The impact of galactic- scale gas motions on cloud stability

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PAWS
PdBI Arcsecond Whirlpool Survey

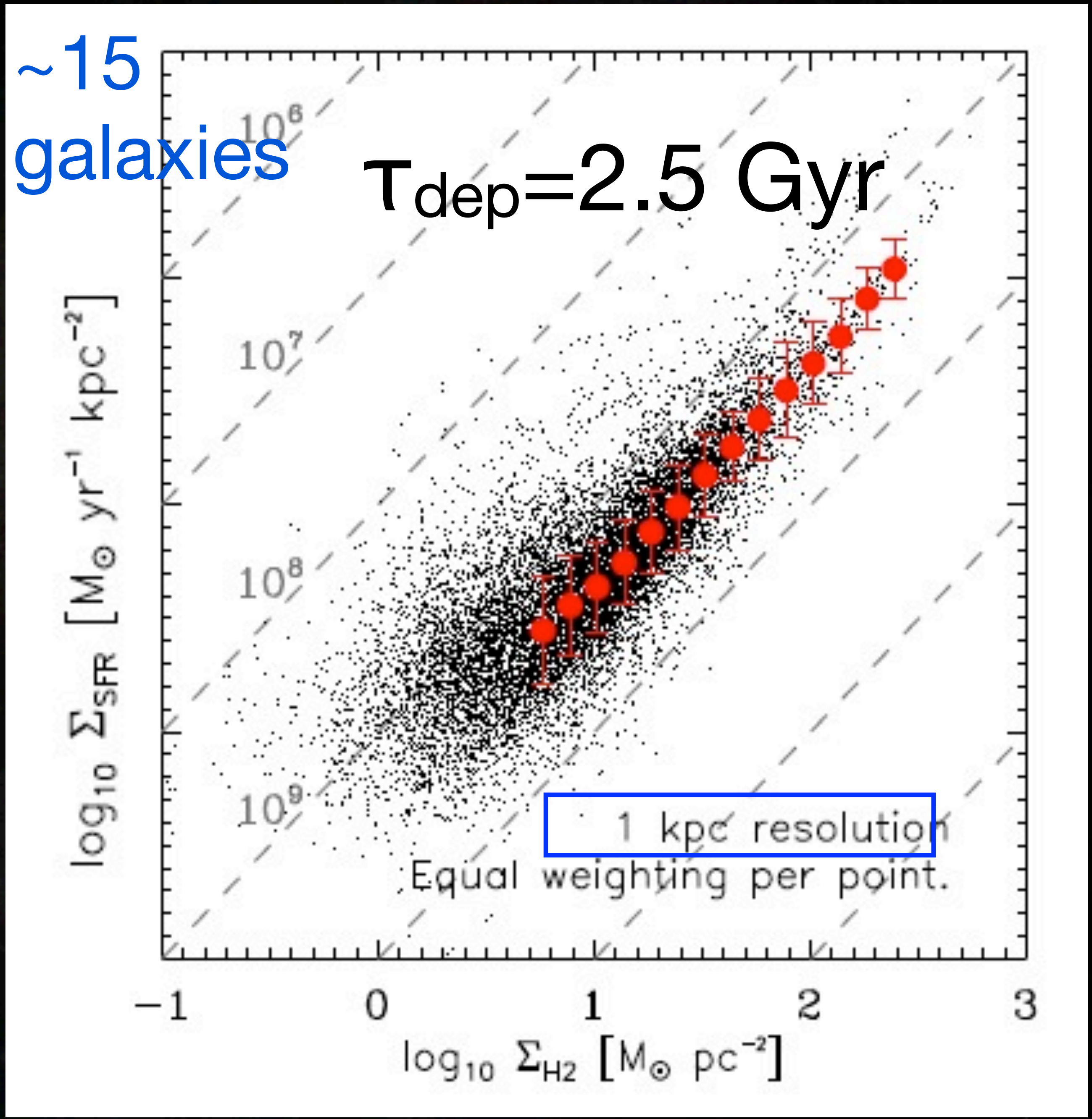
(sub-)kpc star formation relation

Bigiel et al. (2008;2011)

molecular gas depletion time

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

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



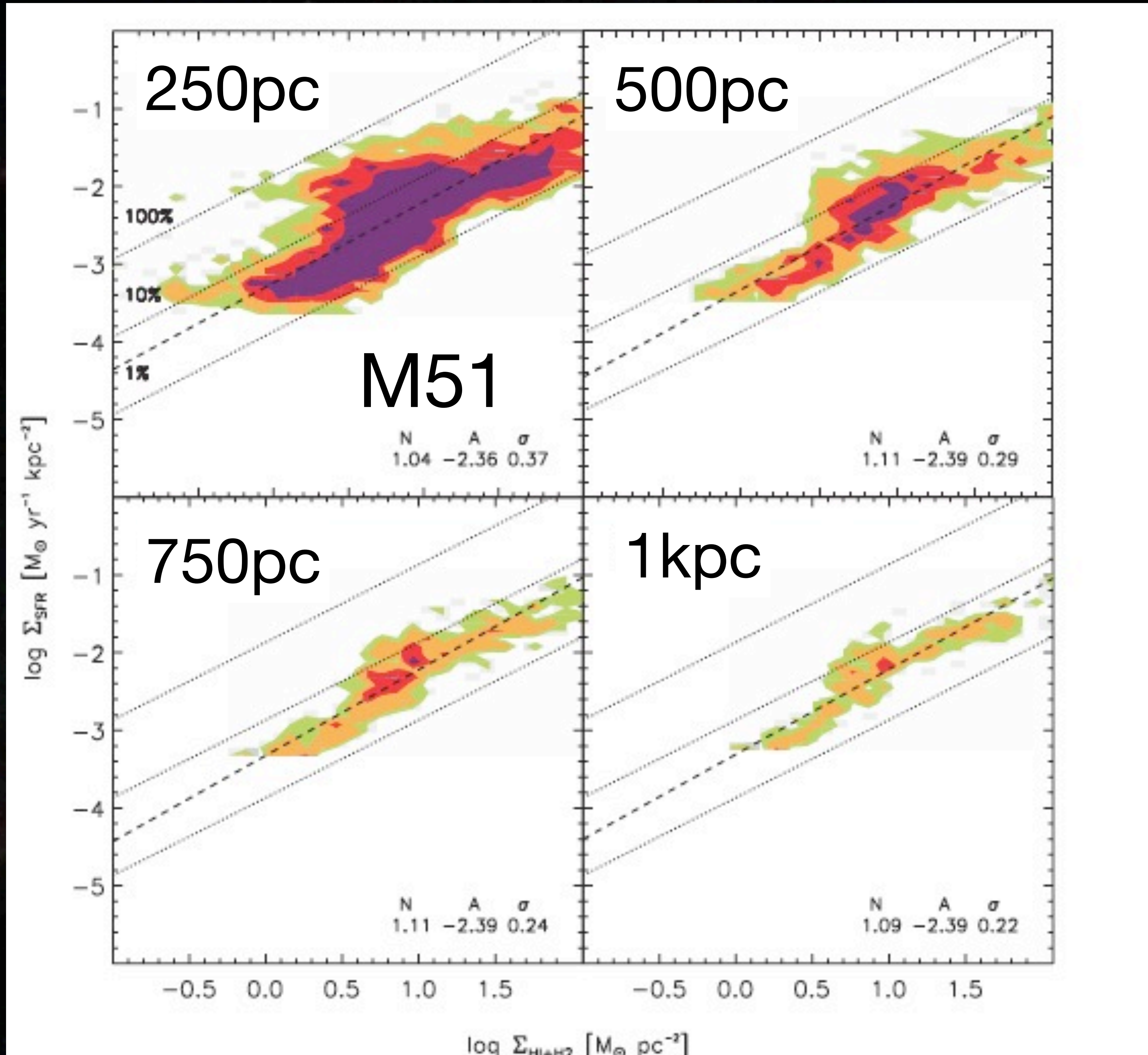
$\Sigma_{SFR} = \Sigma_{H2}^{n}$

n=1

≠1.4-1.5

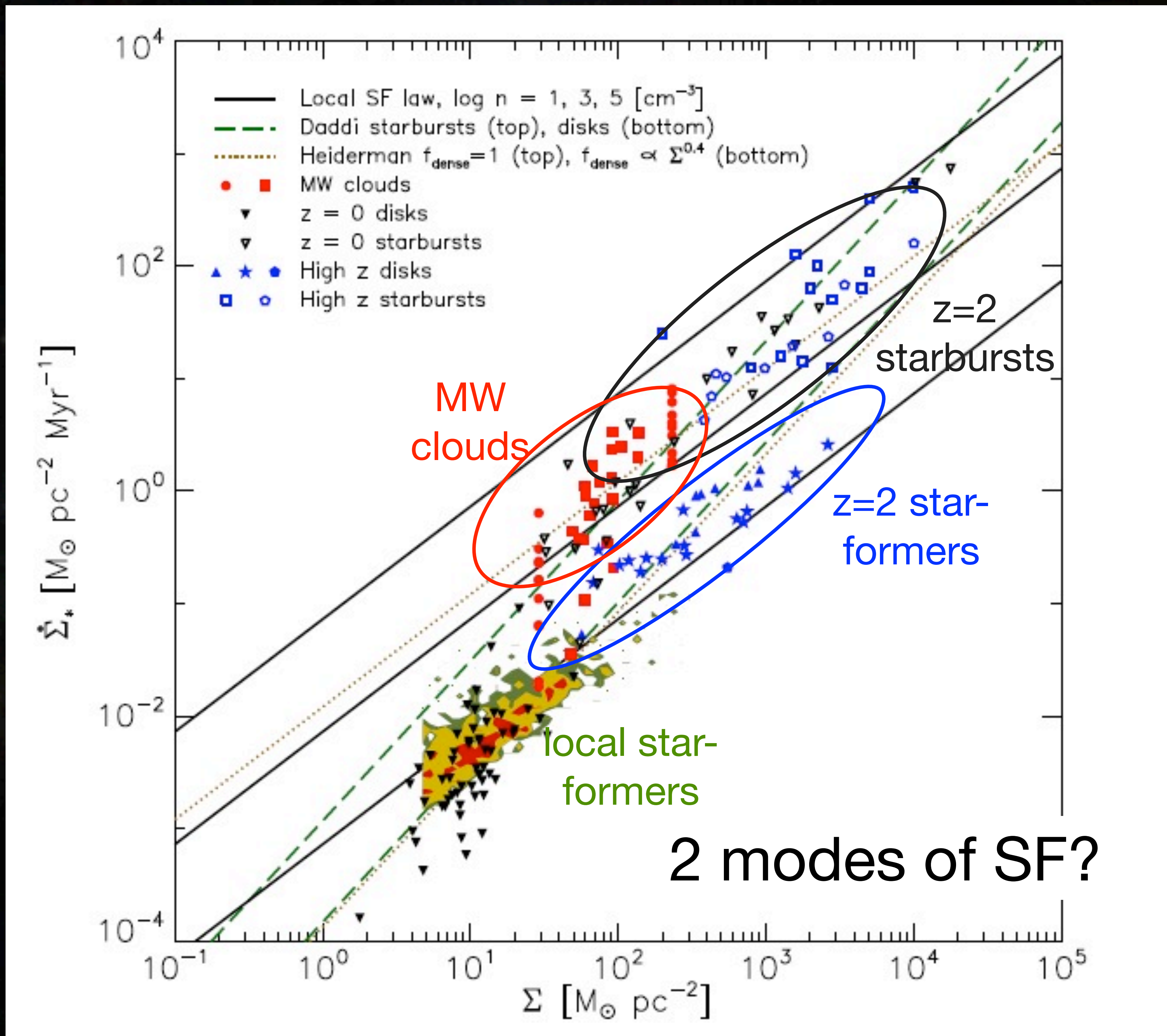
universal molecular gas depletion time ??

Bigiel et al. (2008)



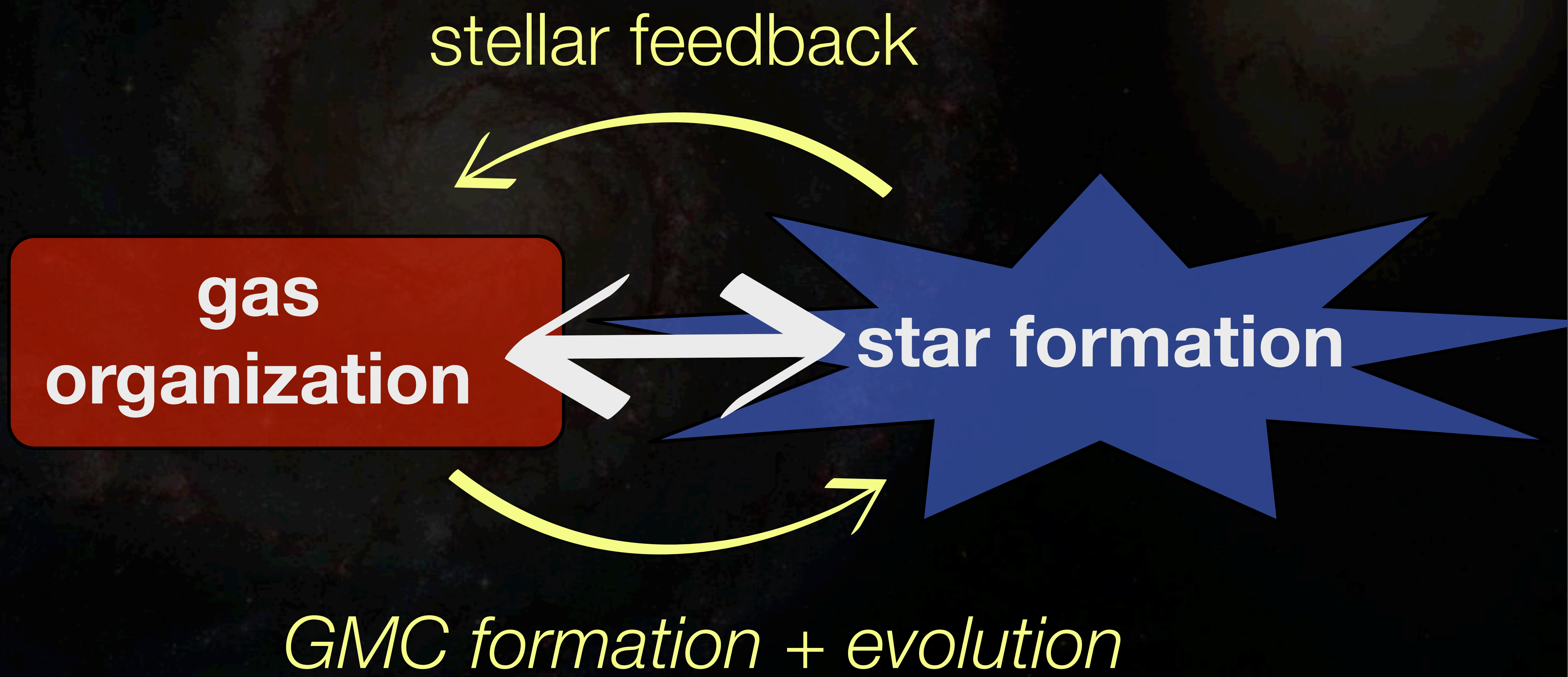
what's the physics behind the scatter ?

Krumholz, Dekel & McKee (2011)



2 modes of SF?

gas kinematics in spiral potentials



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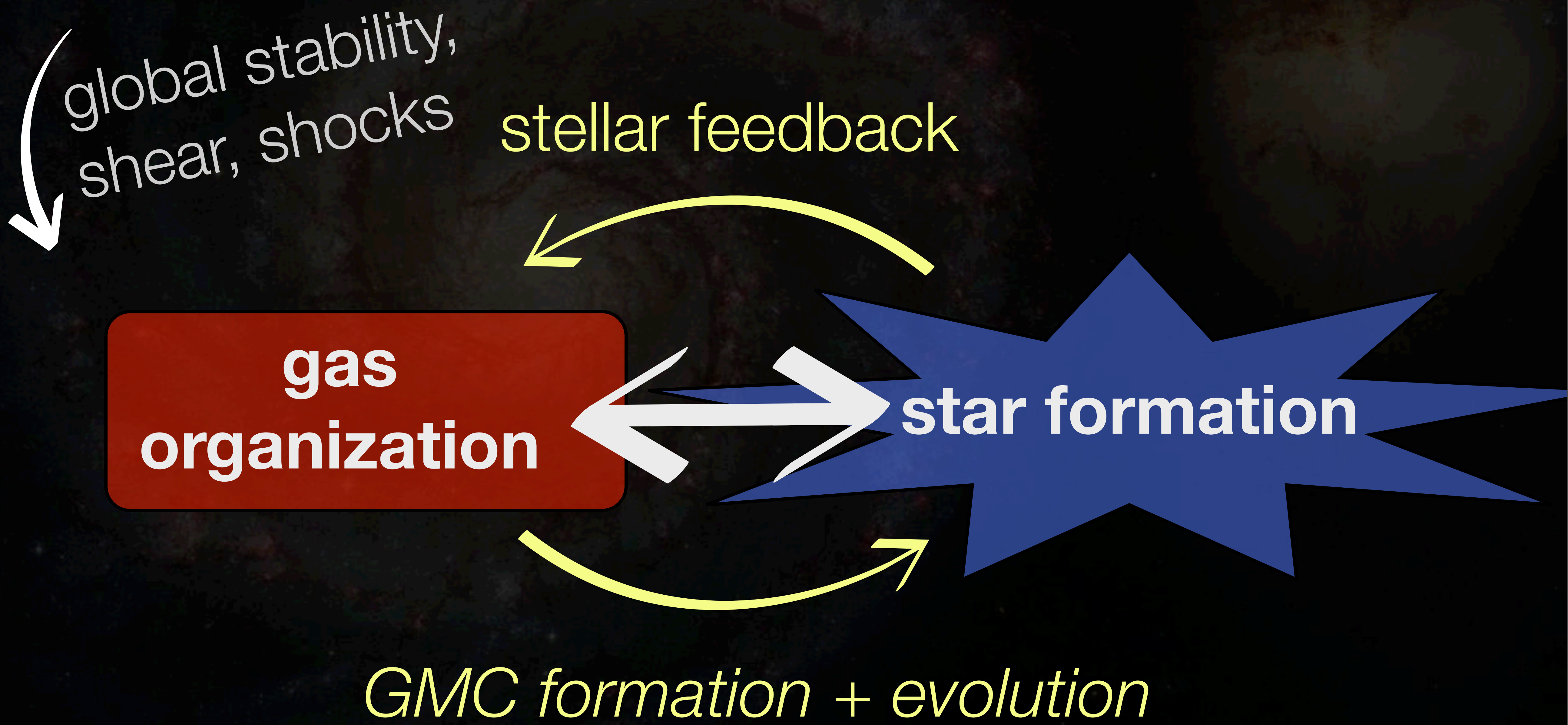


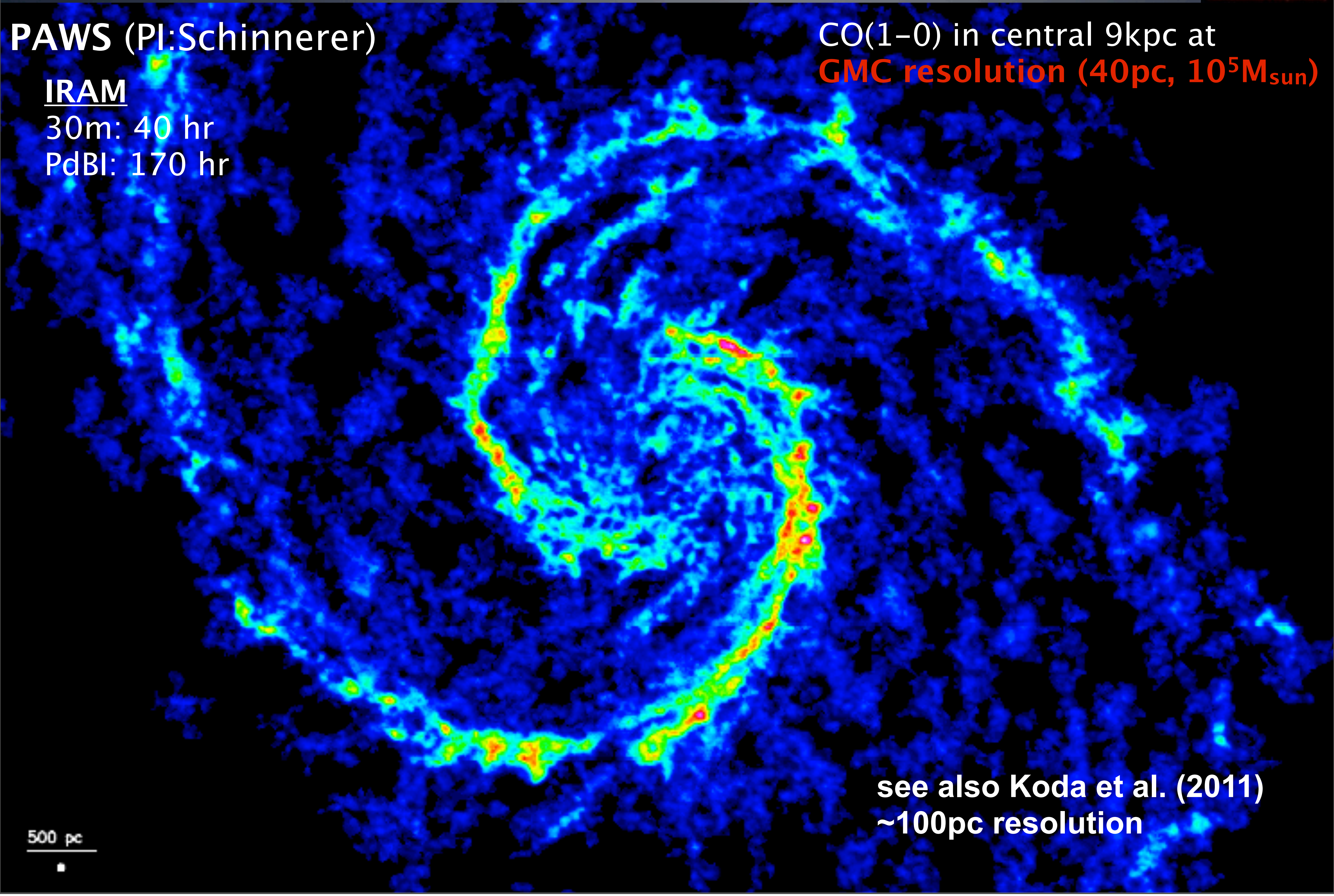
- **shocks**: build high densities, trigger SF, enhance turbulence?
- **shear**: stabilize+destroy clouds
  - SF favored in regions of low shear (spiral arms)
- **non-circular motions**: dynamical coupling to environment
- which controls cloud stability?

Molecular Gas disk of M51

PAWS (PI:Schinnerer)

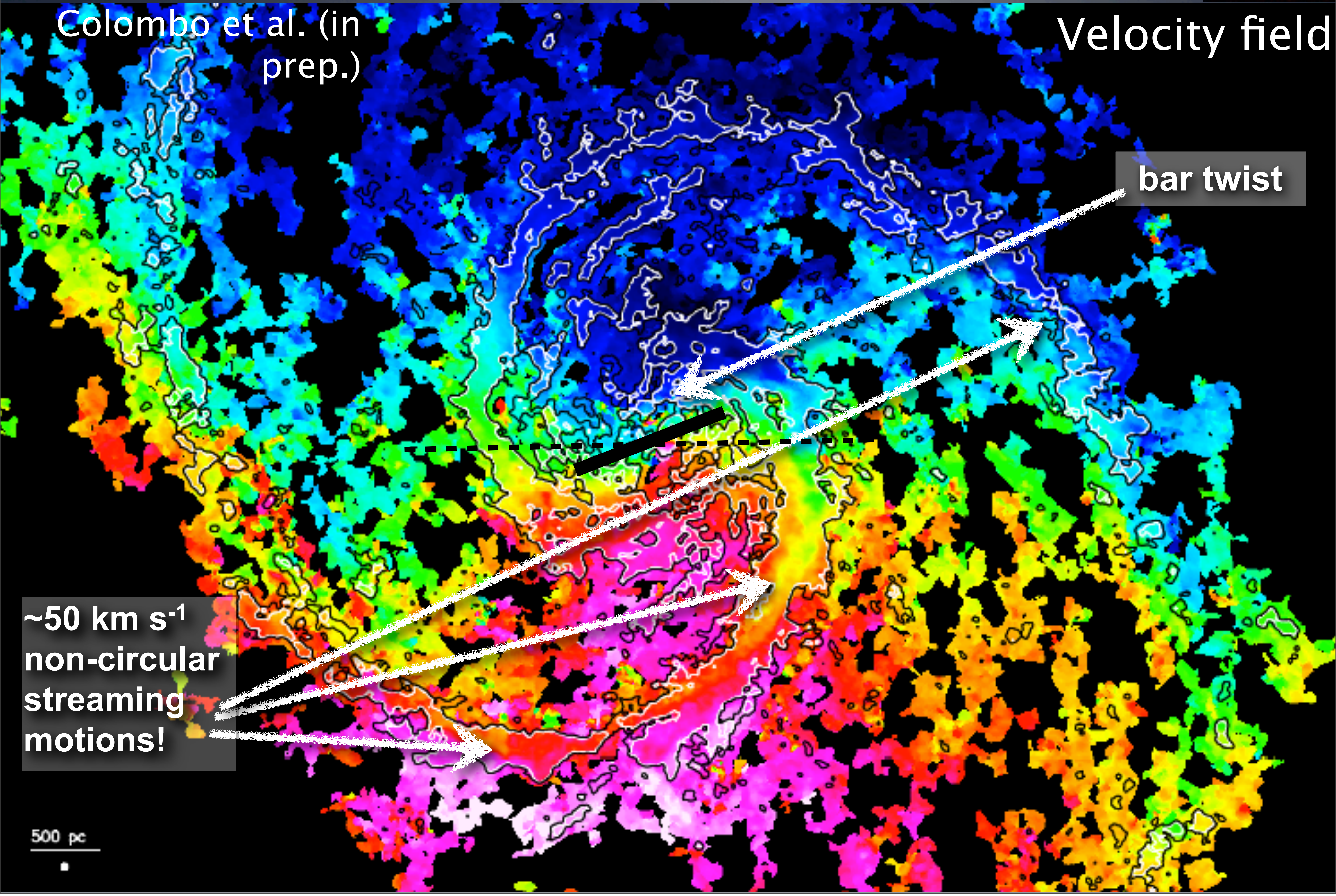
IRAM
30m: 40 hr
PdBI: 170 hr

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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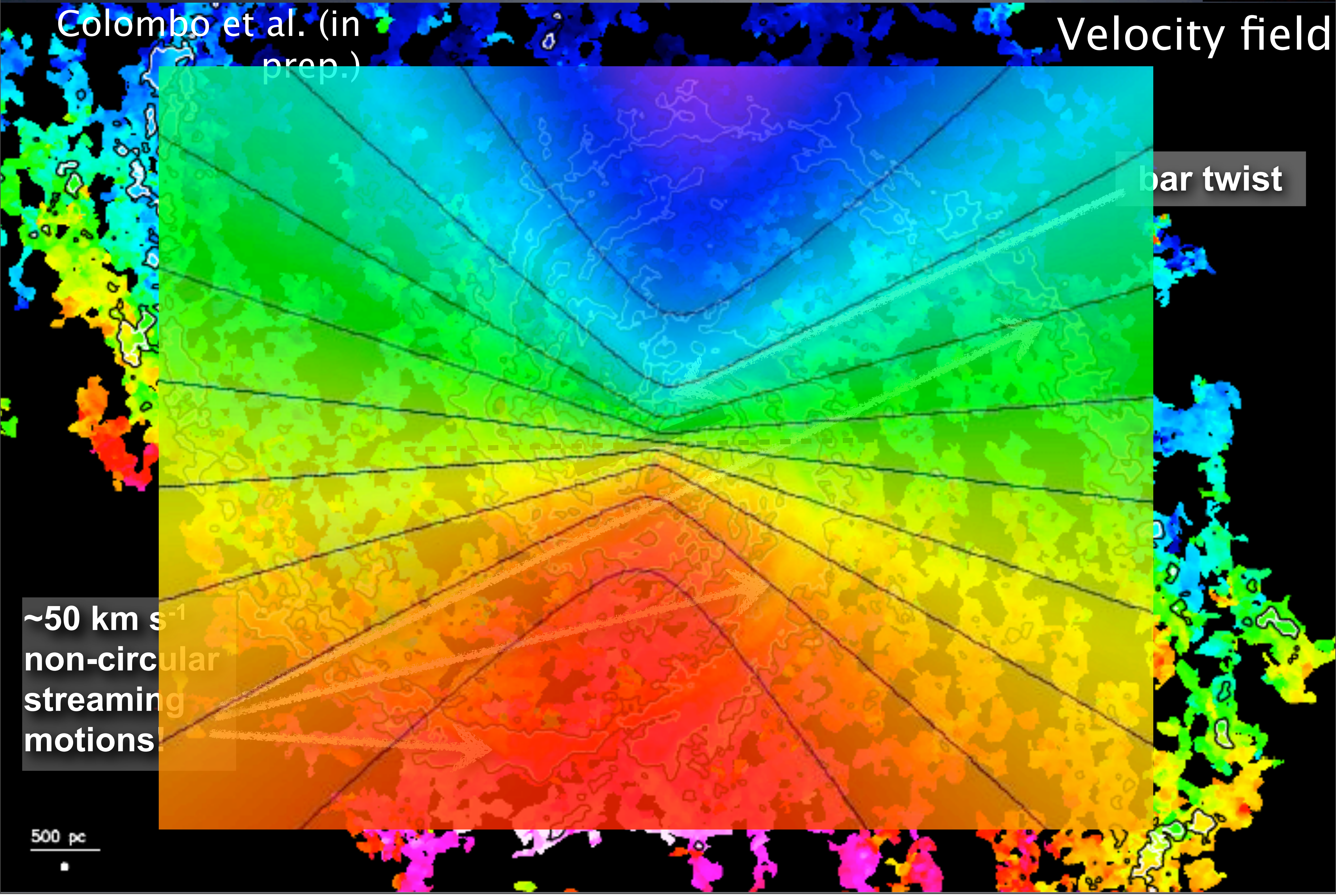

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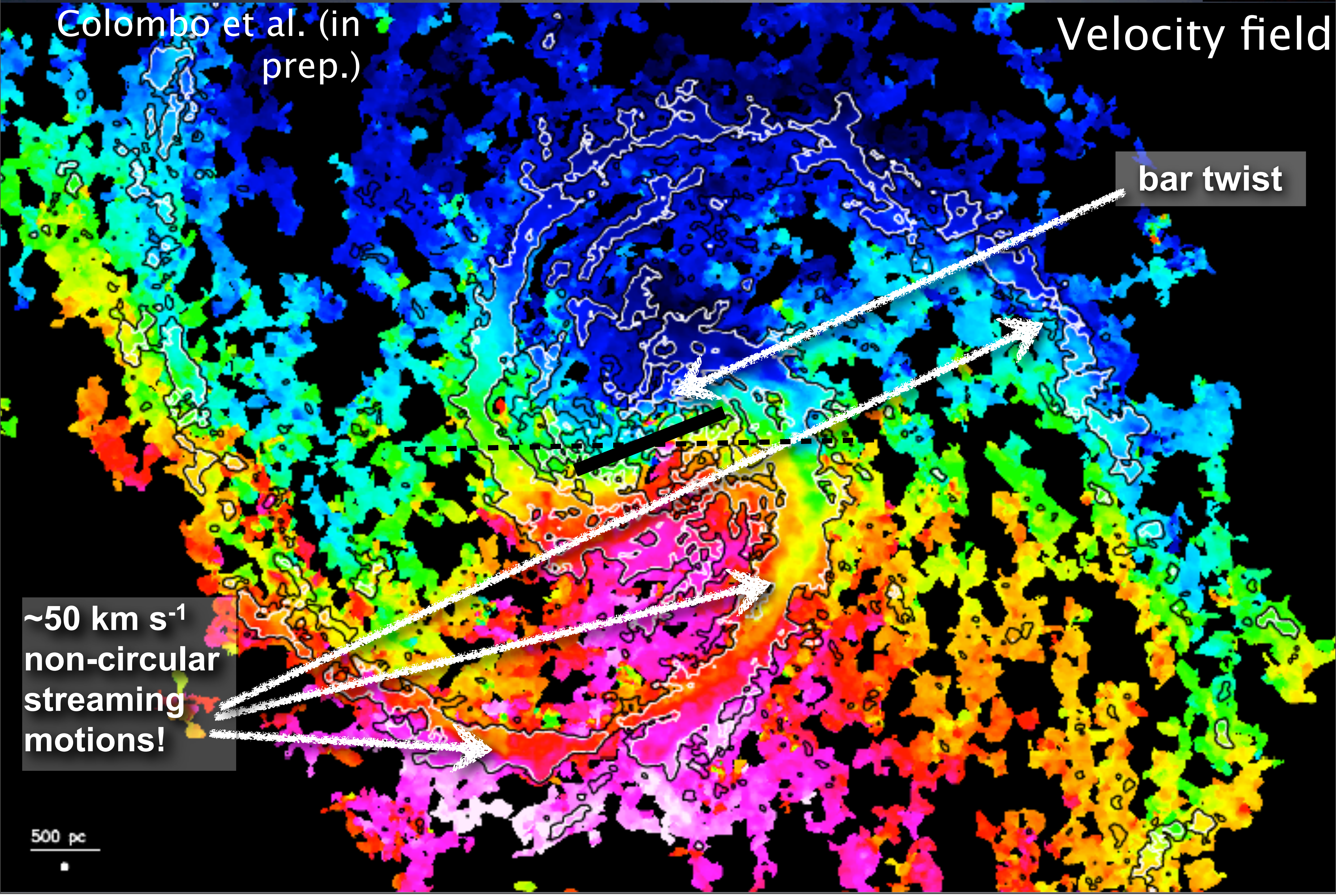

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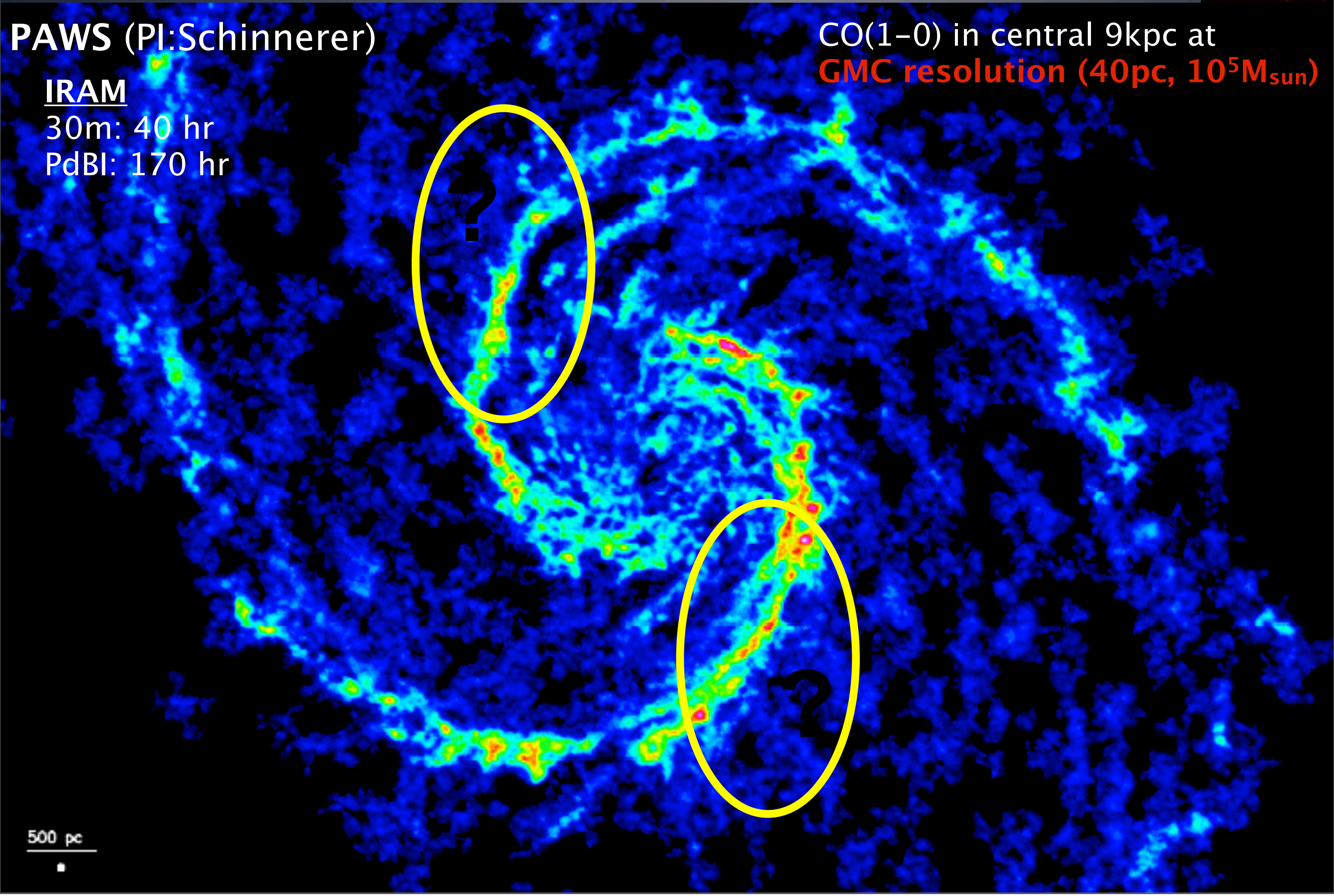
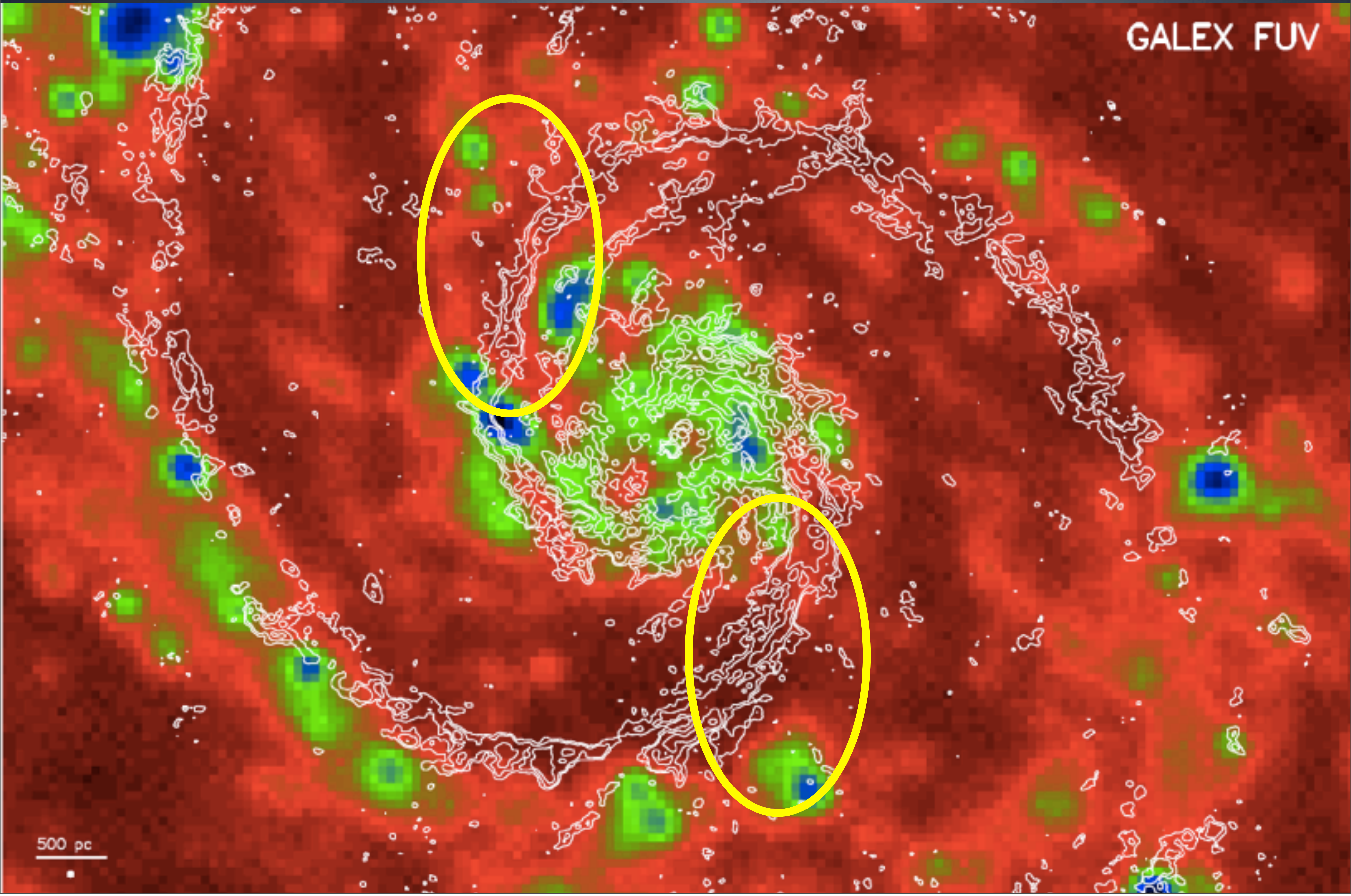


Spatial Relation b/n Gas and Star Formation

Schinnerer et al. (in prep.)



