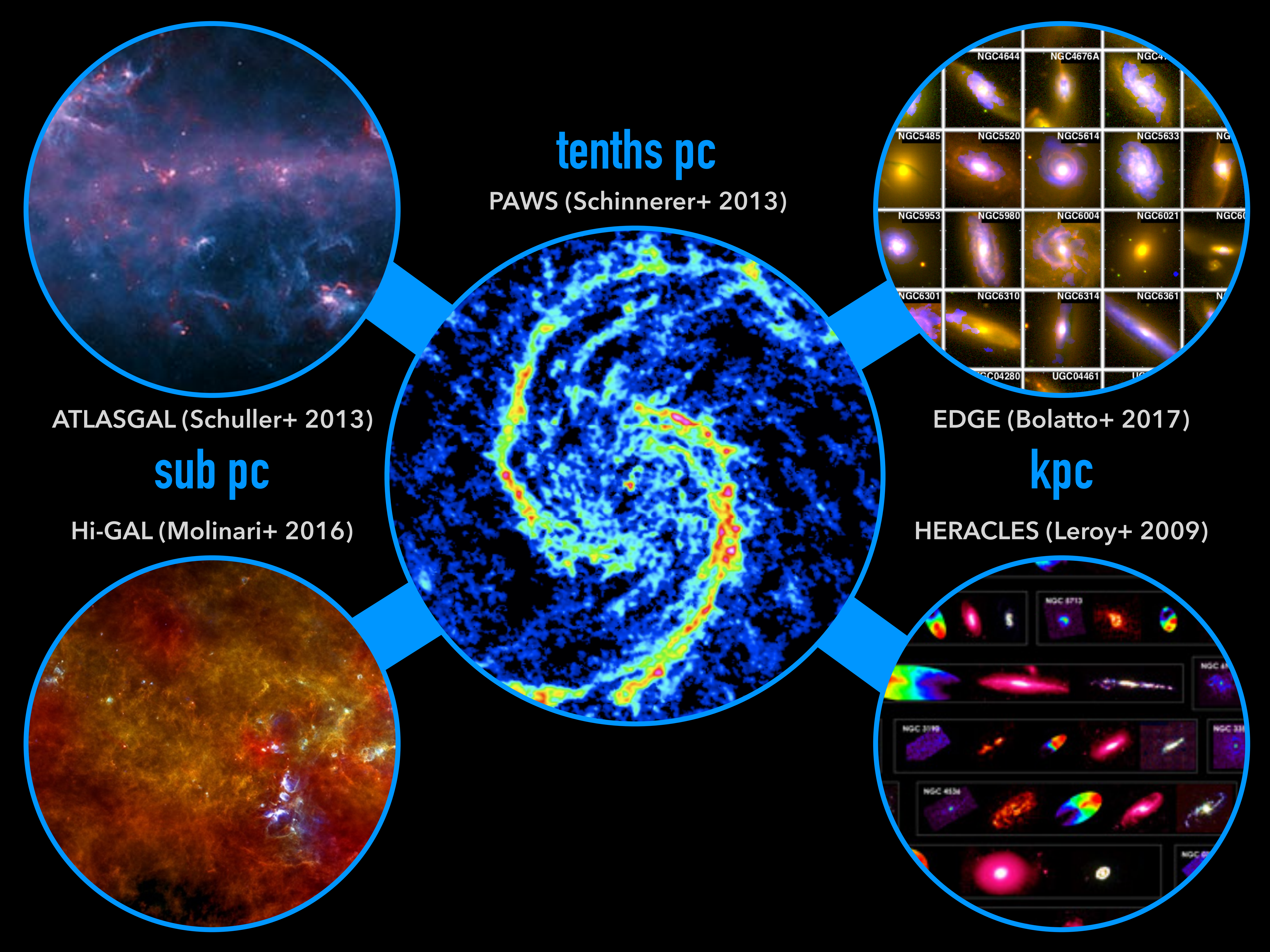
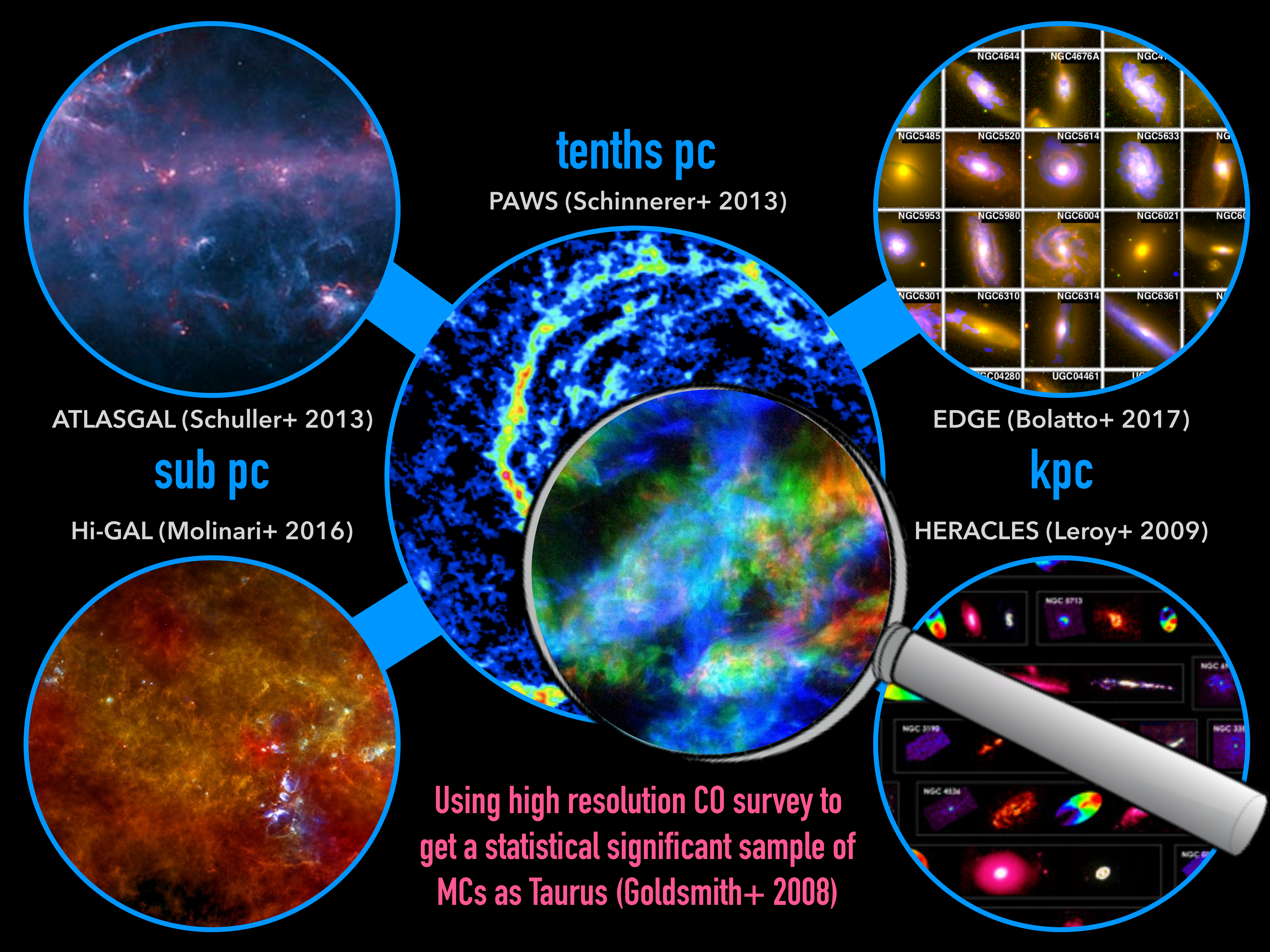
THE RESOLVED PROPERTIES OF THE MOLECULAR CLOUDS IN THE INNER AND OUTER GALAXY

AND THE GALAXY CENTER

Dario Colombo (MPIfR)

Zooming in on Star Formation, June 11th, 2019


tenths pc
PAWS (Schinnerer+ 2013)
ATLASGAL (Schuller+ 2013)
sub pc
Hi-GAL (Molinari+ 2016)
EDGE (Bolatto+ 2017)
kpc
HERACLES (Leroy+ 2009)


tenths pc
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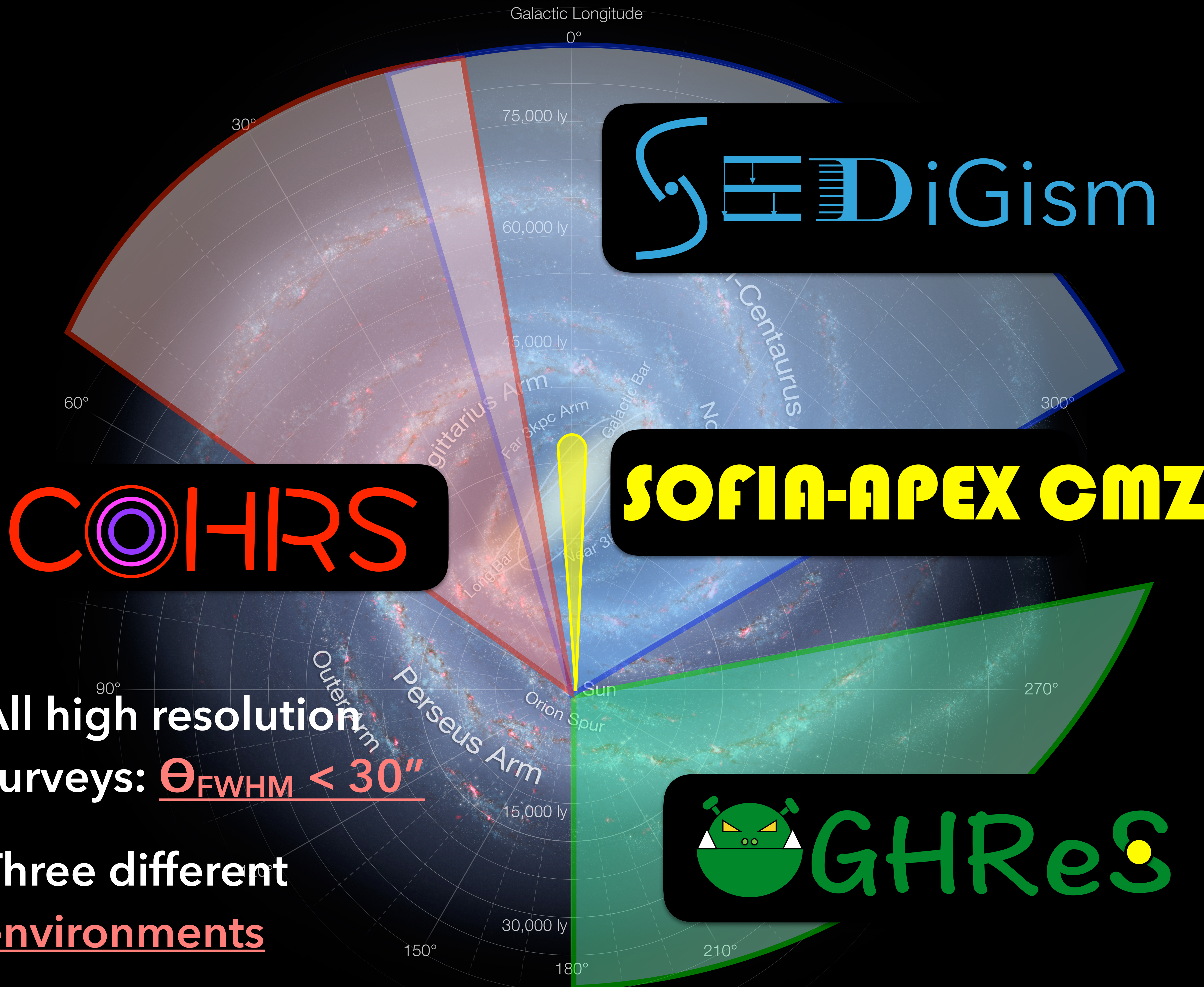
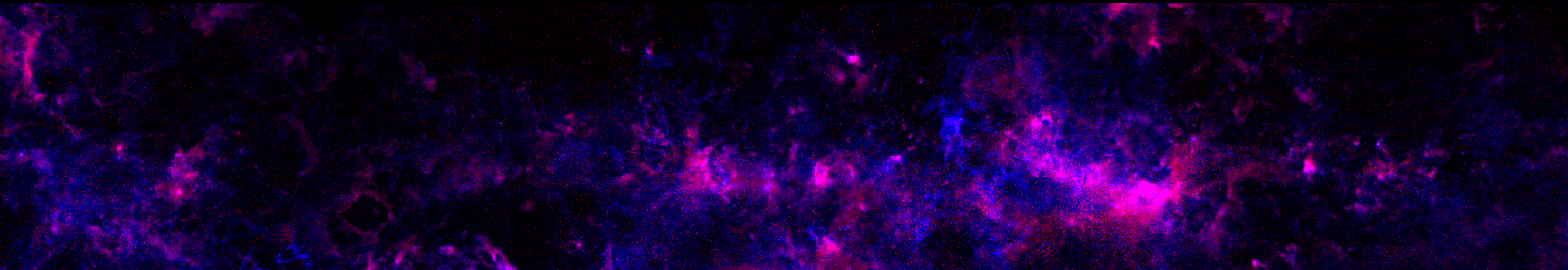
ATLASGAL (Schuller+ 2013)
sub pc
Hi-GAL (Molinari+ 2016)
EDGE (Bolatto+ 2017)
kpc
HERACLES (Leroy+ 2009)
Using high resolution CO survey to
get a statistical significant sample of
MCs as Taurus (Goldsmith+ 2008)



- All high resolution surveys: $\theta_{FWHM} < 30''$
- Three different environments

Inner Galaxy



COHRS 12CO(3-2): blue, SEDIGISM 13CO(2-1): red

COHRS

Dempsey et al. 2013

CO High Resolution Survey

JCMT 12CO(3-2)

$\theta_{FWHM} = 17''$, $\Delta v = 1$ km/s

$10.25 < l < 55.25$

SEDiGism

Schuller et al. 2017

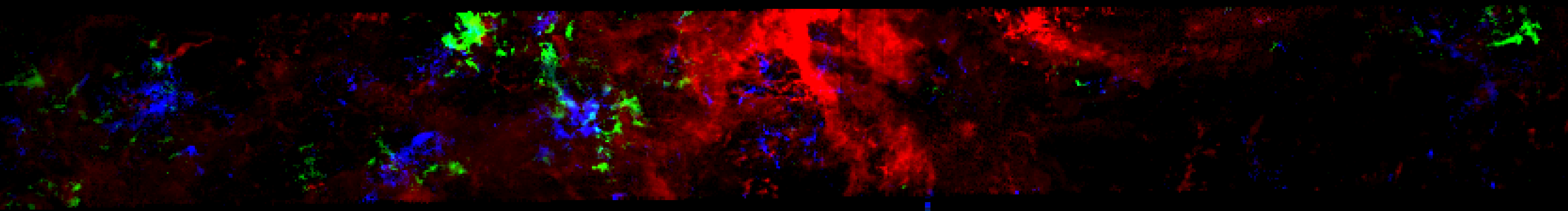
Structure, excitation, and dynamics of the inner Galactic interstellar medium

APEX 13CO(2-1) , C18O(2-1)

$\theta_{FWHM} = 28''$, $\Delta v = 0.25$ km/s

$15 < l < 300$

Outer Galaxy



$V_{LSR} < 25$ km/s: red, $25 < V_{LSR} < 60$ km/s: green, $V_{LSR} > 60$ km/s: blue

local emission — outer Galaxy emission

GHReS

Outer Galaxy High Resolution Survey

APEX 12CO(2-1), 13CO(2-1), C18O(2-1)

$\theta_{FWHM} = 27''$, $\Delta v = 0.25$ km/s

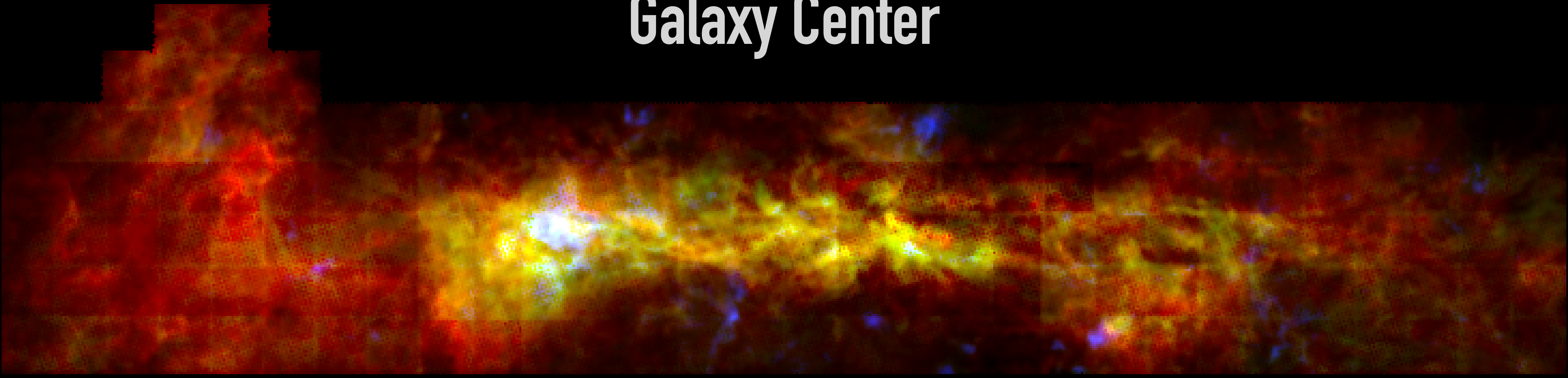
Sensitivity ~ 0.45 K

$180 < l < 280$, $b \sim 1$ => ~ 60 deg^2 currently mapped

People

C. Koenig (PI, MPIfR)
D. Colombo (MPIfR)
J. Urquhart (U. Kent)
F. Wyrowski (MPIfR)
A. Giannetti (INAF)
J. Brand (INAF)
T. Moore (U. Liverpool)
F. Schuller (CEA)
K. Menten (MPIfR)
R. Guesten (MPIfR)
M. Wienen (U. Exeter)
M.-Y. Lee (MPIfR)
P. Mazumdar (MPIfR)
S. Leurini (INAF)

Galaxy Center



12CO(2-1): red, 13CO(2-1): green, C18O(2-1): blue

SOFIA-APEX CMZ

APEX 12CO(2-1), 13CO(2-1), C18O(2-1)
CH3OH, HNCO, H2S …

$\theta_{FWHM} = 27''$, $\Delta v = 0.5$ km/s

Sensitivity ~ 60 mK

$-1.3 < l < 1.8$

SOFIA upGREAT [CII]

$\theta_{FWHM} = 14''$

$-0.5 < l < 0.7$

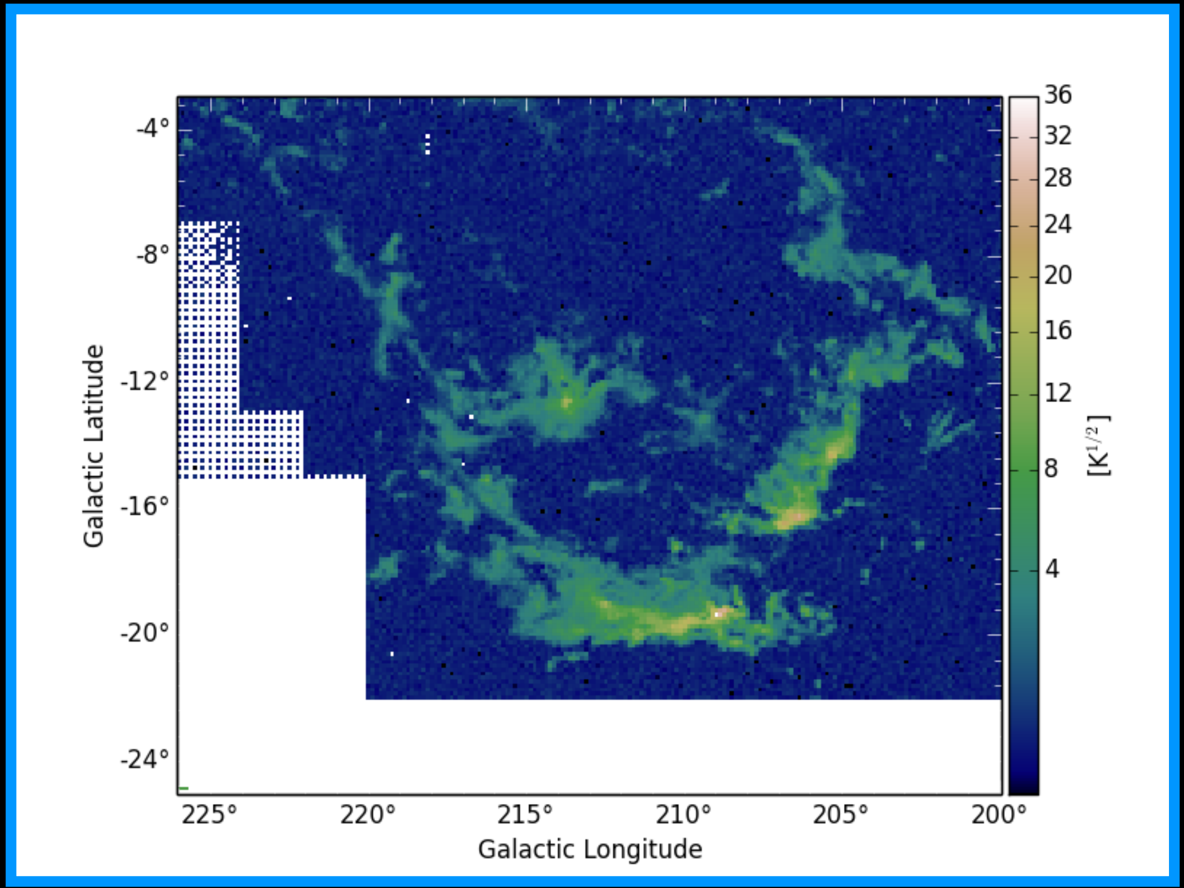
People

R. Güsten (PI, MPIfR)

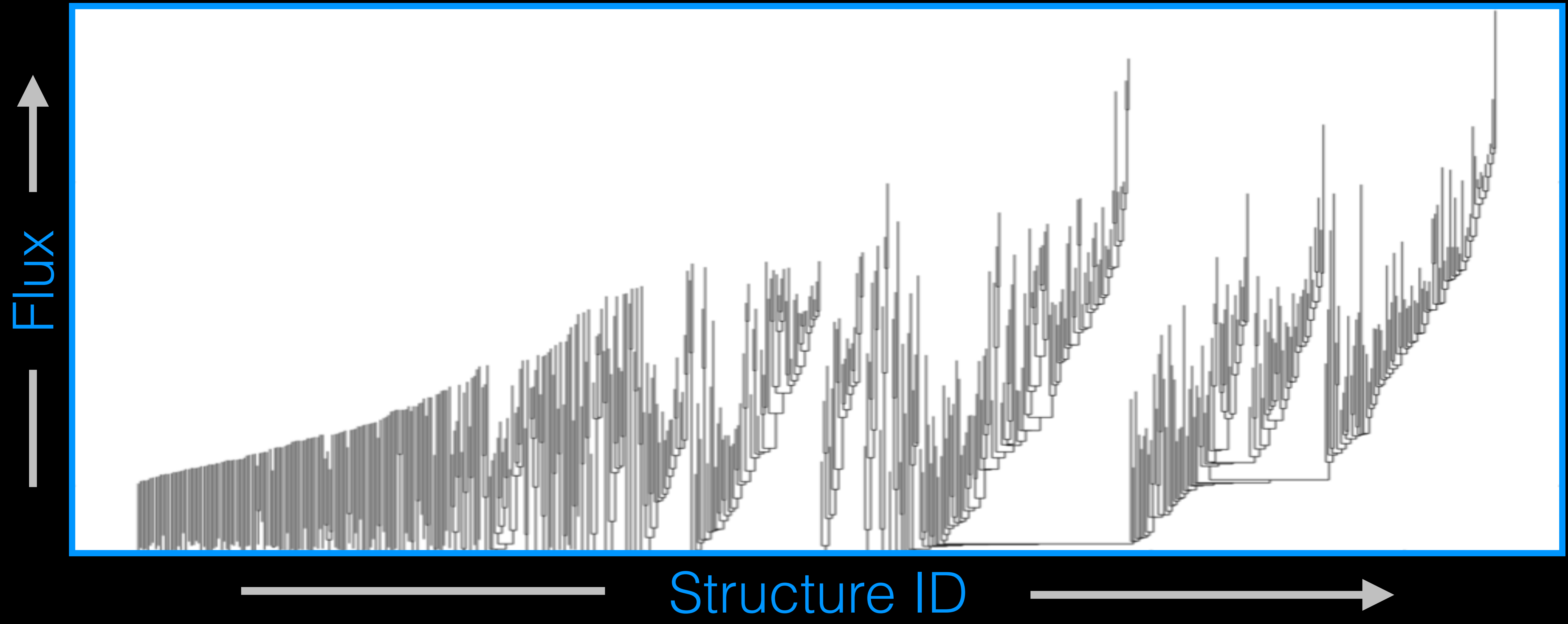
A. Harris (UMD)

