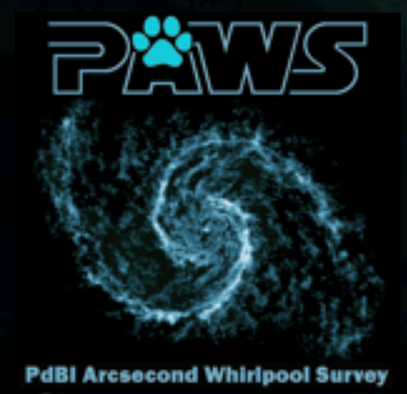
beyond the classic archetype: the role of spiral arms on *gas organization* and *star formation*

Sharon Meidt
(MPIA)



spiral structures: organize gas

Elmegreen & Elmegreen 1983
LaVigne et al. 2006

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spiral

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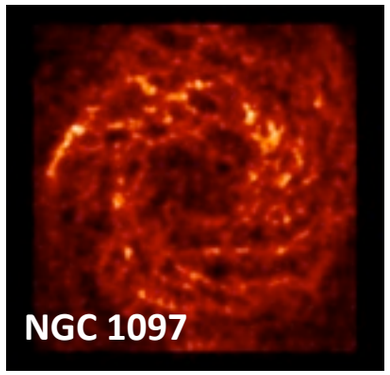

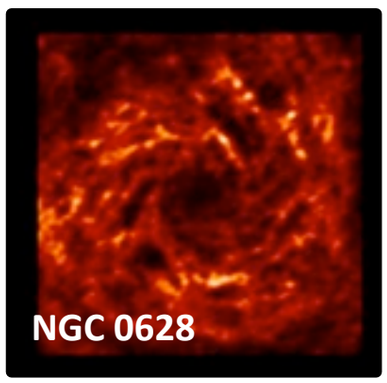

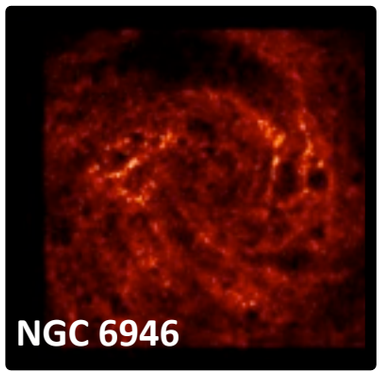

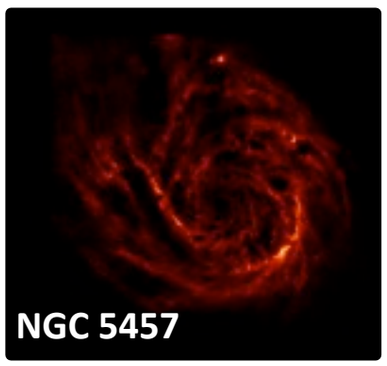

Leroy et al. (2008)

spiral

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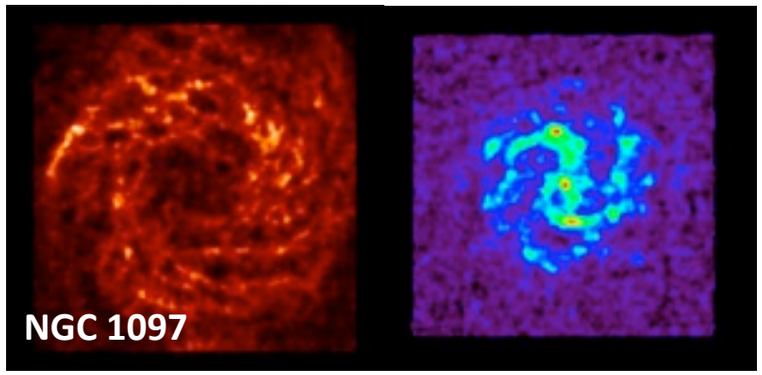

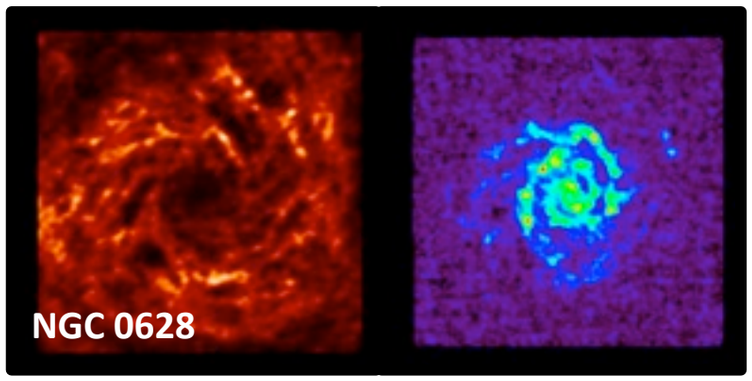

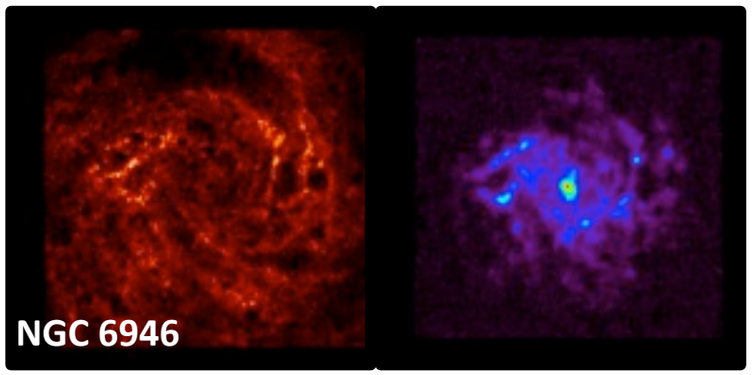

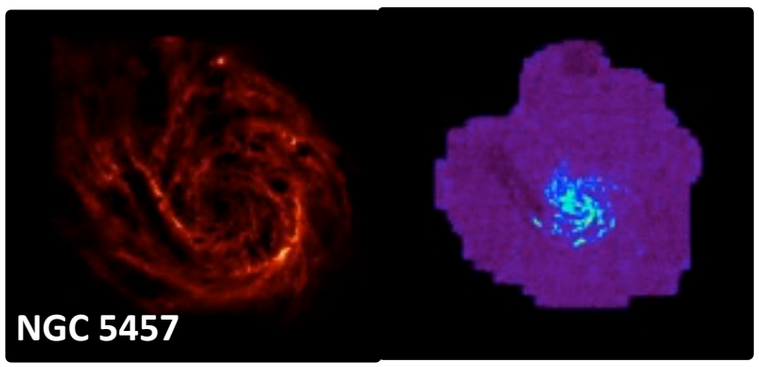

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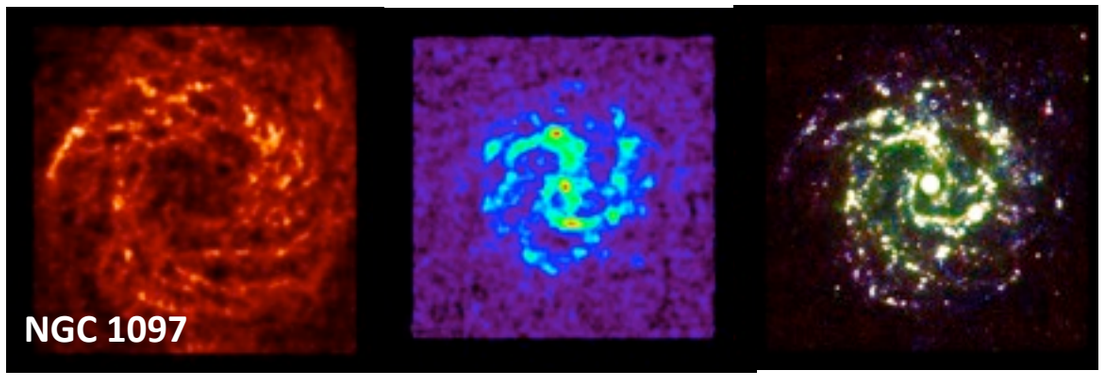

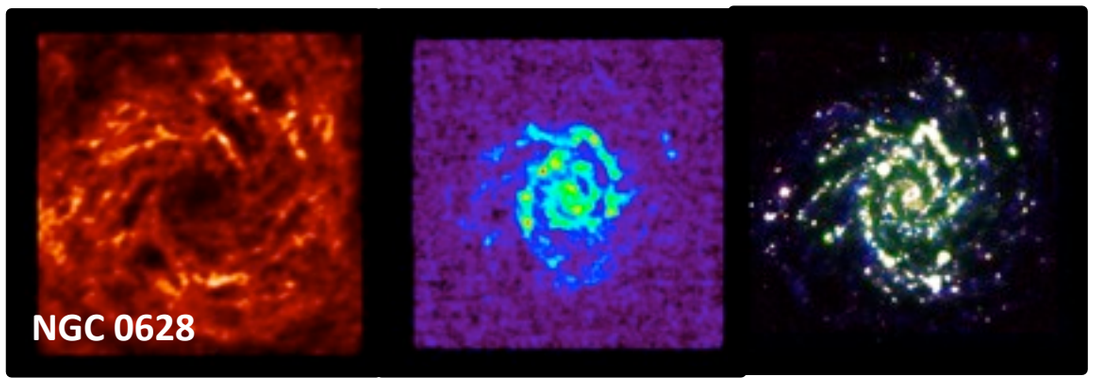

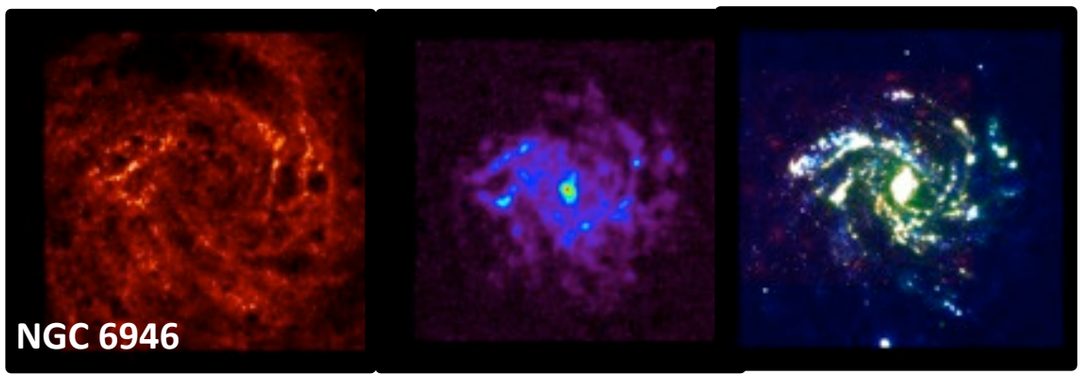

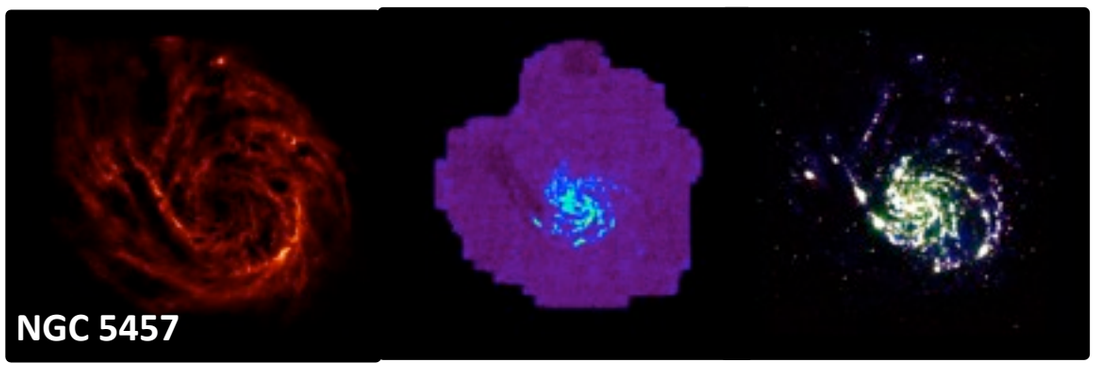

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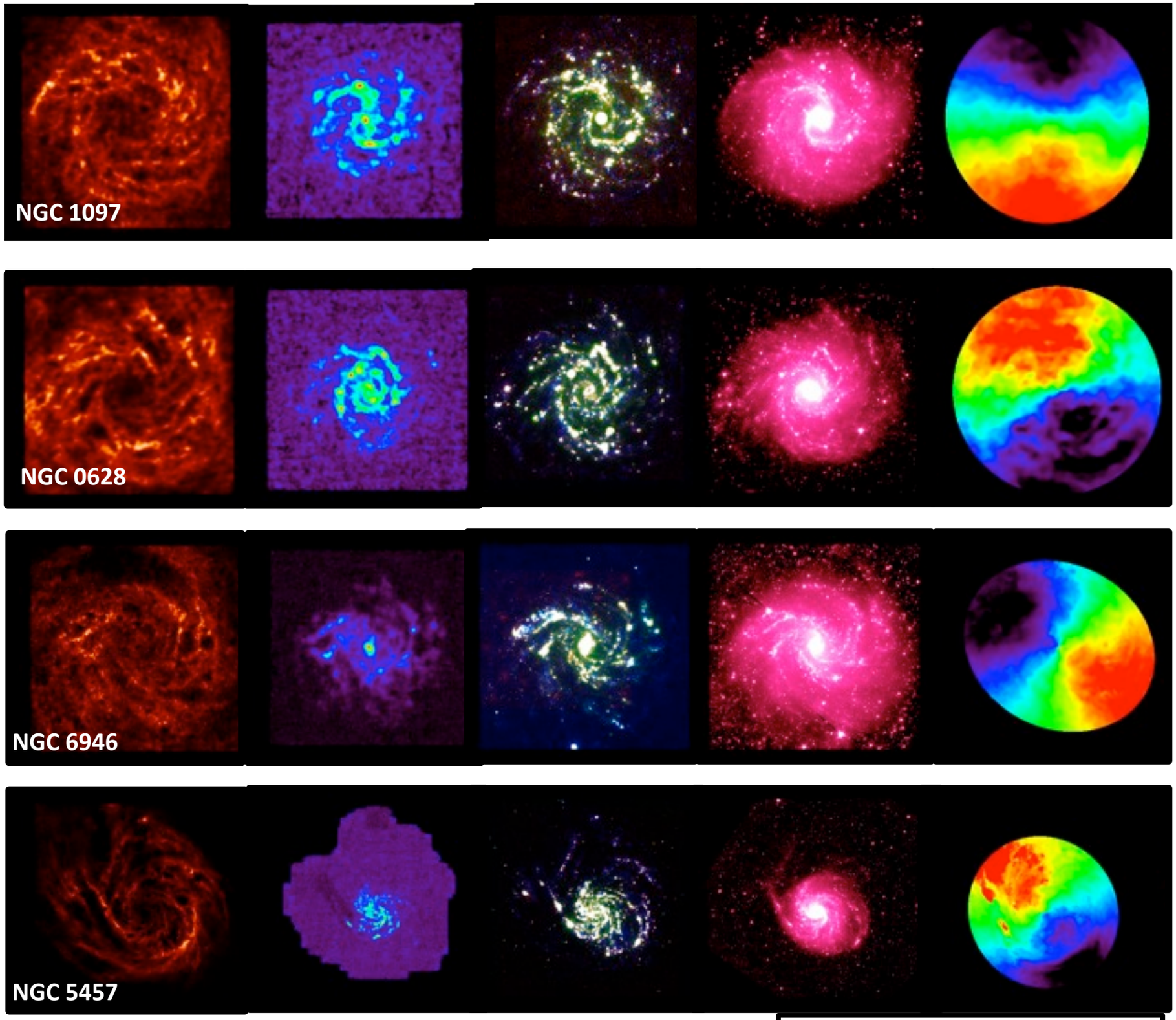

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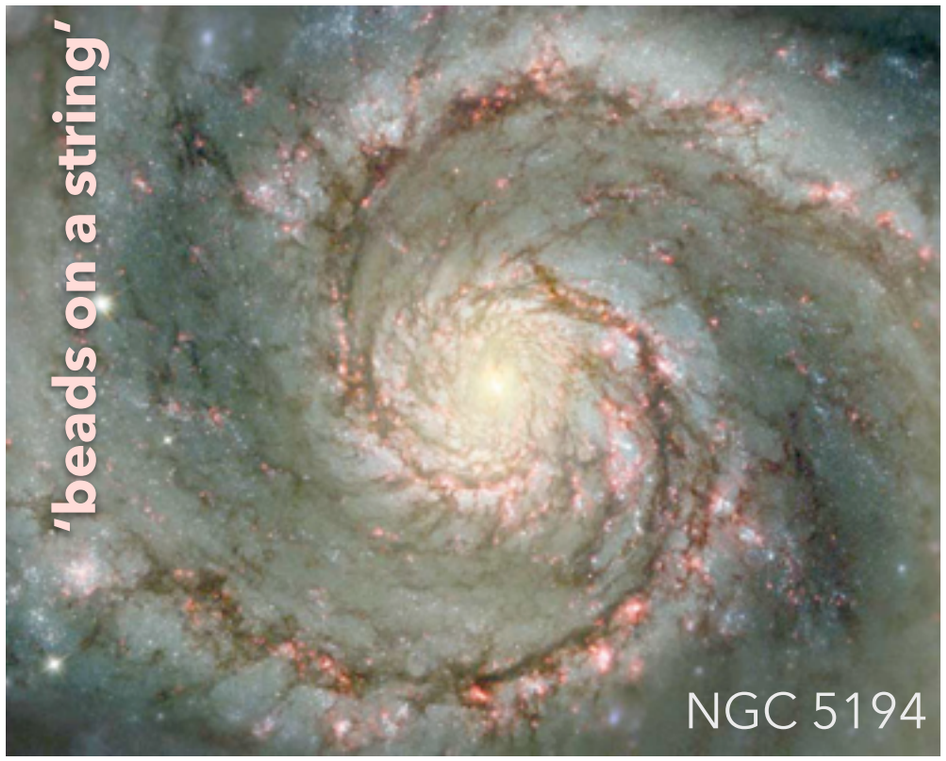
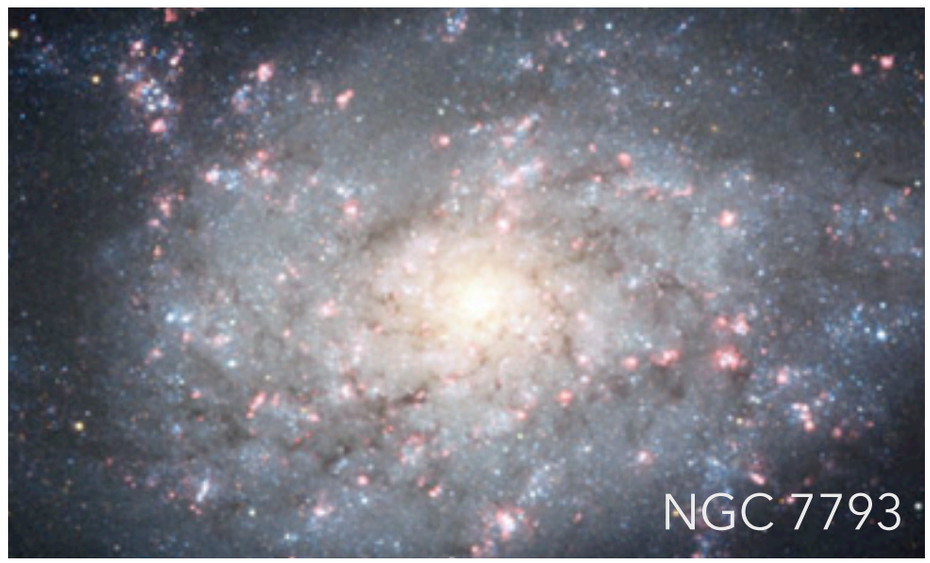




