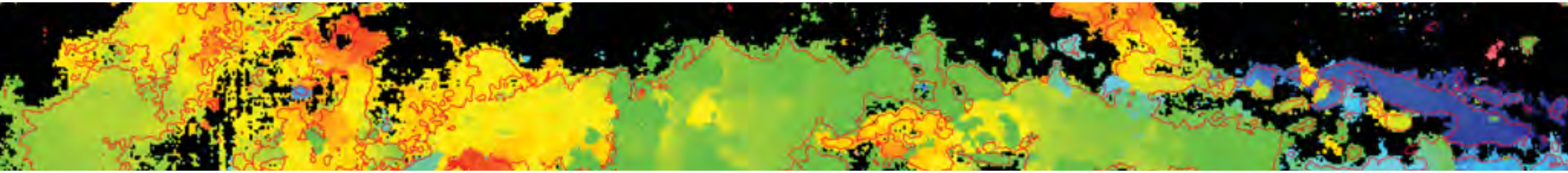
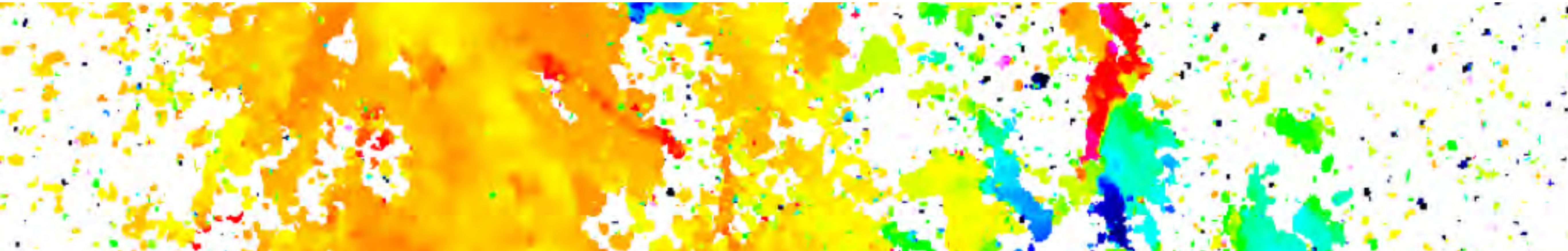
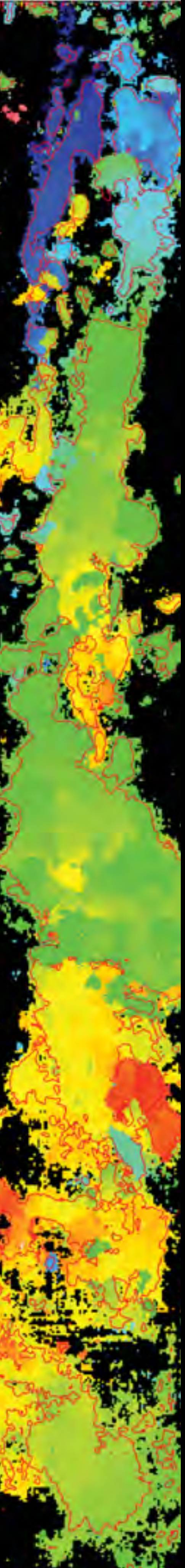
The Central Molecular Zone:



Prospecting for STAR FORMATION

Elisabeth A.C. Mills (Jansky Fellow, NRAO)





Introduce the Galactic center

Overview of star formation in this region

Review what we know about gas conditions

Highlight the open questions

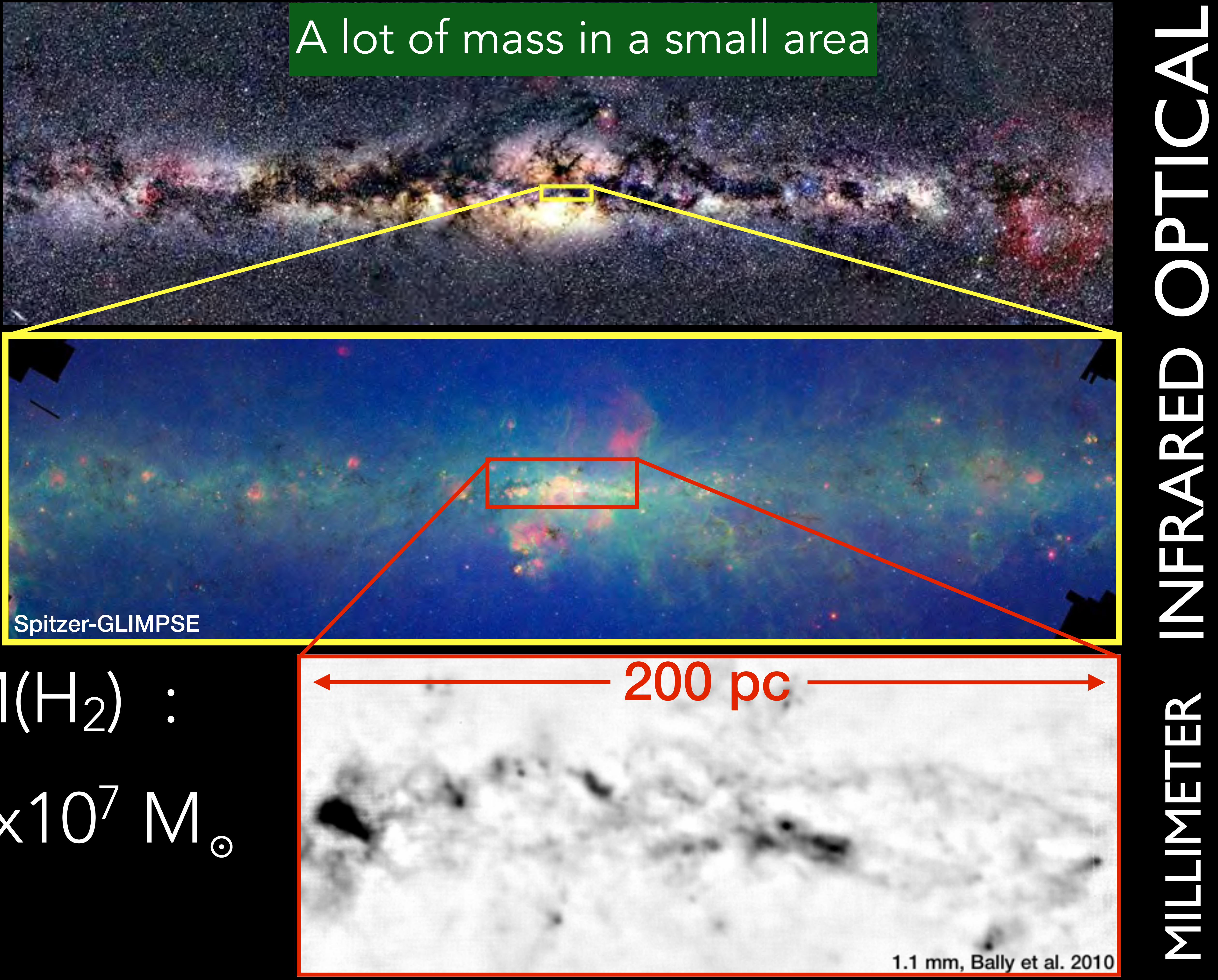
Finish with a few challenges and opportunities

OUR GALACTIC CENTER

The nearest galactic nucleus

} ~8.5 kiloparsecs away

A lot of mass in a small area

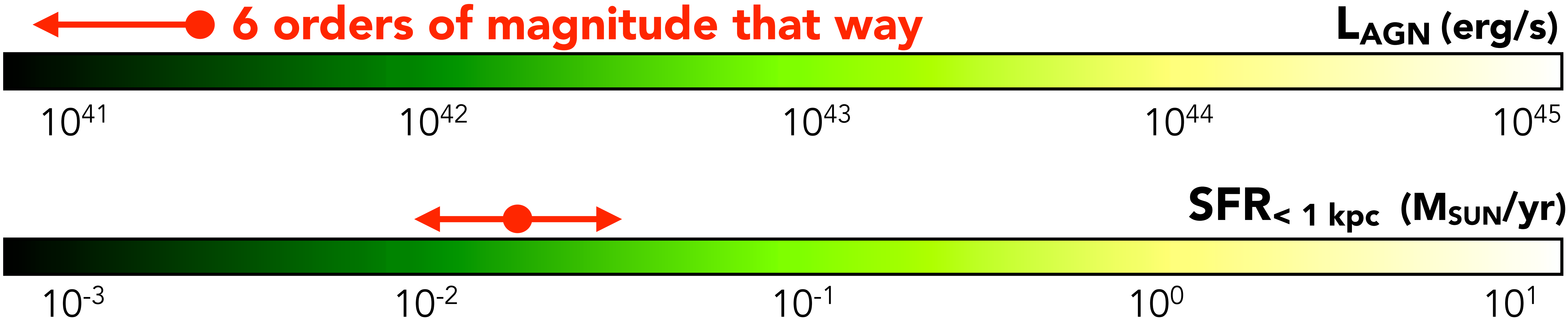


M(H_2) :

$4\times10^7\ M_\odot$

Most ‘extreme’ environment we can resolve

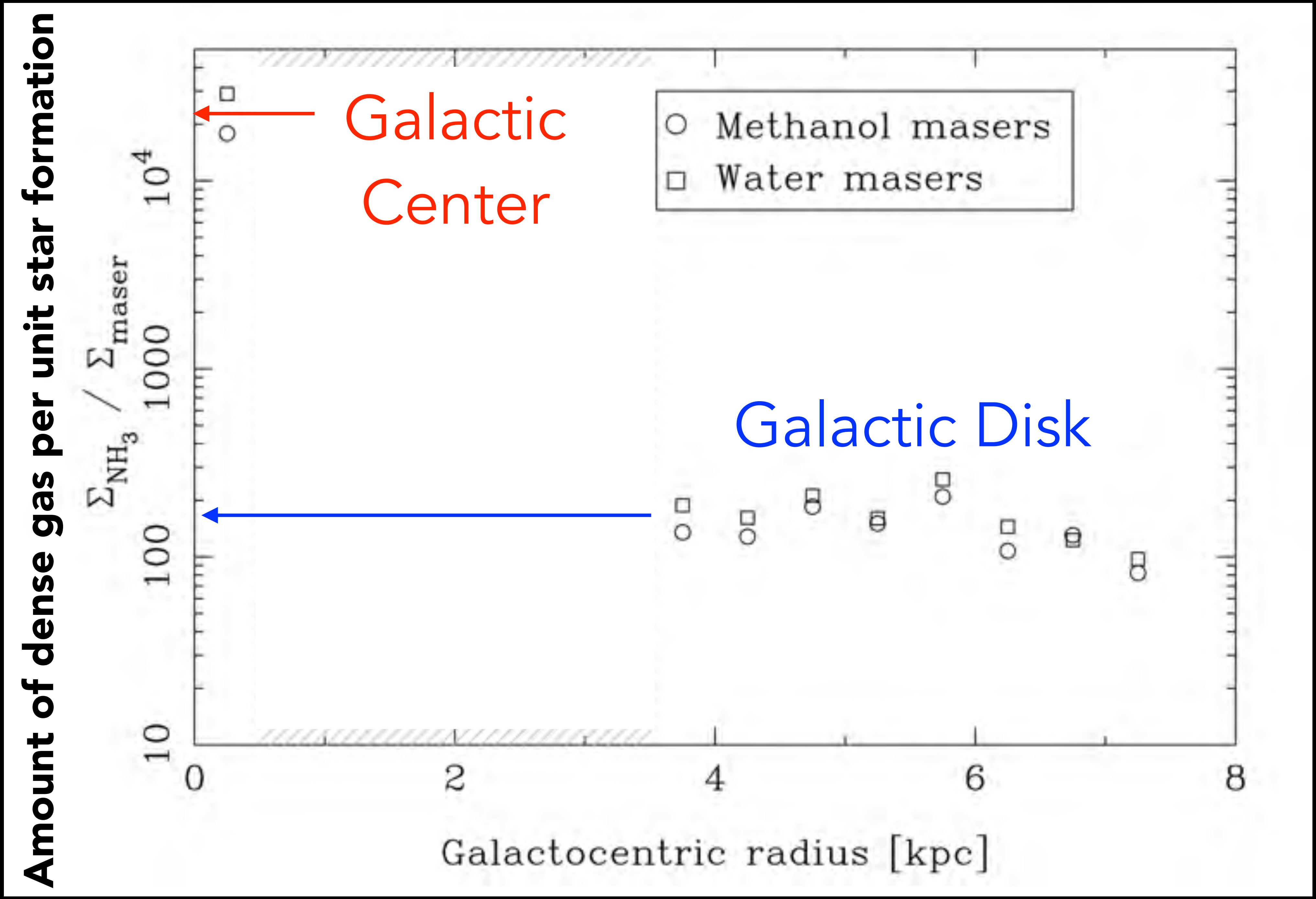
Milky Way Galactic Center vs. Seyferts:



(range of Seyfert properties from a sample by Diamond-Stanic & Rieke 2012)

- Hot $T= 50 - 150$ K (Guesten et al. 1985, Huettemeister et al. 1993)
- Dense $n > 10^4$ cm^{-3} (Bally et al. 1987, Serabyn, Lacy & Achtermann 1992)
- Turbulent $\Delta v \sim 15-50$ km s^{-1} (Bally et al. 1987)

But, where is the star formation?



Longmore et al. 2013

STAR FORMATION

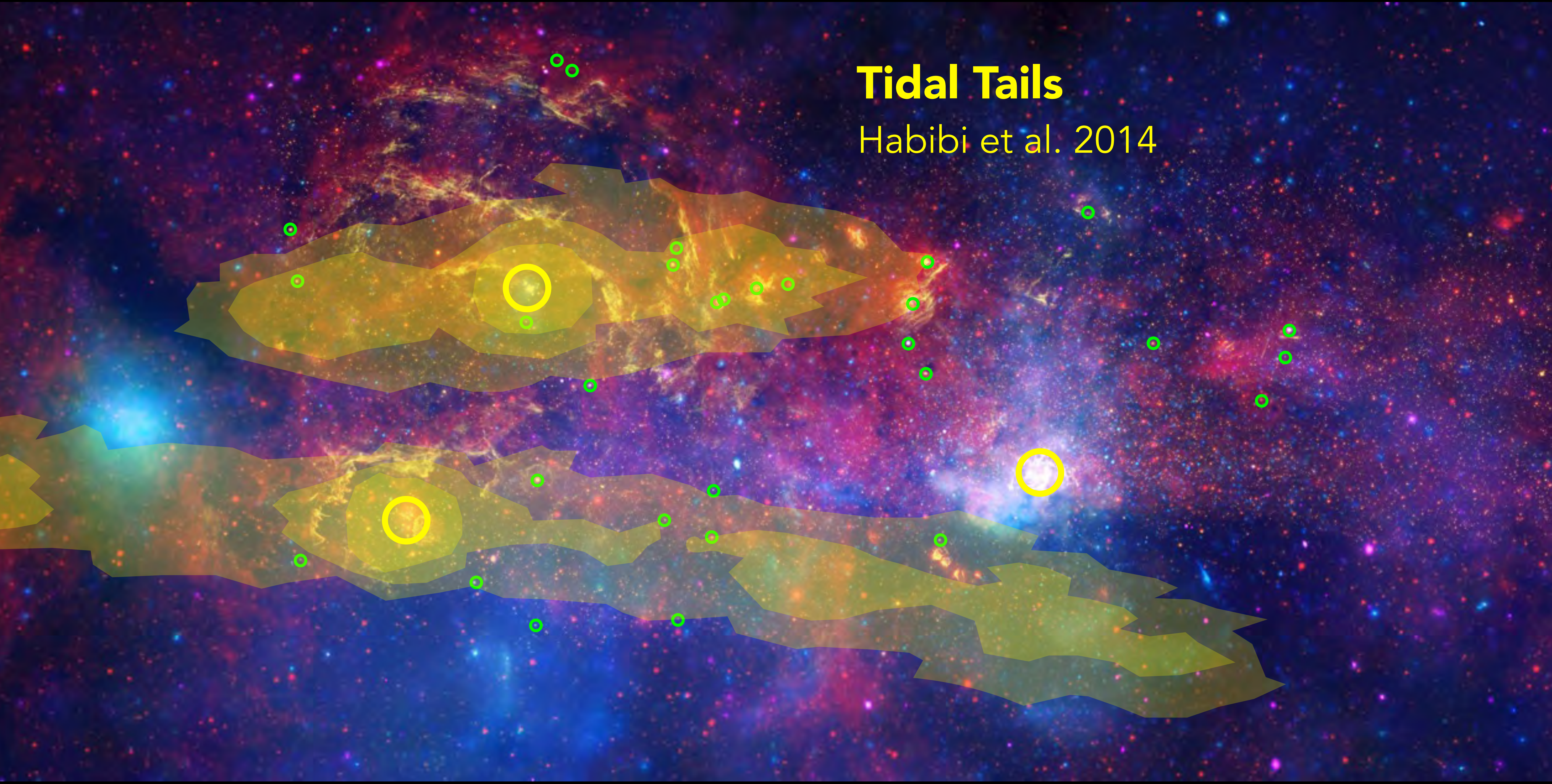
Historically, lots of star and cluster formation

3 young, massive clusters

(e.g., Stolte et al. 2009, Hußman et al. 2012, Lu et al. 2013)

An equal number of massive stars **outside** of these clusters

(e.g.,Mauerhan et al. 2007,2009,2010)



