The CHIMPS/2 Galactic CO Surveys

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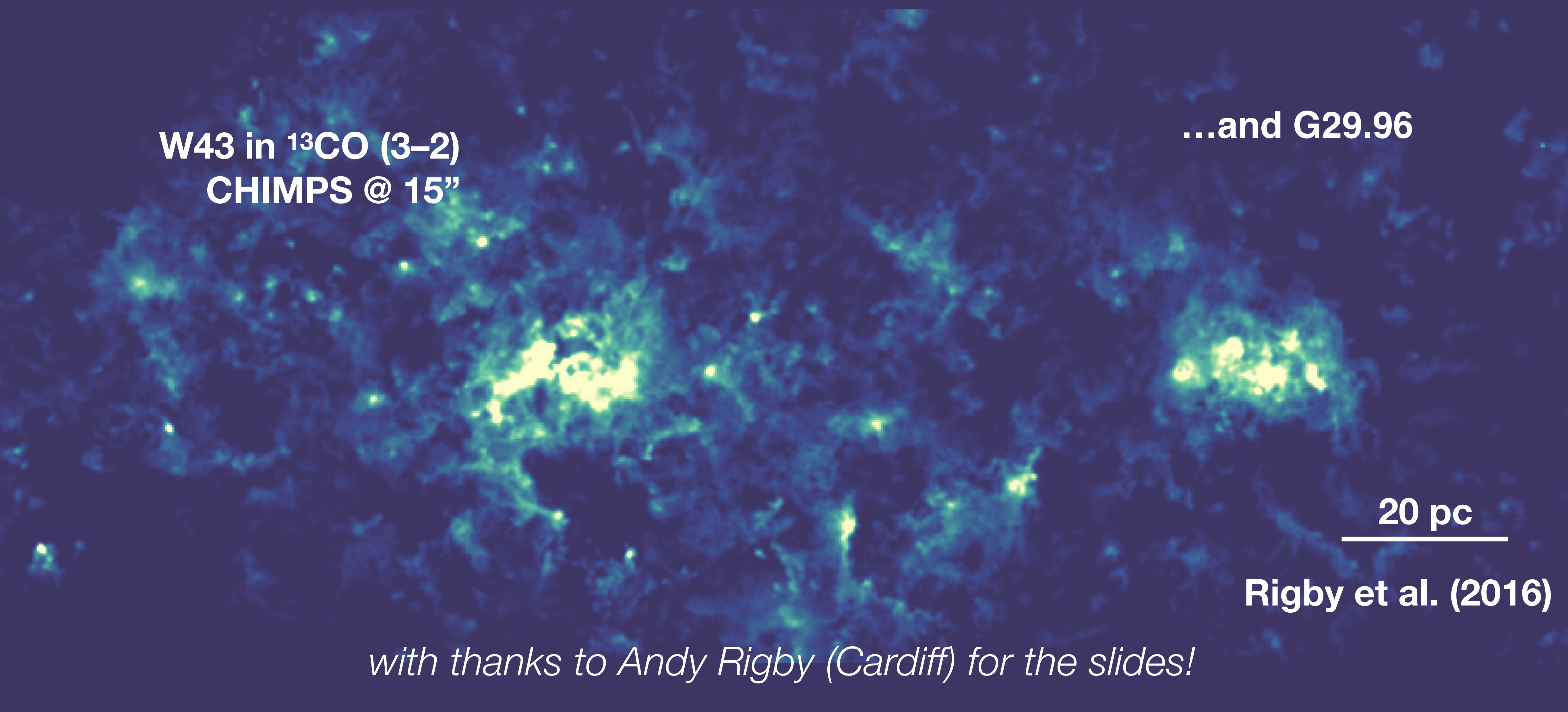
+ the CHIMPS team and the CHIMPS2 consortium



with thanks to Andy Rigby (Cardiff) for the slides!

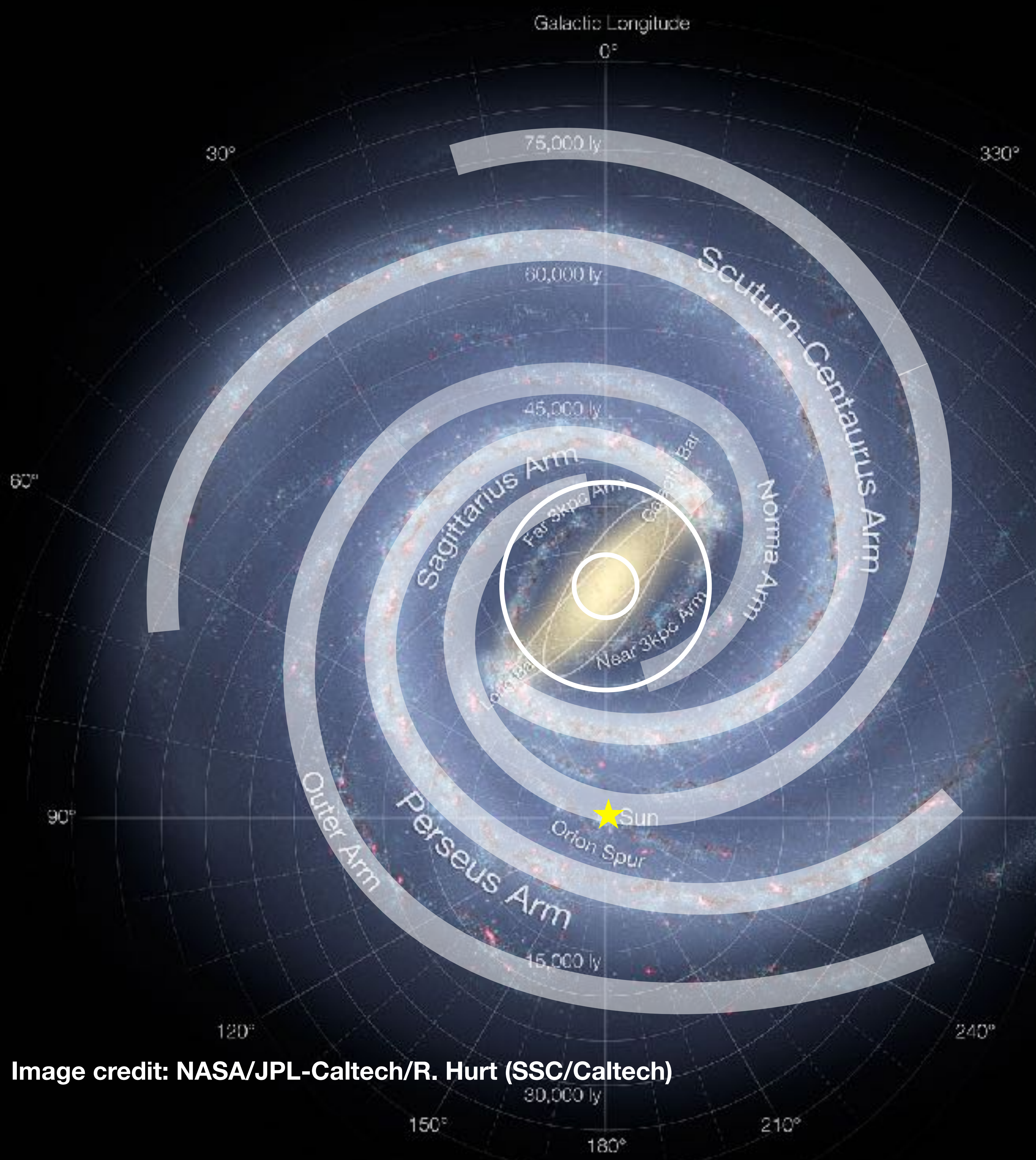


Image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

What impact does Galactic environment have upon star formation?

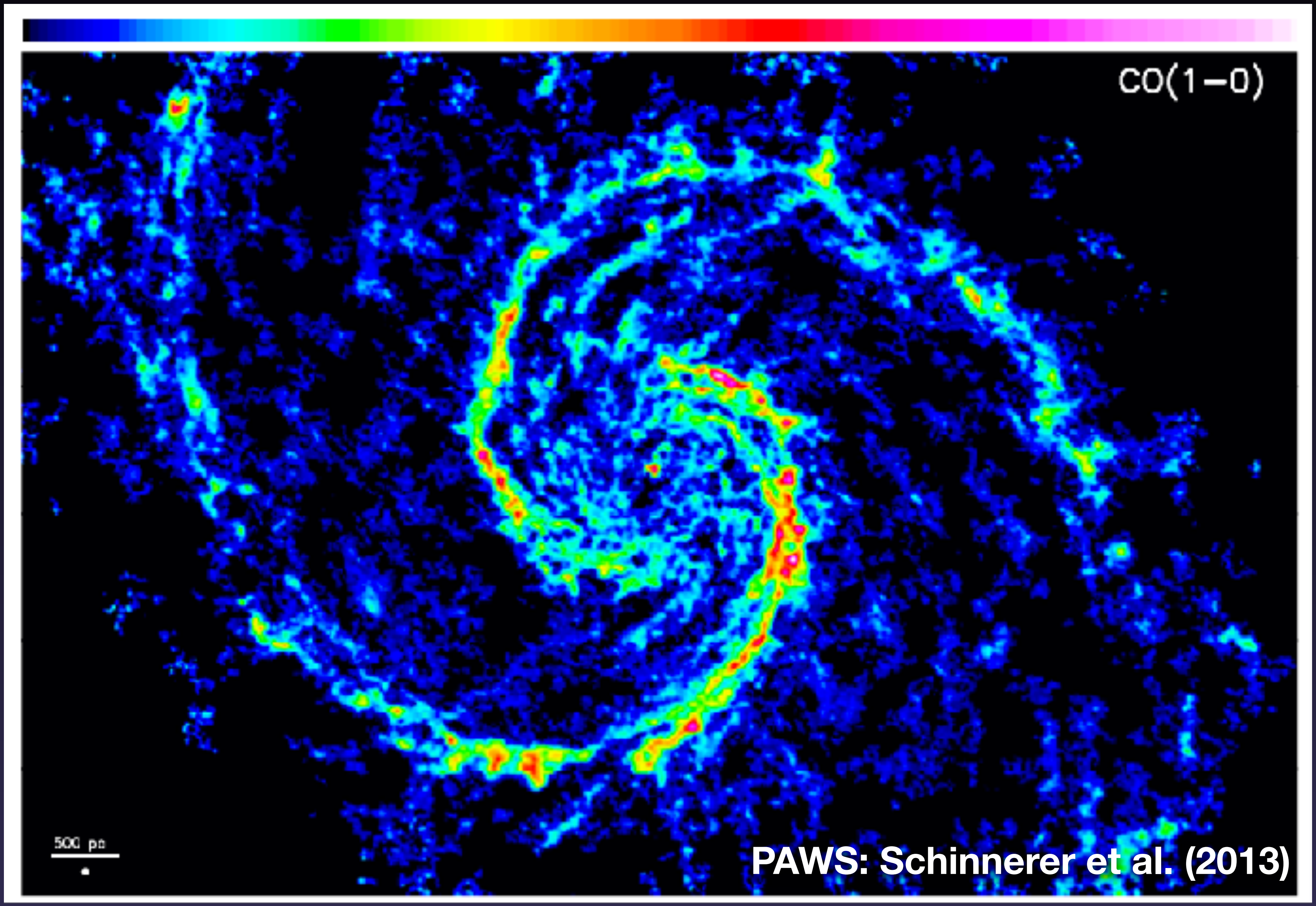
The SFE in the Central Molecular Zone (CMZ) appears to be lower by an order of magnitude than predicted by the volume & column density SF thresholds (e.g. Longmore et al. 2013).

