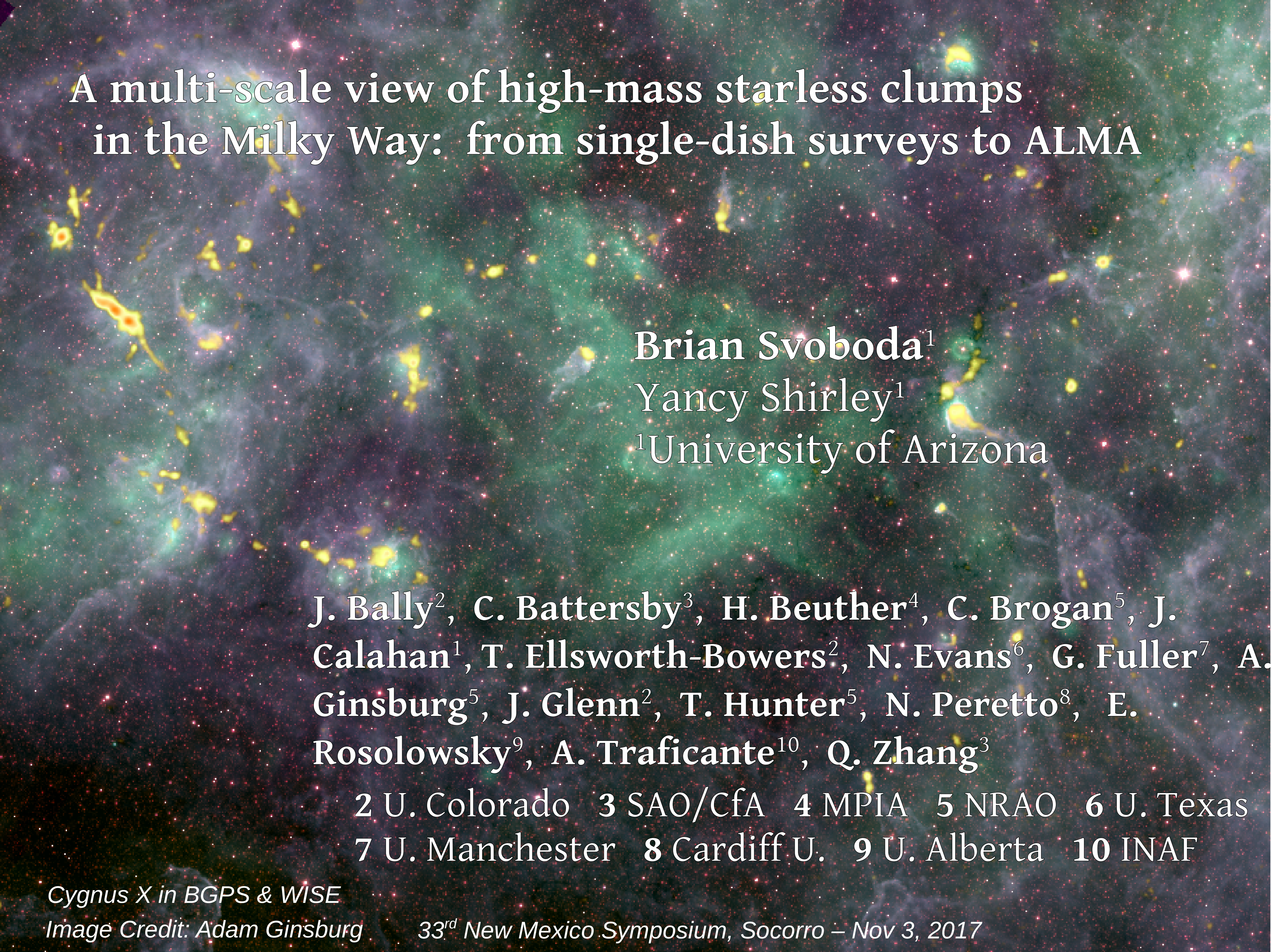
A multi-scale view of high-mass starless clumps in the Milky Way: from single-dish surveys to ALMA

Brian Svoboda[1]
Yancy Shirley[1]
[1]University of Arizona

J. Bally[2], C. Battersby[3], H. Beuther[4], C. Brogan[5], J. Calahan[1], T. Ellsworth-Bowers[2], N. Evans[6], G. Fuller[7], A. Ginsburg[5], J. Glenn[2], T. Hunter[5], N. Peretto[8], E. Rosolowsky[9], A. Traficante[10], Q. Zhang[3]

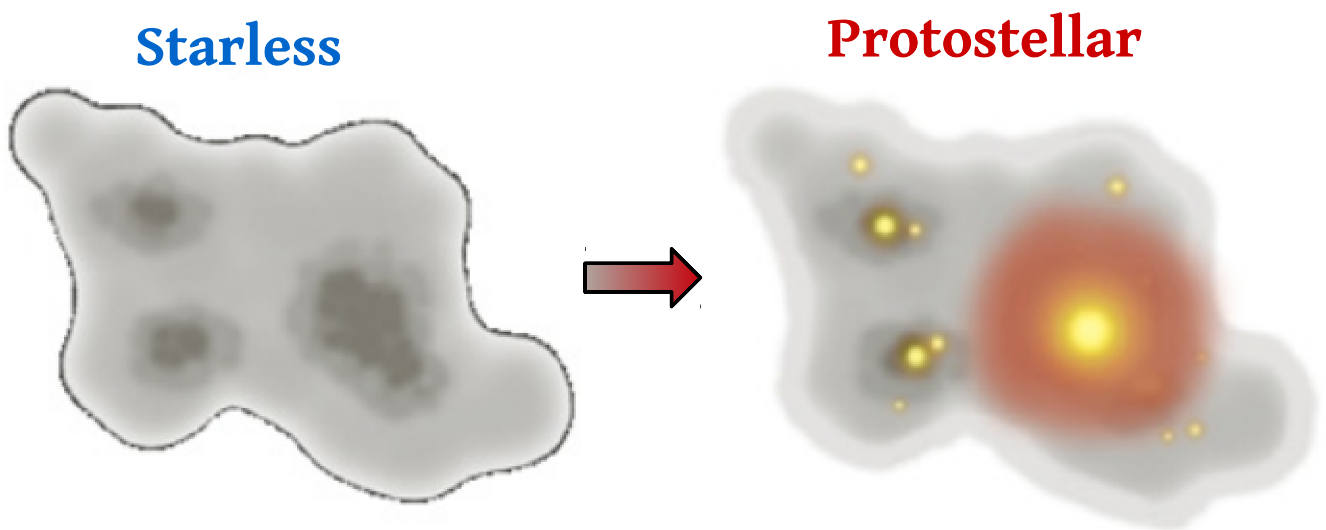
2 U. Colorado **3** SAO/CfA **4** MPIA **5** NRAO **6** U. Texas
7 U. Manchester **8** Cardiff U. **9** U. Alberta **10** INAF



Cygnus X in BGPS & WISE
Image Credit: Adam Ginsburg

33rd New Mexico Symposium, Socorro – Nov 3, 2017

Clump initial physical conditions?
Level of fragmentation before SF?
What processes set the fragmentation?
Do we observe massive starless cores?
Do low- or high-mass stars form first?



Mass ~ 10^2—10^4 M_{sun}
Radius ~ 1 pc
Col. Dens. ~ 10^2—10^3 M_{sun} pc^{-2}
Vol. Dens. ~ 10^3 cm^{-3}

Image Credit: Battersby et al. (2010)

Discovering starless clump candidates from blind surveys of star formation tracers, radio to mid-IR

Svoboda, Shirley, Battersby, et al. (2016), ApJ, 822, 59

In 10-65 degree survey region

4683 clumps in survey overlap
2925 unique velocities
1462 GBT NH_3 gas kinetic temps.
1650 well-constrained distances

Discovering starless clump candidates from blind surveys of star formation tracers, radio to mid-IR

Svoboda, Shirley, Battersby, et al. (2016), ApJ, 822, 59

In 10-65 degree survey region

4683 clumps in survey overlap
2925 unique velocities
1462 GBT NH_3 gas kinetic temps.
1650 well-constrained distances

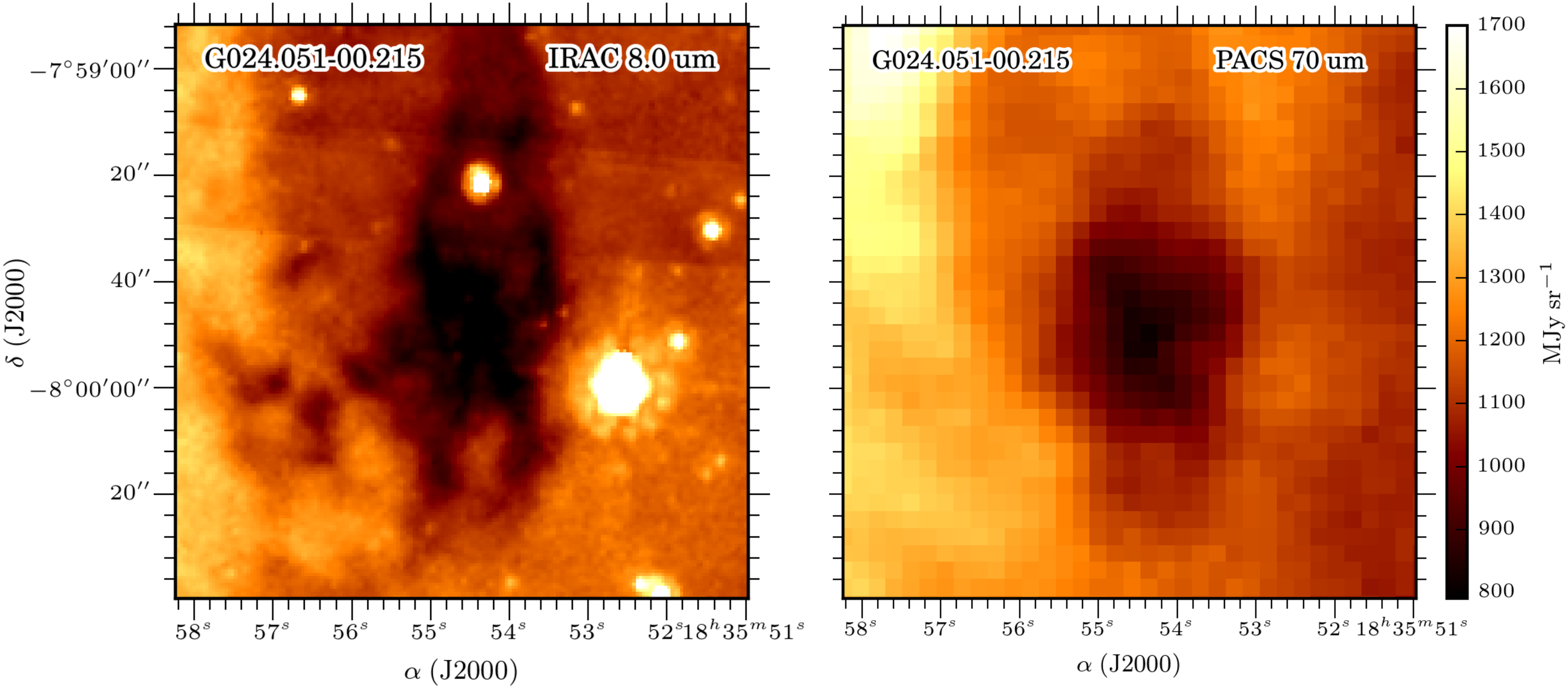
~2200 Starless Clump Candidates

48% of clumps in survey
90% completeness to 50-100 L_{sun}

cf. Dunham ea. (2014) : median ~1 in GB

2238 (48%) **Starless Candidate**
2446 (52%) **Protostellar**
1043 (22%) **70 um Unique**
Hi-GAL 70 um visual inspection
1022 (22%) **Mid-IR**
Red MSX, EGO, Robitaille+08
556 (12%) **Water Maser**
GBT, Arcetri, HOPS
296 (6%) **Methanol Maser**
MMB, Arecibo, Pestalozzi+05
170 (4%) **UCHII**
CORNISH

