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

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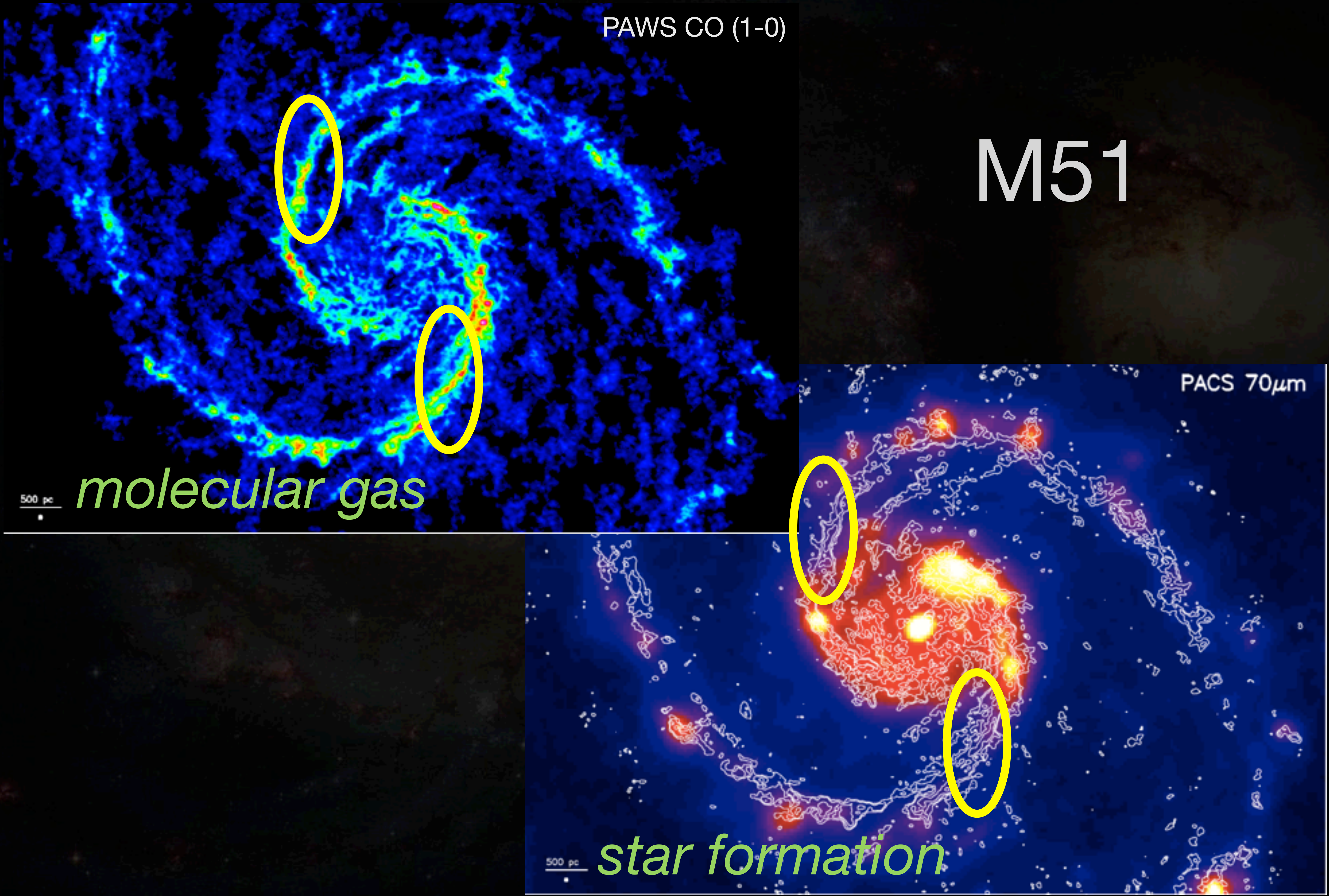
PAWS
PdBI Arcsecond Whirlpool Survey

M51


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

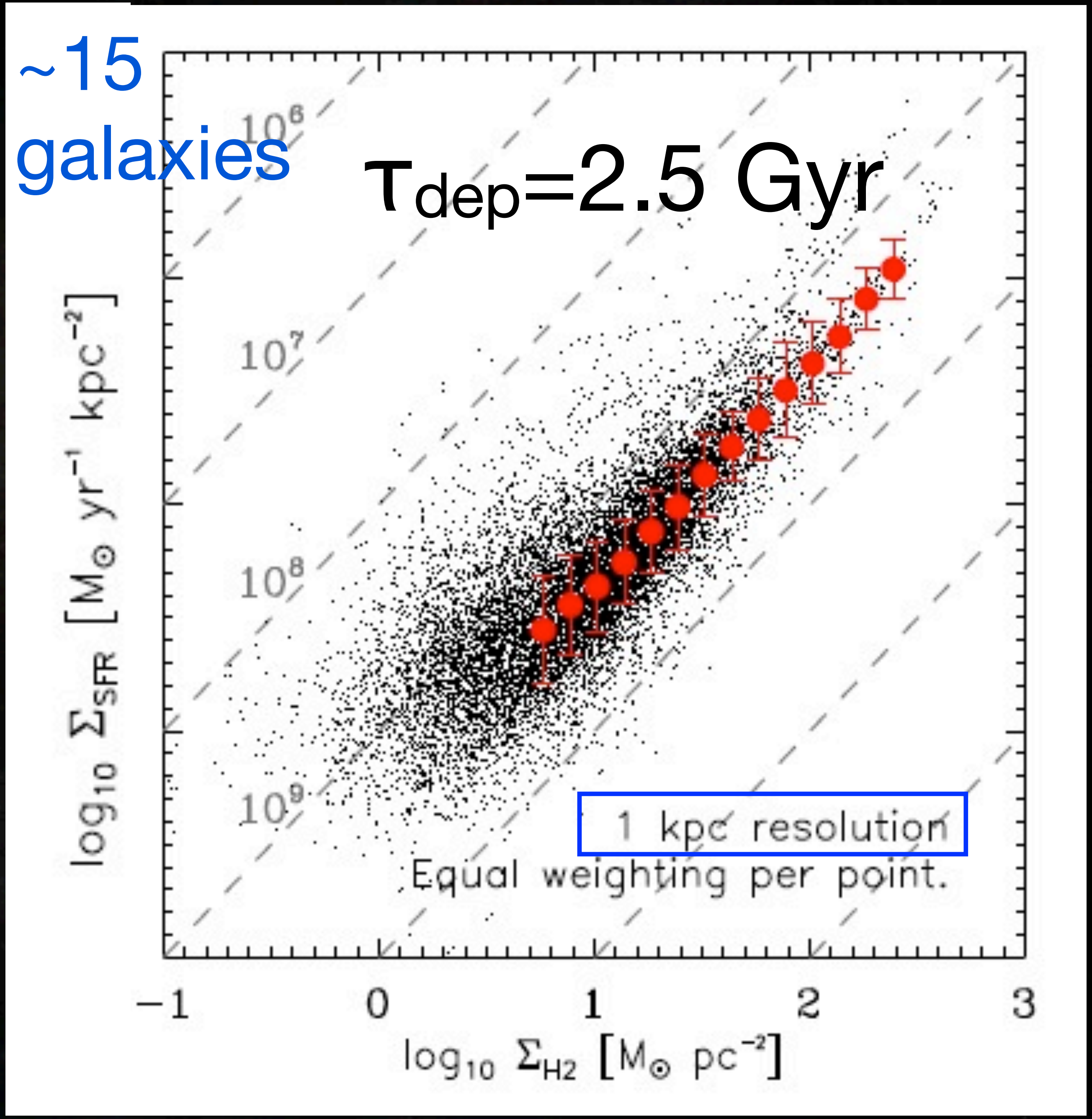
(sub-)kpc star formation relation

Bigiel et al. (2008;2011)

molecular gas depletion time

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

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



~15 galaxies

τ_{dep}=2.5 Gyr

1 kpc resolution

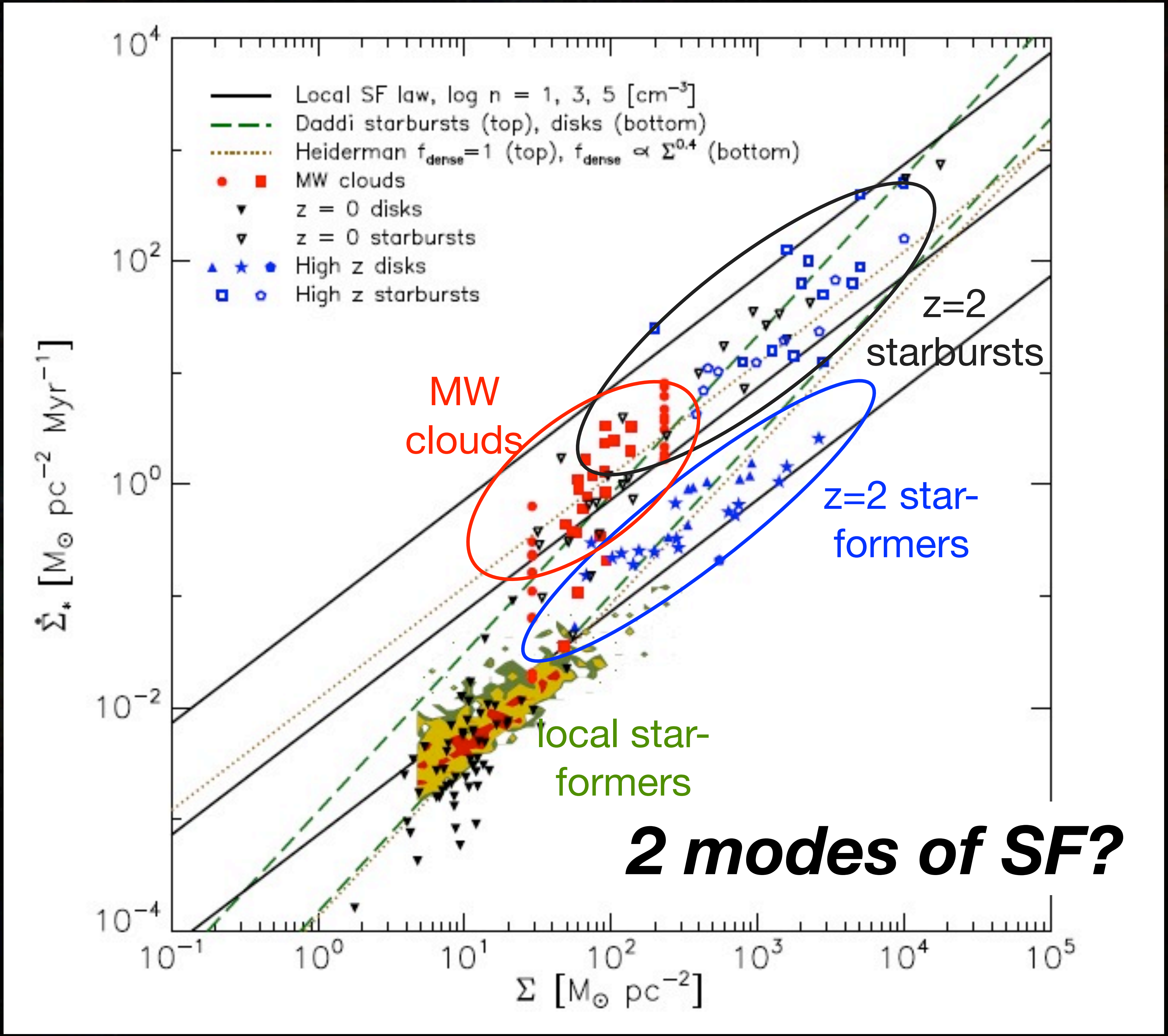
$\Sigma_{SFR}=\Sigma_{H2}^{n}$

n=1

≠1.4-1.5

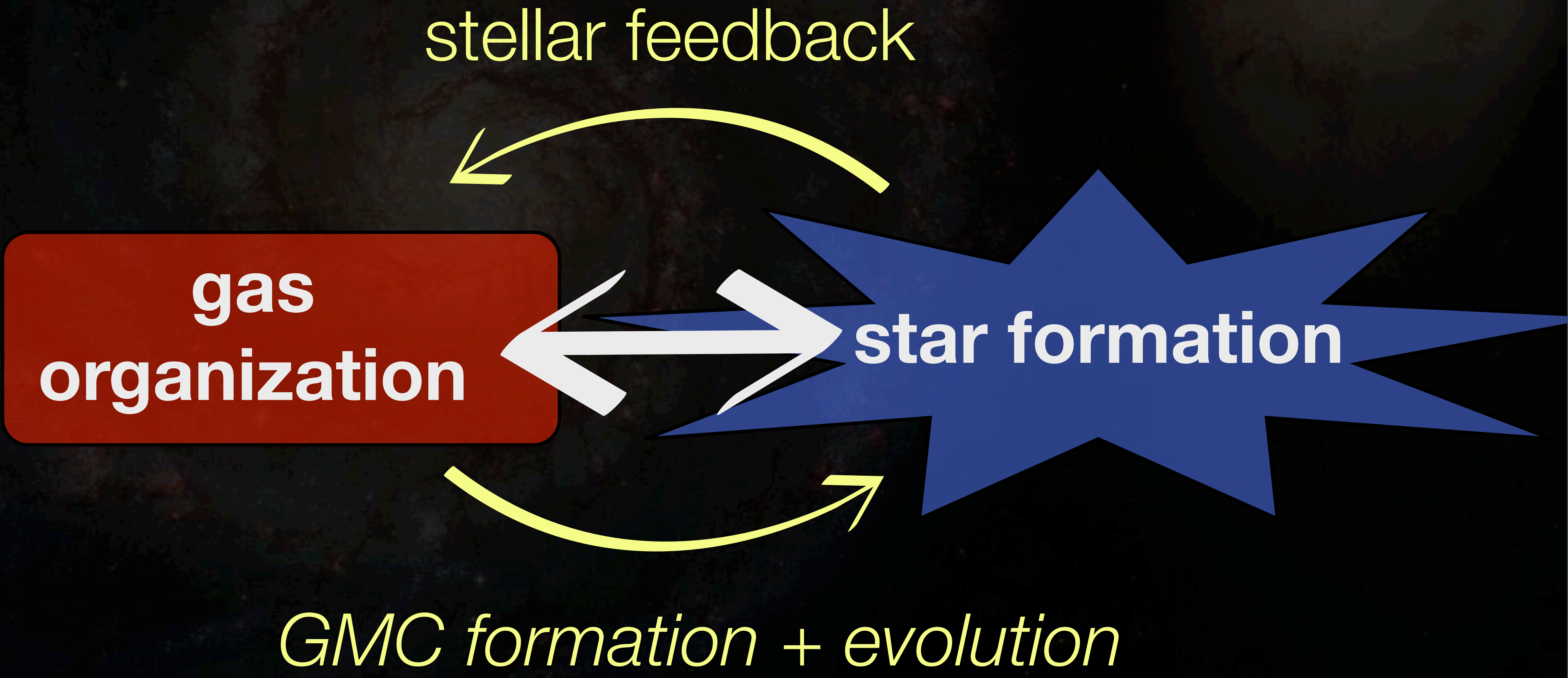
universal molecular gas depletion time ??

Krumholz, Dekel & McKee (2011)



2 modes of SF?

gas kinematics in spiral potentials



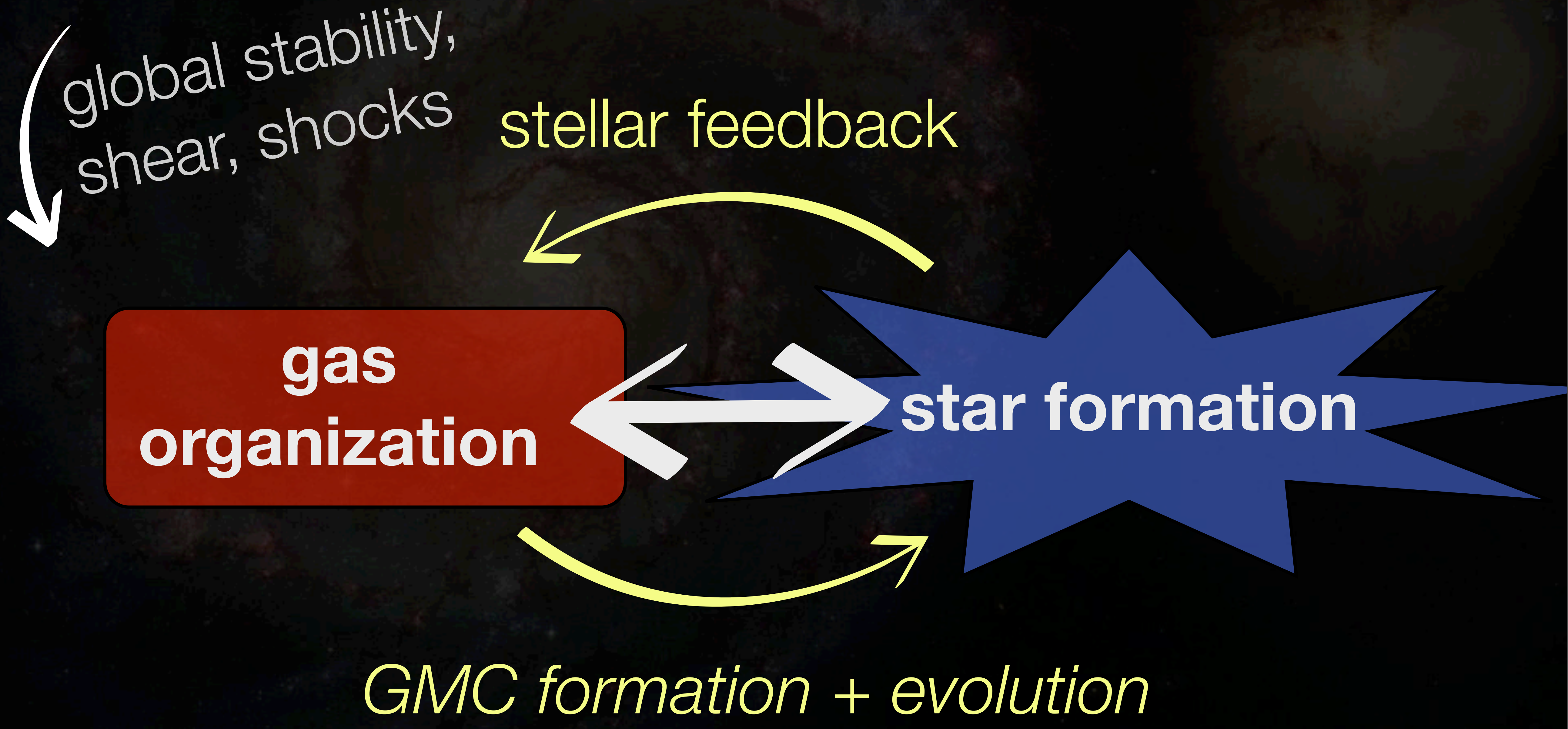
stellar feedback

gas organization

star formation

GMC formation + evolution

gas kinematics in spiral potentials



global stability, shear, shocks

stellar feedback

gas organization

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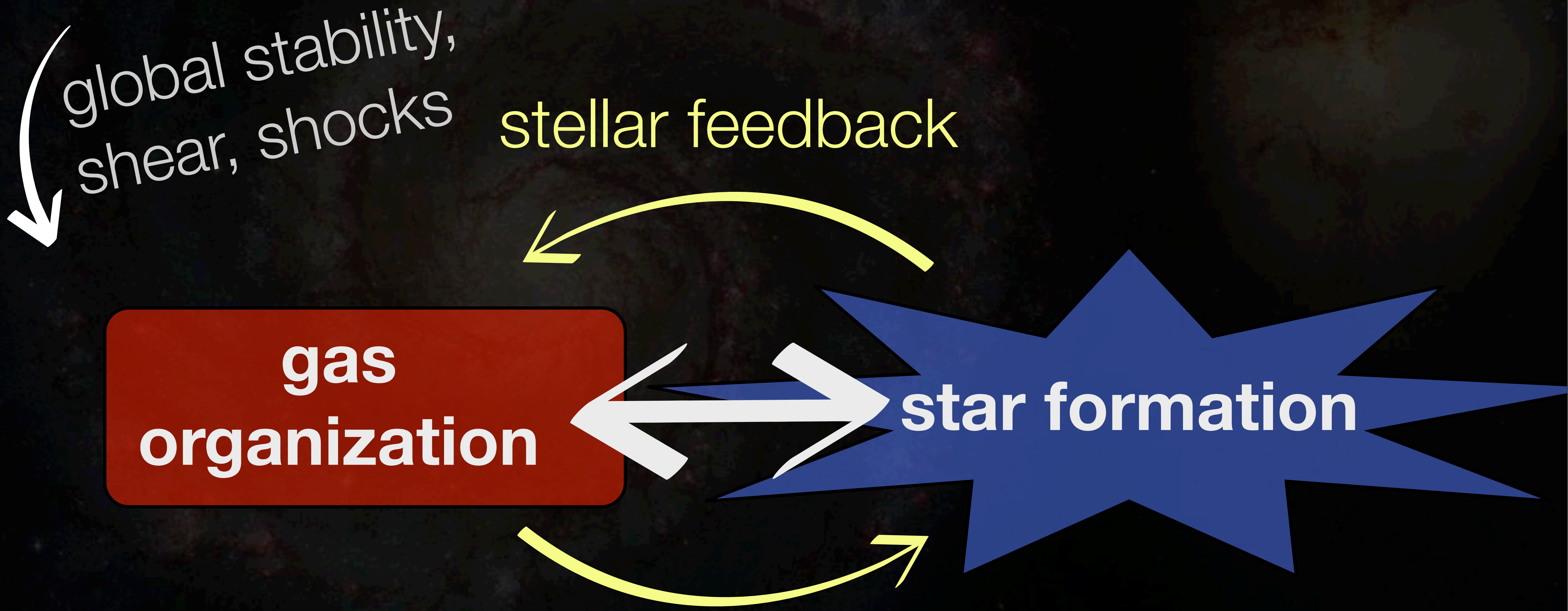


global stability, shear, shocks

stellar feedback

gas organization

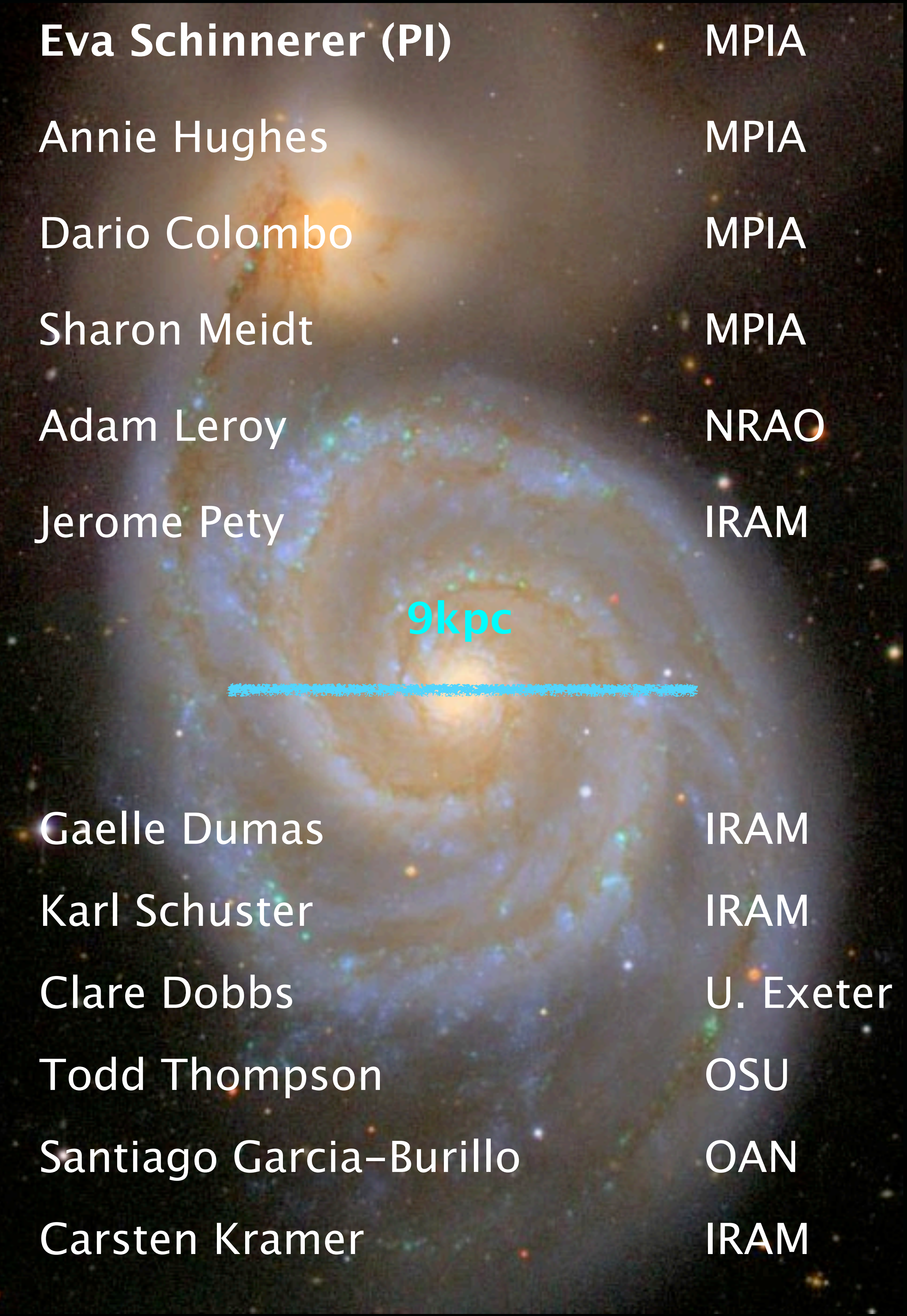
star formation

non-circular motions:

