The Formation of Young Massive Clusters:

A Monolithic or Sub-structured Process?

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Young Massive Clusters (YMCs)

What are they?

- Gravitationally bound
- Young: few Myrs
- Massive: $\geq 10^4$ $M_\odot$

Why do we care?

- Birthplaces of most massive stars (e.g. ‘Pistol’ star in Quintuplet).
- Rival stellar mass & density of globular clusters.
- May reveal a cluster mass continuum, from low-mass open clusters to high-mass YMCs.

Young Massive Cluster Formation

How do they form?

- Continuum in mass may suggest that *all* stellar clusters may form in a similar way.
- YMC formation currently not well understood.
- Two commonly proposed formation scenarios:
    - ‘Monolithic Collapse’
    - ‘Hierarchical Merging’

‘Monolithic Collapse’

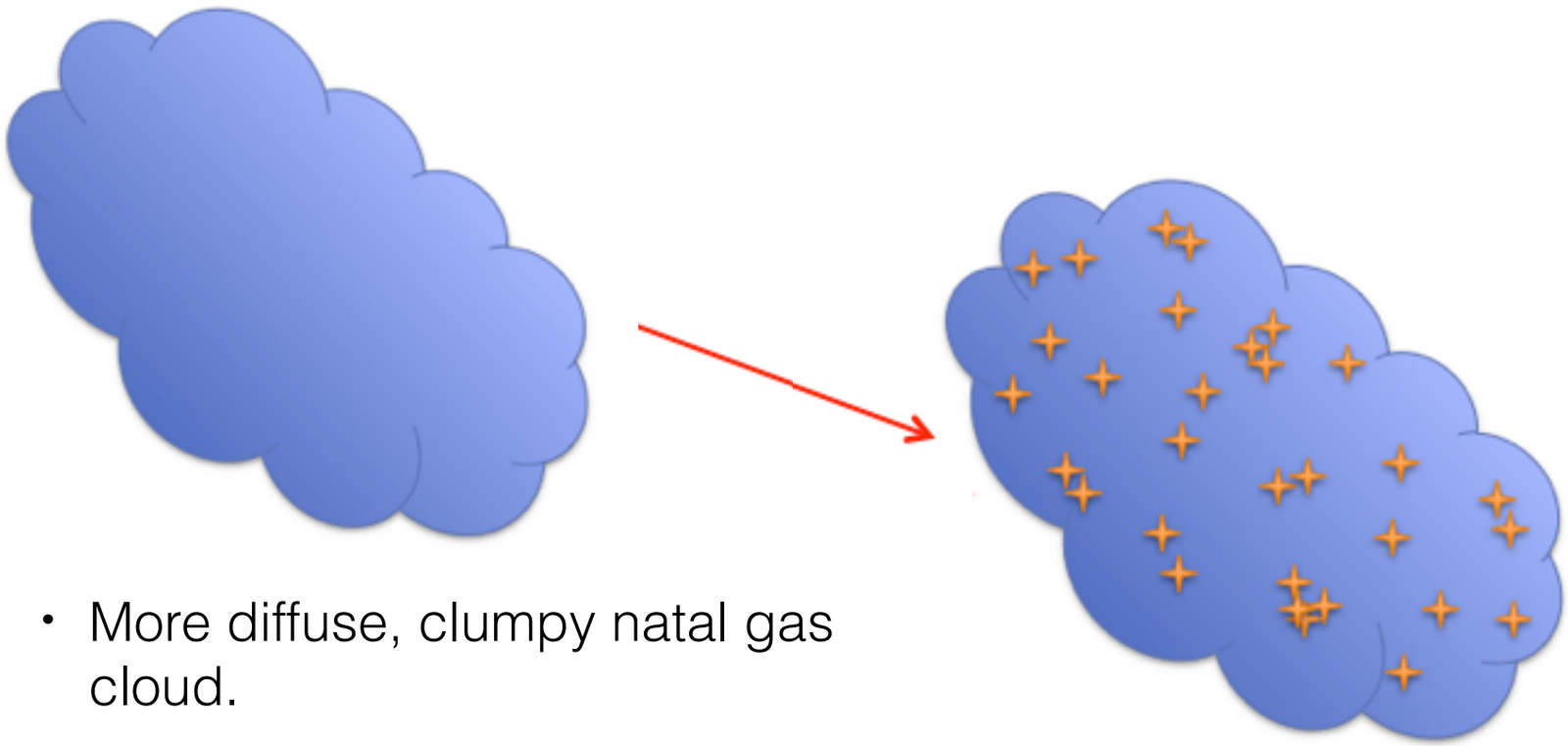
- Compact, centrally-condensed natal gas cloud.

- Gravitationally bound, centrally-condensed stellar population forms.

- Feedback processes remove gas. Stellar cluster expands due to diluted gravitational potential.

e.g. Lada, Margulis & Dearborn 1984;
Boily & Kroupa 2003; Bastian & Goodwin 2006;
Baumgardt & Kroupa 2007, Banerjee & Kroupa ’13, ’14, ‘15

‘Hierarchical Merging’



- More diffuse, clumpy natal gas cloud.

- Stars and sub-clusters form throughout the spatial extent of the natal gas cloud.

- Stars decouple from the gas. Stars and sub-clusters merge. Centrally-condensed, bound stellar cluster is formed.

e.g. Kruijssen et al. 2012; Girichidis et al. 2012; Fujii, Saitoh & Portegies Zwart 2012; Parker et al. 2014

Young Massive Clusters Progenitors

How to distinguish these two scenarios observationally?

- Scenarios require different initial conditions:
    - ‘Monolithic Collapse’ — Initially very dense, centrally-concentrated gas.
    - ‘Hierarchical Merging’ — Initially clumpy, sub-structured gas.
- Search for gas cloud progenitors to YMCs:
    - Reveal initial conditions.
    - Compare to later stages of formation/evolution.

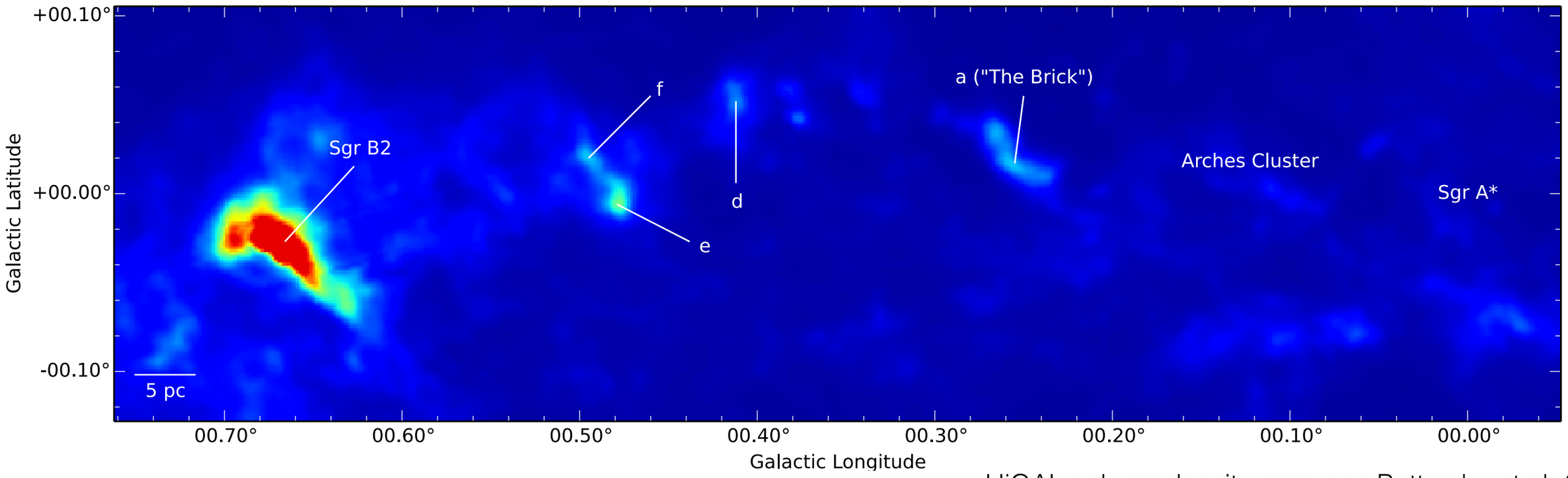
Galactic Centre

YMC evolutionary sequence at Galactic Centre:

- Clouds '**a**', '**d**', '**e**' and '**f**' all ~ **10^5 $M_\odot$**, R ~ **few pc**, with little-to-no widespread star formation (Longmore et al 2012, Immer et al. 2012, Walker et al. 2015).
  ➔ Likely YMC precursors

- Sagittarius B2 contains two clusters of high mass stars (Main & North, e.g. Qin et al. 2011).
  ➔ Likely proto-YMCs

- Arches YMC is ~ 2 Myr and gas-free.



