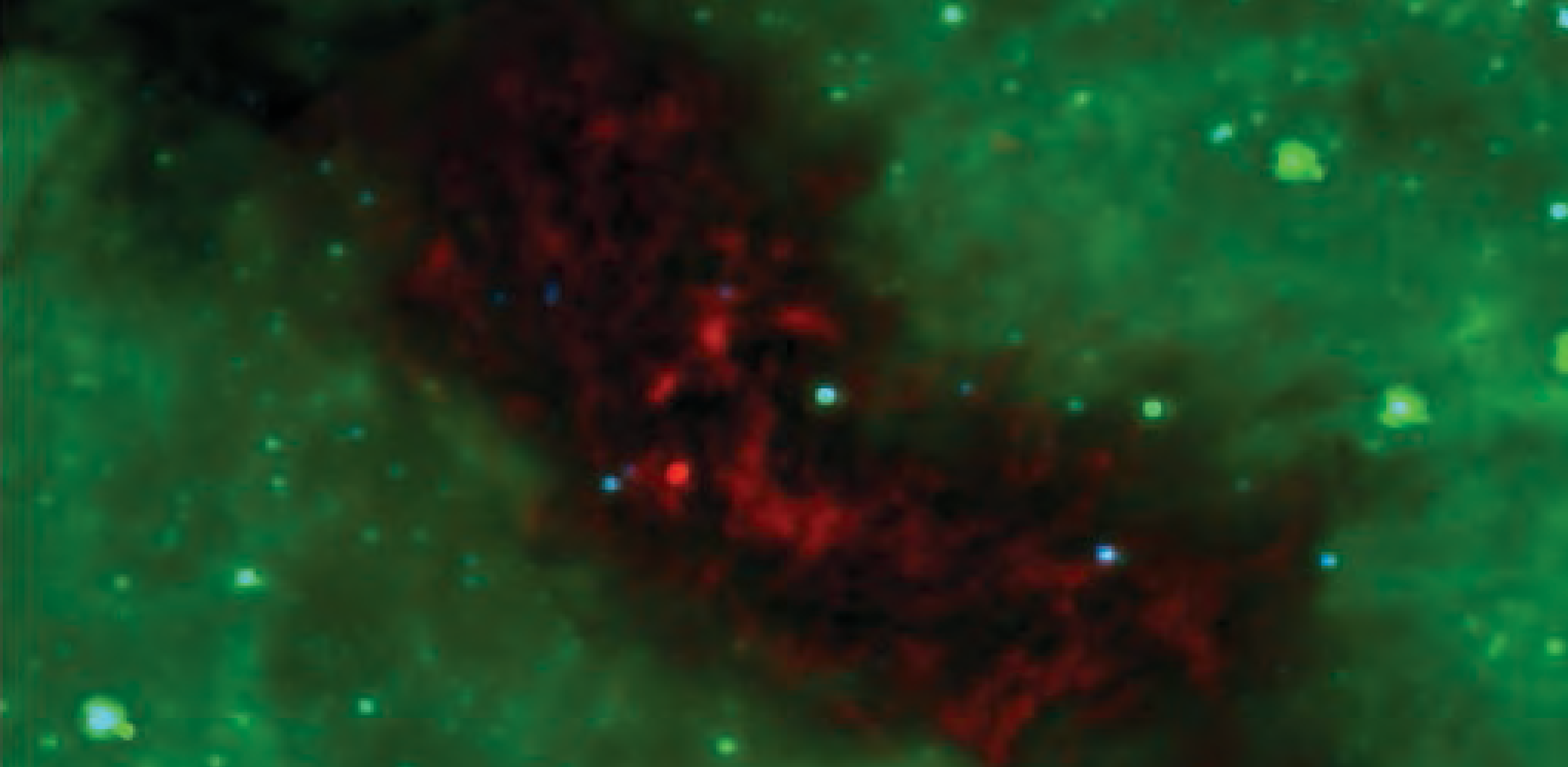

A cluster in the making:

ALMA reveals the initial conditions for high-mass cluster formation

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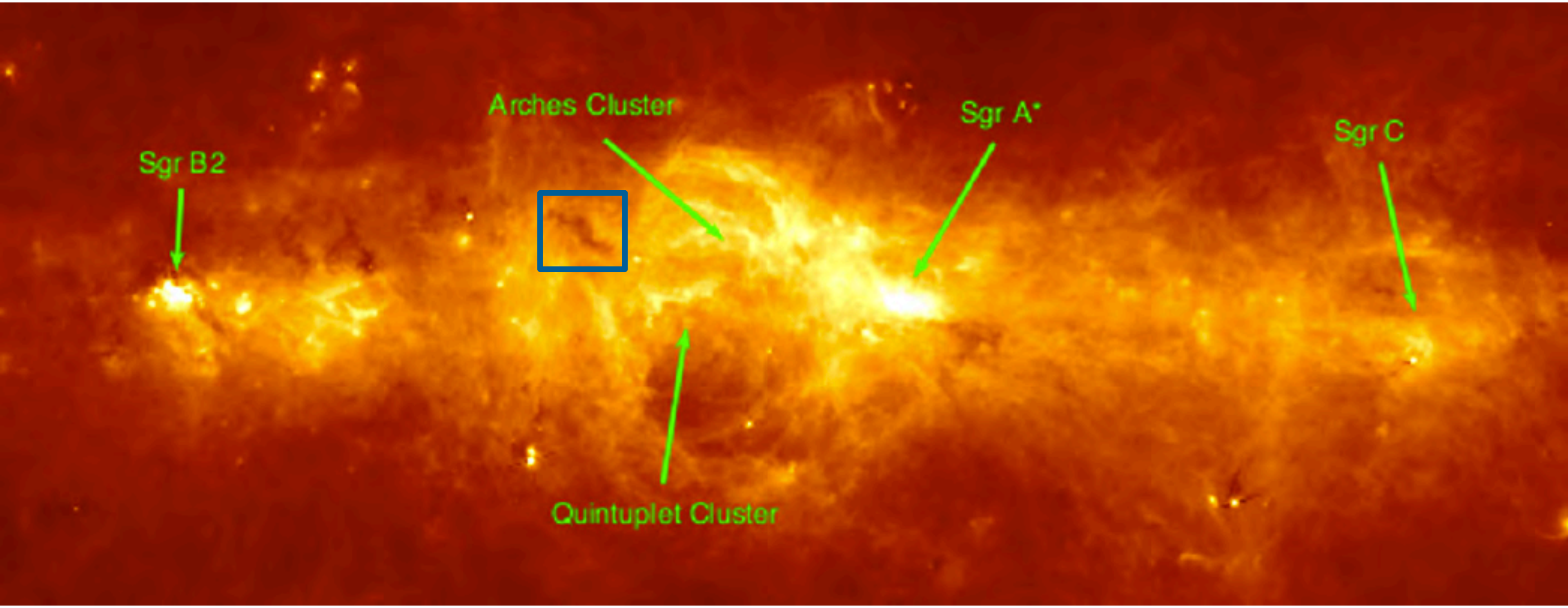
The Central Molecular Zone

