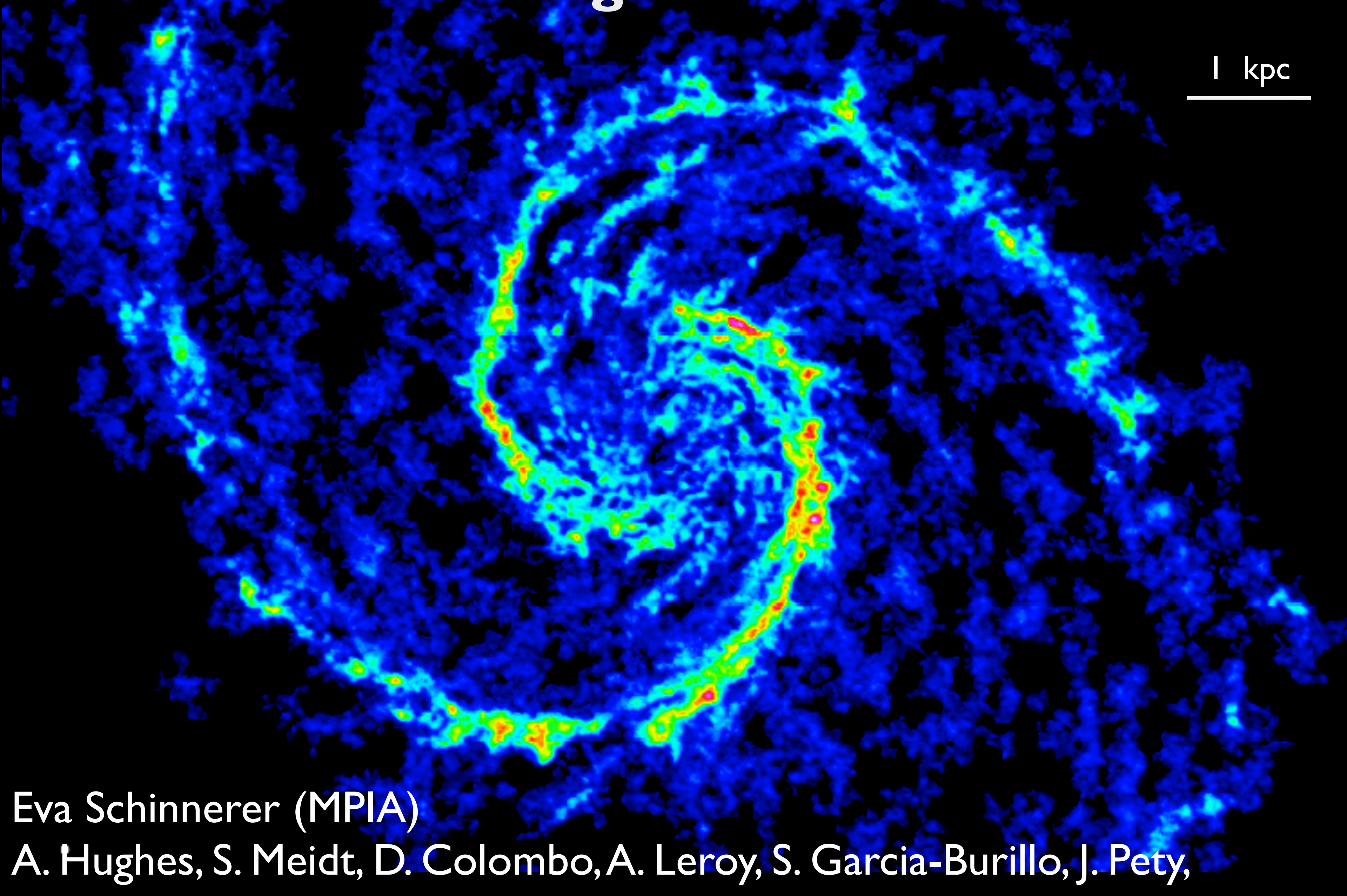
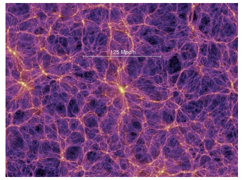
Star Formation Regulation on Cloud Scales



Eva Schinnerer (MPIA)
A. Hughes, S. Meidt, D. Colombo, A. Leroy, S. Garcia-Burillo, J. Pety,
C. Dobbs, T. Thompson, G. Dumas, K. Schuster, C. Kramer, M. Querejeta

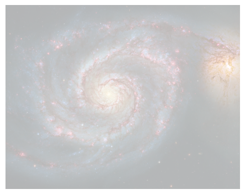
What regulates star formation?

scale^{-1}



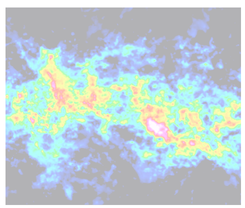
universe

dark matter → structure evolution



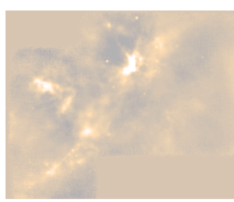
galaxies

dark,baryonic matter → molecular gas



GMC (Giant Molecular Cloud)

GMC,molecular gas → dense gas



dense gas

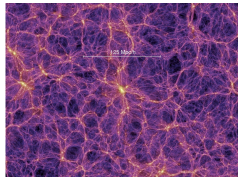
dense gas fraction → dense cores

dense core

dense core → formation of stars

What regulates star formation?

scale^{-1}

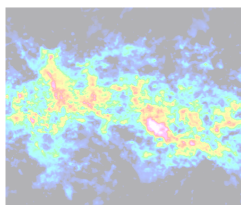


universe

dark matter → structure evolution

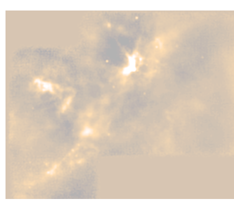
galaxies

dark,baryonic matter → molecular gas



GMC (Giant Molecular Cloud)

GMC,molecular gas → dense gas



dense gas

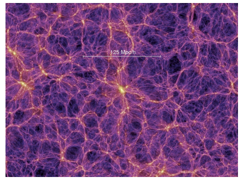
dense gas fraction → dense cores

dense core

dense core → formation of stars

What regulates star formation?

scale^{-1}

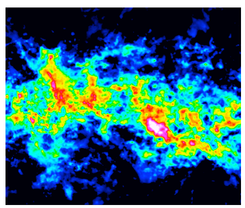


universe

dark matter → structure evolution

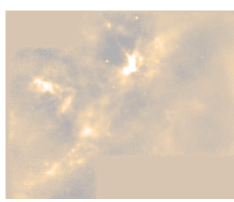
galaxies

dark,baryonic matter → molecular gas



GMC (Giant Molecular Cloud)

GMC,molecular gas → dense gas



dense gas

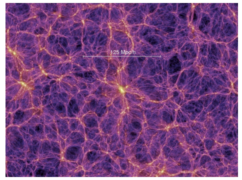
dense gas fraction → dense cores

dense core

dense core → formation of stars

What regulates star formation?

scale^{-1}

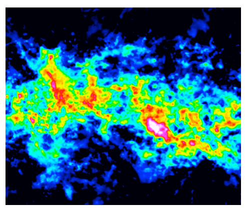


universe

dark matter → structure evolution

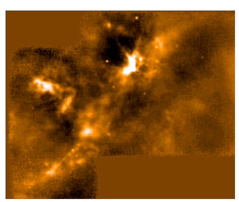
galaxies

dark,baryonic matter → molecular gas



GMC (Giant Molecular Cloud)

GMC,molecular gas → dense gas



dense gas

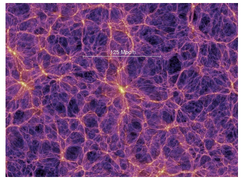
dense gas fraction → dense cores

dense core

dense core → formation of stars

What regulates star formation?

scale^{-1}

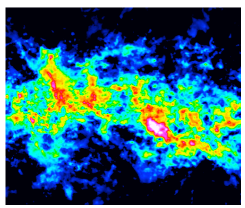


universe

dark matter → structure evolution

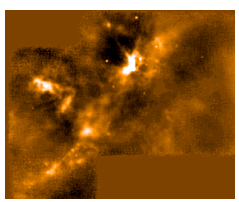
galaxies

dark,baryonic matter → molecular gas



GMC (Giant Molecular Cloud)

GMC,molecular gas → dense gas



dense gas

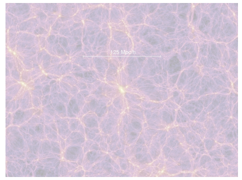
dense gas fraction → dense cores

dense core

dense core → formation of stars

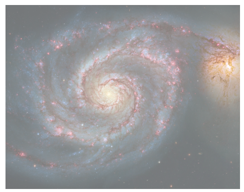
What regulates star formation?

Impact of galactic structure ?



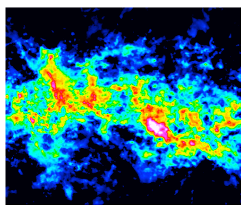
universe

dark matter → structure evolution



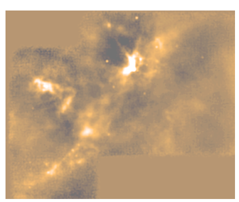
galaxies

dark, baryonic matter → molecular gas



GMC (Giant Molecular Cloud)

GMC, molecular gas → dense gas



dense gas

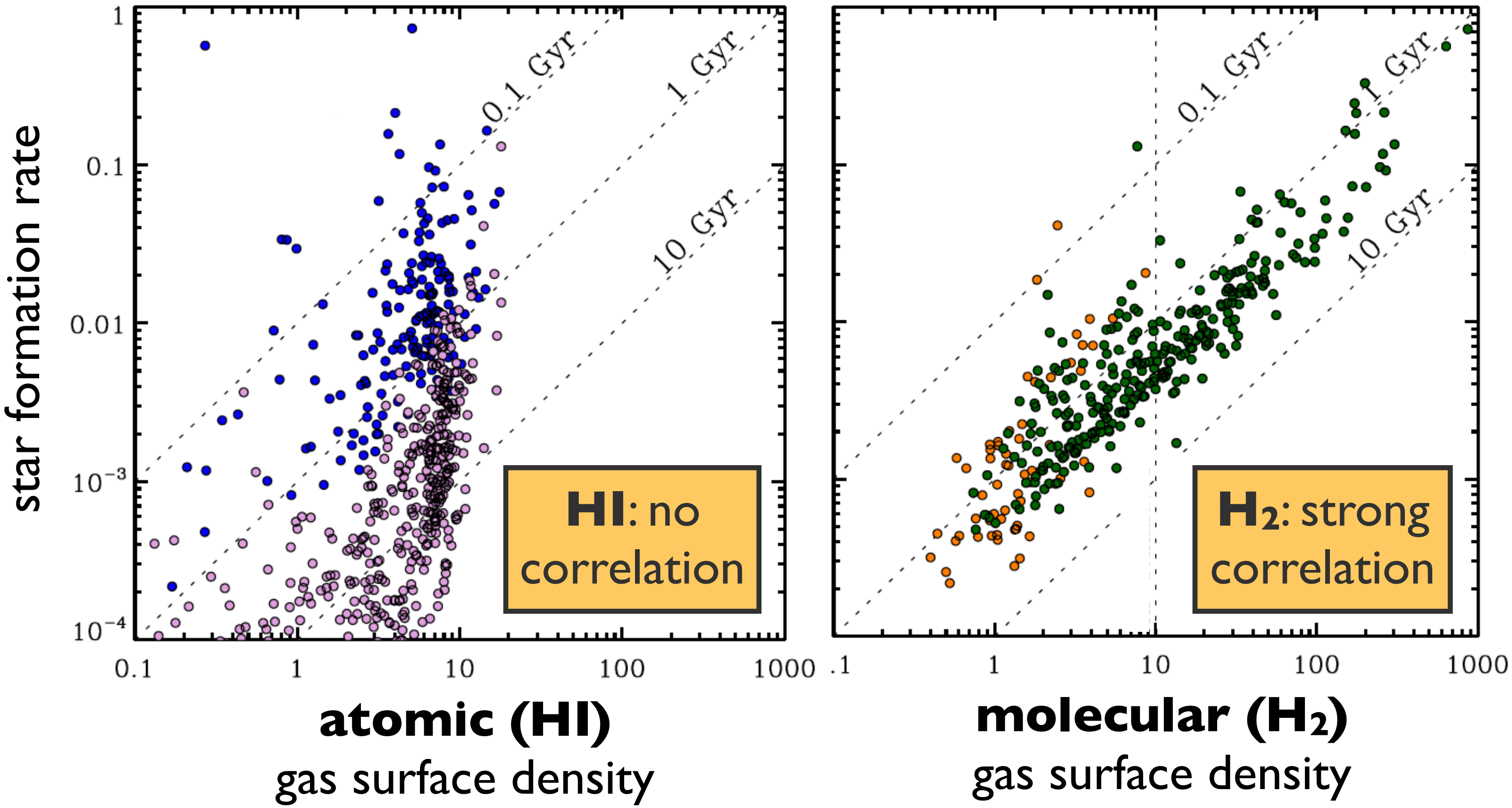
dense gas fraction → dense cores

dense core

dense core → formation of stars

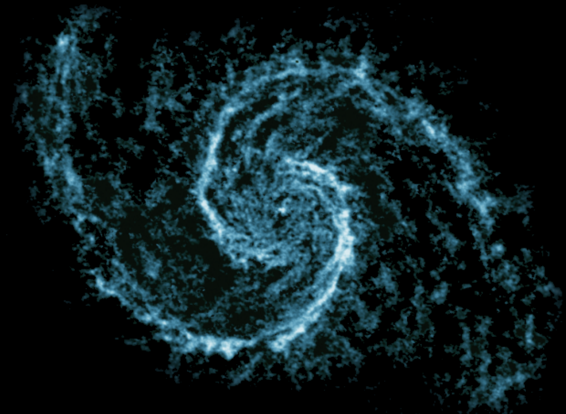
Molecular Gas & Star Formation Closely Related

Results from 40 nearby galaxies, resolution: 1 kpc.



→ Stars form in molecular gas...
...with roughly constant efficiency (a.k.a 'SF law').

PAWS



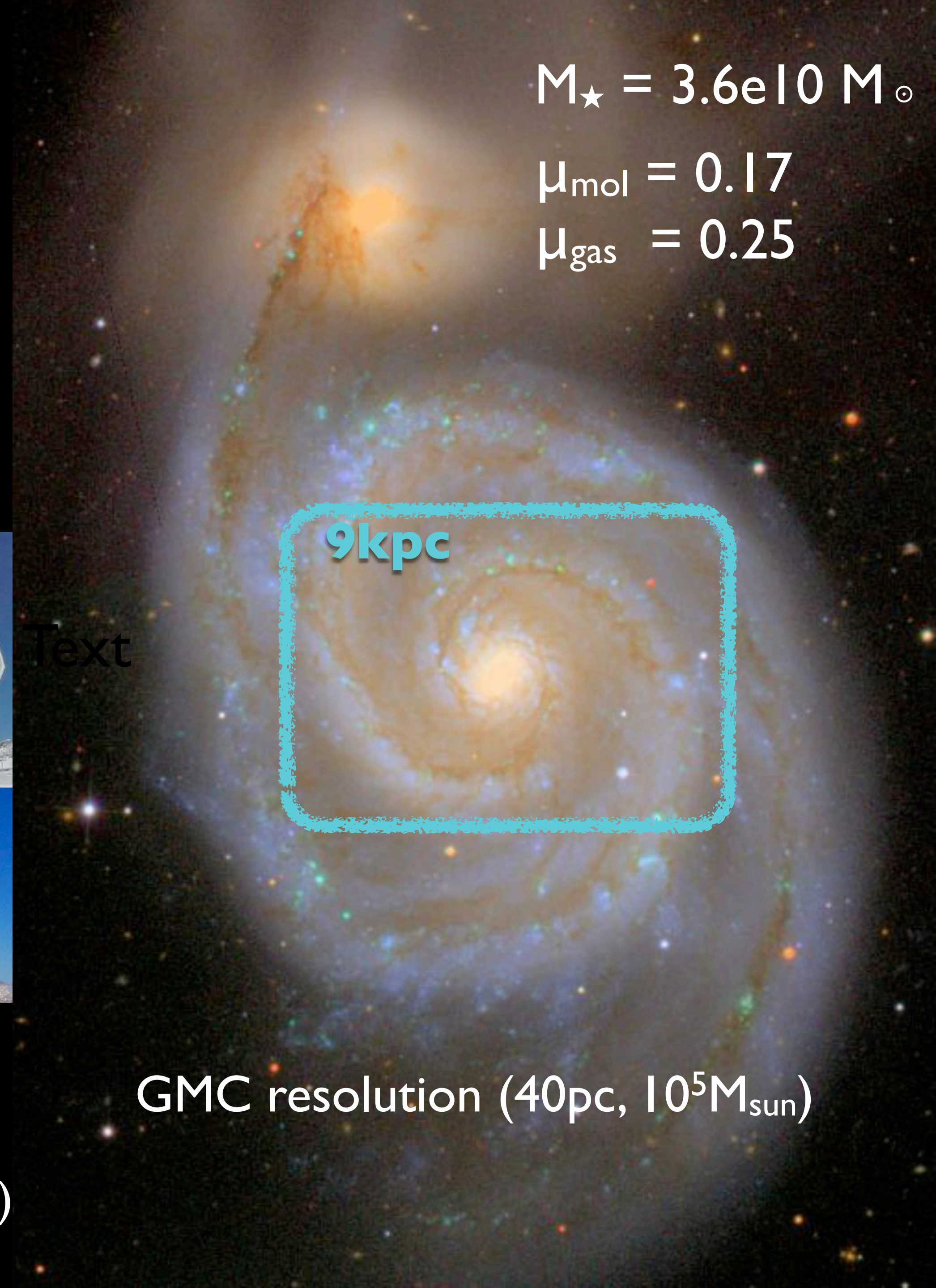
PdBI Arcsecond Whirlpool Survey

iram
Institut de Radioastronomie Millimétrique

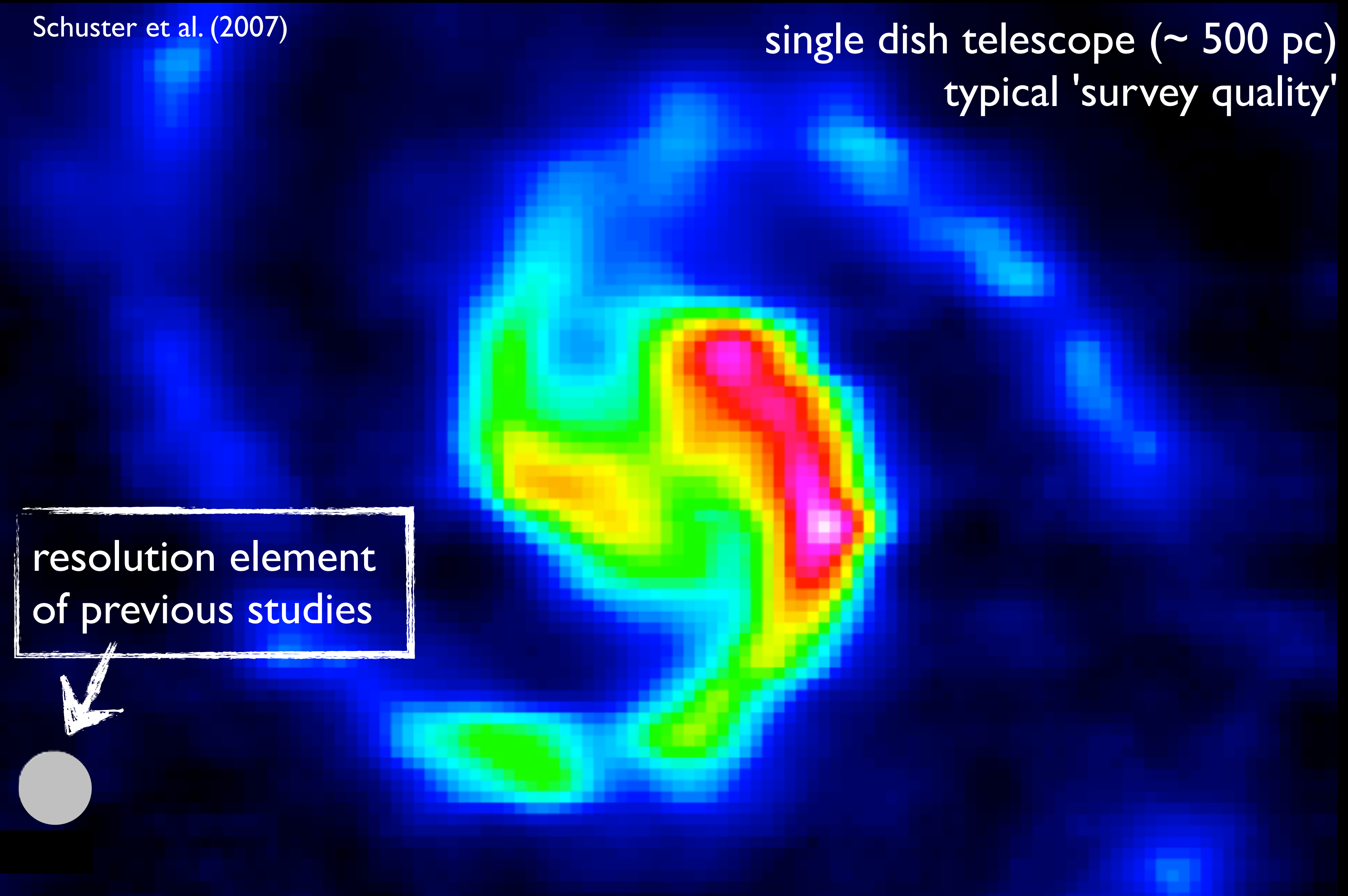
30m: 40 h
PdBI:170 h

http://www.mpia.de/PAWS

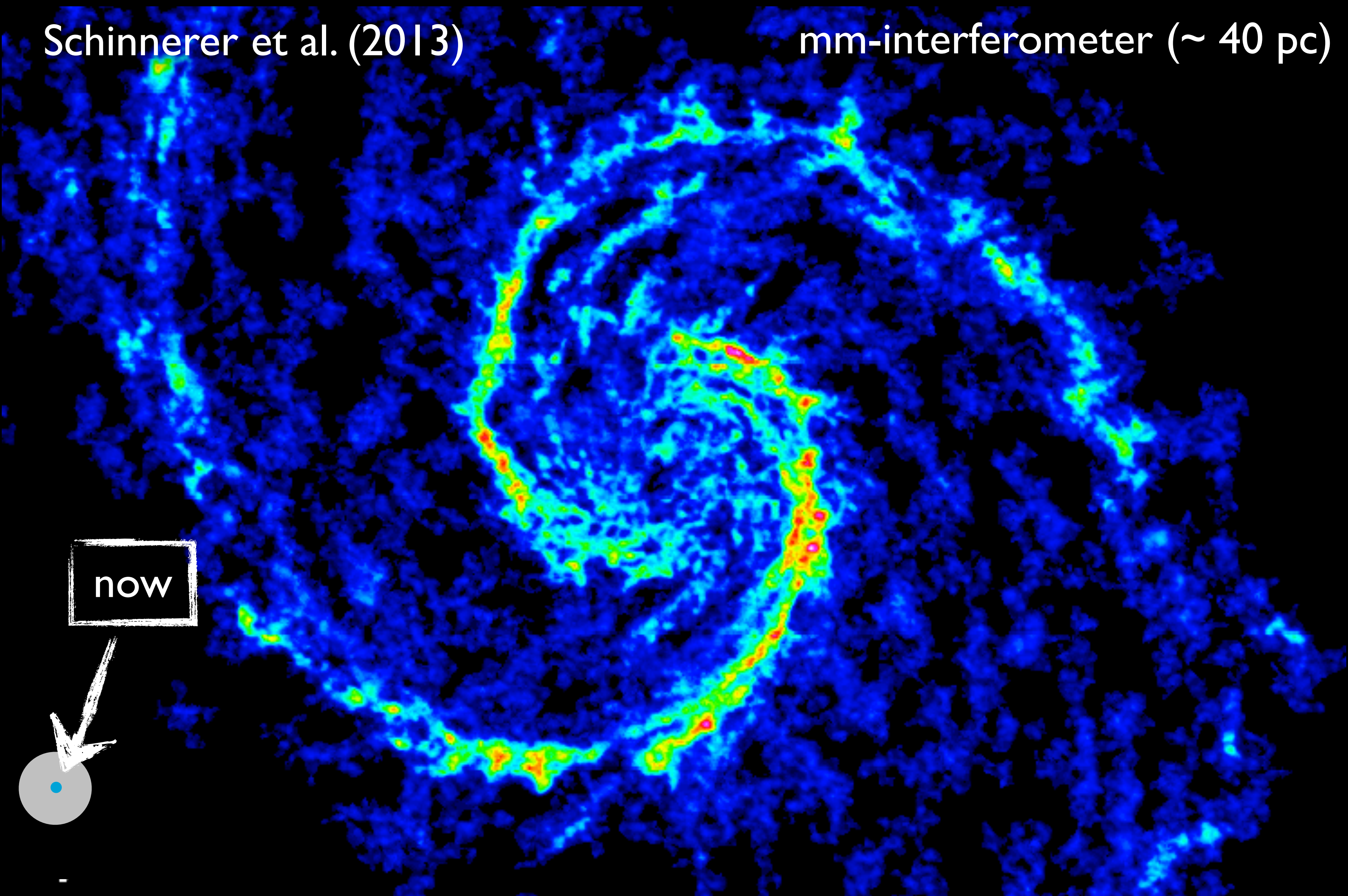
data cubes, moment maps, GMC catalog
@ 1", 3", 6" resolution for $^{12}CO(1\text{-}0)$
22" resolution for $^{12}CO(1\text{-}0)$, $^{13}CO(1\text{-}0)$
for entire M51a



molecular gas disk of M51 - resolution is key



molecular gas disk of M51 - resolution is key



Molecular gas and star formation in spiral galaxies

#1:
3D distribution of molecular gas differs from atomic gas one

#2:
Giant Molecular Cloud properties are set by environment

#3:
Conversion of molecular gas into stars is complex process

Molecular gas and star formation in spiral galaxies

#1:

3D distribution of molecular gas differs from atomic gas one

#2:

Giant Molecular Cloud properties are set by environment

#3:

Conversion of molecular gas into stars is complex process

Molecular & atomic gas are distributed differently

molecular gas is more clumped than atomic gas ...

... small scale distributions can vary significantly

Leroy et al. (2013)

Molecular & atomic gas are distributed differently

molecular gas is more clumped than atomic gas ...
... small scale distributions can vary significantly

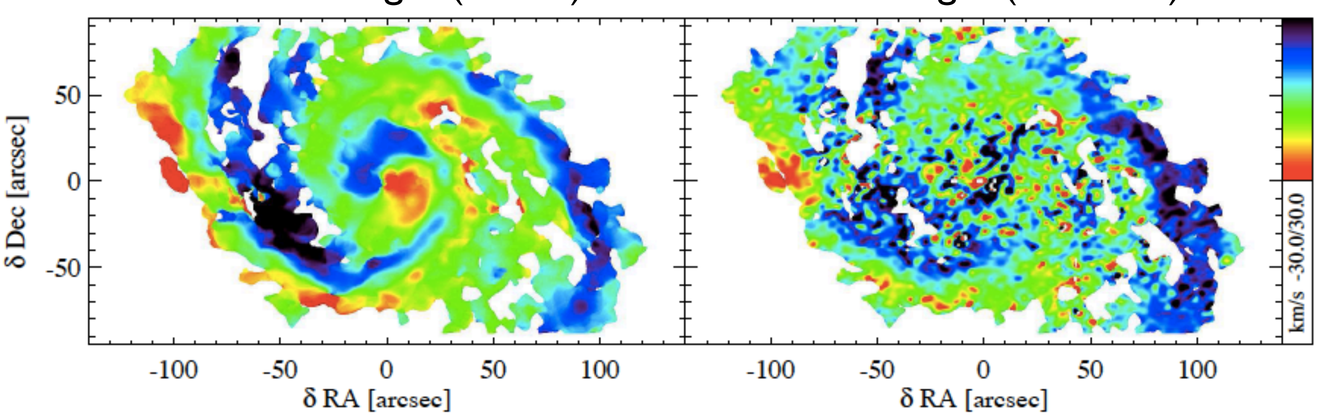
Leroy et al. (2013)

molecular and atomic gas kinematics are not the same ...
... molecular and atomic phase probe different gas distributions

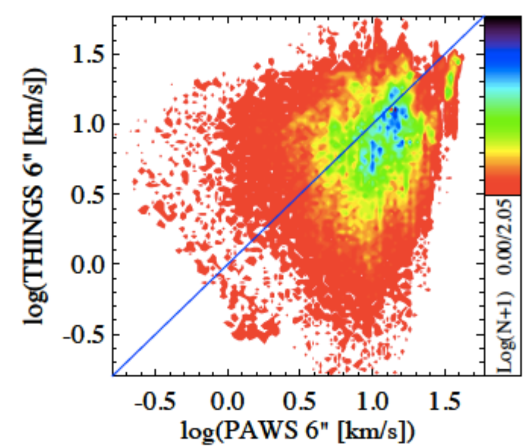
Colombo et al. (2014b)

residual velocity fields

molecular gas (PAWS) atomic gas (THINGS)



pixel-by-pixel comparison



Extra-planar molecular gas in M51

Pety et al. (2013)

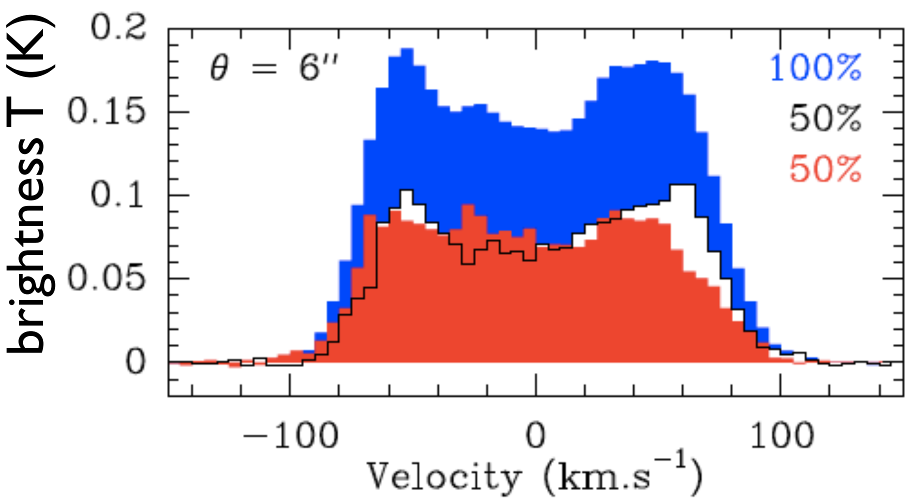
interferometer = spatial filter:

PdBI+30m : all scales

PdBI-only : small scales

'missing flux' : large scales

global spectrum



~ 50% of emission from >1.3kpc

Extra-planar molecular gas in M51

Pety et al. (2013)

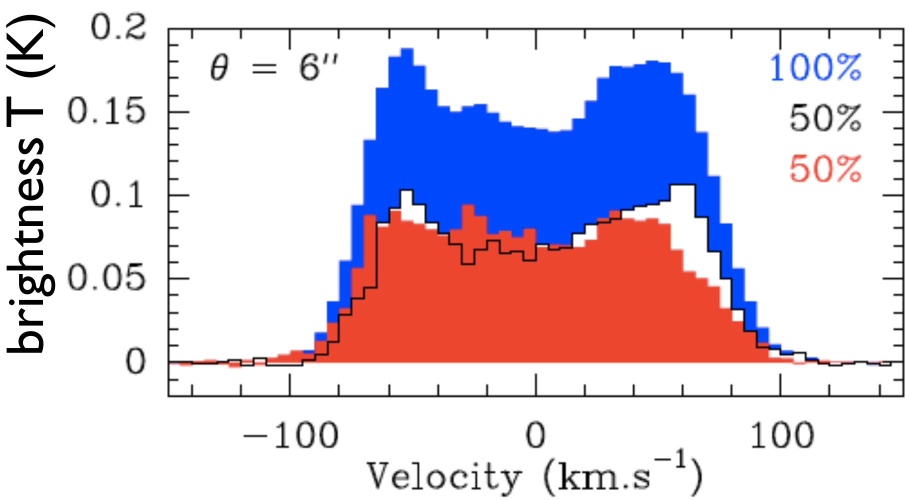
interferometer = spatial filter:

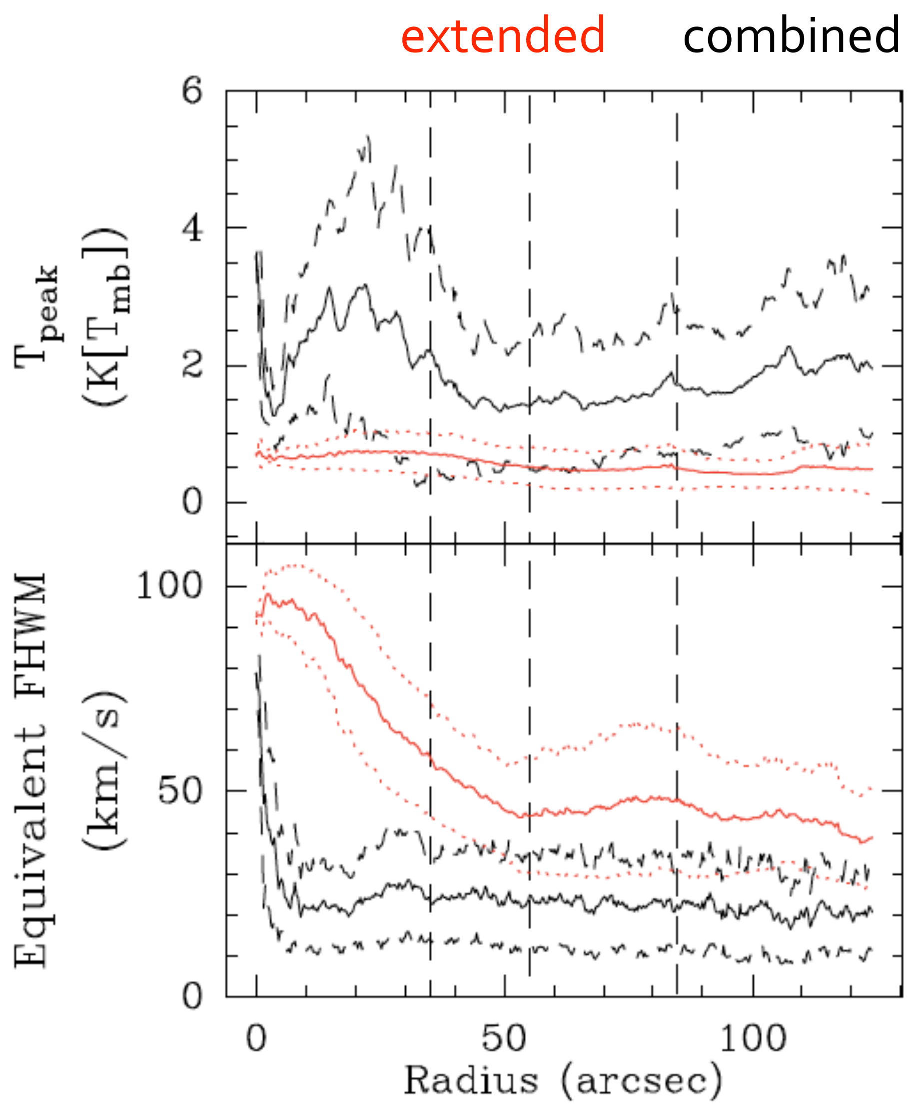
PdBI+30m : all scales

PdBI-only : small scales

'missing flux' : large scales

global spectrum





~ 50% of emission from scales >1.3kpc

in dynamically hot, thick disk

Extra-planar molecular gas

in M51:
evidence for extended extra-planar (~250pc scale height) molecular gas

Pety et al. (2013)

in 12 nearby galaxies:
similar CO(2-1) and HI line widths suggest presence of extra-planar gas

