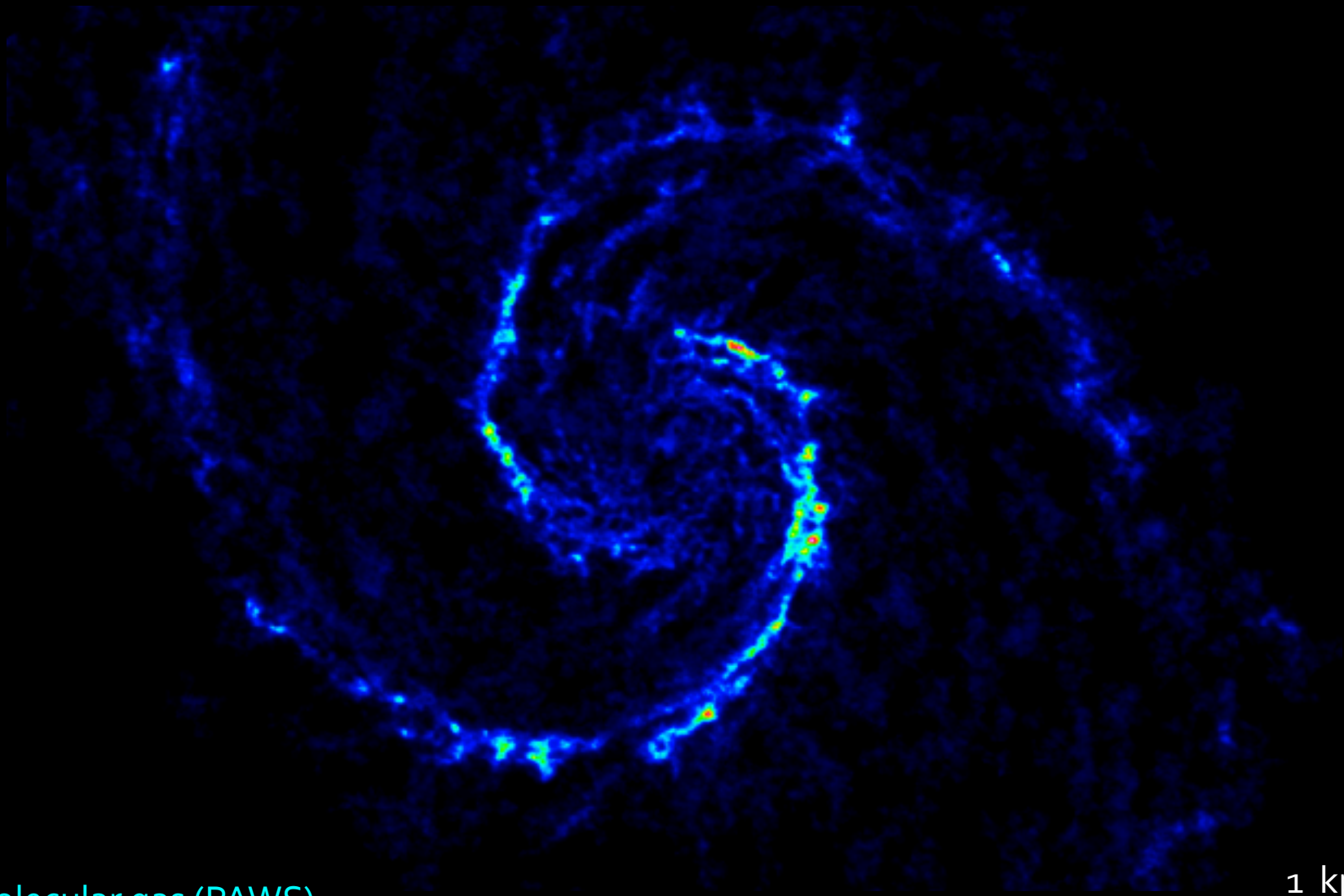
Molecular Gas and Star Formation at GMC Resolution
Lessons from PAWS

Eva Schinnerer

Max Planck Institute for Astronomy

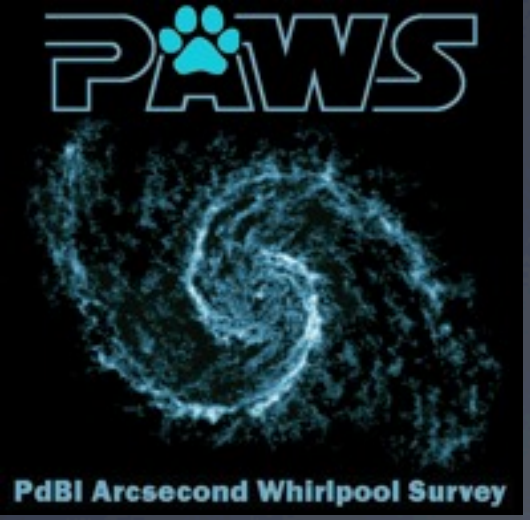
Molecular Gas and Star Formation at GMC Resolution
Lessons from PAWS



molecular gas (PAWS)

Eva Schinnerer

Max Planck Institute for Astronomy



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

IRAM

30m: 40 hr

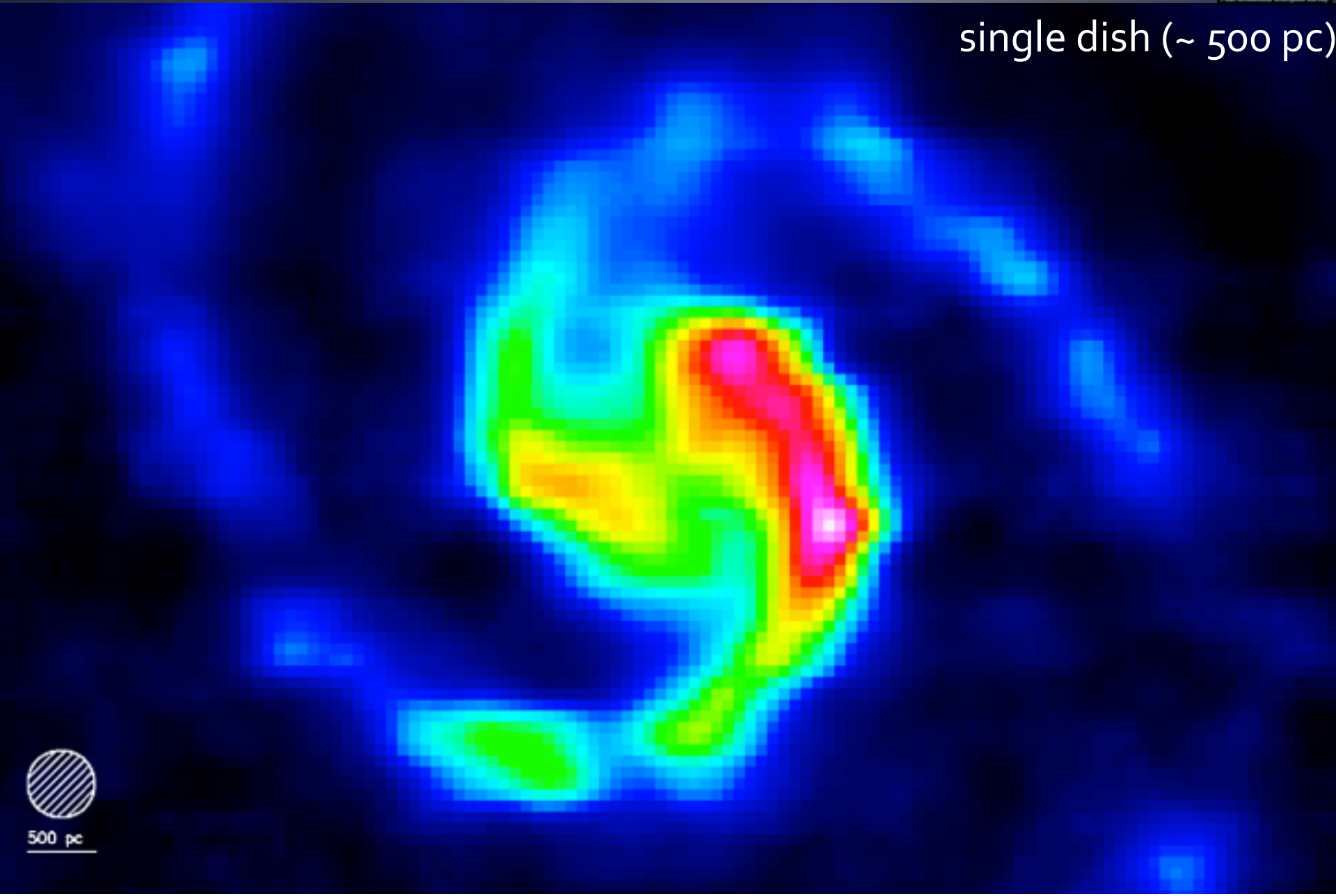
PdBI: 170 hr

Eva Schinnerer (PI)	MPIA
Annie Hughes	MPIA
Dario Colombo	MPIA
Sharon Meidt	MPIA
Adam Leroy	NRAO
Jerome Pety	IRAM
Gaelle Dumas	IRAM
Karl Schuster	IRAM
Clare Dobbs	U. Exeter
Todd Thompson	OSU
Santiago Garcia-Burillo	OAN
Carsten Kramer	IRAM

9kpc

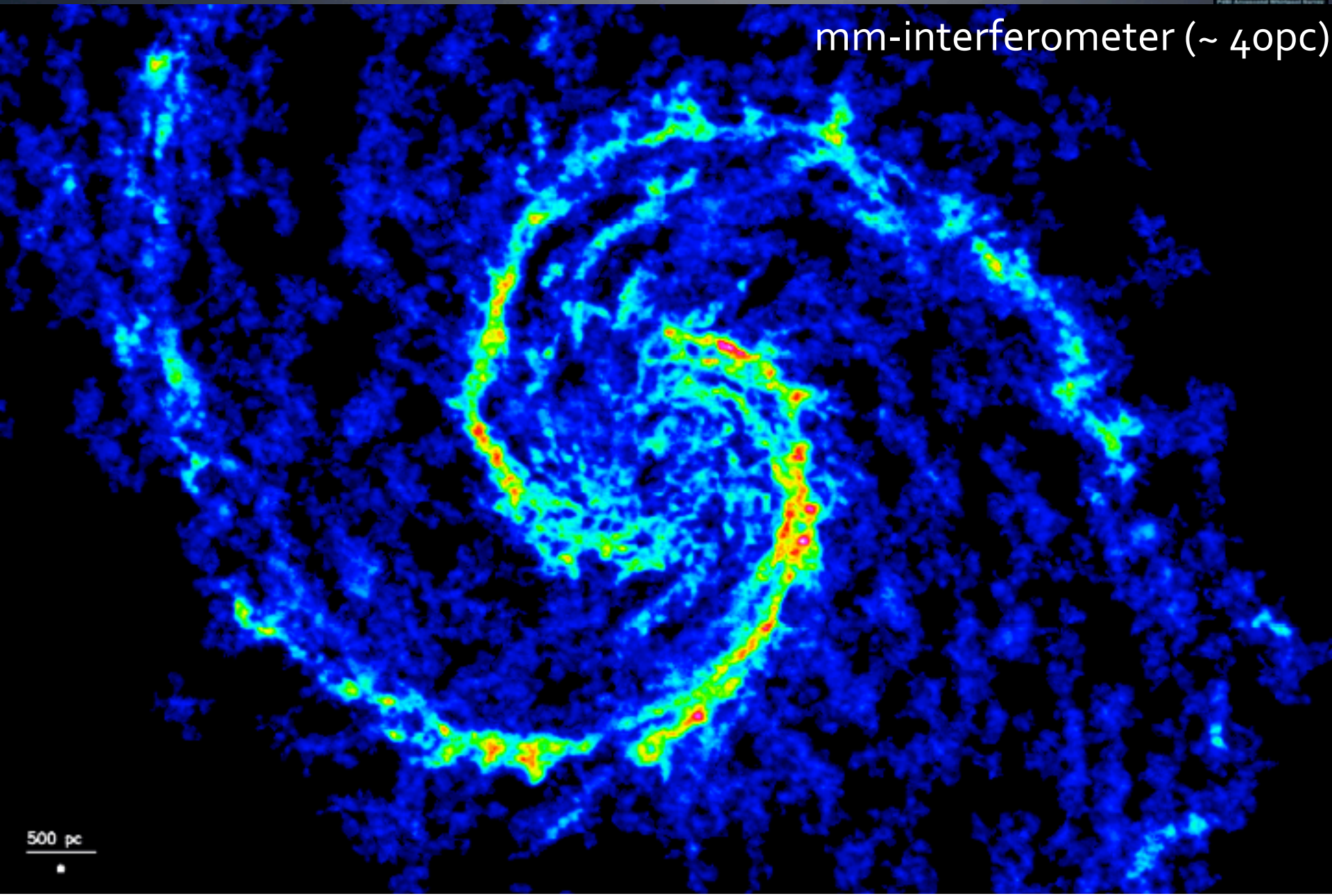
Molecular Gas Disk of M51

Schuster et al. (2007)



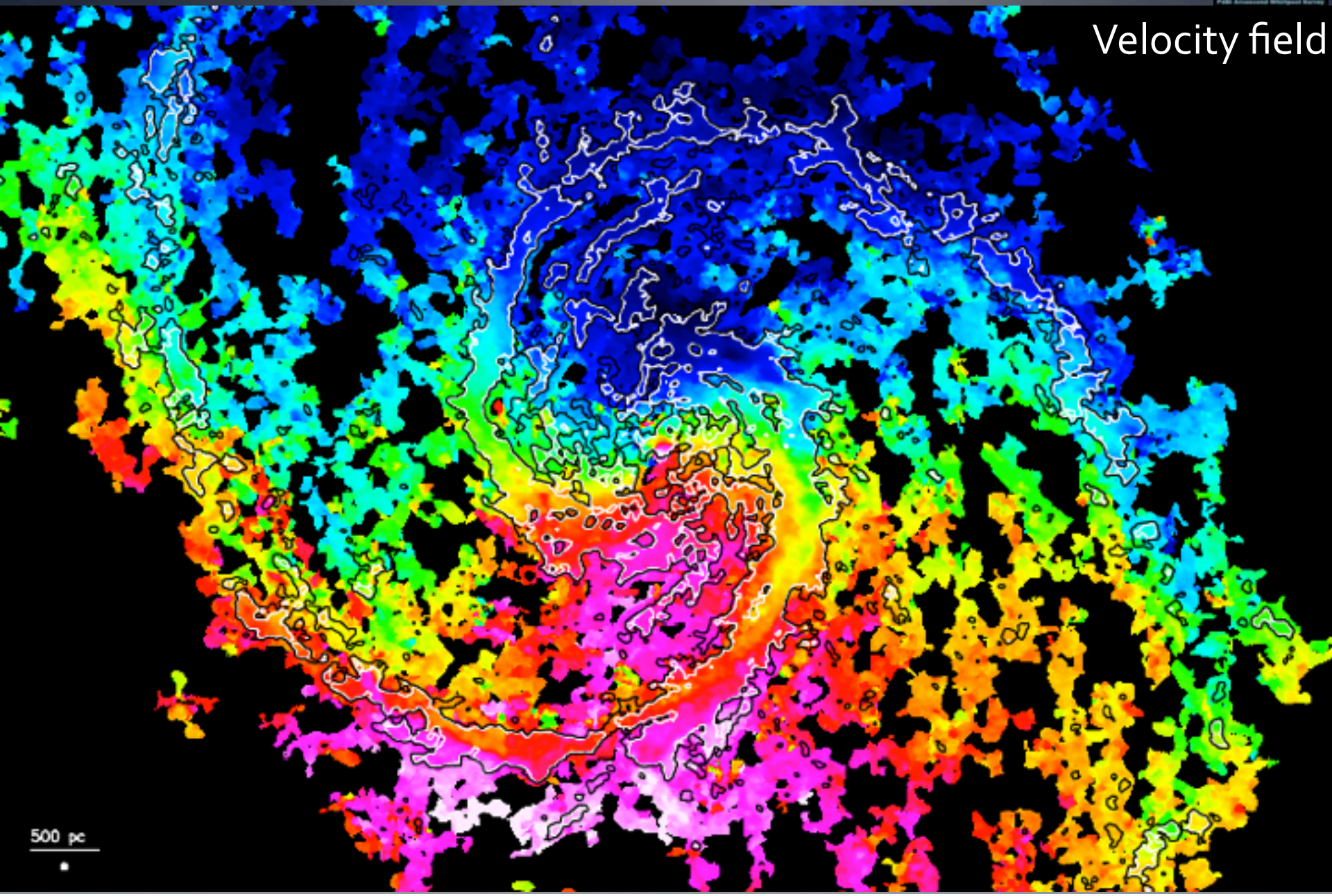
Molecular Gas Disk of M51

Schinnerer et al. (in prep.)