Tidal Tails

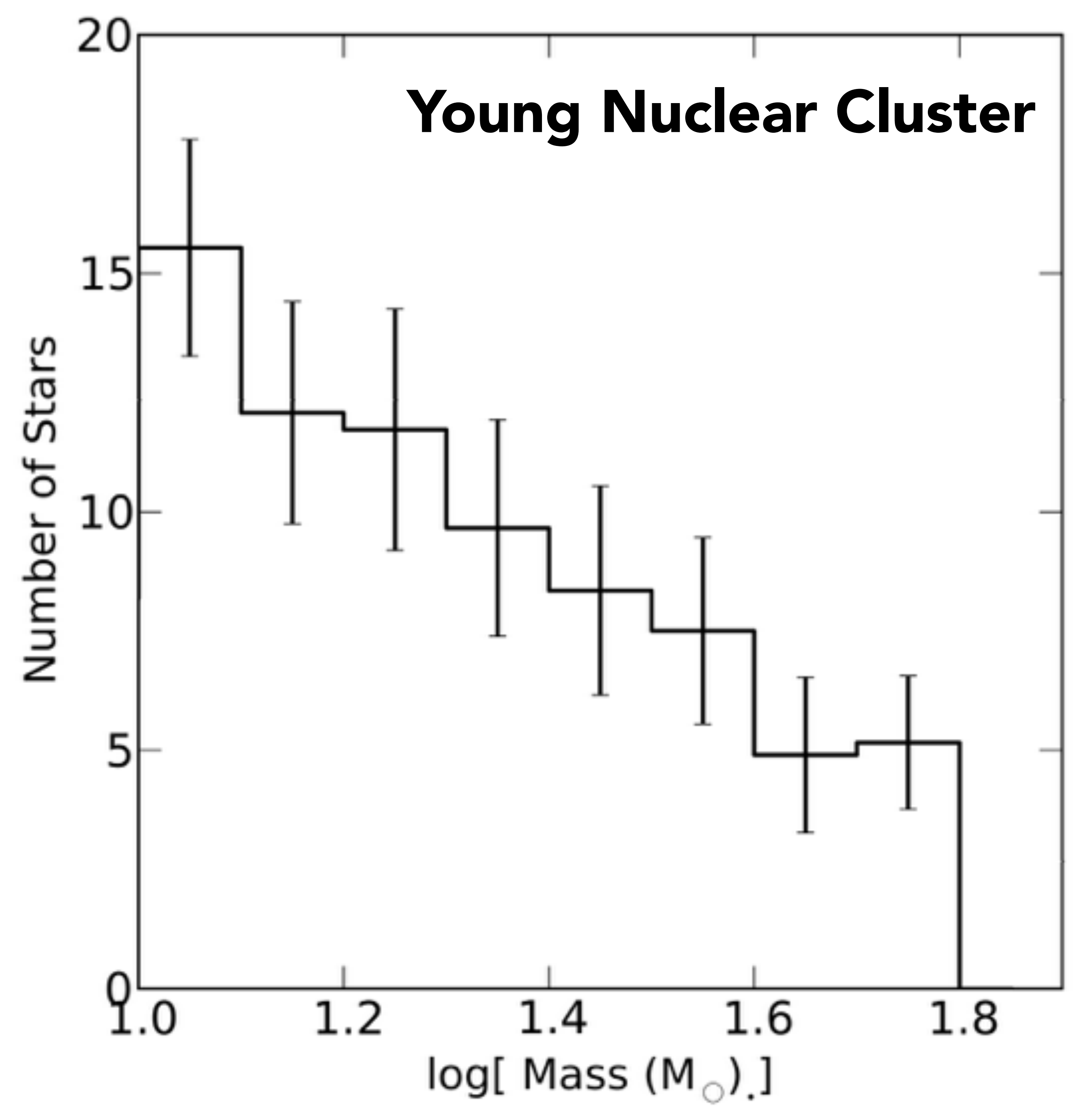
Habibi et al. 2014

Outside of central parsec, no deviant IMF

$\alpha_{\text{measured}} = 1.7 \pm 0.2$

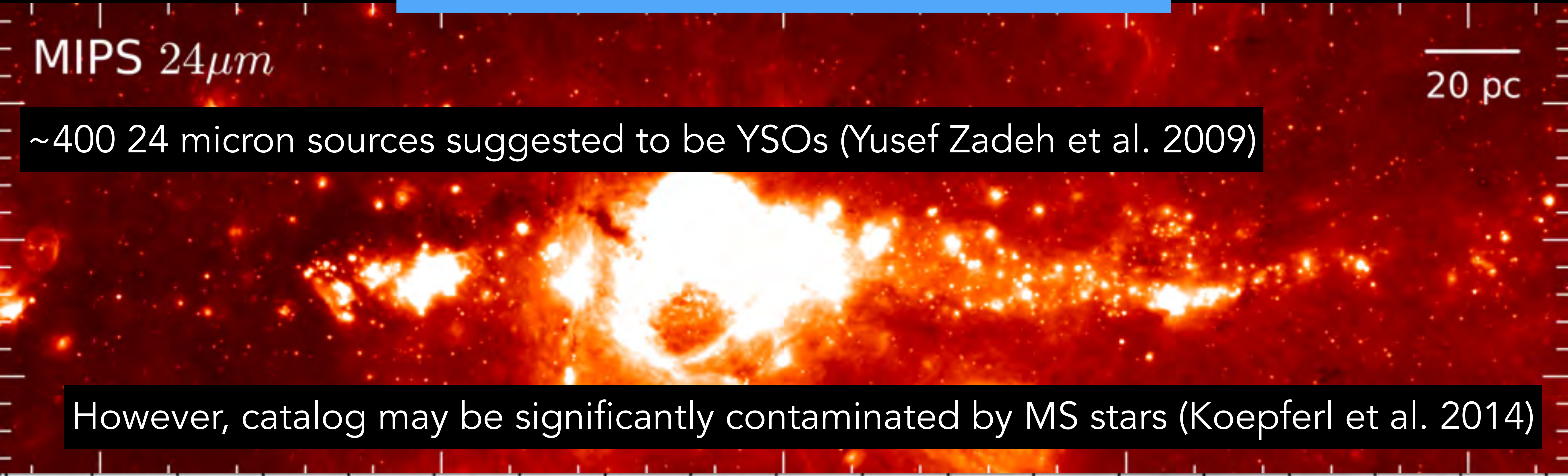
$\alpha_{\text{Salpeter}} = 2.35$

Only clear example of a top-heavy IMF in the GC.



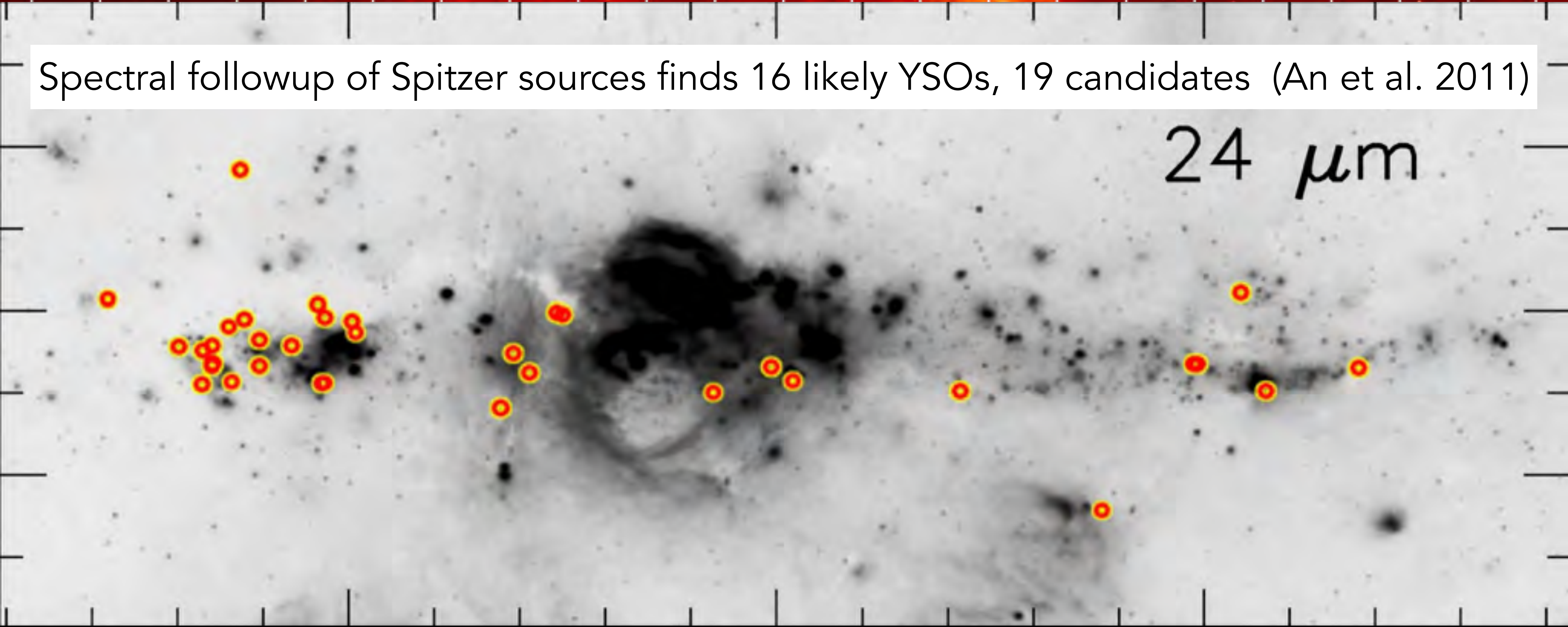
Lu et al. (2013)

Search for true YSOs continues



~400 24 micron sources suggested to be YSOs (Yusef Zadeh et al. 2009)

However, catalog may be significantly contaminated by MS stars (Koepferl et al. 2014)



Spectral followup of Spitzer sources finds 16 likely YSOs, 19 candidates (An et al. 2011)

Actual SFR is somewhat uncertain

IRAS: **0.08 M_{SUN}/yr**
(Crocker et al. 2011)

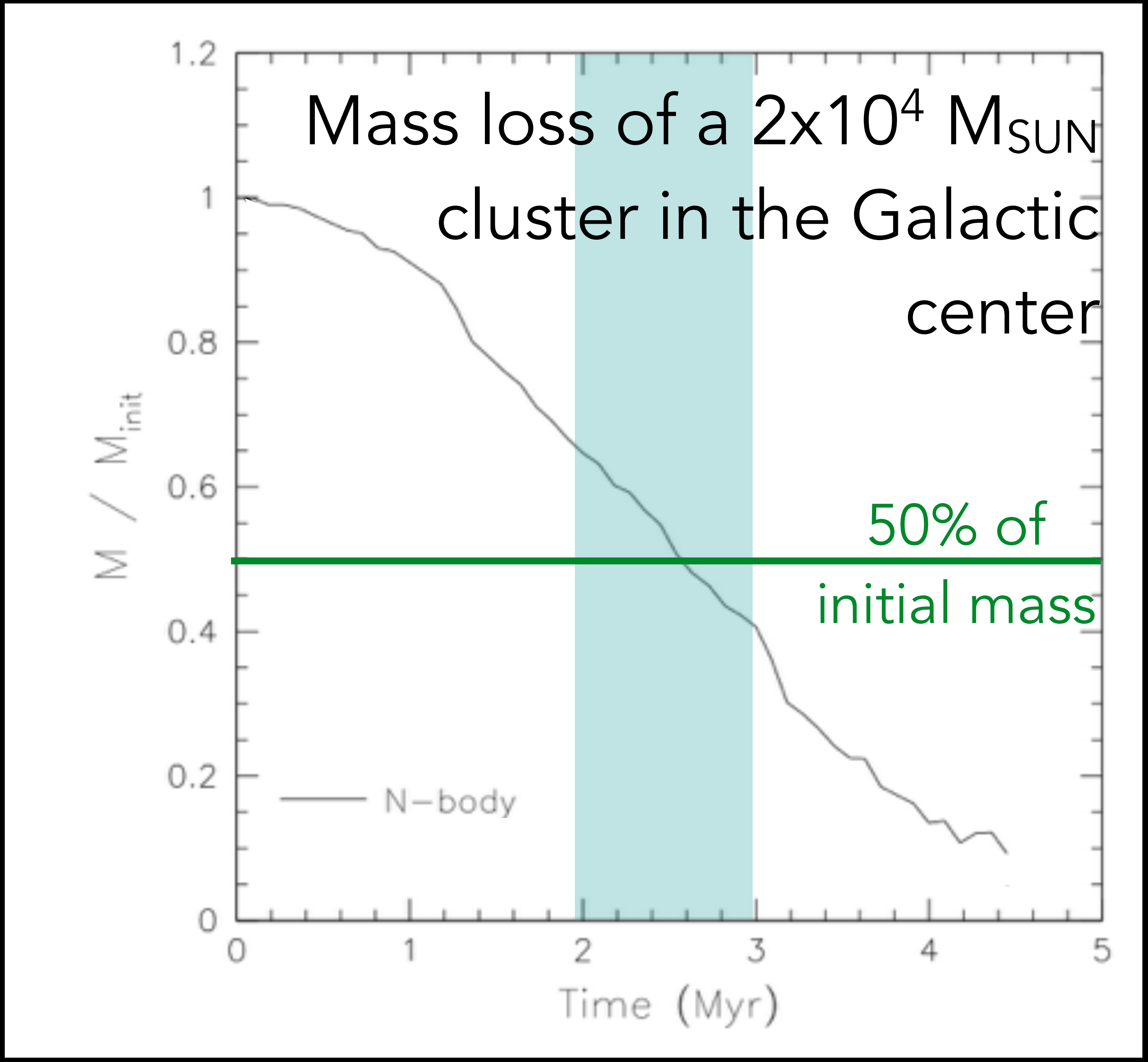
WMAP: **0.06 M_{SUN}/yr**
(Longmore et al. 2012)

24 µm: **0.07 M_{SUN}/yr**
(Yusef Zadeh 2009)

24 µm YSOs: **0.14 M_{SUN}/yr**
(Yusef Zadeh 2009)
(**0.05 M_{SUN}/yr**, Koepferl et al. 2015)

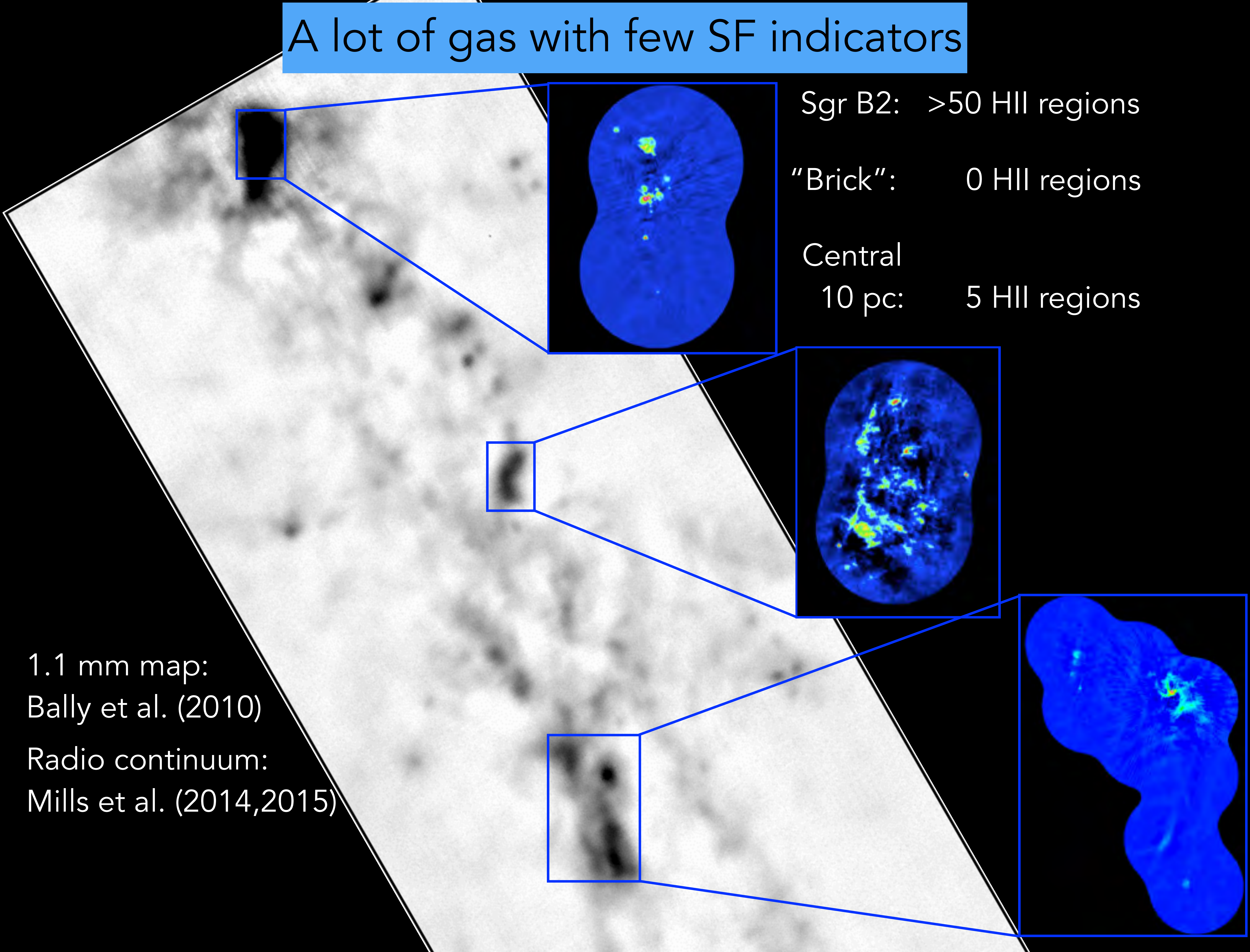
Young, massive clusters:
0.02 - 0.18 M_{SUN}/yr

Older clusters may be invisible



Kim et al. (2000)