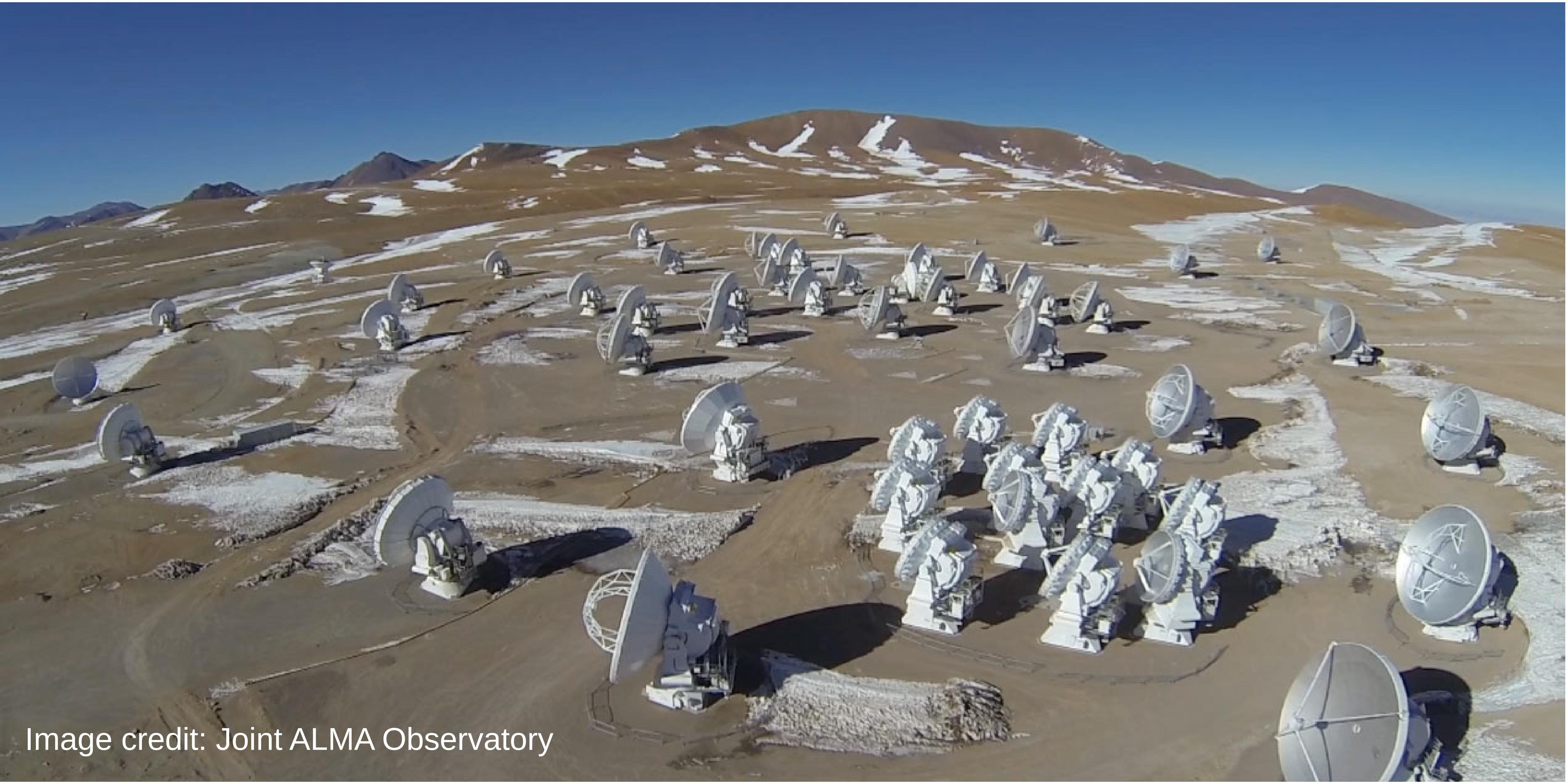
[Global View]: Compared to protostellar clumps, SCCs are colder, smaller, lower mass, less turbulent, but have similar virial parameters (0.75; 50 uG to 1)



Example high-mass SCC: 1000 M_{sun}, 11 K, 1 pc, 4.5 kpc

Svoboda, Shirley, Battersby, et al. (2016), ApJ, 822, 59

ALMA View: Observing protocluster initial conditions



ALMA ideally suited for high-resolution (<1”, <3000 AU) observations towards clumps that can resolve the thermal Jeans length and detect the thermal Jeans mass.

ALMA Survey: Targets and parameters

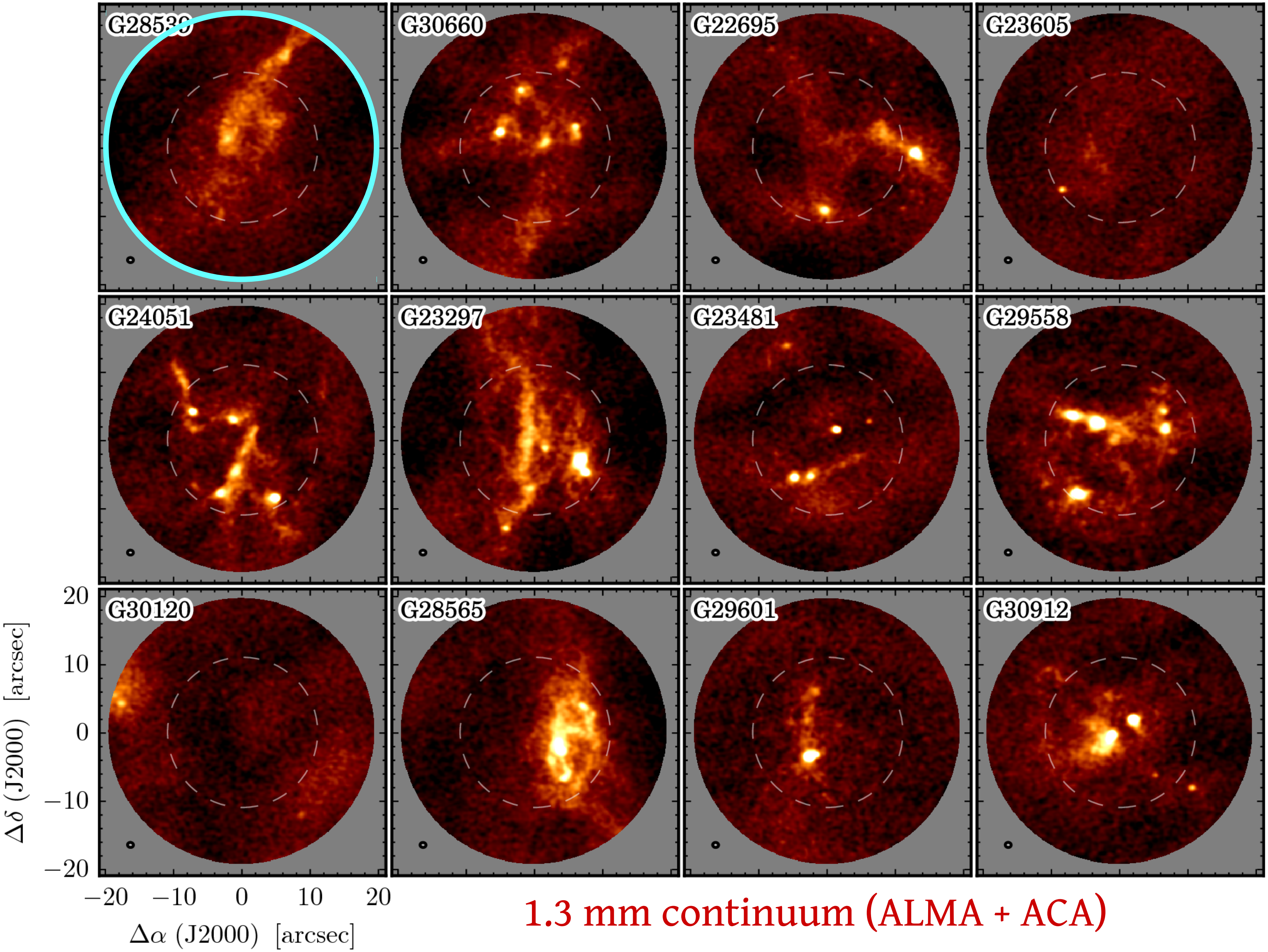
- 12 most massive clumps within 5 kpc (10-65°)
- 500 – 3000 M_{sun}, T_d ~ 12 K, L/M ~ 0.01 – 0.1

- ALMA Band 6 at 215 and 230 GHz
- 12m HPBW ~22" (0.5 pc), beam ~0.8" (3000 AU)
- With ACA, recoverable scales up to ~30"
- 50 uJy continuum RMS (~0.3 M_{sun} at 6x)

Molecular Lines

Core kinematics	H_2CO $3_{0,3}$-$2_{0,2}$, $C^{18}O$ 2-1
Kinetic temperature	H_2CO $3_{2,1}$-$2_{2,0}$ $3_{2,2}$-$2_{2,1}$
Outflows	CO 2-1, SiO 5-4
Protostellar activity	CH_3OH, SiO, H_2CO
Deuteration	DCO^+, $N2D^+$, DCN 3-2
Other chemistry	c-HC_3H