Caldu Primo et al. (2013)

Extra-planar molecular gas

PdBI Arcsecond Whirlpool Survey

in M51:
evidence for extended extra-planar (~250pc scale height) molecular gas

Pety et al. (2013)

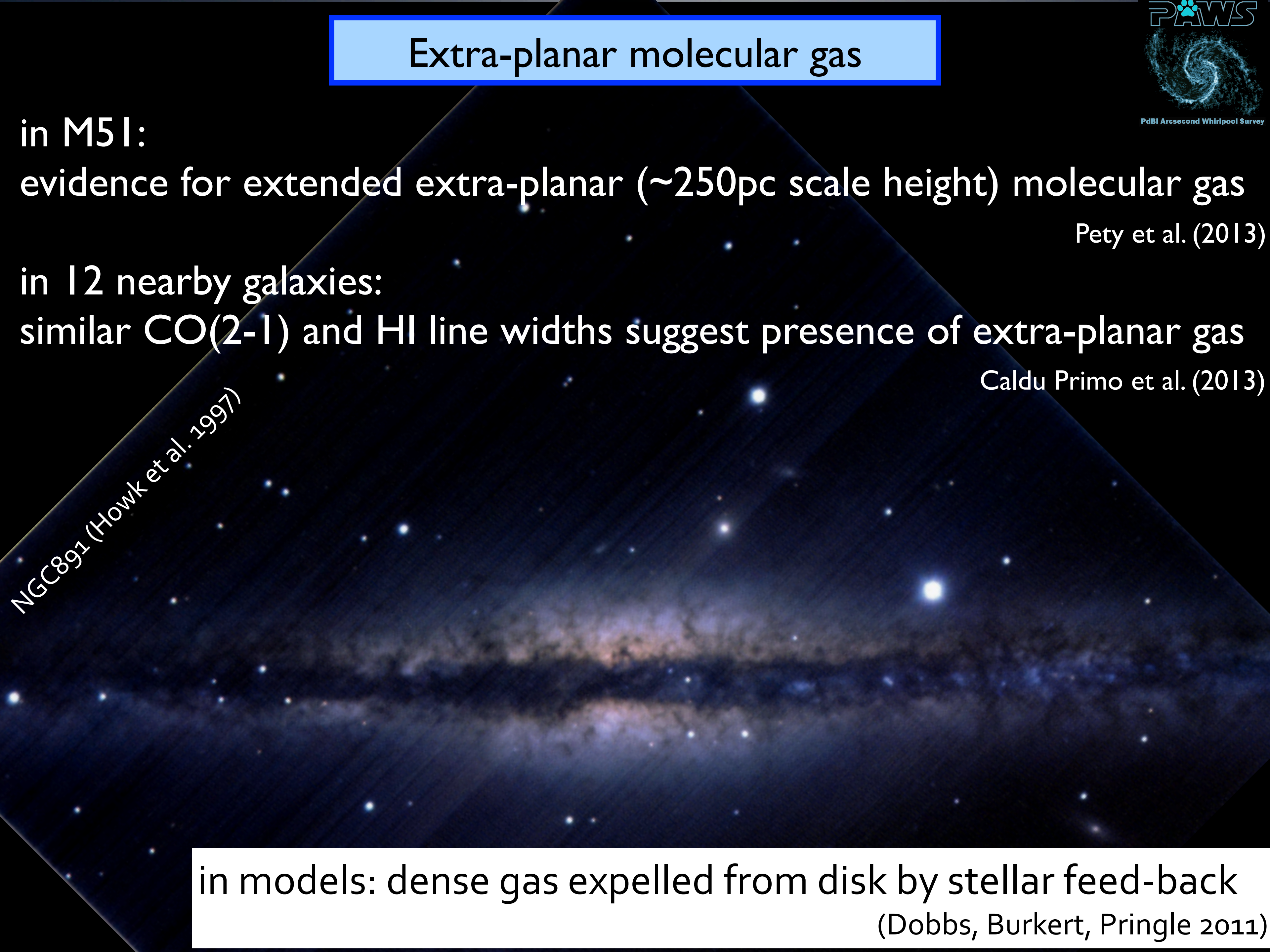
in 12 nearby galaxies:
similar CO(2-1) and HI line widths suggest presence of extra-planar gas

Caldu Primo et al. (2013)

NGC891 (Howk et al. 1997)

Extra-planar molecular gas

PdBI Arcsecond Whirlpool Survey



in M51:

evidence for extended extra-planar (~250pc scale height) molecular gas

Pety et al. (2013)

in 12 nearby galaxies:

similar CO(2-1) and HI line widths suggest presence of extra-planar gas

Caldu Primo et al. (2013)

in models: dense gas expelled from disk by stellar feed-back

(Dobbs, Burkert, Pringle 2011)

Molecular gas and star formation in spiral galaxies

#1:
3D distribution of molecular gas differs from atomic gas one

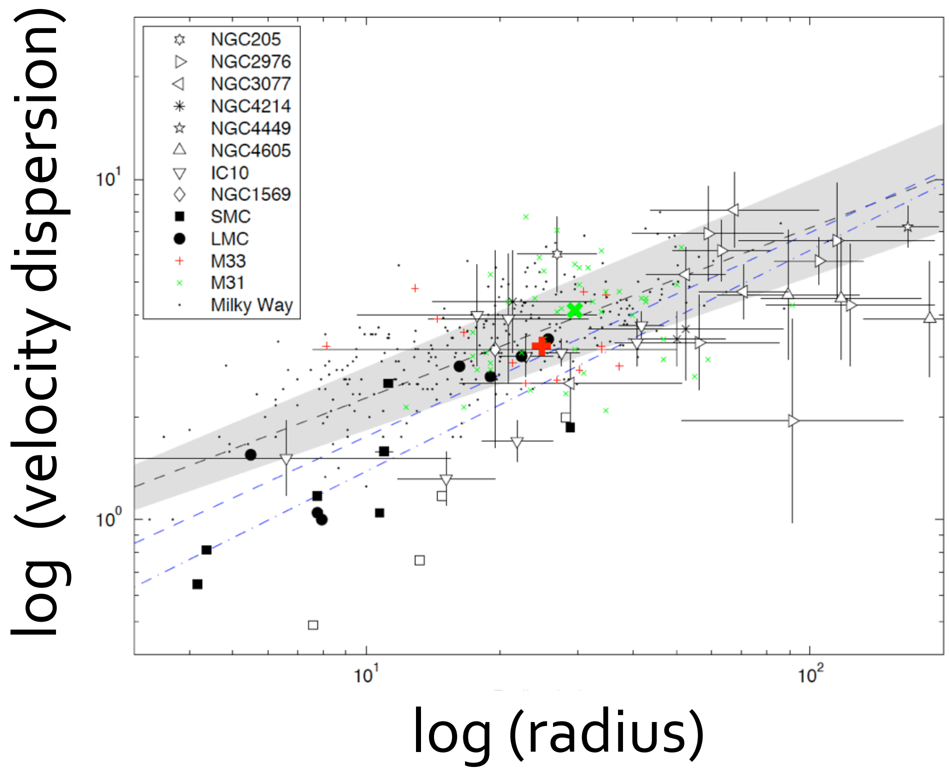
#2:
Giant Molecular Cloud properties are set by environment

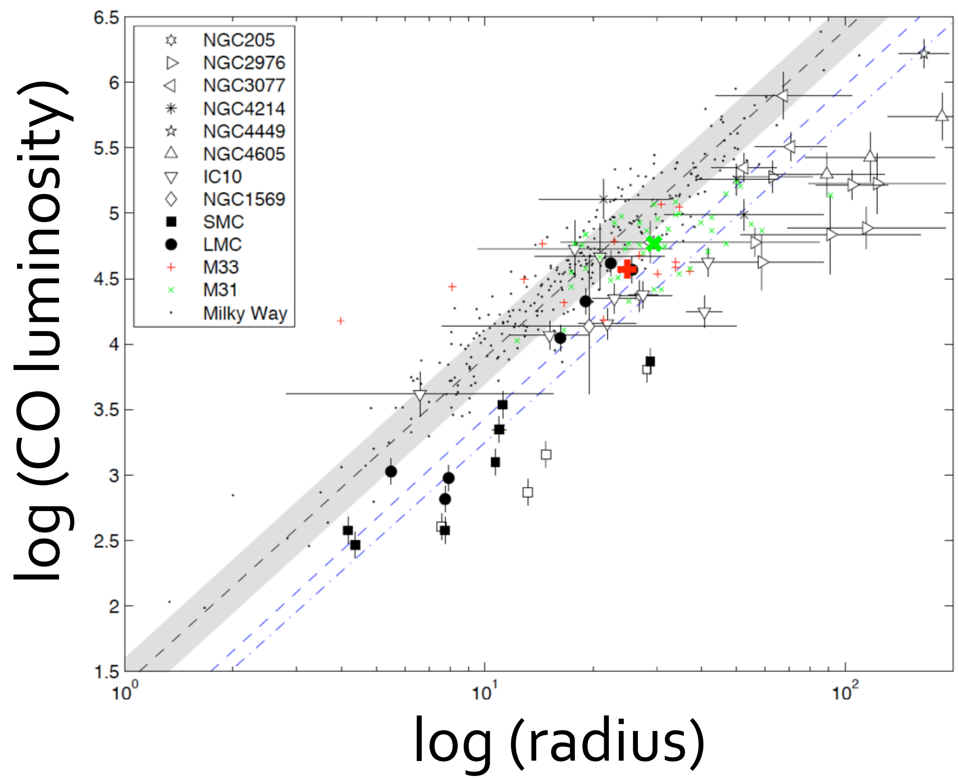
#3:
Conversion of molecular gas into stars is complex process

Cloud properties are universal

Consistent study of 12 nearby galaxies

(Bolatto et al. 2008)



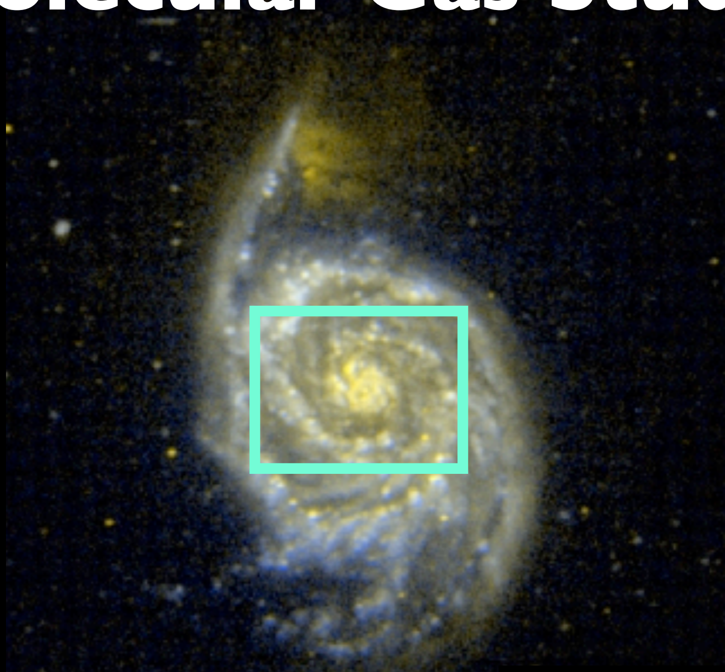


GMCs are/have:

virialized

constant surface density

Molecular Gas Studies in Nearby Galaxies

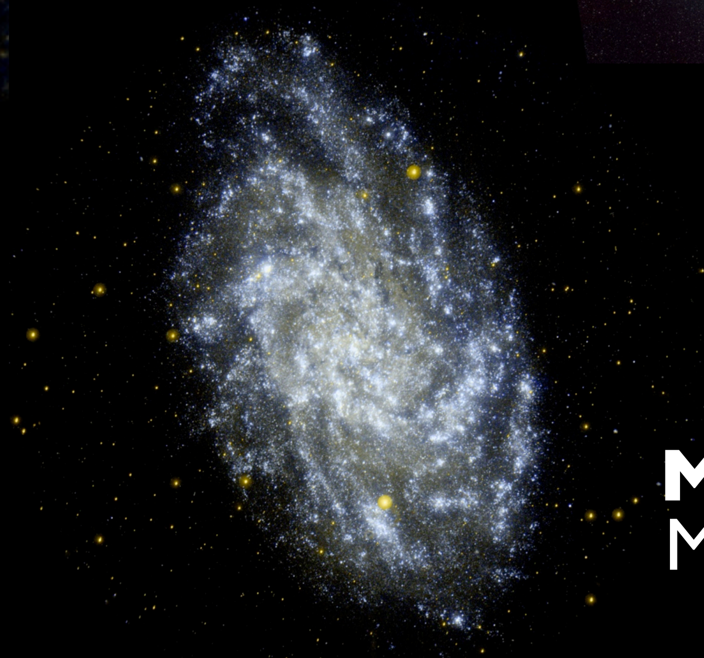


M51

M_* : 3.6e10 M_{sun}

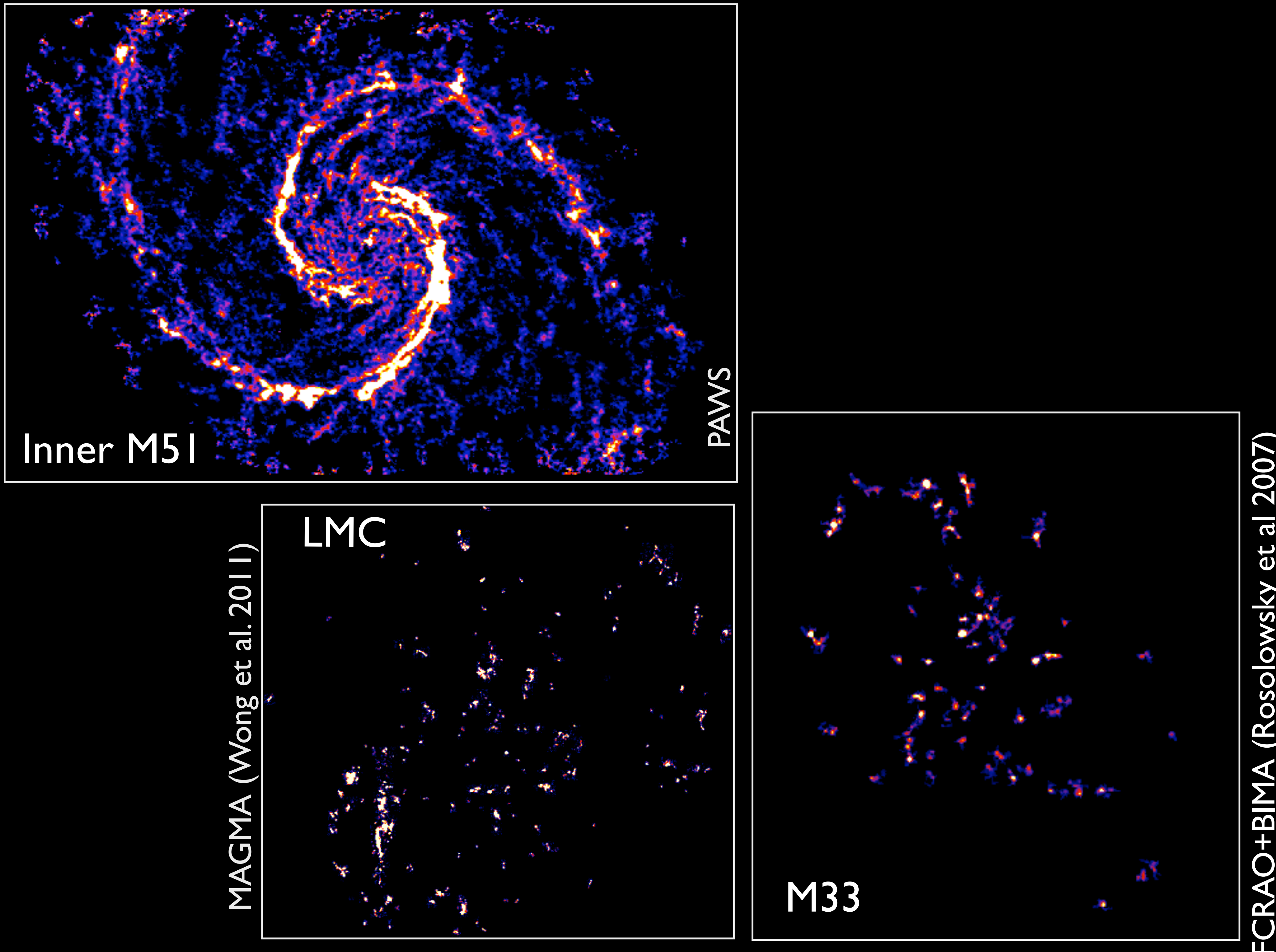
LMC

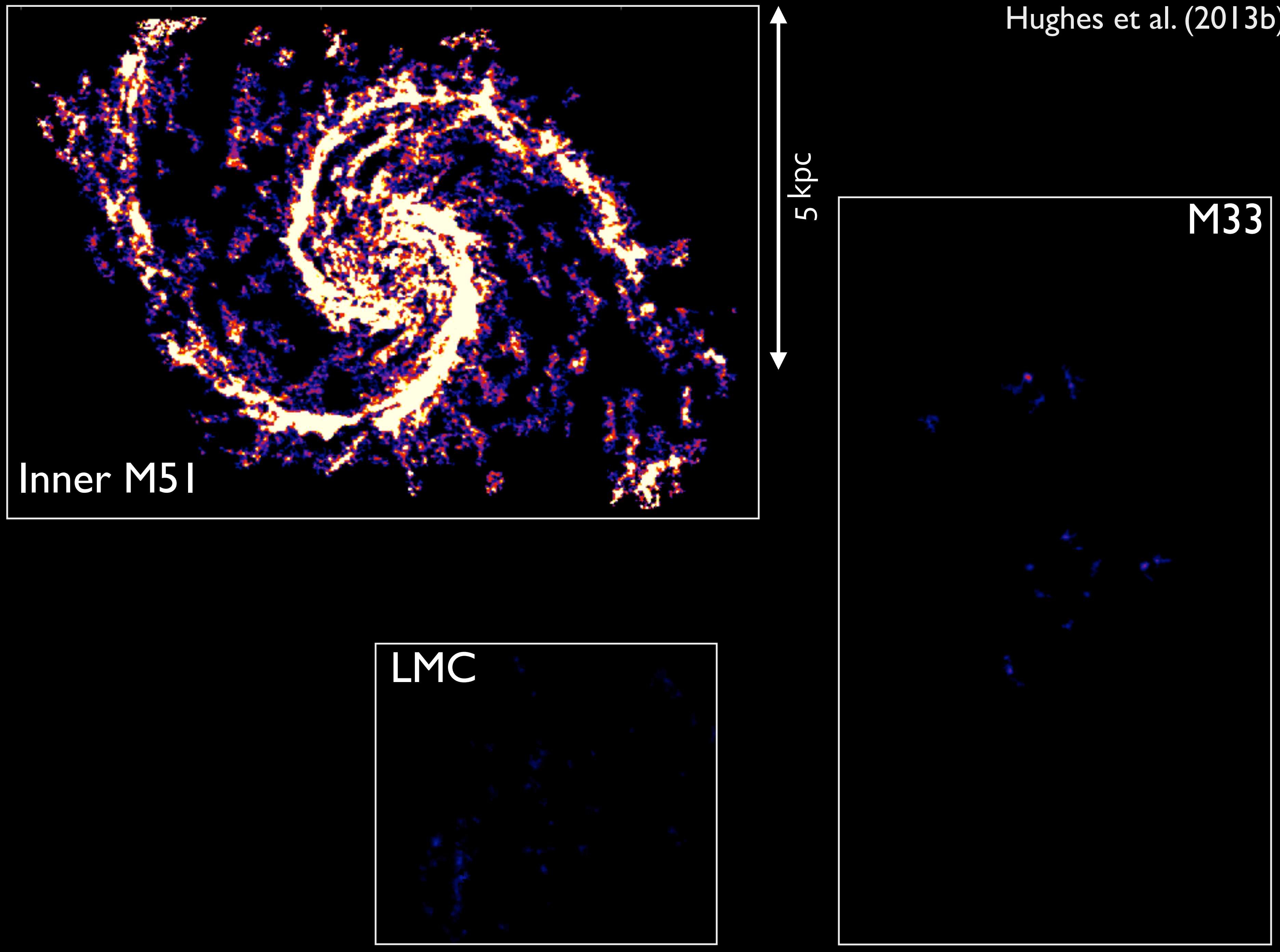
M_* : 2.7e9 M_{sun}



M33

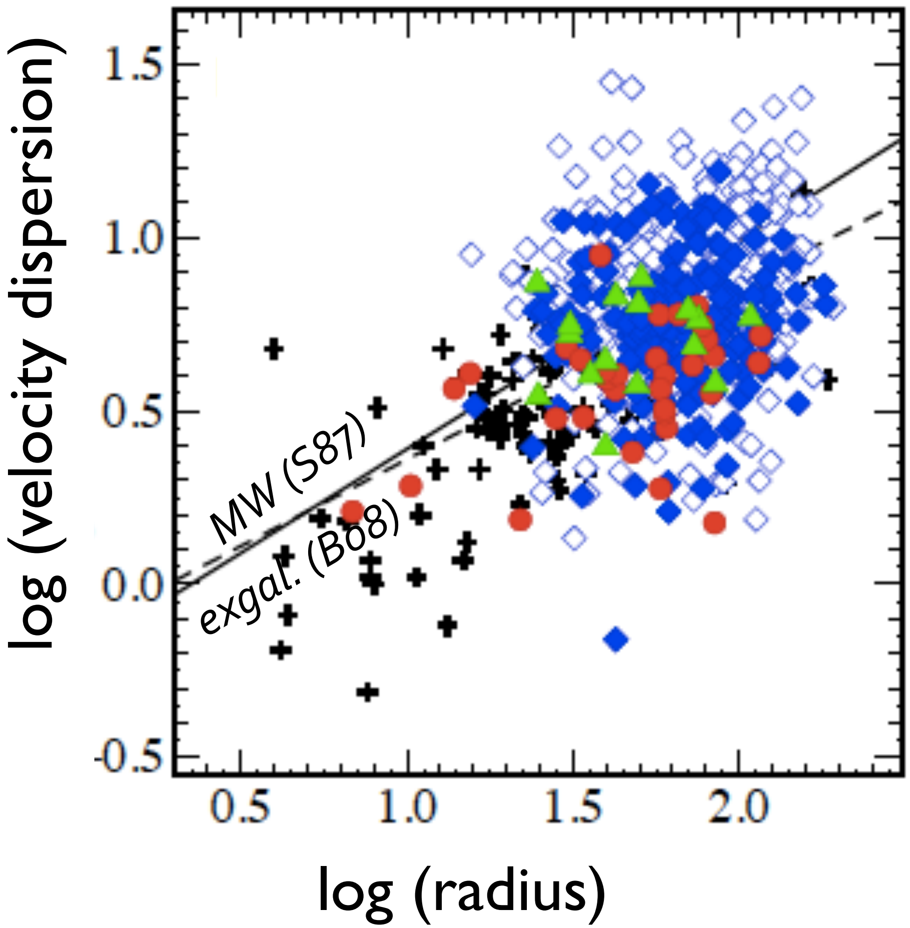
M_* : ~5e9 M_{sun}

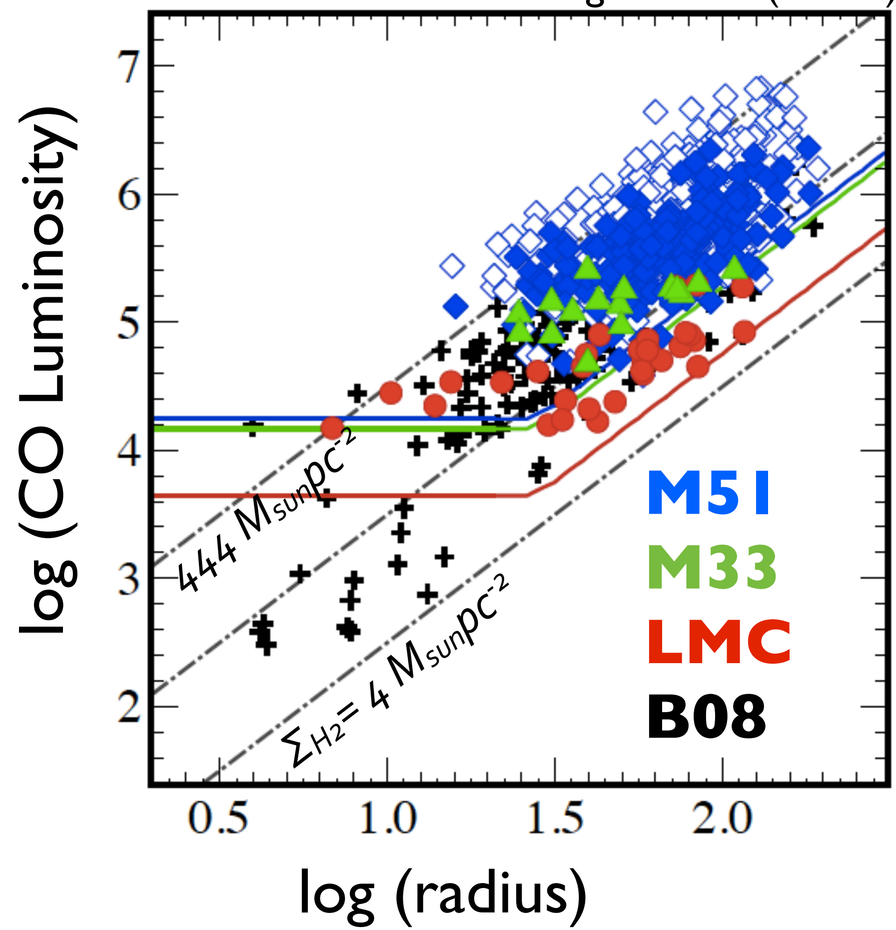

Inner M51
PAWS
LMC
MAGMA (Wong et al. 2011)
M33
FCRAO+BIMA (Rosolowsky et al 2007)


Hughes et al. (2013b)
5 kpc
Inner M51
M33
LMC

Cloud properties are not universal

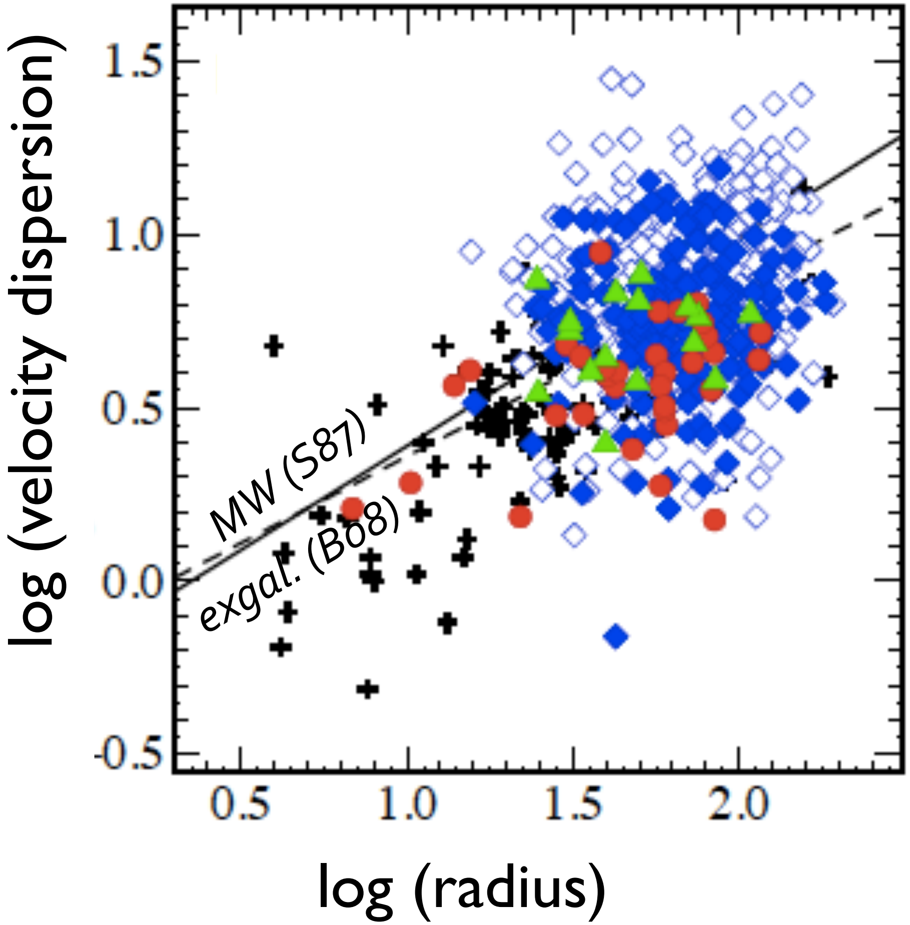
Hughes et al. (2013b)

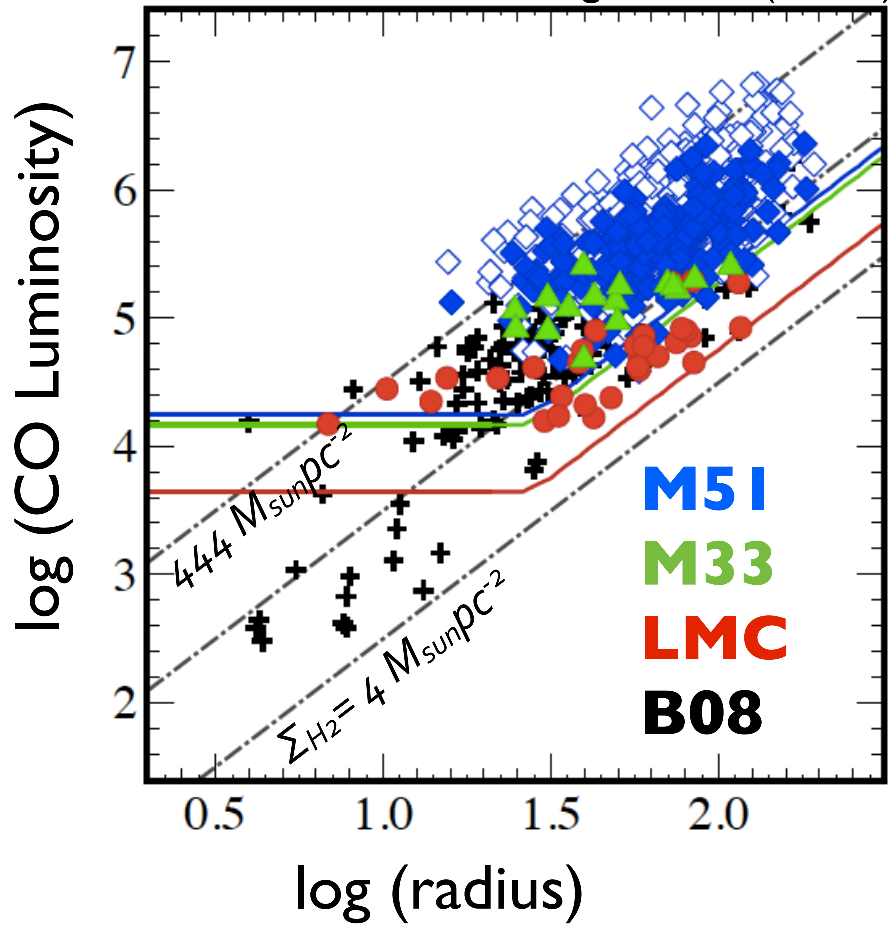




Cloud properties are not universal

Hughes et al. (2013b)





no size-line width relation

⇨

clouds are not (always) virialized

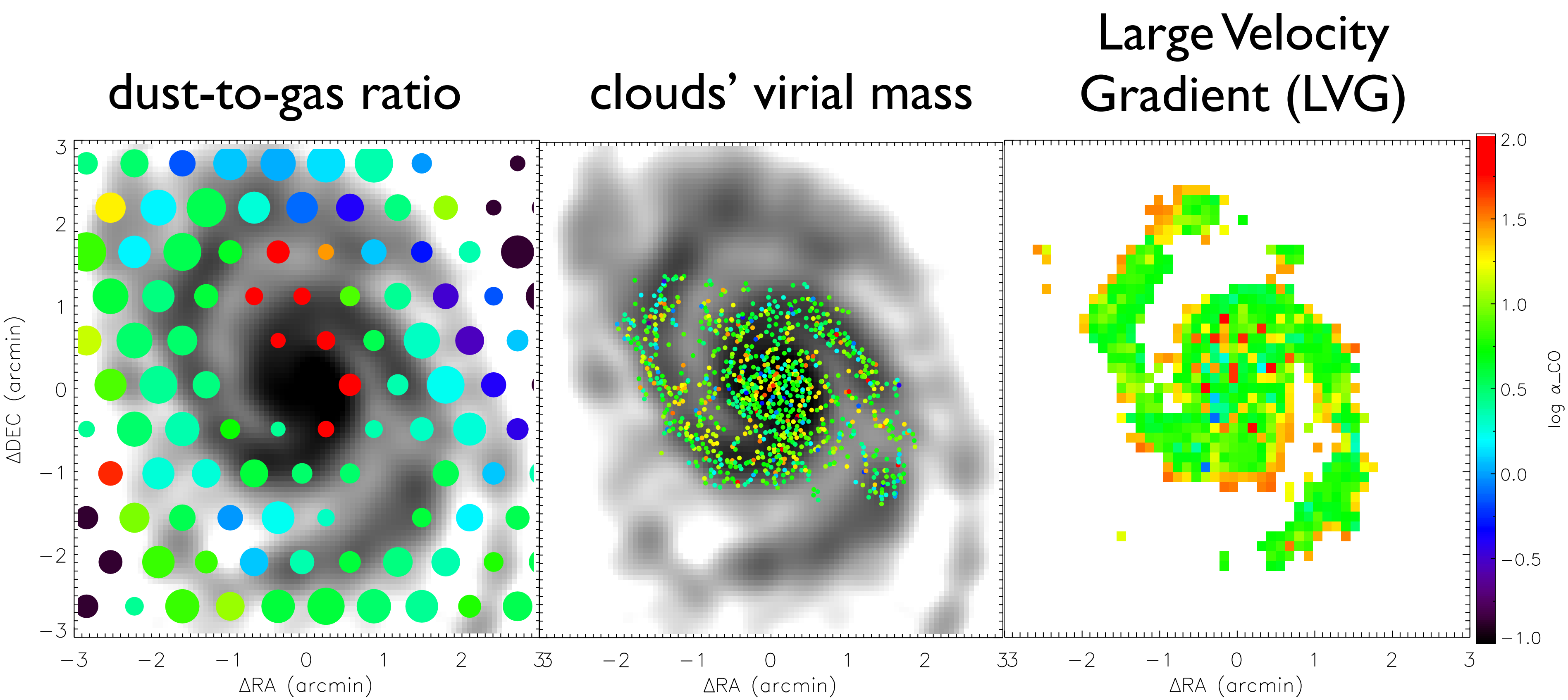
large range of gas surface densities

⇨

GMC properties are not universal

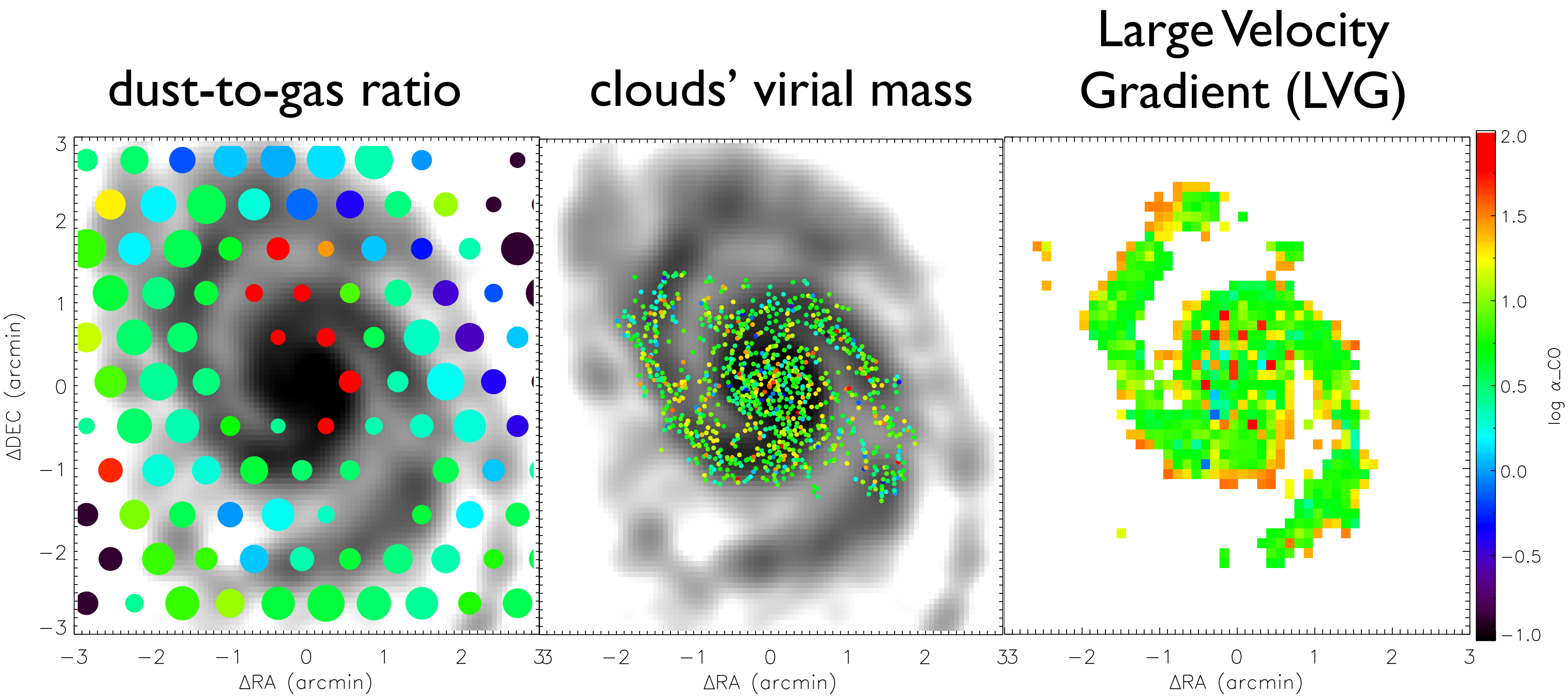
Consistent conversion factor in M51

Groves et al. (in prep.)



