Linking Galactic and Extragalactic

Gas and Dust Surveys

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Supported by the NSF through grant AST- 1211680

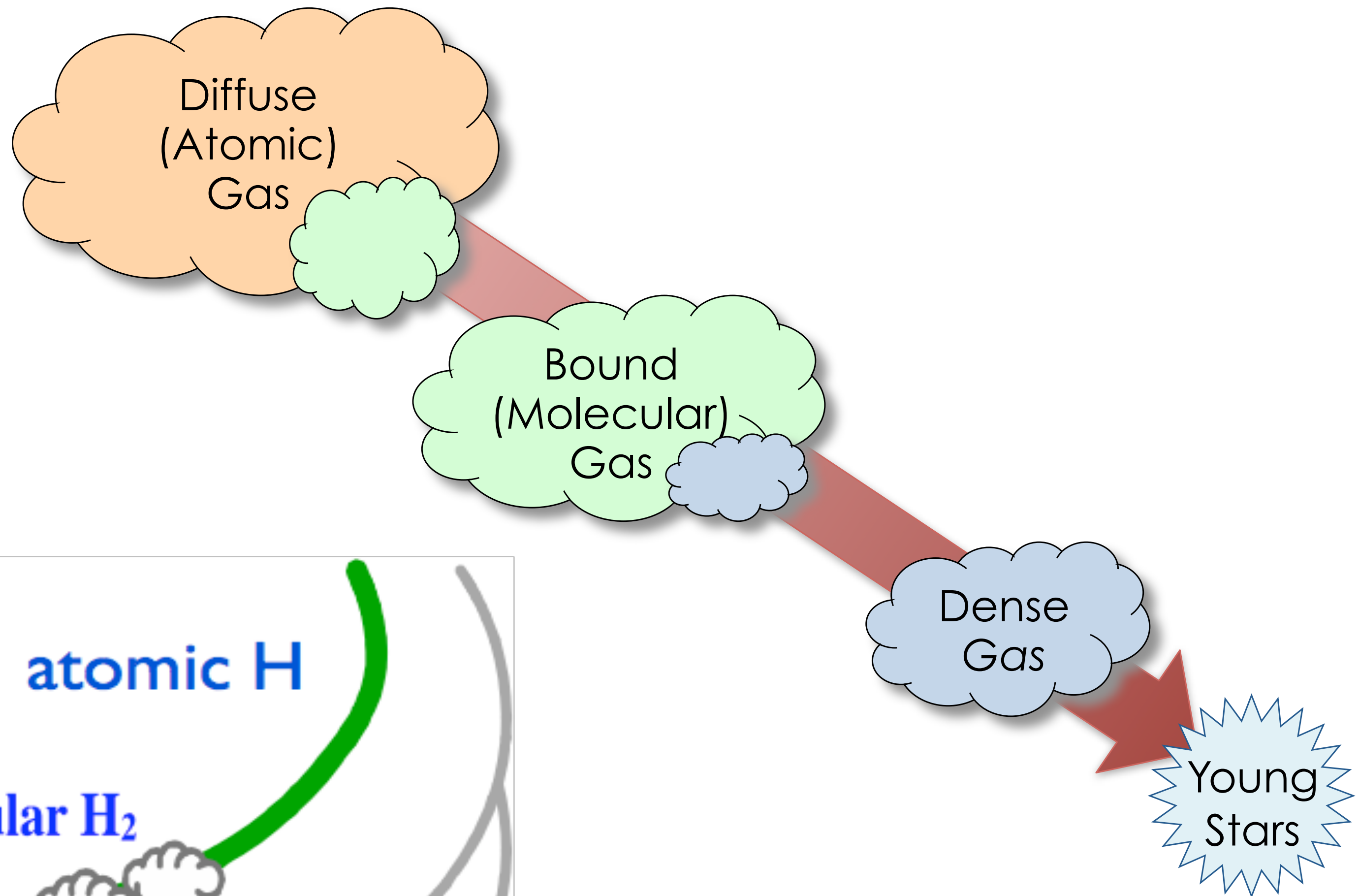
Outline

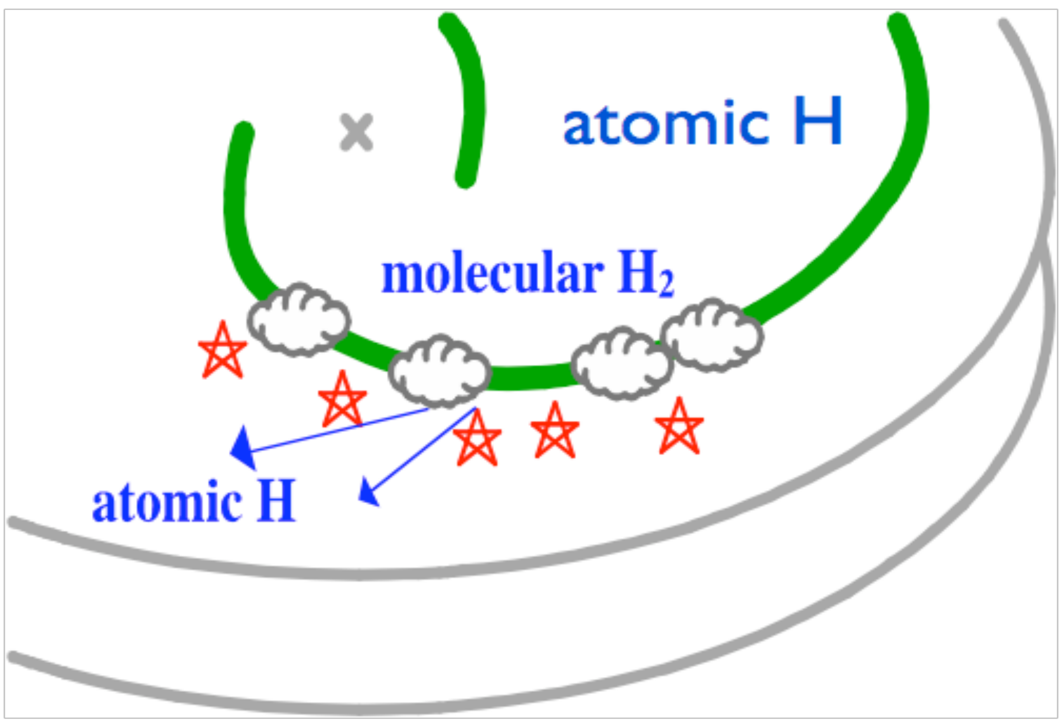
- Atomic/molecular phase evolution in spiral galaxies (atom-dominant vs molecule-dominant)

- Development of small dense clumps in the ISM (w.r.t. spiral arms)

Gas Phase
Atom Dominant Case

Classic Picture of ISM Evolution





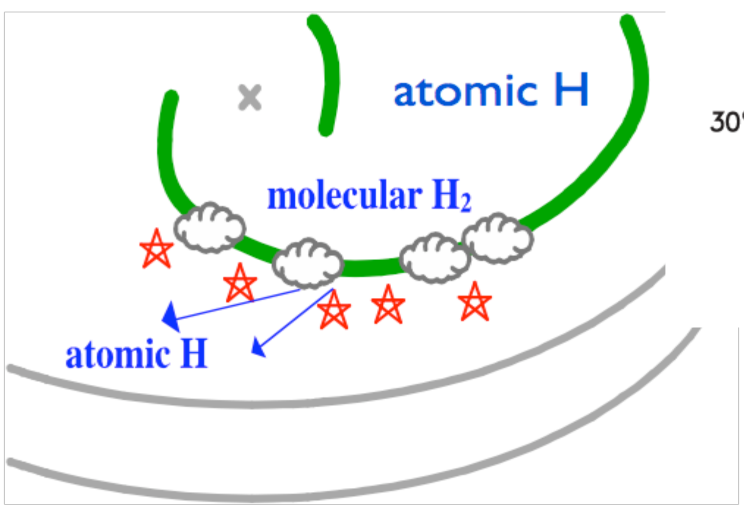
Provided by Adam Leroy

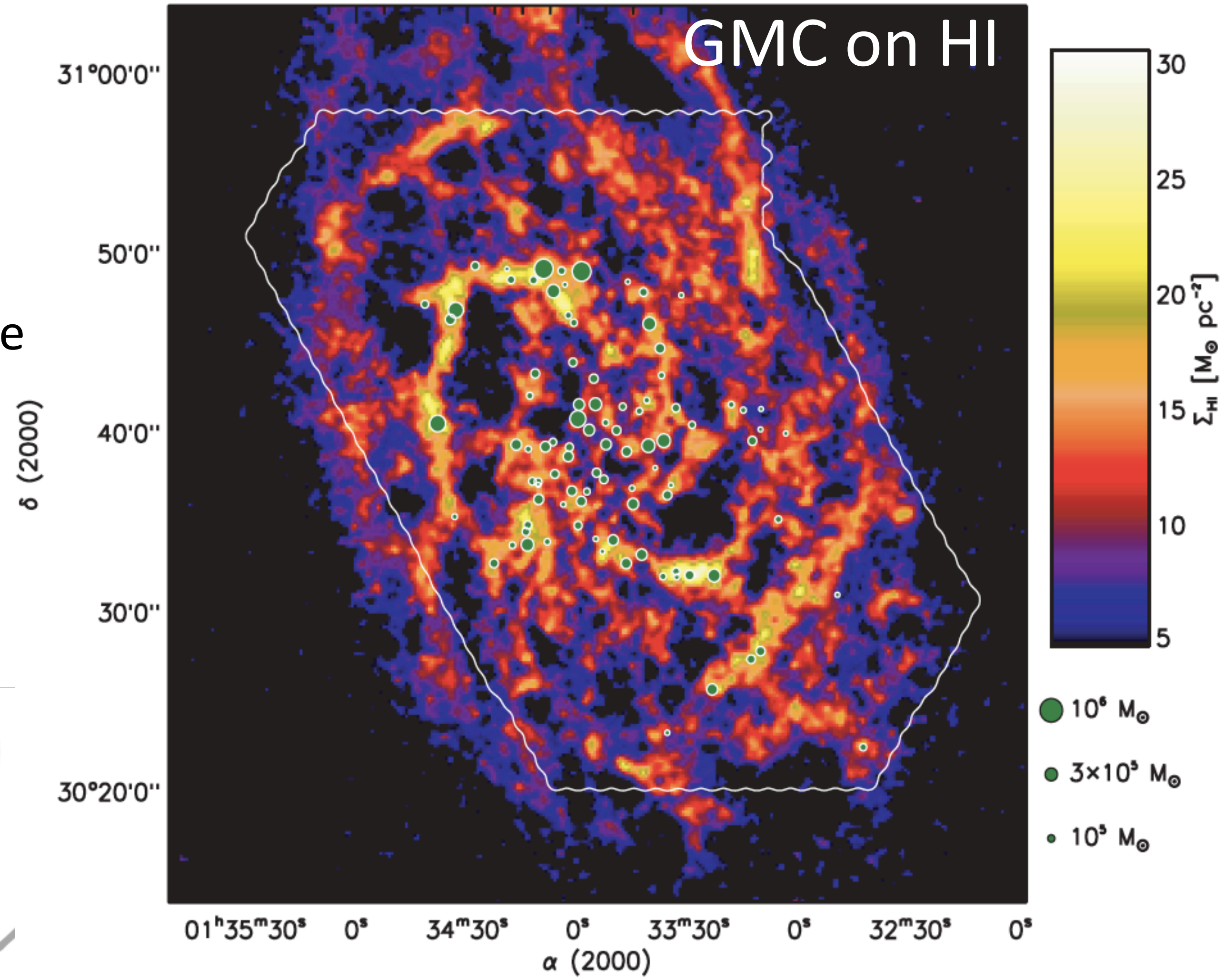
M33 - GMCs on HI Spiral Arms

GMC lifetime

~ Arm crossing timescale

~20-30Myr?

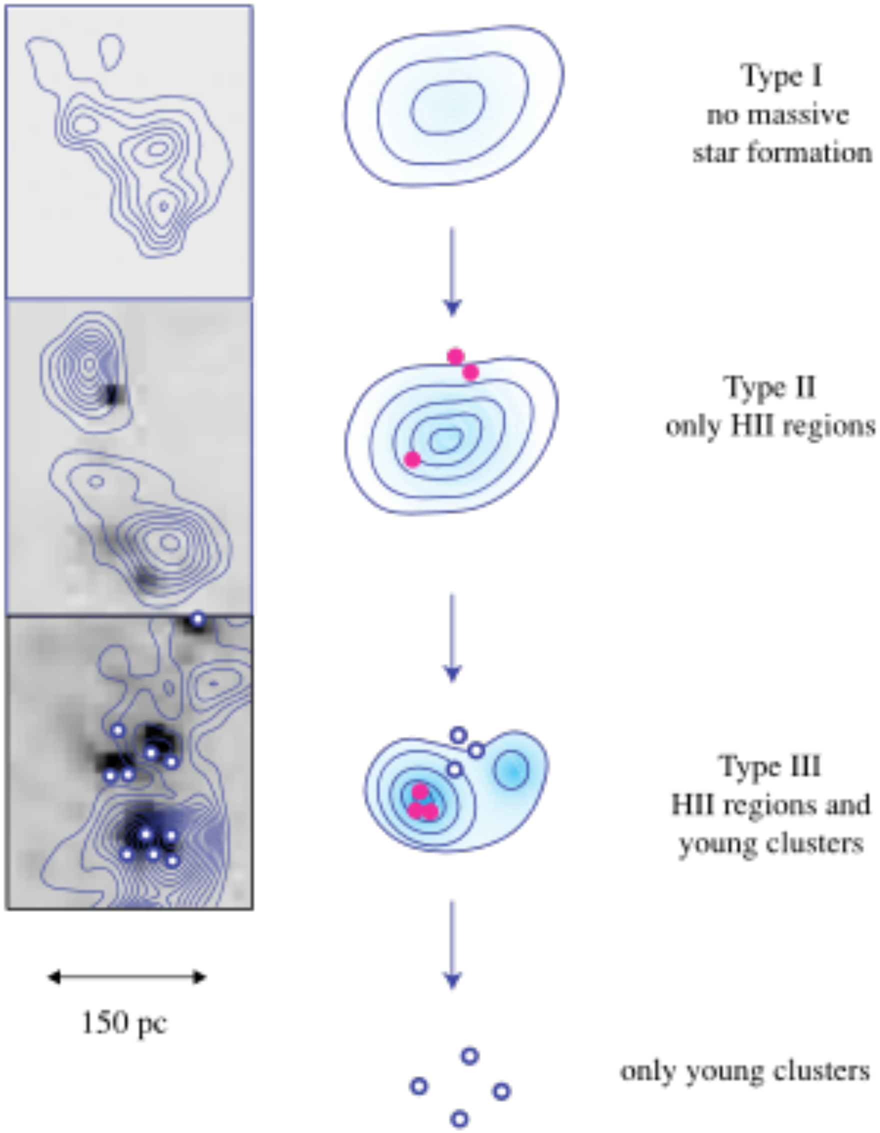




Engargiola et al. 2003

GMC Evolutionary Sequence in LMC

Kawamura et al. 2009



24% ~6Myr

50% ~13Myr

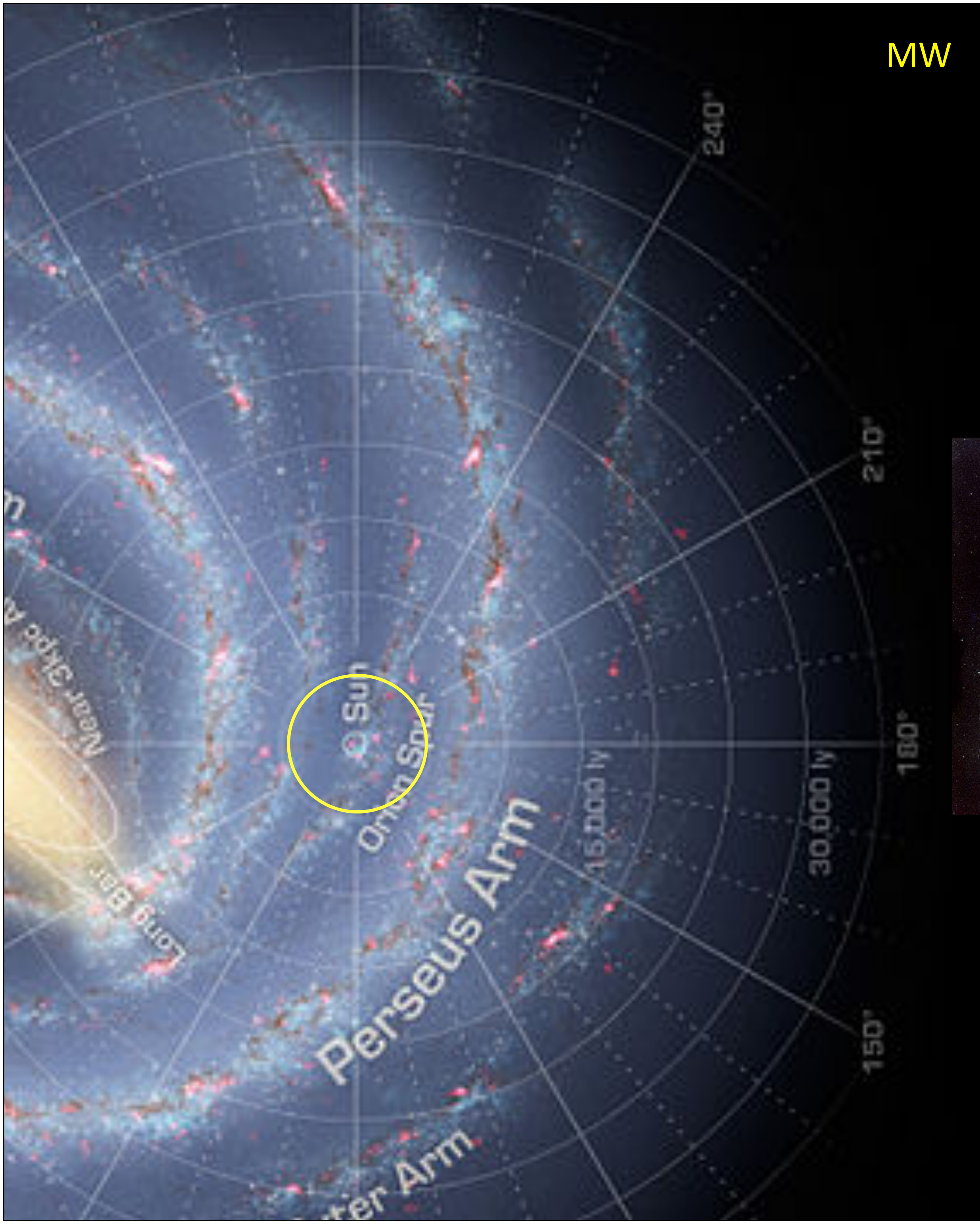
26% ~7Myr

~66% of young clusters (<10Myr) are associated with GMCs.