HiGAL column density map: see Battersby et al. (2011)

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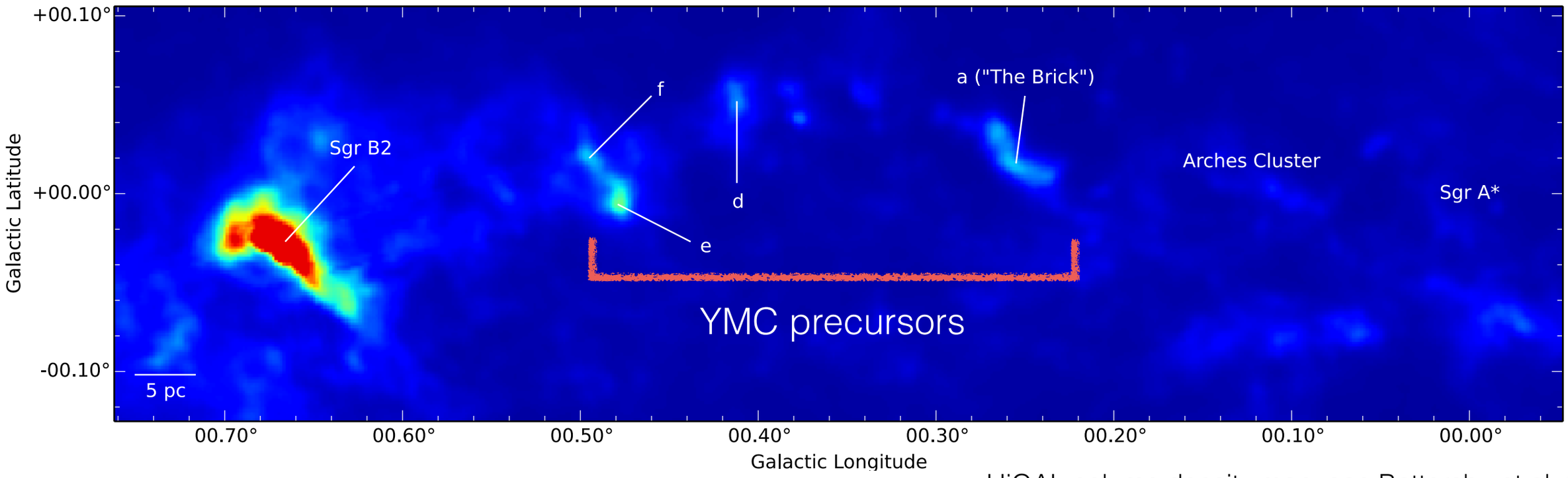

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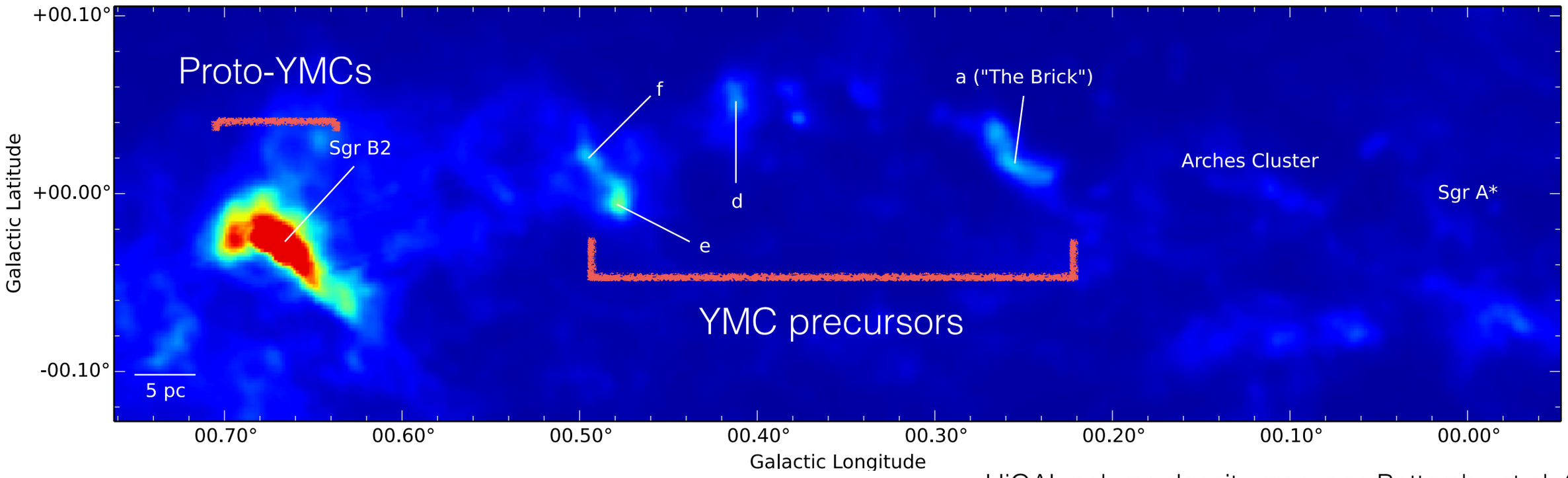

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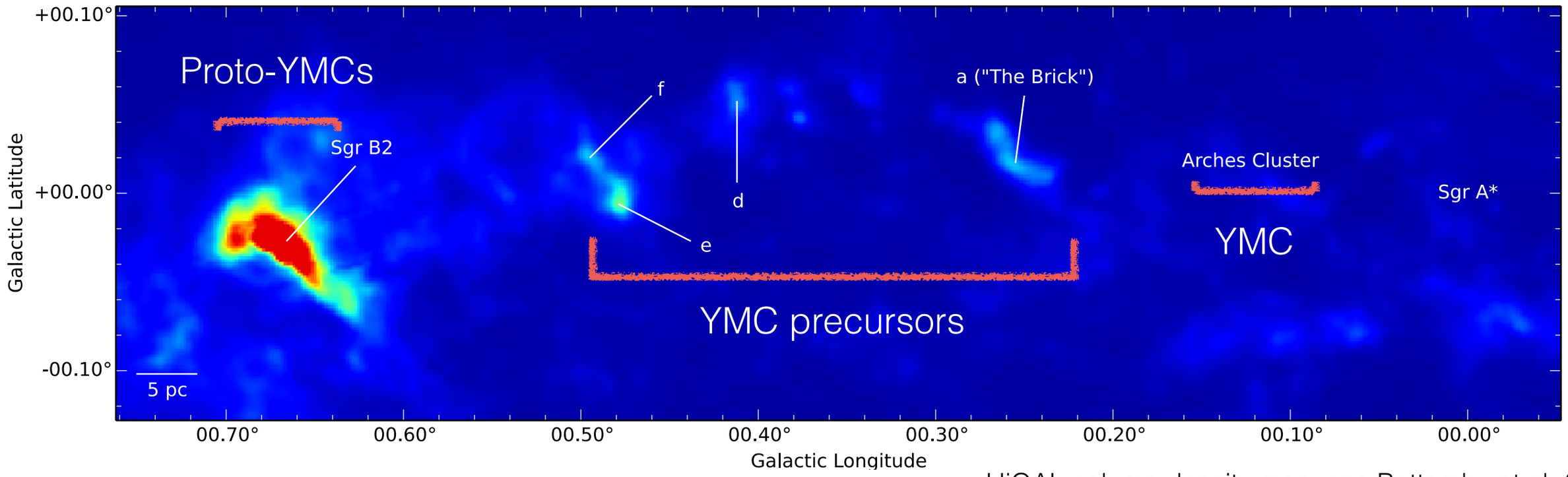

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Galactic Centre

INITIAL, INTERMEDIATE & FINAL EVOLUTIONARY STAGES, ALL AT SIMILAR DISTANCE AND ENVIRONMENT!