Herschel 70μm image – dust continuum emission

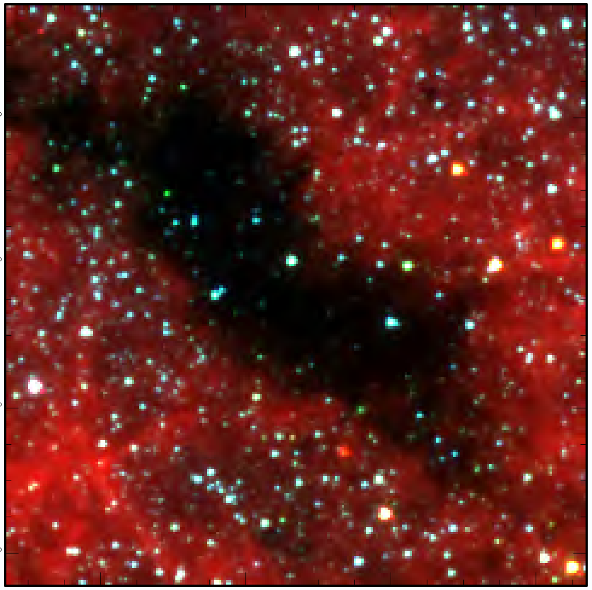


Detailed studies of CMZ clouds are relevant for understanding star formation in high-pressure environments

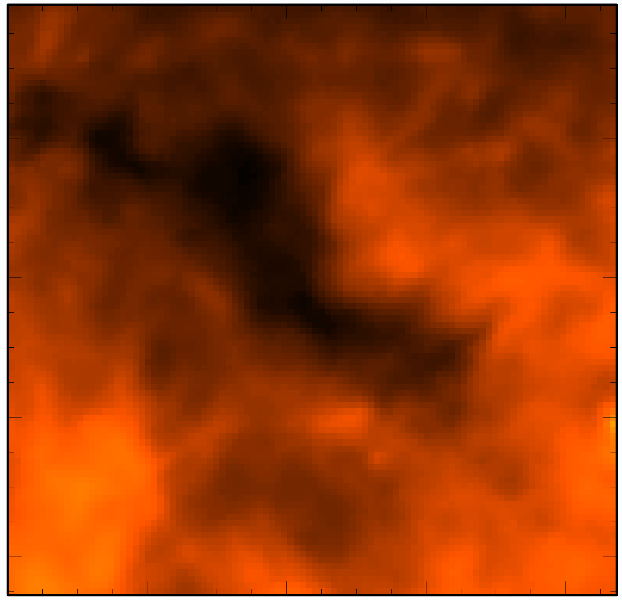
Is the process of mass assembly for star formation different in different environments?

G0.253+0.016: a cold, dense, high-mass clump

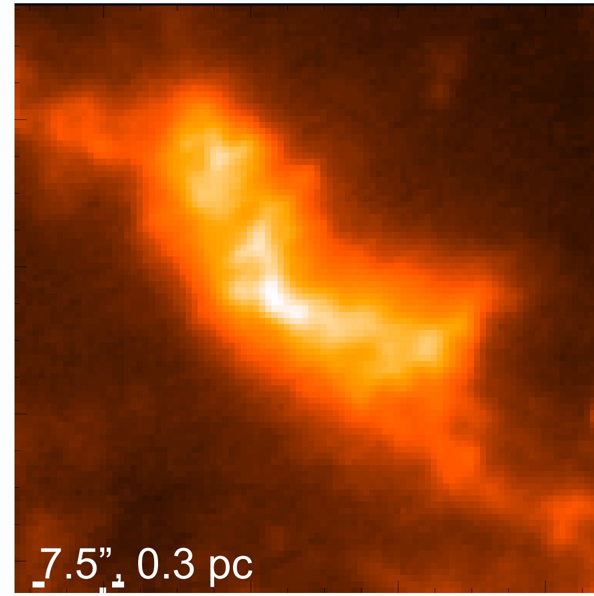
Spitzer 3-8μm



Herschel 70μm



JCMT 450μm



Its low dust temperature (<20 K), high mass (>10^5 $M_\odot$), and high volume density (>10^4 cm^{-3}) combined with its lack of prevalent star-formation, make it an excellent candidate for a high-mass cluster in a very early stage of formation

ALMA Cycle 0 proposal : What is the distribution and kinematics of its small-scale structure?

Lis et al. 1994; Lis & Menten 1998; Lis et al. 2001; Molinari et al. 2011; Longmore et al. 2012;
ALMA cycle 0 proposal – PI J. Rathborne

In the past 3 years….