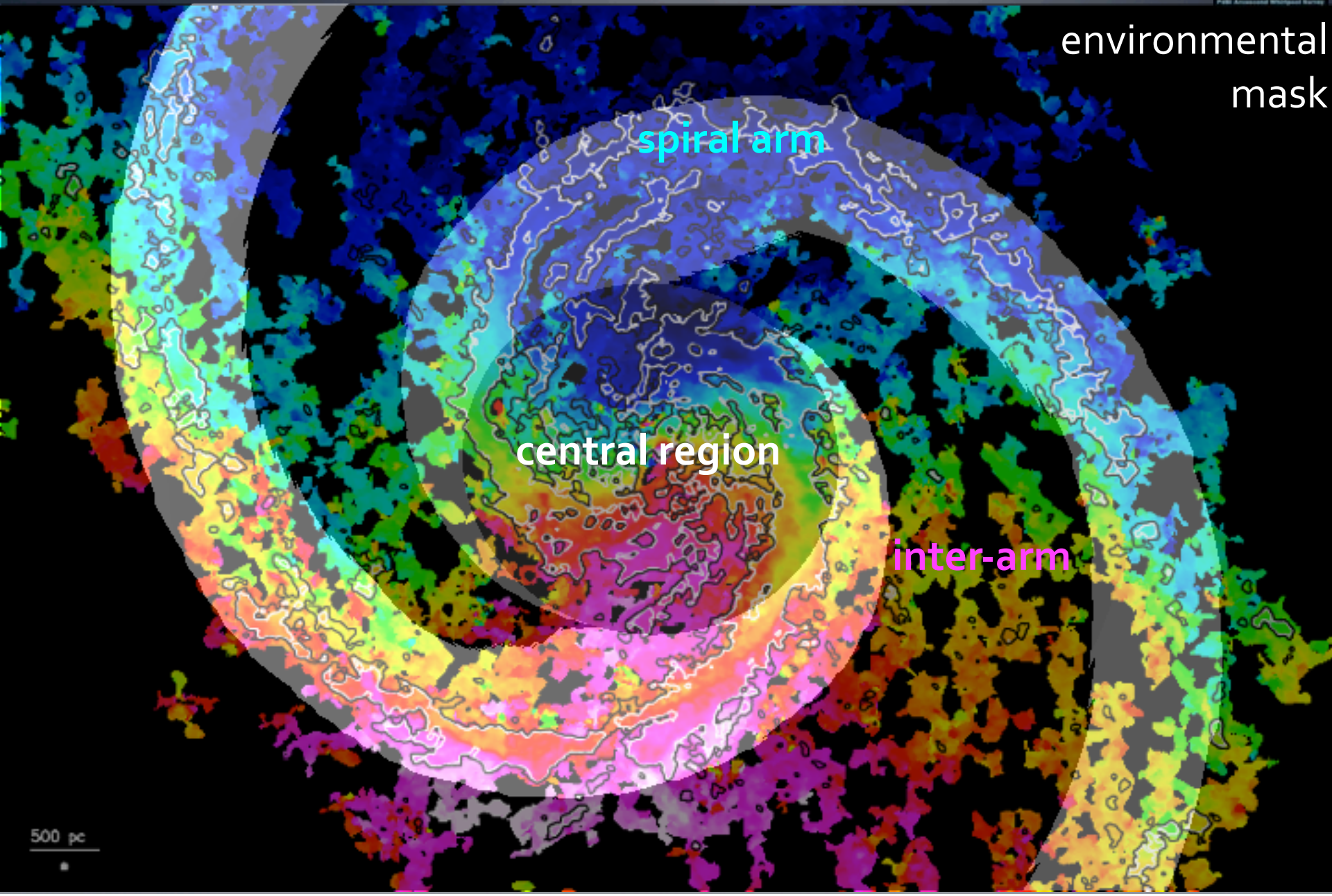
Molecular Gas disk of M51

Colombo et al. (in prep.)



Molecular Gas disk of M51

Colombo et al. (in prep.)



3 Paradigms on Giant Molecular Clouds

1. most of the molecular gas resides in GMCs
2. GMC properties are universal across environments/galaxies
3. massive star formation and GMCs are closely associated

Most Molecular Gas Resides in GMCs

Galactic single dish studies in CO line(s)

(Sanders et al. 1985)

85% of molecular gas (in R < 2 kpc) in GMCs (i.e. discrete structures) with

H_2 mass > 10^5 M_{sun}

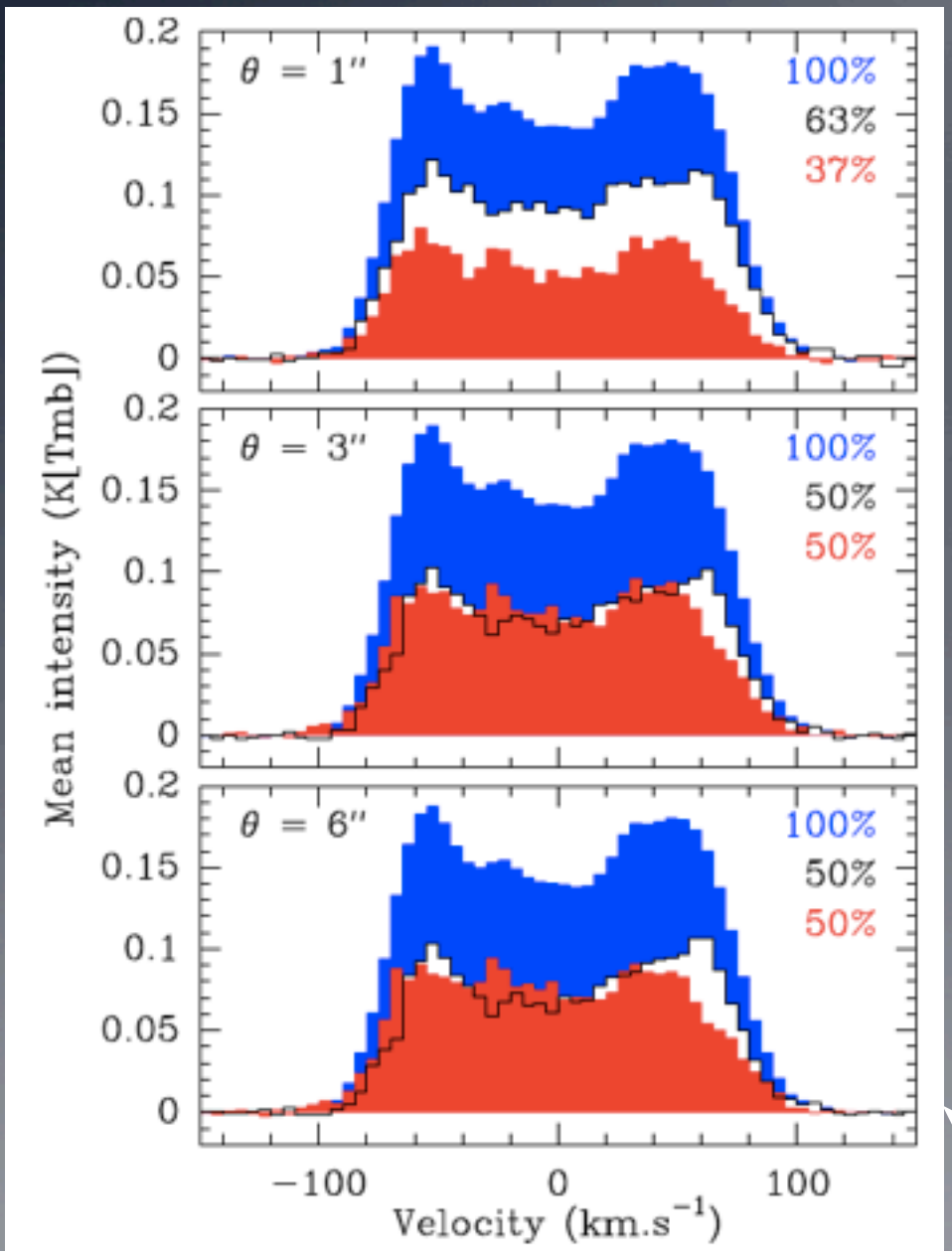
size > 22 pc

(Casoli et al. 1984, Dame et al. 1986)

But: see recent paper by Sawada et al. (2012)

Resolved Emission in Molecular Gas Disk

Pety et al. (in prep.)



brightness sensitivity

Integrated spectrum:

PdBI+30m

PdBI-only

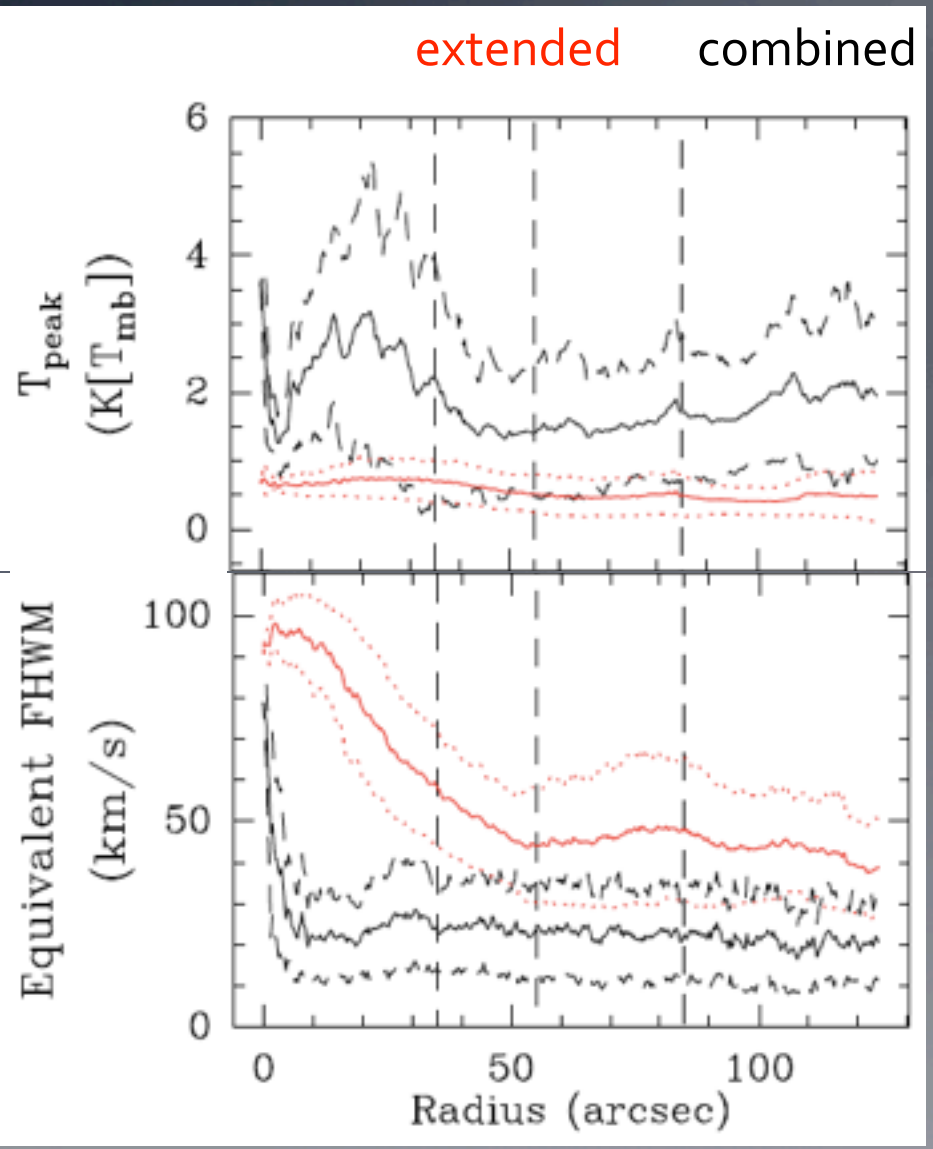
'missing flux'

~ 50% of emission is resolved

w/ typical size of >20", i.e. 750pc

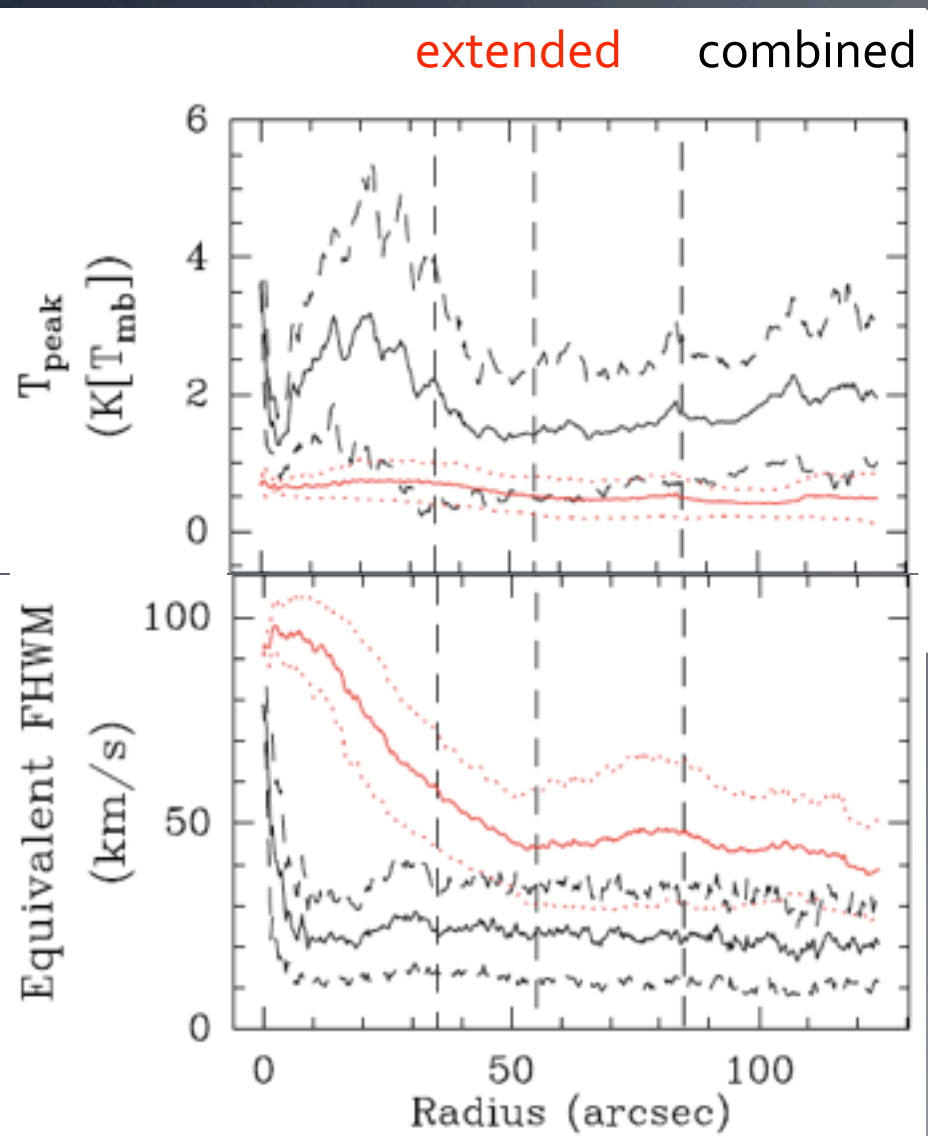
Extra-planar Molecular Gas Disk

Pety et al. (in prep.)

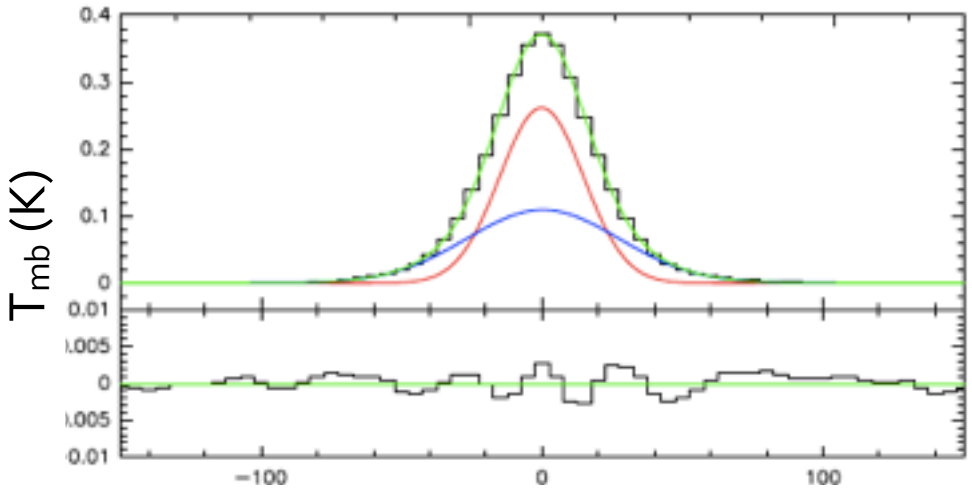


Extra-planar Molecular Gas Disk

Pety et al. (in prep.)



stacked 30m spectrum



properties of diffuse component:

dynamically hot

--> extra-planar gas

Extra-planar Molecular Gas Disk

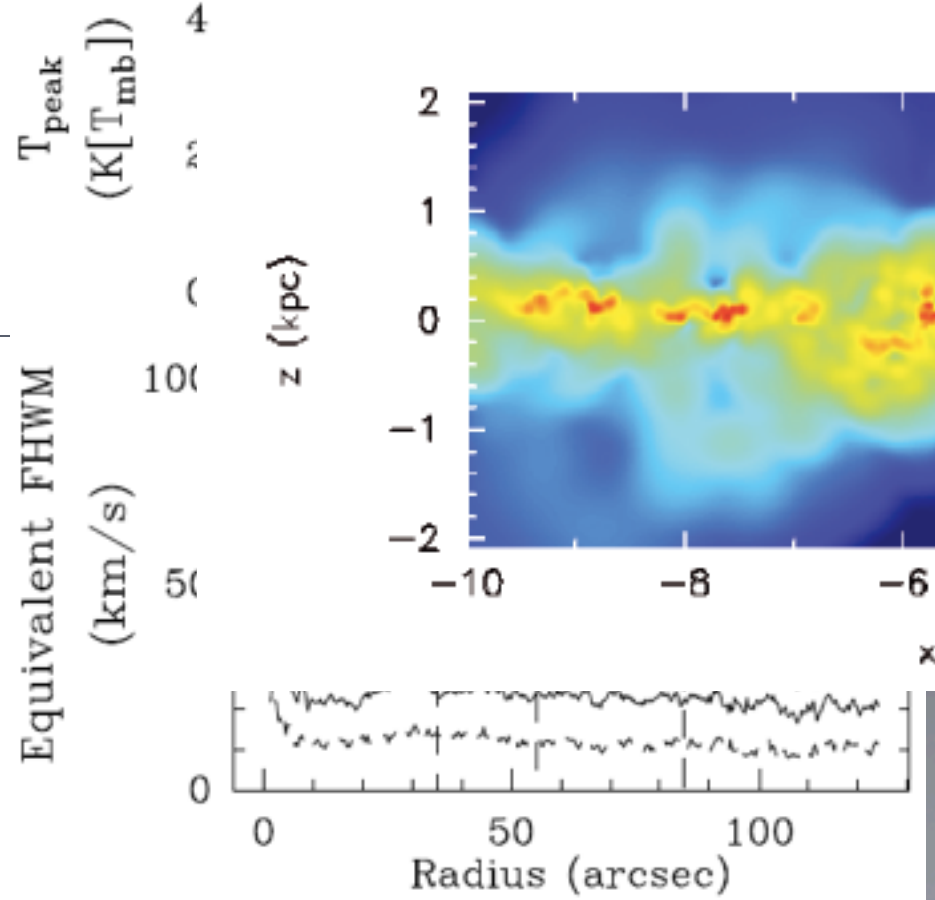
Pety et al. (in prep.)

extended combined

stacked 30m spectrum

Dense gas expelled from cold disk by stellar feed-back?