Fragmentation: Substantial sub-structure observed

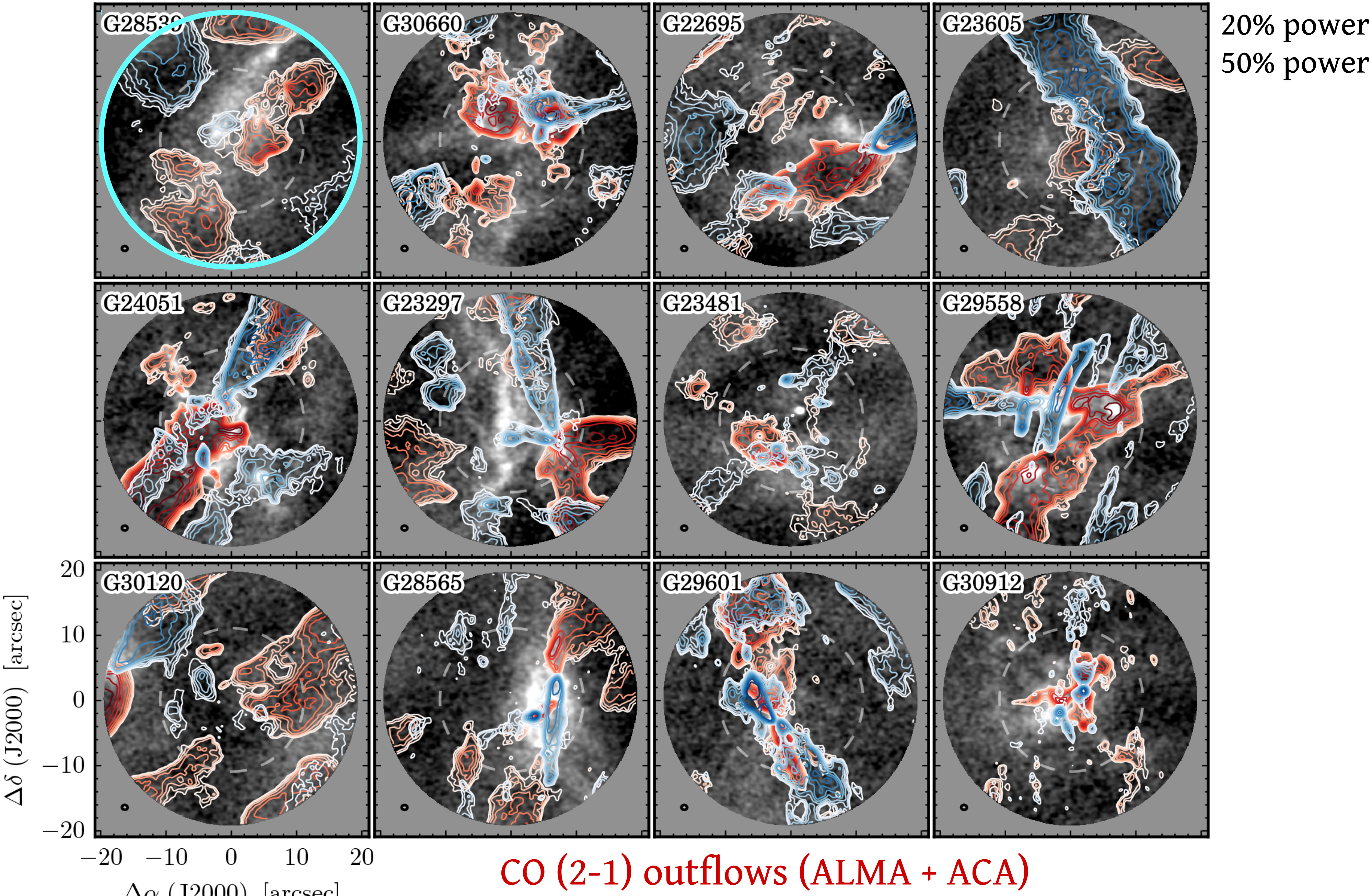


20% power
50% power

1.3 mm continuum (ALMA + ACA)

Svoboda, Shirley et al. 2018a *in prep.*

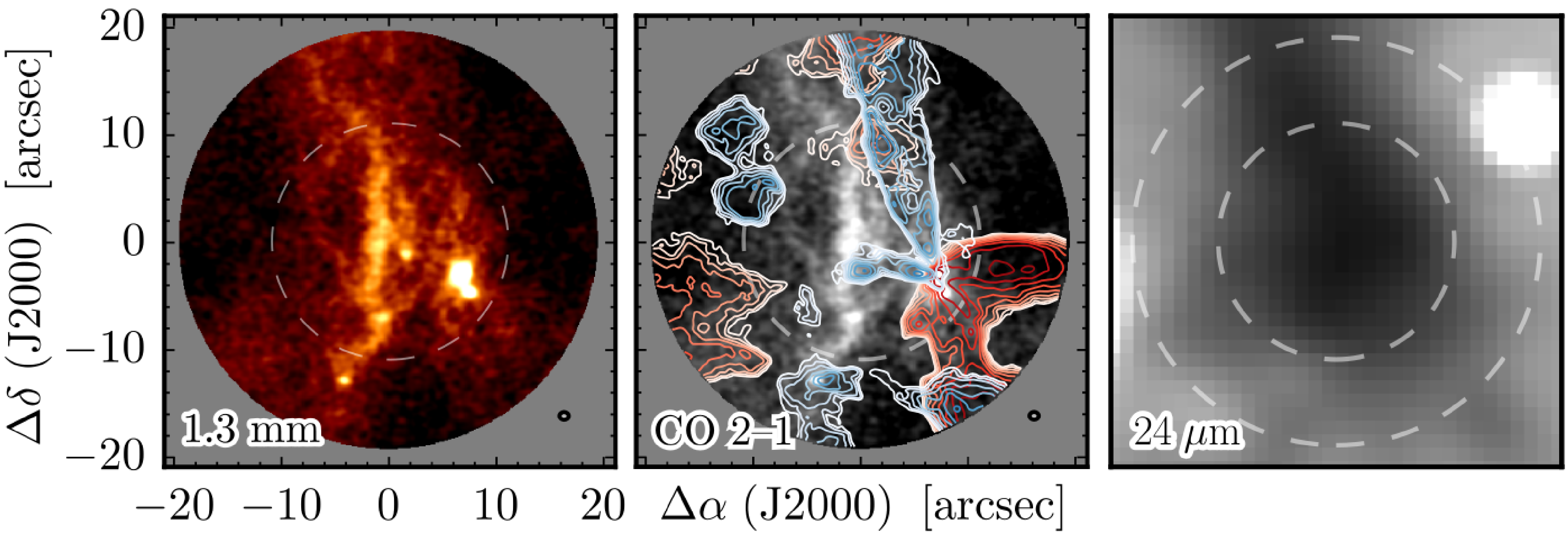
Outflows: 9/12 seen in CO, 3/12 seen in SiO



CO (2-1) outflows (ALMA + ACA)

Svoboda, Shirley et al. 2018a *in prep.*

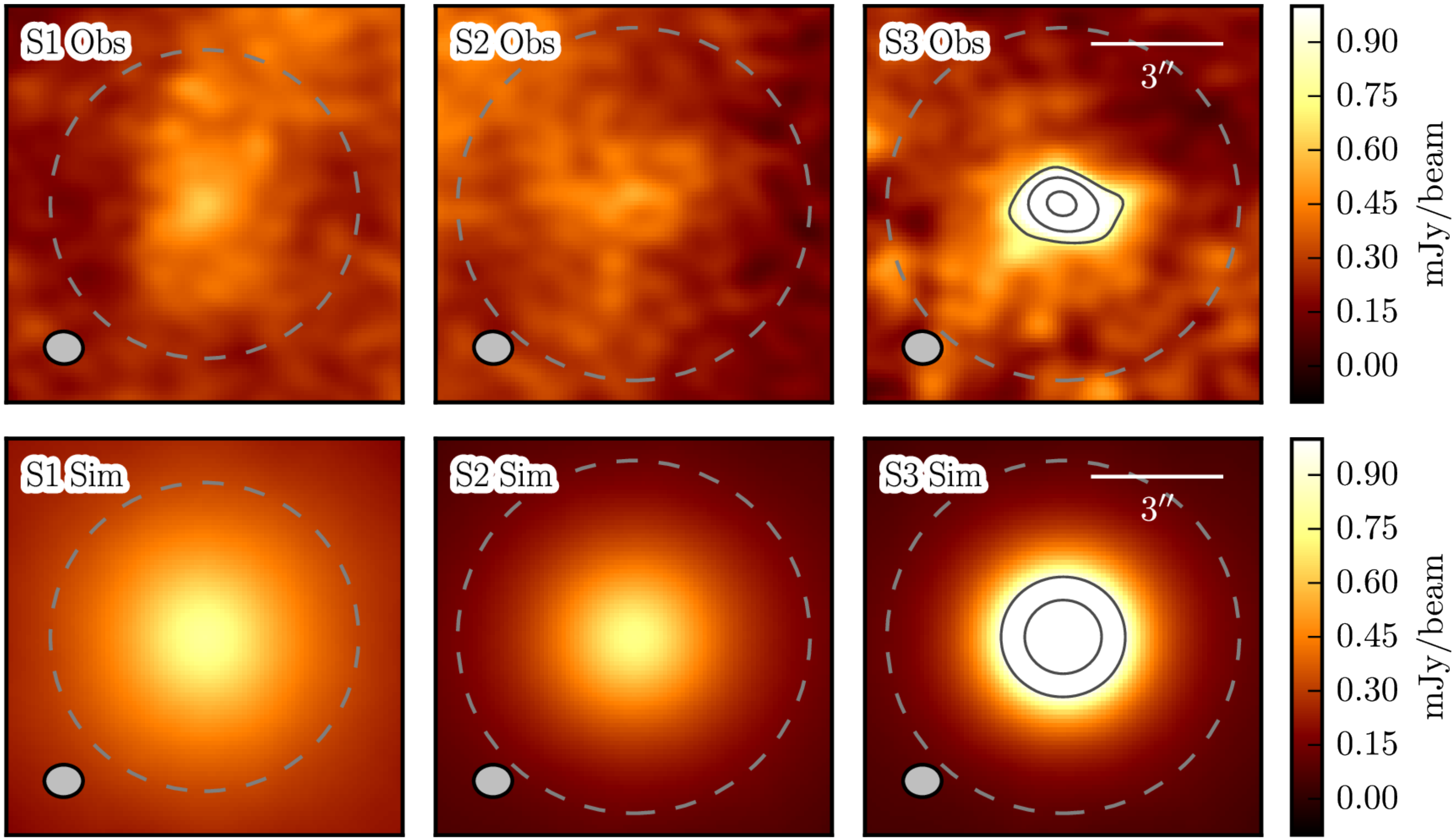
How starless are SCCs? Undetected low- and intermediate-mass star formation in SCCs.



Unique detections of protostars of less 50 solar luminosities. Do low-mass stars form first then accrete to high-mass via gravitationally driven cloud inflow? (Bonnel, Bate, R. Smith, Gomez, Vazquez-Semadini, ea.)

Svoboda, Shirley et al. 2018a *in prep.*

Continuum sources: When simulated, compact-unresolved sources are disfavored as starless



10,000 self-consistent models of starless cores computed with RADMC-3D and imaged with CASA. Unresolved sources (sizes less than 1500 au) are poor fits. Masses uncertain without temperature. Separations?

Svoboda, Shirley et al. 2018a *in prep.*

Fragmentation: What physical processes regulate the fragmentation scales?