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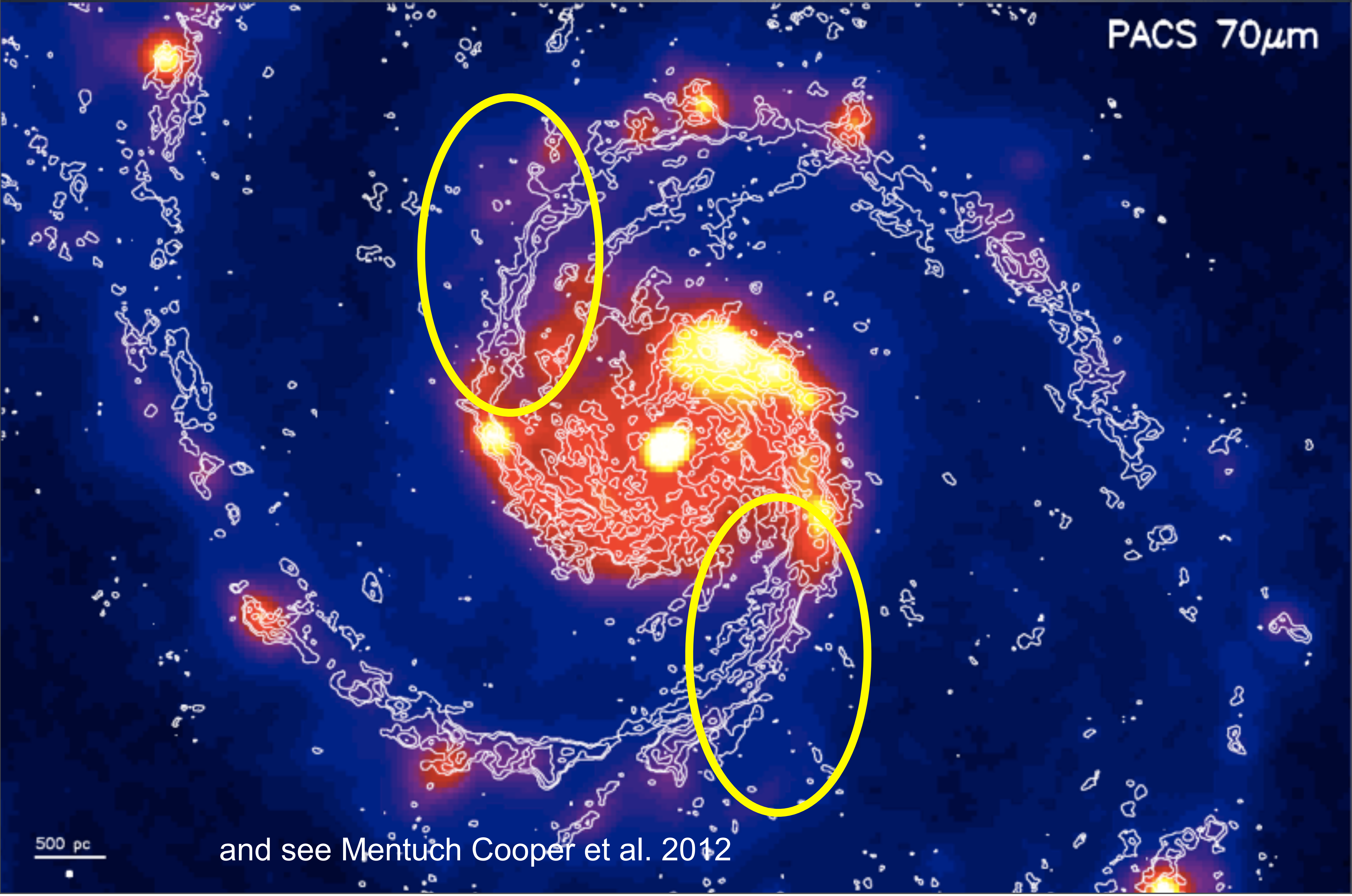

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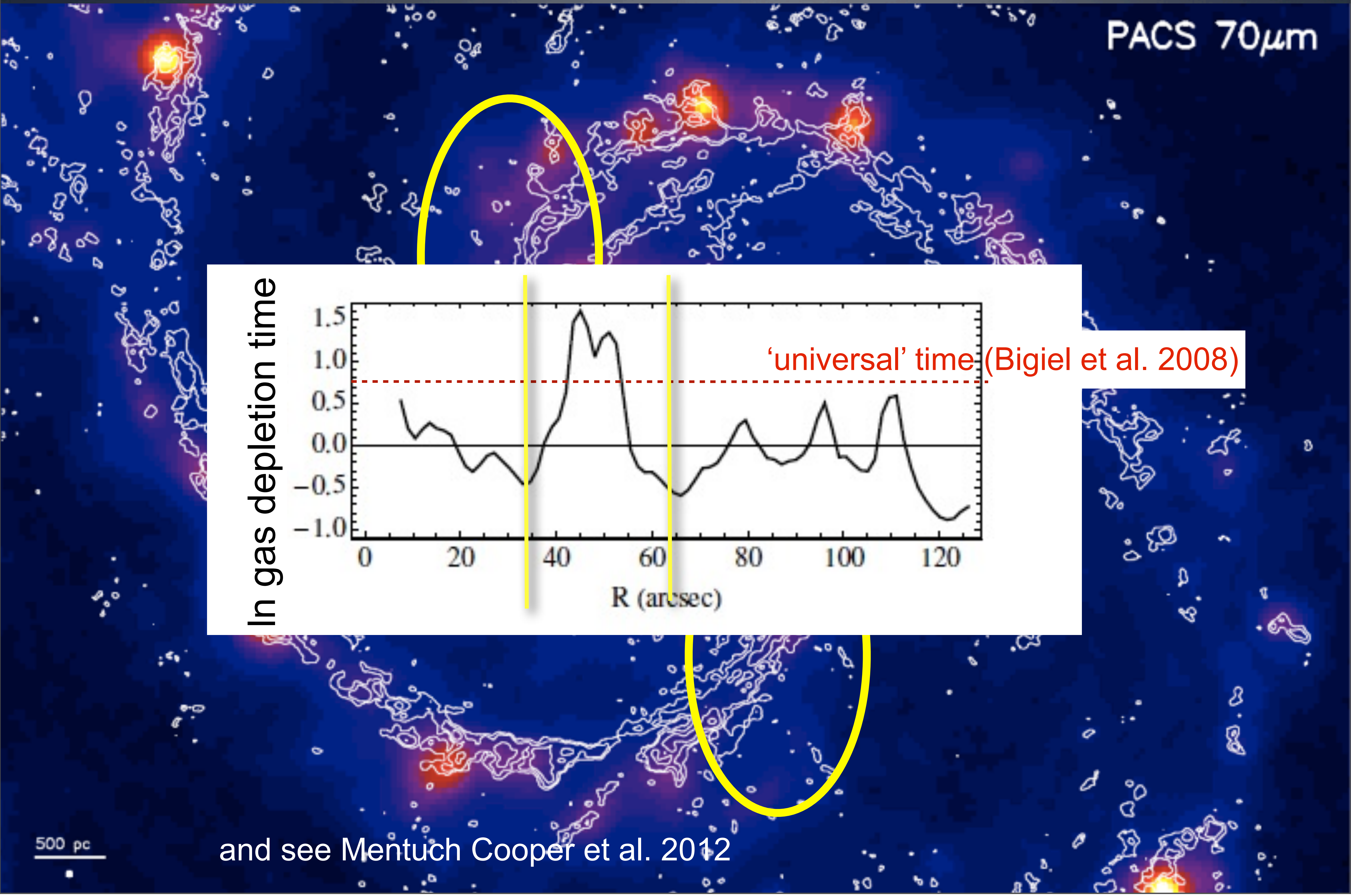
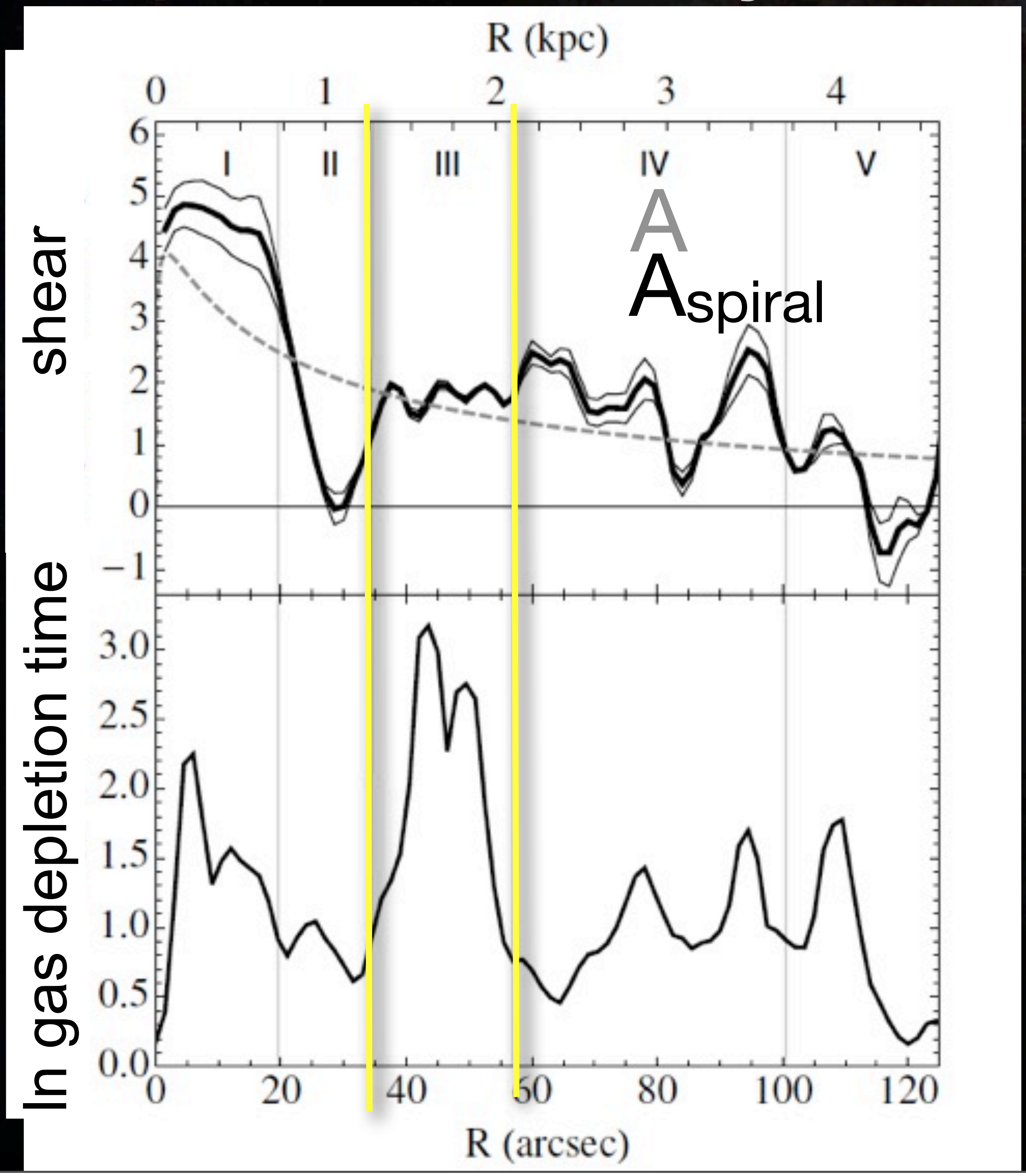


GMC Stabilization in M51

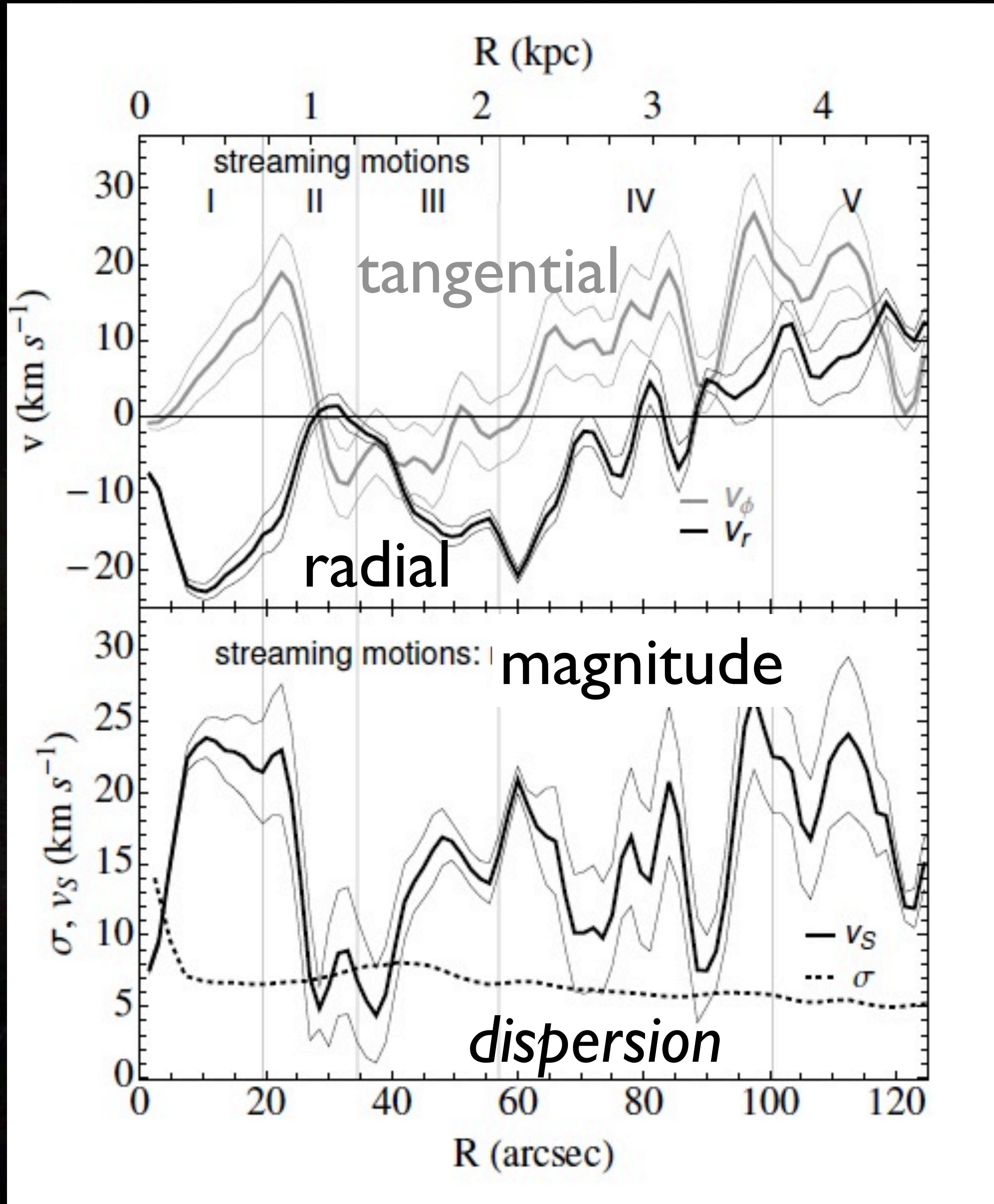
what shuts off star formation?

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)

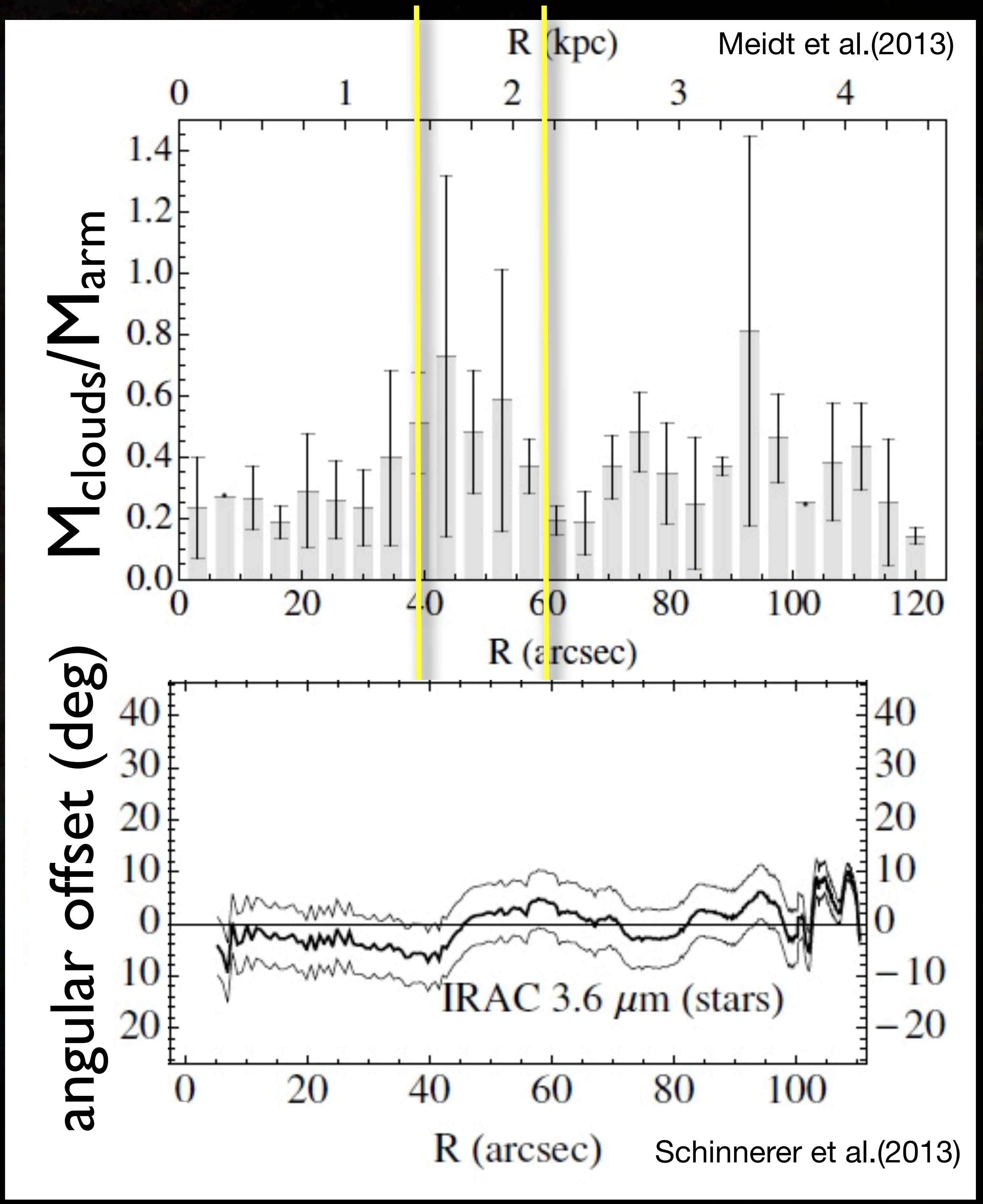
Meidt et al. (2013)


R (kpc)
0
1
2
3
4
streaming motions
I
II
III
IV
V
tangential
radial
v (km s^-1)
30
20
10
0
−10
−20
v_φ
v_r
streaming motions:
magnitude
σ, v_S (km s^-1)
25
15
5
v_S
σ
dispersion
0
20
40
60
80
100
120
R (arcsec)

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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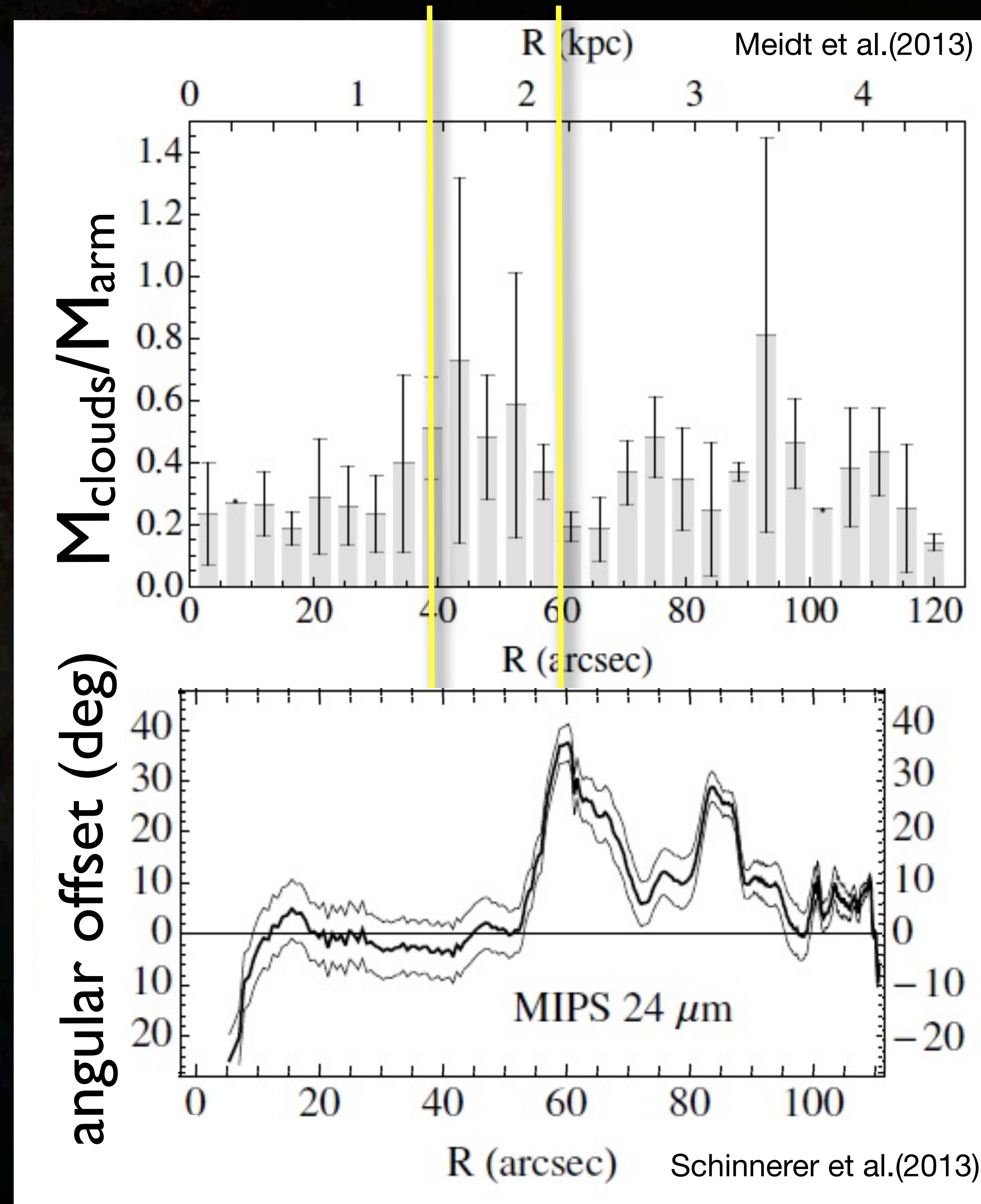

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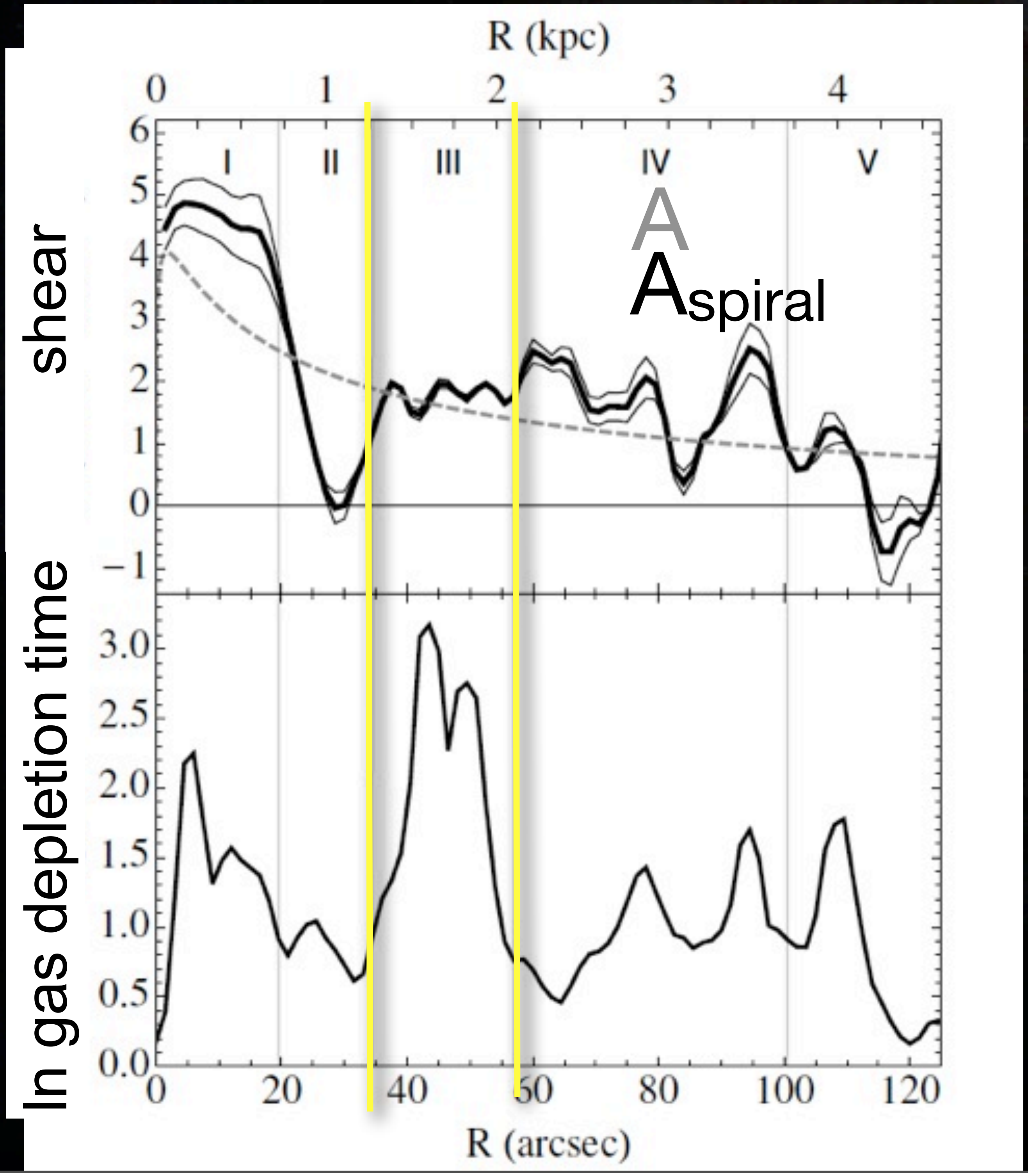

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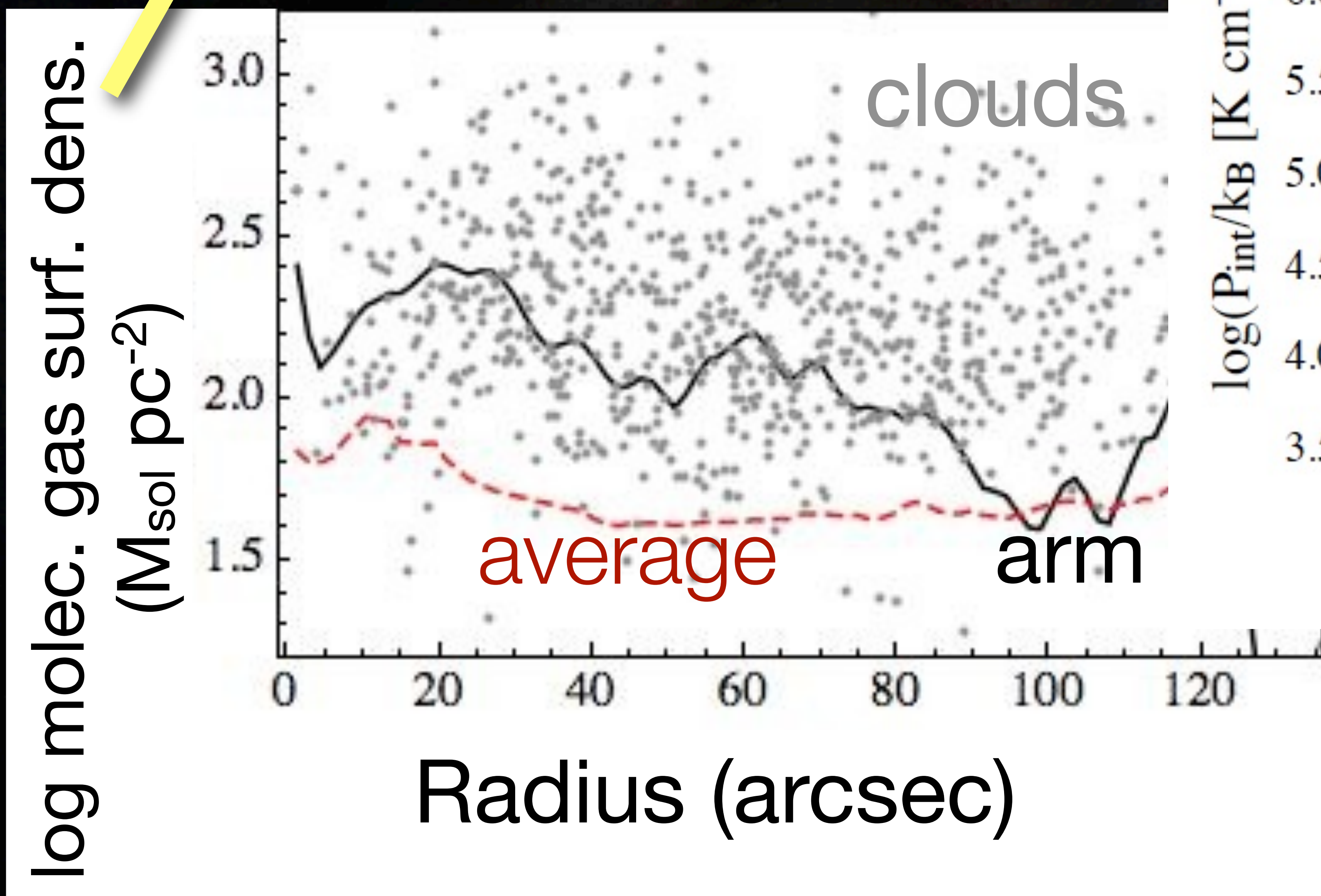
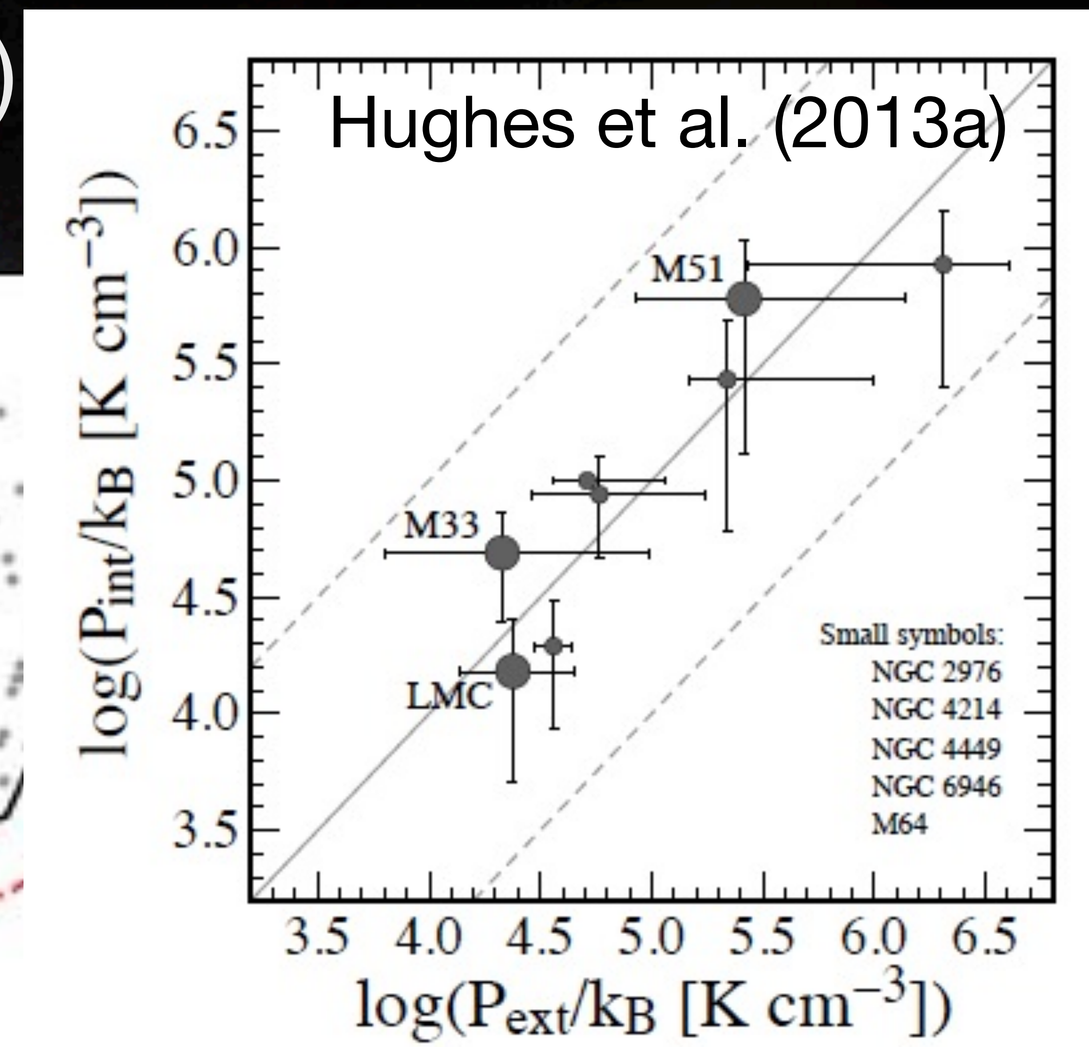
Meidt et al. (2013)

Pressure Stabilization

prop. to log (Pressure) (P~GΣ^2)

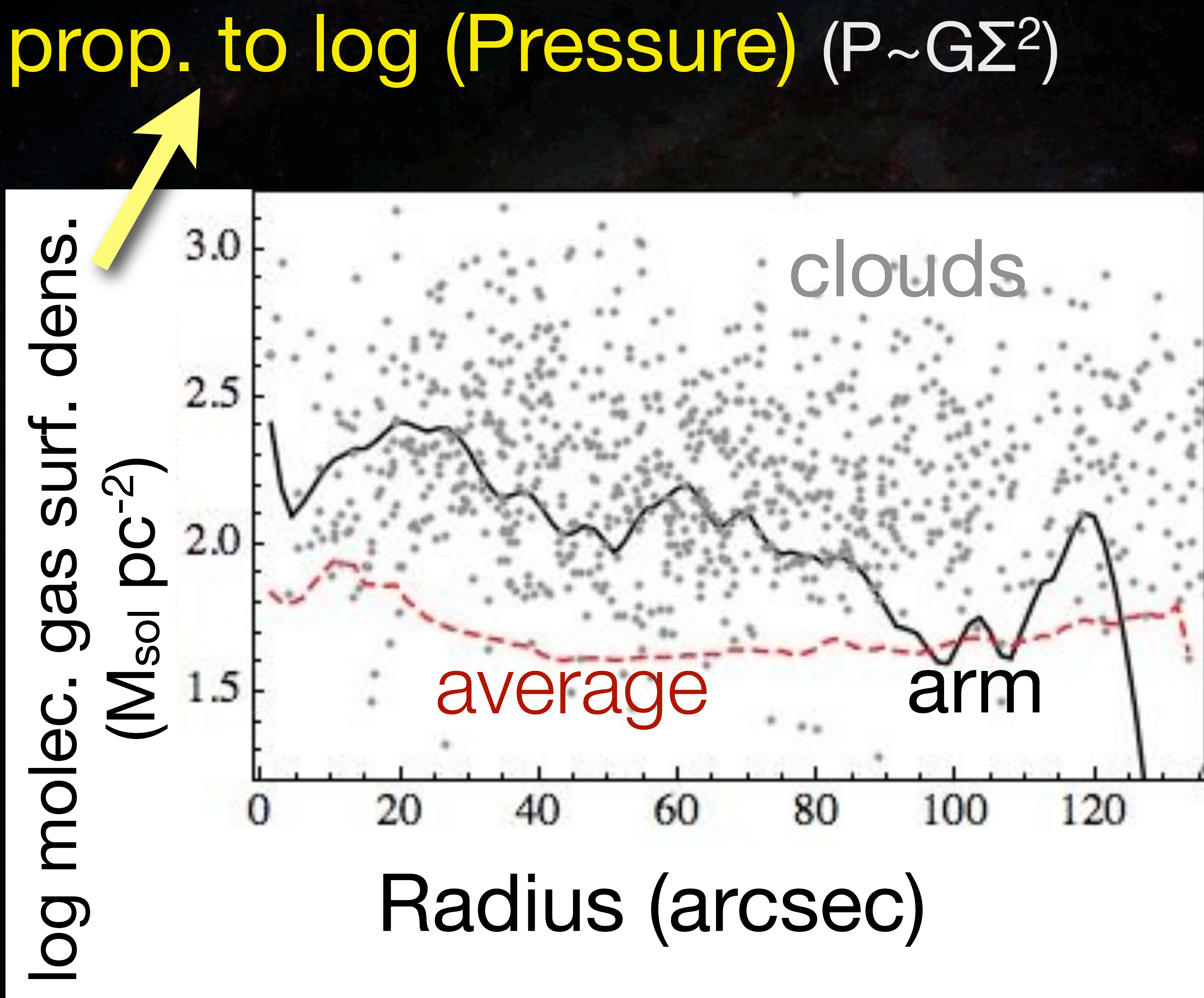




surface pressure important

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

Pressure Stabilization



ambient P comparable to internal cloud P

cloud surface pressure important

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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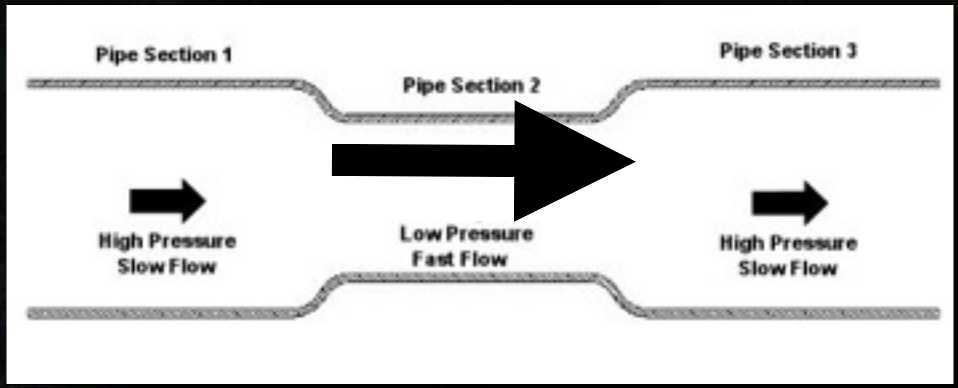
clouds in motion in arm:

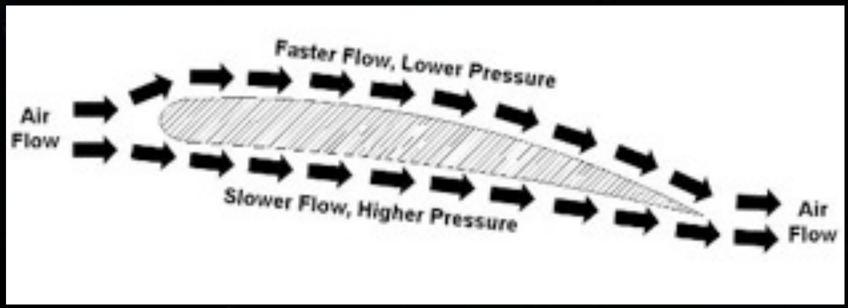
1). **reduced surface pressure** (Bernoulli)

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

2b). reduced collapse-unstable fraction

3). **lower SFE**





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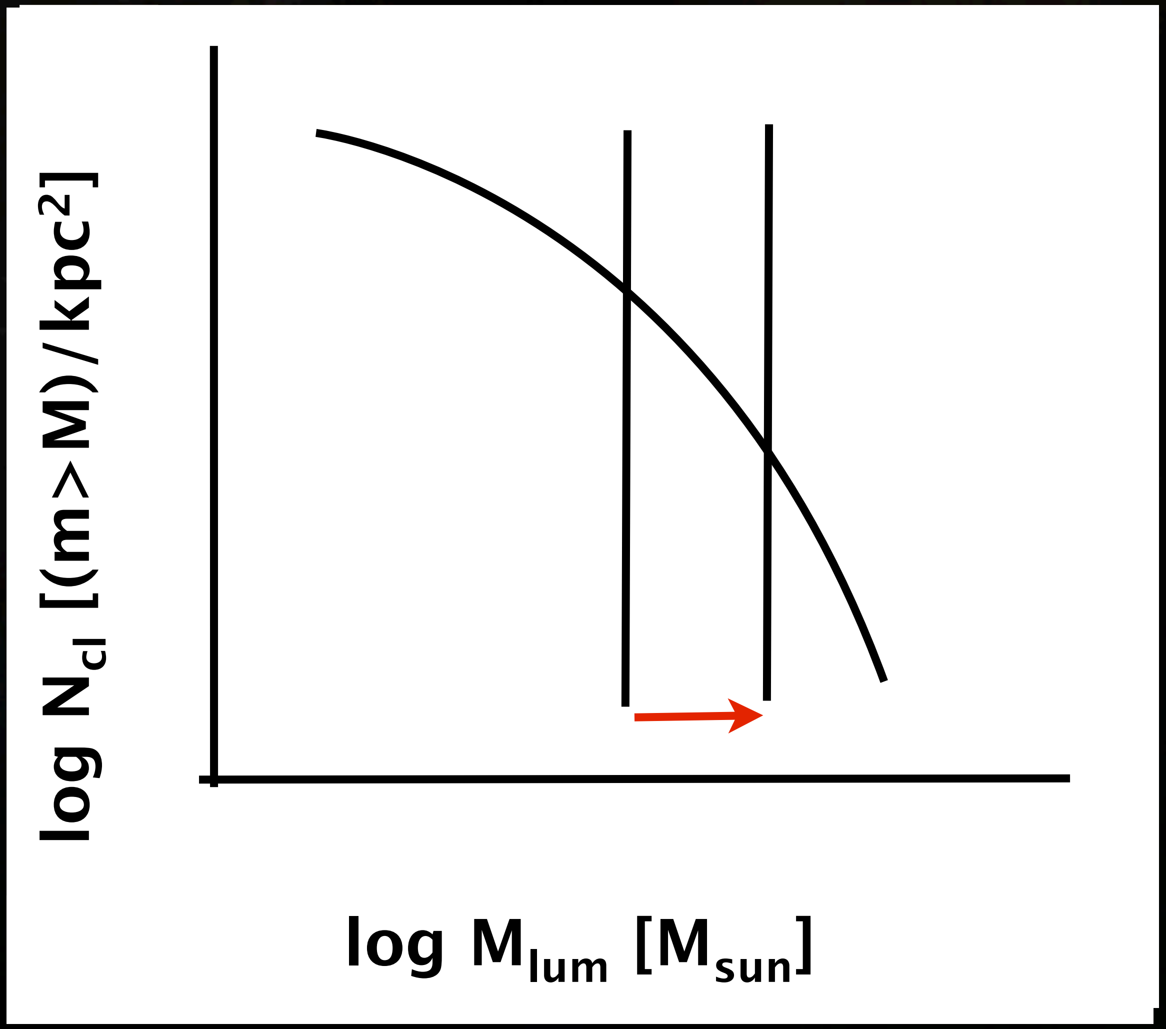

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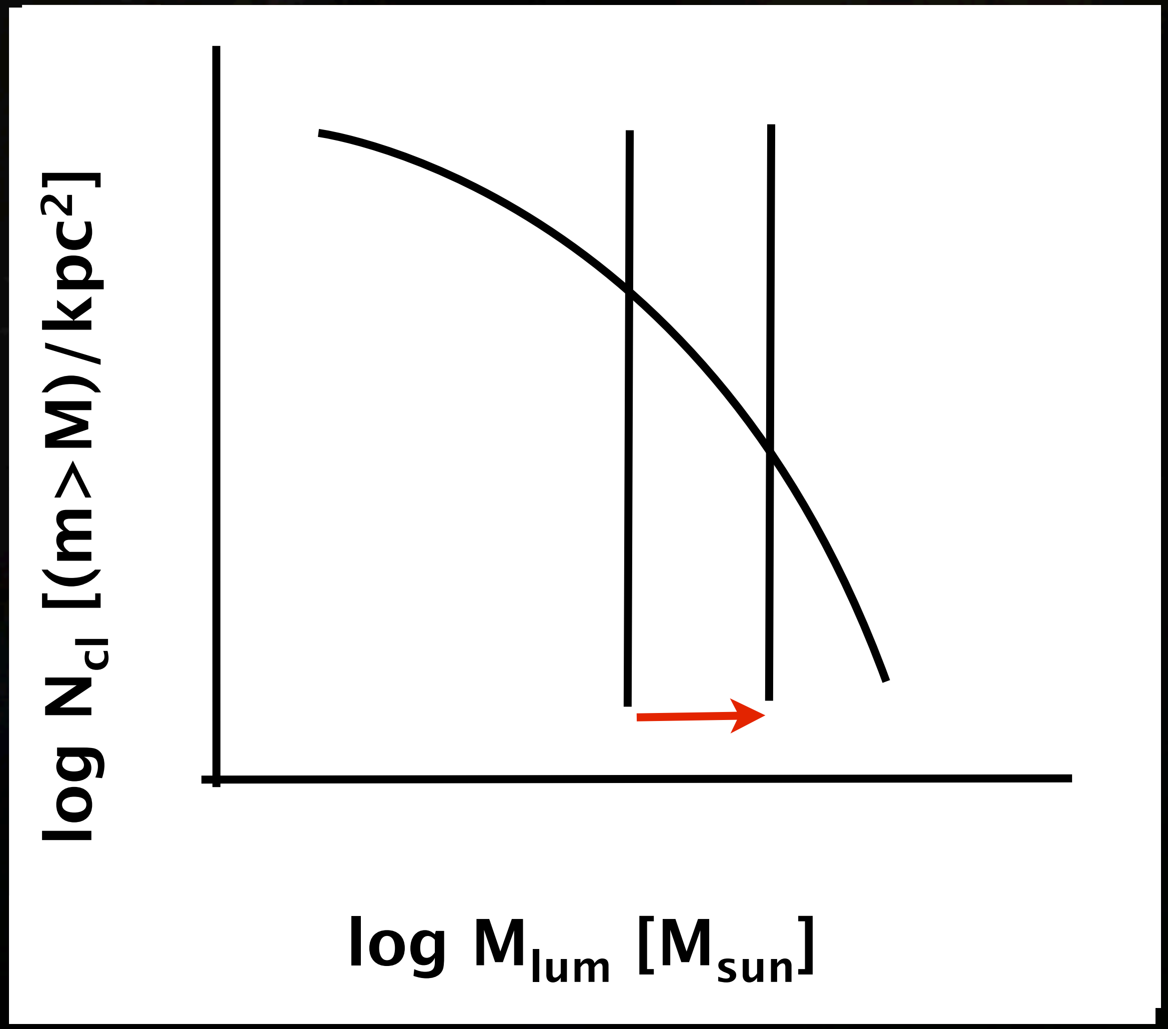
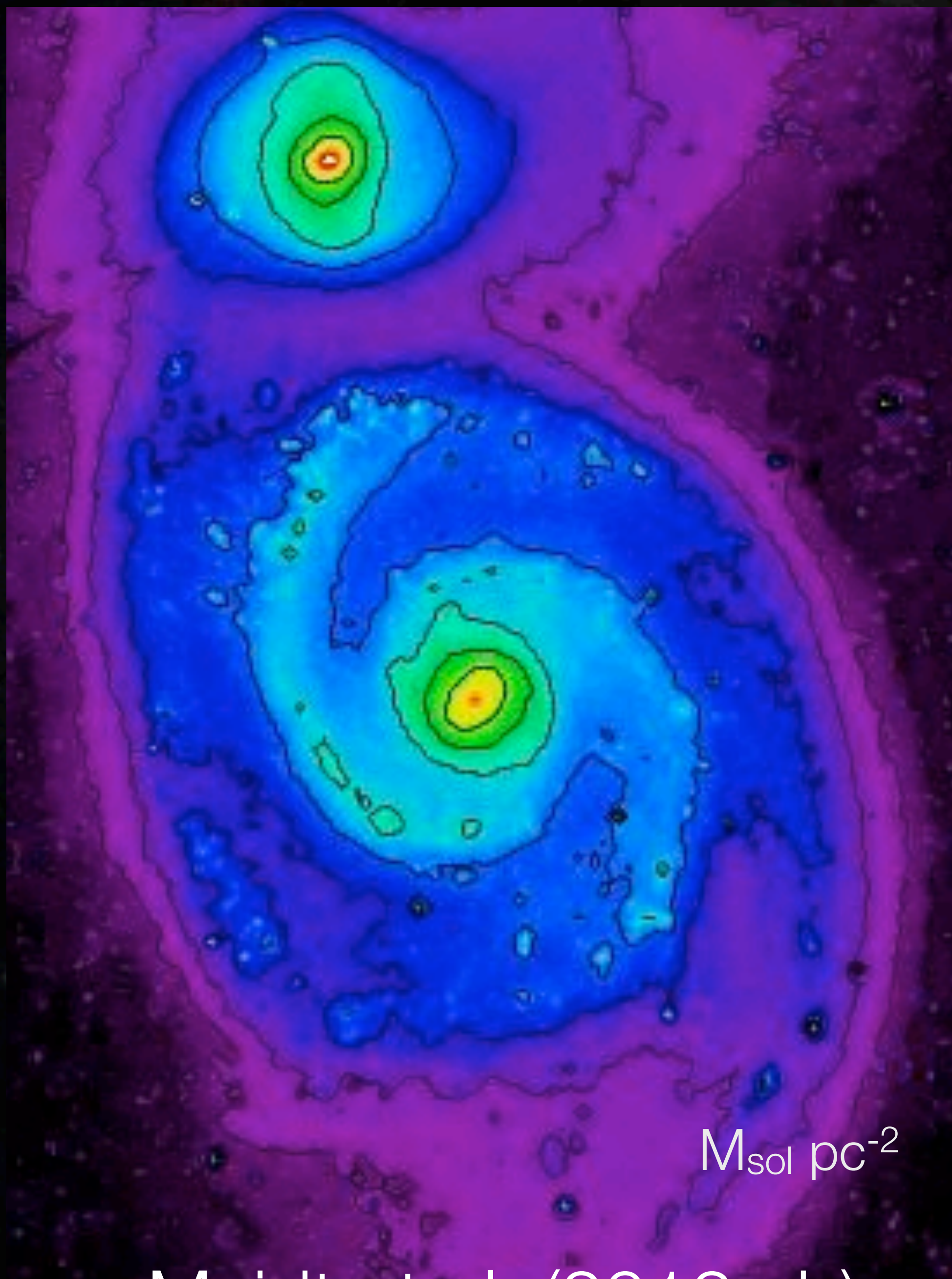
for $dN/dM \propto M^{\Upsilon}$



non-circular gas motions: *Present-day Torques*



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

S^4G
stellar
mass
surface
density

DAGAL
Detailed Anatomy of GALaxies

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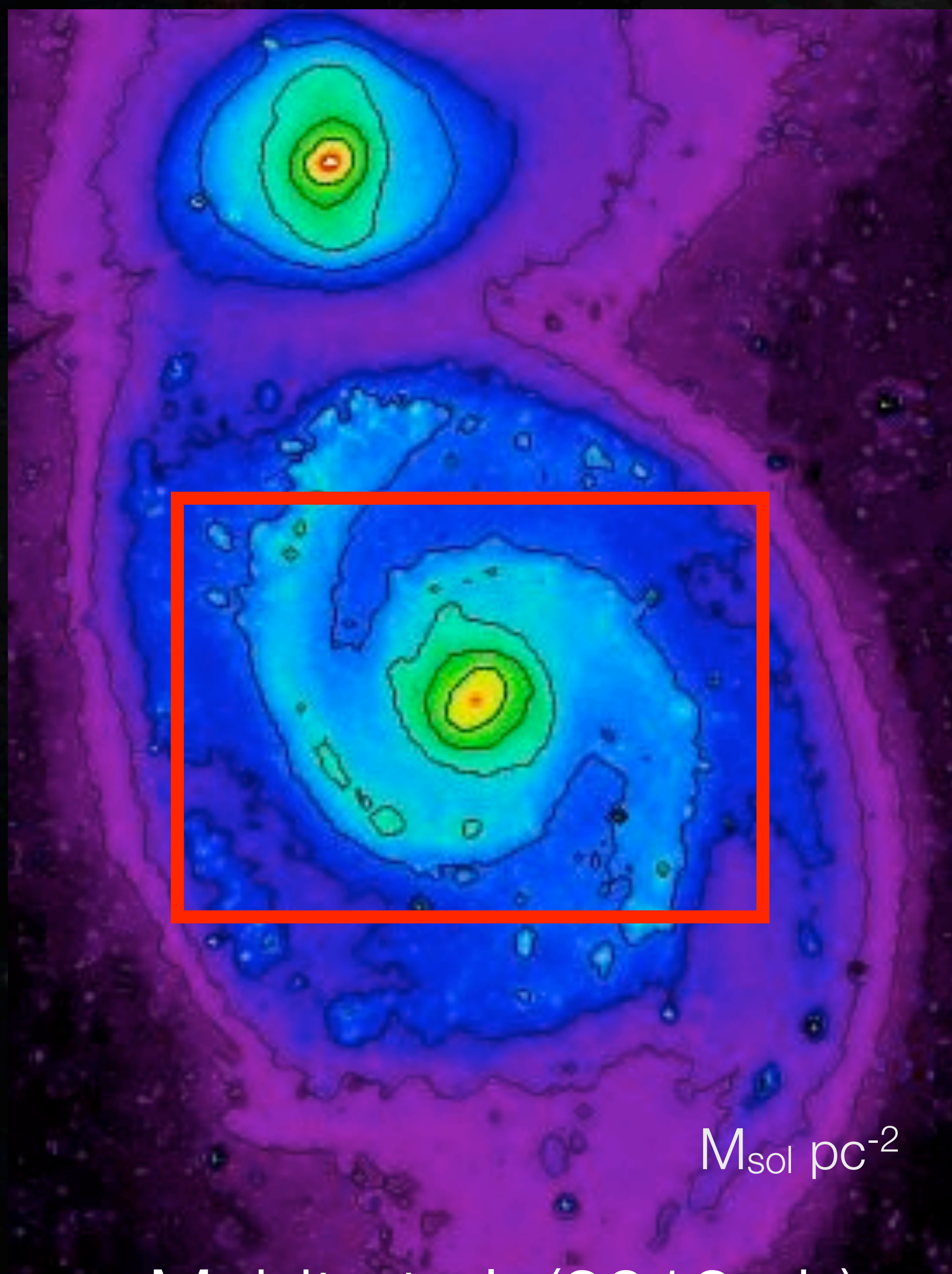