How does star formation differ in the bar-dominated region?

What role do the spiral arms play in star formation? If they trigger star formation, we should expect to see an enhanced SFE associated with them.

Do we see any systematic changes with increasing Galactocentric distance?

High-spatial resolution studies in nearby galaxies



The spatial resolutions now achievable with interferometer facilities are now enabling studies on ~10s pc scales to study environmental conditions within more nearby galaxies.

e.g. PAWS (Schinnerer et al. 2013) with PdBI (now NOEMA), 1” -> 40 pc resolution in M51.

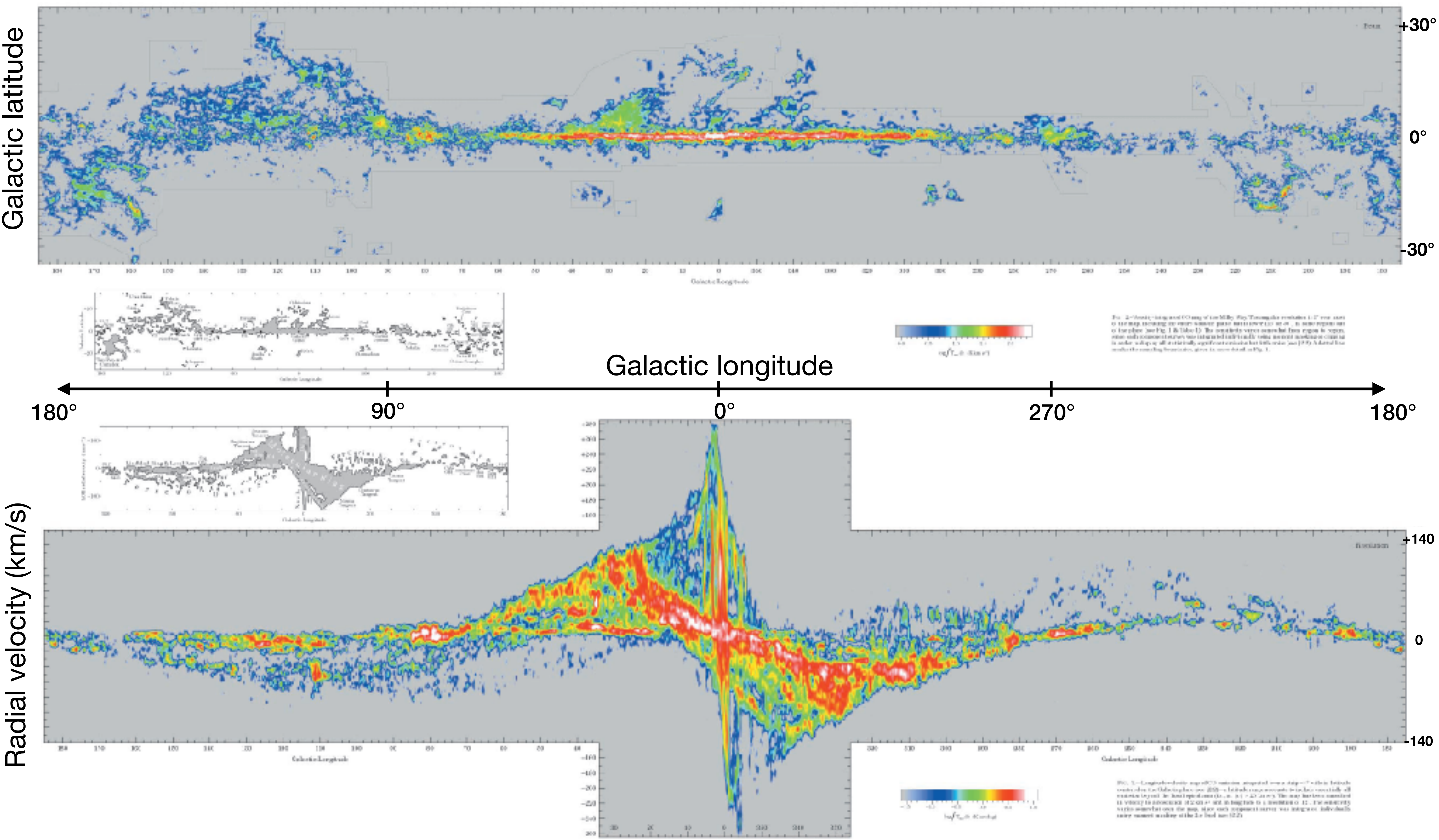
PHANGS-ALMA (PI: Schinnerer)
is now extending these studies to 74 nearby galaxies at 1”.

For the foreseeable future, only the Milky Way (& LMC/SMC) can be studied on scales below ~10 pc…

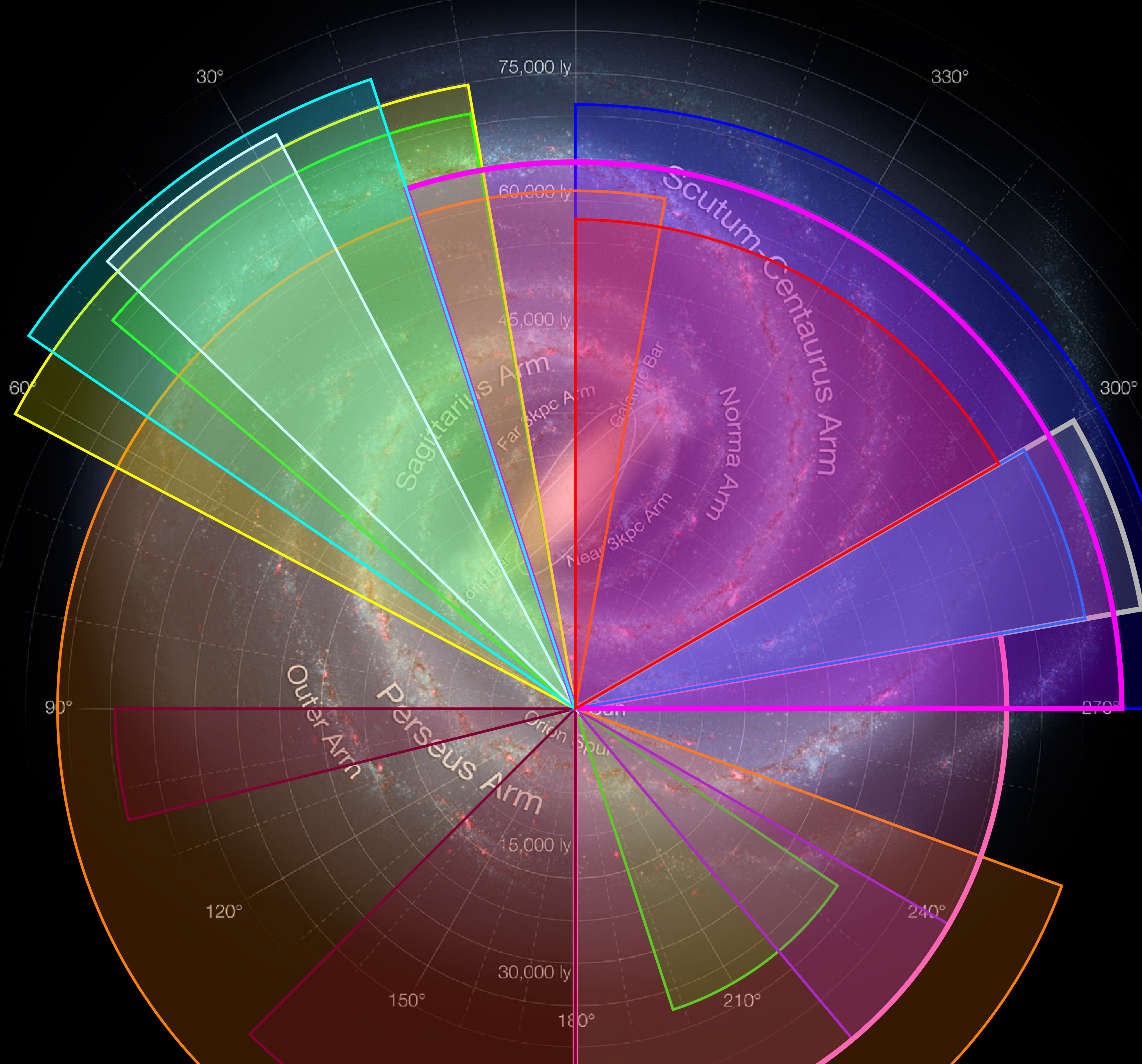
Surveys of the Milky Way

Dame et al. (2001)

^{12}CO (1–0), resolution ~(1/8)°



Sub-arcmin CO Surveys of the Galactic Plane



CHIMPS: Rigby+ (2016)
JCMT 15m, 15”,
0.5 km/s, σ ~ 0.6 K
^{13}CO & C^{18}O J=3–2

COHRS: Dempsey+ (2013)
JCMT 15m, 15”,
1 km/s, σ ~ 1 K
^{12}CO 3–2

GRS: Jackson+ (2006)
FCRAO 14m, 46”
0.21 km/s, σ ~ 0.1 K
^{13}CO 1–0

FUGIN: Umemoto+ (2017)
NRO 45m,
1.0 km/s, σ ~ 1 K
^{12}CO ^{13}CO C^{18}O 1–0, 15”

MWISP: Yang Su+ (2019)
^{12}CO ^{13}CO C^{18}O 1–0; 50”

Exeter FCRAO CO GPS:
Brunt+ (in prep.) ^{13}CO 1-0

SEDIGISM: Schuller+ (2017)

OGHRES: König+ (in prep)

COCA: (PI: Yeh)
^{13}CO 2-1 + (some 4-3) 29”