Consistent conversion factor in M51

Groves et al. (in prep.)



α_{CO} ~ Galactic value &
consistent (w/i 2x) across methods

Do spiral arms impact cloud properties?

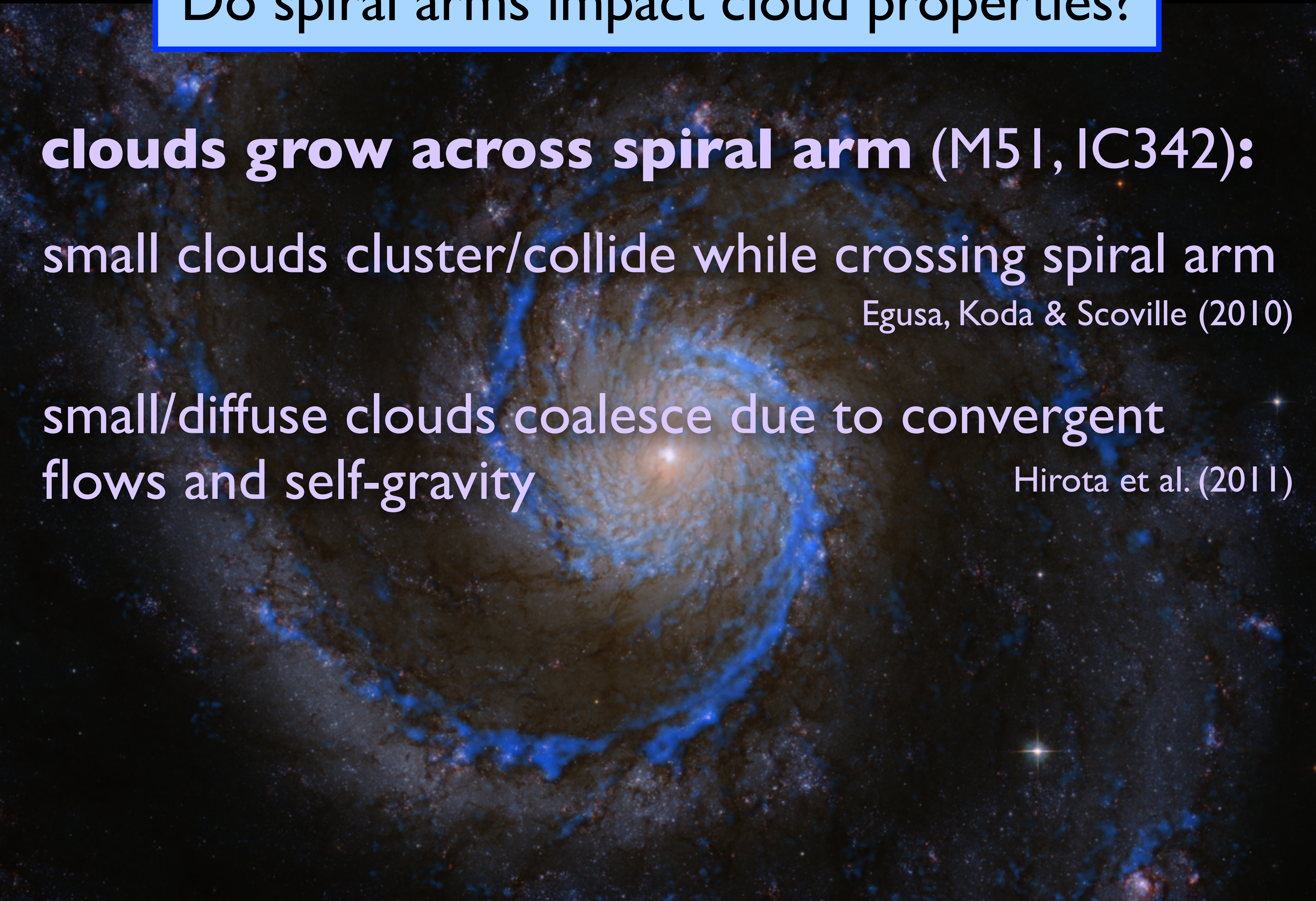
clouds grow across spiral arm (M51, IC342):

small clouds cluster/collide while crossing spiral arm

Egusa, Koda & Scoville (2010)

small/diffuse clouds coalesce due to convergent flows and self-gravity

Hirota et al. (2011)



Do spiral arms impact cloud properties?

clouds grow across spiral arm (M51, IC342):

small clouds cluster/collide while crossing spiral arm

Egusa, Koda & Scoville (2010)

small/diffuse clouds coalesce due to convergent flows and self-gravity

Hirota et al. (2011)

numerical simulations:

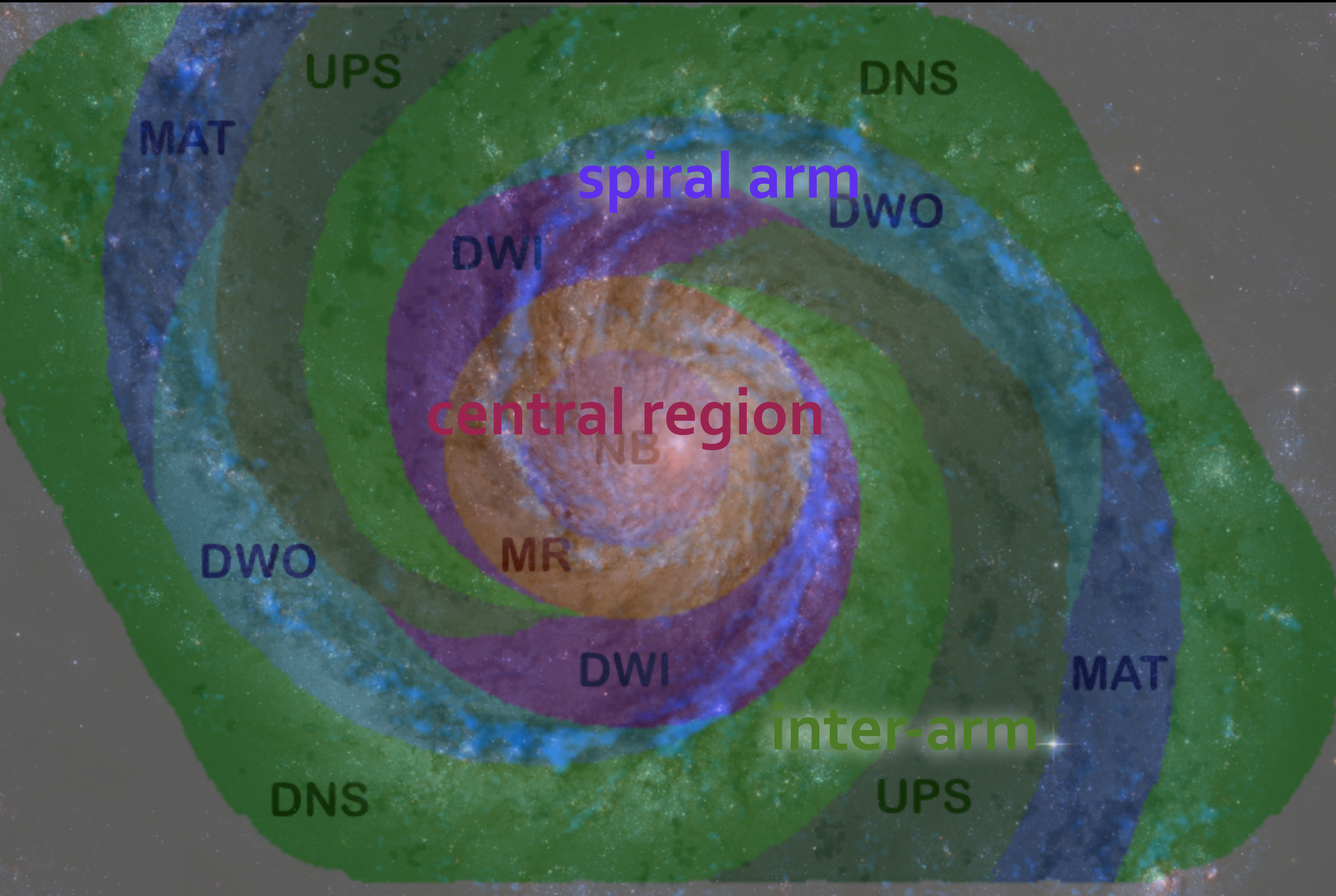
more high mass clouds, but typical cloud unchanged

Fujimoto et al. (2014)

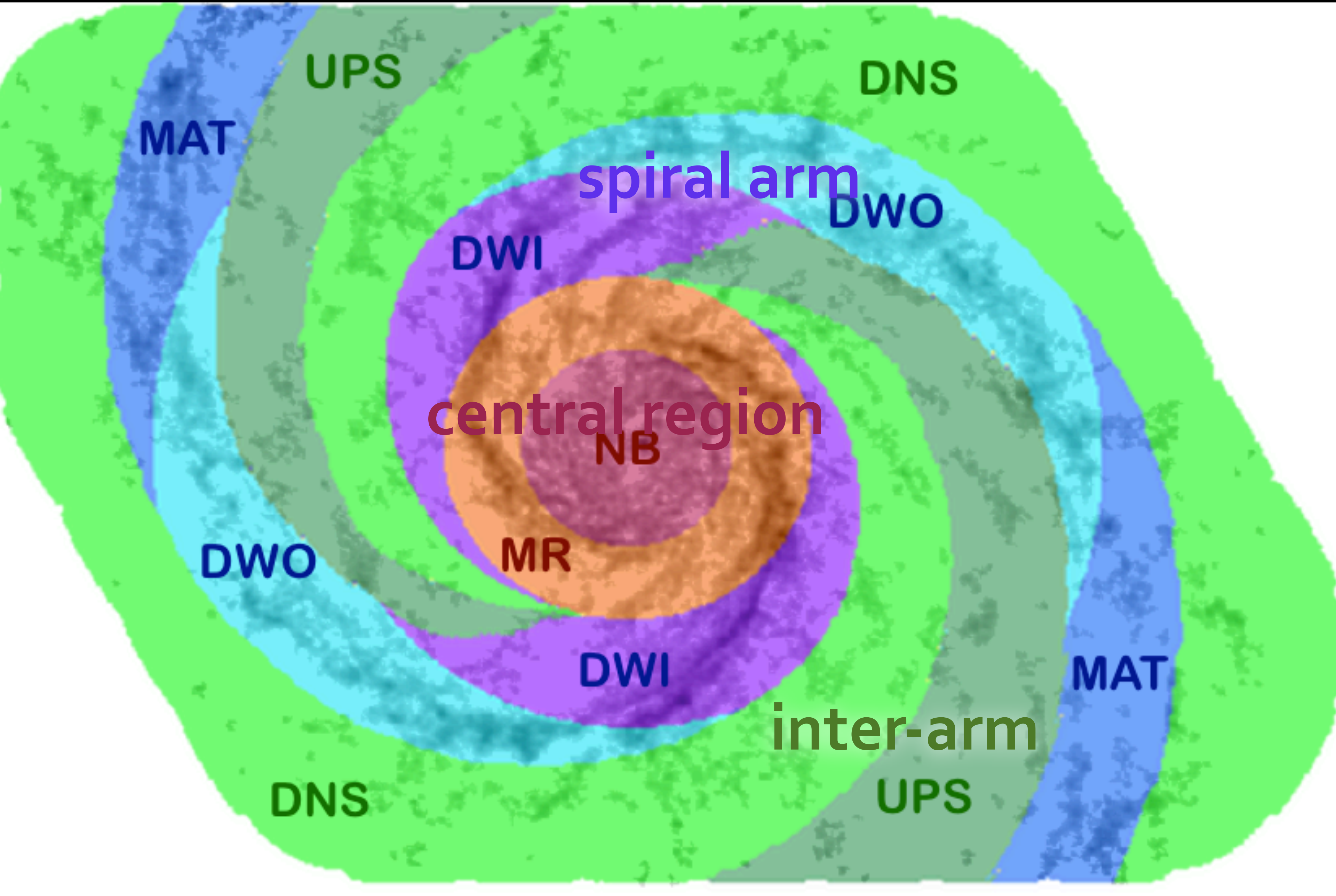
Galactic environments in M51

PAWS
PdBI Arcsecond Whirlpool Survey

Galactic environments in M51



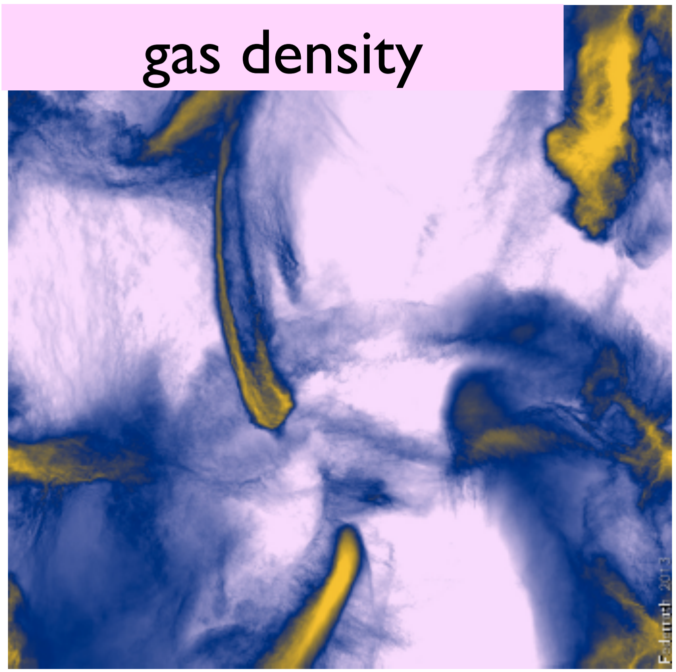
Galactic environments in M51



Molecular gas structure varies with environment

PDF - Probability Distribution Function

(local) MW clouds



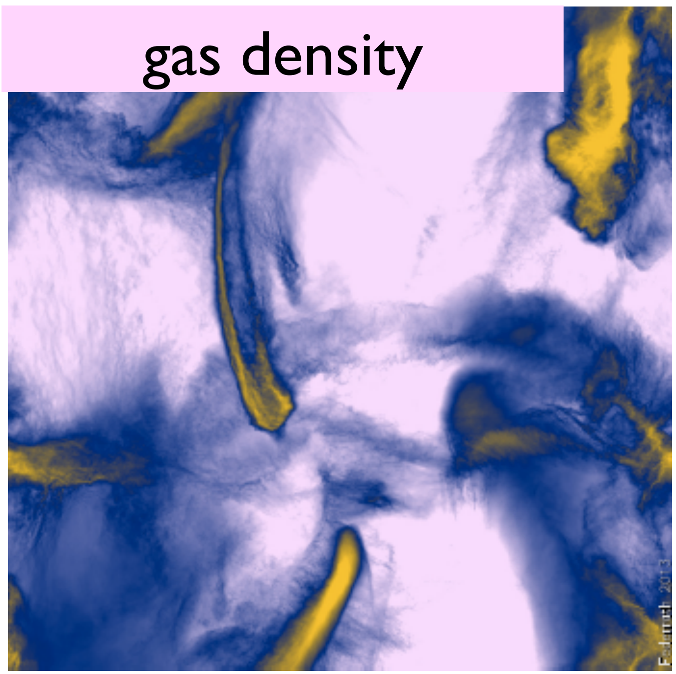
e.g. Federrath (2013)

Molecular gas structure varies with environment

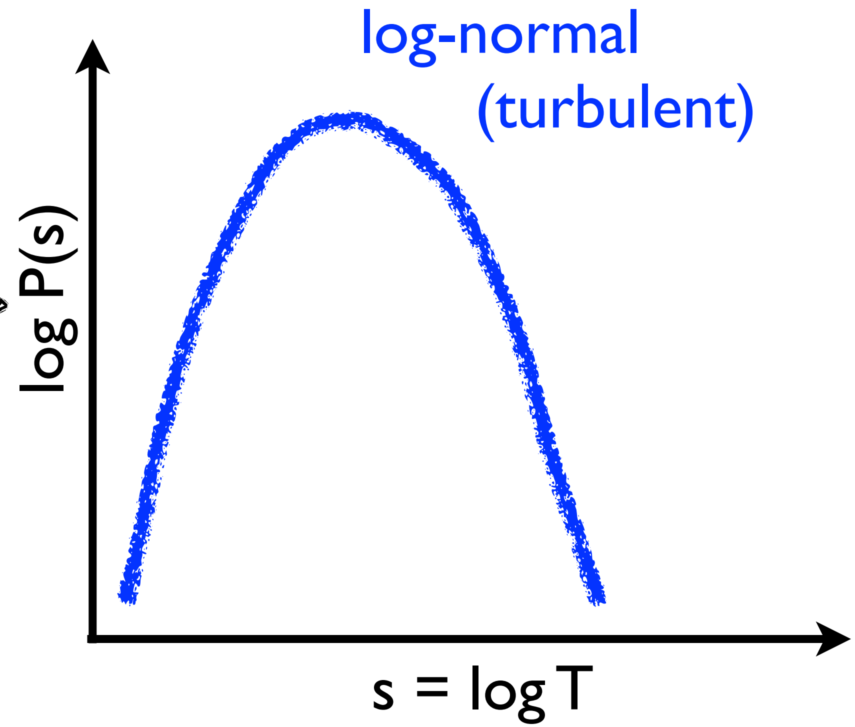
PDF - Probability Distribution Function

Kainulainen et al. (2011)

(local) MW clouds



e.g. Federrath (2013)

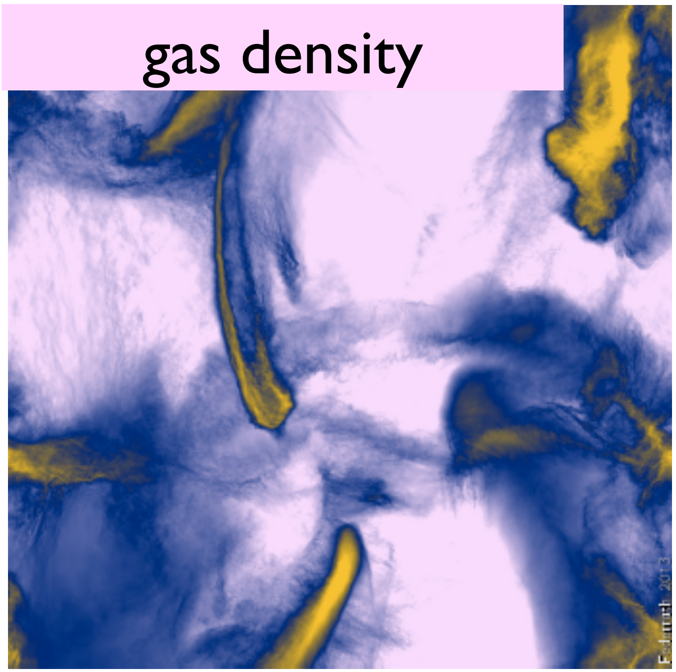


Molecular gas structure varies with environment

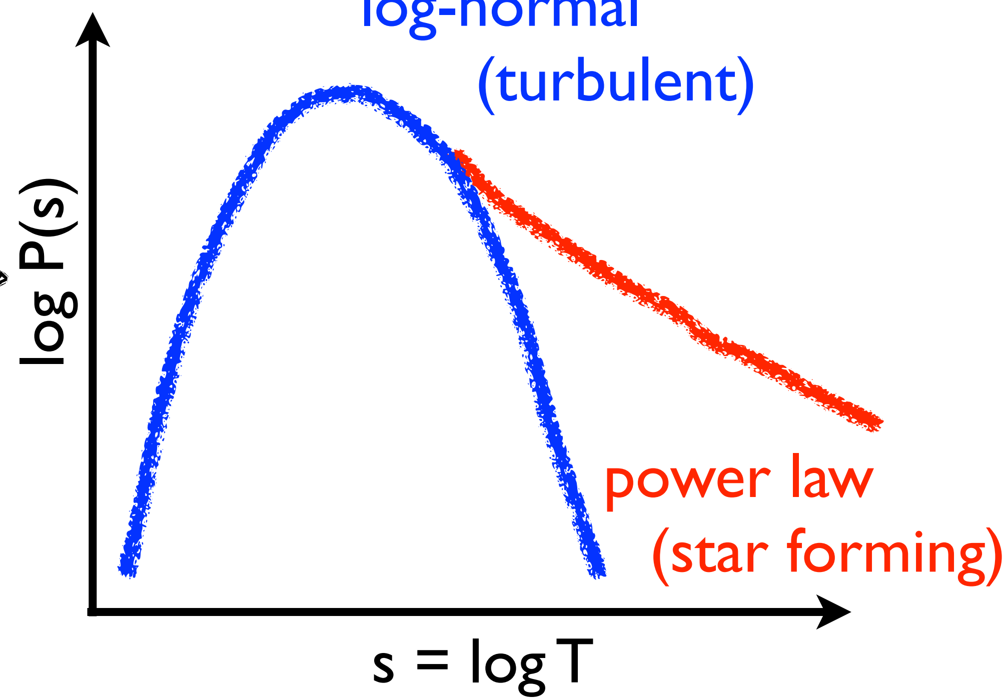
PDF - Probability Distribution Function

Kainulainen et al. (2011)

(local) MW clouds



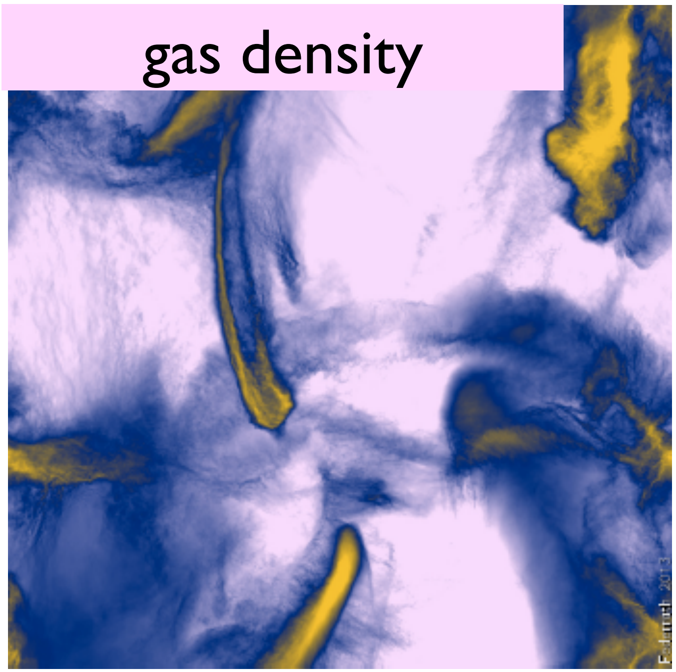
e.g. Federrath (2013)



Molecular gas structure varies with environment

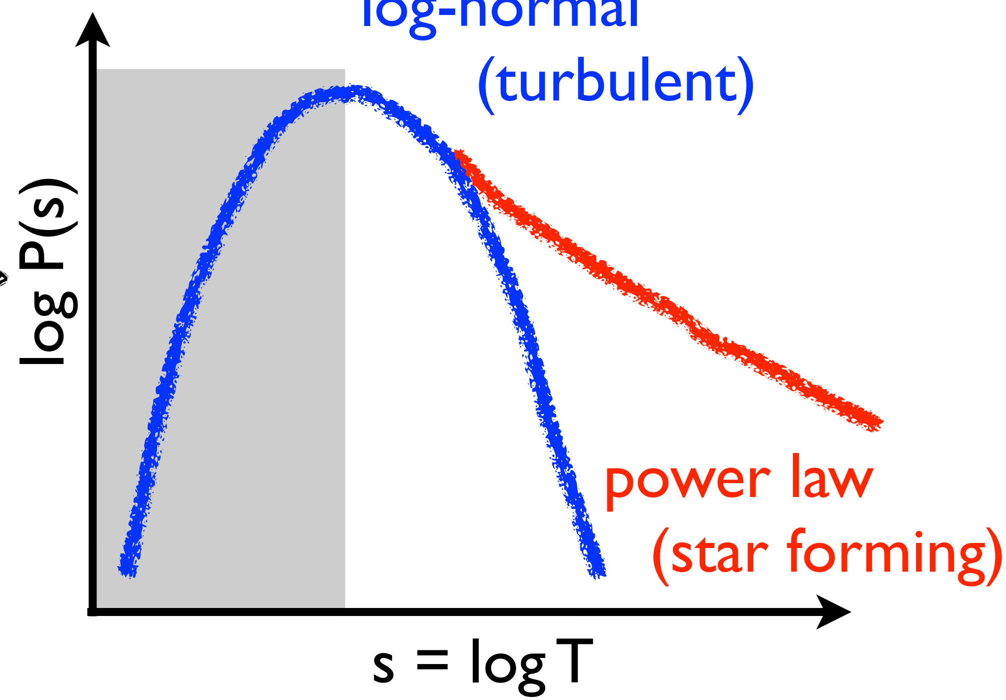
PDF - Probability Distribution Function

(local) MW clouds



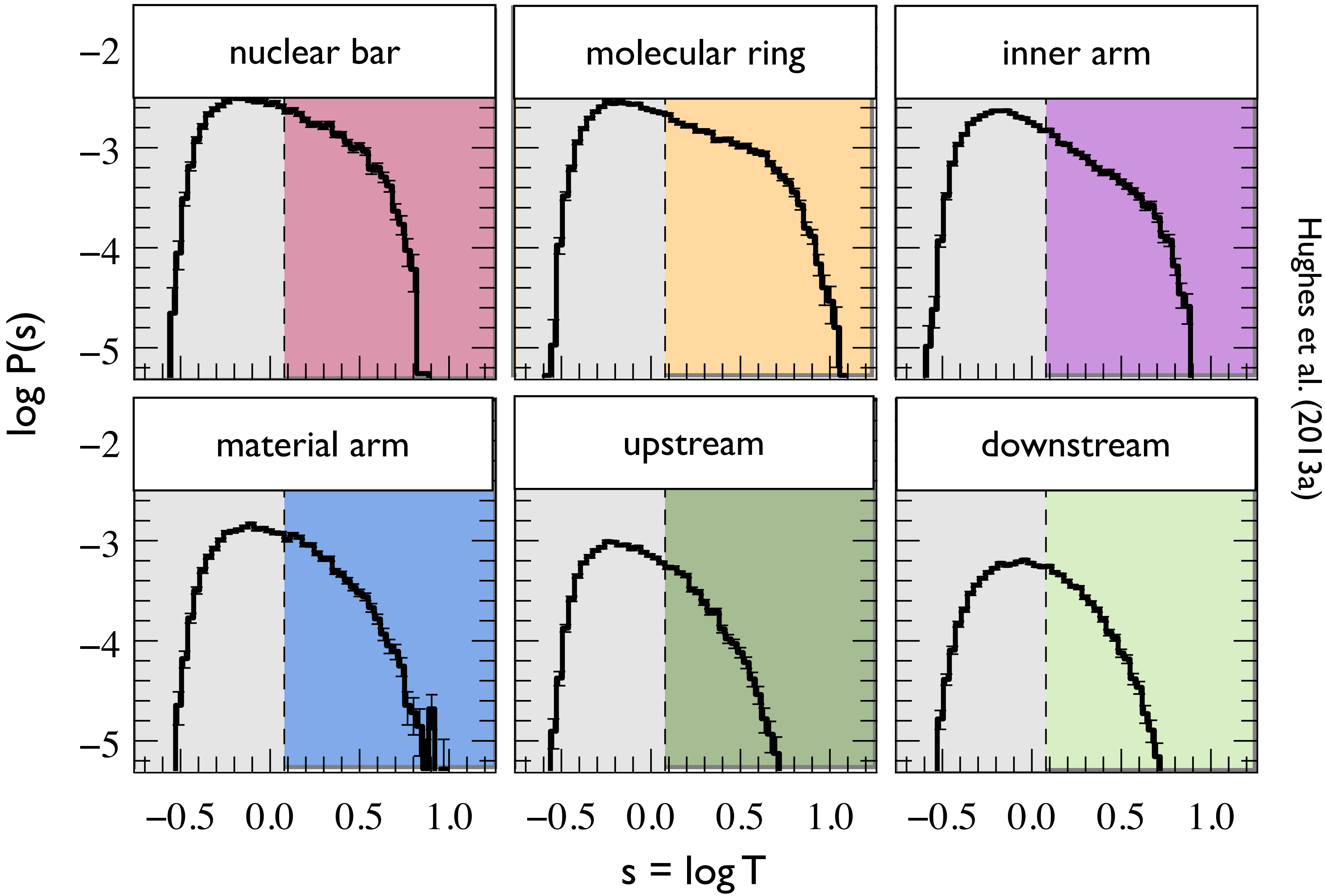
e.g. Federrath (2013)

Kainulainen et al. (2011)



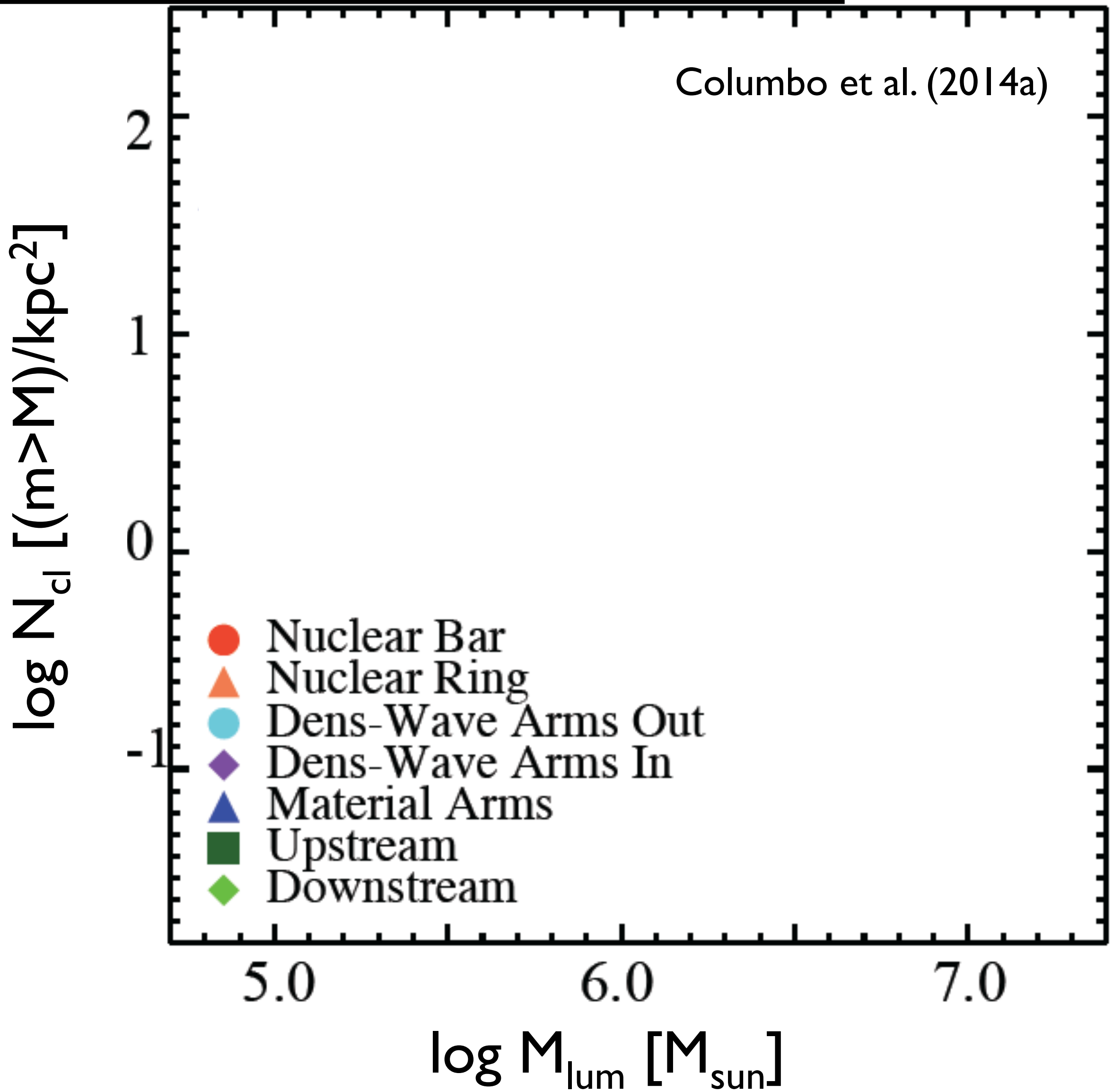
Molecular gas structure varies with environment