D. Riquelme (MPIfR)

D. Colombo (MPIfR)



Galactic Latitude
Galactic Longitude
-4°
-8°
-12°
-16°
-20°
-24°
225°
220°
215°
210°
205°
200°
36
32
28
24
20
16
12
8
4
[K$^{1/2}$]



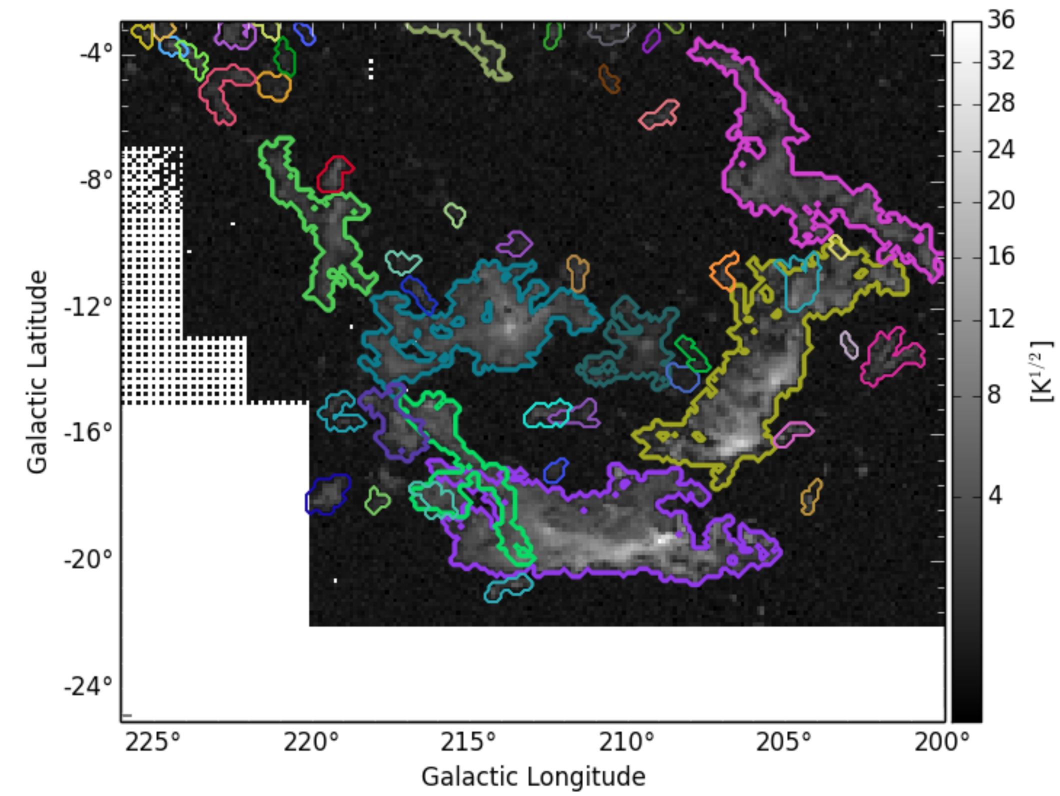
Flux
Structure ID

Colombo et al. 2015,
https://github.com/Astroua/SCIMES

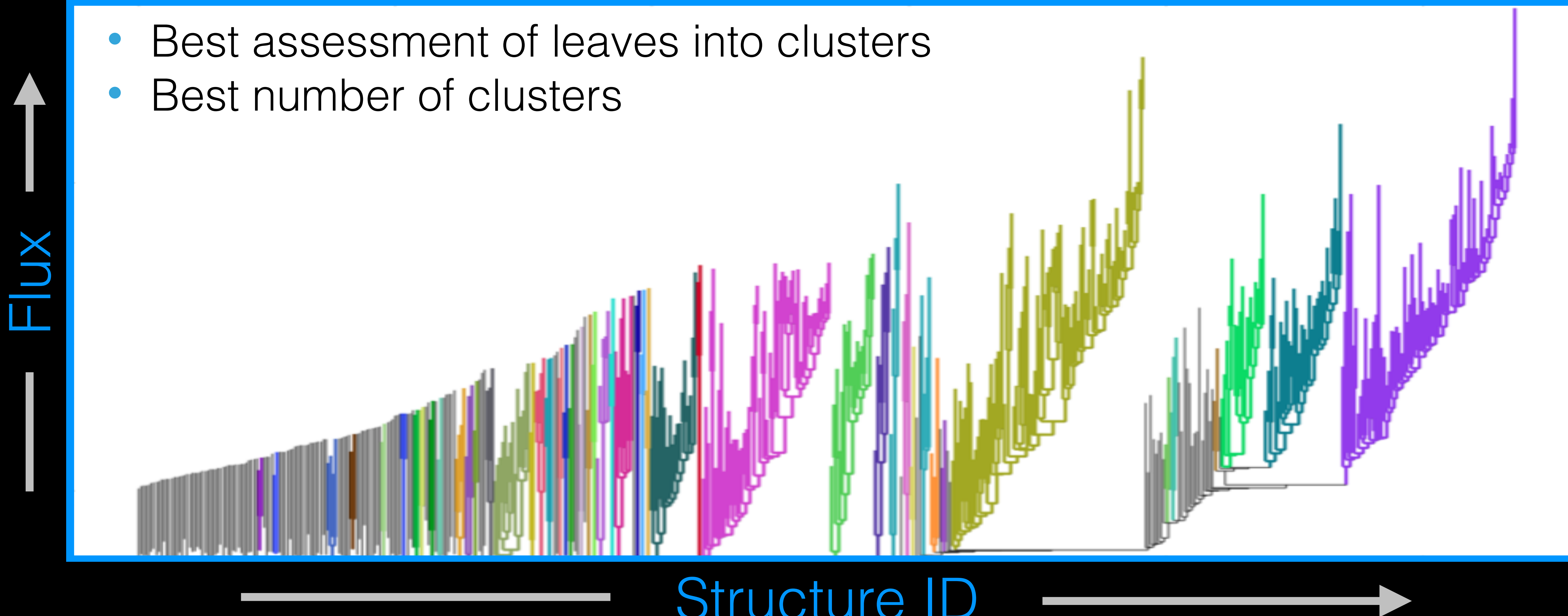
SCIMES

Spectral Clustering for Interstellar Molecular Emission Segmentation

New release v0.3.2 available on Github!



- Best assessment of leaves into clusters
- Best number of clusters

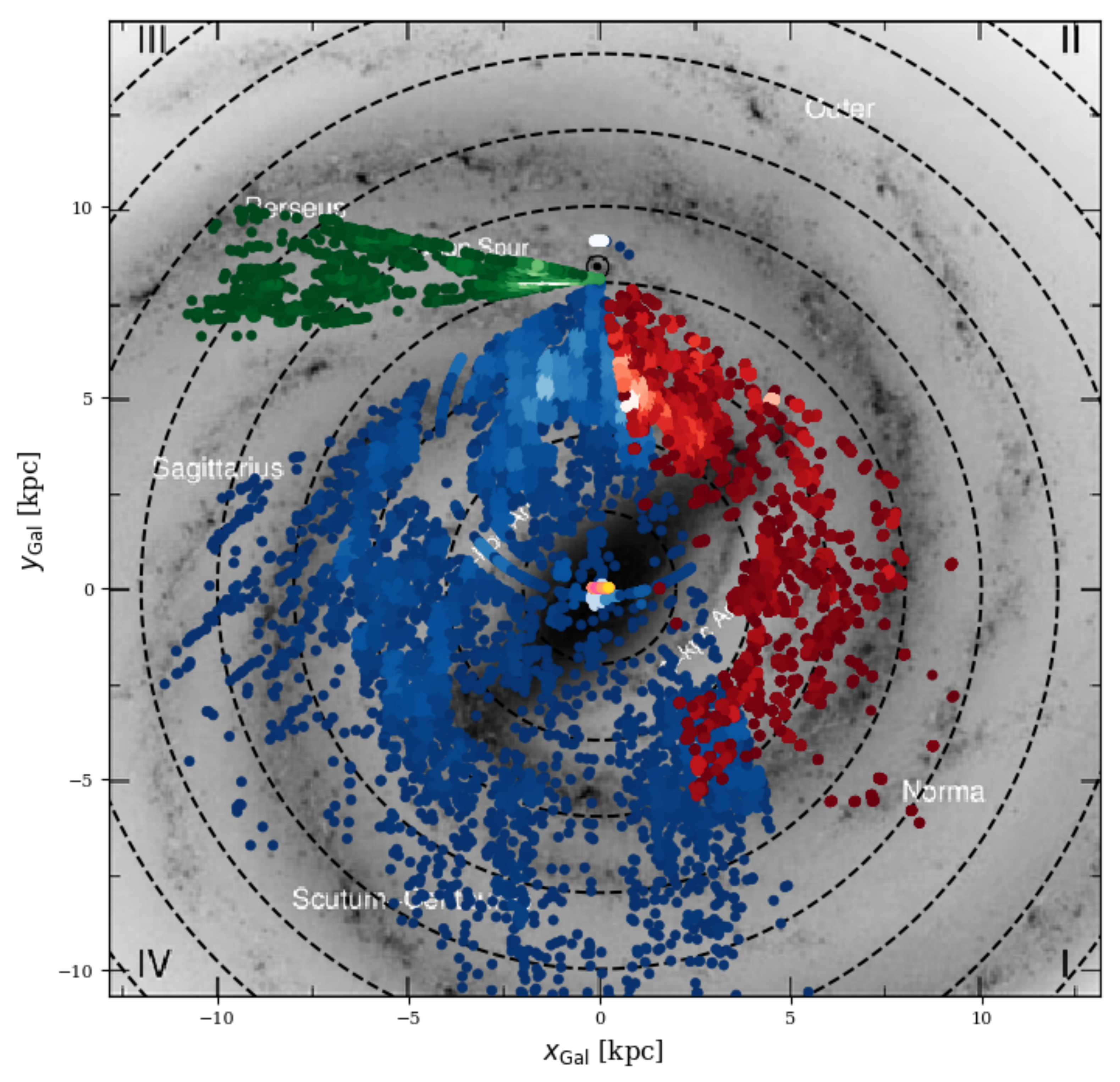


GHReS

COHRS

4405 well resolved objects

Colombo, König, Urquhart et al. in prep.



35560 well resolved objects

Colombo, Rosolowsky, Duarte-Cabral et al. 2019

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

8634 well resolved objects

Riquelme, Colombo, Güsten et al. in prep.

4980 well resolved objects

SEDiGism

SOFIA-APEX CMZ

GHReS

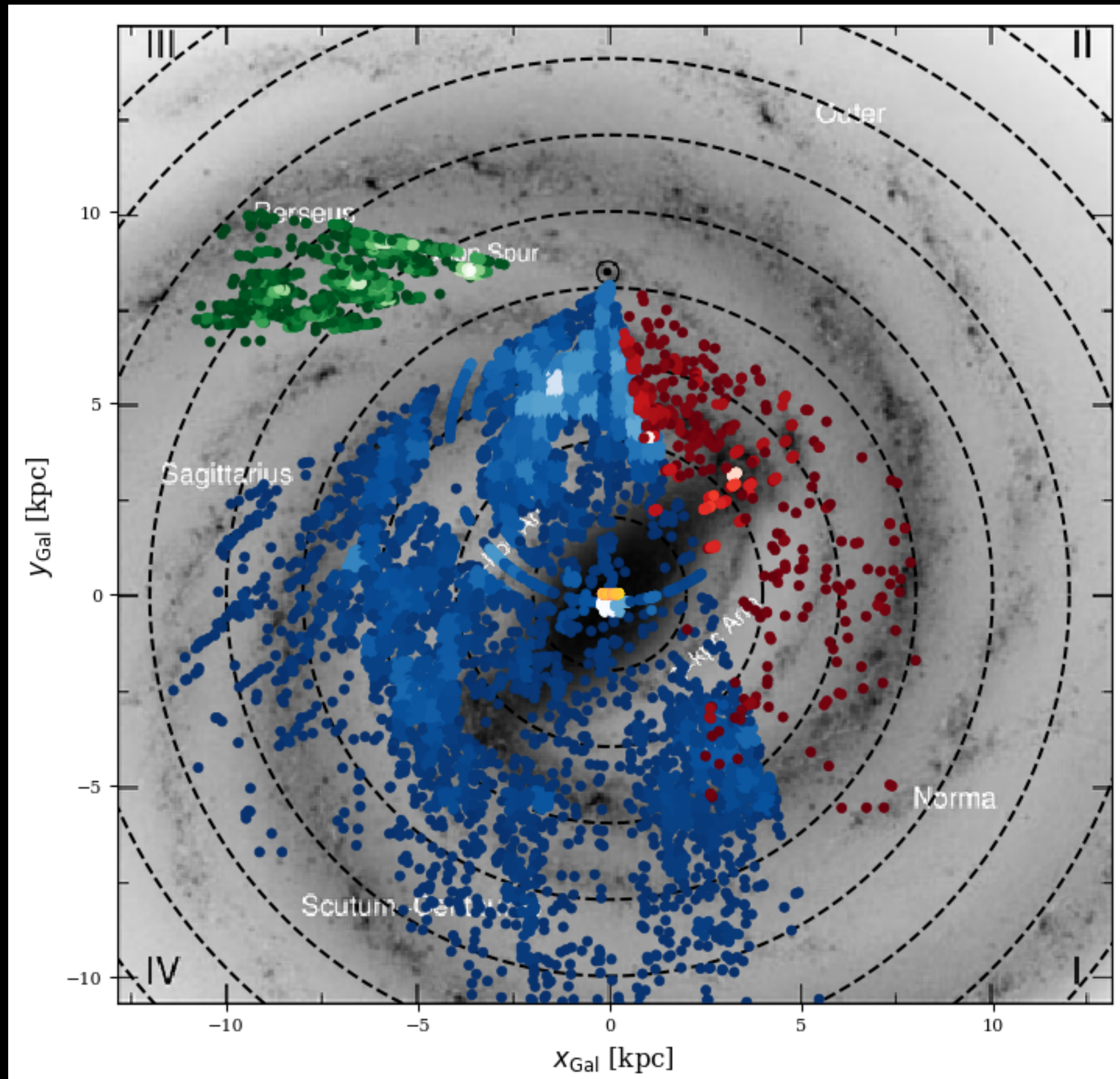
COHRS

1286 objects with V_{LSR} > 24 km/s

Colombo, König, Urquhart et al. in prep.

540 objects with reliable distance

Colombo, Rosolowsky, Duarte-Cabral et al. 2019



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

8365 objects with reliable distance

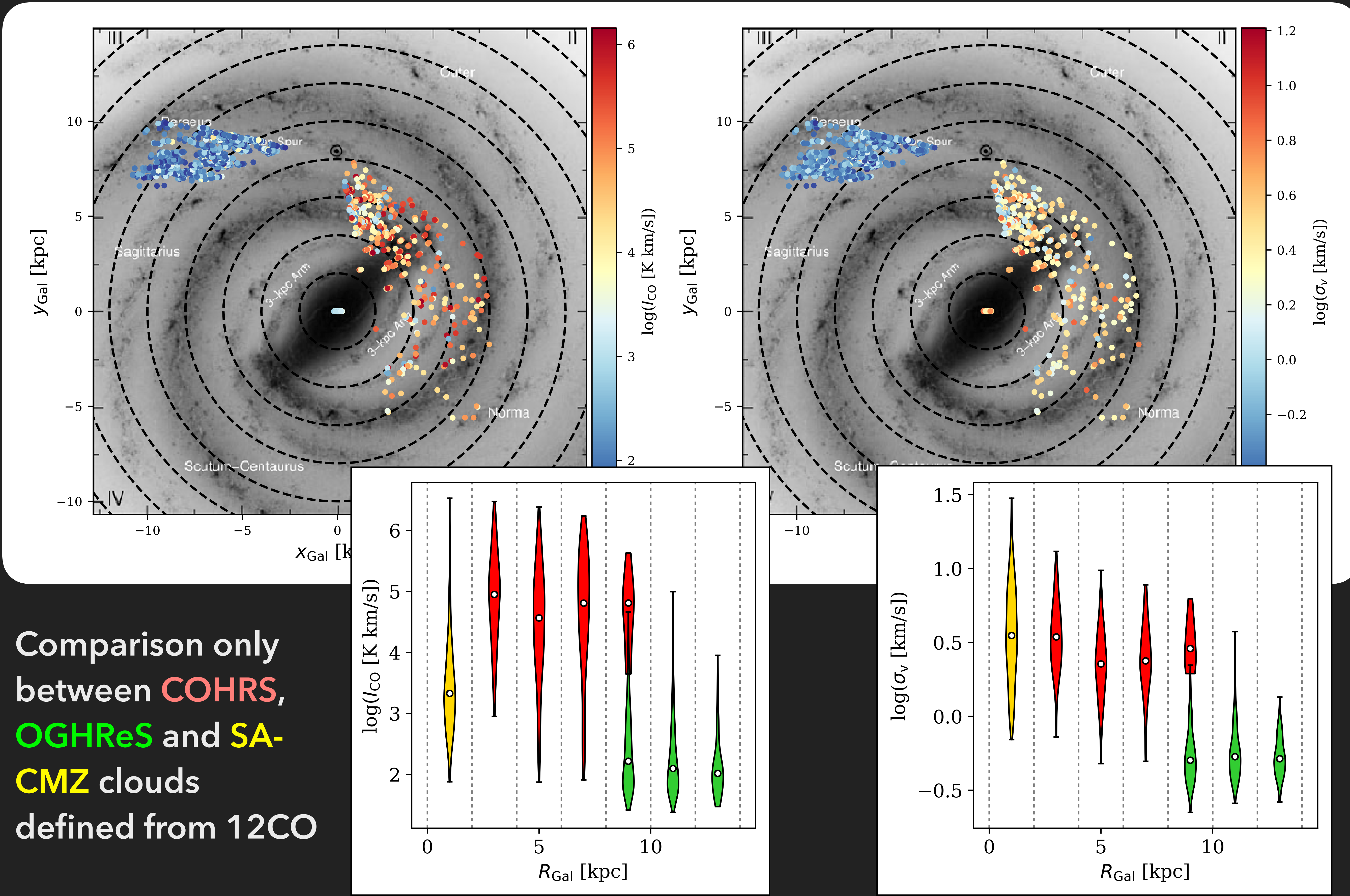
Riquelme, Colombo, Güsten et al. in prep.