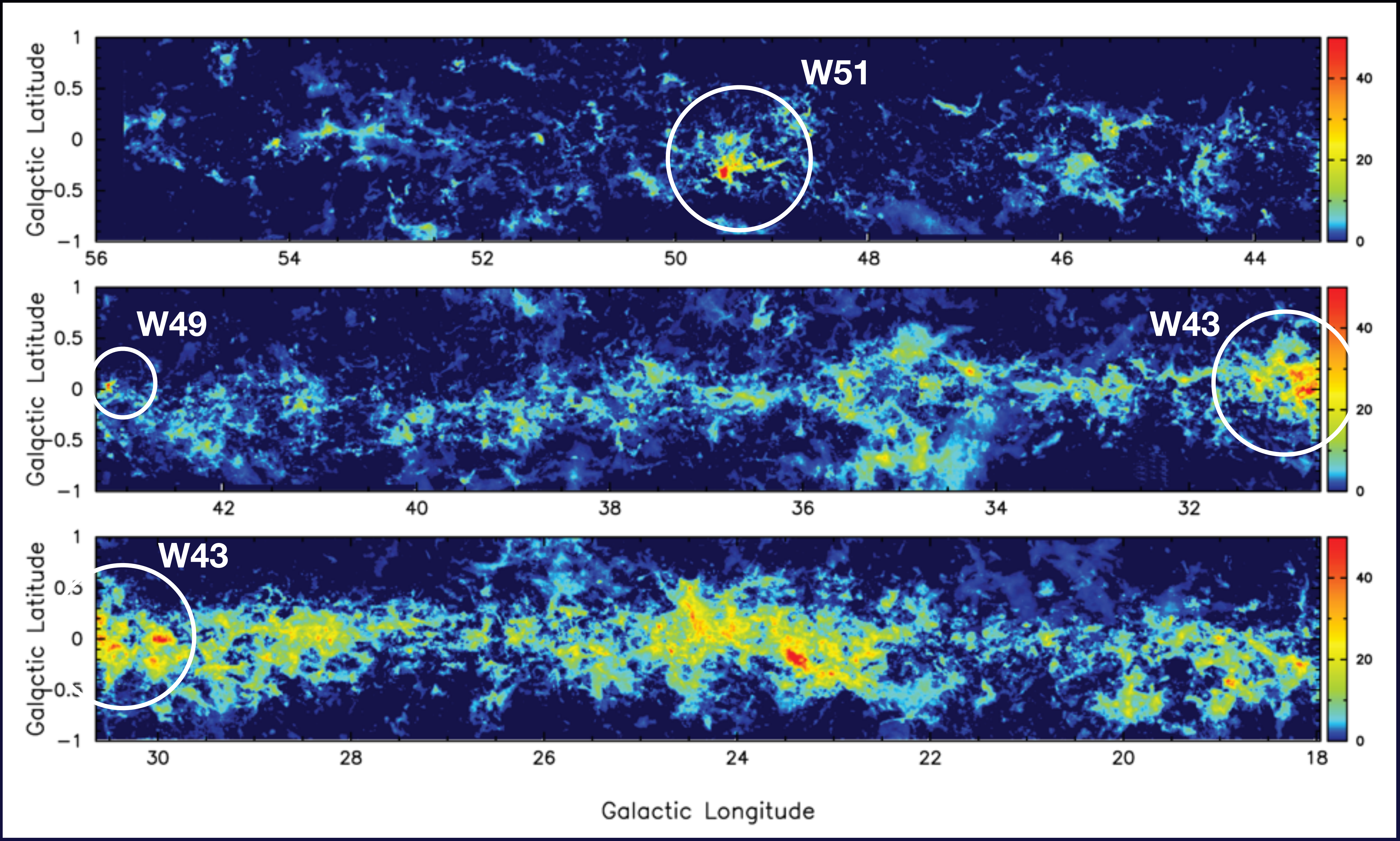
Mopra Southern CO GPS:
Burton+ (2013)
^{12}CO ^{13}CO C^{18}O 1–0 35”

ThrUMMS: Barnes+ (2015)

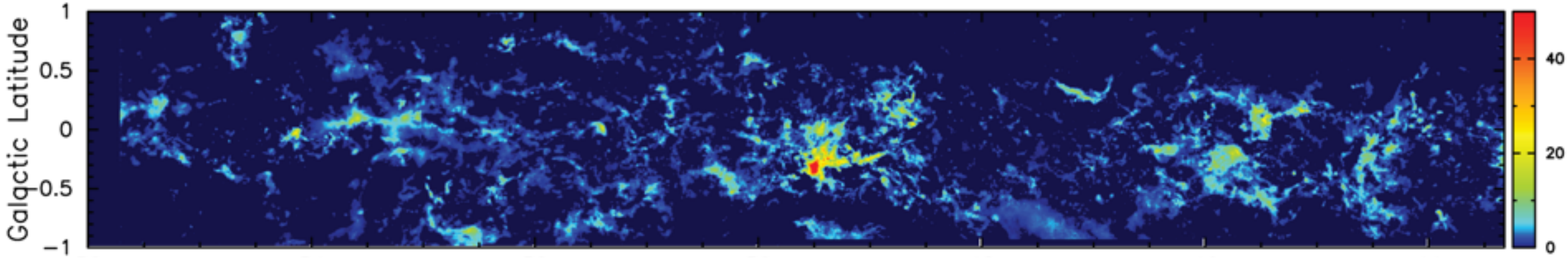
CHaMP: Barnes+ (in prep)
CO 1-0 x 3; 35”

Forgotten Quadrant Survey:
KP 12m Benedettini+ (2017)
^{12}CO ^{13}CO 1-0 56”

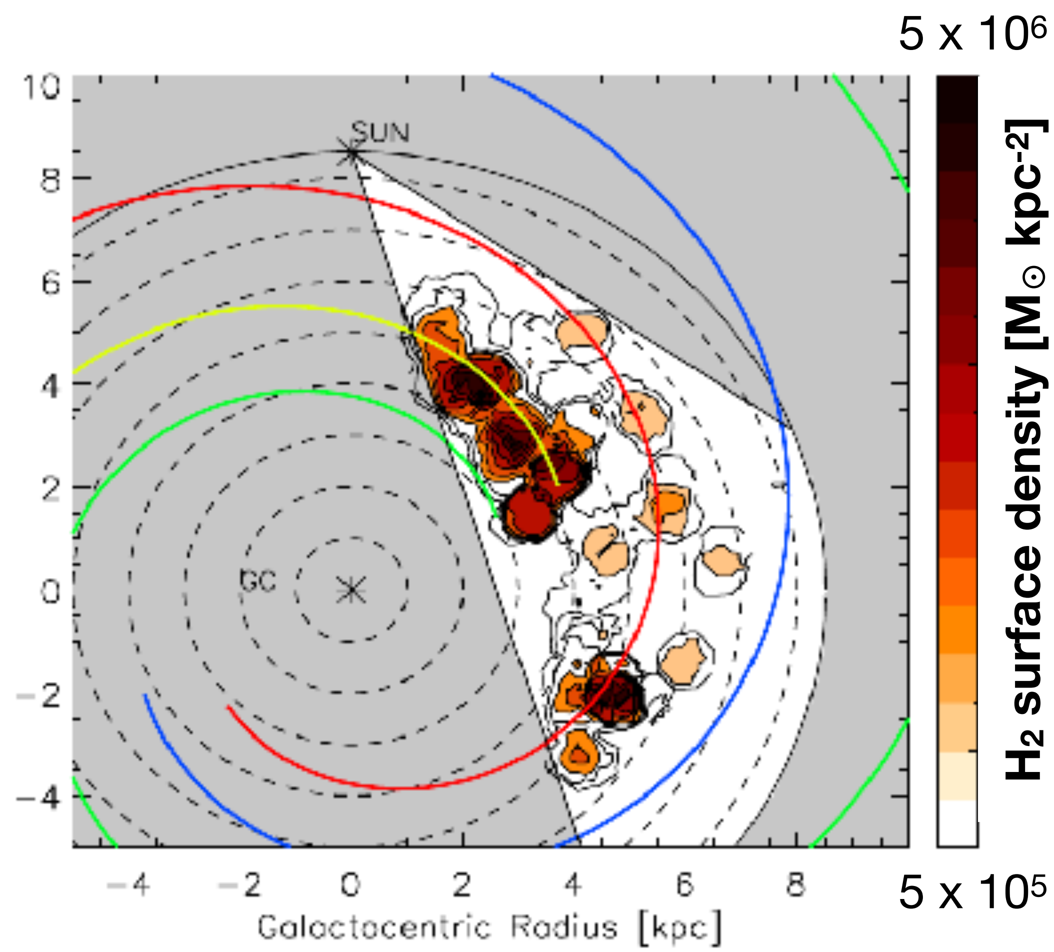
The Galactic Ring Survey

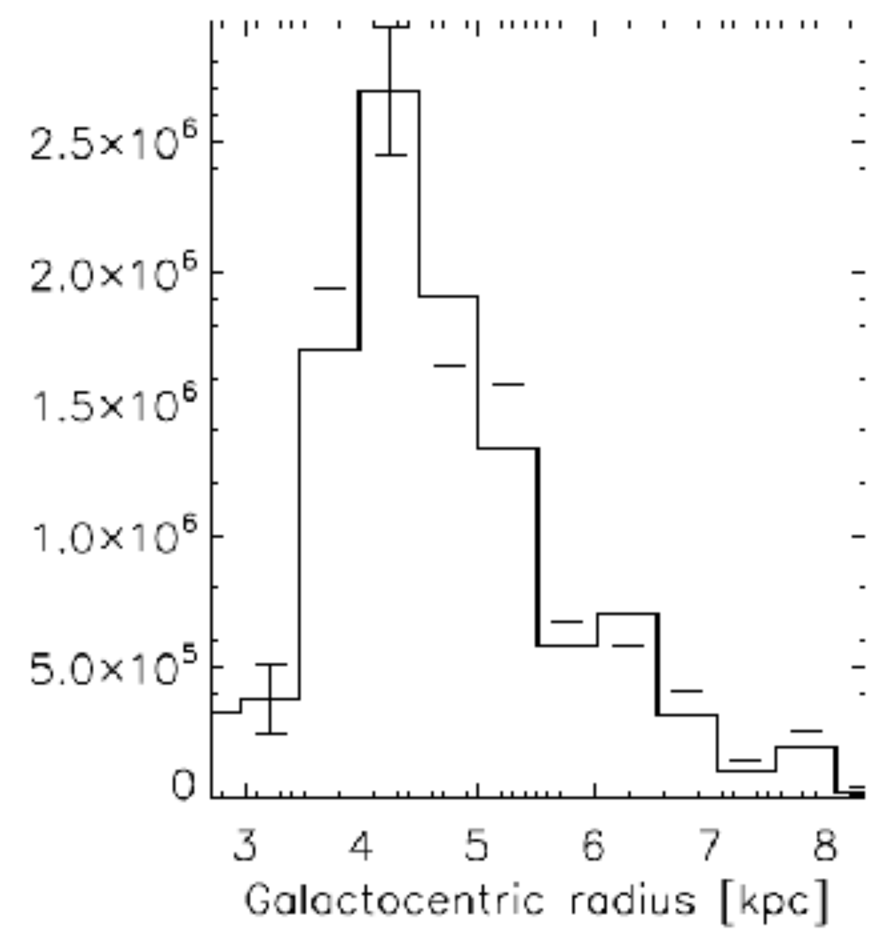


The Galactic Ring Survey



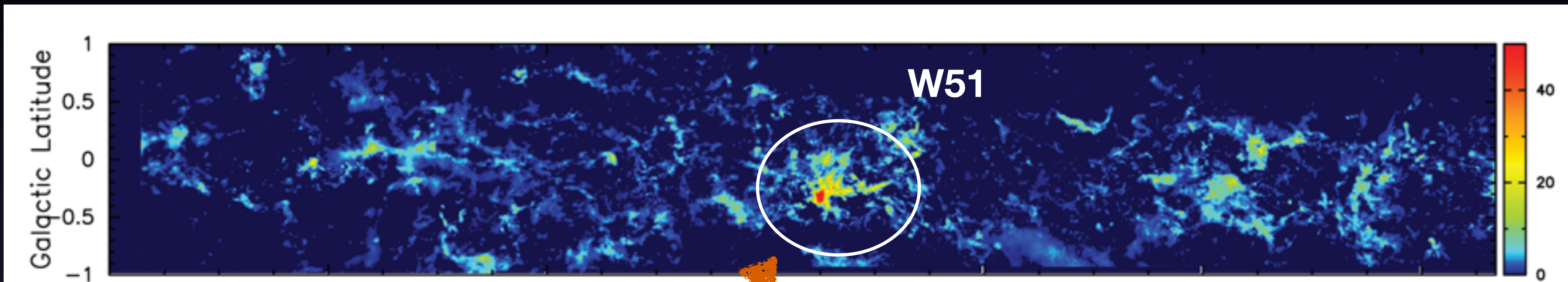
Roman-Duval et al. (2010) measured the surface density of molecular clouds, with a sharp decline as a function of Galactocentric radius.

