How galactic-scale gas motions regulate the structure of molecular gas and star formation

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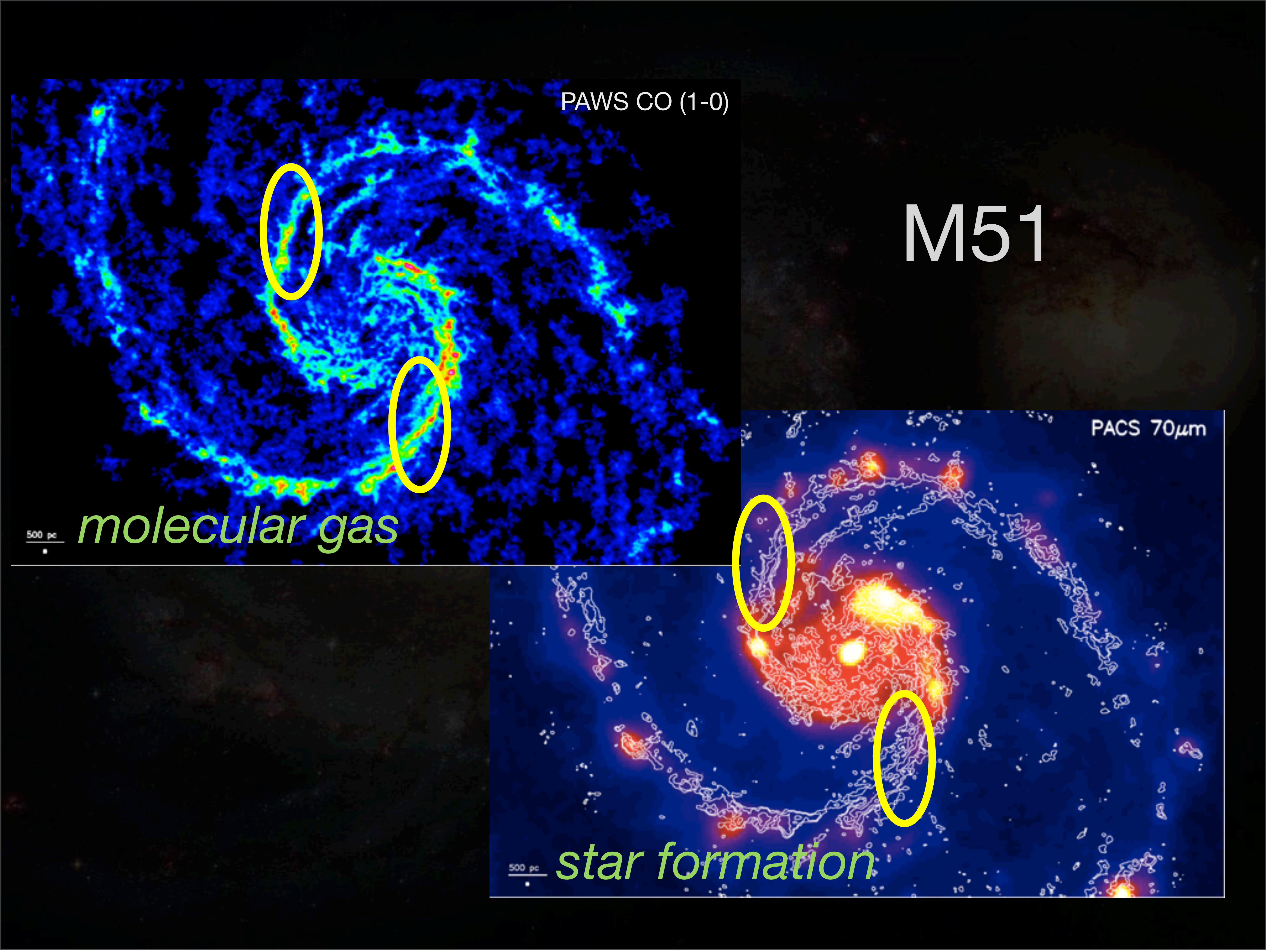
PAWS
PdBI Arcsecond Whirlpool Survey


PAWS CO (1-0)
M51
500 pc
molecular gas
PACS 70μm
500 pc
star formation

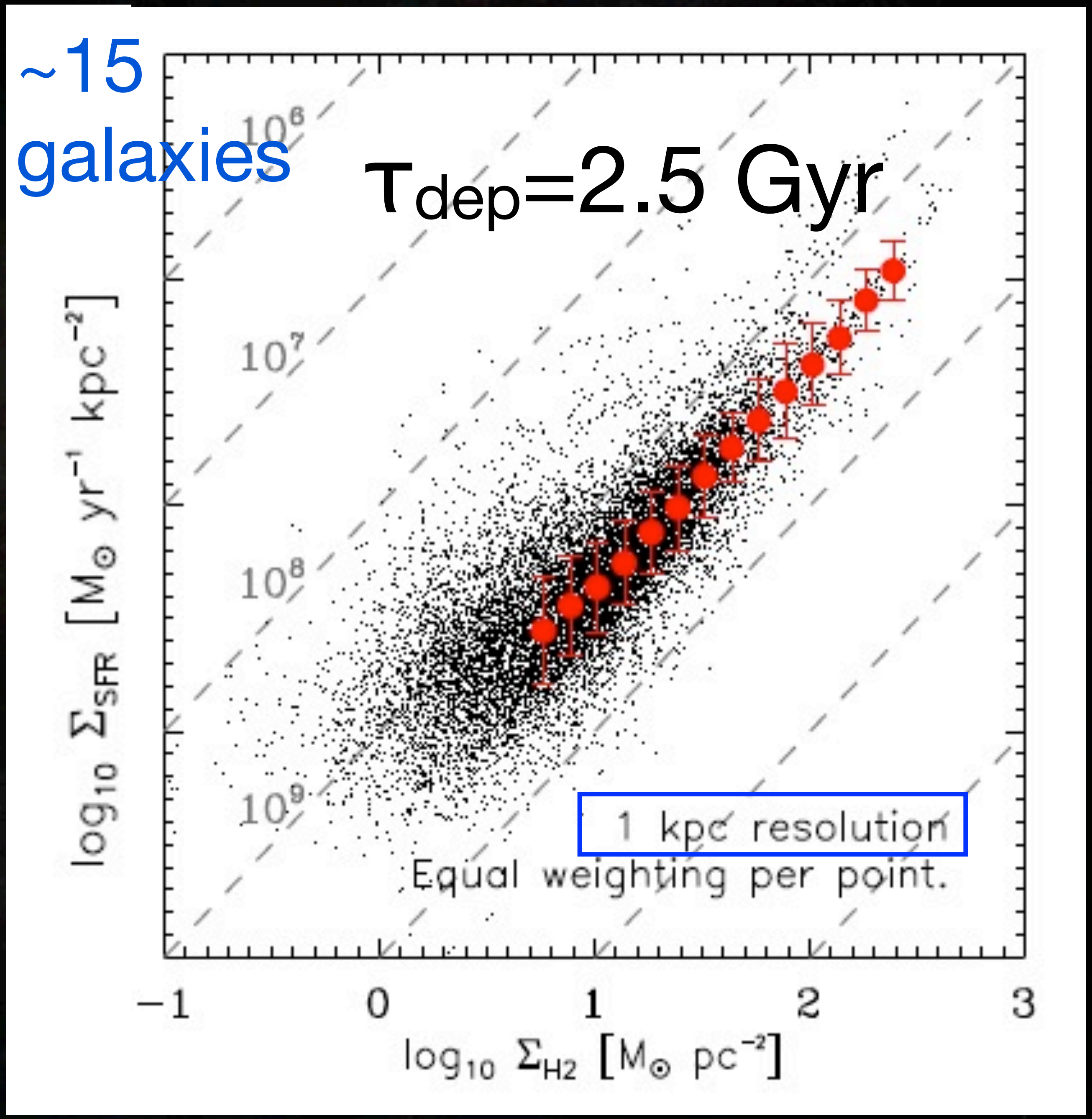
(sub-)kpc star formation relation

Bigiel et al. (2008;2011)

molecular gas depletion time

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

$\tau_{dep} = SFE^{-1}$



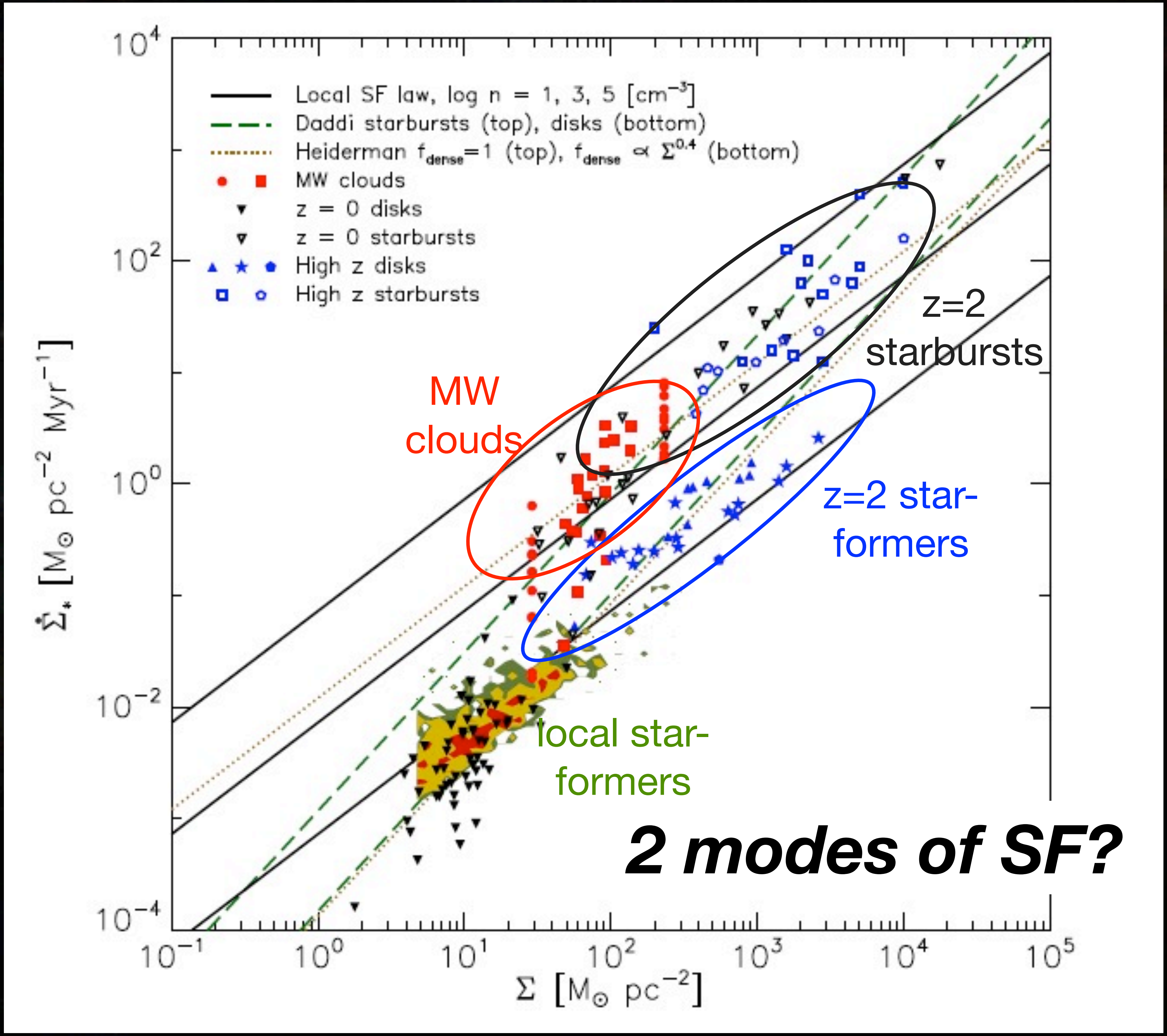
$\Sigma_{SFR} = \Sigma_{H2}^{n}$

n=1

≠1.4-1.5

universal molecular gas depletion time ??

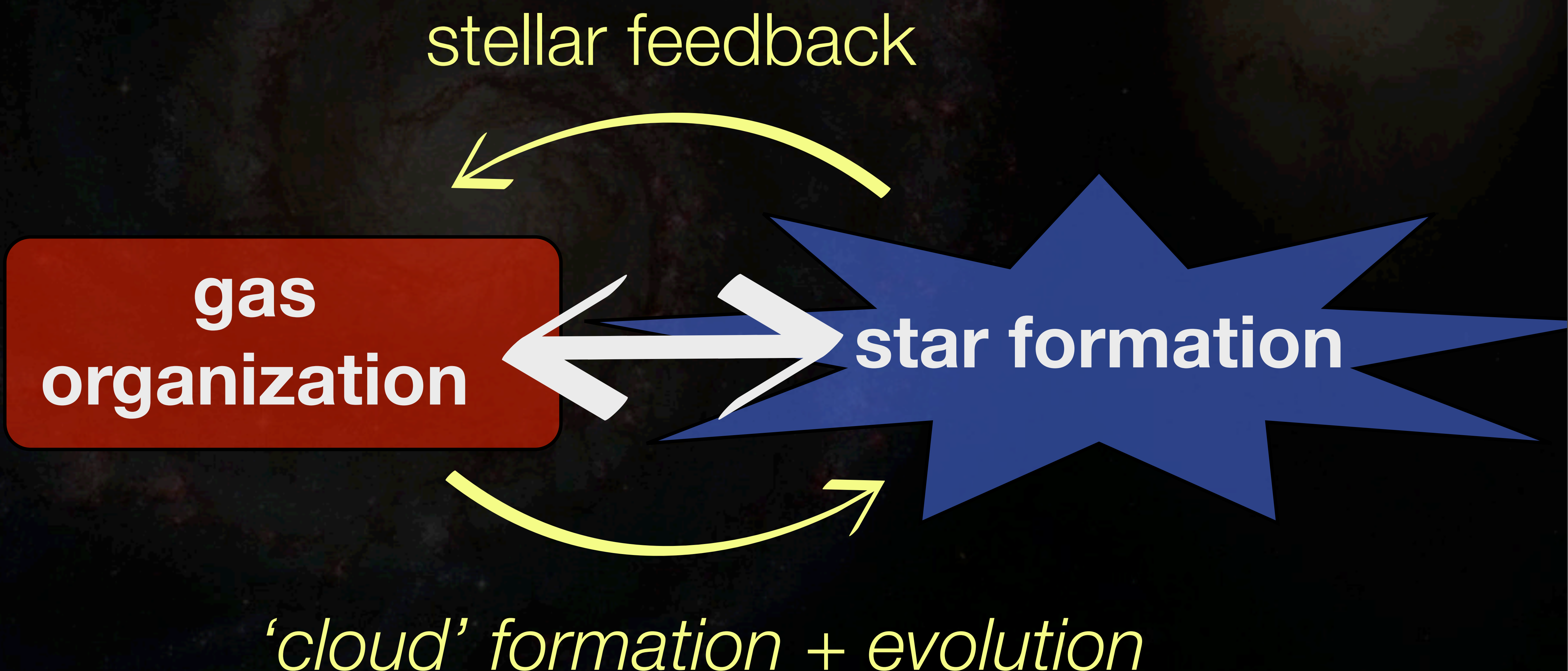
Krumholz, Dekel & McKee (2011)



2 modes of SF?

see also Sandstrom et al. (2013)

gas kinematics in spiral potentials



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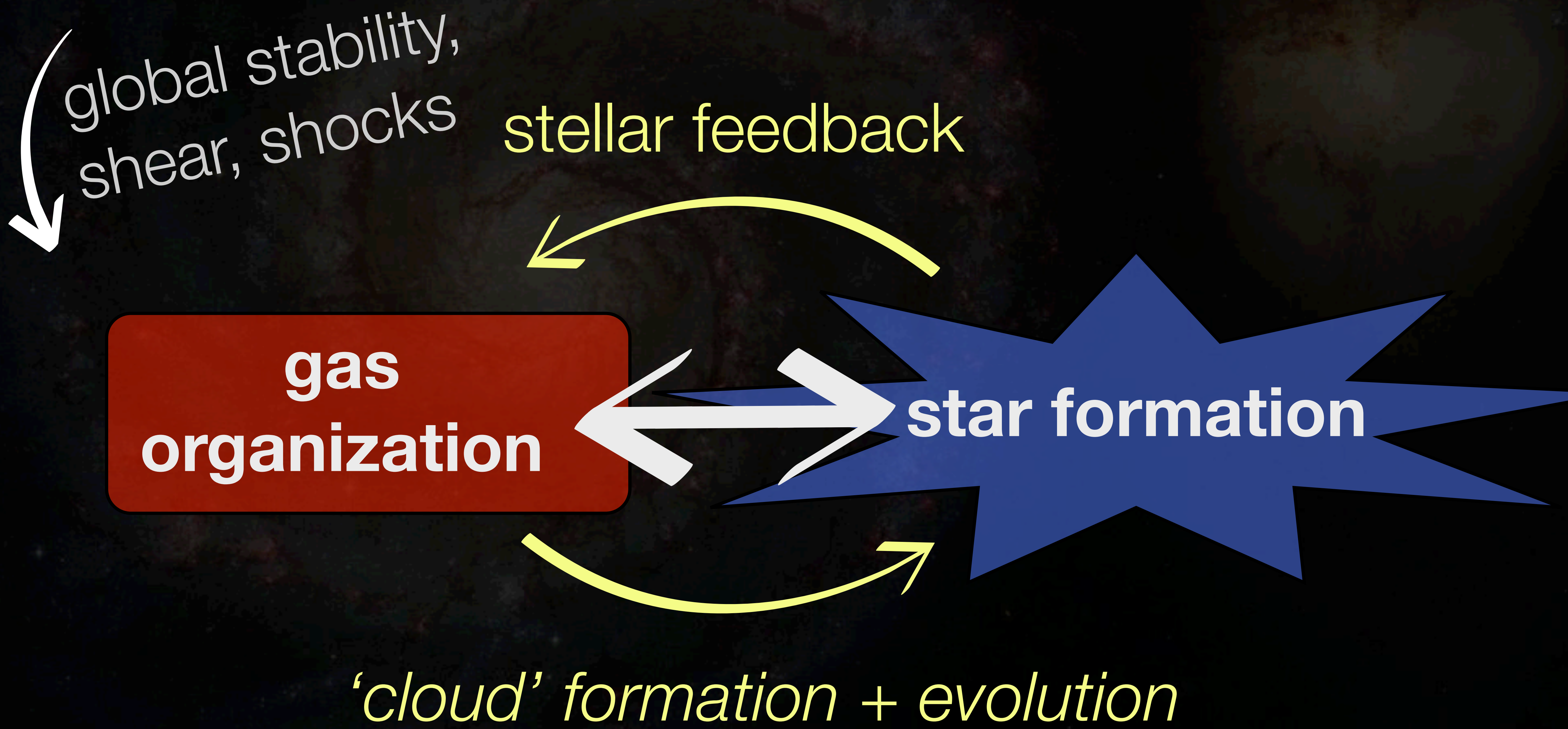

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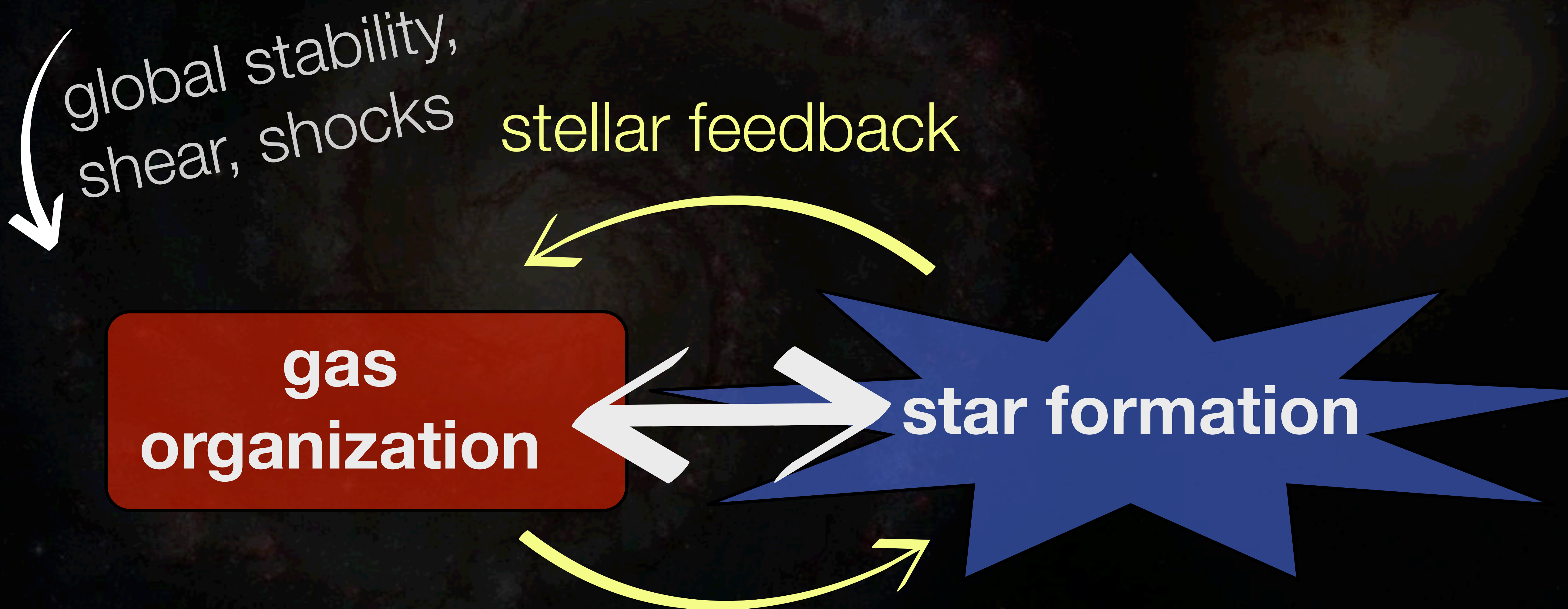


non-circular motions:

dynamical coupling of clouds to environment

- **shocks**: build high densities, trigger SF, enhance turbulence?

- **shear**: stabilize+destroy clouds
  - SF favored in regions of low shear (spiral arms)

- **non-circular motions**: dynamical coupling to environment

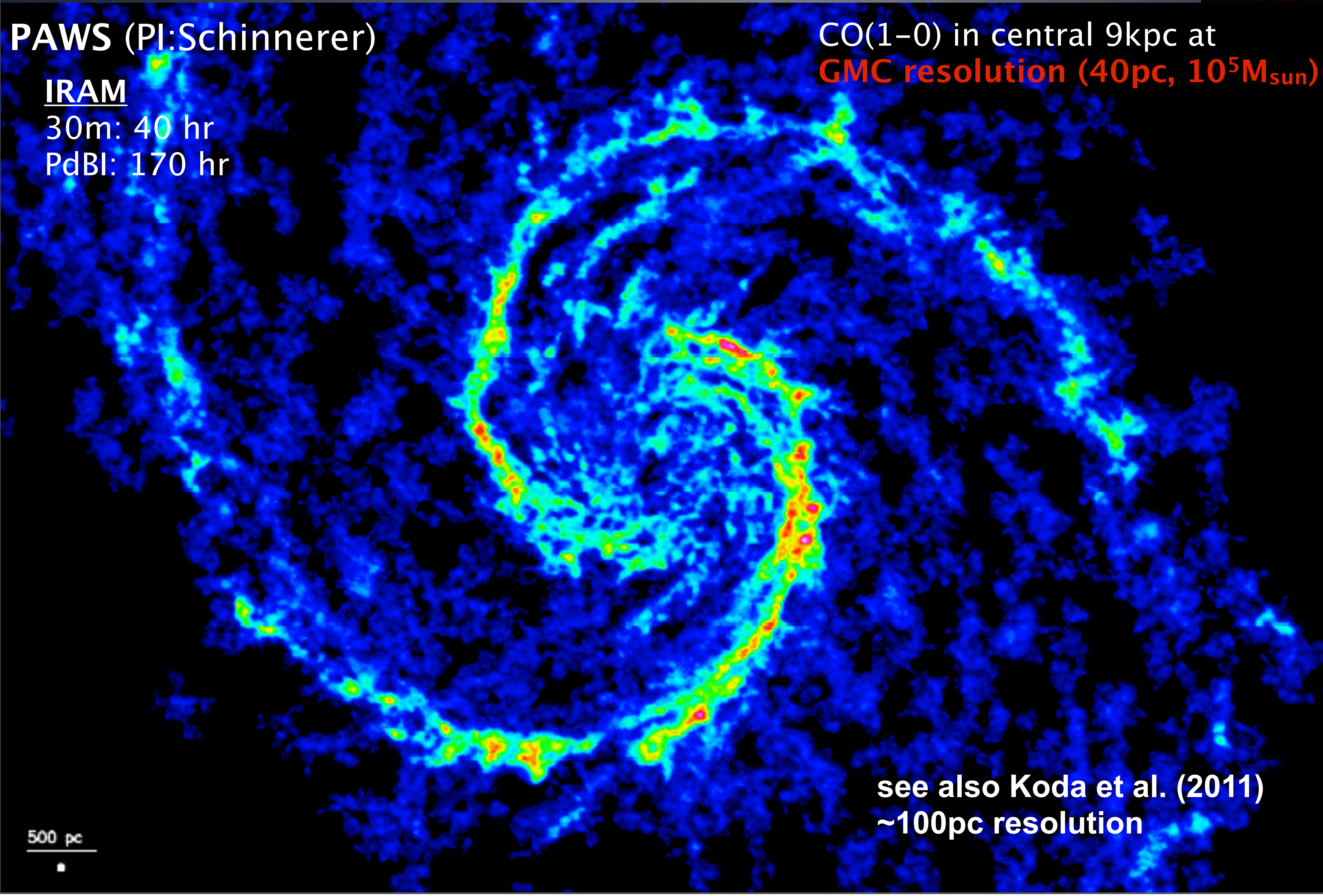
- which controls cloud stability?