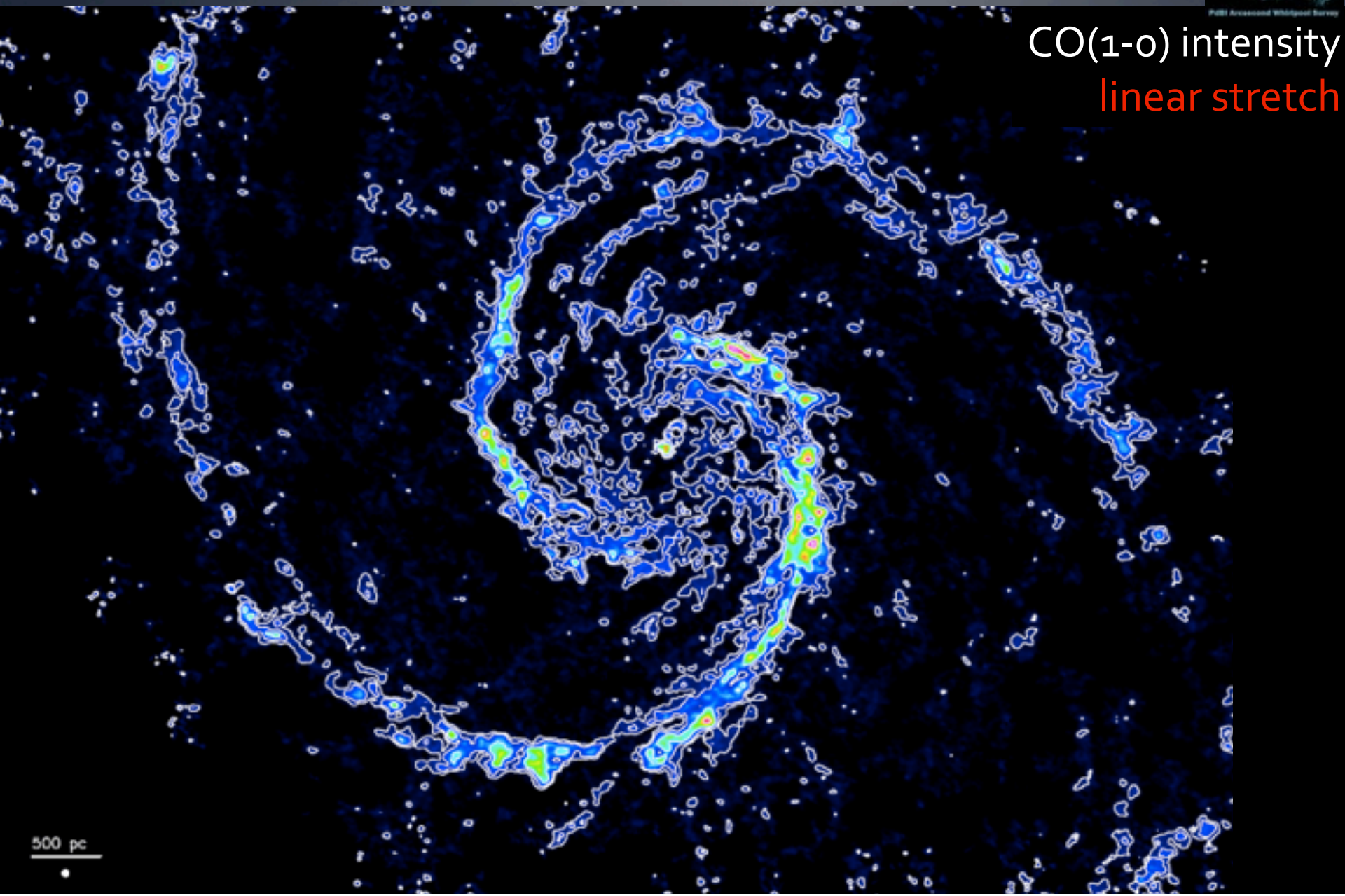
(Dobbs, Burkert, Pringle 2011)



dynamically hot

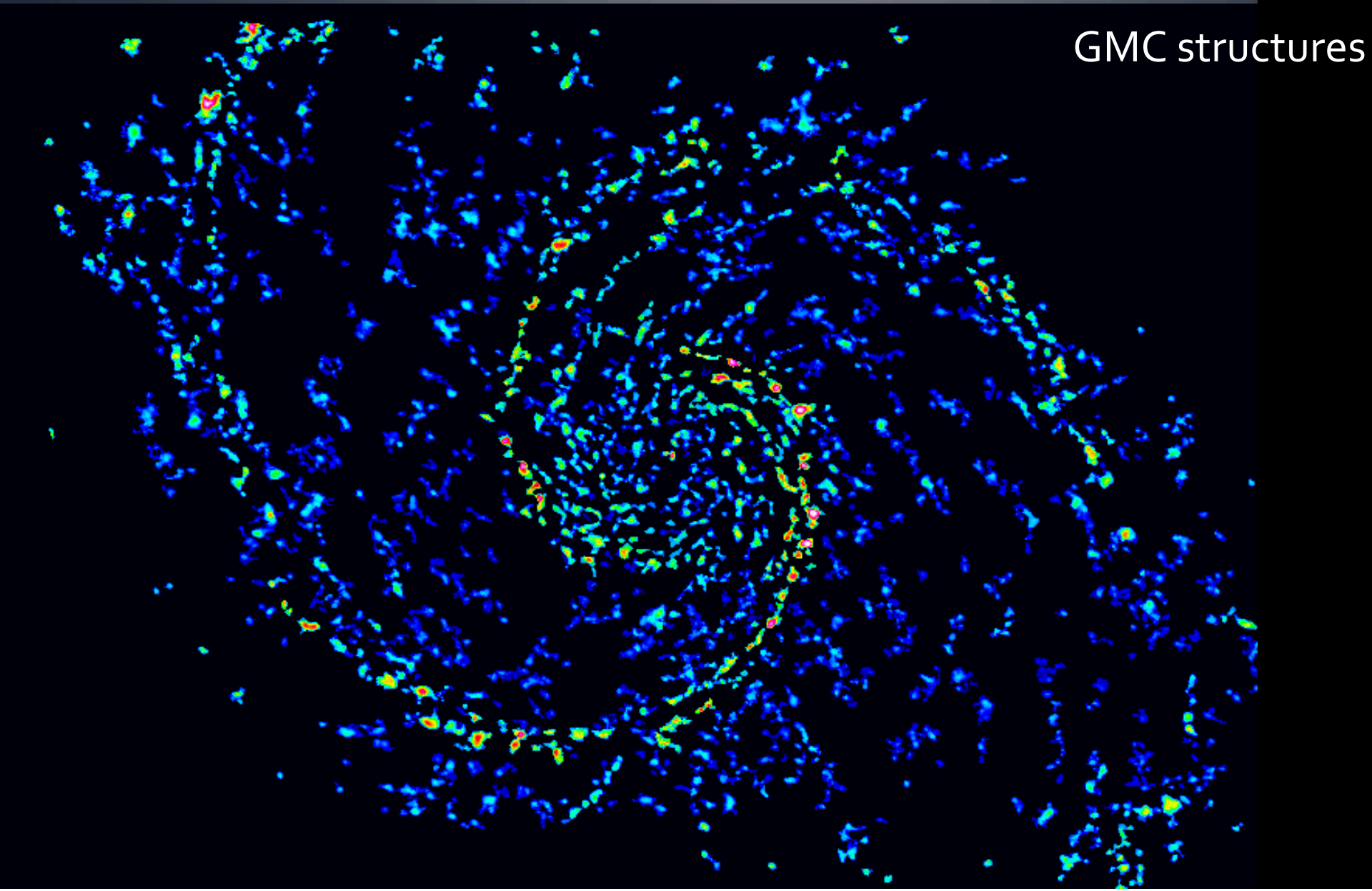
--> extra-planar gas

GMC Fraction in Molecular Gas Disk



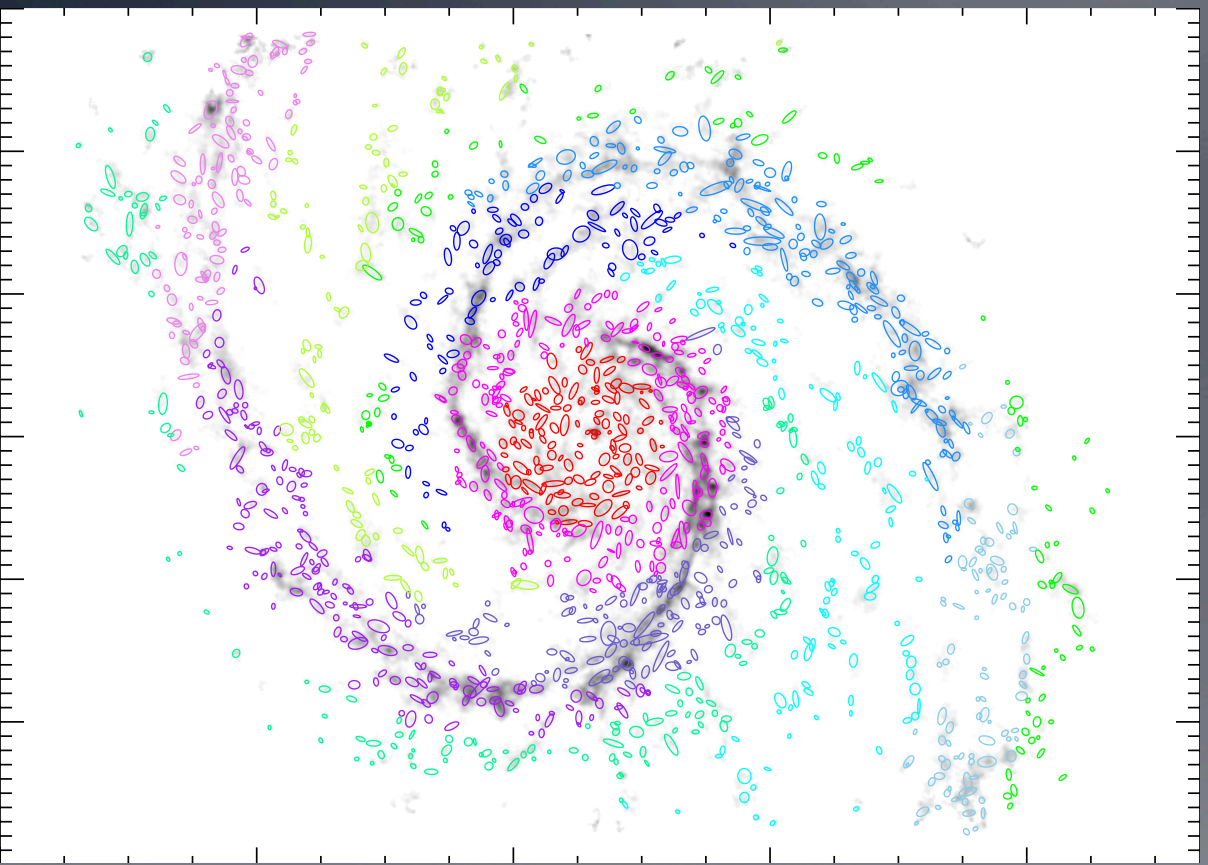
GMC Fraction in Molecular Gas Disk

Colombo et al. (in prep.)



GMC Fraction in Molecular Gas Disk

Colombo et al. (in prep.)



~55% of emission is in GMCs,
i.e. discrete structures

GMC statistics:

1,507 GMCs identified
~ 55% of total CO flux
= $M(H_2)$ ~ $2 \times 10^9 M_{sun}$

distribution:

center	23%
inter-arm	29%
spiral arms	48%

fraction of flux contained:

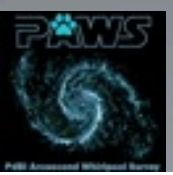
center	55%
inter-arm	40%
spiral arms	60%

3 Paradigms on Giant Molecular Clouds

1. most of the molecular gas resides in GMCs
   ➔ Only about 50%

2. **GMC properties are universal across environments/galaxies**

3. massive star formation and GMCs are closely associated

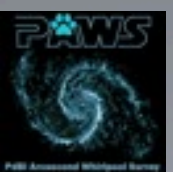


3 Paradigms on Giant Molecular Clouds

1. most of the molecular gas resides in GMCs
   ➔ Only about 50%

2. **GMC properties are universal across environments/galaxies**

3. massive star formation and GMCs are closely associated



GMCs properties are universal I. MW

Milky Way view (late 1980's):

(e.g. Larson 1981, Solomon et al. 1987)

1. $\sigma_v \sim R^{0.5}$

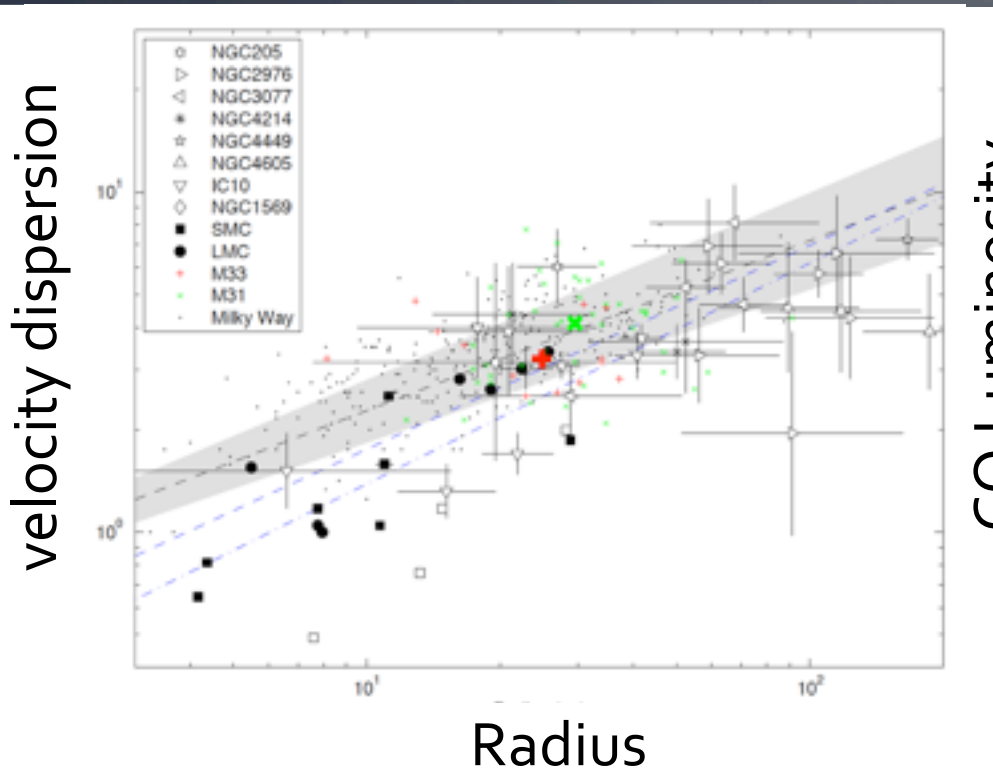
2. virial equilibrium : $M \propto R\ \sigma_v^2$

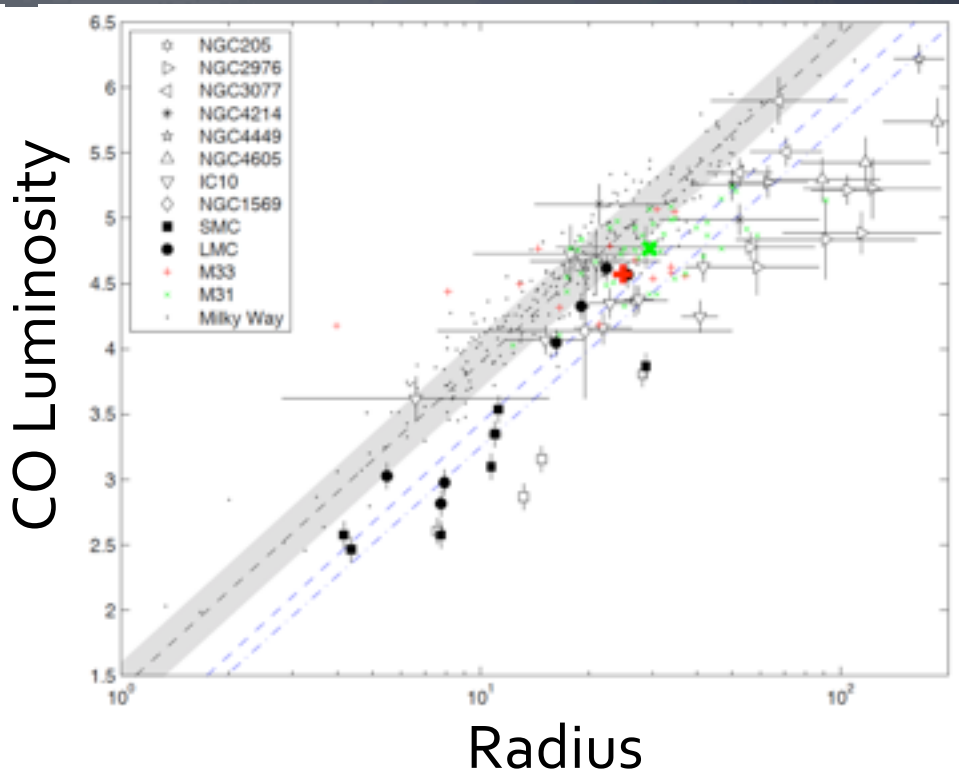
3. constant surface density: ~ 100 M_{sun}/pc^2

