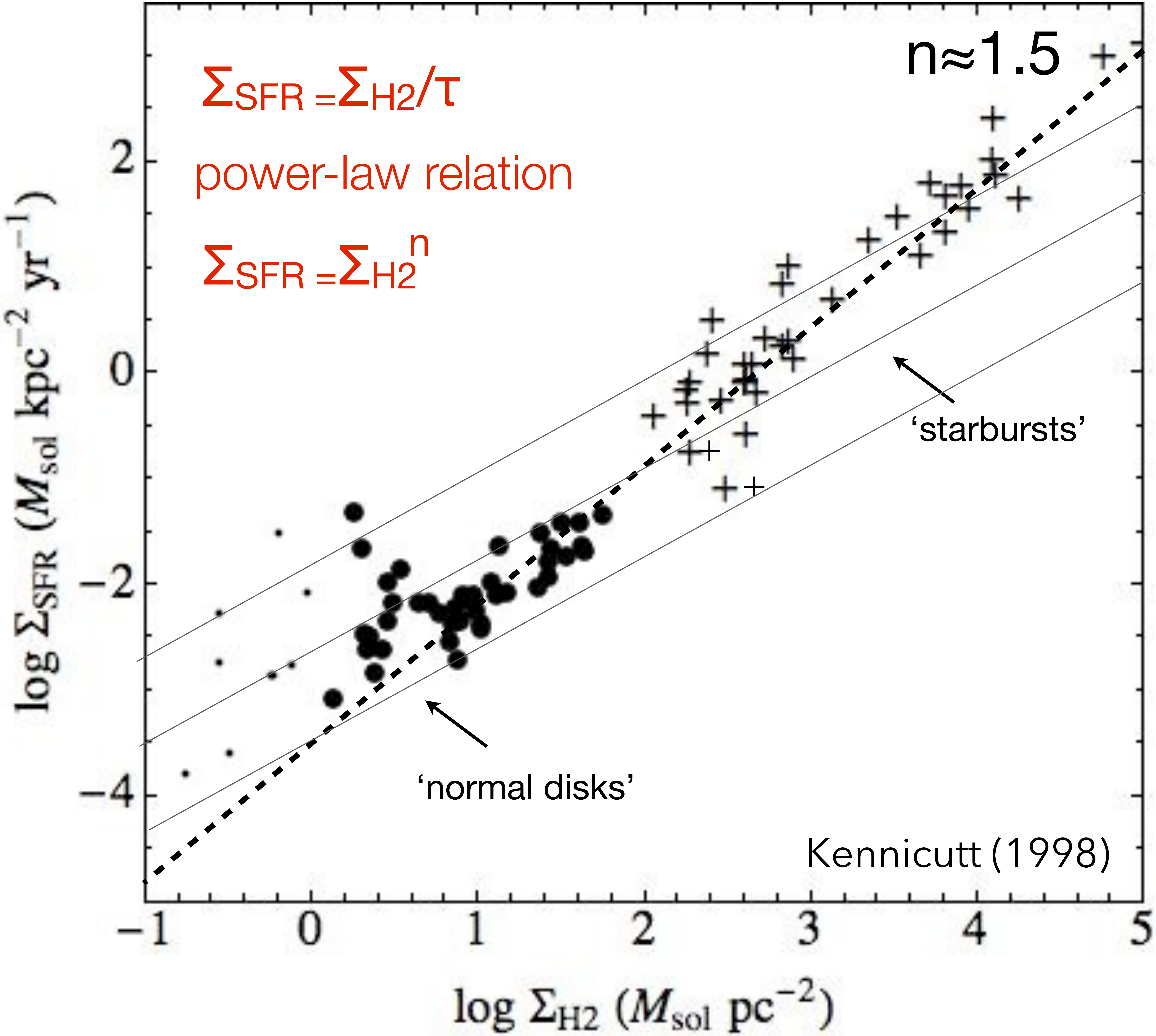
dynamical regulation of star formation

Sharon E. Meidt
(MPIA)

A. Hughes, E. Schinnerer, S. Garcia-Burillo,
D. Colombo, C. Dobbs, A. Leroy, C. Kramer,
K. Schuster, G. Dumas, T. Thompson

PAWS
PdBI Arcsecond Whirlpool Survey

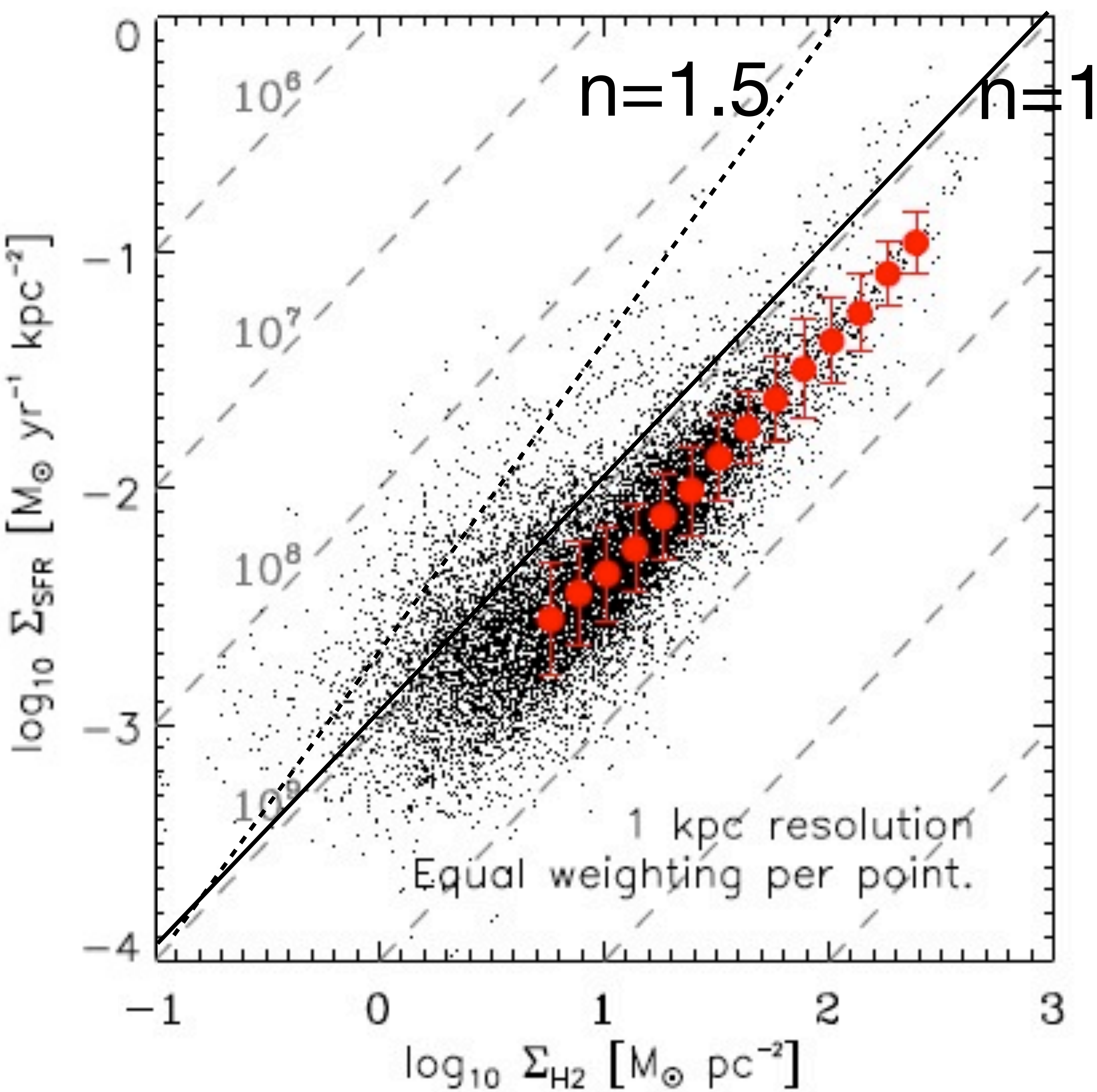
Global Star Formation Relation



$\tau = \tau_{ff}$

= cloud free-fall time??

spatially-resolved Star Formation Relation



Bigiel et al.
(2008;2011)

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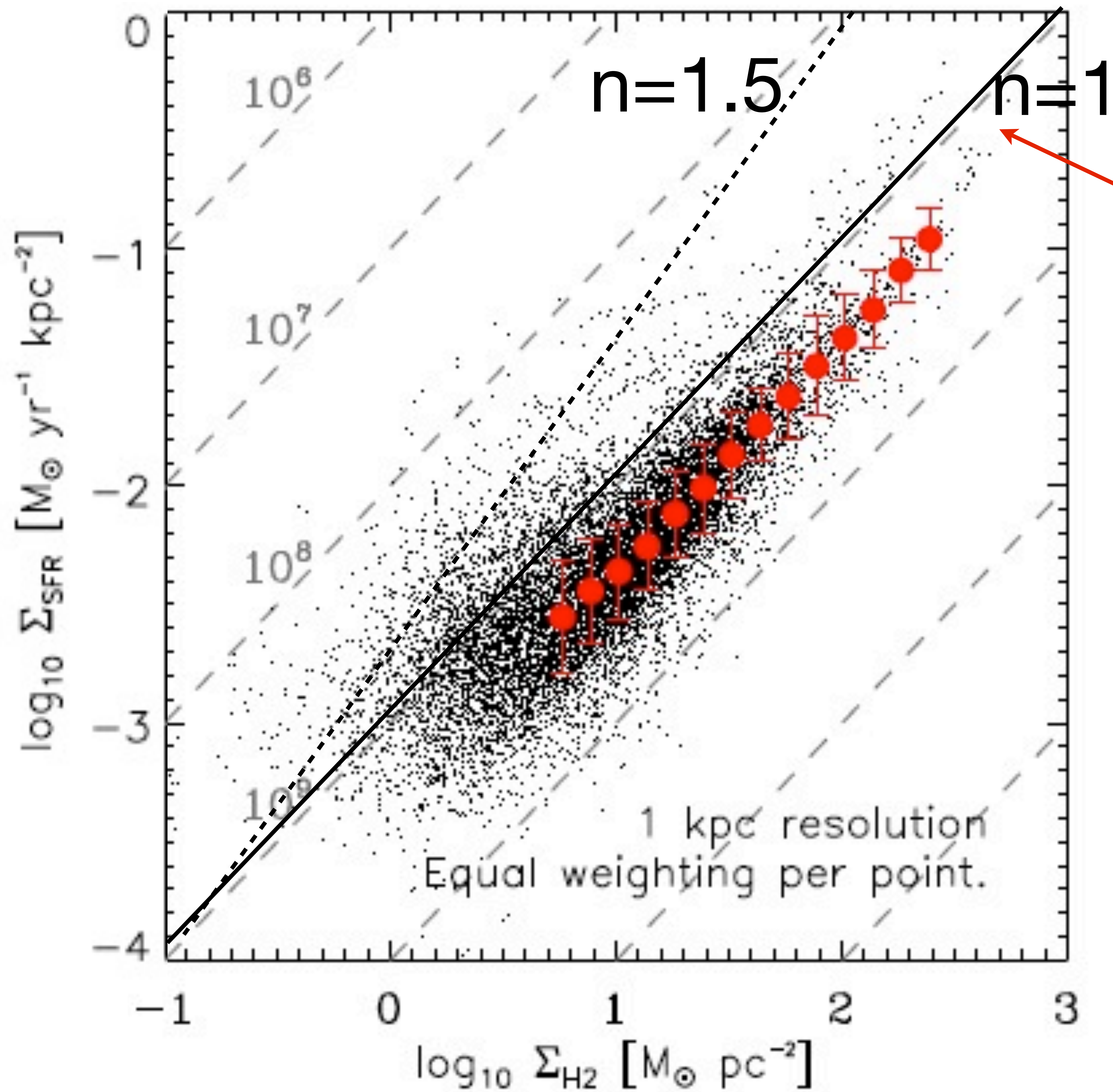

constant
molecular gas
depletion time
$\tau_{dep} = \Sigma_{H2} / \Sigma_{SFR}$

Bigiel et al. (2008;2011)

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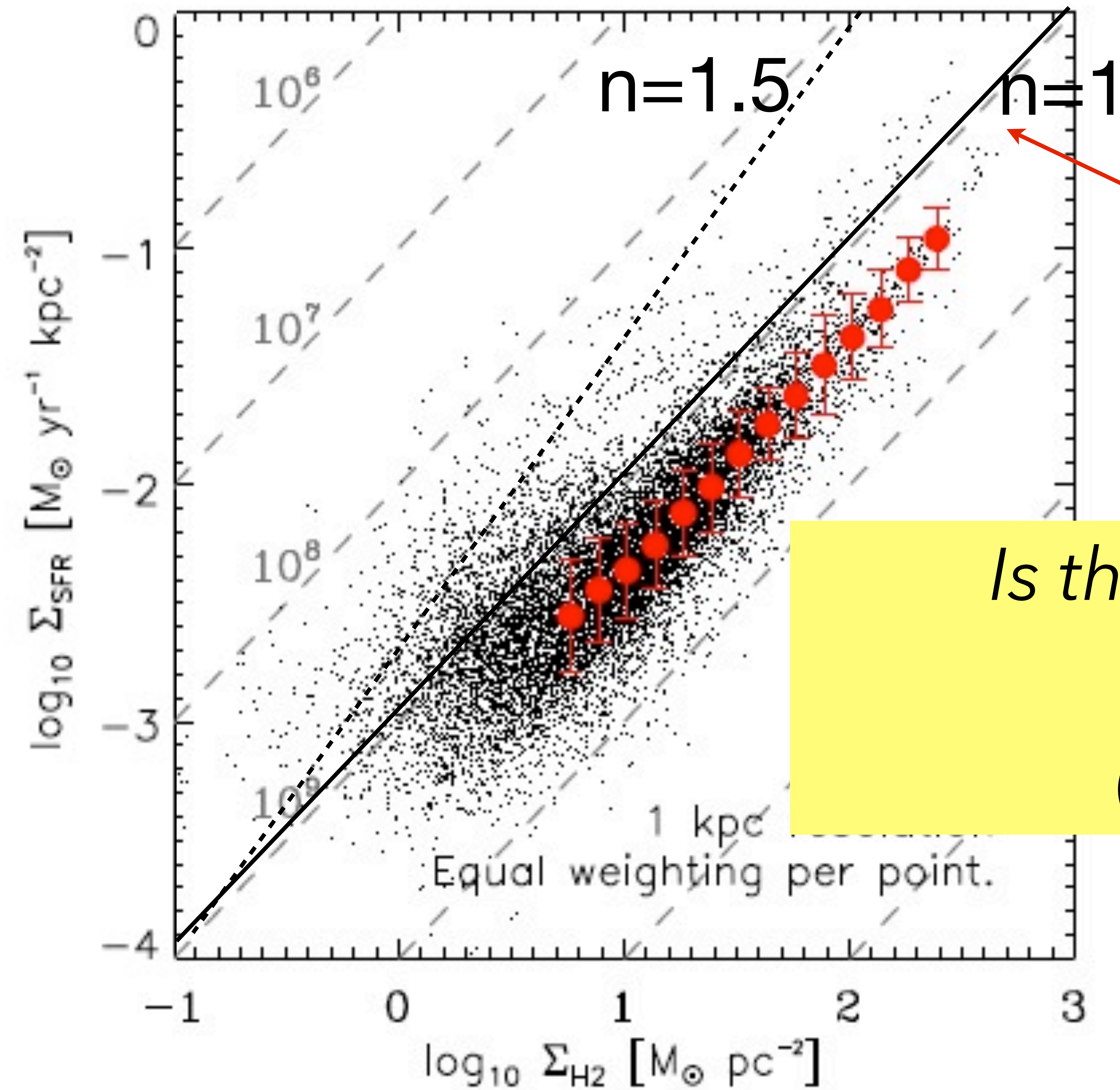

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$\tau_{dep} = \Sigma_{H2} / \Sigma_{SFR}$

Is there a ‘universal cloud’?
(one t_{ff}, one Σ?)

Bigiel et al. (2008;2011)

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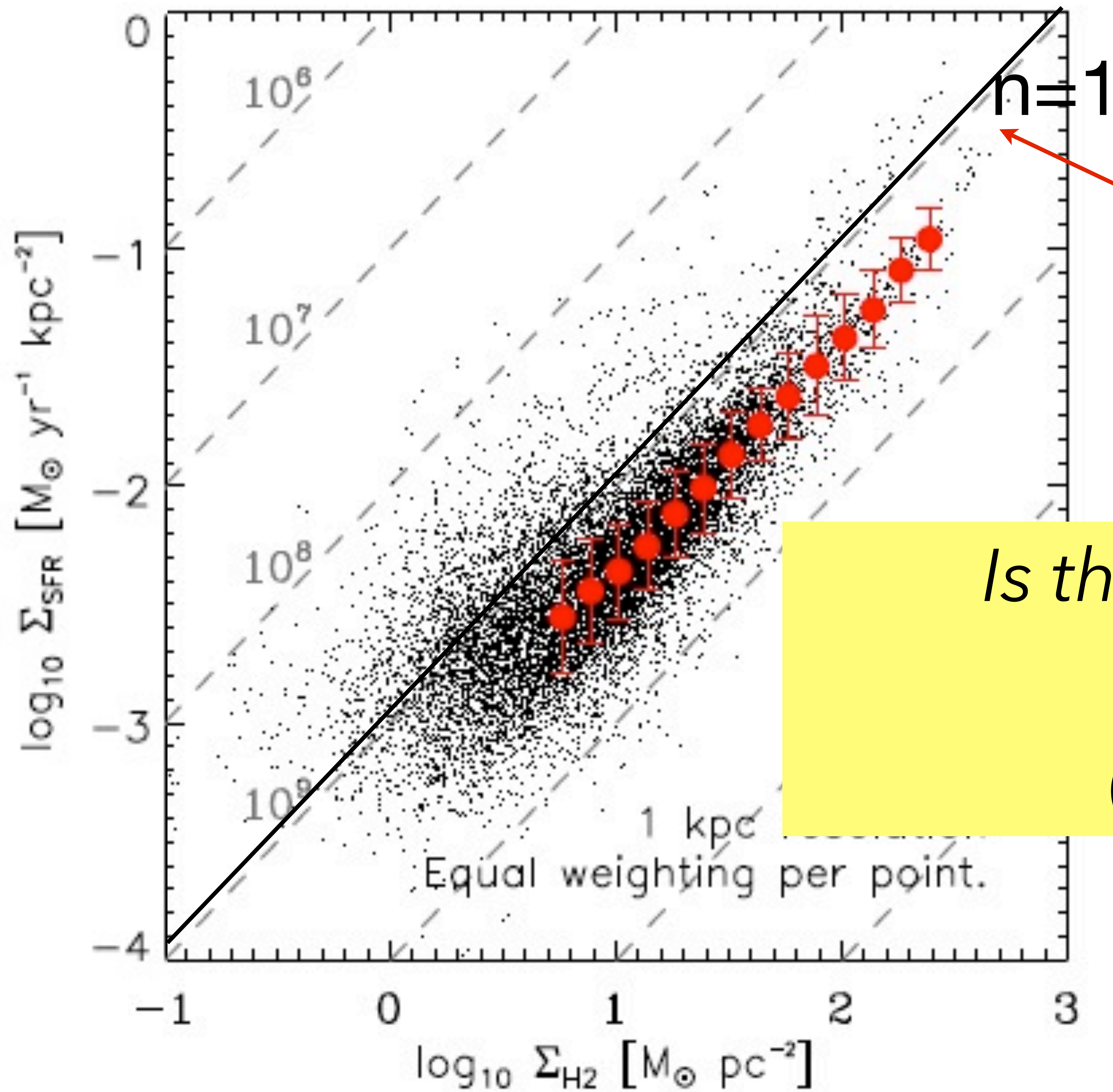

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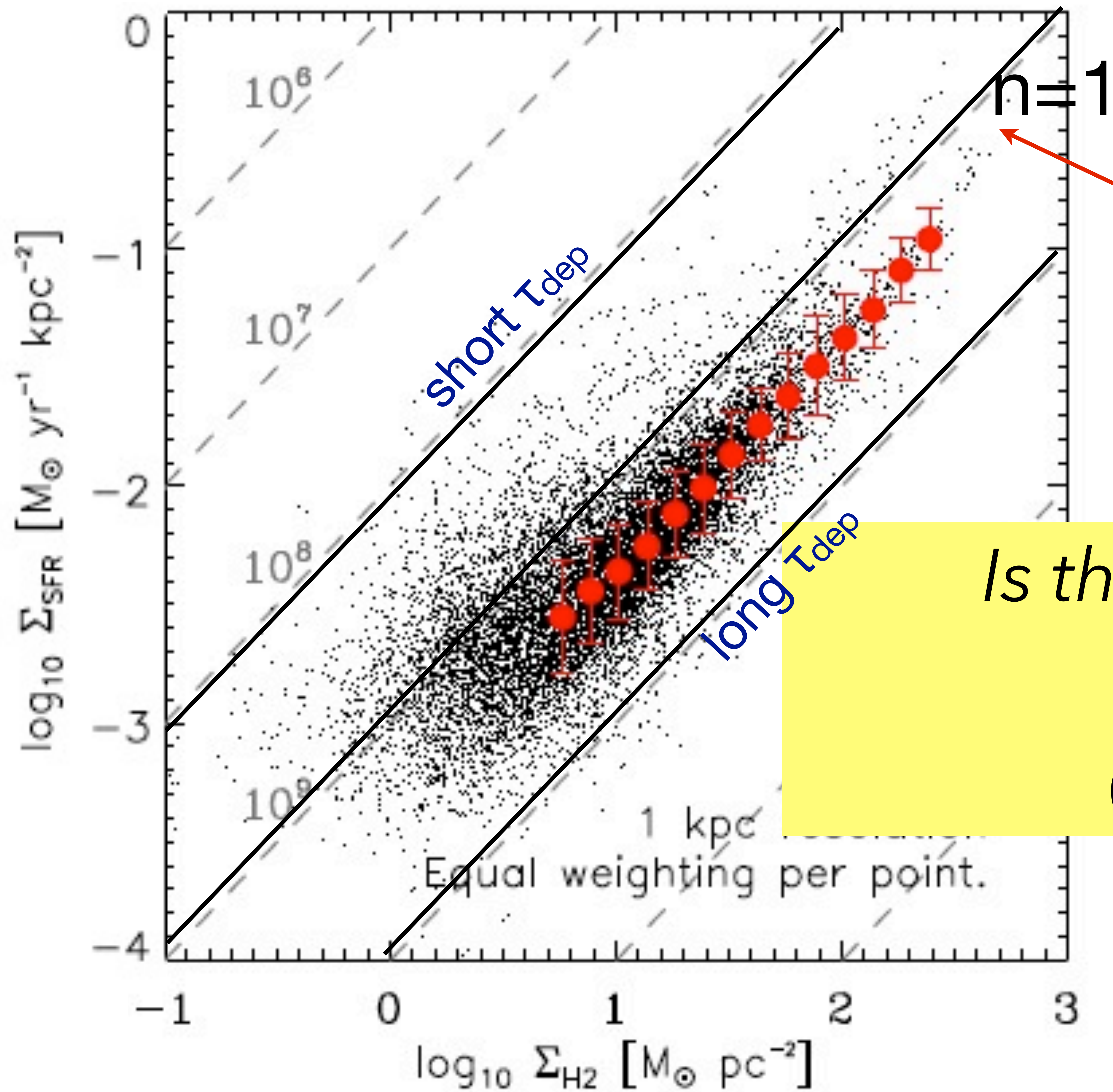

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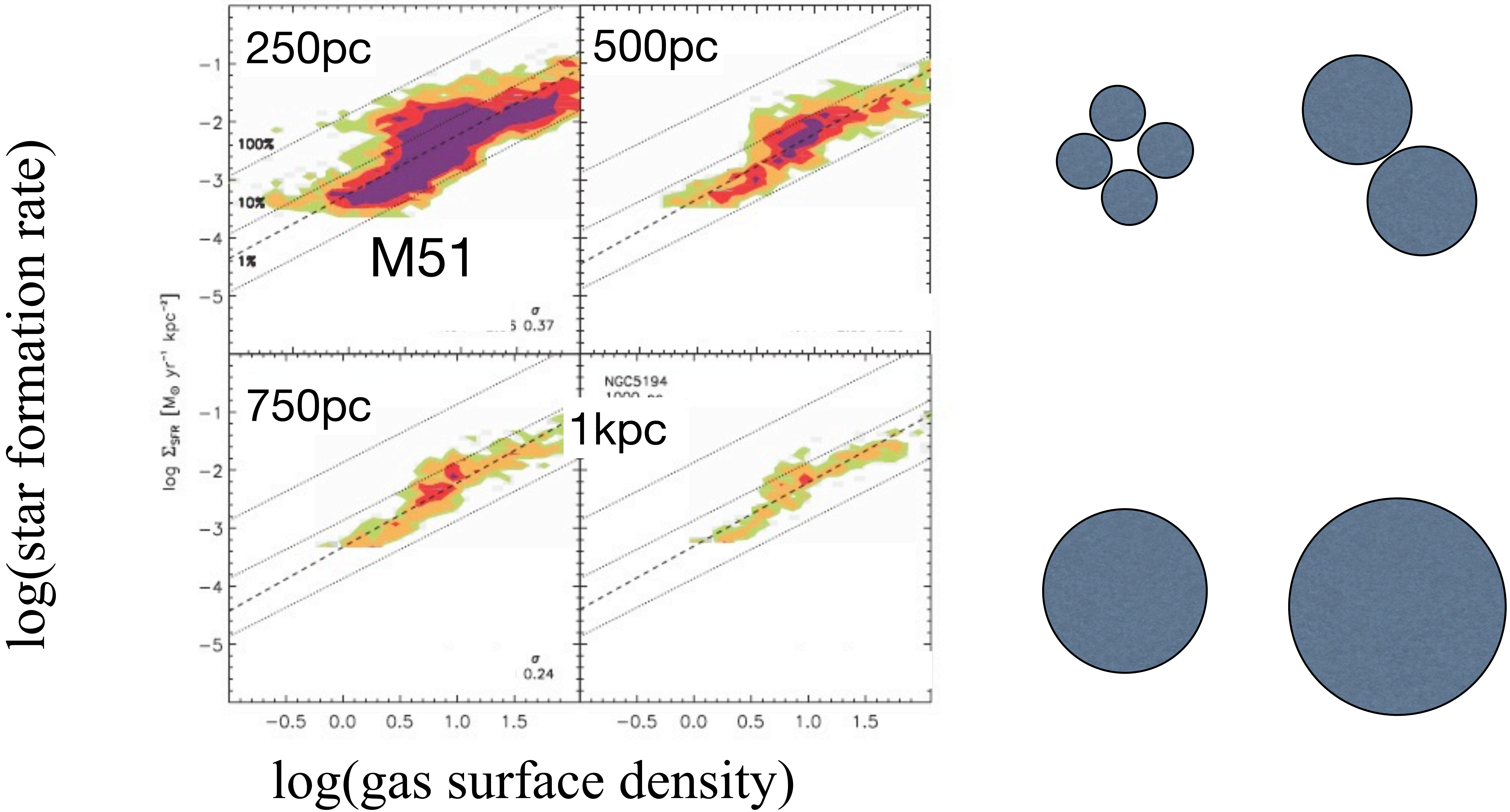
Scatter in the Star Formation relation



Bigiel et al. (2008)

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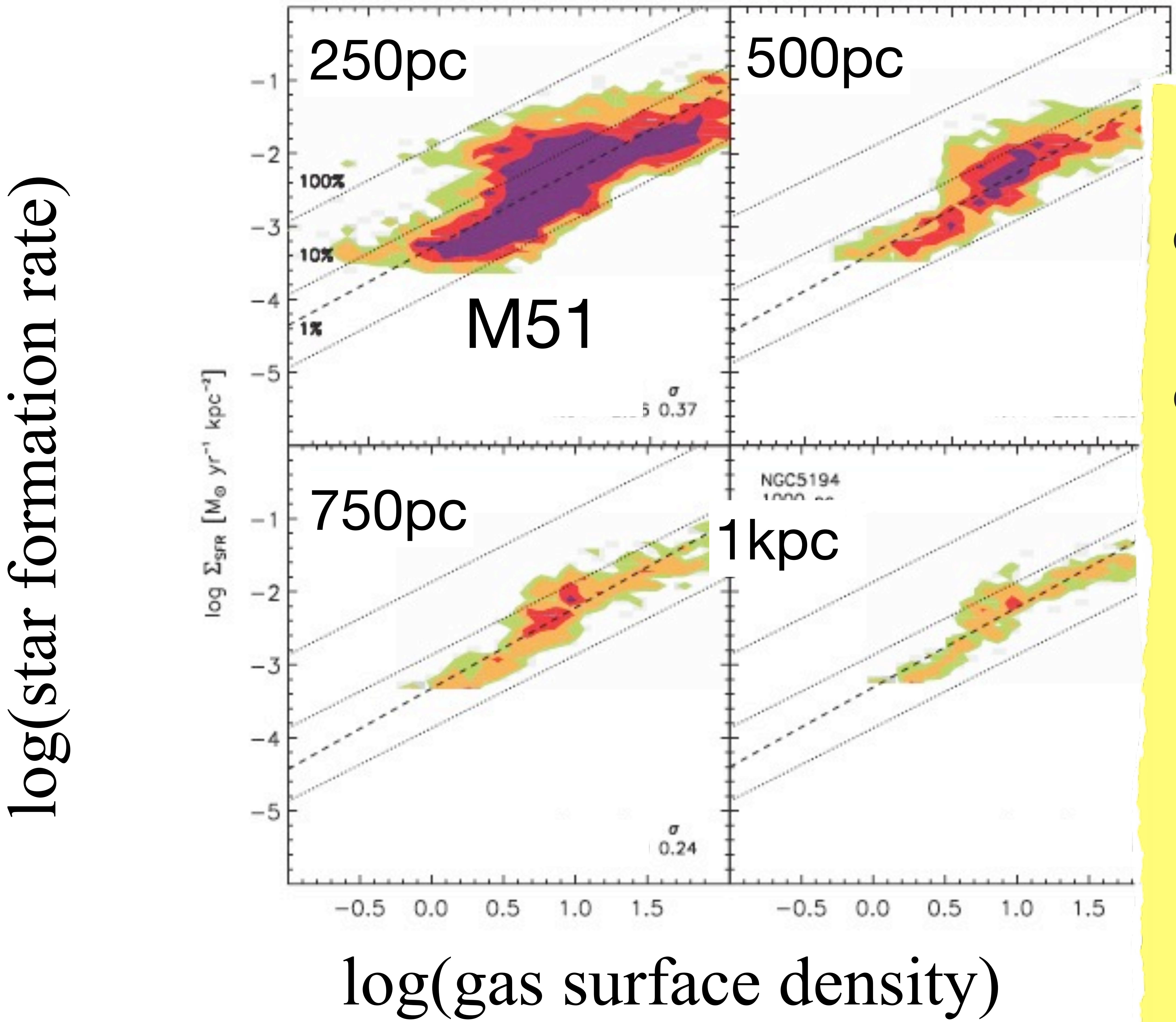

Bigiel et al. (2008)

- **2 modes of star formation**? (Krumholz et al. 2011)
- scale-dependent scatter: **'discreteness +stochasticity'**:
  - temporal & spatial decoupling of gas and stars (Feldman et al. 2011)
  - stellar feedback--cloud dispersal/ destruction

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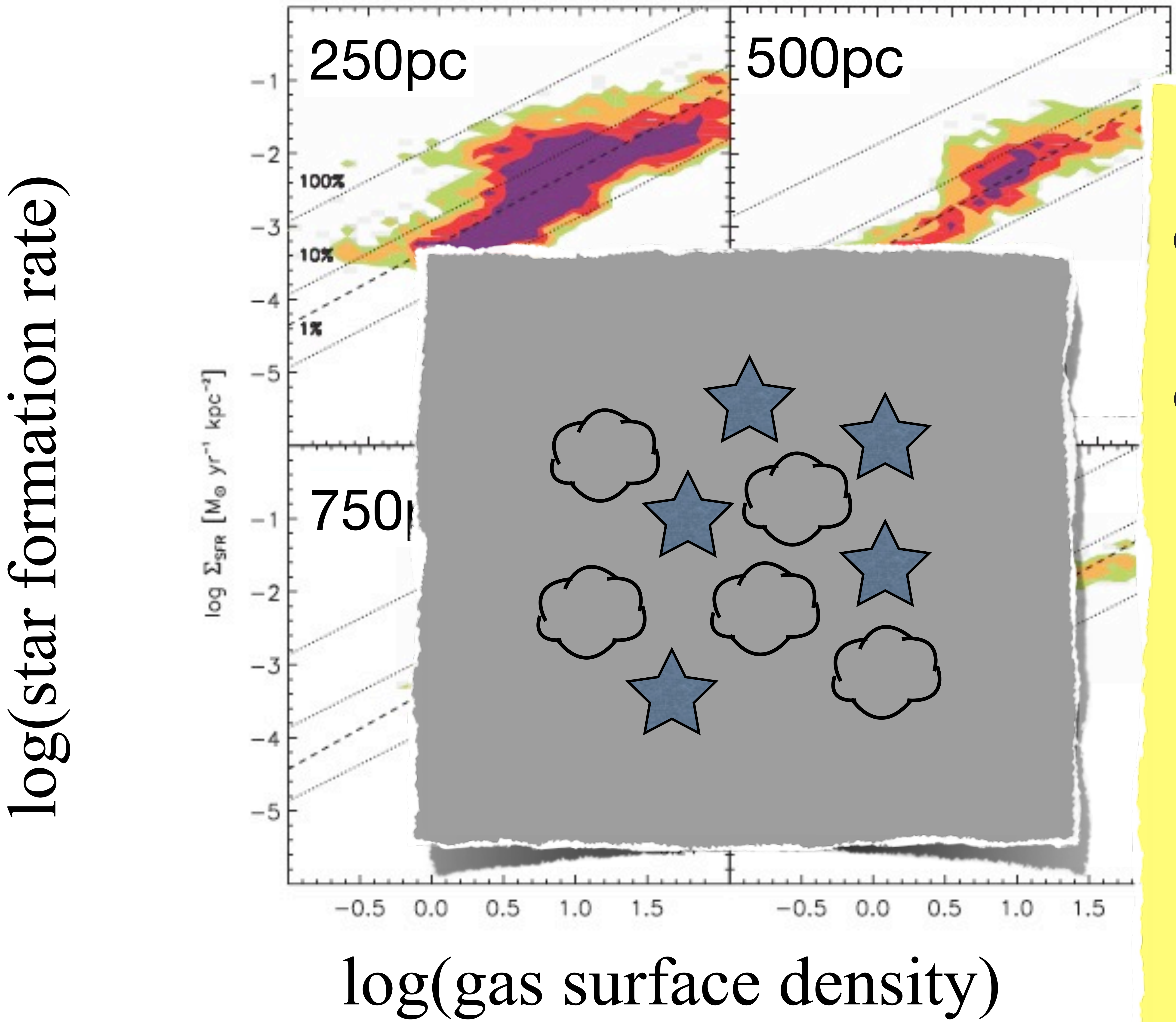

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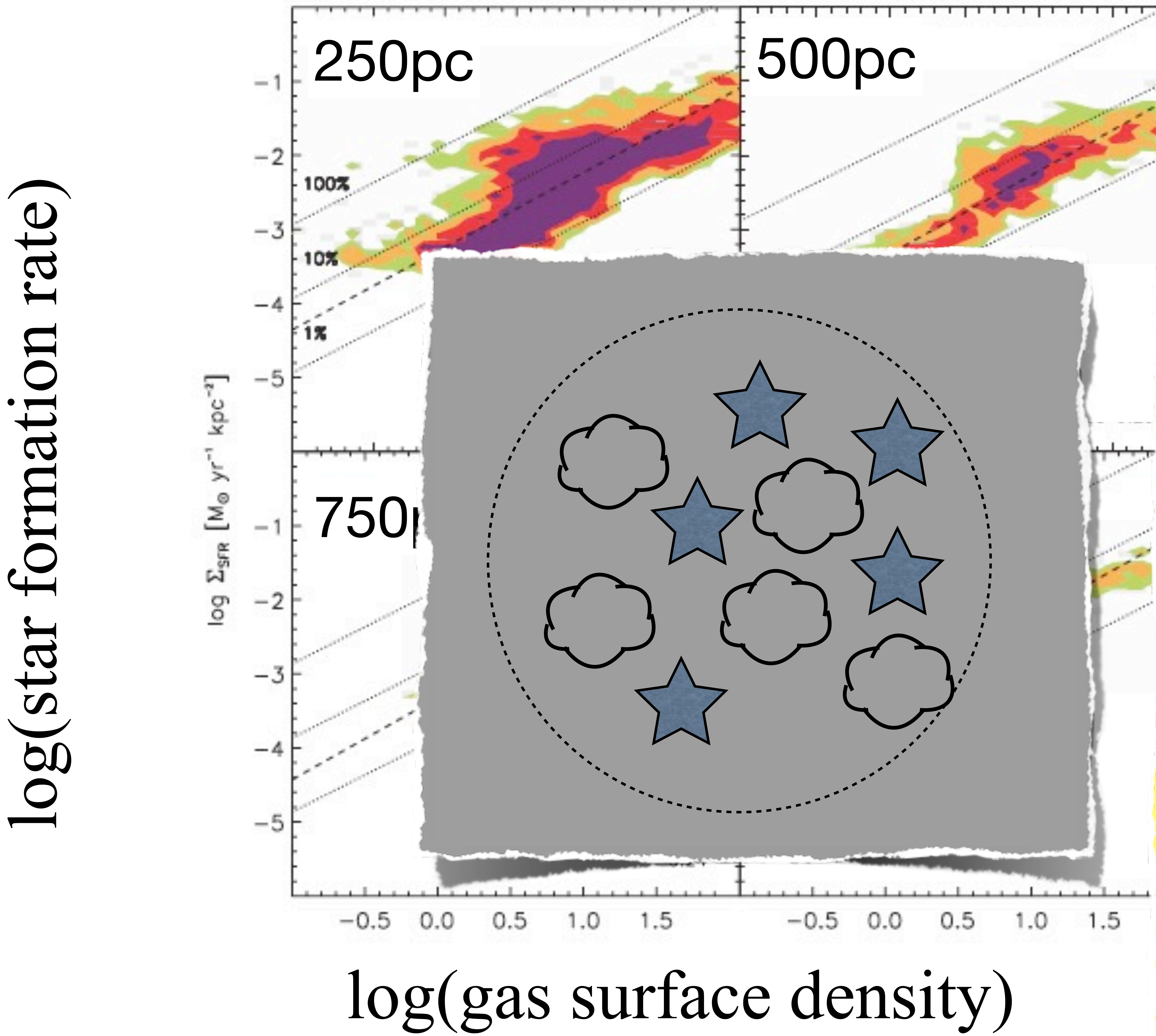

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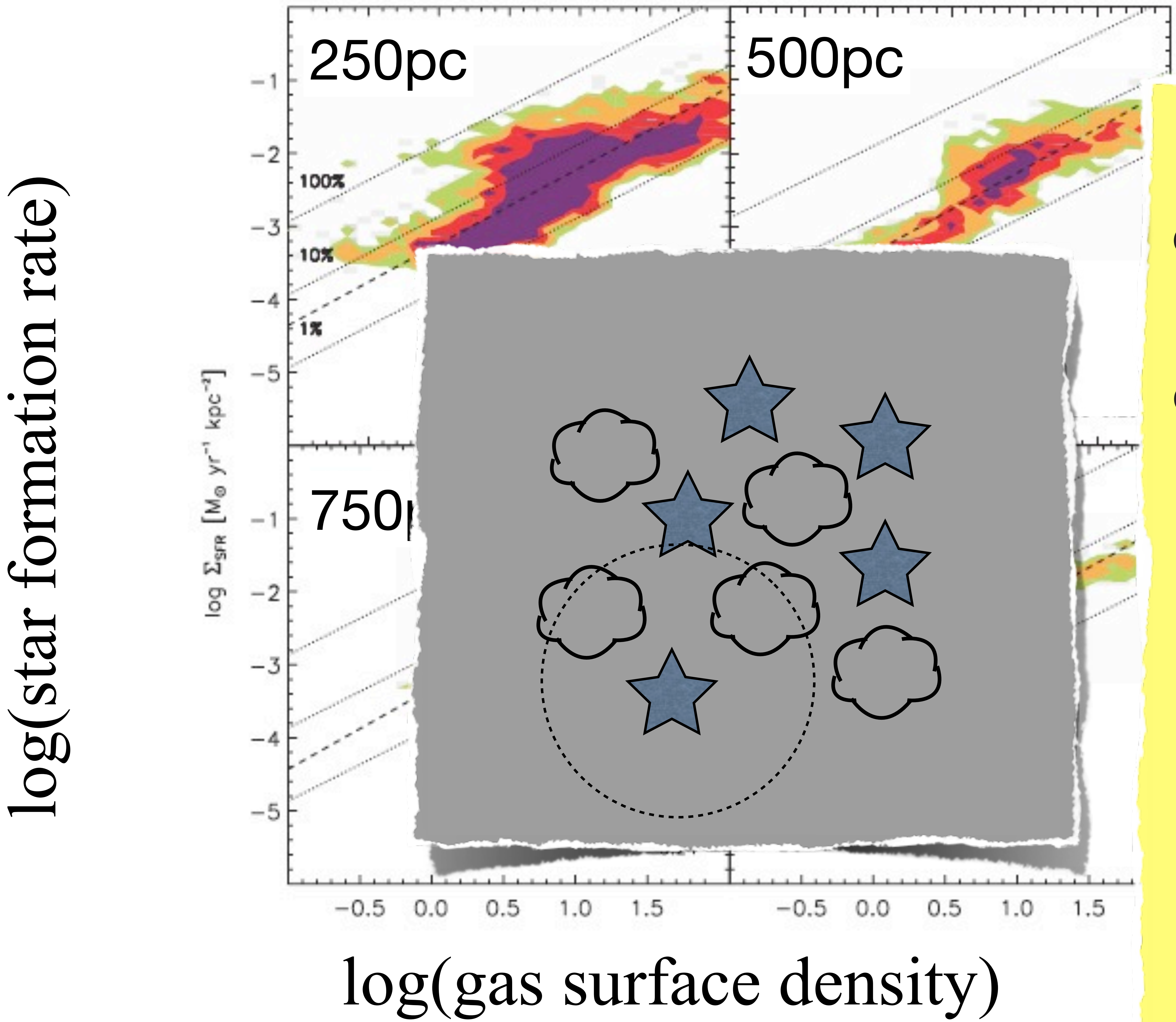

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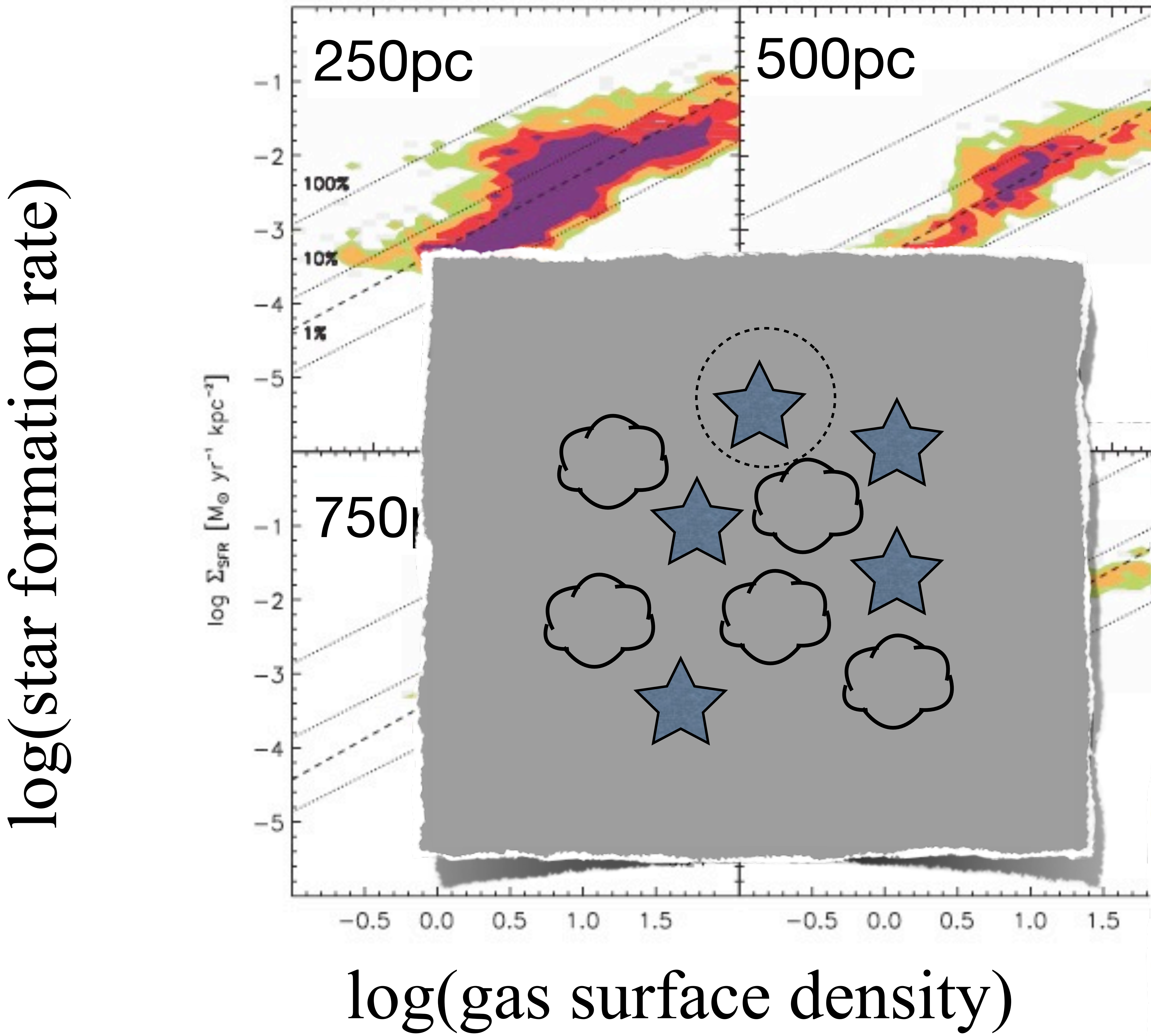

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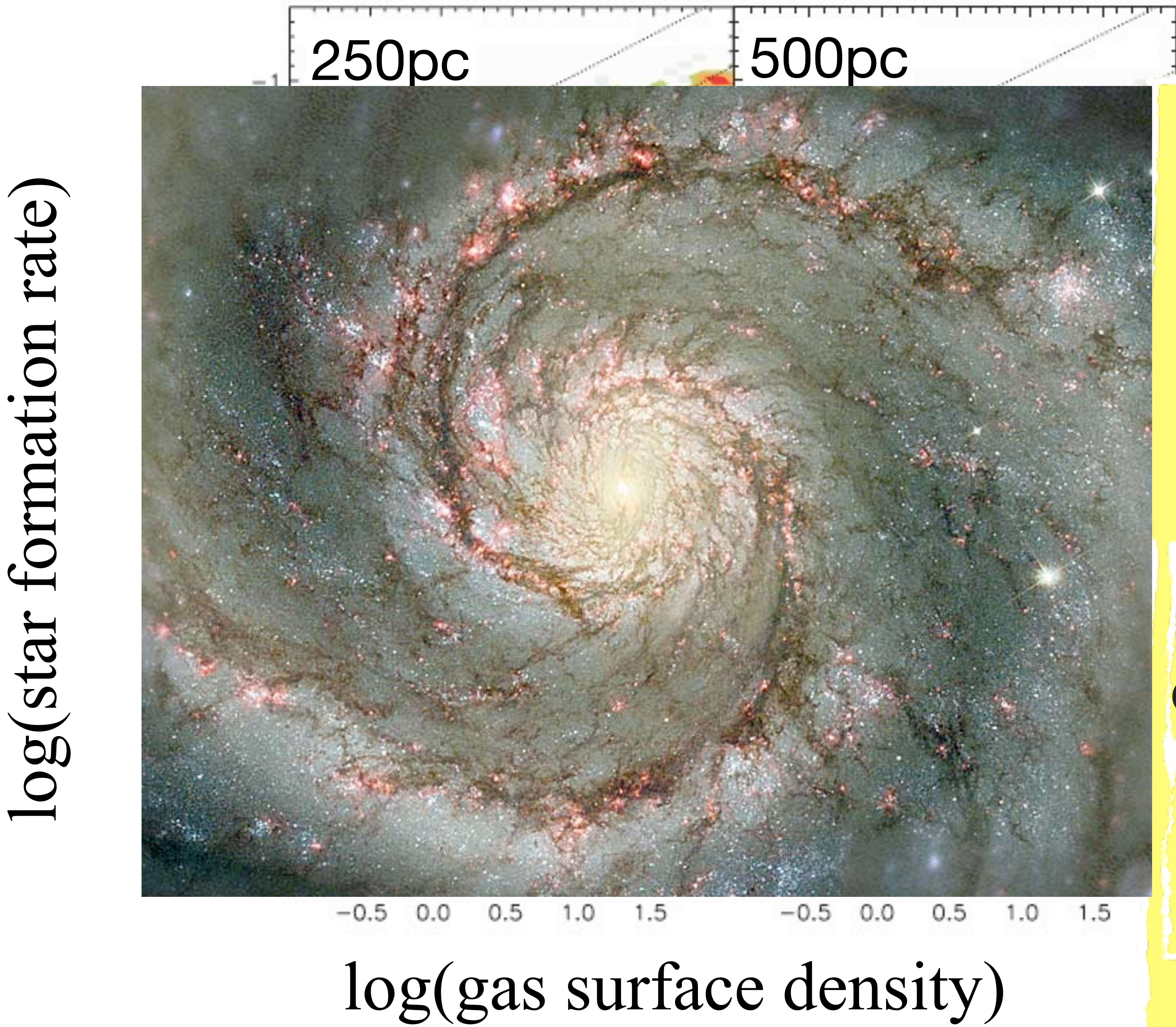

Bigiel et al. (2008)

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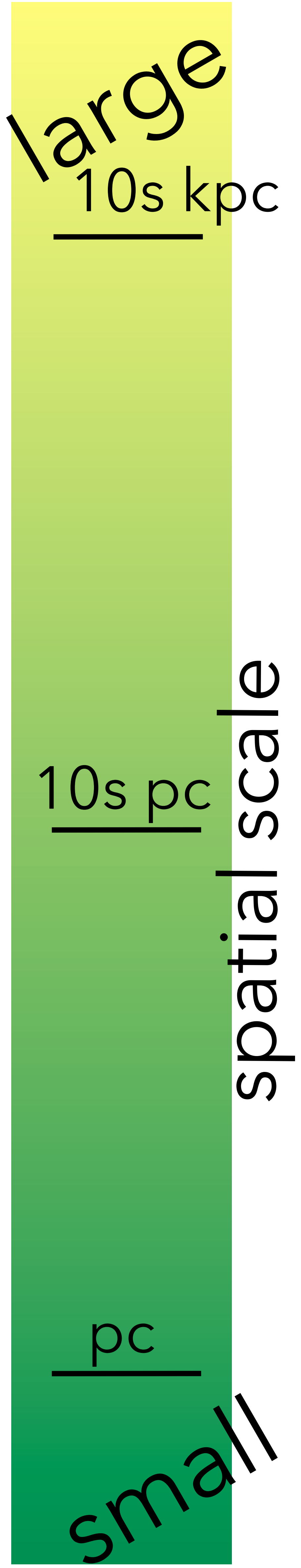
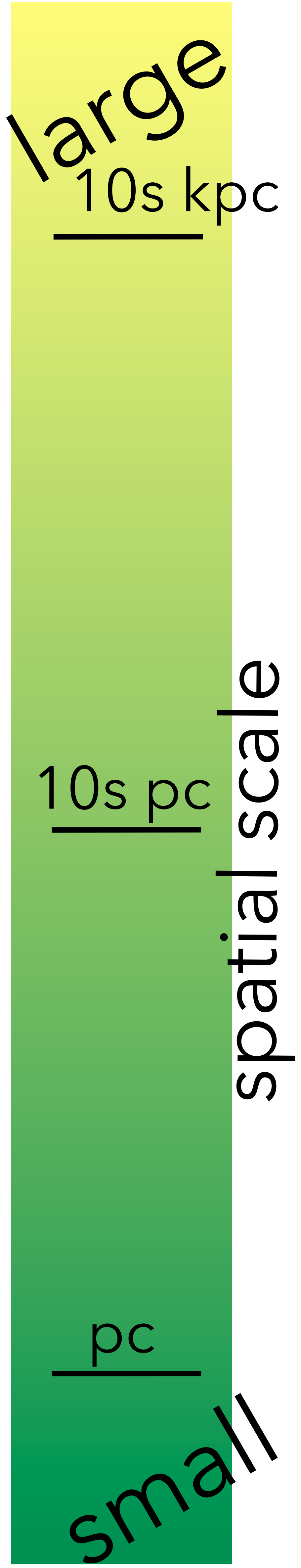
  (Krumholz et al. 2011)
- scale-dependent scatter:
  'discreteness
- **galaxy dynamics**

dynamical regulation of star formation

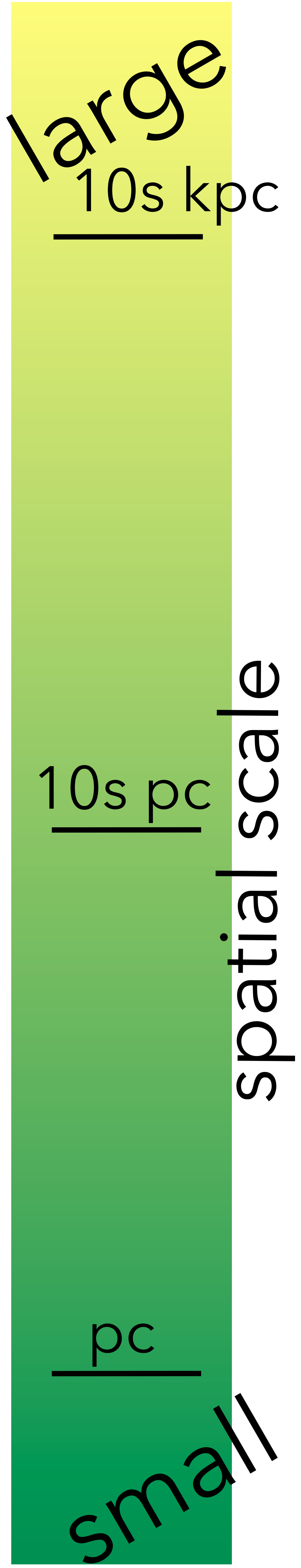


dynamical regulation of star formation

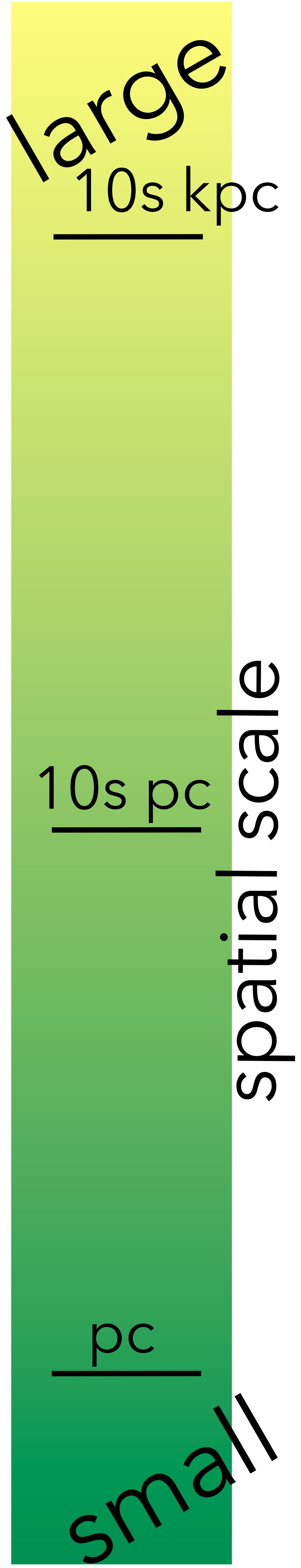


- Torques drive large-scale gas motions in disk

dynamical regulation of star formation



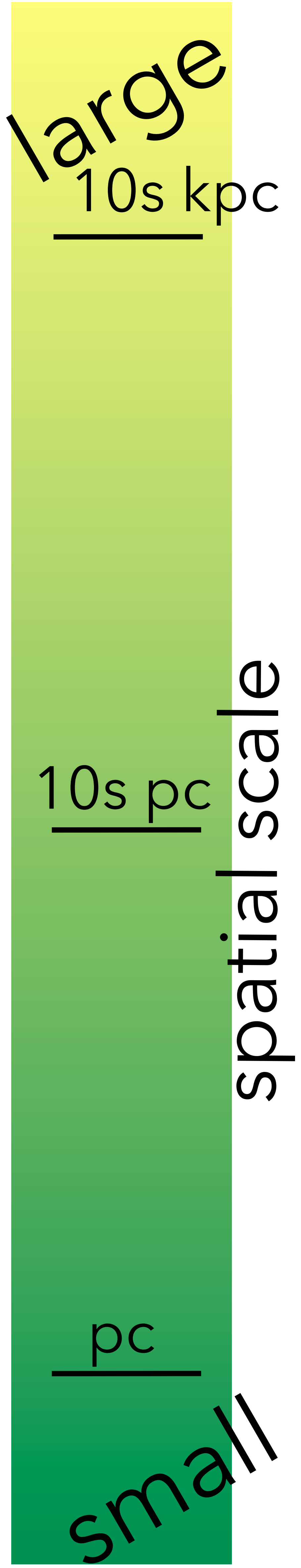
- Torques drive large-scale gas motions in disk
    - Gas brought from large to small R



dynamical regulation of star formation

- Torques drive large-scale gas motions in disk
  - Gas brought from large to small R
    - On the way, gas can be **stabilized**
    - dynamical suppression of SF = ‘effective feedback’
    - clouds can be **sheared** ⇒ finite lifetimes

dynamical regulation of star formation



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        - dynamical suppression of SF = 'effective feedback'
        - clouds can be **sheared** ⇒ finite lifetimes
            - other gas makes it to center
            - BH growth and feedback

