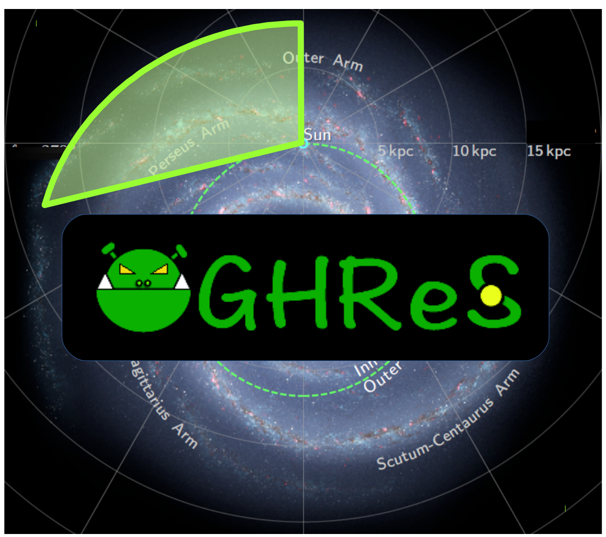
# OGHReS

## The Outer Galaxy High Resolution Survey in CO




Carsten König

Max-Planck-Institut für Radioastronomie, Bonn

J. S. Urquhart, D. Colombo, F. Wyrowski, M.Mattern, S. Leurini, J. Brand, T. Moore, F. Schuller, K. M. Menten,
M. Wienen, M.-Y. Lee, P. Mazumdar

# Max Planck Institute for Radio Astronomy

MAX-PLANCK-INSTITUT
FÜR RADIOASTRONOMIE

Bonn, Germany

3 Research Groups:

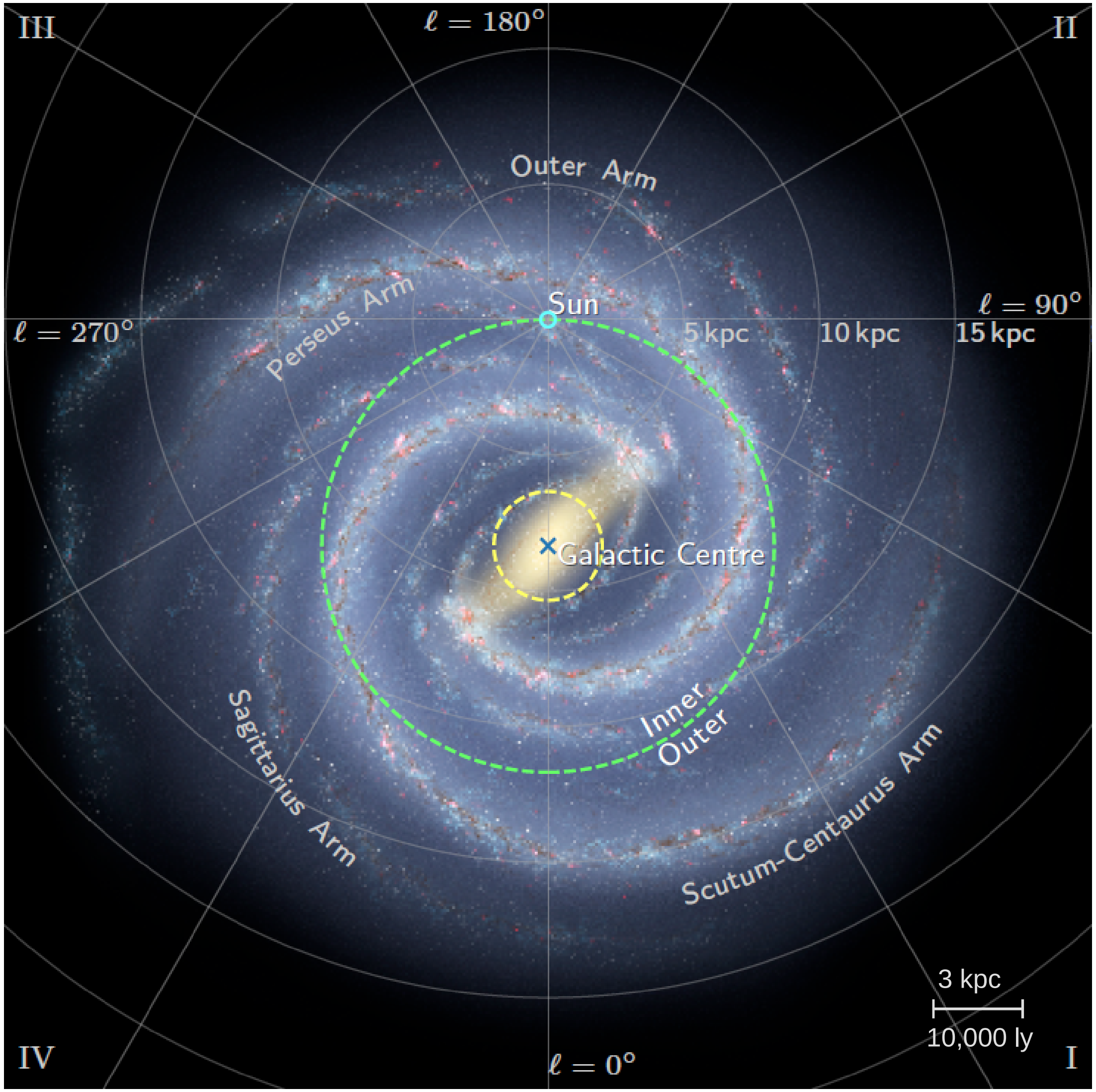
- Fundamental Physics in Radio Astronomy
- Millimeter and Submillimeter Astronomy
- Radio Astronomy/VLBI

+5 Technical Development Groups

Effelsberg 100m Telescope,
Bad Münstereifel, Germany

Atacama Pathfinder Experiment
San Pedro de Atacama, Chile

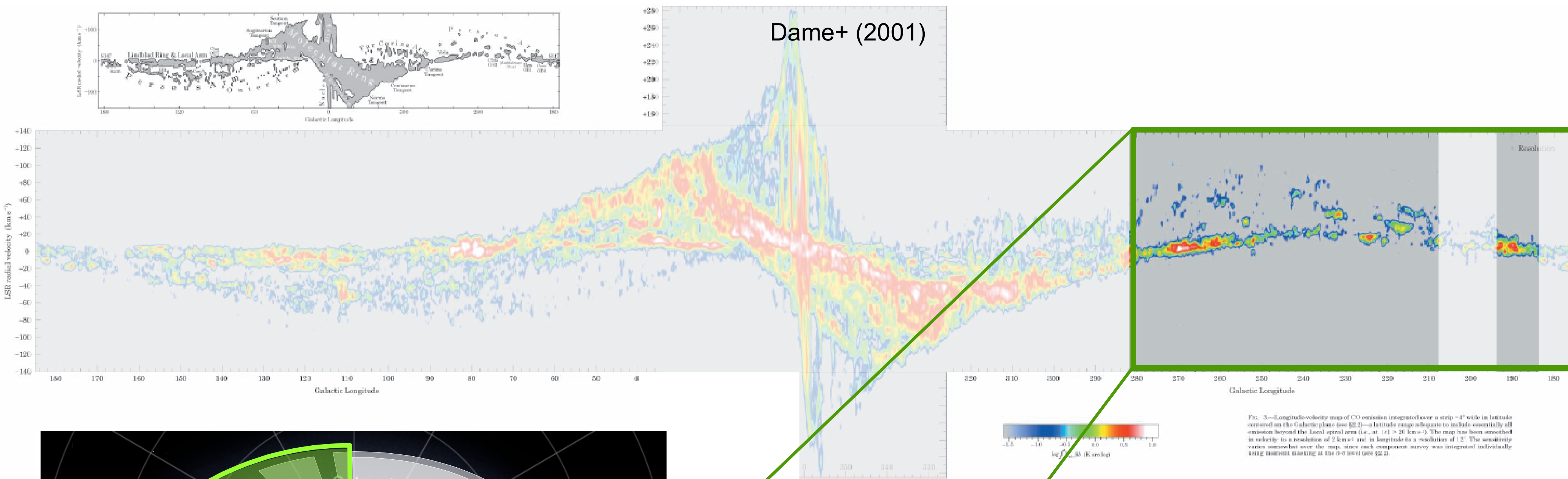
# Star Formation throughout the Milky Way



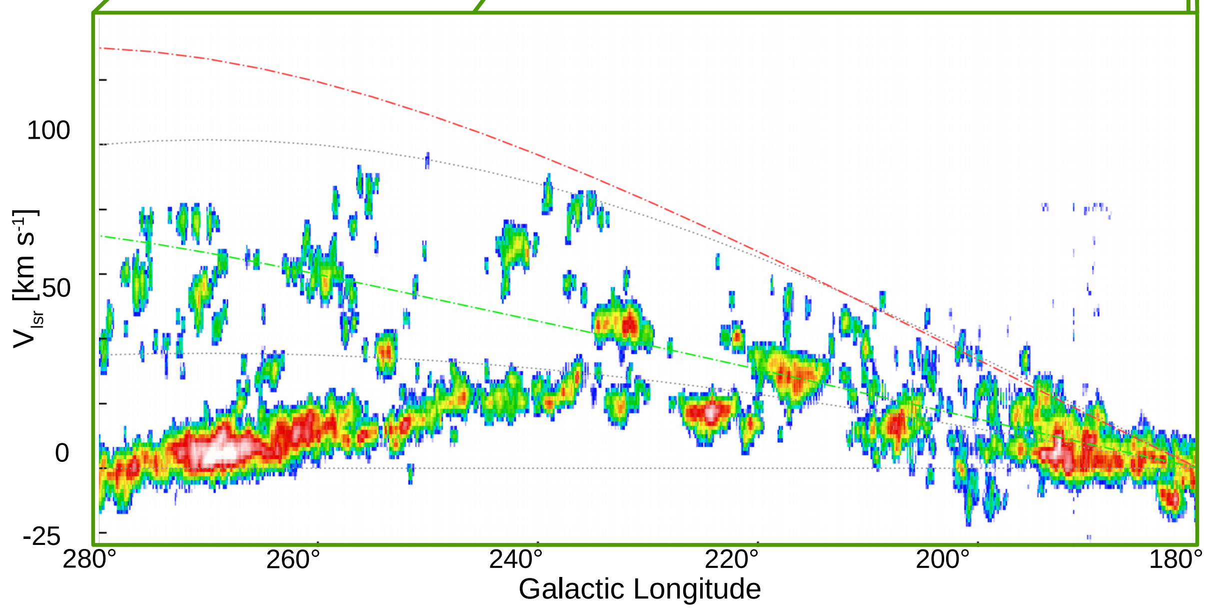

Background (artist impression): NASA/JPL-Caltech/ESO/R. Hurt

- Few hundred billion stars
- Size:
  - ~20 kpc radius in CO (Kobayashi+ 2008)
  - Sun is 8.34 kpc from GC (Reid+ 2014)
- Three major regions:
  - Galactic Center (few hundred pc)
  - Inner Galaxy ($R_{GC}$ < 8.34 kpc)
  - Outer Galaxy ($R_{GC}$ > 8.34 kpc)
- Environment changes with $R_{GC}$:
  - Metallicity decreases (Rudolph+ 1997)
  - Smaller cosmic ray flux (Bloemen+ 1984)
  - Higher gas-to-dust ratio (Giannetti+ 2017)
  - Lower $H_2$ surface density (Heyer+ 2015)