GMCs properties are universal II. Local Group

Consistent study of 12 nearby galaxies

(Bolatto et al. 2008)

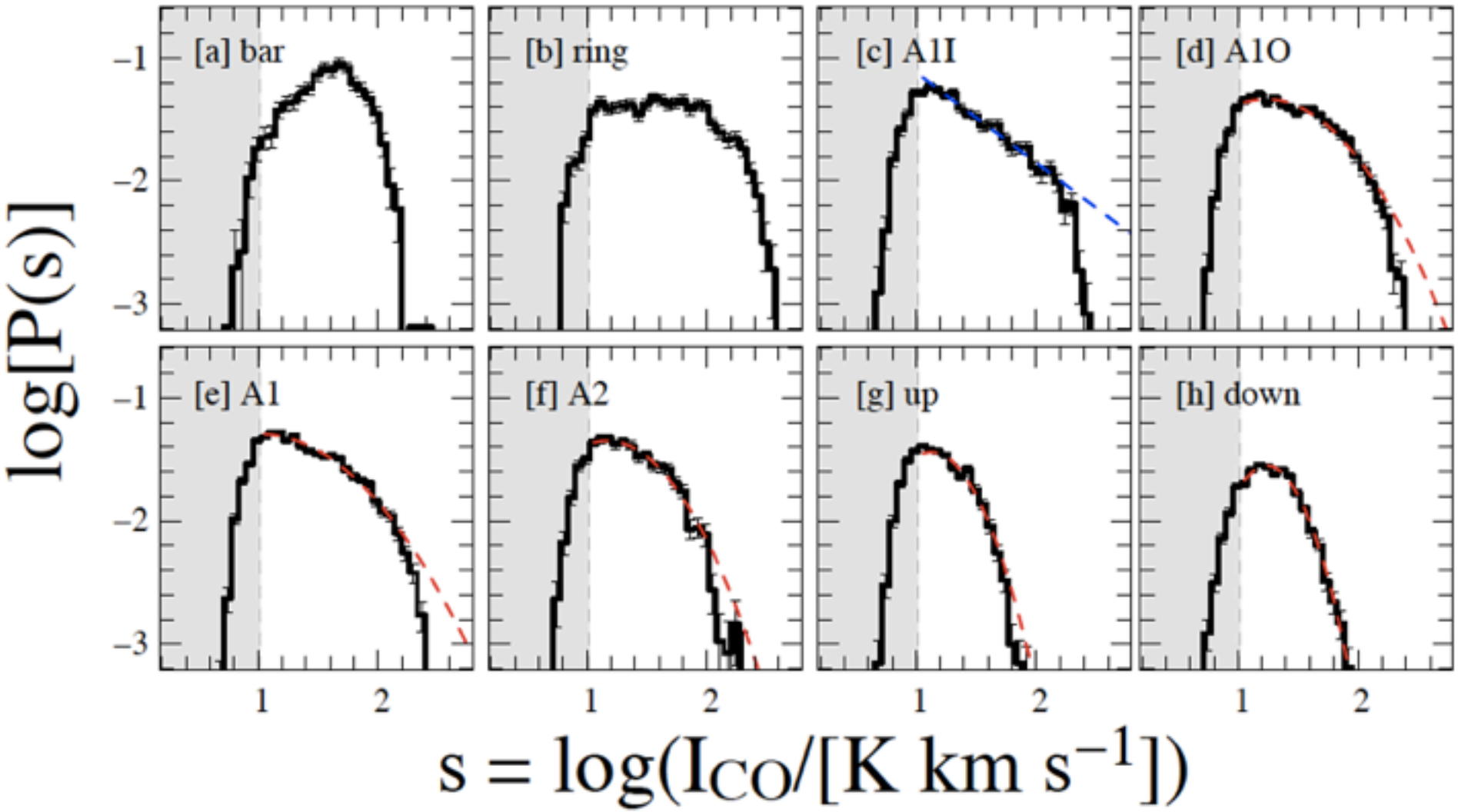




GMC properties are universal across galaxies

GMC Properties I. Galactic Environment

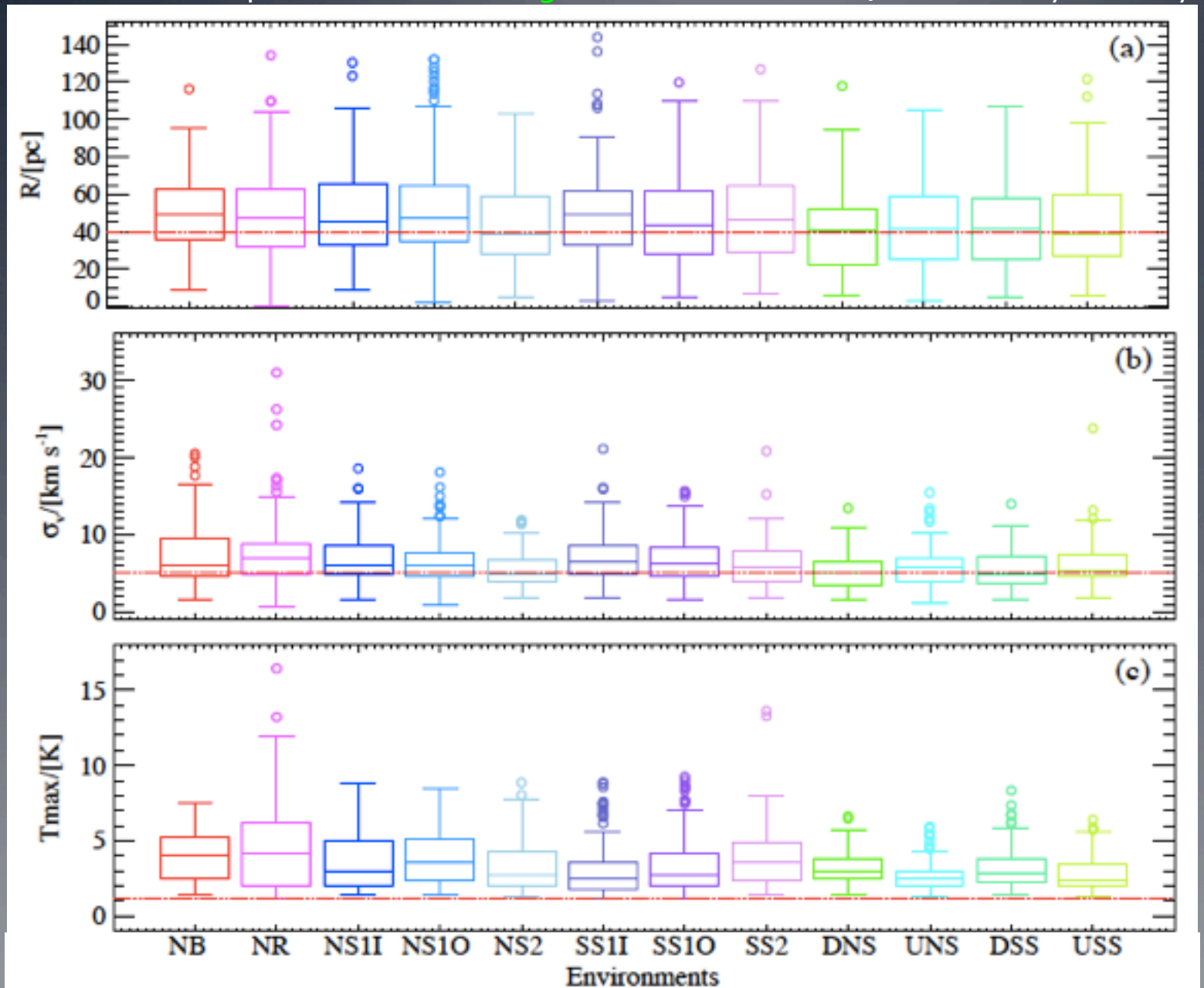
PDF - Probability Distribution Function **(see poster by A. Hughes)**



Hughes et al. (in prep.)

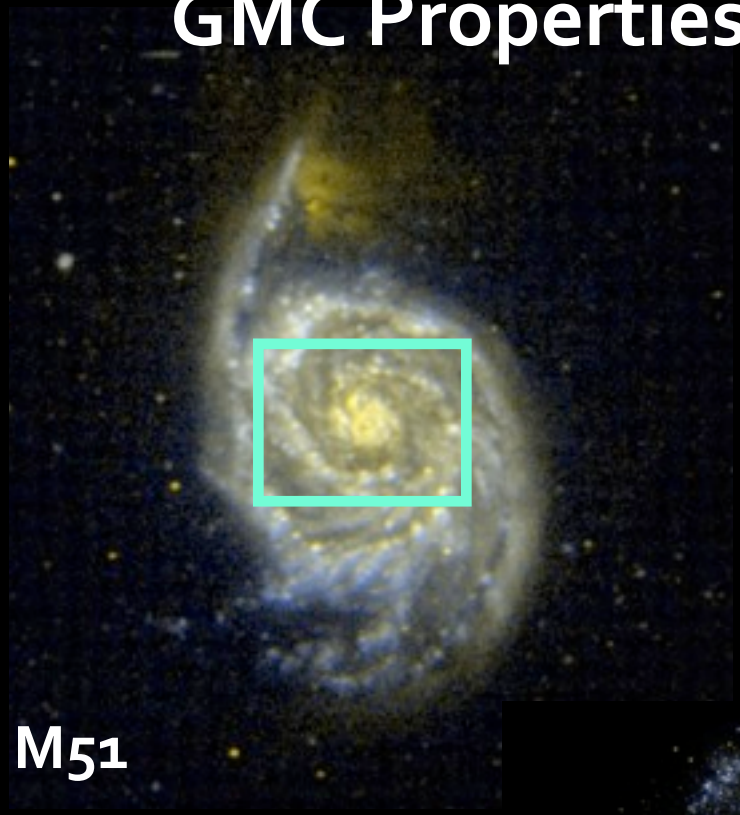
GMC Properties I. Galactic Environment

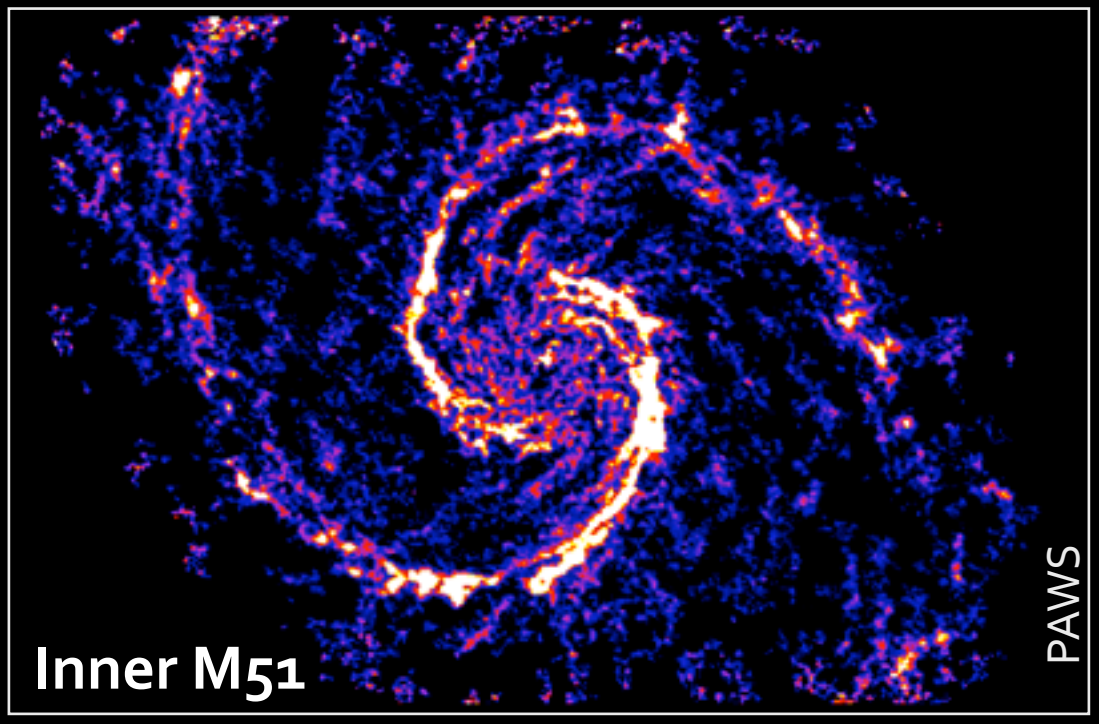
(Same extraction parameters) on single data set: CPROPS, Rosolowsky & Leroy 2006)

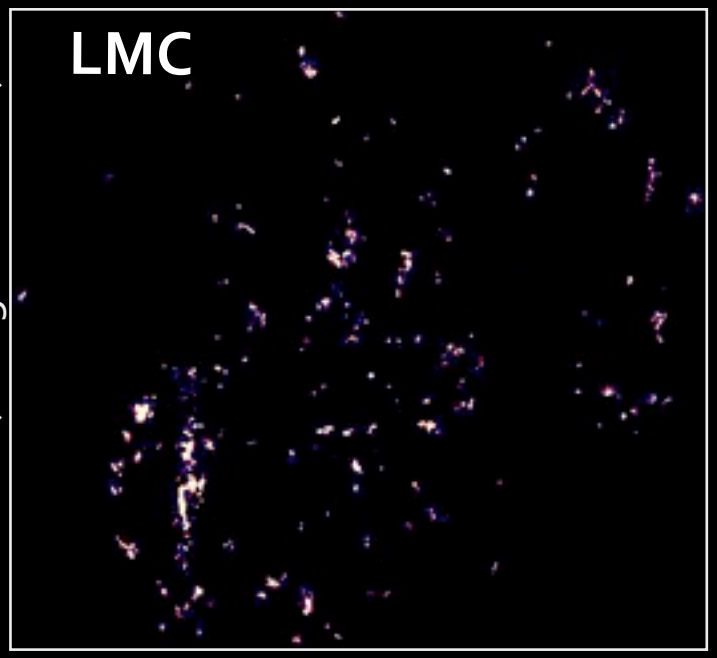


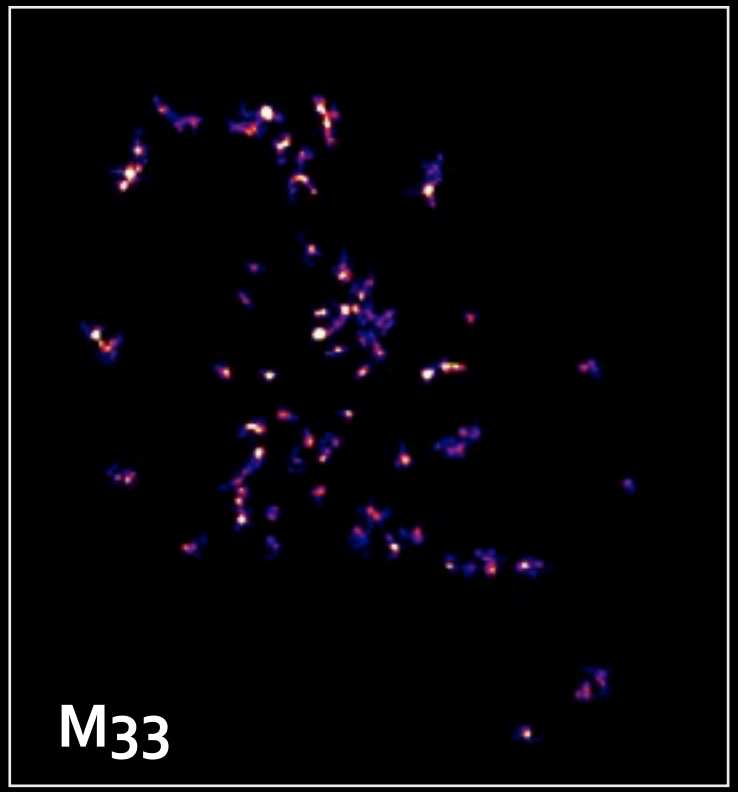
Colombo et al. (in prep.)

