Protoclusters in the Milky Way: Physical properties of massive starless & star-forming clumps from the BGPS

Brian Svoboda (Arizona)
Y. Shirley (Arizona)
C. Battersby (Harvard)
E. Rosolowsky (Alberta)
T. Ellsworth-Bowers (Colorado)
A. Ginsburg (ESO)
J. Bally (Colorado)
N. Evans (Texas)
J. Glenn (Colorado)
& the BGPS Team

Cygnus X in BGPS & WISE
Image Credit: Adam Ginsburg

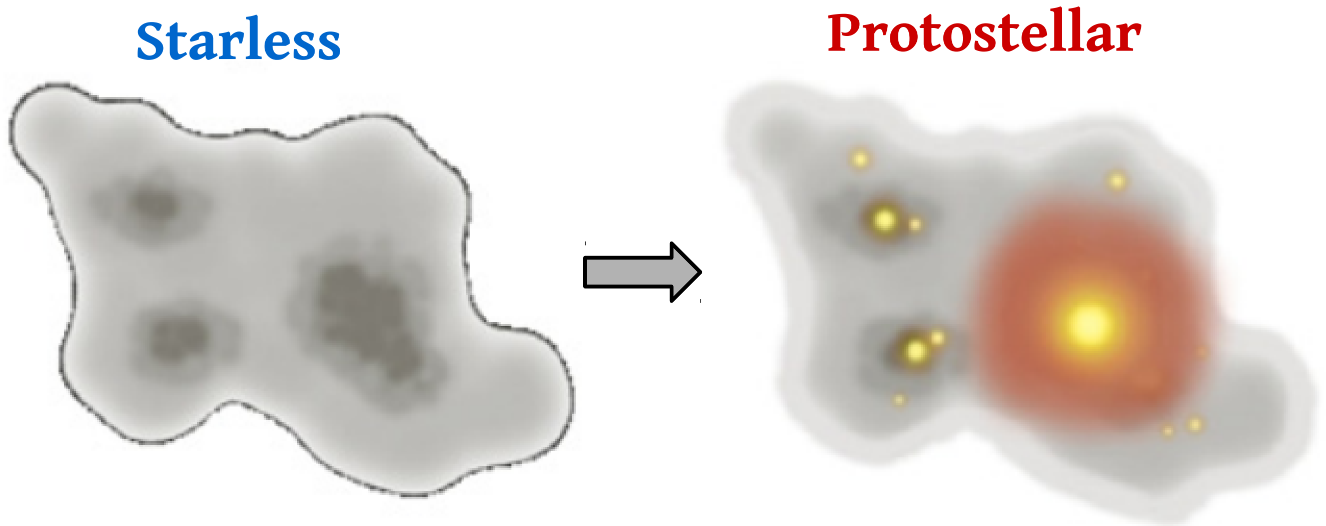
New Mexico Symposium – Nov 4, 2016

Many fundamental questions remain open in high-mass star and cluster formation

Initial protocluster physical conditions

Inflow in the mass growth of protoclusters

Fragmentation before star formation occurs



Mass ~ 10^2—10^4 M_{sun}

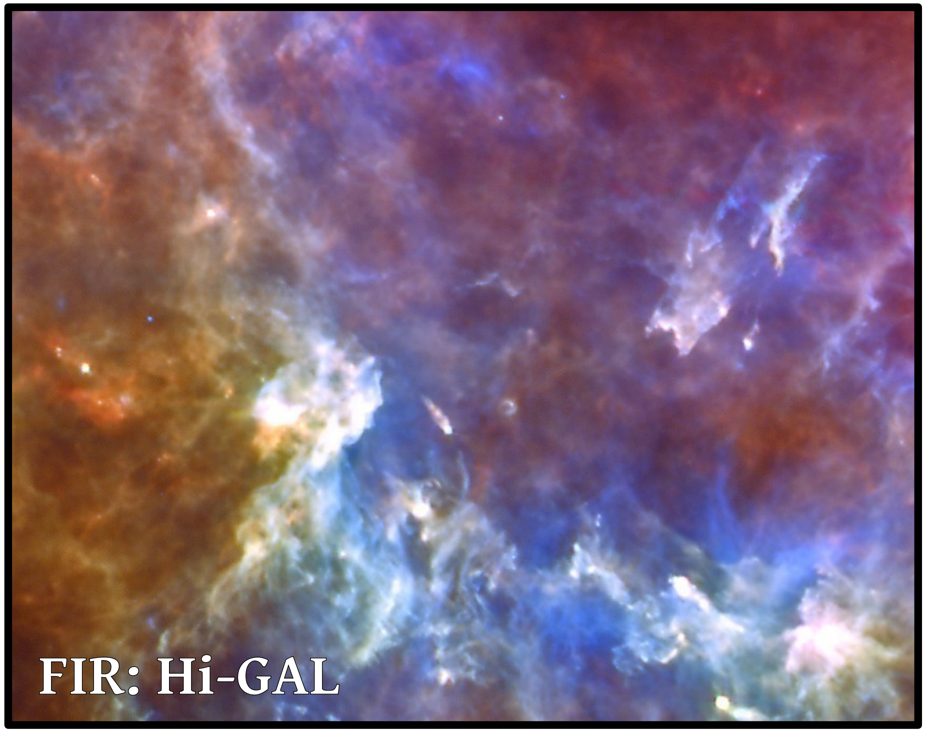
Radius ~ 1 pc

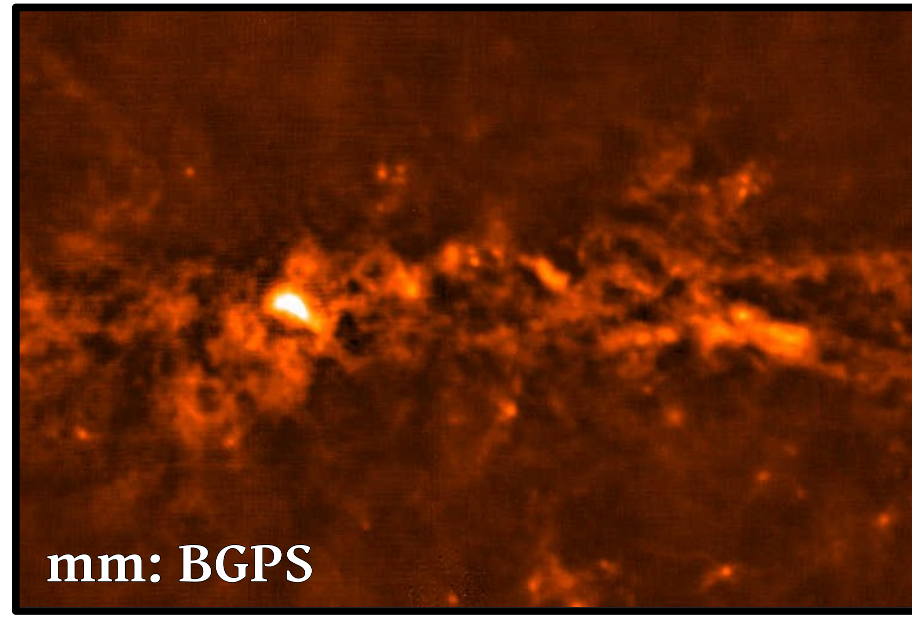
Col. Dens. ~ 10^2—10^3 M_{sun} pc^{-2}

Vol. Dens. ~ 10^3 cm^{-3}

Image Credit: Battersby et al. (2010)

Future is now: Galactic plane surveys now exist to study pre-protoclusters / starless clumps





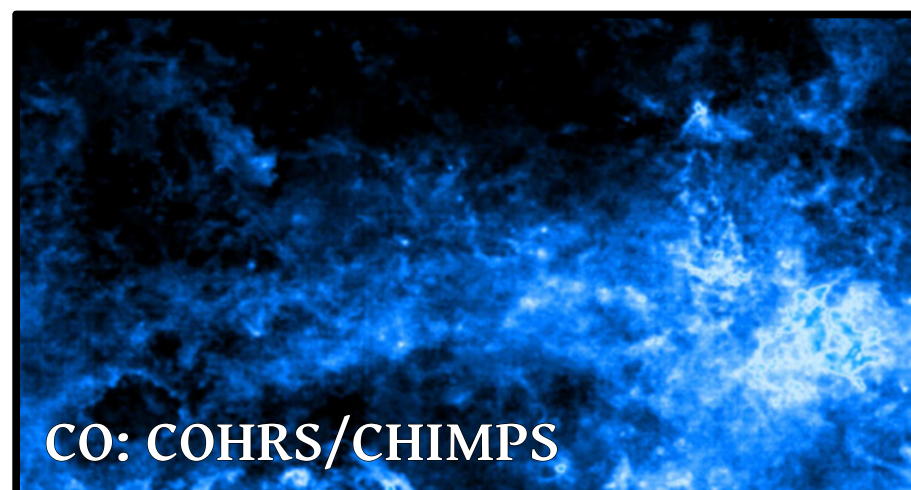
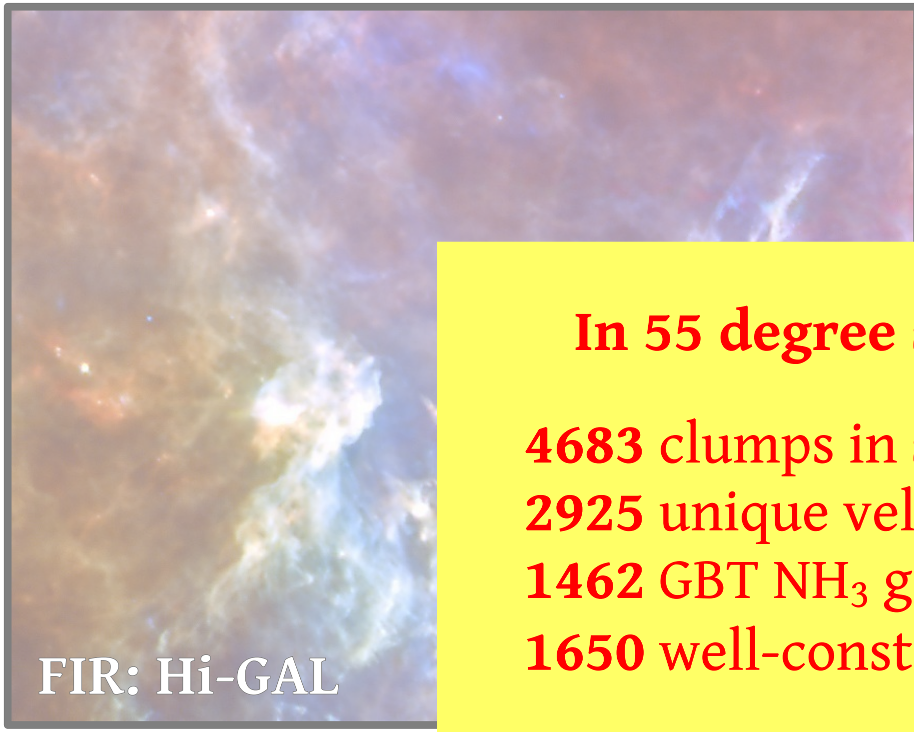
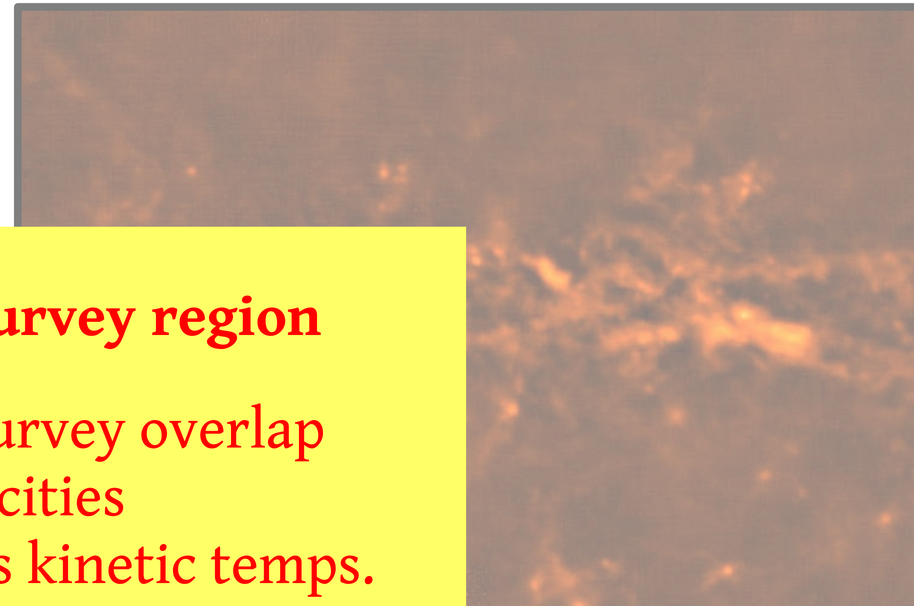


