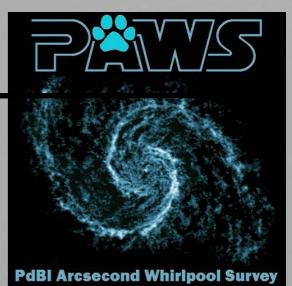


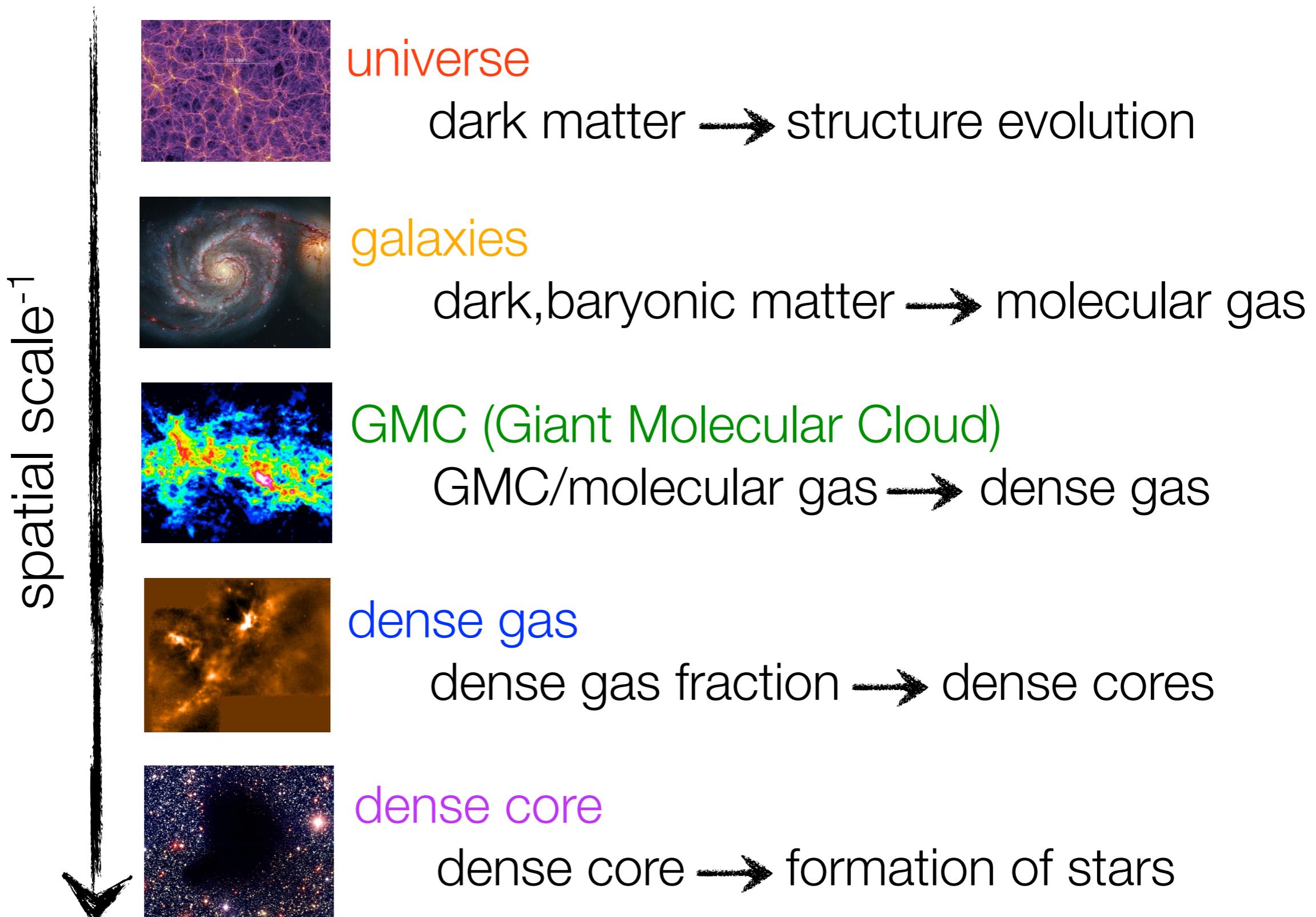
Molecular gas, star formation and spiral arms: insights from PAWS

Annie Hughes, MPIA

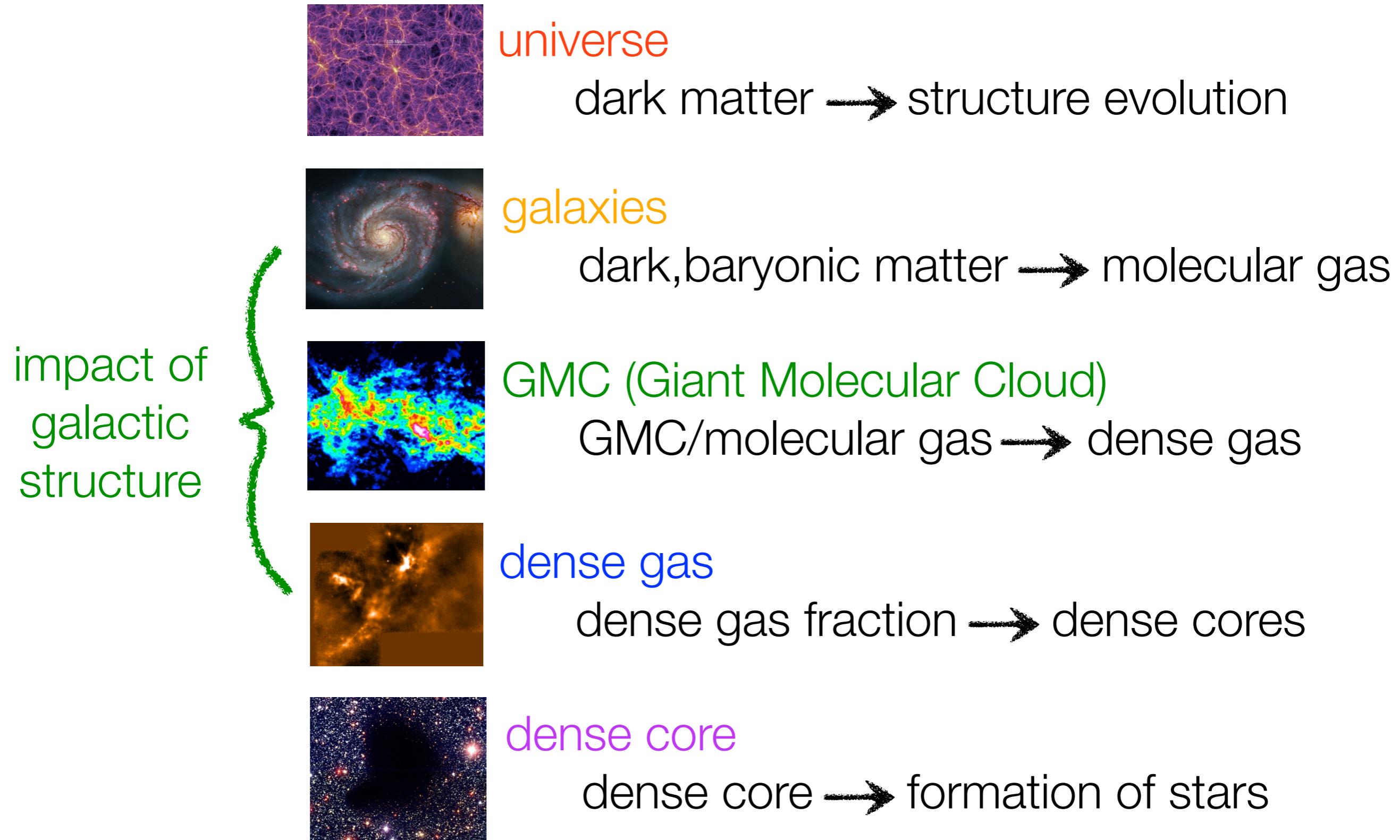
Eva Schinnerer, Sharon Meidt, Dario Colombo, Jerome Pety, Adam Leroy,
Clare Dobbs, Gaelle Dumas, Santiago Garcia-Burillo, Karl Schuster, Todd
Thompson & Carsten Kramer, Tony Wong, Jin Koda & Jen Donovan-Meyer



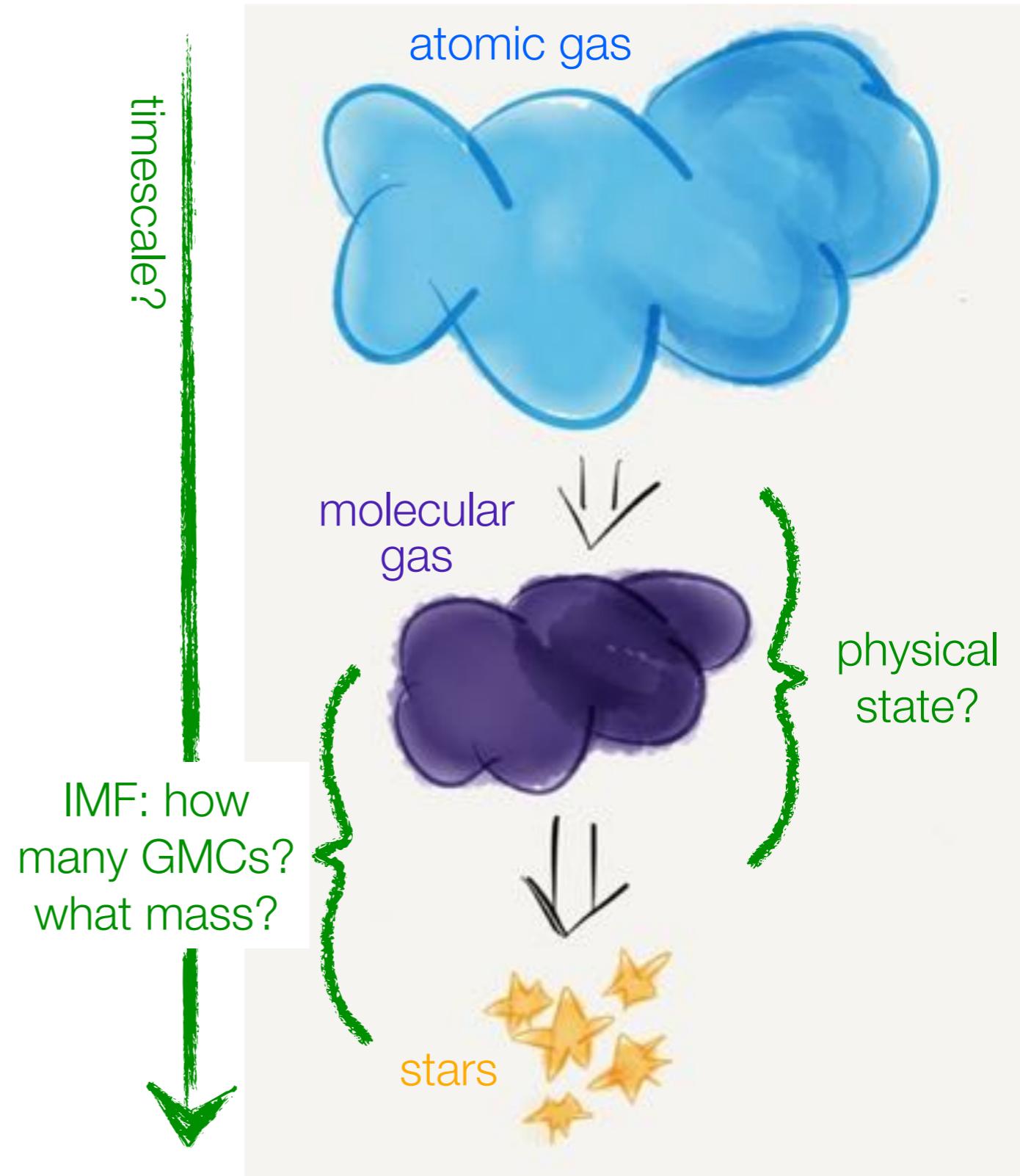
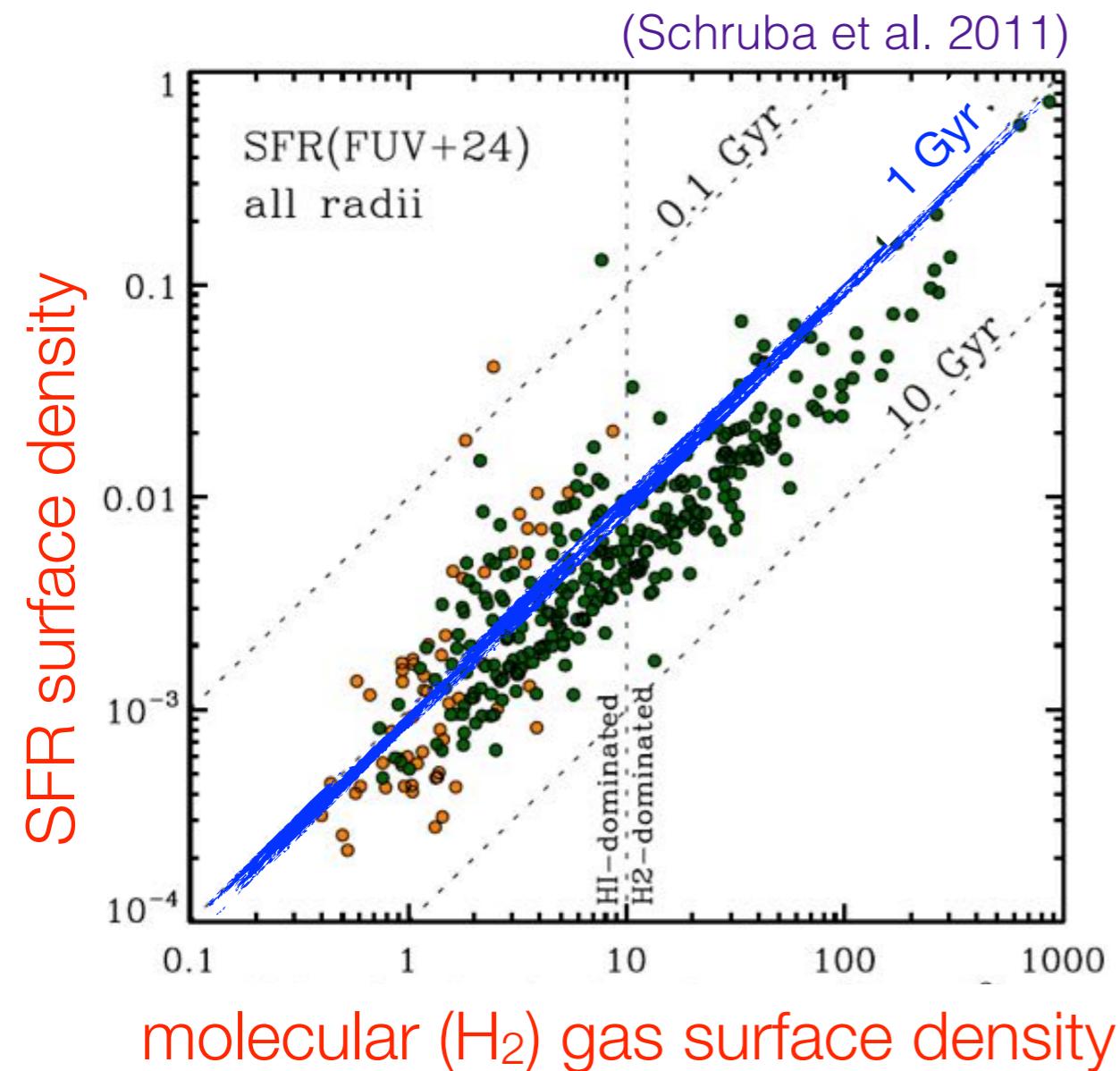
What regulates star formation?



What regulates star formation?



Motivation



→ many talks on Thursday



What is the impact of spiral arms?

Observations:

- small clouds cluster/coalesce while crossing spiral arm
Koda et al. (2009), Egusa et al. (2010)
- cloud properties change across the spiral arm
Hirota et al. (2011)

Theory:

- host cloud-cloud collisions needed for MYSCs
Fukui (2014)
- more high mass clouds in arms, but cloud properties similar
Fujimoto et al (2014)
- spiral arms bring clouds together but SF unaffected
Dobbs et al. (2011), Elmegreen & Elmegreen (1986)

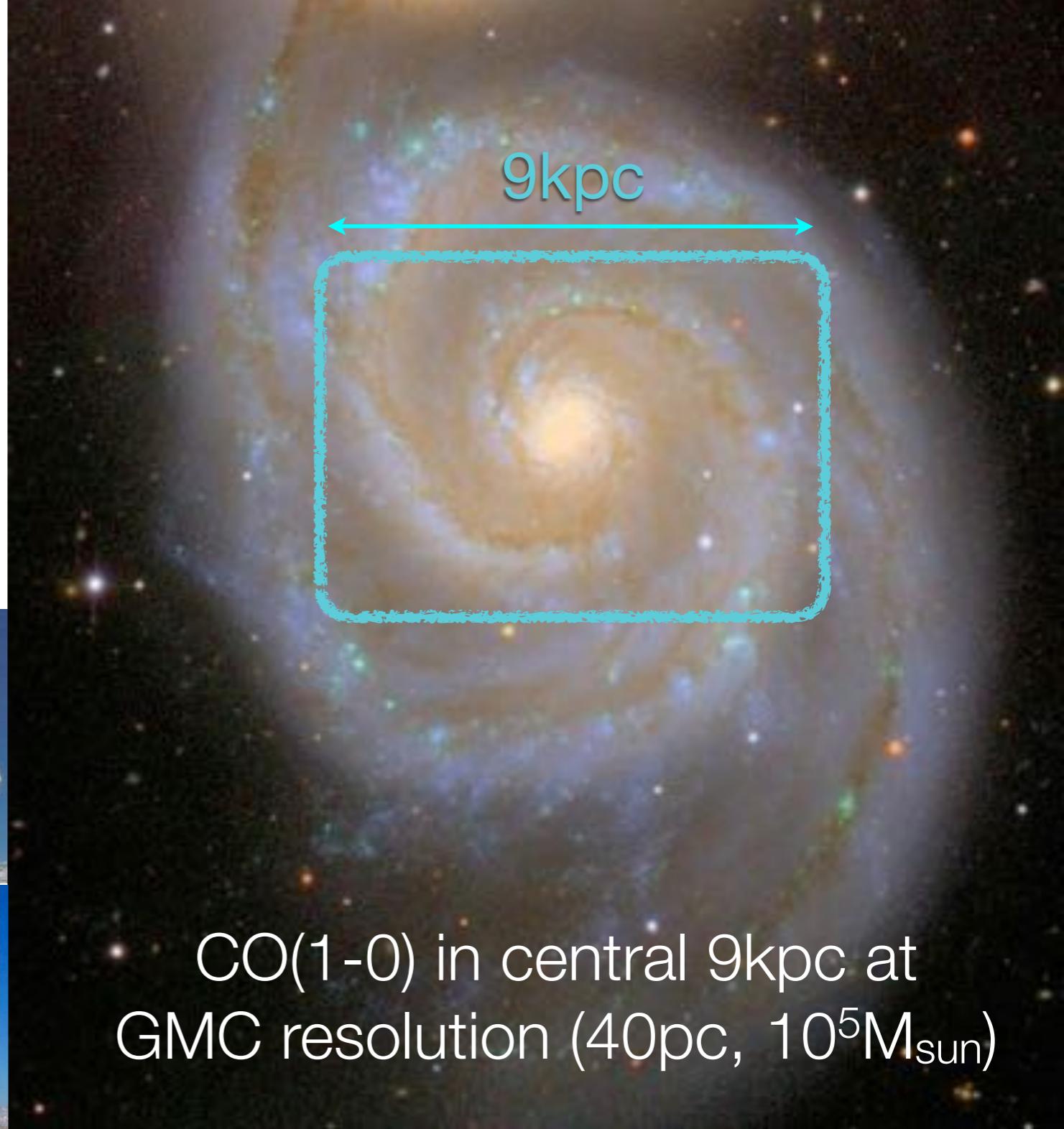


PdBI Arcsecond Whirlpool Survey

www.mpia.de/PAWS

IRAM 30m: 40 hr

PdBI: 170 hr



CO(1-0) in central 9kpc at
GMC resolution (40pc, $10^5 M_{\odot}$)