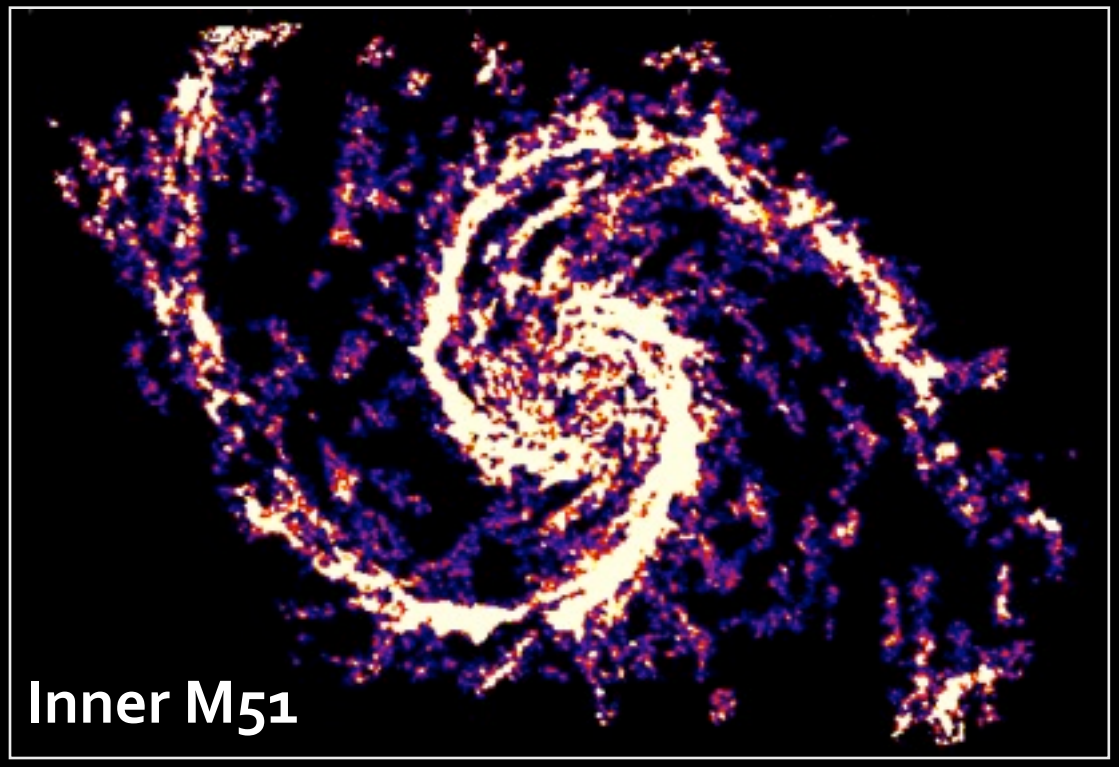
GMC Properties II. Nearby Galaxies



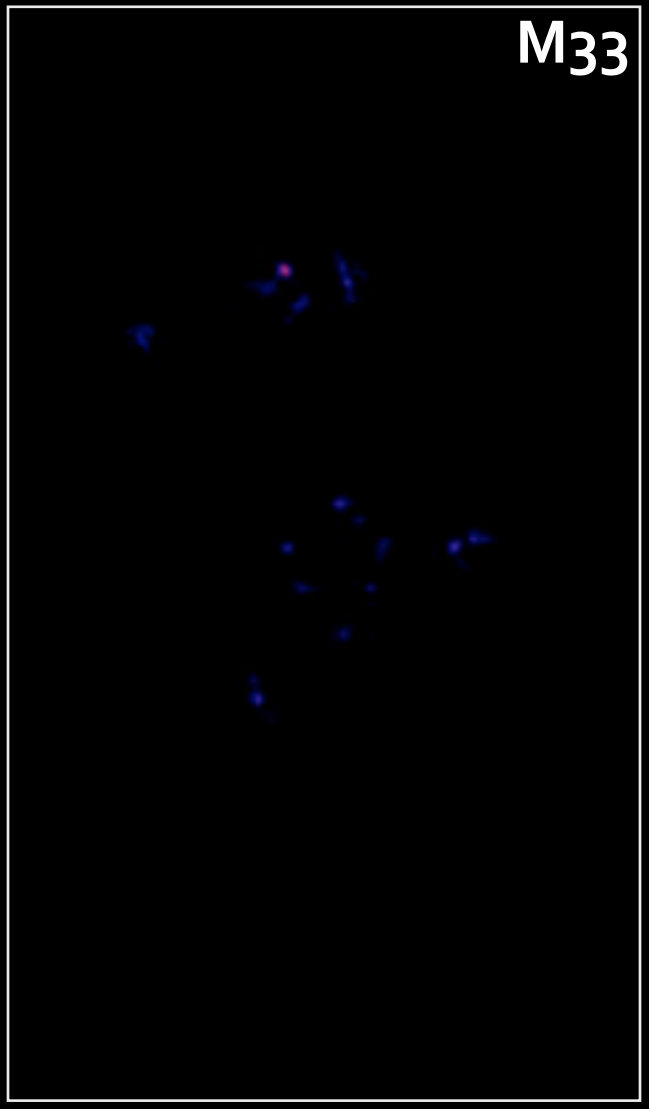

Inner M51
PAWS

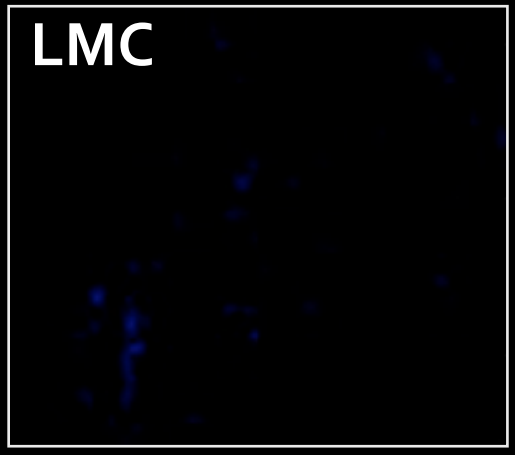

LMC
MAGMA (Wong et al. 2011)


M33
FCRAO+BIMA (Rosolowsky et al 2007)



5 kpc

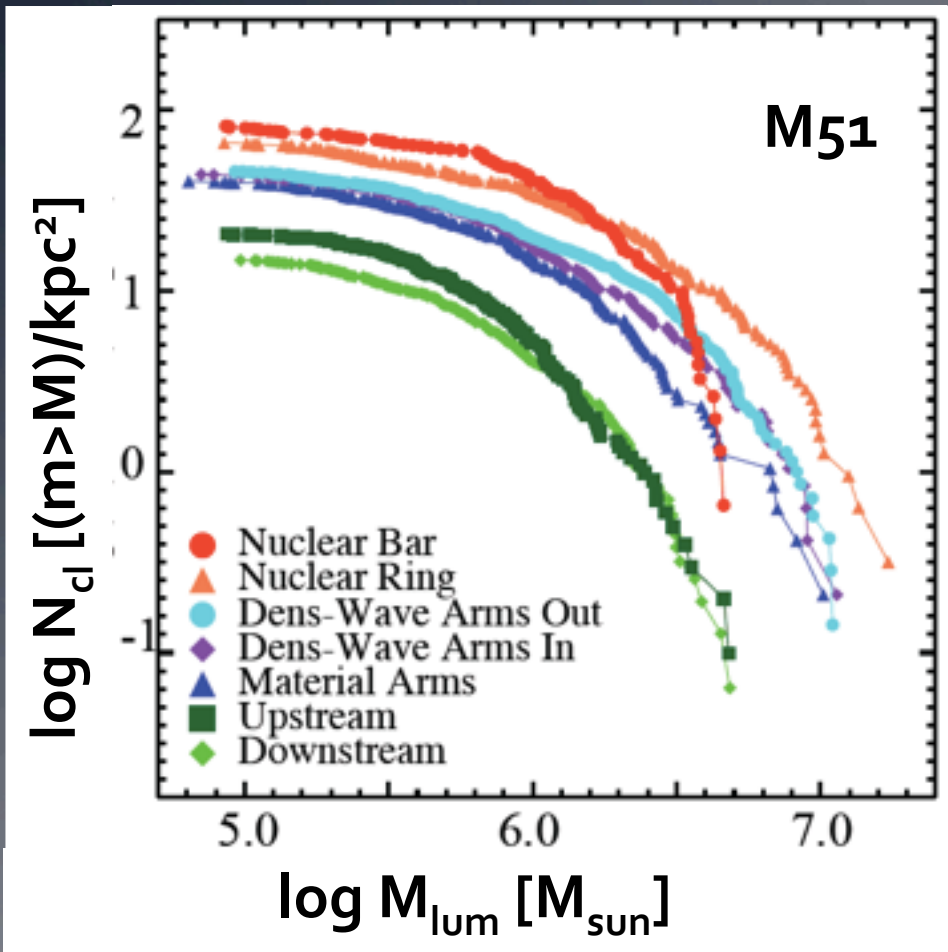


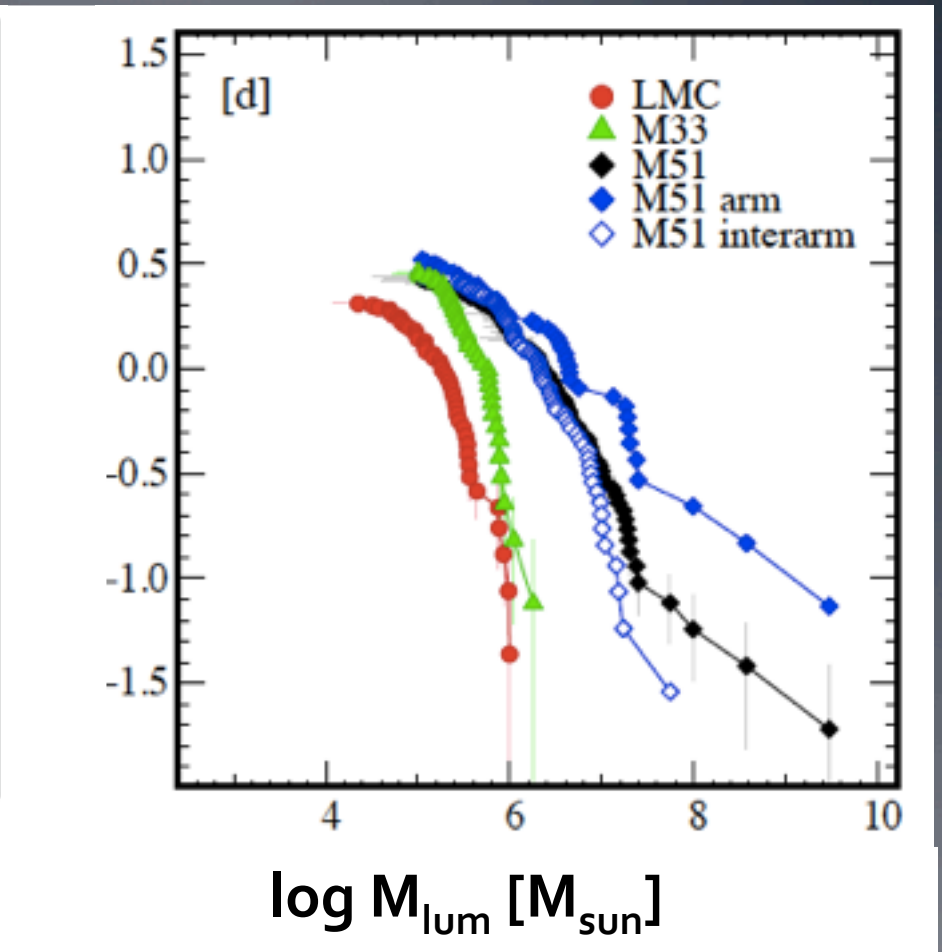


GMC Properties II. Nearby Galaxies

Colombo et al. (in prep.)

Hughes et al. (in prep.)





--> GMC formation is different in spiral arms (M51 arm, MW) and disks (M51 inter-arm, LMC, M33),

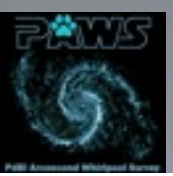
--> importance of photo-ionization (?) **(see poster by D. Colombo)**

3 Paradigms on Giant Molecular Clouds

1. most of the molecular gas resides in GMCs
   ➔ Very likely not

2. GMC properties are universal across environments/galaxies
   ➔ No, arm/inter-arm, low/high Σ_{gas}

3. **massive star formation and GMCs are closely associated**

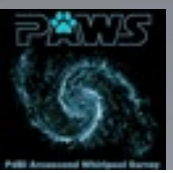


3 Paradigms on Giant Molecular Clouds

1. most of the molecular gas resides in GMCs
   ➔ Very likely not

2. GMC properties are universal across environments/galaxies
   ➔ No, arm/inter-arm, low/high Σ_{gas}

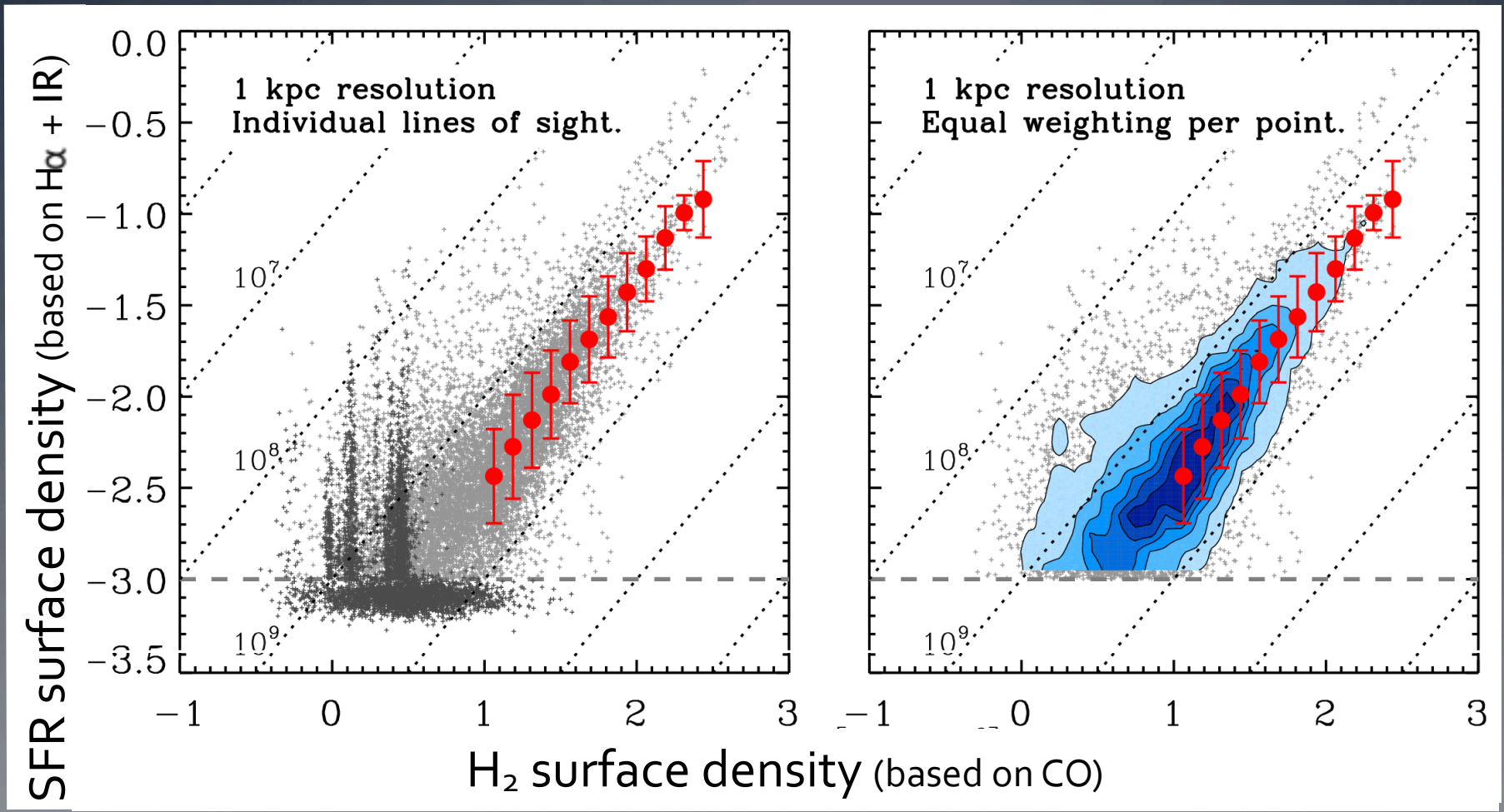
3. **massive star formation and GMCs are closely associated**



Star Formation and Molecular Gas Correlate

> 10,000 independent data points from 48 nearby galaxies

(Leroy et al. subm.)

