Galactic Center Star Formation

Jens Kauffmann

Max–Planck–Institut für Radioastronomie

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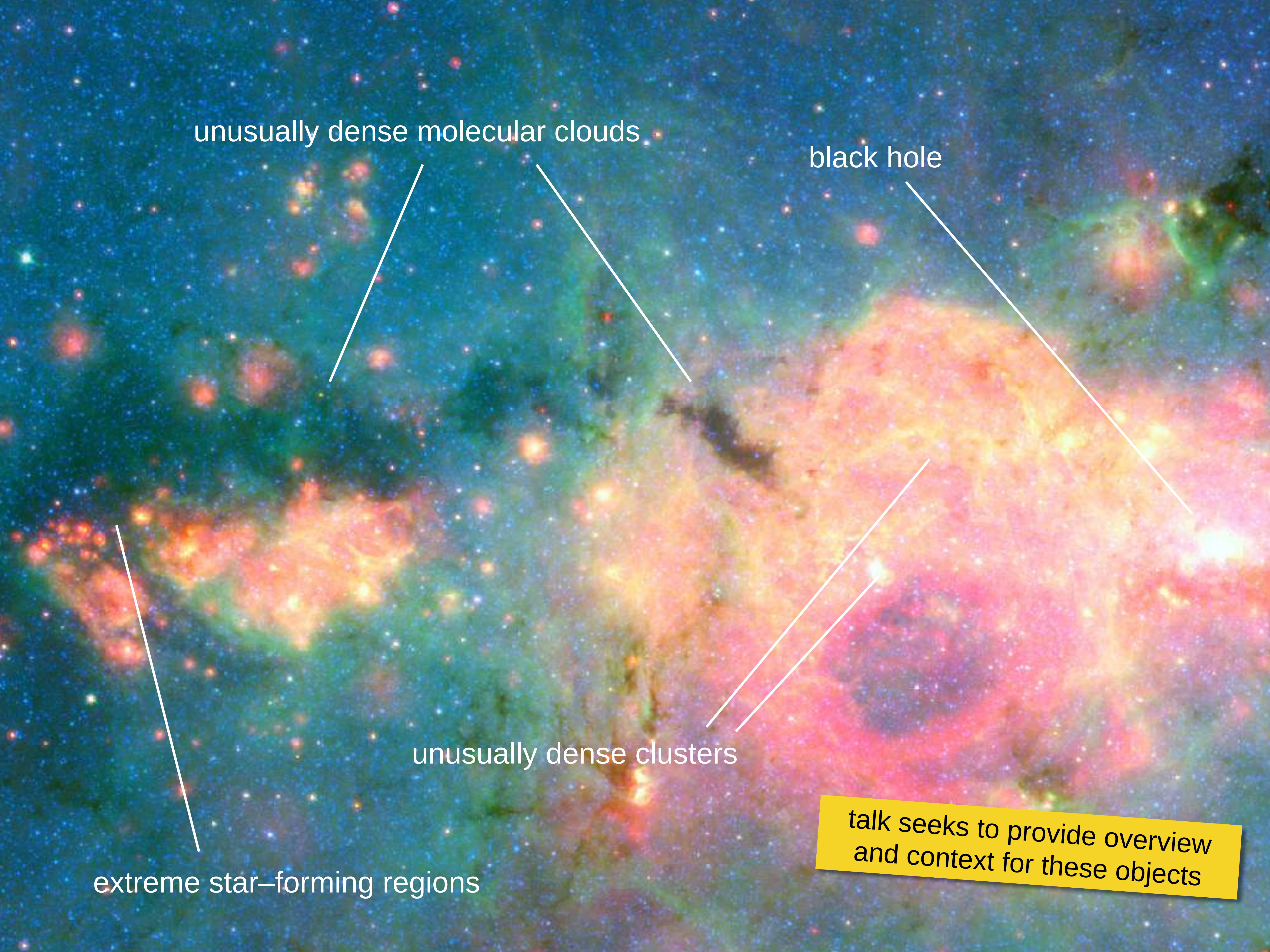
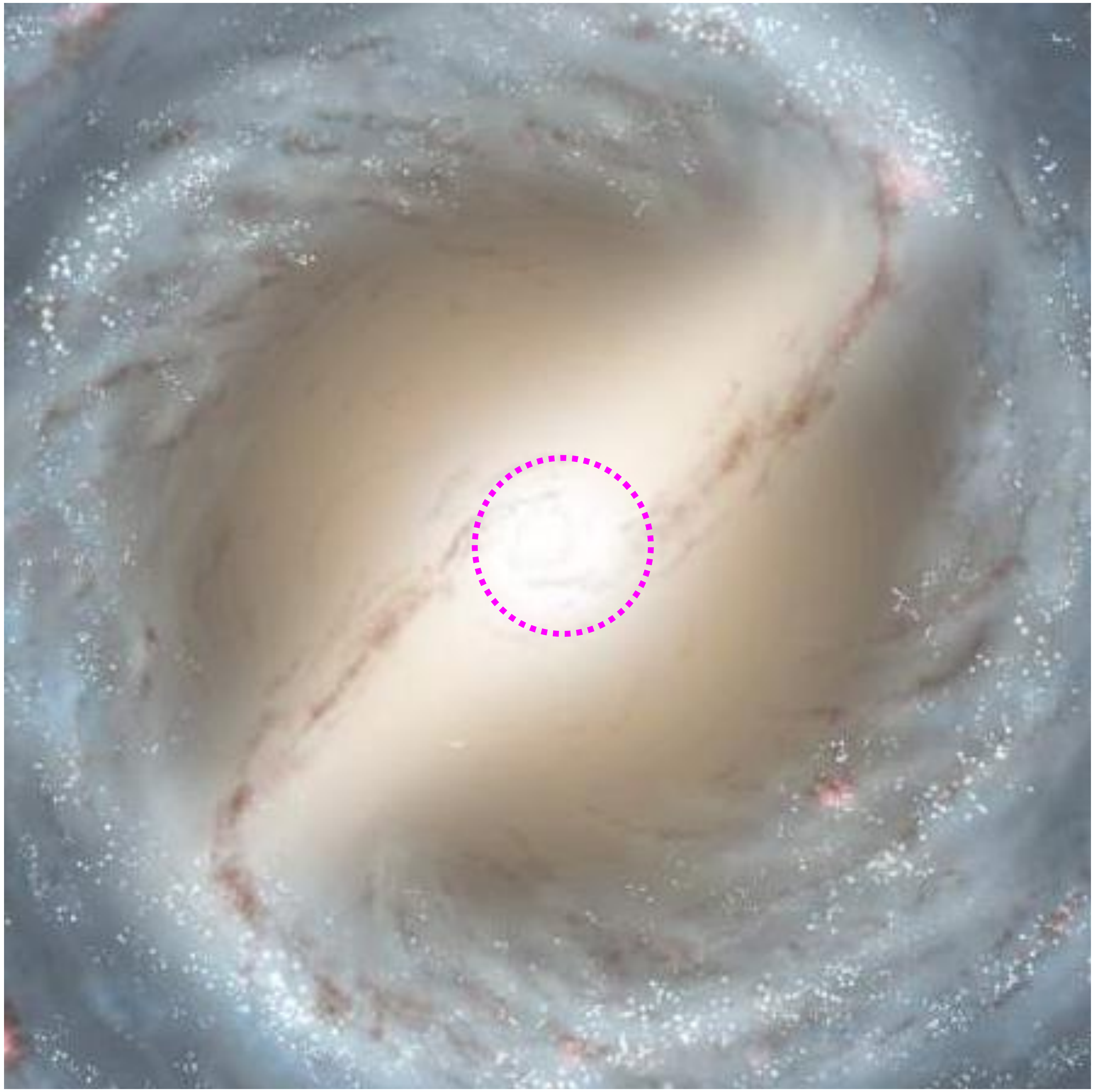

unusually dense molecular clouds
black hole
unusually dense clusters
extreme star–forming regions
talk seeks to provide overview and context for these objects

Context: Inner Milky Way

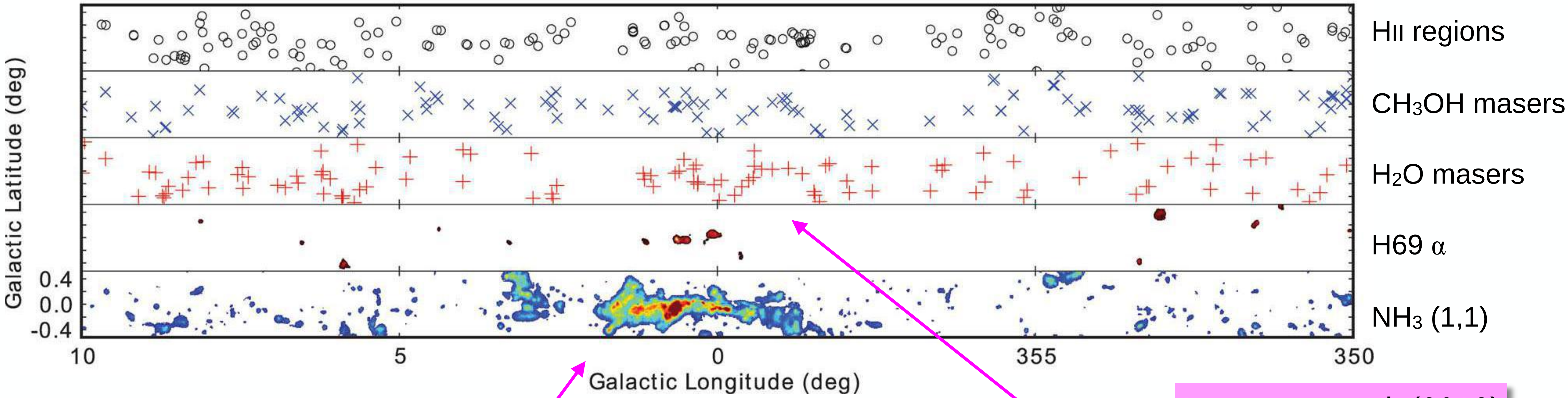


Central Bar
out to ~3 kpc radius
feeding the innermost region

Central Molecular Zone (CMZ)
innermost ~200 pc ($|\ell| < 1.5$ deg)
largely molecular gas
main focus of this review

Central Engine
region within few pc of Sgr A* not covered here

The CMZ Star Formation Problem



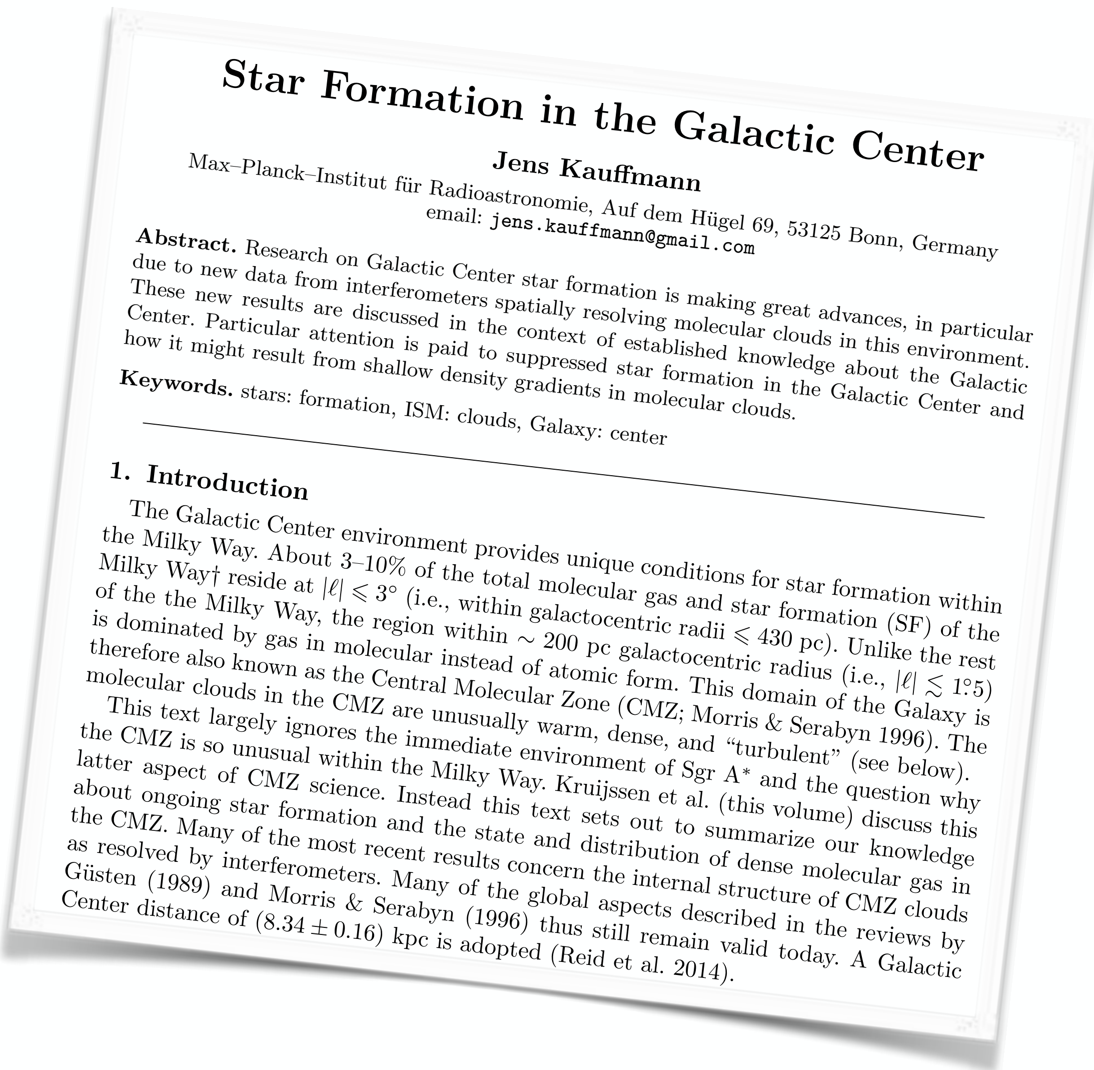
Longmore et al. (2013)

star formation
not concentrated

dense gas concentrated
around $\ell = 0°$

⇒ star formation in dense gas is suppressed topics of this review:

- distribution of young stars and gas in the CMZ
- physical processes in CMZ Clouds
- suppression of CMZ star formation



Star Formation in the Galactic Center

Jens Kauffmann

Max–Planck–Institut für Radioastronomie, Auf dem Hügel 69, 53125 Bonn, Germany
email: jens.kauffmann@gmail.com

Abstract. Research on Galactic Center star formation is making great advances, in particular due to new data from interferometers spatially resolving molecular clouds in this environment. These new results are discussed in the context of established knowledge about the Galactic Center. Particular attention is paid to suppressed star formation in the Galactic Center and how it might result from shallow density gradients in molecular clouds.

Keywords. stars: formation, ISM: clouds, Galaxy: center

1. Introduction

The Galactic Center environment provides unique conditions for star formation within the Milky Way. About 3–10% of the total molecular gas and star formation (SF) of the Milky Way† reside at $|\ell| \leqslant 3^\circ$ (i.e., within galactocentric radii $\leqslant 430$ pc). Unlike the rest of the the Milky Way, the region within ~ 200 pc galactocentric radius (i.e., $|\ell| \lesssim 1.^\circ5$) is dominated by gas in molecular instead of atomic form. This domain of the Galaxy is therefore also known as the Central Molecular Zone (CMZ; Morris & Serabyn 1996). The molecular clouds in the CMZ are unusually warm, dense, and "turbulent" (see below).

This text largely ignores the immediate environment of Sgr A* and the question why the CMZ is so unusual within the Milky Way. Kruijssen et al. (this volume) discuss this latter aspect of CMZ science. Instead this text sets out to summarize our knowledge about ongoing star formation and the state and distribution of dense molecular gas in the CMZ. Many of the most recent results concern the internal structure of CMZ clouds as resolved by interferometers. Many of the global aspects described in the reviews by Güsten (1989) and Morris & Serabyn (1996) thus still remain valid today. A Galactic Center distance of (8.34 ± 0.16) kpc is adopted (Reid et al. 2014).

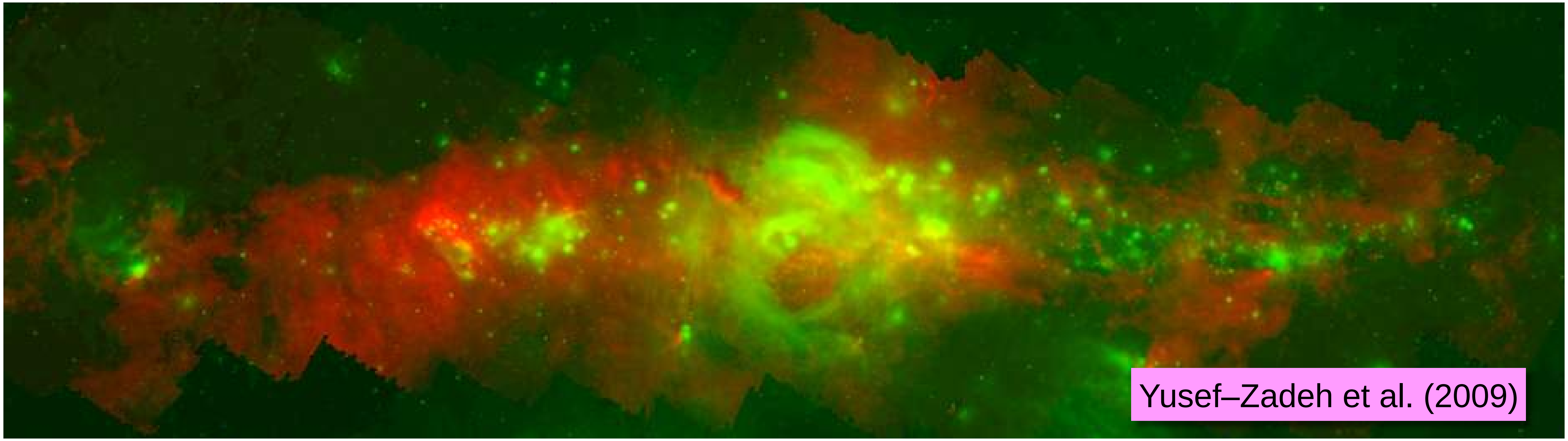
most material detailed in proceedings of IAUS322

this in particular includes references

see arXiv:1611.07022

Kauffmann (2017)

Gas and Stars in the CMZ



Gas and Stars in the CMZ

observations of star formation

Hard to probe the Center in IR Bands

extreme foreground obscuration:

$A_K \approx 2$ mag $\Rightarrow$ $A_V \approx 20$ mag

Spitzer little help:

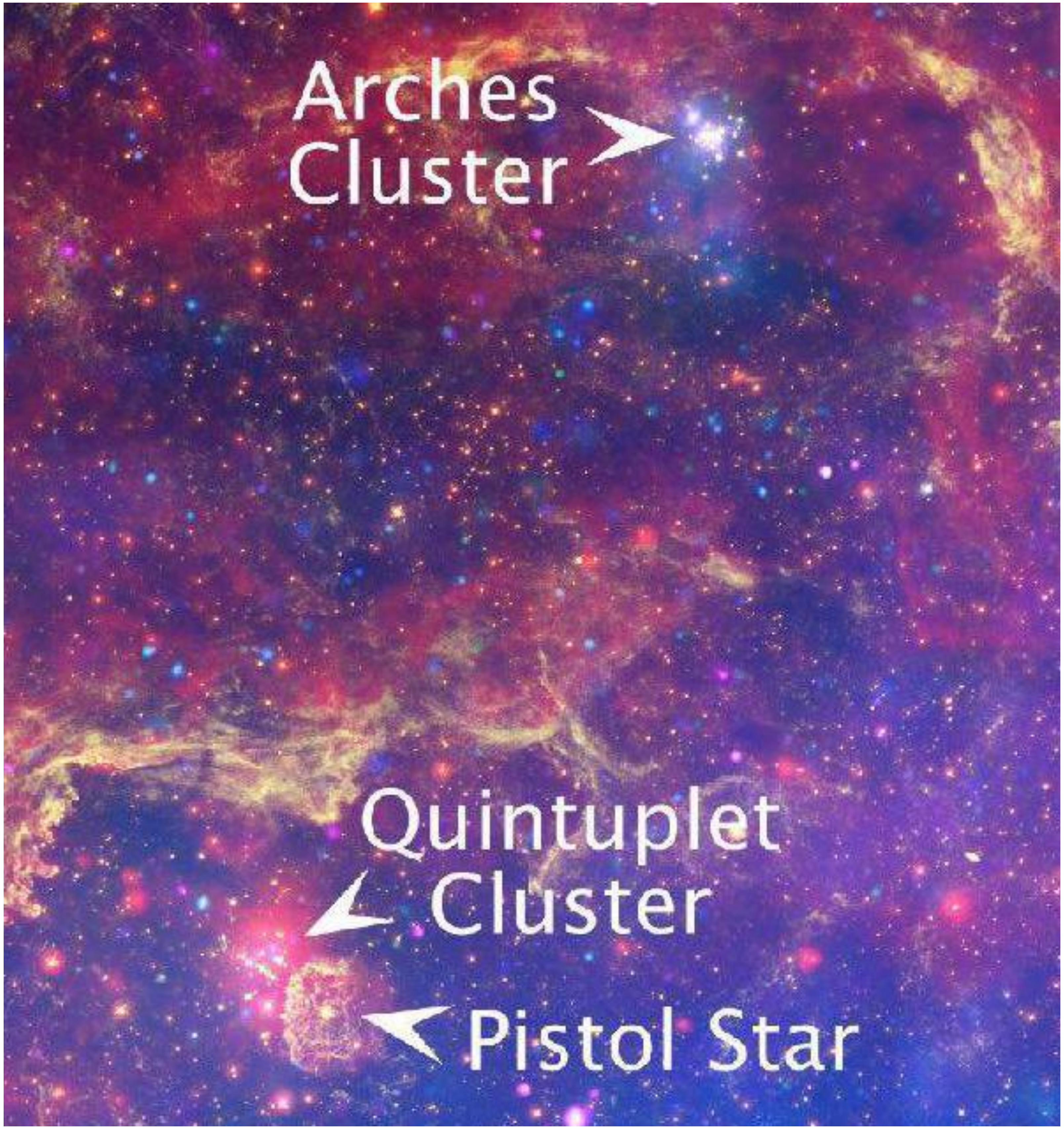
sensitive to $L_{int} \gtrsim 10^3 L_{sun}$ in „regular“ clouds

…but some clouds are opaque even at 70 µm

$\Rightarrow$ can only probe high–mass stars, using

wavelengths $\gtrsim 2$ µm

High–Mass Stars in IR Bands

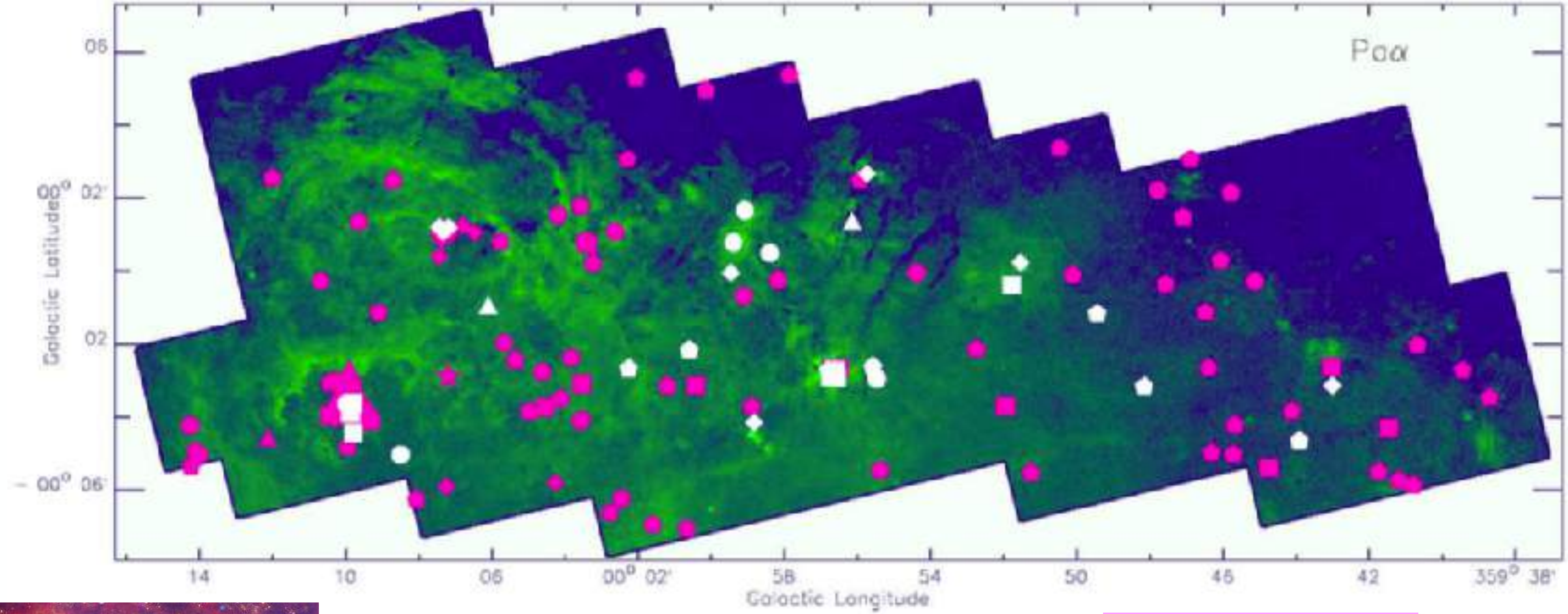


cluster properties:

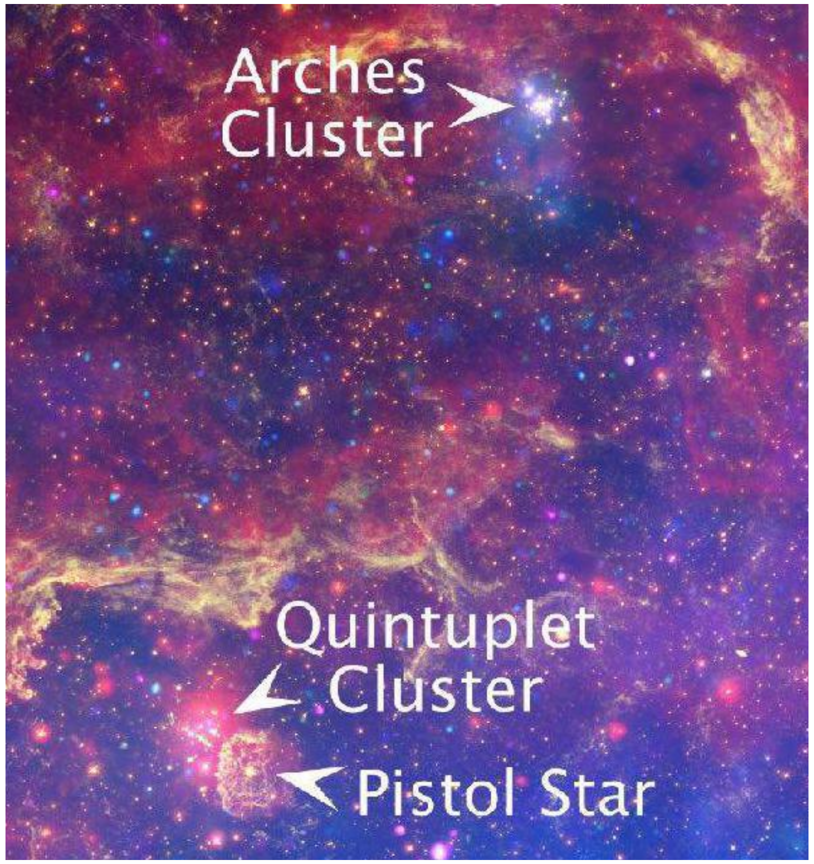
- total of 200 OB stars
- 2×10^4 M_{sun} in 0.4 pc radius (e.g., in Arches)
- unusual — but not exceptional — in Milky Way

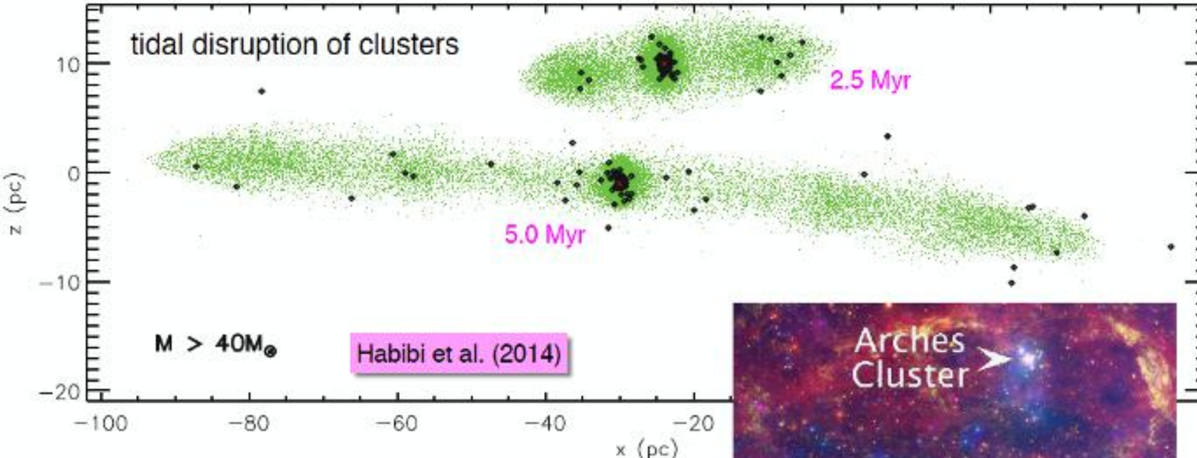
Spitzer, Hubble, Chandra

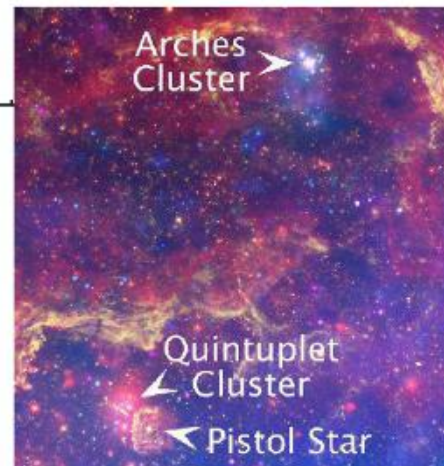
High–Mass Stars in IR Bands



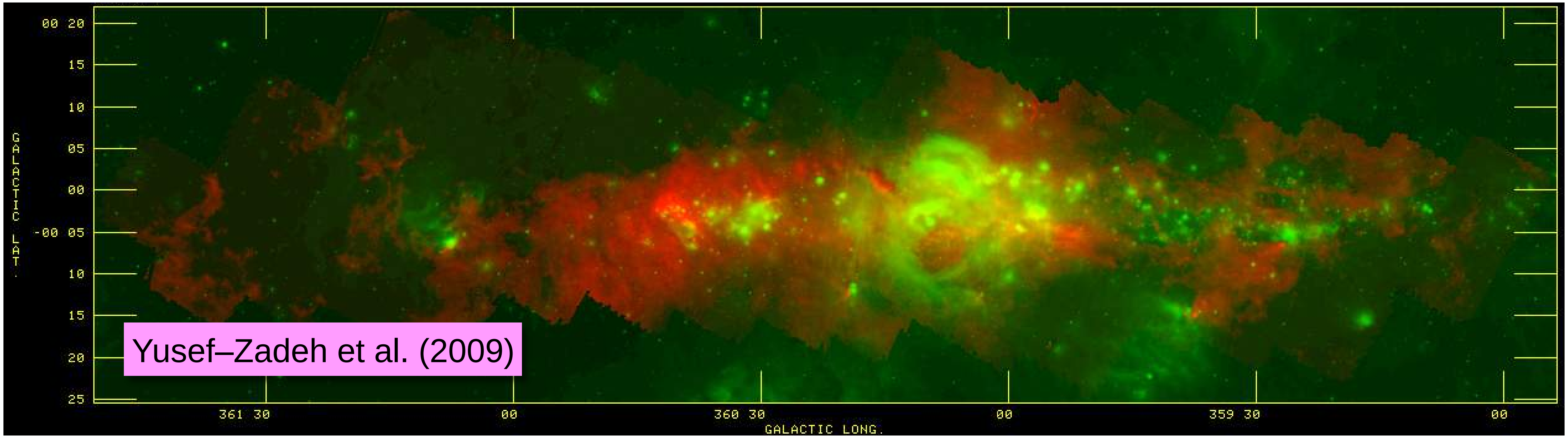
Dong et al. (2009)



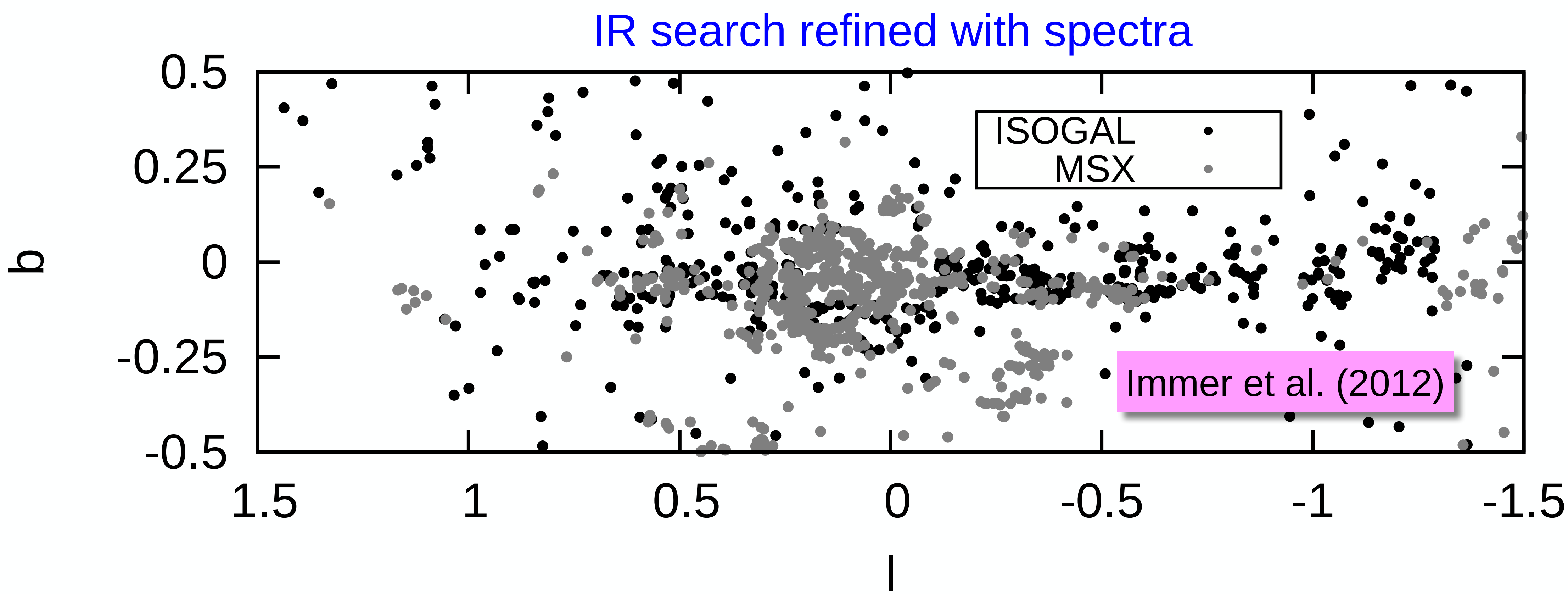

tidal disruption of clusters
2.5 Myr
5.0 Myr
M > 40M$_\odot$
Habibi et al. (2014)
z (pc)
x (pc)
10
0
−10
−20
−100
−80
−60
−40
−20

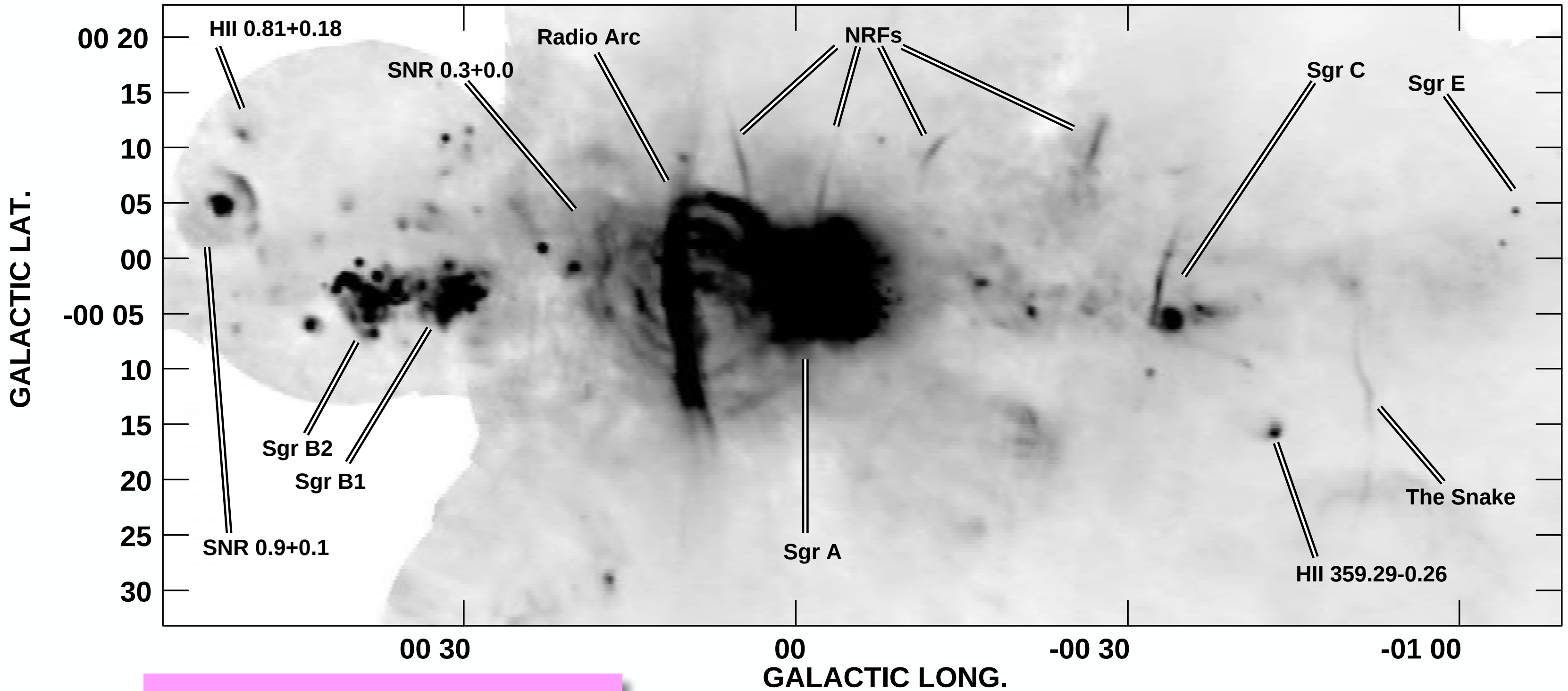

Arches Cluster
Quintuplet Cluster
Pistol Star

Spitzer: An asymmetric Distribution of Young Stars?