Molecular Gas disk of M51

PAWS (PI:Schinnerer)

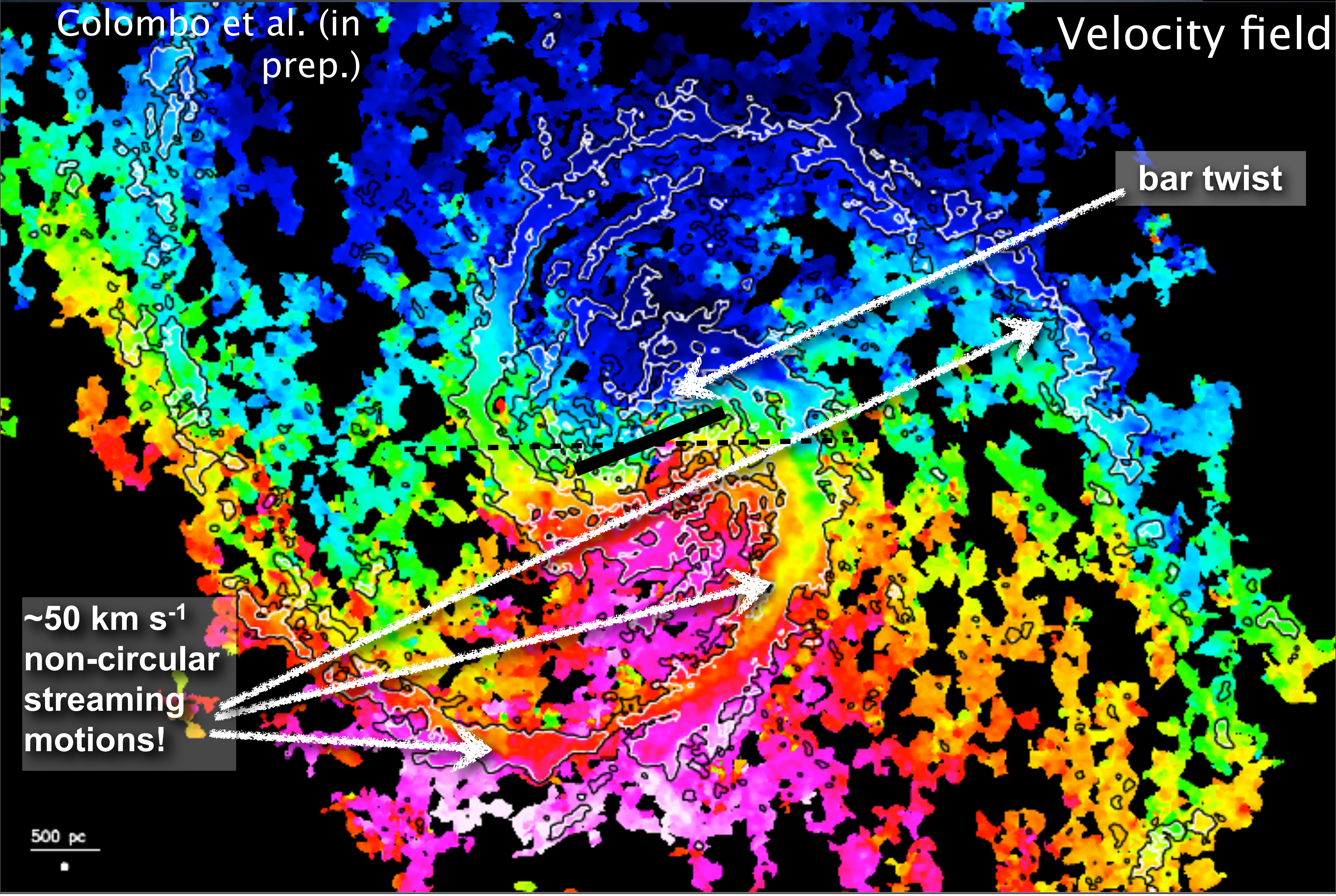
IRAM
30m: 40 hr
PdBI: 170 hr

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



see also Koda et al. (2011)
~100pc resolution

Molecular Gas disk of M51



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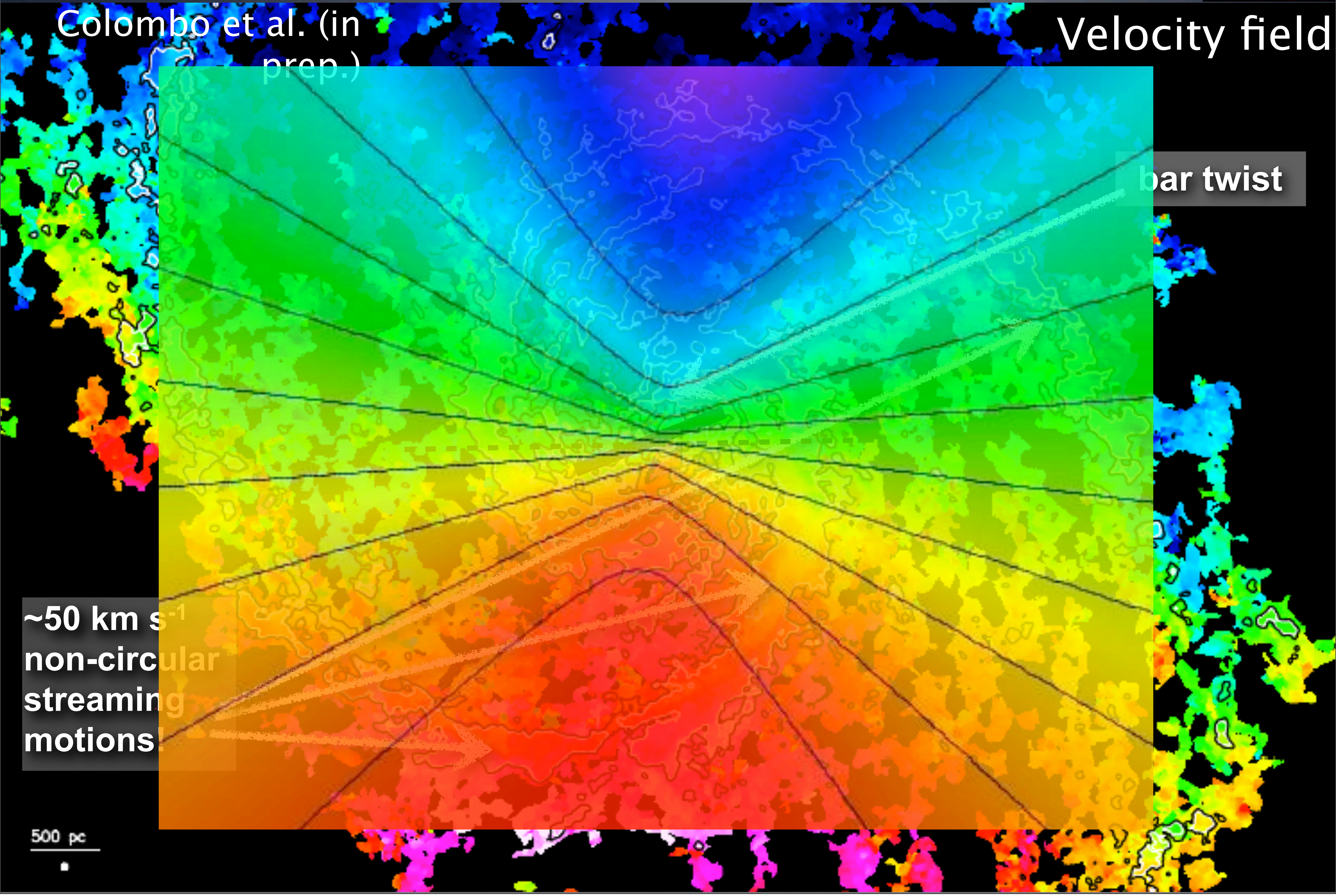

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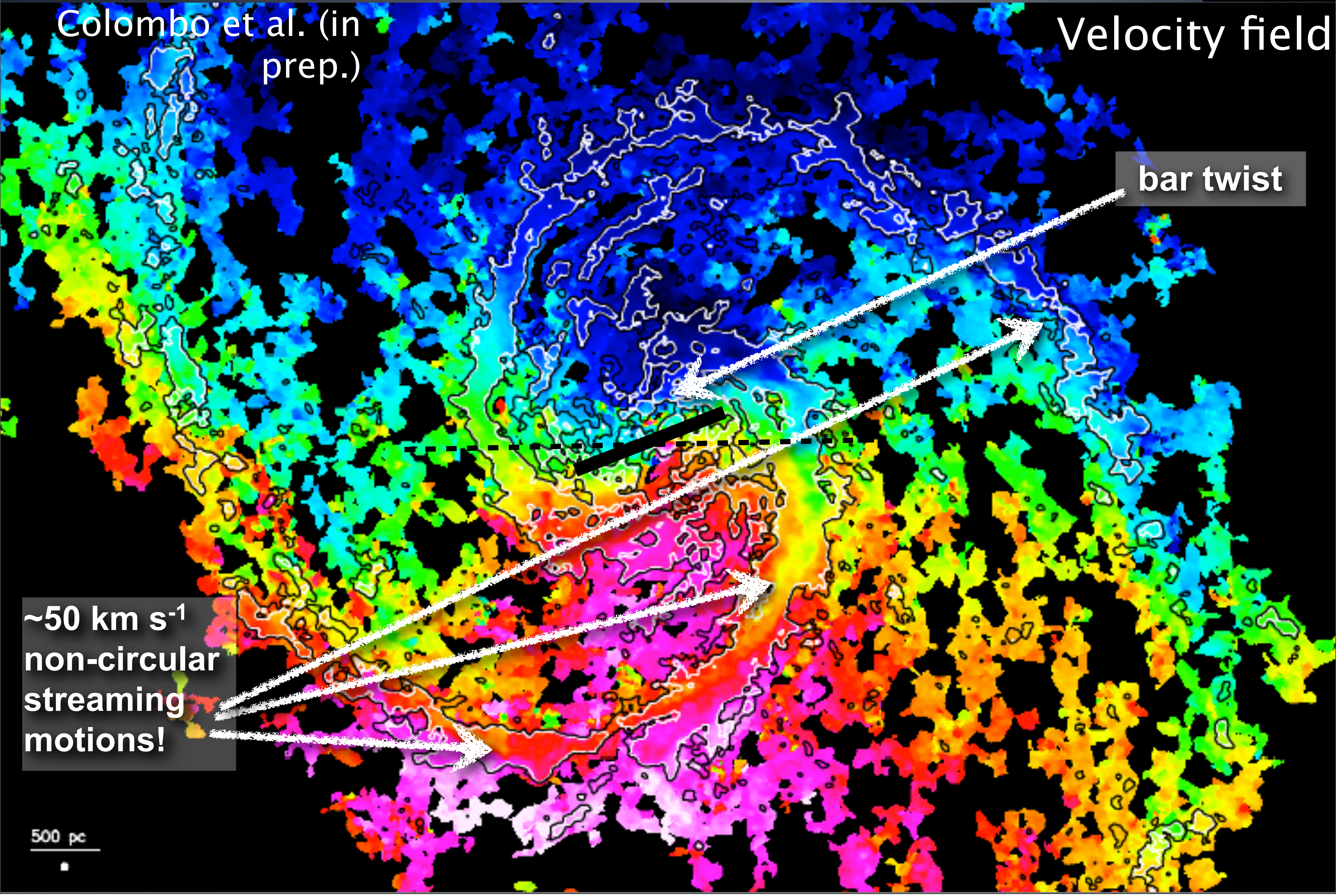
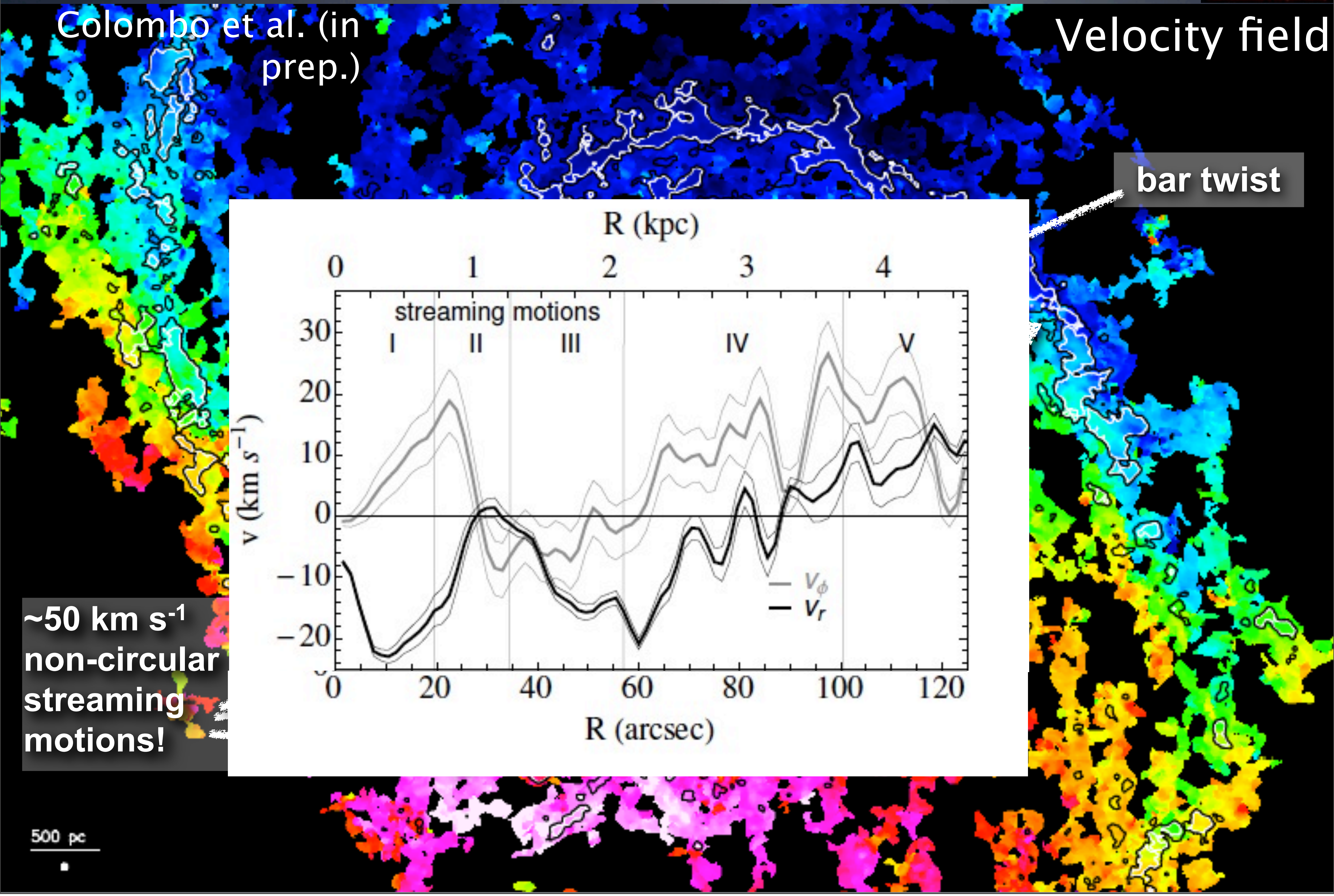


Molecular Gas disk of M51

Colombo et al. (in prep.)

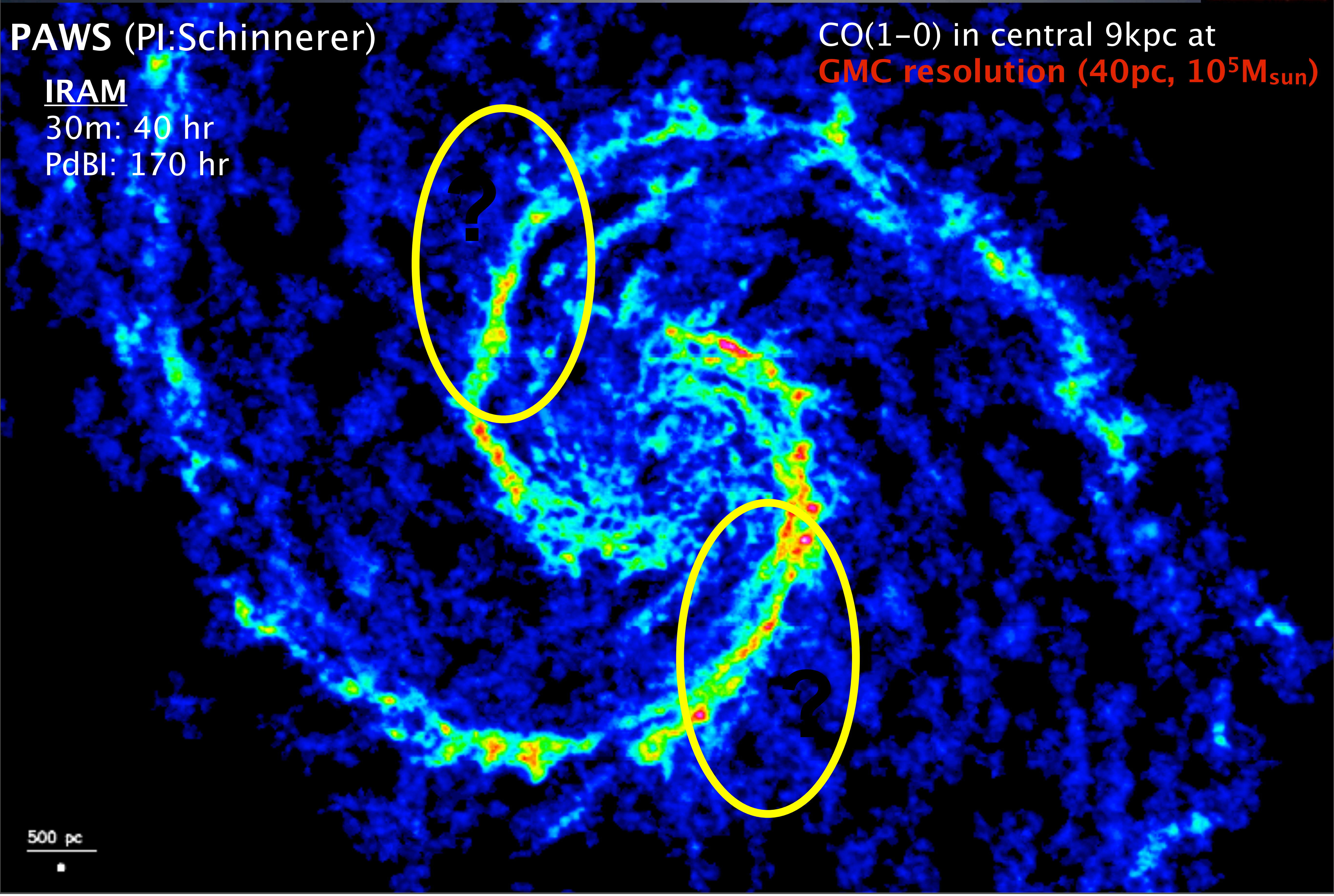
Velocity field



bar twist

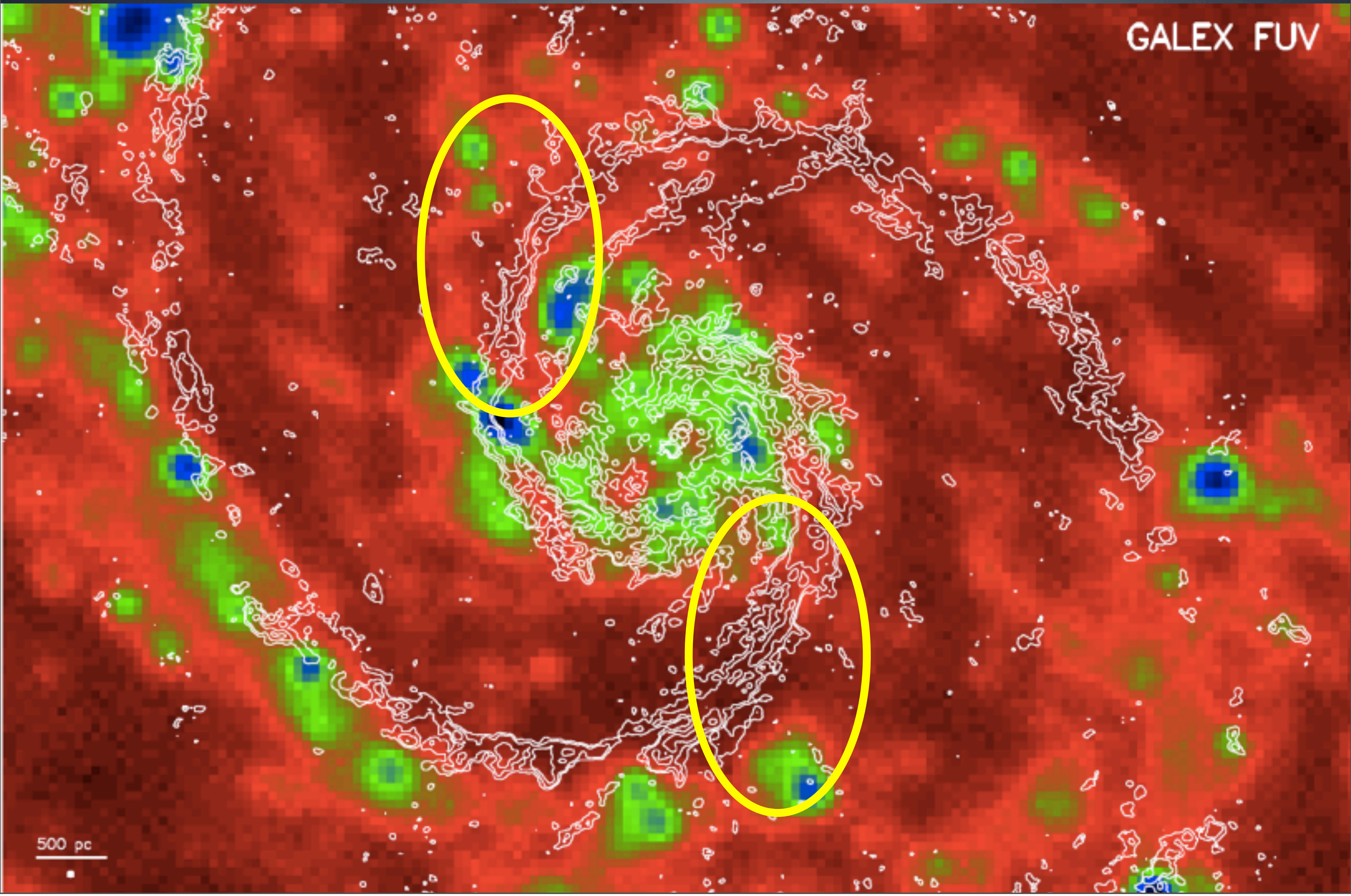
~50 km s^{-1} non-circular streaming motions!

Molecular Gas disk of M51



Spatial Relation b/n Gas and Star Formation

Schinnerer et al. (in prep.)



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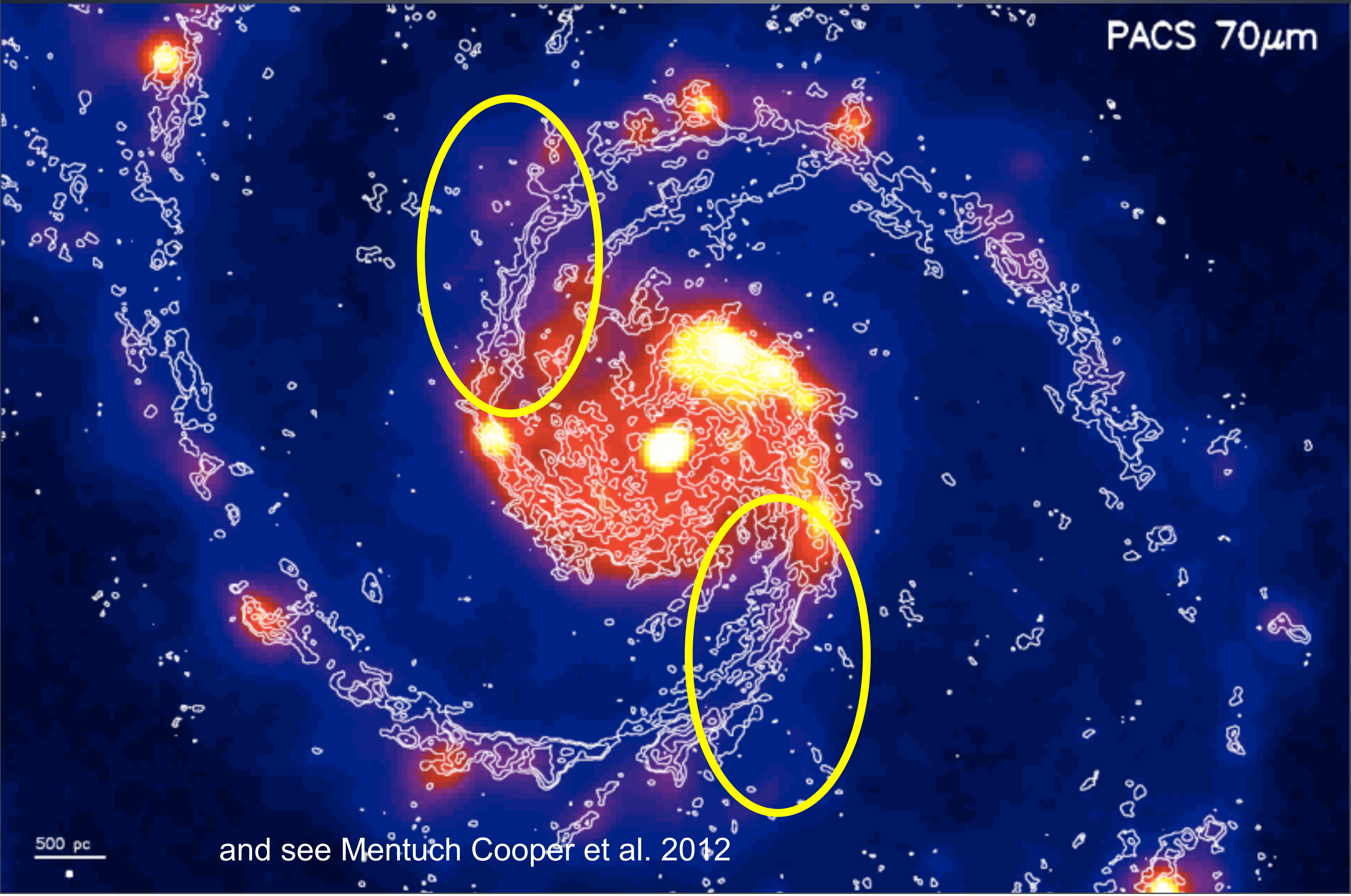

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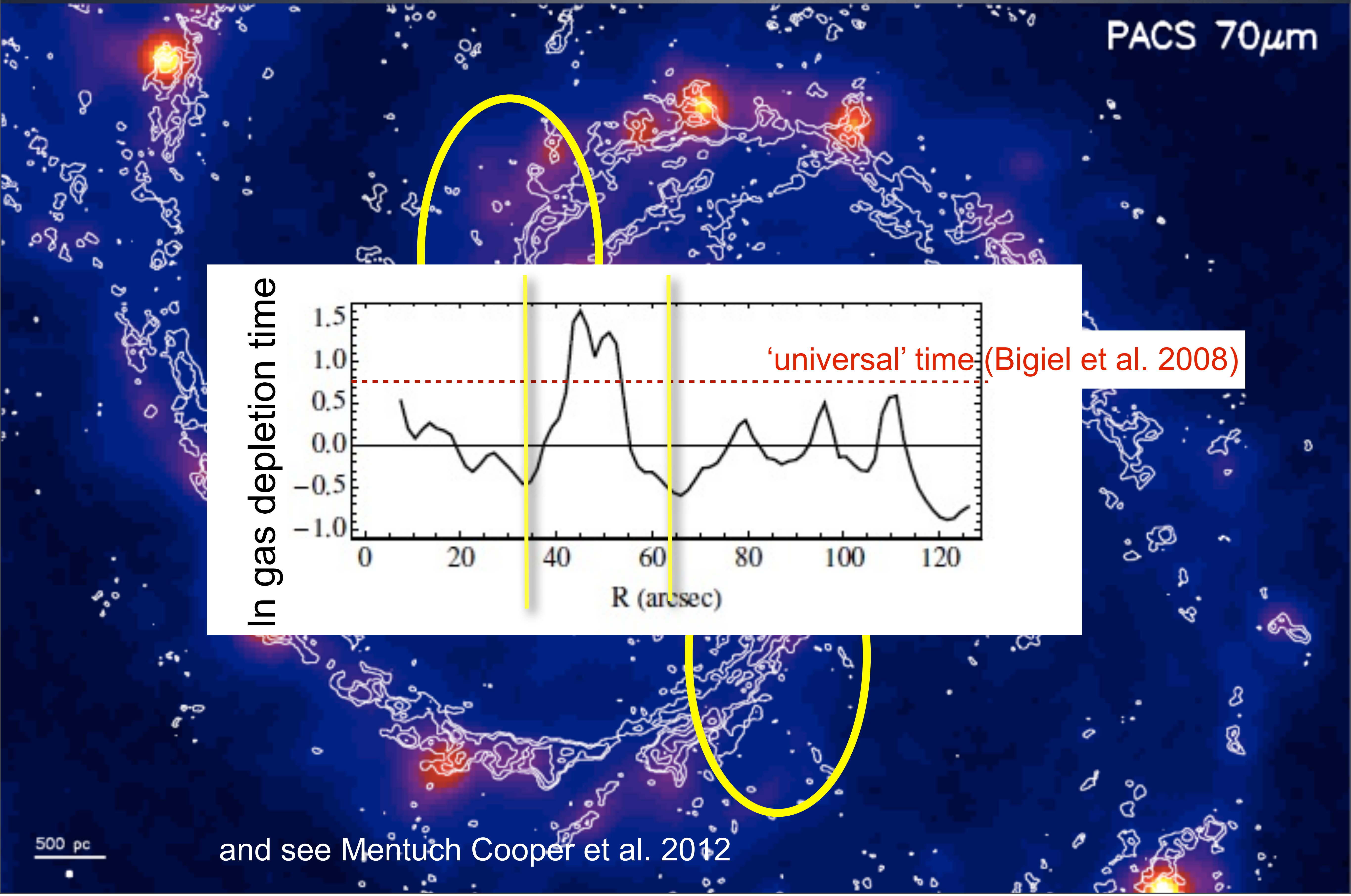
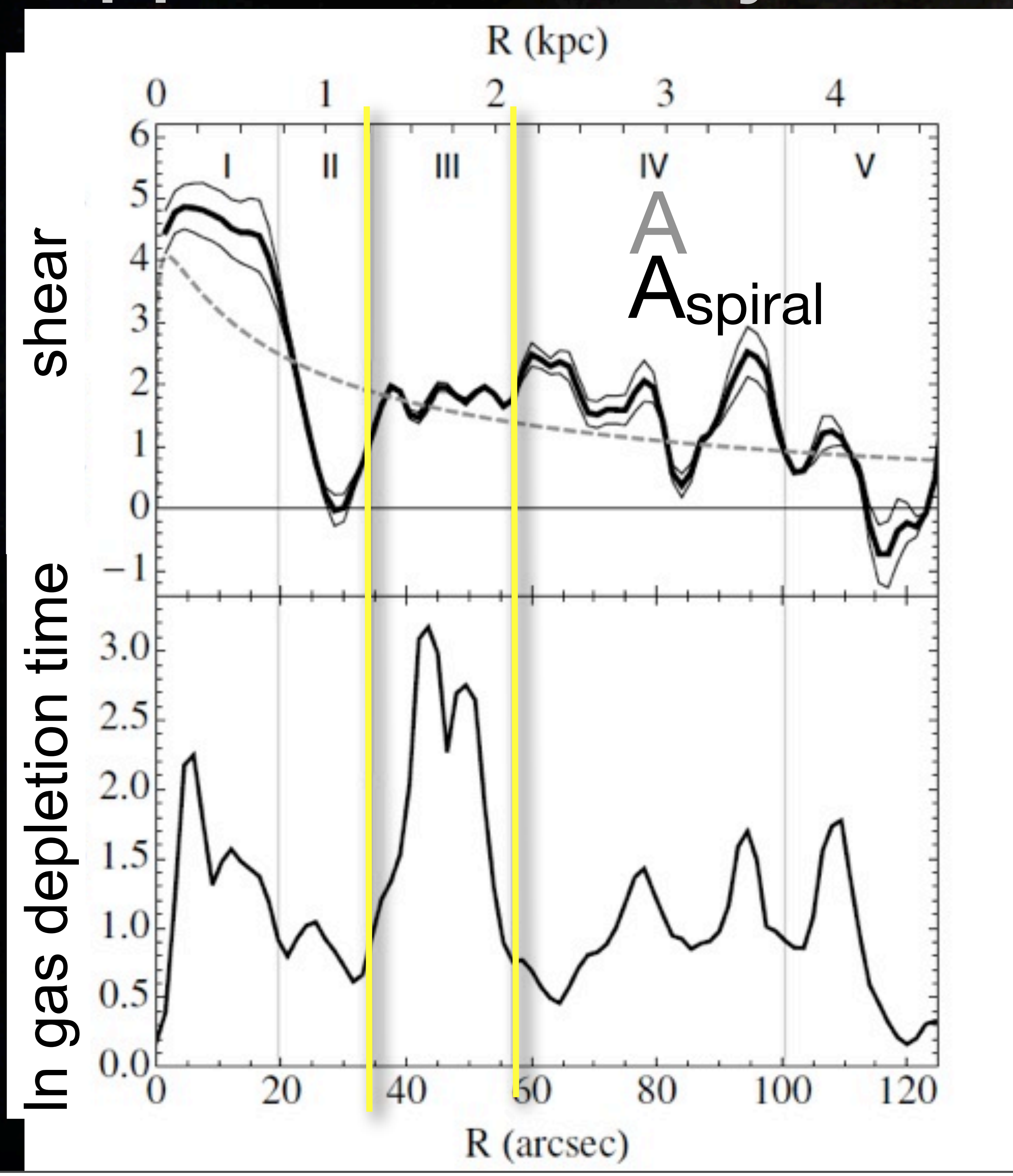


and see Mentuch Cooper et al. 2012

GMC Stabilization in M51

what shuts off star formation?