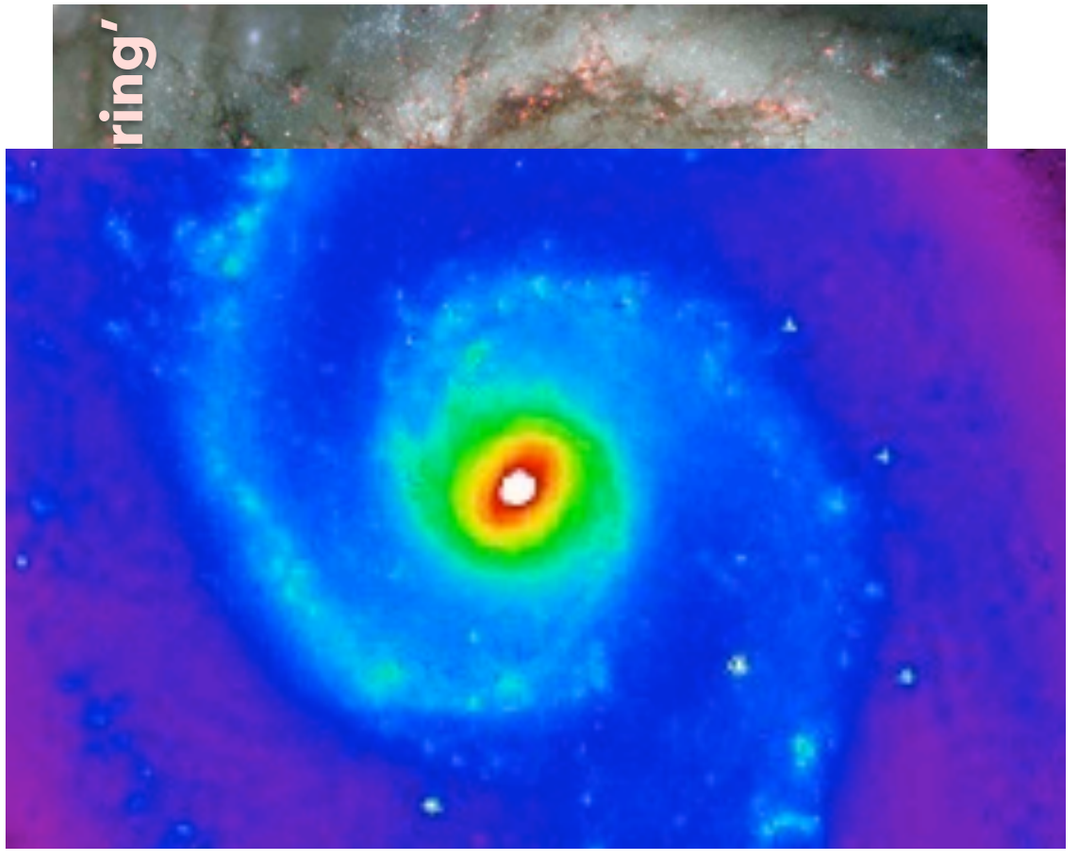
(not present in underlying stellar density)

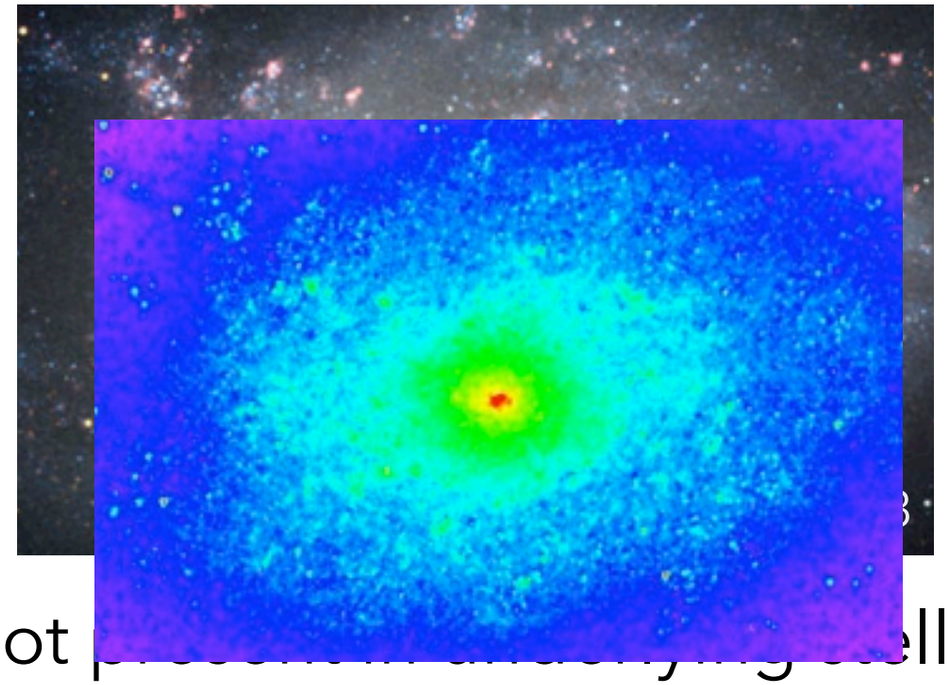
spirals **featureless**

(massive disks) (low-mass disks)

grand-design multi-arm flocculent

spiral arms: organize gas





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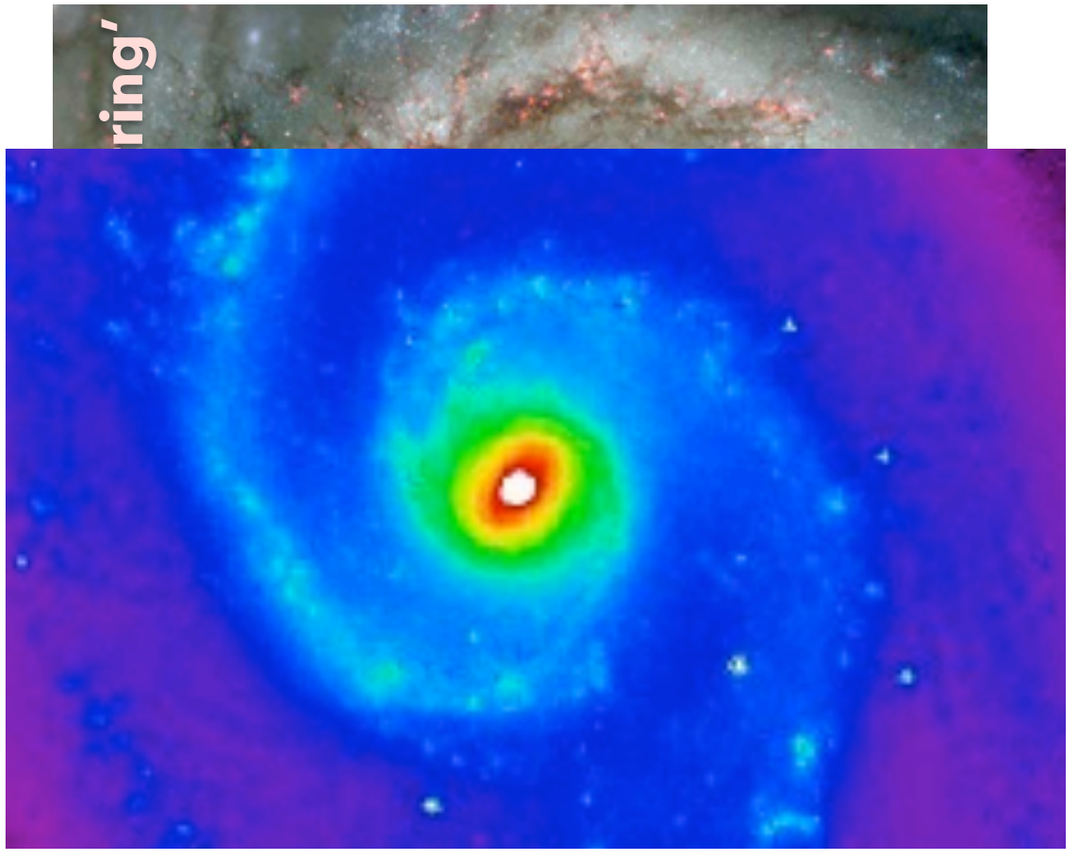

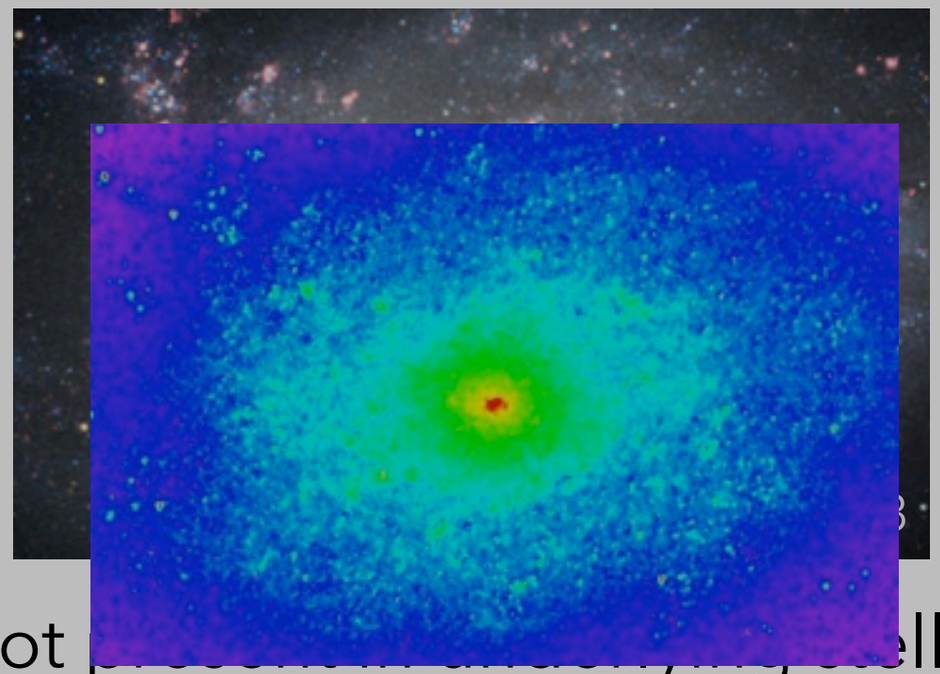

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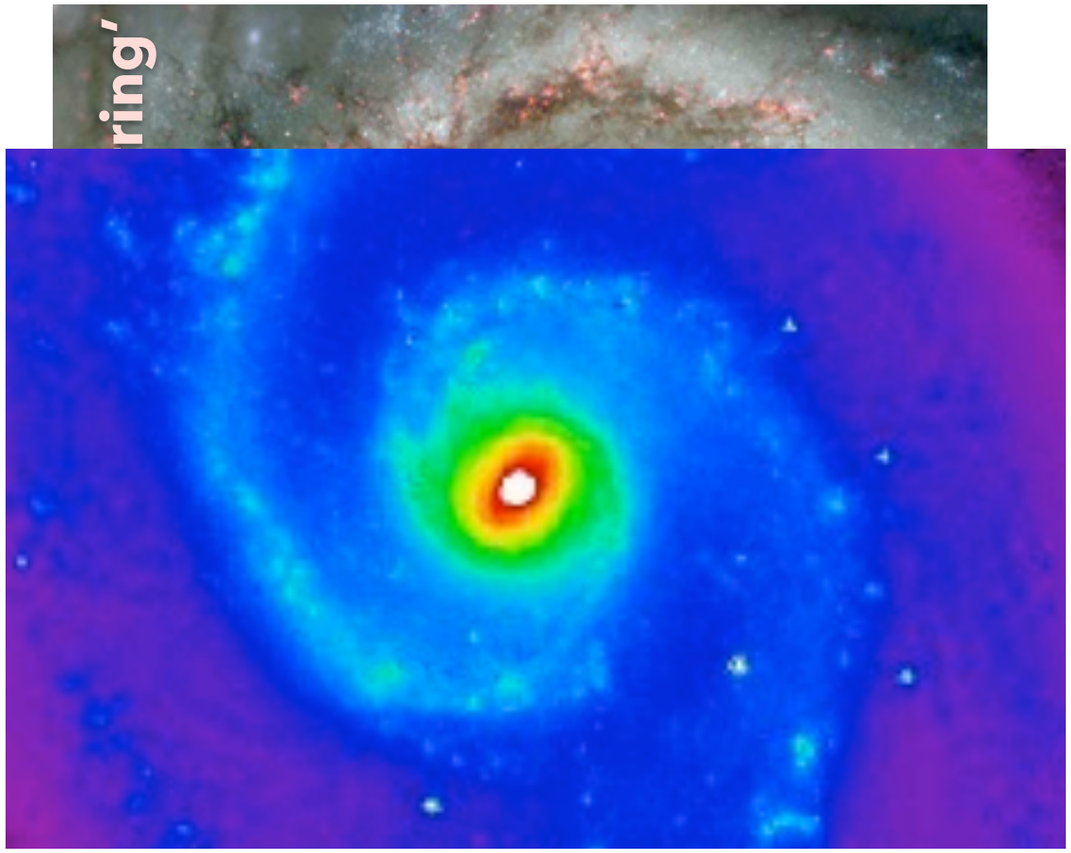

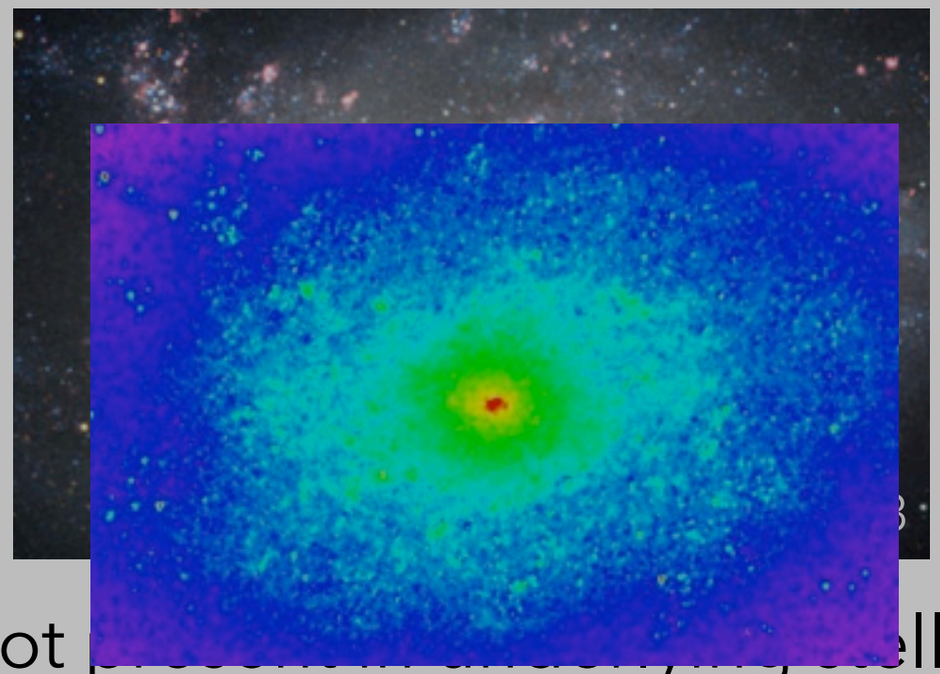

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mergers/interaction **spirals** **featureless**

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non-axisymmetric perturbations

Spitzer Survey of Stellar Structure in Nearby Galaxies
Sheth et al. (2010)
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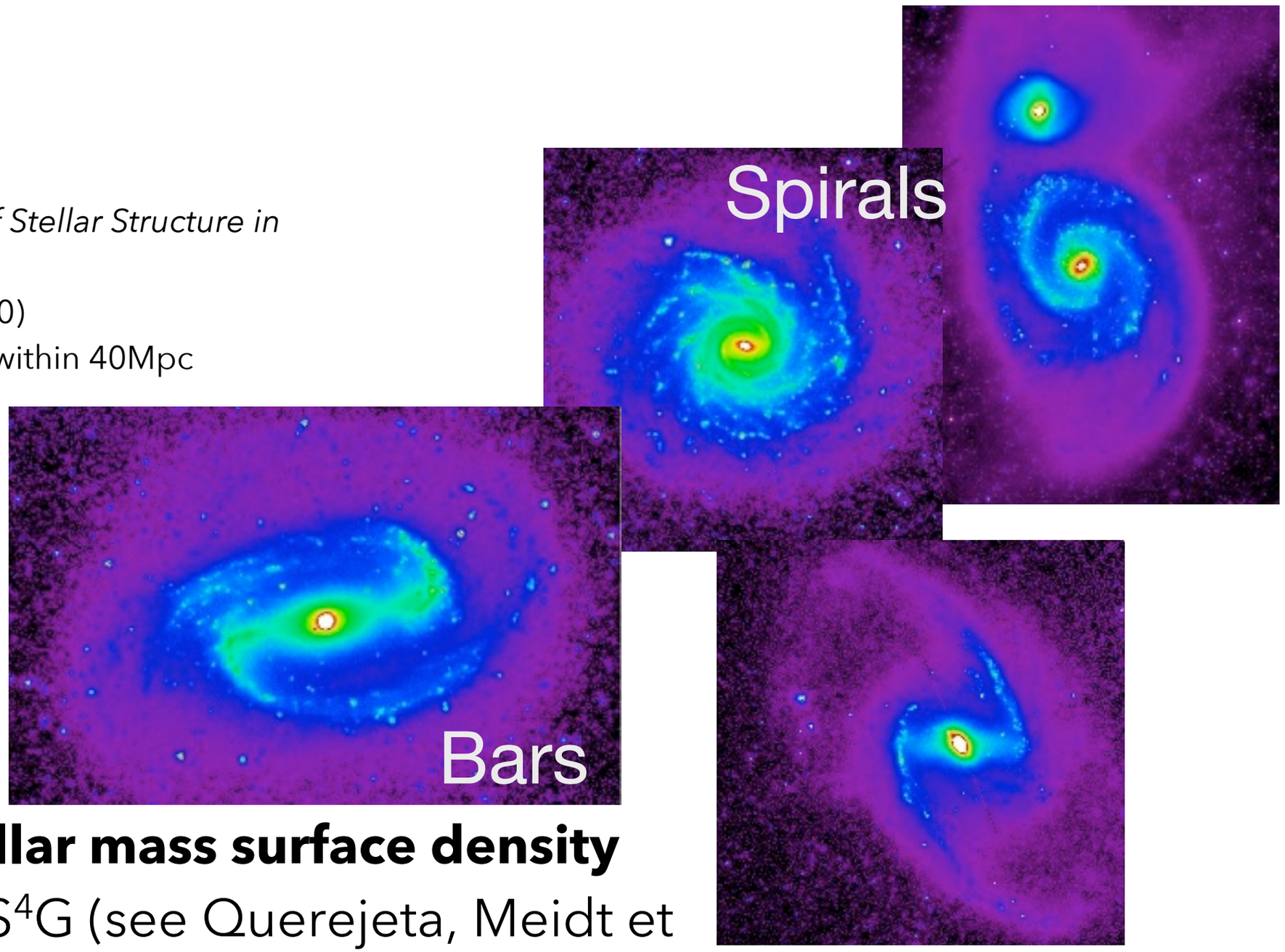
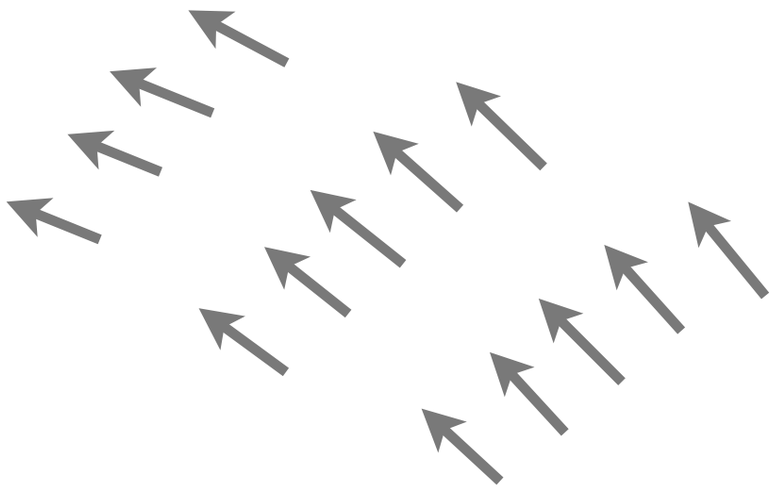


