A New Perspective on Star Formation and Spiral Structure in Our Home Galaxy

EWASS 2019
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Lyon

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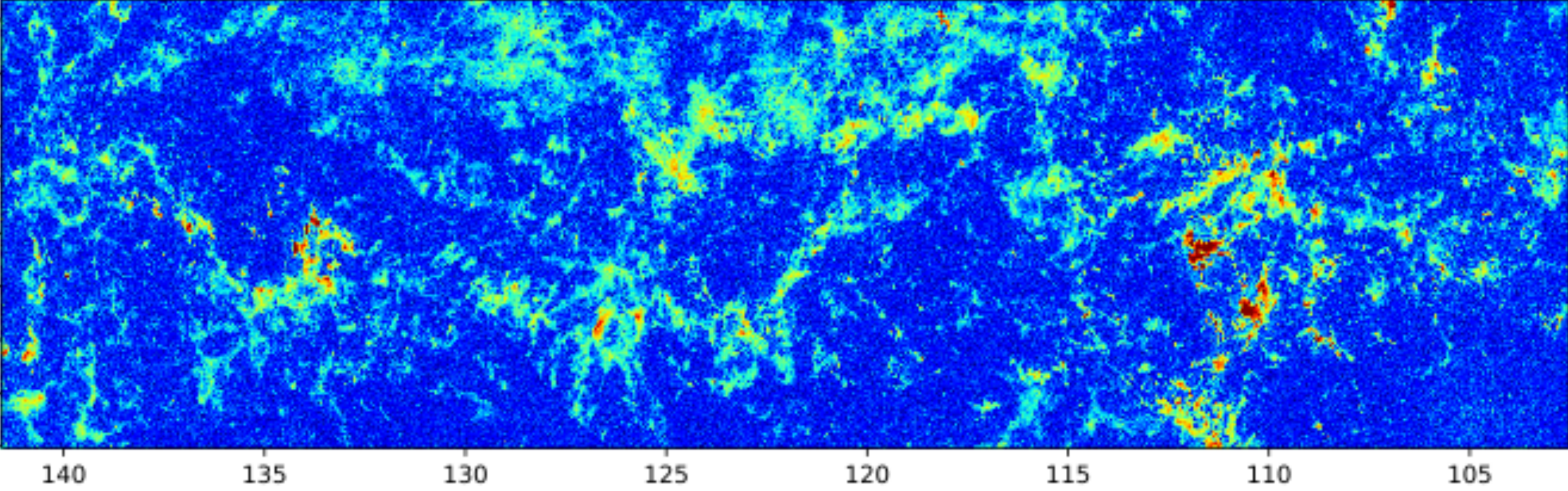
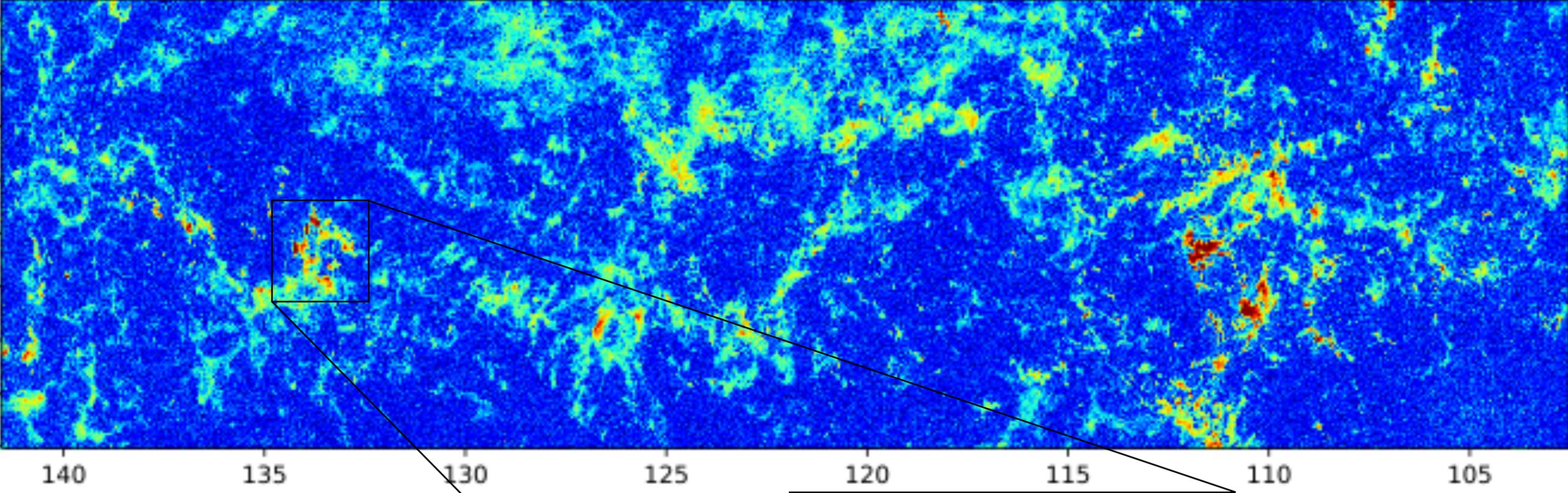
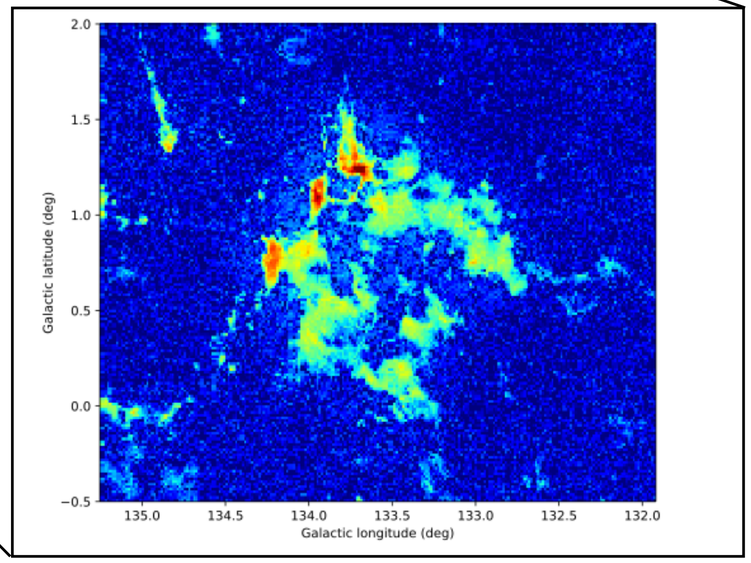
UNIVERSITY OF EXETER



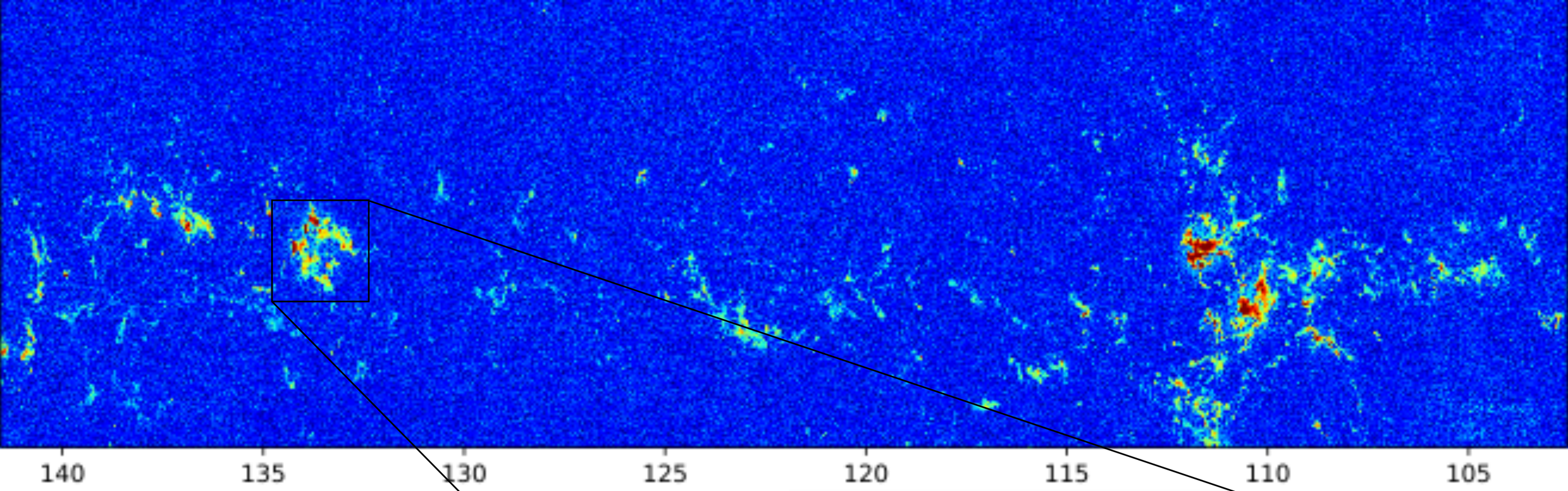
FCRAO CO (1-0) map,
longitude range of 35 deg



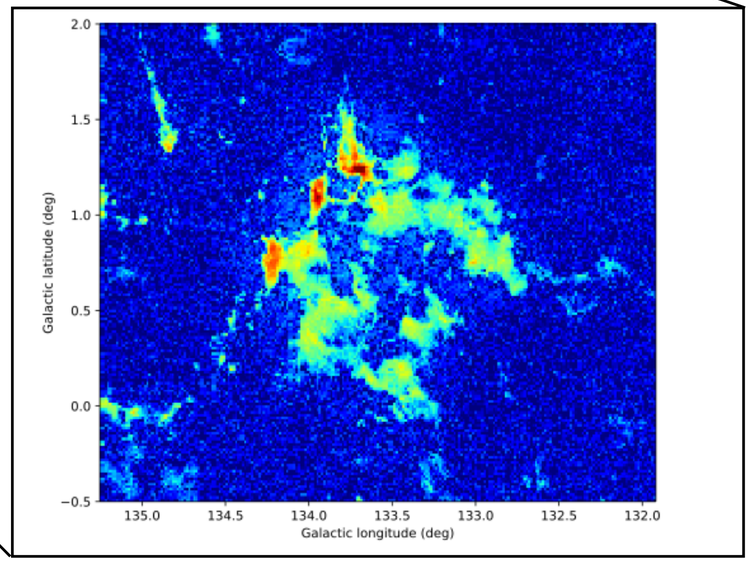
FCRAO CO (1-0) map,
longitude range of 35 deg



FCRAO CO (1-0) map of W3



FCRAO CO (1-0) map,
longitude range of 35 deg
(Perseus arm only)



FCRAO CO (1-0) map of W3

Outline

- Introduction:
  - Molecular clouds in the Milky Way and nearby spiral galaxies
- Observations:
  - ^{12}CO (1-0) in the outer Galaxy
- Mapping the Perseus arm at linear resolution:
  - Identification of the Perseus arm
  - Convolution of ^{12}CO data to fixed spatial resolution
- Large scale structure along the Perseus arm:
  - Angular vs linear scale maps
  - Arm length and height distribution
- Summary