PDF - Probability Distribution Function



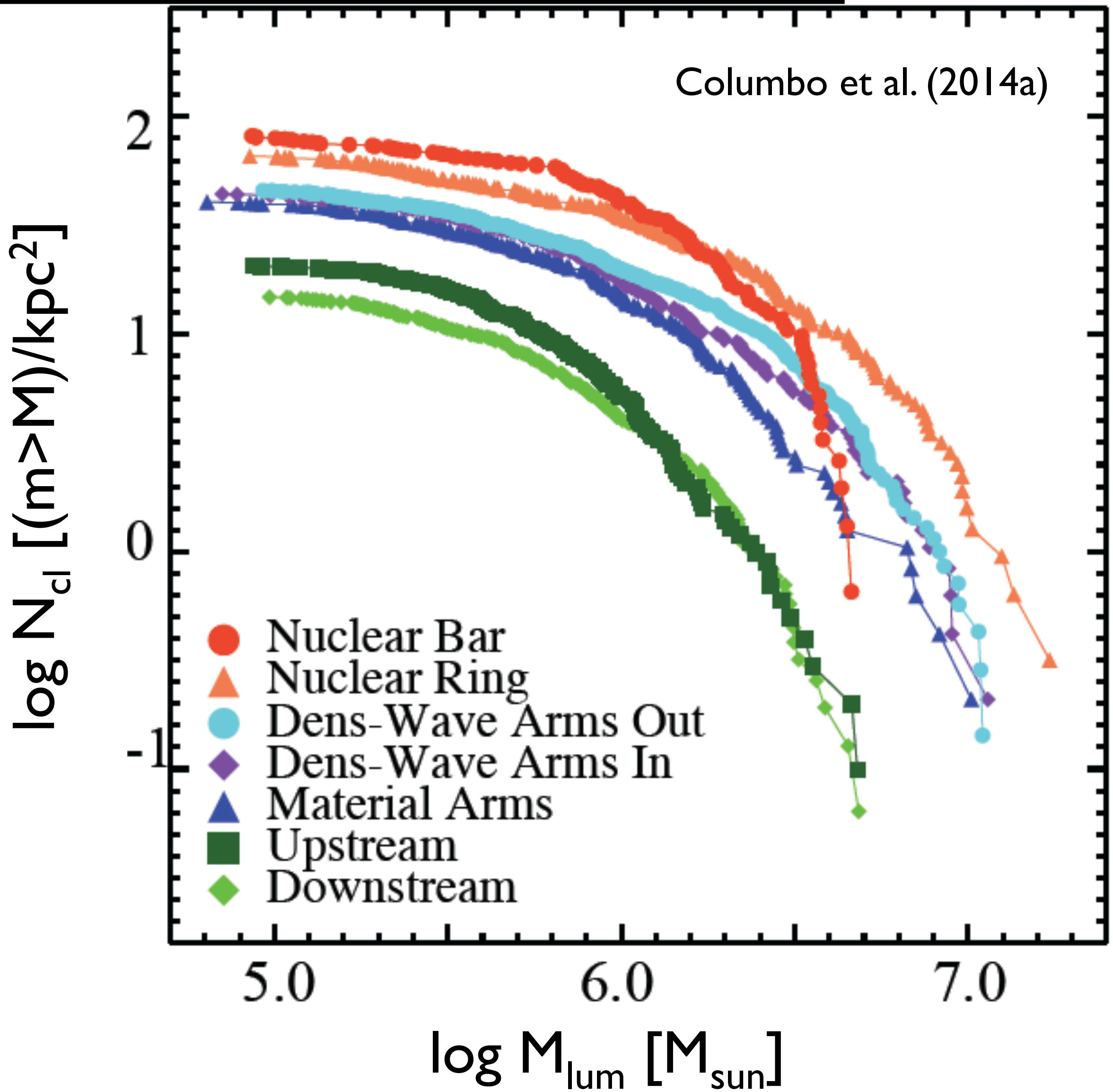
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function



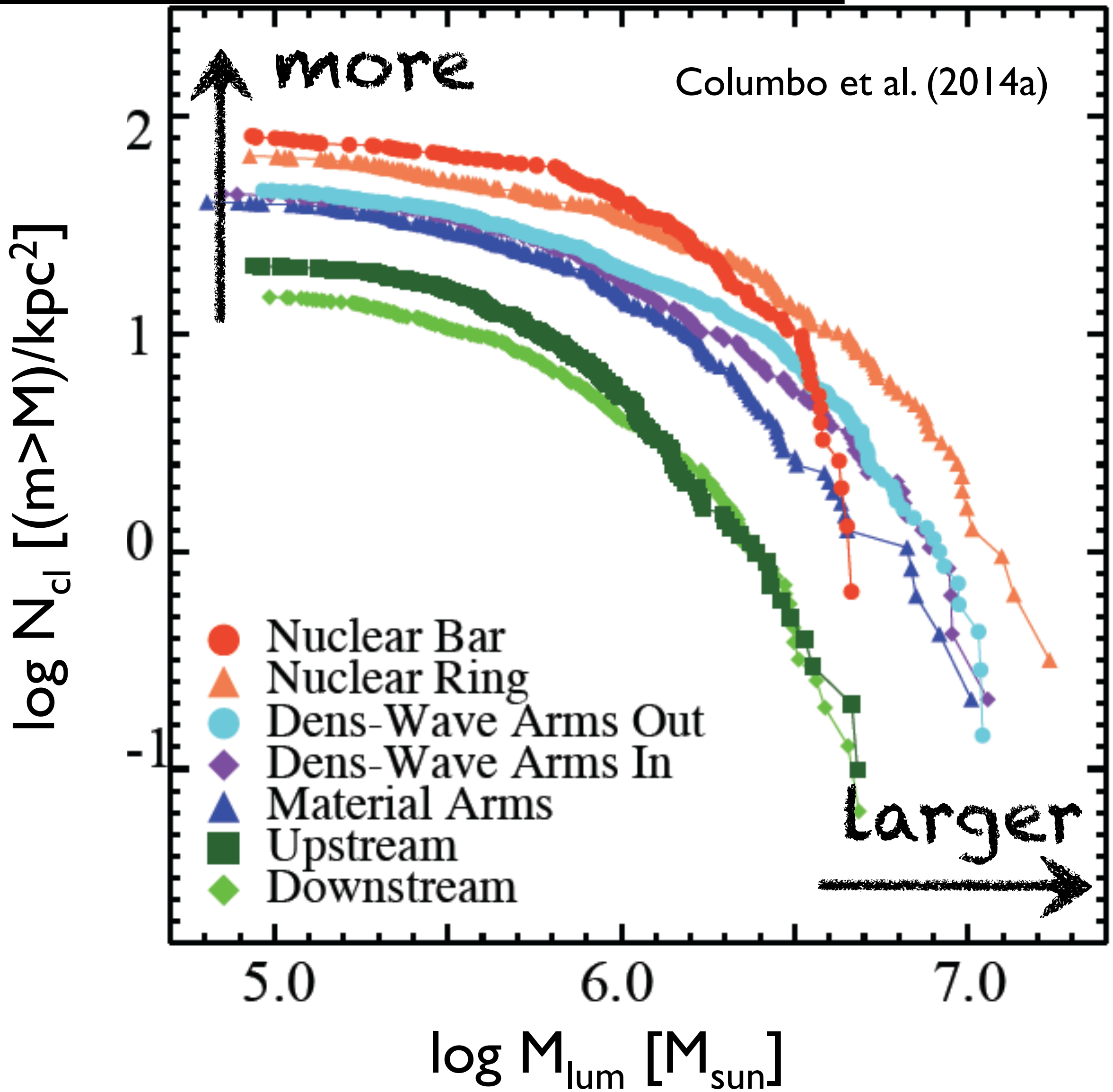
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function



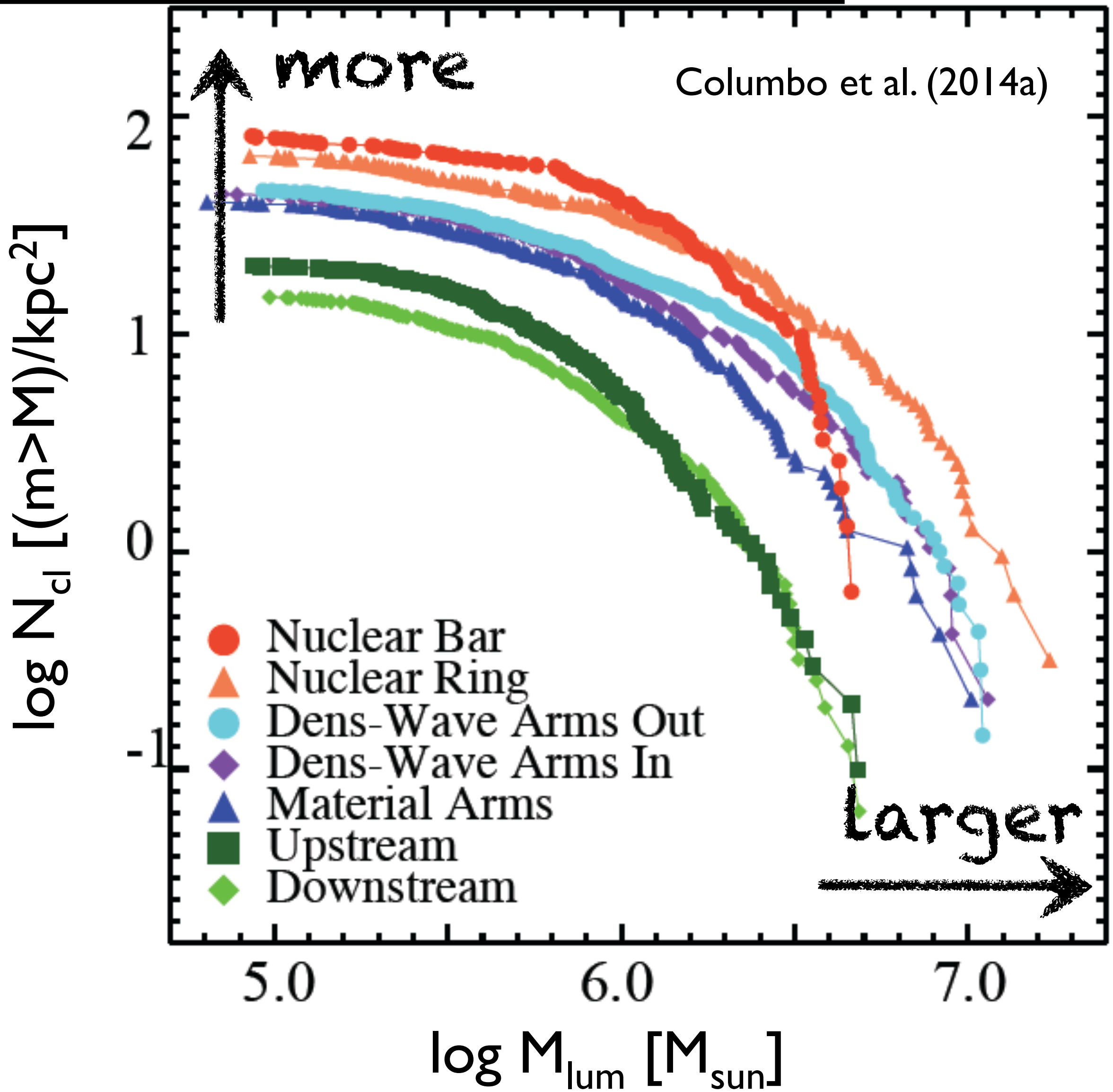
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function



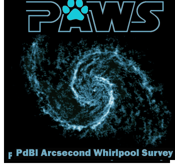
GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

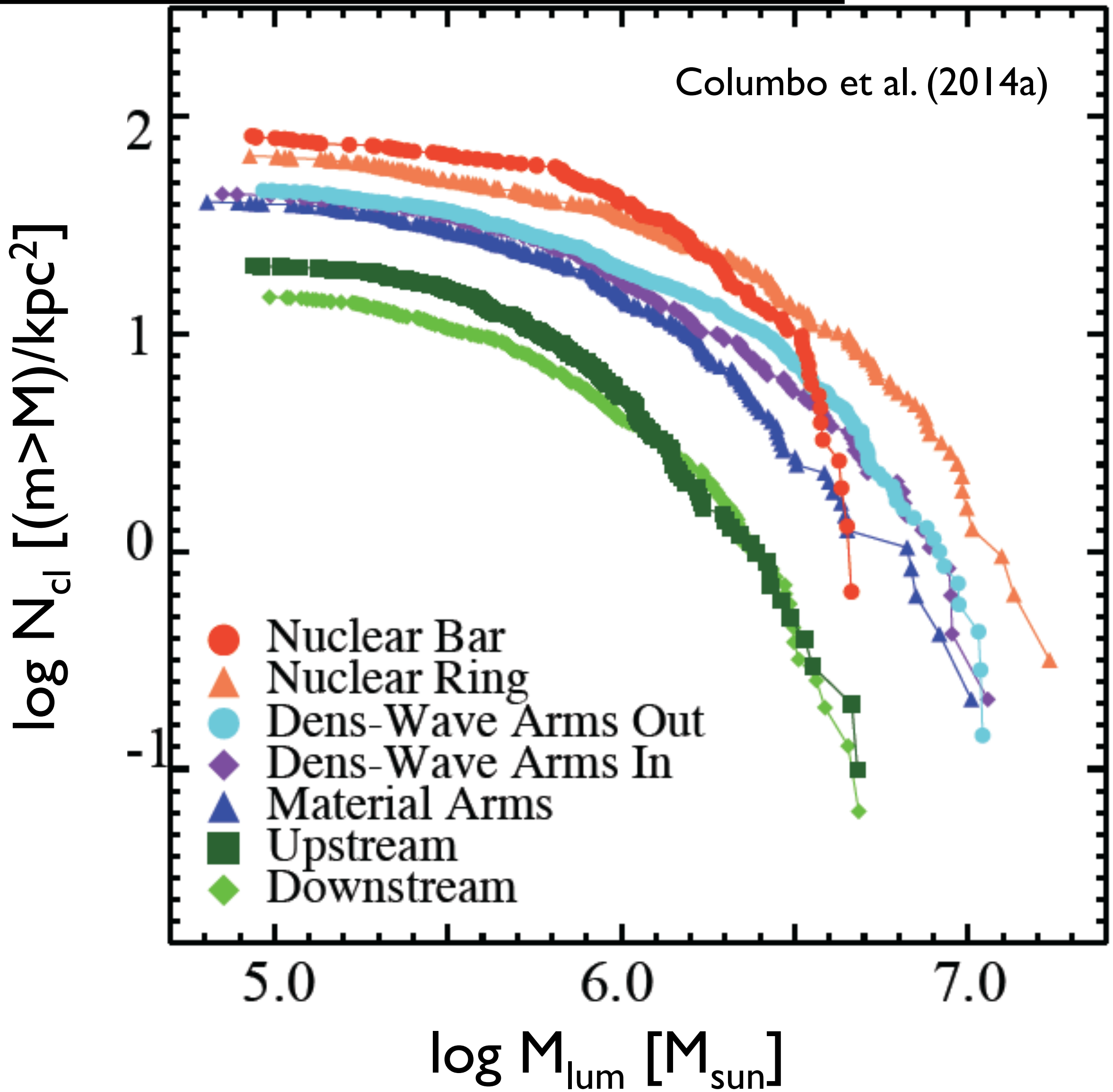


more & larger
clouds
in arm and center

GMC properties vary with environment



Giant Molecular Cloud (GMC) mass function

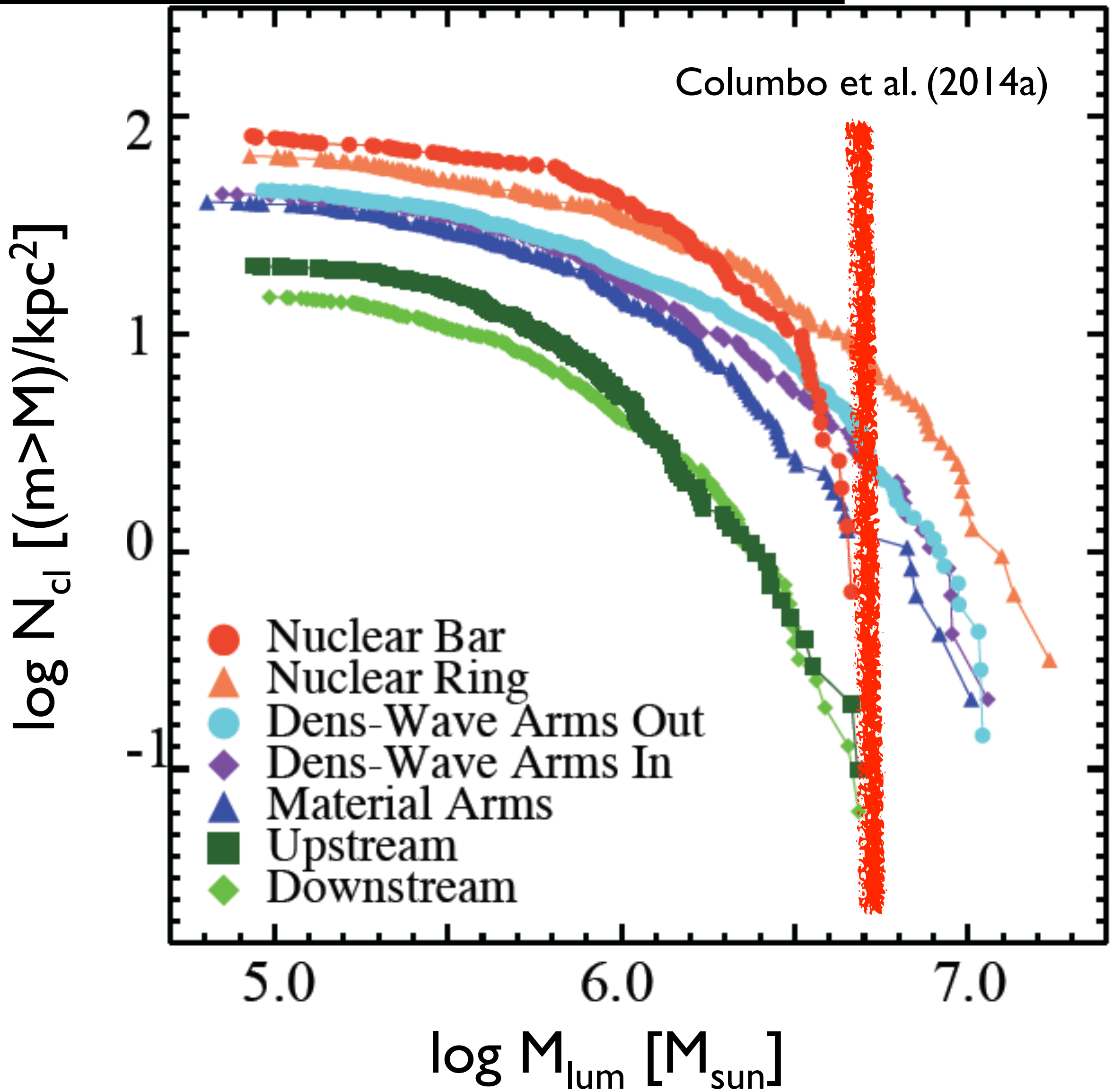


disk clouds

- grow in spiral arm via
  - agglomeration
  - merging/collision
- dispelled in inter-arm
  - star formation
  - shear

GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function

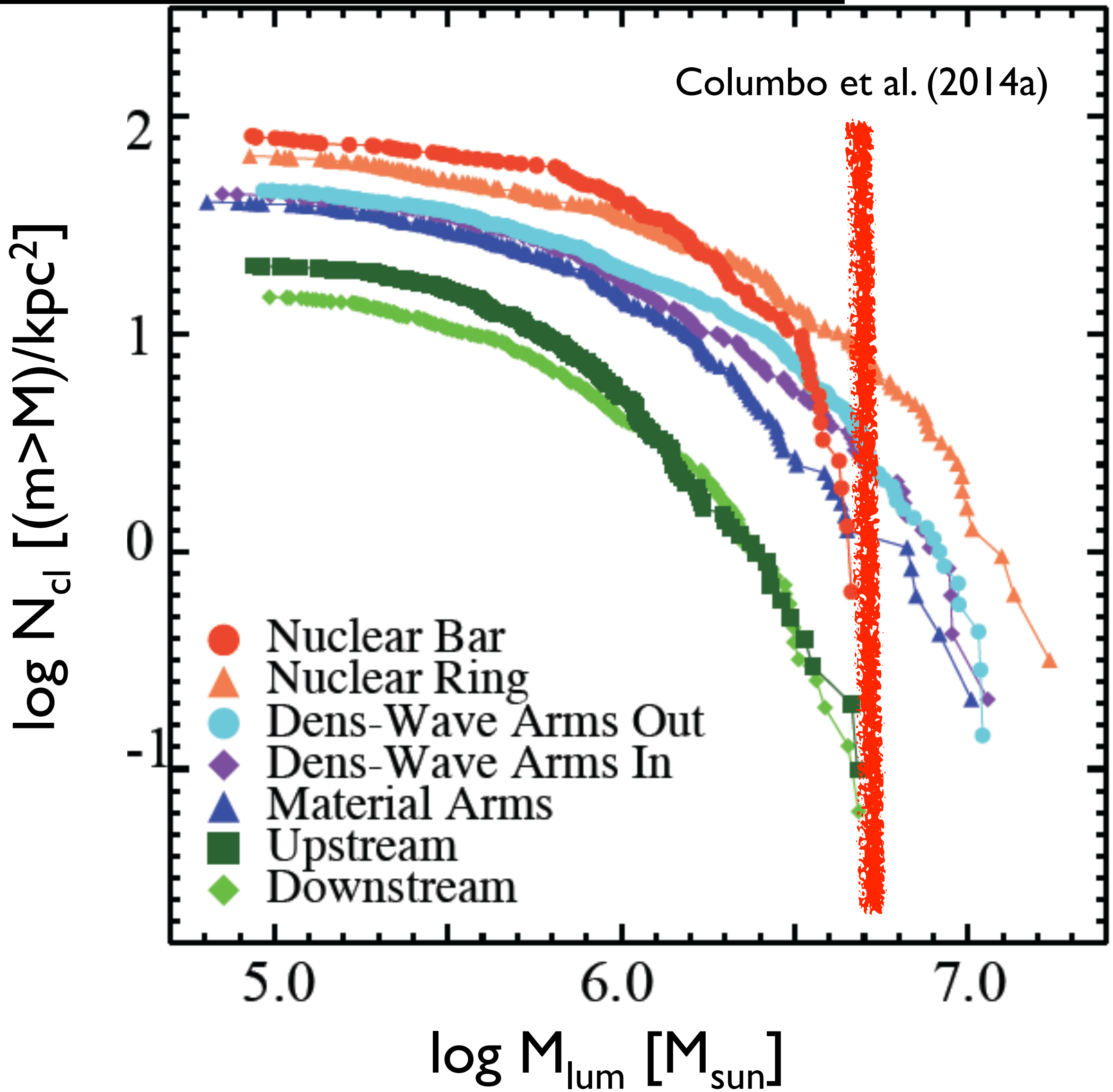


disk clouds

- grow in spiral arm via
  - agglomeration
  - merging/collision
- dispelled in inter-arm
  - star formation
  - shear

GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function



disk clouds

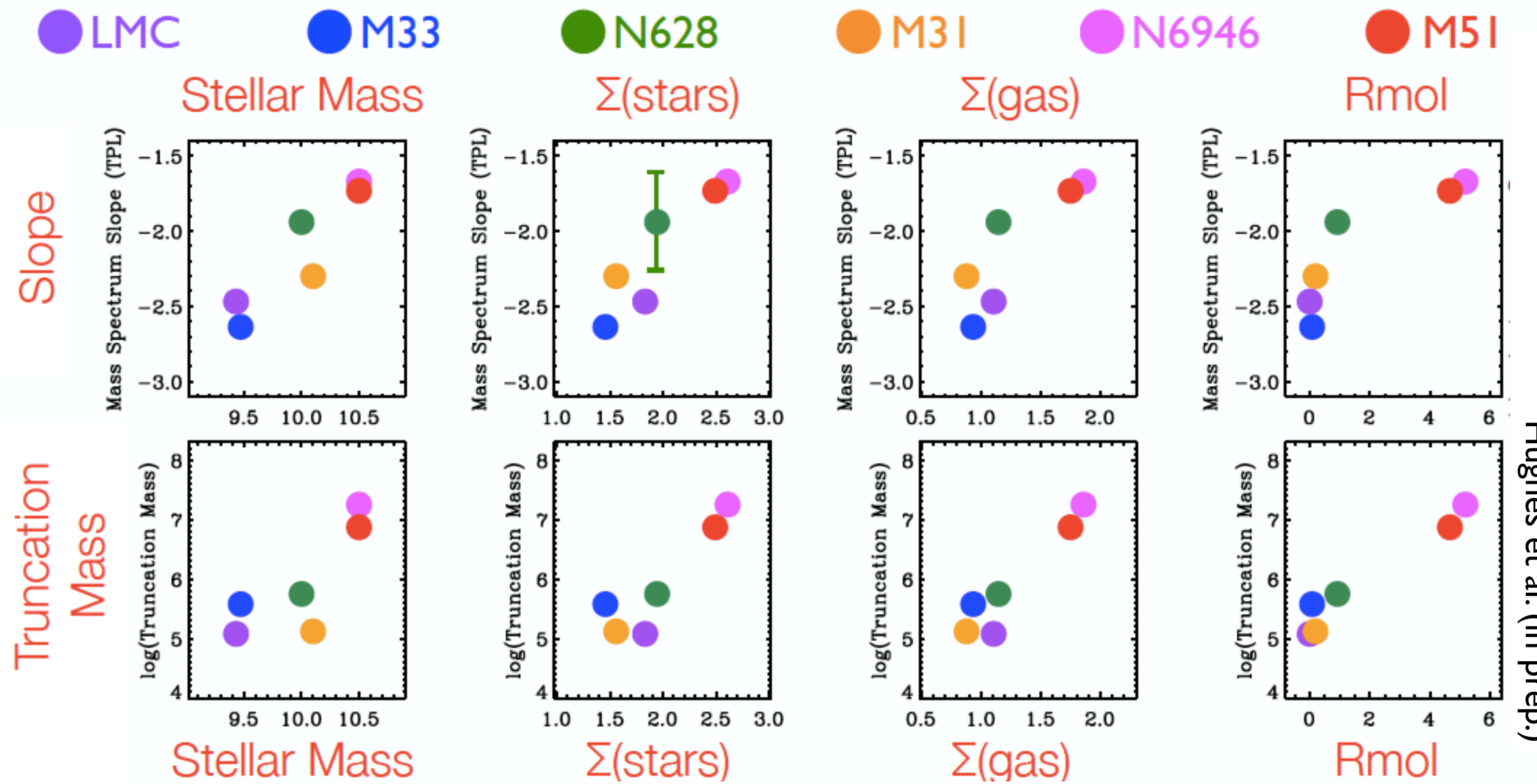
- grow in spiral arm via
  - agglomeration
  - merging/collision
- dispelled in inter-arm
  - star formation
  - shear

center clouds

- growth limited due to
  - radiation field
  - AGN
  - central bar

GMC properties vary with environment

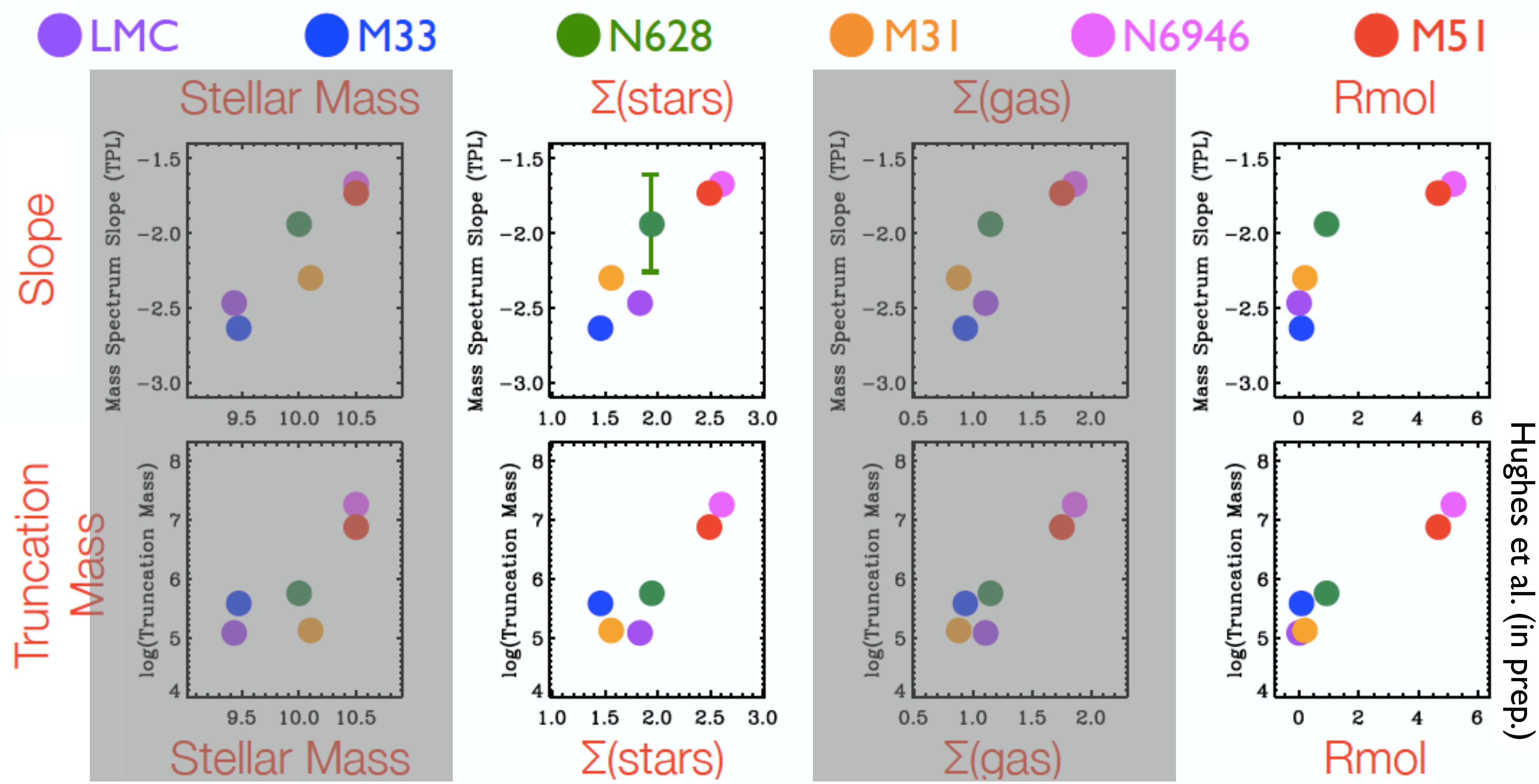
Giant Molecular Cloud (GMC) mass function: slope & truncation mass



Hughes et al. (in prep.)