dynamical coupling of clouds to environment

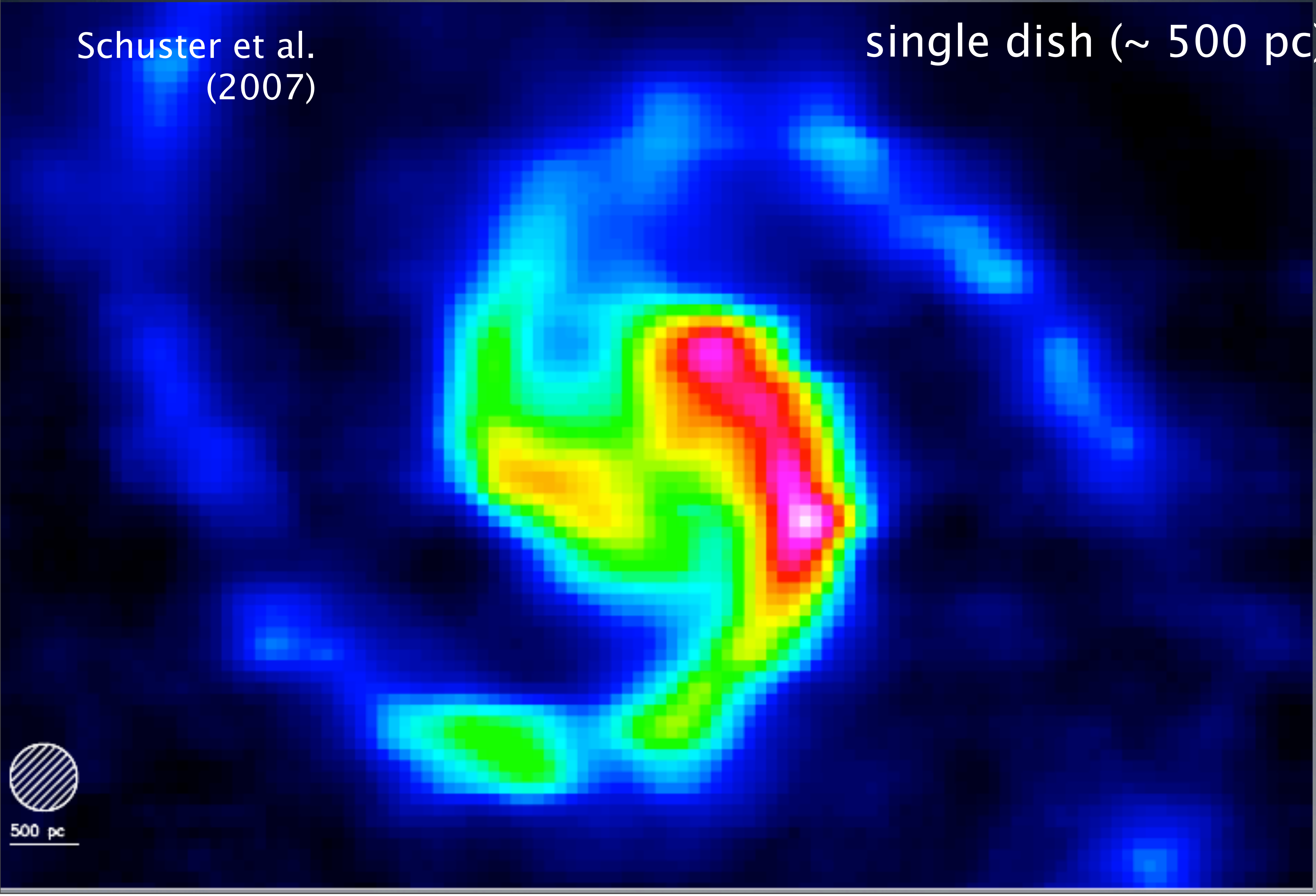
CO(1-0) in central 9kpc at
GMC resolution (40pc, $10^5 M_{sun}$)

IRAM
30m: 40 hr
PdBI: 170 hr



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

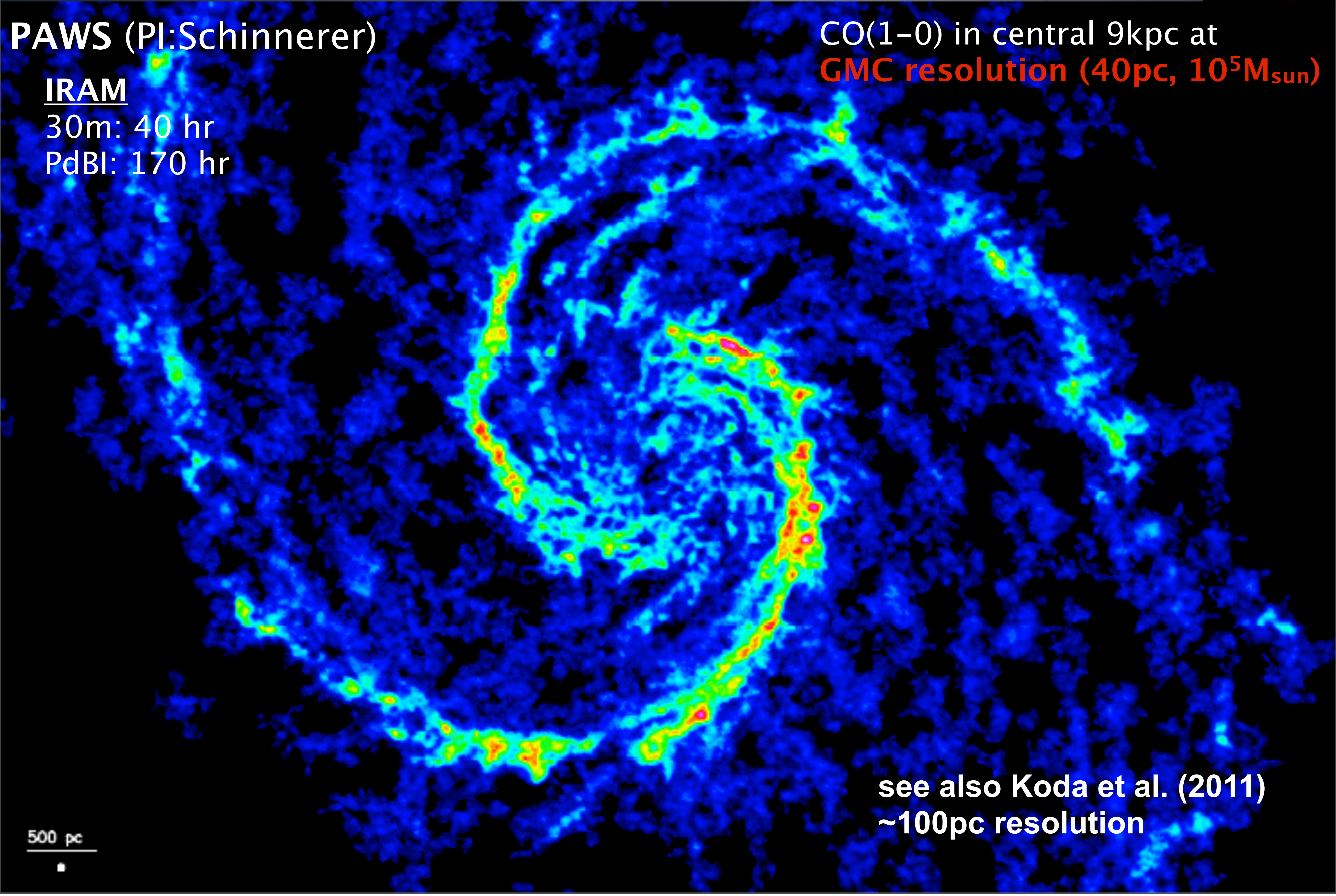
Molecular Gas disk of M51



Schuster et al. (2007)

single dish (~ 500 pc)

Molecular Gas disk of M51



PAWS (PI:Schinnerer)

IRAM
30m: 40 hr
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CO(1-0) in central 9kpc at
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see also Koda et al. (2011)
~100pc resolution

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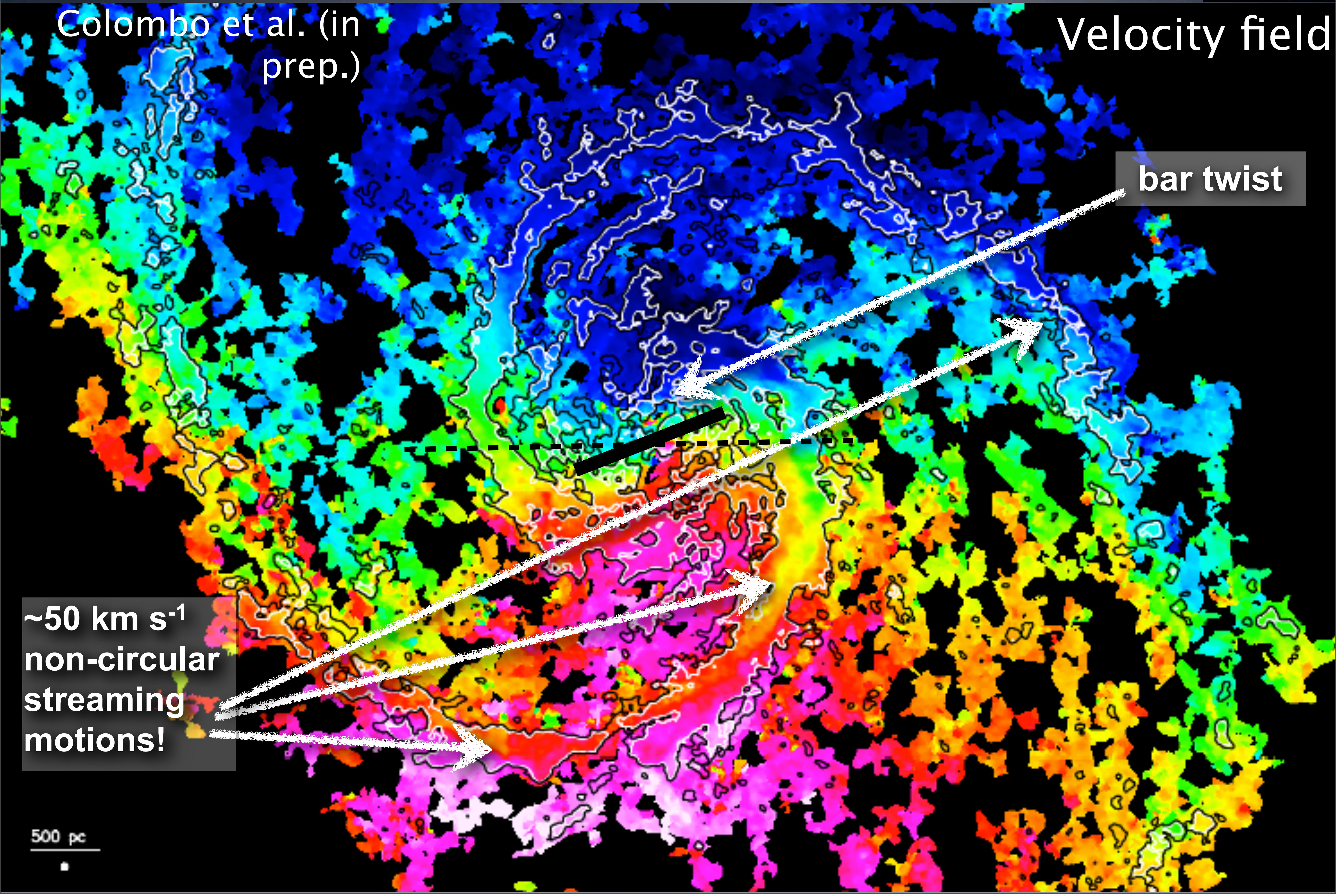


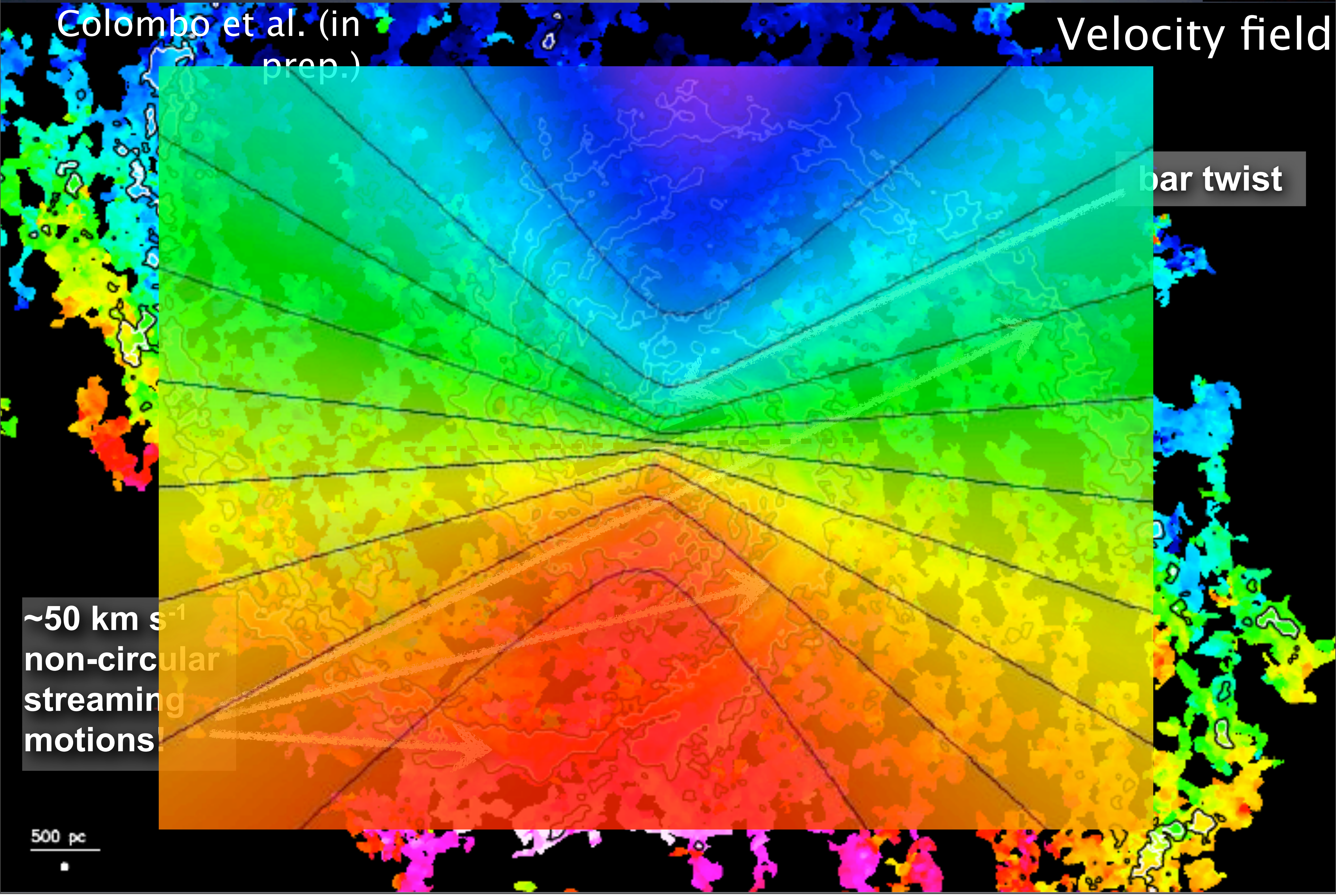
Colombo et al. (in prep.)

Velocity field

bar twist

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

Molecular Gas disk of M51



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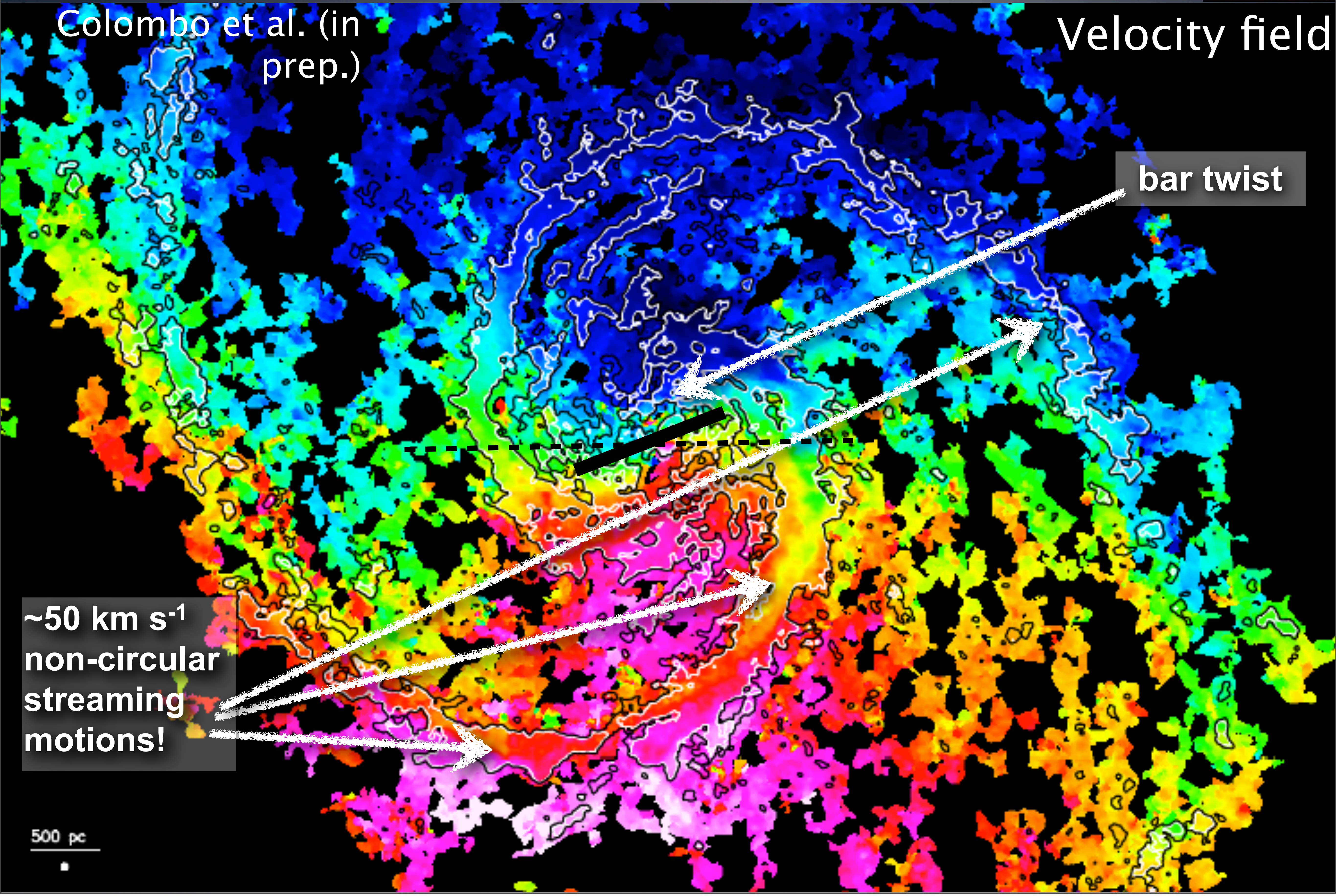

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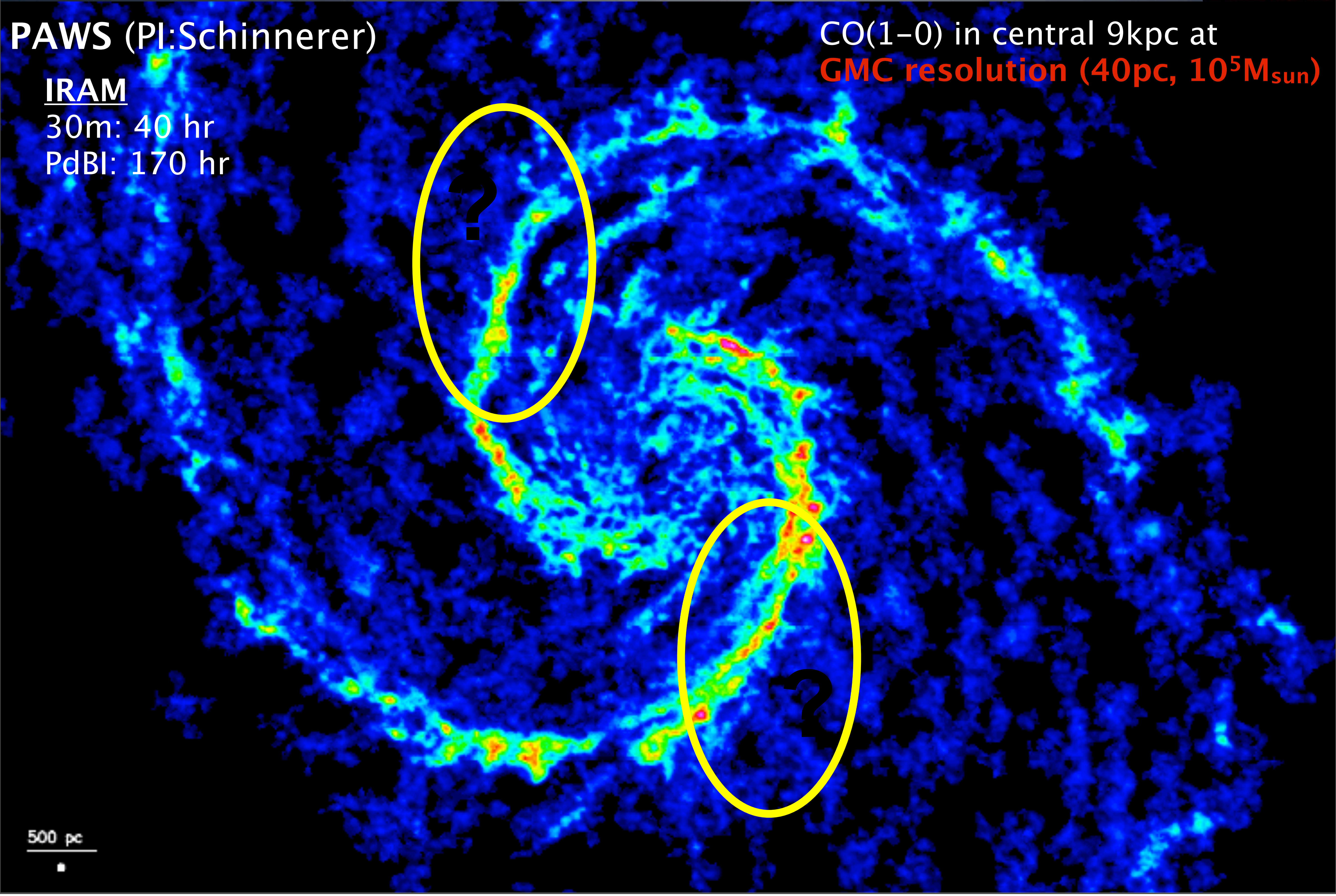

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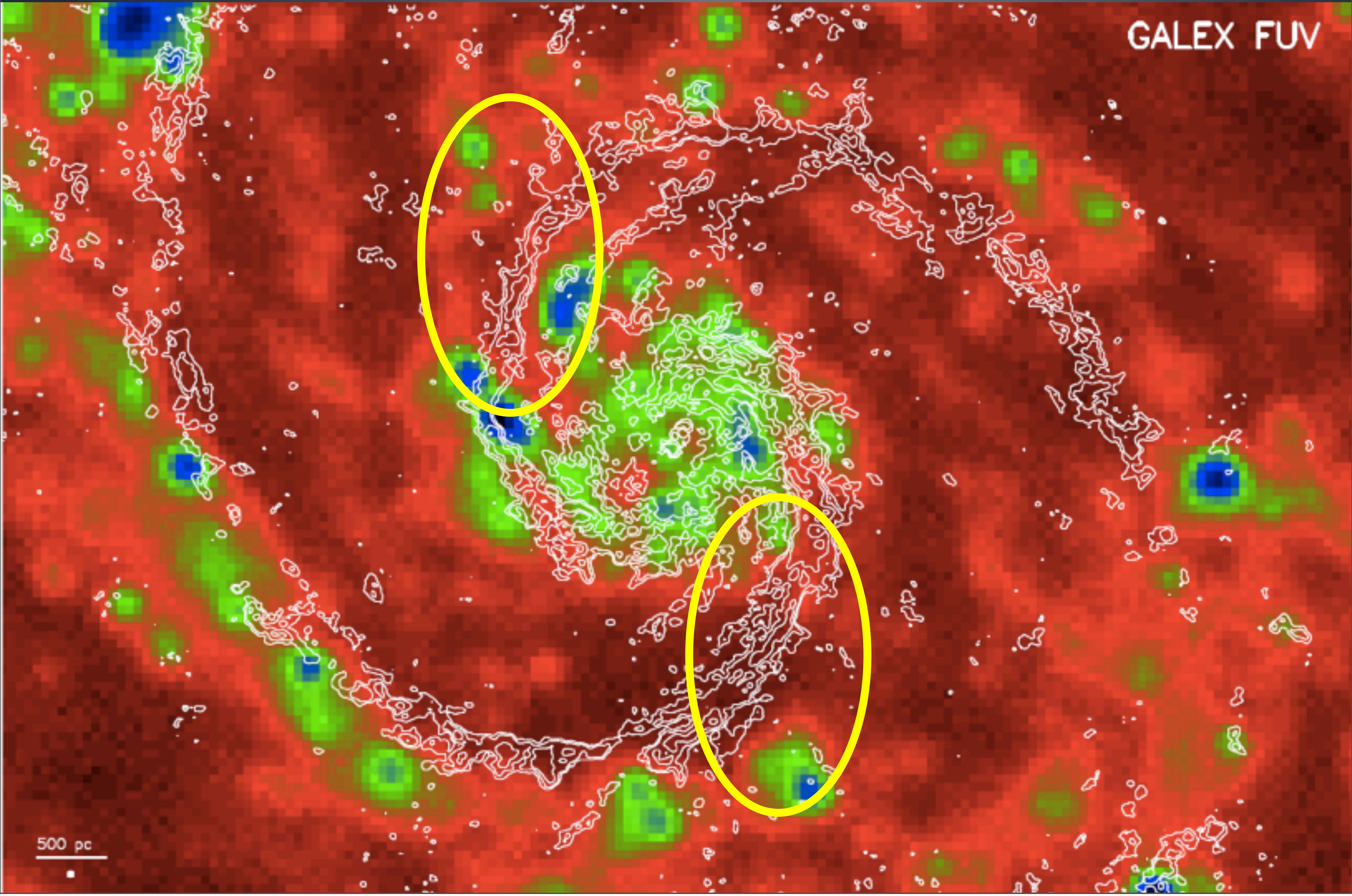
Spatial Relation b/n Gas and Star Formation

Schinnerer et al. (in prep.)