Outline

- Torques drive large-scale gas motions in disk
    - Gas brought from large to small R
        - On the way, gas can be **stabilized**
        - dynamical suppression of SF = ‘effective feedback’
        - clouds can be **sheared** ⇒ finite lifetimes

high resolution molecular gas **key**

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        - On the way, gas can be **stabilized**
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        - clouds can be **sheared** ⇒ finite lifetimes

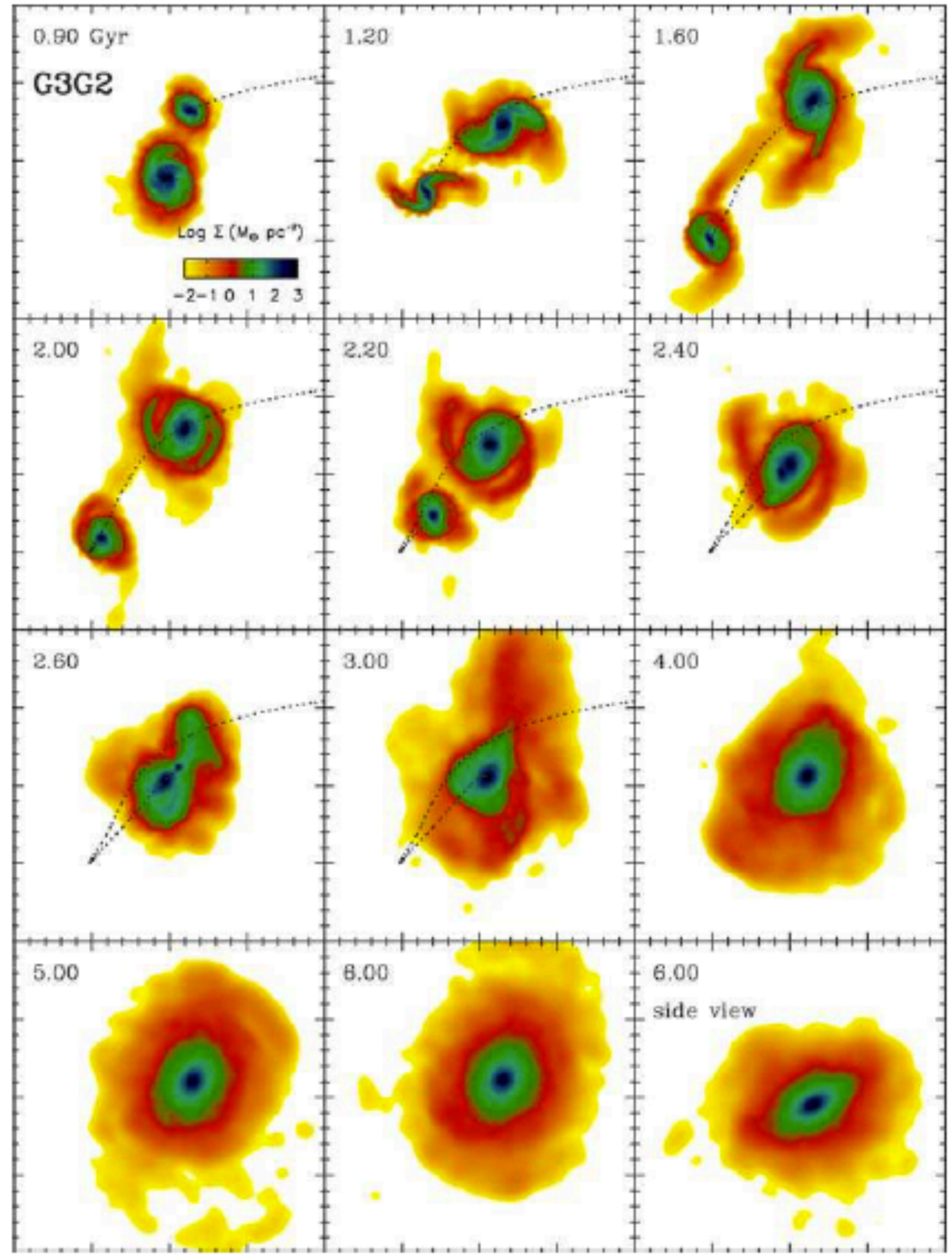
high resolution molecular gas **key**

(also: precise maps of stellar mass)

gravitational Torques via non-axisymmetric perturbations

gravitational Torques via non-axisymmetric perturbations

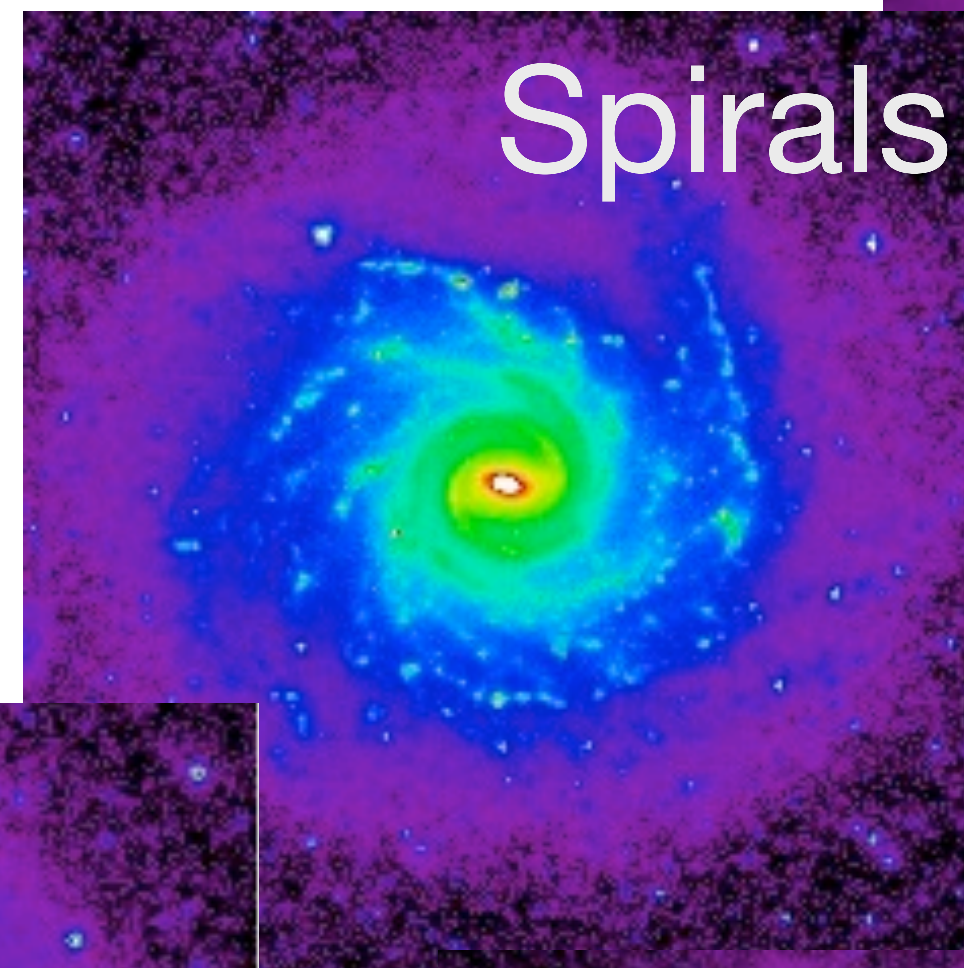
mergers and interactions

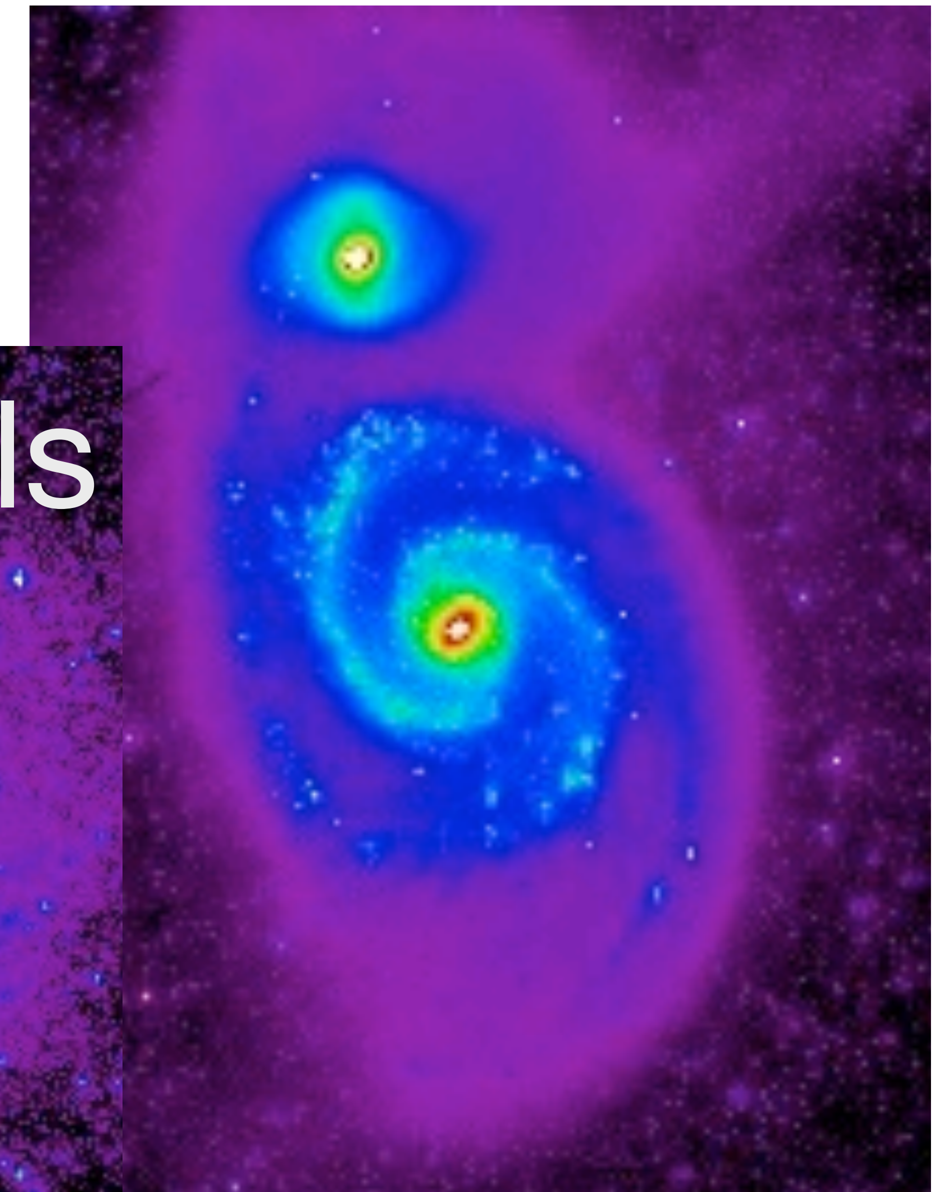


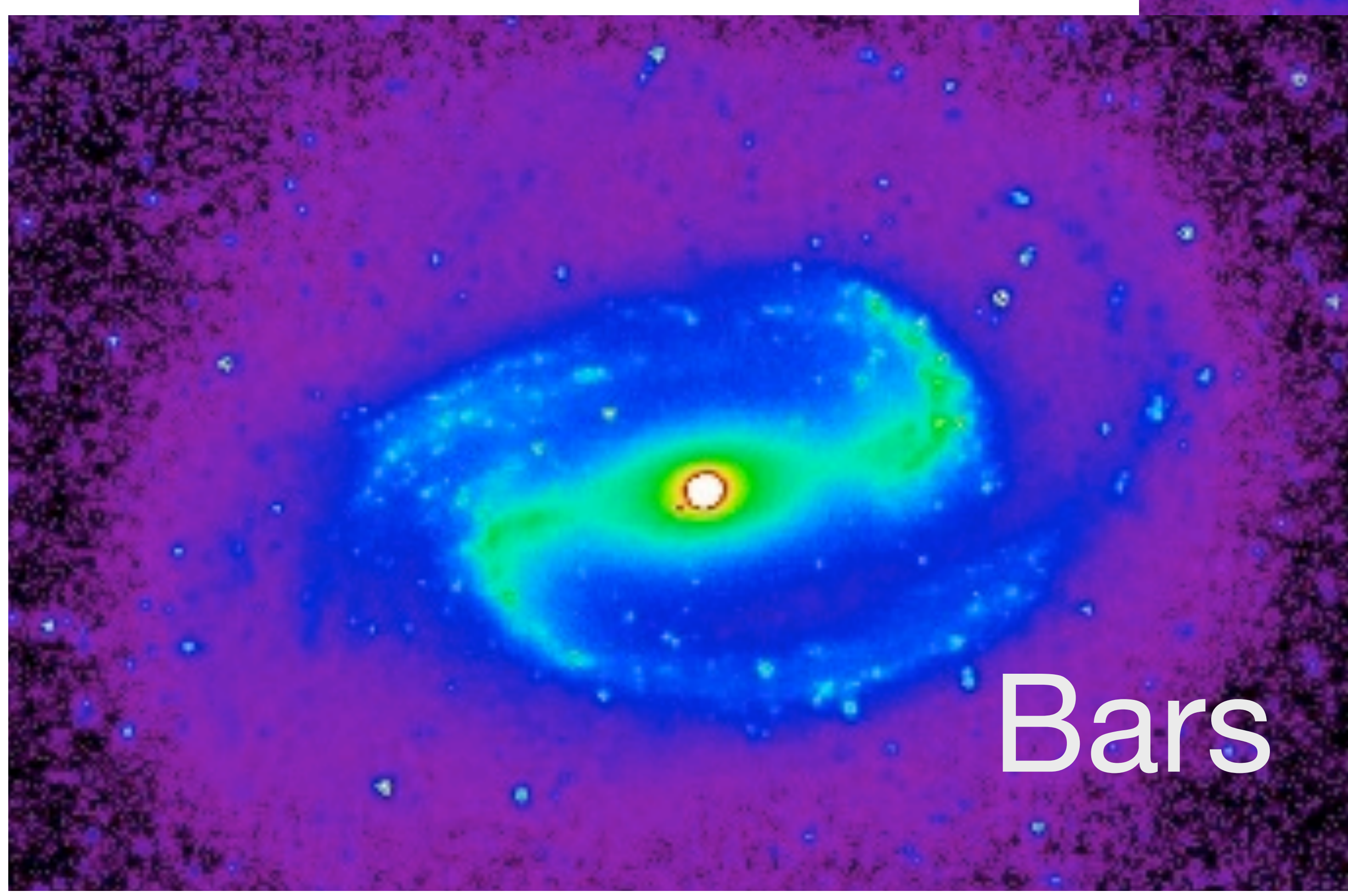
Cox et al. 2008, MNRAS, 384, 386

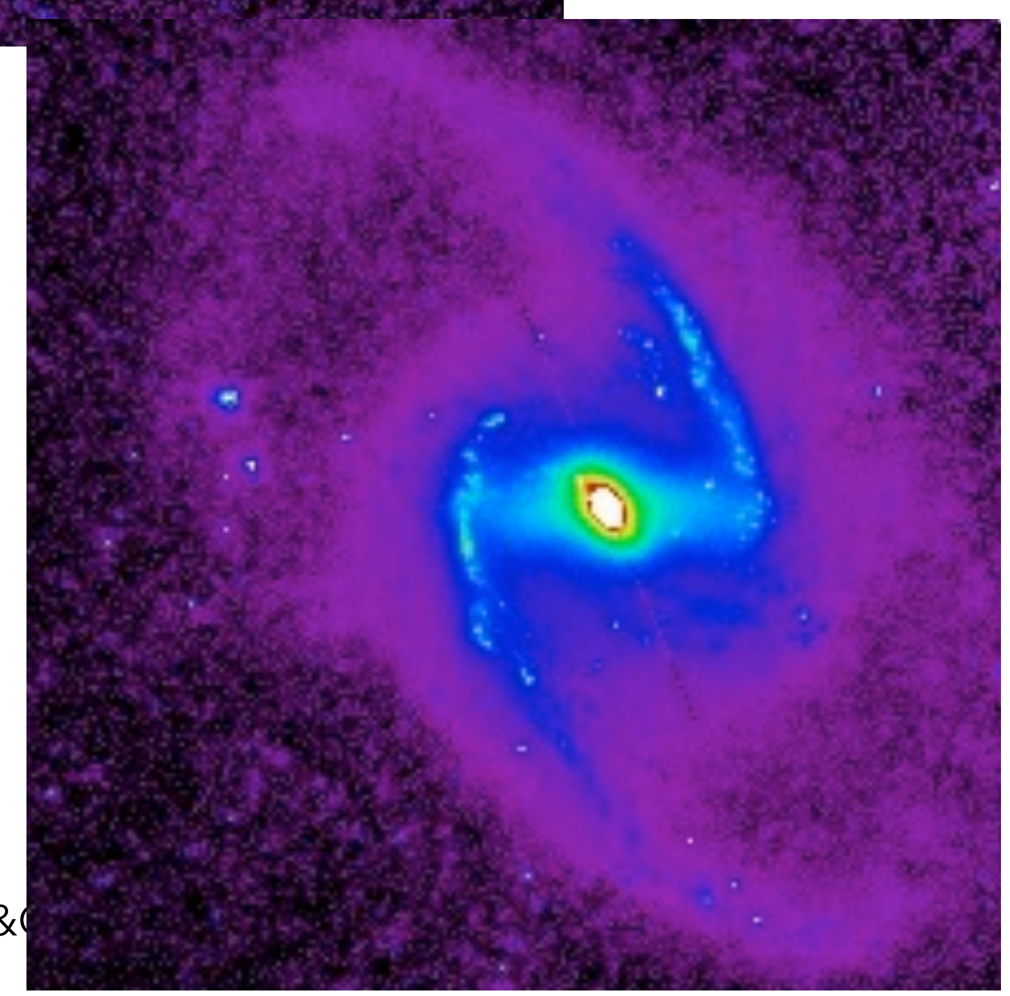
gravitational Torques via non-axisymmetric perturbations

disk galaxy potentials







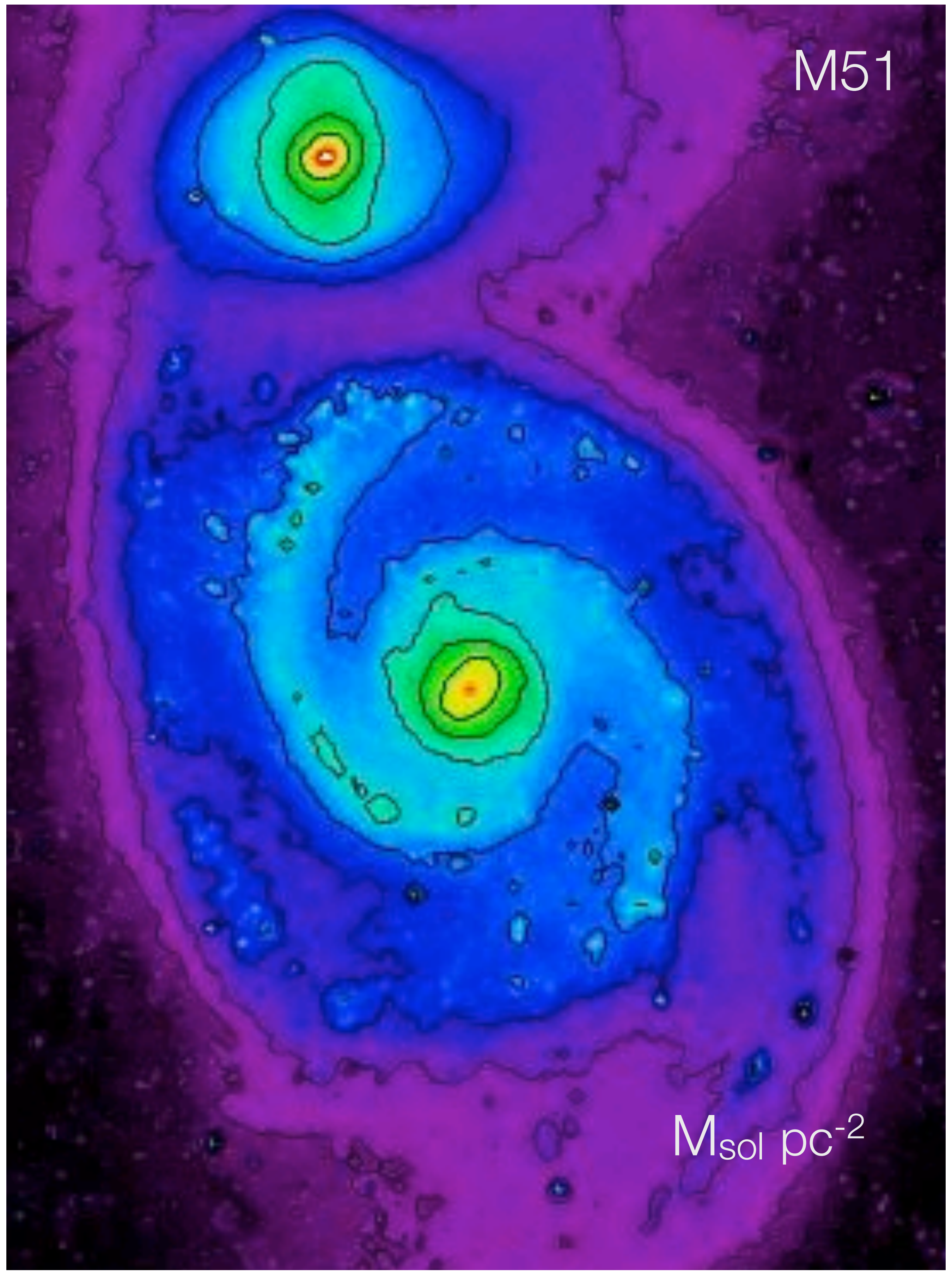


Late-type disks

Present-day gravitational Torques

Garcia-Burillo et al. (2005, 2009); NUGA
Meidt et al. (2013)

stellar mass distribution



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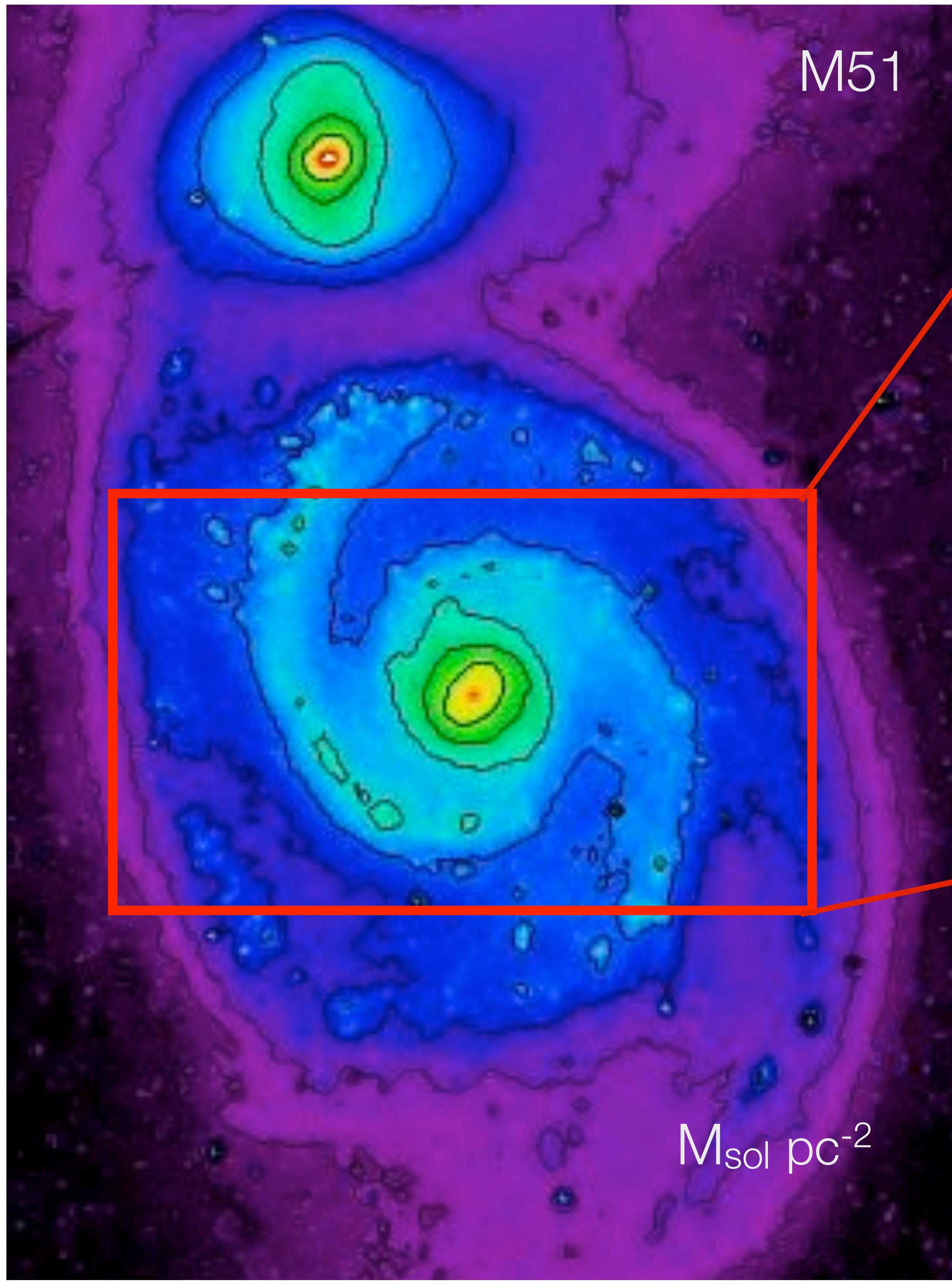

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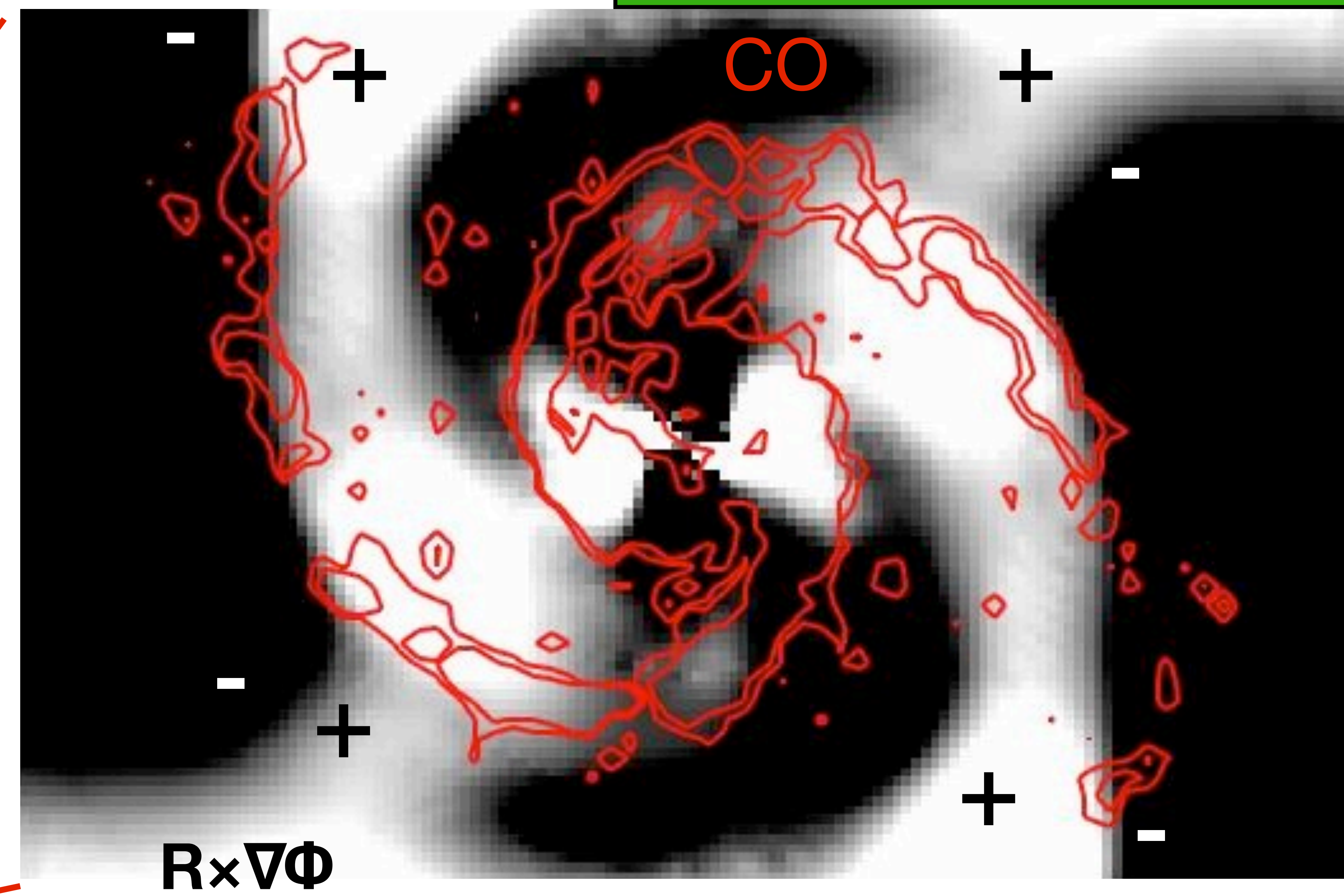
inertial torques **outflow inflow**



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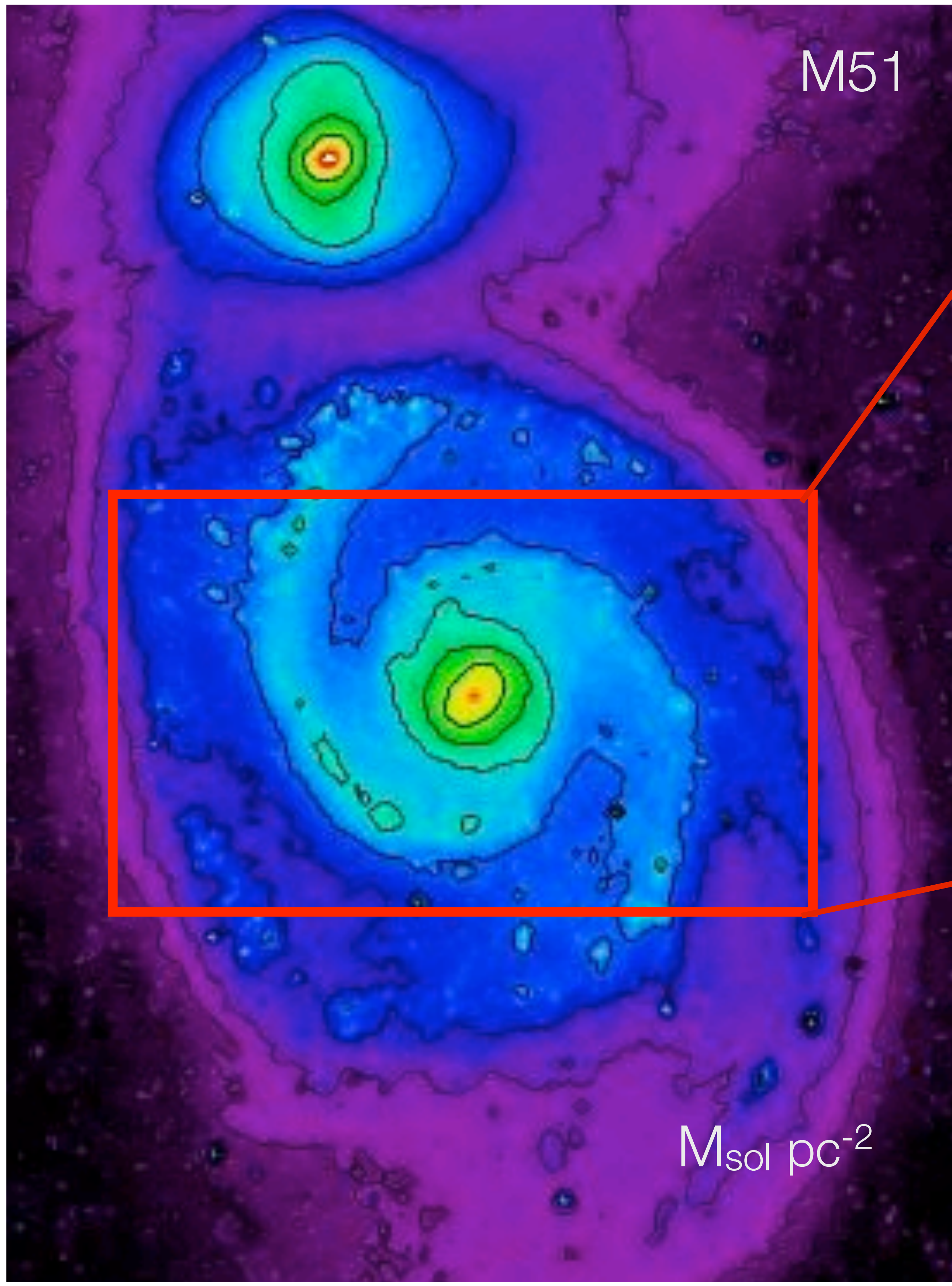

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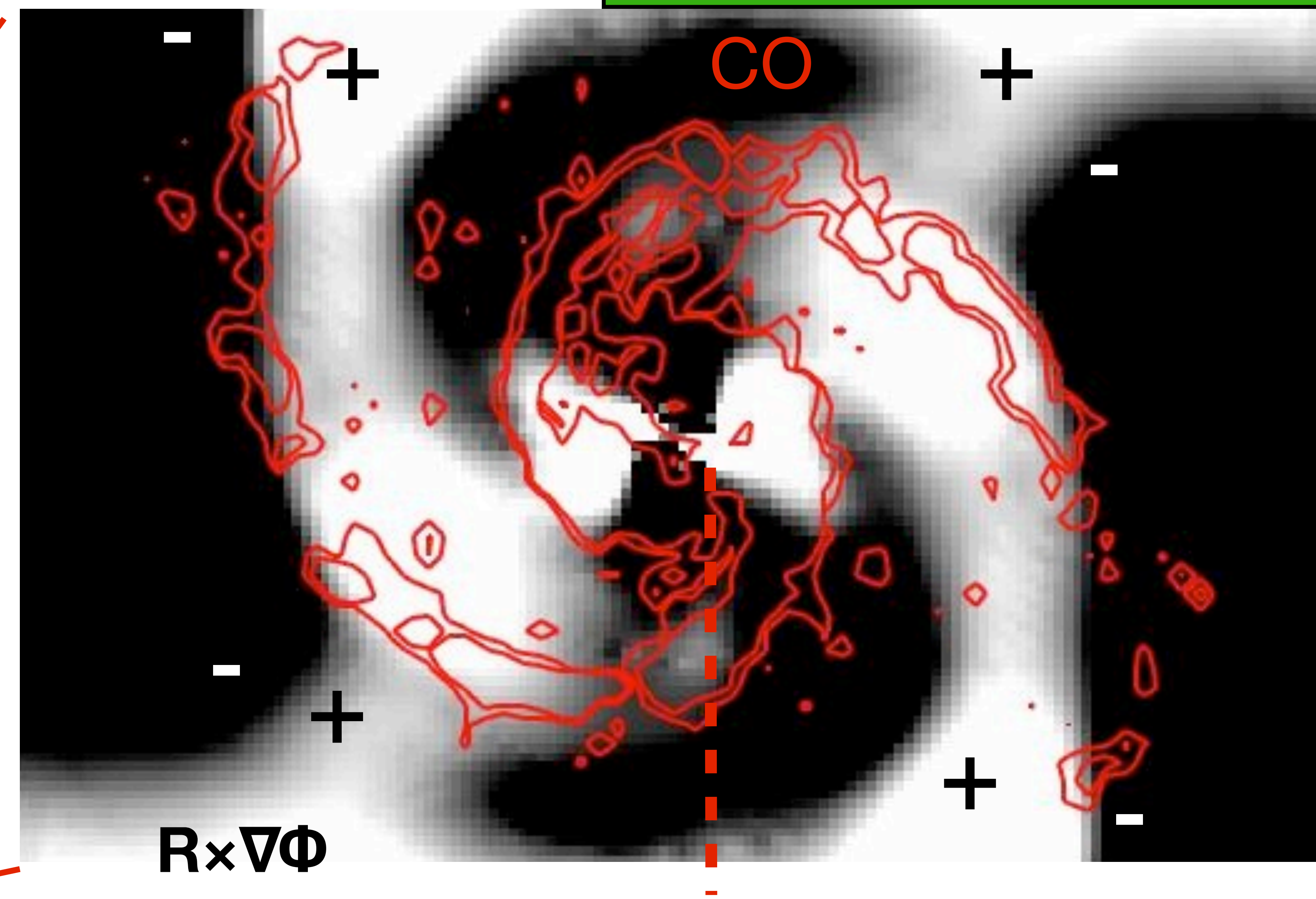

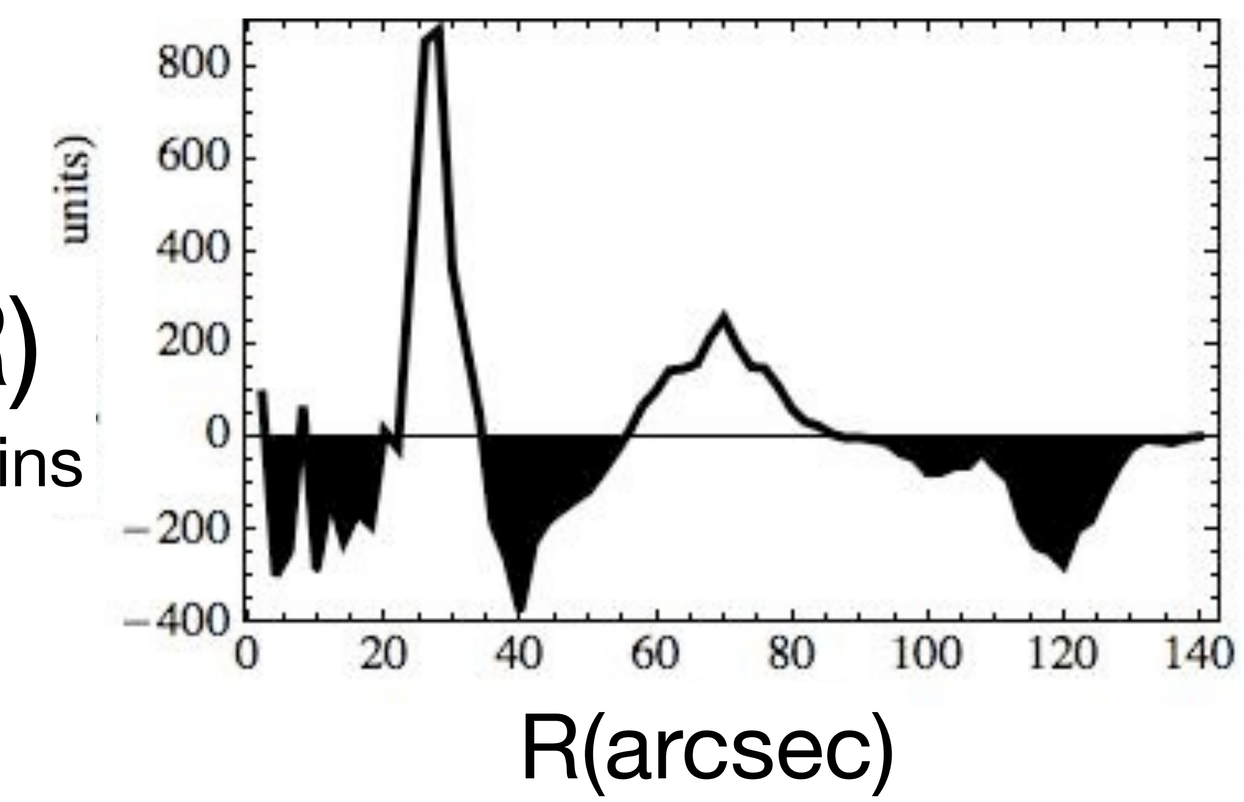

<Γ>(R)
azimuthal bins

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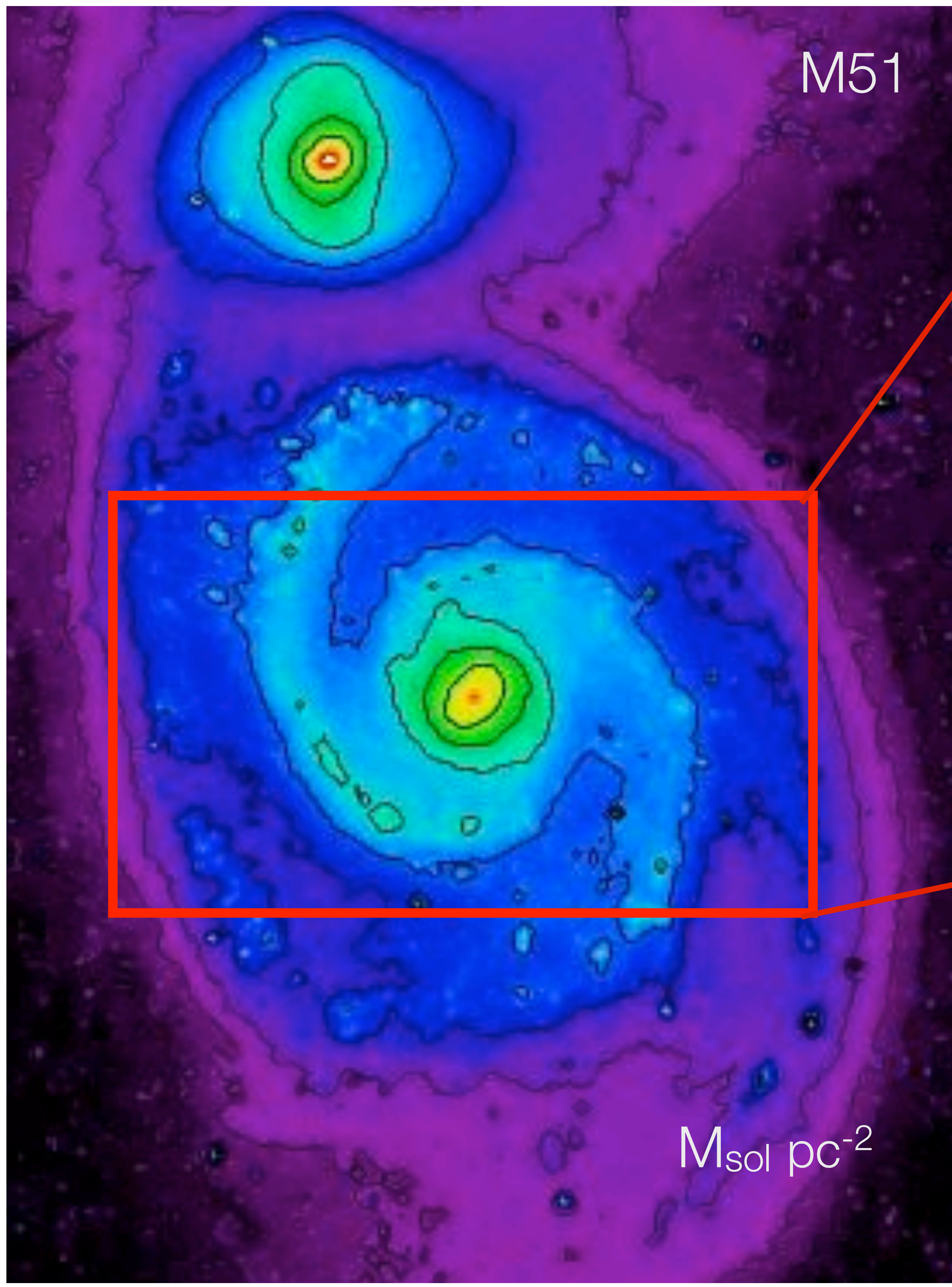

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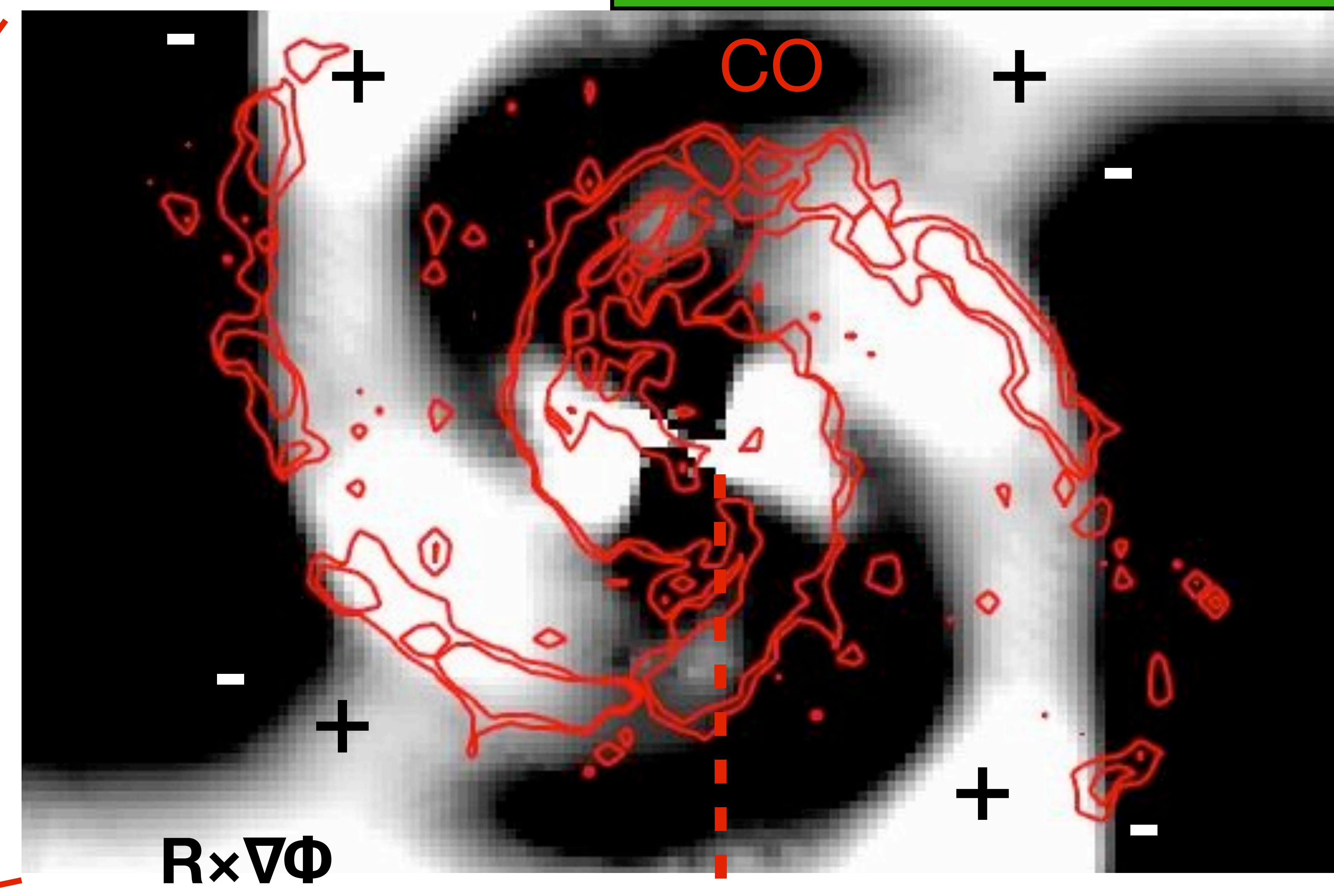

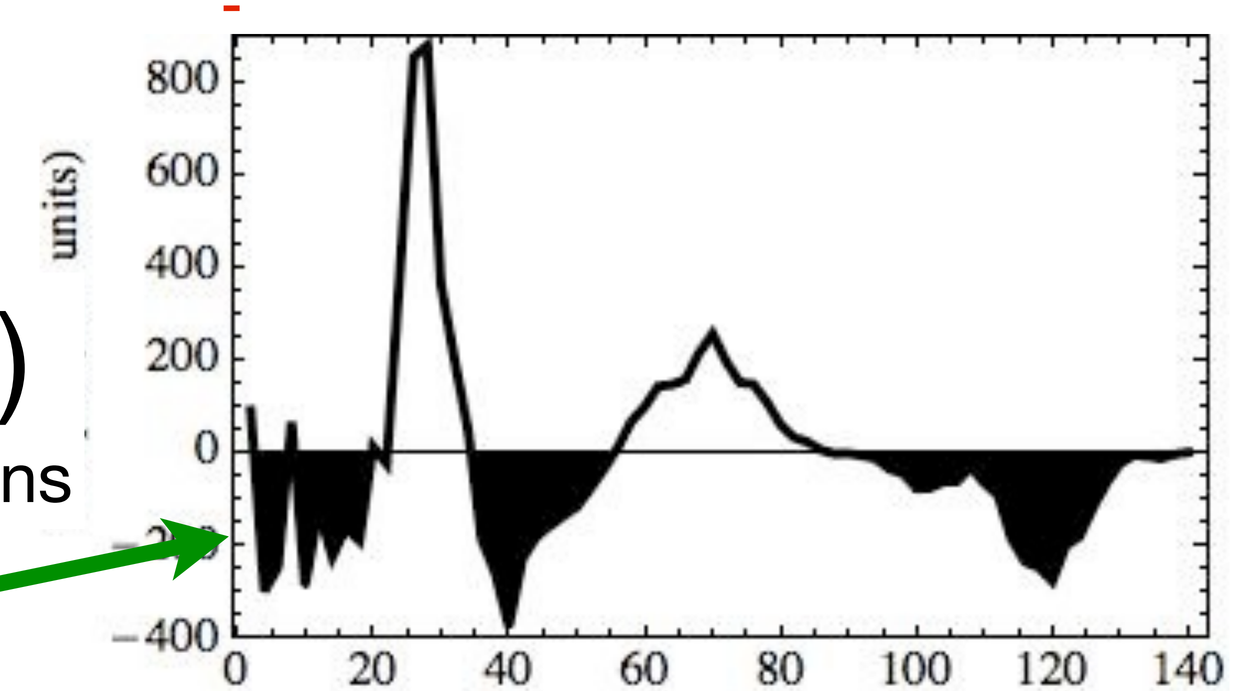

<Γ>(R)

azimuthal bins

R(arcsec)

inflow to center!

S. E. Meidt--Q&Q July 2014

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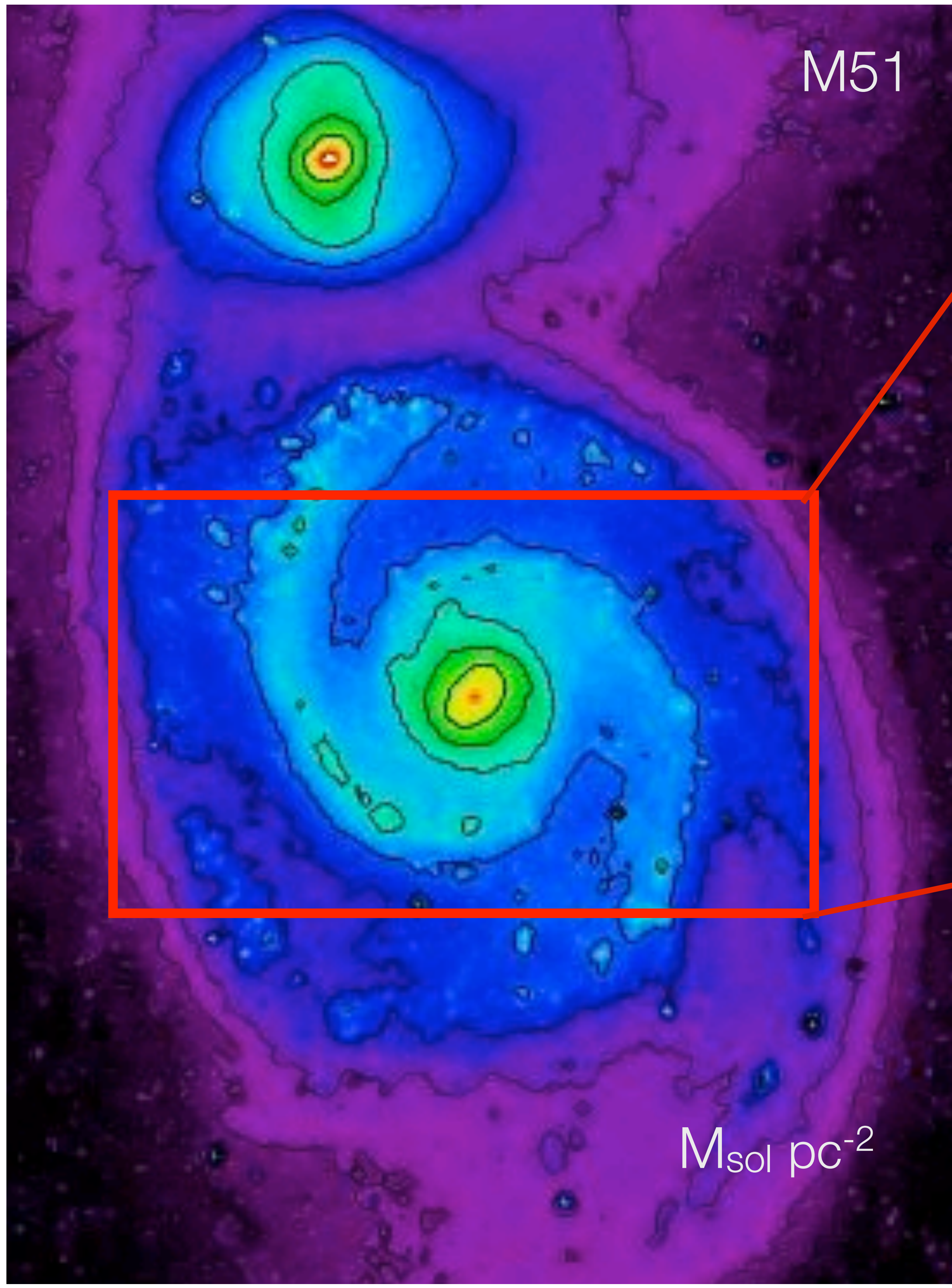

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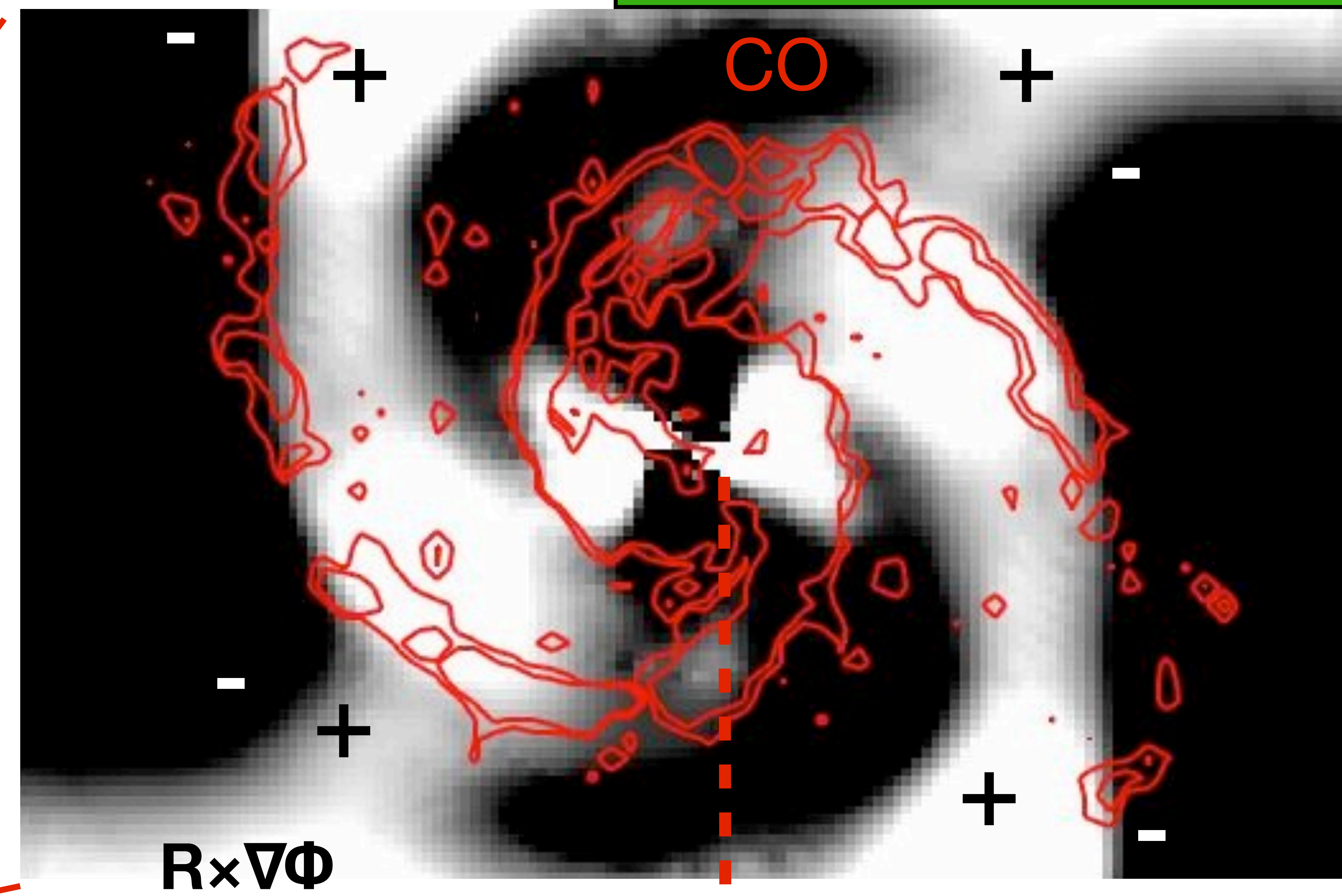
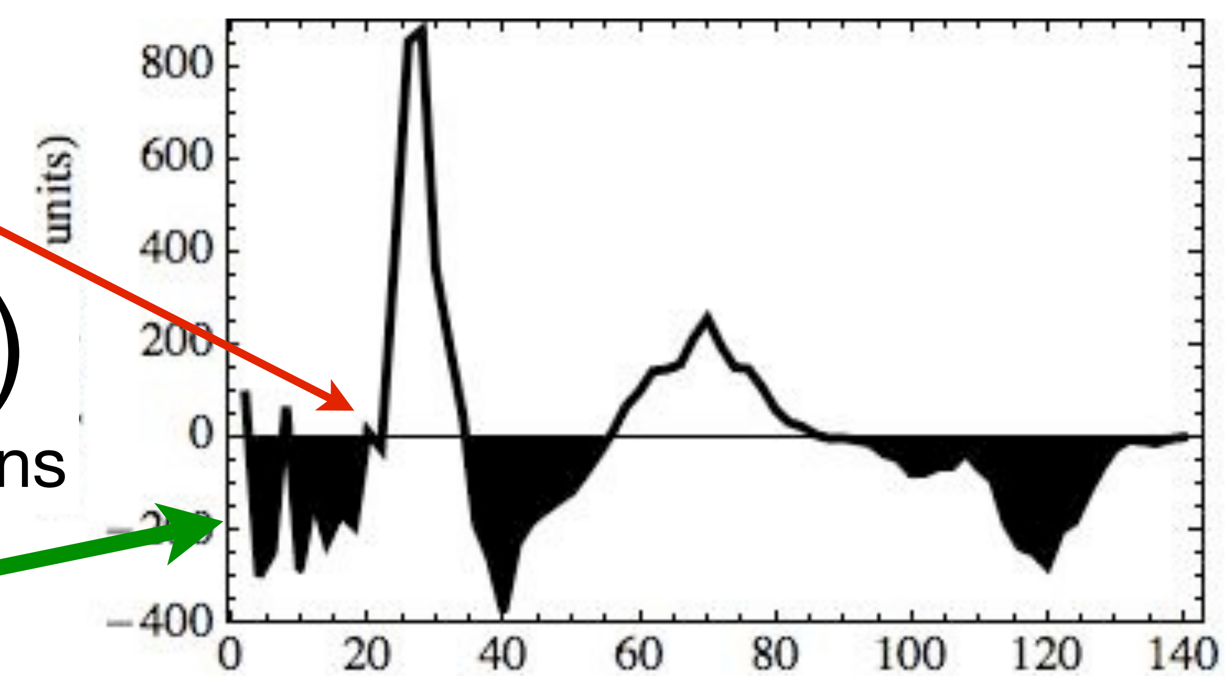


bar end

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

inflow to center!