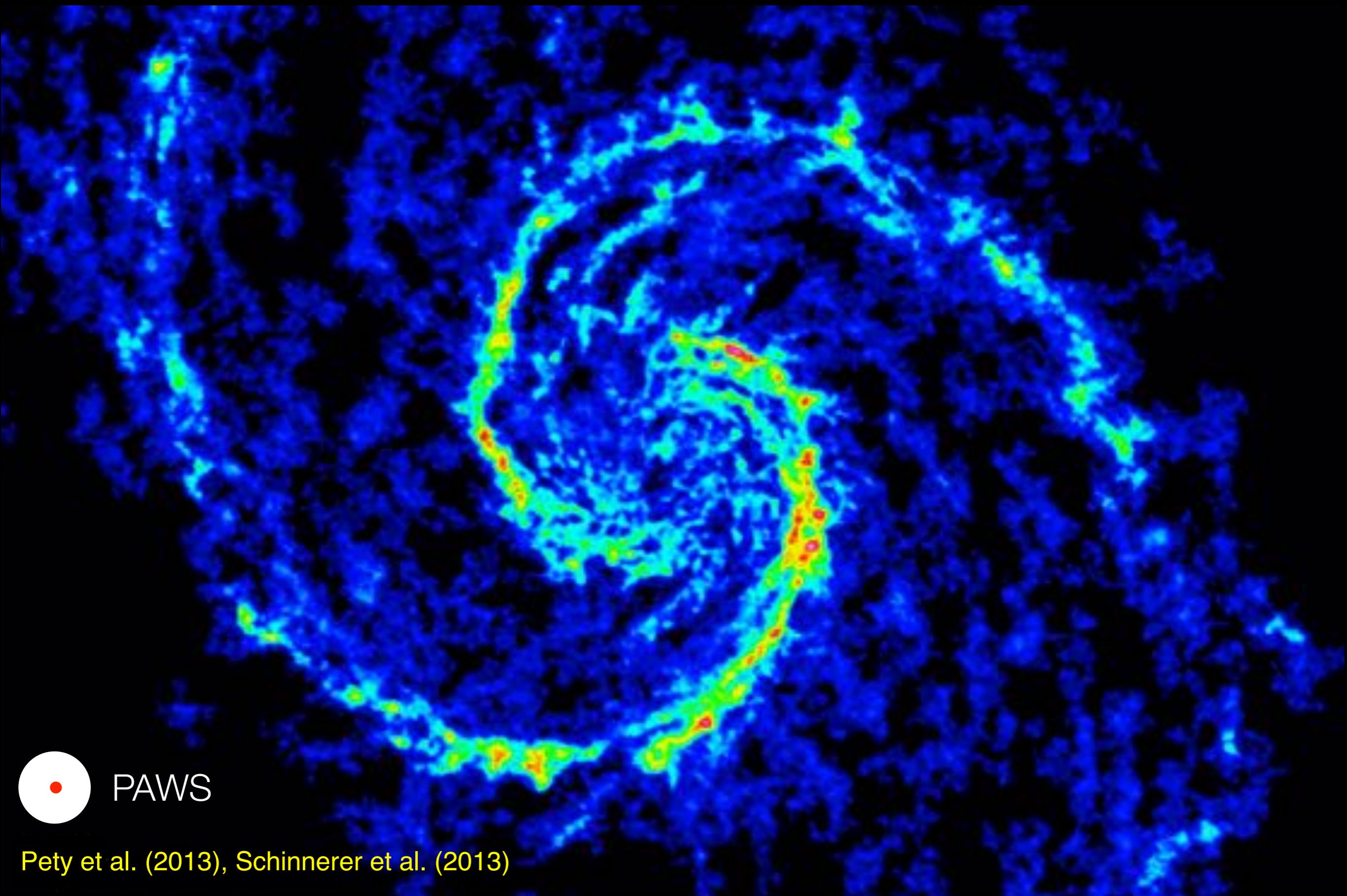
PI: Eva Schinnerer, Annie Hughes, Sharon Meidt, Miguel Querejeta (MPIA)

Gaelle Dumas, Carsten Kramer, Jerome Pety, Karl Schuster (IRAM)

Dario Colombo (U. Alberta), Clare Dobbs (U. Exeter),

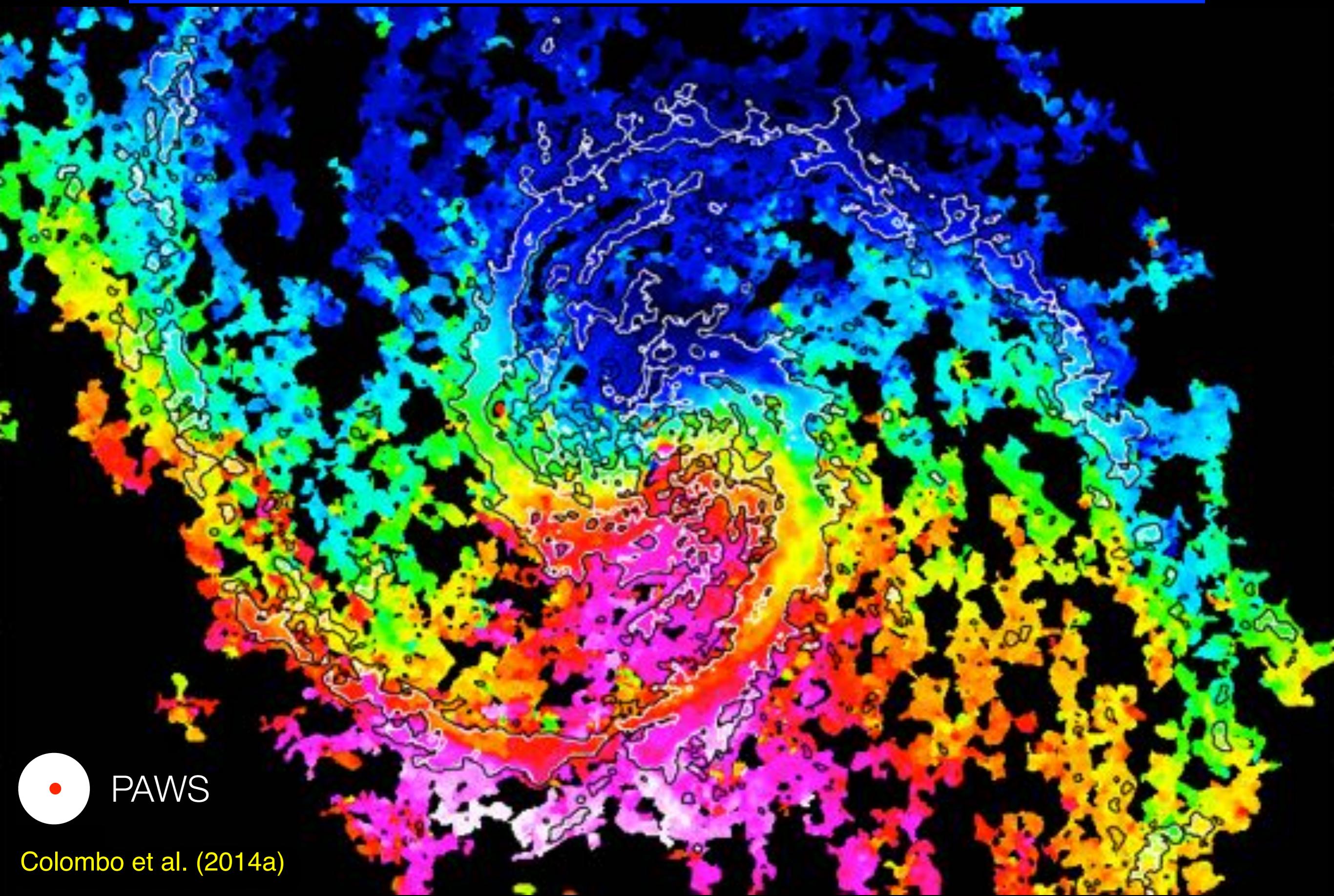
Santiago Garcia-Burillo (OAN), Adam Leroy (NRAO), Todd Thompson (OSU)

Molecular gas disk in inner M51



PAWS

CO velocity field in inner M51



Outline

1. Molecular gas distribution and kinematics
2. Environmental variations in molecular gas properties
3. A dynamical estimate for GMC lifetimes
4. Conversion of GMCs to stars is complex

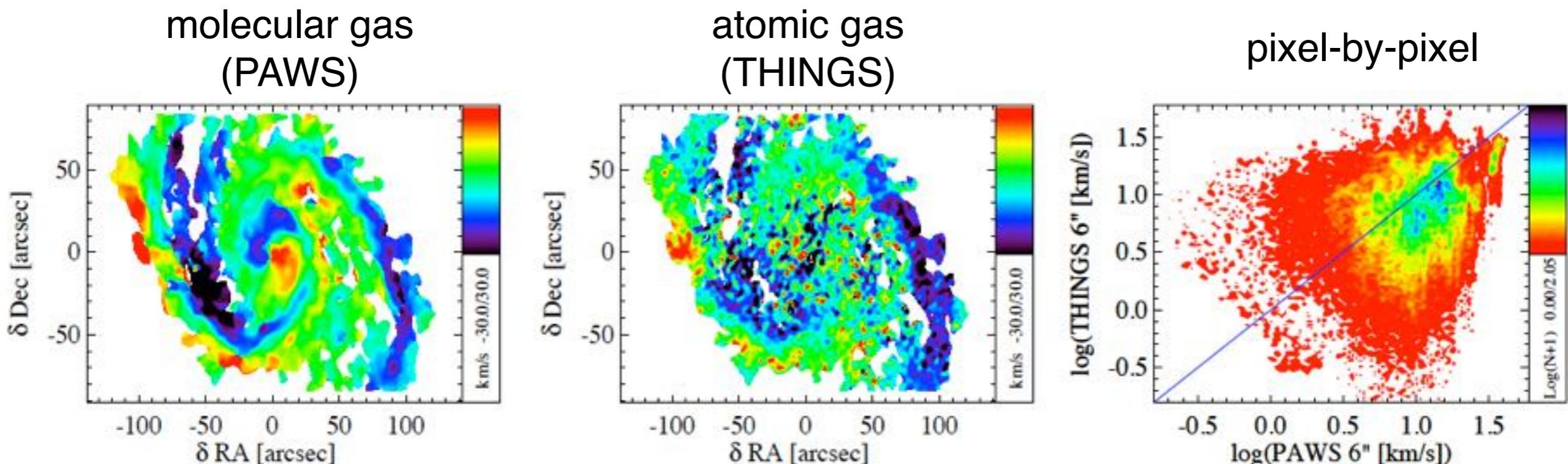
Cool gas in a spiral potential

Colombo et al (2014a)

molecular gas more clumpy than atomic gas

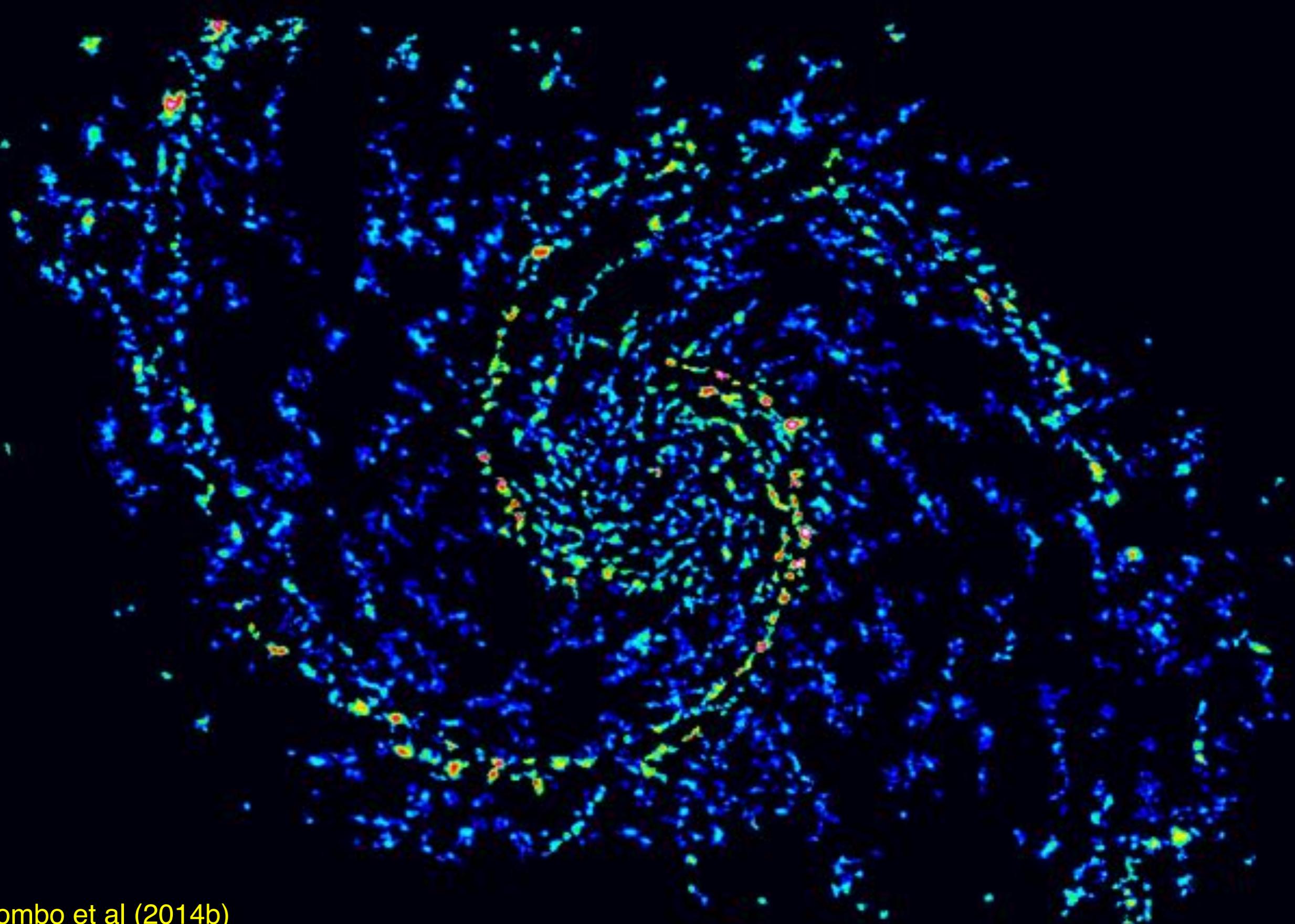
Leroy et al (2013)

PAWS: molecular and atomic gas kinematics not the same

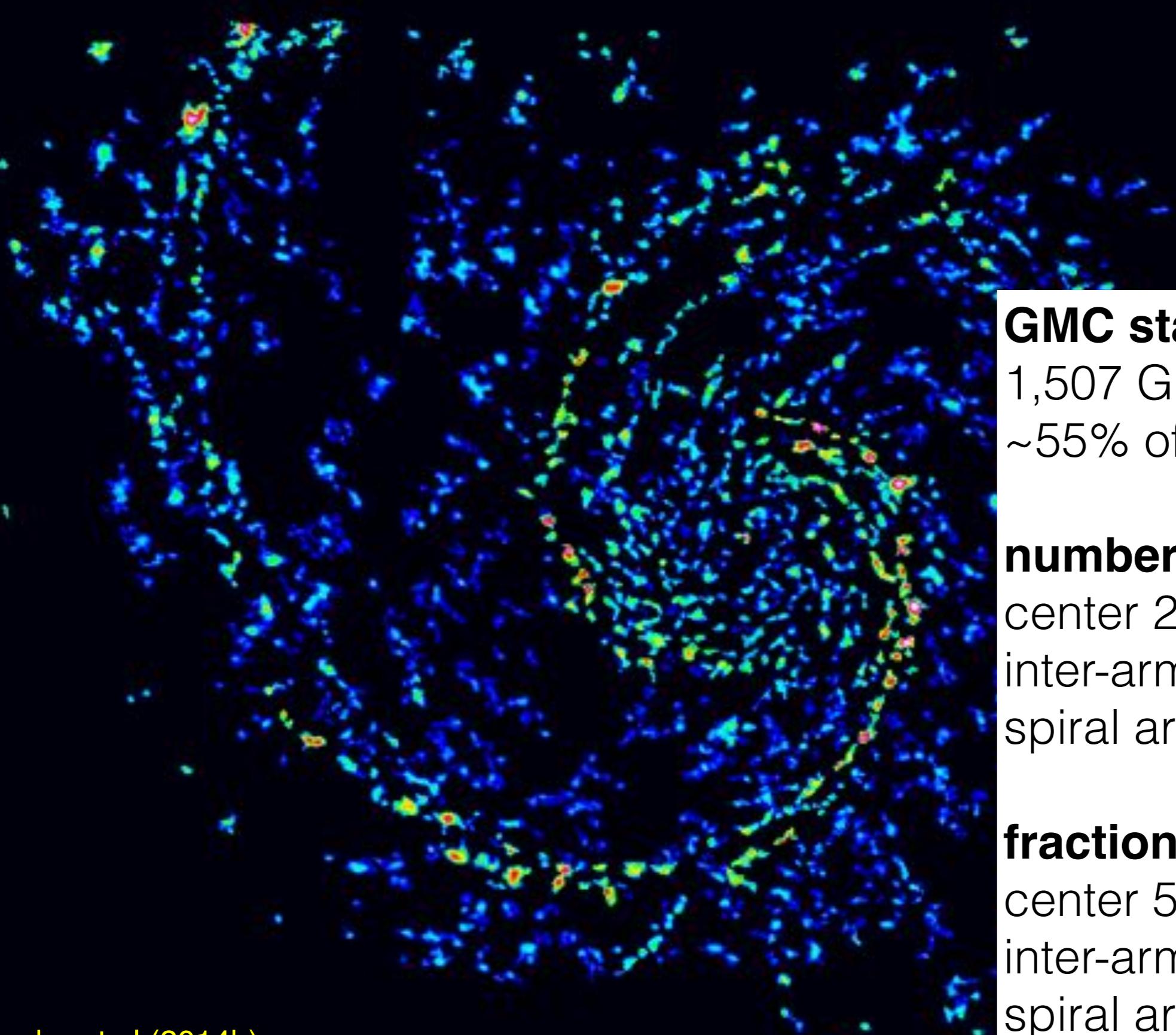


→ atomic and molecular gas phases respond differently to spiral/bar perturbations

Half the CO emission is in GMCs



Half the CO emission is in GMCs



GMC statistics

1,507 GMCs identified
~55% of total CO flux

number distribution:

center 22%
inter-arm 34%
spiral arms 44%

fraction of total flux:

center 57%
inter-arm 45%
spiral arms 57%

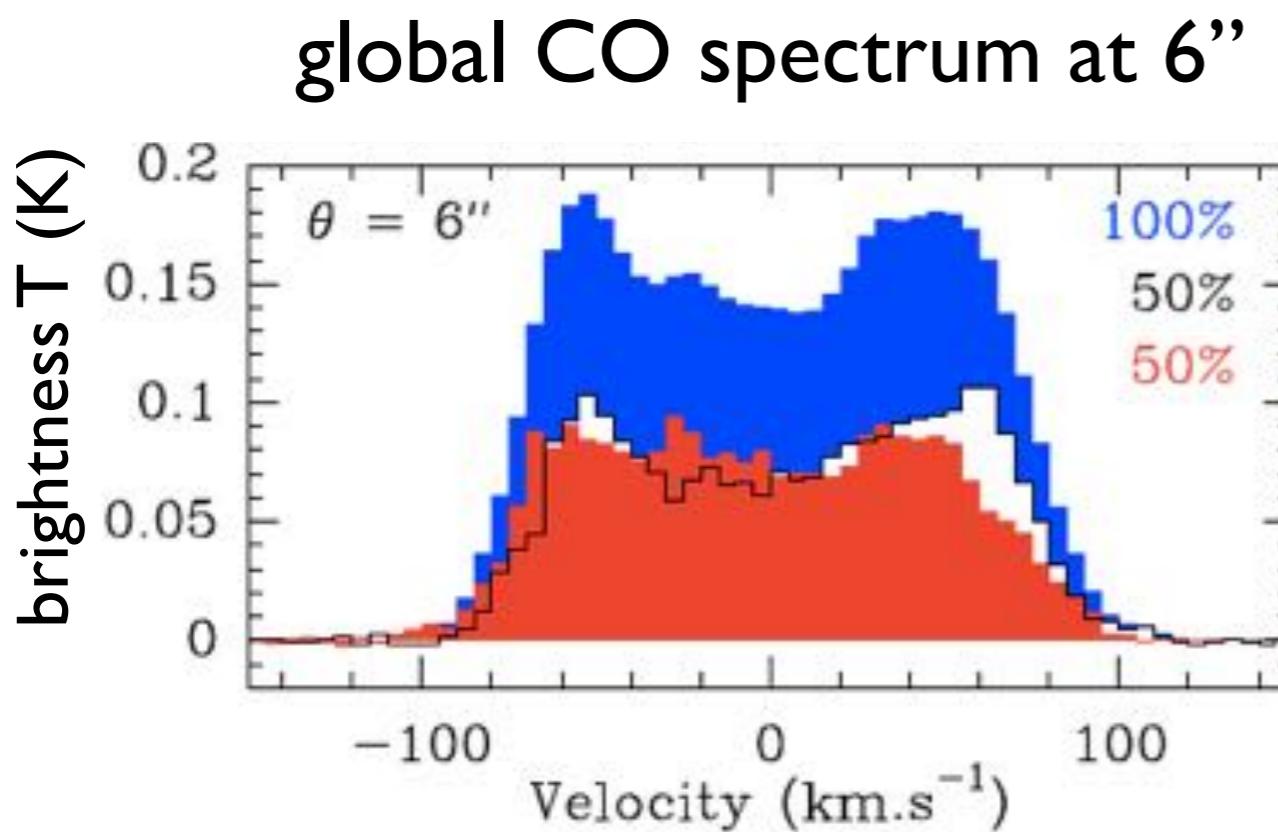
Where is the rest of the CO?