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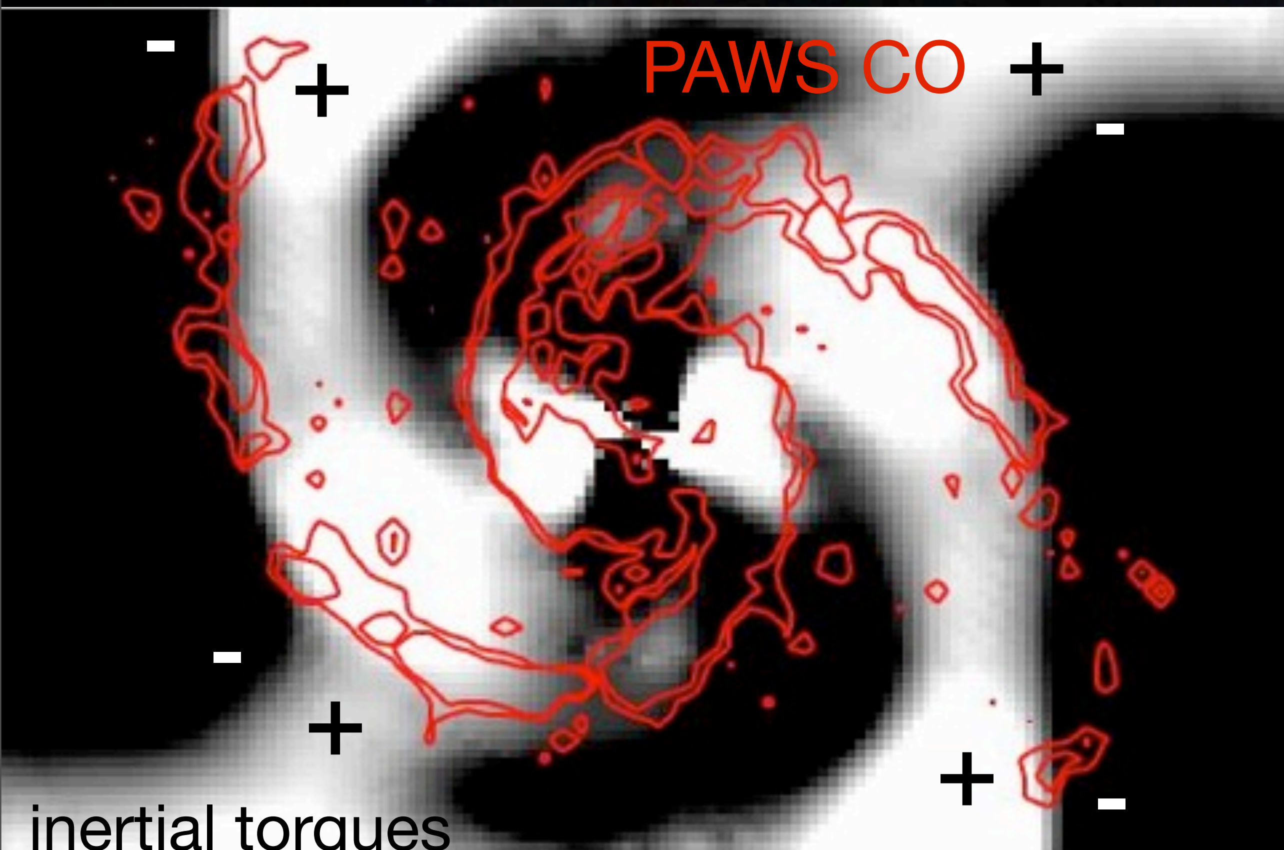
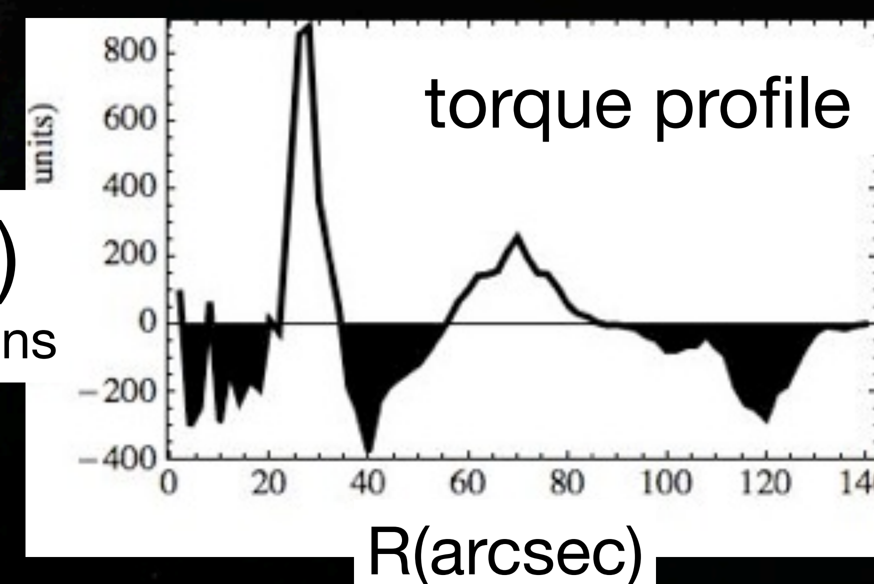


$R \times \nabla\Phi$

outflow inflow

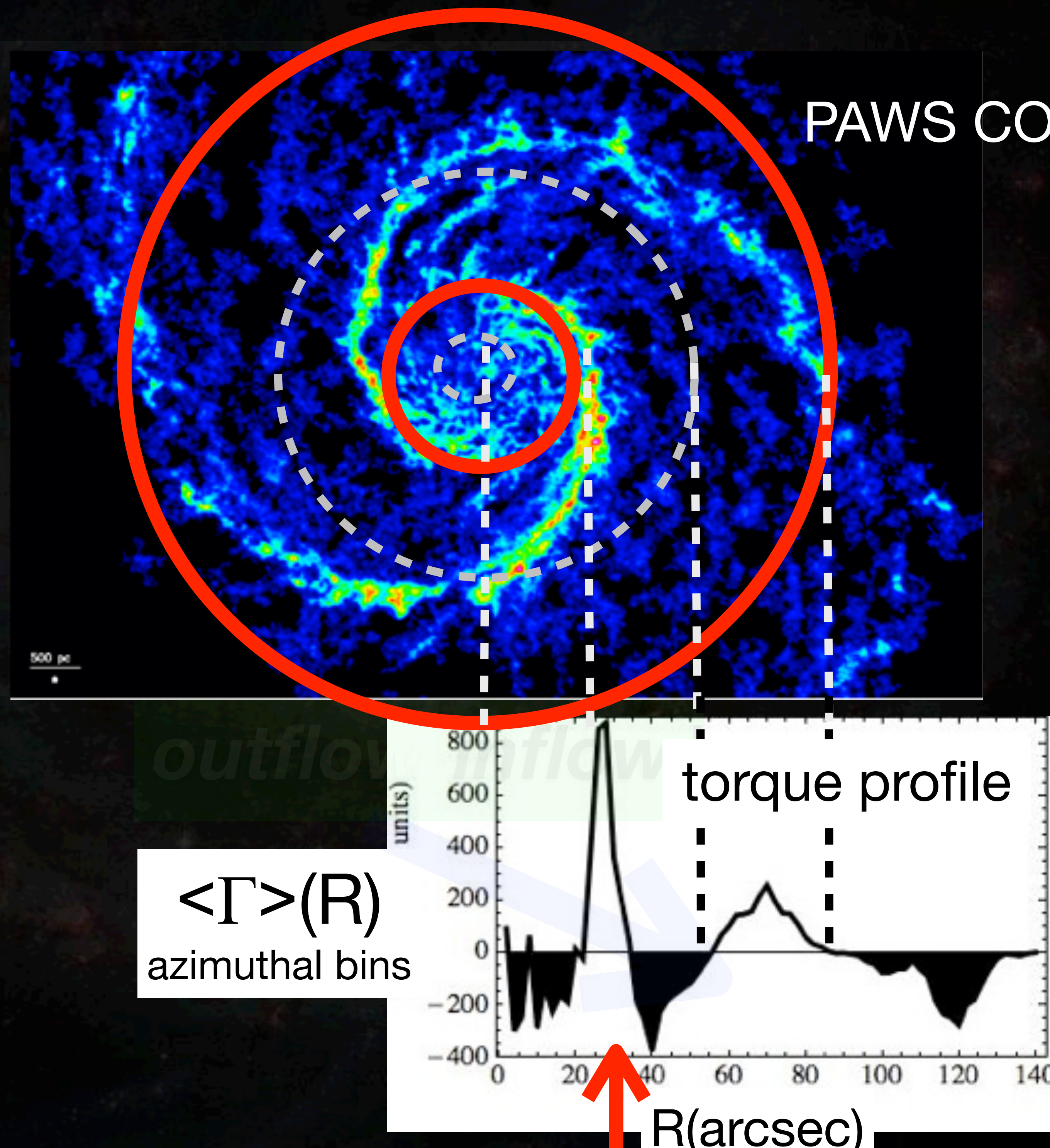
$\langle\Gamma\rangle(R)$

azimuthal bins



Radius = proxy for environment (bar, spiral)

Present-day Torques



molecular ring

(consistent with Meidt et al. 2008)

Spiral arm Torques

from PAWS kinematics

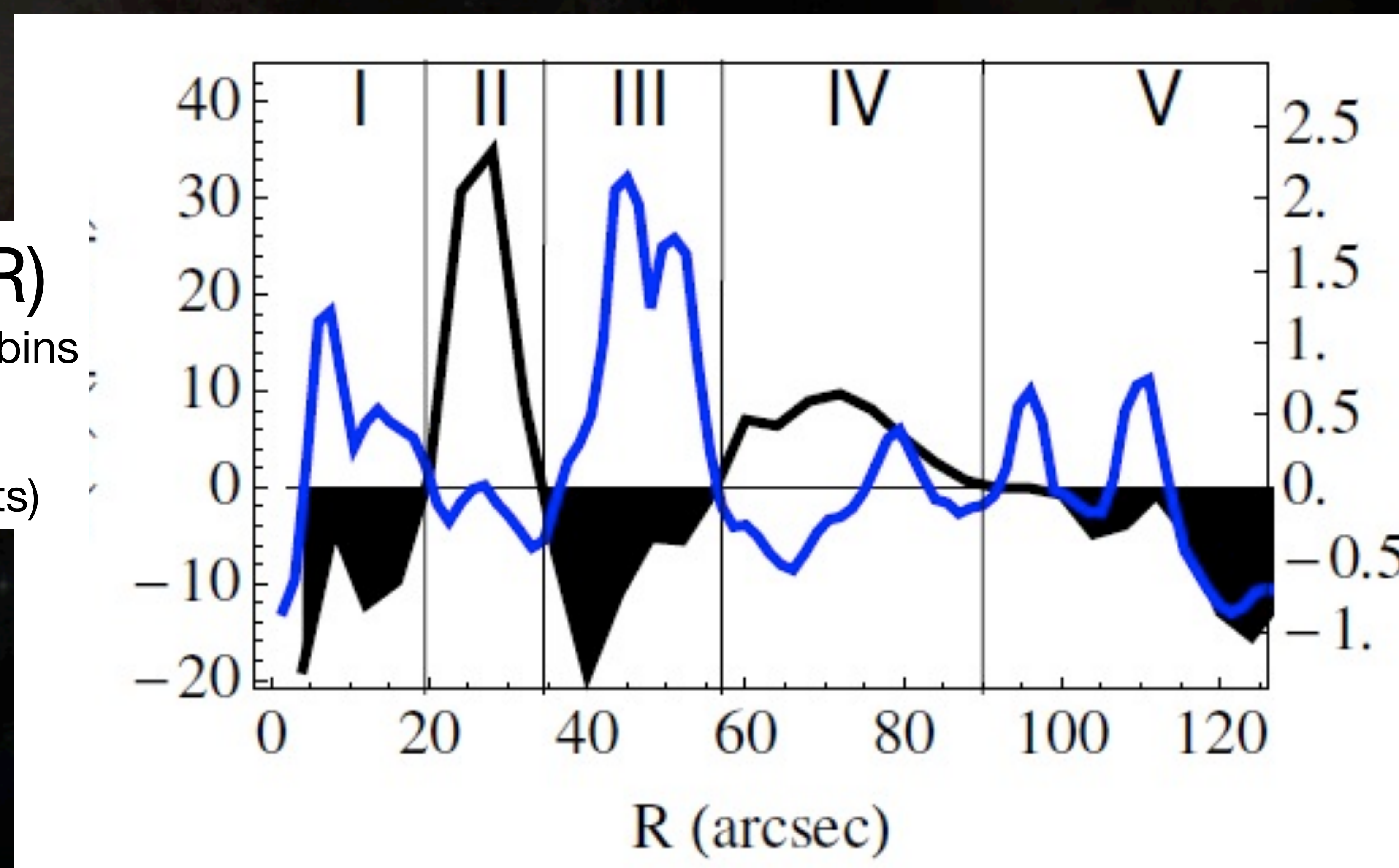
inflow=large $|V_{stream}|$

$\langle\Gamma\rangle(R)$

azimuthal bins

τ_{dep}

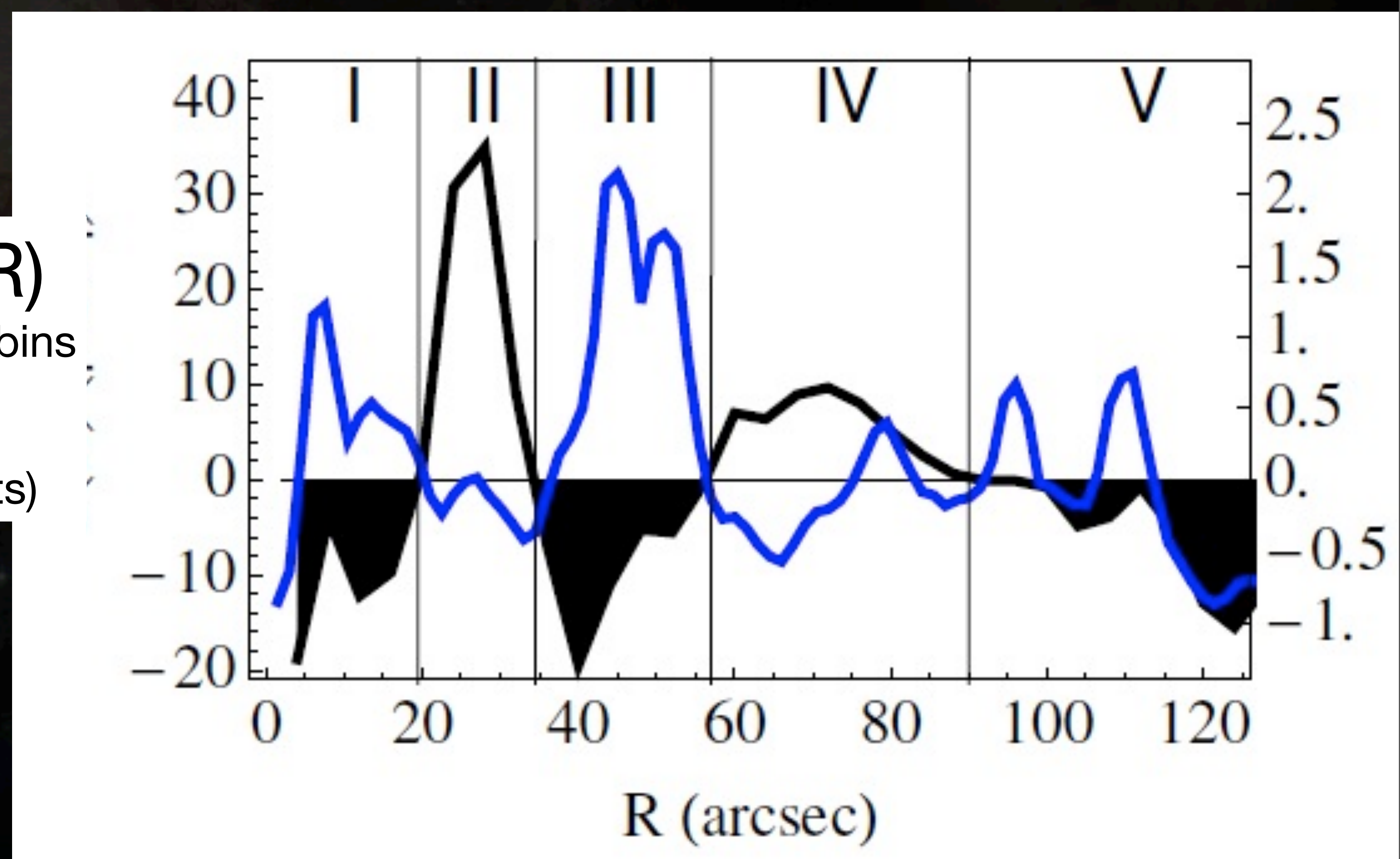
(arb. units)



Spiral arm Torques

<Γ>(R)
azimuthal bins

τ_{dep}
(arb. units)



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inflow=large |V_{stream}|

cf. Knapen et al. (1992)

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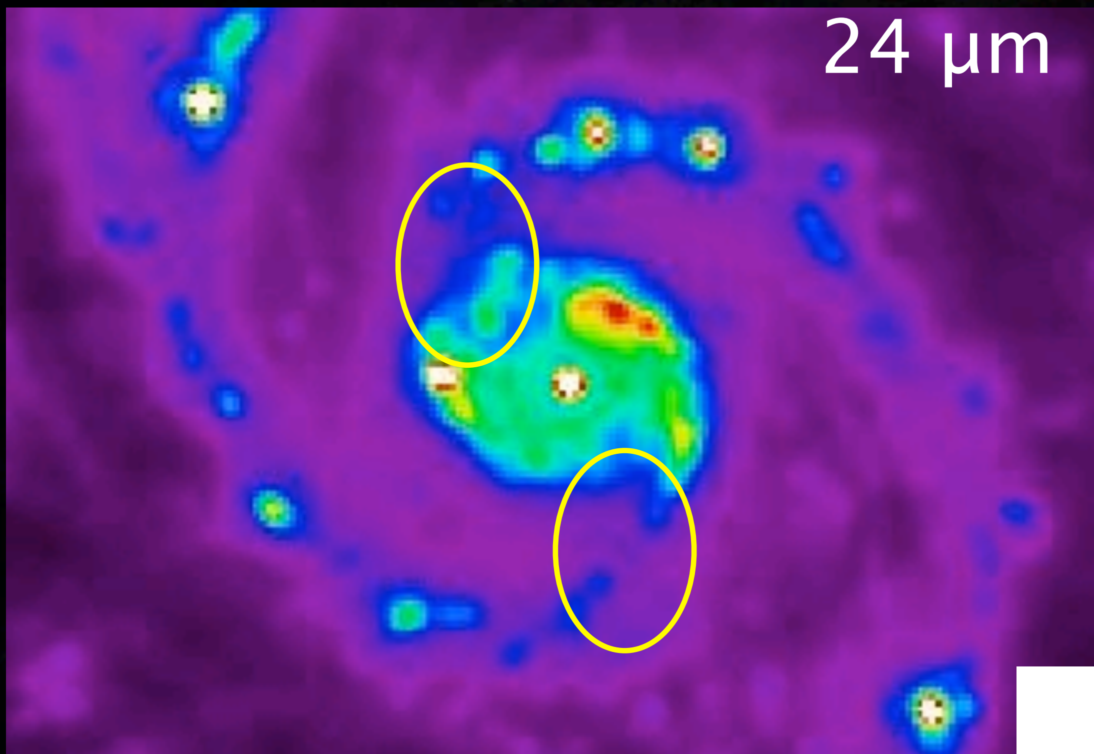

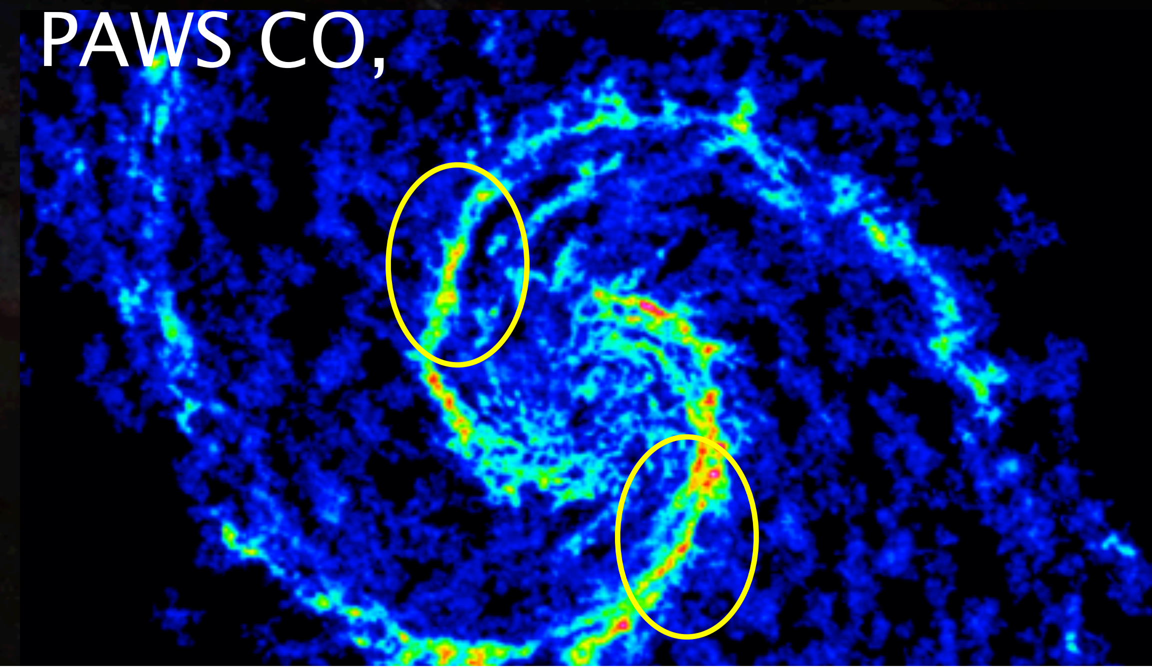

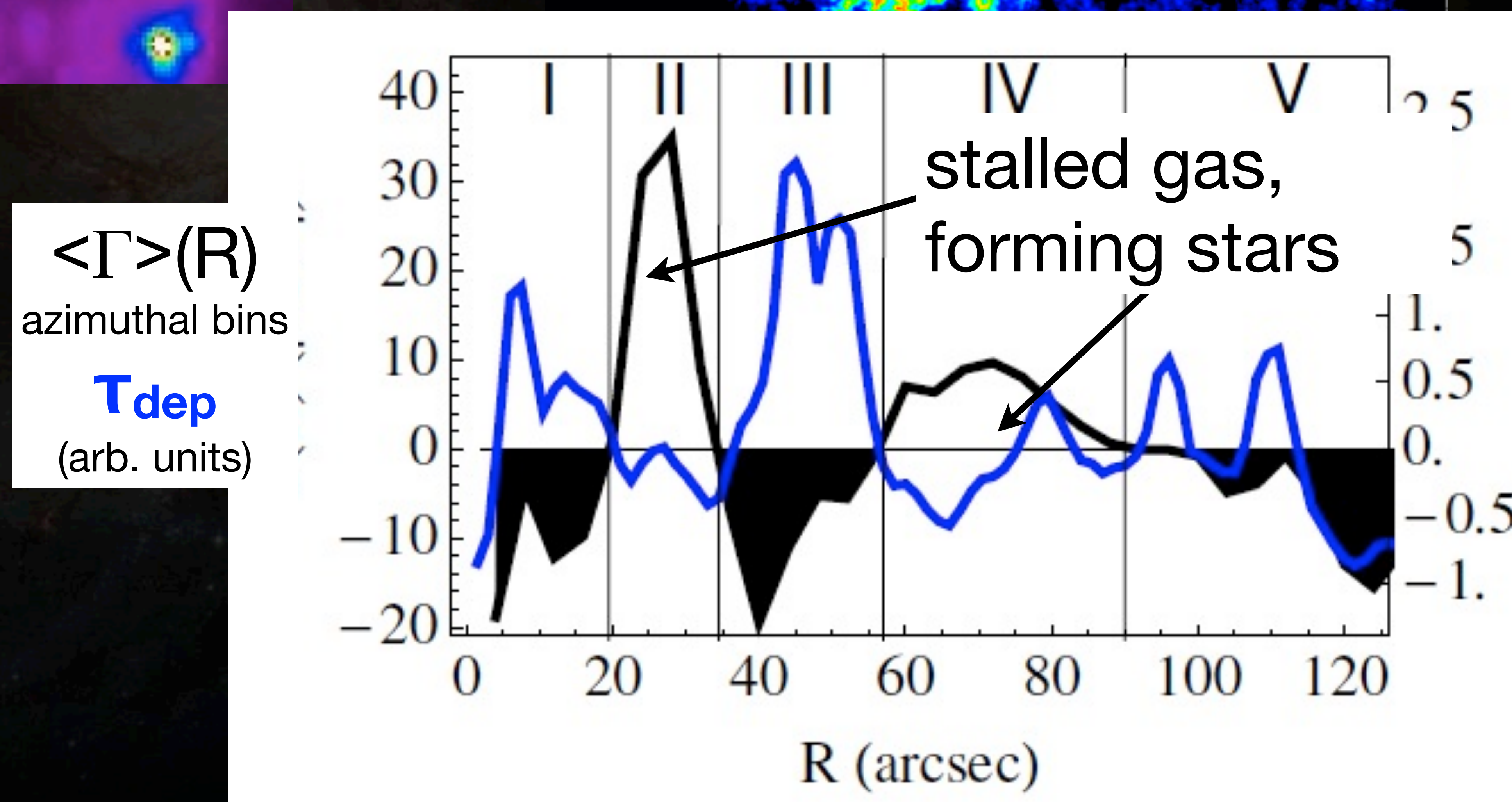

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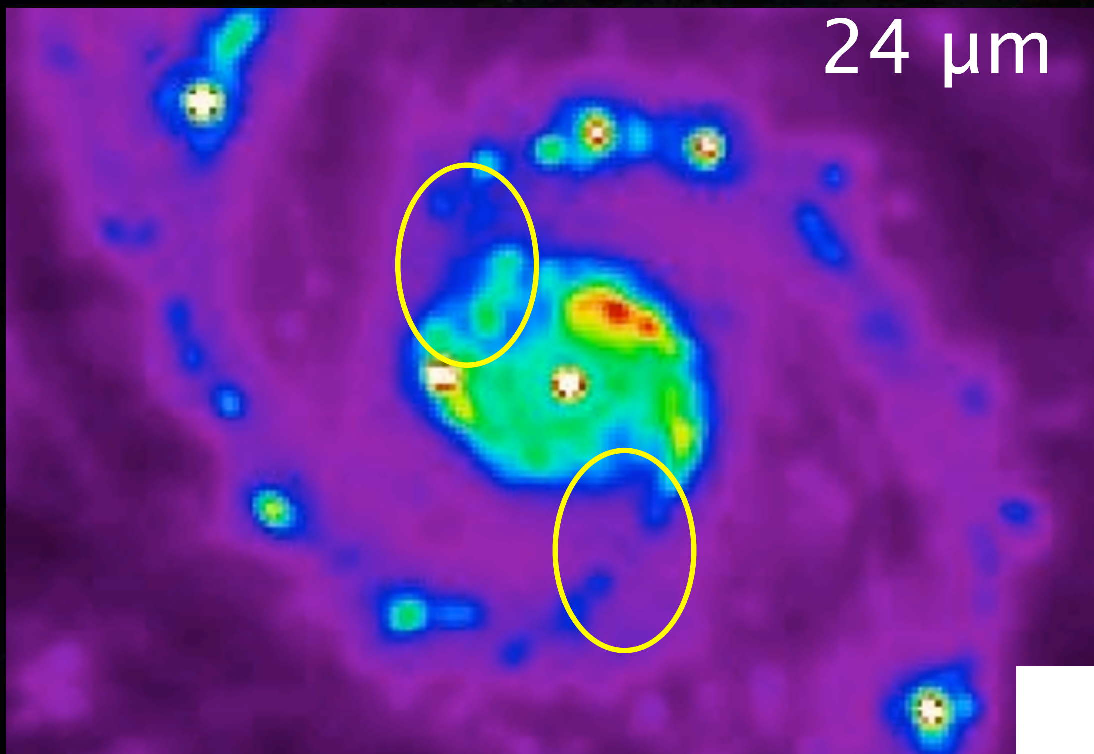

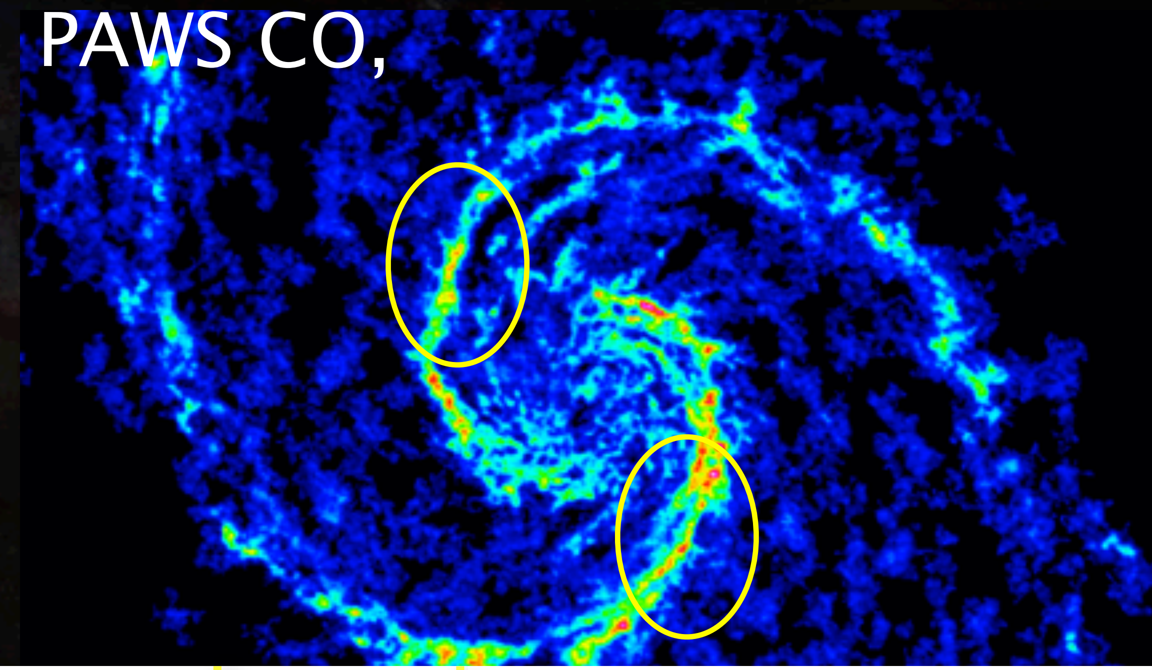

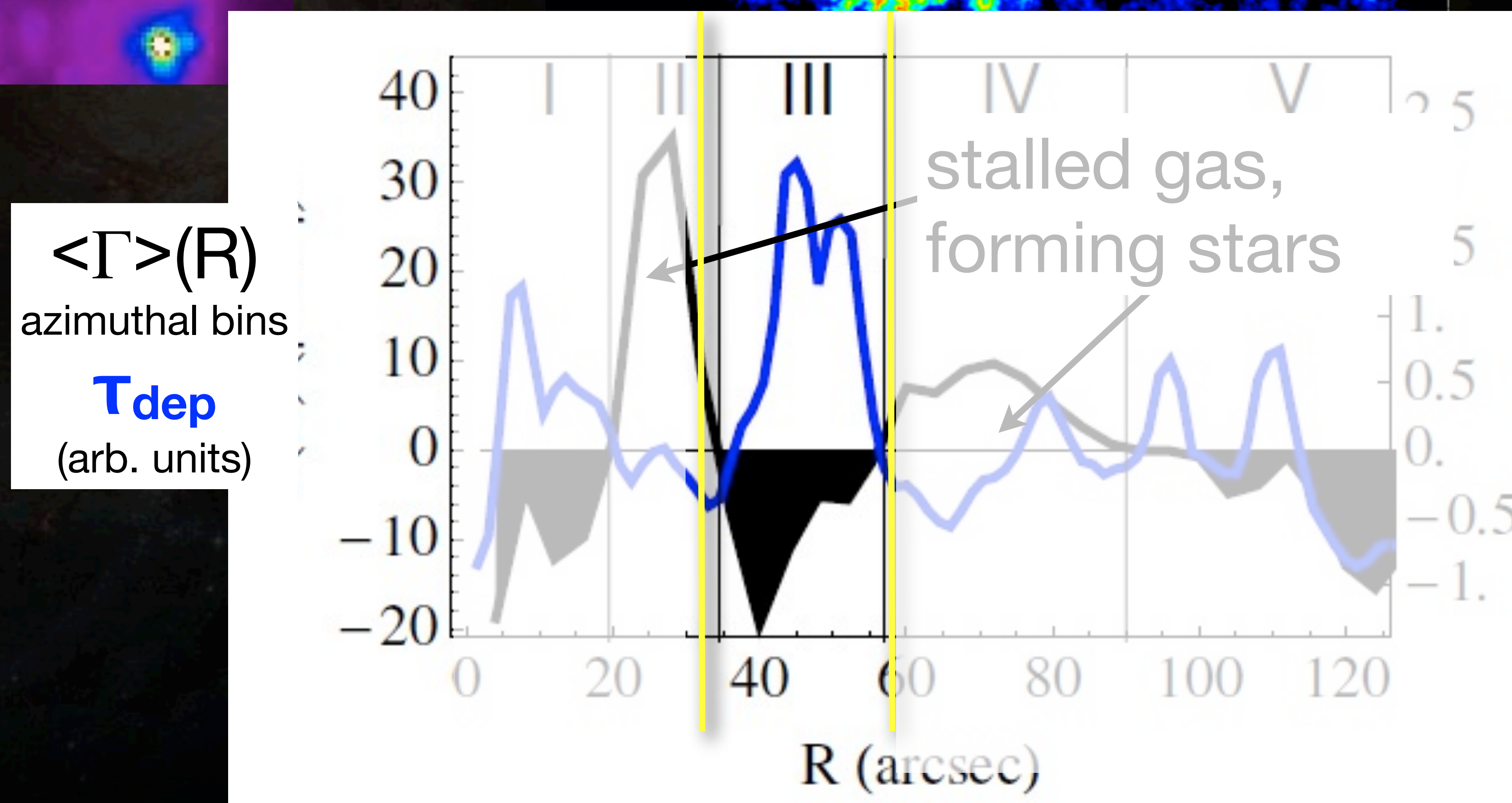

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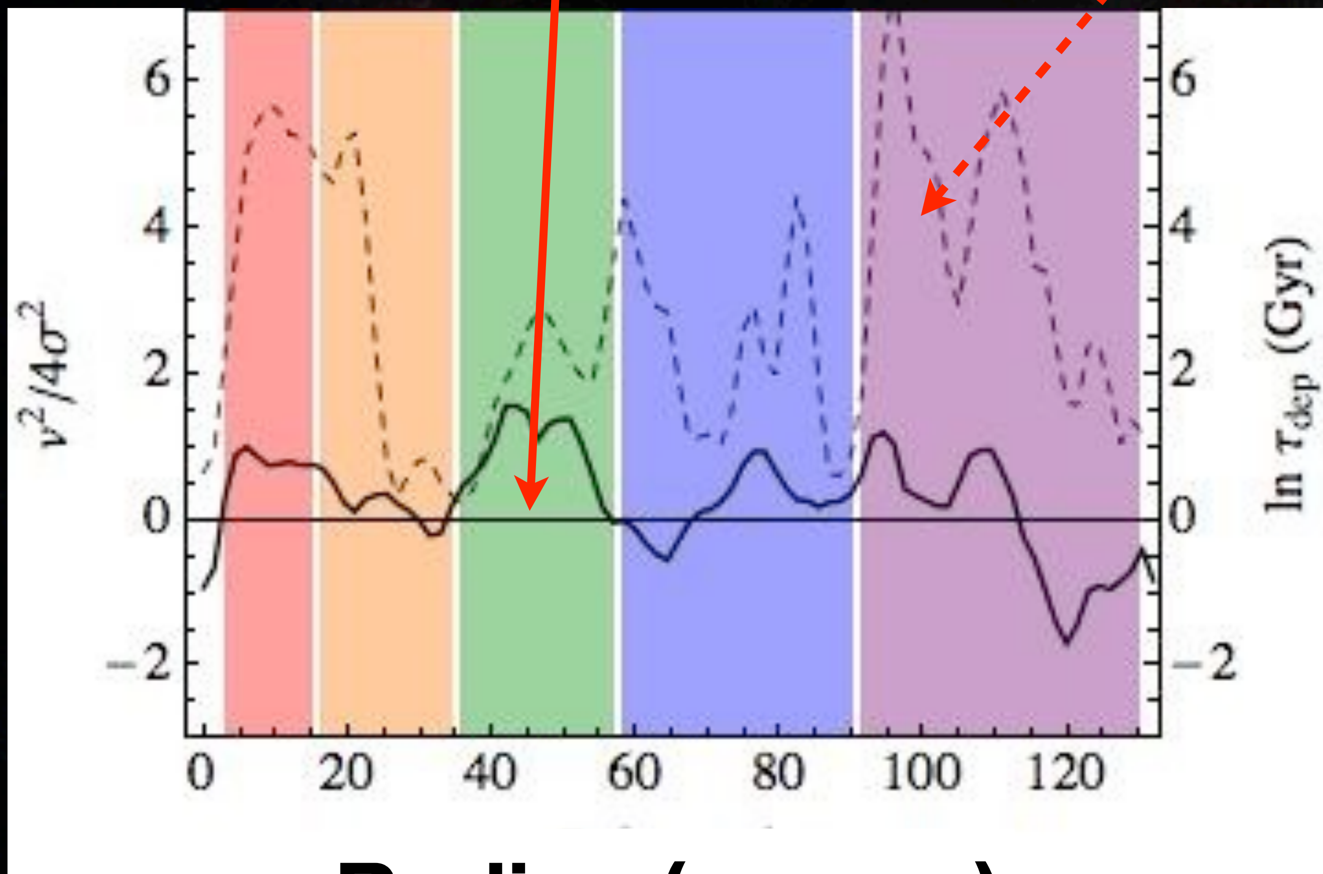
cf. Knapen et al. (1992)