662 objects with N_{leaves} > 1

SEDiGism

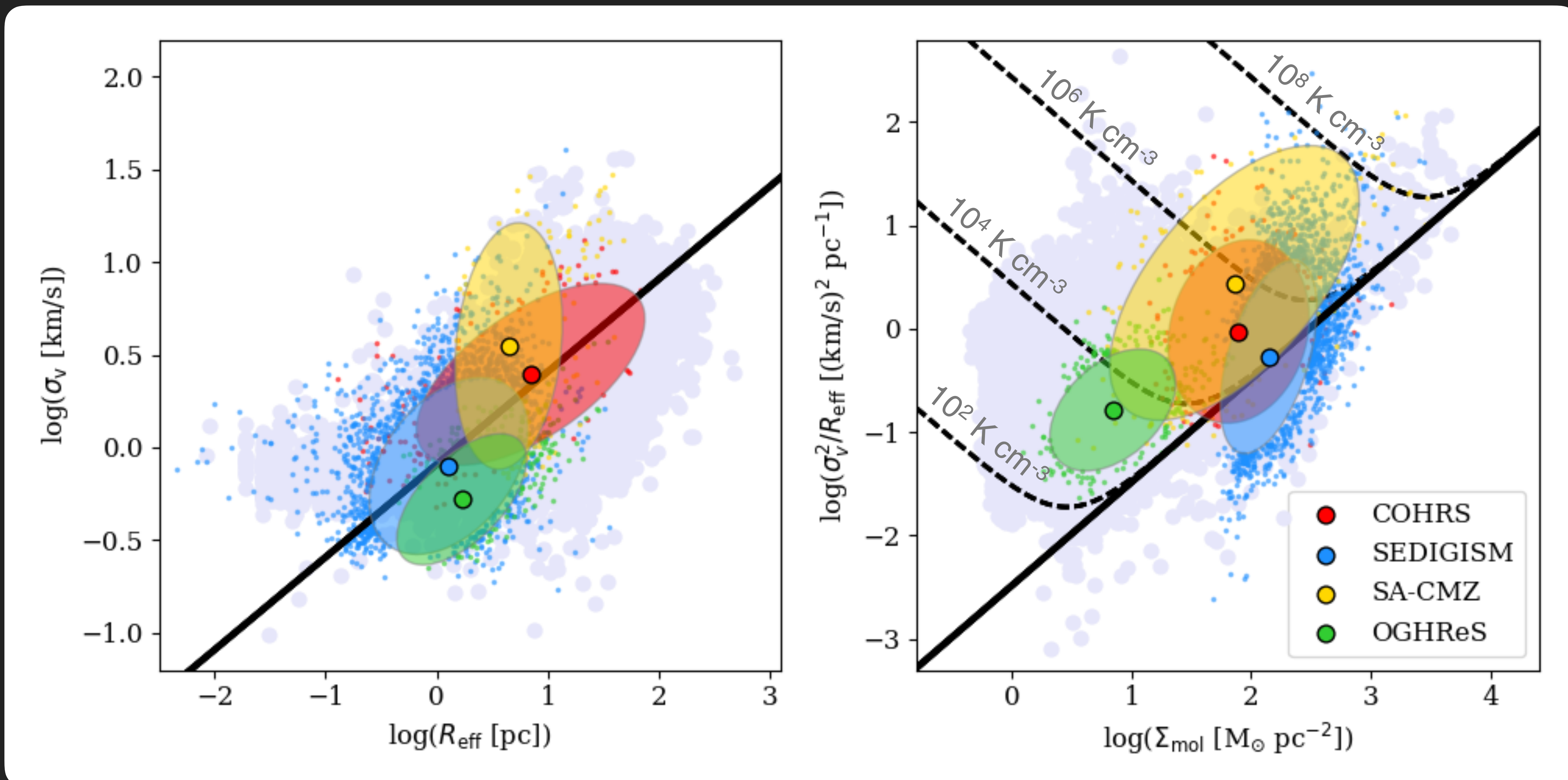
SOFIA-APEX CMZ

Cloud property gradients across Galactic environments



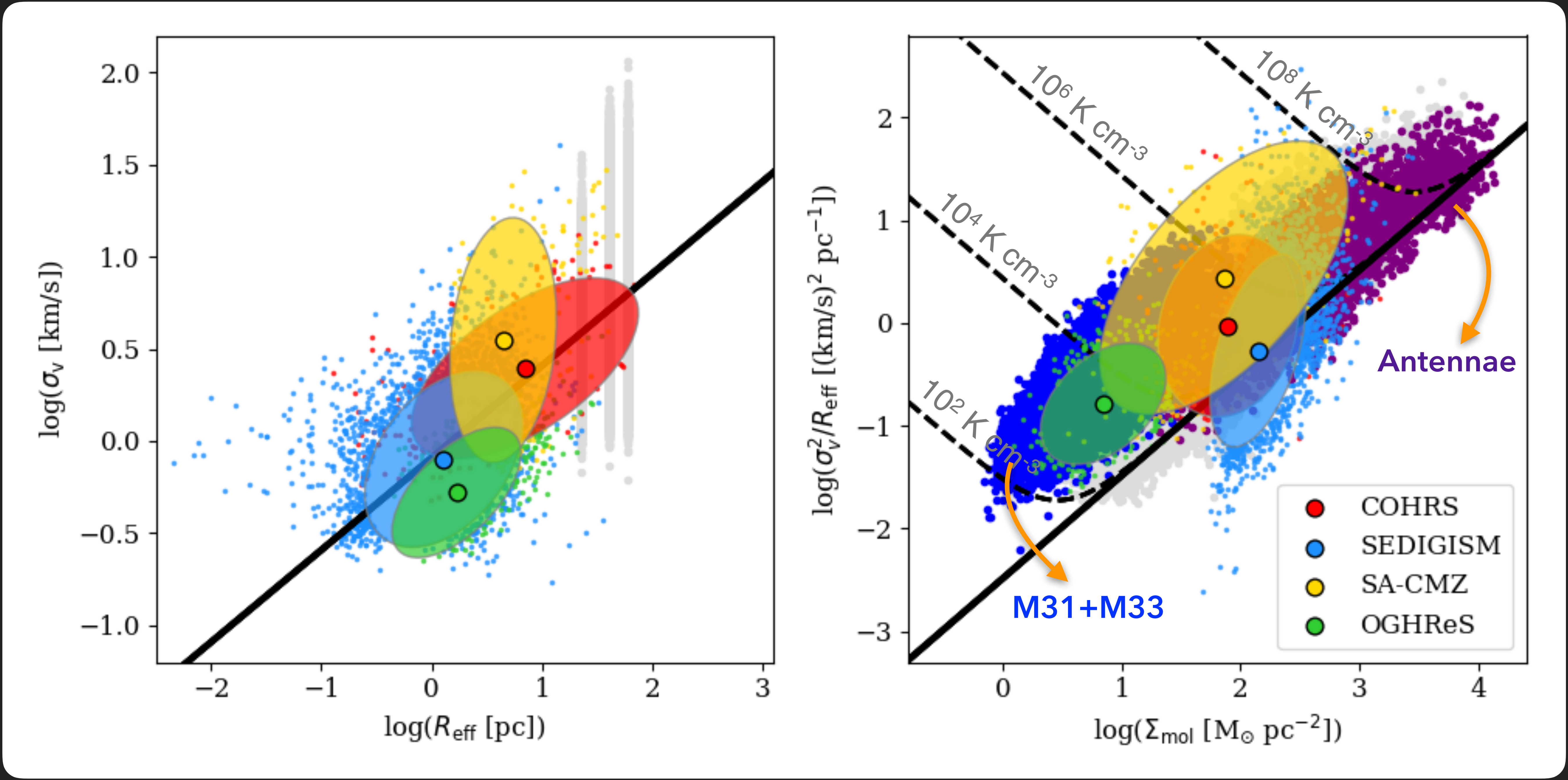
Comparison only between COHRS, OGHReS and SA-CMZ clouds defined from 12CO

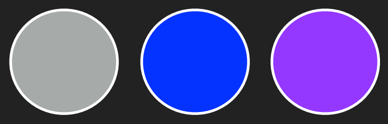
Scaling relations across Galactic environments



Milky Way compilation: *Inner Galaxy* (Roman-Duval+ 2009, Heyer+ 2009), *Galaxy Center* (Oka+ 2001), *Outer Galaxy* (Heyer+ 2001), *Whole Galaxy* (Rice+ 2016, Mivielle-Deschenes+ 2017)

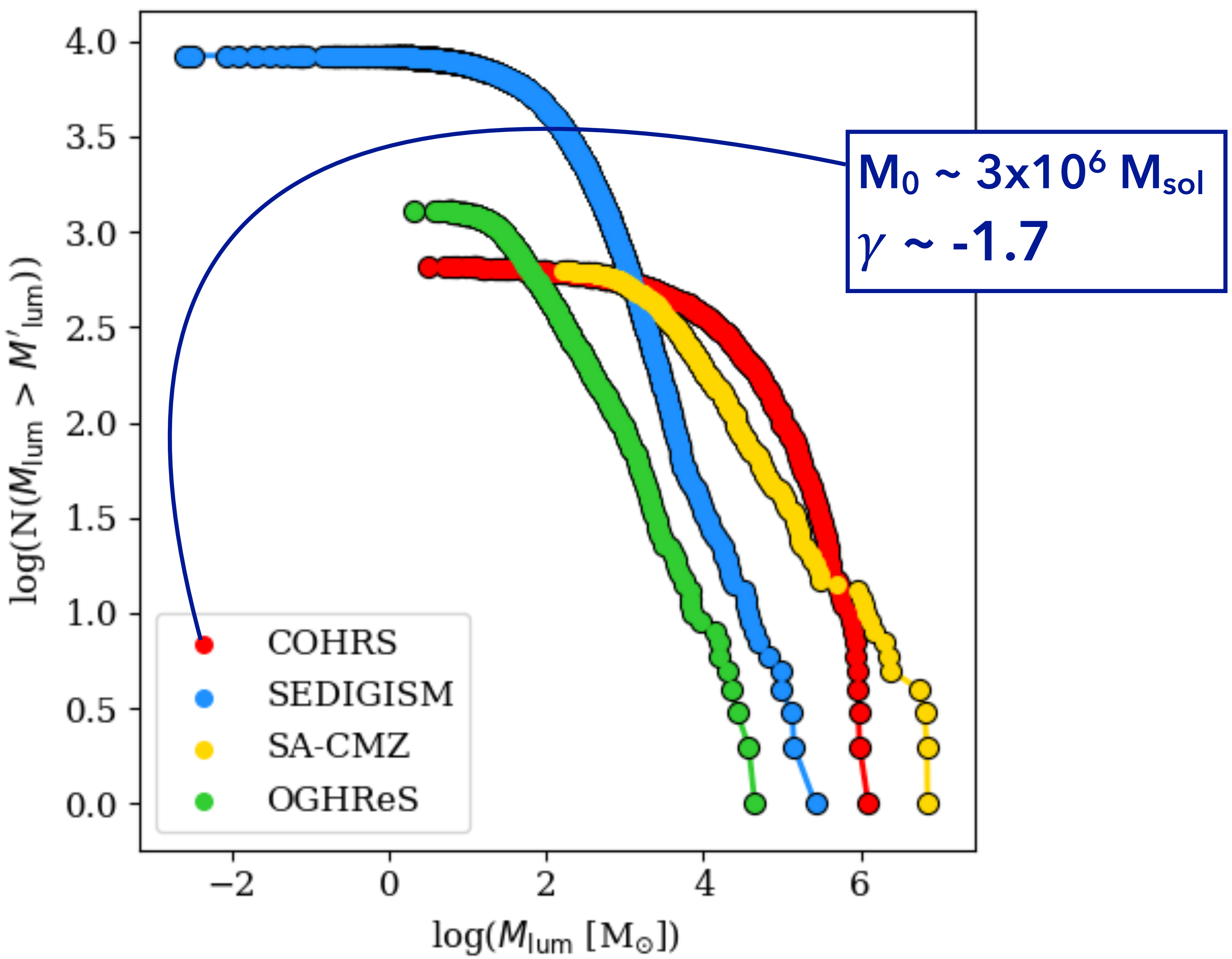
Scaling relations across Galactic environments

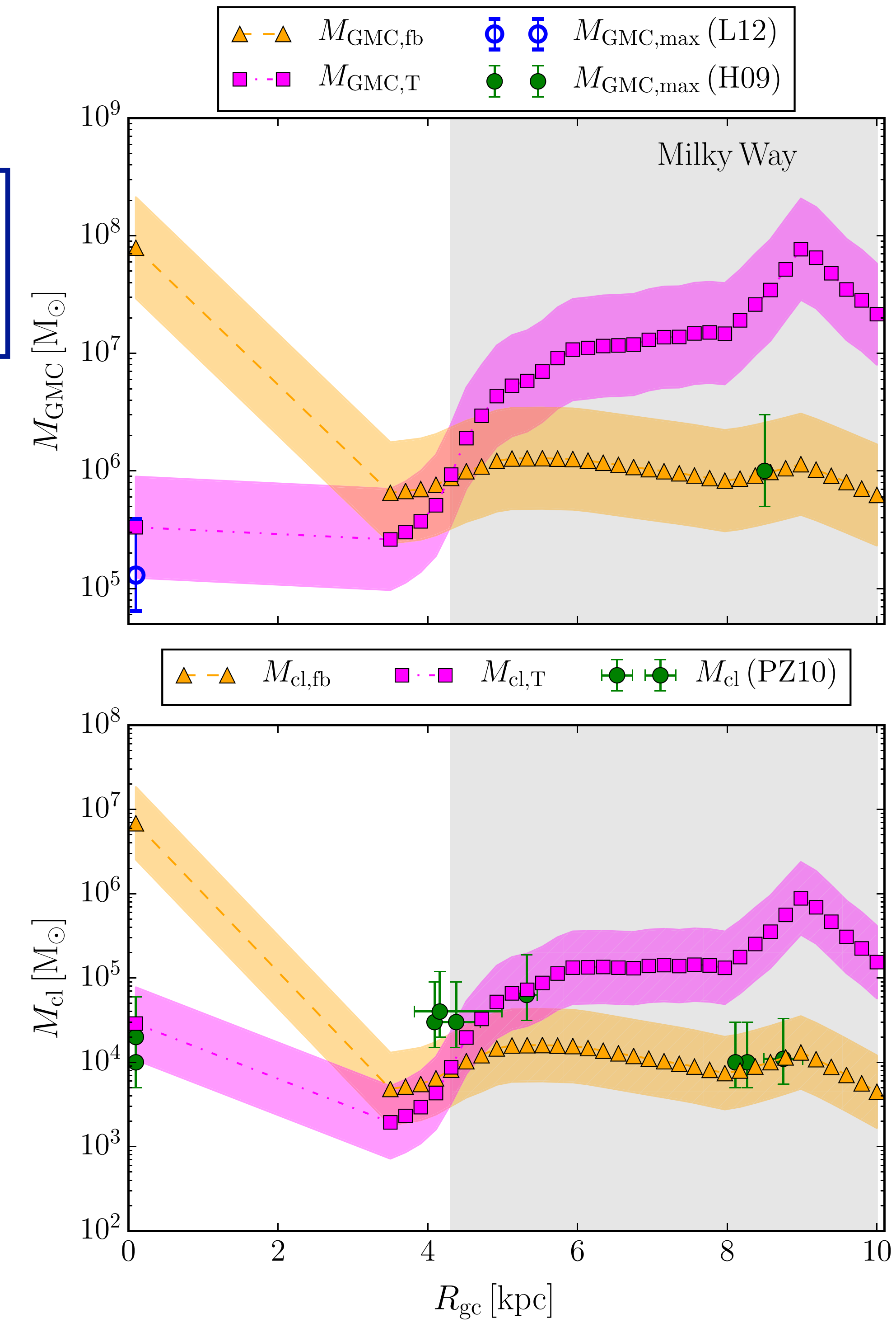




Nearby galaxy compilation from PHANGS (Sun et al. 2018), 12CO beam size measurements

Mass spectra across Galactic environments

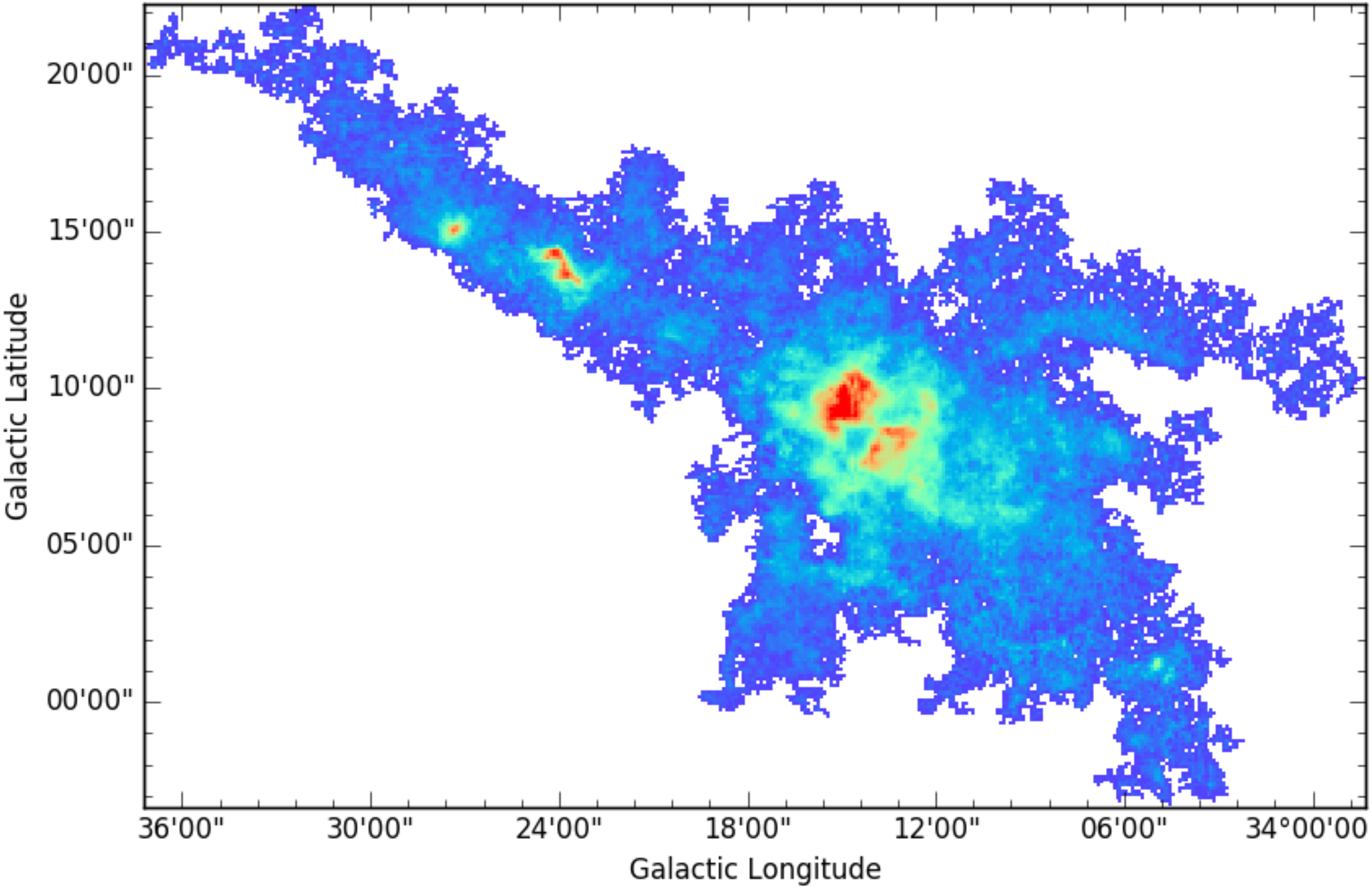




Mass spectra from clouds in different environments show different slopes and truncation values

Observed GMC truncation mass from COHRS consistent with theoretical models of cloud formation controlled by feedback and shear (Reina-Campos & Kruijssen 2017)

Defining morphology for highly resolved clouds

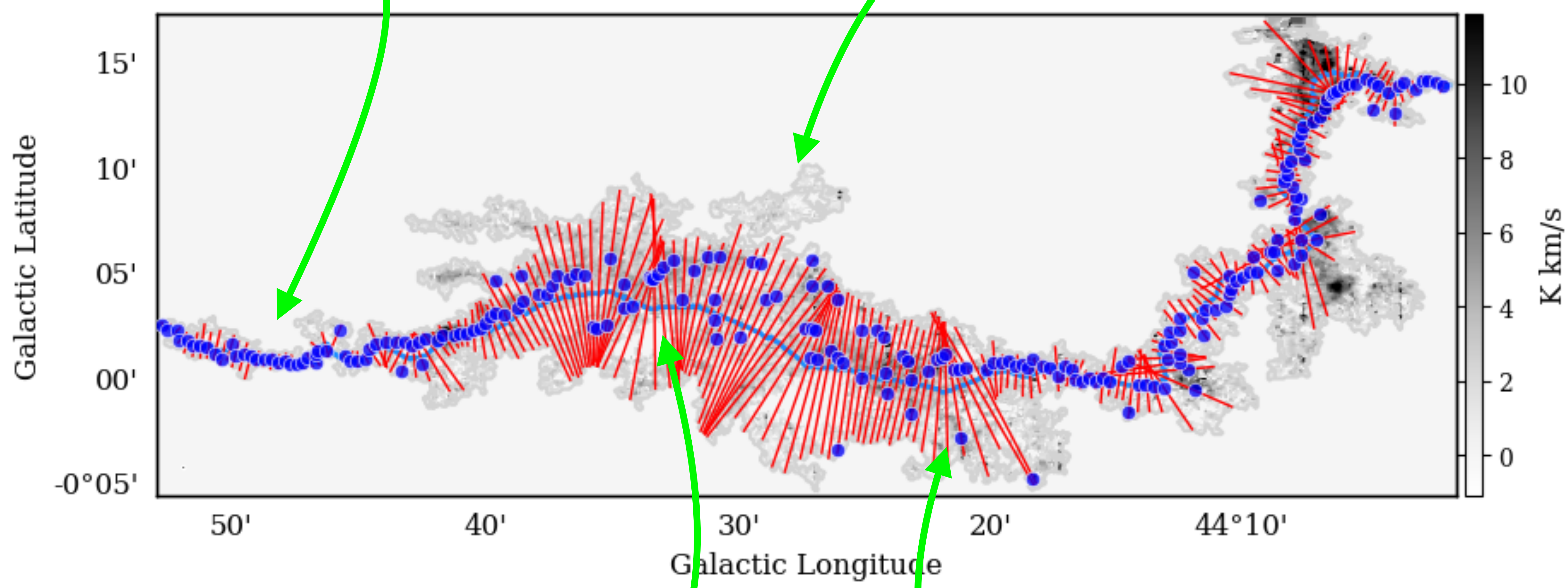


Defining morphology for highly resolved clouds

Cloud skeleton from skimage task <u>medial_axis</u>
https://github.com/scikit-image/scikit-image

Removing small branches using SKAN https://jni.github.io/skan/index.html

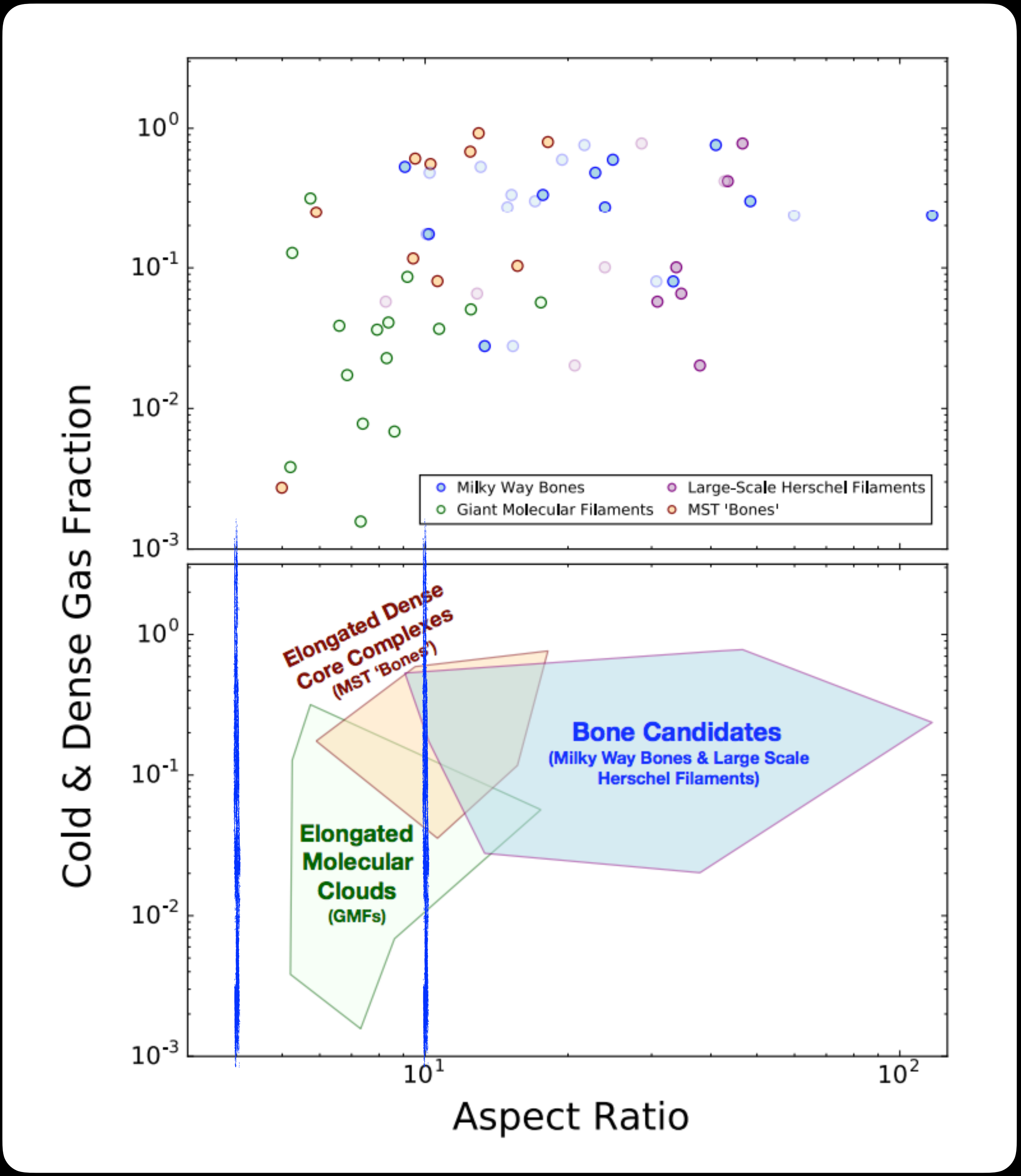
Colombo et al. in prep.