Pety et al (2013)

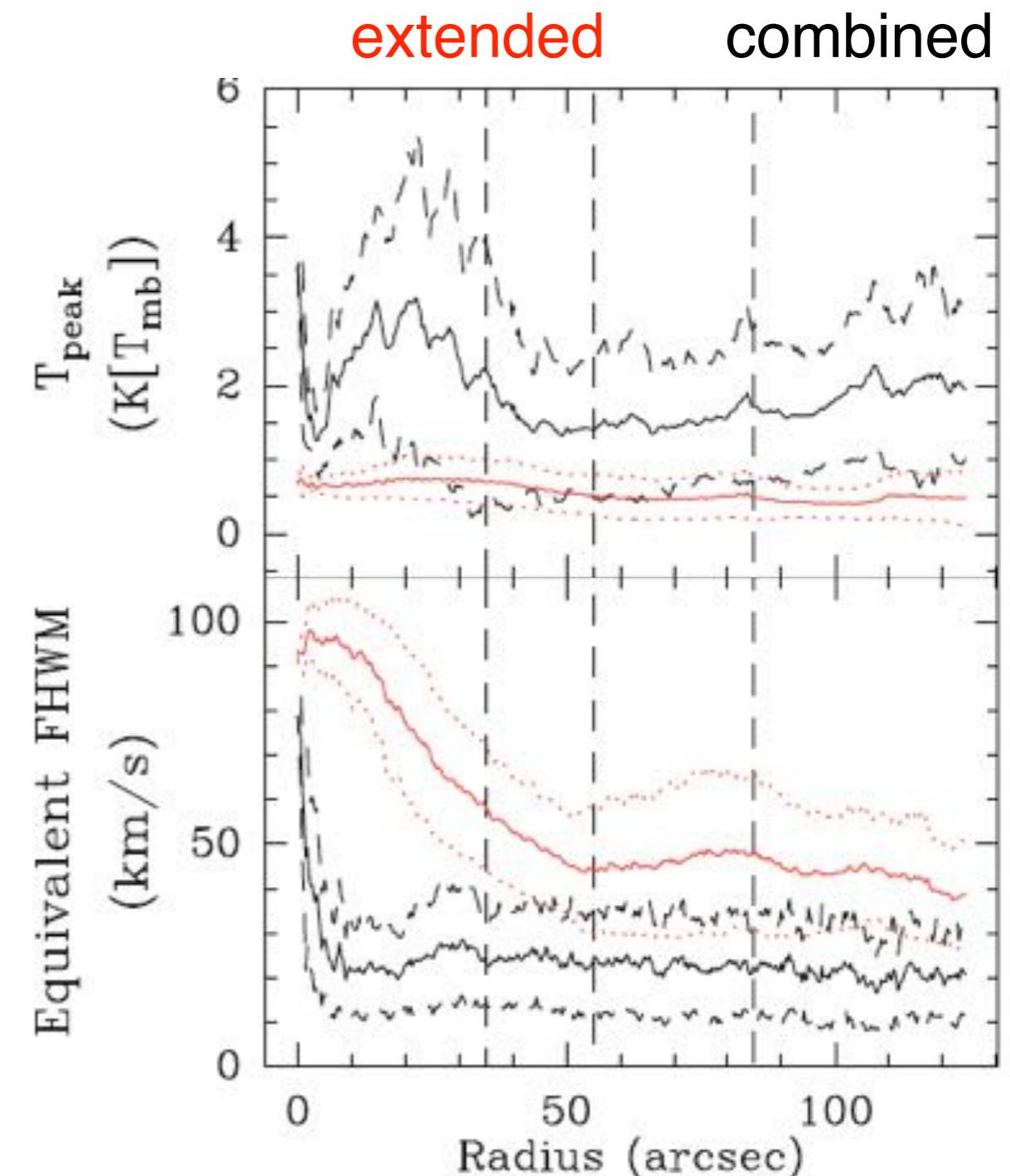
PdBI+30m: all spatial scales

PdBI-only: small scales only

Extended: large scales only

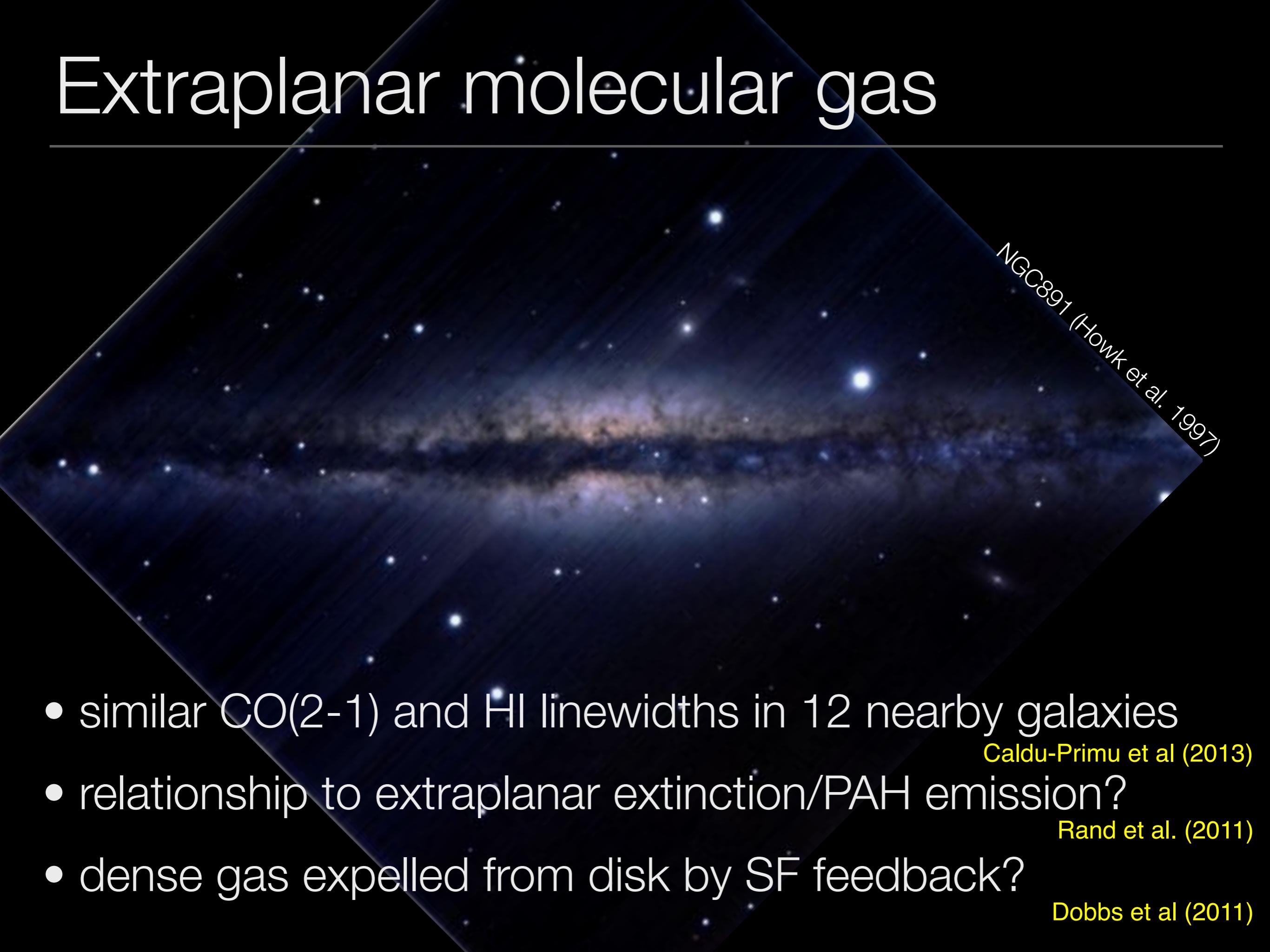


extended component is
structured on >1kpc scales



a dynamically hot, thick
molecular gas disk?

Extrapolanar molecular gas



NGC891 (Howk et al. 1997)

- similar CO(2-1) and HI linewidths in 12 nearby galaxies
Caldu-Primu et al (2013)
- relationship to extrapolanar extinction/PAH emission?
Rand et al. (2011)
- dense gas expelled from disk by SF feedback?
Dobbs et al (2011)

Outline

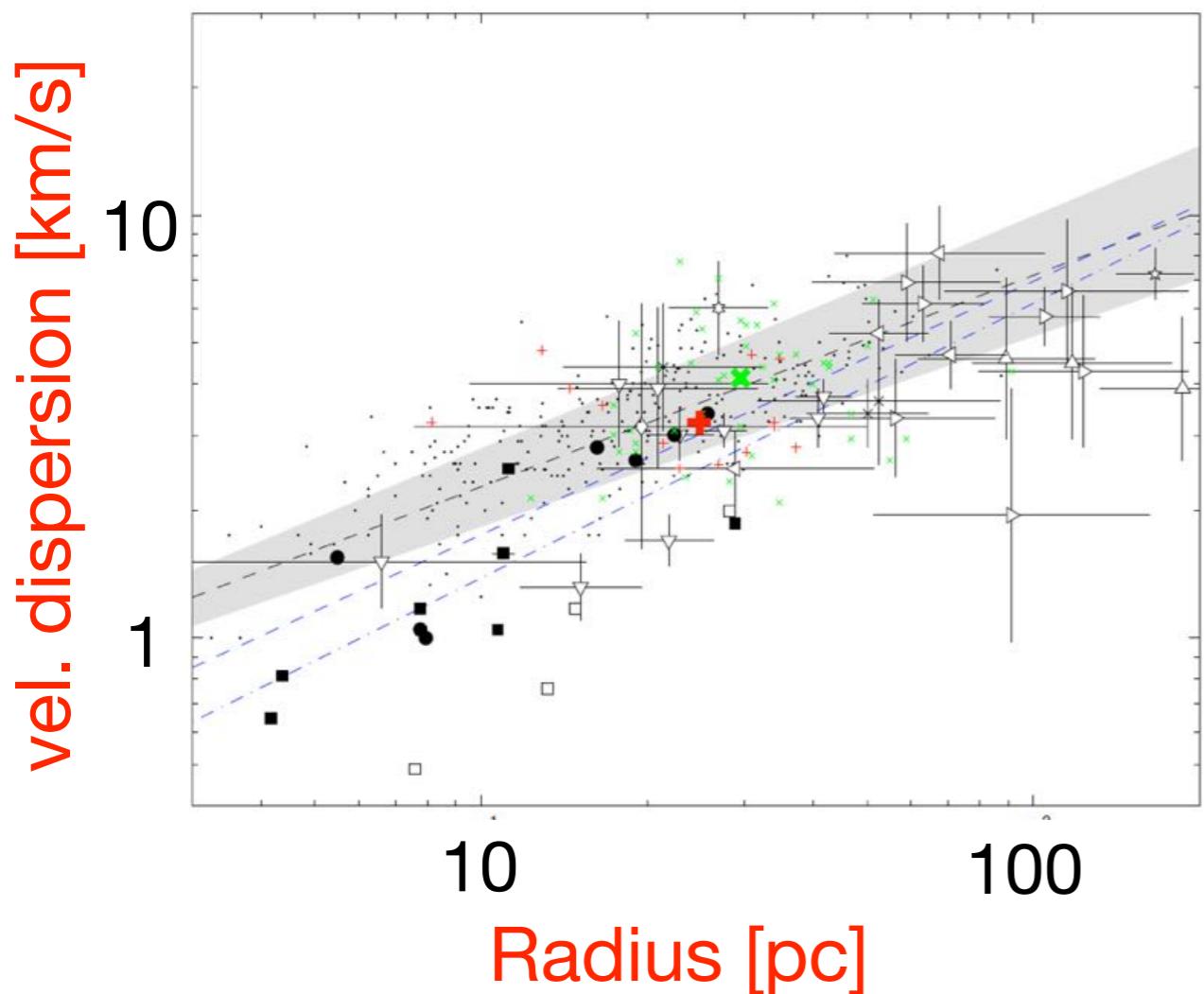
1. Molecular gas distribution and kinematics
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Do GMCs have universal properties?

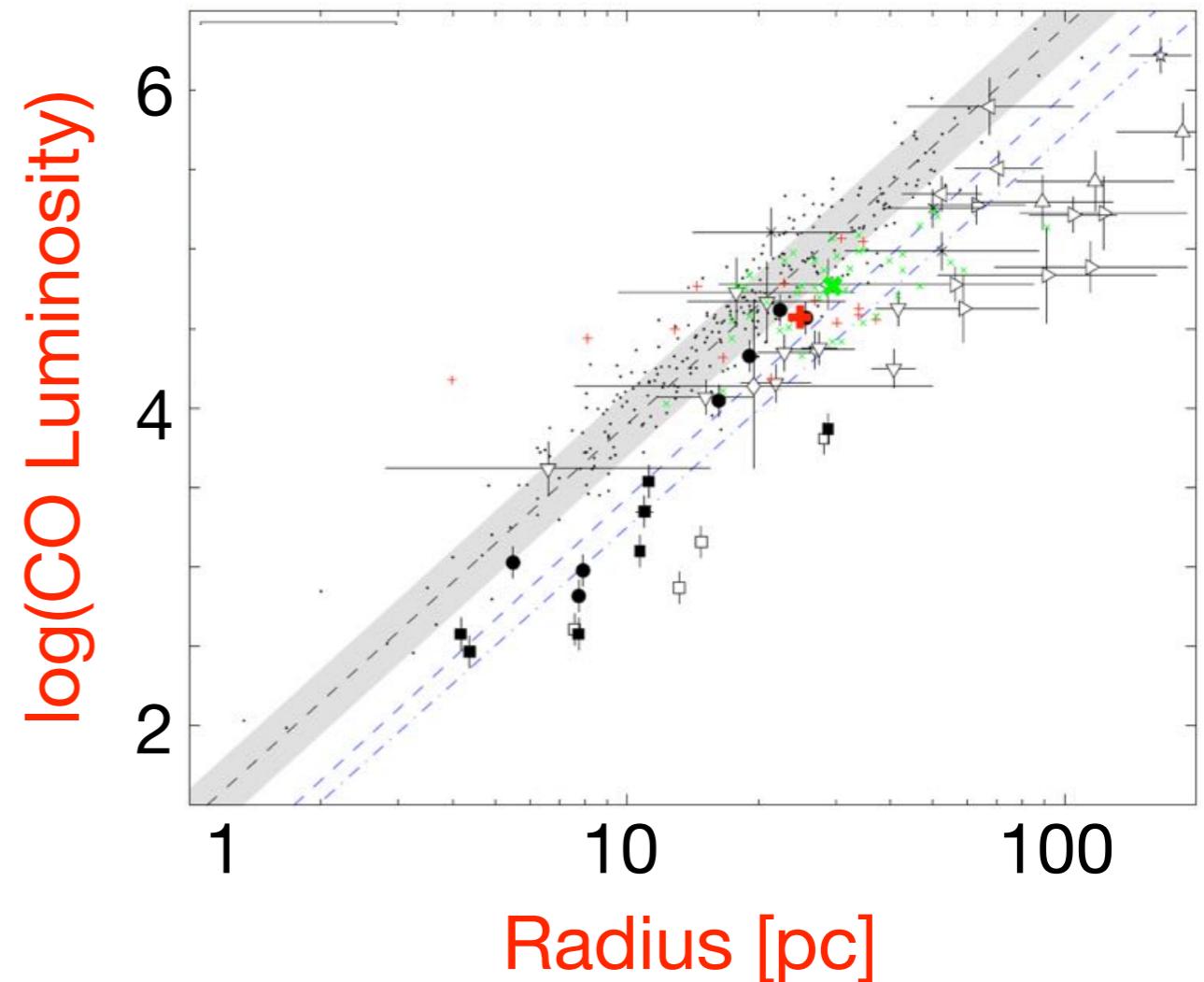
Extragalactic GMCs obey Larson-type scaling relations