# The Milky Way in CO

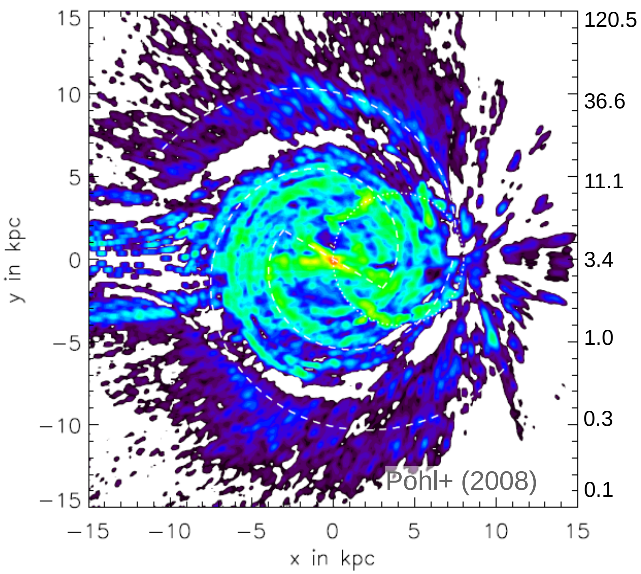


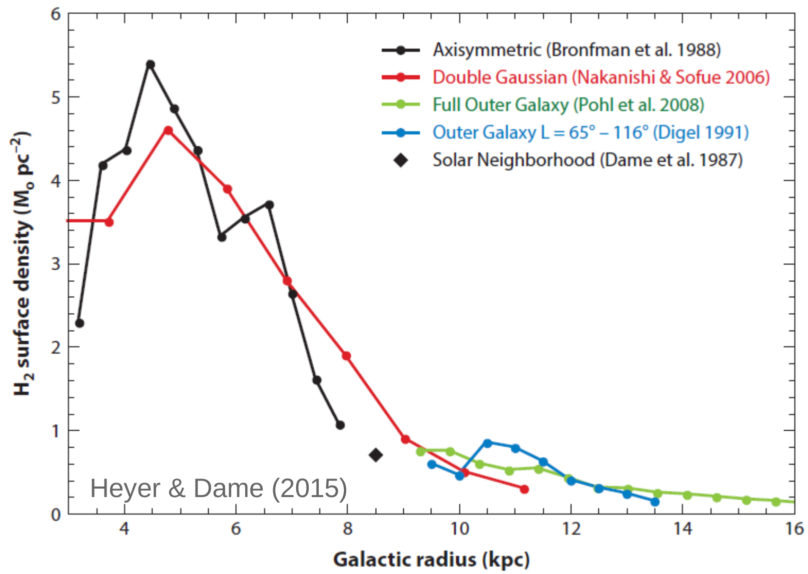


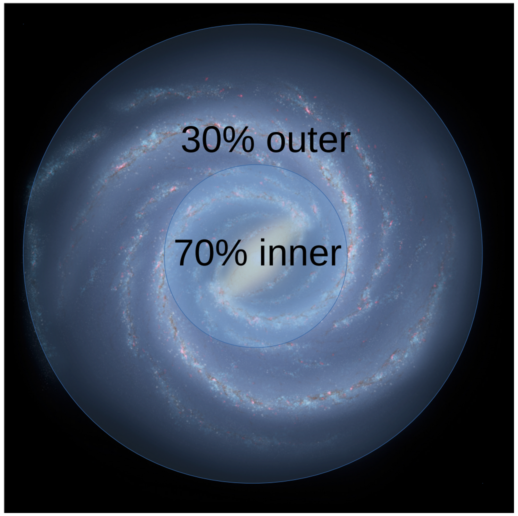


# The Milky Way: Star Formation

## Mass Distribution

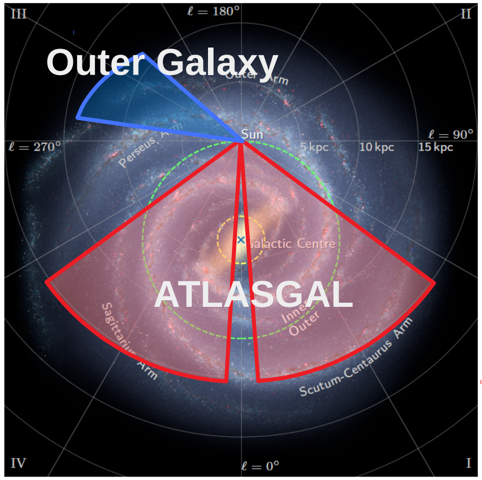



Background: NASA/R. Hurt

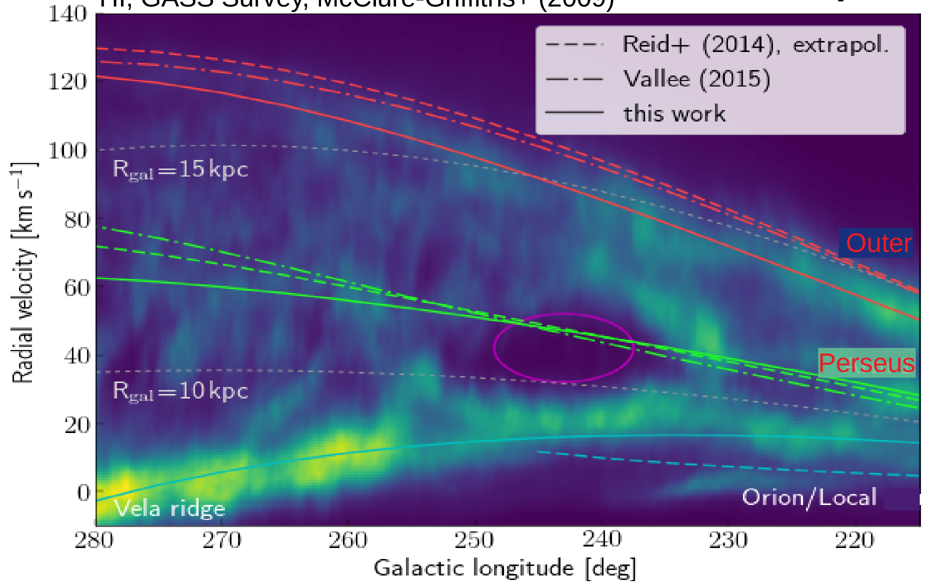
## High Mass Star Formation

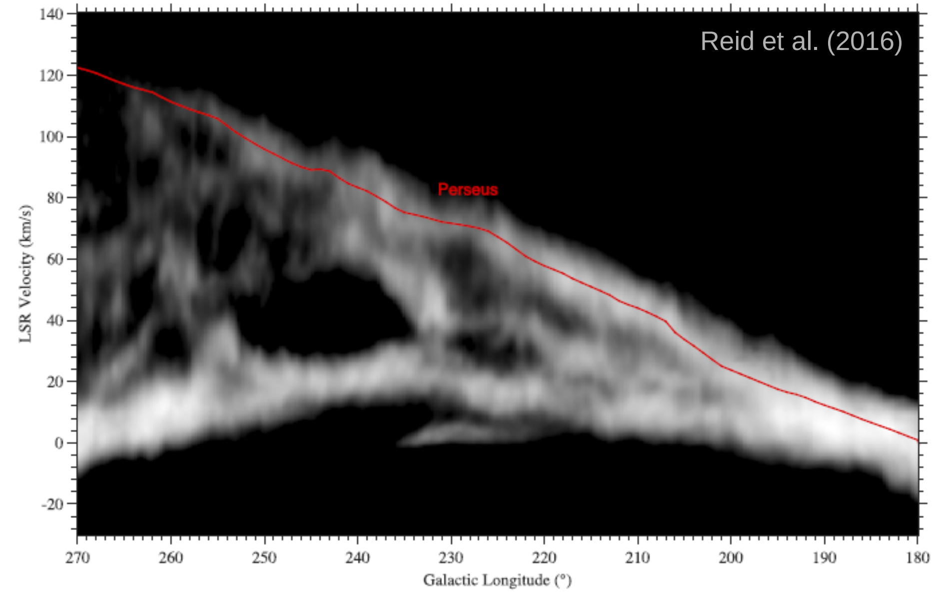


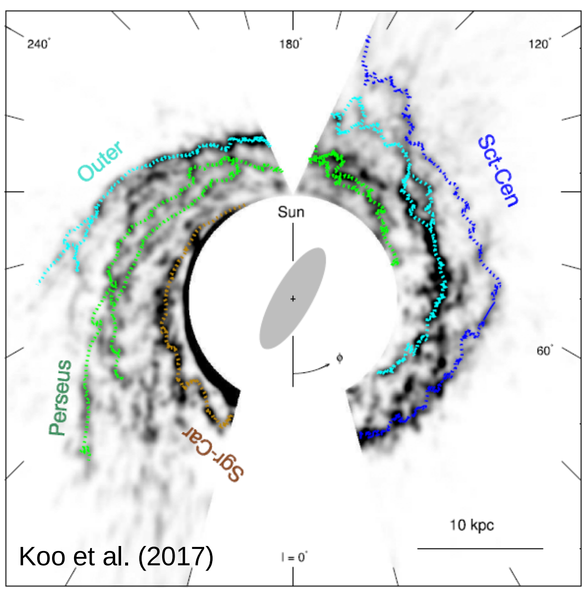

| | Inner Galaxy | | Outer Galaxy | |
|---|---|---|---|---|
| Methanol Masers | >577 | >82.4 / 10° | 2 | 0.6 / 10° |
| HII regions | >1,145 | >104.1 / 10° | 10 (+24) | 2.9 / 10°<br>(9.7 / 10°) |

## Spiral Arms

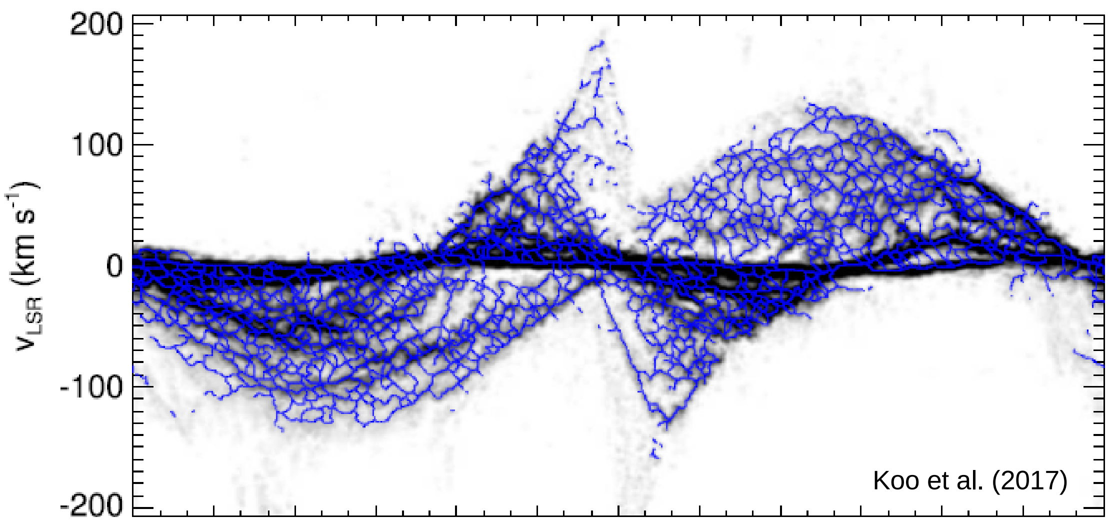
HI, GASS Survey, McClure-Griffiths+ (2009)



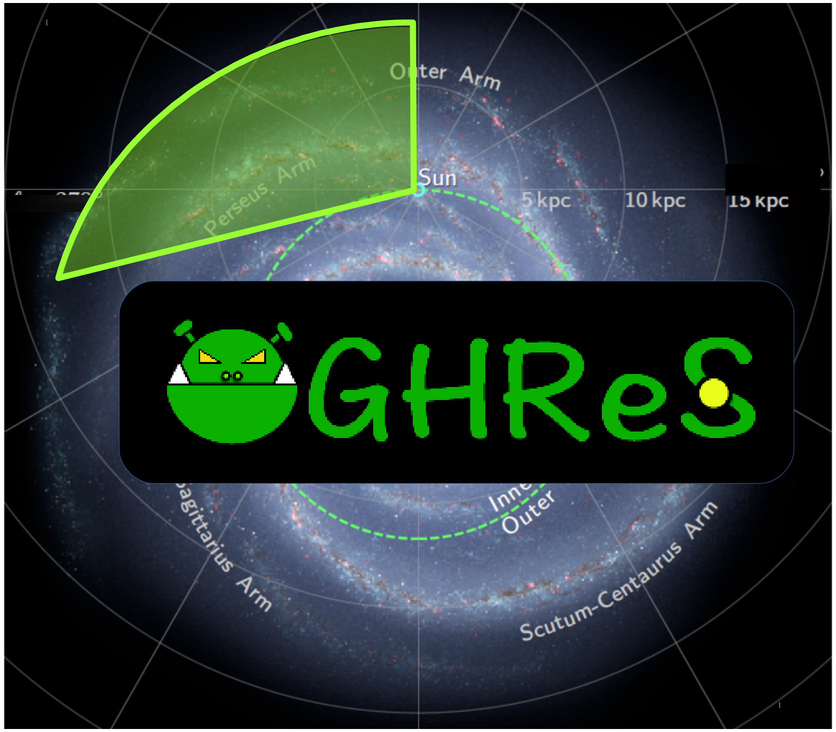




## Filaments



# A New Survey for the South





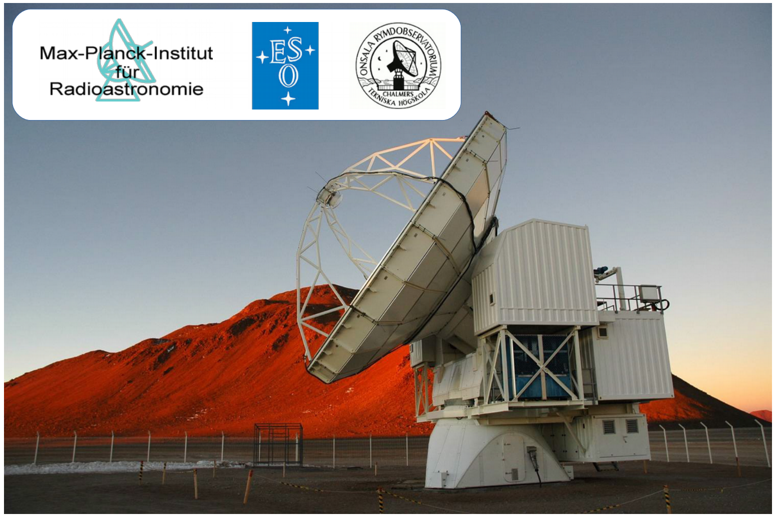
## **O**uter **G**alaxy **H**igh **Re**solution **S**urvey

## Science Goals:

- Observe an **un-explored Galactic environment**
- Investigate **GMC and star formation properties**
- Study **dynamics at all scales** (e.g. clouds, clumps, filaments)
- Constrain **3D structure of the ISM** out to 20 kpc
- Constrain **Milky Way global parameters** (e.g. XCO, gas-to-dust ratio)

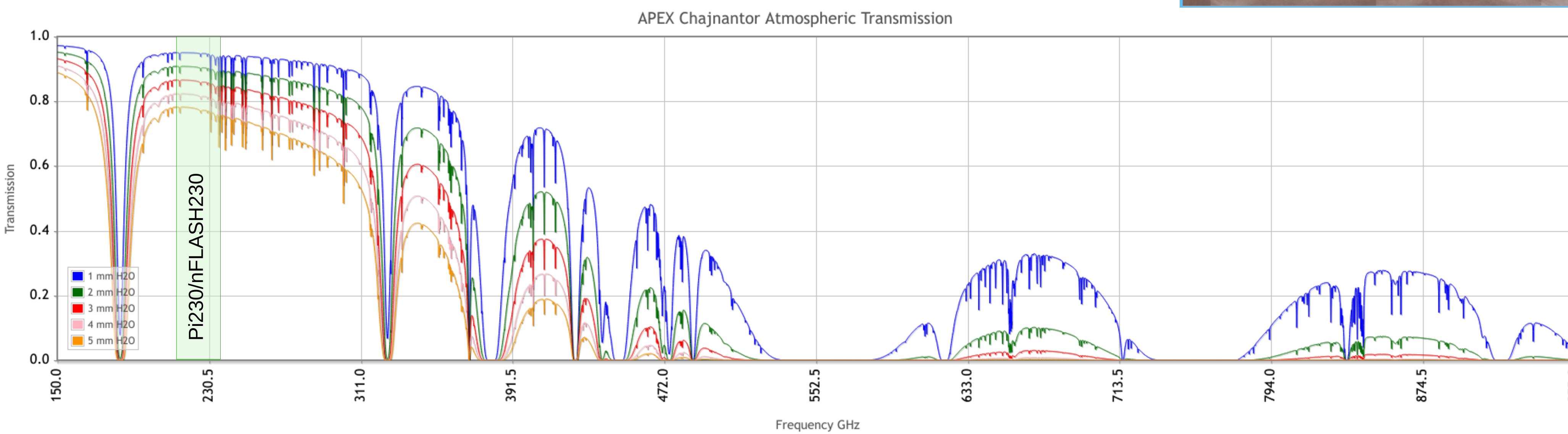
**Telescope:** APEX
**Receiver:** PI230 / nFlash230
**Lines:** $^{12}CO(2\text{-}1)$, $^{13}CO(2\text{-}1)$, $C^{18}O(2\text{-}1)$
**Coverage:** $180° < \ell < 280°$, $\Delta b = 1°$
**Resolution:** 29” (~2 pc at 10-15 kpc)
**Sensitivity:** 0.4 K @ 0.5 km/s
**Time:** ~790 hr (allocated) / 1150 hr (total)

# APEX – The Atacama Pathfinder Experiment

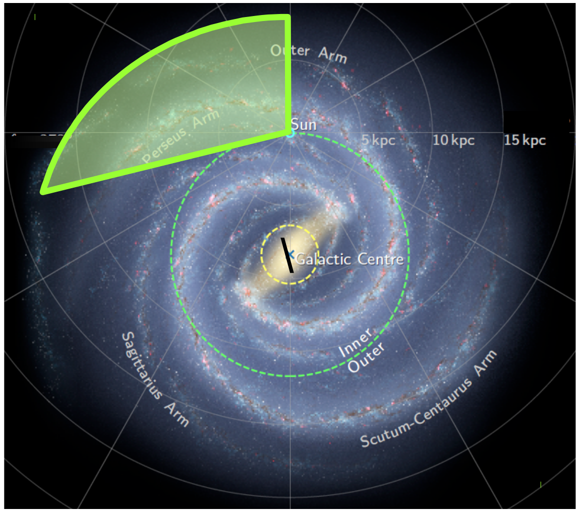


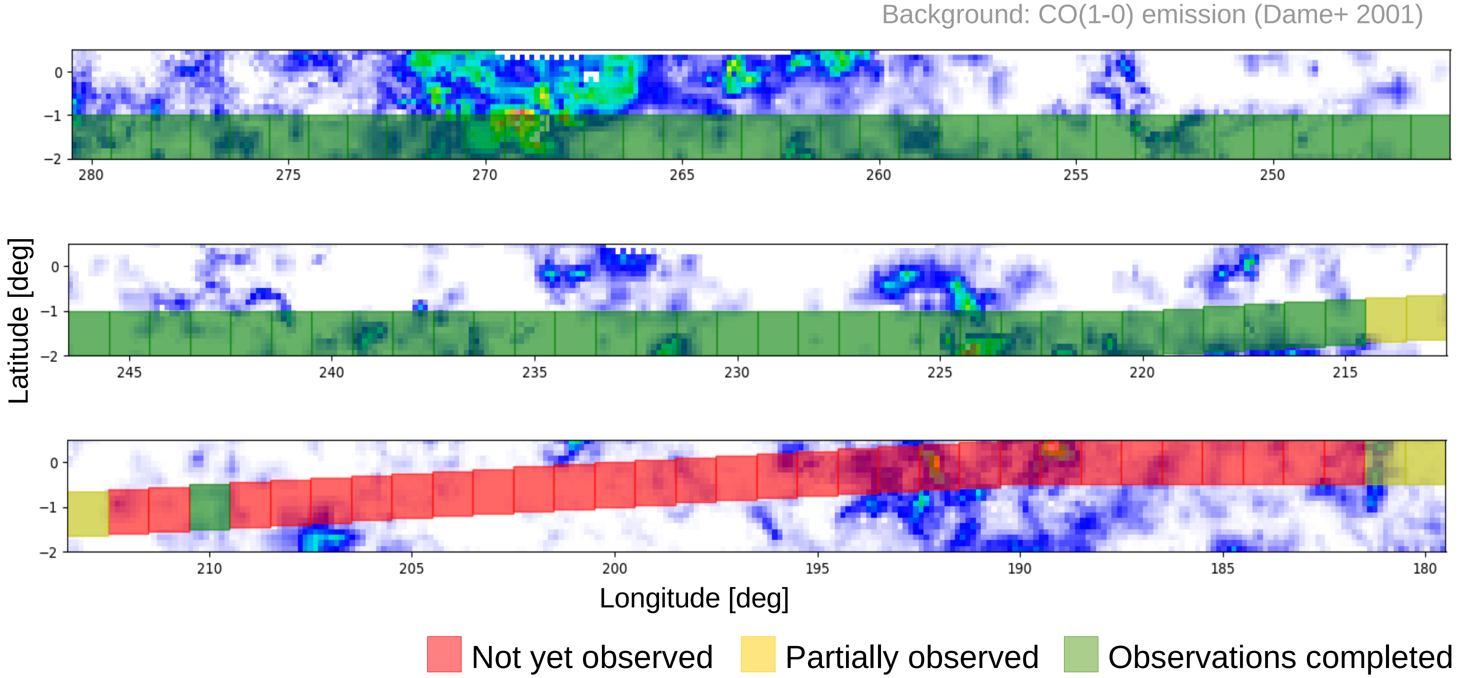


**Inauguration:** Sept. 25, 2005
**Location:** Chajnantor/San Pedro de Atacama, Chile
**Altitude:** 5 104 m
**Spectral Range:** 157 – 850 GHz (Instruments)