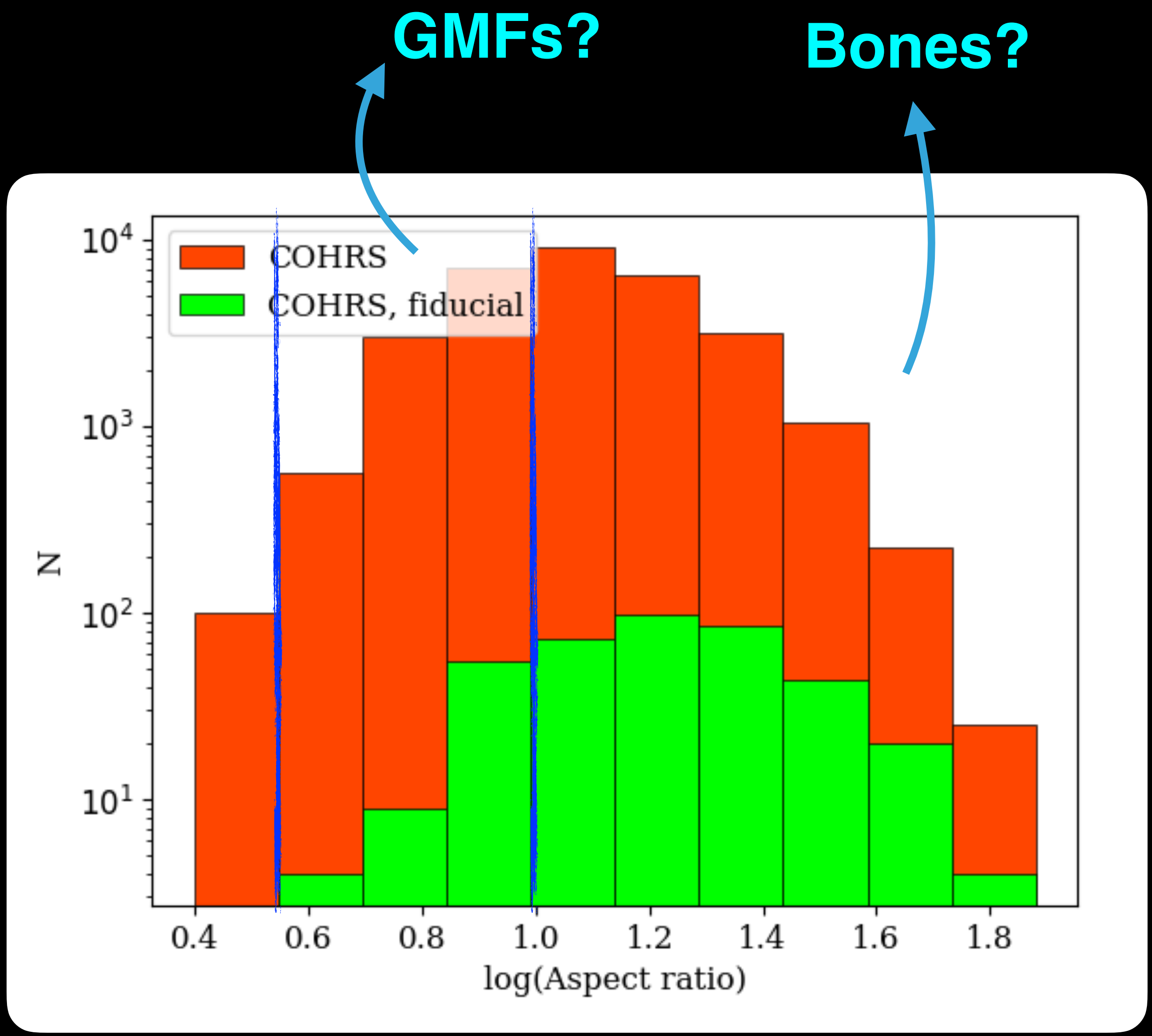


Finding longest path across the skeleton with NetworkX https://networkx.github.io/

Cloud width as median of the perpendicular cuts across cloud spine via RadFil (Zucker et al. 2018b) https://github.com/catherinezucker/radfil

Giant Molecular Clouds or Filaments?





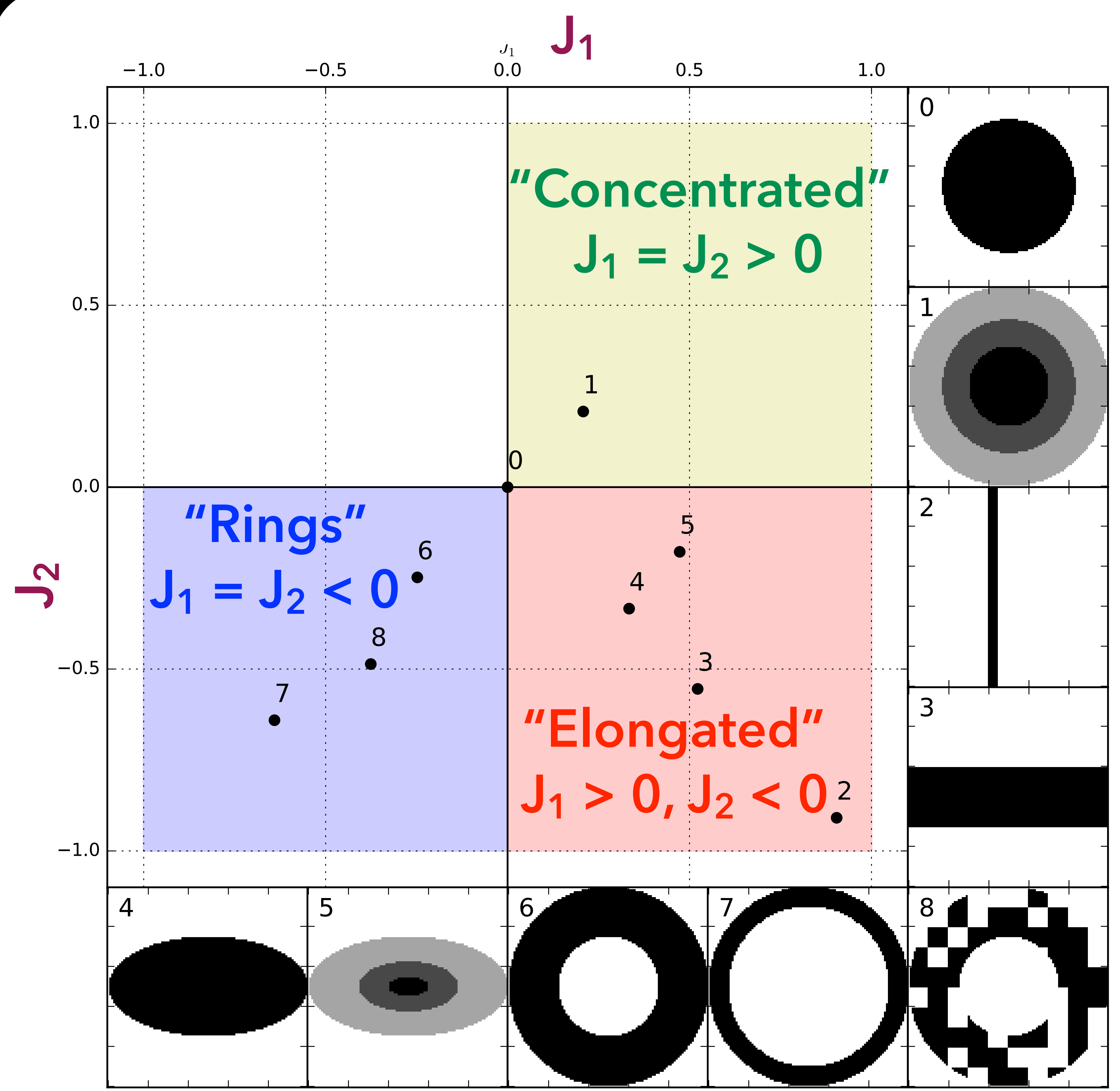
Round: < 1%, 0%

GMFs: 40%, 19%

Bones: 60%, 81%

Zucker et al. 2018a
(see also, e.g. Ragan et al. 2014, Wang et al. 2015)

J-plots



$$I_0 = \frac{AM}{4\pi}$$

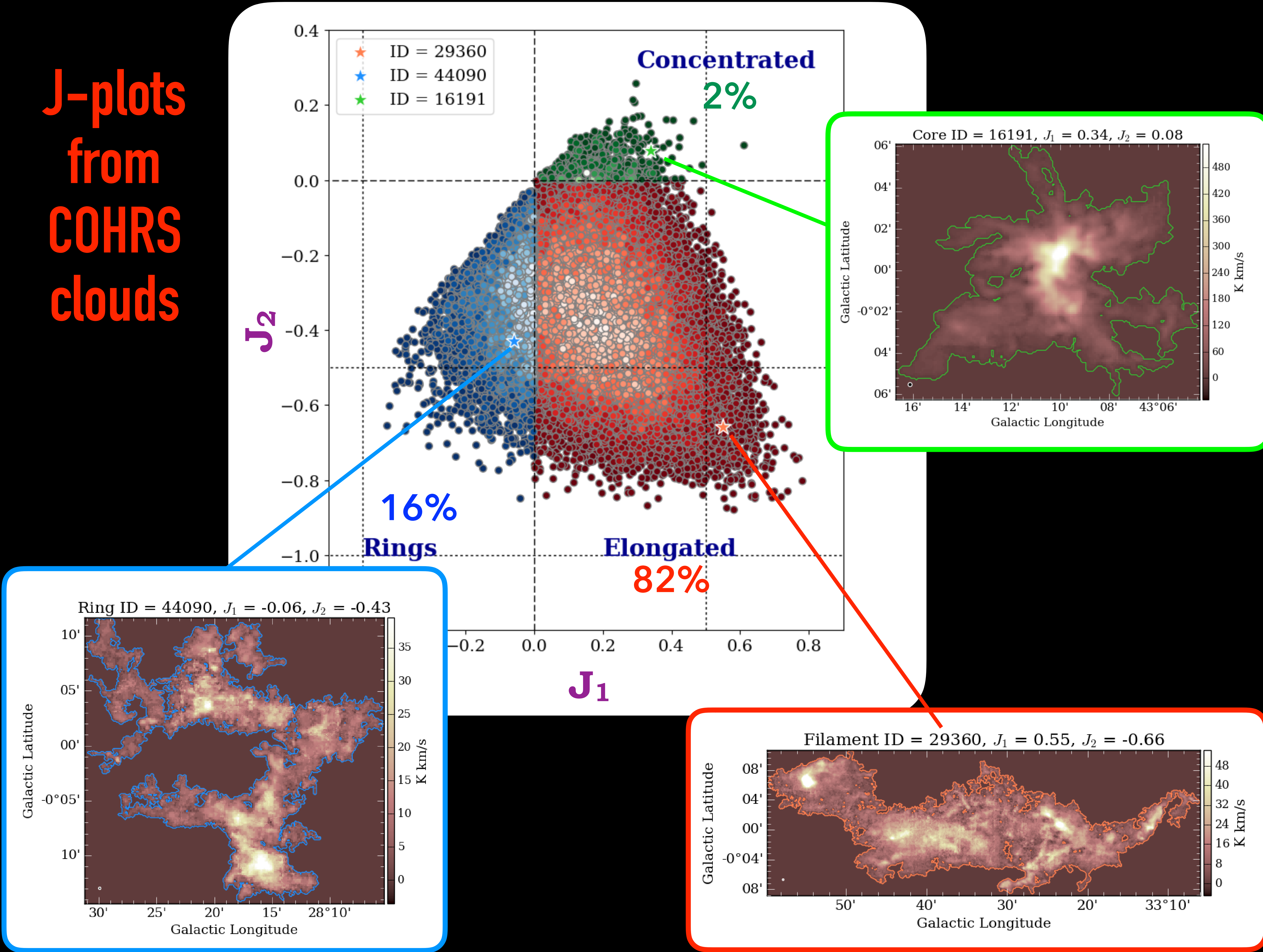
Inertia moment of an uniform circle with area A and mass M

$$J_{1,2} = \frac{I_0 - I_{1,2}}{I_0 + I_{1,2}}$$

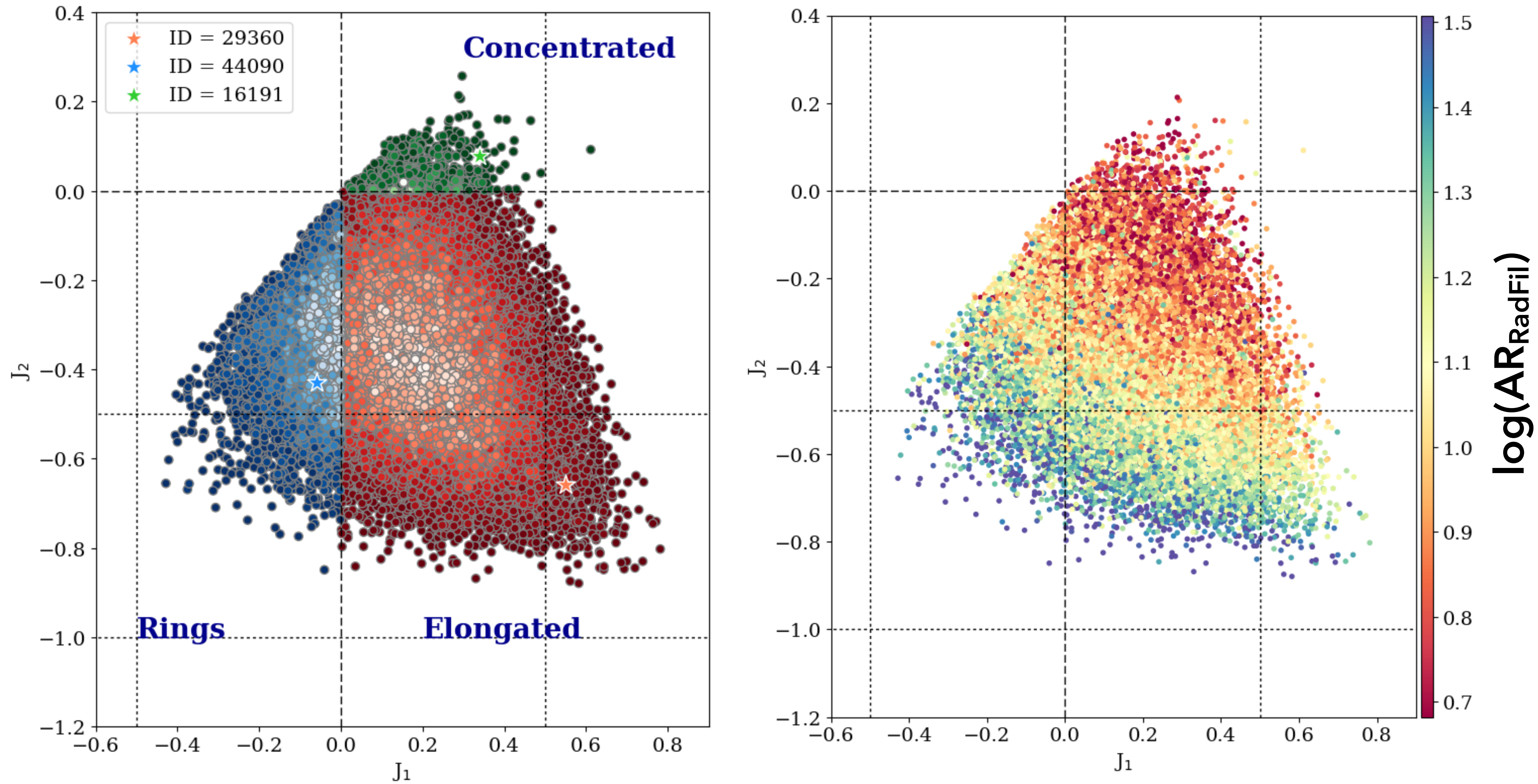
J-moments, with I_1 and I_2 being the inertia moments across the two principal component axis