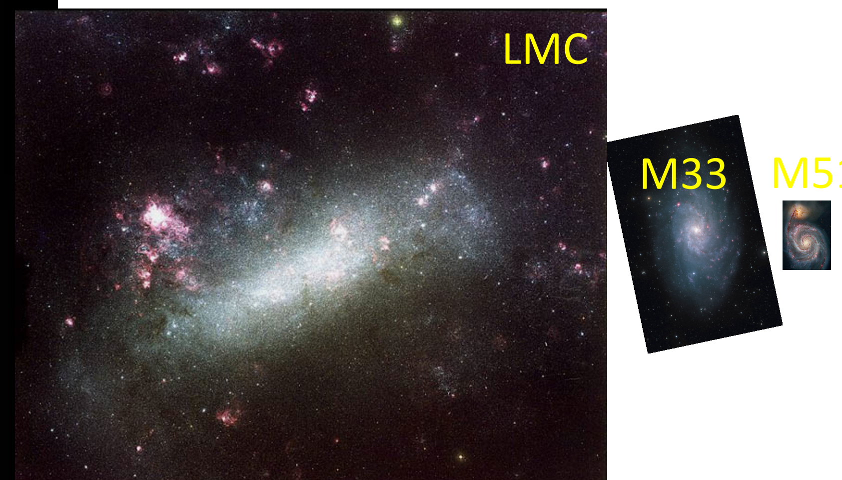
GMC lifetime ~ 20-30Myr

Complete >5x10^{4}Msun

~20-40Myr in M33 (Miura et al. 2012)



Angular Size



Standard picture:

based on

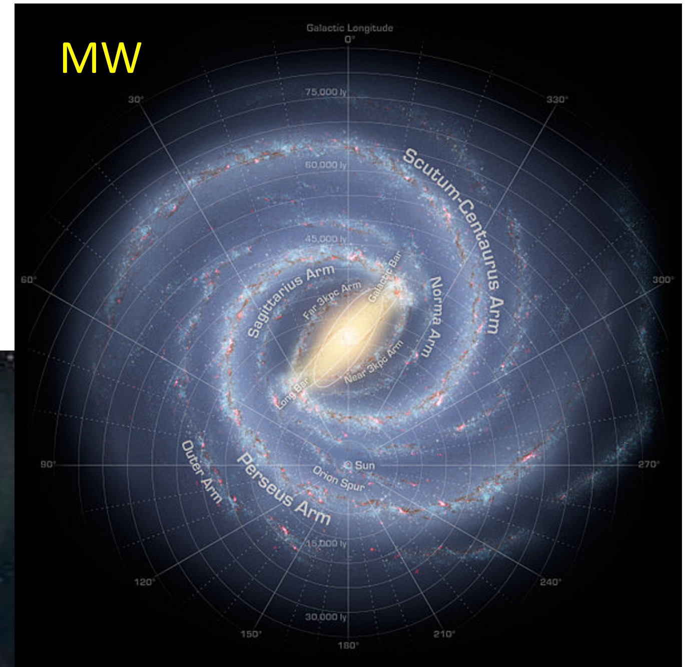
MW outskirts (around Sun)

& dwarf galaxies

Linear Size

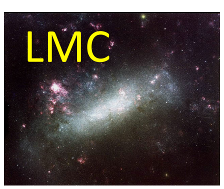
Molecule-rich

Disks (major parts) of
M51, MW, etc.



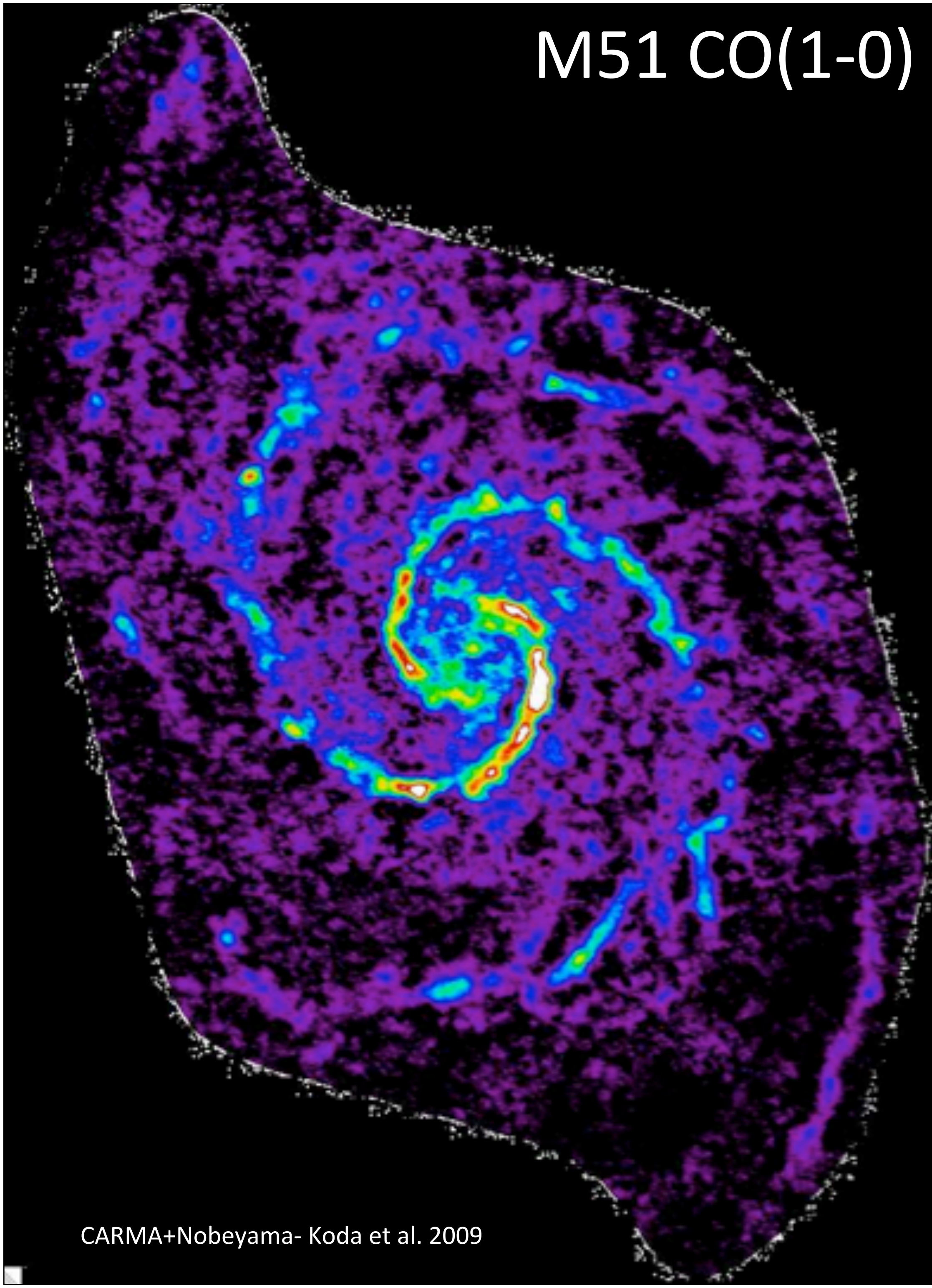
Atom-rich

LMC, M33,
(Outskirts of MW, etc)

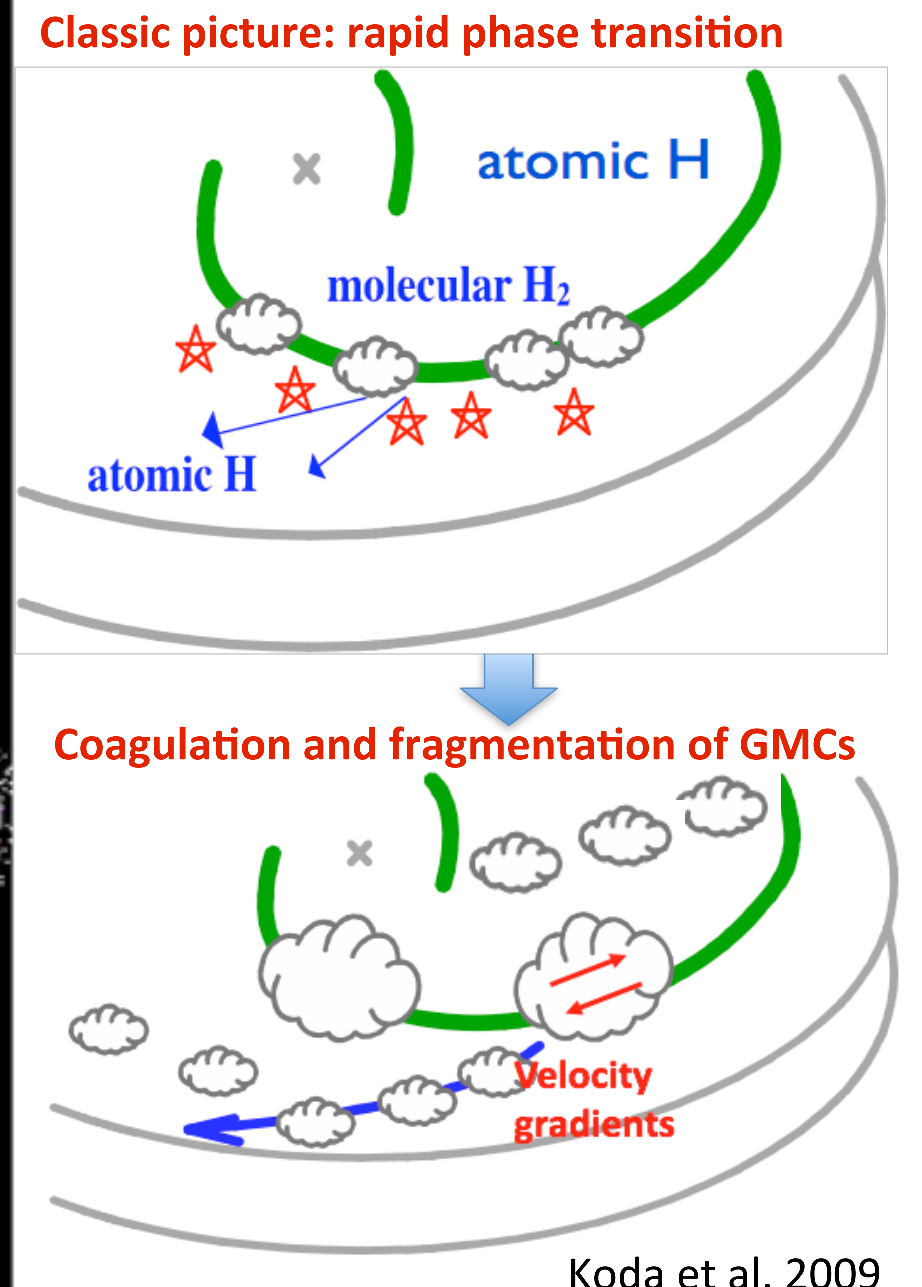


What about the main parts of major disk galaxies?

Gas Phase:
Molecule Dominant Case



Suggested Picture



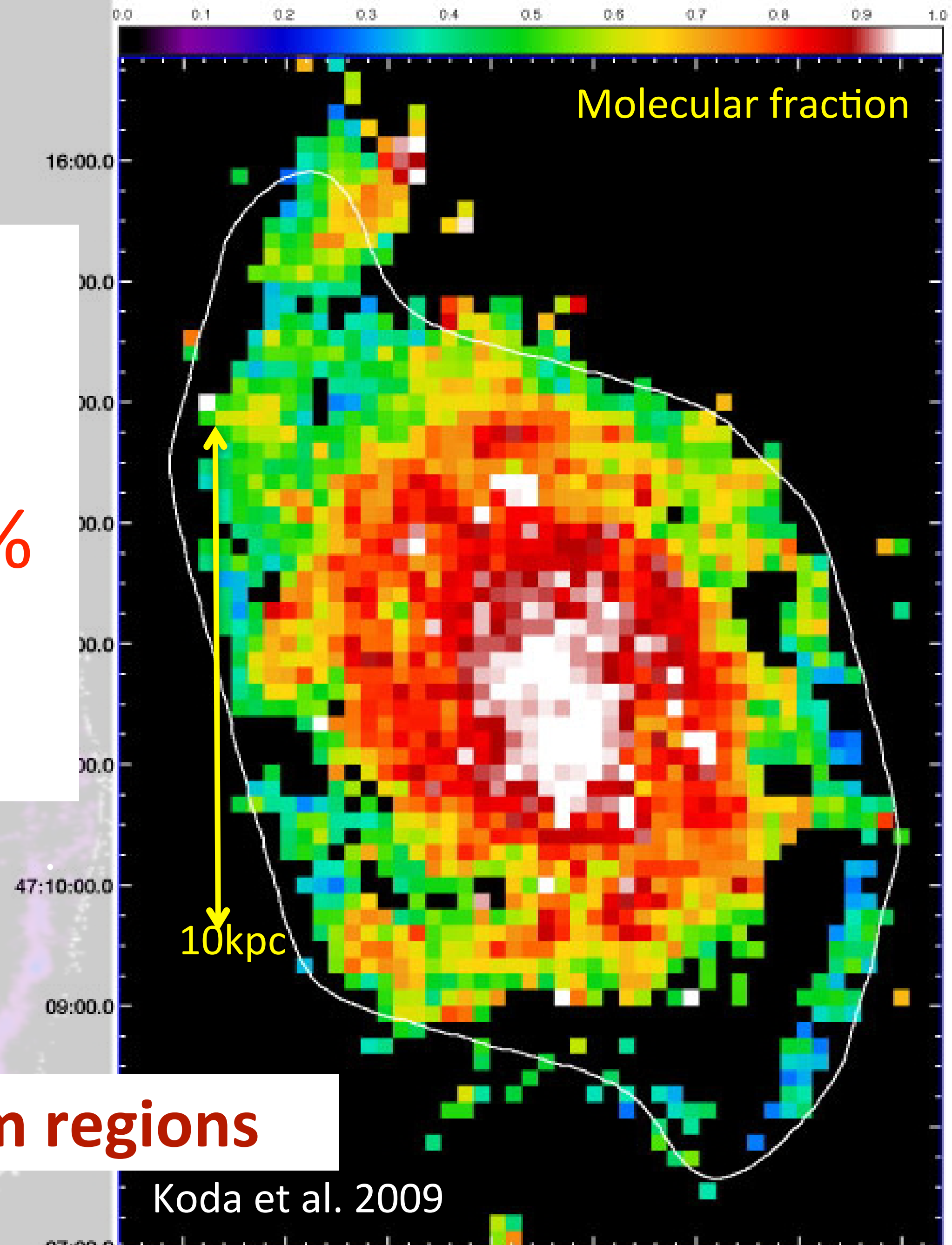
Large Molecular Fraction

M51 CO(1-0)

