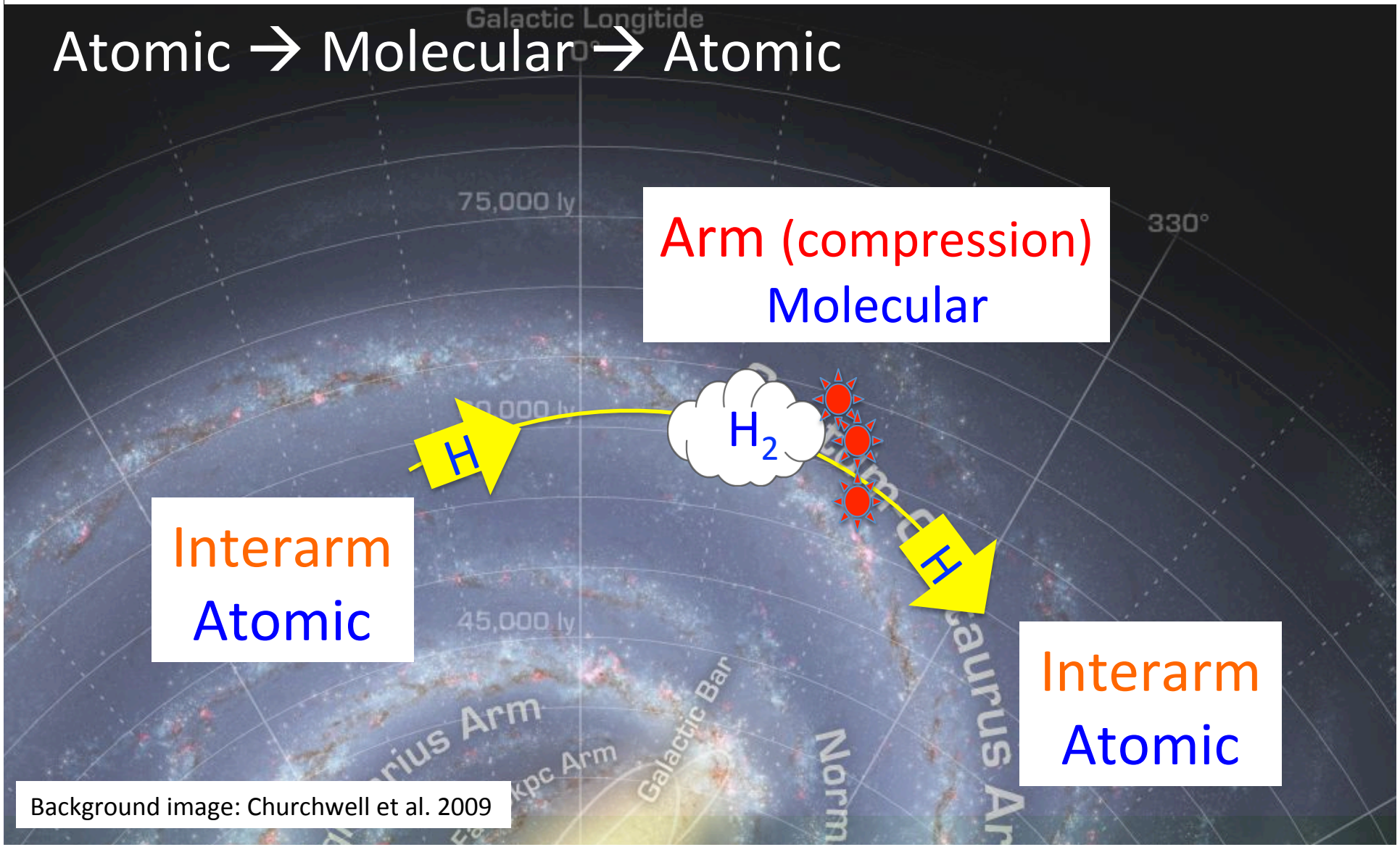
Evolution of Molecular Gas in Spiral Galaxies

How do molecular gas/clouds evolve across spiral arms?

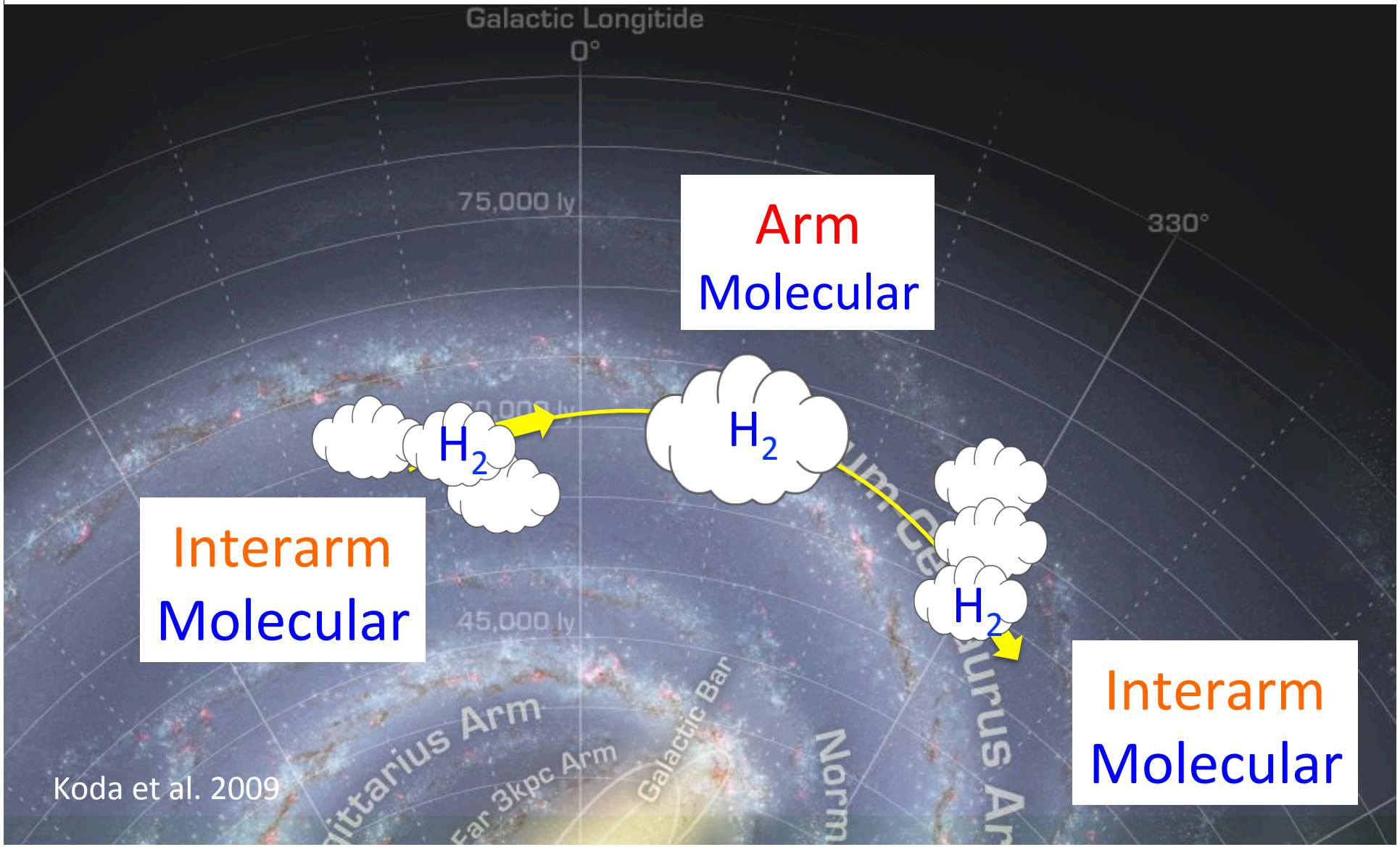
Jin Koda (Stony Brook University)

Textbook Picture

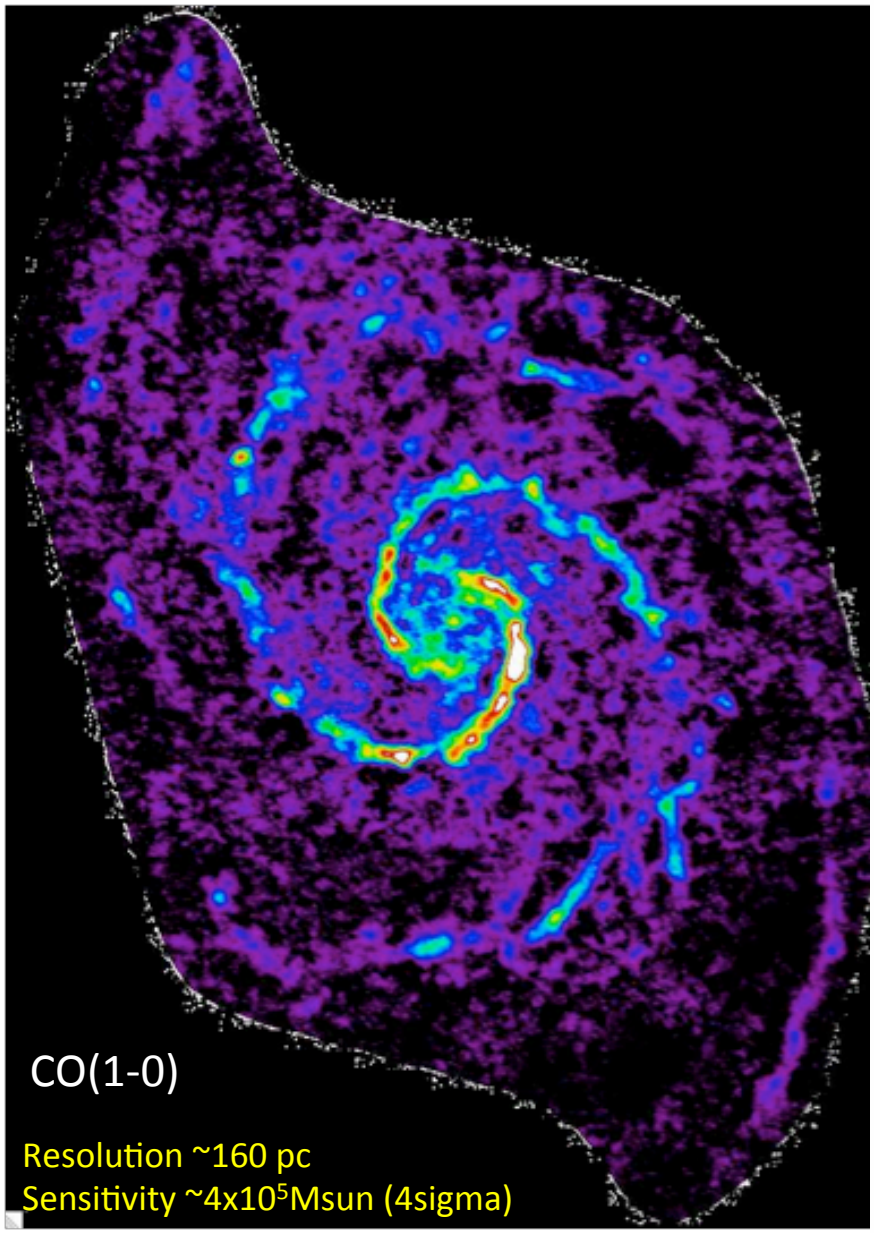
How do molecular gas/clouds evolve across spiral arms?