Jaffa et al. 2018

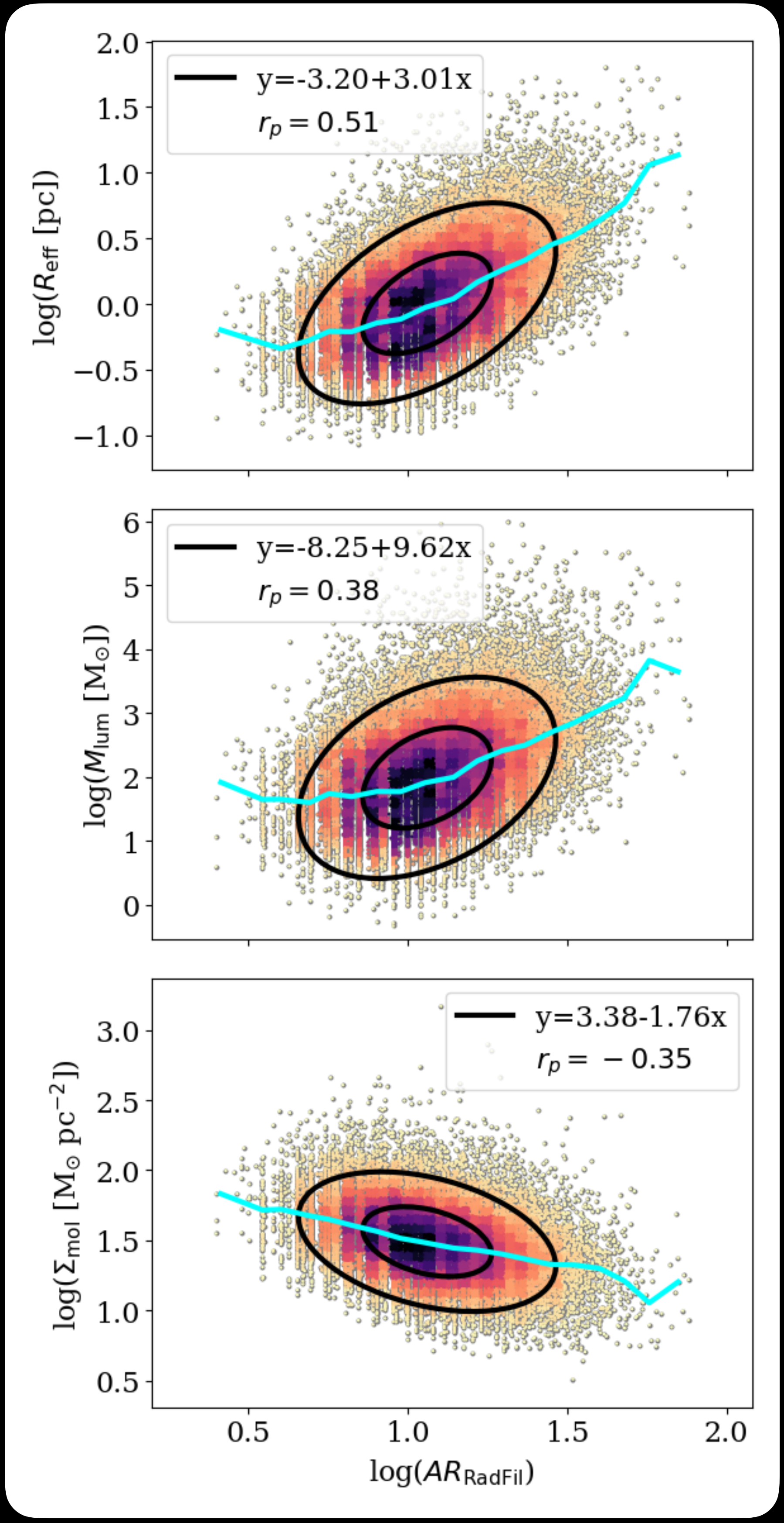
J-plots from COHRS clouds



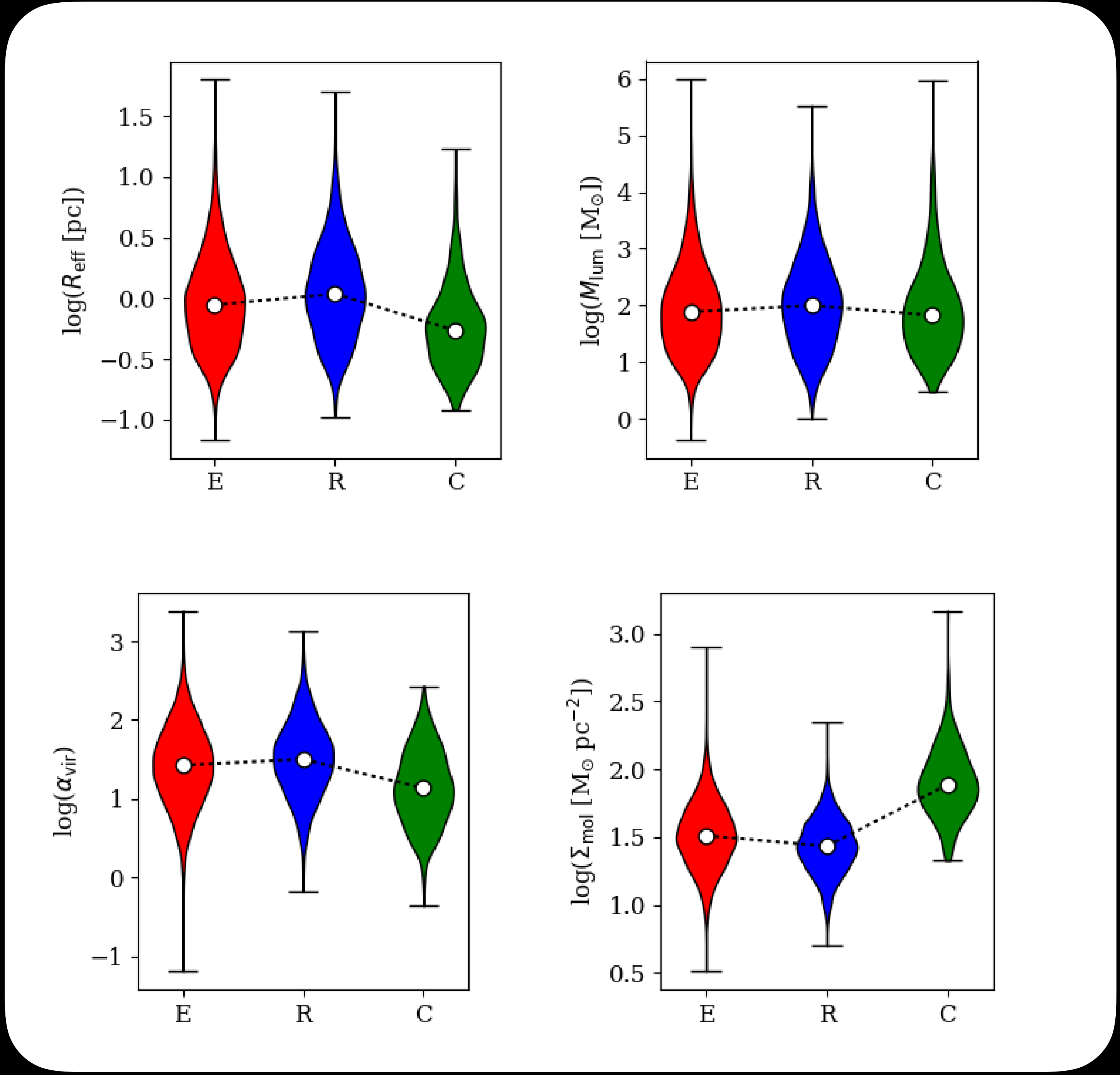
J-plots versus RadFil aspect ratio



Morphology and integrated properties

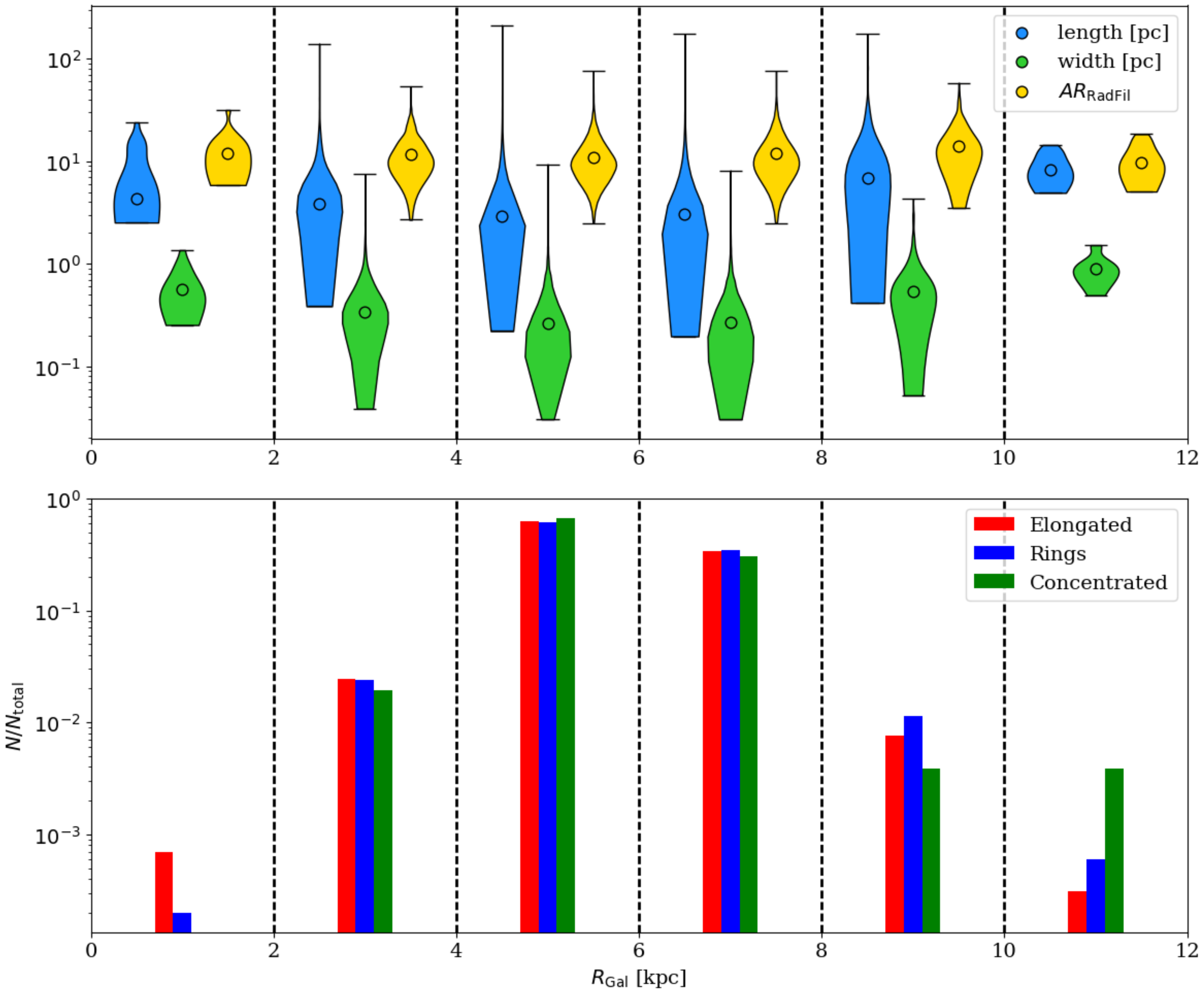


Large and massive objects are also the most elongated.
Those objects are also the less dense.



Concentrated clouds are smaller and denser, closer to virial equilibrium, but not necessary less massive than elongated and ring clouds

Cloud morphology variation with Galactocentric radius

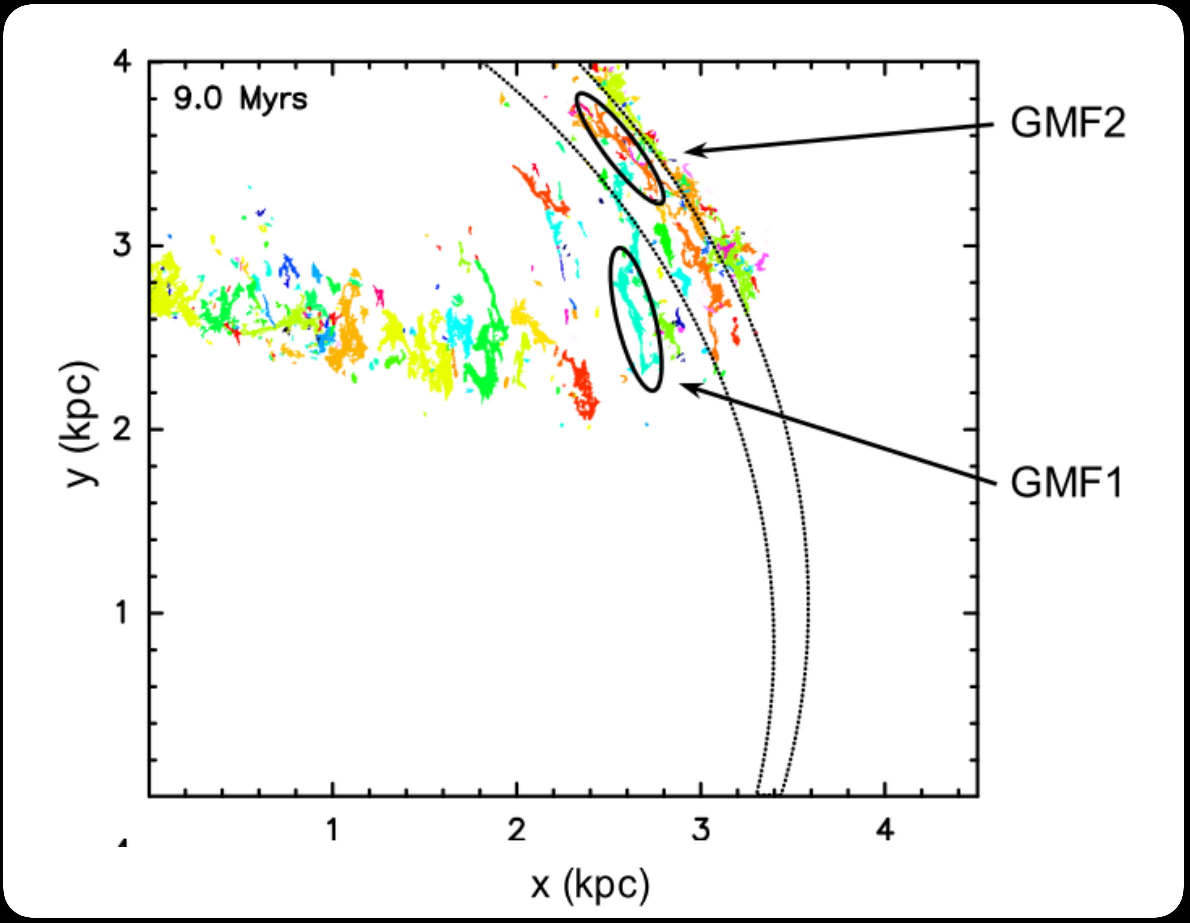


No clear pattern between Galactocentric radius and morphological descriptors from the geometrical medial axis

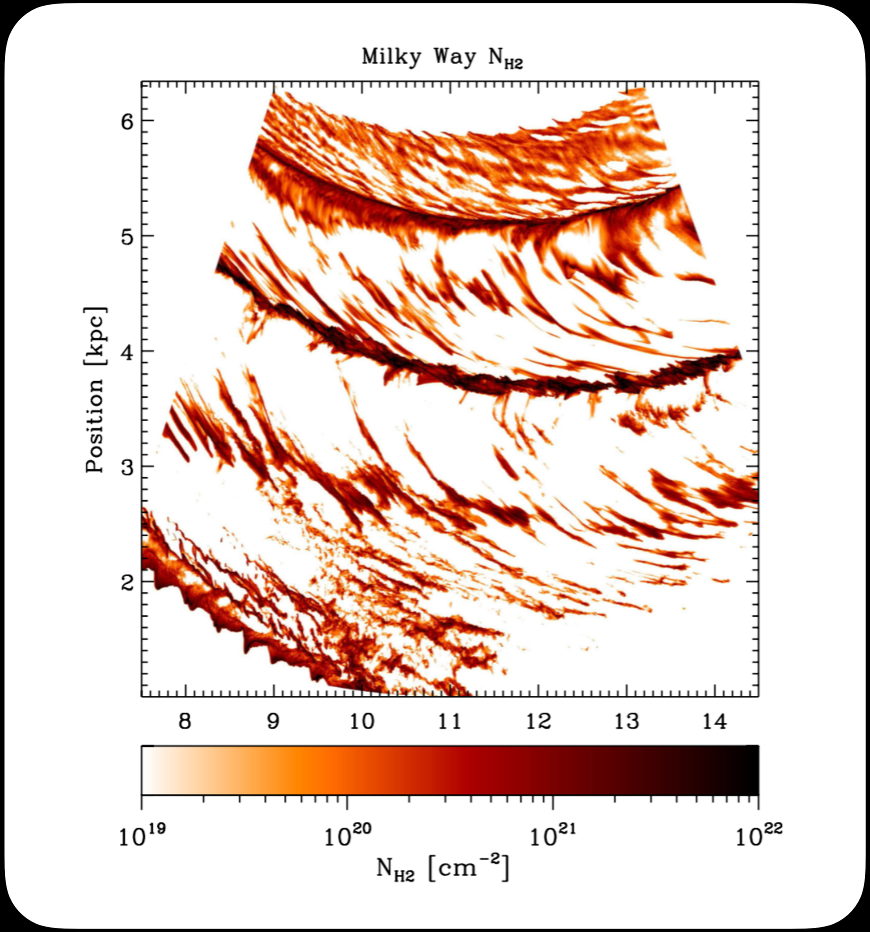
Surplus of elongated and concentrated structures at small and large radii probably due to distance effect

Cloud morphology relation to the spiral arms

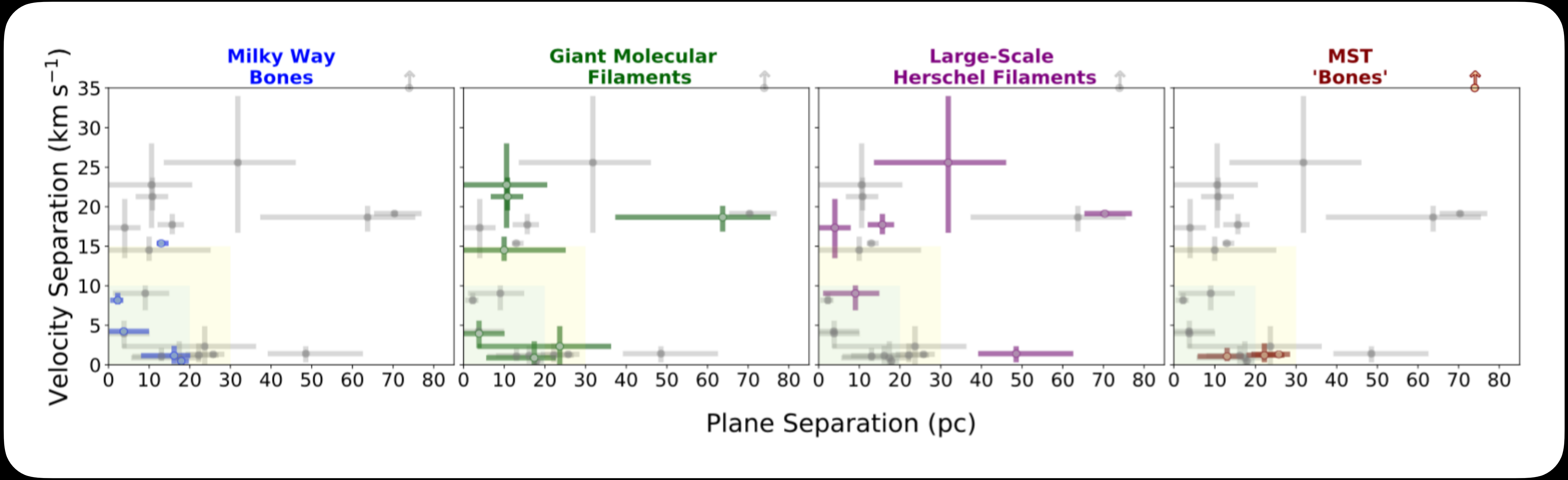
Duarte-Cabral & Dobbs 2016



Simulations show **elongated structures in the inter-arm region**



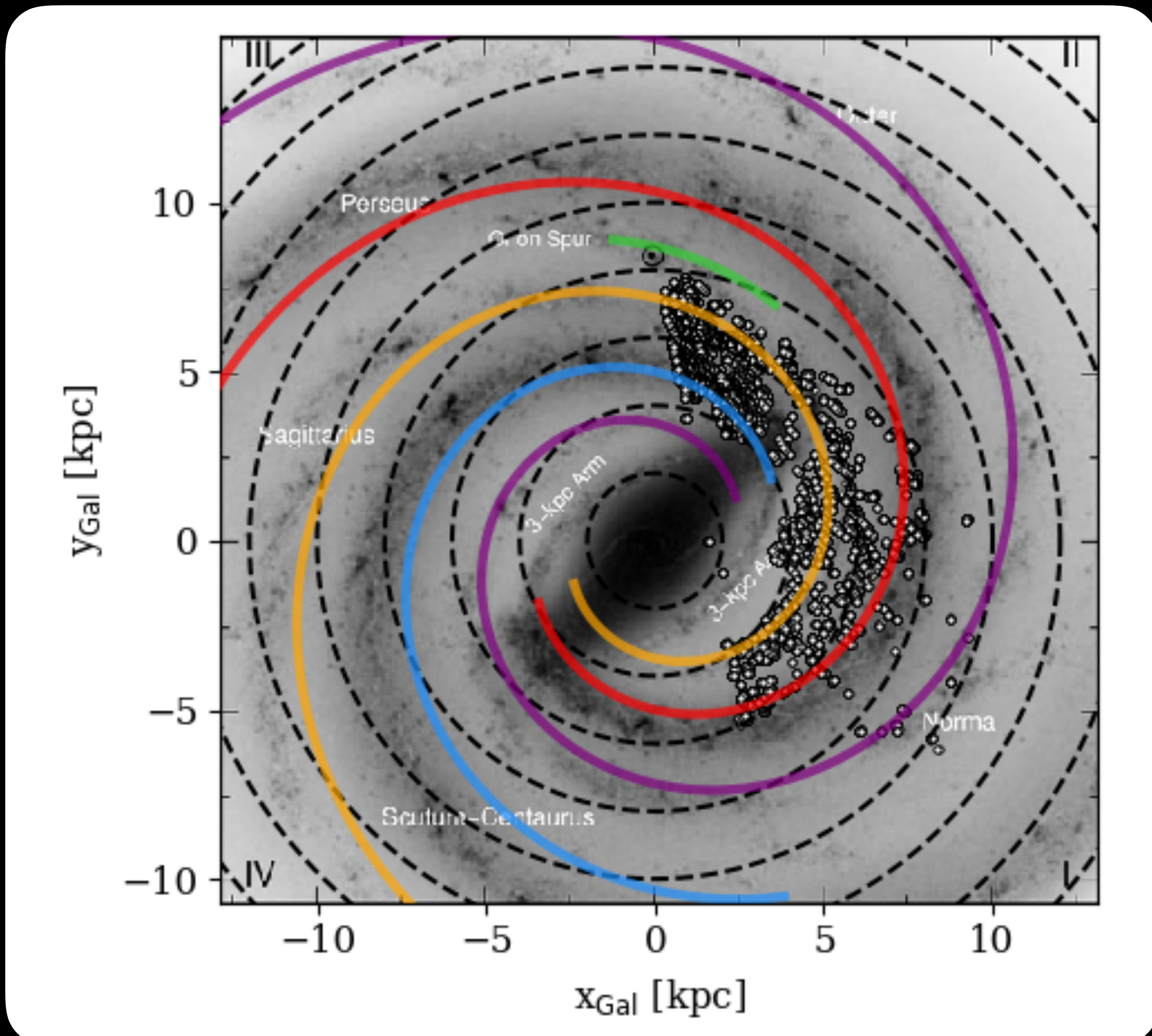
Smith et al. 2014



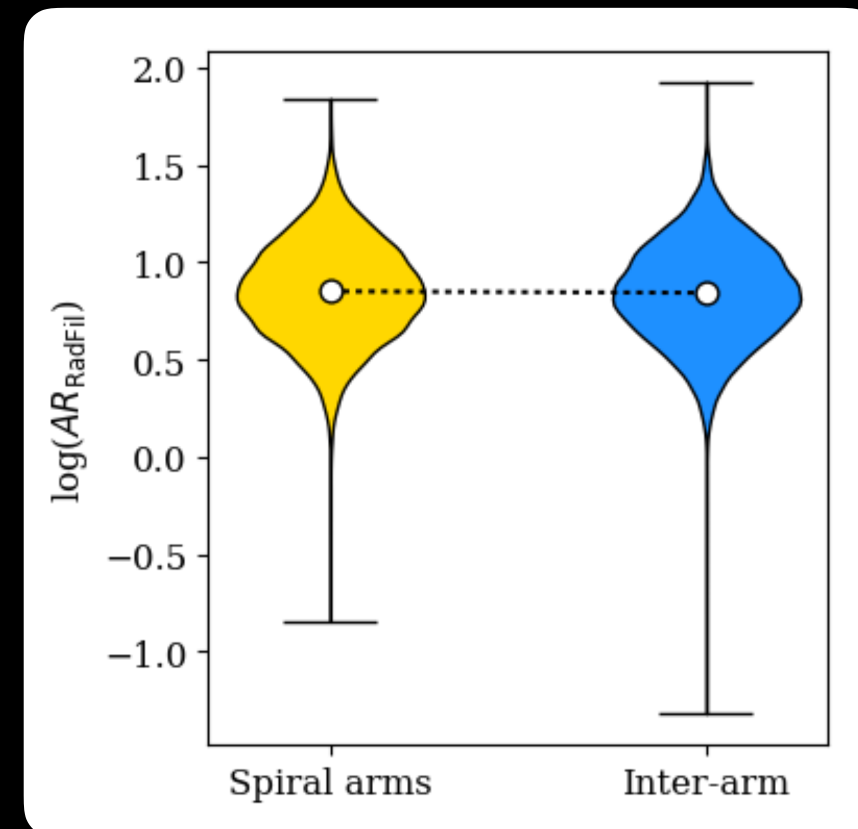
35%-55% of filaments associated to spiral arms (Zucker et al. 2018a)