Molecular Fraction

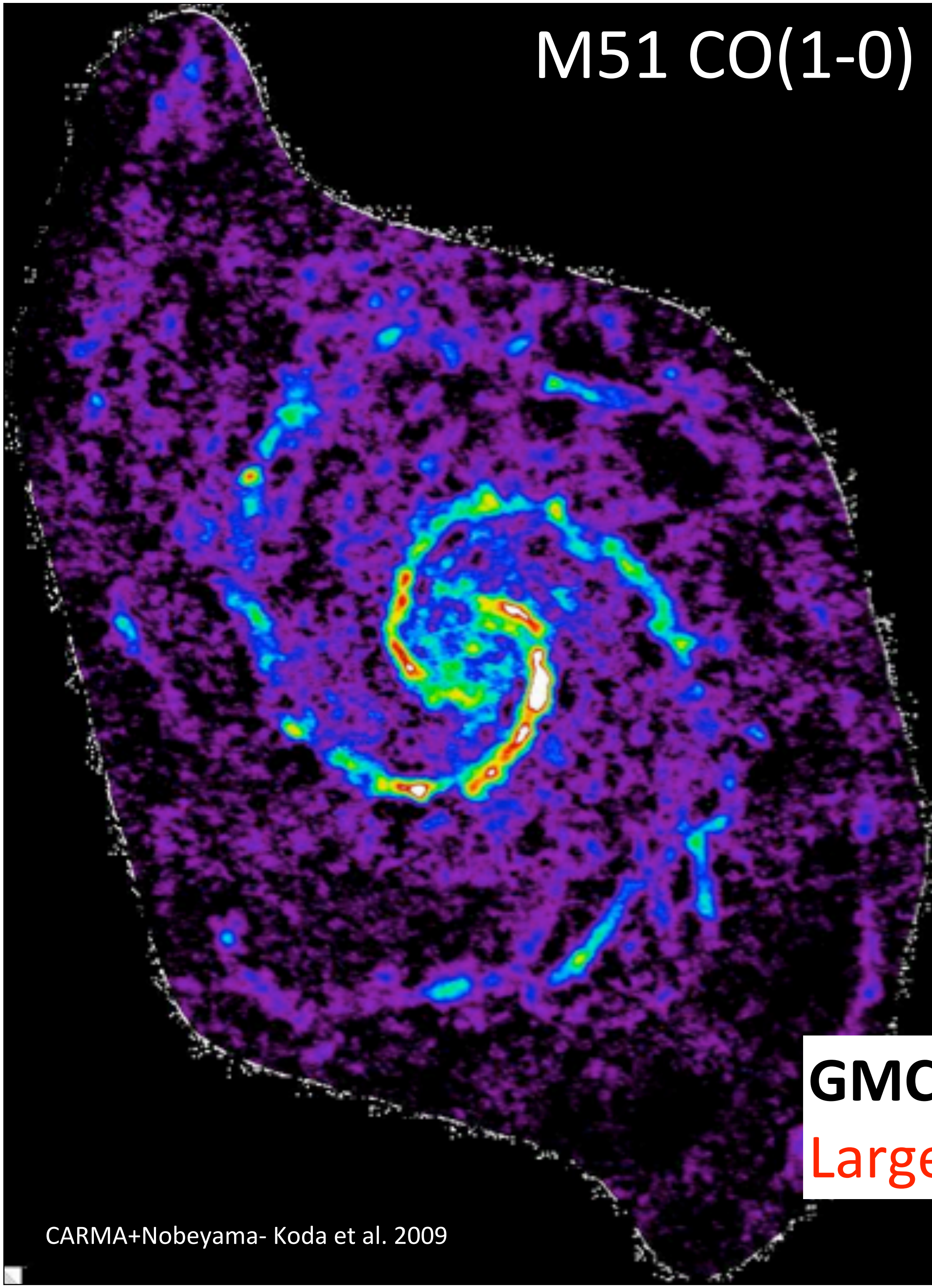
$$f_{mol} = \frac{\Sigma_{H_2}}{\Sigma_{H_2} + \Sigma_{HI}} > 70\text{-}80\%$$

Little Azimuthal Change

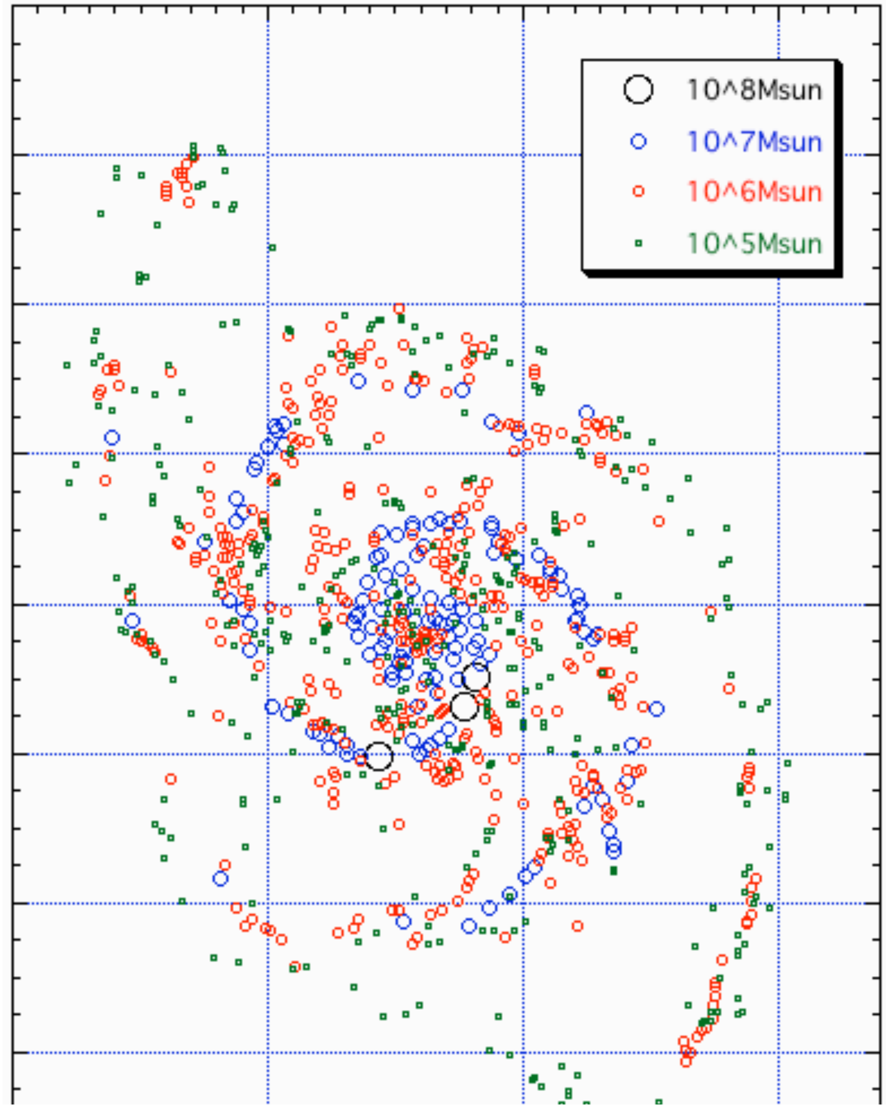


Not much atomic H in interarm regions

CARMA+Nobeyama- Koda et al. 2009



GMC Distribution

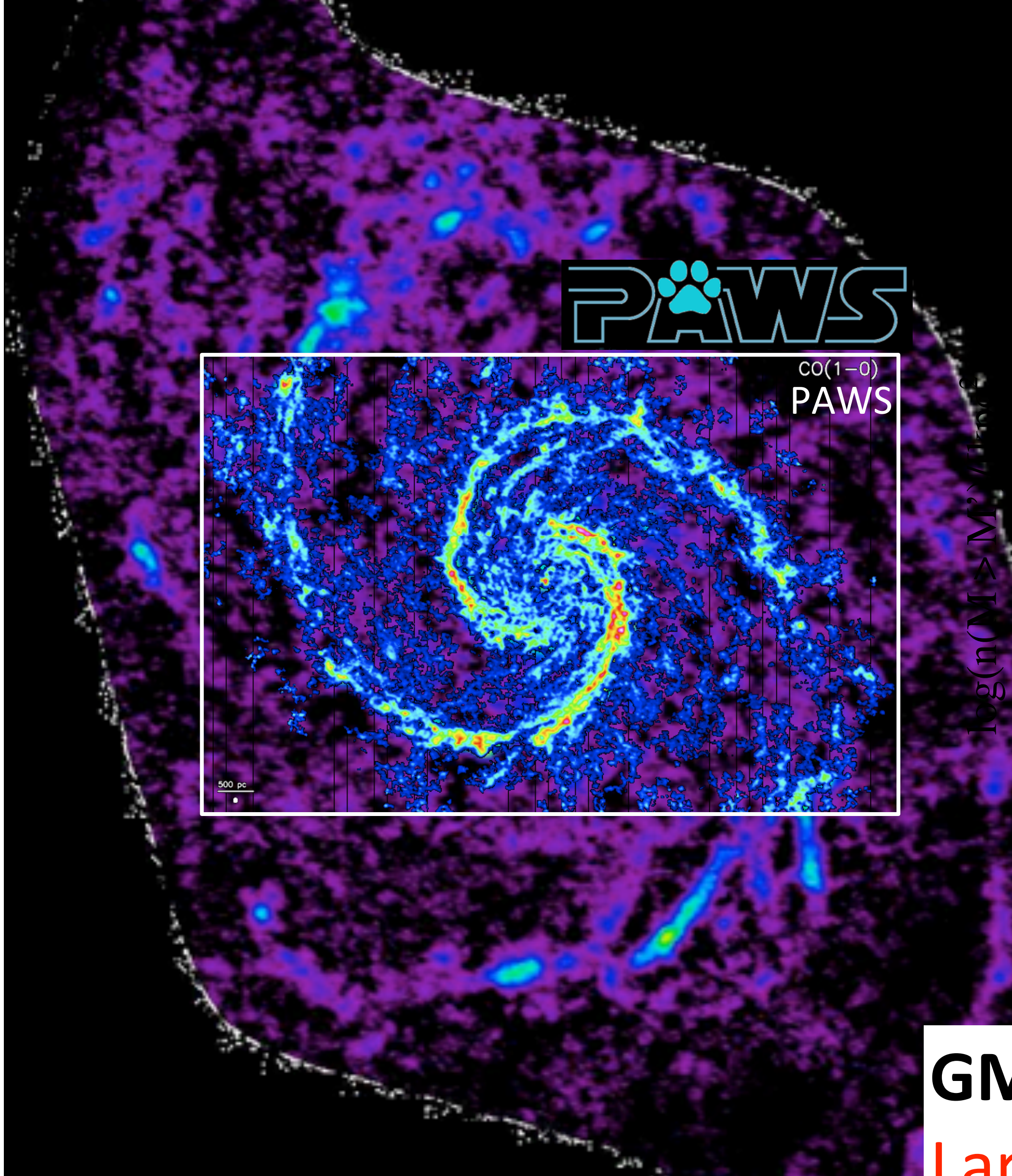


GMC evolution

Large (arm) → Small (interarm)

Koda et al. 2009

M51 CO(1-0)

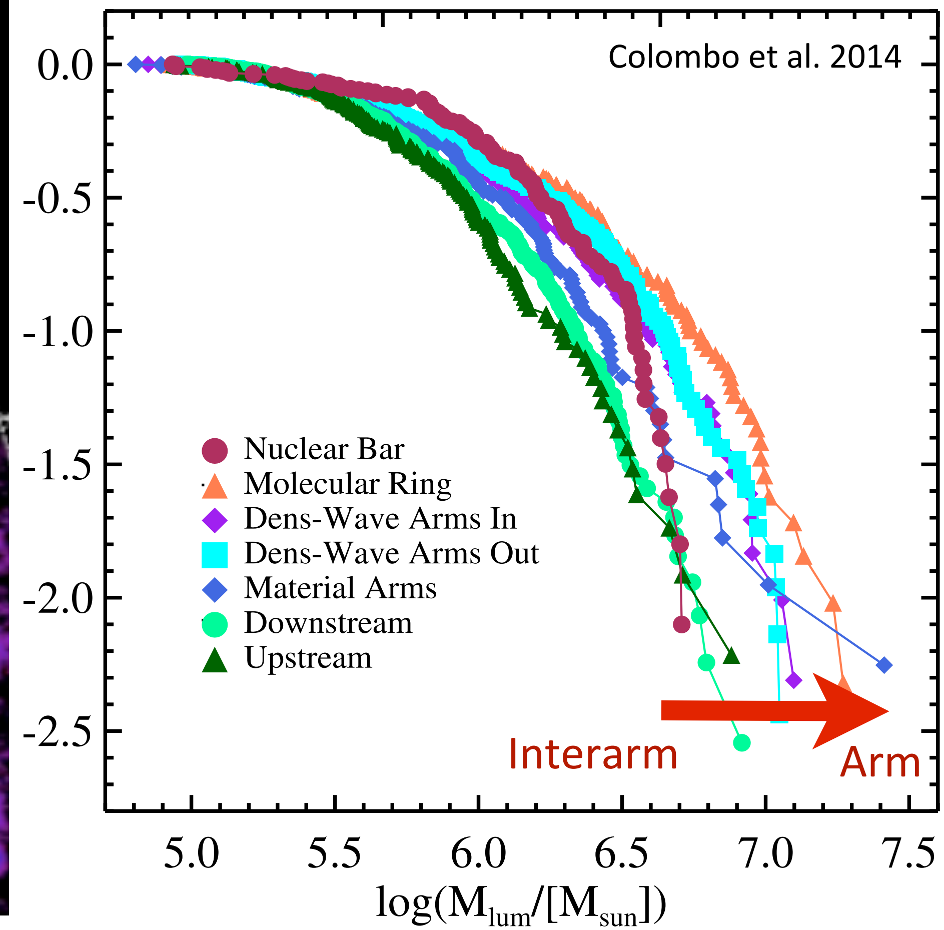


The PdBI Arcsecond Whirlpool Survey (PAWS)- Schinnerer et al. 2014

CARMA+Nobeyama- Koda et al. 2009

GMC Distribution

Cumulative/Normalized
GMC mass function

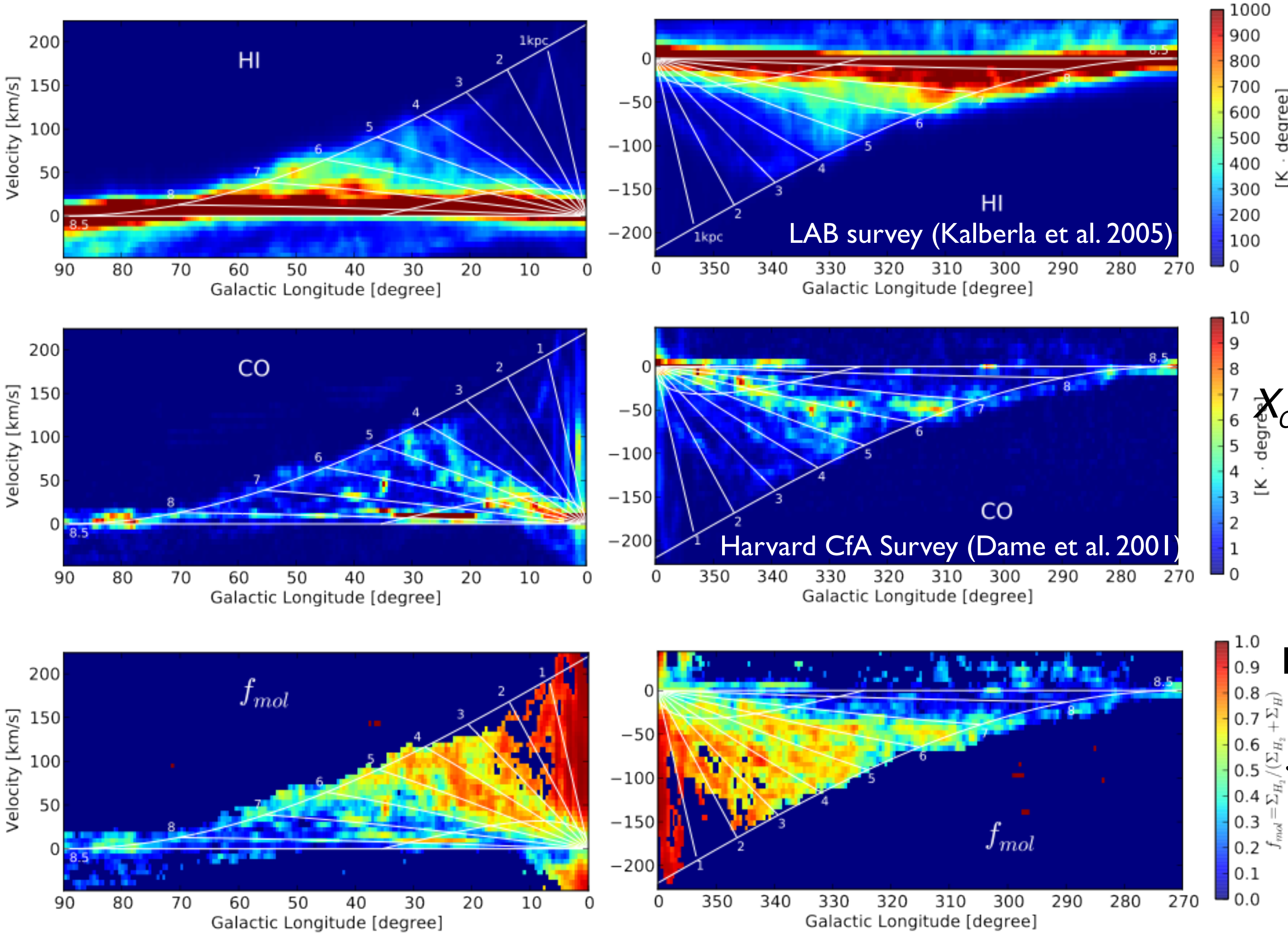


GMC evolution

Large (arm) → Small (interarm)