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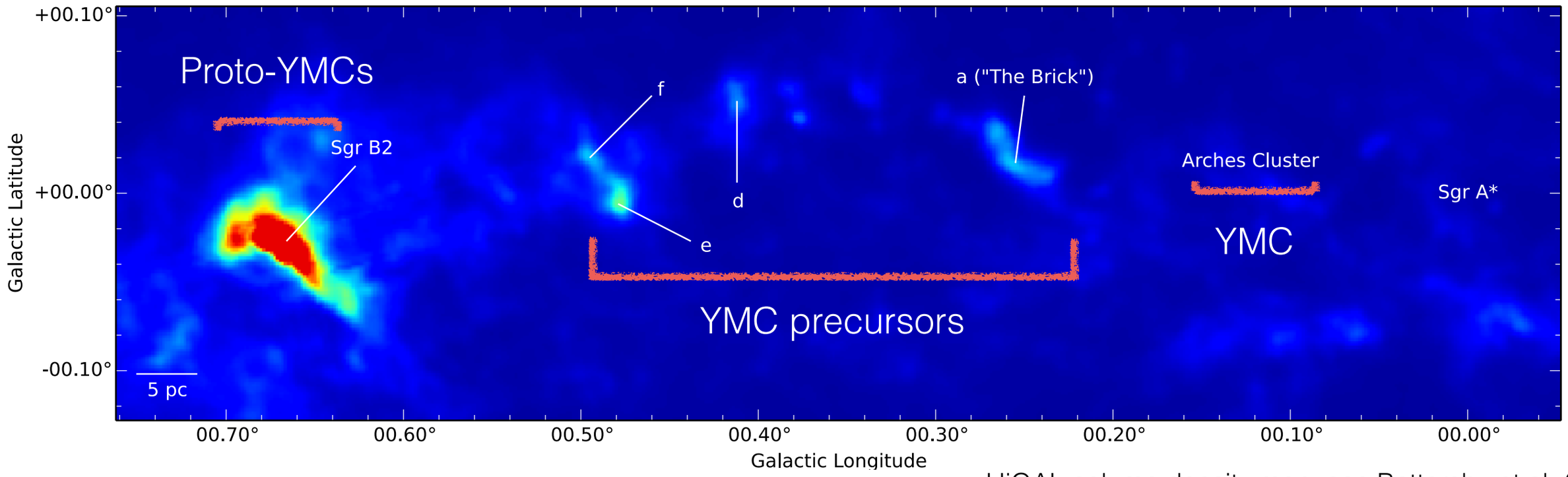

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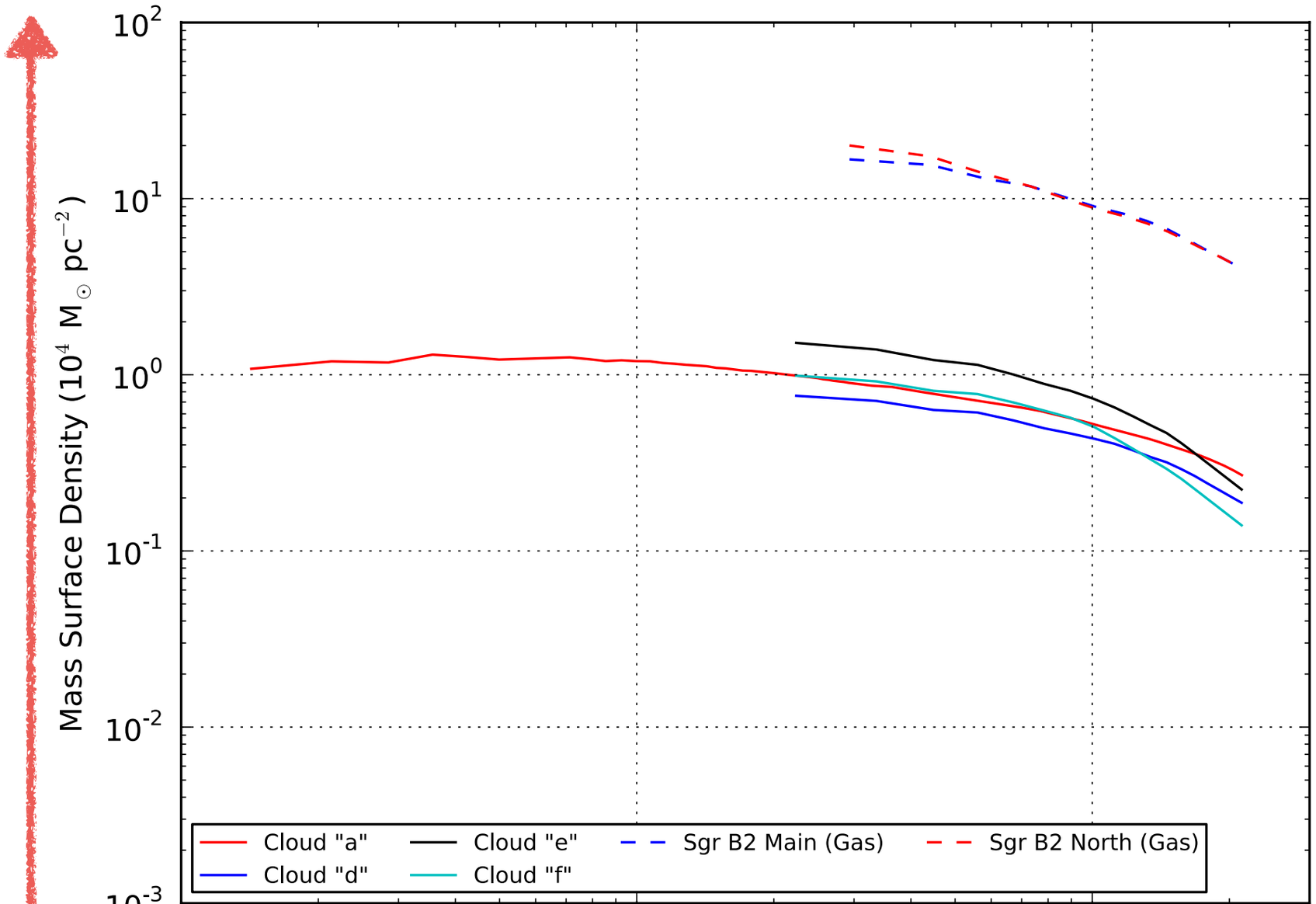
Surface Density Profiles (Gas)

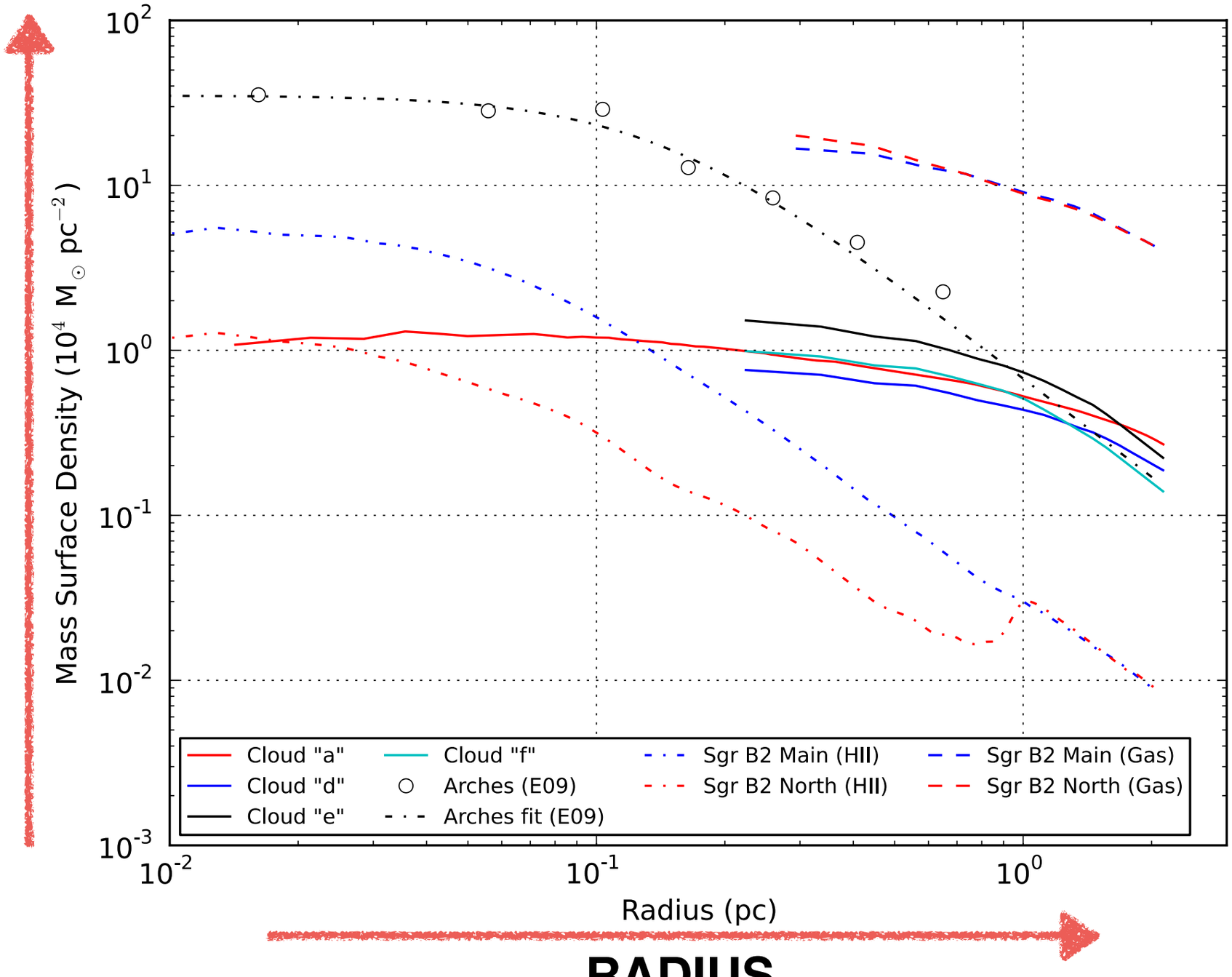
MASS SURFACE DENSITY



RADIUS

Surface Density Profiles (Gas & Stars)