Stellar mass surface density
from S^{4}G (see Querejeta, Meidt et al. 2014)

disk galaxies

gas motions in spiral arm potentials

flow pattern through spiral arm
(i.e. **Roberts & Stewart 1987**)



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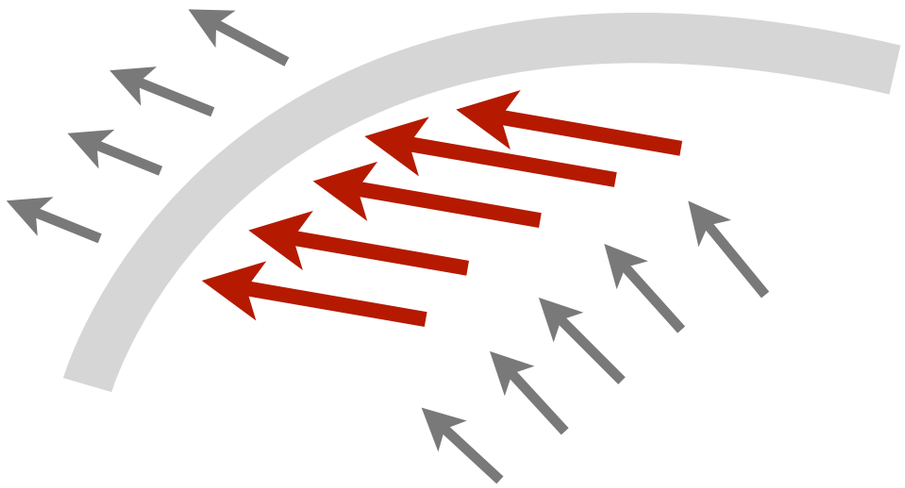

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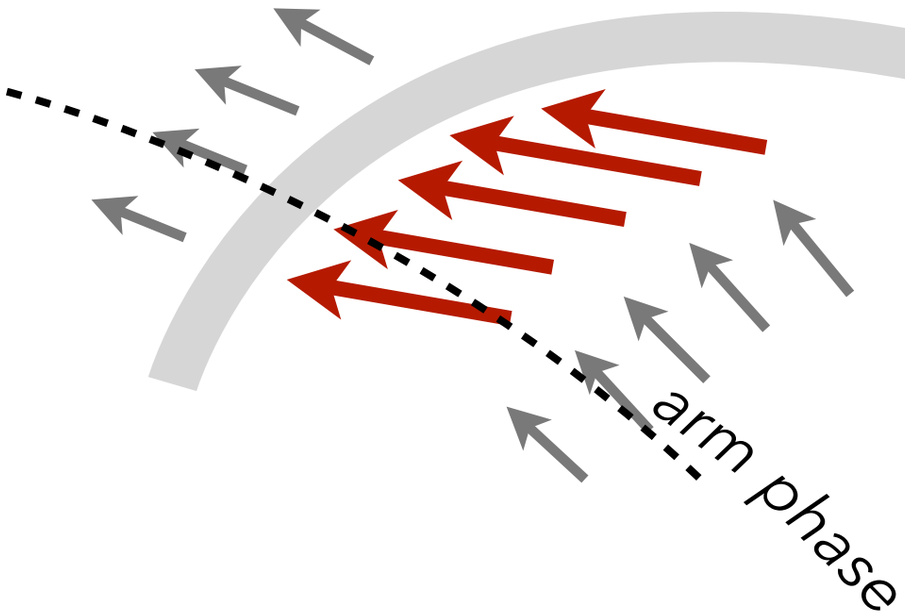

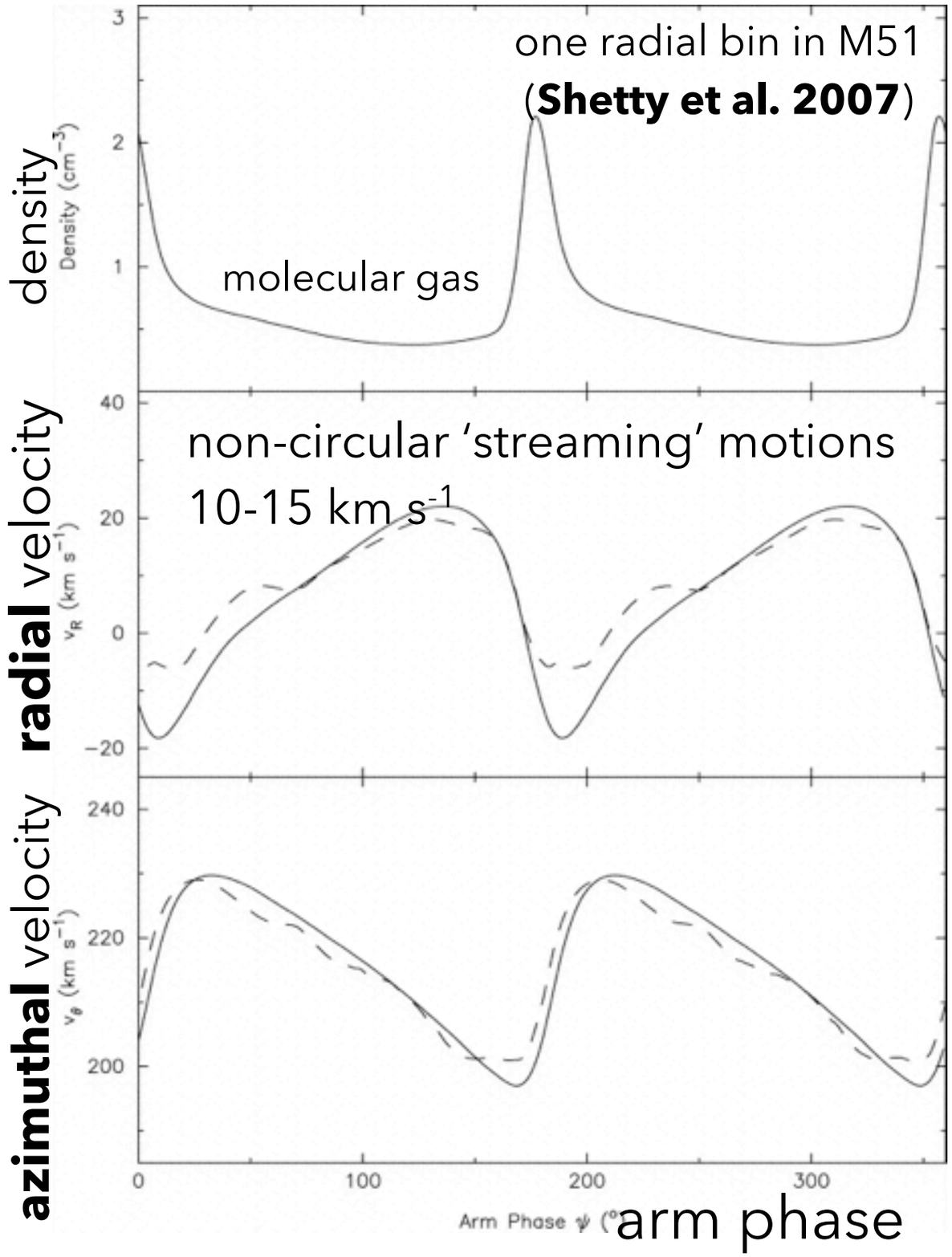

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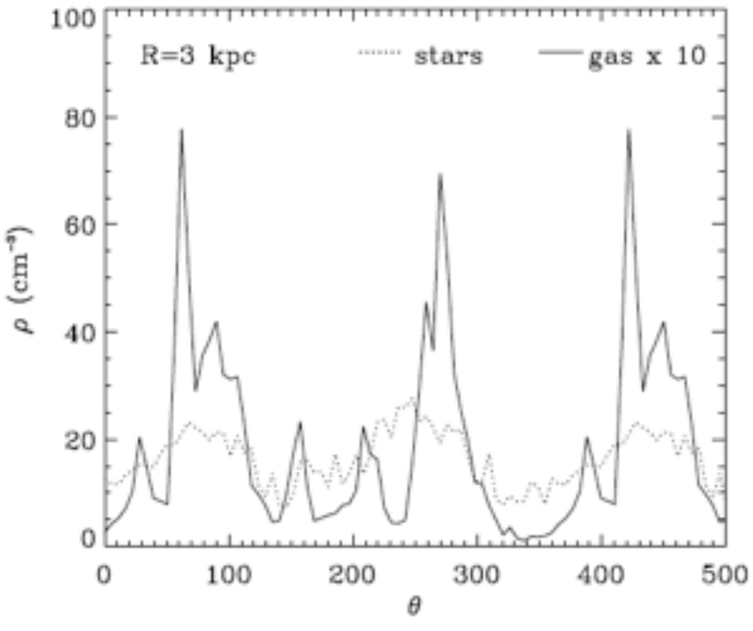
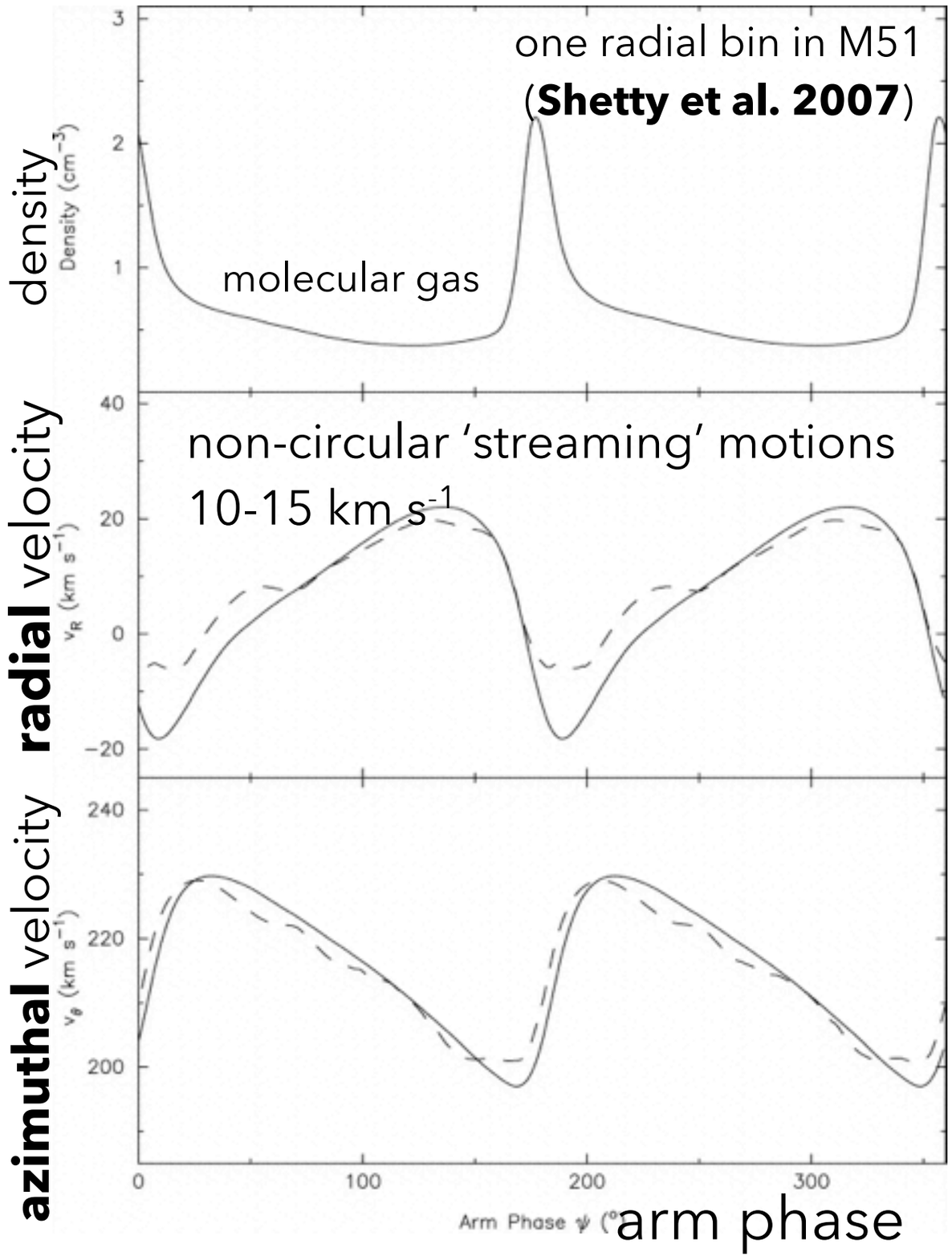
non-linear gas response

Dobbs et al. (2009)





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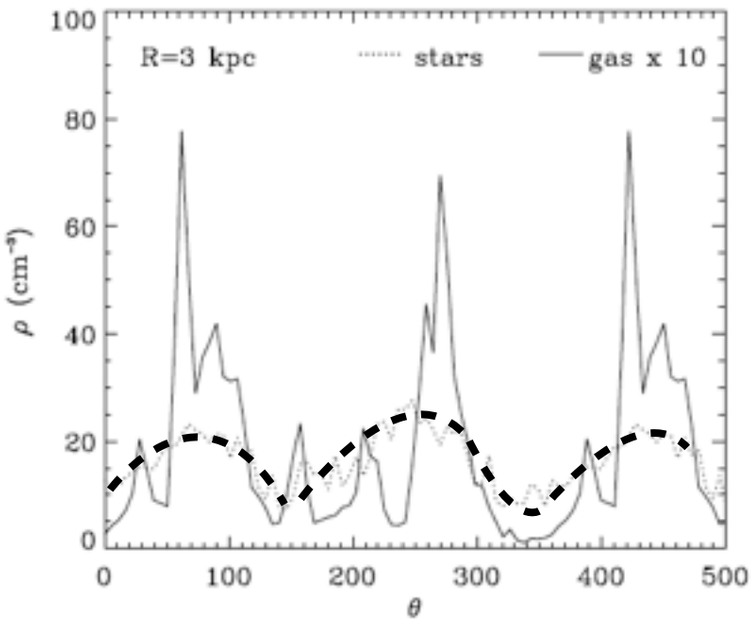
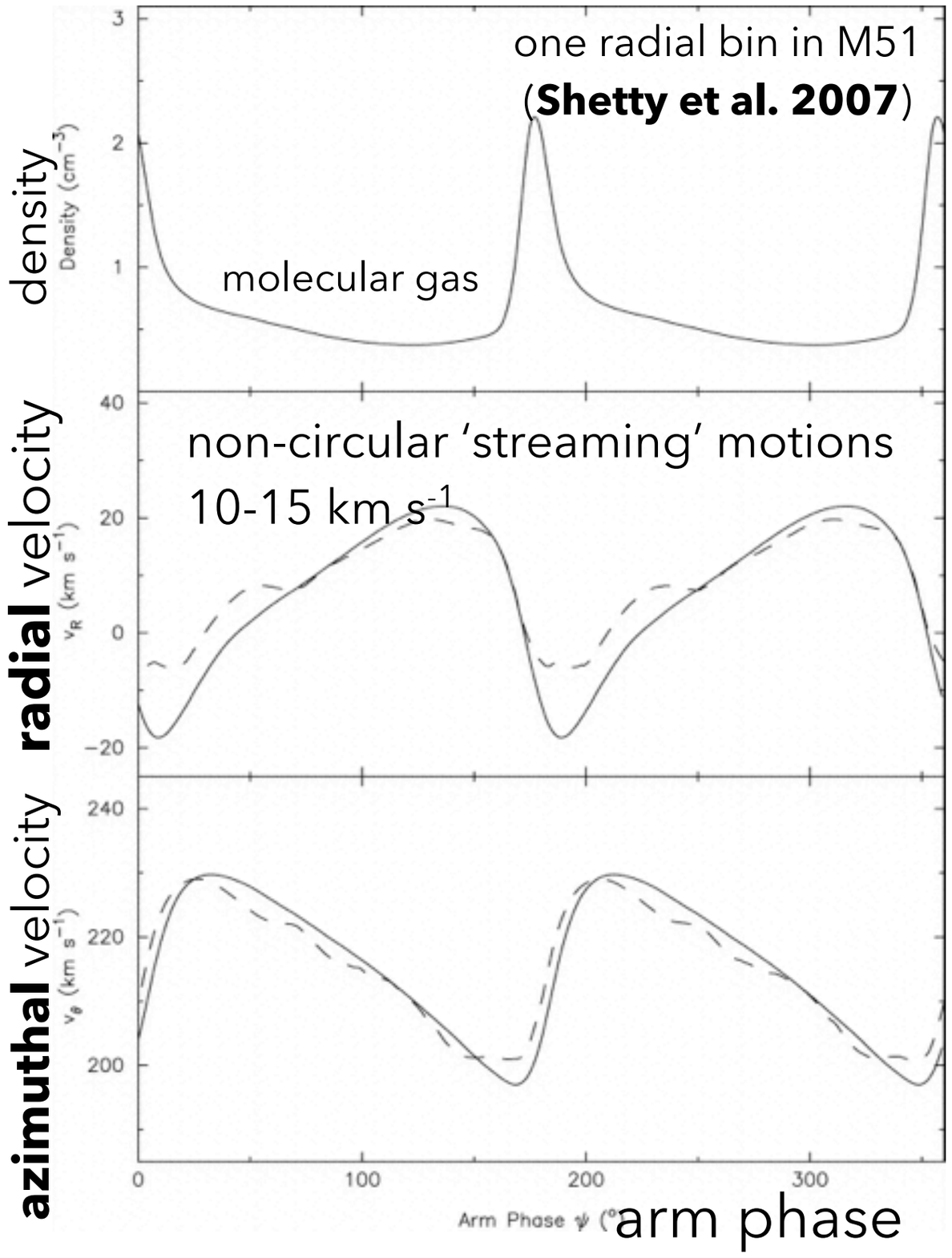
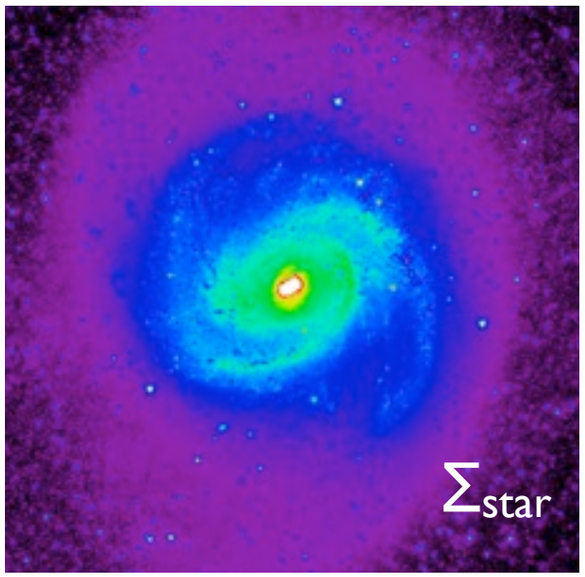
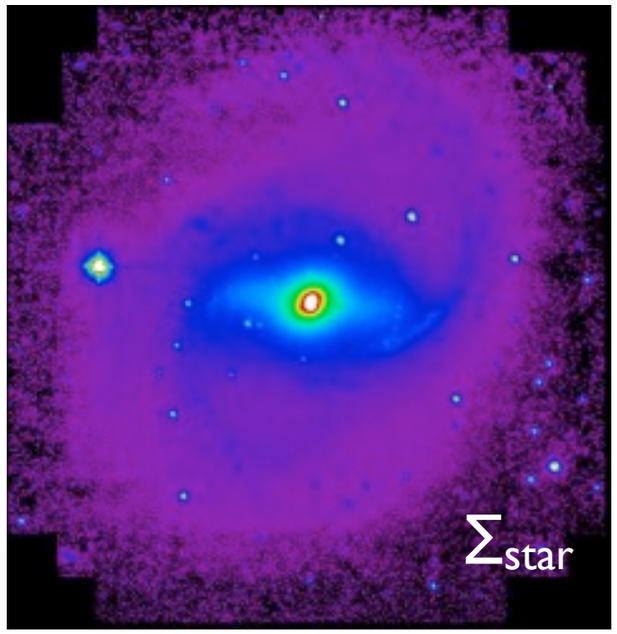




grav. torques drive gas flows

Haan et al. (2009)