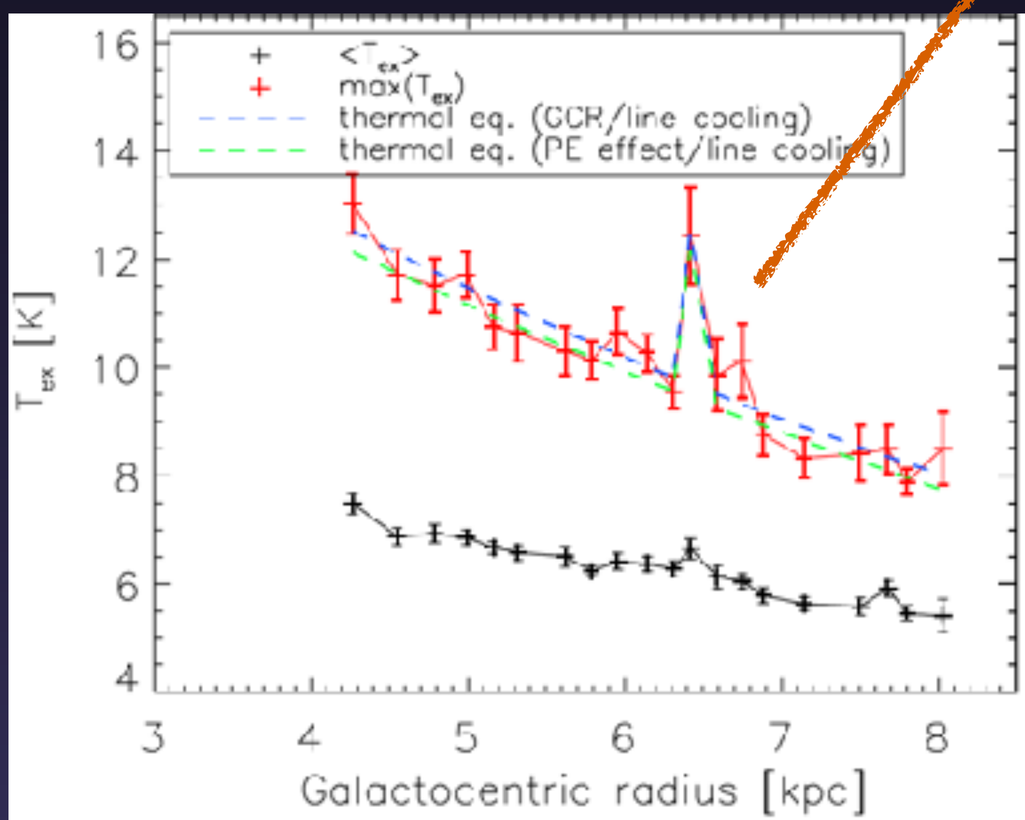




Roman-Duval et al. (2010)

The Galactic Ring Survey



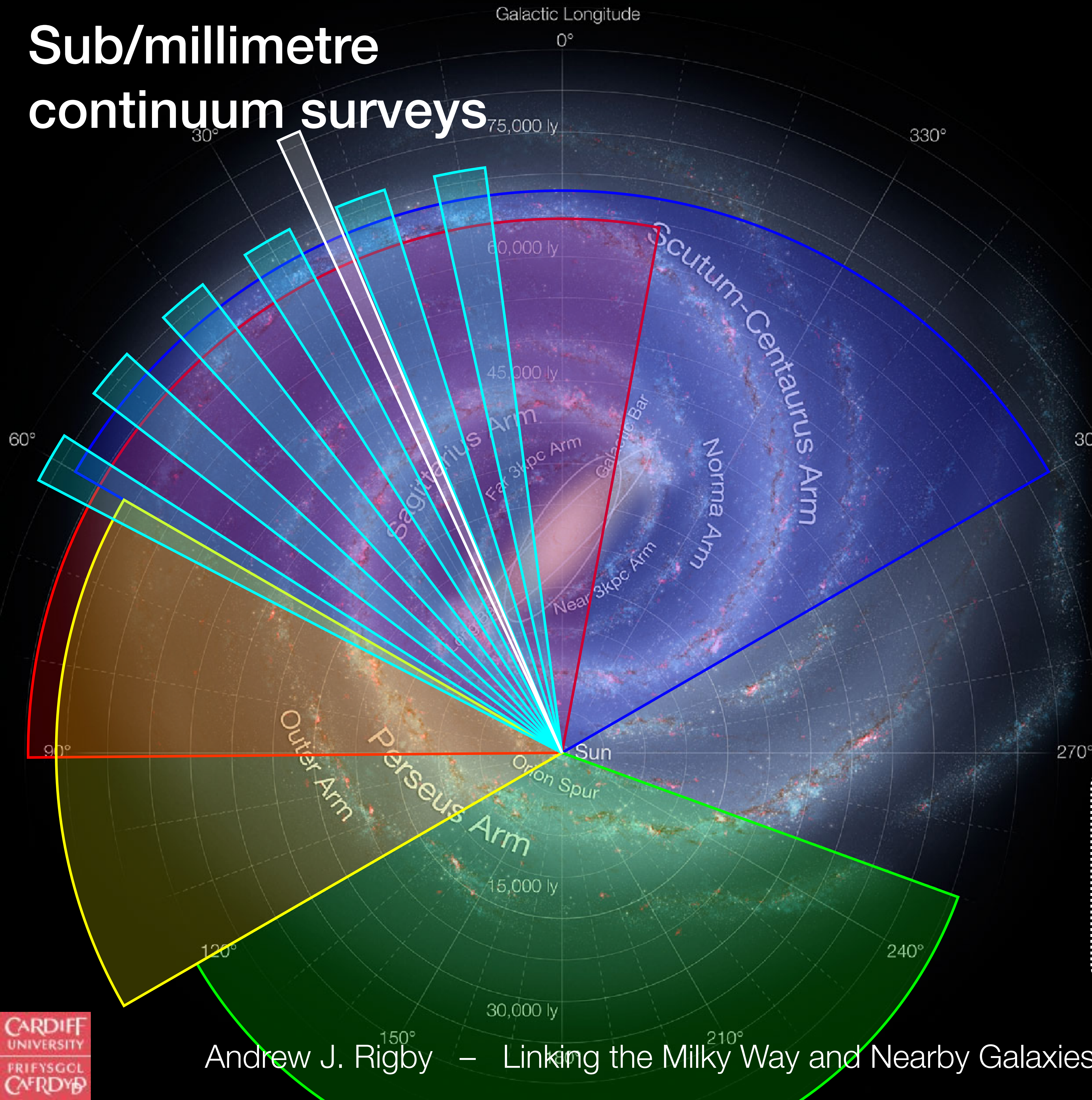


Roman-Duval et al. (2010) also measured the decline in gas temperature with Galactocentric radius.

Decline in heating due to cosmic ray flux (SNe) and interstellar radiation field from a decreasing SFR.

Individual star-forming regions can dominate in these metrics.

Sub/millimetre continuum surveys



ATLASGAL: Schuller+ (2019)
APEX 12 m, LABOCA,
19.2” @ 870 µm

BGPS: Aguirre+ (2011)
CSO 10.4 m, Bolocam
33” @1.1 mm

JPS: Moore+ (2015)
JCMT 15 m, SCUBA-2
15” @ 850 µm (also 450 µm)

GASTON: Rigby+ (in prep.)
IRAM 30 m, NIKA2,
12” @ 1.2 mm, 18” @ 2.0 mm

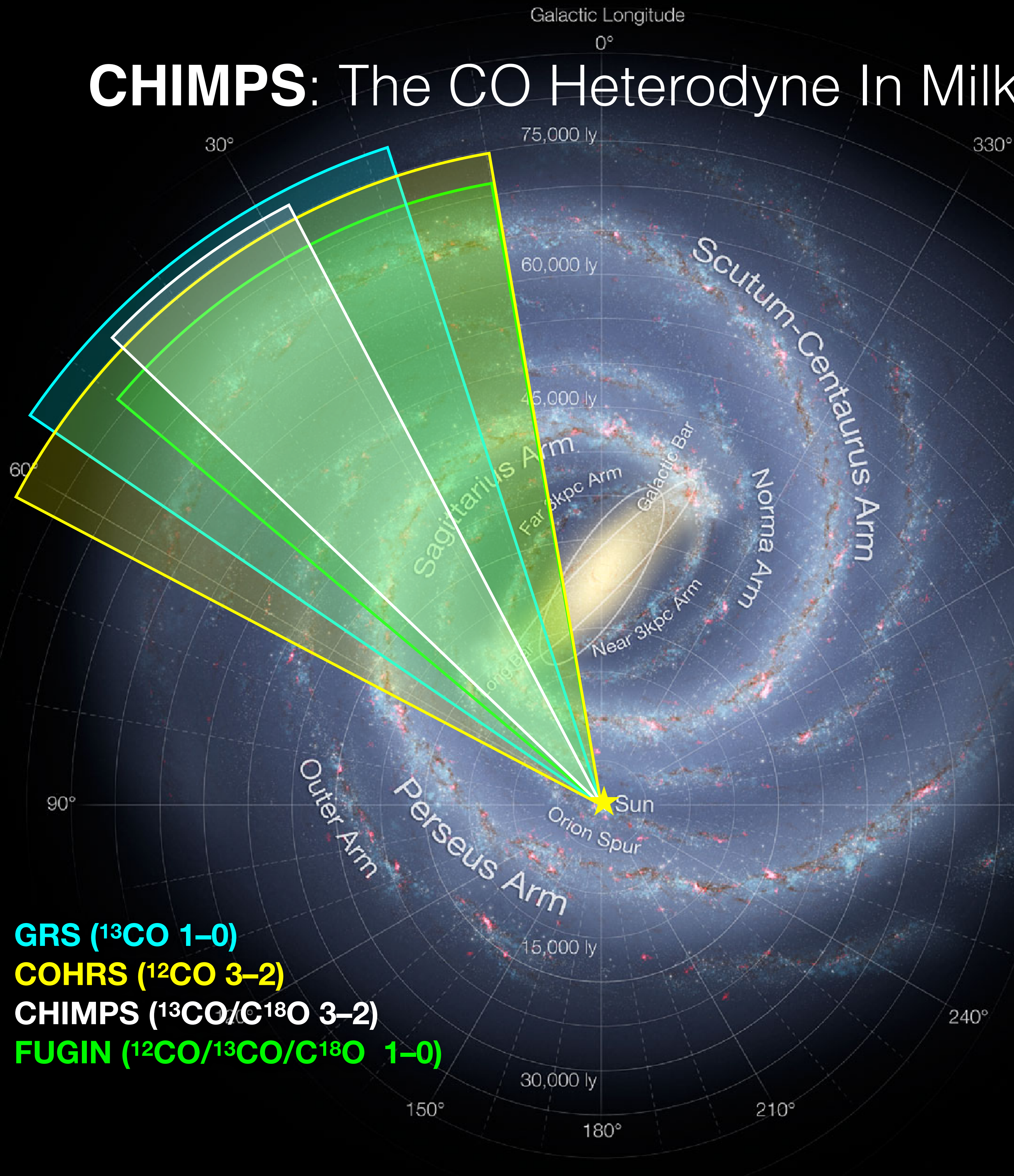
SASSy: Nettke+ (2017)
JCMT 15 m, SCUBA-2
15” @ 850 µm (also 450 µm)