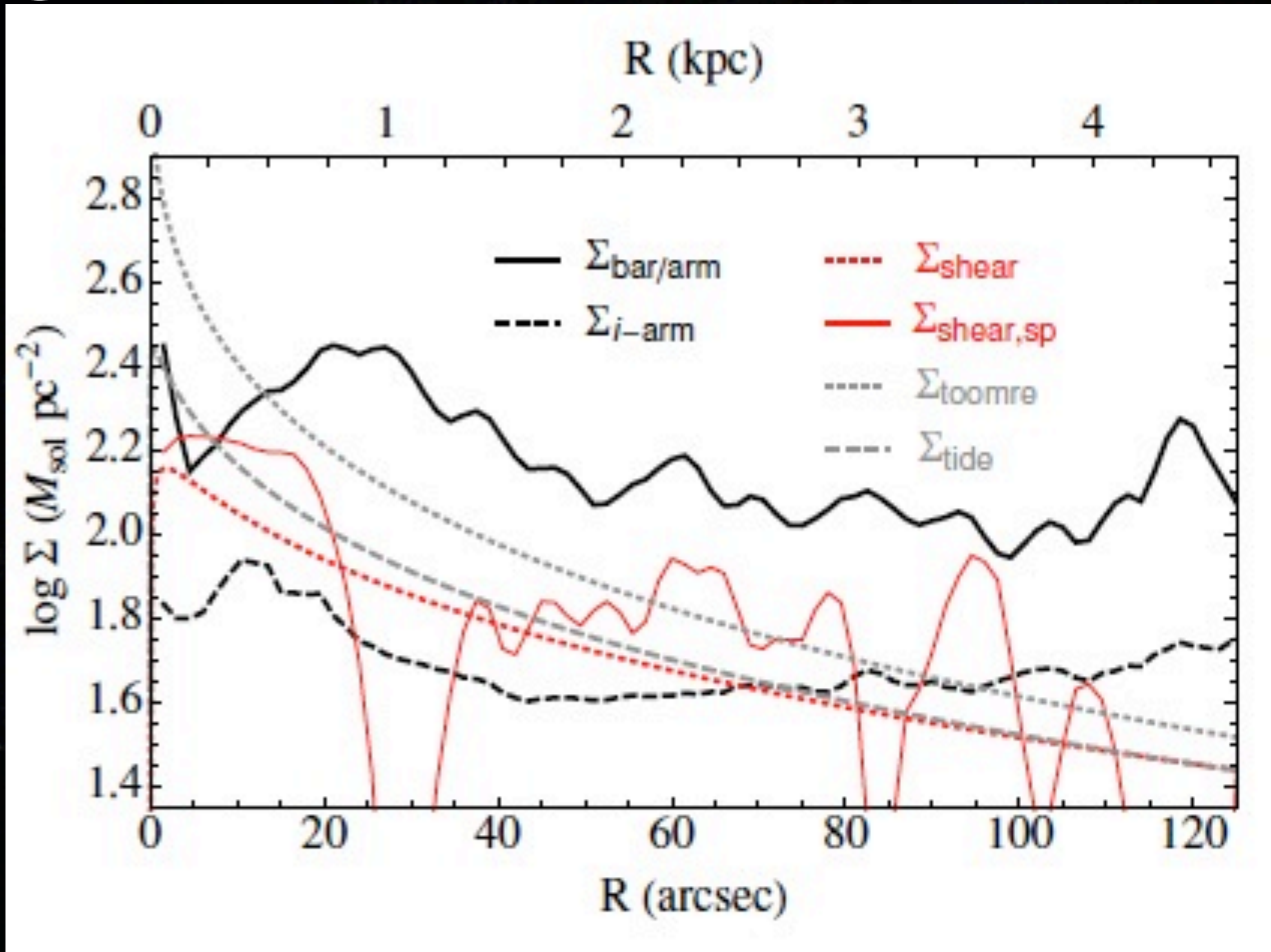
support *not* entirely from



- spiral arm shear (Oort A; cf. Dib & Helou 2012)
- **preferentially enhanced turbulent motions** (regular σ along spiral)
- **stellar feedback** (little Hα, UV, clusters <70Myr)

Meidt et al. (2013)

gravitational disk stability



$$\Sigma_{shear} = \frac{2.5\alpha_A \sigma A}{\pi G}$$

$$\Sigma_{toomre} = \frac{\alpha \sigma \kappa}{\pi G}$$

$$\Sigma_{tide} = \frac{\sigma[3A(A-B)]^{1/2}}{\pi G}$$

Meidt et al.(2013)

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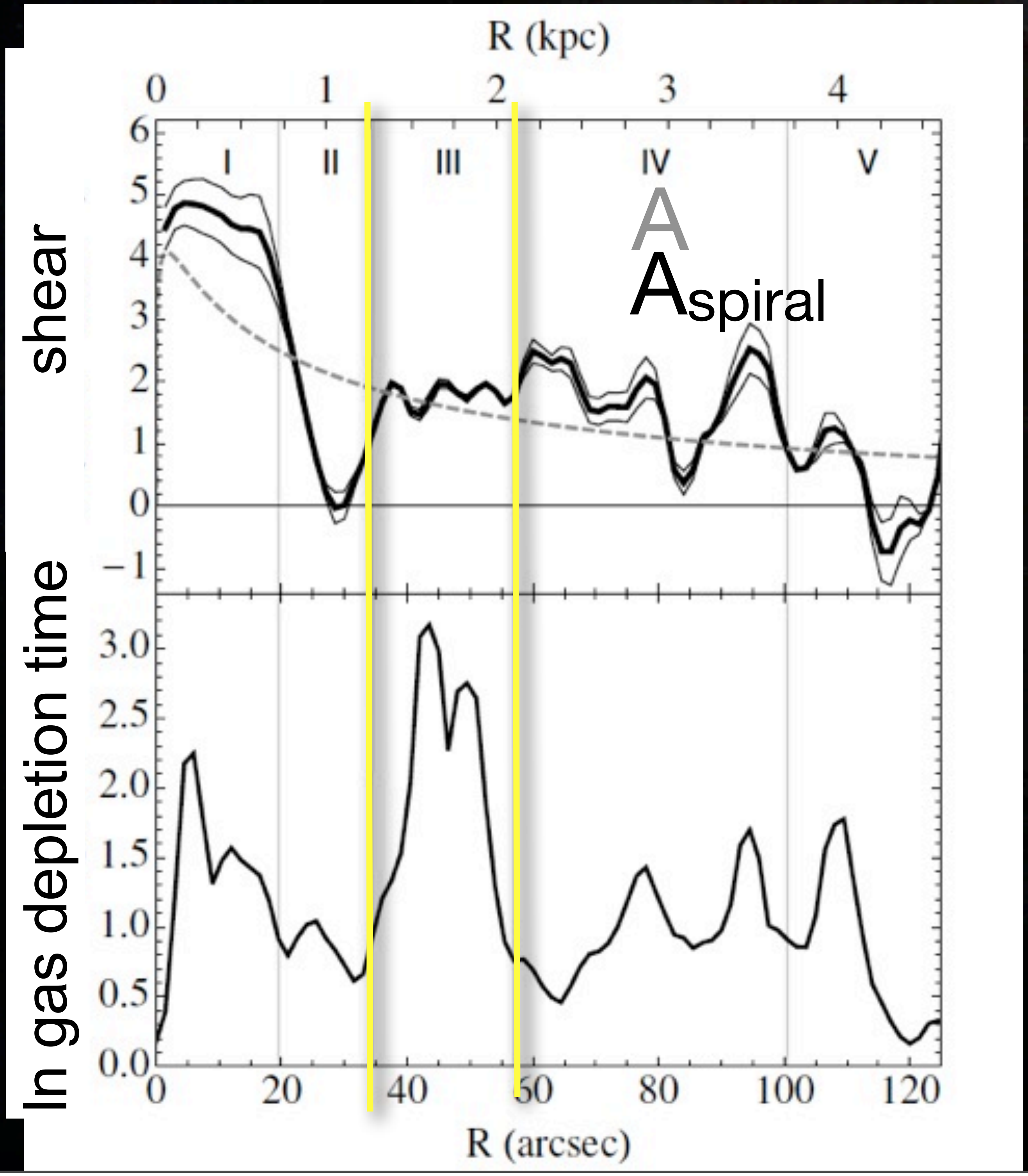

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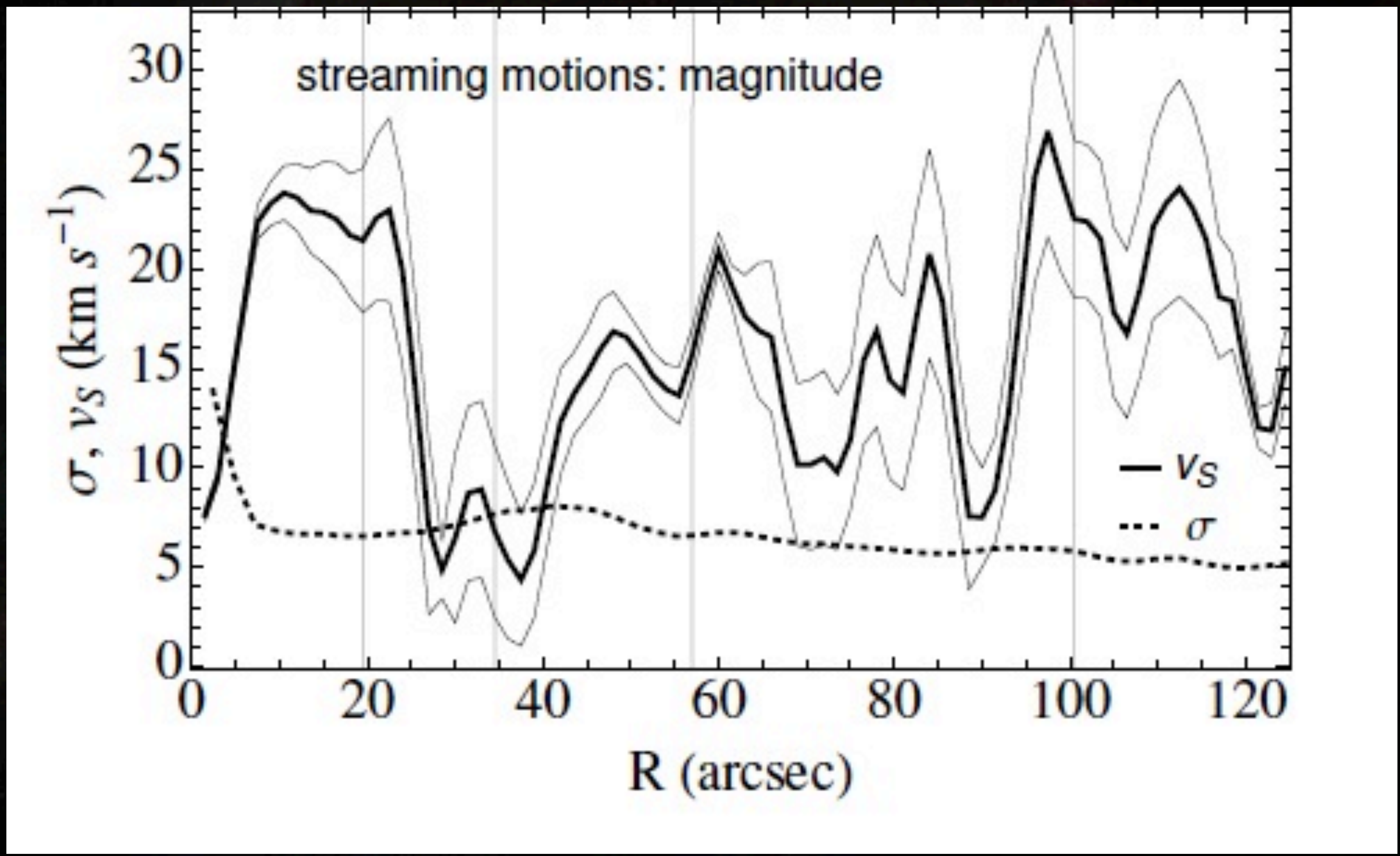
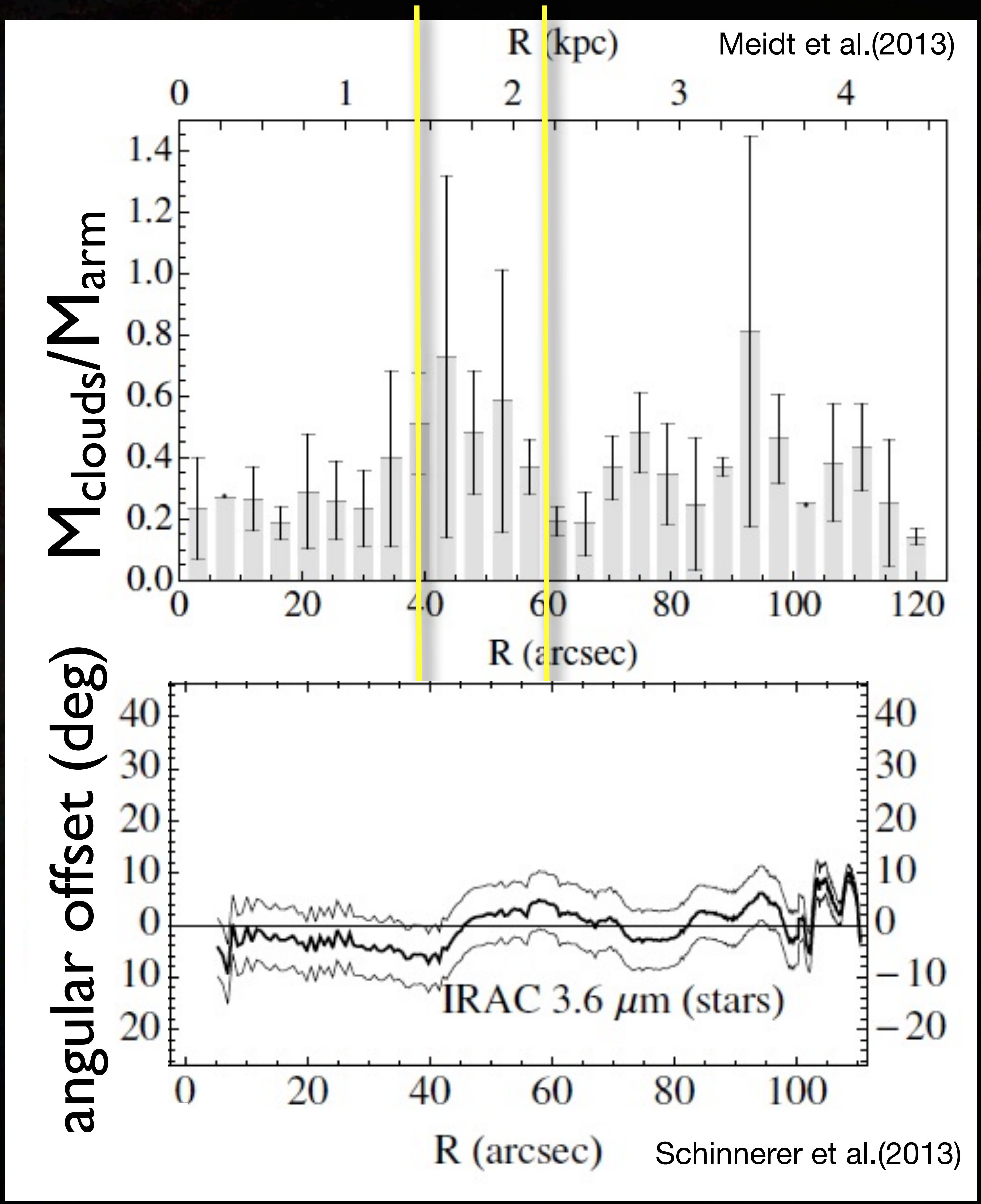

streaming motions: magnitude
σ, v_S (km s^-1)
R (arcsec)
v_S
σ

cloud stability

*in the **spiral shock***

- ***cloud collisions/ agglomeration***: σ increases (Bonnell et al. 2006; Kim, Kim & Ostriker 2006), unbound fraction increases?
- do we see individual bound clouds embedded in a larger unbound structure?
- --> low overall SFE?



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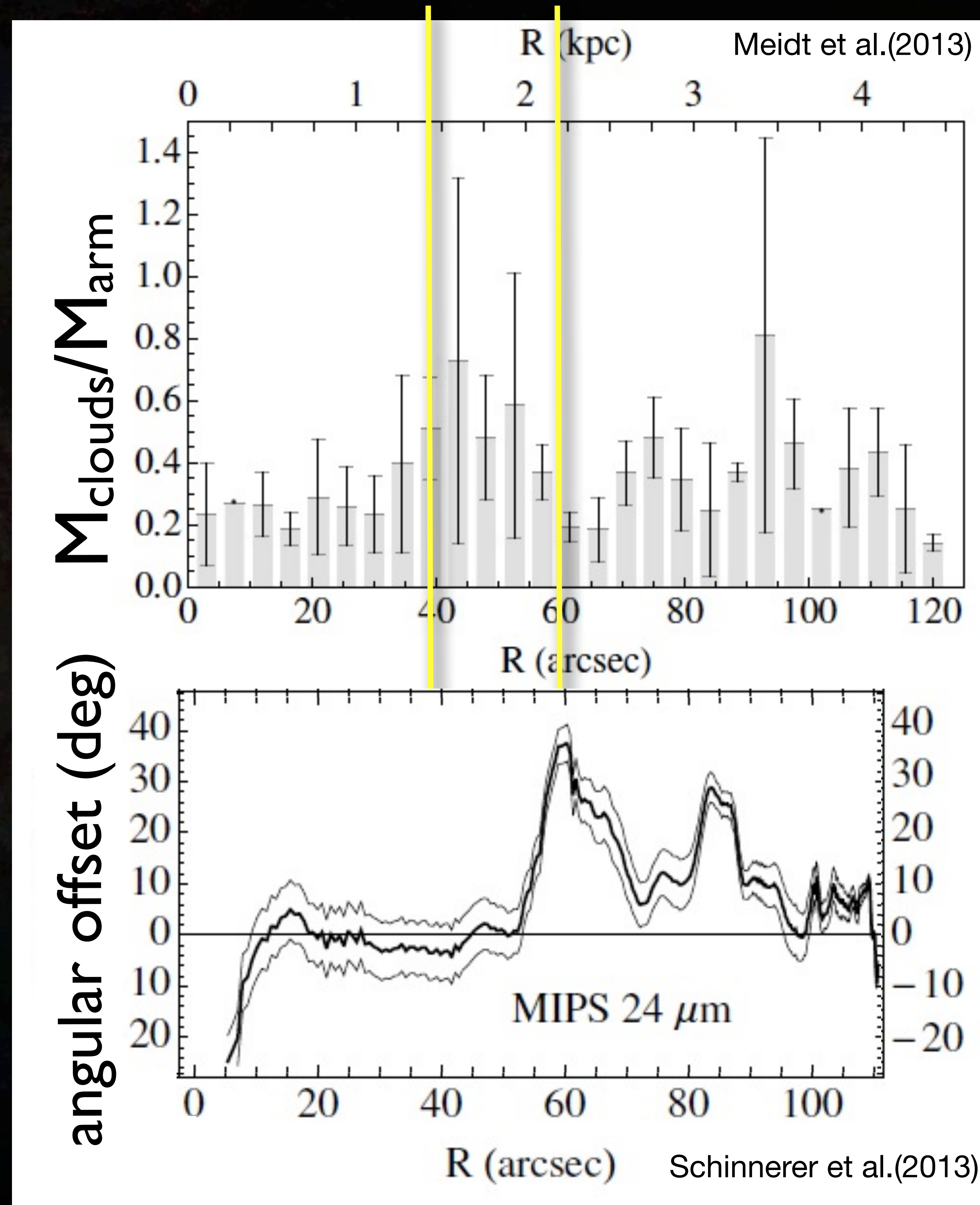
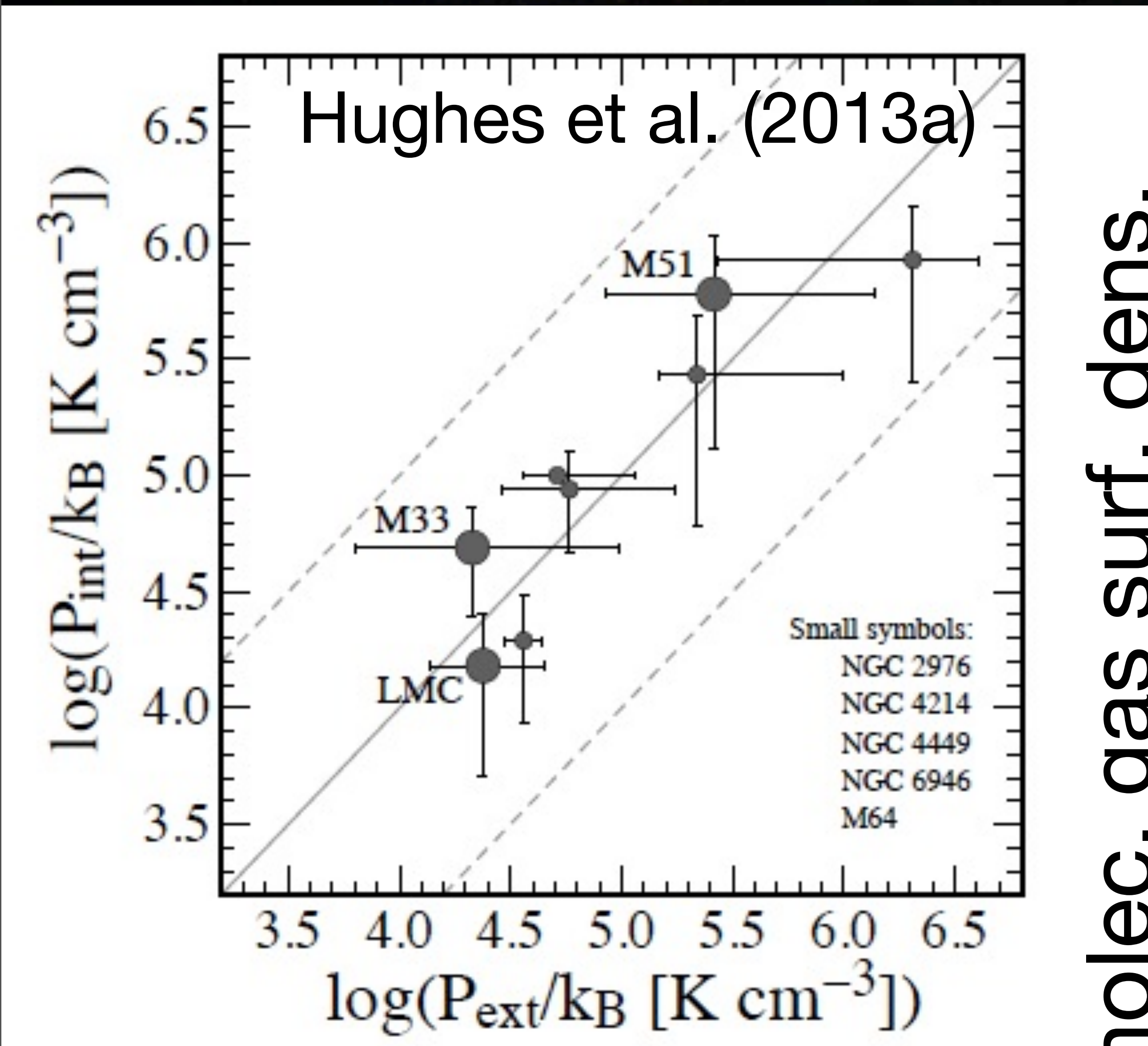
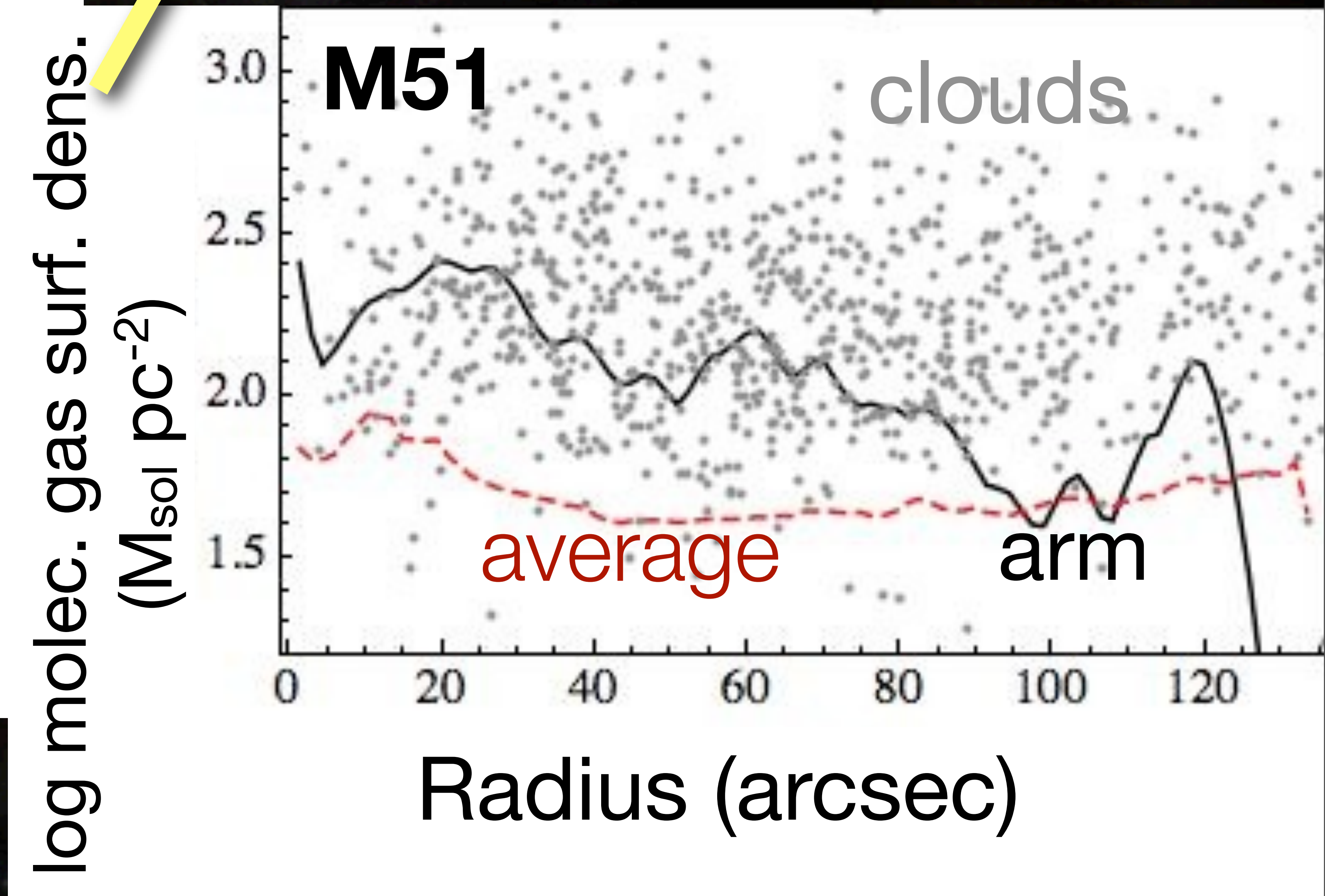


Pressure Stabilization



surface pressure important

prop. to log (Pressure) ($P \sim G\Sigma^2$)