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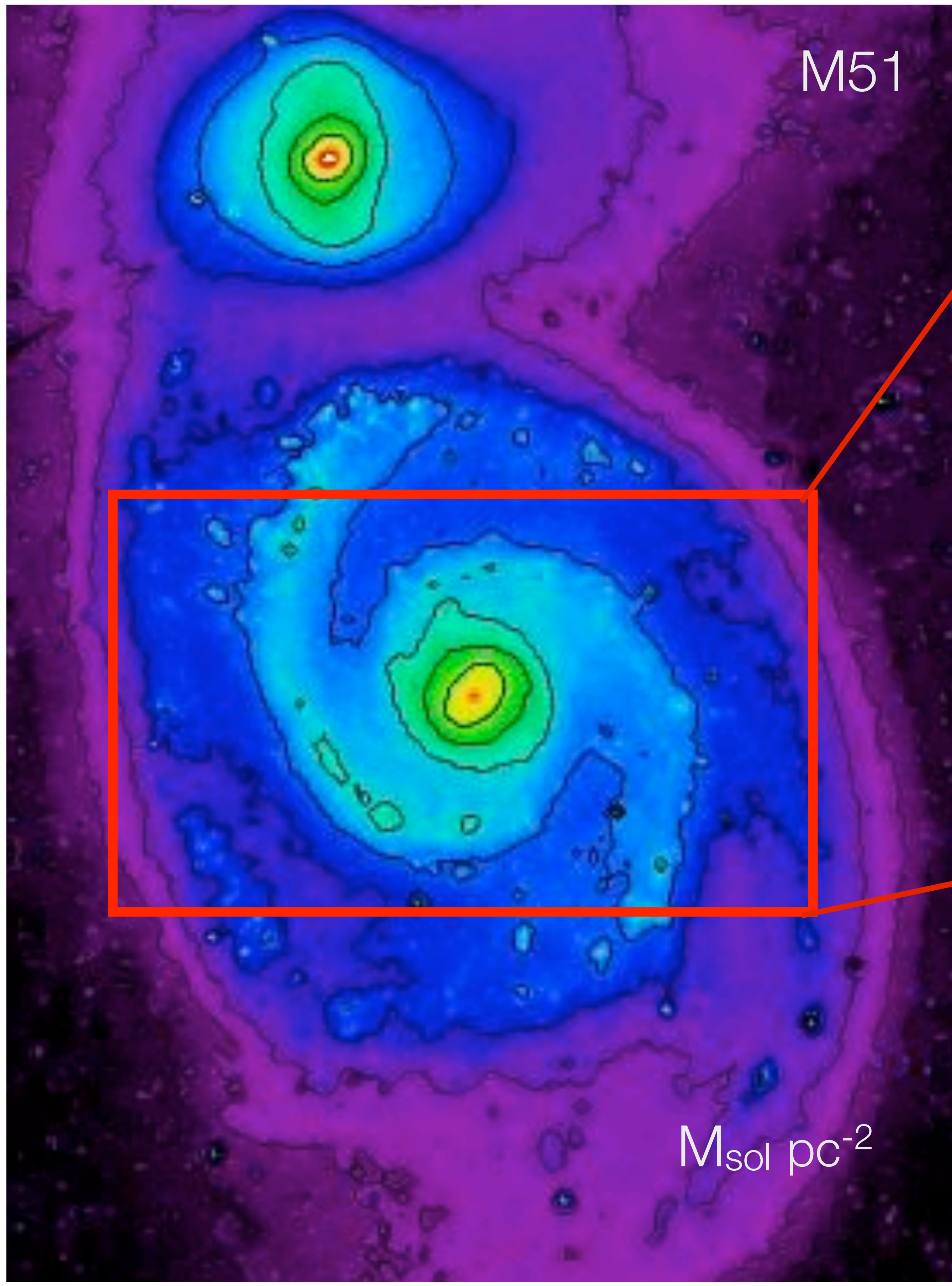

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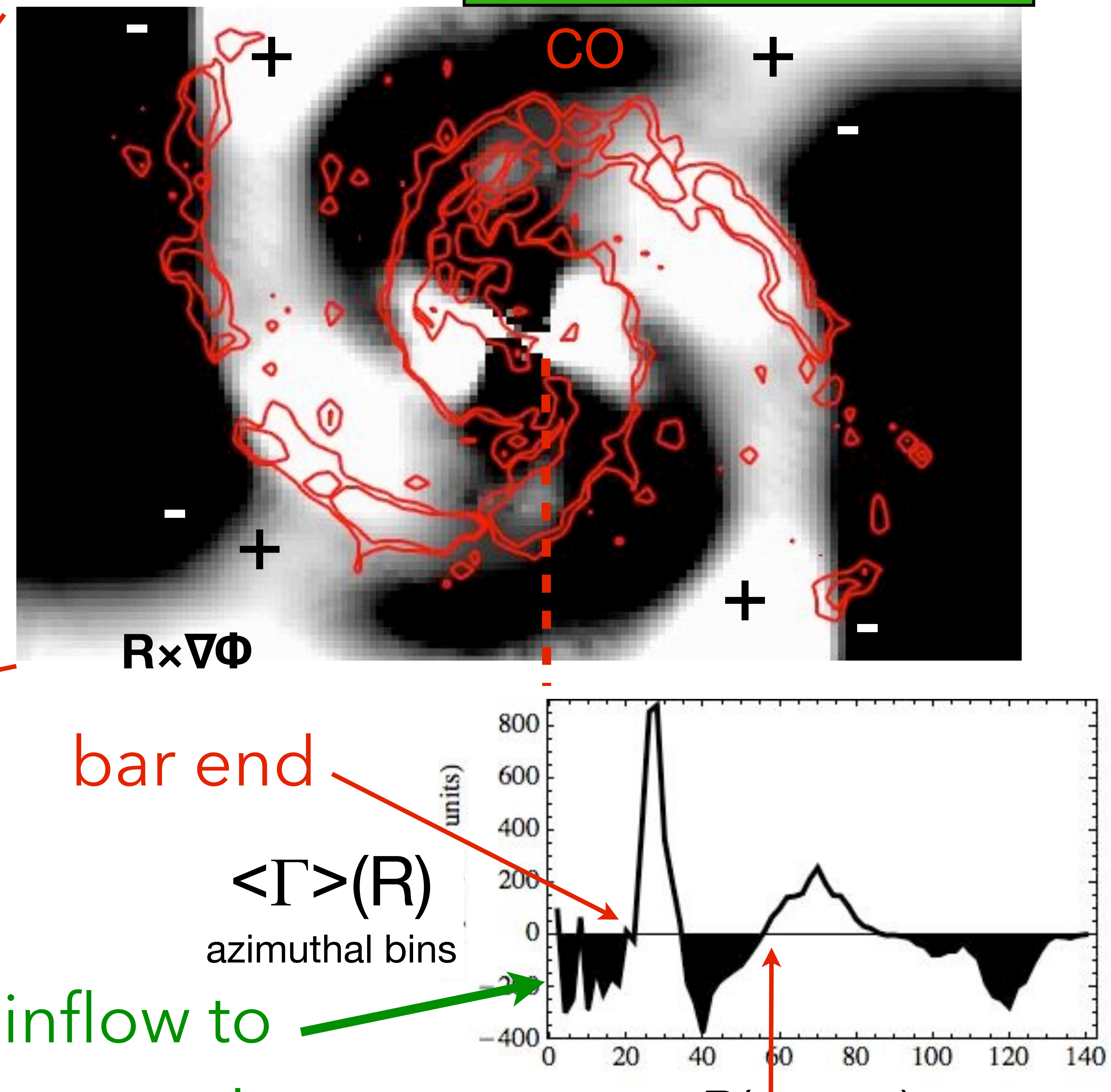

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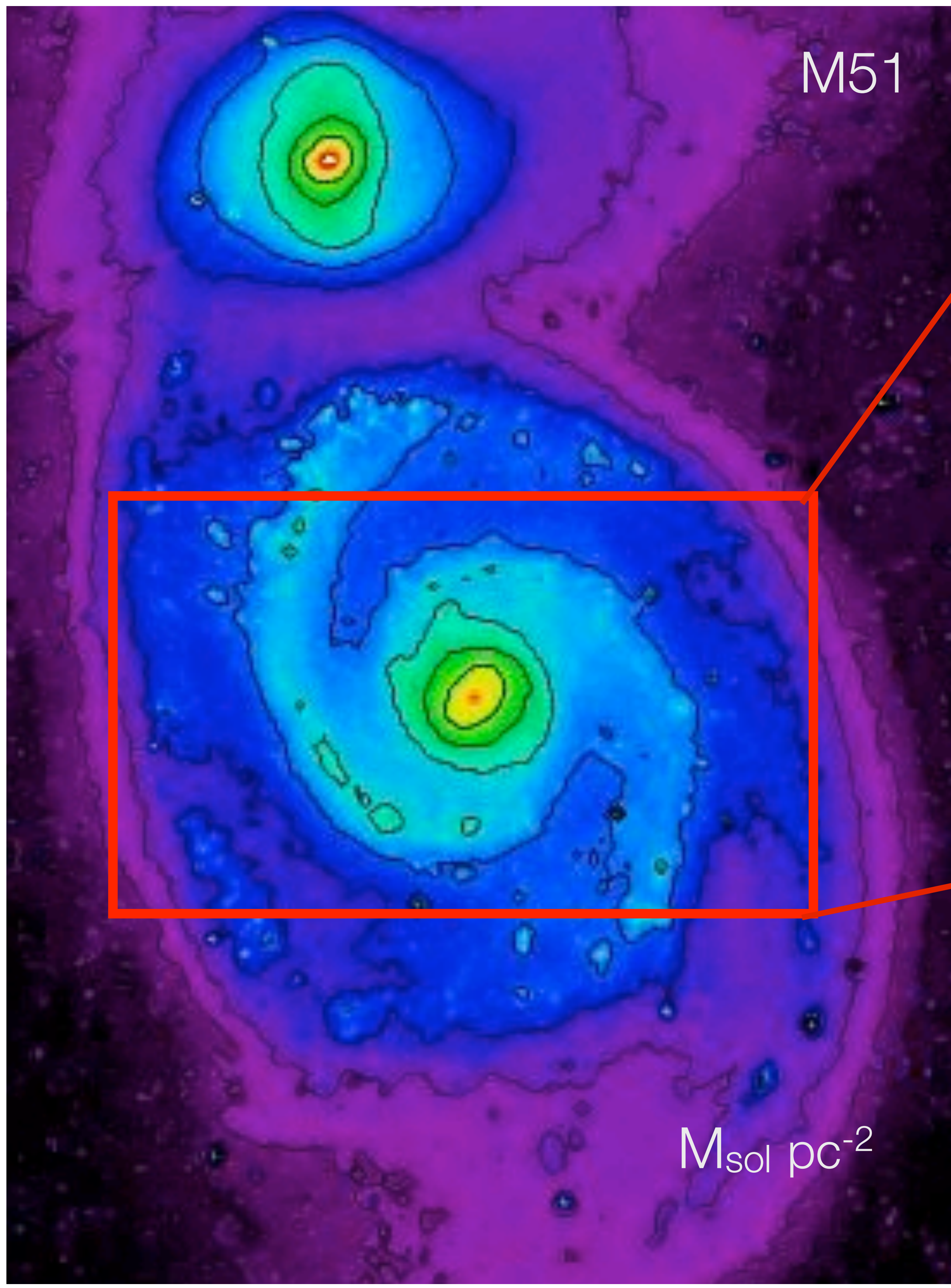

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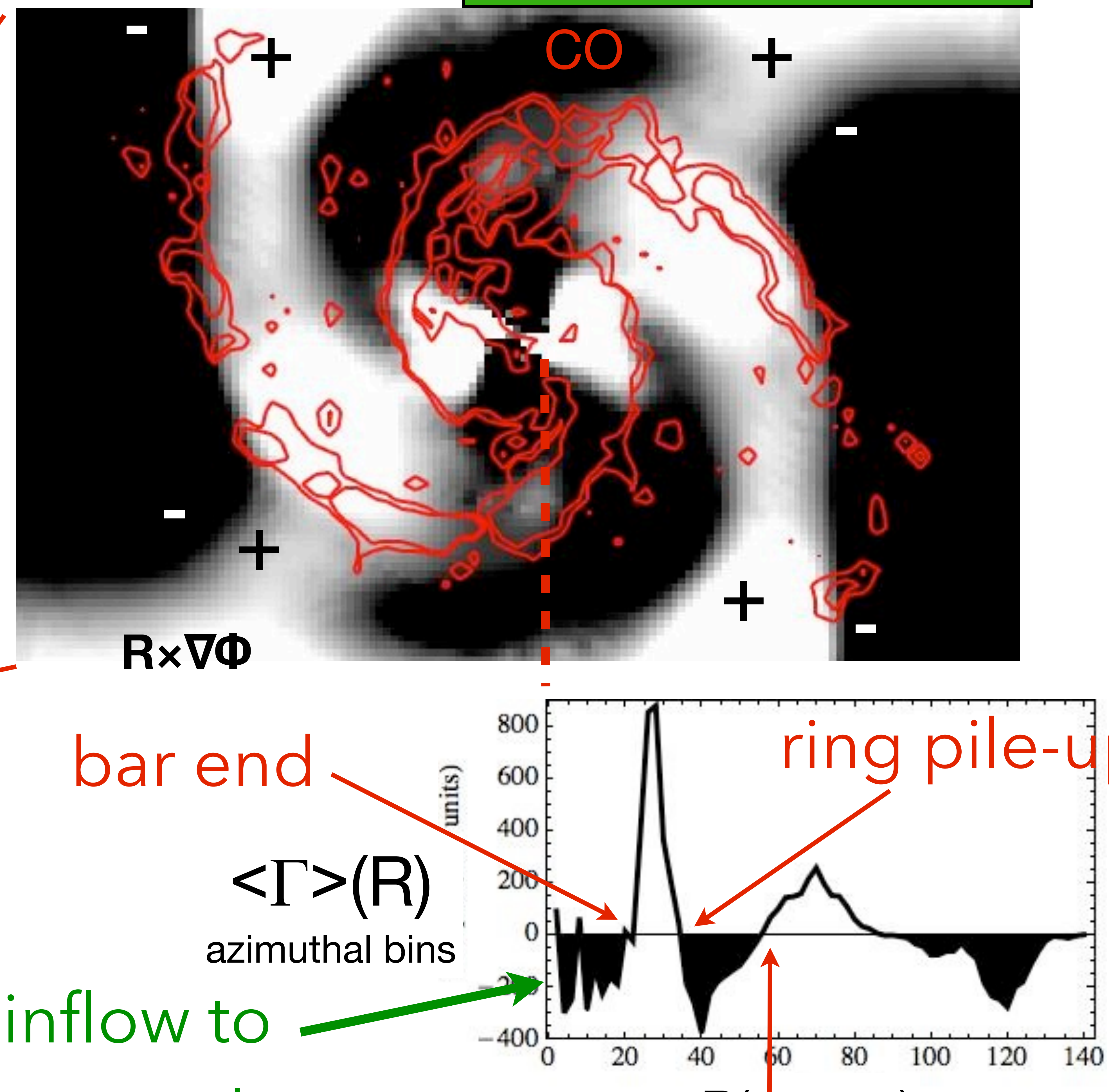

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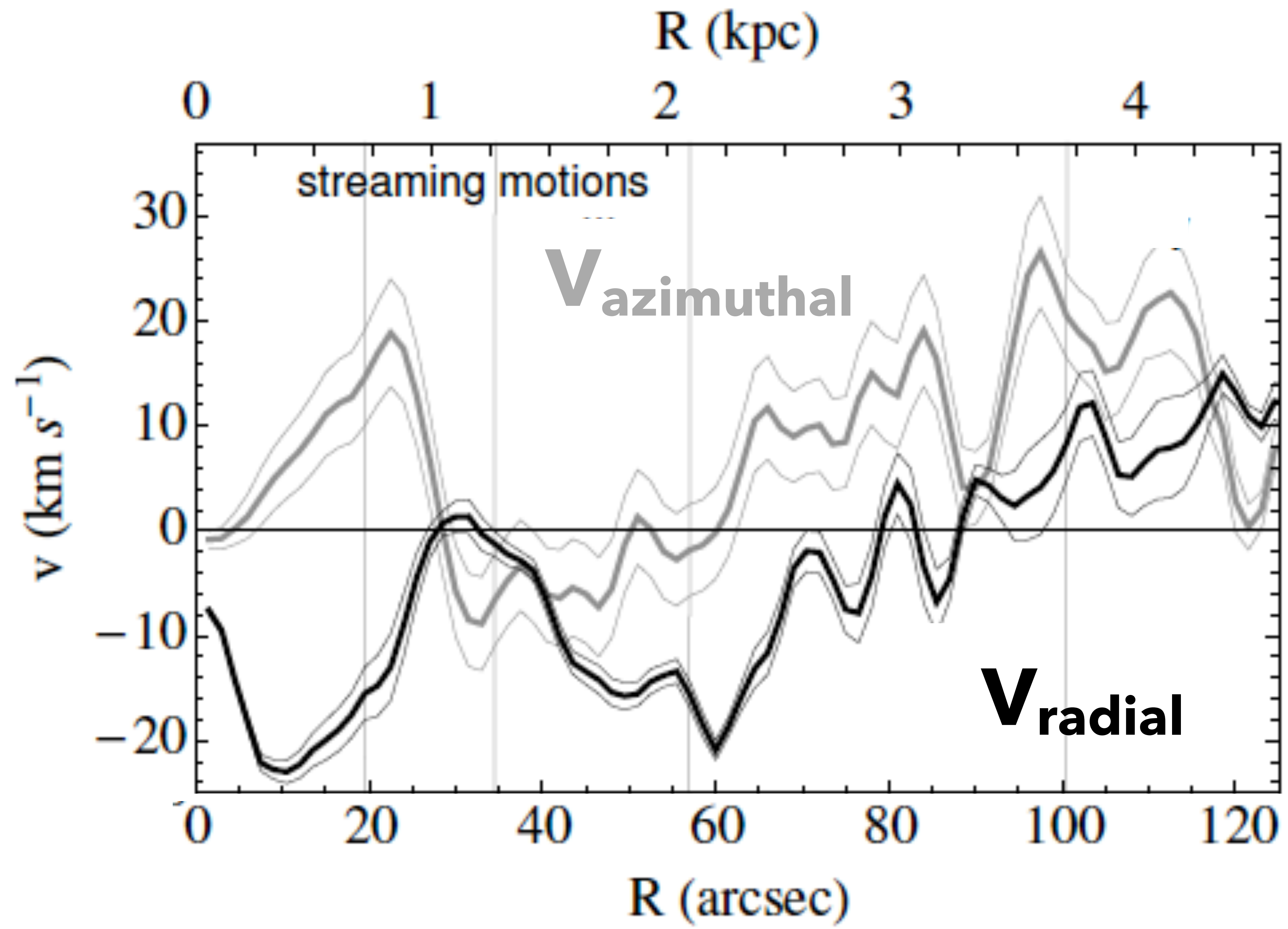
gas kinematics

motions directed
along and **through**
spiral arm
(see Roberts & Stewart 1987;
Wong, Blitz & Bosma 2004)

non-circular streaming motions



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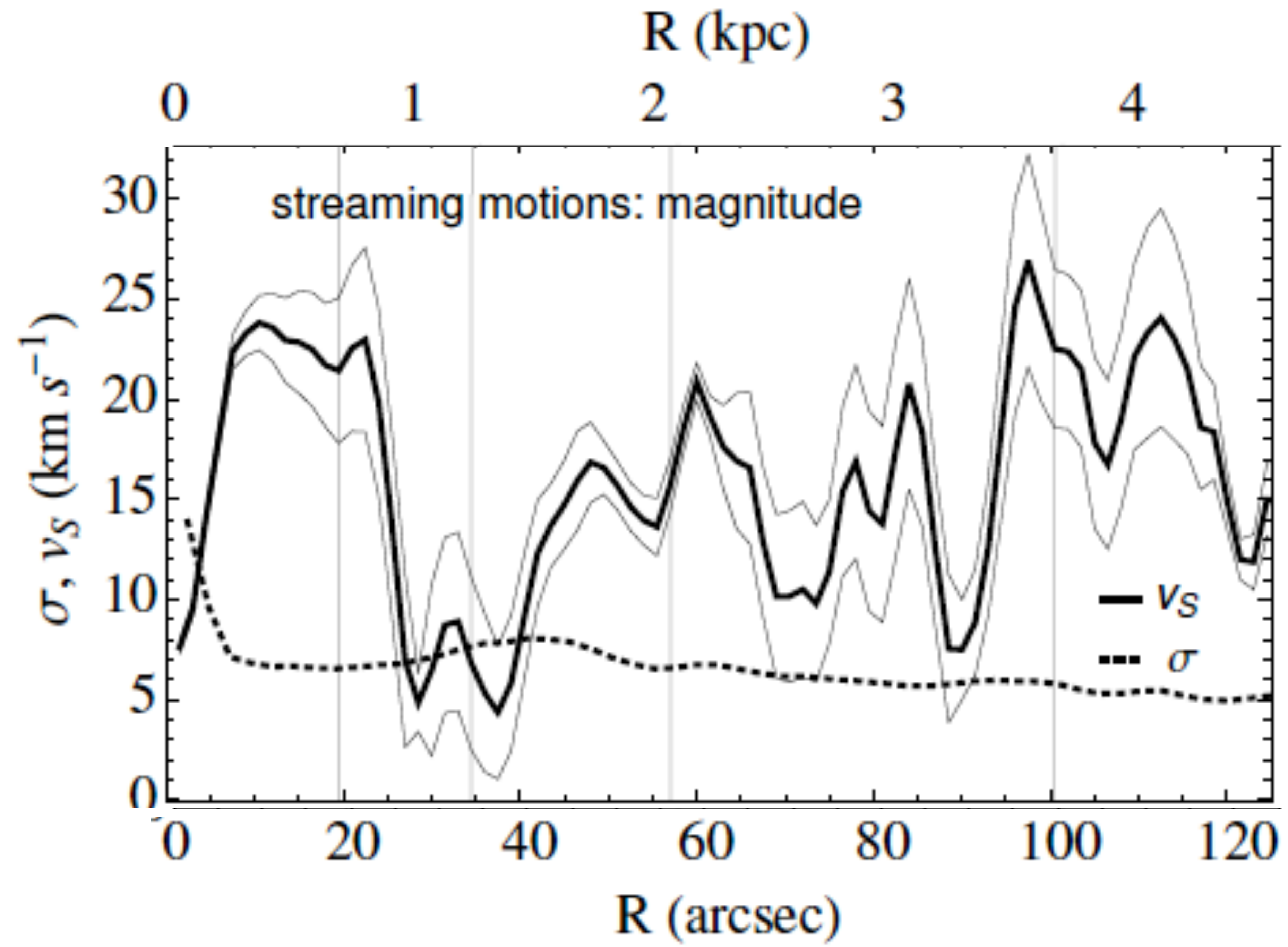

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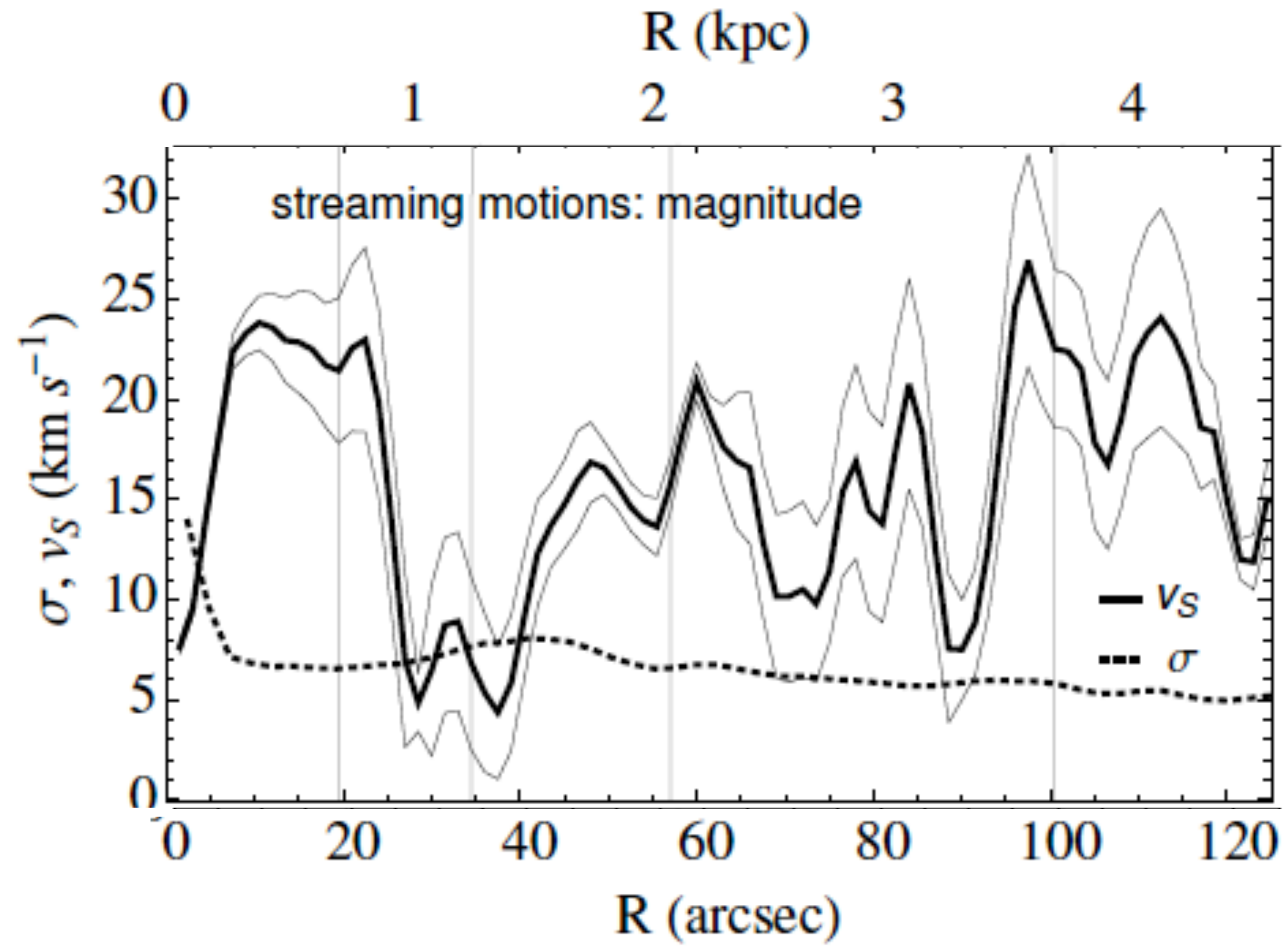

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(see Roberts & Stewart 1987;
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view depends on choice of tracer!

gas kinematics

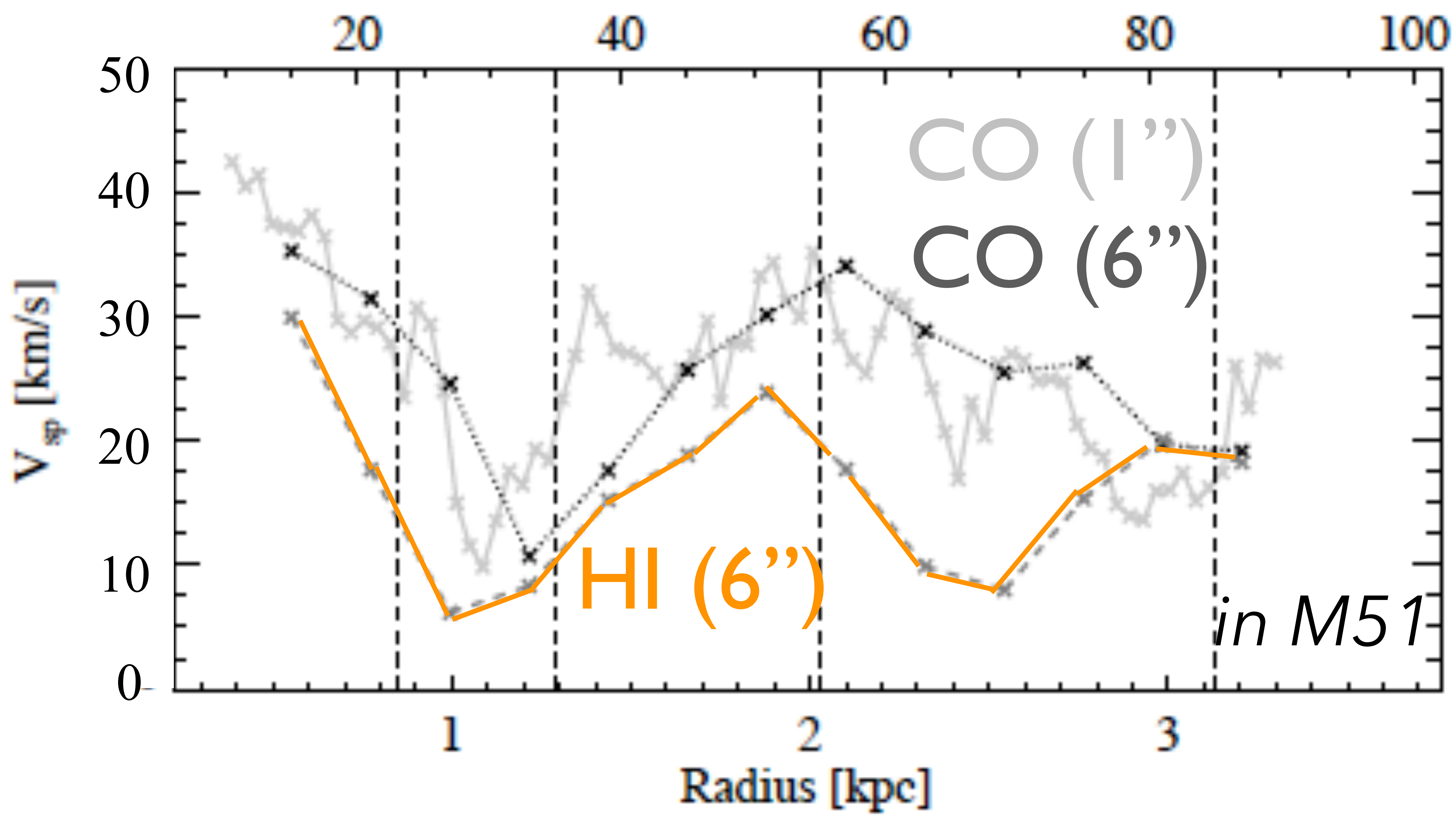
different distributions

==

different kinematics

(Colombo, SEM et al. 2014b)

non-circular streaming motions



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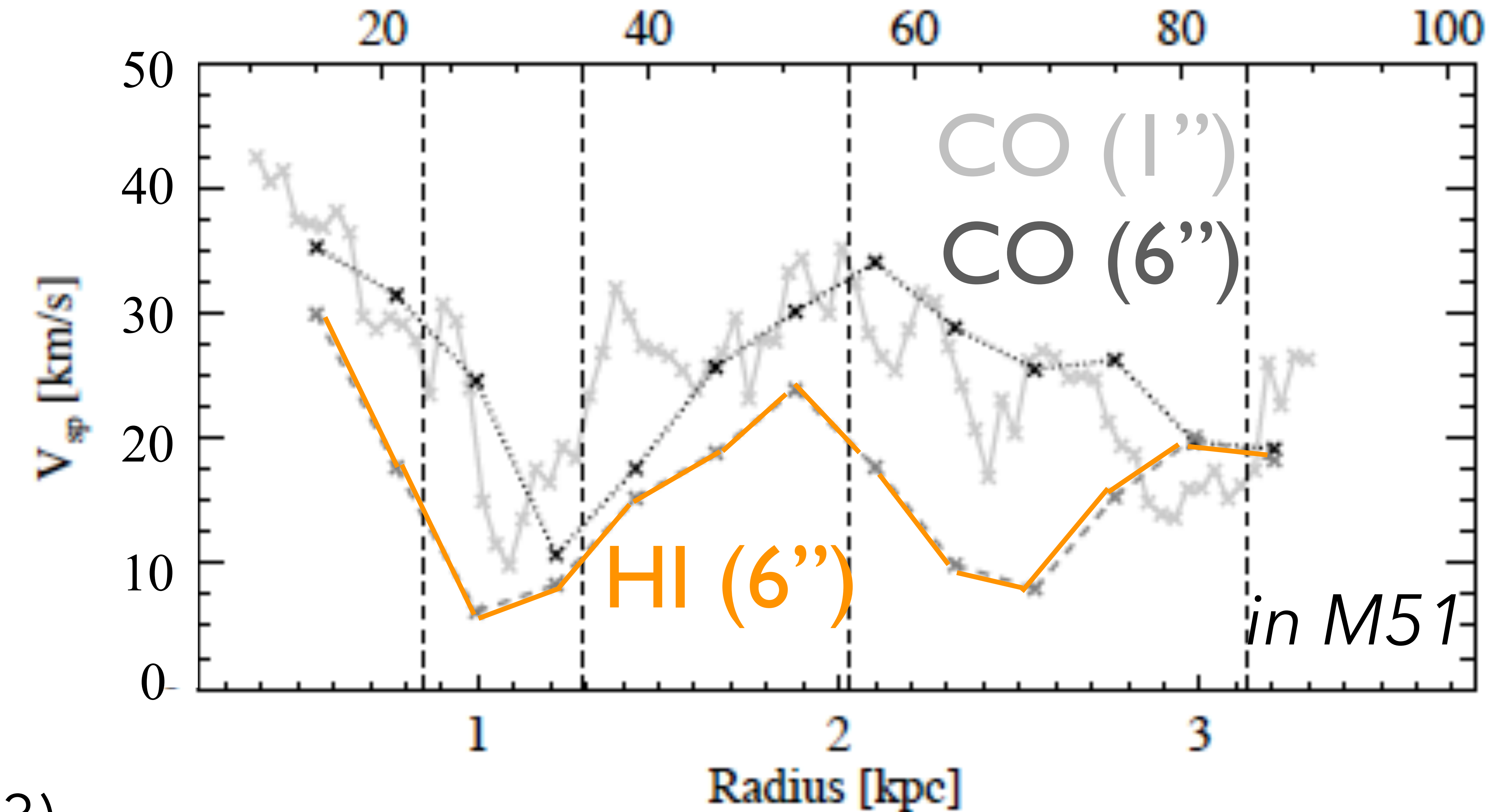
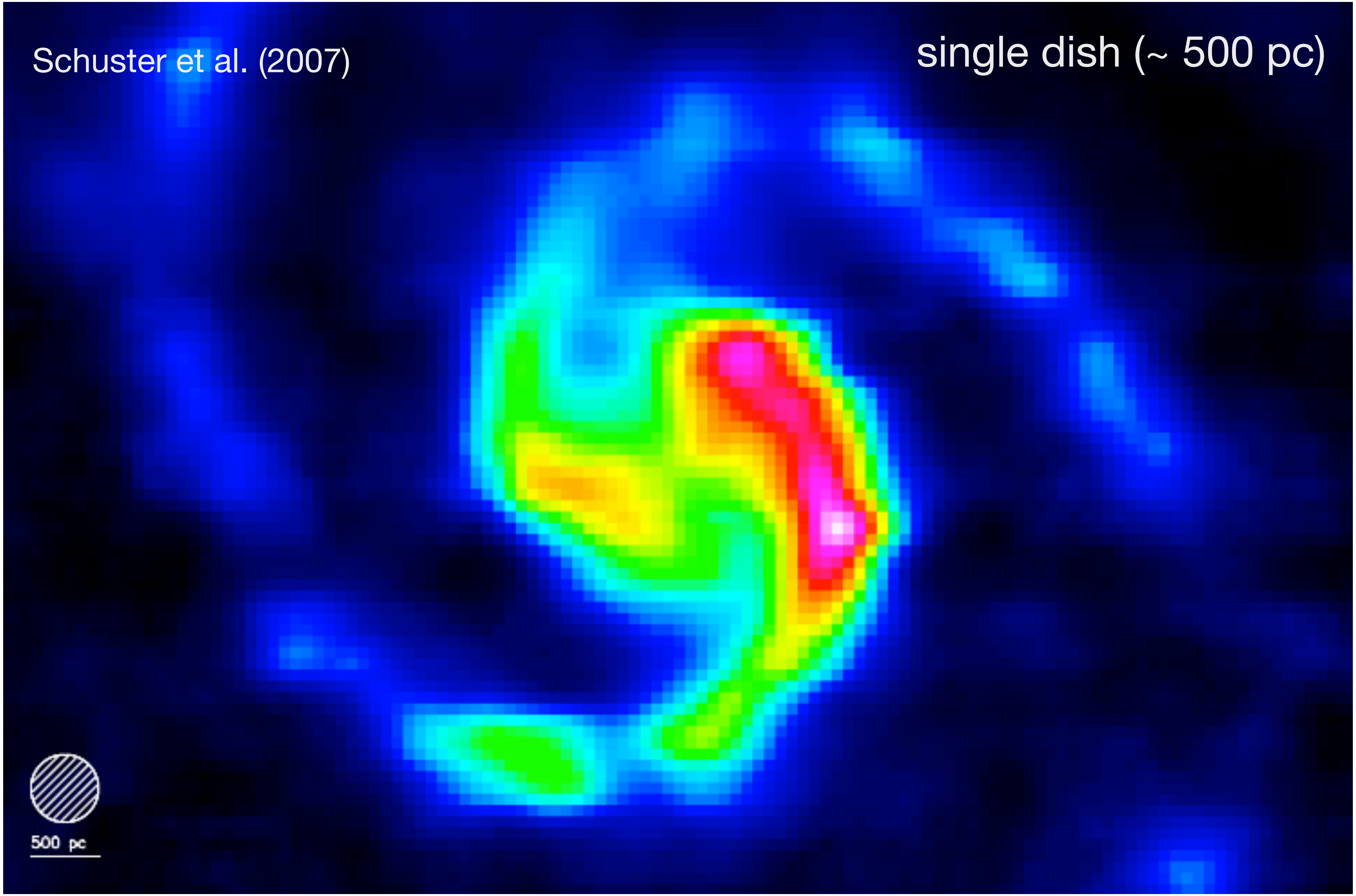


- molecular gas is
    - clumpier (Leroy et al. 2013)
    - denser, confined more to mid-plane
    - in spiral potential well minimum
      (HI typically offset; e.g. Rand & Kulkarni 1990)

Molecular Gas disk of M51



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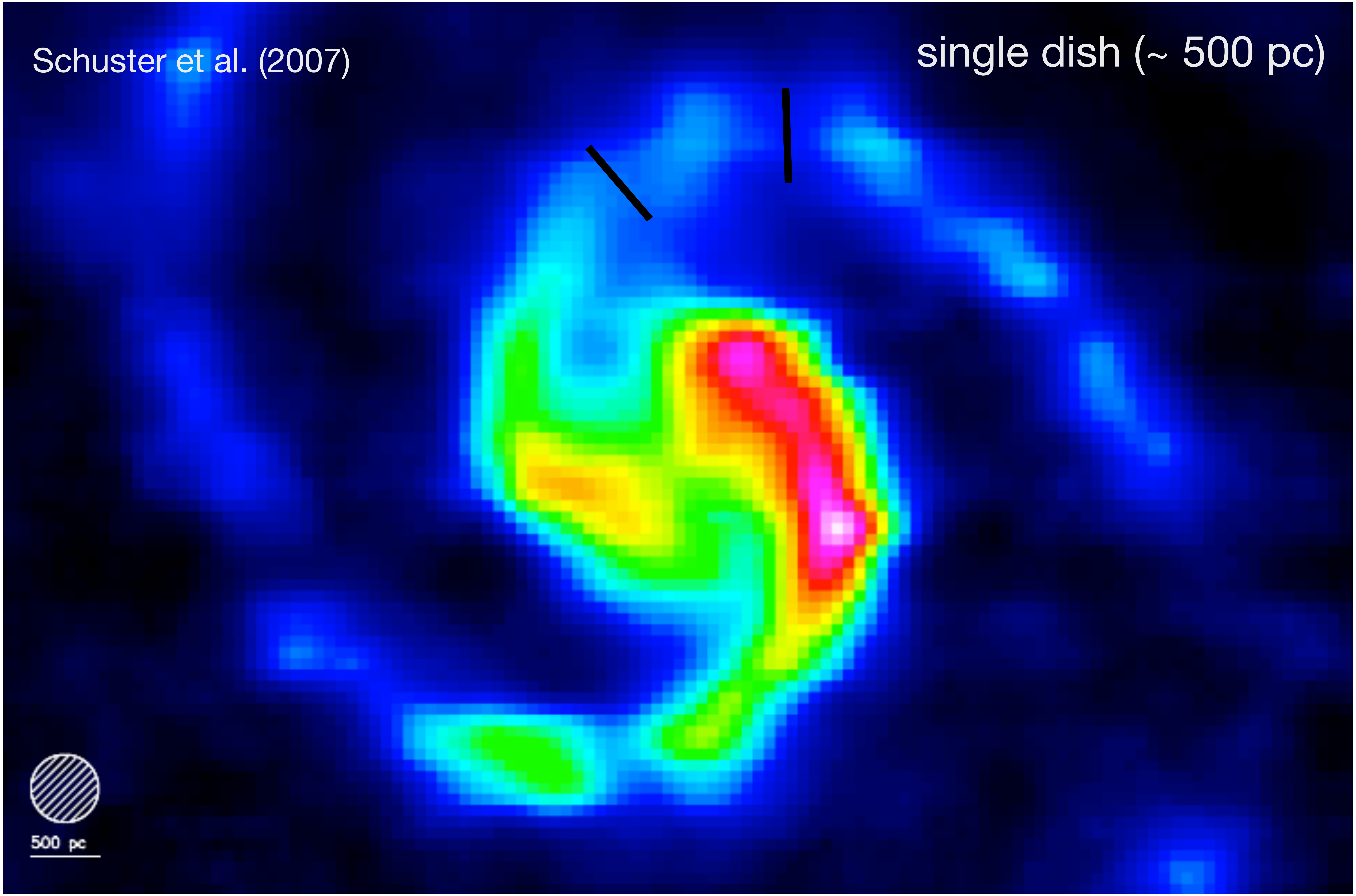
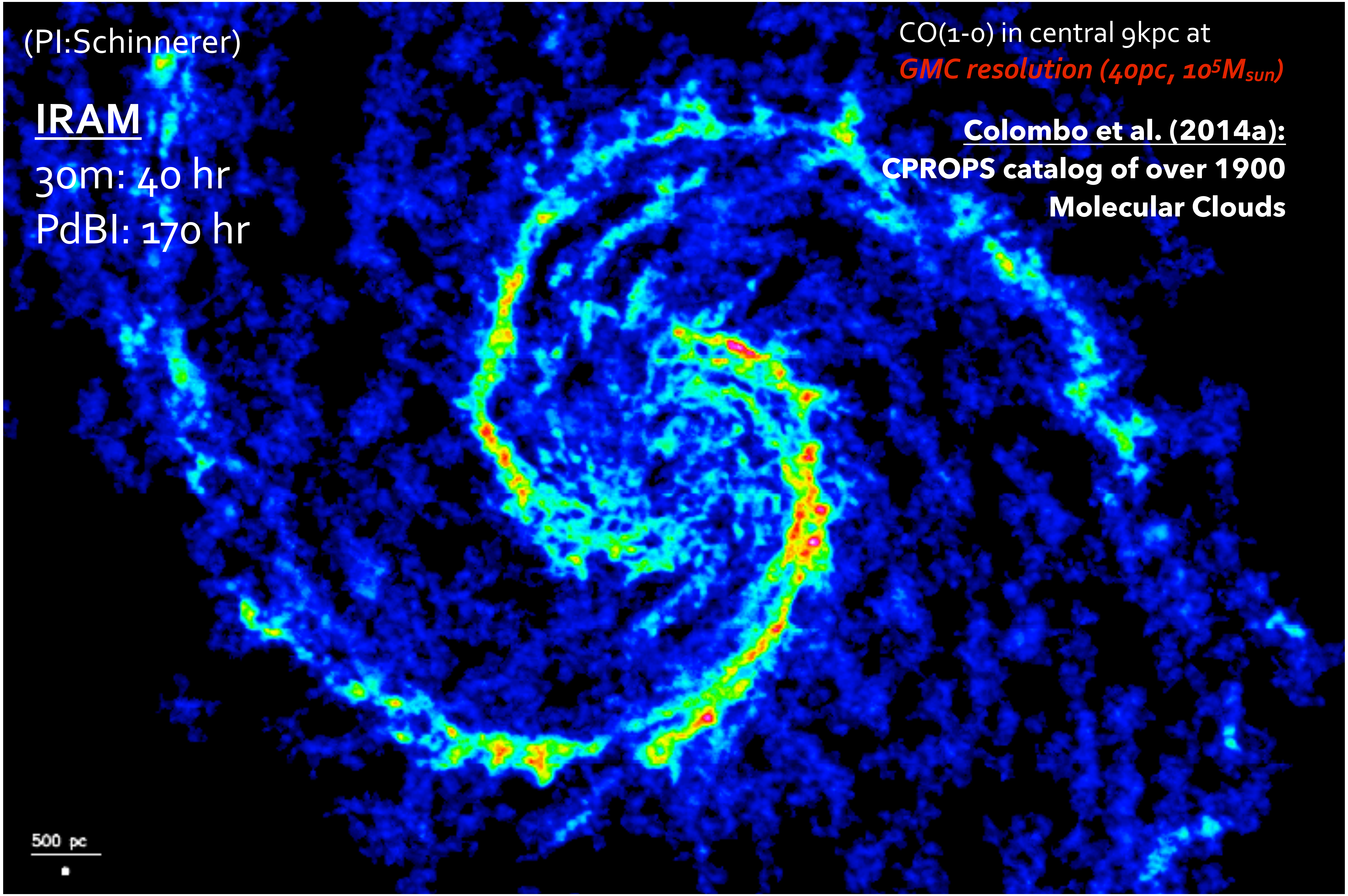


PAWS view

(Pety et al. 2013; Schinnerer et al. 2013)



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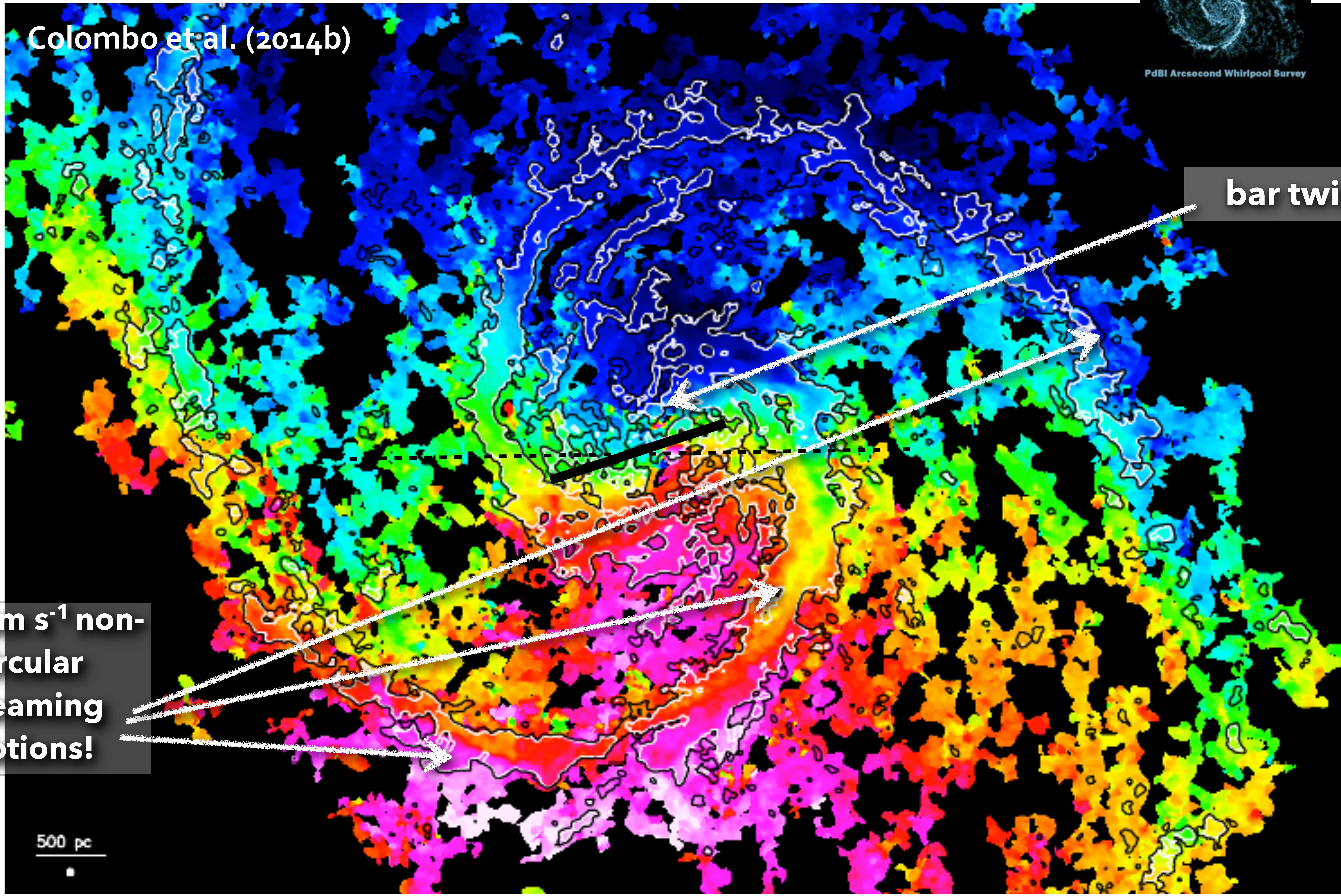

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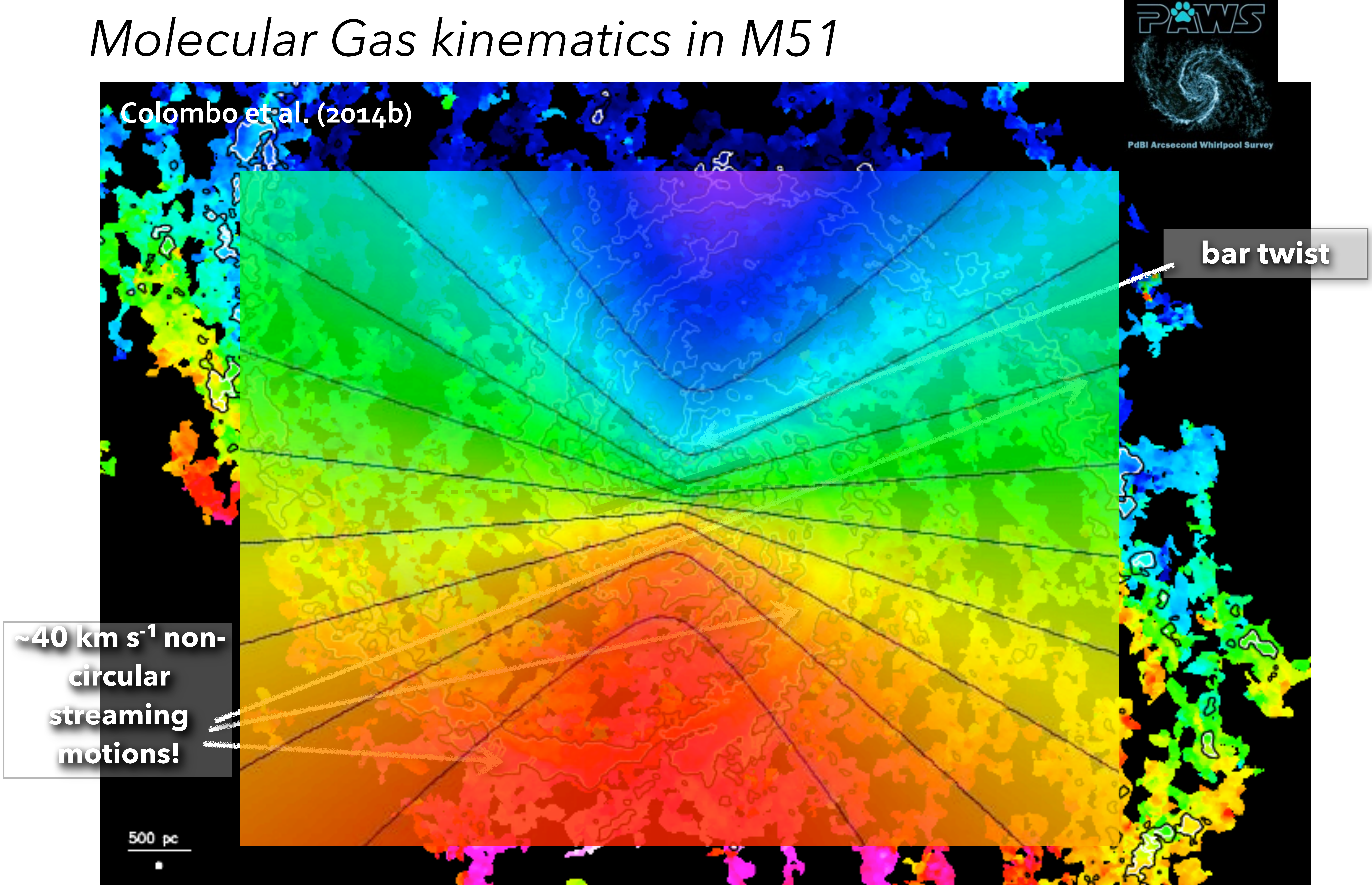

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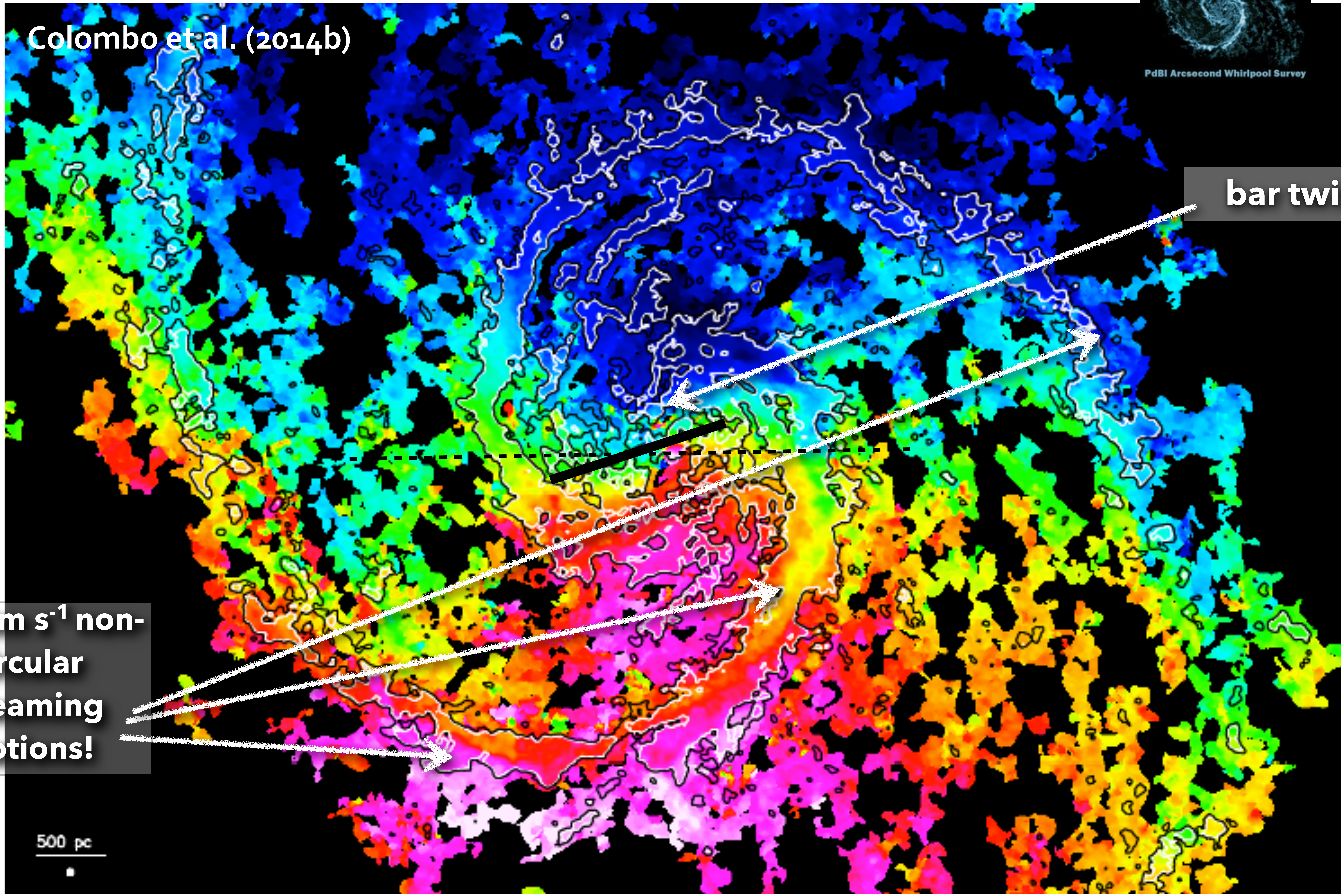
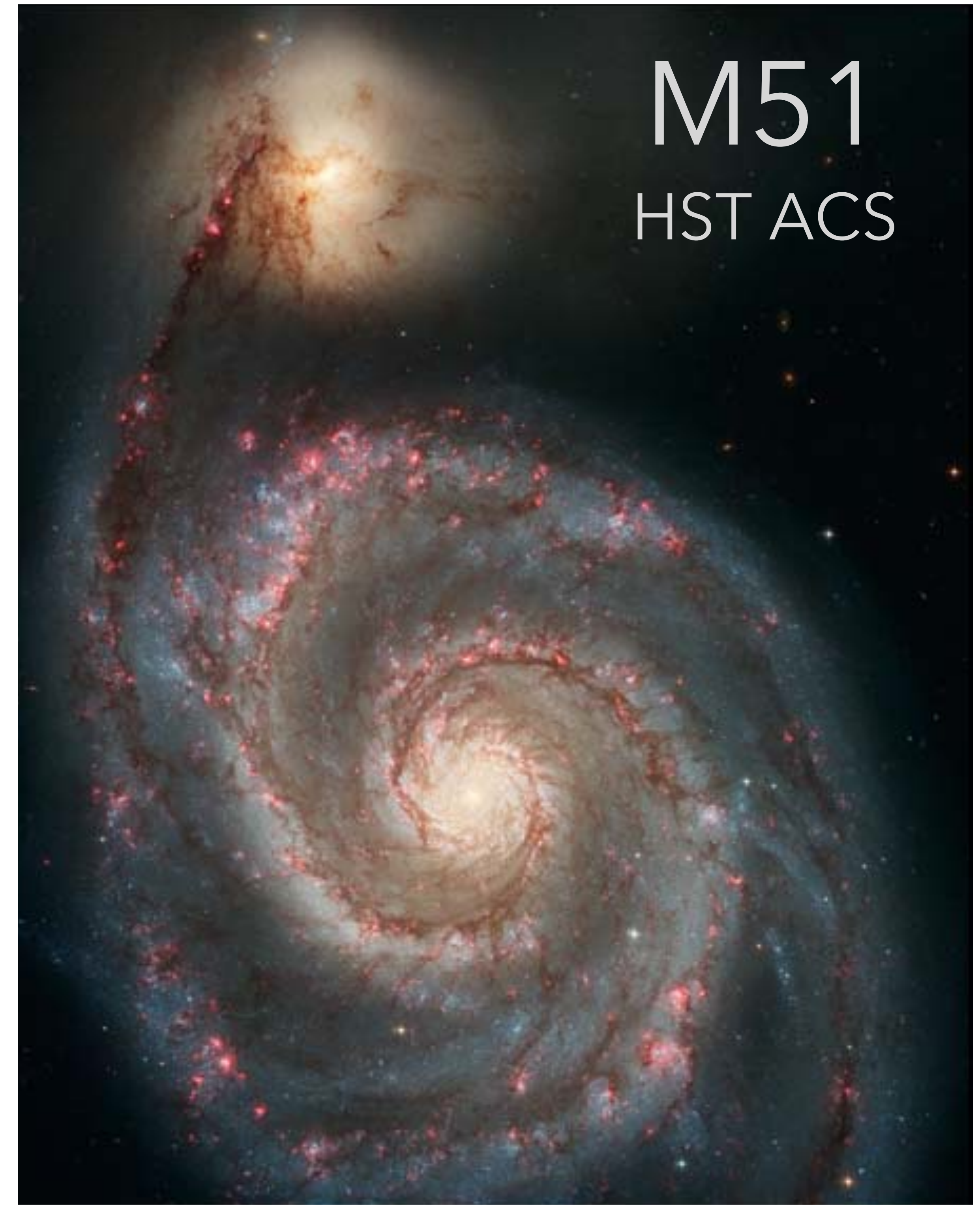


the role of spiral arms

ORGANIZATION & *STRUCTURE*

- streaming motions funnel gas through/along spiral arms
- build up high densities
- + reduce shear

> **star formation** (always?)