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

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



Radius (arcsec)

fit predicts

slope of mass spectrum γ

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

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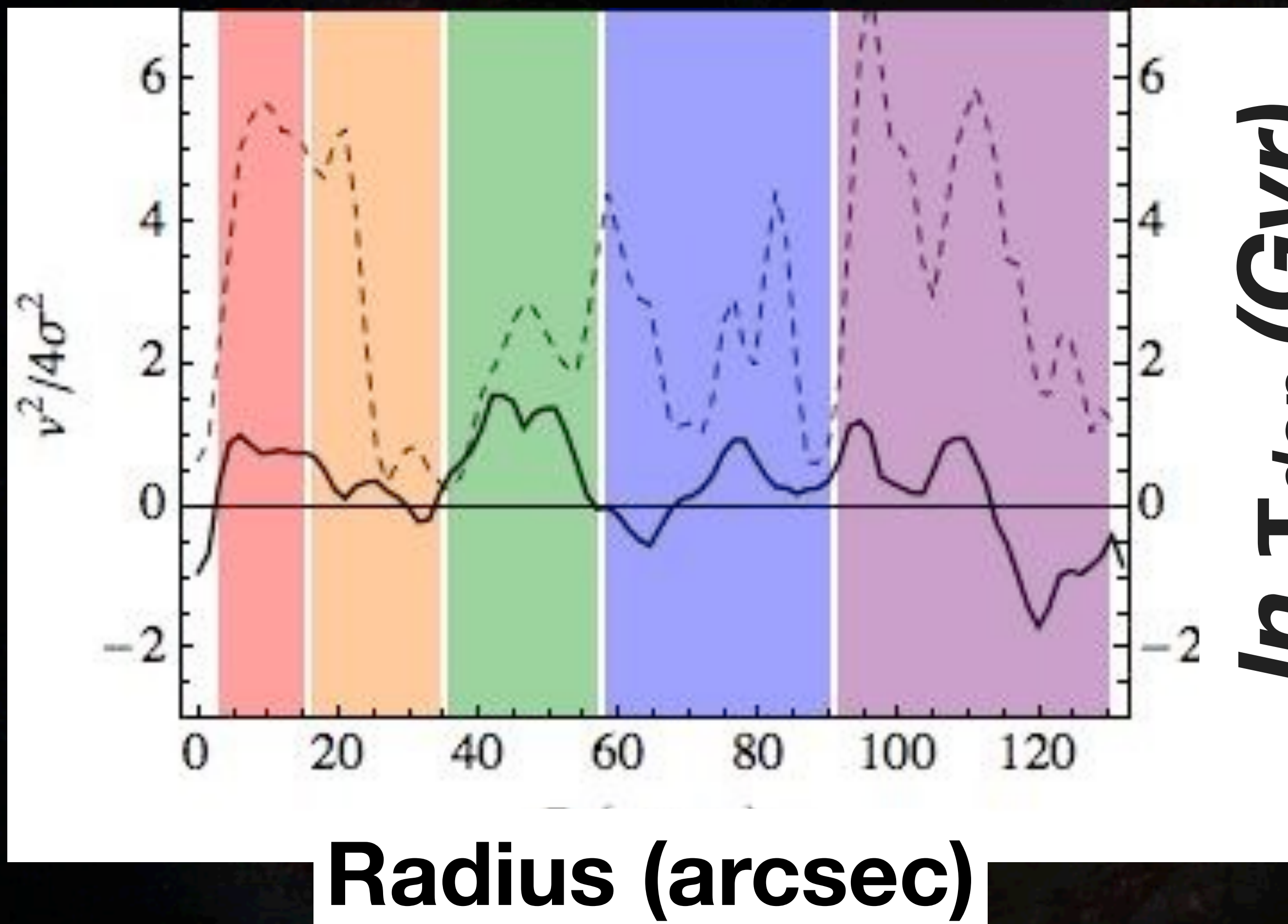

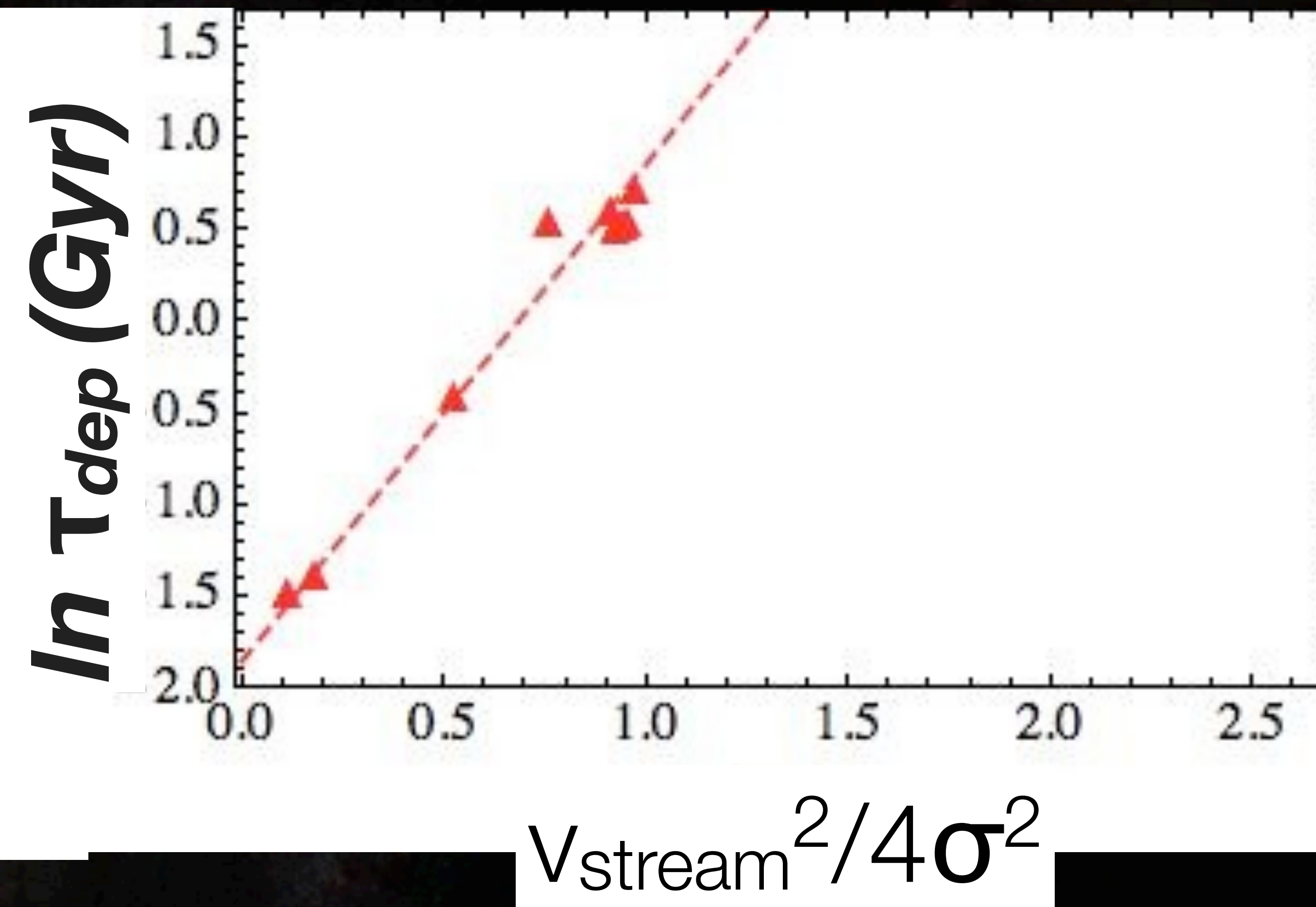

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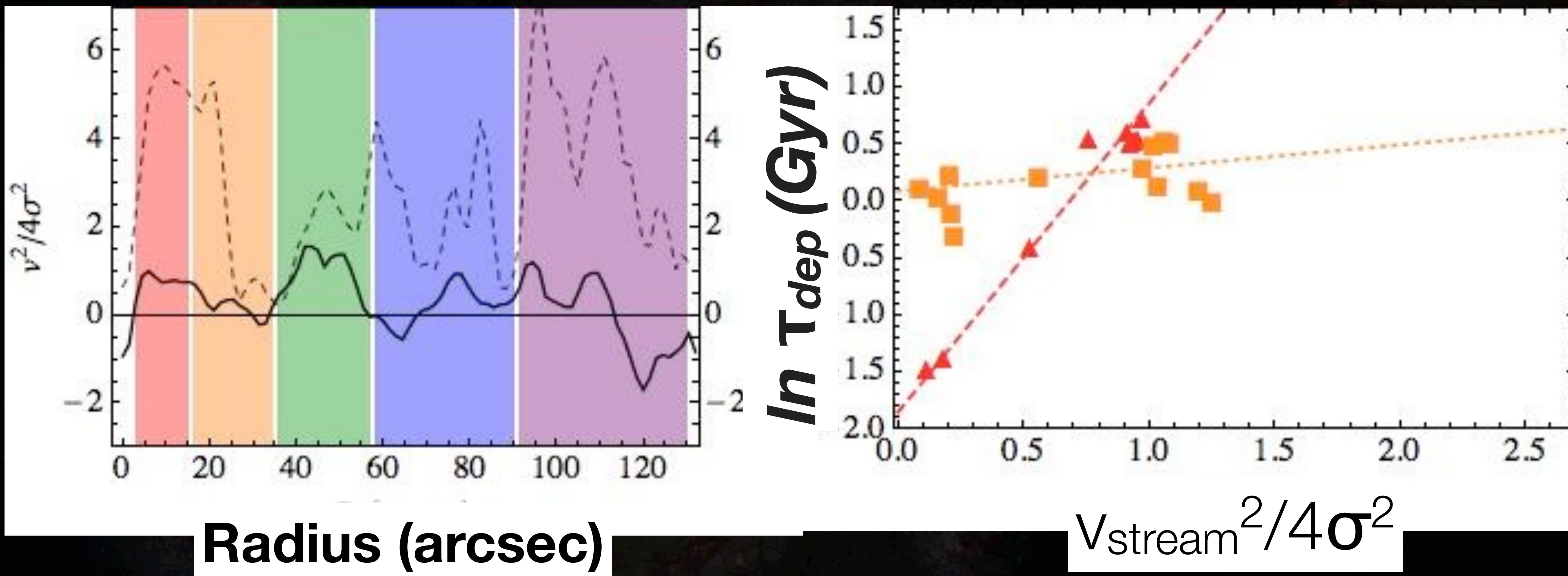

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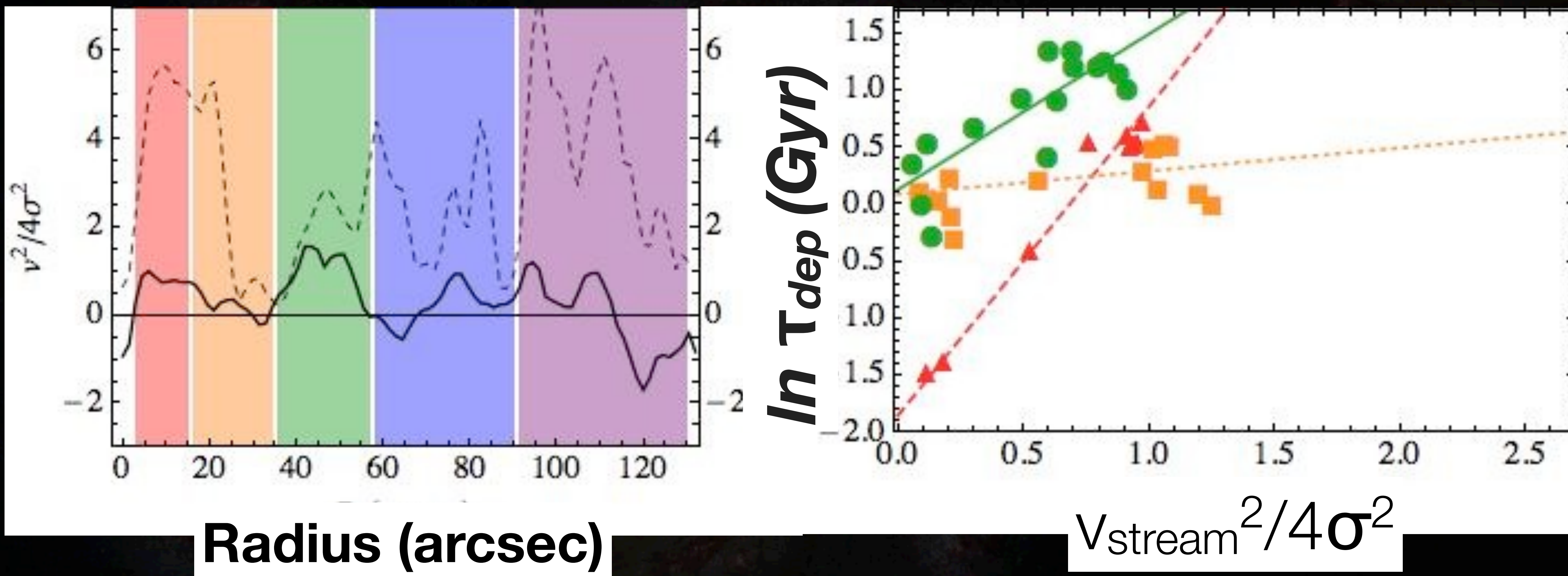

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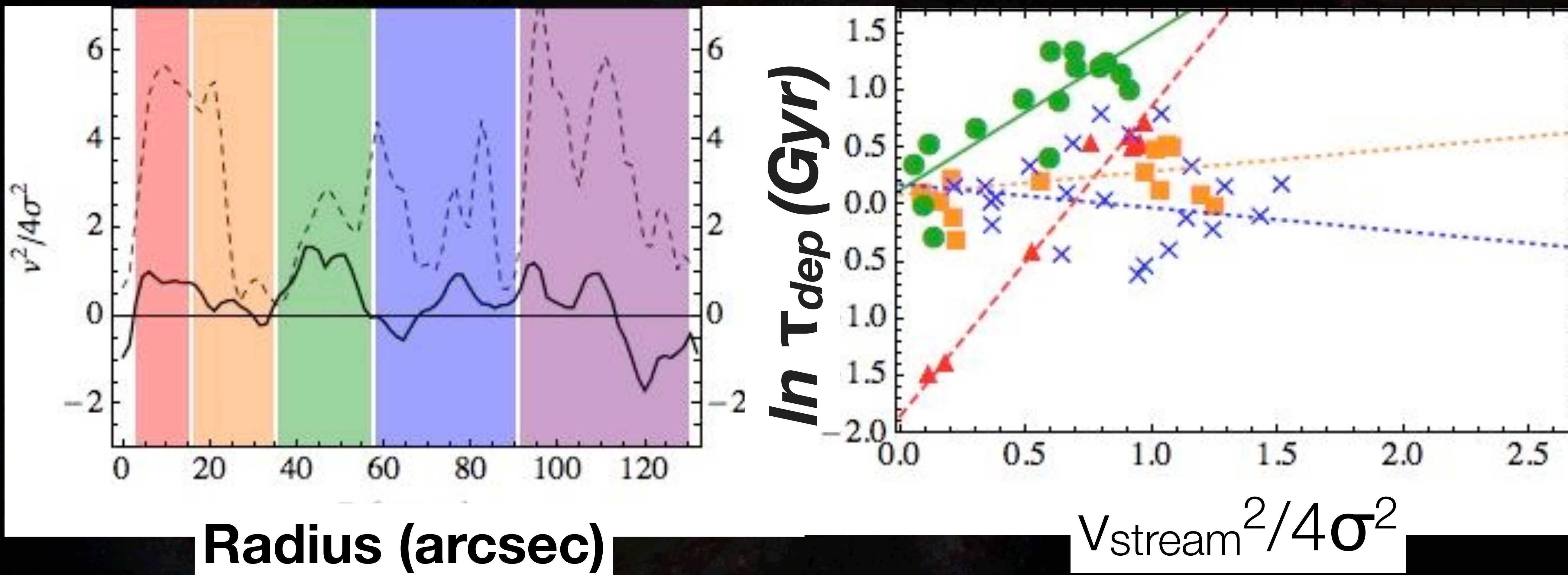

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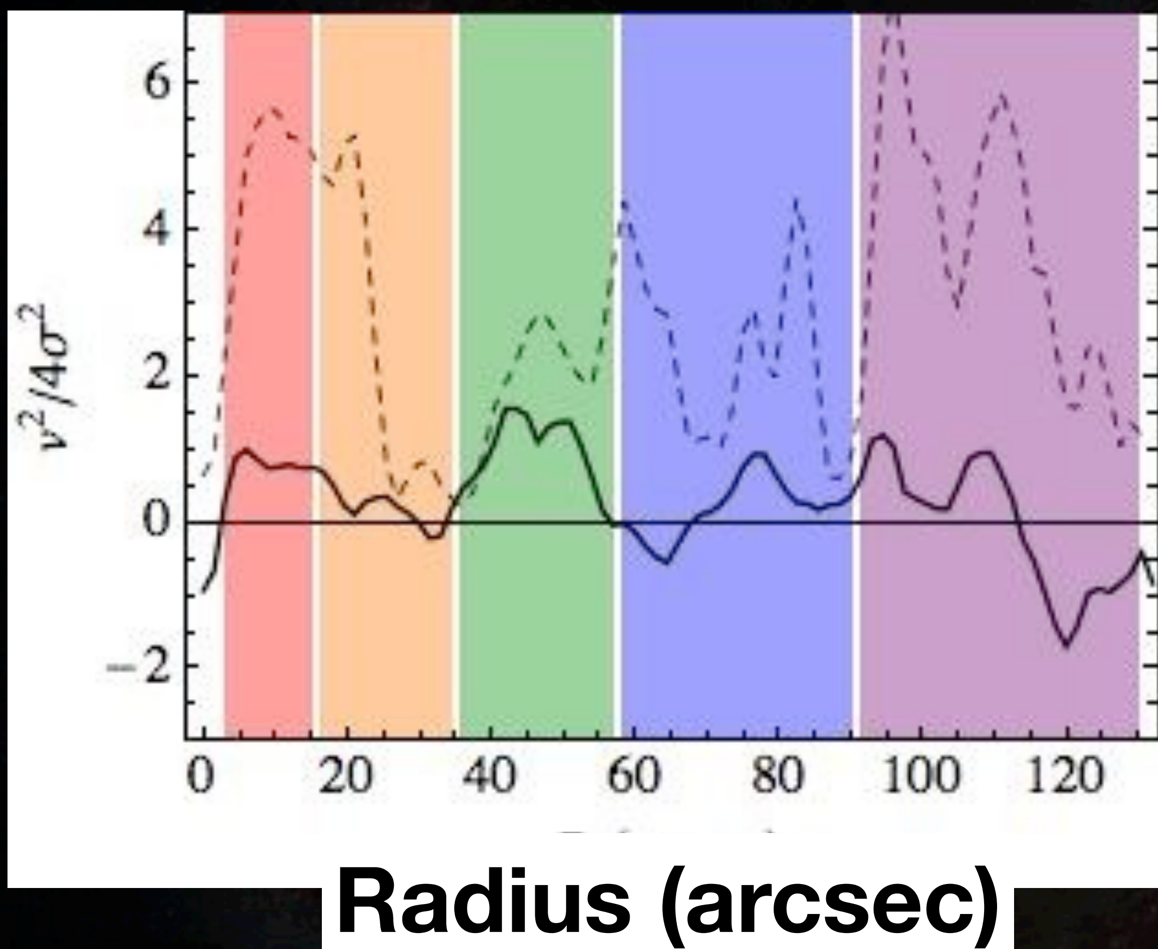

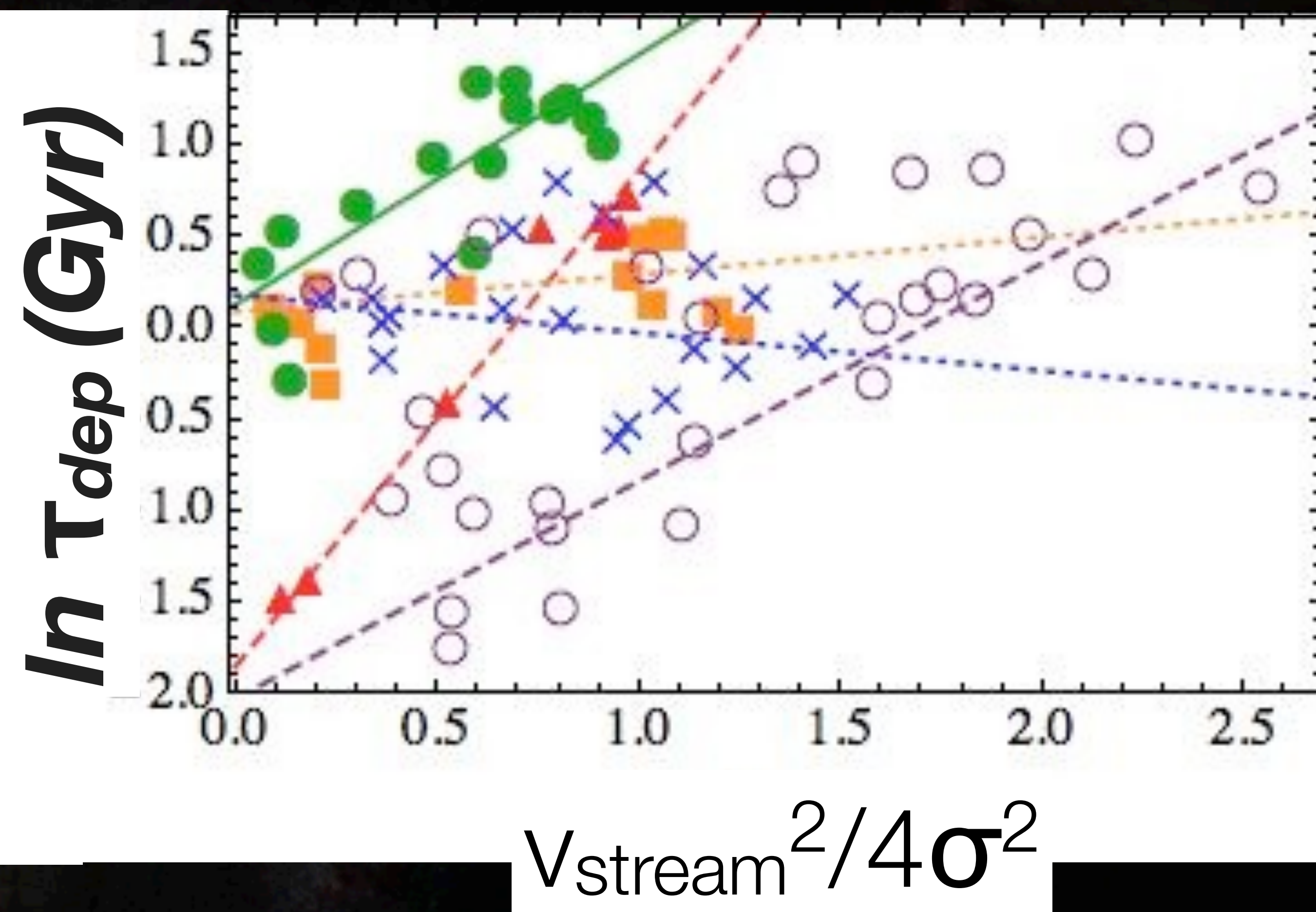

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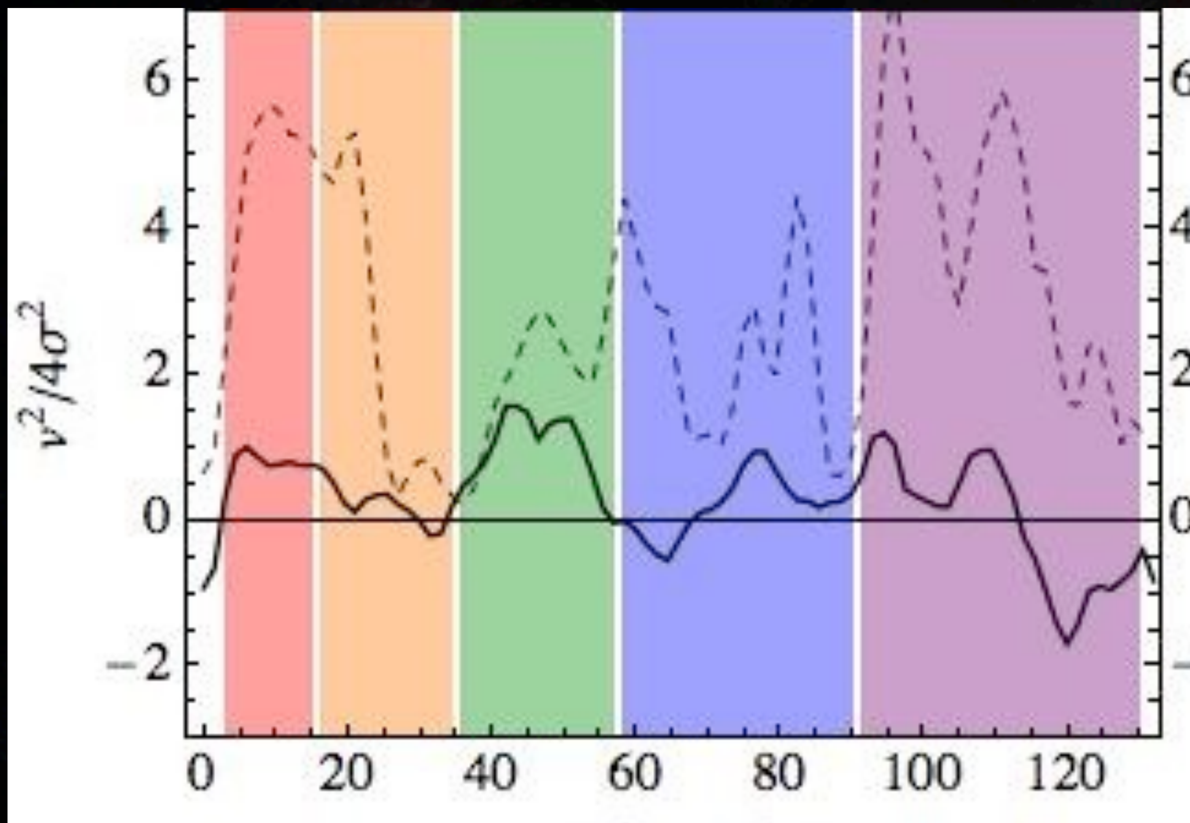

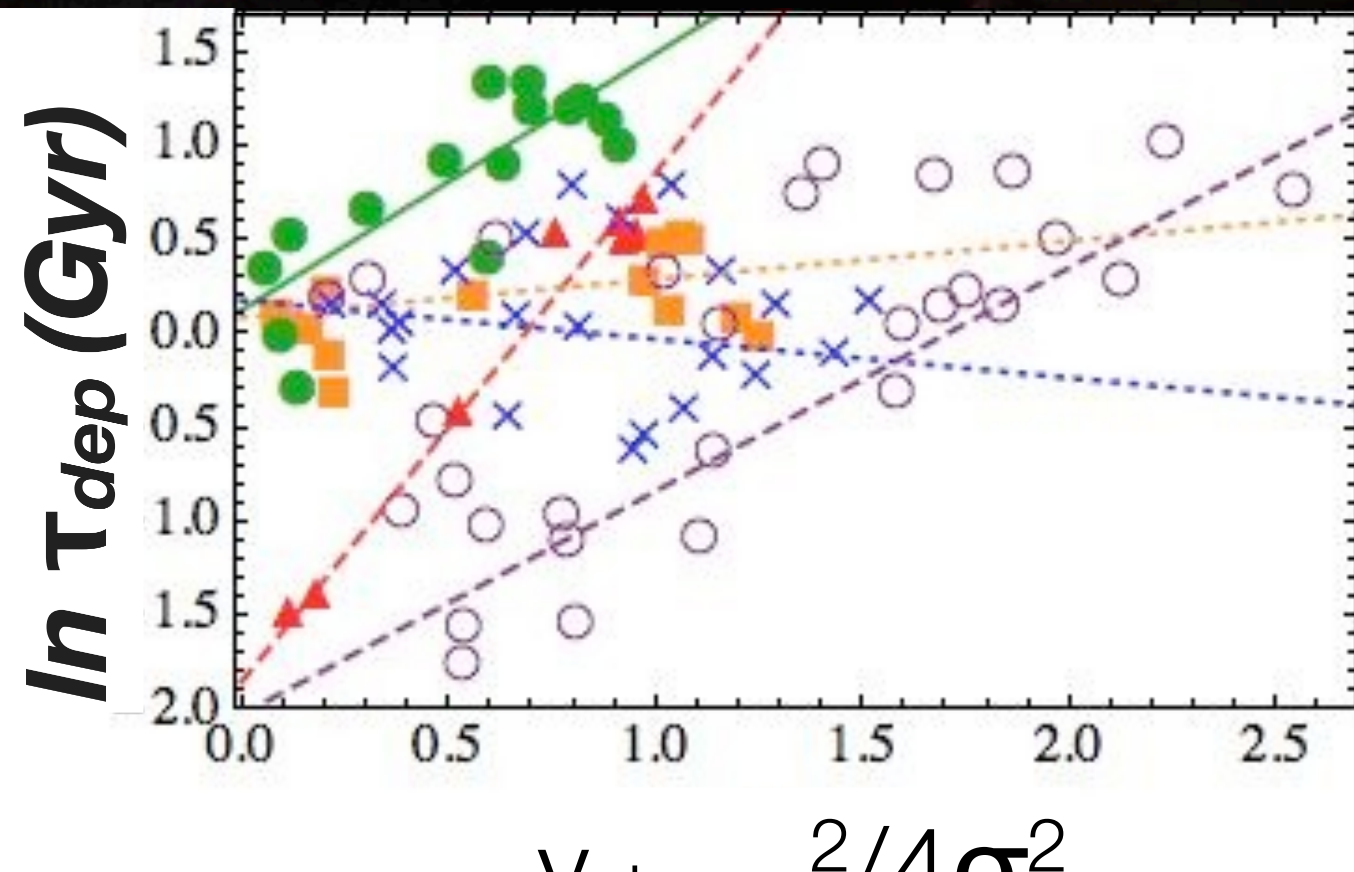

fit predicts

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)

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

$\langle\tau_{dep}\rangle = 2.5Gyr$

~ ‘universal’ depletion time (Bigiel et al. 2008)

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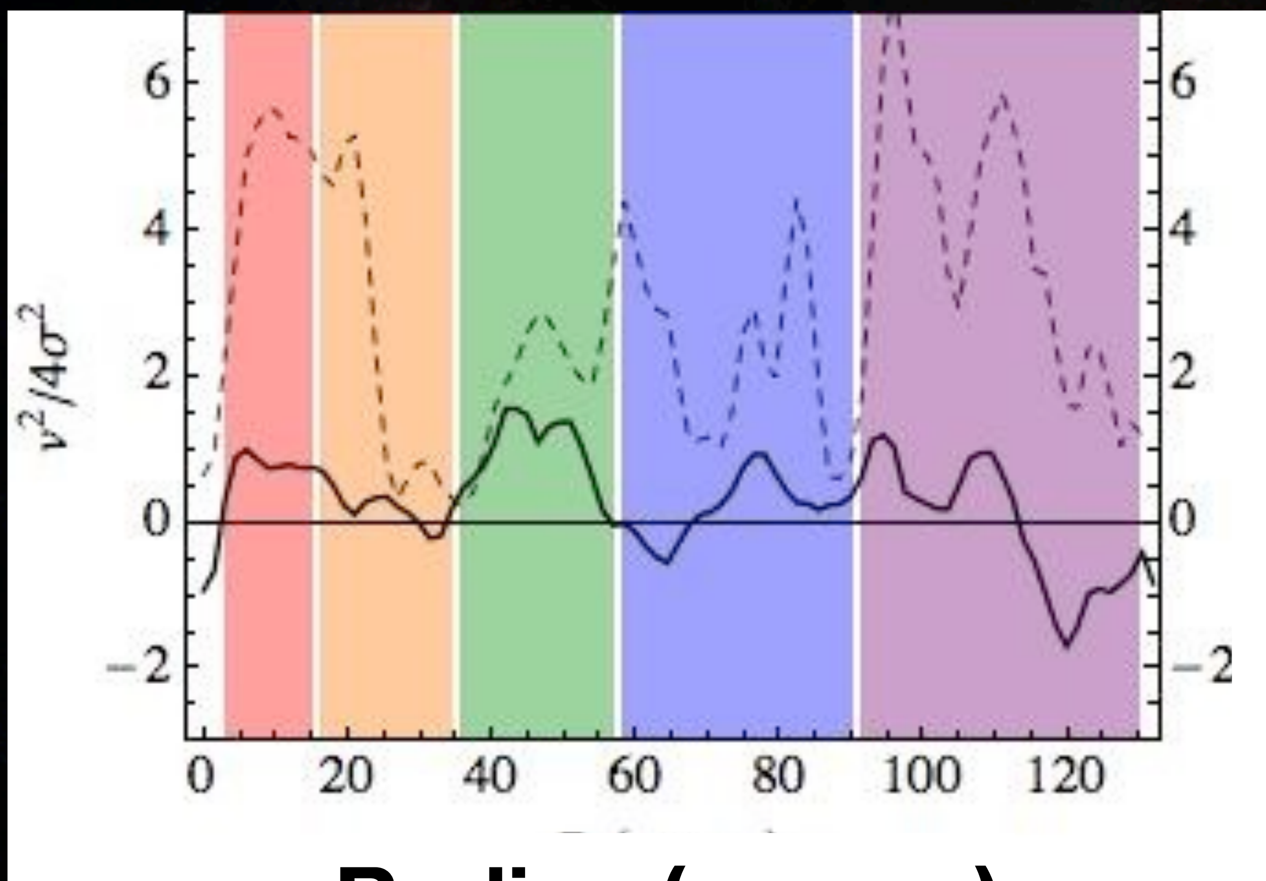

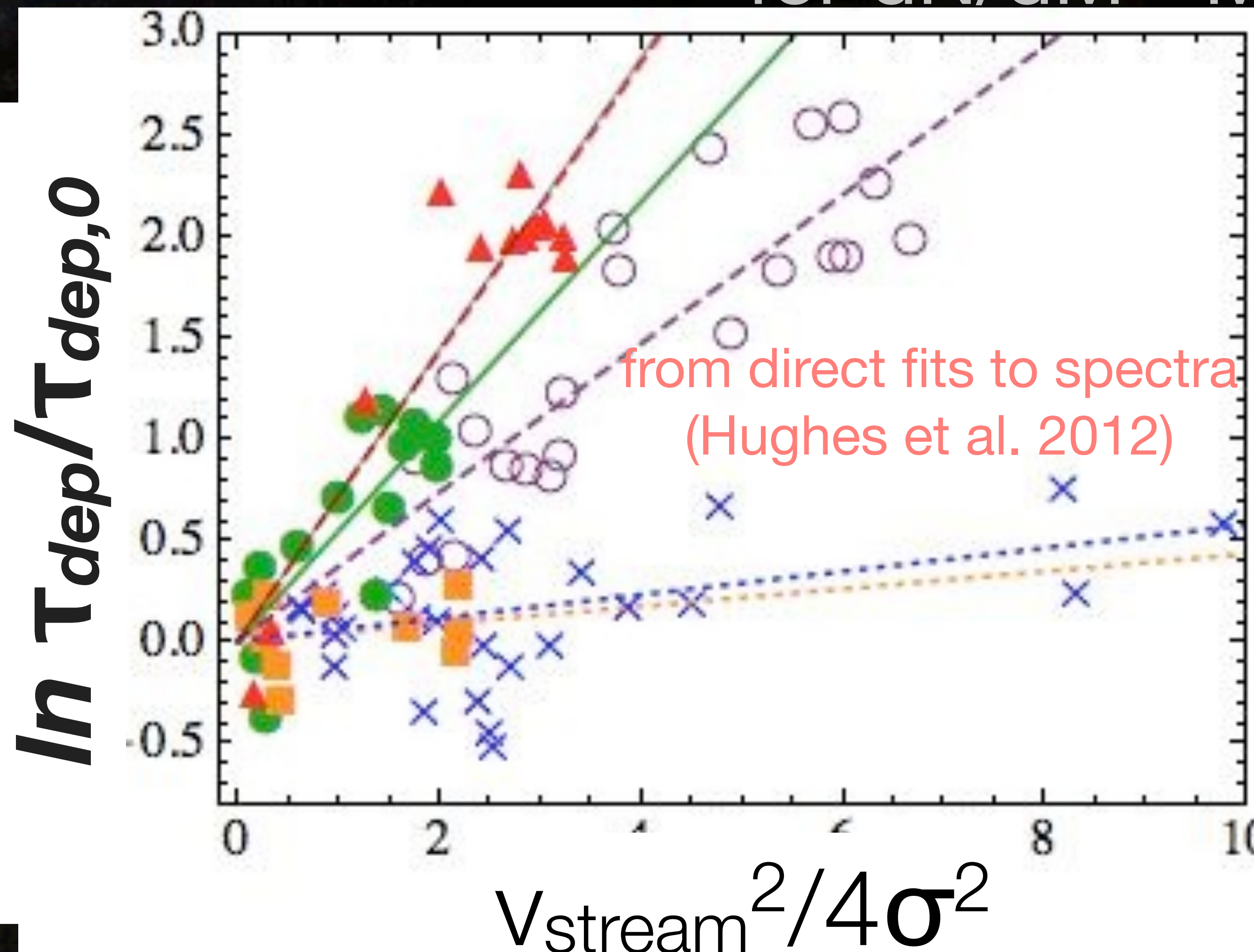

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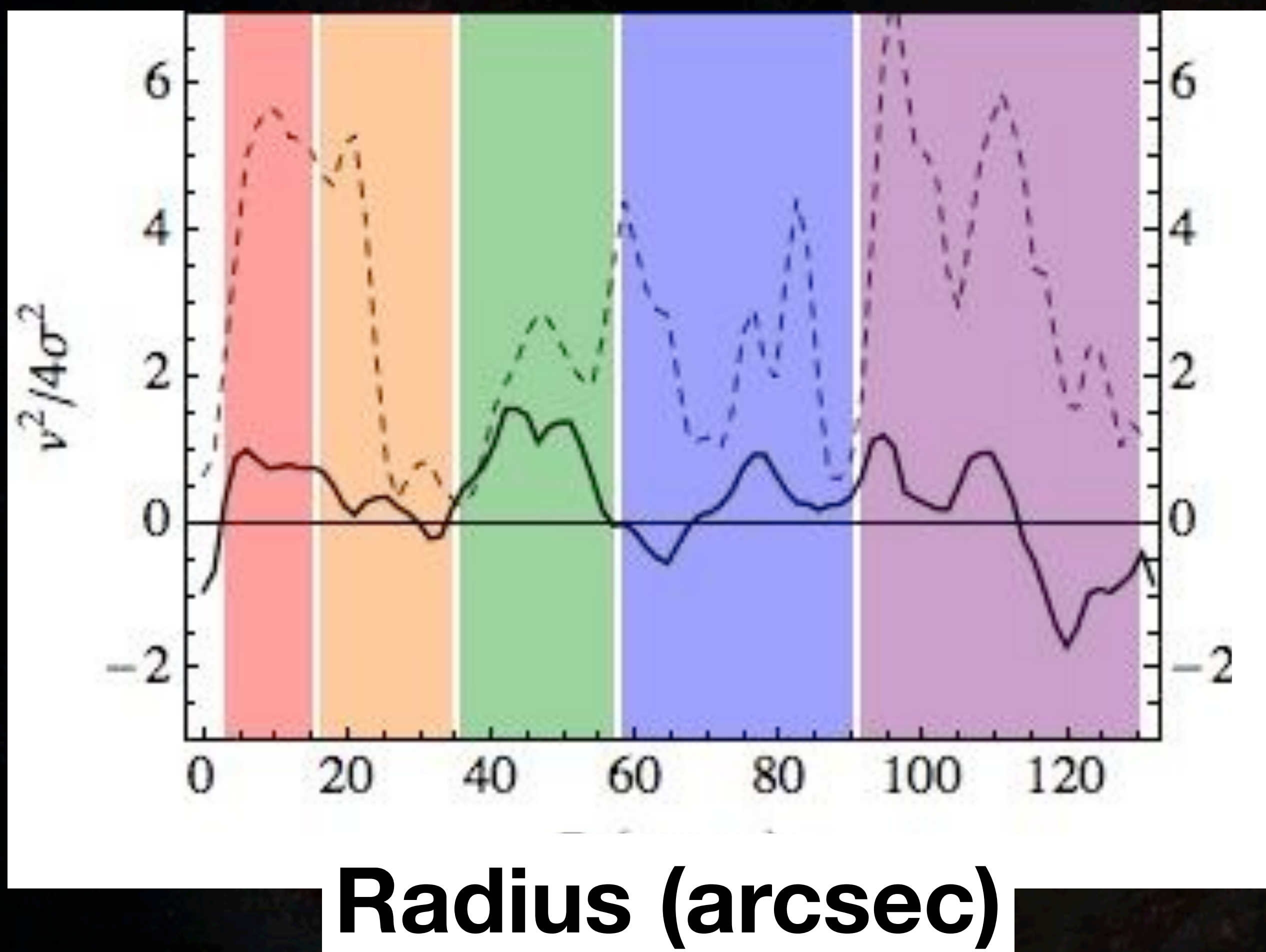

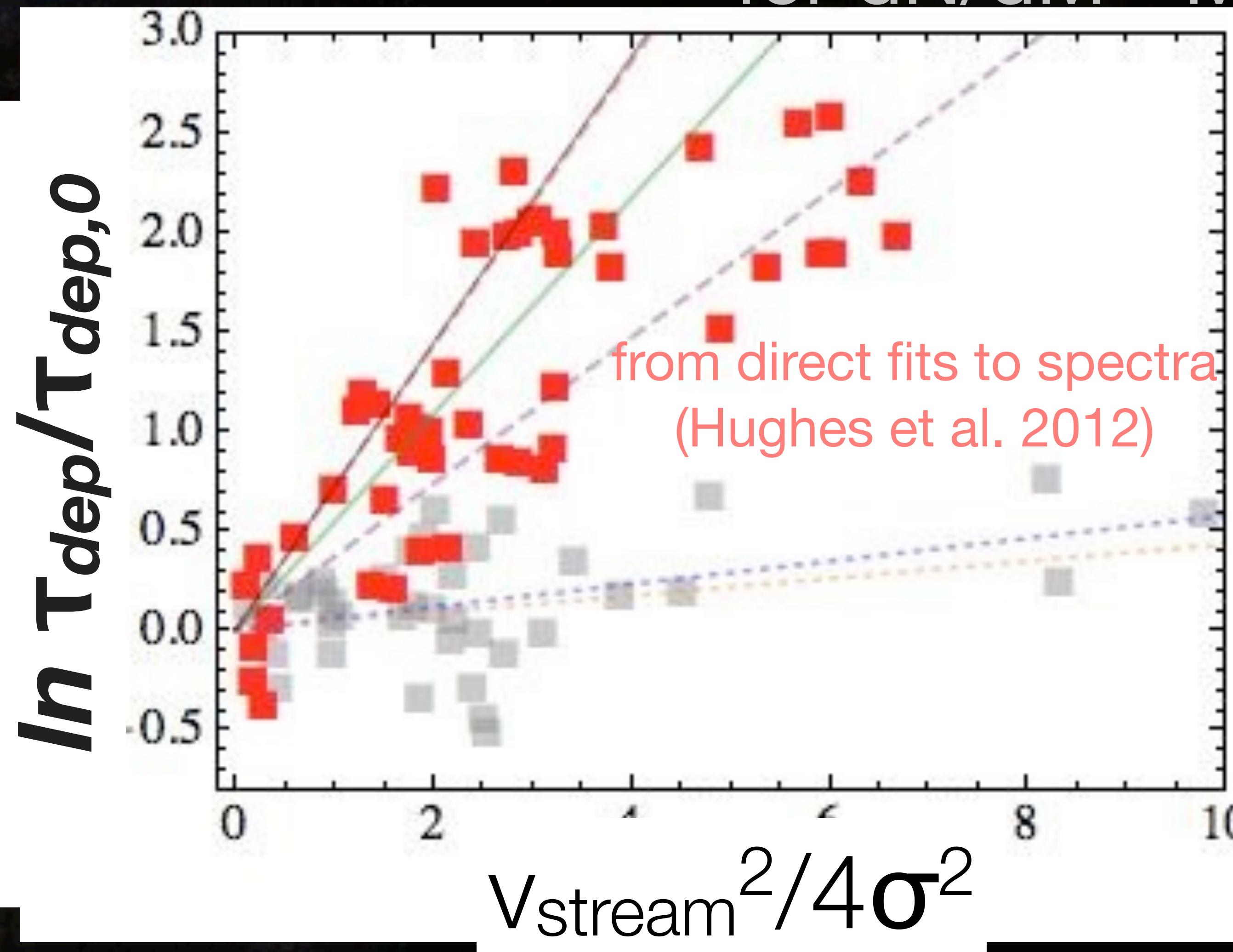

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direct fits to spectra (Hughes et al. 2012)

$\langle\tau_{dep0}\rangle = 1\,Gyr$

$\langle\tau_{dep}\rangle = 2.5\,Gyr$

~ ‘universal’ depletion time (Bigiel et al. 2008)

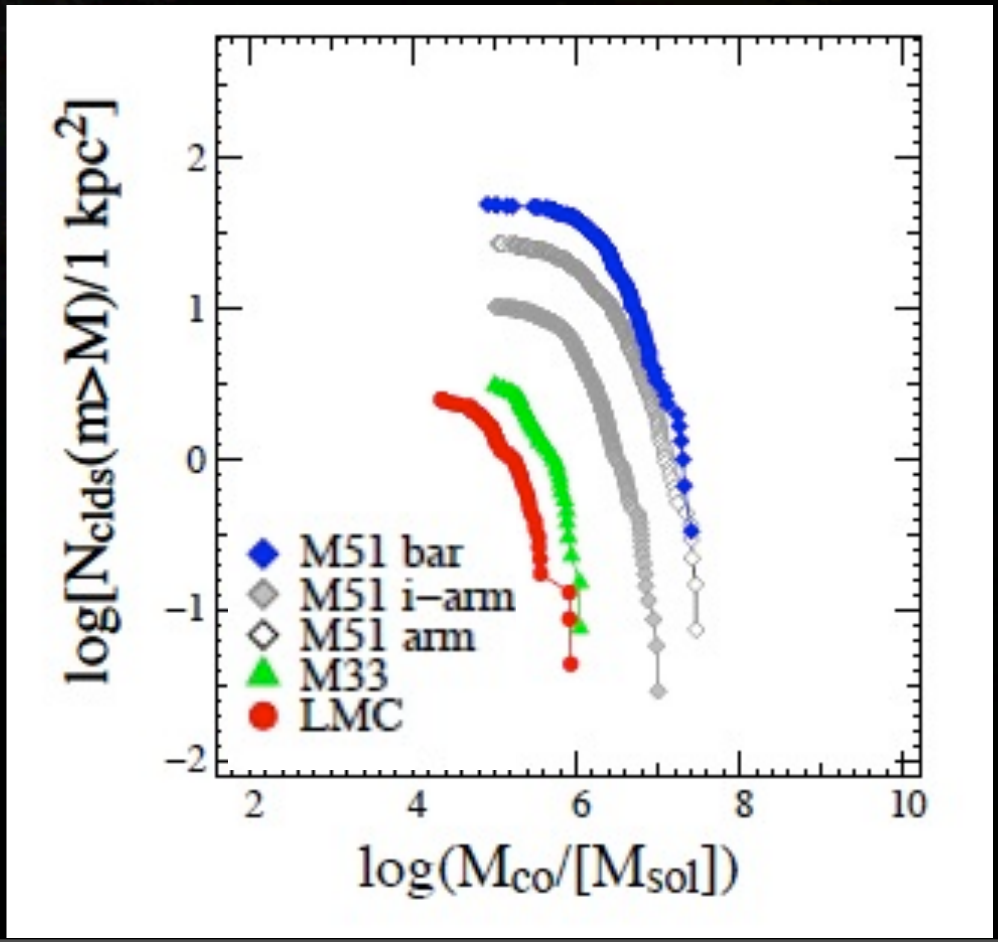
implications, locally and at high-z

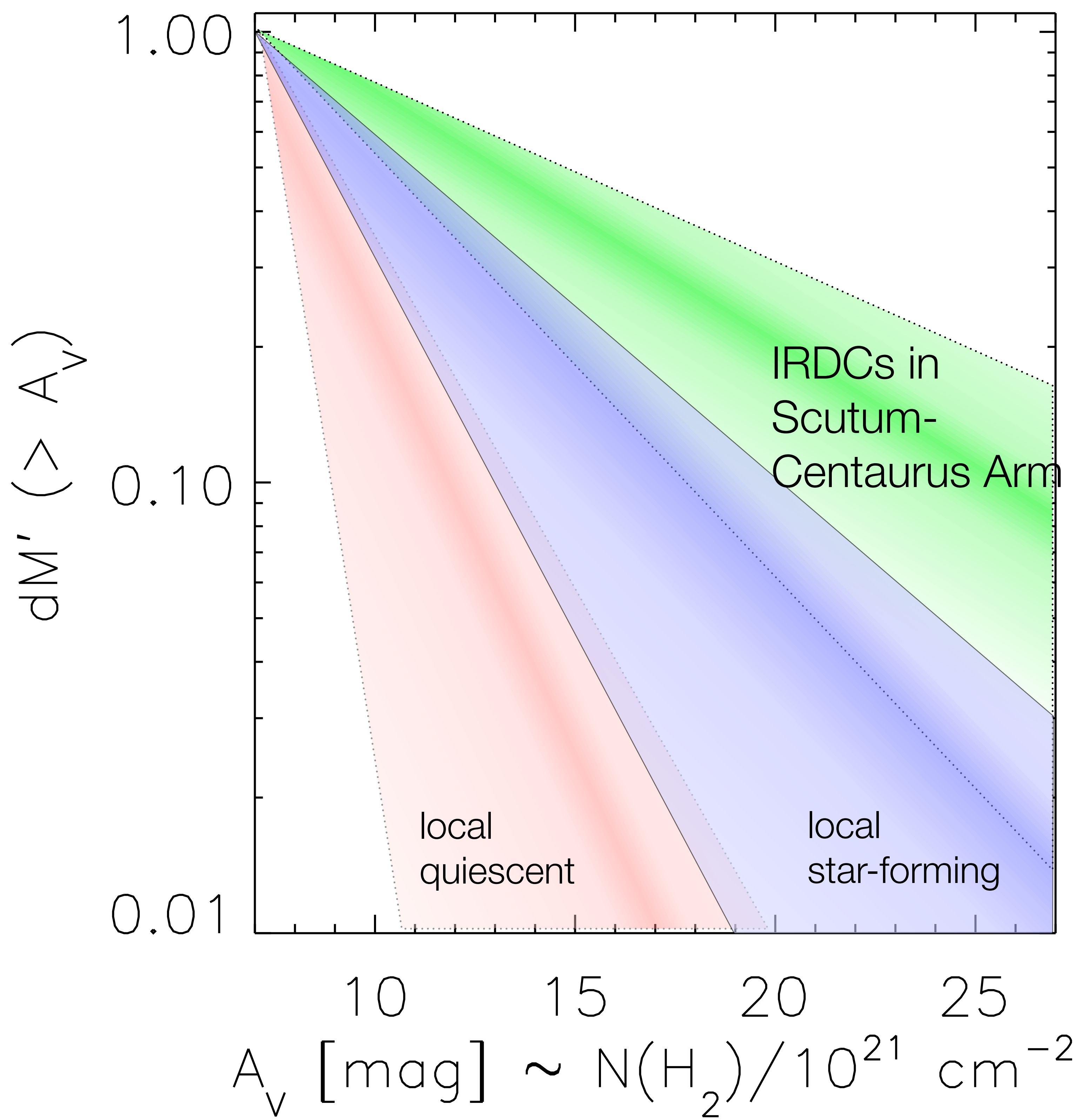
1) cloud scale:

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)?