Gas Phase in the MW

Milky Way
Molecular Fraction (f_{mol}) in *l-v* diagram



optically thin → Σ_{HI}

$X_{CO} = 2 \times 10^{20}$ → Σ_{H_2}

Molecular fraction

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

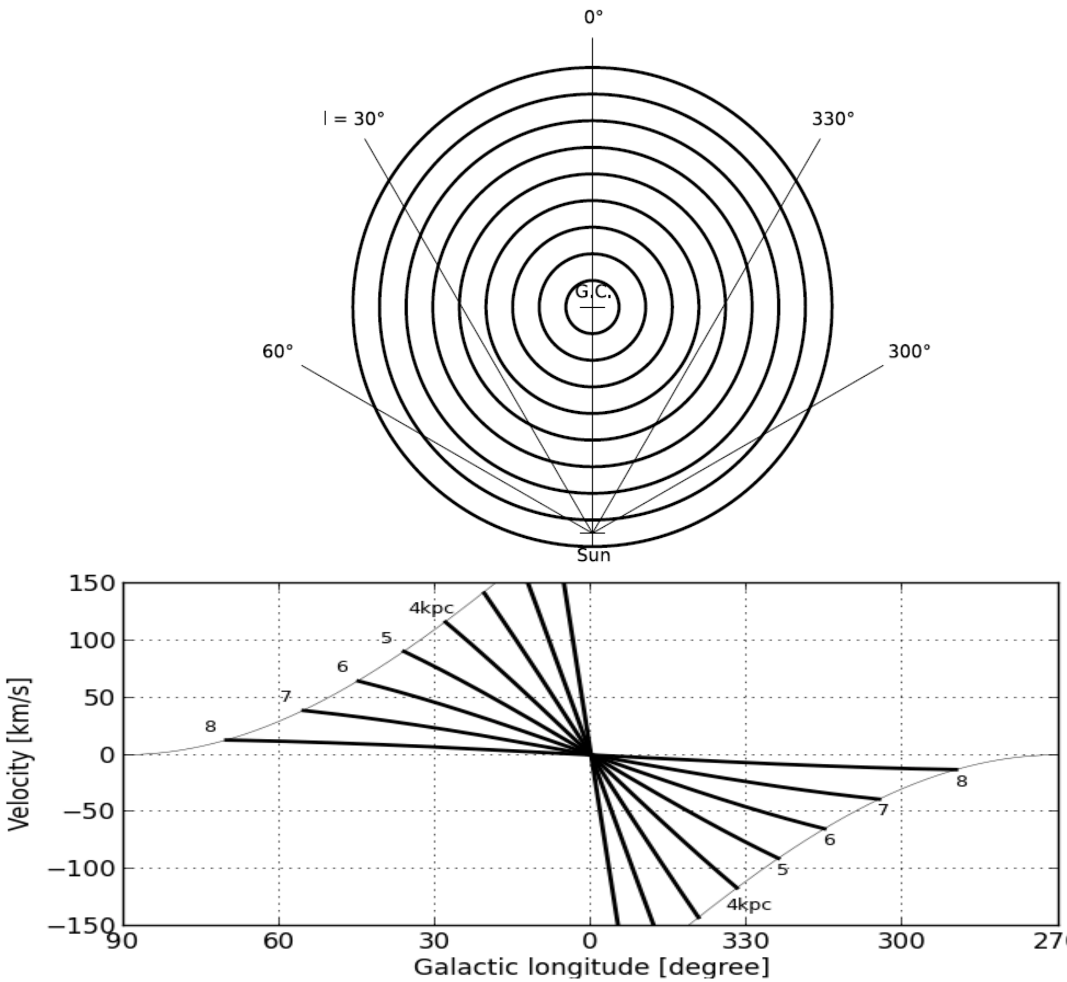
f_{mol} - independent of heliocentric distance

Koda in prep.

l-v diagram

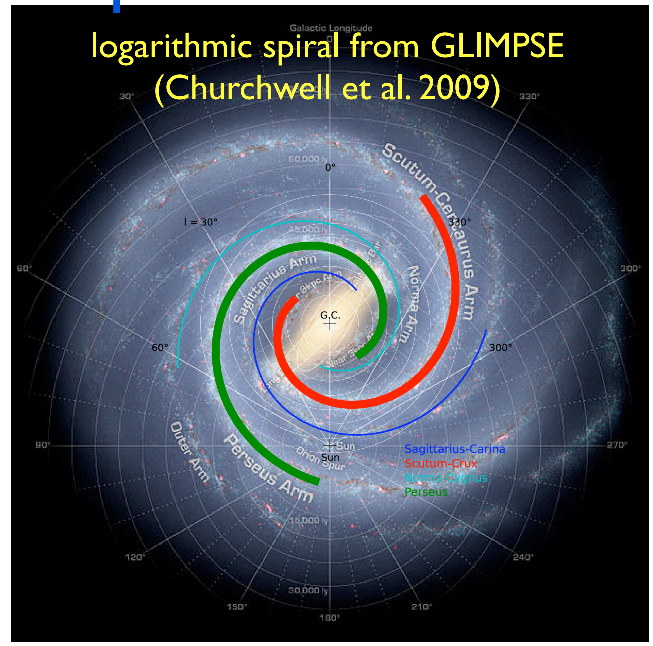
Flat circular rotation

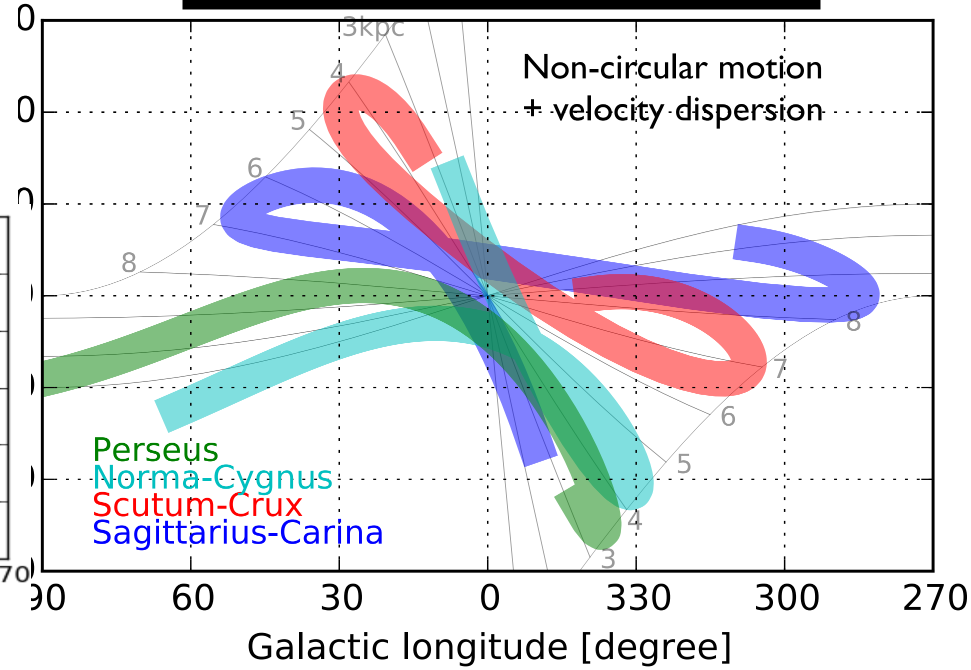
(V_0=220km/s, R_0=8.5kpc)



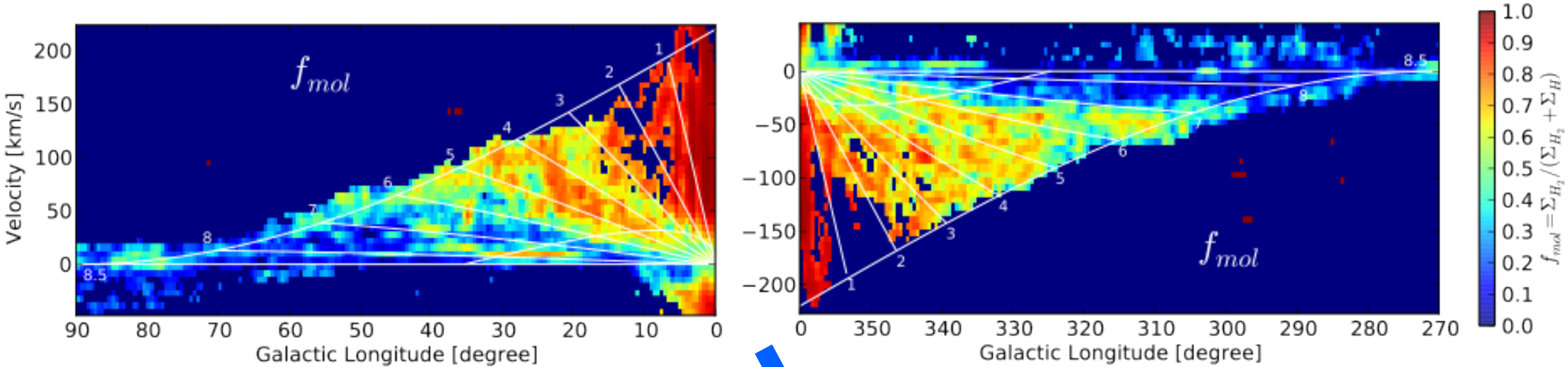
(l,v) to R_{GAL}

Spiral arms in l-v

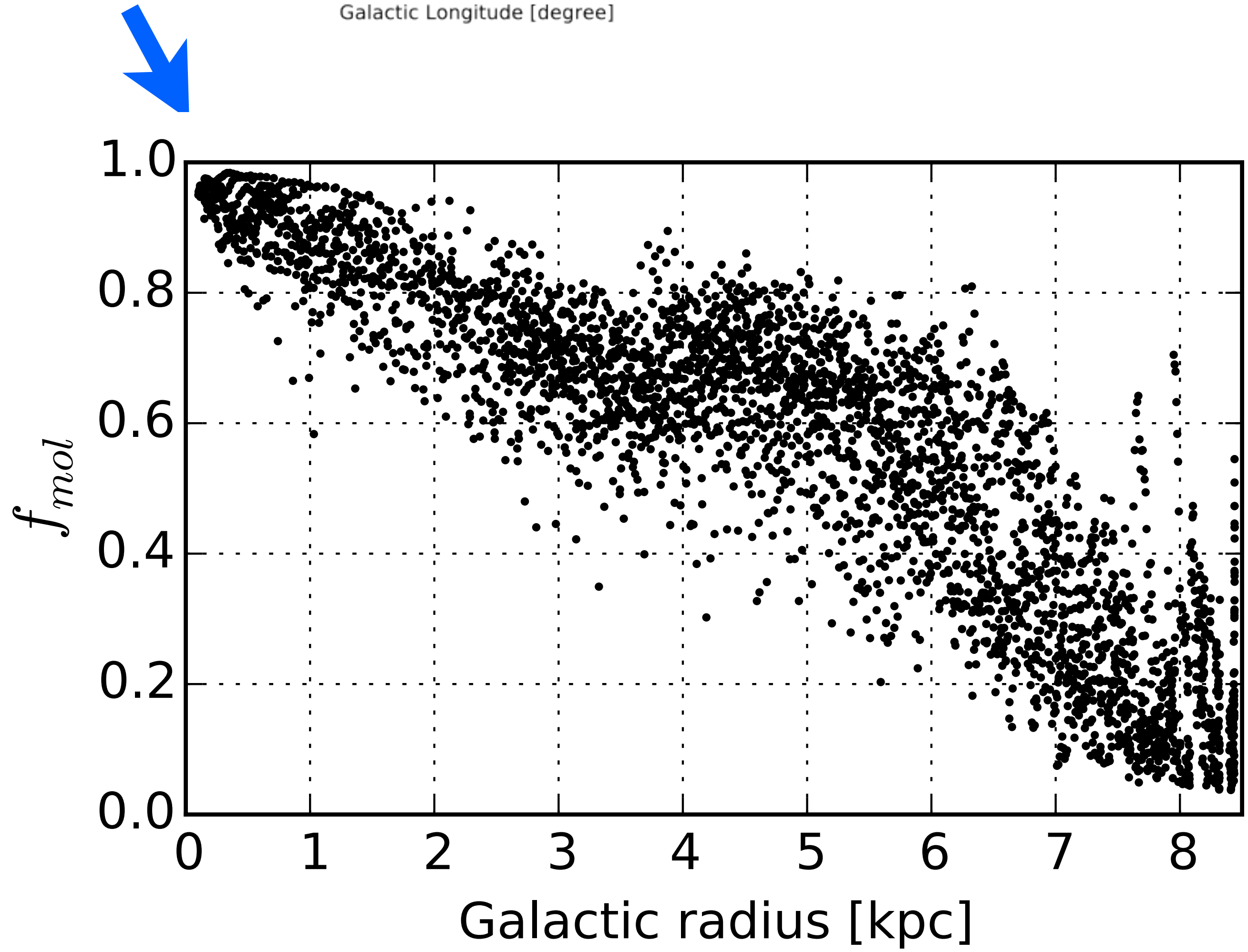




Trace both arm and interarm in l-v

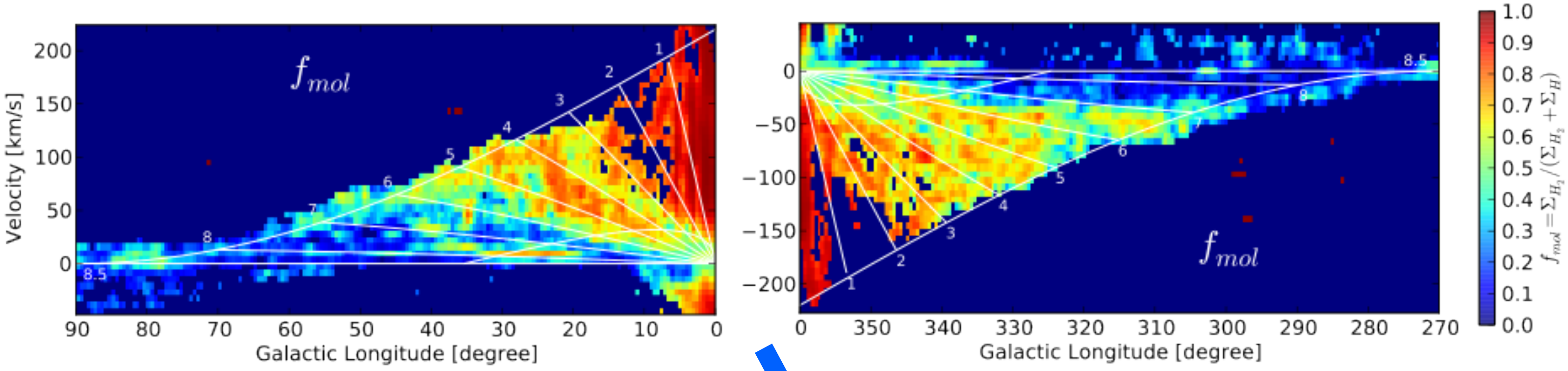


f_{mol}
Velocity [km/s]
Galactic Longitude [degree]
$f_{mol} = \Sigma_{H_2}/(\Sigma_{H_2}+\Sigma_{H})$