Image Credit: ESA, NASA, JPL-Caltech, S. Carey, A. Ginsburg, Dempsey et al. (2013)

Future is now: Galactic plane surveys now exist to study pre-protoclusters / starless clumps





In 55 degree survey region

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

Image Credit: ESA, NASA, JPL-Caltech, S. Carey, A. Ginsburg, Dempsey et al. (2013)

Indicators: Blind surveys of star formation activity from the radio to mid-IR, half of clumps are starless

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

Only 70 um, deeply embedded candidates

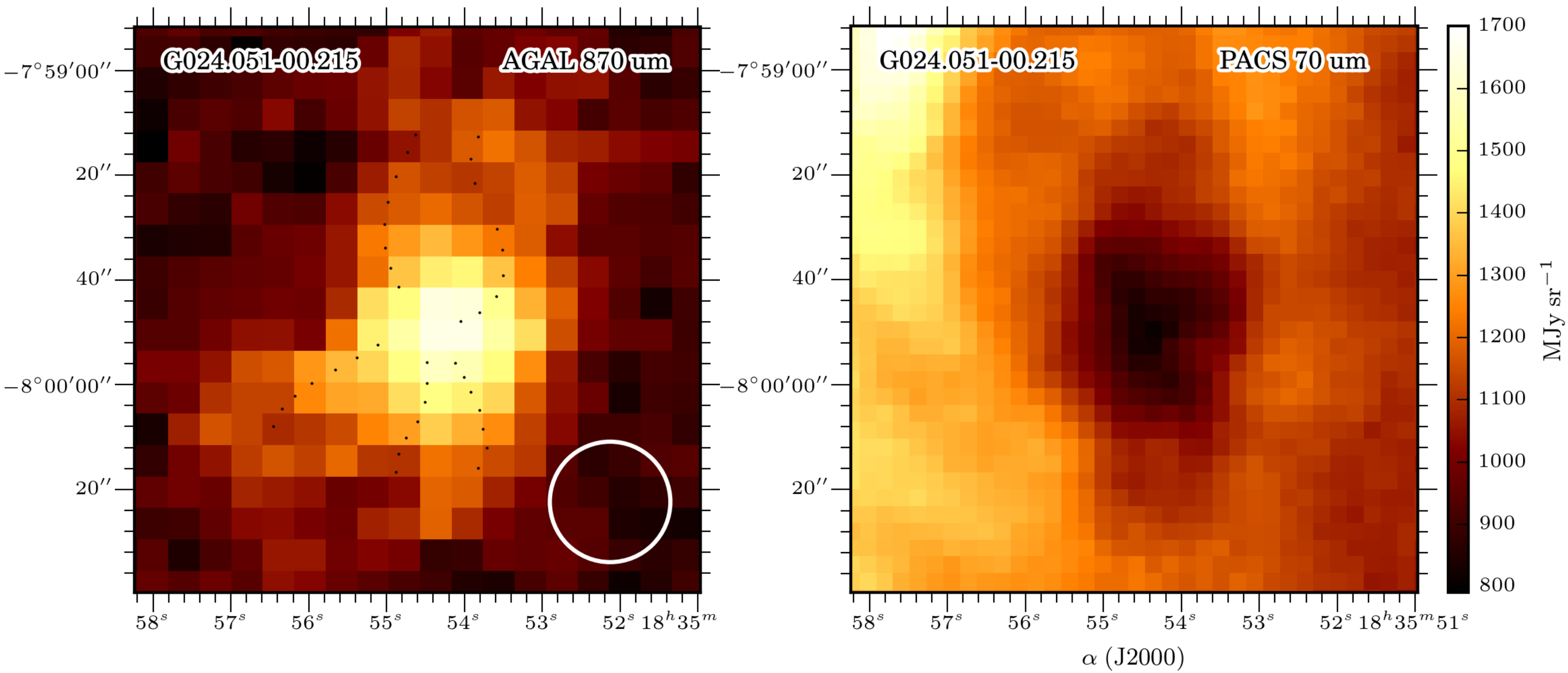
Includes over 2000 targeted GBT observ.

Uniquely OB stars, not all clumps may produce these indicators

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

~2200 starless clump candidates identified

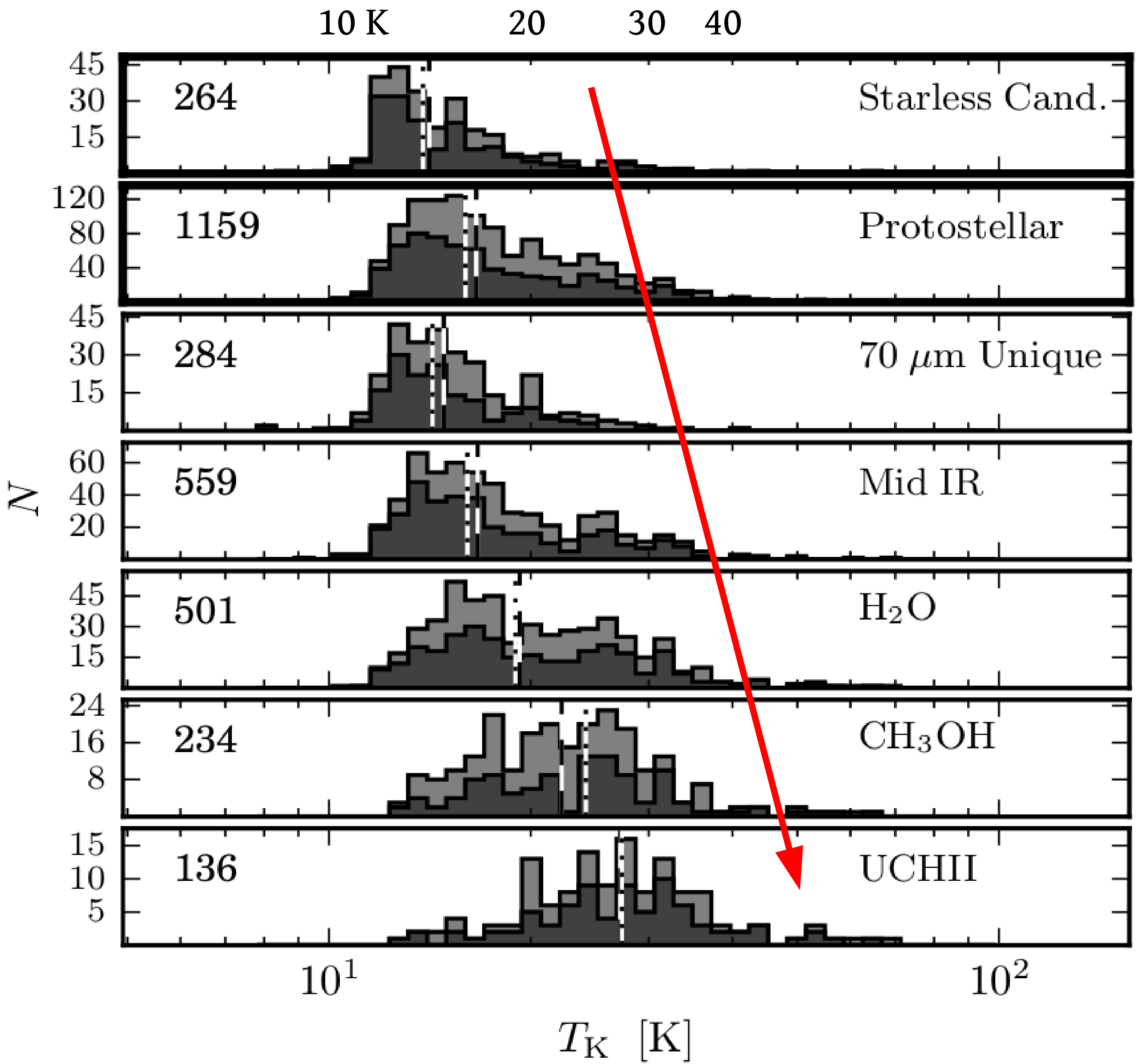
candidates: 90% complete at 50-100 L_{sun}



High Mass SCC example: 1000 M_{sun}, 11 K, 1 pc, 4.5 kpc

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

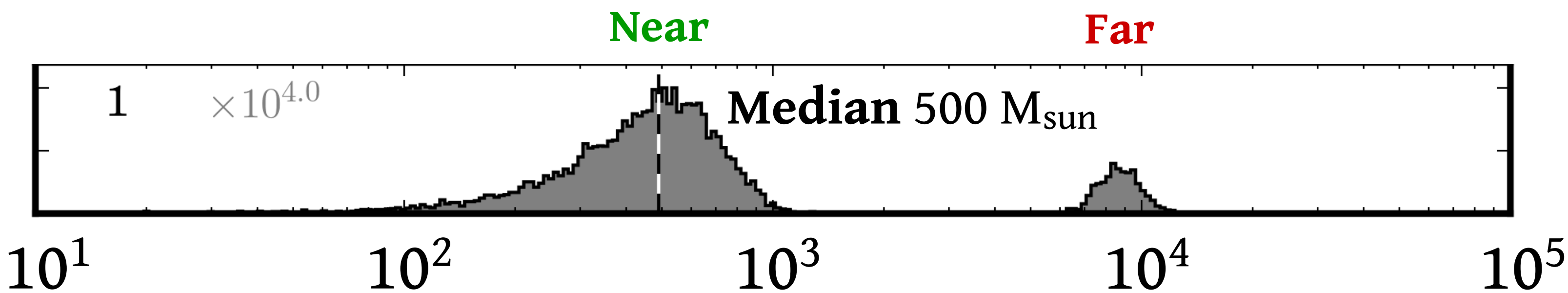
NH$_3$ Gas Temperatures: Increasing temperatures with star formation activity, median for SCC = 13.9 K.