…or maybe just main–sequence stars illuminating clouds? Koepferl et al. (2015)

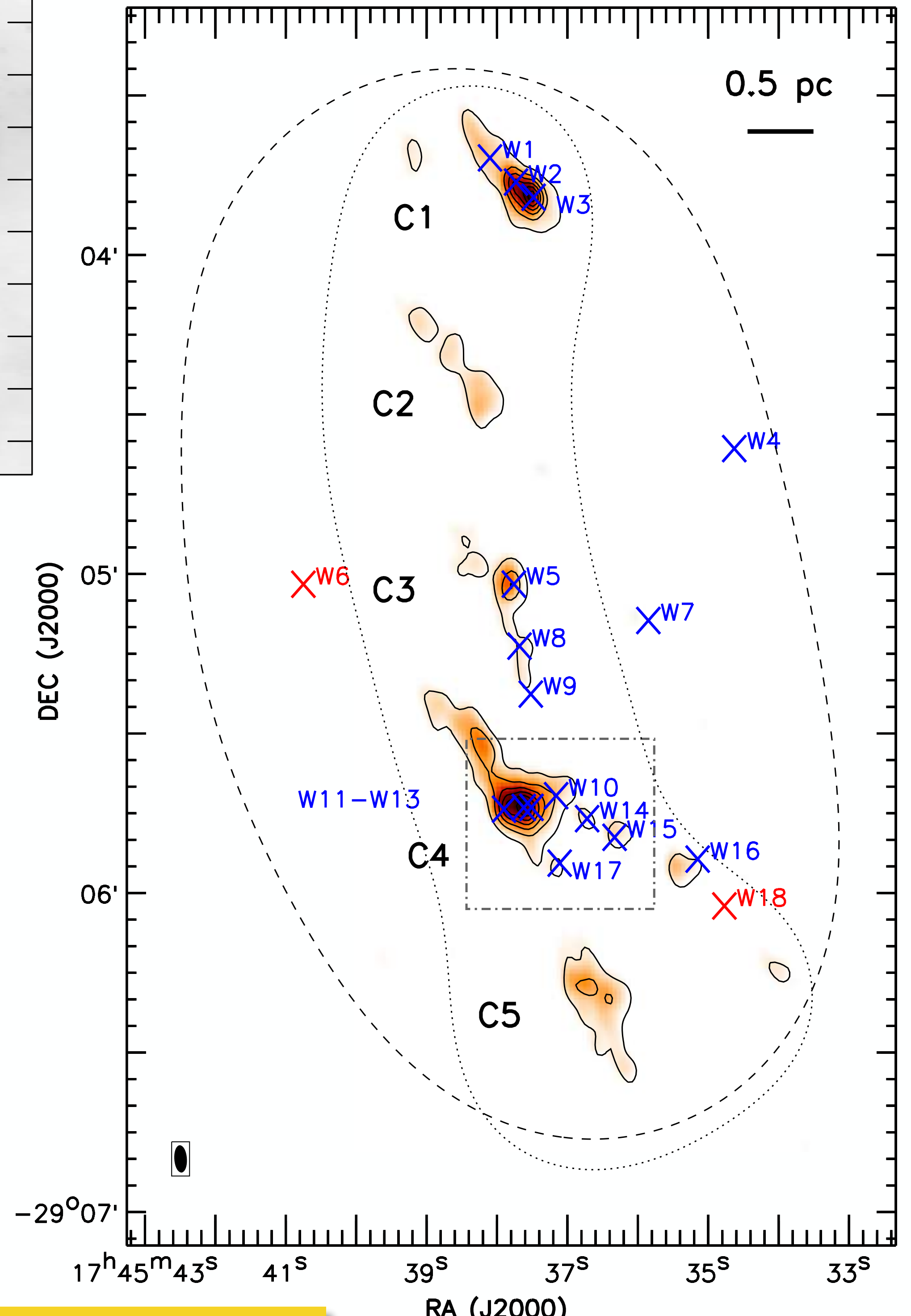




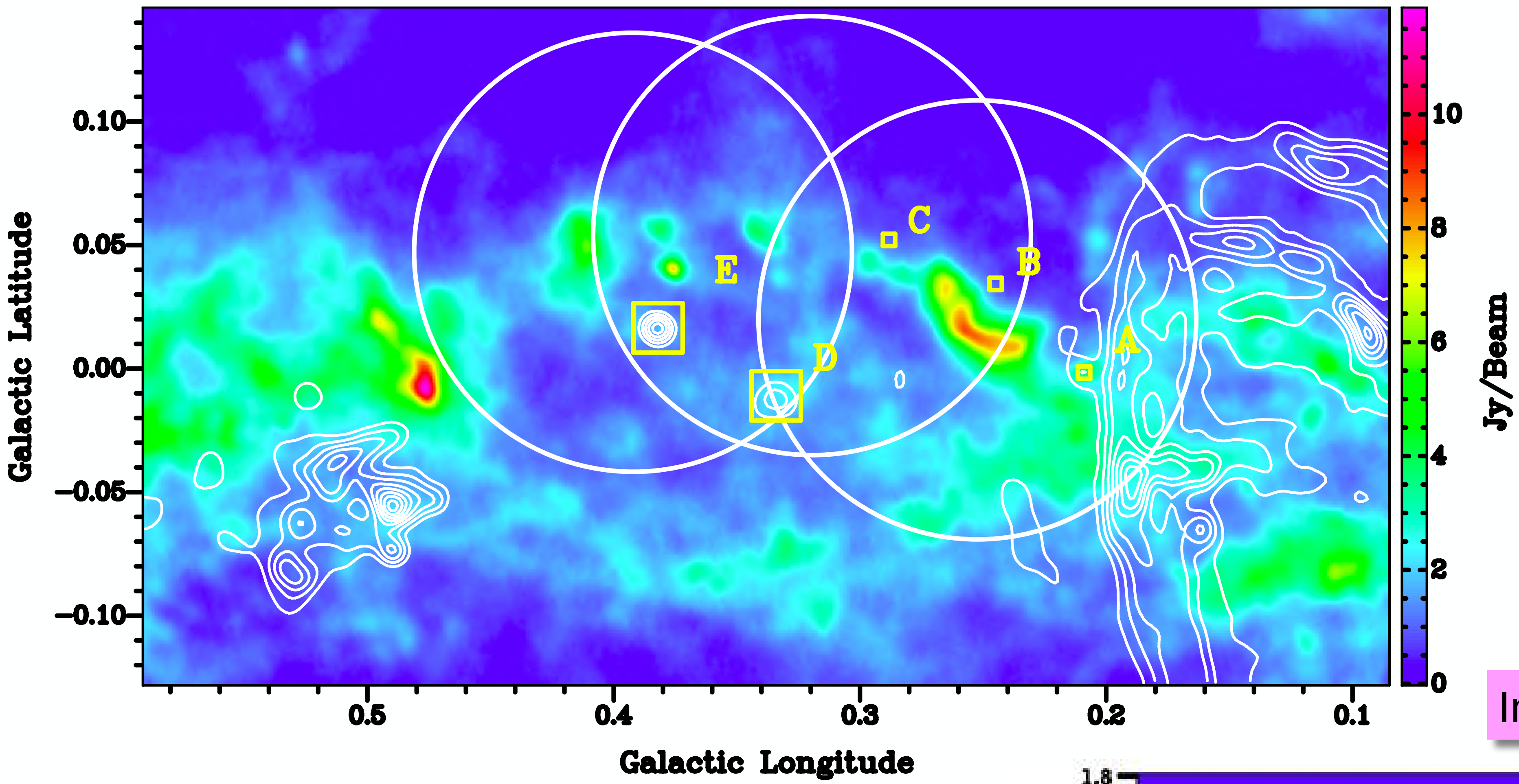
Yusef–Zadeh (2009)

continuum and recombination lines:
near ionizing sources

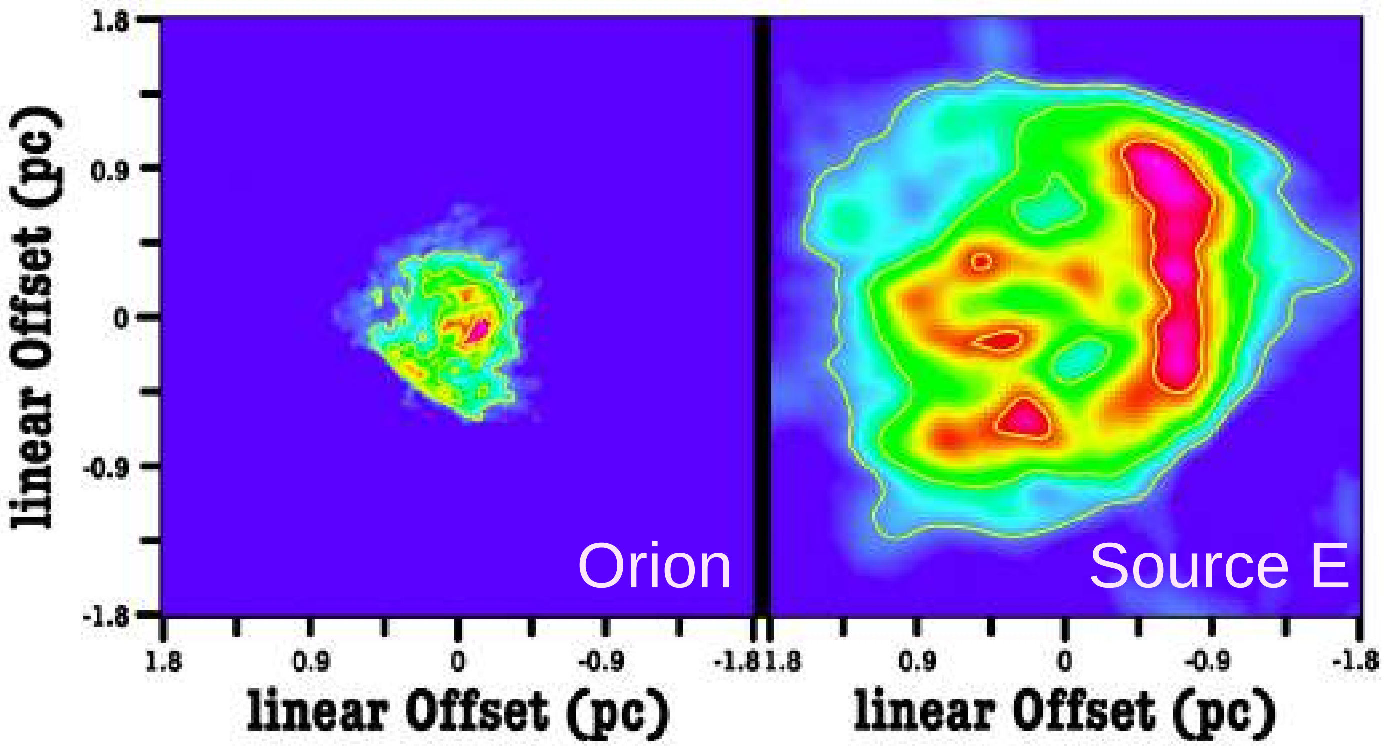
masers (H_2O, CH_3OH):
excitation due to shocks (outflows) and infrared radiation



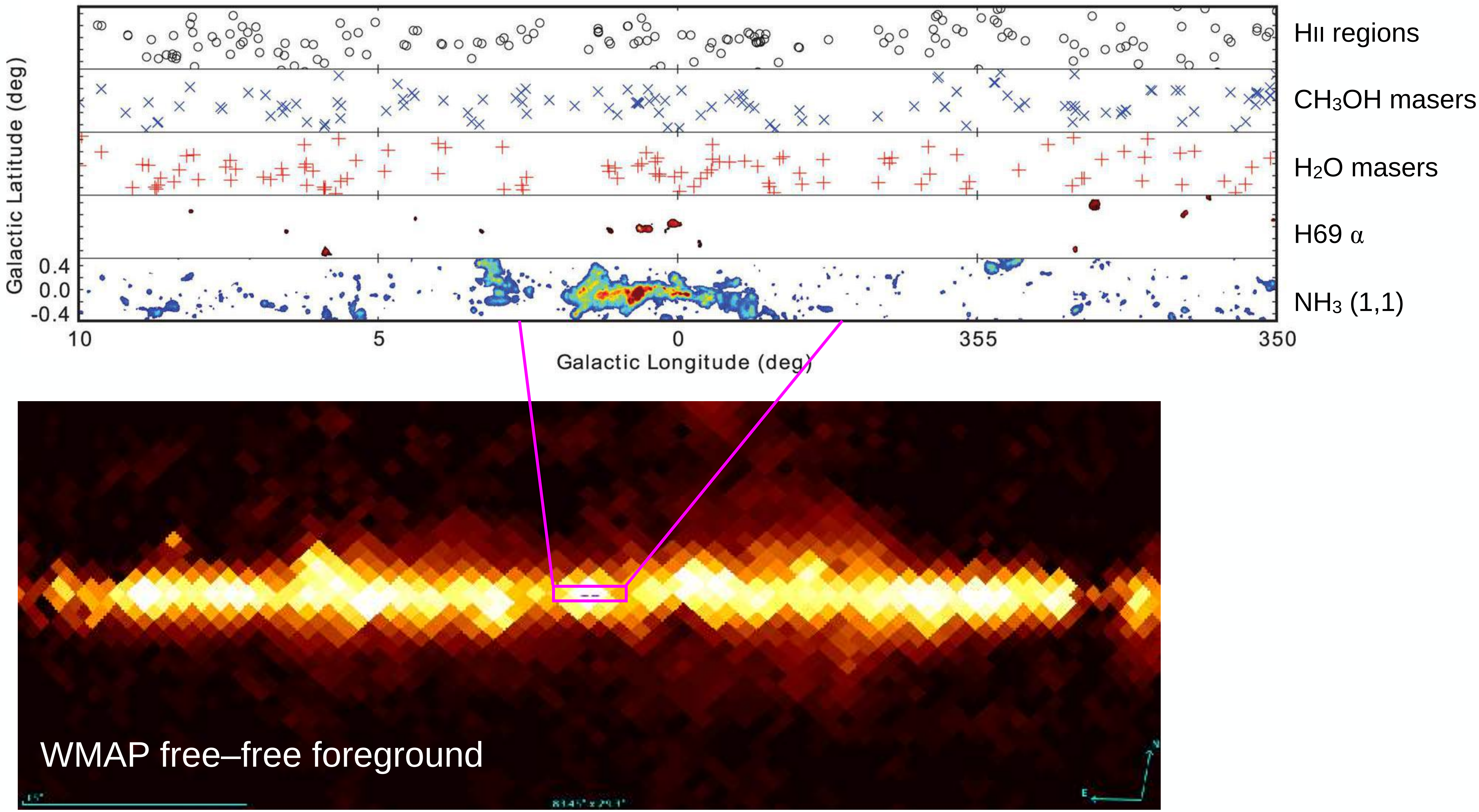
Lu et al. (2016)



Immer et al. (2012)



observations at 8.4 GHz



=> total ~0.1 M_{sun} yr^{-1} in $|\ell| < 3$ deg

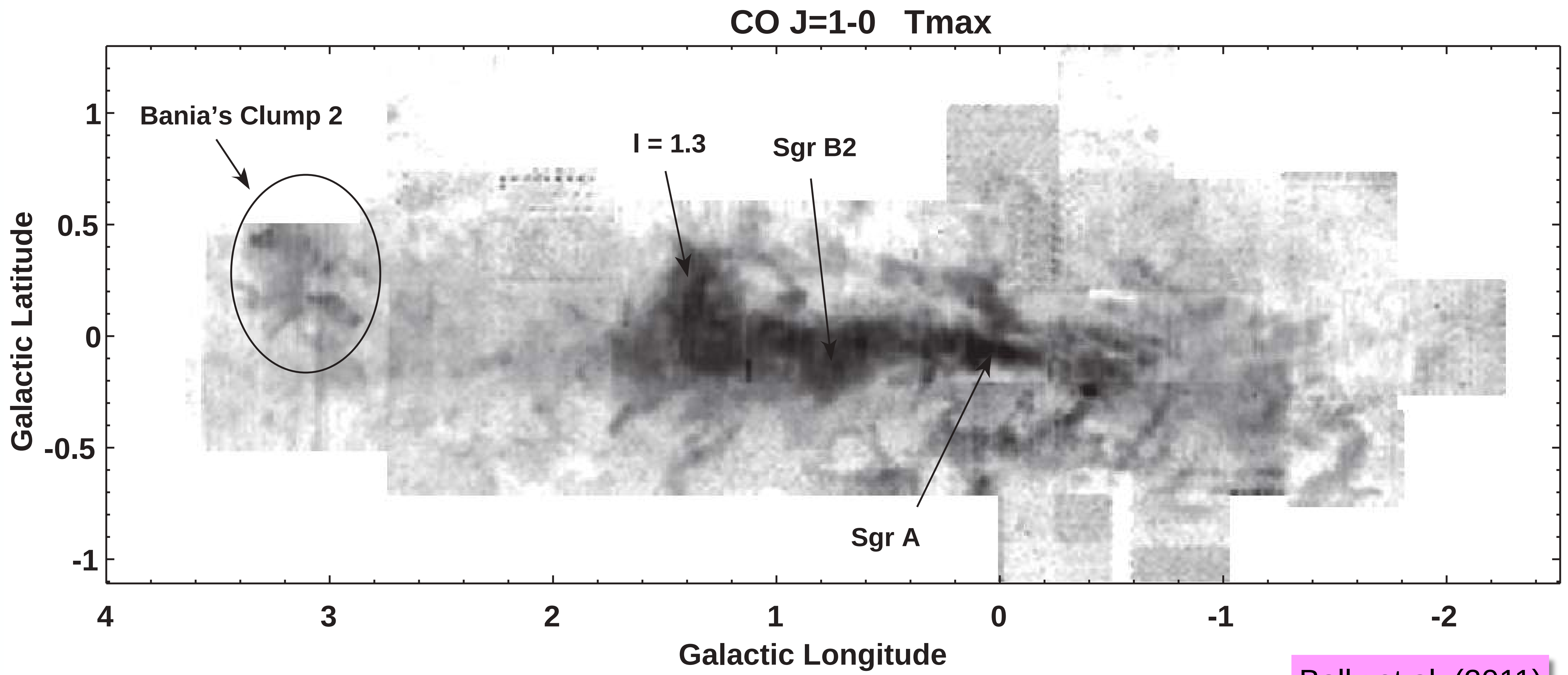
=> ~10% of SF in Milky Way

Longmore et al. (2013)

Gas and Stars in the CMZ

Distribution of Dense Gas in the CMZ

Distribution of Dense Gas in CMZ

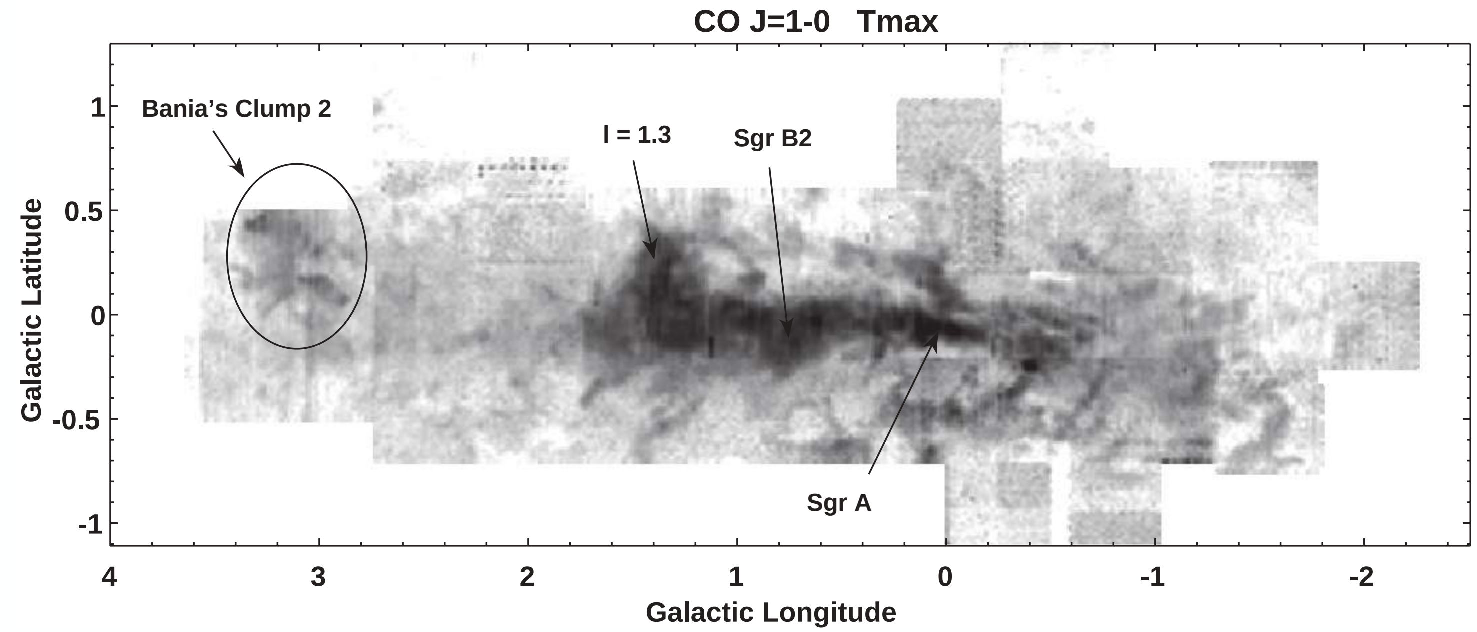


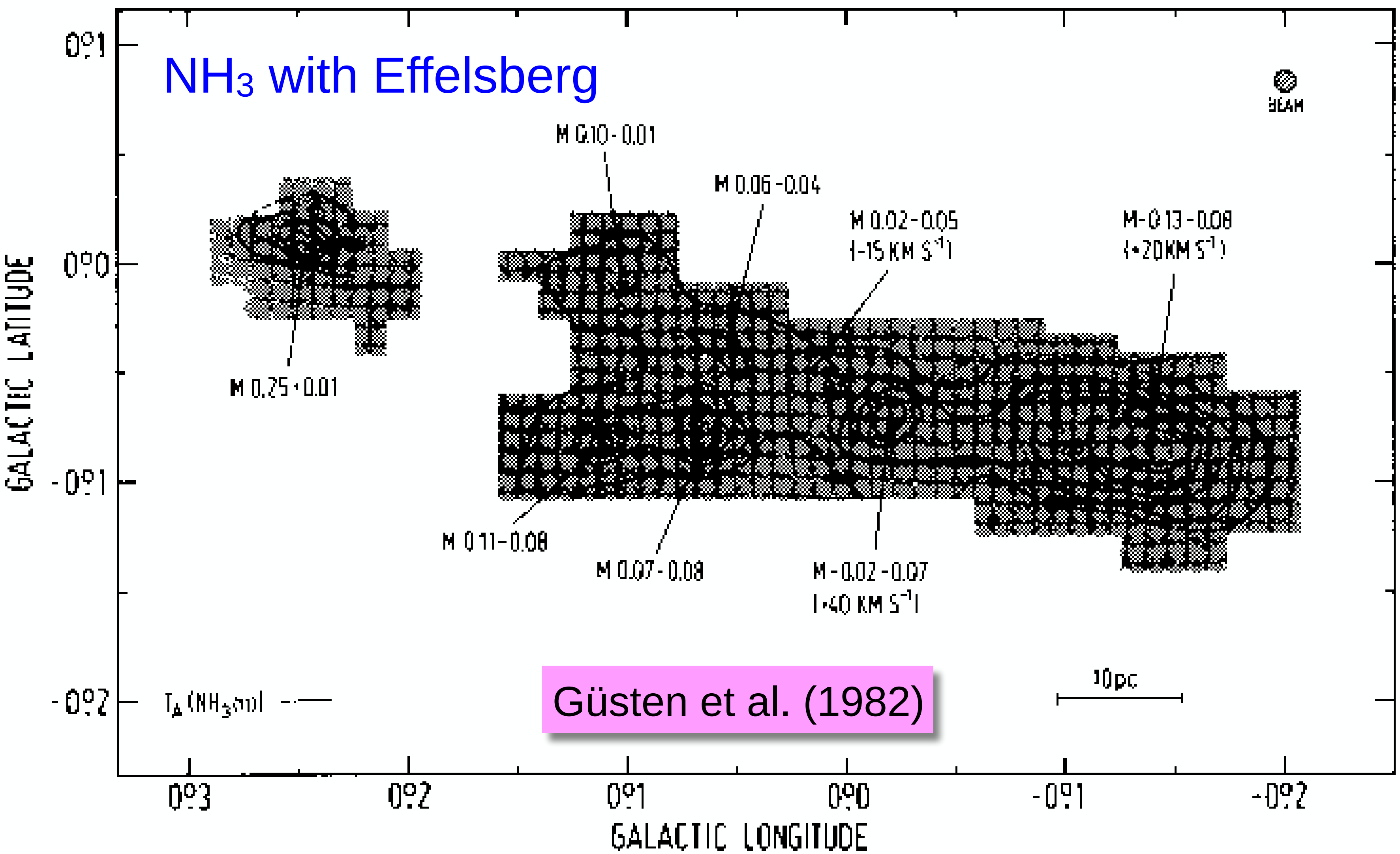
Bally et al. (2011)

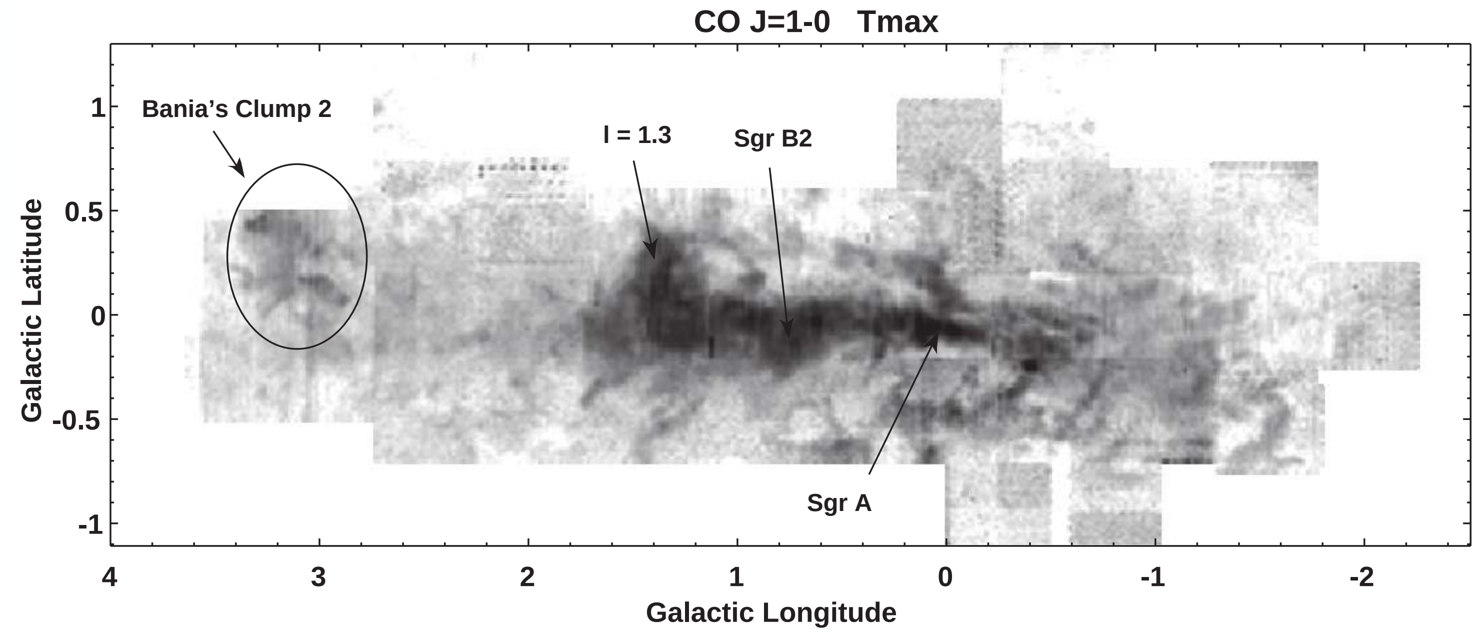
$\sim 5 \cdot 10^7\ M_{sun}$ in $|\ell| < 3$ deg

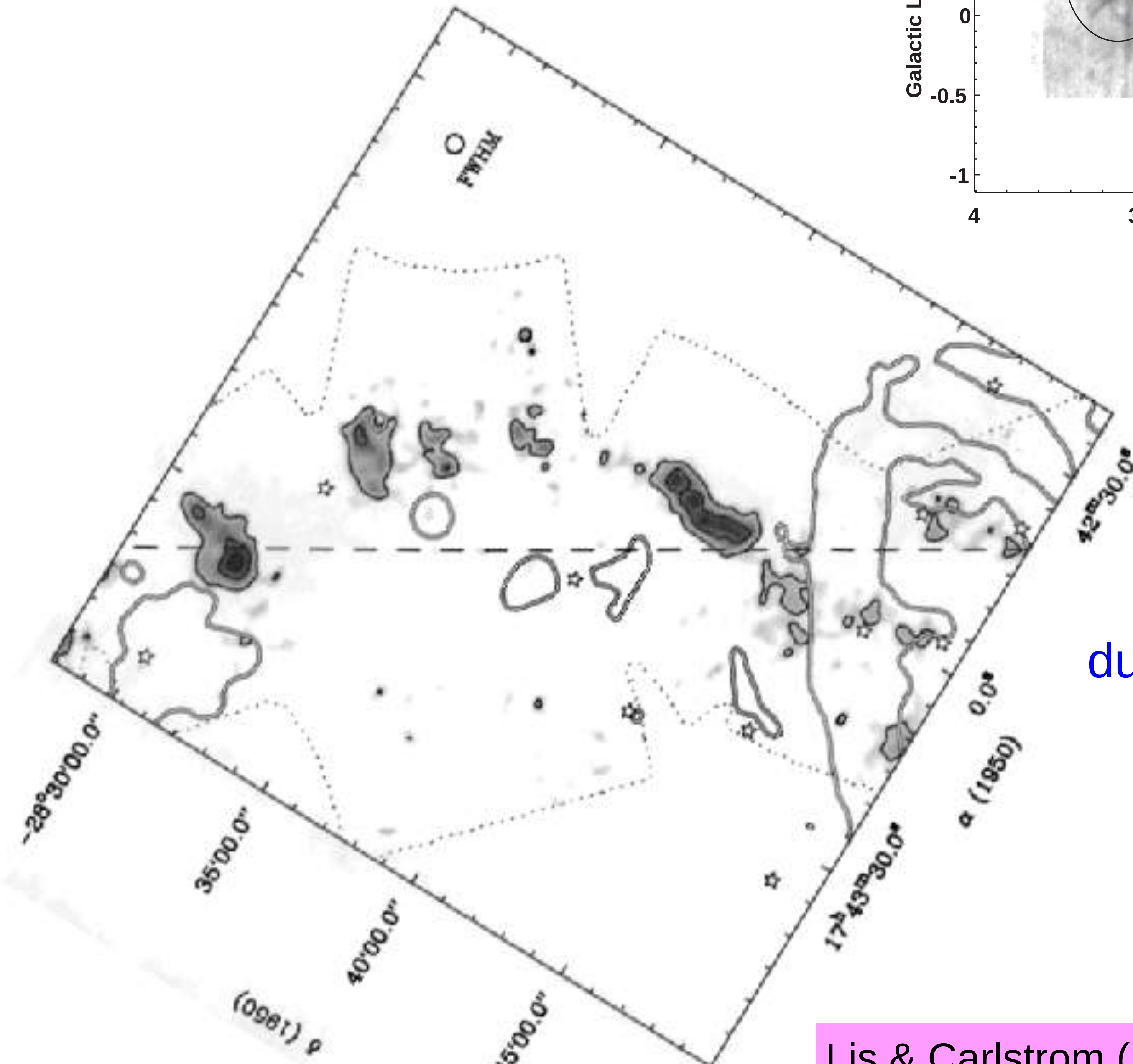
$\sim 2 \cdot 10^7\ M_{sun}$ in $|\ell| < 1$ deg