MASS SURFACE DENSITY



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Surface Density Profiles (Gas & Stars, Normalised)

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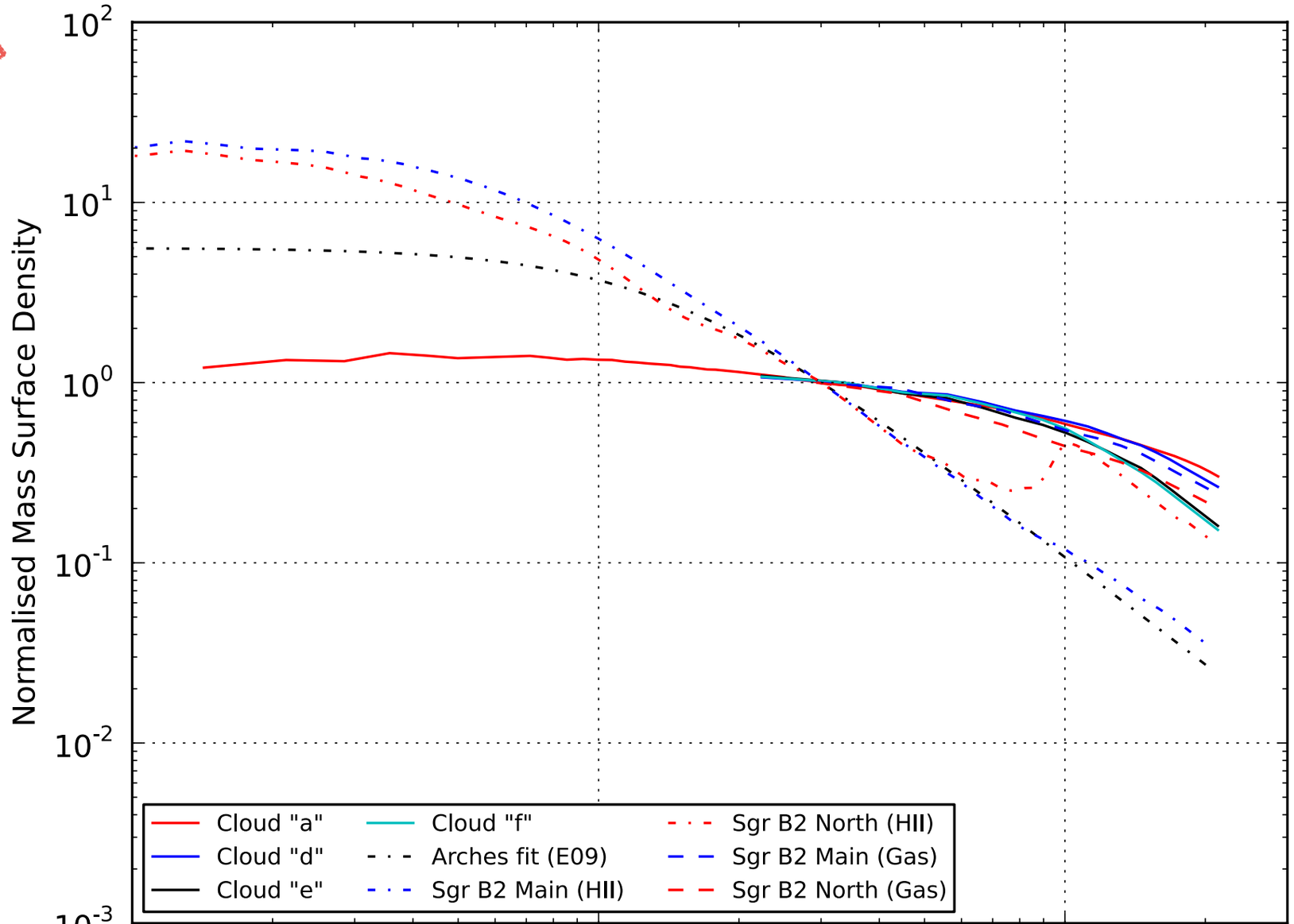

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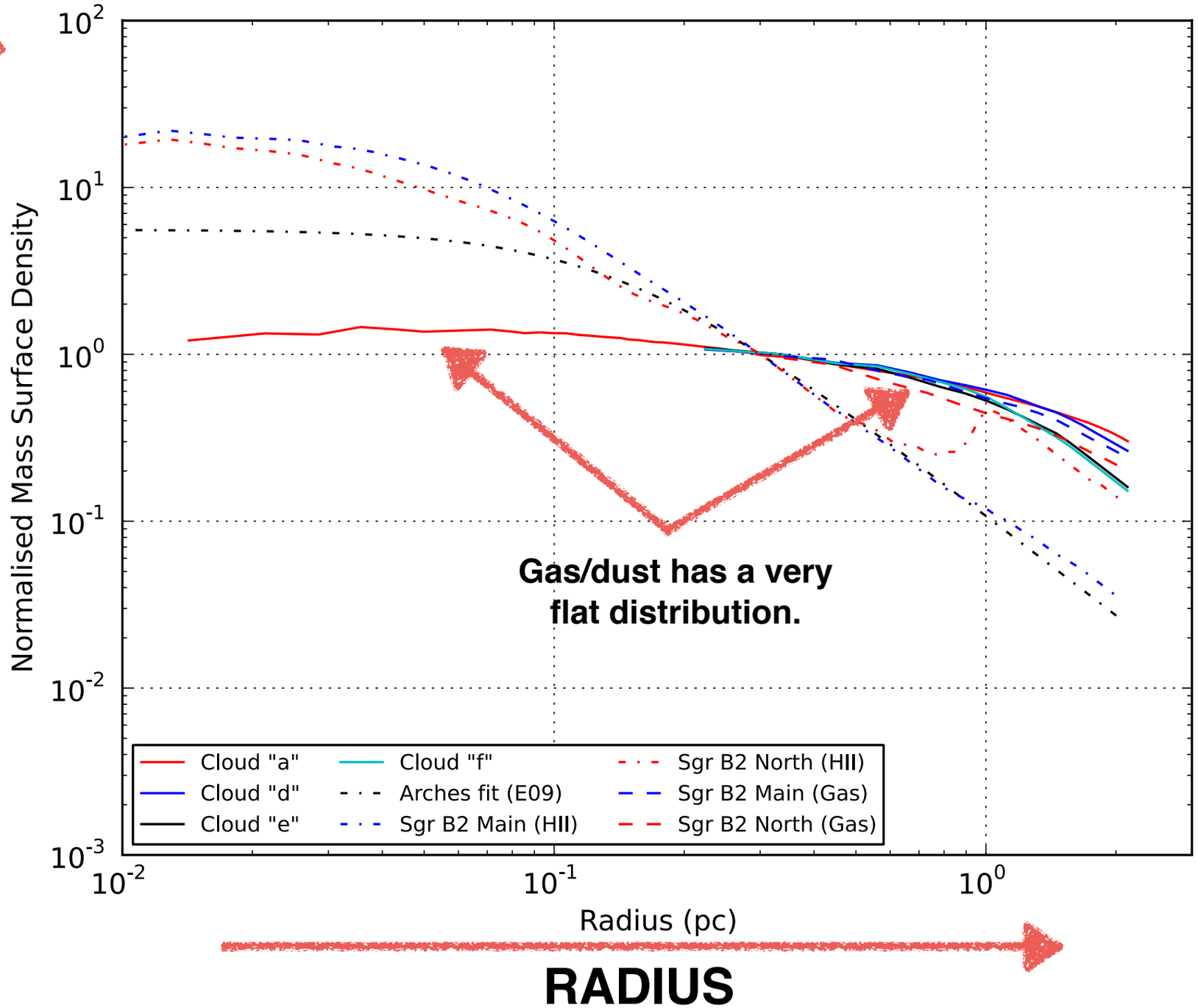