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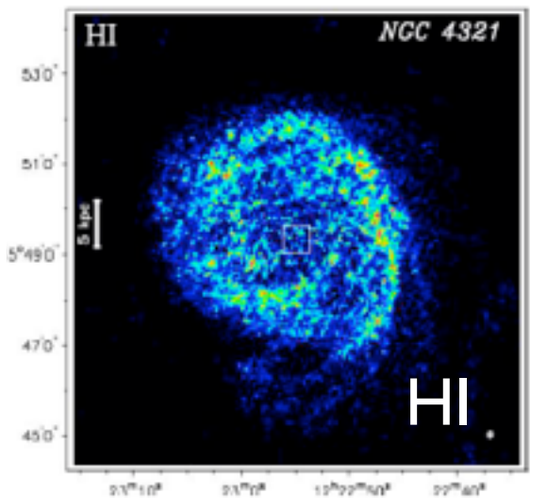

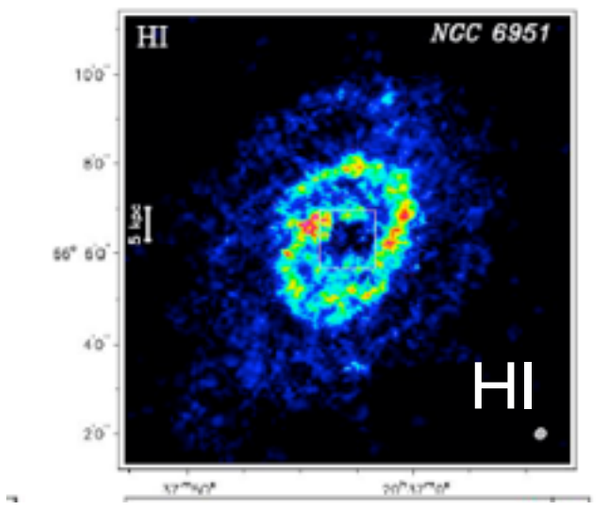

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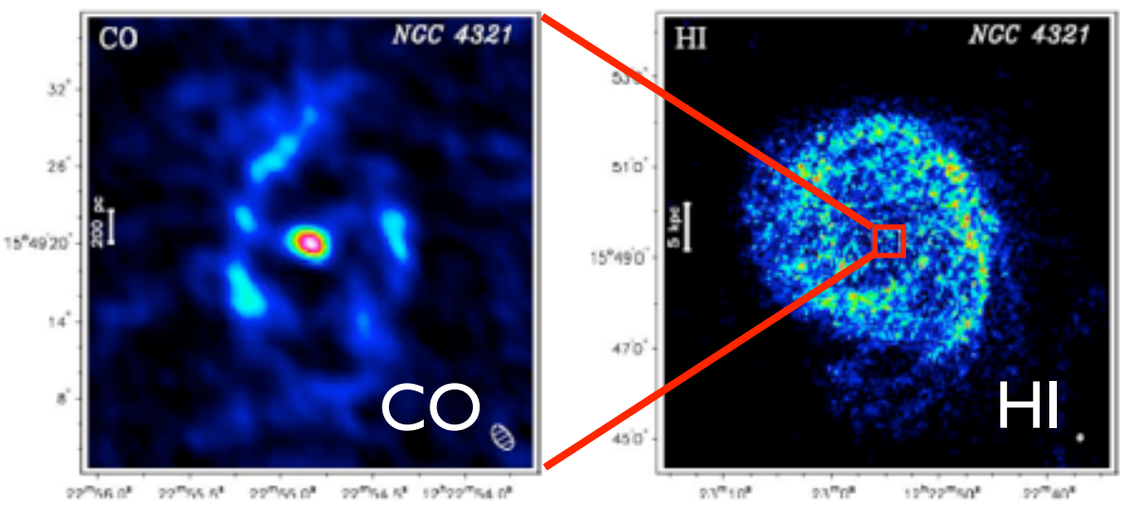

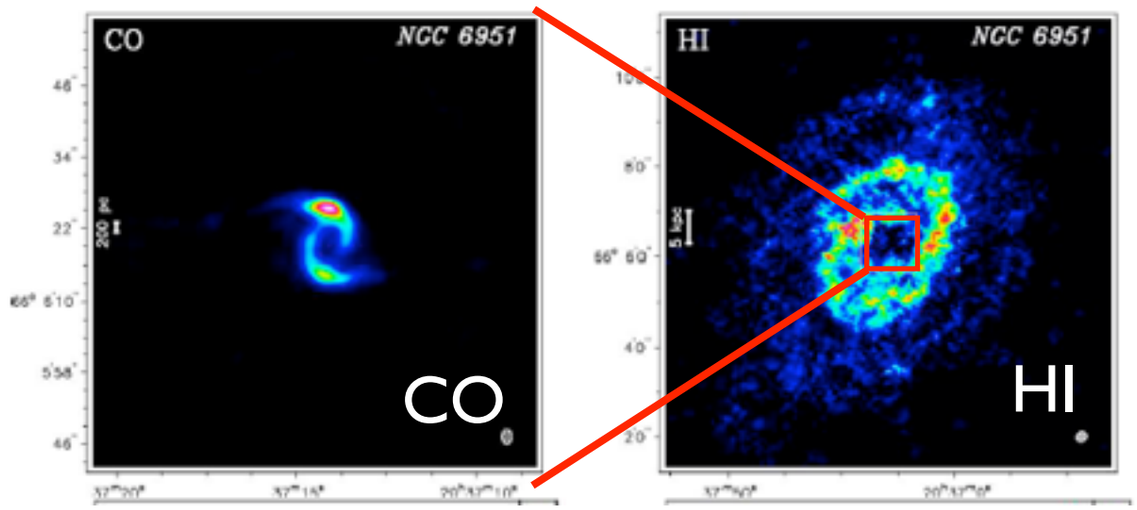

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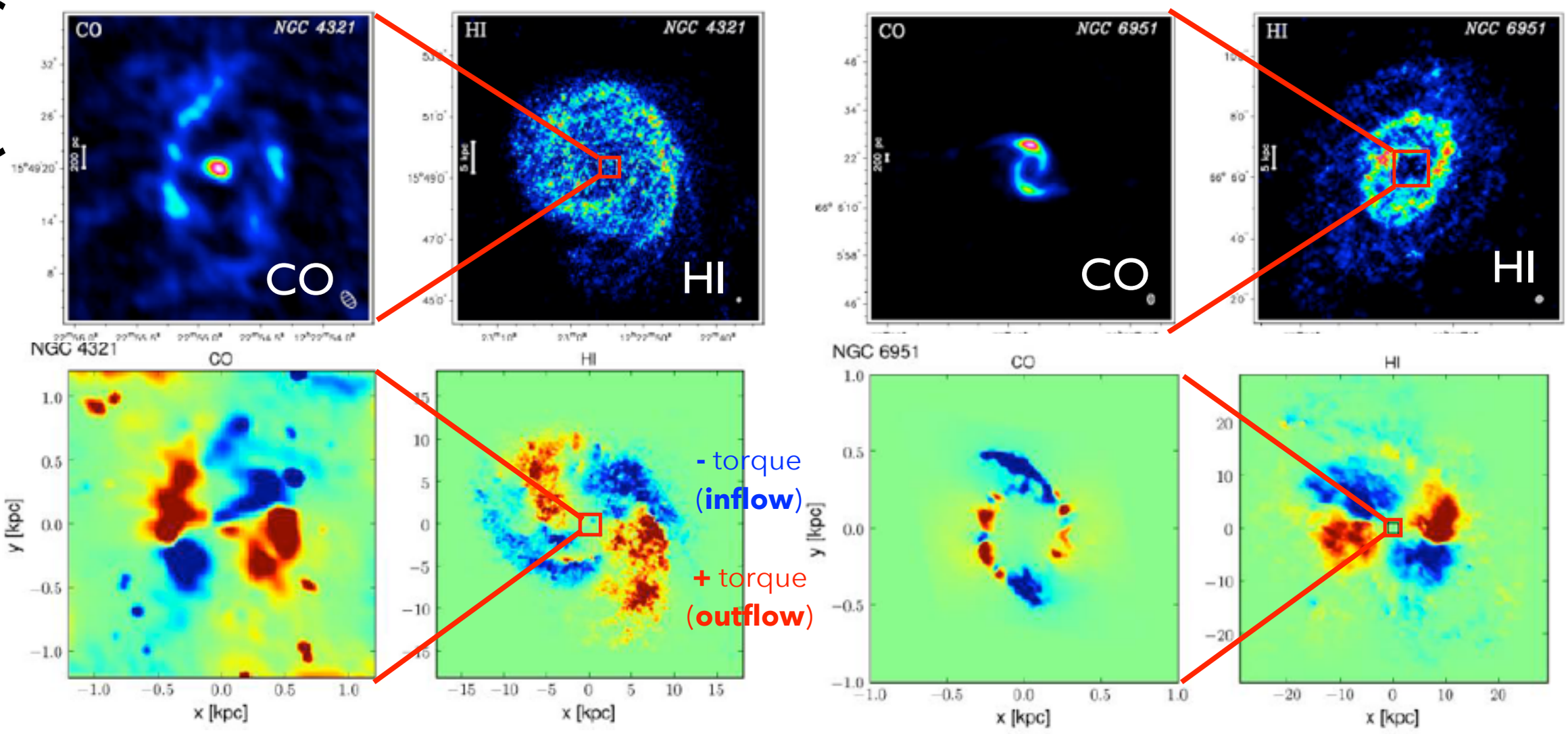

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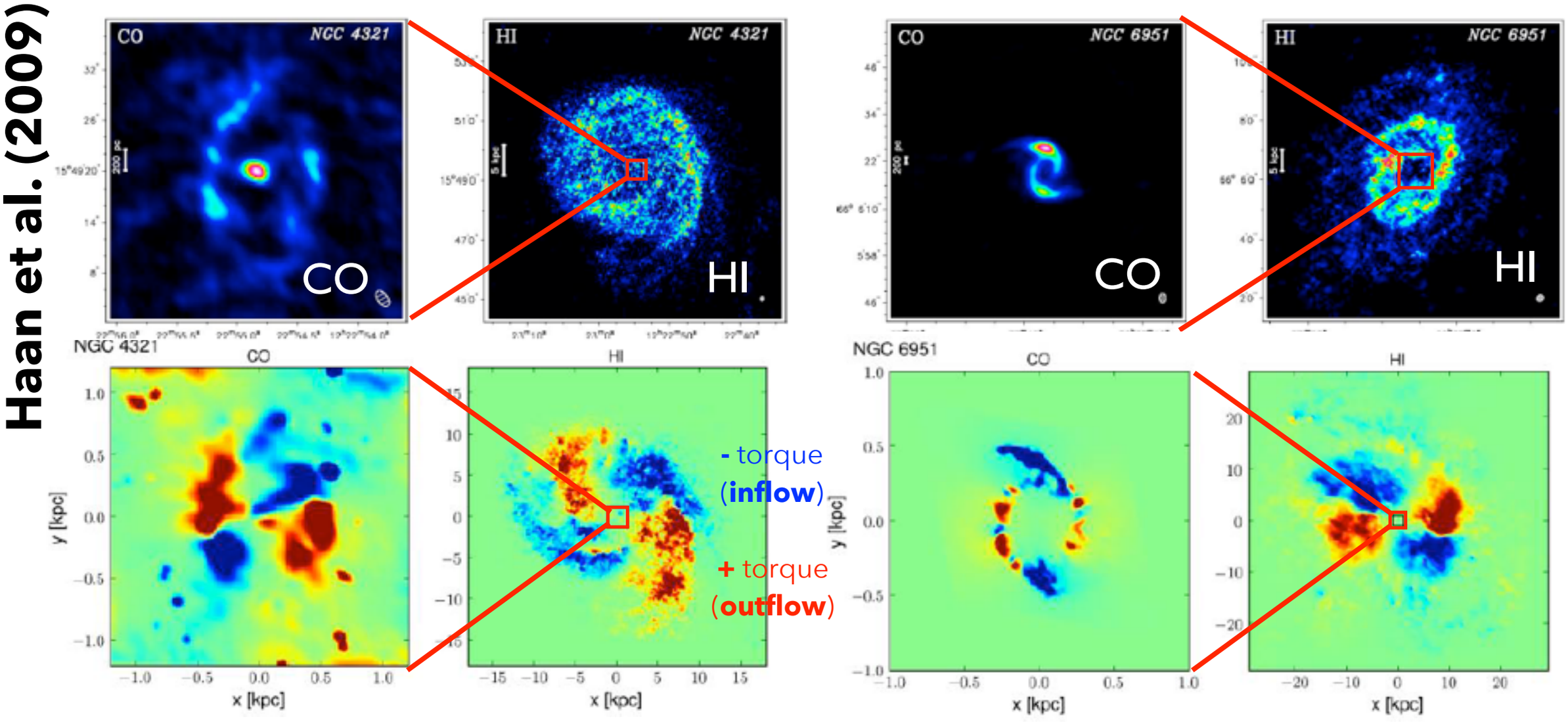

- torques drive gas from large to small radius
- bars + nuclear spirals can feed central BH growth, starburst activity

see also: Garcia-Burillo et al. (2009); Combes et al. (2014); Querejeta, Meidt et al. in prep.)

focusing our view of spiral arms

textbook:

- organize gas
- favor star formation

focusing our view of spiral arms

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next steps:

revise the standard picture

- reduce shear ??

focusing our view of spiral arms

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focusing our view of spiral arms

<u>textbook</u>:

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<u>next steps</u>:

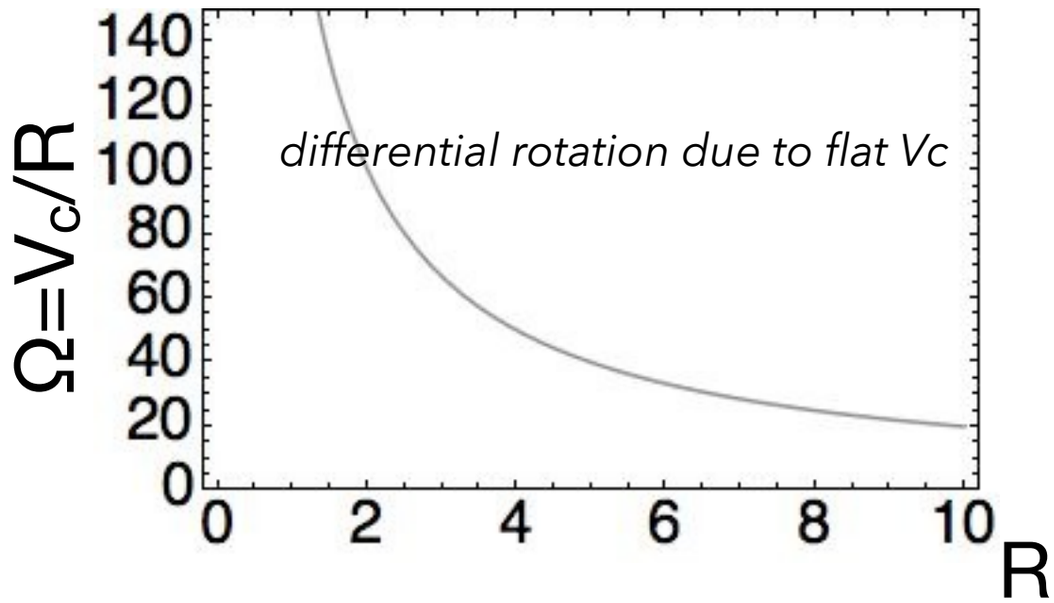
revise the standard picture

- reduce shear ??
- ‘trigger’ star formation??
    - influence cloud properties
    - stabilize gas, suppress star formation

spiral arms: where SF occurs

- galactic shear disfavors growth of structure
  (build-up of molec. material, clouds; stabilizes clouds)

- spiral streaming motions counter shear
  [*that's why SF occurs there*]