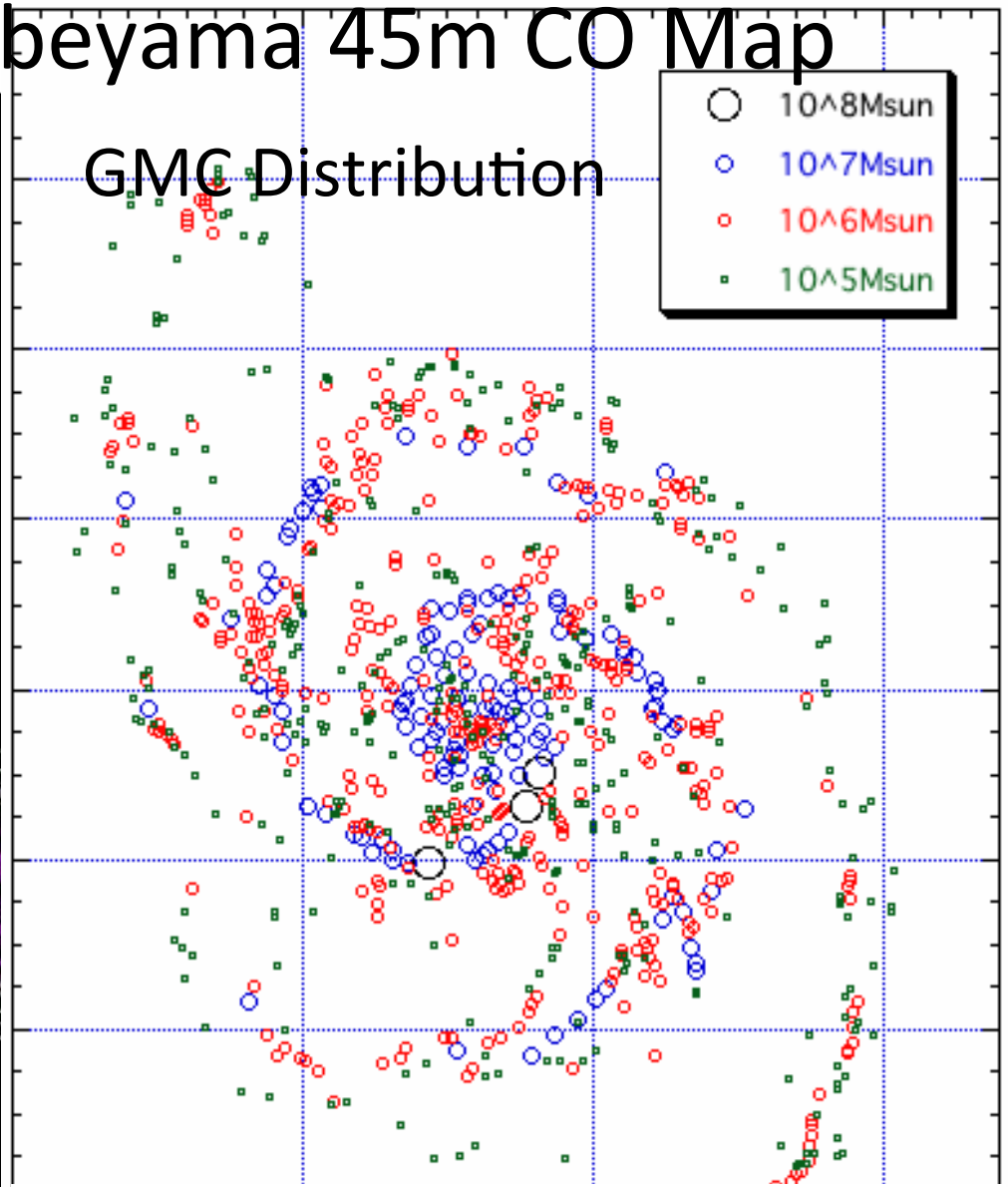
Suggested New Picture



M51: CARMA + Nobeyama 45m CO Map



Koda et al. 2009; Schinnerer et al. 2013

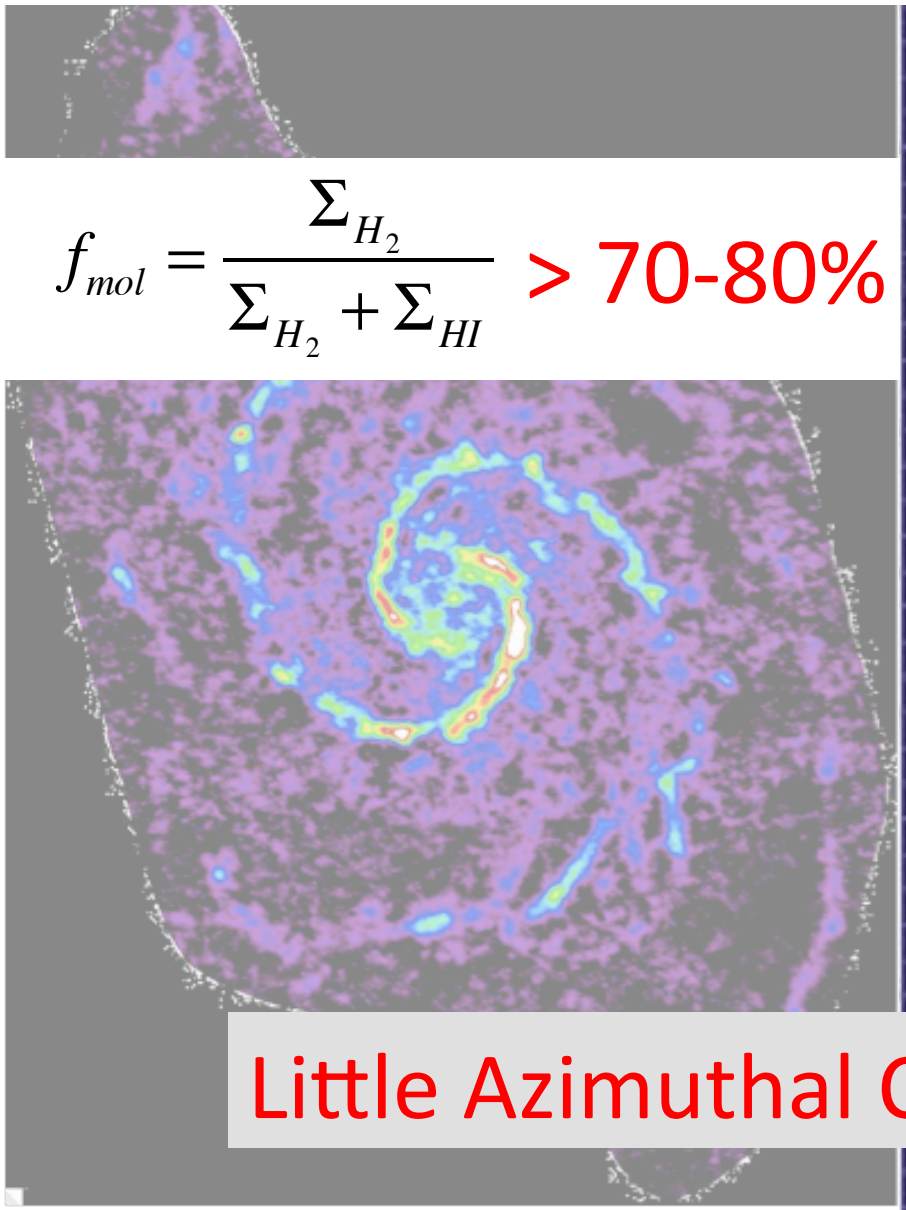


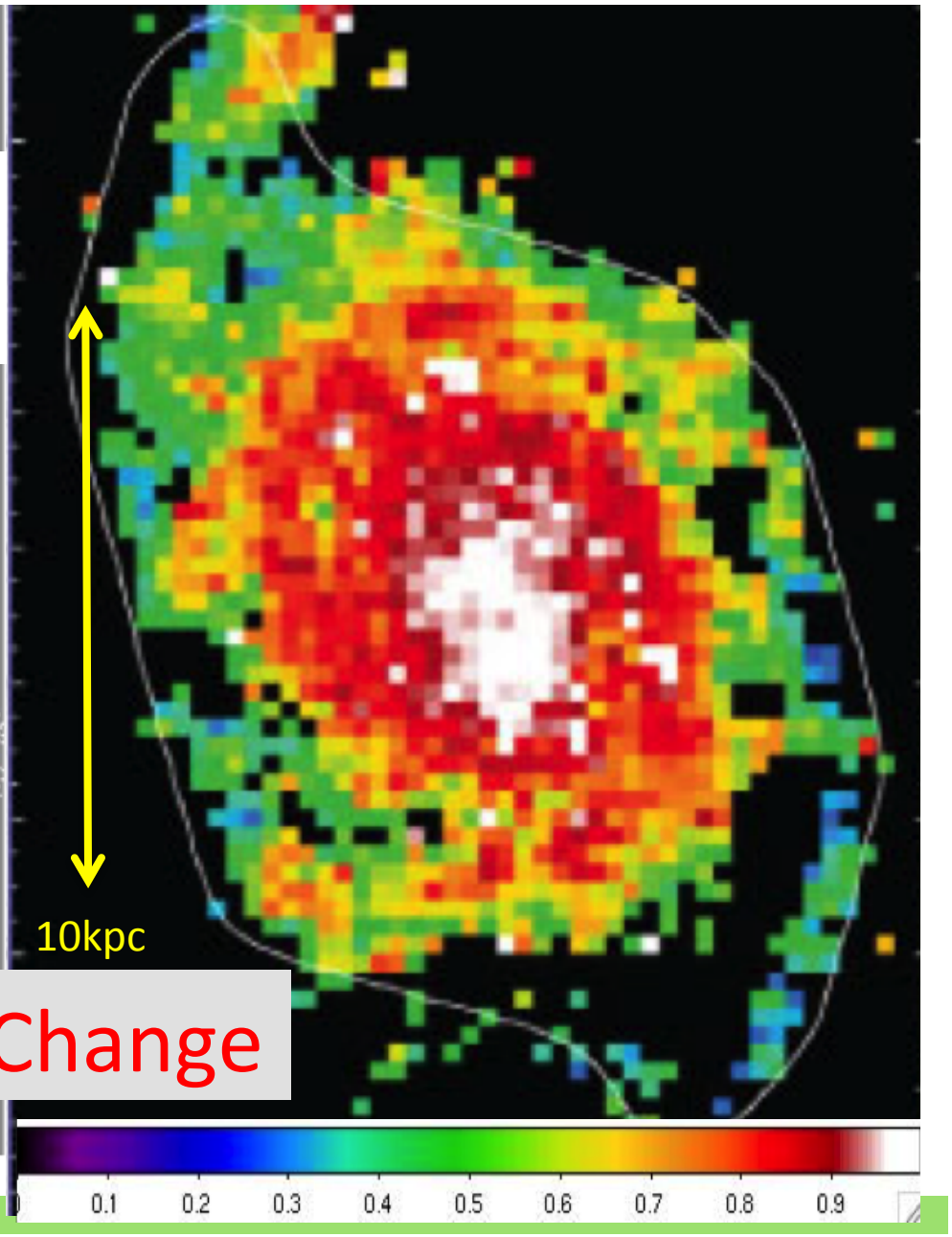
GMC evolution

Large (arm) → Small (interarm)