A lot of gas with few SF indicators



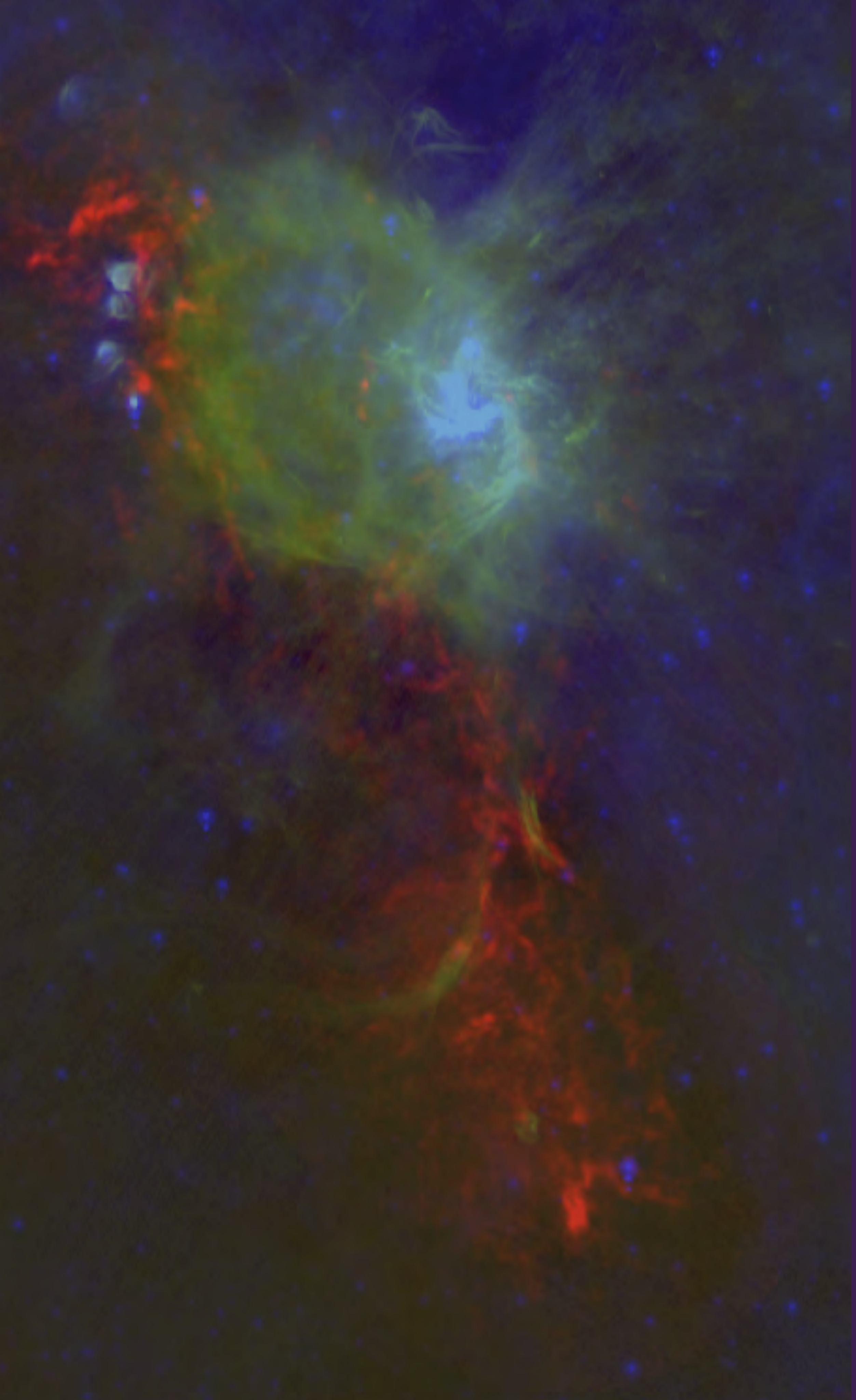
Sgr B2: >50 HII regions

"Brick": 0 HII regions

Central 10 pc: 5 HII regions

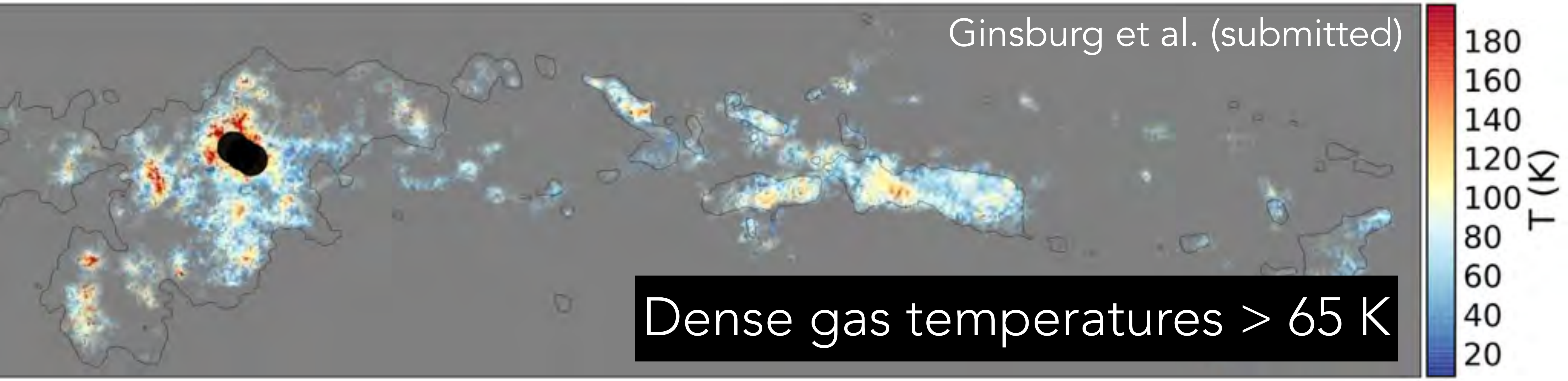
1.1 mm map: Bally et al. (2010)

Radio continuum: Mills et al. (2014,2015)



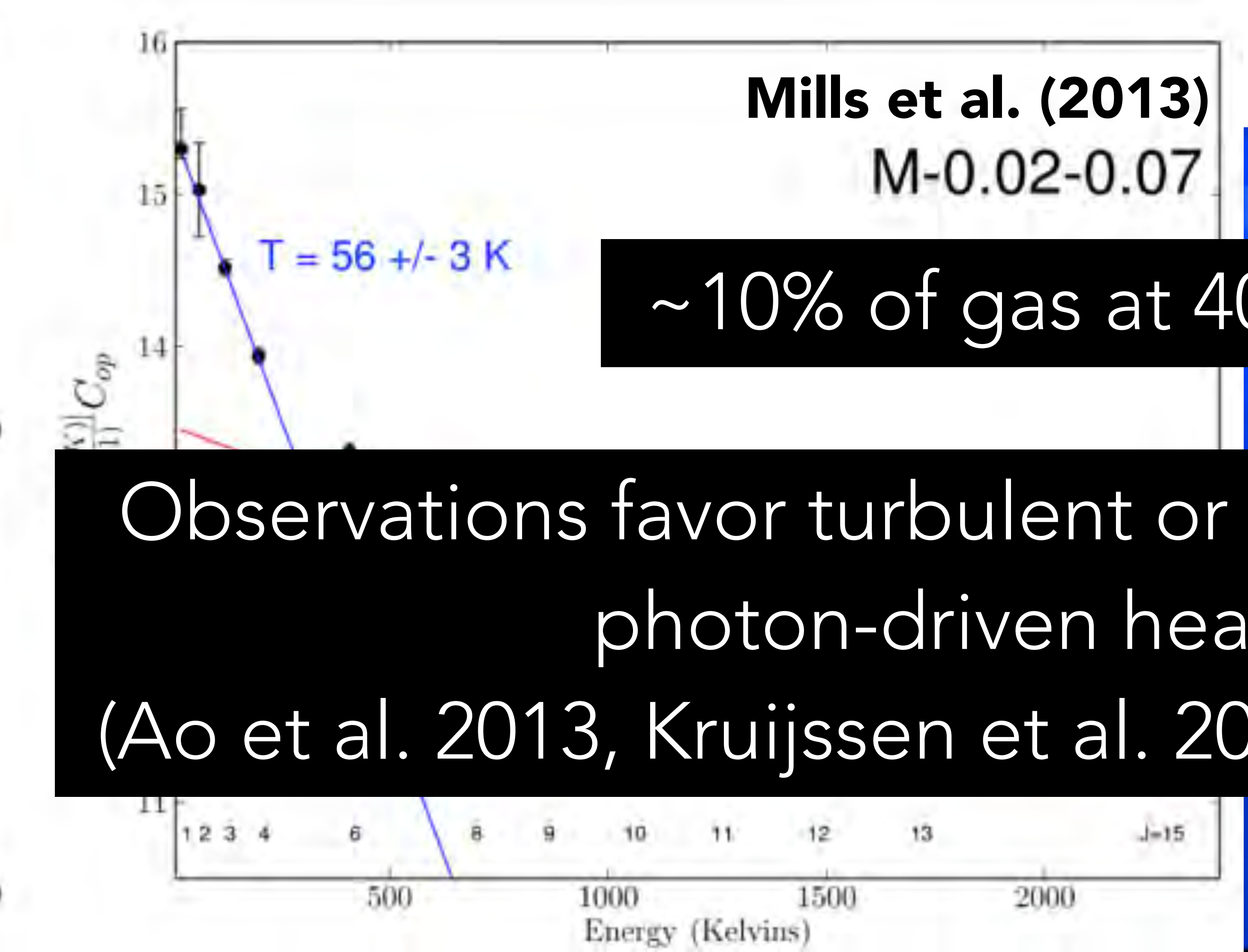
THE
(molecular)
GAS

Hot Gas, and Lots of it



Ginsburg et al. (submitted)

Dense gas temperatures > 65 K

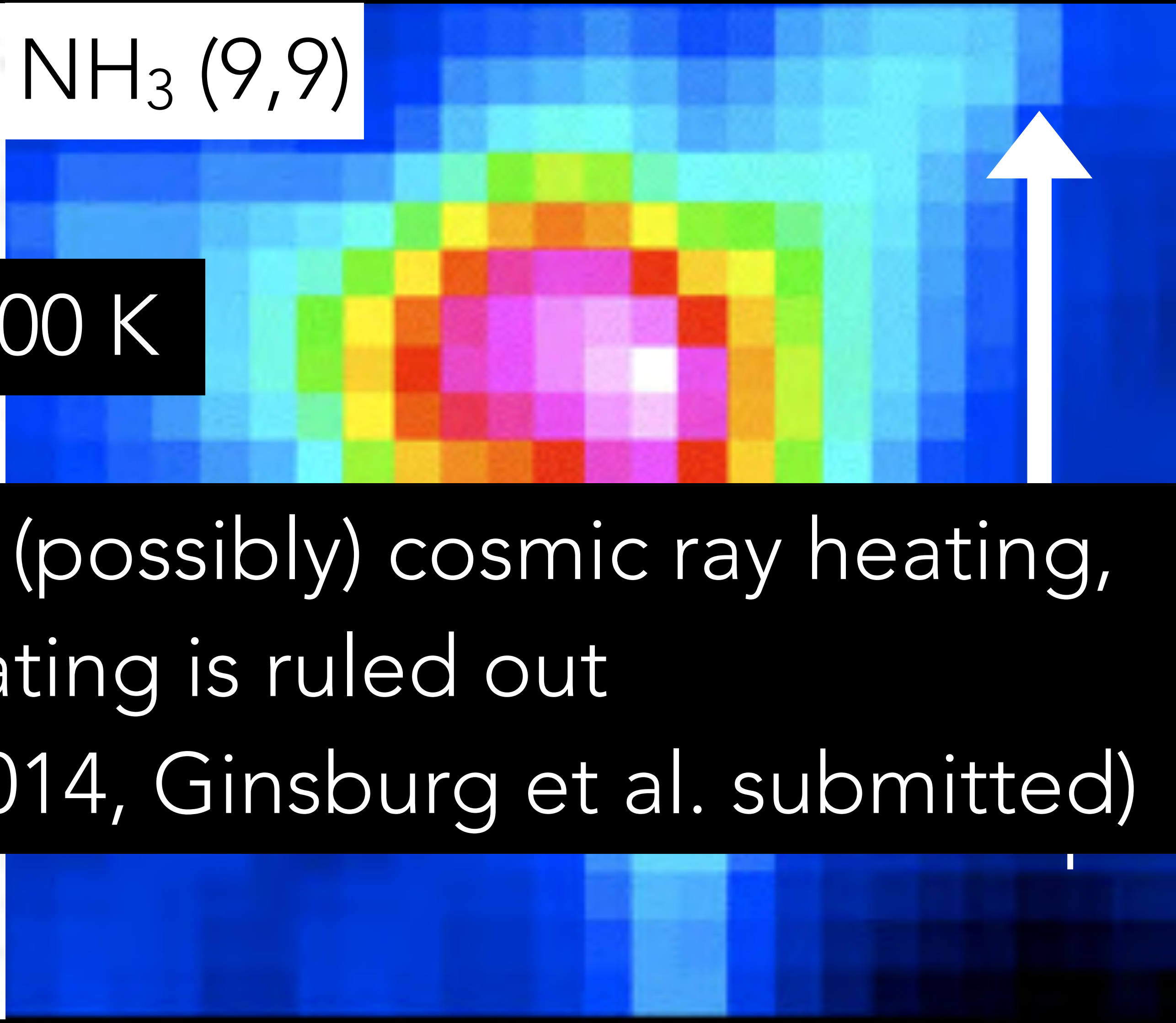


Mills et al. (2013)

M-0.02-0.07

T = 56 +/- 3 K

~10% of gas at 400 K



NH$_3$ (9,9)

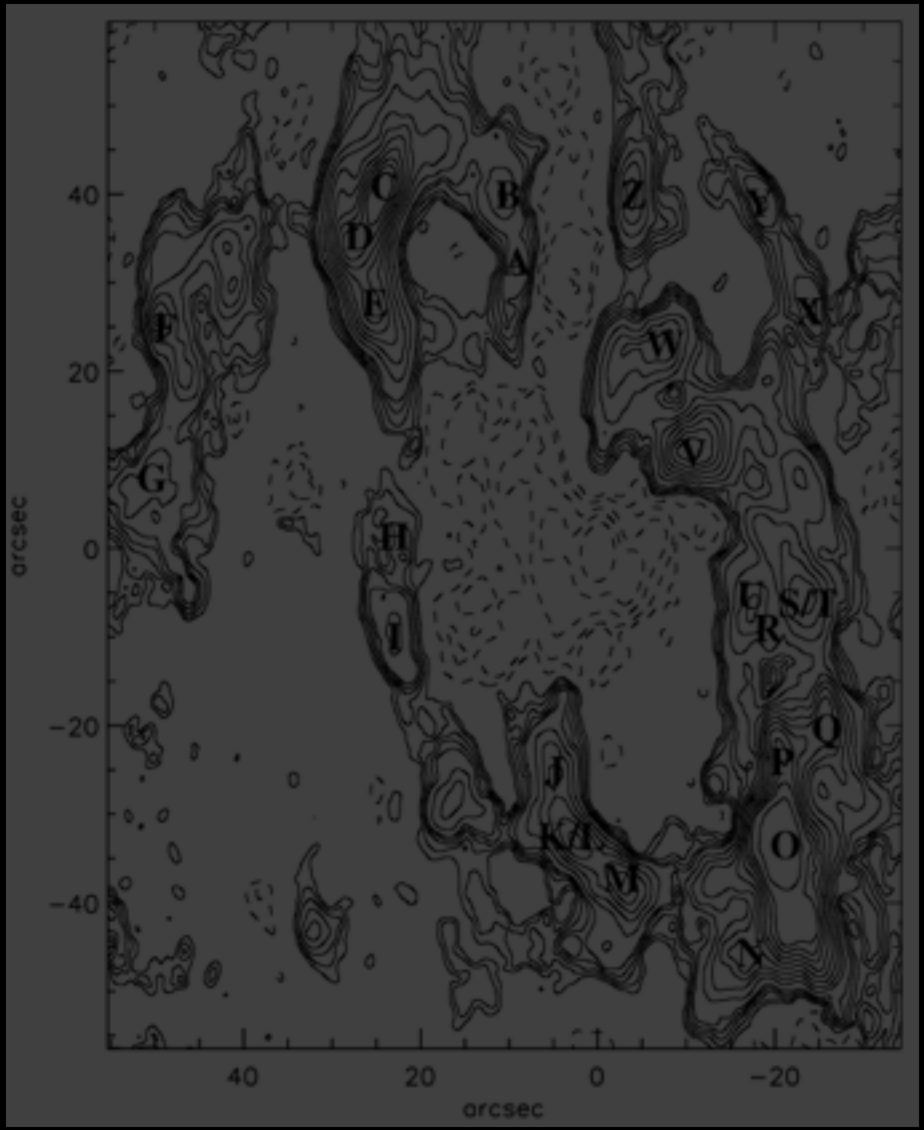
Observations favor turbulent or (possibly) cosmic ray heating, photon-driven heating is ruled out (Ao et al. 2013, Kruijssen et al. 2014, Ginsburg et al. submitted)