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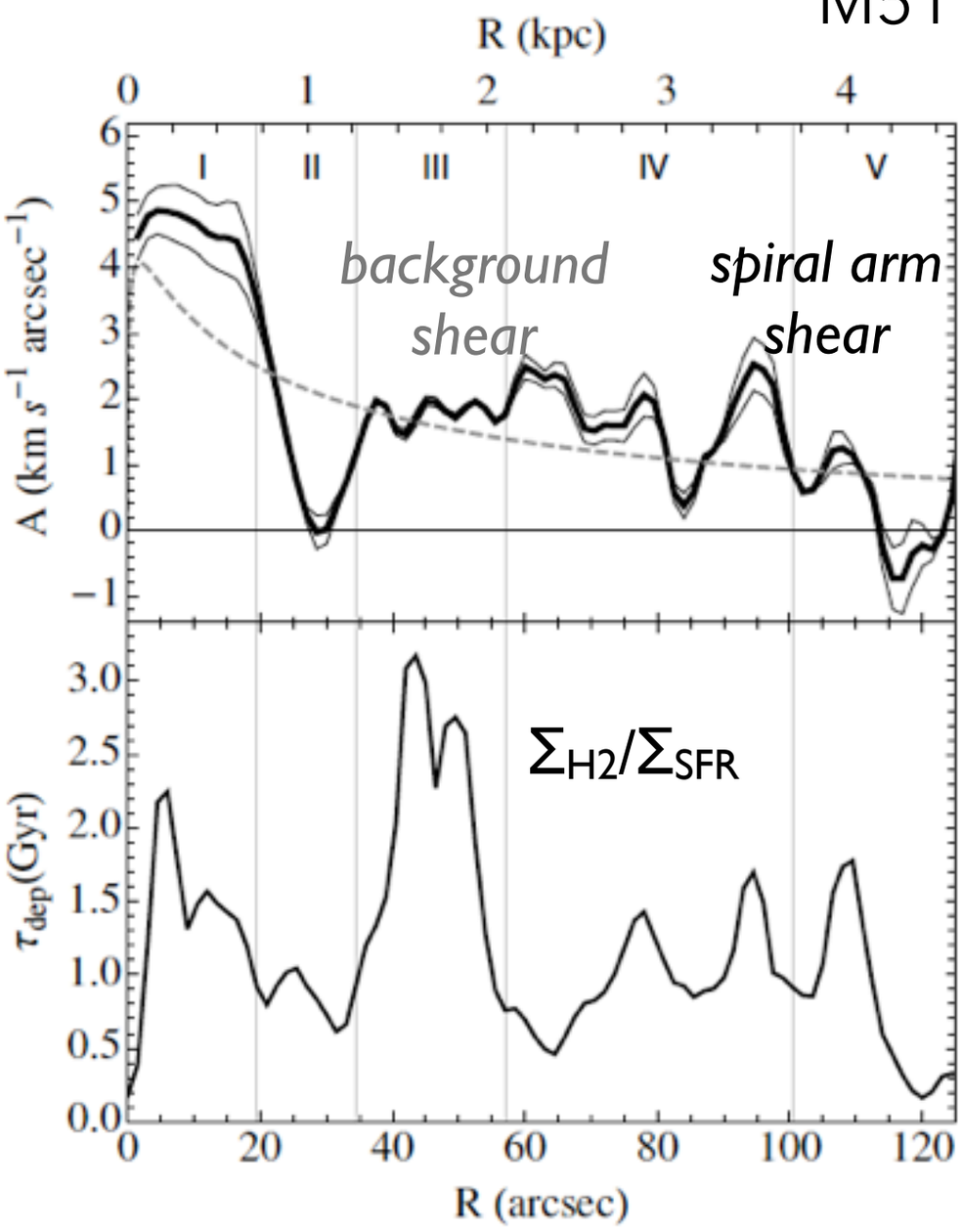
  - strong shear variations in M51
  - shear is not the stabilizer expected in MW GPS
  - see also Elmegreen (1995): gas surface density mostly exceeds shear crit. density

M51



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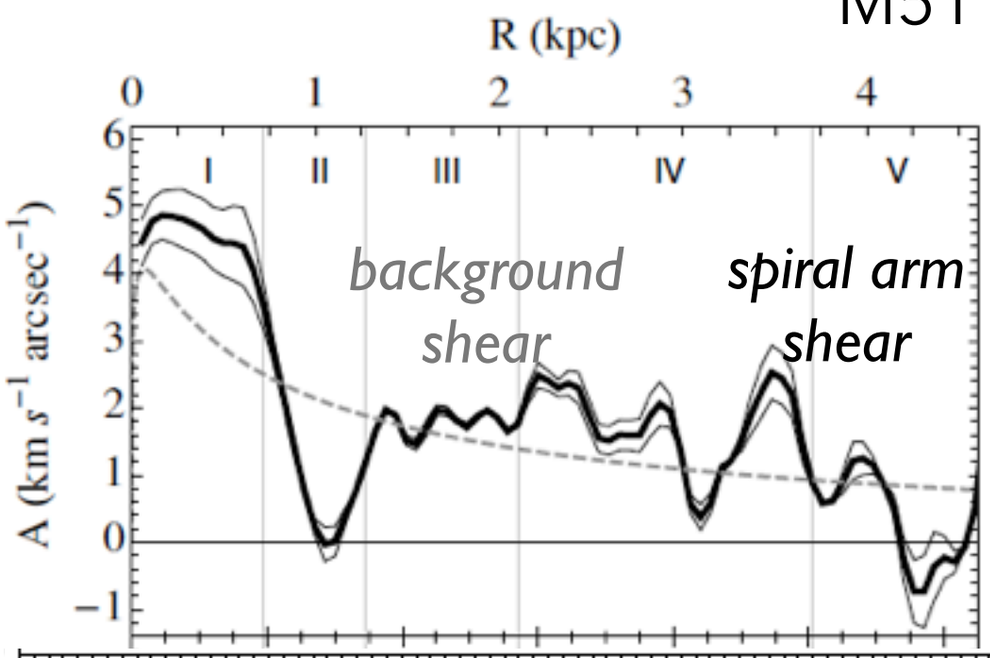

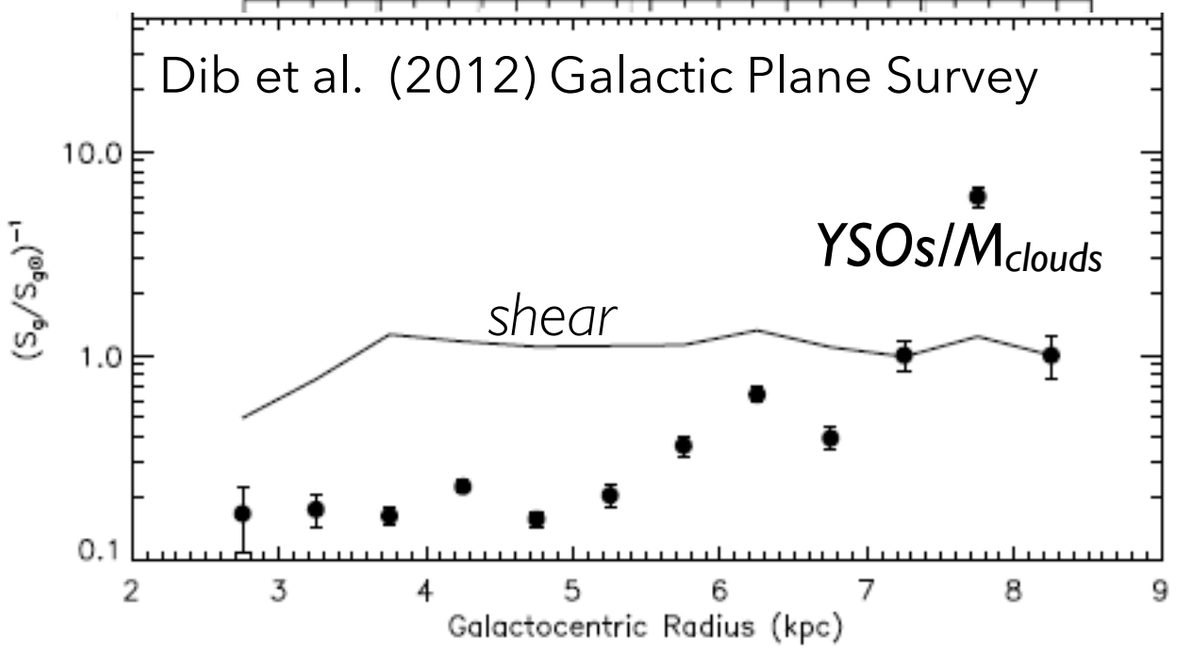

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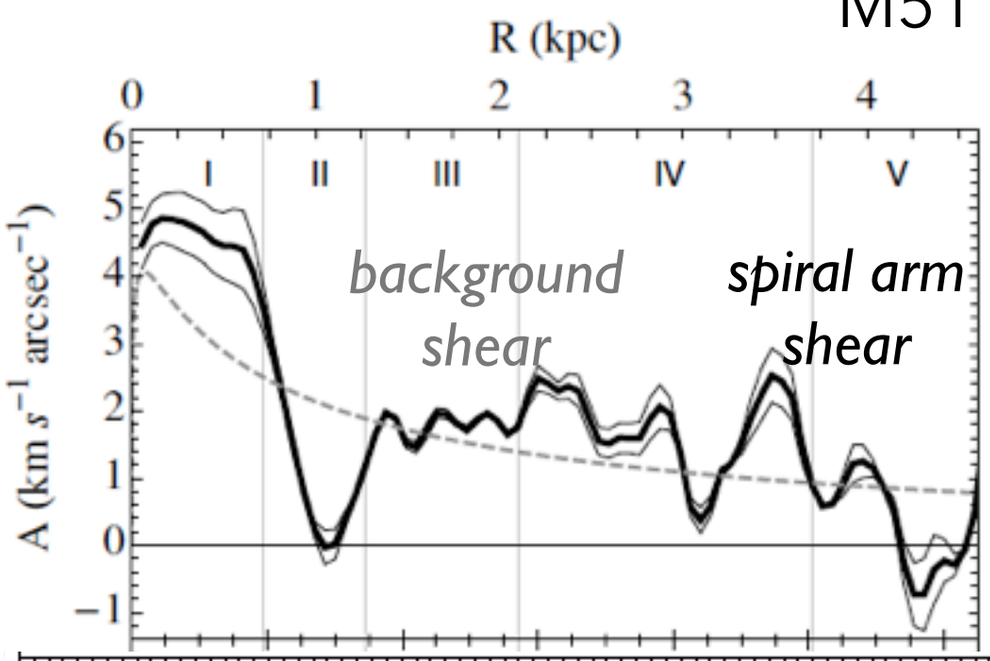
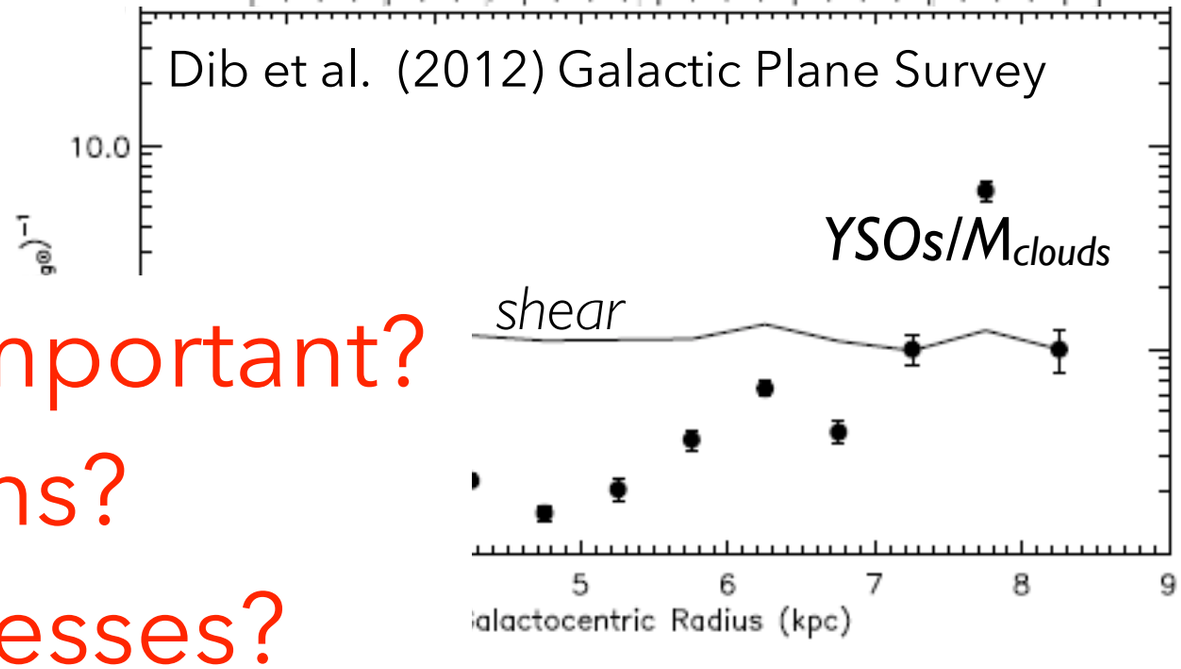


Dib et al. (2012) Galactic Plane Survey

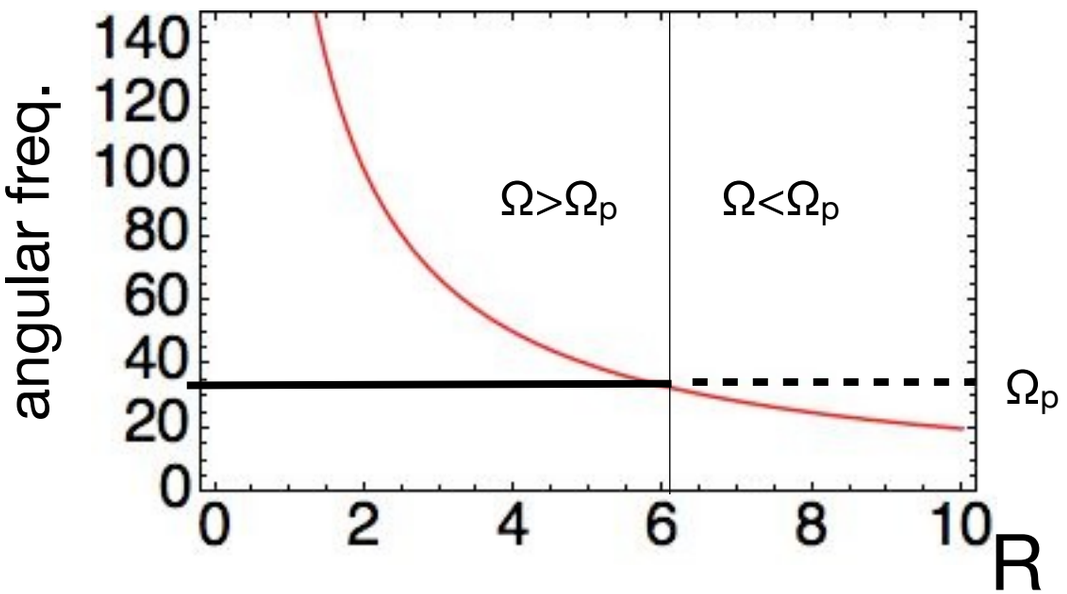


just clouds themselves important?

local gas conditions?

other dynamical processes?

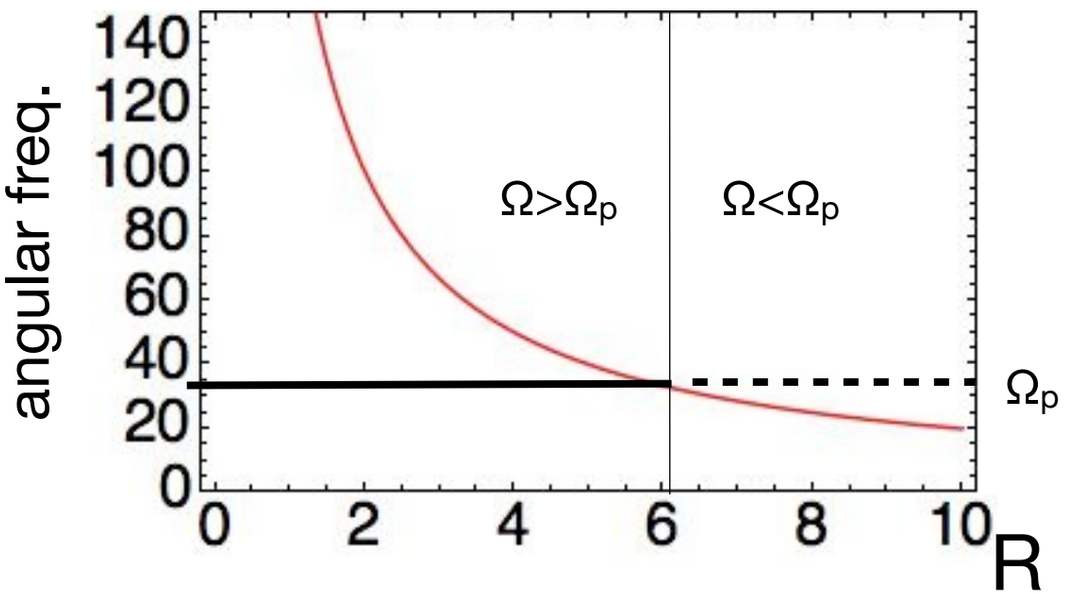
spiral density waves: offset star formation

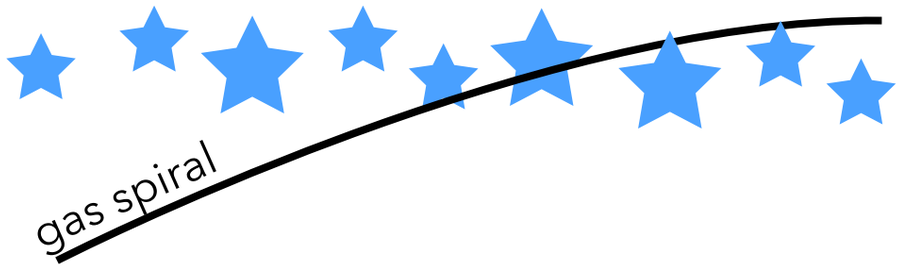


spiral density waves:

- self-reinforcing, present in density + gravitational potential (viz. Lin-Shu QSSS)
- well-defined dispersion relation *(shape, number, pattern speed* Ω_p *over set radial range)*
- co-rotating frame in which spiral fixed

spiral density waves: offset star formation





★ =HII region, t=10Myr

see also Egusa et al. (2004) for a nice sketch

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offset star formation ??

- Egusa et al. (2009): 5/13 SINGS galaxies
  6″ BIMA SONG CO ≈ **500 pc**

- Foyle et al. (2009): 0/12 SINGS galaxies
  13″ HERACLES CO + THINGS HI ≈ **1 kpc**
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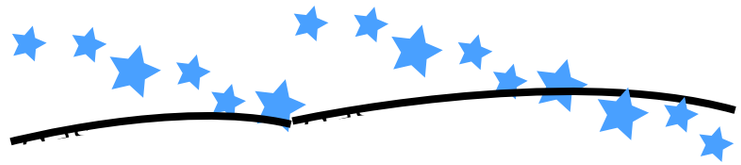
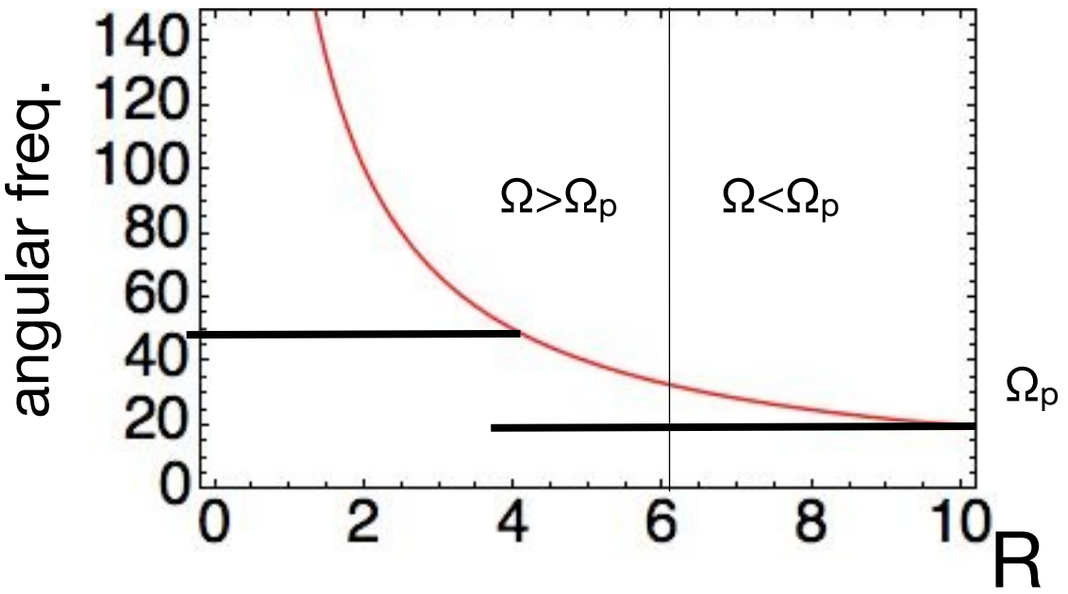
- high res. key: typical spiral width
  ~300pc

offset star formation ??