1. Mills, Butterfield, Ludovici, Lang, Ott, Morris, Schmitz, 2015, ApJ, submitted, *Abundant CH3OH masers but no new evidence for star formation in GCM0.253+0.016*
2. Walker, D. L.; Longmore, S. N.; Bastian, N.; Kruijssen, J. M. D.; Rathborne, J. M.; Jackson, J. M.; Foster, J. B.; Contreras, Y., 2015, MNRAS, in press, *Tracing the Conversion of Gas into Stars in Young Massive Cluster Progenitors*
3. Kruijssen, J. M. D; Dale, J. E.; Longmore, S. N., 2015, MNRAS, *The dynamical evolution of molecular clouds near the Galactic Centre - I. Orbital structure and evolutionary timeline*
4. Rathborne, J. M.; Longmore, S. N.; Jackson, J. M.; Kruijssen, J. M. D.; Alves, J. F.; Bally, J.; Bastian, N.; Contreras, Y.; Foster, J. B.; Garay, G.; and 2 coauthors, 2015, ApJ, *A cluster in the making: ALMA reveals the initial conditions for high-mass cluster formation*
5. Pillai, T.; Kauffmann, J.; Tan, J. C.; Goldsmith, P. F.; Carey, S. J.; Menten, K. M., 2015, ApJ, *Magnetic Fields in High-mass Infrared Dark Clouds*
6. Rathborne, J. M.; Longmore, S. N.; Jackson, J. M.; Kruijssen, J. M. D.; Alves, J. F.; Bally, J.; Bastian, N.; Contreras, Y.; Foster, J. B.; Garay, G.; and 2 coauthors, 2014, ApJL, *Turbulence Sets the Initial Conditions for Star Formation in High-pressure Environments*
7. Bally, John; Rathborne, J. M.; Longmore, S. N.; Jackson, J. M.; Alves, J. F.; Bressert, E.; Contreras, Y.; Foster, J. B.; Garay, G.; Ginsburg, A.; and 4 coauthors, 2014, ApJ, *Absorption Filaments toward the Massive Clump G0.253+0.016*
8. Johnston, K. G.; Beuther, H.; Linz, H.; Schmiedeke, A.; Ragan, S. E.; Henning, Th., 2014, ApJ, *The dynamics and star-forming potential of the massive Galactic centre cloud G0.253+0.016*
9. Rathborne, J. M.; Longmore, S. N.; Jackson, J. M.; Foster, J. B.; Contreras, Y.; Garay, G.; Testi, L.; Alves, J. F.; Bally, J.; Bastian, N.; and 2 coauthors, 2014, ApJ, *G0.253+0.016: A Centrally Condensed, High-mass Protocluster*
10. Longmore, S. N.; Kruijssen, J. M. D.; Bally, J.; Ott, J.; Testi, L.; Rathborne, J.; Bastian, N.; Bressert, E.; Molinari, S.; Battersby, C.; Walsh, A. J., 2013, MNRAS, *Candidate super star cluster progenitor gas clouds possibly triggered by close passage to Sgr A**
11. Clark, Paul C.; Glover, Simon C. O.; Ragan, Sarah E.; Shetty, Rahul; Klessen, Ralf S., 2013, ApJ, *On the Temperature Structure of the Galactic Center Cloud G0.253+0.016*
12. Rodríguez, Luis F.; Zapata, Luis A., 2013, ApJ, *Star Formation in the Massive "Starless" Infrared Dark Cloud G0.253+0.016*
13. Kauffmann, Jens; Pillai, Thushara; Zhang, Qizhou, 2013, ApJ, *The Galactic Center Cloud G0.253+0.016: A Massive Dense Cloud with low Star Formation Potential*
14. Longmore, Steven N.; Rathborne, Jill; Bastian, Nate; Alves, Joao; Ascenso, Joana; Bally, John; Testi, Leonardo; Longmore, Andy; Battersby, Cara; Bressert, Eli; and 13 coauthors, 2012, MNRAS, *G0.253 + 0.016: A Molecular Cloud Progenitor of an Arches-like Cluster*

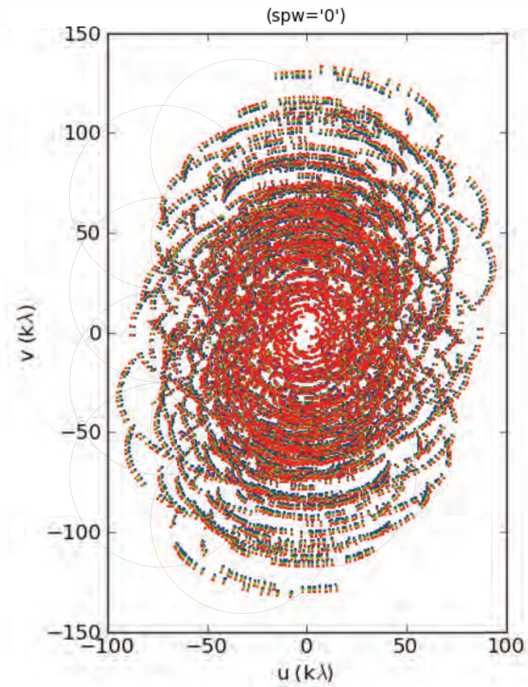
ALMA's view of G0.253+0.016 : highlights

- The gas and dust show a complex network of emission features (emission and absorption)
- The dust column density is well traced by molecules with higher excitation energies and critical densities, consistent with a clump that has a denser interior
- The emission is highly fragmented on small spatial scales
- "CMF" "resembles" a scaled-up IMF
- The N-PDF shows a small deviation from a log-normal distribution at high column densities, pinpointing self-gravitating gas where star formation can progress
- The gas mass distribution is hierarchical and extended (i.e. not smooth or centrally condensed) – Dan Walker's talk
- Its lack of star formation is consistent with an environmentally dependent volume density threshold for star formation

G0.253+0.016 is on the verge of forming a cluster from hierarchical, filamentary structures that arise from a highly turbulent medium