GMC properties vary with environment

Giant Molecular Cloud (GMC) mass function: slope & truncation mass

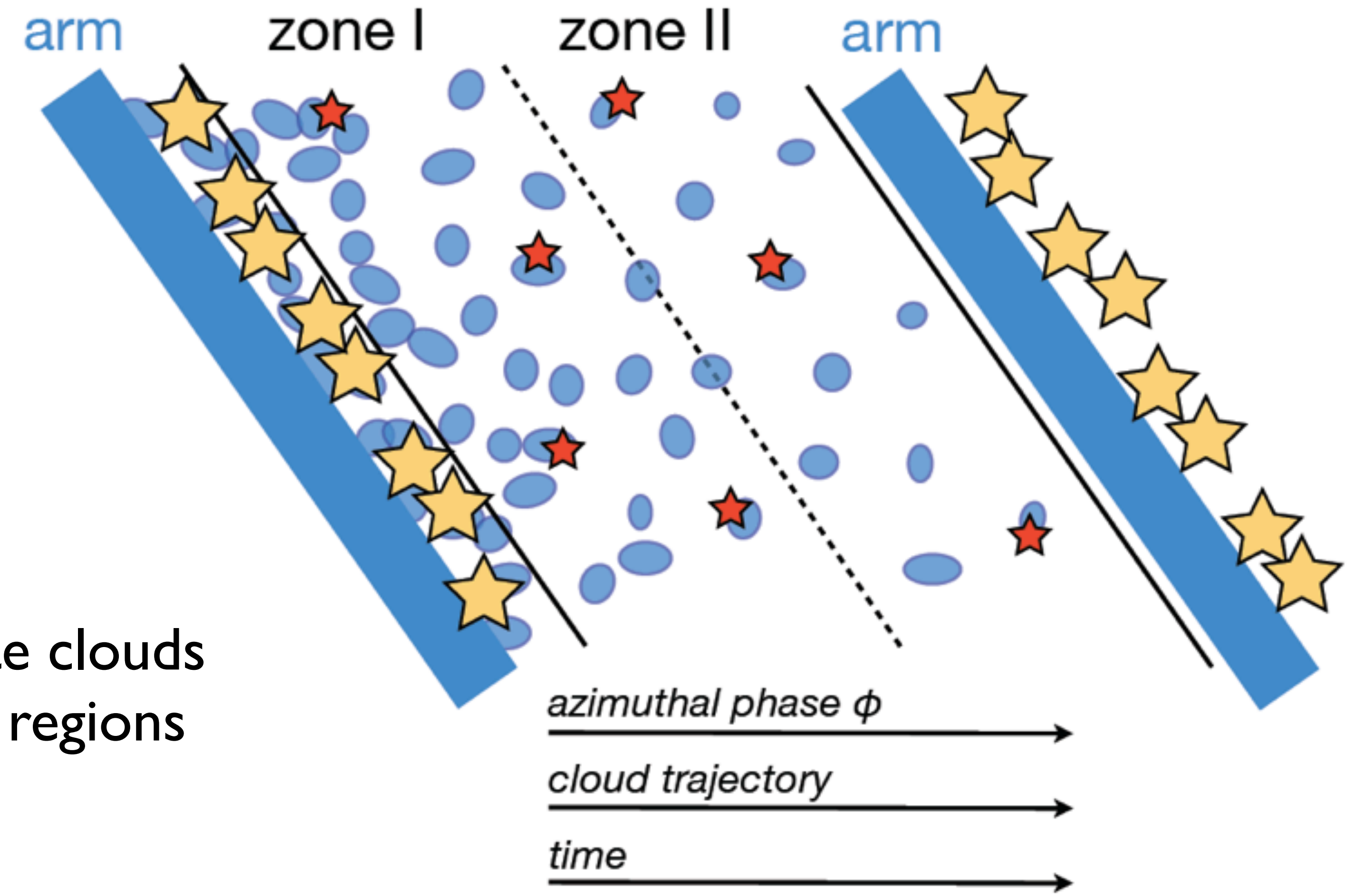


GMC mass function is not universal: strong trend w/ mass of system

GMC lifetimes in M51

Meidt et al. (2015)

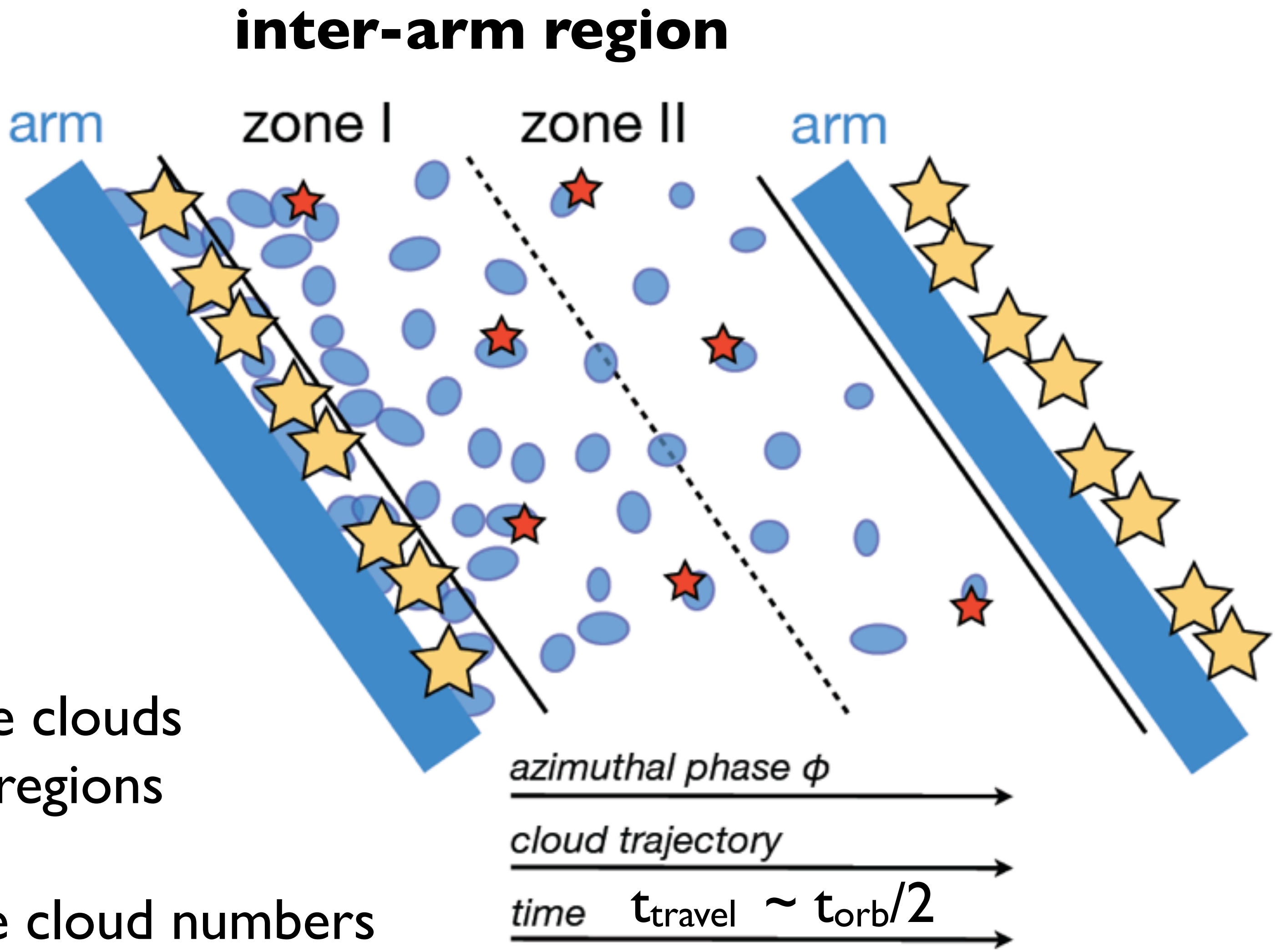
inter-arm region



1) associate clouds with SF regions

GMC lifetimes in M51

Meidt et al. (2015)



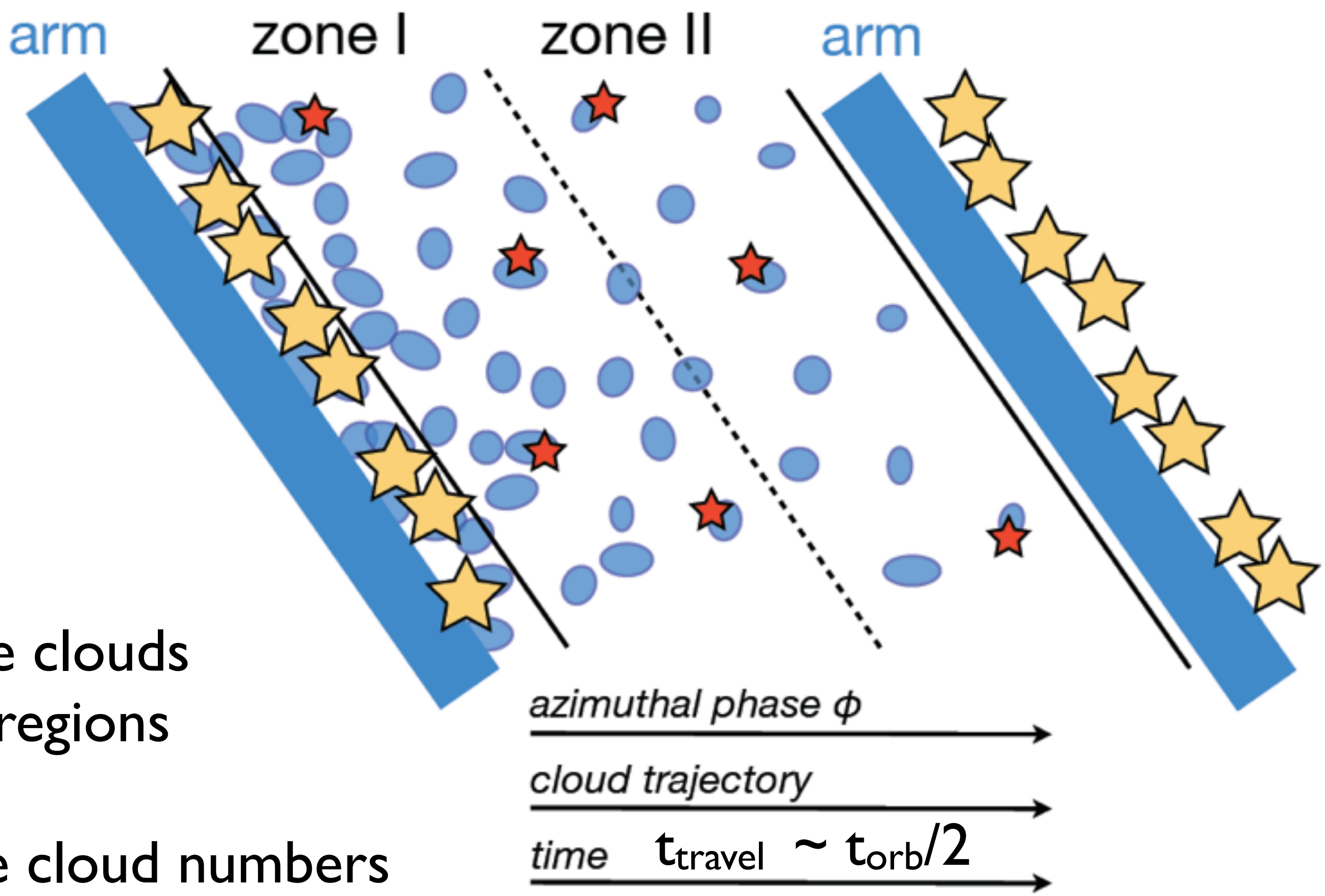
1) associate clouds with SF regions

2) compare cloud numbers associate with travel time t_{travel}

GMC lifetimes in M51

Meidt et al. (2015)

inter-arm region



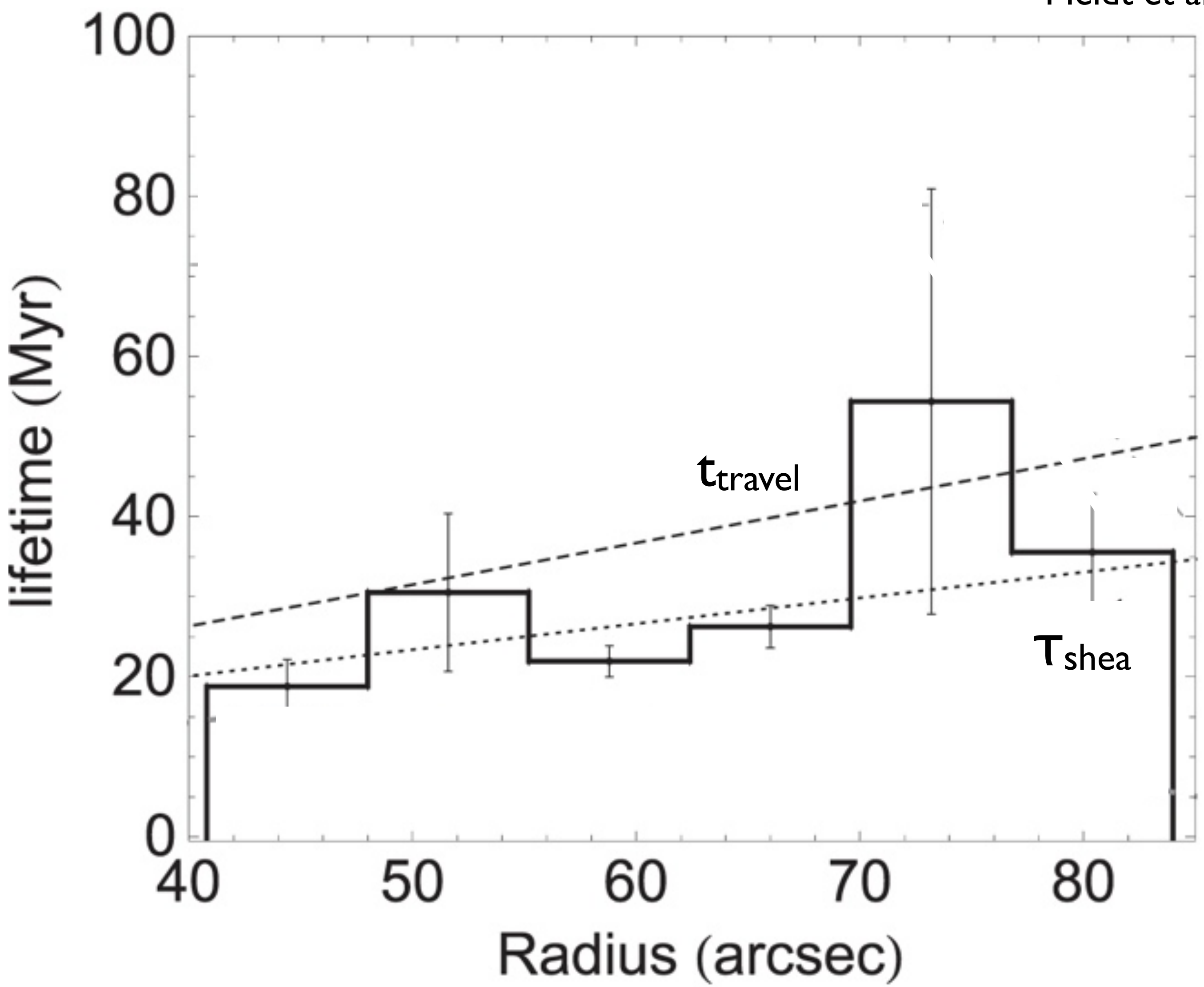
1) associate clouds with SF regions

2) compare cloud numbers associate with travel time t_{travel}

$$\tau_{GMC} = t_{travel}/2 * N_I/(N_I - N_{II})$$

GMC lifetimes in M51

Meidt et al. (2015)

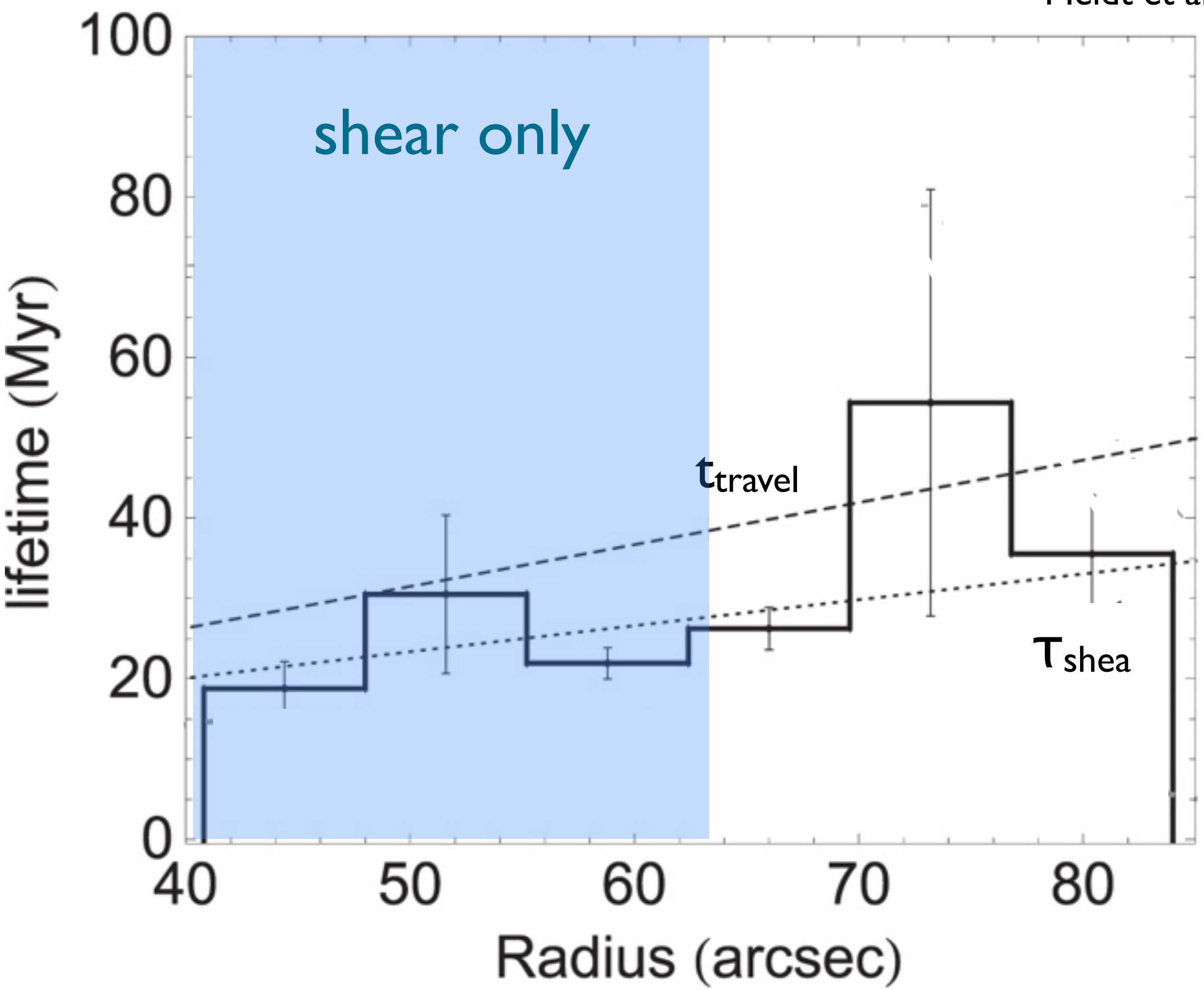


τ_{shear} =

(Oort

GMC lifetimes in M51

Meidt et al. (2015)

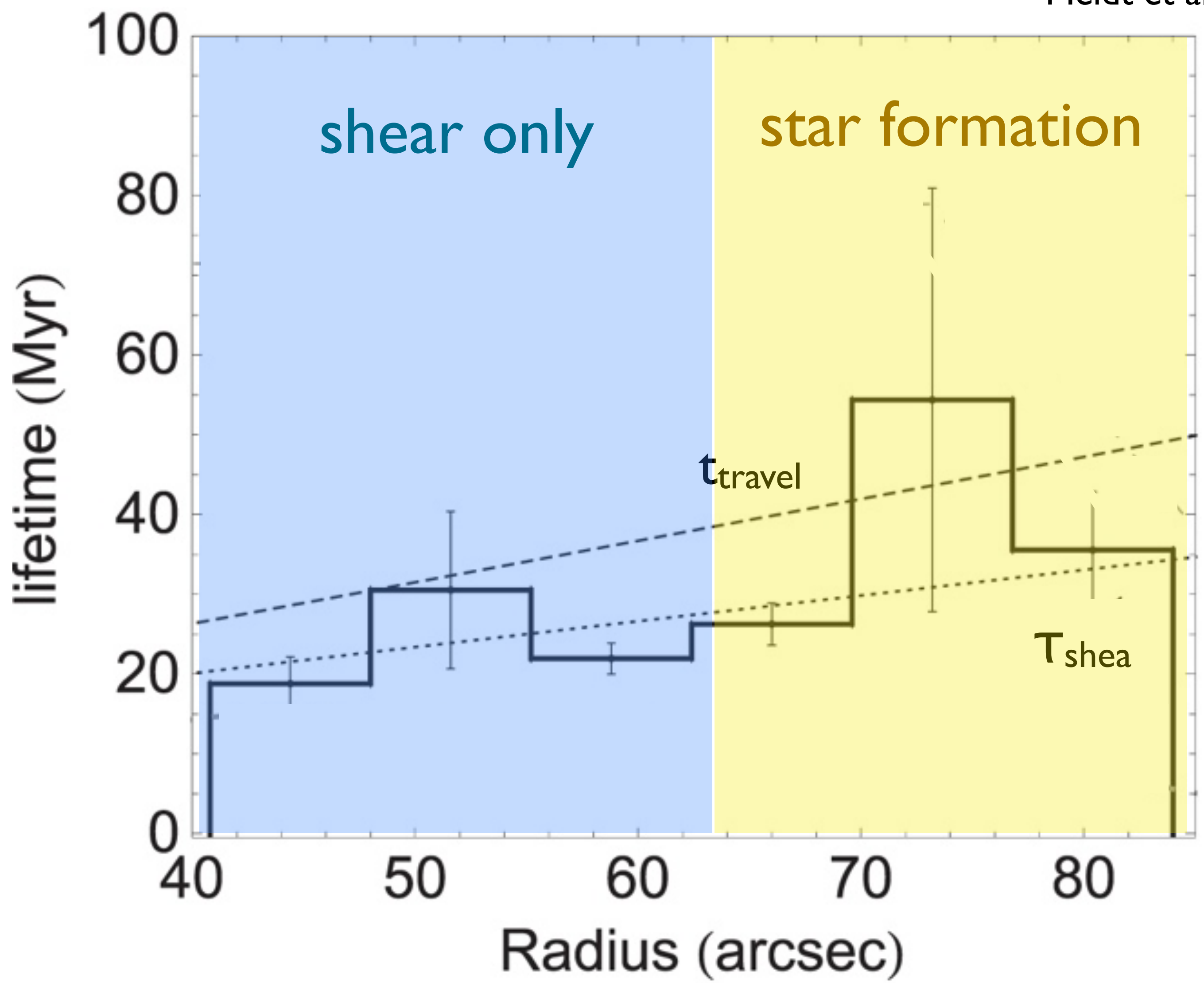


τ_{shear} =

(Oort

GMC lifetimes in M51

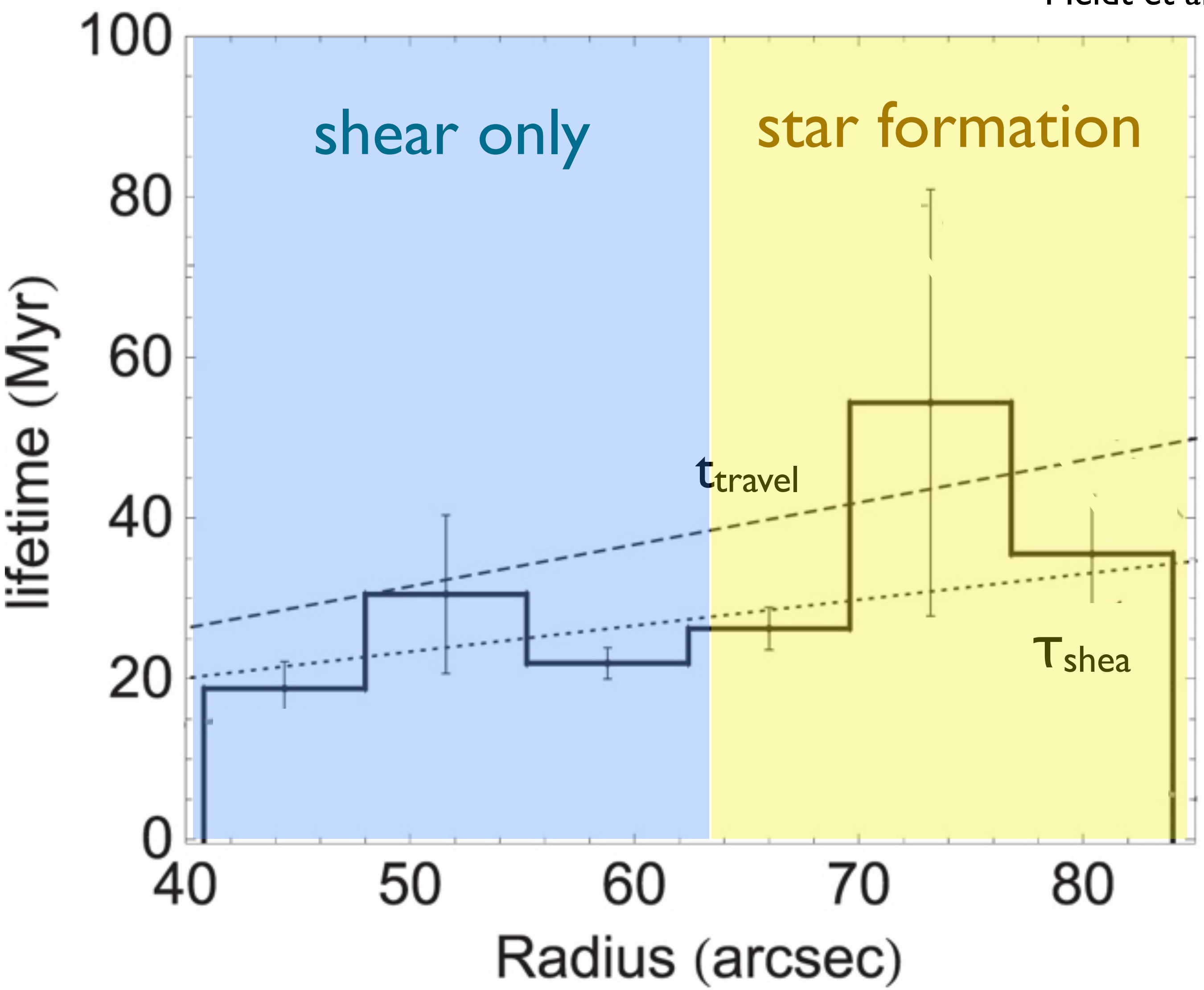
Meidt et al. (2015)



τ_{shear} =
(Oort

GMC lifetimes in M51

Meidt et al. (2015)



τ_{shear} =
(Oort

GMC lifetimes ~20-30 Myr set by shear timescale

similar value: LMC (Kawamura et al. 2009), M33 (Miura et al. 2012), MW (e.g. Bash et al. 1977)

Molecular gas and star formation in spiral galaxies

#1:

3D distribution of molecular gas differs from atomic gas one

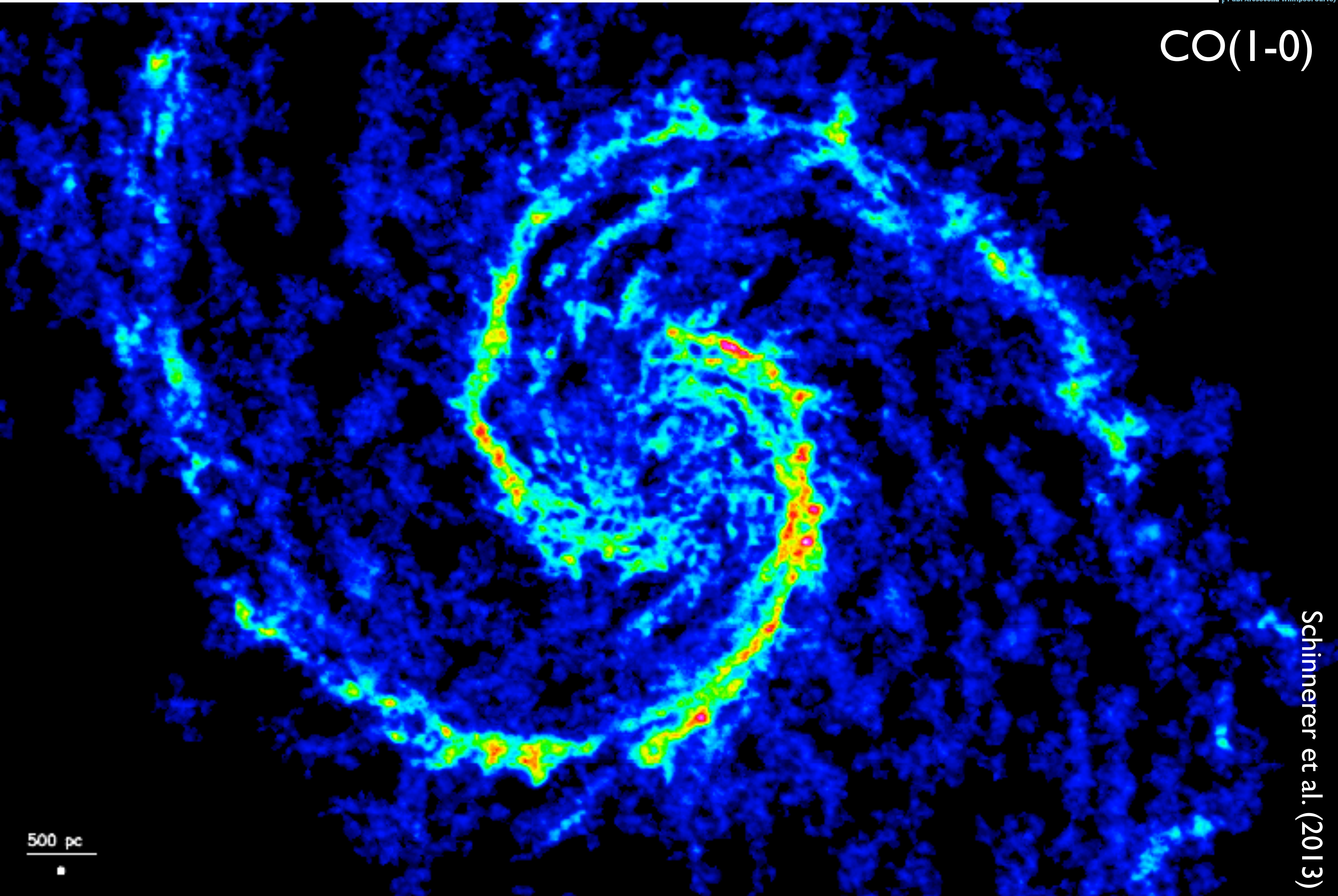
#2:

Giant Molecular Cloud properties are set by environment

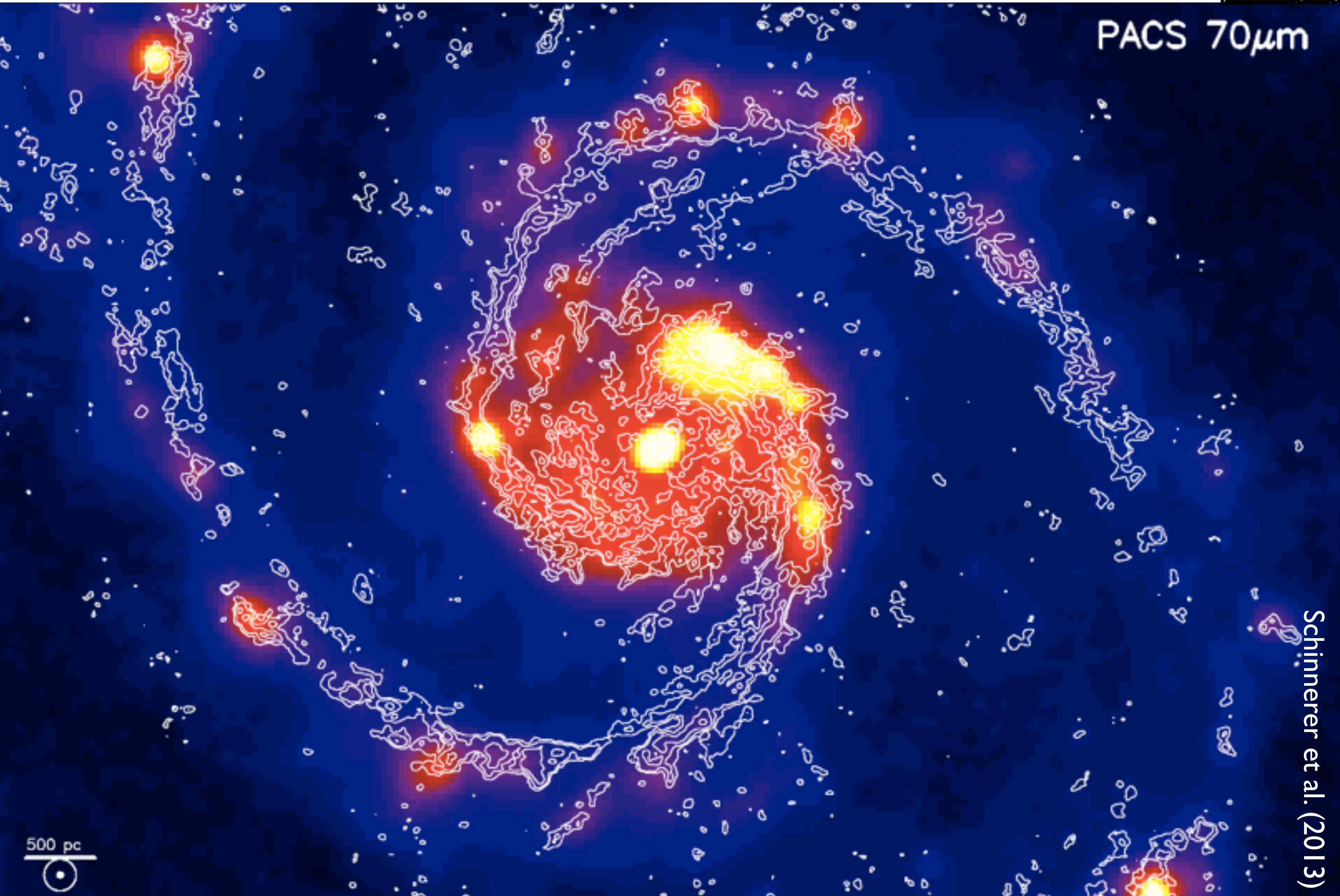
#3:

Conversion of molecular gas into stars is complex process

No relation between gas density and star formation

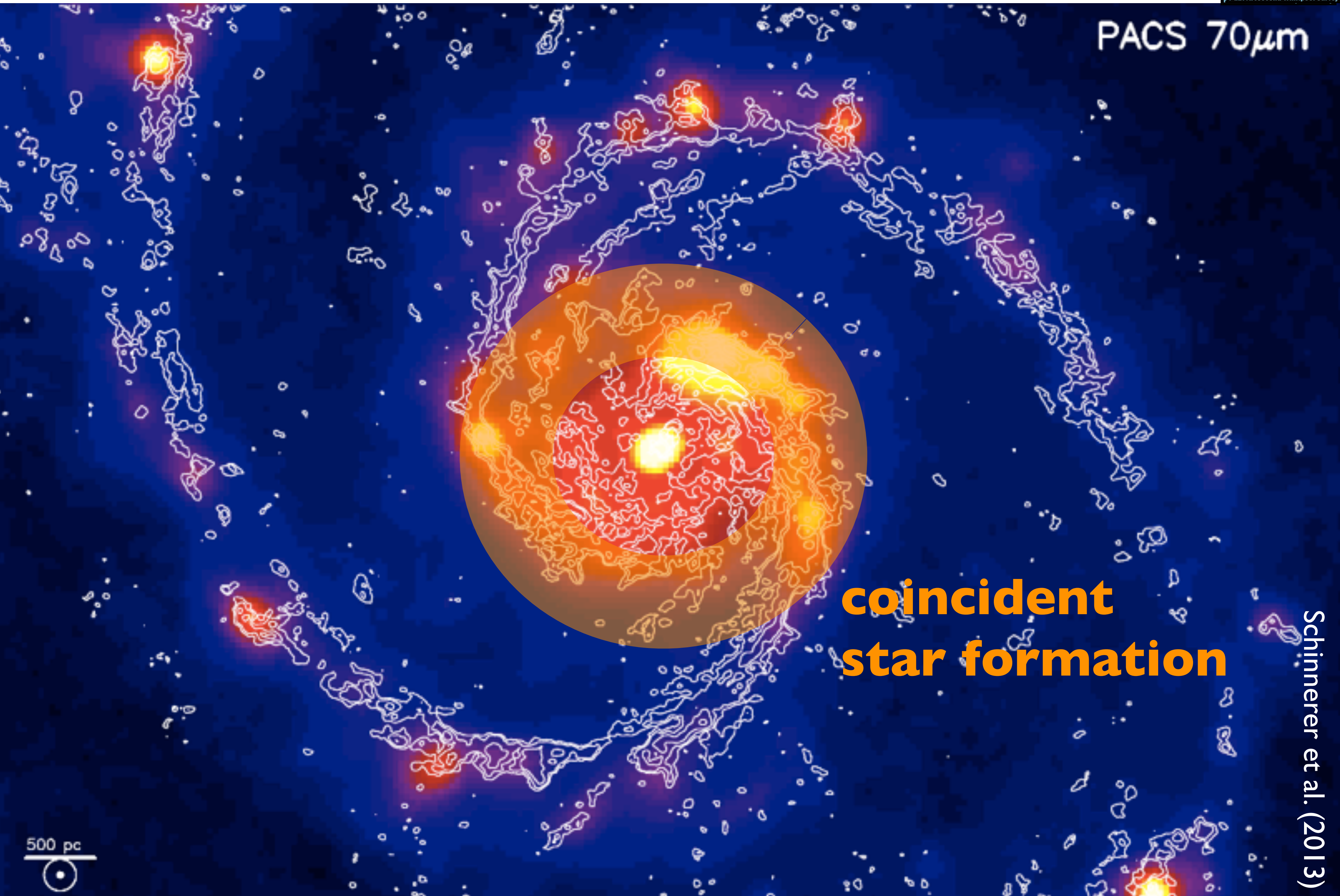


No relation between gas density and star formation

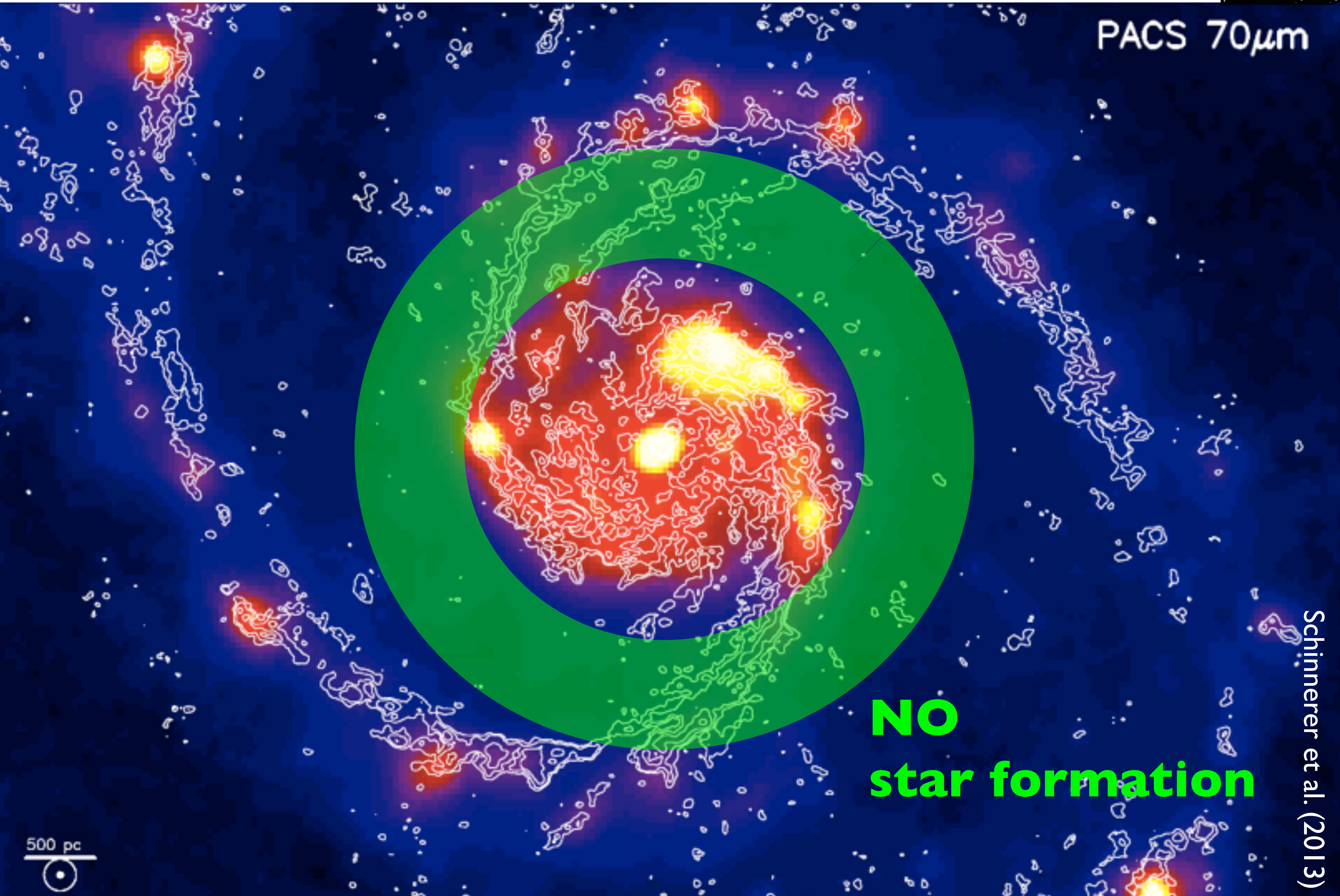


Schinnerer et al. (2013)

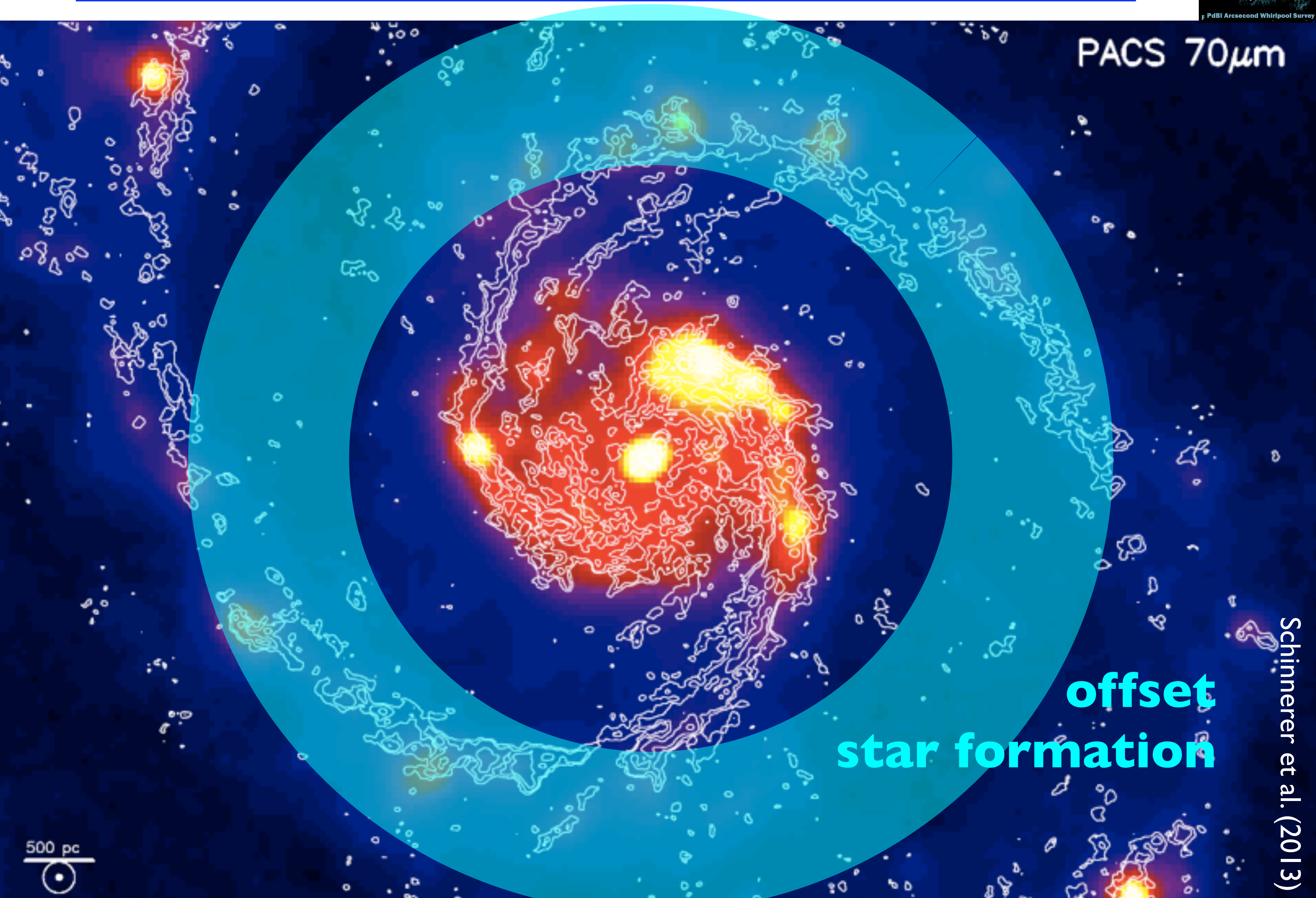
No relation between gas density and star formation



No relation between gas density and star formation

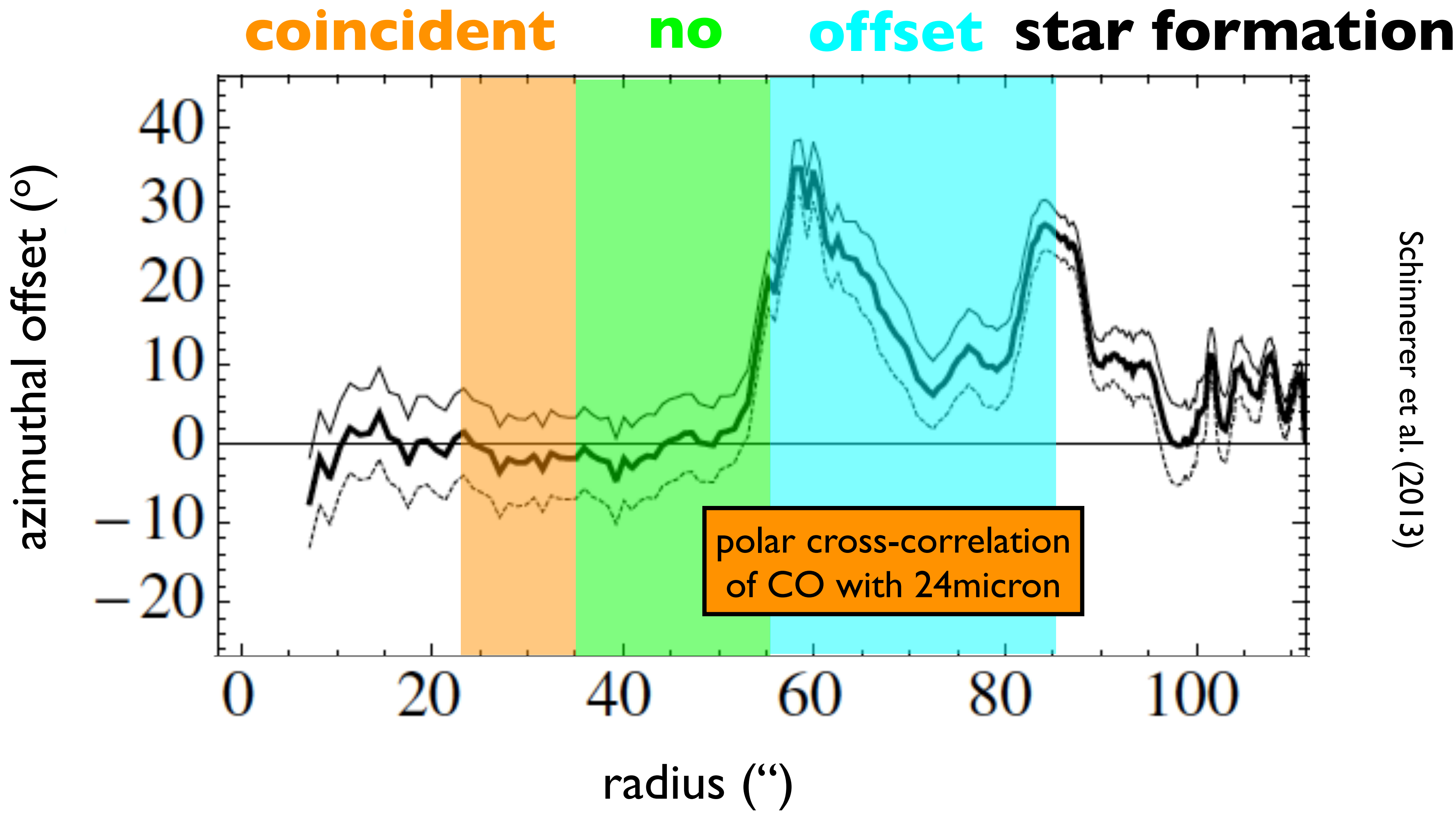


No relation between gas density and star formation



Schinnerer et al. (2013)

No relation between gas density and star formation



⇨ molecular gas surface density is bad predictor for star formation rate surface density

The gas-SFR relation in M51

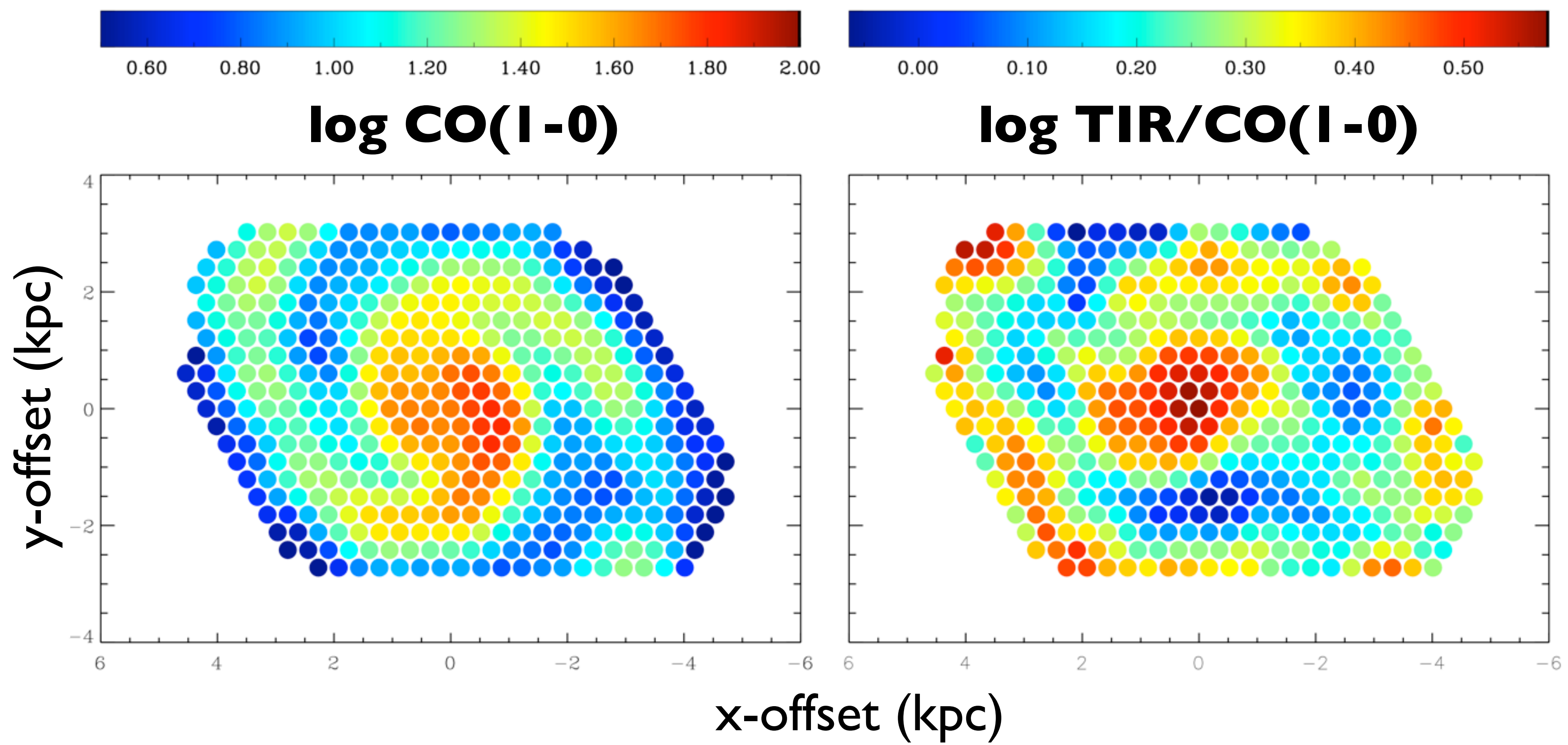
Leroy et al. (in prep.)

@ 800pc: ^{12}CO(1-0),(2-1),(3-2),^{13}CO(1-0), 24μm, TIR, Hα, FUV, 20cm, 6cm, 3.6cm ...

The gas-SFR relation in M51

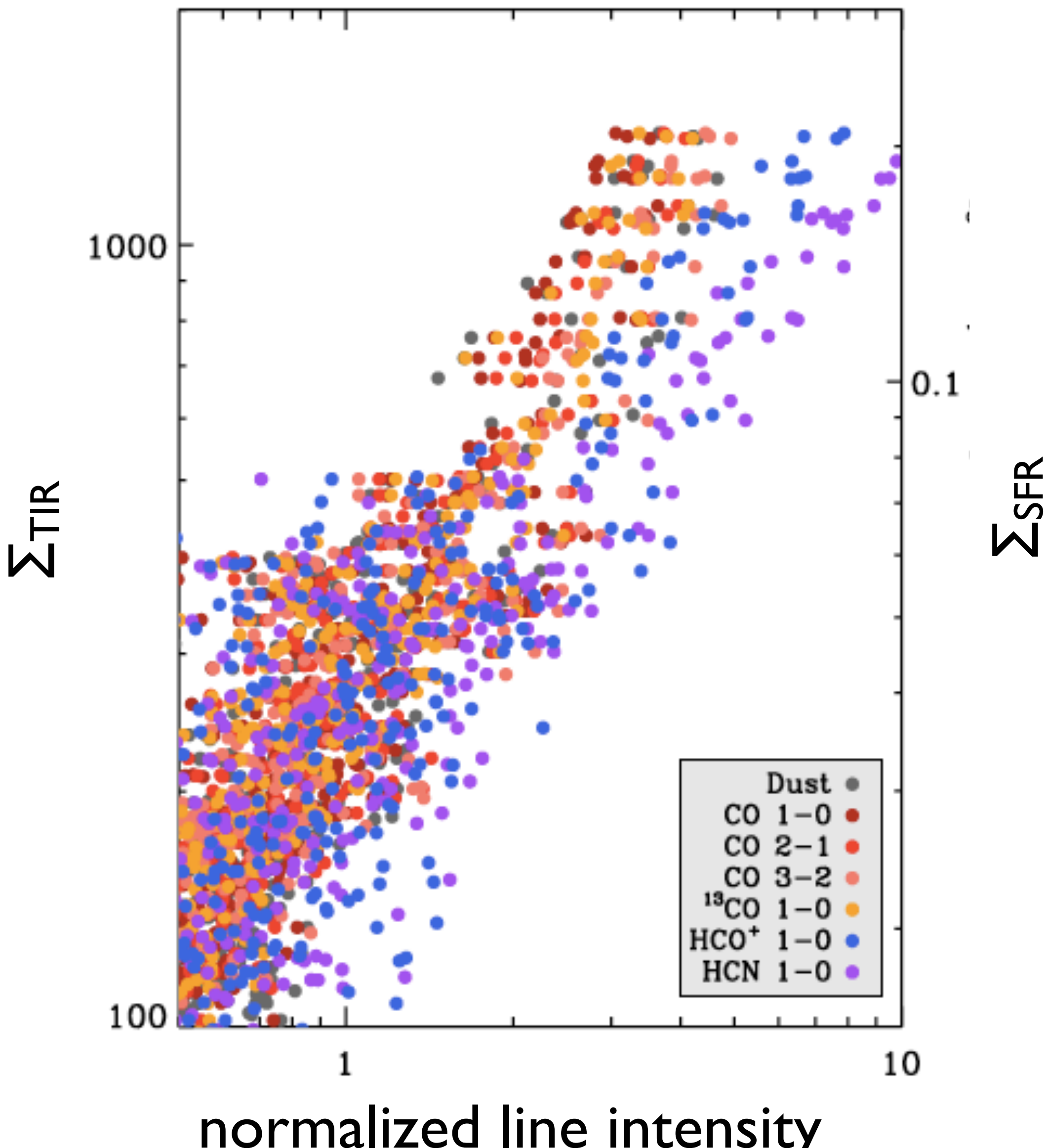
Leroy et al. (in prep.)

@ 800pc: ^{12}CO(1-0),(2-1),(3-2),^{13}CO(1-0), 24μm, TIR, Hα, FUV, 20cm, 6cm, 3.6cm ...



The gas-SFR relation in M51

Leroy et al. (in prep.)



^{12}CO(1-0),(2-1),(3-2)

^{13}CO(1-0)

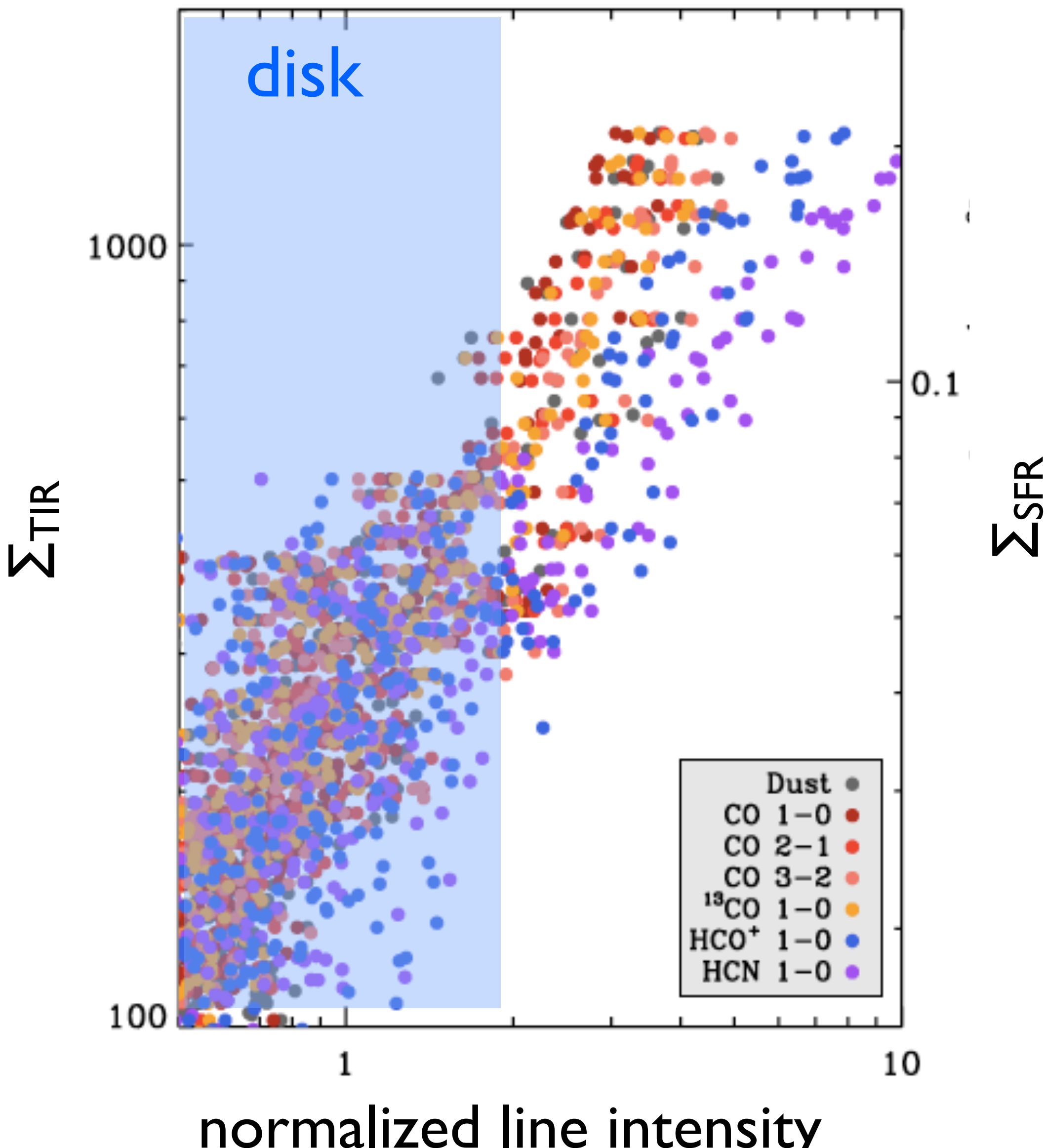
HCN(1-0)

HCO+(1-0)

dust

The gas-SFR relation in M51

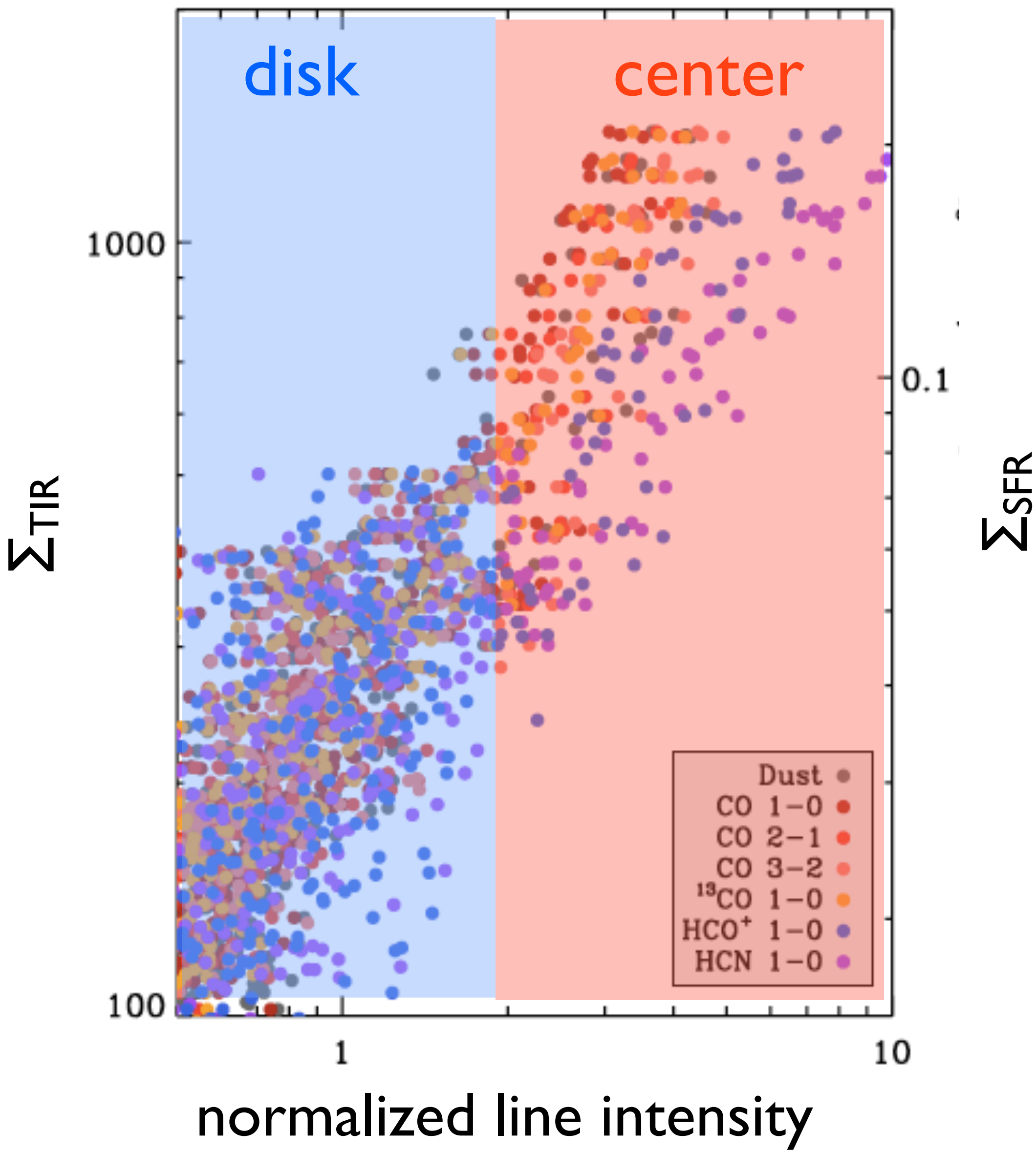
Leroy et al. (in prep.)



^{12}CO(1-0),(2-1),(3-2)
^{13}CO(1-0)
HCN(1-0)
HCO+(1-0)
dust

The gas-SFR relation in M51

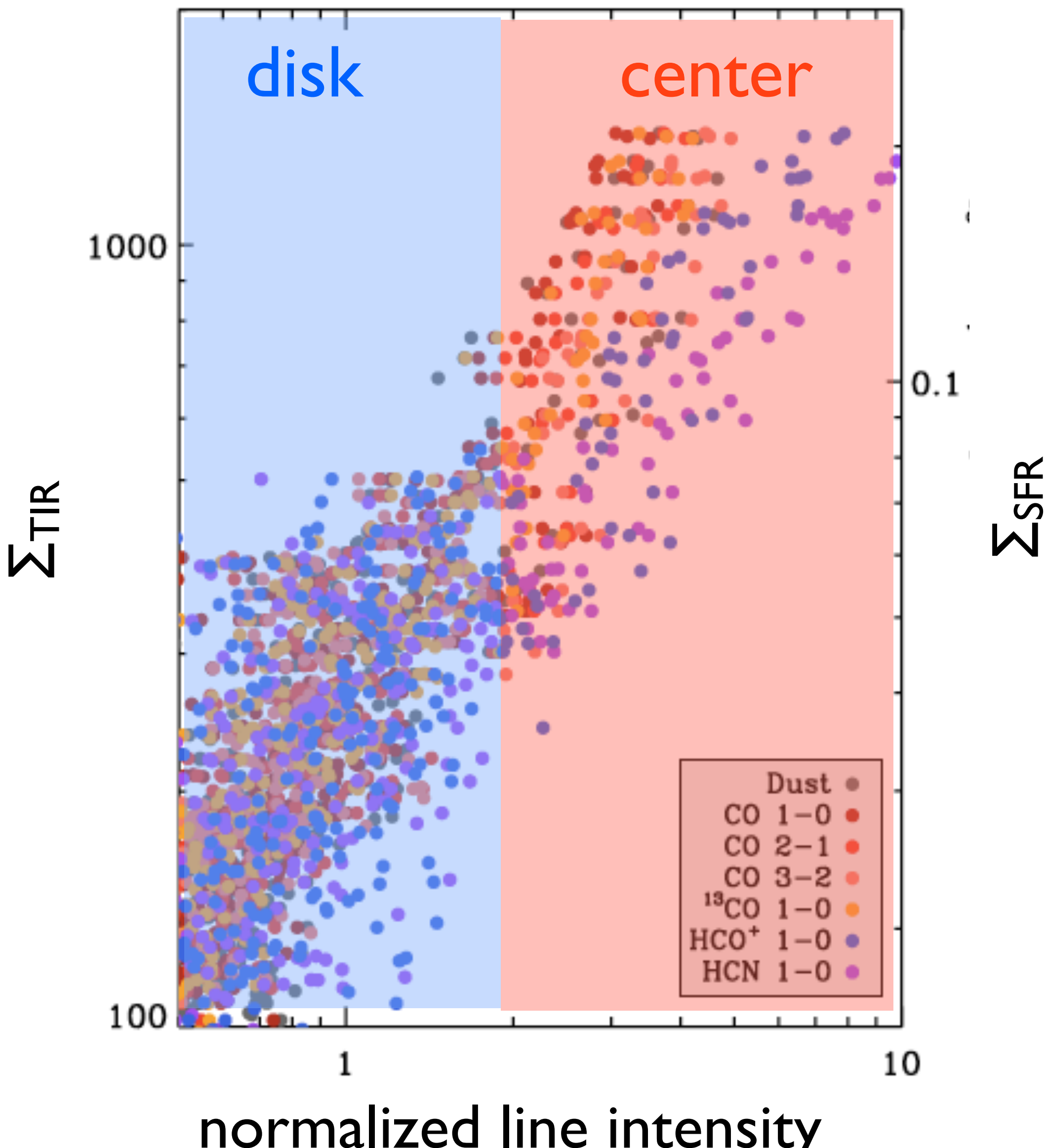
Leroy et al. (in prep.)



^{12}CO(1-0),(2-1),(3-2)
^{13}CO(1-0)
HCN(1-0)
HCO+(1-0)
dust

The gas-SFR relation in M51

Leroy et al. (in prep.)



^{12}CO(1-0),(2-1),(3-2)
^{13}CO(1-0)
HCN(1-0)
HCO+(1-0)
dust

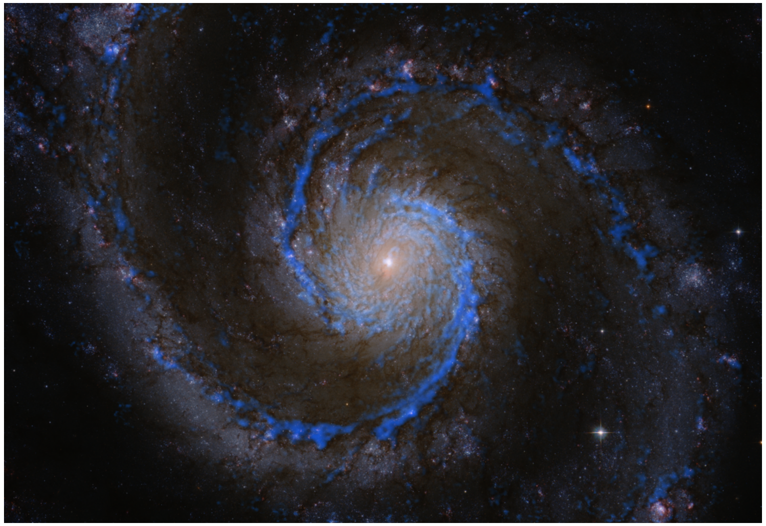
scatter persists

in center:
slope flattens
(excitation effects?)

What if not all gas clouds form stars equally?