f_{mol}: Molecular Fraction

$$f_{mol} = \frac{\Sigma_{H_2}}{\Sigma_{H_2} + \Sigma_{HI}}$$ > 70-80%



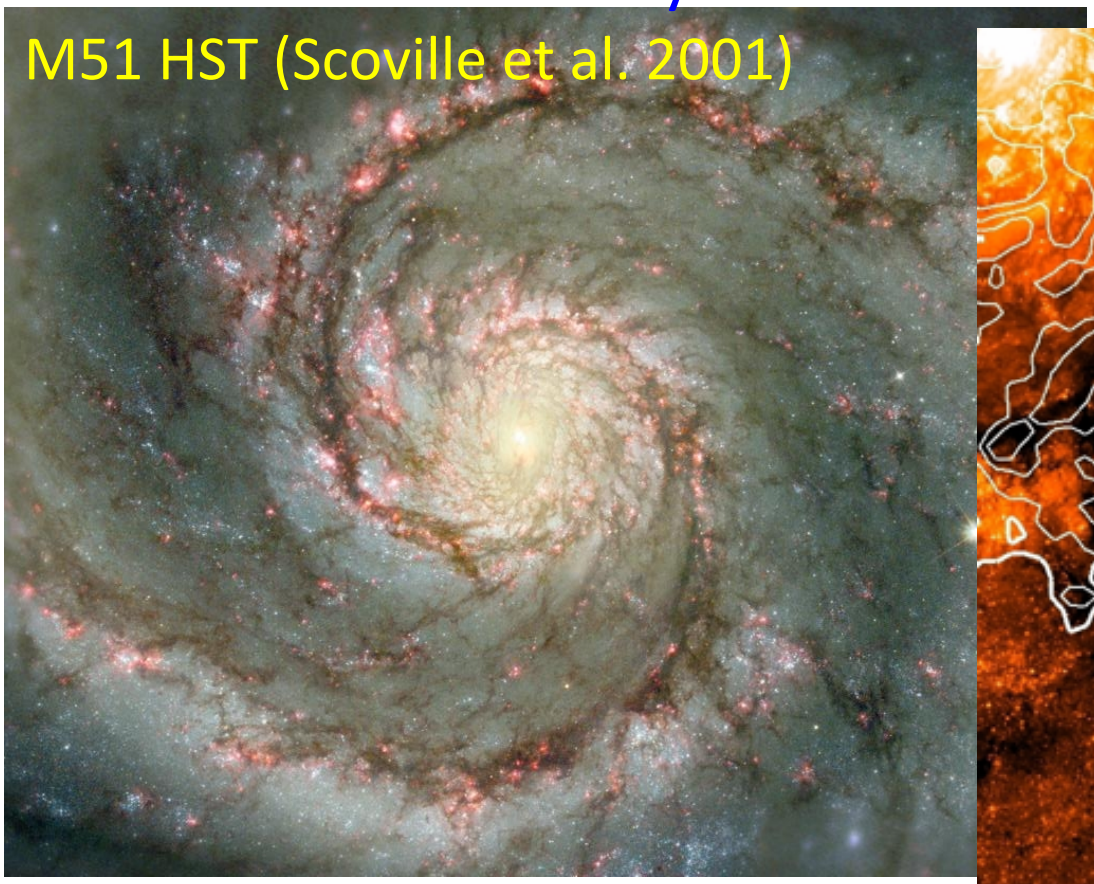


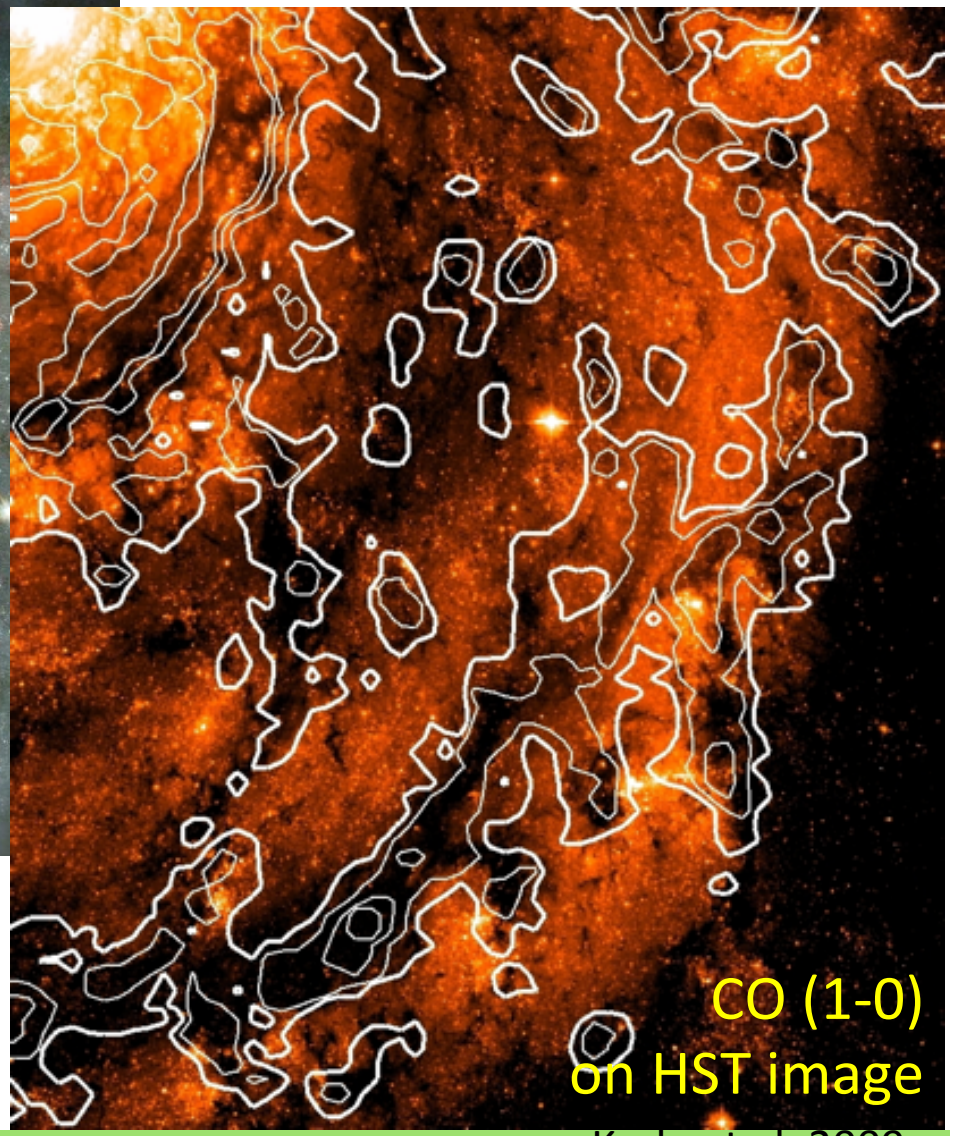
Little Azimuthal Change

Koda et al. 2009

Spurs/Feathers in CO(1-0)