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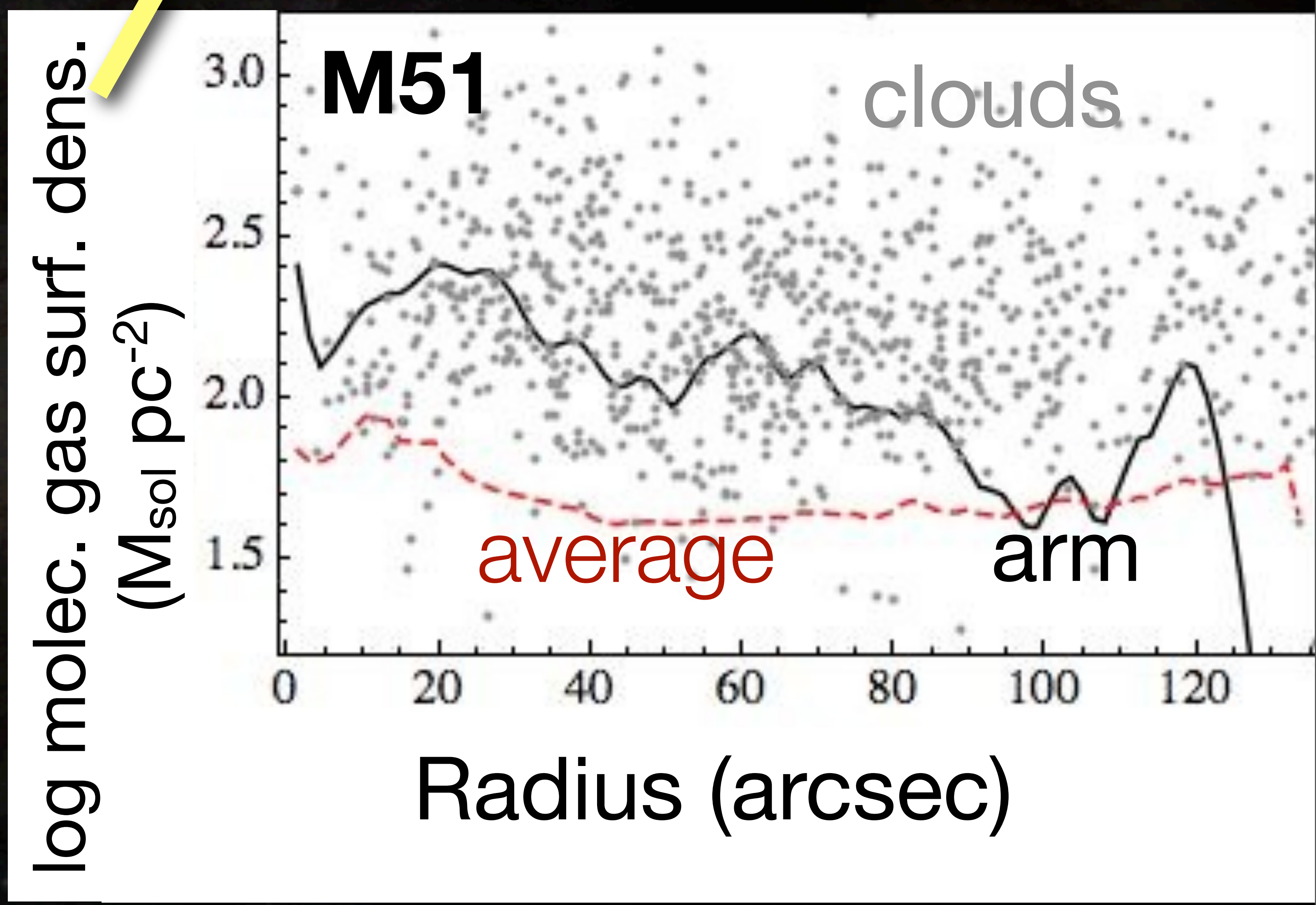
ambient P
comparable to
internal cloud P

cloud surface pressure important



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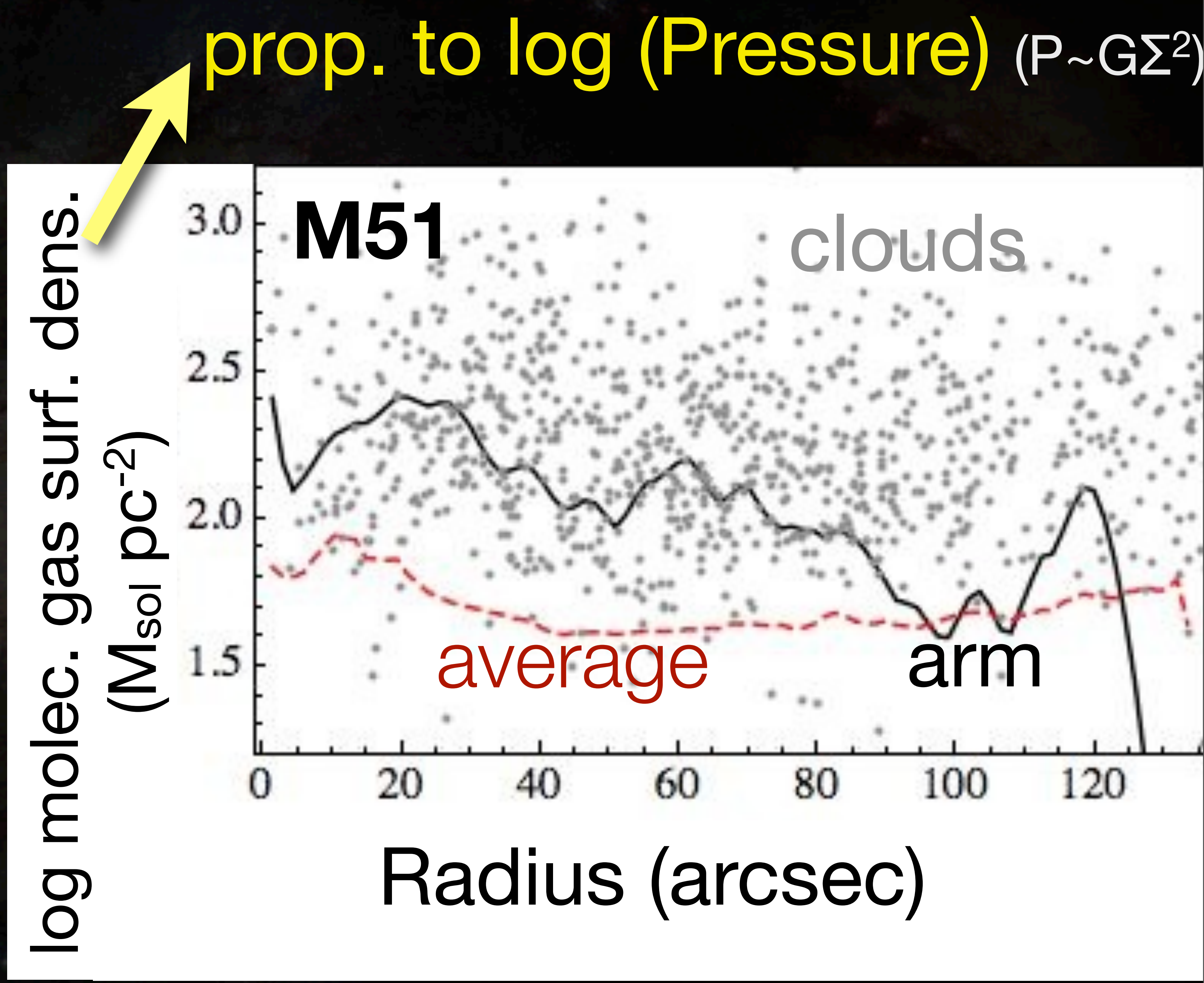

what happens if we perturb the cloud surface in the presence of (relative) motion?

change in stable mass threshold: *dynamical pressure*

Meidt et al. (2013)

cf. Jog (2013, in prep.)

change in stable mass threshold: *dynamical pressure*

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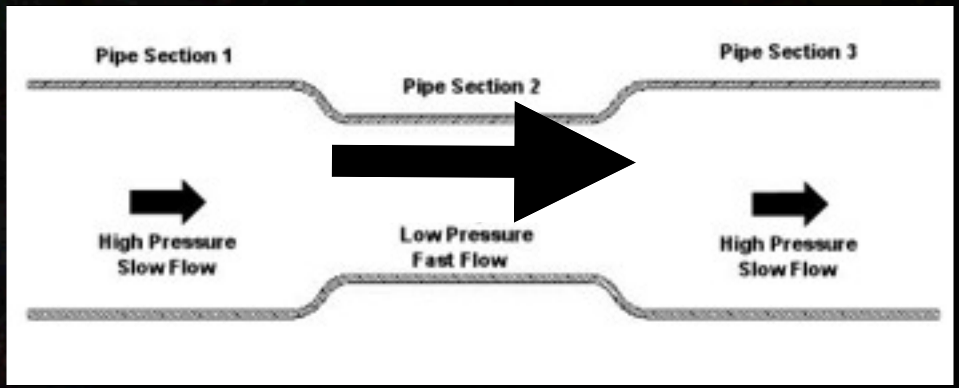
clouds in motion in arm:

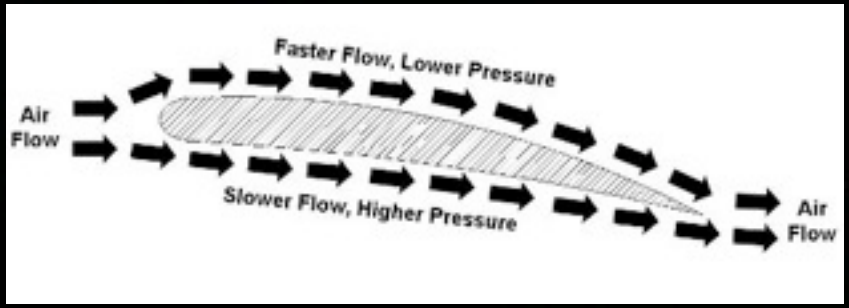
1). **reduced surface pressure** (Bernoulli)

2). **increased** (Bonnor-Ebert) **stable mass**

2b). reduced collapse-unstable fraction

3). **lower SFE**





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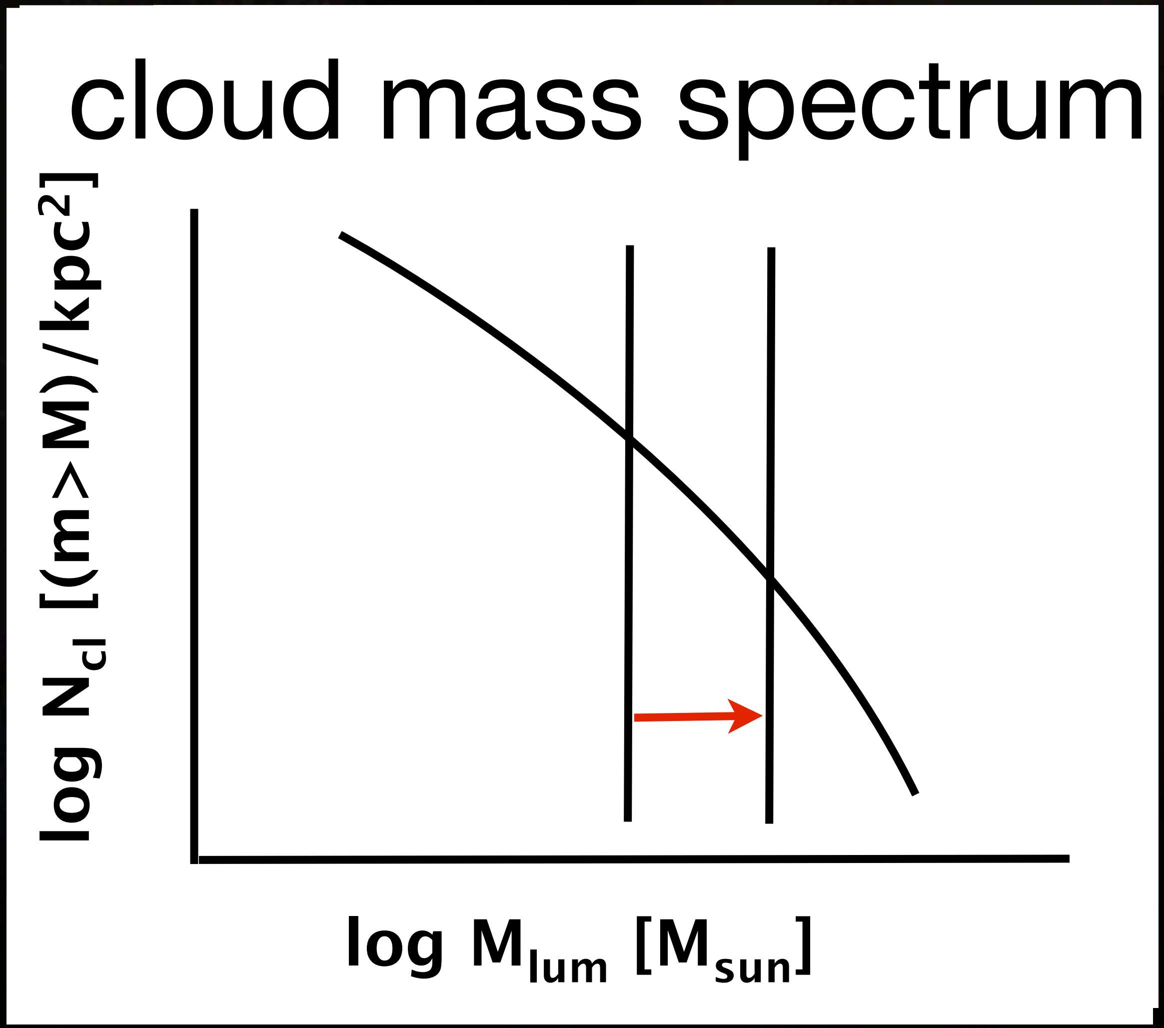

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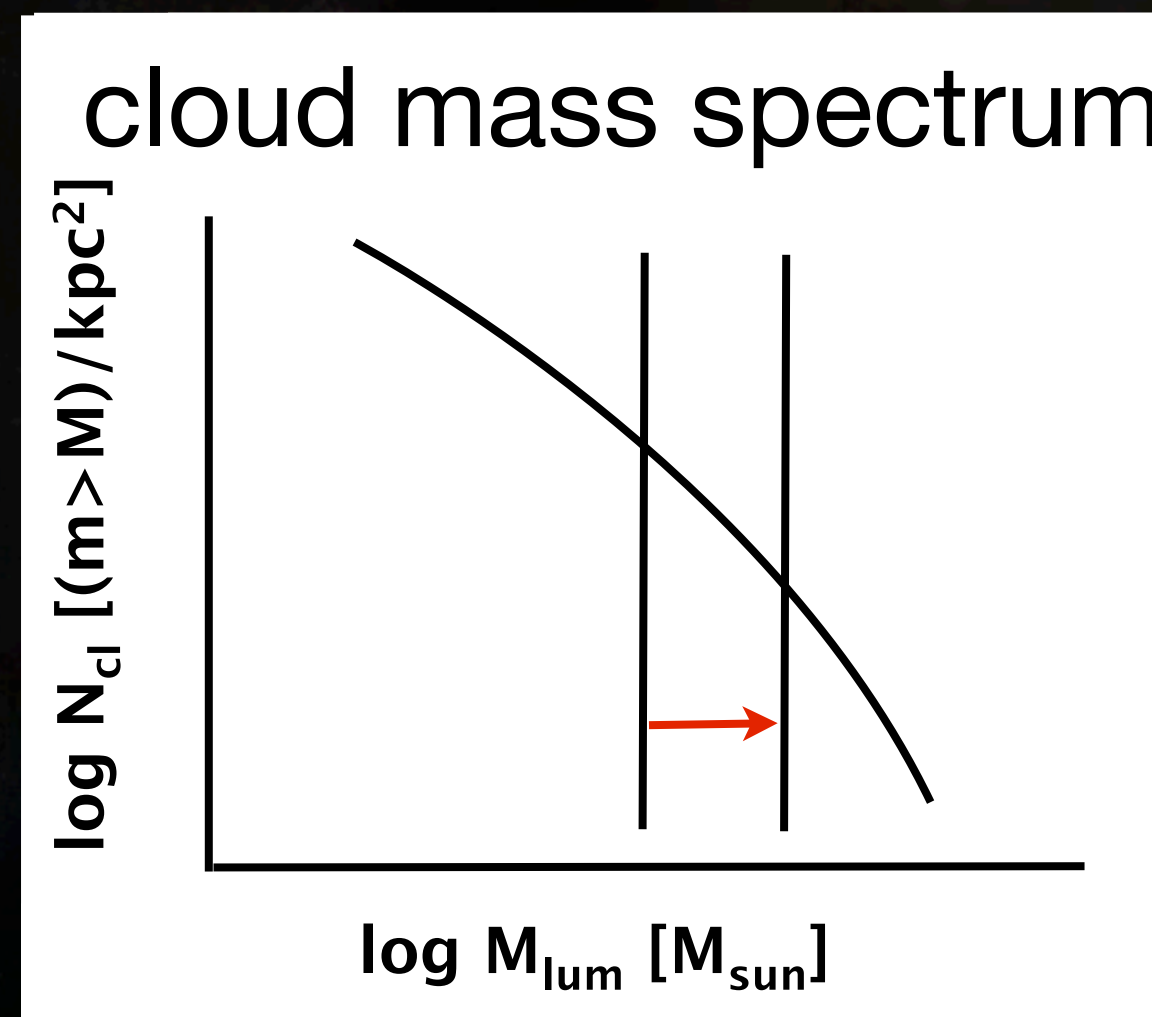
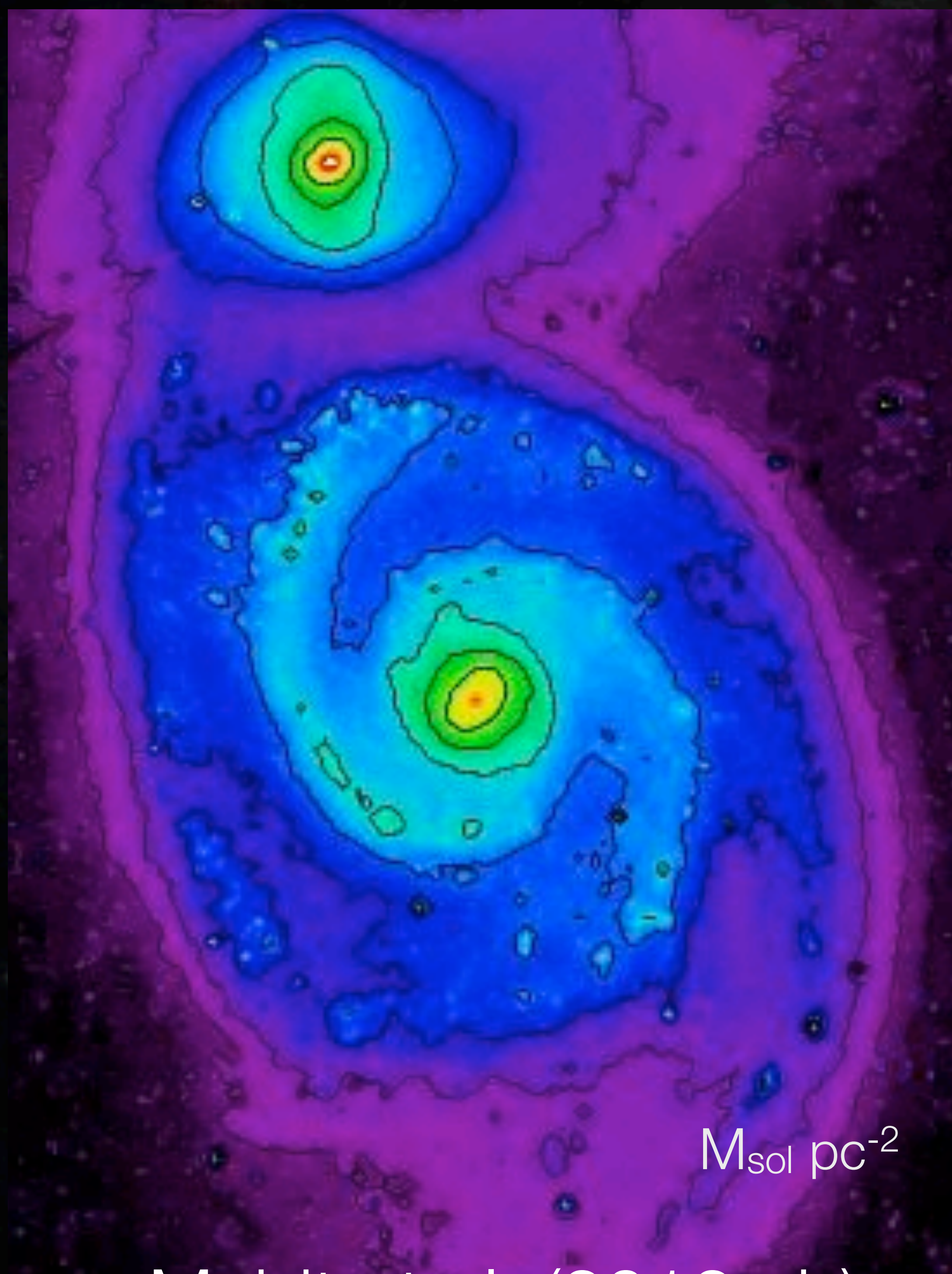
$$\ln \tau_{dep} \approx -(\Upsilon+1)\, \frac{v_{stream}^2}{4\sigma^2}$$

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



non-circular gas motions:
Present-day Torques

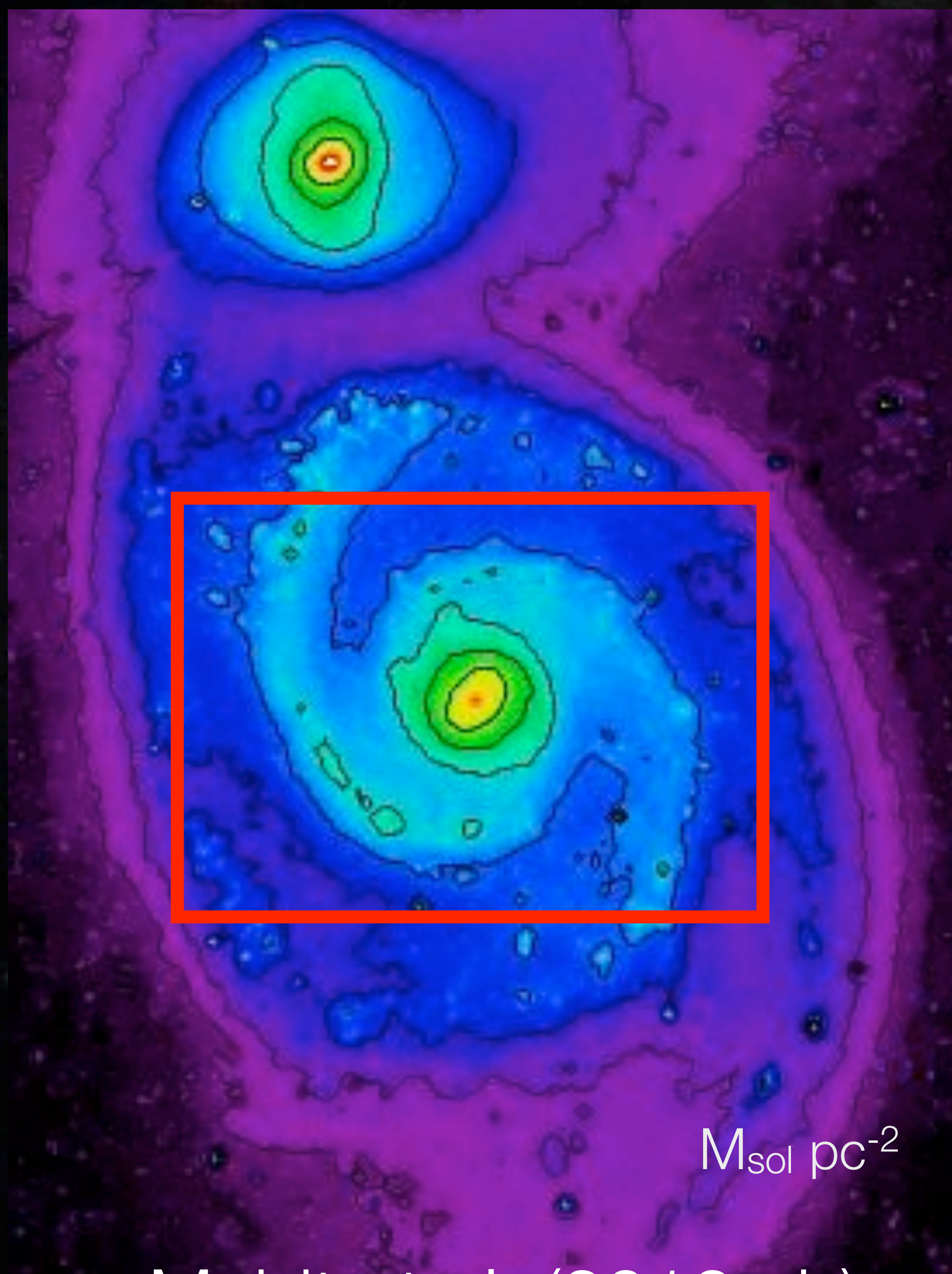


Meidt et al. (2012a,b)
Eskew, Zaritsky & Meidt (2012)

S^{4}G
stellar
mass
surface
density

see *poster*:
Miguel Querejeta

non-circular gas motions:
Present-day Torques



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S^4G
stellar
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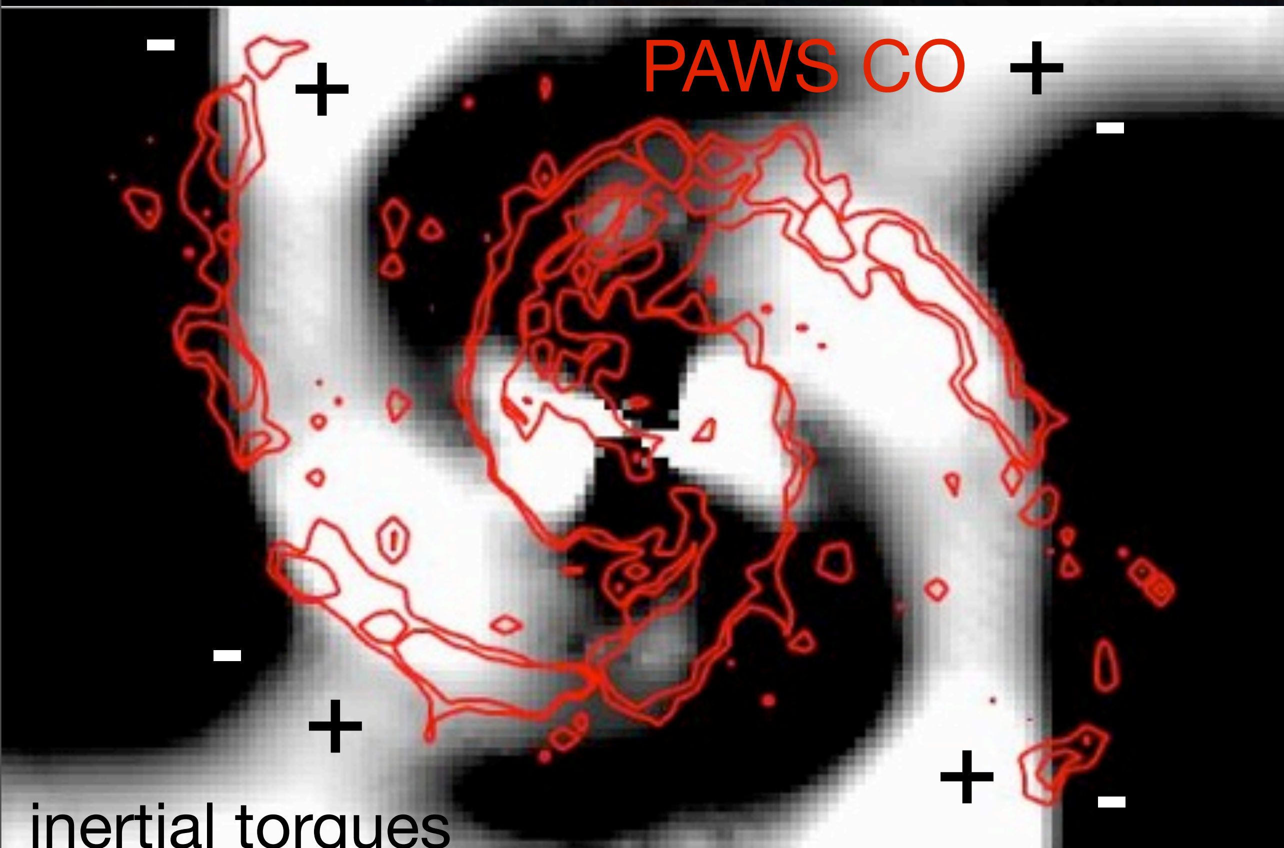
S4G