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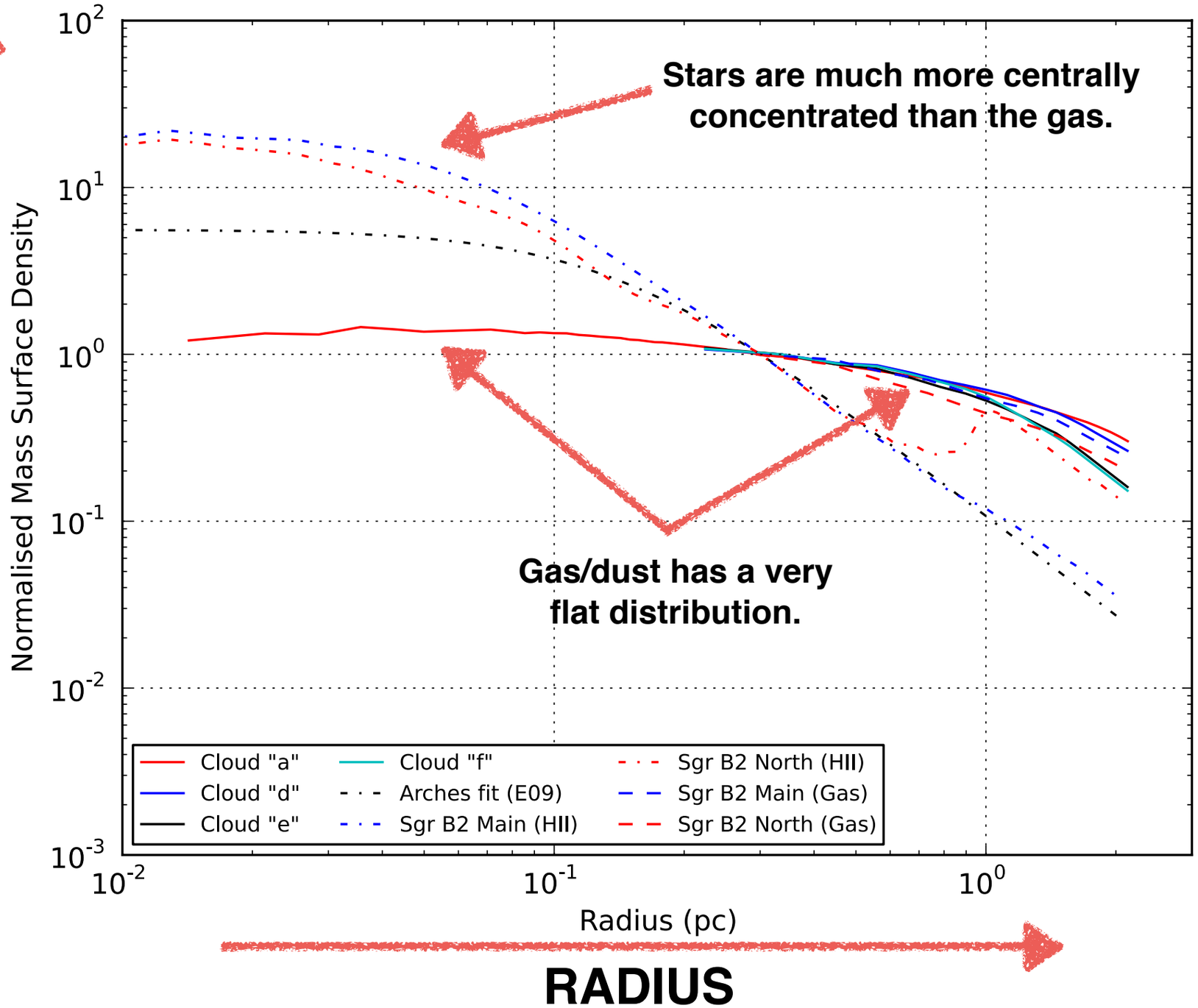

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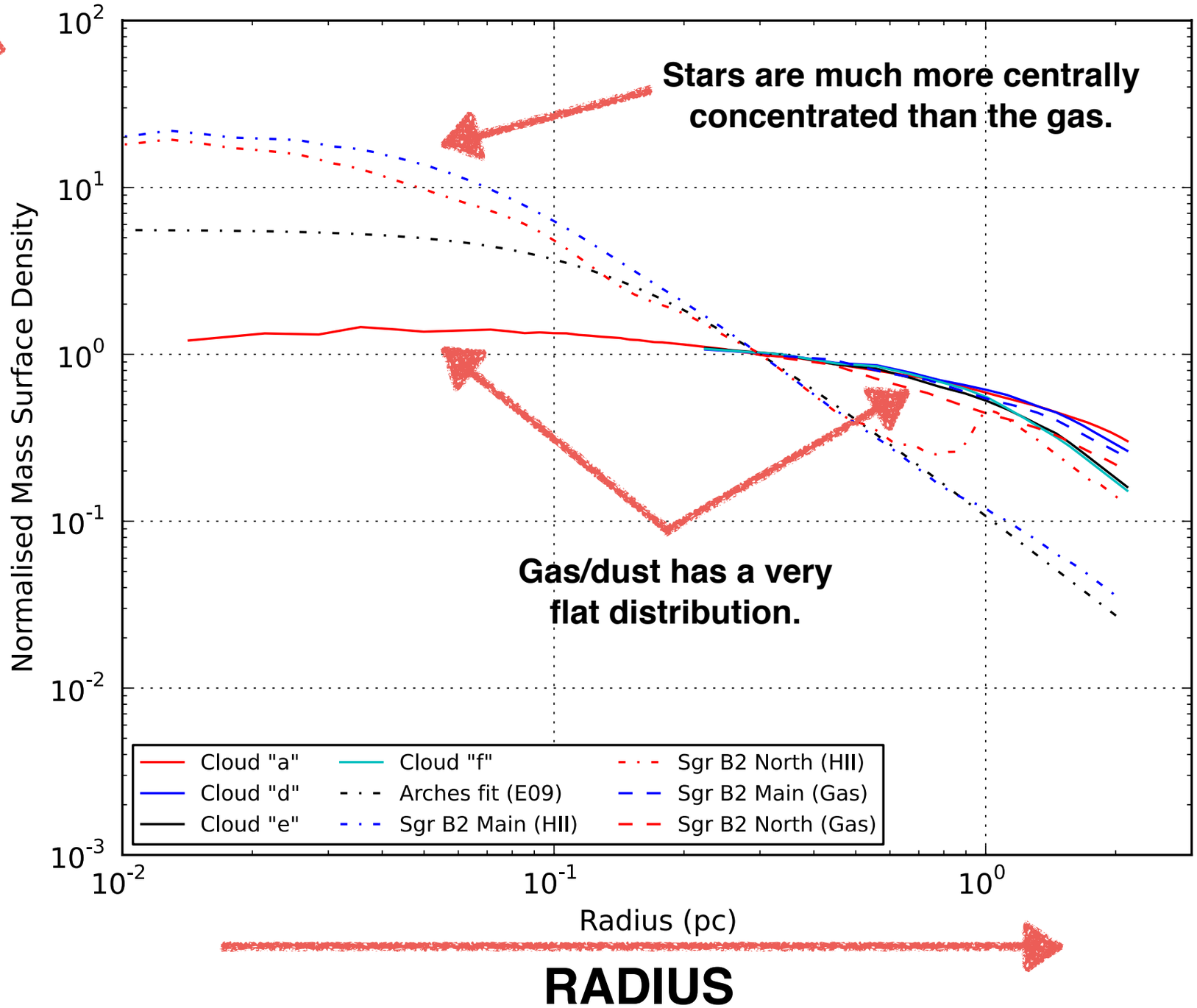
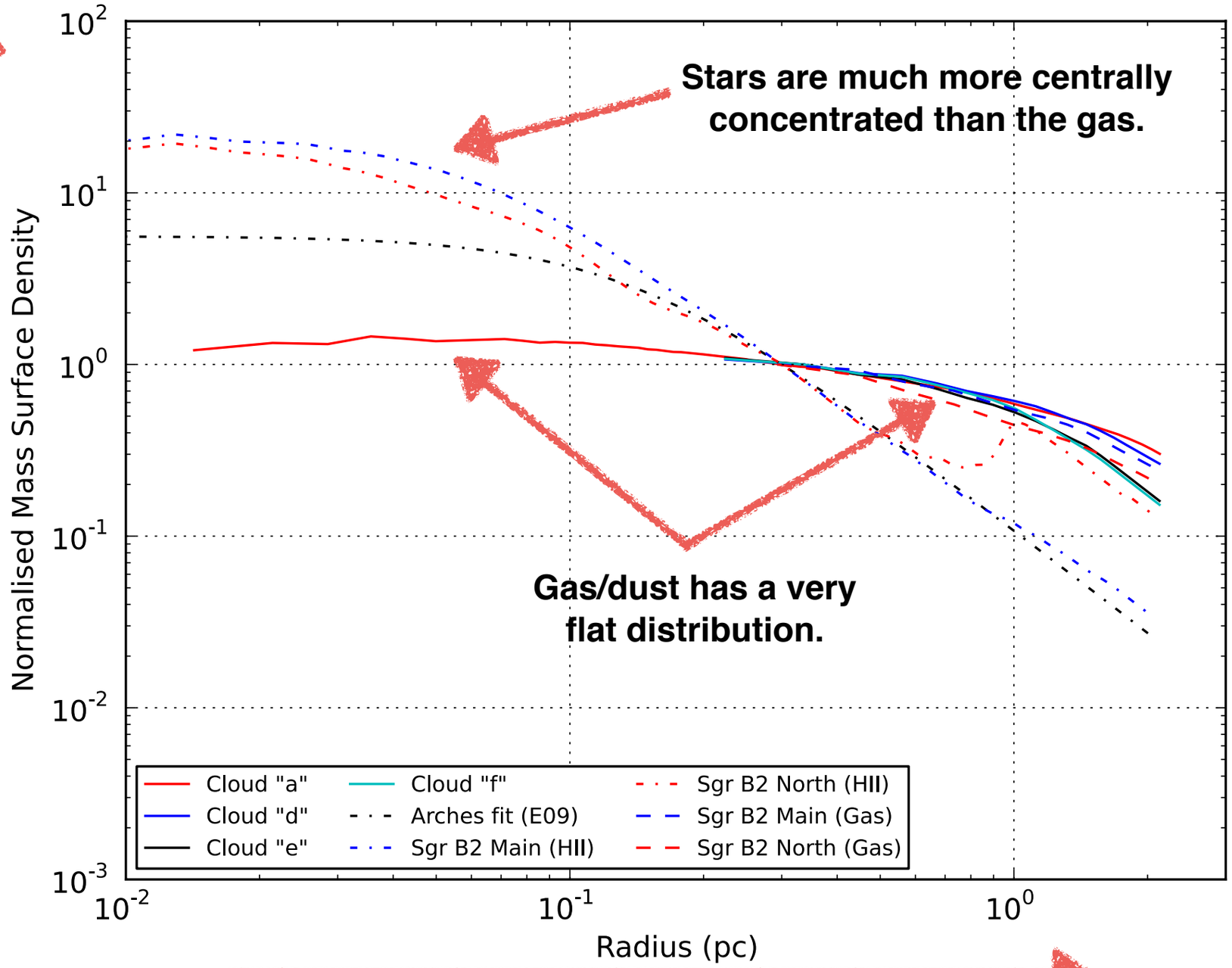