The Densest Gas is Less Dense

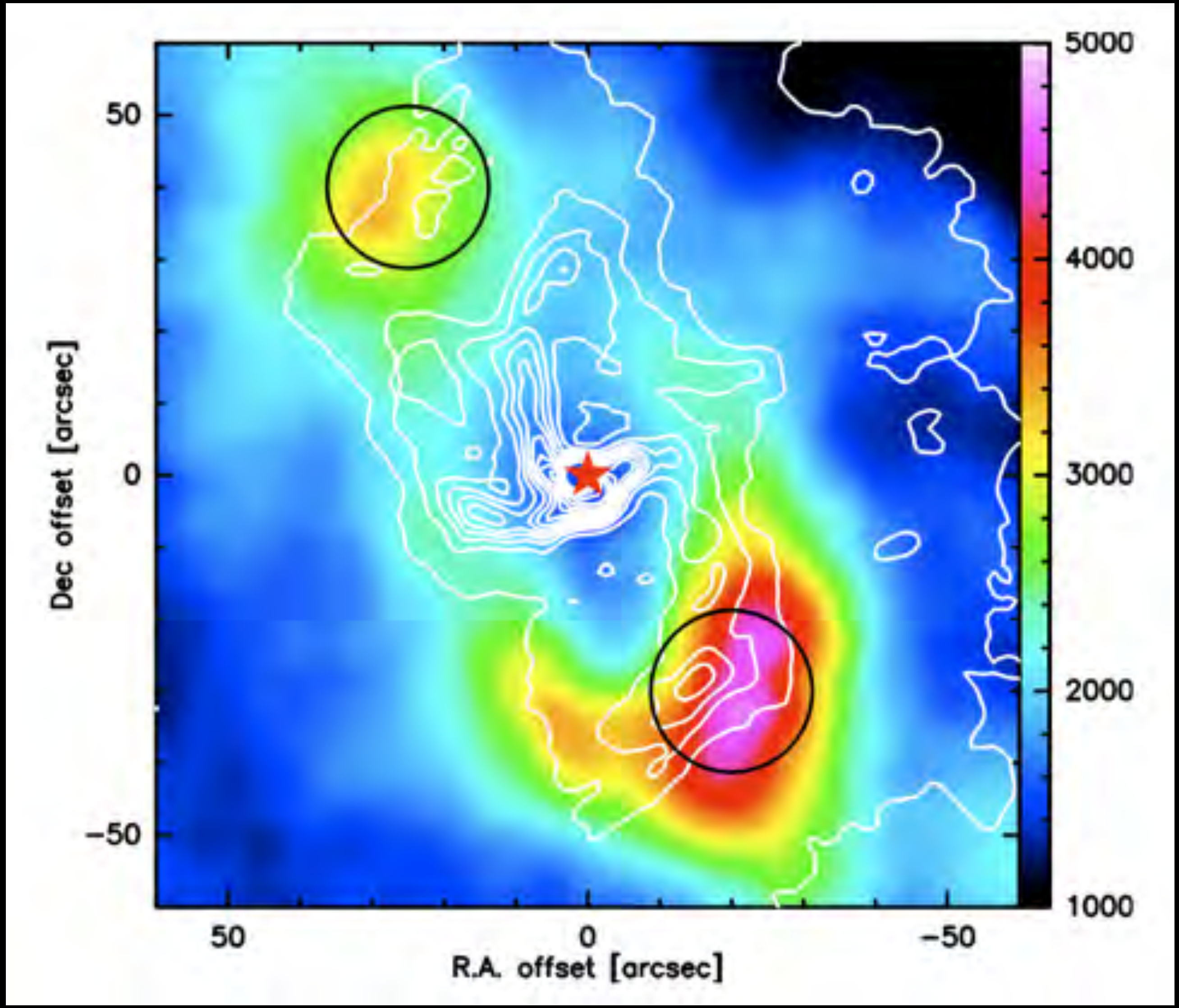
The Circumnuclear Disk: dense enough to form stars?

YES: Interferometry indicates virial densities >10^8 cm^{-3}

NO: Single-dish excitation analyses find densities ≤ 10^6 cm^{-3}

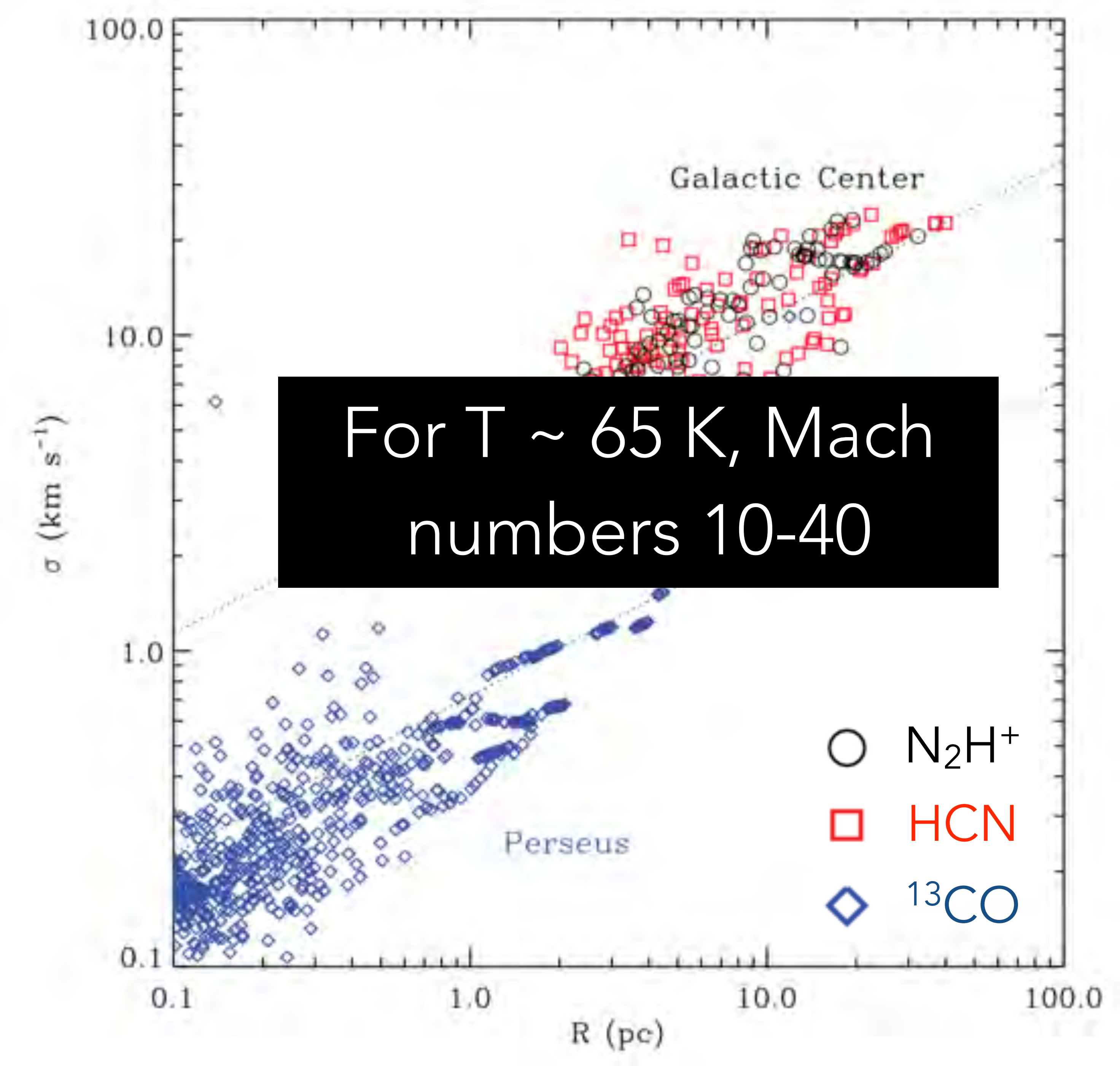


Christopher et al. 2005



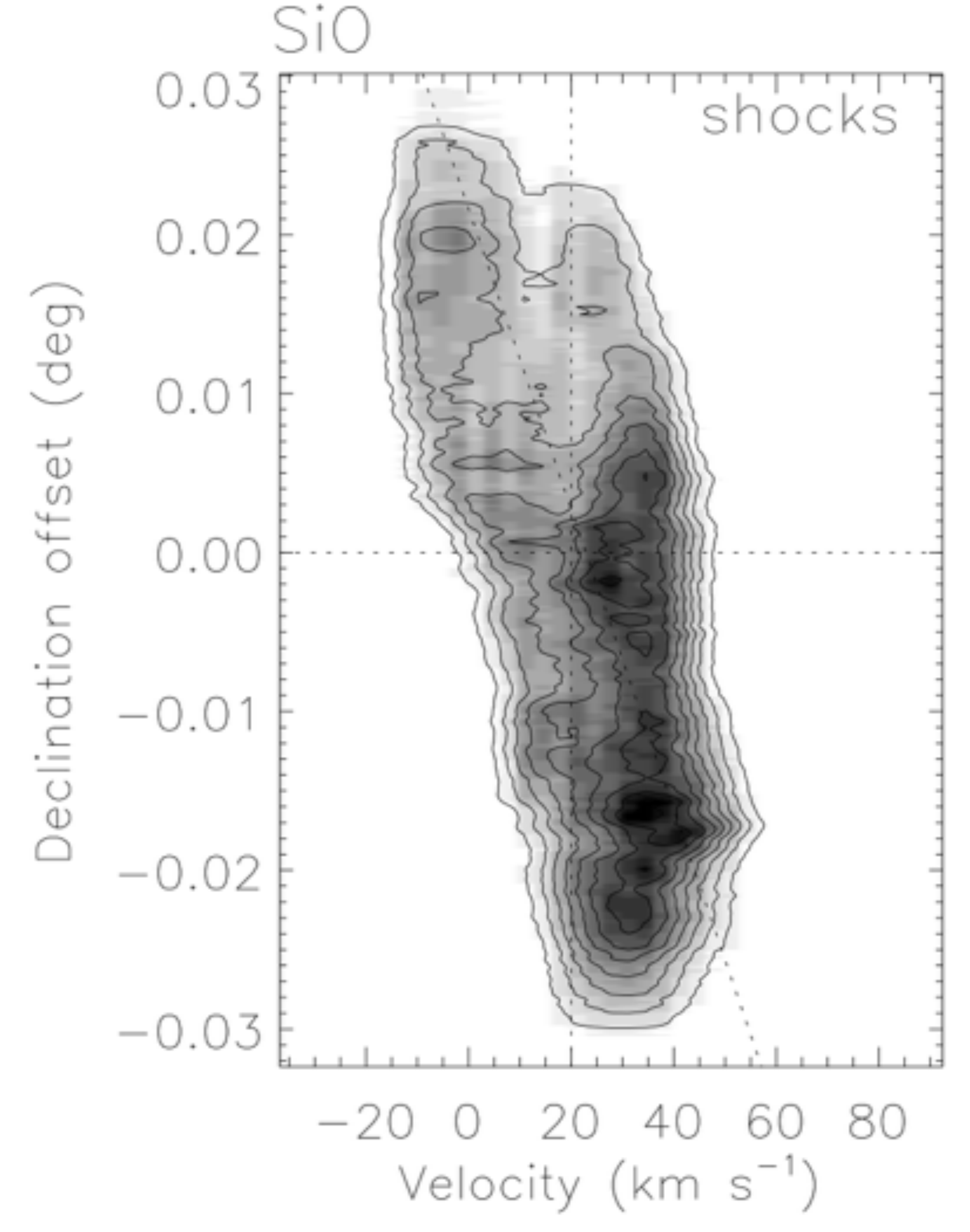
Requena Torres et al. 2012, Mills et al. 2013

See Both Turbulence and Large Velocity Gradients



For T ~ 65 K, Mach numbers 10-40

Shetty et al. (2012)



Rathborne et al. (2015)

A Disputed Cosmic Ray Ionization Rate

Galactic Plane: $\zeta \sim 10^{-16}$ s^{-1} (Indriolo et al. 2014)

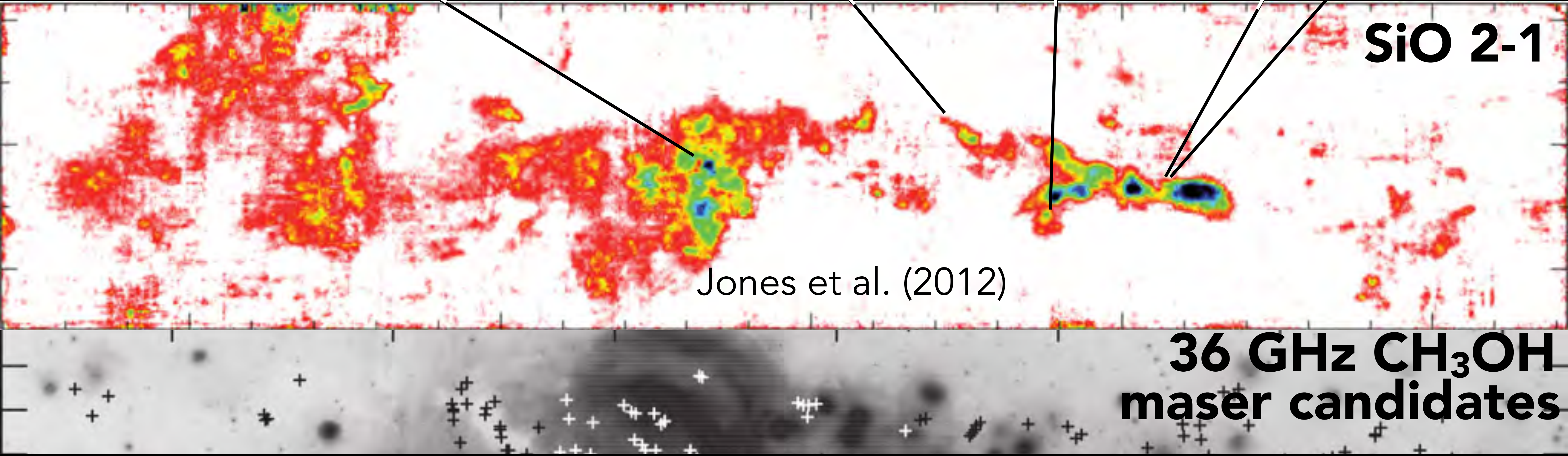
$\zeta \sim 10^{-14}$ s^{-1} (Harada et al. 2013)

$\zeta \sim 10^{-15}$ s^{-1} (Goto et al. 2013)

$\zeta \sim 10^{-16}$ s^{-1} van der Tak 2006

$\zeta \sim 10^{-13}$ s^{-1} Yusef Zadeh et al. 2013c

$\zeta \sim 10^{-14}$ s^{-1} Clark et al. 2013



SiO 2-1

Jones et al. (2012)

36 GHz CH_3OH maser candidates

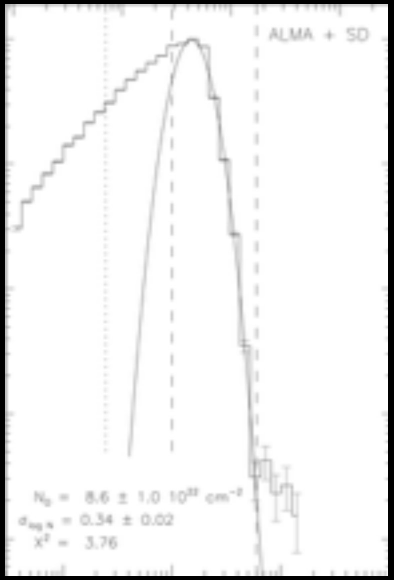
Caution: Turbulence and Cosmic rays can have similar chemical and heating signatures.

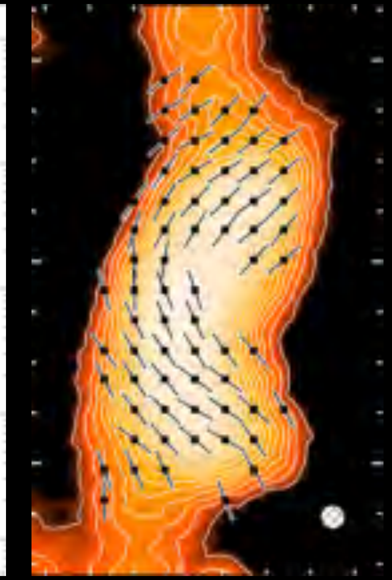
Yusef Zadeh et al. (2012)

Implications for Star Formation

High temperatures imply M_{Jeans} ~ 2 M_{SUN}

(Ginsburg et al. submitted)



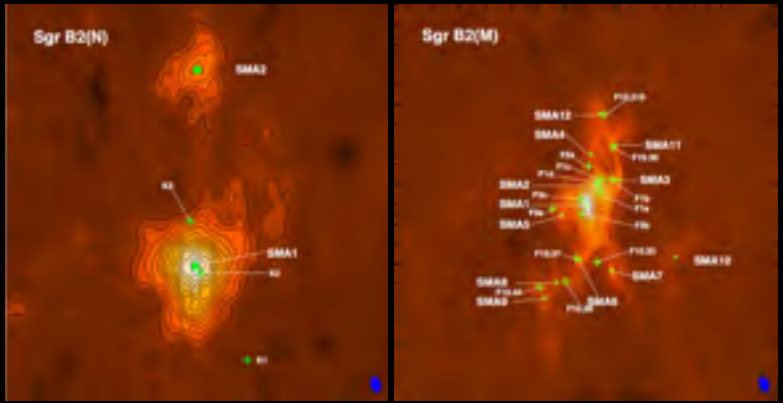


BUT core masses may be set by turbulence

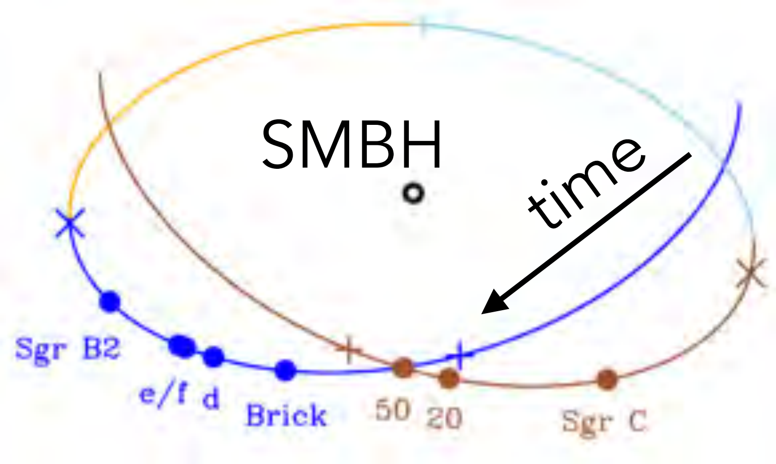
(Rathborne et al. 2014).