DAGAL
Detailed
Anatomy of
GALaxies

see *poster*:
Miguel Querejeta

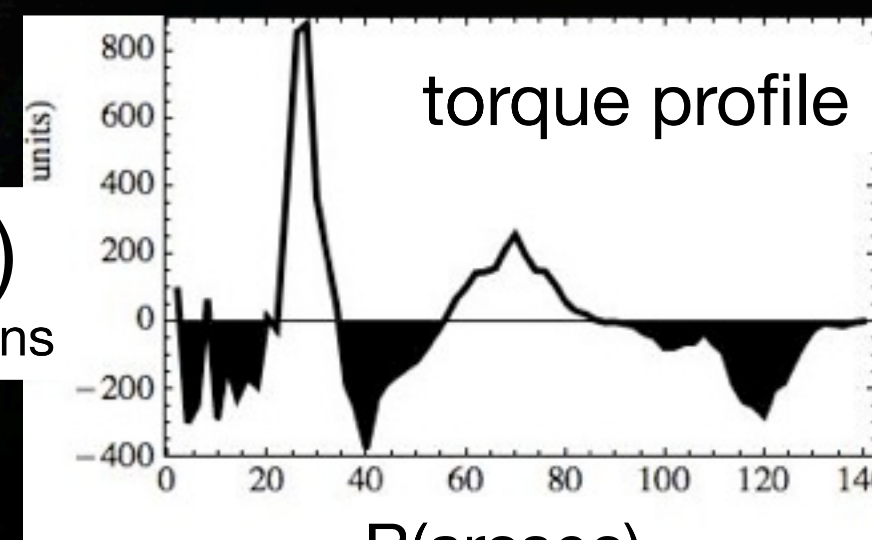
Present-day Torques



R×∇Φ

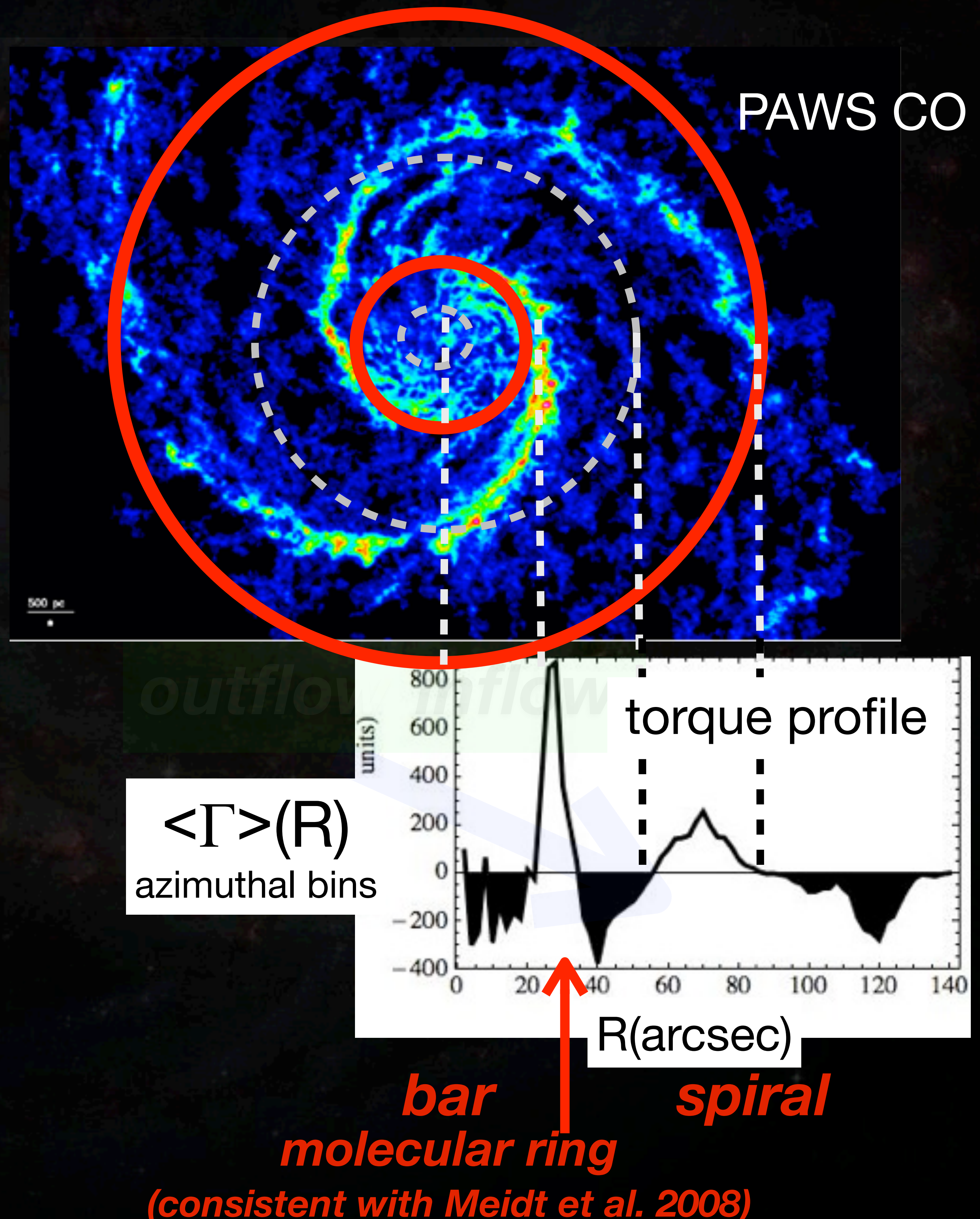
outflow inflow

<Γ>(R)
azimuthal bins



Radius = proxy for environment (bar, spiral)

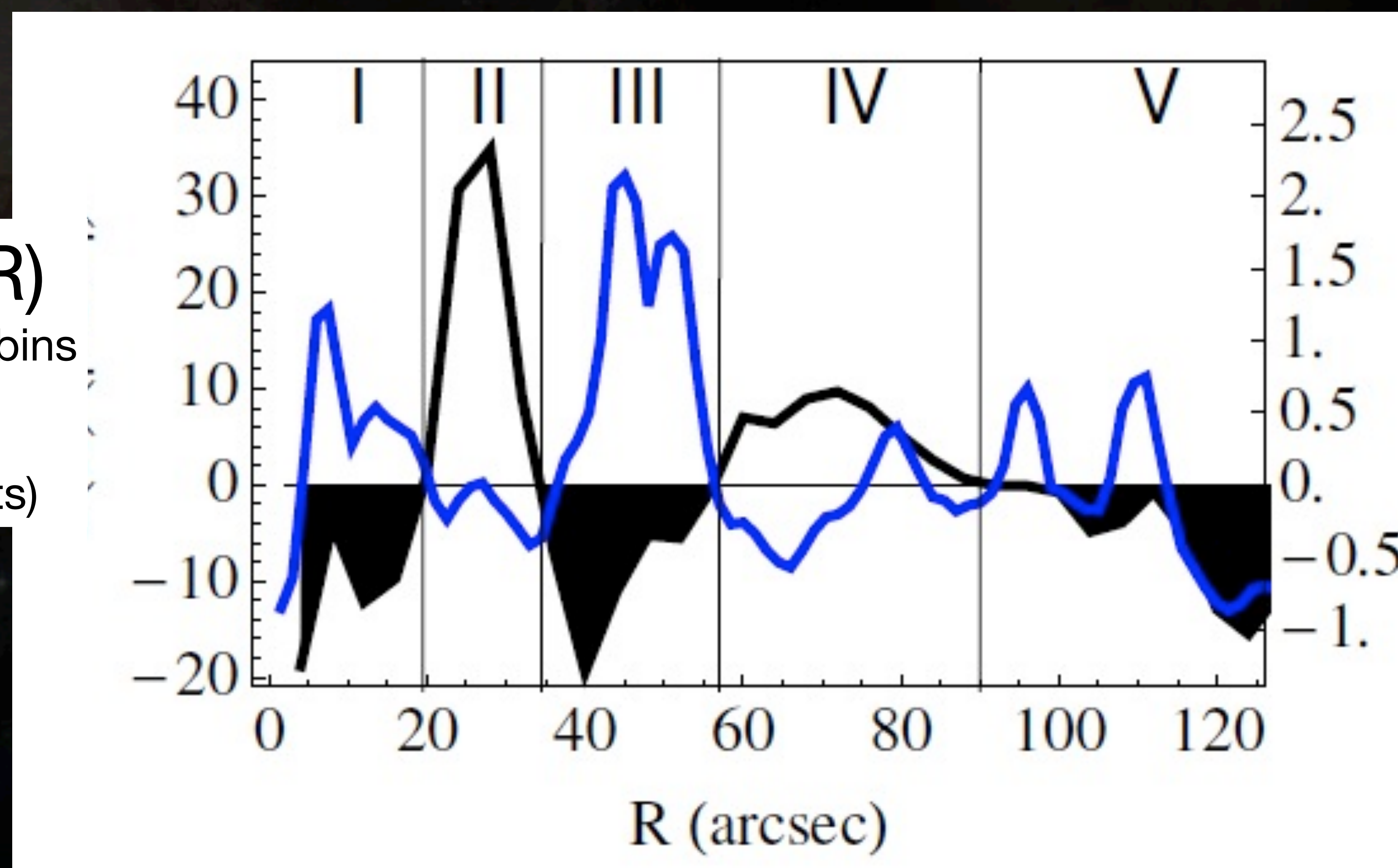
Present-day Torques



Spiral arm Torques

$\langle\Gamma\rangle(R)$
azimuthal bins

τ_{dep}
(arb. units)



from PAWS kinematics

inflow=large $|V_{stream}|$

Spiral arm Torques

$\langle\Gamma\rangle(R)$
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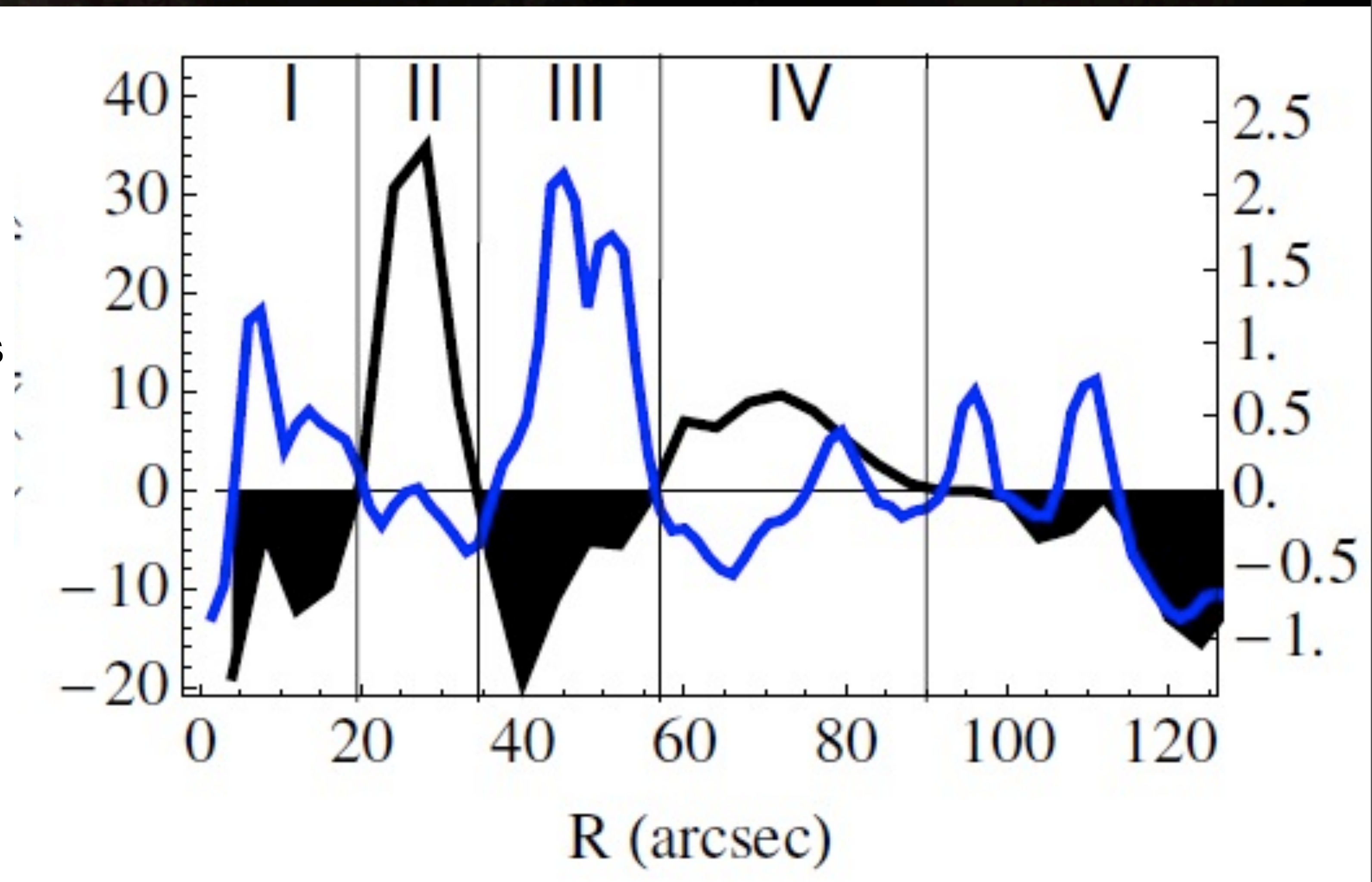
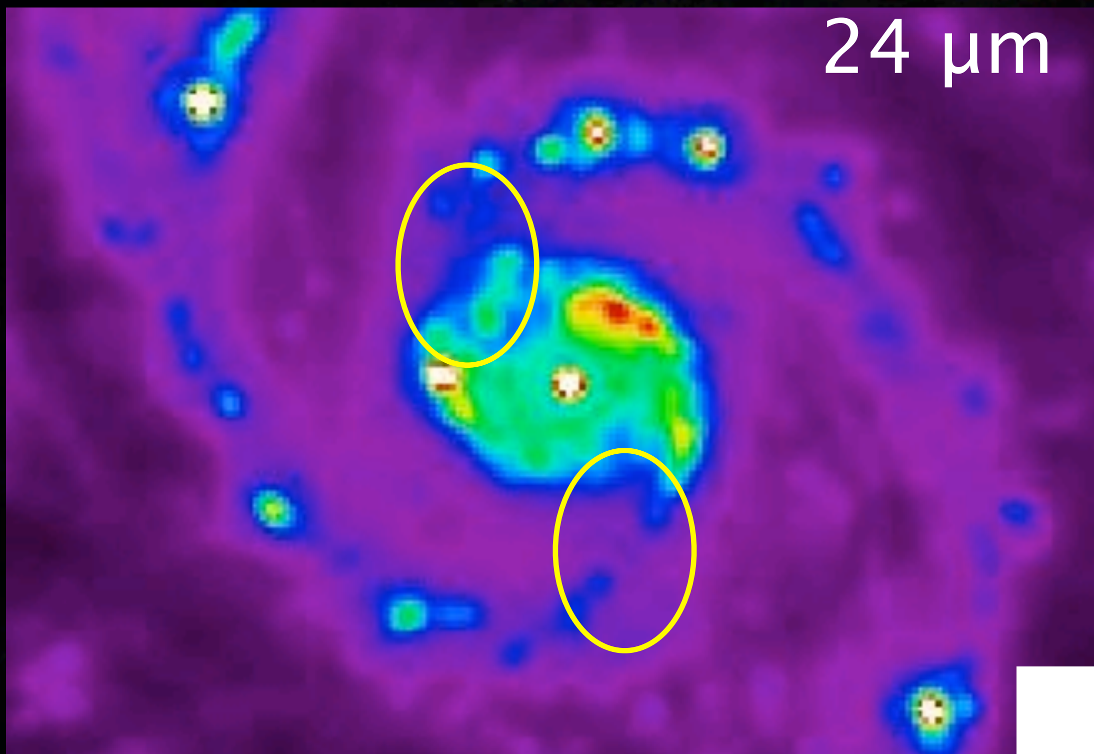
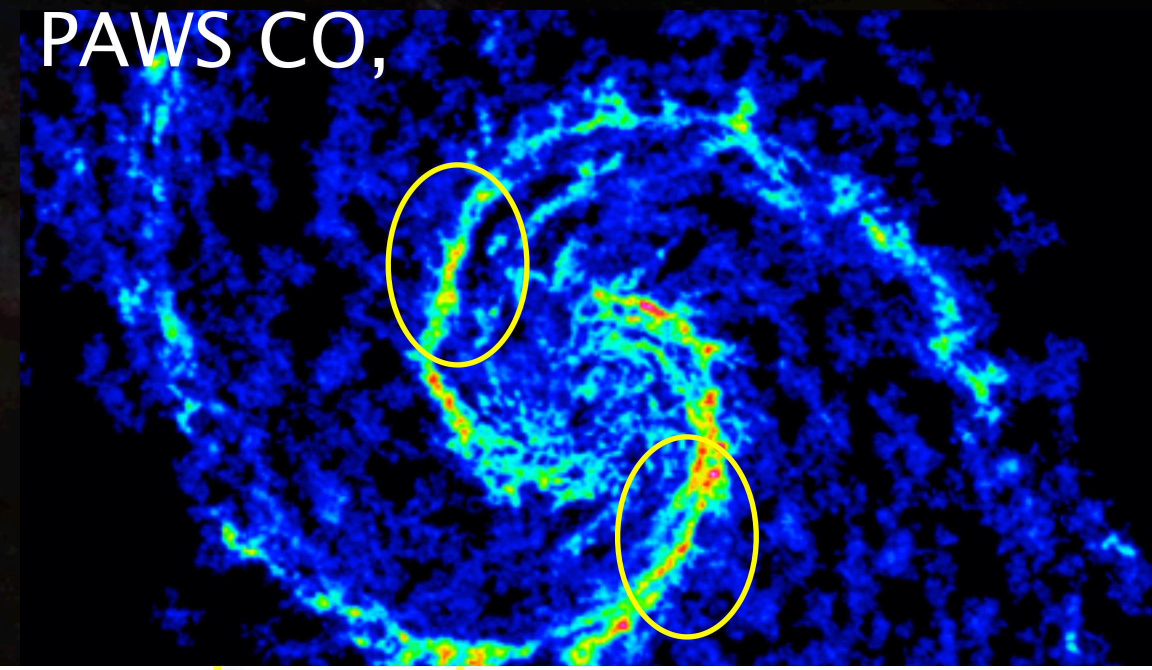


cf. Knapen et al. (1992)

from PAWS kinematics
inflow=large
$|V_{stream}|$

Spiral arm Torques





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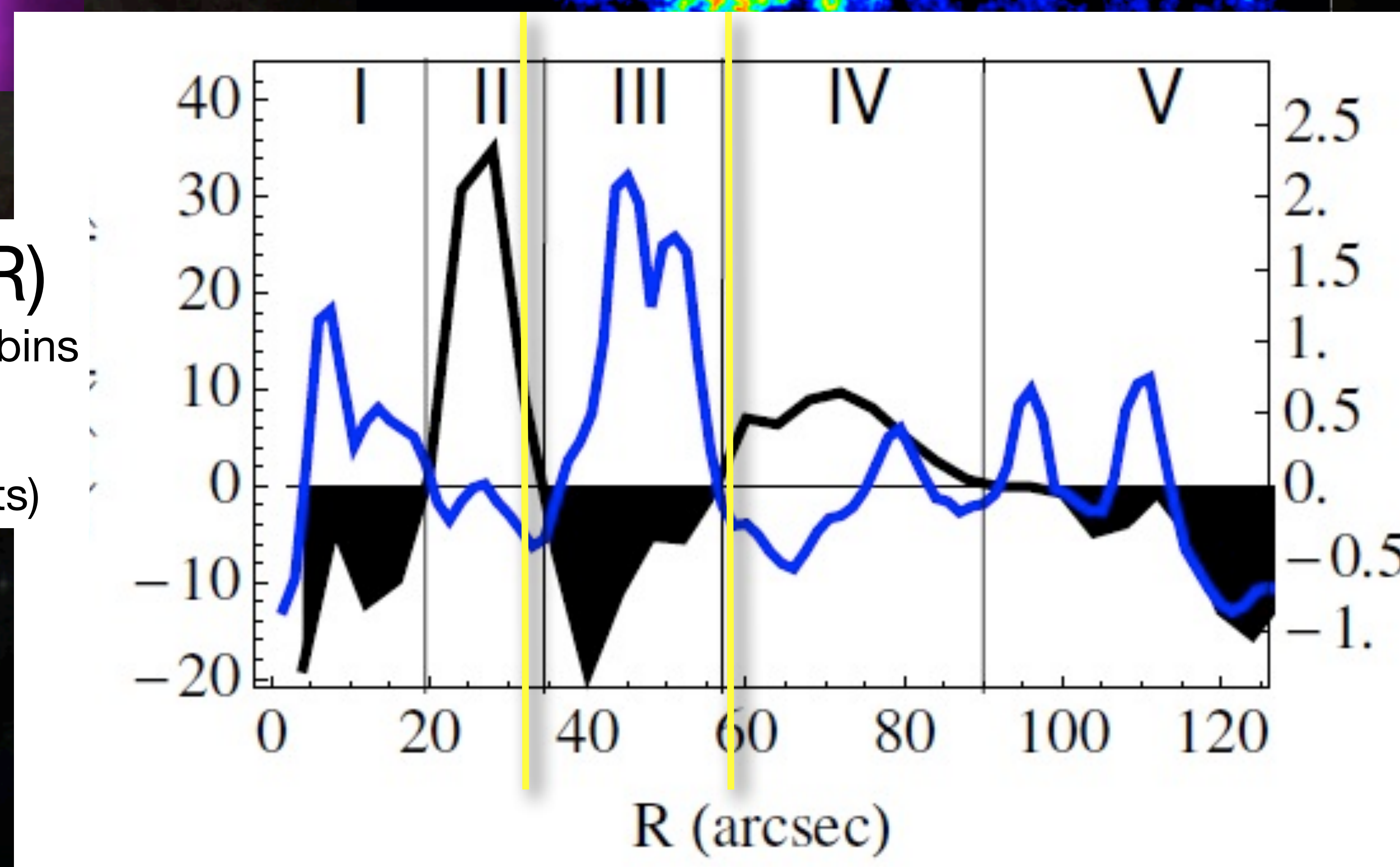

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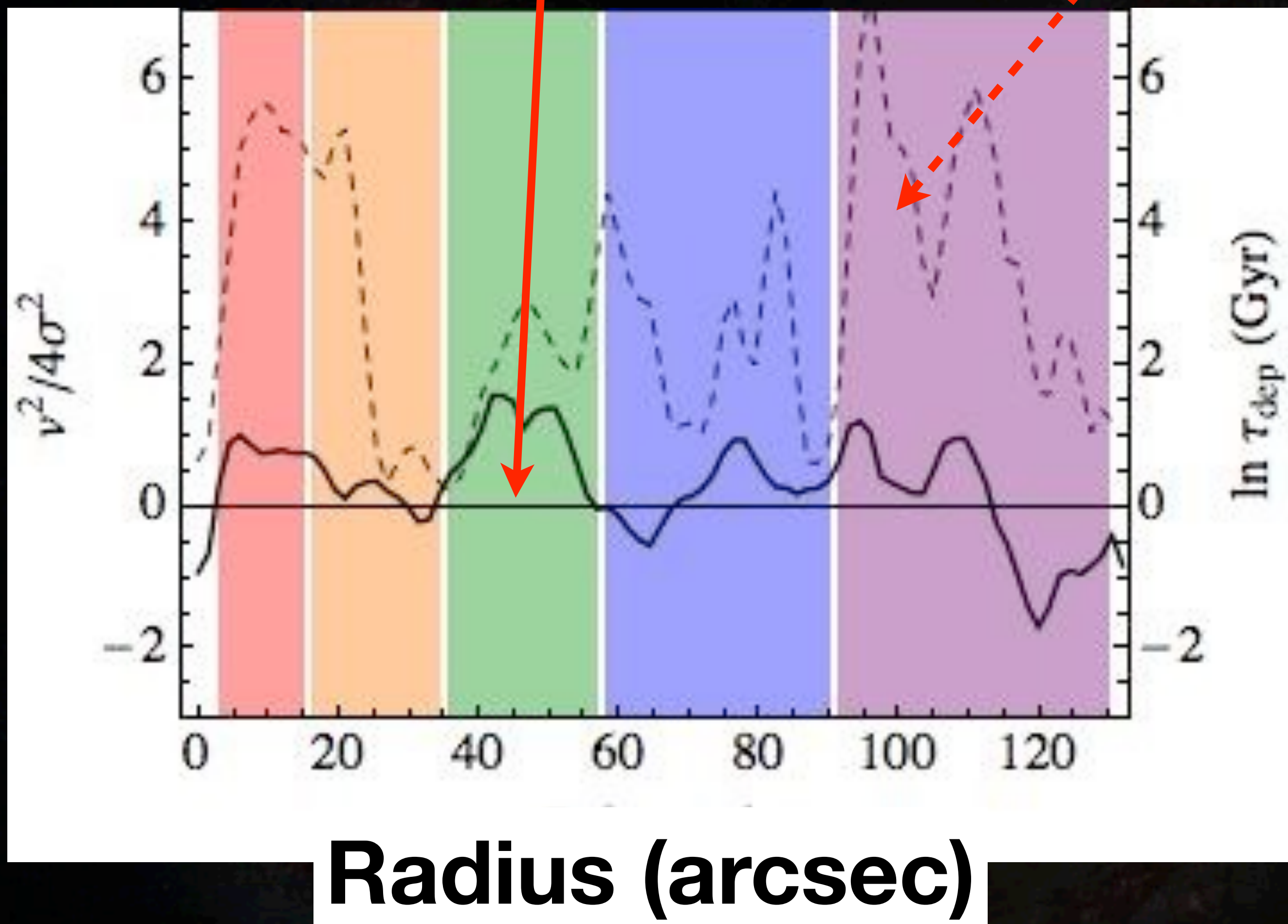
inflow=large
$|V_{stream}|$

cf. Knapen et al. (1992)

$$\ln \tau_{dep} \approx -(\gamma+1)\frac{|v_{stream}|^2}{4\sigma^2} + \ln \tau_{dep,0}$$

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



fit predicts

slope of mass spectrum γ

intersection w/ y-axis: $\tau_{dep,0}$

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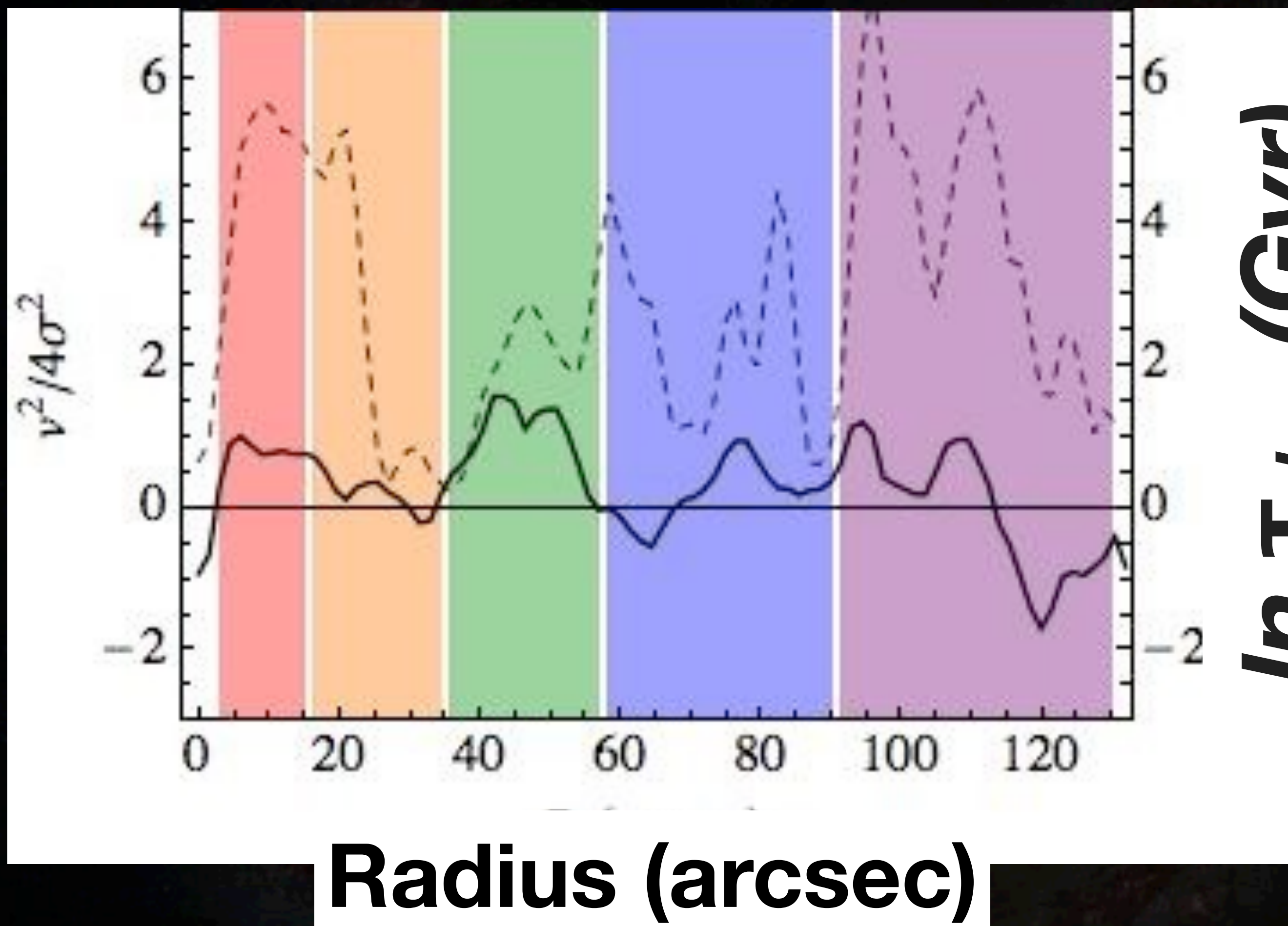