Distribution of Dense Gas in CMZ







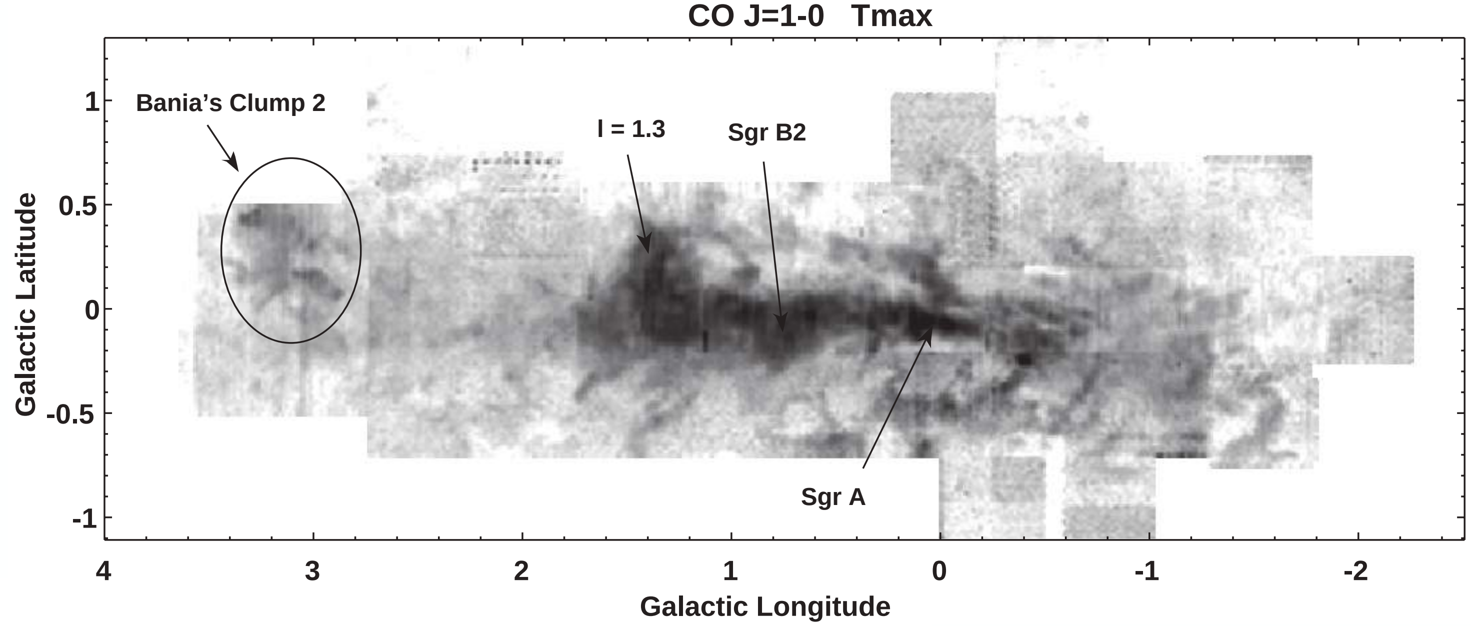


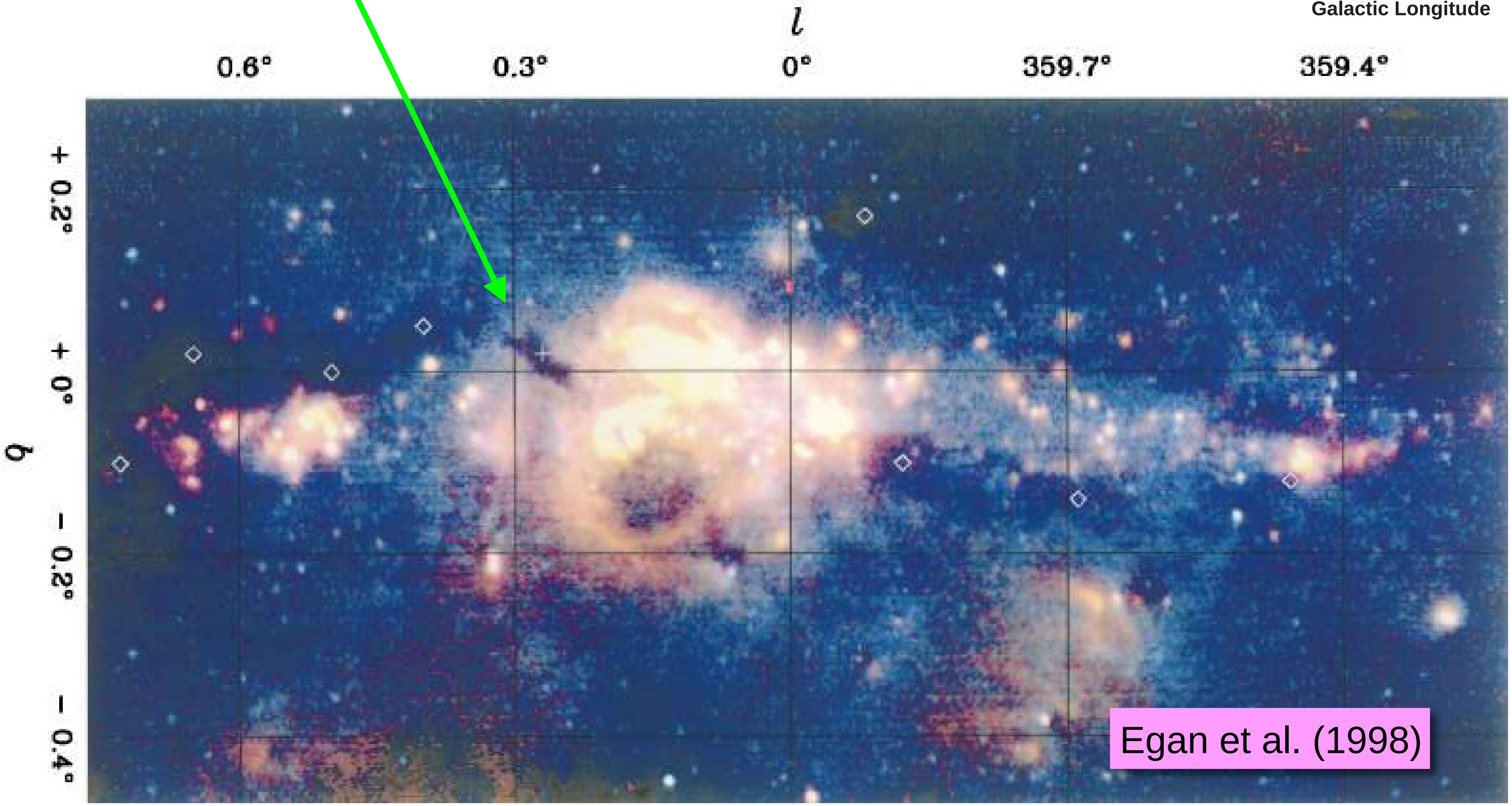
dust from the CSO

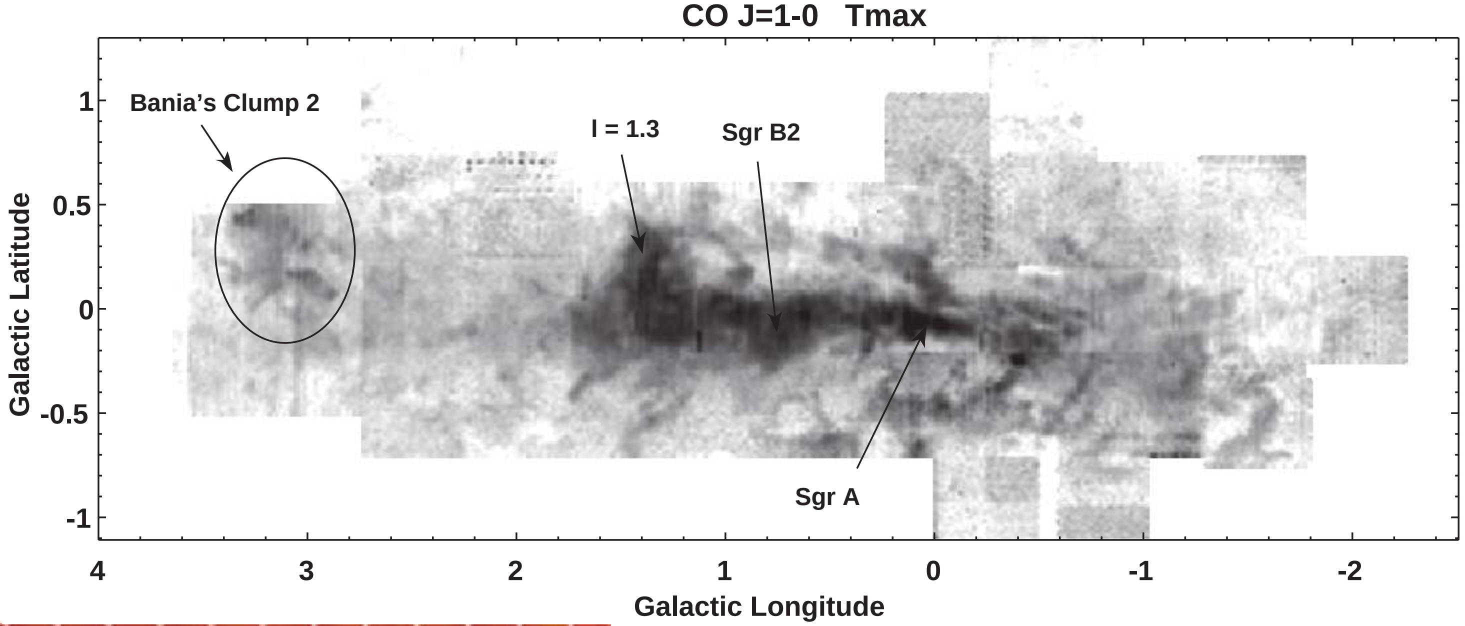
Lis & Carlstrom (1994)

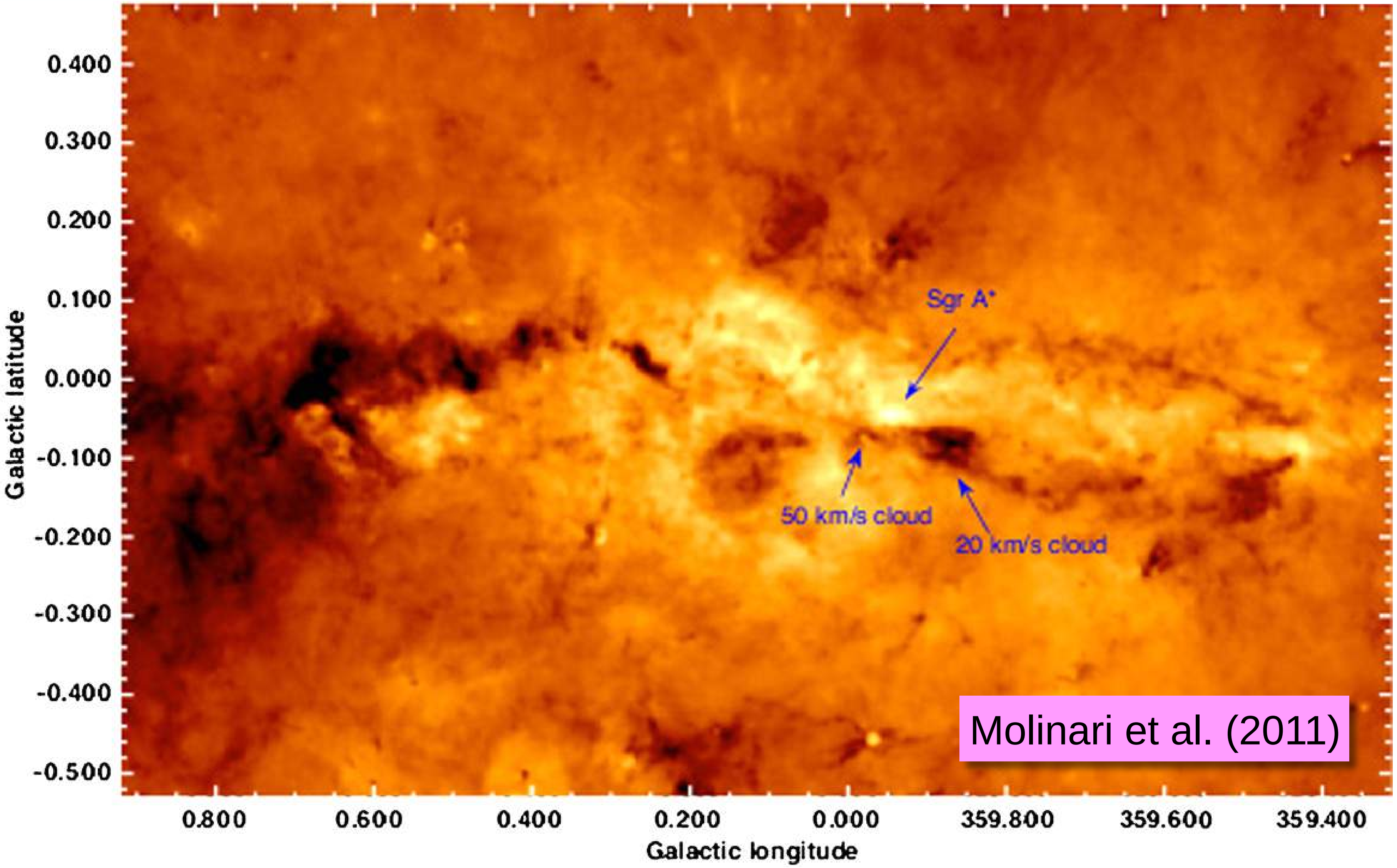
Infrared Dark Clouds (IRDCs):
invented to describe G0.253+0.016
(the “Brick”)

=> not all IRDCs are actually dense!

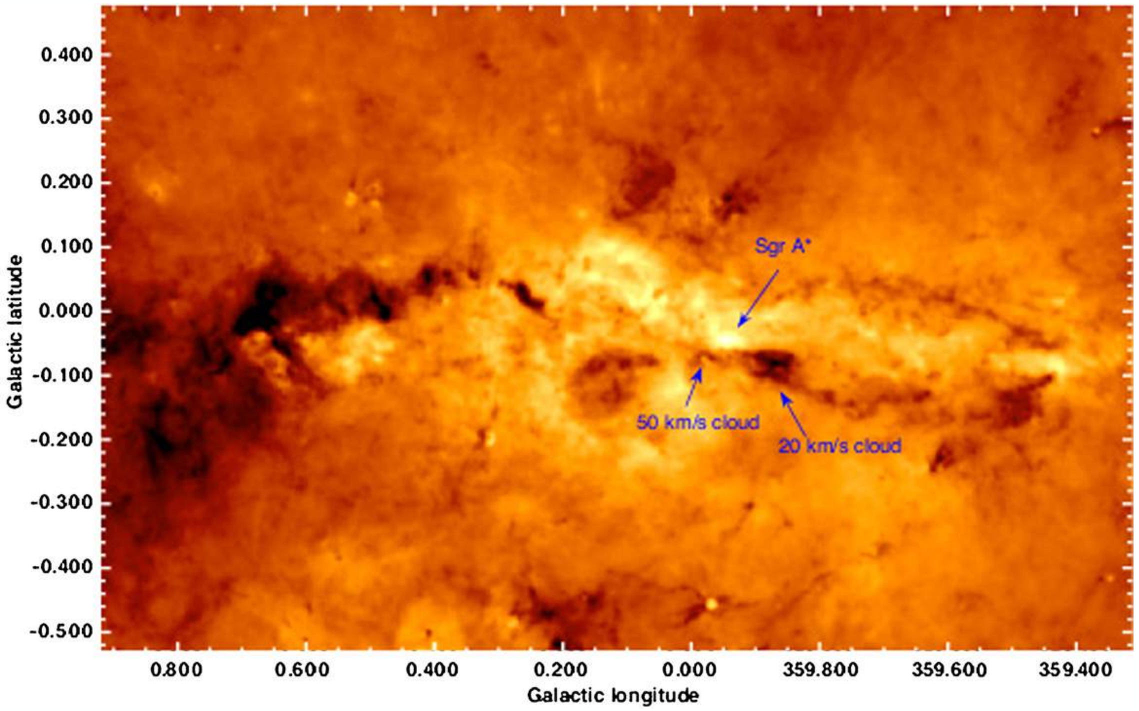





CO J=1-0 Tmax
Bania's Clump 2
l = 1.3
Sgr B2
Sgr A
Galactic Latitude
1
0.5
0
-0.5
-1
4
3
2
1
0
-1
-2
Galactic Longitude

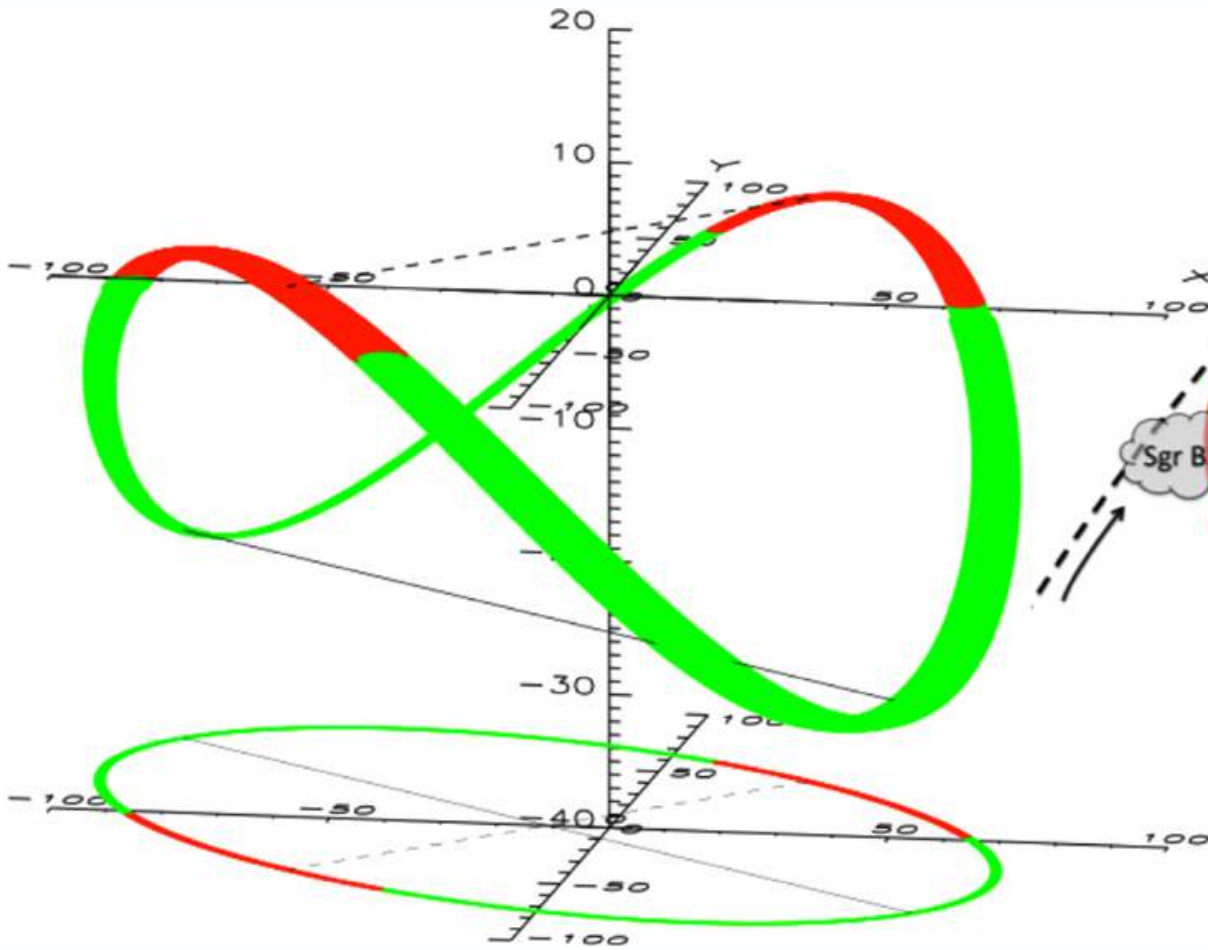

Sgr A*
50 km/s cloud
20 km/s cloud
Molinari et al. (2011)
Galactic latitude
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
0.800
0.600
0.400
0.200
0.000
359.800
359.600
359.400
Galactic longitude

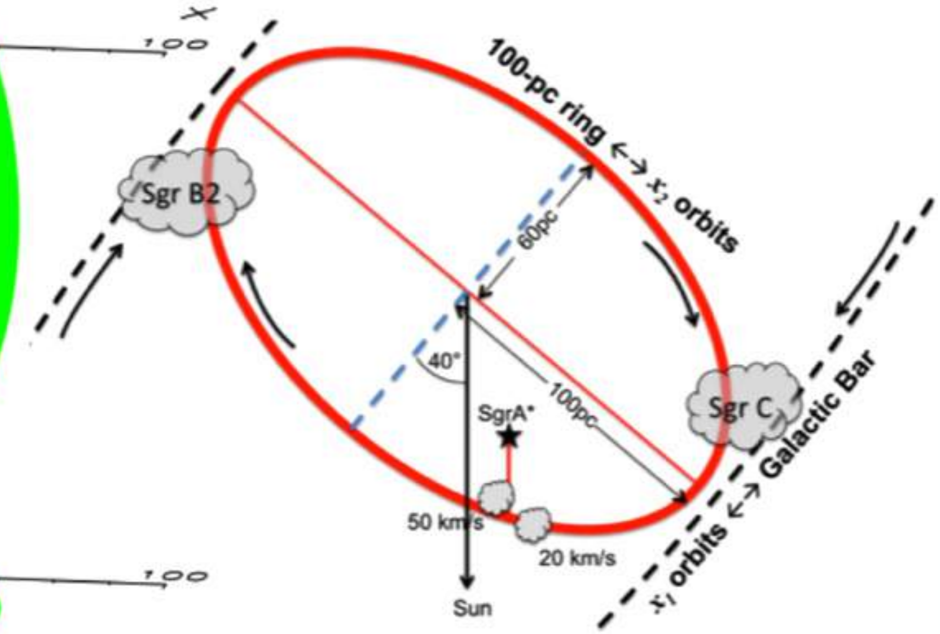
Distribution of Dense Gas in CMZ



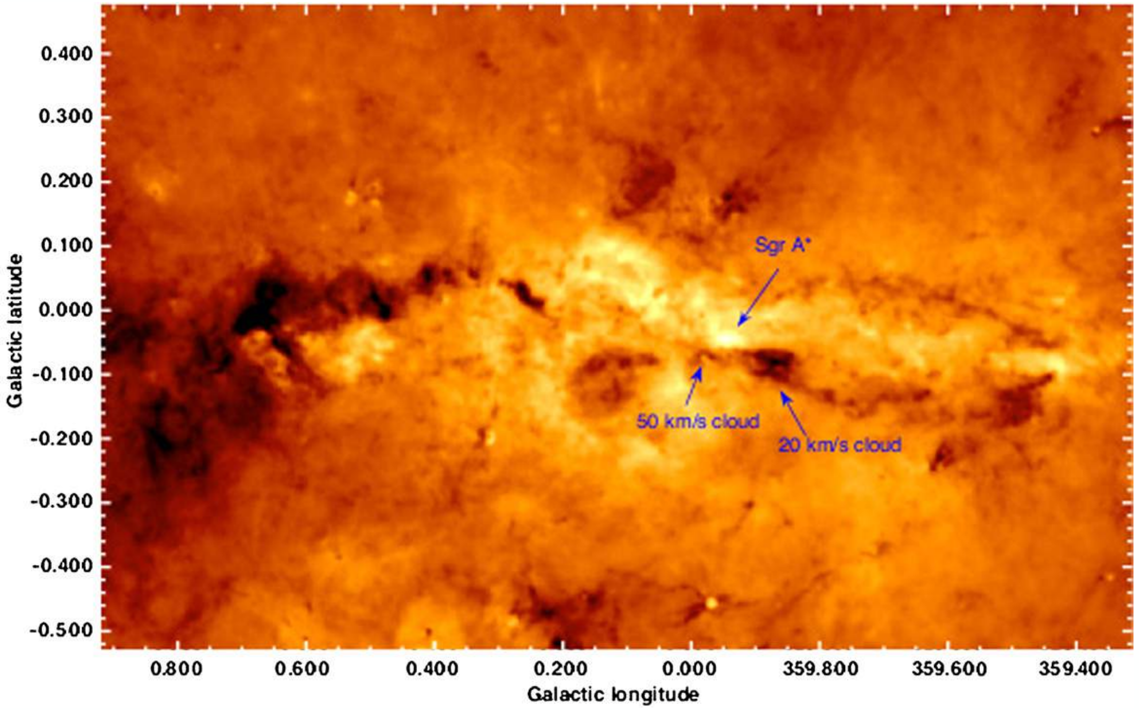
suggestion:
a twisted infinity loop

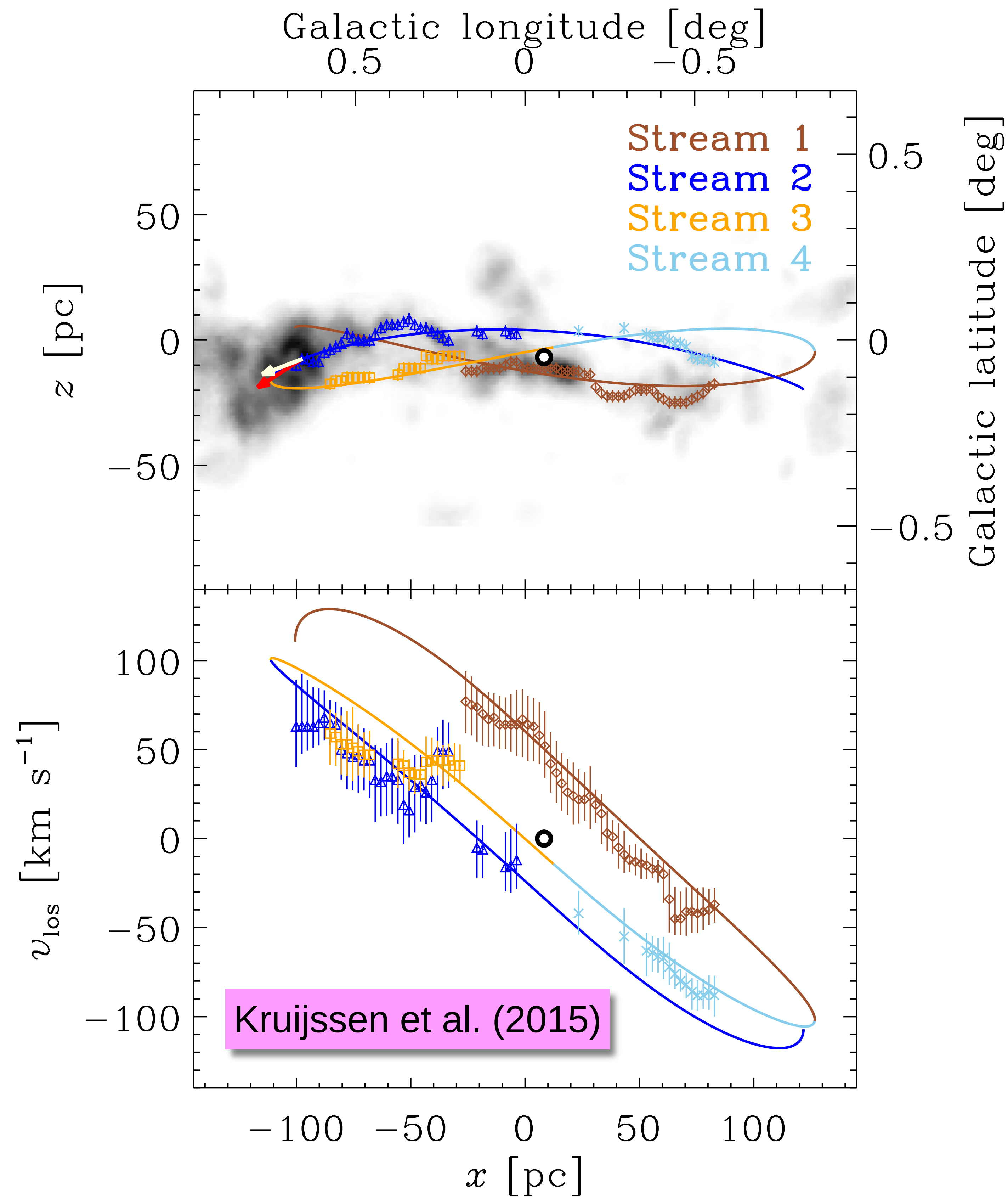
Molinari et al. (2011)





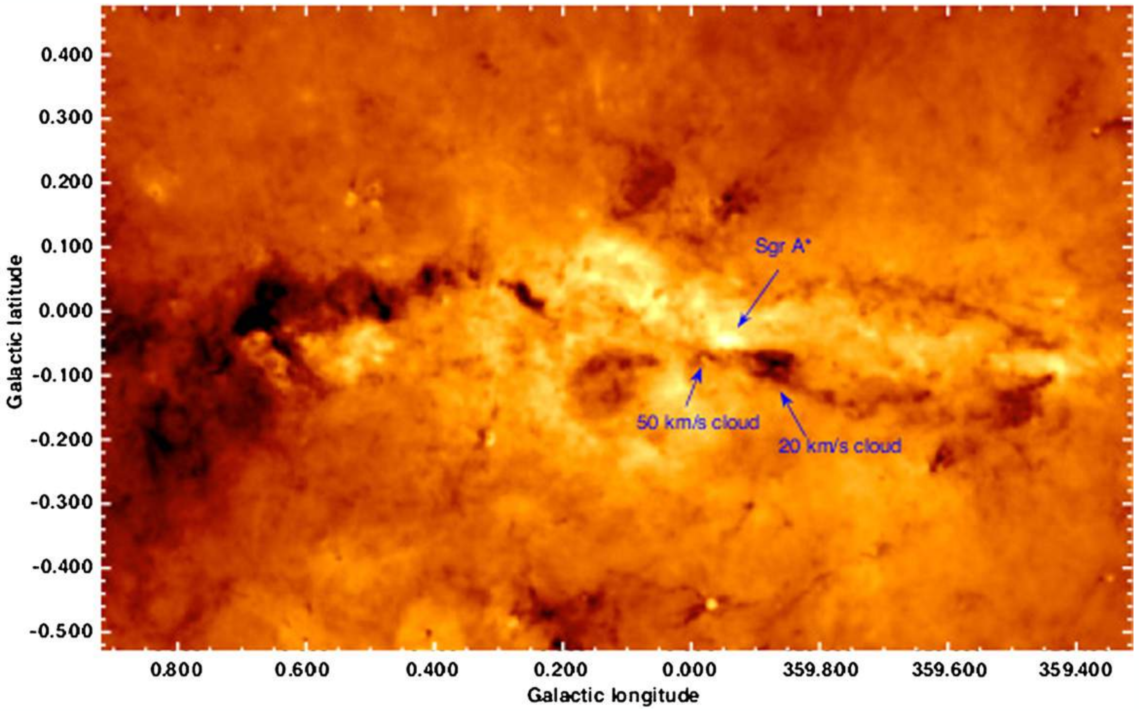
Distribution of Dense Gas in CMZ



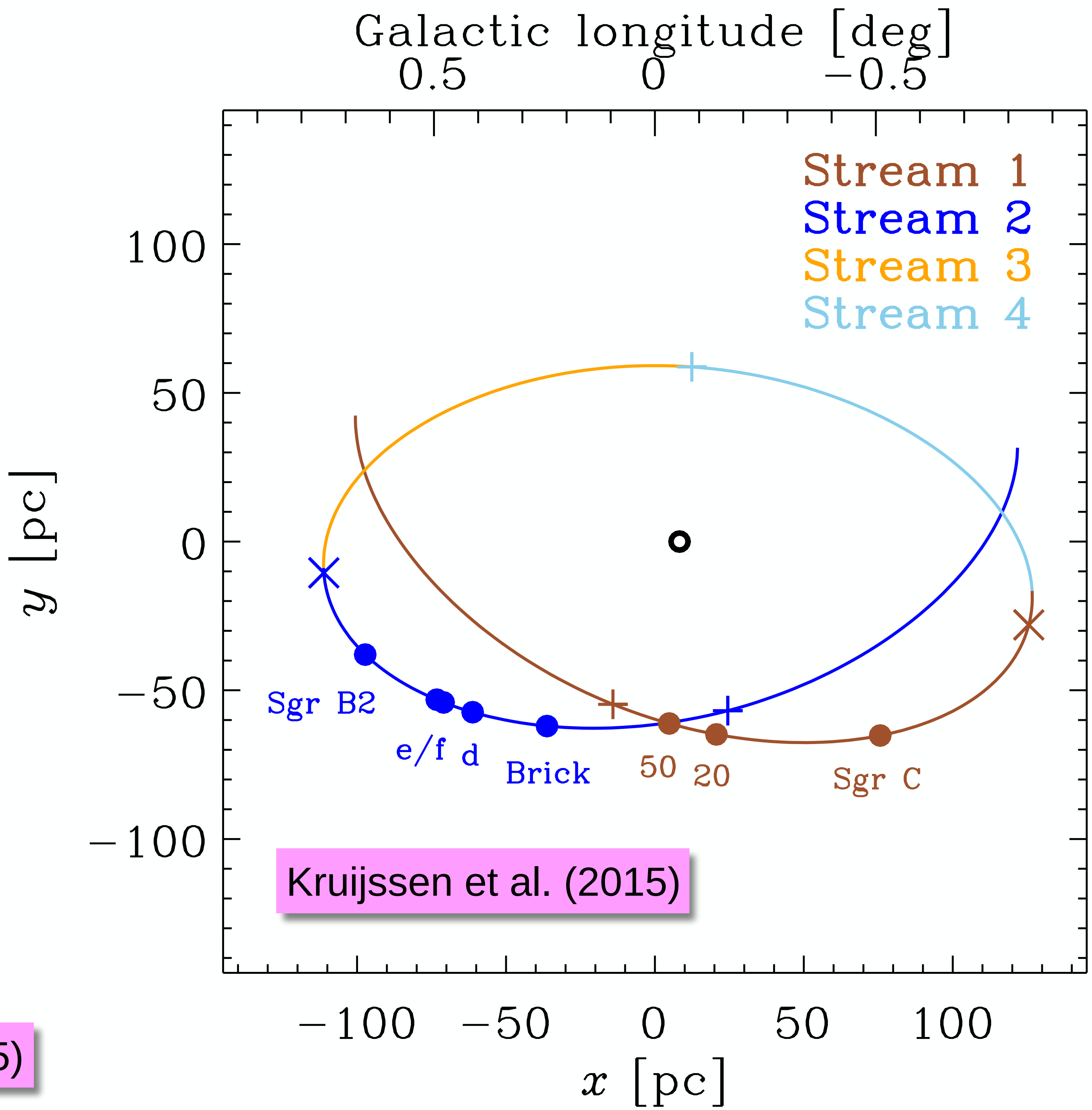


model: point mass on orbit

Distribution of Dense Gas in CMZ



model: point mass on orbit



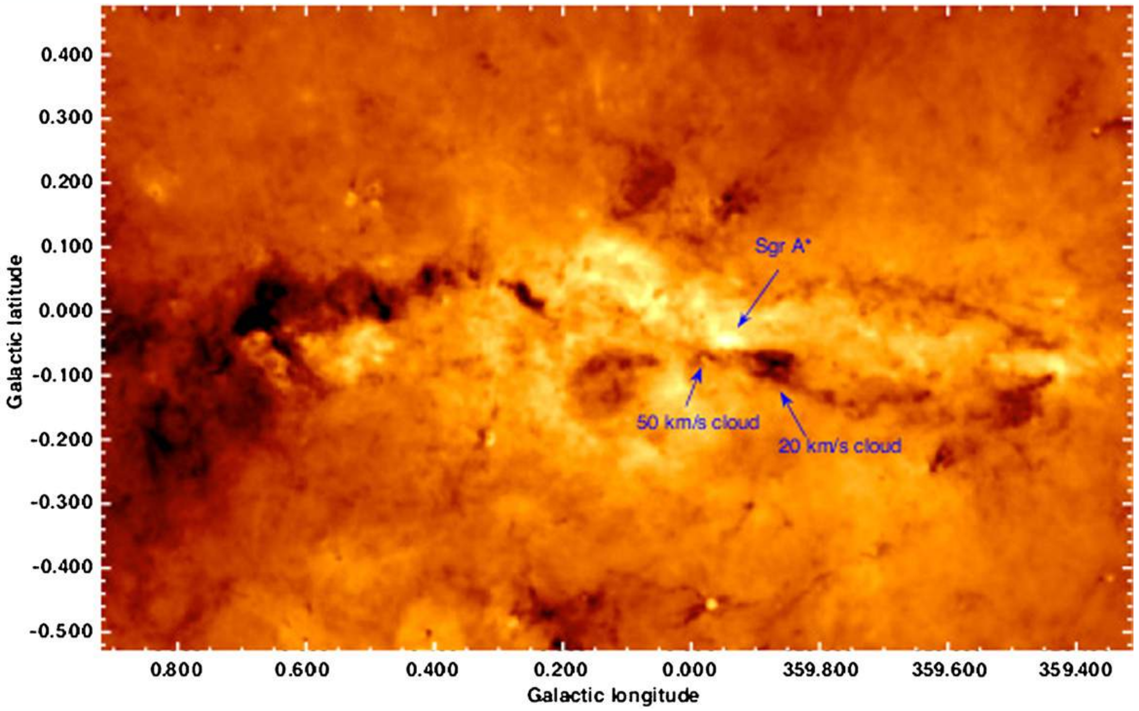
Kruijssen et al. (2015)

problem:

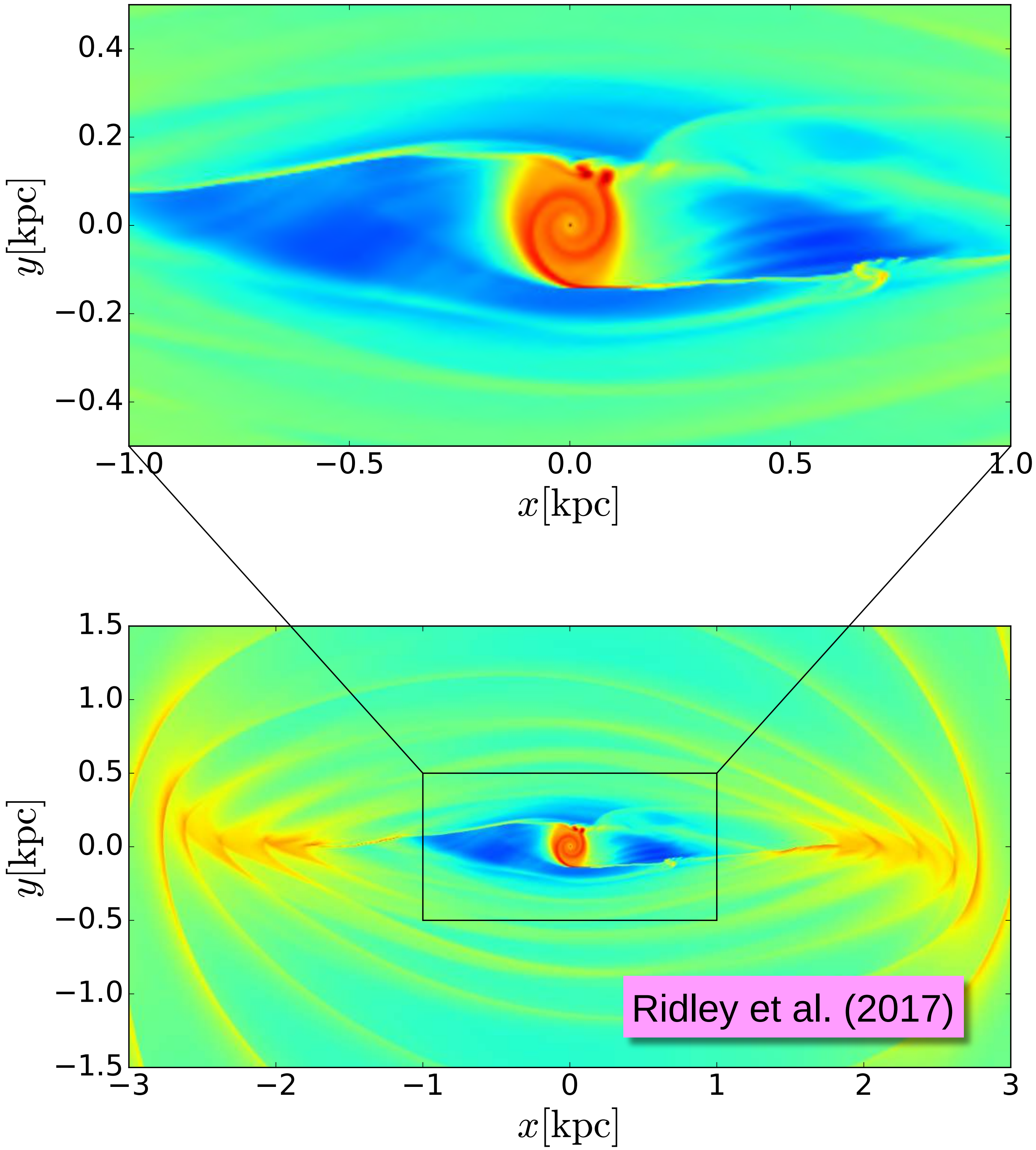
- need to feed orbit for ~4 Myr with source not changing in position or injection velocity (strict interpretation)
- must dump ~10^7 M_{sun} on orbit in single event (workaround)

Lucas (2015)