Cloud morphology relation to the spiral arms

Spiral arm model from Vallee 2017

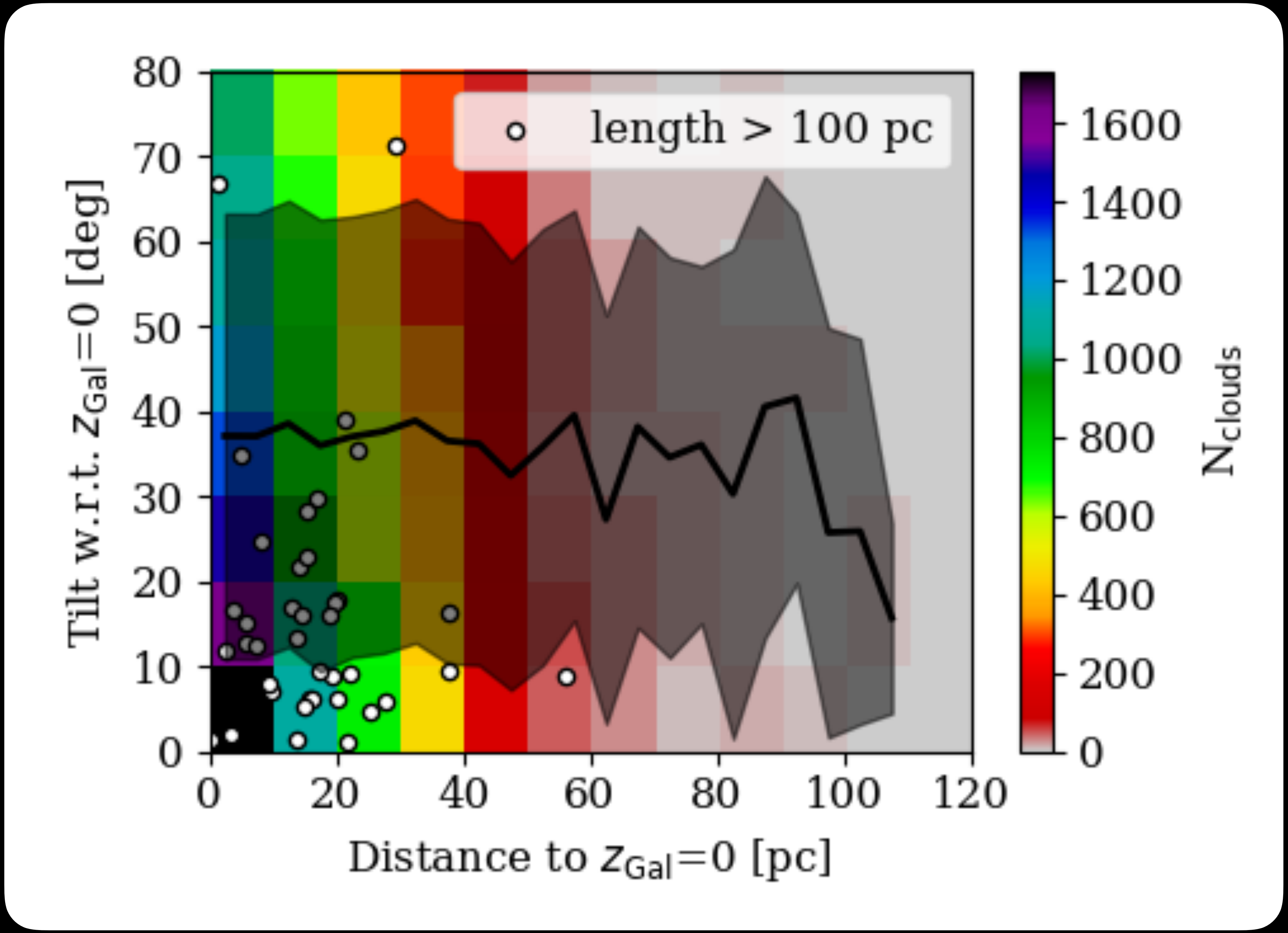


~30% - 50% of elongated, ring, or concentrated structures within the spiral arms considering a width of 600-800 pc

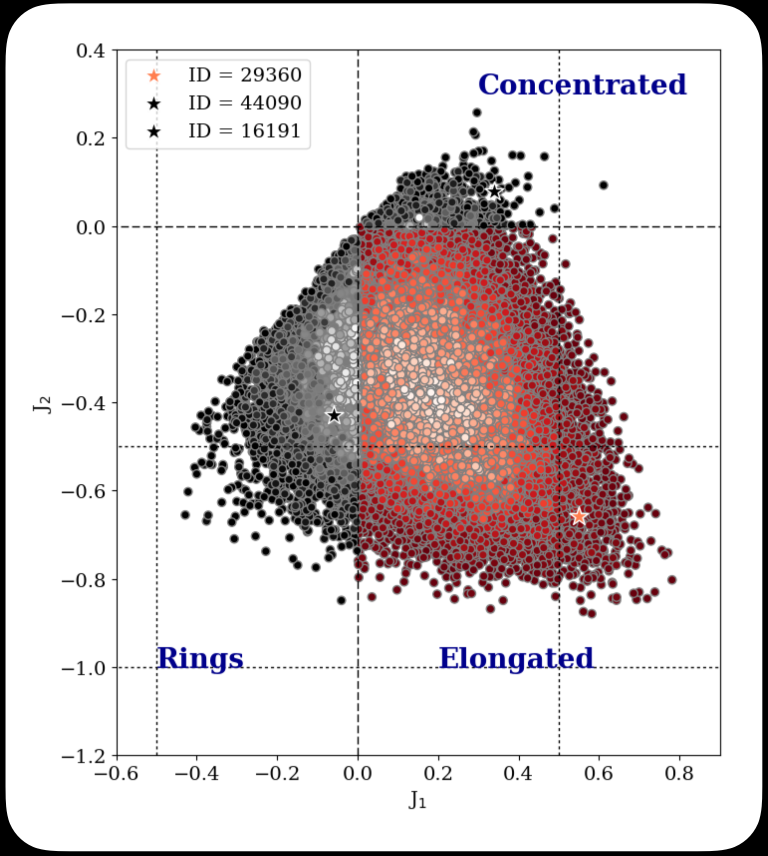


Elongated structures equally distributed between spiral arms and inter-arm

Elongated clouds relation to the Galactic plane



Elongated clouds selected via J-plots



Most of elongated clouds are close and parallel to the Galactic plane

INTEGRATED

Radius,
Velocity dispersion,
Luminosity,
Column density,
Surface density,
Pressure,
Masses,
Virial parameter ...

INTEGRATED

Radius,
Velocity dispersion,
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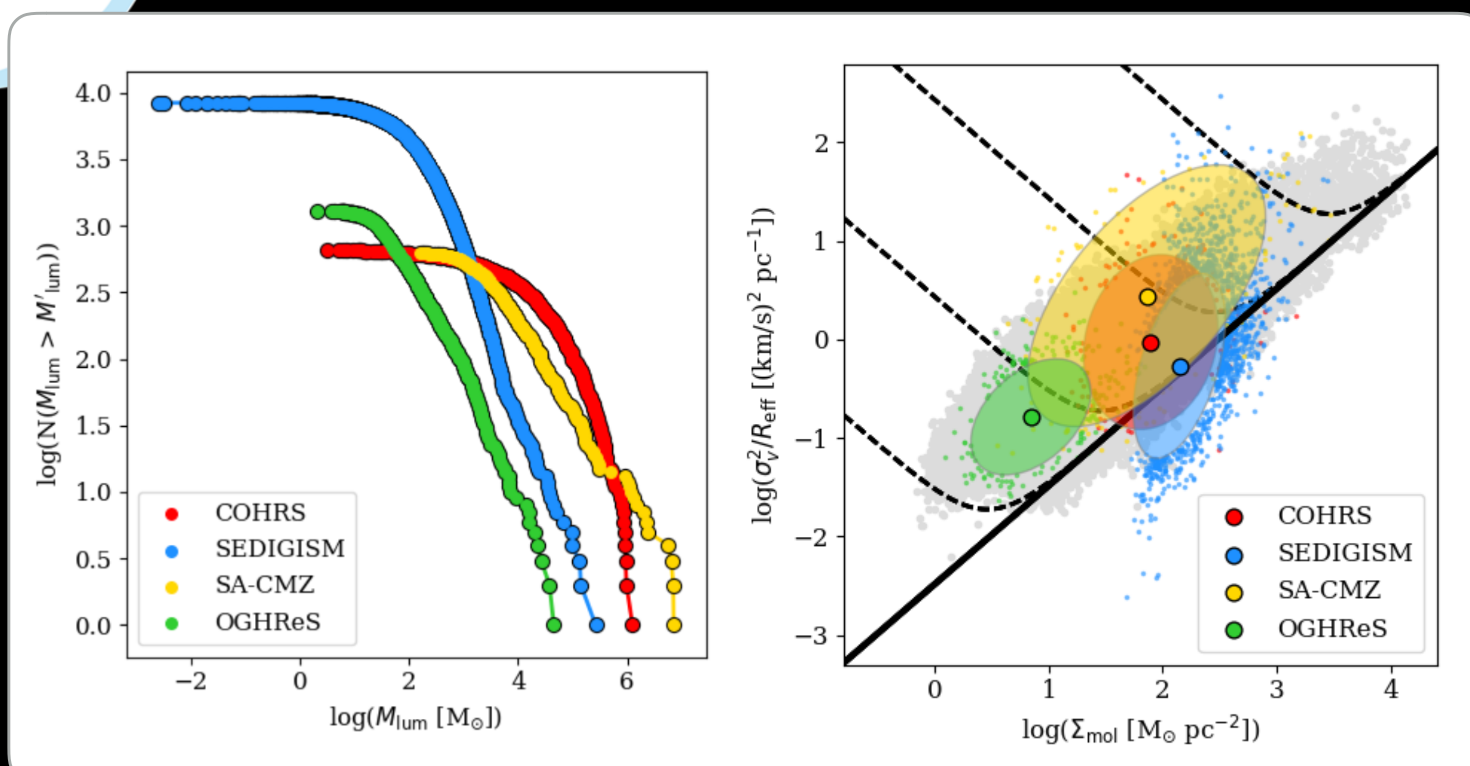
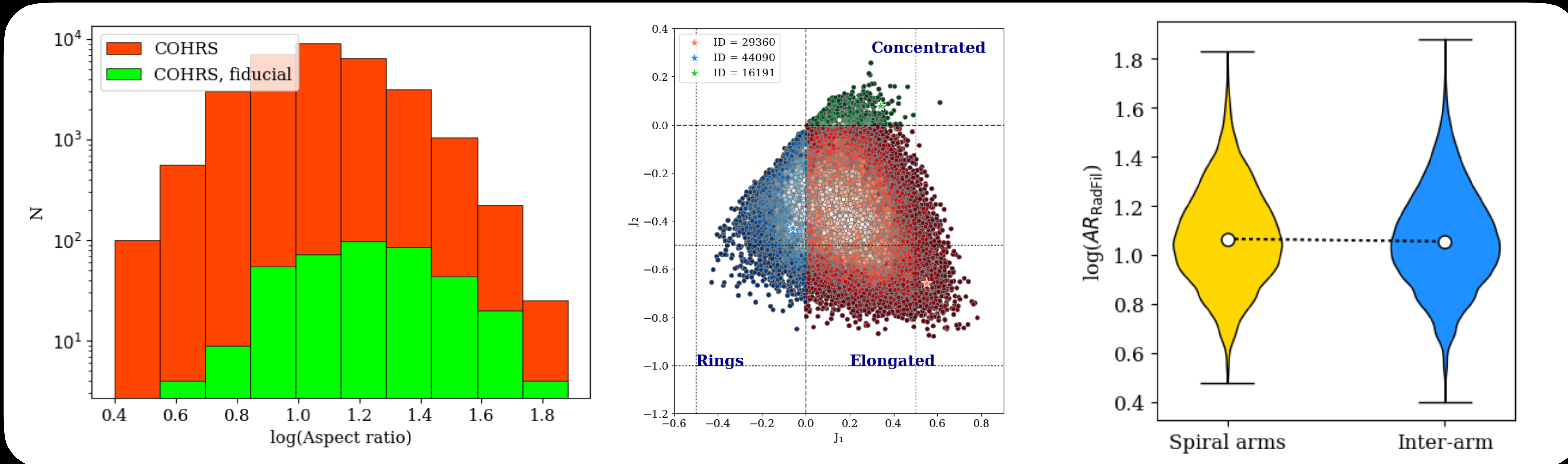


Cloud mass distributions show different truncations and slopes in different environments

Clouds are in pressurized virial equilibrium, clouds in different environments show different values of molecular gas mass surface density

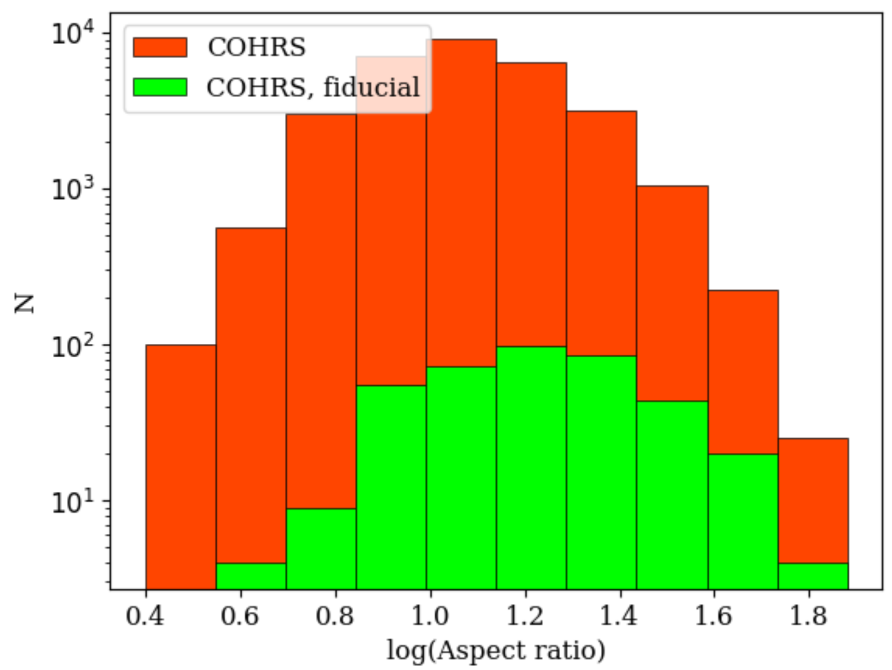


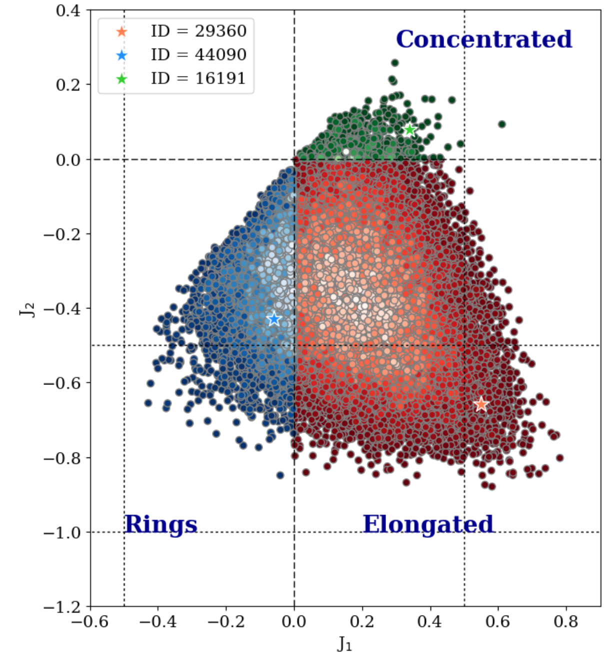
Clouds are generally elongated or complex objects, but their shapes do not seem related to spiral arms and only marginally with the distance with respect to the Galactic center.

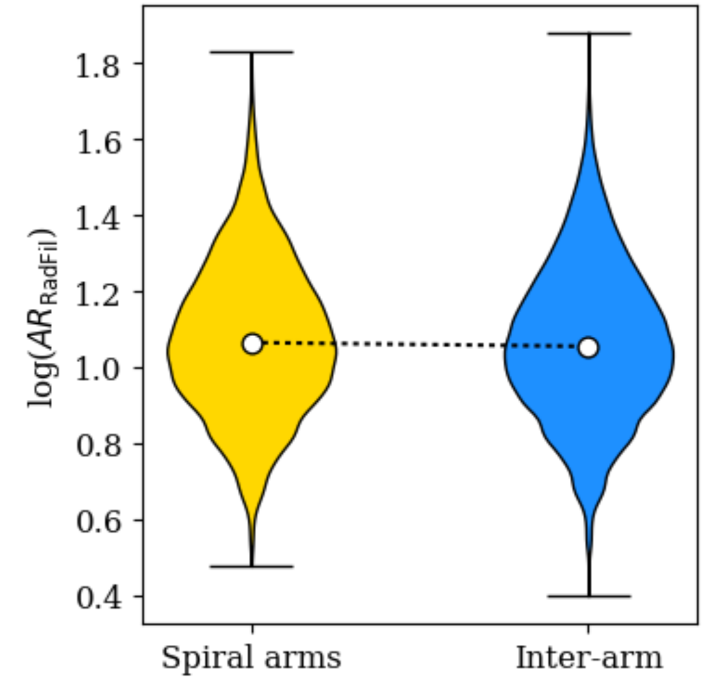
COHRS
GHReS
SEDIGism
SA-CMZ

RESOLVED

Morphology,
Inner structure,
Kinematics,
Turbulence,
PDFs ...