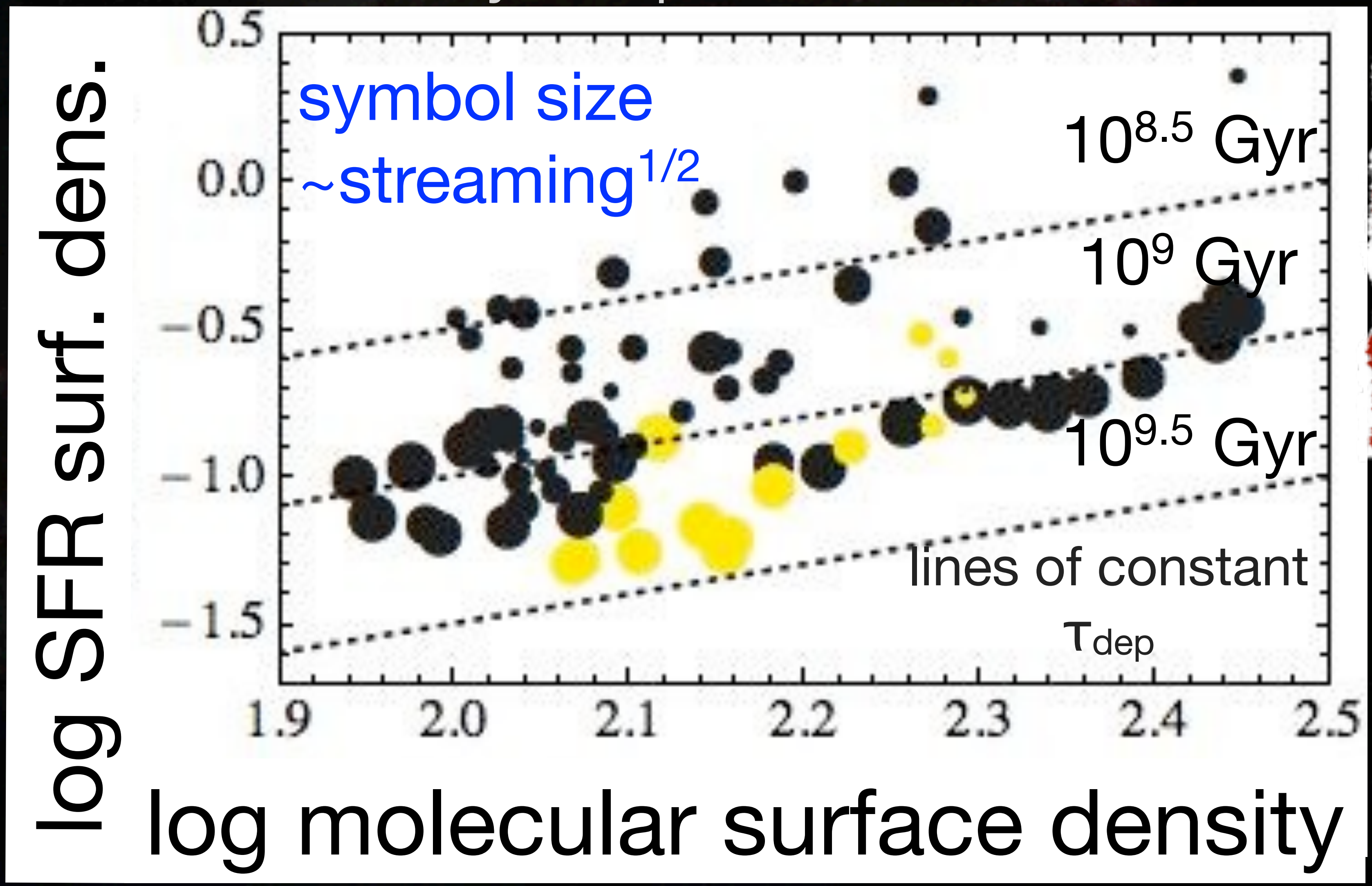




Adapted from: Kainulainen & Tan (2013), Kainulainen et al. (2013), Kainulainen et al. (2011)

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?

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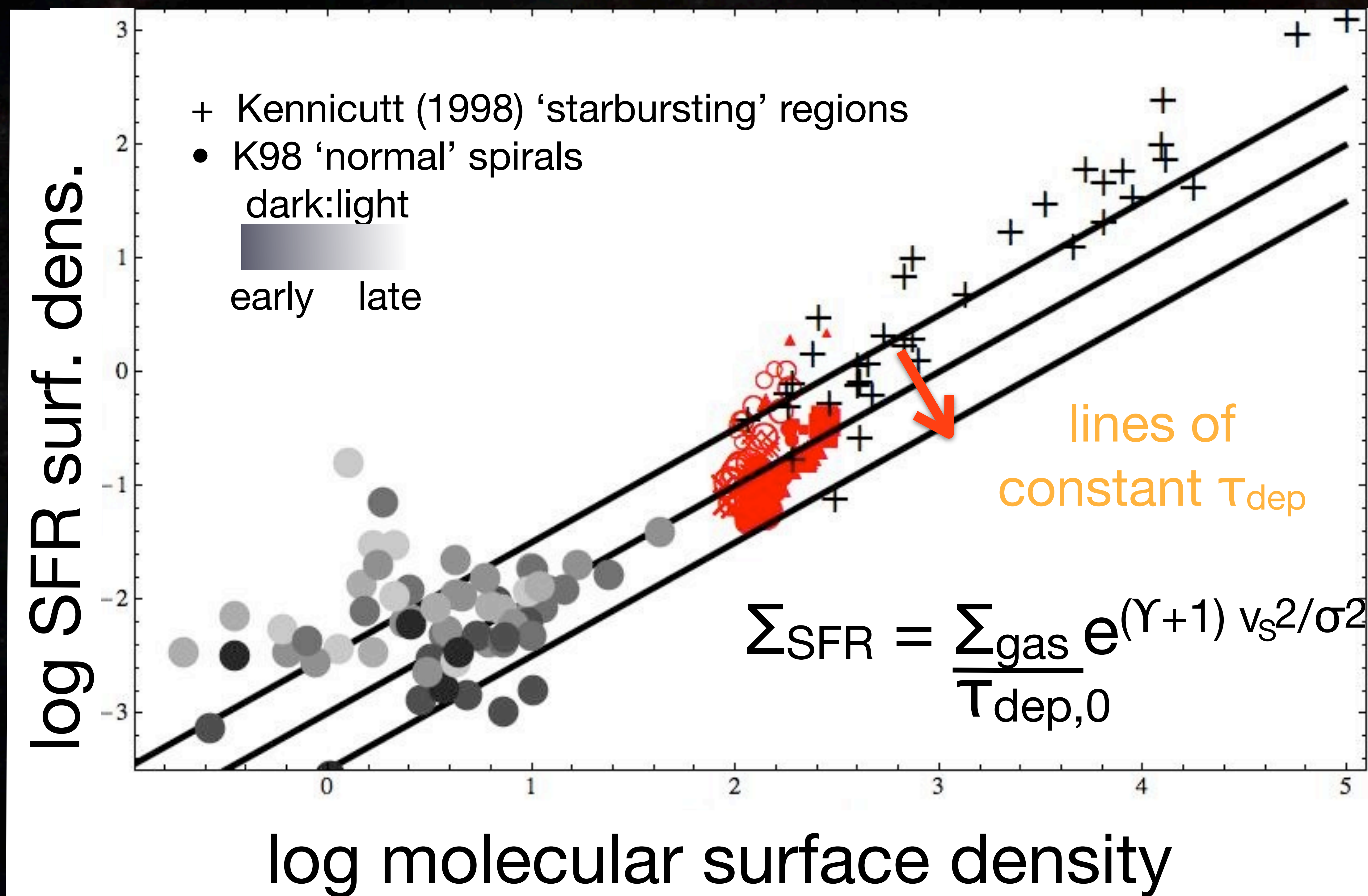

Trends with Morph. type

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

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

$\sim V_c/m\, \Sigma/\Sigma_0$

i_p =pitch angle

V_c =rot. velocity

m-armed symmetry

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

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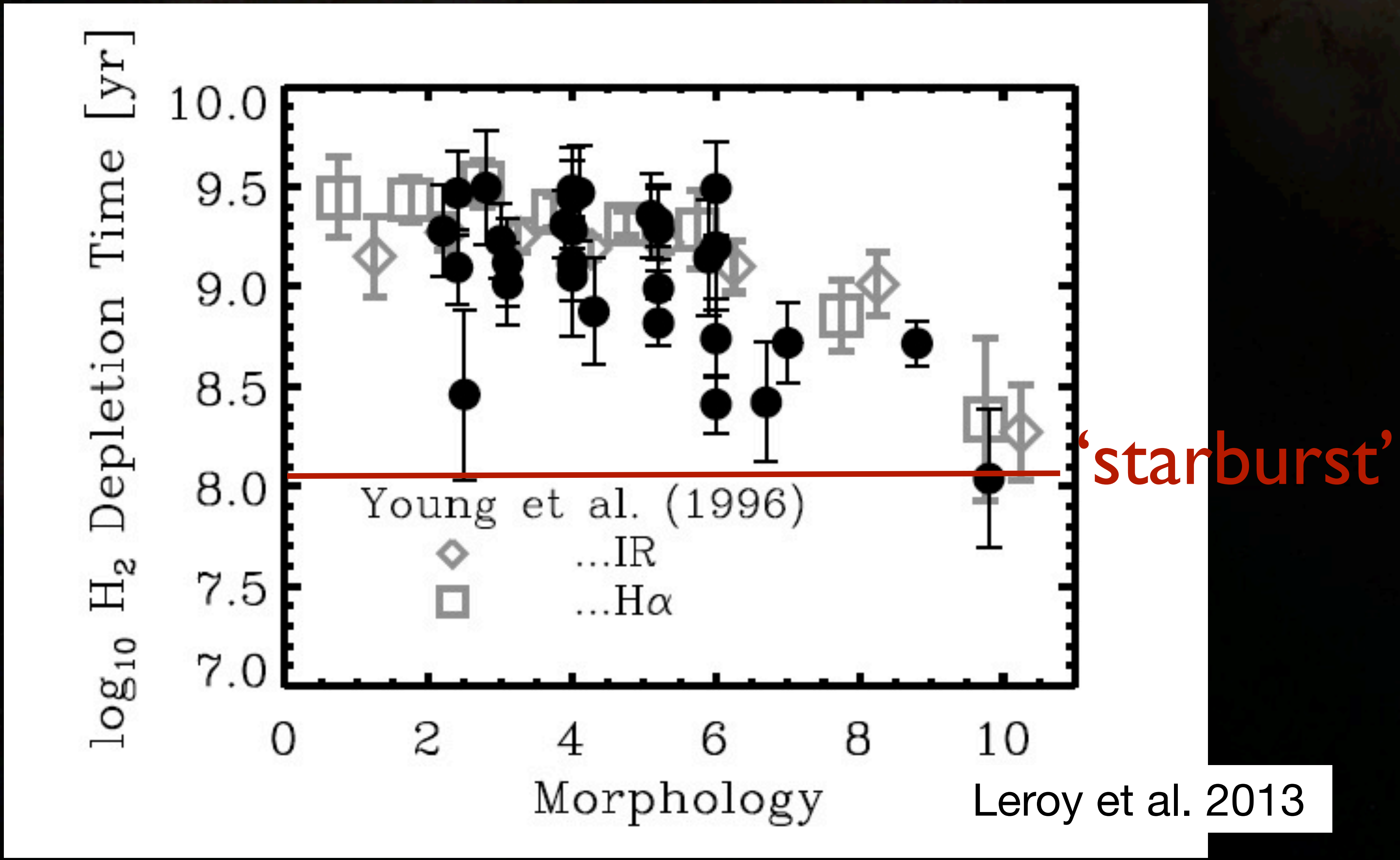
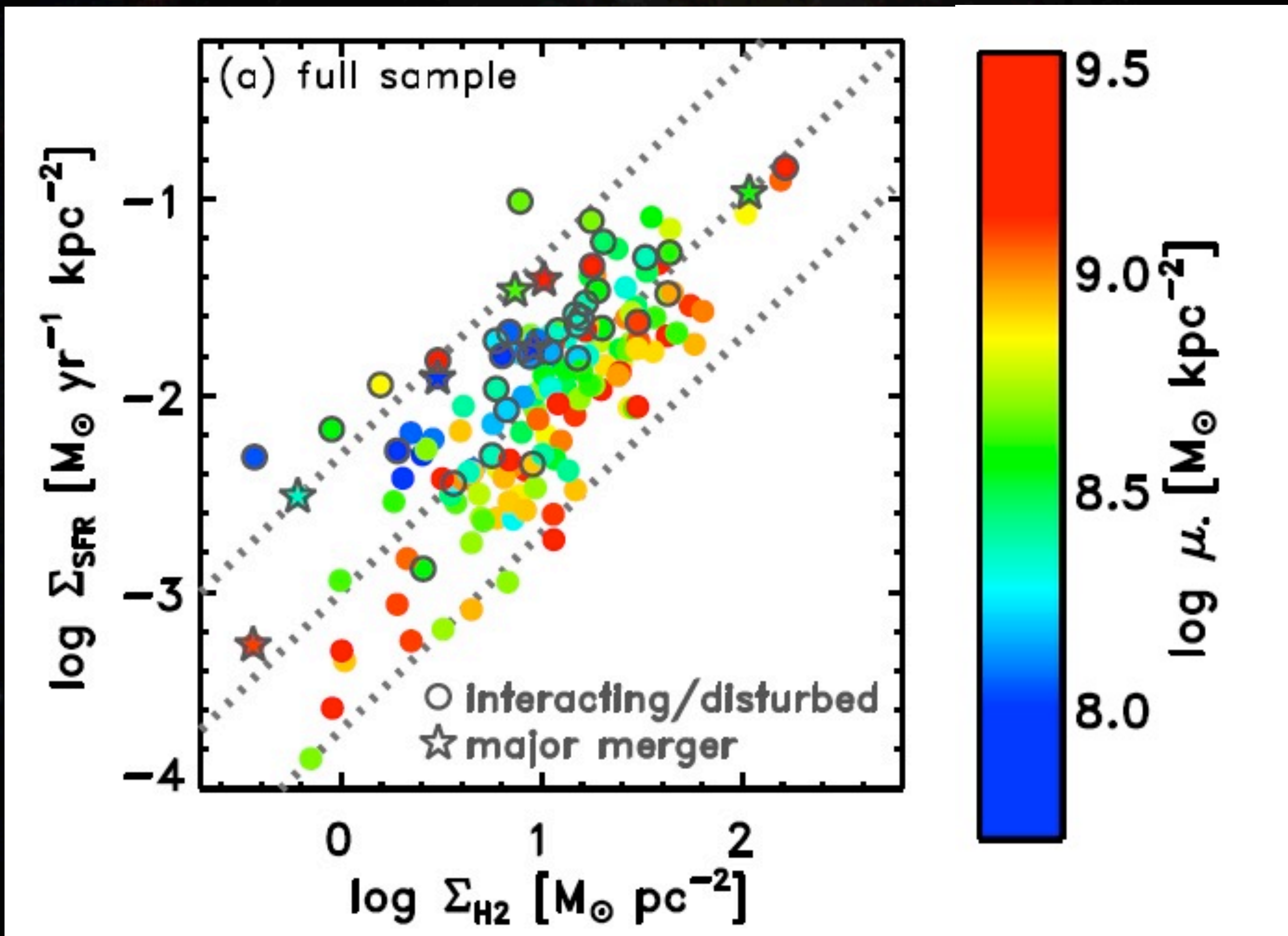


Leroy et al. 2013

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?


M83
(ESO)

implications, locally and at high-z

- **early-type spirals** have *longest* depletion times
- **dwarfs, starbursts** (little spiral-driven streaming): *short* depletion times
- **at high-z** high gas fraction: *short* depletion time

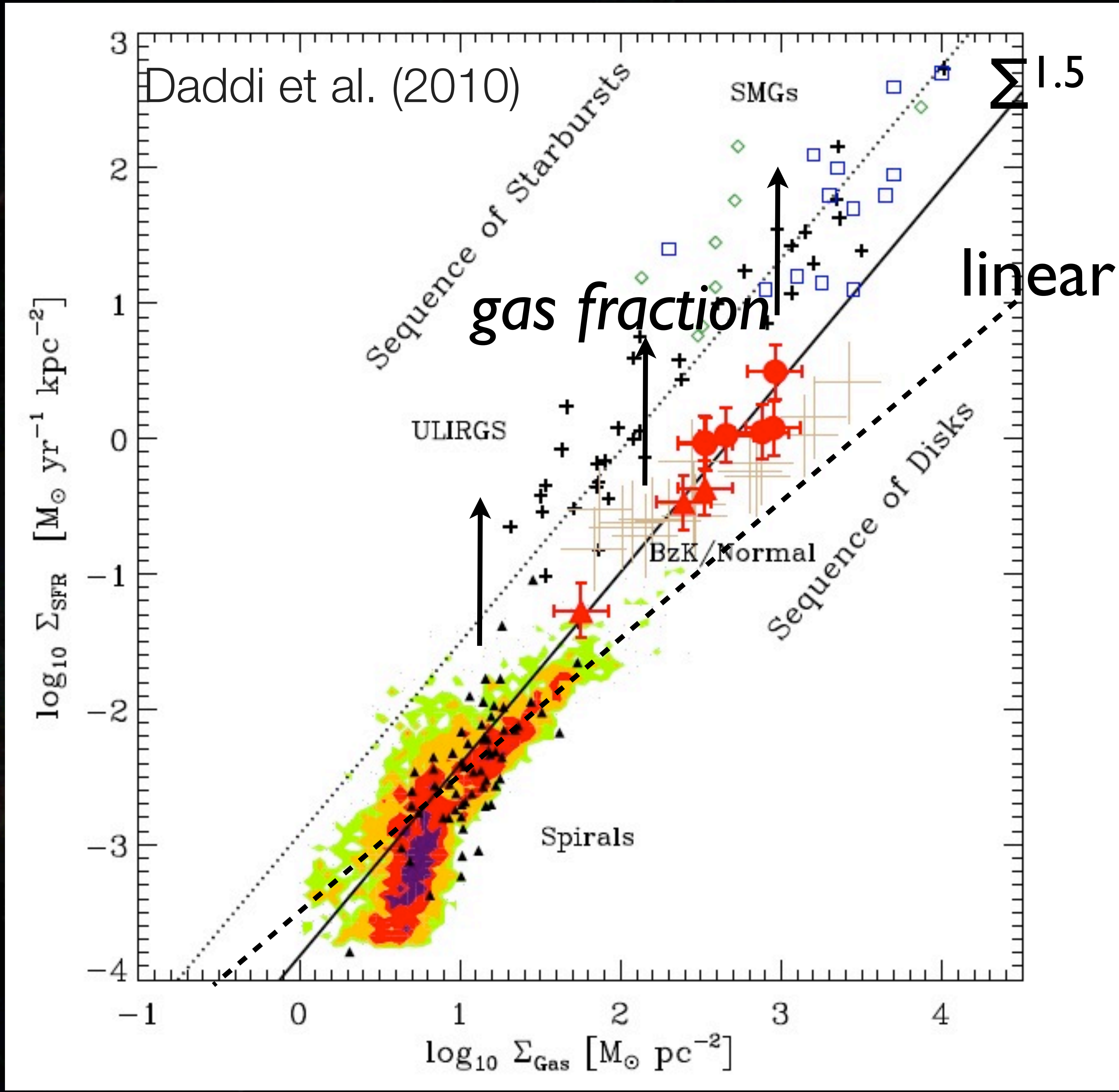
$$\tau_{dep} \propto \frac{Vs}{\sigma} \propto \frac{(2\beta+1)^{1/2}}{QF_g}$$

RC shape → $(2\beta+1)$

Toomre Q → Q

gas fraction → F_g

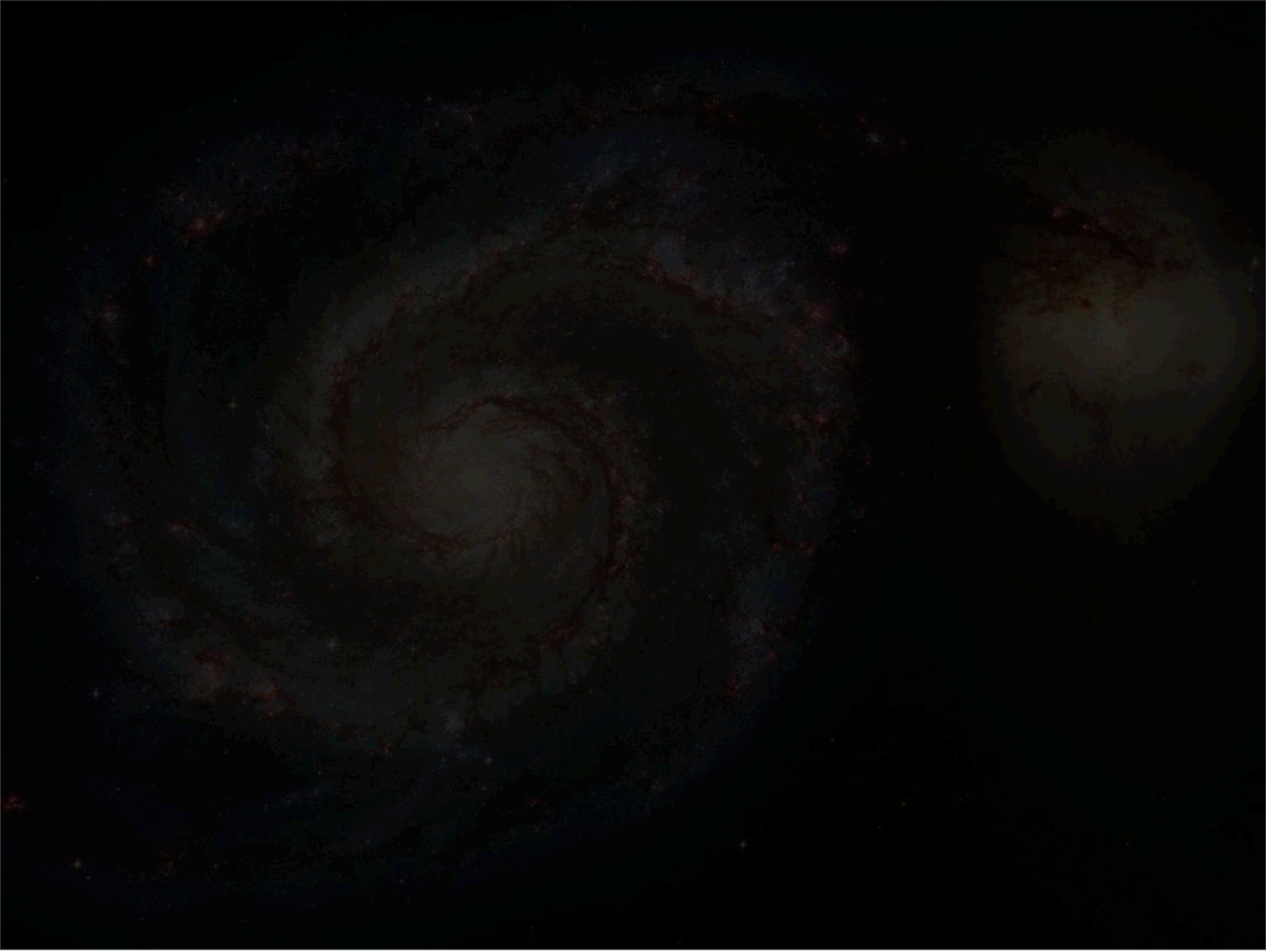
τ_{dep} more fundamentally linked to gas fraction (high F_g --> weakened sensitivity to environment-decoupling)

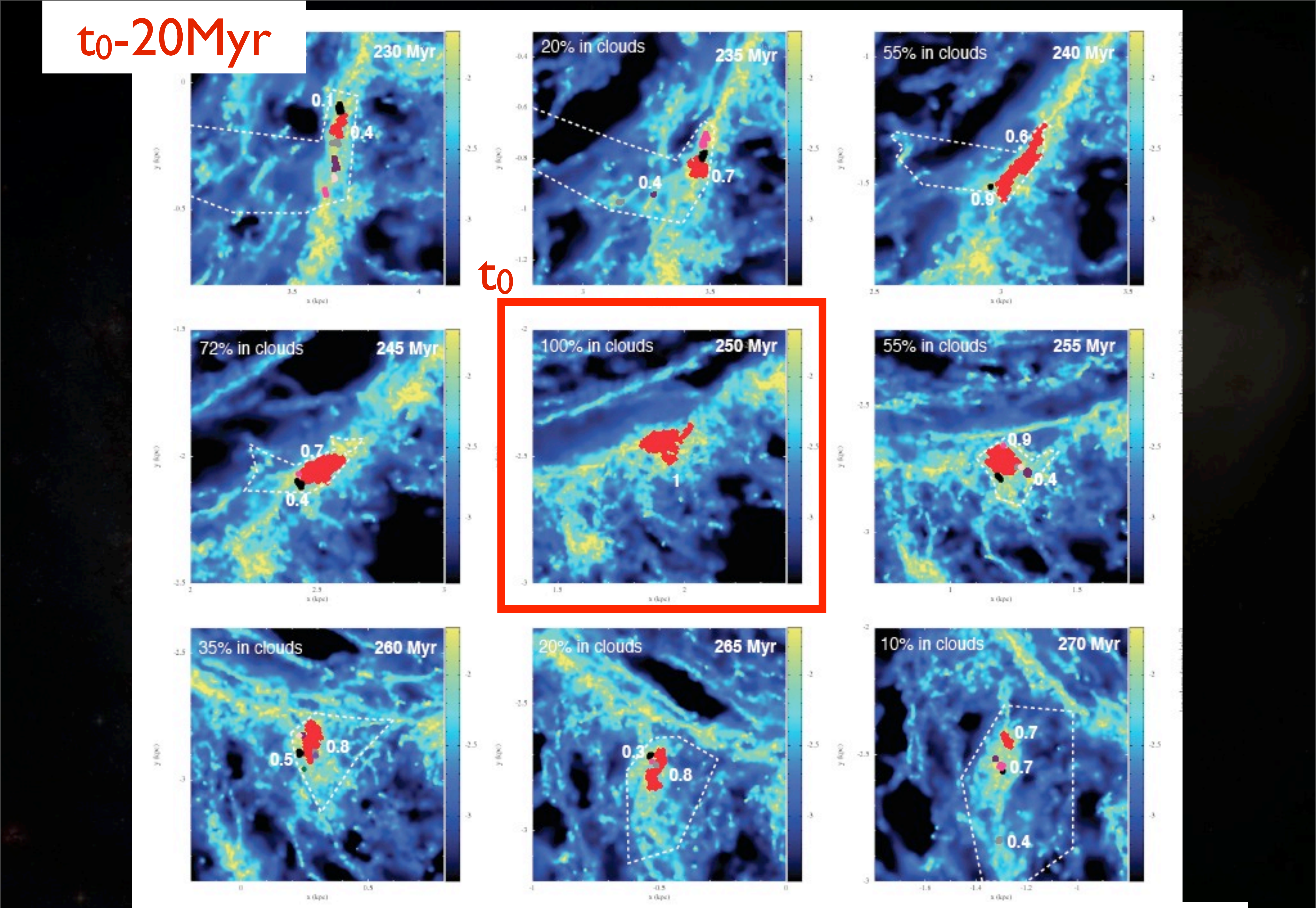


Daddi et al. (2010)
$\Sigma^{1.5}$
linear
gas fraction
Sequence of Starbursts
Sequence of Disks
SMGs
ULIRGS
BzK/Normal
Spirals
$\log_{10} \Sigma_{SFR}$ [$M_\odot$ yr^{-1} kpc^{-2}]
$\log_{10} \Sigma_{Gas}$ [$M_\odot$ pc^{-2}]

Take-away

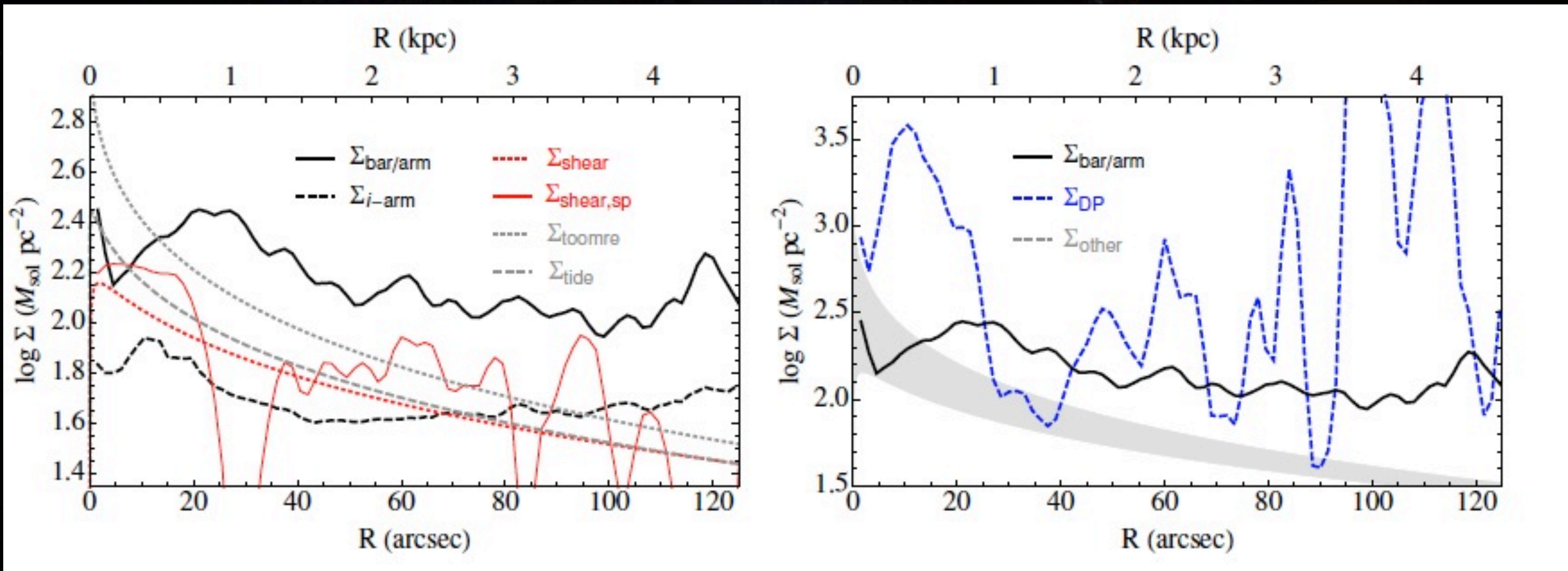
- Non-axisymmetric structures, like M51's bar and spiral, exert ***torques*** that drive strong non-circular gas ***'streaming' motions***
- these motions ***stabilize*** clouds by reducing the cloud surface pressure
- fewer collapse-unstable clouds per free fall time ***lengthens*** the ***gas depletion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

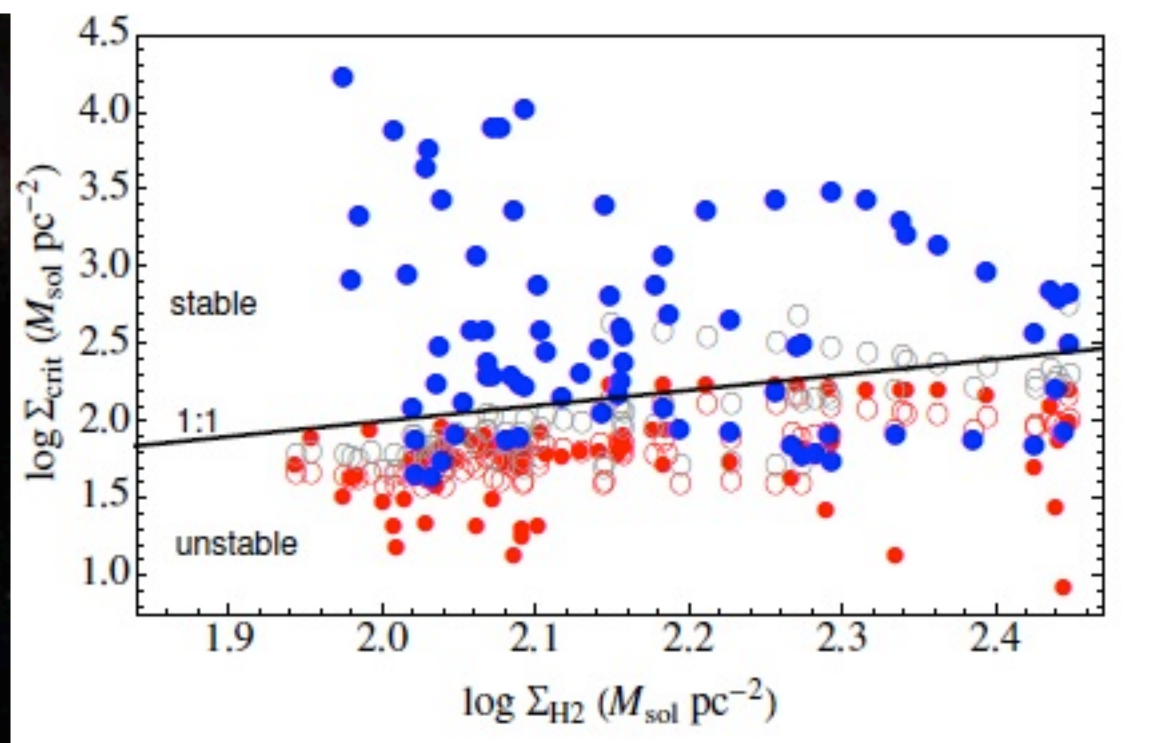




Dobbs & Pringle (2013)

gravitational disk stability

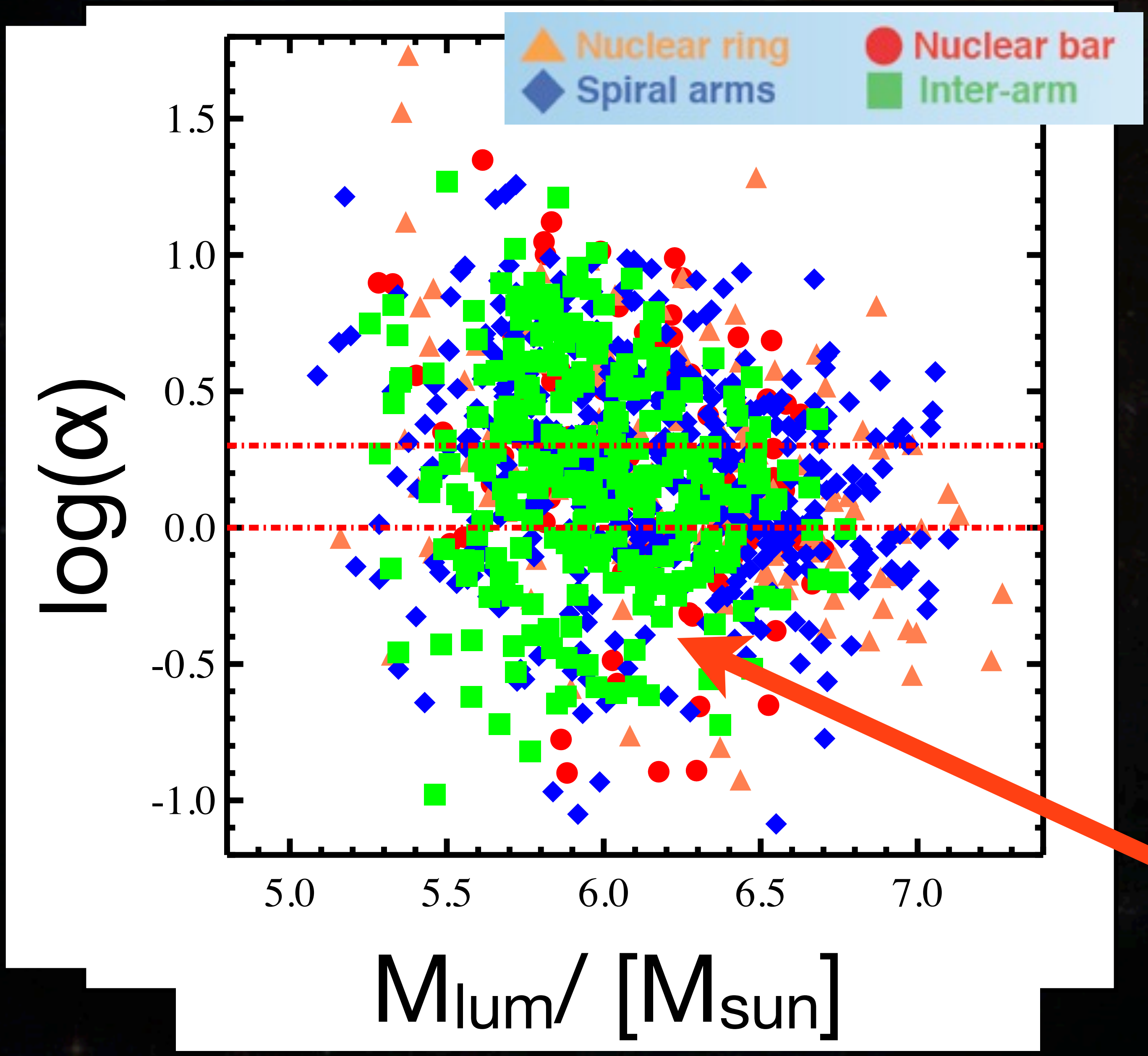




Meidt et al.(2013)

GMC Stabilization in M51

α: measure of virialization
(McKee & Bertoldi)

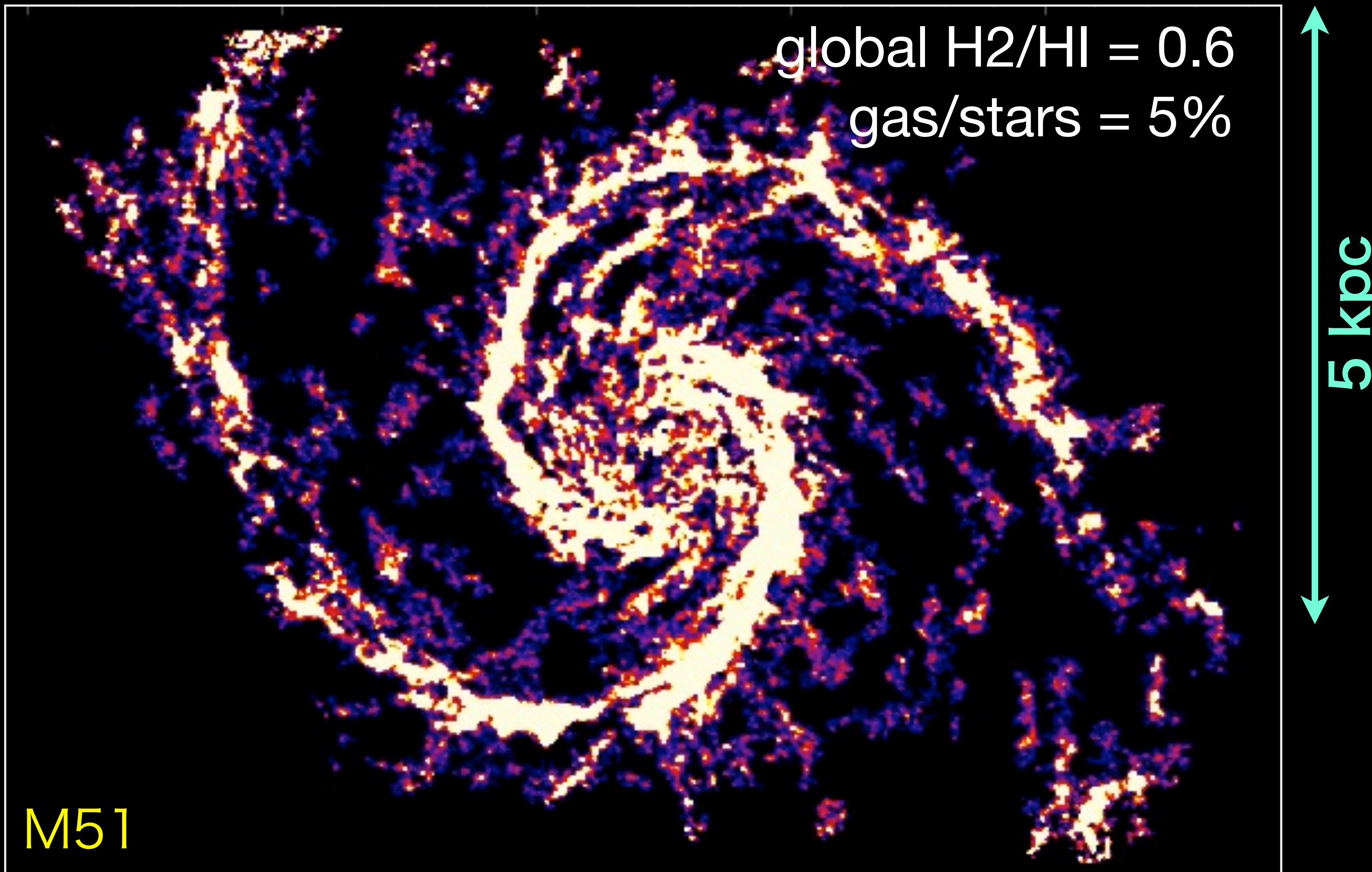


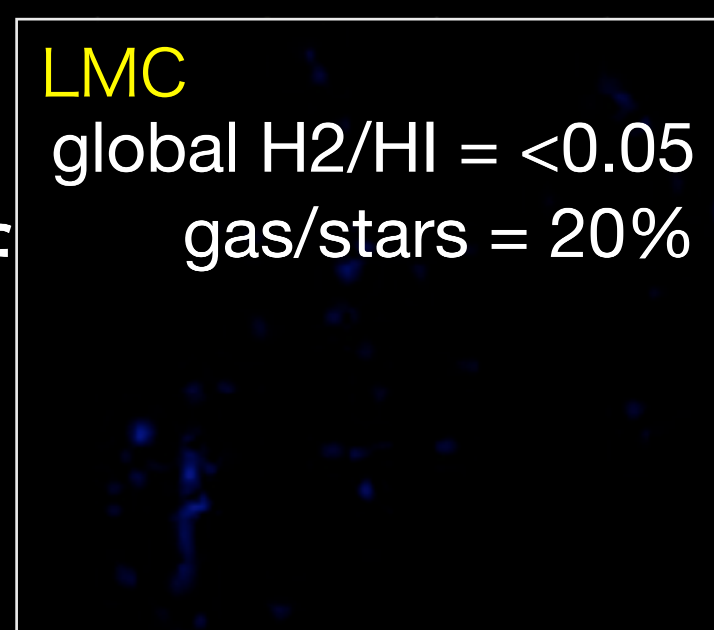
clouds unbound
or
pressure confined?