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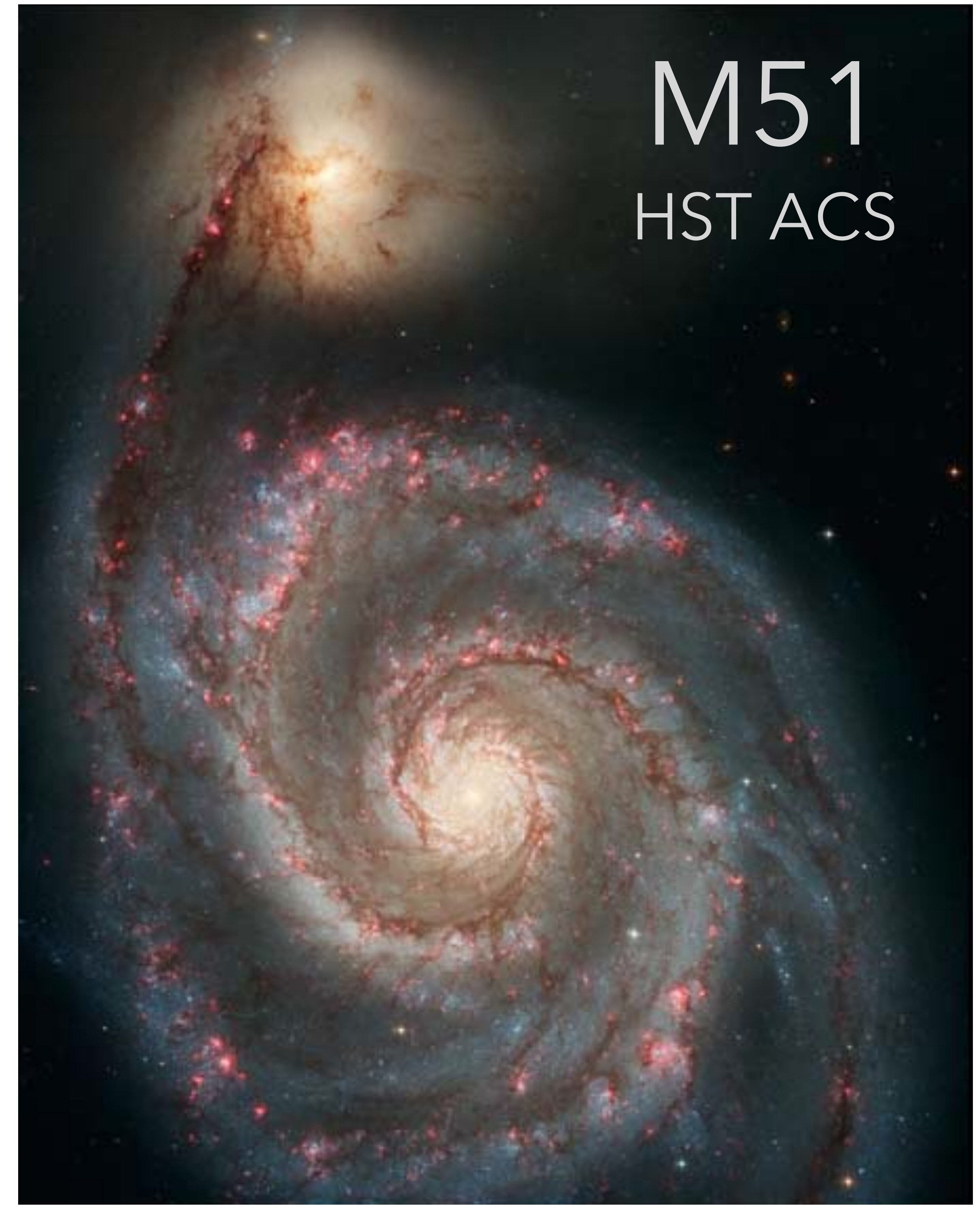

the role of spiral arms

ORGANIZATION

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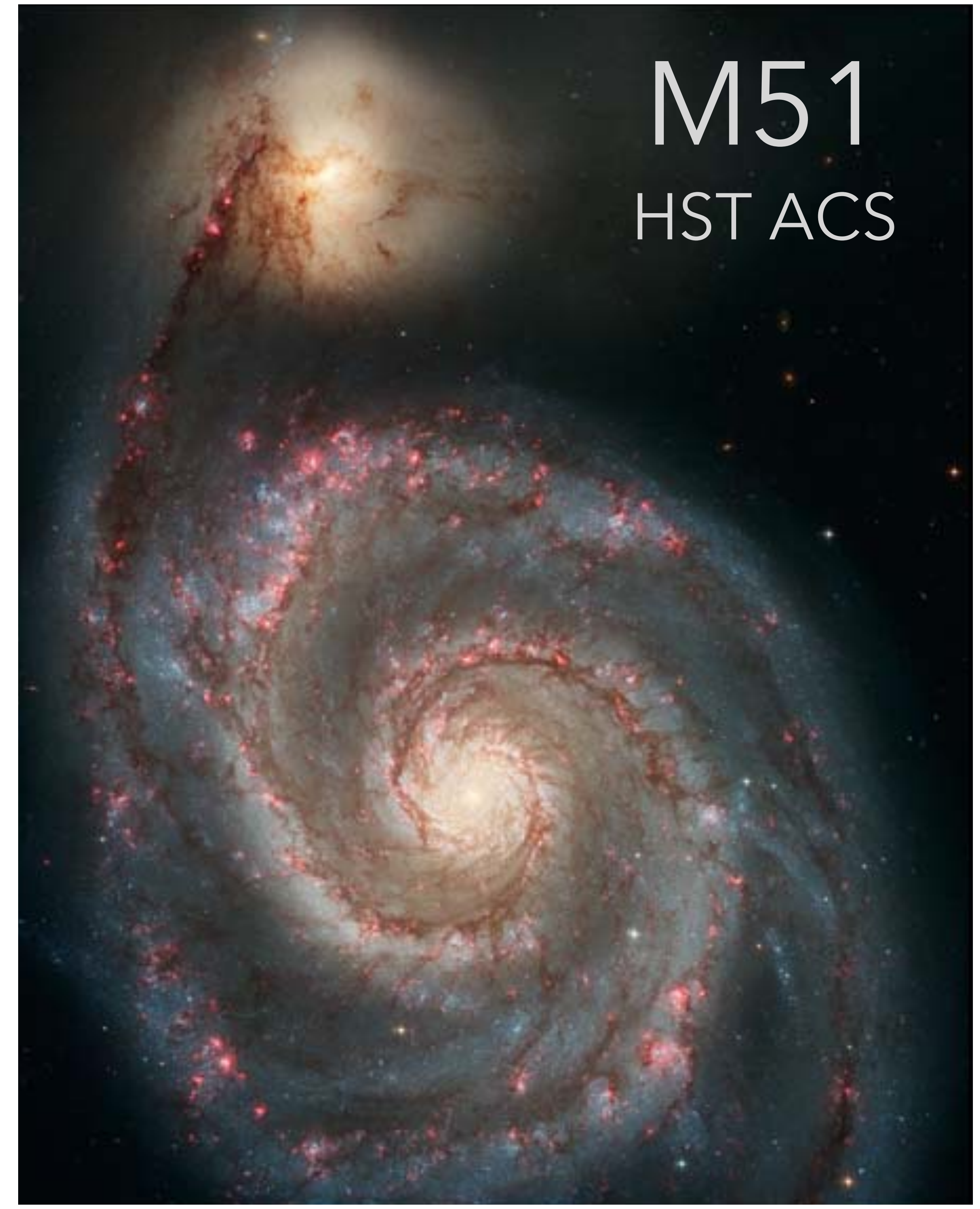
> **star formation** (always?)

STRUCTURE

- large-scale down to scale of **Giant Molecular Clouds**, the star-forming unit !!

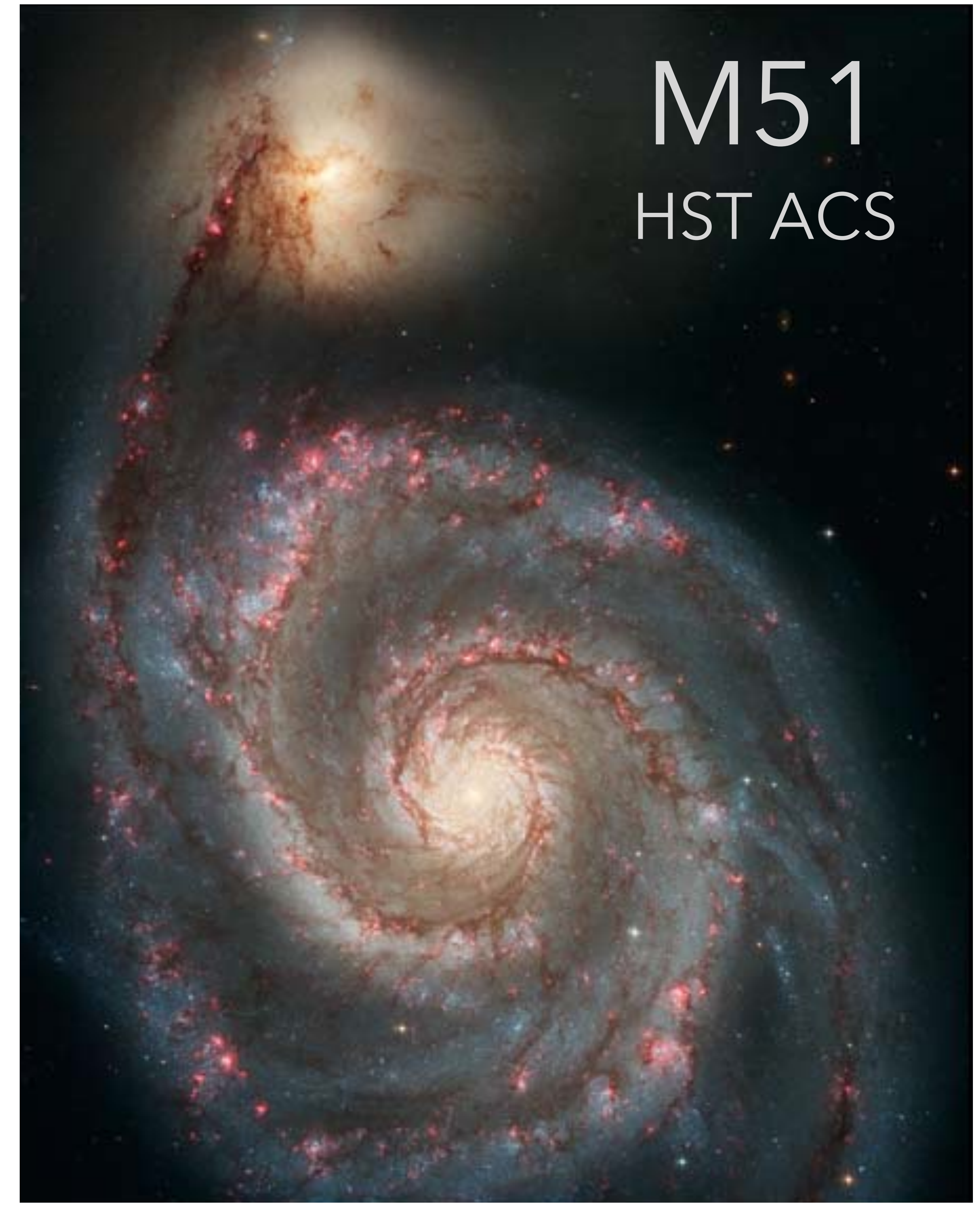


the role of spiral arms

ORGANIZATION

- streaming motions funnel gas through/along spiral arms
- build up high densities
- + reduce shear

> **star formation** (always?)



STRUCTURE

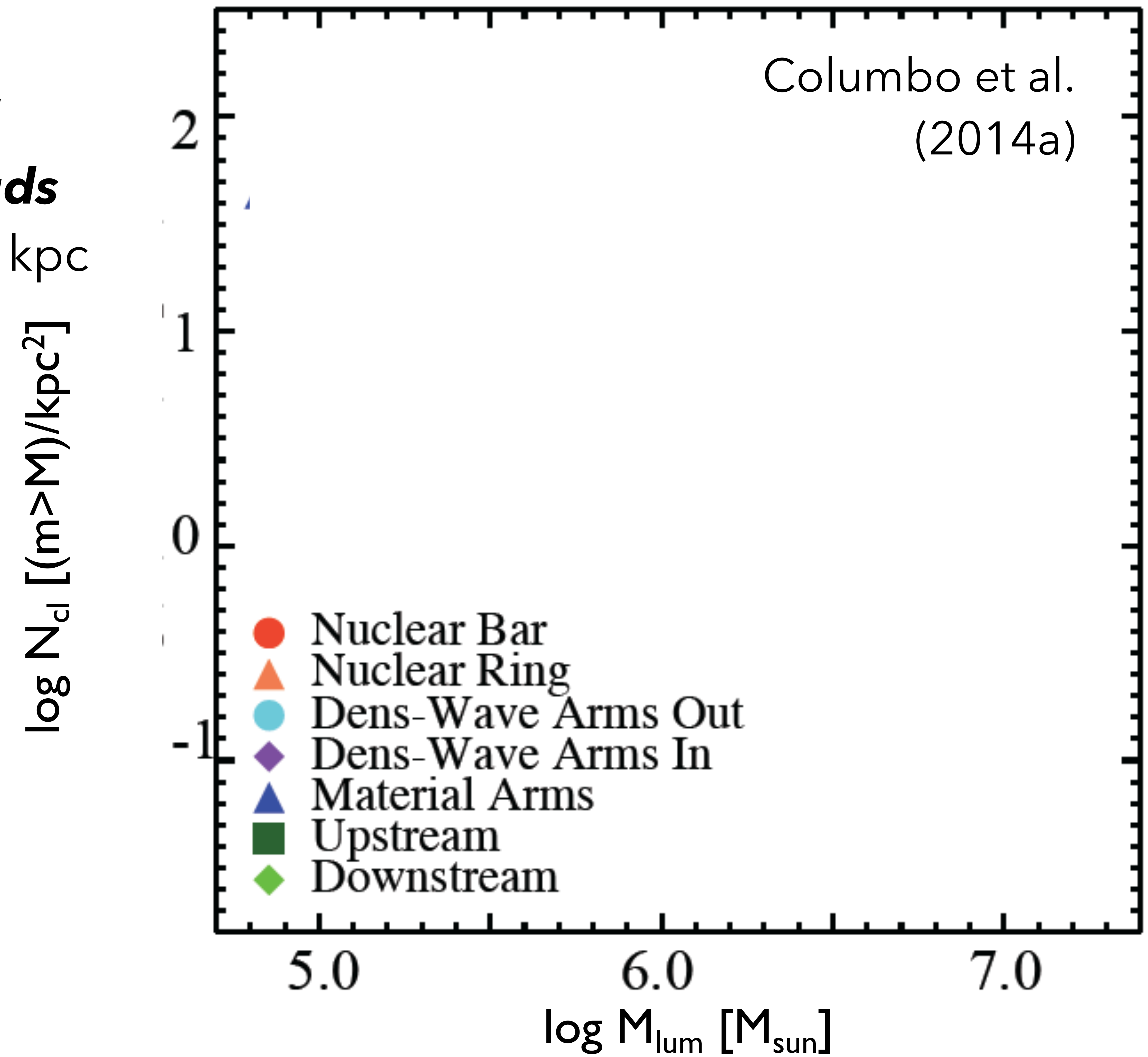
- large-scale down to scale of **Giant Molecular Clouds**, the star-forming unit !!

- massive clouds build/form in spiral arms via convergent flows, collisions & self-gravity (M51, IC 342; Hirota et al. 2011; Koda et al. 2009; Egusa, Koda & Scoville 2010)

the role of spiral arms

- Colombo et al. (2014a): PAWS GMC catalog of ***over 1900 clouds*** across central 9 kpc in M51

- cloud Cumulative Mass Spectra



spiral arms help build more and larger clouds

dispersal in inter-arm due to shear, feedback

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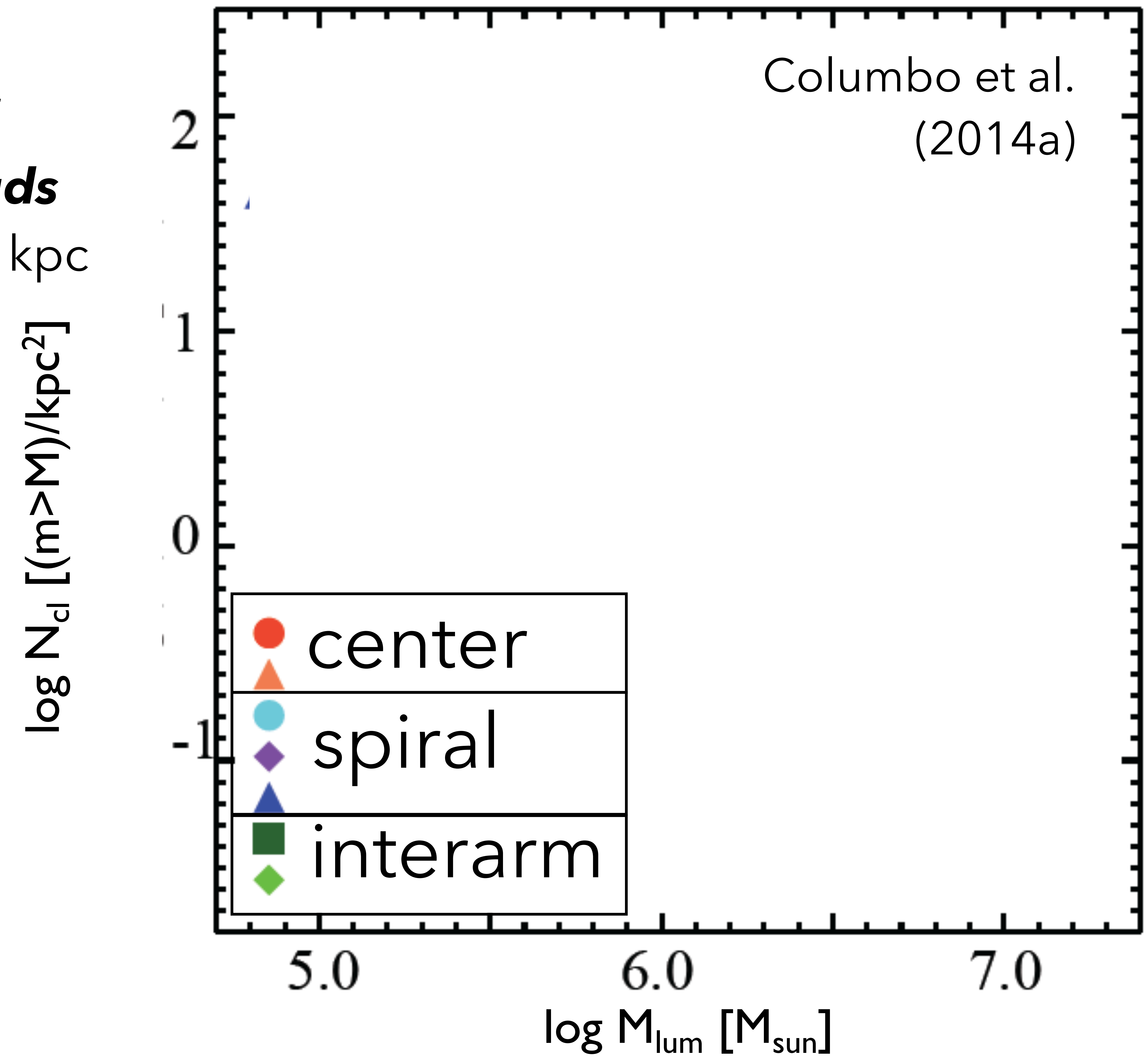

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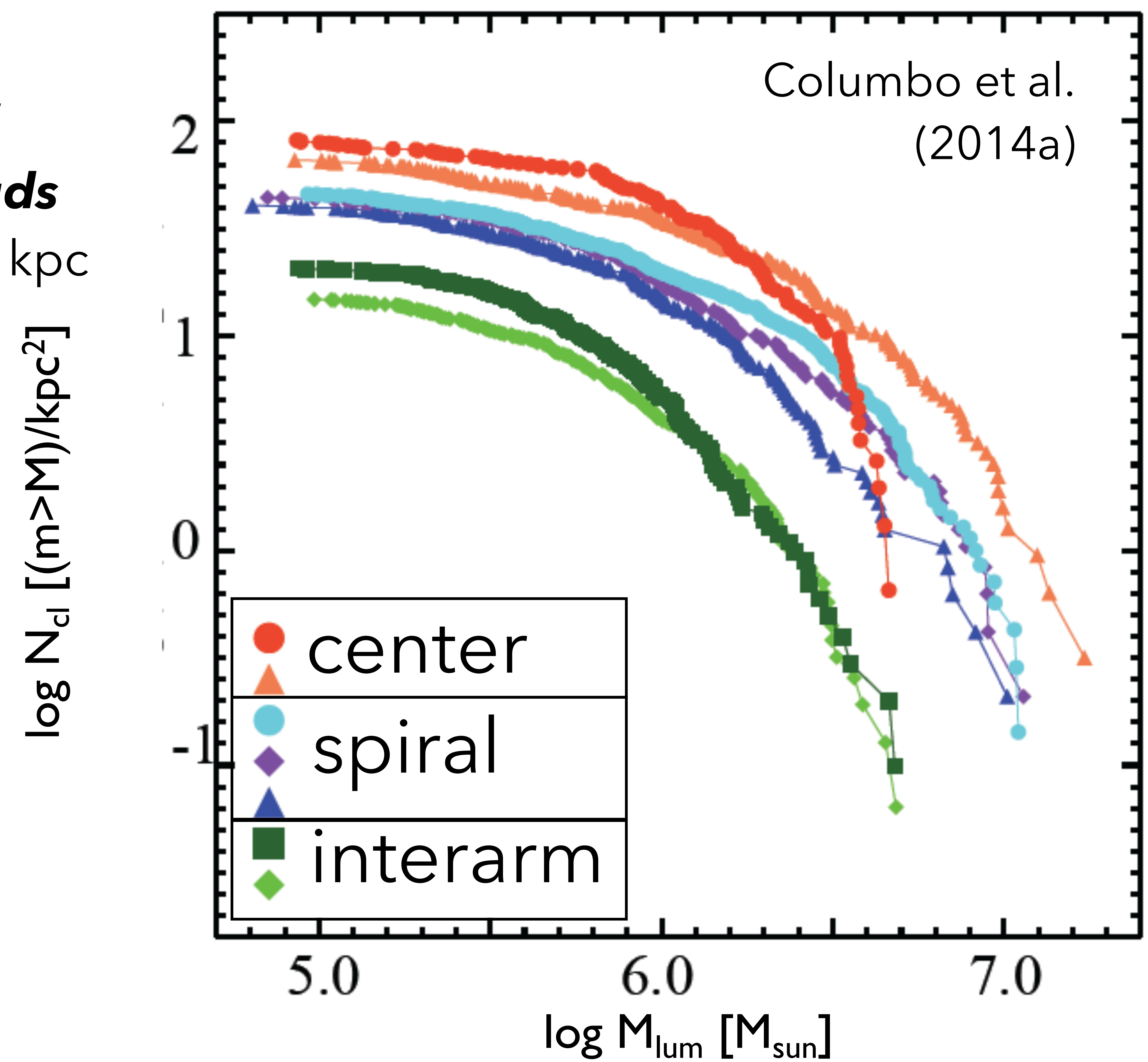

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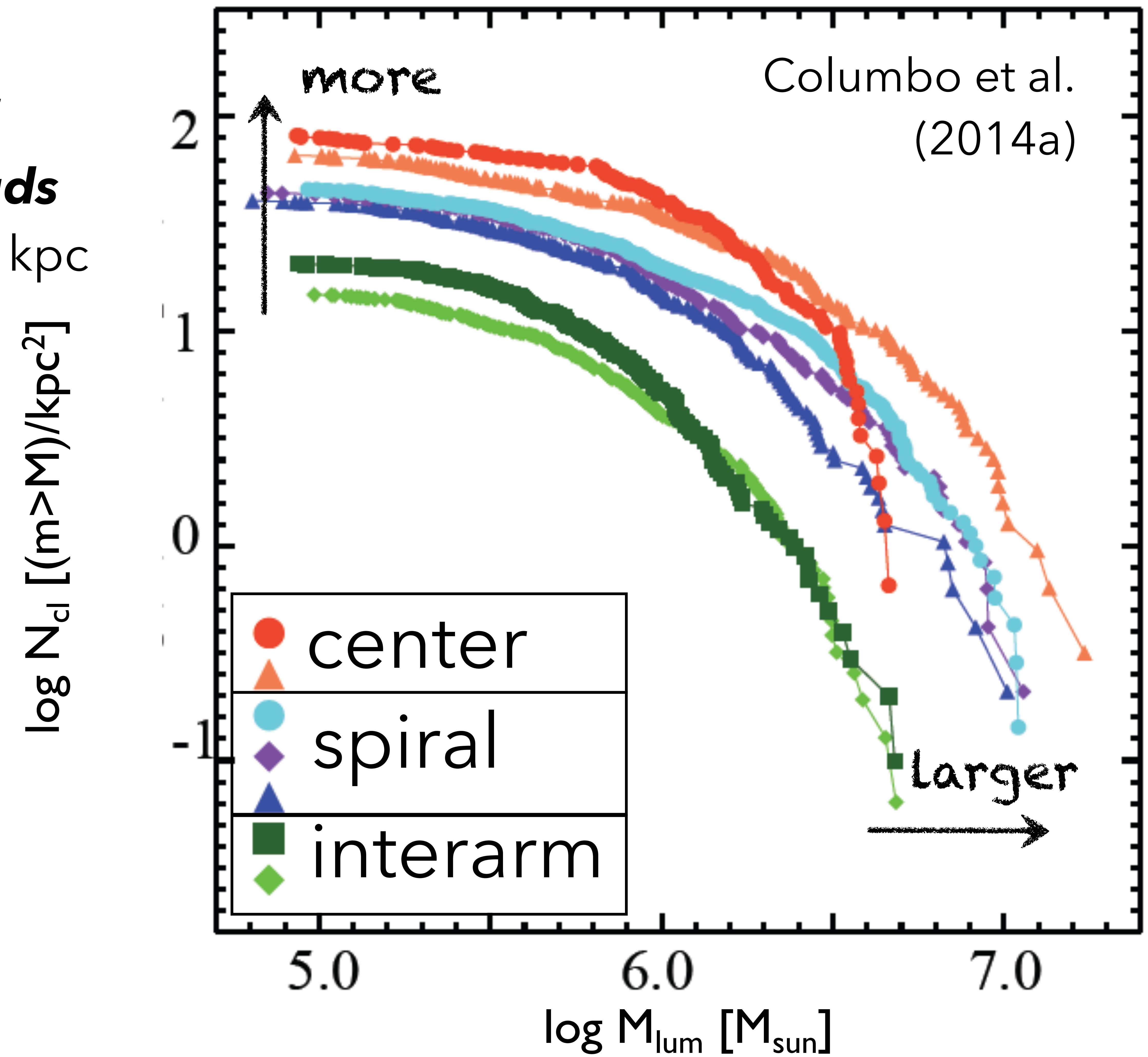


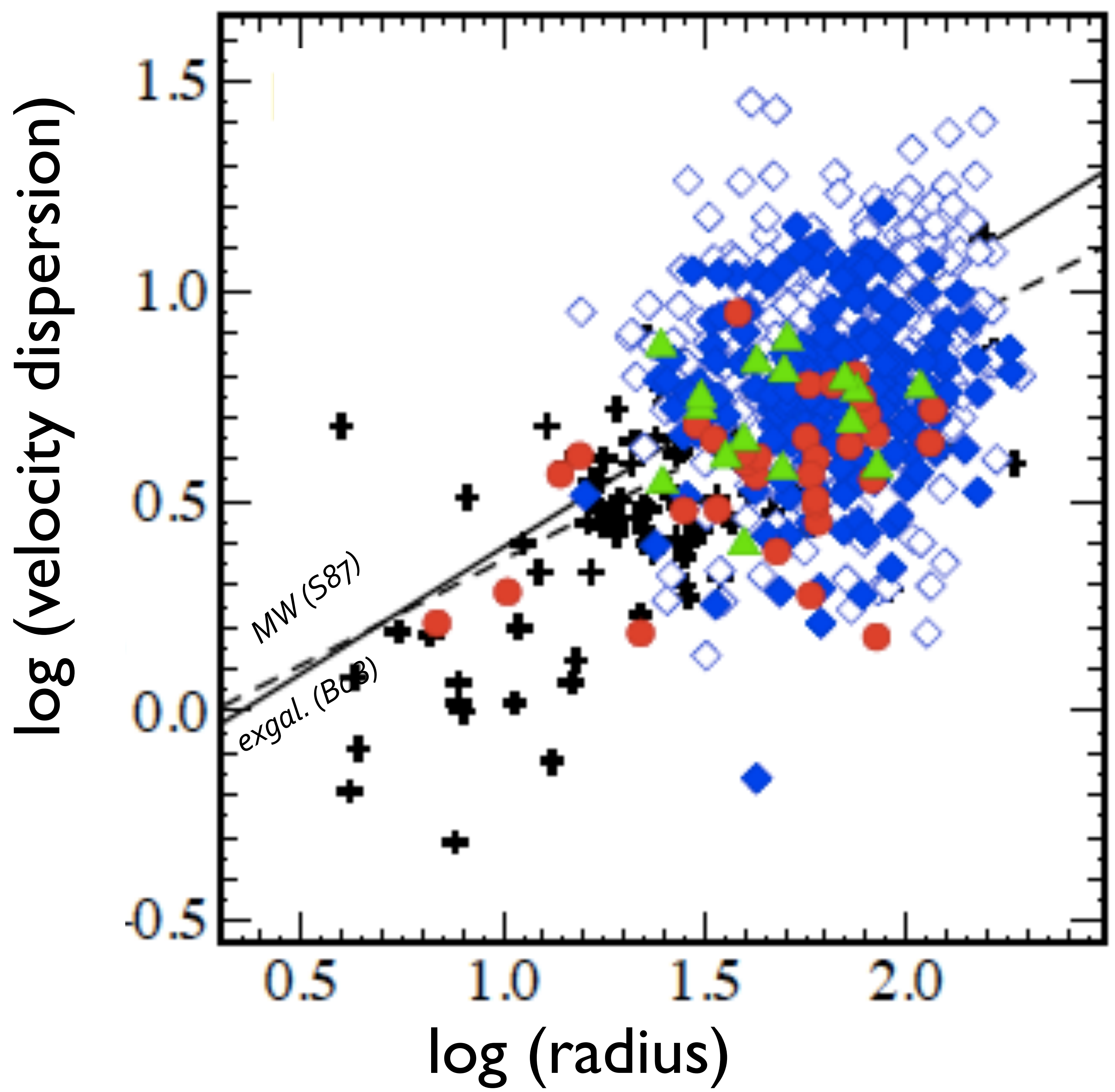
spiral arms help build more and larger clouds

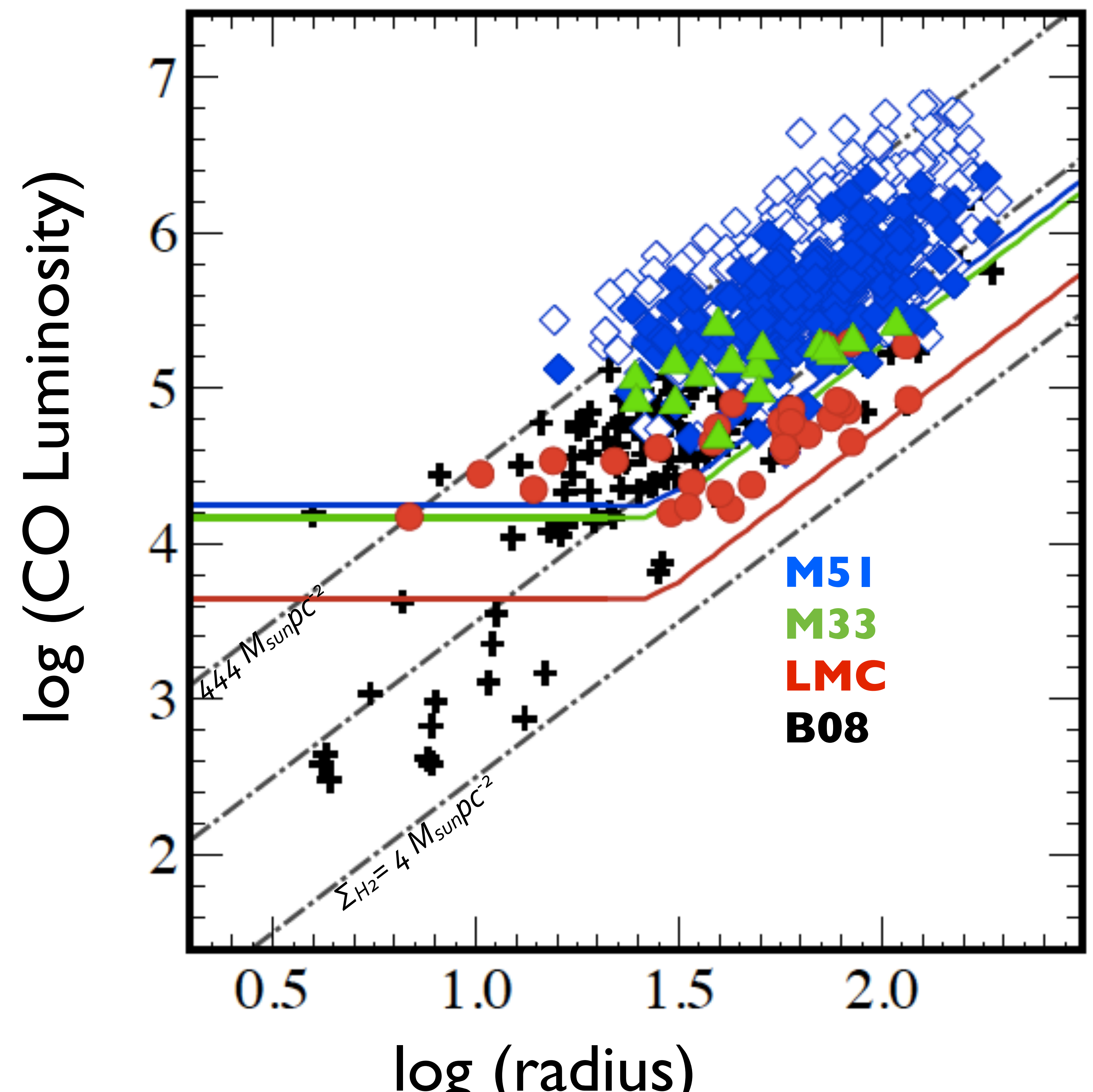
dispersal in inter-arm due to shear, feedback

the role of spiral arms

- cloud properties, scaling relations

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

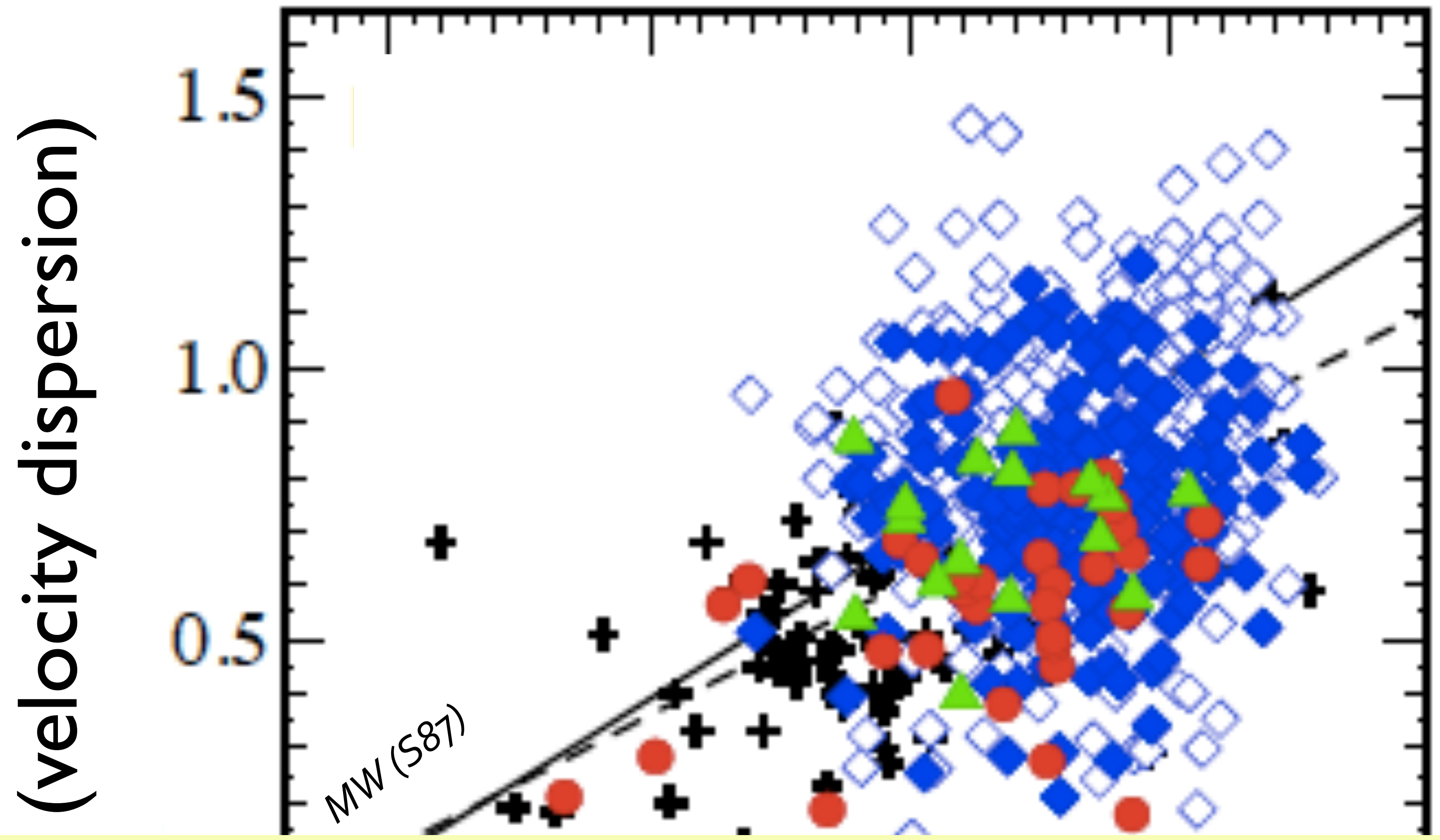
no universal free-fall time!

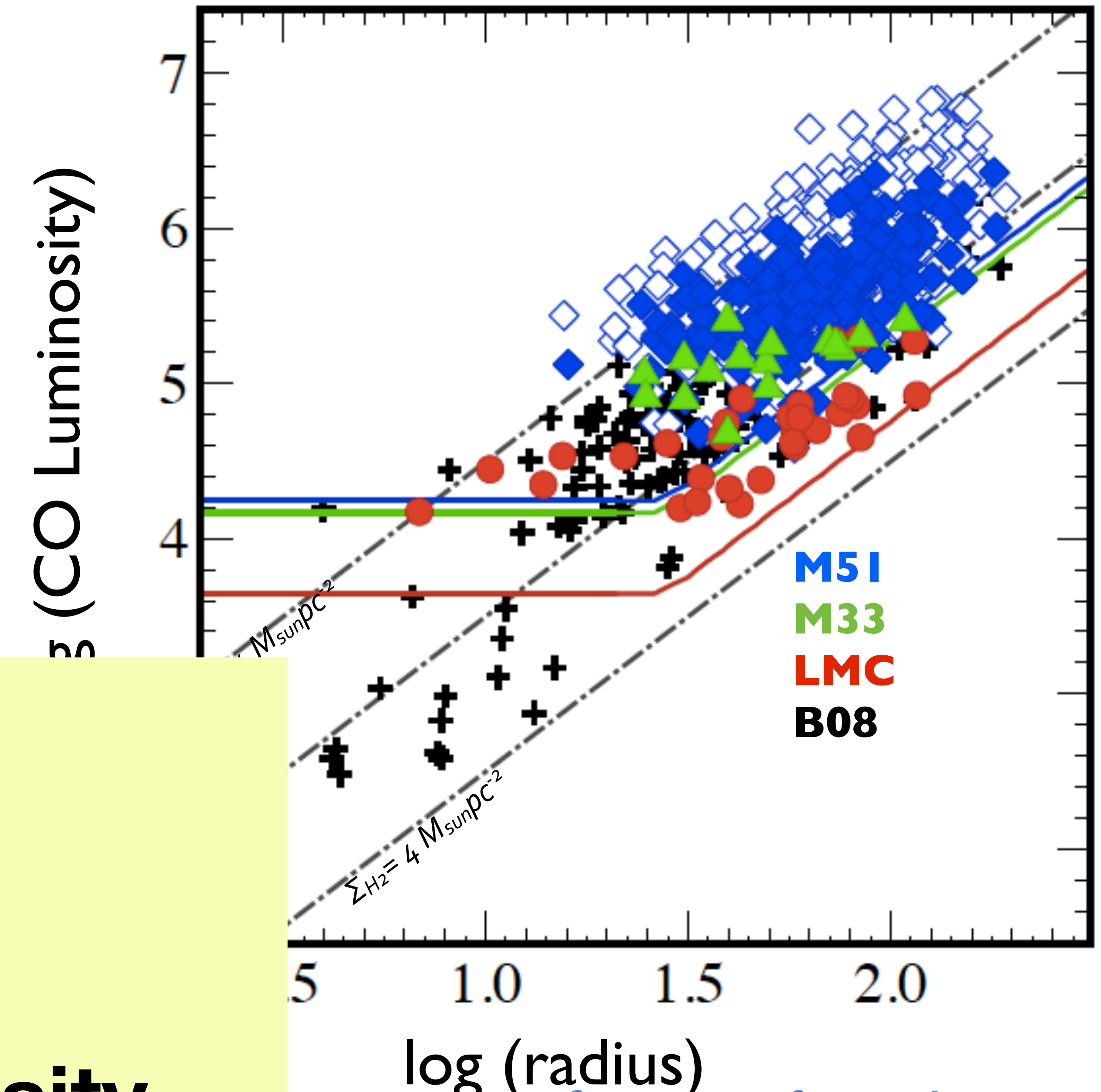
scatter in KS relation

the role of spiral arms

- cloud properties, scaling relations

Hughes et al. (2013b)





clouds in **ARM** are

- **brighter,**
- **more massive,**
- **higher gas surface density**

compared to **inter-ARM**

ge range of gas surface densities

⇨

MC properties are not universal

no universal free-fall time!

scatter in KS relation

varying properties with dynamical environment

the role of external pressure

varying properties with dynamical environment

the role of external pressure

- how do clouds inherit from environment?
- Pint~Pext *(Hughes, SEM et al. 2013a)*

varying properties with dynamical environment

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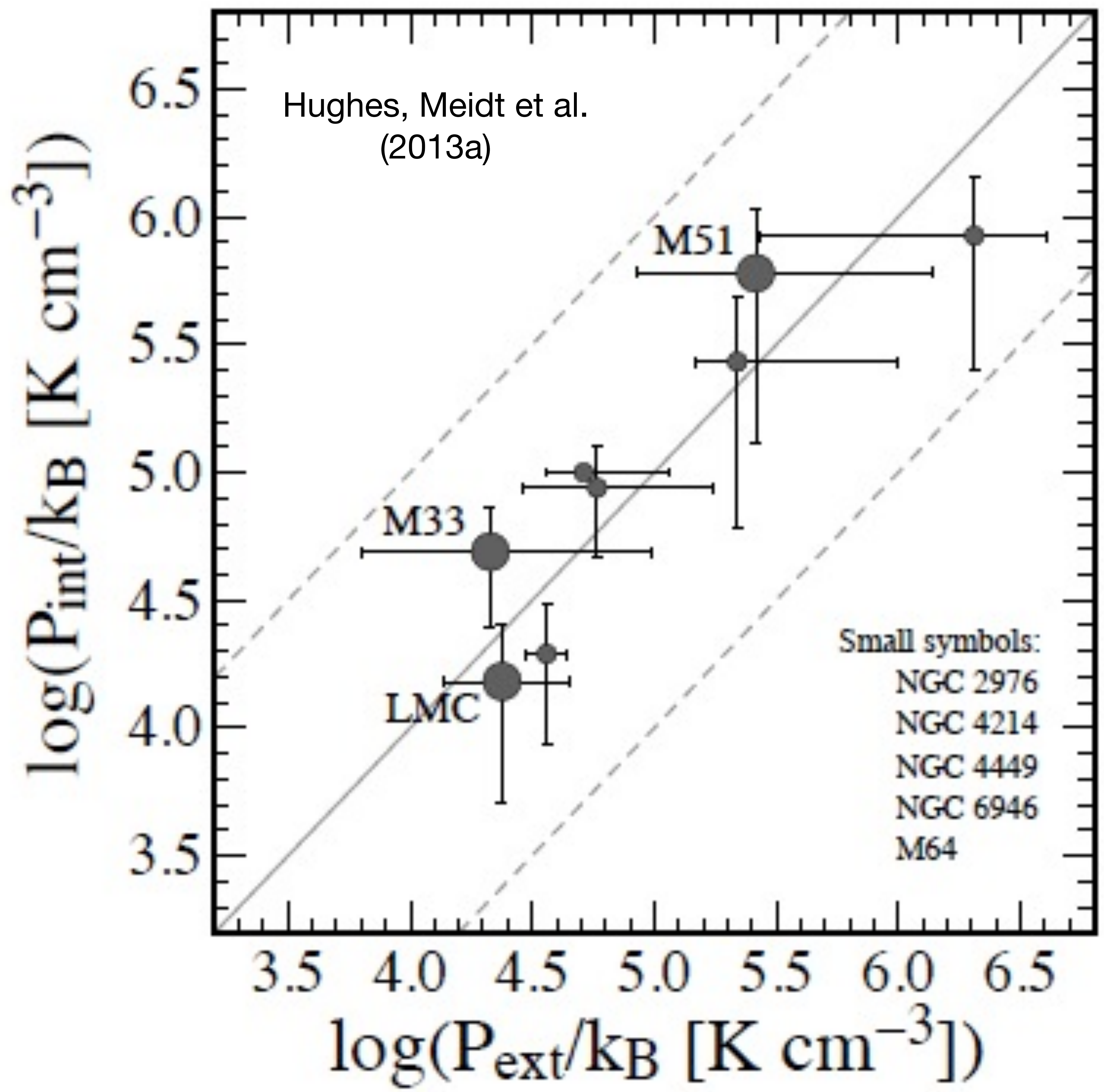

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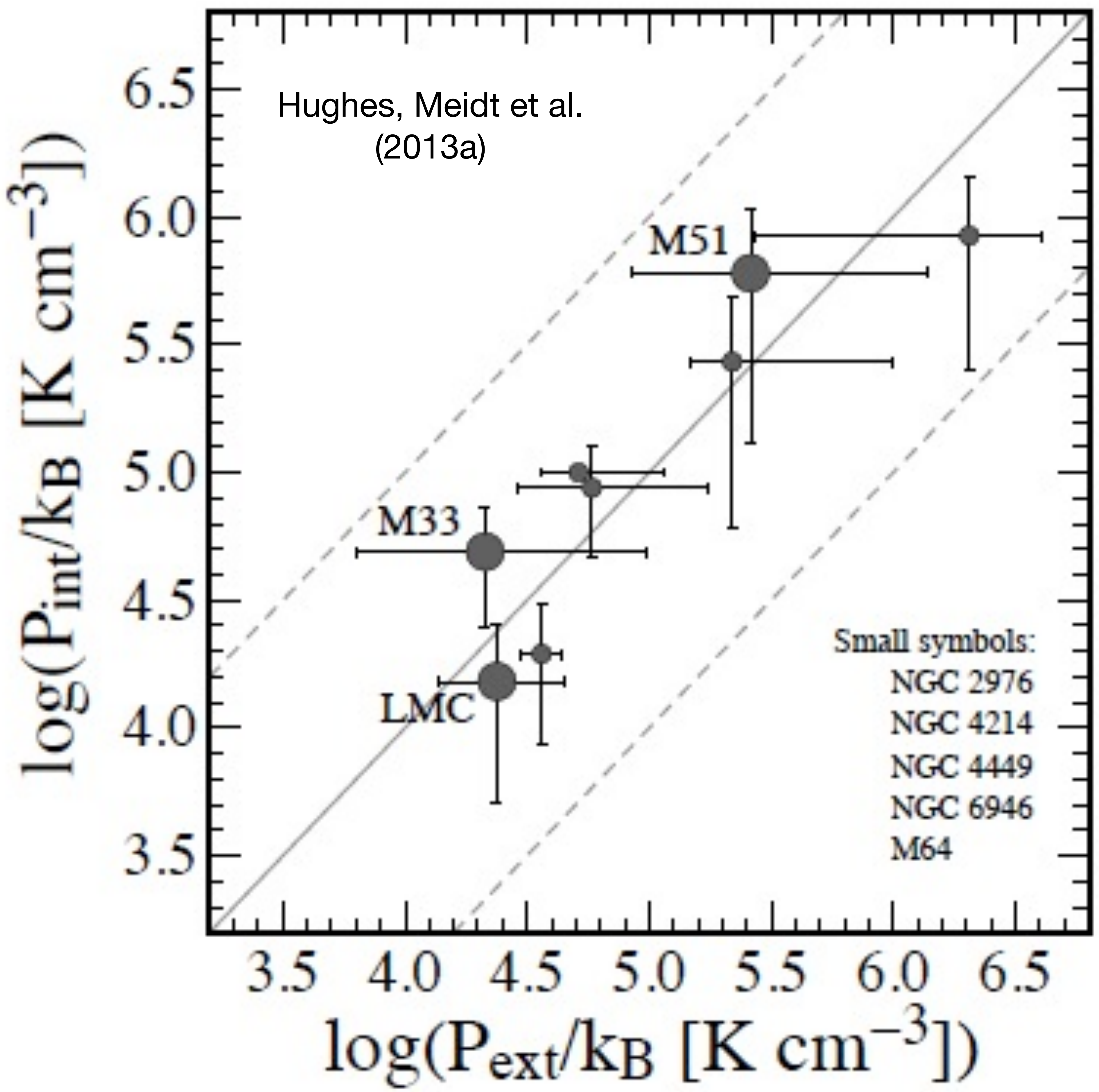