Distribution of Dense Gas in CMZ

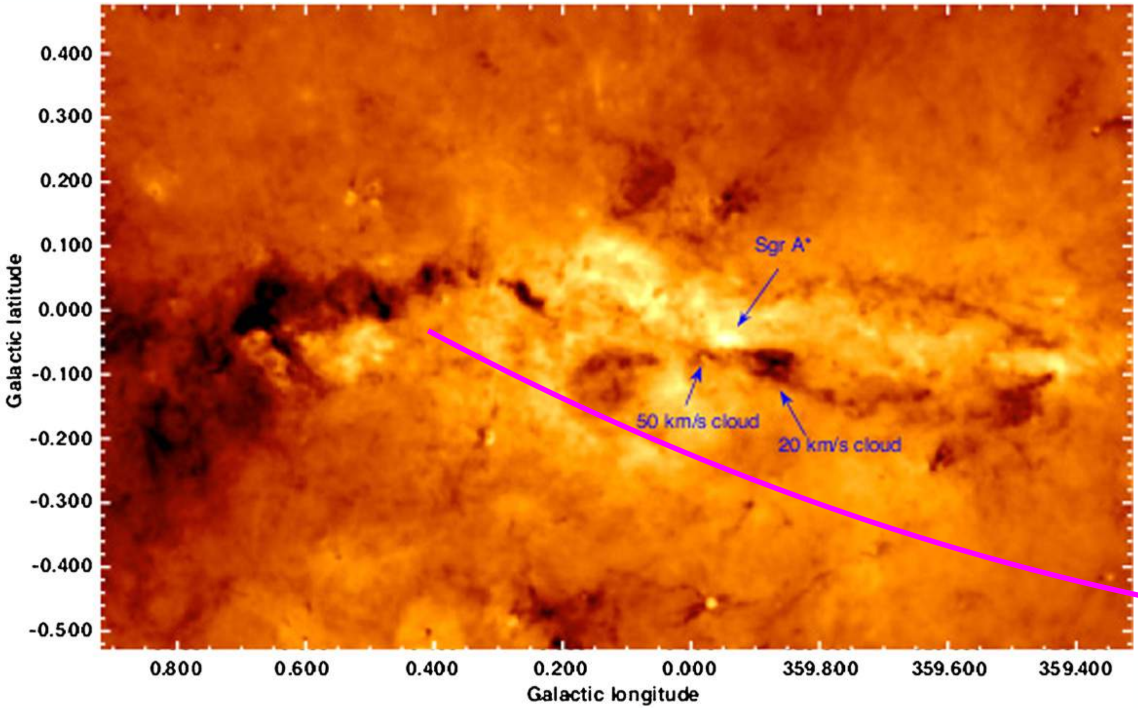


model: hydrodynamical flow



Ridley et al. (2017)

Distribution of Dense Gas in CMZ

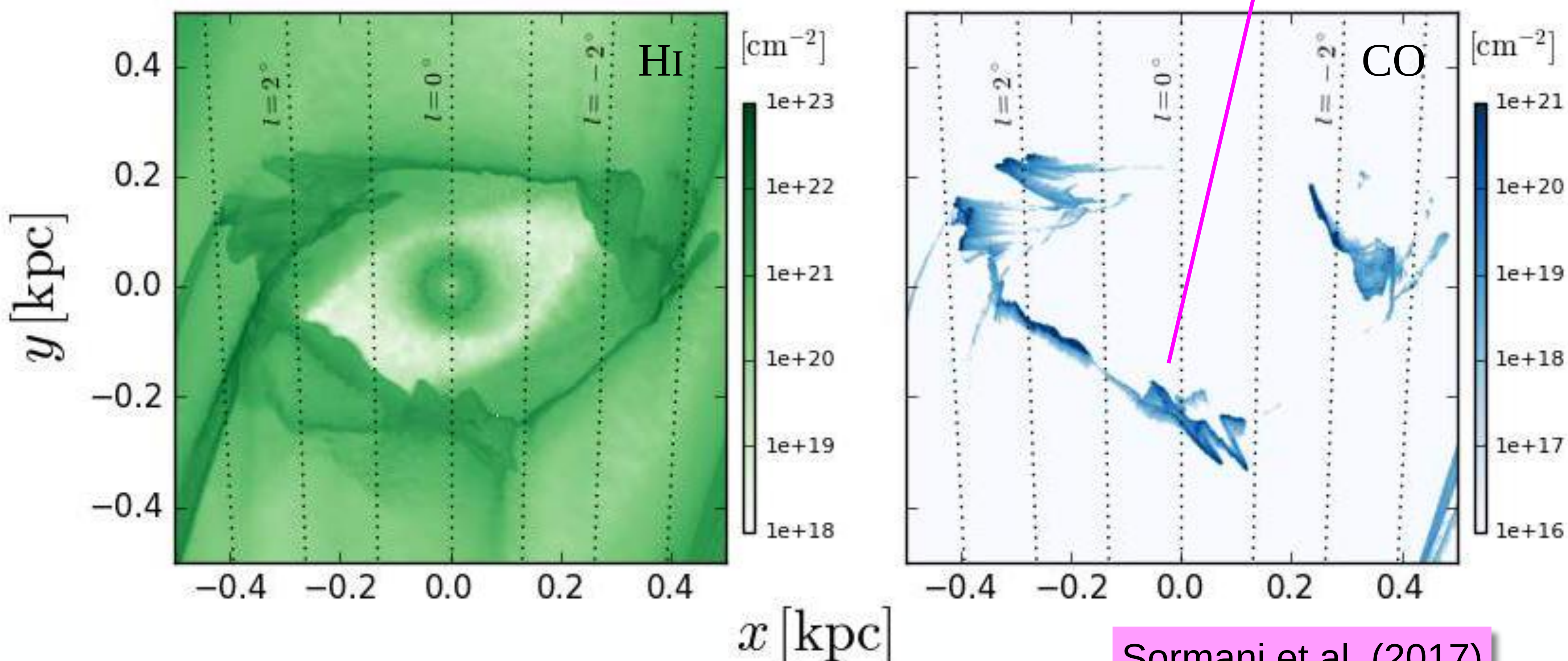


problem:

- not clear whether vertical structure reproducible — but limited physics included
- CMZ too large — but potential could be adjusted

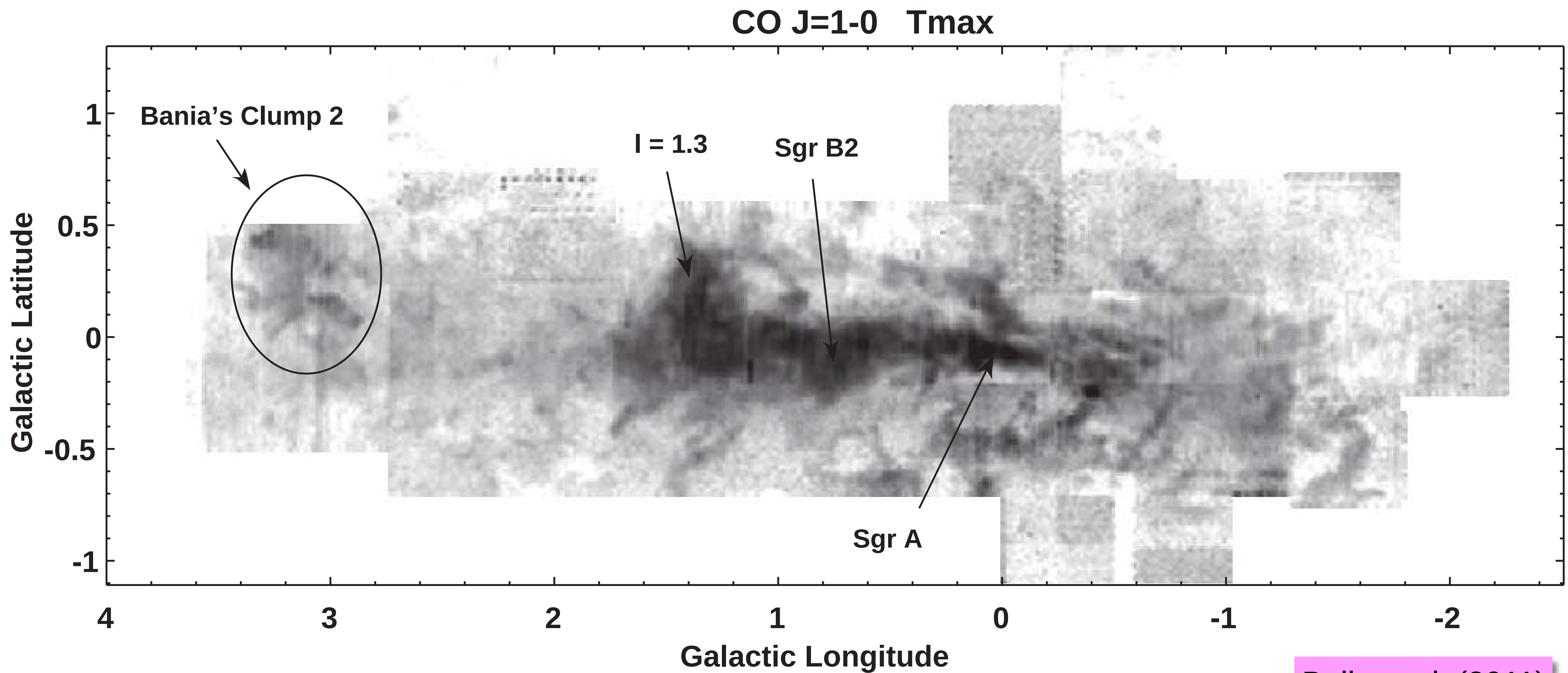
structure like dust ridge?

model: hydrodynamical flow



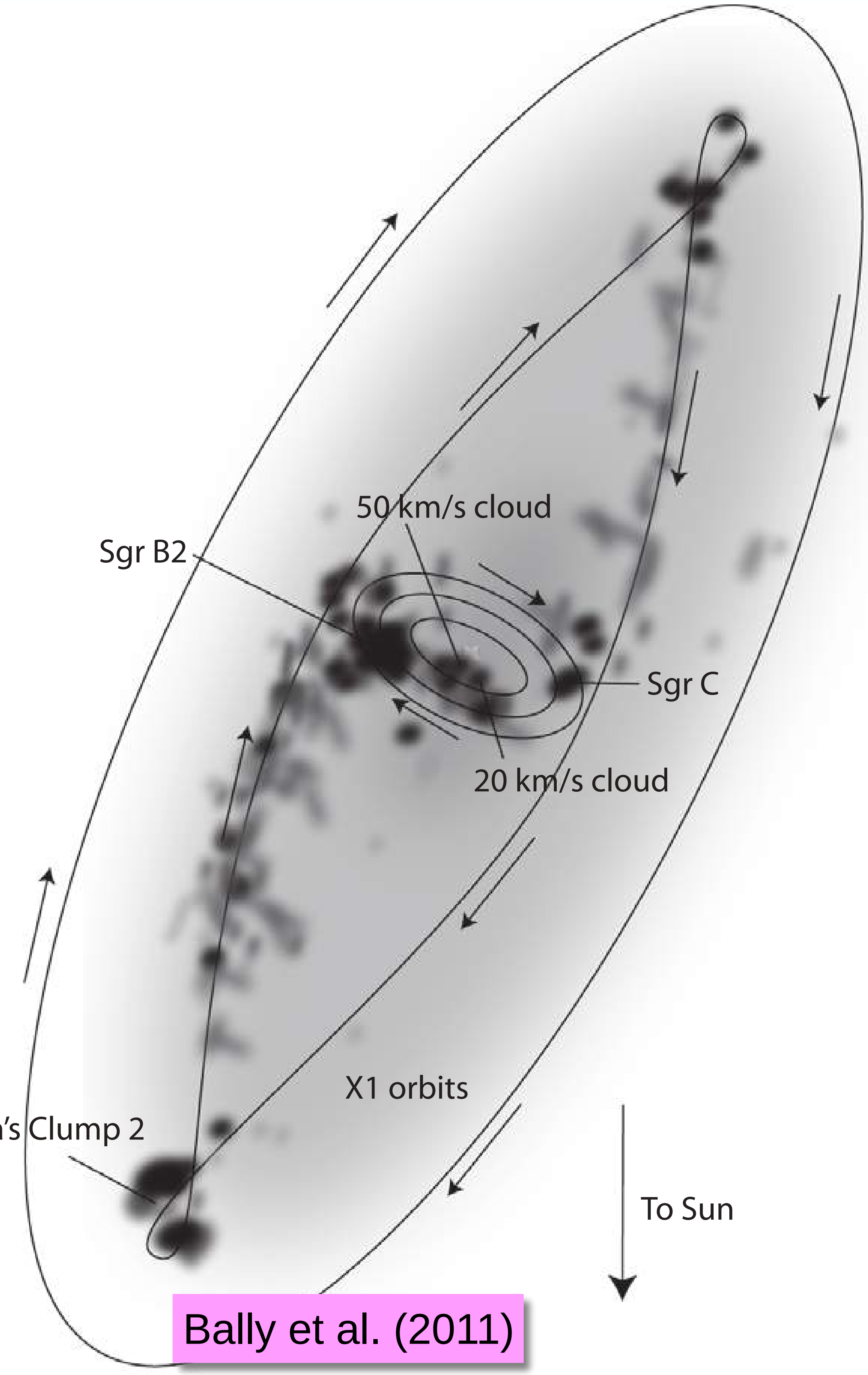
Sormani et al. (2017)

Gas Distribution is Asymmetric

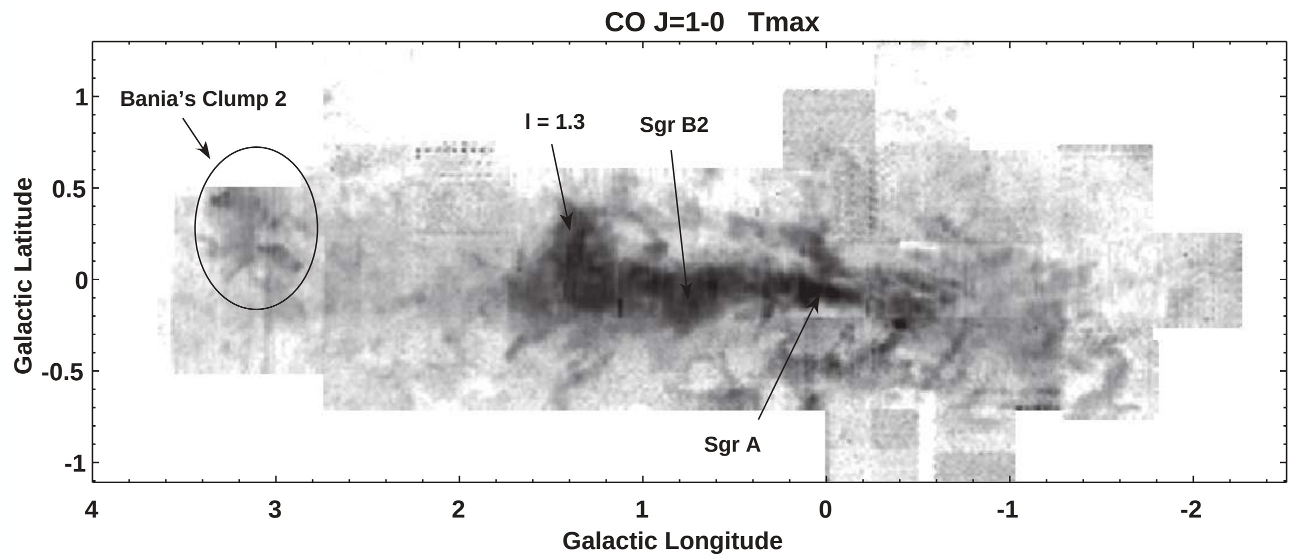


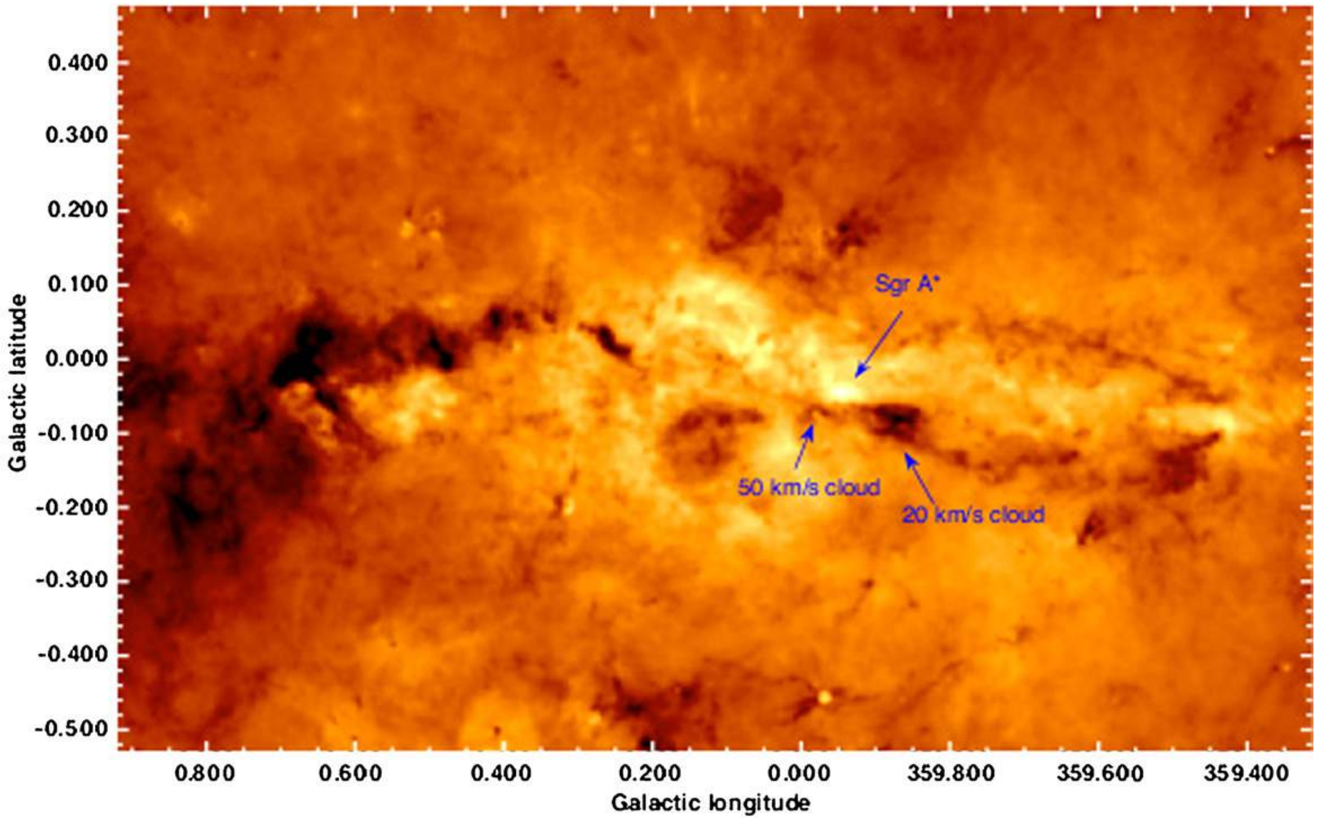
Bally et al. (2011)

Gas Distribution is Asymmetric

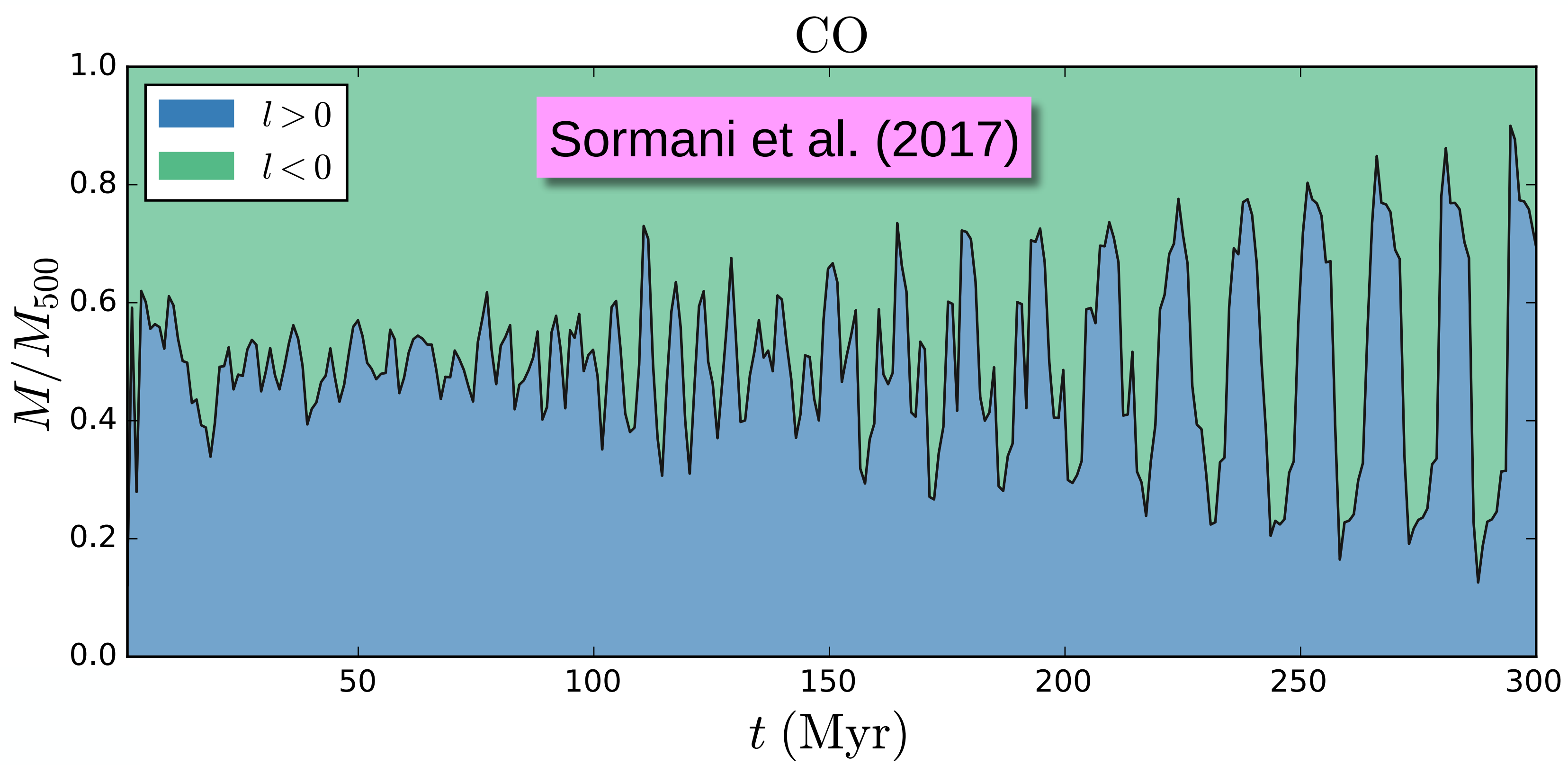


Bally et al. (2011)

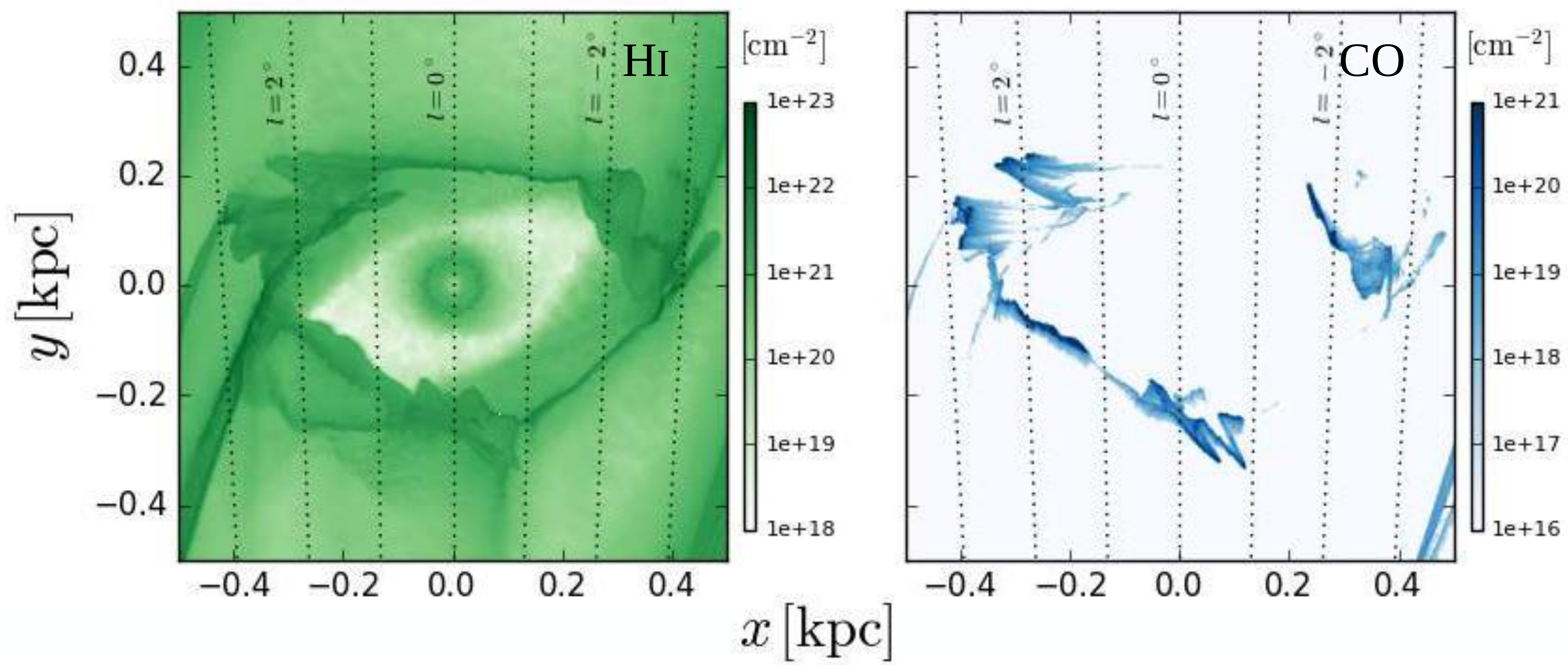




Gas Distribution is Asymmetric

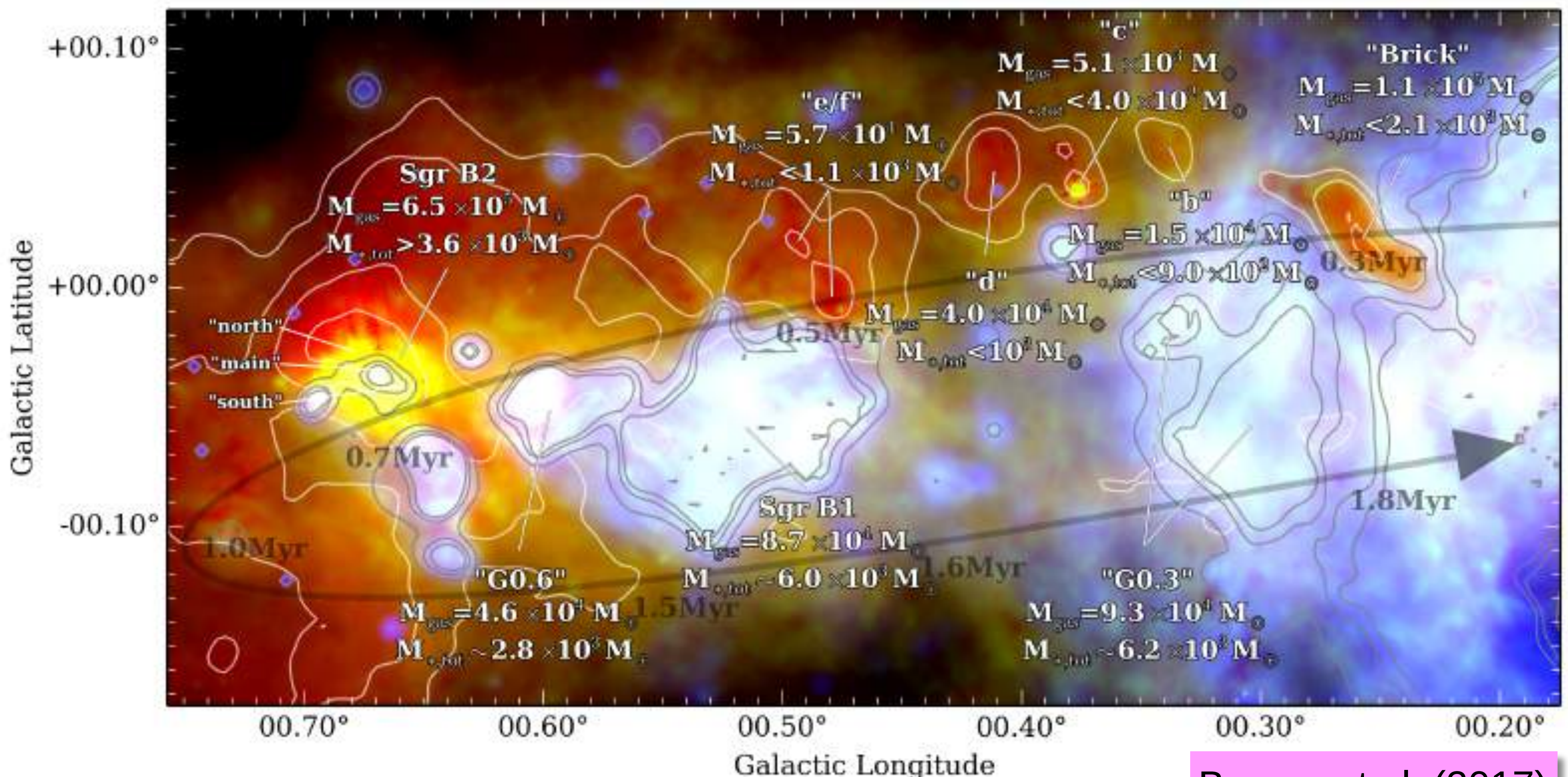


asymmetries naturally arise in hydrodynamical flows



Gas and Stars in the CMZ

Connection between Gas and Stars



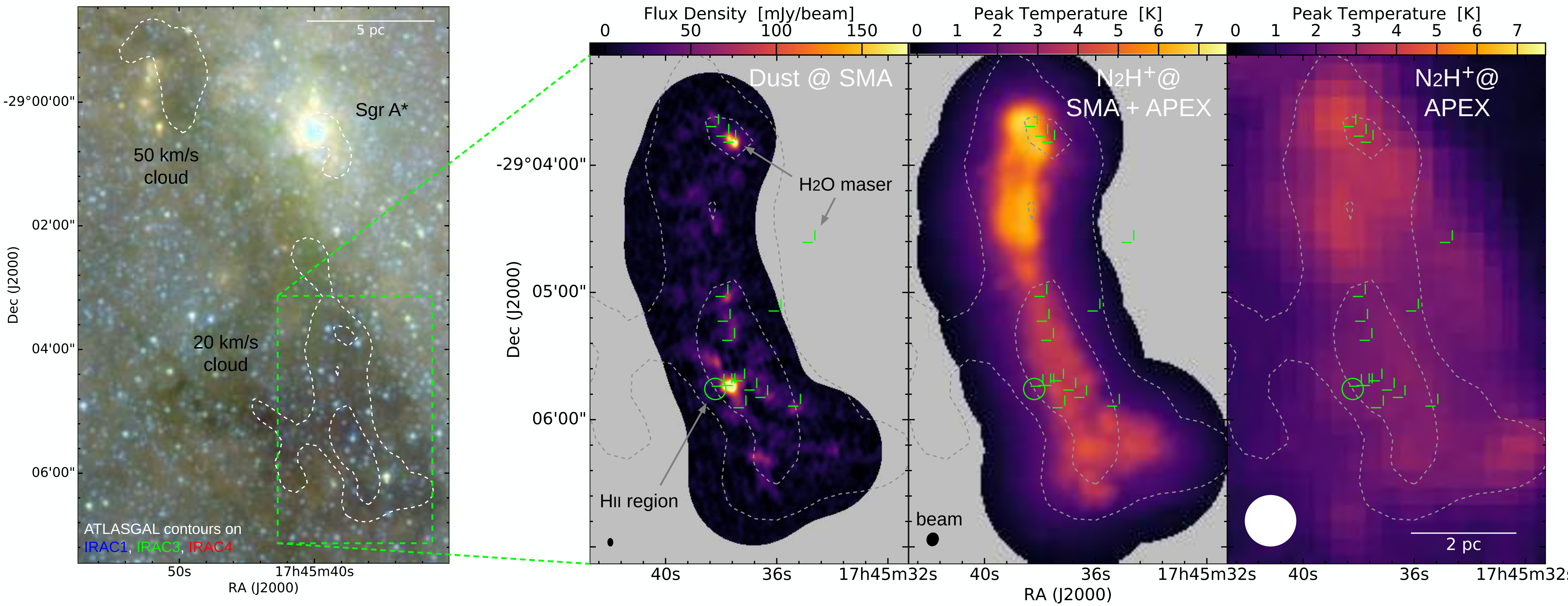
Barnes et al. (2017)

idea:
close passage to Sgr A* triggers SF via compression

Longmore et al. (2013)
Kruijssen et al. (2015)

plausible in the „dust ridge“
(but not proven)

Counter Example: SF ahead of Passage near Sgr A*

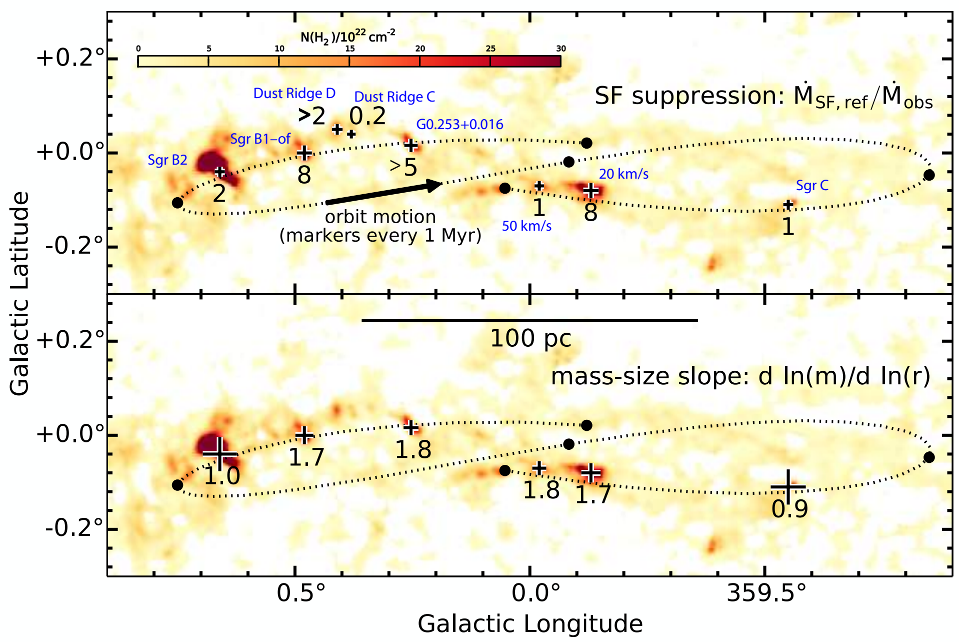


Lu et al. (2015)
Kauffmann et al. (2016a,b)

„mature“ star–forming cloud containing HII regions and H_2O masers

but 0.2 Myr to go until passage near Sgr A*

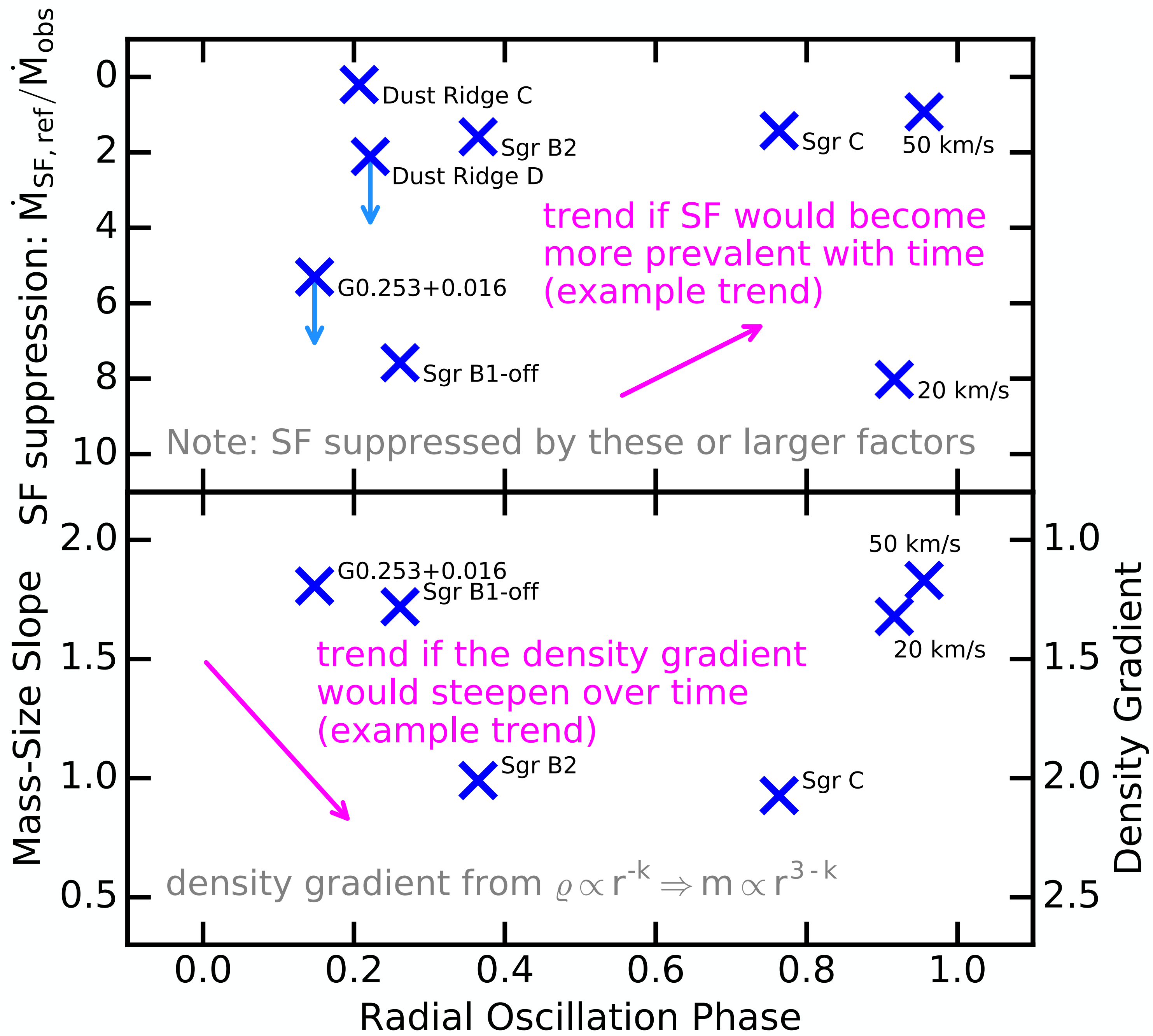
⇒ star formation ahead of supposed trigger