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RESOLVED

Morphology,
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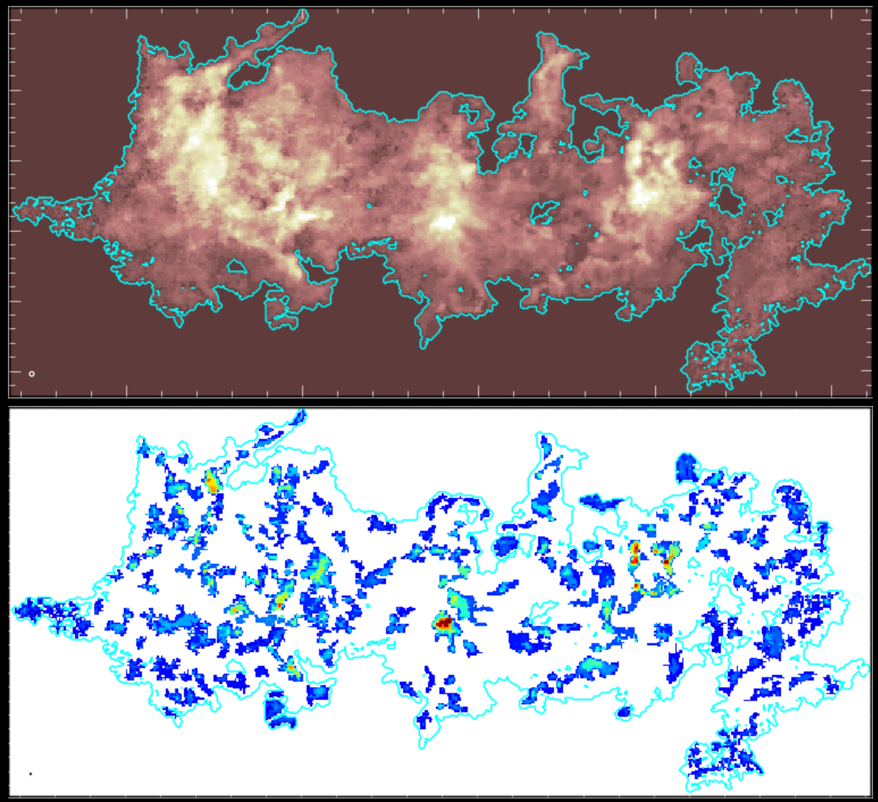
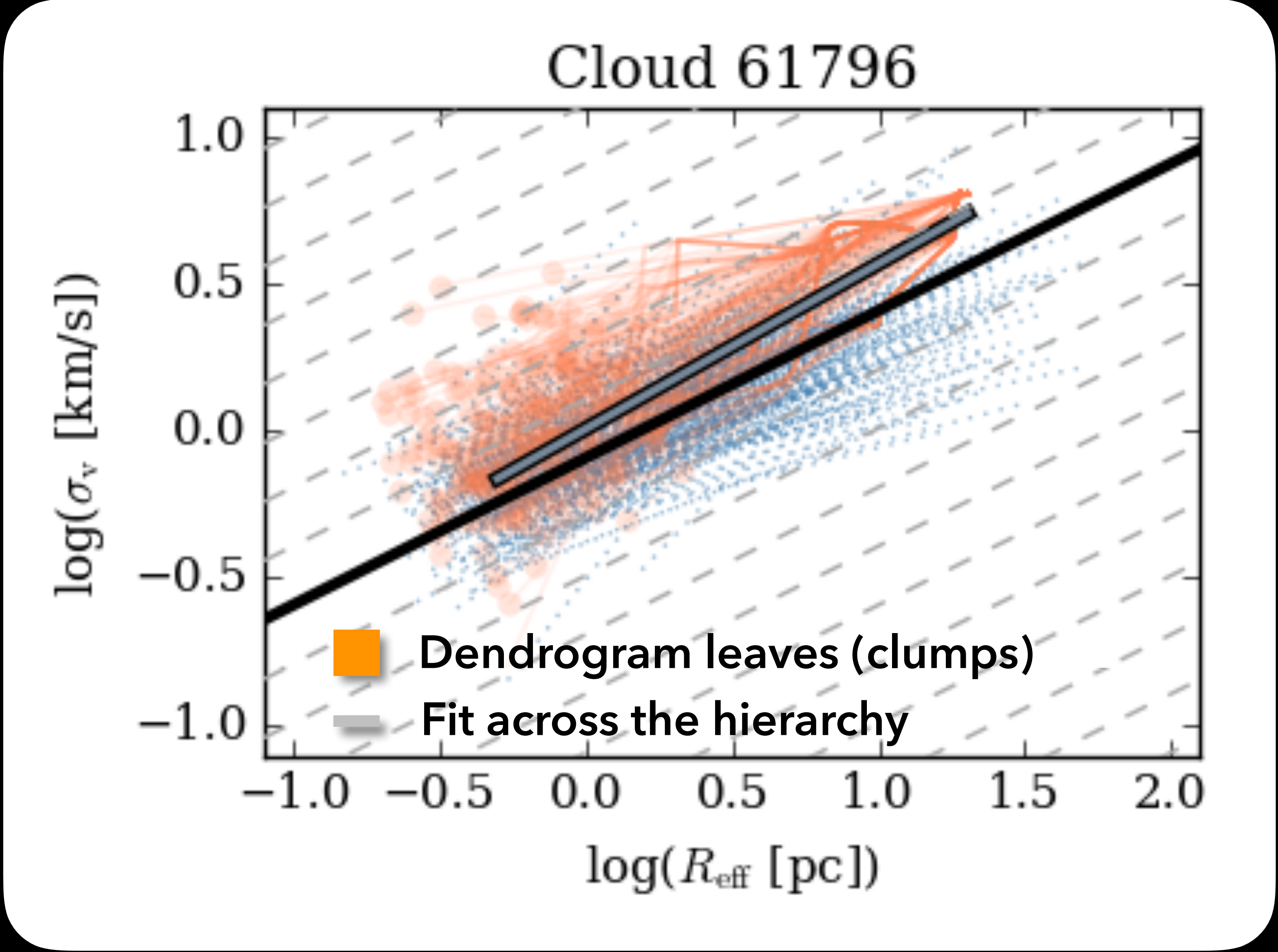
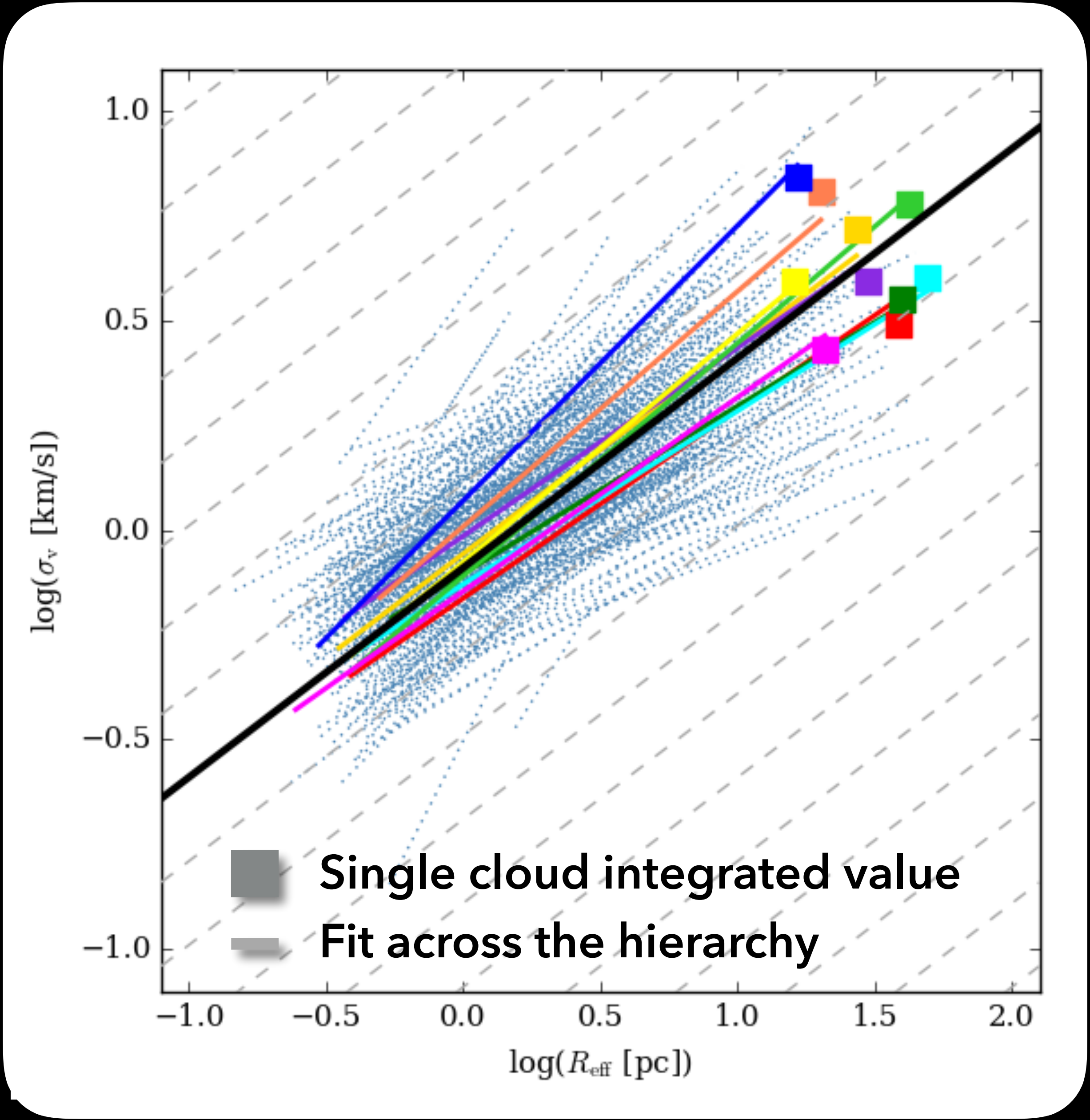
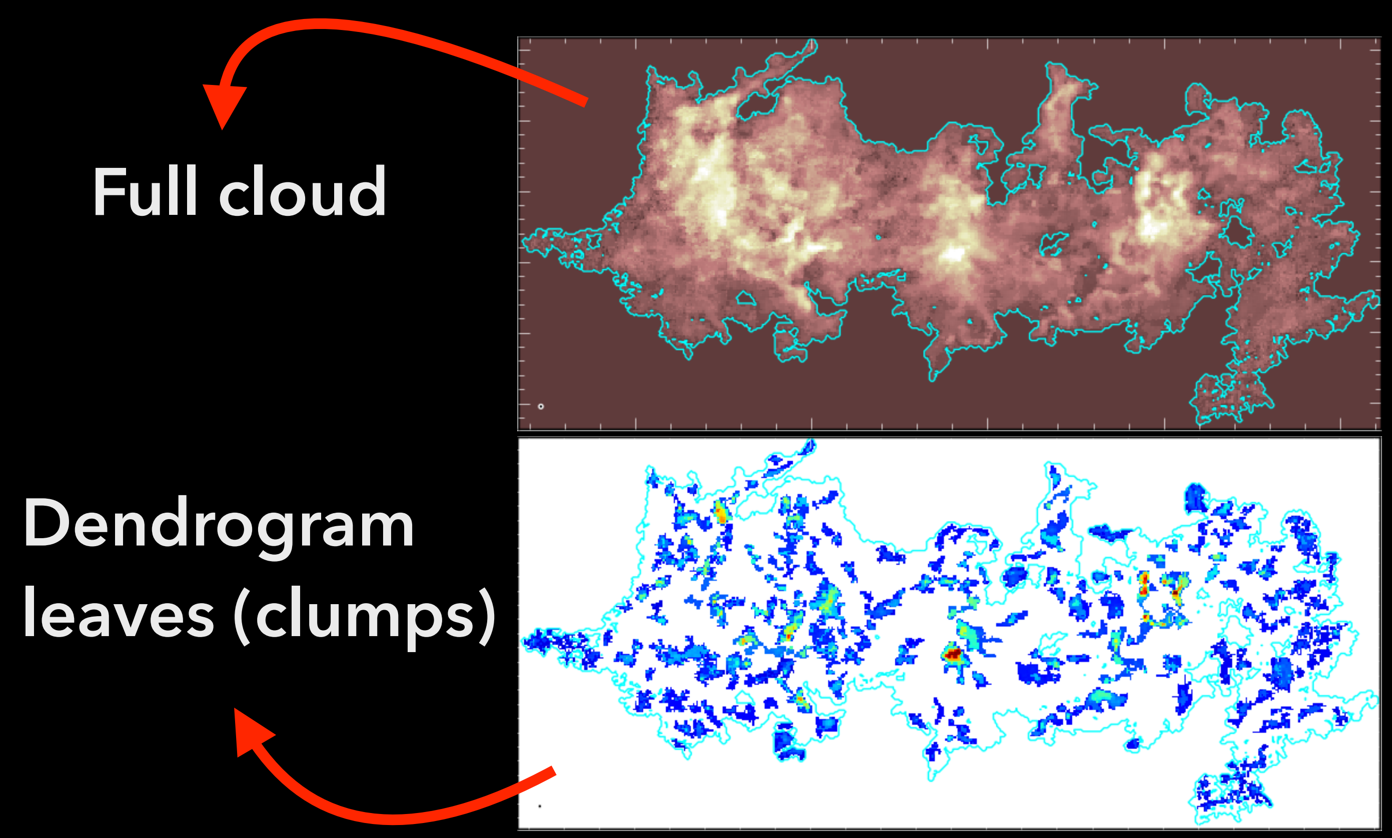
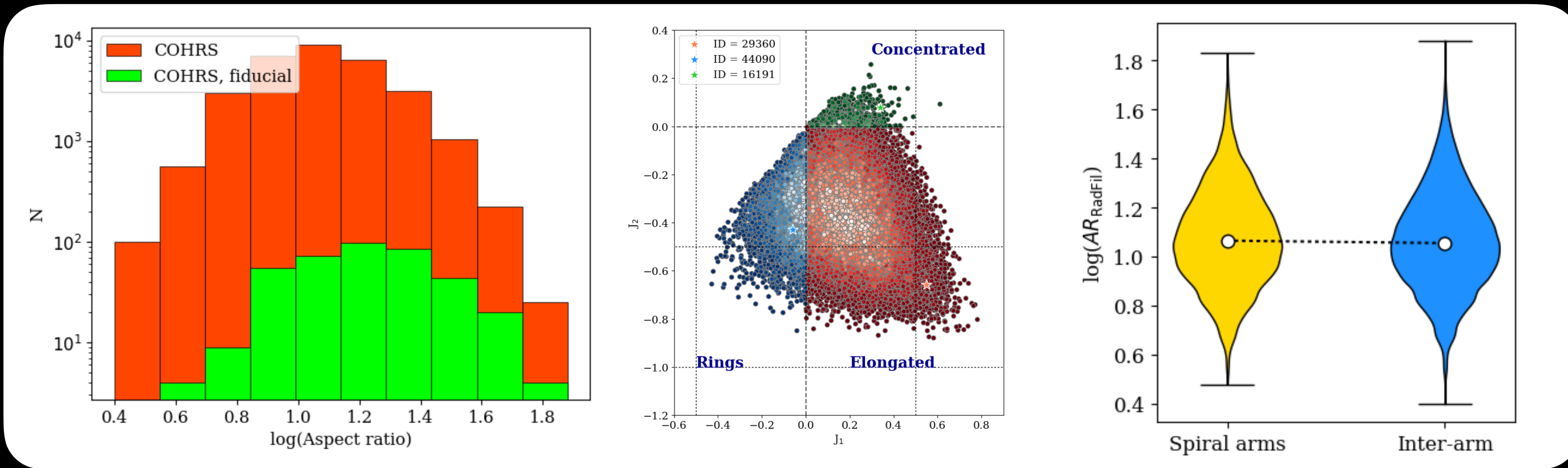


Cloud inner structure: Type 2-4 size-linewidth relations









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RESOLVED

Morphology,
Inner structure,
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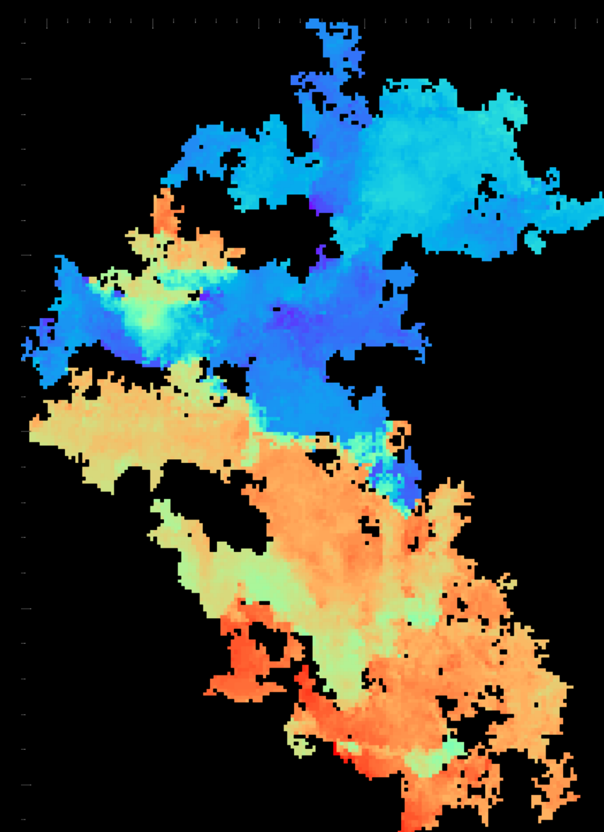
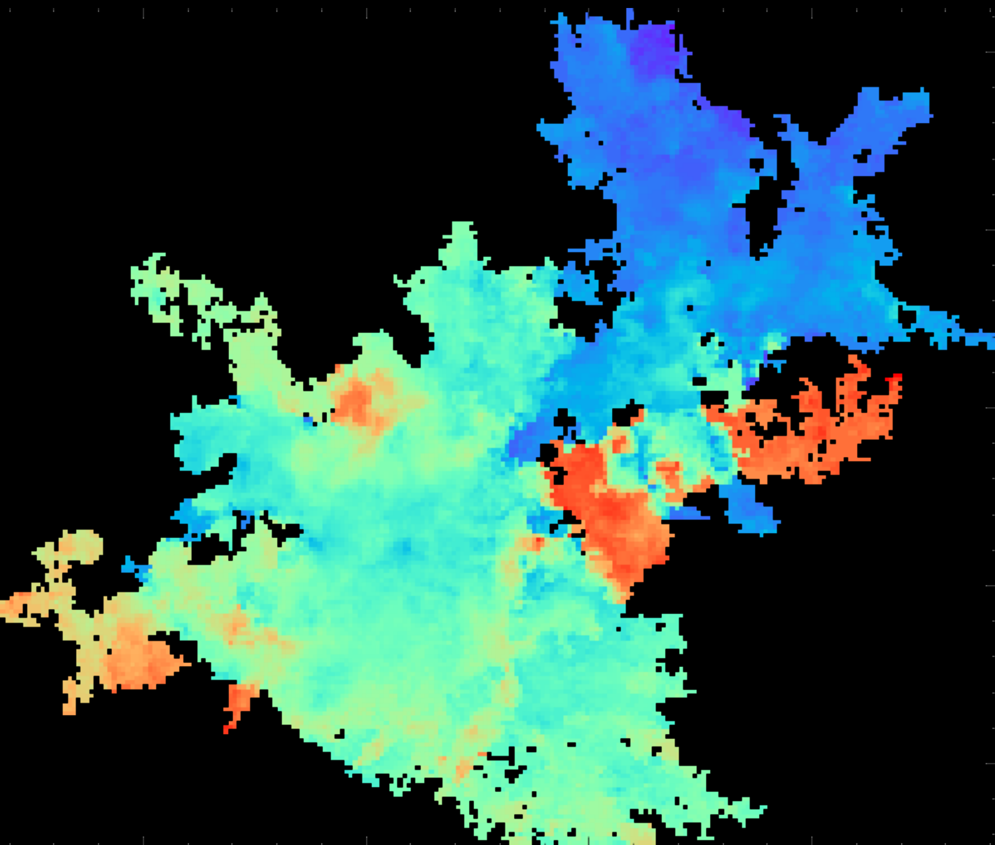
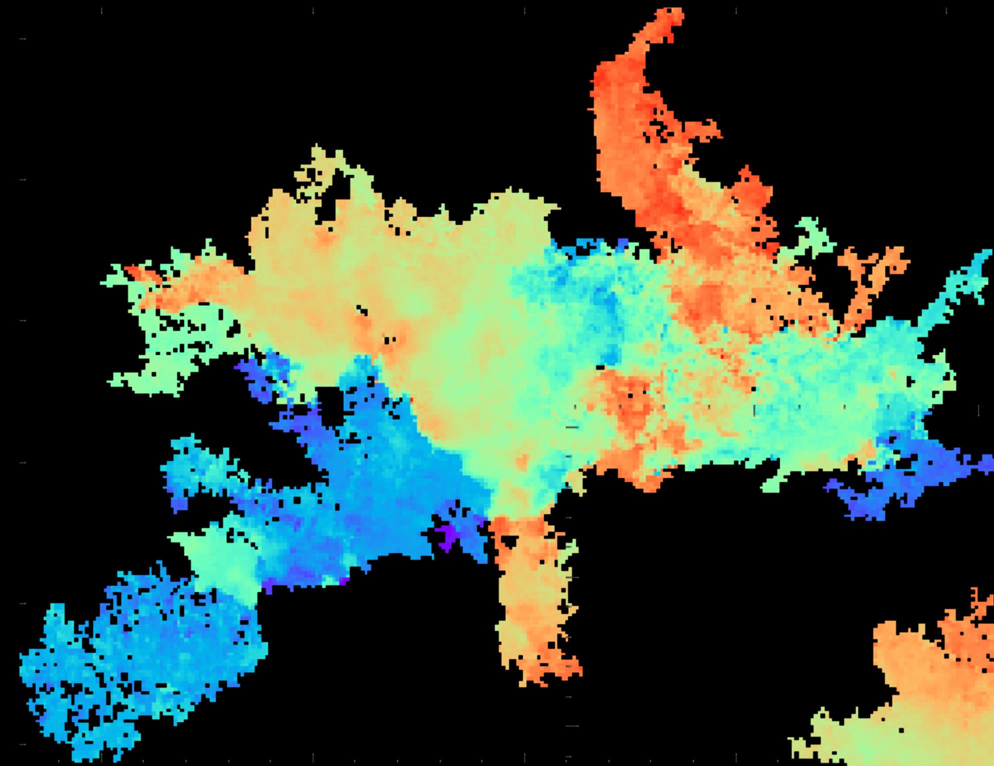
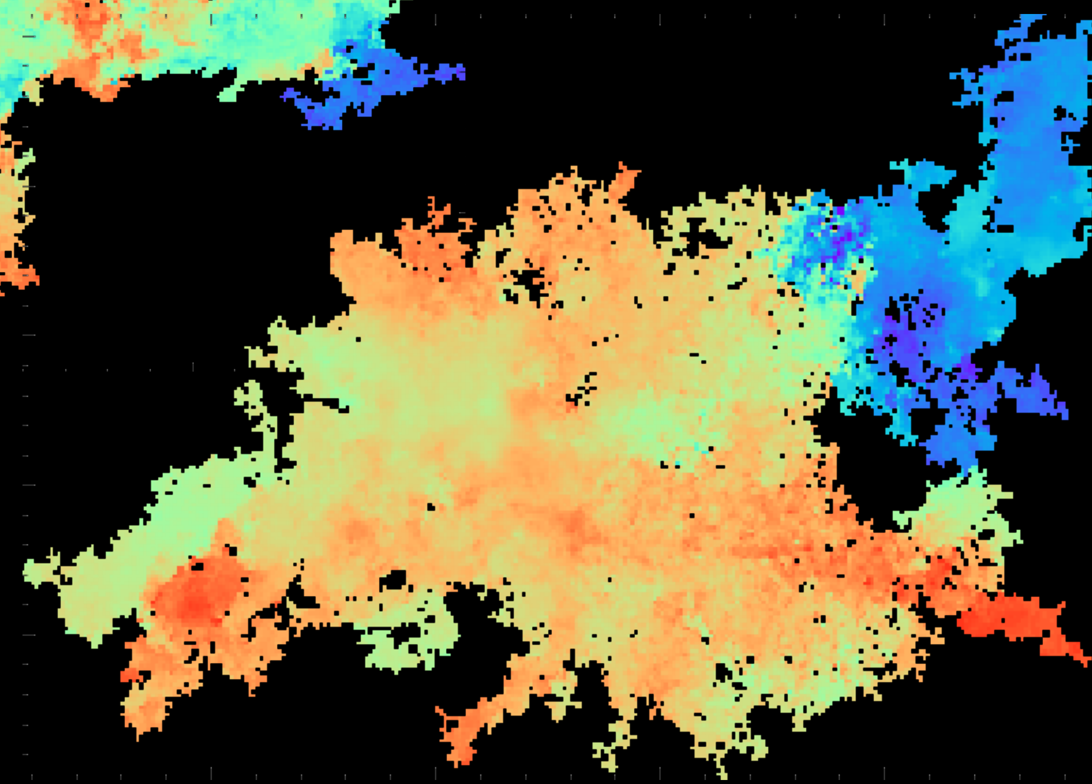
PDFs ...