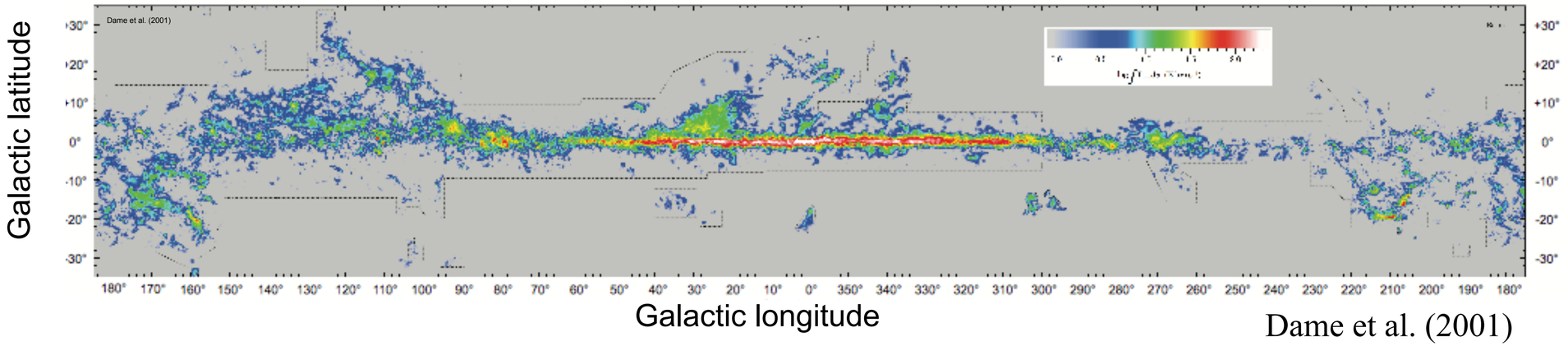
Molecular clouds

Optical image of the Milky Way

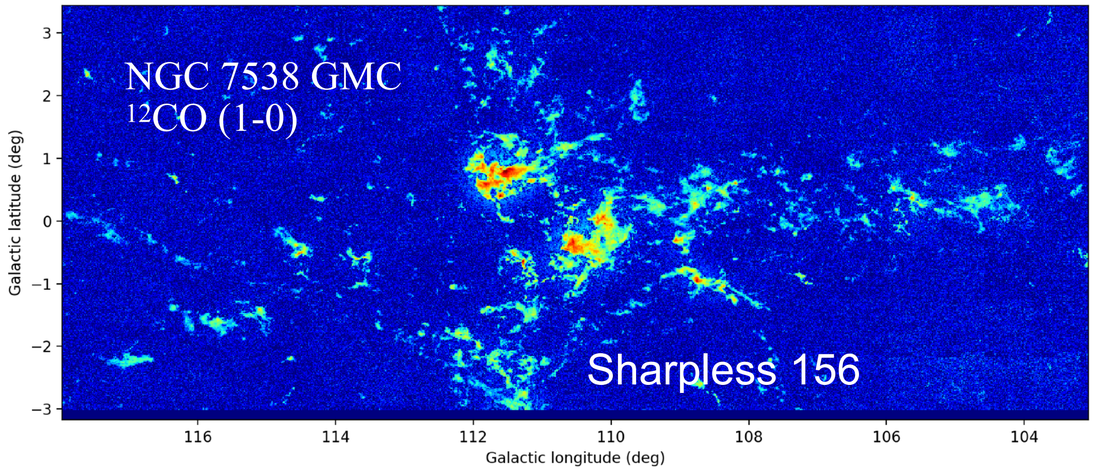
- Birthplaces in giant molecular clouds:
  - masses of 10^4 – $10^6 M_\odot$ and sizes of 50 -200 pc

Molecular clouds

Velocity-integrated CO map of the Milky Way



Dame et al. (2001)



- Birthplaces in giant molecular clouds:
  - masses of 10^4 – $10^6 M_\odot$ and sizes of 50 -200 pc

- ^{12}CO tracing GMC

Milky Way vs nearby spiral galaxies

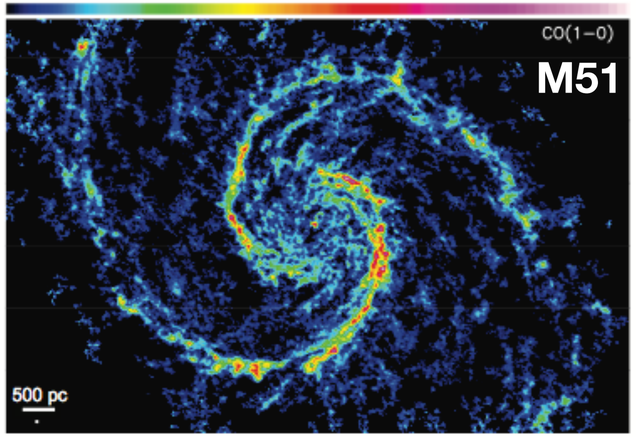
- PAWS: CO (1-0) maps of central 9 kpc of M51 observed by PdBI Arcsecond Whirlpool Survey (Schinnerer et al. 2013)

- Resolution of 20 - 40 pc enables identification of GMCs in external galaxies (e.g. Gratier et al. 2012: Donovan Meyer et al. 2013)

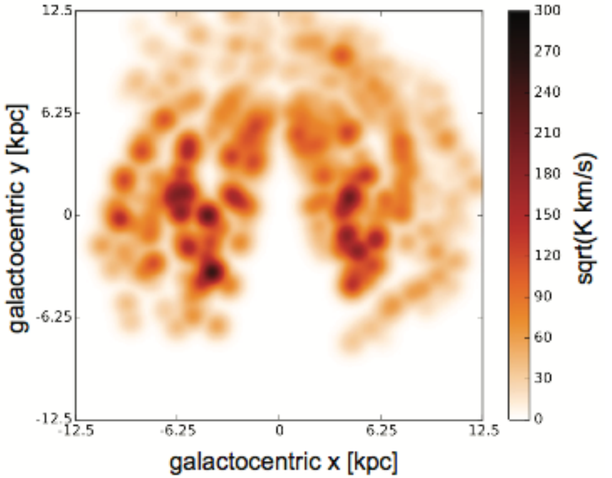
- Spiral arm structure derived in central part of nearby galaxies (Helfer et al. 2003; Schinnerer et al. 2013)

- Milky Way spiral structure kinematically derived from GMCs

- Poorer view than M51 because of the Milky Way's immediate proximity



(Schinnerer et al. 2013)



(Rice et al. 2016)

Milky Way vs nearby spiral galaxies

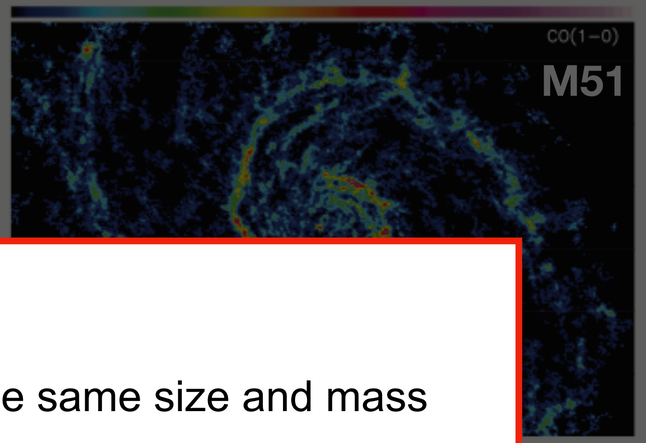
- PAWS: CO (1-0) maps of central 9 kpc of M51 observed by PdBI Arcsecond Whirlpool Survey (Schinnerer et al. 2013)

- Resoluti
  of GMCs
  2012: D

- Spiral ar
  nearby g
  et al. 20

- Milky W
  derived

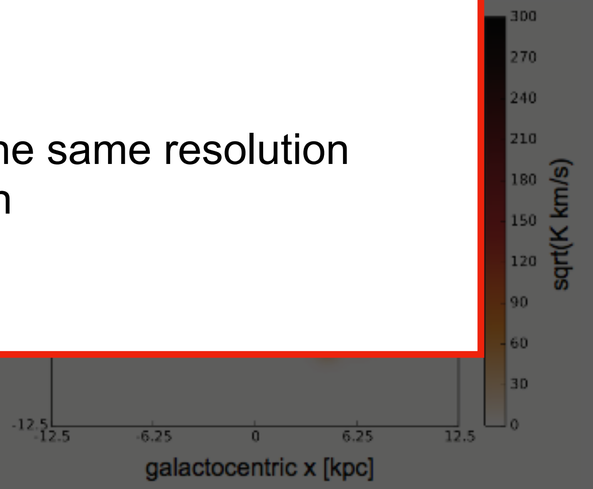
- Poorer
  Milky Way's immediate proximity



- Galactic/extragalactic comparison requires to be sensitive to the same size and mass scale
- How would our high resolution galactic GMCs appear if observed at extragalactic distances?

Goals:

- Provide a direct comparison between our and other galaxies at the same resolution
- Understand how degradation of resolution affects the comparison

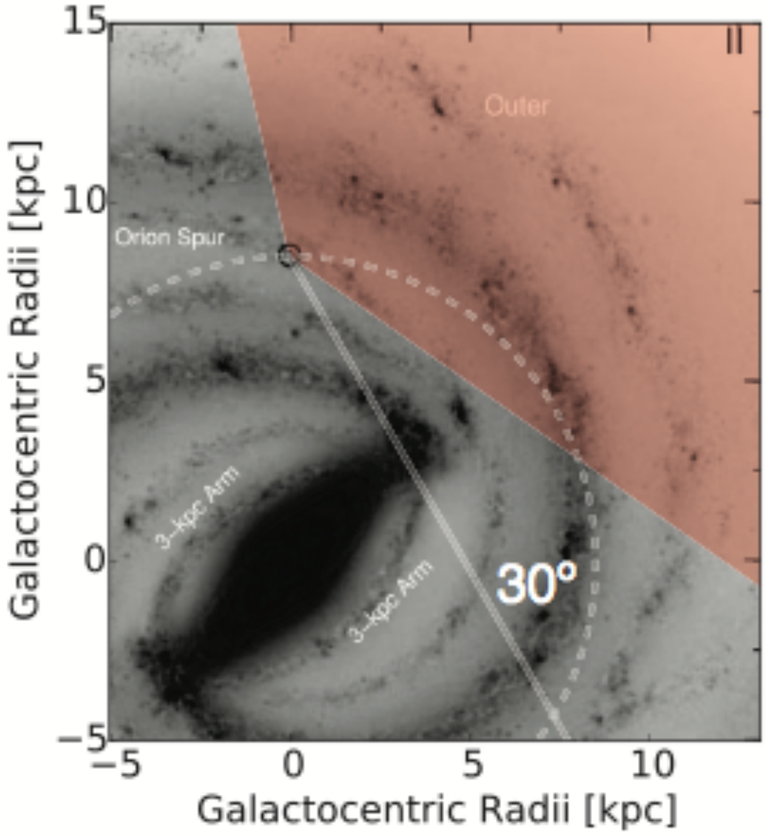


(Rice et al. 2016)

Milky Way - outer Perseus arm

- Kinematic distance ambiguity in the inner Galaxy
- Clean separation of spiral arms difficult
- Unique distance in the outer Galaxy

- **Exeter-FCRAO** (Five College Radio Astronomy Observatory) **^{12}CO survey** in the part of the Perseus Arm in the outer Galaxy of an order-of-magnitude improvement in angular resolution to Galaxy-wide CO survey by Dame et al. (2001)
- High resolution observations of intense CH_3OH and H_2O maser emission by BeSSeL survey (Reid et al. 2014)
- Available trigonomtric parallaxes and radial velocities combined with CO data for a precise distance-velocity maser calibration



Artist impression of Milky Way (R.Hurt)