Kauffmann et al. (2017b)

trend in SF activity

trend in cloud structure

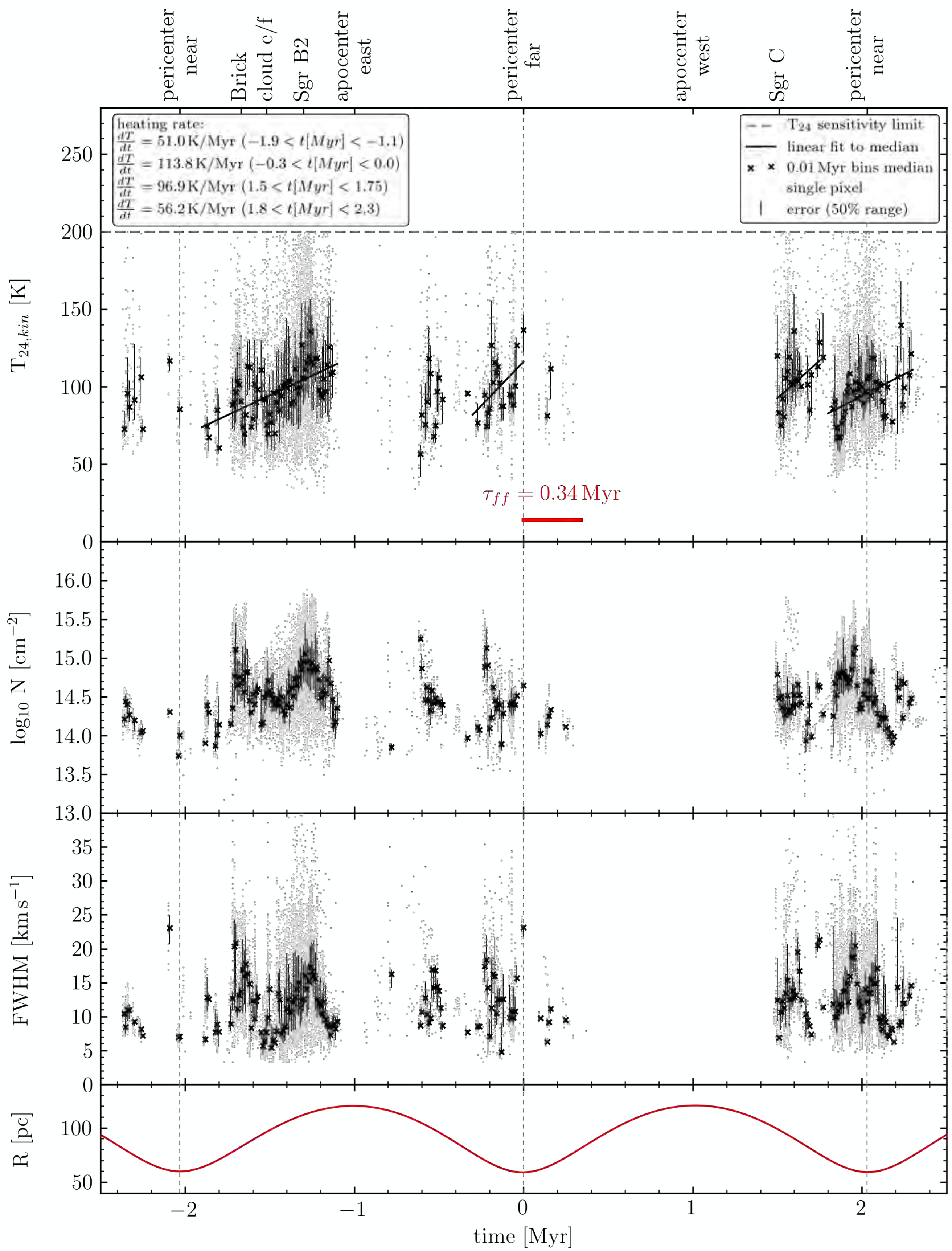


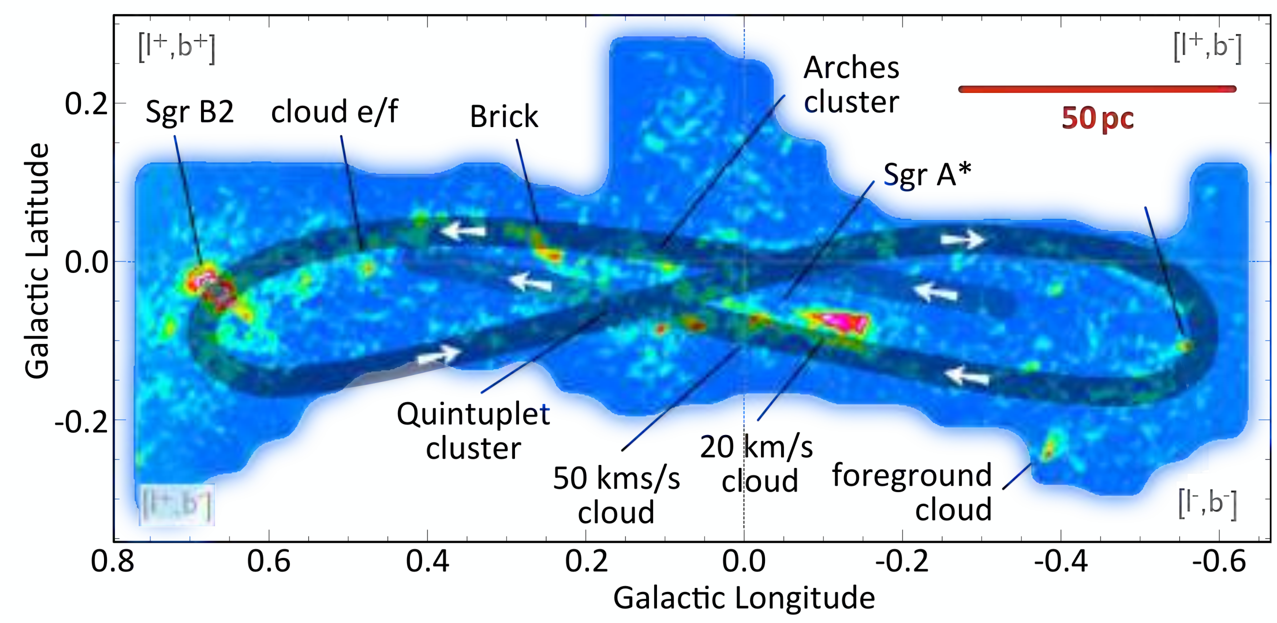
no obvious trend along orbit

=> no evolutionary timeline along orbit

SF triggering near Sgr A*
does not describe CMZ well

Global Evolution: NH_3 seen by the VLA



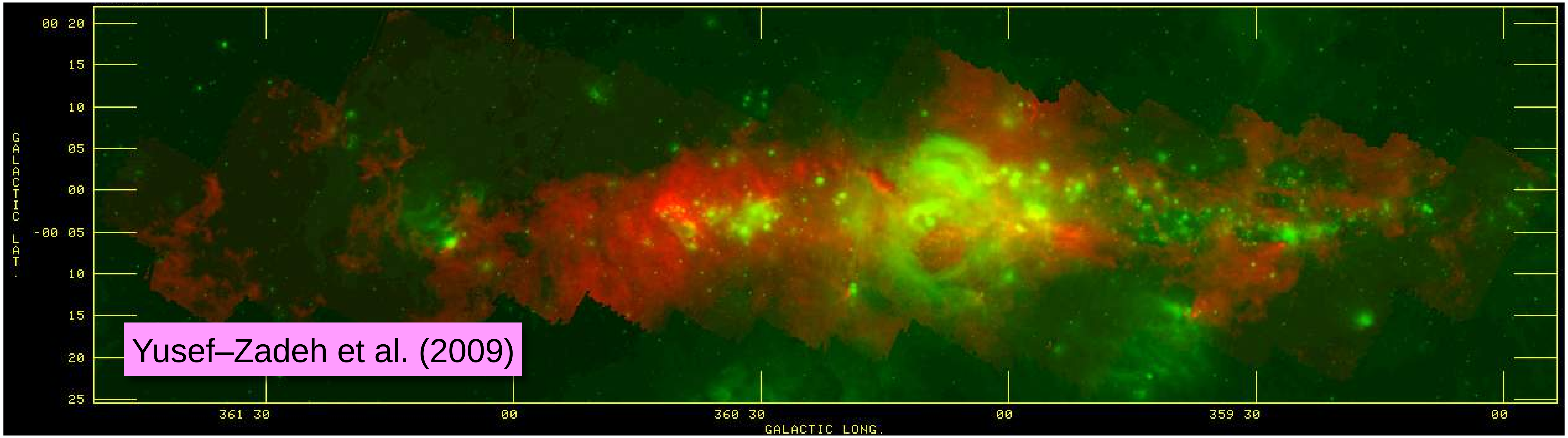


study of various NH_3–derived cloud properties

mixed evidence for global evolution

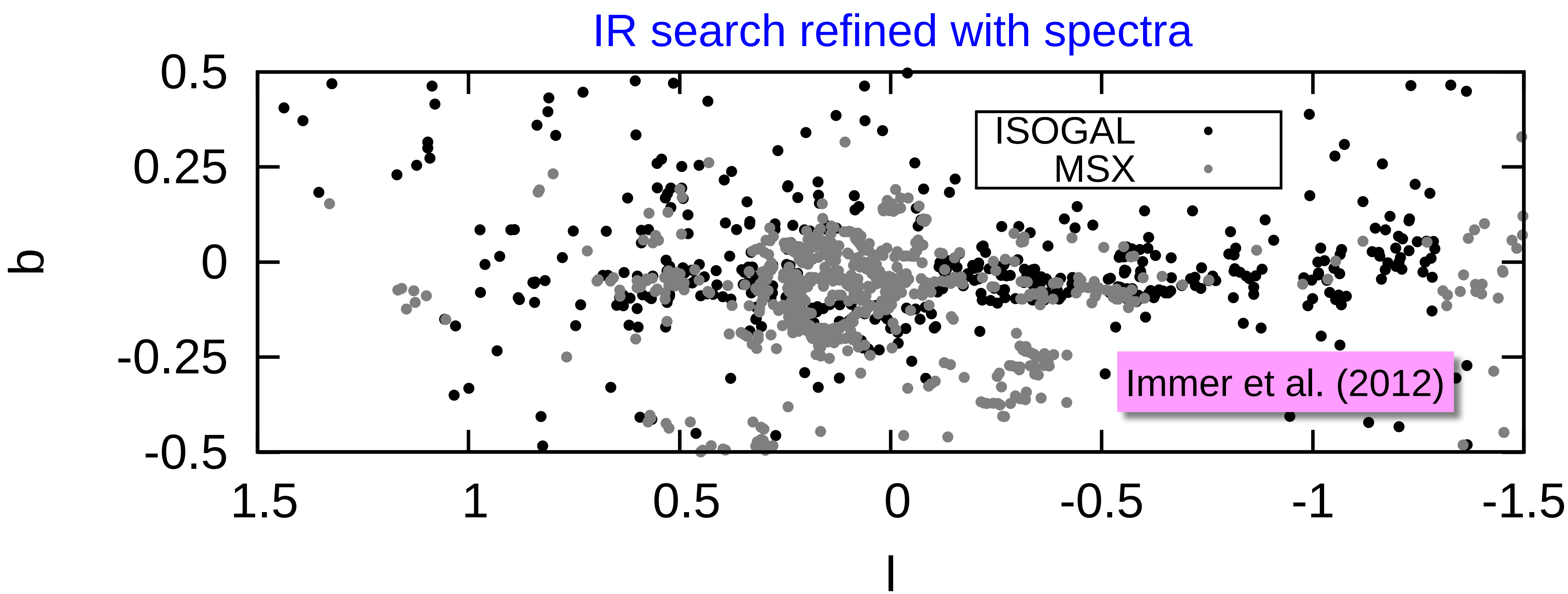
Krieger et al. (subm.)

Anticorrelation between Stars and Gas?



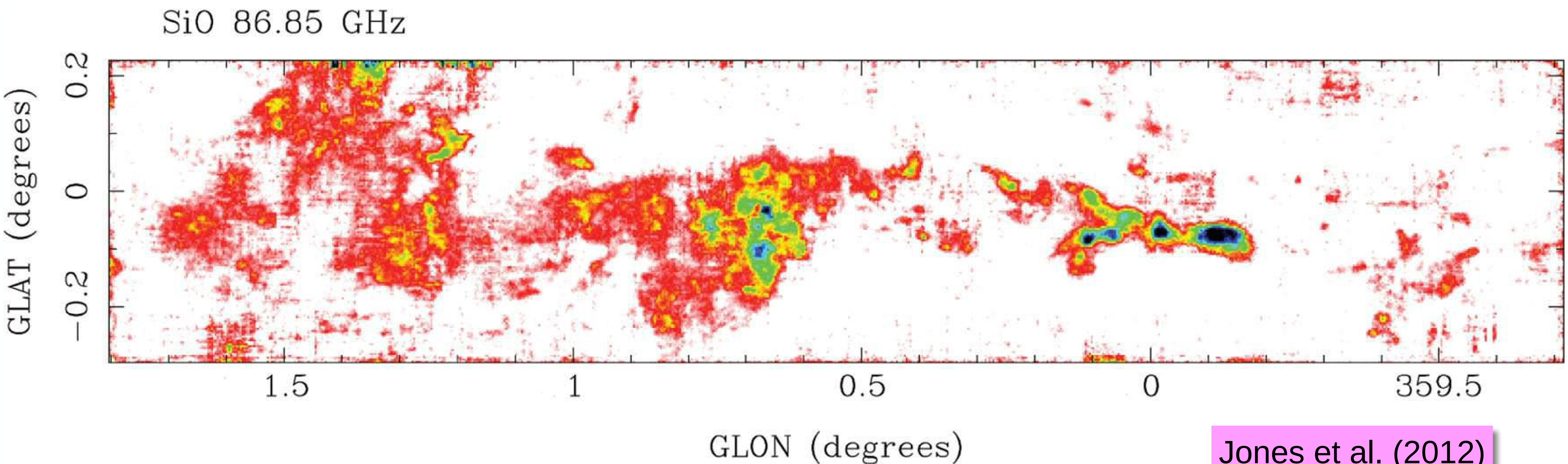
Yusef–Zadeh et al. (2009)

…or maybe just main–sequence stars illuminating clouds? Koepferl et al. (2015)



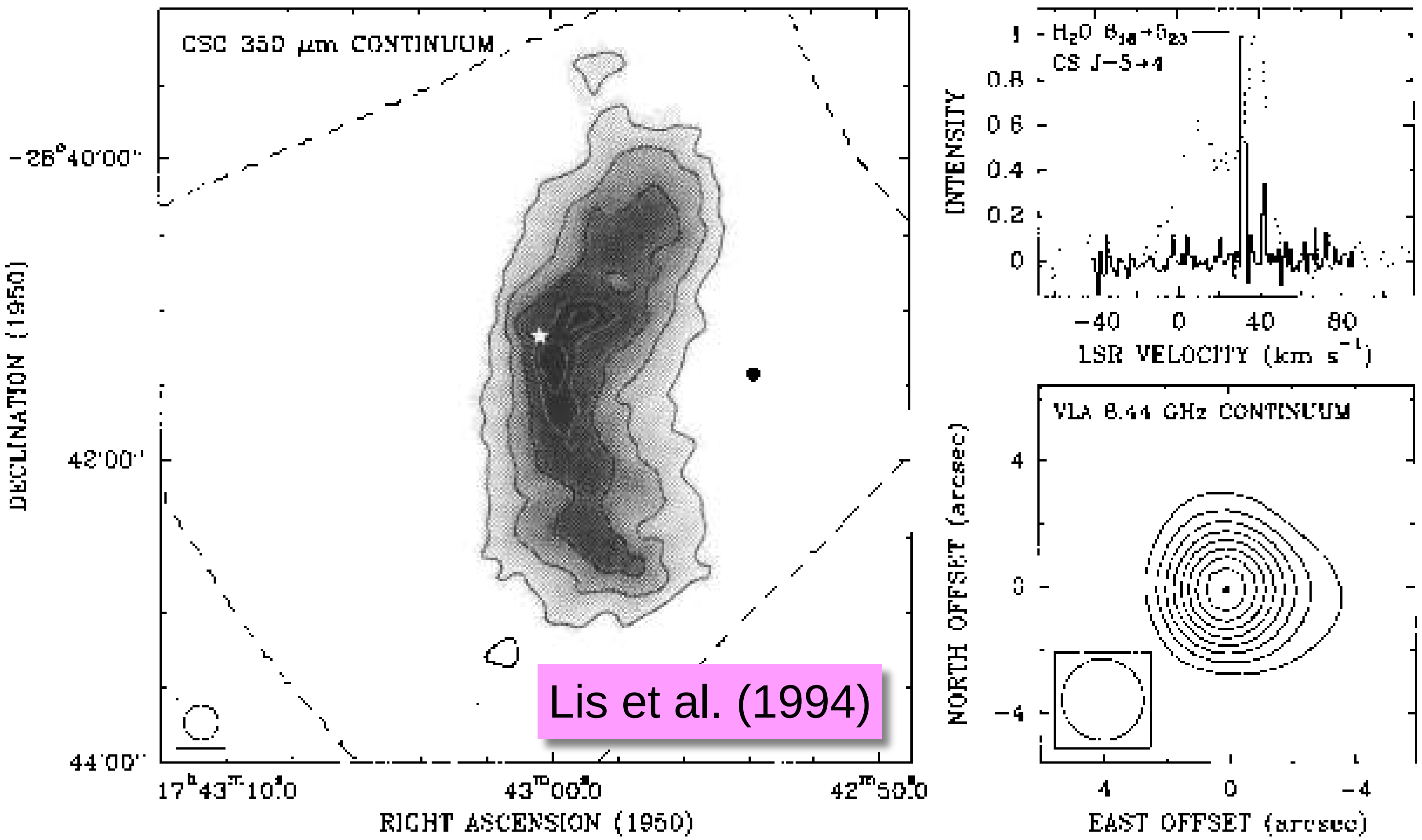
Immer et al. (2012)

Physical Processes in CMZ Clouds

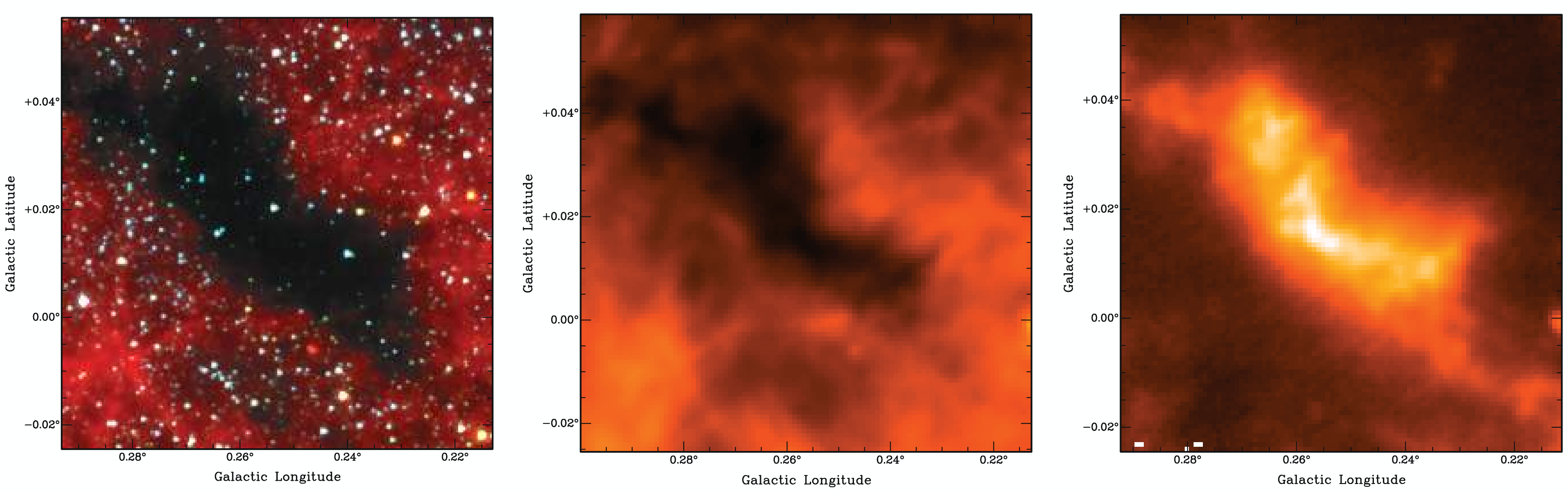


Jones et al. (2012)

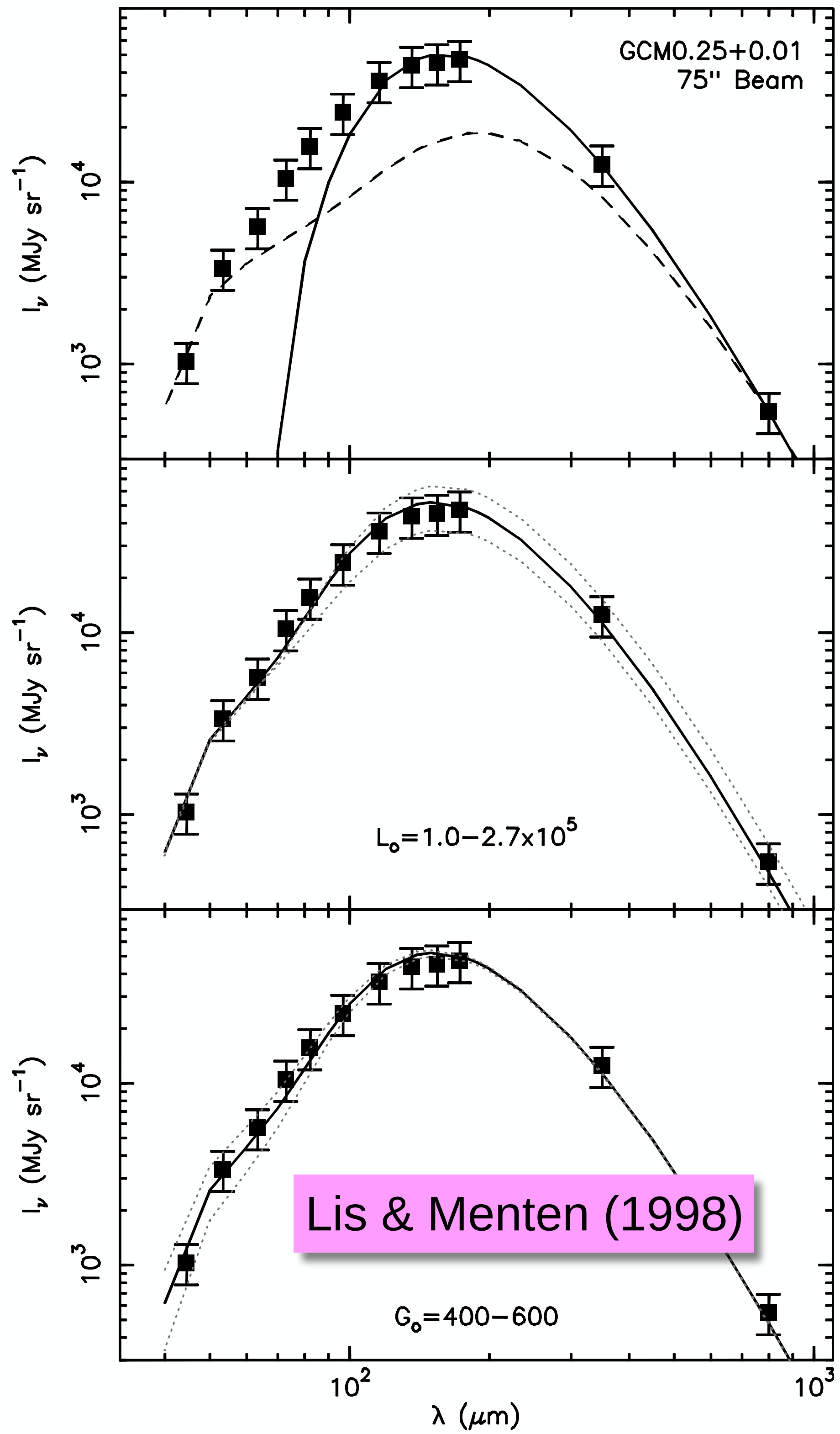
Original Research: Single–Dish Studies



Lis et al. (1994)

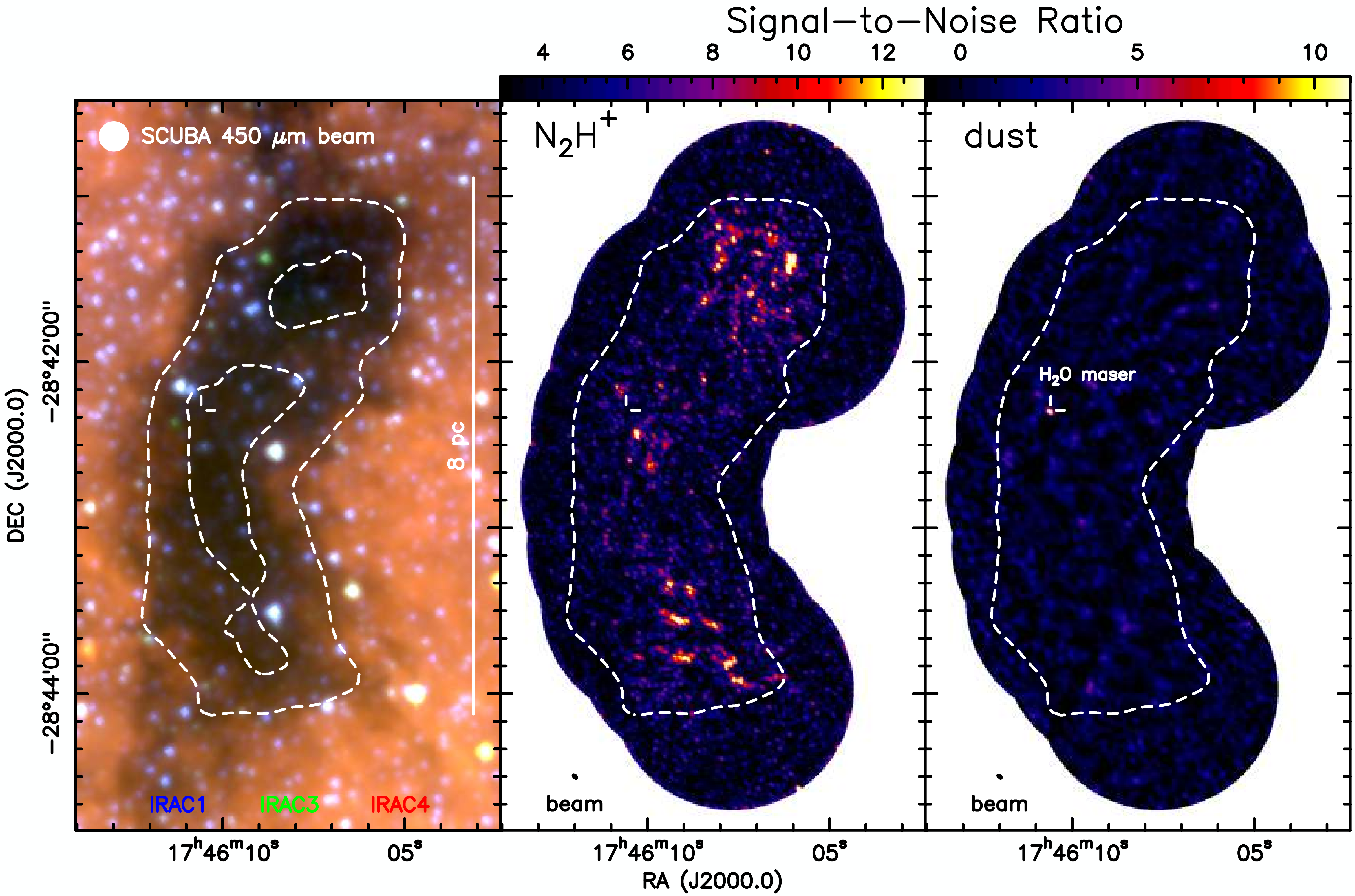


Longmore et al. (2012)

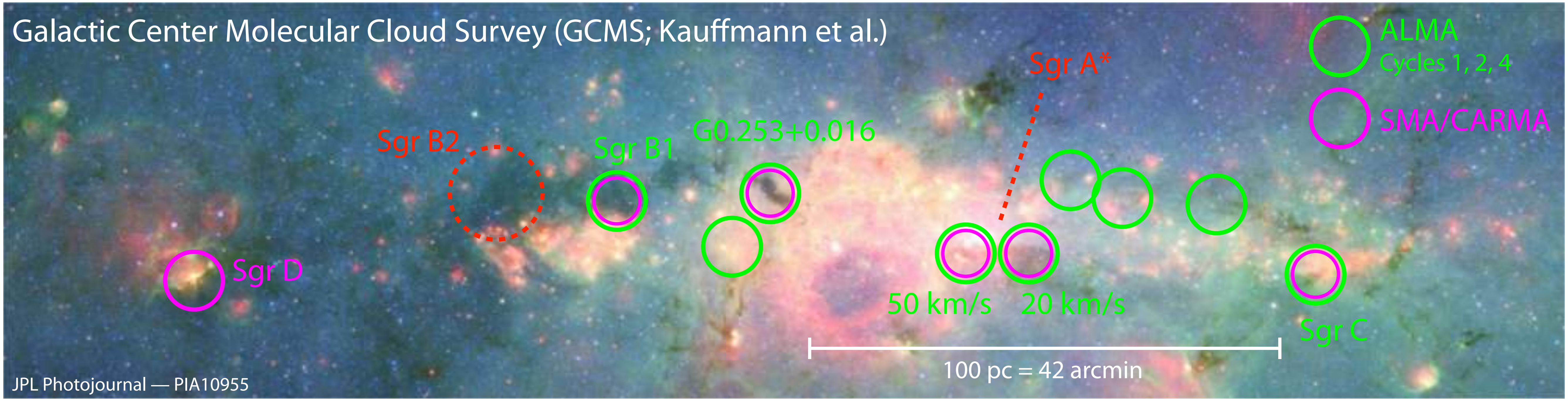


Lis & Menten (1998)

Recent Development: Resolved Views of CMZ Clouds



Kauffmann et al. (2013a)



Galactic Center Molecular Cloud Survey (GCMS):

ALMA (~30h), SMA (~100h), CARMA (~100h)

includes first high–resolution study of all major CMZ clouds

Kauffmann et al. (2013a, 2017a,b)

numerous studies of selected fields:

using ALMA, VLA, and SMA

Rathborne et al., Mills et al., Lu et al., Walker et al., Kendrew et al., Yusef–Zadeh et al.

CMZoom: SMA (~500h)

covers all area at high column density

Battersby, Keto et al. (in prep.)

C–band survey: VLA (~3h)

covers all area at high column density

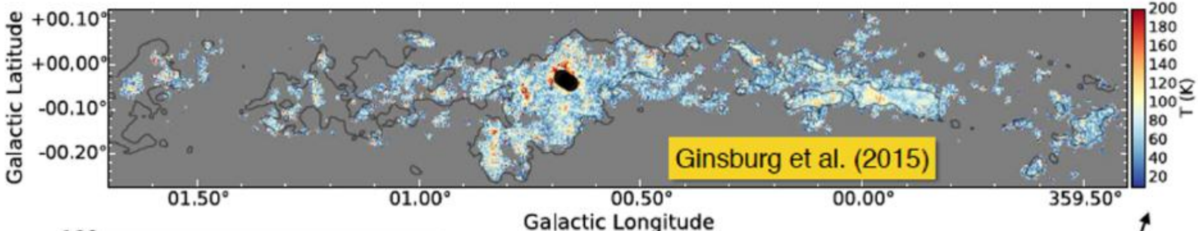
Lu et al. (in prep.)

Physical Processes in CMZ Clouds

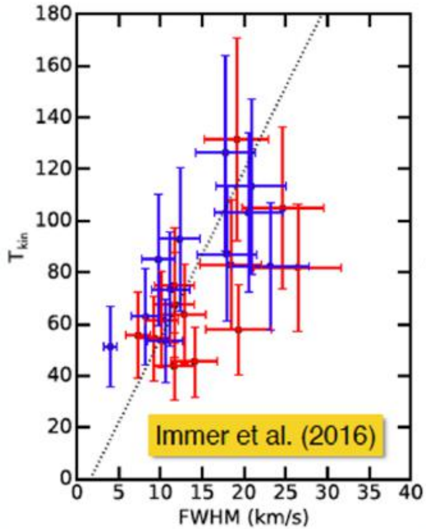
gas is warm (T_{gas} = 50–100 K)

thermal Jeans Mass high

Observations of Gas Temperatures



gas is warm



gas is heated by turbulence

gas temperature matters for SF:

$$M_{\rm BE} = 20\,M_\odot \cdot (\,T_{\rm gas}/50\ {\rm K})^{3/2} \cdot (n_{\rm H_2}/10^5\ {\rm cm}^{-3})^{-1/2}$$

=> hard to form stars?!