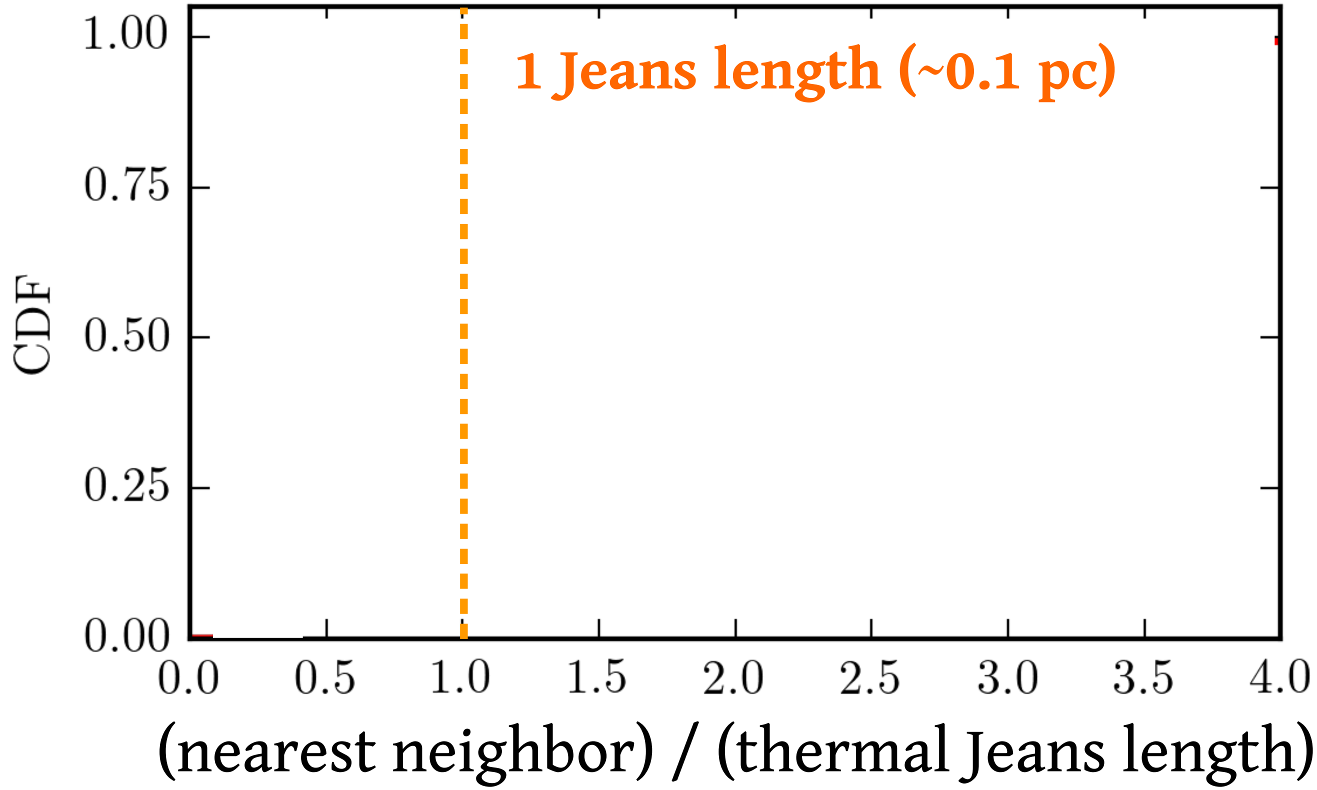
Thermal Jeans in clumps with 12 K, 4e4 cm^{-3}
$c_s \sim 0.2$ km/s, $\lambda_j \sim 0.1$ pc, $M_j \sim 1\ M_{sun}$

Turbulent Jeans in clumps
$\sigma \sim 0.6$ km/s, $\lambda_j \sim 0.3$ pc, $M_j \sim 30\ M_{sun}$

Results should be consistent in matching **both** the mass and length. Recent observations towards comparable regions suggest thermal Jeans, but such measurements have not been made towards 70 um dark, low-luminosity clumps.

Palau ea (2015) : Collected HMSF cores
Texeira ea (2016) : N OMC-1 filament
Beuther ea (2015) : IRDC18223
Ohashi ea (2016) : G14.225-0.506

Fragmentation: Measuring the characteristic separation from the data

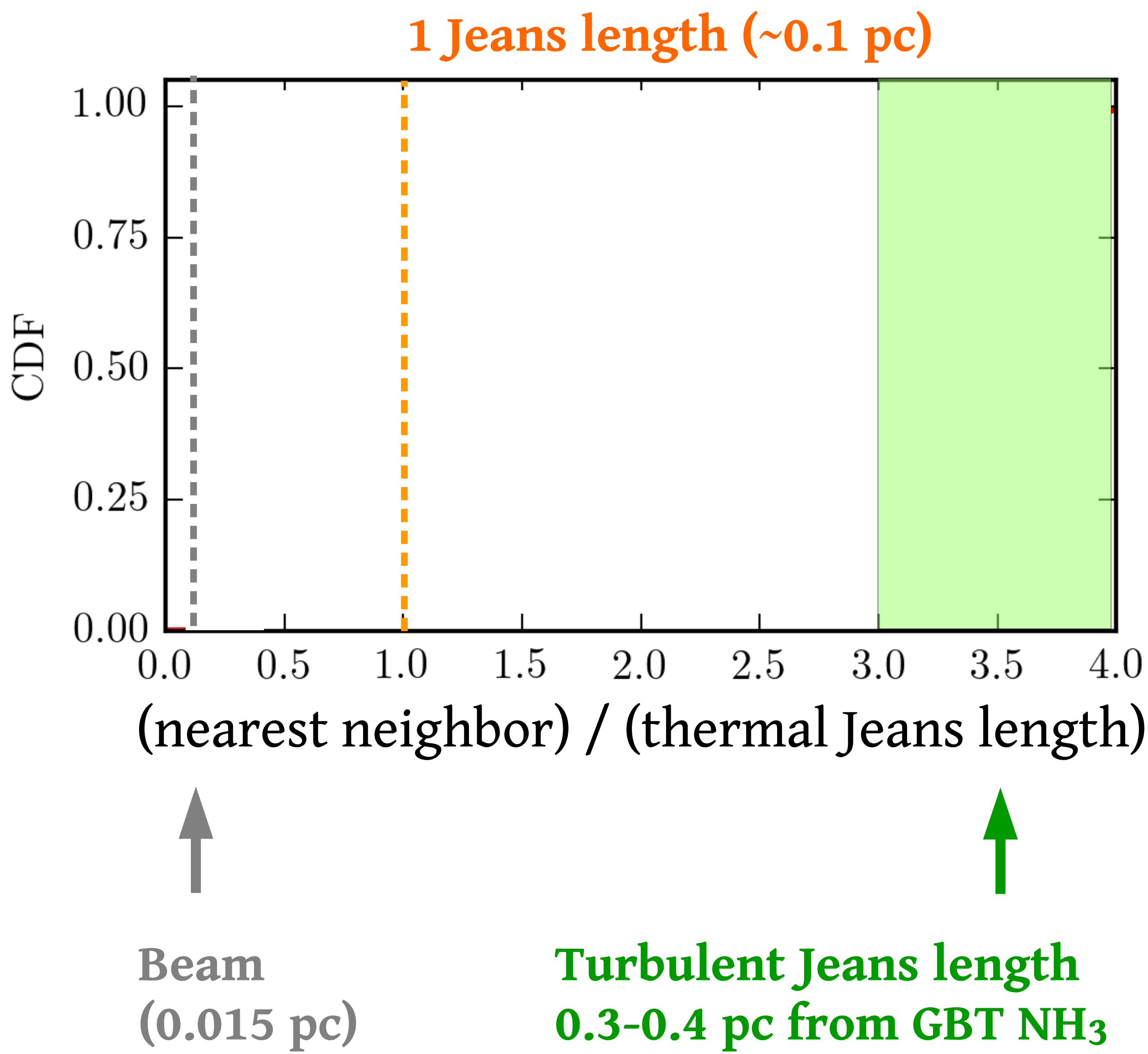


Monte Carlo sample:

- Line-of-sight positions
- Flux (peak) uncertainty
- Dust temperature uncertainty
- Heliocentric distance uncertainty

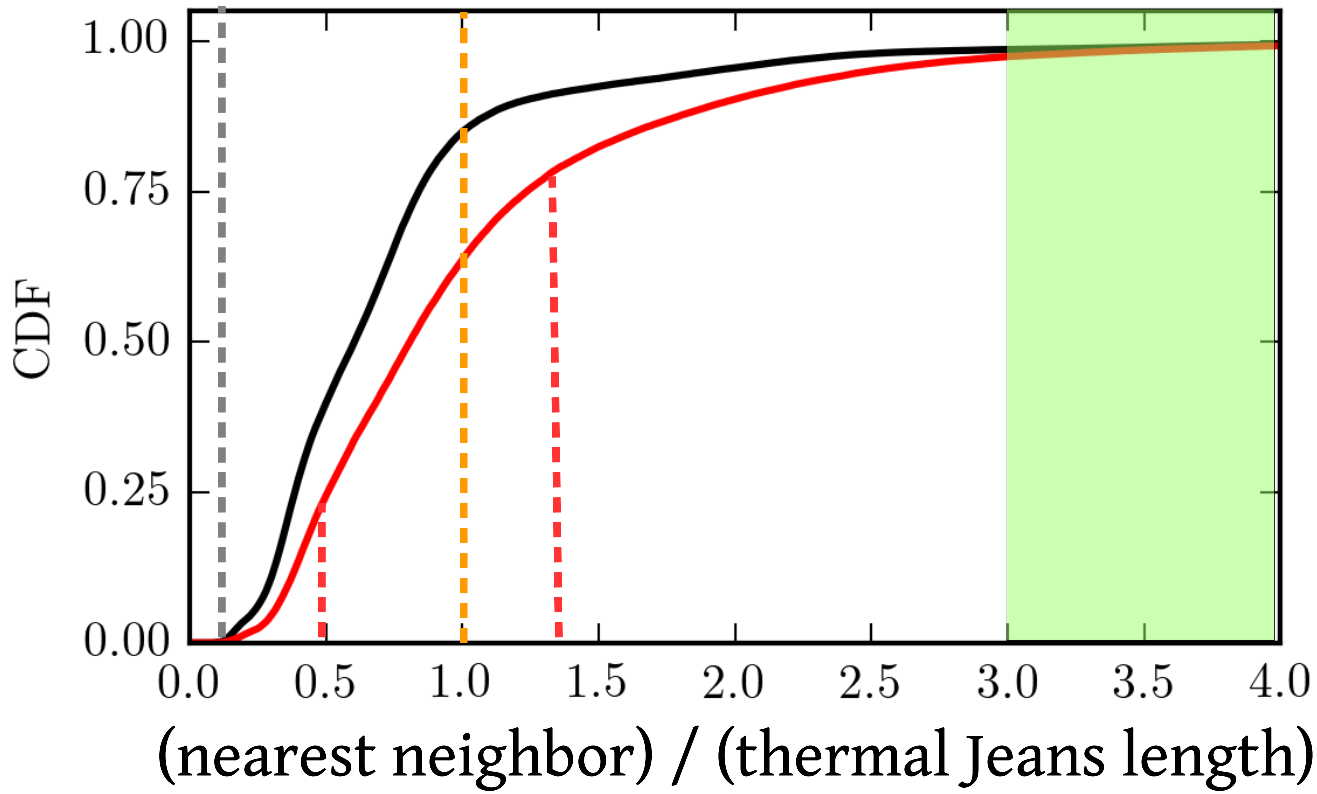
Svoboda, Shirley et al. 2018a *in prep.*