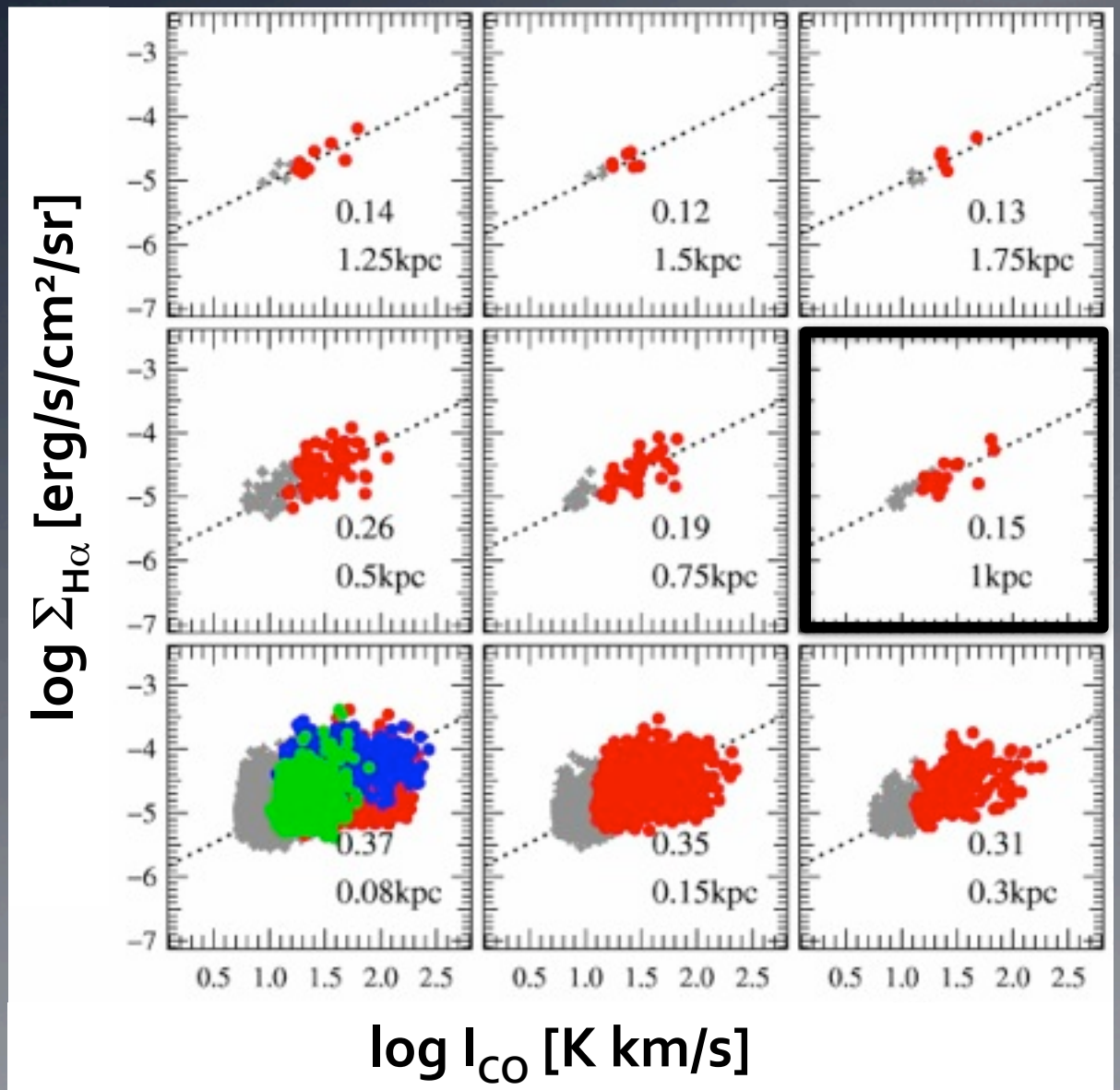


very tight correlation even on 1kpc scale

Relation of Gas and Star Formation

Leroy,Hughes et al. (in prep.)

aperture size →



I(CO) > 3 σ

inter-arm

center

CO non-detection

.... OLS fit @ 1kpc

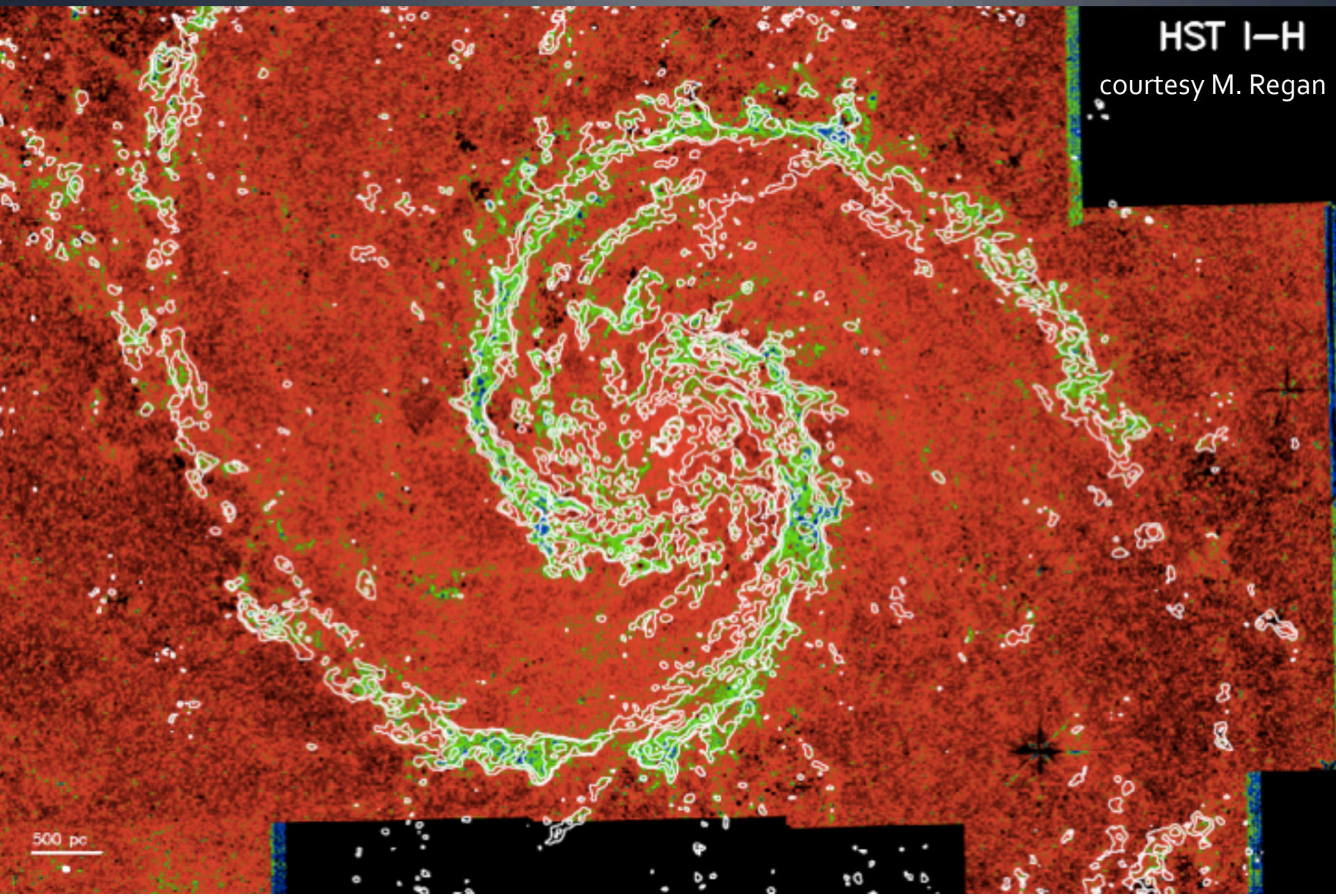
Larger apertures:

- scatter decreases
- slope steepens

SFR	I(CO)	HI+H_2
1.4 GHz	0.8	0.9
24 μm	0.9	1.3
Hα	1.1	0.9
8 μm	0.9	1.0

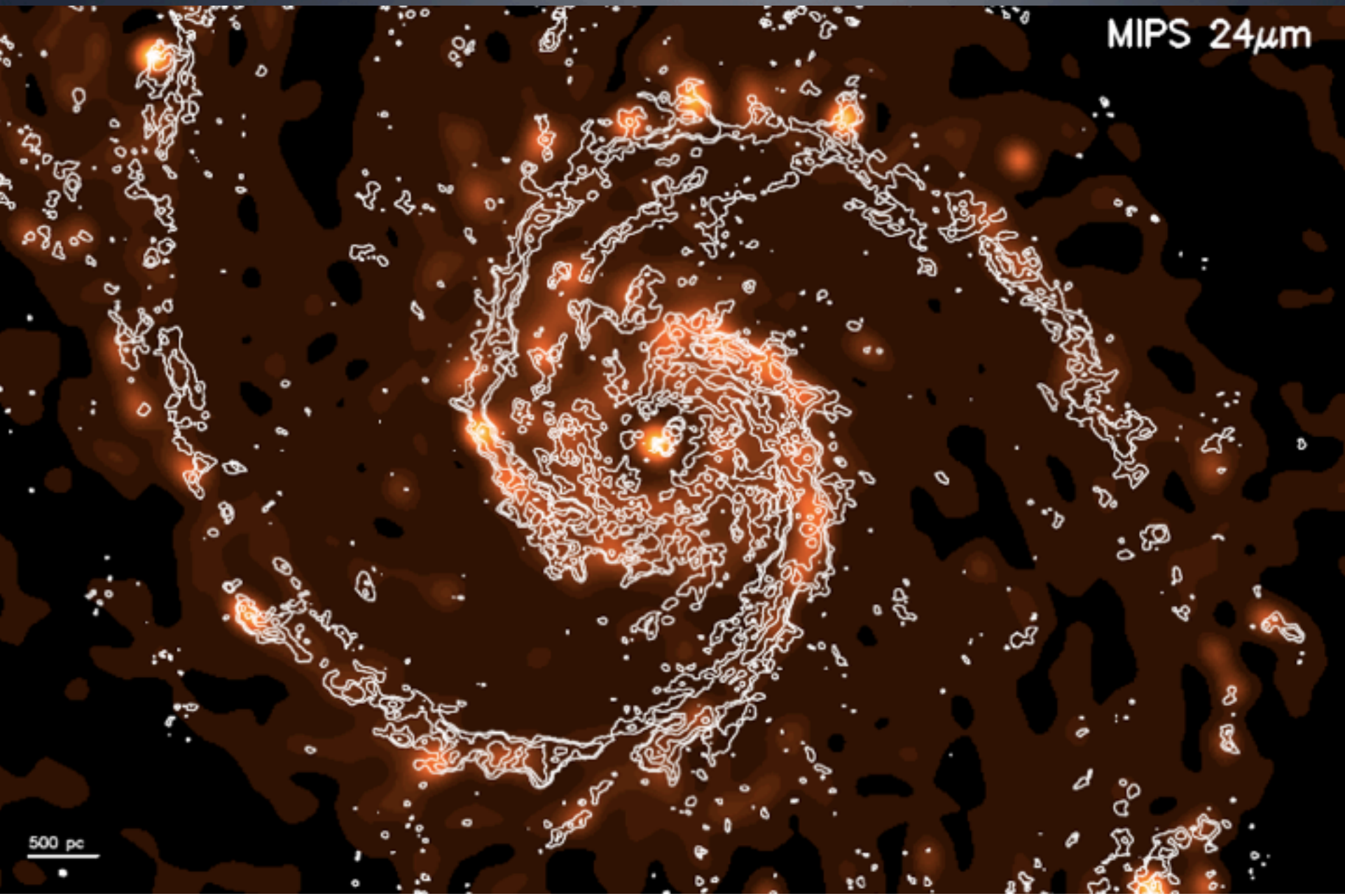
Spatial Relation of Gas and Star Formation

Schinnerer et al. (in prep.)



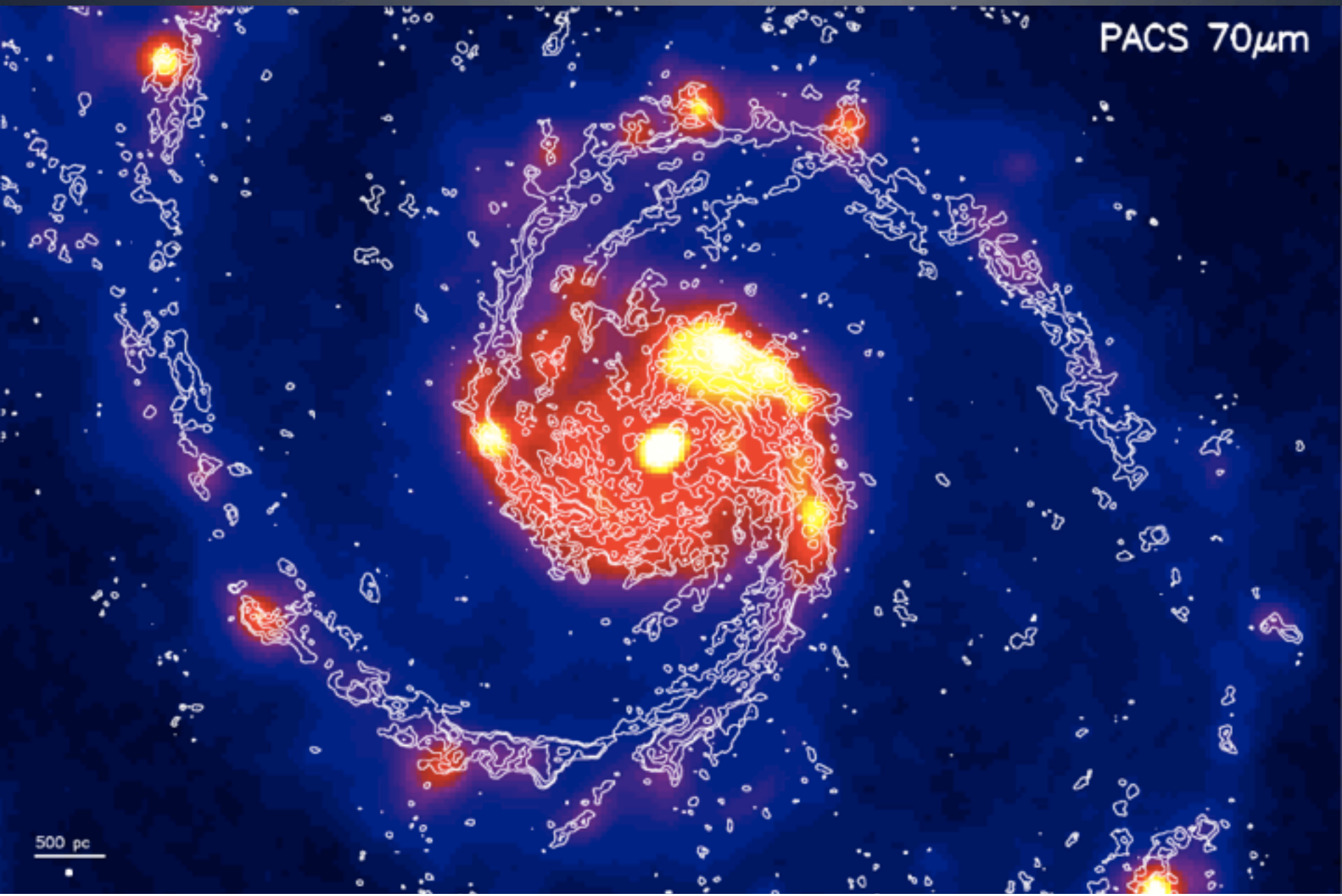
Spatial Relation of Gas and Star Formation

Schinnerer et al. (in prep.)



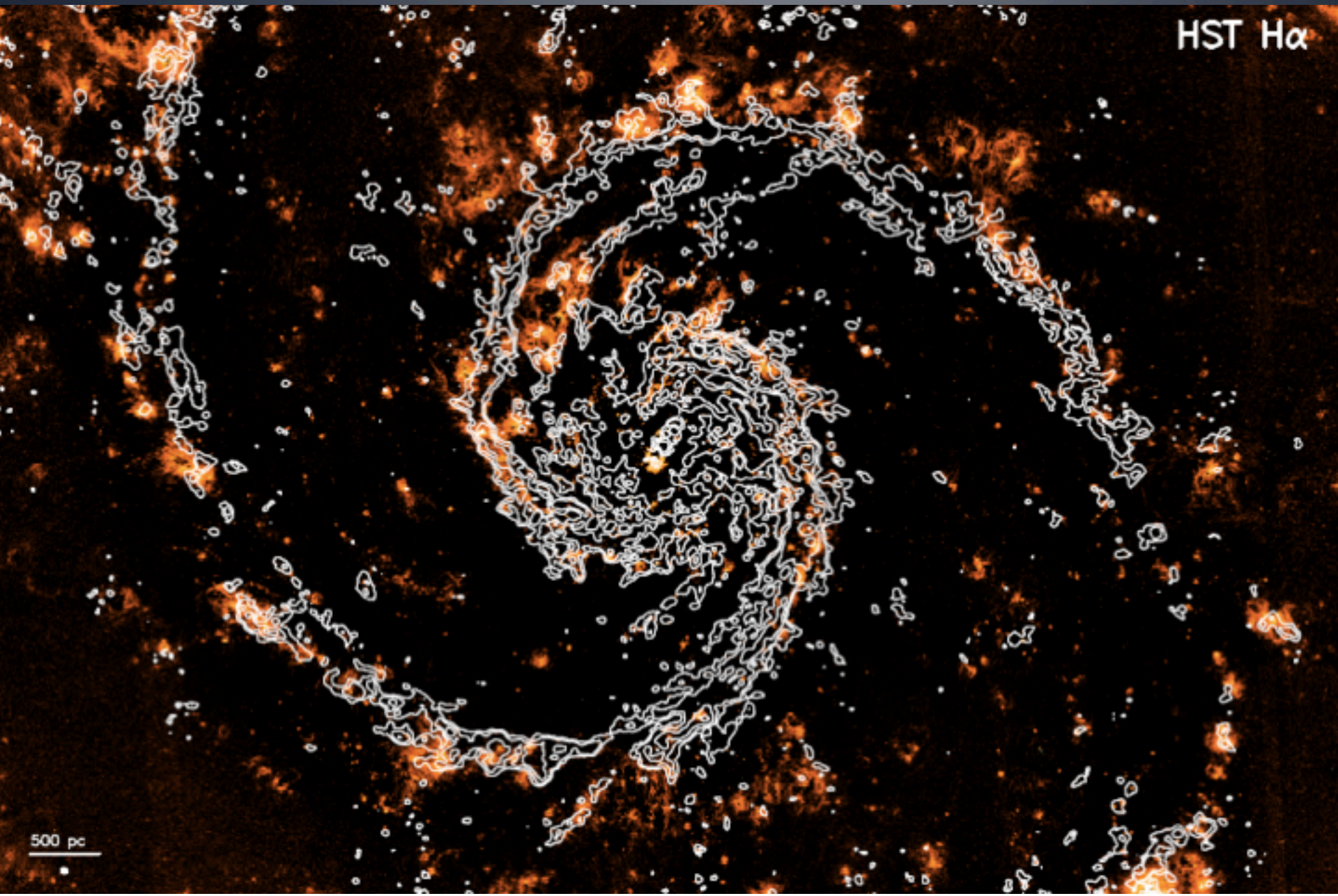
Spatial Relation of Gas and Star Formation

Schinnerer et al. (in prep.)