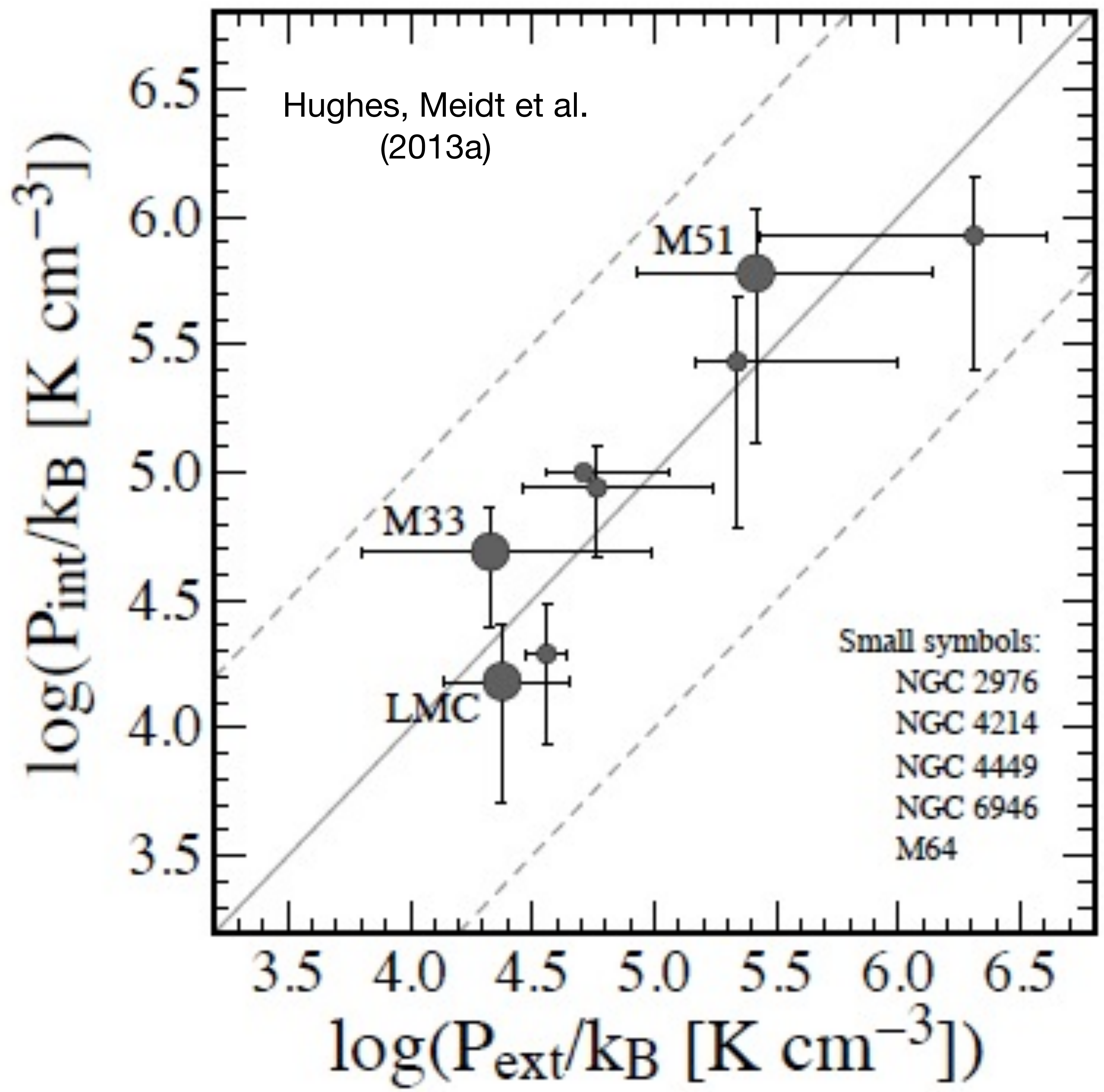
varying properties with dynamical environment

the role of external pressure

- how do clouds inherit from environment?
- Pint~Pext *(Hughes, SEM et al. 2013a)*

clouds coupled to surroundings

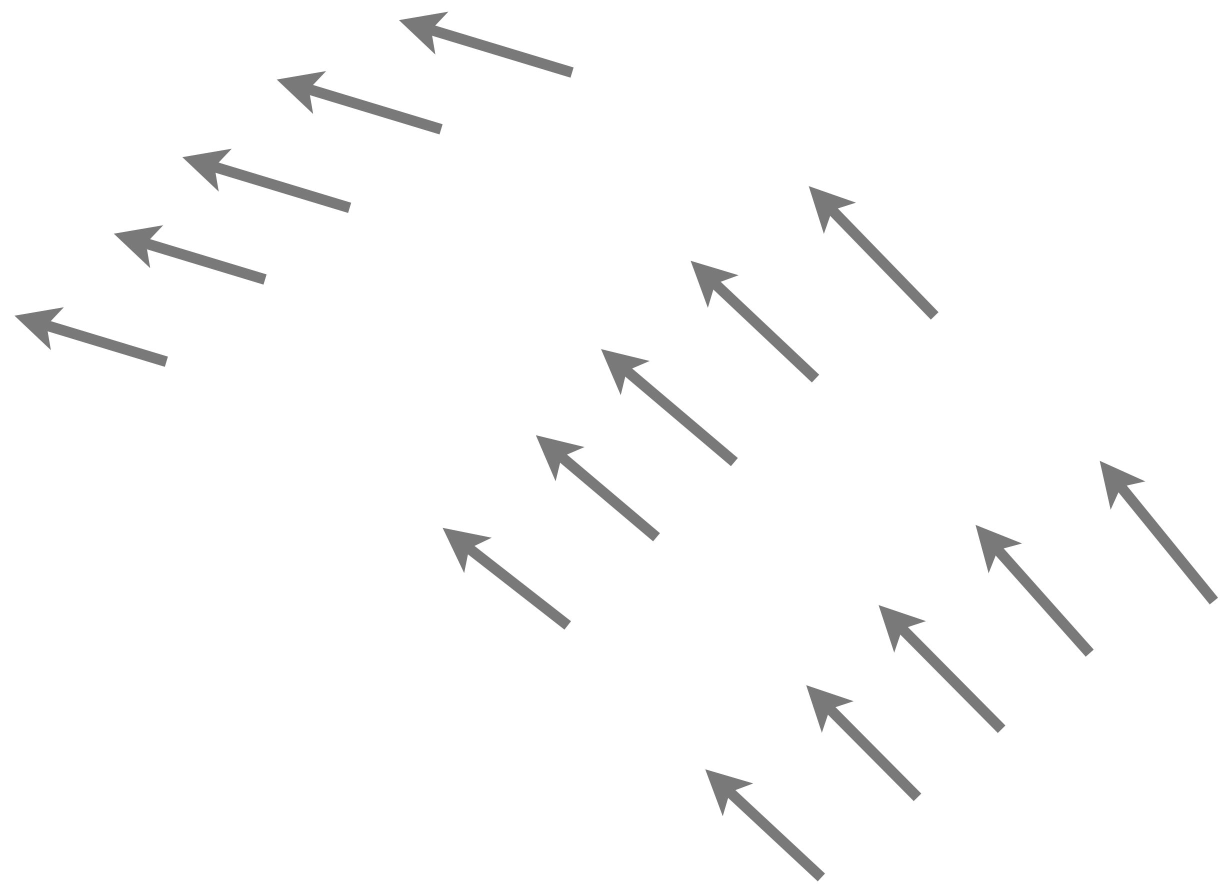
- changes in pressure-balance (due to non-circ motions) alter cloud stability *(Meidt et al. 2013)*



***KEY:** surface pressure important!*

dynamical pressure

Meidt et al. (2013)
cf. Jog (2013a,b)



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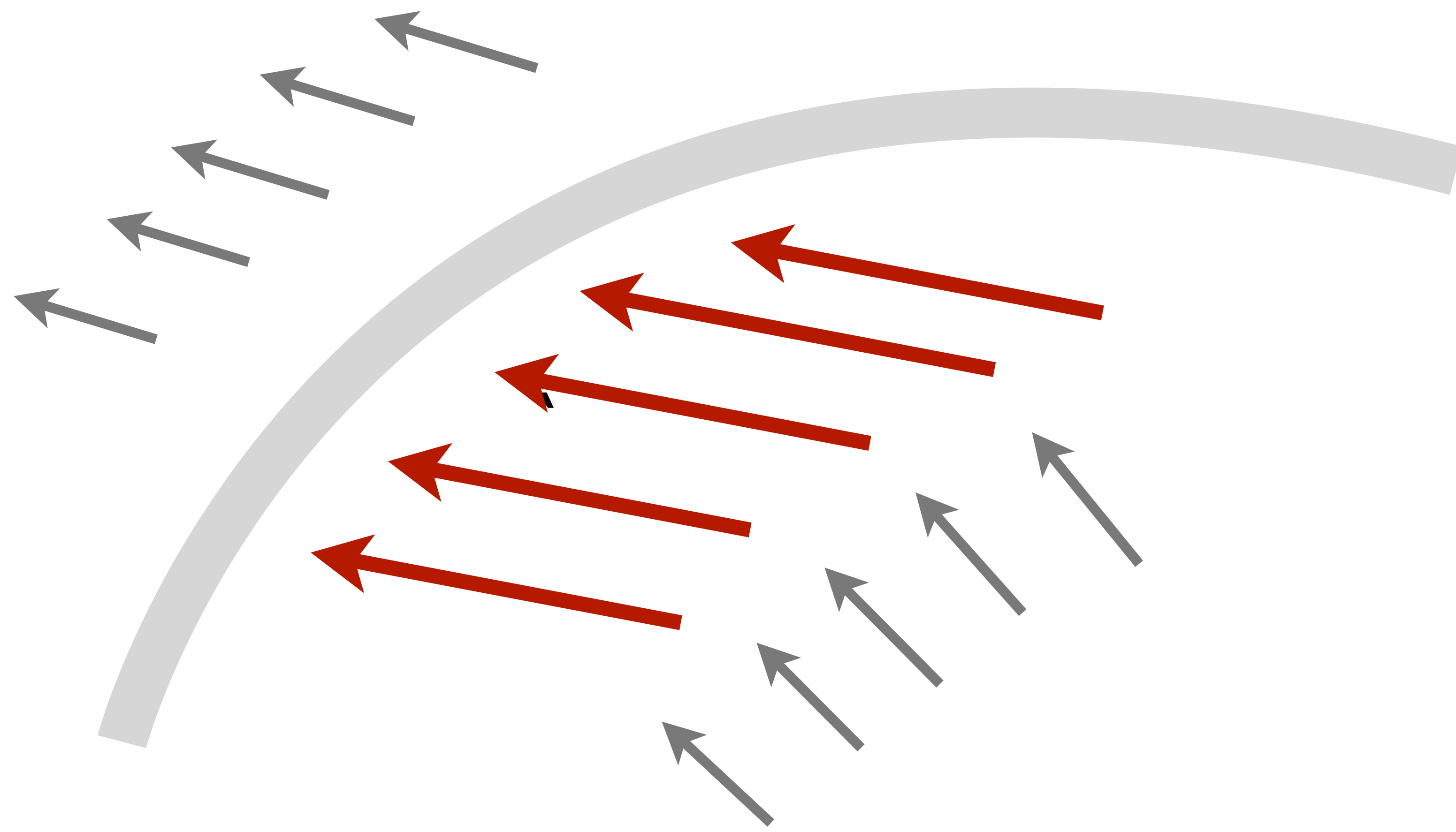

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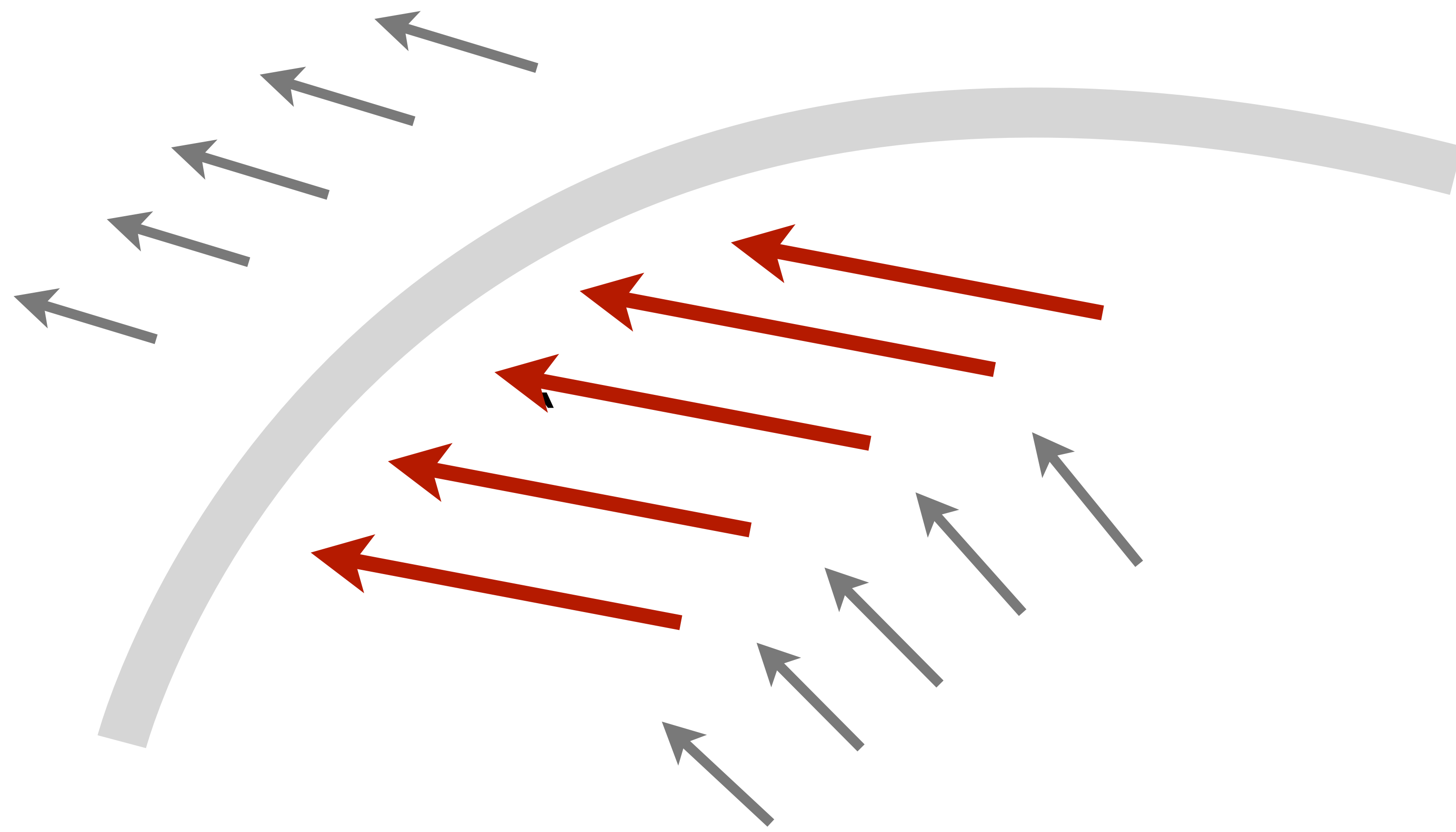

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  reduced pressure
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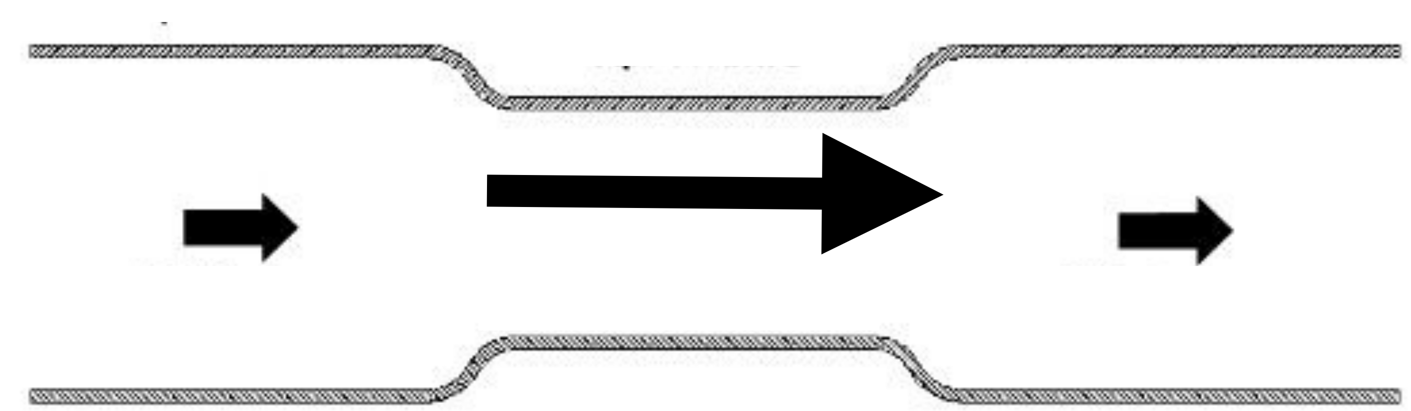

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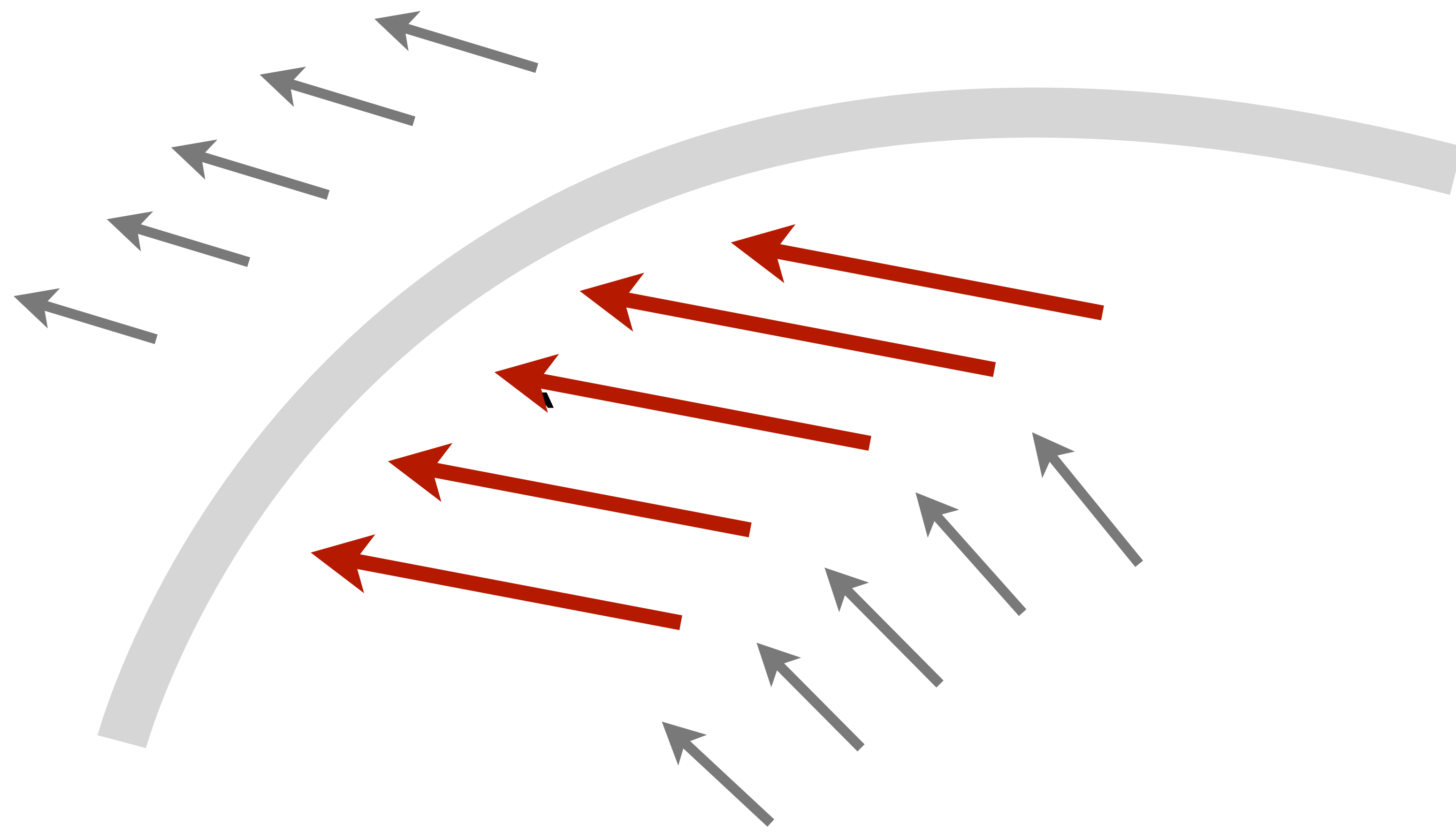

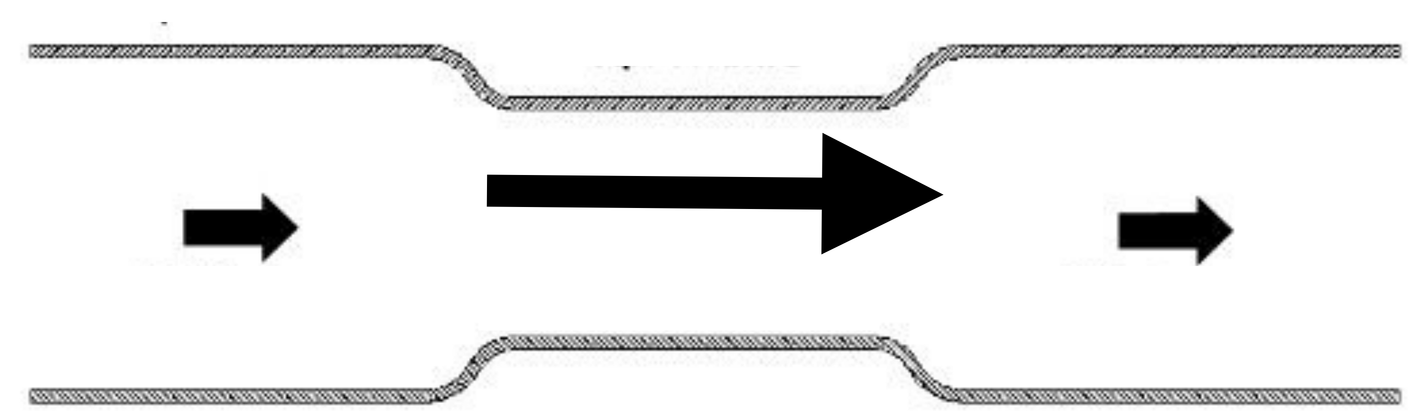

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  (bigger before collapse)
- fewer collapse-unstable clouds
- **lower star formation, longer τ_{dep}**

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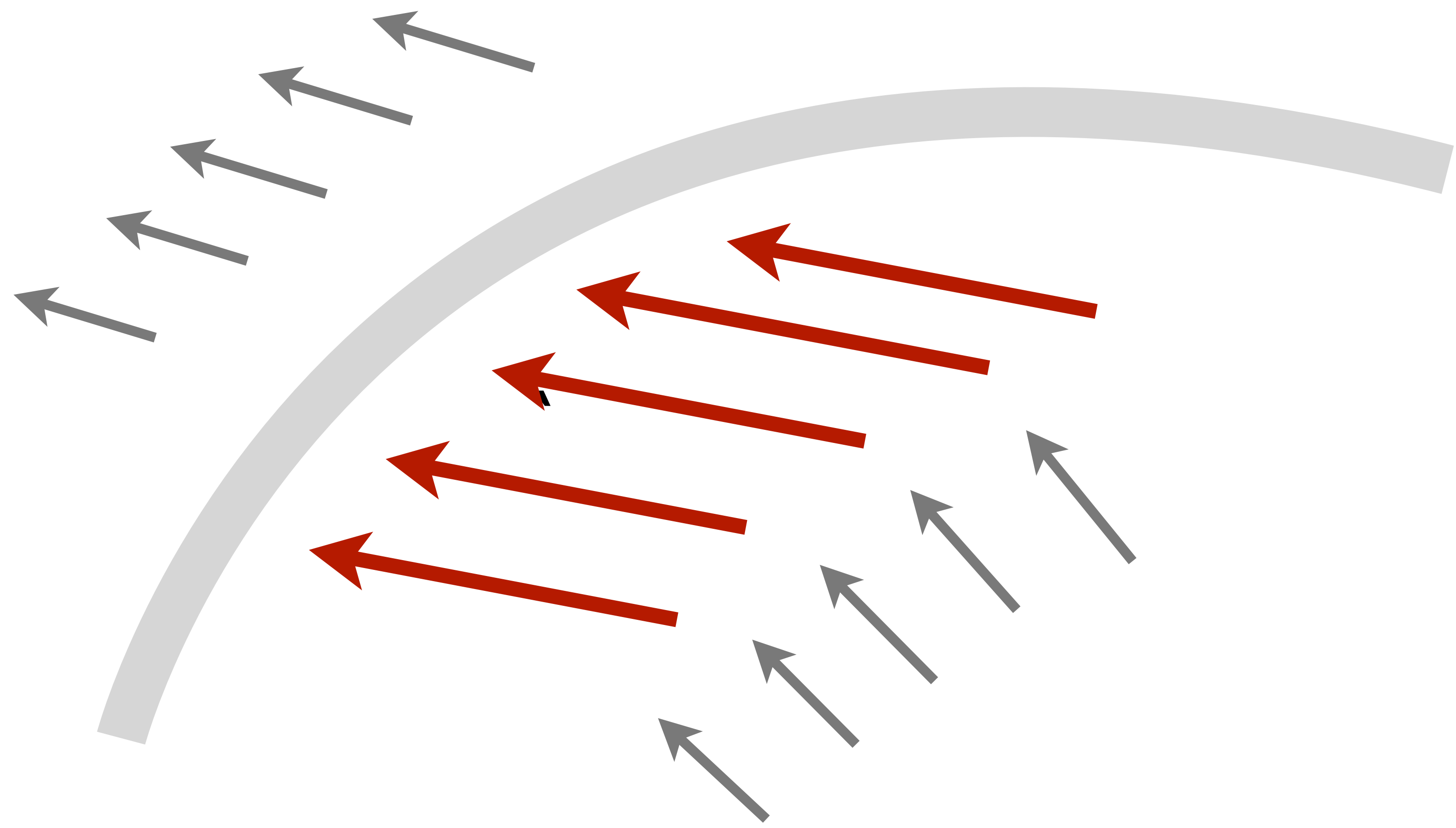

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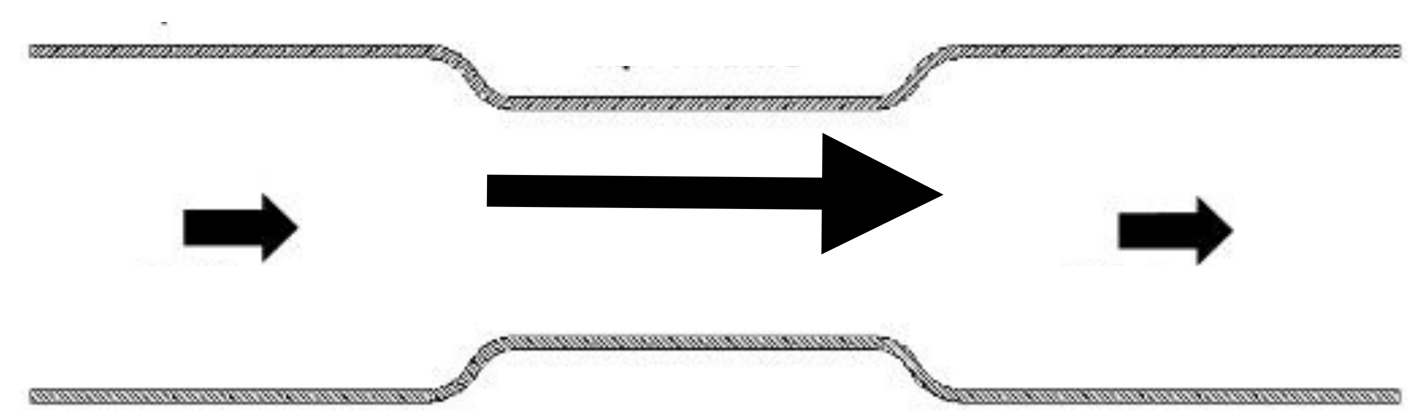
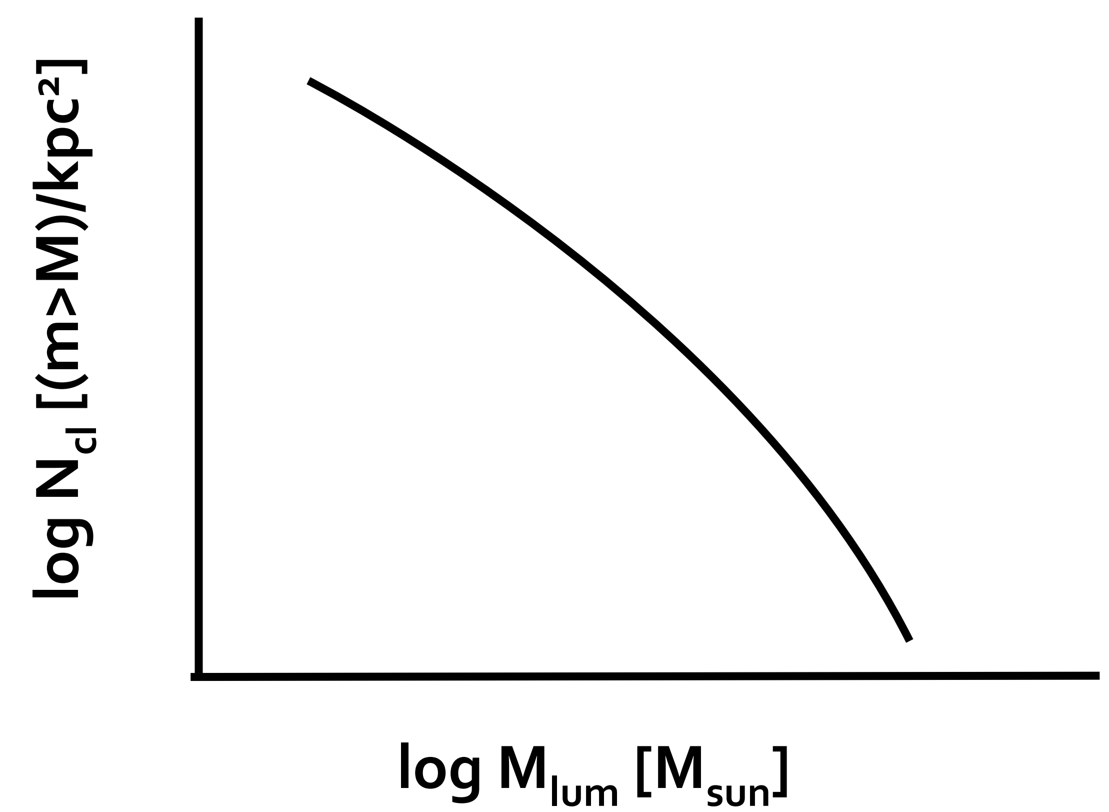


cloud mass spectrum



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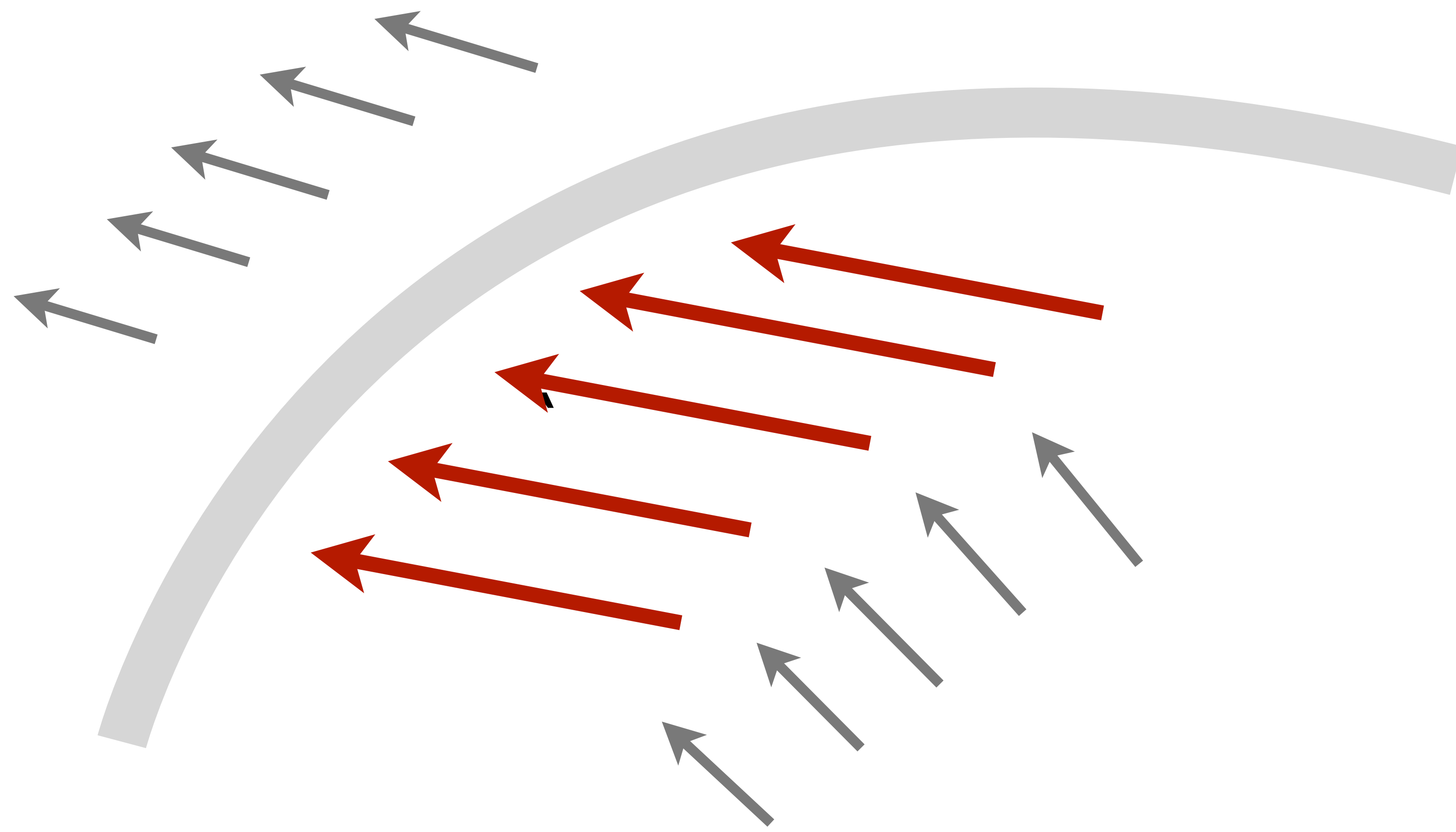

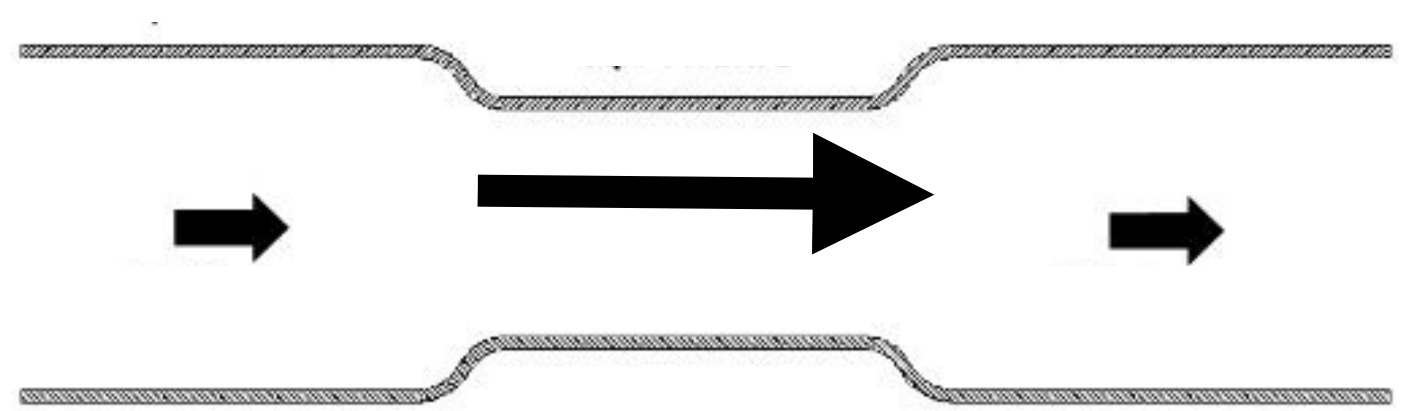

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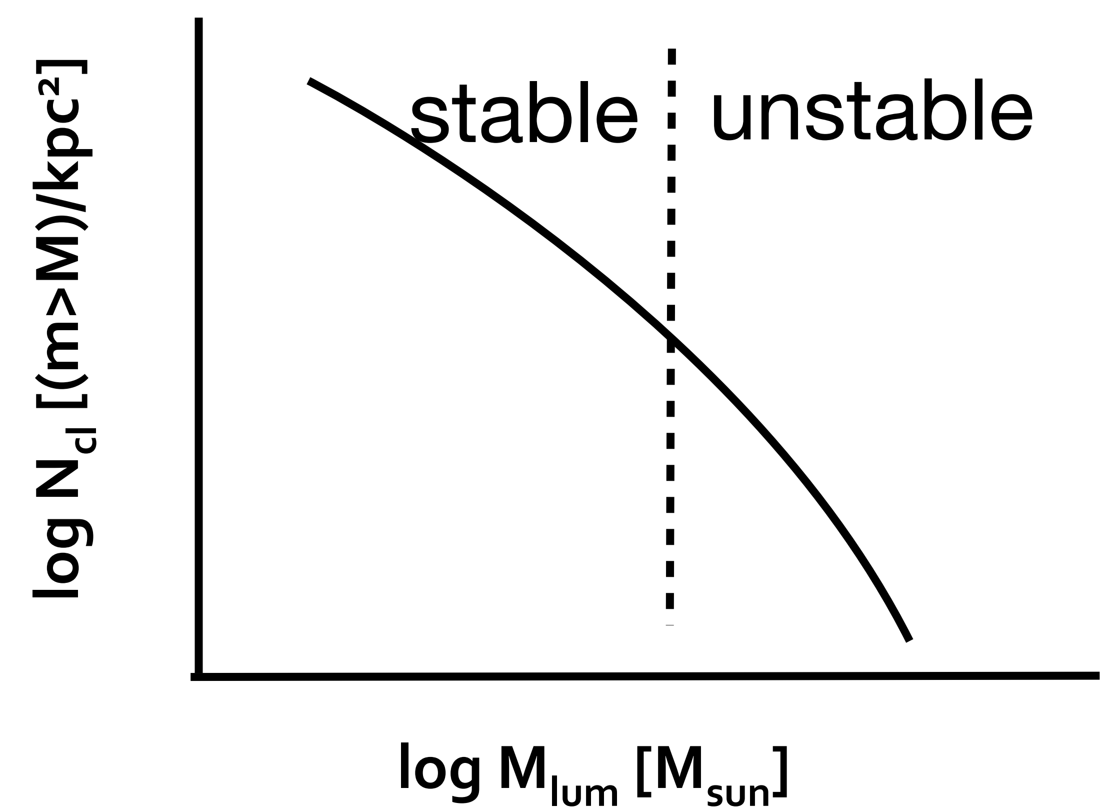

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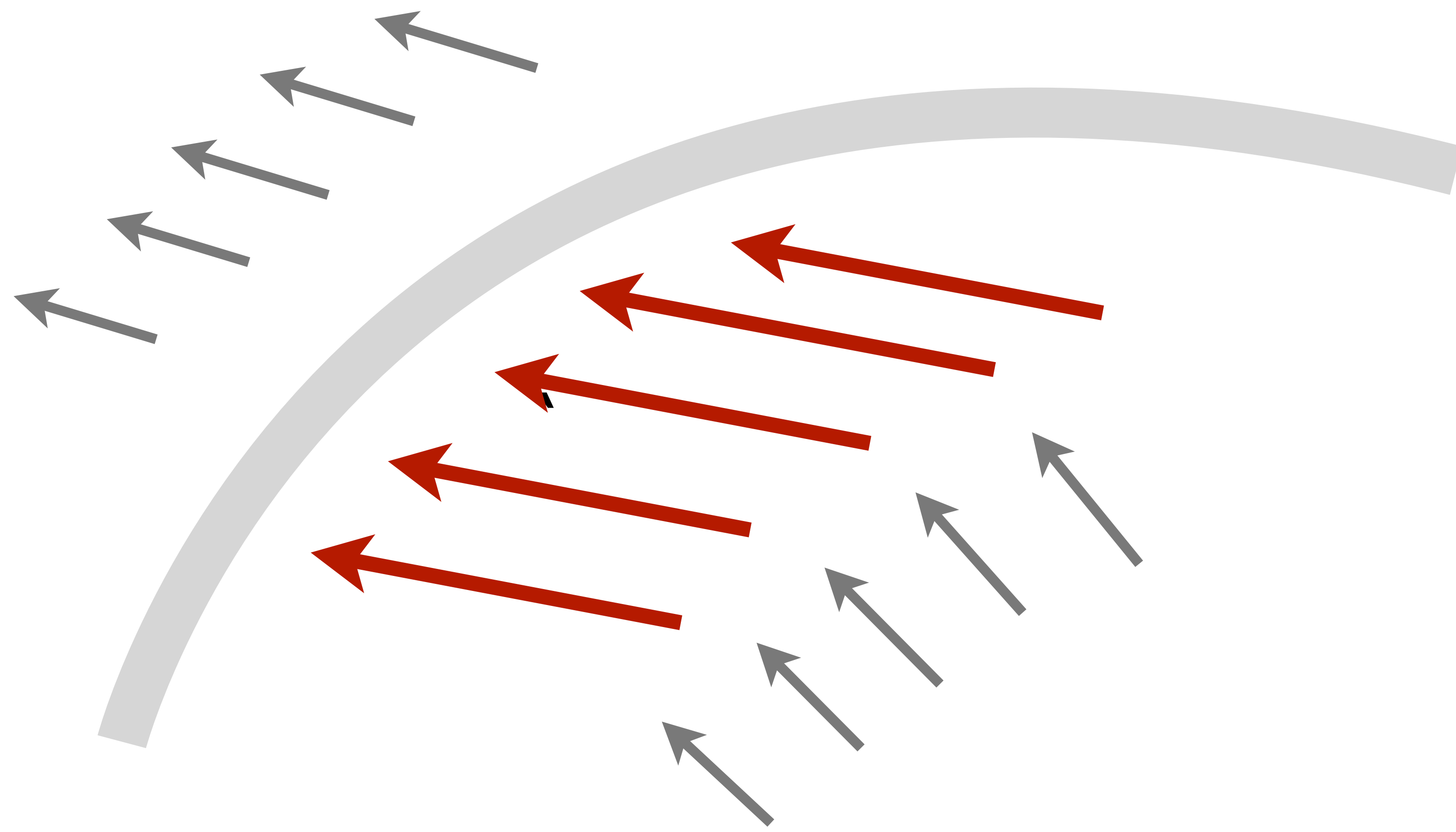

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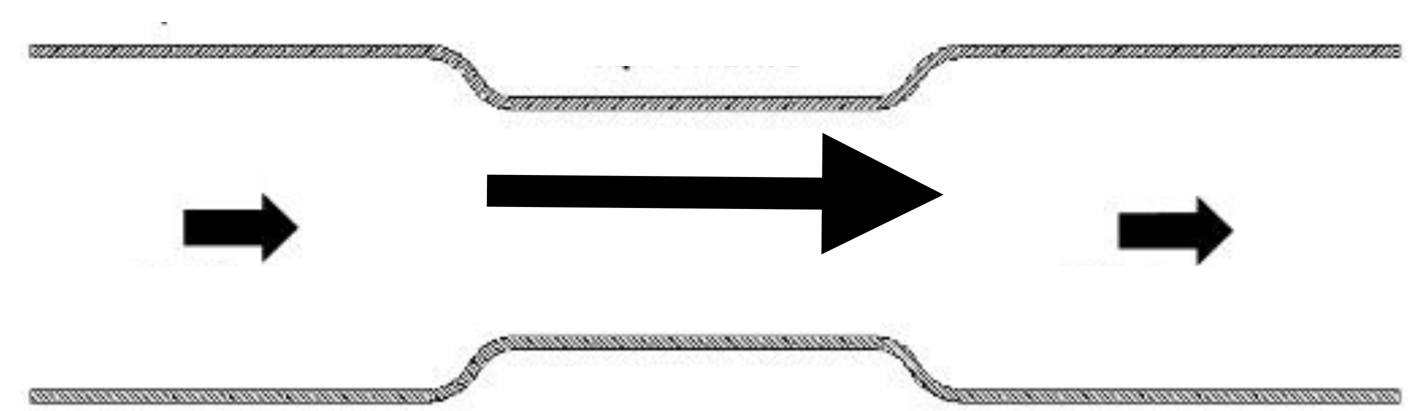

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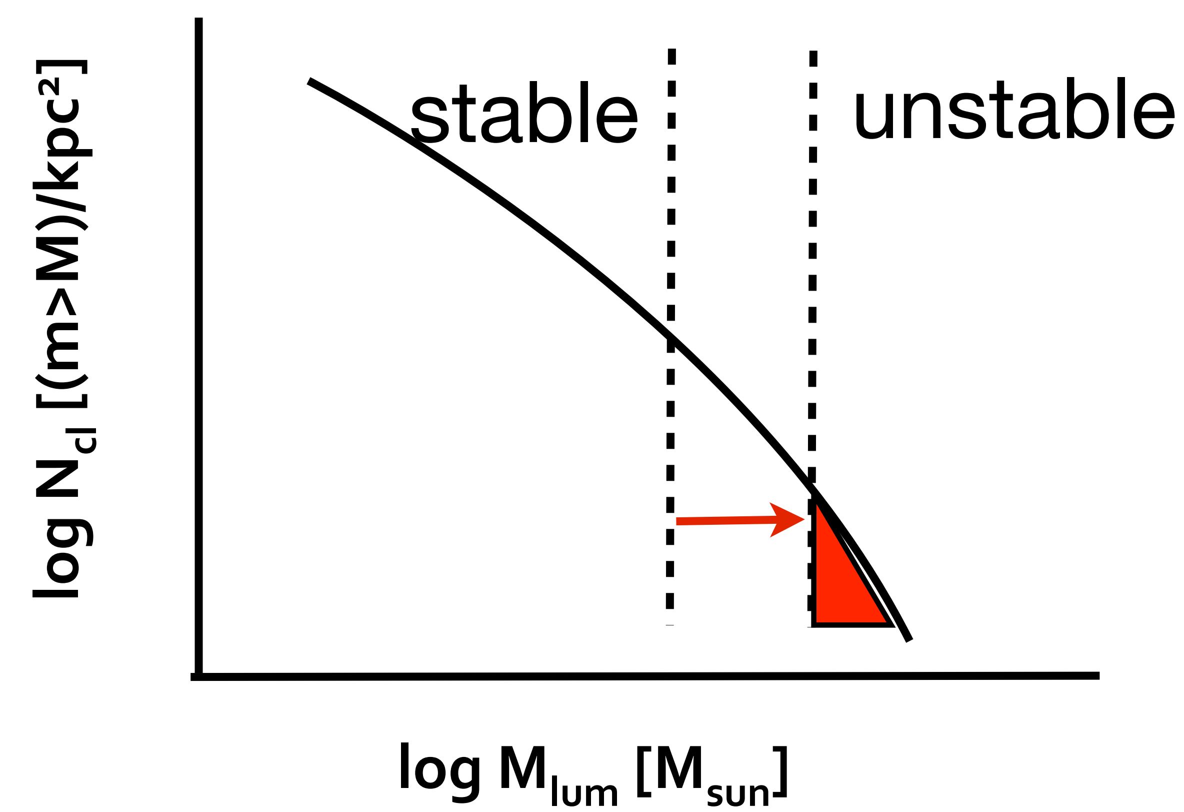
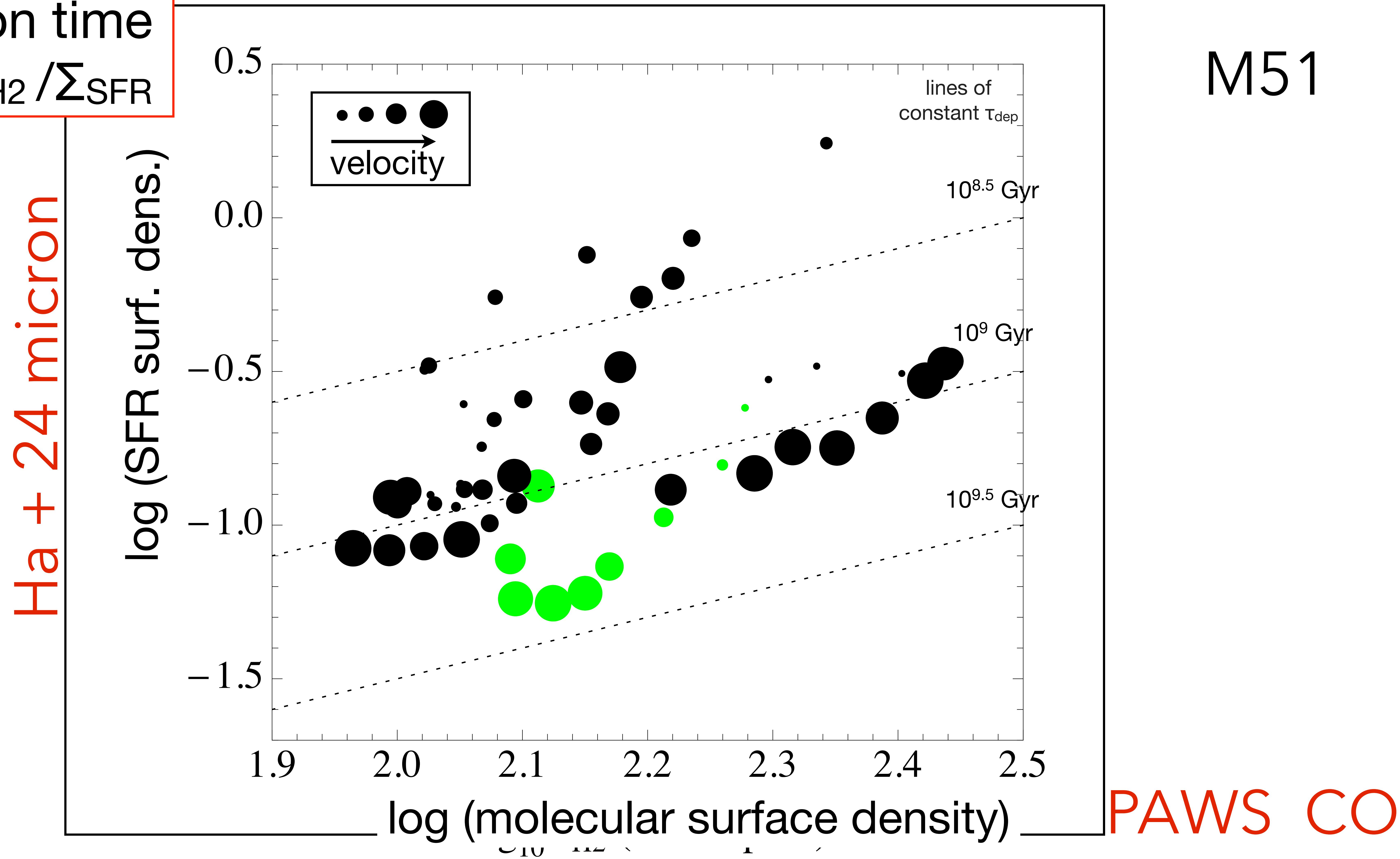


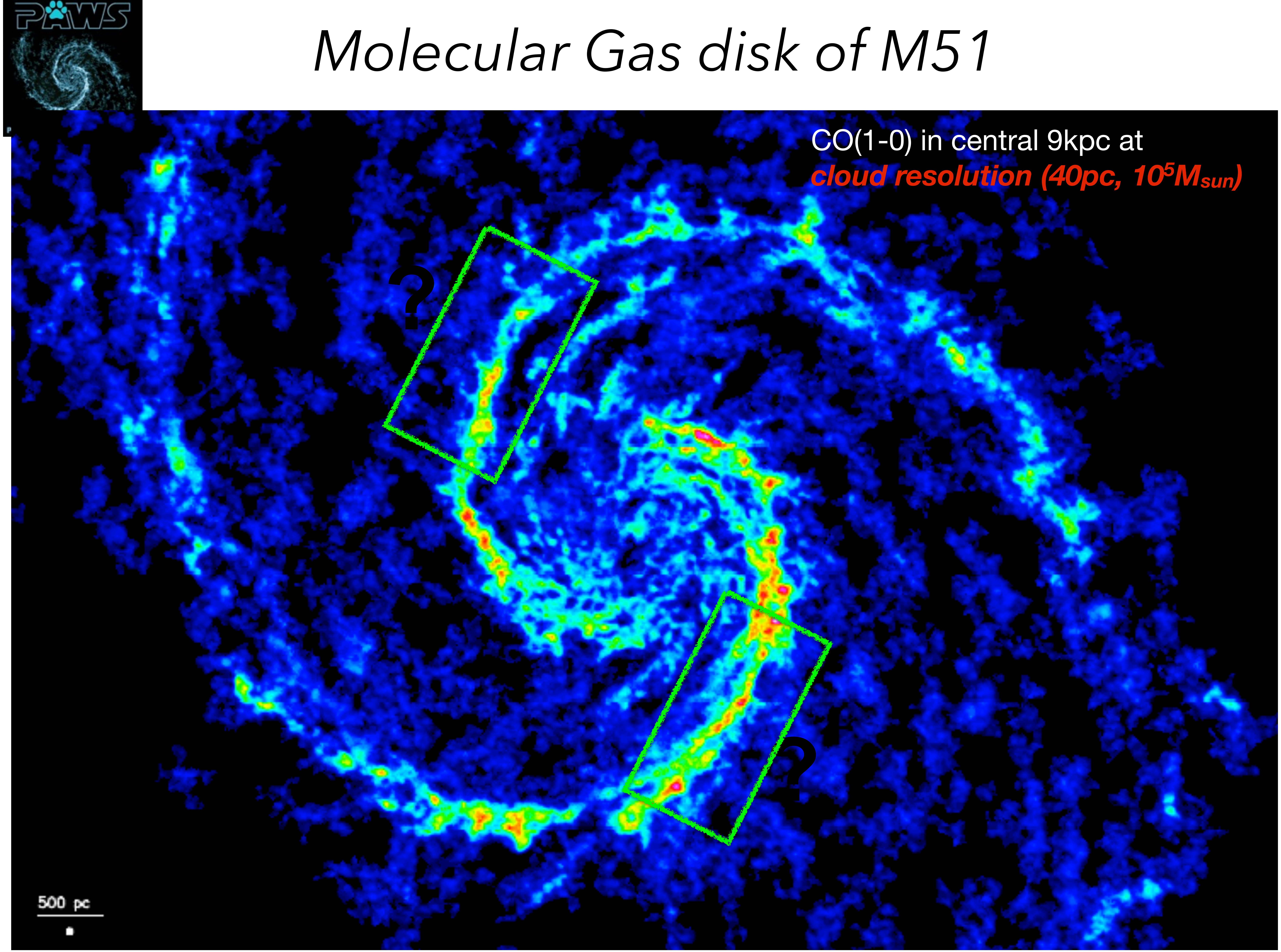
depletion time variation due to dynamics