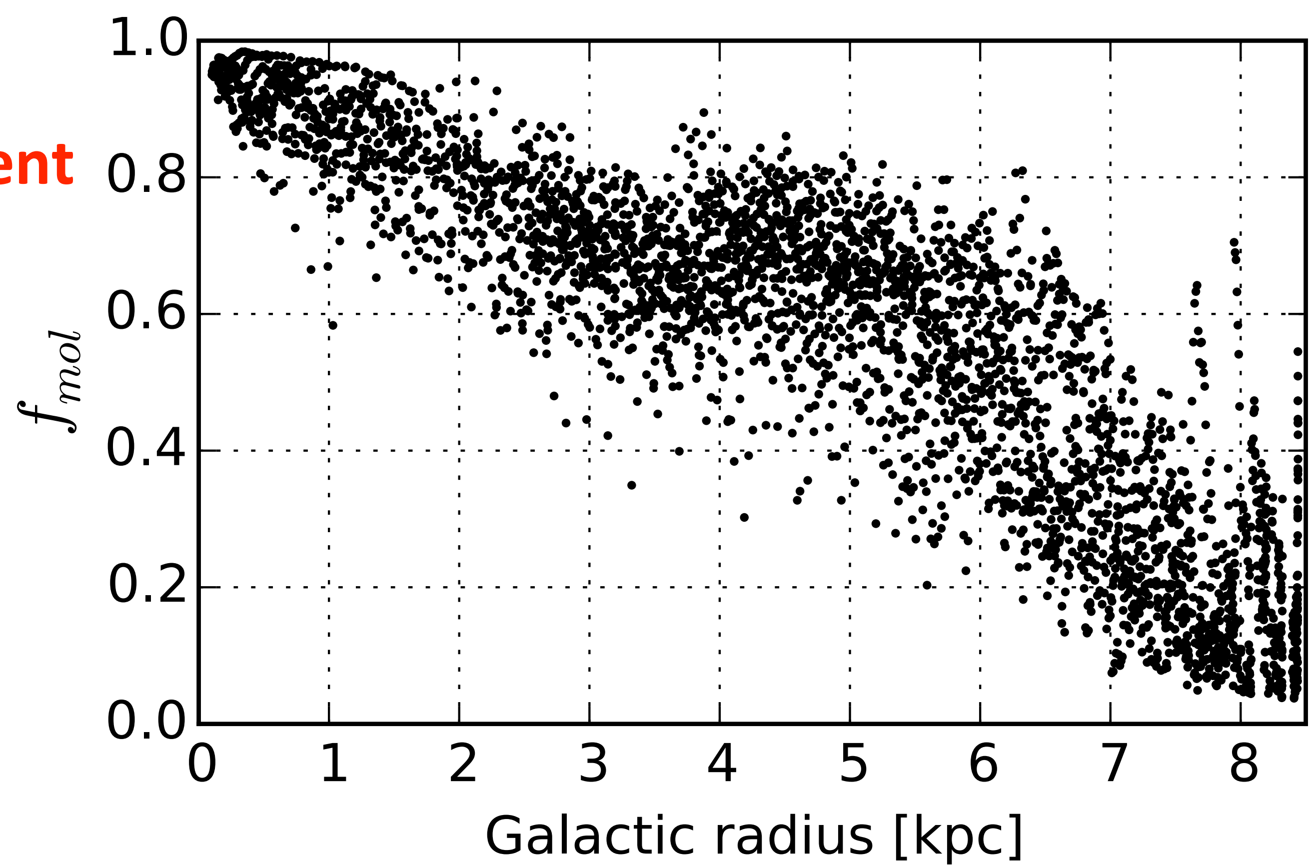
f_{mol}
Galactic radius [kpc]

Koda in prep.

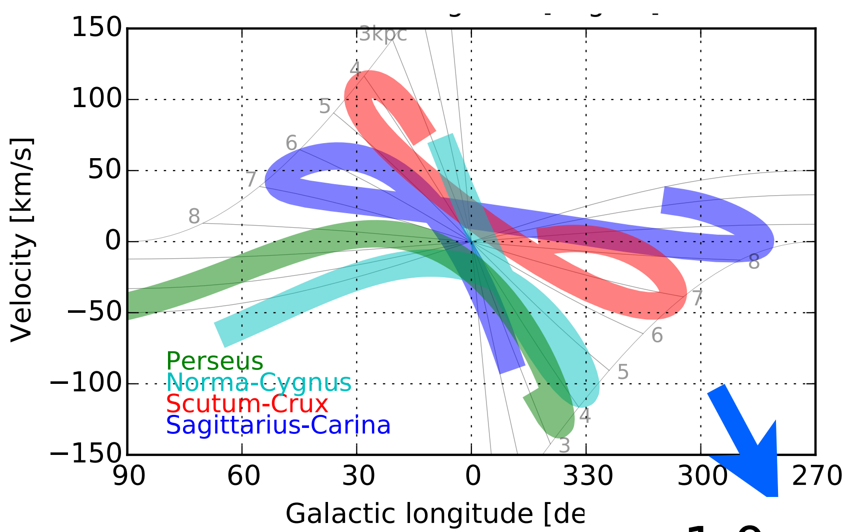


Primarily radial gradient

f_{mol}>50% at R<6kpc



Koda in prep.

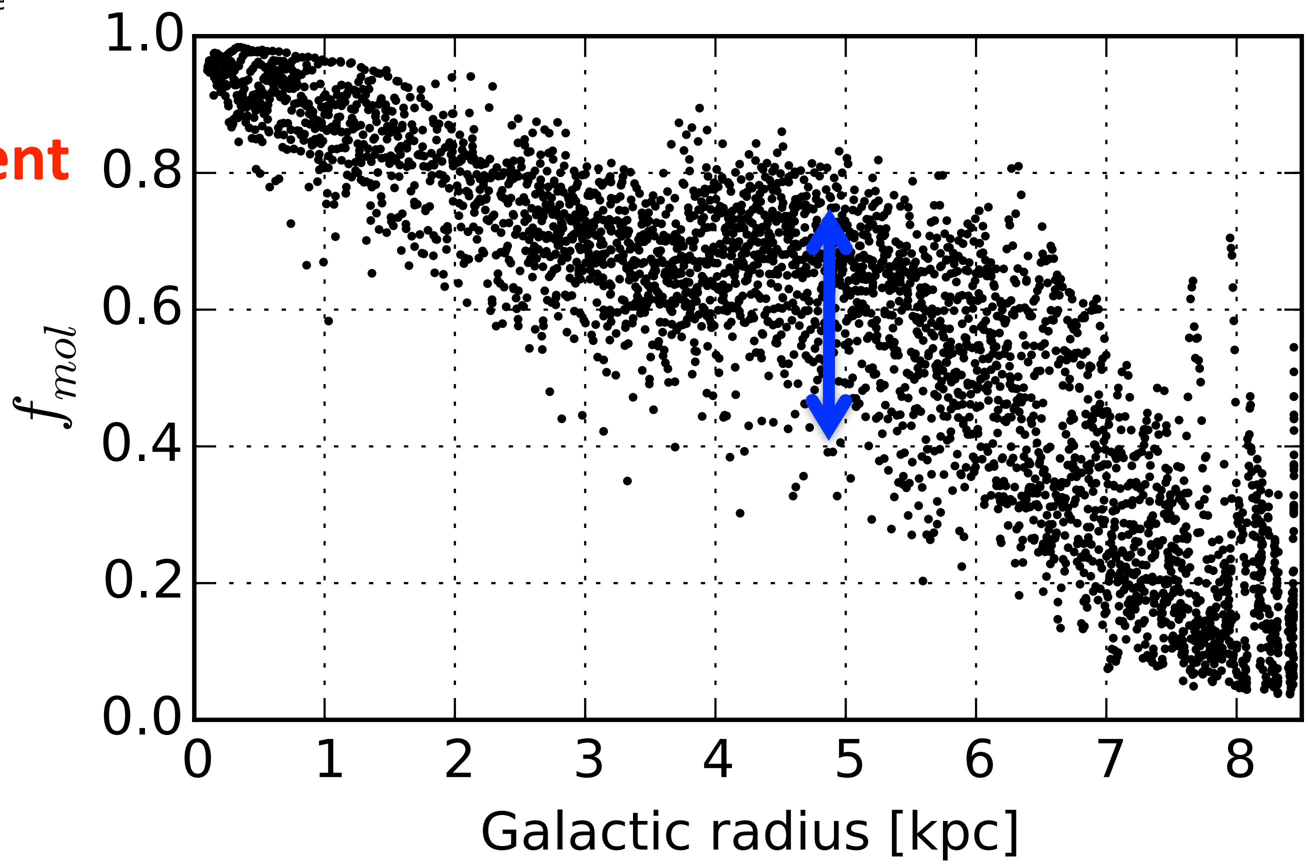


Primarily radial gradient

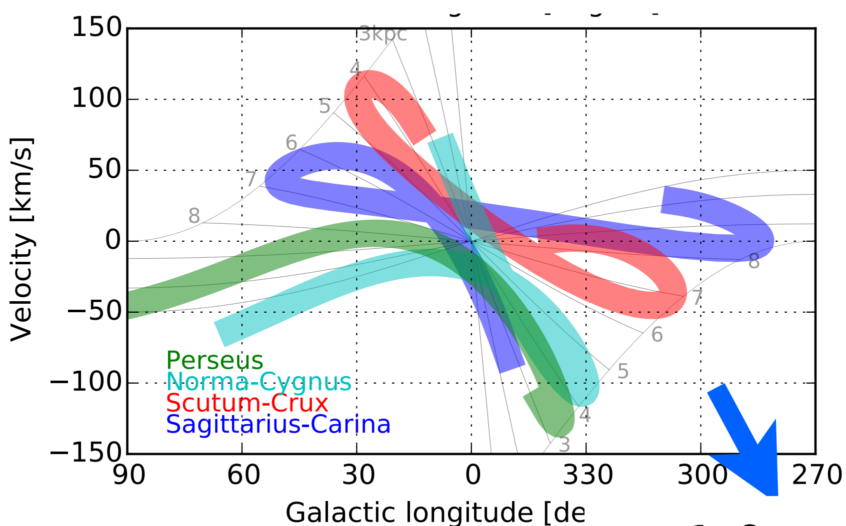
f_{mol}>50% at R<6kpc

Azimuthal variations

Only 20-30%



Koda in prep.



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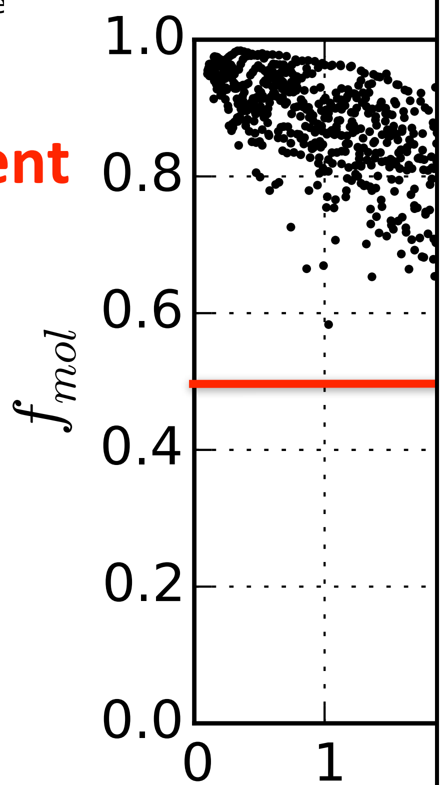
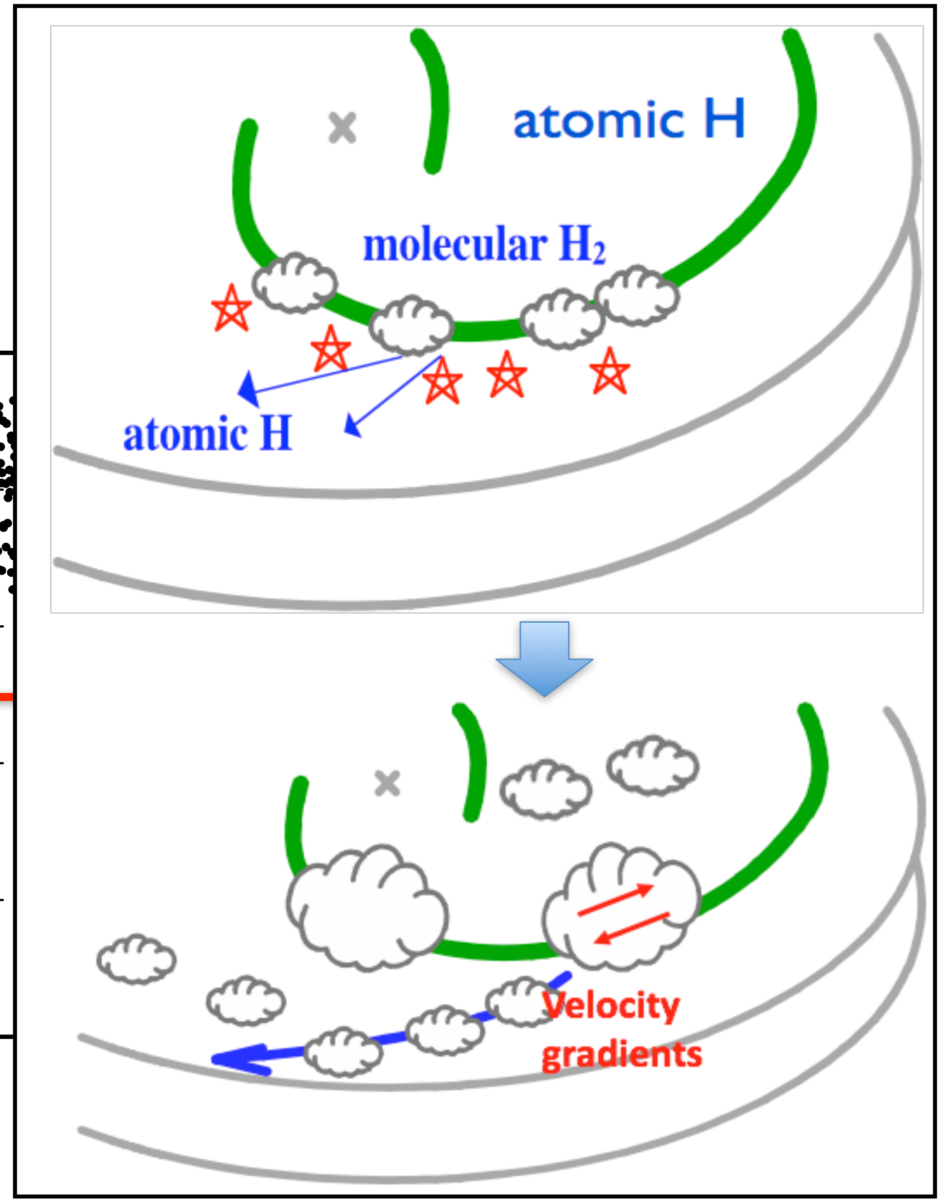
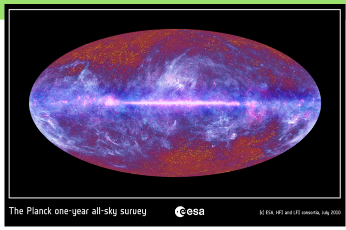


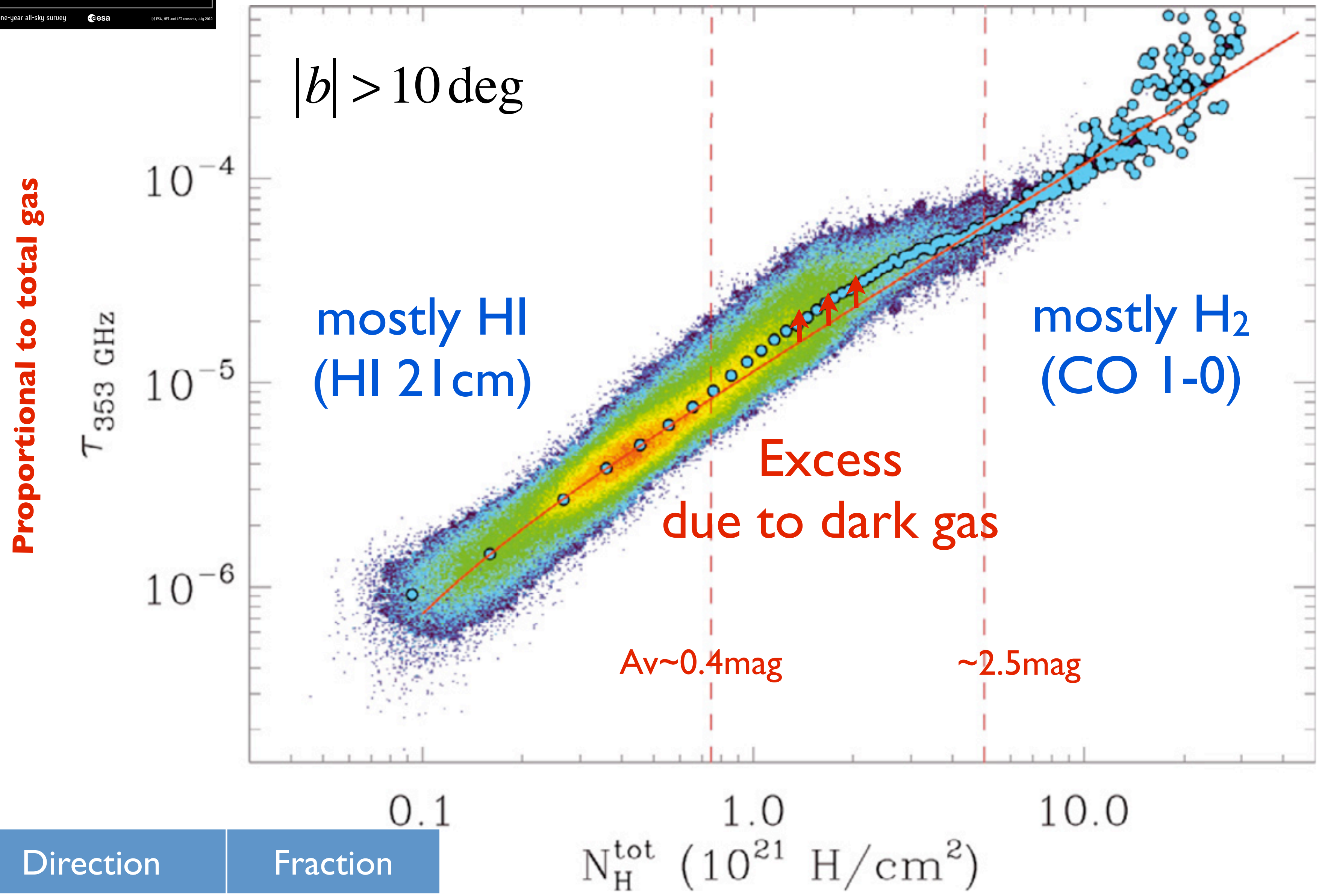


Koda in prep.