BUT, B fields may be dynamically dominant.

(Pillai et al. 2015)



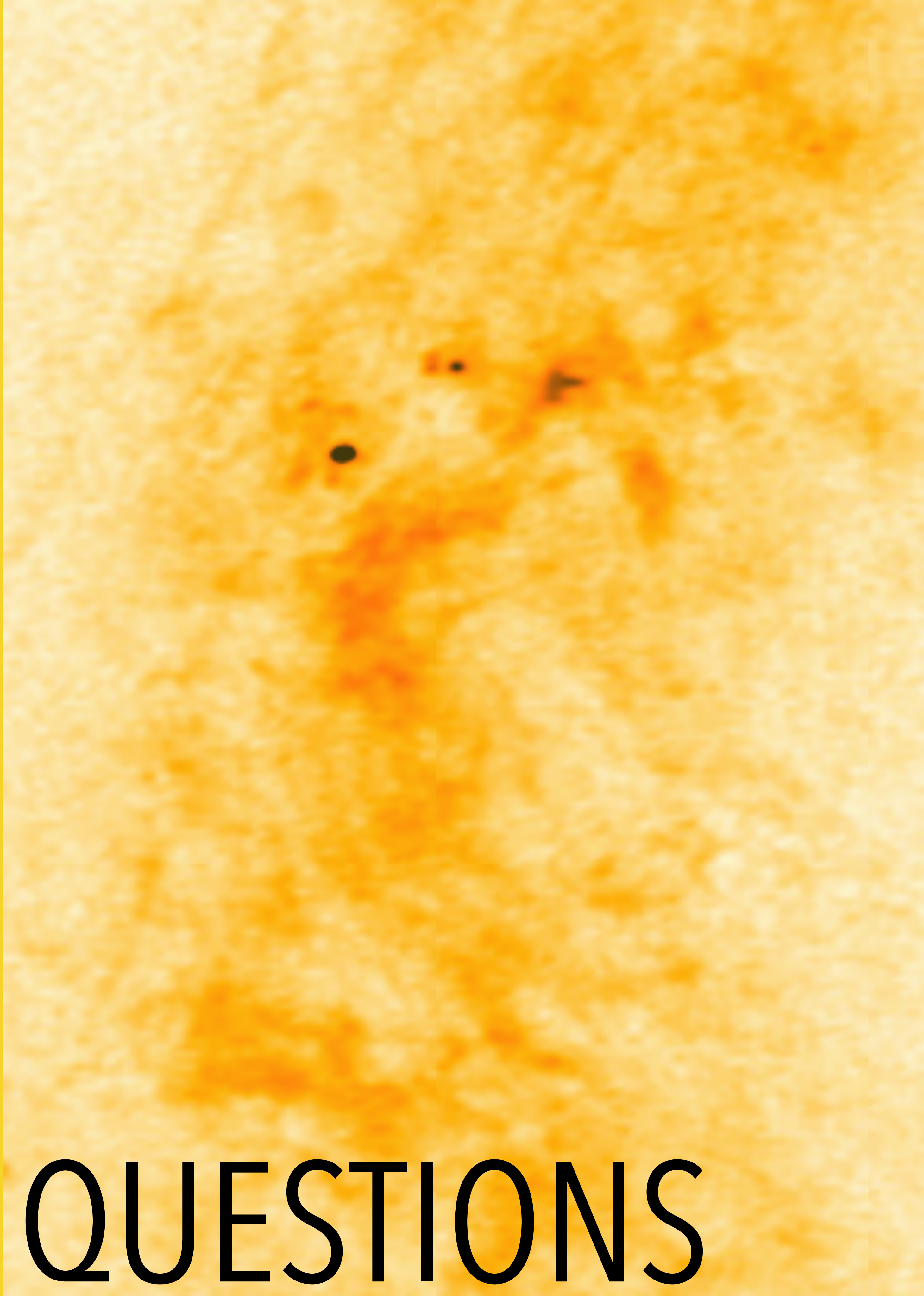
Suggestion of progressive fragmentation with core evolution (Qin et al. 2011)



May have the opportunity to observe a time-sequence of massive star formation

(Kruijssen et al. 2015)

?



OPEN QUESTIONS

What is the true distribution of volume densities?

Need n > 2x10^4 cm^{-3} to be bound at r=50 pc

> 4x10^5 cm^{-3} to be bound at r=10 pc (Gusten & Downes 1980)

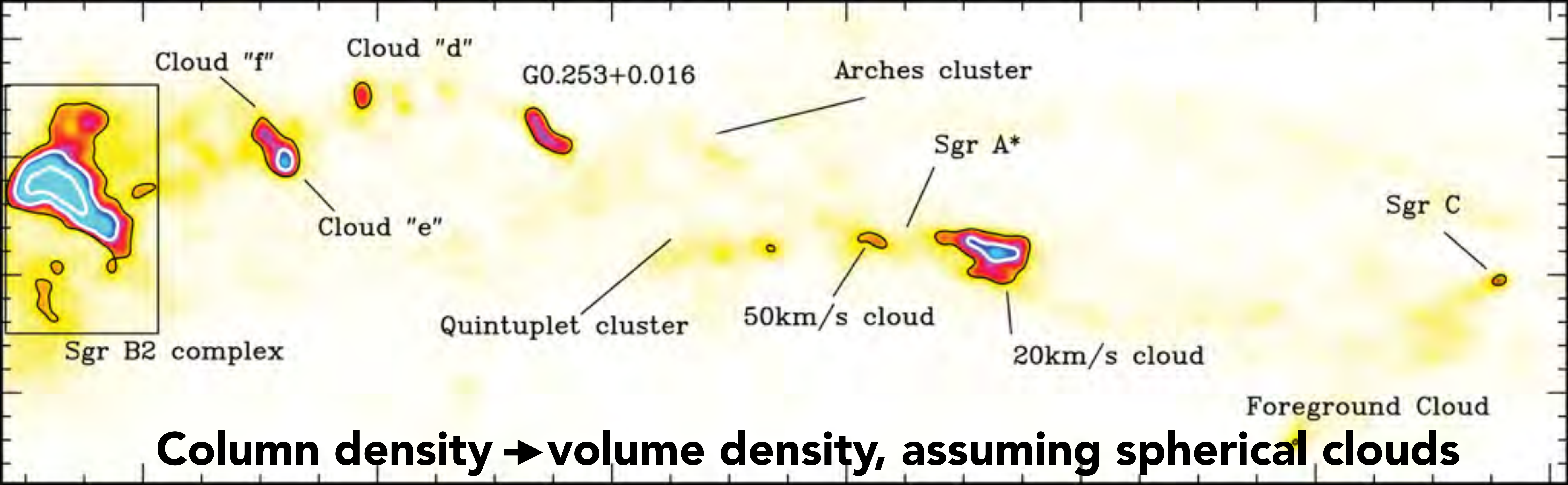
Need ~~>2x10^4 cm^{-3} to see CS 2-1 (Bally et al. 1987)~~

n_{eff}~6x10^3 cm^{-3} / n_{eff}~8x10^4 cm^{-3} from CH_3CN 6-5 (Shirley 2015)

H_2CO densitometry: ~10^5 cm^{-3} in the central 30 pc

(Guesten et al. 1983, extended by Zylka et al. 1992)

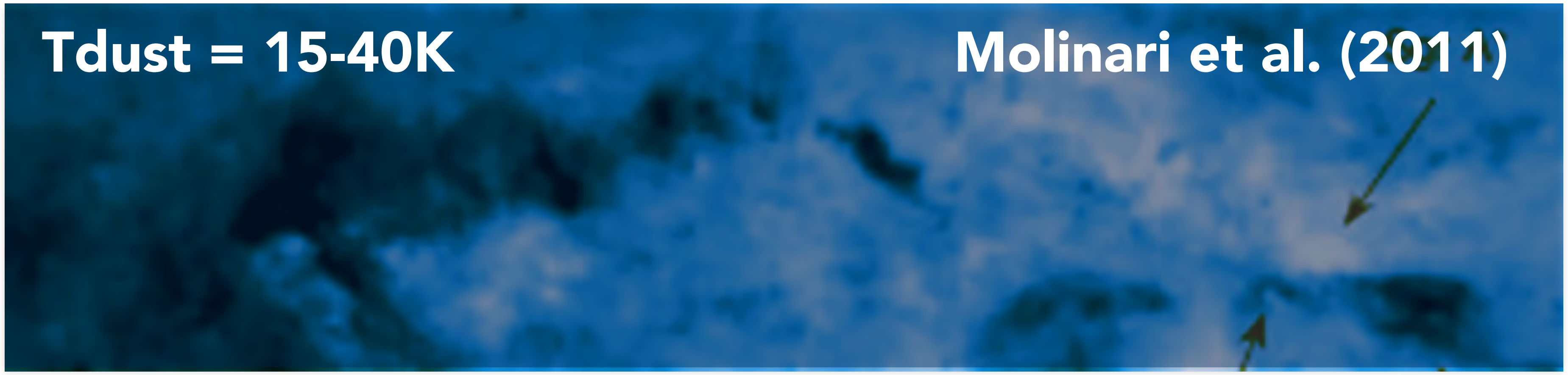
CS excitation: 1-2x10^6 cm^{-3} for one cloud (Serabyn et al. 1992)



Column density → volume density, assuming spherical clouds

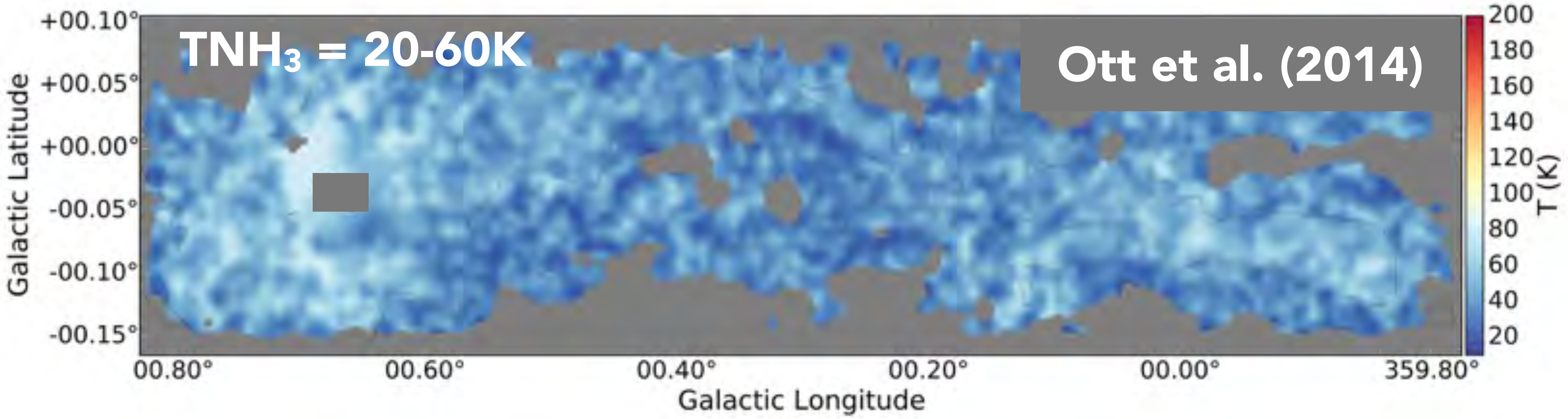
Longmore et al. (2013)

Where is the cool gas?



Tdust = 15-40K

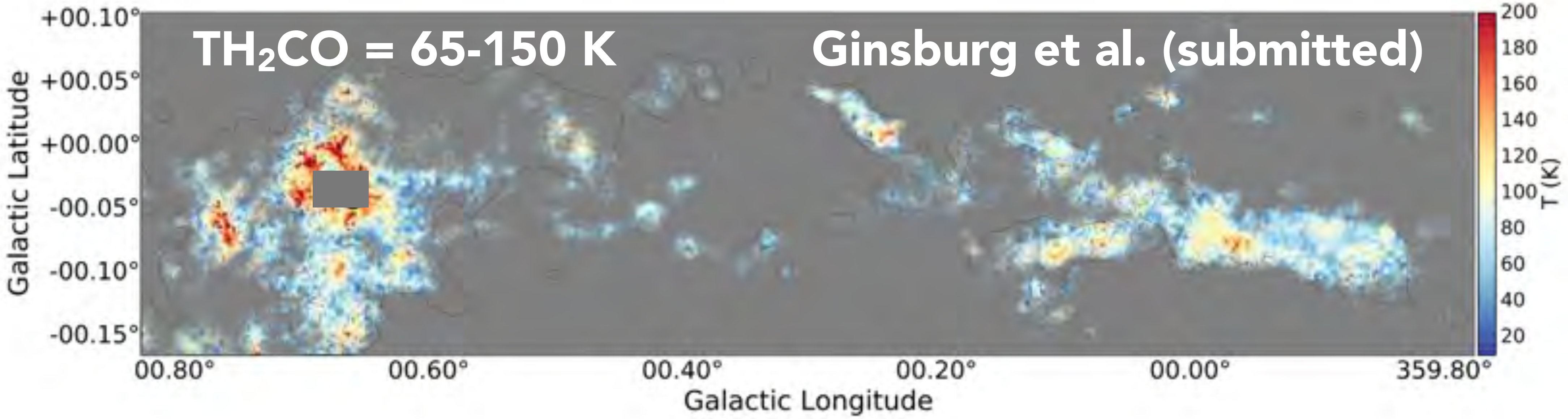
Molinari et al. (2011)



T_{NH_3} = 20-60K

Ott et al. (2014)

(a)



T_{H_2CO} = 65-150 K

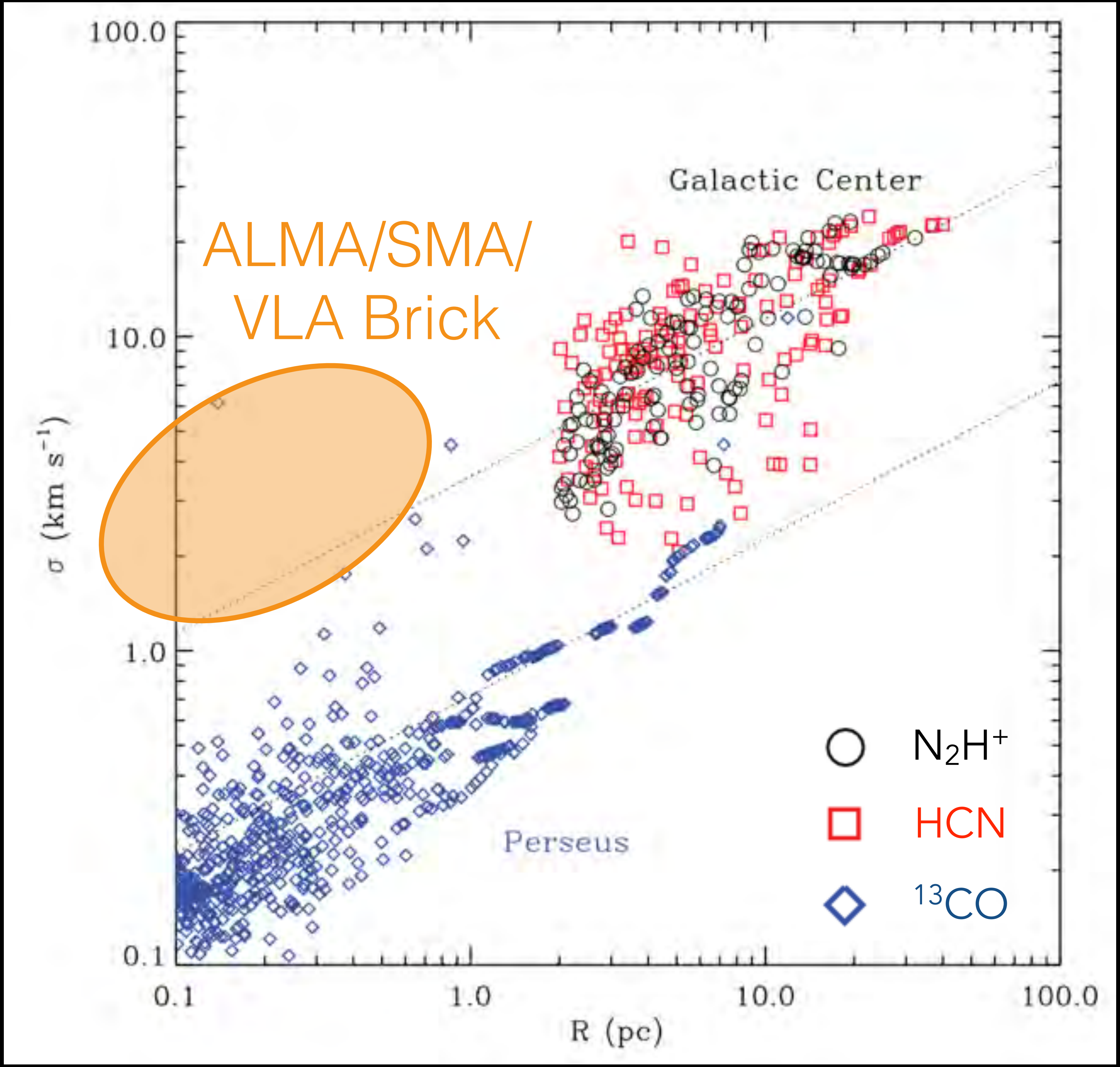
Ginsburg et al. (submitted)

(b)

What is the turbulence spectrum?

