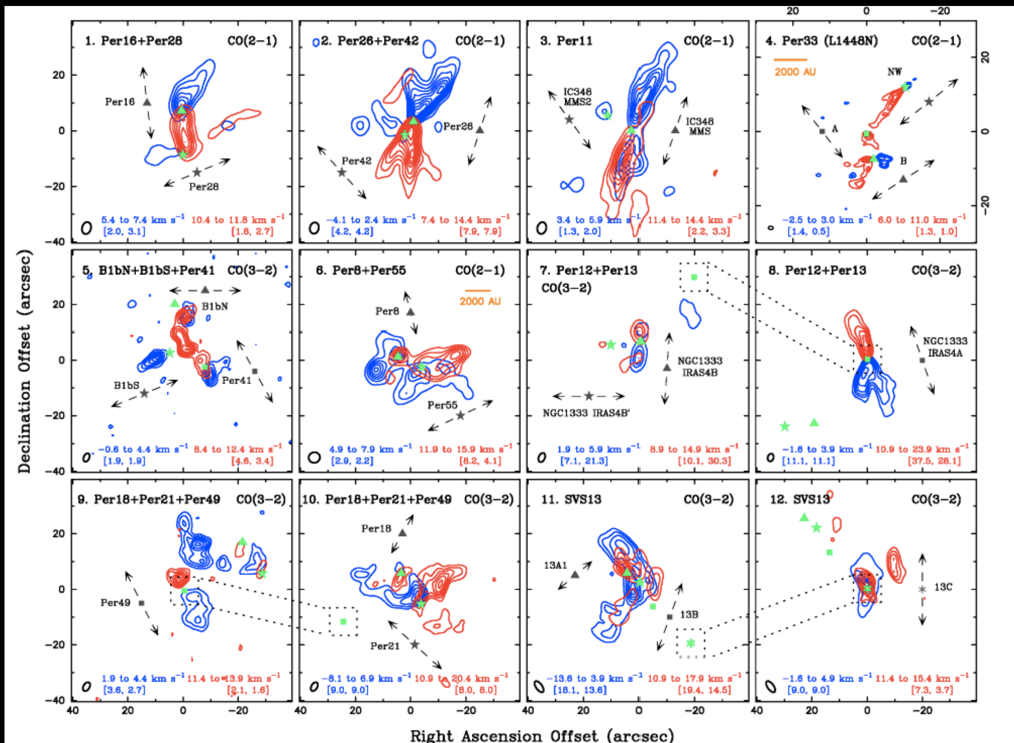


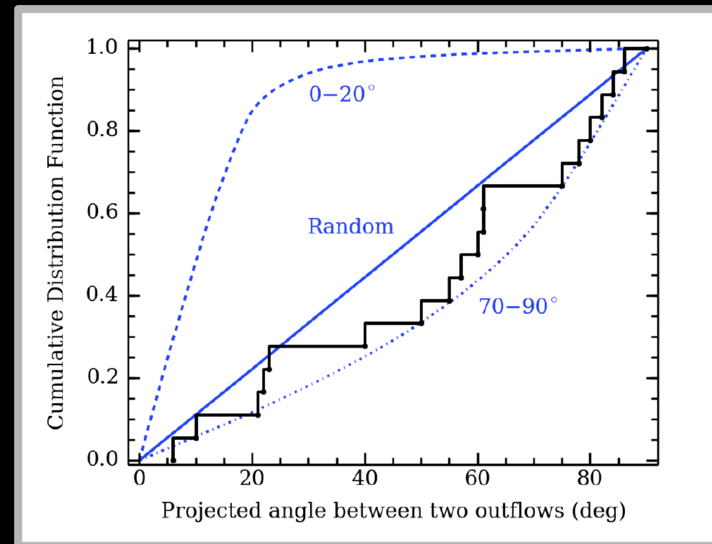
Fragmentation is a multi-scale, hierarchical process

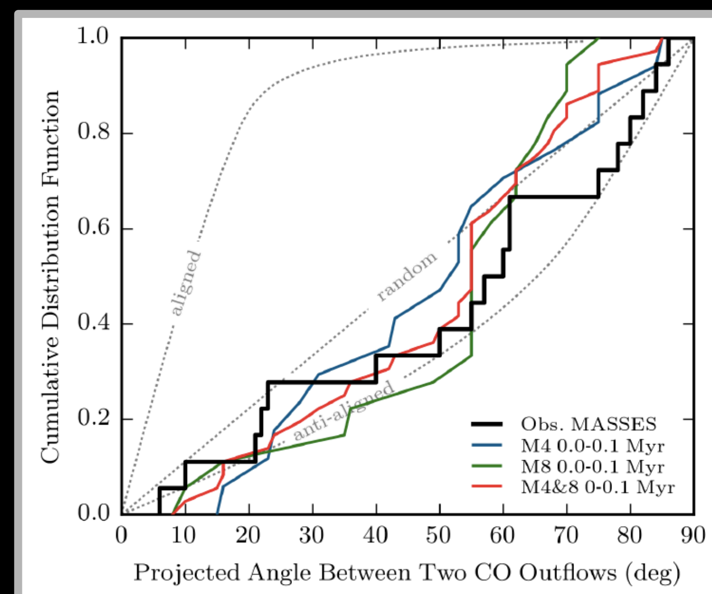
Different physical mechanisms may be relevant on different size scales

