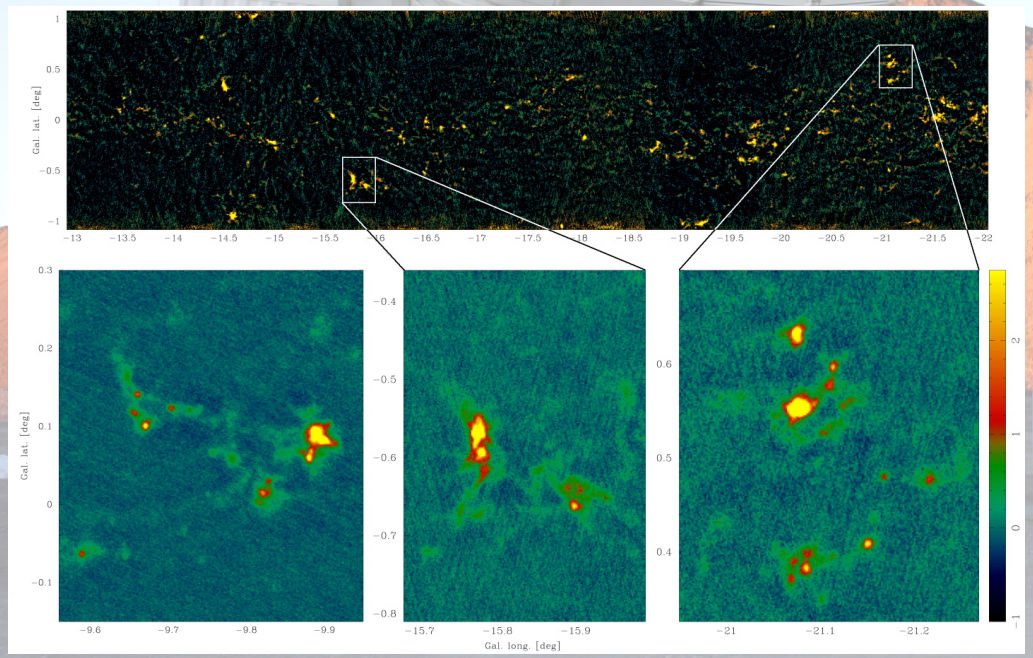
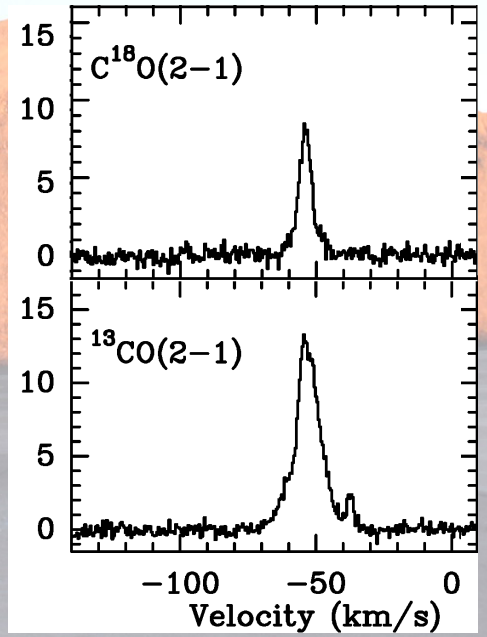
Galactic Star Formation with APEX Surveys

Frédéric Schuller
CEA / IRFU / DAp / LFEMI / Office 265





Post-doc Seminar – 2017, June 20

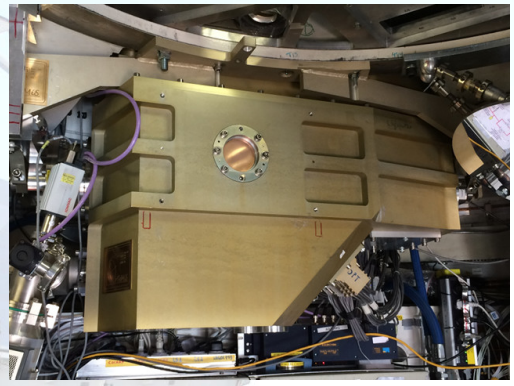
My resume

- 1998 : 3-month at IAS (Orsay), working on S^3 (Spectromètre Submillimétrique au Sol) – instrumental development for the **CSO**
- 1999-2002 : PhD thesis in IAP (A. Omont), *Massive star formation in the Galaxy as seen by the ISOGAL infrared survey* – work on **ISO** data
- 2002-2011 : post-doc at MPIfR (Bonn, Germany). Software development for bolometers at APEX (**BoA**); PI of the **ATLASGAL** survey
- 2011-2015 : ESO staff astronomer at APEX (Chile). PI of the **SEDIGISM** survey
- Now: Eurotalents CDD in Ph. André's group – working on **ArTéMiS** data (calibration & SCIENCE)

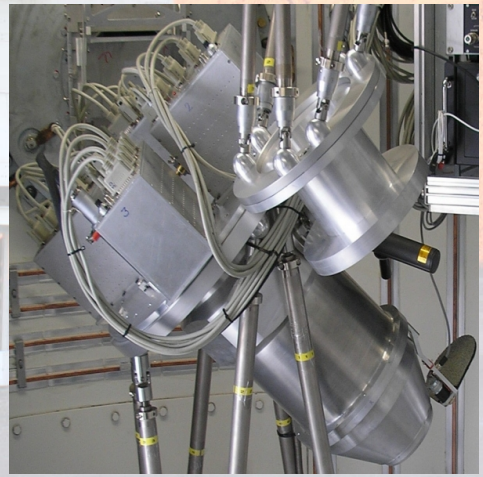
APEX Telescope and Instruments

APEX

ArTéMiS



LABOCA



SEPIA

APEX Telescope and Instruments

APEX: Atacama Pathfinder EXperiment

- Copy of north-american (Vertex) ALMA 12 m antenna
  + two Nasmyth cabins ⇒ many instruments
  + surface accuracy ∼15 μm ⇒ up to THz
- On Chajnantor plateau (5,100 m a.s.l), next to ALMA
- Partnership MPIfR (Germany) + OSO (Sweden) + ESO

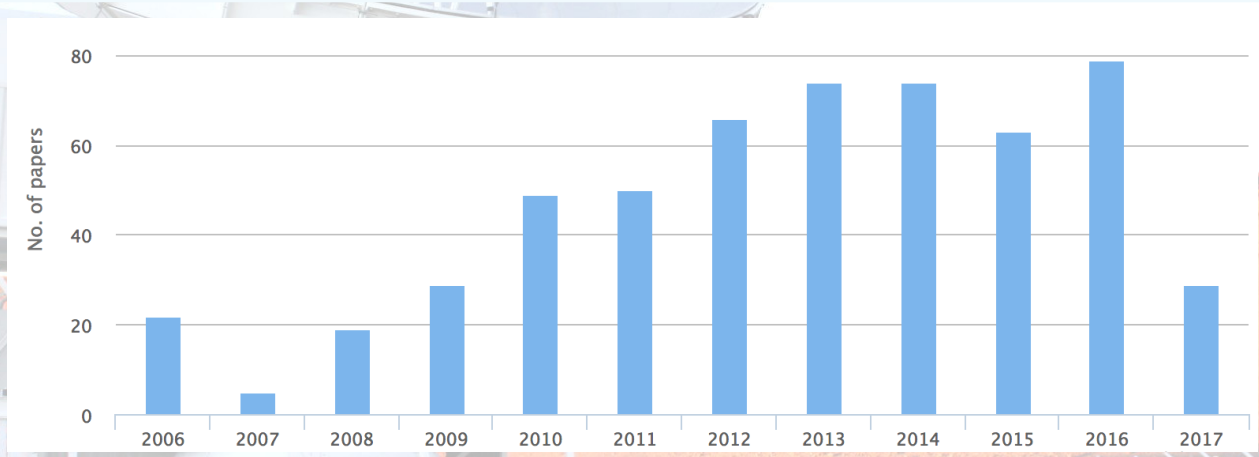
Instruments

- Heterodyne: SEPIA (180 + 660 GHz), PI230 (230 GHz), SHeFI (213–506 GHz), FLASH (345 + 460 GHz), CHAMP+ (7×660 + 7×850 GHz), LASMA (7×345 GHz)
- Bolometers: LABOCA (∼200 pix. @ 870 μm), SABOCA (37 pix. @ 350 μm) [decommissioned], **ArTéMiS** (1700 pix. @ 350 μm+ 720 pix. @ 450 μm), A-MKIDS (3k pix. @ 870 μm+ 20k pix. @ 350 μm)

The APEX Telescope

APEX operations outcome

- In operation since 2005
- >550 refereed papers



The APEX Telescope

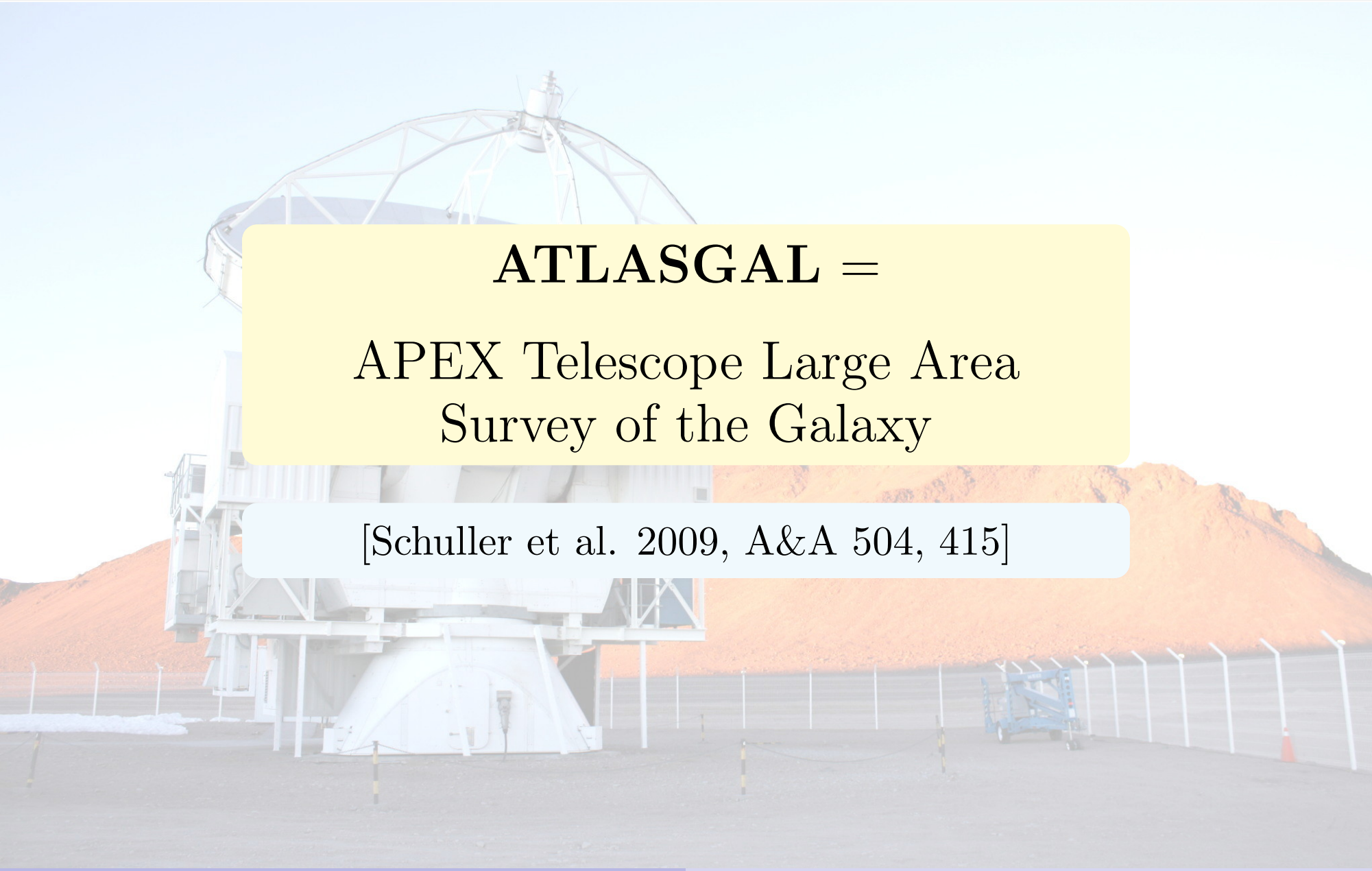
APEX operations outcome

- In operation since 2005
- >550 refereed papers
- >4,000 hours on-sky / year
- Pathfinder for ALMA (many ALMA proposals based on work with APEX)