# Coverage & Progress

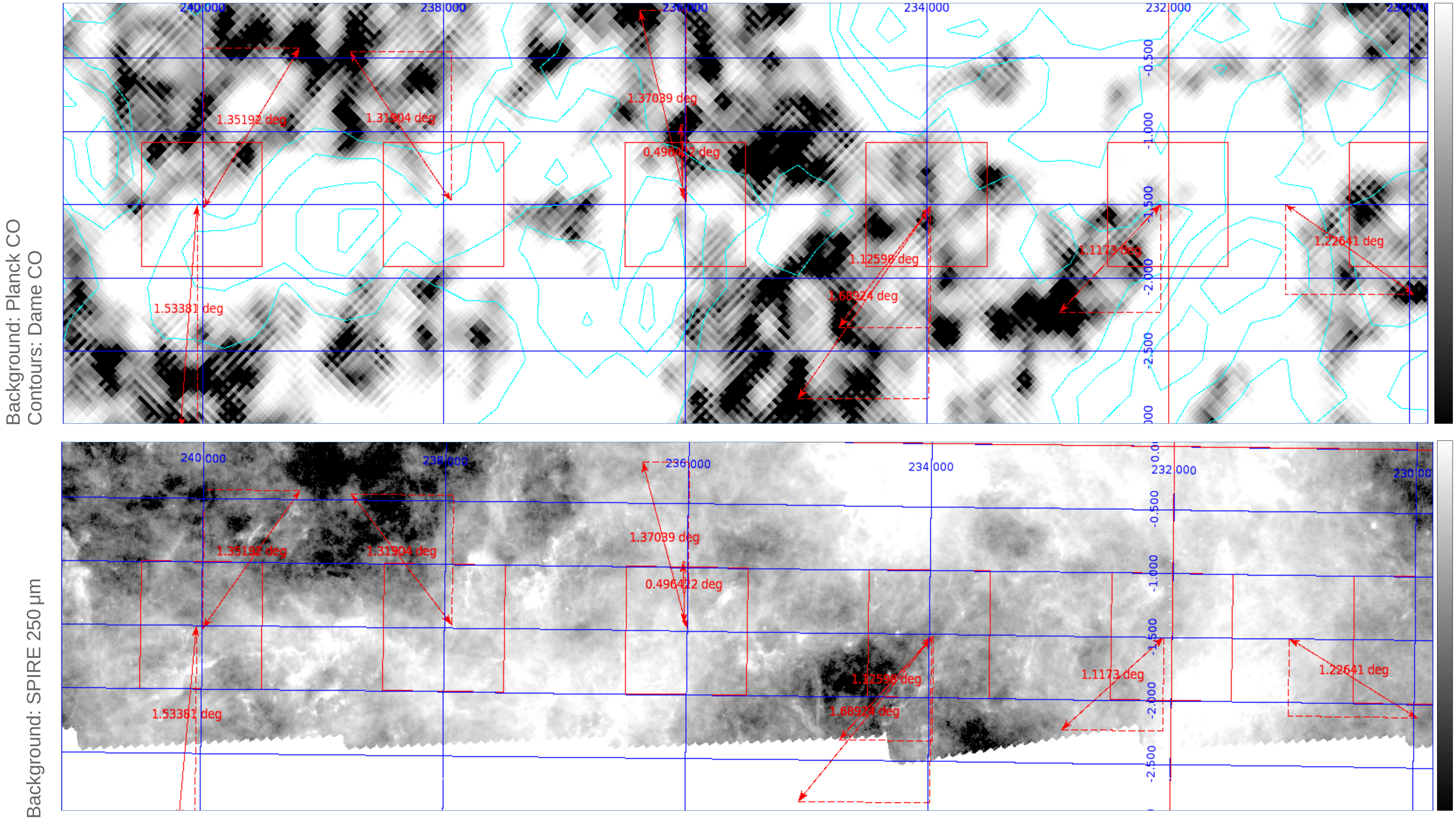



- **100 1x1 deg² fields** organized into 2x8 sub-maps in x- and y-direction for dual coverage in order to reduce noise and striping effects.
- **Latitude range follows Galactic warp** similar to lowest Herschel Hi-GAL latitudes in order to allow complementary dust continuum analysis.
- So far 67 **fields have been observed** and 5 more started. Off-Positions have been observed for all fields.

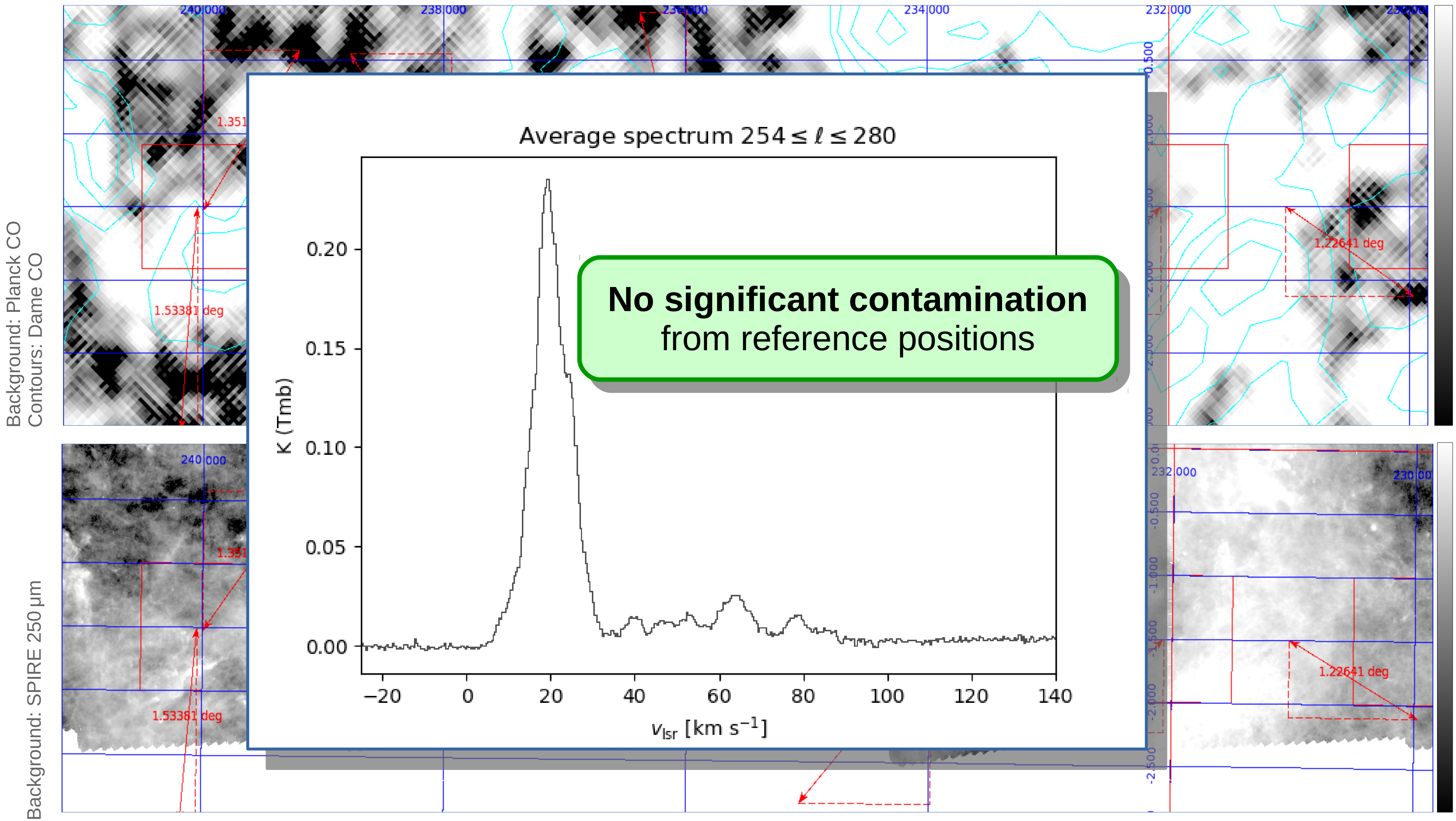
OGHReS is **~70% finished**.

# Selection of Reference Positions



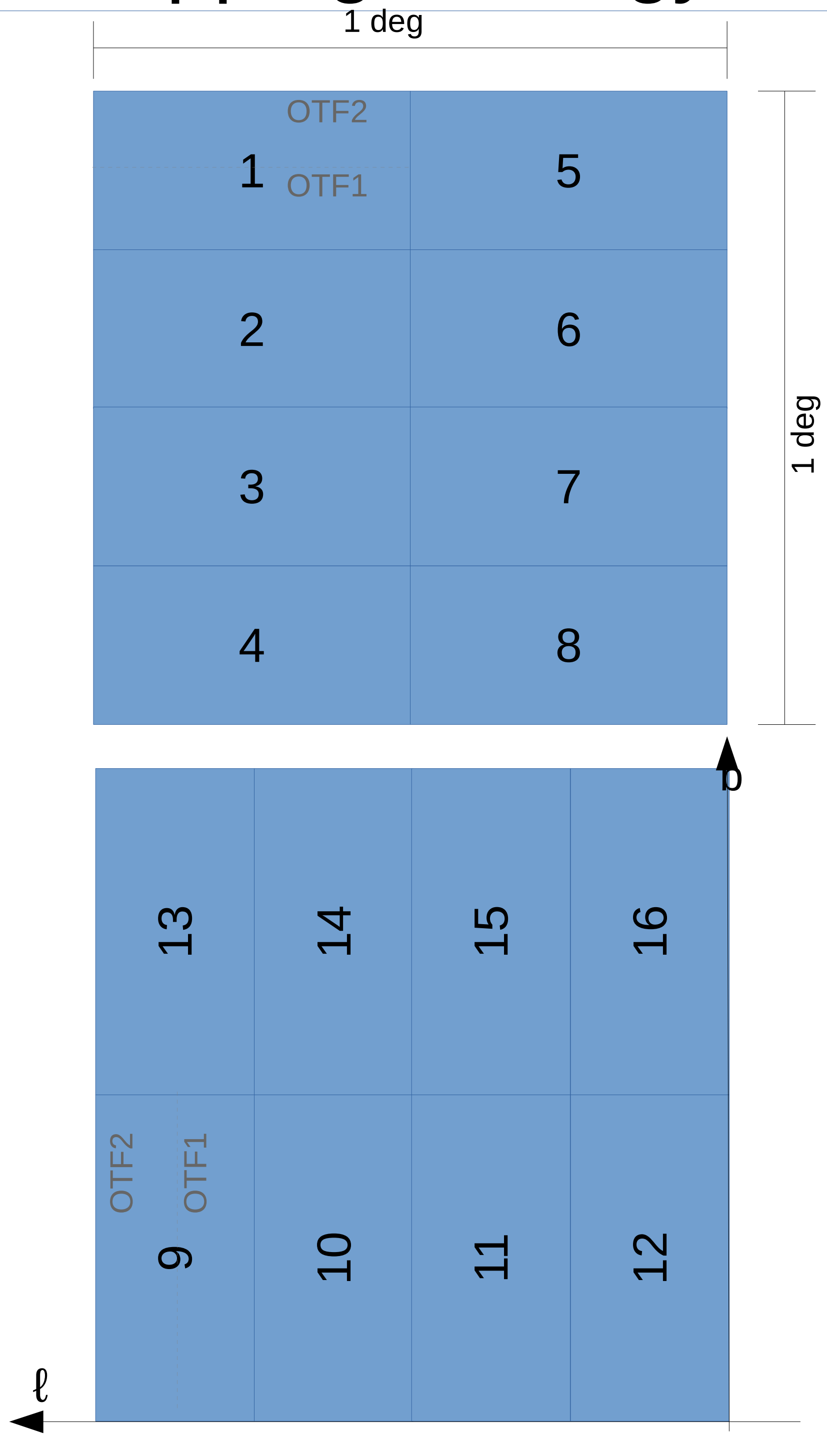

- Off-positions carefully selected from Dame+ 2001 and Planck CO maps for minimum contamination.
- Herschel Spire 250µm dust continuum is less useful as dust is everywhere

# Selection of Reference Positions




- Off-positions carefully selected from Dame+ 2001 and Planck CO maps for minimum contamination.
- Herschel Spire 250µm dust continuum is less useful as dust is everywhere

# Mapping Strategy and Observer Assistance

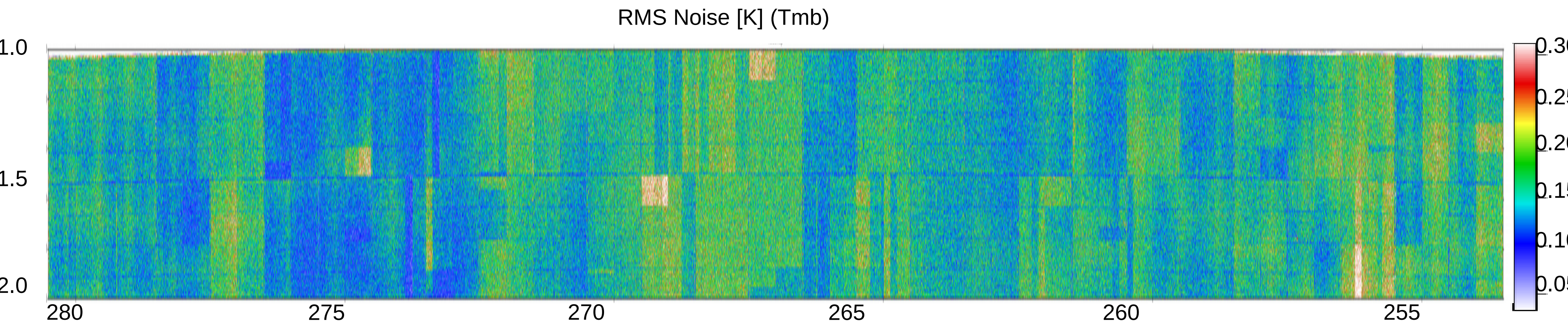


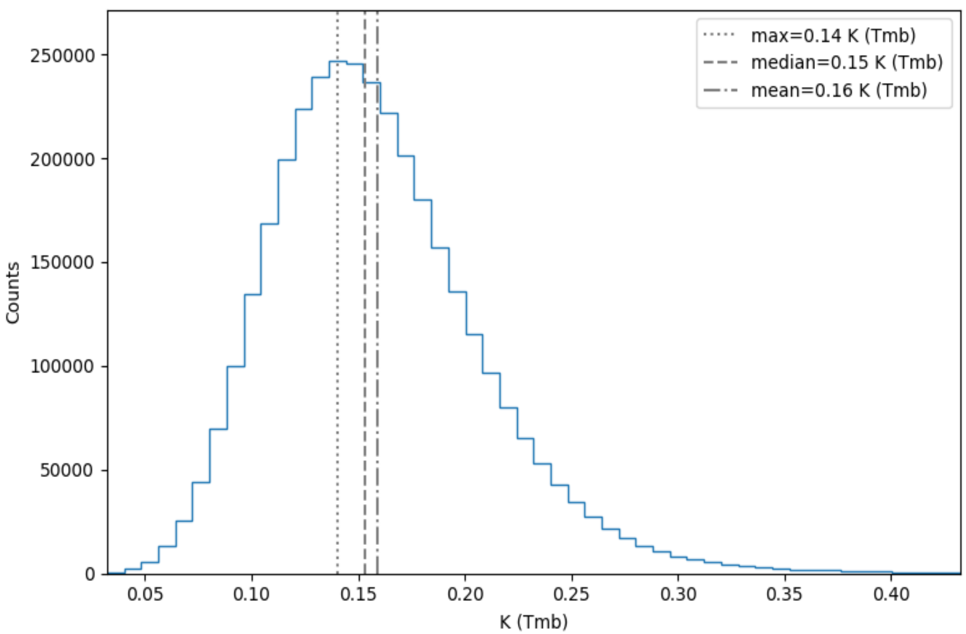

Observer Assistance:

- Script **checks if sub-map was already observed** and gives a warning to the observer if necessary
- Script **checks elapsed time and suggests number of sub-maps** for next execution such that ~1.5 hours are continuously used for observations
- Script **checks PWV and PWV variance** over last 15 min (soft limit at ΔPWV≥0.5mm, hard limit at ΔPWV≥1mm)
- Script **checks distance to the Sun** of sub-field corners

**Improved observing efficiency.**

# Noise Variation




Fully **automated adjustment of observing parameters** dependent on weather conditions (PWV) in order to maintain minimum RMS noise variation.