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

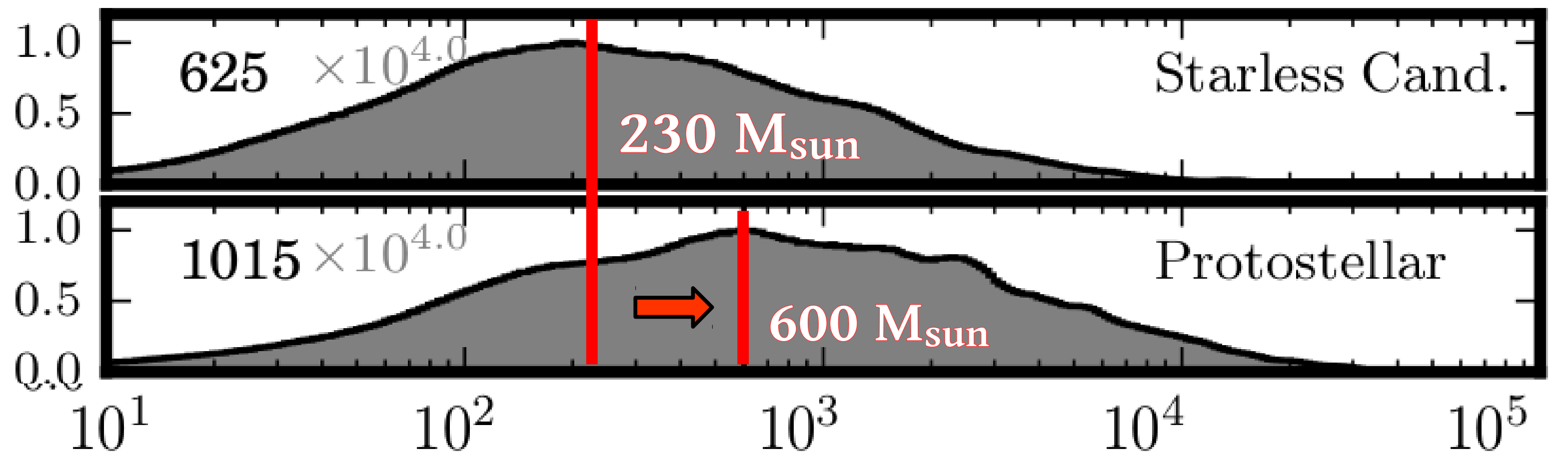
Property estimation: MC samples are drawn for each clump based on PDFs for distance, flux, and temperature

Example: 1 Clump with 10,000 Monte Carlo mass samples



Clump total mass (M_{sun}) from MC samples that draw from flux, temperature, and heliocentric distance.

Mass Segregation: Increase in median mass from 230 to 600 from Starless to Protostellar. Evidence for growth?



Clump total mass (M_{sun}) from MC samples that draw from flux, temperature, and heliocentric distance.

Cannot be due to:

- Incompleteness in distance or SF indicators
- Mass incompleteness for starless candidates
- NH_3 underestimate of kinetic temperature
- Isothermal temperature assumption

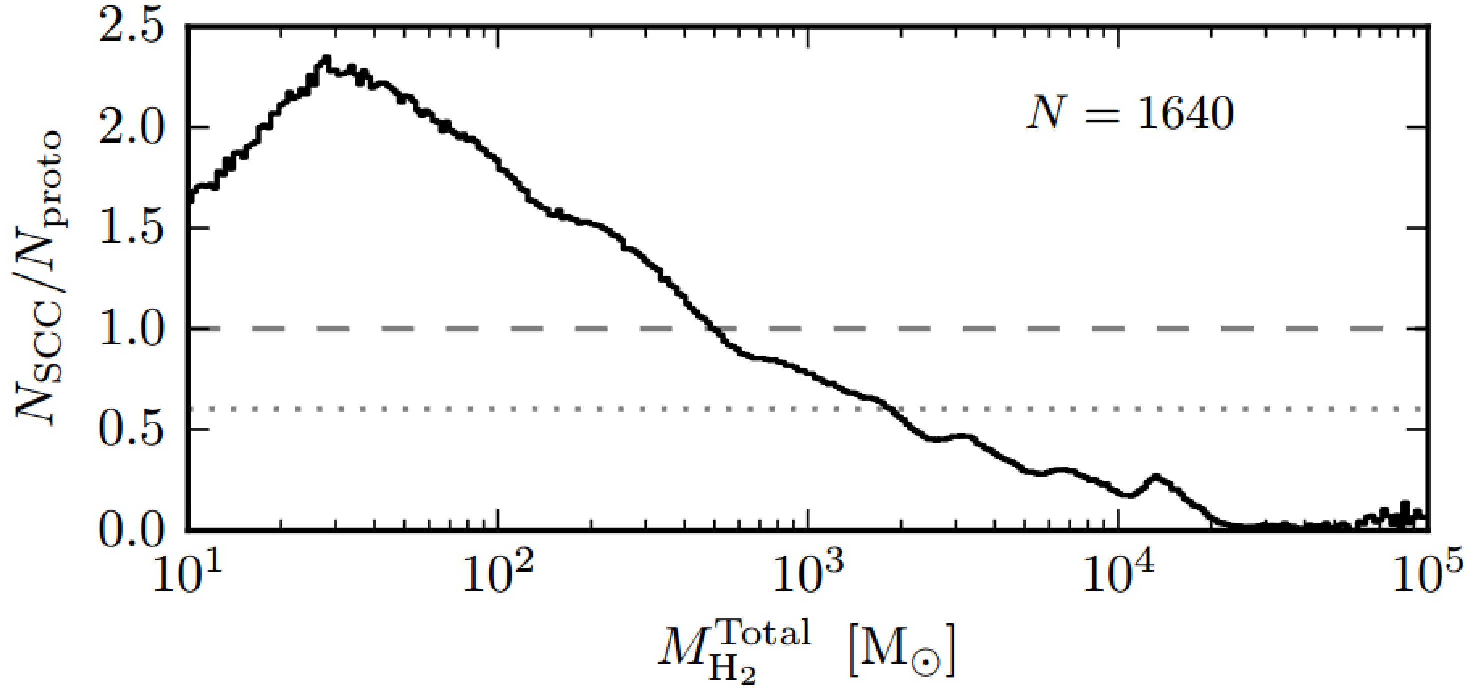
Svoboda, Shirley, Battersby, et al. (2016), ApJ, 822, 59

Growth only scenario

200 – 400 M_{sun} / Myr

Lifetime only scenario

Starless lifetime ~ $M^{-0.4}$



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

Infall survey towards 100 SCCs suggests this is unlikely (Calahan et al. in prep.)

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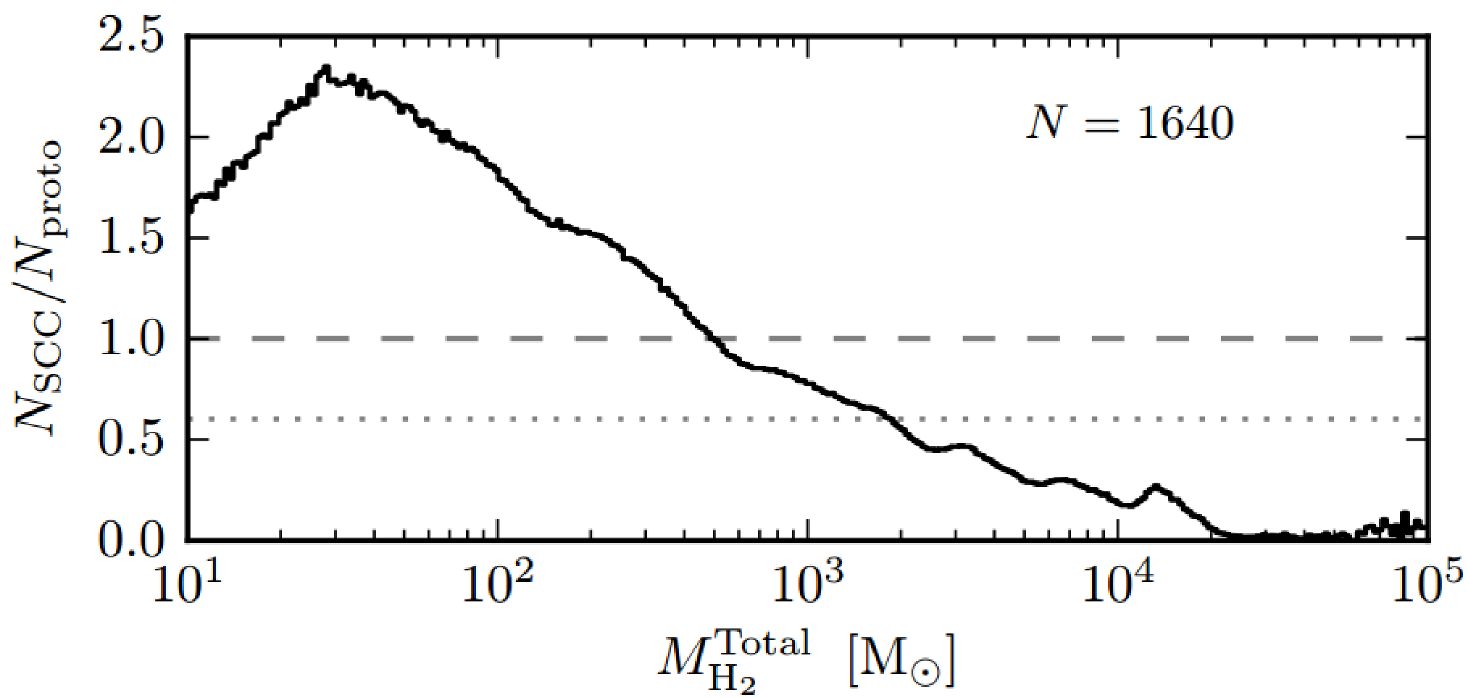
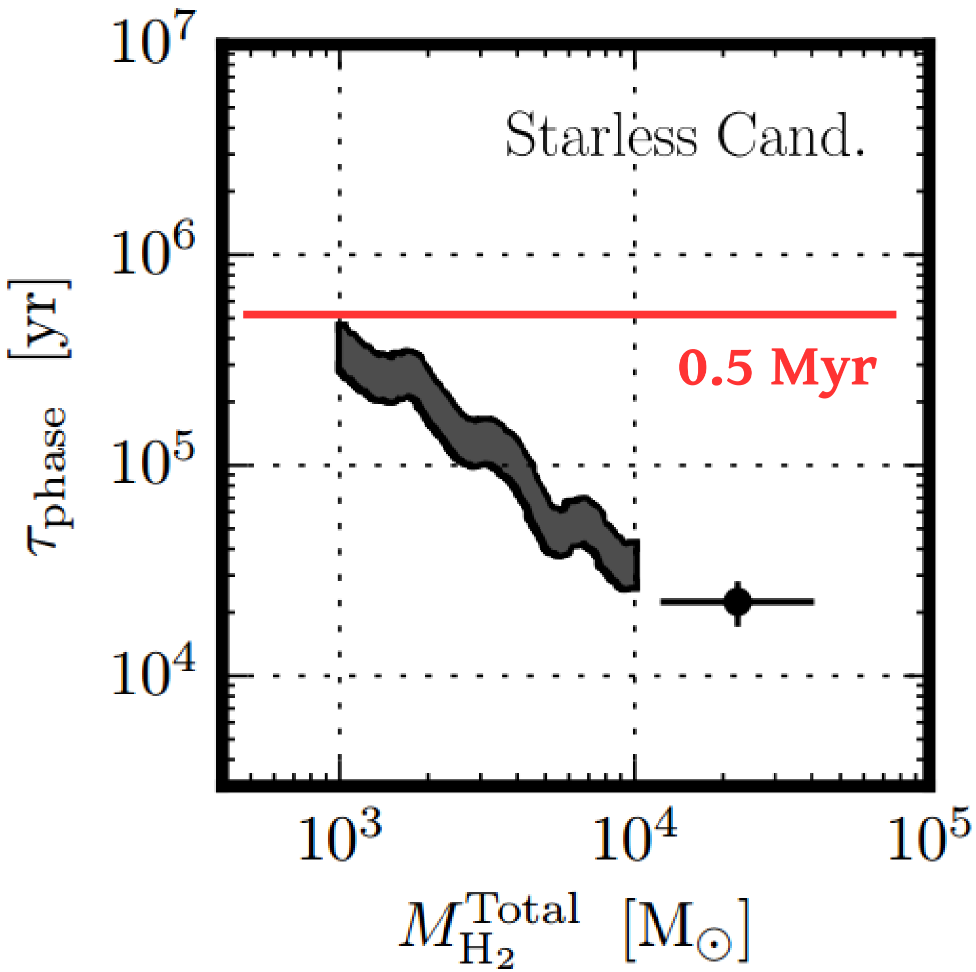