Agreement between partners extended until

end of 2022

ATLASGAL



ATLASGAL =

APEX Telescope Large Area Survey of the Galaxy

[Schuller et al. 2009, A&A 504, 415]

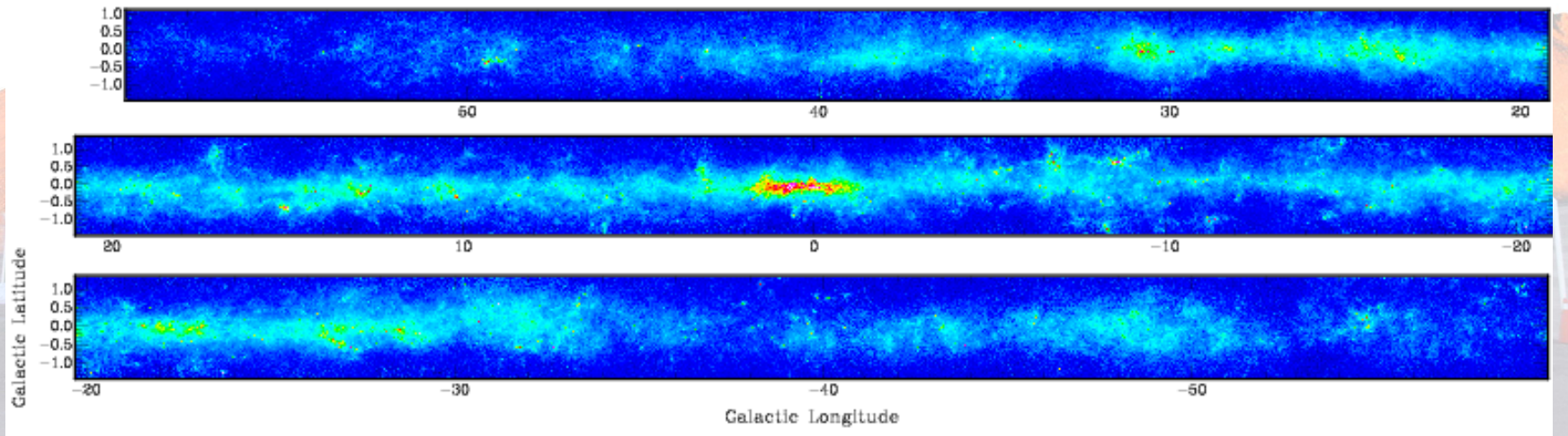
APEX Telescope Large Area Survey of the Galaxy

The 1^{st} systematic survey of the Galactic Plane in submm

- Unbiased survey of the inner Galactic Plane at 870 μm
- Continuum @ 870 μm = thermal emission from dust
- LABOCA @ APEX: angular resolution = $19''$
- Mapping $-80° \leq l \leq 60°$, $|b| \leq 1.5°$, $r.m.s. \sim 50$ mJy/beam

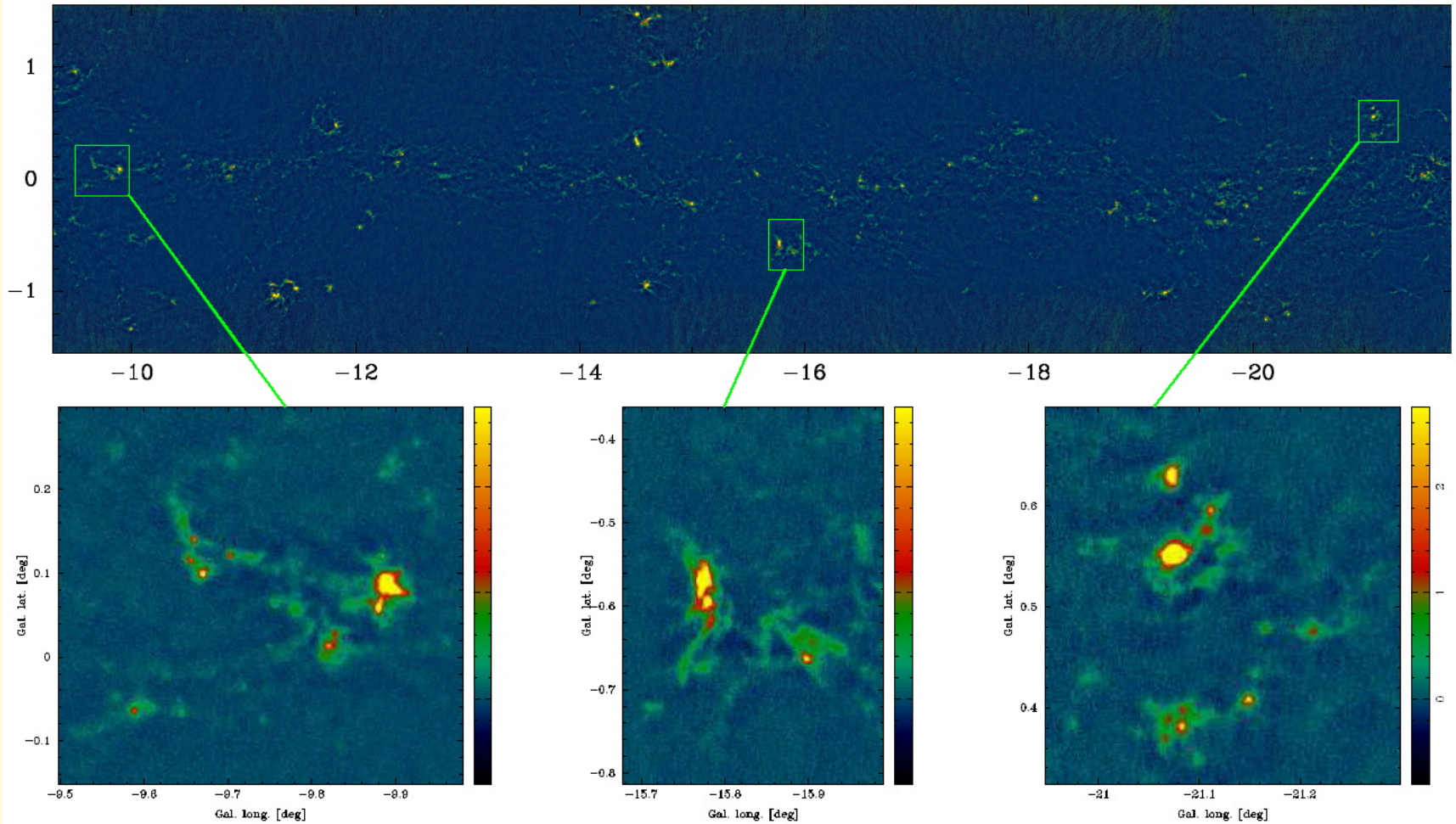
$\Rightarrow$ 420 deg^2, 5σ detection :

0.5 $M_\odot$ at 500 pc, 20 $M_\odot$ at 3 kpc, ~100 $M_\odot$ at 8 kpc



Overview

A sample of the data (∼10% of the survey)



Diffuse extended gas + Filaments + Compact clumps

Compact source catalogues

Compact Source Catalogue (CSC)

- Produced using SExtractor on the reduced maps
- Identified ∼10,000 sources [Contreras et al., 2013; Urquhart et al., 2014]

GaussClump Source Catalogue (GCSC)

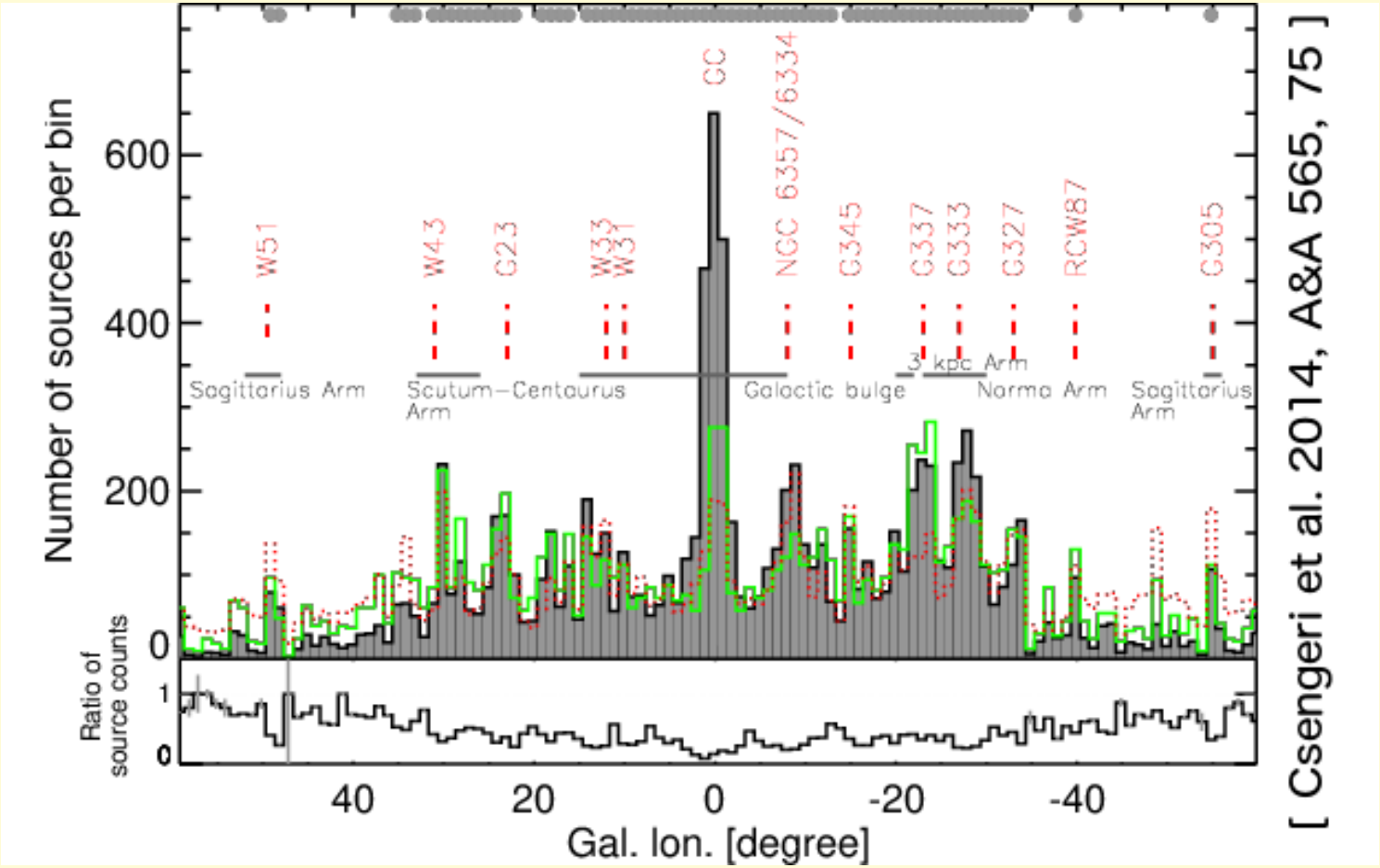
- Produced using GaussClump on images filtered with multi-resolution method to remove extended emission
- Identified ∼10,000 sources [Csengeri et al., 2014]

The CSC and GCSC are very complementary:

- the former better probing the whole clump structure
- the latter probing the (dense) gas directly associated with star formation

http://atlasgal.mpifr-bonn.mpg.de/

Compact sources: longitude distribution

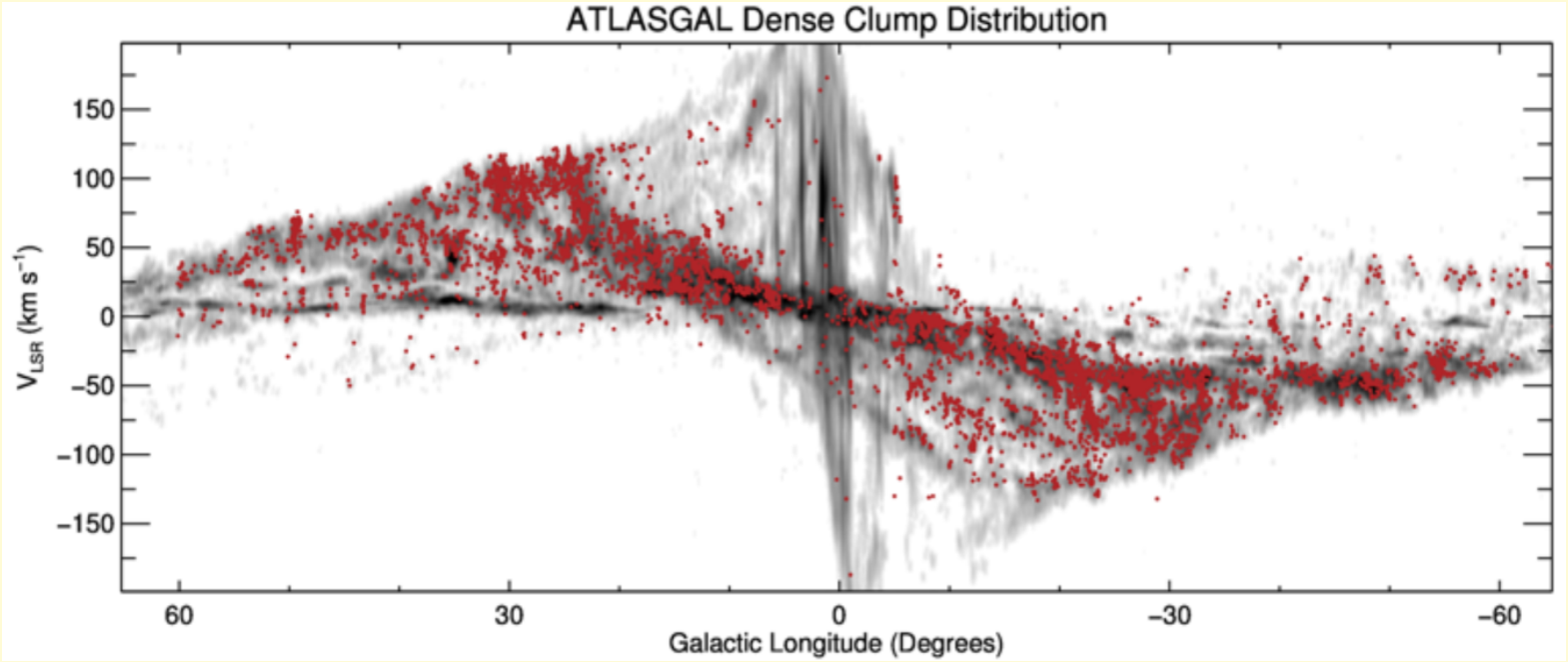


- Overdensities toward known star-forming complexes
- Ratio of star-forming vs. quiescent sources drops in CMZ

Compact sources: Galactic distribution

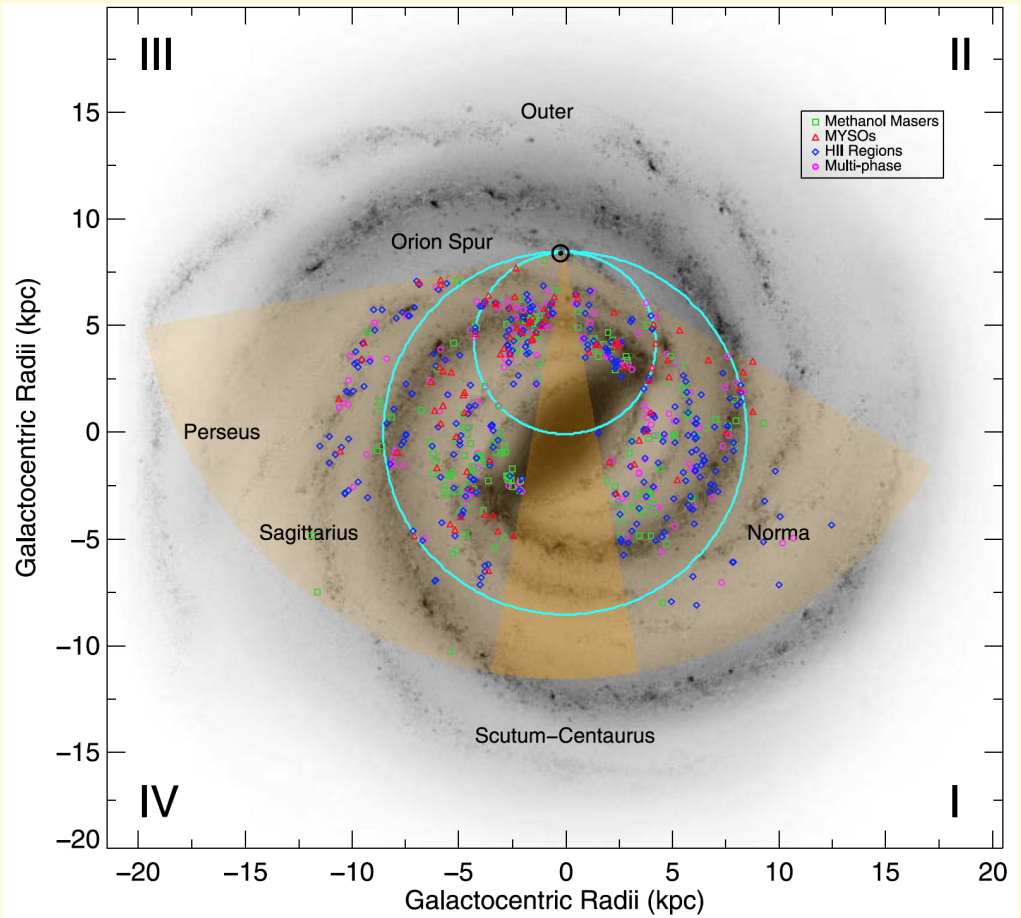
Distance determination

- Spectro. follow-up + literature → 8,000 radial velocities



- Friend-of-friend algorithm →∼75% clumps in ∼200 big complexes, ∼50% in the 60 largest complexes
- Distribution follows spiral structure

High-mass Star Forming clumps

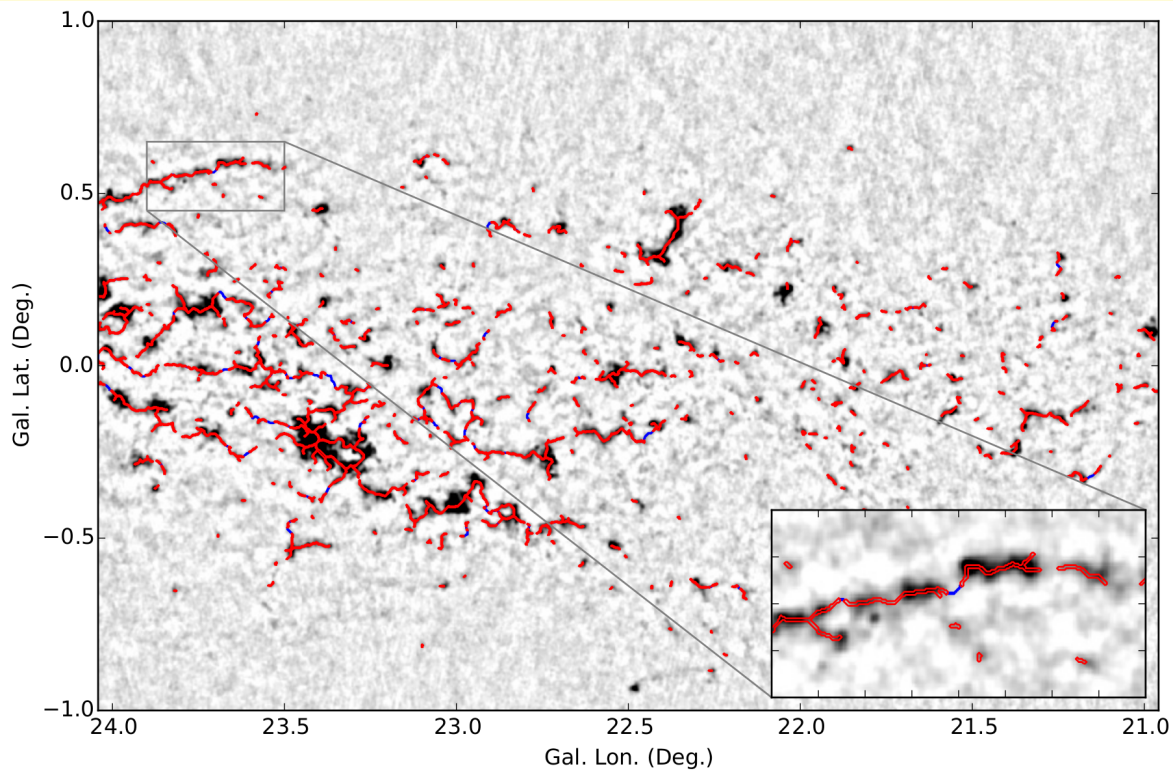


[Urquhart et al. 2014, MNRAS 443, 1555]

Association with other catalogues (methanol masers, massive YSOs, HII regions)

- ∼1,300 clumps with signs of HMSF
- + distances ⇒ distribution & physical properties
- L/M ∼7 $L_\odot/M_\odot$ for methanol masers, to 16 $L_\odot/M_\odot$ for MYSO and HII regions

Extraction of filaments with DisPerSE

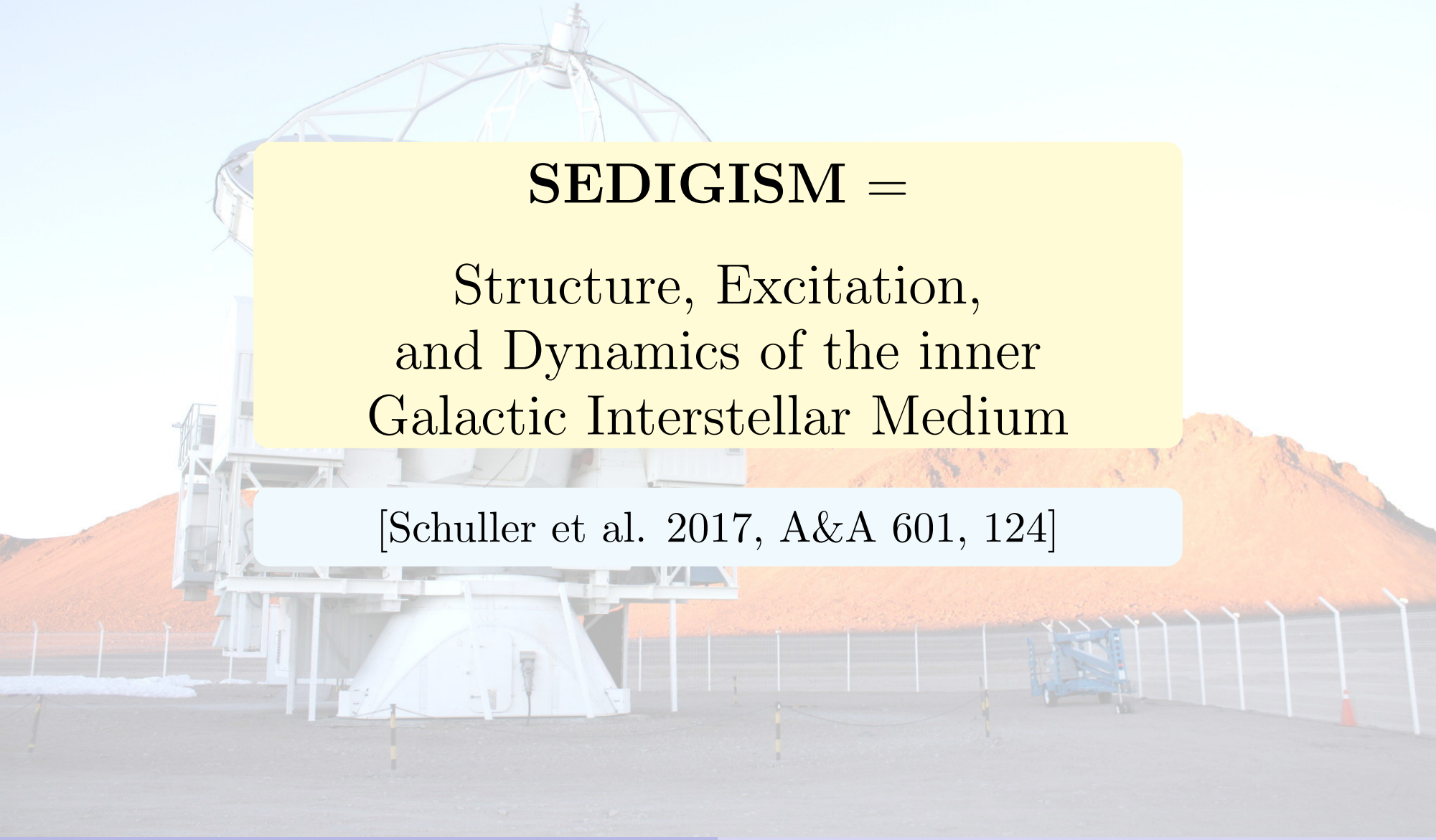


[Li, G.-X. et al. 2016, A&A 591, 5]