INCONSISTENT WITH 'MONOLITHIC COLLAPSE'!

RADIUS

Surface Density Profiles (Gas & Stars, Normalised)

MASS SURFACE DENSITY



RADIUS

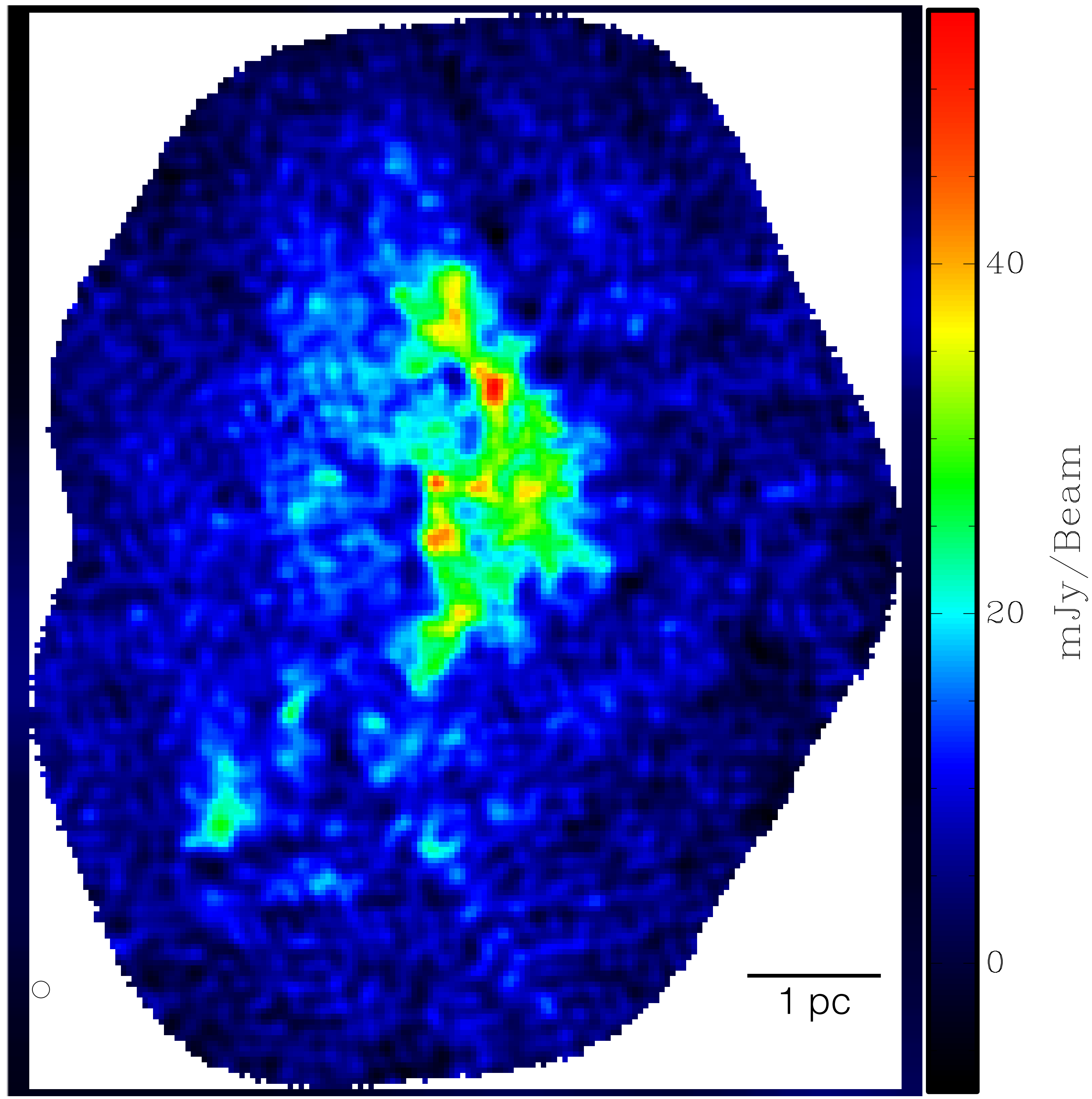
INCONSISTENT WITH 'MONOLITHIC COLLAPSE'!

WHAT ABOUT 'HIERARCHICAL FRAGMENTATION'?

SMA 1.3mm dust continuum (Cloud ‘d’)

HIGAL Column Density (Cloud ‘d’)

(See Cara Battersby’s talk on Friday & SMA posters.)