Svoboda, Shirley, Battersby, et al. (2016), ApJ, 822, 59

Time Scales: SCC phase short, less than 0.5 Myr

Class II Methanol Maser: Absolute timescale between 0.06 to 0.09 Myr (van der Walt 2005; Battersby et al., in press)



High-mass starless phase < 0.5 Myr

Assumes no clump growth

Extrapolated to ~200 M_{sun}, starless phase would be 2-3 the free-fall time

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

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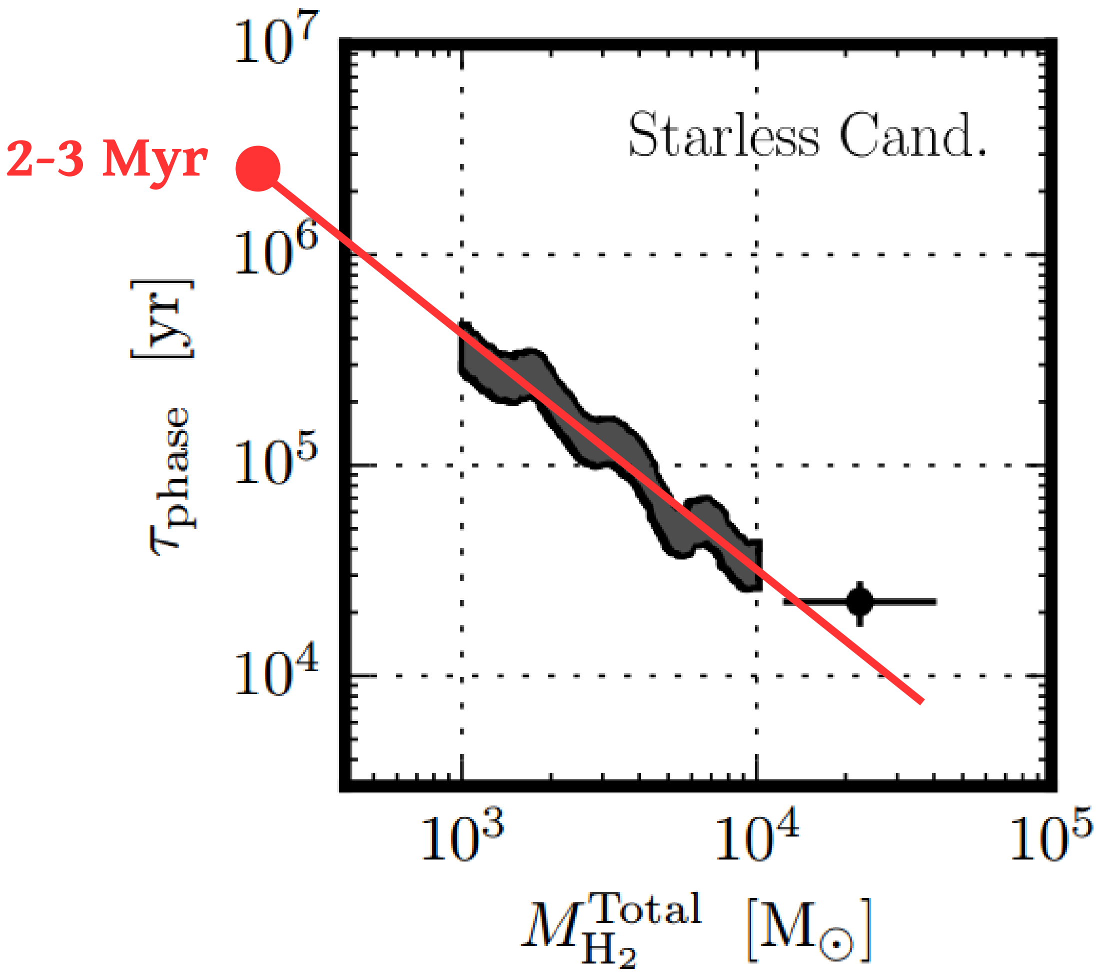

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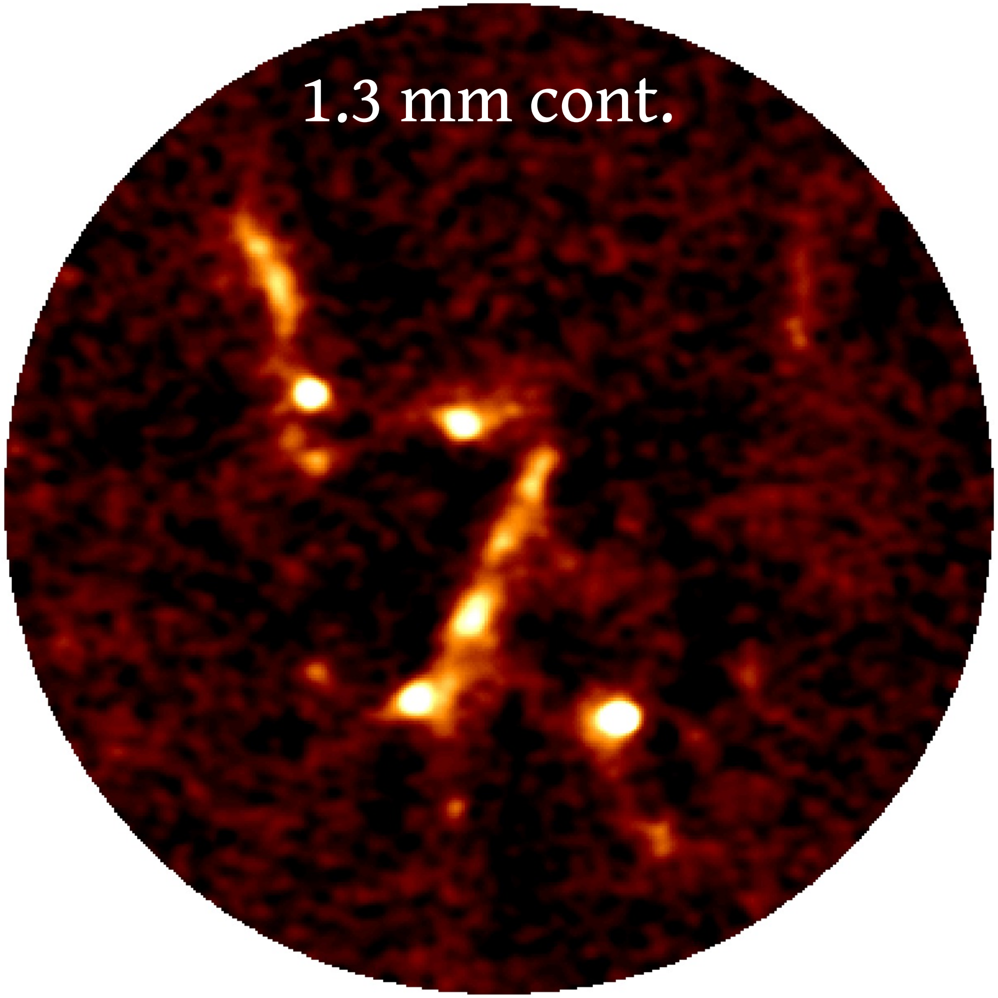
ALMA Survey: 12 highest mass SCCs within 5 kpc



40” ~0.8 pc (3000 AU resolution)

Constraining the core mass function (CMF) down to 0.3 M_{sun}.

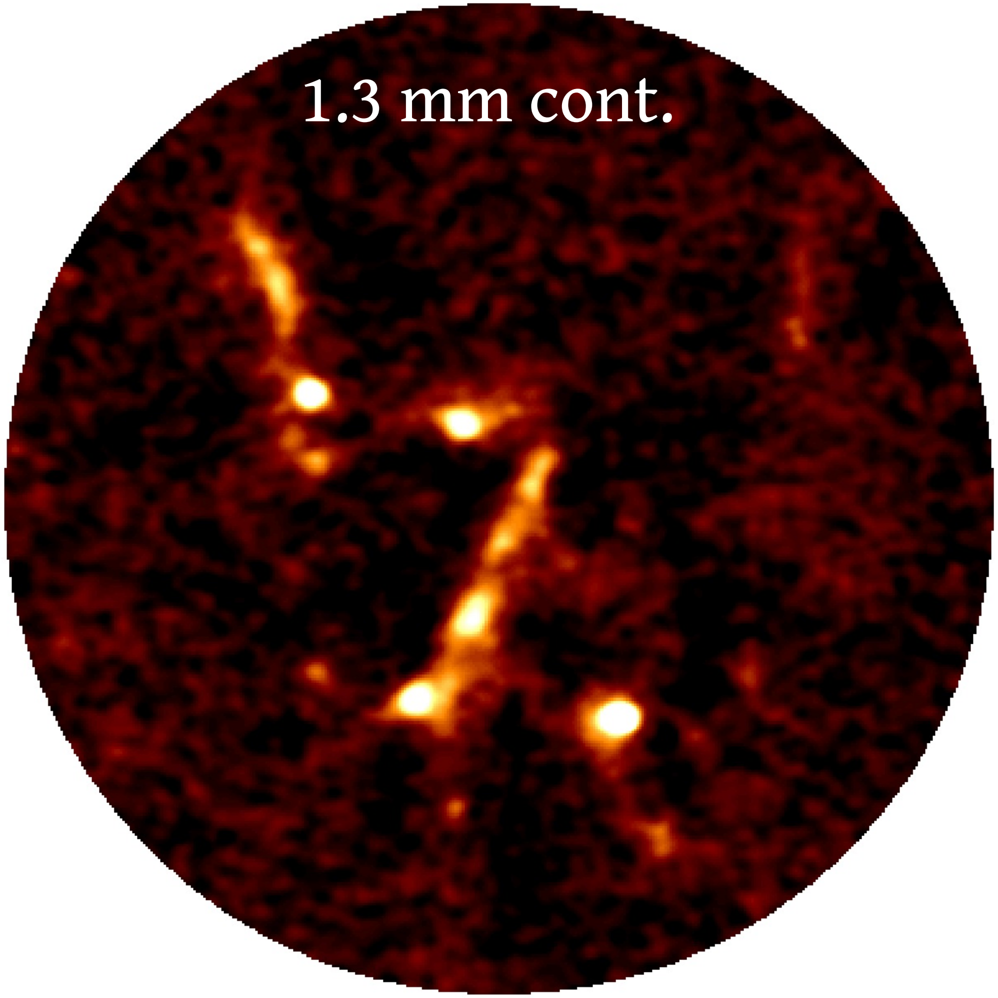
Turbulent or thermal Jeans? Do we observe massive starless cores?

Identifying hitherto undetected indicators of star formation.

Deuteration, stability, and kinematics...

Svoboda, Shirley et al. in prep.