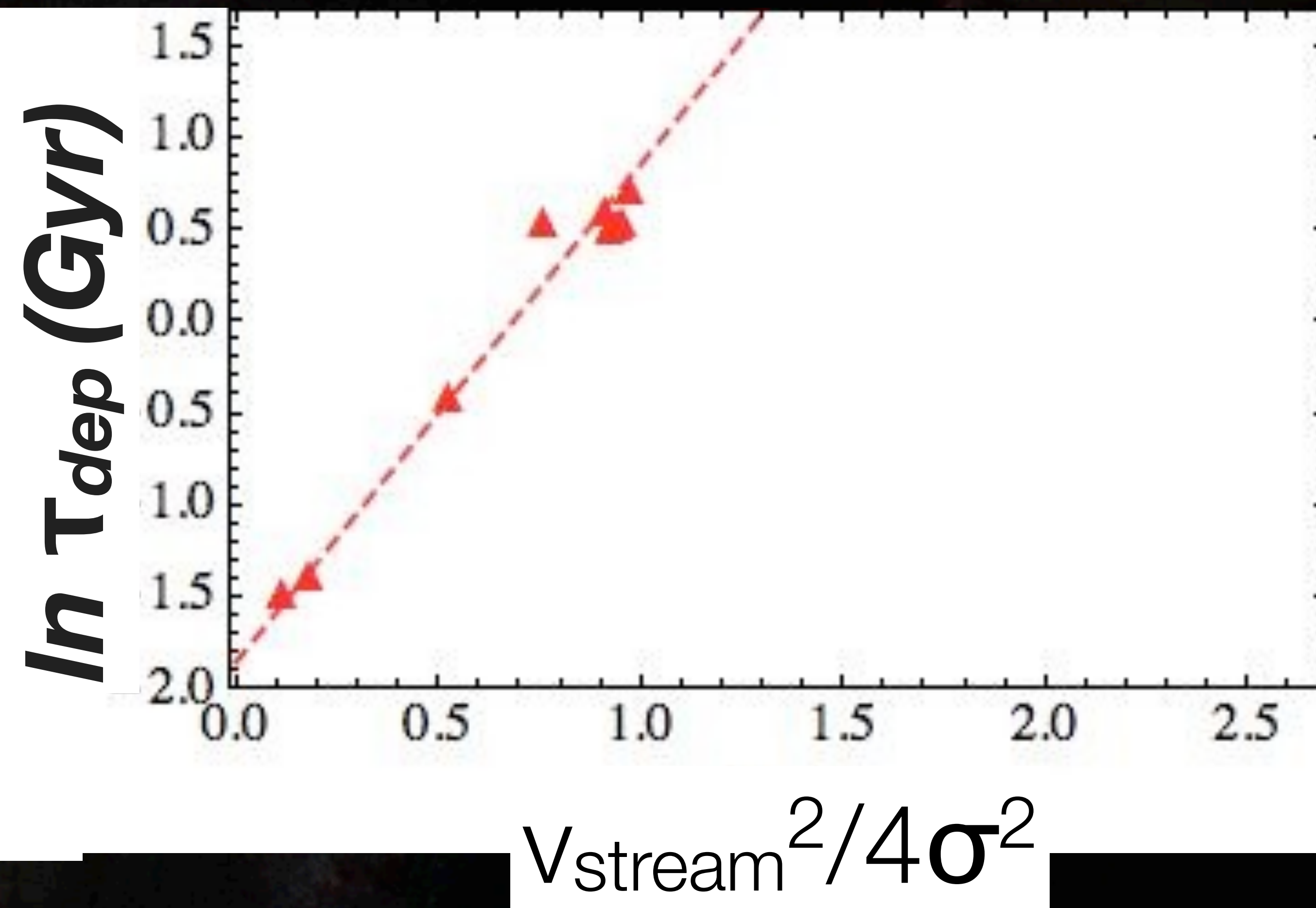

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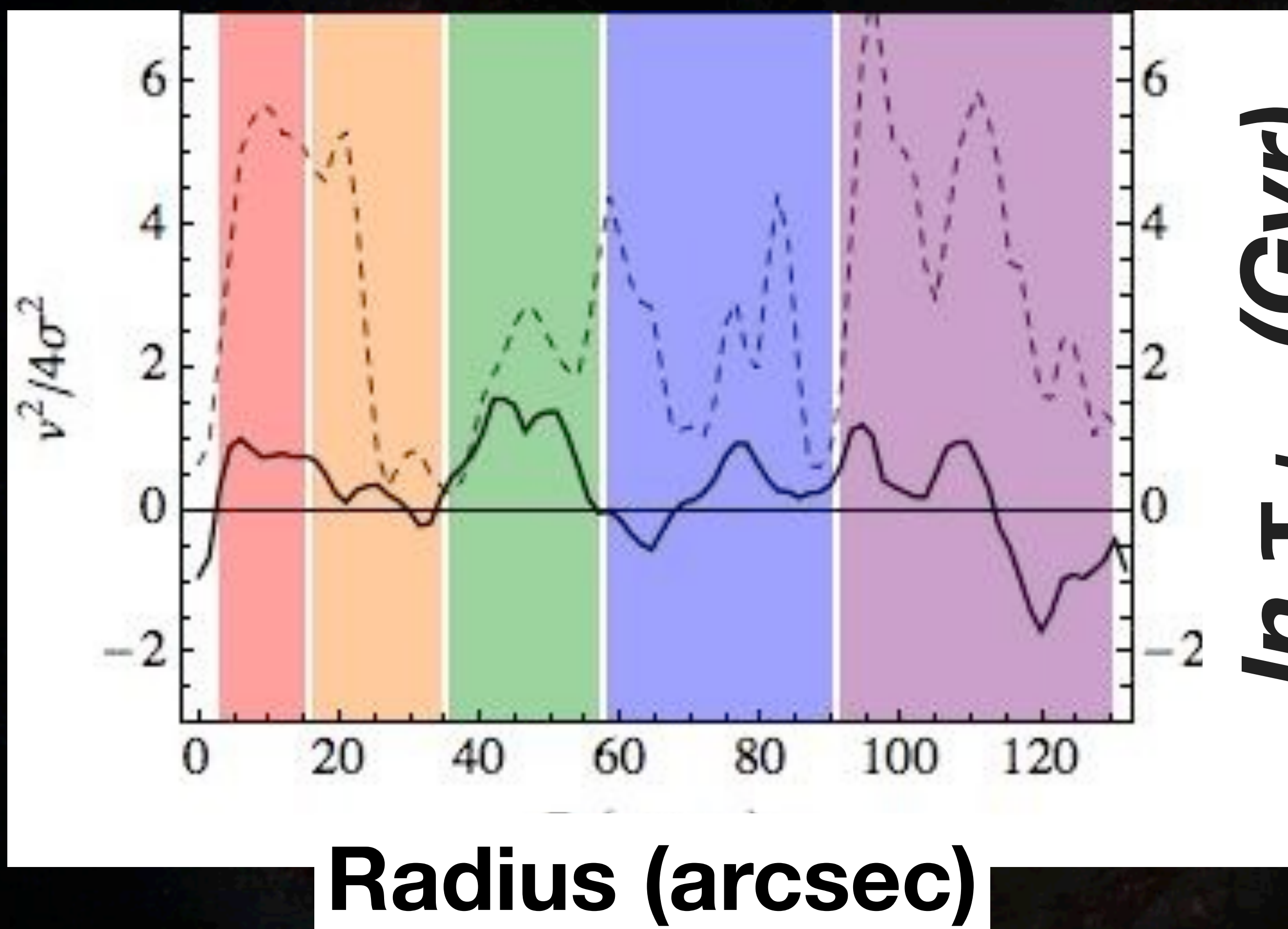

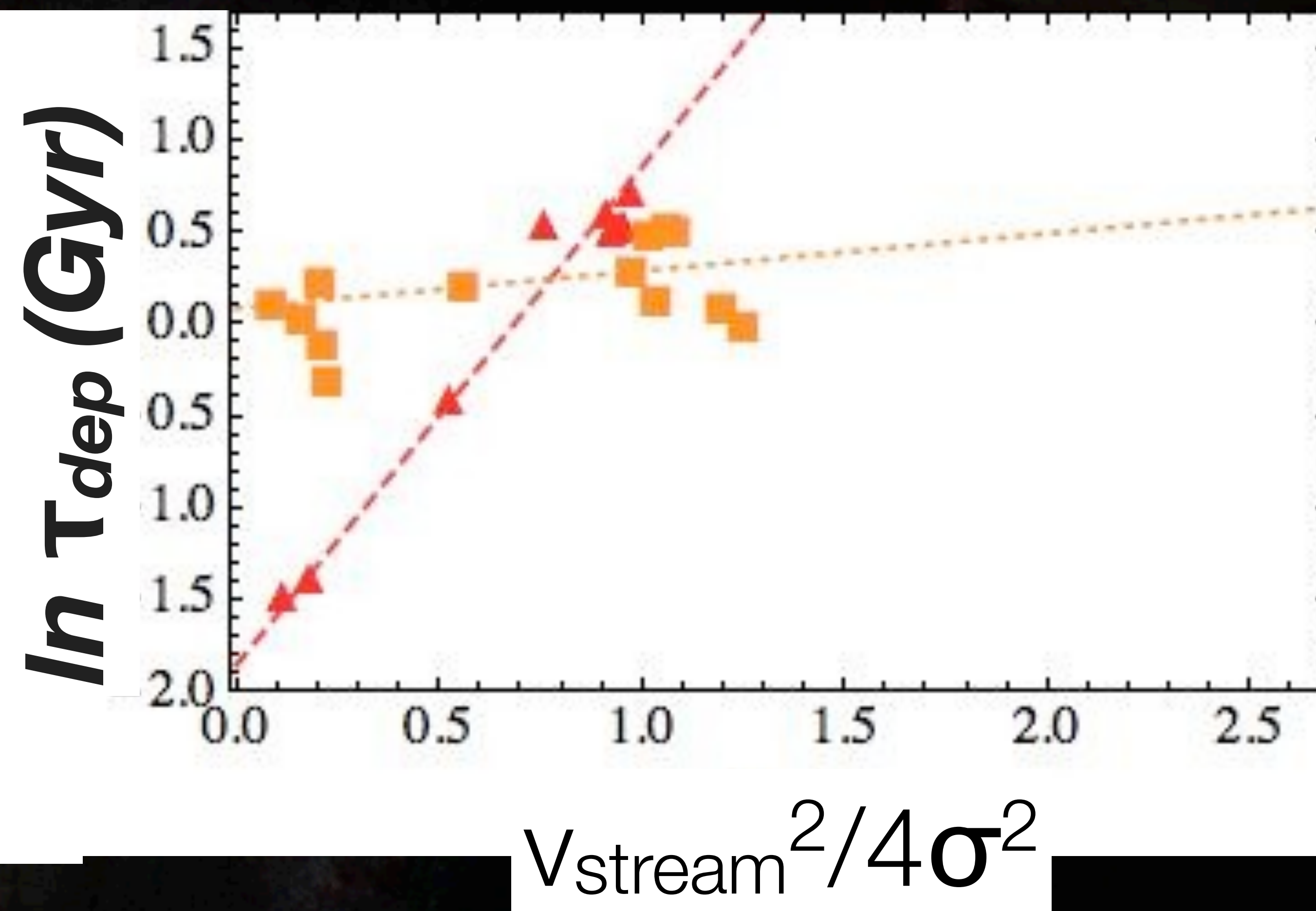

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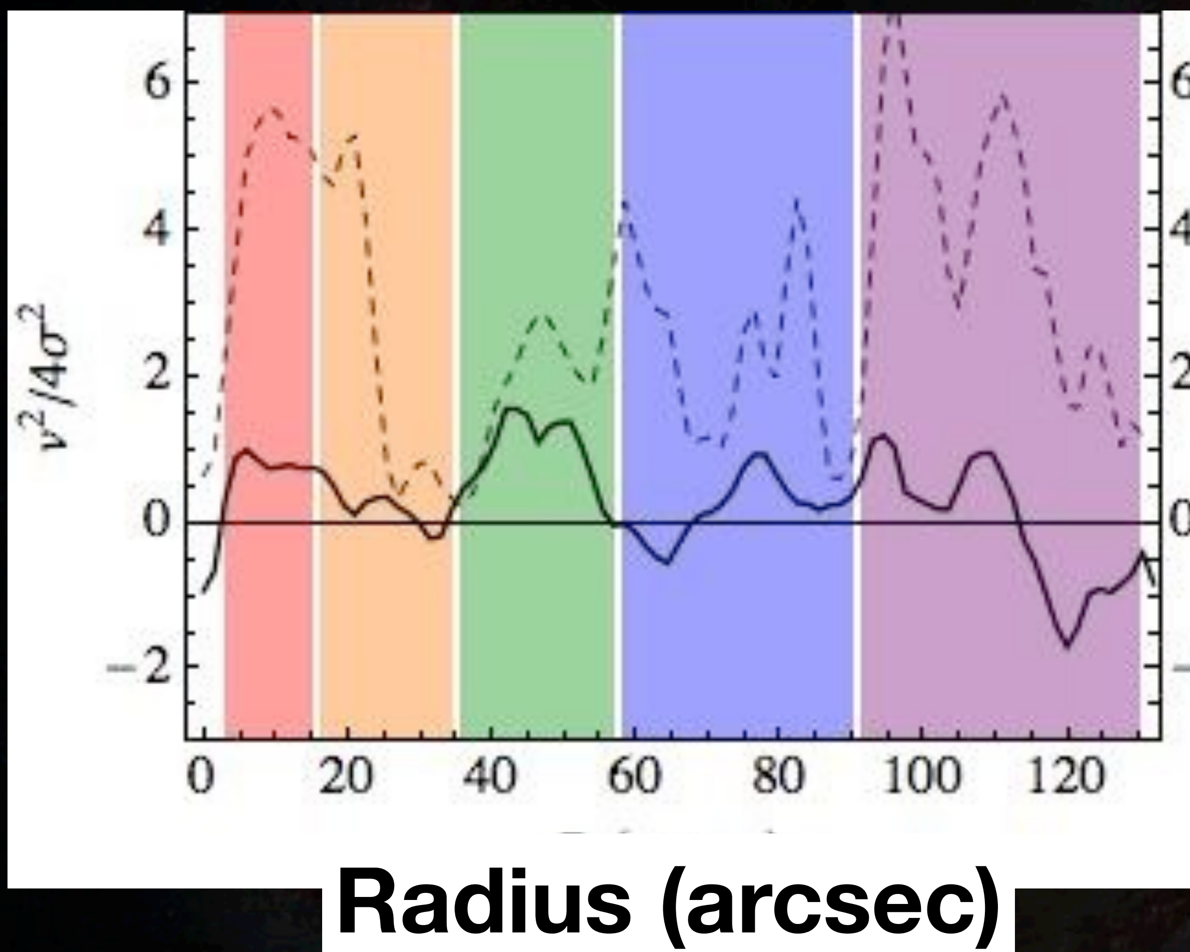

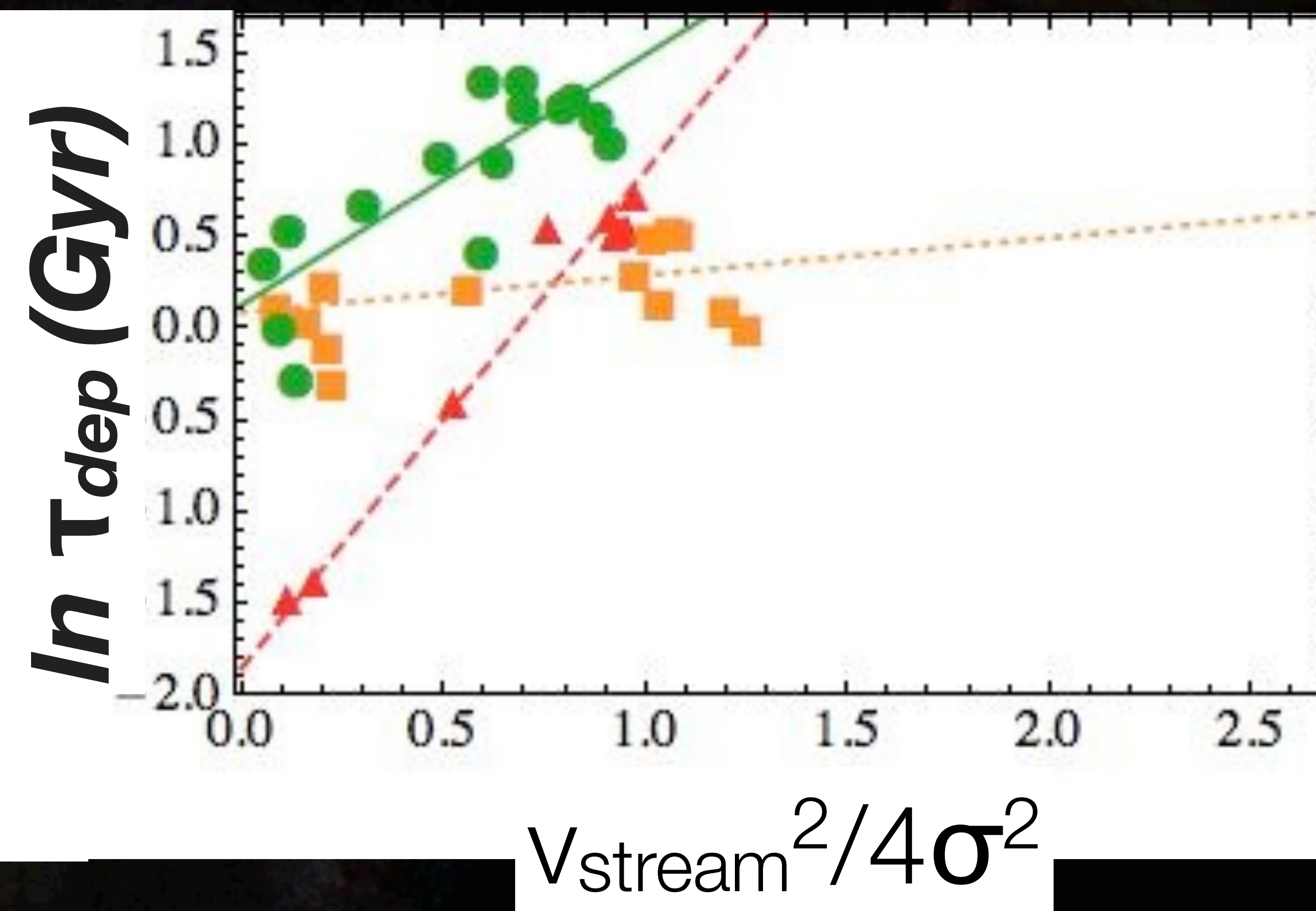

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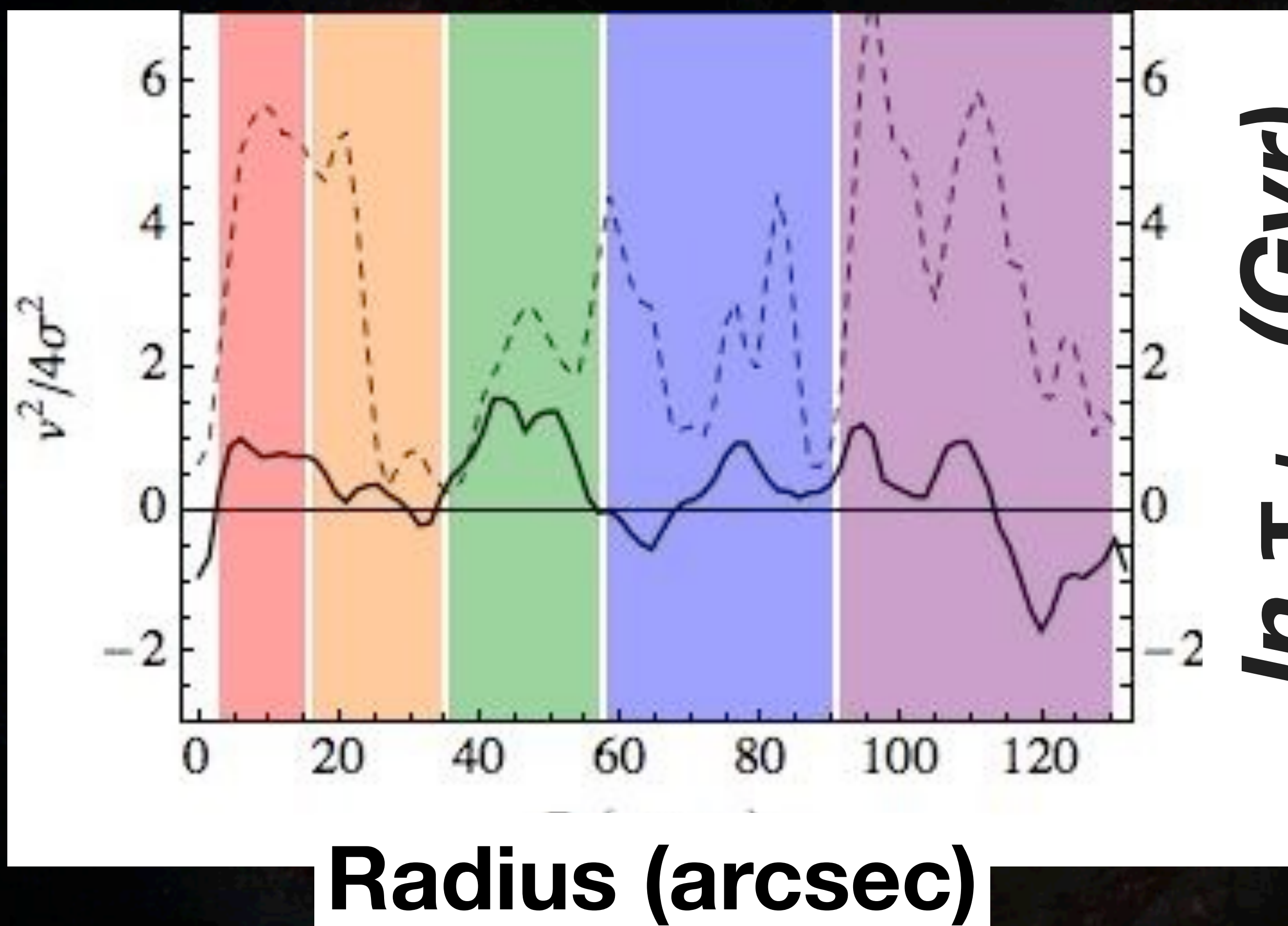

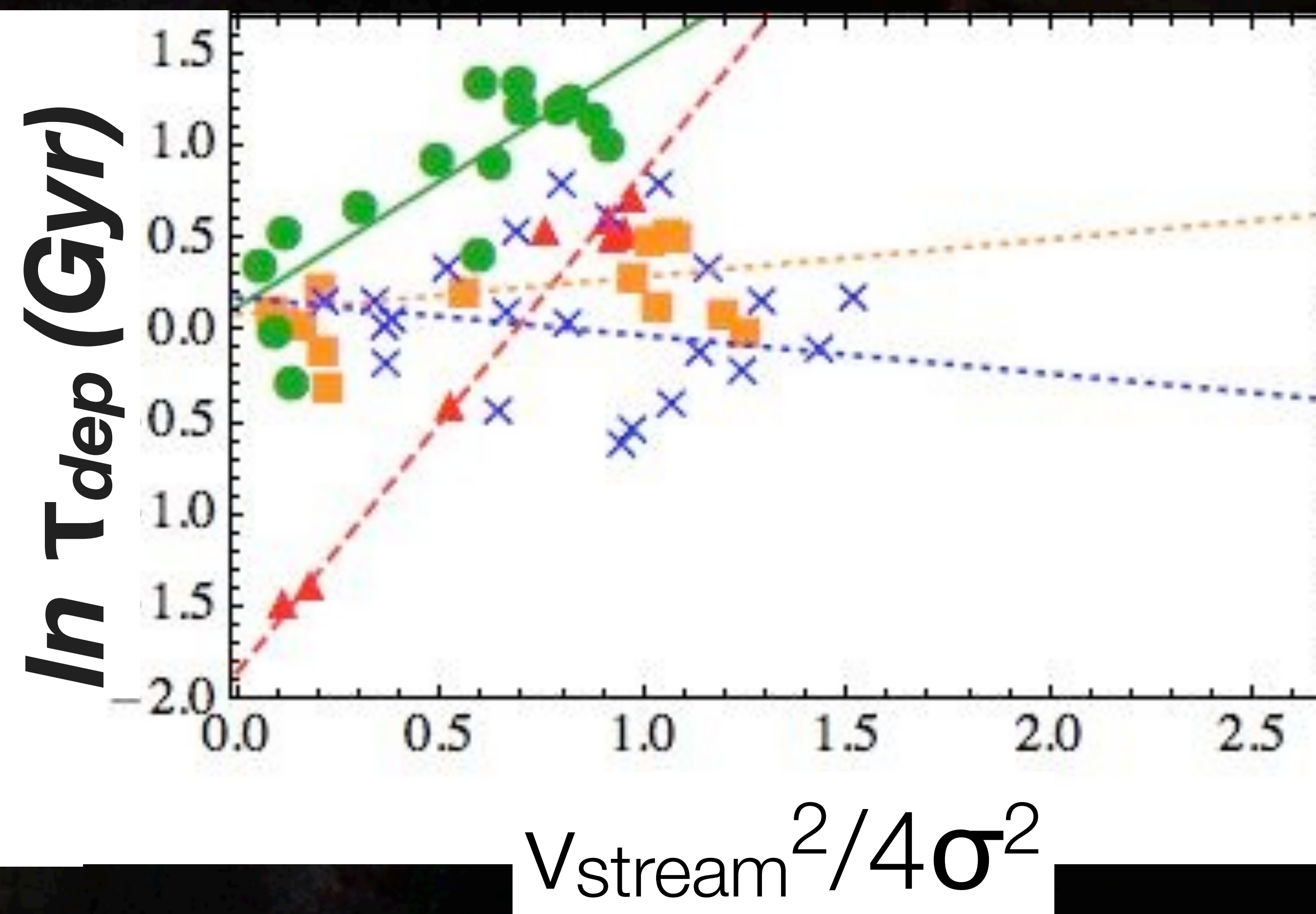

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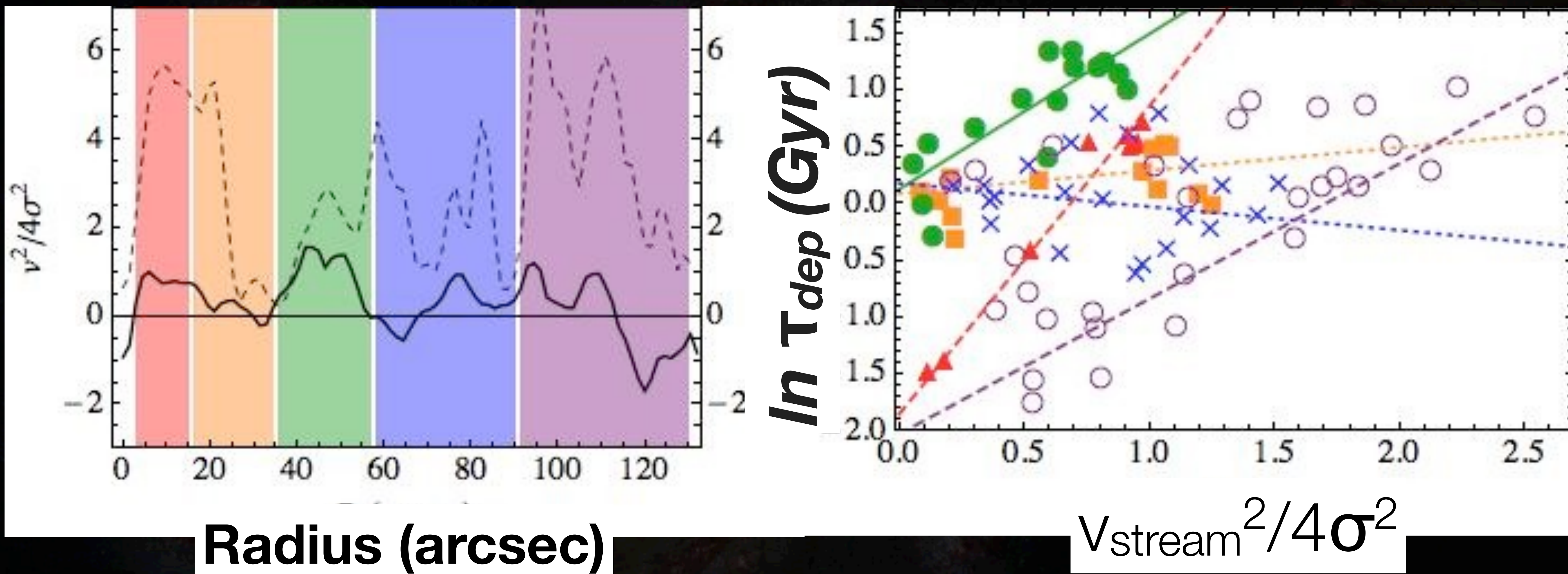