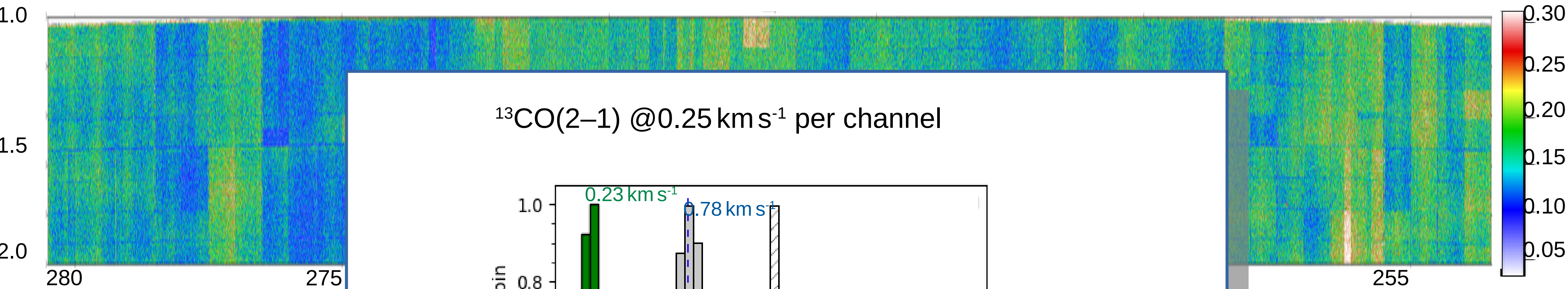
Adjusting:

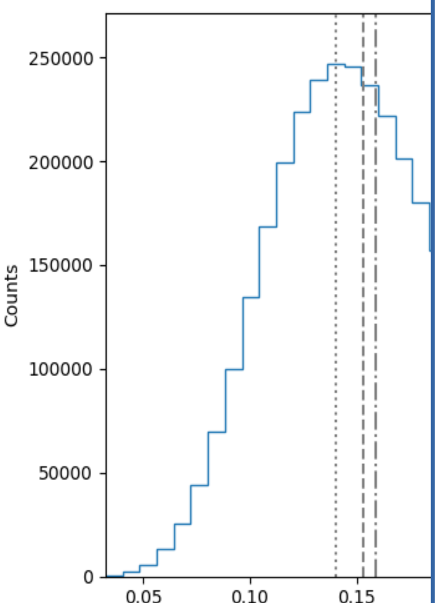
- Integration time
- Number of calibrations
- “On per Off”

**$\sigma_{RMS} \approx$ 0.15 ± 0.04 K @ 0.5 km/s resolution**
0.2mm < PWV < 5.5 mm

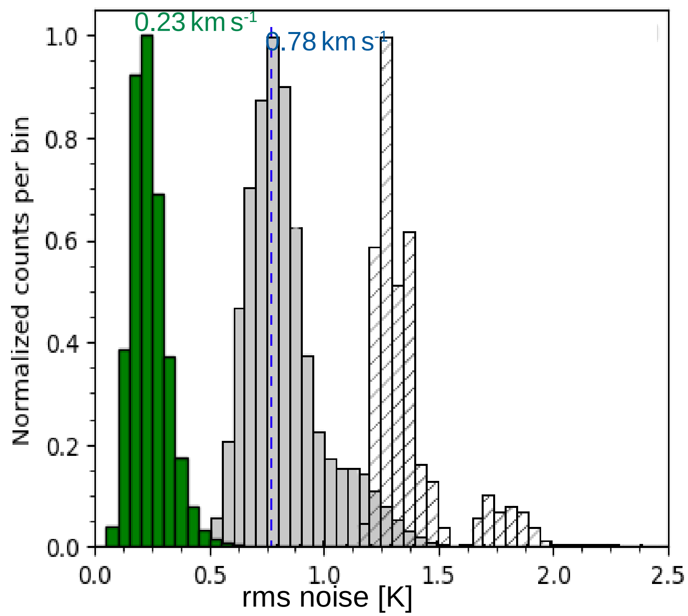
# Noise Variation

RMS Noise [K] (Tmb)




$^{13}CO(2–1)$ @0.25 km s$^{-1}$ per channel




SEDIGISM: PWV<3.4 mm, Δrms=1.1 K

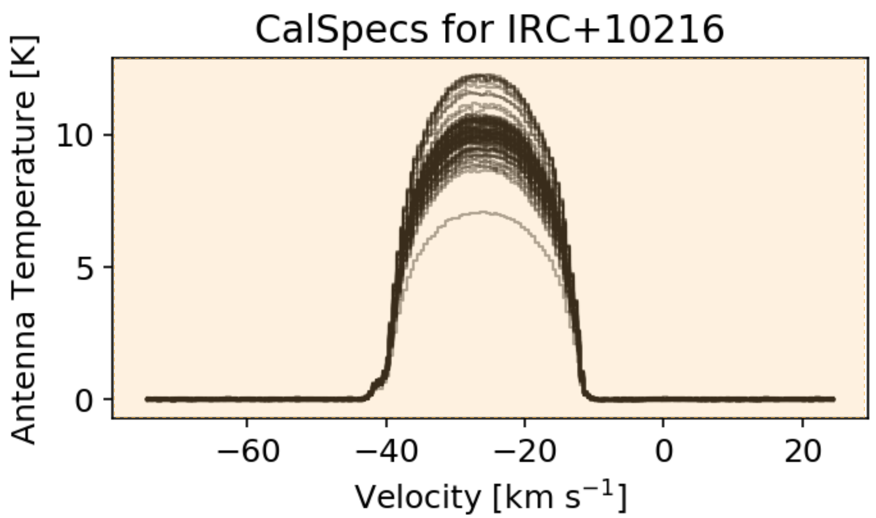
OGHReS: PWV<5.5 mm, Δrms=0.6 K

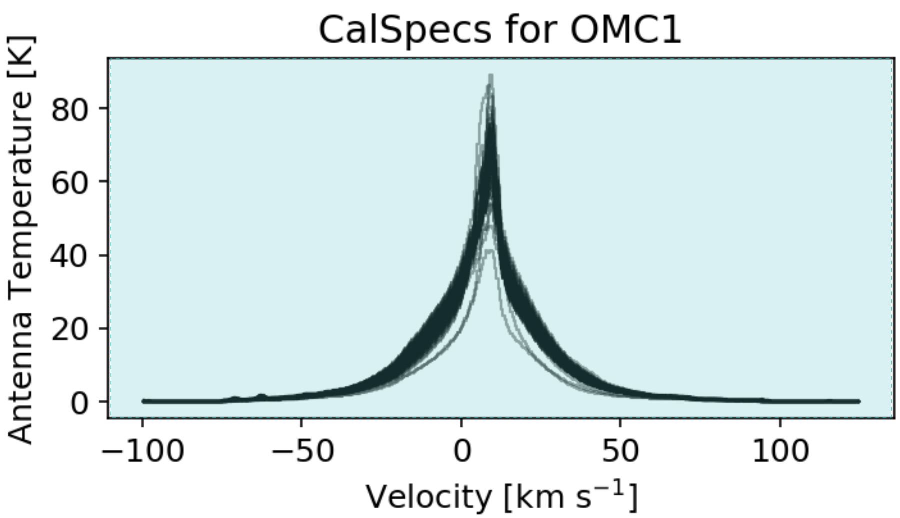
Low and uniform noise distribution.

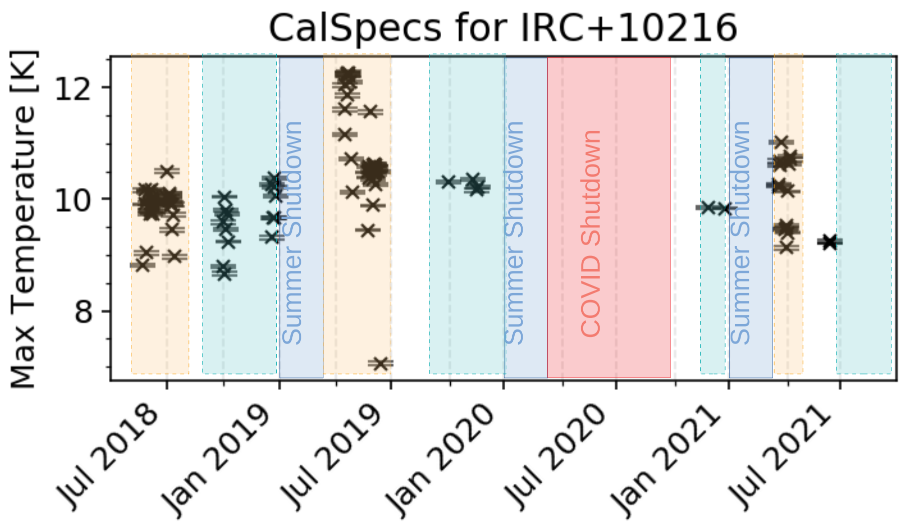
**…ent of observing**
…n weather
… to maintain
…ation.

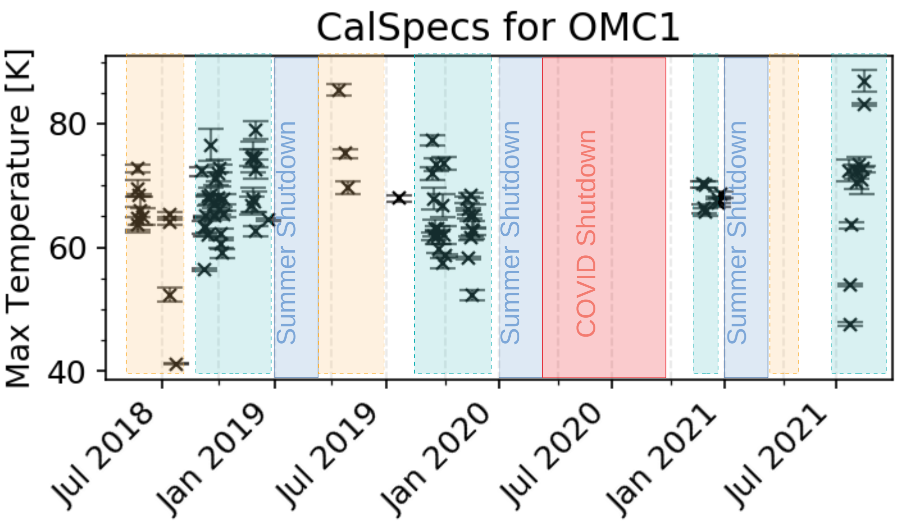
… RMS … **.5 km/s resolution**
0.2mm < PWV < 5.5 mm