- Egusa et al. (2009): 5/13 SINGS galaxies
  6″ BIMA SONG CO ≈ **500 pc**

- Foyle et al. (2009): 0/12 SINGS galaxies
  13″ HERACLES CO + THINGS HI ≈ **1 kpc**
  (using angular cross-correlation)





- high res. key: typical spiral width ~300pc
- multiple distinct pattern speeds?? Meidt et al. (2008, 2009); Rautiainen & Salo (2006); D'Onghia et al. (2012)

offset star formation ??

- **delayed** star formation (in spurs NOT arms? Schinnerer et al., in prep.)

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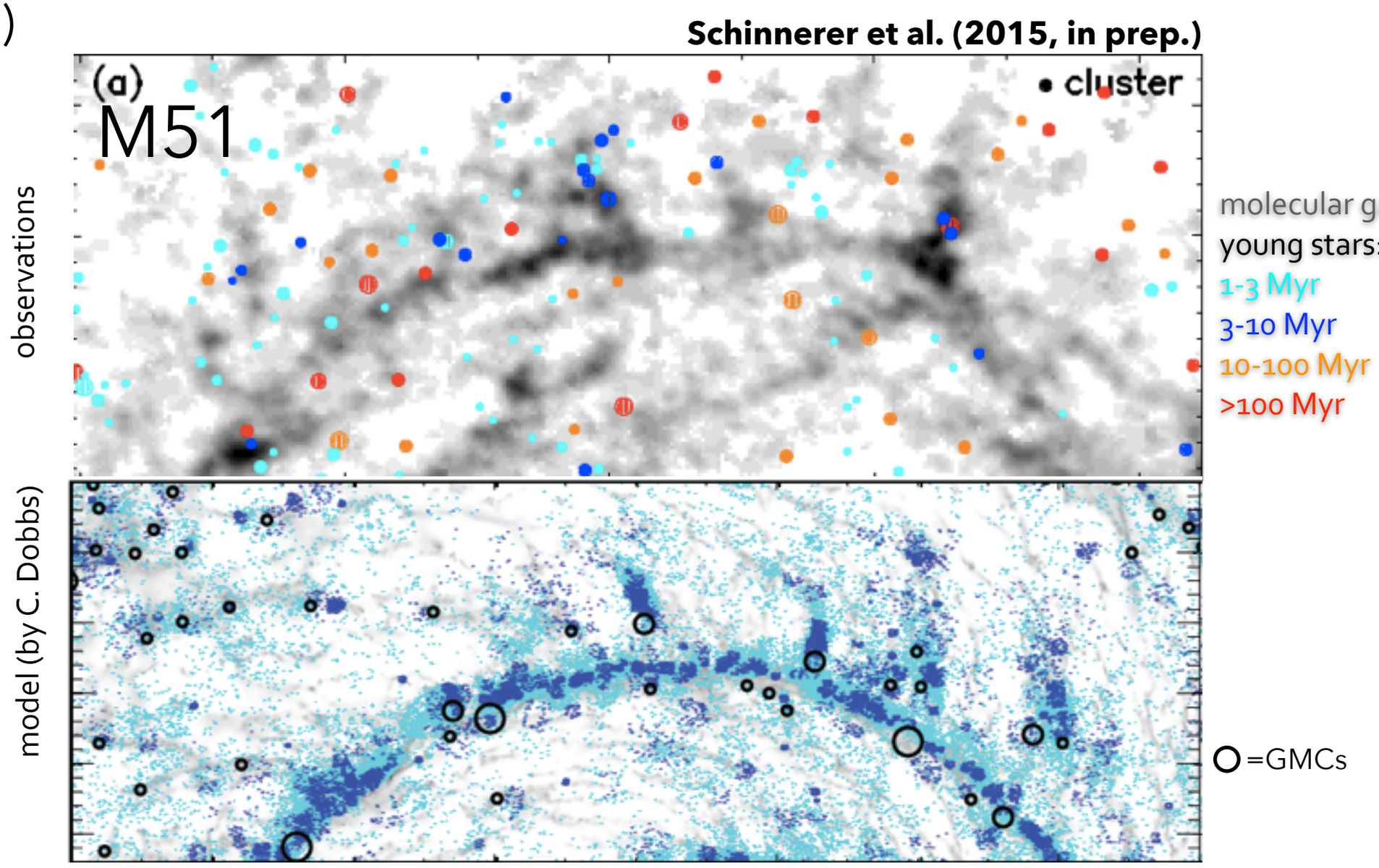


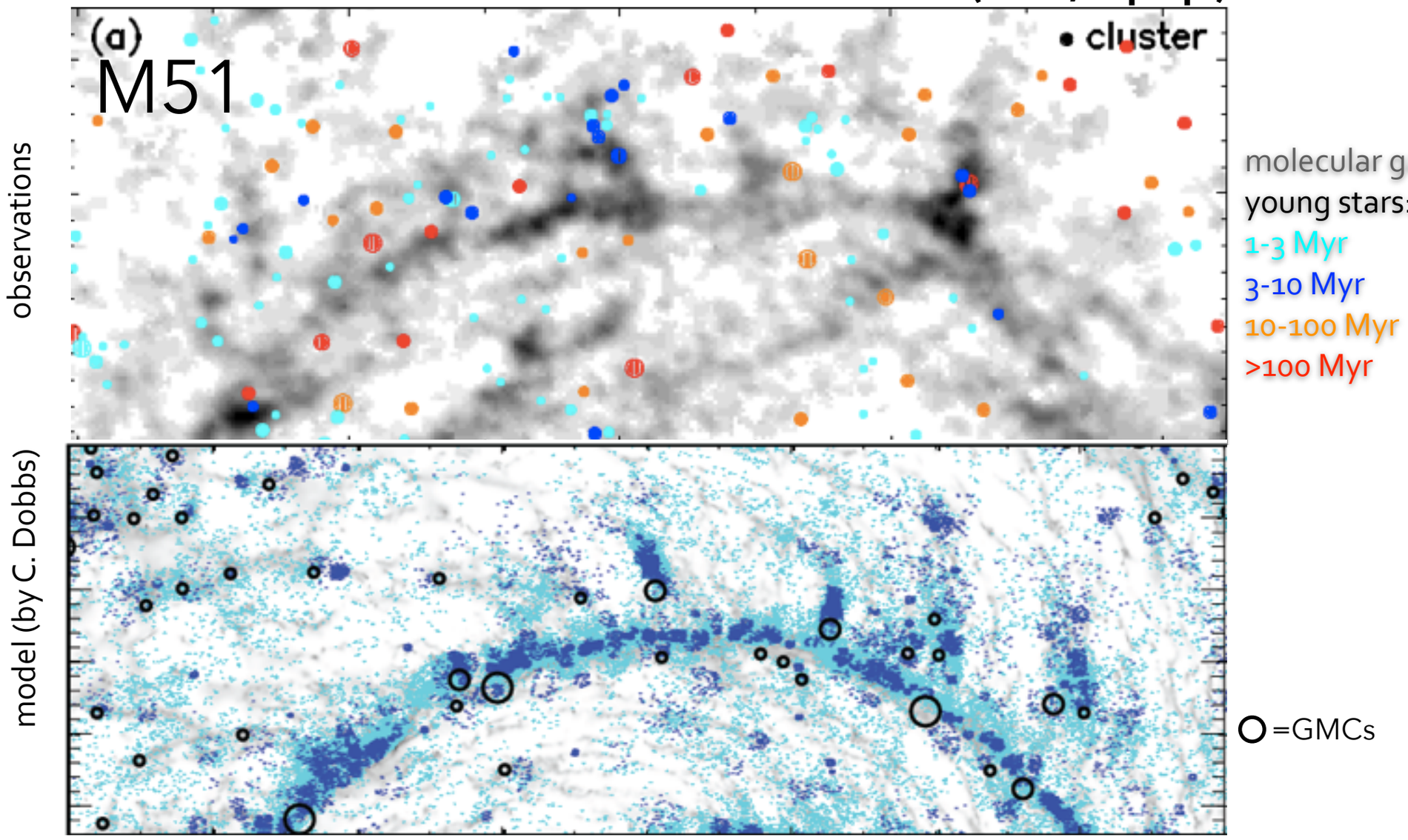
no significant star formation in arms, restricted to gas spurs

collapse of clouds delayed or prevented in spiral arm

offset star formation ??

- **delayed** star formation (in spurs NOT arms? Schinnerer et al., in prep.)
- **suppressed** star formation (Meidt et al. 2014)

Schinnerer et al. (2015, in prep.)



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Molecular Gas disk of M51

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

?

?

500 pc

Molecular Gas disk of M51

- ***spatially extended*** map of CO(1-0) in central 9kpc
- ***cloud resolution (40pc, $10^5 M_{sun}$)***
- *in a* ***prototypical star-forming*** *galaxy!*

IRAM large program
30m: 40 hr
PdBI: 170 hr

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

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

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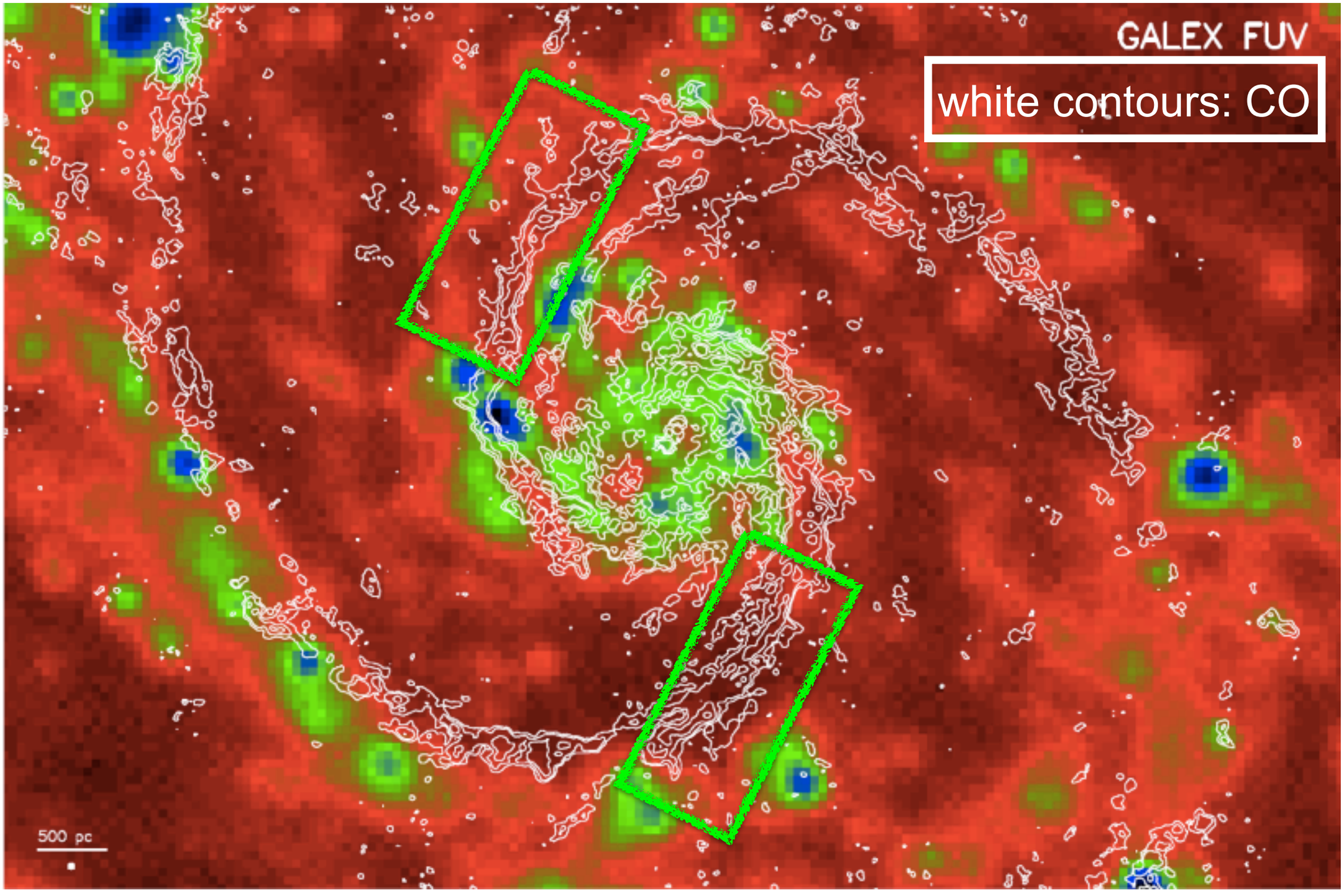
Spatial Relation b/n Gas and Star Formation



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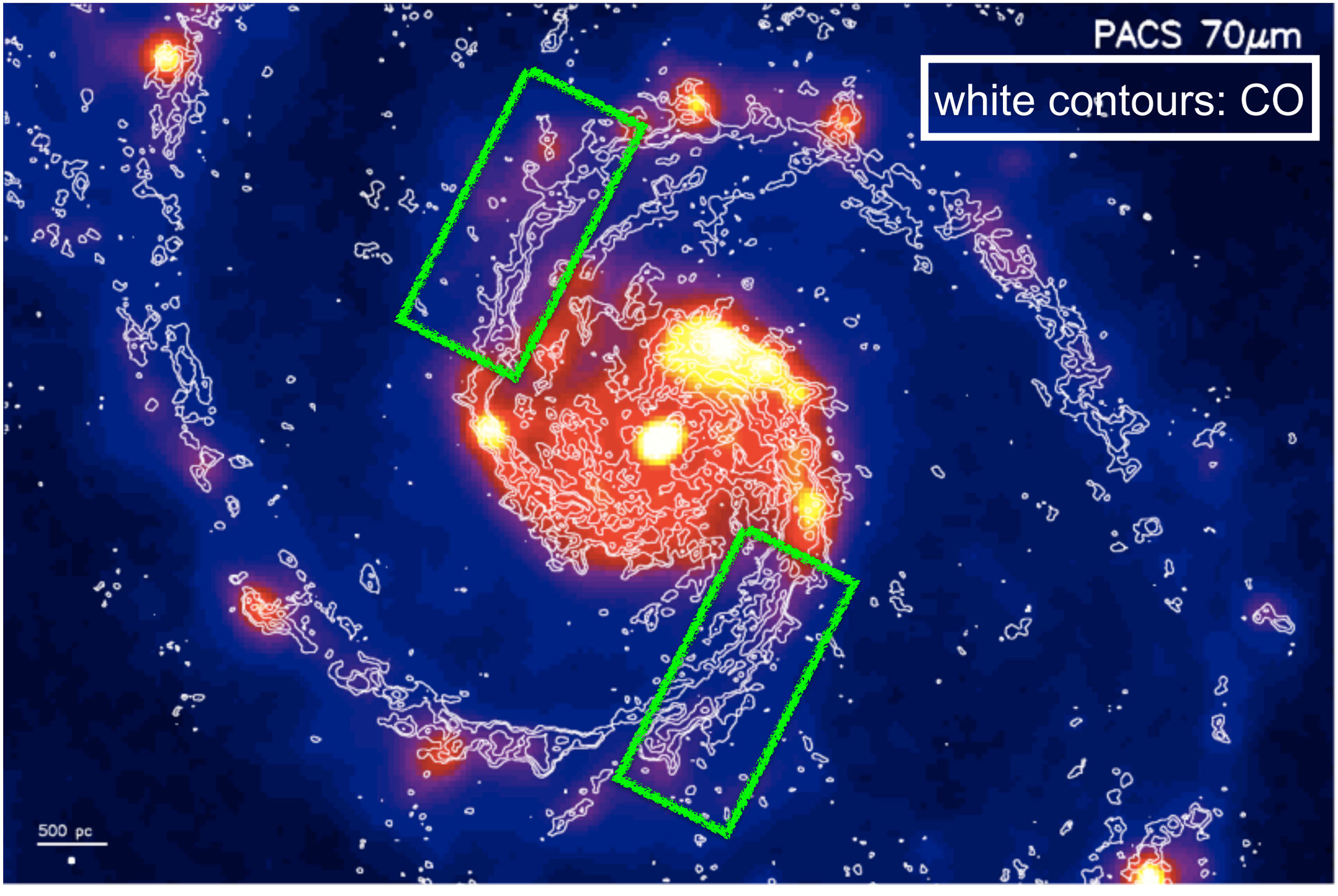