Dust -- Dark Gas



Dark gas



Direction	Fraction
|b|>10deg	~22%

traced by emission of HI 21cm + CO(J=1-0)

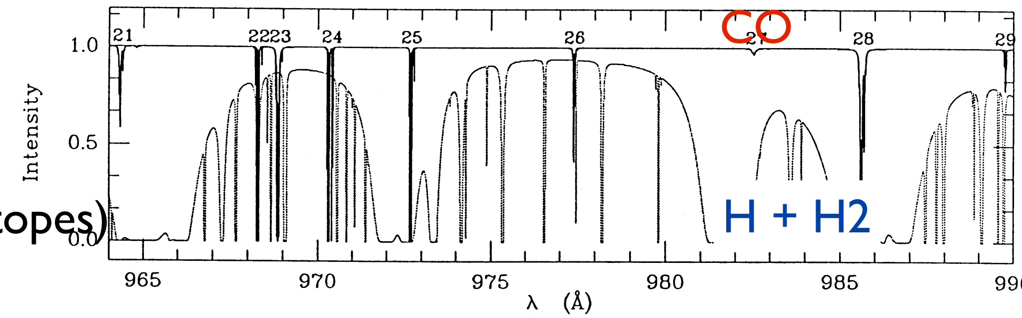
Planck Collaboration 2011a,b

CO-dark H_2?: Photo-dissociation of H_2 and CO

Line absorption

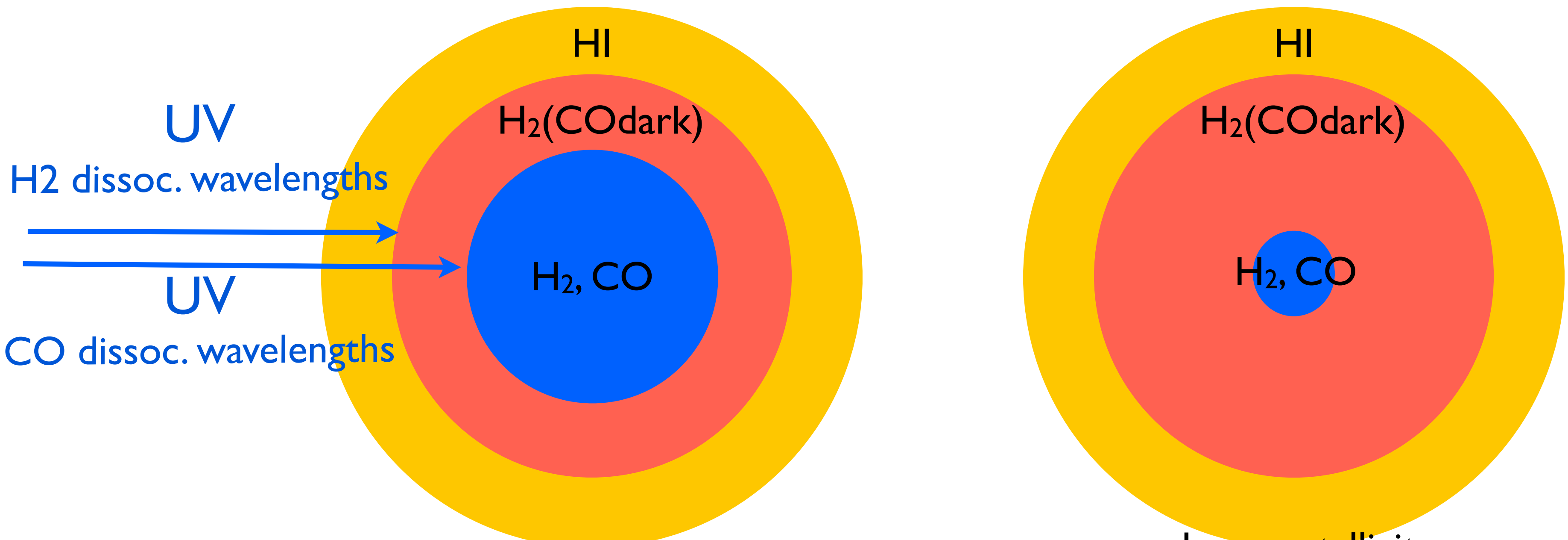
(photoelectronic effect--> exceed E_{bind})

- Self-shielding (by H2 or CO)
- Mutual-shielding (by H&H2 lines, by CO isotopes)



van Dishoeck & Black 1988

Dust attenuation

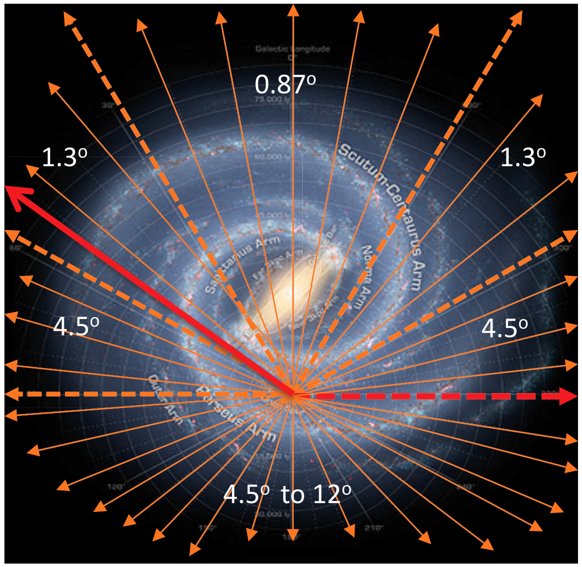


High-metallicity
Less dust attenuation

Low-metallicity
low CO abundance
High dust attenuation

Wolfire, Hollenbach & McKee 2010

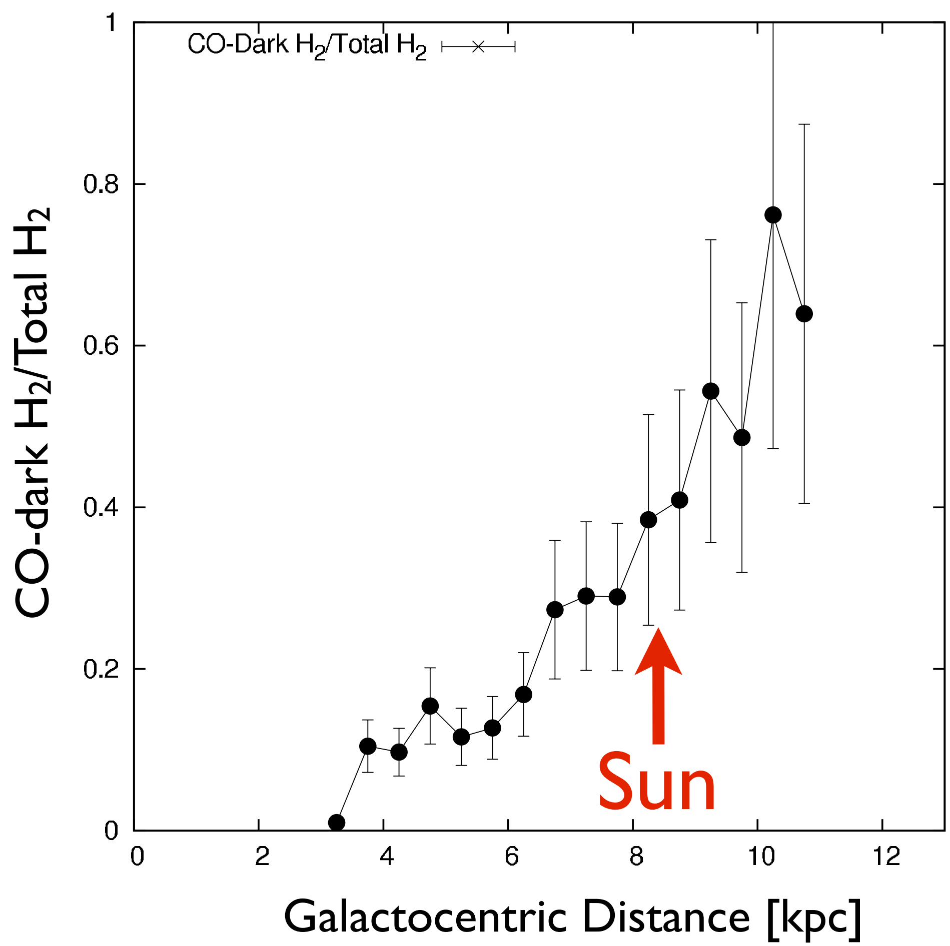
CO-dark H_2?-- from [CII]



GOT C+

Galactic Observations of Terahertz C+

Langer et al. 2010
Velusamy et al. 2010



Conceptually,

CO dark H2

$= N_{H+H2}$ from [CII]

$- N_H$ from HI 21cm

$- N_{H2}$ from CO(J=1-0)

Pineda et al. 2013

Optically-Thick HI?

One can find a solution of cold, optically-thick HI gas to explain *all* dark gas.

HI optically-thin regions for calibration:

$$\tau_{dust} \rightarrow N_{HI}$$

HI optically-thicker regions:

Two equations for T_{spin} and tau_{HI}

1. Spontaneous emission

$$\tau_{HI} \simeq \frac{3c^2}{32\pi} \frac{A_{HI} N_{HI}}{\nu_{HI}} \frac{h}{kT_{spin}} \frac{1}{\Delta V_{HI}}$$

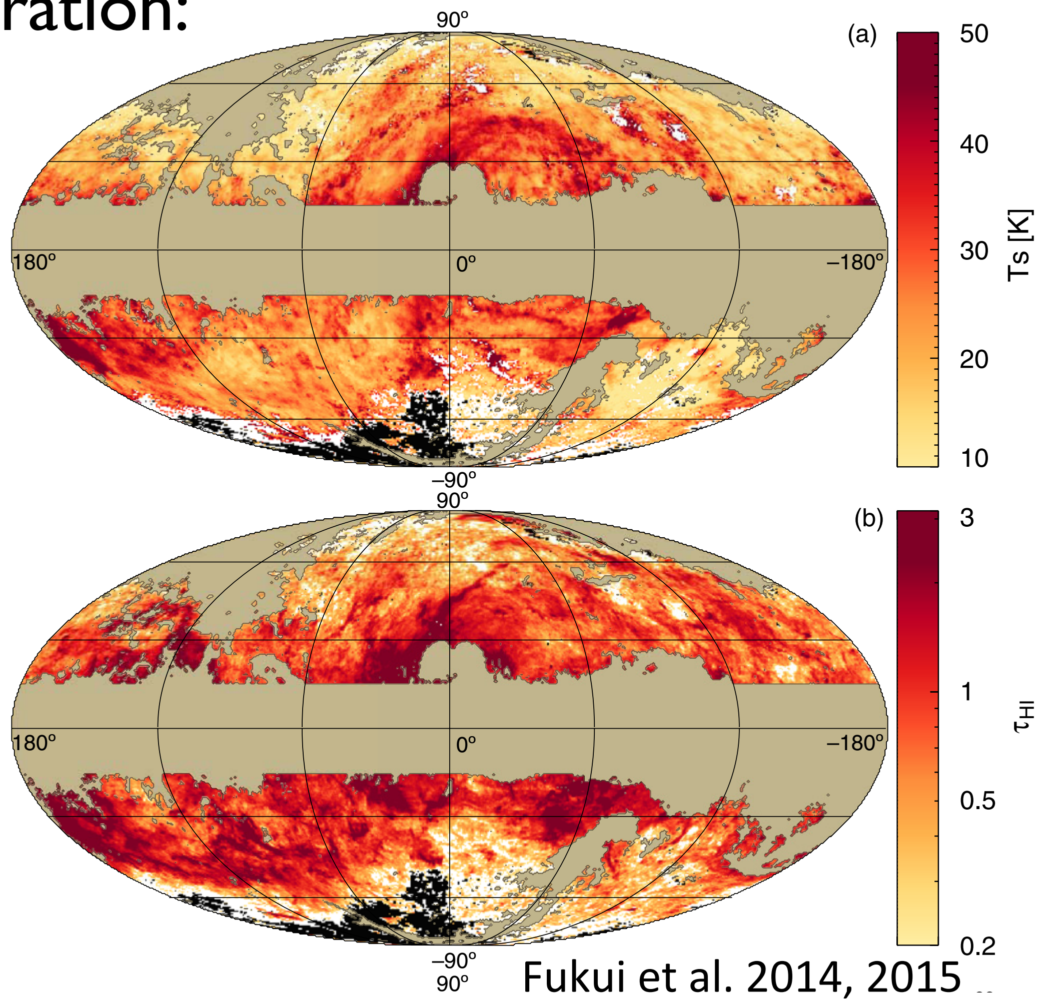
2. Radiative transfer

$$W_{HI} = (T_{spin} - T_{bg})\left[1 - e^{-\tau_{HI}}\right]\Delta V_{HI}$$

85% of the total HI gas

$$\rightarrow \quad \tau_{HI} \sim 0.5 - 3$$

$$T_{spin} \sim 10 - 60\,K$$



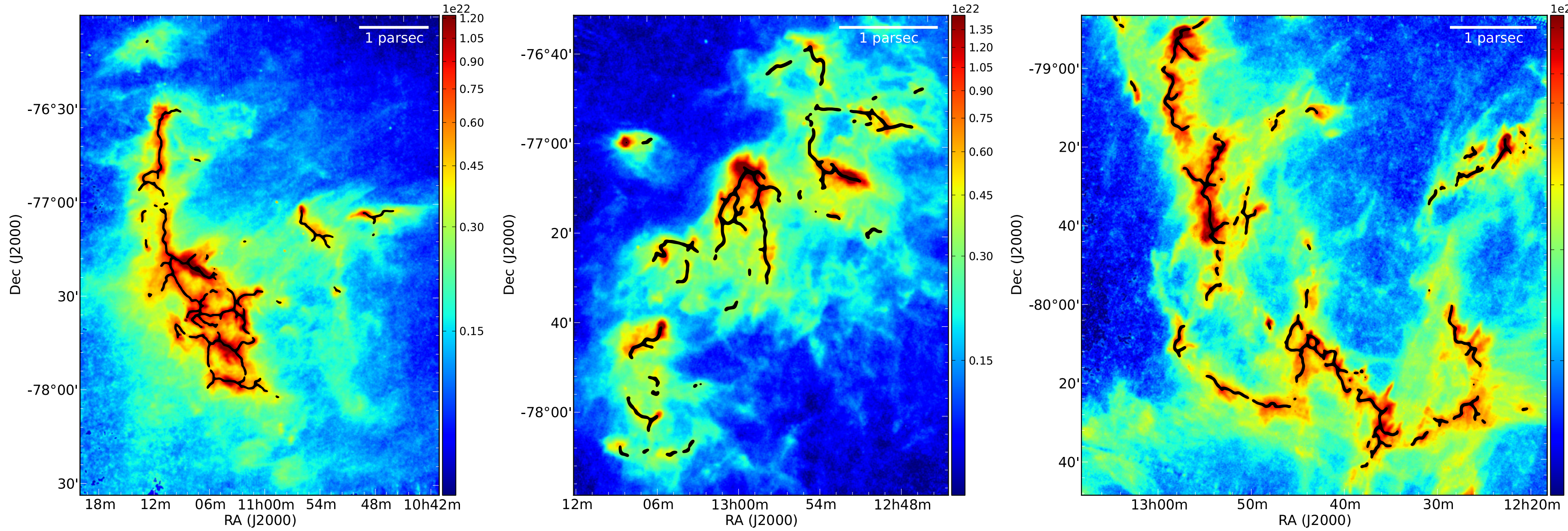
Fukui et al. 2014, 2015

A question from HI absorption studies (Stanimirovic et al. 2014)