e.g. Bolatto et al 2008, Donovan-Meyer et al 2013

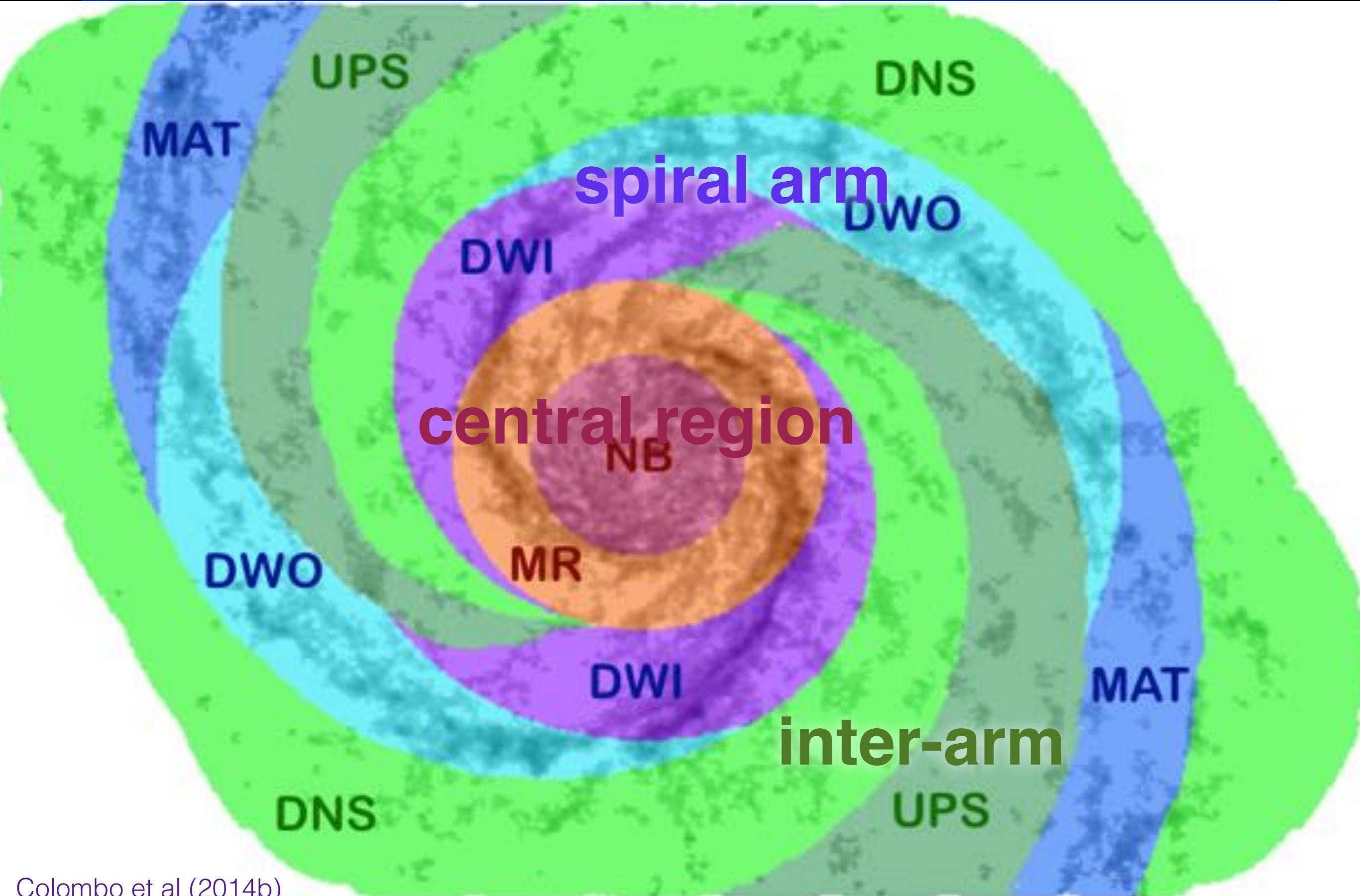
size-linewidth relation



size-luminosity relation

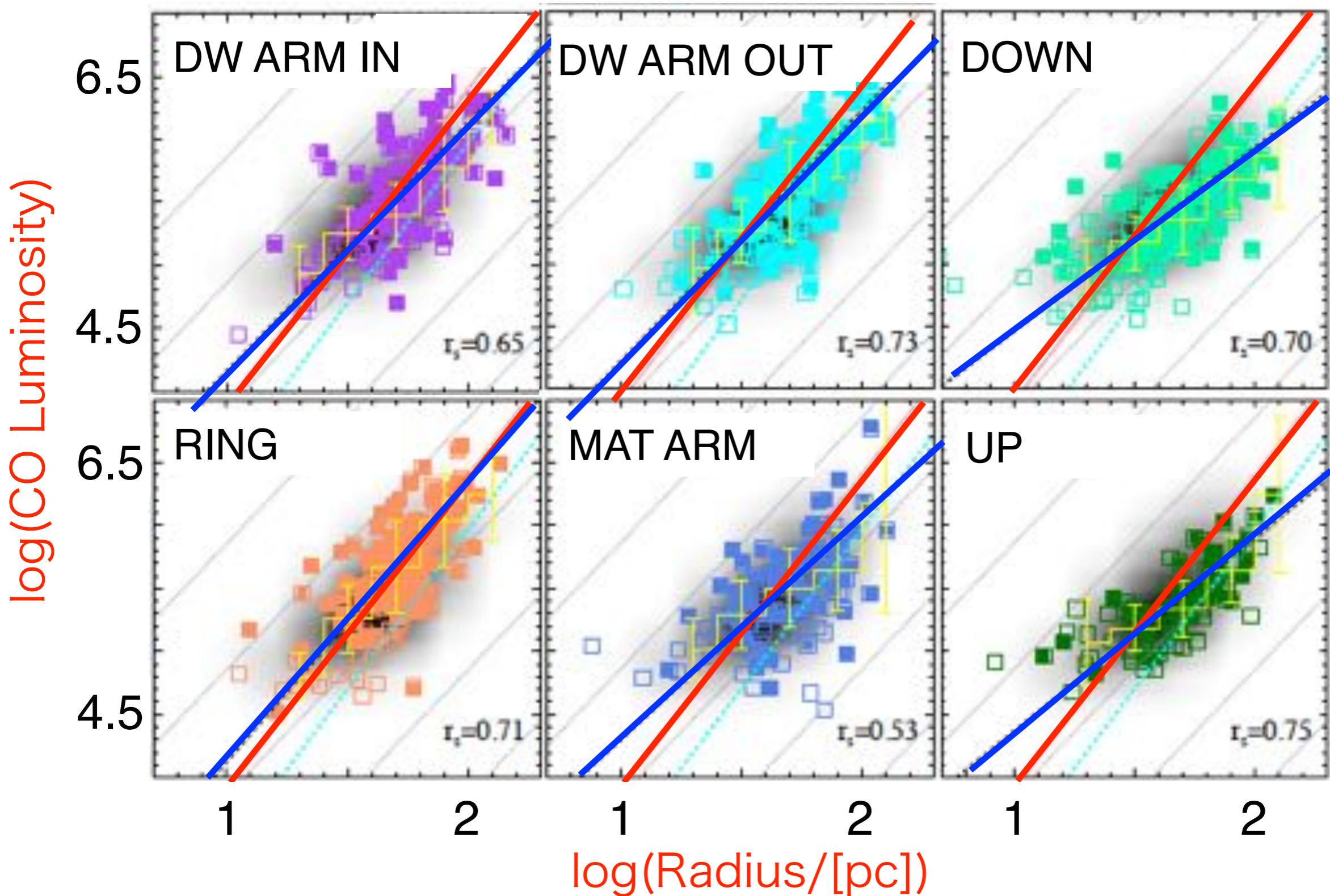


Dynamical environments within PAWS field



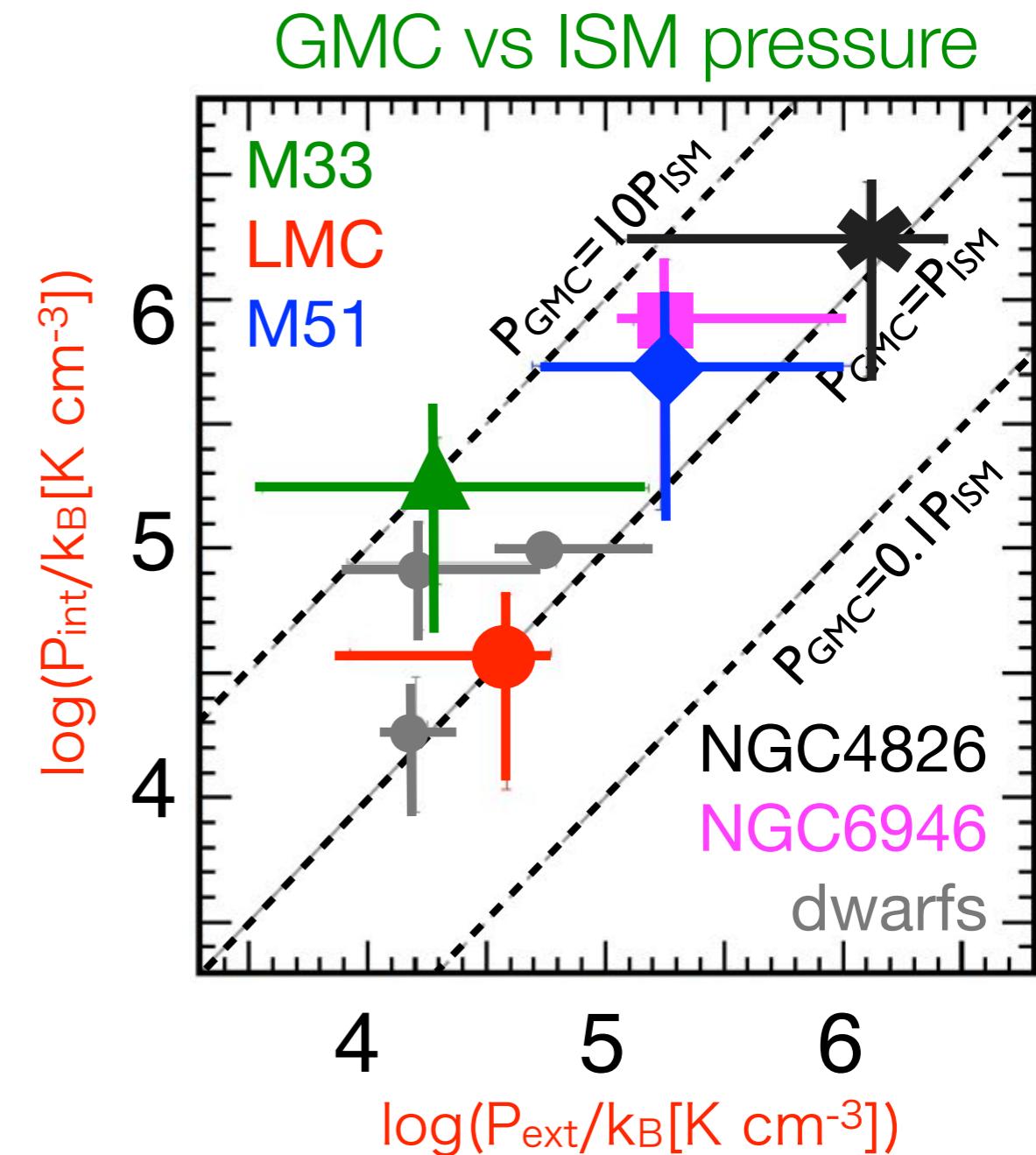
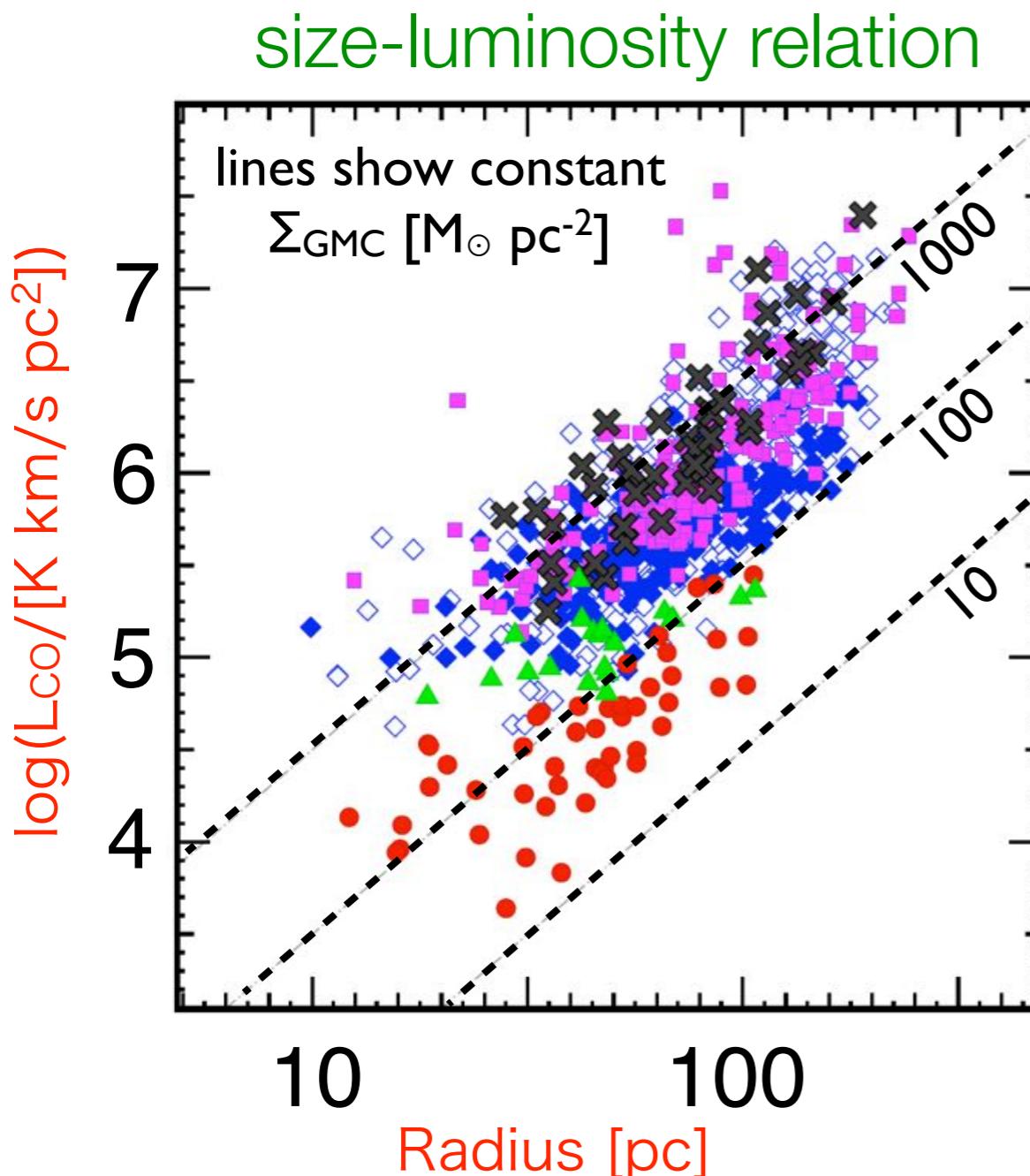
Size-luminosity relation: M51

Colombo et al (2014b)



GMC Properties: Nearby Galaxies

Hughes et al (2013b)



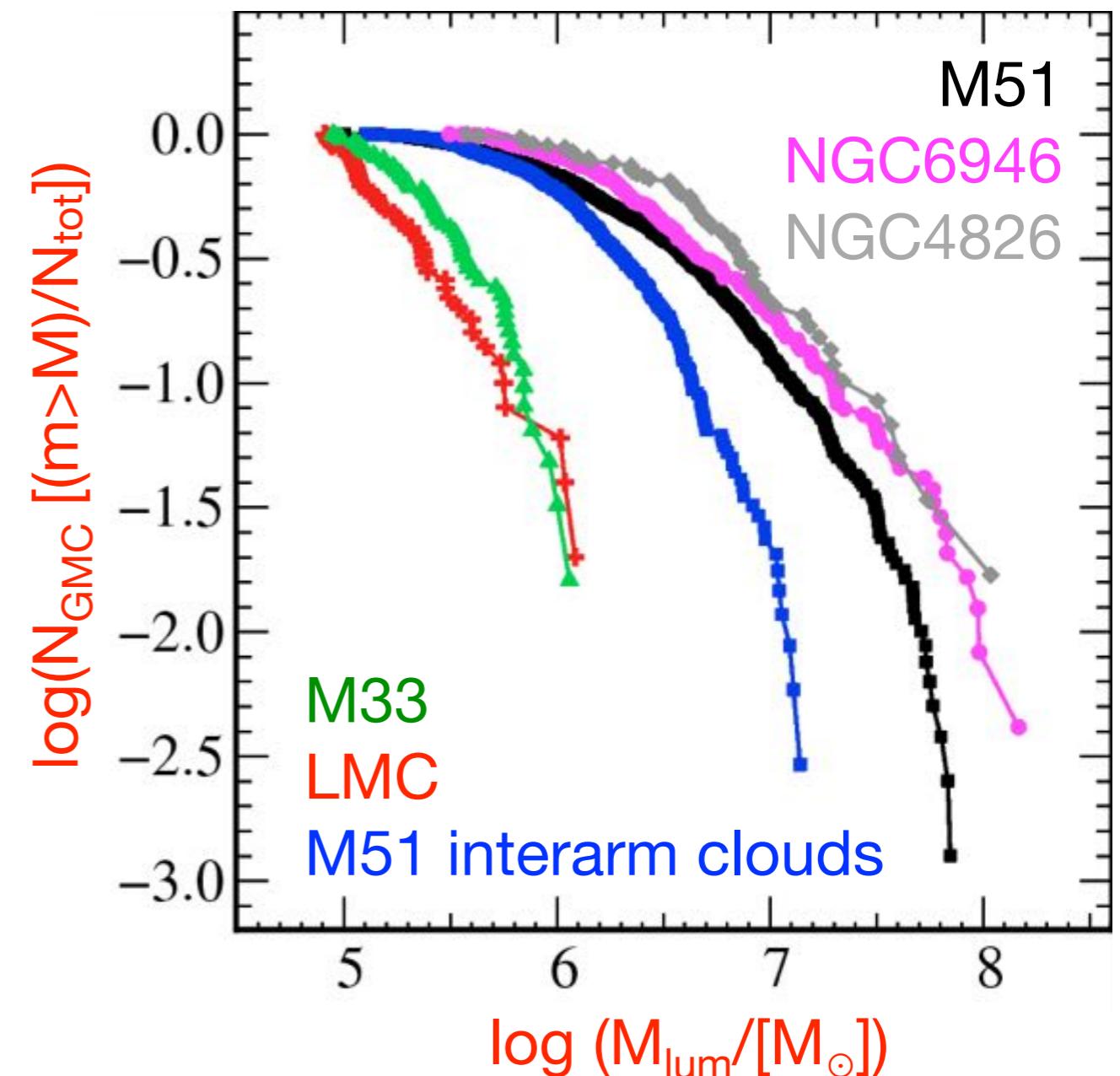
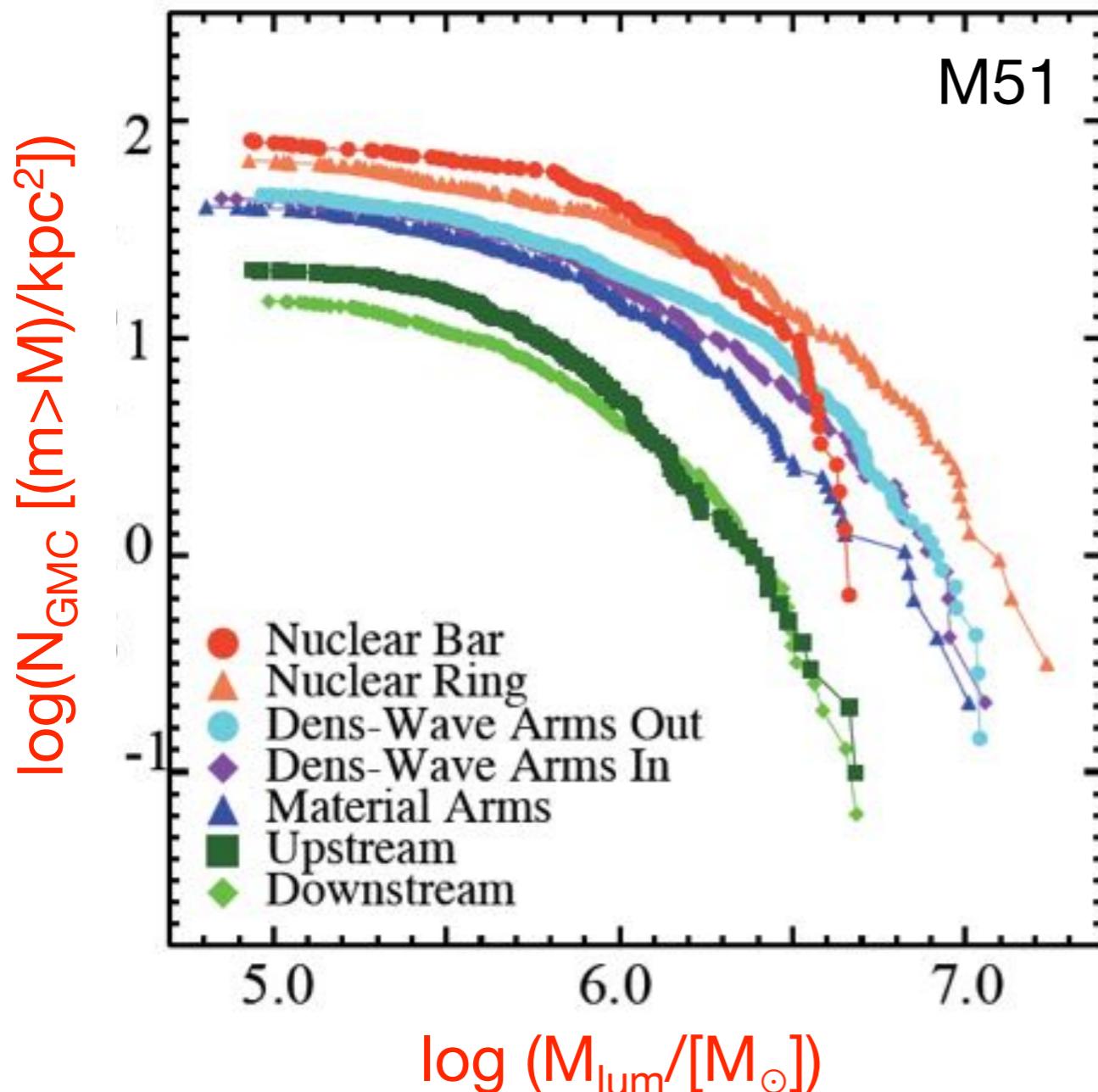
→ if $P_{\text{int}} \sim P_{\text{ext}}$, environment more likely to influence cloud stability, dense gas mass function, star formation activity, GMC evolution...

GMC Mass Functions

Colombo et al (2013a), Hughes et al (in prep.)



talk by Braine



- spiral arms play key role in assembling high mass GMCs
- small clouds dominate total H₂ budget in diffuse environments

What Determines the GMC MF?

Hughes et al (in prep.)