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

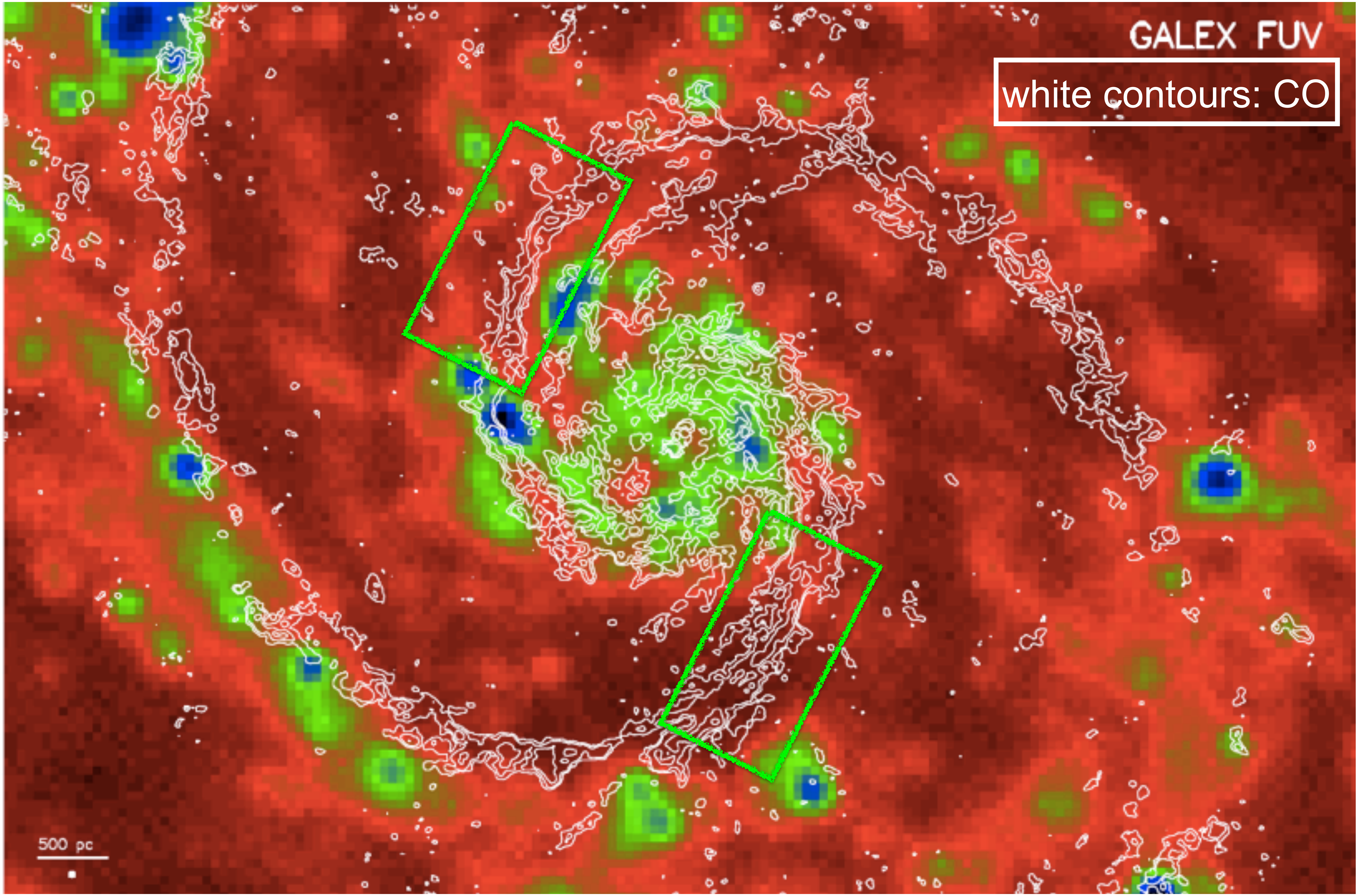
M51



Molecular Gas disk of M51



Spatial Relation b/n Gas and Star Formation



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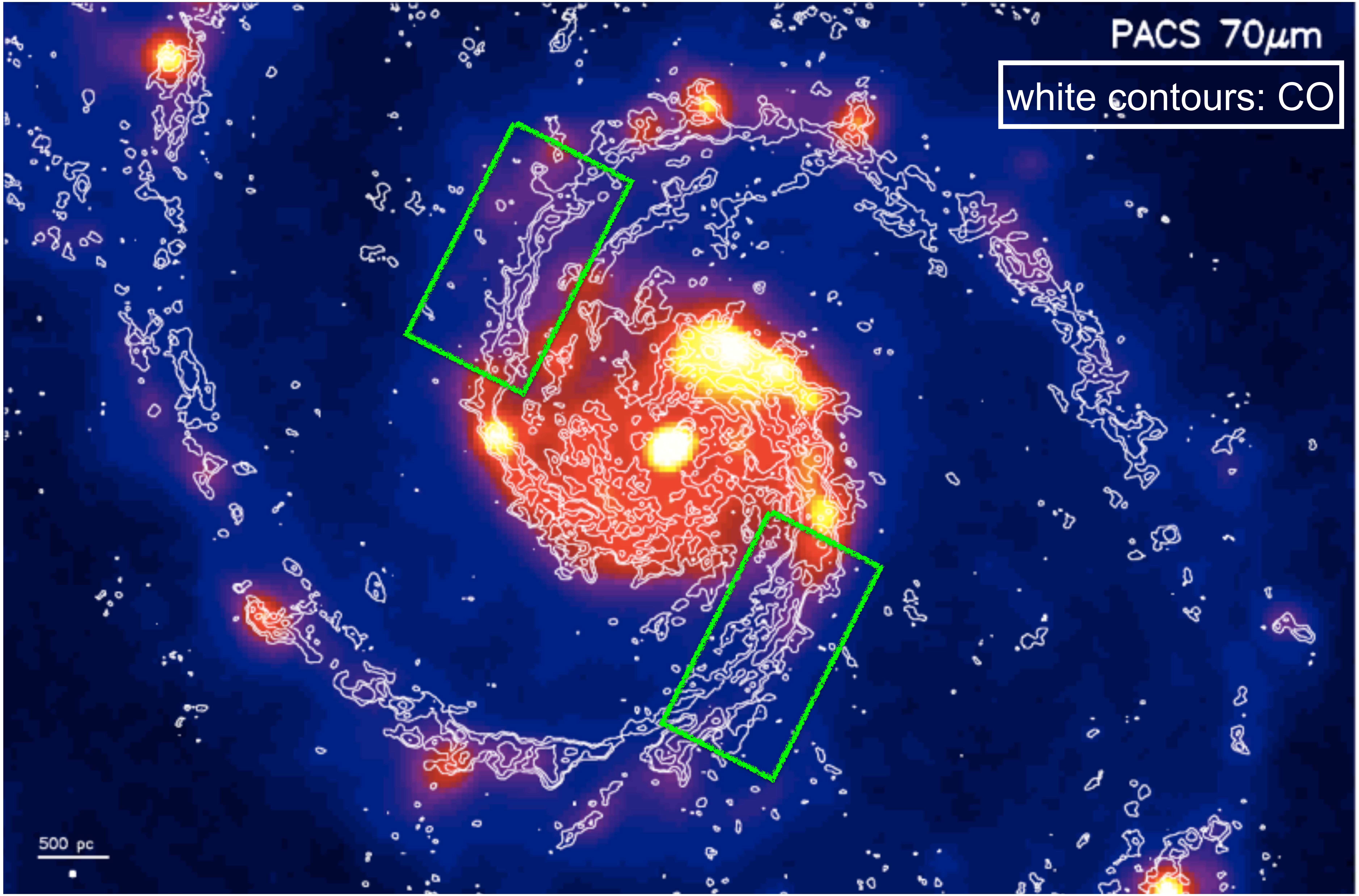

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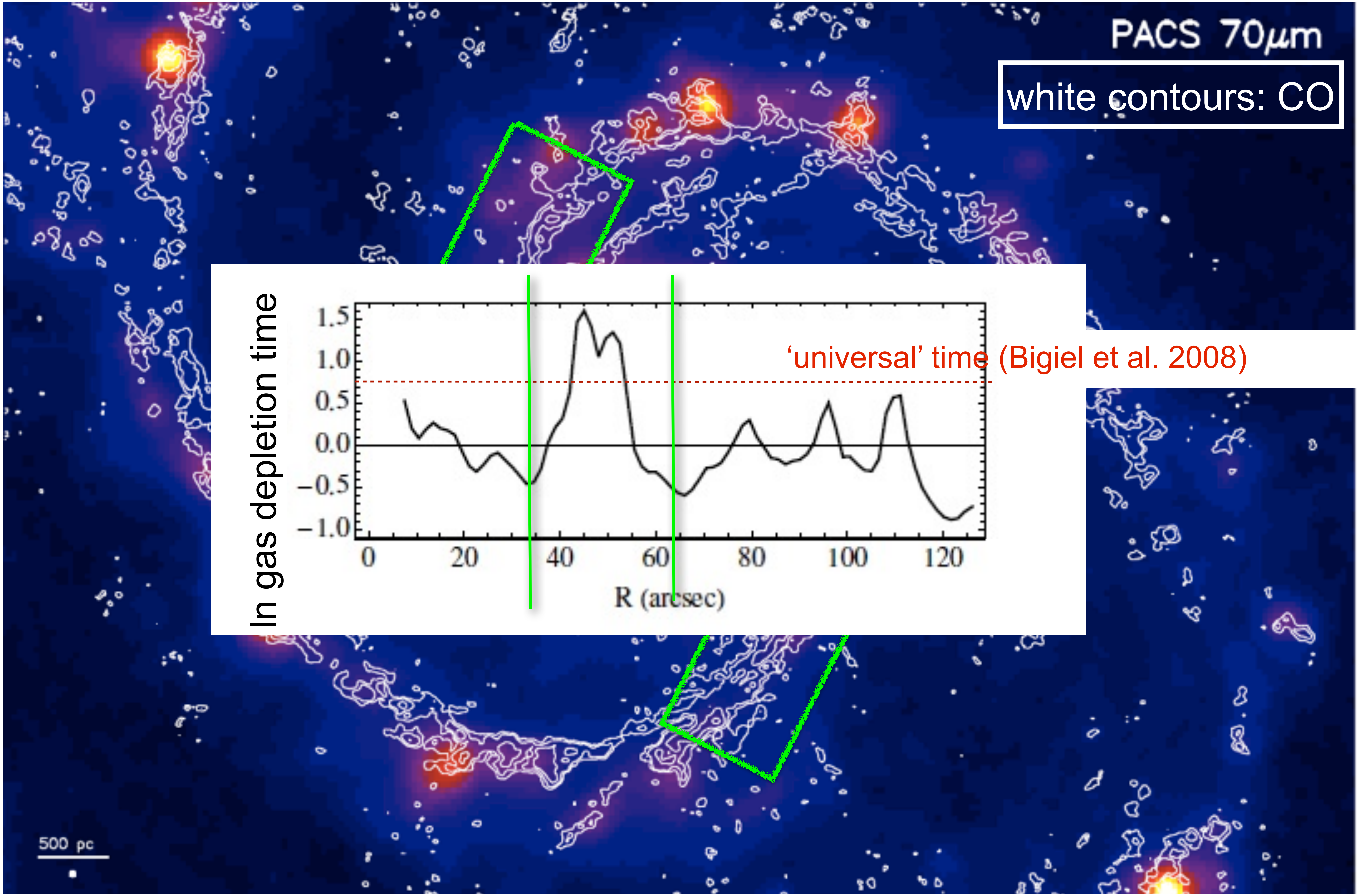

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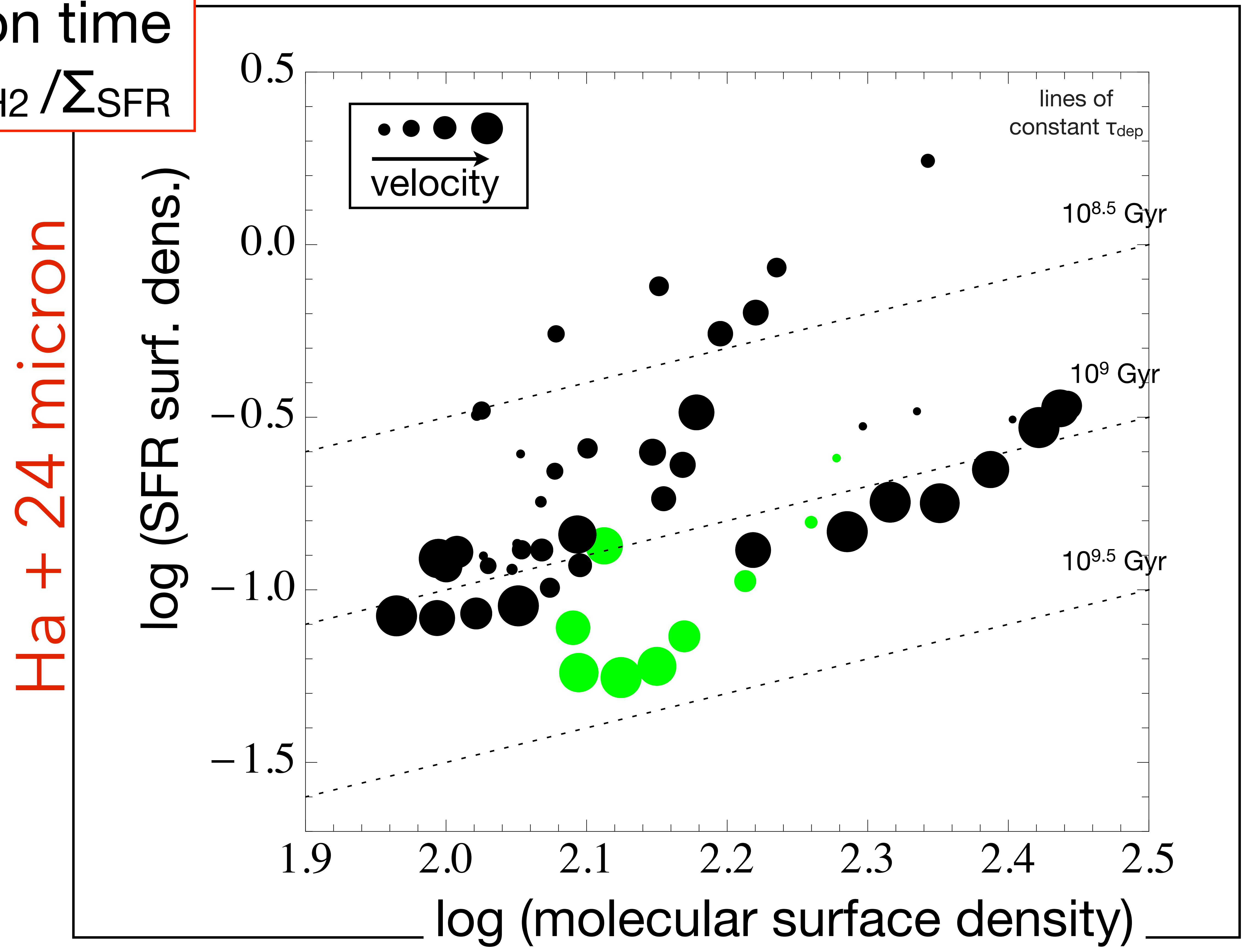

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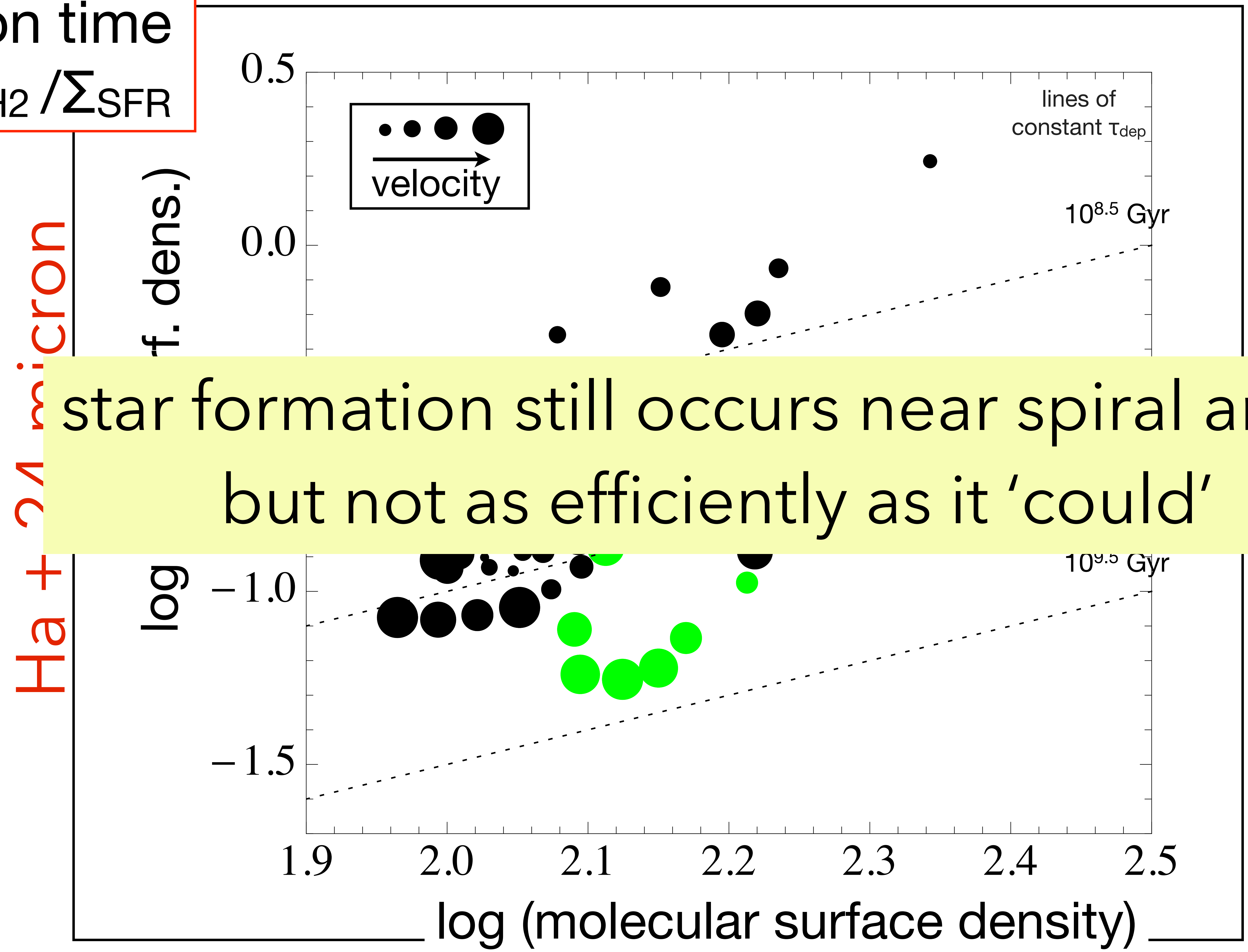


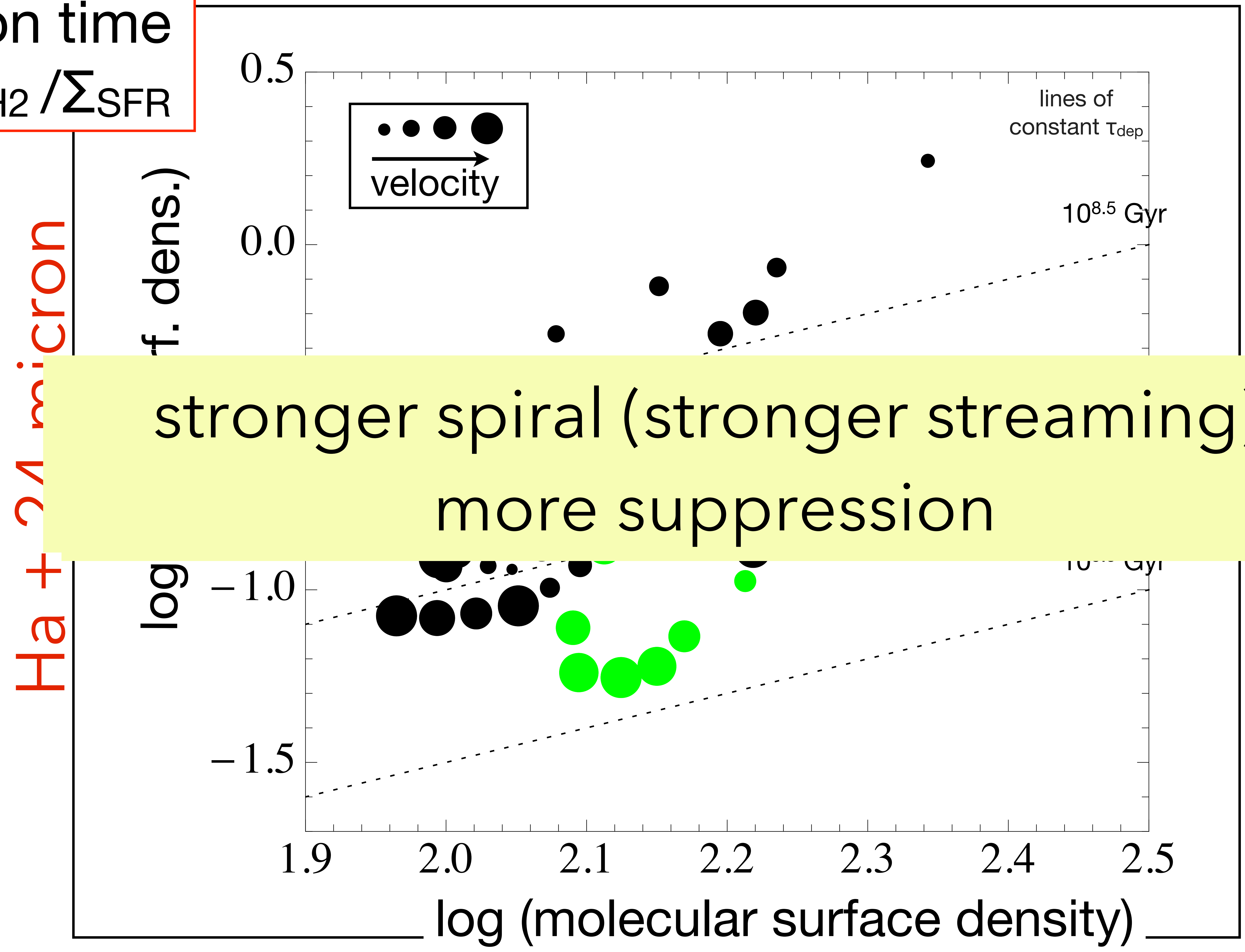
PAWS CO

star formation still occurs near spiral arms,
but not as efficiently as it 'could'

depletion time variation due to dynamics

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

M51

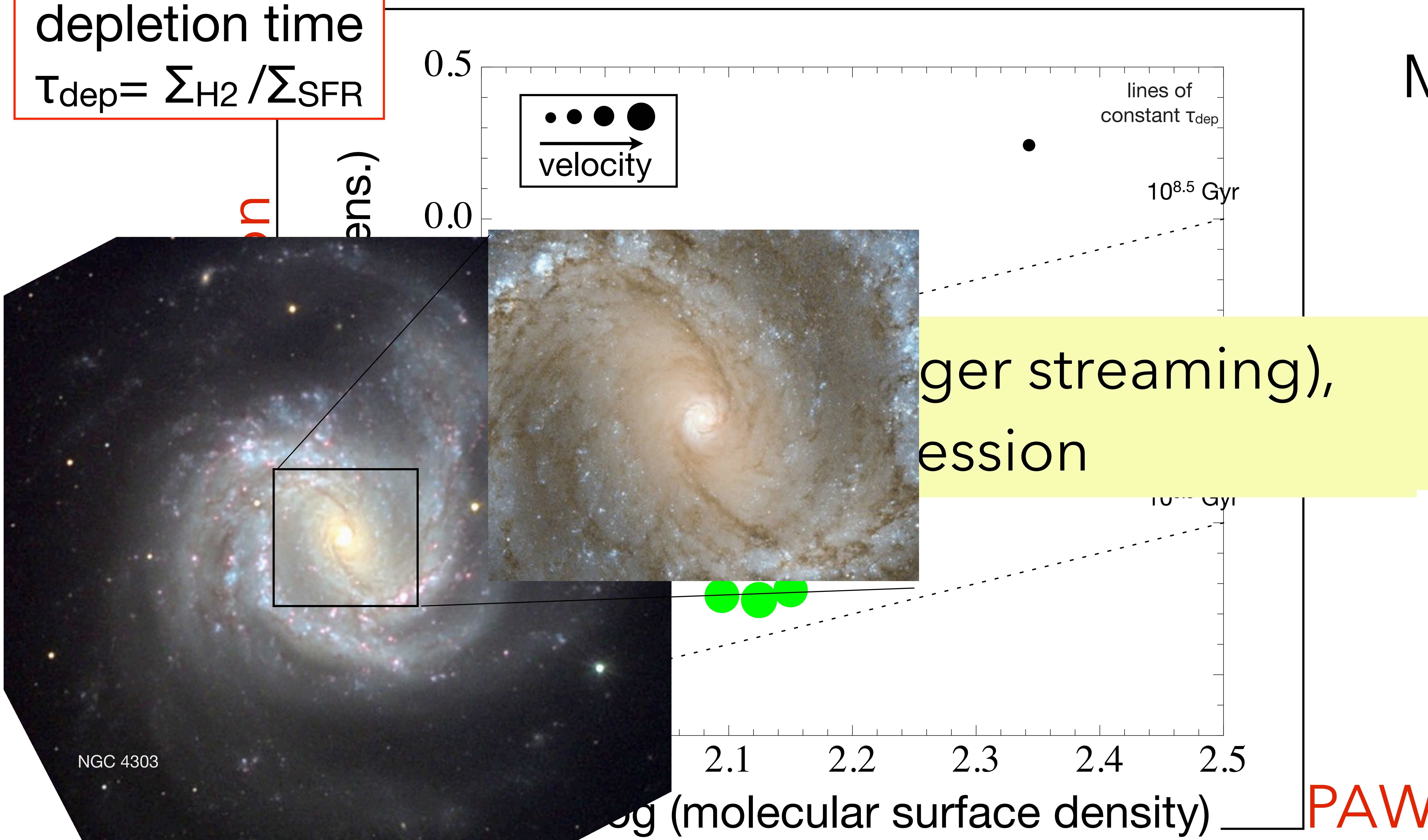


stronger spiral (stronger streaming), more suppression

depletion time variation due to dynamics

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

M51



PAWS CO

depletion time variation due to dynamics

since spirals stronger in more massive disks, τ_{dep} larger in

(well-defined dispersion relation)

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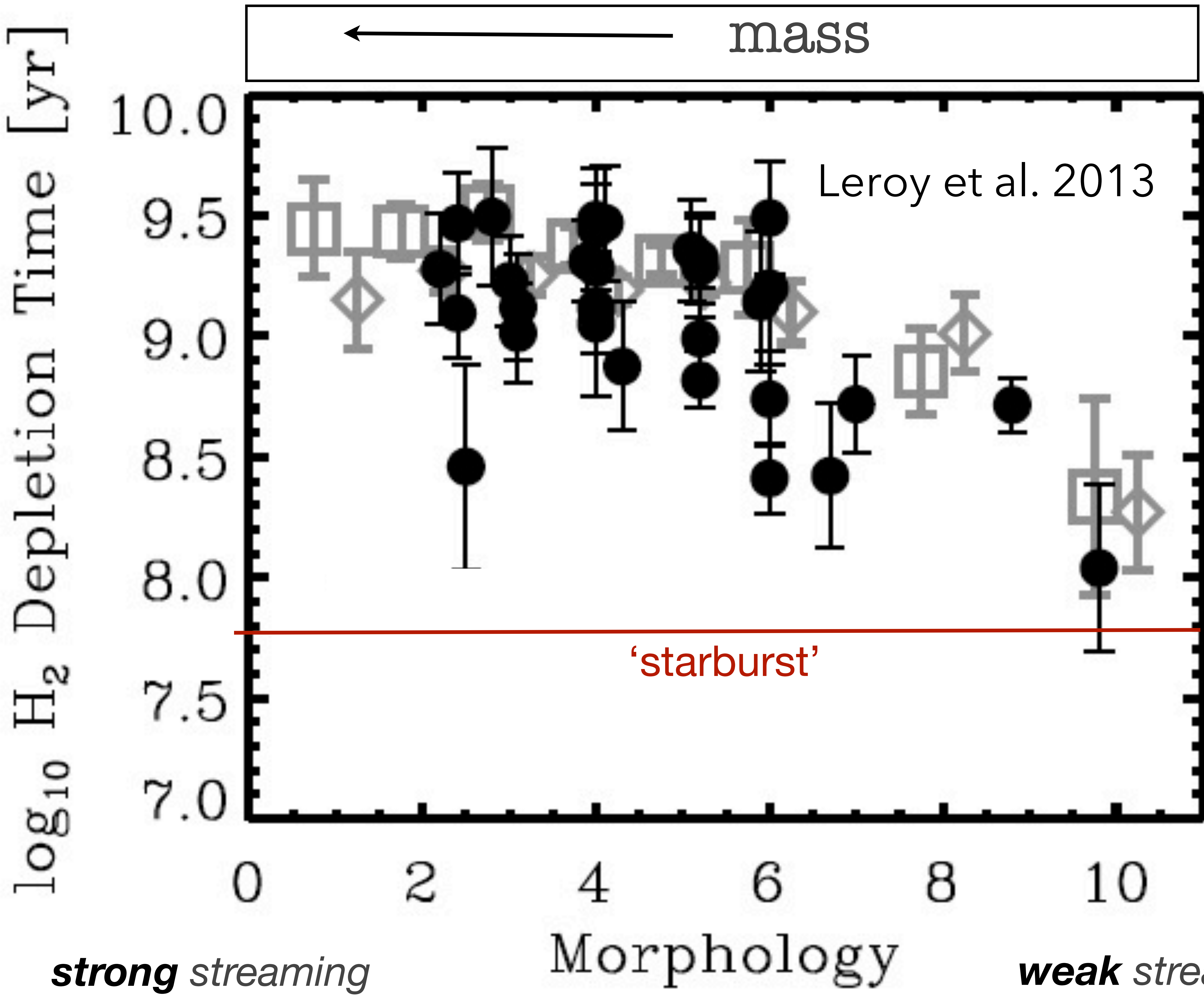
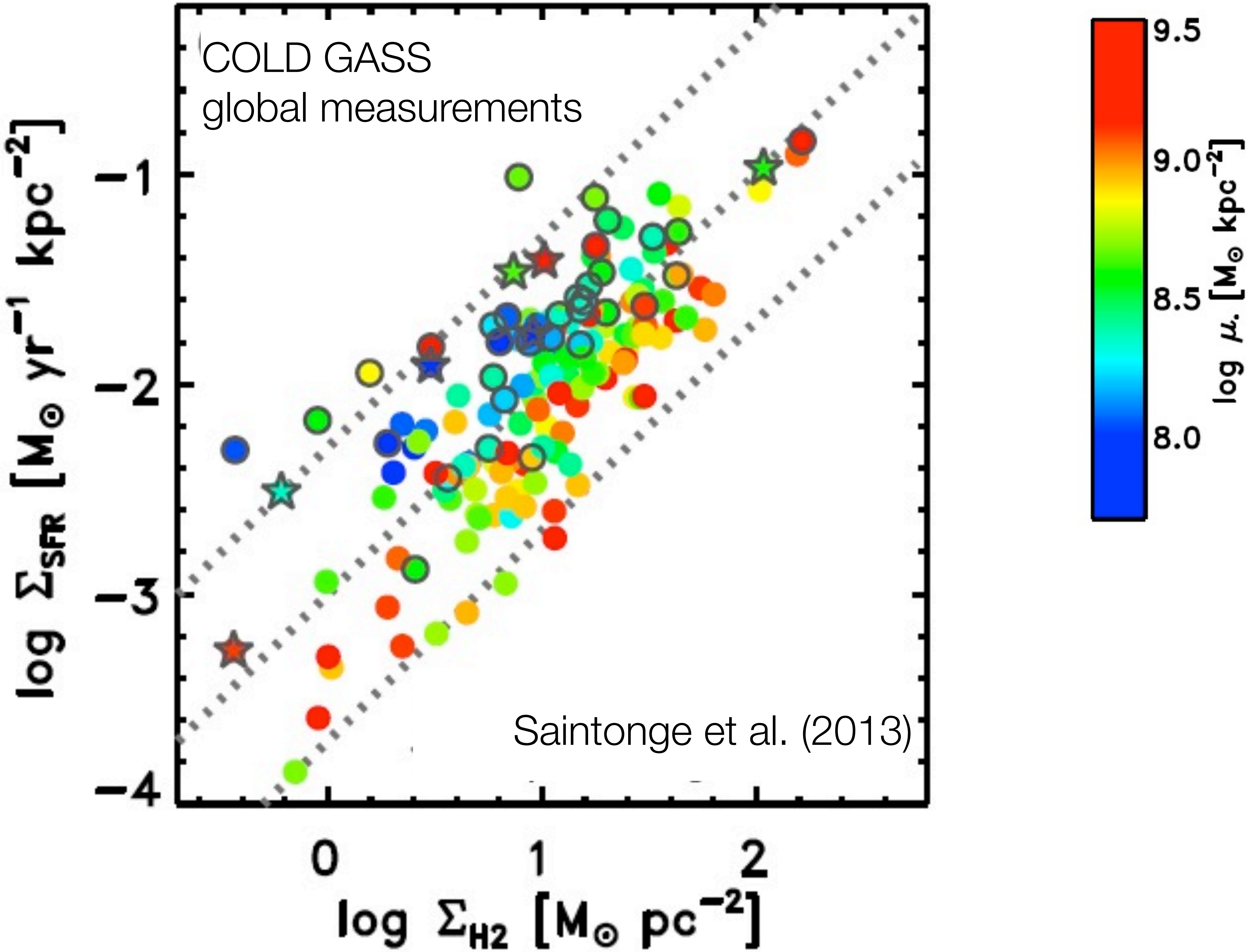


strong *streaming* ***weak*** *streaming*

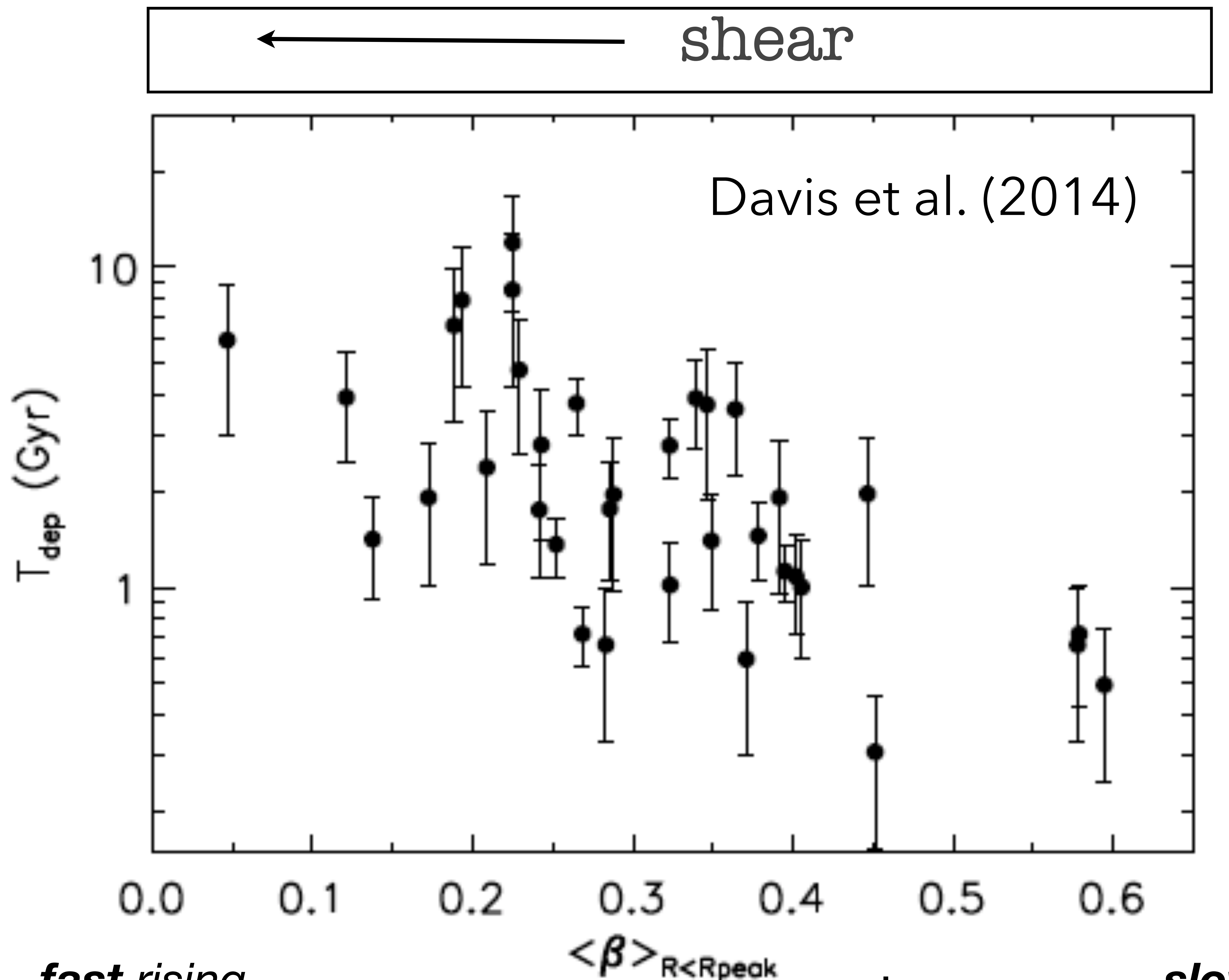

COLD GASS
global measurements
Saintonge et al. (2013)
log Σ_{SFR} [$M_\odot$ yr^{-1} kpc^{-2}]
log Σ_{H2} [$M_\odot$ pc^{-2}]
log μ_* [$M_\odot$ kpc^{-2}]
−1
−2
−3
−4
0
1
2
9.5
9.0
8.5
8.0

depletion time variation due to dynamics

in massive
Early-type
galaxies

depletion time variation due to dynamics

in massive Early-type galaxies



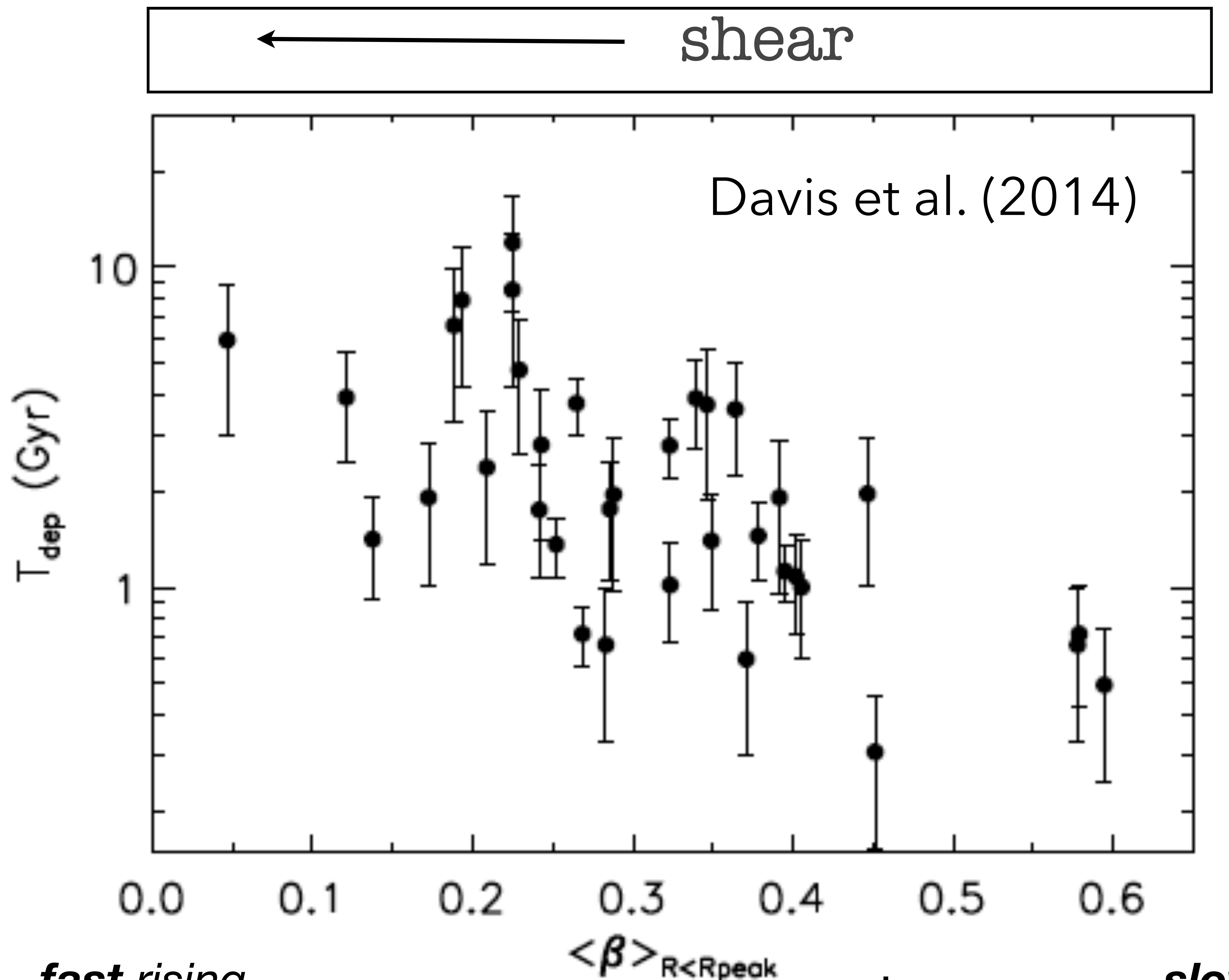
fast *rising (flat)*

= rotation curve shape

slow *rising (solid-body=1)*

depletion time variation due to dynamics

in massive Early-type galaxies



(but β=0 in disks)

fast *rising (flat)* = rotation curve shape ***slow*** *rising (solid-body=1)*

Shear limits cloud lifetimes

- cloud lifetime in M51 ~ shear timescale Oort A^{-1} (Meidt & PAWS in prep.)
  - also found in numerical simulations (Dobbs & Pringle 2013)

$$A^{-1} = \frac{t_{orb}}{\pi} \frac{1}{(1-\beta)}$$

in disks,
β=0 and t_{orb} very long!

in the centers,
β=0 but t_{orb} short!

- short cloud lifetimes<t_{ff}, perhaps not long enough for star formation

Take Away

- *not all cold, dense (molecular) clouds form stars.....*

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➡dynamics regulates ***organization, structure and stability*** of molecular gas

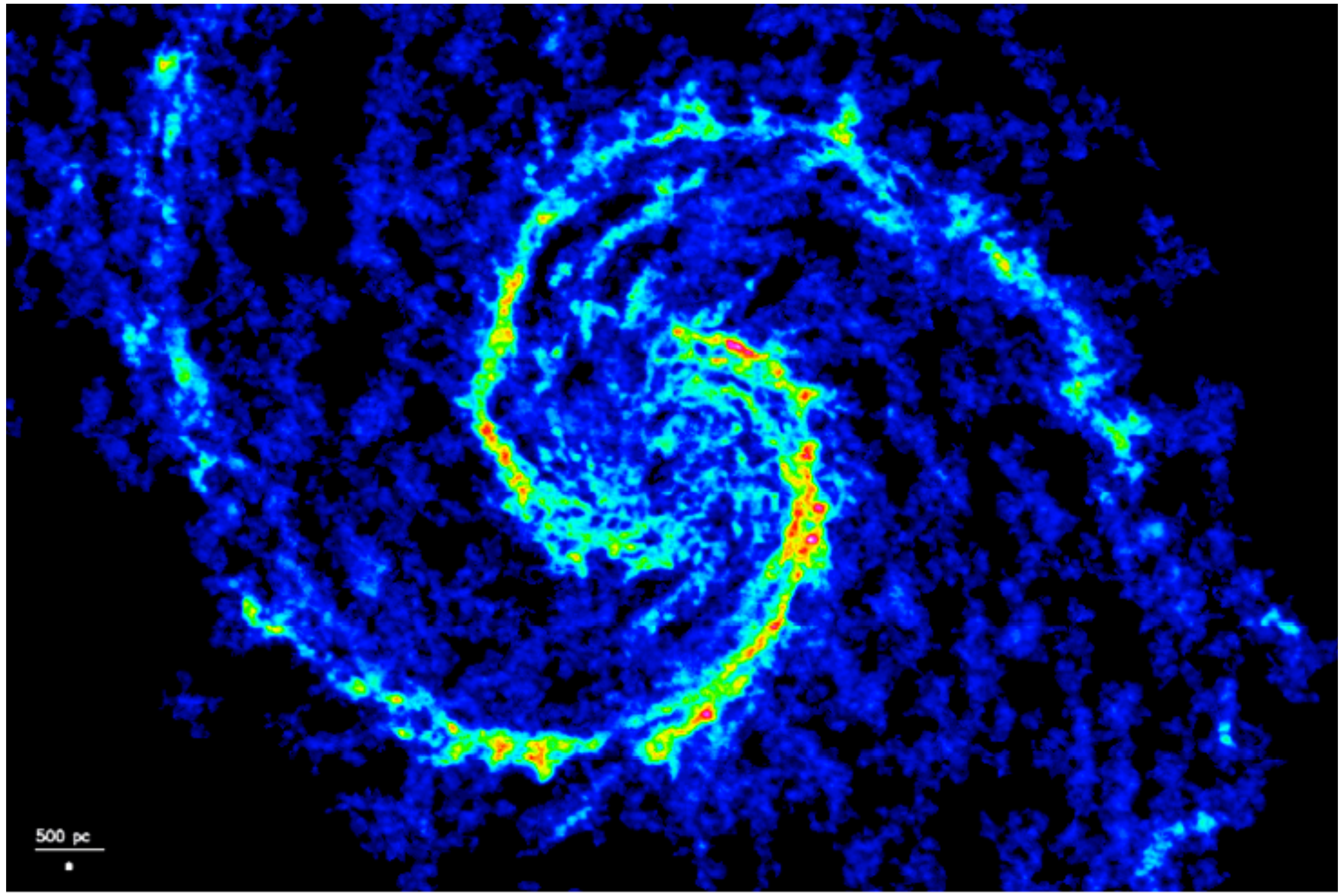
Take Away

- *not all cold, dense (molecular) clouds form stars.....*

➡dynamics regulates ***organization, structure and stability*** of molecular gas

➡same large-scale processes that ***fuel centers*** also ***suppress star formation***

short gmc lifetimes: an observational estimate with PAWS!



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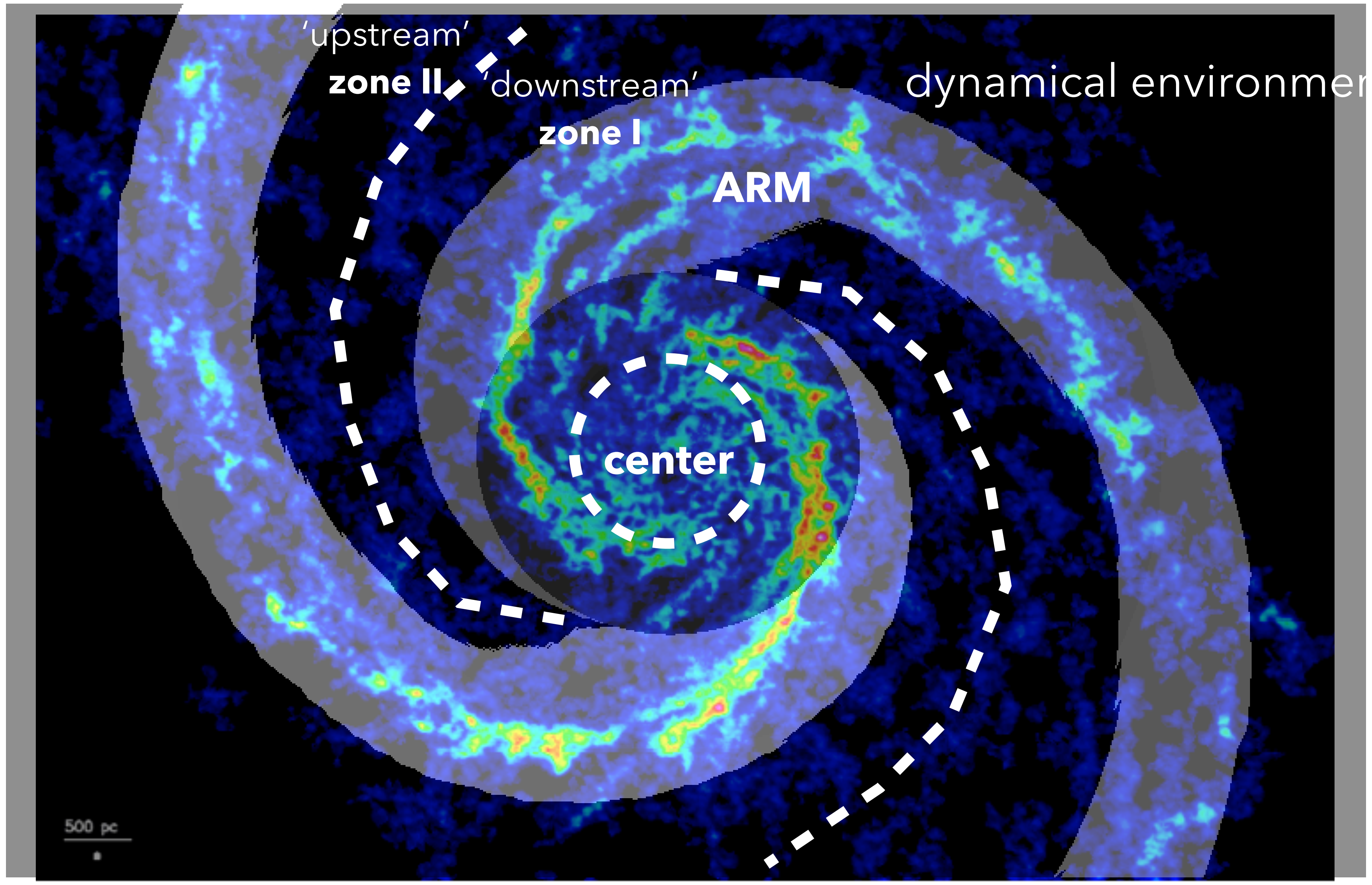

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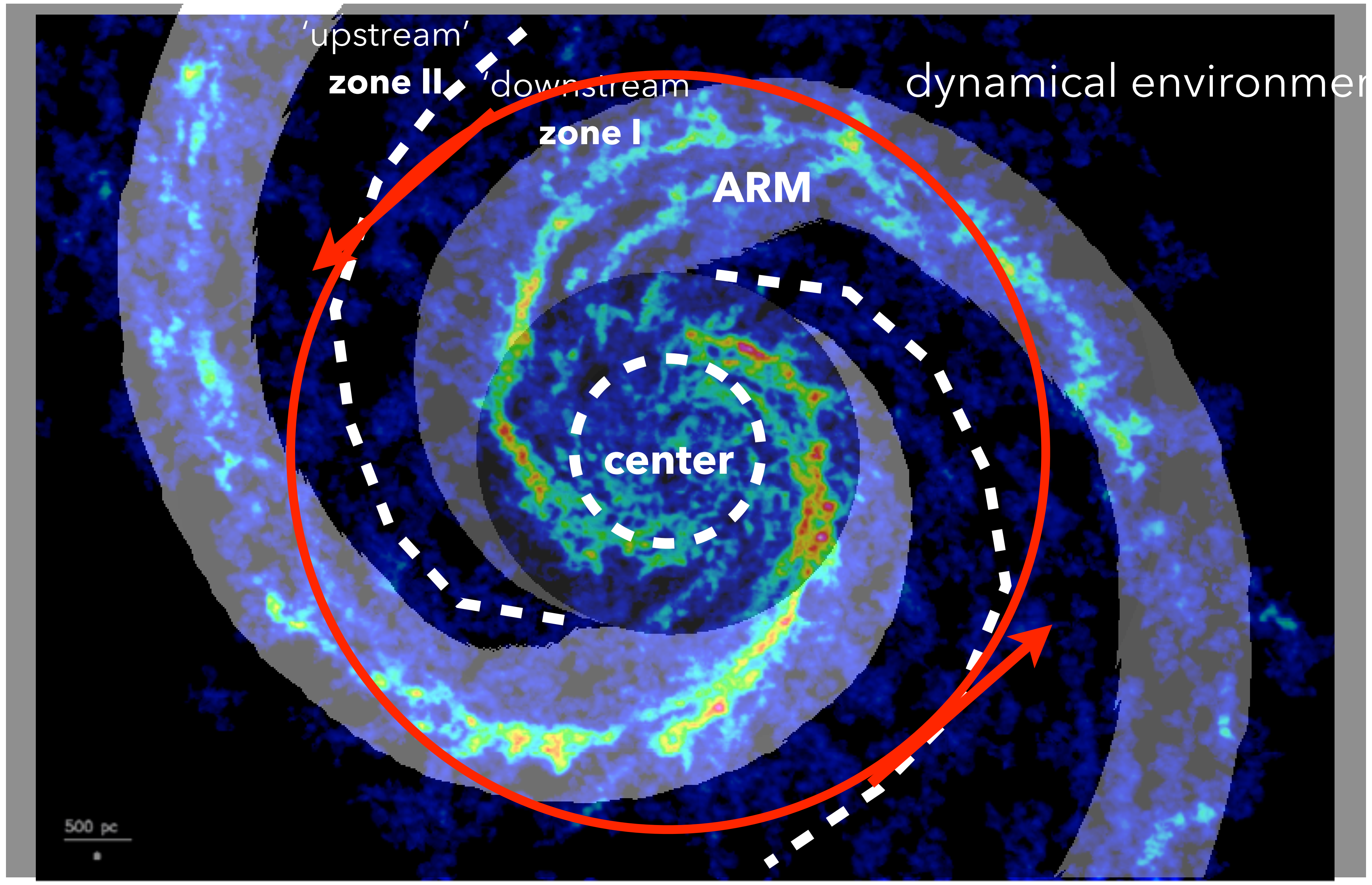

- mostly only destruction
- interarm easy to dynamically characterize
- clouds follow circular paths (very little radial excursion)

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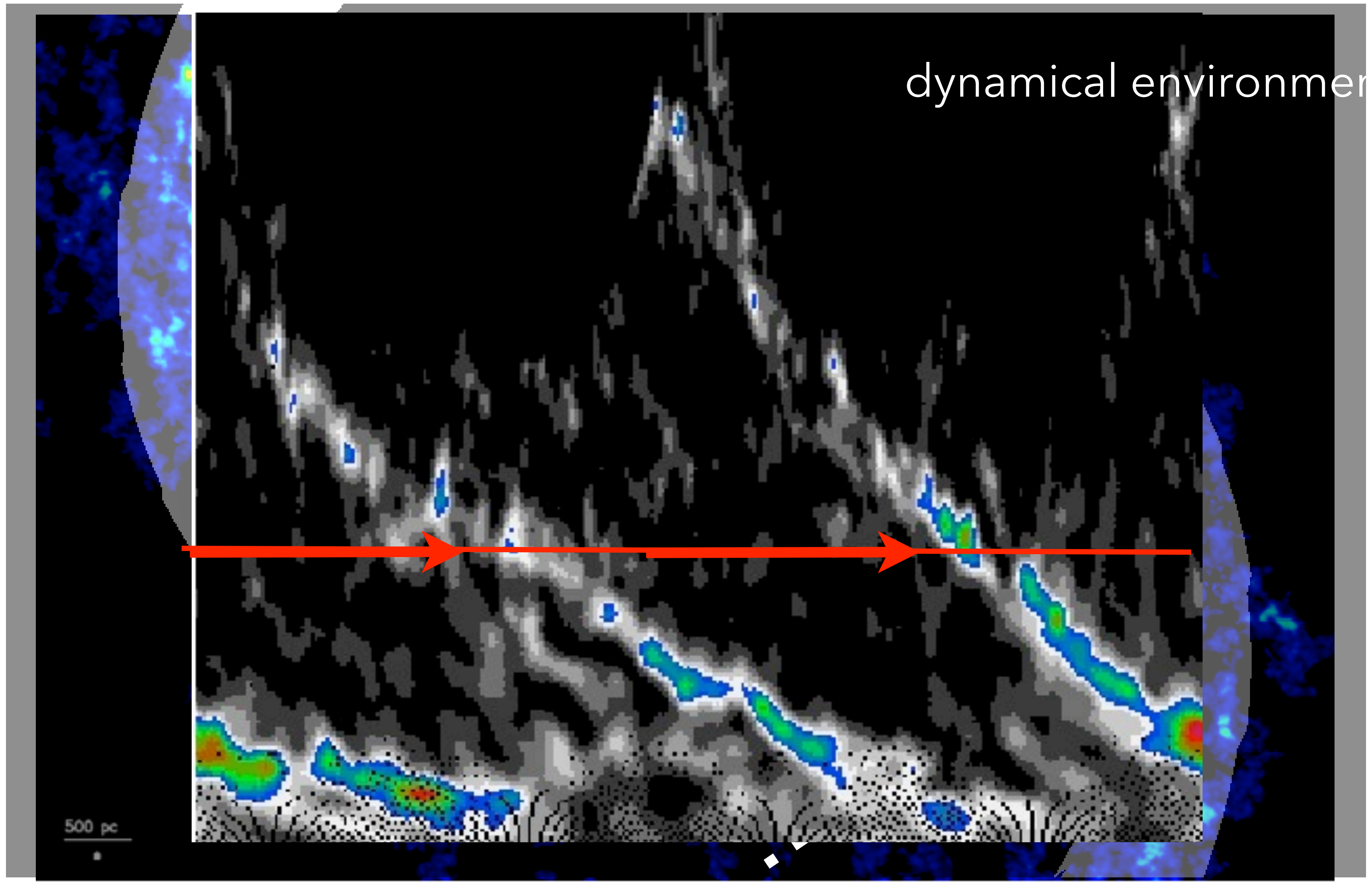