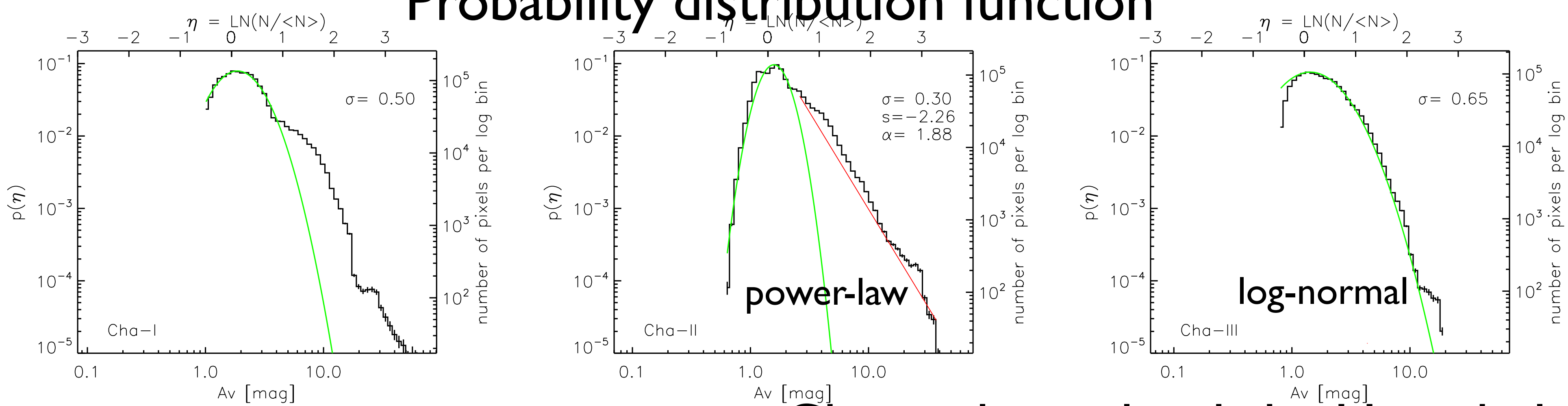
Structures w/i Clouds

Nearby Clouds observed with Herschel

filaments and clumps



Probability distribution function

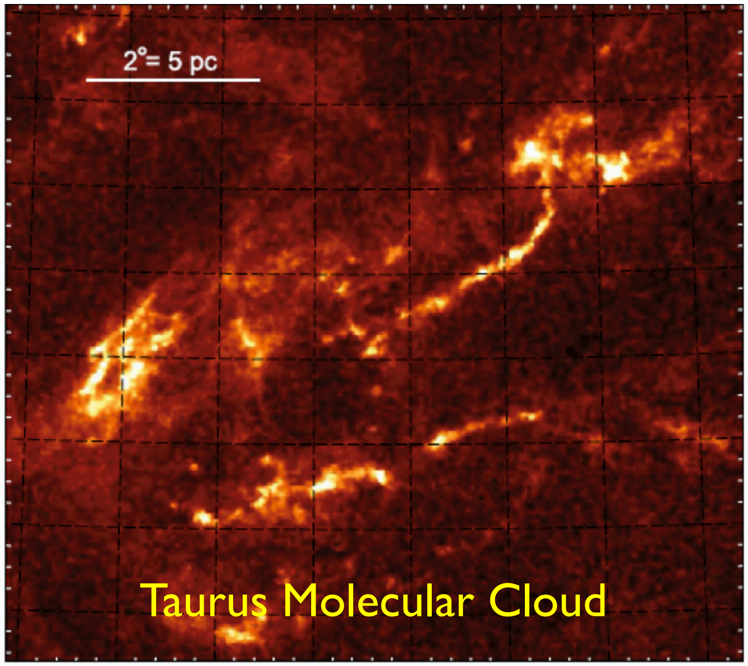


Chamaeleon clouds by Herschel

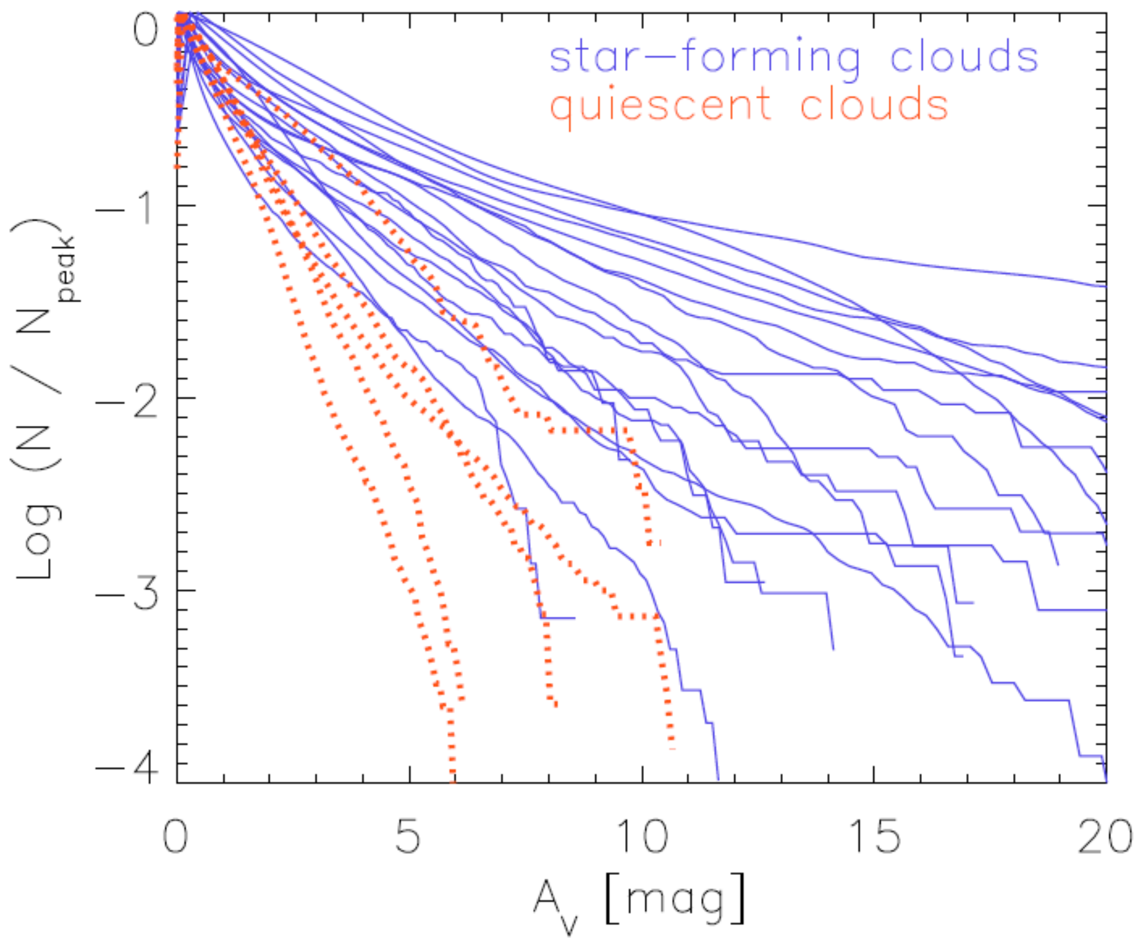
Avles de Oliveira et al. 2014

Quiescent vs Star-forming Local Clouds

Extinction mapping → Probability Distribution Function

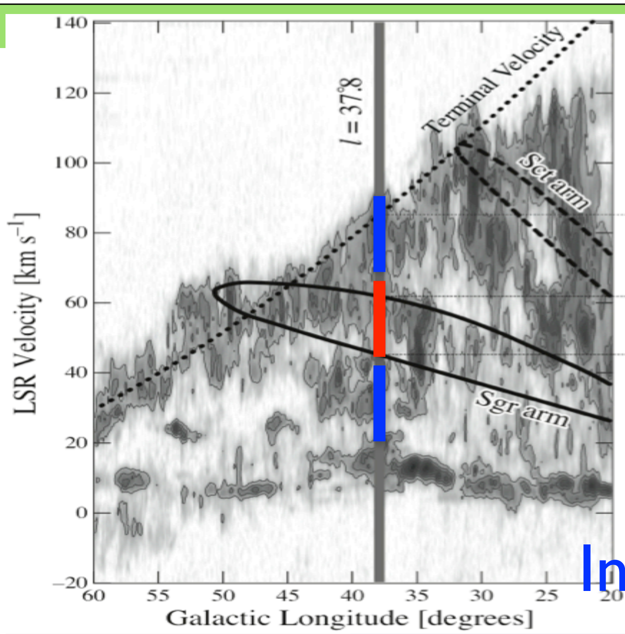


23 molecular clouds within 500pc distance from the Sun



Kainulainen et al. 2009

Growth of Dense Clumps

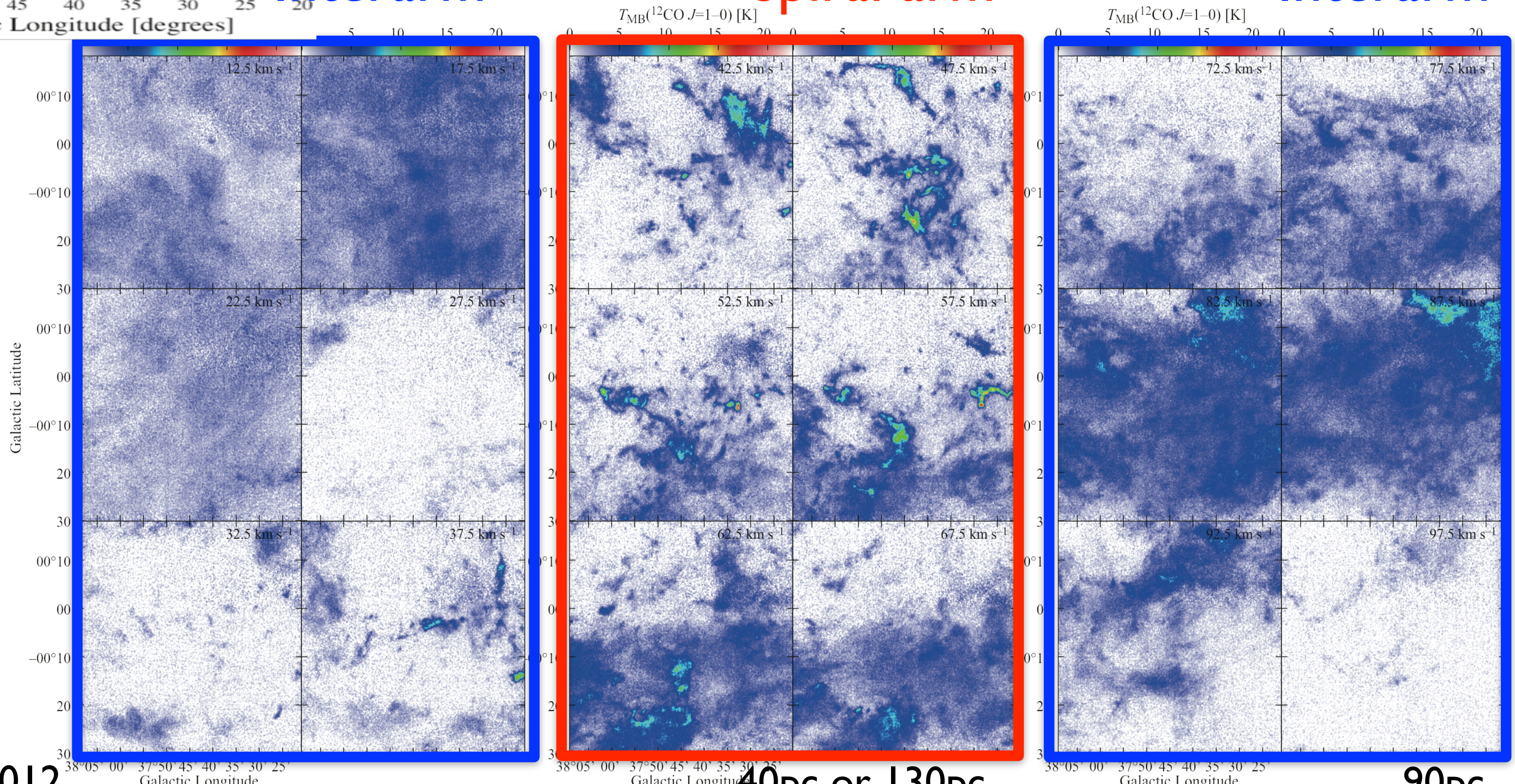


^{12}CO Obs. of l~38deg region
with Nobeyama 45m telescope
Channel maps: 50 arcmin x 50 arcmin, 15" resolution (<0.7pc)

Interarm

Spiral arm

Interarm

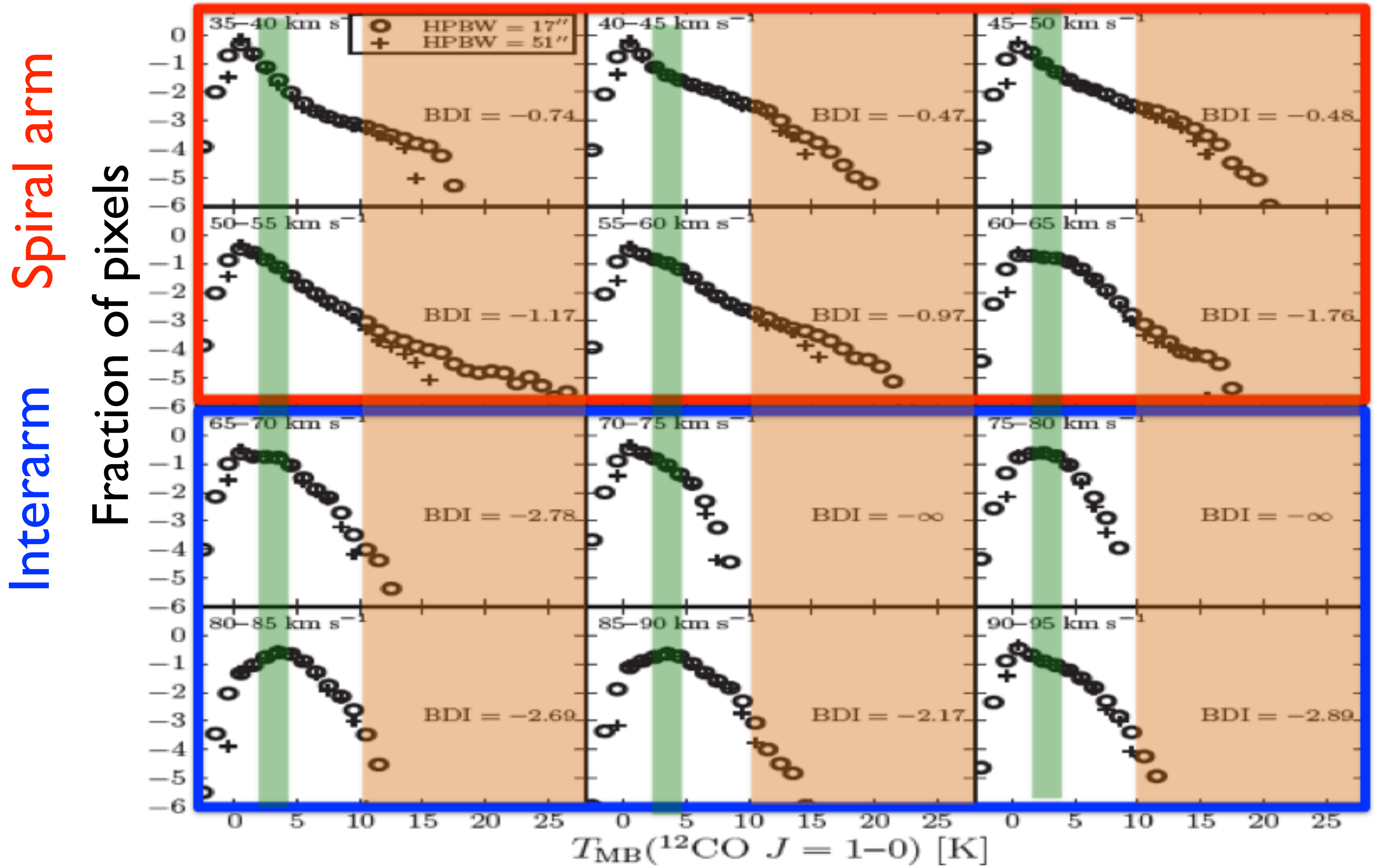


Sawada et al. 2012

40pc or 130pc

90pc

Brightness Distribution Function (BDF)