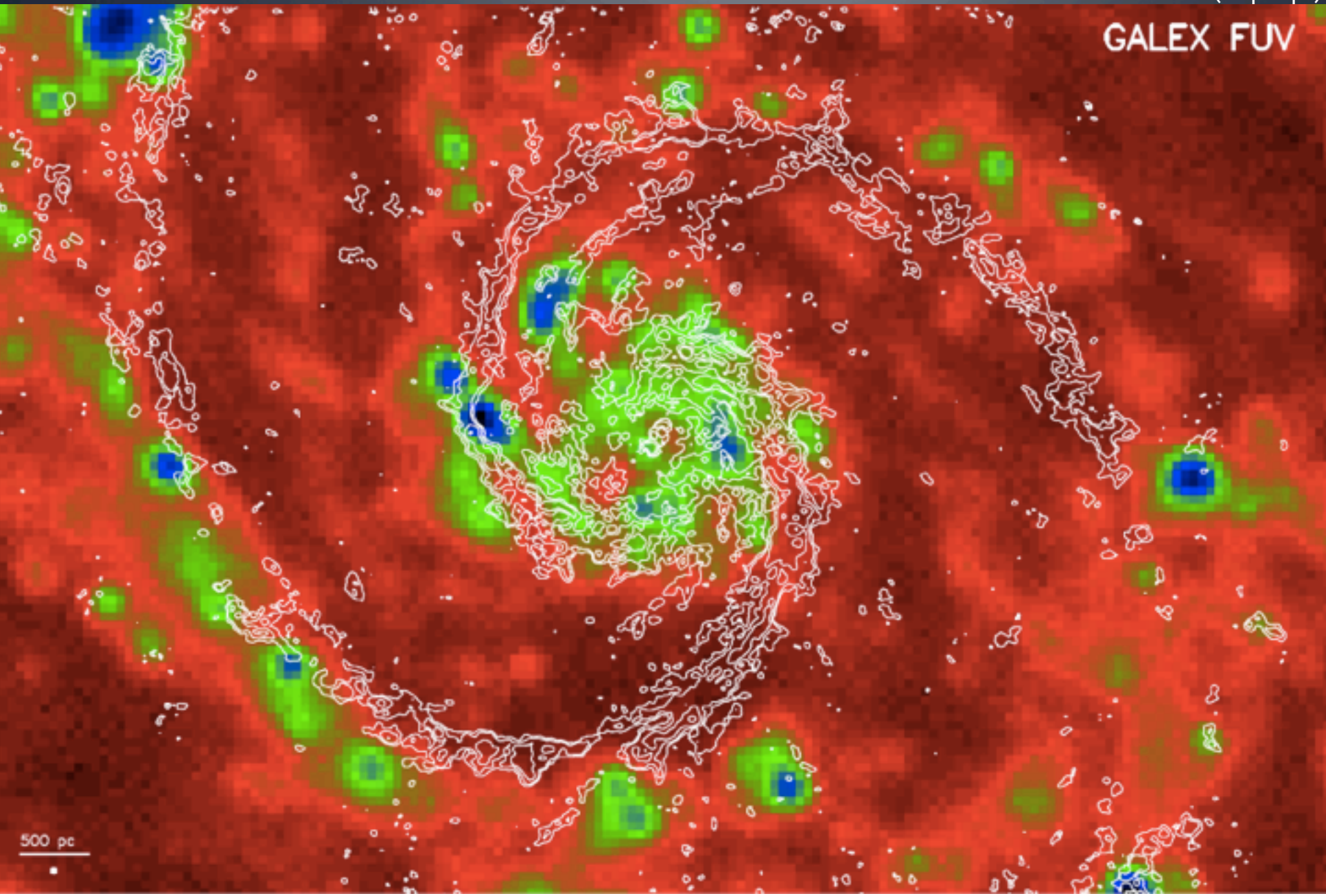
Spatial Relation of Gas and Star Formation

Schinnerer et al. (in prep.)



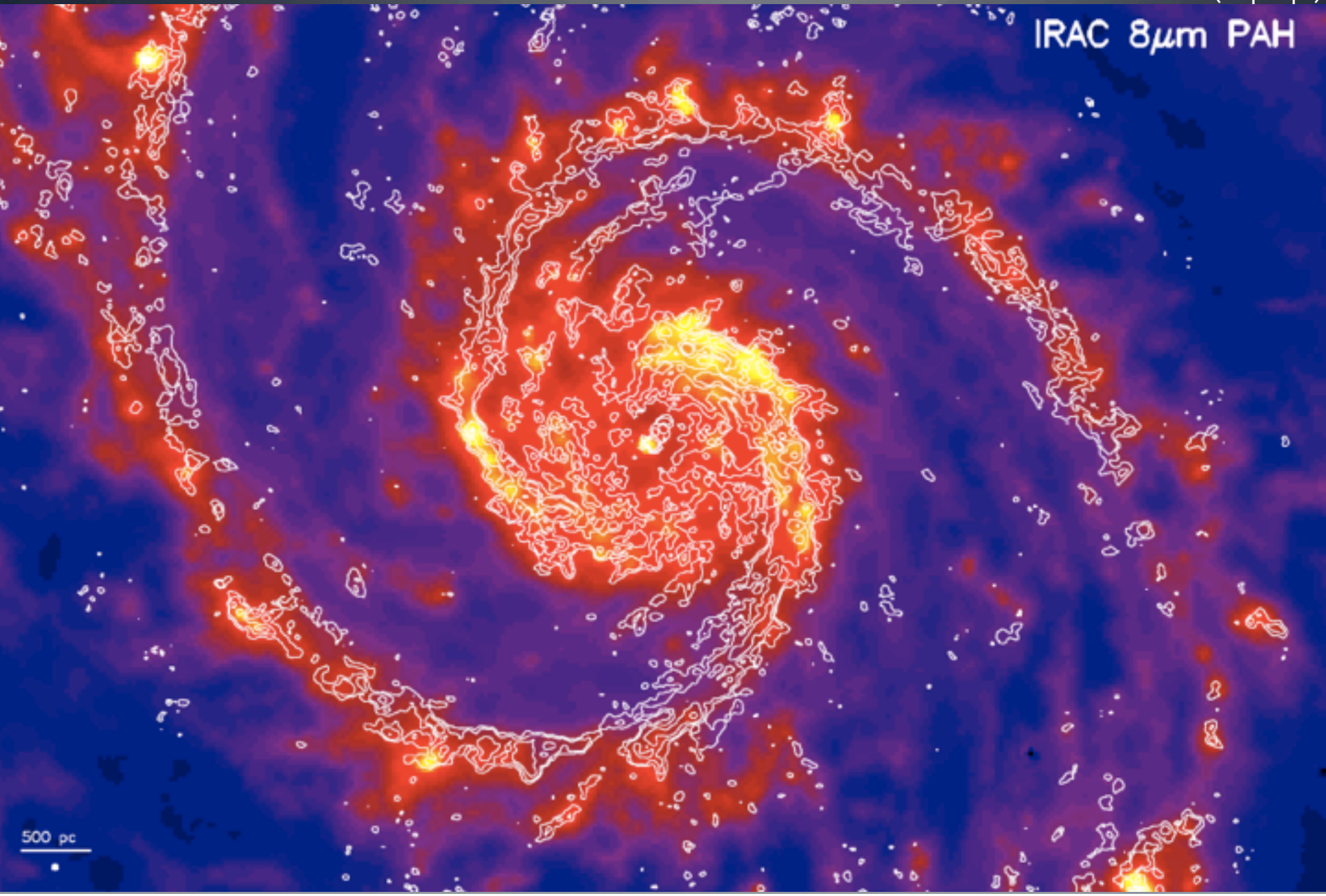
Spatial Relation of Gas and Star Formation

Schinnerer et al. (in prep.)



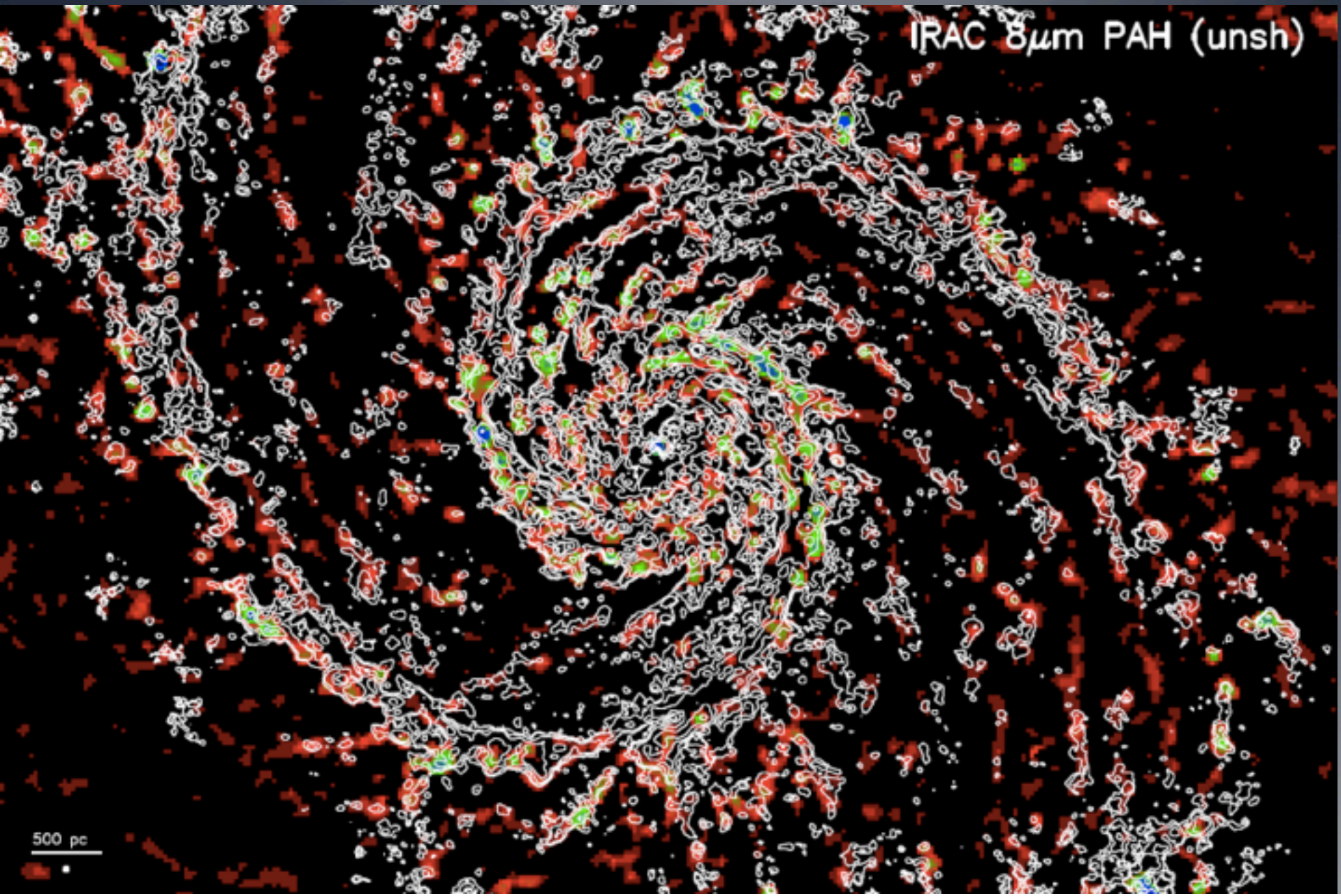
Spatial Relation of Gas and Star Formation

Schinnerer et al. (in prep.)

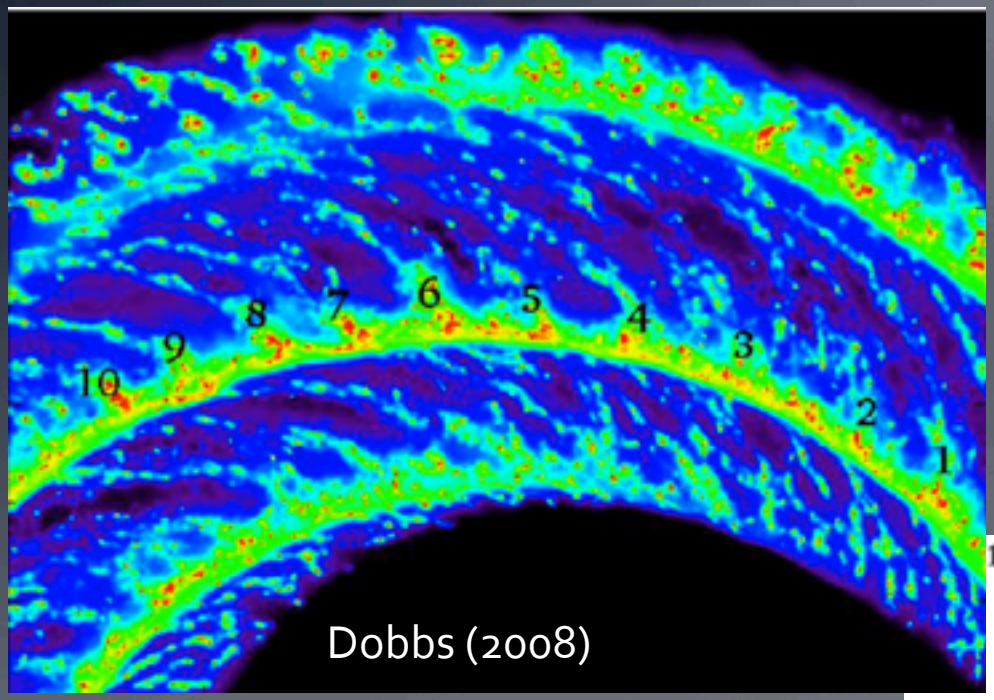


Spatial Relation of Gas and Star Formation

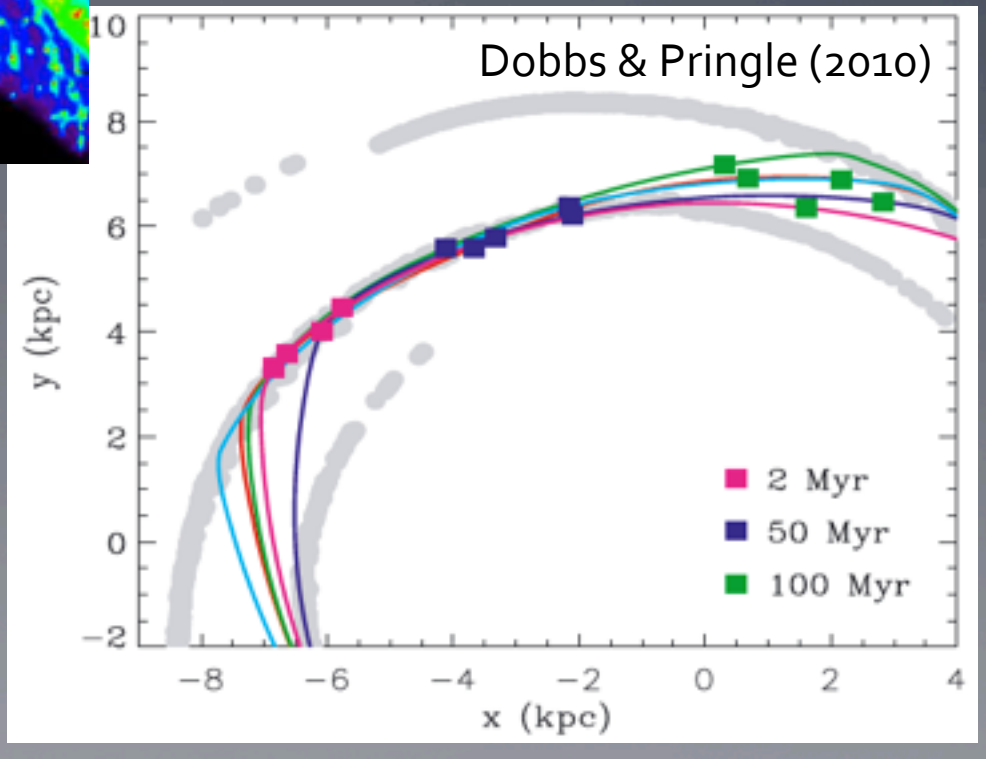
Schinnerer et al. (in prep.)