SASSy-Perseus: PI: Thompson
JCMT 15 m, SCUBA-2
15” @ 850 µm (also 450 µm)

Hi-GAL: Molinari+ (2016)
Herschel 3.5 m, PACS & SPIRE
6”–36” @ 70–500 µm

Planck: Early results. XXIII
Planck 3.5 m, HFI
5’–31’ @ 350 µm – 3mm

CHIMPS: The CO Heterodyne In Milky Way Plane Survey



What role does the Galactic environment play in star formation?

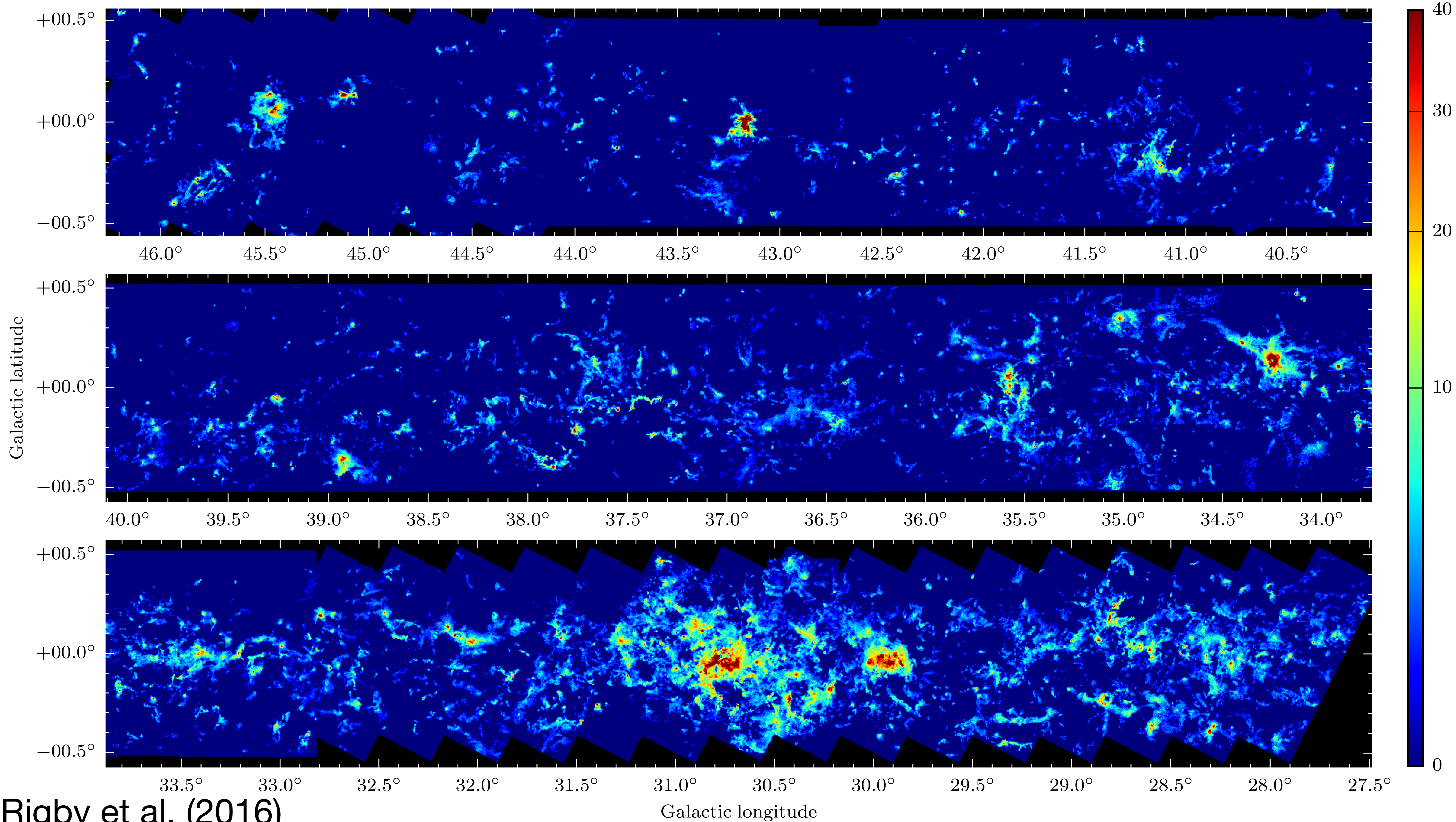
JCMT (15m)
- ^{13}CO & $C^{18}O$, J =3–2
- 15 arcsec angular resolution
- 0.5 km/s velocity channels
- 27.5° < l < 46.5°, |b| < 0.5°

Traces **dense** (ish) gas, with a critical density of the 3–2 transition ~ 10^4 cm^{-3} (compared to ~10^3 cm^{-3} for 1–0).

Rare isotopologues have lower optical depths → cloud **interiors**

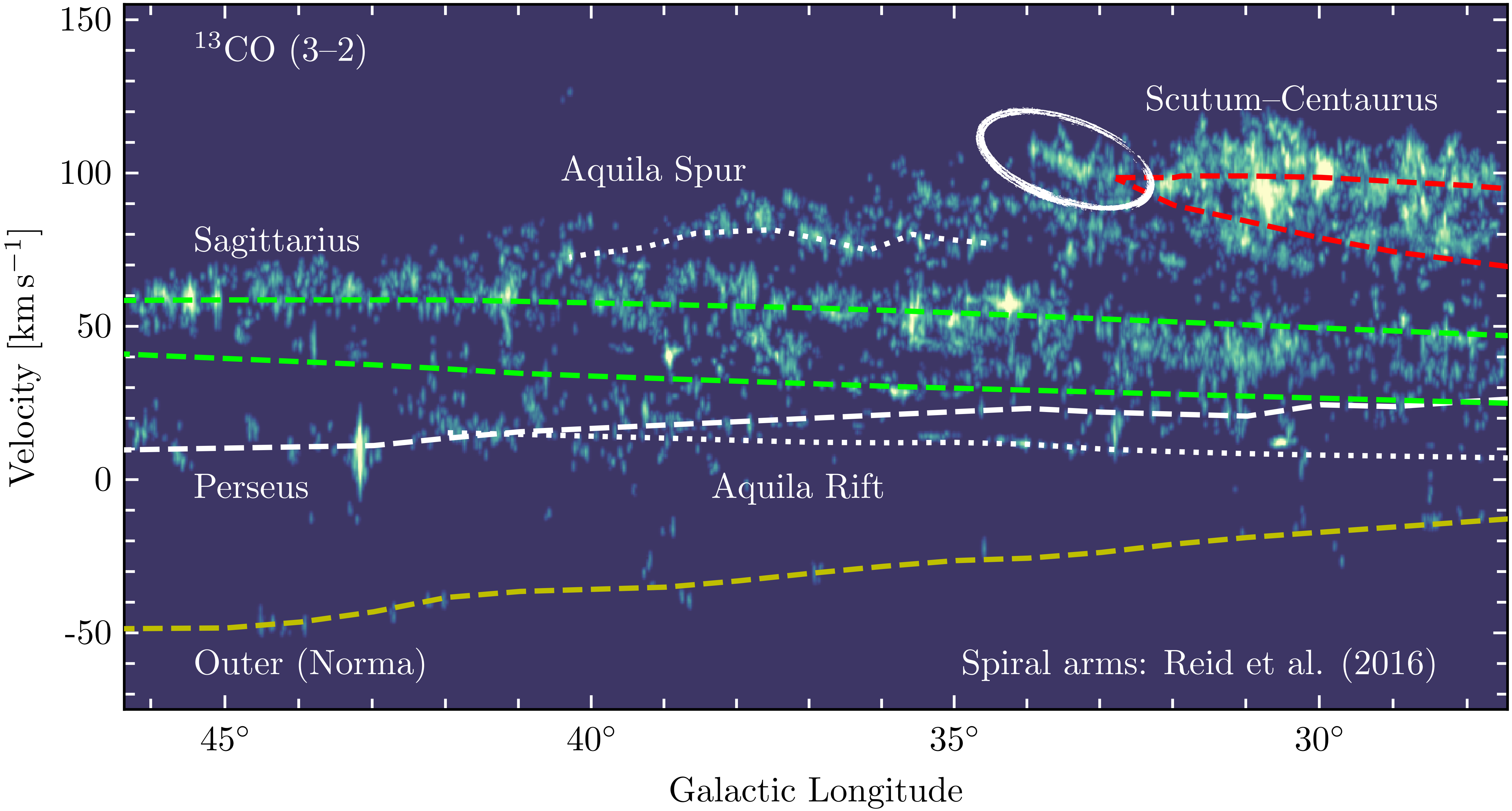
Survey description & first look in **Rigby et al. (2016)**

CHIMPS: The CO Heterodyne in Milky Way Plane Survey



Rigby et al. (2016)