Filamentary structures in interarm regions

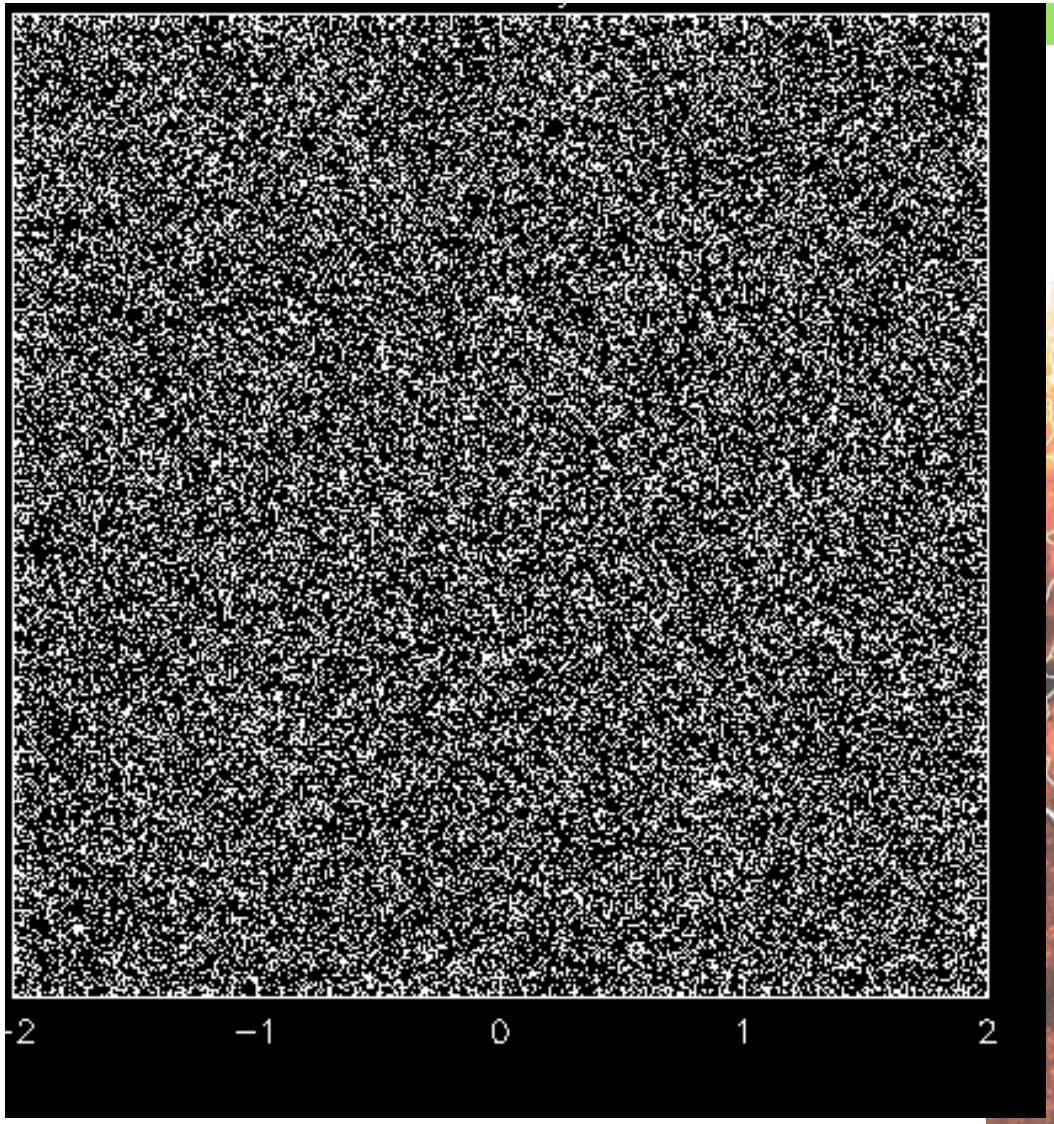




Spurs = chains of GMCs

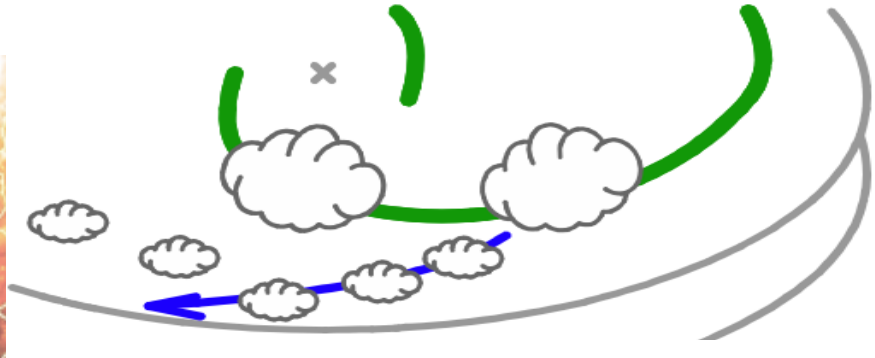
Koda et al. 2009

Dynamically-Driven Evolution

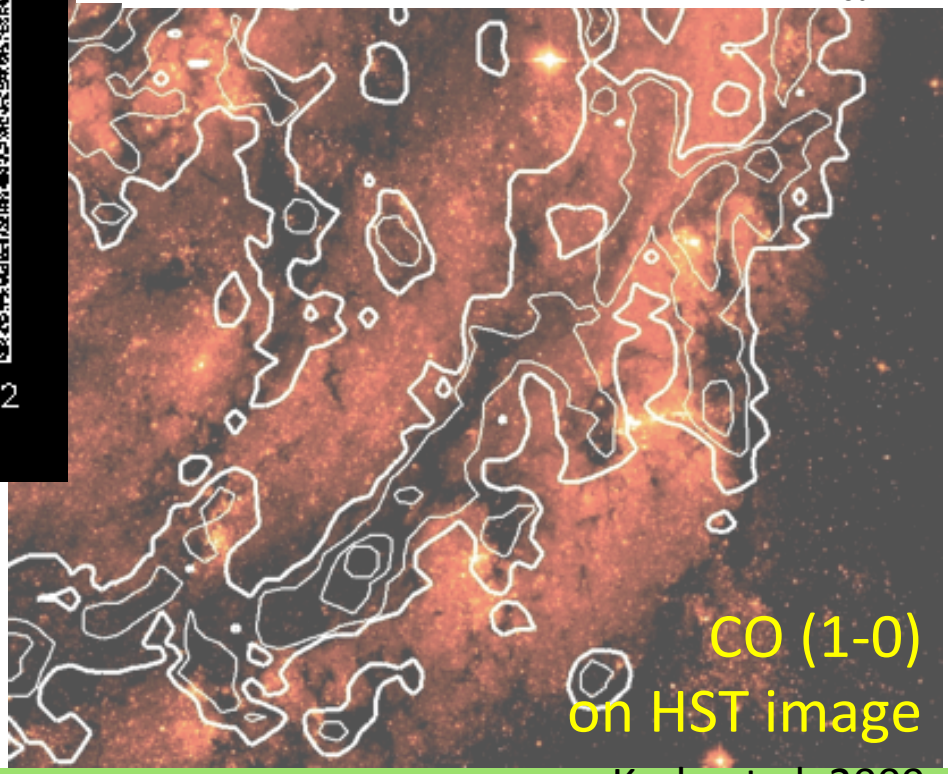


Wada & Koda 2004

SPH simulation
Isothermal gas
Stellar spiral potential



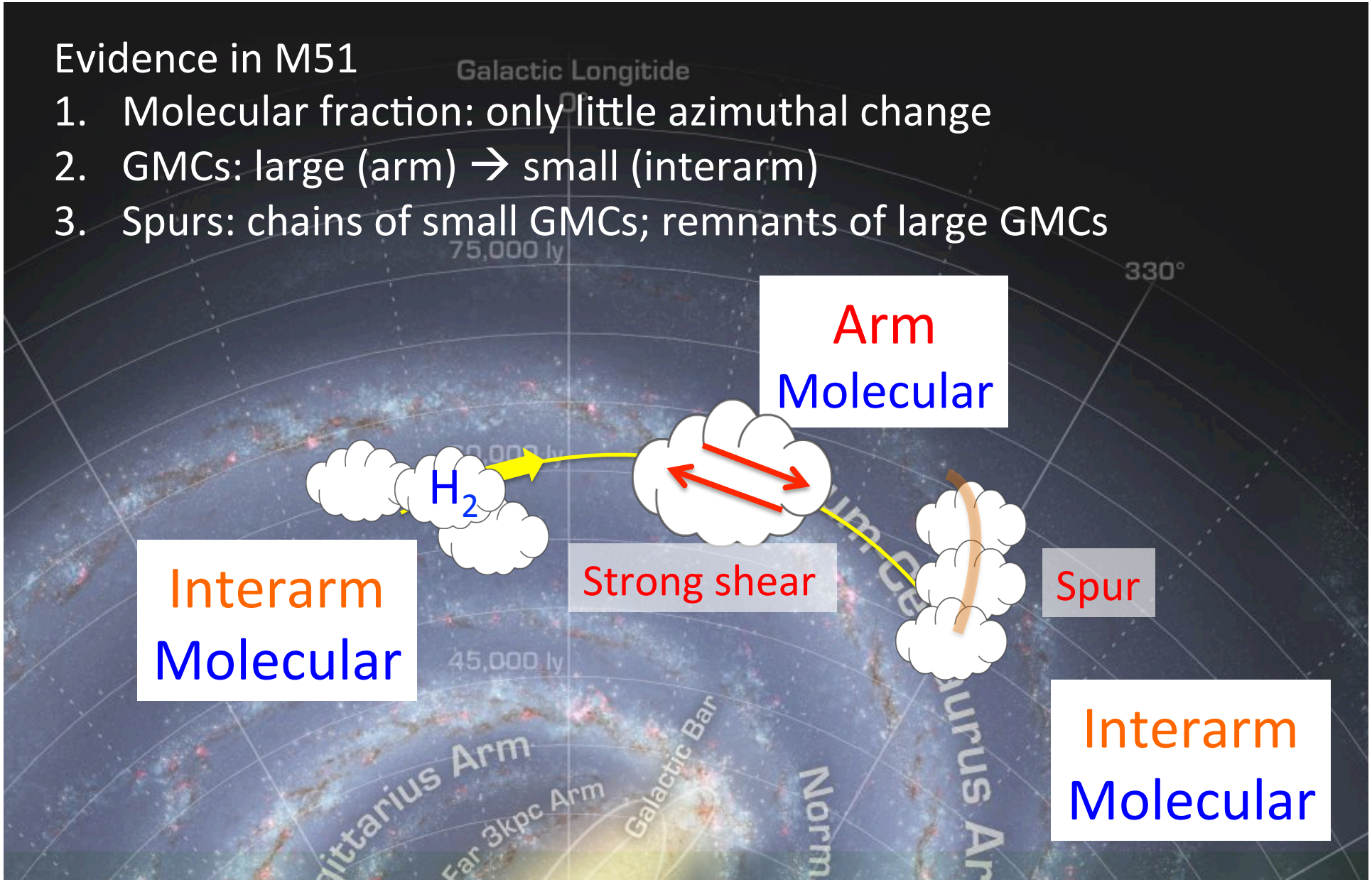
Mass: GMC on spiral ~ spurs ~ $10^7 M_{sun}$



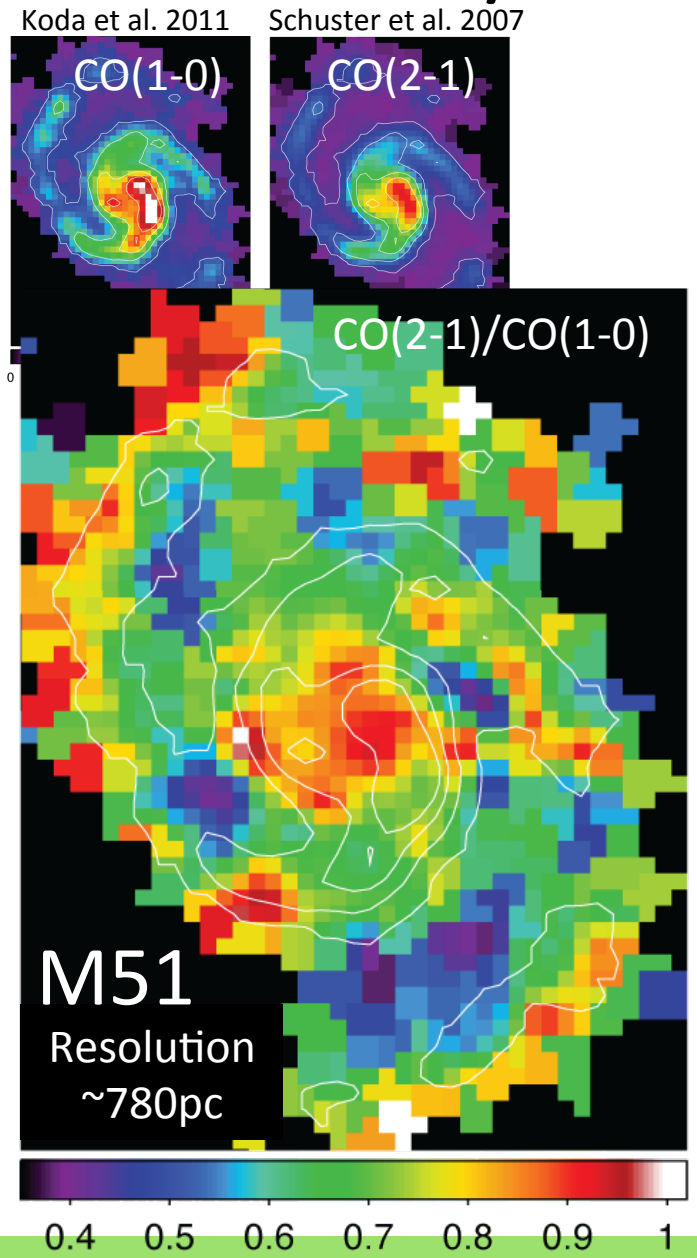
Koda et al. 2009

Spurs=
Remnants of massive GMCs?

New Picture


Evidence in M51
1. Molecular fraction: only little azimuthal change
2. GMCs: large (arm) → small (interarm)
3. Spurs: chains of small GMCs; remnants of large GMCs
Galactic Longitide
75,000 ly
330°
45,000 ly
Arm
Molecular
H_2
Interarm
Molecular
Strong shear
Spur
Interarm
Molecular
Galactic Bar

CO 2-1/1-0: Systematic Variations



Spiral arms (mostly downstream)

High ratio ~ 0.8-1.0

Interarm regions

Low ratio ~ 0.4-0.6

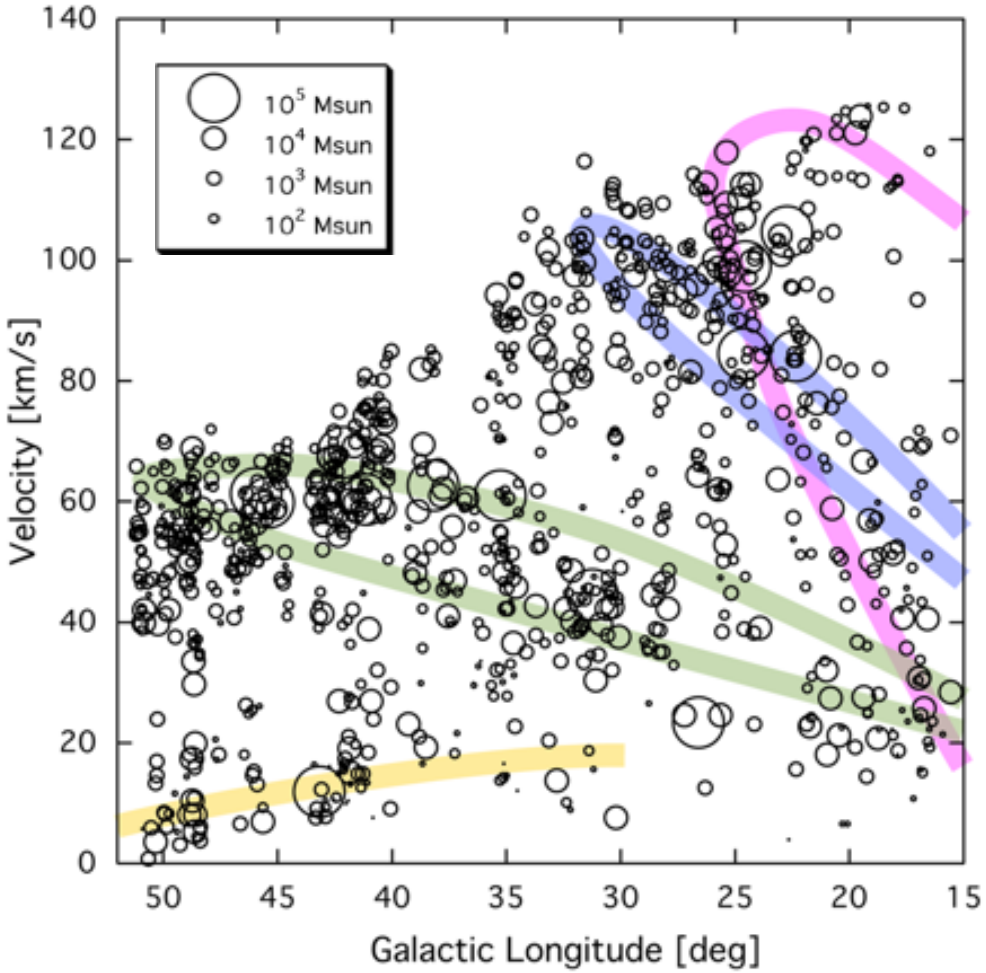
LVG analysis

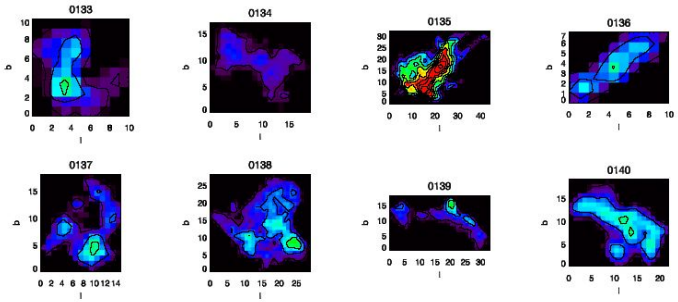
→x2-3 increases in ρ and/or T

The gas stays mostly molecular, but physical conditions evolve across spiral arms.