ALMA cycle 0 observations

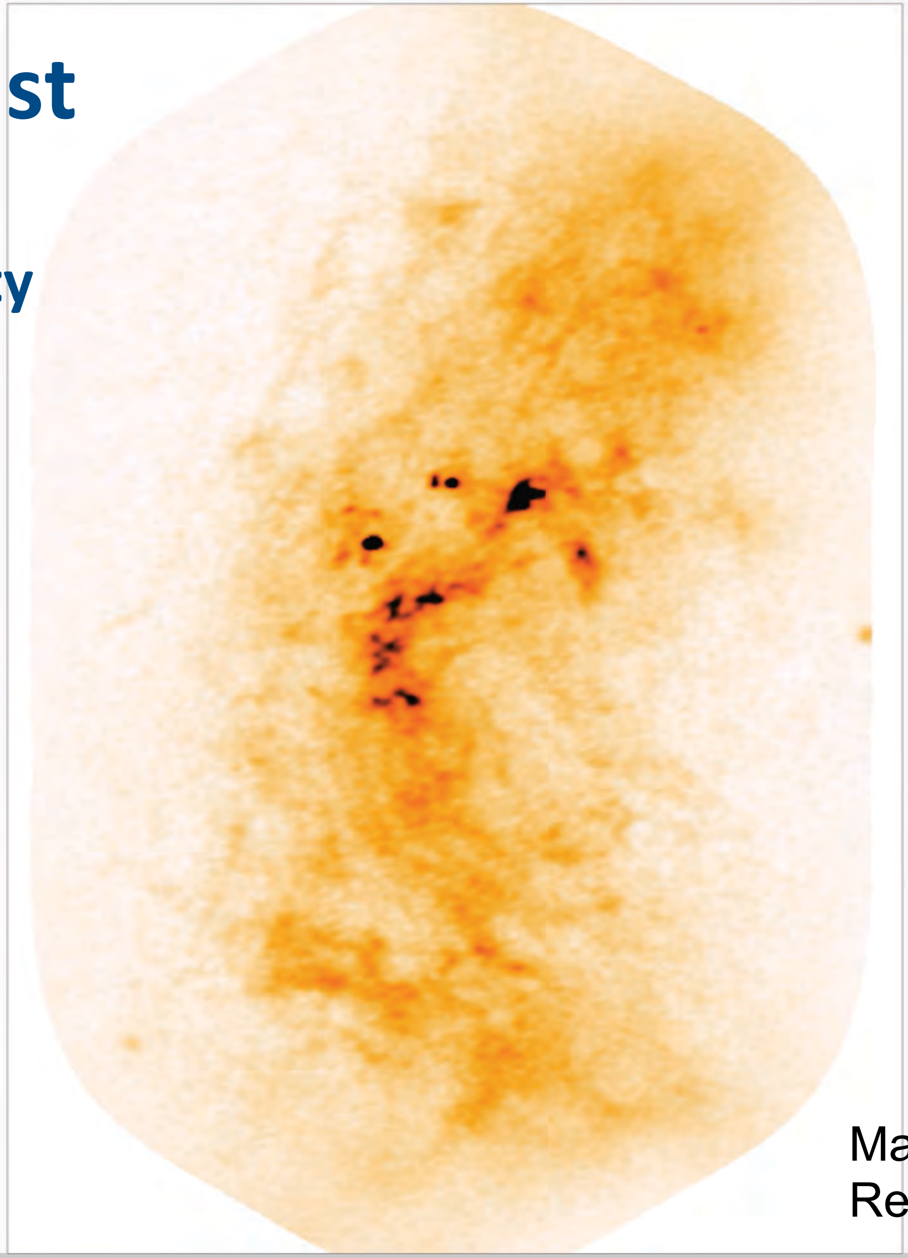
- 90 GHz (3mm) line and continuum emission
- 13 point mosaic (primary beam 69")
- Excellent uv-coverage (25 antennas)
  - Synthesized beam 1.7" (0.07 pc)
  - Missing zero spacing information
- Velocity resolution of 3.5 kms^{-1}
- Continuum emission : rms of 20 μJy/beam
- Line emission : rms of 0.7 mJy/beam per channel



- Images of 3mm continuum emission (ALMA + *Herschel*)
  - Use 500μm continuum scaled to 3mm assuming ν^{-4}
- Line integrated intensity images and channel maps (ALMA + Mopra)
  - **HCN**, **HCO^+**, **C_2H**, **HNCO**, **SiO**, SO, $H^{13}CN$, **$H^{13}CO^+$**, $HN^{13}C$, $HCC^{13}CN$, H_2CS, CH_3SH, NH_2CHO, CH_3CHO, NH_2CN, HC_5N