ALMA Survey: 12 highest mass SCCs within 5 kpc



40" ~0.8 pc (3000 AU resolution)

Significant level of fragmentation observed, consistent with thermal Jeans mass and length

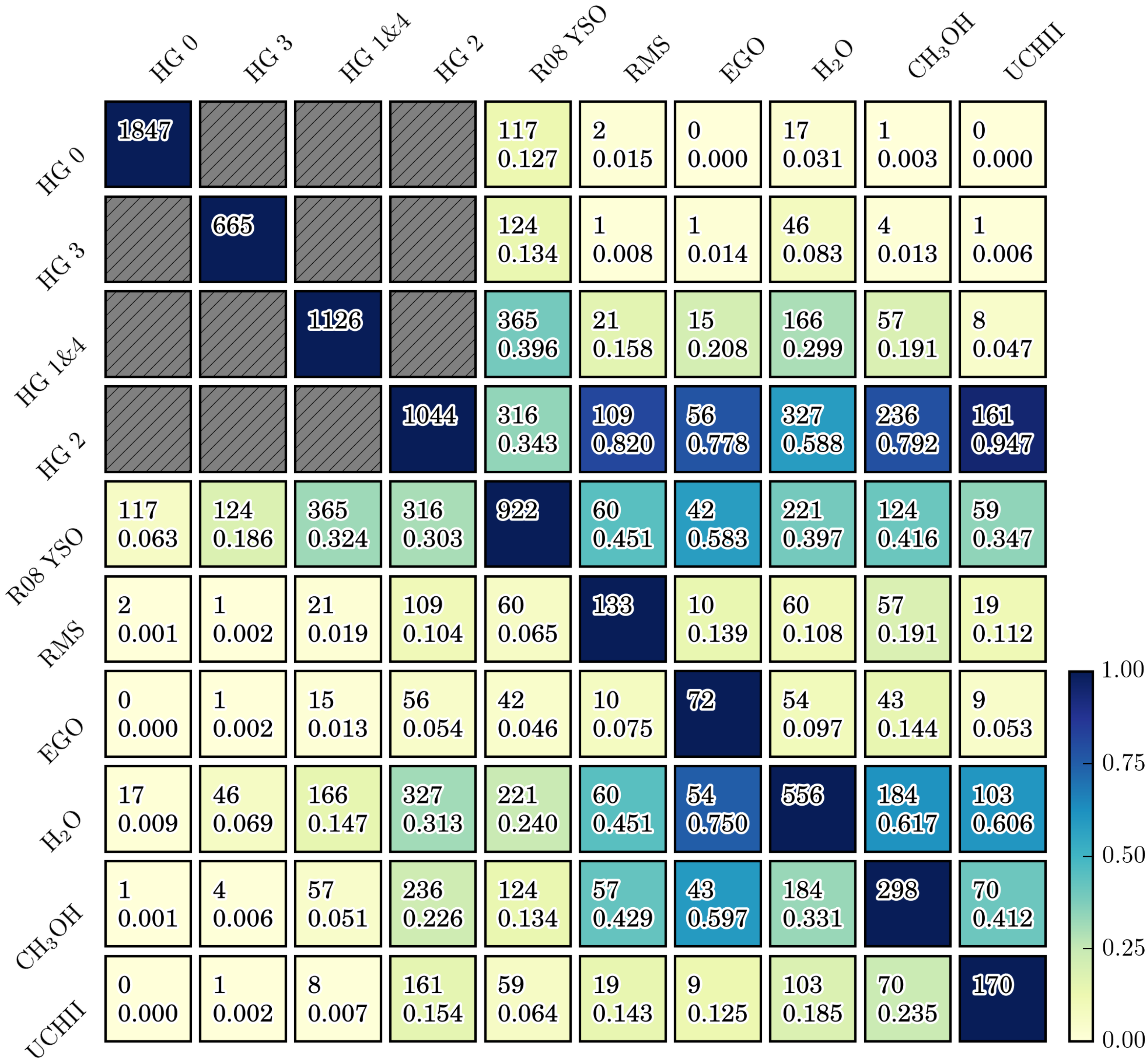
10/12 show SF! Existing Galactic surveys are incomplete to low-mass SF. Requires inter-ferometric followup.

Coeval low-mass cores but no HMSF, consistent with LMSF first?

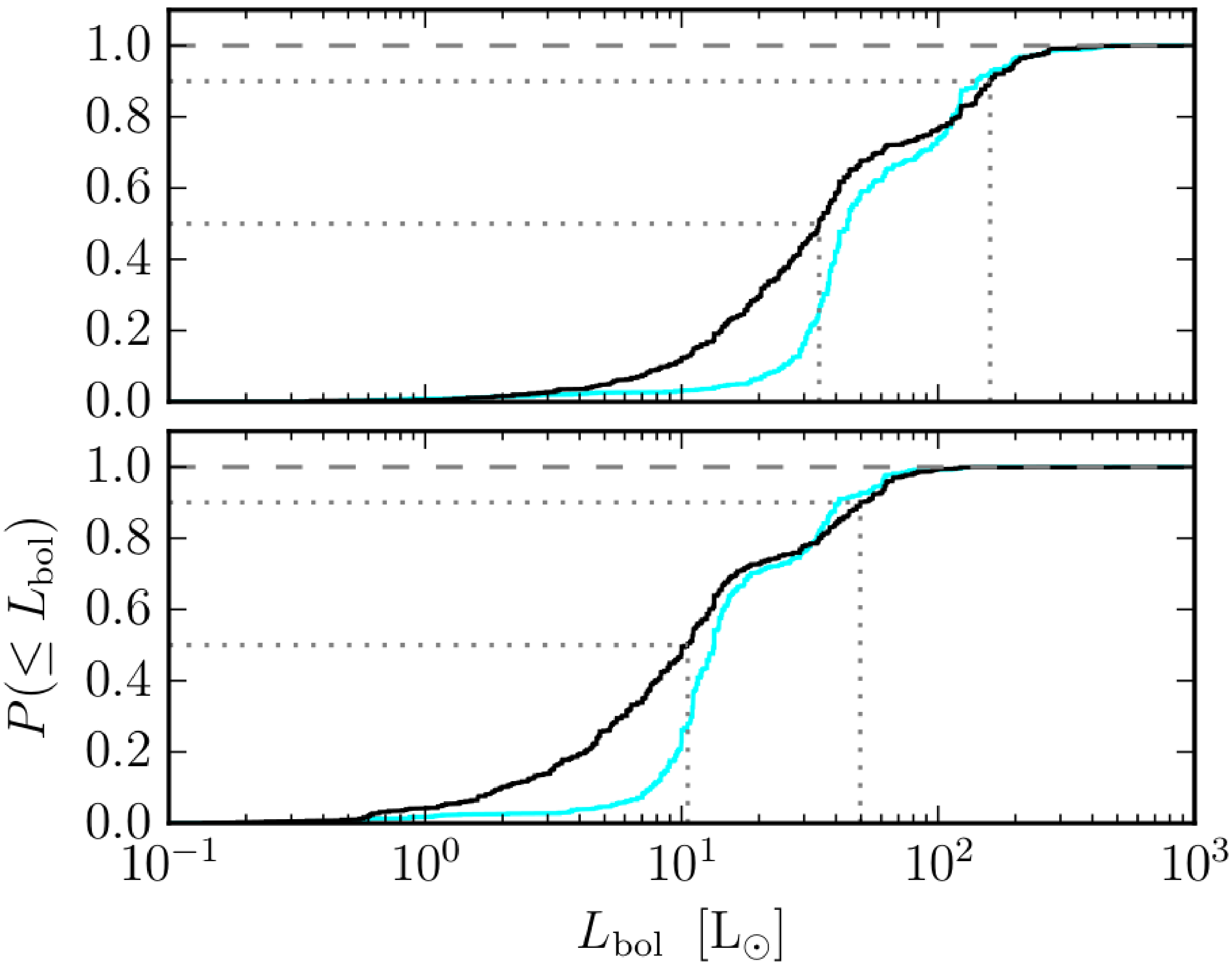
Svoboda, Shirley et al. in prep.

Summary & Conclusions

- **~2200** blindly identified starless clump candidates (SCCs): large & robust sample for followup
- SCCs are colder, lower mass, less turbulent, less concentrated, smaller, less dense, and lower column density than protostellar clumps. Majority (75%) of clumps are gravitationally bound.
- Increase in median mass is suggestive of growth via infall or a decreasing lifetime with mass.
- Timescale for high-mass SCCs < 0.5 Myr with no single value. Low-mass SCCs phase longer than free-fall time.
- ALMA surveys to study the fragmentation and kinematics of the highest mass SCCs.


HG 0
HG 3
HG 1&4
HG 2
R08 YSO
RMS
EGO
H_2O
CH_3OH
UCHII
1847
117 0.127
2 0.015
0 0.000
17 0.031
1 0.003
0 0.000
665
124 0.134
1 0.008
1 0.014
46 0.083
4 0.013
1 0.006
1126
365 0.396
21 0.158
15 0.208
166 0.299
57 0.191
8 0.047
1044
316 0.343
109 0.820
56 0.778
327 0.588
236 0.792
161 0.947
117 0.063
124 0.186
365 0.324
316 0.303
922
60 0.451
42 0.583
221 0.397
124 0.416
59 0.347
2 0.001
1 0.002
21 0.019
109 0.104
60 0.065
133
10 0.139
60 0.108
57 0.191
19 0.112
0 0.000
1 0.002
15 0.013
56 0.054
42 0.046
10 0.075
72
54 0.097
43 0.144
9 0.053
17 0.009
46 0.069
166 0.147
327 0.313
221 0.240
60 0.451
54 0.750
556
184 0.617
103 0.606
1 0.001
4 0.006
57 0.051
236 0.226
124 0.134
57 0.429
43 0.597
184 0.331
298
70 0.412
0 0.000
1 0.002
8 0.007
161 0.154
59 0.064
19 0.143
9 0.125
103 0.185
70 0.235
170
1.00
0.75
0.50
0.25
0.00