Observations with the FCRAO telescope

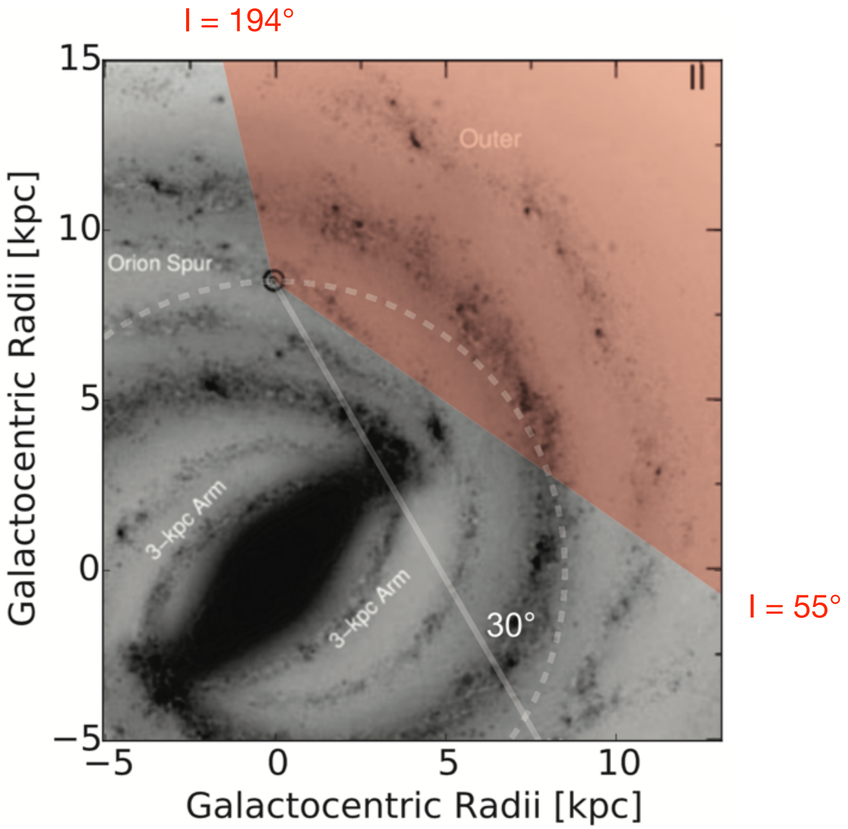
- Spectral line imaging of the ^{12}CO J = 1-0 line

- **FCRAO Outer Galaxy Survey**: l ~ 102° - 141° (Heyer et al. 1998)
- **Exeter Five College Survey**: l ~ 55° - 102°, 102° - 194° (Brunt in prep.)

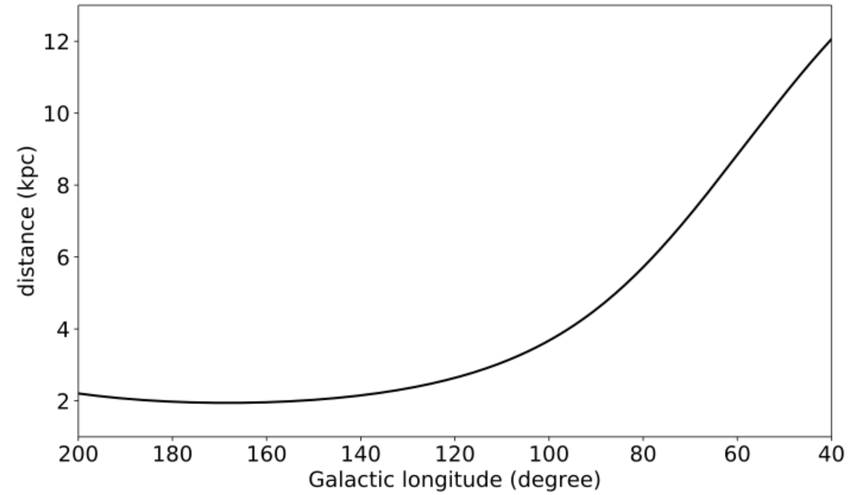
	Parameter
coordinate range	l = 55°–194°, b = -3° - 5.4°
beamwidth at 115 GHz	45”
beamsize at ~9 kpc	2 pc
integration time	10 s
observing mode	position switching/OTF
sampling	every 50”/22.5”
velocity resolution	0.98/0.13 km/s
number of spectra	15 x 10^6

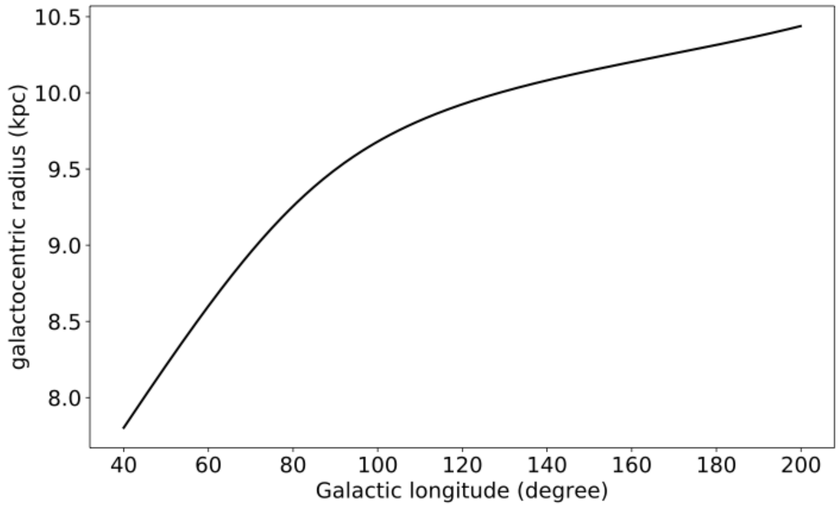
FCRAO 14 m telescope

Location of the outer Perseus arm in the Milky Way



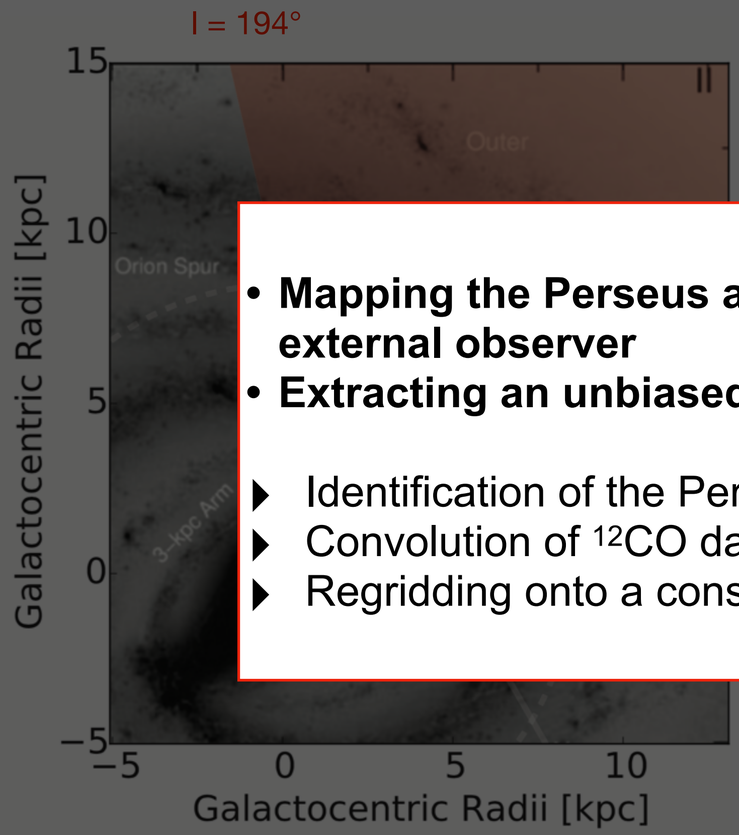
- Wide range of distances (~ 2 - 11 kpc)
- Various spatial resolutions (~ 0.5 - 3 pc) along the whole Perseus arm





Based on model for the rotation curve of the Milky Way from Reid et al. (2014)

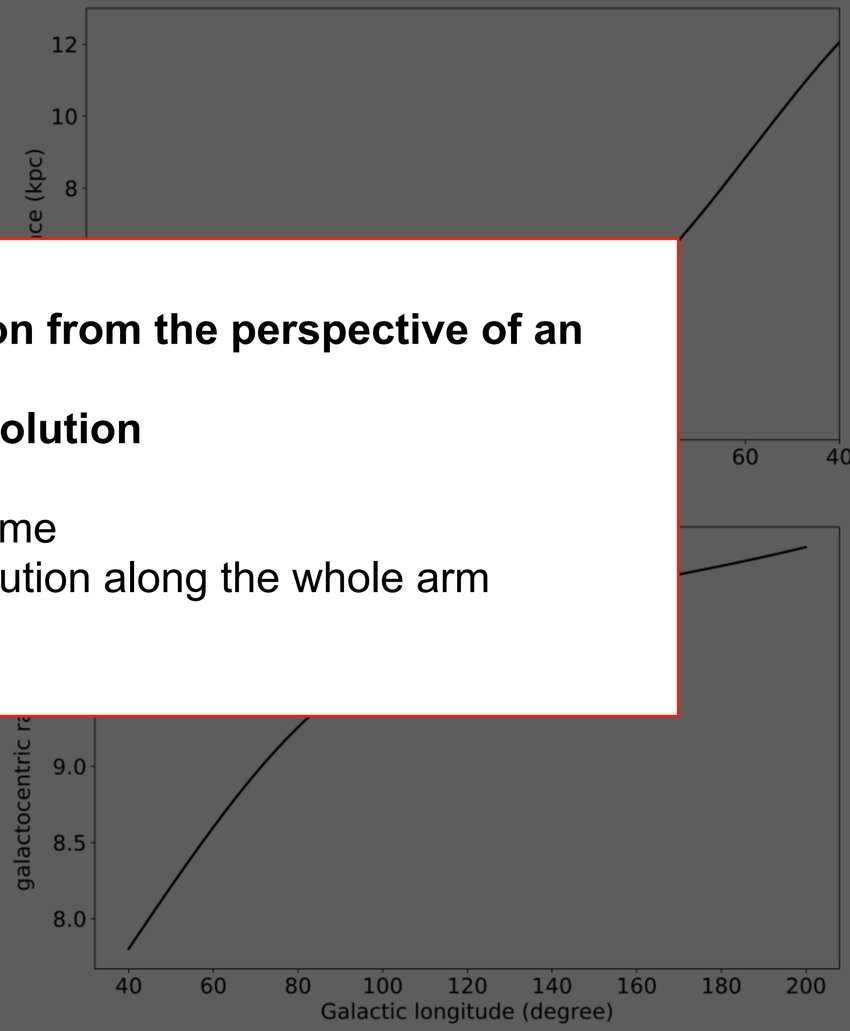
Location of the outer Perseus arm in the Milky Way



- **Mapping the Perseus arm at a common resolution from the perspective of an external observer**
- **Extracting an unbiased GMC sample at fixed resolution**

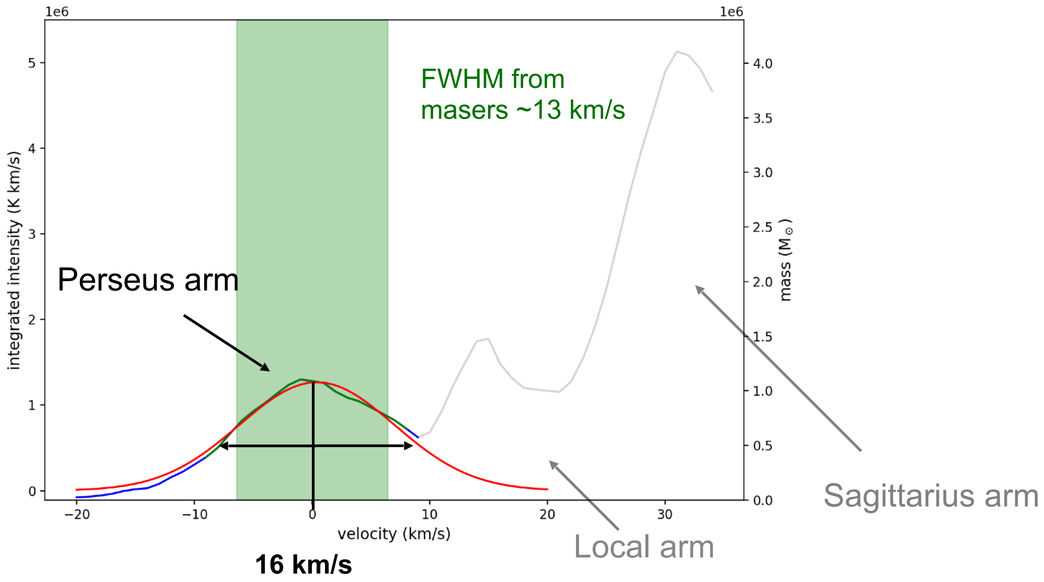
- Identification of the Perseus arm kinematic rest frame
- Convolution of ^{12}CO data to the same spatial resolution along the whole arm
- Regridding onto a constant linear scale map