- 517 filamentary structures in full survey
- 241 with distances: lengths 2–20 pc, widths 0.1–2.5 pc, M 10^2–$10^5 M_\odot$, M/l ∼200 to 2000 $M_\odot$ pc^{-1}

- Good correlation with spiral arms
- Ongoing massive star formation in ∼20%
- Many = high column-density parts of larger scale filaments

SEDIGISM

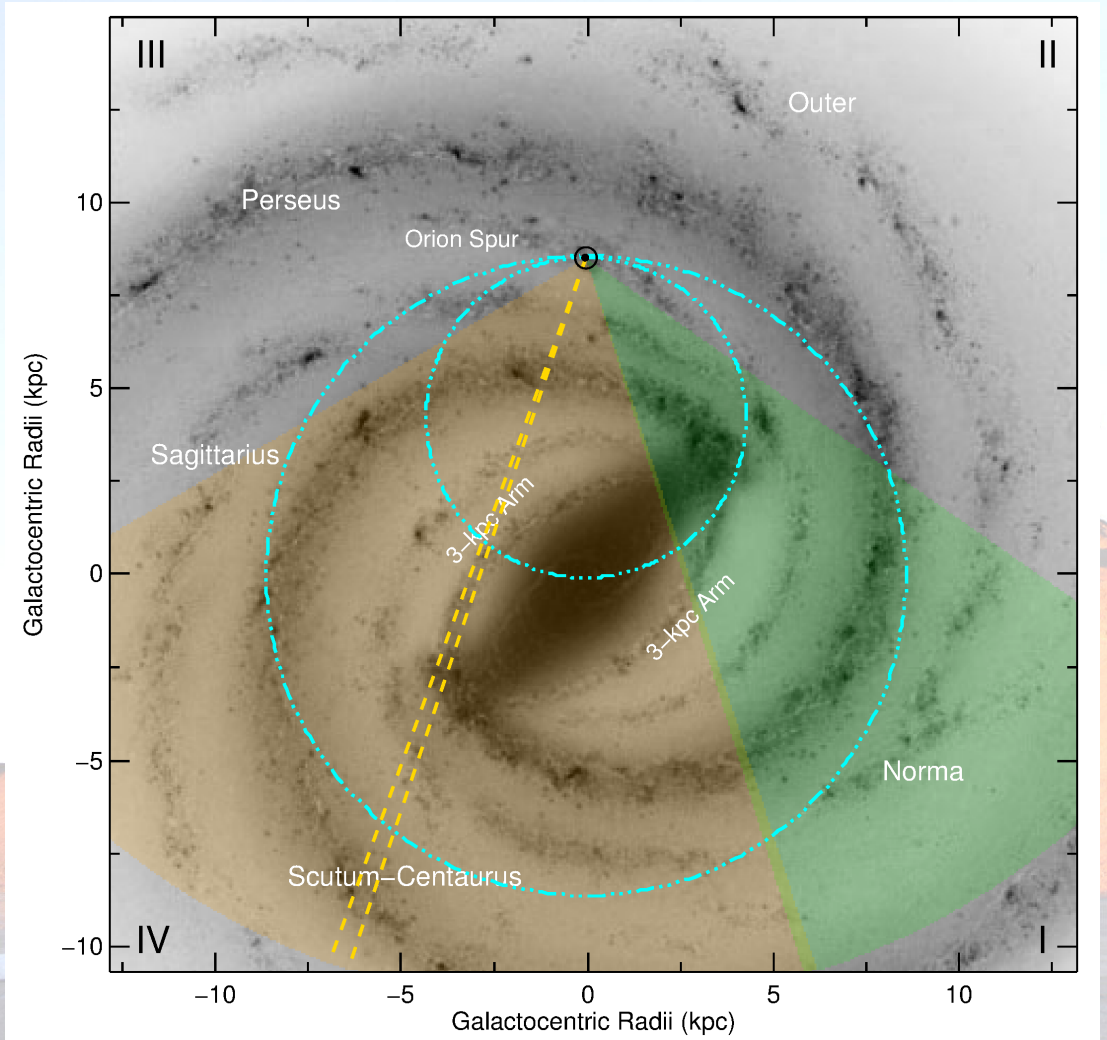


SEDIGISM =

Structure, Excitation,
and Dynamics of the inner
Galactic Interstellar Medium

[Schuller et al. 2017, A&A 601, 124]

Observing strategy: the coverage



SEDIGISM

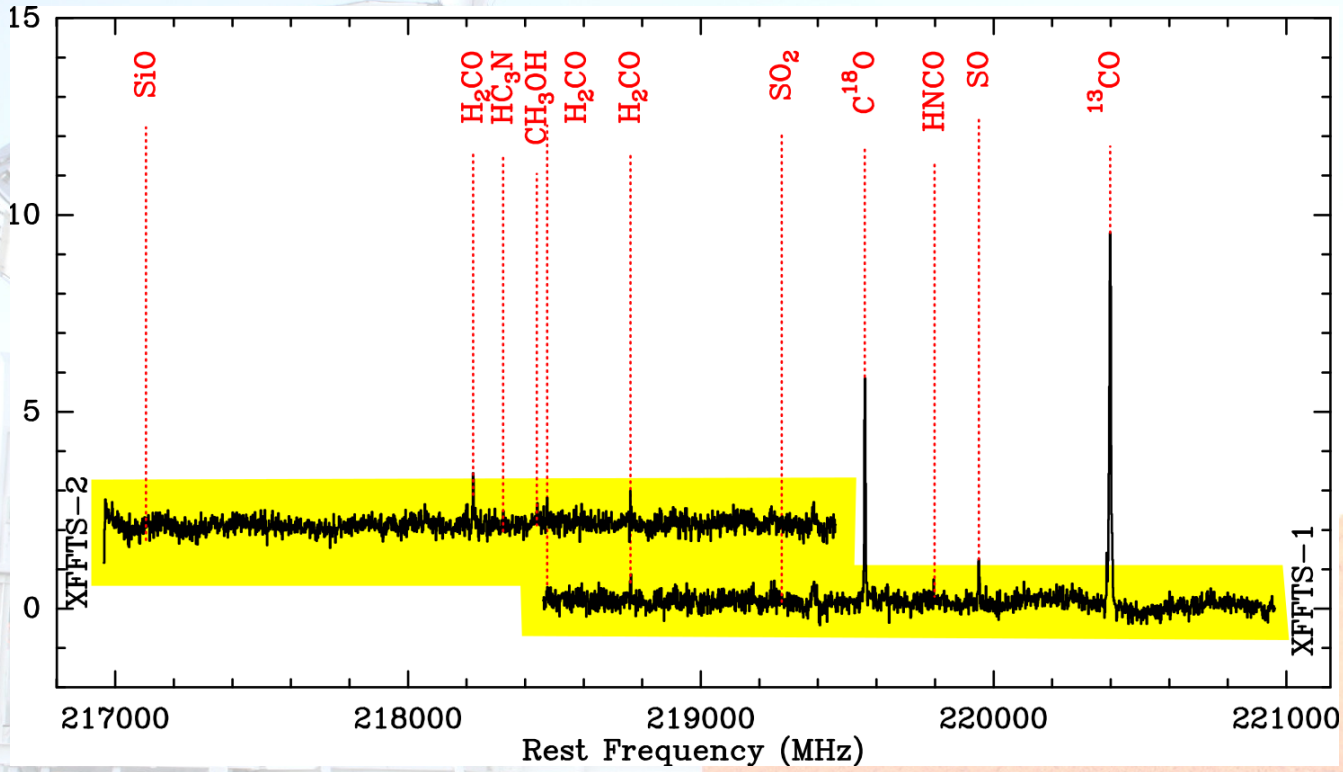
- $-60° \leq l \leq +18°$, $|b| \leq 0.5°$ (78 deg^2)
- ^{13}CO(2–1) + C^{18}O(2–1)
- Resolution $= 28''$
- $\sigma \approx 0.8$ K @ 0.25 km/s

The GRS [Jackson et al. 2006]

- $+17.5° \leq \ell \leq +55.7°$, $|b| \leq 1°$ (76 deg^2)
- ^{13}CO(1–0)
- Resolution $= 46''$
- $\sigma \approx 0.27$ K @ 0.21 km/s

Observing strategy: spectral setup

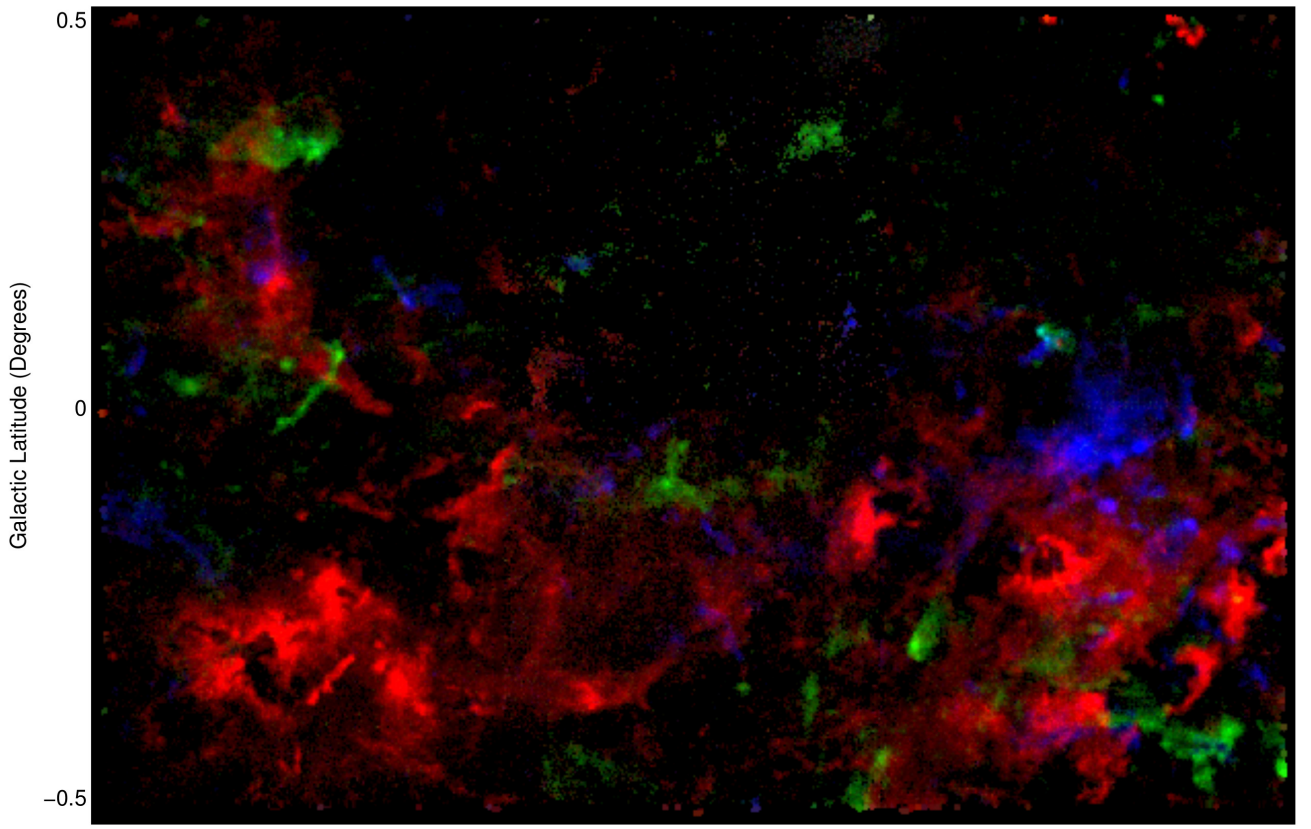
ν = 217–221 GHz $\Rightarrow$ **^{13}CO(2–1)** & C^{18}O(2–1) + others