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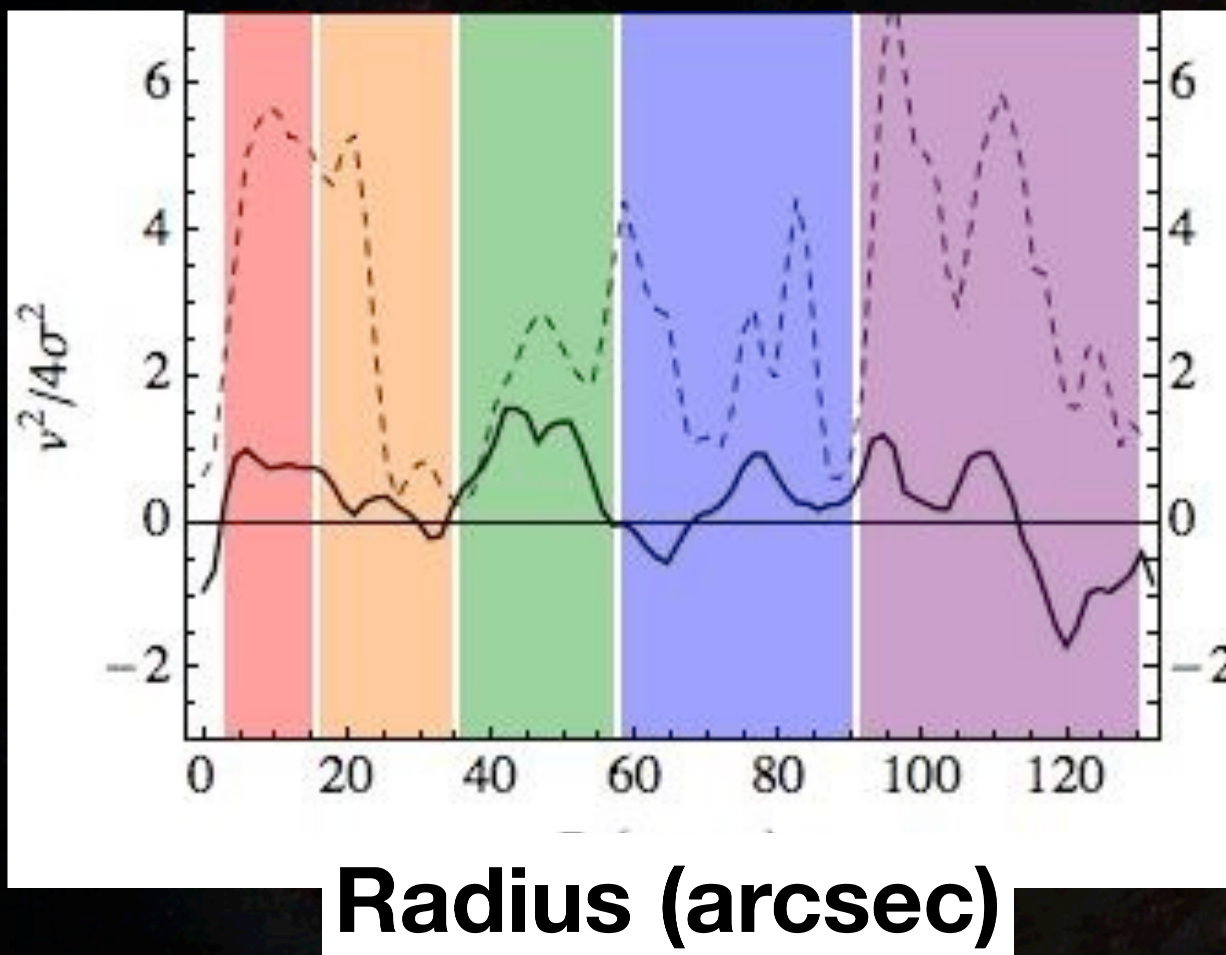
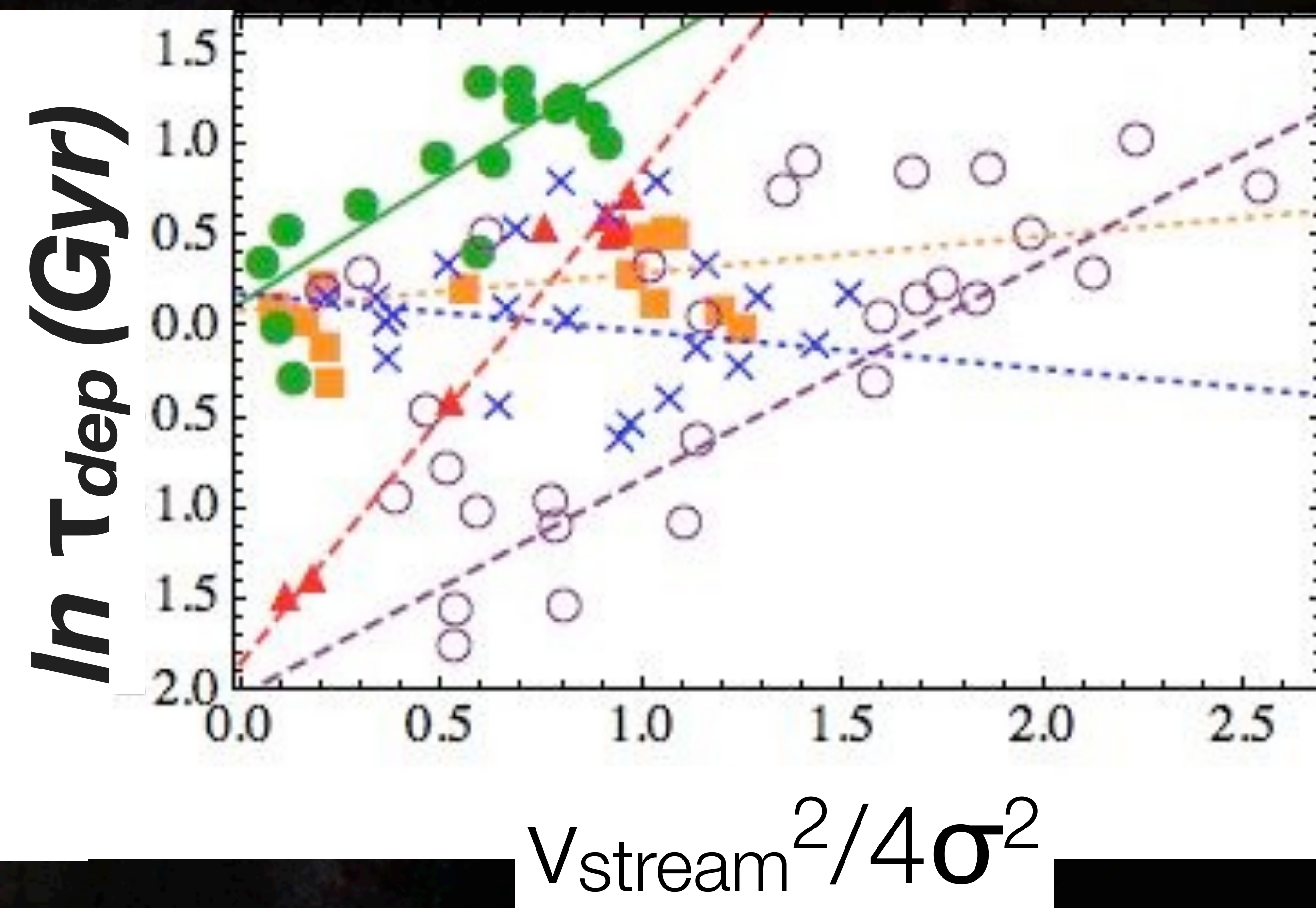




fit predicts

slope of mass spectrum γ

intersection w/ y-axis: $\tau_{dep,0}$

$\langle\gamma\rangle = -1.6 \pm 0.5$

$\langle\gamma\rangle = -1.7 \pm 0.25$ direct fits to spectra (Hughes et al. 2012)

$\langle\tau_{dep0}\rangle \sim 1 Gyr$

$\langle\tau_{dep}\rangle = 2.5 Gyr$ ~ ‘universal’ depletion time (Bigiel et al. 2008)

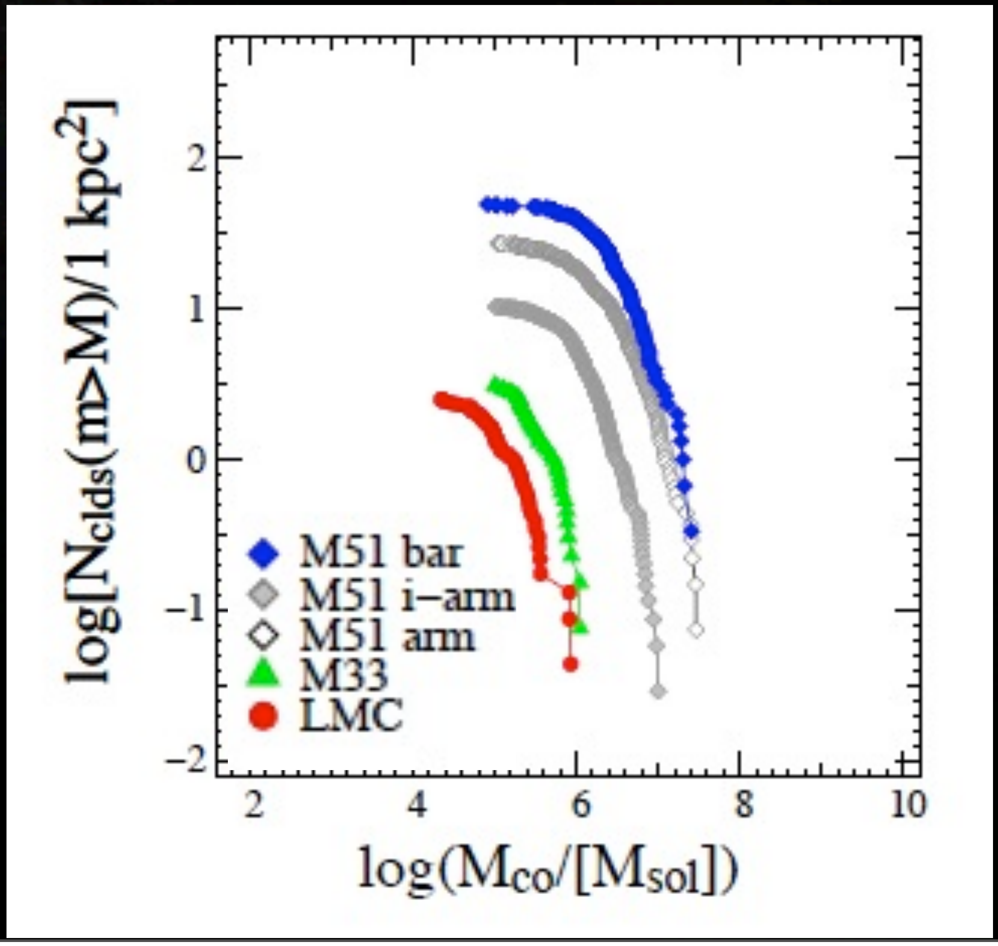
implications, locally and at high-z

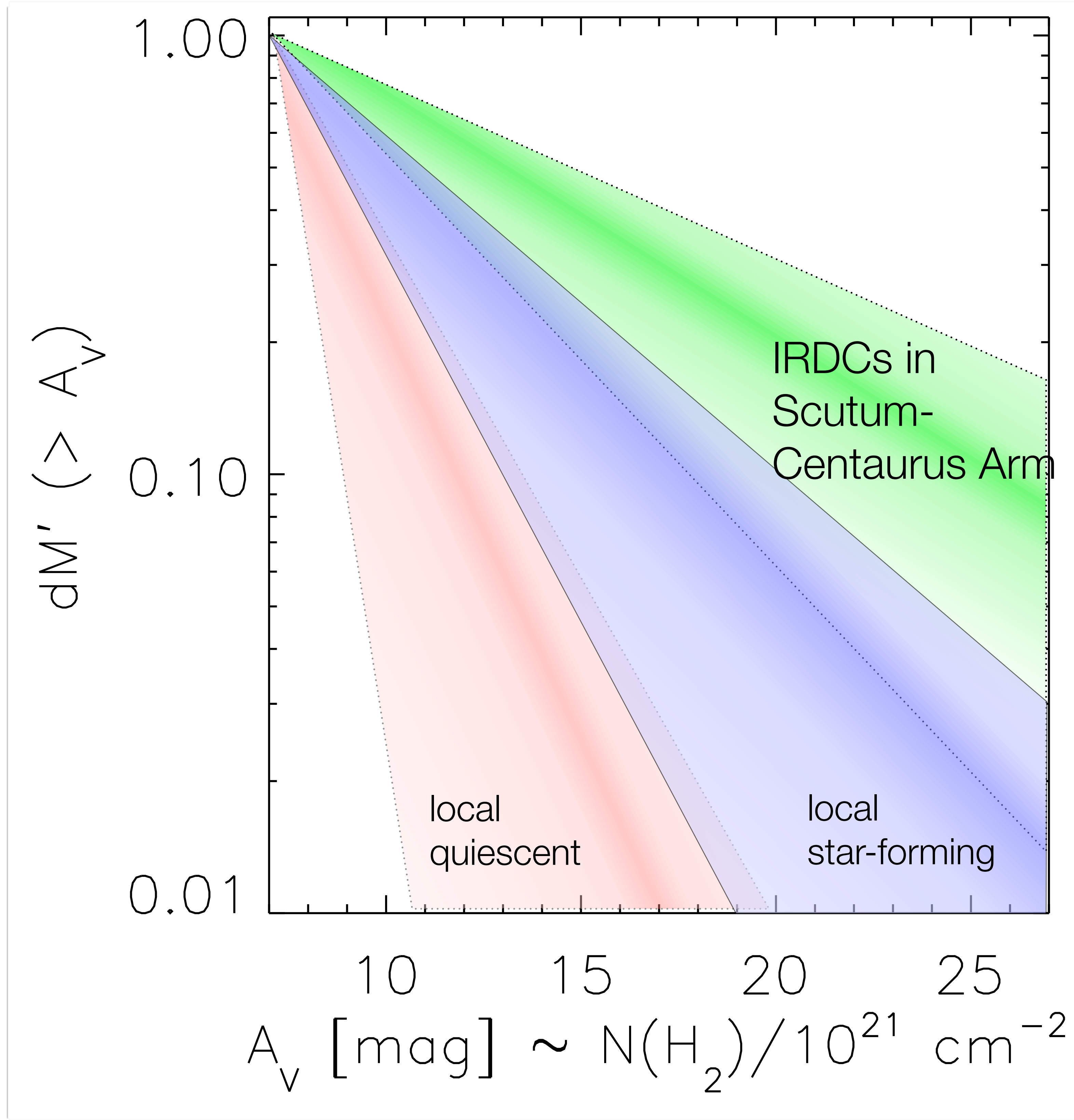
1) cloud scale:

raised stable mass threshold

→ *more massive clouds* *(before SF onset)*

explains ~0.5 dex higher cloud masses in M51s spiral arm vs. interarm (Hughes et al. 2013;Colombo et al. 2013;Koda et al. 2012)?

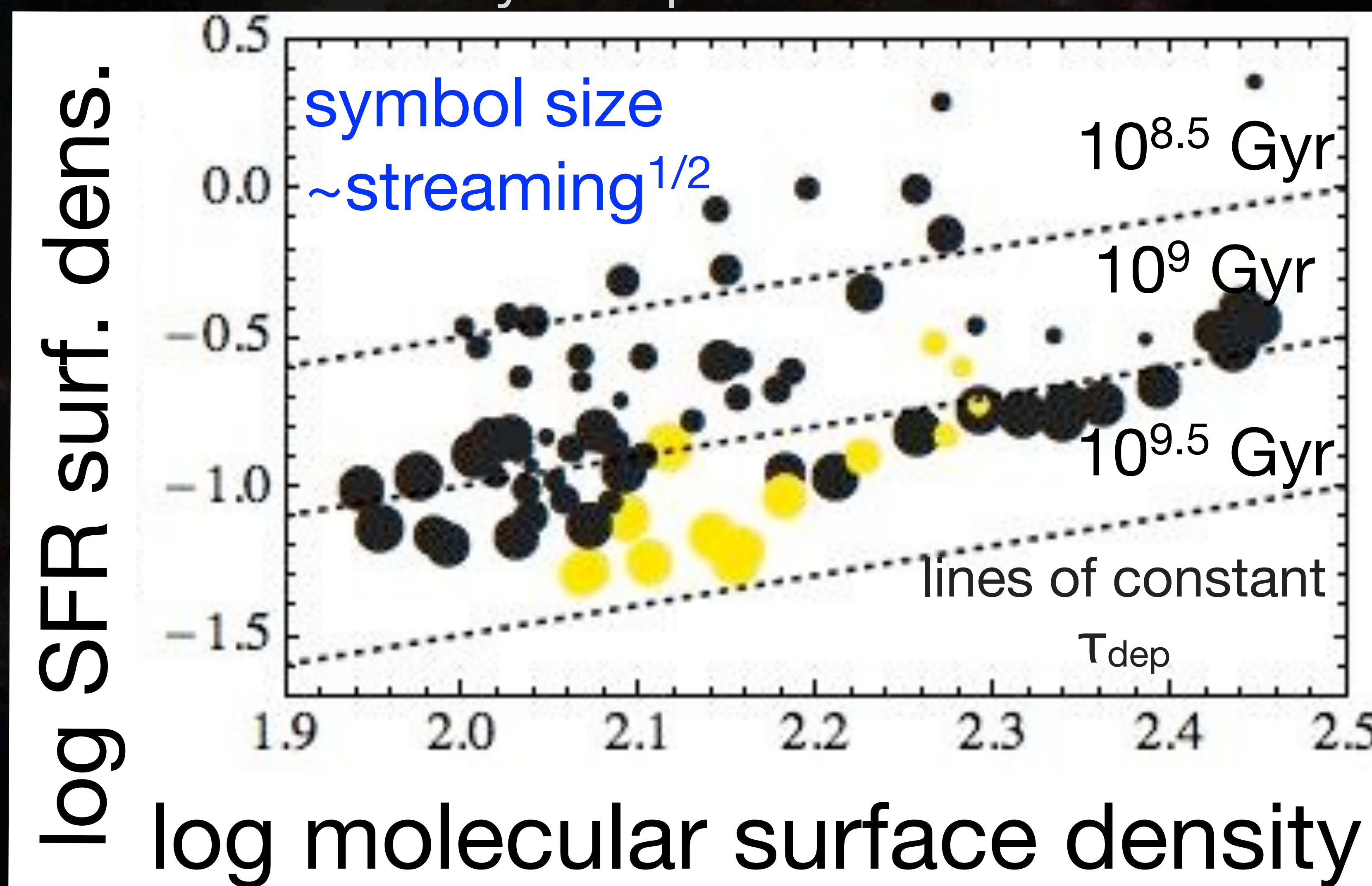




Adapted from: Kainulainen & Tan (2013), Kainulainen et al. (2013), Kainulainen et al. (2011)

are the ‘normal’ spiral galaxies really normal?

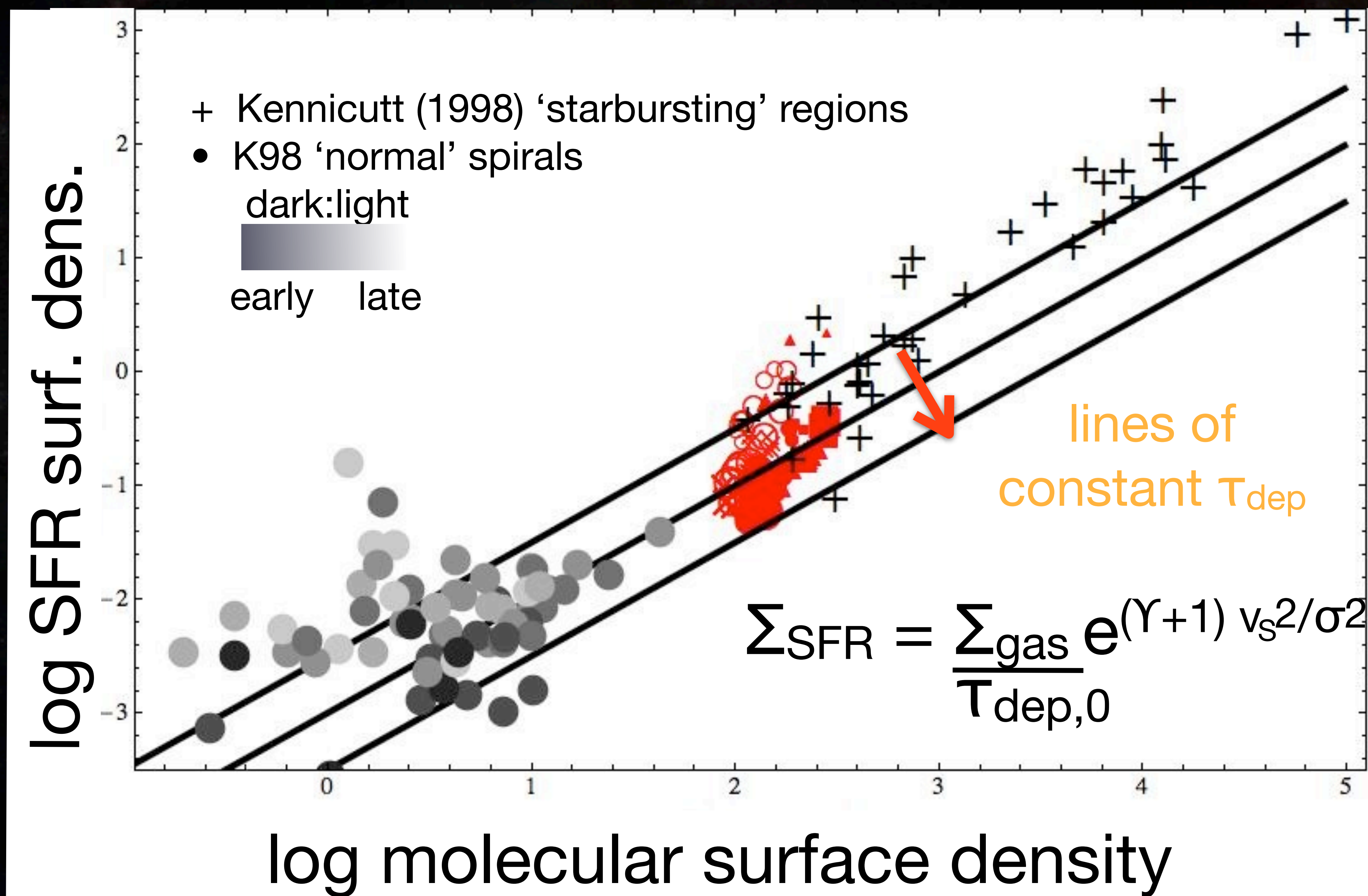
- dynamical pressure in the presence of streaming motions driven by torques



streaming lengthens τ_{dep} to 2 Gyr

- comparable to dwarfs with Galactic X_{CO}, starbursts?

are the ‘normal’ spiral galaxies really normal?



Thursday, August 1, 2013

Trends with Morph. type

$v_{stream} \sim m\ (\Omega - \Omega_p)\ R \tan i_p\ \Sigma/\Sigma_0$

$\sim m\ V_c \tan i_p\ \Sigma/\Sigma_0$

$\sim V_c/m\ \Sigma/\Sigma_0$ } away from CR

i_p =pitch angle

V_c =rot. velocity

m-armed symmetry

→ **early type spirals have longer globally-averaged τ_{dep}**

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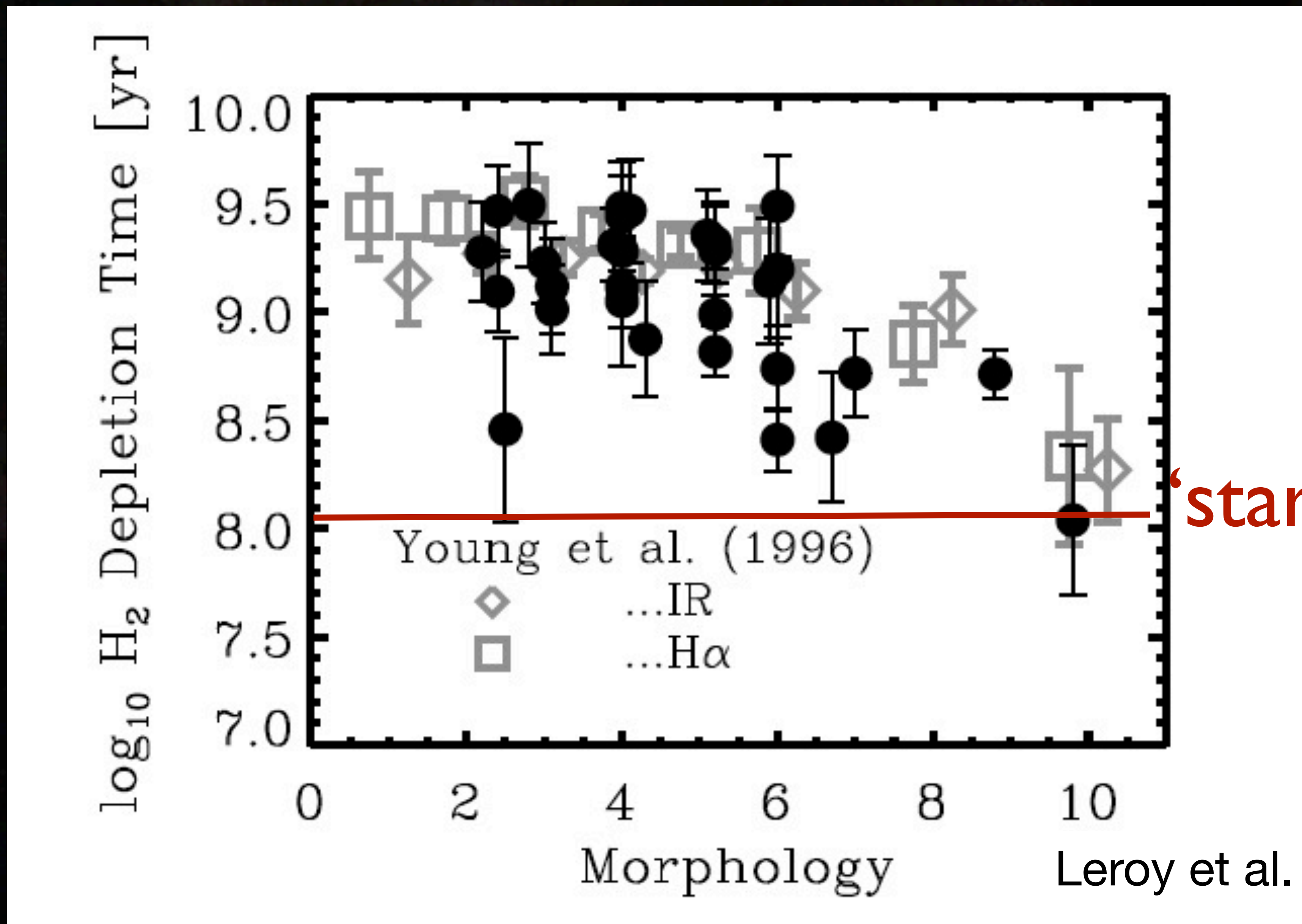
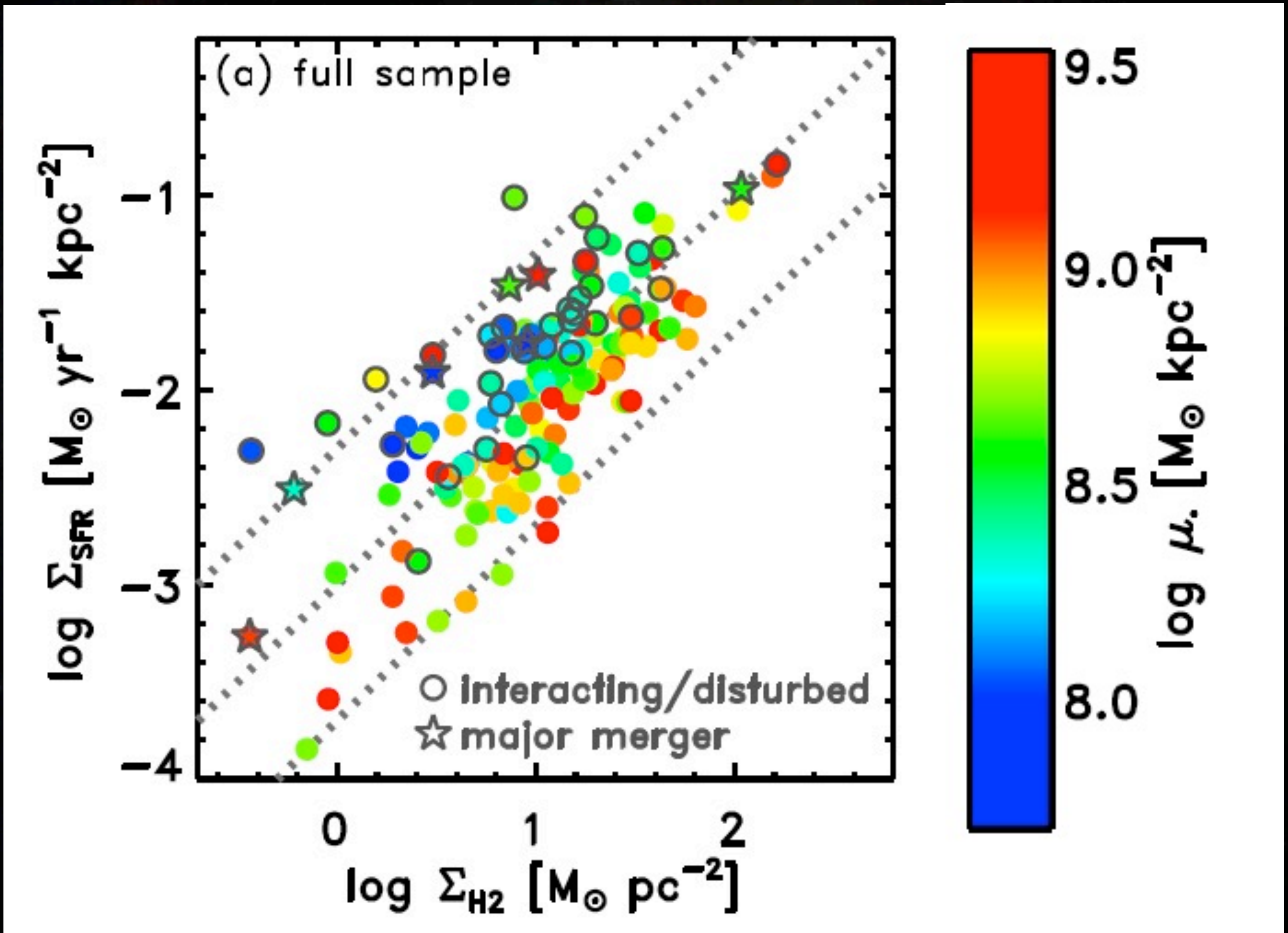


Leroy et al. 2013

COLD GASS:
Saintonge et al. (2013)



implications, locally and at high-z

- **early-type spirals** have *longest* depletion times
- **dwarfs, starbursts** (little spiral-driven streaming): *short* depletion times
- *why 2 Gyr? because spirals typically drive streaming v_S=10-15 km s^{-1}*
- **sublinearity of KS-law (Shetty et al. 2013)?**

high surface densities → high streaming

perturbed continuity eqn.
(i.e. Binney & Tremaine):

$$v_R = \frac{m(\Omega - \Omega_p)}{\kappa} \frac{\Sigma}{\Sigma_0}$$

or high gas fraction?

implications, locally and at high-z

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Meidt et al. (2013)

implications, locally and at high-z

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- *why 2 Gyr? because spirals typically drive streaming v_S=10-15 km s^{-1}*
- **at high-z** high gas fraction: *short* depletion time