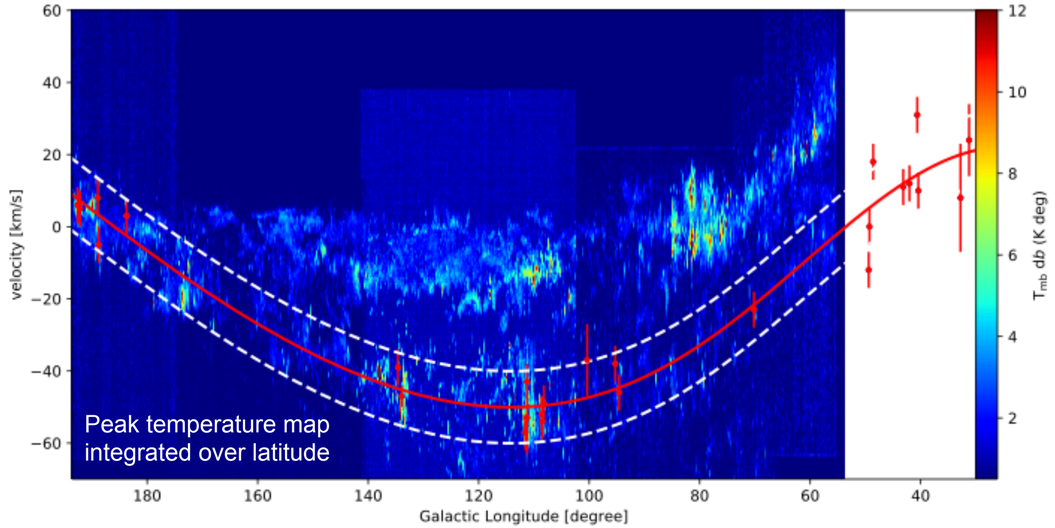
- Wide range of distances (~ 2 - 11 kpc)
- Various spatial resolutions (~ 0.5 - 3 pc) along the whole Perseus arm



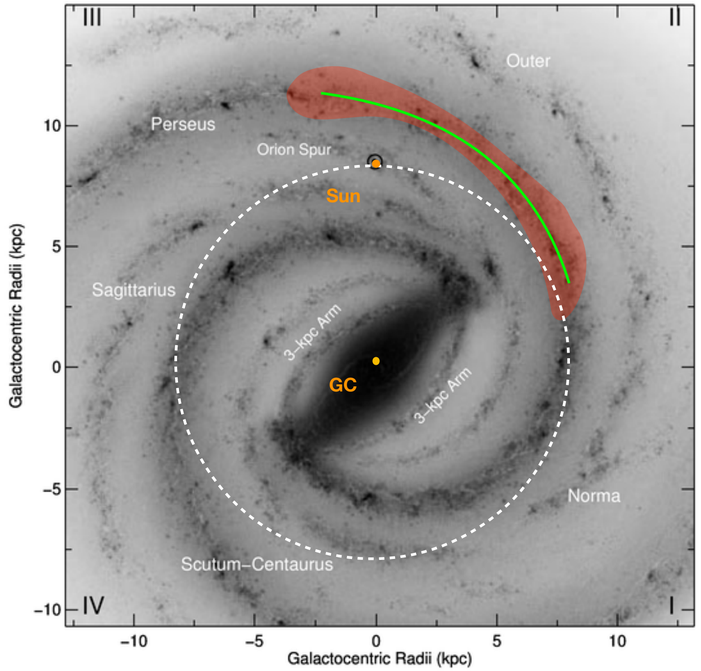
Based on model for the rotation curve of the Milky Way from Reid et al. (2014)

Identification of the Perseus arm

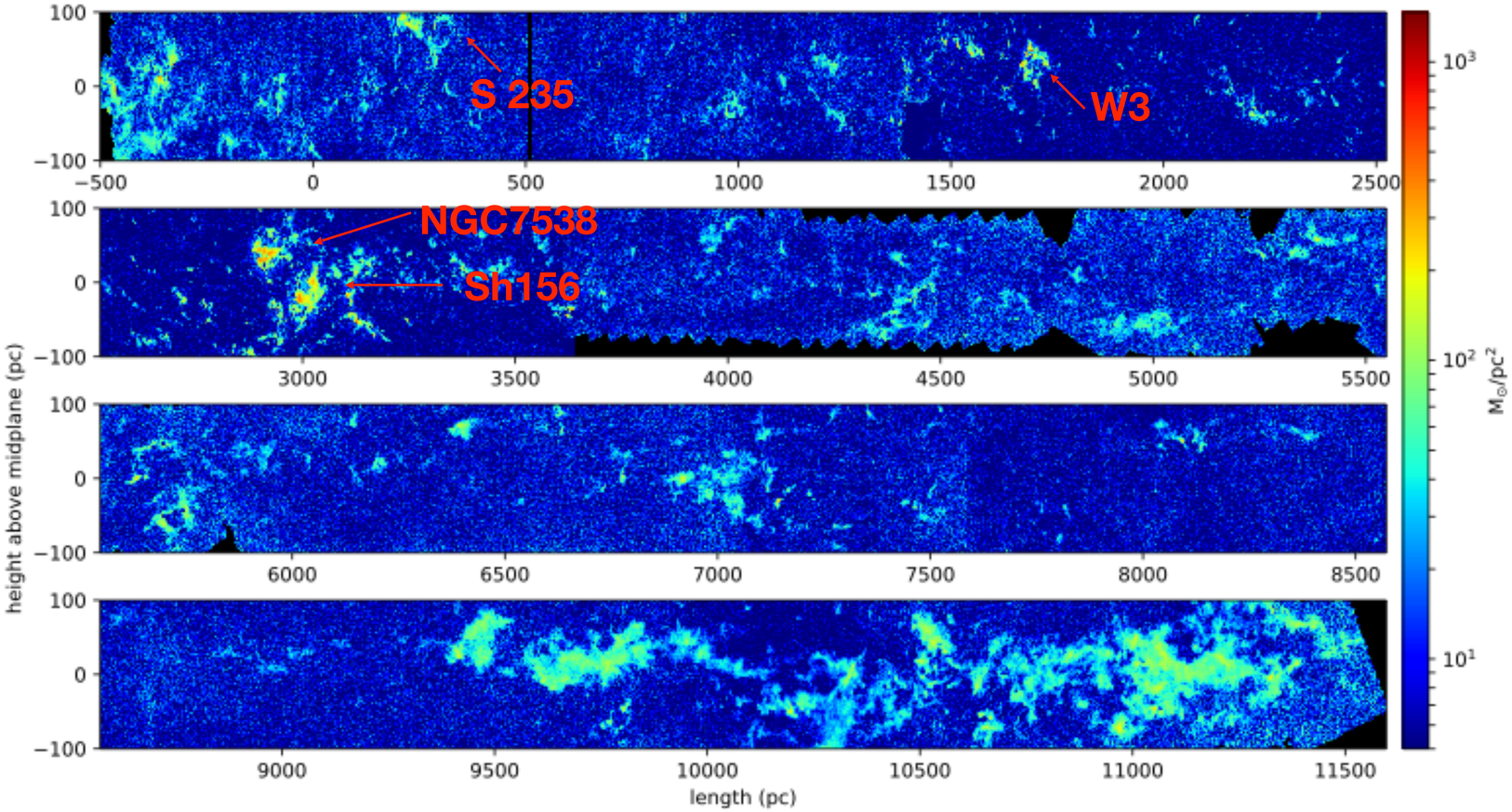




- Gaussian fit to the velocity distribution:
  velocity window from FWHM of +/- 8 km/s