- ~800 hours (Aug. 2013 – Aug. 2016) → COMPLETED
- $> 12 \times 10^6$ spectra
- 1-$\sigma \approx 0.8$ K $\Rightarrow$ 3-$\sigma \rightarrow N_{H_2} \approx 3 \times 10^{21}$ cm^{-2} or $A_V \approx 3$ mag

Science demonstration field

A 1.5 deg^2 field representative of the full survey



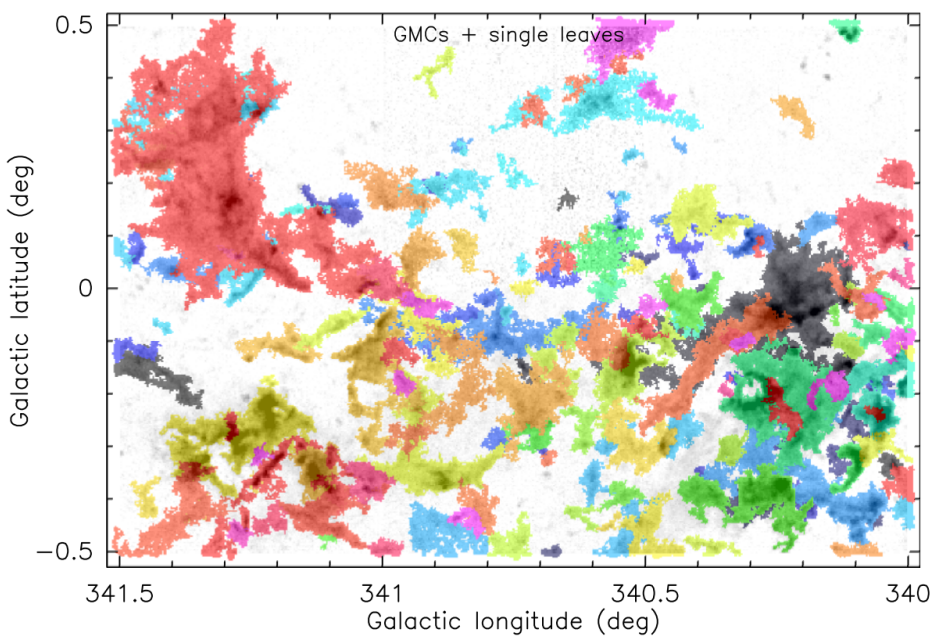
Peak ^{13}CO emission

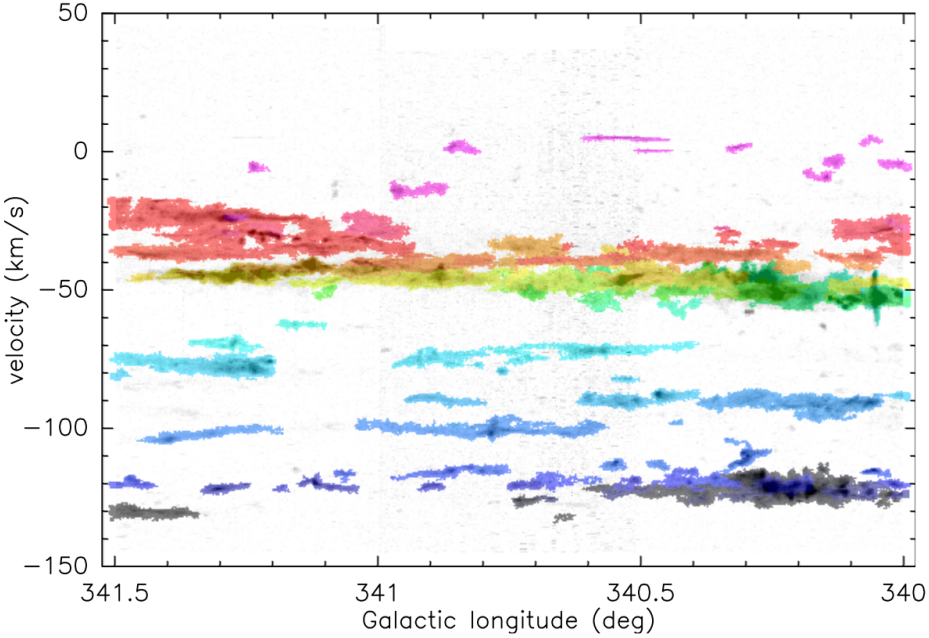
-130 to -110 km s^{-1}
-110 to -60 km s^{-1}
-60 to +5 km s^{-1}

Extraction of molecular clumps and GMCs

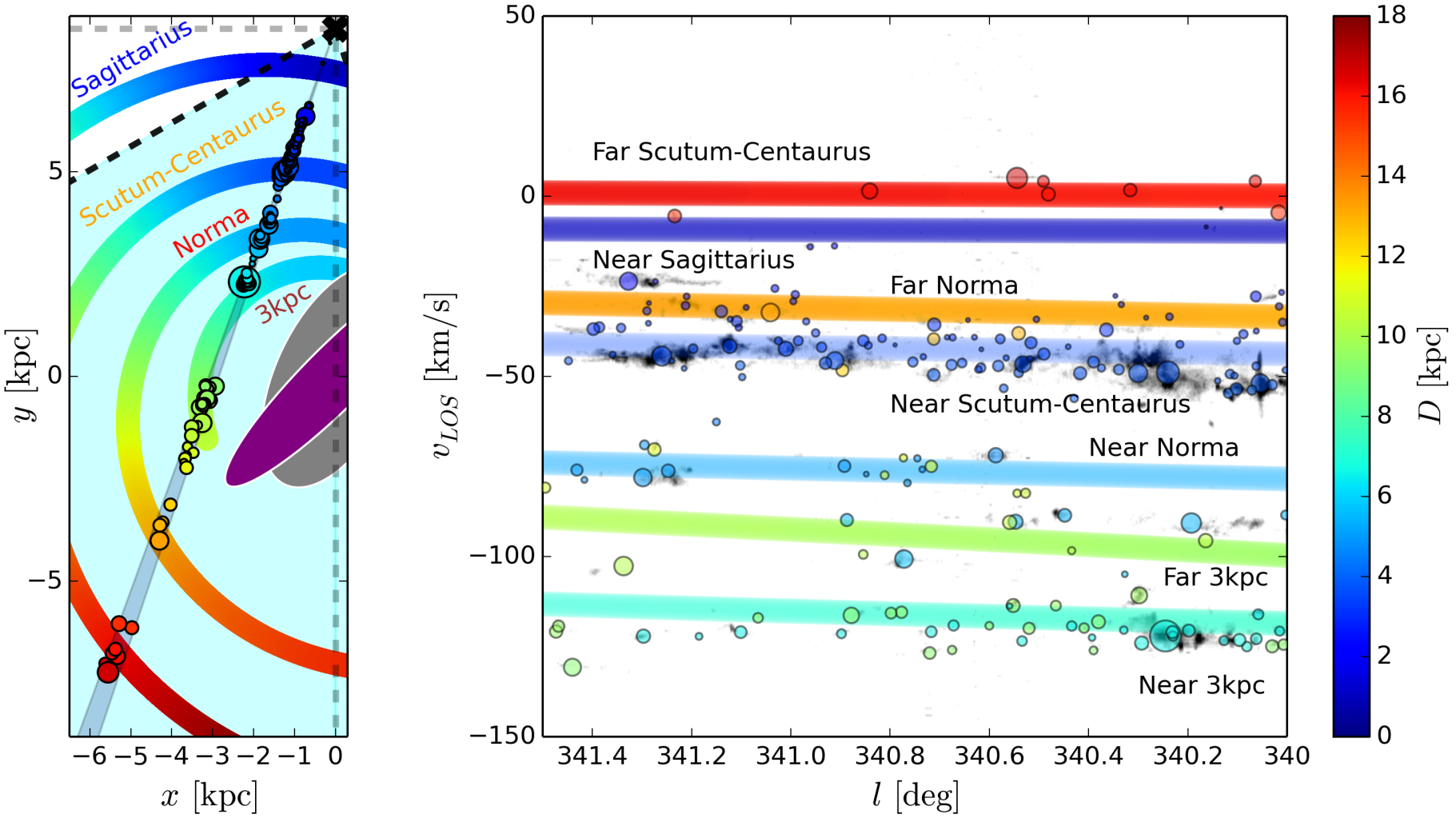
Cloud extraction with SCIMES

- SCIMES: Spectral Clustering for Interstellar Molecular Emission Segmentation [Colombo et al. 2015, MNRAS]
- Science demo. field (1.5 deg^2): 182 molecular clouds:
  58 complexes + 124 single-leaf clouds
- **Only 35 clouds associated with ATLASGAL**