Fragmentation: Measuring the characteristic separation from the data



Svoboda, Shirley et al. 2018a *in prep.*

Fragmentation: Measuring the characteristic separation from the data

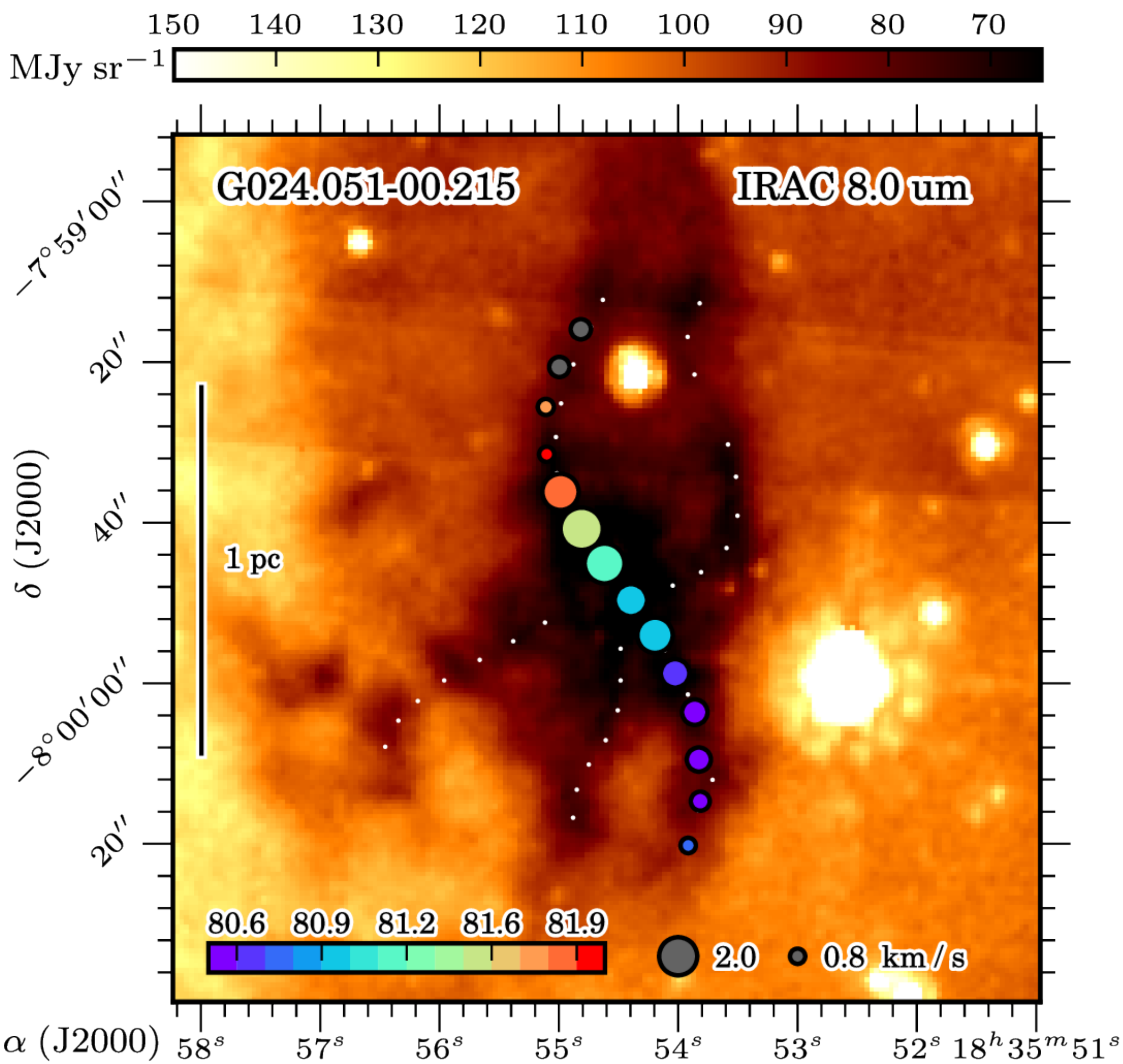


(Black) Uncorrected for projection
(Red) Corrected for projection

Typical values range between 0.5 to 1.3 thermal Jeans

Svoboda, Shirley et al. 2018a *in prep.*

In Progress: Core mass function and infall in SCCs

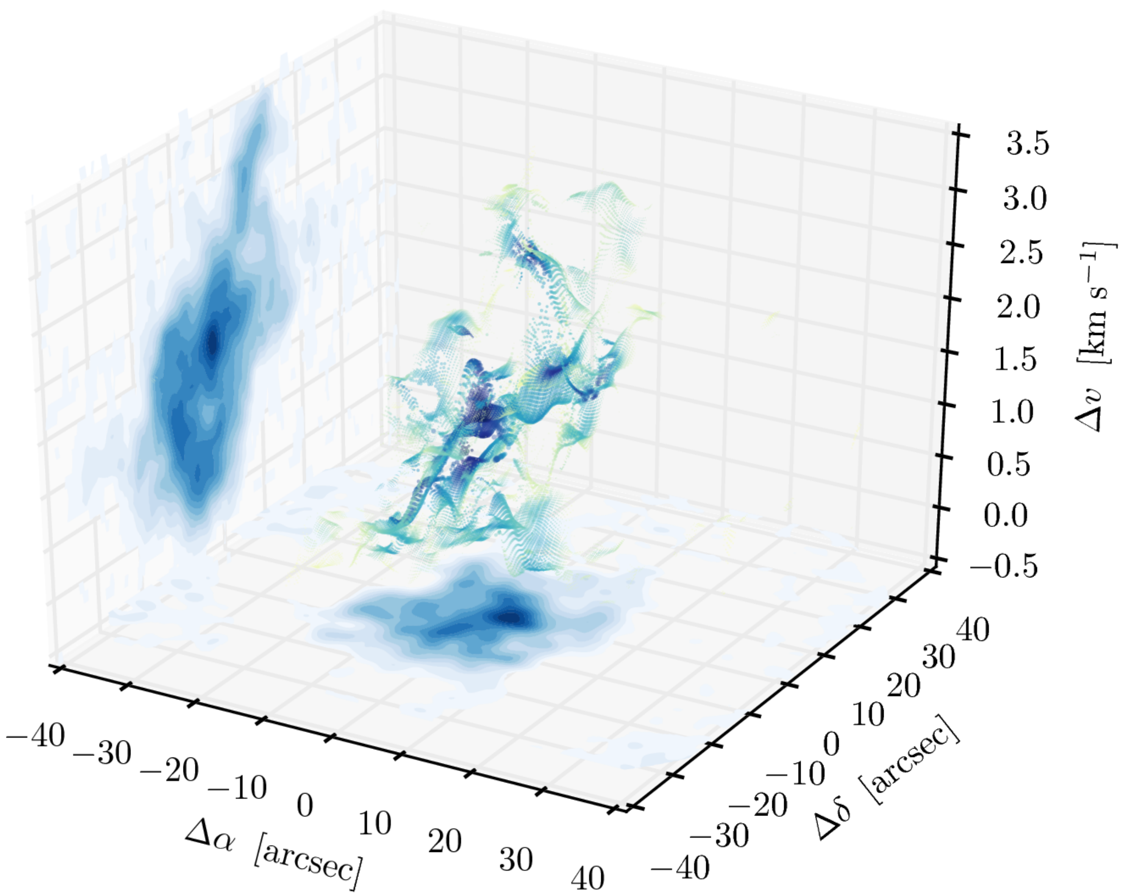


(1) From an ARO 12m survey of over 100 SCCs, mapping and modeling infall with combined GBT/ARGUS + ALMA-B3. Global or local collapse?

(2) Measuring the core mass function and kinematics in SCCs using ALMA cont. and JVLA ammonia observations. How turbulent are quiescent clumps?

Svoboda, Shirley, Battersby et al. 2018b,c in prep.

Future Work: Filaments as conduits in star formation



(1) Will low-mass stars in SCCs become high-mass stars through accretion mediated by filaments?

(2) Are B-field entrained from flows in filaments? How frequent, and how does it compare by clump properties?

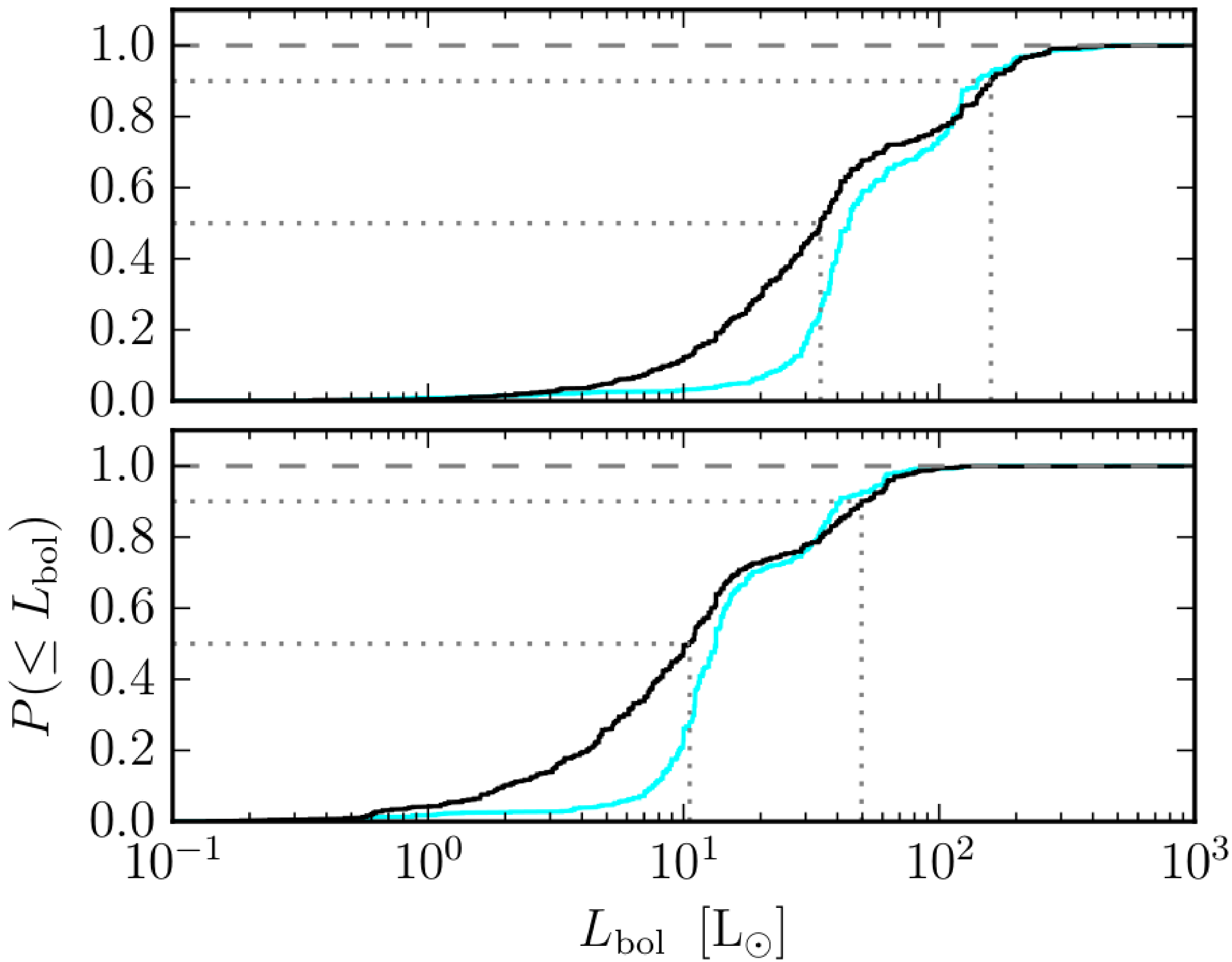
(3) Protostars with high-luminosities in cold clumps uniquely detected at 70 um. How do high-mass stars gain their mass?

Svoboda, Shirley, Battersby et al. in prep.

Summary & Conclusions

- **~2200** blindly identified starless clump candidates (SCCs): large & robust sample for followup observations
- ALMA survey of 12 most massive SCCs within 5 kpc, showing significant fragmentation before HMSF.
- All except 1 show signs of low- and intermediate-mass SF, unambiguously detected with ALMA. Uniquely detected outflows.
- Uncertainties about SF-efficiency remain, but population of low-mass cores in high-mass clumps with thermal Jeans fragmentation support models of HMSF via gravitationally driven cloud inflow ("competitive"-like)

Completeness: 70 um completeness depends on high or low background, but small luminosity limit



High Background
2000 – 3000 MJy / sr

Low Background
500 – 1000 MJy / sr

Astrohysical Cuts: Remove low-mass, low-density, and/or unbound objects. Mass difference robust.