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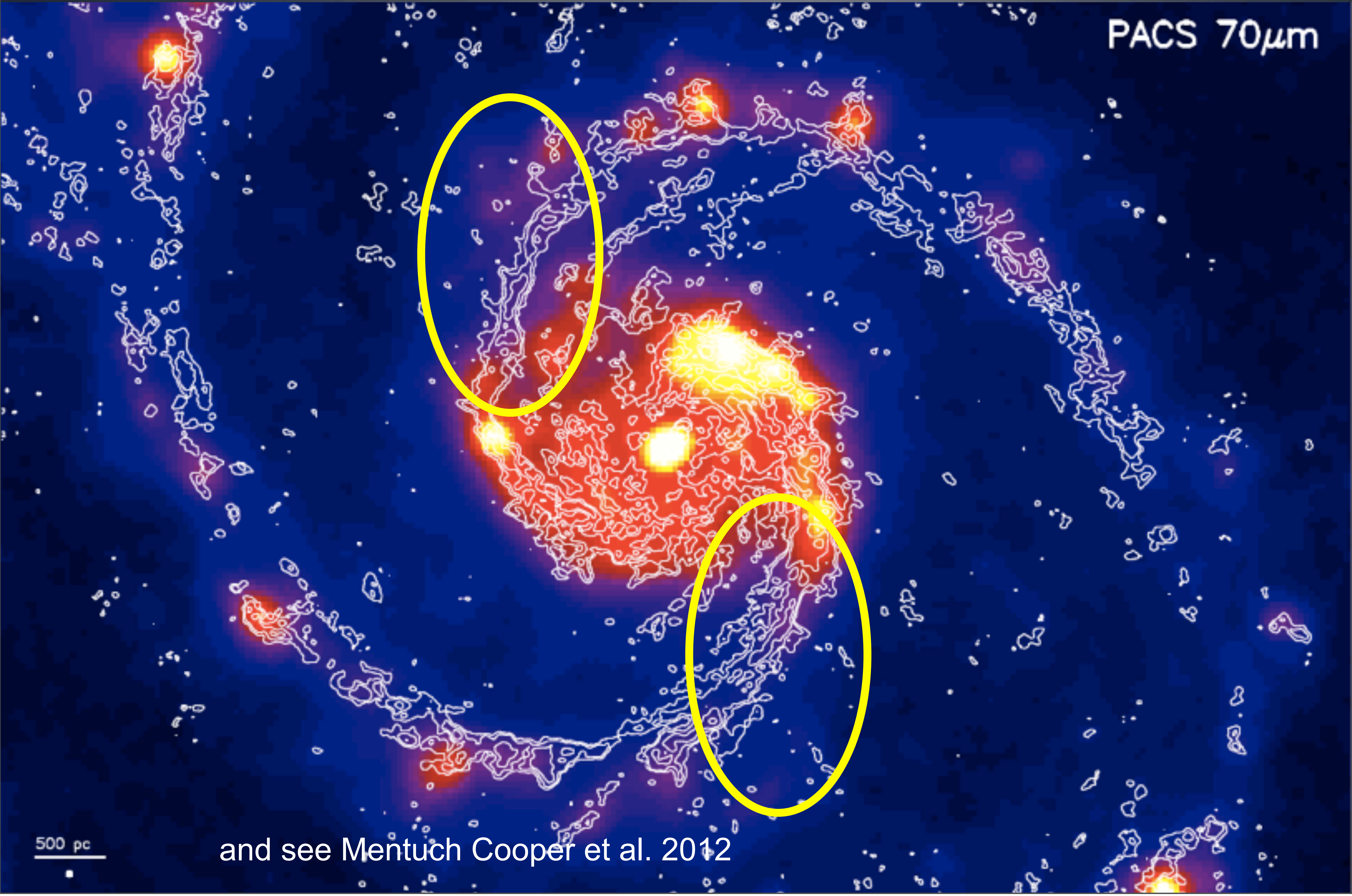

and see Mentuch Cooper et al. 2012

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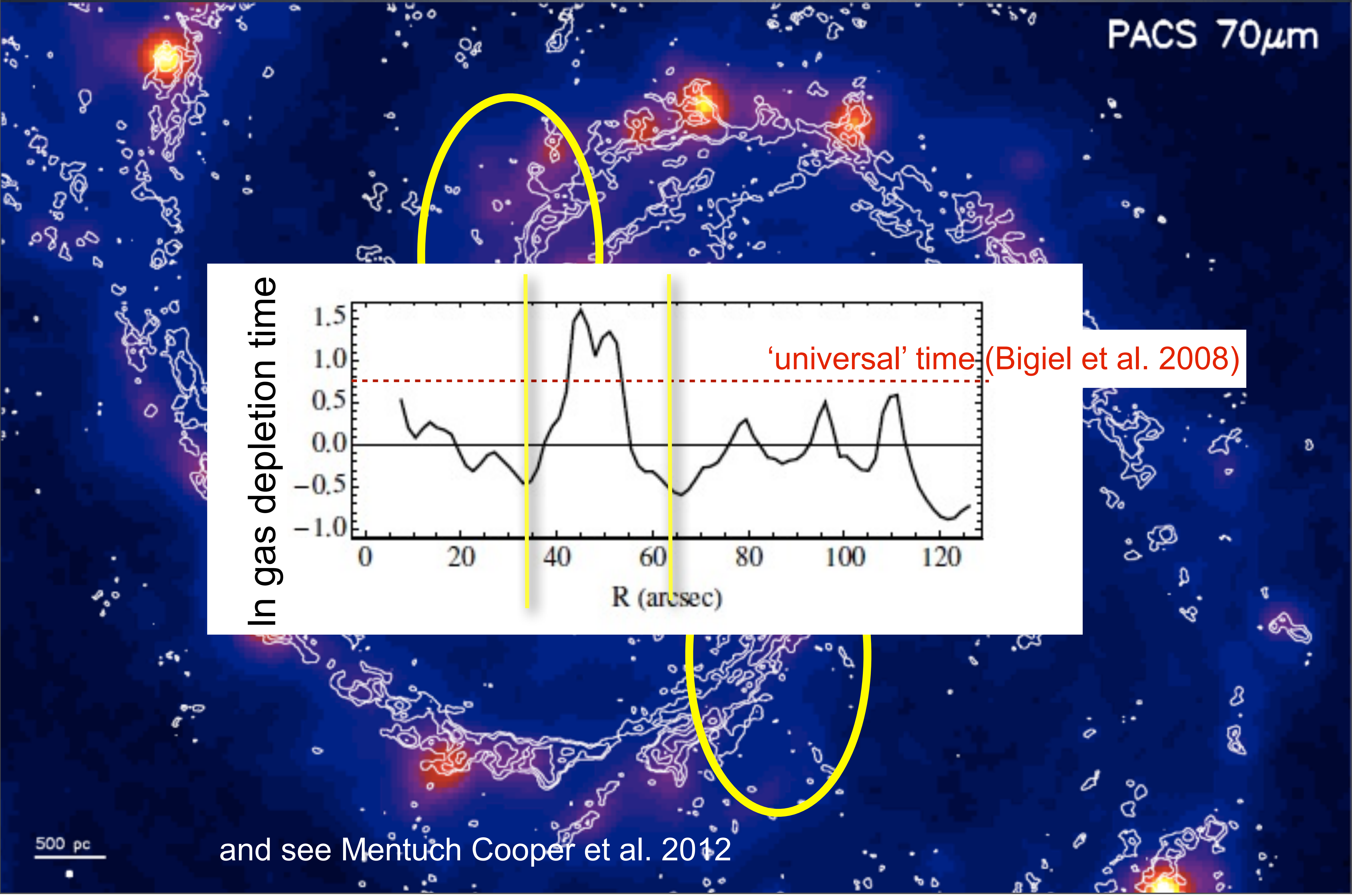


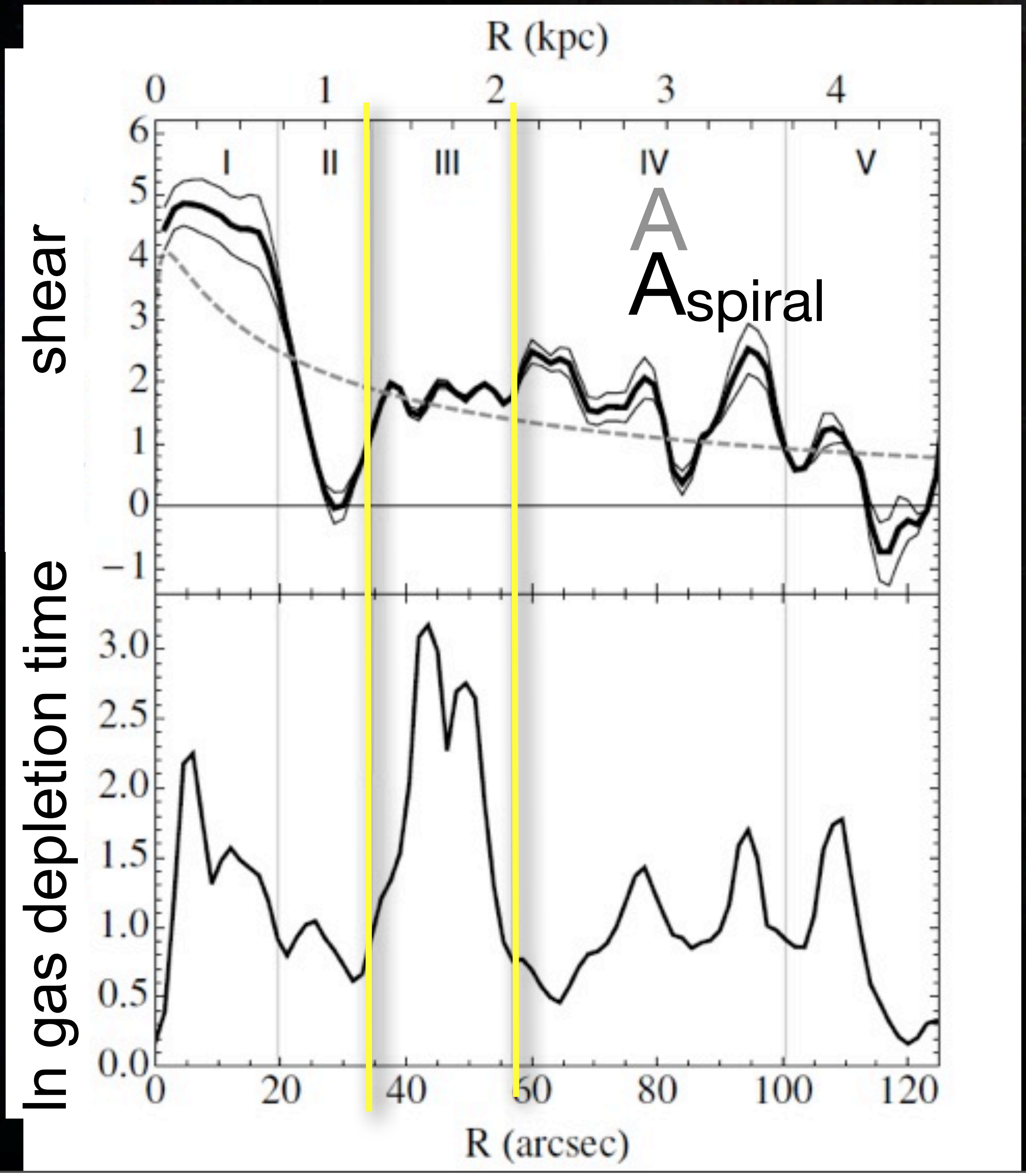
‘universal’ time (Bigiel et al. 2008)

and see Mentuch Cooper et al. 2012

GMC Stabilization in M51

what shuts off star formation?

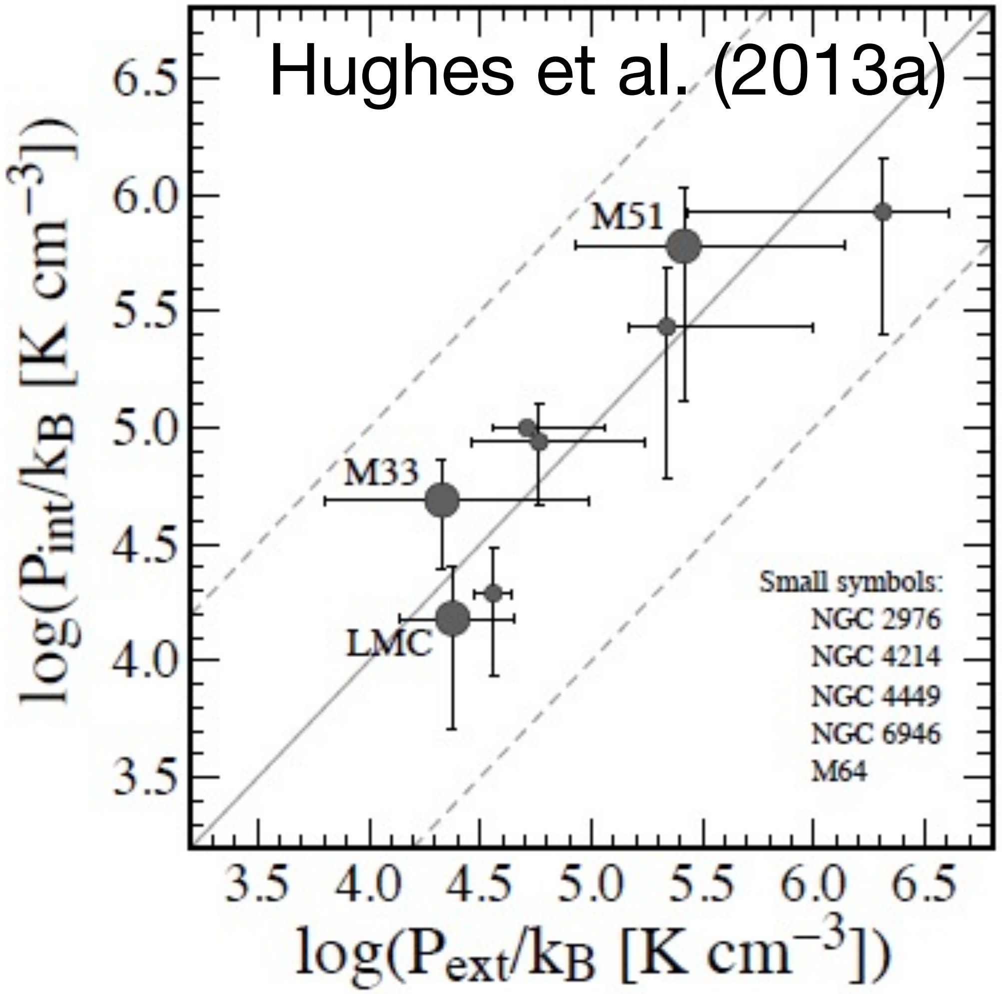
support *not* entirely from



- **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)

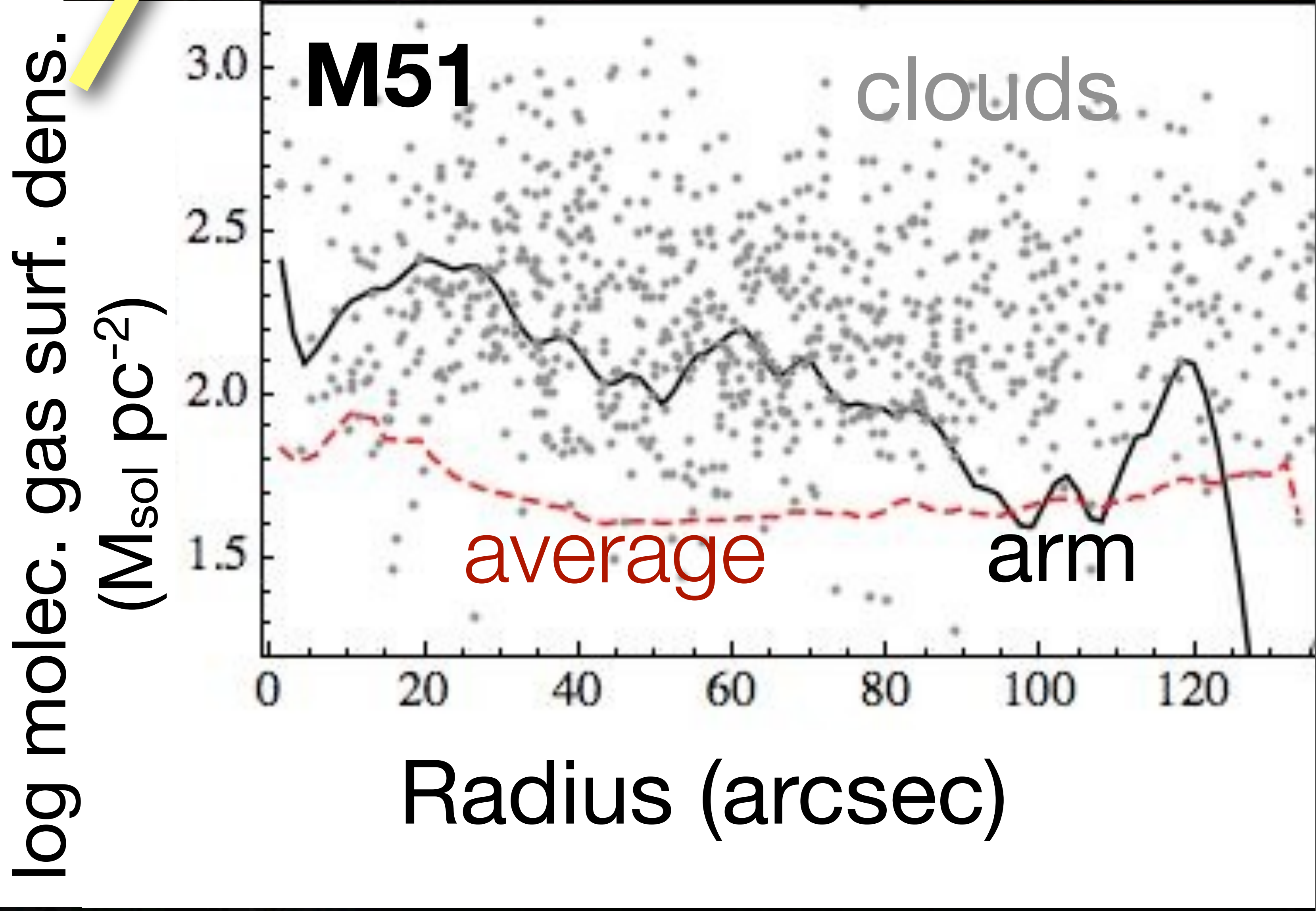
Pressure Stabilization



Hughes et al. (2013a)

surface pressure important

prop. to log (Pressure) (P~GΣ^2)