Question addressed by MASSES: What causes "envelopes" (~1000 AU structures) to fragment into multiple protostars

Alignment of Multiple Systems





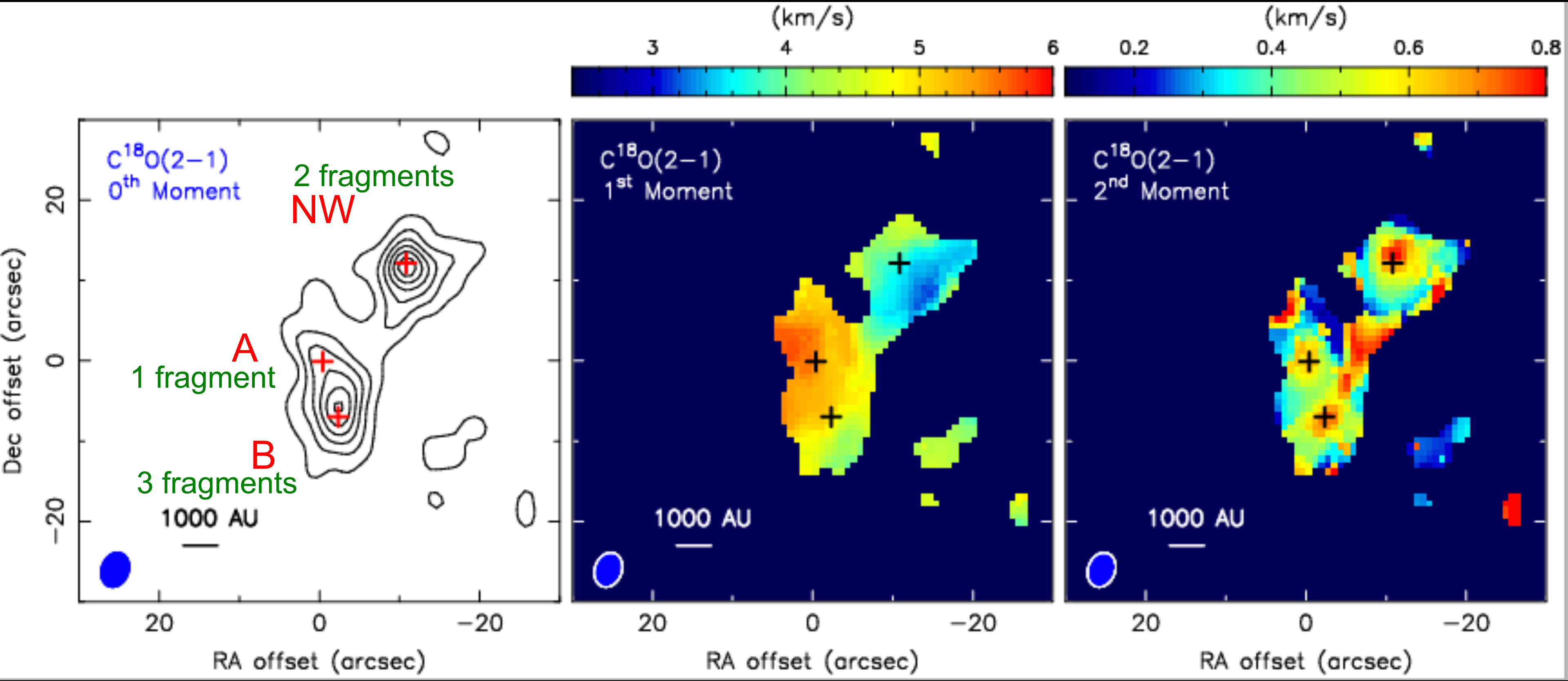


Wide multiple systems are randomly aligned, an unexpected result that agrees with theoretical predictions of turbulent fragmentation

Lee, Dunham, et al. (2016)
Offner, Dunham, et al. (2016)

Fragmentation in L1448-N

Lee, Dunham, Myers, et al. (2015)