CHIMPS: The CO Heterodyne in Milky Way Plane Survey

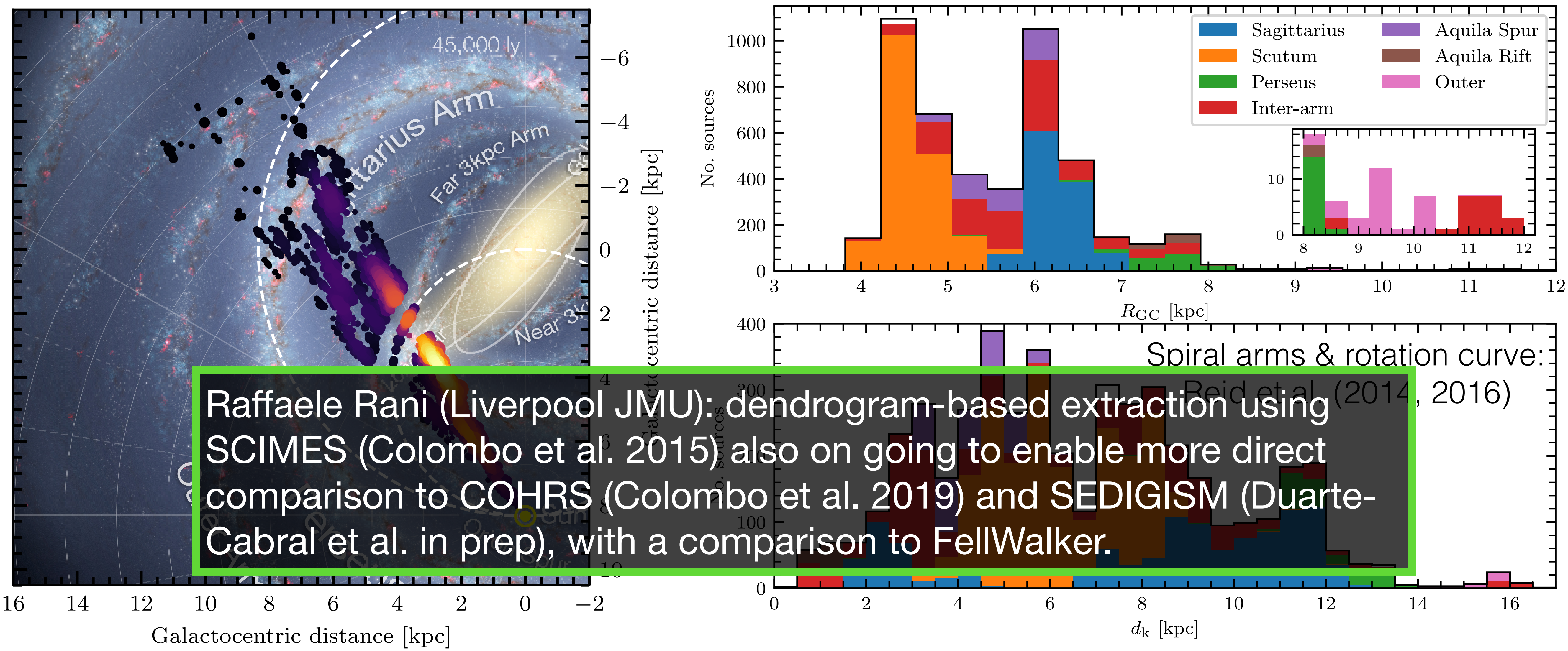


Distance determinations

4999 sources identified with **FellWalker** (Berry 2015).

Kinematic distances to adopted 94% of these using the **Reid et al. (2016)** rotation curve, with distance ambiguity resolved by l, b, v association with literature sources

- **ATLASGAL** (Urquhart et al. 2018, Wienen et al. 2015), **BGPS** (Ellsworth-Bowers et al. 2015, Eden et al. 2012, 2013), and **GRS** (Roman-Duval et al. (2009)



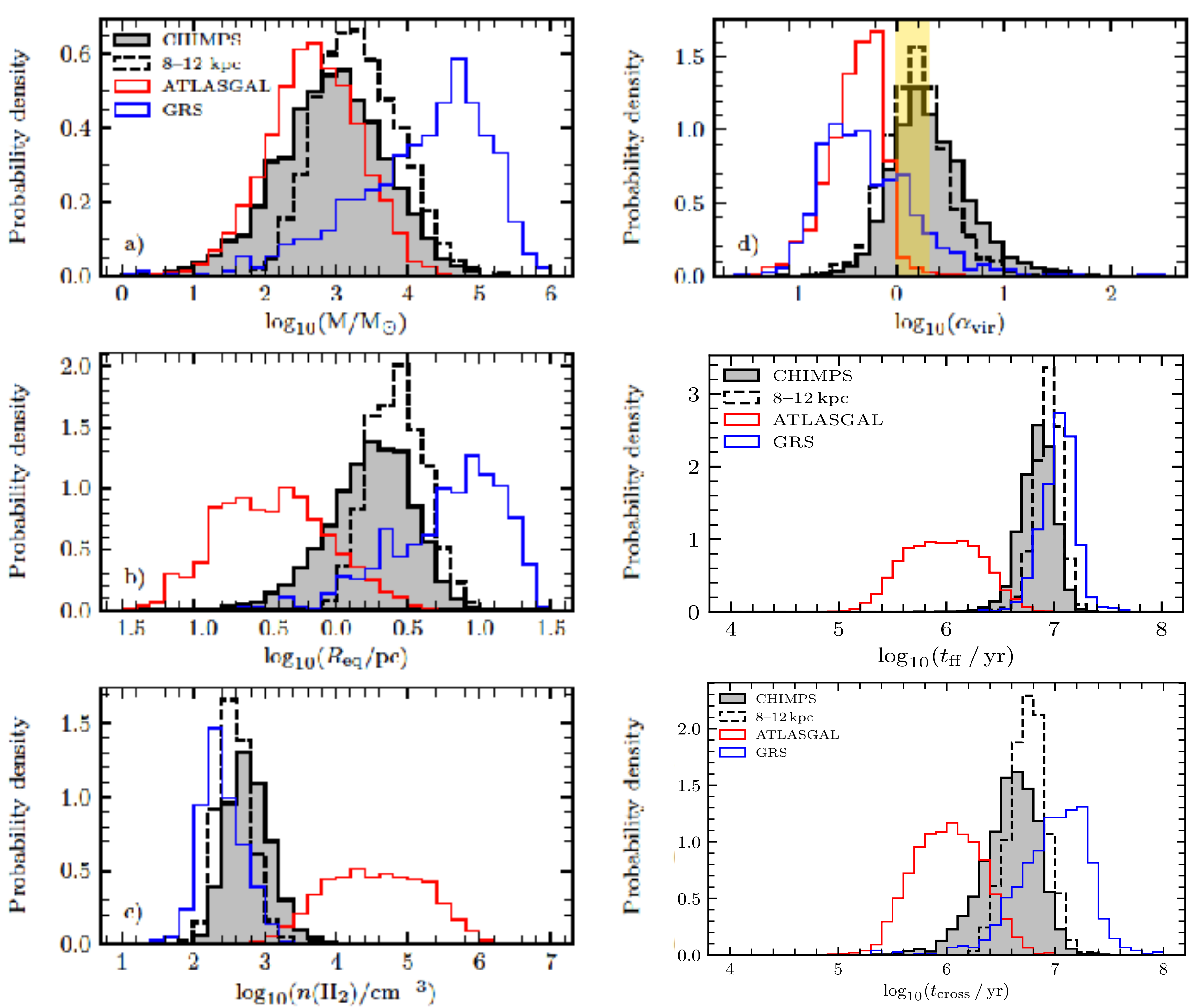
Spiral arms & rotation curve: Reid et al. (2014, 2016)

Raffaele Rani (Liverpool JMU): dendrogram-based extraction using SCIMES (Colombo et al. 2015) also on going to enable more direct comparison to COHRS (Colombo et al. 2019) and SEDIGISM (Duarte-Cabral et al. in prep), with a comparison to FellWalker.

Rigby et al. (A&A, *subm.*)

Ensemble properties

Rigby et al. (A&A, *in press*)



CHIMPS clumps **ATLASGAL clumps** **GRS molecular clouds**

(This work) **(Urquhart et al. 2018)** **(Roman-Duval et al. 2010)**

LTE analysis determined in conjunction COHRS (^{12}CO 3–2 @ 16”) and GRS (^{13}CO 1–0 @ 46”)

-> cubes of column density & excitation temperature @ 27”

In terms of mass, size & density, CHIMPS clumps appear to trace an intermediate phase between molecular clouds and dense clumps.

Only exception in virial parameters. A greater fraction of the CHIMPS clumps appear to be gravitationally unbound.

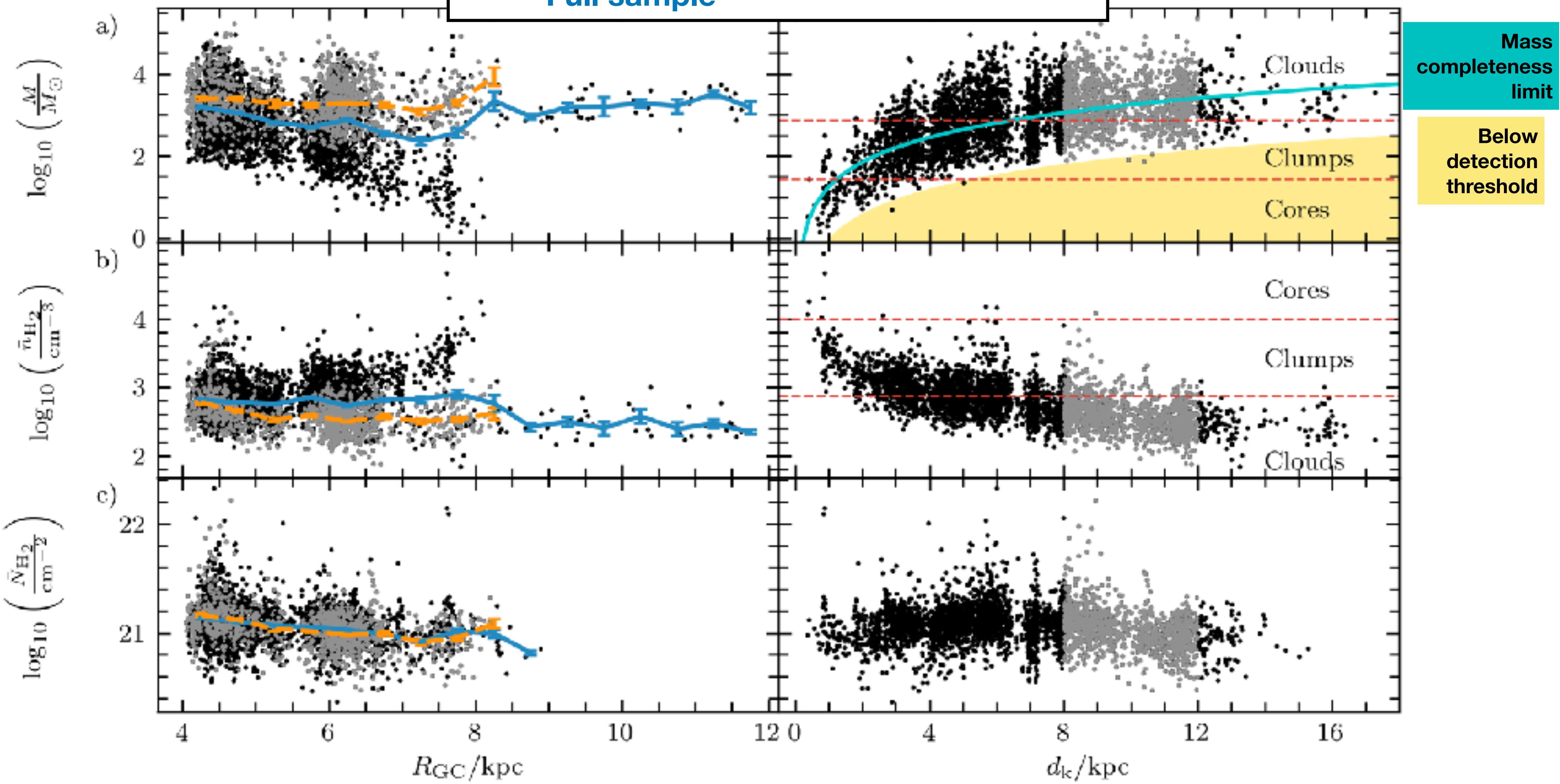
Radial variations in clump properties?