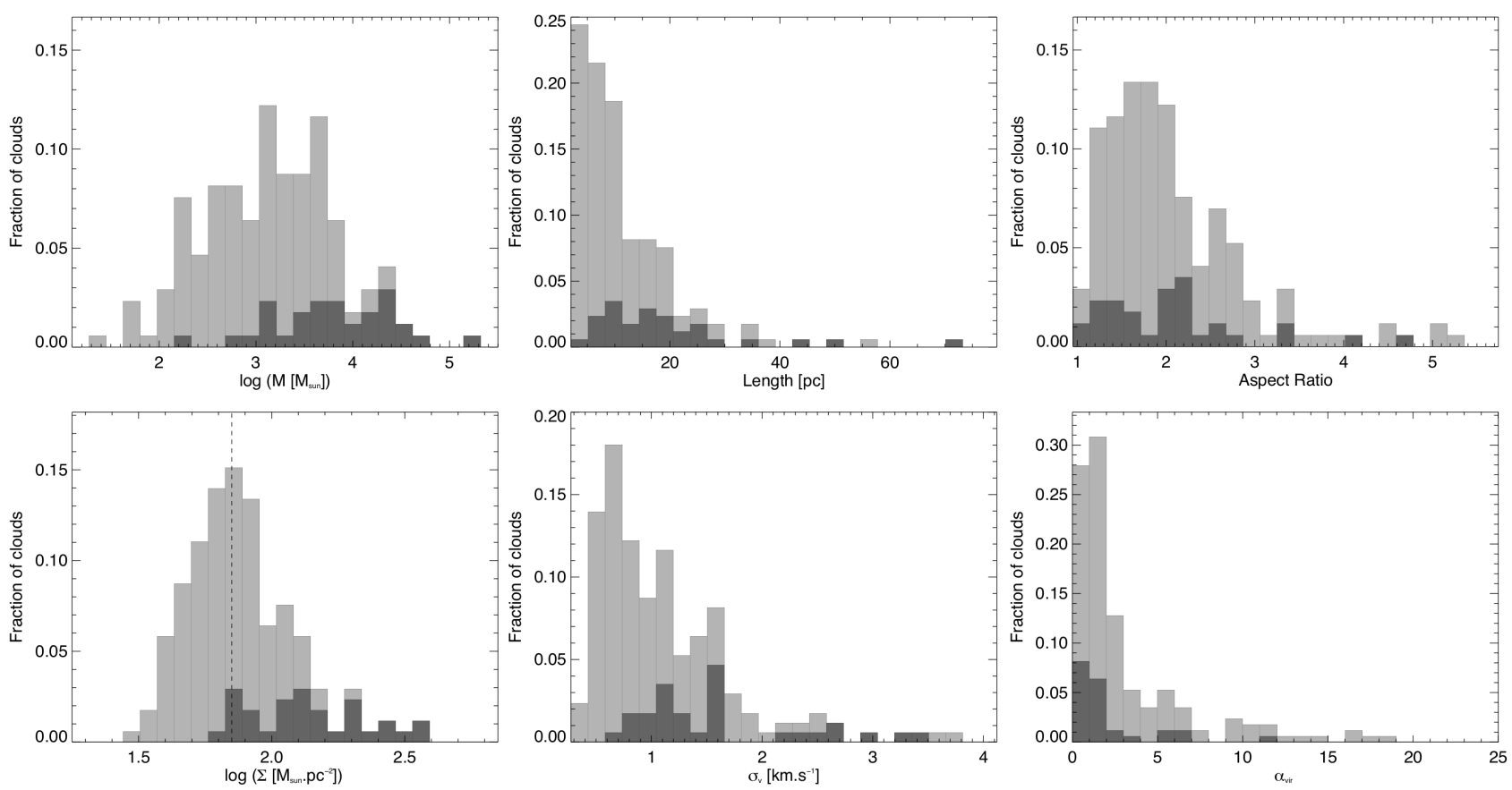




Distribution with respect to Galactic arms



Physical properties

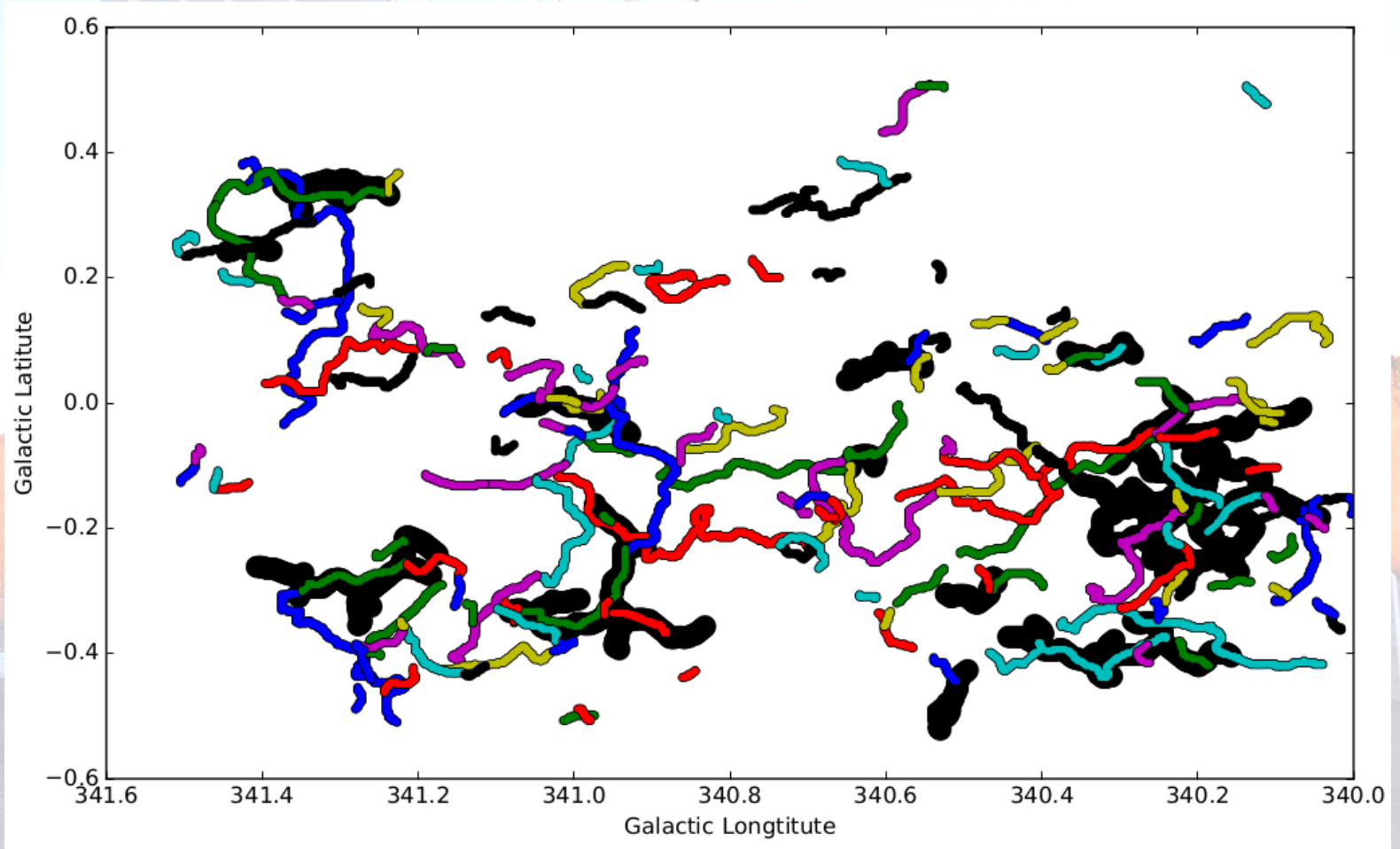


- Masses from a few 10 to $\sim 10^5$ $M_\odot$
- Most clouds may well be self-gravitating

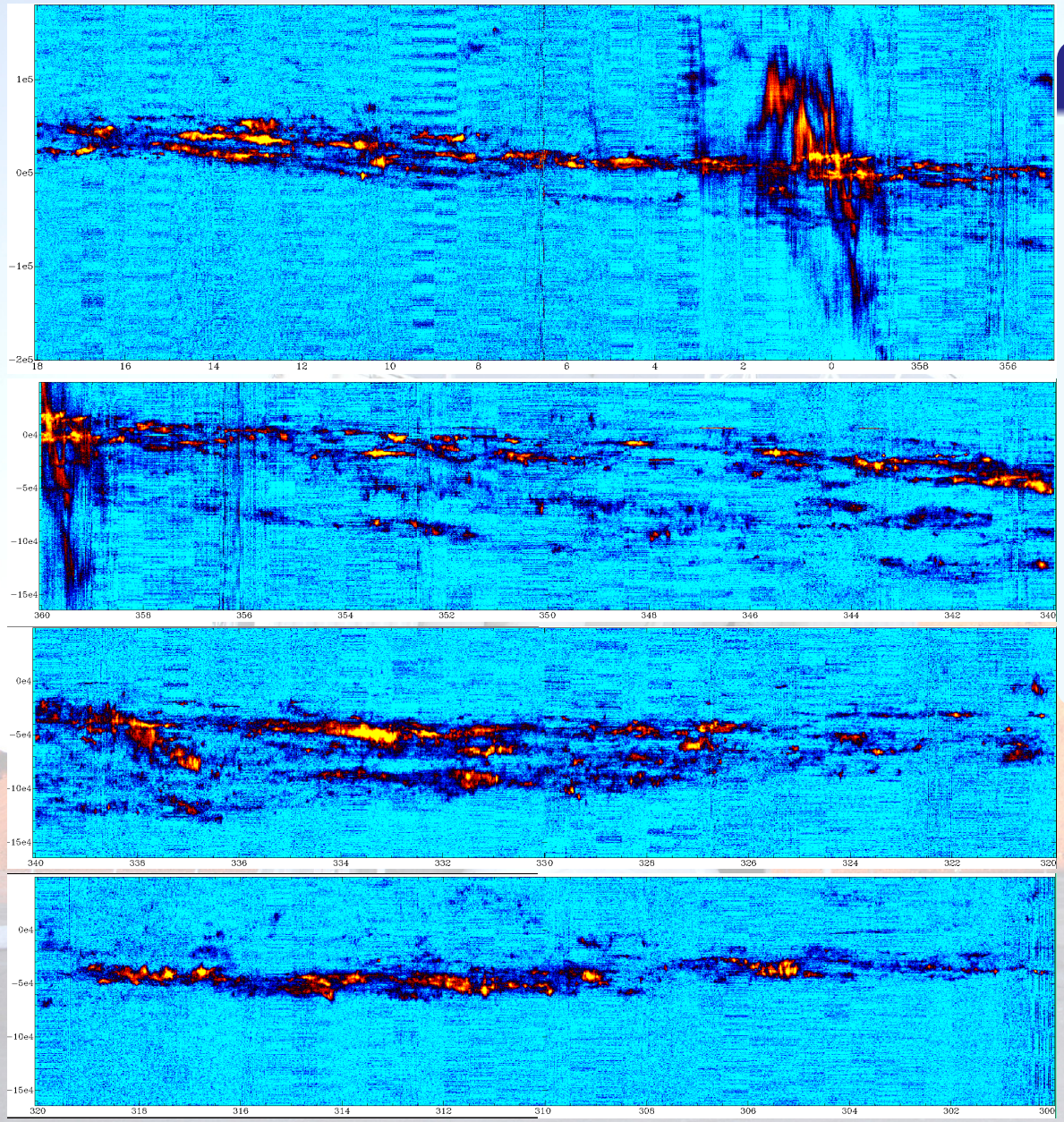
ATLASGAL vs. ^{13}CO filaments

Extraction of new filaments

Using DisPerSE algorithm (Sousbie 2011) on ^{13}CO data
$\rightarrow$ 145 structures with length $> 150''$, 33 with aspect ratio > 5

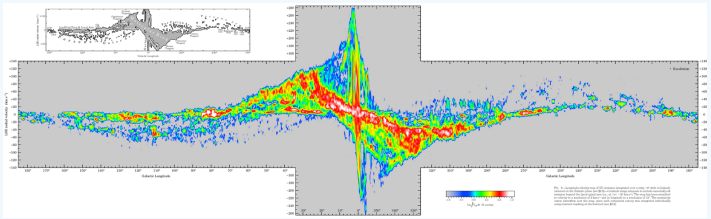


Longitude-velocity plots



l,v plots

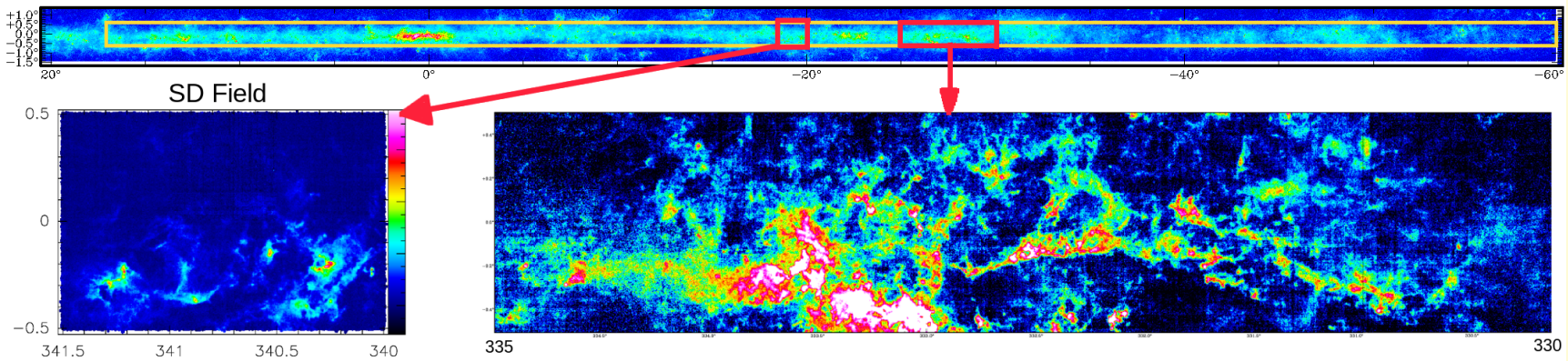
- Trace the spiral arms
- Angular resolution $\sim 15\times$ better than Dame et al. 2001



Work in progress...