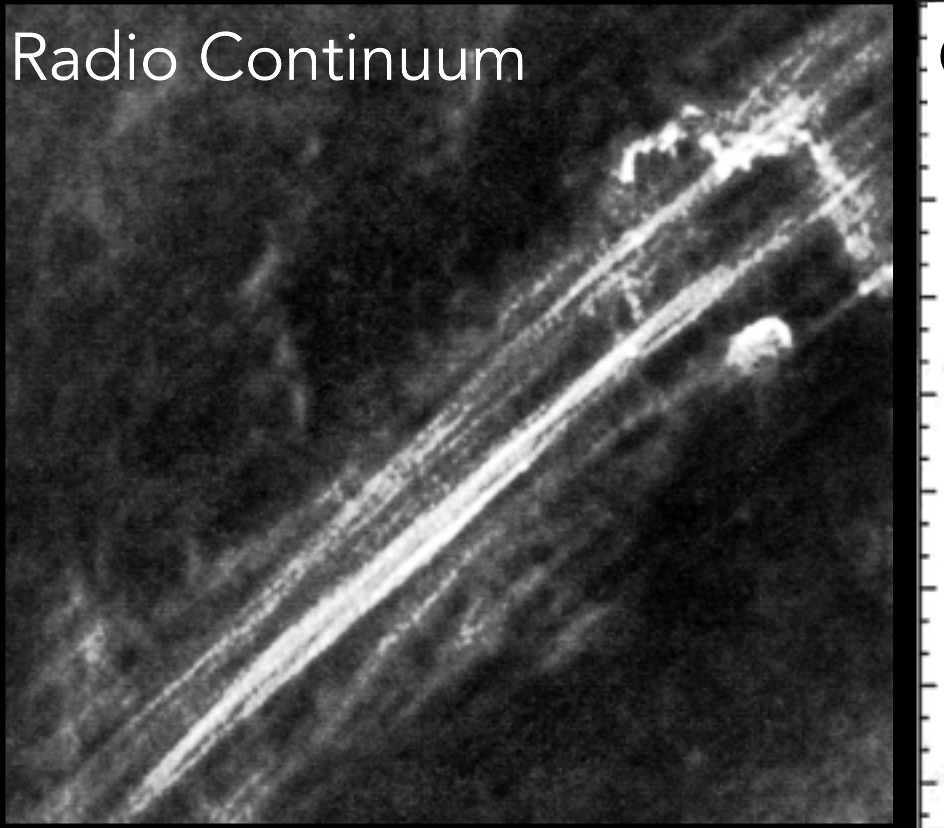
Is a single power law fit well characterized?

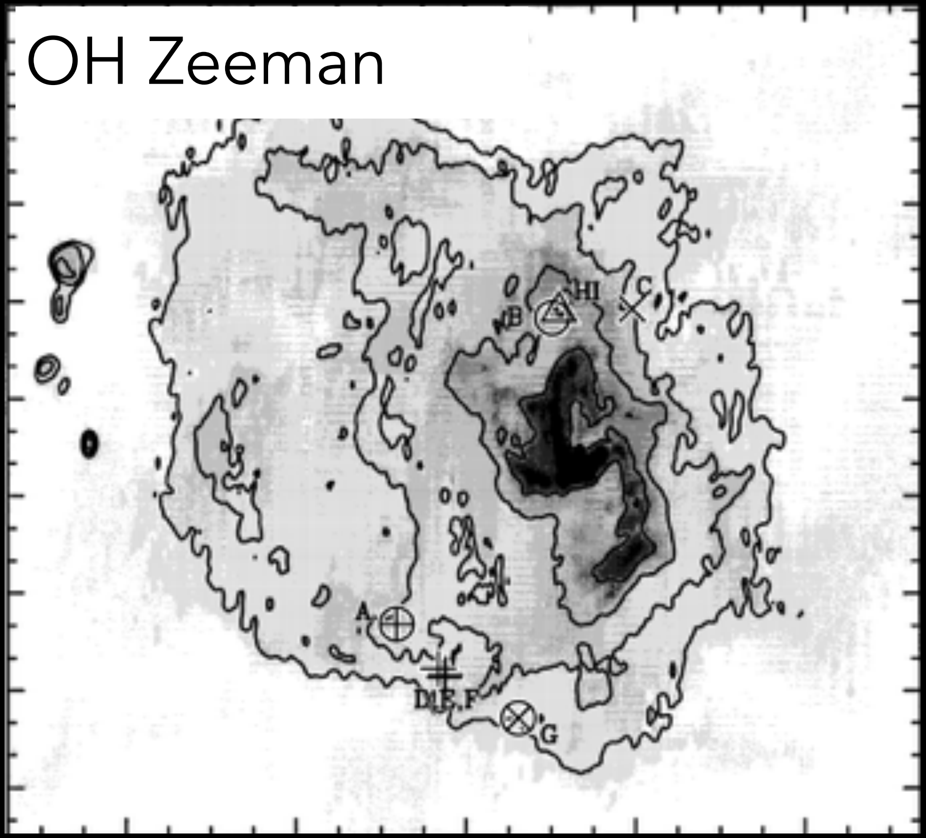
Are the properties the same in all Galactic center clouds?

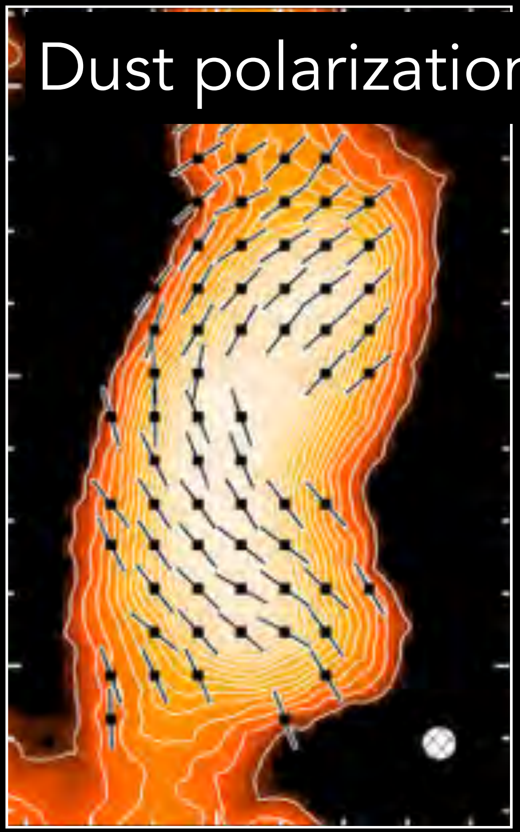


Shetty et al. (2012)

How strong are the magnetic fields?


Radio Continuum


OH Zeeman


Dust polarizatio

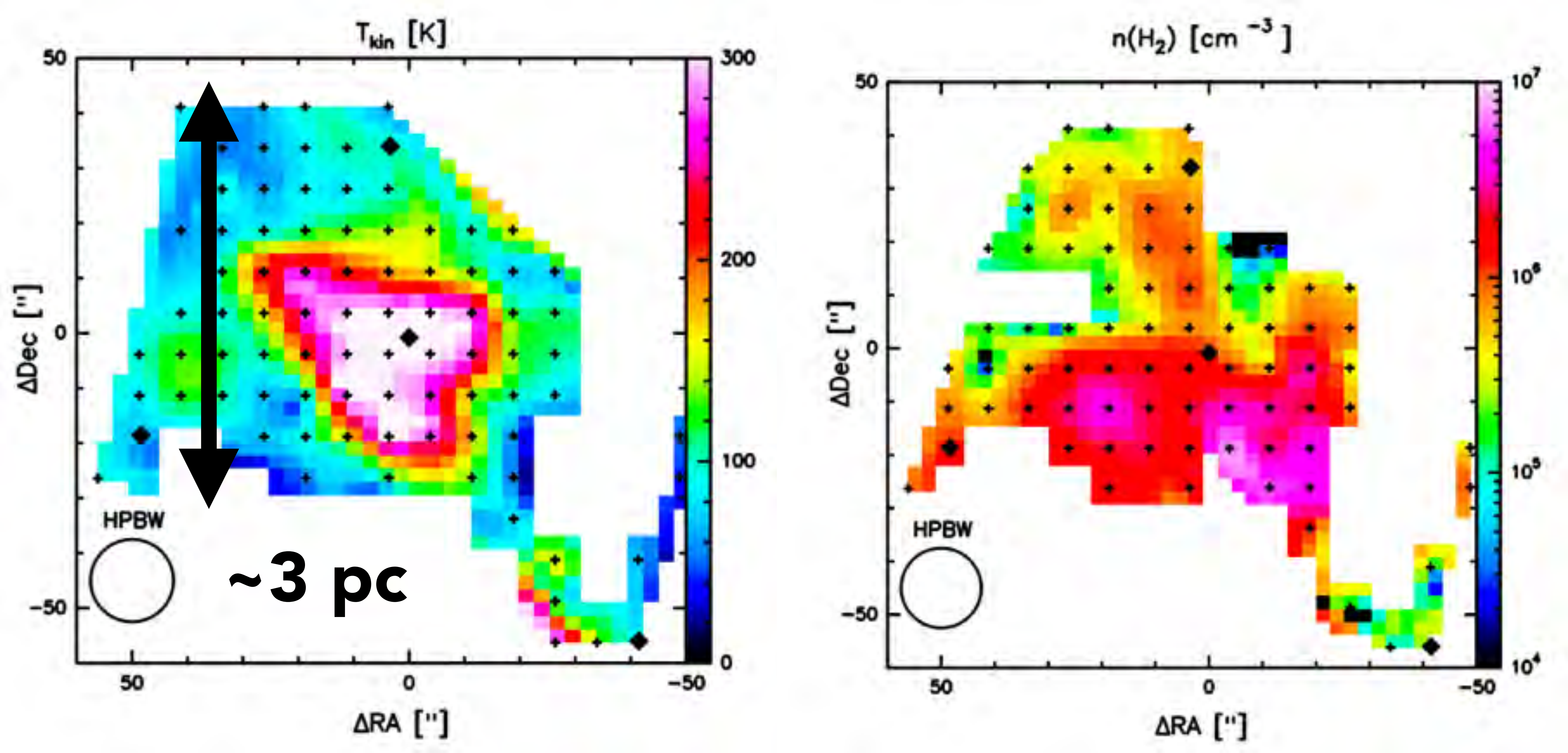
Linear (over 10’s of pc) nonthermal filaments suggested ~mG fields in the diffuse gas (Yusef Zadeh & Morris 1987, 1988)

2-4 mG fields measured from OH Zeeman in the central parsecs (Killeen et al. 1992, Yusef-Zadeh et al. 1996)

New polarization measurement of ~5 mG fields, the first for a more typical dense cloud (Pillai et al. 2015)

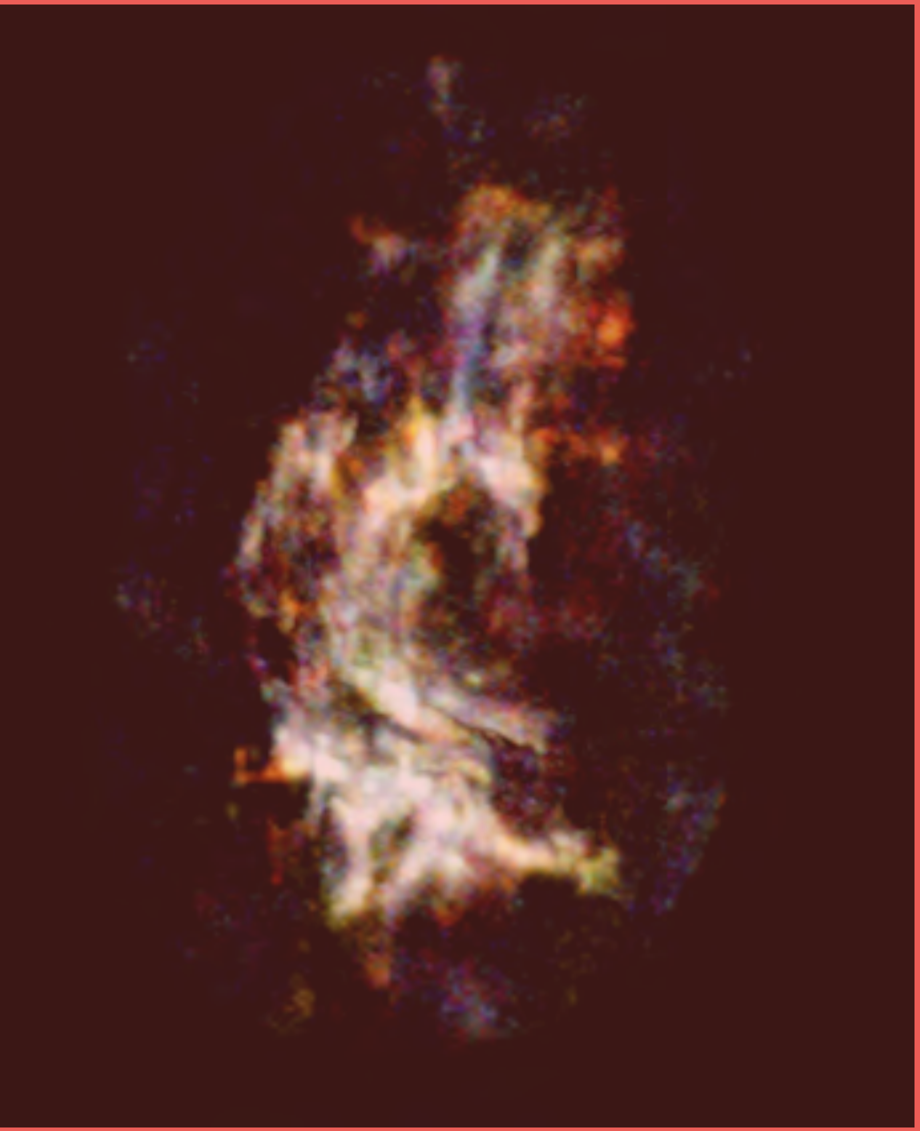
Which conditions are actually unique?

Extended hot, dense gas in W49



Nagy et al. (2012)

CHALLENGES

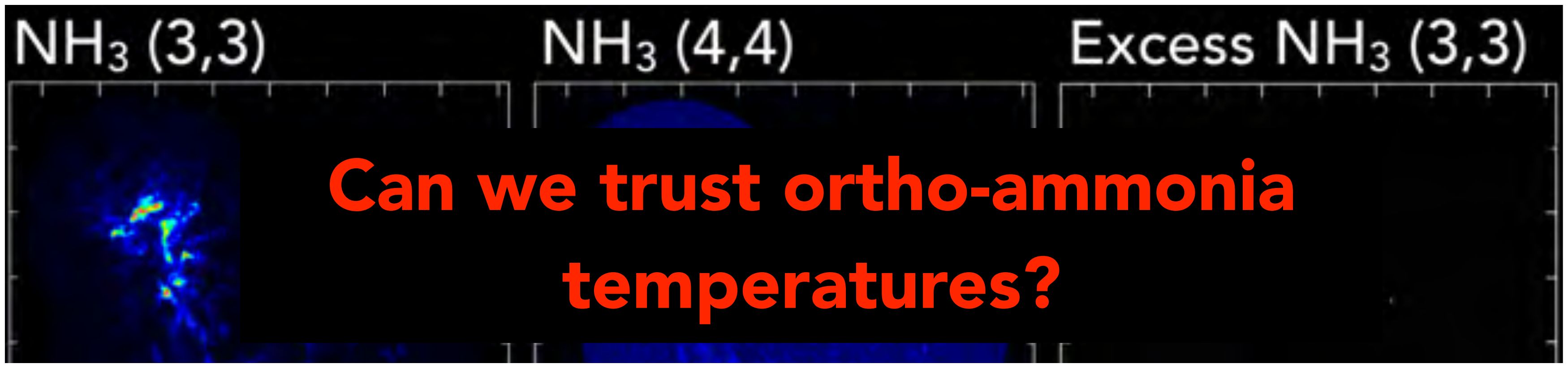


AND

OPPORTUNITIES

Challenge #1: Correctly inferring conditions

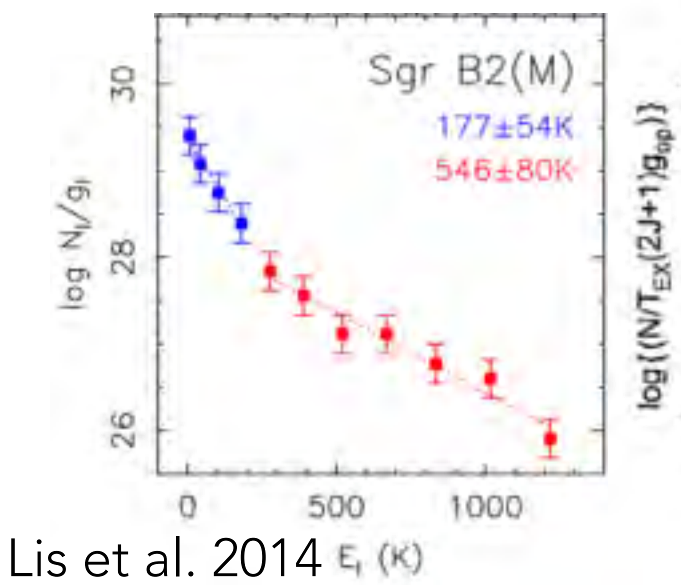
masers



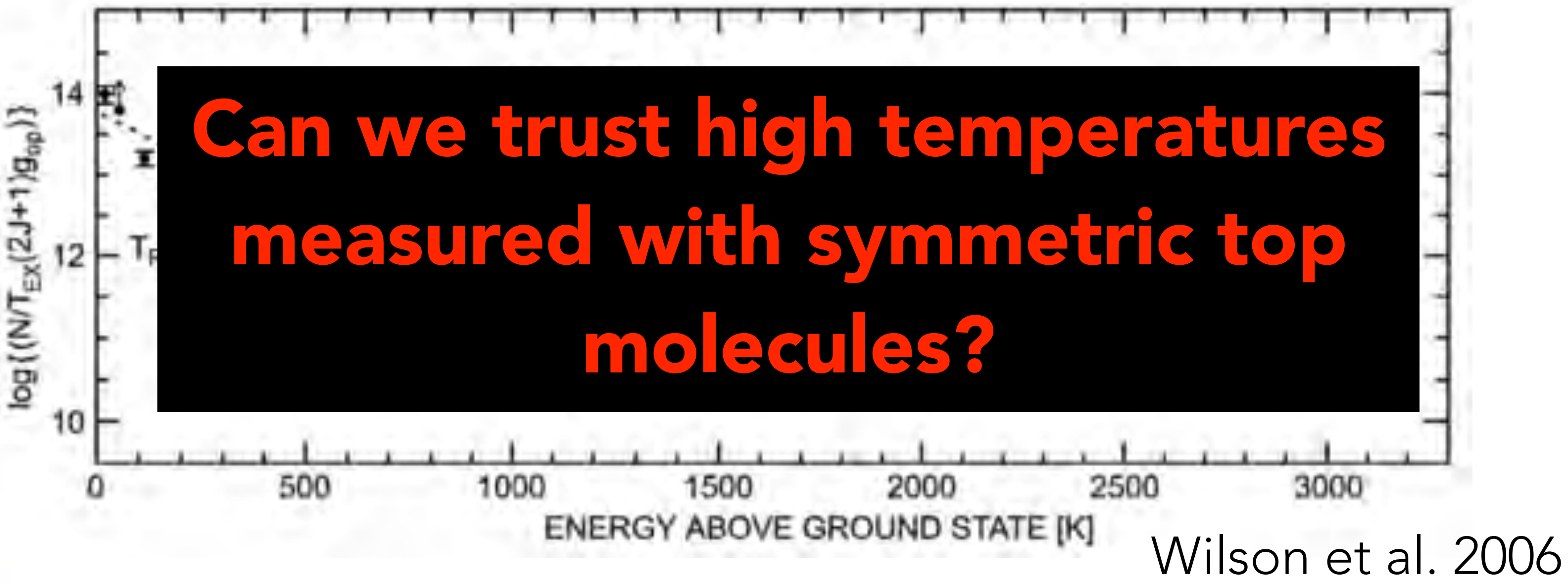
Can we trust ortho-ammonia temperatures?