Rigby et al. (A&A, *subm.*)

Trendlines: averages within 0.5 kpc bins

– – Distance limited sample (8 – 12 kpc)

– – Full sample



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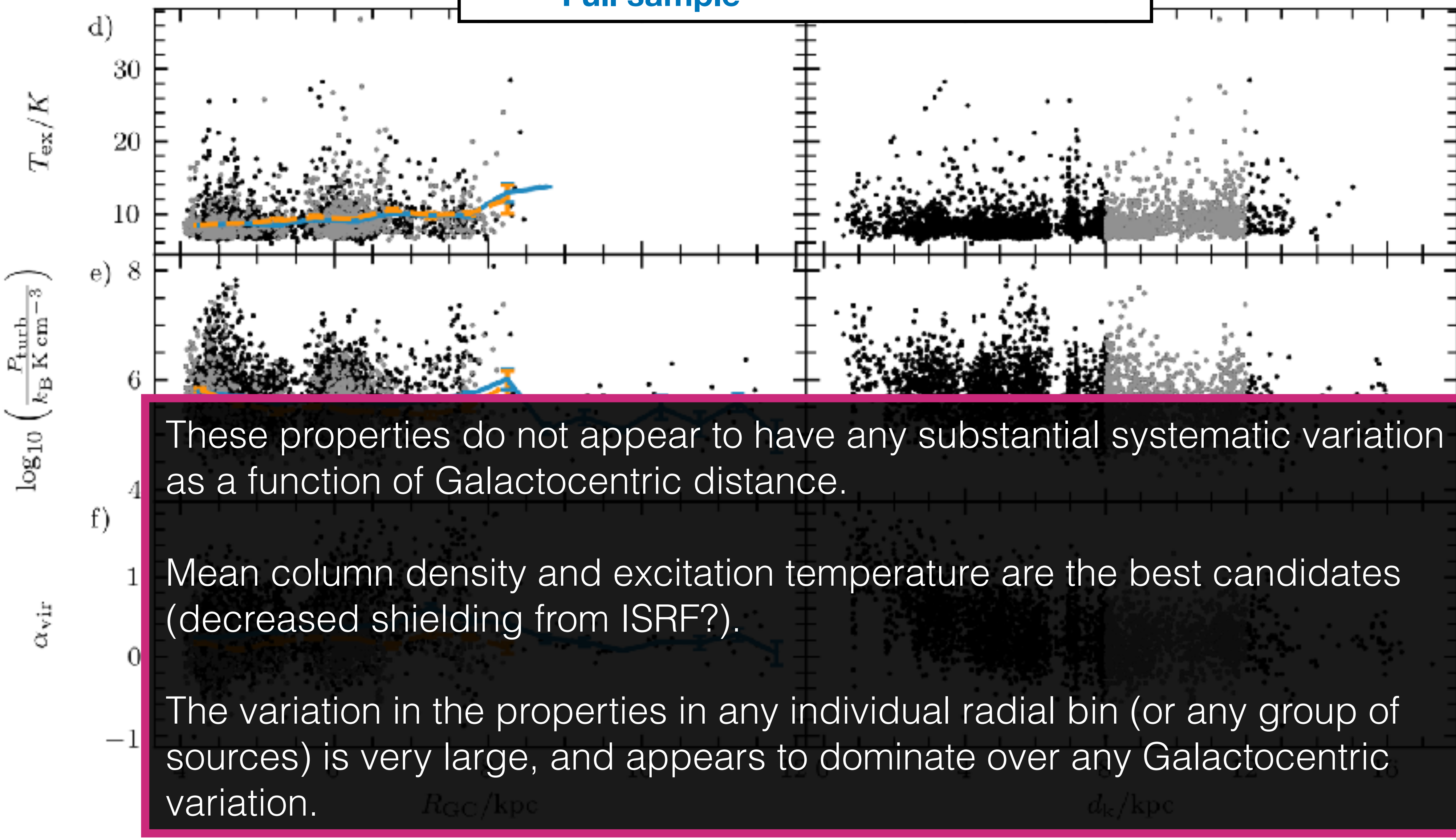
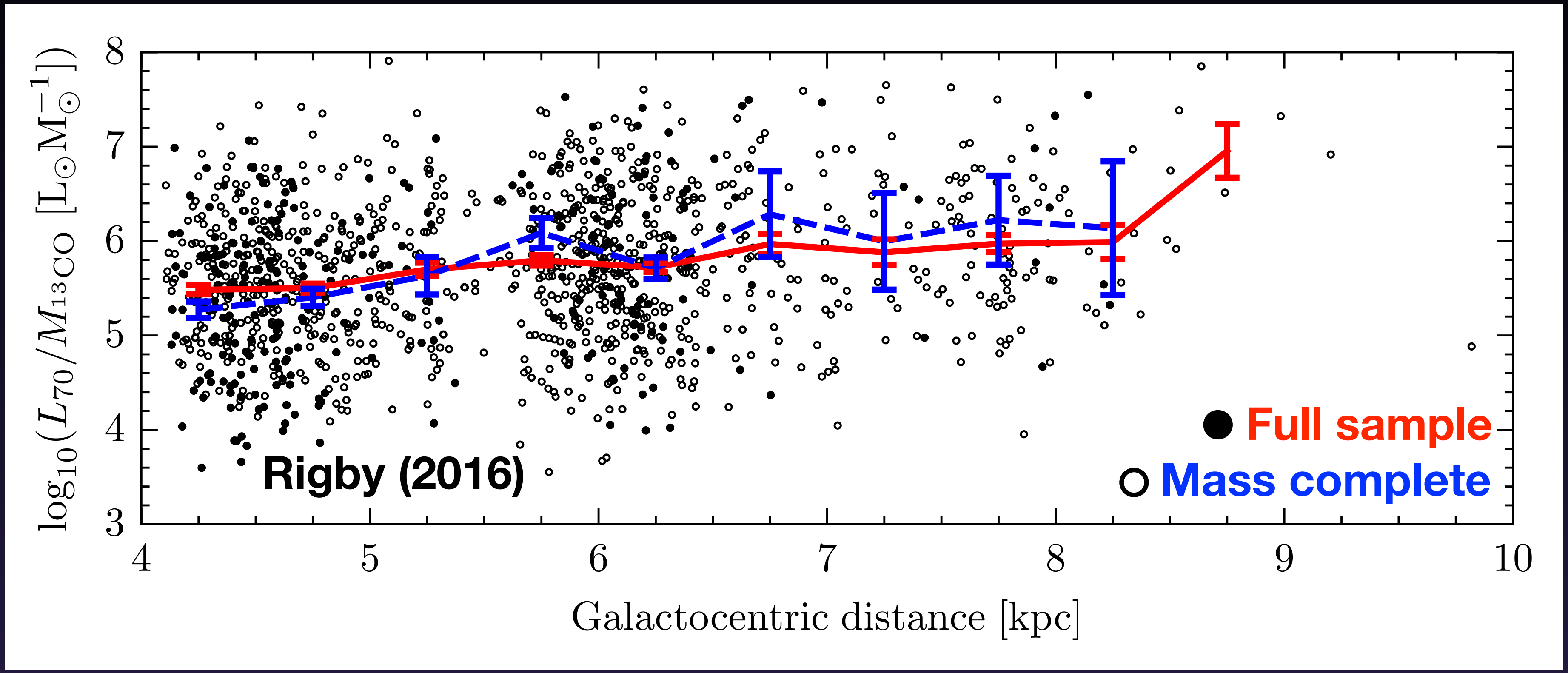


These properties do not appear to have any substantial systematic variation as a function of Galactocentric distance.

Mean column density and excitation temperature are the best candidates (decreased shielding from ISRF?).

The variation in the properties in any individual radial bin (or any group of sources) is very large, and appears to dominate over any Galactocentric variation.

Radial variations in star formation efficiency?