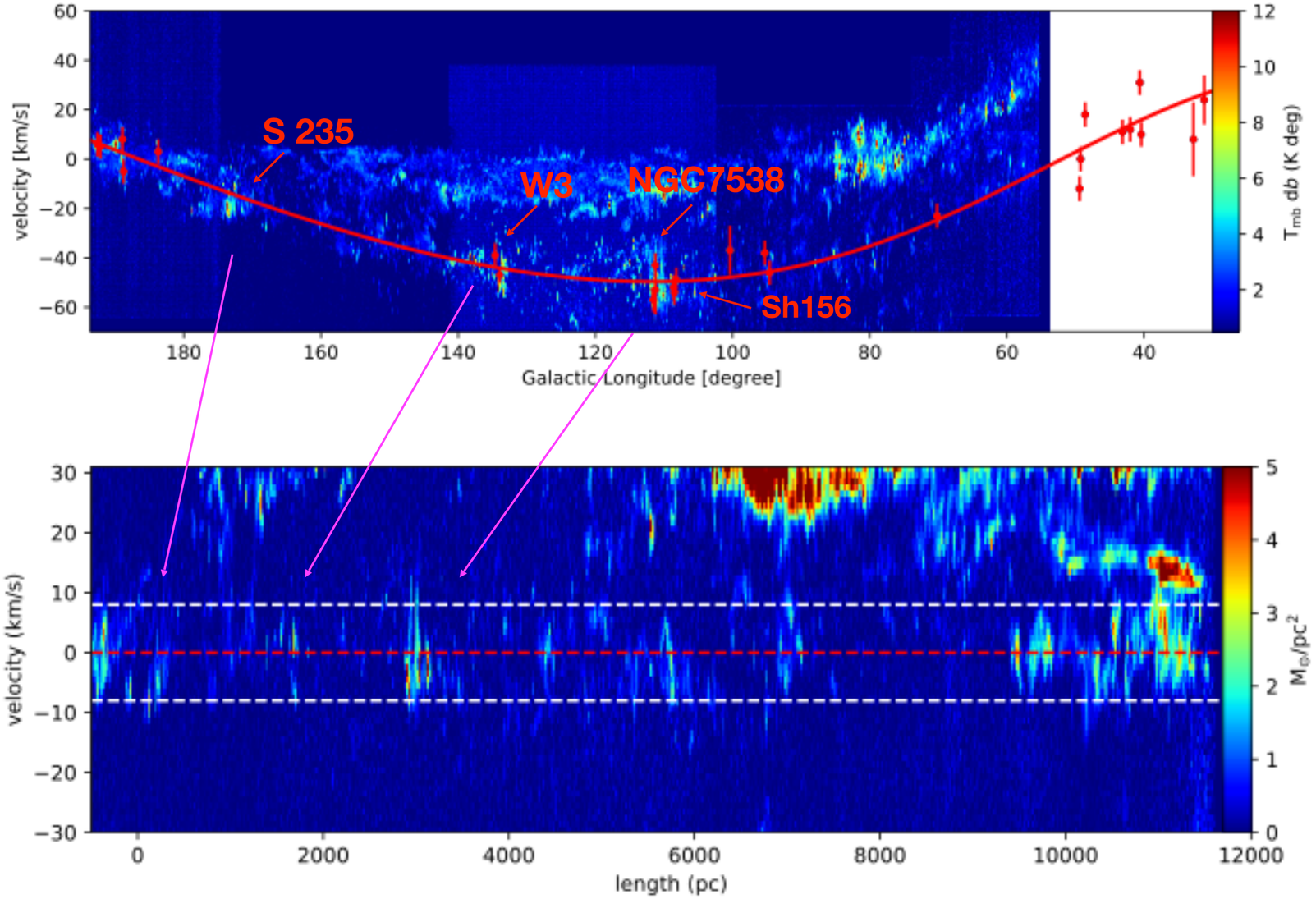


Linear mass surface density map

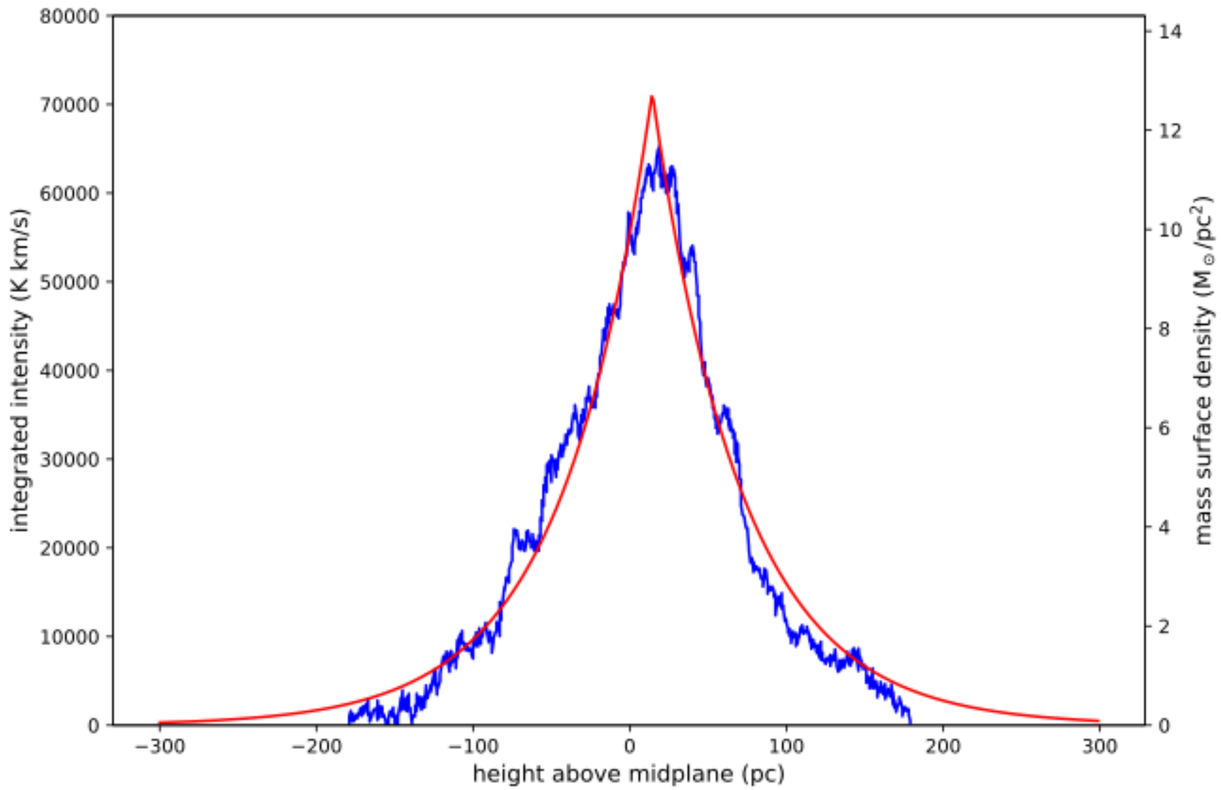


- **Constant linear scale 3D data cubes with**
  - **length along the Perseus arm (reference point at 180°)**
  - **displacement from the Galactic midplane**
  - **velocity difference to the kinematic arm centre**

Longitude/Length - velocity map

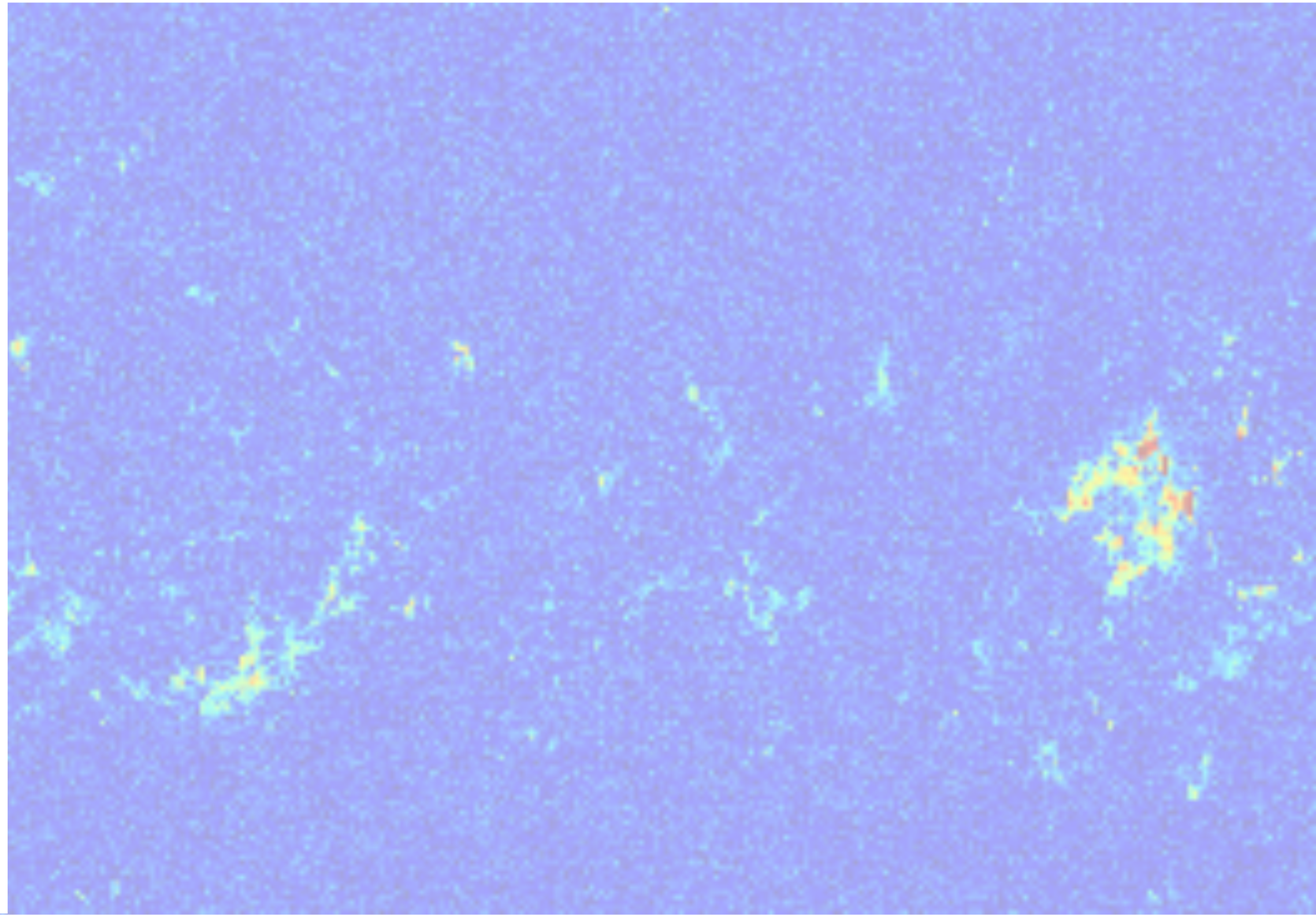


Height distribution



- scale height of 73 pc from ^{12}CO
- similar to the scale height of ~ 76 pc of the inner galactic disc (Malhotra et al. 1994) and between ~ 77 – 100 pc of the outer galactic disc (Wouterloot et al. 1990) using CO

Summary



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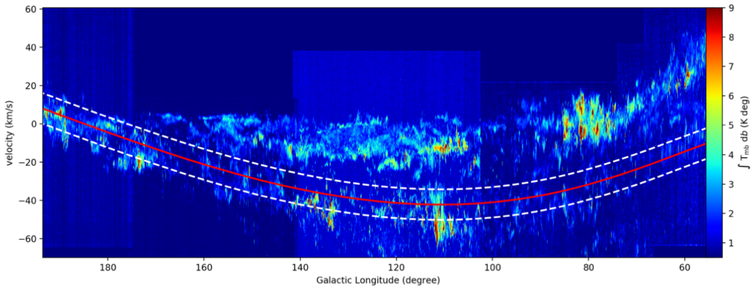
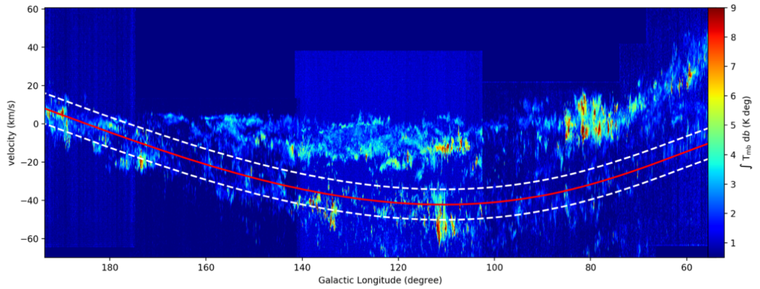
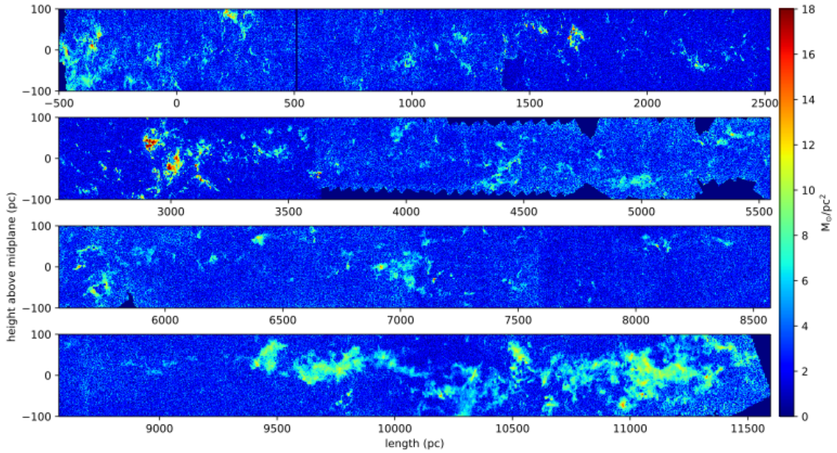