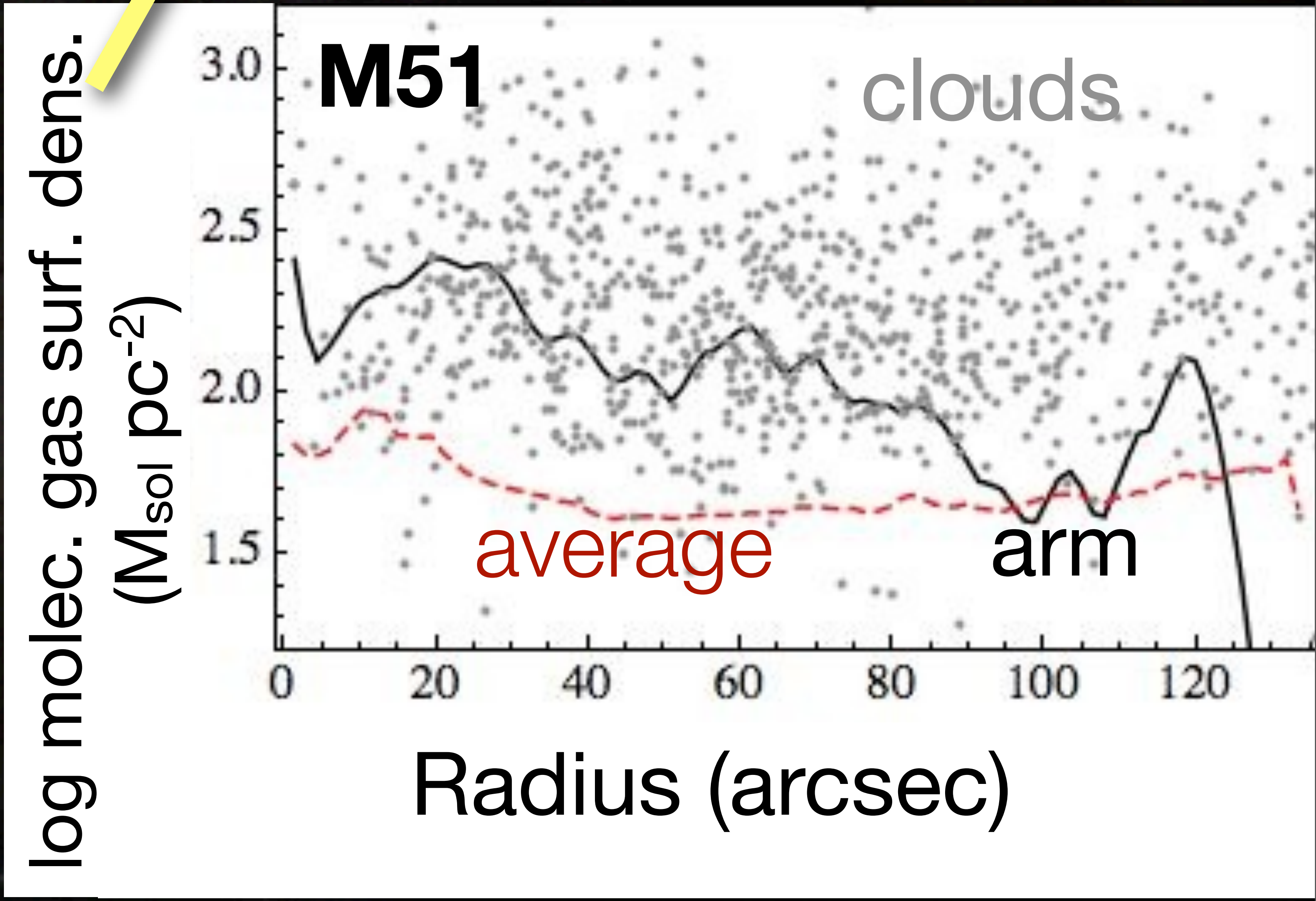


Pressure Stabilization

prop. to log (Pressure) (P~GΣ^2)

ambient P
comparable to
internal cloud P

***cloud
surface pressure
important***



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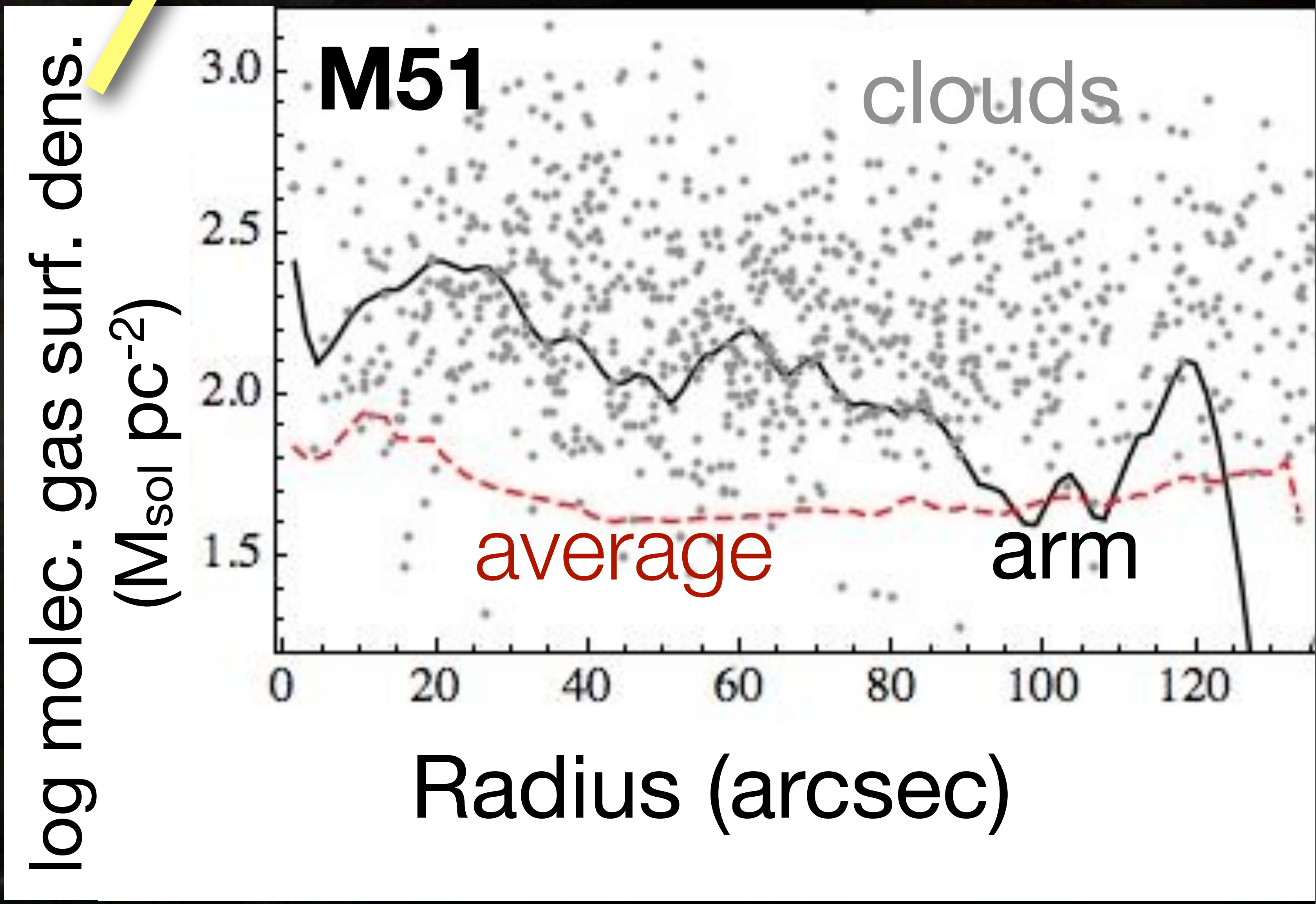


prop. to log (Pressure) ($P \sim G\Sigma^2$)

*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*

Meidt et al. (2013)

cf. Jog (2013, in prep.)

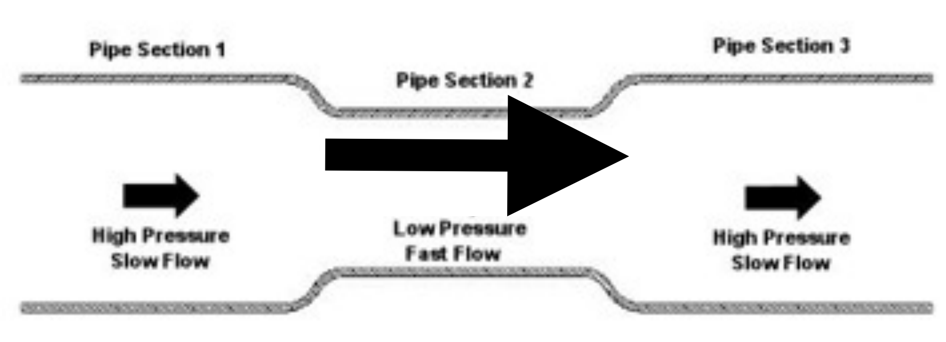
clouds in motion in arm:

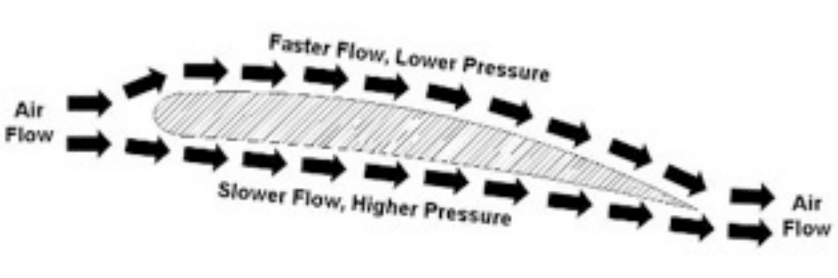
1). **reduced surface pressure** (Bernoulli)

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

2b). reduced collapse-unstable fraction

3). **lower SFE**





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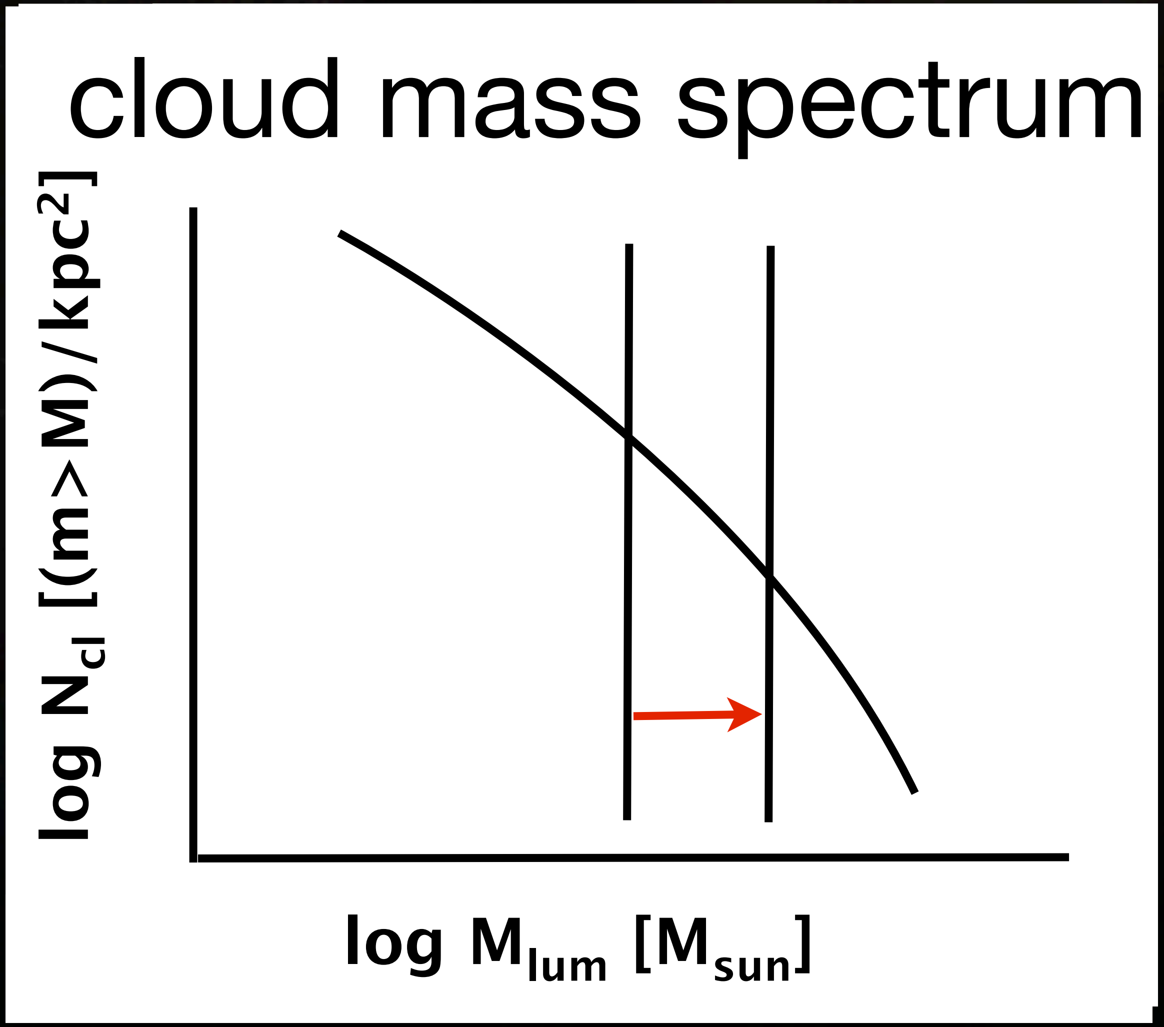

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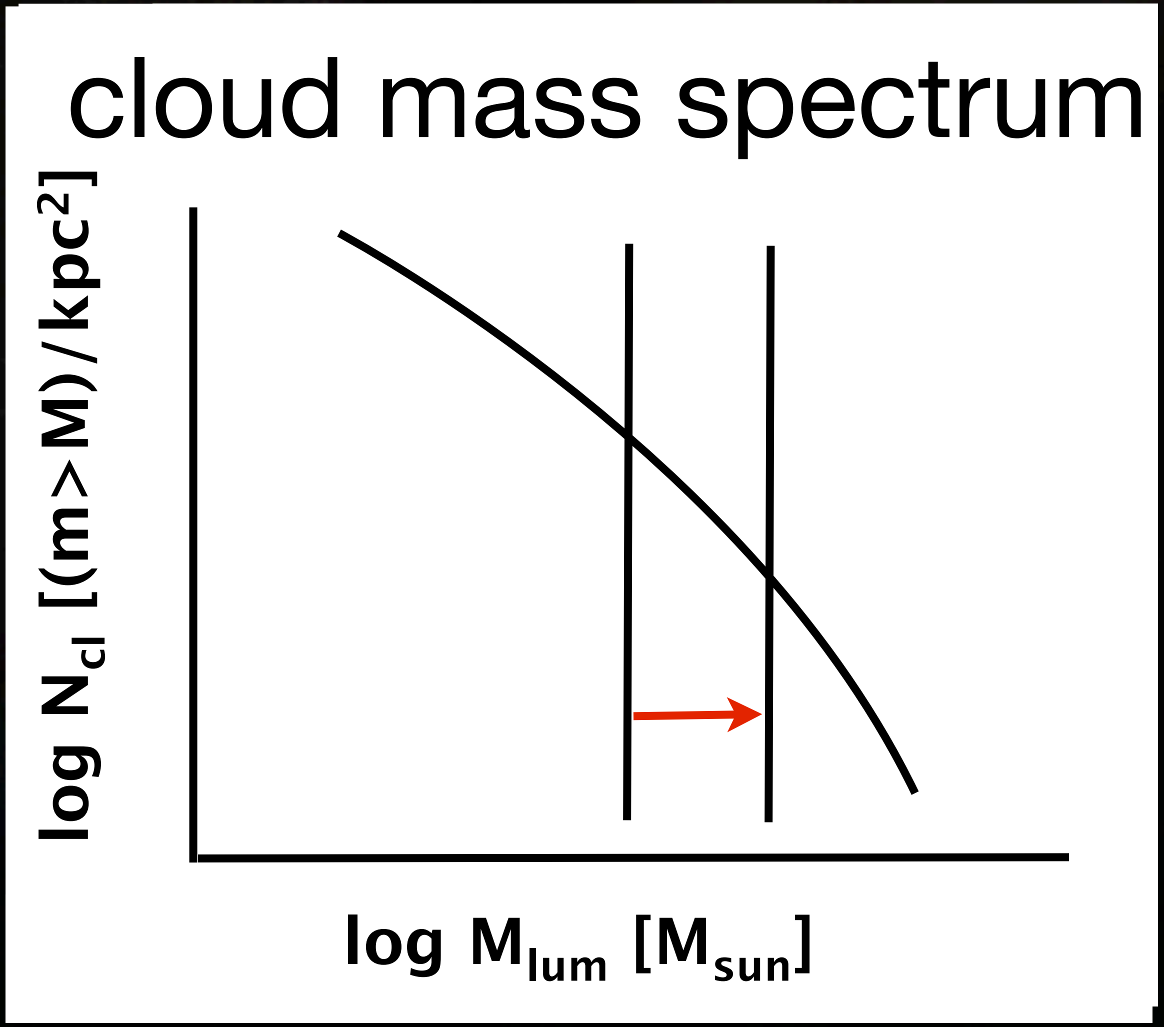
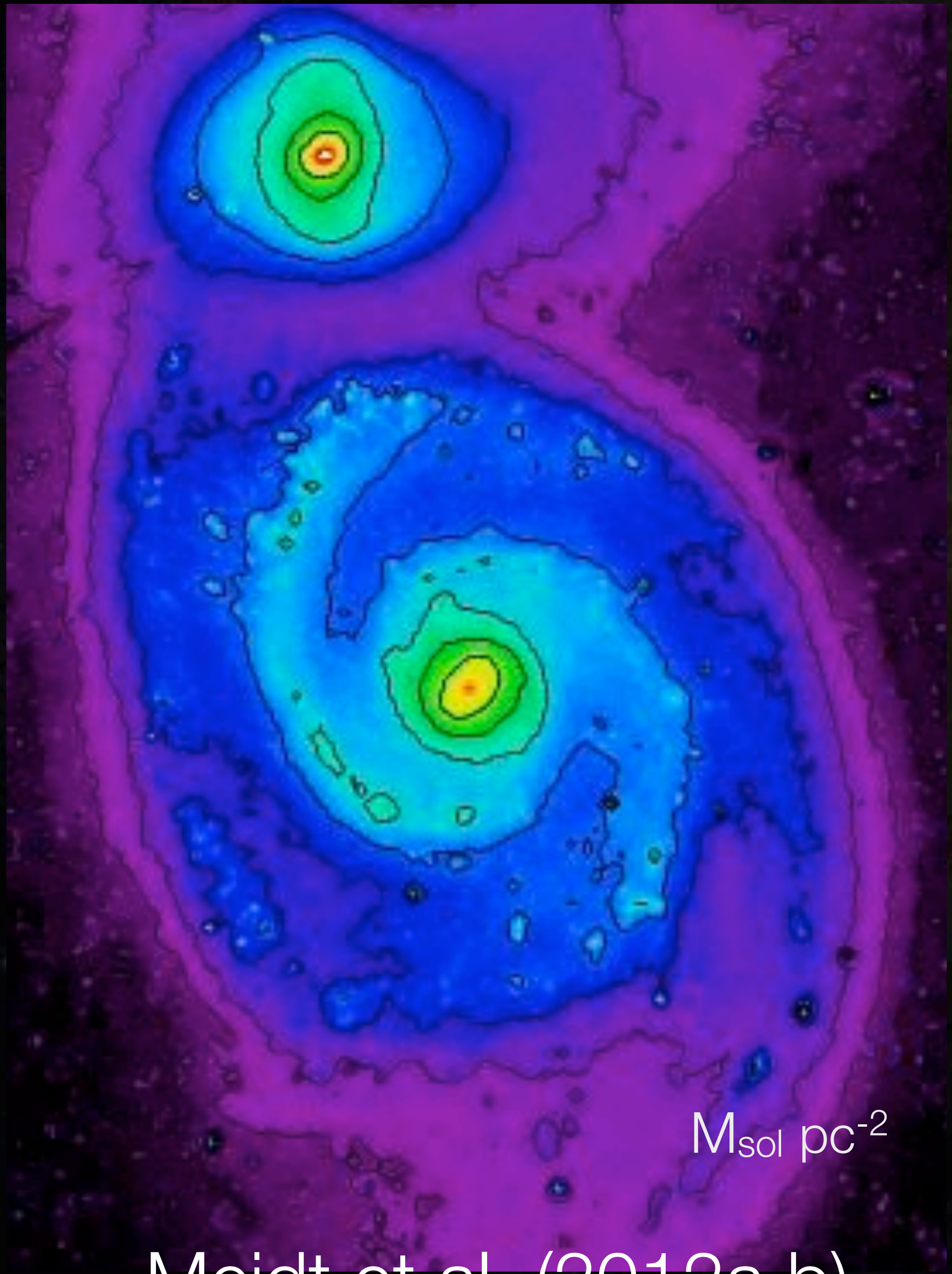
$$\ln \tau_{dep} \approx -(\Upsilon+1)\ \frac{V_{stream}^2}{4\sigma^2}$$

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



non-circular gas motions:
Present-day Torques

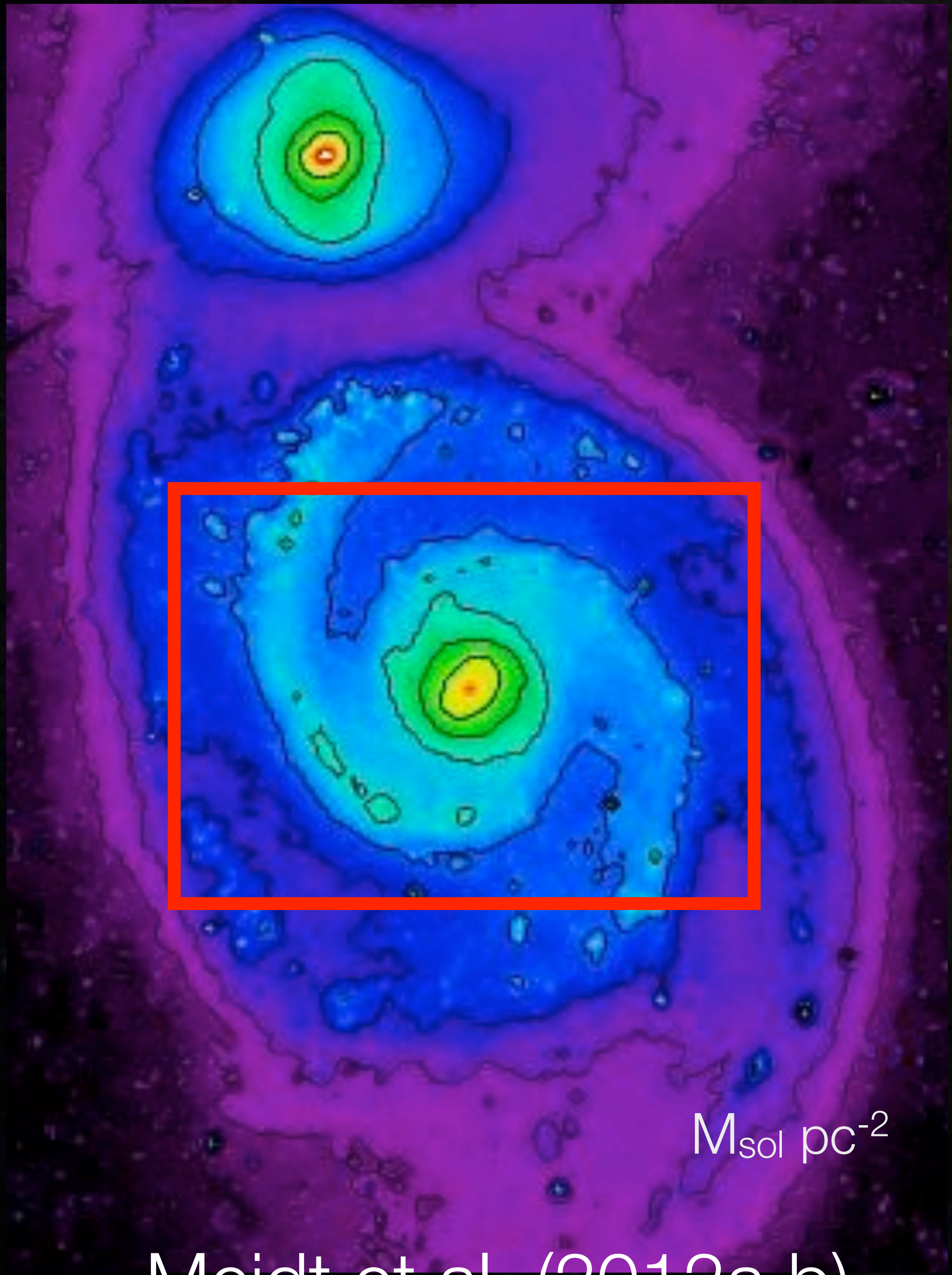


Meidt et al. (2012a,b)
Eskew, Zaritsky & Meidt (2012)

S^4G
stellar
mass
surface
density

DETAILED ANATOMY OF GALAXIES

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



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S^4G
stellar
mass
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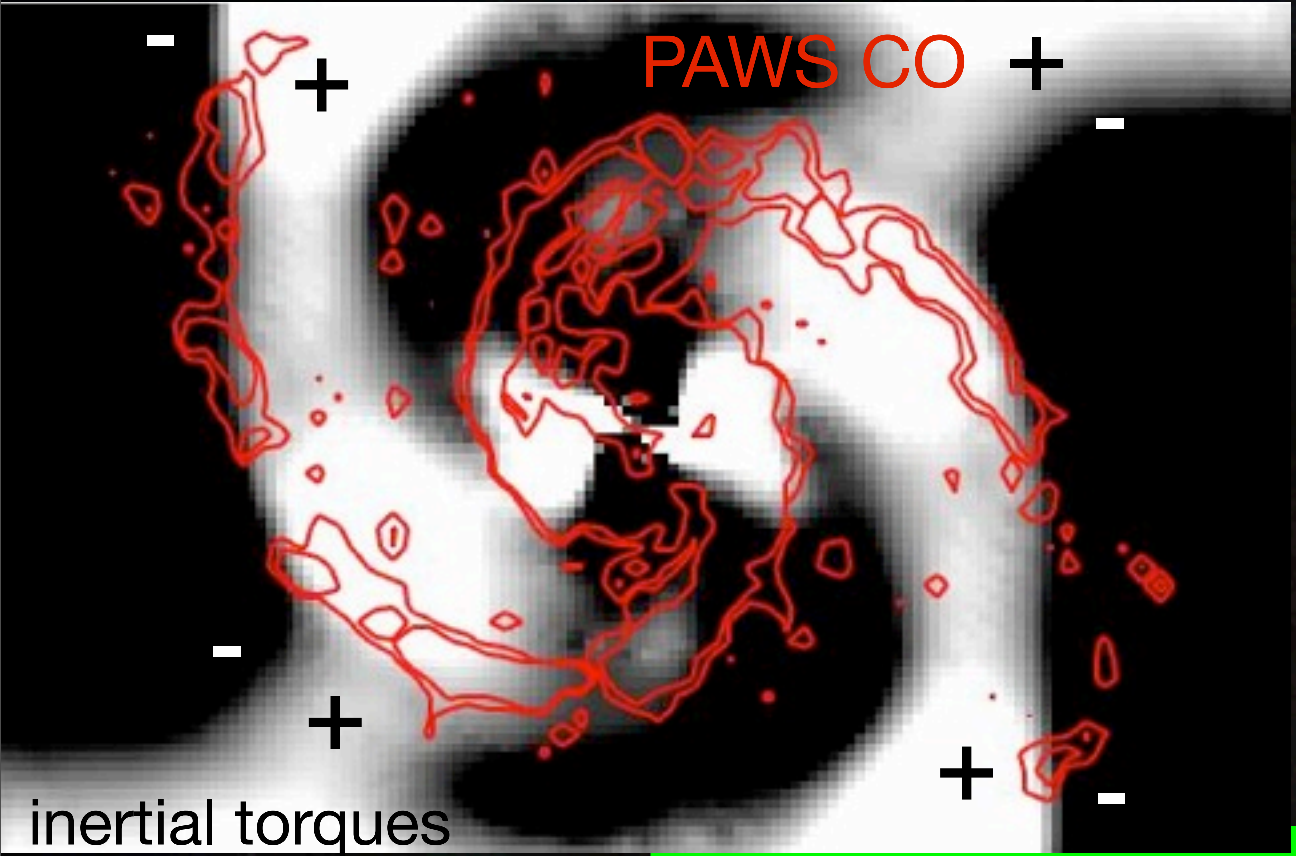
DAGAL
Detailed
Anatomy of
GALaxies