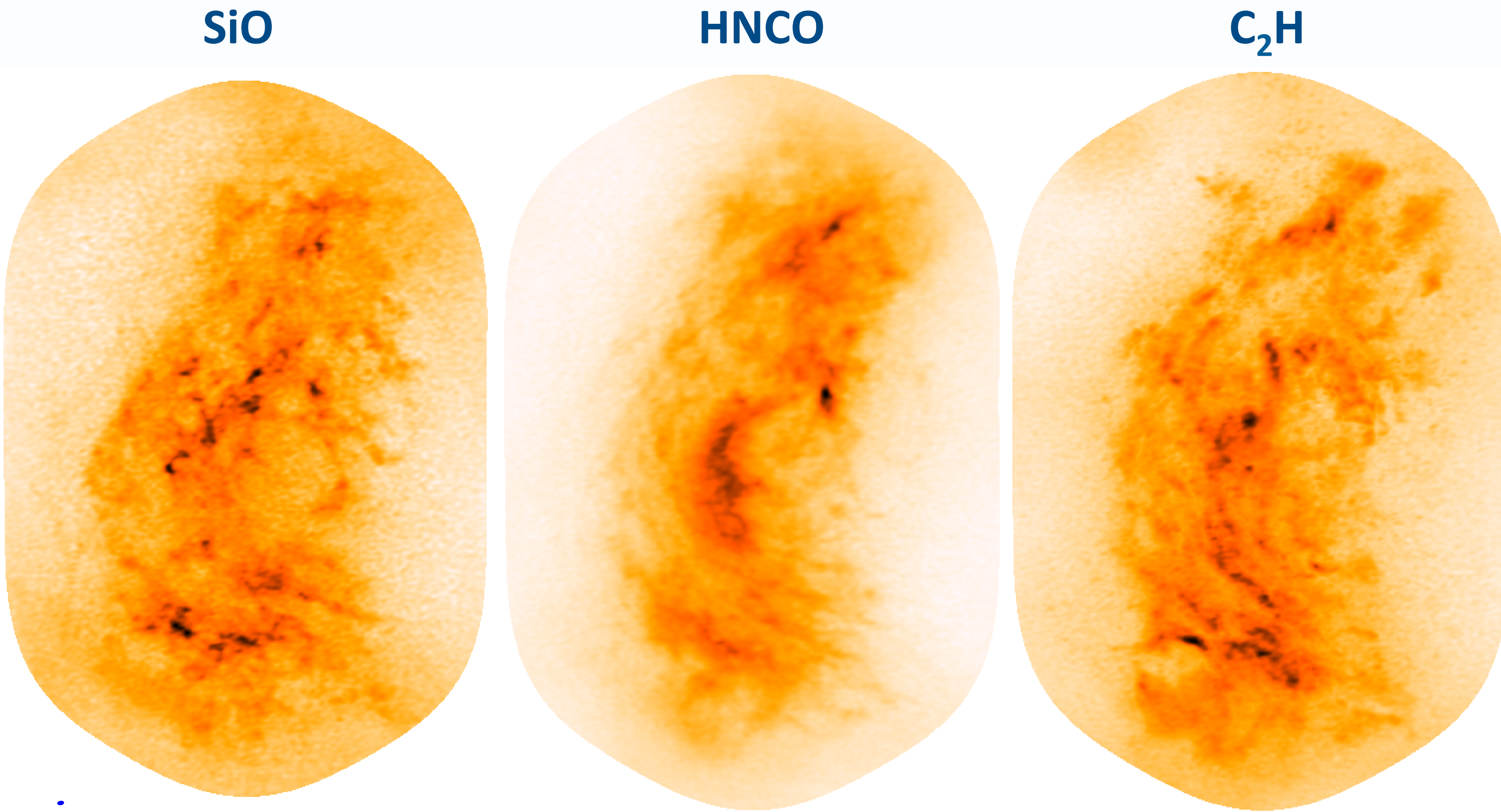
Thermal dust emission

H_2 column density



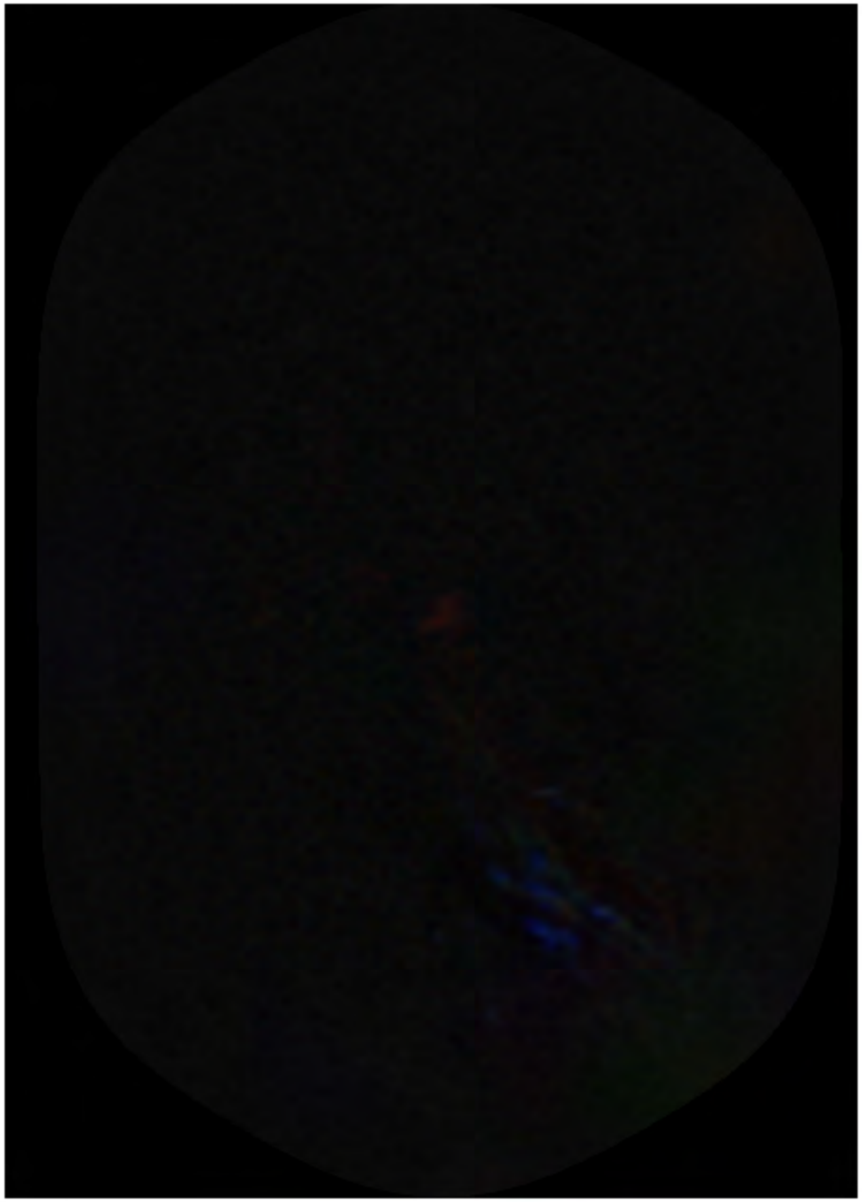
Map coverage : 3' x 1.5'
Resolution : 1.7" (0.07pc)