Cloud-to-clump infall of **200 to 400 solar masses per Myr** (over 0.8 Myr)

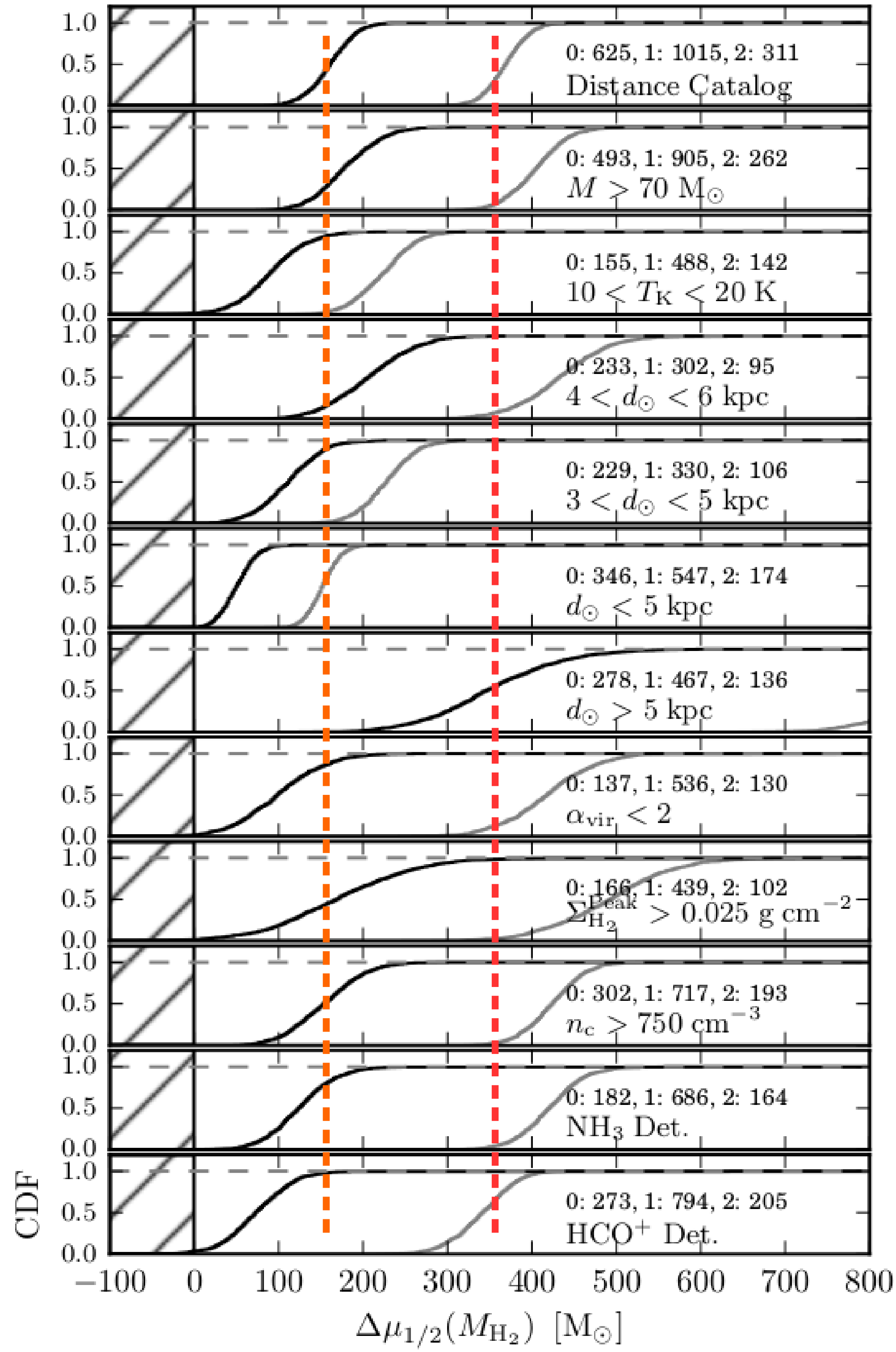
~ 1000 Msun / Myr (high-mass):

Battersby et al. (in prep.)
Peretto et al. (2013)
Schneider et al. (2010)

~ 100 Msun / Myr (low-mass):

Kirk et al. (2013)
Fernandez-Lopez et al. (2014)
Palmeirim et al. (2013)

No large, systematic samples exist, but inflow rates required are reasonable given existing observations.



Time Scales: Several of methods generally point to short SCC phase-lifetimes, less than 0.5 Myr

IMF: Kroupa IMF (Kroupa 2001)

SFR: 1.9 ± 0.4 M_{sun} yr^{-1} (Chomiuk & Povich 2011)

Galactic population of clumps is in steady state

$$\epsilon_{\rm SF} M_{\rm clump} = \frac{\int_{0.08}^{150} N(M) M dM}{\int_{M_{\rm max}}^{150} N(M) dM}$$

$$M_{\rm max} \approx 20\,{\rm M}_\odot \left(\frac{\epsilon_{\rm SF}}{0.3} \frac{M_{\rm clump}}{1064\,{\rm M}_\odot} \right)^{1/1.3}$$

$$\tau_{\rm clump} = \frac{N(M > M_{\rm max})}{\rm SFR} \frac{\langle M \rangle}{P(M > M_{\rm max})}$$

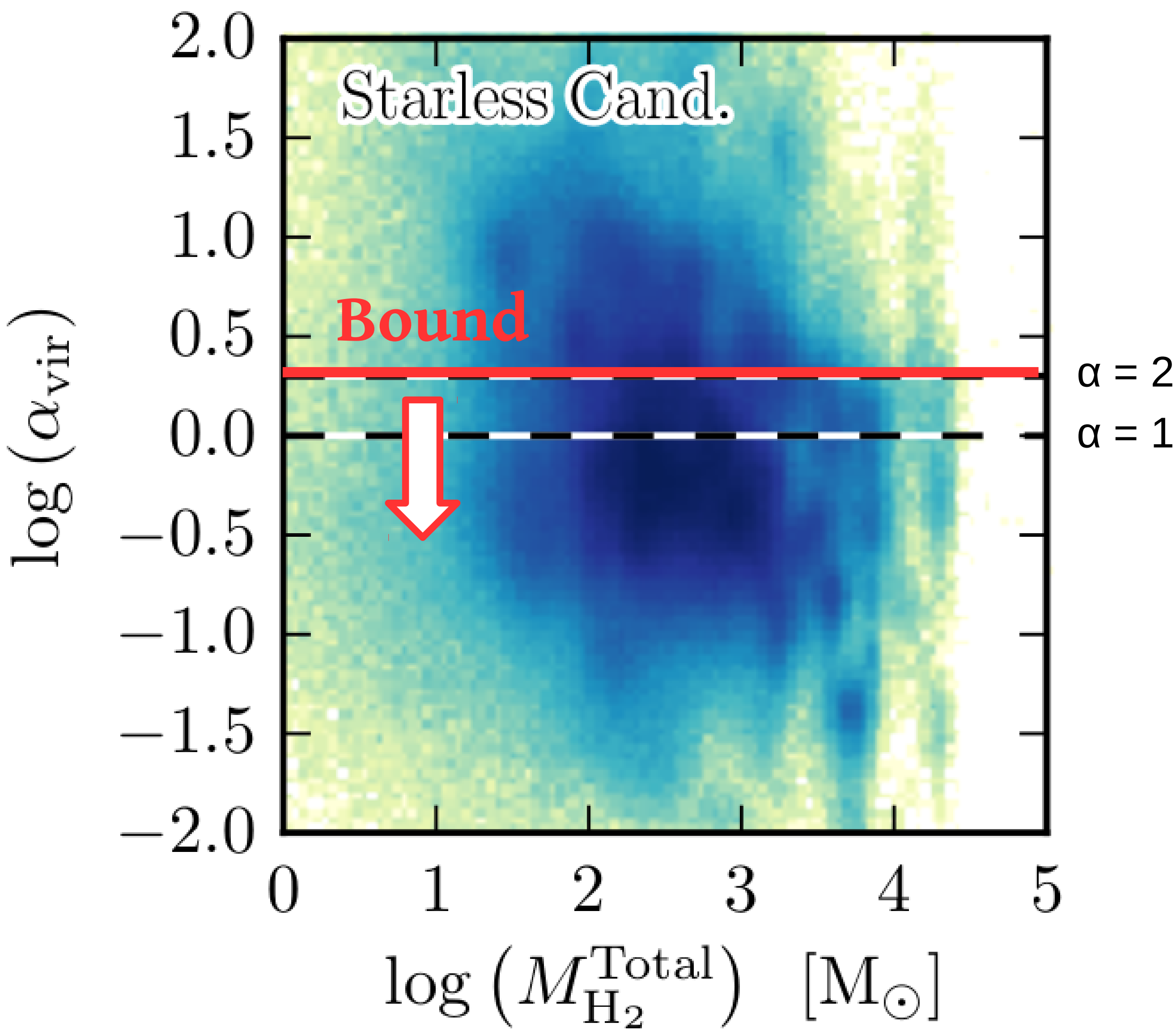
98 SCCs
Distance Sample

224 SCCs
Full Sample

1445 SCCs
Galactic Total

SCC Lifetime
0.2 – 0.3 Myr

Virial parameter: More than 75% of clumps in "gravitationally bound", no strong dependence on mass.