Perspectives: Galactic structure

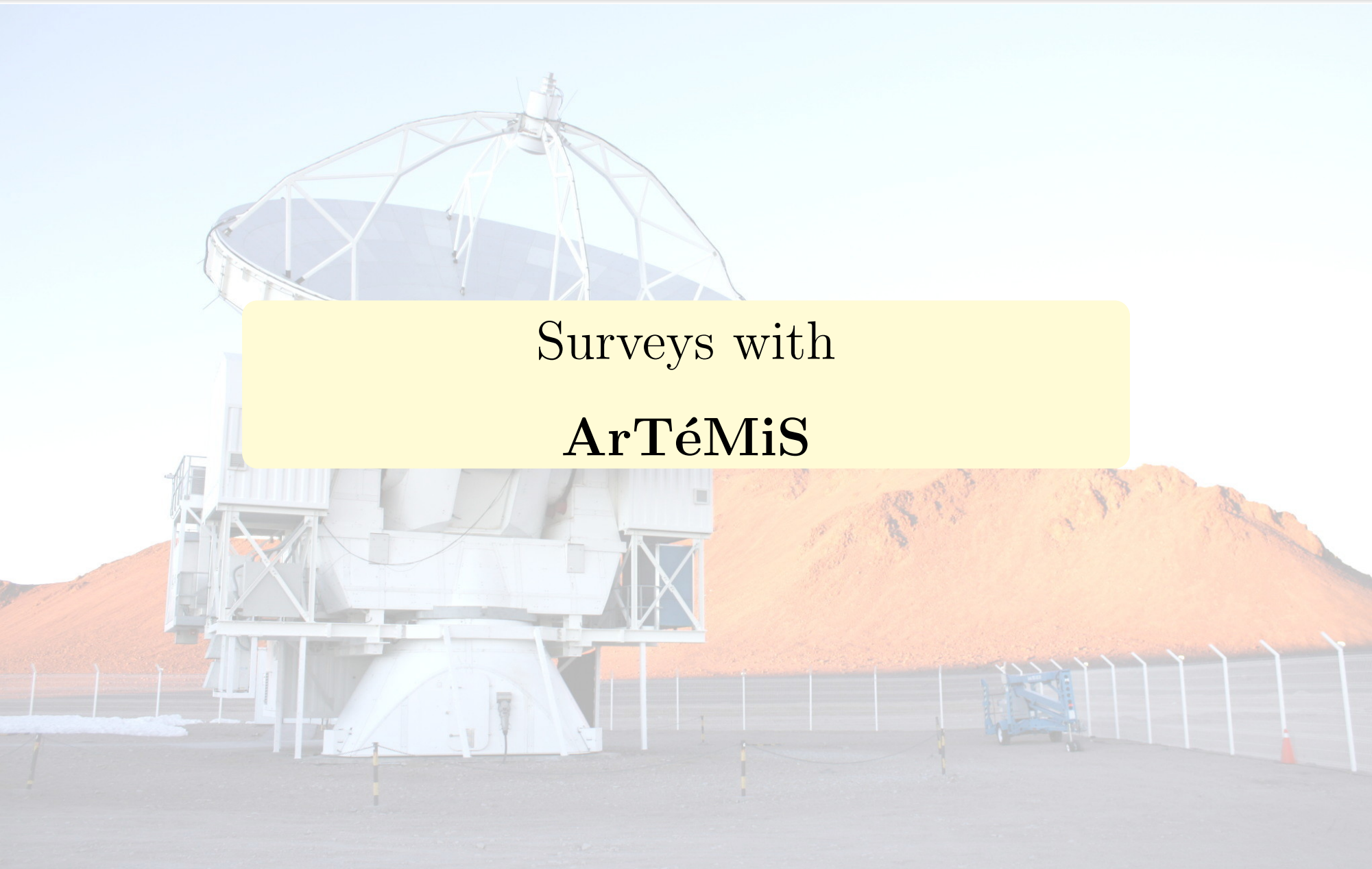
Full survey: 80 deg^2



Perspectives

- Complete census of the cold, dense ISM ($N_{H_2} > 3 \times 10^{21}$ cm^{-2}), from 30″ to Galactic scale
- 1000s clouds and GMCs, very long filaments
- Data will be public ⇒ High legacy value
- **Complementary to many Galactic surveys**

A r T é M i S



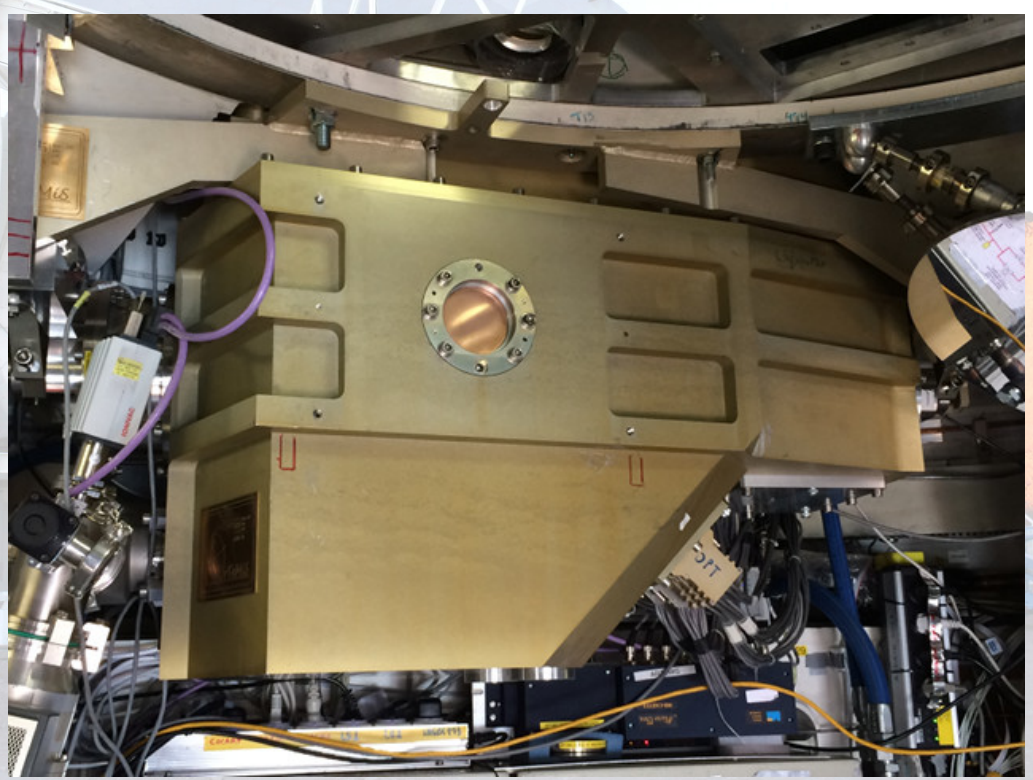
Surveys with

ArTéMiS

The ArTéMiS instrument

ArTéMiS: Architectures de bolomètres pour des Télescopes à grand champ de vue dans le domaine sub-Millimétrique au Sol

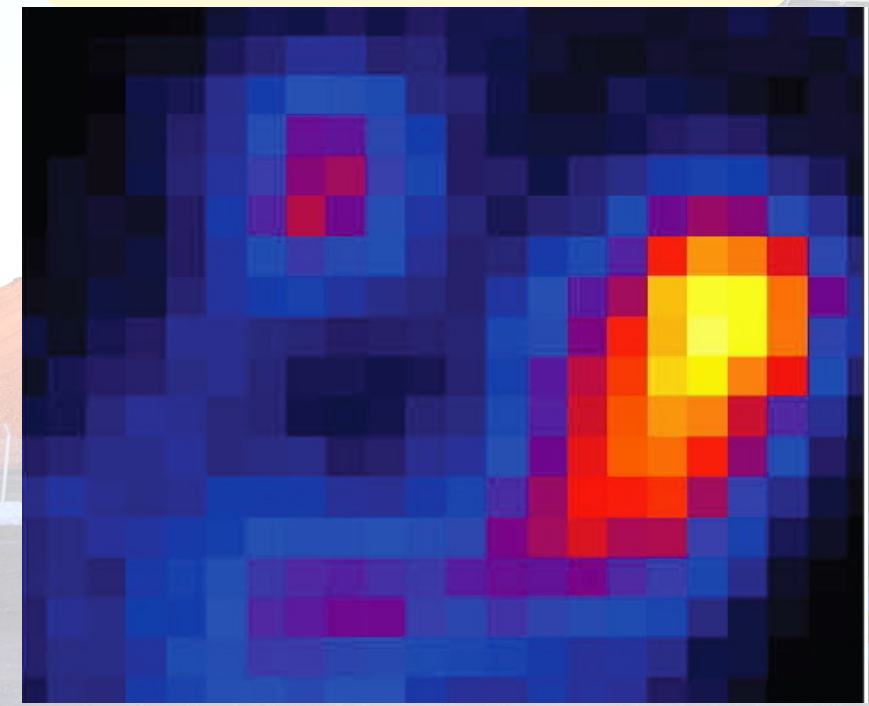
- Instrument built by CEA / DAp - based on detectors used in Herschel/PACS
- Currently: 1700 pix. @ 350 μm + 720 pix. @ 450 μm



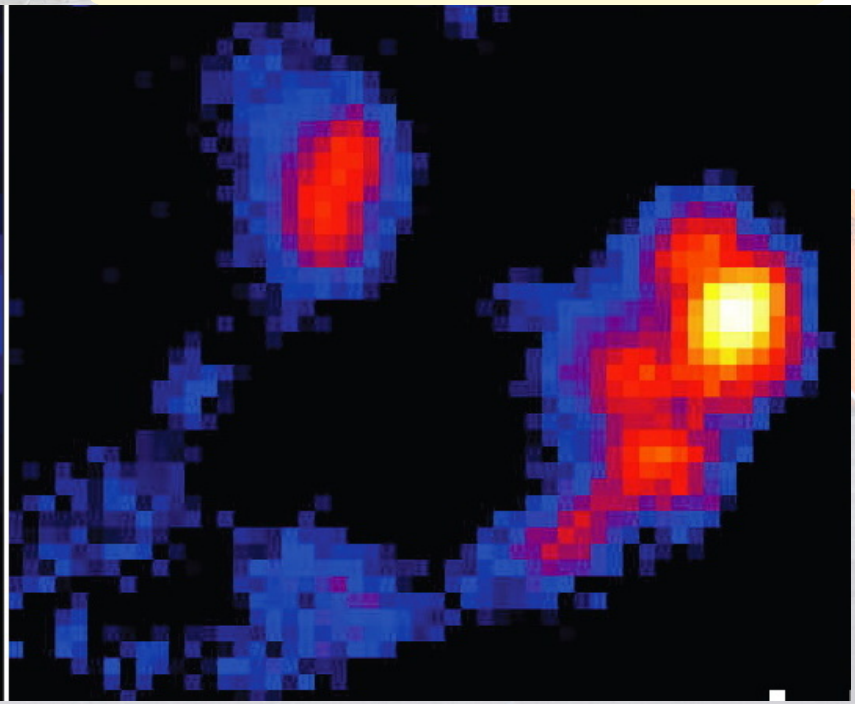
The power of ArTéMiS

- **Angular resolution 7.5″ @ 350 μm**, 9″ @ 450 μm
  $\Rightarrow$ 2.5× better than LABOCA @ 870 μm
  $\Rightarrow$ 3× better than Herschel at same wavelength
  $\Rightarrow$ study fragmentation

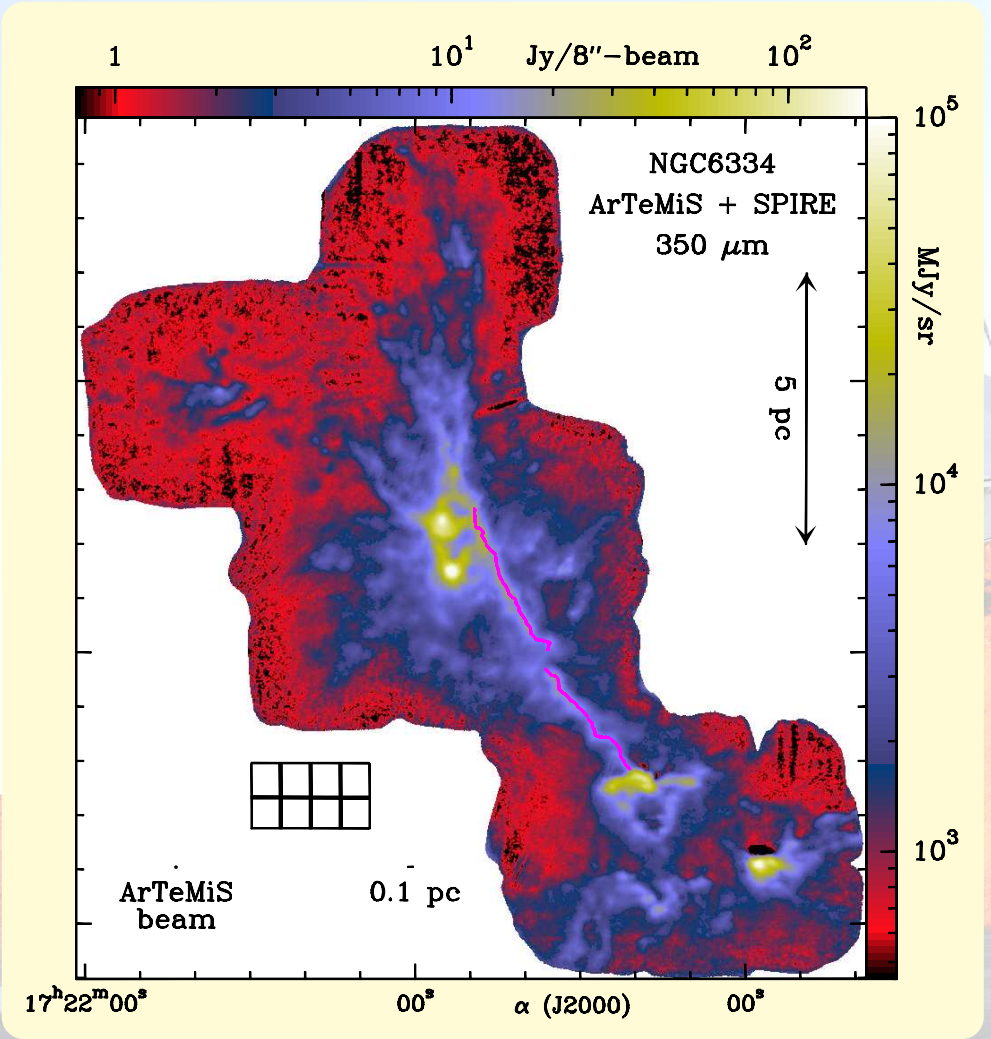
L A B O C A (870 μm)