# Calibrated spectra of reference sources



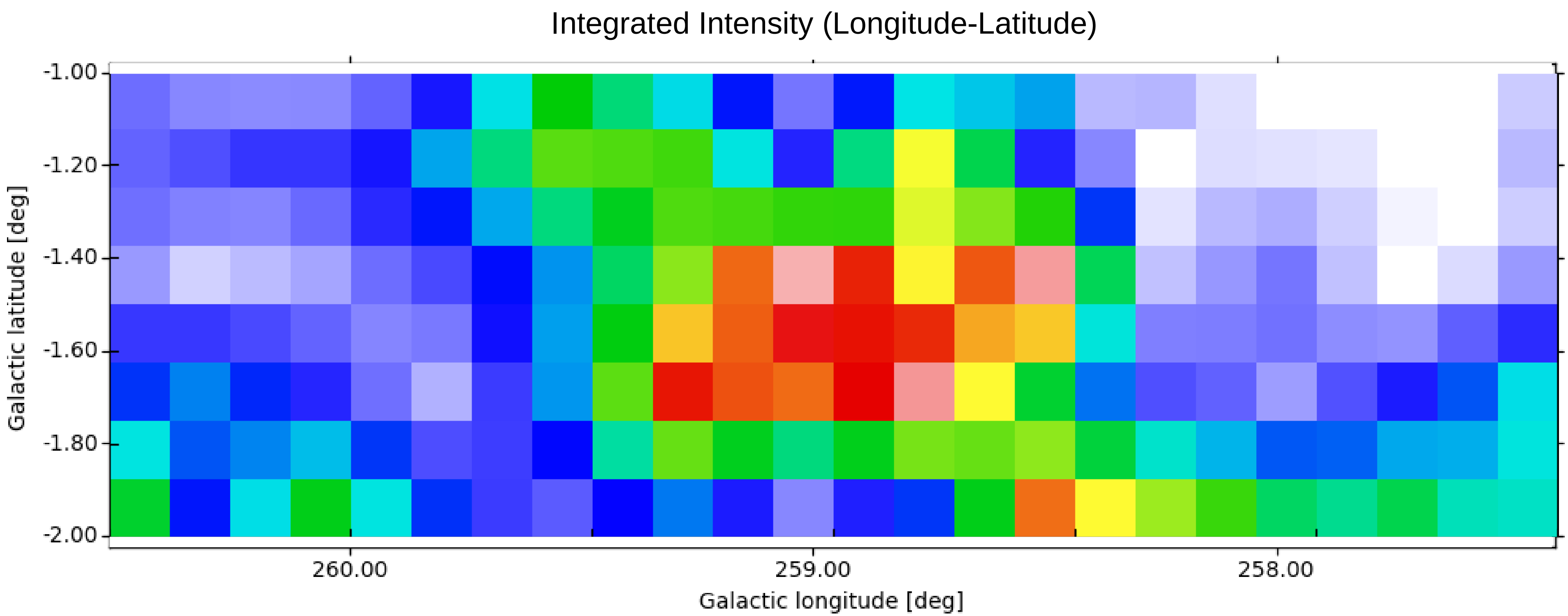



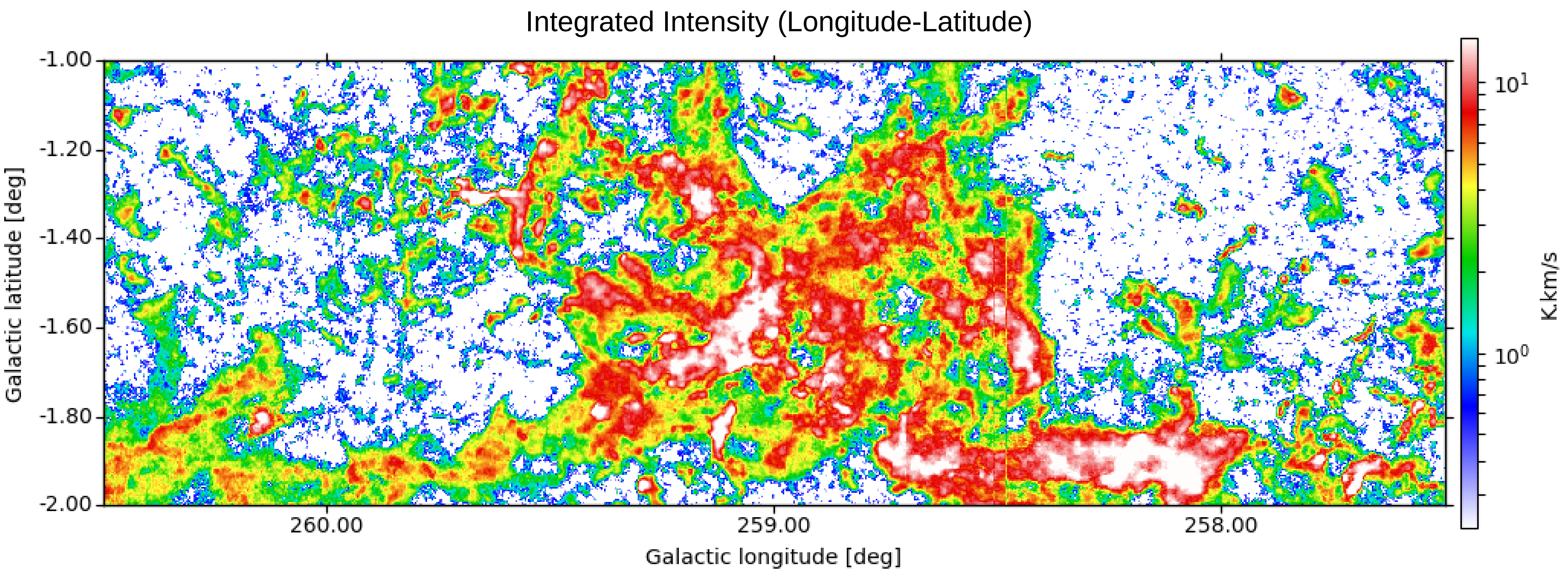




**Calibration variance can be compensated**
as we have CalSpecs for all observing days.

# Integrated Intensity

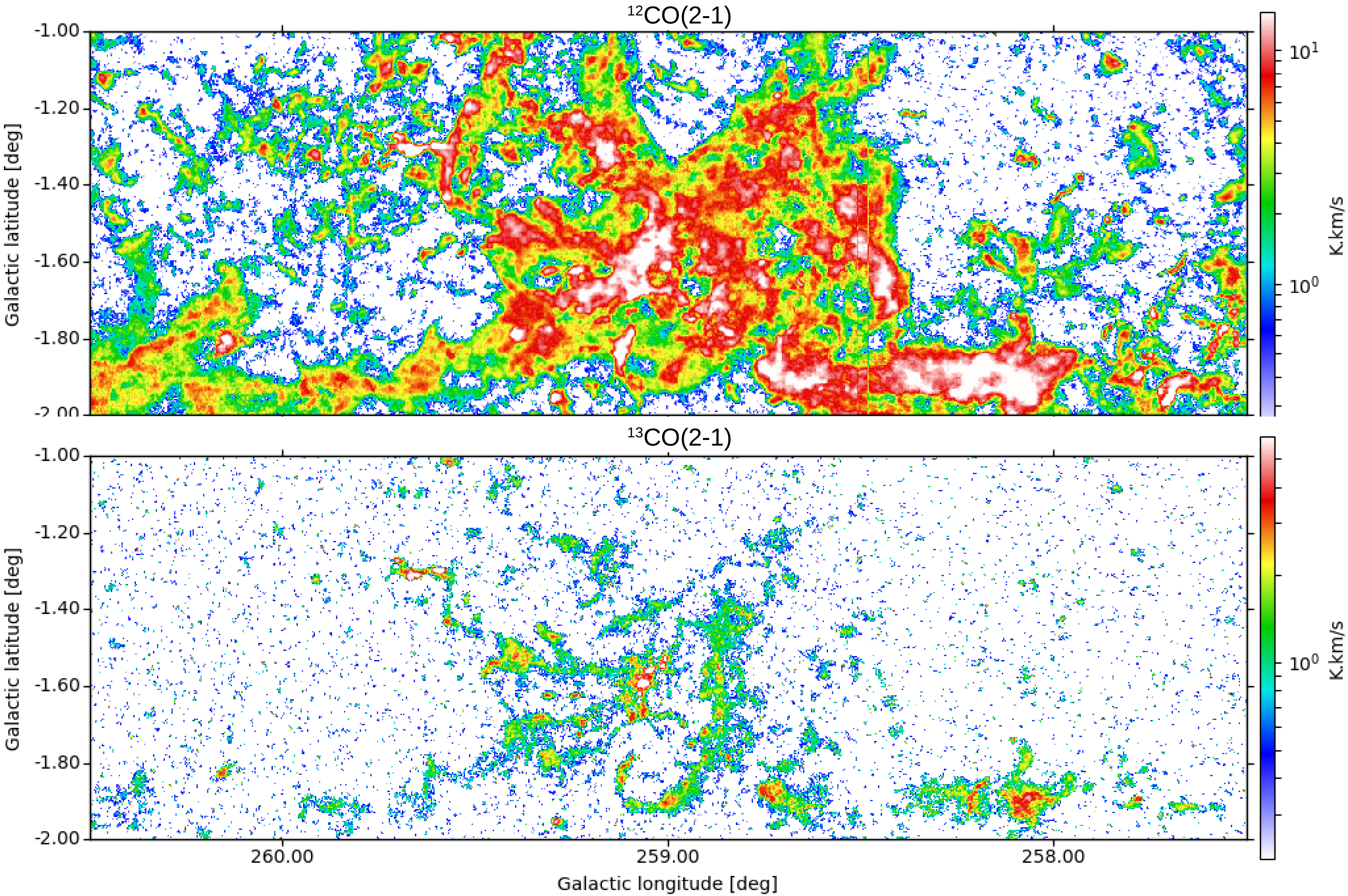


# Integrated Intensity




**Significant improvement in resolution** over Dame+ (2001) CO(1-0) emission by a factor of 18 (8.7 arcmin vs. 29 arcsec) **and in sensitivity**.

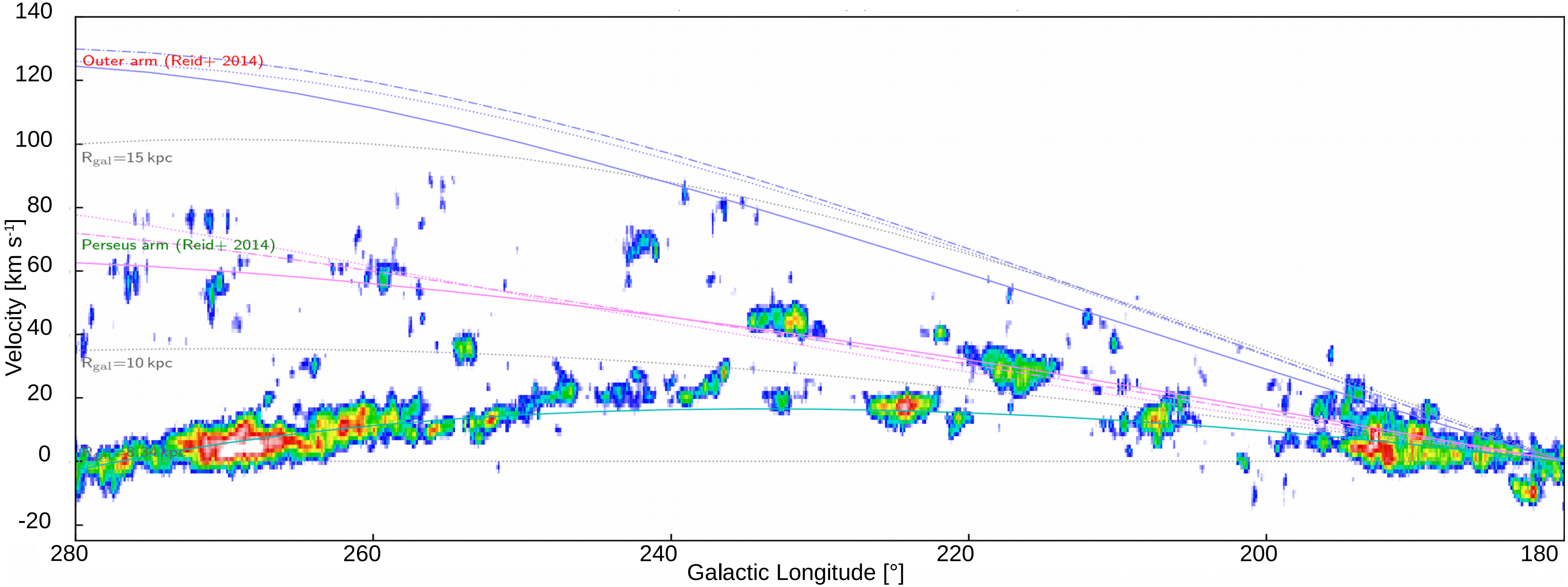
# $^{12}CO$ / $^{13}CO$



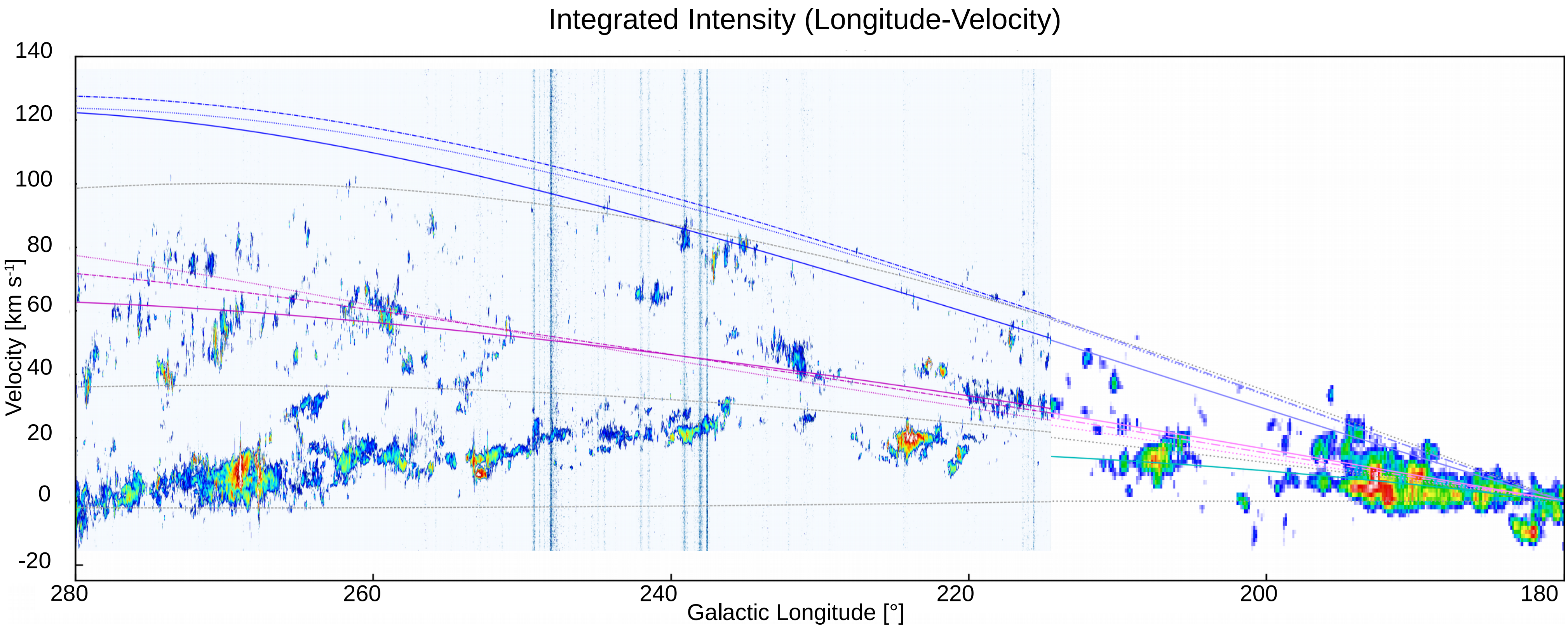
12CO(2-1)
13CO(2-1)
Galactic latitude [deg]
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00
Galactic longitude [deg]
260.00
259.00
258.00
K.km/s
10^1
10^0

# Longitude-Velocity

Integrated Intensity (Longitude-Velocity)