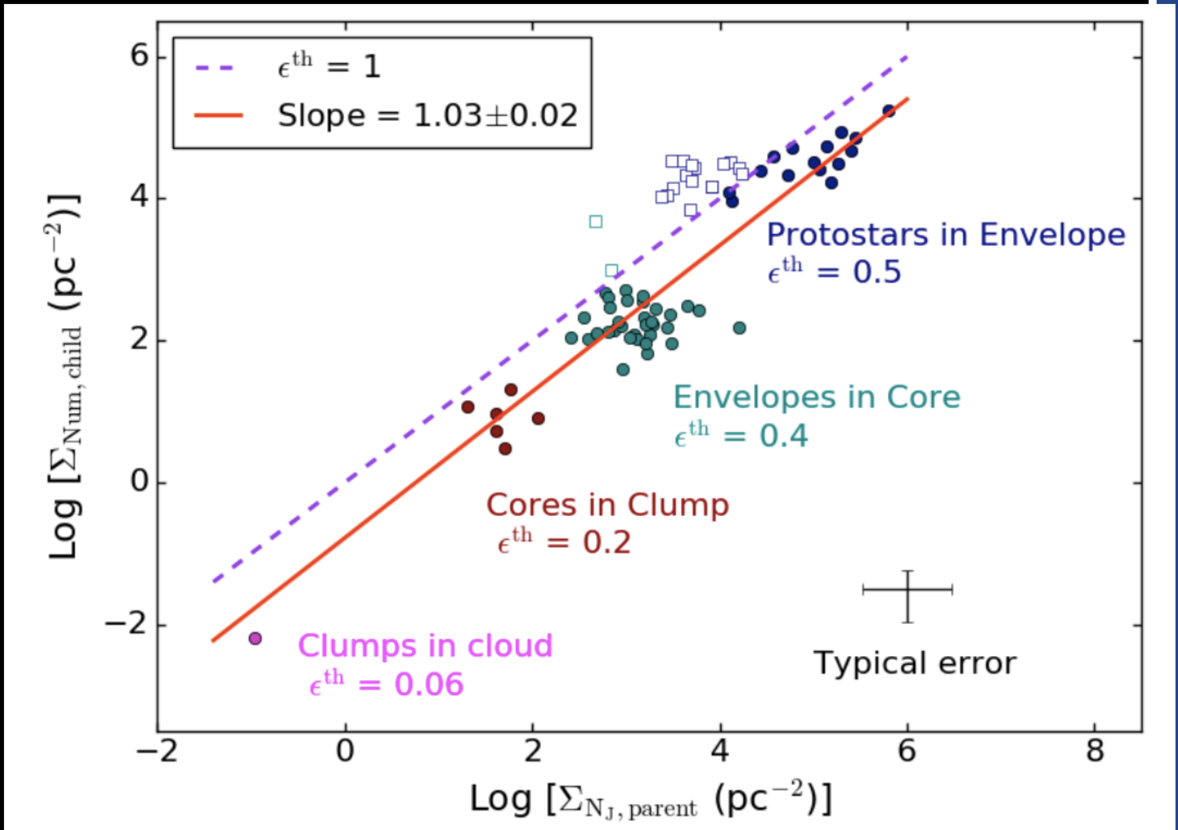


Number of <100 AU fragments within 1000 AU SMA objects:

- **Does not** correlate with β (rotational/gravitational energy)
- **Does not** correlate with σ (non-thermal velocity dispersion)
- **Does** correlate w/thermal Jeans number (core mass / Jeans mass)

Hierarchical Fragmentation of a Molecular Cloud

Pokhrel, Myers, Dunham, et al. (2018)



y-axis: number of fragments within parent (divided by surface area of parent)
x-axis: thermal Jeans number of parent (divided by surface area of parent)

At all levels, number of fragments correlates with thermal Jeans number

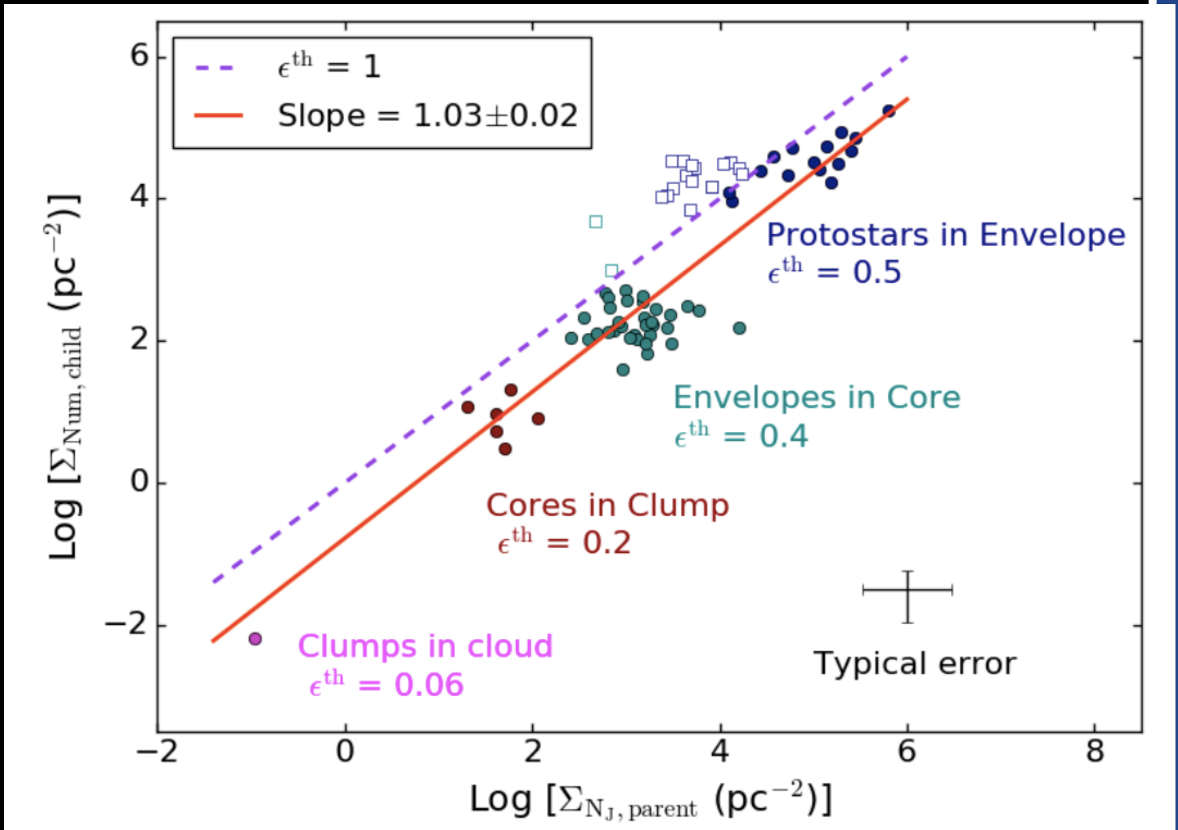
At all levels, number of fragments is also less than predicted by thermal Jeans number