Koda et al. 2012; Vlahakis et al. 2013

GMC Distribution in the MW





Large (arm)
→ Small (interarm)

Koda et al. 2006

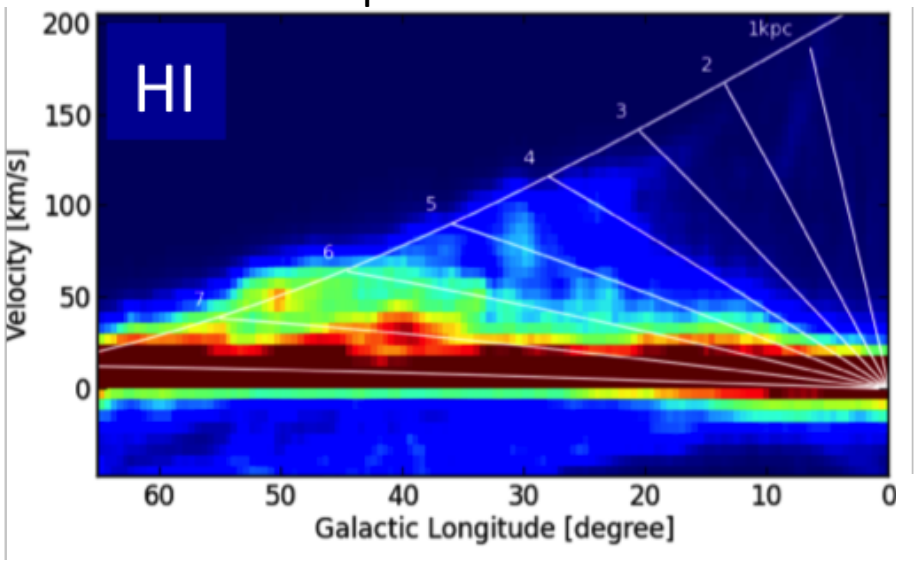
Spiral arms – from HII regions (radio recombination line obs)

BU-FCRAO ^{13}CO Galactic Ring Survey

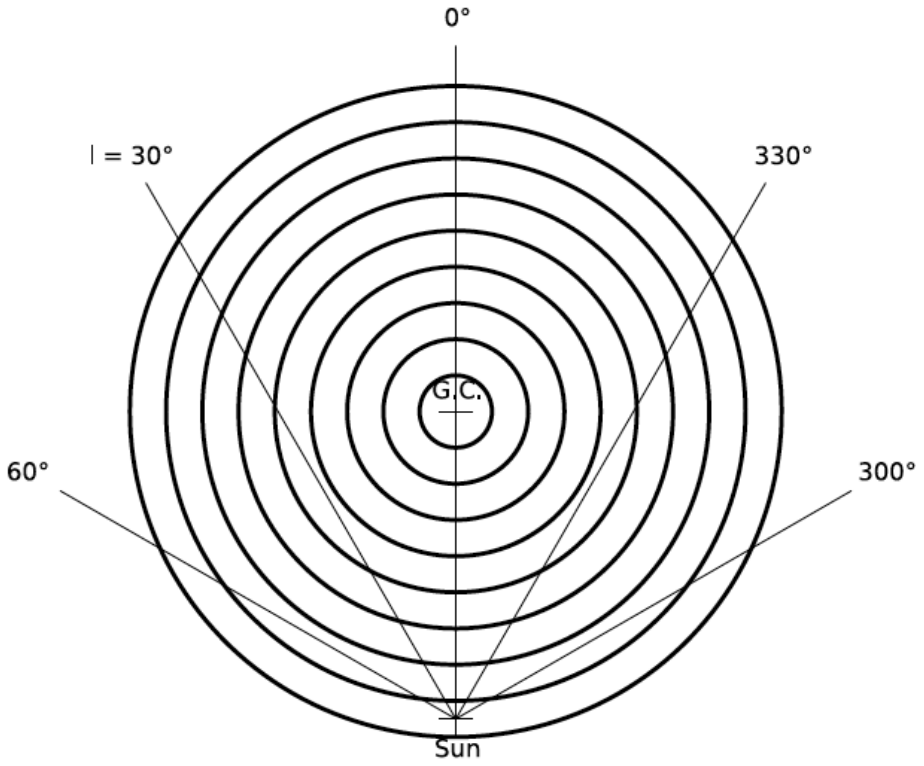
Jackson et al. 2006

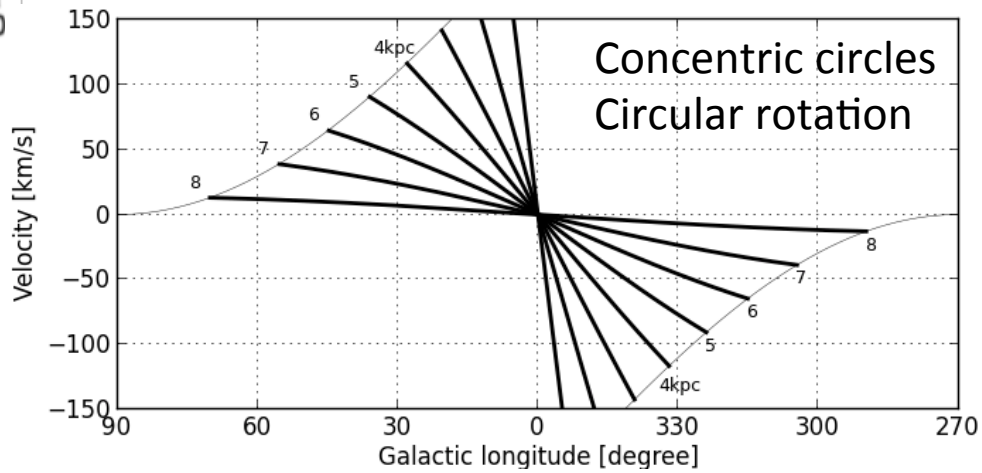
l-v Diagram I: Radial trend

Example: HI distribution



The LAB survey (Kalberla et al. 2005)

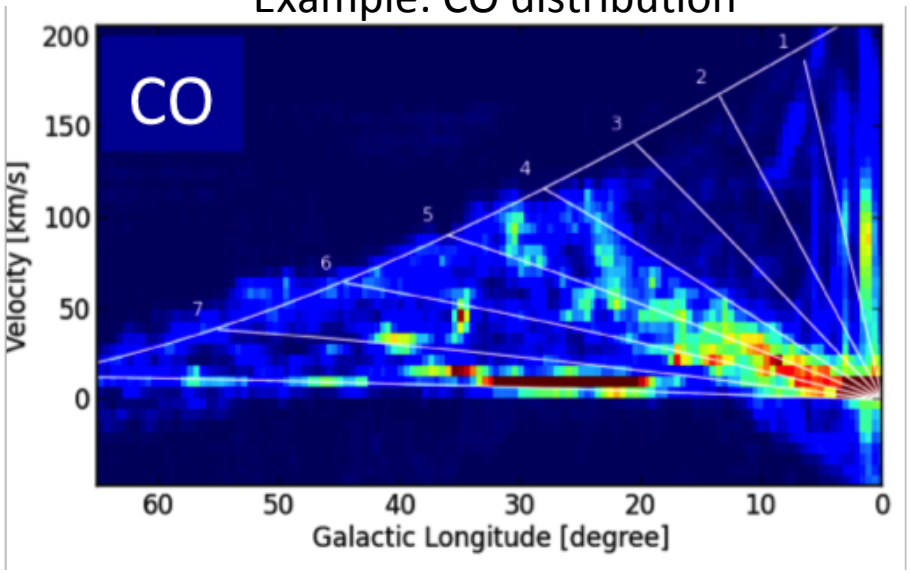




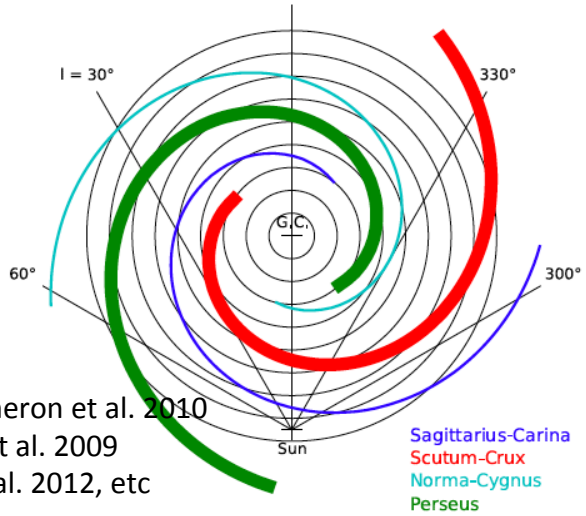
Koda in prep.

l-v Diagram II: Spiral Arms

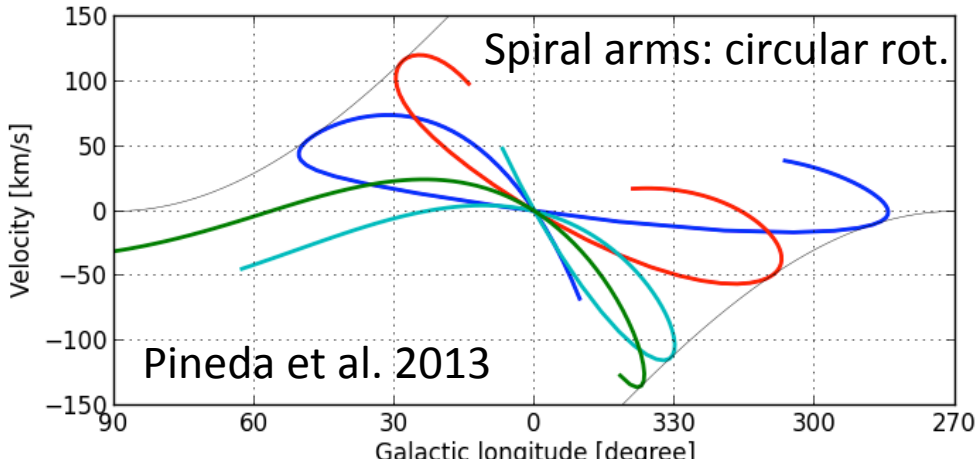
Example: CO distribution

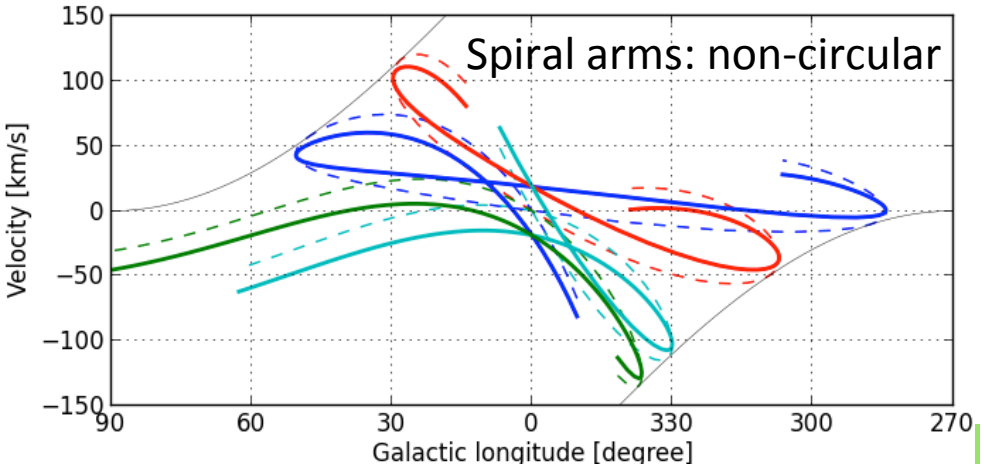


Columbia-CfA survey (Dame e al. 2001)



Steiman-Cameron et al. 2010
Churchwell et al. 2009
Robitaille et al. 2012, etc





Koda in prep.