virialized

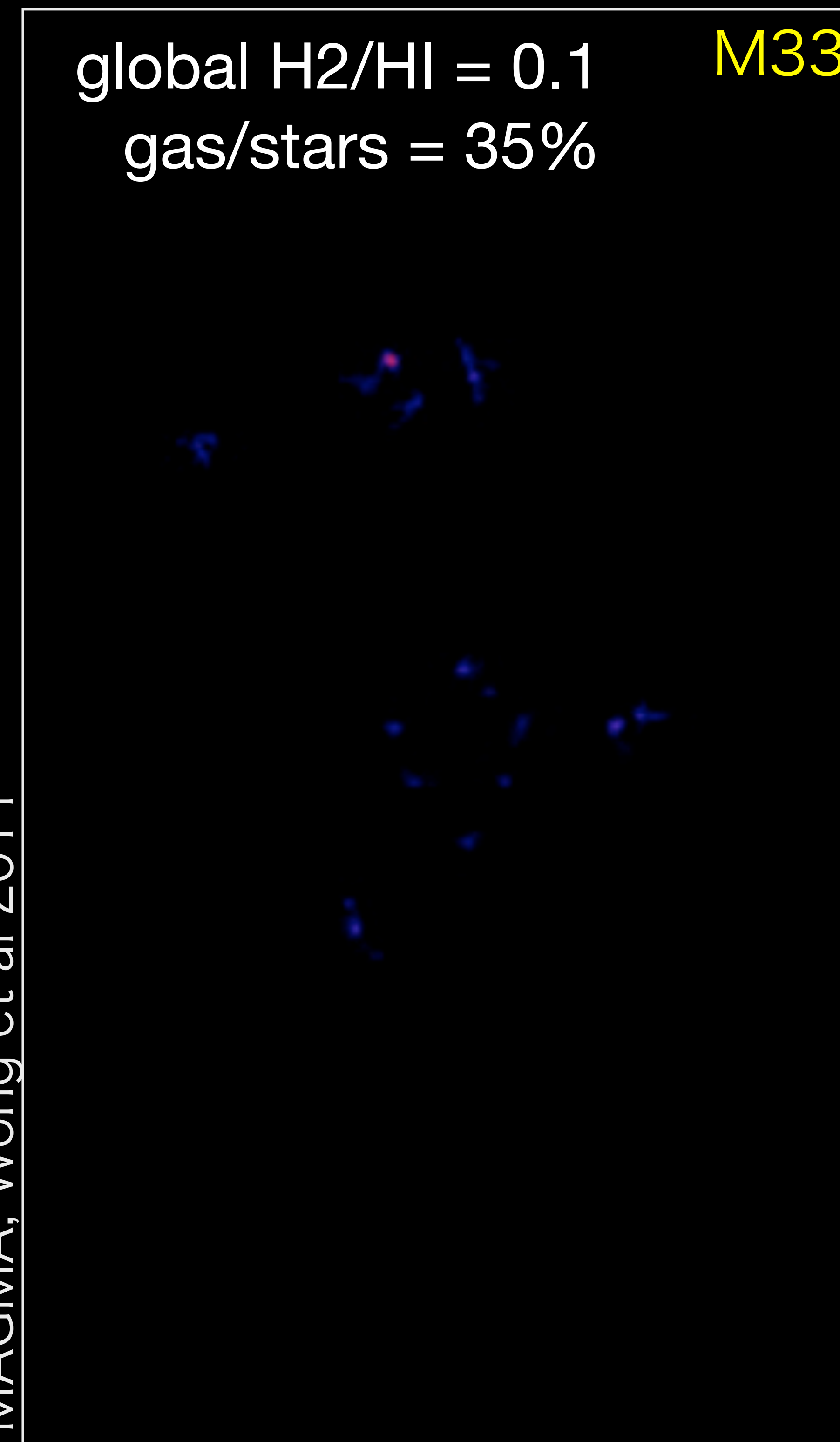
only 25% grav. bound
clouds, mostly inter-arm at low M

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

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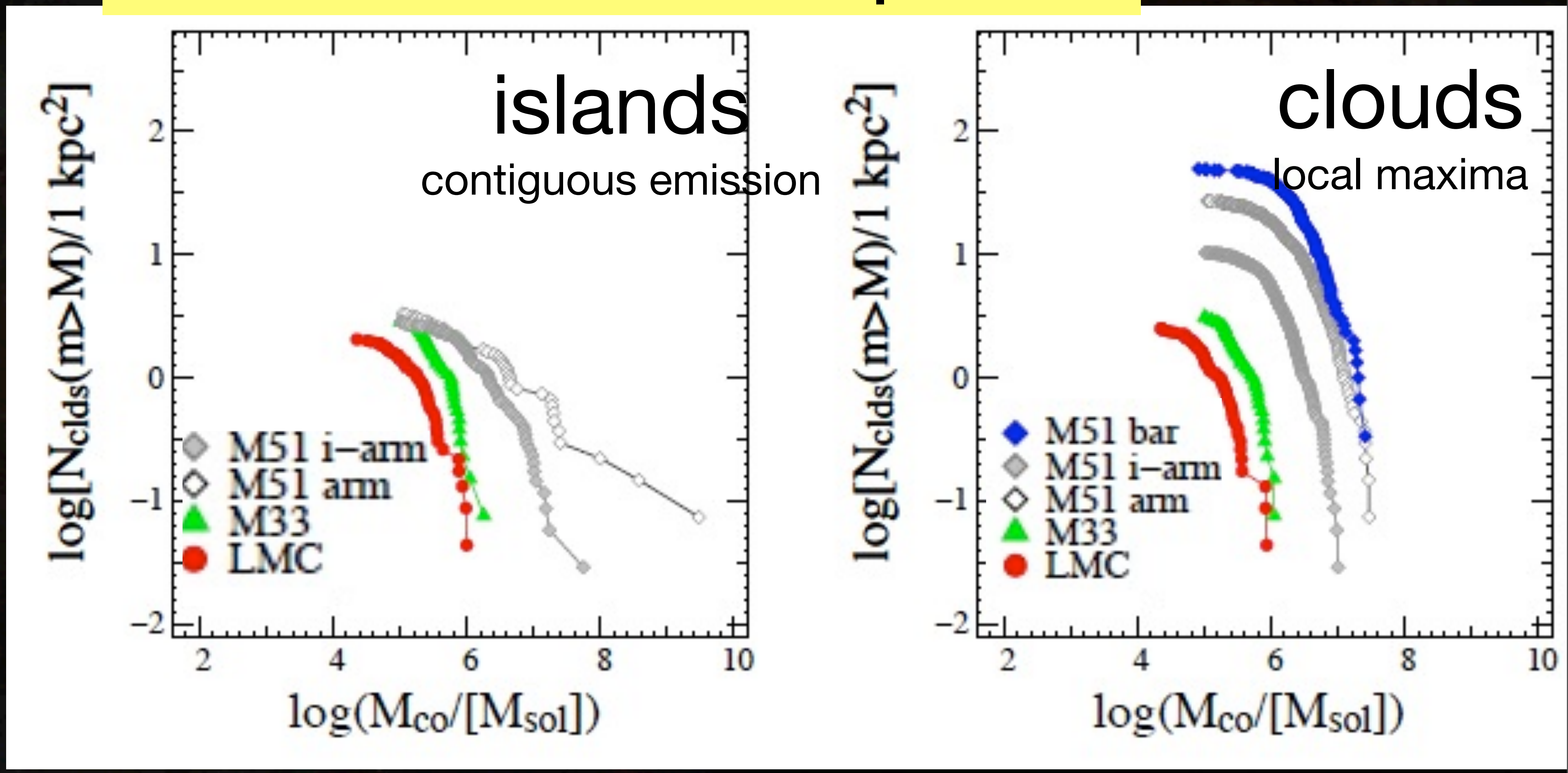
• have **larger linewidths** (relative to size)

than GMCs in M33 and the LMC

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

cumulative mass spectra *constant XCO*



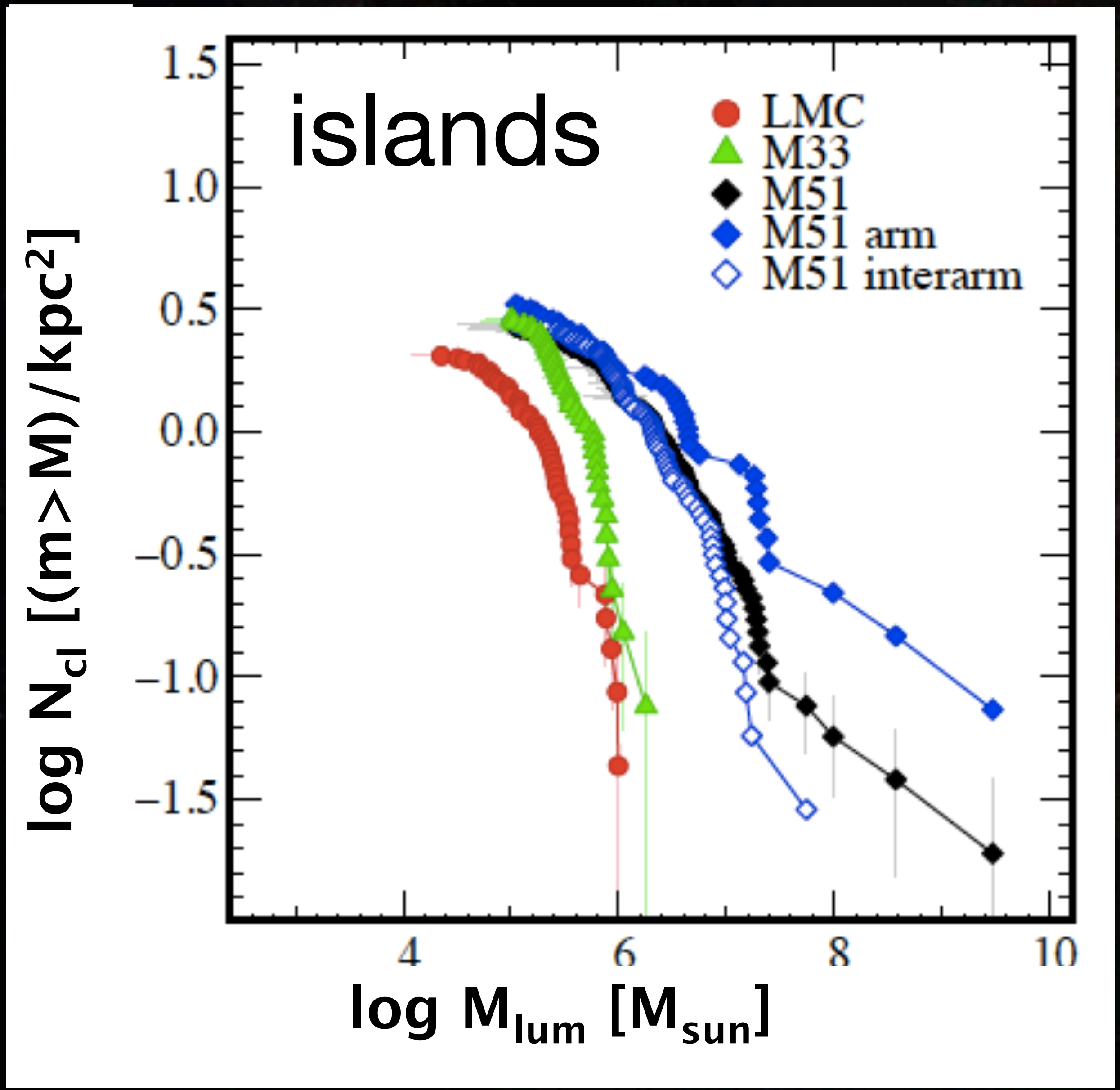
Hughes et al. 2012

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

Cloud mass spectra

Colombo et al. (in prep.)
Hughes et al. (in prep.)

M51 clouds



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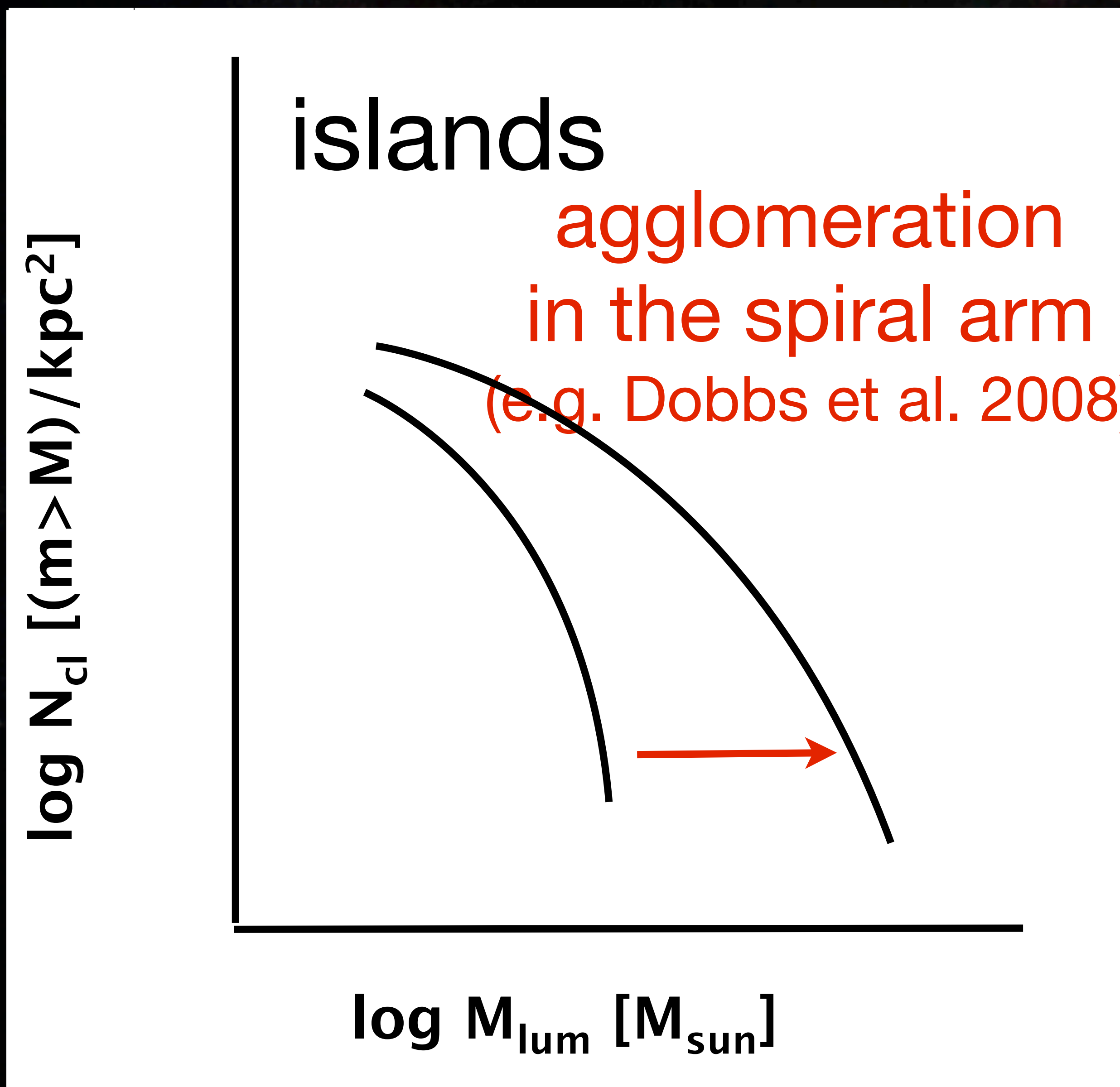

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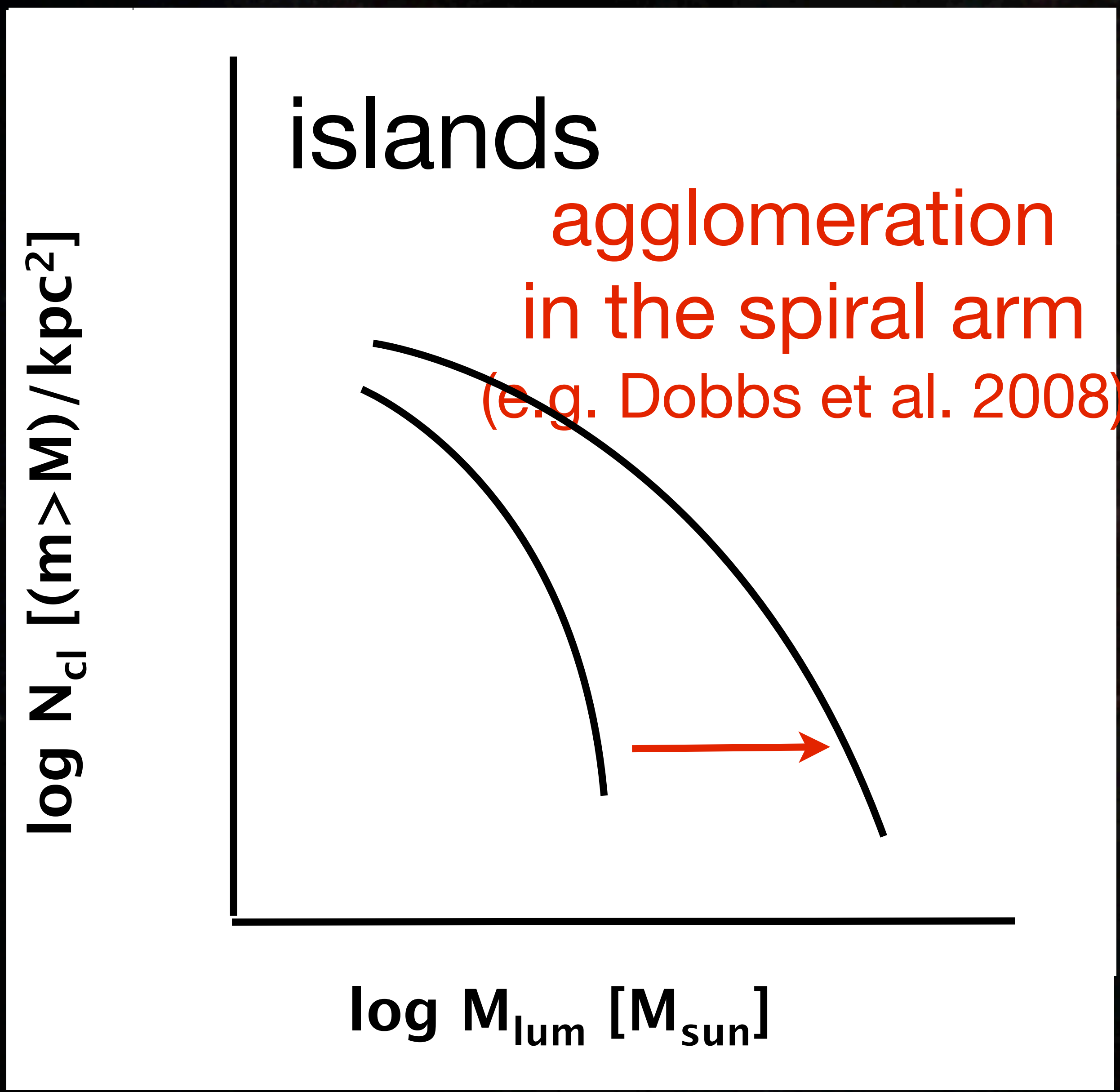

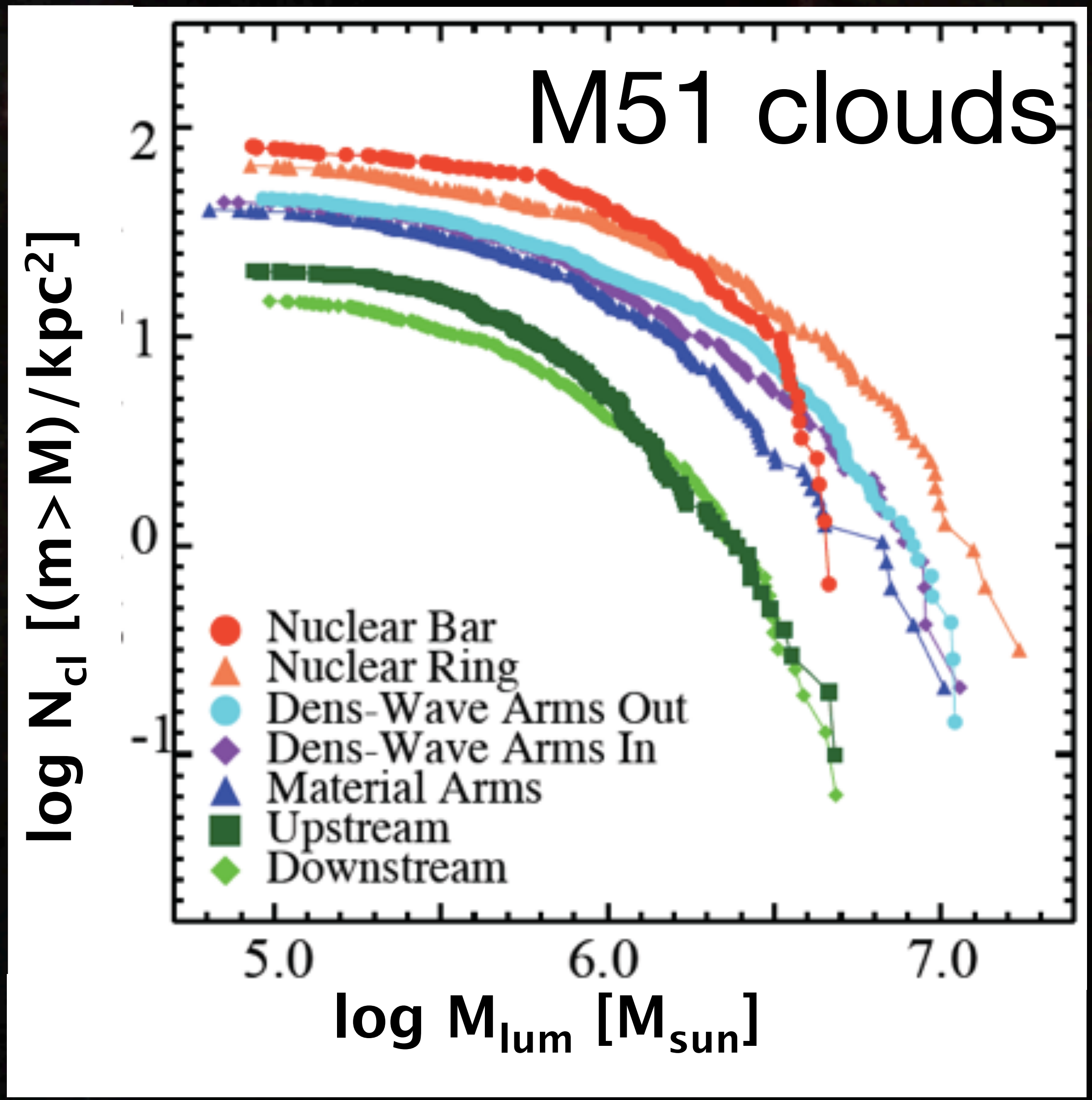

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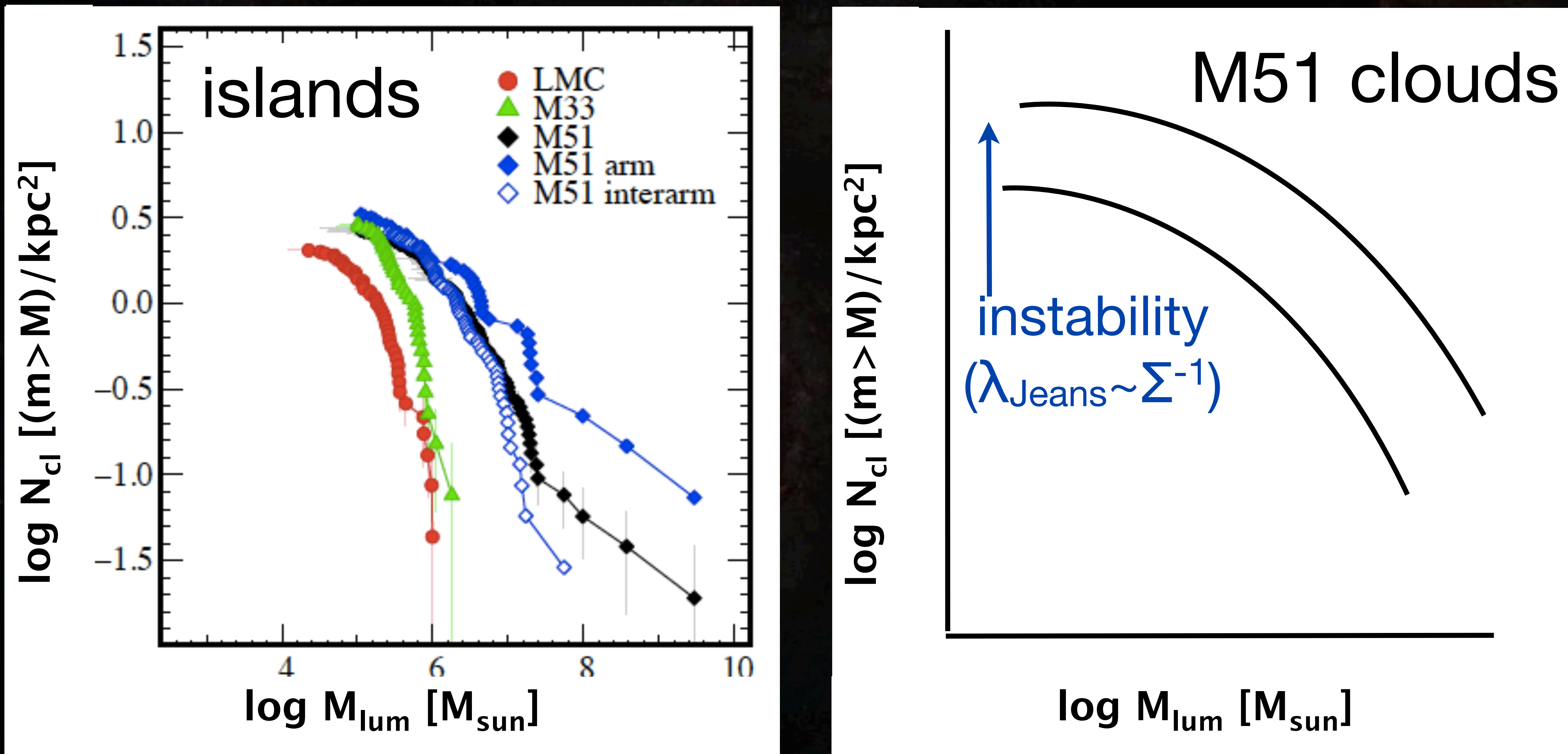

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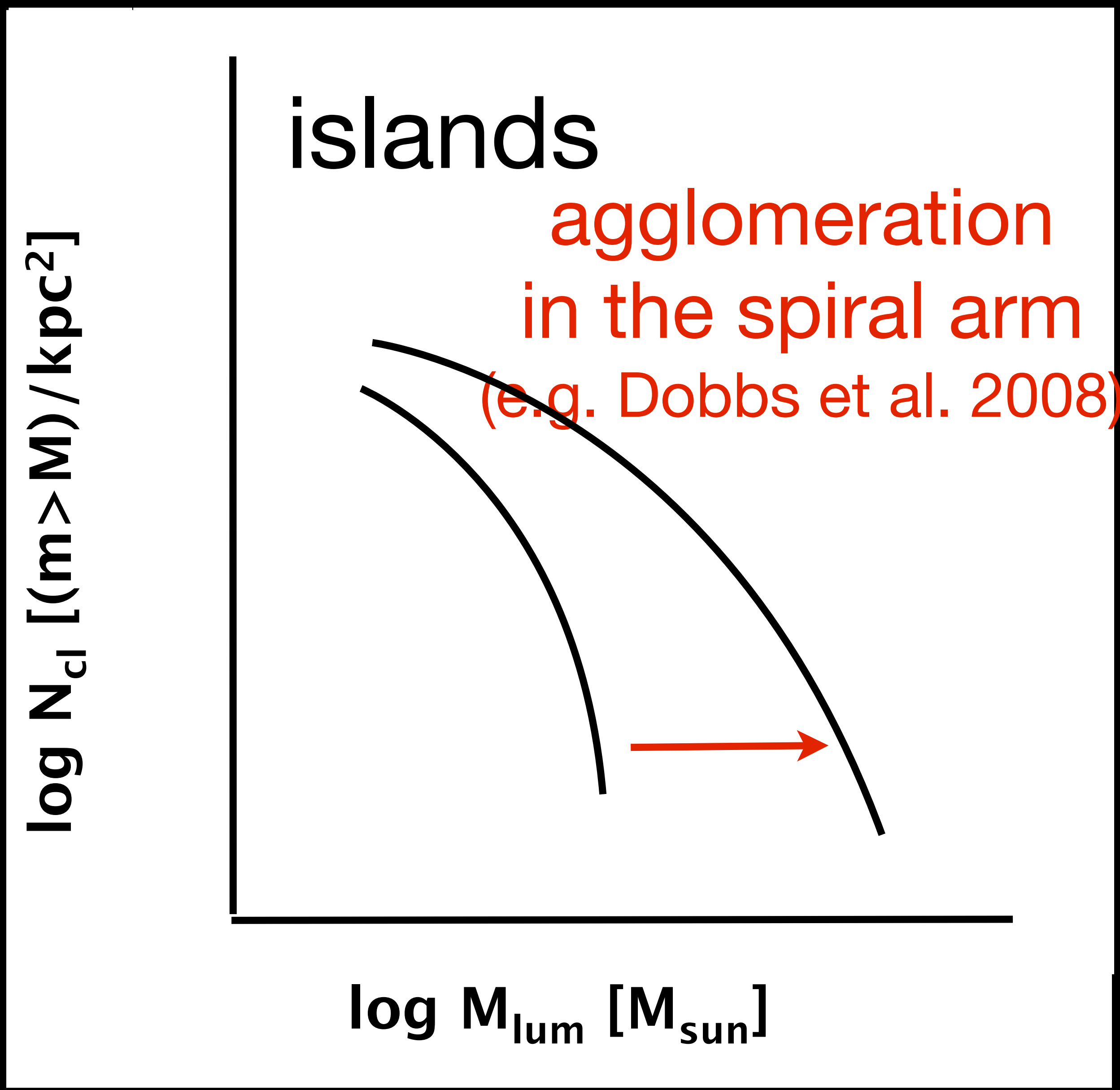

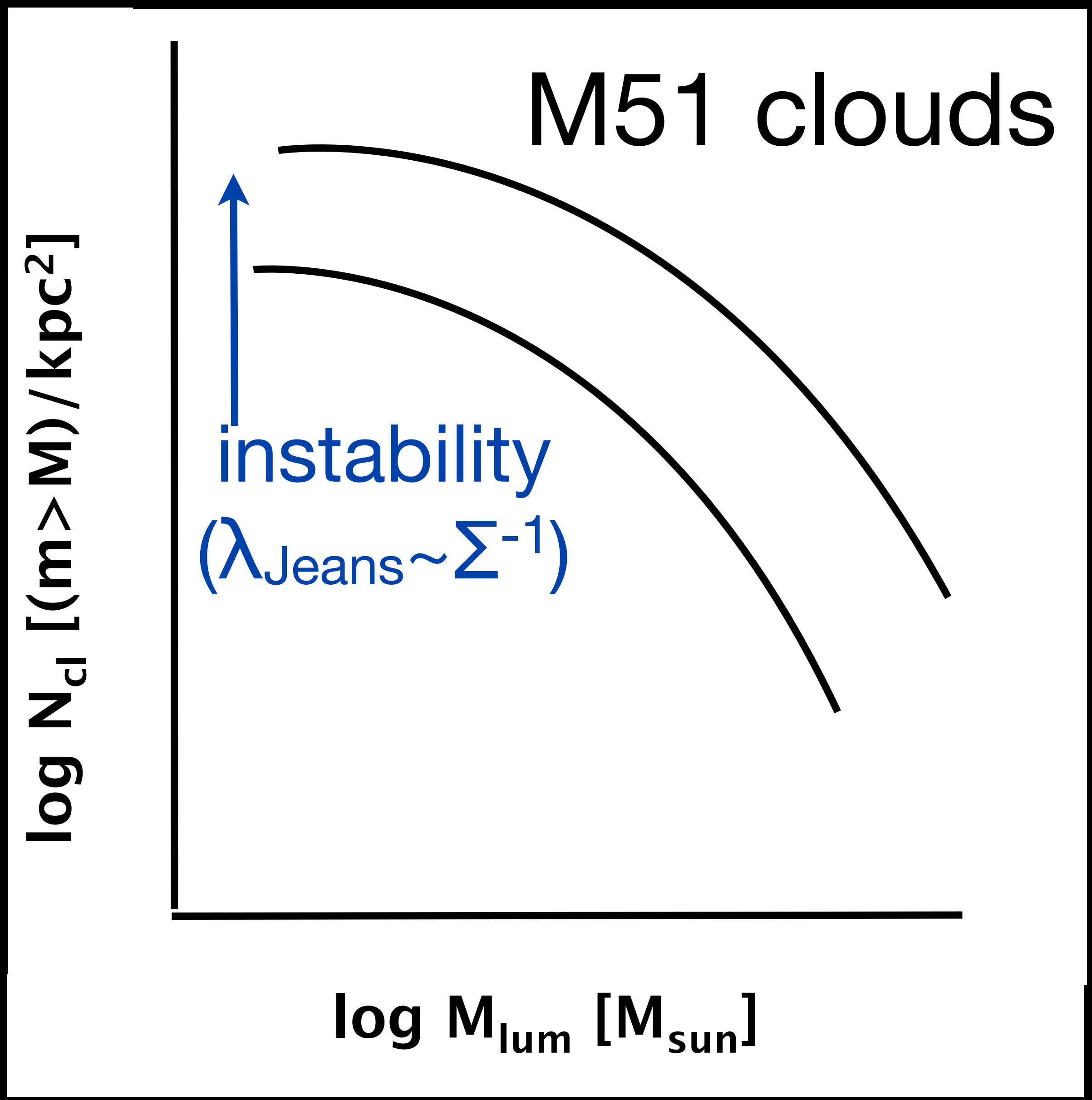

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Summary

1. Does dynamical environment matter? **Yes.**

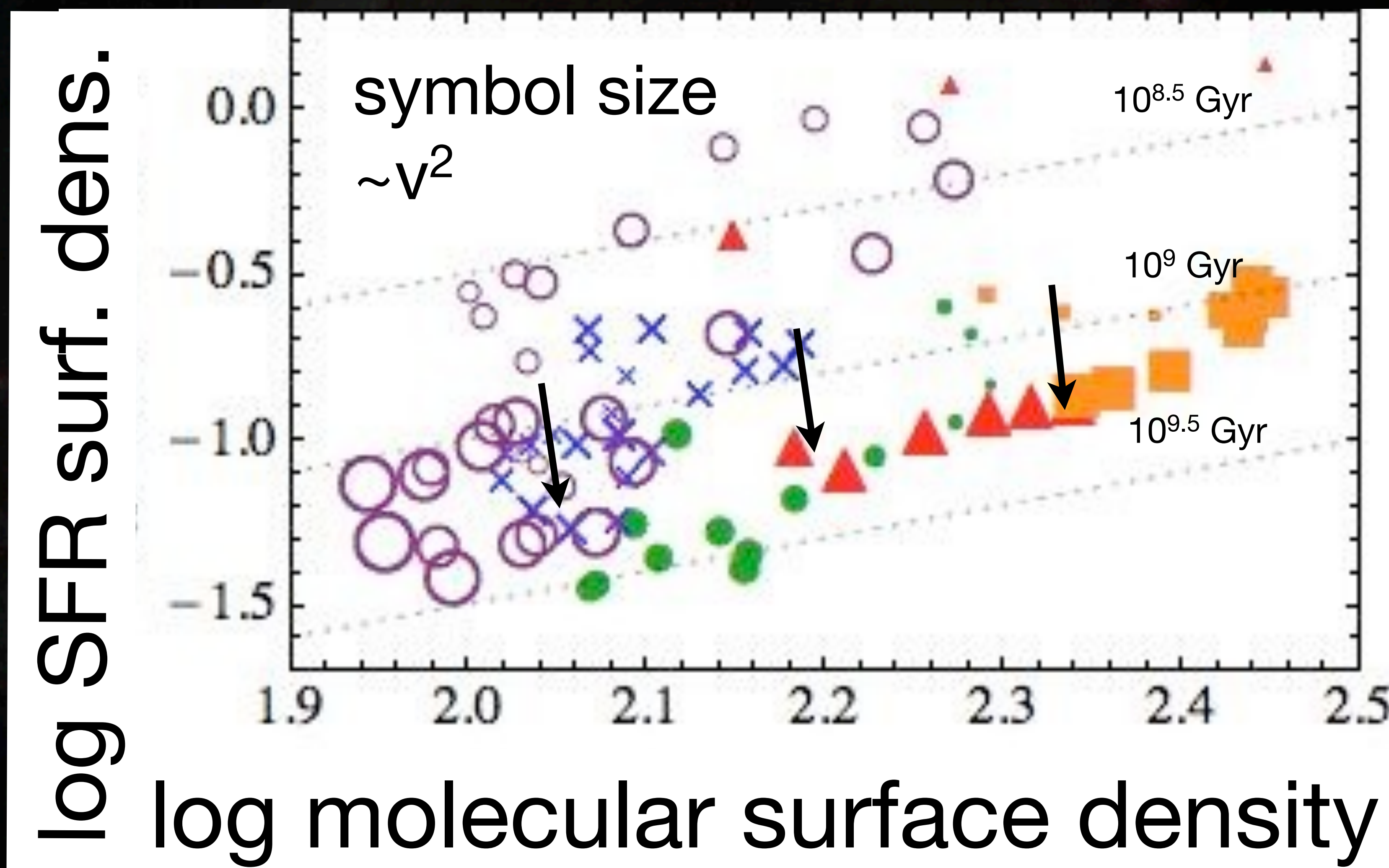
2. Do extragalactic GMCs have uniform physical properties? **No.**

3. Do gas flows impact cloud equilibrium ? **Yes.**

are the ‘normal’ spiral galaxies really normal?