Teachey et al. (in prep)

formation pumping



Lis et al. 2014

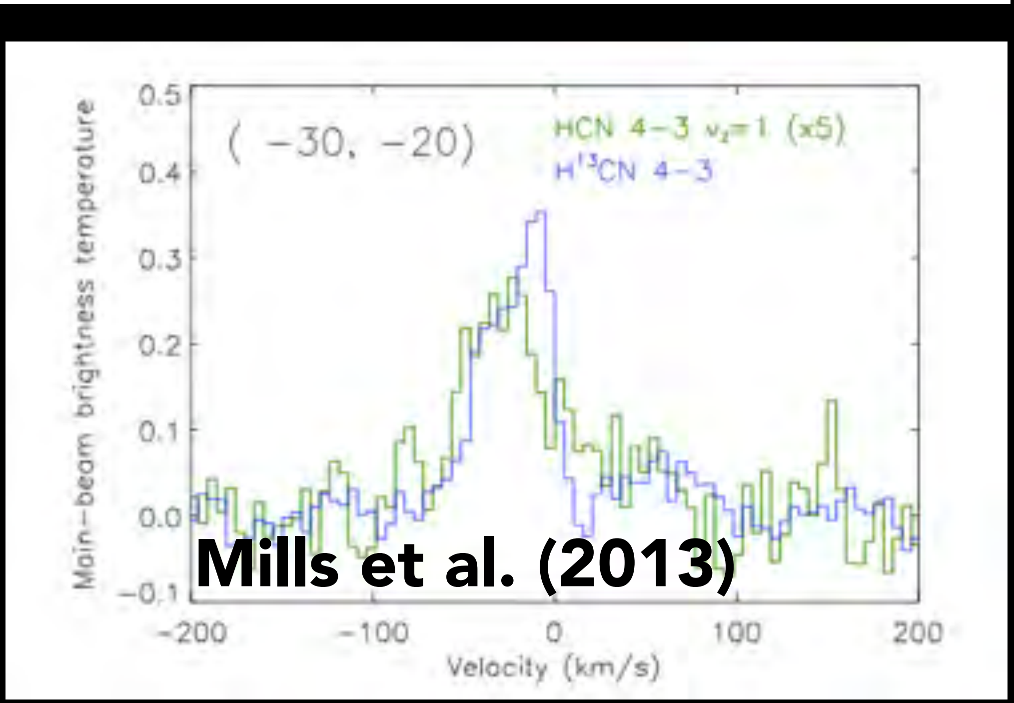


Can we trust high temperatures measured with symmetric top molecules?

Wilson et al. 2006

radiative excitation

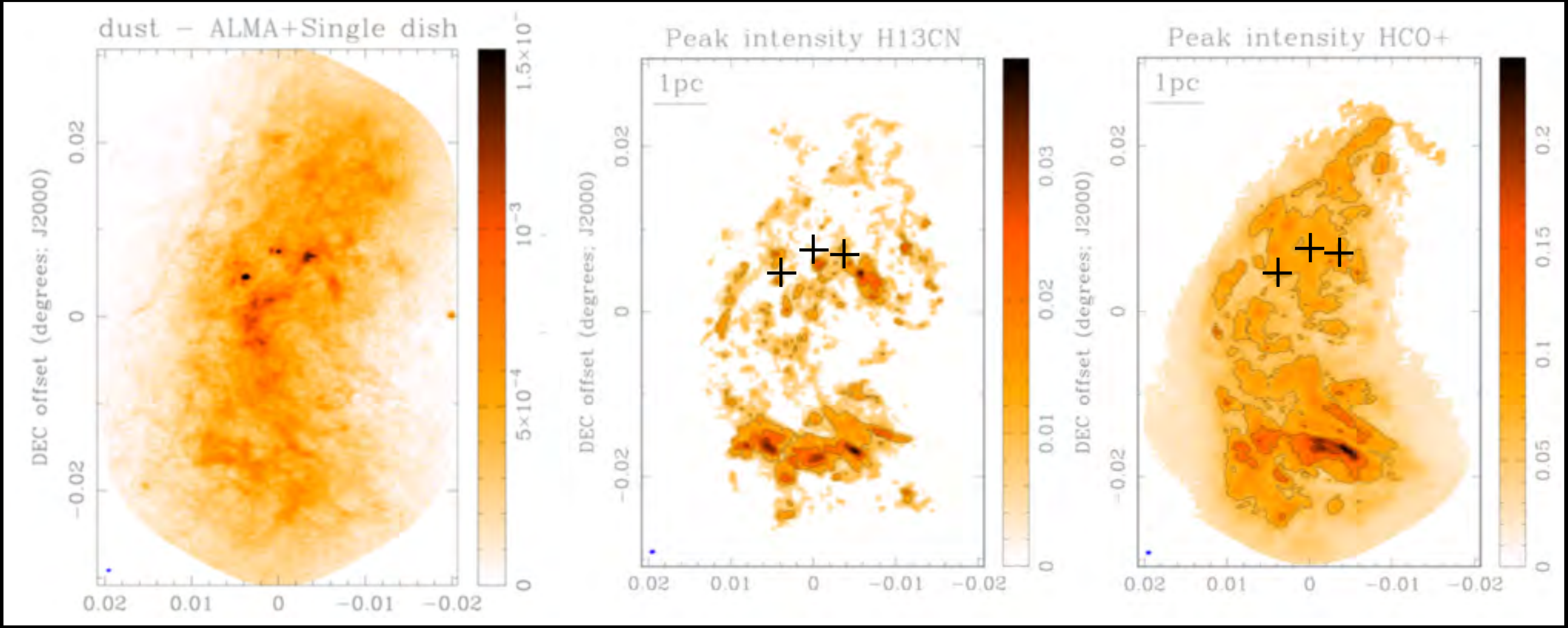
If there is hot dust or mid-IR radiation, an excitation analysis can OVERESTIMATE densities.



Mills et al. (2013)

Challenge #1: Correctly inferring conditions

If the densest cores are significantly depleted — do we actually know their physical conditions?



Rathborne et al. (2015)

Challenge #2: Finding the star formation

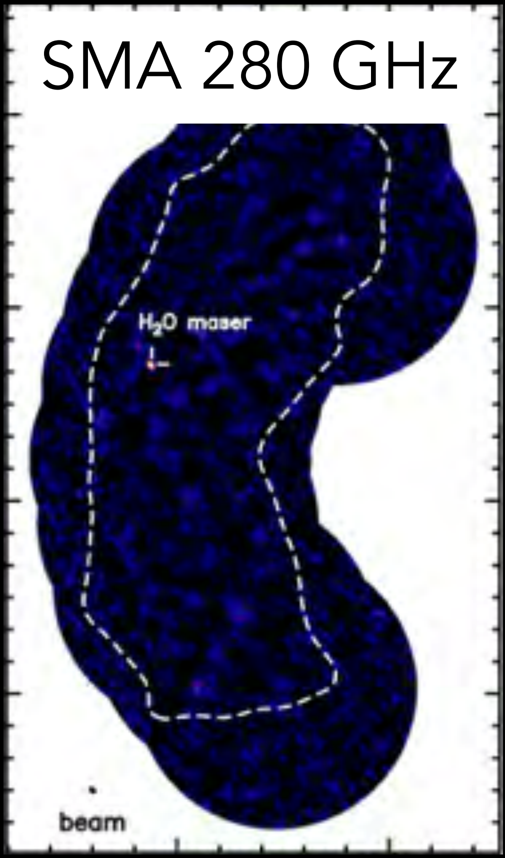
Hot EVERYWHERE

Complex chemistry EVERYWHERE

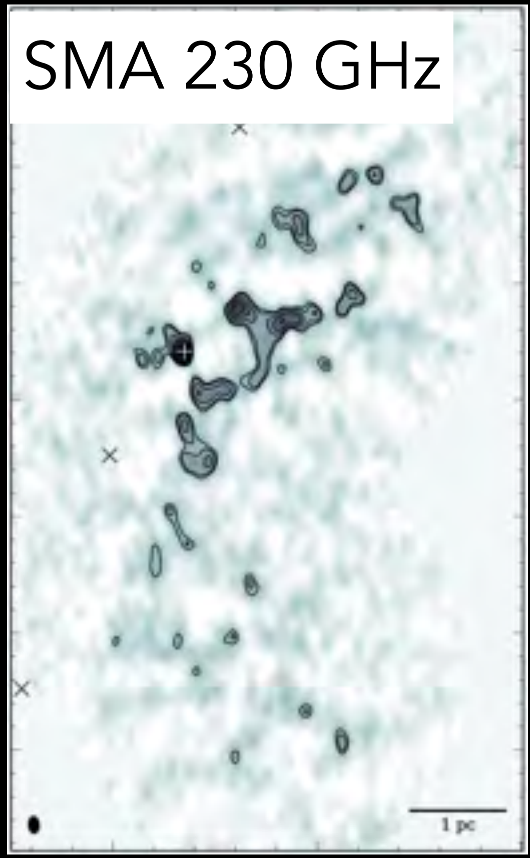
Shocks EVERYWHERE

Complex velocity fields —> Outflows hidden?

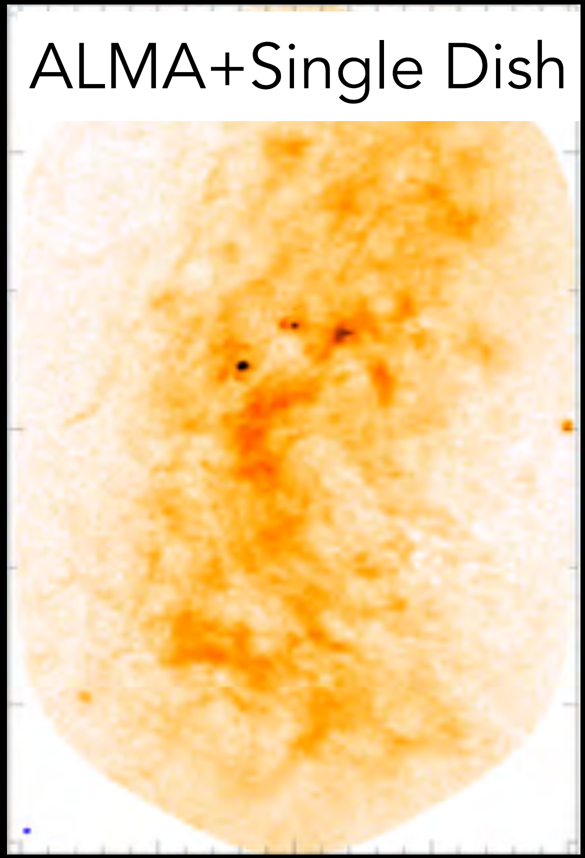
SMA 280 GHz



SMA 230 GHz

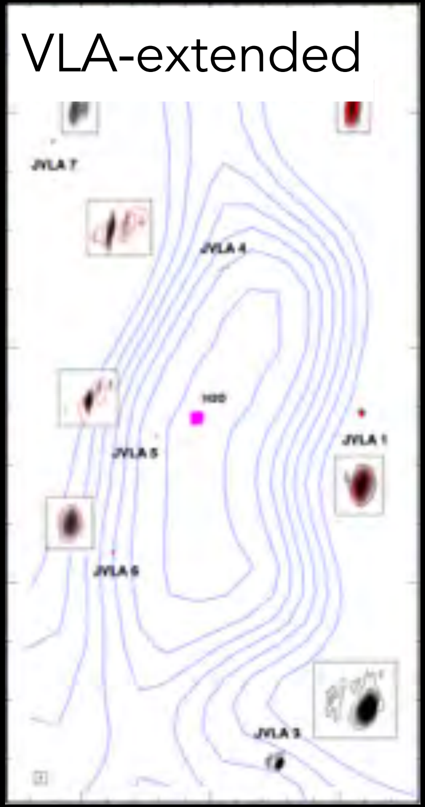


ALMA+Single Dish

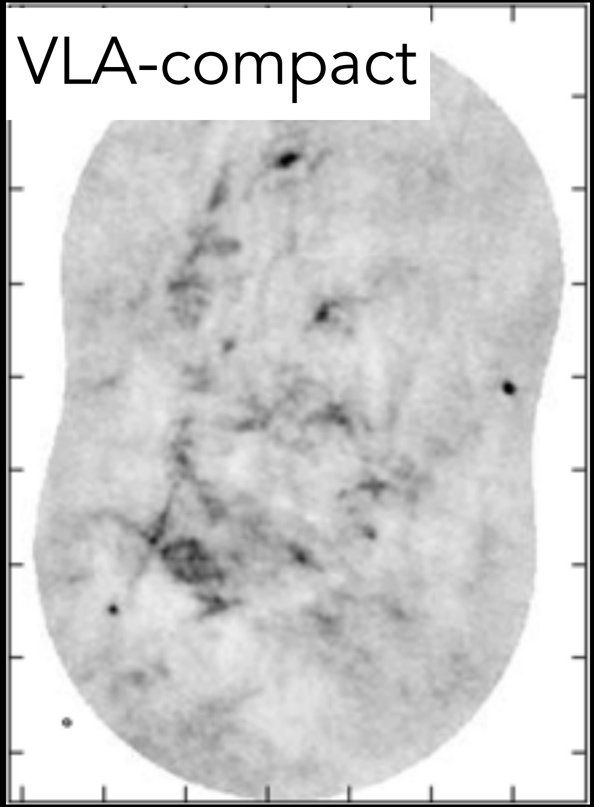


Beware observational biases

VLA-extended



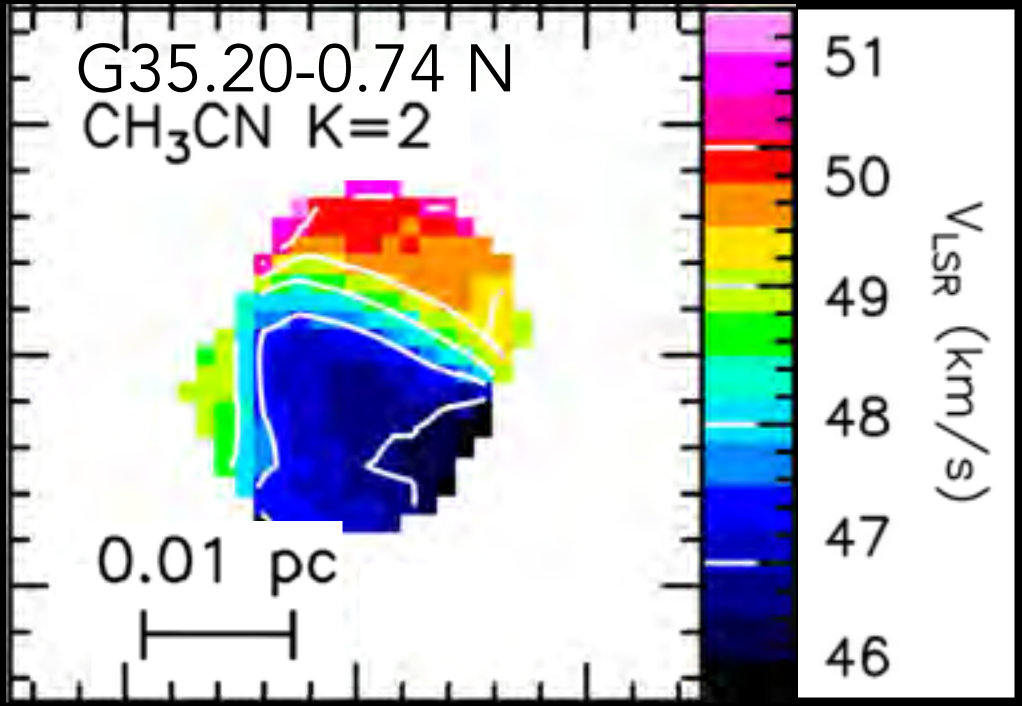
VLA-compact



VLA+ Single Dish

?