M51 Key:

ambient ISM: CO

- PAWS FoV
- ◆ + centre
- ▲▲▲ interarm
- spiral arms

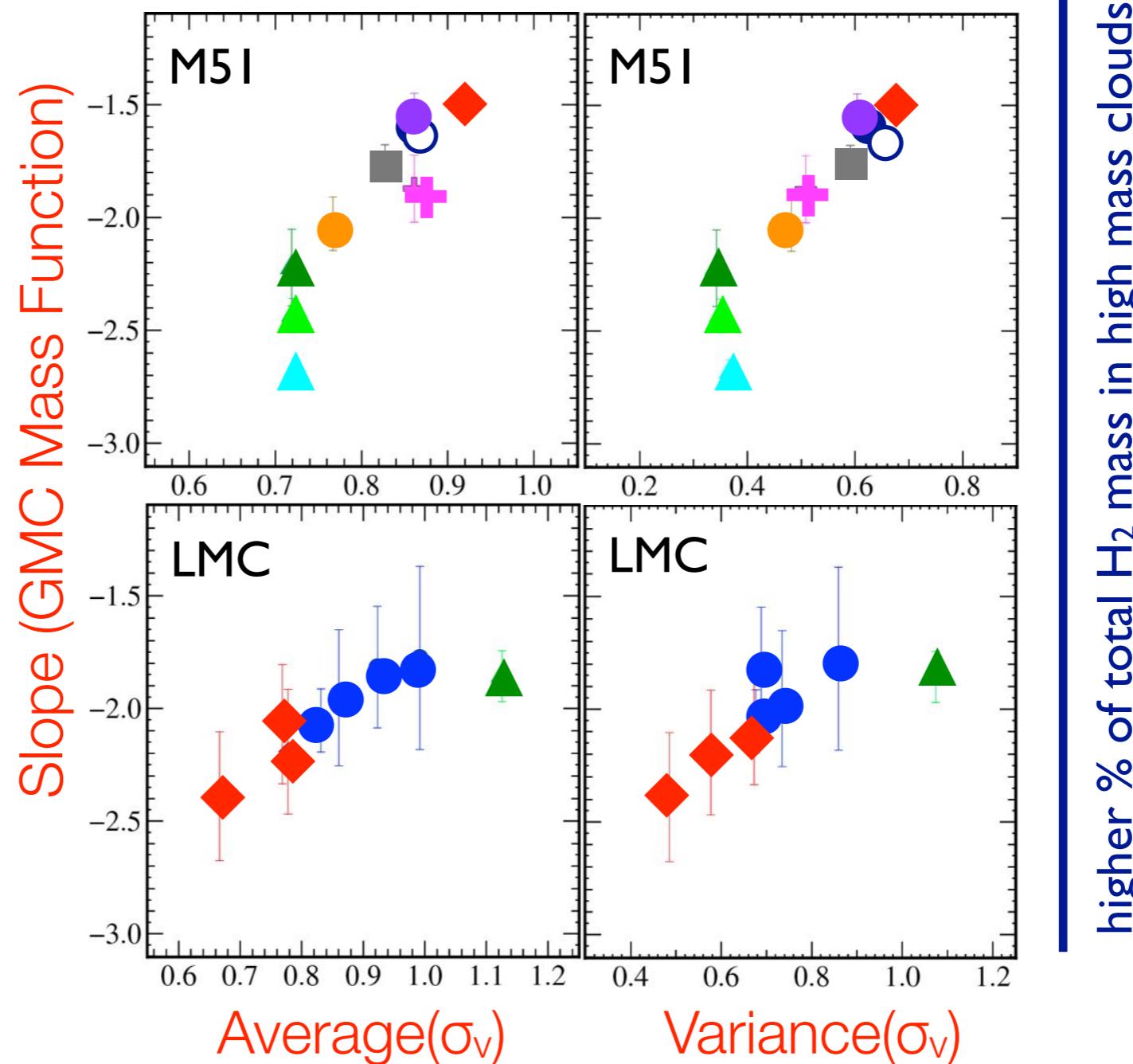
LMC Key:

ambient ISM: HI

- ◆ $R_{\text{gal}} > 1.6 \text{kpc}$
- $R_{\text{gal}} < 1.6 \text{kpc}$
- ▲ interaction zone (SEHO)

greater variance in ISM velocity dispersion

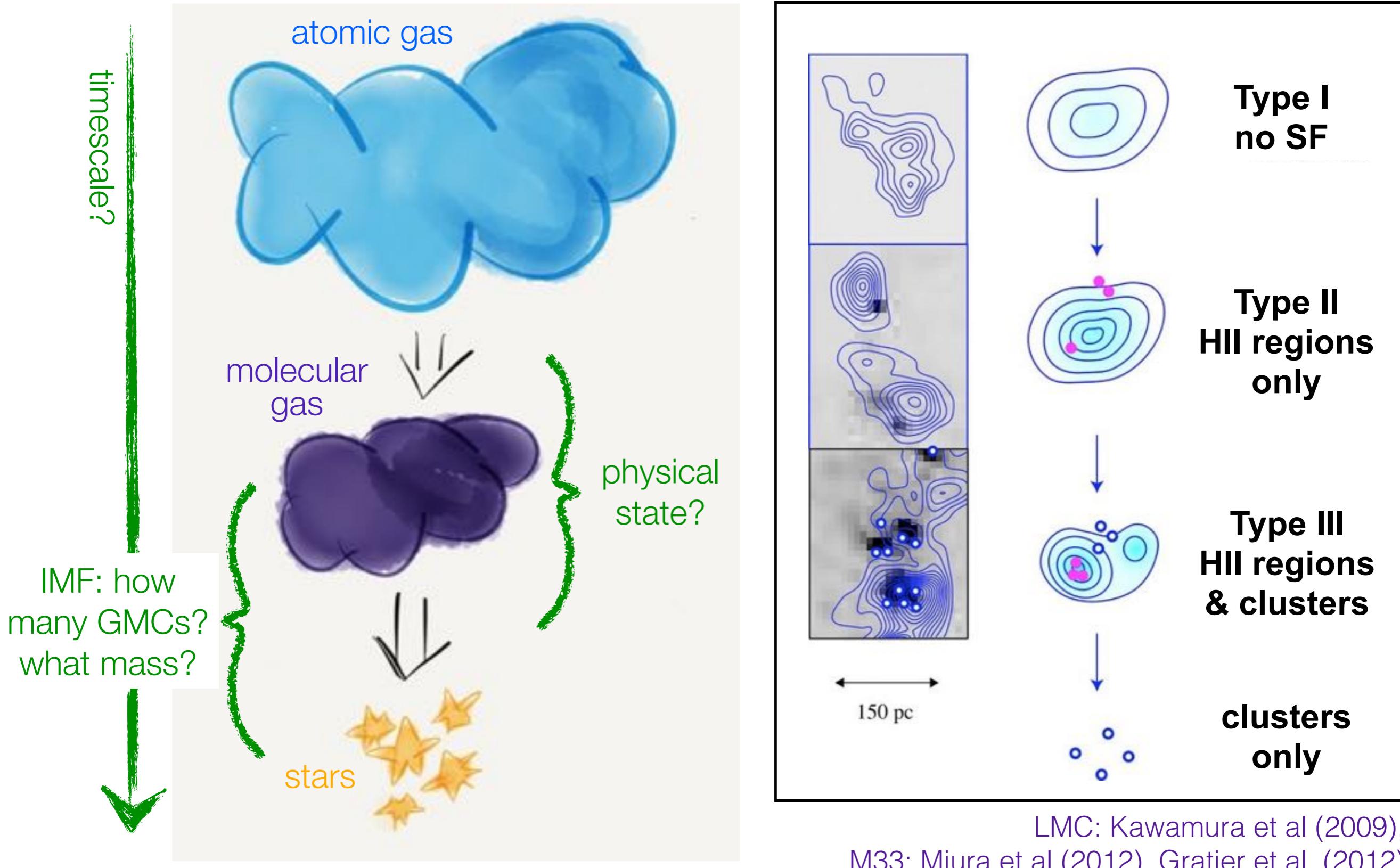
higher velocity dispersion in ambient gas



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Estimating GMC lifetimes

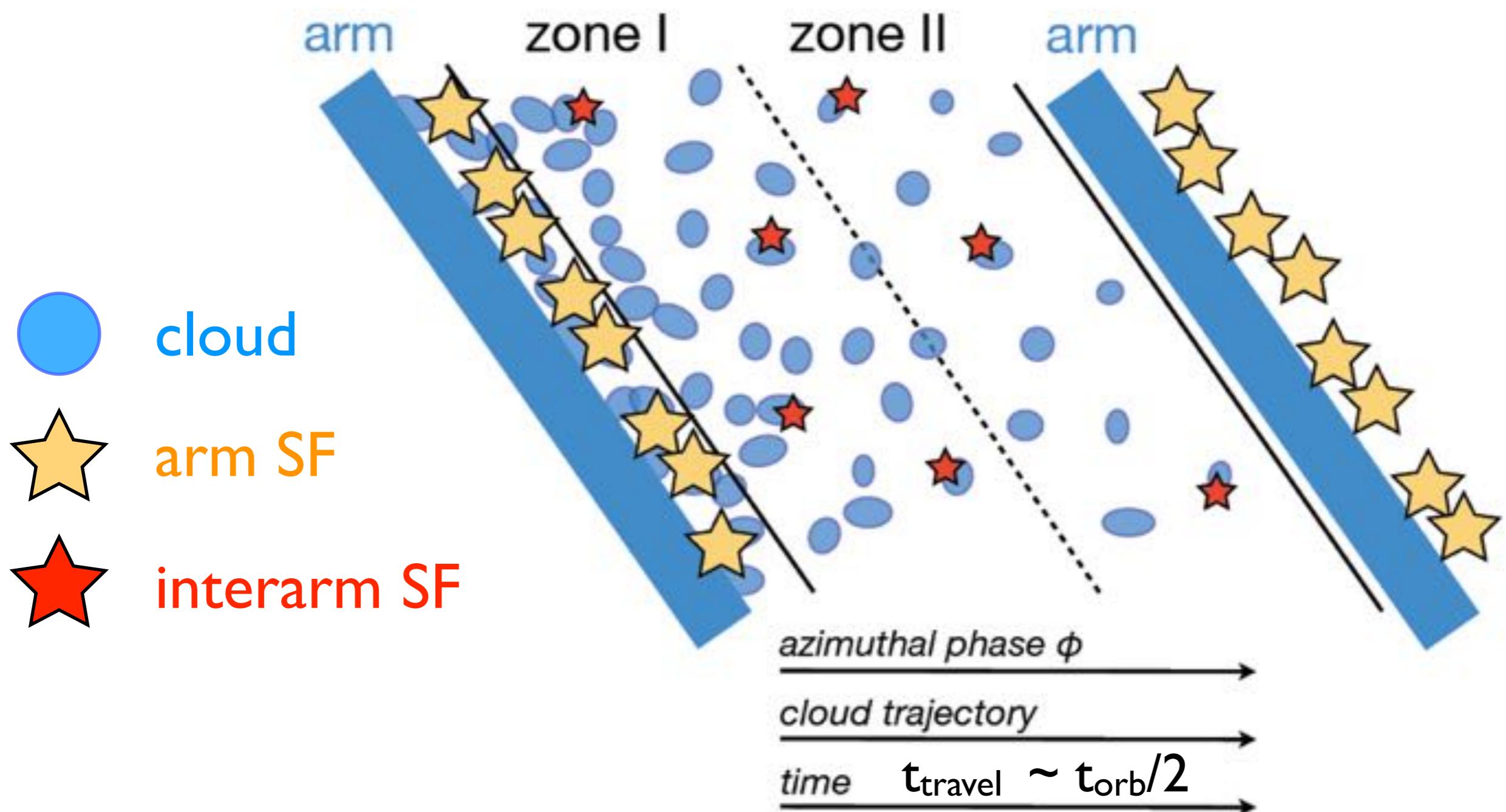


GMC lifetimes in interarm

Meidt et al. (submitted)

in disk galaxies, galactic orbital period provides fiducial clock

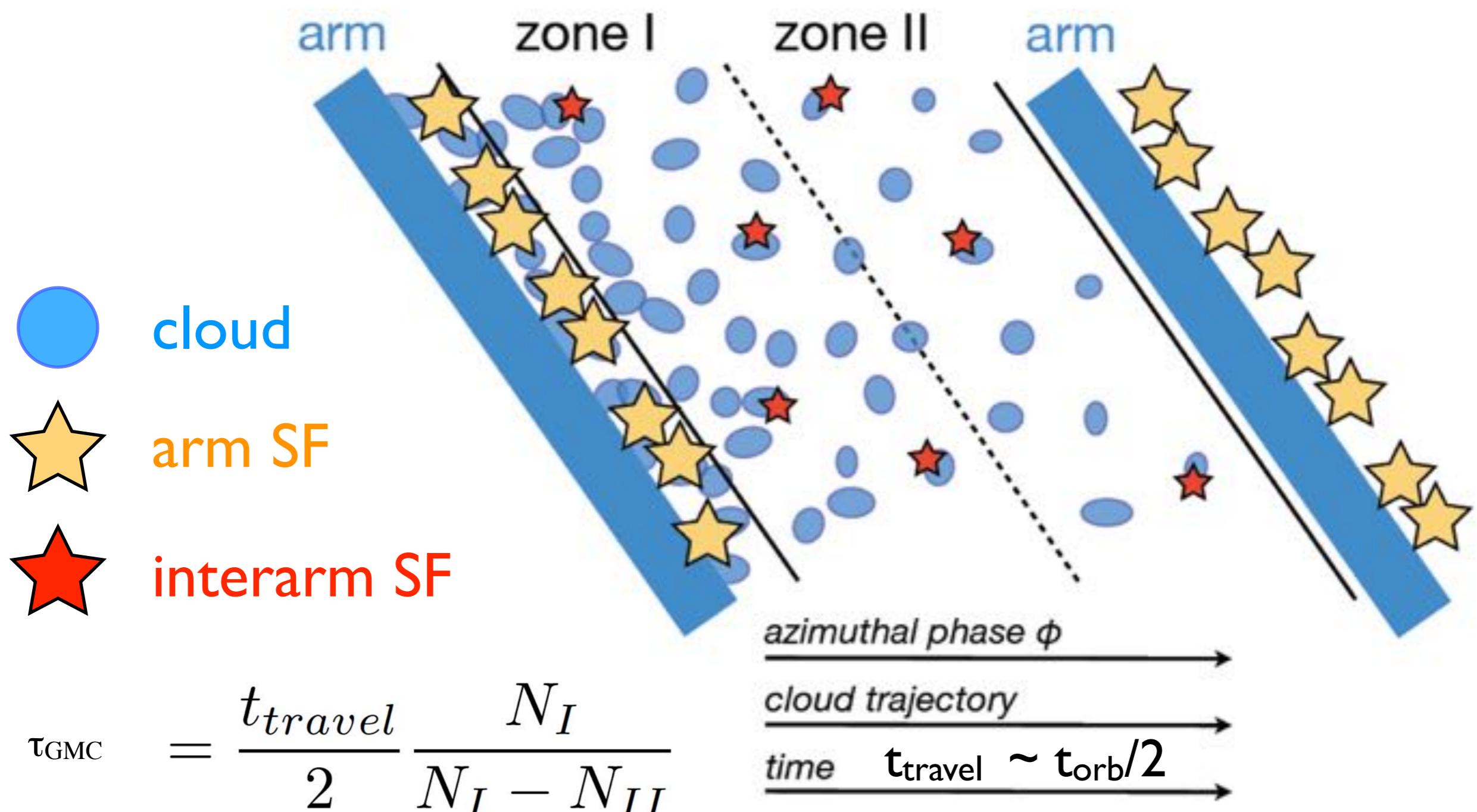
Koda et al (2009)



GMC lifetimes in interarm

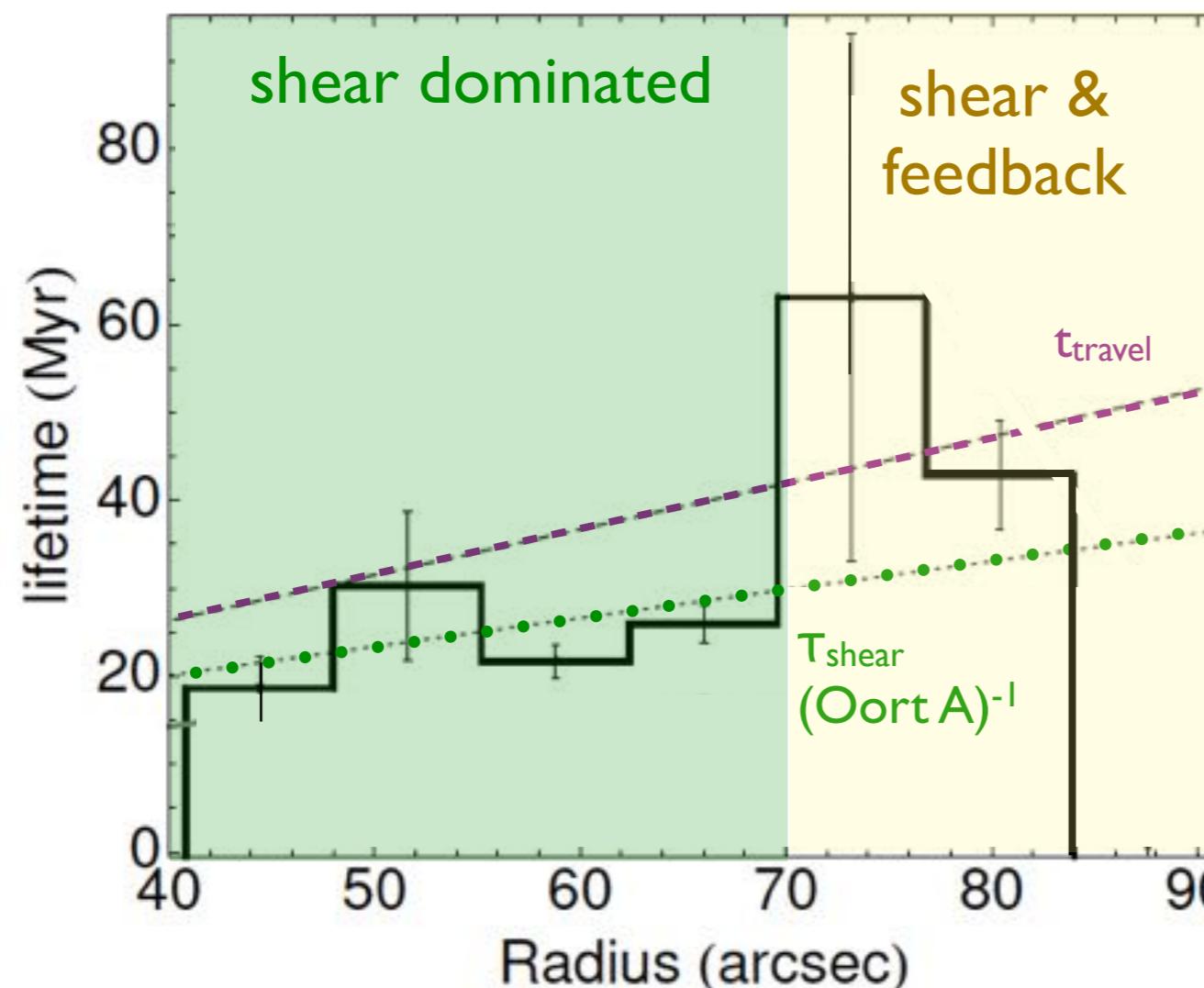
Meidt et al. (submitted)

decrease in cloud numbers yields characteristic lifetime



GMC lifetimes in M51

Meidt et al. (submitted)



→ talk by
Kruijssen

- typical lifetime of M51 interarm GMC is 20~30 Myr
- predict that GMC lifetimes should vary with shear strength and Hubble type