- **Identification of the Perseus arm based on maser parallaxes**

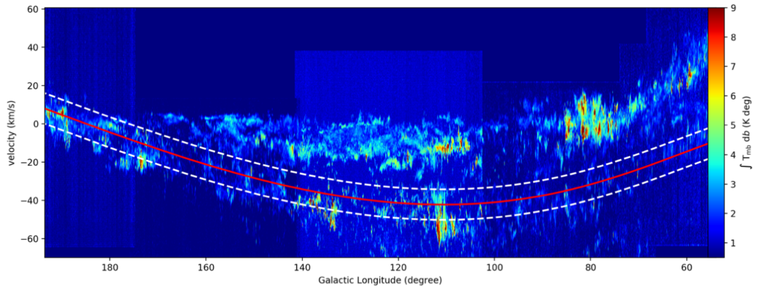
Summary

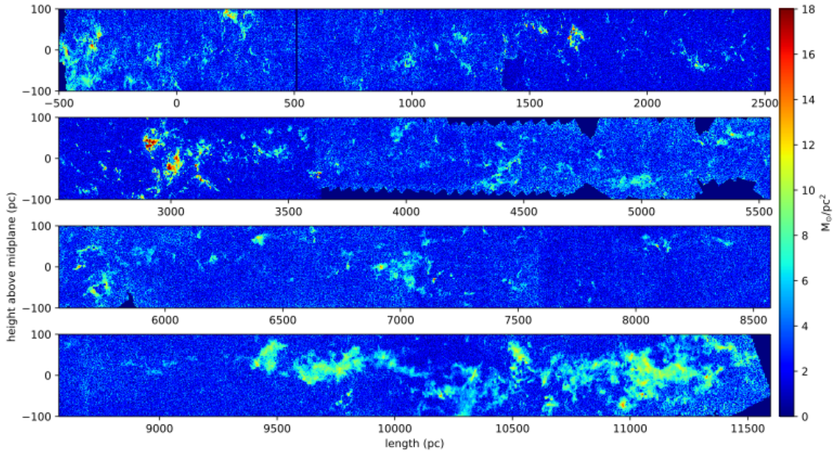


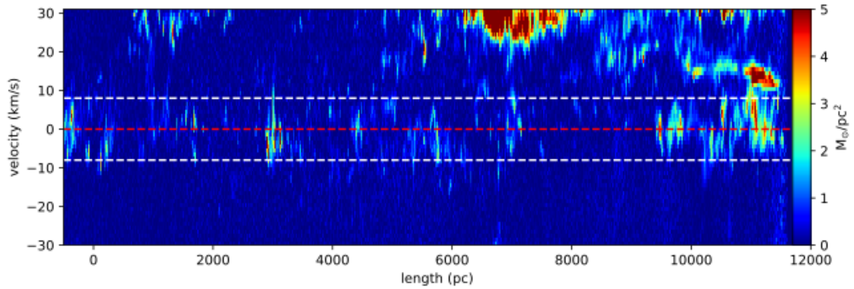


- **Identification of the Perseus arm based on maser parallaxes**
- **Linear scale 3D data cubes at fixed resolution**

Summary

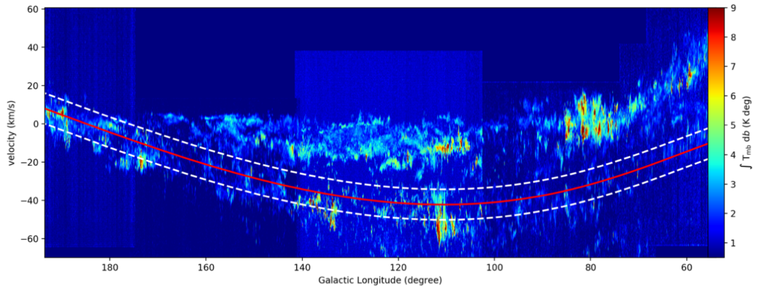


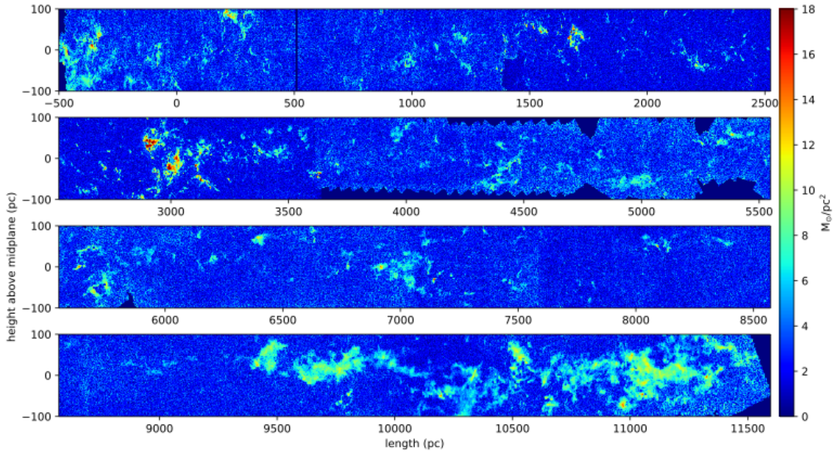


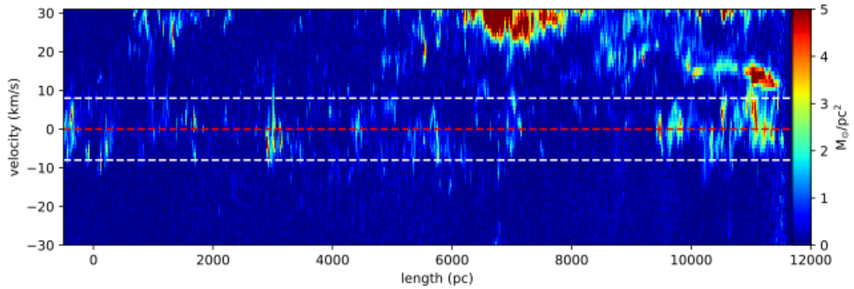


- **Identification of the Perseus arm based on maser parallaxes**
- **Linear scale 3D data cubes at fixed resolution**
- **Large scale studies:**
  Length along the arm vs velocity

Summary

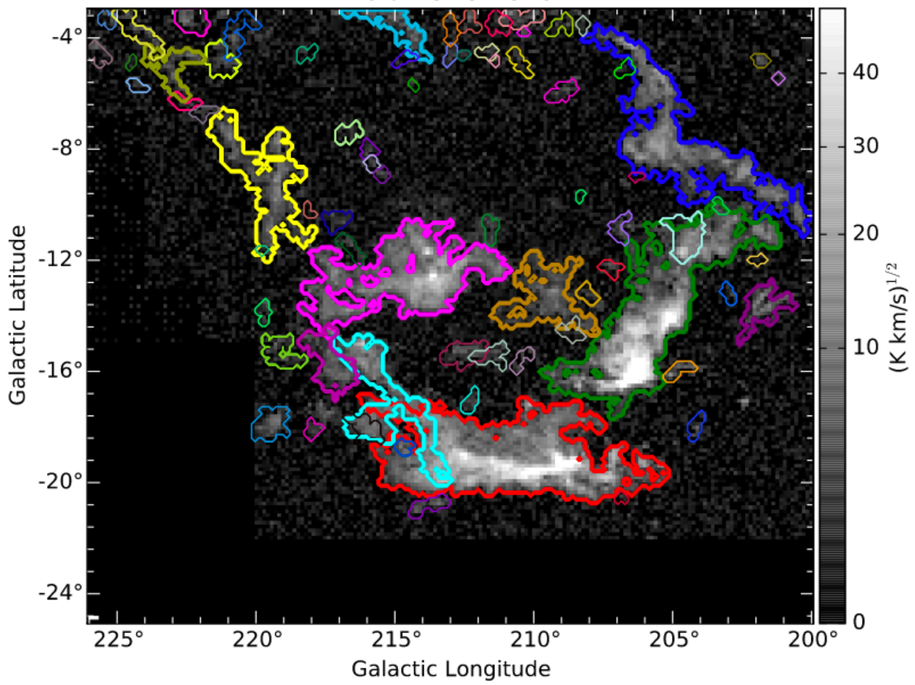






- **Identification of the Perseus arm based on maser parallaxes**
- **Linear scale 3D data cubes at fixed resolution**
- **Large scale studies: Length along the arm vs velocity**
- **Publish CO data cube**

Outlook



Orion-Monoceros complex from Colombo et al. (2015)

- **Cloud decomposition using cloud finding algorithm (SCIMES)**
  - Publish cloud catalogue
- **Statistical study of cloud properties, e.g. velocities, line widths, radii**
- **Trends along the arm length, height and velocity:**
  - H_2 mass surface density → H_2-to-HI mass surface density ratio cube
  - clump and cloud mass → clump formation efficiency
  - FIR luminosity → star formation rate
- **Comparison of cloud properties in the outer and inner Galaxy**, e.g. samples from Galactic Ring survey (Roman-Duval et al. 2010) and COHRS (Colombo et al. 2019)

Outlook

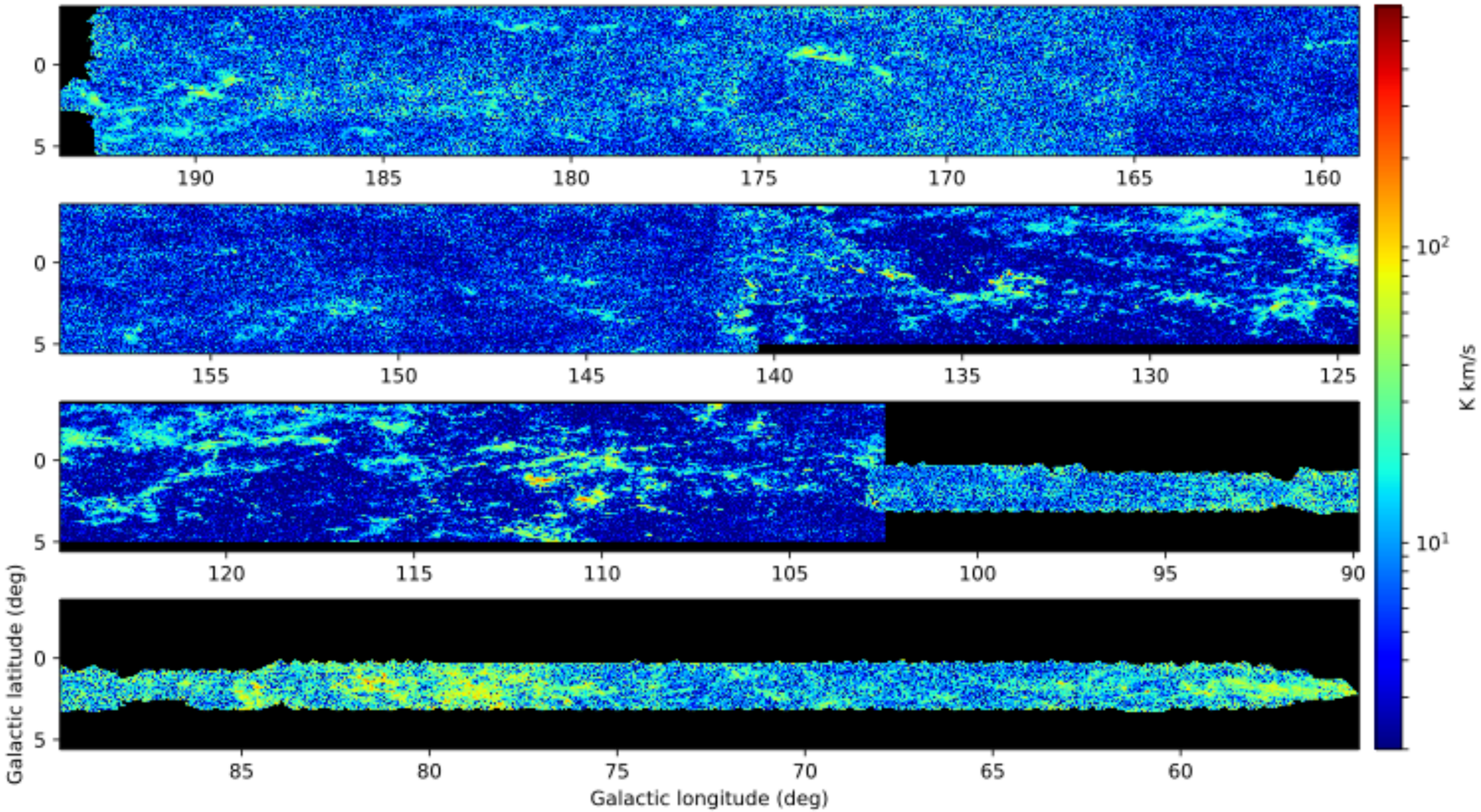
Comparison to extragalactic observations