Physical Processes in CMZ Clouds

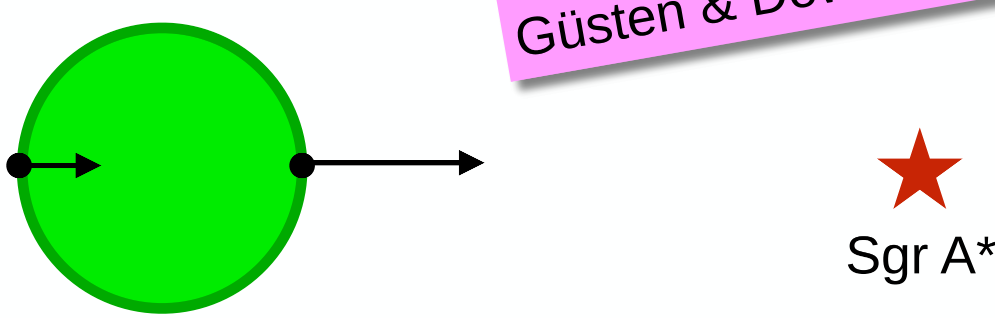
clouds are *not* disrupted by tidal forces

classical treatment:

cloud sectors closer to Sgr A* are torn away
if binding is not strong enough

=> CMZ clouds must be dense

Güsten & Downes (1980)

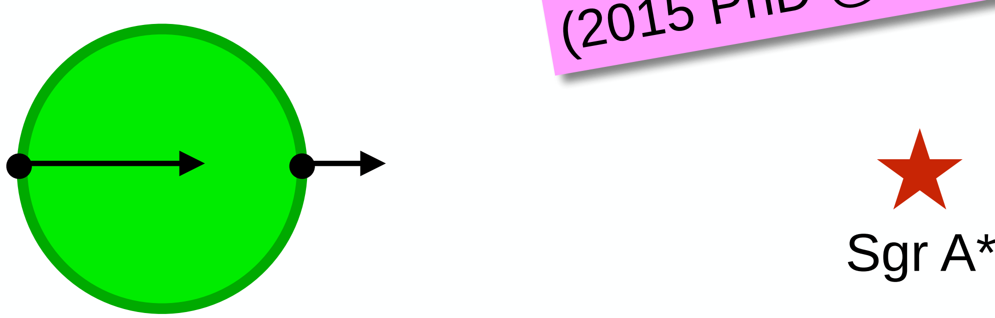


with new potential:

$$M(r) \propto r^{\gamma}\,, \quad F_{\rm grav} = G\,\frac{M(r)\,m}{r^2}$$

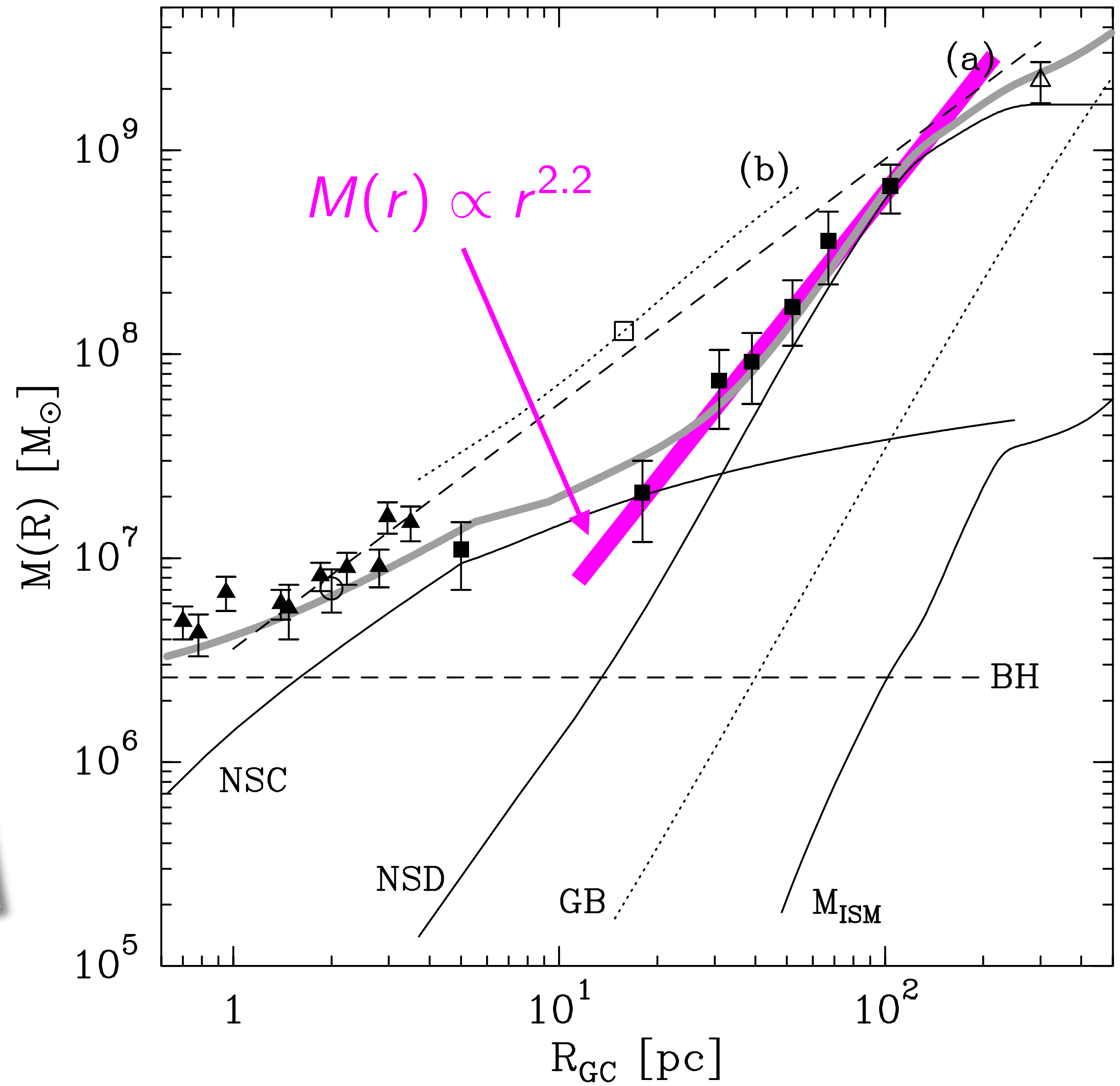
$$\Rightarrow F_{\rm grav} \propto r^{\gamma-2} = r^{0.2}$$

William Lucas
(2015 PhD @ St. Andrews)



=> no limit on cloud density

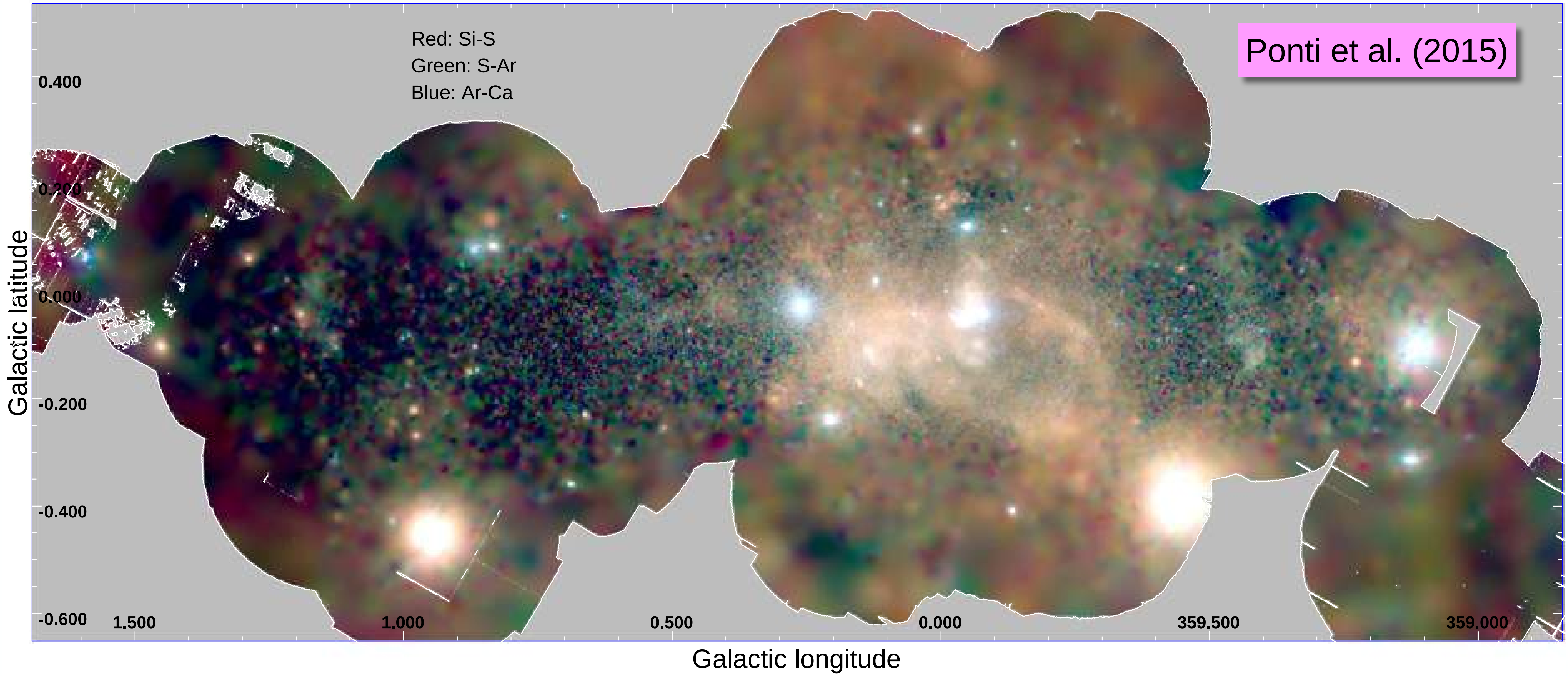
Launhardt et al. (2002)



Physical Processes in CMZ Clouds

clouds are dense due to confining pressure(?)

High Thermal Plasma Pressure confining Clouds



hot plasma from X–ray data

=> confining pressure

in pressure equilibrium:

$$T_{\rm plasma} = 10^7~{\rm K}\,, \quad n_{\rm plasma} \sim 0.1~{\rm cm}^{-3}$$

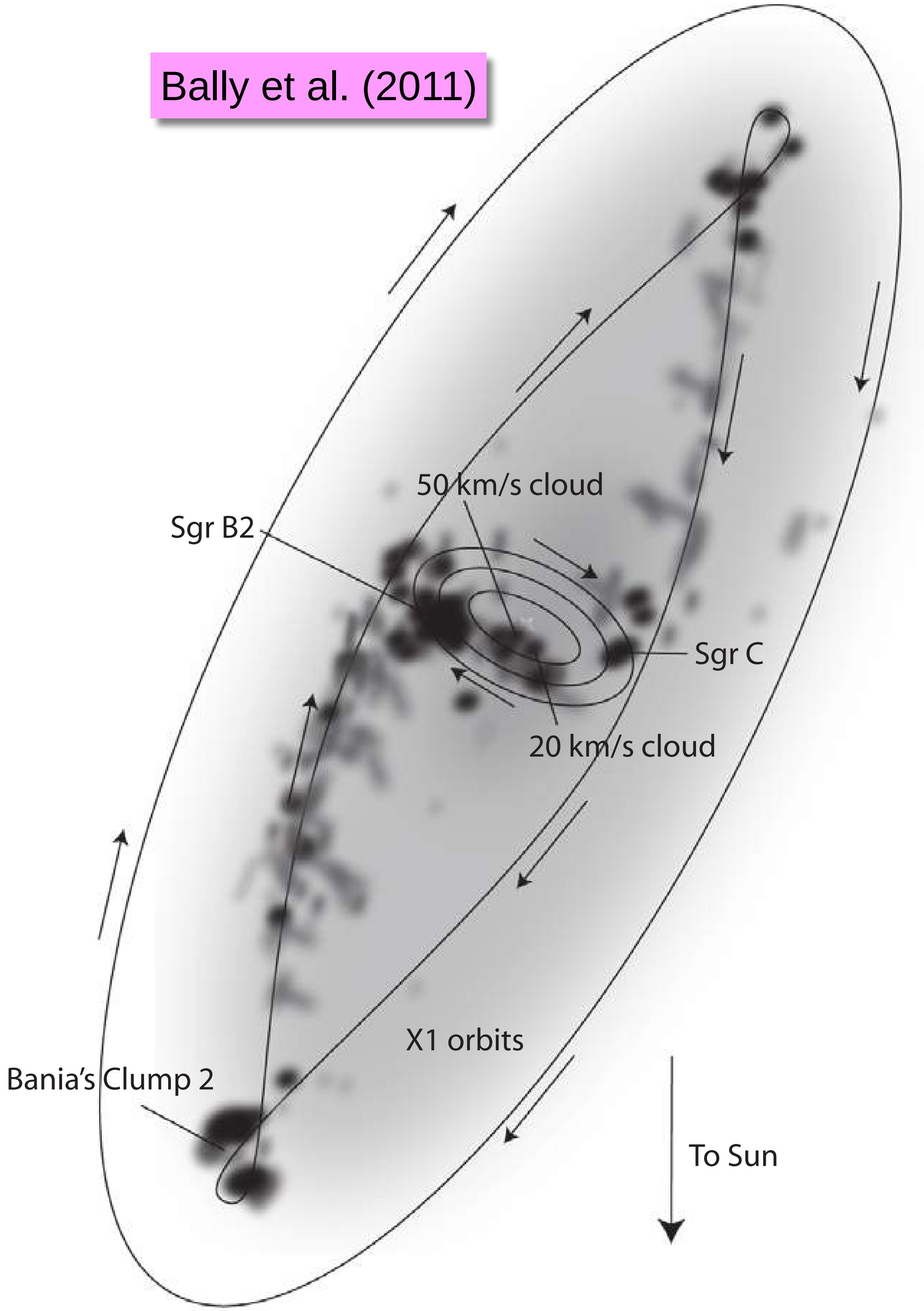
$$\Rightarrow~n_{\rm dense} = 10^4~{\rm cm}^{-3} \cdot (\,T_{\rm dense}/100~{\rm K})^{-1}$$

Physical Processes in CMZ Clouds

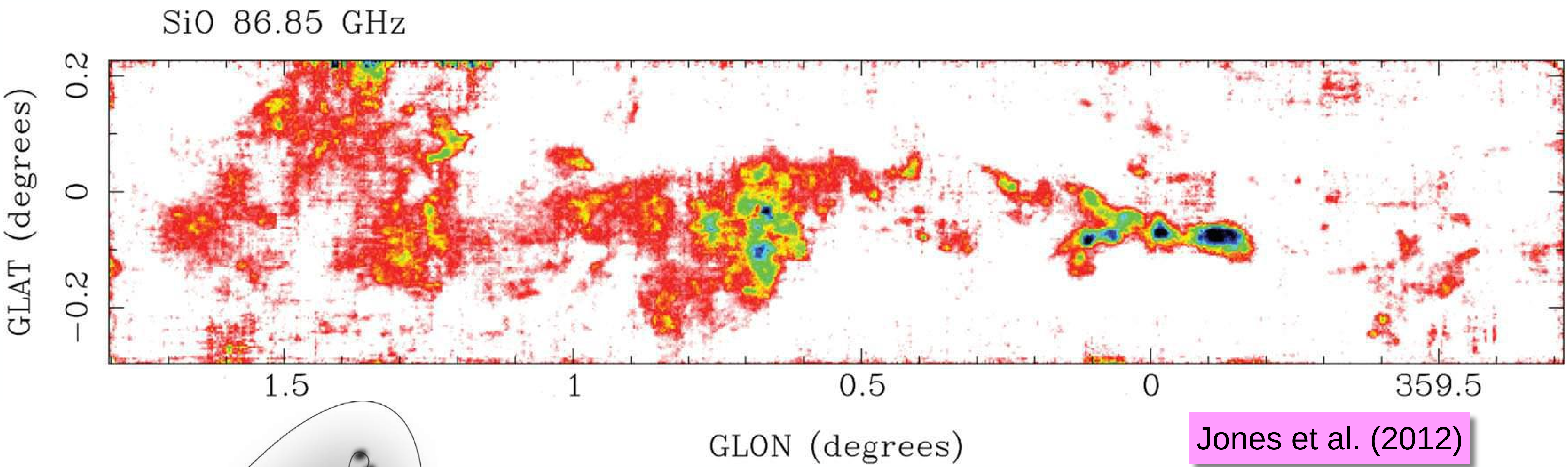
clouds are — probably — highly disturbed

Cartoon of CMZ Orbits

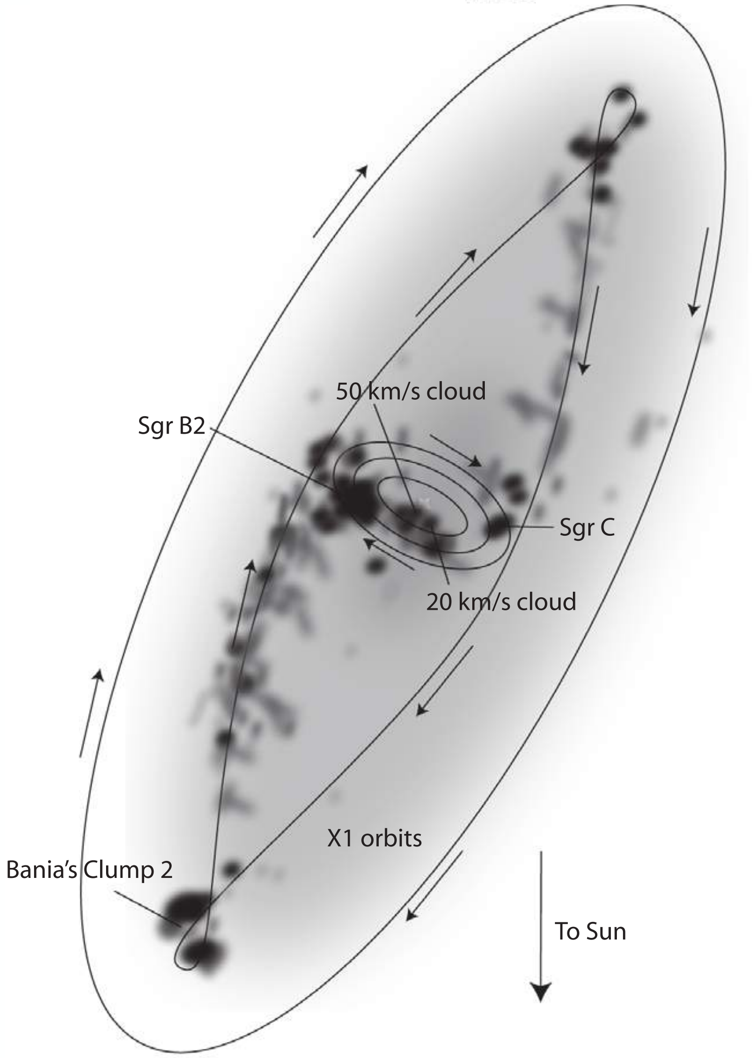
Bally et al. (2011)



Cartoon of CMZ Orbits



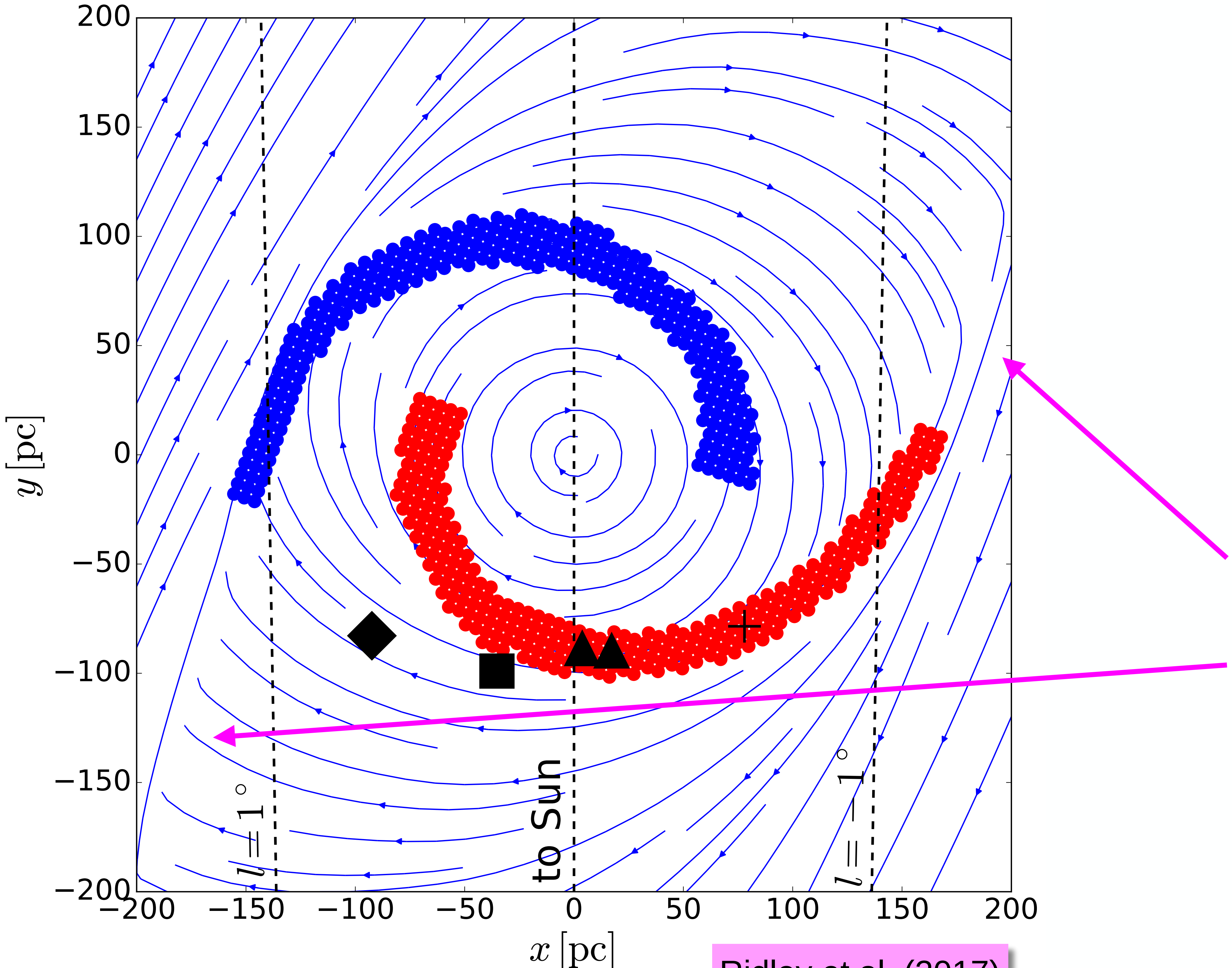
Jones et al. (2012)



mass transfer between orbits

=> energy losses needed

=> shocks?!

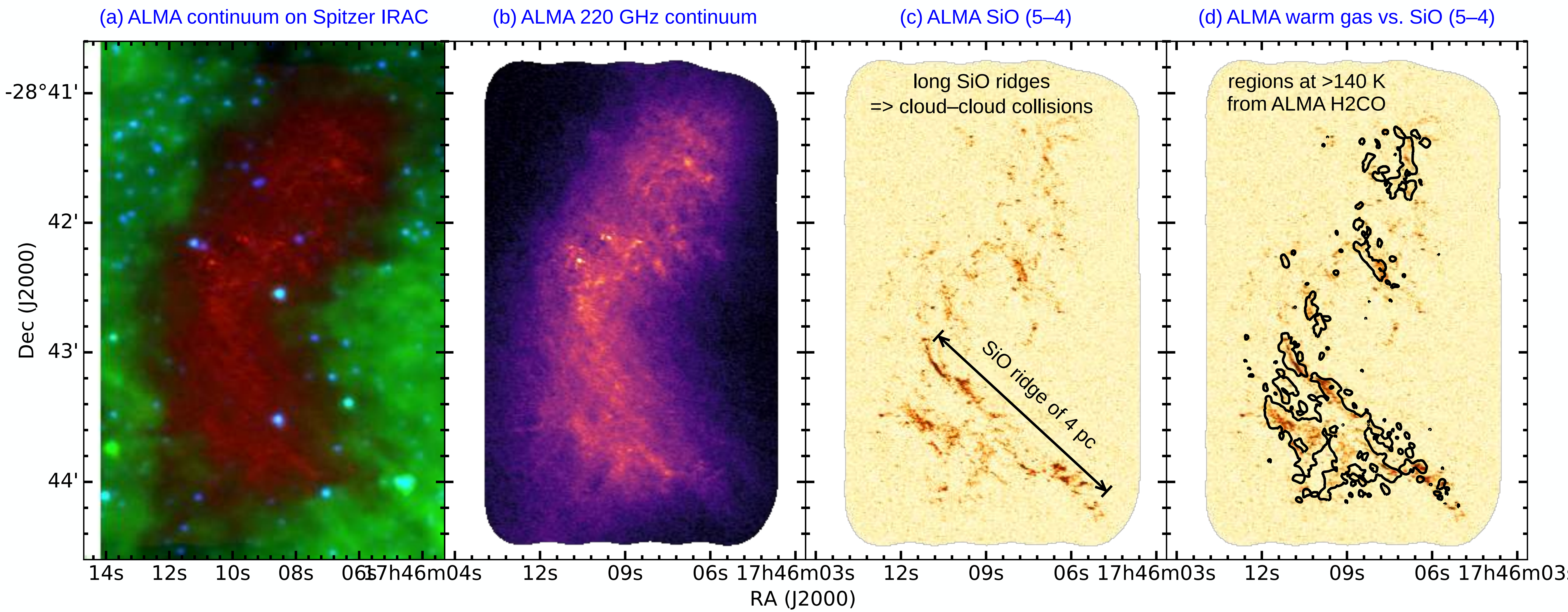


Ridley et al. (2017)

colliding flow lines

=> shocks

Shocks also prevail in Clouds



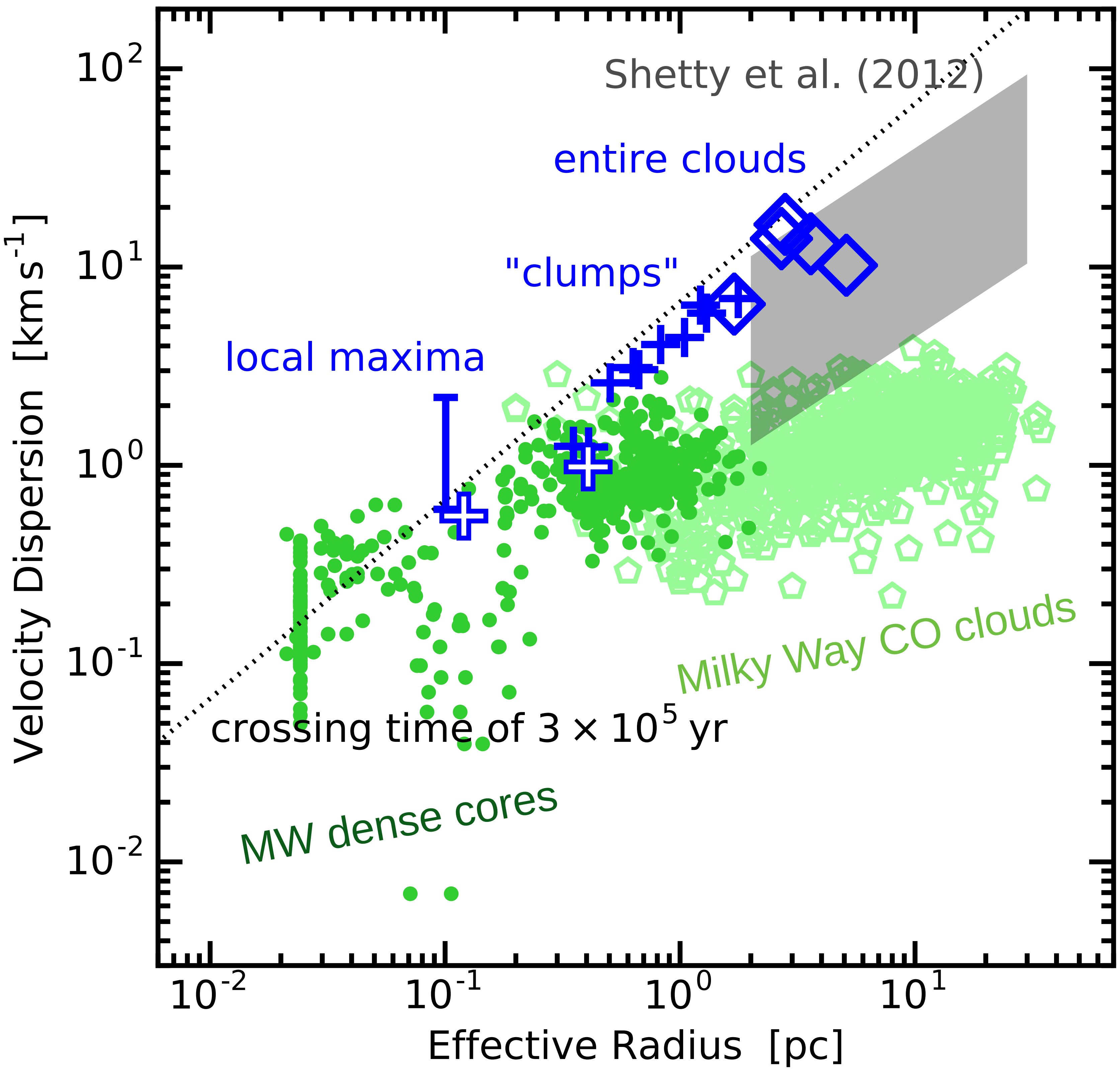
Kauffmann et al. (in prep.)

Physical Processes in CMZ Clouds

clouds have steep linewidth–size relations

(calm cores in turbulent clouds)

„Calm“ Dense Cores in „turbulent“ Clouds



moderate turbulence on spatial scales ≲1 pc!

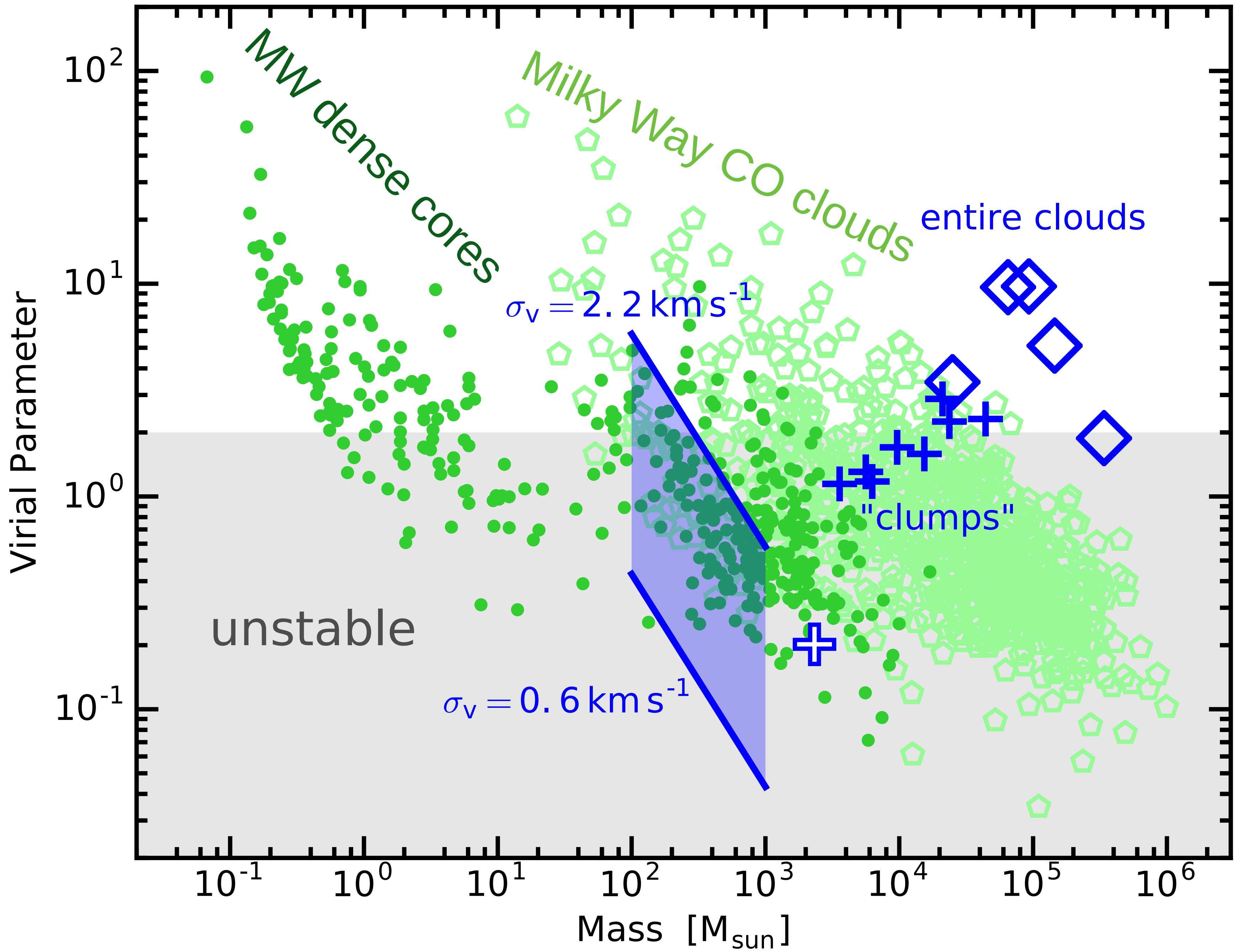
unusually steep linewidth–size relation

Kauffmann et al. (2013a,b)
Kauffmann et al. (2016a,b)

Physical Processes in CMZ Clouds

bound cores reside in marginally bound clouds

Bound Cores within Marginally Bound Clouds



$$\alpha = a\,\frac{2E_{\rm kin}}{|E_{\rm pot}|}$$

(second Larson rel.)

moderate gravitational binding
compared to HMSF clouds in the plane

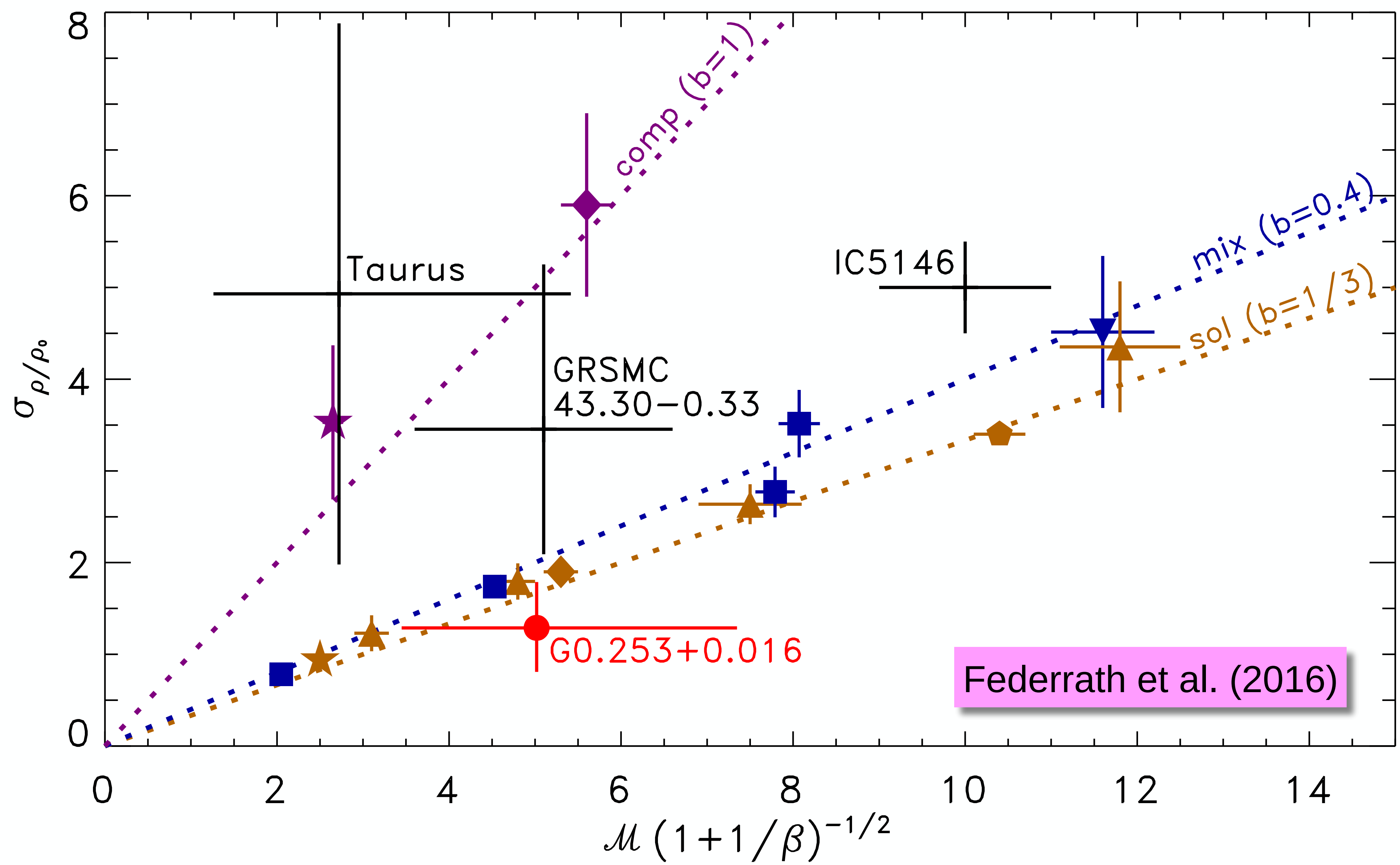
Pillai et al. (2011)
Li et al. (2013)
Kauffmann et al. (2013a,b)
Kauffmann et al. (2016a,b)

Physical Processes in CMZ Clouds

turbulence primarily solenoidal

(in contrast to rest of Milky Way)

Relation between Density Fluctuation and Velocity Dispersion

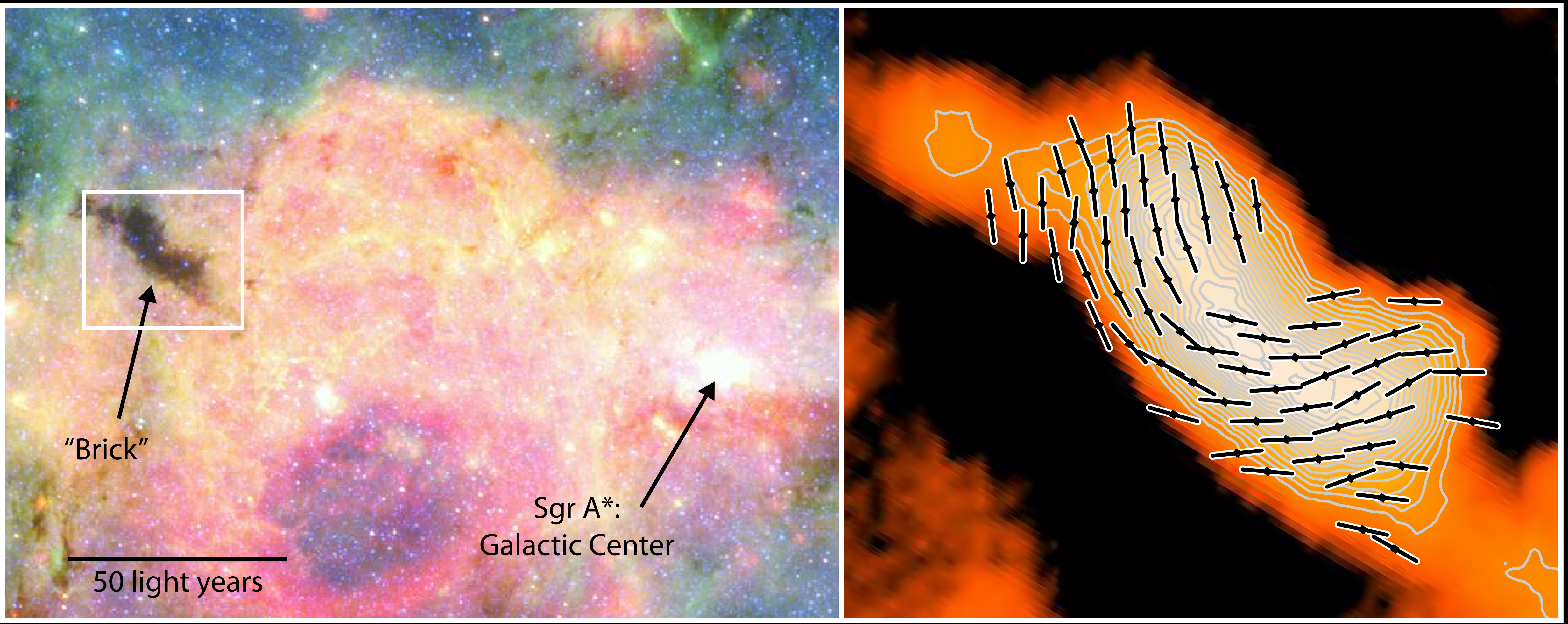


nature of turbulence in CMZ might be different from rest of Milky Way

Physical Processes in CMZ Clouds

magnetic support is strong

Magnetic Fields in CMZ Clouds



Pillai, Kauffmann et al.   MPG & MPIfR Press Release 1/2015

dust polarization observations:
~5500 µG in G0.253+0.016

Pillai et al. (2015)

strong magnetic fields in CMZ!