Outline

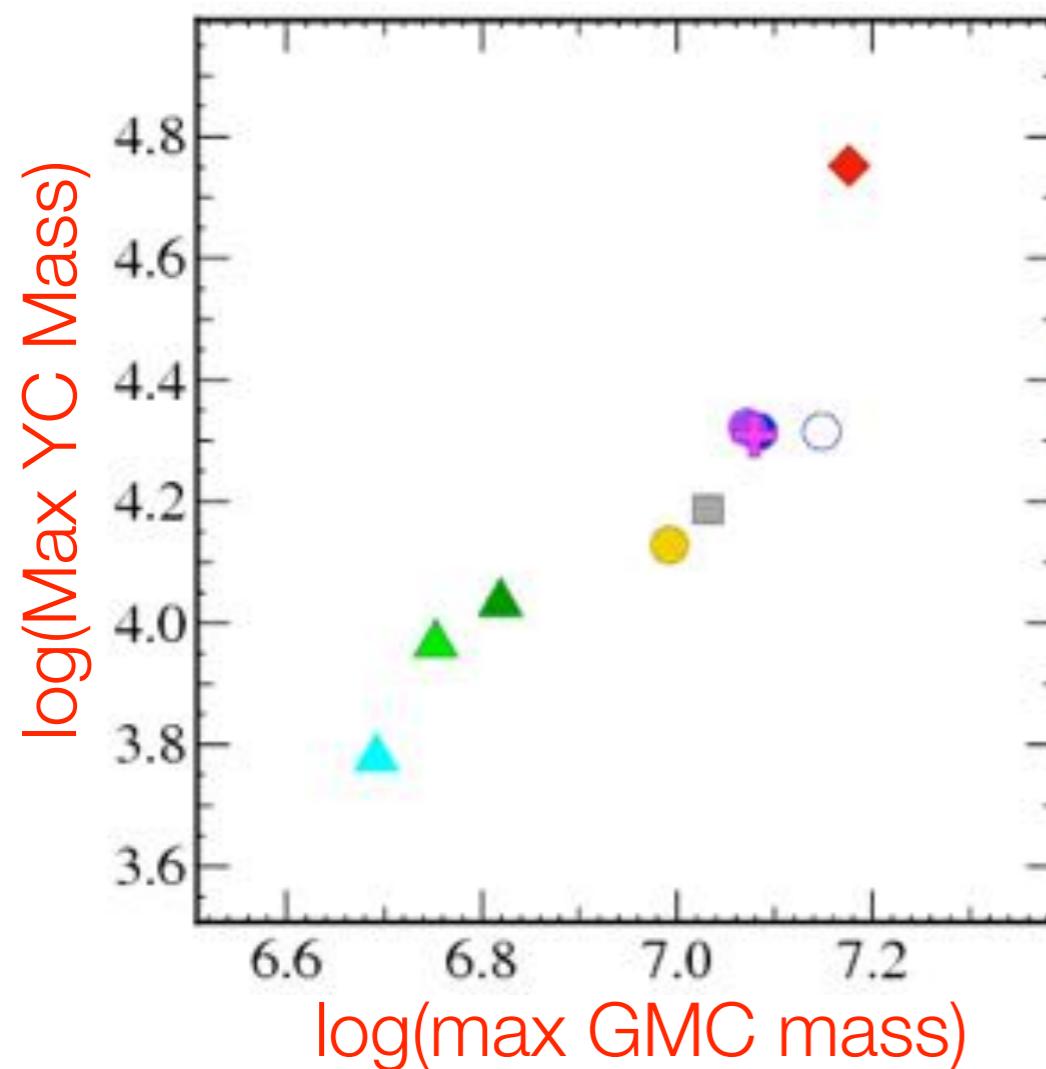
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GMCs and Young Clusters in M51

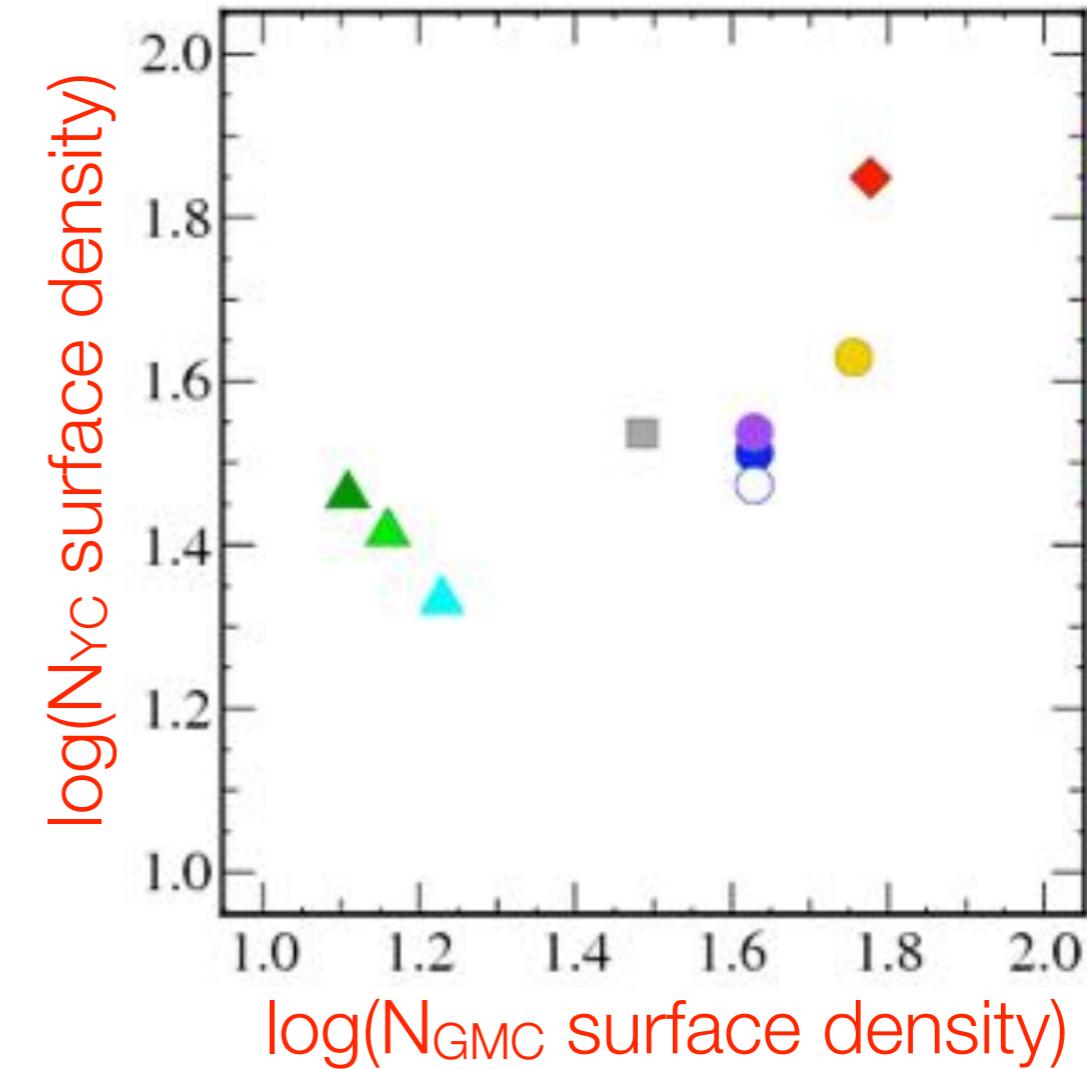
Hughes et al (2013a)

Some young cluster (YC) and GMC properties track each other:

95th Percentile Mass



Number Density



■ M51 overall

✚ bar

◆ ring

● arm1

○ arm1 in

● arm1 out

○ arm2

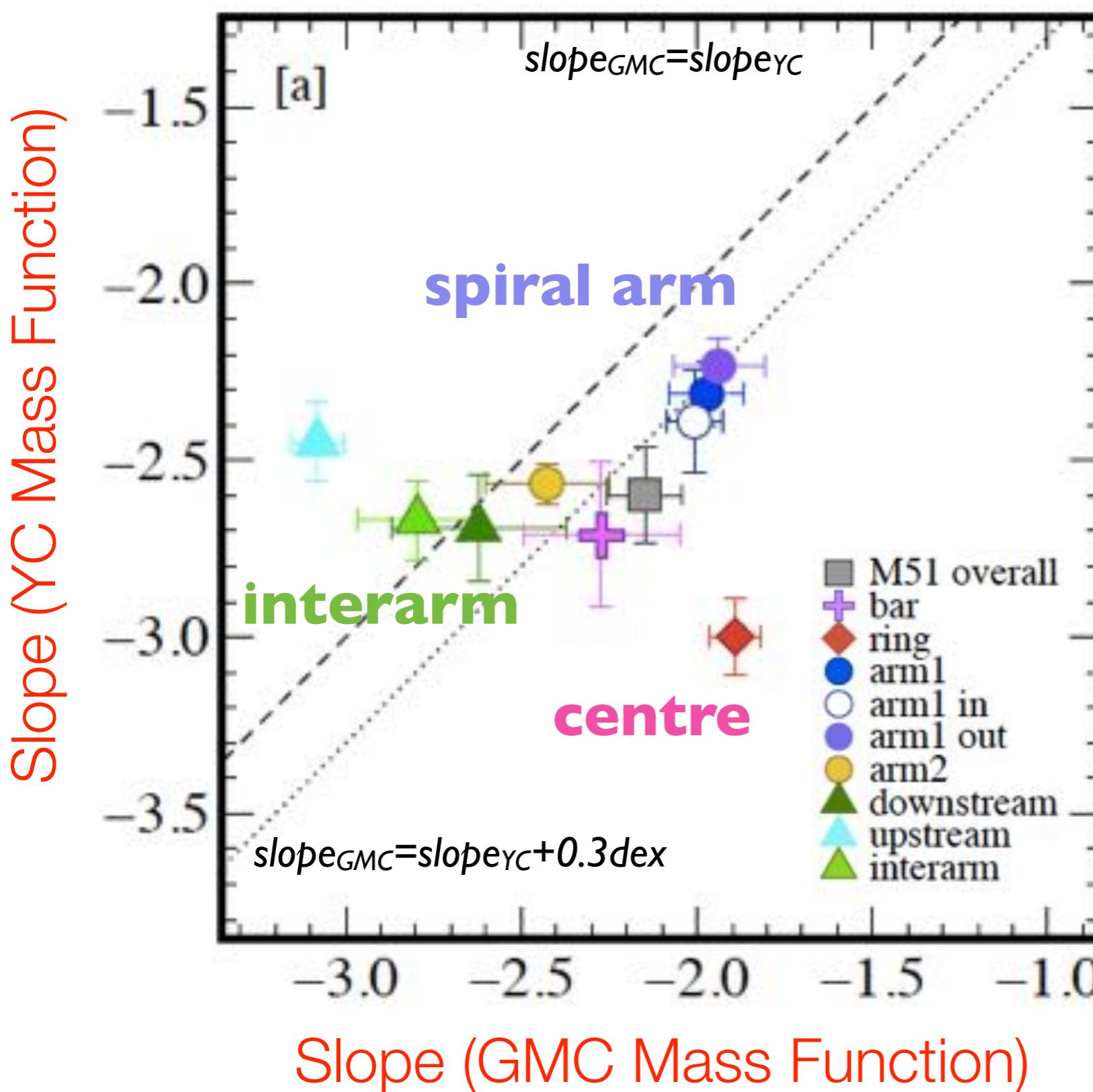
▲ interarm

▲ downstream

▲ upstream

GMCs and YC Mass Functions

Hughes et al (2013a)



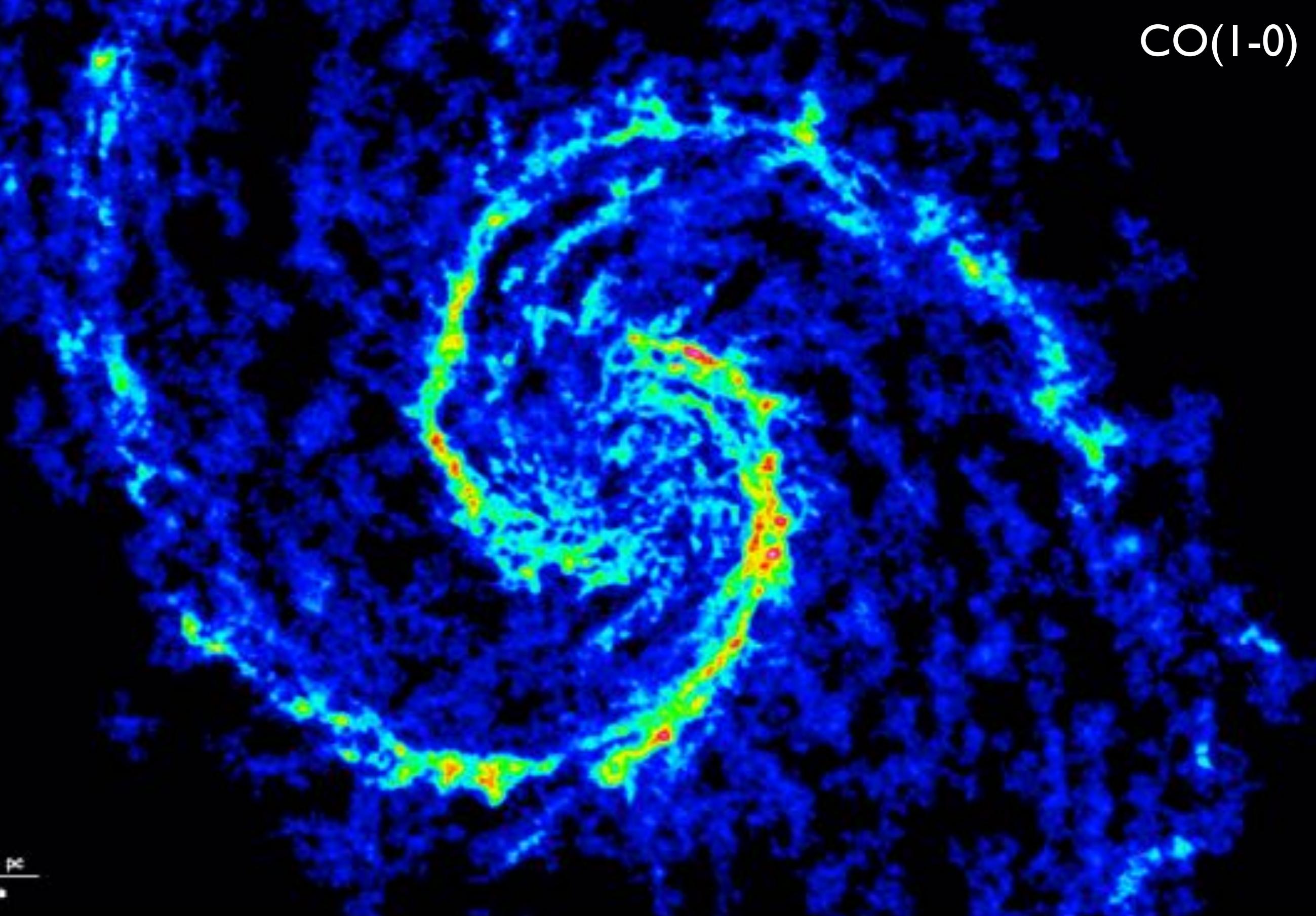
no universal relation
between MFs of
GMCs and YCs

→ diverse set of
formation & disruption
mechanisms that
depend on galactic
environment

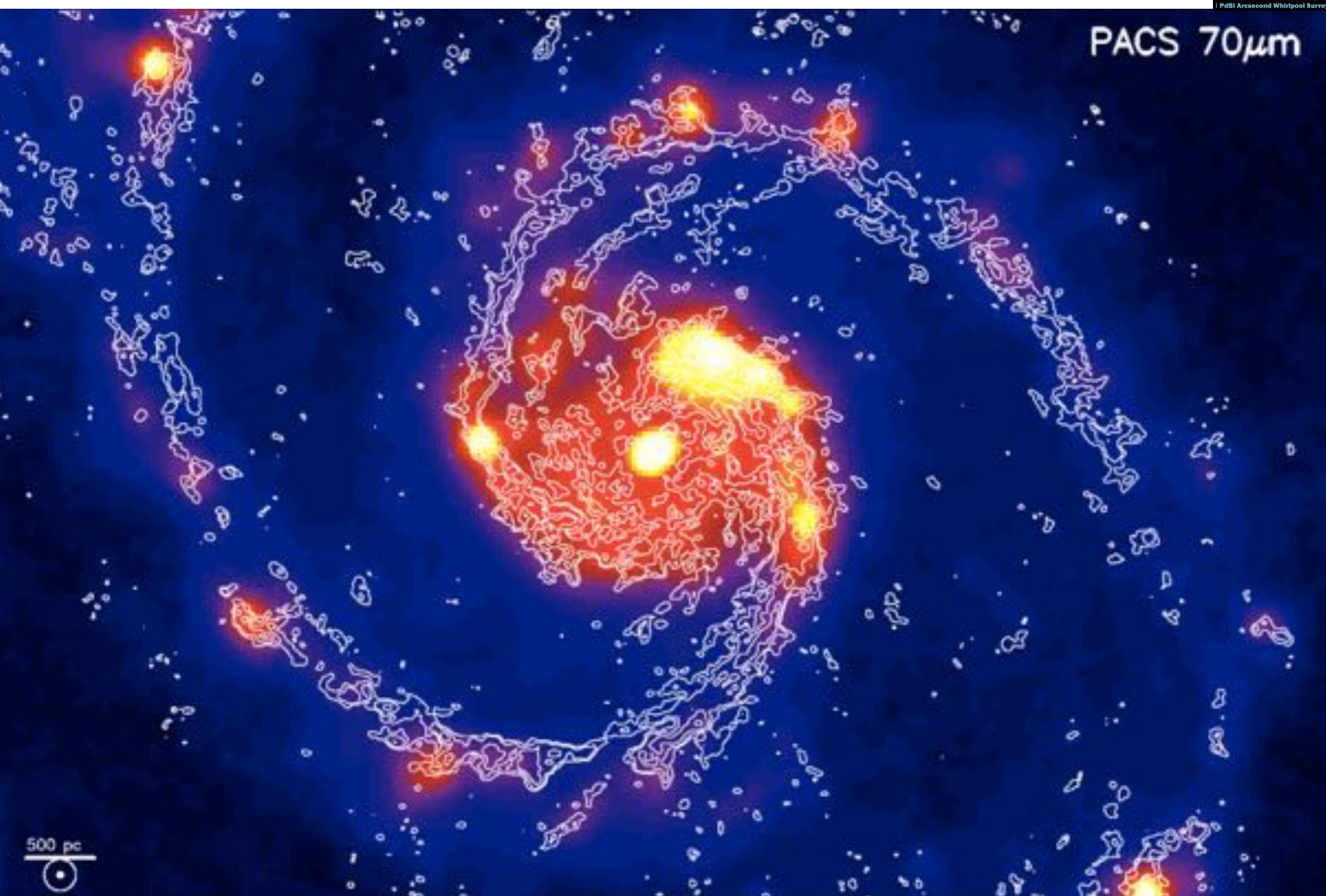
→ talk by Fouesneau

Relationship between CO and SF tracers in M51 is complex

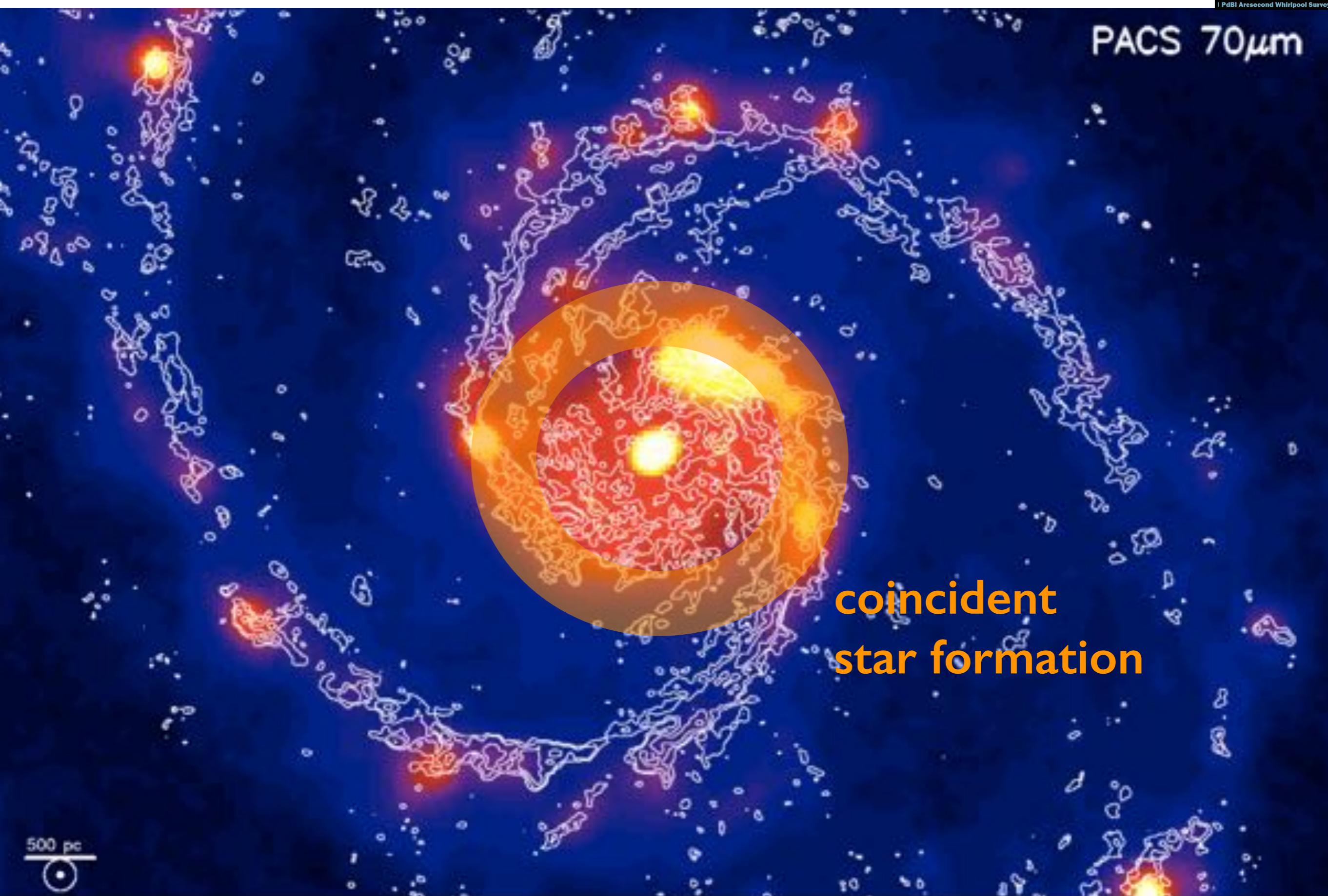
CO(1-0)