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

Distance PDFs: A novel Bayesian approach to resolving heliocentric distances

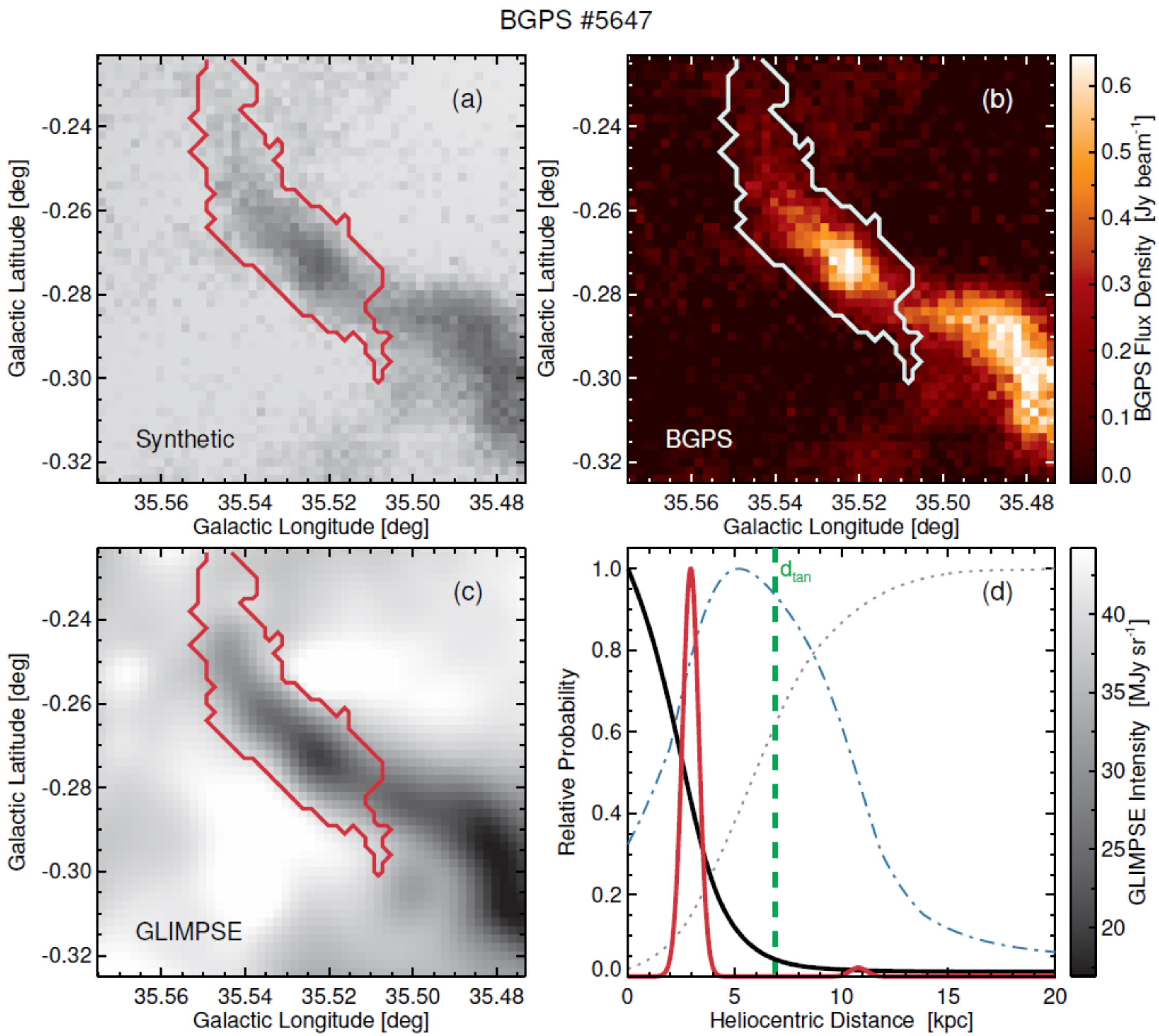


Image Credit: Ellsworth-Bowers+ (2013)

Distance PDFs: A novel Bayesian approach to resolving heliocentric distances

$$\mathrm{DPDF}(d_\odot) = \mathcal{L}(v_{\mathrm{LSR}}, l, b; d_\odot) \prod_i P_i(l, b; d_\odot)$$

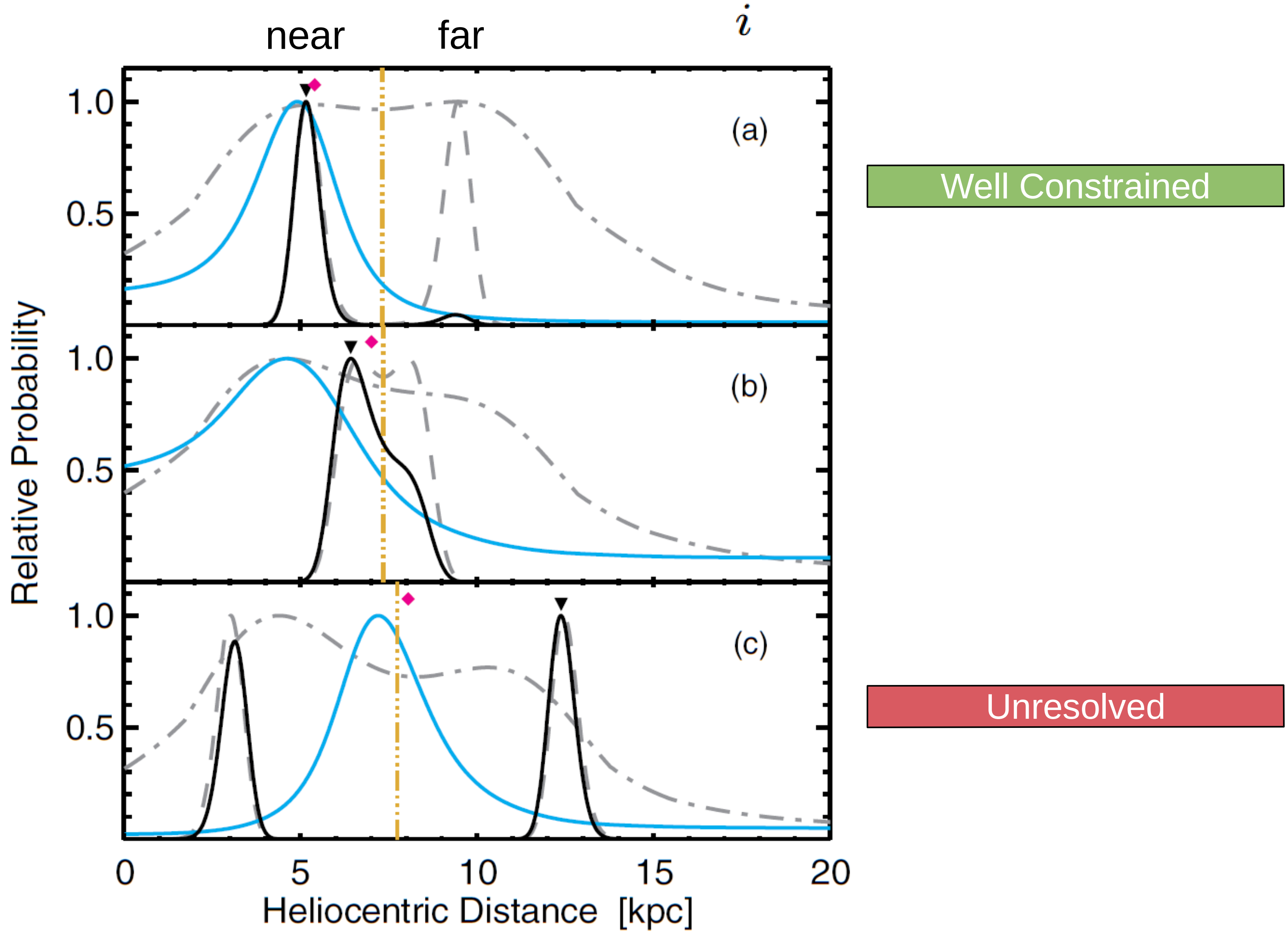
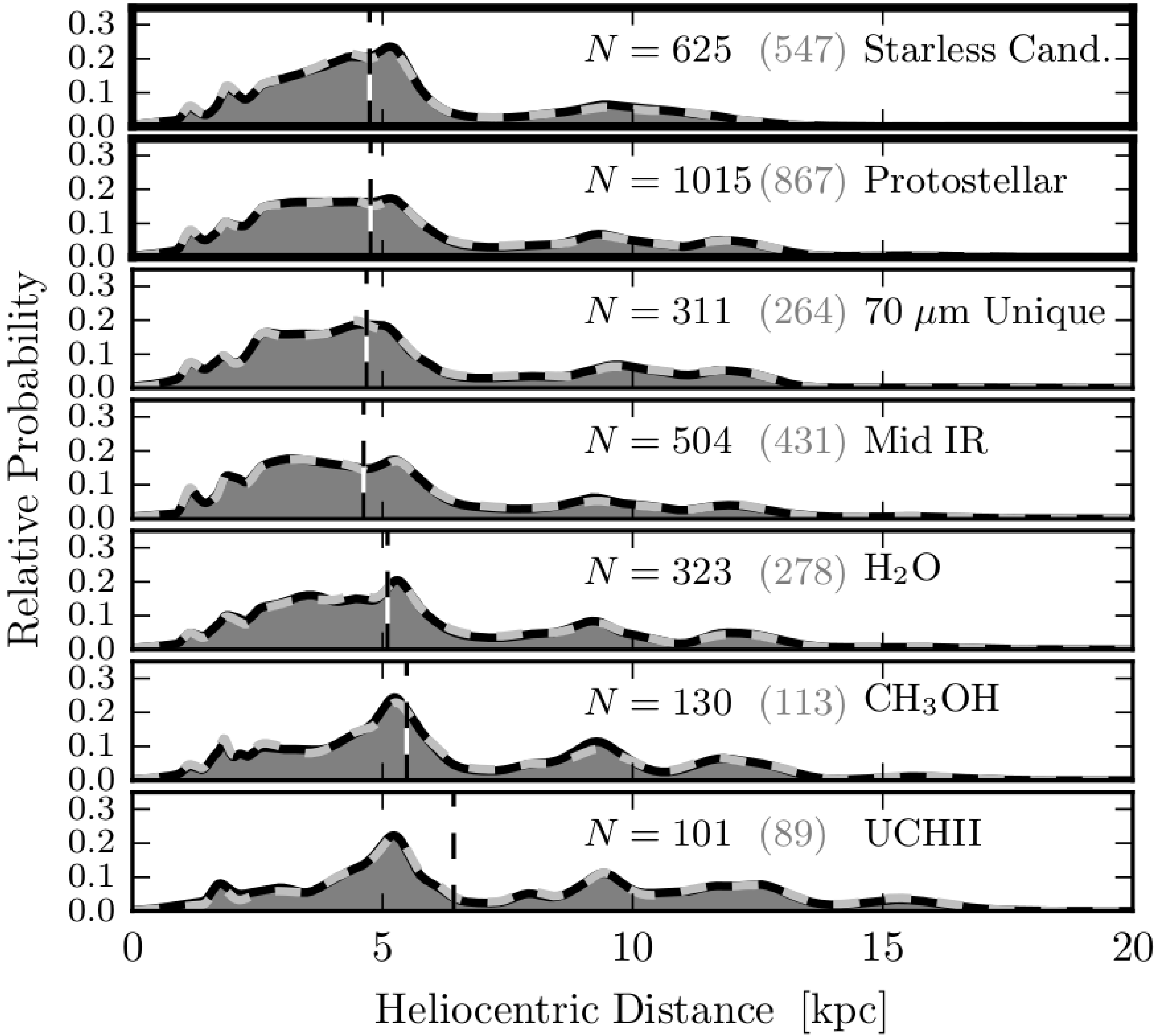
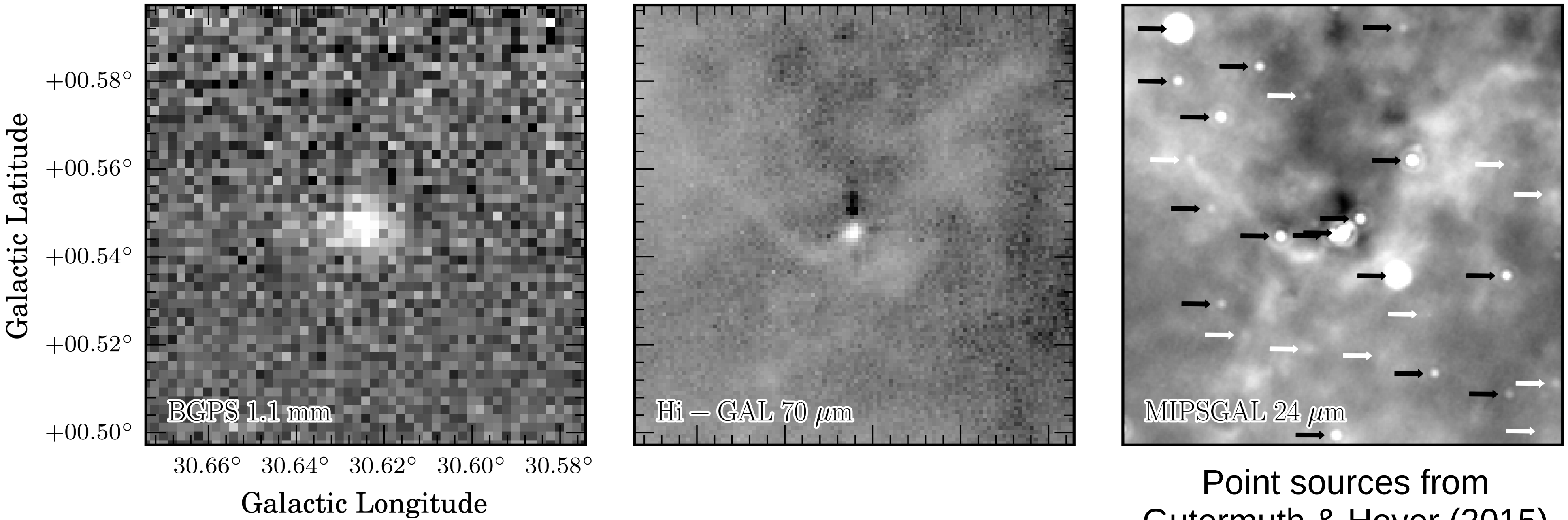


Image Credit: Ellsworth-Bowers+ (2013, 2015a)

Distance PDFs: Group distances are similar. Does not suggest strong distance bias.