Impact of dynamical pressure

Meidt et al. (2013)



disk structures drive gas **flows**

gas flows **increase cloud stability**

⇨ **lower SFR (star formation rate)**

increase in depletion time

Requirements for dynamical pressure

1,500 clouds identified in M51

Colombo et al. (2014)

clouds in arm are:

- brighter
- more massive
- higher gas surface density

Requirements for dynamical pressure

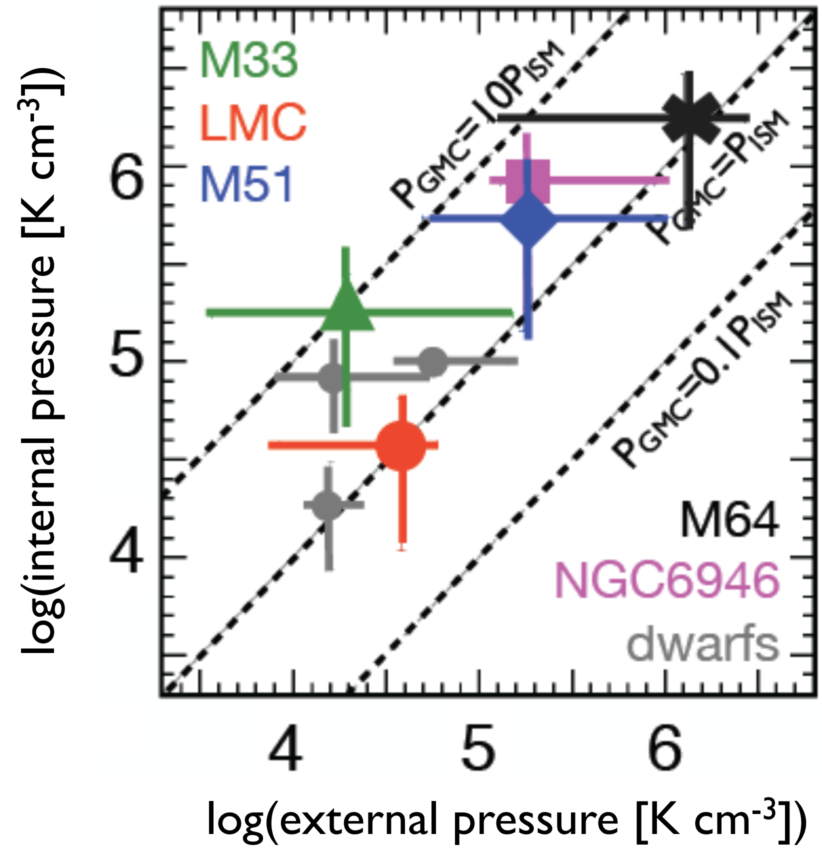
1,500 clouds identified in M51

Colombo et al. (2014)

clouds in arm are:

- brighter
- more massive
- higher gas surface density

Hughes et al. (2013b, in prep.)



Requirements for dynamical pressure

1,500 clouds identified in M51

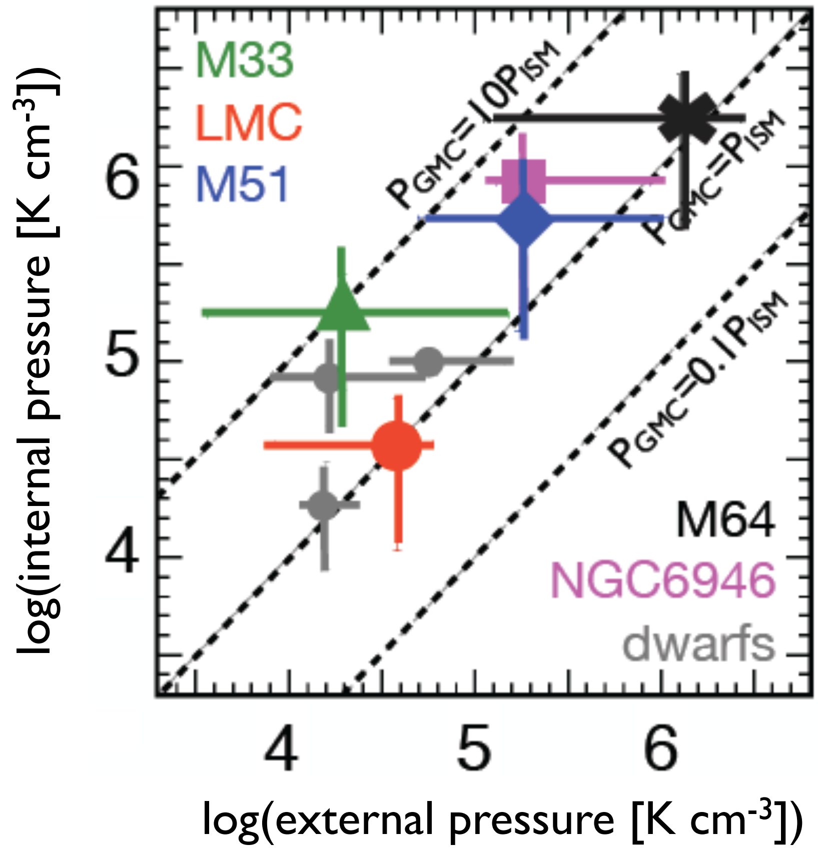
Colombo et al. (2014)

clouds in arm are:

- brighter
- more massive
- higher gas surface density

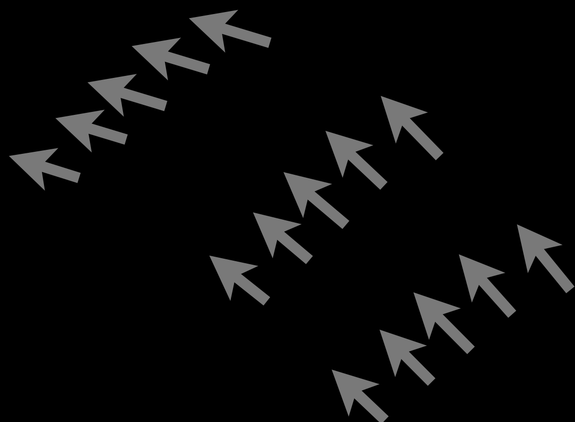
clouds must "know" about environment

Hughes et al. (2013b, in prep.)



dynamical pressure

Meidt et al. (2013)



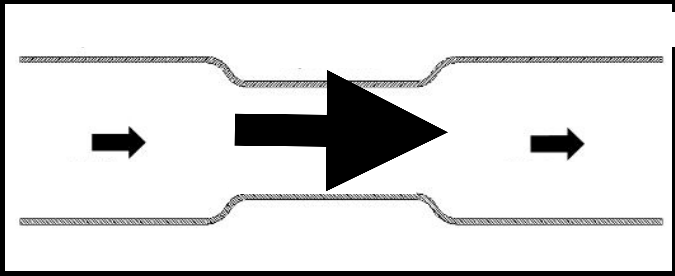
dynamical pressure

Meidt et al. (2013)

dynamical pressure

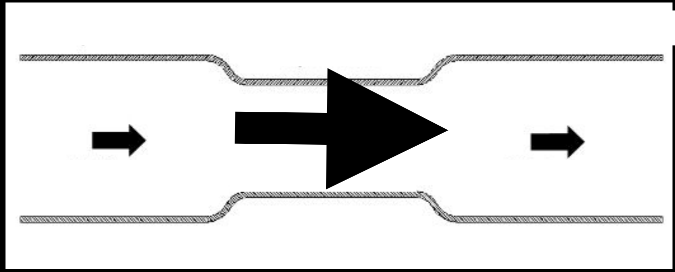
Meidt et al. (2013)

- *Bernoulli*: **gas in motion, reduced pressure**



dynamical pressure

Meidt et al. (2013)

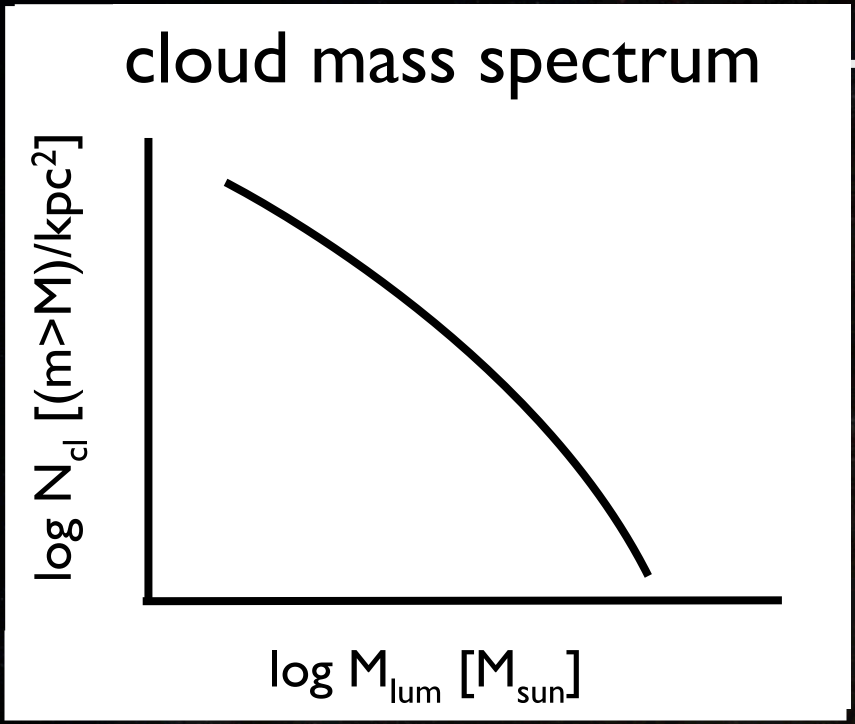


- *Bernoulli*: **gas in motion, reduced pressure**
- **increased cloud stable mass** (bigger before collapse)
- fewer collapse-unstable clouds
- **lower star formation, longer T_{dep}**

dynamical pressure

A Quantitative approach

Meidt et al. (2013)



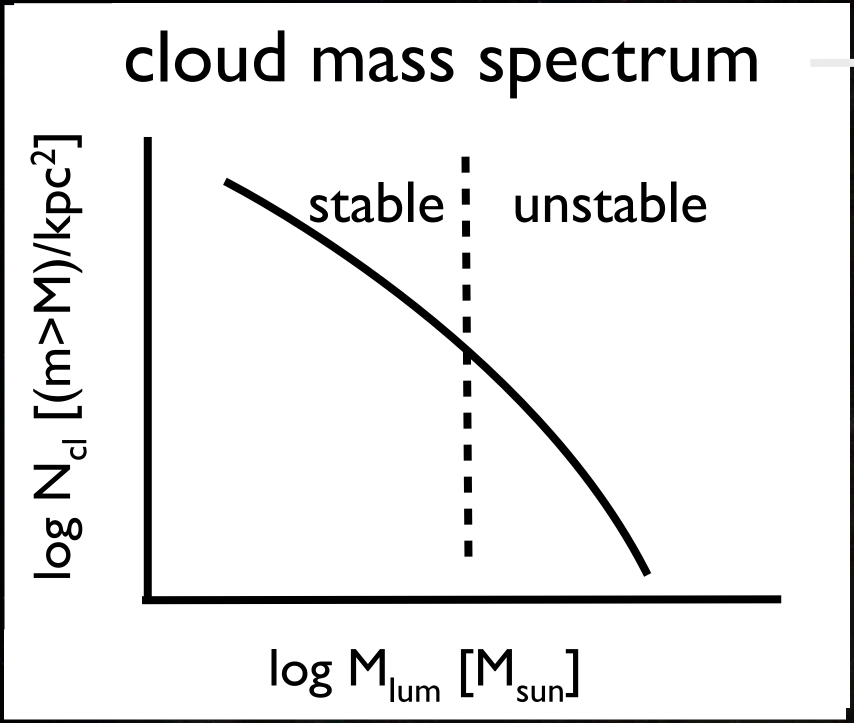
→ power-law with

$dN/dM \propto M^{\gamma}$

dynamical pressure

A Quantitative approach

Meidt et al. (2013)



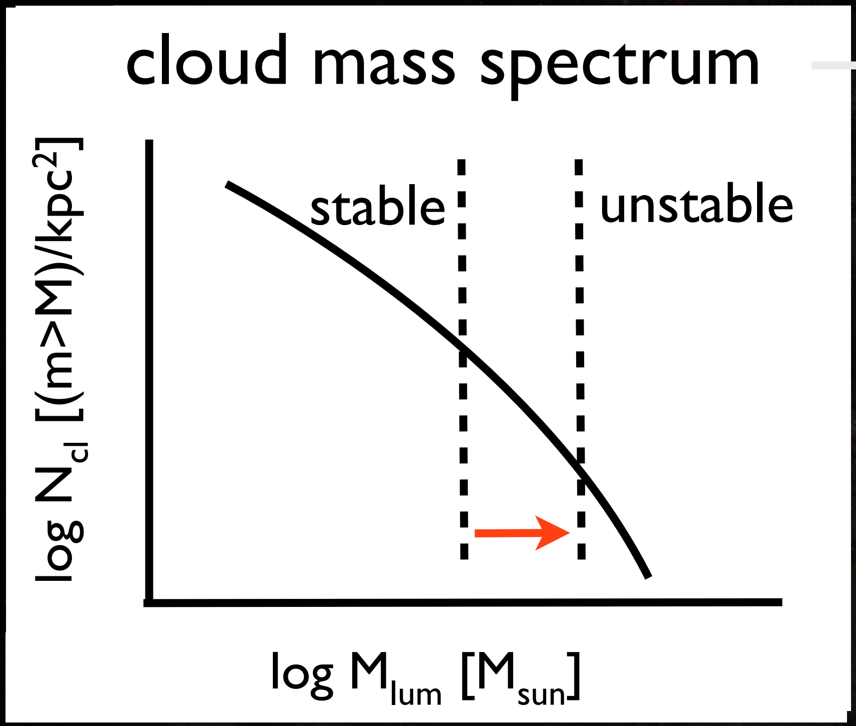
→ power-law with

$dN/dM \propto M^{\gamma}$

dynamical pressure

A Quantitative approach

Meidt et al. (2013)



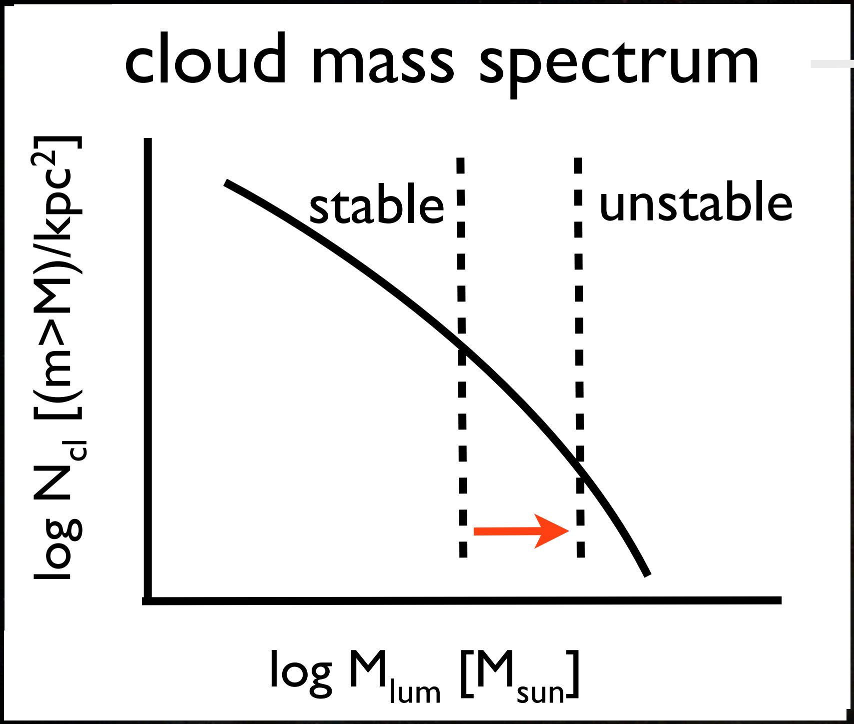
power-law with

$dN/dM \propto M^{\gamma}$

dynamical pressure

A Quantitative approach

Meidt et al. (2013)



→ power-law with

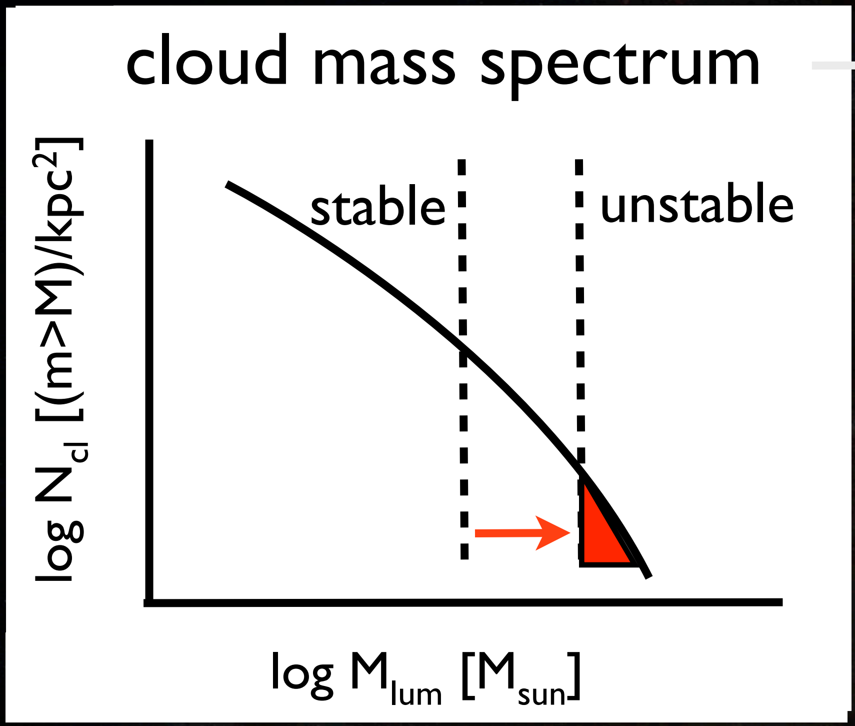
$dN/dM \propto M^{\gamma}$

with v_{stream}
pressure decreased,
stable mass raised

dynamical pressure

A Quantitative approach

Meidt et al. (2013)



power-law with

$dN/dM \propto M^{\gamma}$

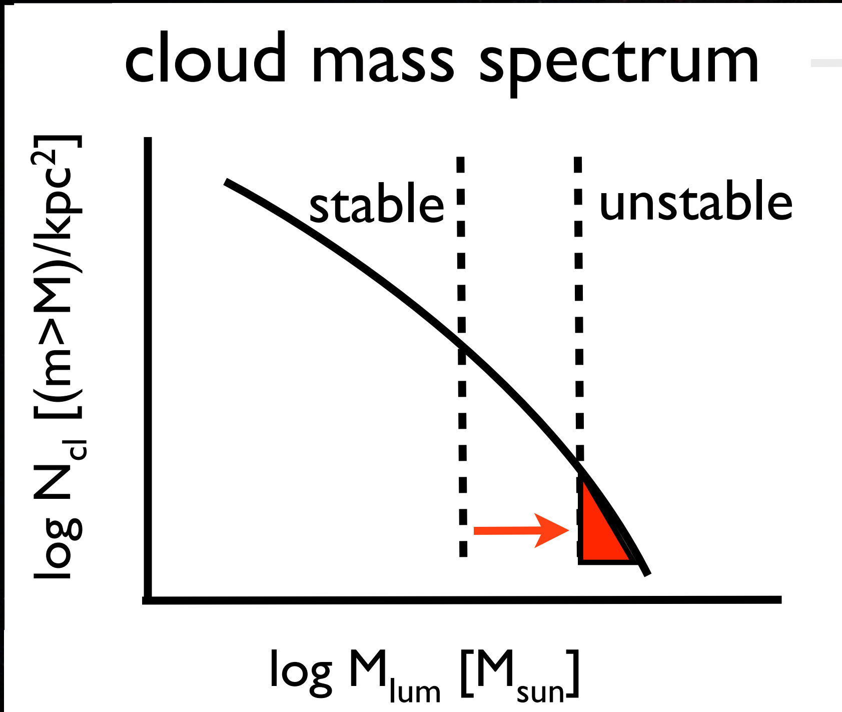
with v_{stream}
pressure decreased,
stable mass raised

$$\ln \tau_{dep} \approx -(\gamma+1)\ \frac{v_{stream}^2}{4\sigma^2}$$

dynamical pressure

A Quantitative approach

Meidt et al. (2013)



→ power-law with

$dN/dM \propto M^{\gamma}$

with v_{stream}
pressure decreased,
stable mass raised

$$\ln \boxed{\tau_{dep}} \approx -(\gamma+1)\ \frac{v_{stream}^2}{4\sigma^2}$$

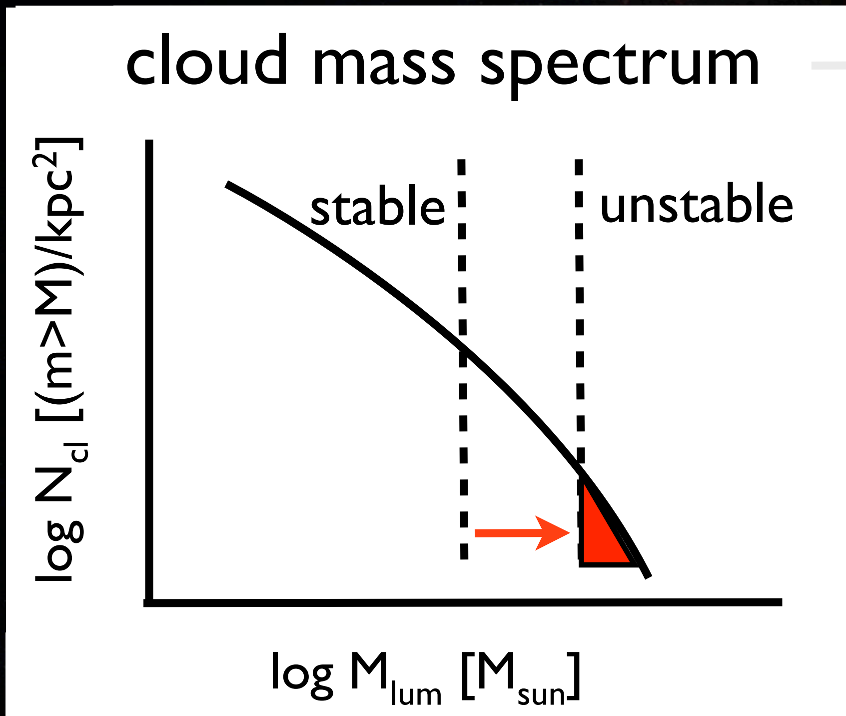
depletion time

$\tau_{dep} = \Sigma_{H2} / \Sigma_{SFR}$

dynamical pressure

A Quantitative approach

Meidt et al. (2013)



→ power-law with

$dN/dM \propto M^{\gamma}$

with v_{stream}

pressure decreased,

stable mass raised

$$\ln \boxed{\tau_{dep}} \approx -(\boxed{\gamma}+1)\ \frac{v_{stream}^{2}}{4\sigma^{2}}$$

depletion time

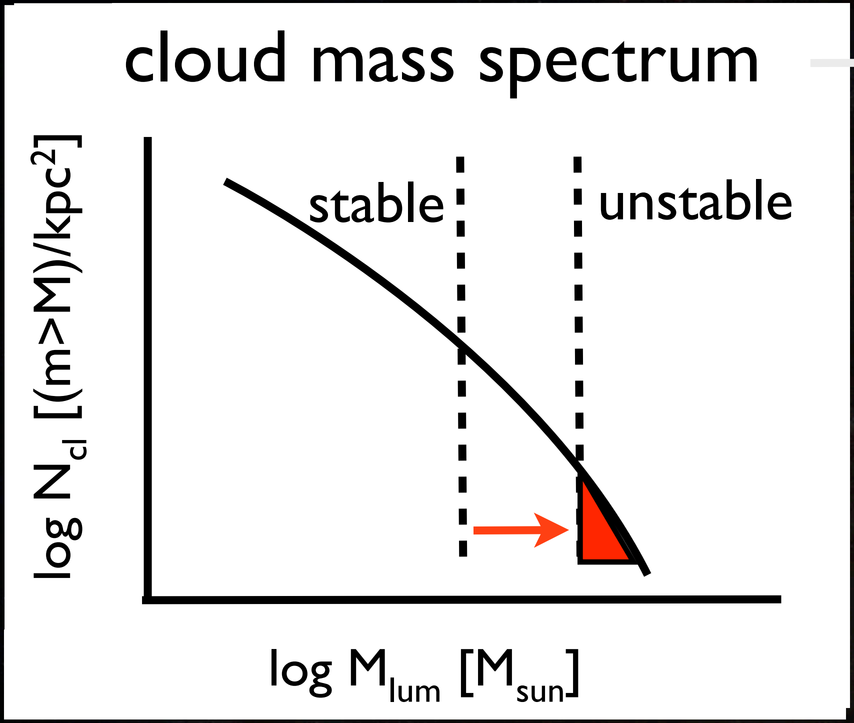
$\tau_{dep} = \Sigma_{H2} / \Sigma_{SFR}$

slope of cloud mass spectrum ~ -1.5

dynamical pressure

A Quantitative approach

Meidt et al. (2013)



→ power-law with

$dN/dM \propto M^{\gamma}$

with v_{stream}
pressure decreased,
stable mass raised

$$\ln \tau_{dep} \approx -(\gamma+1)\ \frac{v_{stream}^2}{4\sigma^2}$$

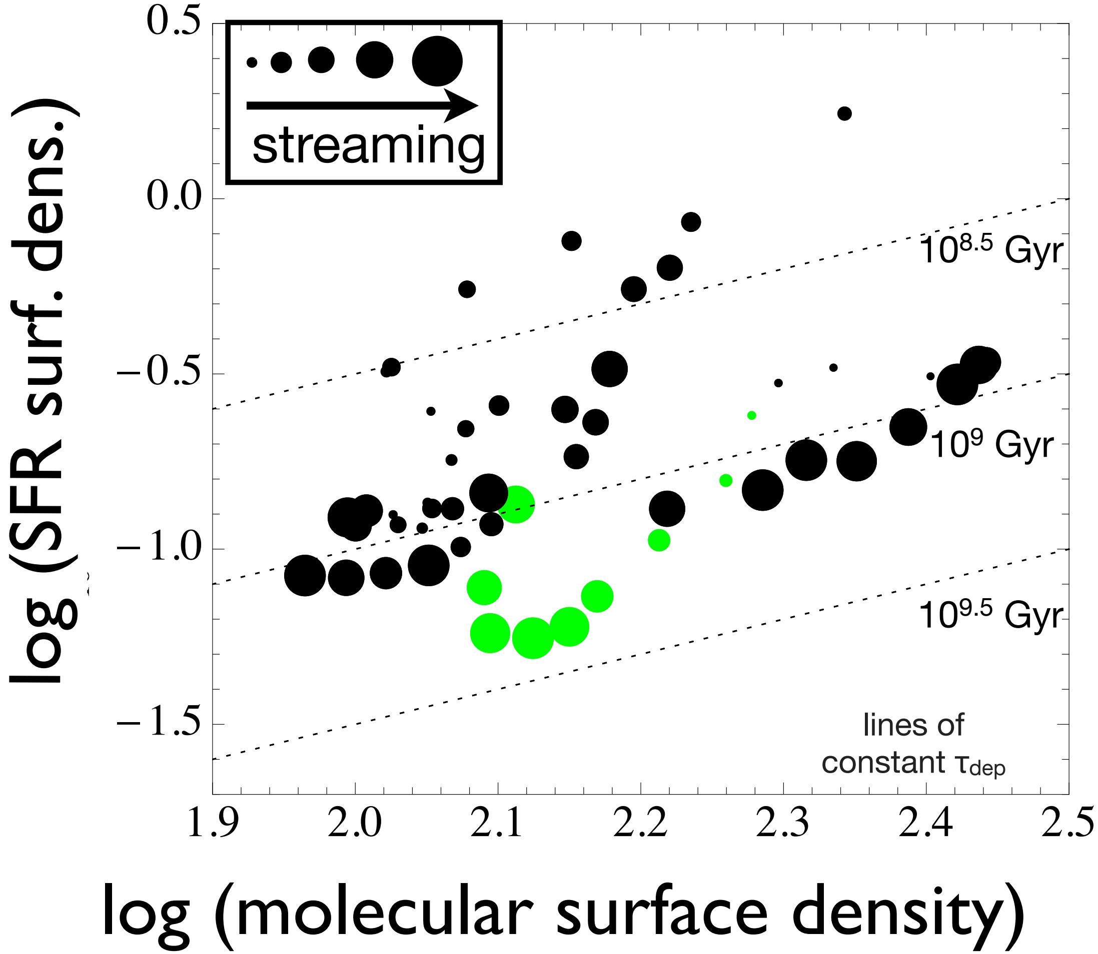
depletion time
$\tau_{dep} = \Sigma_{H2} / \Sigma_{SFR}$

measure from observed kinematics

slope of cloud mass spectrum ~ -1.5

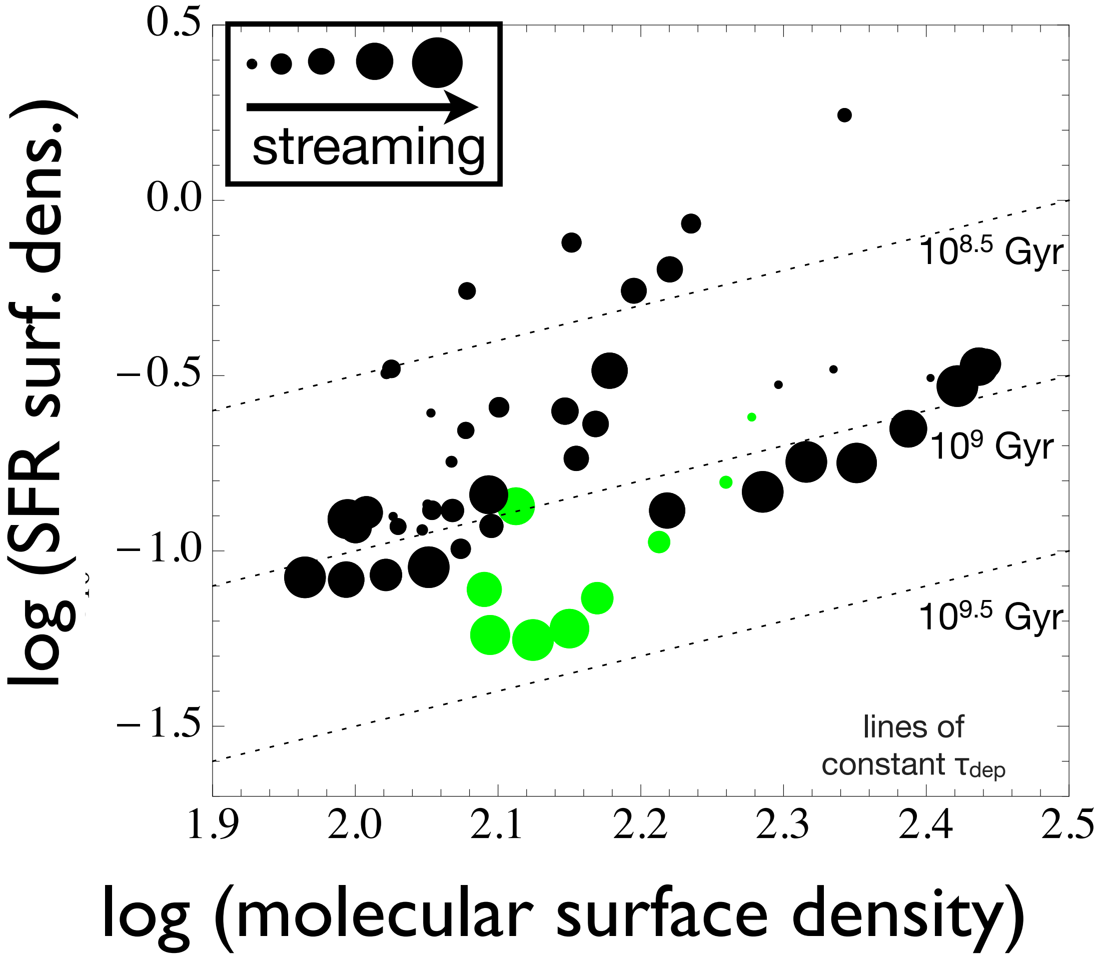
Gas motion introduces scatter in gas-SFR relation

Meidt et al. (2013)



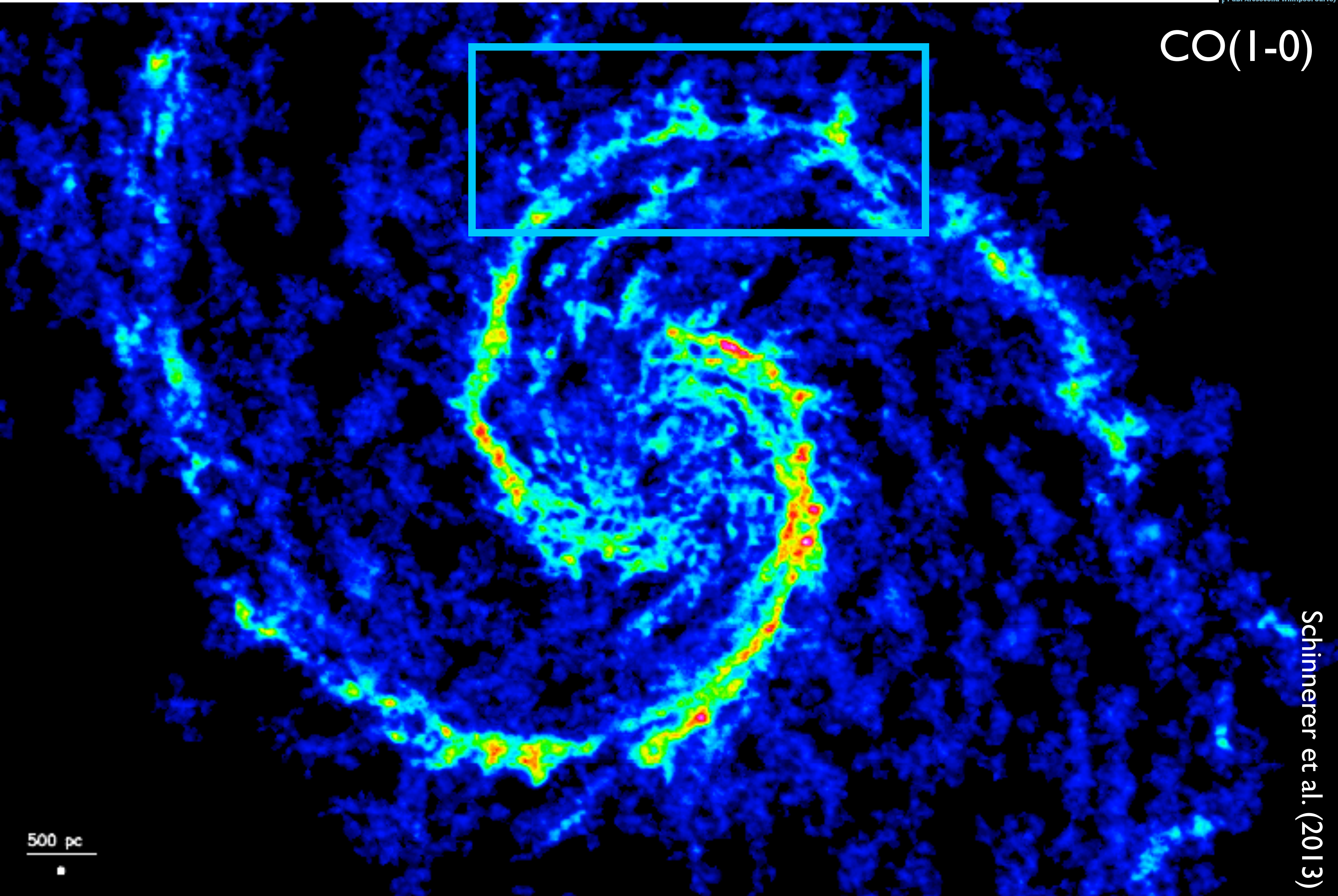
Gas motion introduces scatter in gas-SFR relation

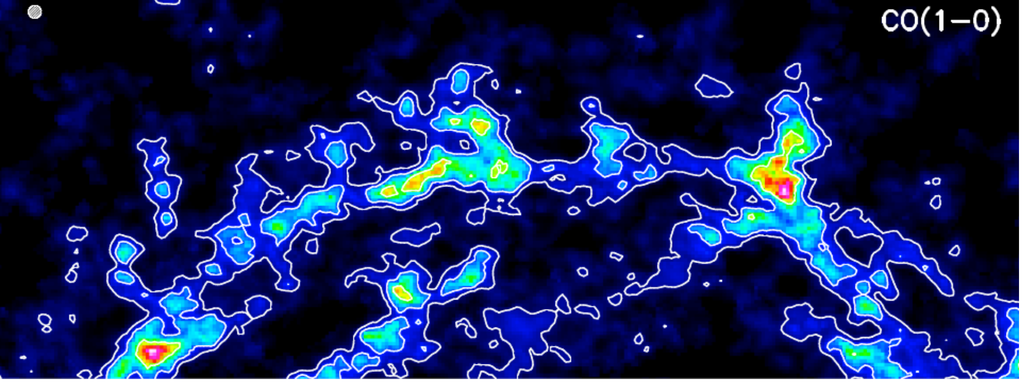
Meidt et al. (2013)



⇨ **gas streaming increases depletion time**

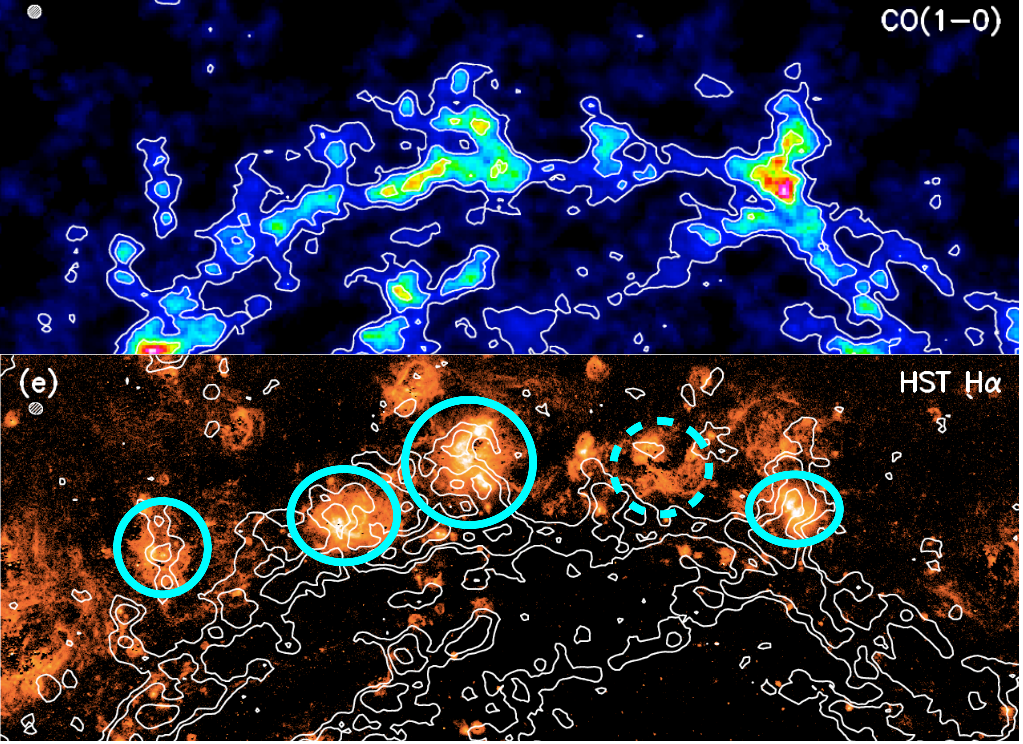
Close look at spiral arm segment





Off-set star formation
= stars form in spurs?