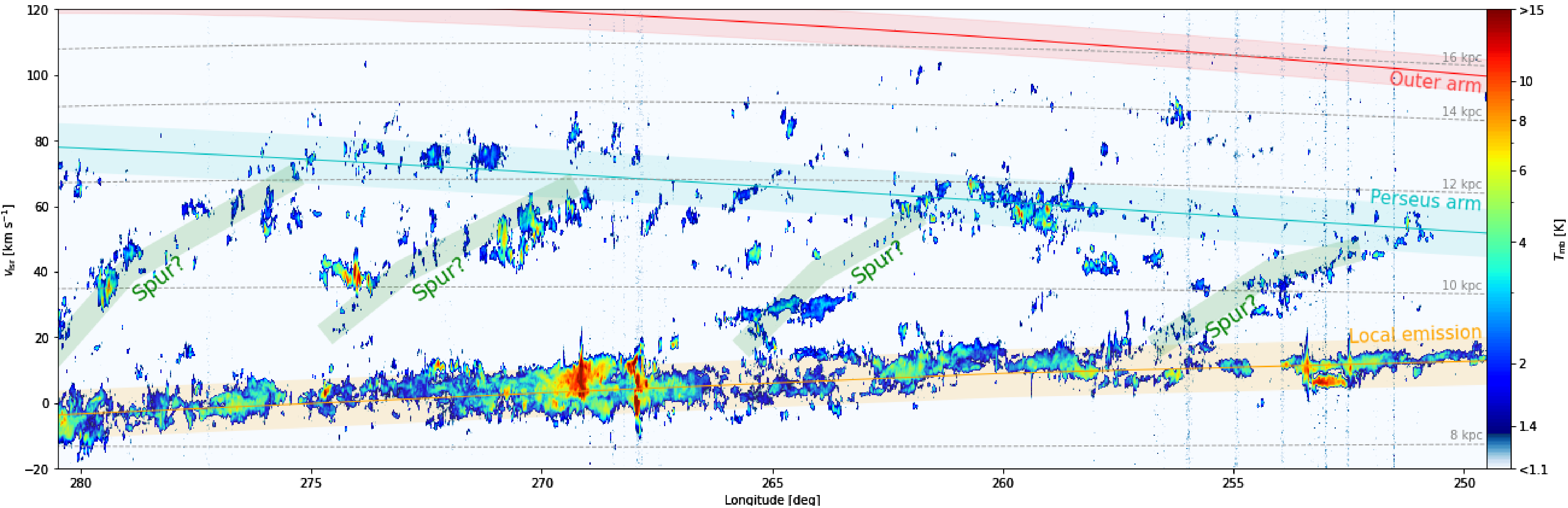


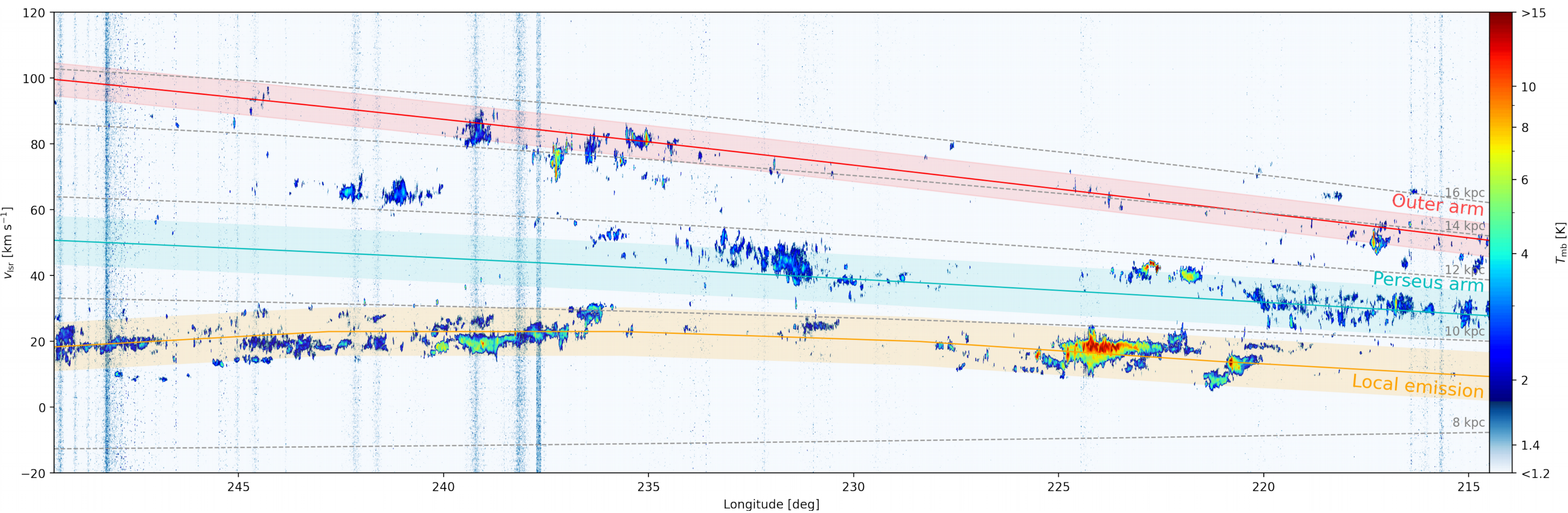
# Longitude-Velocity



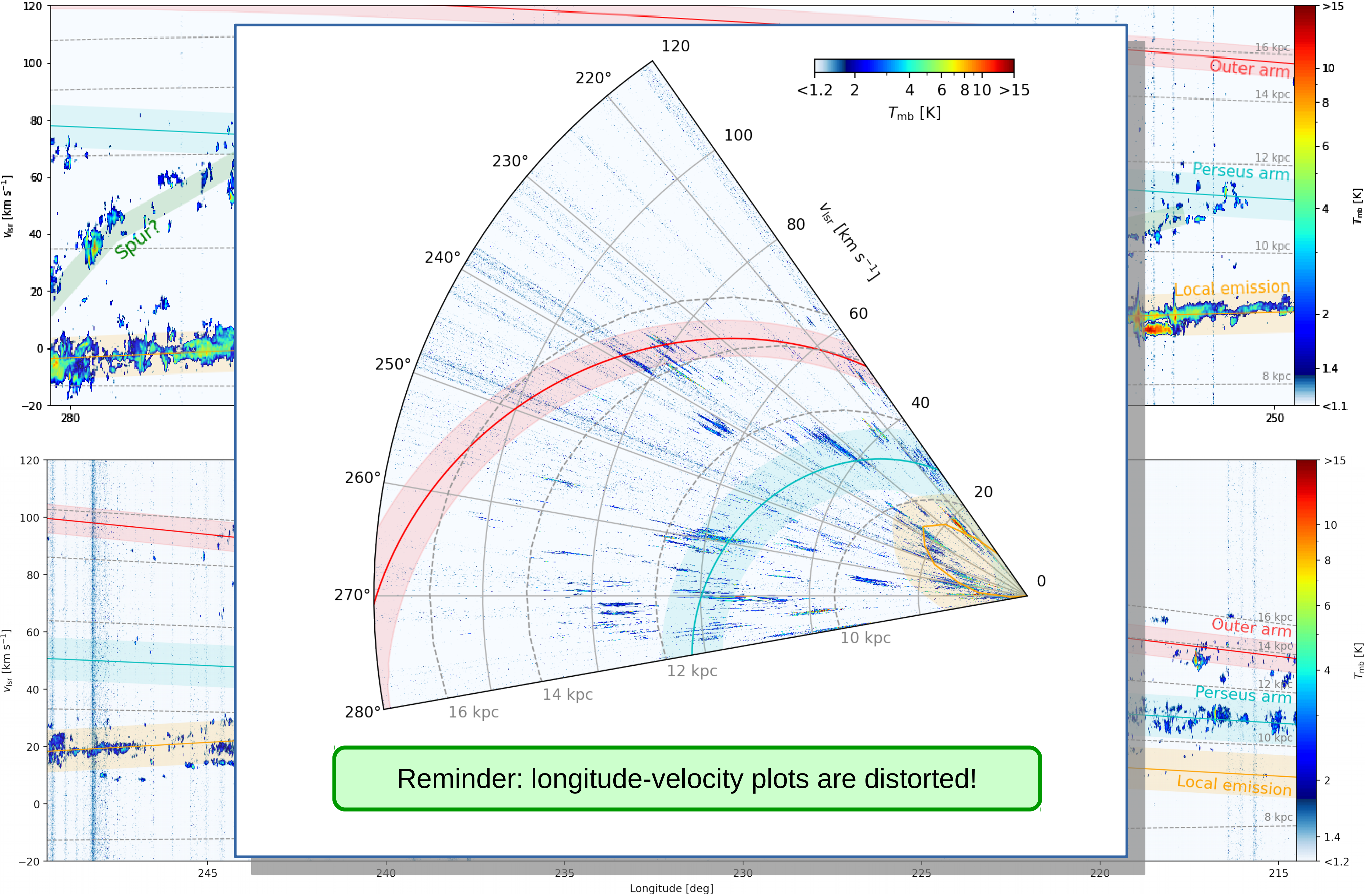

OGHReS detects **smaller objects farther out** in the Milky Way.

# Velocity/Spiral Arms



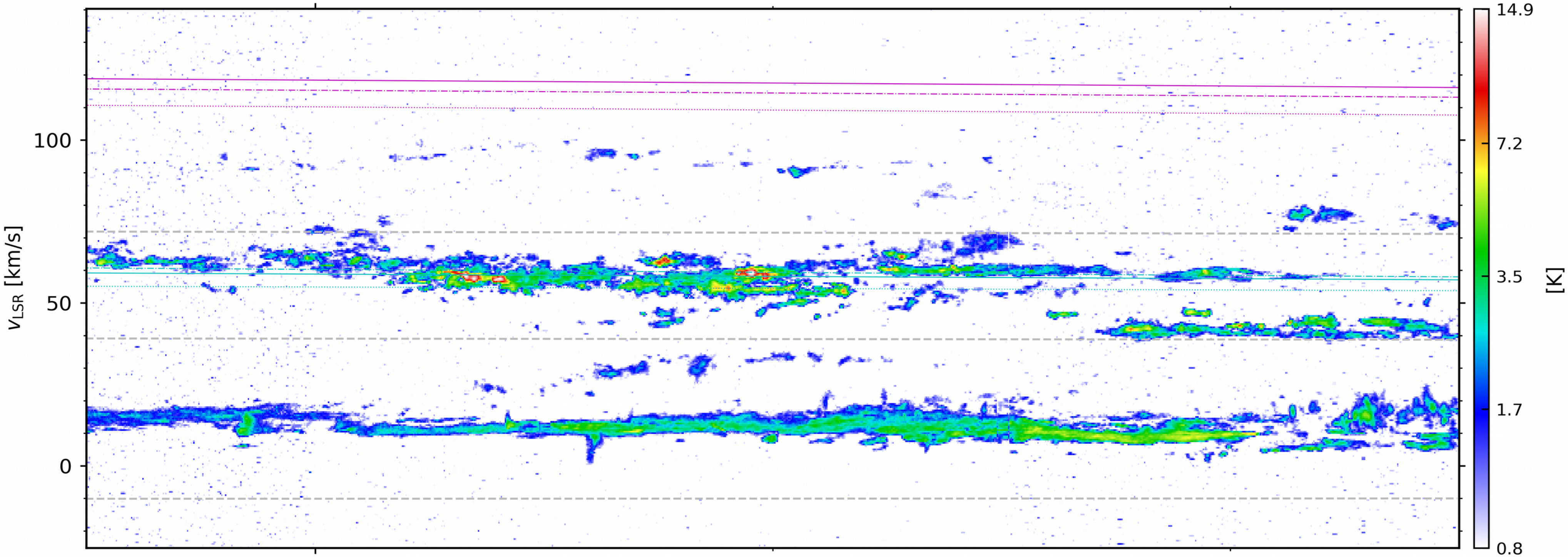



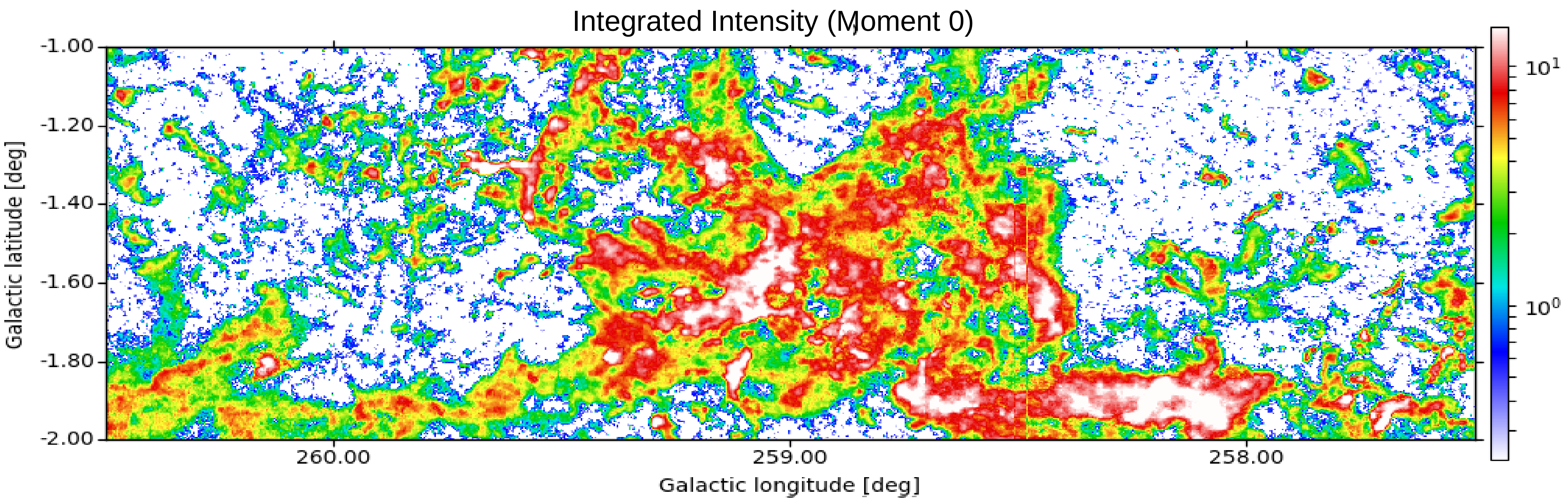
# Velocity/Spiral Arms




Reminder: longitude-velocity plots are distorted!

# Velocities / Moment 1



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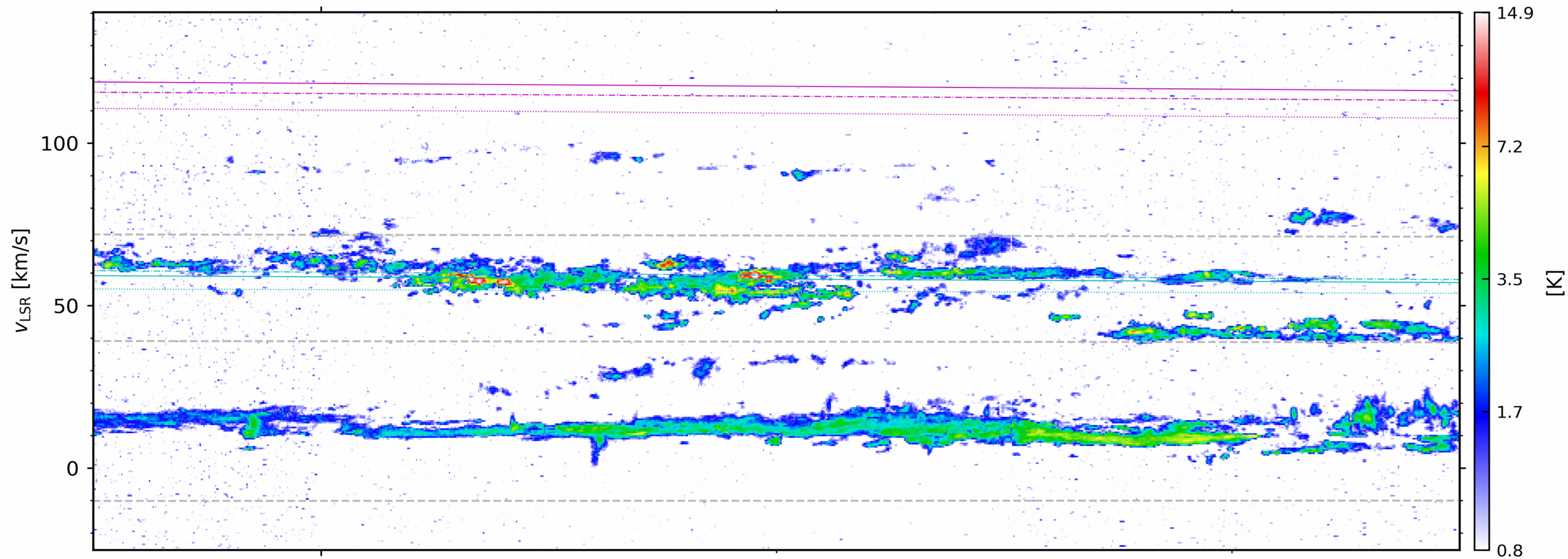
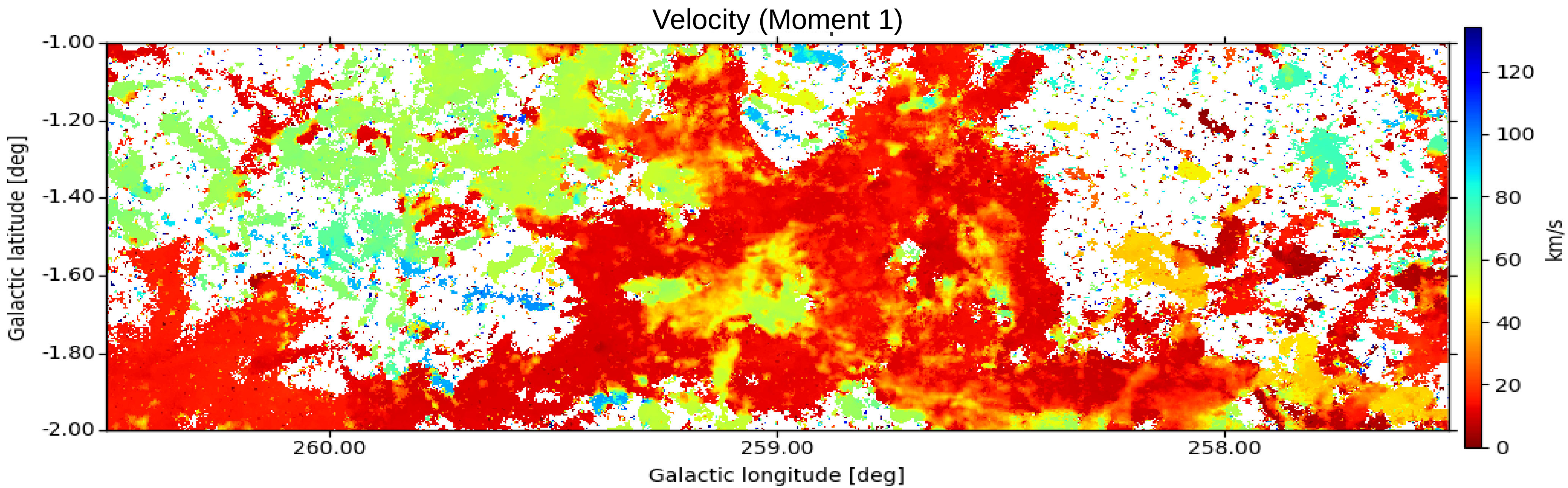
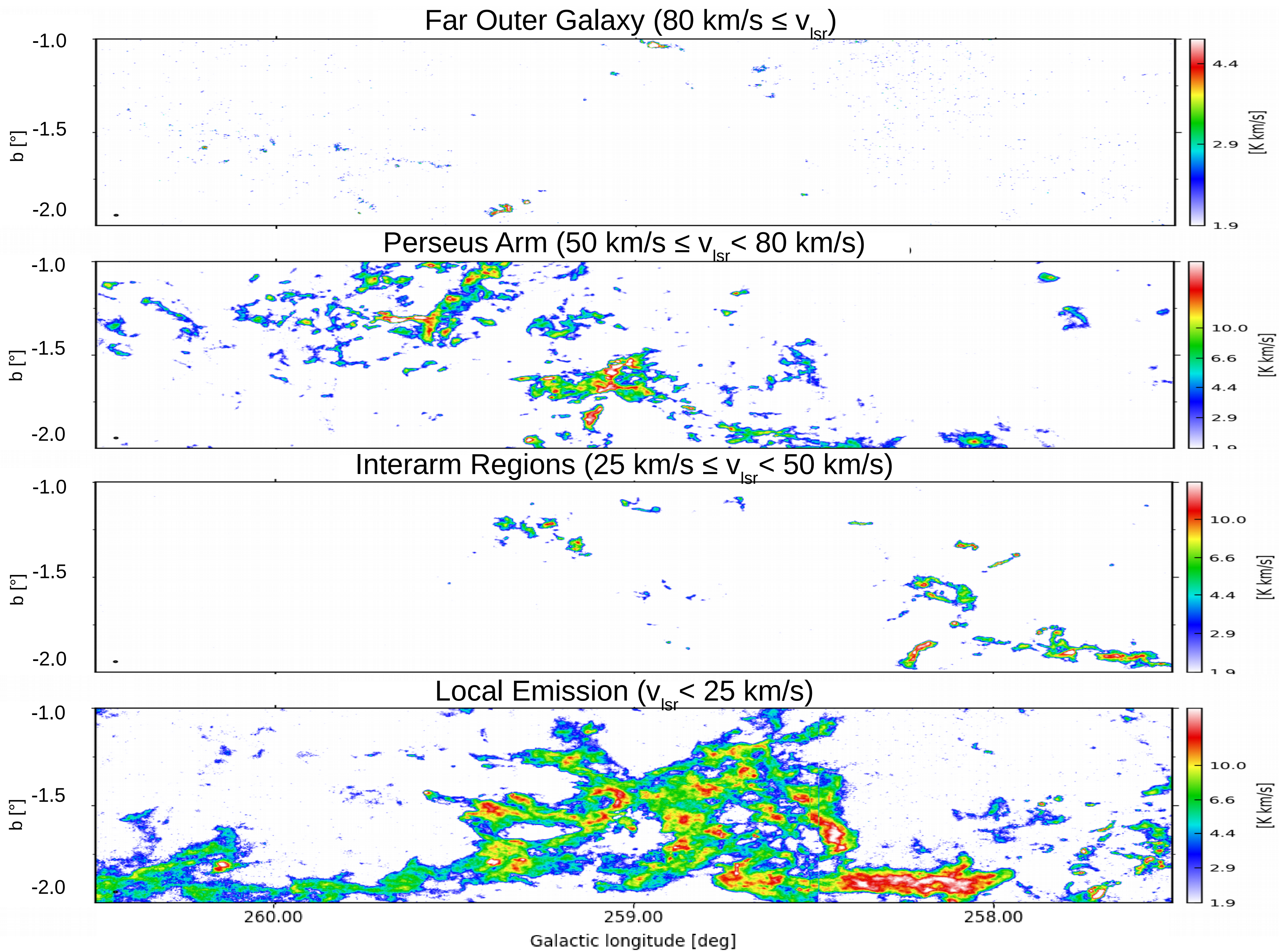