Complex morphology, chemistry



Rathborne et al. 2015

Intricate network of emission features



HNCO three colour image

$r = v_{channel} + 1$

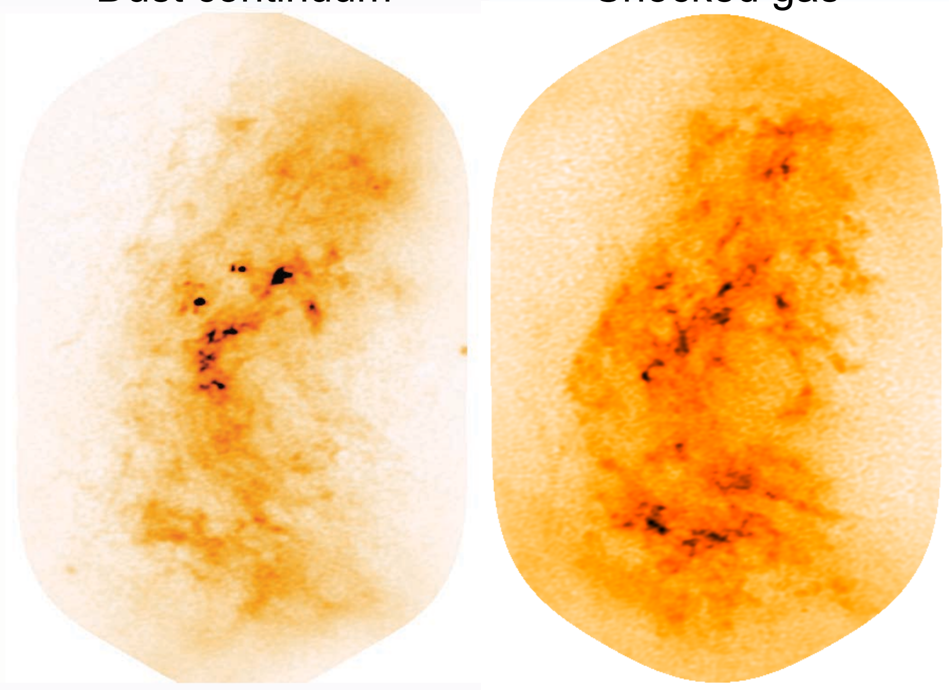
$g = v_{channel}$

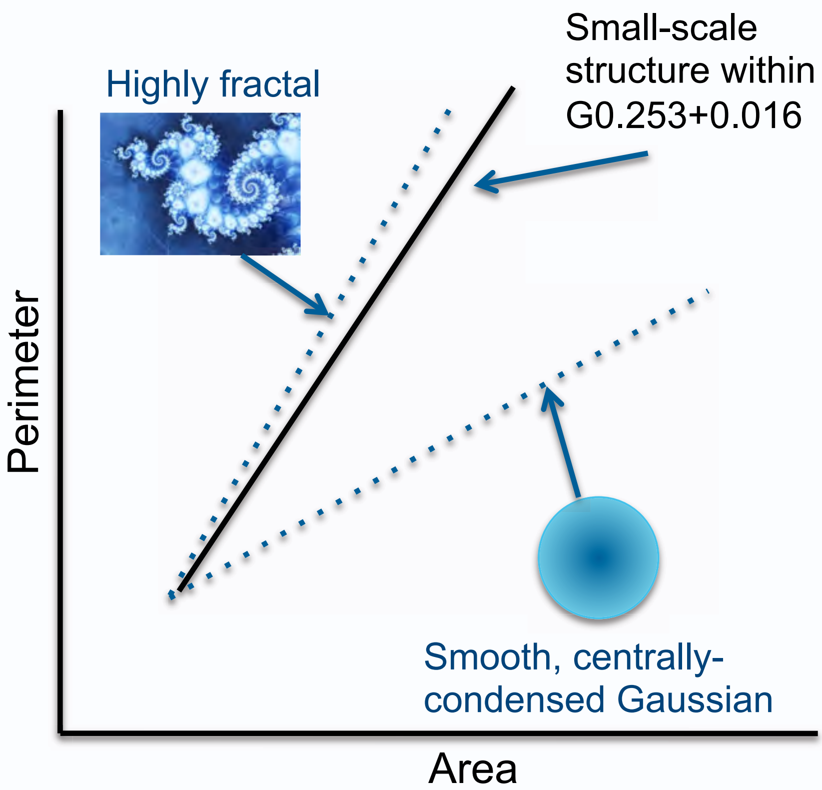
$b = v_{channel} - 1$

Small-scale structure within G0.253+0.016

Dust continuum

Shocked gas



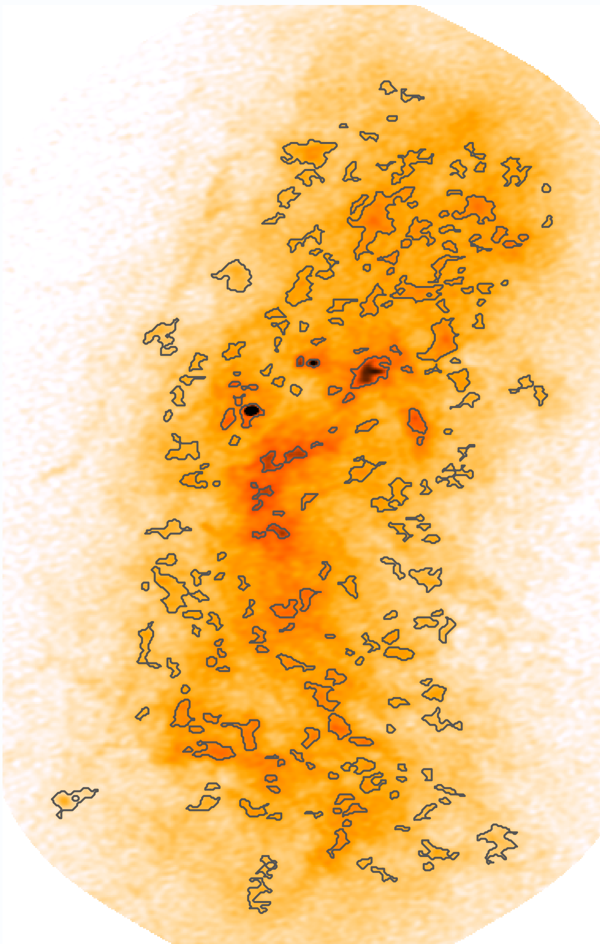


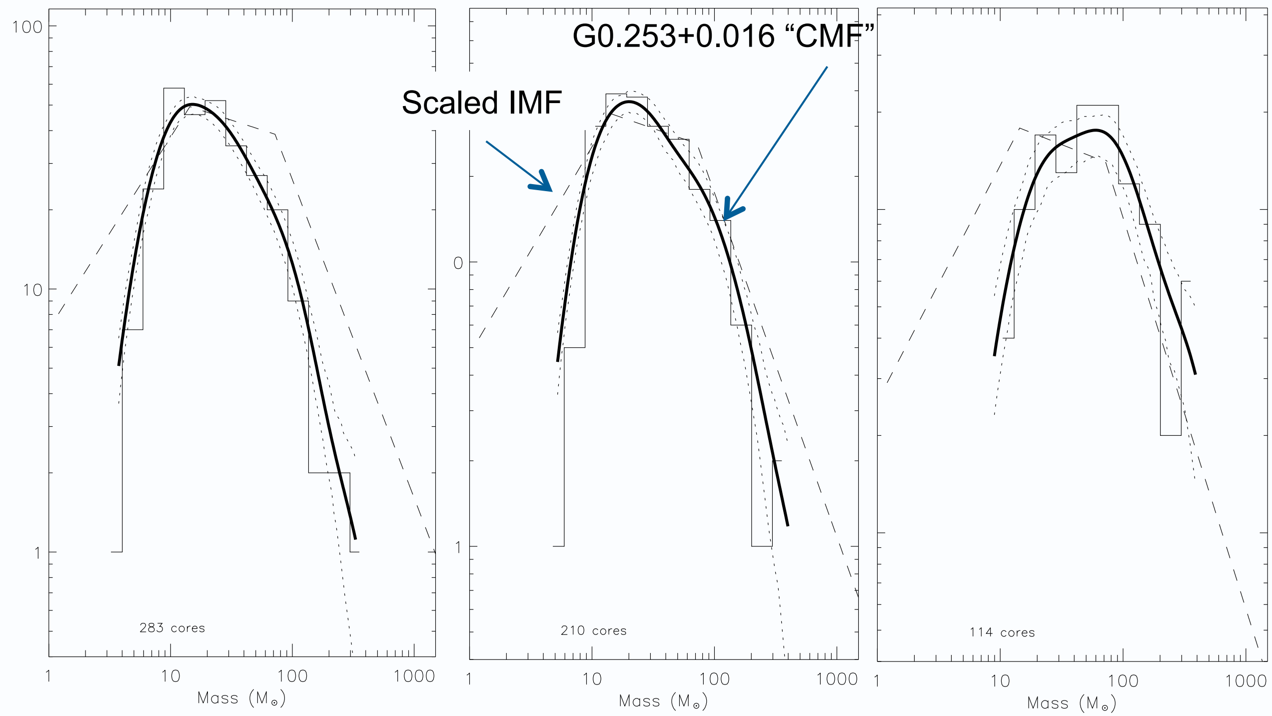
Gas and dust emission is highly fractal with marginally higher values ($D_p \sim 1.6$) compared to typical molecular clouds ($D_p \sim 1.35$)