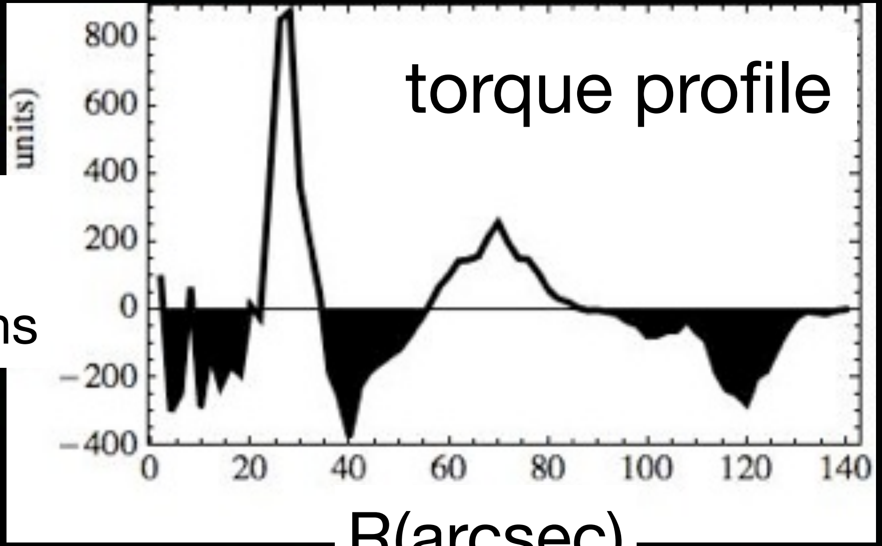
Present-day Torques



inertial torques
R×∇Φ

outflow inflow

<Γ>(R)
azimuthal bins

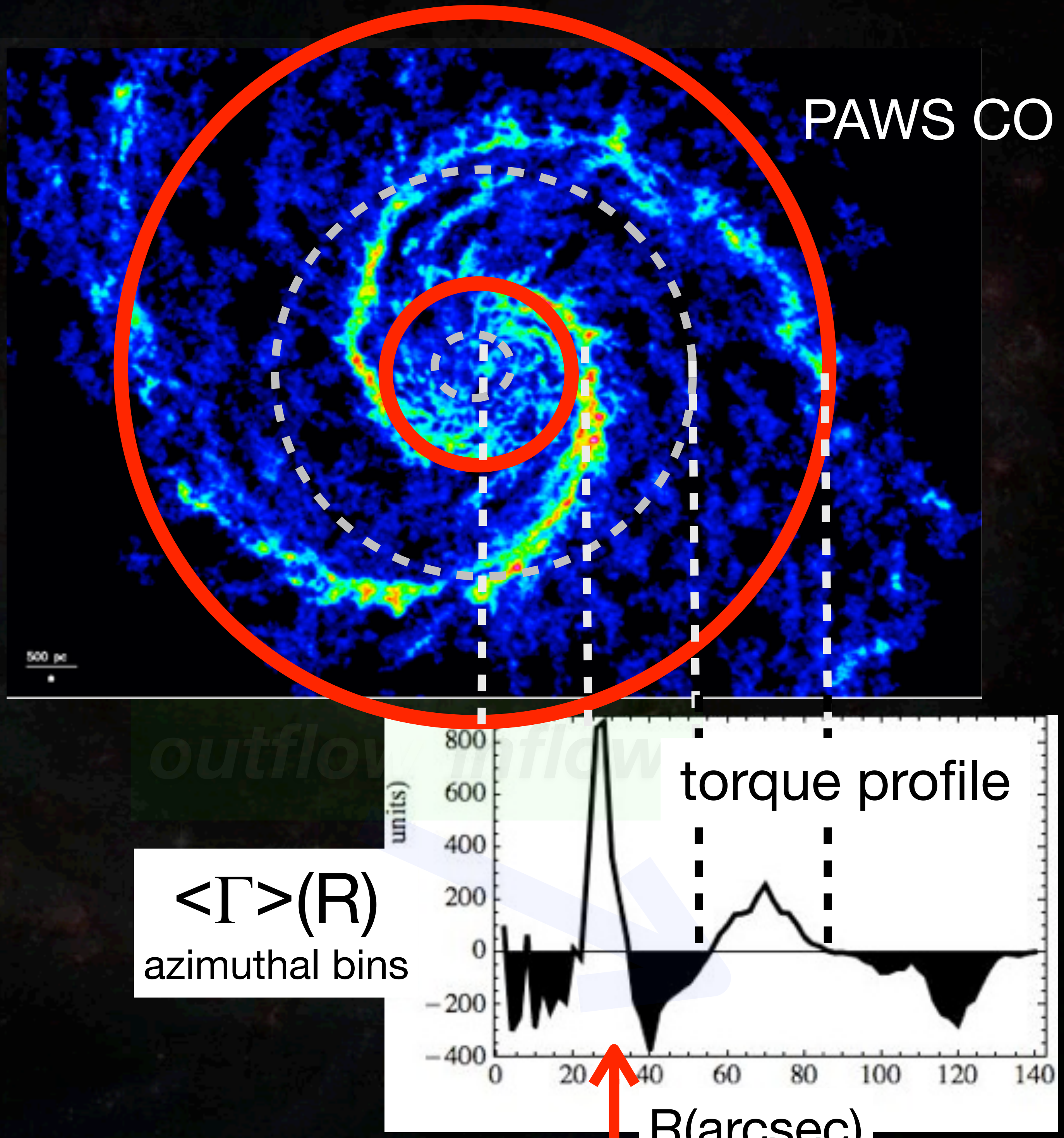


torque profile

R(arcsec)

Radius = proxy for environment (bar, spiral)

Present-day Torques



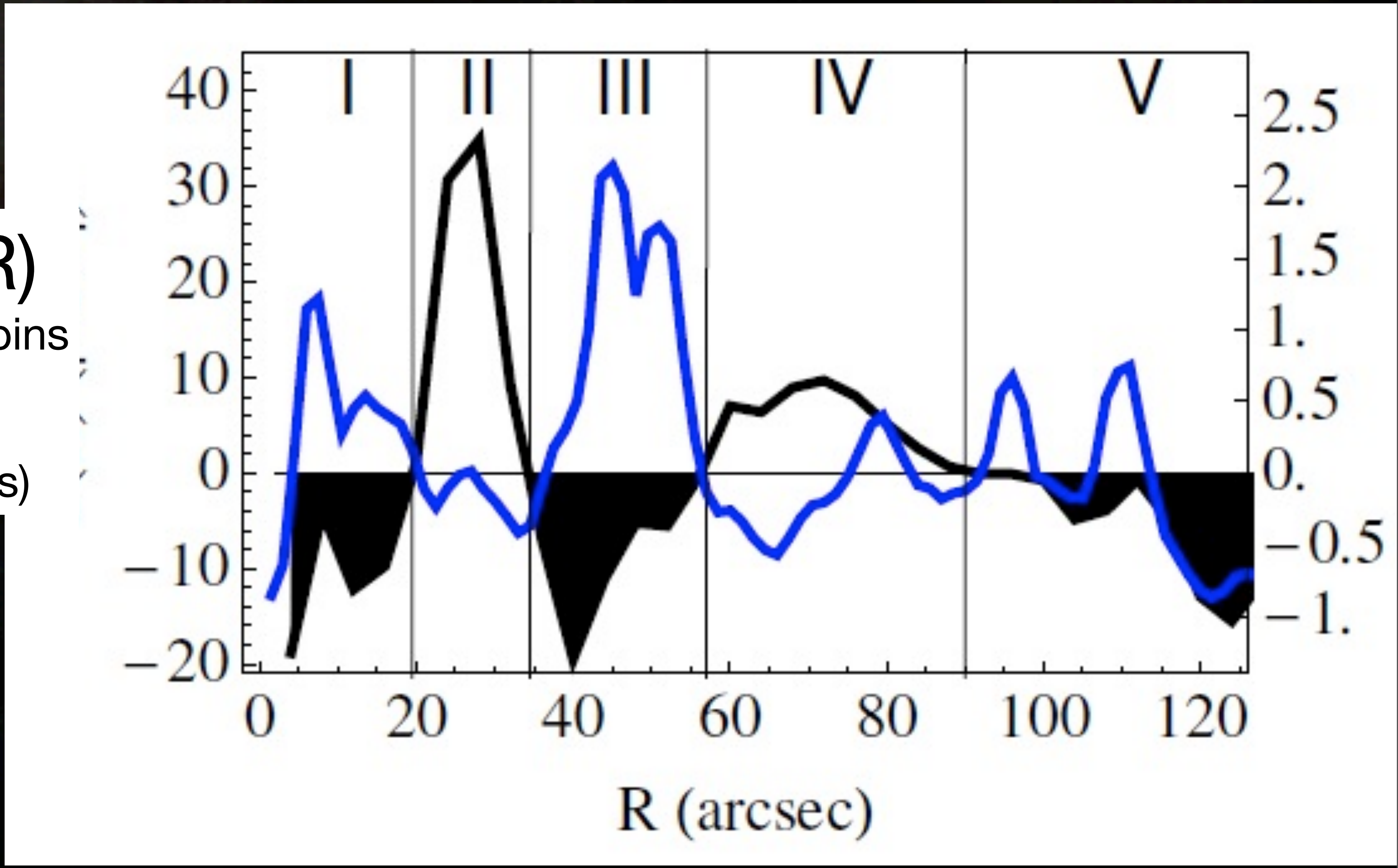
bar

spiral

molecular ring

(consistent with Meidt et al. 2008)

Spiral arm Torques



$<\Gamma>(R)$

azimuthal bins

τ_{dep}

(arb. units)

from PAWS kinematics

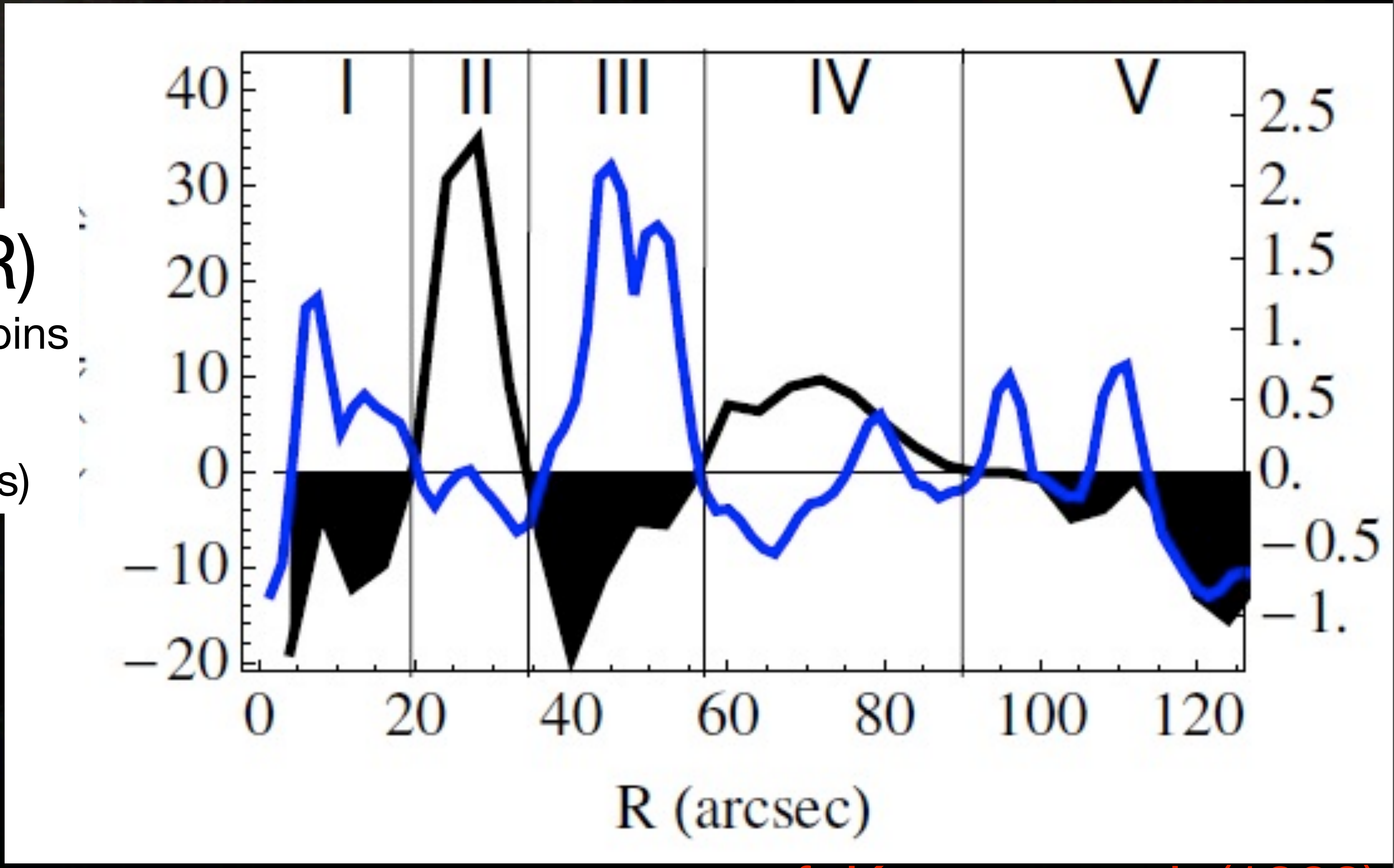
inflow=large

$|V_{stream}|$

Spiral arm Torques

from PAWS kinematics

inflow=large $|V_{stream}|$



$<\Gamma>(R)$
azimuthal bins

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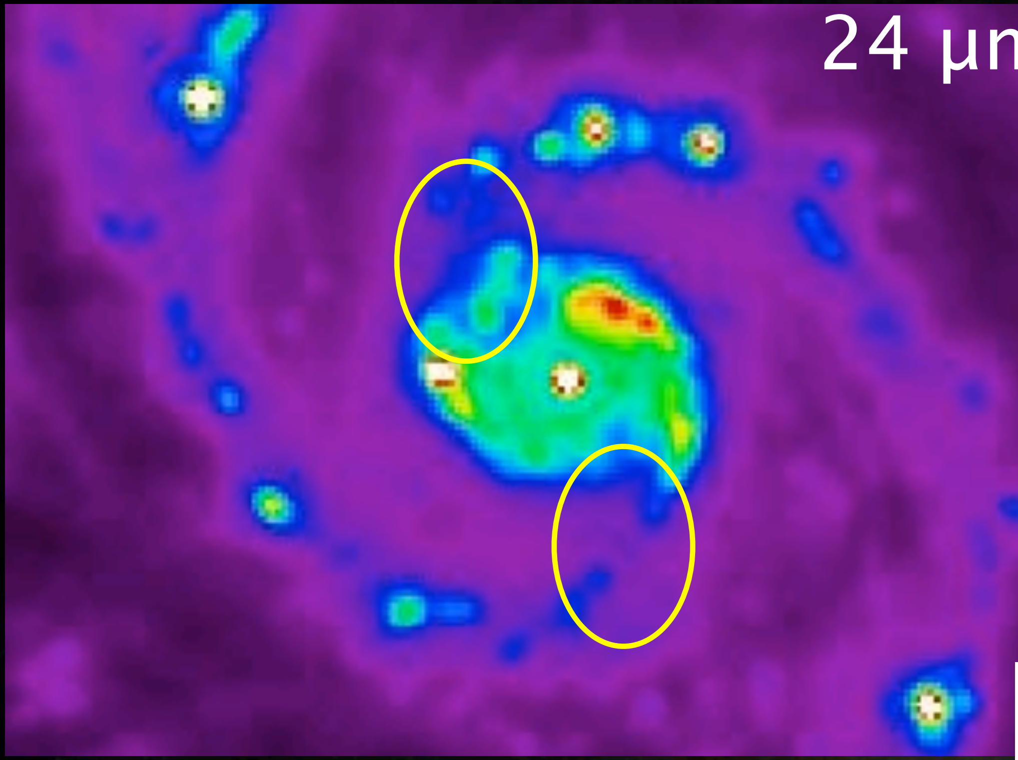
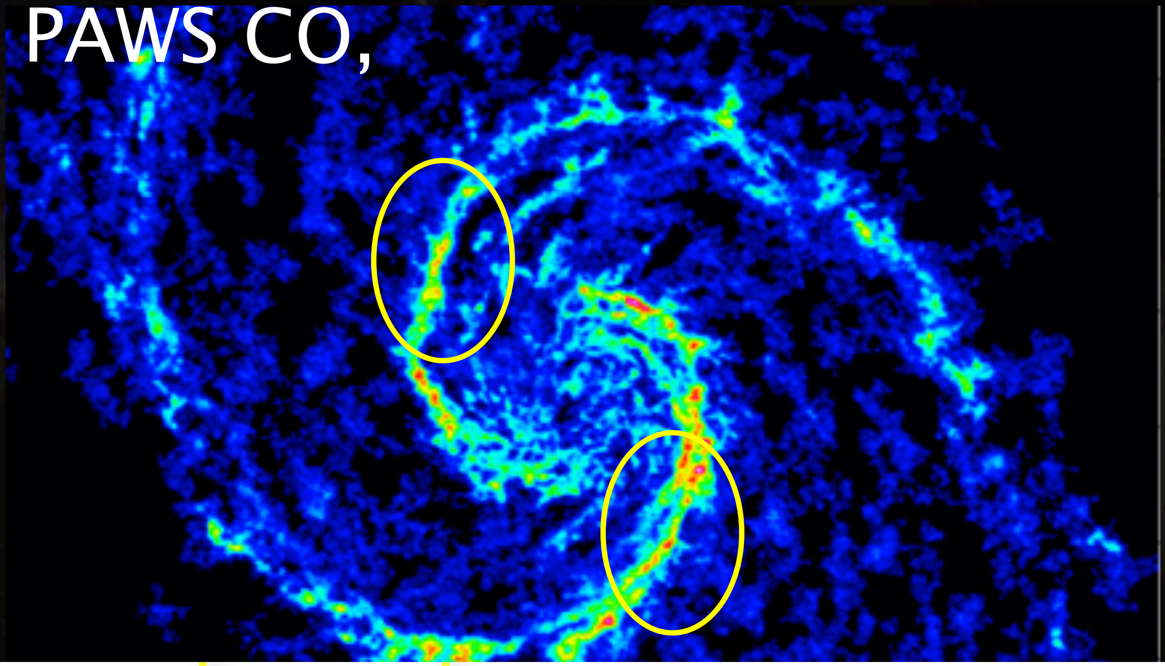
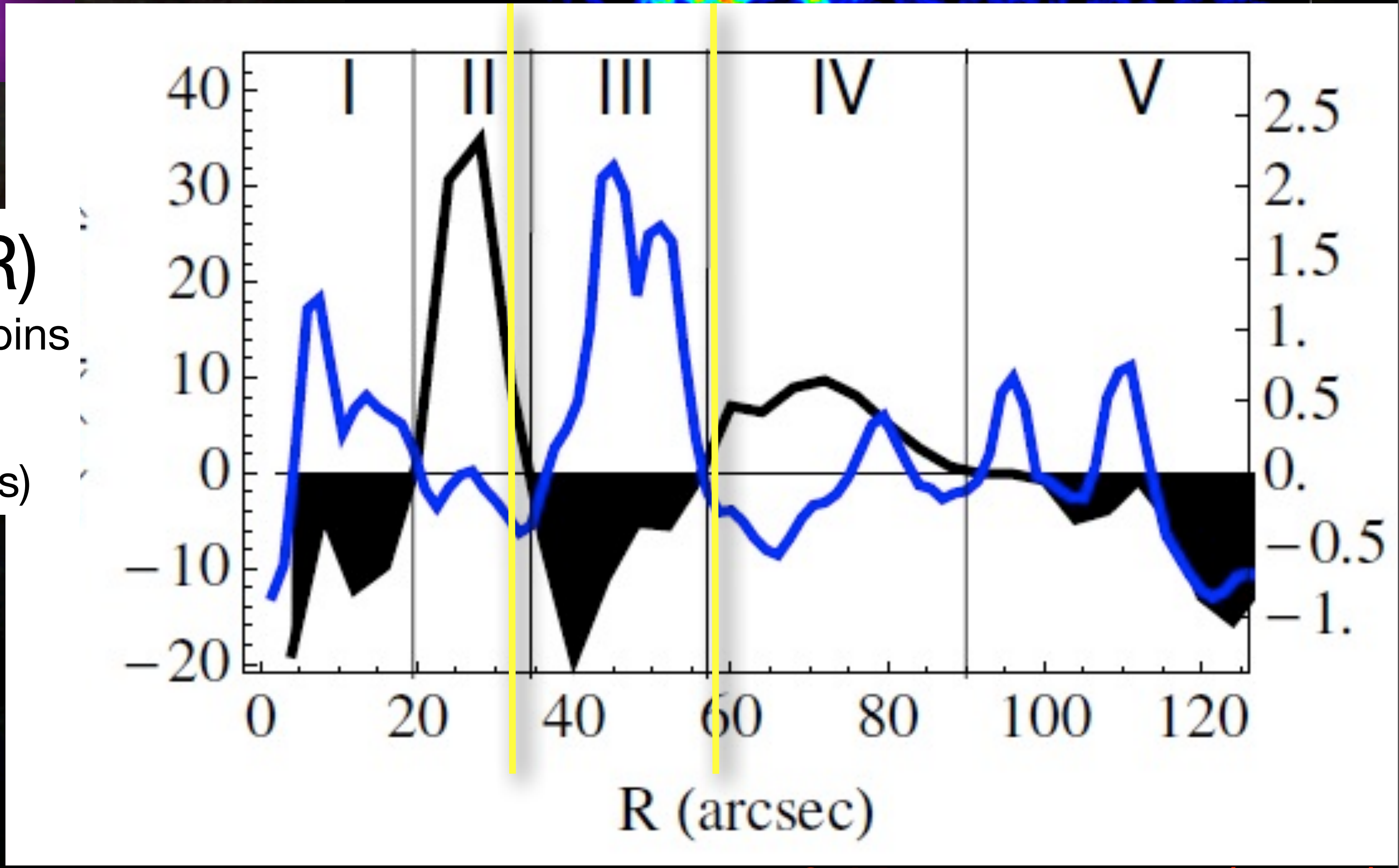
cf. Knapen et al. (1992)