SMA 1.3mm dust continuum

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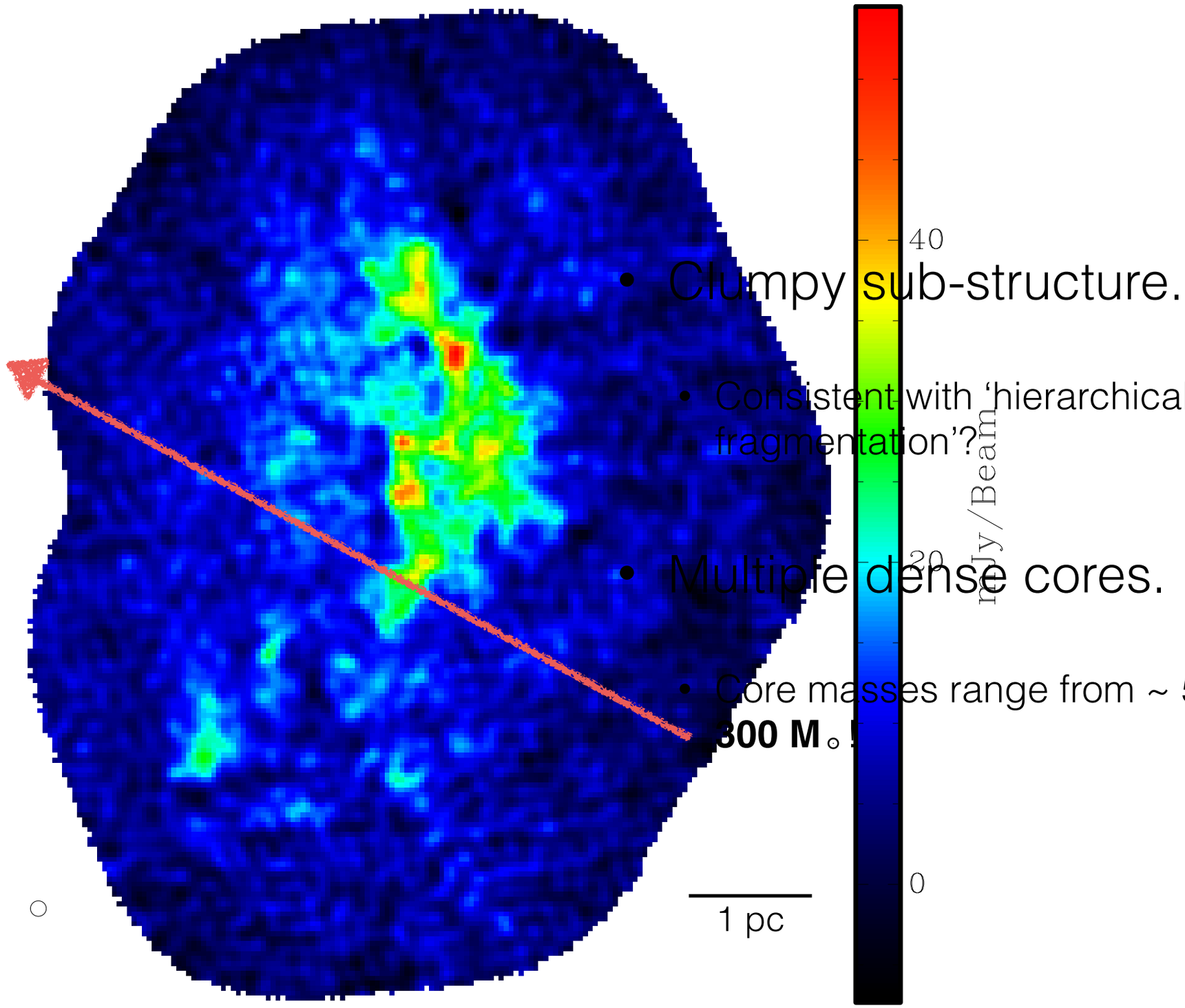
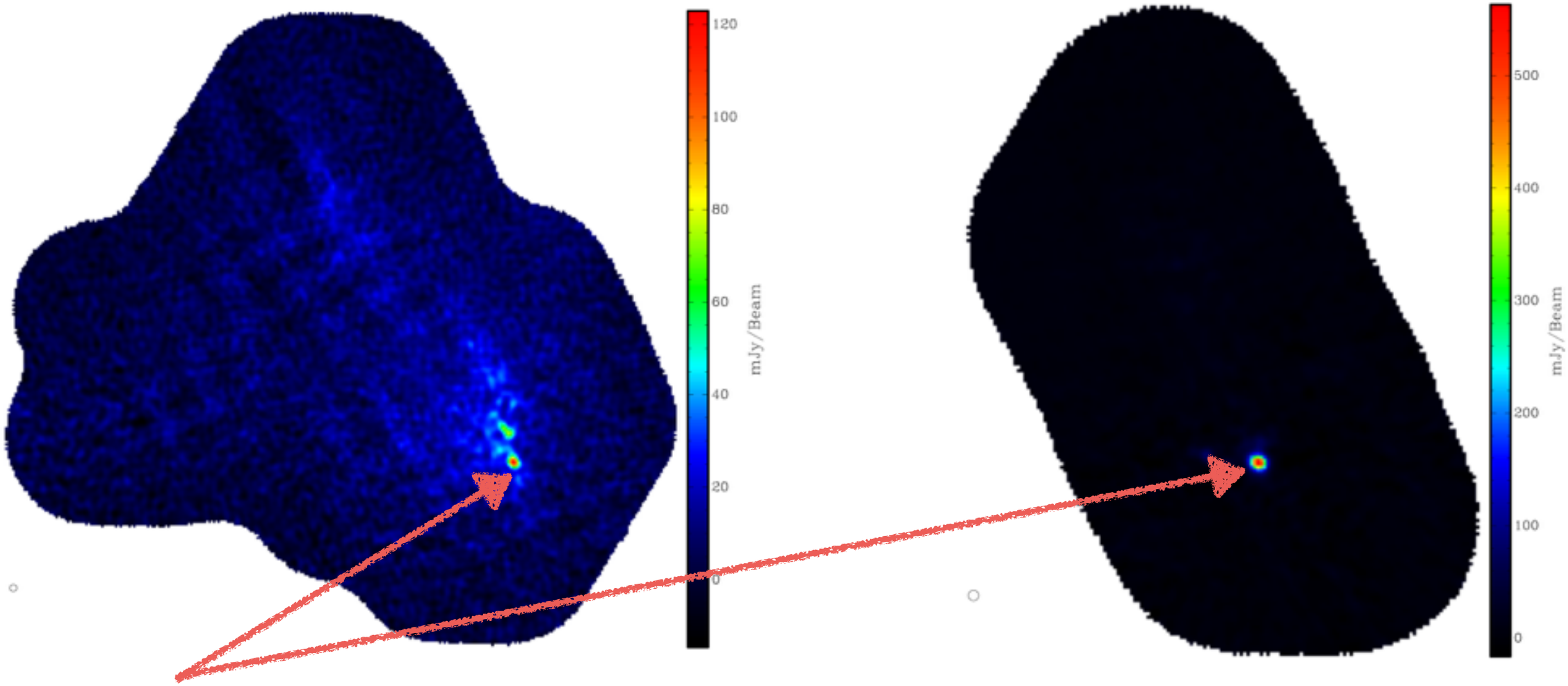


- Clumpy sub-structure.
- Consistent with 'hierarchical fragmentation'?
- Multiple dense cores.
- Core masses range from ~ 50 to **300 M$_\odot$!**

SMA 1.3mm dust continuum (See Cara Battersby's talk on Friday & SMA posters.)



- Mass estimates for these cores difficult due to maser emission (Caswell et al. 2010)
- $M_{Core} > 100\ M_{\odot}$, but require temperature estimates for exact masses.

Summary

- Galactic centre YMC progenitors are not consistent with a ‘monolithic’ formation scenario (Walker et al. 2015). [Also true in the Galactic disk (Walker et al., in prep.)]

- SMA data reveal clumpy sub-structure — possibly consistent with hierarchical growth and merging of substructure.

- Galactic centre YMC precursor clouds contain extremely massive cores (**M >> 100 M$_\odot$**).

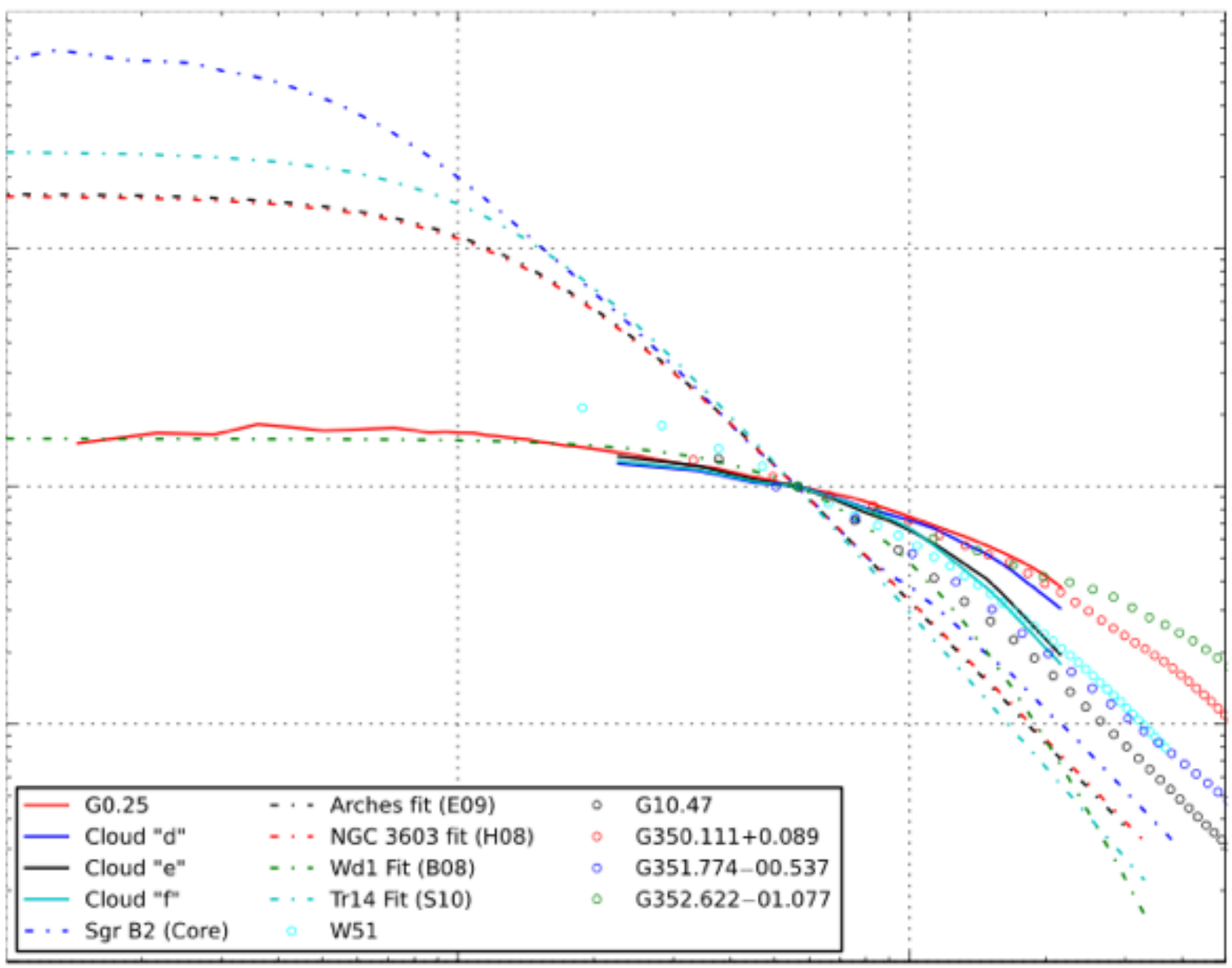
Next Steps:

- Study the chemistry and kinematics of the small-scale massive cores in these clouds.