GMC & SF Formation in Spiral Density Wave

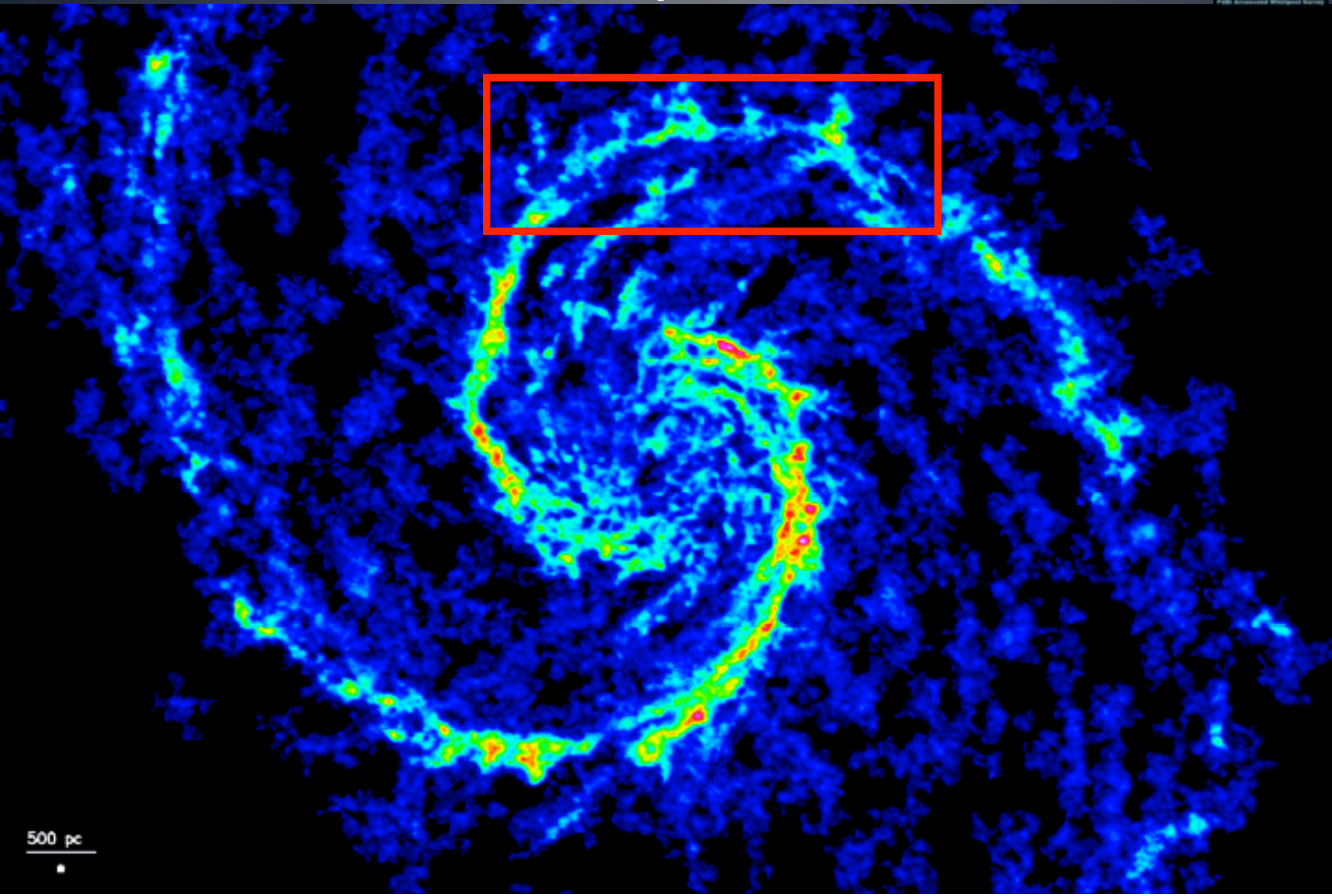


➔ gas spurs/feathers should develop



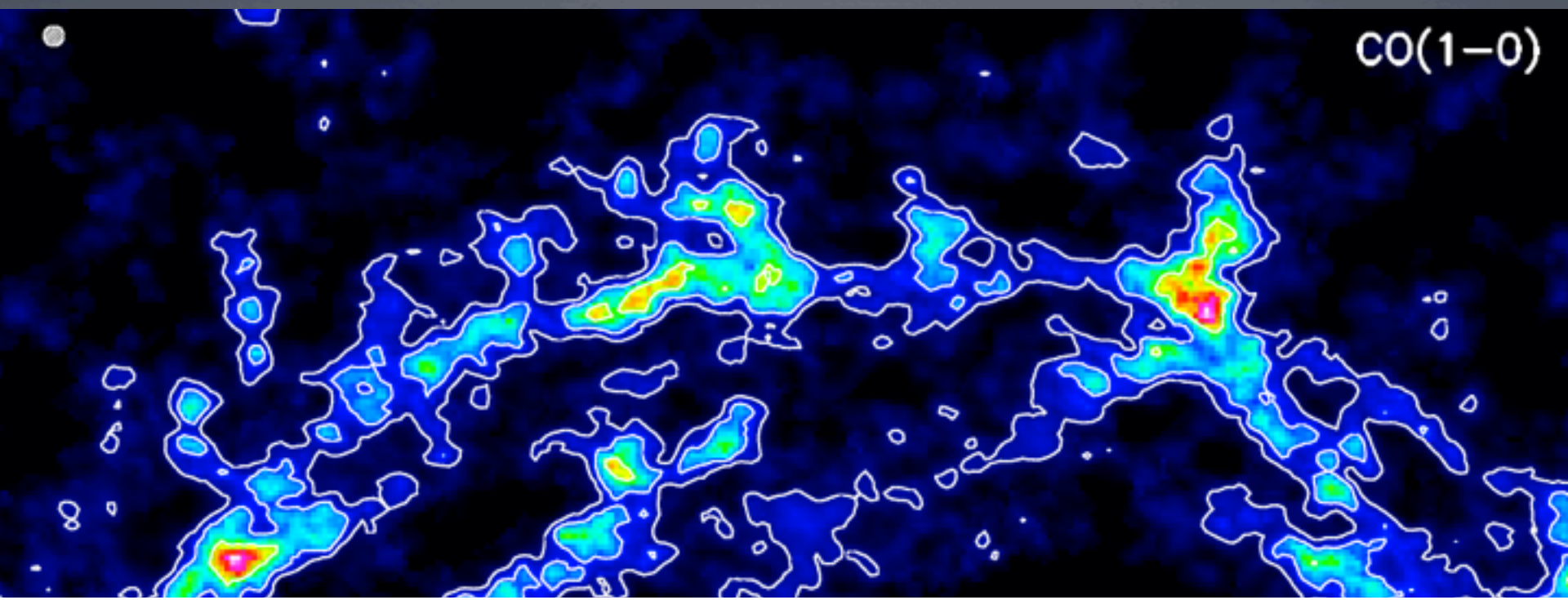
when and where does SF start? ➔

Northern spiral arm



Northern spiral arm

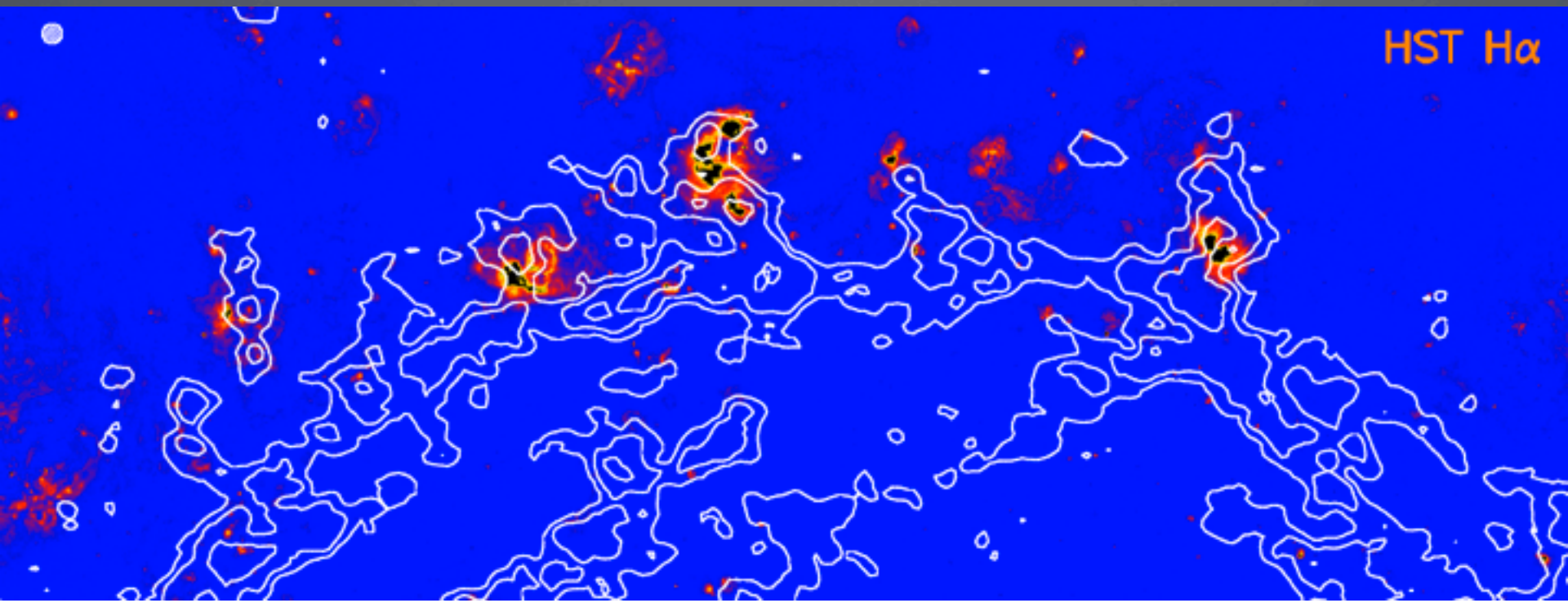
molecular gas in arms and spurs/feathers (as expected from models)



Northern spiral arm

molecular gas in arms and spurs/feathers

HII regions w/i spurs/feathers, no Hα in gas arm (Vogel ea 1988)



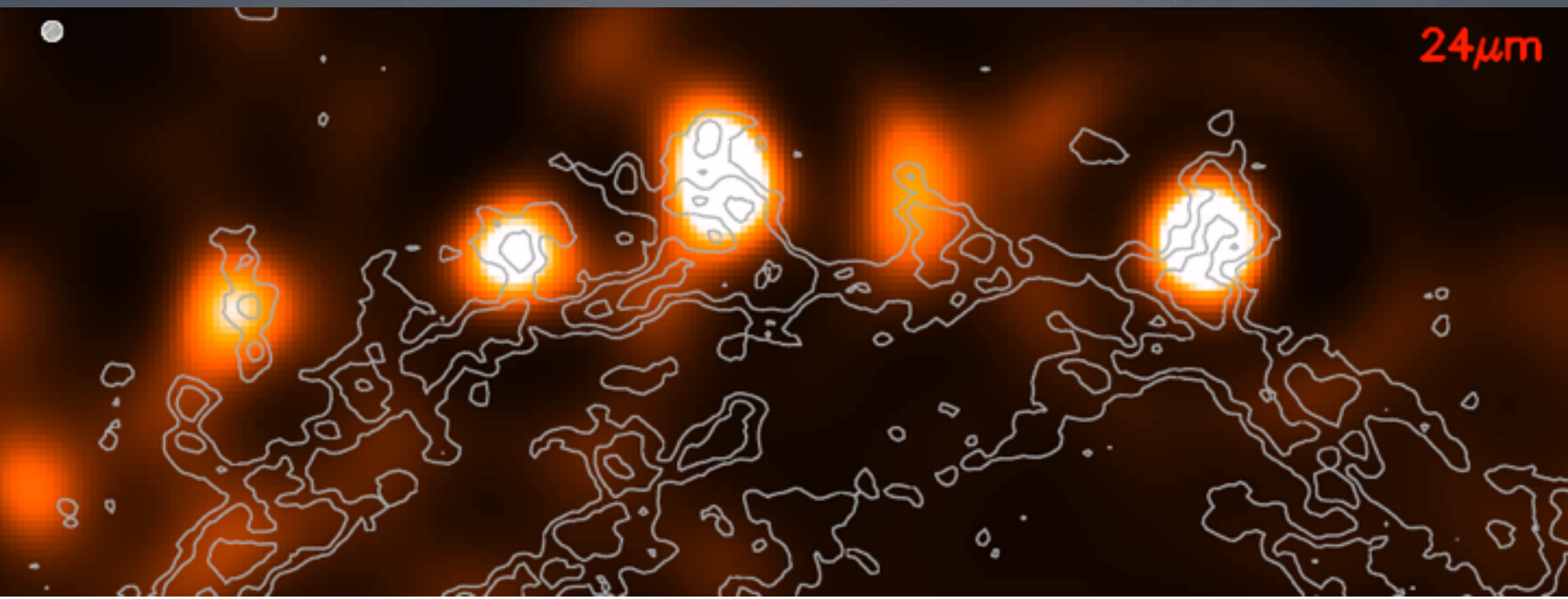
Northern spiral arm

molecular gas in arms and spurs/feathers

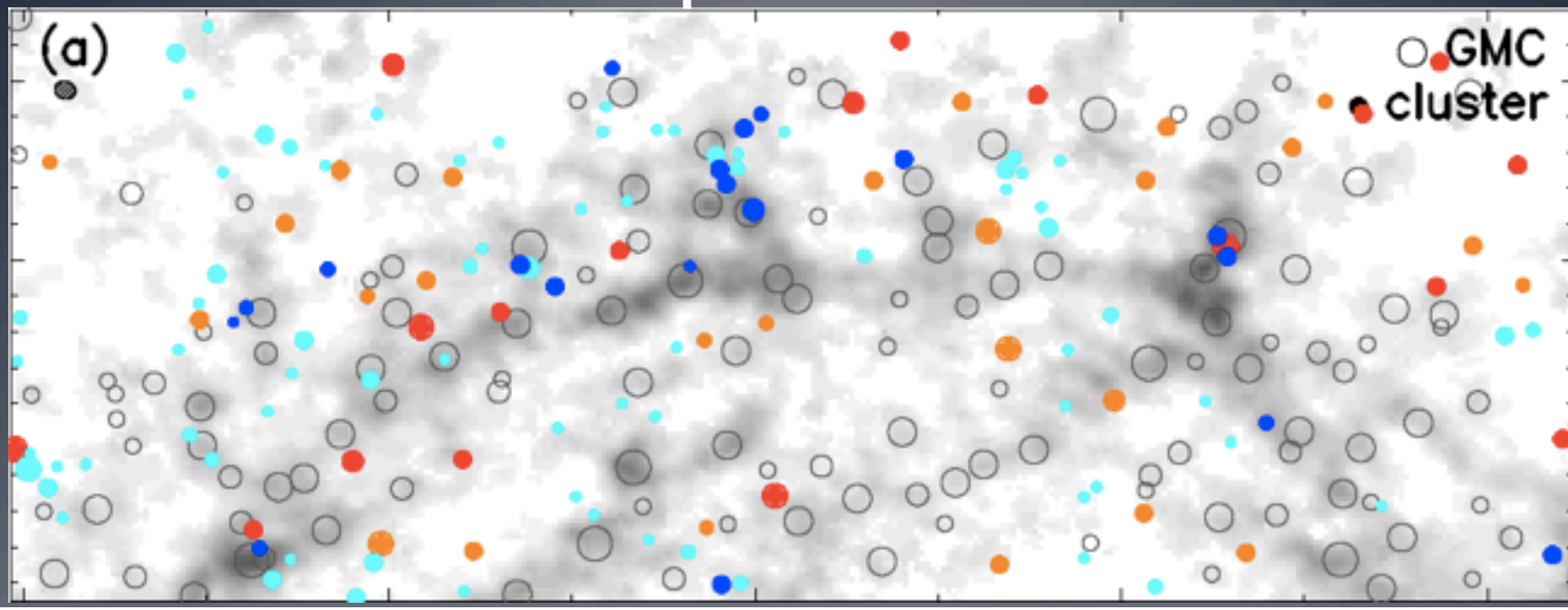
HII regions w/i spurs/feathers, no Hα in gas arm

no hot dust emission in gas arm

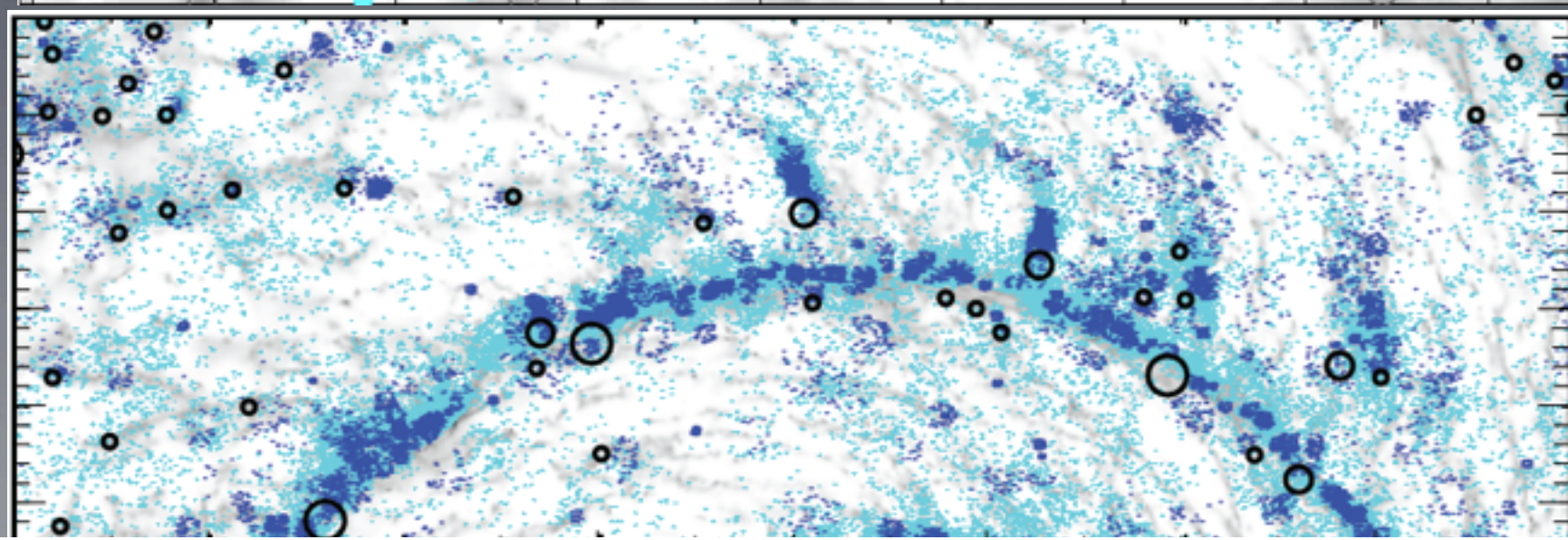
➔ delay between GMC and star formation?



Northern spiral arm



data vs. model



3 Paradigms on Giant Molecular Clouds

1. most of the molecular gas resides in GMCs
   ➔ Very likely not

2. GMC properties are universal across environments/galaxies
   ➔ No, arm/inter-arm, low/high Σ_{gas}

3. massive star formation and GMCs are closely associated
   ➔ Not always, environment is important