Spiral arm Torques







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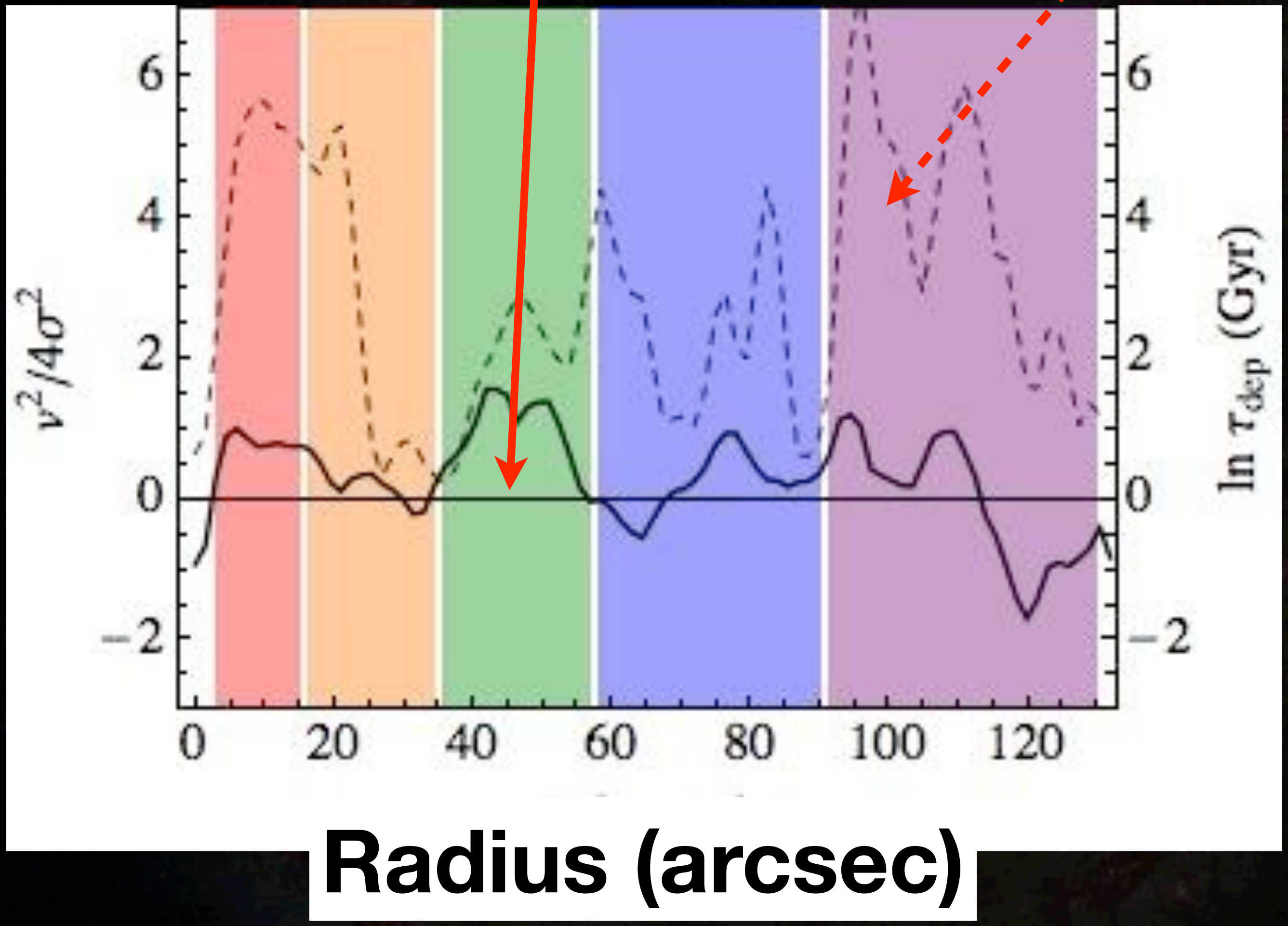
cf. Knapen et al. (1992)

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

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



fit predicts

slope of mass spectrum γ

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

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

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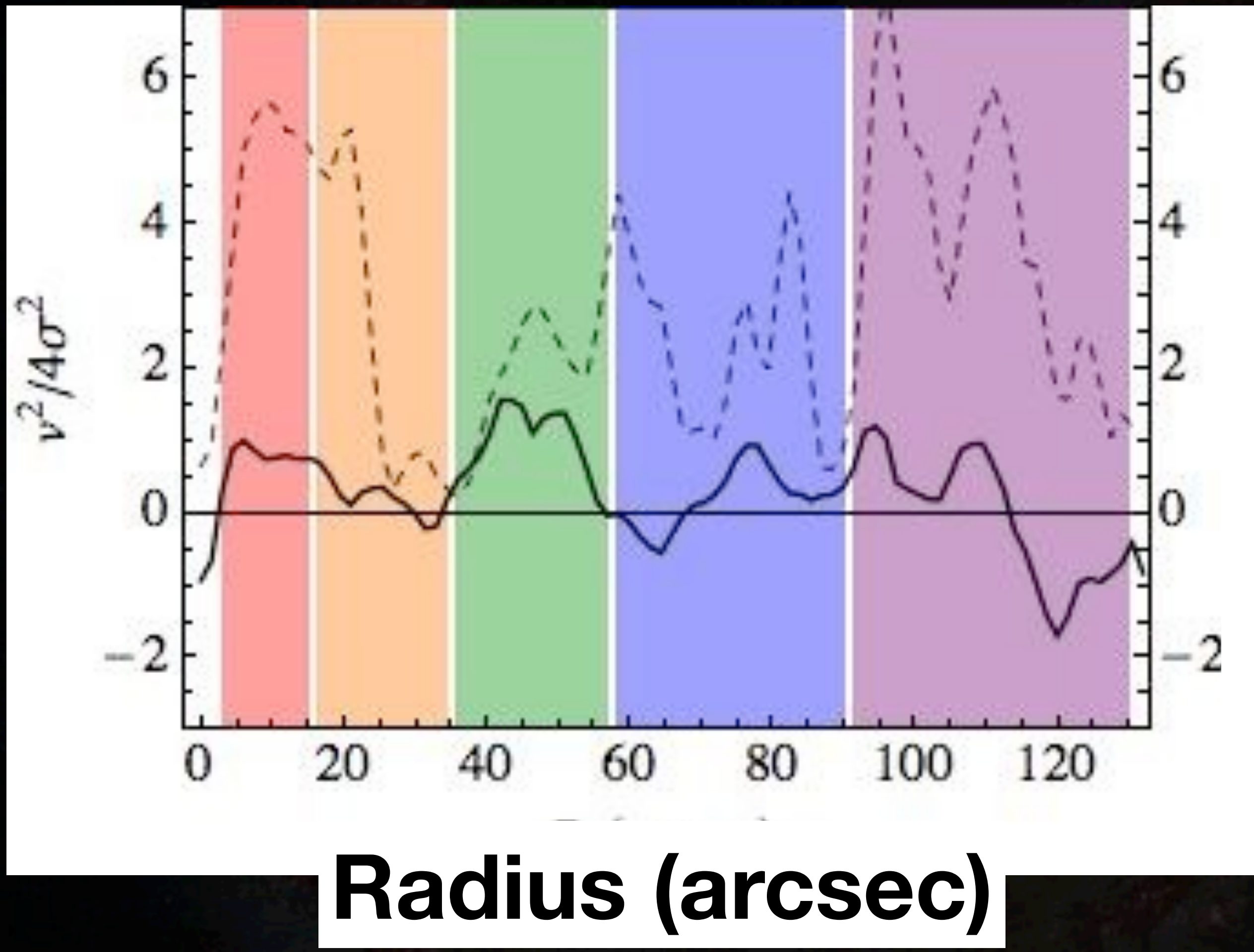

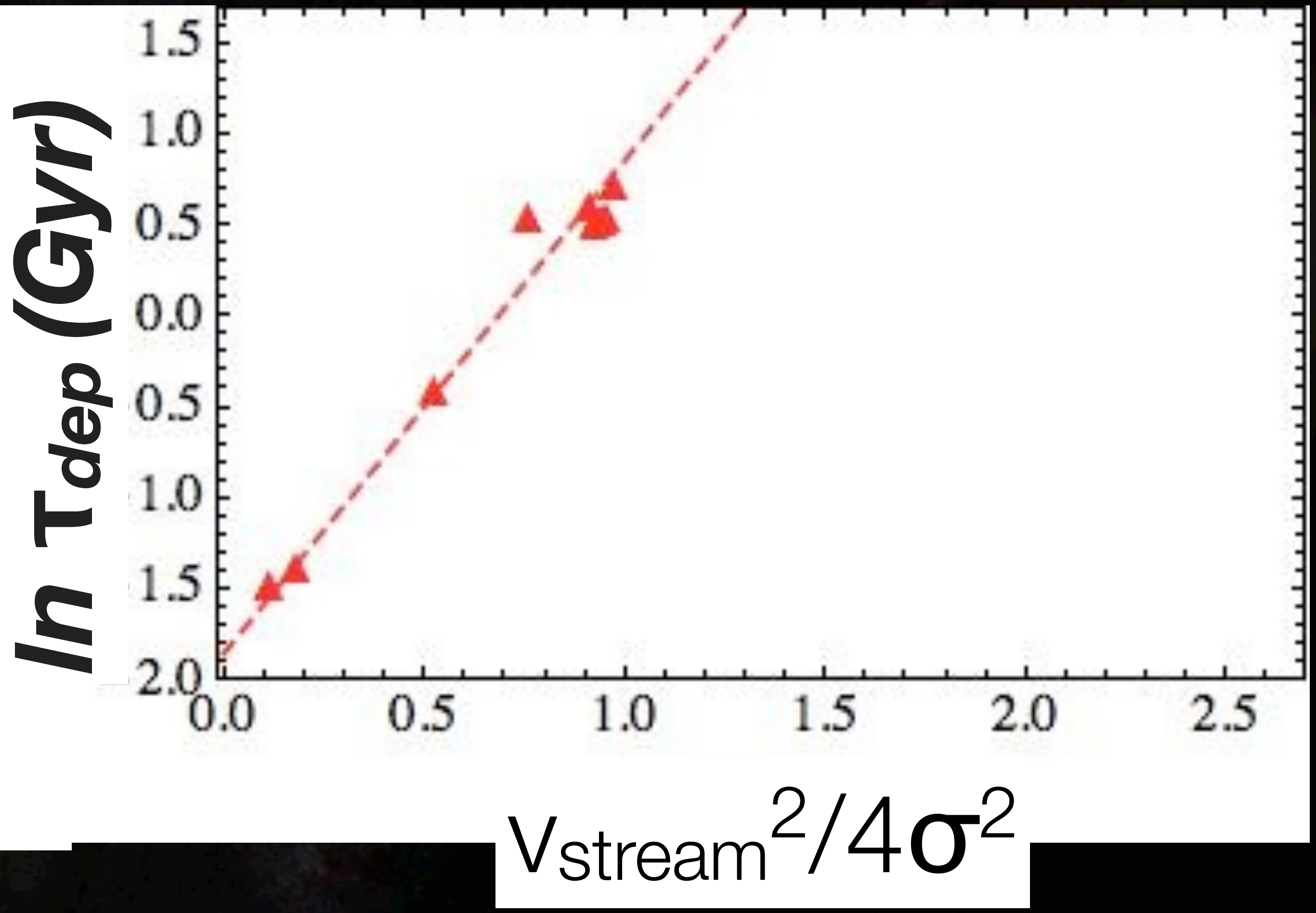

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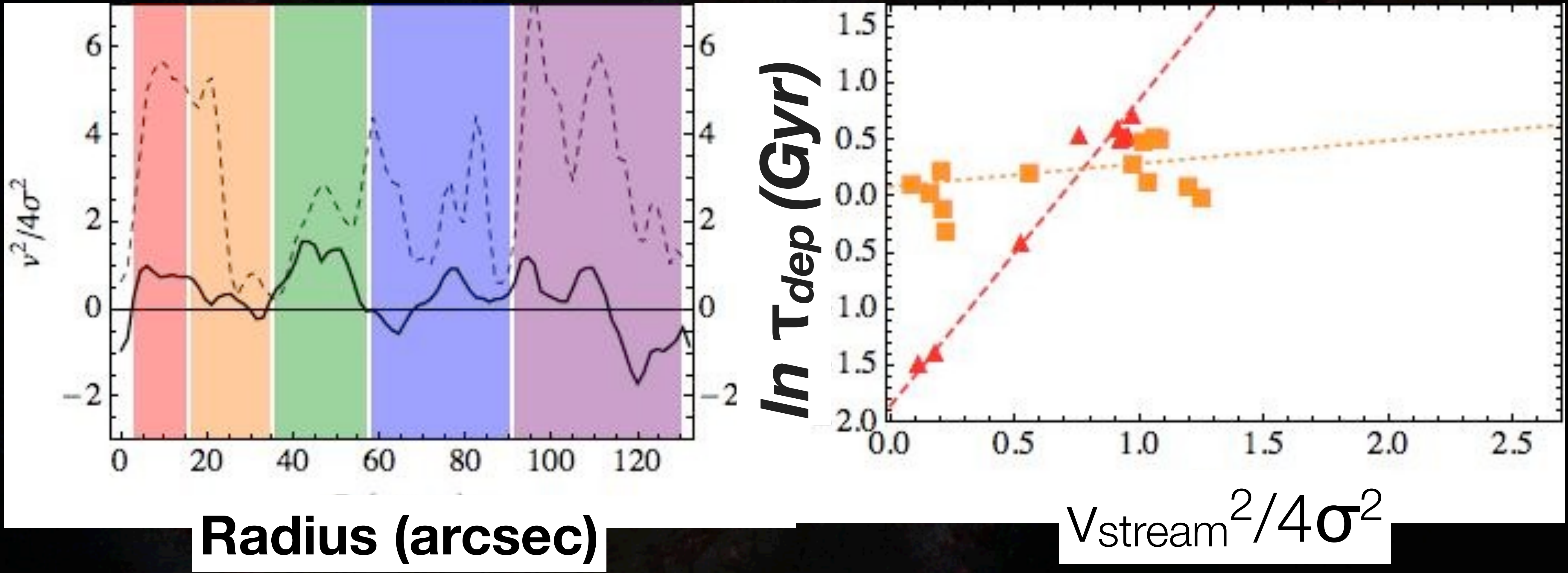

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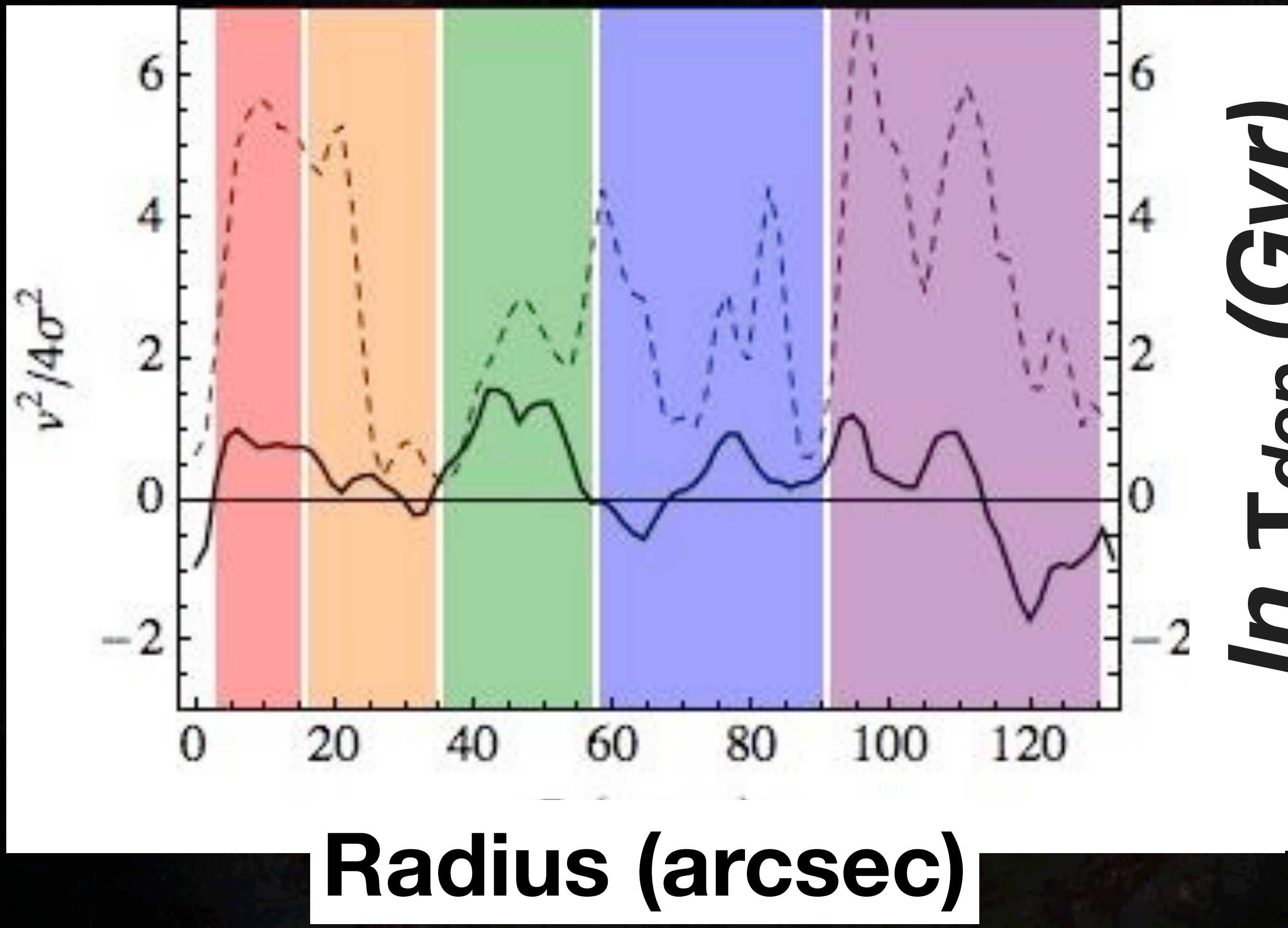

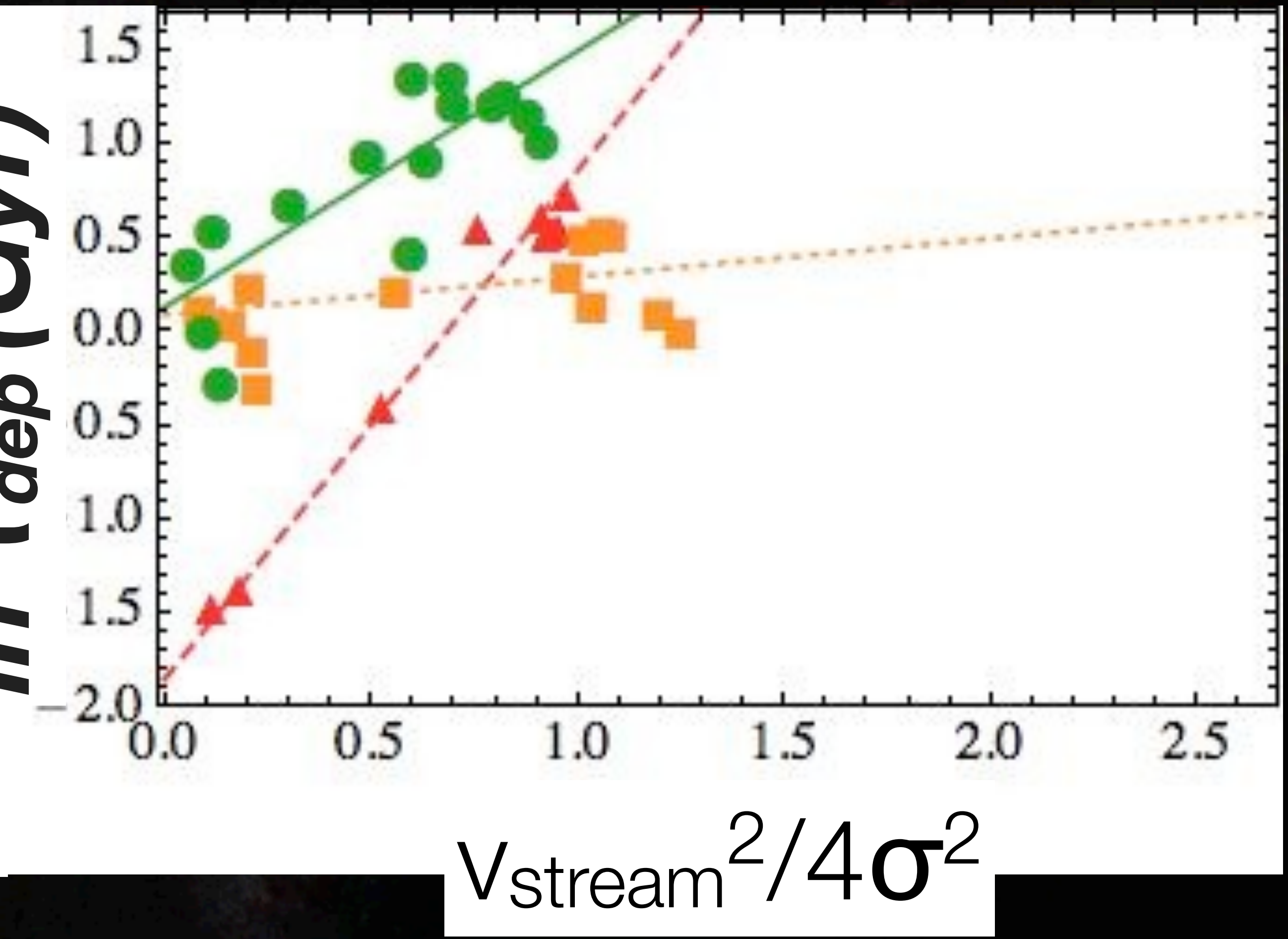

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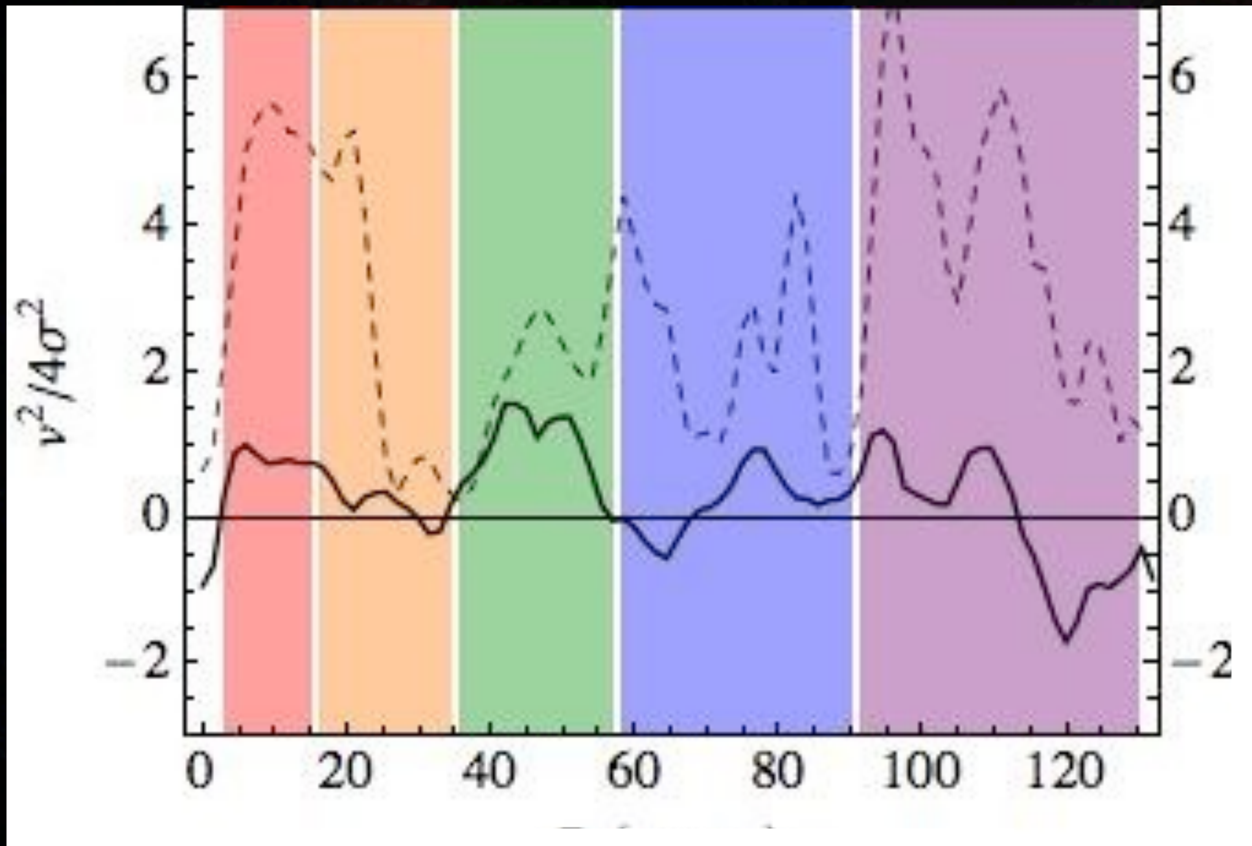
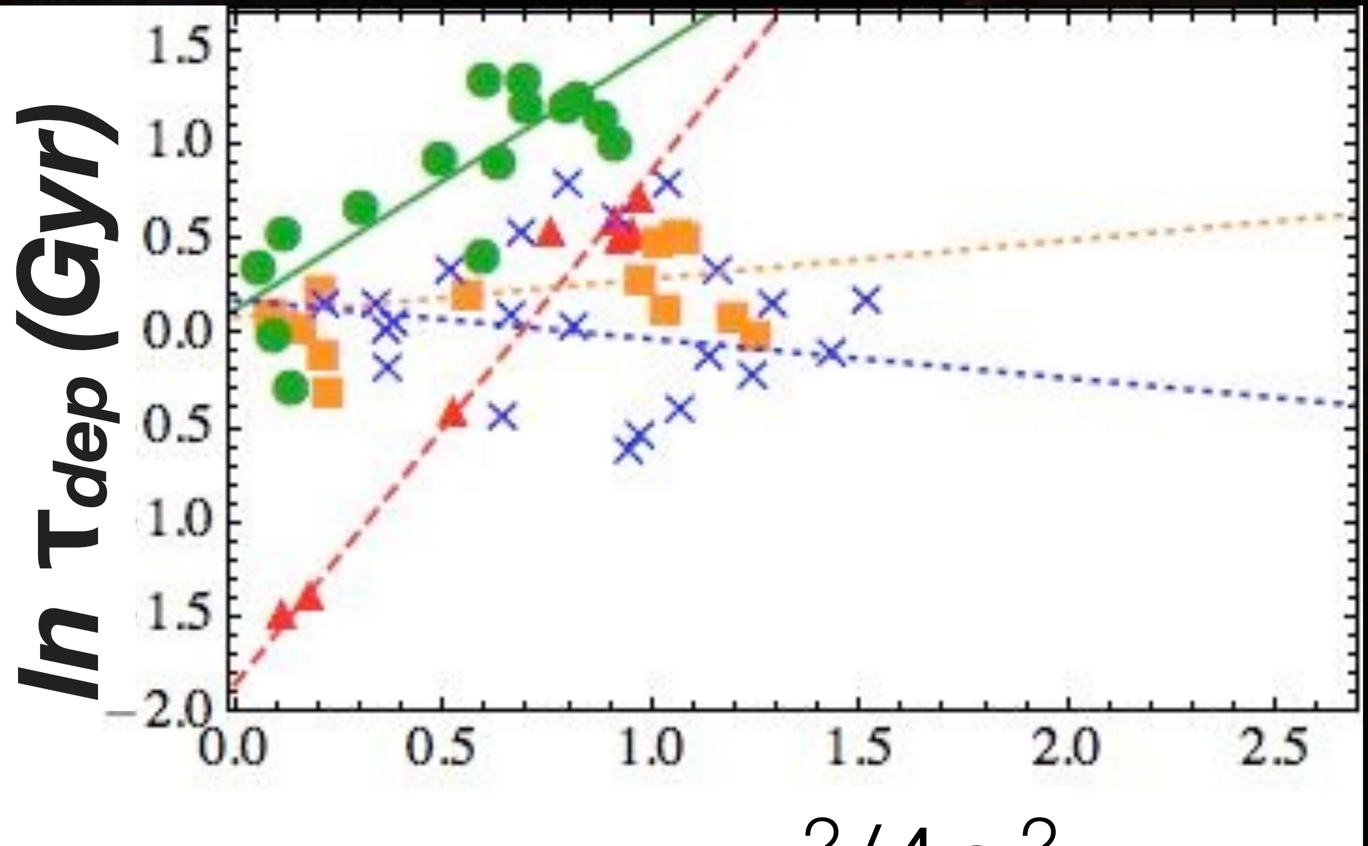