Median α = 0.75

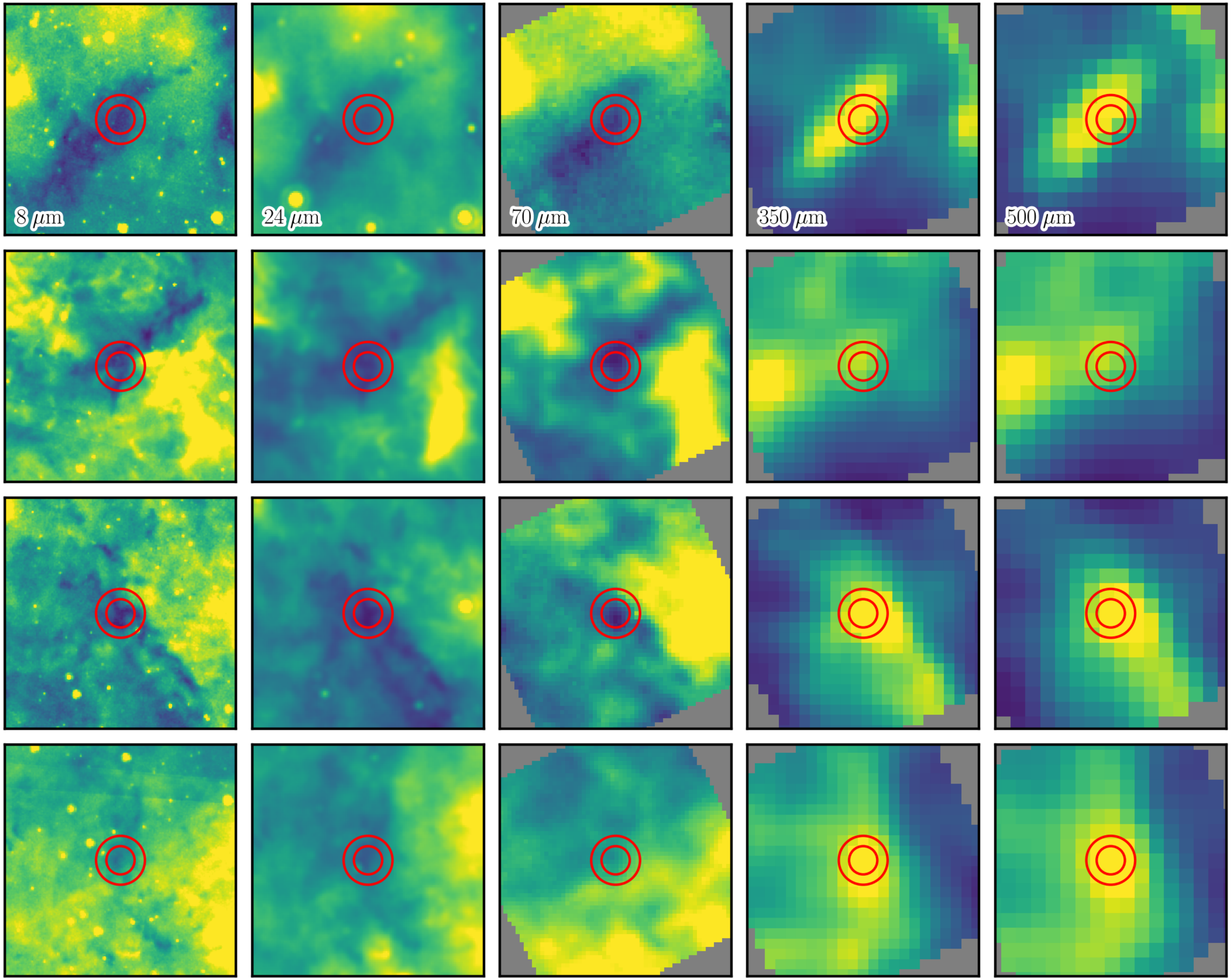
75% with α < 2

Same for starless and protostellar

To virialize would need 50–100 uG (see Pillai+ 2015)

Svoboda, Shirley, Battersby, et al. (2016), ApJ, 822, 59

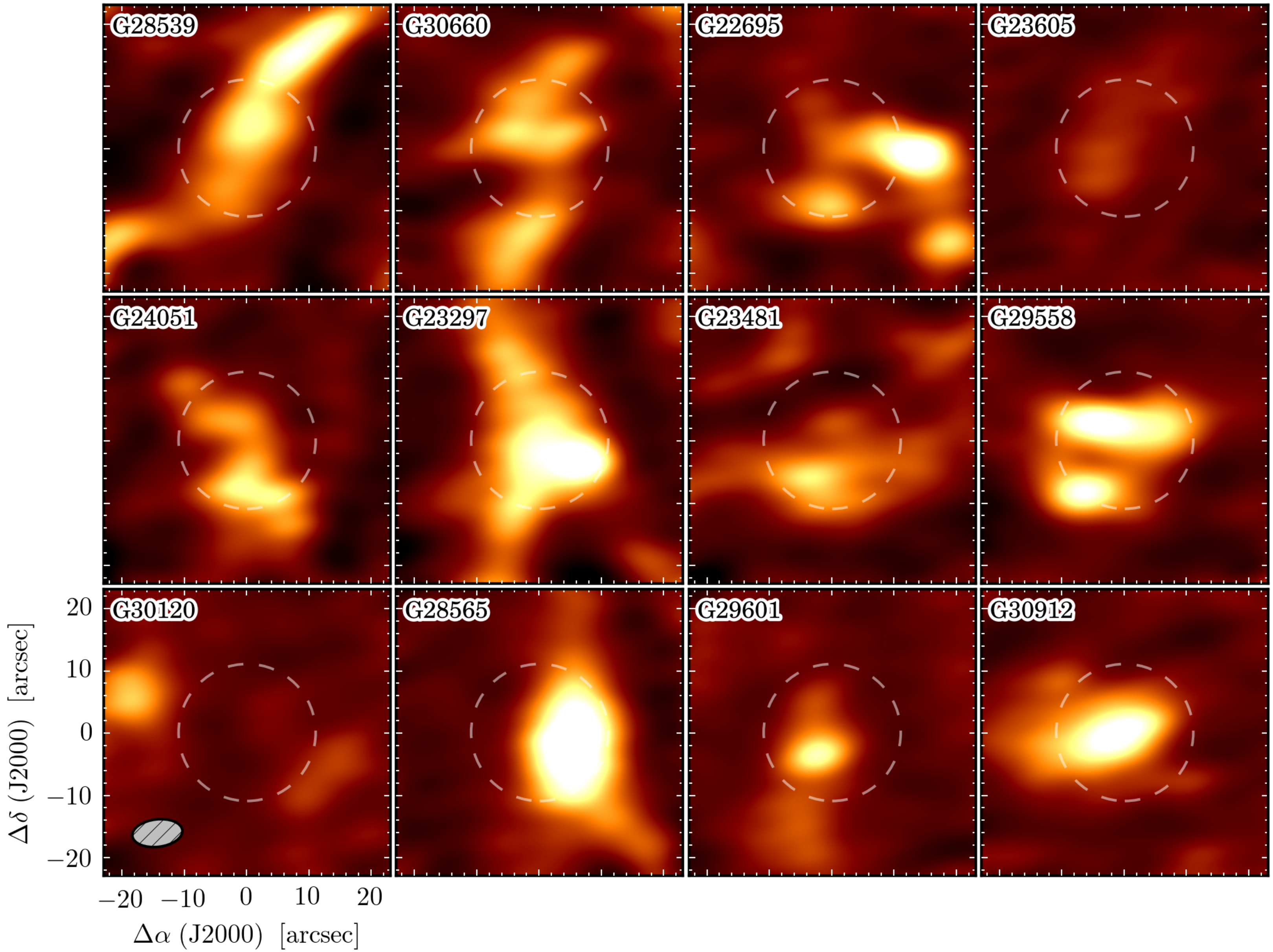
ALMA Targets: Targeted towards clump peak



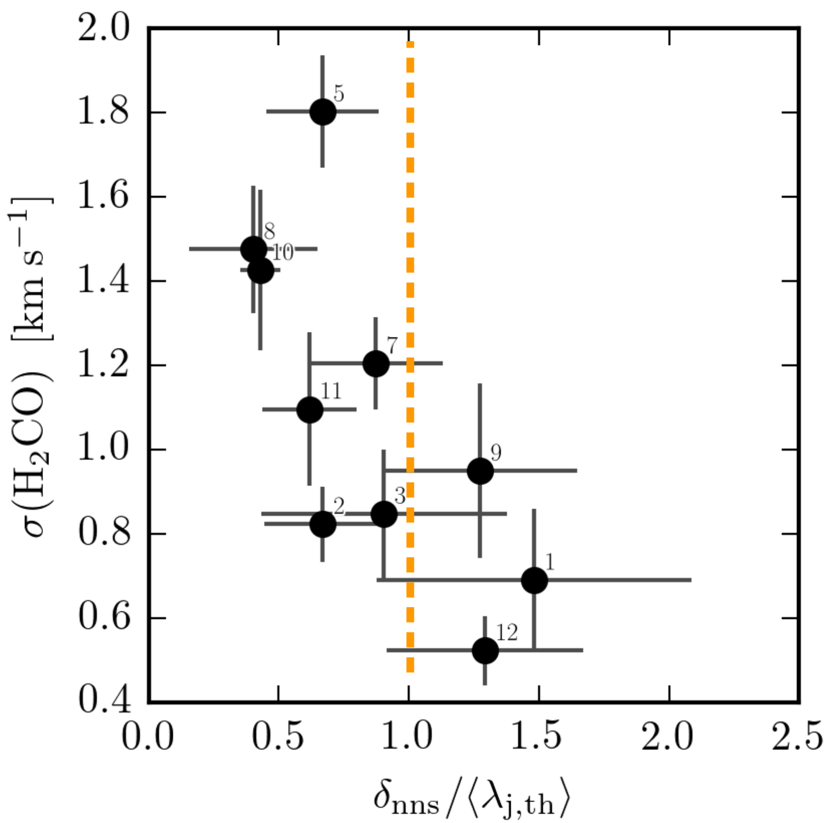
8 um 24 um 70 um 350 um 500 um

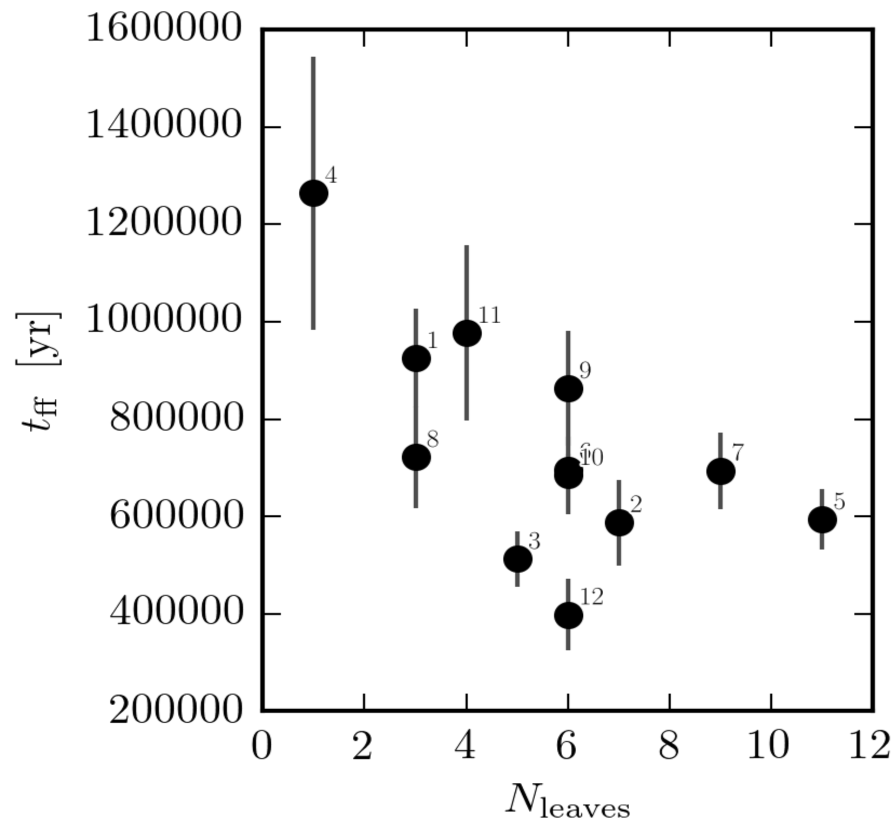
Svoboda, Shirley et al. 2018a *in prep.*

Fragmentation: Substantial sub-structure observed



Svoboda, Shirley et al. in prep.