S A B O C A (350 μm)



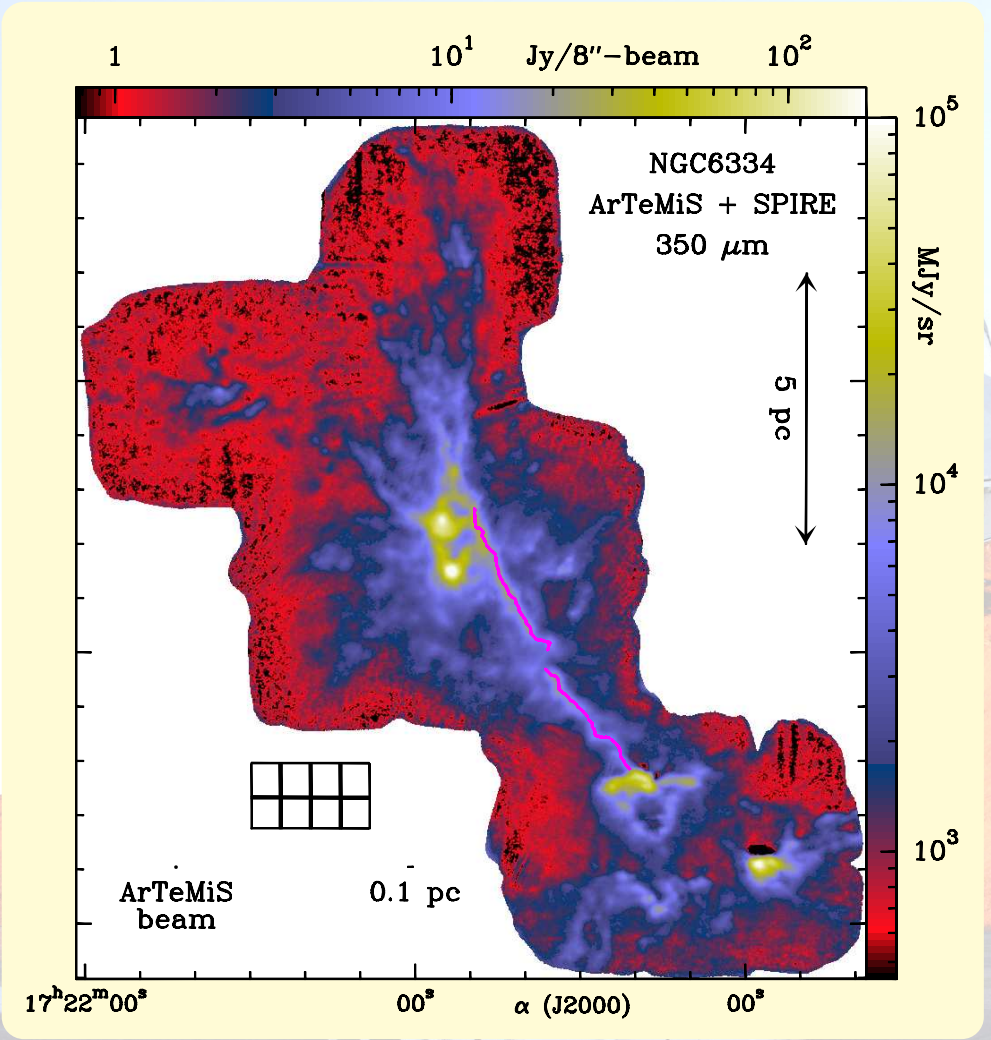
ArTéMiS + SPIRE map of NGC6334

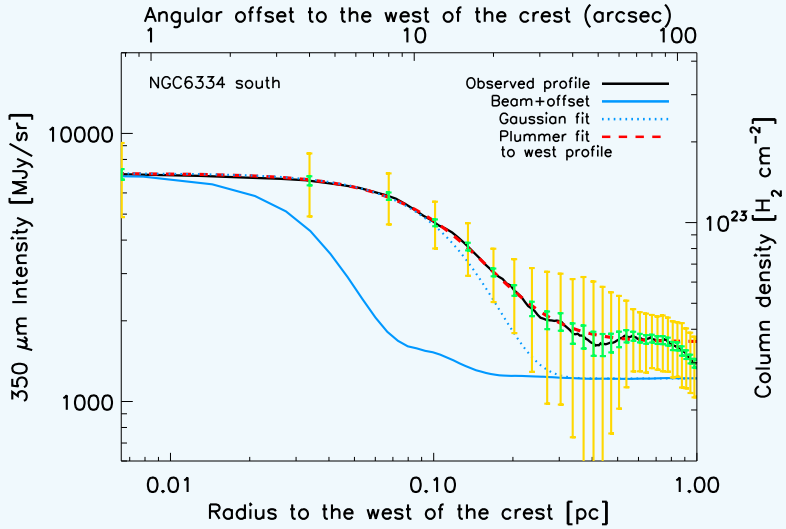


- NGC6334 (Cat paw nebula) : high-mass star forming region at 1.7 kpc $\Rightarrow 7.5''$-beam ≈ 0.06 pc
- Do results derived from Herschel data in nearby low-mass star forming regions also apply to high-mass star formation?

[André et al. 2016, A&A 592, 54]

ArTéMiS + SPIRE map of NGC6334

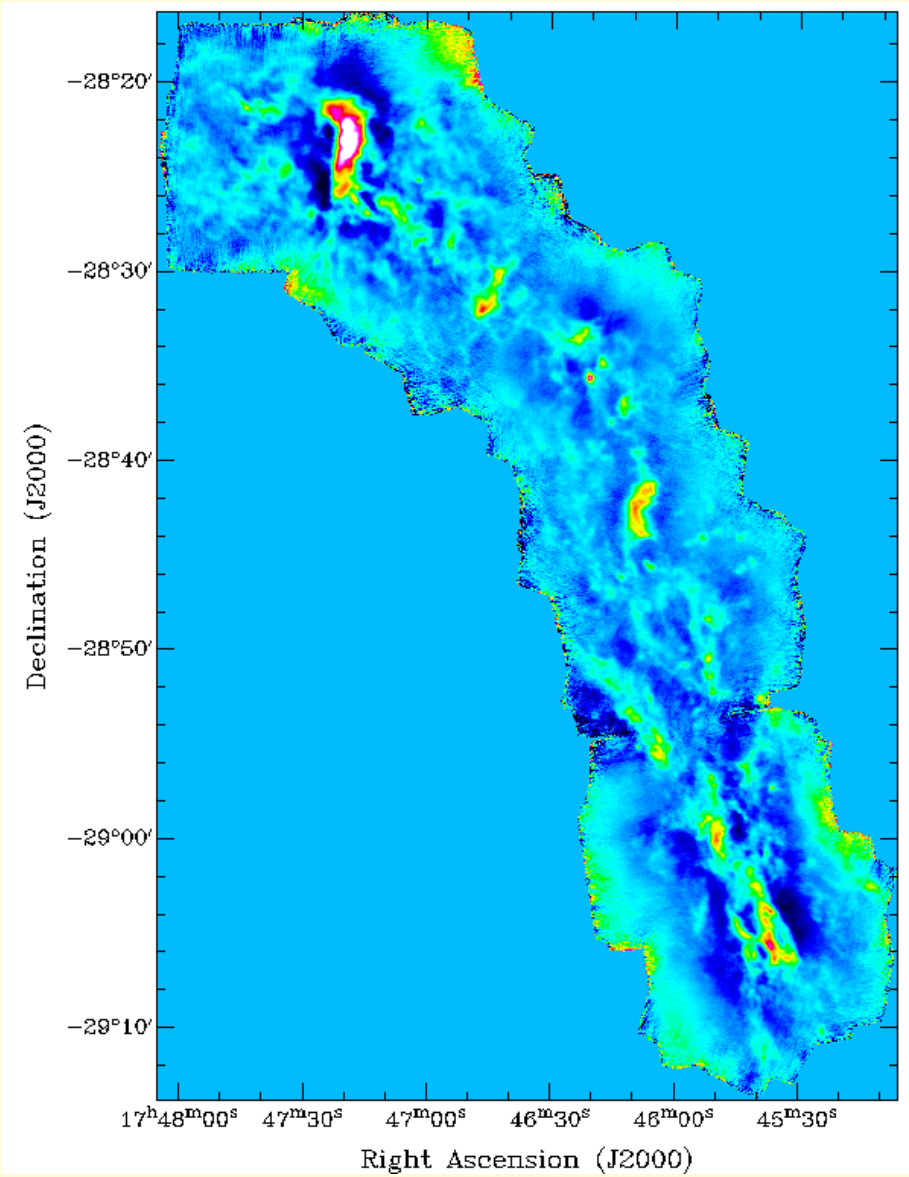




- **Inner width:**
  W = 0.15 ± 0.05 pc
- M/L high enough to form massive stars

[André et al. 2016, A&A 592, 54]

Mapping the CMZ



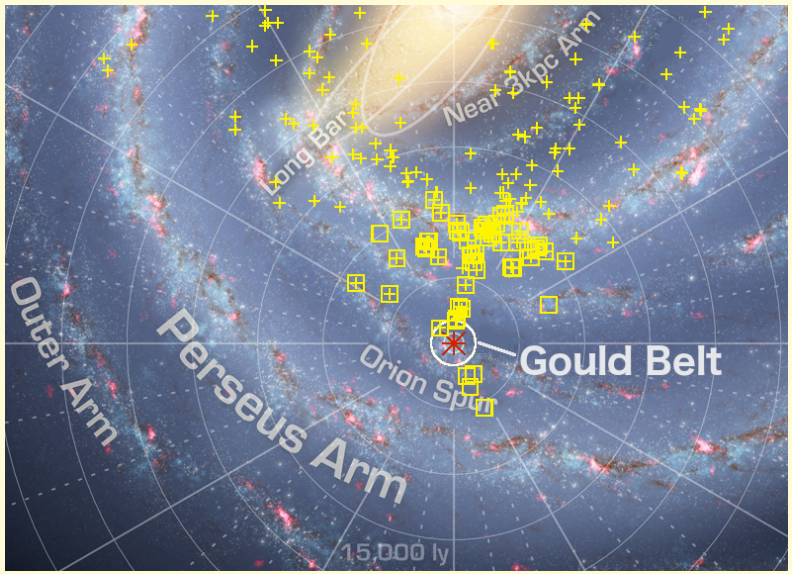
Ongoing:

- Project to map the Central Molecular Zone at 350 μm
- Preliminary map (May 2017) obtained after ∼15 hr telescope time
- More than 2× time spent now

⇒ **study star formation in <u>extreme environment</u>**

Future steps

A large mapping survey with ArTéMiS



- Mapping **all** massive molecular complexes in the inner Gal. Plane at distances $\leq$3 kpc
- Selected from ATLASGAL maps + HOBYS targets
- Total: $\sim$9 deg^2
- ESO P100: M17 (d = 1.7 kpc) and W48 (d = 3.2 kpc)

$\Rightarrow$ **High-resolution** view of clumps, filaments and bubbles in the massive star-forming complexes of the Galaxy

Conclusion

Summary

Large scale (systematic) surveys are essential to:

- fully address a question (e.g. how do local conditions affect high-mass star formation?)
- provide well designed samples for follow-ups (e.g. with ALMA)

Complementarity between imaging and spectroscopic surveys

Complementarity between ground-based (APEX) and space-based (Herschel) data

... Thank you!