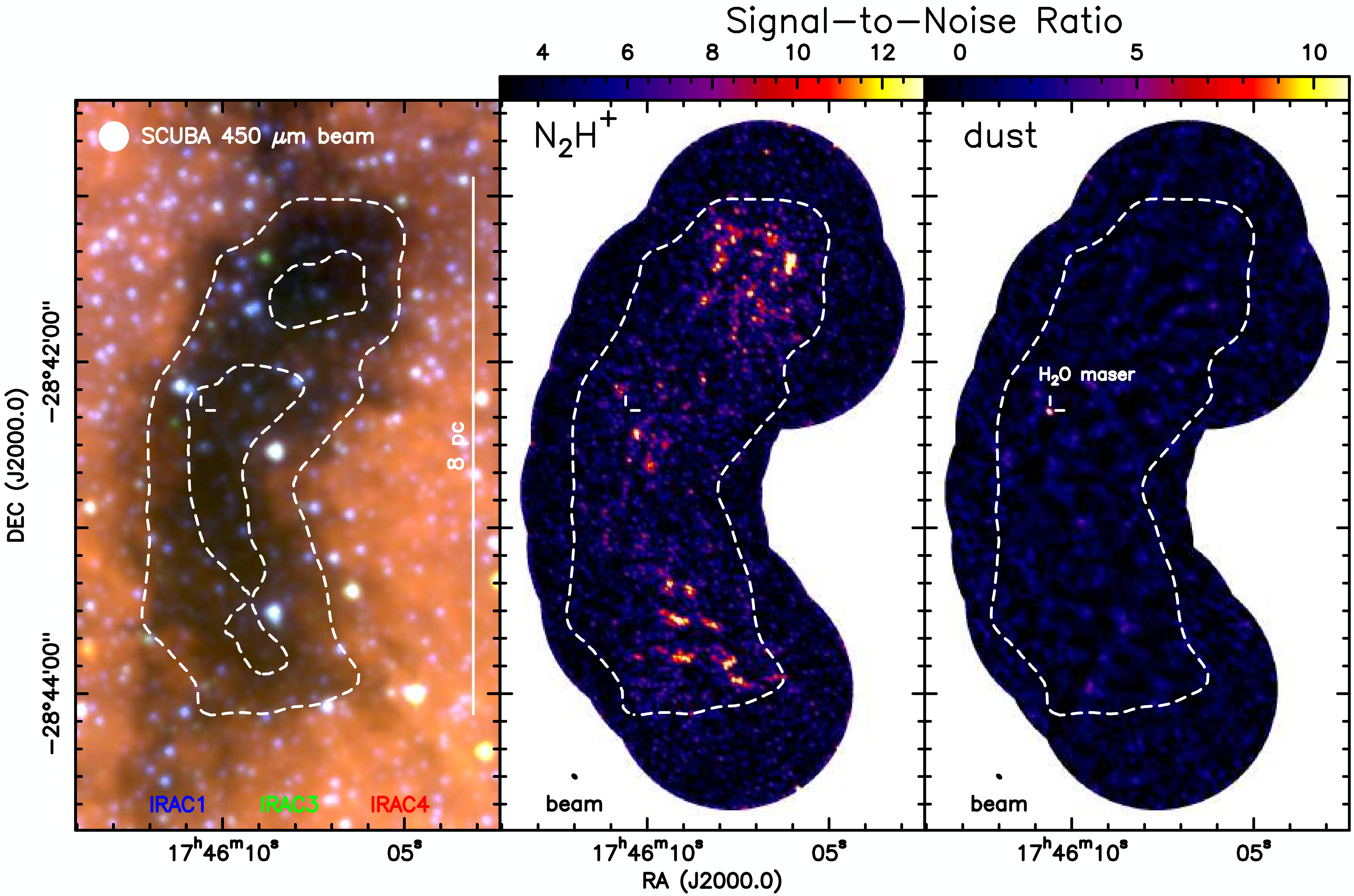
comparable to "turbulent" pressure

this might suppress fragmentation and delay collapse

Physical Processes in CMZ Clouds

CMZ clouds contain few dense cores

First Resolved Views of a CMZ Cloud



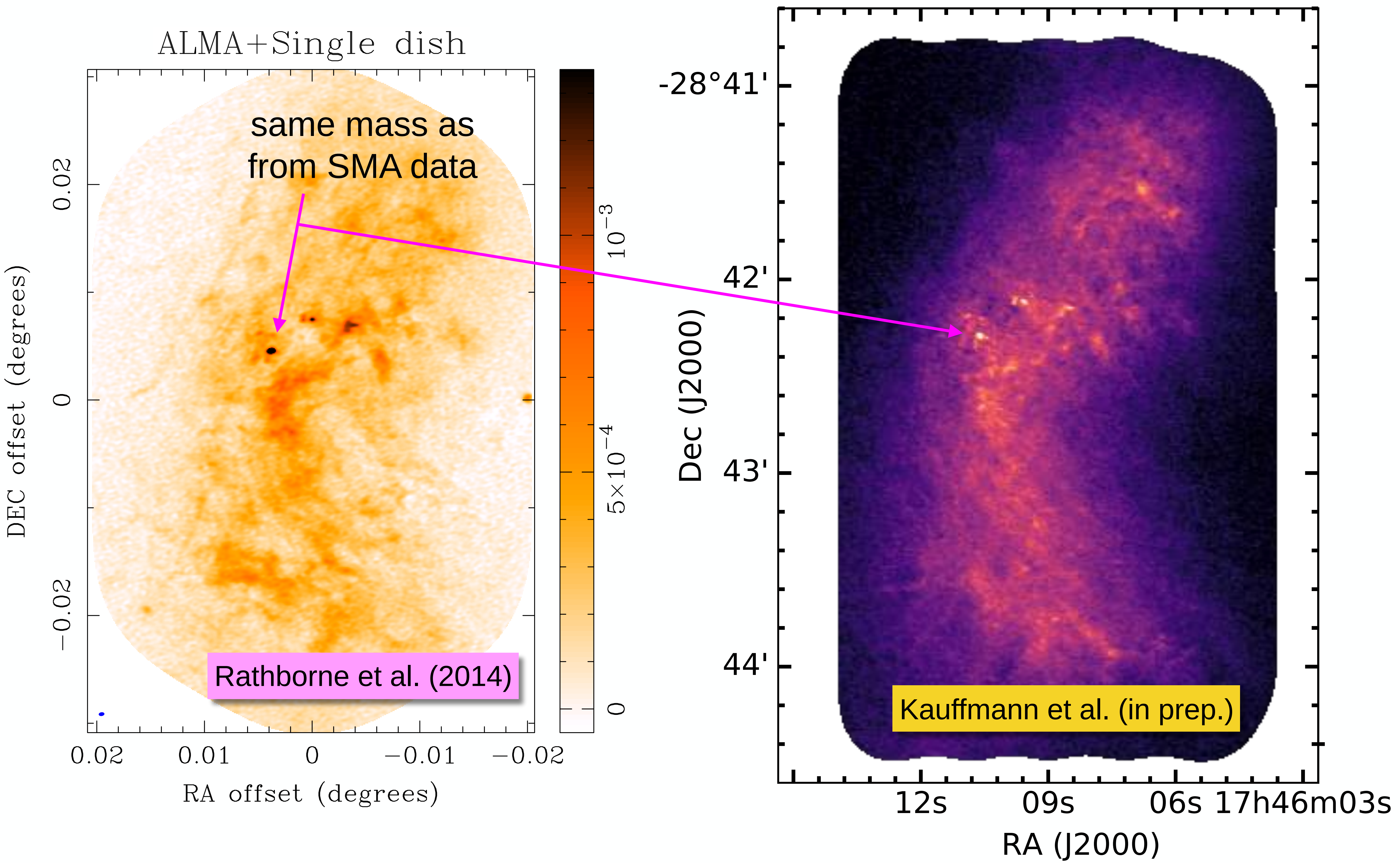
little evidence for dense gas!

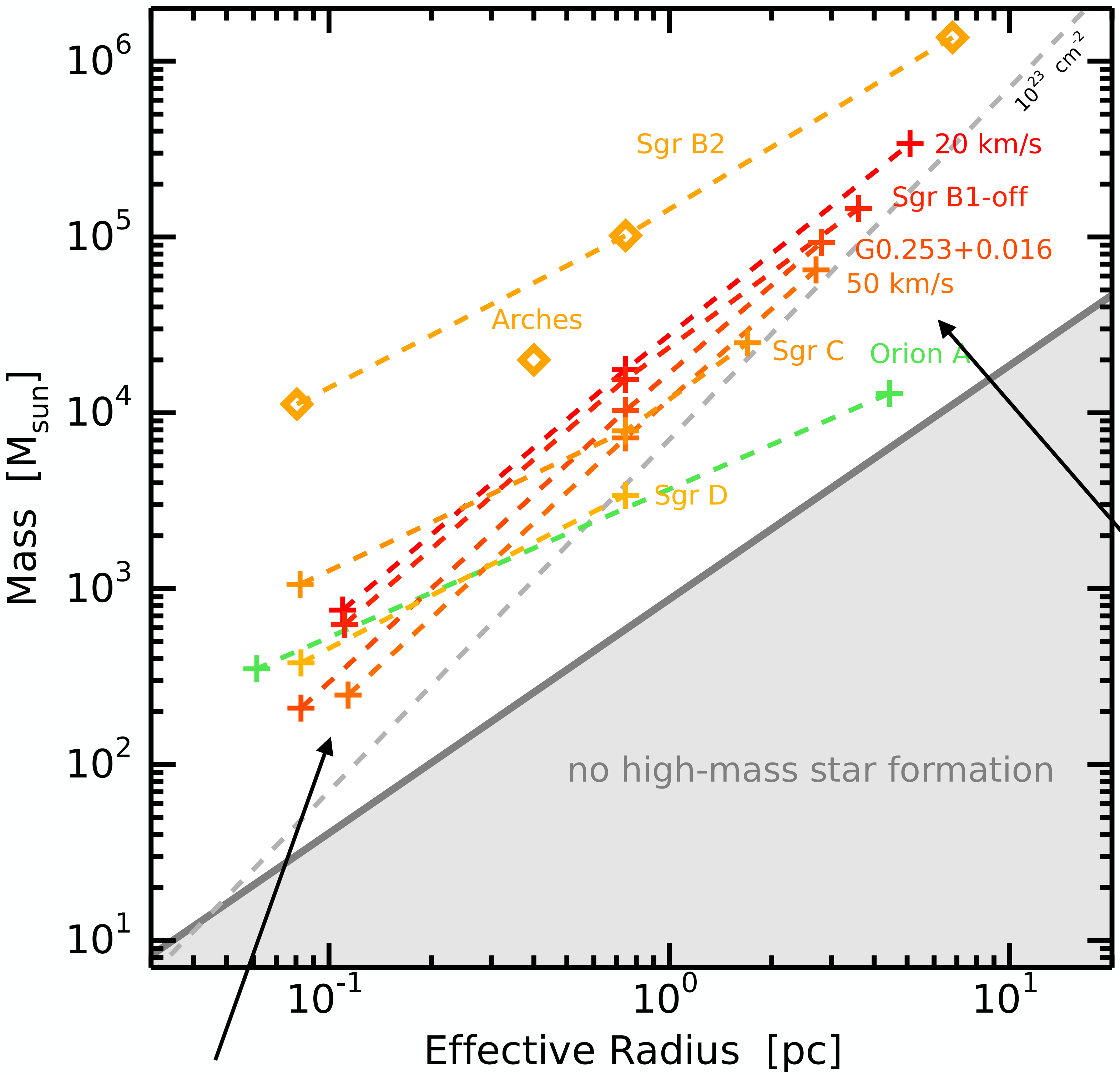
Kauffmann et al. (2013a)

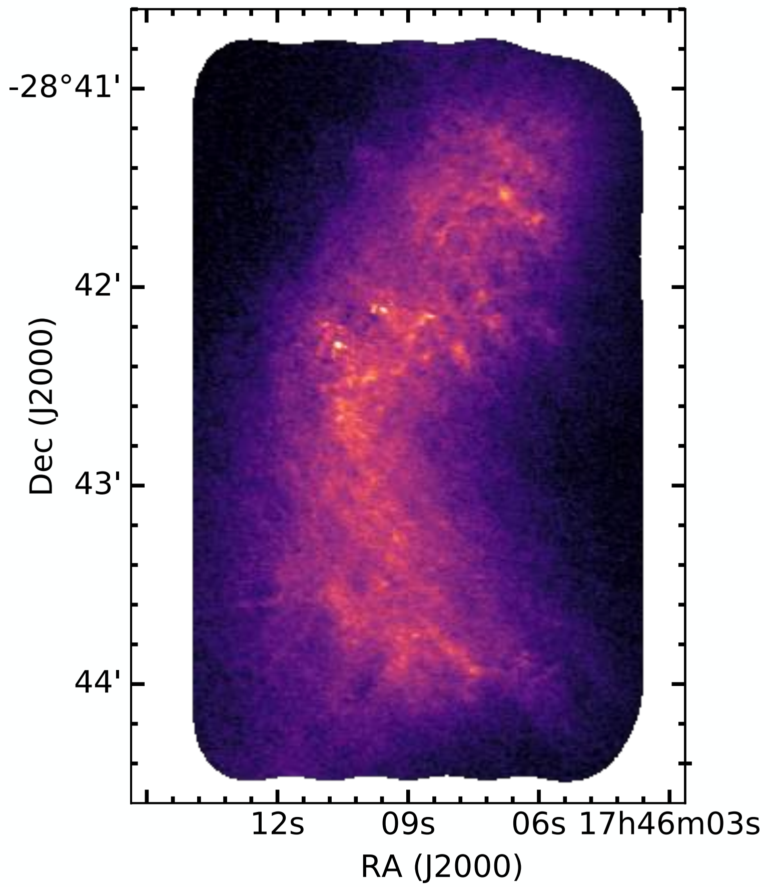
Absence of Dense Cores: Not an Issue of Sensitivity

dust at 90 GHz

dust at 220 GHz







clouds with *average* densities much above Orion A…

…that often contain nothing like Orion KL

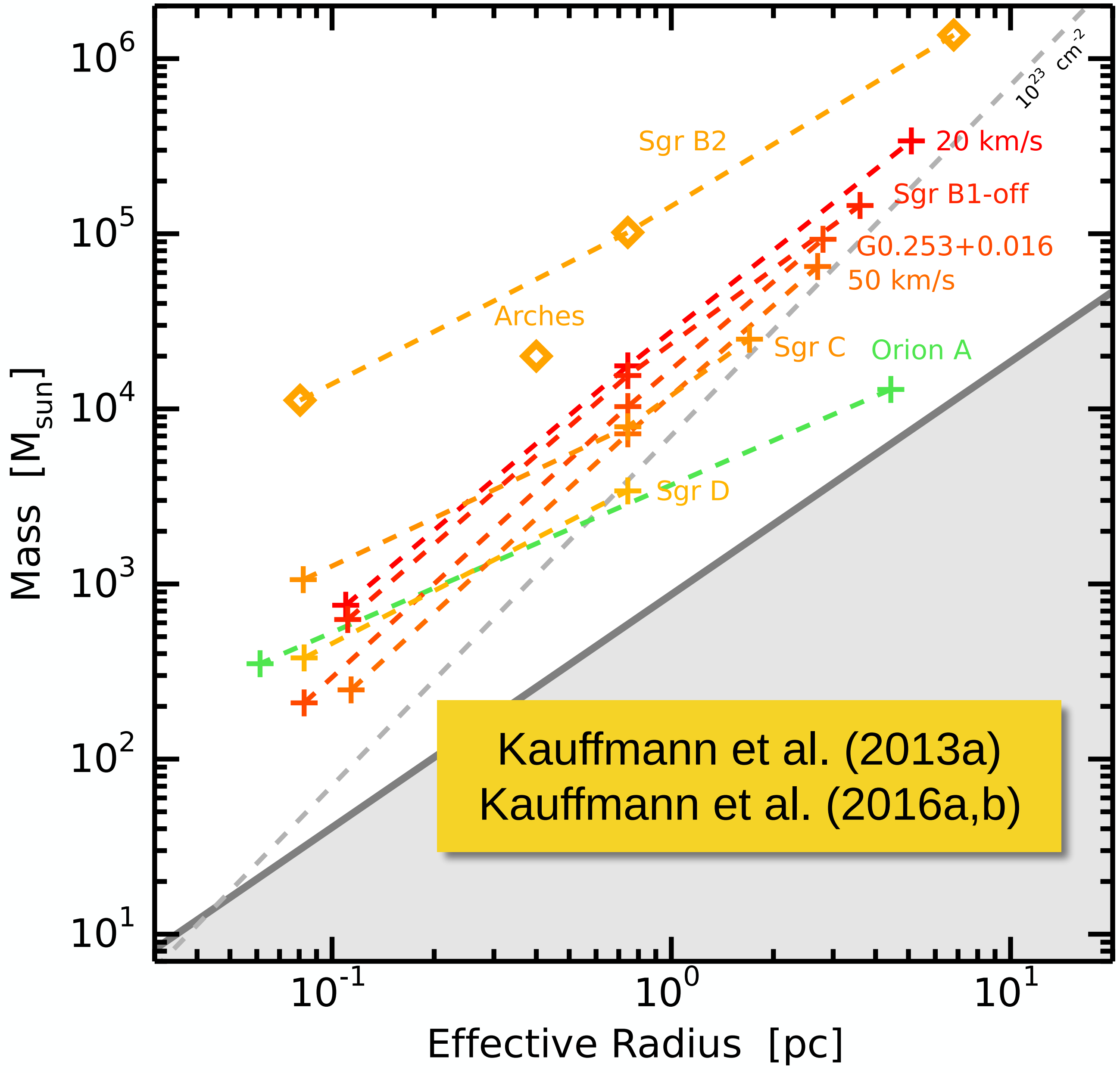
shallow density gradients:

$\varrho \propto r^{-1.3}$

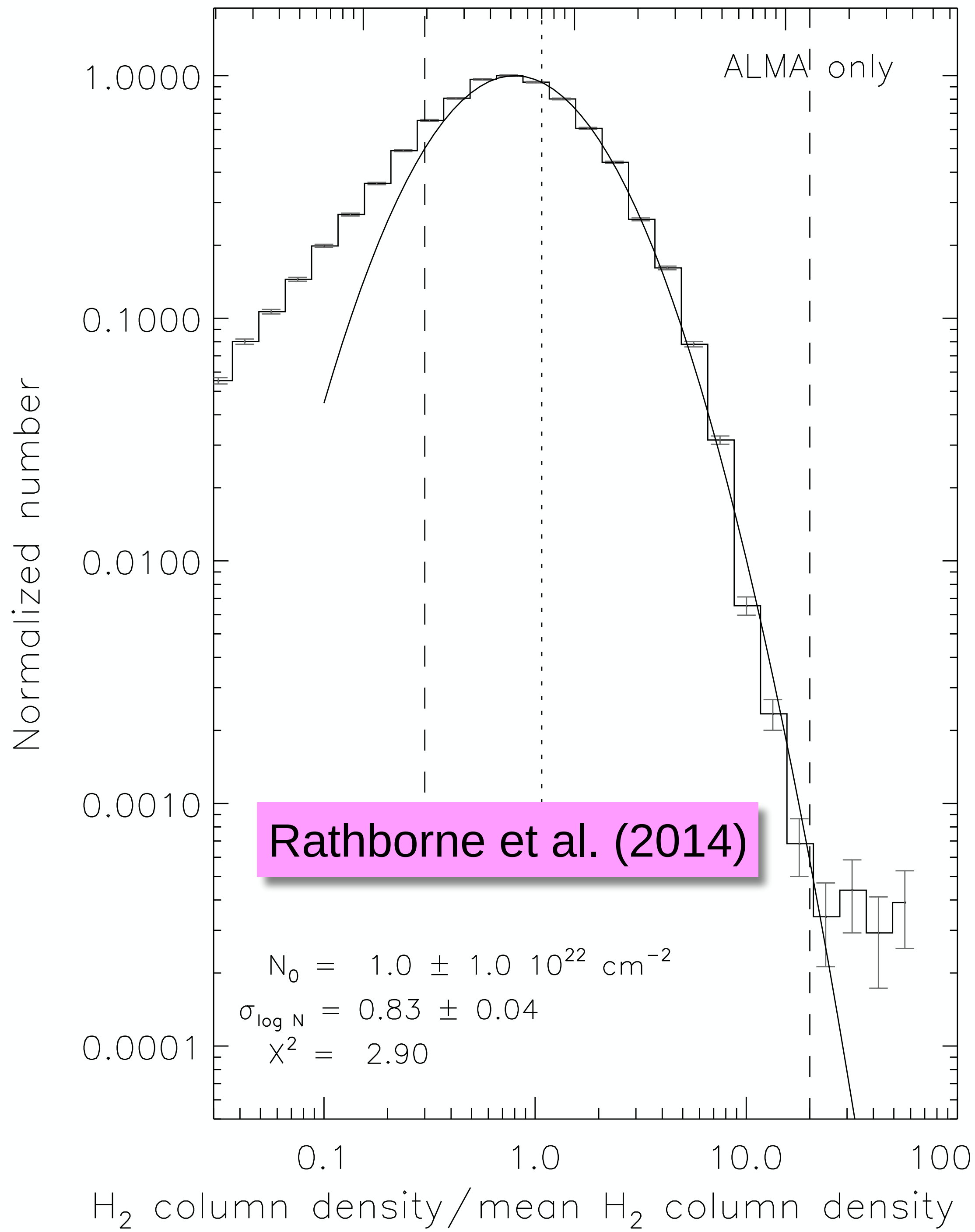
Kauffmann et al. (2013a)
Kauffmann et al. (2016a,b)

Summary of Density Structure

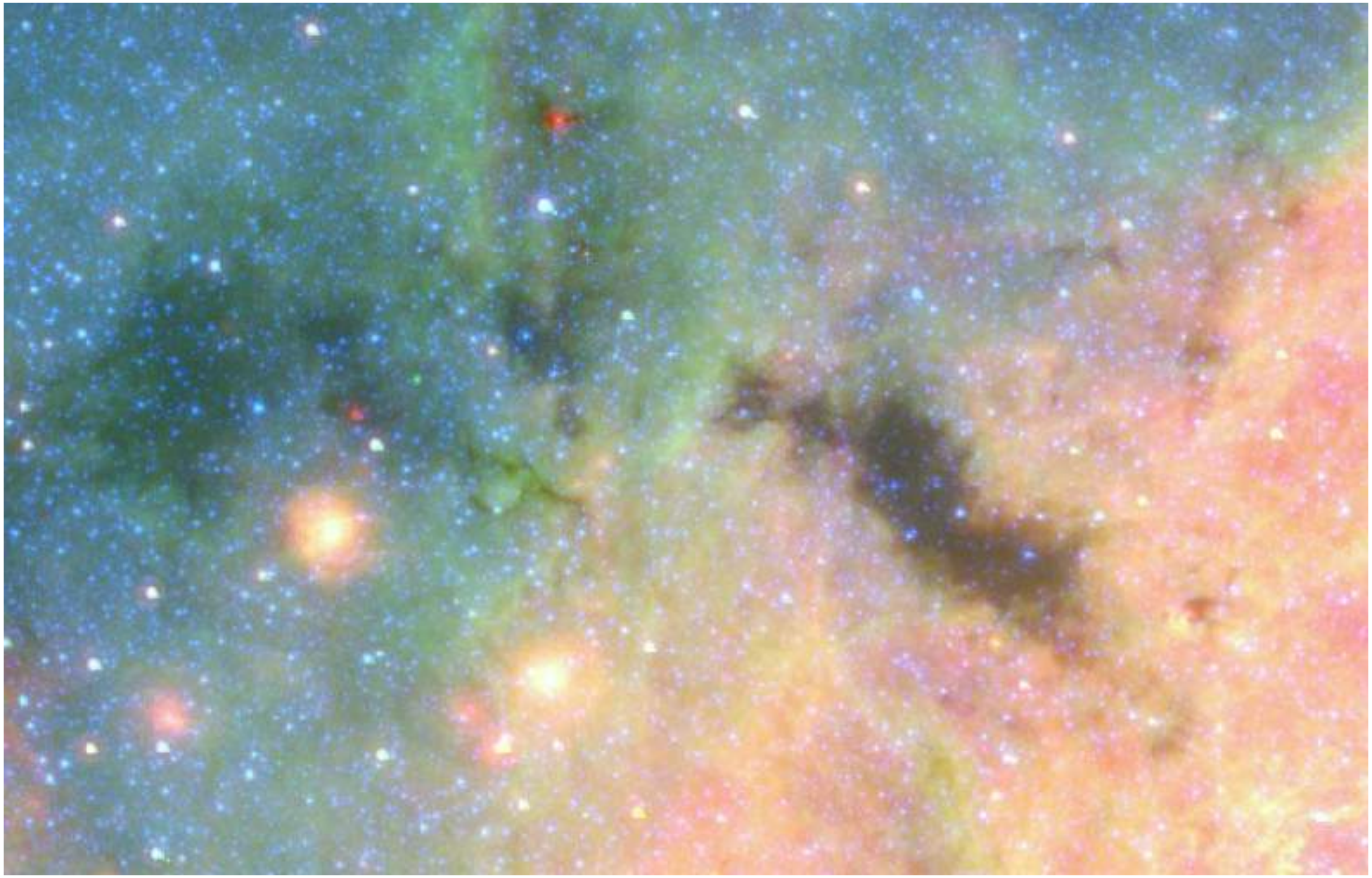
mass–size analysis



column density PDF

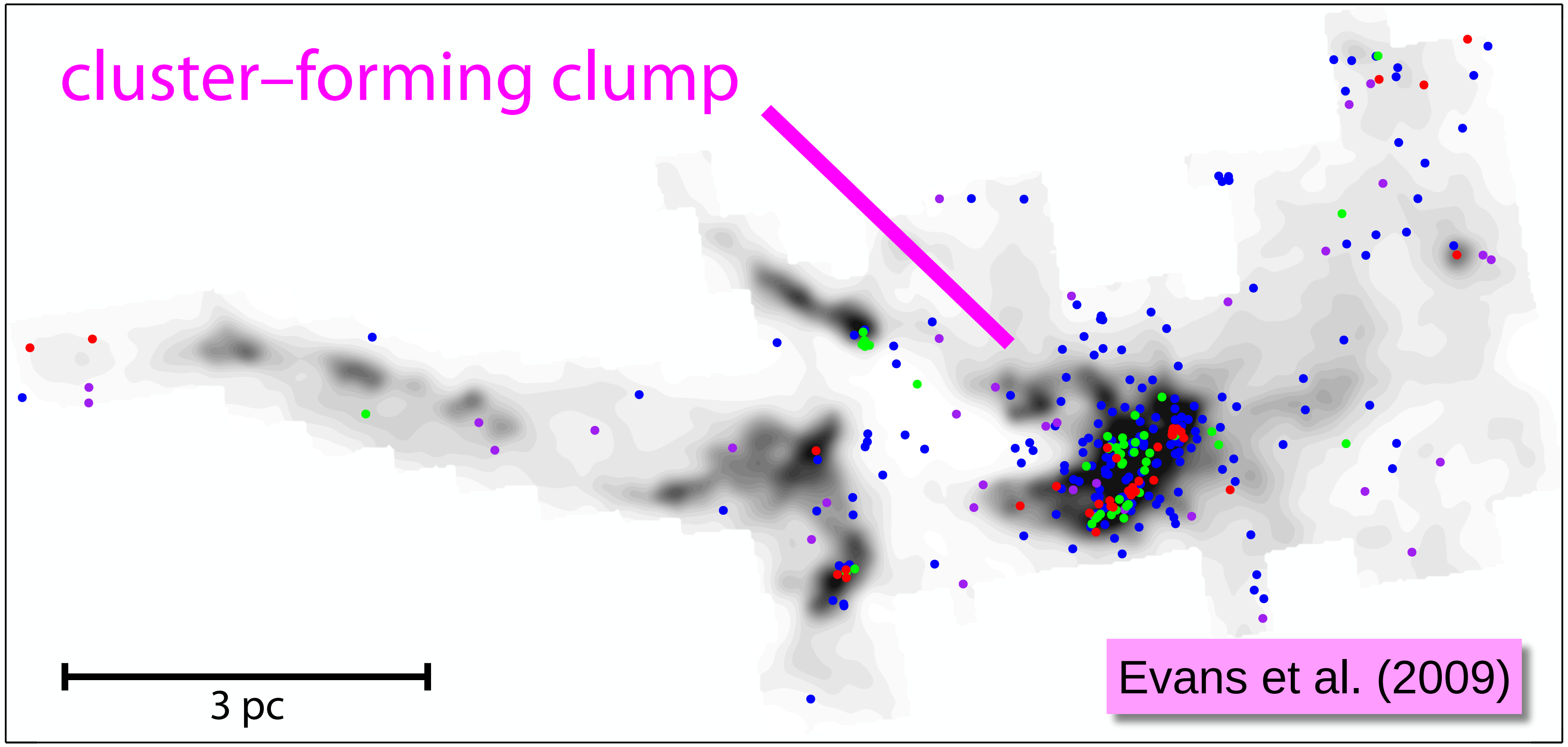


Suppression of Star Formation in Dense Gas



Suppression of Star Formation in Dense Gas

concept: star formation thresholds



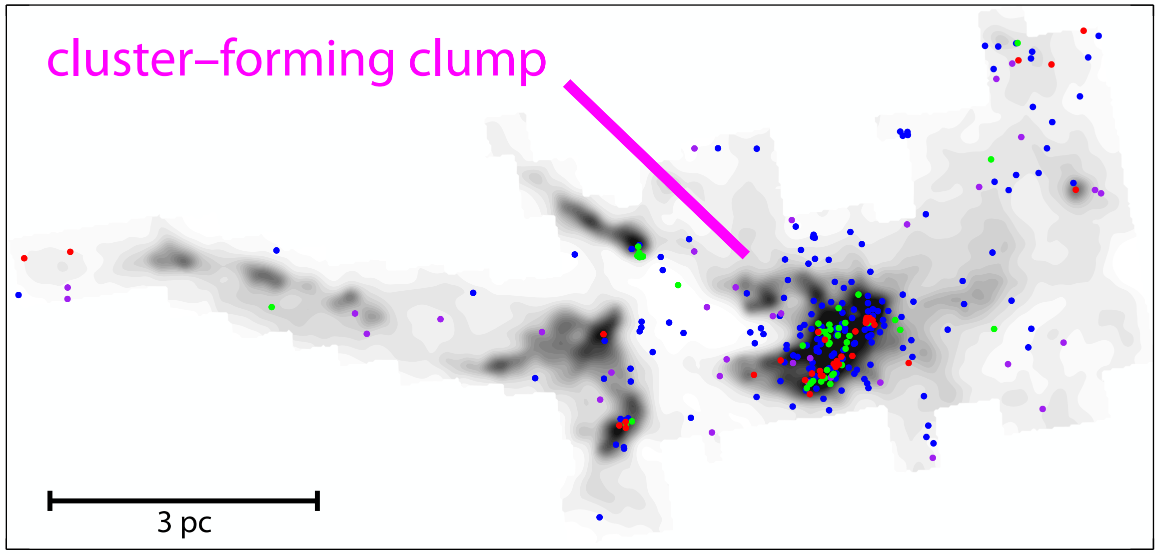
observation:

young stars reside near dense gas

challenge:

exact definition of „dense gas“

Association of Young Stars and Dense Gas



one possible choice:

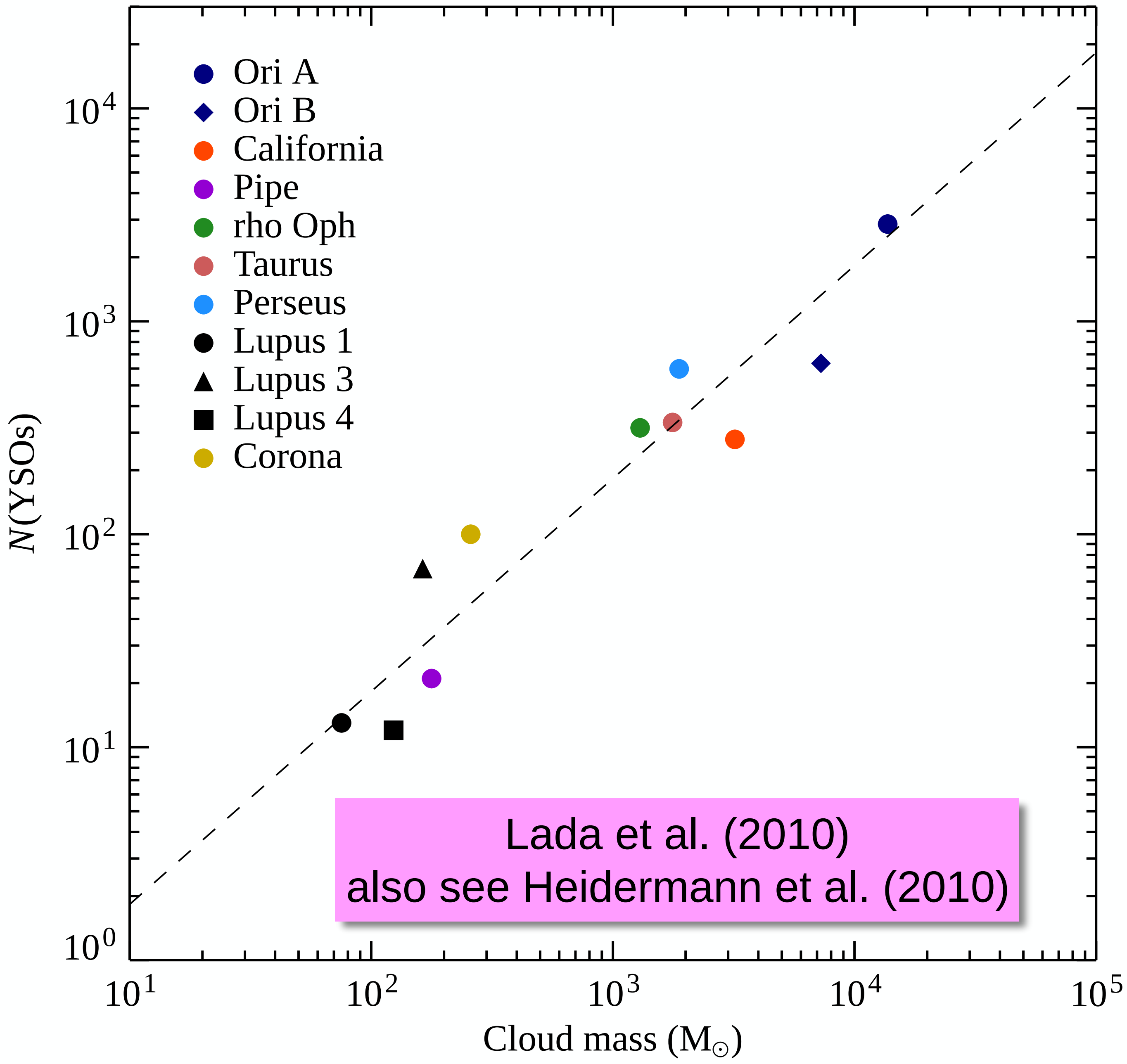
define „dense gas“ as material at $A_V > 7$ mag

=> then $N_{YSO} \propto M_{dense}$

then $A_V = 7$ mag can be considered a threshold…

…but SF above this threshold is inefficient!