- fiducial τ_{dep} 1 Gyr

lines of constant τ_{dep}



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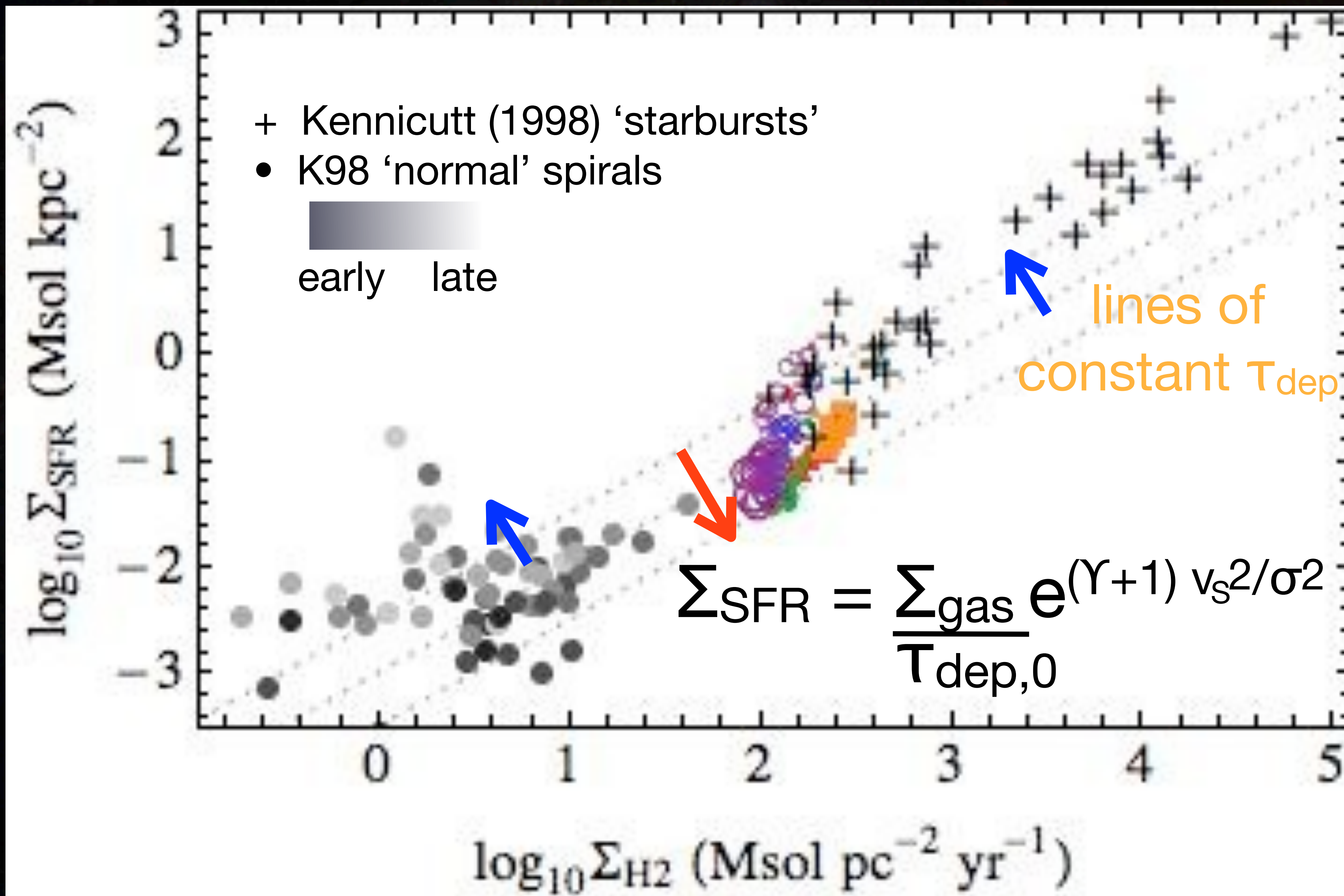
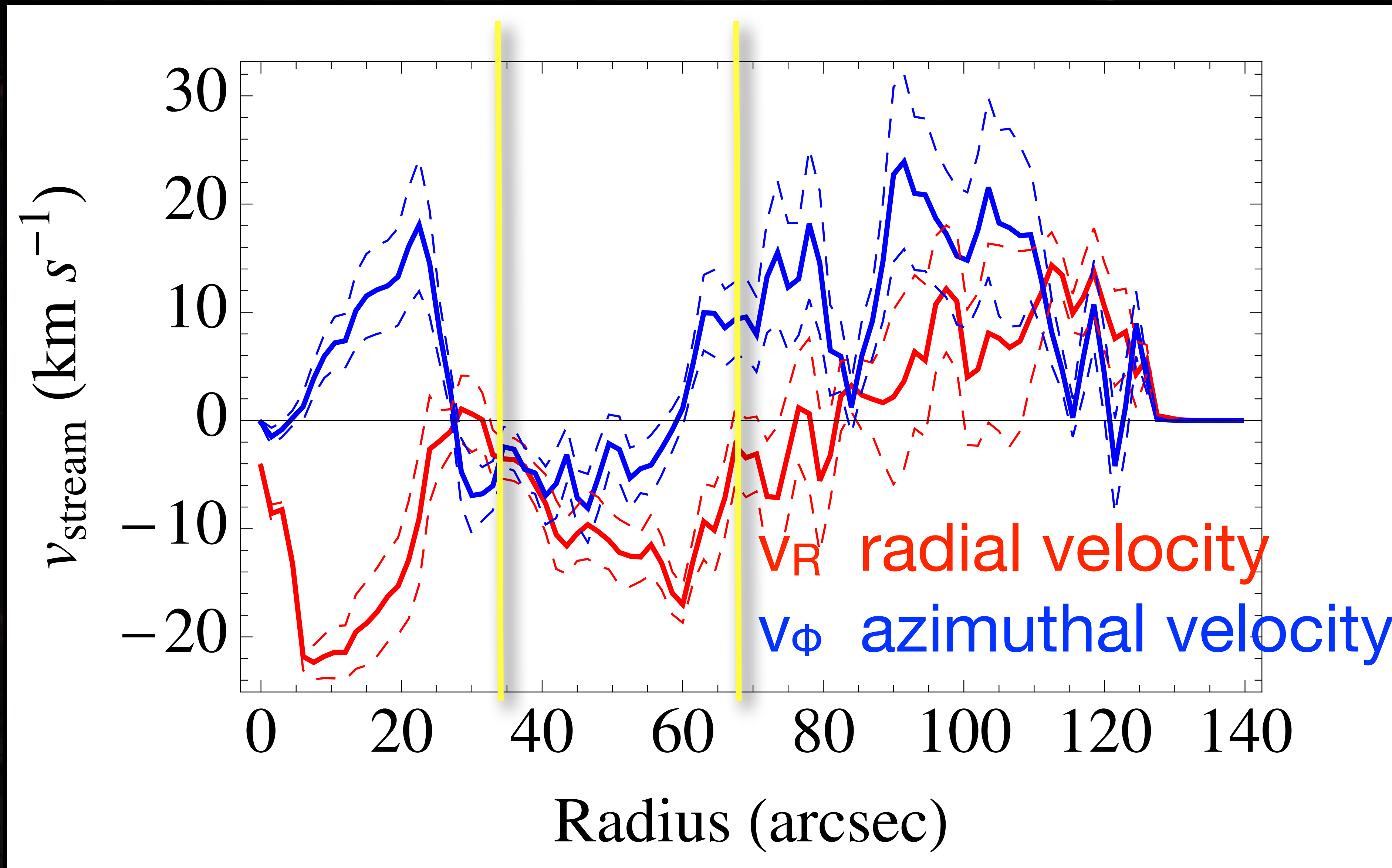


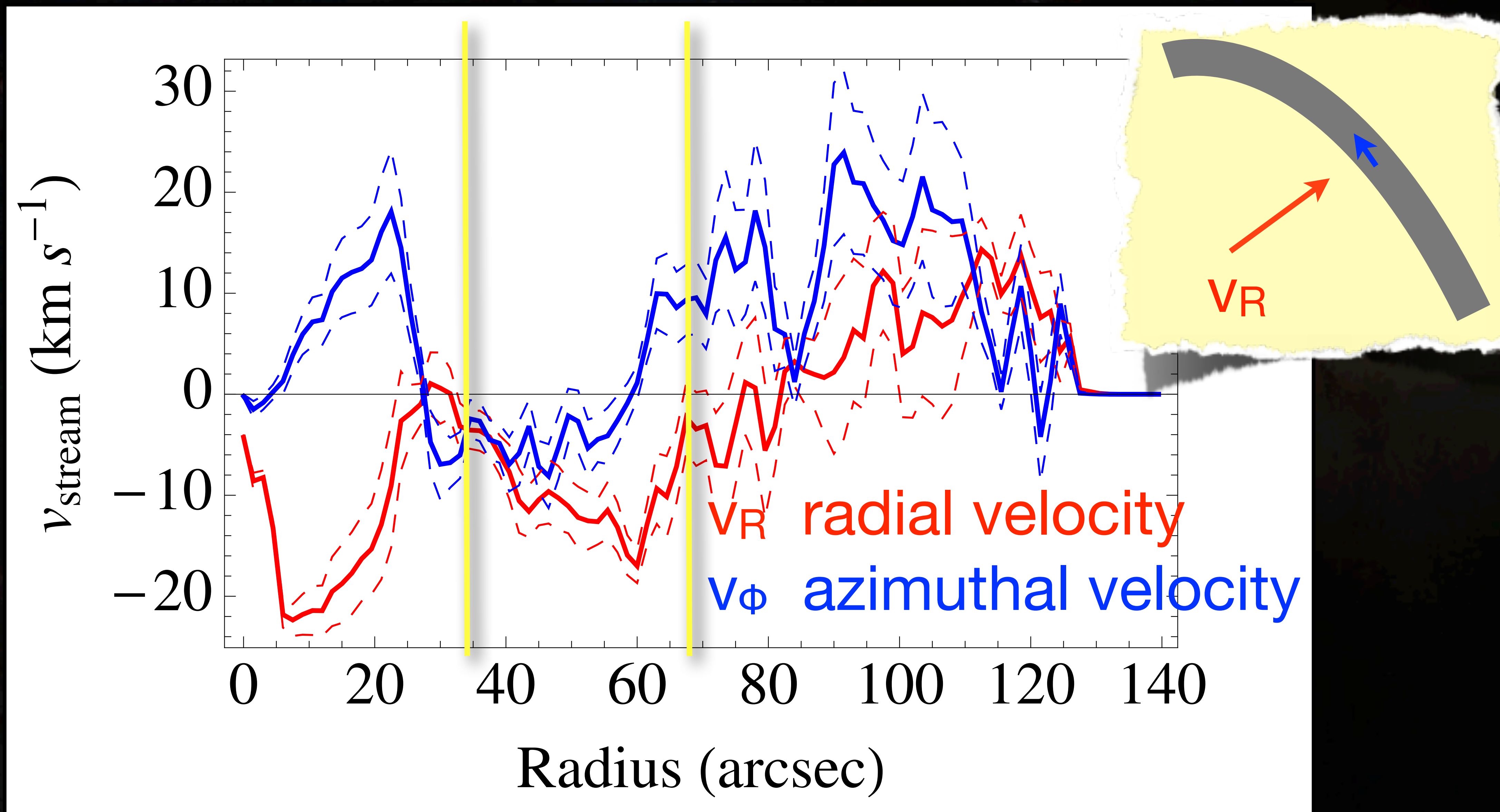
Non-circular streaming motions



V reconstructed from within spiral arm frame (assuming constant i_p)

(Note: shear~ $d\, v_\Phi / dR$)

Non-circular streaming motions



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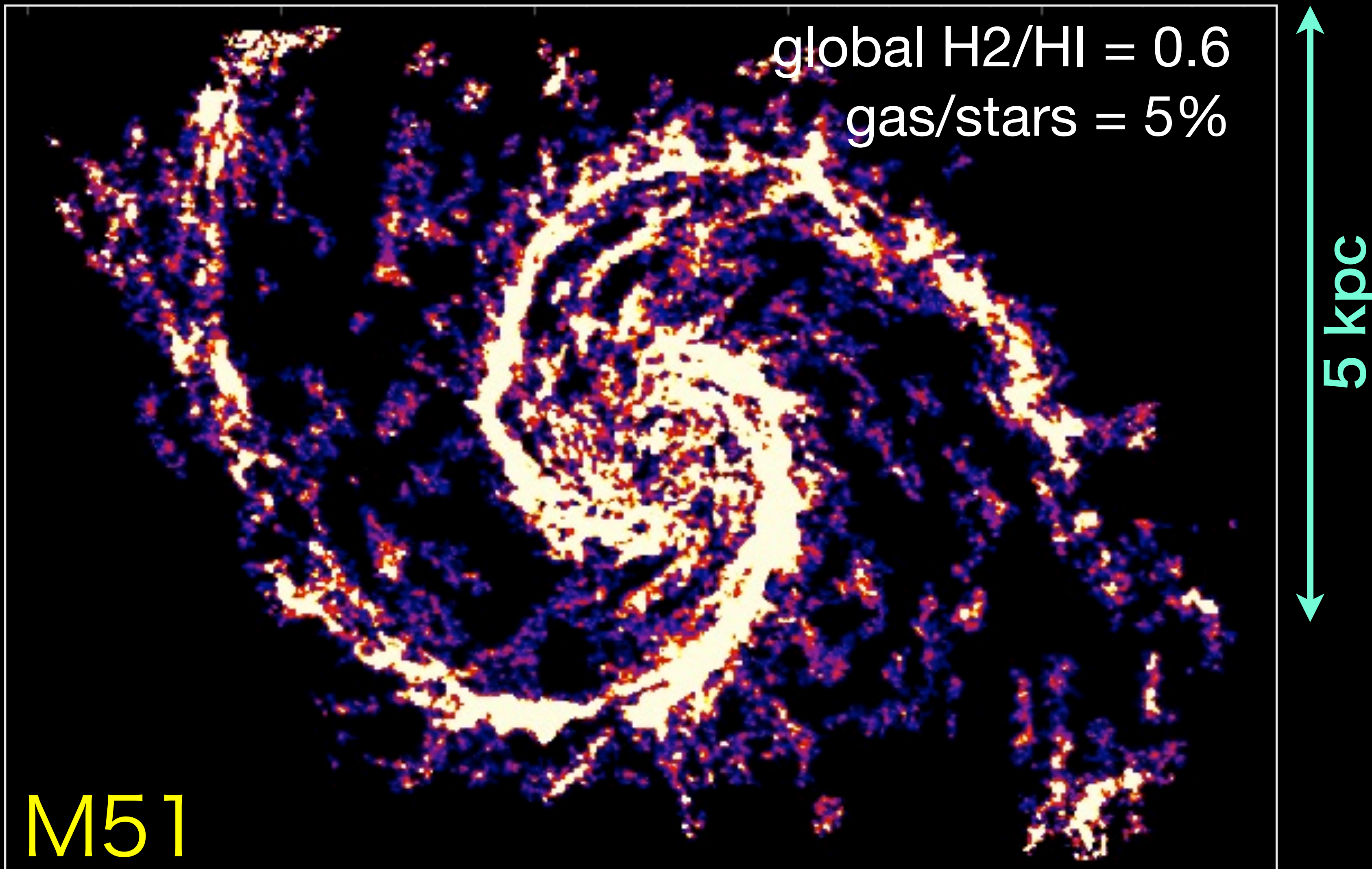
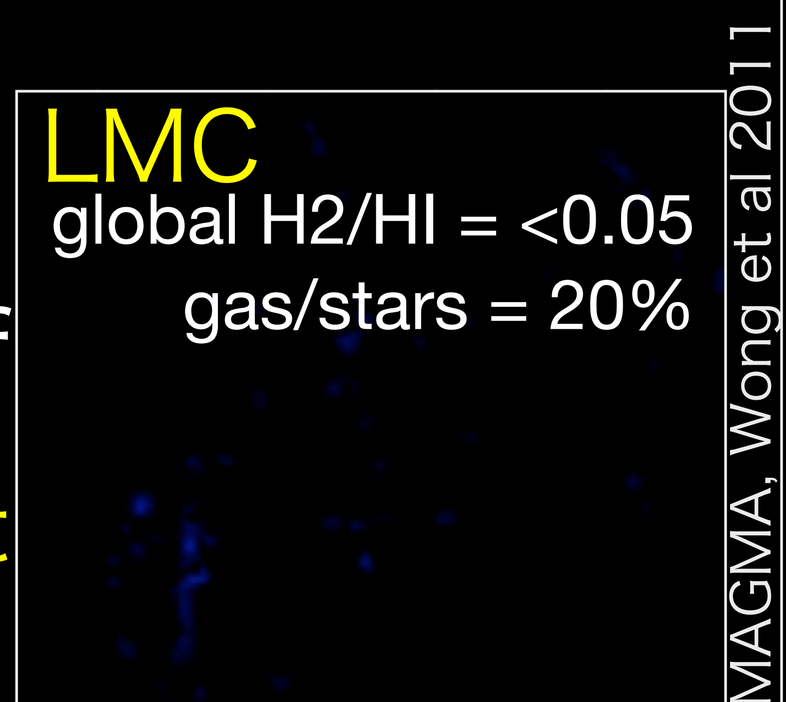
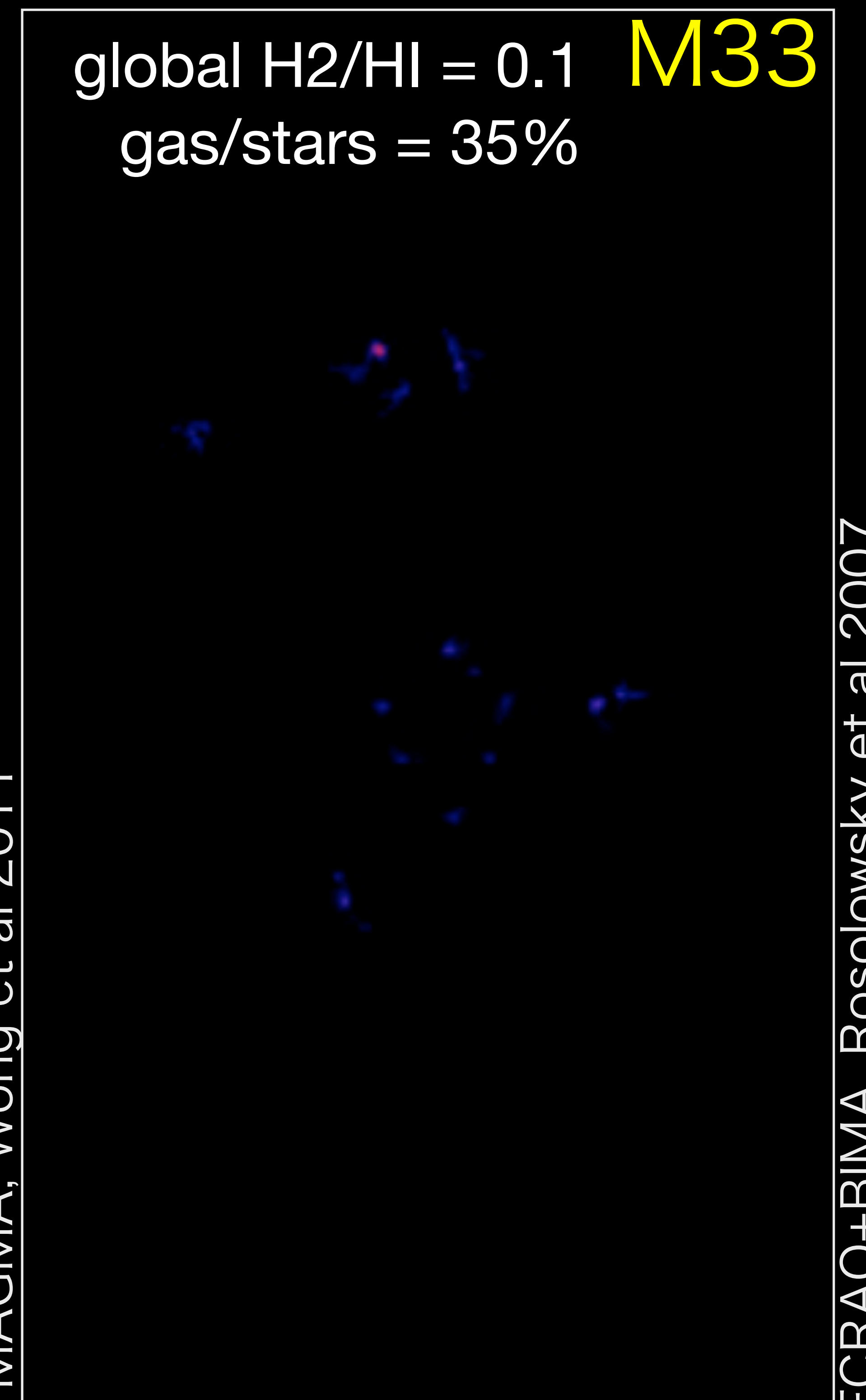


Properties of GMCs in M51 vs two nearby dwarf galaxies (Hughes et al., 2013, in prep)





diff. cloud 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

cloud decomposition

bottom up

top down

diff. cloud properties

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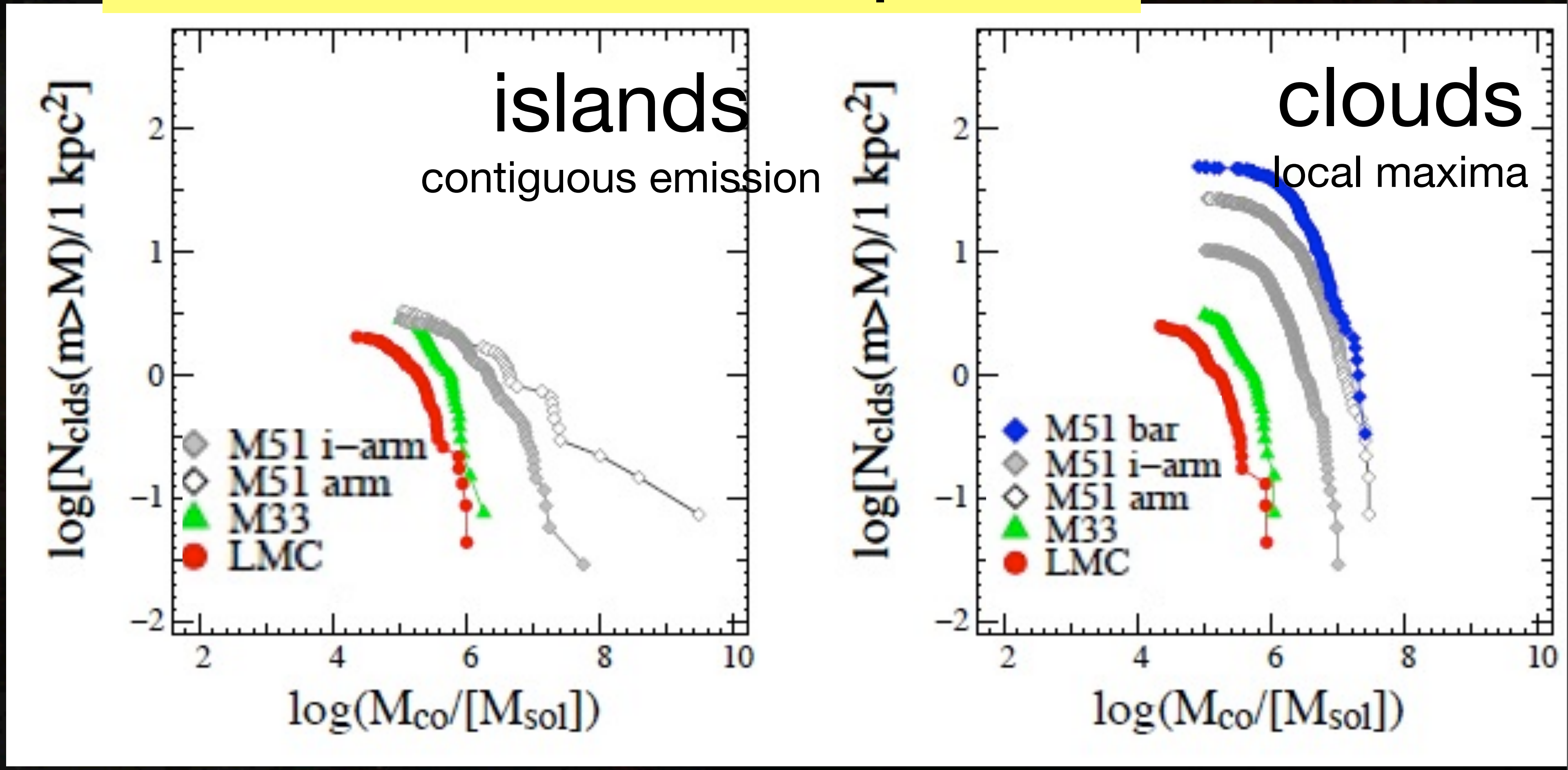

Hughes et al. 2013
Colombo et al. 2013

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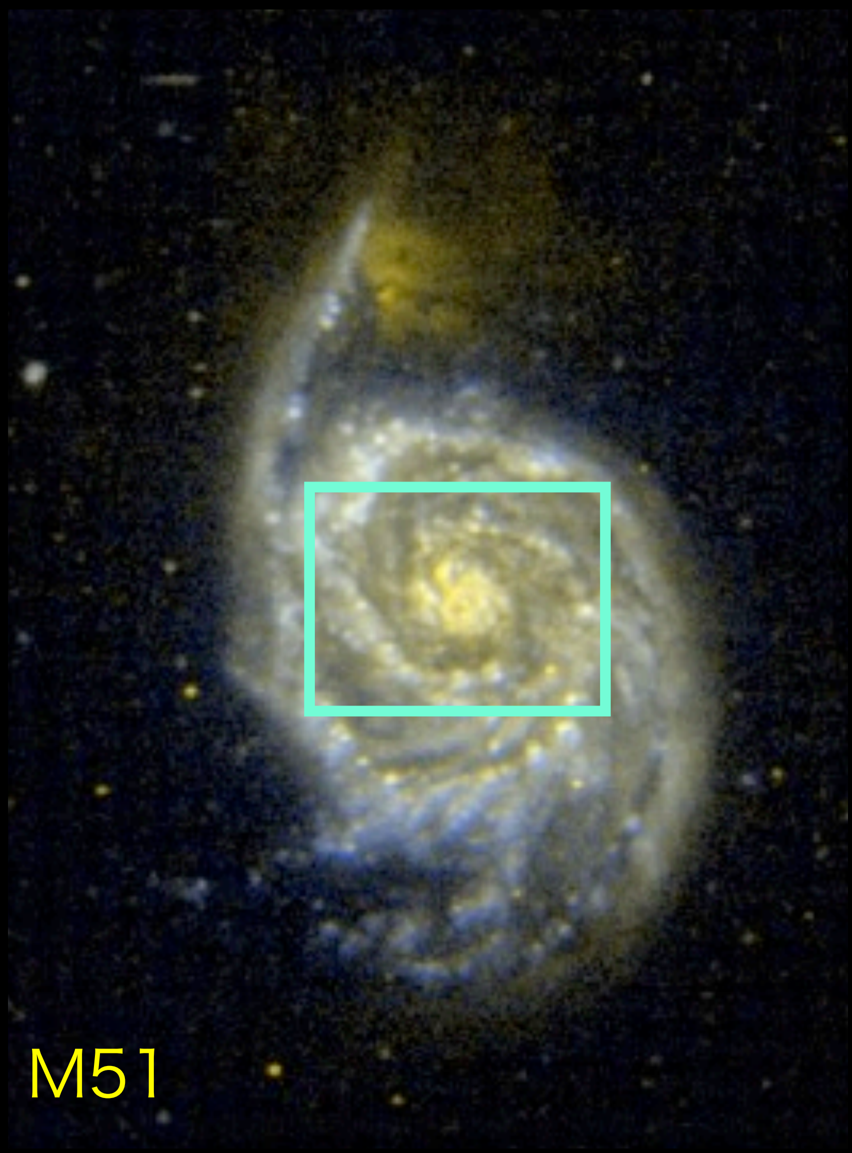
GALEX, Gil de Paz et al 2006



MCELS, Smith et al 1999

GALEX, Gil de Paz et al 2006

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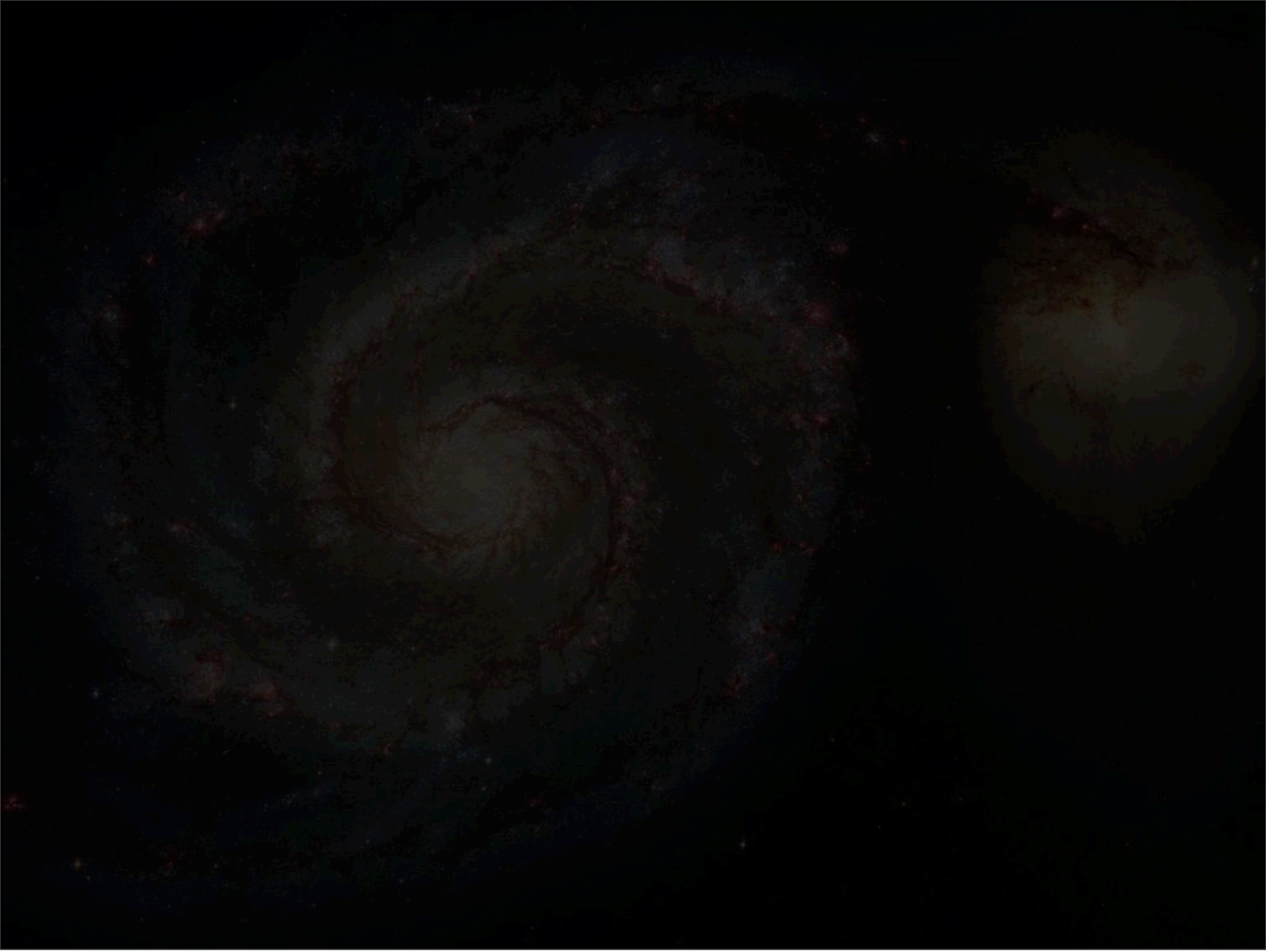
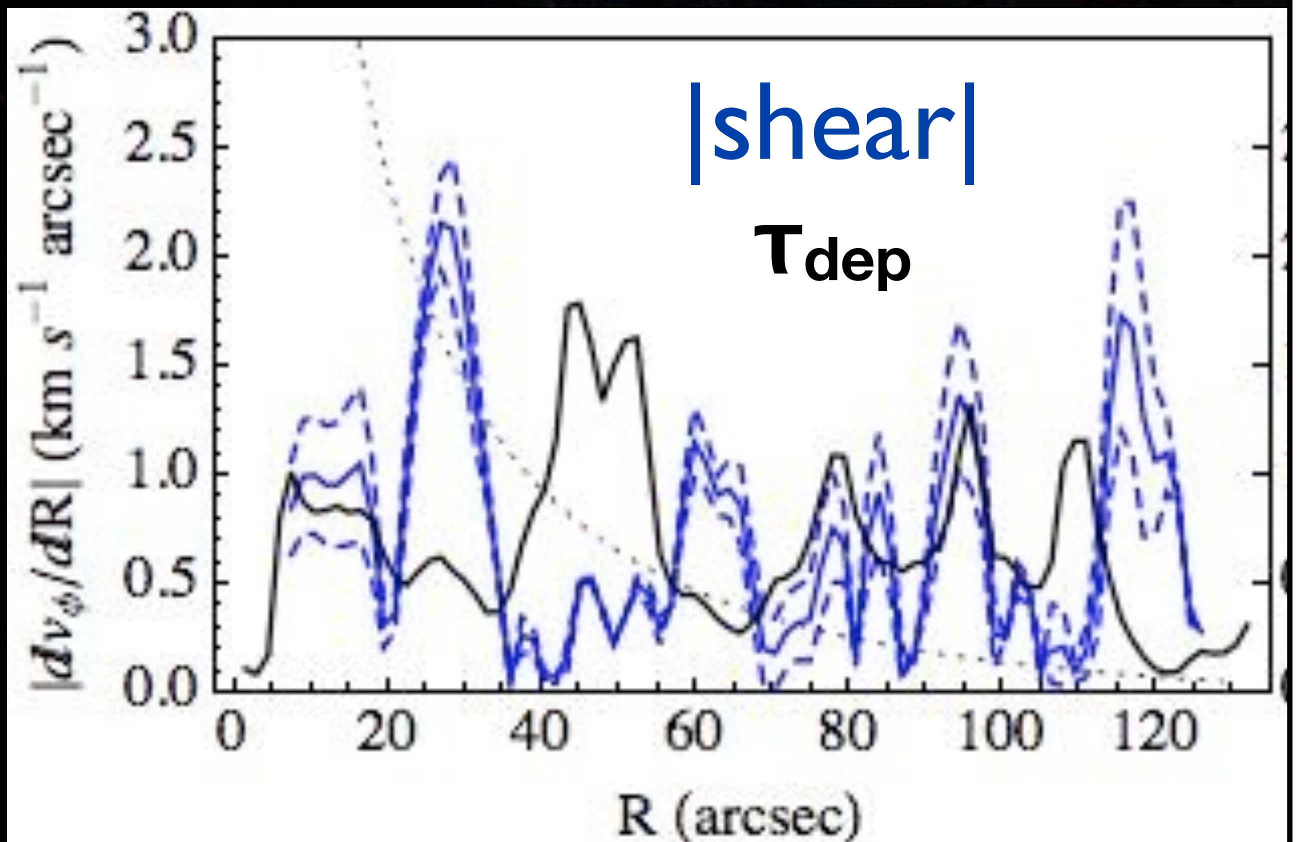
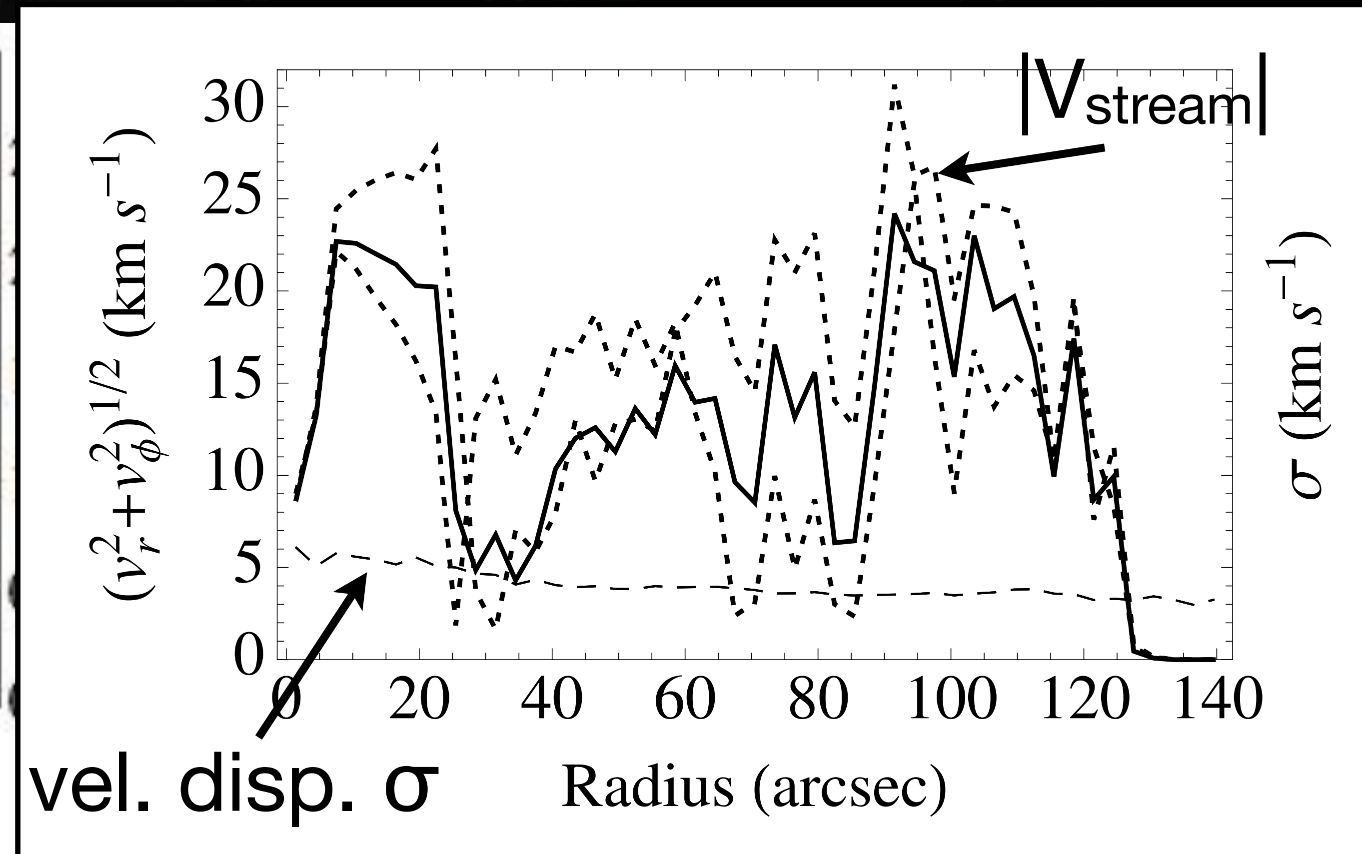
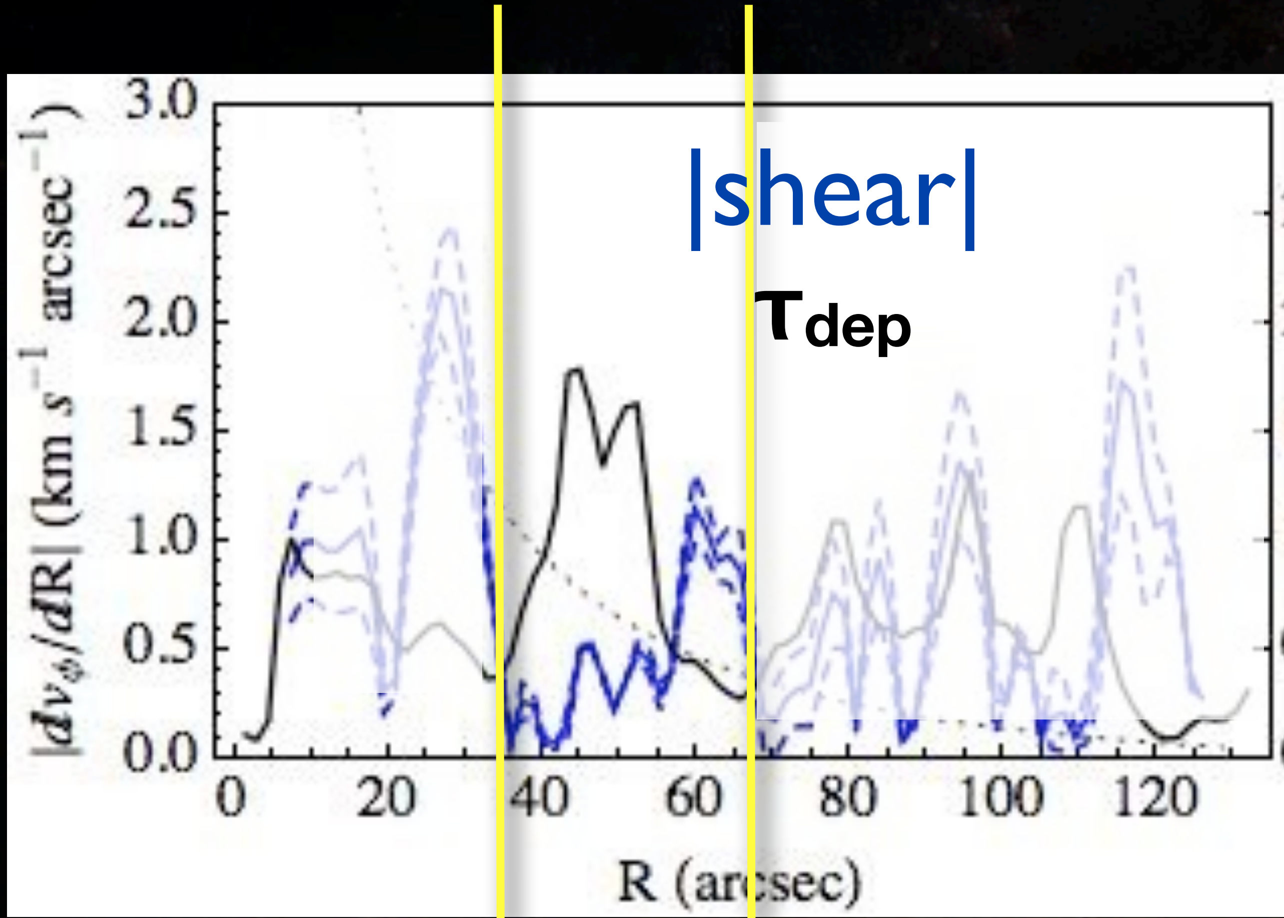


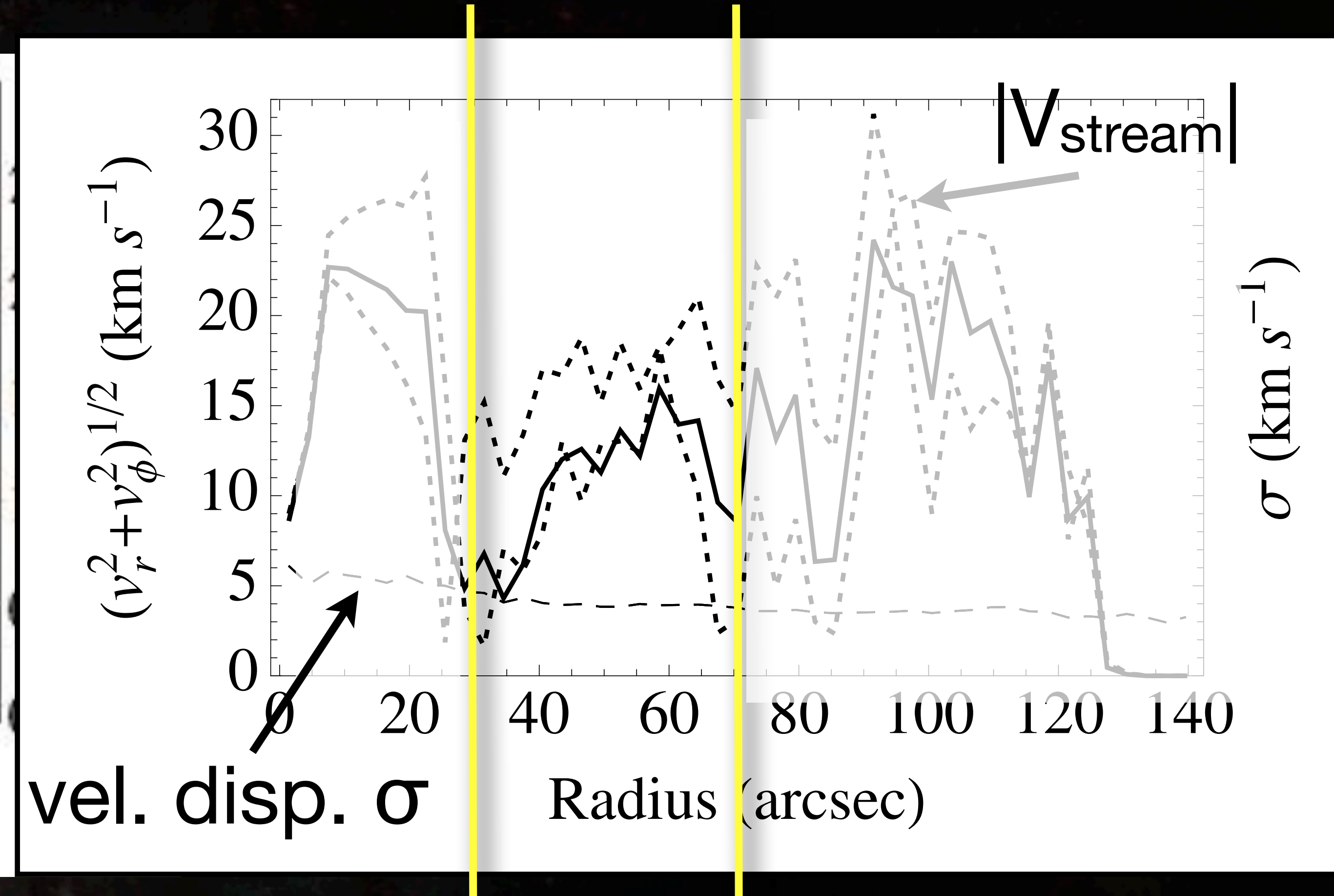




- support *not* from
  - shear (=*d*ln v_Φ/*d*lnR; cf. Dib & Helou 2012)
  - turbulent motions (regular σ along spiral)
  - stellar feedback

\+ arm shocks regular (Shetty et al. 2008)





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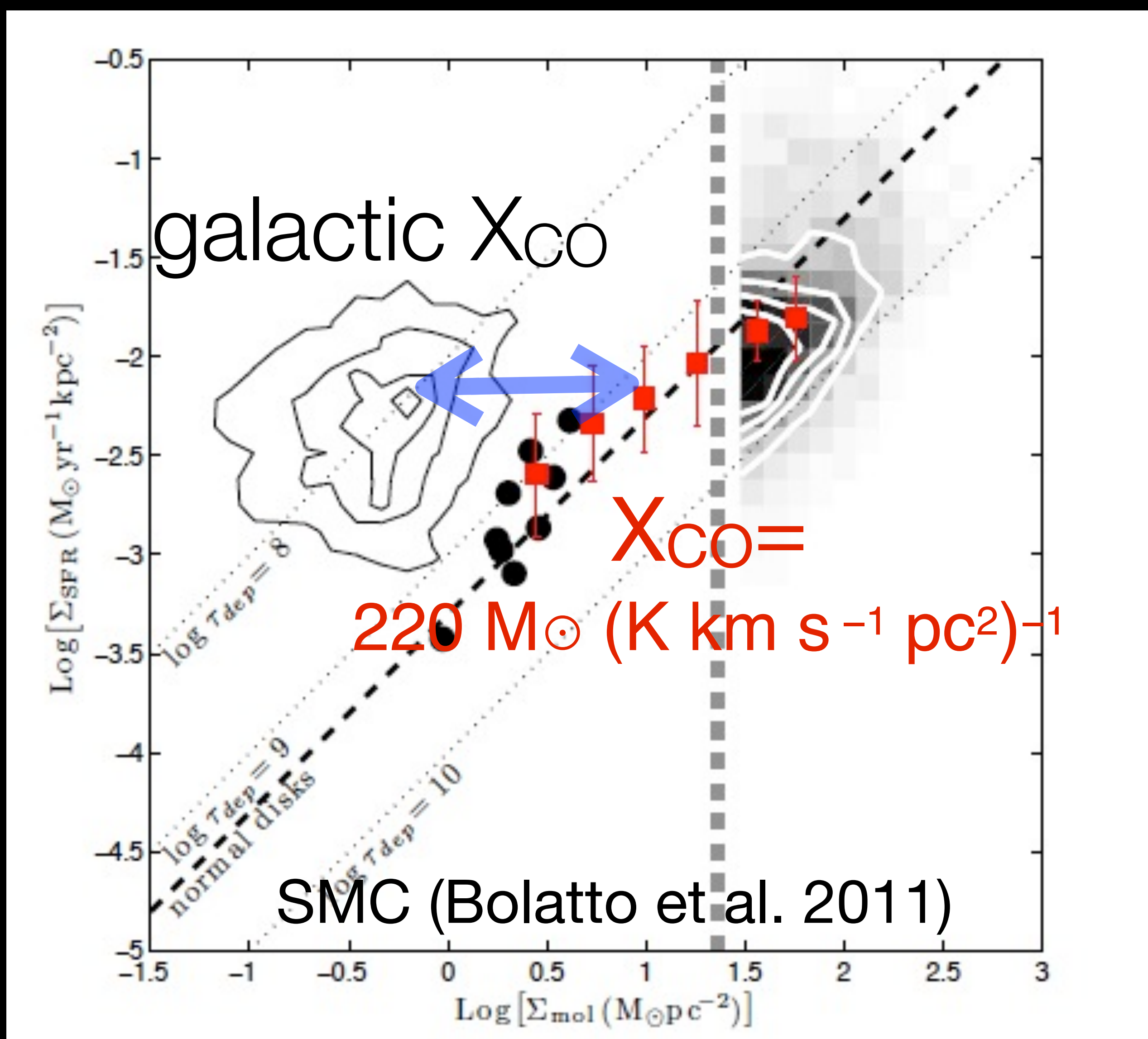
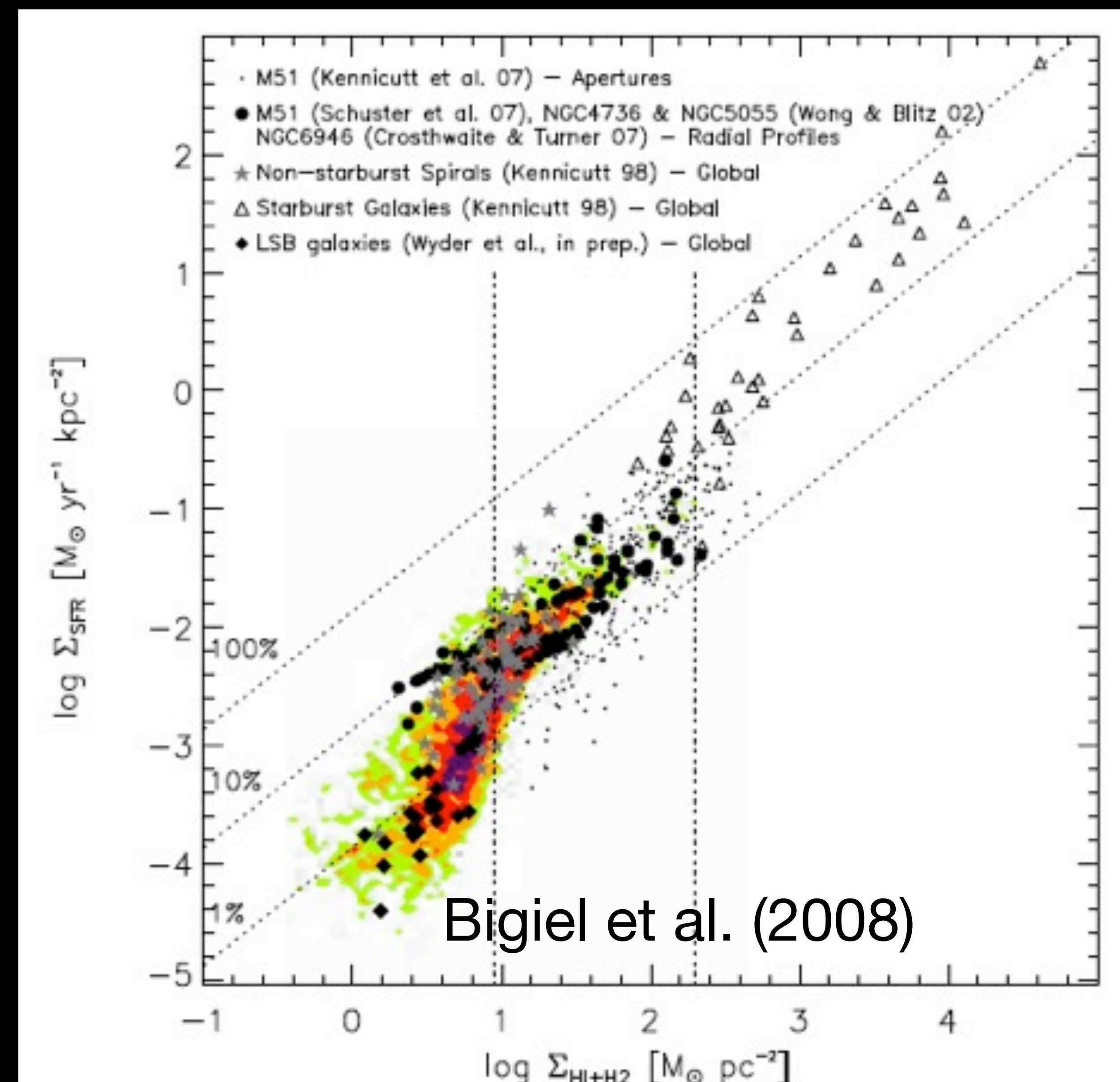

galactic XCO
XCO=
220 M⊙ (K km s⁻¹ pc²)⁻¹
log τdep = 8
log τdep = 9
normal disks
log τdep = 10
Log[ΣSFR (M⊙ yr⁻¹ kpc⁻²)]
Log[Σmol (M⊙ pc⁻²)]
SMC (Bolatto et al. 2011)