Including non-thermal support predicts no fragmentation on large scales, and has no effect on small scales

Fragmentation appears to be best described as "inefficient thermal Jeans fragmentation"

Hierarchical Fragmentation of a Molecular Cloud

Pokhrel, Myers, Dunham, et al. (2018)



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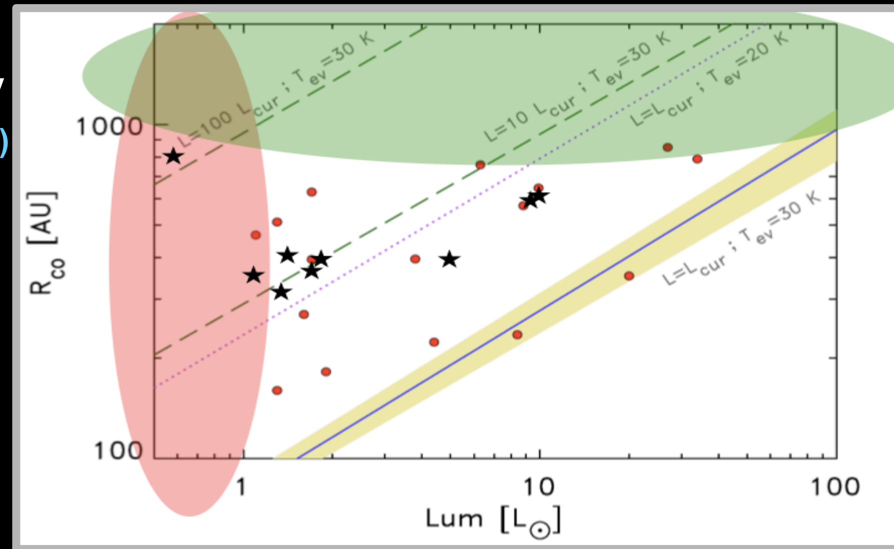
Fragmentation appears to be best described as "inefficient thermal Jeans fragmentation"

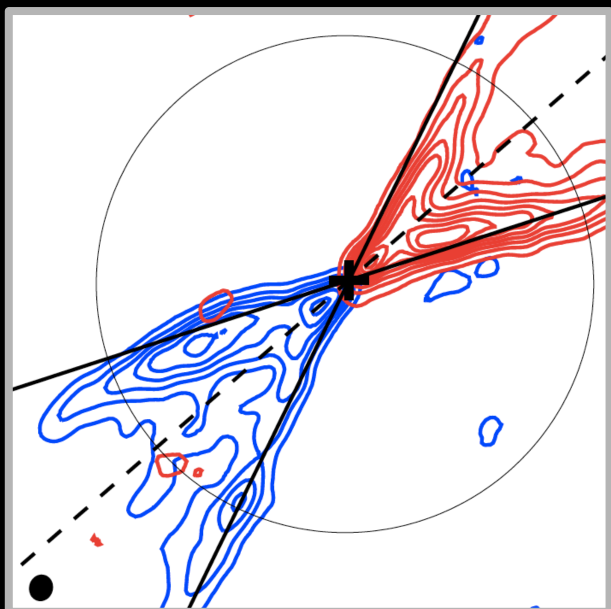
Kinematics vs. multiplicity in progress. Consistency with turbulent fragmentation under investigation.

MASSES is About More than Fragmentation...

Accretion histories traced by chemistry

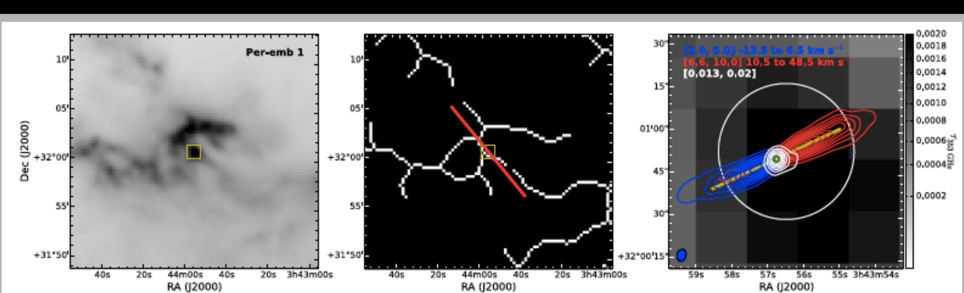
Frimann et al. (2017)