Contamination: Far-IR 70 um much more effective indicator of deeply embedded YSOs without contamination from evolved stars.



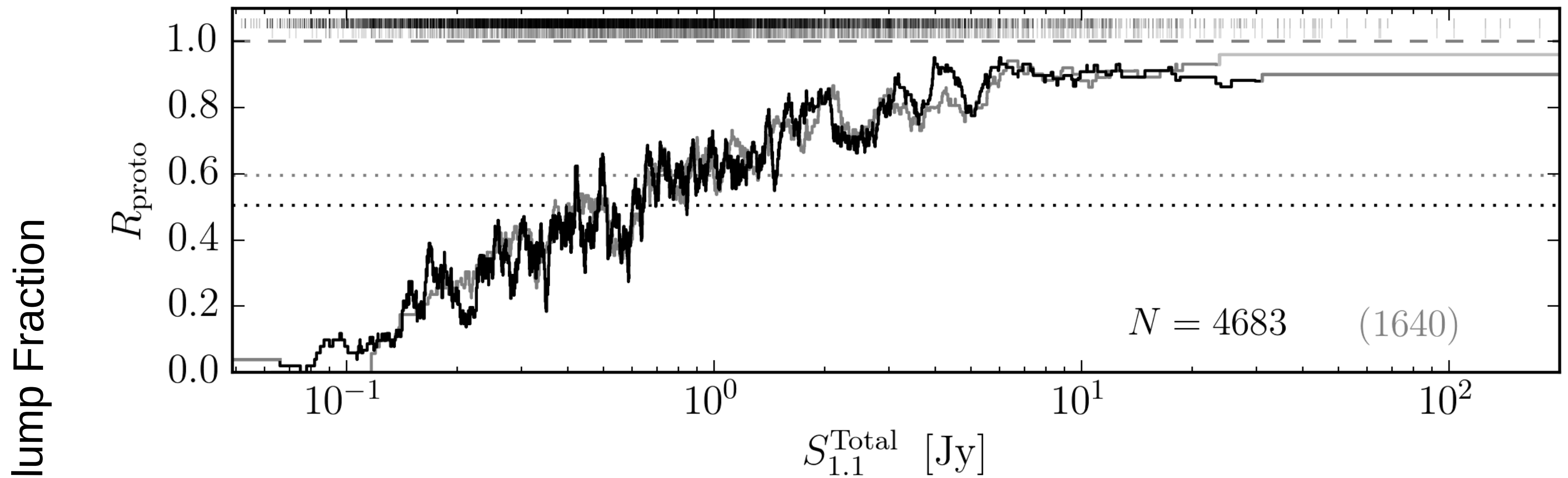
Point sources from Gutermuth & Heyer (2015)

Severe contamination in 24 um data from evolved stars

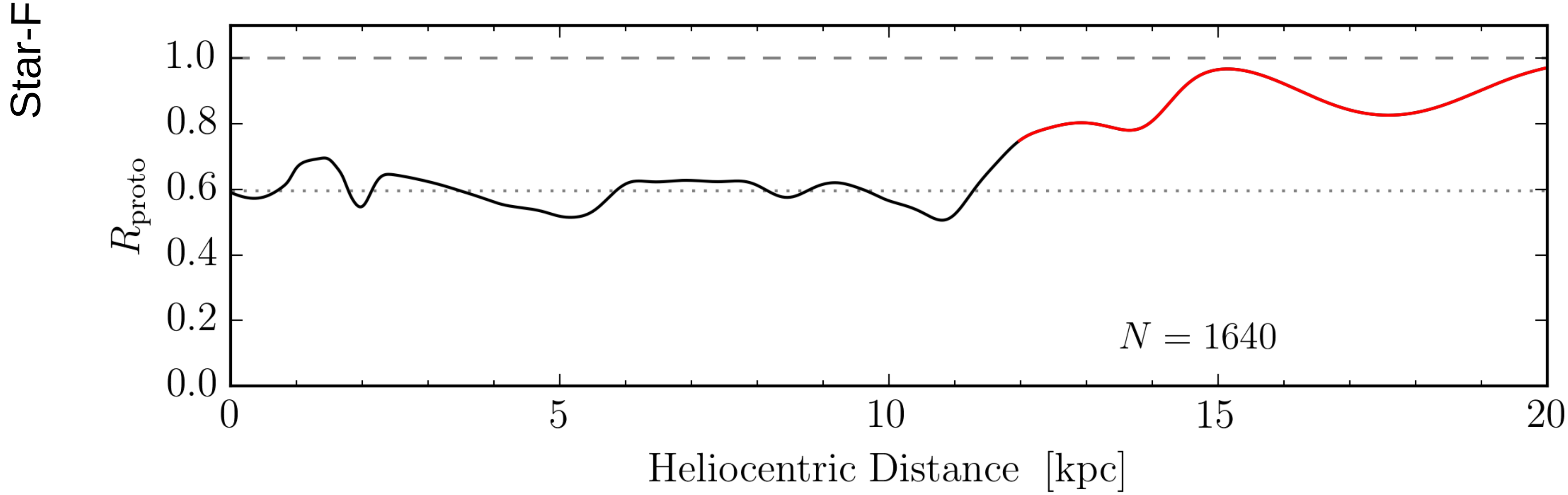
More than 80% of clumps are LOS associated to 24 um

70 um is a superior indicator of deeply embedded YSOs

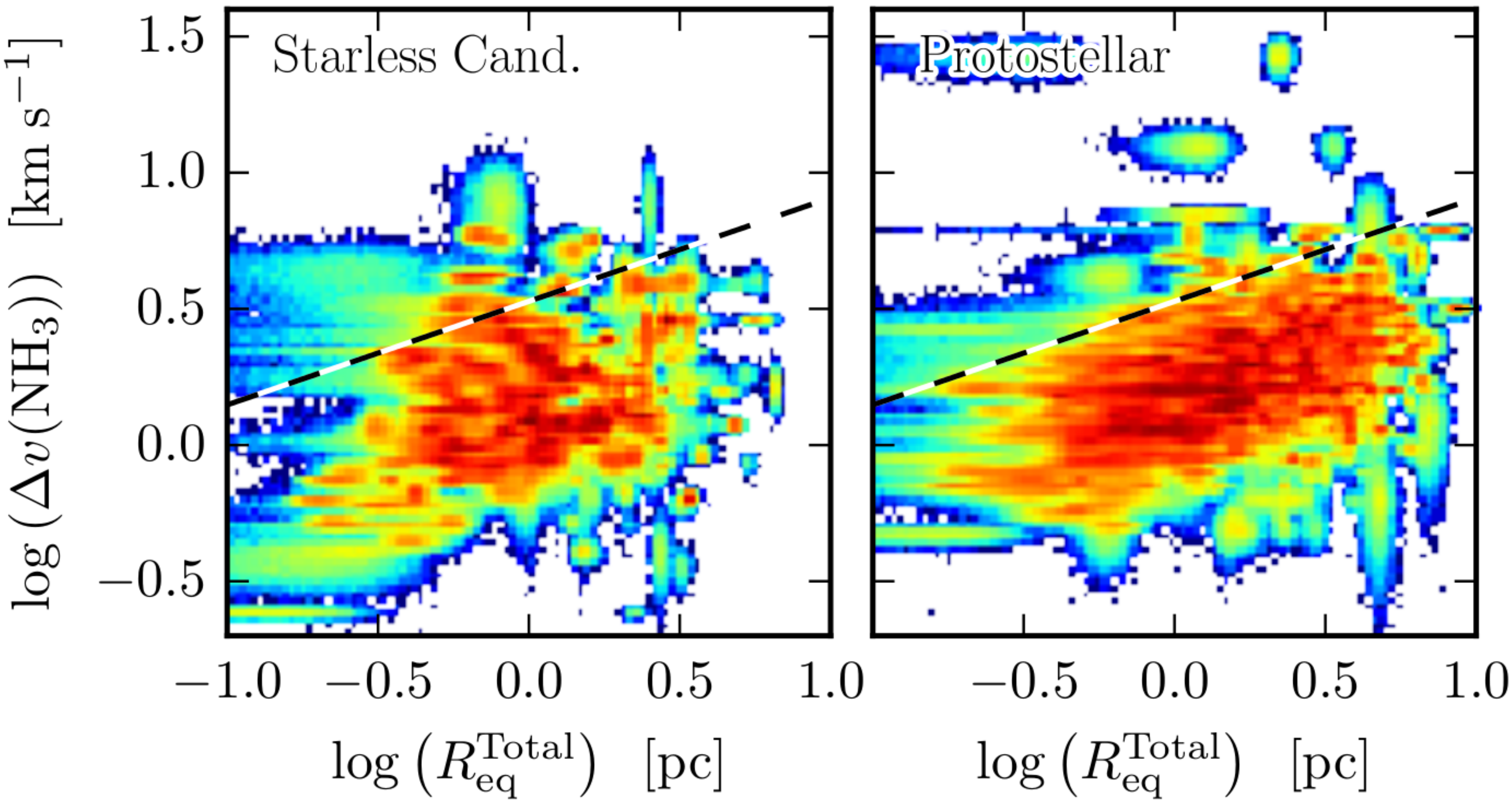
Flux Density: Lower flux clumps more frequently starless, but Full and Distance samples similar.



Distance PDFs: Fraction is constant. Does not suggest significant incompleteness in indicators.