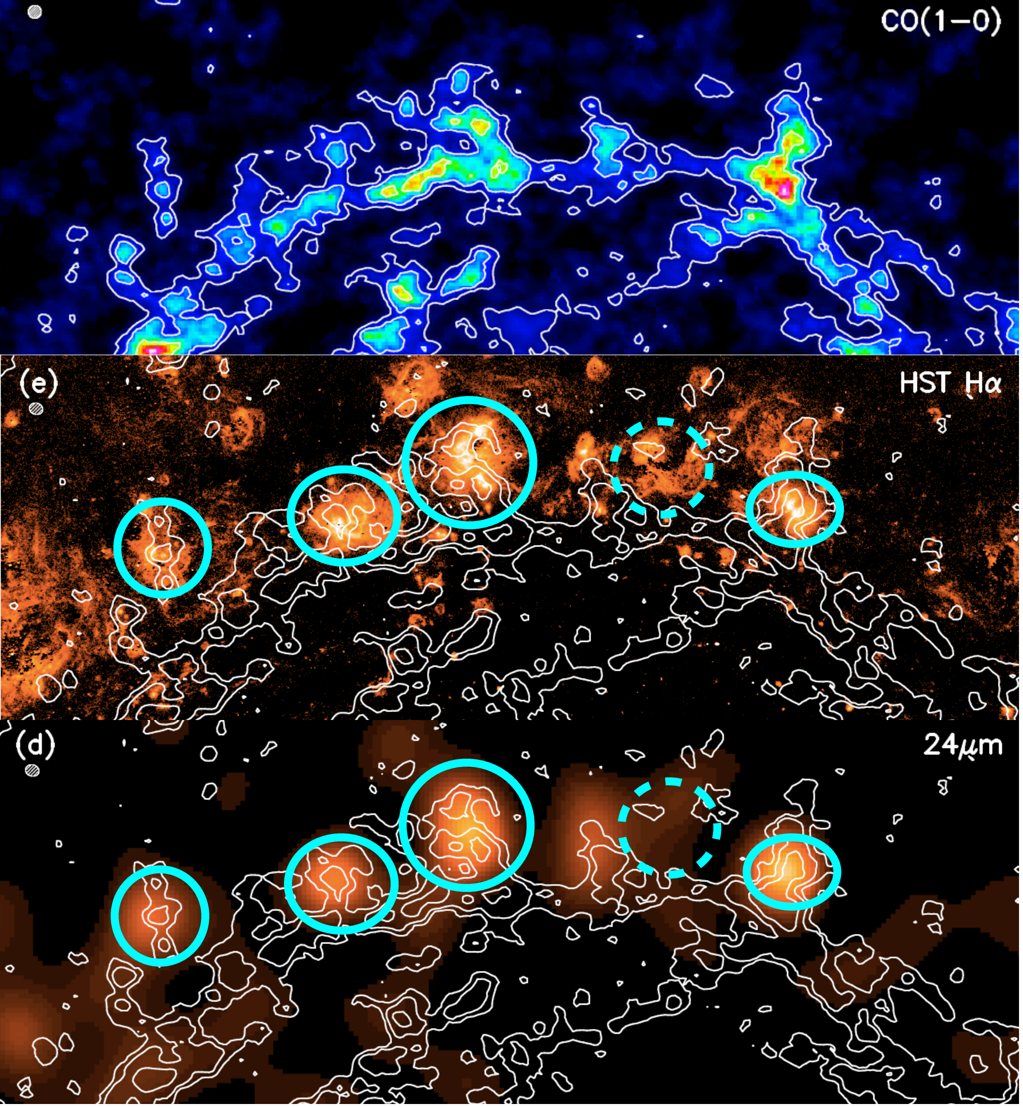
Schinnerer et al. (in prep.)



Off-set star formation
= stars form in spurs?

Schinnerer et al. (in prep.)

HII regions are off gas arm along spurs, but varying

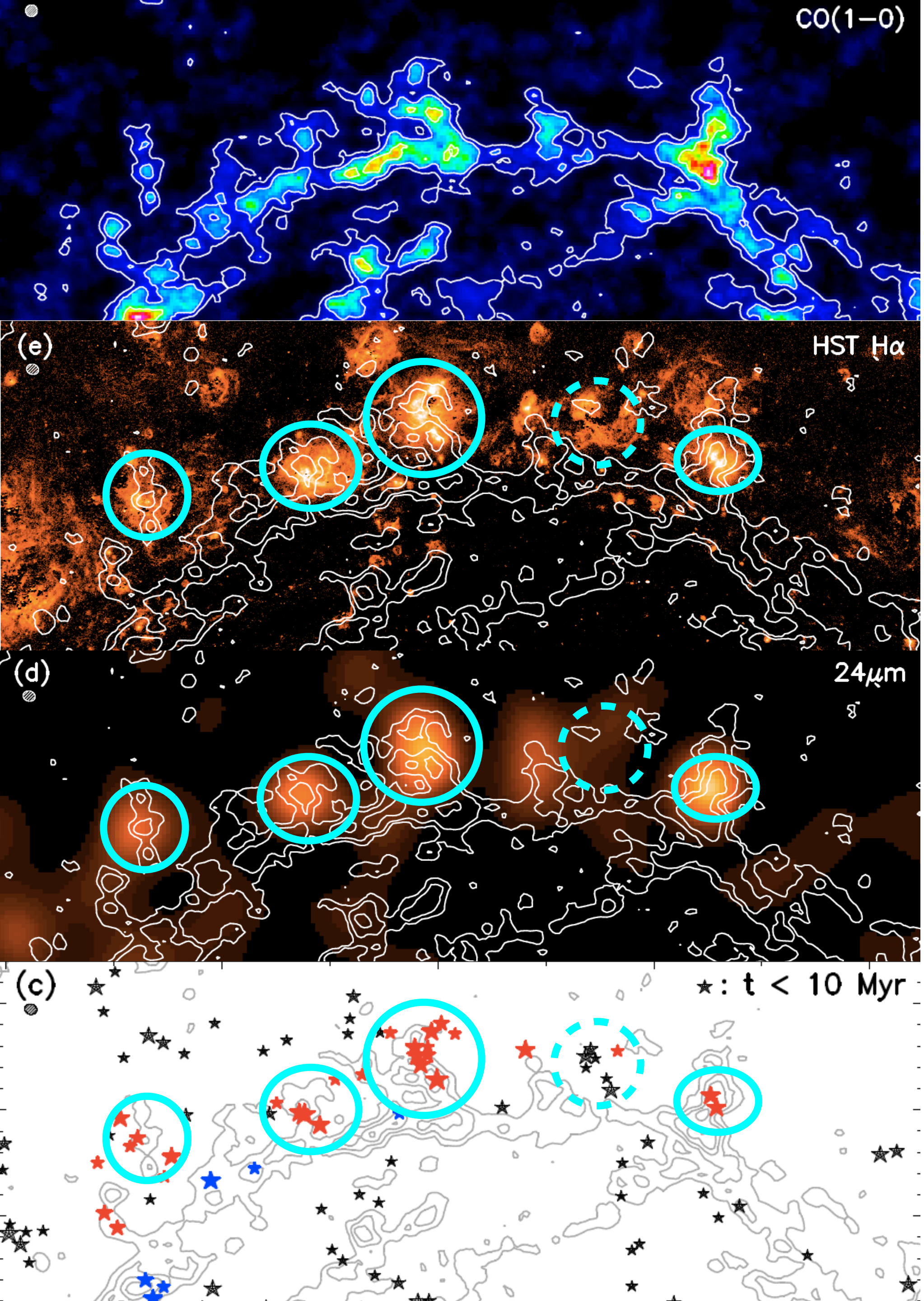


Off-set star formation
= stars form in spurs?

Schinnerer et al. (in prep.)

HII regions are off gas arm
along spurs, but varying

hot dust (24 μm)
associated with HII regions



Off-set star formation
= stars form in spurs?

Schinnerer et al. (in prep.)

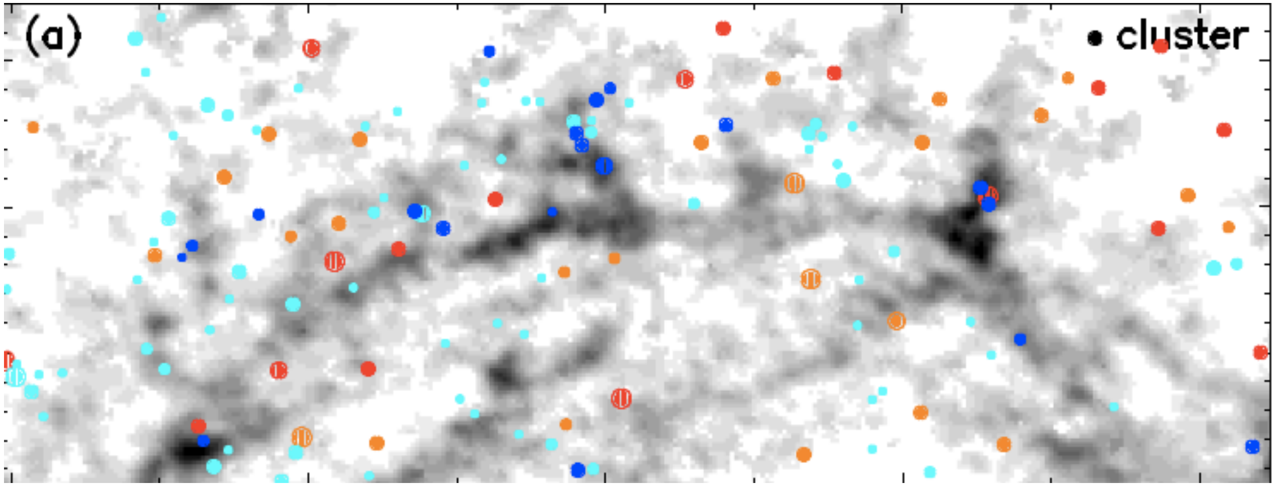
HII regions are off gas arm
along spurs, but varying

hot dust (24 μm)
associated with HII regions

young stellar clusters
abundant off arm, along spurs

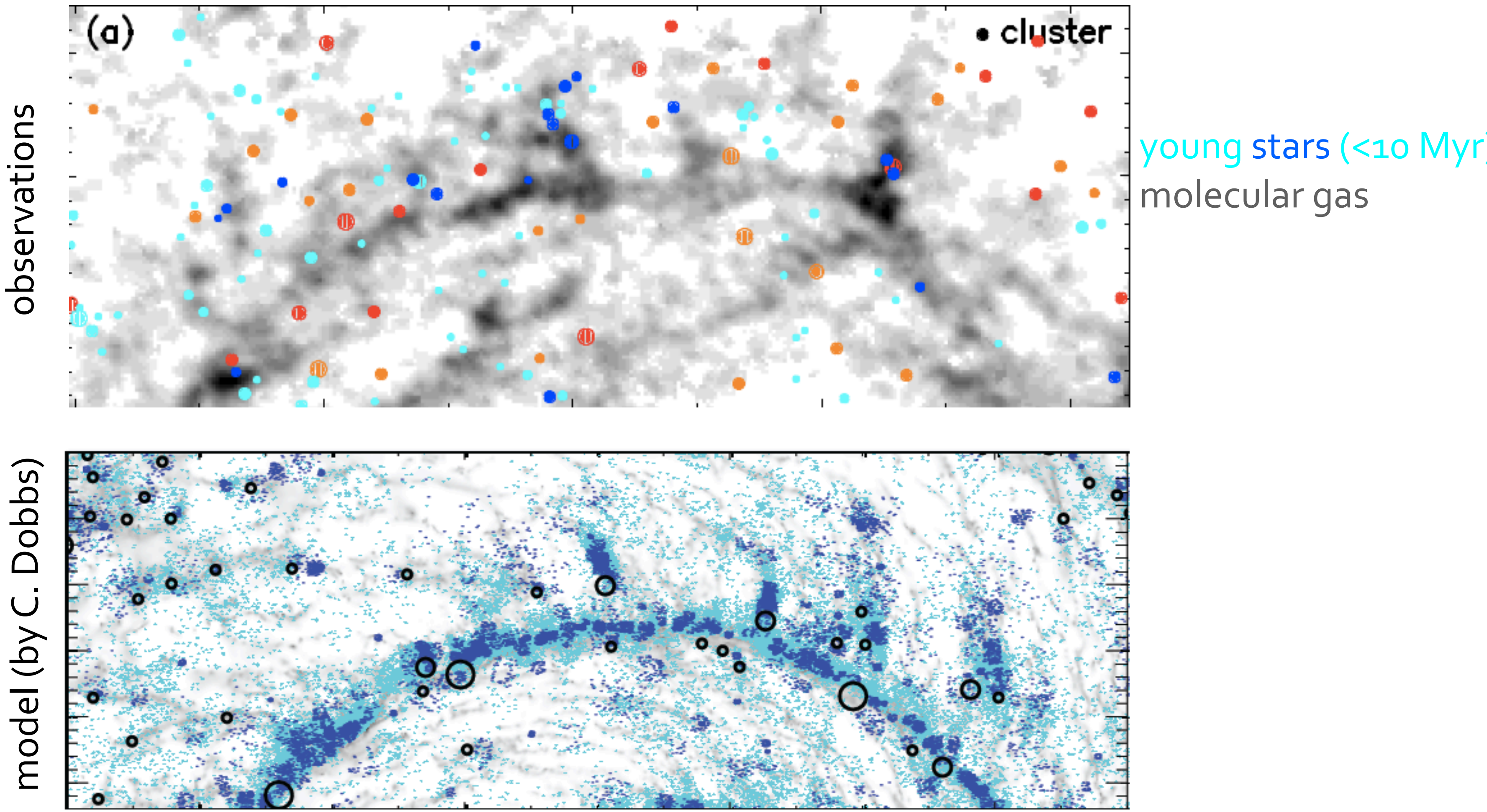
Onset of star formation delayed/prevented in spiral arm

observations



young stars (<10 Myr)
molecular gas

Onset of star formation delayed/prevented in spiral arm



no significant star formation in arms, restricted to gas spurs

⇨ collapse of clouds delayed or prevented in spiral arm

Complex relation between clouds and stellar clusters

YSC :
Young Stellar Cluster
GMC :
Giant Molecular Cloud

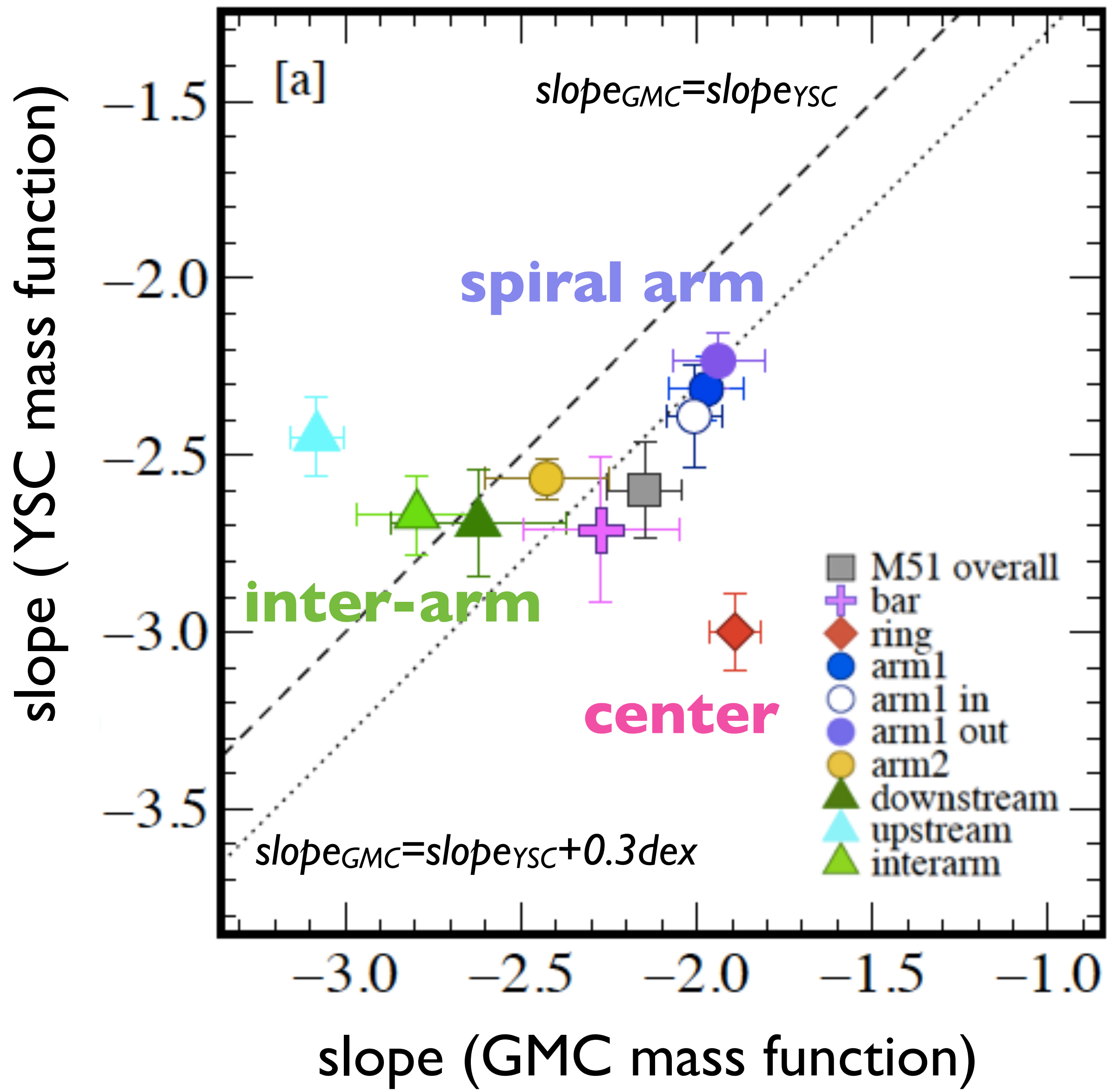
YSC and GMC properties tracked:

- maximum mass
- number density
- mass surface density

But ...

Hughes et al. (2013a)

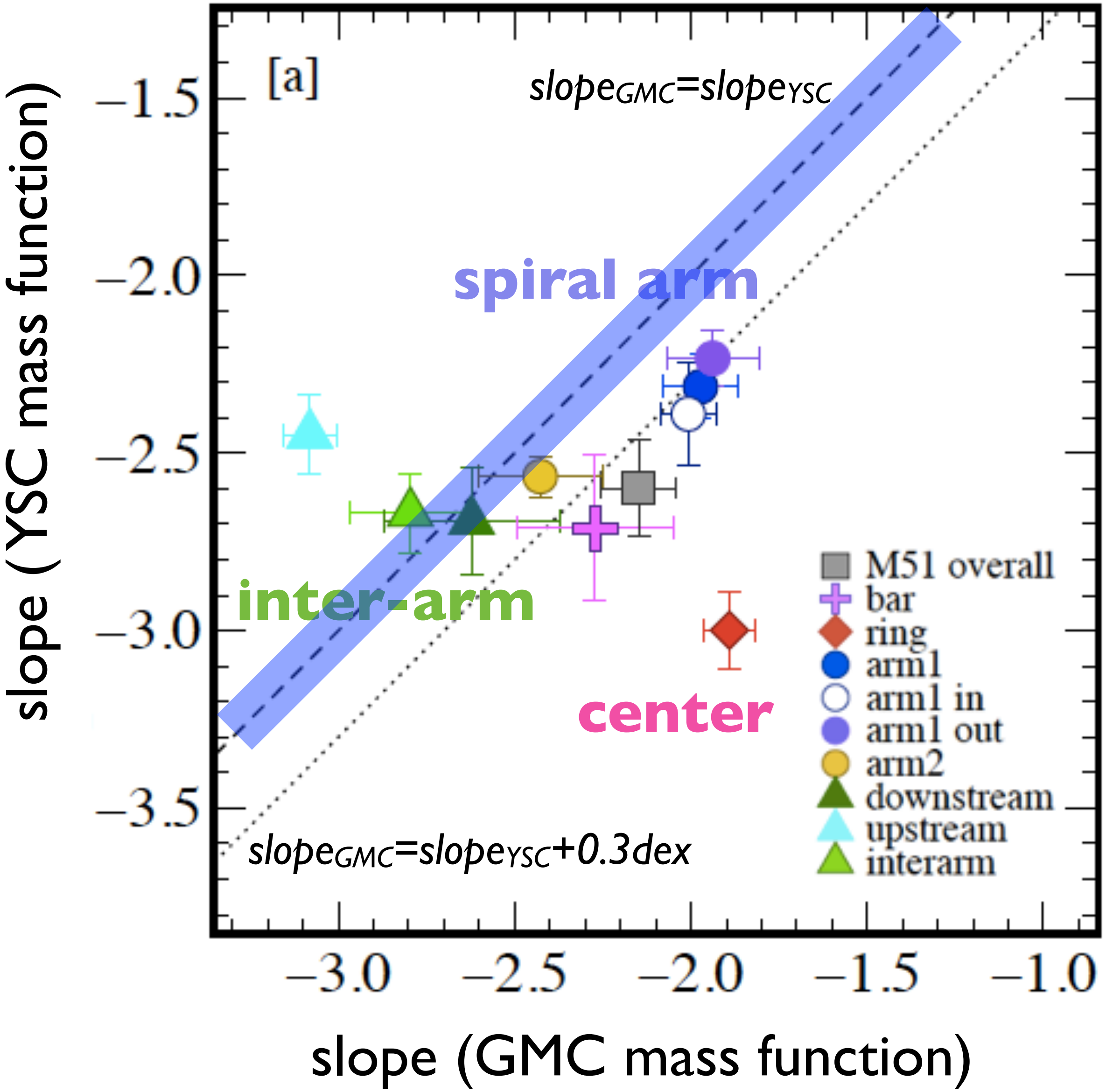
Complex relation between clouds and stellar clusters



YSC :
Young Stellar Cluster
GMC :
Giant Molecular Cloud

Hughes et al. (2013a)

Complex relation between clouds and stellar clusters

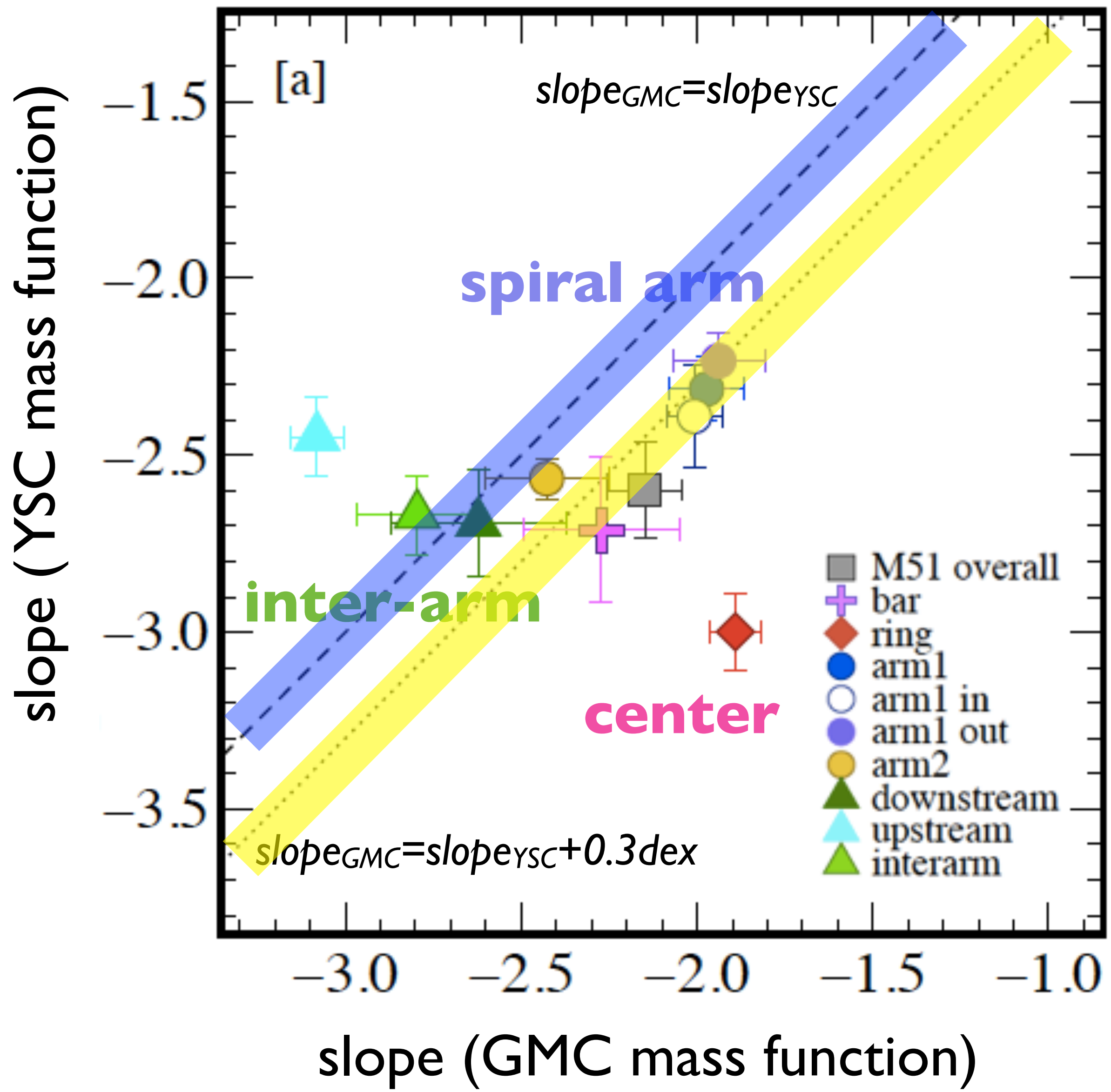


YSC :
Young Stellar Cluster
GMC :
Giant Molecular Cloud

no feed-back

Hughes et al. (2013a)

Complex relation between clouds and stellar clusters



YSC :
Young Stellar Cluster
GMC :
Giant Molecular Cloud

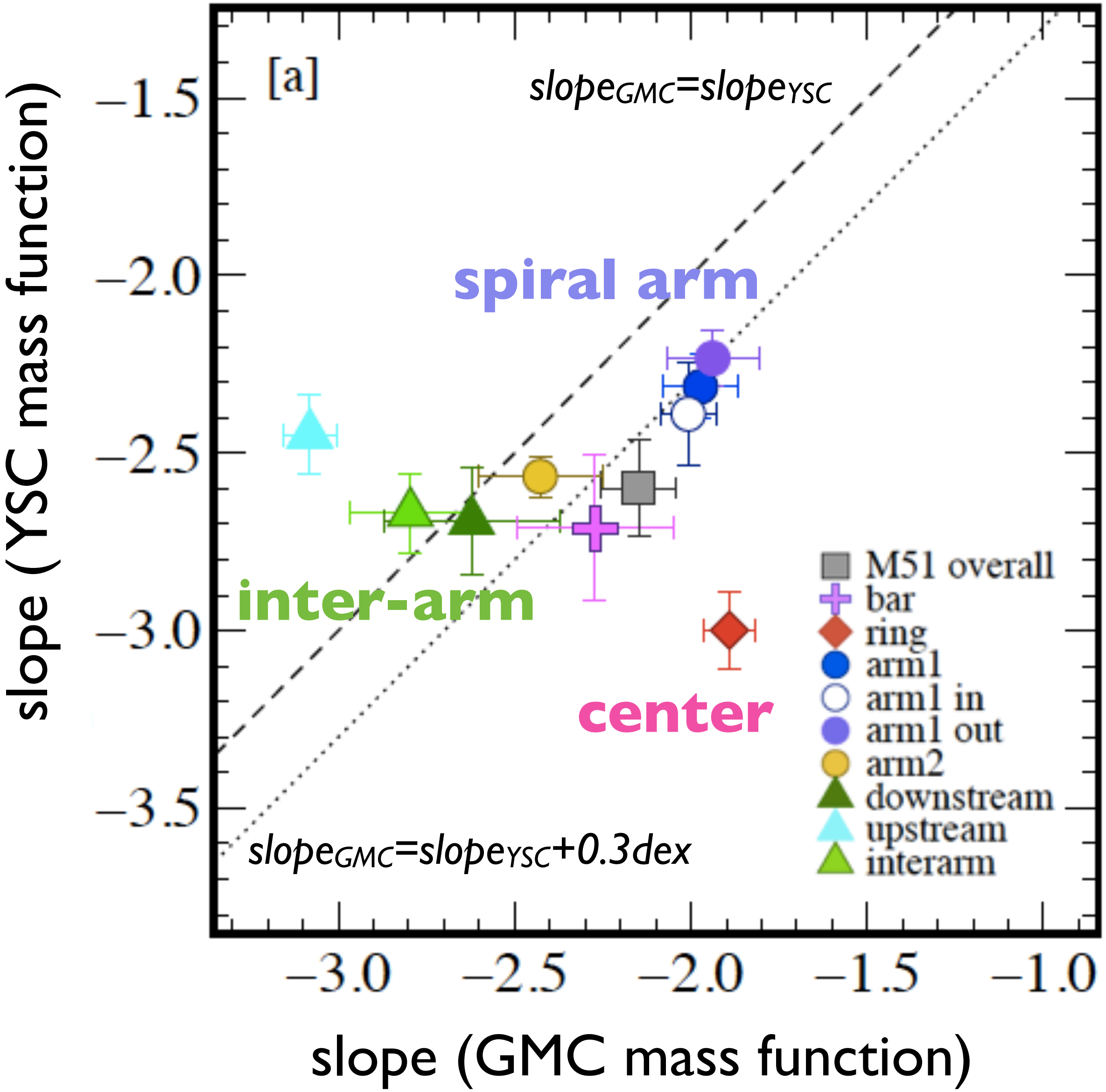
no feed-back

radiation feed-back

Fall et al. (2010)

Hughes et al. (2013a)

Complex relation between clouds and stellar clusters



YSC : Young Stellar Cluster
GMC : Giant Molecular Cloud

no simple relation

⇨

diverse set of mechanisms at work

Hughes et al. (2013a)

Star formation regulation on molecular cloud scales

#1:

3D distribution of molecular gas differs from atomic gas one

#2:

Giant Molecular Cloud properties are set by environment

#3:

Conversion of molecular gas into stars is complex process

spiral arms have significant impact &
ALMA will open up this research field