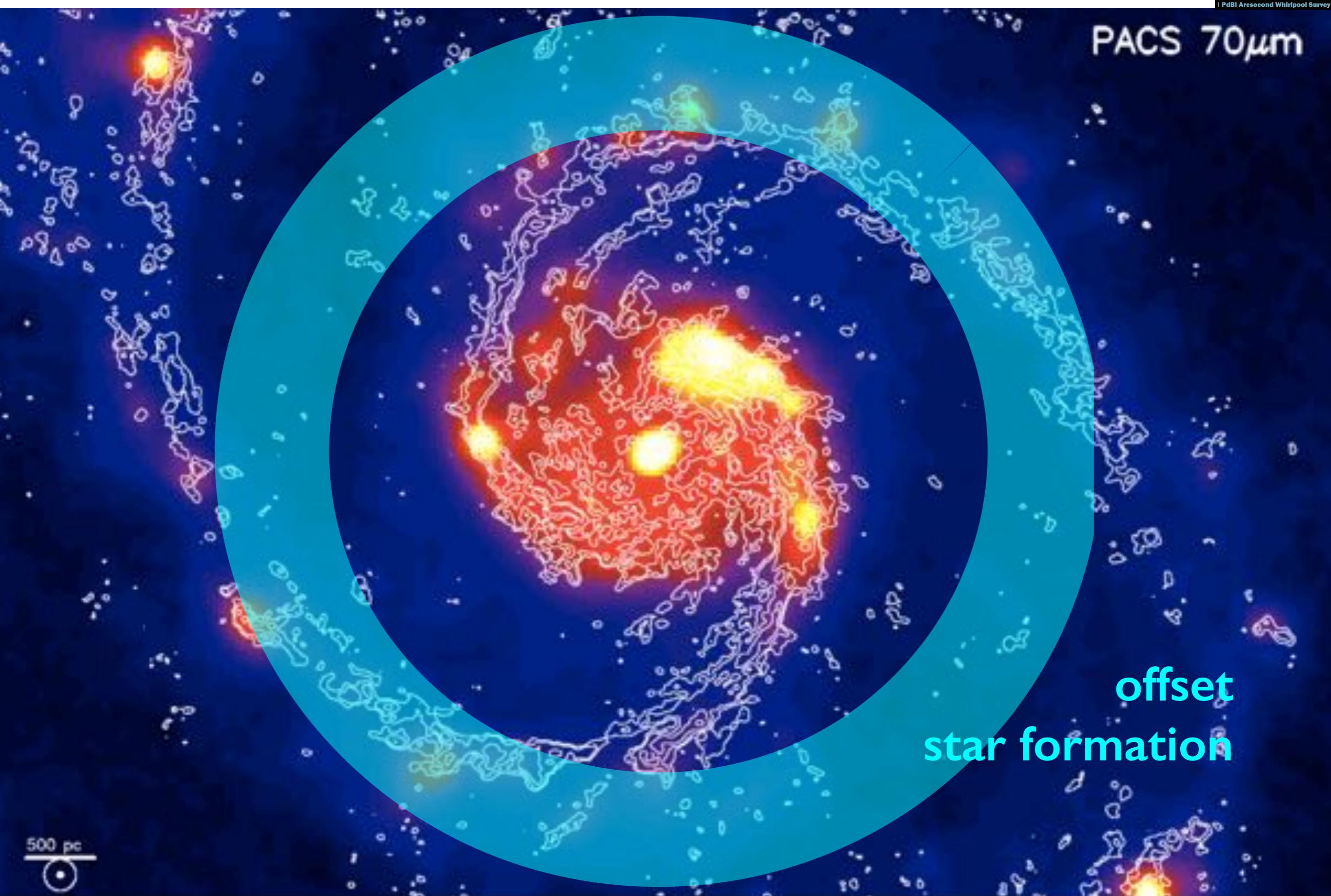
Relationship between CO and SF tracers in M51 is complex



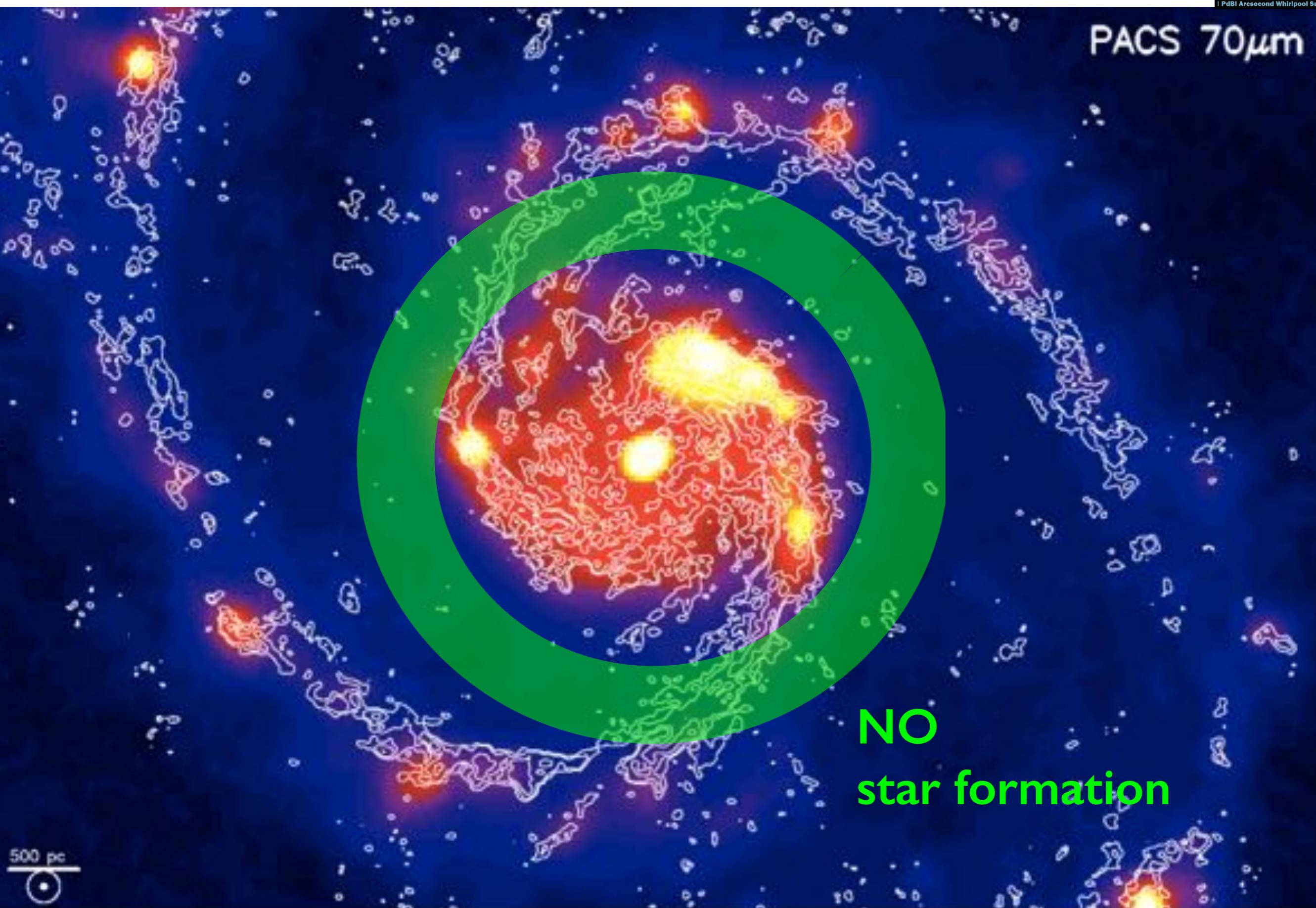
Relationship between CO and SF tracers in M51 is complex