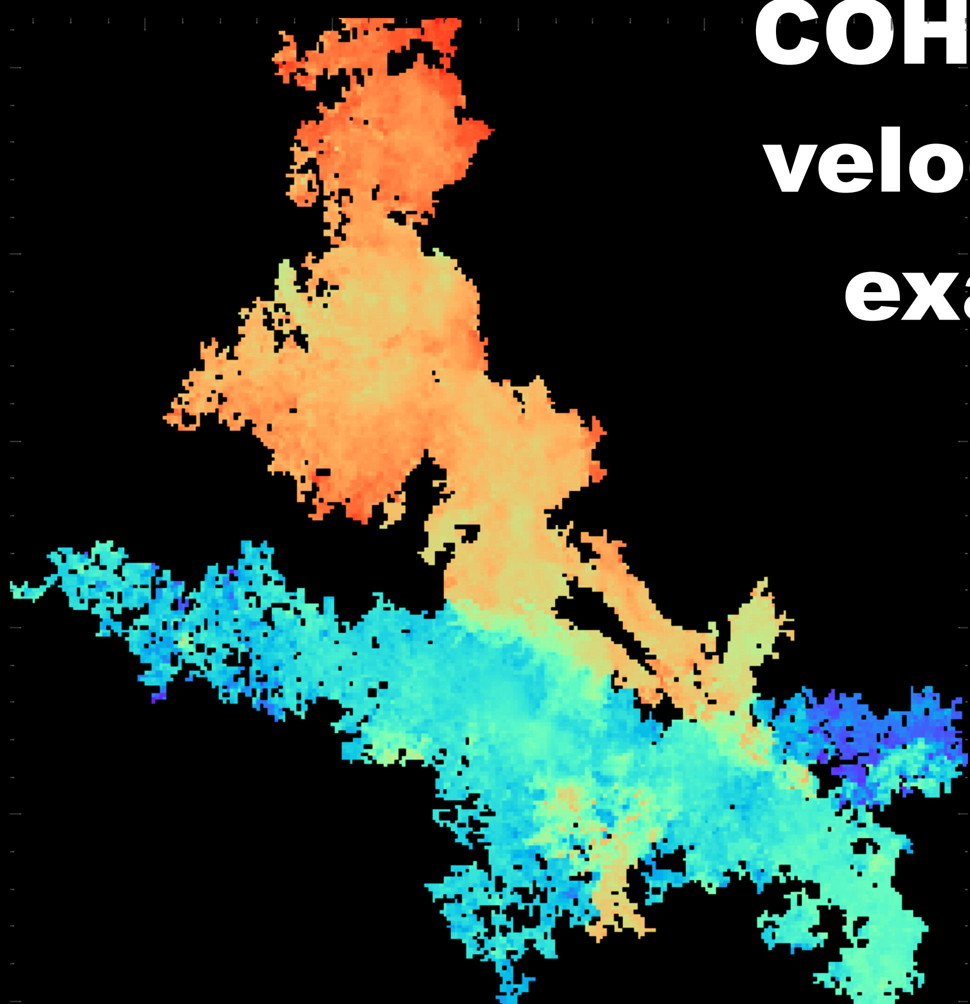


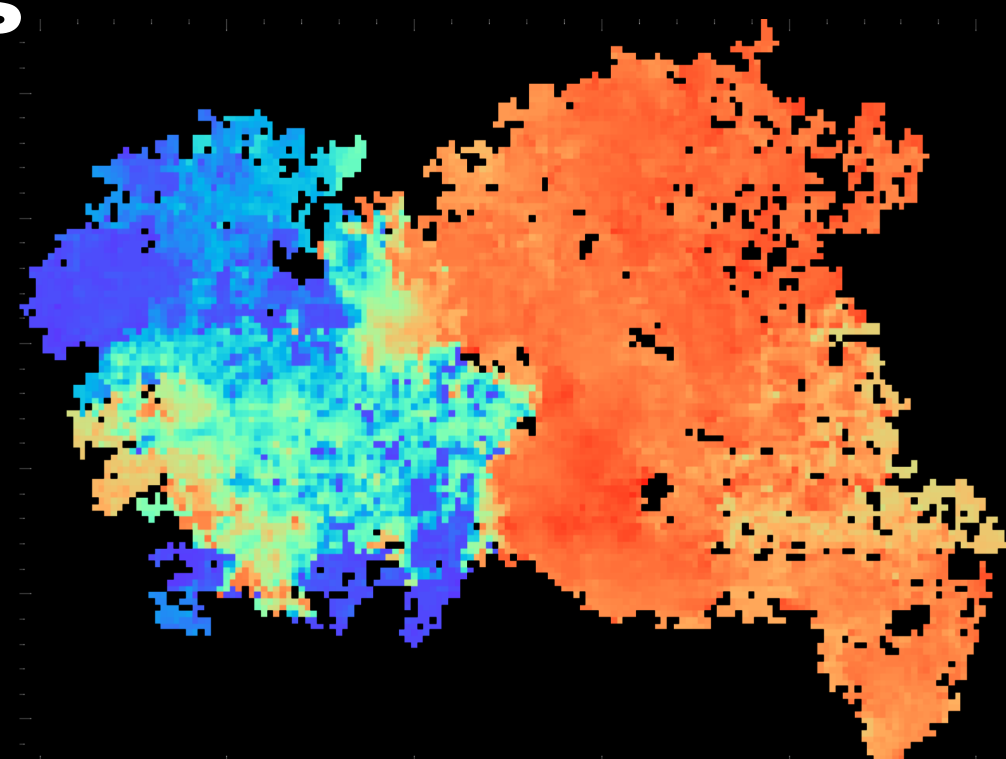


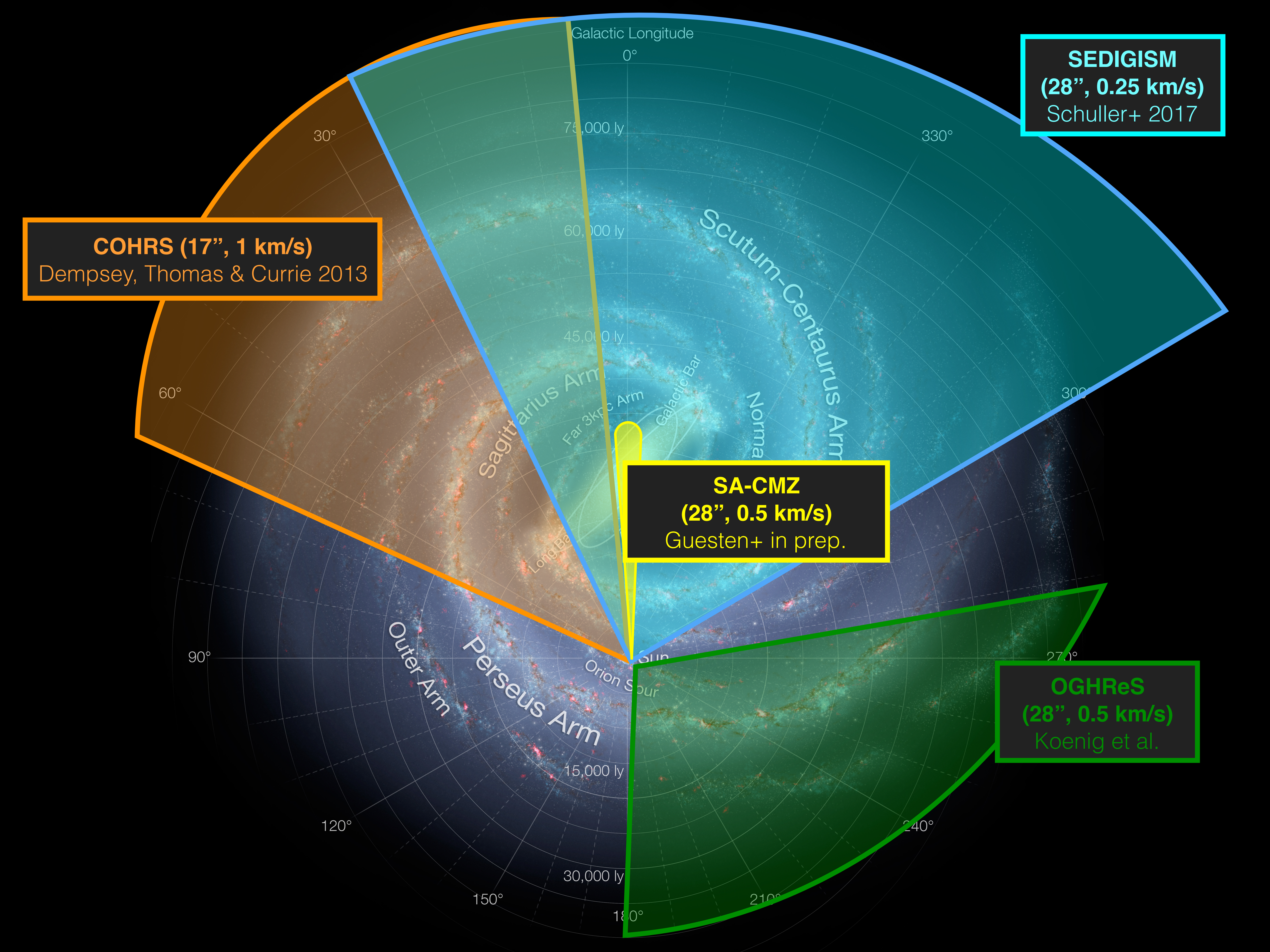




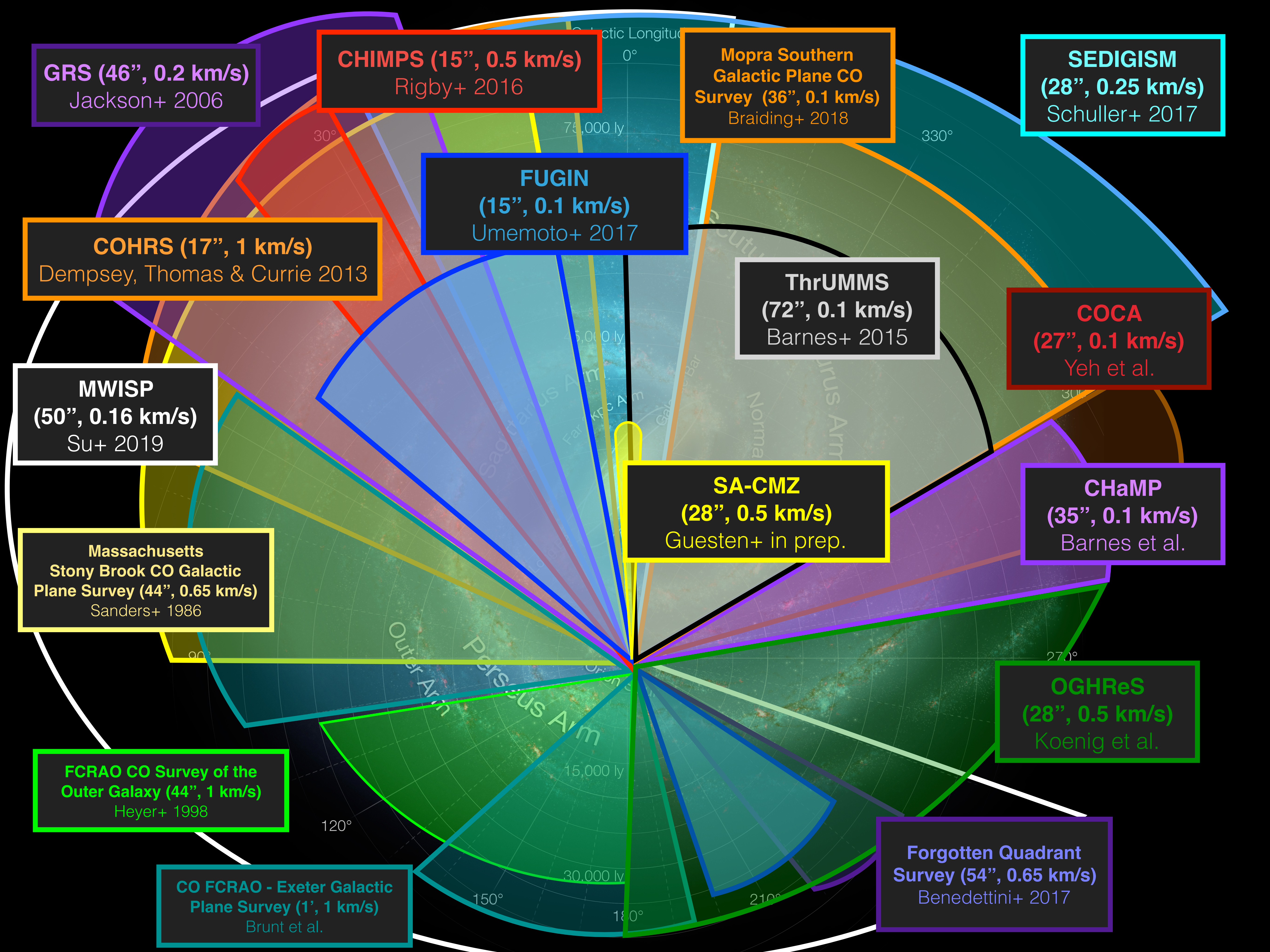
COHRS cloud velocity field examples

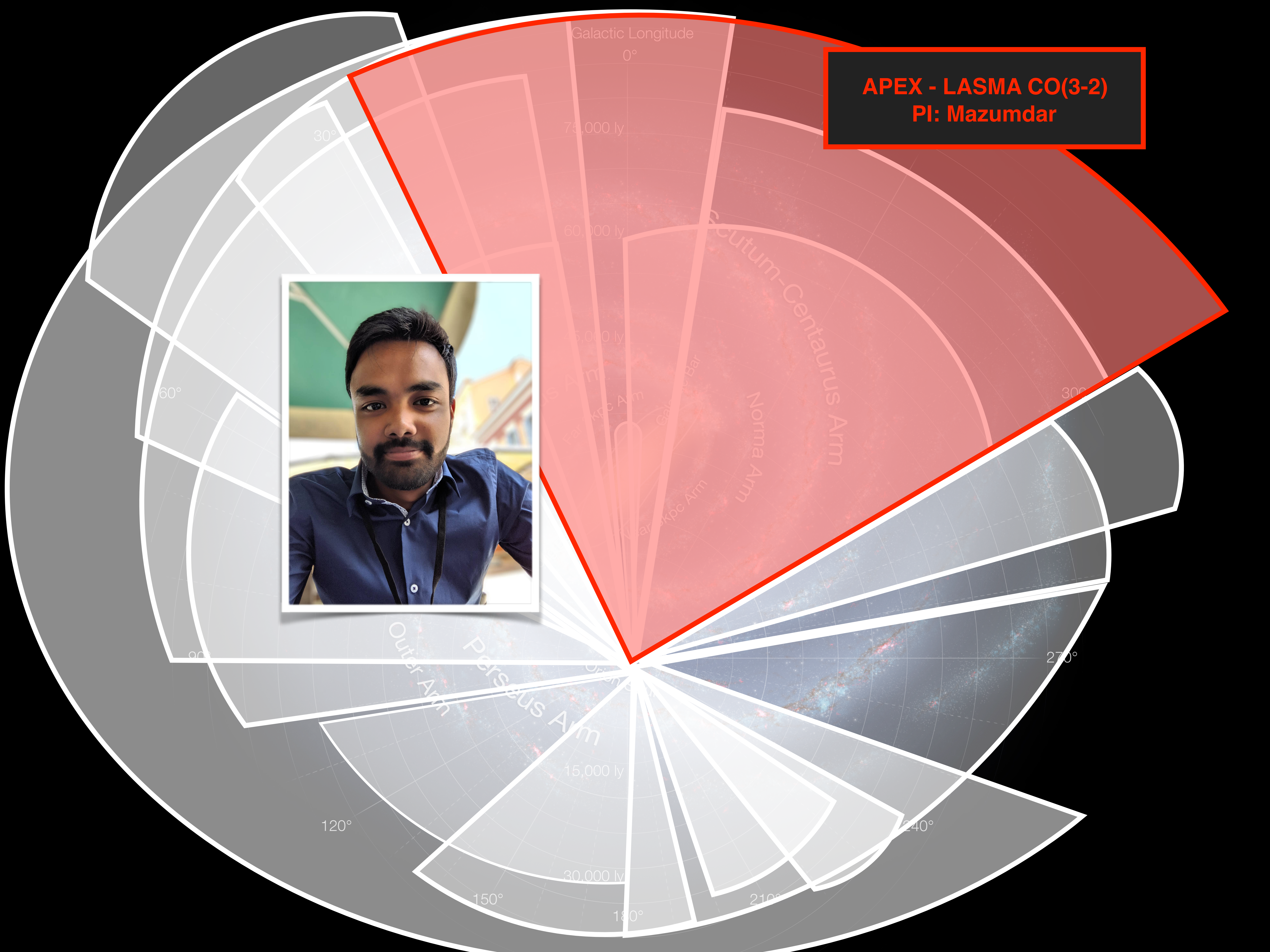






SEDIGISM
(28”, 0.25 km/s)
Schuller+ 2017
COHRS (17”, 1 km/s)
Dempsey, Thomas & Currie 2013
SA-CMZ
(28”, 0.5 km/s)
Guesten+ in prep.
OGHReS
(28”, 0.5 km/s)
Koenig et al.
Galactic Longitude
0°
30°
330°
60°
90°
120°
150°
240°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Norma
Galactic Bar
Far 3kpc Arm
Sagittarius Arm
Perseus Arm
Outer Arm
Orion Spur
Sun


GRS (46”, 0.2 km/s)
Jackson+ 2006
CHIMPS (15”, 0.5 km/s)
Rigby+ 2016
Mopra Southern Galactic Plane CO Survey (36”, 0.1 km/s)
Braiding+ 2018
SEDIGISM (28”, 0.25 km/s)
Schuller+ 2017
FUGIN (15”, 0.1 km/s)
Umemoto+ 2017
COHRS (17”, 1 km/s)
Dempsey, Thomas & Currie 2013
ThrUMMS (72”, 0.1 km/s)
Barnes+ 2015
COCA (27”, 0.1 km/s)
Yeh et al.
MWISP (50”, 0.16 km/s)
Su+ 2019
SA-CMZ (28”, 0.5 km/s)
Guesten+ in prep.
CHaMP (35”, 0.1 km/s)
Barnes et al.
Massachusetts Stony Brook CO Galactic Plane Survey (44”, 0.65 km/s)
Sanders+ 1986
OGHReS (28”, 0.5 km/s)
Koenig et al.
FCRAO CO Survey of the Outer Galaxy (44”, 1 km/s)
Heyer+ 1998
Forgotten Quadrant Survey (54”, 0.65 km/s)
Benedettini+ 2017
CO FCRAO - Exeter Galactic Plane Survey (1’, 1 km/s)
Brunt et al.
0°
30°
330°
300°
270°
210°
180°
150°
120°
90°
75,000 ly
15,000 ly
30,000 ly
Norma
Perseus Arm
Outer Arm
Sagittarius Arm


APEX - LASMA CO(3-2)
PI: Mazumdar
Galactic Longitude
0°
75,000 ly
60,000 ly
30°
60°
Scutum-Centaurus Arm
Norma Arm
Outer Arm
Perseus Arm
270°
15,000 ly
120°
240°
30,000 ly
150°
180°

x 10000

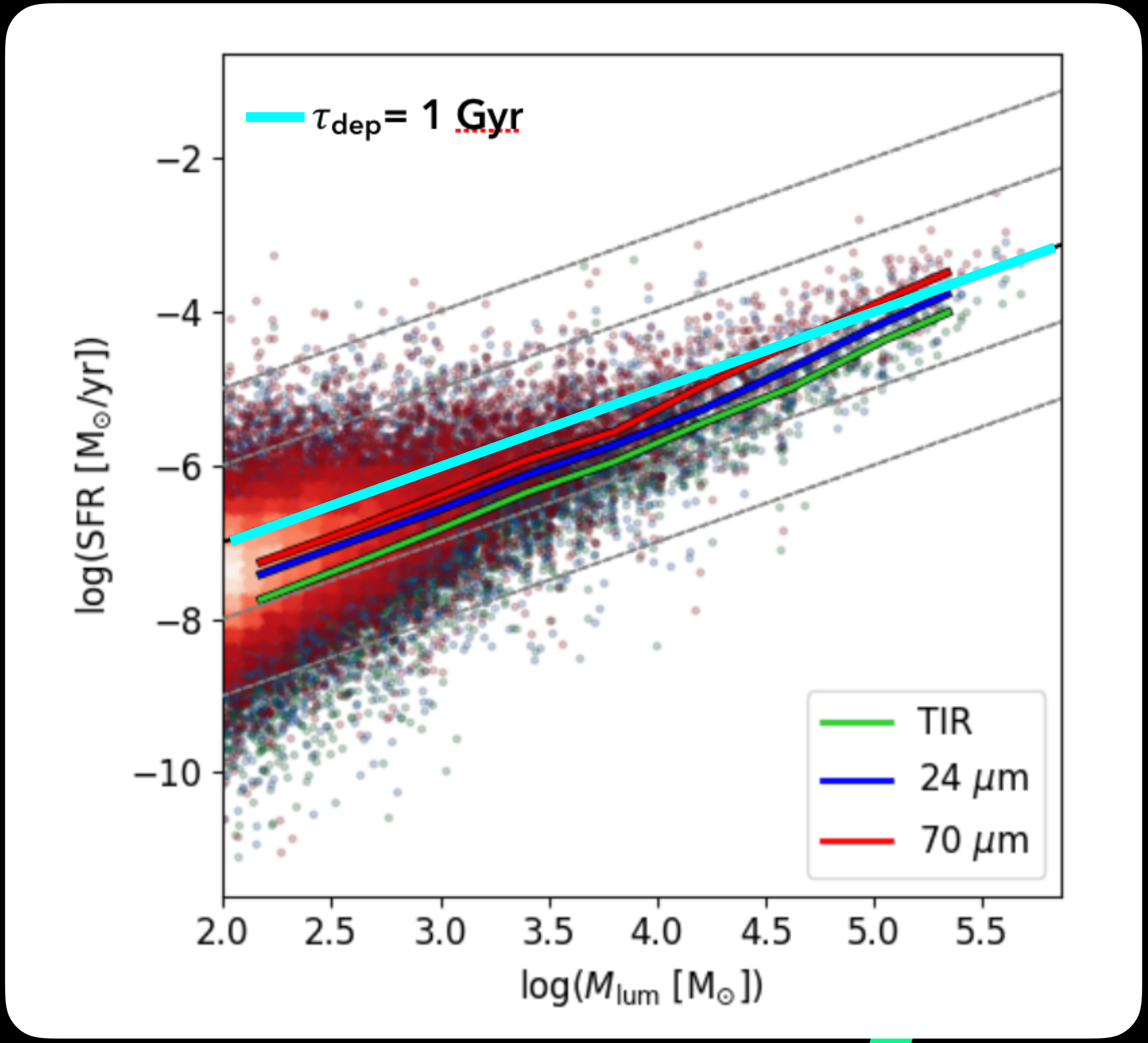
INTEGRATED

Radius,
Velocity dispersion,
Luminosity,
Column density,
Surface density,
Pressure,
Masses,
Virial parameter ...

RESOLVED

Morphology,
Inner structures,
Kinematics,
Turbulence,
PDFs ...

x 10000



Matching COHRS clouds with Hi-GAL IR emission (Rosolowsky, Colombo et al. in prep.)

COHRS
GHRes
SEDiGism
SA-CMZ

RESOLVED

Morphology,
Inner structures,
Kinematics,
Turbulence,
PDFs …