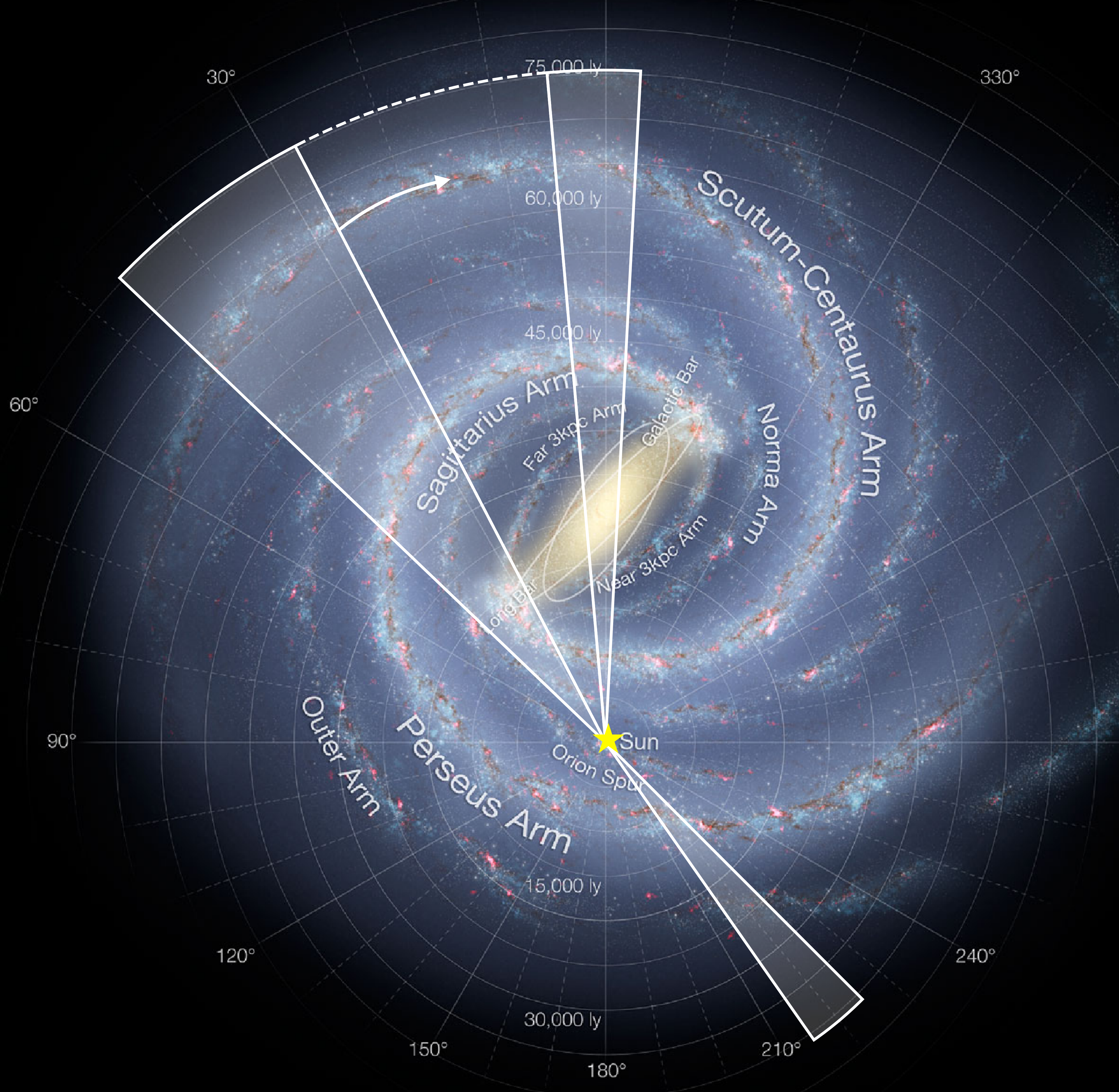


L_{70} / M gives us a *distance-independent* proxy for the star formation efficiency.

When considering a mass-complete sample, we don't see much variation over the ~6 kpc range in R_{GC} probed.

The largest variations occur on the clump-to-clump scale, similar to that seen in GMCs (Moore et al. 2012), clump formation efficiencies (Eden et al. 2015), star formation fractions (Ragan et al. 2016), L_{bol}/M for clump complexes (Urquhart et al. 2018).

CHIMPS2



JCMT Large Programme now underway ~400 hrs approx. 60% complete

More environments:

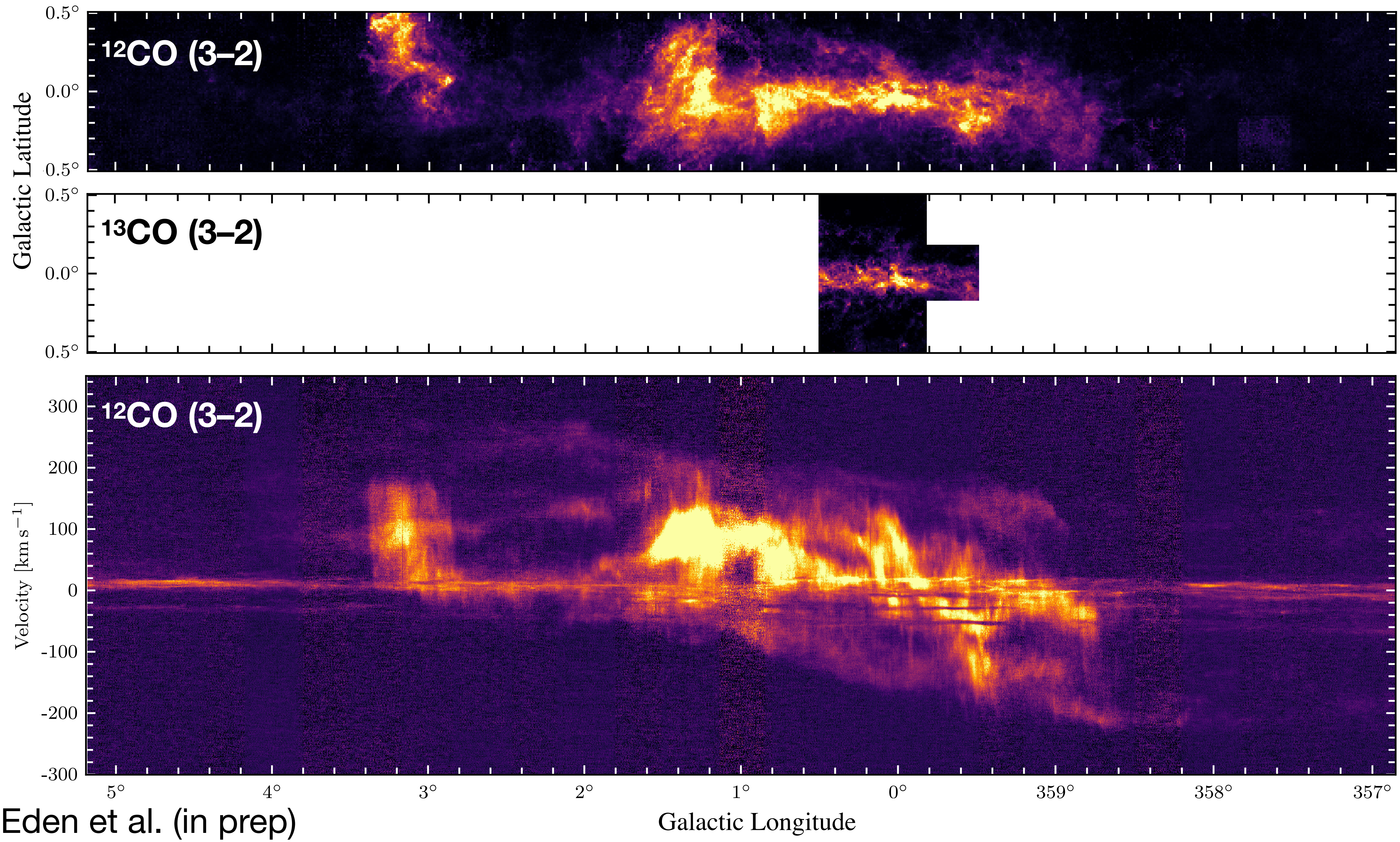
- Central Molecular Zone
- Outer Galaxy
- Bar-dominated region

Includes ^{12}CO (3–2) in areas not covered by COHRS.

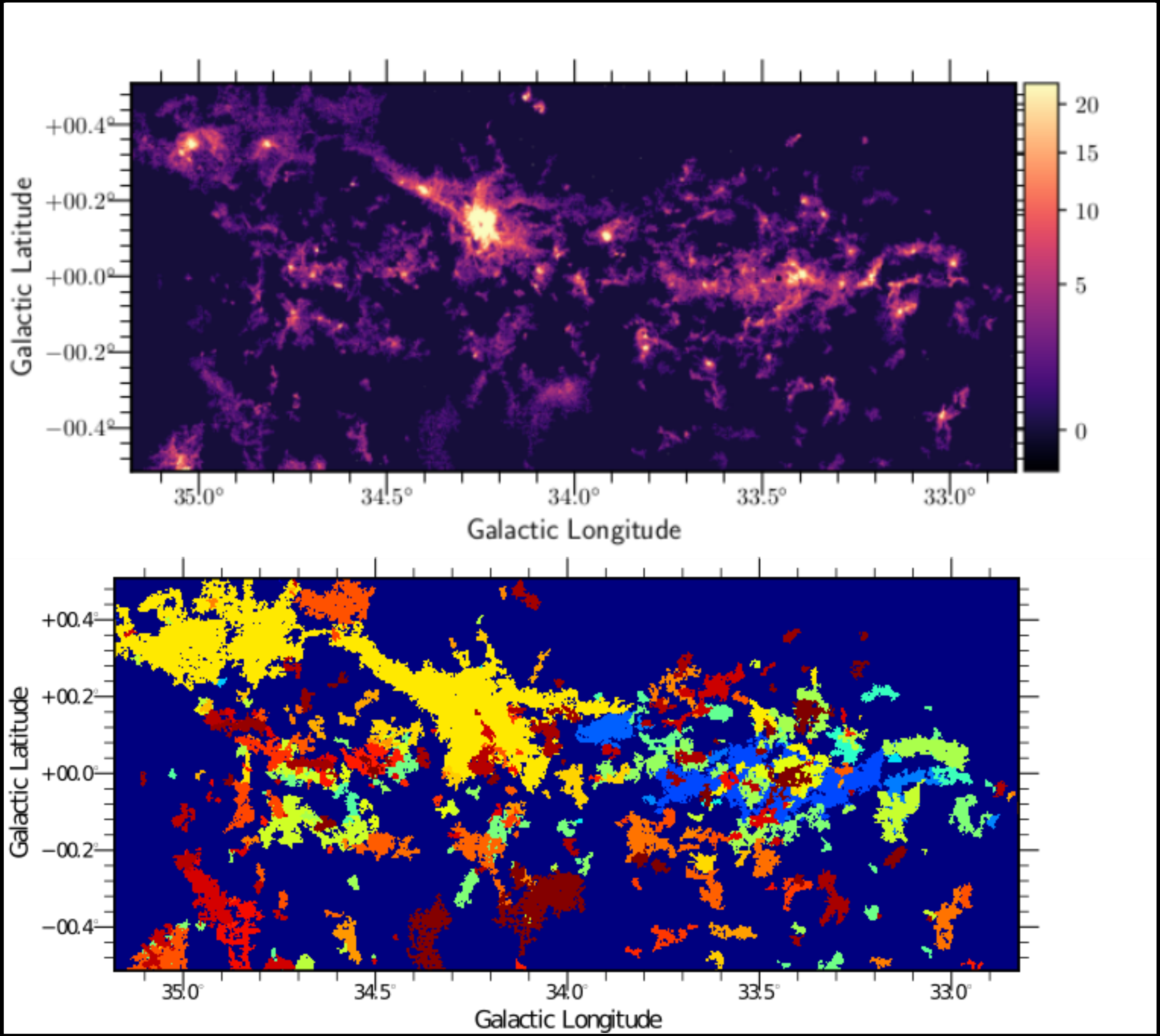
…Limited ^{13}CO (3–2) so far due to historically bad 2018 weather at JCMT.

CHIMPS2

Galactic Centre



Eden et al. (in prep)



SCIMES dendrogram analysis of a section of the CHIMPS data: Rani et al in prep

Summary

- CO GP surveys give us the molecular gas spatial distribution, cloud physical properties and, in combination with continuum data, estimates of SFE, dense gas mass fraction, etc., & relationships between these. Also potentially the flow of gas through the disc, bar and CMZ

- Work done to date finds little change in fraction of dense gas in clouds or star formation in dense clumps related to spiral arms or position in the disc.

- Variations in L_{70}/M, an analogue of the star formation efficiency, and in the DGMF, from cloud to cloud dwarf any systematic changes with environment.

- CHIMPS2 and other surveys are extending these analyses into new environments, with the Galactic Centre and Outer Galaxy, in addition to extending the Inner Galaxy to include the bar-dominated region.