$M_{YSO} / M_{dense} \approx 0.06$

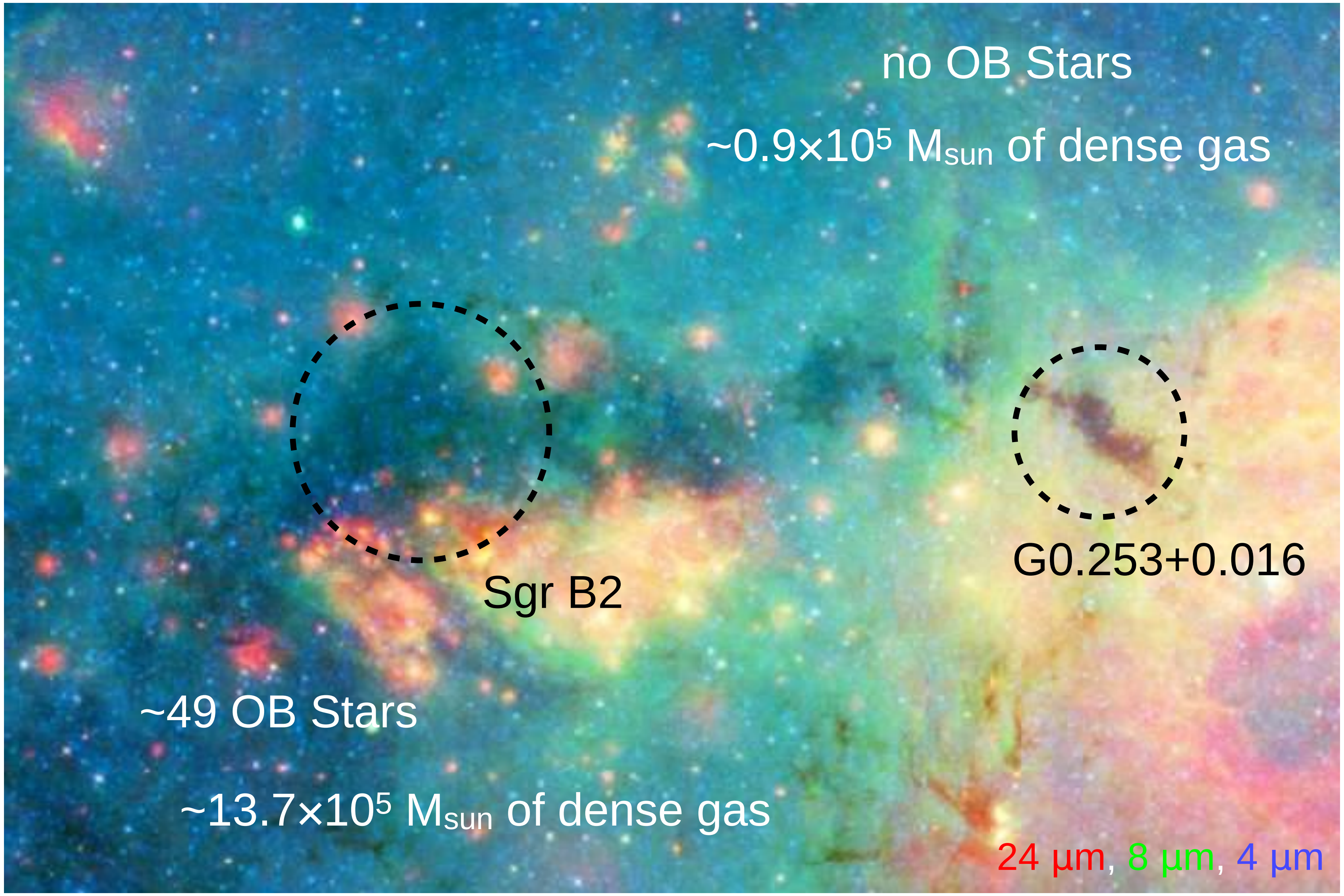


Lada et al. (2010)
also see Heidermann et al. (2010)

Suppression of Star Formation in Dense Gas

observational evidence in CMZ

An Example: G0.253+0.016 vs. Sgr B2

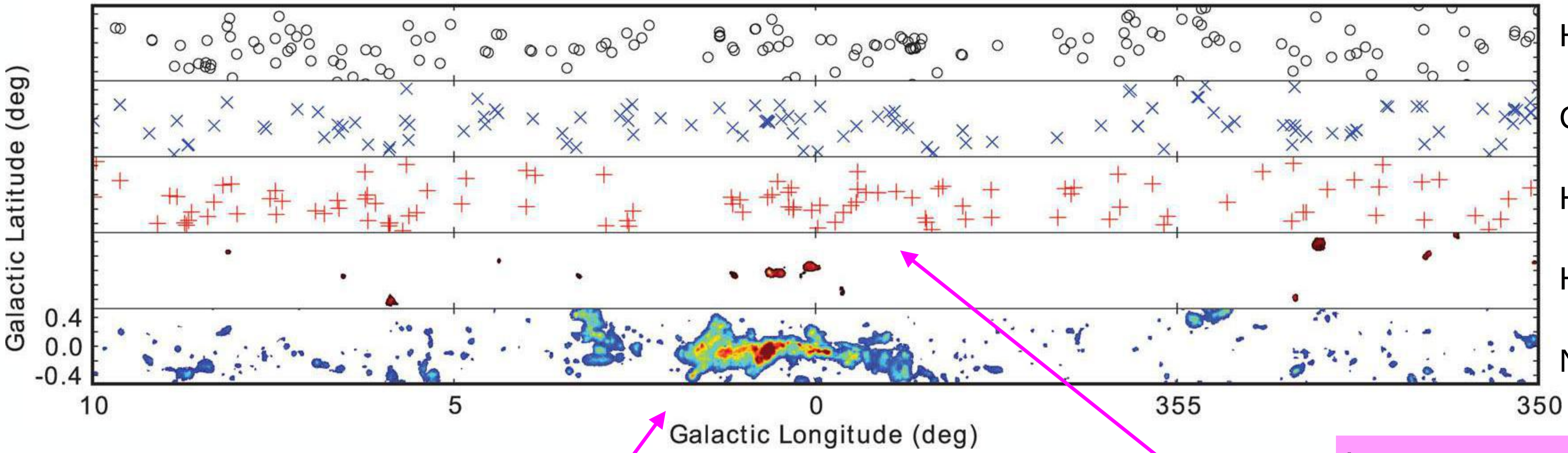


Kauffmann et al. (2017a,b)

rather small difference in SF efficiency!

comparison:

$$\left(\frac{\dot{M}_\star}{M_{\rm dense}}\right)_{\rm Sgr\ B2} \gtrsim 3 \left(\frac{\dot{M}_\star}{M_{\rm dense}}\right)_{\rm G0.253+0.016}$$

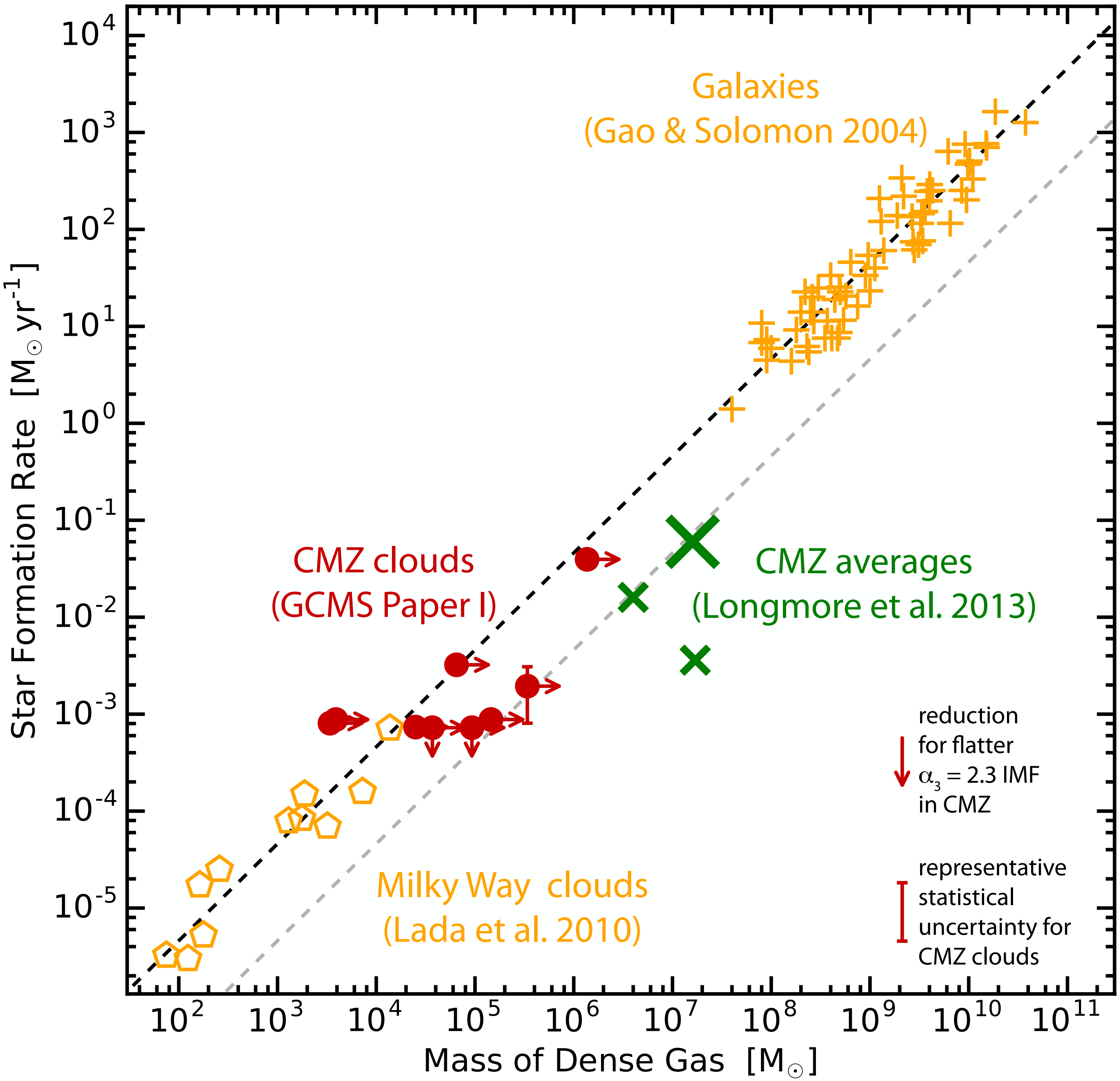


Longmore et al. (2013)

star formation
not concentrated

dense gas concentrated
around $\ell = 0°$

Star Formation Rate in Dense Gas



appears to be not universal!

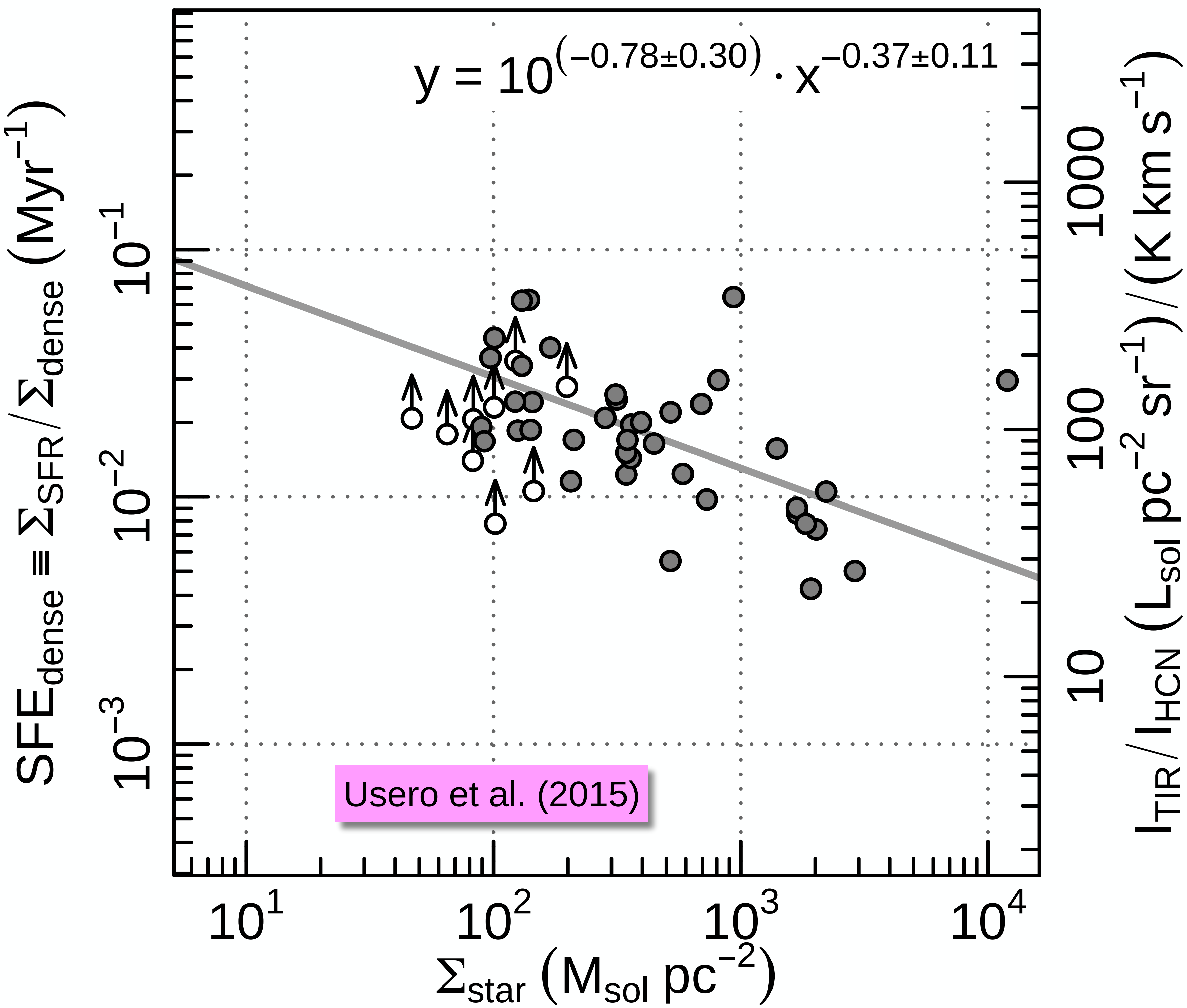
dense gas:
defined as A_V > 7 mag

equivalent of
Gas & Solomon relation

Kauffmann et al. (2017a,b)

Suppression of Star Formation in Dense Gas

connection to extragalactic research



maybe also not universal in galaxies

Suppression of Star Formation in Dense Gas

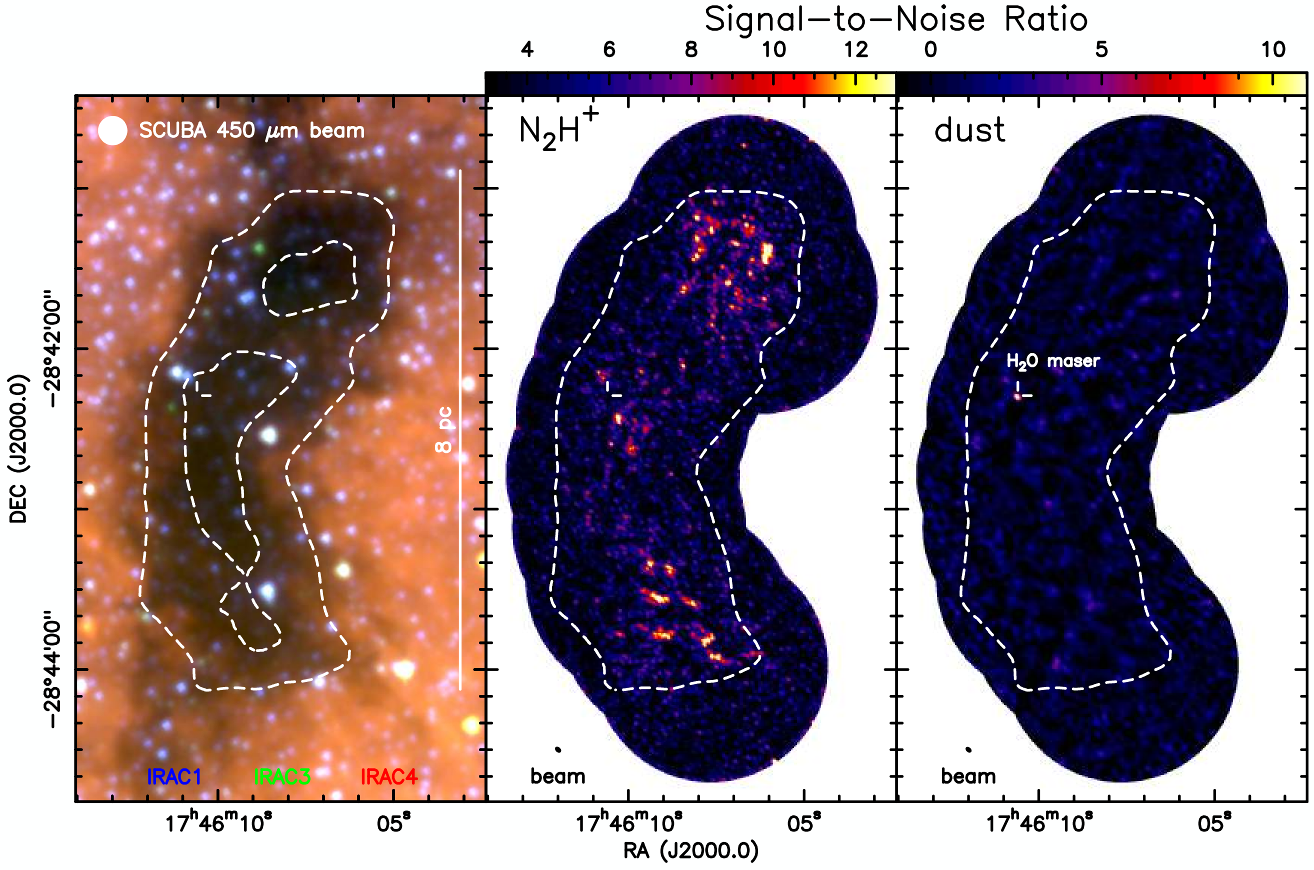
processes to suppress star formation

Possible Mechanisms

„intermediate“ explanation:

clouds contain few dense cores…

…but what is the reason for that?



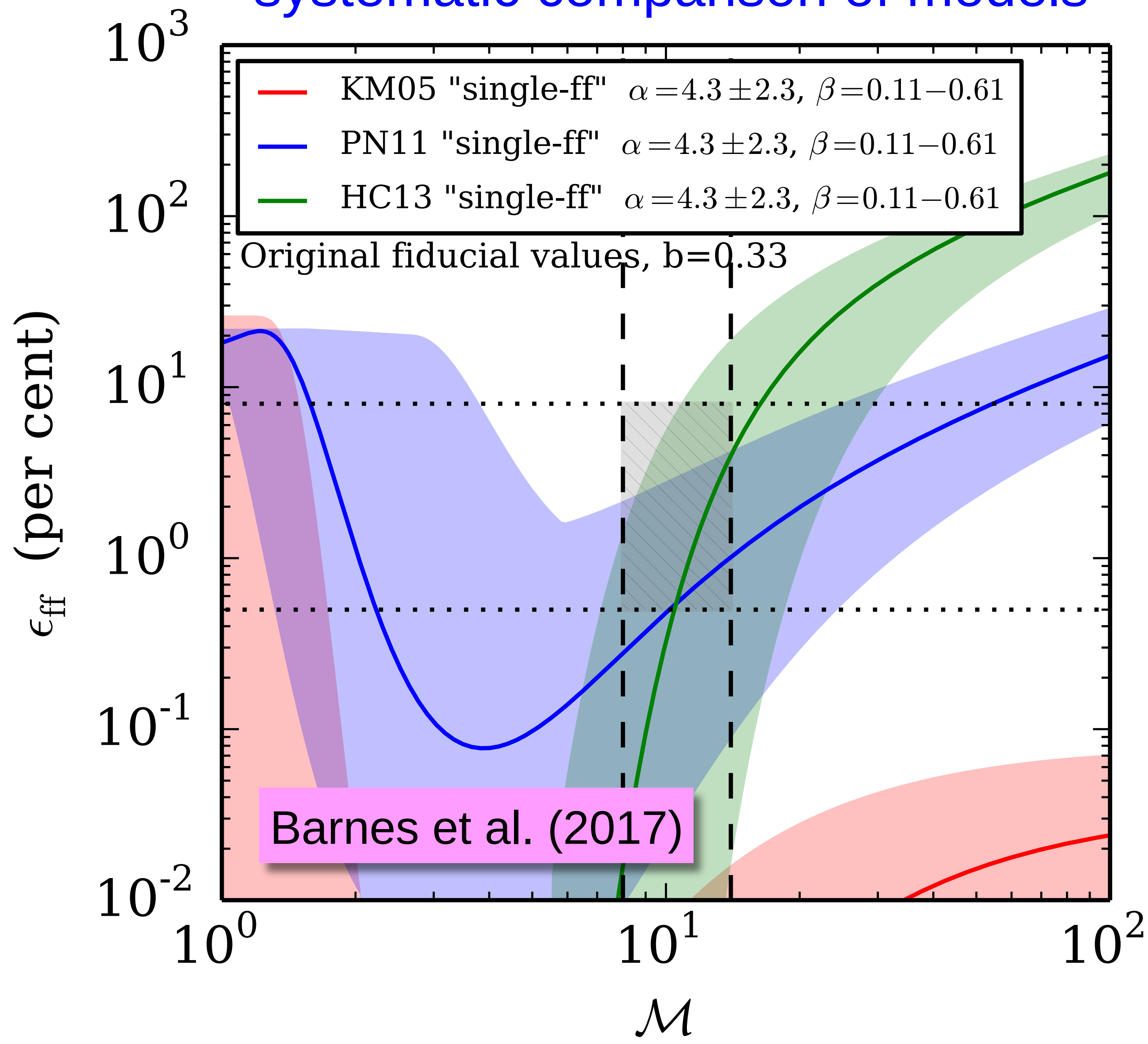
list of potentially relevant factors:

- turbulence (but how driven?)
- high gas temperature, high thermal Jeans mass
- strong magnetic fields
- tidal forces
- cloud–cloud interactions on orbit

(too) many possible explanations!

Possible Mechanisms

systematic comparison of models



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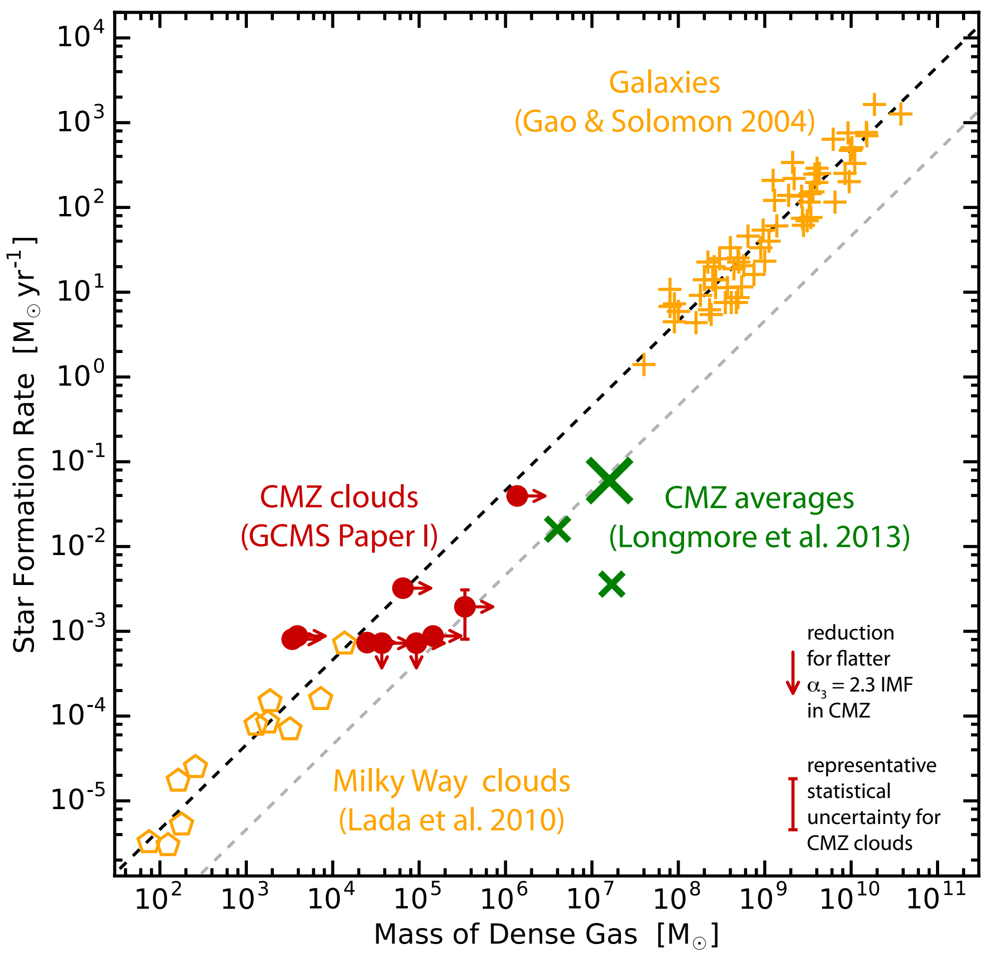
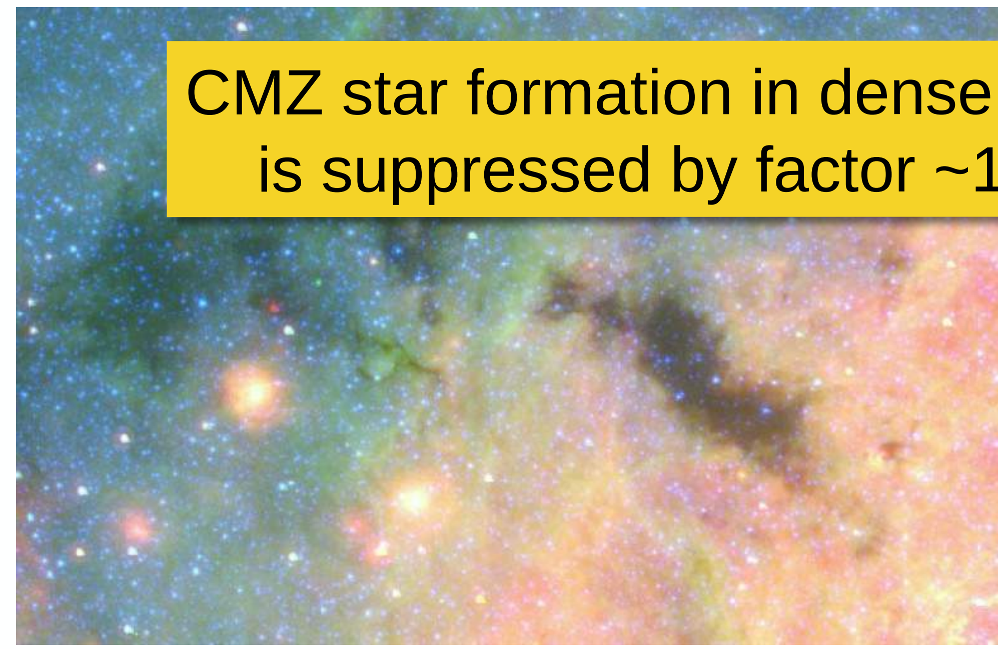
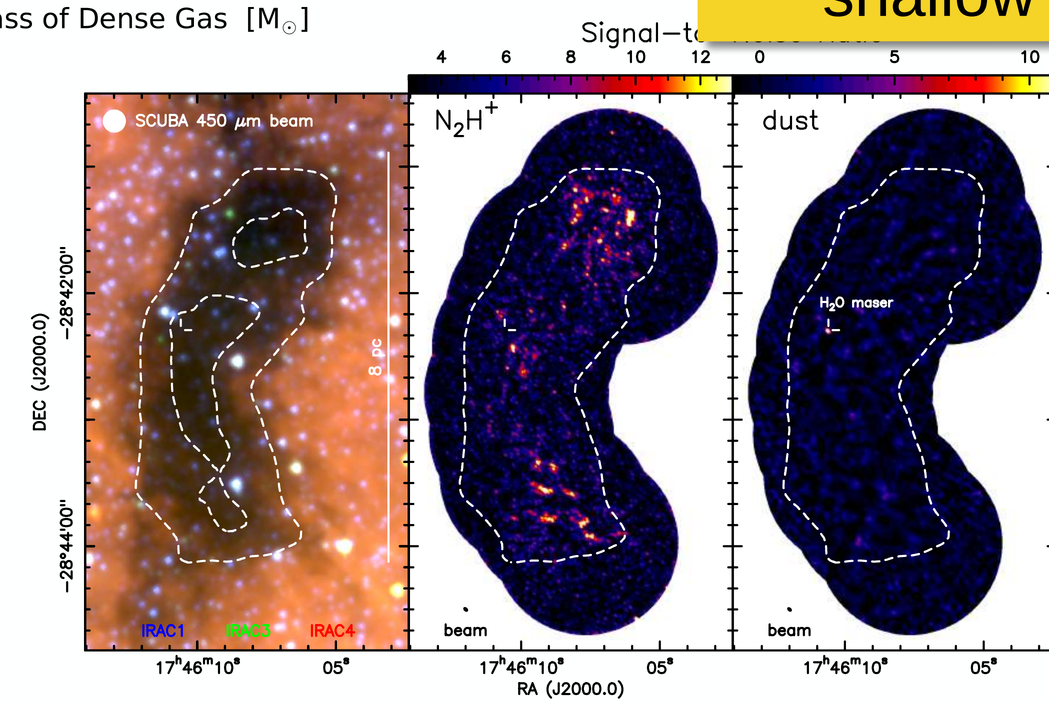
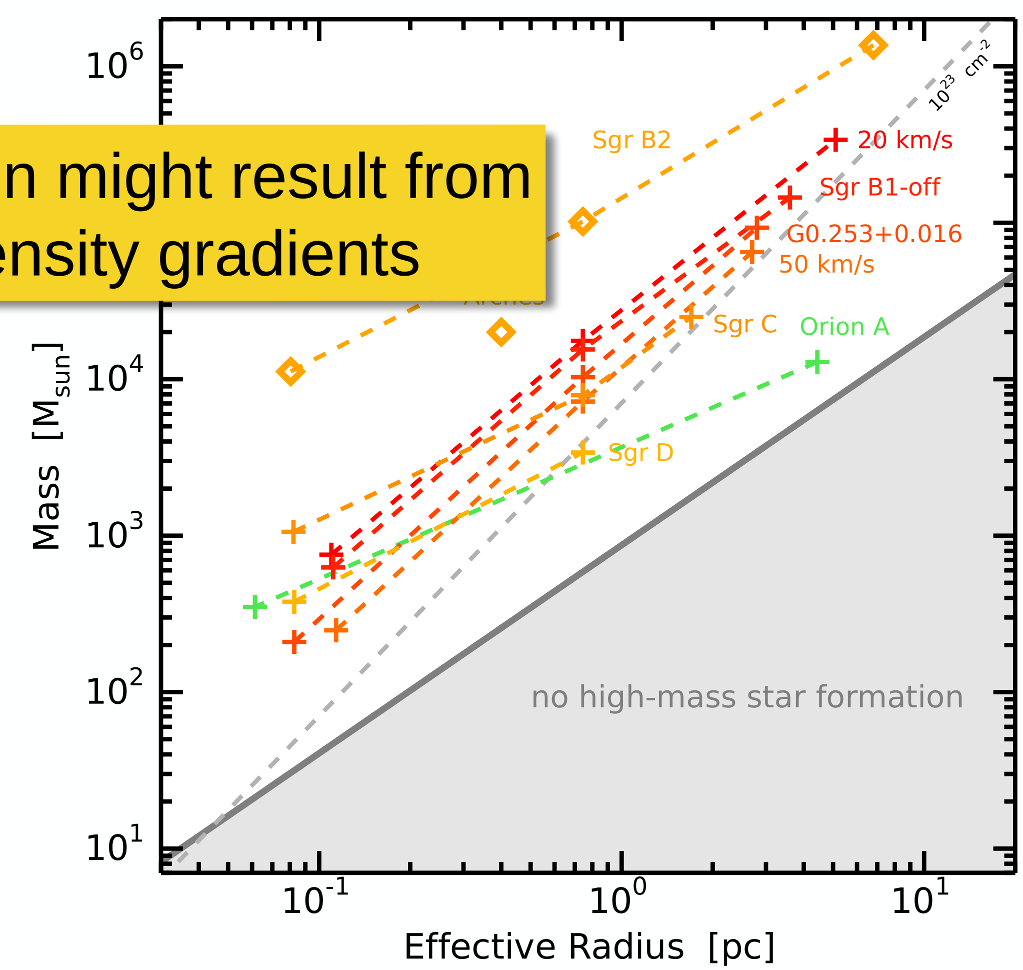
Summary: Star Formation in CMZ





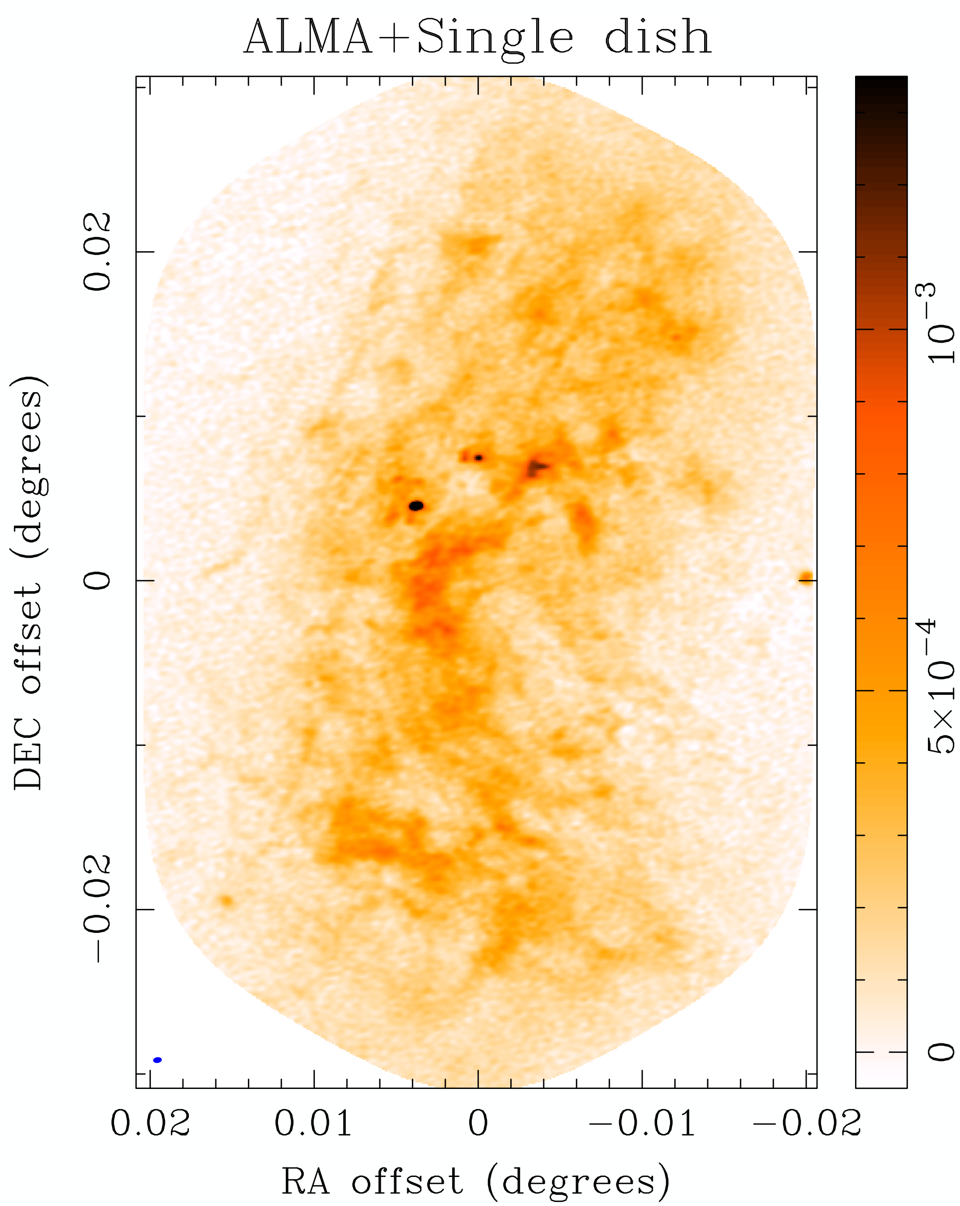
CMZ star formation in dense gas is suppressed by factor ~10



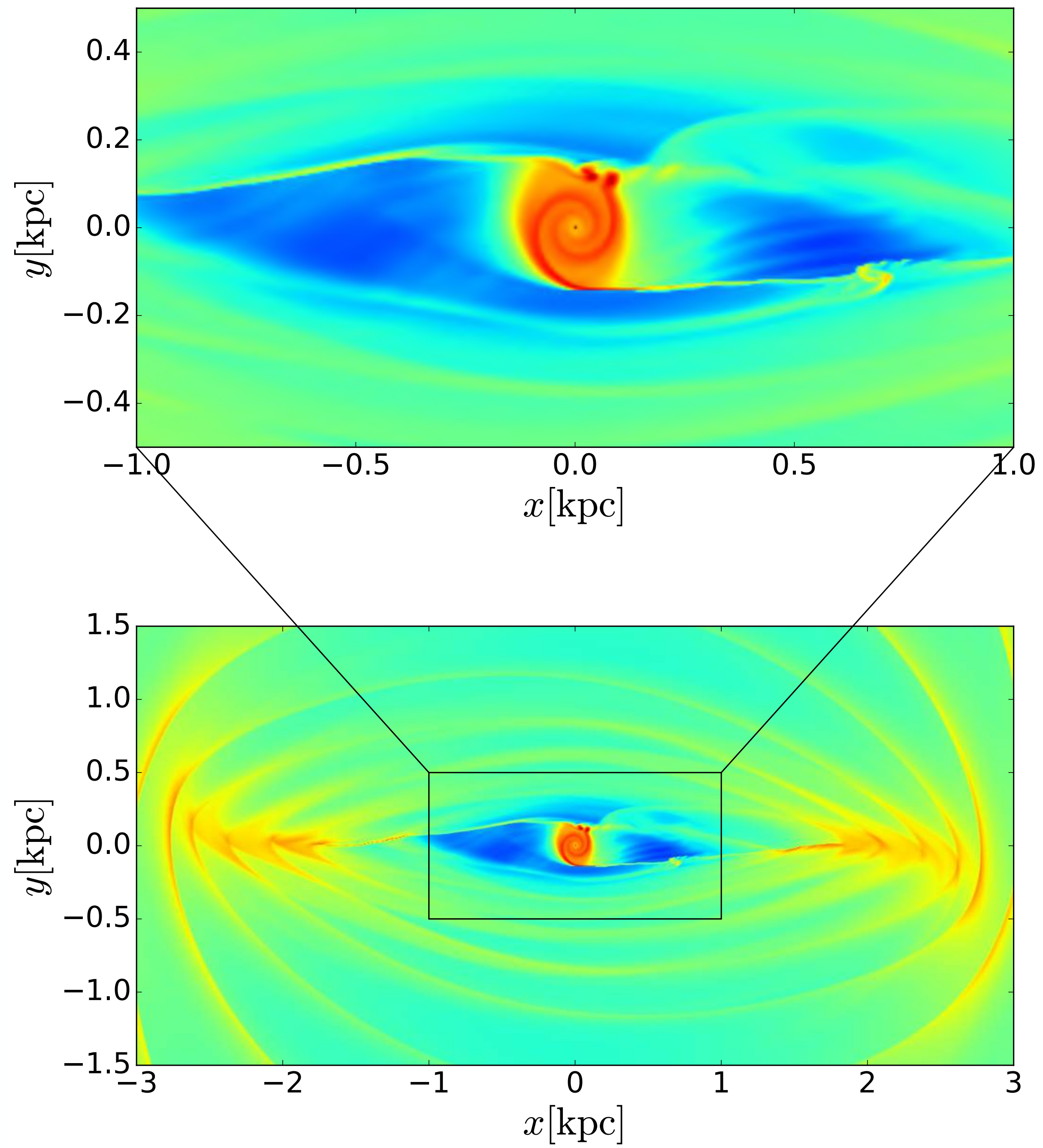


SF suppression might result from shallow density gradients

Summary: Enabling Technologies



interferometers resolving clouds



simulations of entire CMZ