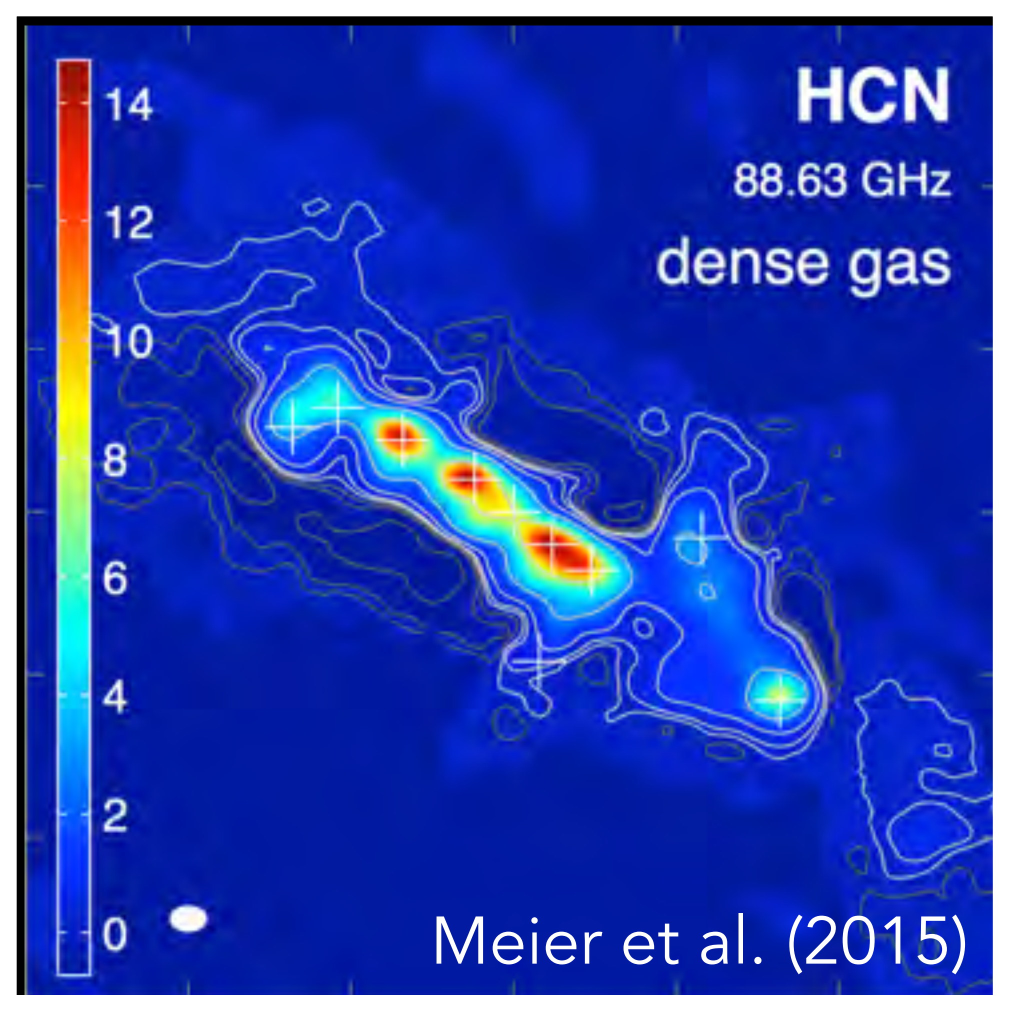
Challenge #3: Making apples-to-apples comparisons



Beltran et al. (2014)

We COULD look at a massive disk in the Galactic center with ALMA— if we could find one!

For the Galactic center,
d = 8.4 kpc (1″ = 0.04 pc)

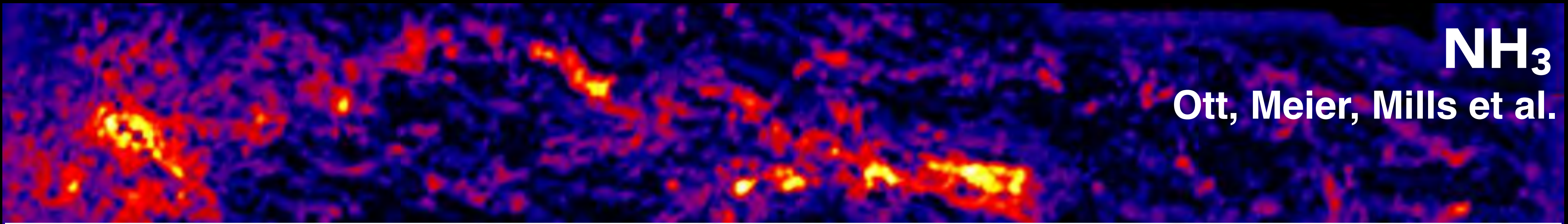


Meier et al. (2015)

Even with ALMA, sub-parsec resolution in another (large) Galaxy is still a pipe dream.

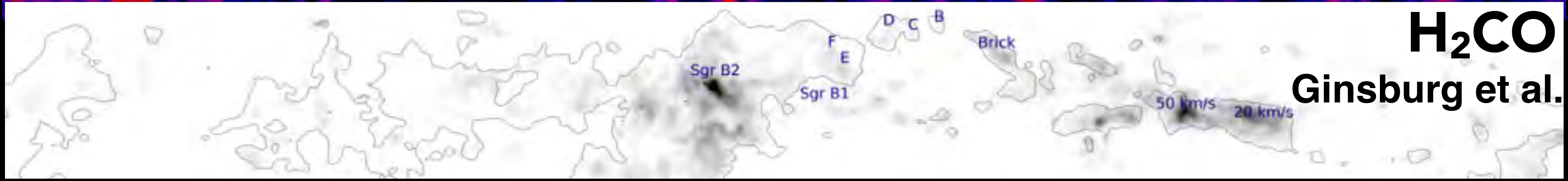
50 pc resolution in NGC 253,
d = 3.5 Mpc (1″ = 17 pc)

Opportunity #1: Large-scale Excitation Studies



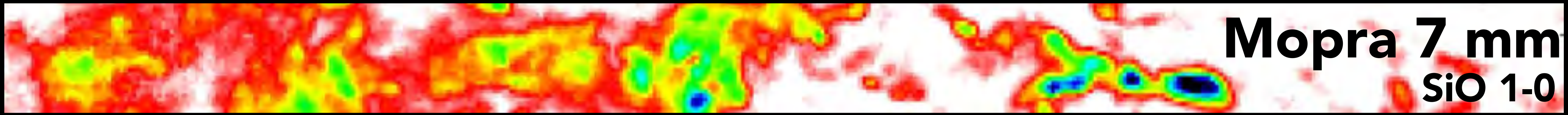
NH_3

Ott, Meier, Mills et al.



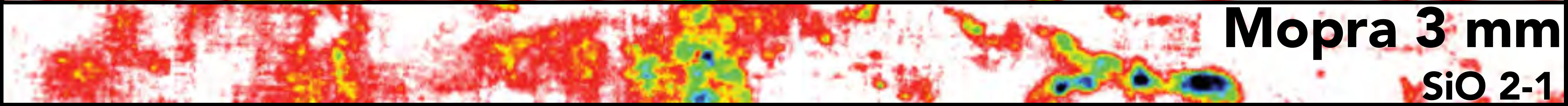
H_2CO

Ginsburg et al.



Mopra 7 mm

SiO 1-0



Mopra 3 mm

SiO 2-1

APEX 1 mm

(SiO 5-4)

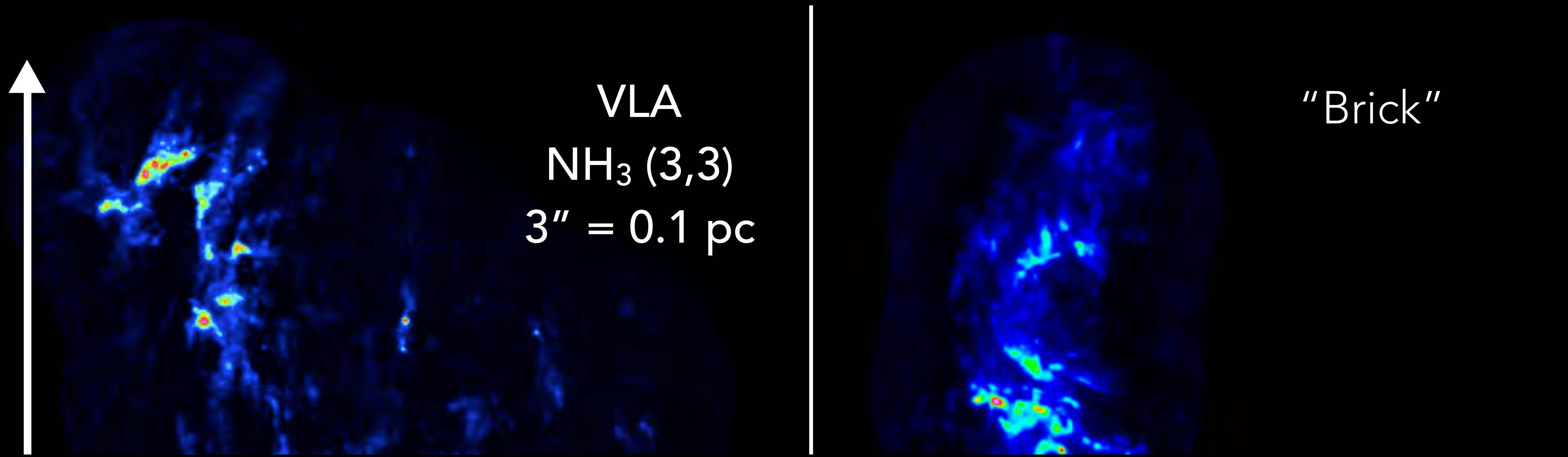
SEDIGISM - in progress

APEX 800 µm

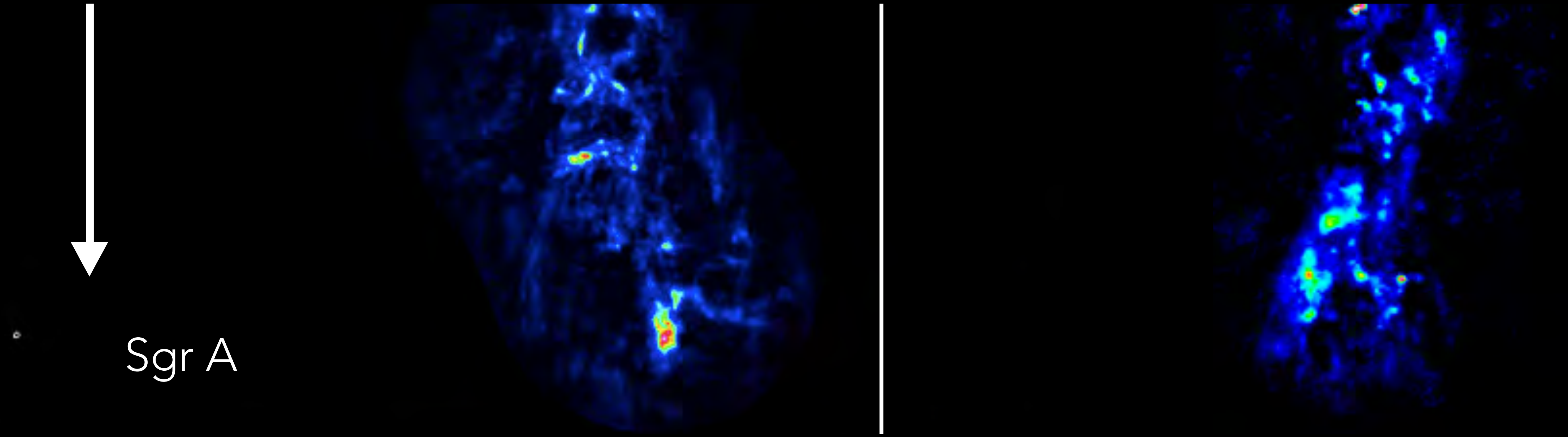
(SiO 8-7)

LASMA: 7 pixel array - coming soon!

Opportunity #2: Small-scale Studies

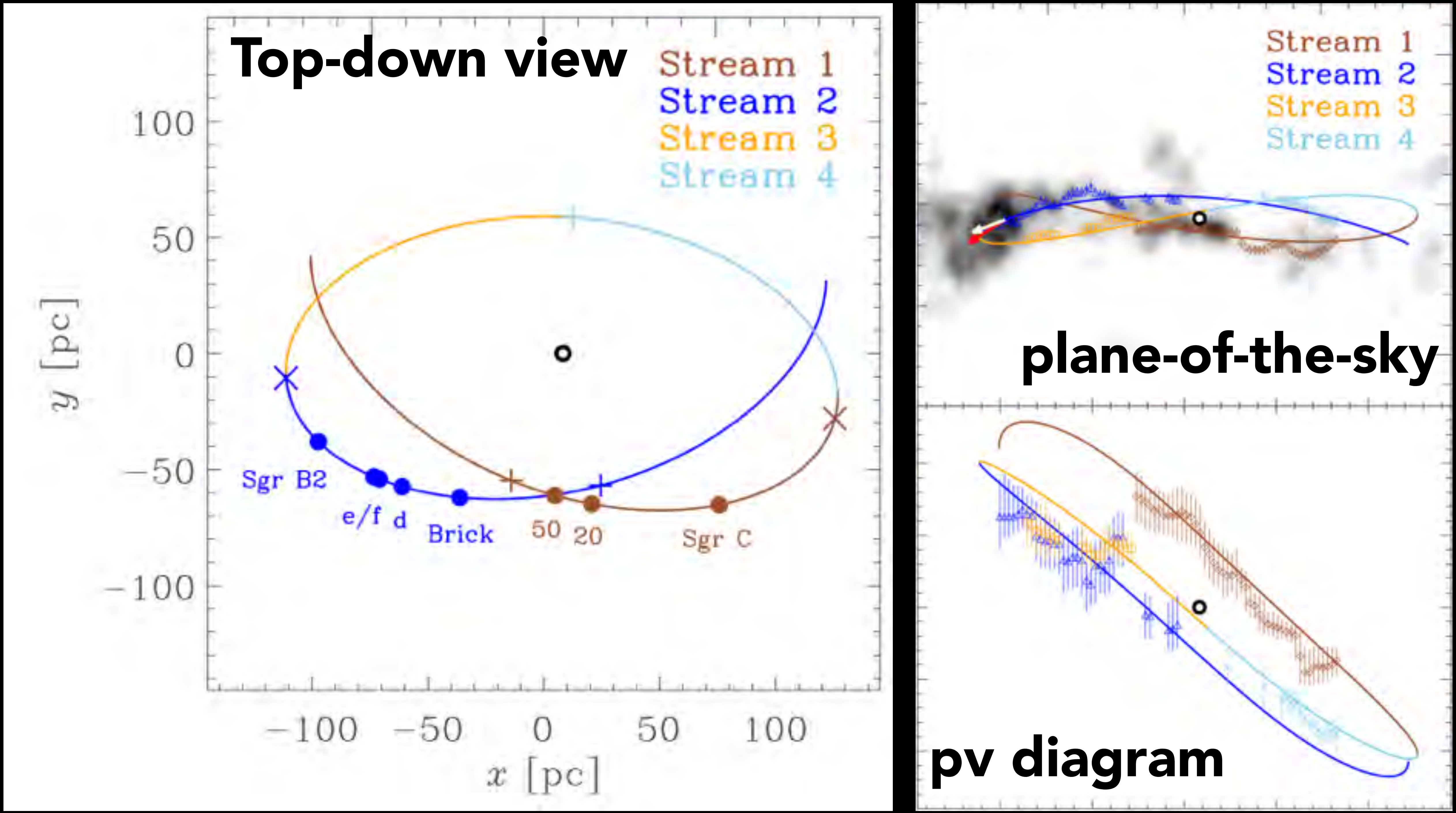


See also ongoing SMA surveys of Battersby et al., and Kauffmann & Pillai et al; and ALMA studies by Rathborne, Kauffmann, & Mills

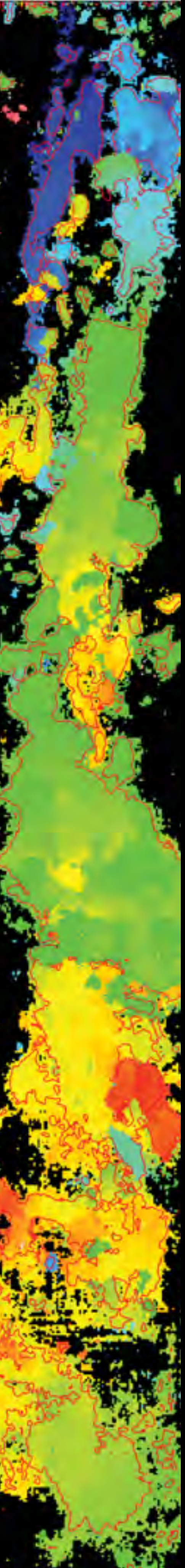


Mills et al. (2014, submitted)

Opportunity #3: Time Series of Star Formation



Kruijssen et al. (2015)



Galactic center: a lot of gas in a small space.

Historically, lots of star formation. Less at present?

Beginning to fully constrain how “extreme” the gas is

Still determining what governs star formation: better B-field, density, and turbulence measurements will help.

While there are challenges, current opportunities should yield significant advances in coming years.