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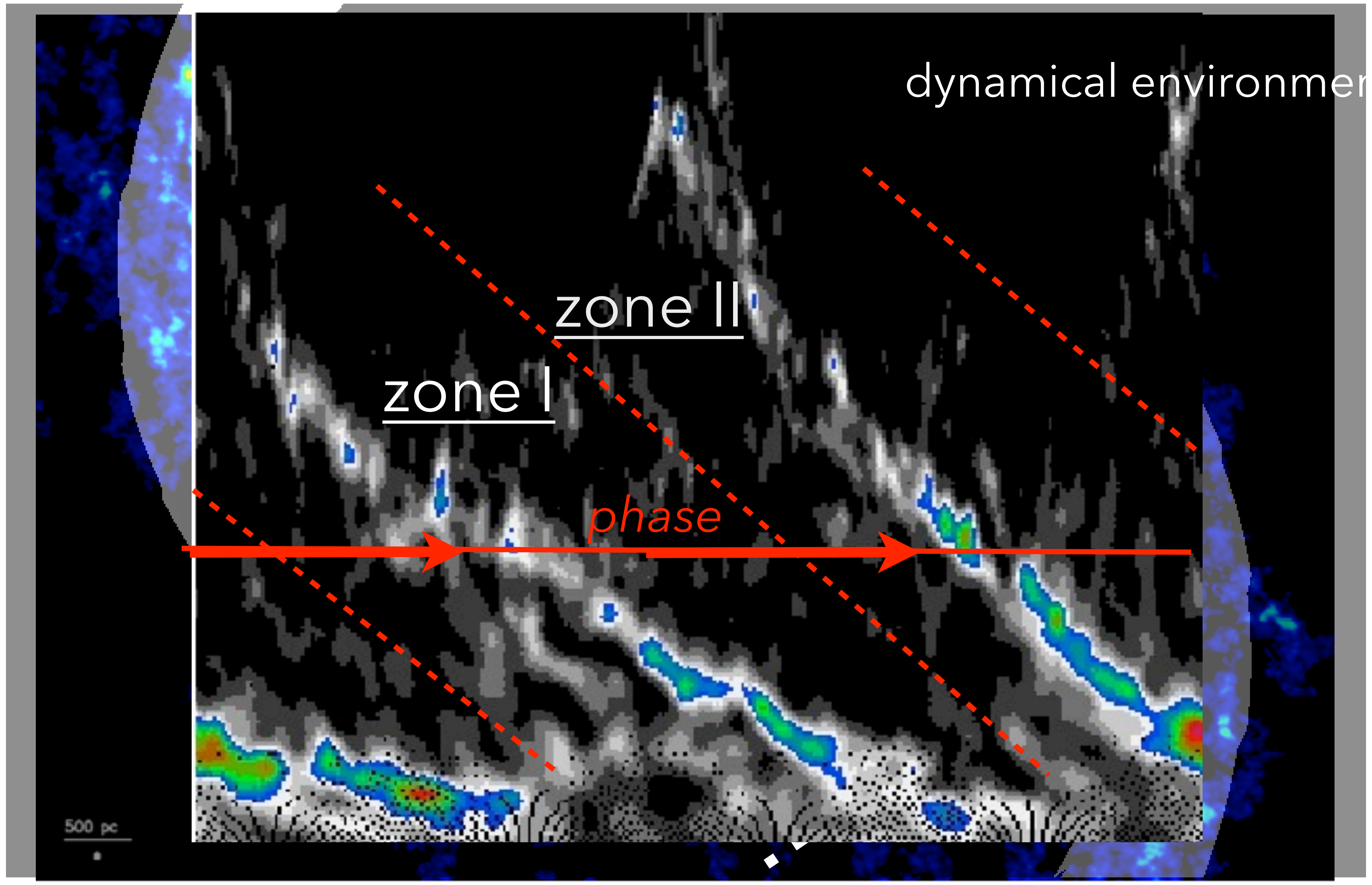

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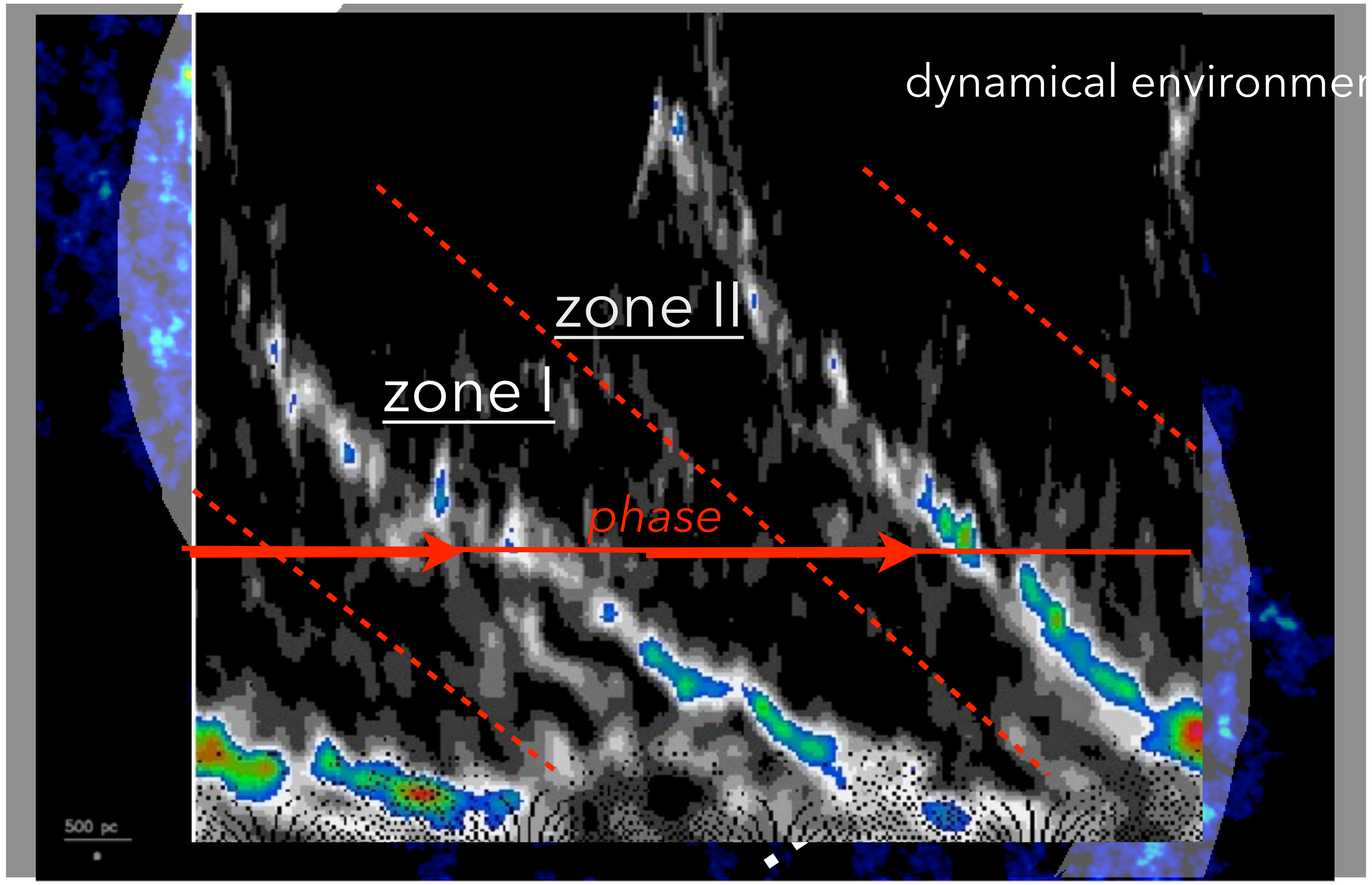

- cloud numbers decreases from zone I to zone II (Colombo et al. 2013)
- mass spectrum evolution: ***shear and star formation feedback destroy clouds, limit lifetimes***

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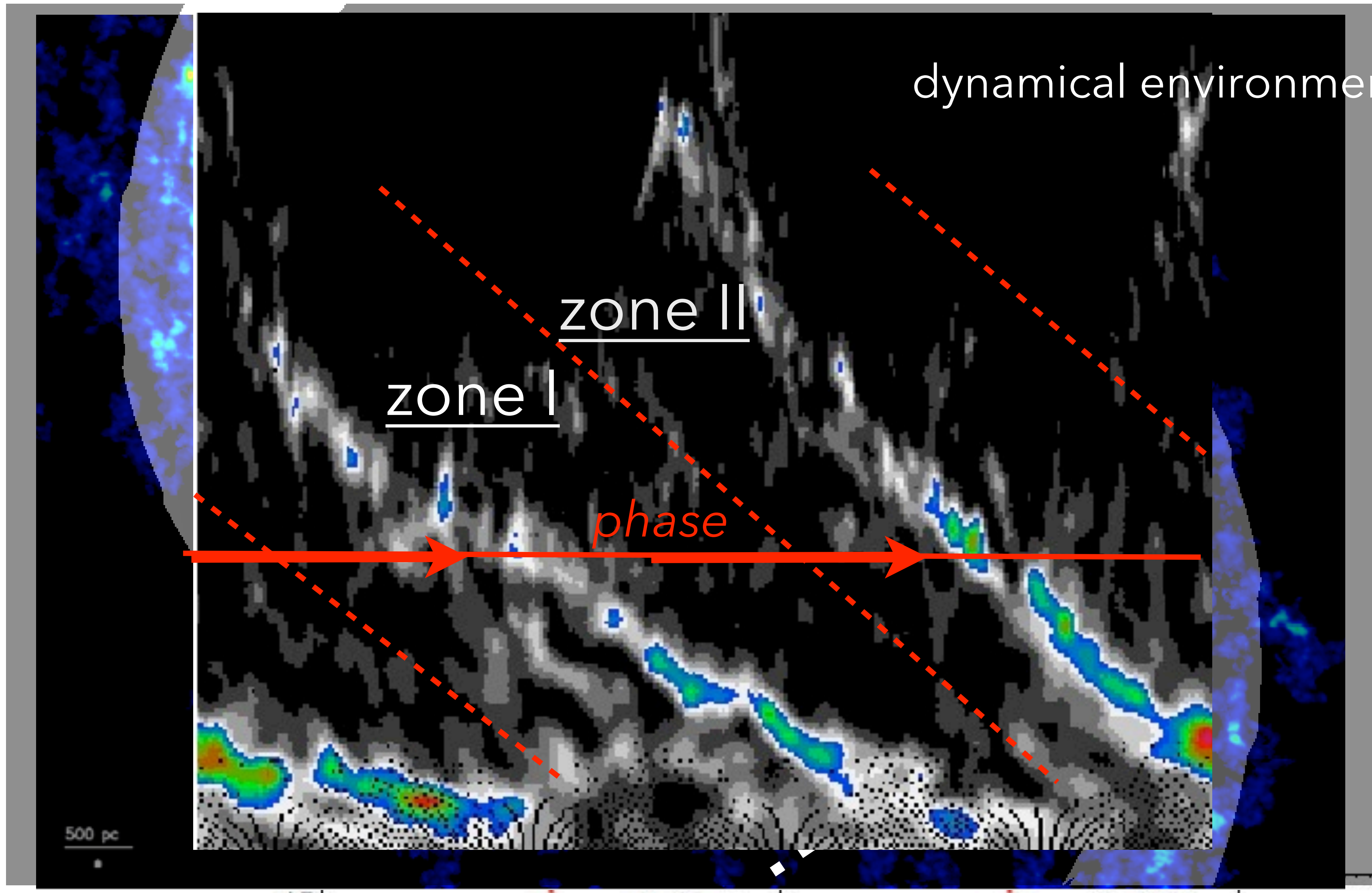

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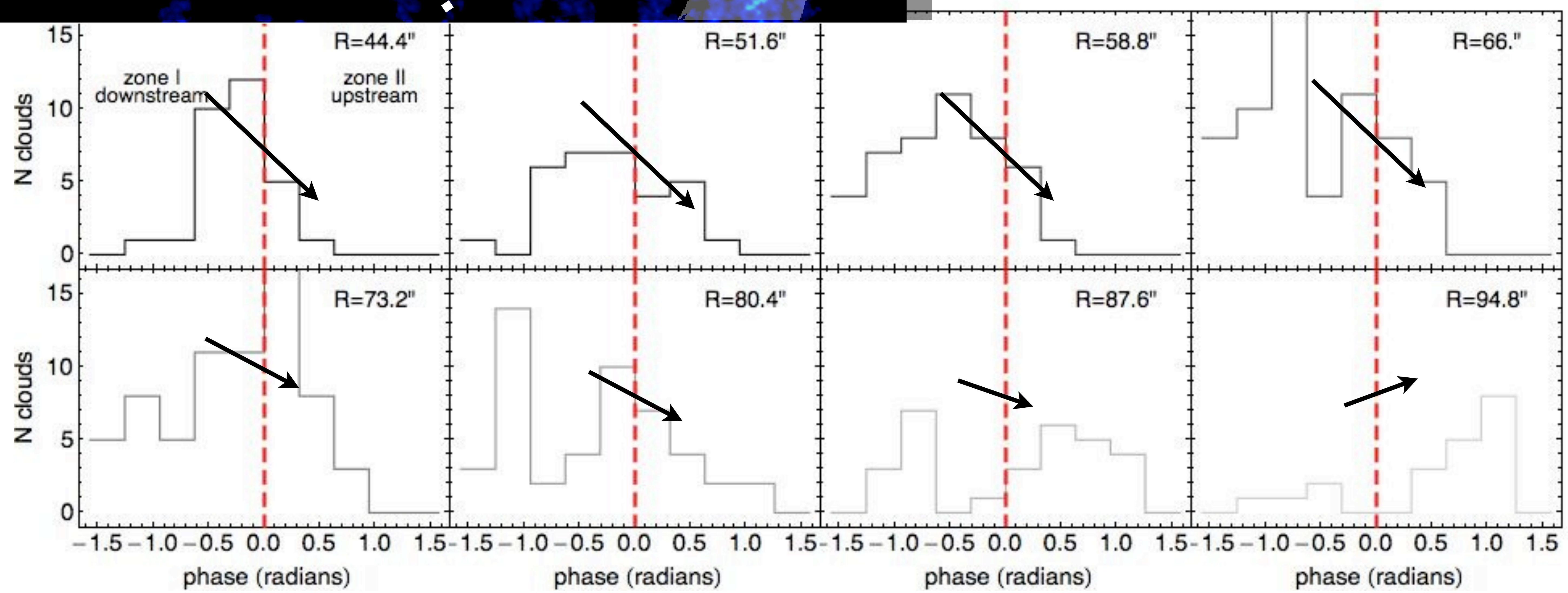

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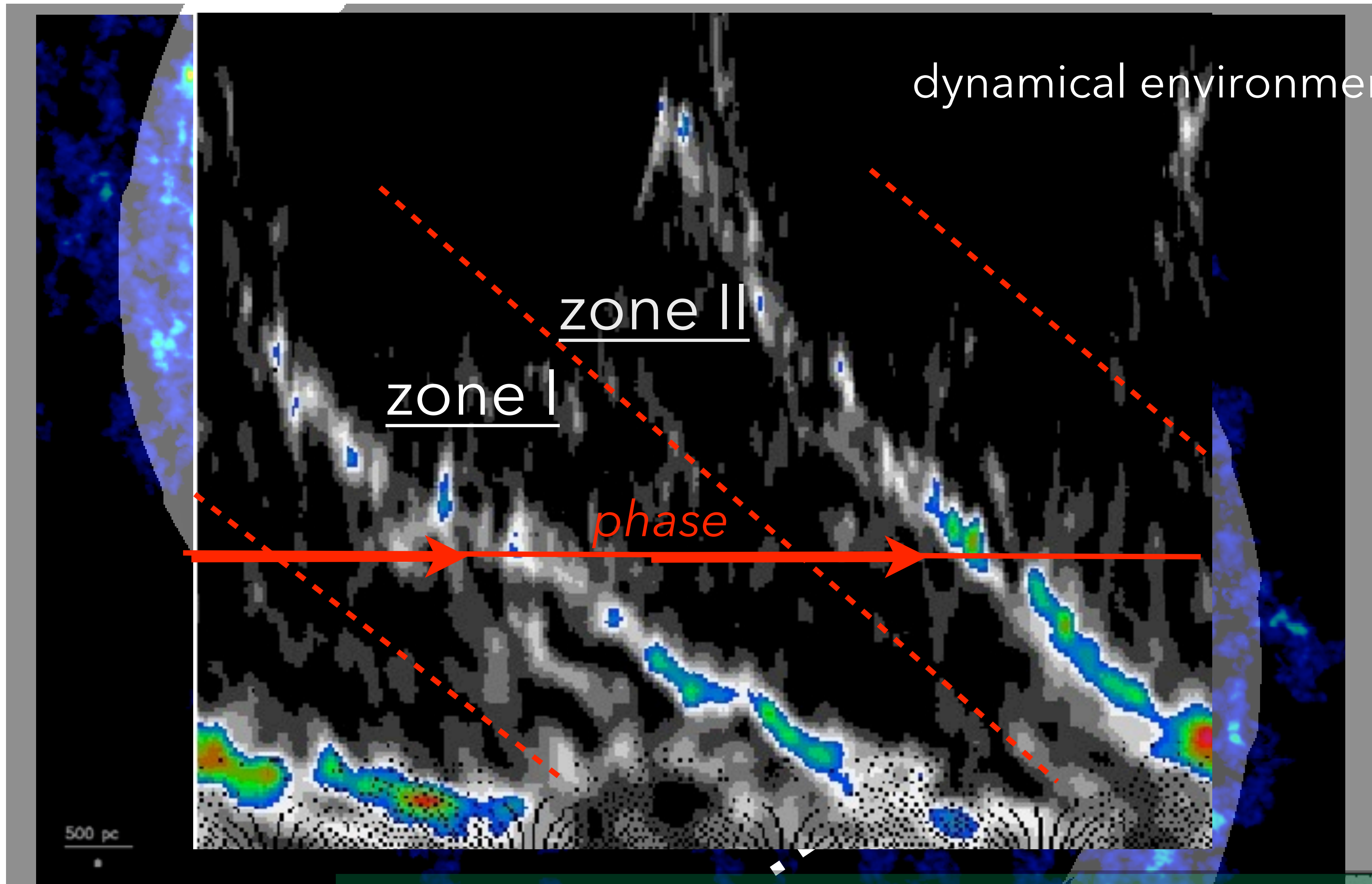

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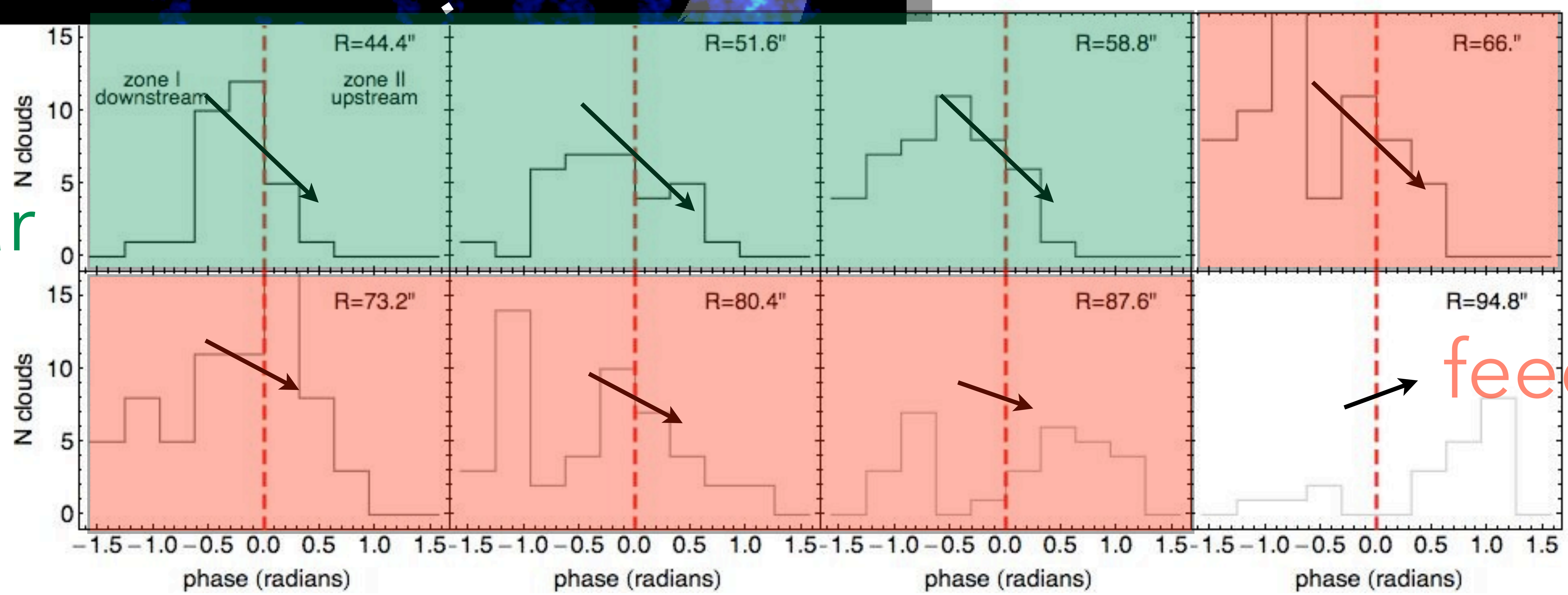
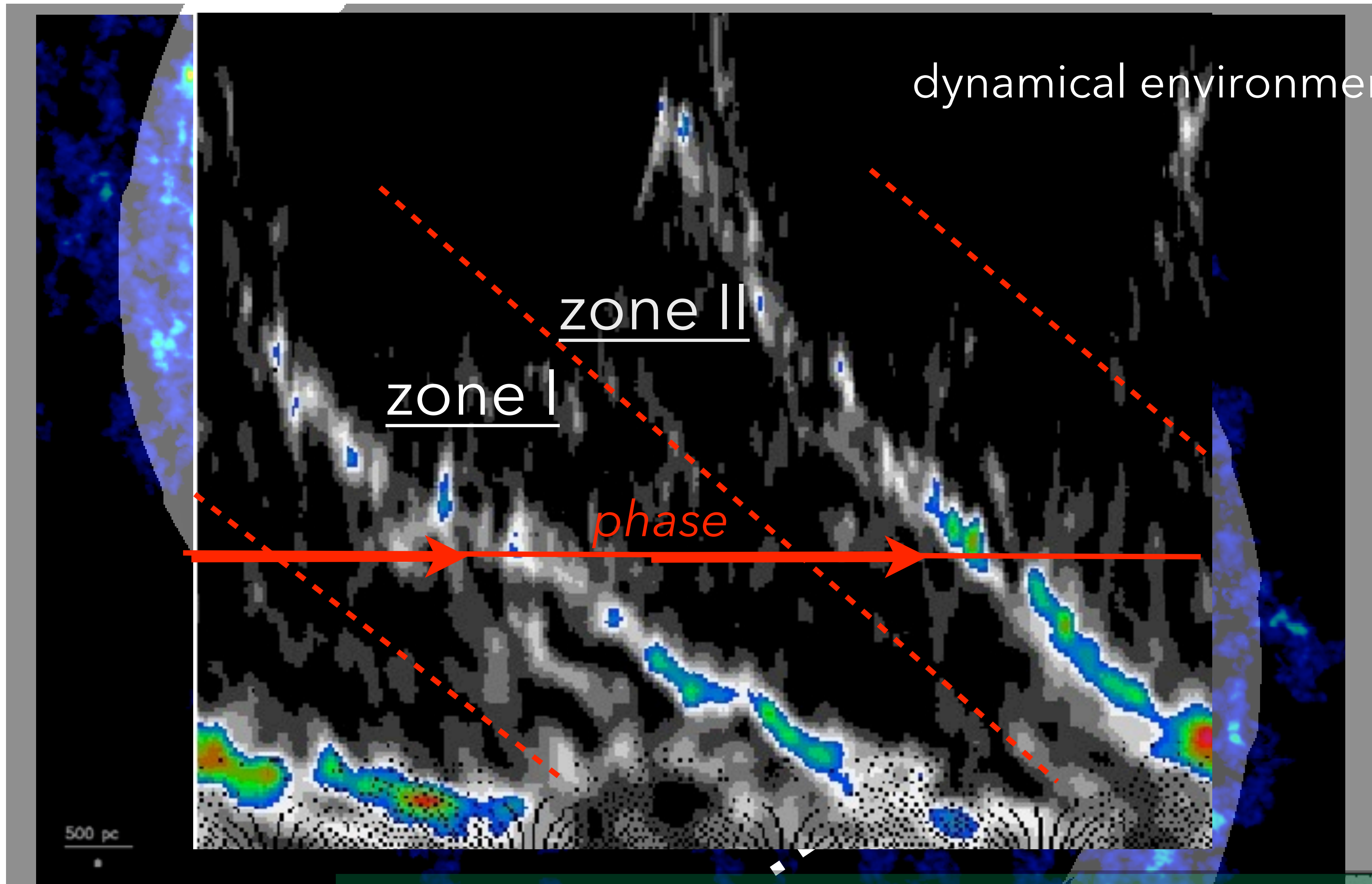
shear

Oort A
=Ω-B
=Ω/2
(for V flat)



feedback

short gmc lifetimes: an observational estimate with PAWS!



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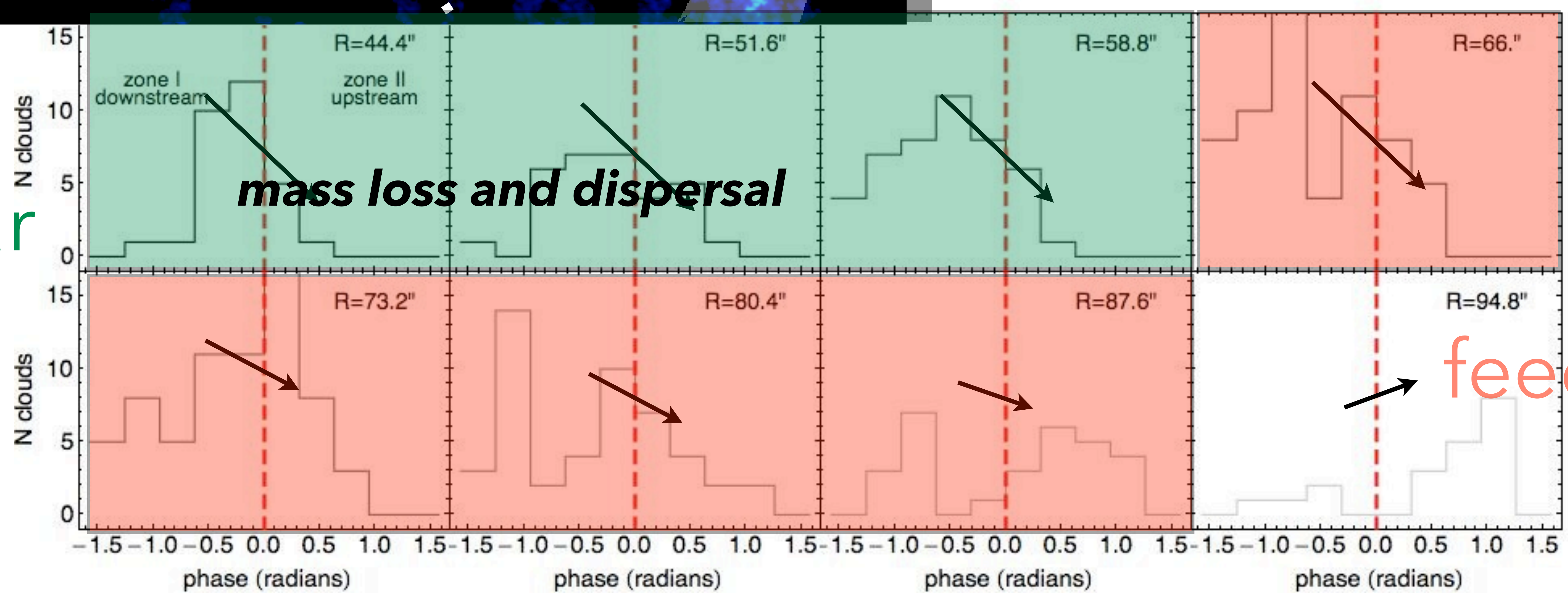
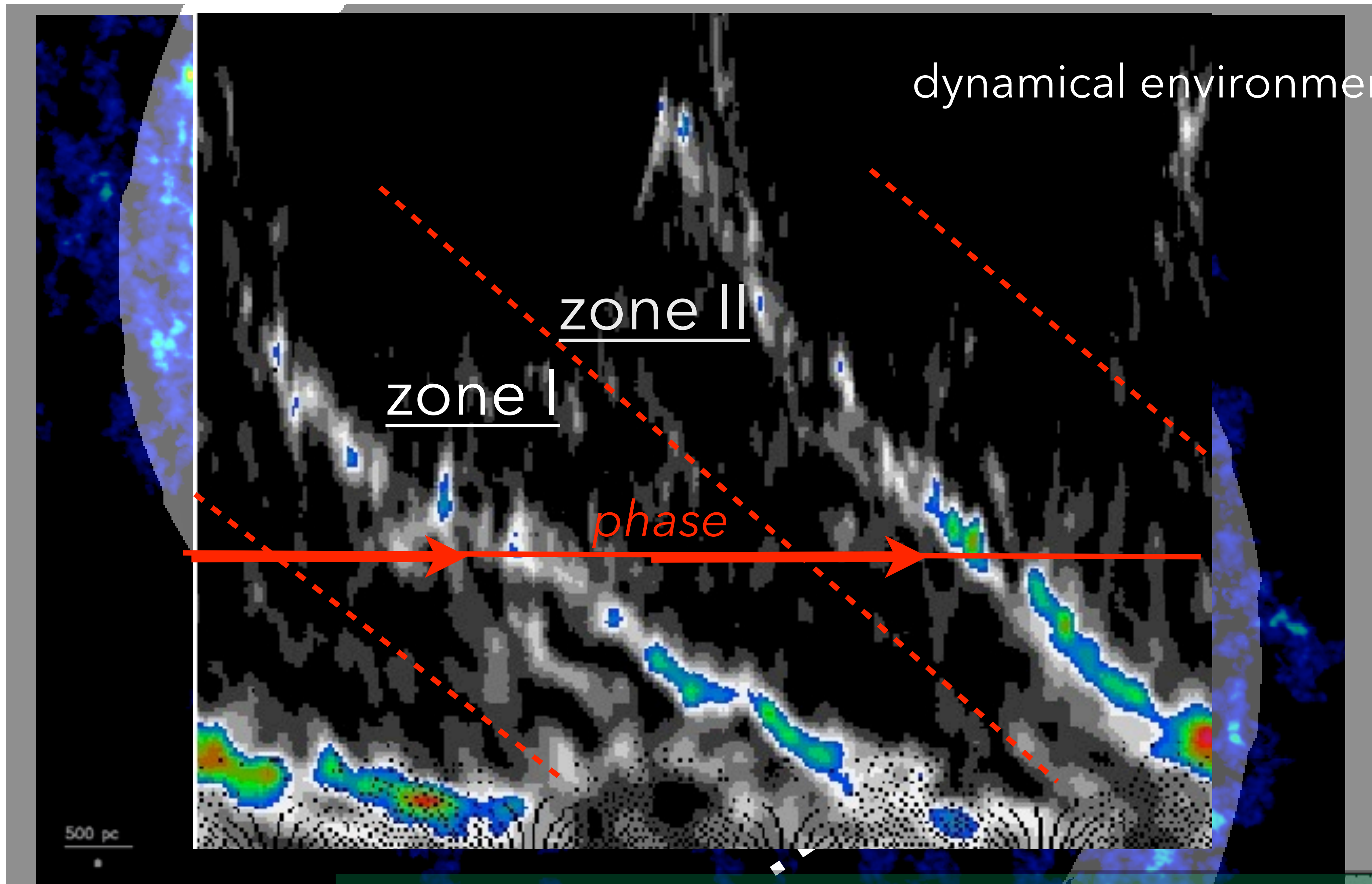
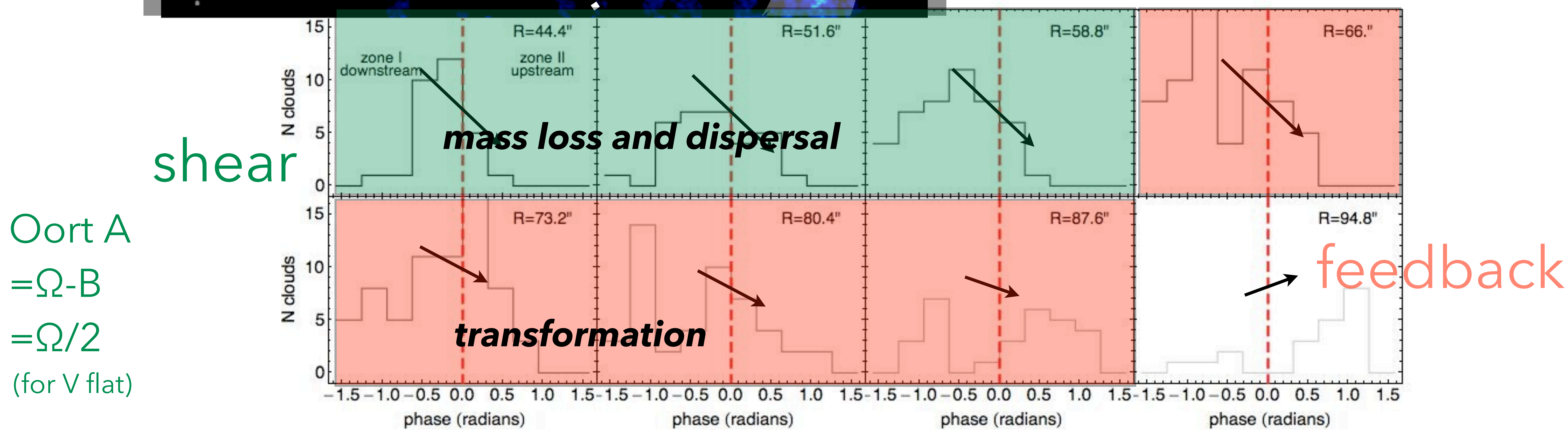
=Ω/2
(for V flat)



short gmc lifetimes: an observational estimate with PAWS!



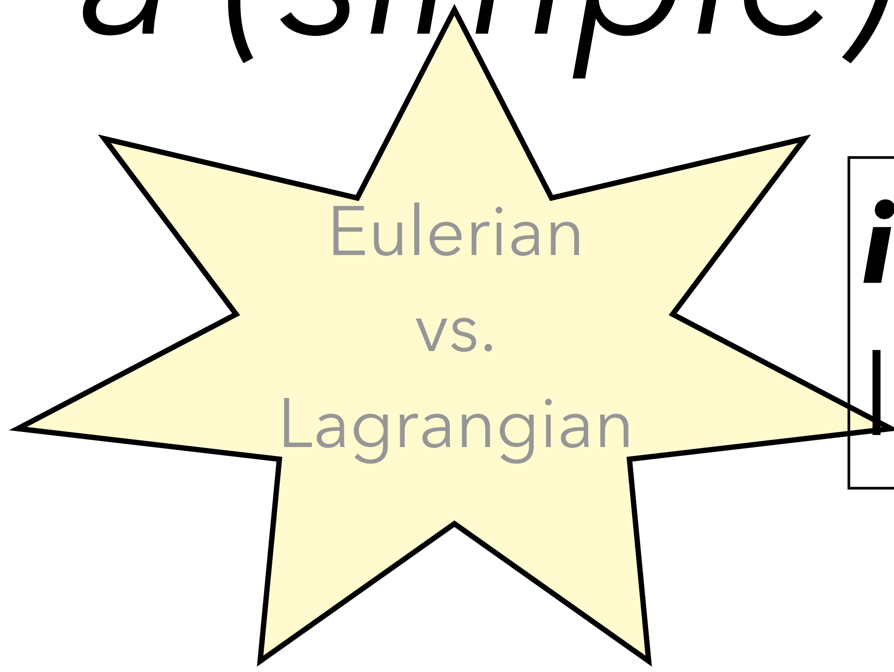
- cloud numbers decreases from zone I to zone II (Colombo et al. 2013)
- mass spectrum evolution: ***shear and star formation feedback destroy clouds, limit lifetimes***



a (simple) framework

if cloud numbers decrease from zone I to zone II ***then*** lifetime < travel time from arm to arm

a (simple) framework



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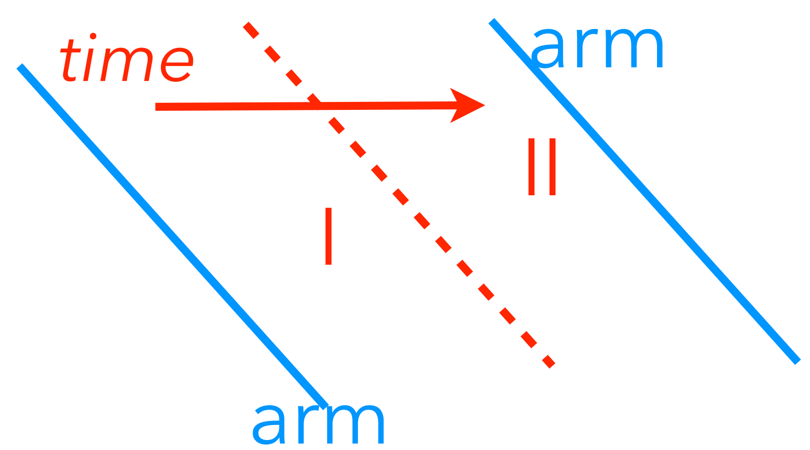
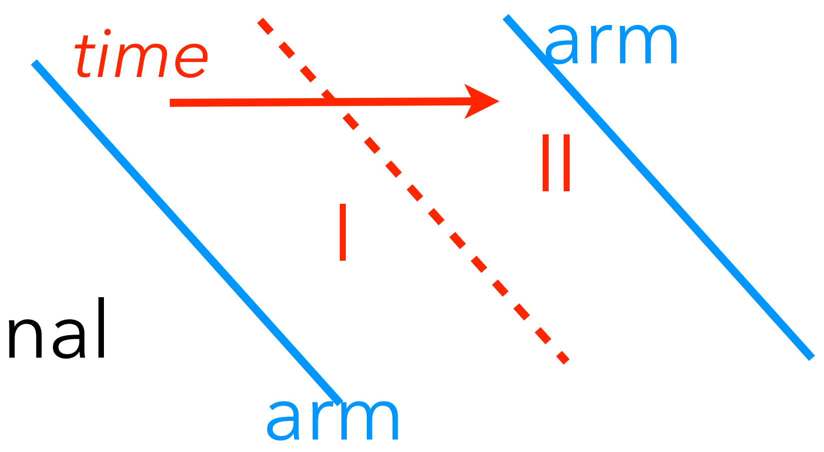


a (simple) framework

Eulerian vs. Lagrangian

if cloud numbers decrease from zone I to zone II ***then*** lifetime < travel time from arm to arm



split interarm in half, count N_I and N_{II}

$$\tau = \frac{t_{travel}}{2}\frac{N_I}{N_I - N_{II}}$$

original

lost

half arm-to-arm travel time; measure from t_{orb}

a (simple) framework

Eulerian vs. Lagrangian

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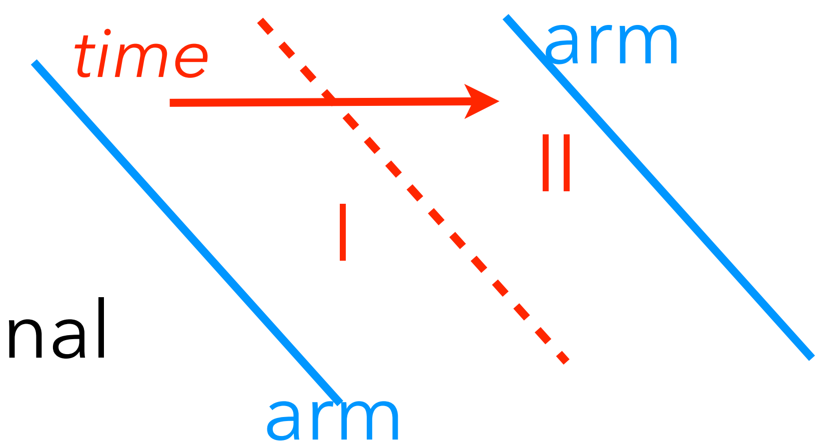

original

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lost

half arm-to-arm travel time;
measure from t_{orb}

- still sources + sinks (feedback cloud splitting, etc.)

$$\frac{1}{\tau} = \frac{1}{\tau_{true}} - \frac{1}{\tau_{grow}}$$

and $\tau \approx \tau_{true}$ *when* $\tau_{grow} >> \tau_{true}$

i.e. ***mostly losses***

a (simple) framework

Eulerian vs. Lagrangian

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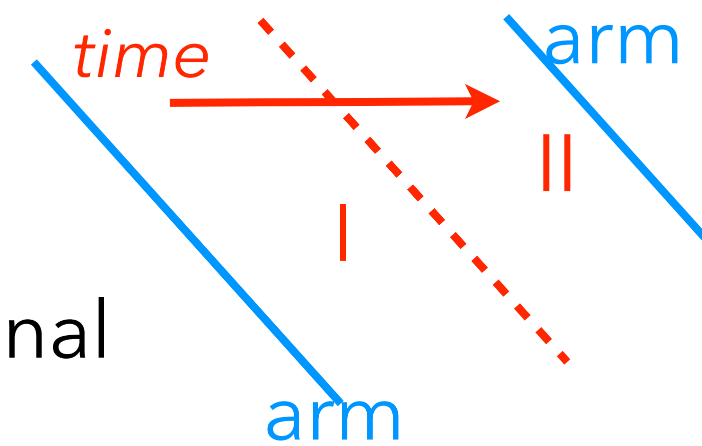
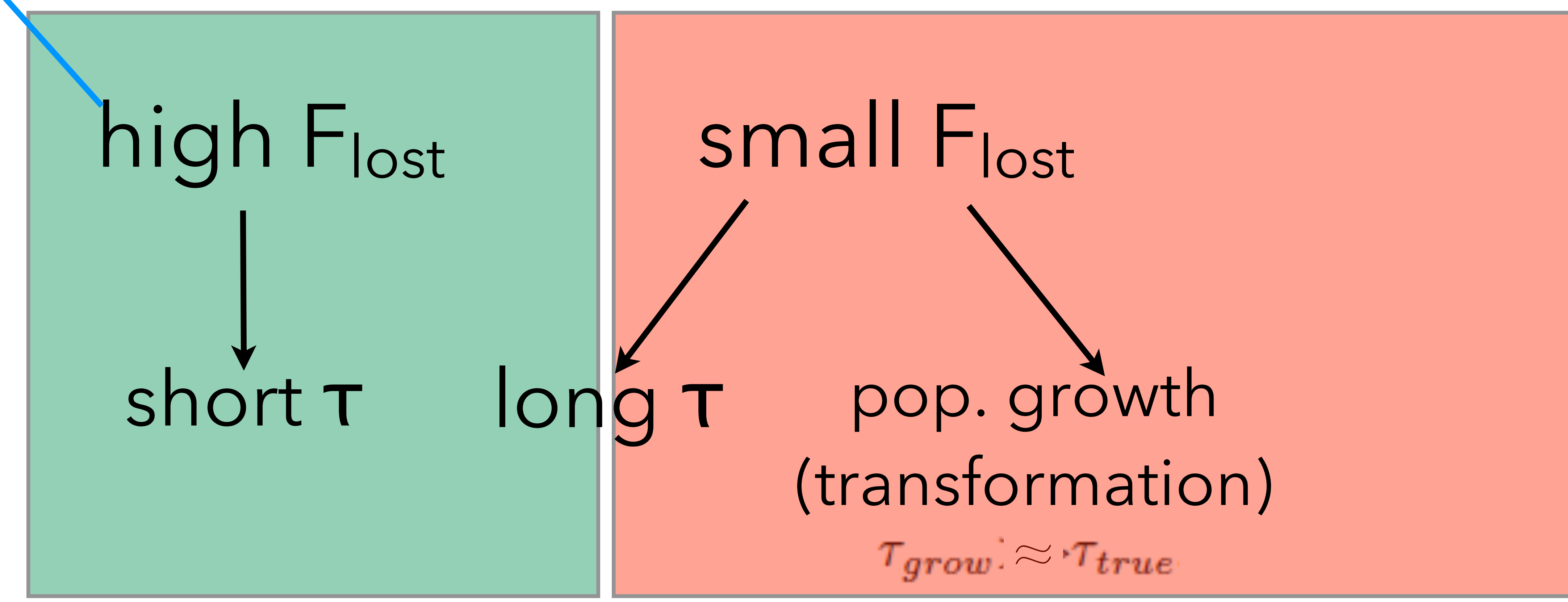


$$\tau = \frac{t_{travel}}{2}\frac{N_I}{N_I - N_{II}} = \frac{t_{travel}}{2}\frac{1}{F_{lost}},$$

original (N_I); lost ($N_I - N_{II}$)

half arm-to-arm travel time; measure from t_{orb}



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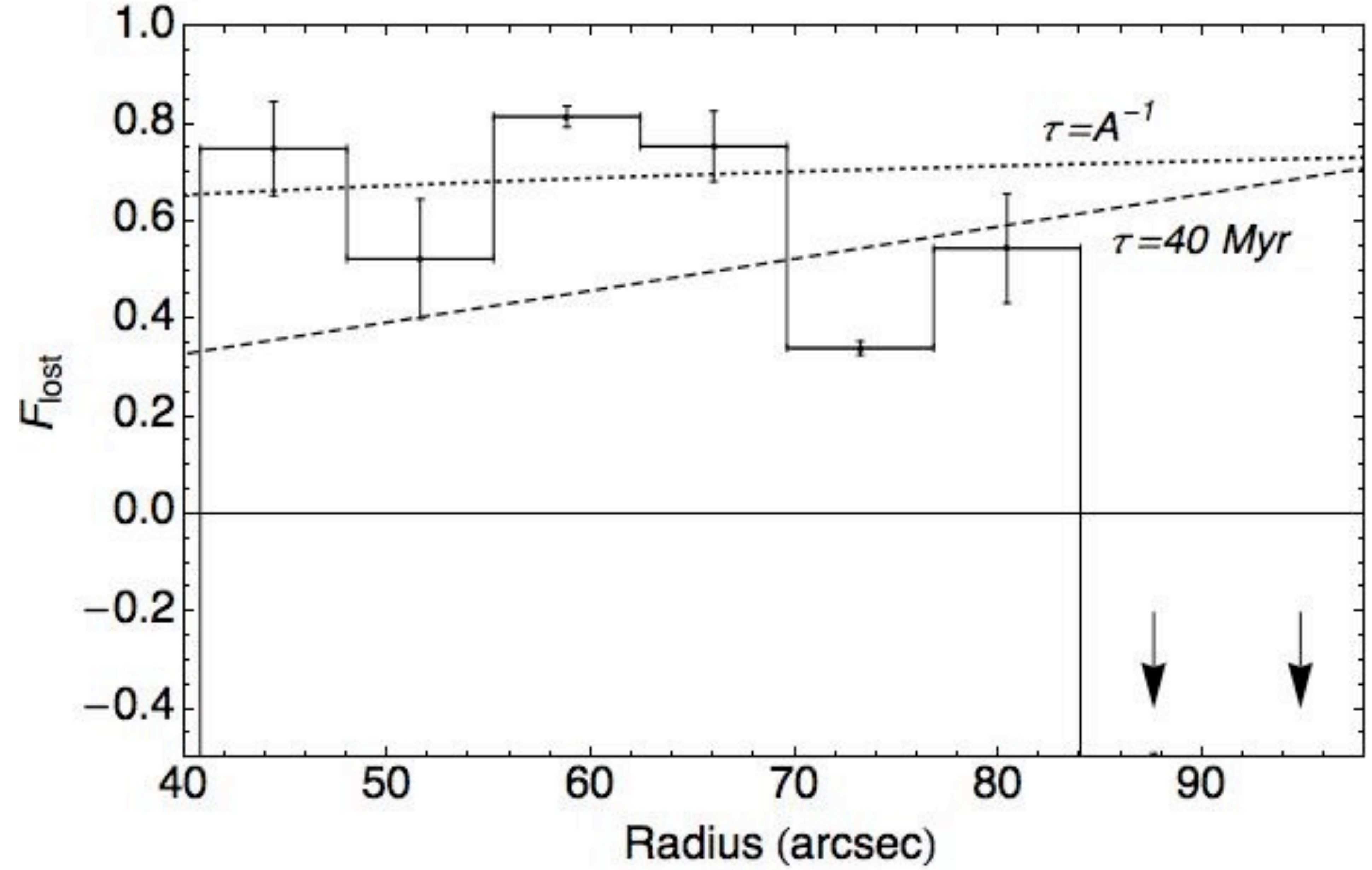
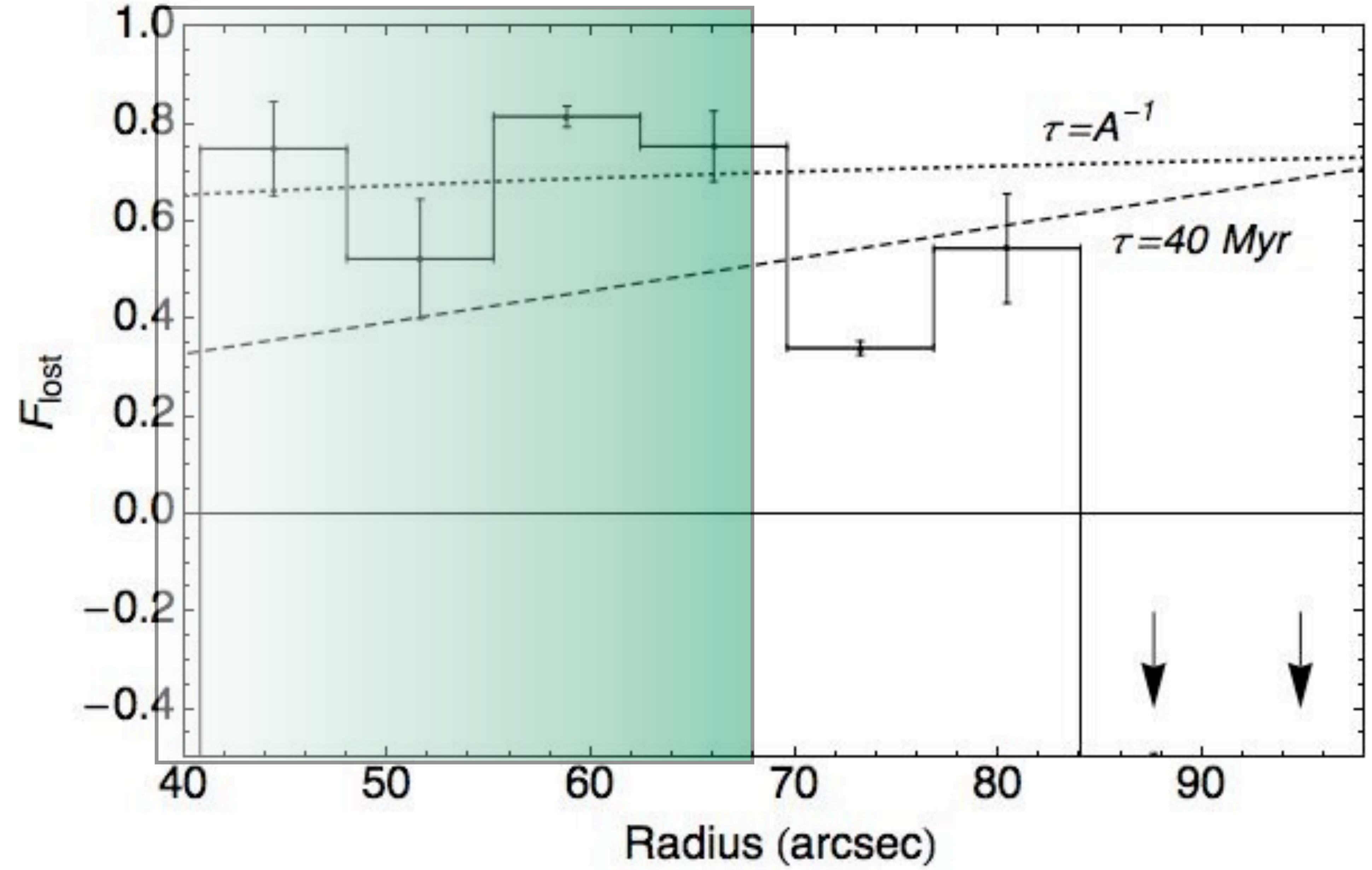
GMC lifetimes

GMC lifetimes

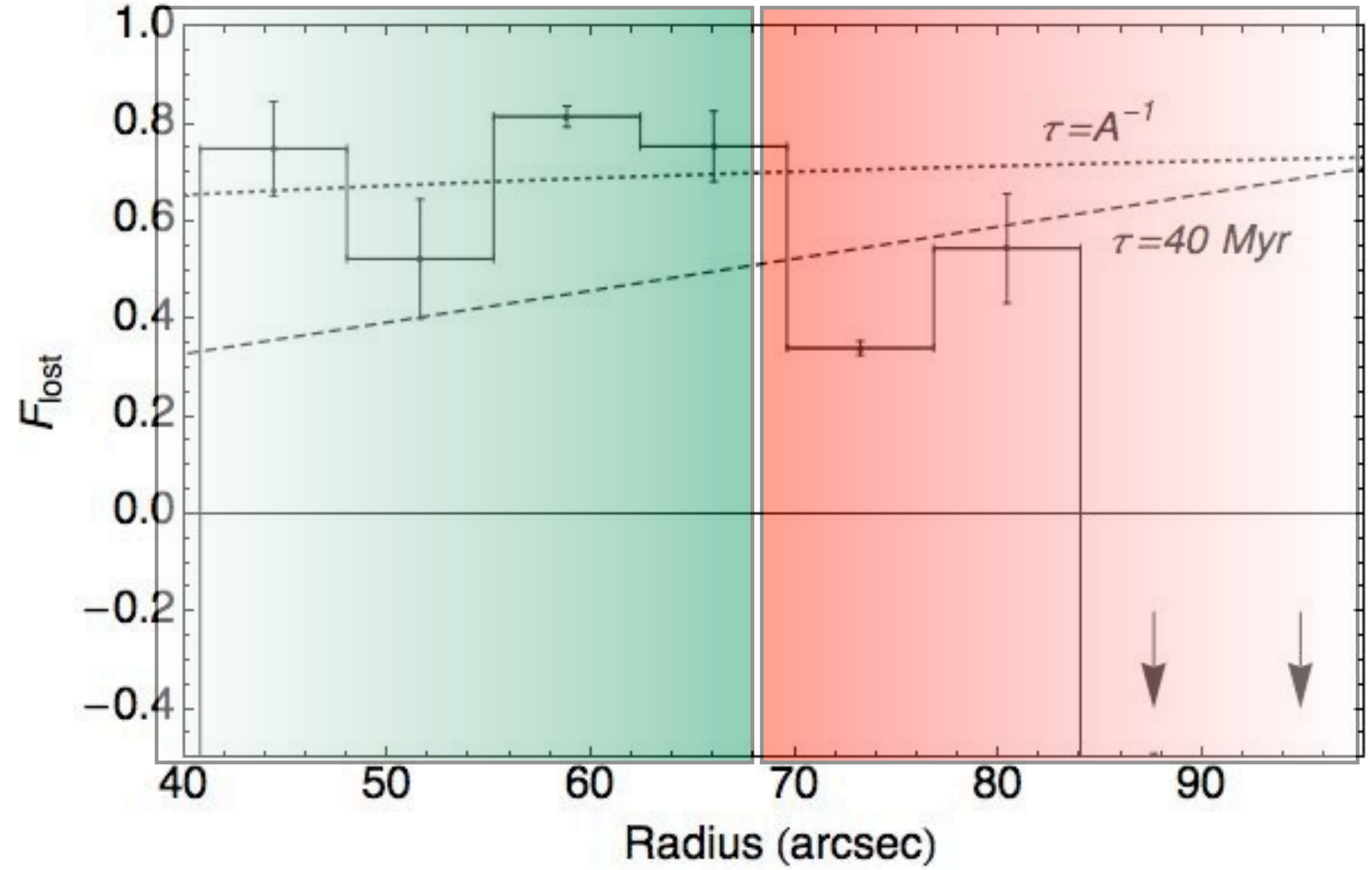


GMC lifetimes



many lost

GMC lifetimes

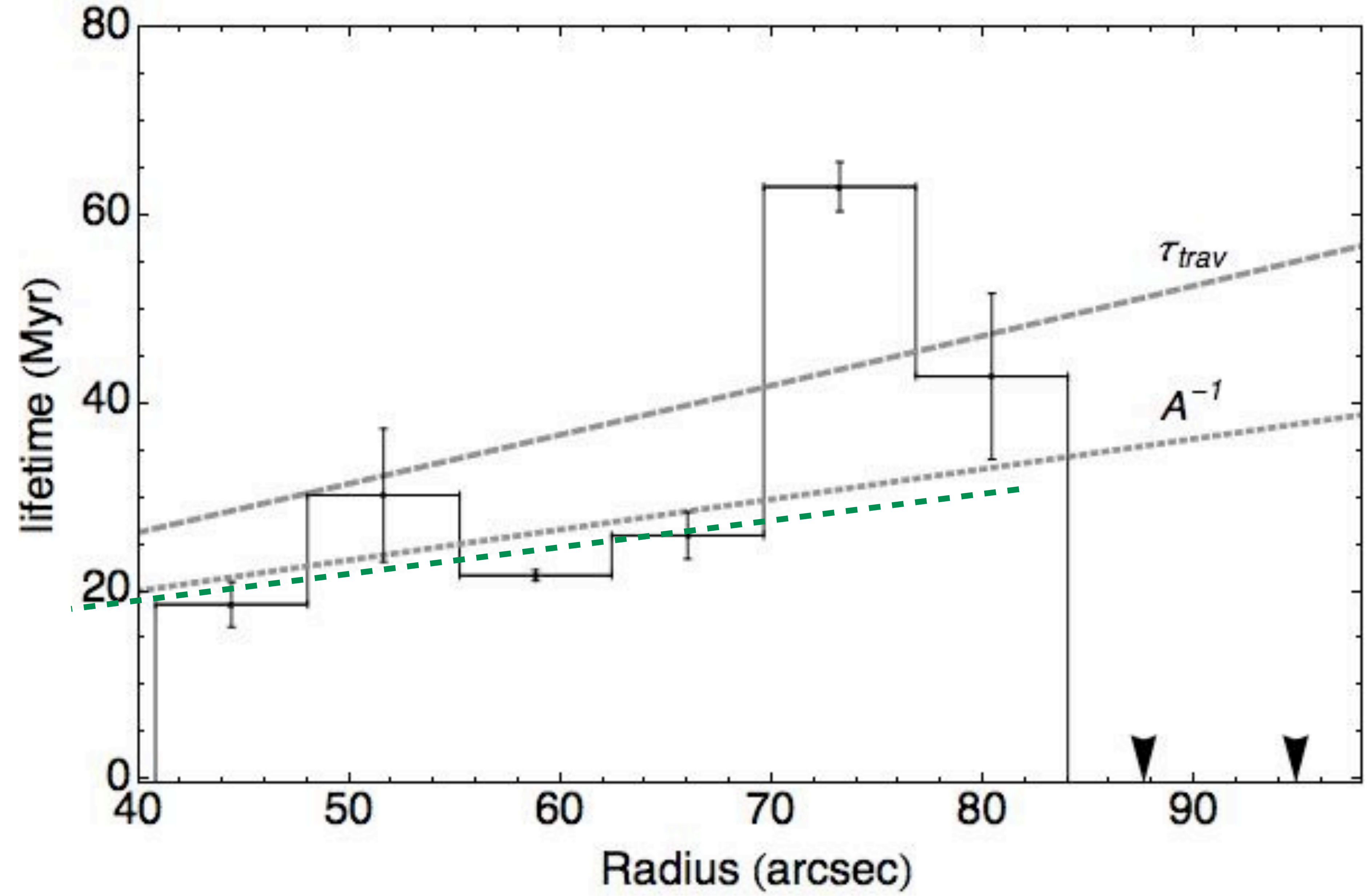


many lost   fewer lost

GMC lifetimes

- shear timescale: short!

  just a few free-fall times!