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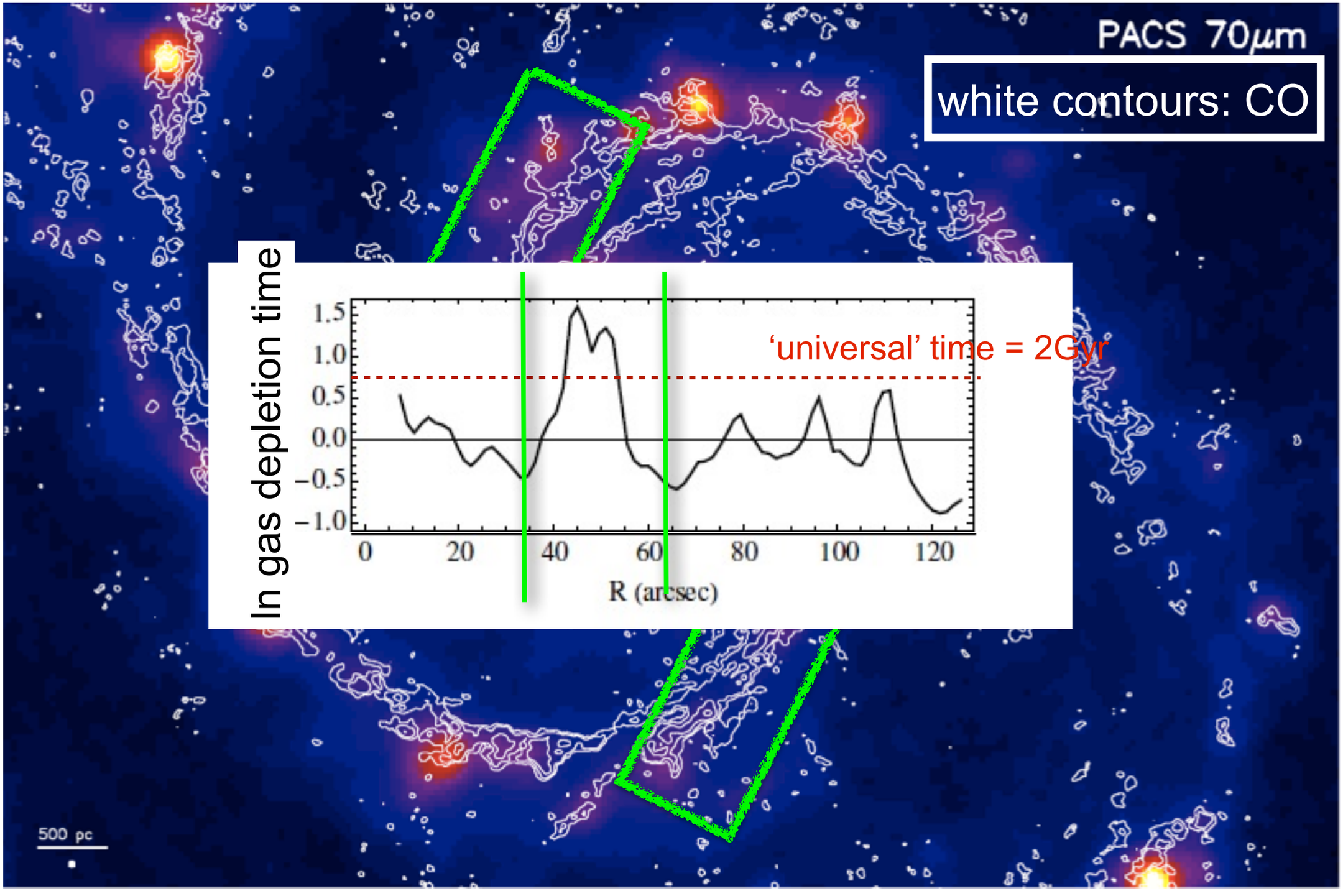
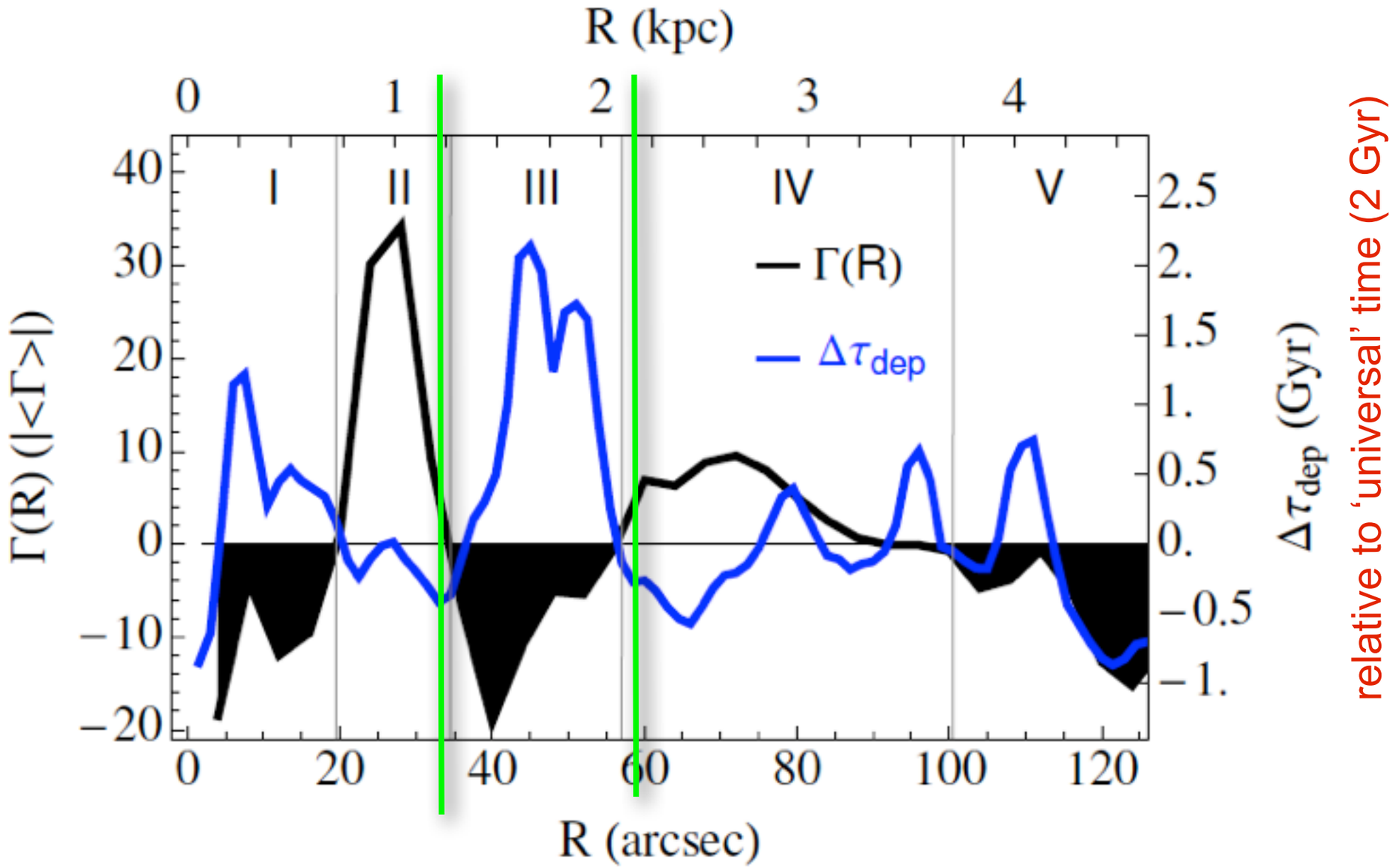


depletion time variations due to dynamics



stability of gas disks

- galaxy gravitational potential important
  some clouds may never collapse and form stars:
    - stable cloud mass (Jeans or Bonnor-Ebert) changes
    - cf. stability (Toomre Q): i.e. include stars (Rafikov et al. 2001), what about perturbations??

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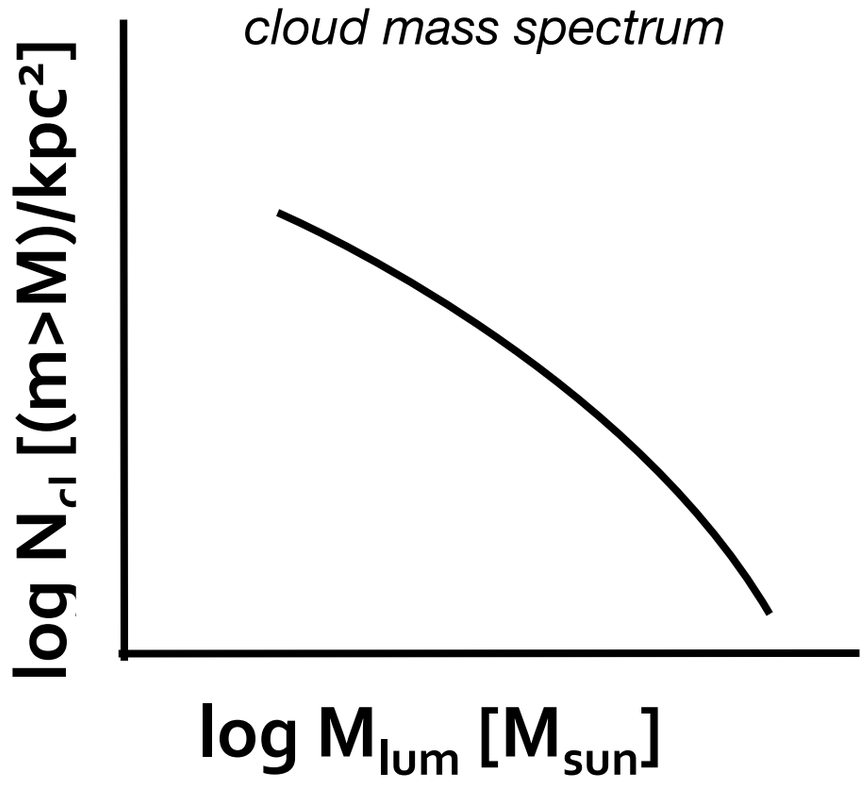

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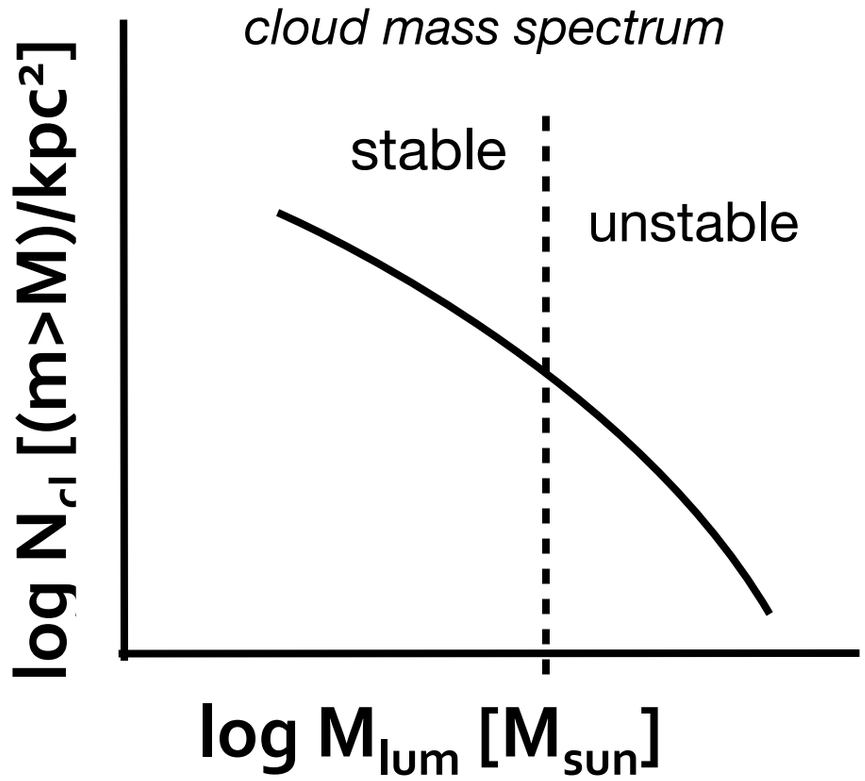

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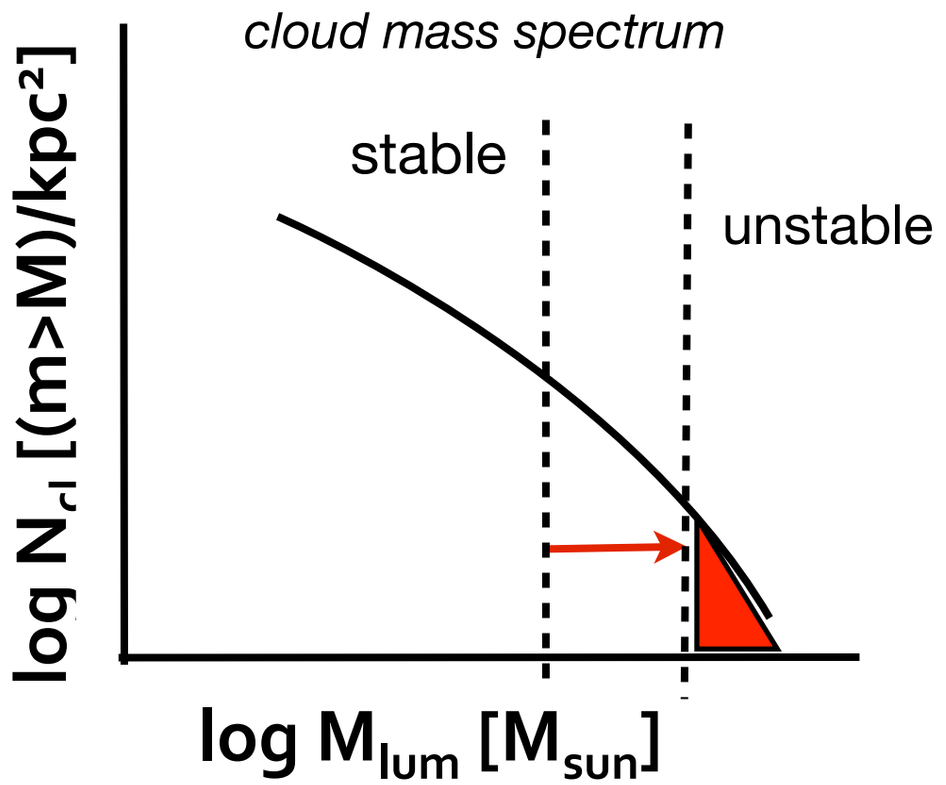
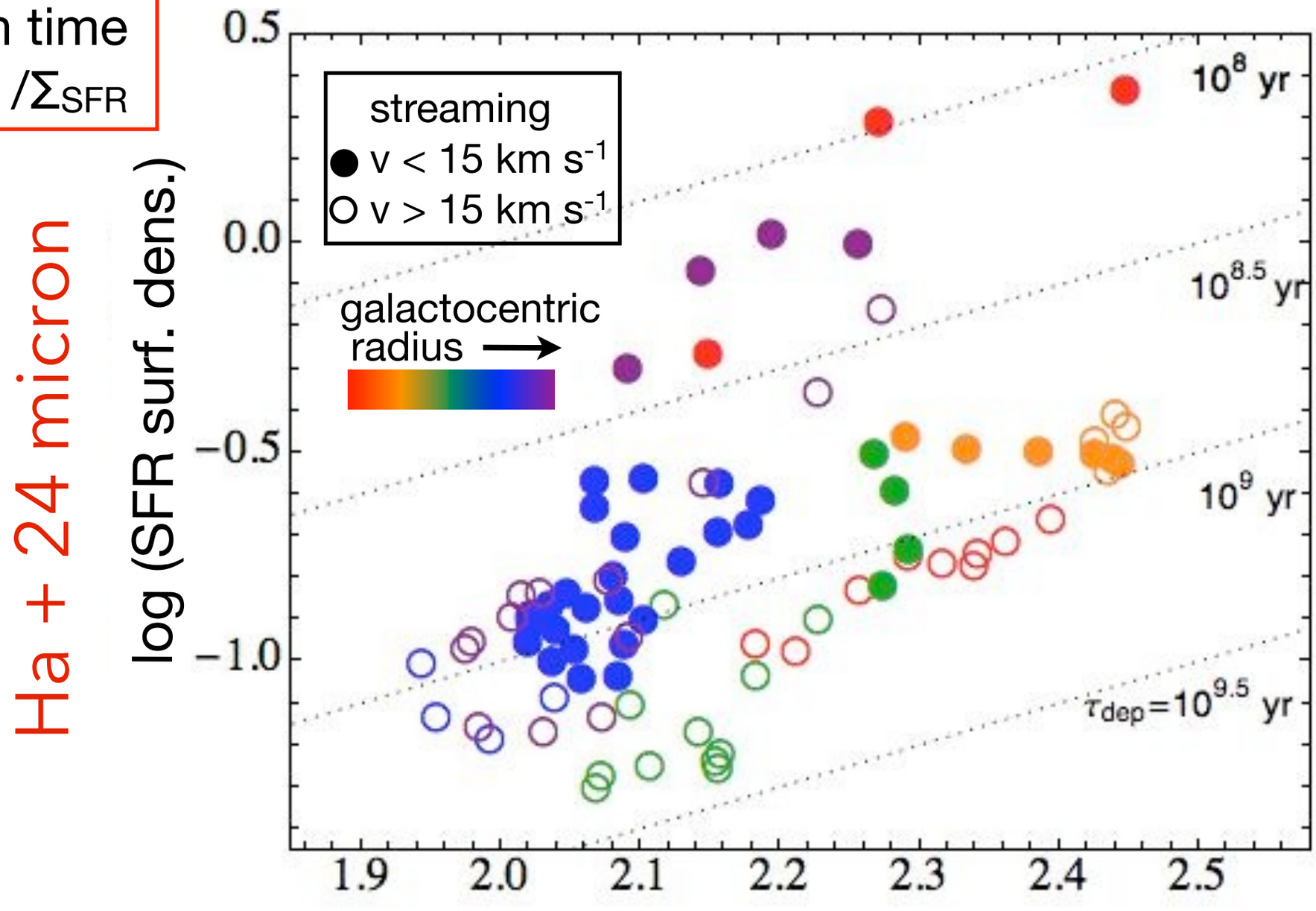