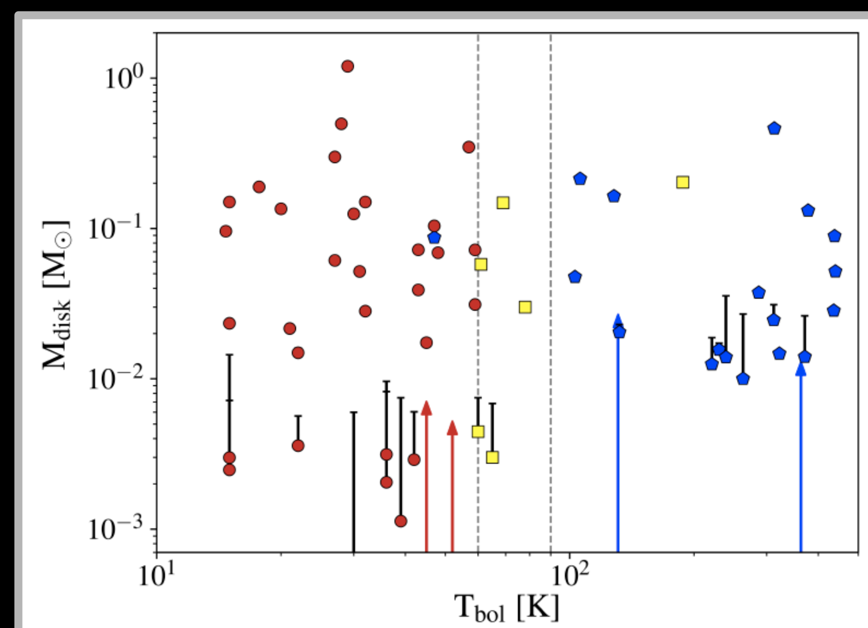
Outflow morphology evolution

Dunham, Stephens, et al. (in prep)



Outflow/filament (mis)alignment

Stephens et al. (2017)



Protostellar disk masses

Andersen et al. (in prep)

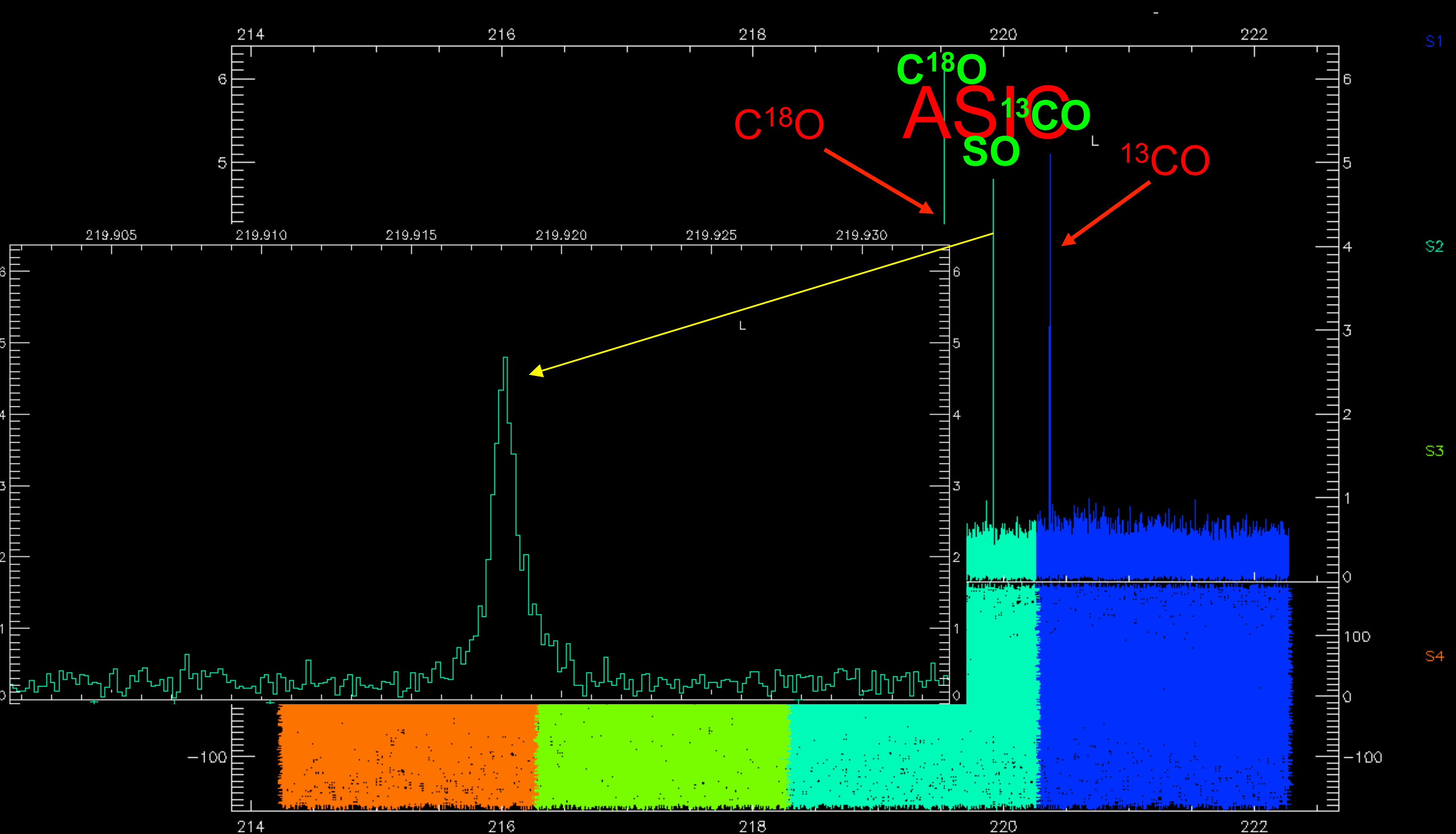
MASSES enables key progress on open questions requiring a statistical approach, and is triggering follow-up theoretical and observational (ALMA, VLA, etc.) work