RC shape

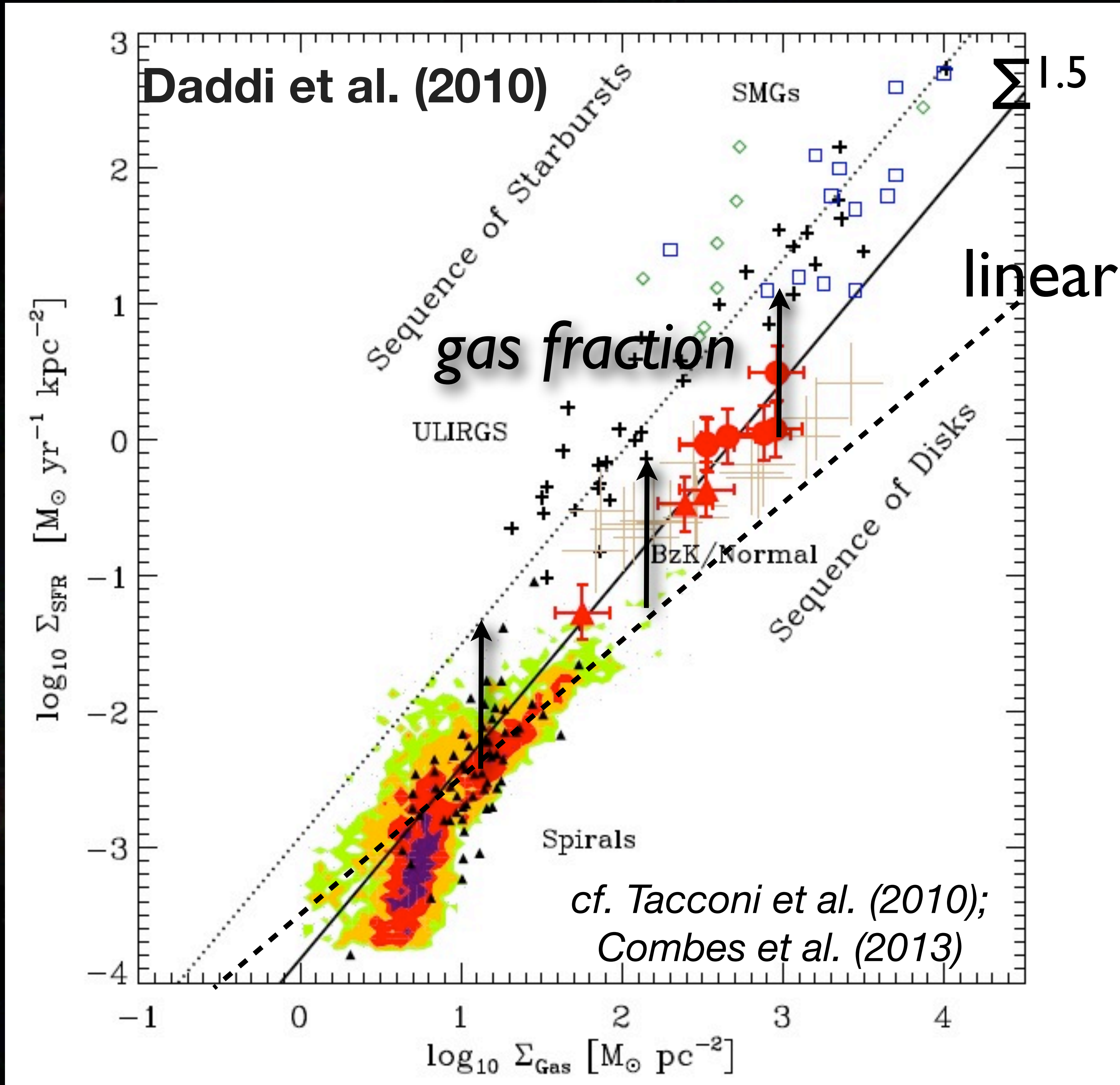
$$\tau_{dep} \propto \frac{V_S}{\sigma} \propto \frac{(2\beta+1)^{1/2}}{QF_g}$$

Meidt et al. (2013)

Toomre Q

gas fraction

τ_{dep} linked to gas fraction
(high F_g --> weakened sensitivity to environment-decoupling)



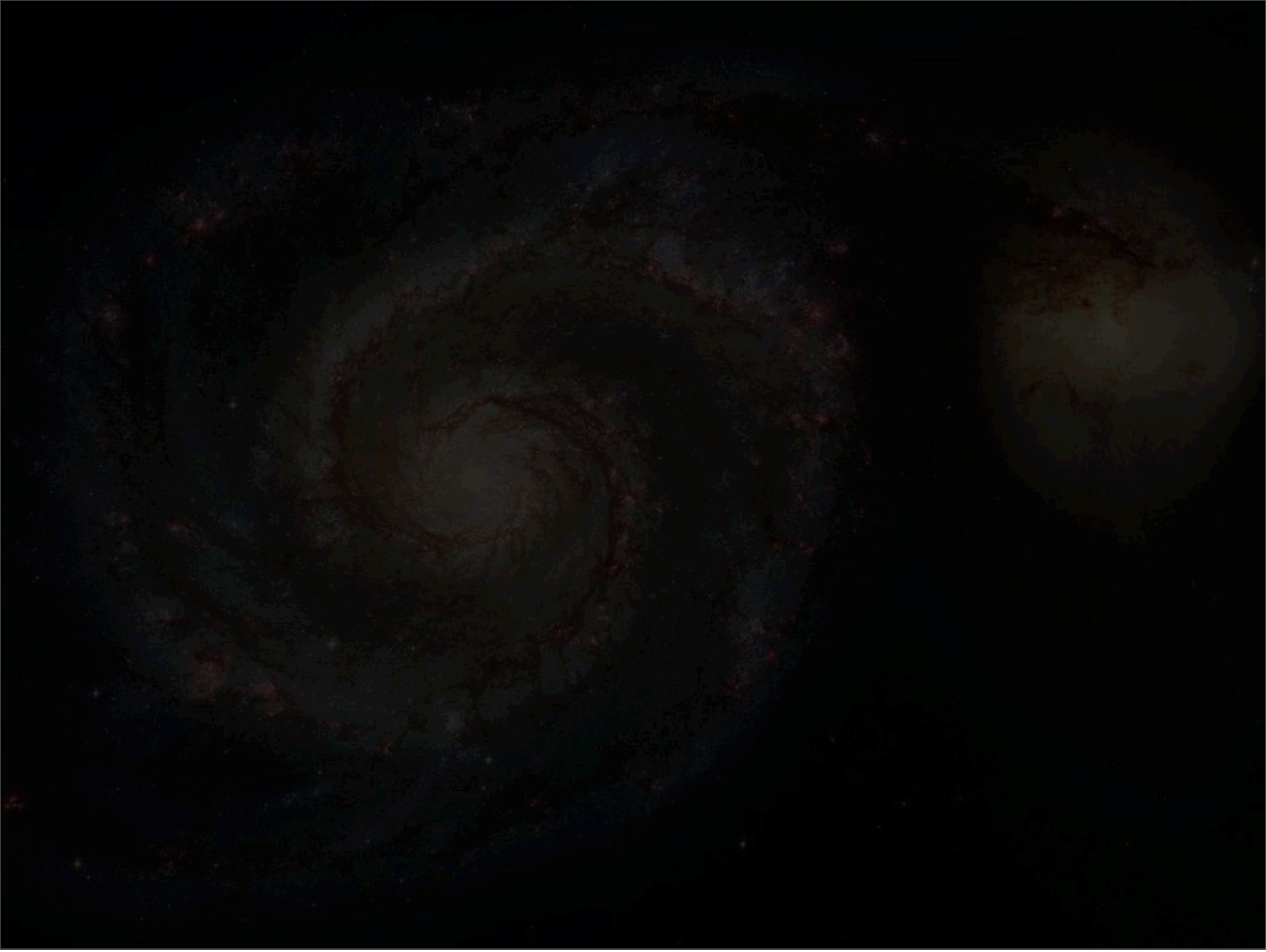
Daddi et al. (2010)
SMGs
Sequence of Starbursts
$\Sigma^{1.5}$
linear
gas fraction
ULIRGS
BzK/Normal
Sequence of Disks
Spirals
cf. Tacconi et al. (2010);
Combes et al. (2013)
$\log_{10} \Sigma_{SFR}$ [$M_\odot$ yr^{-1} kpc^{-2}]
$\log_{10} \Sigma_{Gas}$ [$M_\odot$ pc^{-2}]

Take Away

- non-circular streaming motions ***suppress*** *star formation* and ***lengthen*** *depletion time*

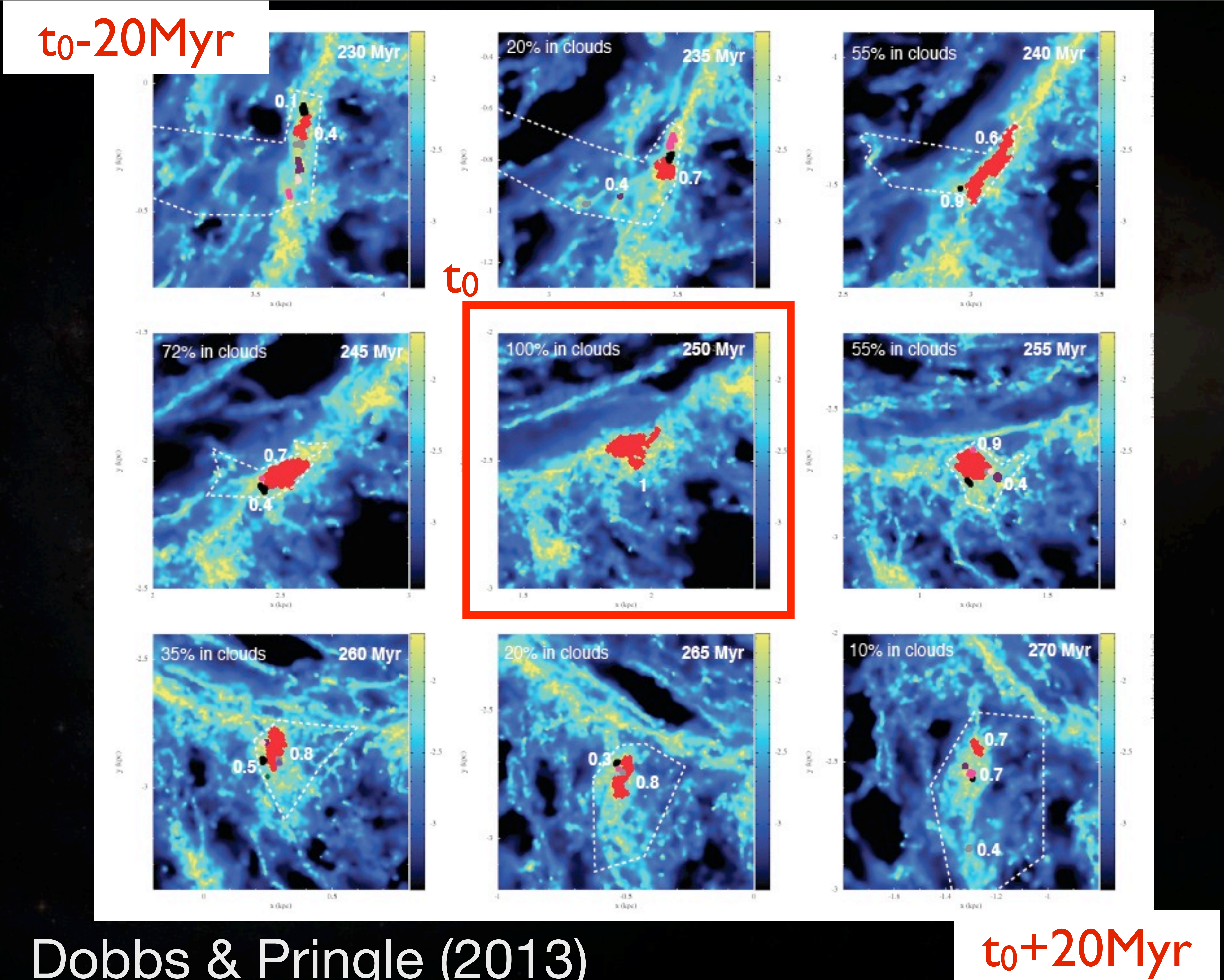
- dynamical pressure introduces ‘scatter’ in KS law between and among galaxies + provides a smooth link b/n low and high-z star formation

- star-forming disk galaxies have τ_{dep}=2 Gyr (in contrast to nominal 1 Gyr in systems without non-axisymmetric structures)?



Take-away

- Non-axisymmetric structures, like M51's bar and spiral, exert ***torques*** that drive strong non-circular gas ***'streaming' motions***
- these motions ***stabilize*** clouds by reducing the cloud surface pressure
- fewer collapse-unstable clouds per free fall time ***lengthens*** the ***gas depletion time***
- dynamical pressure introduces 'scatter' in KS law between and among galaxies + provides a smooth link b/n low and high-z star formation

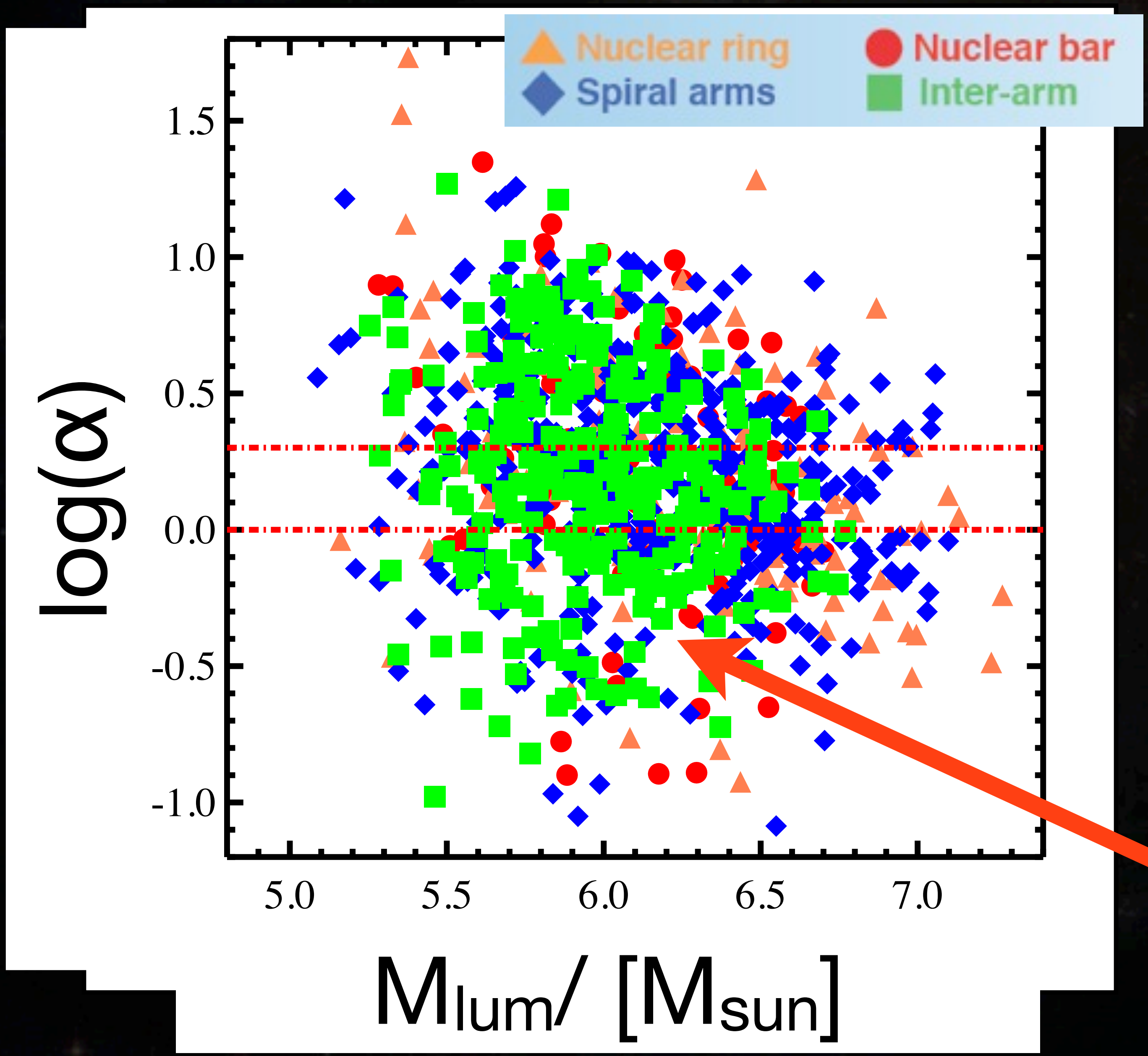


Dobbs & Pringle (2013)


M83
(ESO)

GMC Stabilization in M51

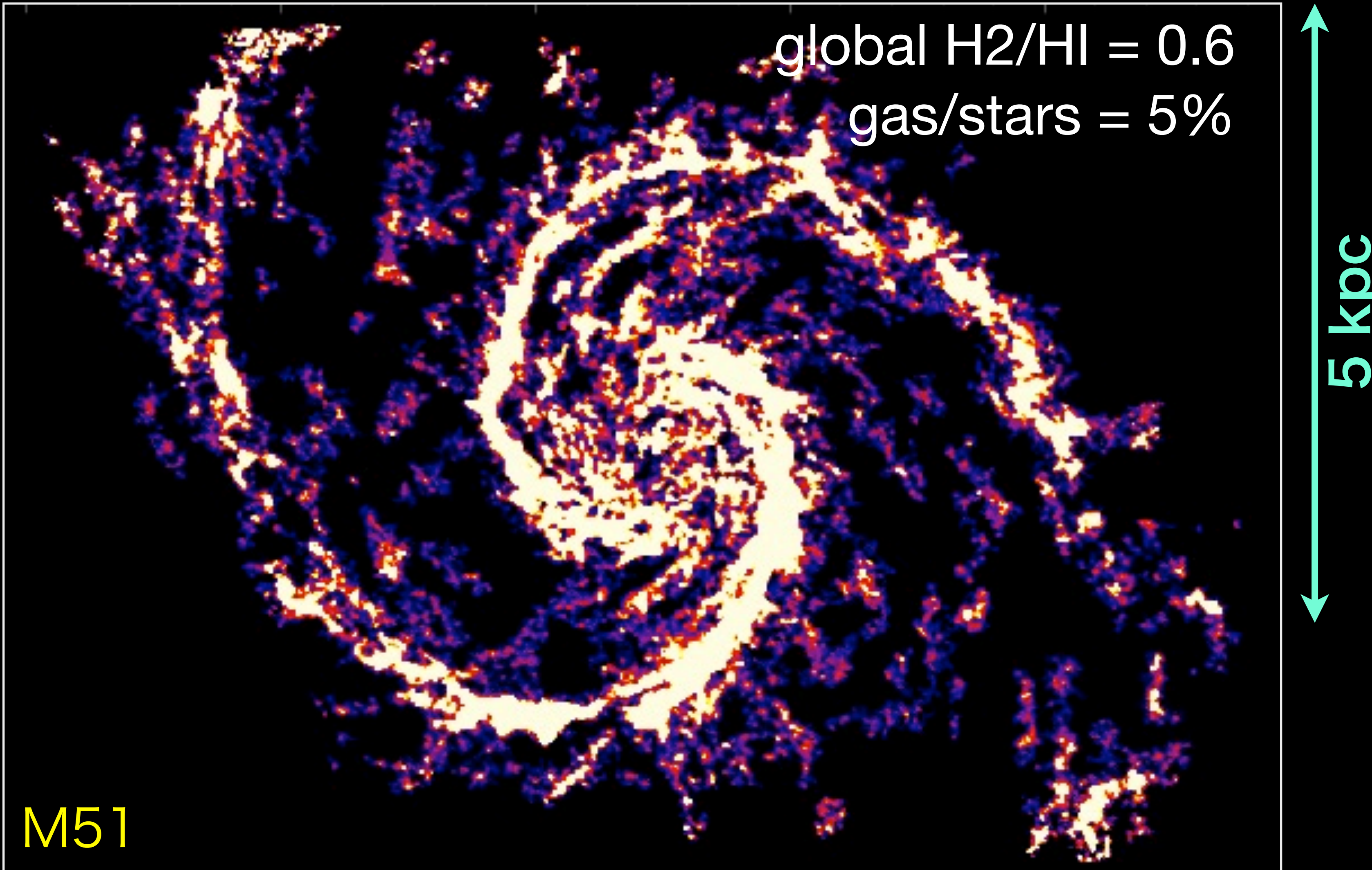
α: measure of virialization
(McKee & Bertoldi)



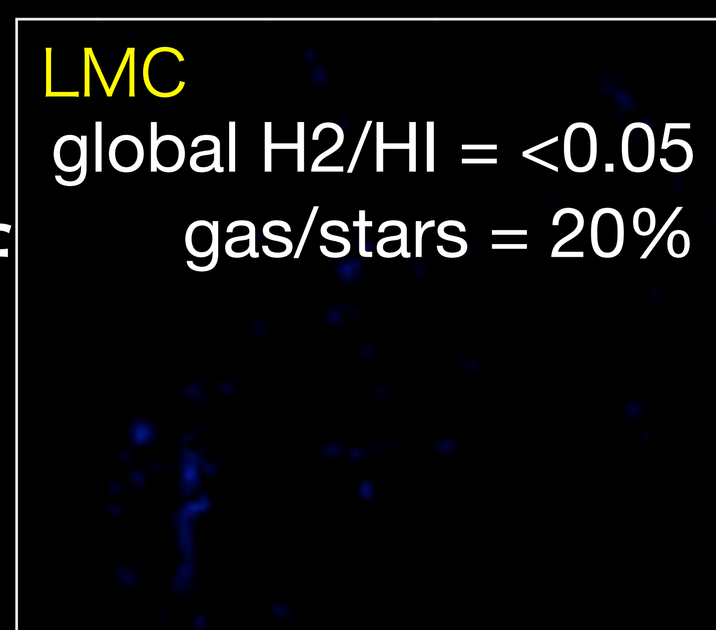
clouds unbound
or
pressure confined?

virialized

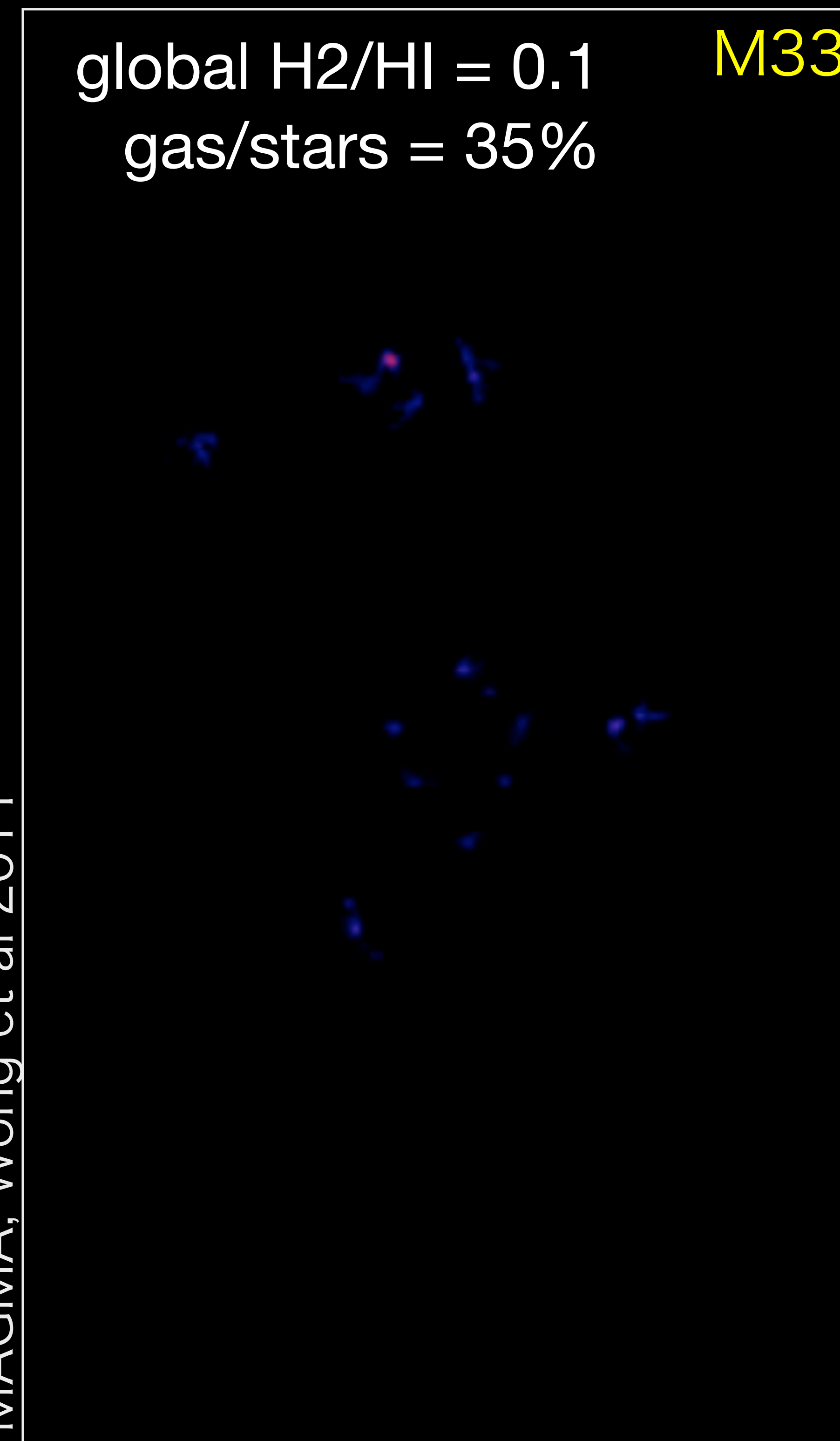
only 25% grav. bound
clouds, mostly inter-arm at low M



Properties of GMCs in M51 vs two nearby dwarf galaxies (Hughes et al., in prep)



MAGMA, Wong et al 2011



FCRAO+BIMA, Rosolowsky et al 2007

molecular gas properties

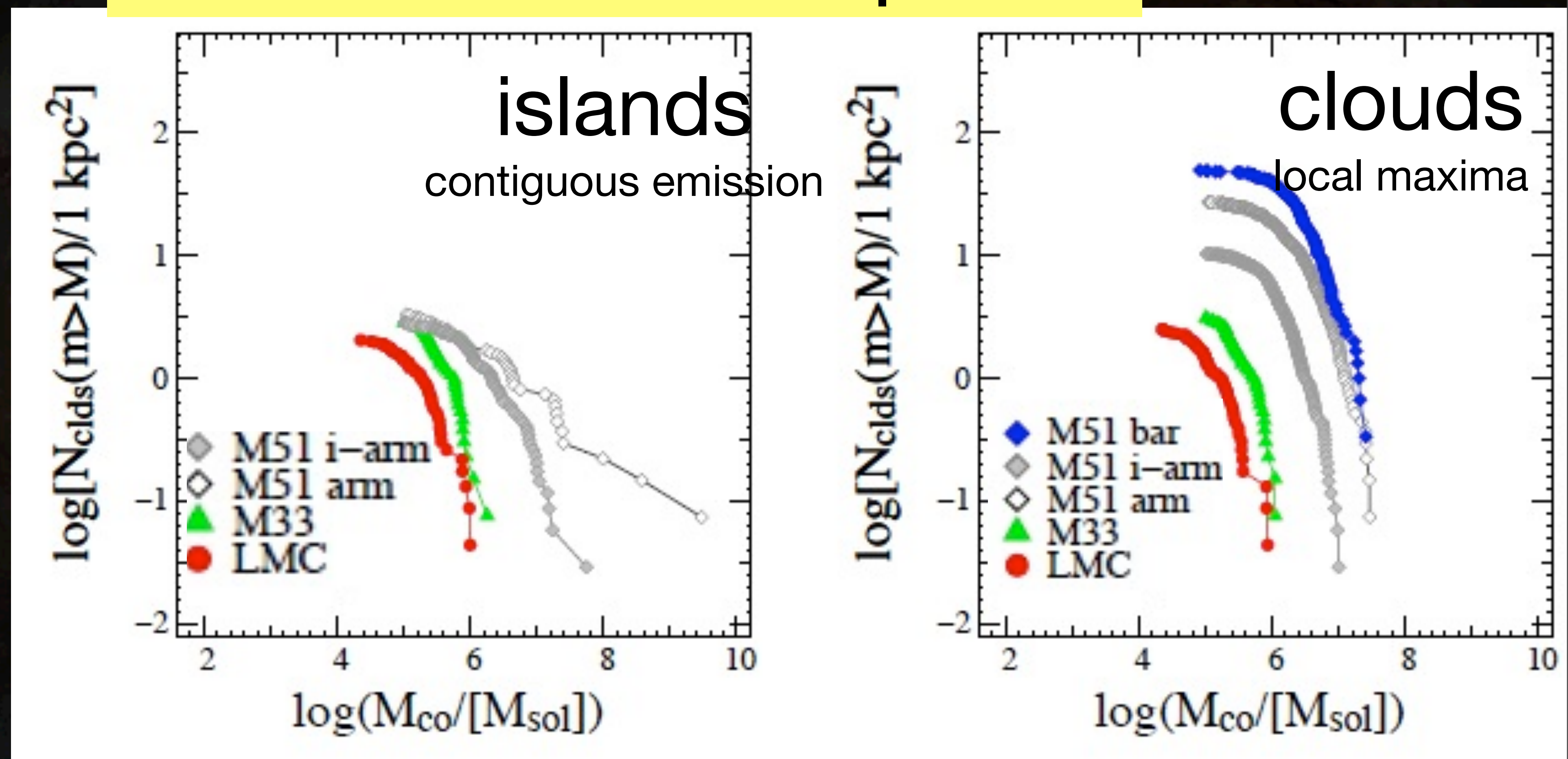
After homogenizing the datasets, M51 GMCs:

- are **brighter** (T_{peak} and surface brightness)
- have **larger linewidths** (relative to size)

than GMCs in M33 and the LMC

- M51 interarm clouds more like clouds in the low-mass galaxies

cumulative mass spectra *constant XCO*



Hughes et al. 2012

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