Radius (arcsec)



ln τ_{dep} *(Gyr)*

$v_{stream}^2/4\sigma^2$

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

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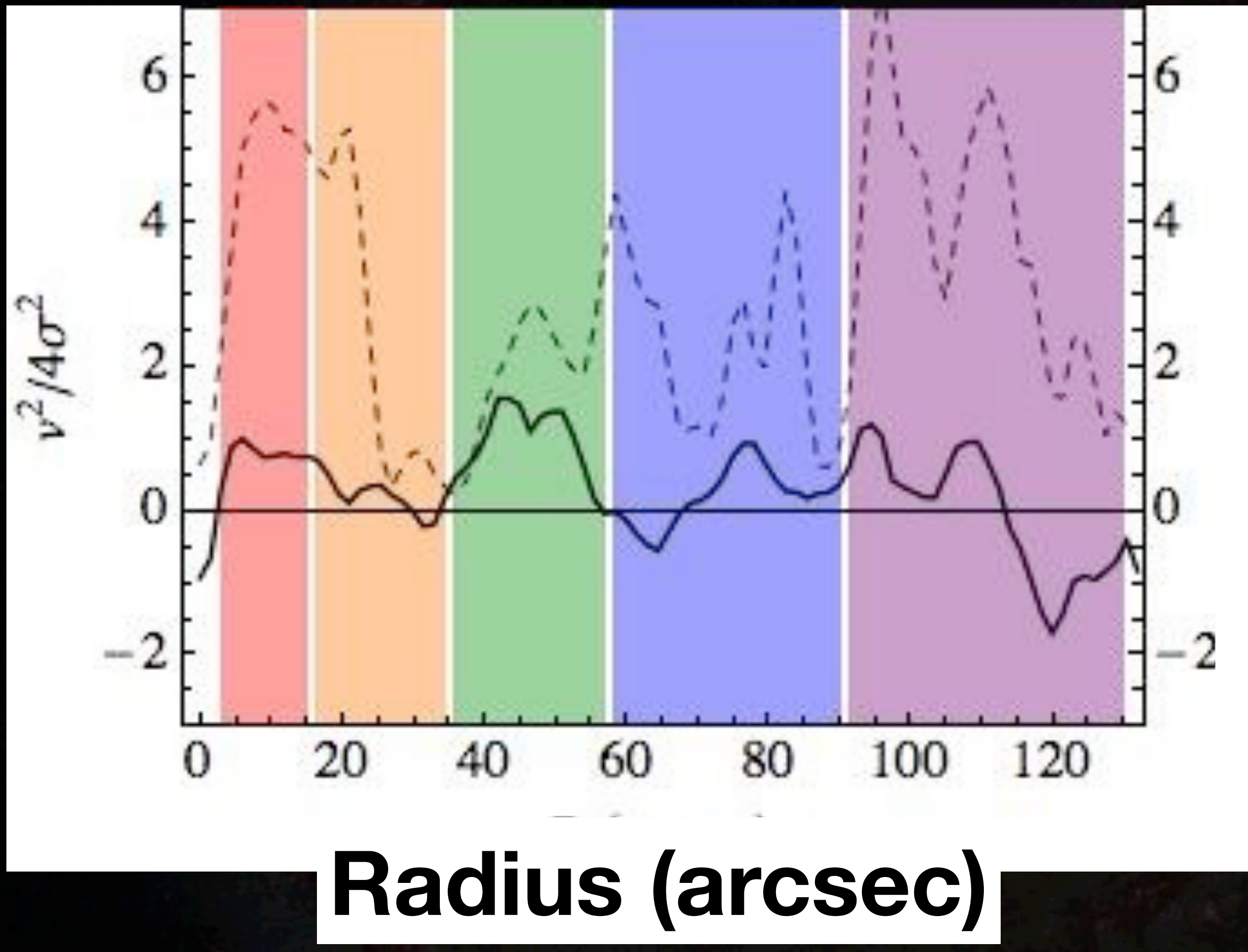

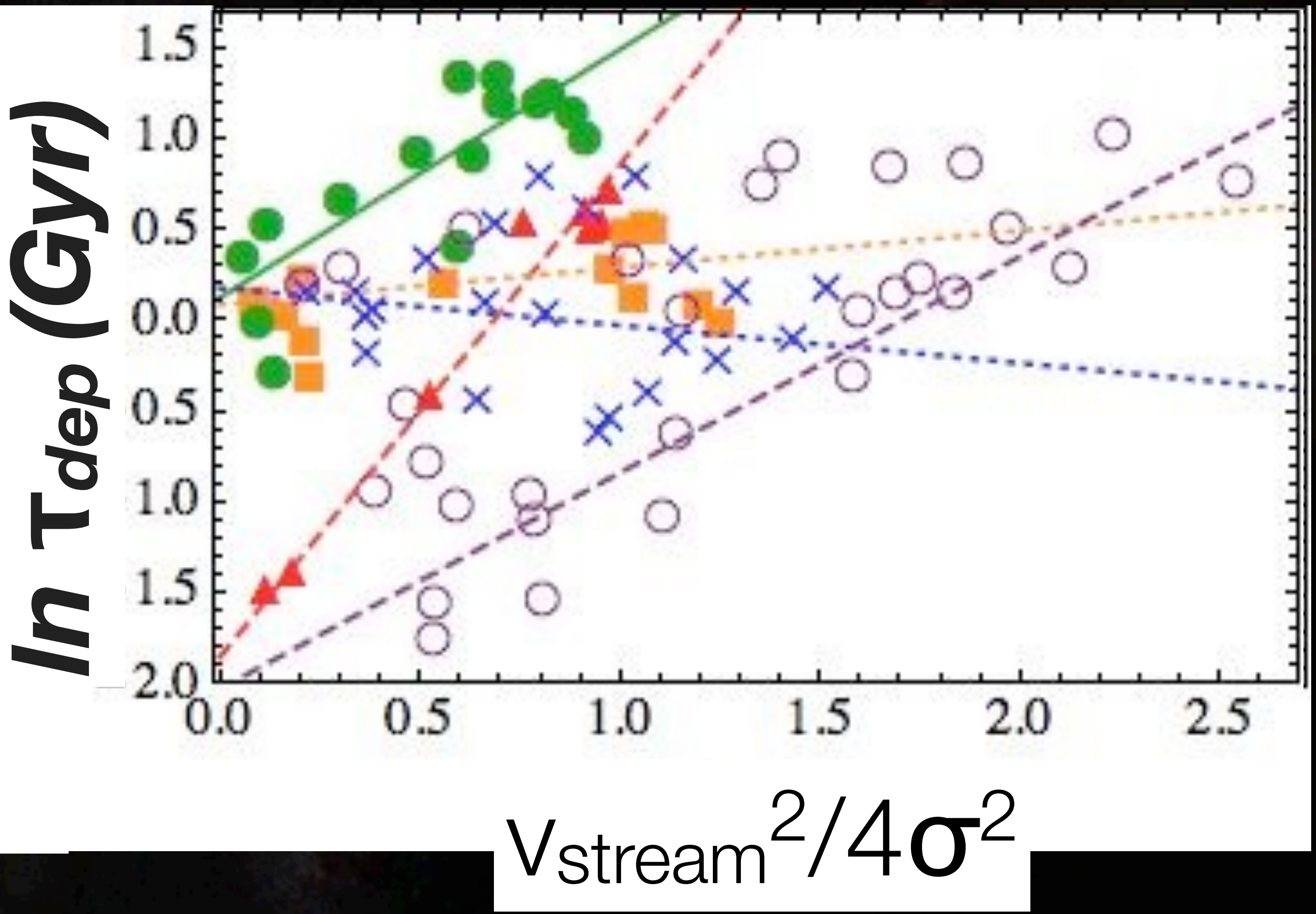

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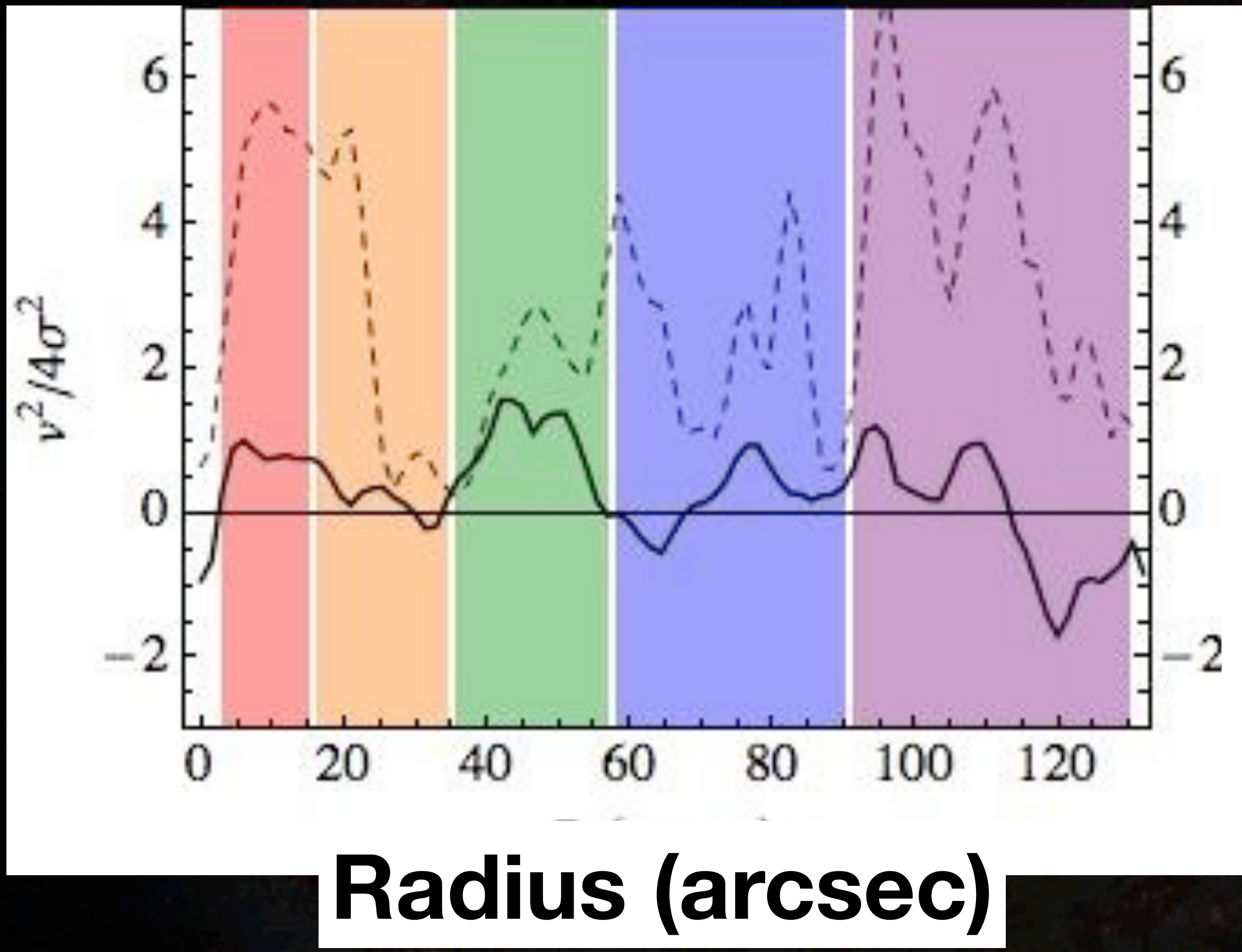
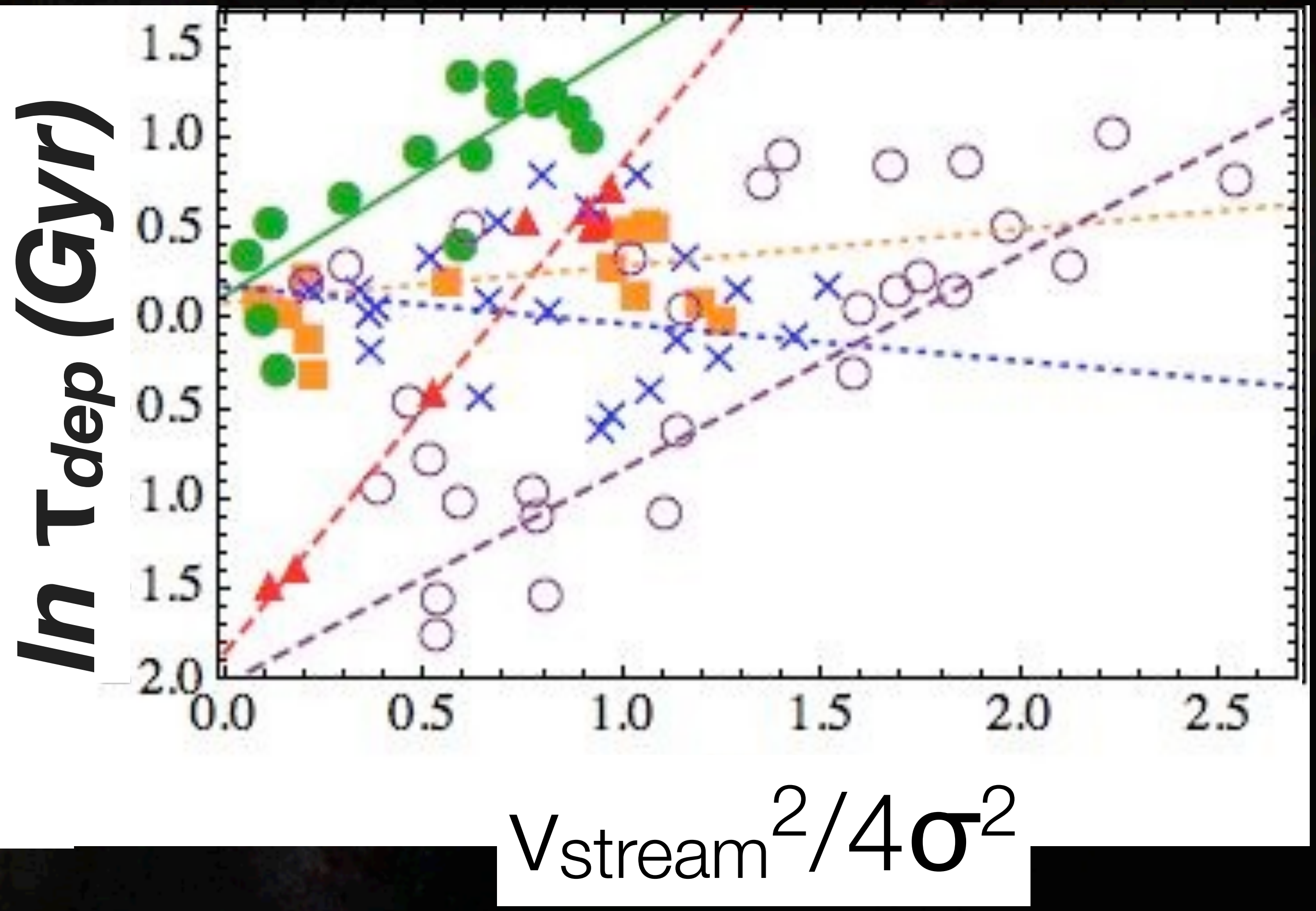




fit predicts

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)

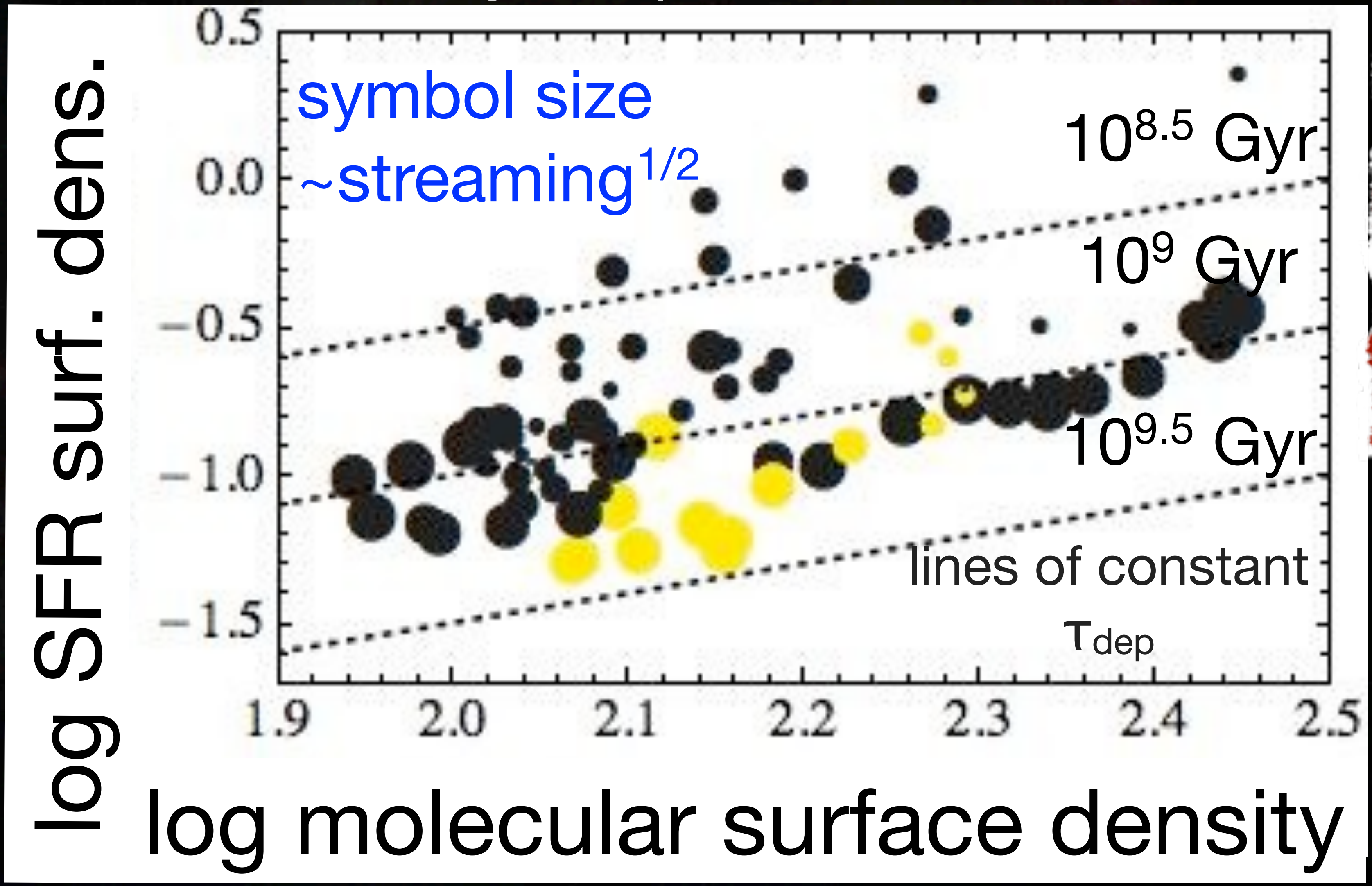
$\langle\tau_{dep0}\rangle \sim 1$ Gyr

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

~ 'universal' depletion time
(Bigiel et al. 2008)

are the 'normal' spiral galaxies really normal?