MASSES Publications

1. Lee, Dunham, Myers, et al., "*Mass Assembly of Stellar Systems and their Evolution with the SMA. Multiplicity and the Physical Environment in L1448N*", 2015, ApJ, 814, 114
2. Lee, Dunham, Myers, et al., "*Misalignment of Outflow Axes in the Proto-multiple Systems in Perseus*", 2016, ApJL, 820, 2
3. Offner, Dunham, Lee, Arce, & Fielding, "*The Turbulent Origin of Outflow and Spin Misalignment in Multiple Star Systems*", 2016, ApJL, 827, 11
4. Frimann, Jørgensen, Dunham, Bourke, et al., "*Protostellar accretion traced with chemistry: High-resolution $C^{18}O$ and continuum observations towards deeply embedded protostars in Perseus*", 2017, A&A, 602, 120
5. Stephens, Dunham, Myers, Pokhrel, et al., "*Alignment Between Protostellar Outflows and Filamentary Structure*", 2017, ApJ, 846, 16
6. Pokhrel, Myers, Dunham, Stephens, et al., "*Hierarchical Fragmentation in the Perseus Molecular Cloud: From the Cloud Scale to Protostellar Objects*", 2018, ApJ, 853, 1
7. Stephens, Dunham, Myers, et al., "*Mass Assembly of Stellar Systems and their Evolution with the SMA – 1.3 mm Subcompact Data Release*", 2018, ApJS, in press
8. Andersen, Stephens, Dunham, et al., "*The Mass Evolution of Protostellar Disks and Envelopes in the Perseus Molecular Cloud*", 2018, ApJ, to be submitted