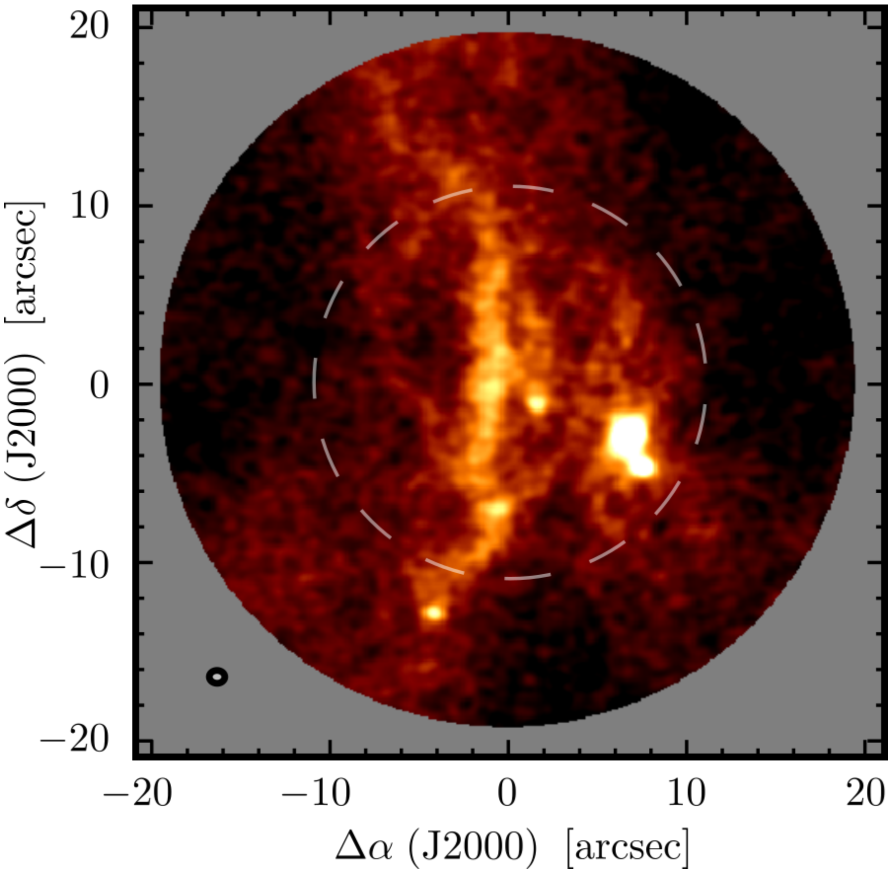


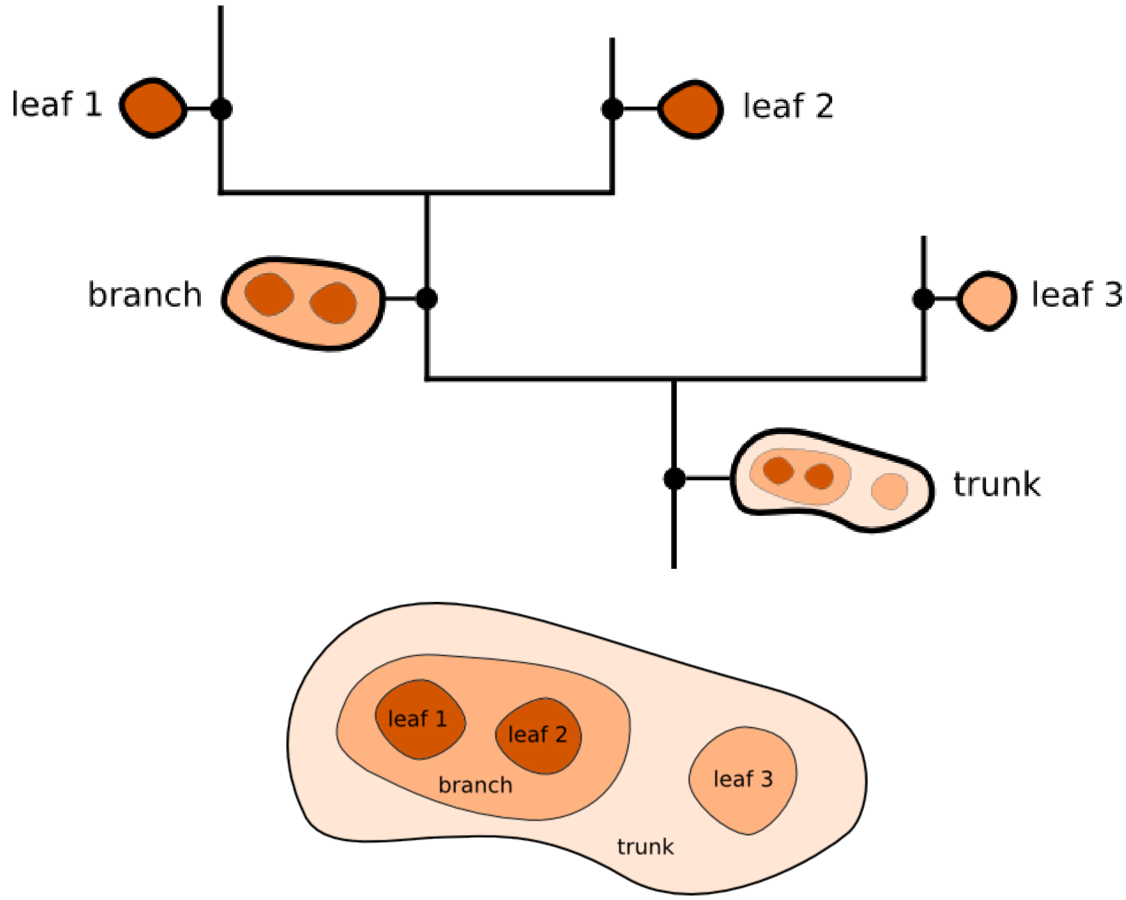
Corrected nearest neighbor separation inversely correlated with clump scale turbulence

Clumps with the shortest free-fall timescale and highest density have the most leaves/sources

Svoboda, Shirley et al. in prep.

Dendrograms: Cataloging sub-structure and correcting the nearest neighbor separations

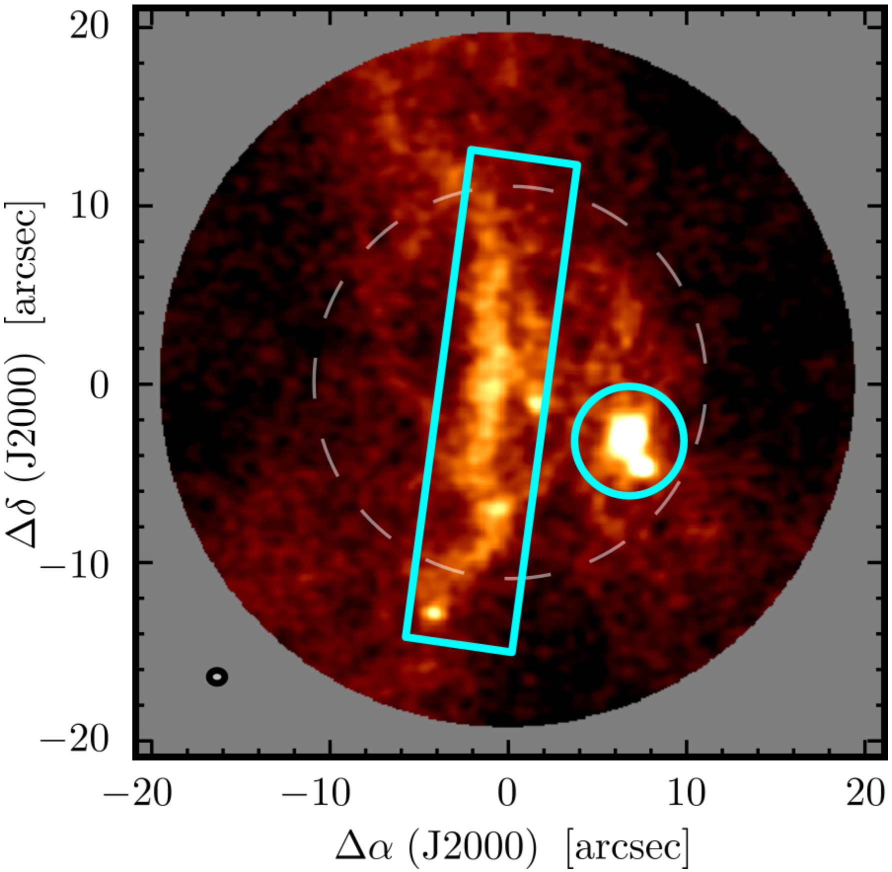


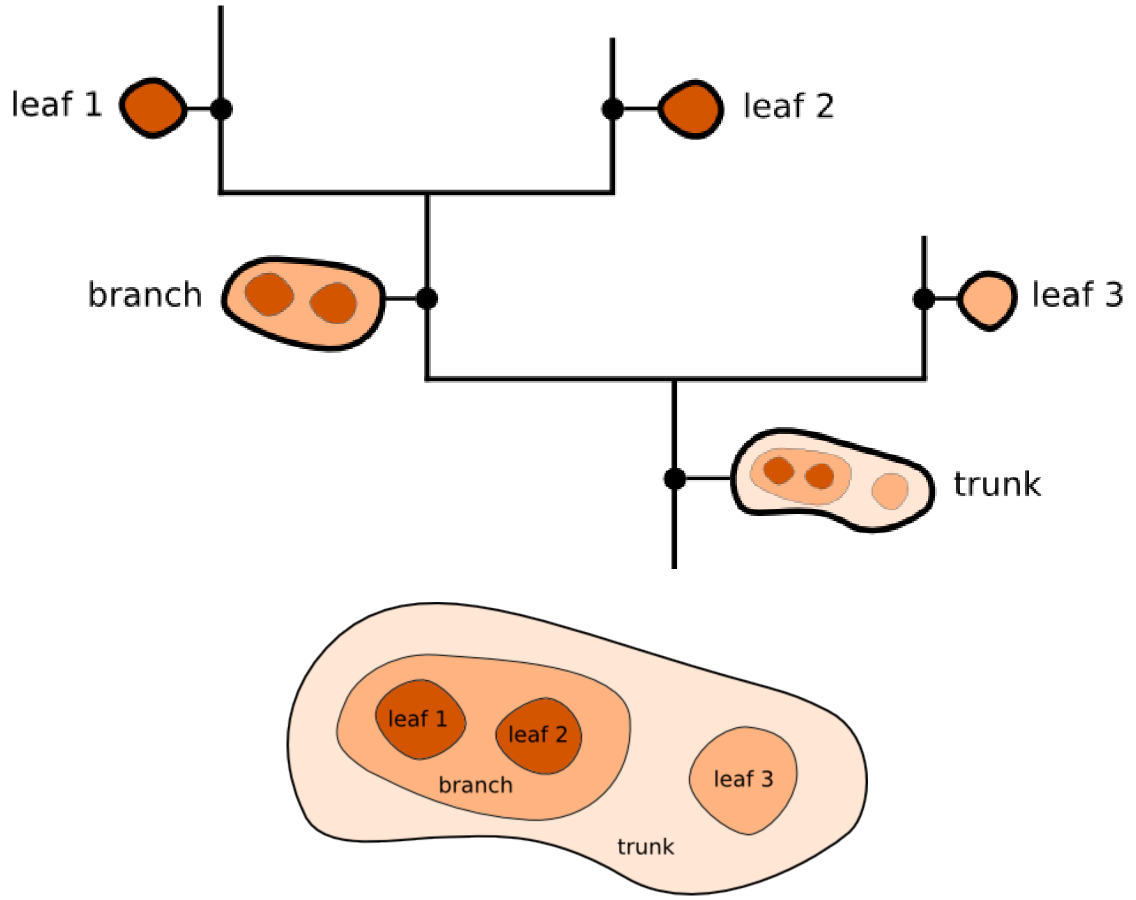


Svoboda, Shirley et al. 2018a *in prep.*

Image credit: dendrograms.org (Robitaille ea.)

Dendrograms: Cataloging sub-structure and correcting the nearest neighbor separations





Svoboda, Shirley et al. 2018a *in prep.*

Image credit: dendrograms.org (Robitaille ea.)