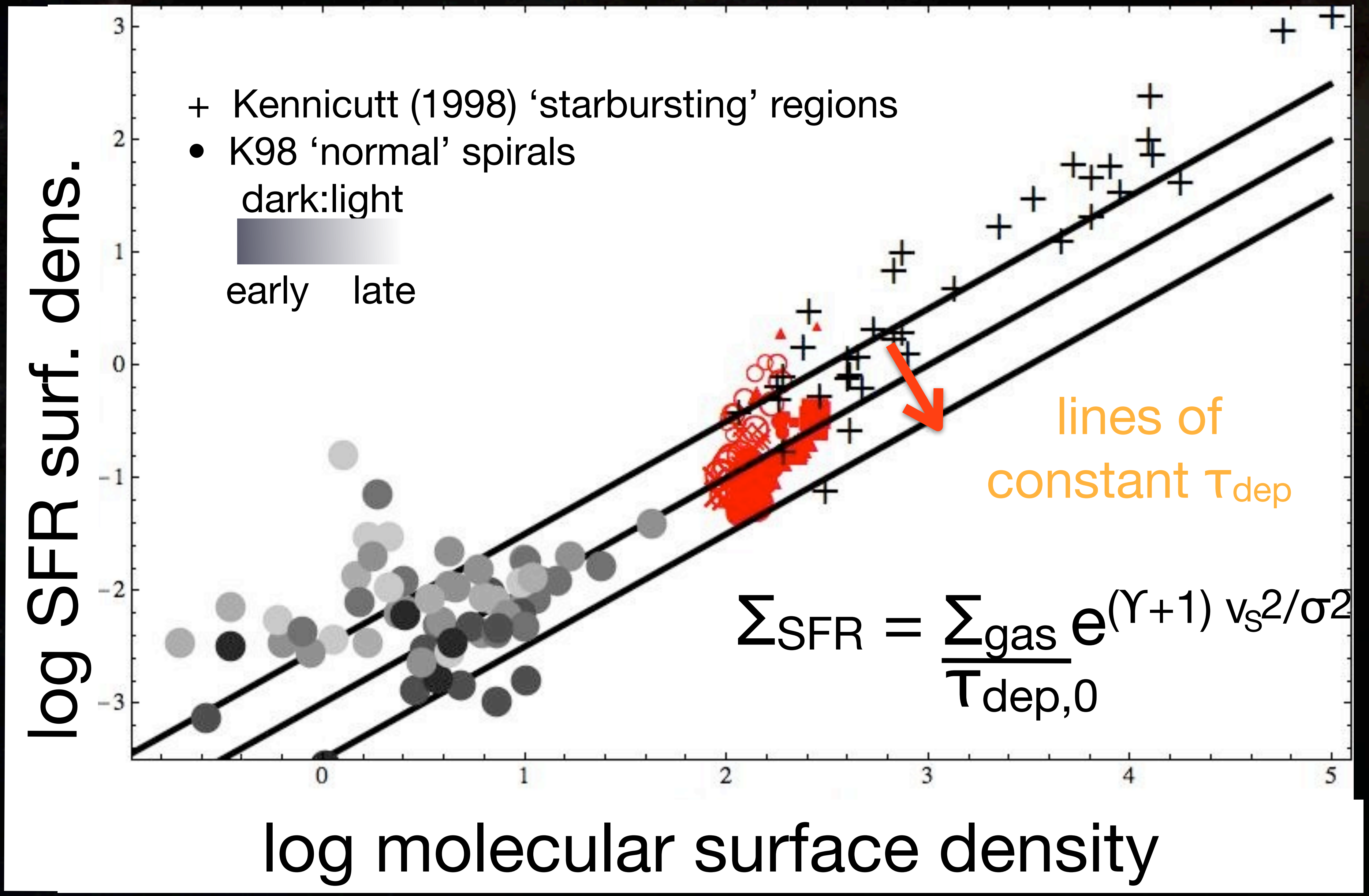
- dynamical pressure in the presence of streaming motions driven by torques



streaming lengthens τ_{dep} to 2 Gyr

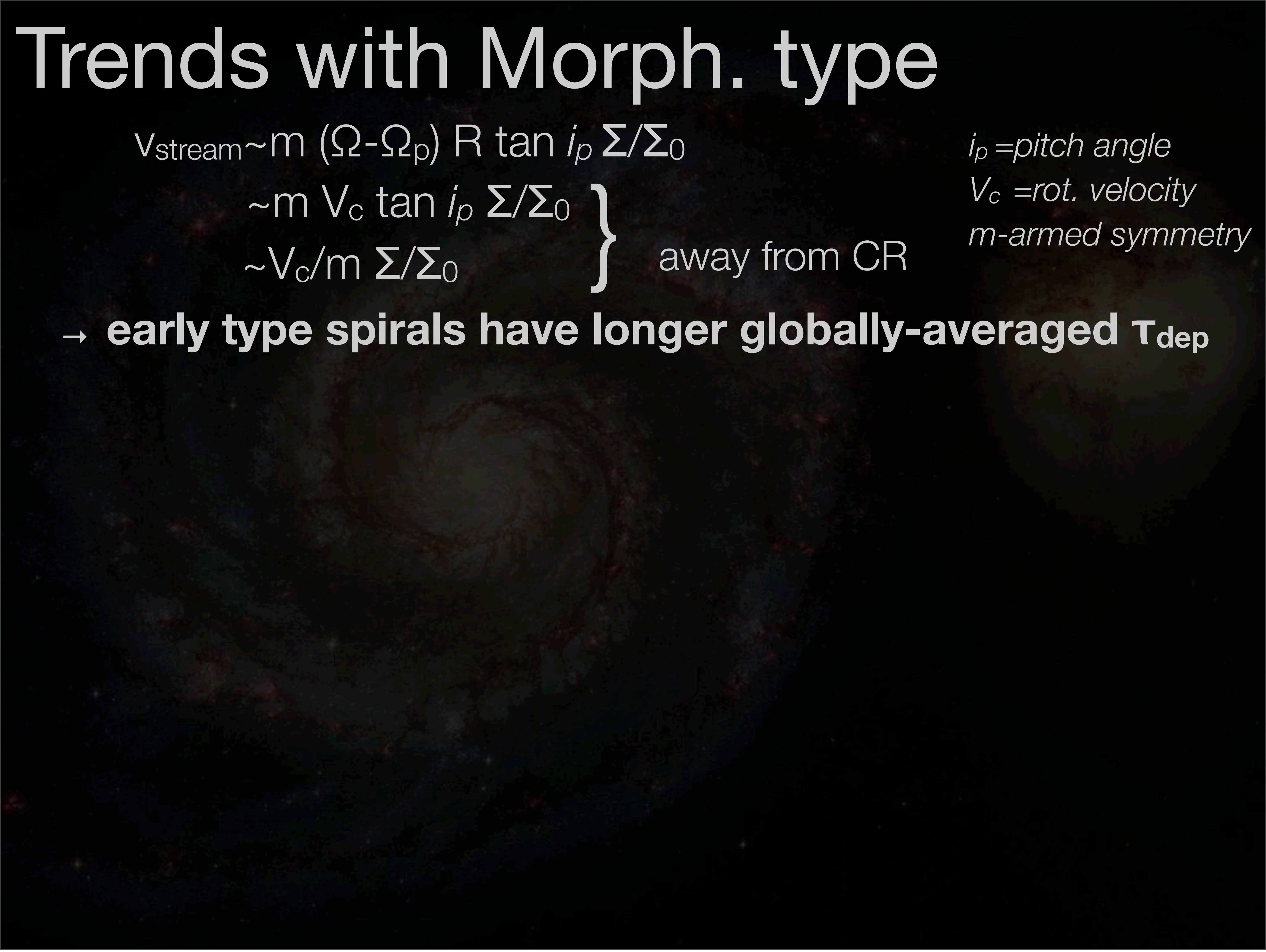
- comparable to dwarfs with Galactic X_{CO}, starbursts?

are the ‘normal’ spiral galaxies really normal?



$$\Sigma_{SFR} = \frac{\Sigma_{gas}}{\tau_{dep,0}} e^{(\Upsilon+1)\, v_S^2/\sigma^2}$$

Trends with Morph. type



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

$$\left.\begin{array}{l} \sim m\,V_c \tan i_p\,\Sigma/\Sigma_0 \\ \sim V_c/m\,\Sigma/\Sigma_0 \end{array}\right\} \text{ away from CR}$$

i_p =pitch angle

V_c =rot. velocity

m-armed symmetry

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

Trends with Morph. type

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

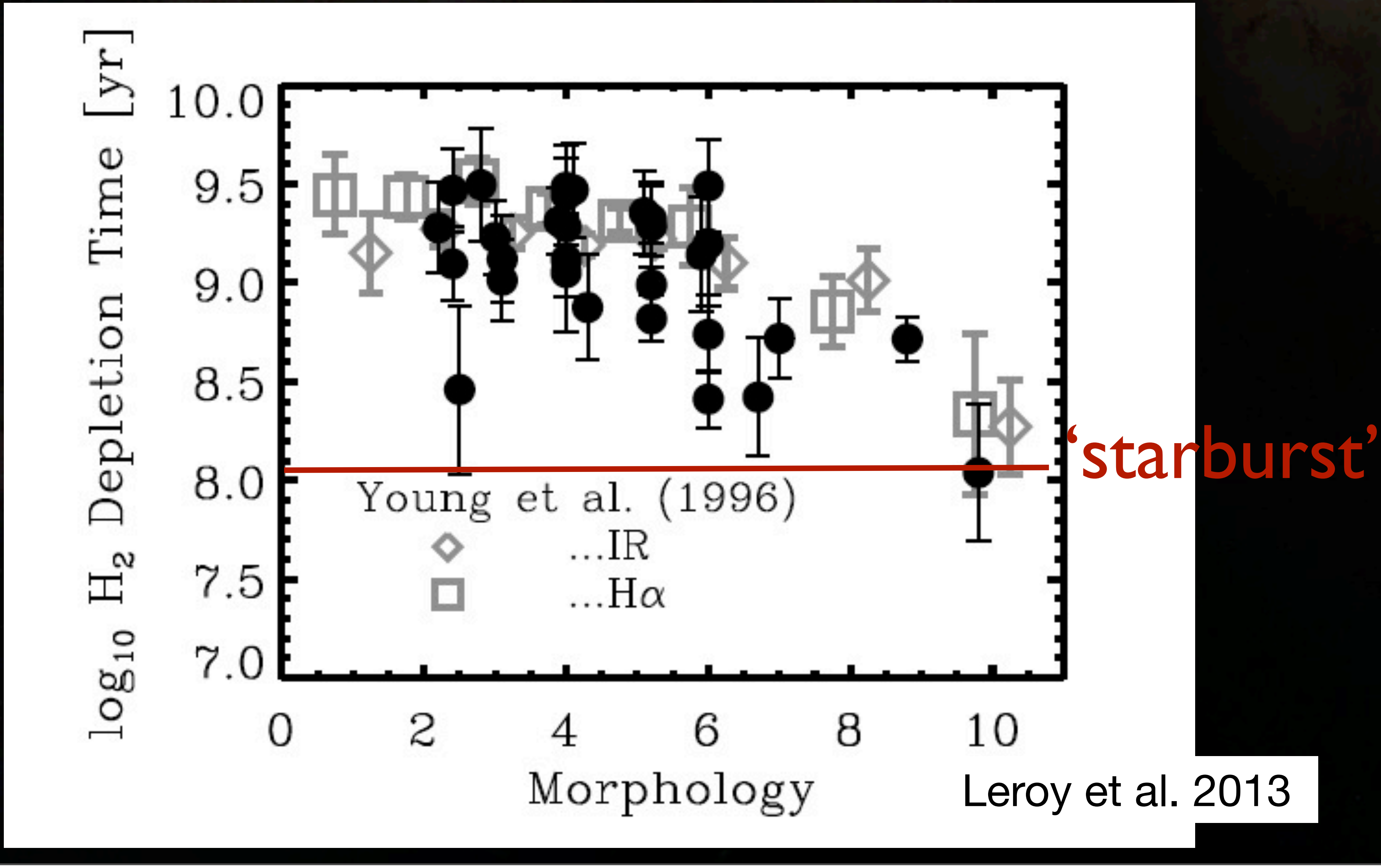
$$\left.\begin{array}{l} \sim m\, V_c \tan i_p\, \Sigma/\Sigma_0 \\ \sim V_c/m\, \Sigma/\Sigma_0 \end{array}\right\} \text{away from CR}$$

i_p =pitch angle

V_c =rot. velocity

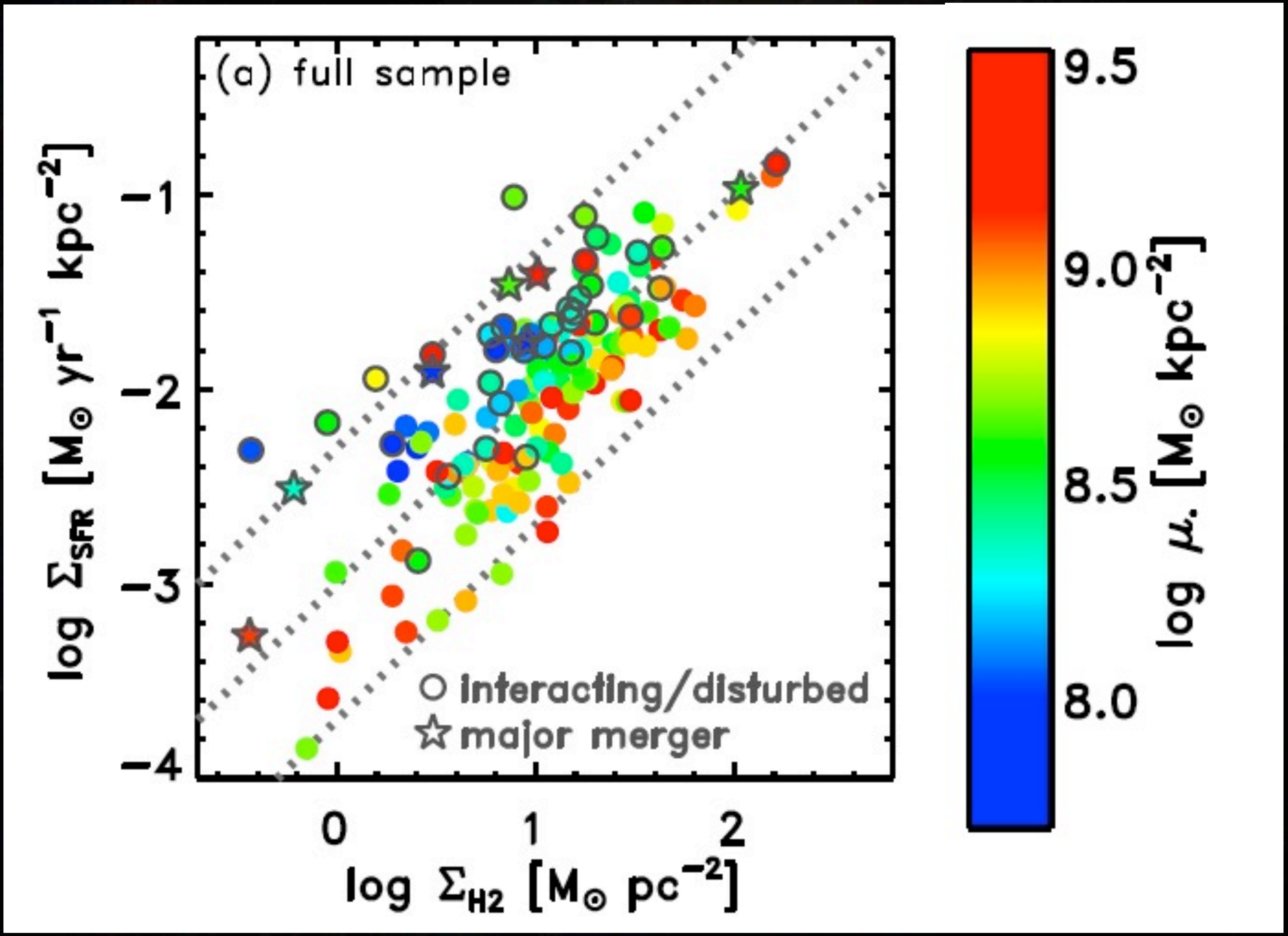
m-armed symmetry

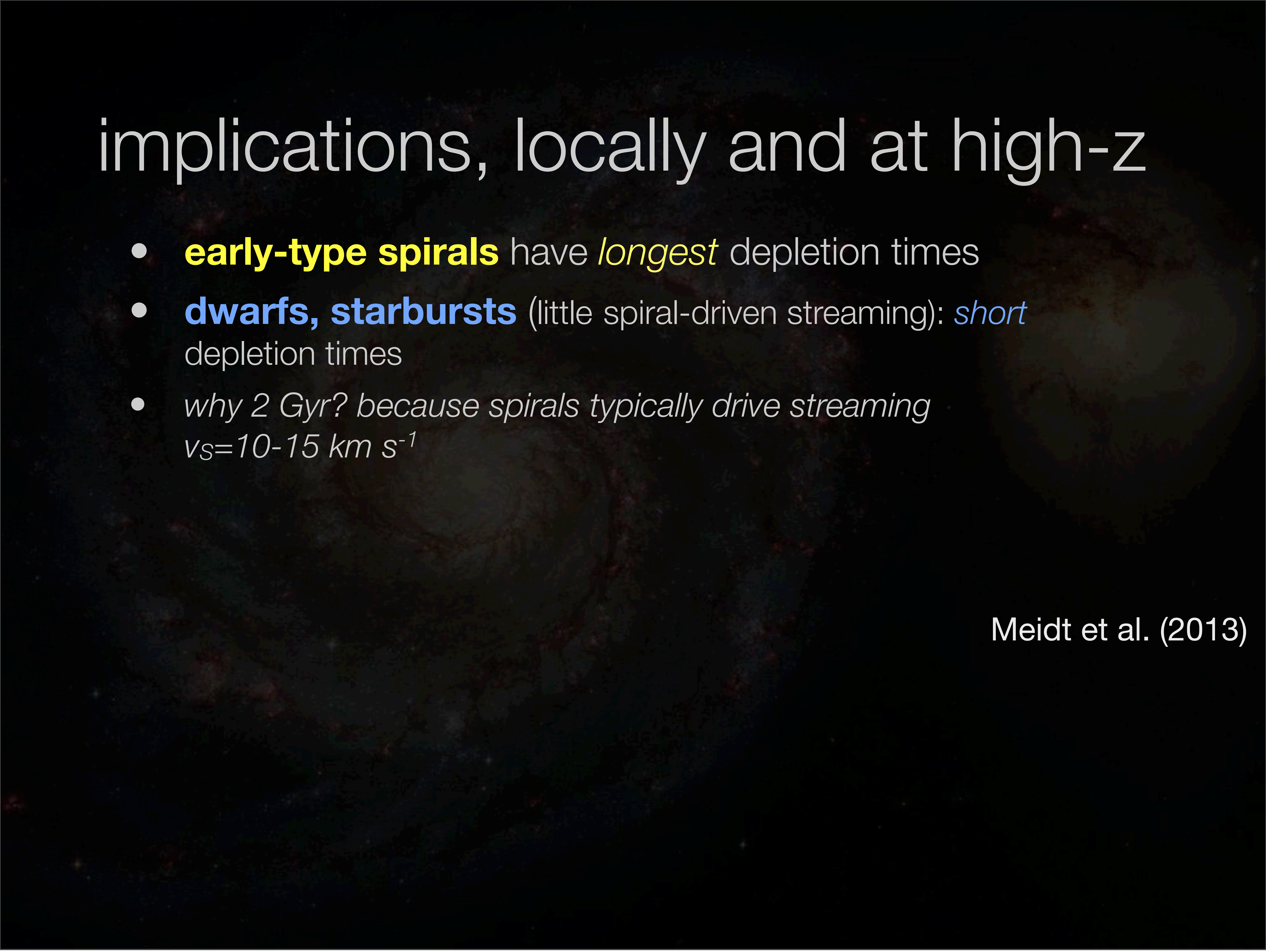
→ **early type spirals have longer globally-averaged τ_{dep}**



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}*

Meidt et al. (2013)

implications, locally and at high-z

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- **dwarfs, starbursts** (little spiral-driven streaming): *short* depletion times
- *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

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

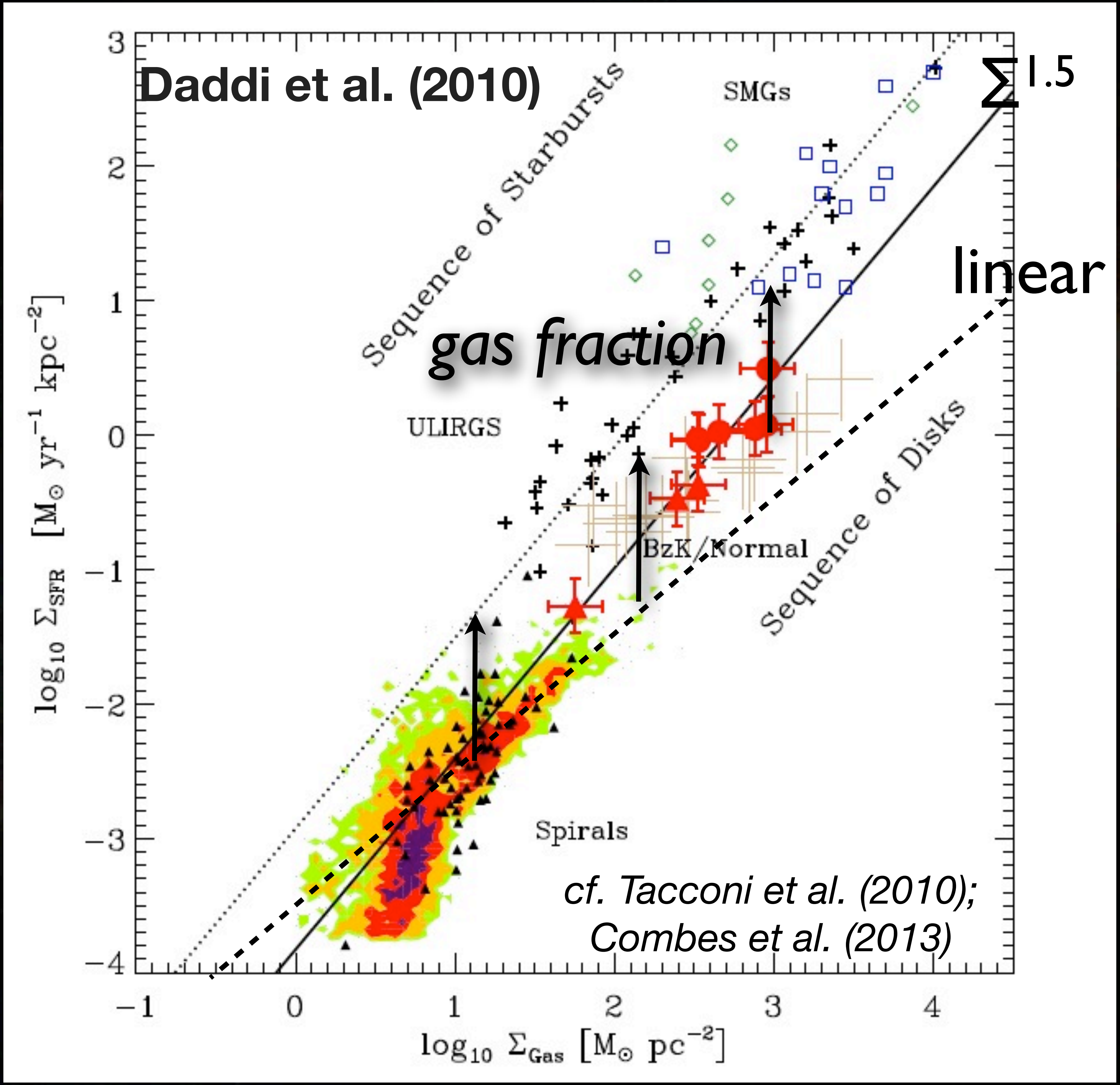
Meidt et al. (2013)

Toomre Q

gas fraction

τ_{dep} linked to gas fraction

(high F_g --> weakened sensitivity to environment-decoupling)



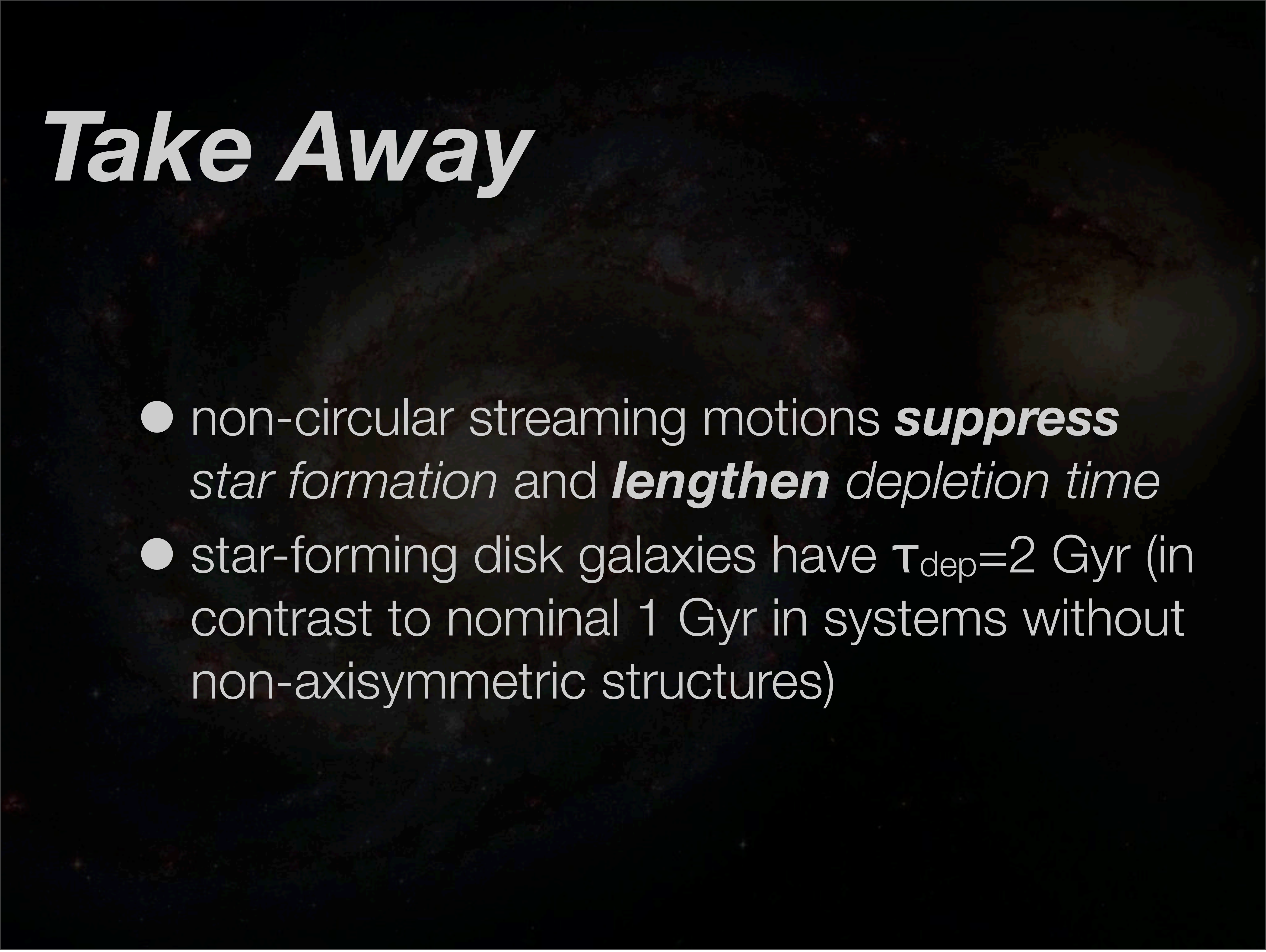
Daddi et al. (2010)

$\Sigma^{1.5}$

linear

gas fraction

cf. Tacconi et al. (2010); Combes et al. (2013)



Take Away

- non-circular streaming motions ***suppress*** *star formation* and ***lengthen*** *depletion time*
- star-forming disk galaxies have τ_{dep}=2 Gyr (in contrast to nominal 1 Gyr in systems without non-axisymmetric structures)