f_{mol} in *l-v* diagrams

$$|b| < \pm 30\,\mathrm{deg}$$

HI surface density

$$\Sigma_{HI} = 1.82 \times 10^{18} \int T\, dv$$

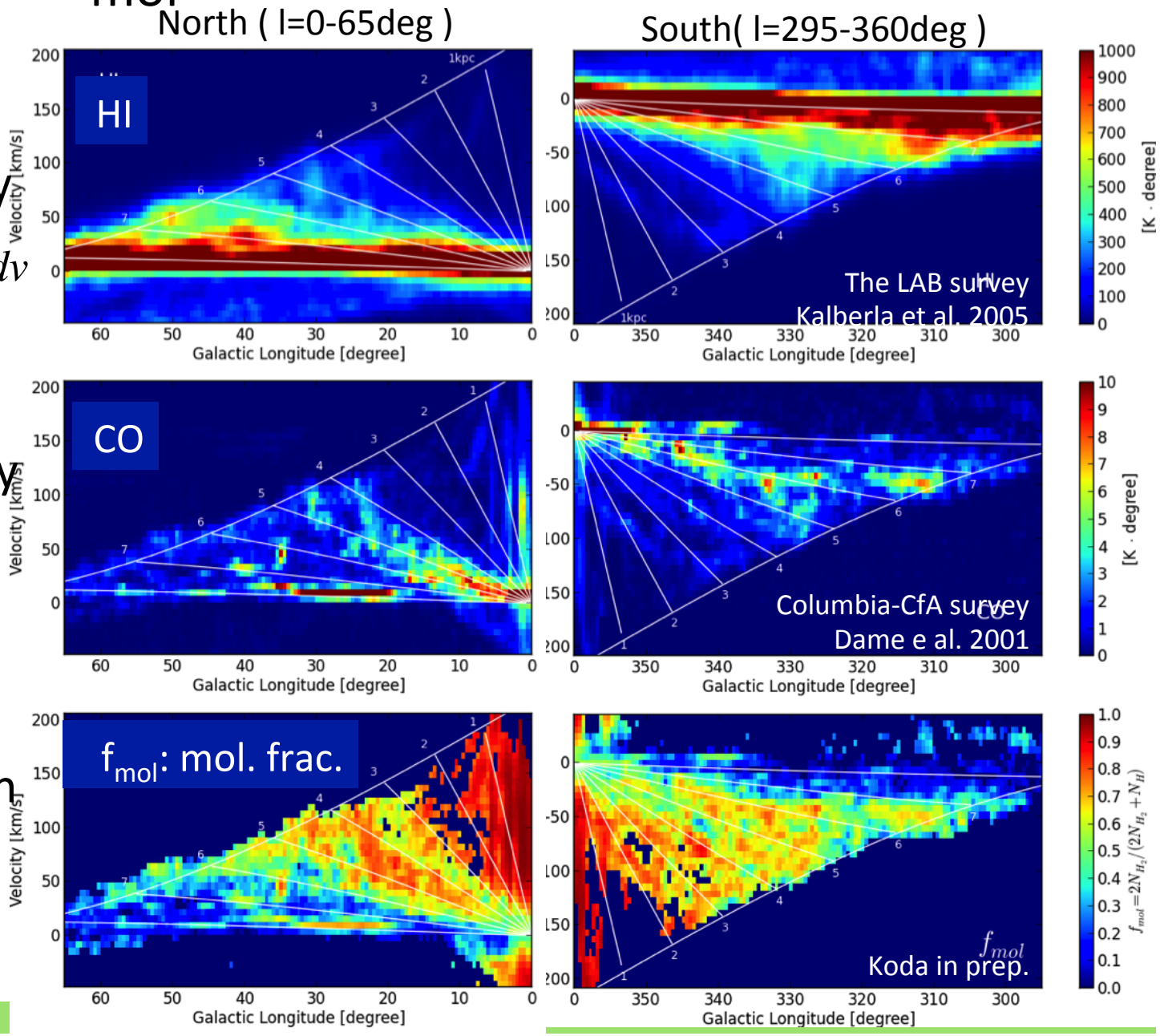
H2 surface density

$$\Sigma_{H_2} = Xco \int T\, dv$$

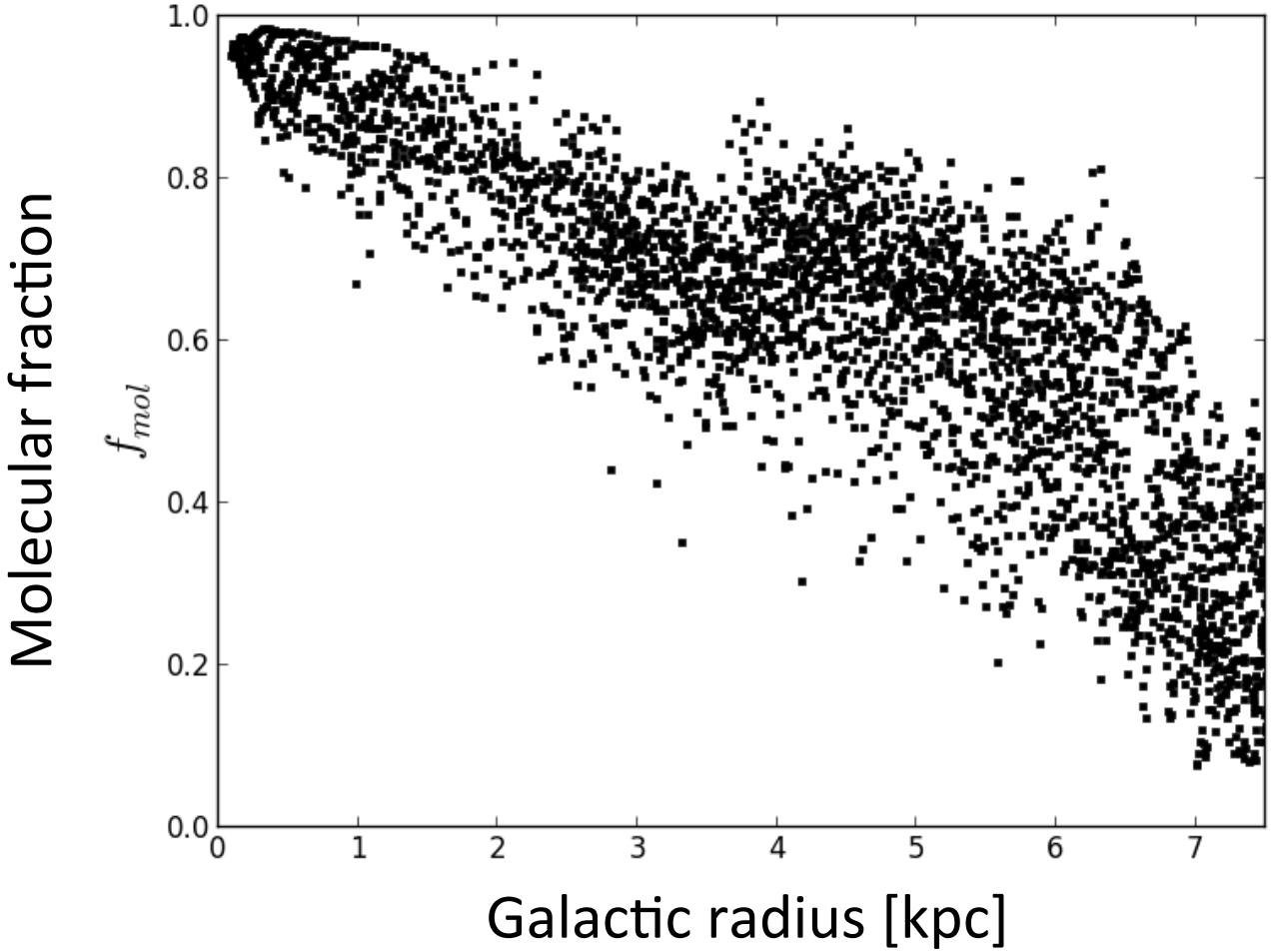
$$X_{CO} = 2 \times 10^{20}$$

Molecular fraction

$$f_{mol} = \frac{\Sigma_{H_2}}{\Sigma_{H_2} + \Sigma_{HI}}$$



f_{mol} in the MW

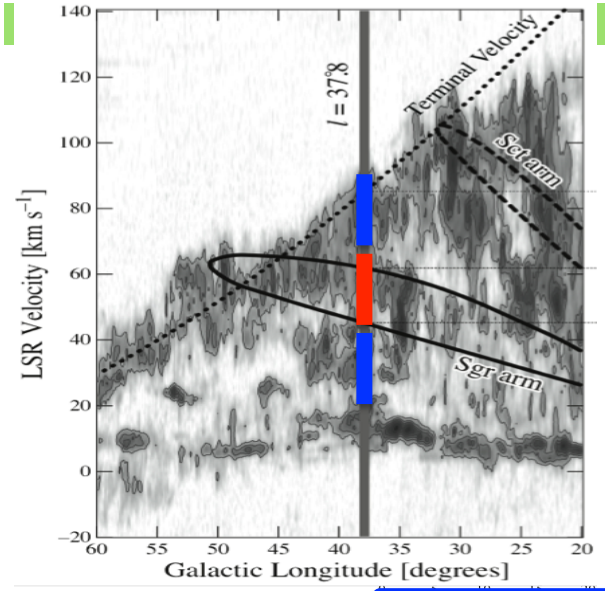


Radial gradient – dominant

Arm/interarm variations (scatters) -- ~20-30%

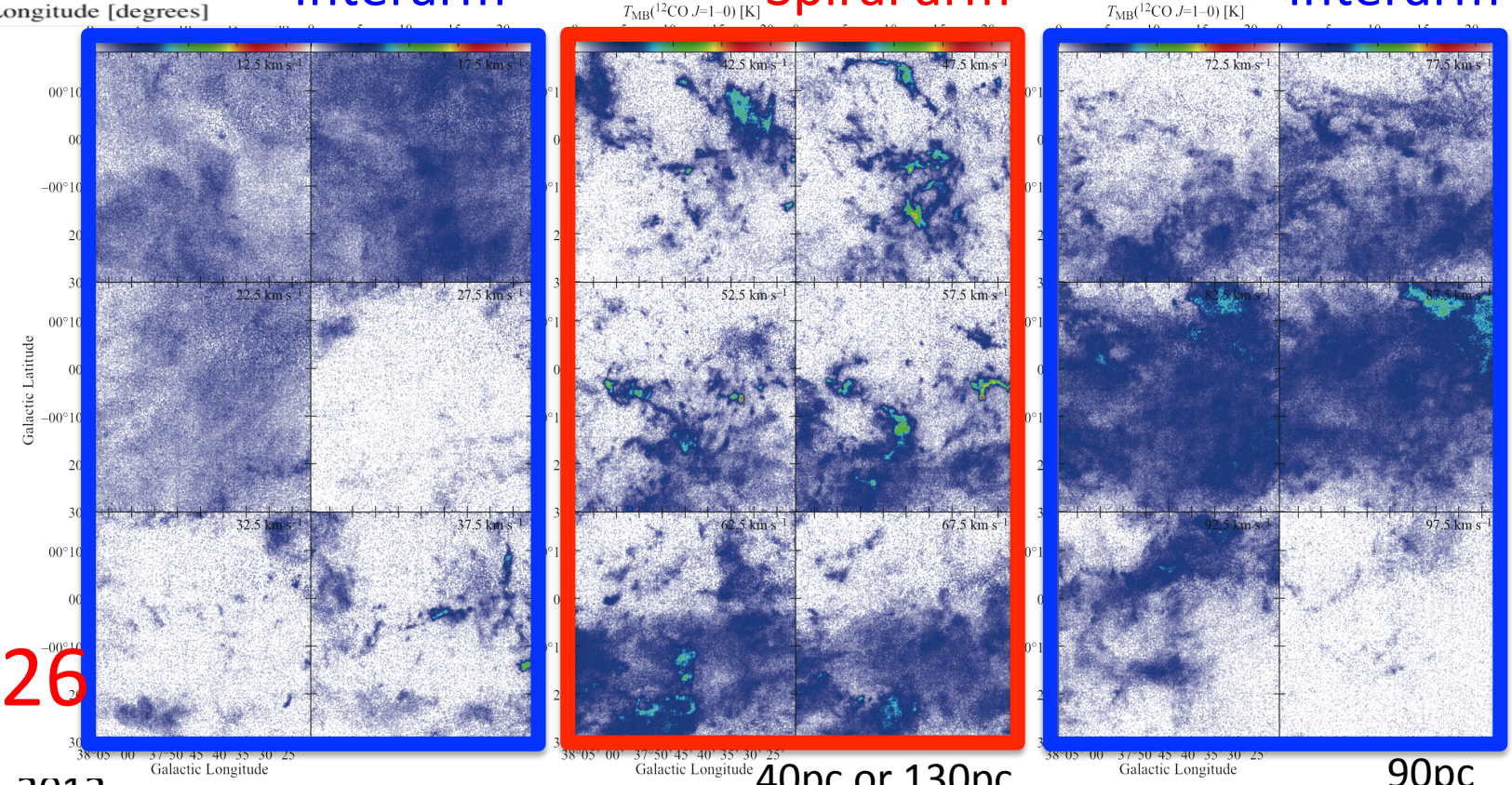
Koda in prep.