- **Physical properties**: GMC line widths, velocity dispersions (Donovan Meyer et al. 2013, Hughes et al. 2013, Colombo et al. 2014), sizes, molecular gas masses, virial masses, H_2 mass surface densities (Hughes et al. 2013)
- **Star formation activity in galactic/extragalactic spiral arms**
  - Virial mass vs FIR luminosity
- **Turbulence and environmental pressure**
  - Scaling parameter vs H_2 mass surface density
- **Dynamical state**
  - Size vs line width

Set into context with models:

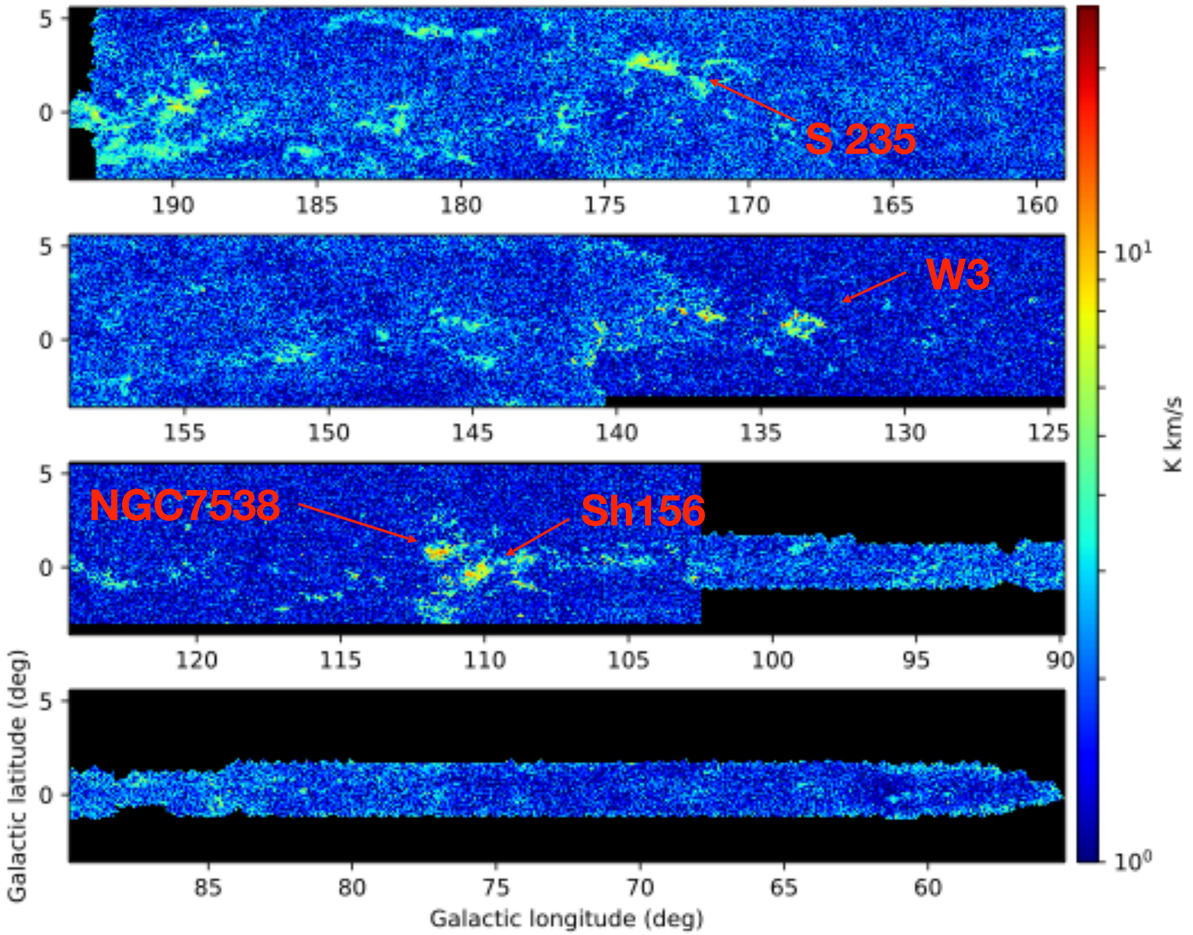
- Simulated observations that can produce CO and HI maps (Duarte-Cabral & Dobbs 2016, cf. Dobbs et al. 2019)
- Simulated spiral arms in nearby galaxies (Dobbs et al. 2018):
  - Trends of physical properties with galactocentric radius

Observed ^{12}CO (1-0) maps



- CO (1-0) velocity integrated intensity map
- Large span of ~ 12 kpc of the Perseus arm observed

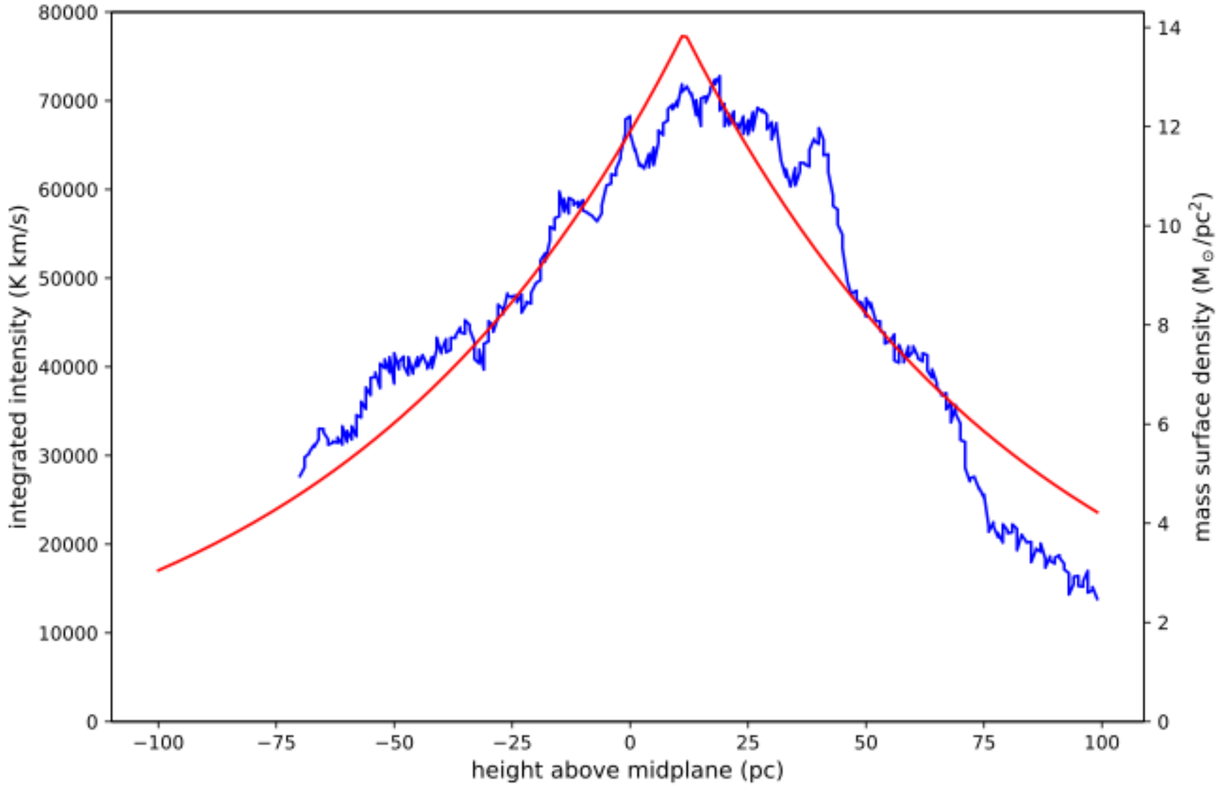
Integrated ^{12}CO intensity map



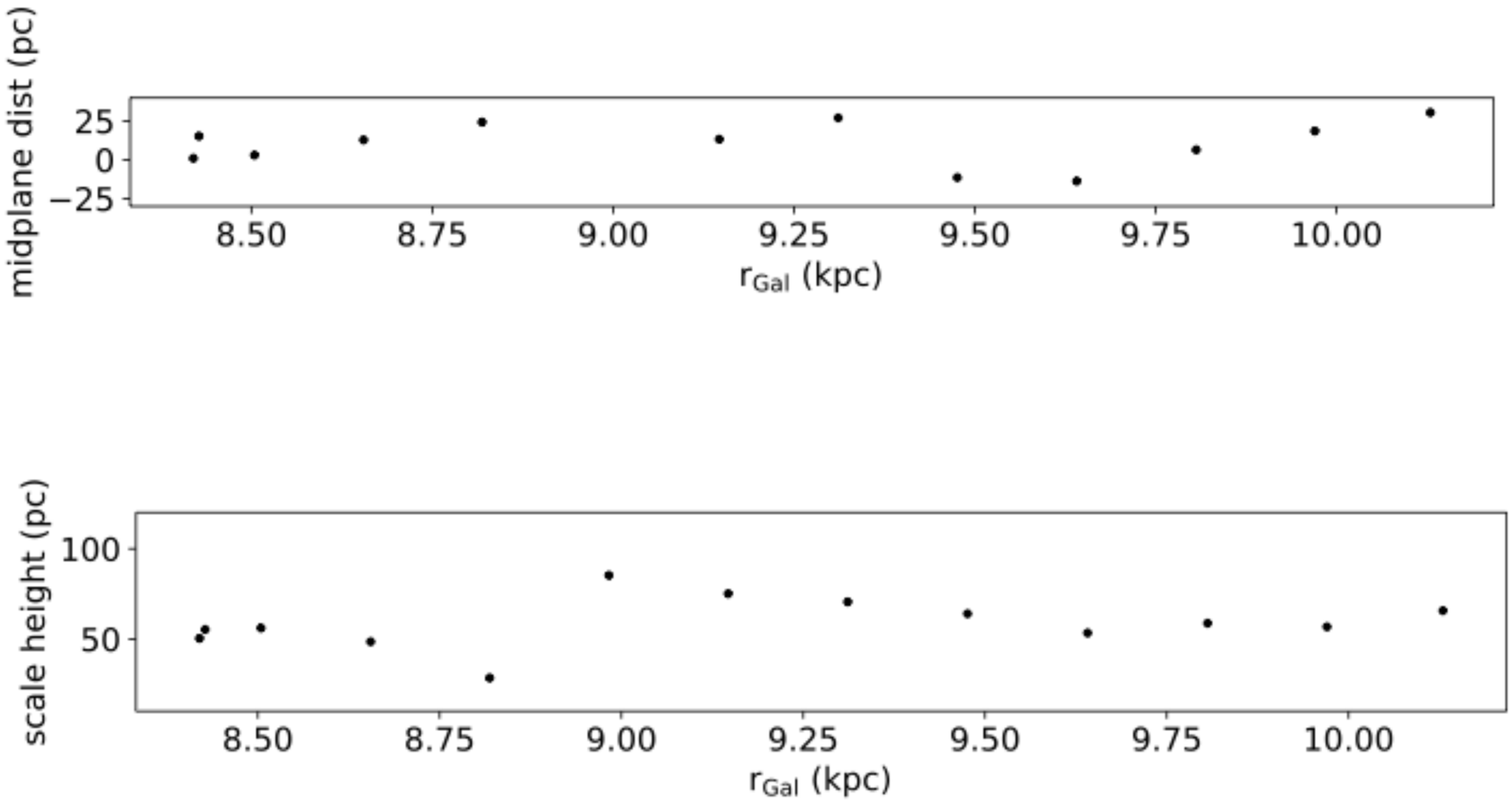
Equalization of the resolution along the whole arm:

- at small *l* : small angular area → large physical area
- at large *l* : large angular area → small physical area