Mandelbrot 1977; Falgarone et al. 1991; Federrath et al. 2009; Sanchez et al. 2005; Rathborne et al. 2015

Star-forming “cores” and a “CMF”

Dendogram “leaves”





Caution – with increased sensitivity comes increased complexity

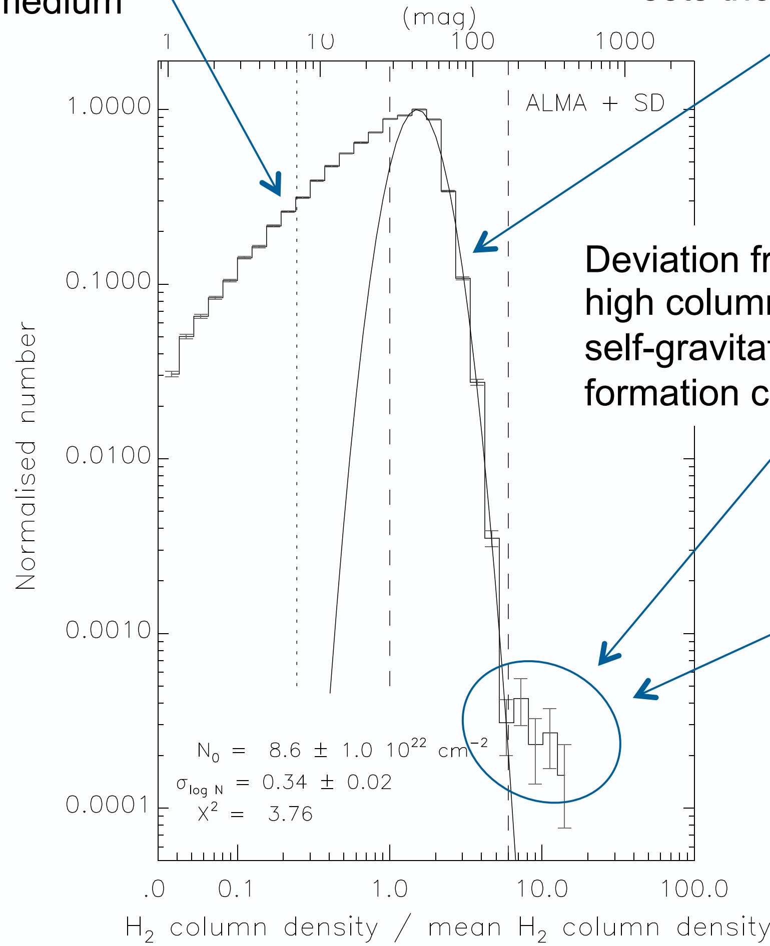
Is a mass function of the structures identified from the (2d) dust column density meaningful? require kinematics from optically thin tracers

How many of these structures are physically coherent and self-gravitating?