Growth of Dense Clumps through Spiral Arm



^{12}CO Obs. of l~38deg region with Nobeyama 45m telescope
Channel maps: 50 arcmin x 50 arcmin, 15" resolution (<0.7pc)

Interarm | Spiral arm | Interarm



40pc or 130pc

90pc

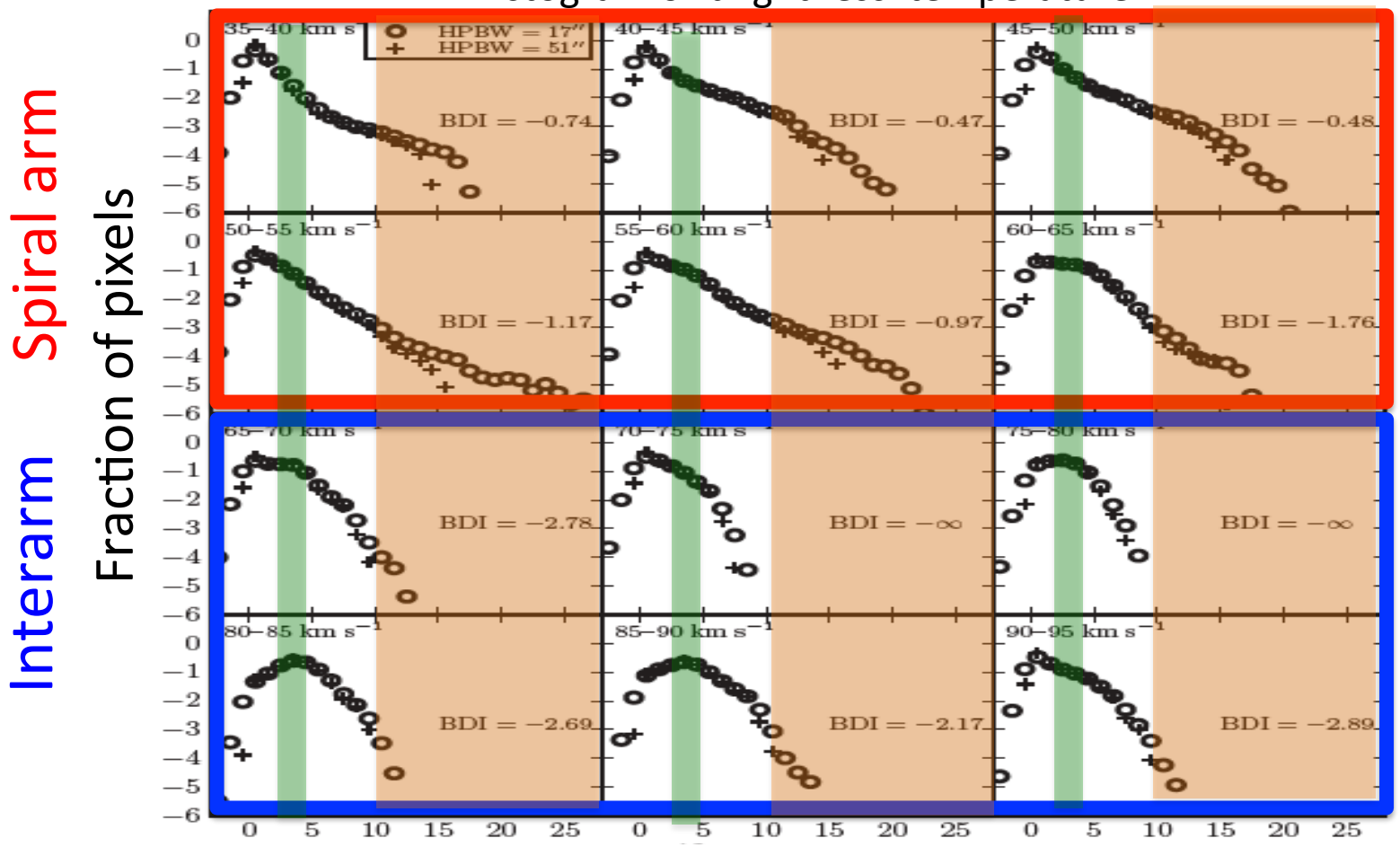
Poster26

Sawada et al. 2012

Brightness Distribution Function (BDF)

Obs. of l~38deg region with Nobeyama 45m telescope

Histogram of brightness temperature



T_{MB}[K] in CO(1-0) ~ column density

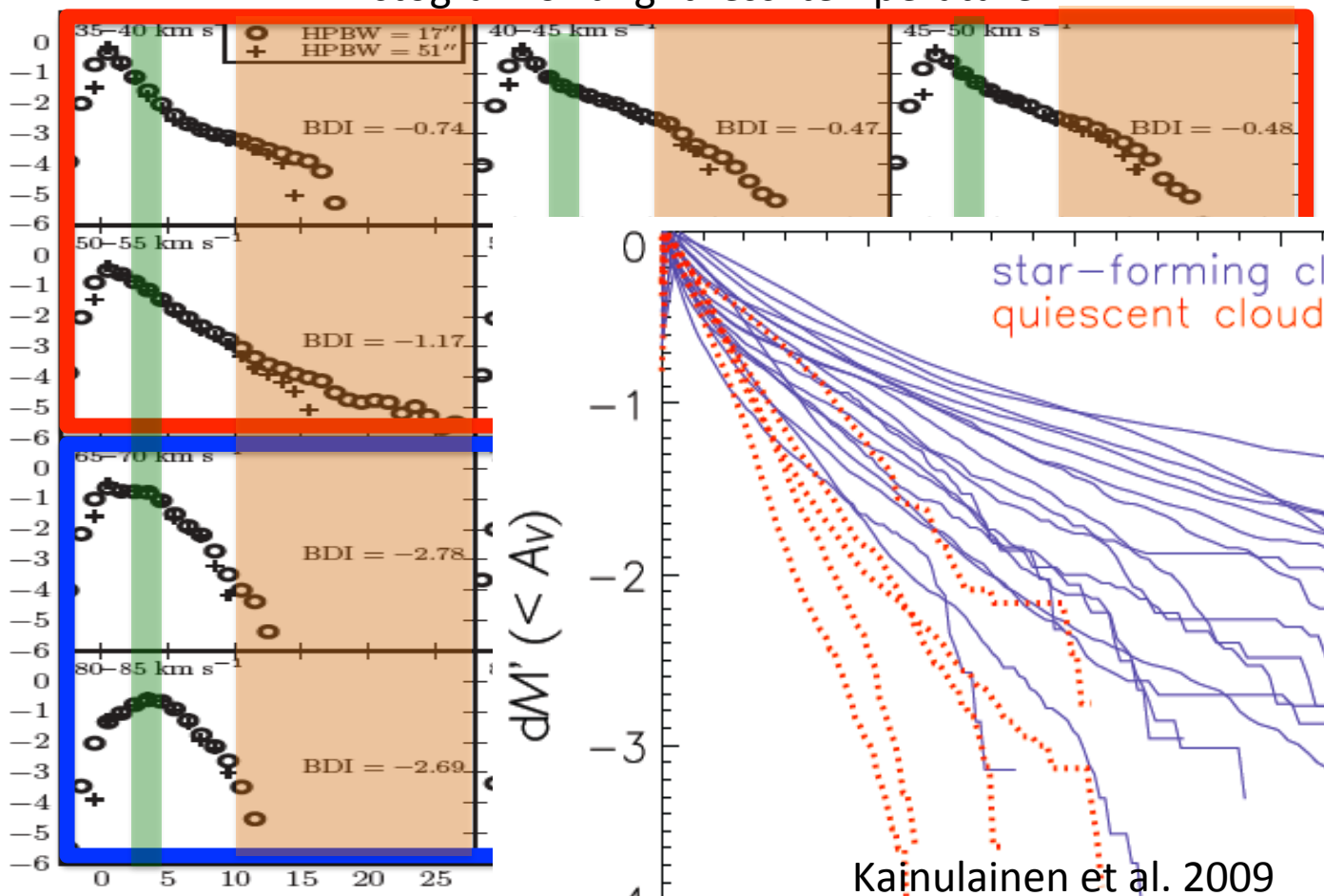
Sawada et al. 2012

High T_{mb} gas in spiral arms in the MW

Brightness Distribution Function (BDF)

Obs. of l~38deg region with Nobeyama 45m telescope

Histogram of brightness temperature



Spiral arm

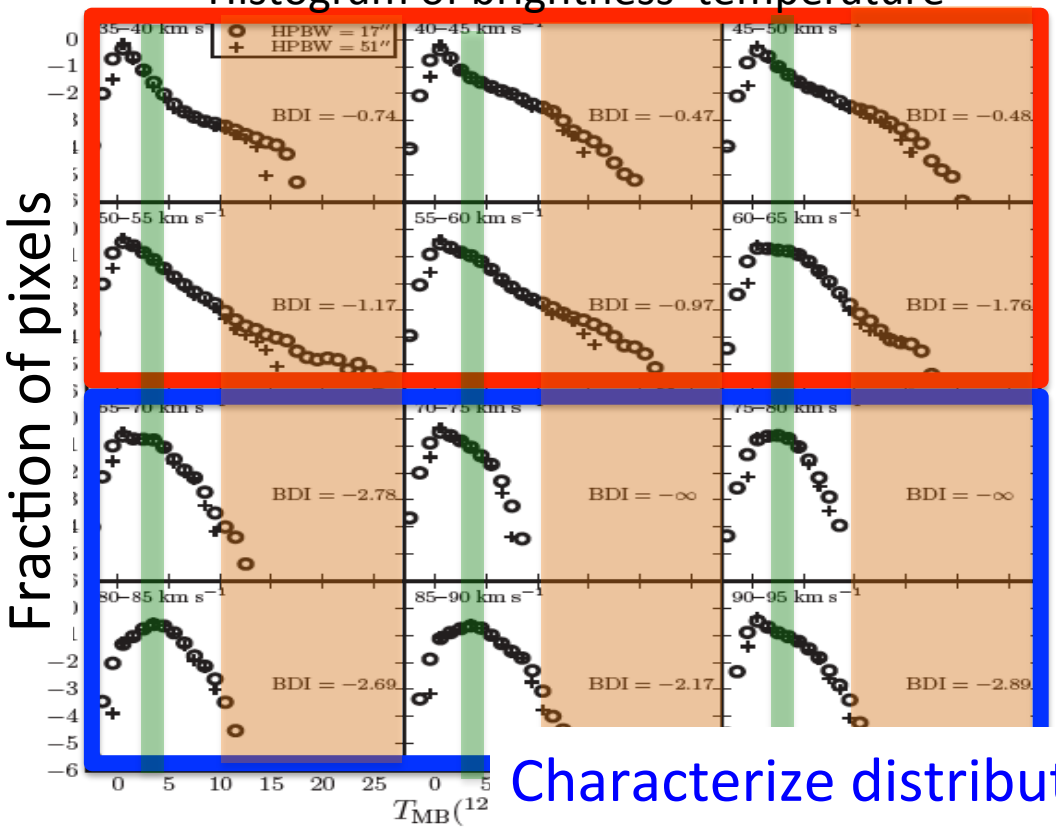
Interarm

Sawada et al. 2012

High T_{mb} &

Brightness Distribution Index (BDI)