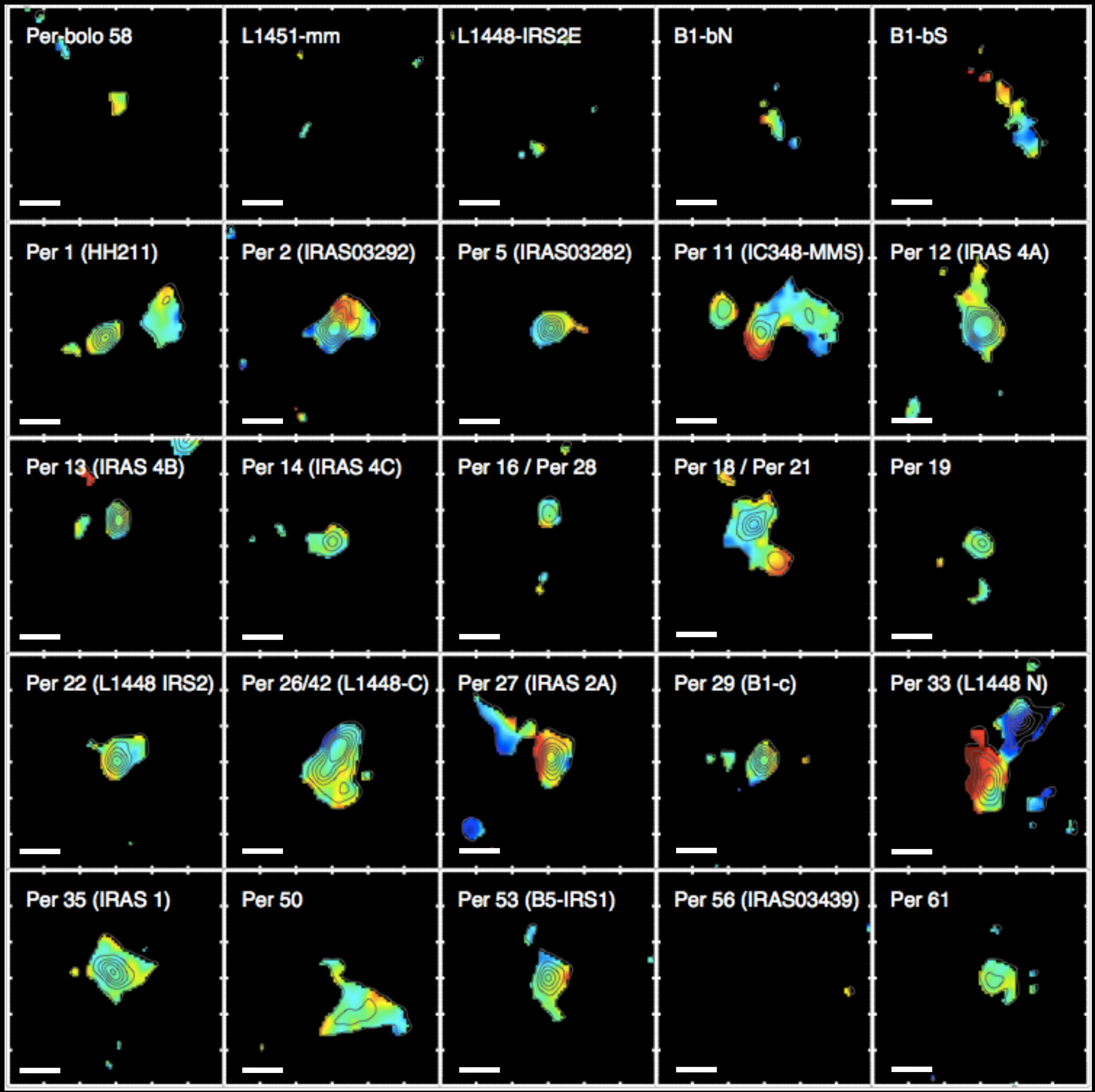
Spanning the ASIC → SWARM Upgrade

Extra SWARM LINES in 230 GHz lower sideband



Origins of Fragmentation: A Survey Approach

Pokhrel, Dunham et al. (in prep)



Kinematics (rotation & turbulence) vs. multiplicity revealed by the VLA

It is in fact likely that accounting for the diversity in core properties is crucial to improving the match between theory and observations of the conversion of gas to (binary) stars.

- Goodwin et al. (2007), PPV

$C^{18}O$ (2-1)
1^{st} moment maps
Scale bars: 2500 AU

Data Reduction and Imaging

	Field	RA	Dec	Target(s)	Common Name(s)	Velocity	Rosolowsky et al. (2008)	SUB Data Obtained	SUB Data Passed	EXT Data Obtained	EXT Data Pass
2	cfc-b1bN	03:33:21.19	31:07:40.60	cfc-b1bN	B1-bN	~7.2	---	Year 1	Year 1	Year 1	Year 1
3	cfc-l1448irss2e	03:25:25.66	30:44:56.70	l1448irs2e	L1448-IRS2E	4.1	---	Year 1	Year 1	Year 2	Year 2
4	cfc-l1451mm	03:25:10.21	30:23:55.30	l1451	L1451-mm	4.0	---	Year 1	Year 1	Year 2	Year 2
5	cfc-pb45	03:29:07.70	31:17:16.80	cfc-pb45	Per-Bolo 45	~9	---	Year 1		Year 1	Year 1
6	cfc-pb58	03:29:25.46	31:28:15.00	cfc-pb58	Per-Bolo 58	~7.3	---	Year 1	Year 1	Year 1	Year 1
7	Per1	03:43:56.53	32:00:52.90	Per1	HH211	9.0	R161?	Year 1	Year 1	Year 1	
8	Per10	03:33:16.45	31:06:52.50	Per10	---	6.4?	R119?	Year 2	Year 2 (400s crate5 problem)		
9	Per11	03:43:56.85	32:03:04.60	Per11	IC348-mm	8.7	R162	Year 1	Year 1	Year 2	
10	Per12	03:29:10.50	31:13:31.00	Per12	IRAS4A	7.3	R75	Year 1	Year 1	Year 1	Year 1
11	Per13	03:29:12.04	31:13:01.50	Per13	IRAS4B	7.3/7.1	R75/R78	Year 1	Year 1	Year 1	Year 1
12	Per14	03:29:13.52	31:13:58.00	Per14	IRAS4C	~7.5	R??	Year 1	Year 1	Year 1	Year 1
13	Per15	03:29:04.05	31:14:46.60	Per15	---	7.4	R68	Year 2, Year 2	Year 2		
14	Per16	03:43:50.96	32:03:16.70	Per16, Per28	---	8.6	R160	Year 1	Year 1	Year 2	
15	Per17	03:27:39.09	30:13:03.00	Per17	RNO-15 FIR	4.8	R32	Year 2	Year 2		
16	Per18	03:29:10.99	31:18:25.50	Per18, Per21	---	8.6	18=R77	Year 1	Year 1	Year 2	
17	Per19	03:29:23.49	31:33:29.50	Per19	---	7.5	R84? 87?	Year 1	Year 1	Year 2	Year 2
18	Per2	03:32:17.95	30:49:47.60	Per2	IRAS 03292	6.9	R103	Year 1	Year 1	Year 1	Year 1
19	Per20	03:27:43.23	30:12:28.80	Per20	L1455-IRS4	5.0	R34	Year 2	Year 2		
20	Per22	03:25:22.33	30:45:14.00	Per22	L1448-IRS2	4.1	R7	Year 1	Year 1	Year 1, Year 2	Year 2
21	Per23	03:29:17.16	31:27:46.40	Per23	---	7.5	R81	Year 2	Year 2 (400s crate5 problem)		
22	Per24	03:28:45.30	31:05:42.00	Per24	---	7.2?	R50?	Year 2	Year 2 (400s crate5 problem)		
23	Per25	03:26:37.46	30:15:28.00	Per25	---	5.15	R22	Year 2	Year 2		