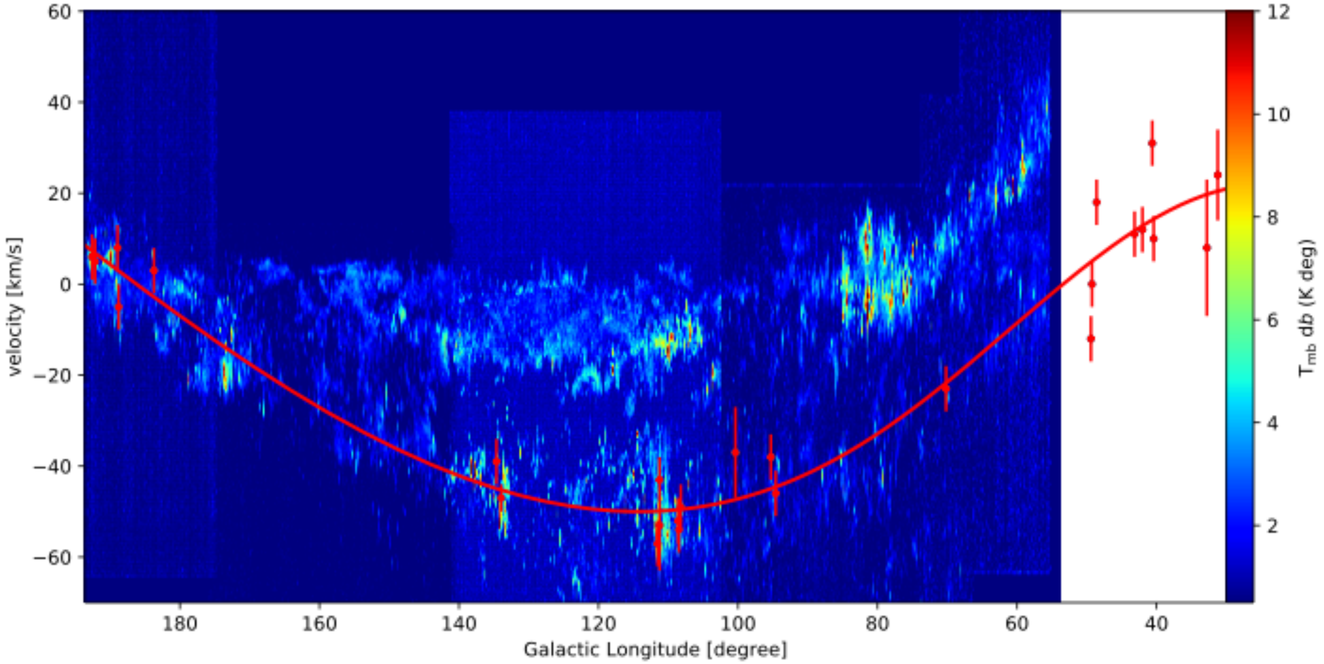
Scale height distribution



Scale height and distance from the midplane



Identification of the Perseus arm



- derivation of radial velocity to Perseus arm using models of the rotation curve from Reid et al. (2014) based on maser parallaxes
- $r = r_{\rm ref} \exp(-(\beta - \beta_{\rm ref}) \tan \psi)$ r = gal. radius ($r_{\rm ref}$= 9.9 kpc), β= azimuth ($\beta_{\rm ref}$= 14.2°), ψ= pitch angle (14.2°)

$$v_{\rm arm} = R_0 \left(\frac{\Theta_0 + v_t}{r} - \frac{\Theta_0}{R_0} \right) \sin l + v_r \sqrt{1 - \frac{R_0^2 \sin^2 l}{r^2}}$$

R_0 = 8.34 kpc, Θ_0 = rot. speed (240 km/s)

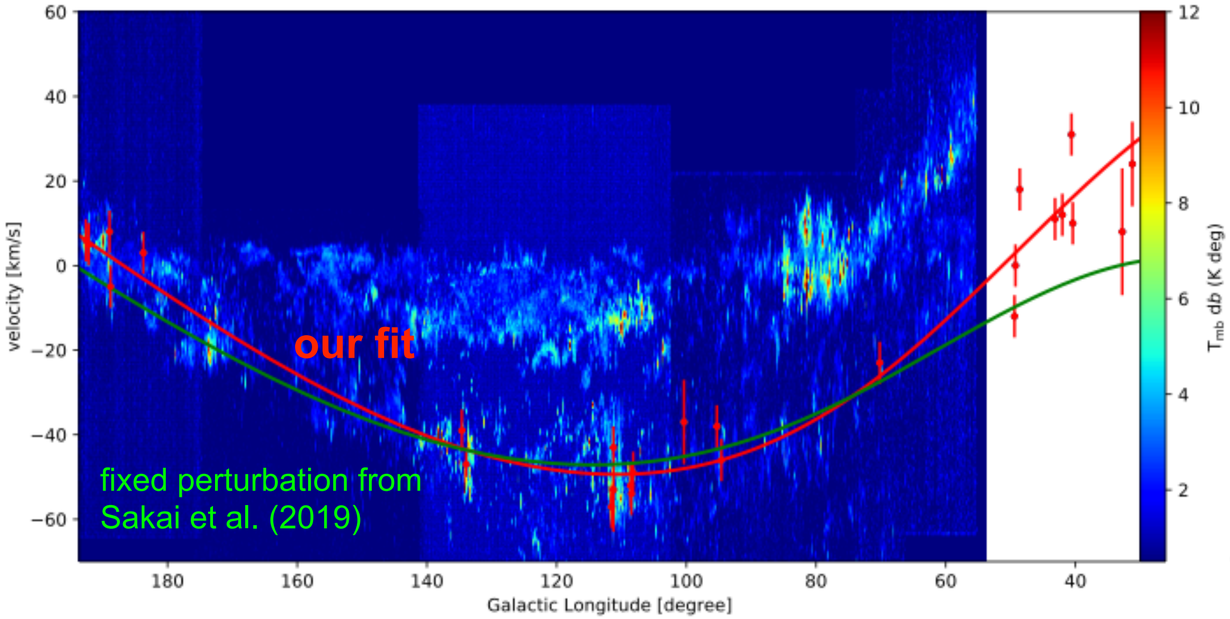
$$v_t = v_{t_0} + \frac{dv}{dr}(r - R_0)$$

v_{t0}~-16 km/s
dv/dr~-1.8 km/s/kpc

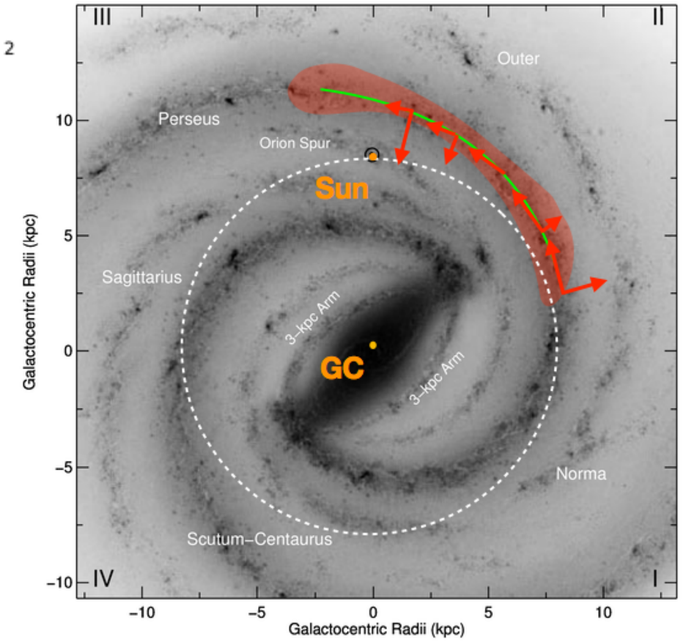
$$v_r = v_{r_0} + \frac{dv}{dr}(r - R_0)$$

v_{r0}~16 km/s
dv/dr~-11.6 km/s/kpc

Identification of the Perseus arm



- Non-circular motions are slowly linearly varying function of galactocentric radius
- Backwards/inwards motion consistent with analysis of 3D motion of masers (Sakai et al. 2019)



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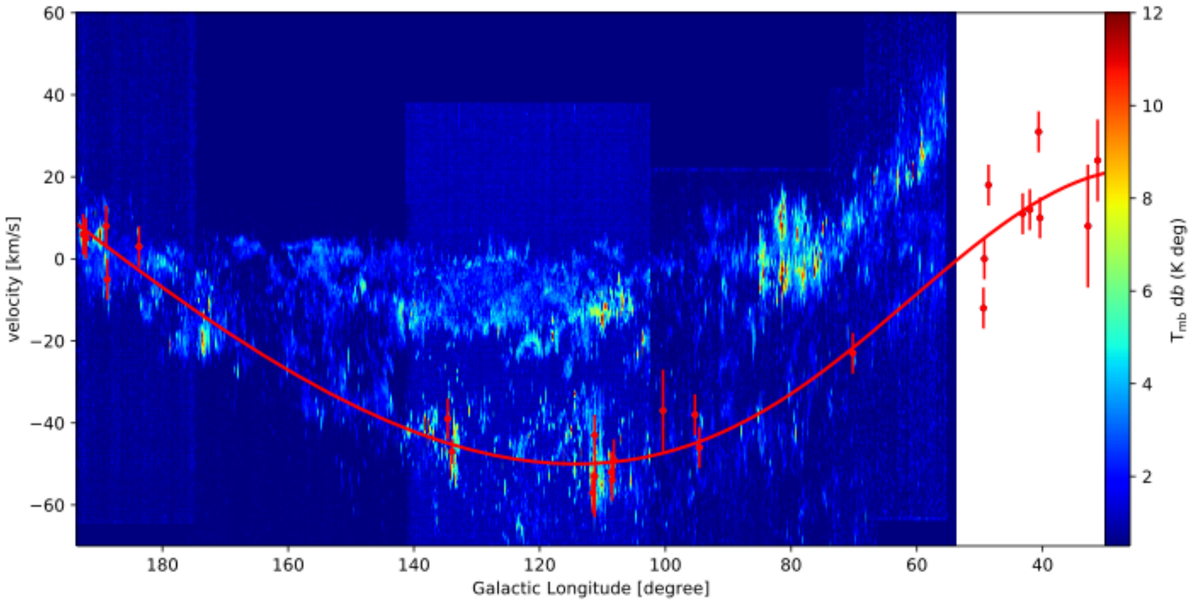
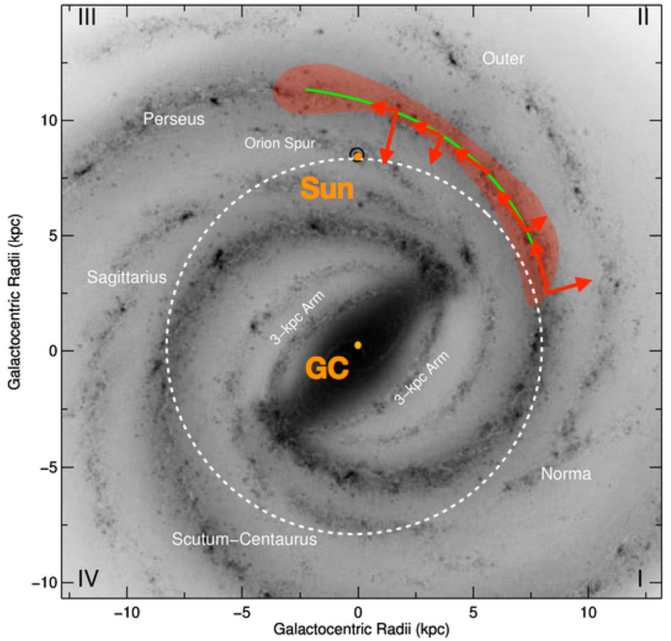


- Empirically determined the relation between Galactic longitude and radial velocity based on logarithmic spiral-arm model from Reid et al. (2014)

- Included a velocity perturbation inwards and backwards to Galactic rotation



CO peak temperature map