Column density PDF – pinpointing star-forming cores

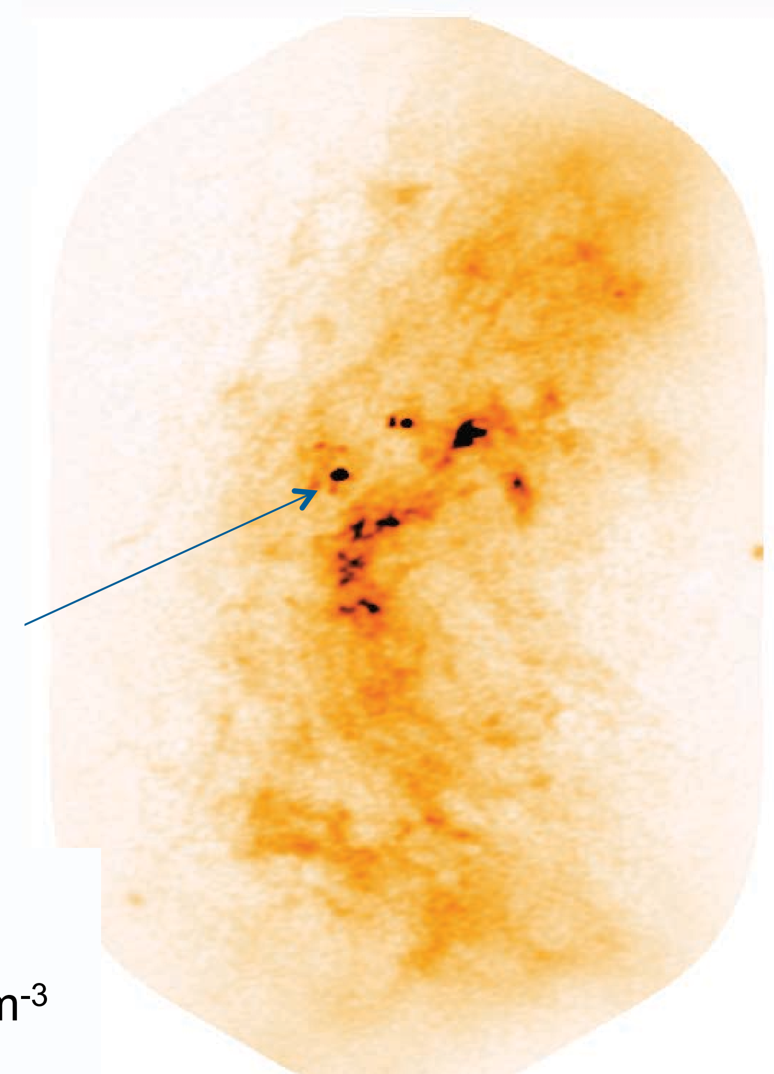
Deviation at low column densities arises from the large-scale diffuse medium

Log-normal distribution is predicted when turbulence sets the initial gas structure



Deviation from log-normal at high column densities pinpoints self-gravitating gas where star formation can progress

Active star formation



$M = 50\text{-}100\ M_\odot$
$R < 0.04$ pc
$n >$ few x 10^6 cm^{-3}
SFR = 0.06%

Vazquez-Semadeni 1994; Padoan et al. 1999; Kainulainen et al. 2009, 2013; Ballesteros-Paredes et al. 2011; Kritsuk et al. 2011; Schneider et al. 2014; Lis & Carlstrom 1994; Rathborne et al. 2014

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An environmentally dependent volume density threshold for star formation

Recent observations of solar neighbourhood clouds suggest a 'universal' column density threshold of ~1.4 x 10^{22} cm^{-2} (which corresponds to volume densities of ~10^4 cm^{-3})

Although this threshold accurately describes the onset of star formation in clouds in the solar neighbourhood, it does not hold for the environment within the CMZ

- the gas in the CMZ has a much higher column density than 1.4 x 10^{22} cm^{-2}, yet it is forming stars 1-2 orders of magnitude less efficiently than predicted

The column density PDF for G0.253+0.016 confirms this result - while the majority of the mass lies at column densities >1.4 x 10^{22} cm^{-2} only one region, corresponding to 0.06% of the total mass, shows evidence for star formation

The derived lower limit on the volume density (>10^6 cm^{-3}) is consistent with the theoretically predicted, environmentally dependent volume density threshold (10^8 cm^{-3})
- which is orders of magnitude higher than derived for solar neighbourhood clouds

Lada et al. 2010, 2012; Longmore et al. 2013; Krumholz and McKee 2005; Padoan and Nordlund 2011; Rathborne et al. 2014

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Summary

ALMA dust continuum and molecular line emission toward G0.253+0.016 reveals a complex network of emission features

Turbulence sets the initial conditions for star formation in high-pressure environments → our current theoretical understanding of gas structure derived from solar neighbourhood clouds also holds in extreme, high-pressure environments

Lack of star formation is consistent with an environmentally dependent volume density threshold for star formation

G0.253+0.016 is on the verge of forming a cluster from hierarchical, filamentary structures that arise from a highly turbulent medium

Thank you

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