Histogram of brightness temperature



Characterize distribution with one parameter

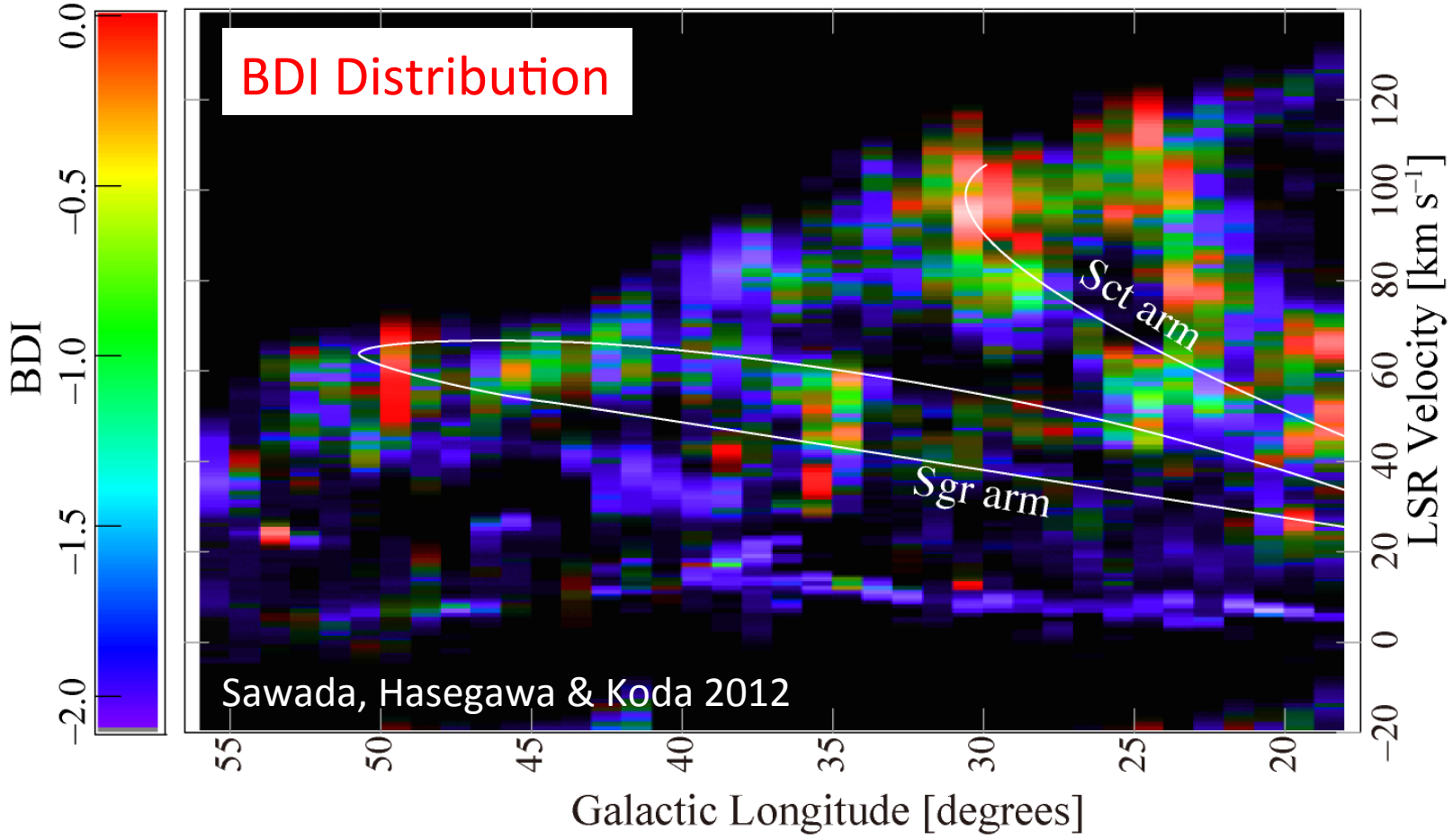
$$BDI = \log_{10}\left(\frac{\int_{T_2}^{T_3} T \cdot B(T)dT}{\int_{T_0}^{T_1} T \cdot B(T)dT}\right)$$

(T_0, T_1, T_2, T_3) = (3, 5, 10,∞)

Sawada et al. 2012

Evolution Across Spiral Arms

BDI – calculated in each *dl* x *db* = 2x1 deg^2 region

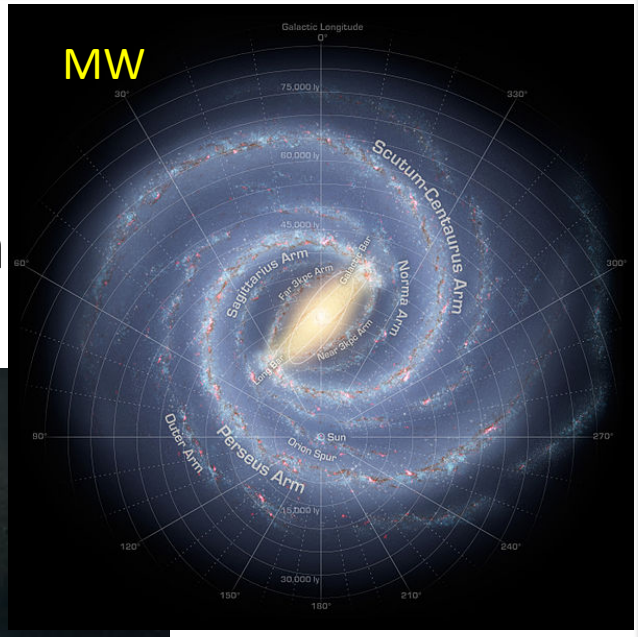


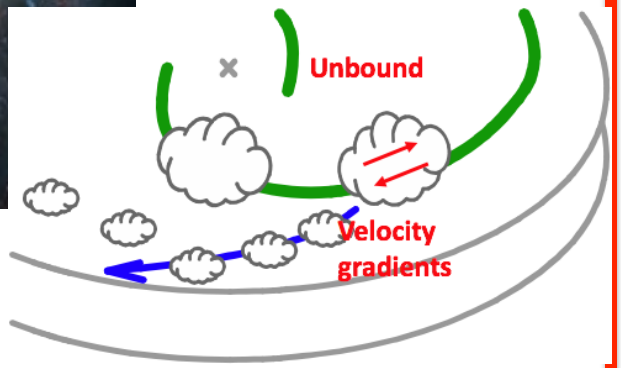
High BDI in spiral arms – Dense (or warm) cores developing

Atomic-rich vs Molecular-rich galaxies

So far

Molecule-rich



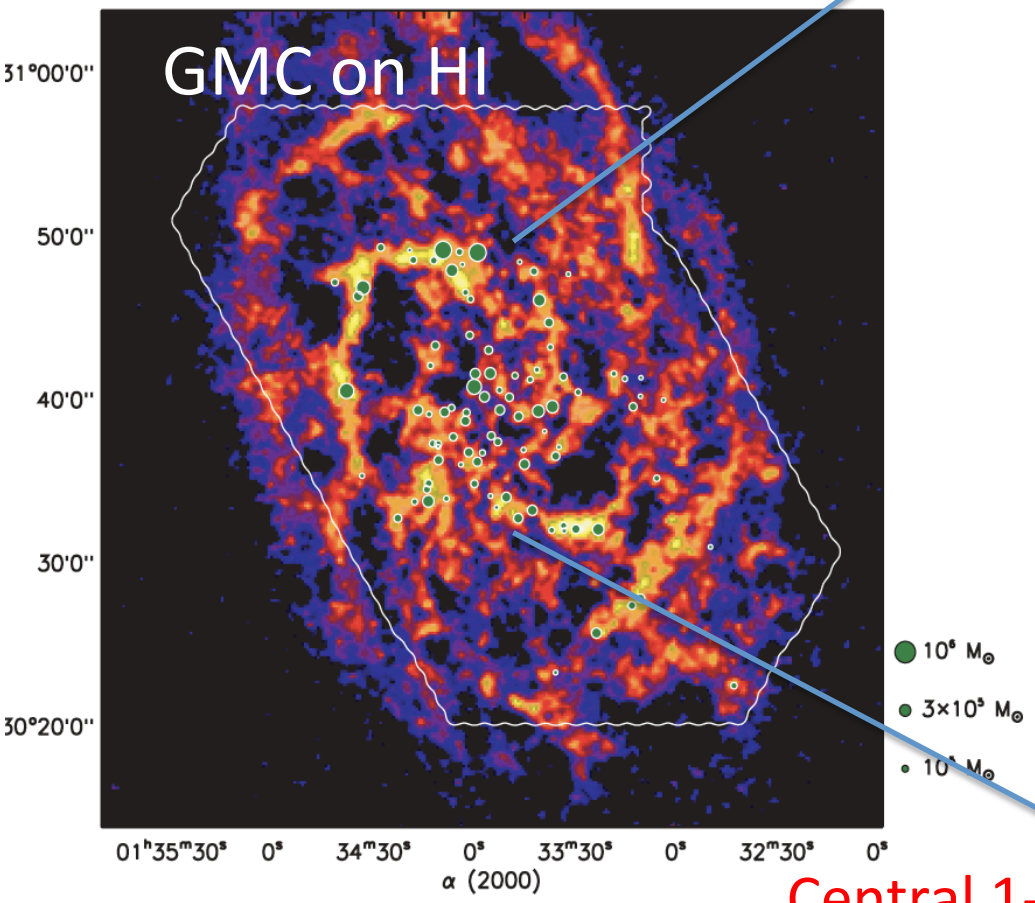


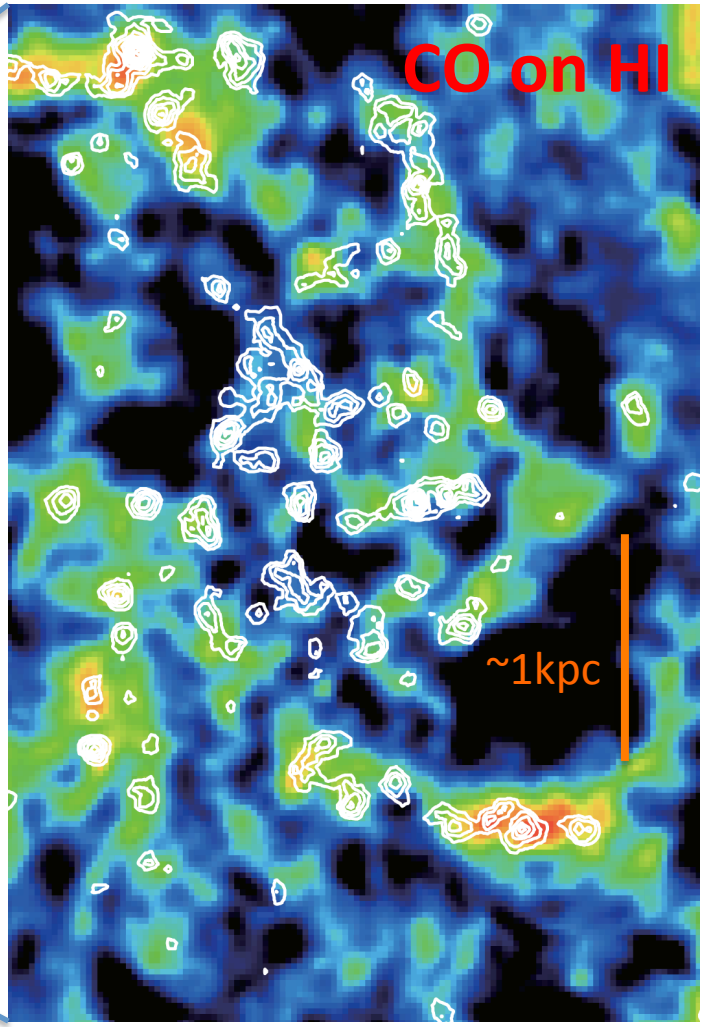
Atom-rich

GMC Distribution in M33

GMCs mostly on HI spiral arms

Not many in interarm regions





Central 1-2kpc region more like M51 & MW

Engargiola et al. 2003

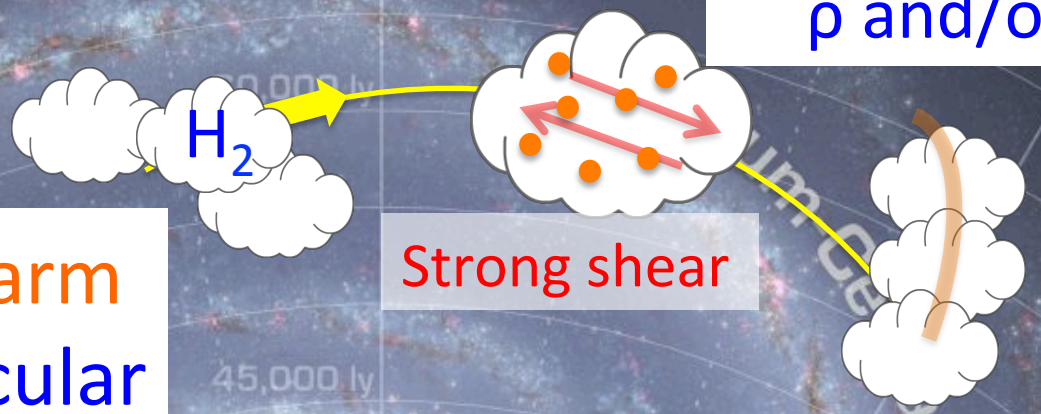
Tosaki et al. 2011

Summary

Molecule-dominated galaxies (or regions)

New picture: the gas stays molecular from arm through interarm.

1. Molecular fraction: only little azimuthal change
2. GMCs: large (arm) → small (interarm)
3. Spurs: chains of small GMCs; remnants of large GMCs



Atom-dominated

Old textbook picture: Atomic → Moleculer → Atomic