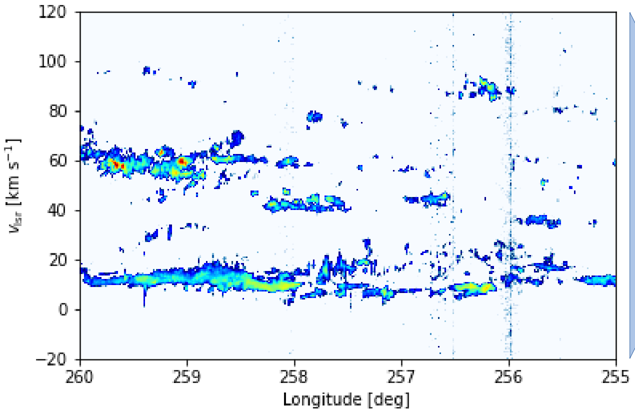



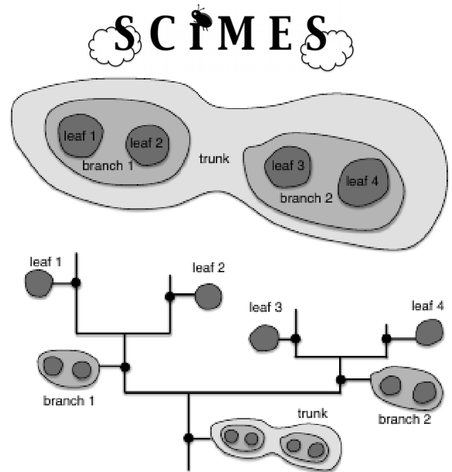
# Environments



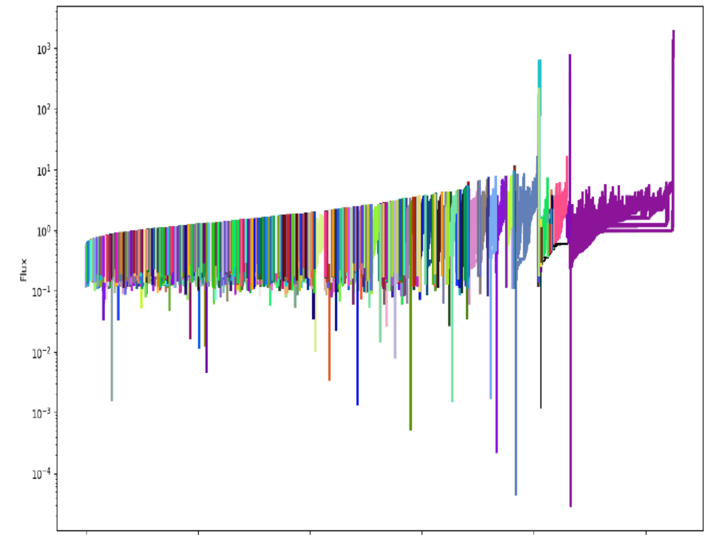
# Application: Hierarchical Spectral Clustering

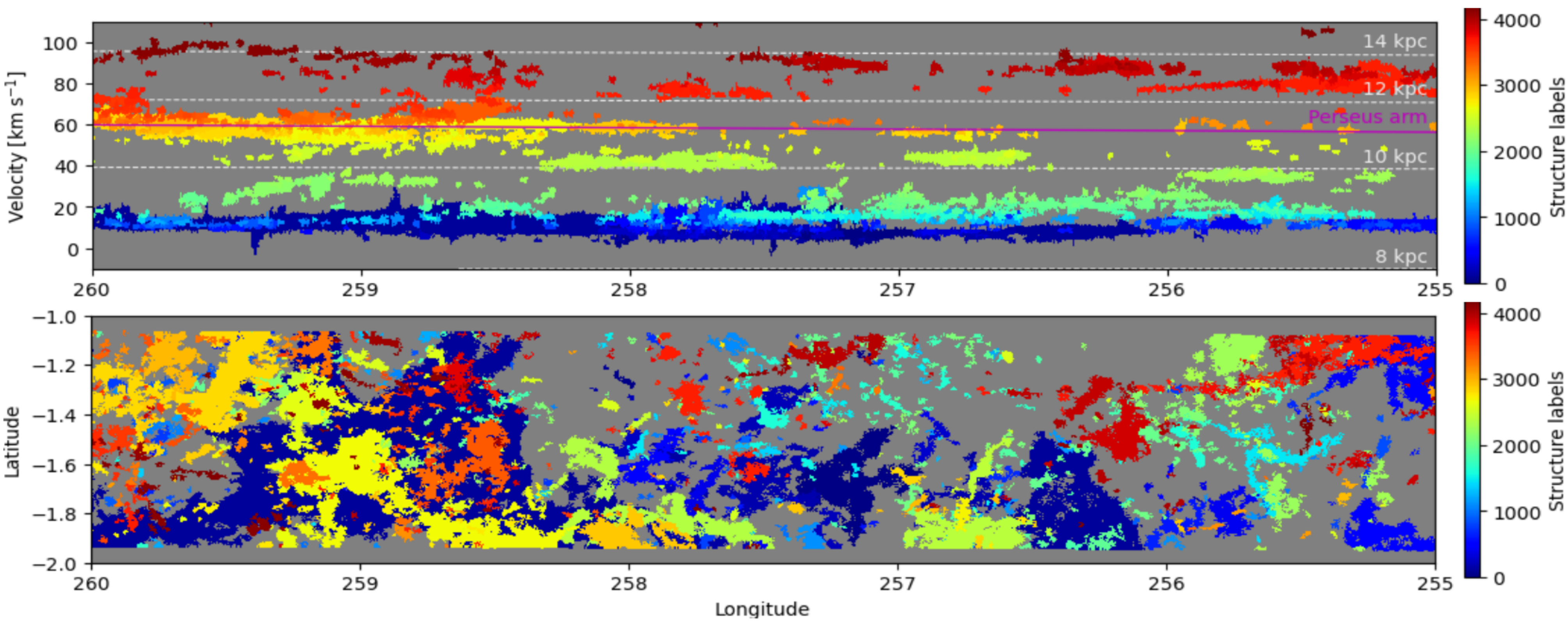

**Shruti Priya**
IIT Kharagpur, India
Internship Summer 2020


Colombo+ (2016)
https://scimes.readthedocs.io



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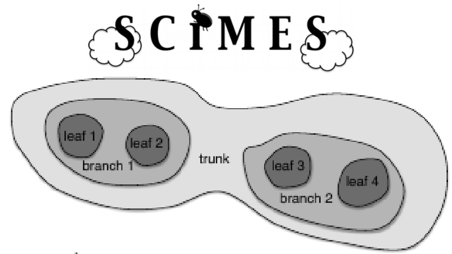
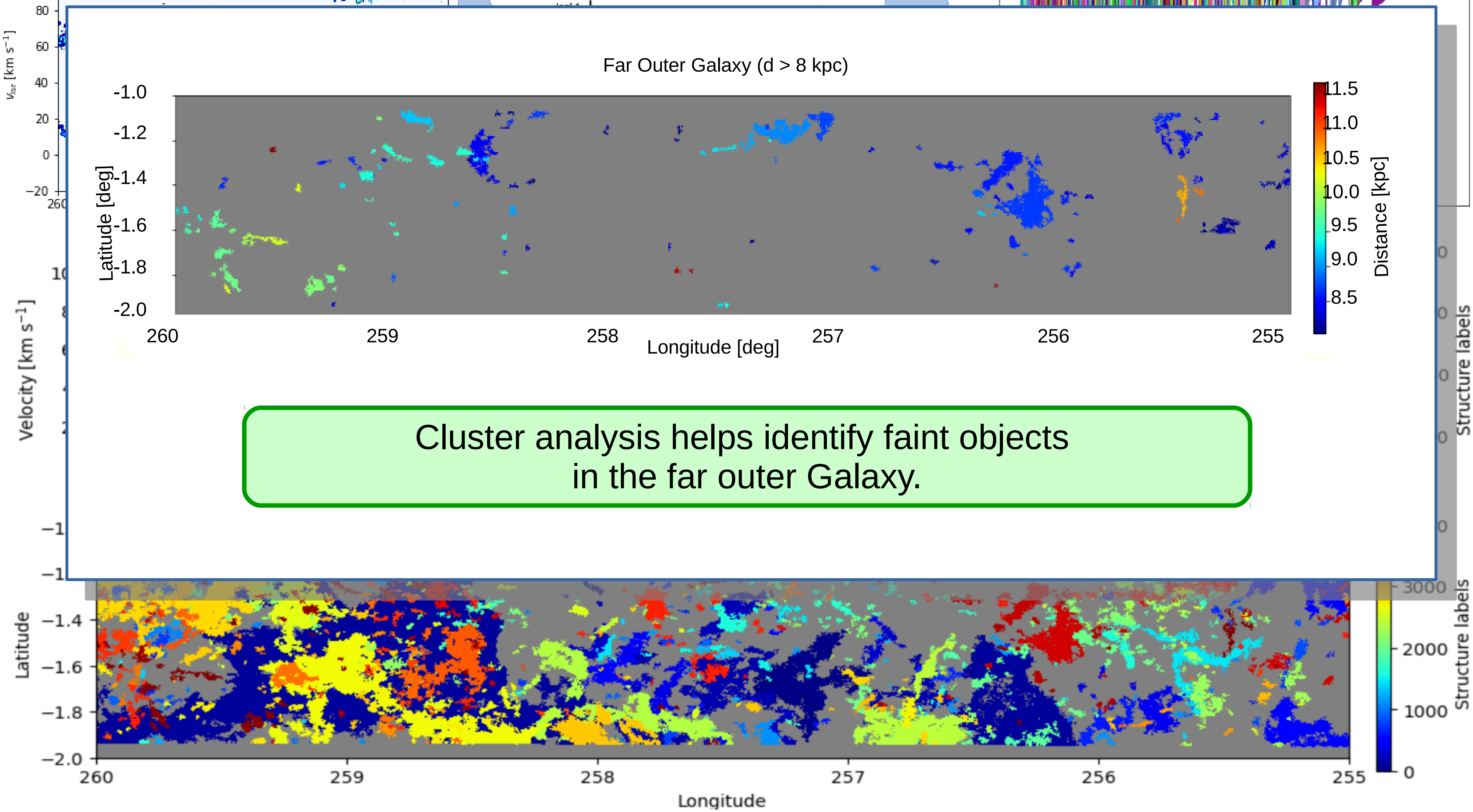



Cluster analysis helps identify faint objects
in the far outer Galaxy.

# Application: a Complete View of SF in Milky Way

**OGHReS**

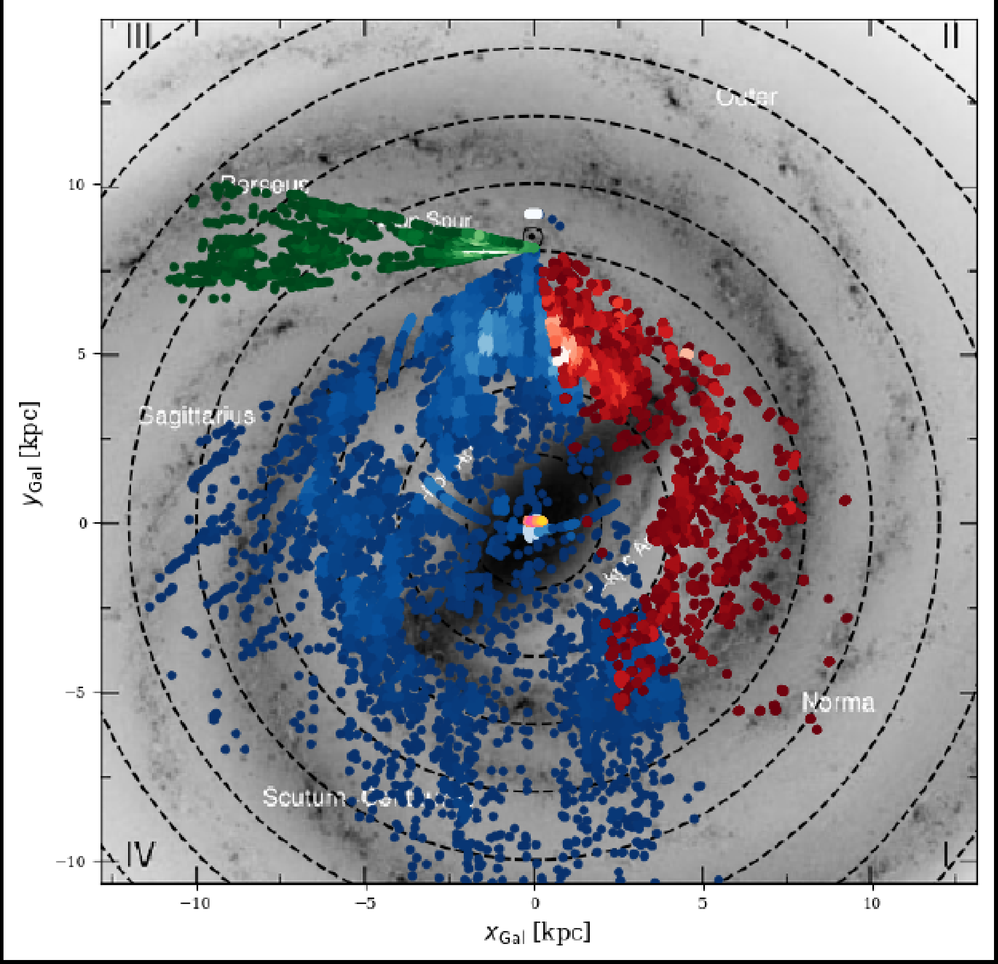
4405 well resolved objects

Colombo, König, Urquhart et al. in prep.