	Date (Track)	Date, Start/End Time (UT)	Target	Assessment	Array	Tau	Quality Comments	Missing Ant	New 230 GHz Calibration
2	140904_07:20:08 (1)	09/04/2014 07:18:19 - 20:26:08 (13 hr)	Per27 Per13	Satisfactory	Extended	tau: 0.12 ~ 0.15	Tau was just good enough. The phase was stable. Sufficient calibration data exist. Antenna 5 400 was not working. -GP	None	Done by Mike (7/03/2015)
3	140905_07:31:26 (2)	09/05/2014 07:29:51 - 20:57:13 (13.5 hr)	Per26Per42 Per33	Satisfactory	Extended	tau started from 0.14 and gradually decreased to 0.1	Tau was higher than I wanted, but still probably OK. Phase was OK until around 18UT. Hopefully there is enough bandpass data. -GP	None	
4	140906_06:18:15 (3)	09/06/2015 06:17:05 - 17:01:08 (10.75 hr)	Per2 Per5	Satisfactory	Extended	tau ~ 0.1	Tau was as good as expected. Phase was OK. A couple problems with warming antennas, but overall not a bad track. -GP	None	Done by Mike (6/03/2015)
5	140907_06:16:26 (4)	09/07/2014 06:06:20 - 17:54:41 (~12 hr)	Per12 Per14	Satisfactory	Extended	tau ~ 0.11	Only 6 antennas, but tau and phase were pretty good. -GP	6	
6	140908_06:06:05 (6)	09/08/2014 05:04:20 - 19:45:25 (14.5 hr)	cfc-pb58 cfc-pb45	Unsatisfactory	Extended	tau varying between 0.1 and 0.15	Tau and phase were OK for most of the night, but not long enough to call this a 'pass'. -GP		
7									
8	141118_02:15:14 (8)	11/18/2014 02:14:25 - 14:09:56 (12 hr)	Per26Per42 Per33	Satisfactory	Subcompact	tau ~ 0.1	Tau was good enough, phase was stable. Sufficient calibration data exist. Still need a baseline solution. -GP	6	Done by Mike (6/20/2015)
9	141120_03:58:22 (7)	11/20/2014 04:00:16 - 14:15:41 (10.3 hr)	Per27 Per13	Satisfactory	Subcompact	tau ~ 0.09	Tau was good. Phase was stable. Sufficient calibration data exist. -GP	6	Done by Mike (7/01/2015)
10									

Source	Notes	230 GHz Continuum 1sigma rms (mJy/beam)	230 GHz Continuum beam size (arcsec)	230 GHz Continuum beam PA (degrees)	12CO (2-1) (dv = 0.5 km/s) 1sigma rms (K)	12CO (2-1) beam size (arcsec)	12CO (2-1) beam PA (degrees)	13CO (2-1) (dv = 0.3km/s) 1sigma rms (K)	13CO (2-1) beam size (arcsec)	13CO (2-1) beam PA (degrees)
SUB - Per1		4.98	4.306 x 3.258	-12.40				0.16	4.365 x 3.330	-12.3
SUB - Per2		8.79	4.254 x 3.345	-15.80						
SUB - Per3		3.32	5.906 x 4.953	57.50						
SUB - Per4										
SUB - Per5		3.82	4.221 x 3.351	-15.60						
SUB - Per6										
SUB - Per9		2.95	5.302 x 3.186	-60.00						
SUB - Per11		6.61	4.301 x 3.249	-13.40	0.13	4.325 x 3.248	-14.60	0.16	4.35" x 3.32"	-12.7
SUB - Per12 (NGC1333 IRAS4A)		58.00	5.027 x 3.229	-30.50	0.16	4.047 x 3.590	5.57	0.17	4.12" x 3.62"	12.4
SUB - Per13 (NGC1333 IRAS4B)		24.30	4.087 x 3.254	-11.00	0.12	4.209 x 3.235	-15.33	0.18	3.88" x 3.29"	-0.7
SUB - Per14 (NGC1333 IRAS 4C)		10.90	5.080 x 3.204	-31.90						
SUB - Per15		3.02	5.295 x 3.227	-61.10						
SUB - Per16Per28		2.19	4.300 x 3.255	-13.10	0.14	4.420 x 3.247	-15.40	0.16	4.36" x 3.33"	-12.6
SUB - Per18Per21		4.68	4.672 x 3.334	-26.20	0.19	4.998 x 3.287	-28.80	0.22	4.67" x 3.41"	-25.5
SUB - Per19		1.83	4.165 x 3.348	-8.90						
SUB - Per22										
SUB - Per25		3.19	3.282 x 2.967	63.60						
SUB - Per26Per42		2.67	4.060 x 3.265	-11.93	0.25	4.085 x 3.232	-13.89	0.17	4.28 x 3.35	-19.0
SUB - Per27 (NGC1333 IRAS2A)										
SUB - Per29		5.62	4.197 x 3.015	-16.80						
SUB - Per33		5.51	4.046 x 3.250	-12.22	0.16	4.066 x 3.236	-13.65	0.17	4.26 x 3.33	-19.0
SUB - Per35										