M51 (Kennicutt et al. 07) – Apertures
M51 (Schuster et al. 07), NGC4736 & NGC5055 (Wong & Blitz 02)
NGC6946 (Crosthwaite & Turner 07) – Radial Profiles
Non–starburst Spirals (Kennicutt 98) – Global
Starburst Galaxies (Kennicutt 98) – Global
LSB galaxies (Wyder et al., in prep.) – Global
100%
10%
1%
log ΣSFR [M⊙ yr⁻¹ kpc⁻²]
log ΣHI+H2 [M⊙ pc⁻²]
Bigiel et al. (2008)

from slope

cloud mass spectrum index γ

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

$\langle\gamma\rangle = -1.7 \pm 0.25$

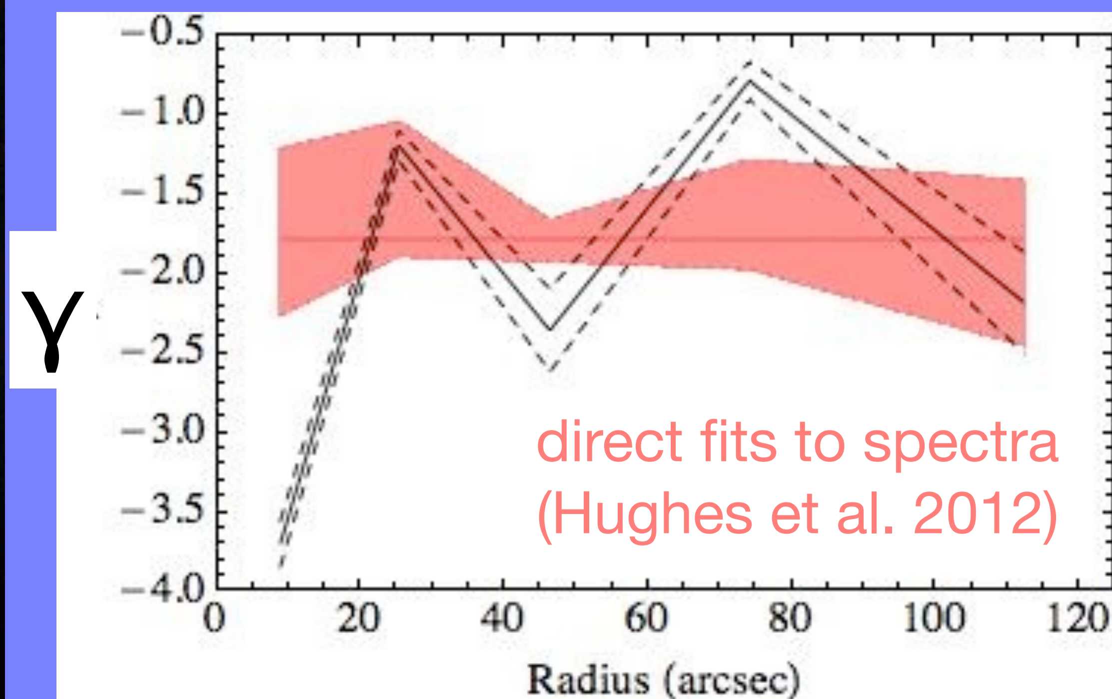
direct fits to spectra
(Hughes et al. 2012)

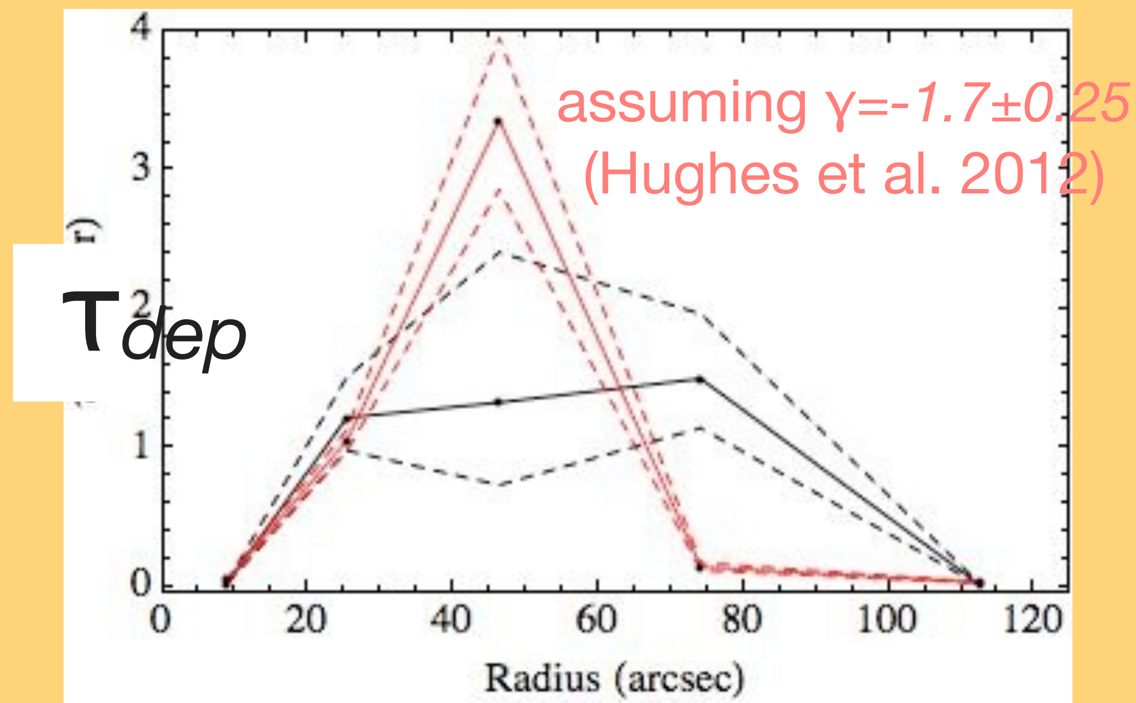
assuming $\gamma = -1.7 \pm 0.25$
(Hughes et al. 2012)

fiducial gas depletion time τ_{dep}

from y-intercept

cloud mass spectrum index γ





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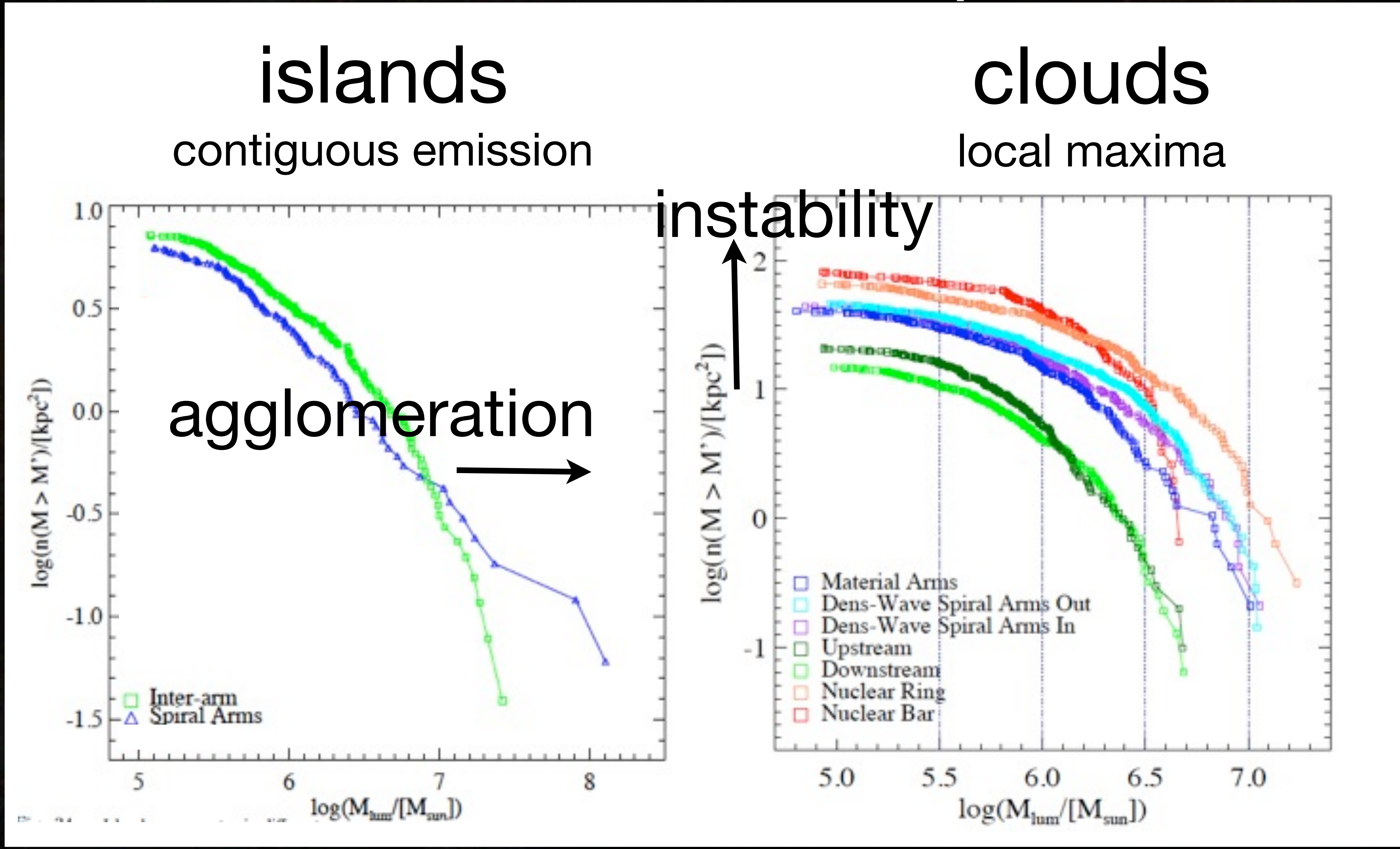
from y-intercept

molecular cloud formation in M51

- 50% of CO emission in cloud structures
- GMC properties vary as a function of environment Colombo et al., 2012, in prep

shapes +normalization different!

cumulative mass spectra



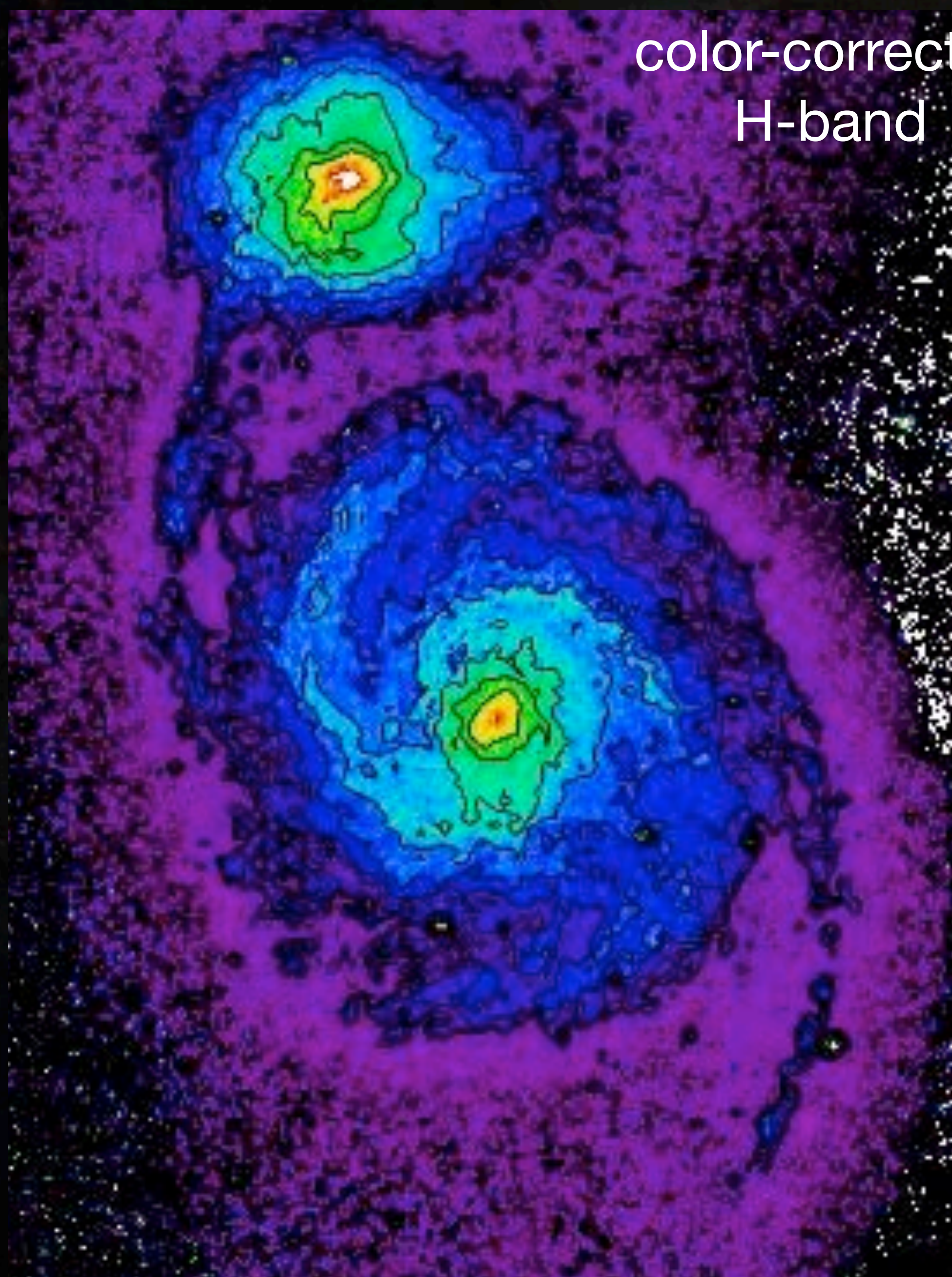
mass fraction of collapse unstable clouds→SFE

Stellar Mass+potential

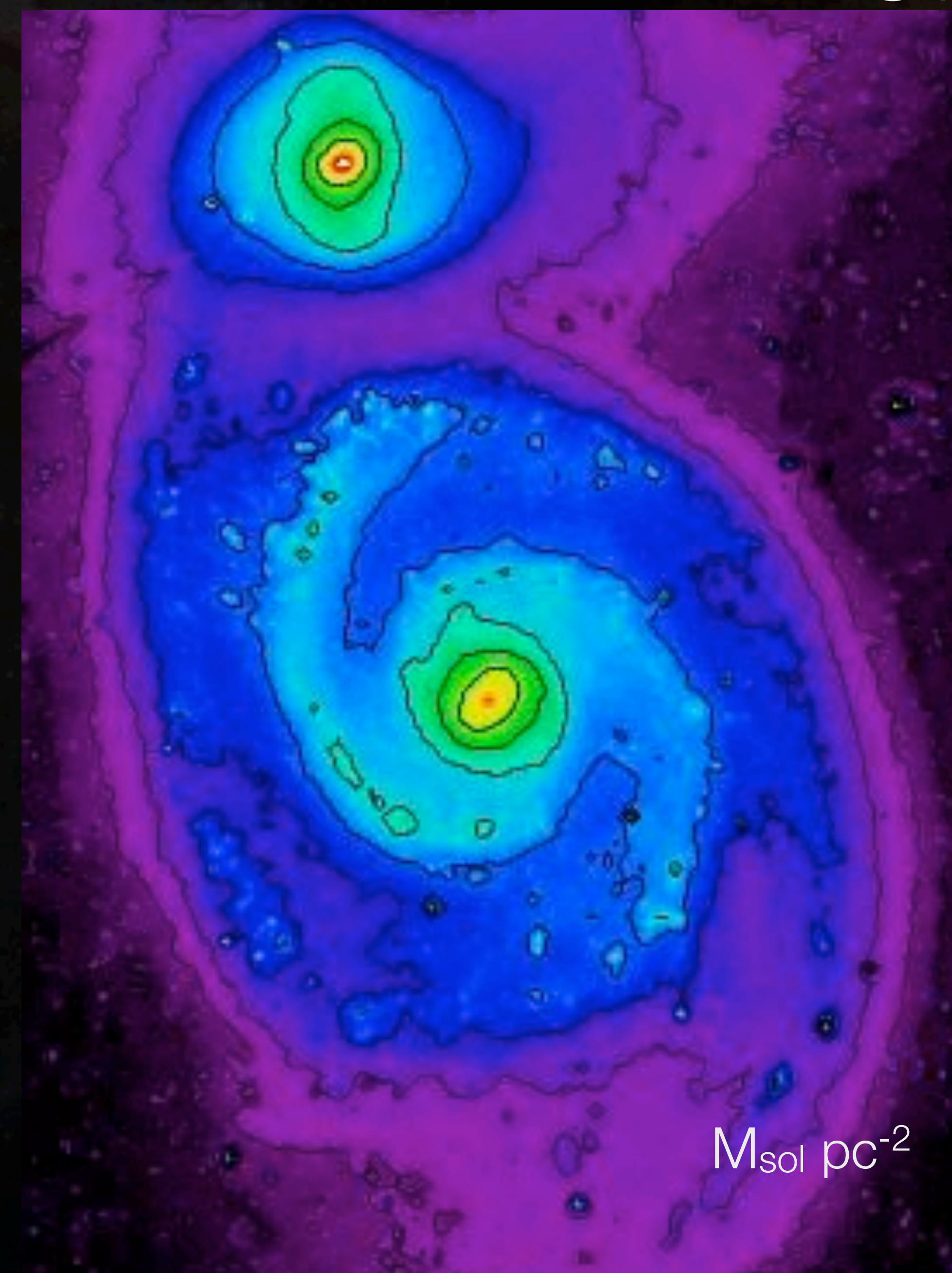
so is it a density wave, or not?

Σ_{Z09}

color-corrected H-band



Σ_{S4G}



Stellar Mass+potential

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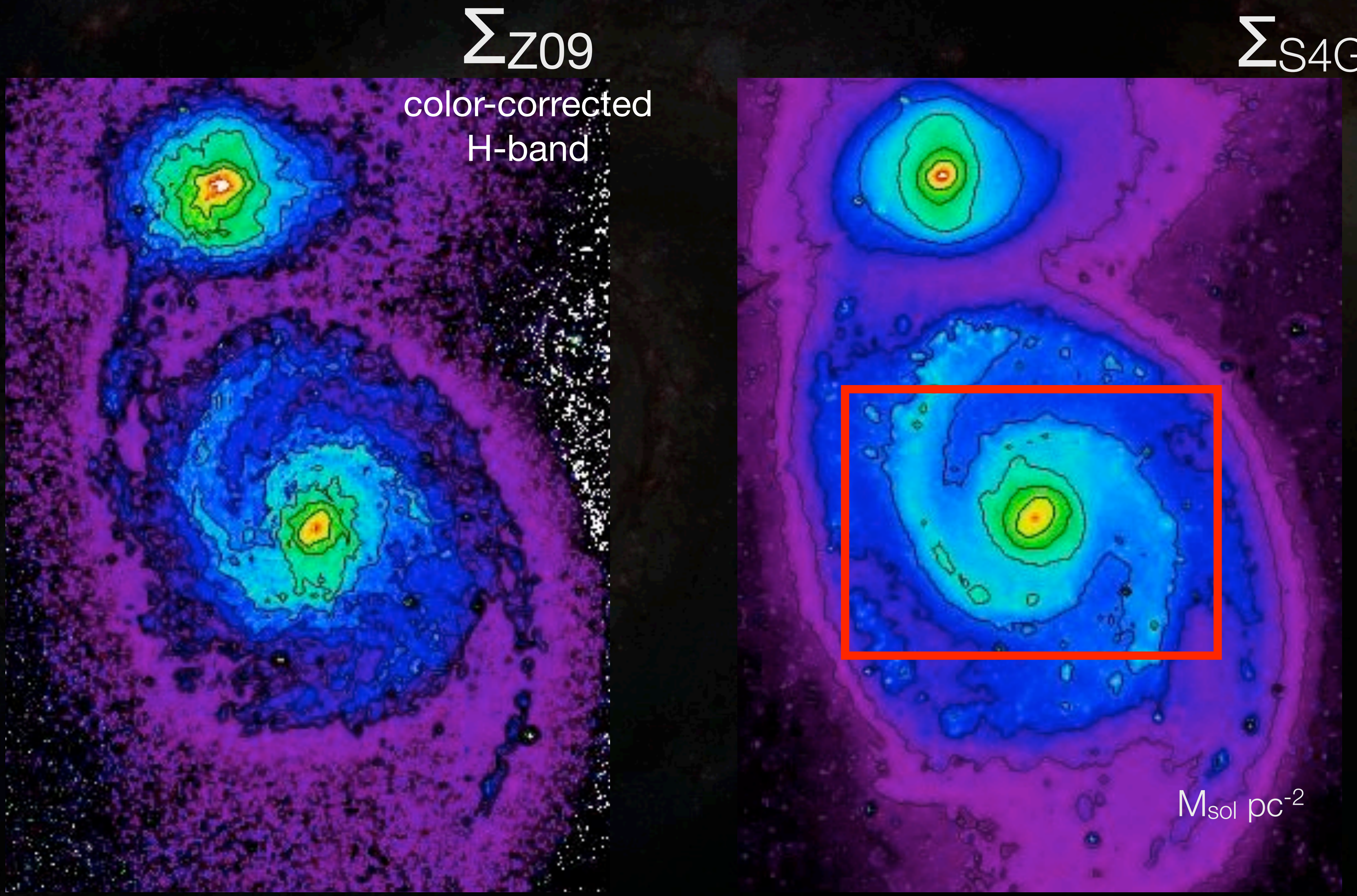

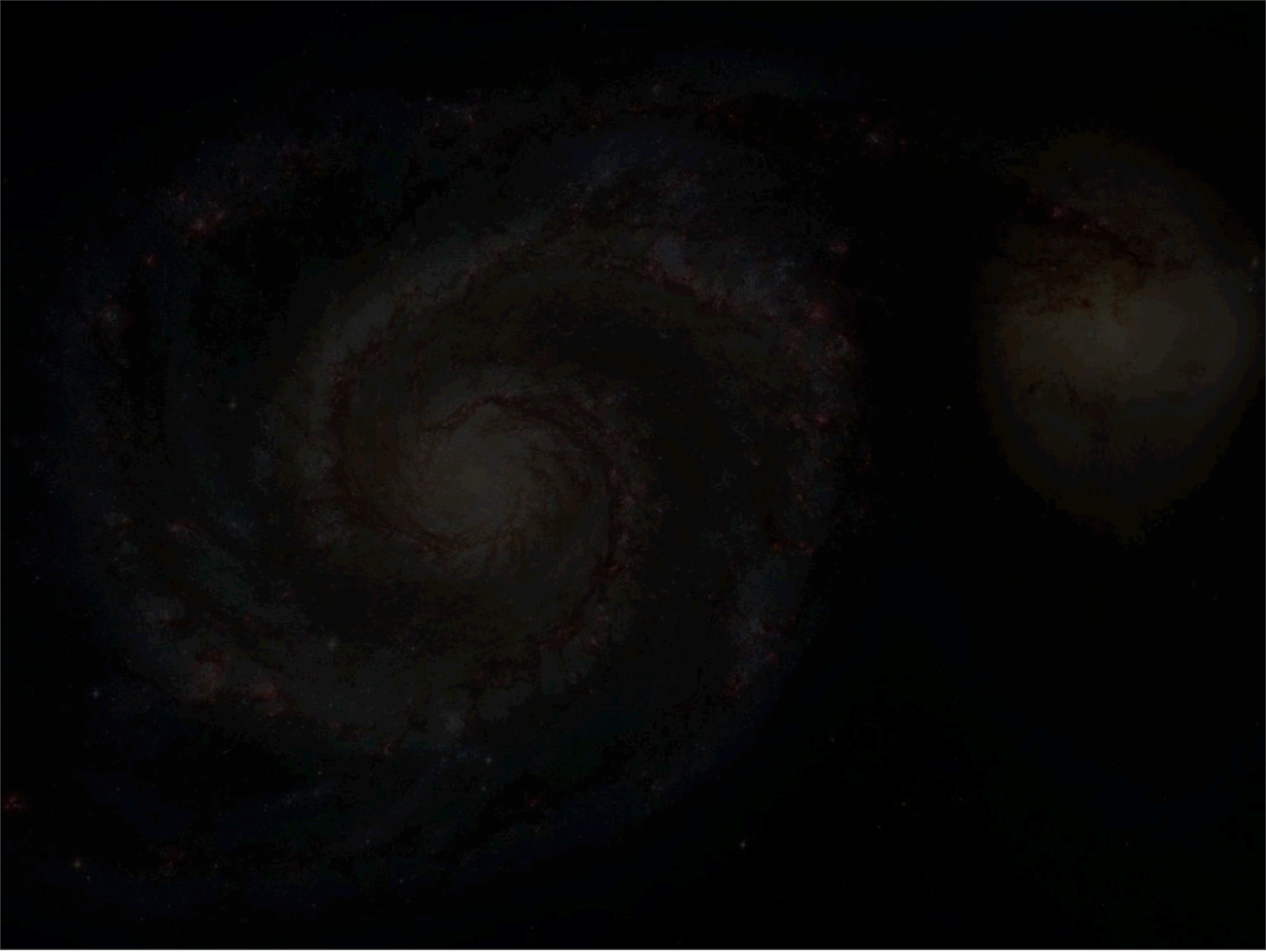

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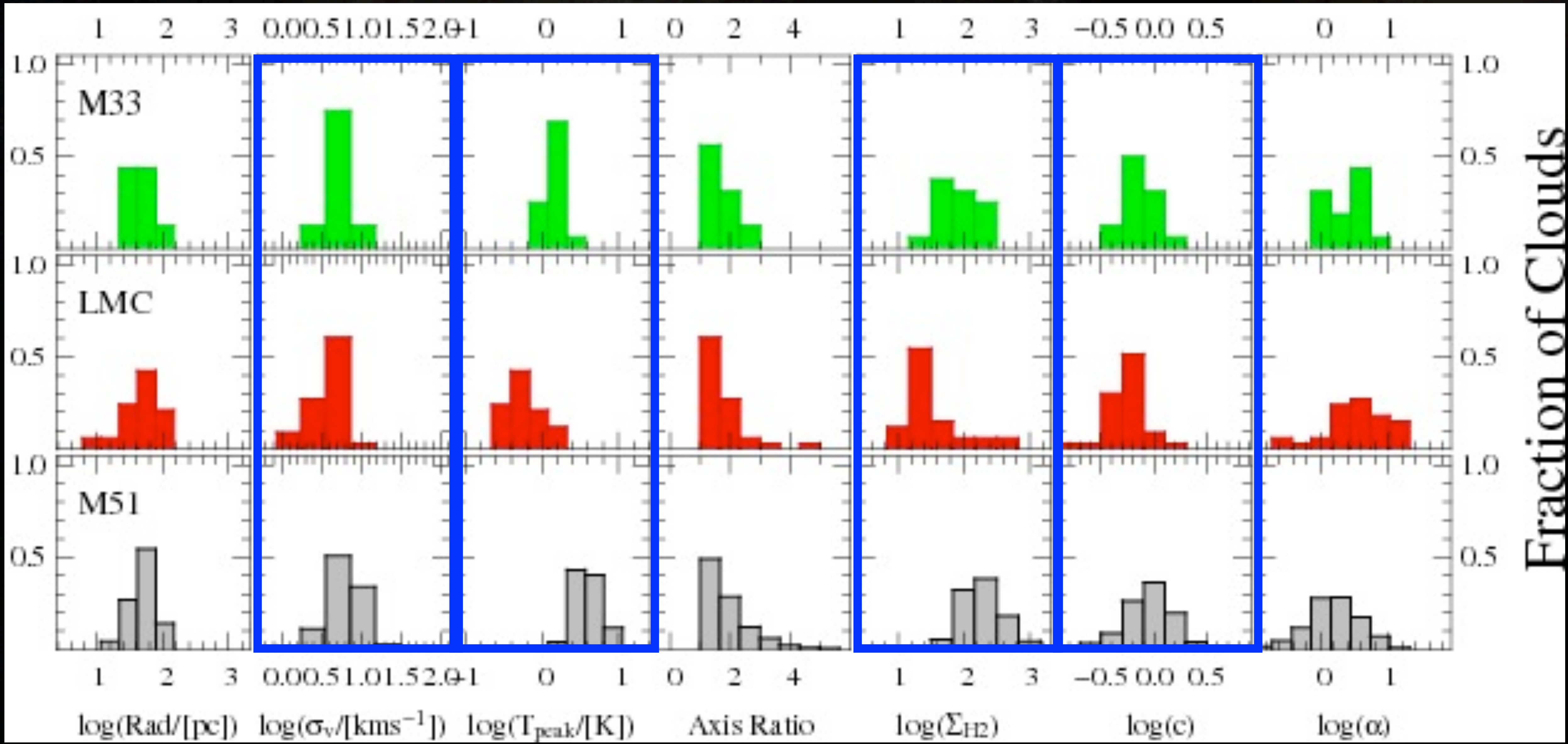
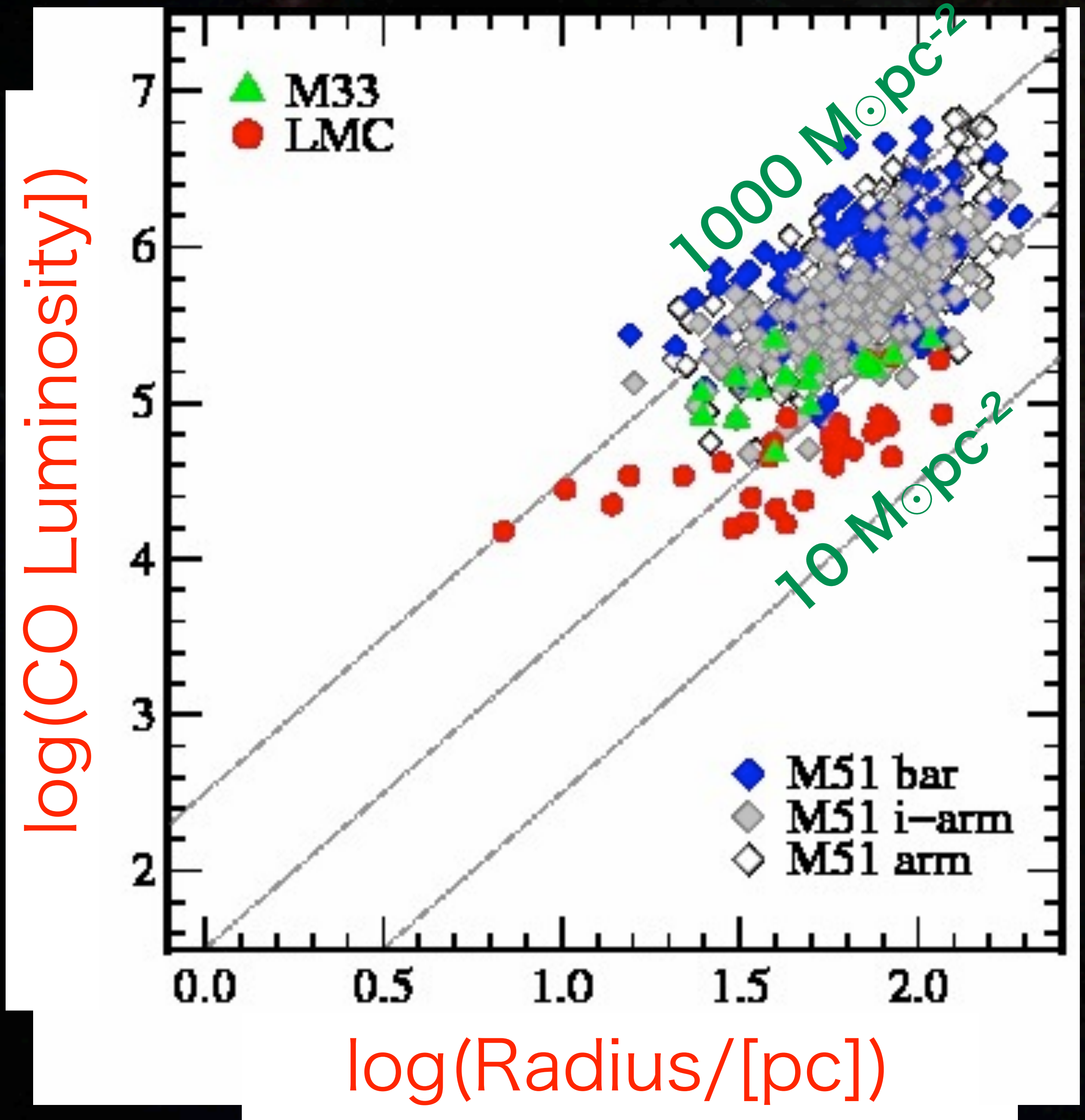
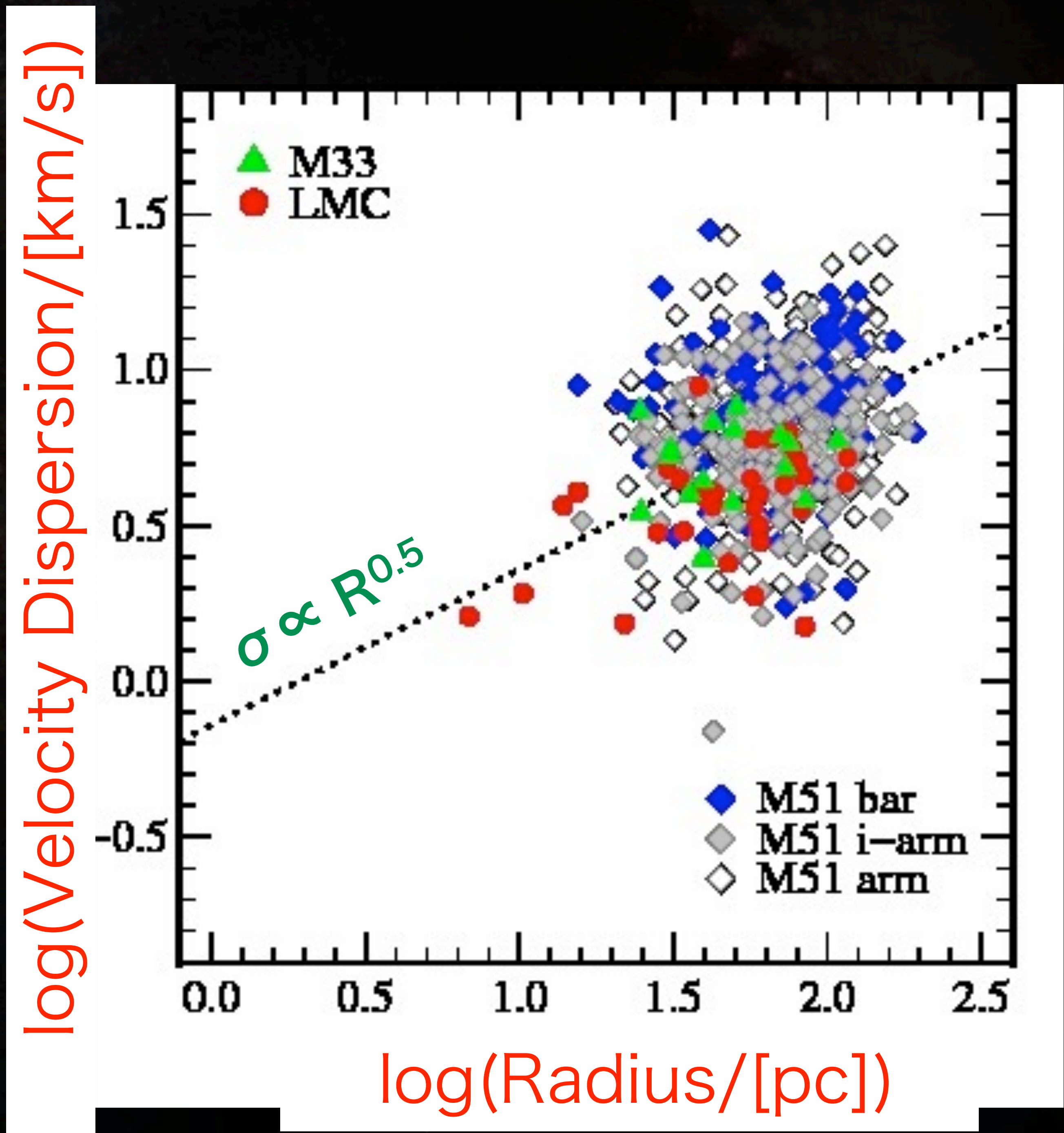




Property	M51	LMC	M33
Type	SA(s)bc pec	SB(s)m	SA(s)cd
Distance	7.6 Mpc	50.1kpc	0.84 Mpc
12 + log[O/H]	8.54	8.26	8.36
SFR [$M_\odot yr^{-1}$]	6	0.2	0.4
Global H_2/HI	0.6	<0.05	0.1
Global Gas/Stars	5%	20%	20 to 50%
Σ_{H2} [$M_\odot pc^{-2}$]	70	1	10
Σ_{HI} [$M_\odot pc^{-2}$]	10	15	10
Σ_* [$M_\odot pc^{-2}$]	500	50	100

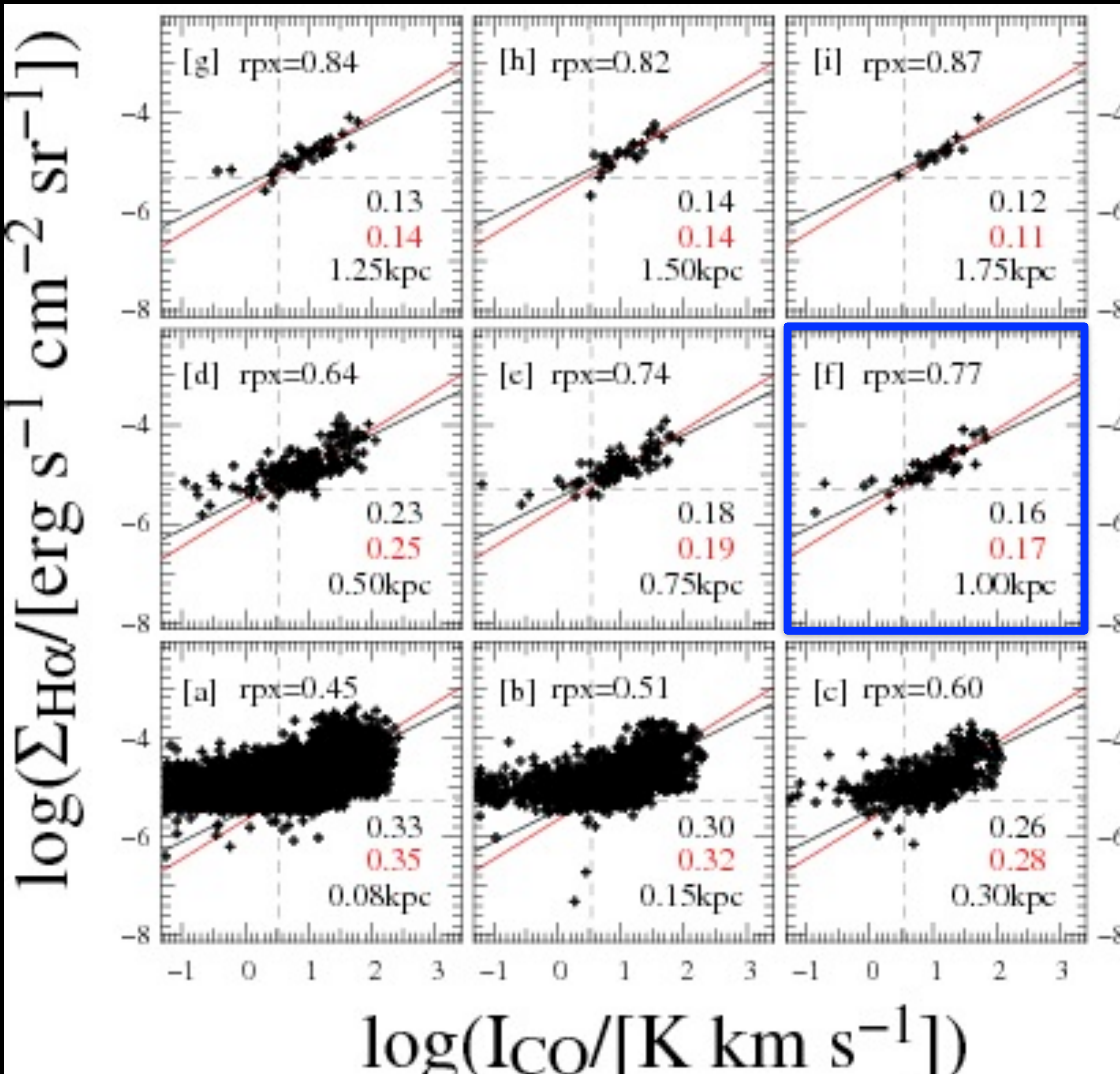
Larson's laws





Region	Total			GMC					
	$^{(1)}S$	$^{(2)}L_{CO}$	$^{(3)}\Sigma$	$^{(4)}L_{CO}^{NX}$	$^{(5)}L_{CO}^{EX}$	$^{(6)}\%^{NX}$	$^{(7)}\%^{EX}$	$^{(8)}\#$	$^{(9)}N$
	$[kpc^2]$	$[10^7\ K\ km/s\ pc^2]$	$M_\odot\ pc^{-2}$	$[10^7\ K\ km/s\ pc^2]$					$[kpc^{-2}]$
Cube	47.00	90.83	84.19	17.81	48.65	19.6	53.6	1507	32.06
NB	1.53	7.48	213.11	1.35	4.01	18.0	53.6	126	82.33
NR	3.15	17.99	248.62	3.37	10.48	18.7	58.2	209	66.28
NS1I	2.36	5.50	101.52	1.09	3.32	19.8	60.2	86	36.40
NS1O	3.46	10.54	132.64	2.12	6.26	20.1	59.4	155	44.78
NS2	2.56	3.50	59.48	0.98	2.38	28.1	68.0	92	35.90
SS1I	2.42	8.21	148.01	1.26	3.98	15.3	48.5	126	52.15
SS1O	3.54	10.13	124.64	2.25	6.01	22.2	59.3	167	47.14
SS2	2.23	5.56	108.88	1.44	3.46	25.9	62.2	103	46.27
DNS	7.74	5.96	33.59	0.85	1.87	14.3	31.3	98	12.67
UNS	5.64	4.54	35.13	0.89	2.11	19.6	46.4	116	20.58
DSS	7.93	6.92	38.04	1.41	2.96	20.4	42.7	135	17.02
USS	4.44	4.45	43.70	0.80	1.83	18.1	41.1	94	21.17

CO & SF tracers in M51



Hughes, Leroy et al., in prep