GMC lifetimes

- shear timescale: short!

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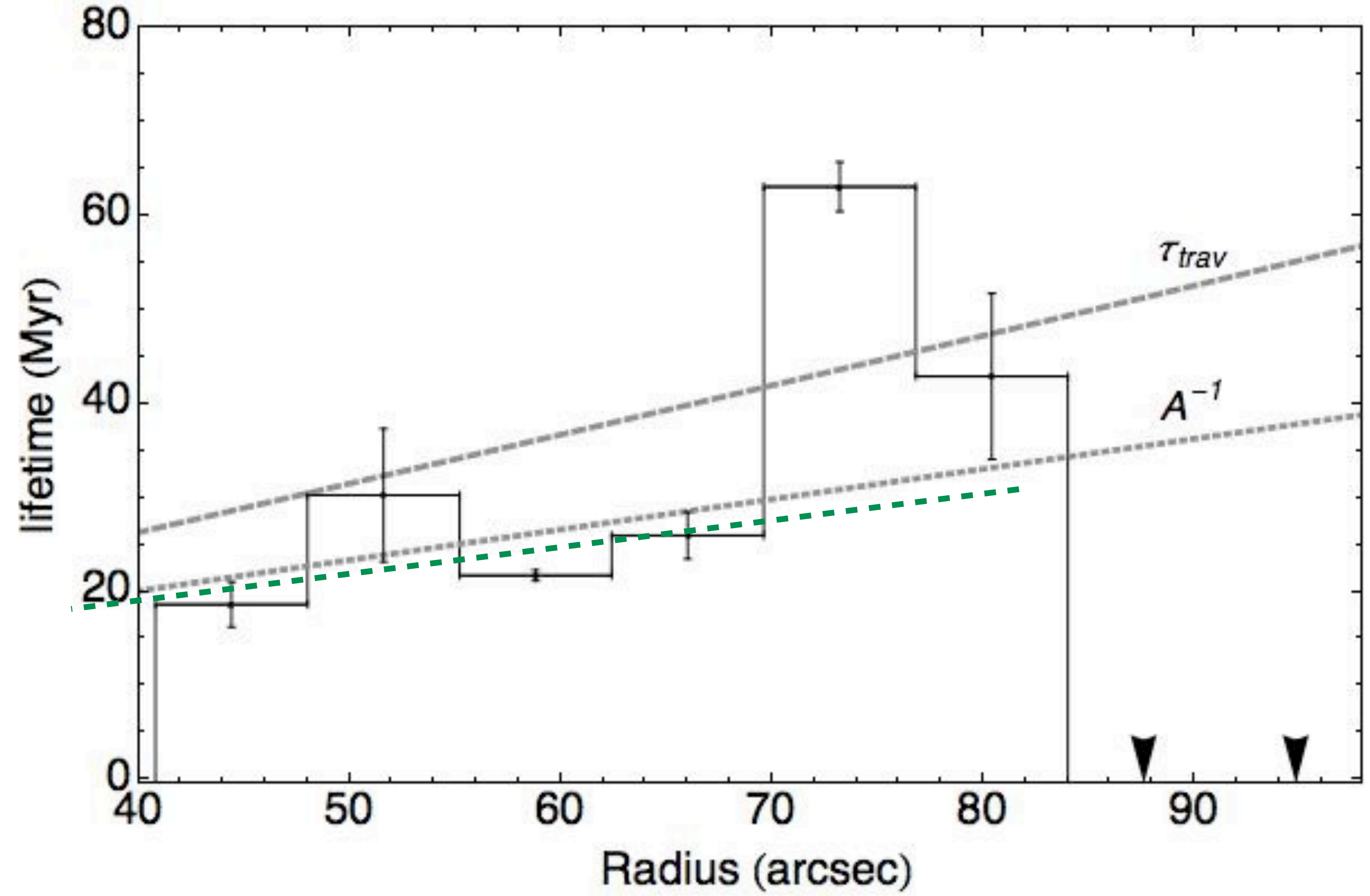
- feedback timescale
  - *here* transformation
    $\tau_{grow} \approx \tau_{true}$ so τ overestimates τ_{true}
  - when F_{lost}=low, in M51: ~25Myr



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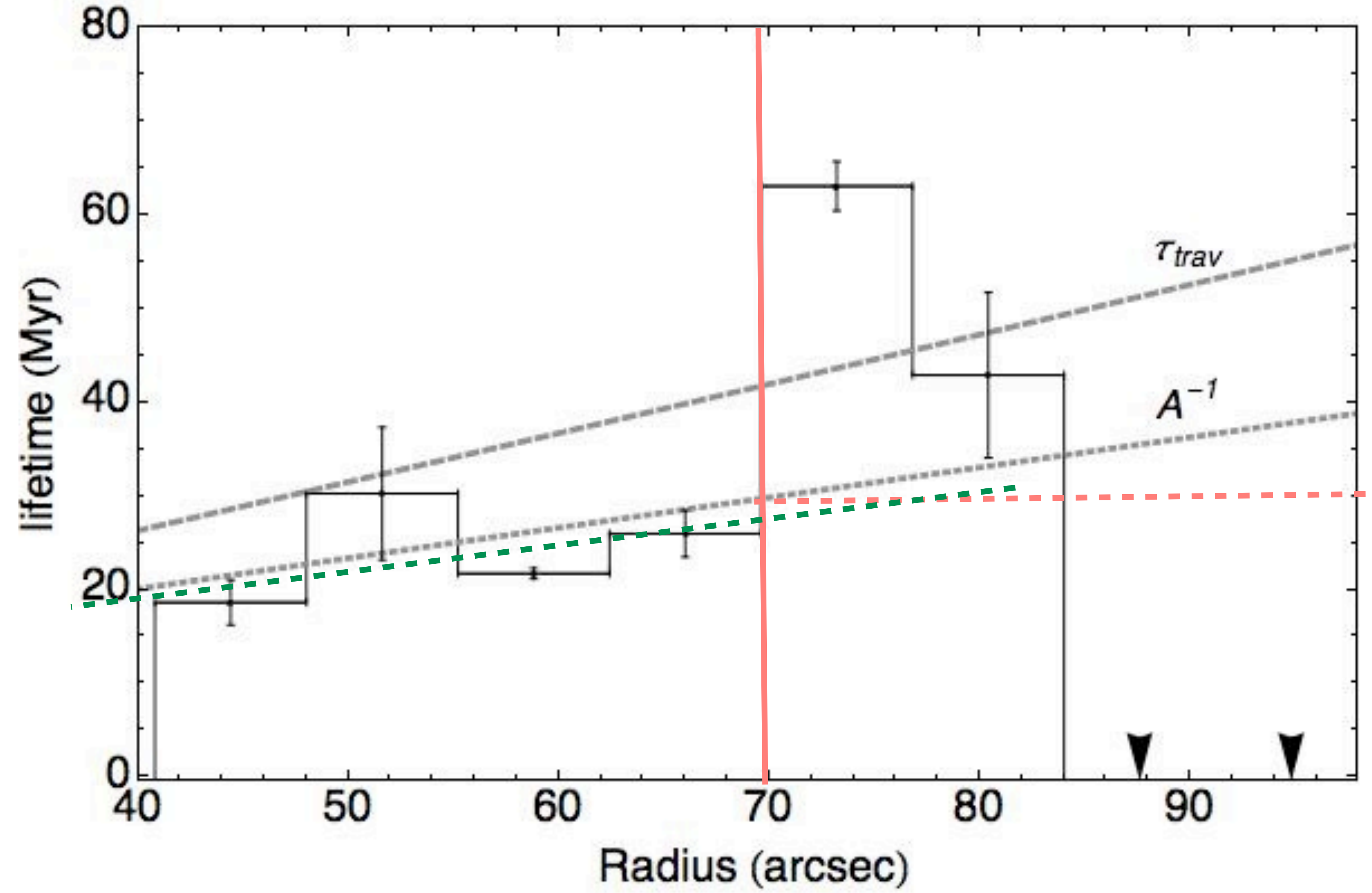

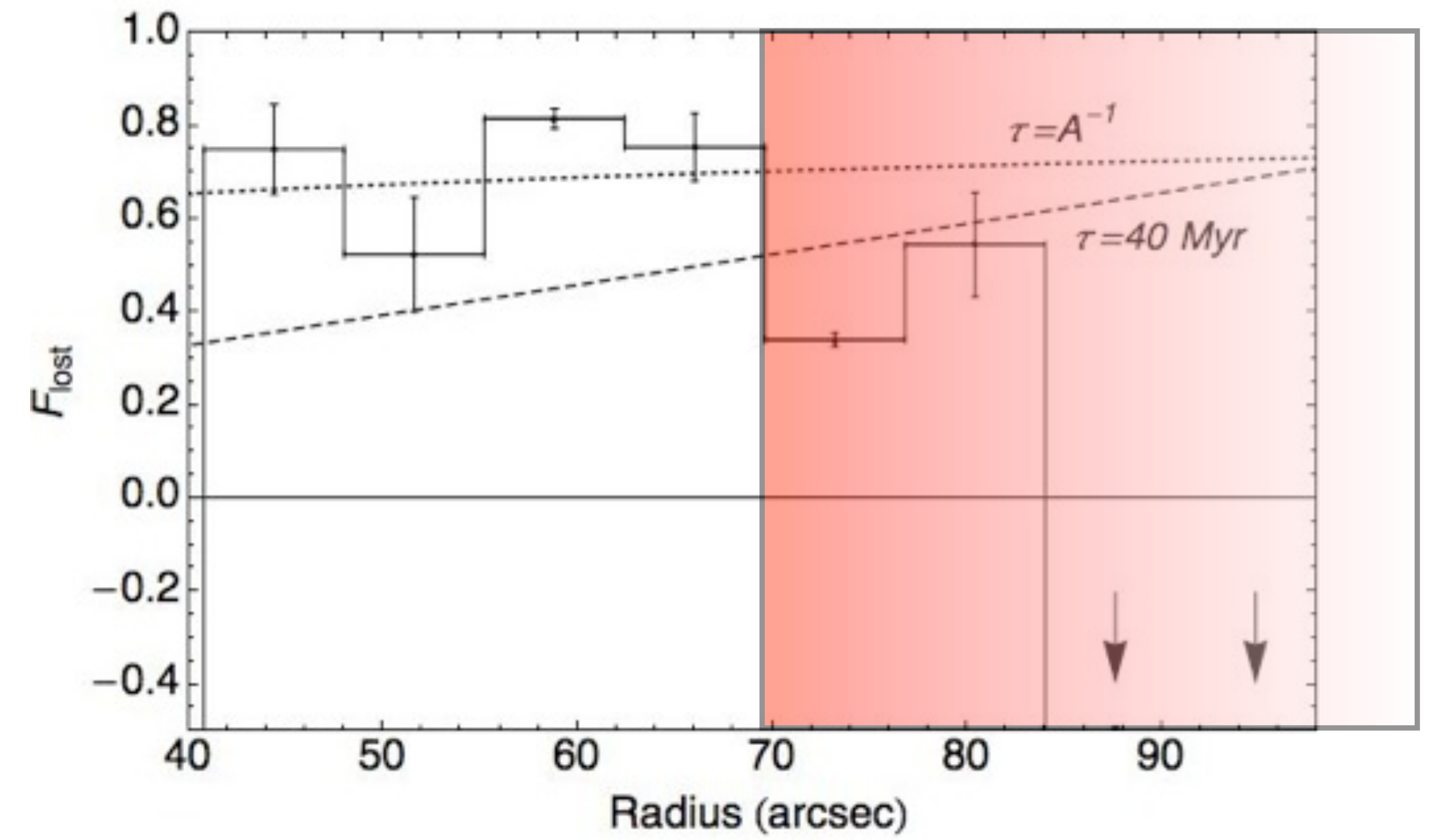

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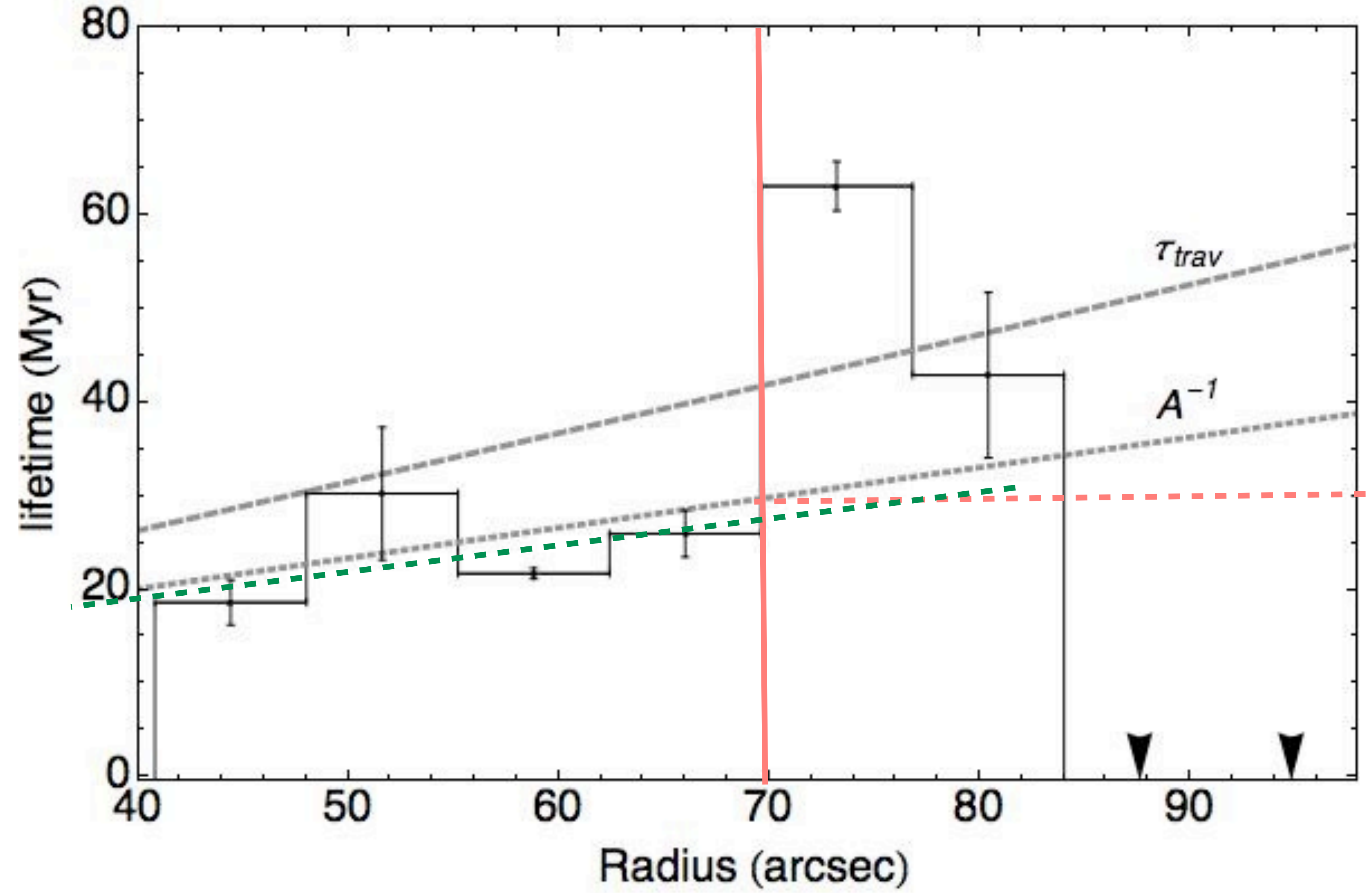
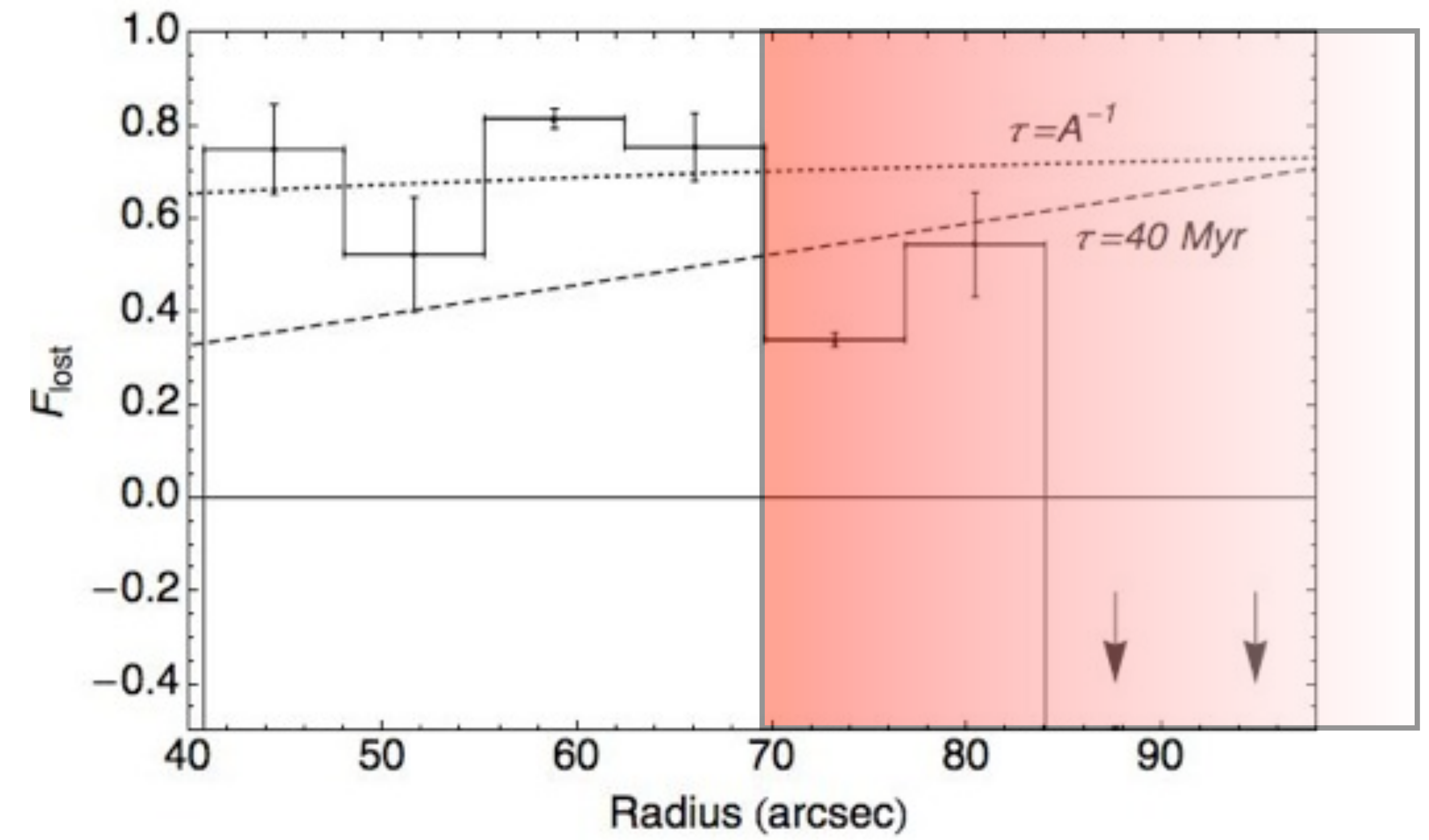
feedback becomes dominant when A^{-1} exceeds 25 Myr





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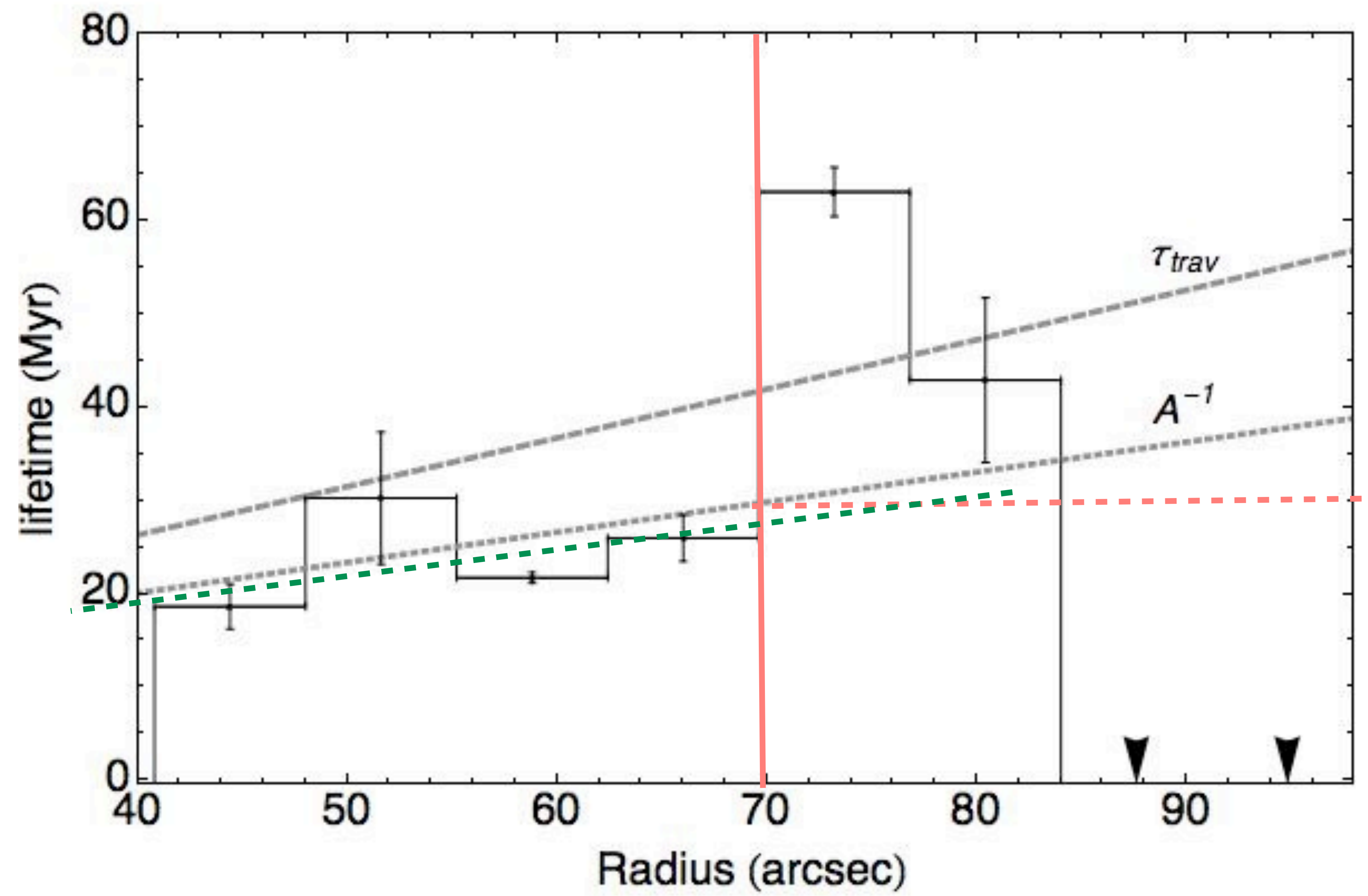

GMC lifetimes

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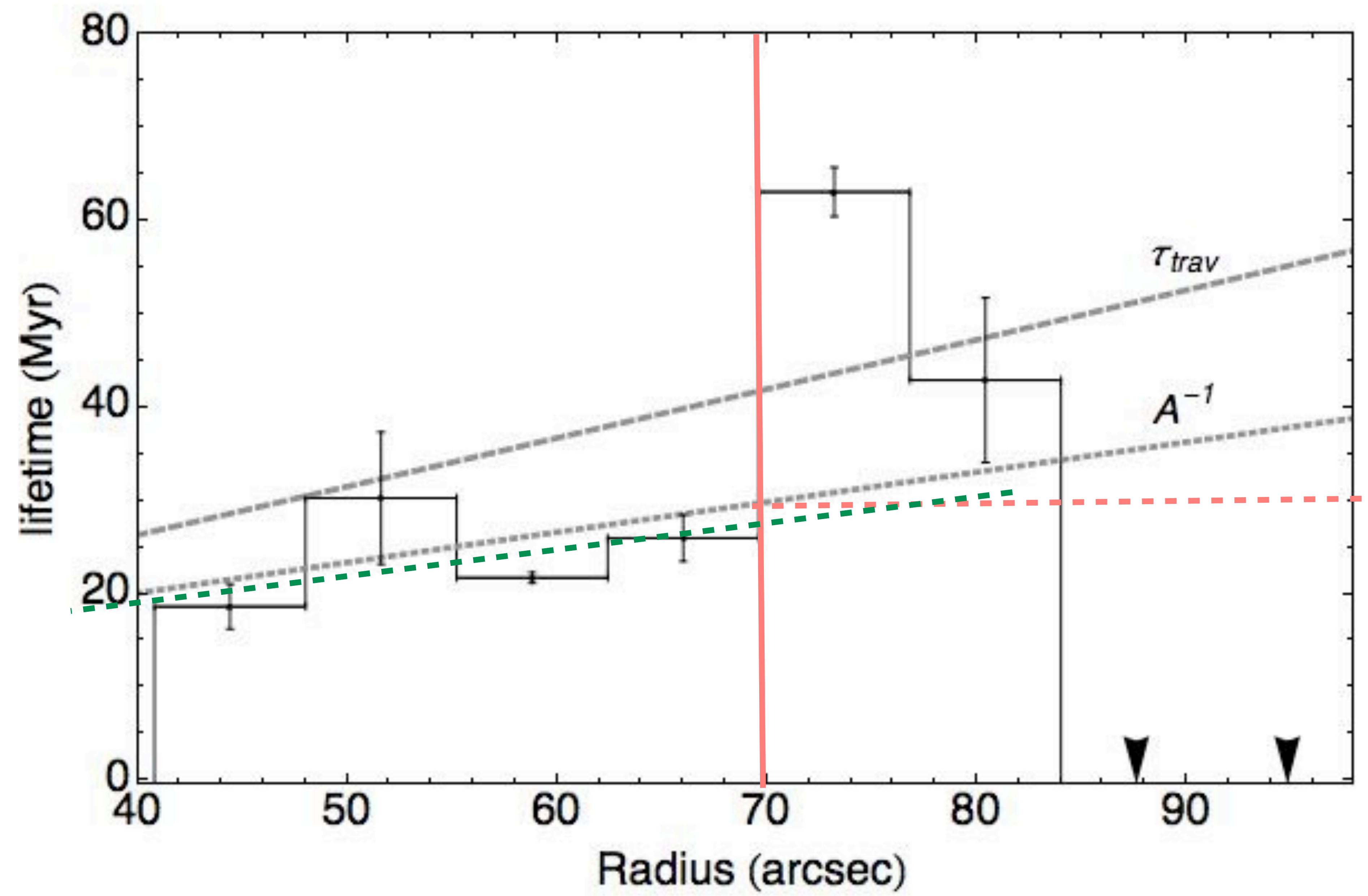


shear timescale **<** feedback timescale

centers of galaxies

normal L* disks

τ is short ~15-20 Myr

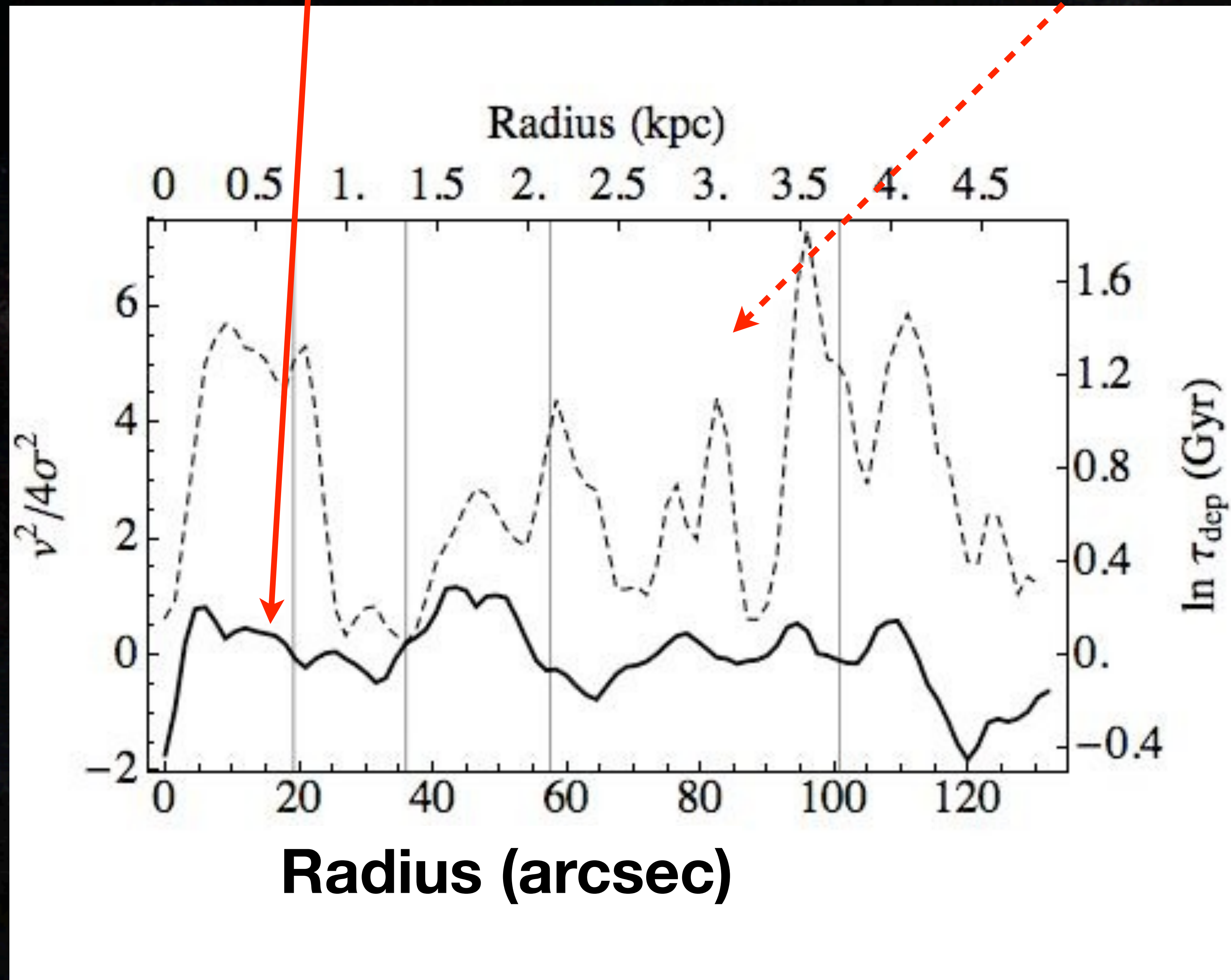
shear timescale **>** feedback timescale

spiral arms

low mass disks

τ is longer ~25Myr

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



Meidt et al. (2013)

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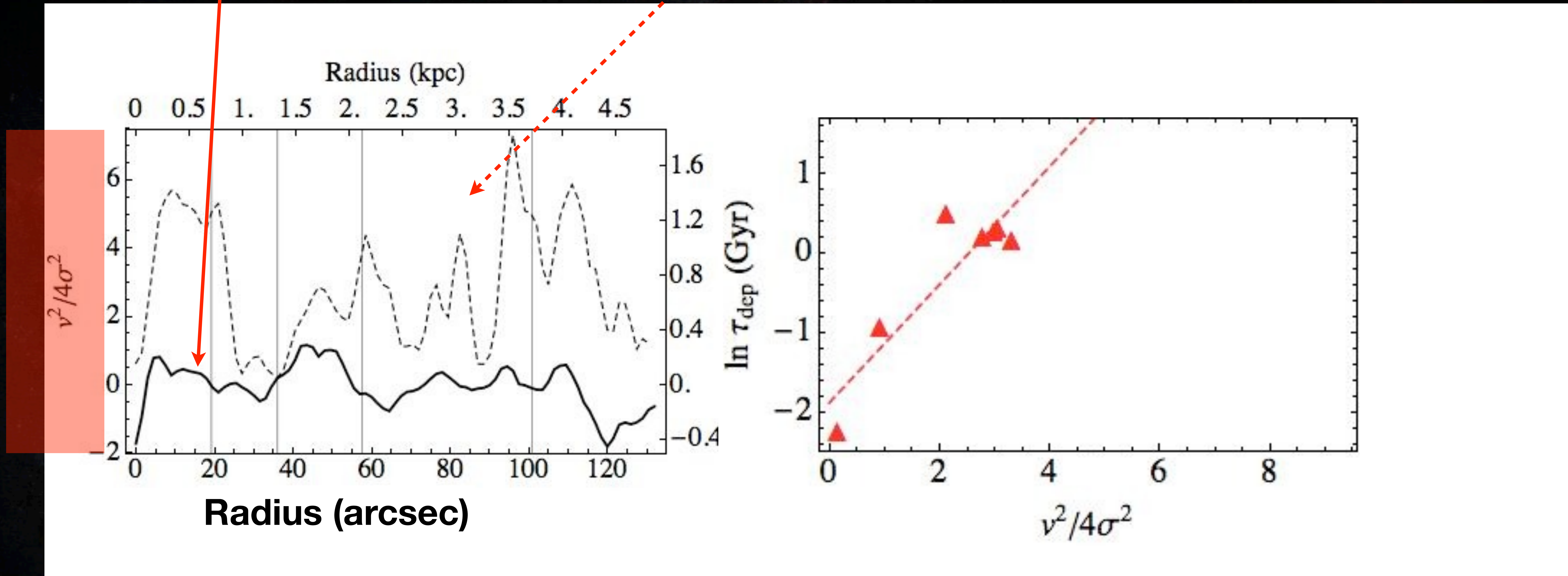

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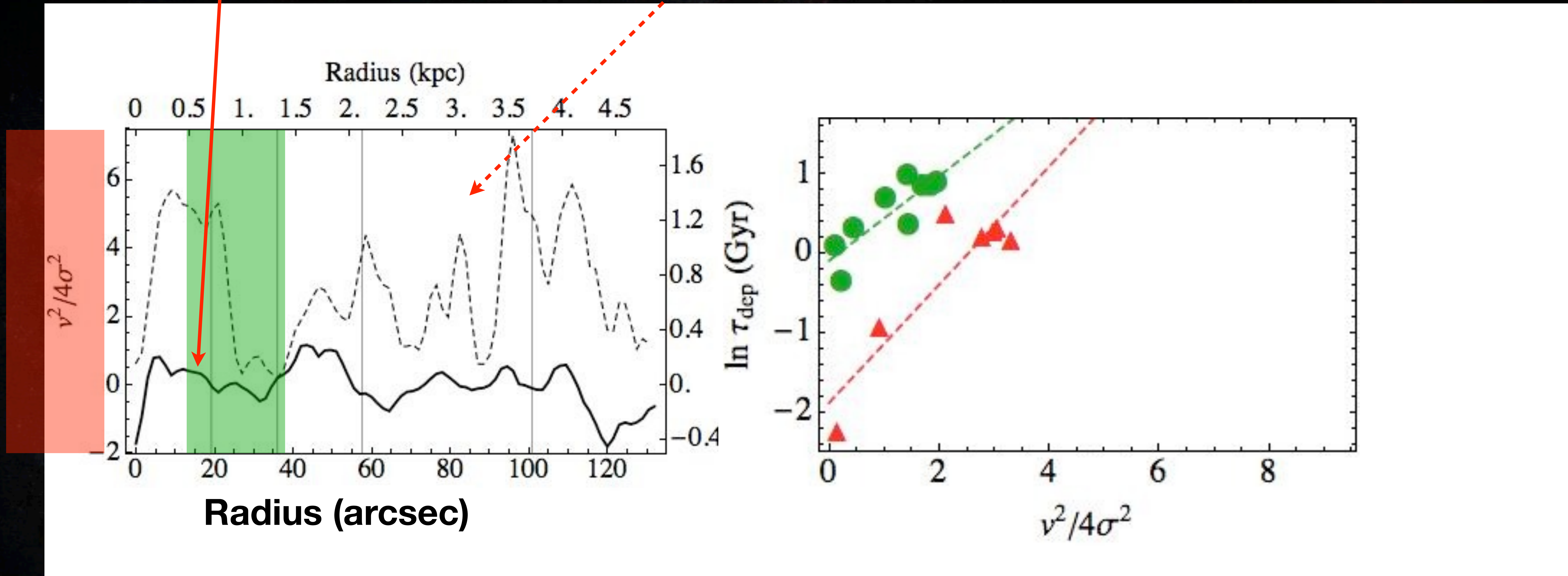

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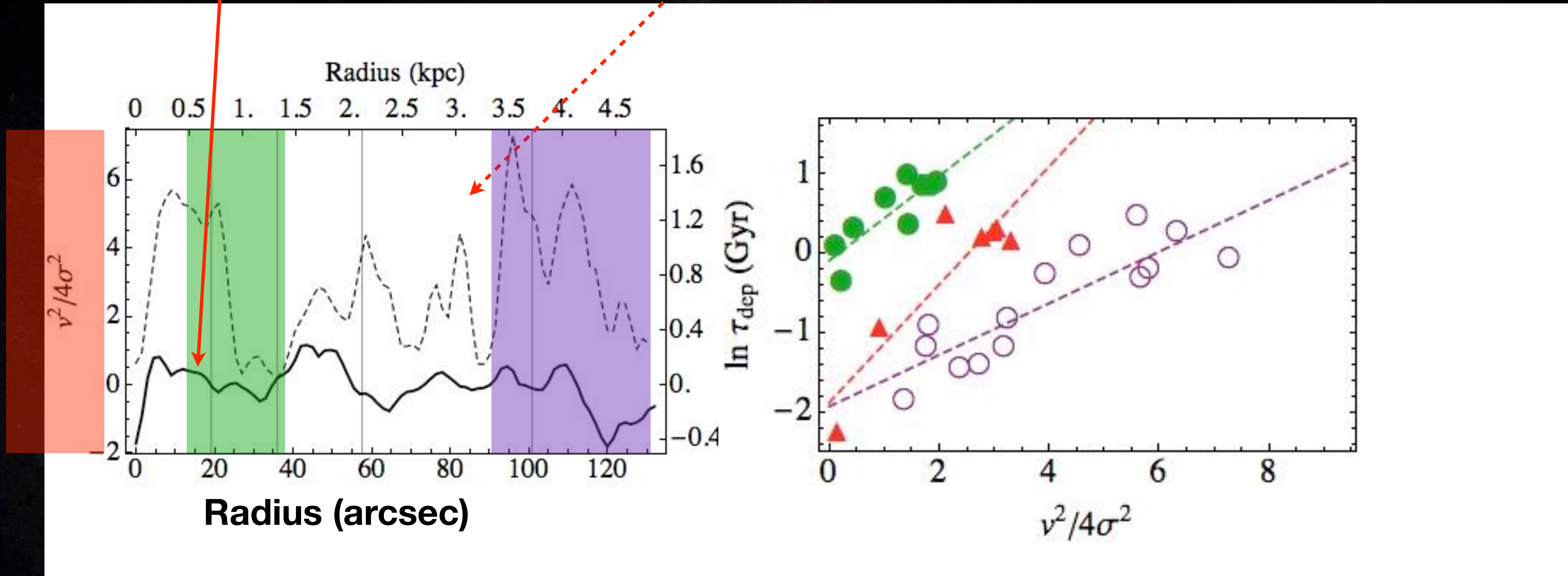

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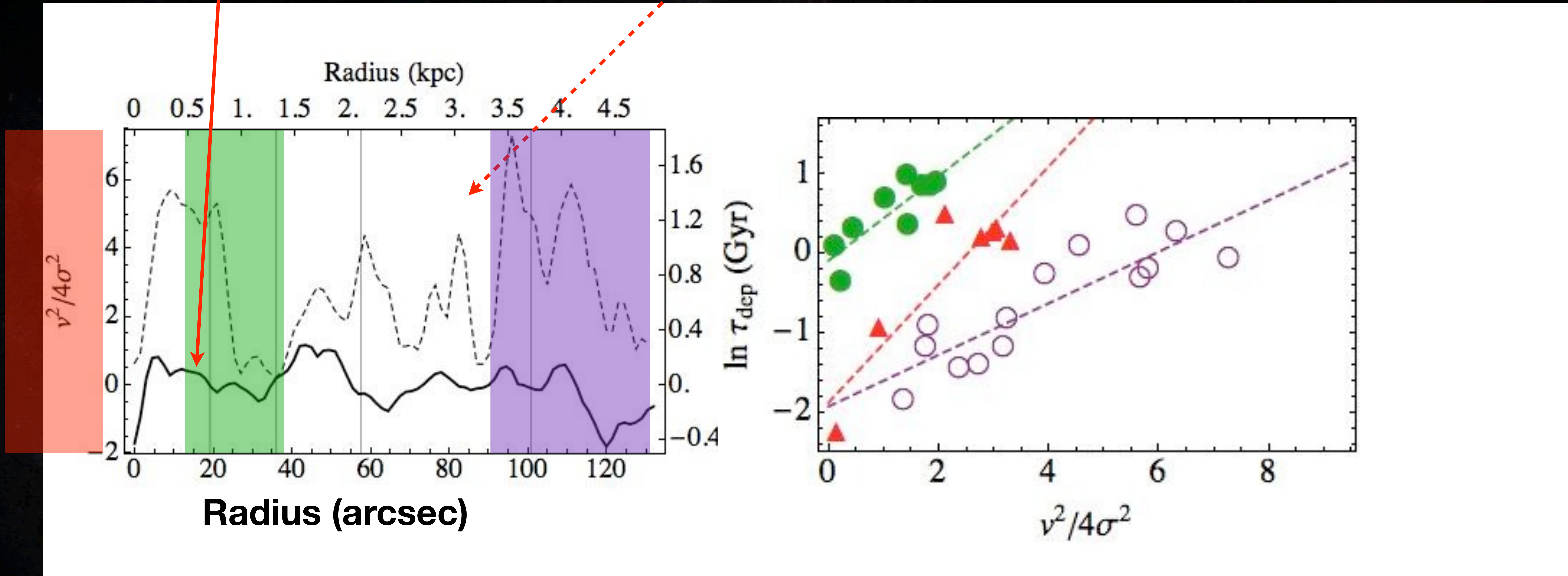
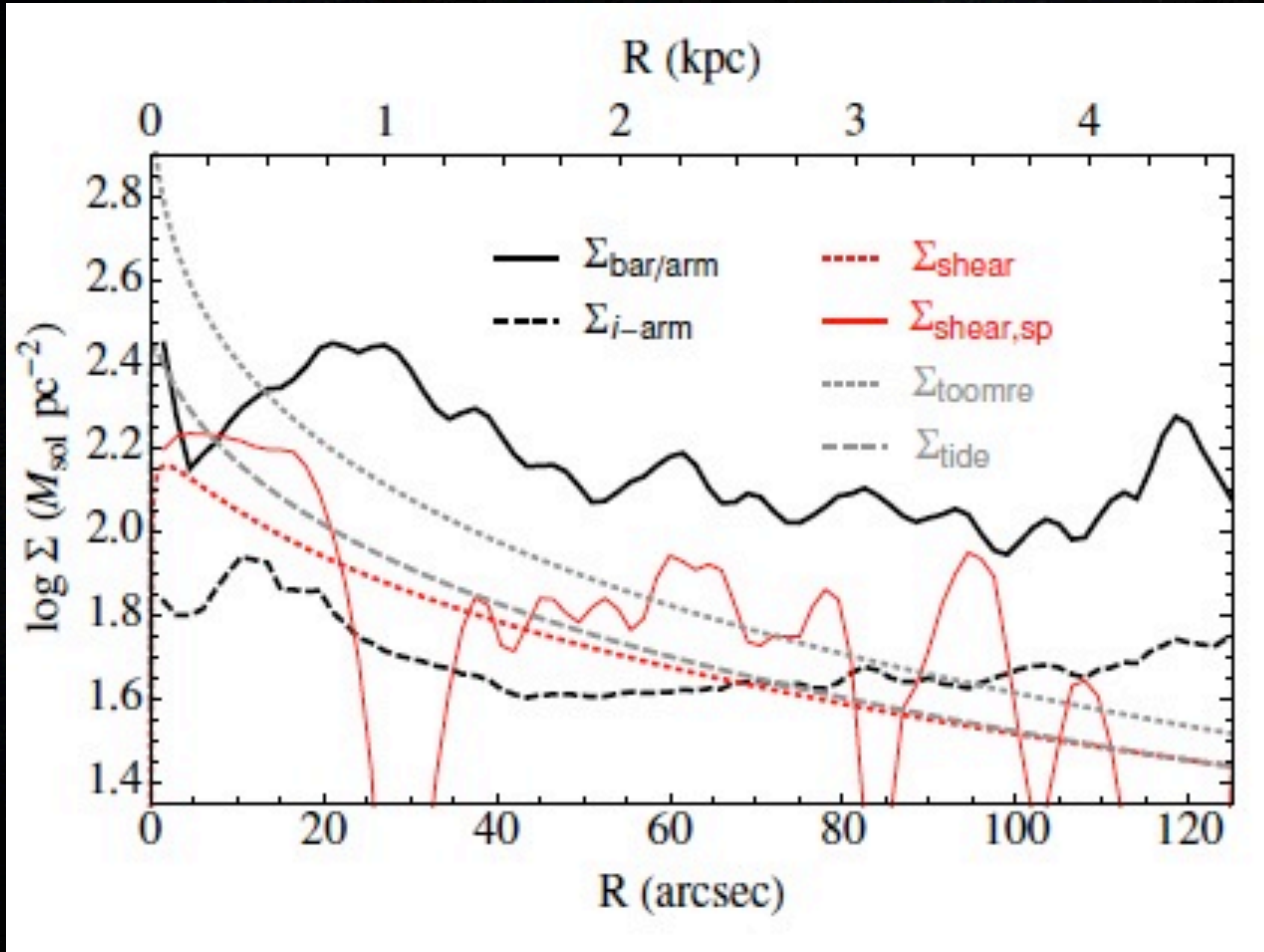


streaming motions lengthen gas depletion time

Meidt et al. (2013)

gravitational disk stability



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

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

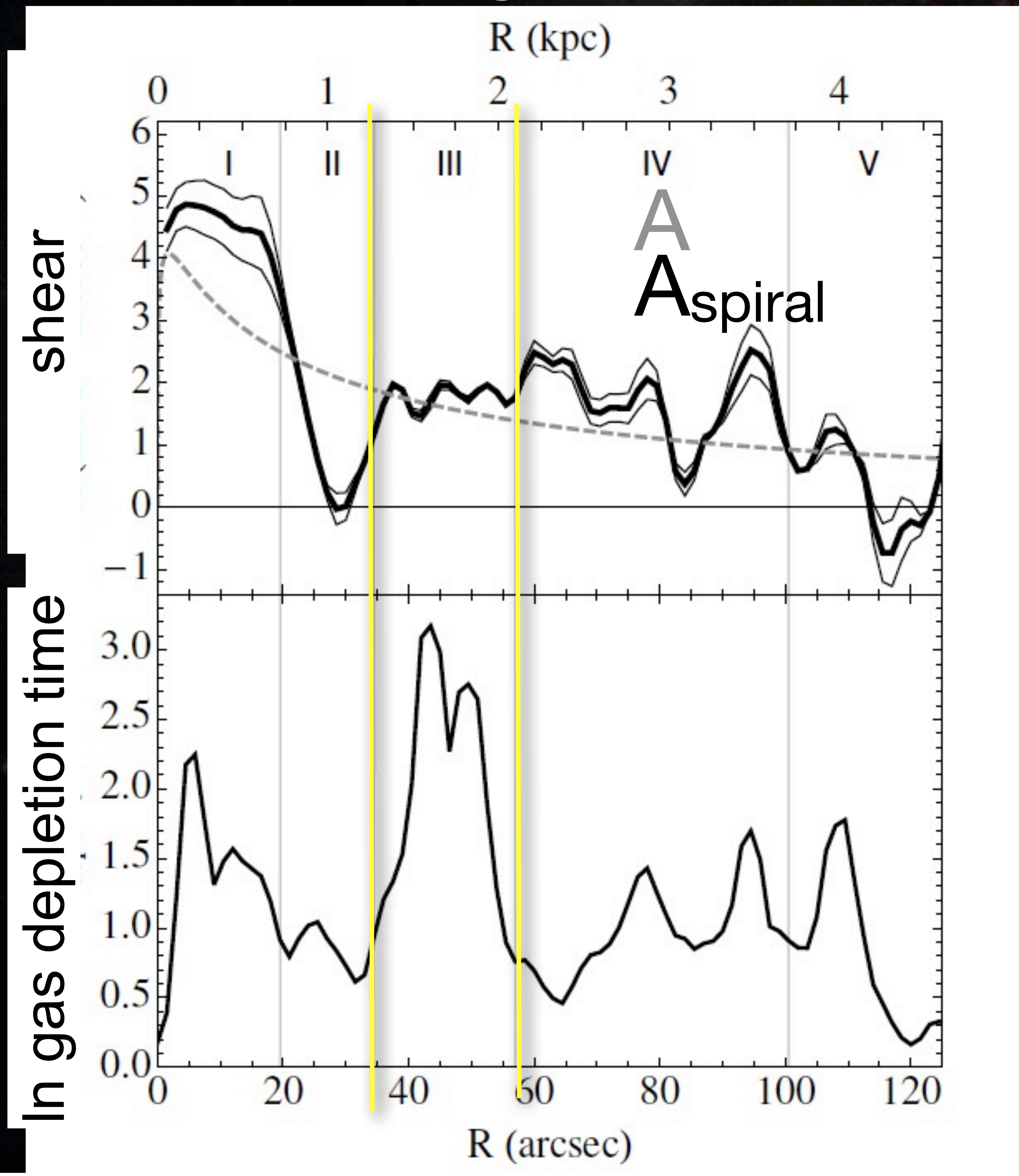
$$\Sigma_{tide} = \frac{\sigma[3A(A-B)]^{1/2}}{\pi G}$$

Meidt et al.(2013)

GMC Stabilization in M51

what shuts off star formation?

support *not* entirely from



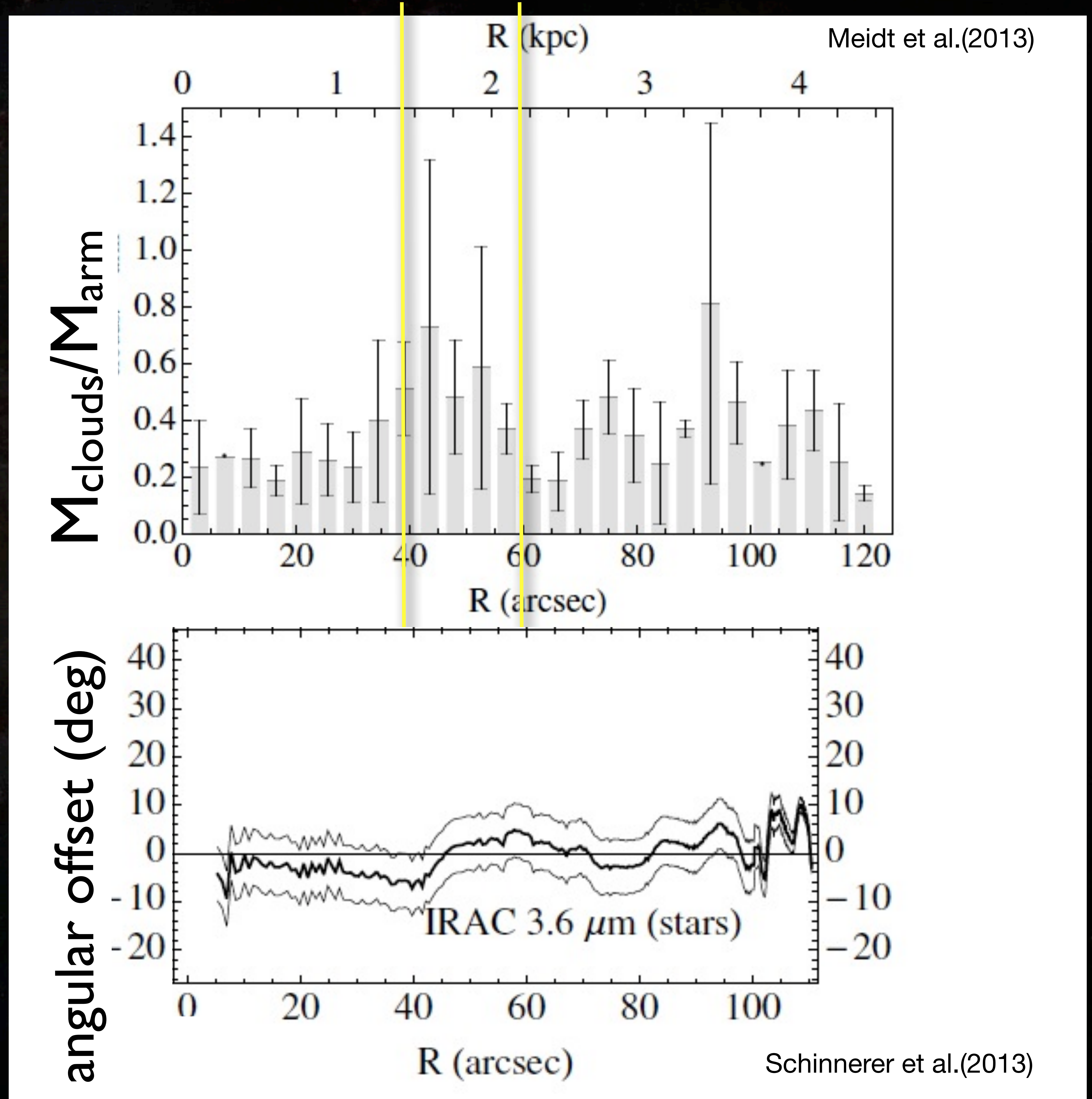
- **spiral arm shear** (Oort A; cf. Dib & Helou 2012)
- **preferentially enhanced turbulent motions** (regular σ along spiral)
- **stellar feedback** (little Hα, UV, clusters <70Myr)

Meidt et al. (2013)

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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