**COHRS**

35560 well resolved objects

Colombo, Rosolowsky, Duarte-Cabral et al. 2019




Duarte-Cabral, Colombo, Urquhart et al. in prep.

10663 well resolved objects

**SEDiGism**

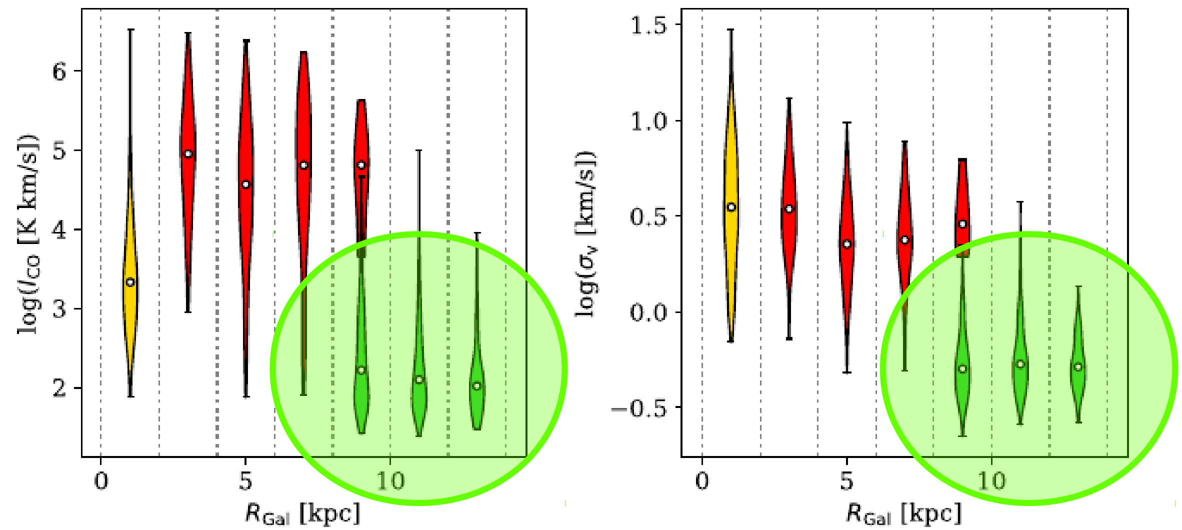
Riquelme, Colombo, Güsten et al. in prep.

4980 well resolved objects

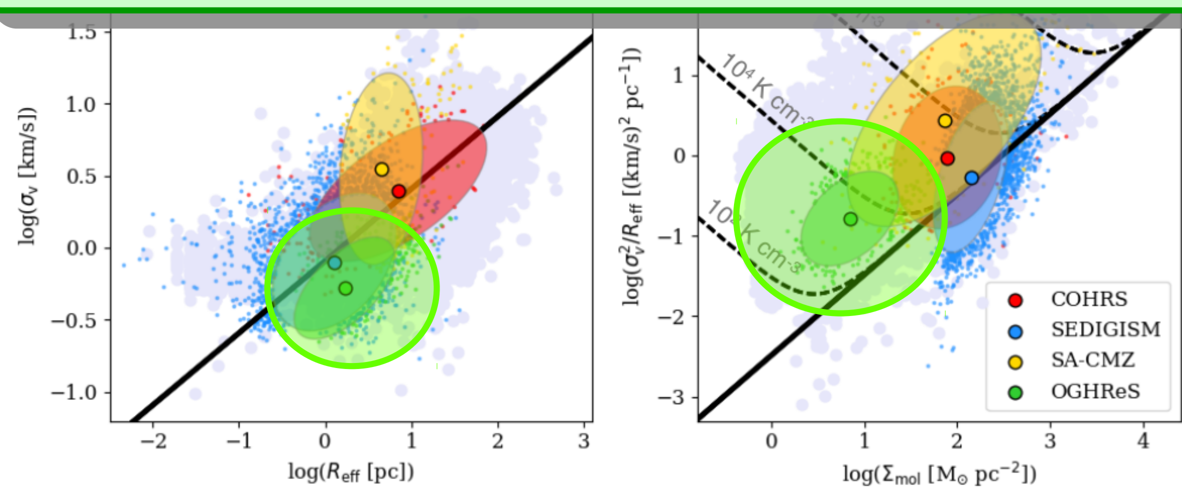
**SOFIA-APEX CMZ**

D. Colombo et al.

# Application: a Complete View of SF in Milky Way

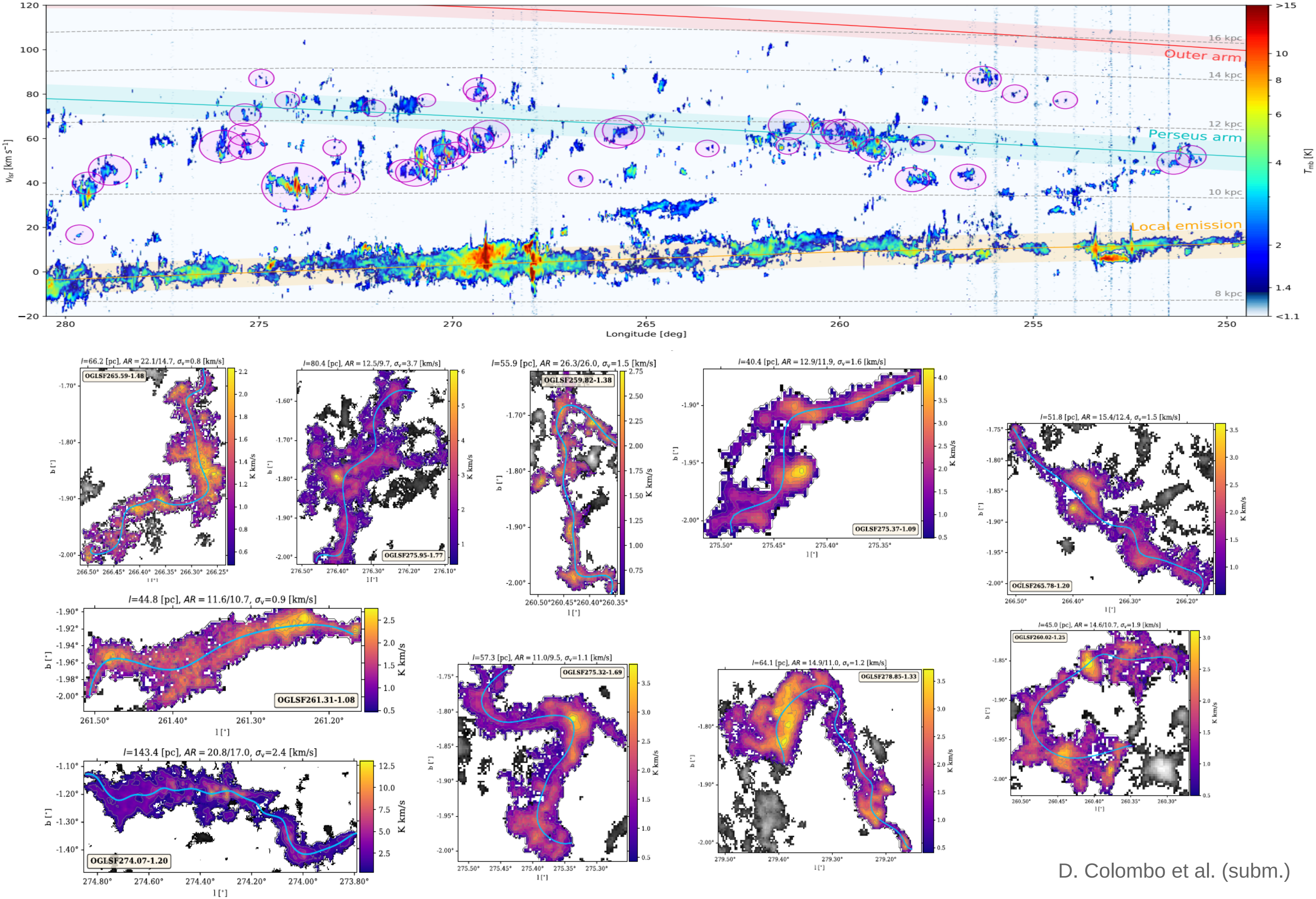



OGHReS occupies distinct part in parameter space.



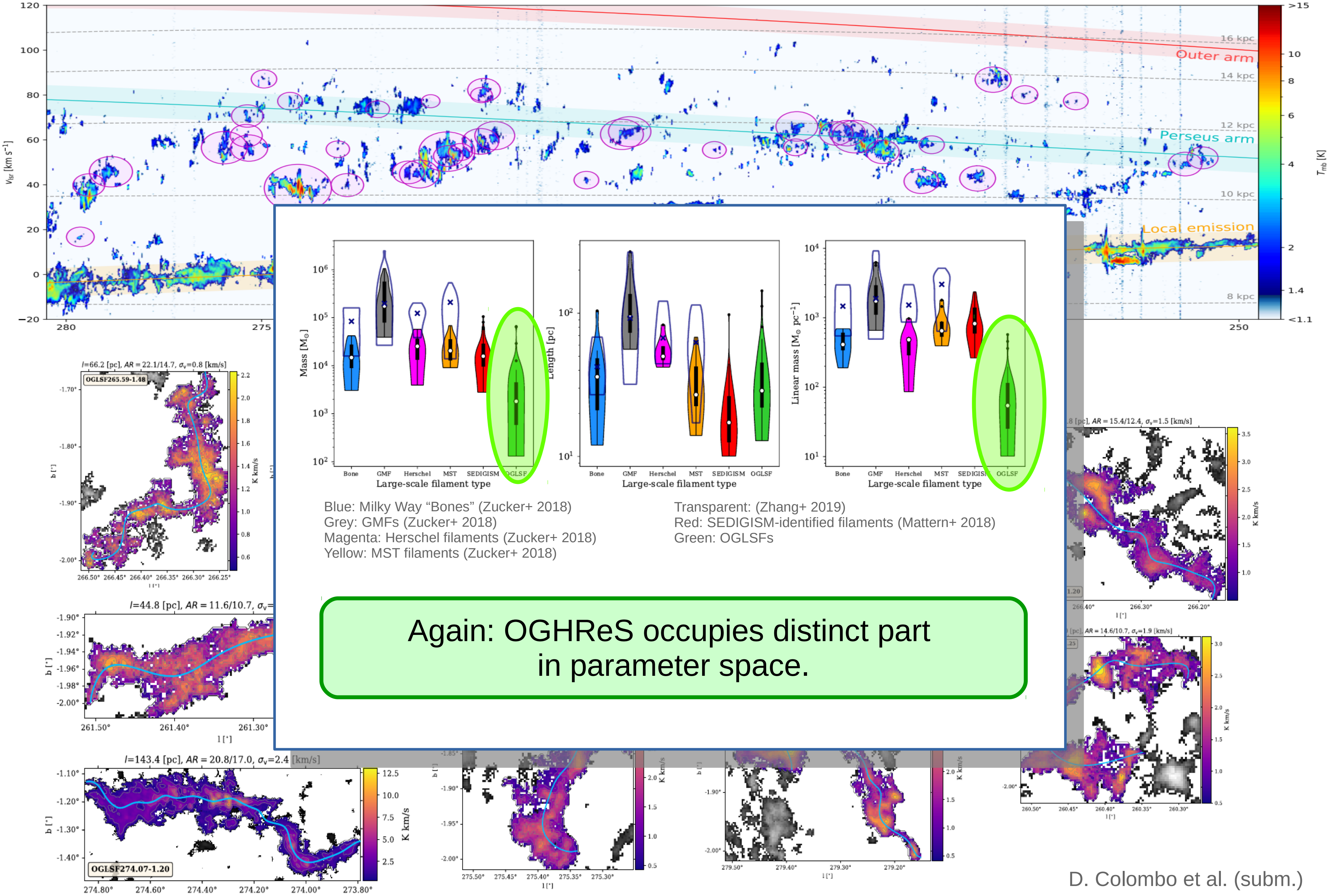

D. Colombo et al.

# Application: Filaments




D. Colombo et al. (subm.)

# Application: Filaments



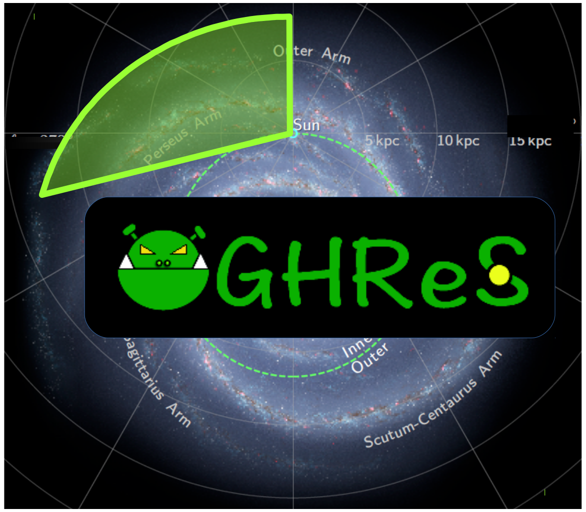

Blue: Milky Way "Bones" (Zucker+ 2018)
Grey: GMFs (Zucker+ 2018)
Magenta: Herschel filaments (Zucker+ 2018)
Yellow: MST filaments (Zucker+ 2018)

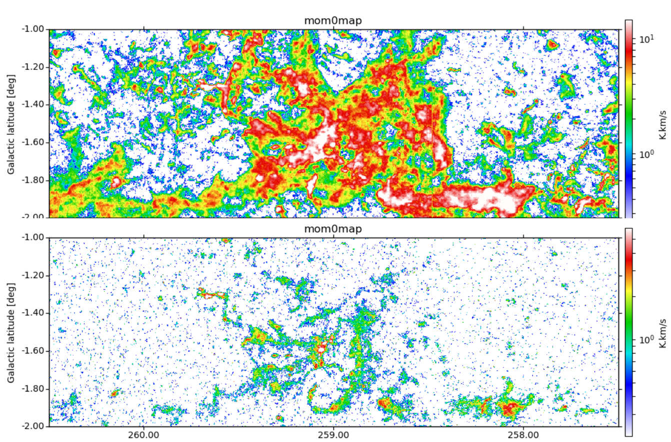
Transparent: (Zhang+ 2019)
Red: SEDIGISM-identified filaments (Mattern+ 2018)
Green: OGLSFs

**Again: OGHReS occupies distinct part in parameter space.**

D. Colombo et al. (subm.)

# Summary/Next Steps




- **Mapping 100 square degrees** in the Outer Galaxy (180° < ℓ < 280°, Δb = 1°)
  - 72/100 fields have been observed/started
- Main lines: **$^{12}CO(2\text{-}1)$, $^{13}CO(2\text{-}1)$, $C^{18}O(2\text{-}1)$**
- Average RMS noise **$\sigma_{RMS} \approx 0.15 \pm 0.04$ K** @ 0.5 km/s resolution
- Clever adaption to PWV improved data quality significantly using simple Python/APECS commands.
- Early science exploitation has started.

## Next Steps:

- Observe 180° < ℓ < 215° part.
- Identify sub-maps that need further integration.
- Calibrate data, taking into account CalSpecs.
- Re-add emission from off-positions where necessary.
- Introduction paper and first data release.