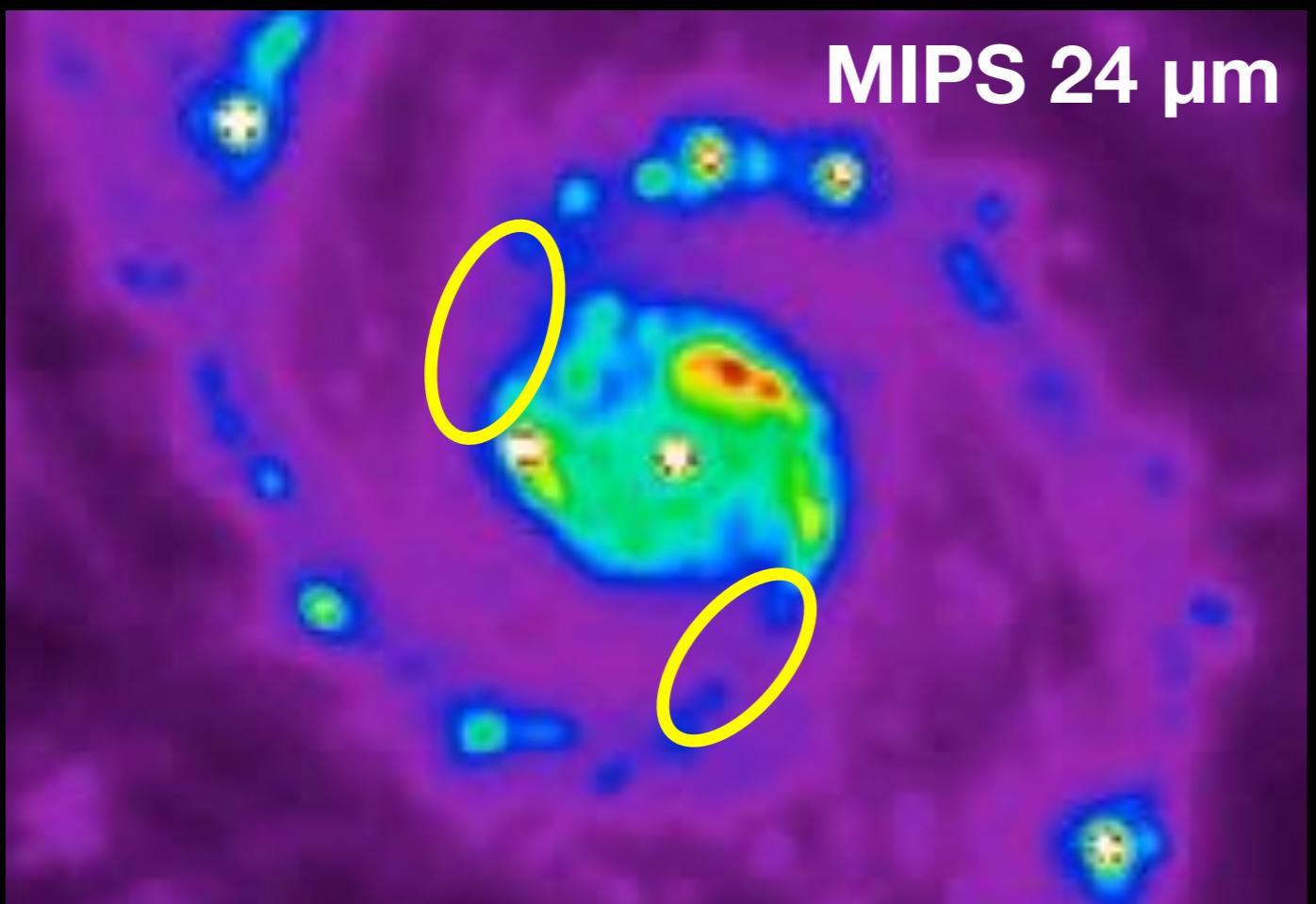


Relationship between CO and SF tracers in M51 is complex

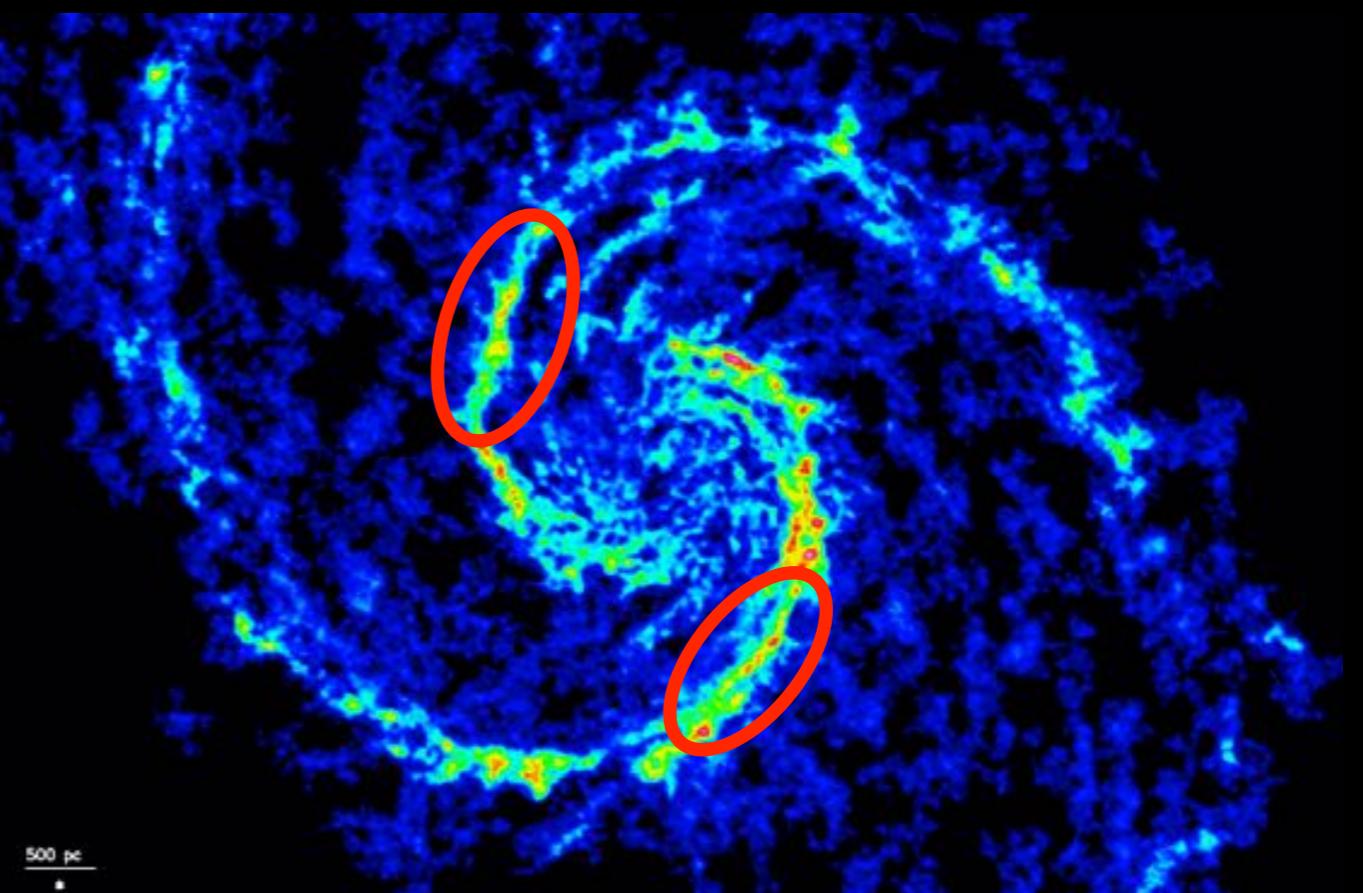


Relationship between CO and SF tracers in M51 is complex

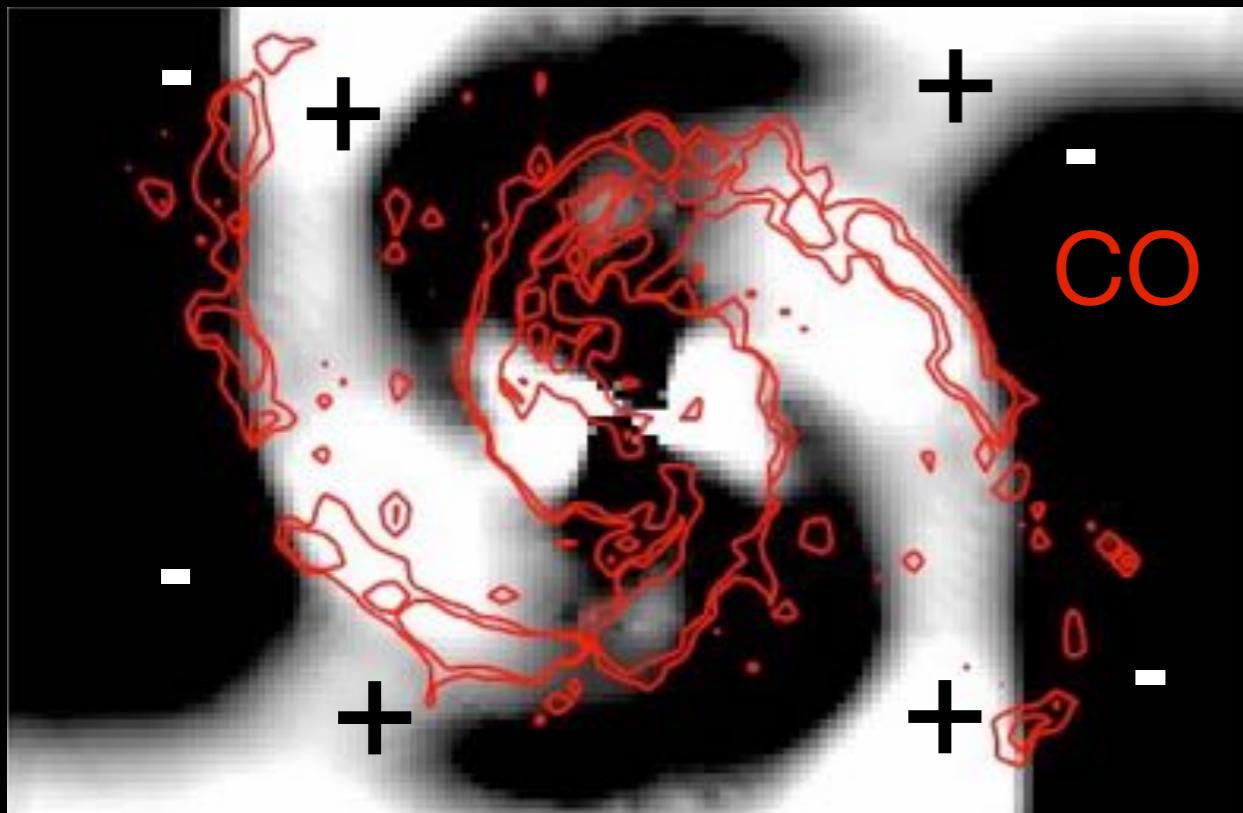




H₂ surface density is not a direct predictor of SFR surface density

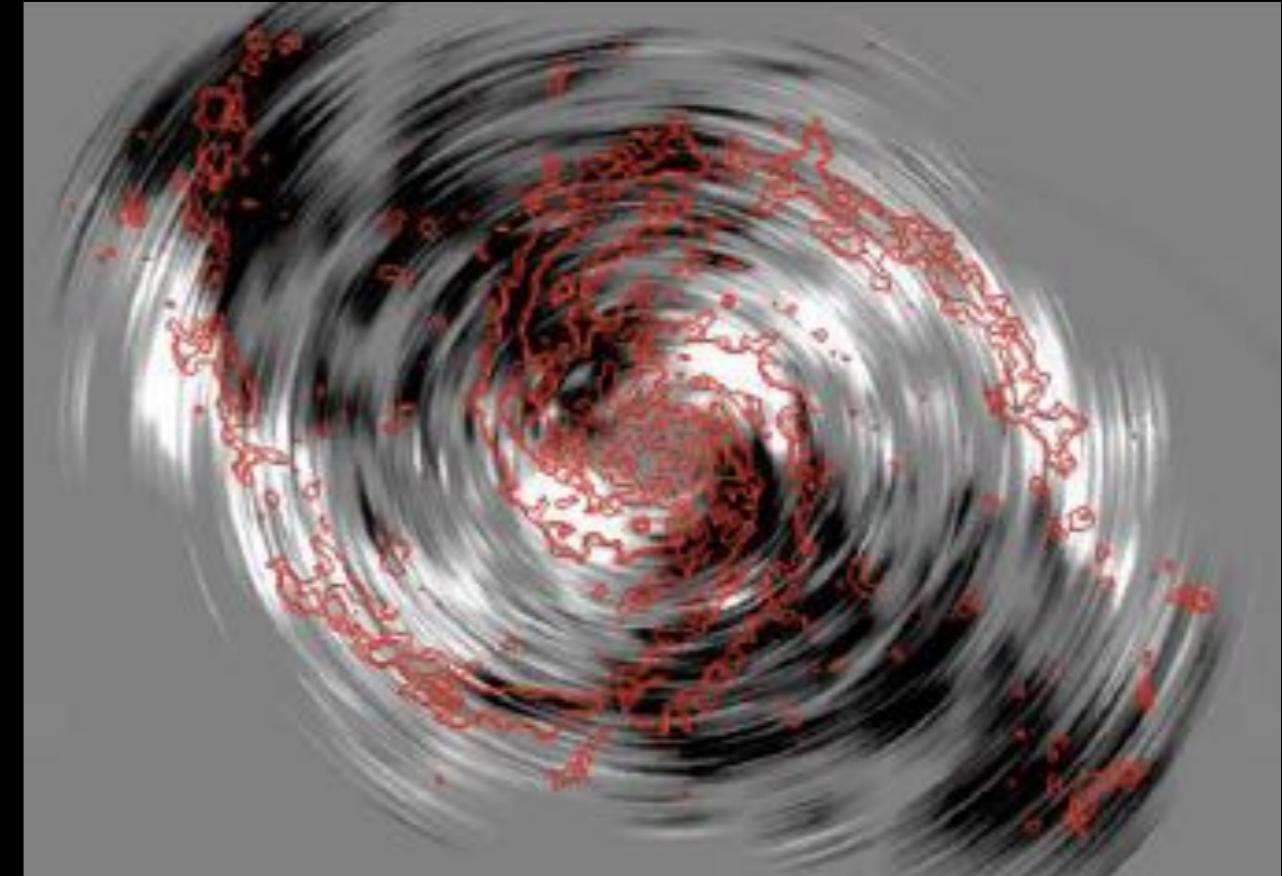


gravitational torques



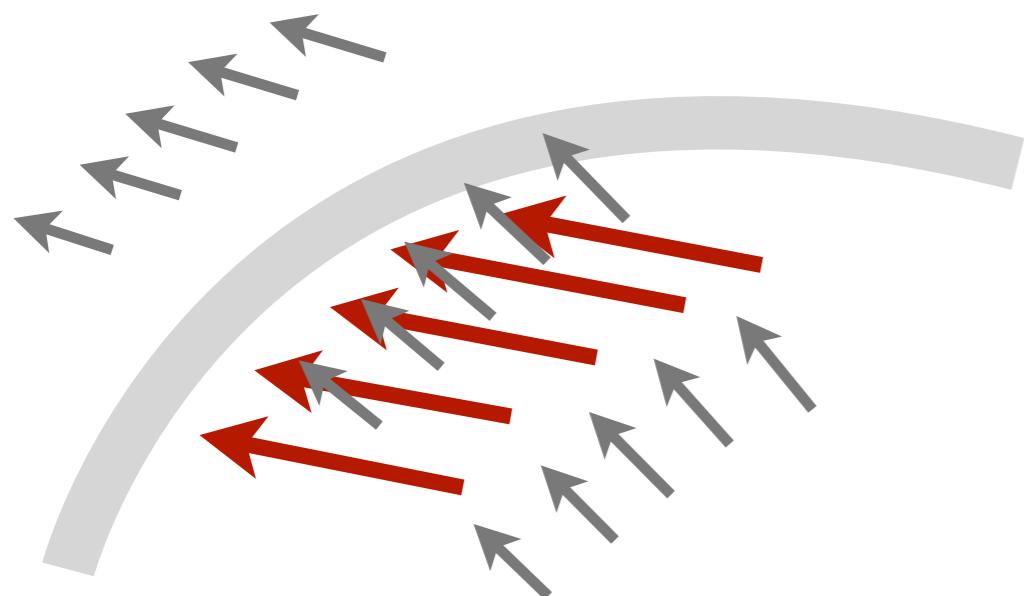
outflow
inflow

radial streaming motions



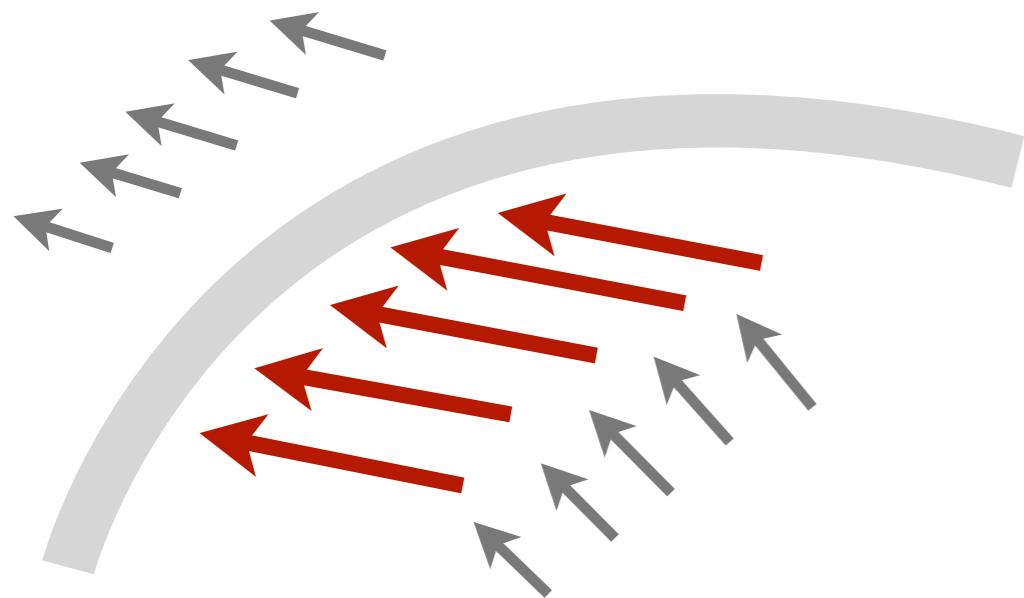
Gas motions introduces scatter in gas-SFR relation

Meidt et al (2013)

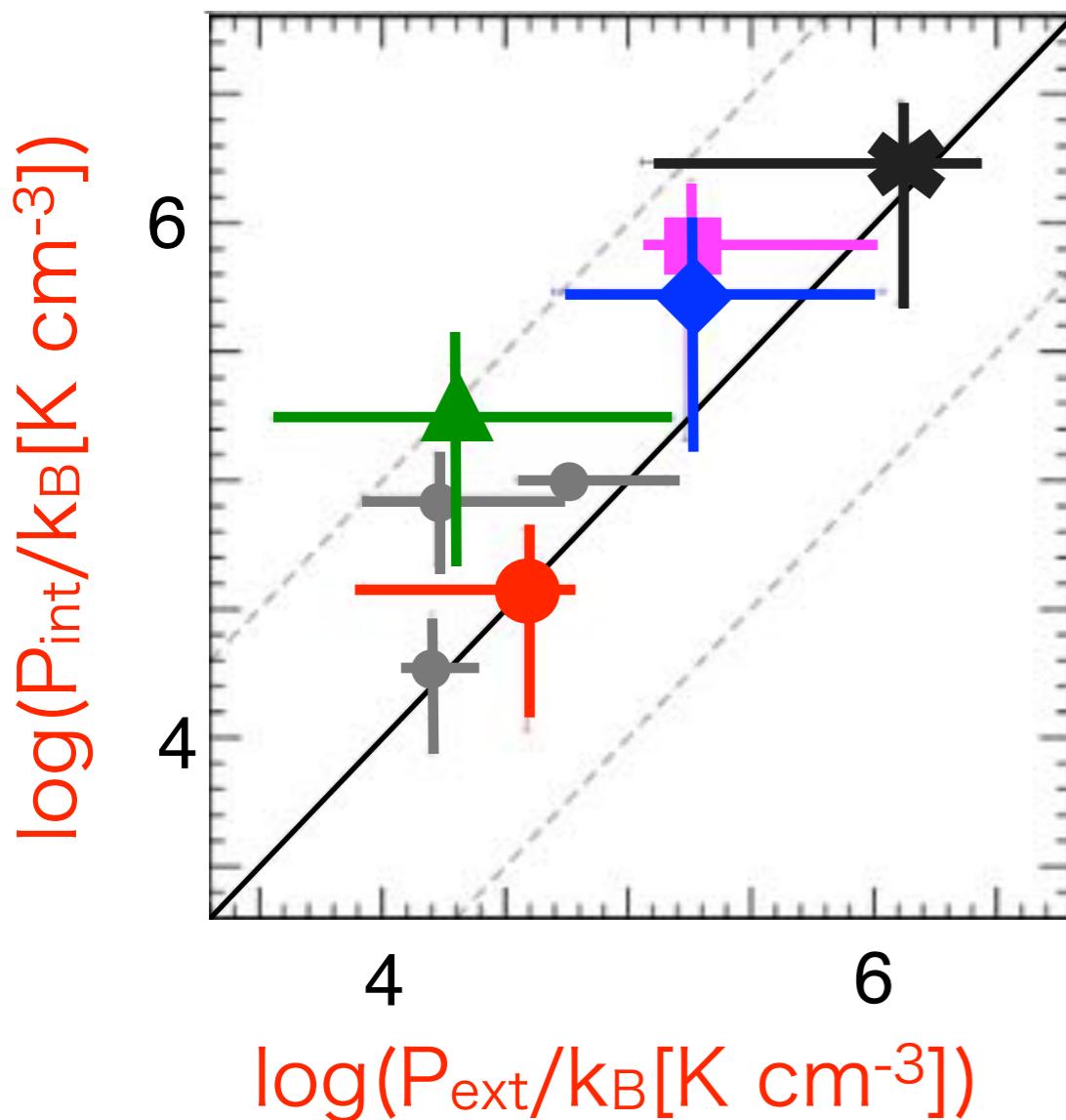
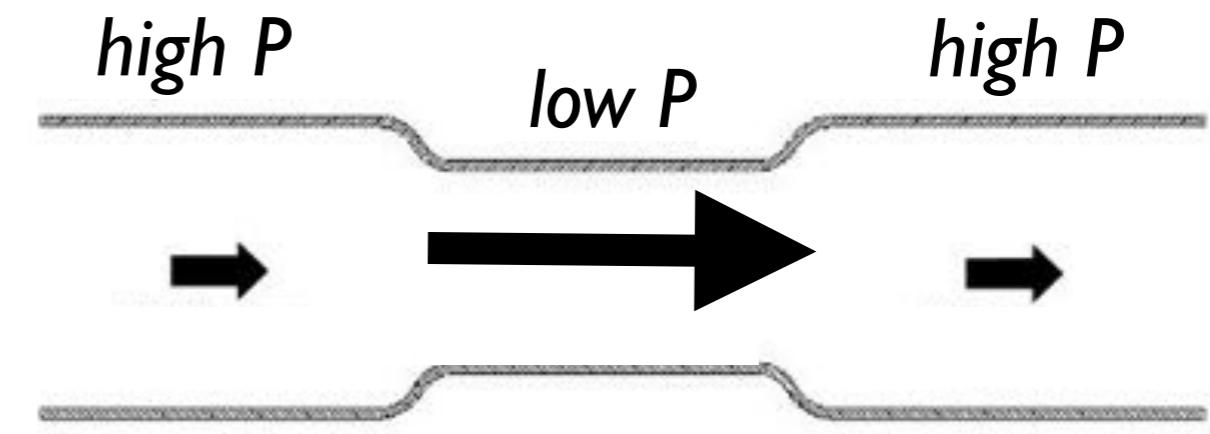


- disk structures drive gas flows
- gas flows increase cloud stability

Gas motions introduces scatter in gas-SFR relation



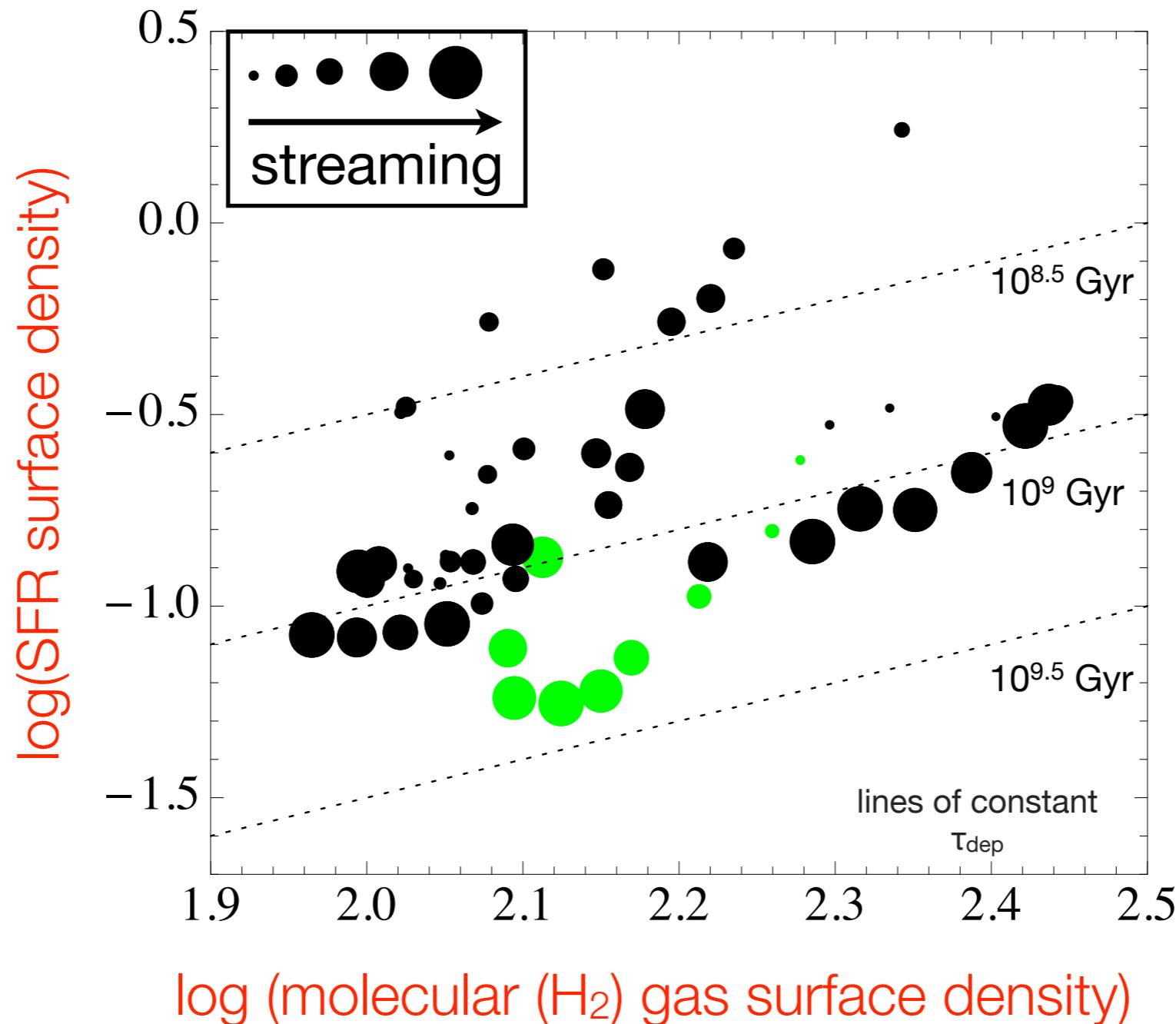
Meidt et al (2013)



- reduced pressure
- increase stable cloud mass
- reduced % of unstable clouds
- lower star formation rate
- increase in depletion time

Gas motions introduces scatter in gas-SFR relation

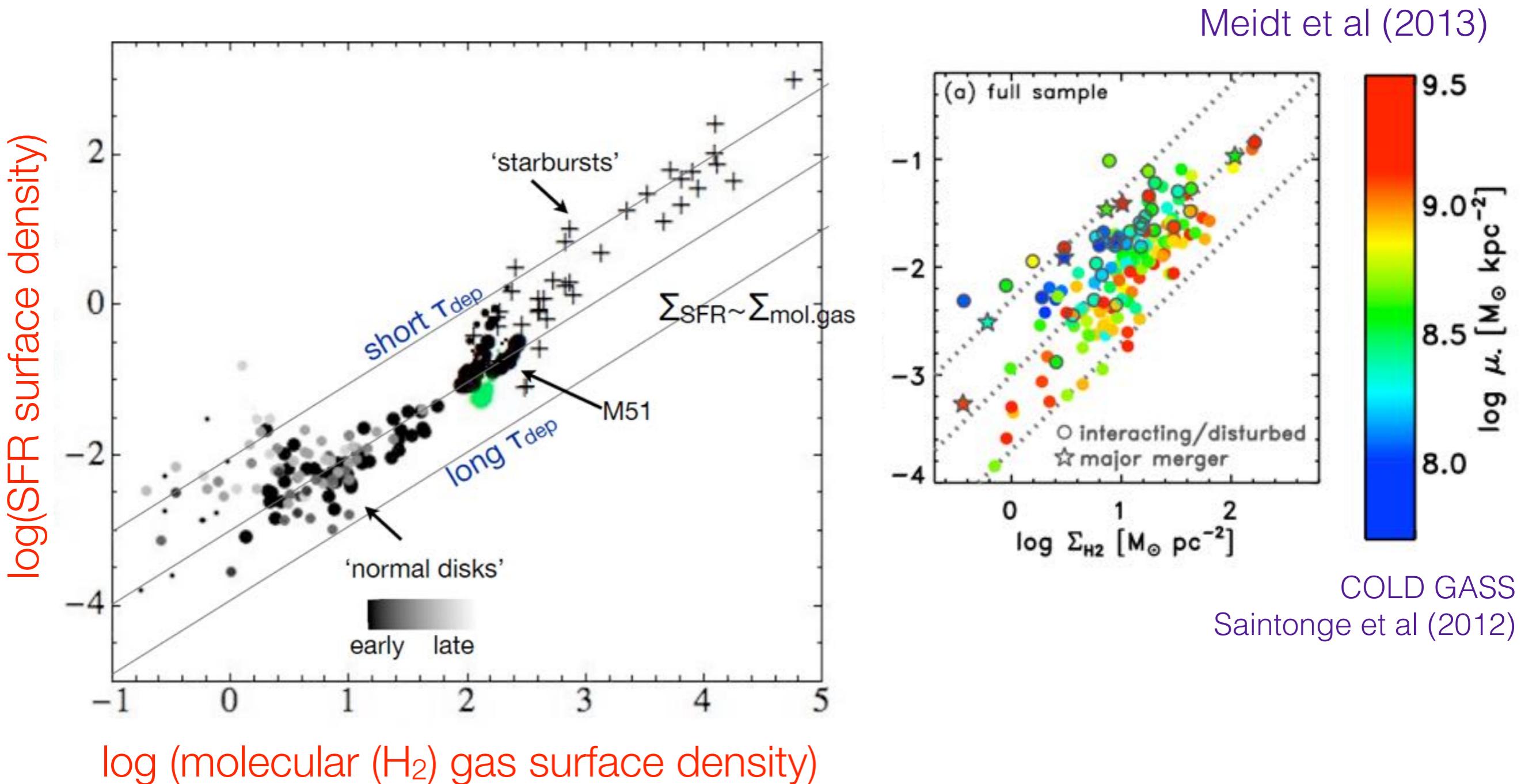
Meidt et al (2013)



➡ gas motions increase gas depletion time

➡ talk by Leroy

Gas motions introduces scatter in gas-SFR relation



ALMA can test this picture in other dynamical contexts:
other disk galaxies, barred galaxies, interacting systems etc.

Summary

1. Molecular gas distribution and kinematics
 2. Environmental variations in molecular gas properties
 3. A dynamical estimate for GMC lifetimes
 4. Conversion of GMCs to stars is complex
- galactic structure has a significant impact on both molecular gas properties and star formation activity
... ALMA will open up this research field