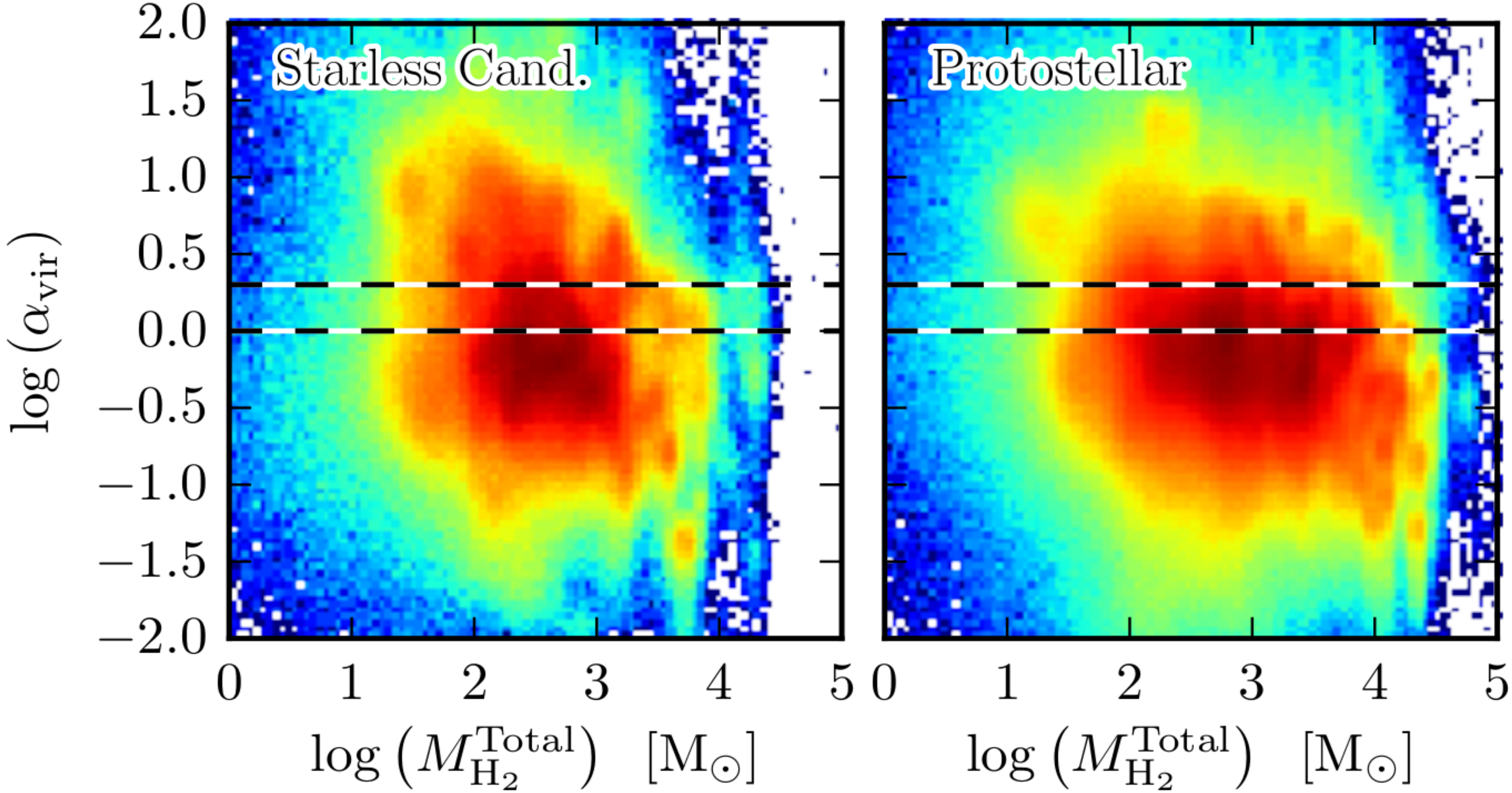


Size Linewidth: No observed size-linewidth trend for SCCs, but protostellar consistent with Larson.



Spearman rank correlation coefficients of 0.24 and 0.50. Ammonia observations corrected for optical depth show better agreement than HCO+ (Schlingman et al. 2011, Shirley et al. 2013).

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



Population of SCCs shows similar distribution of virial parameters, without a large difference in fraction of "unbound" clumps. While sub-virial, 50 uG required to support typical clump to collapse (cf. Kauffmann et al. 2013; Pillai et al. 2015)

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)

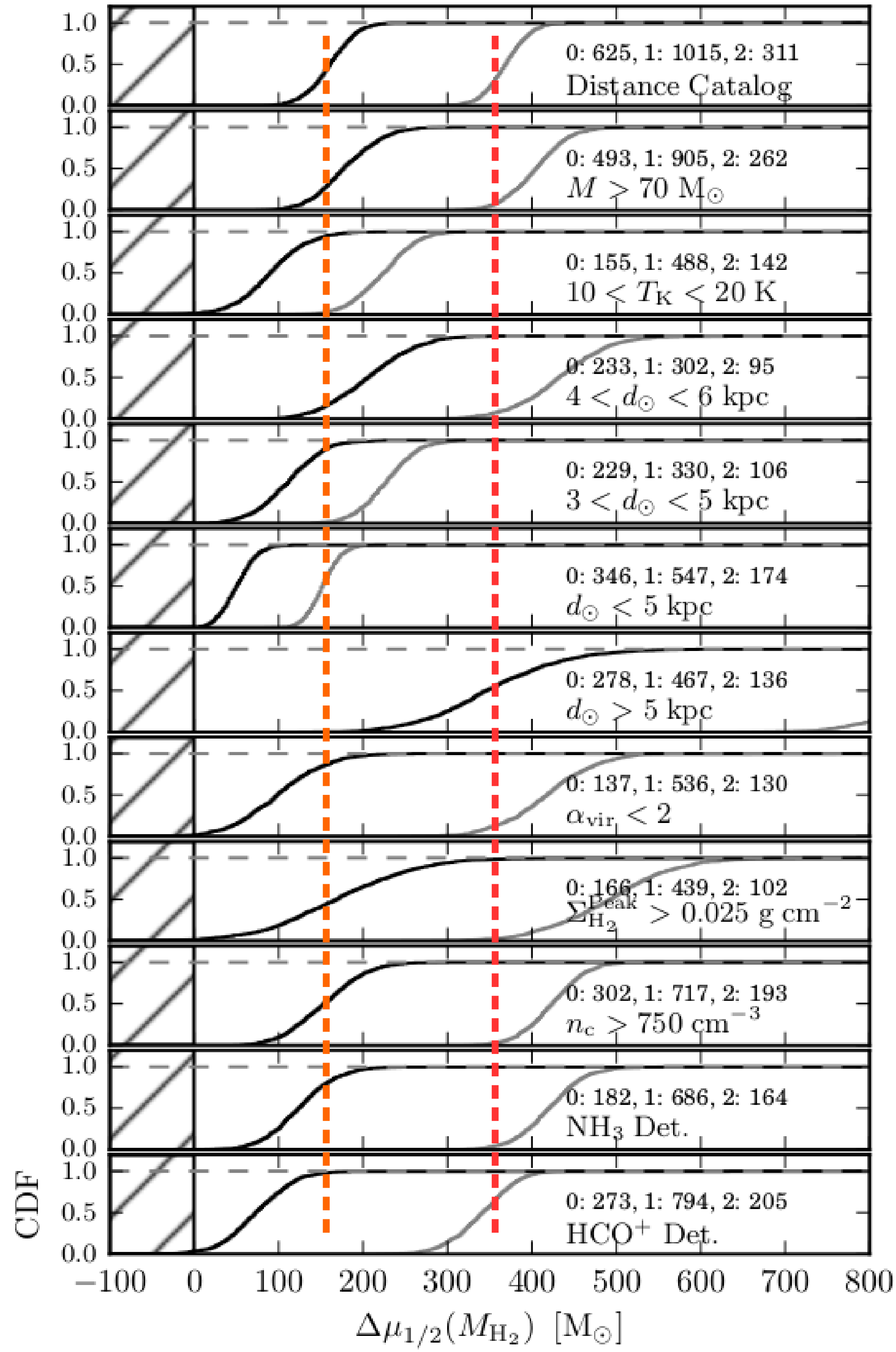
~ 1000 Msun / Myr (high-mass):

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

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

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

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

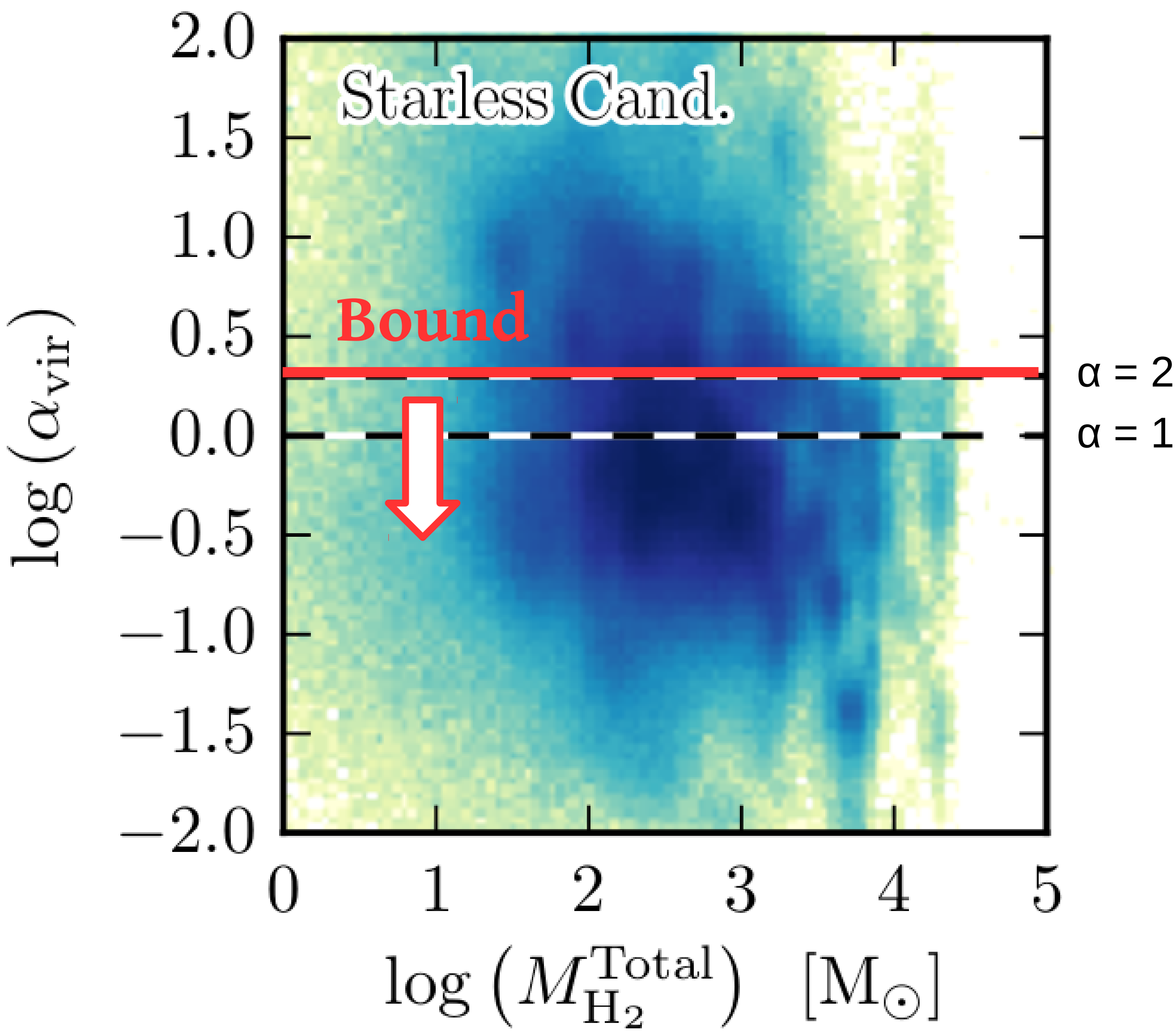
98 SCCs
Distance Sample

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