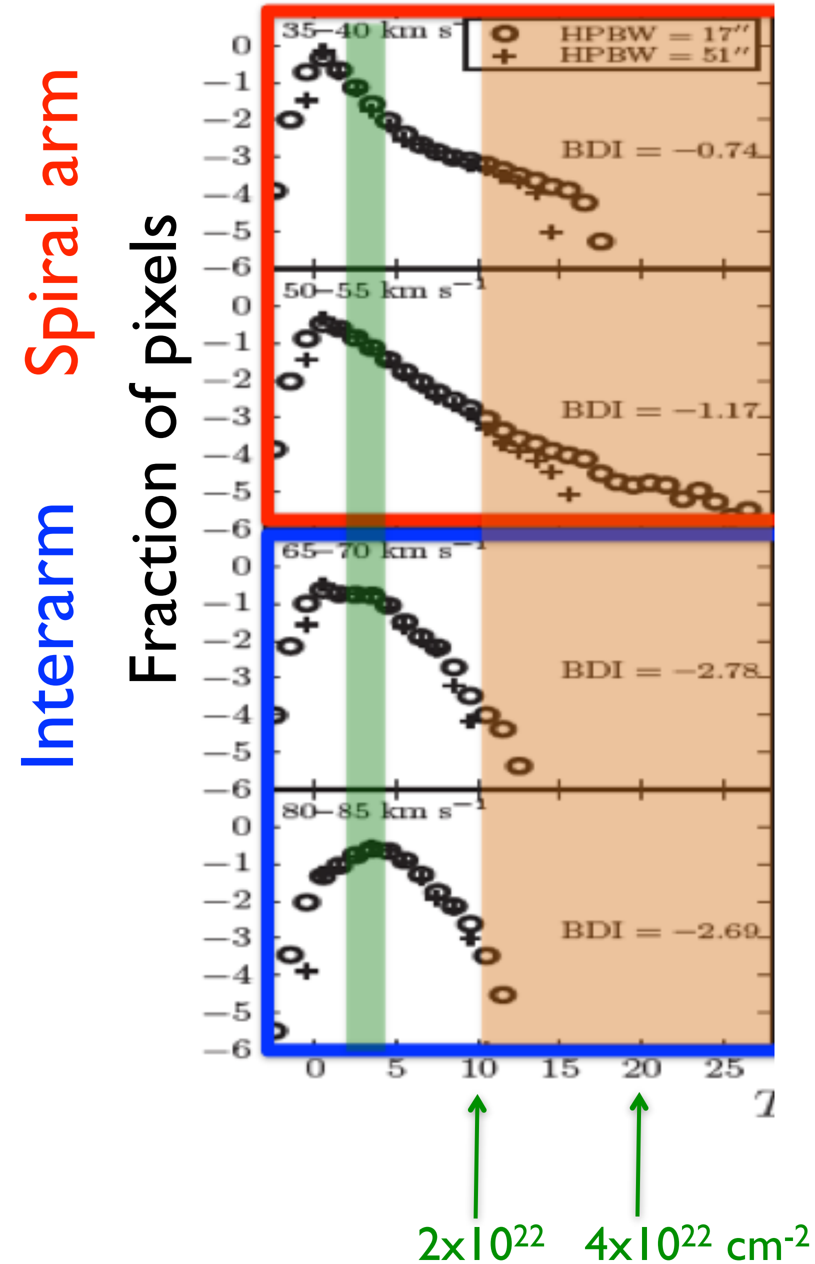


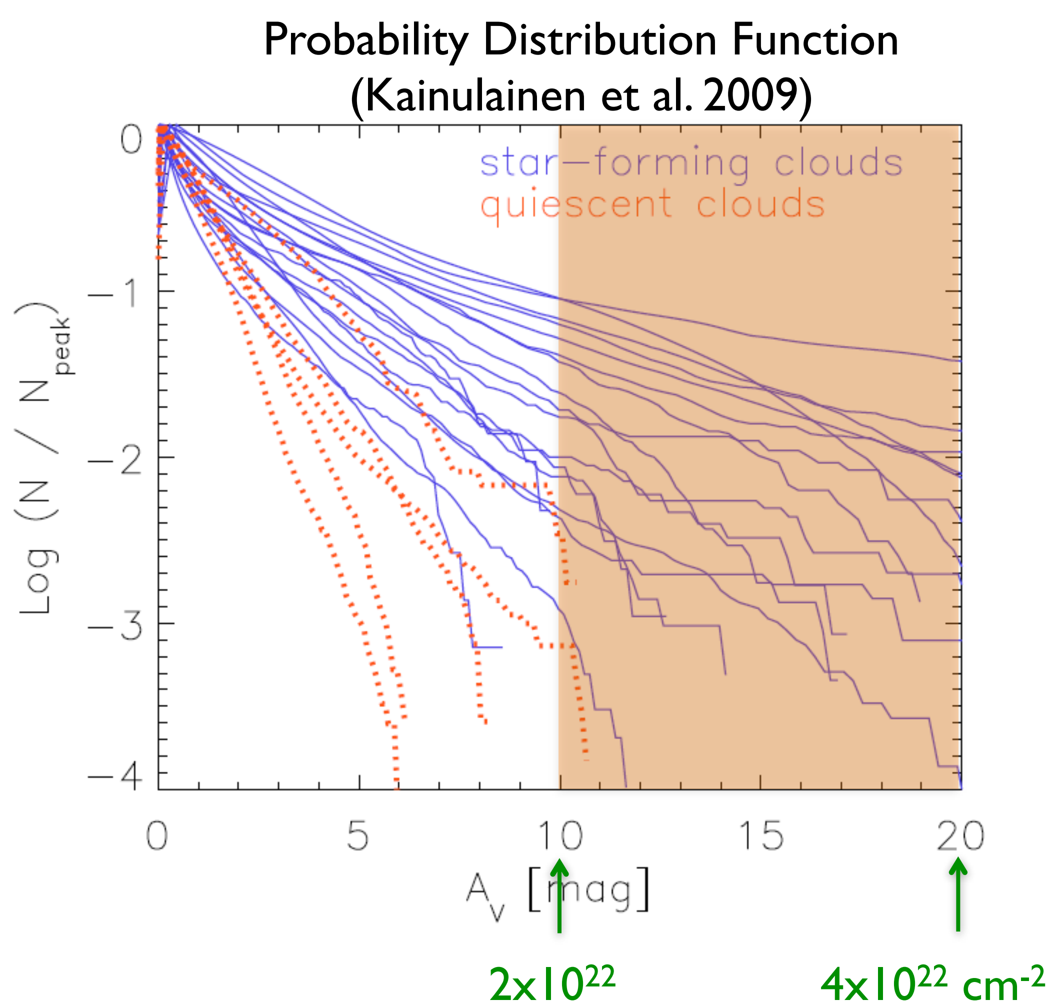
T_{MB}[K] in CO(1-0) ~ **column density**

Sawada et al. 2012

High column density gas in spiral arms

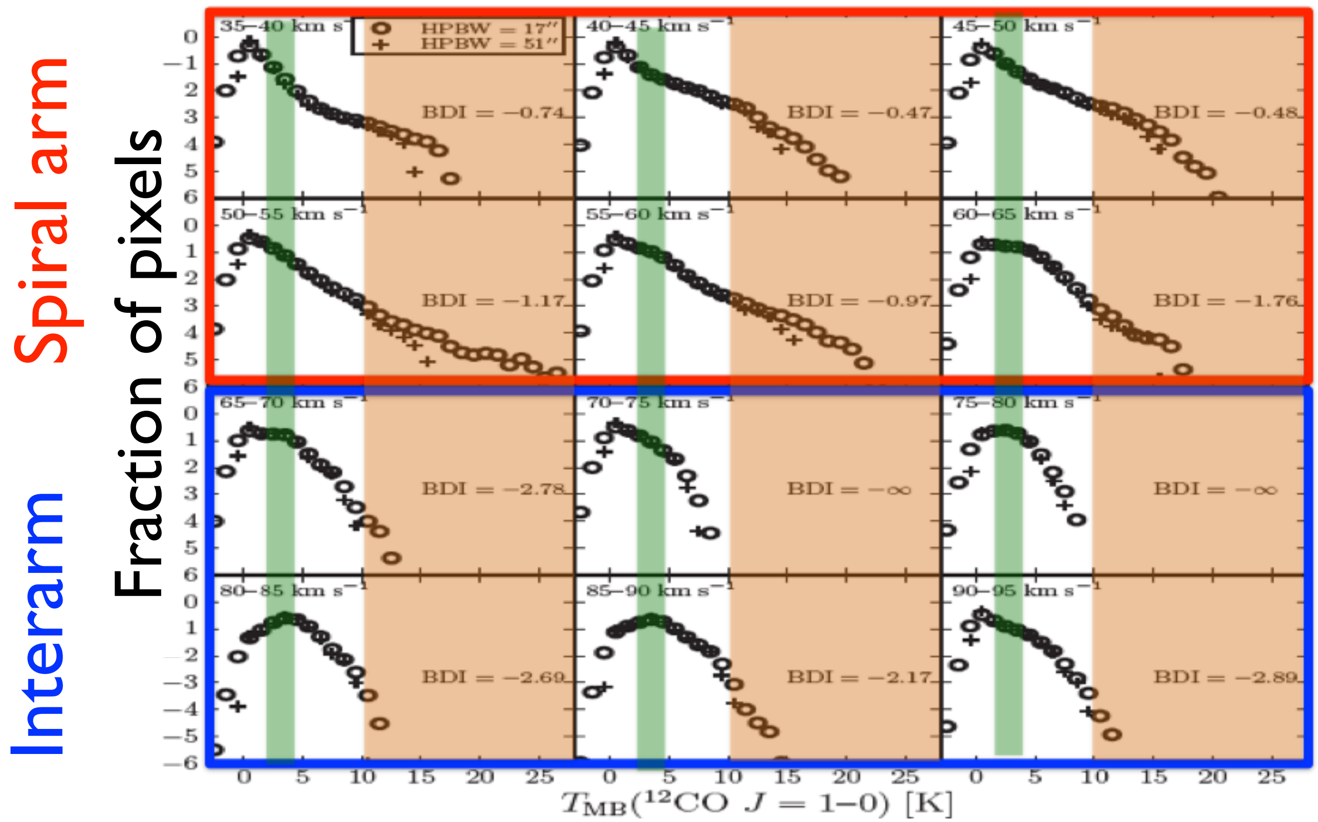
Brightness Distribution Function (BDF)





Brightness Distribution Index (BDI)

Characterize distribution with one parameter



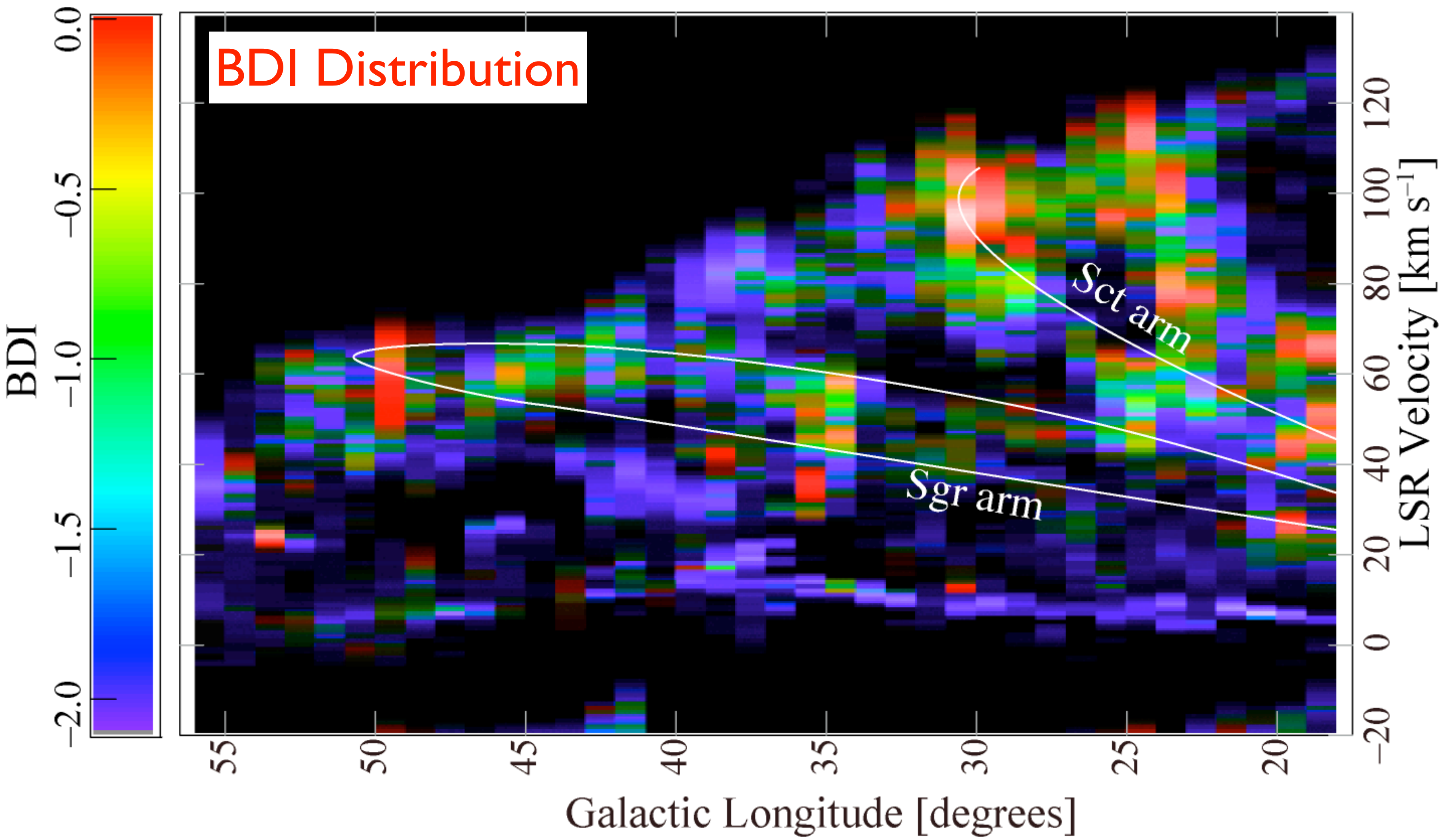
$$BDI = \log_{10}\left(\frac{\int_{T_2}^{T_3} T \cdot B(T)dT}{\int_{T_0}^{T_1} T \cdot B(T)dT}\right)$$

$(T_0, T_1, T_2, T_3) = (3, 5, 10, \infty)$

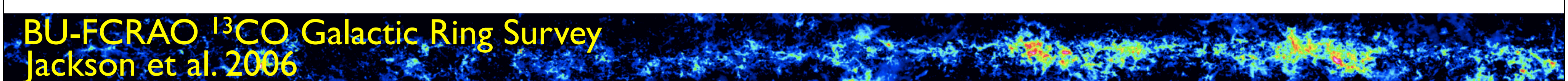
Sawada et al. 2012

Growth of Dense Clumps in Spiral Arms

BDI in each 2degx1degx5km/s grid



Sawada, Hasegawa & Koda 2012



Summary

- Gas phase evolution with galactic revolution
  - Globally atom-dominant region
    - Atom/mol/atom transition across spiral arms
  - Globally molecule-dominant region
    - Very small variation. gas stays molecular
  - Dark gas
    - ~30% of total gas with uncertainties
- Dense structures within clouds
  - Develop in spiral arms
  - PDF: similar to log-normal (interarms) and power-law (arms)