- Follow cores up at higher resolution — single sources or fragmented?

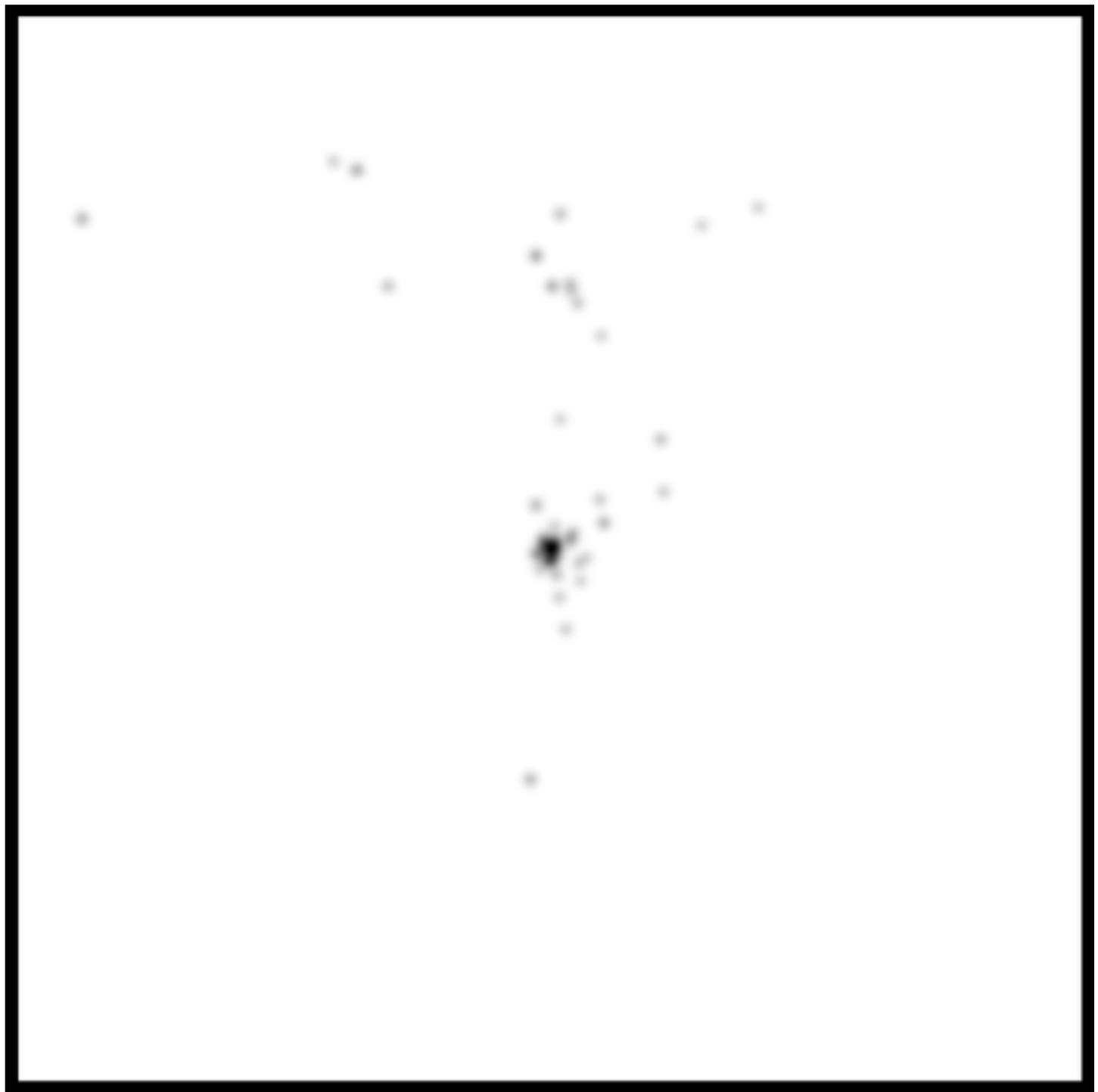
Surface Density Profiles (Galactic Disk & Centre)

MASS SURFACE DENSITY



RADIUS

Sgr B2 UCHII Regions



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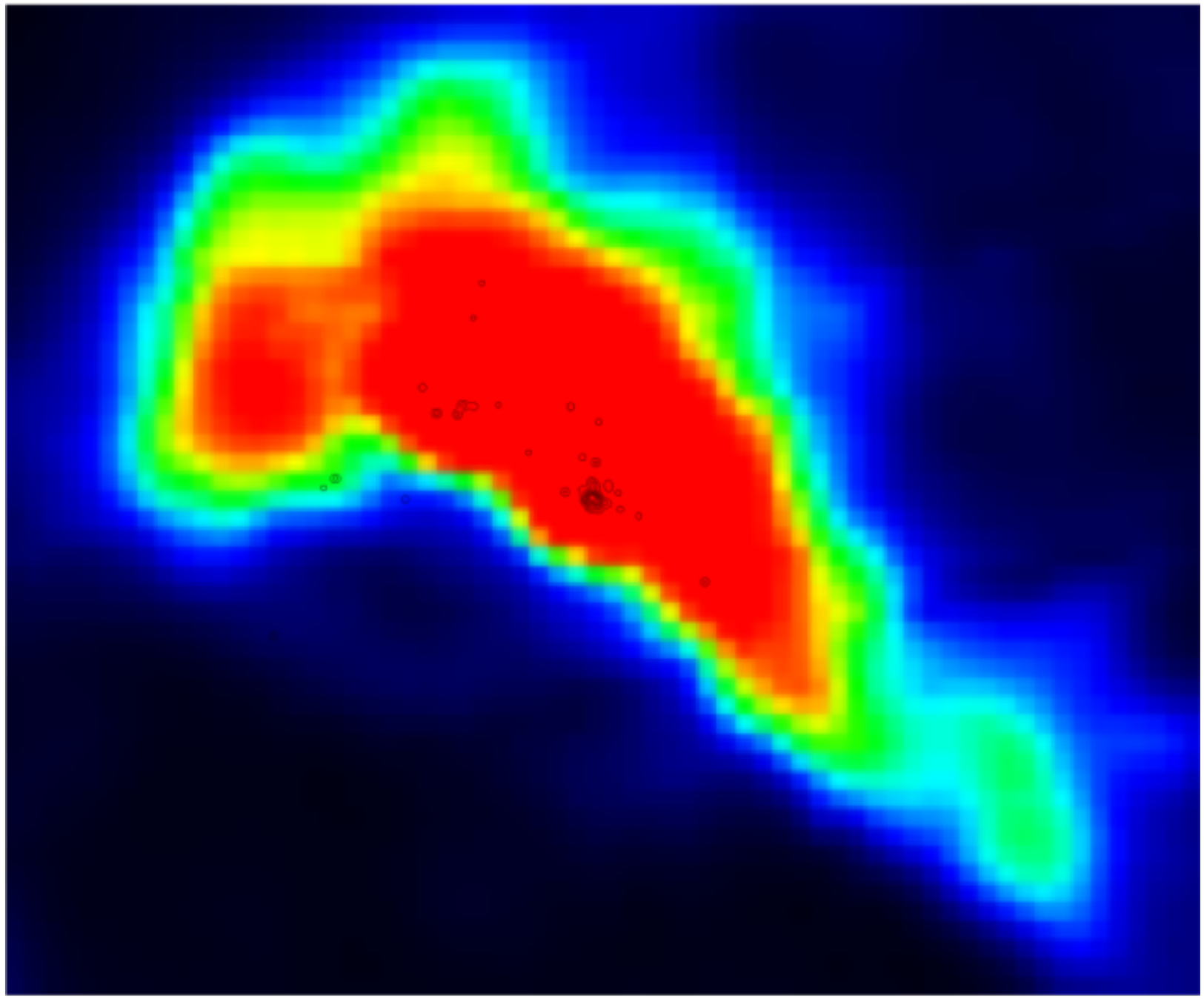

Cloud Kinematics