dynamical scatter in the KS relation

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

M51

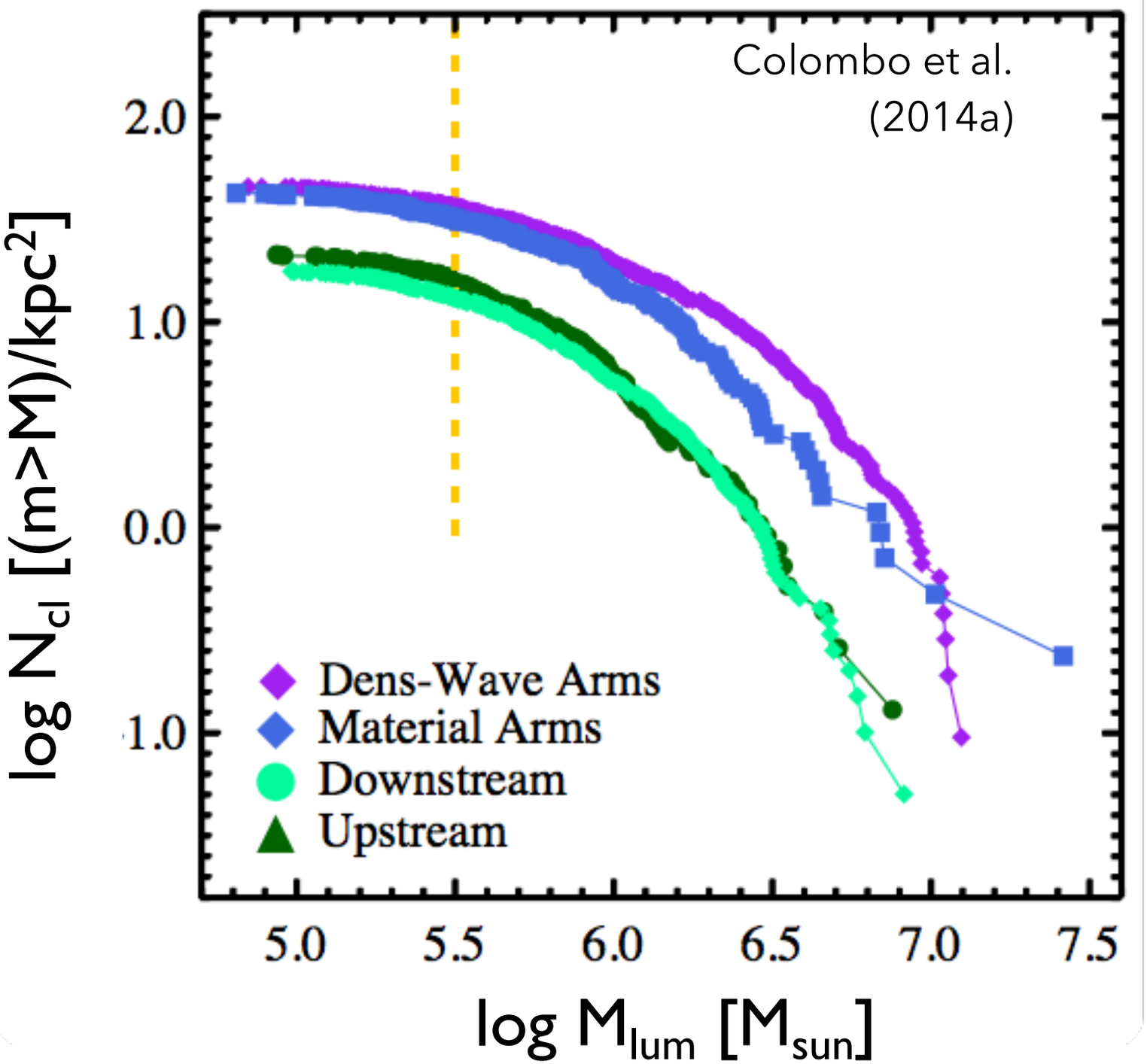


Spiral arms at **Cloud Scale**

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

see also **Koda et al. (2009)**

- cloud Cumulative Mass Functions



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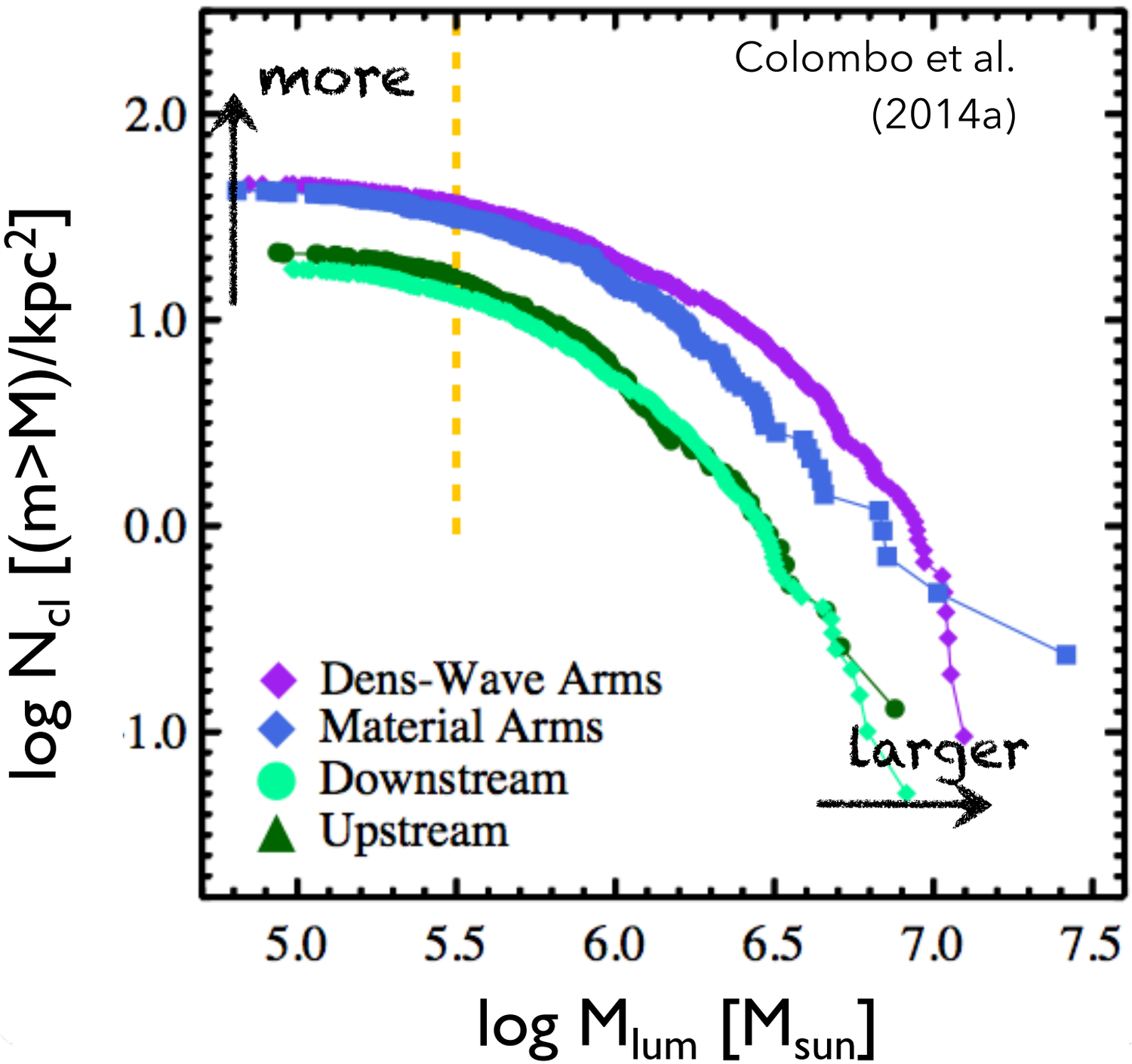

spiral arms help build more and larger clouds

dispersal in inter-arm due to shear, feedback

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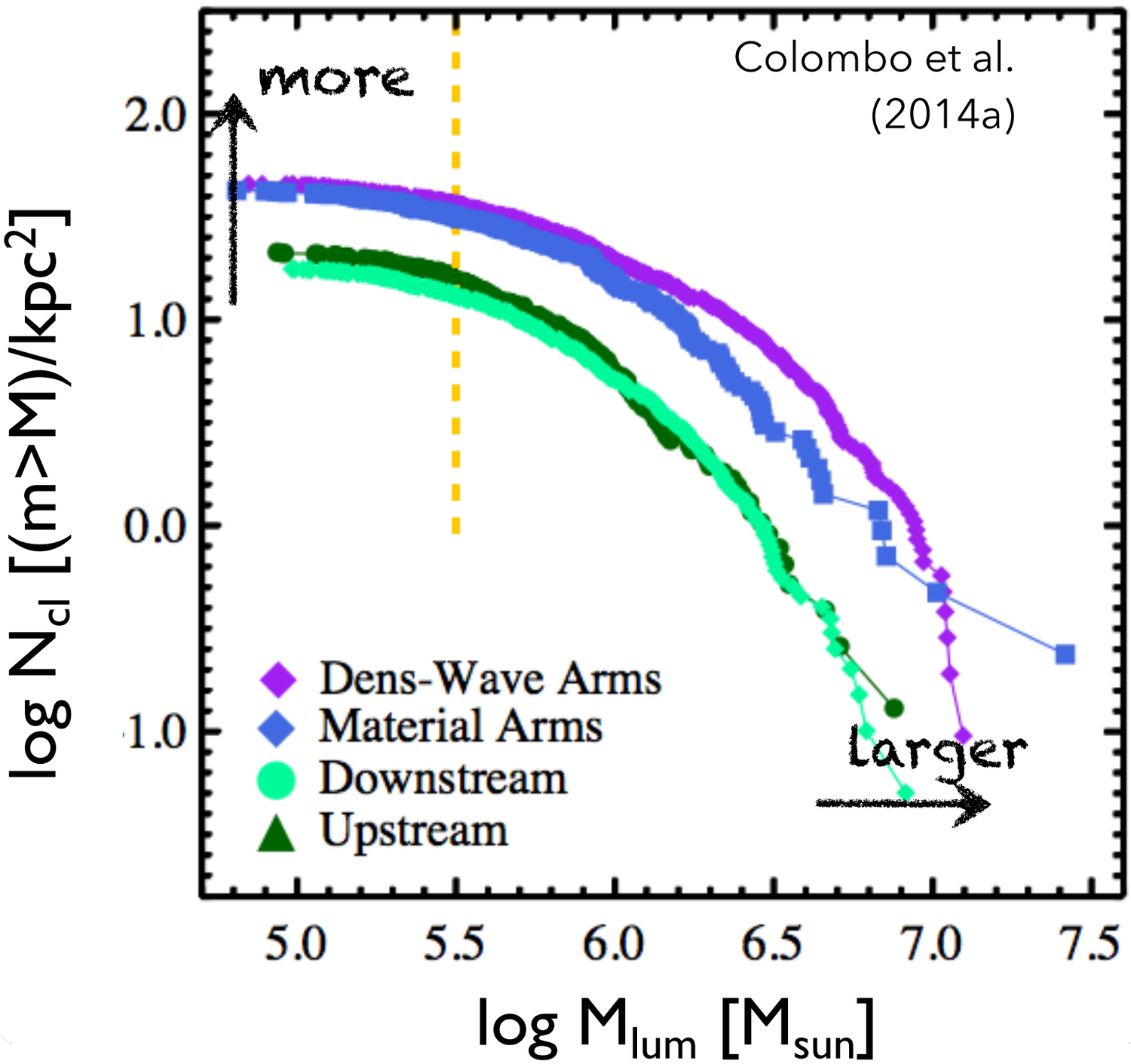

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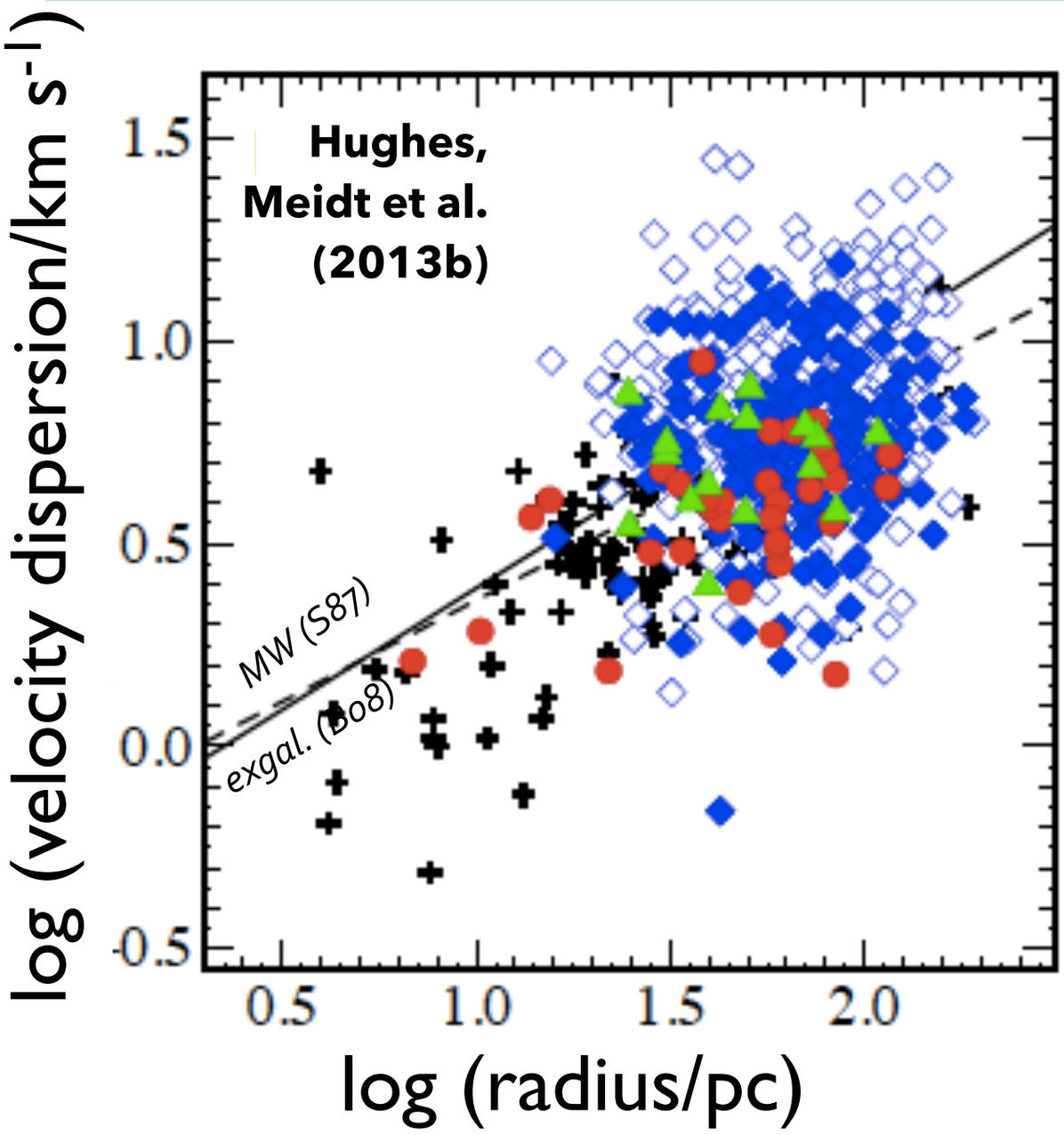
dispersal in inter-arm due to shear, feedback

spiral arm clouds bigger before collapse/SF

non-Universal cloud properties



no size-line width relation

⇨

clouds are not (always) virialized

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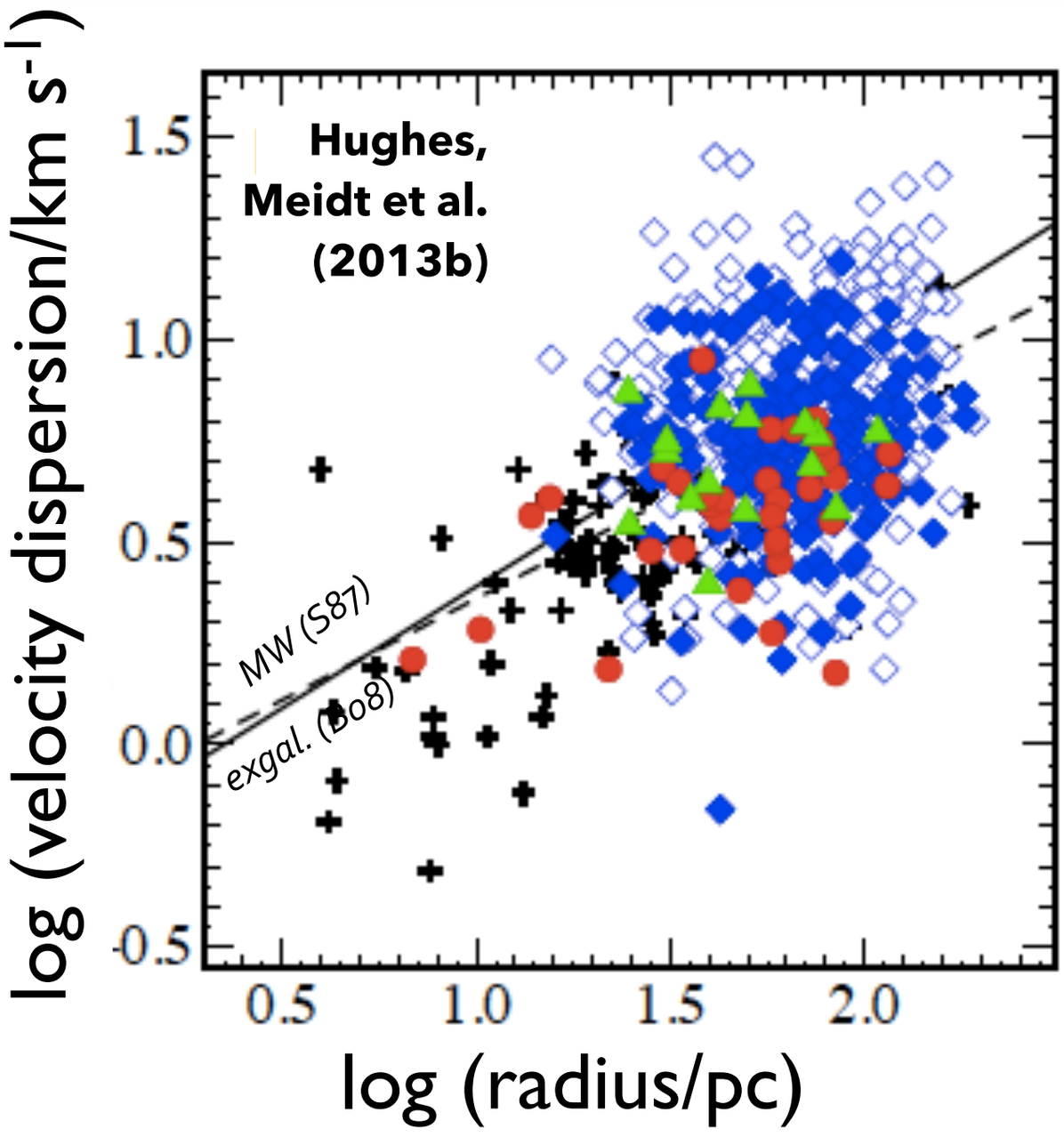

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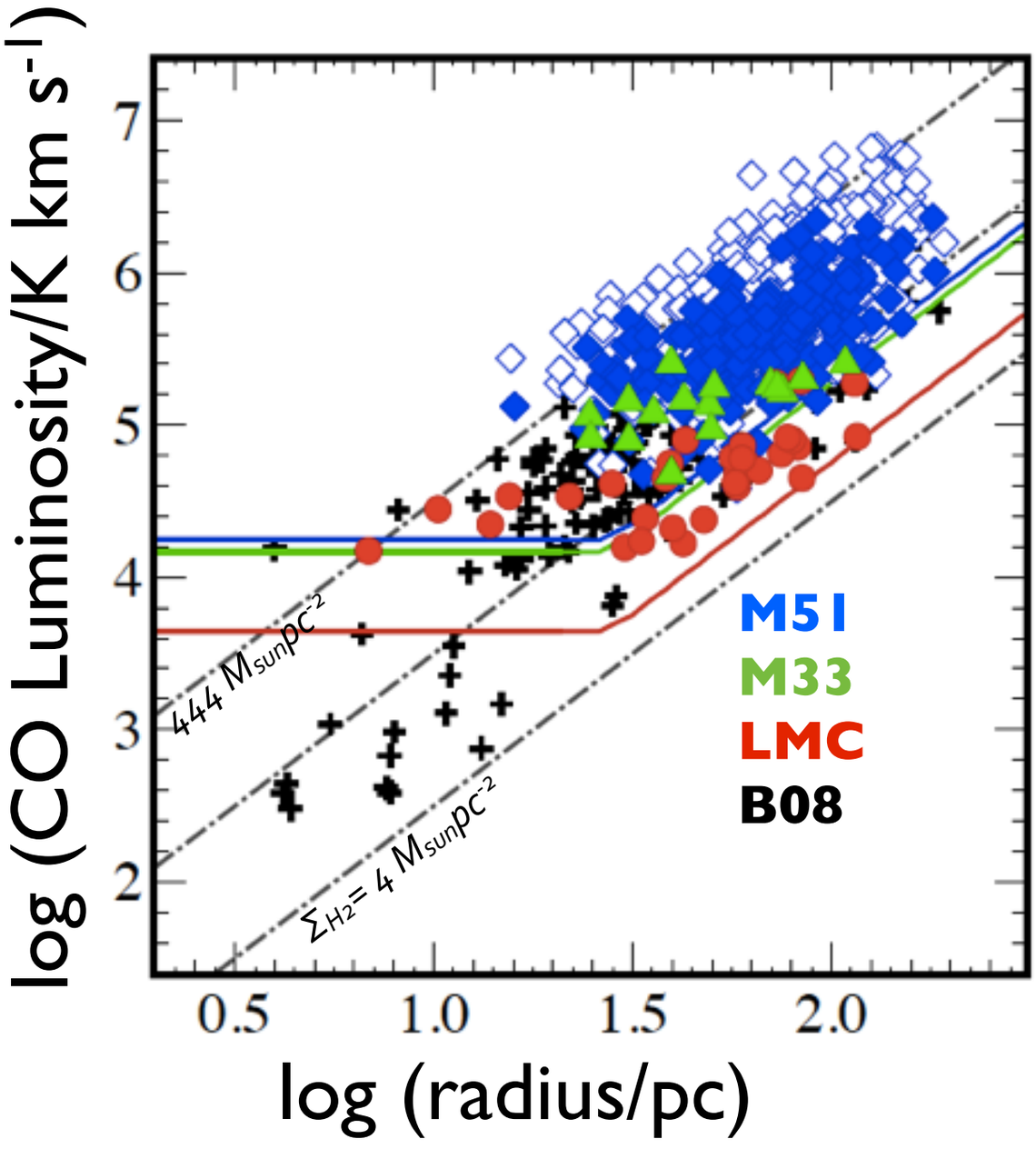


large range of gas surface densities

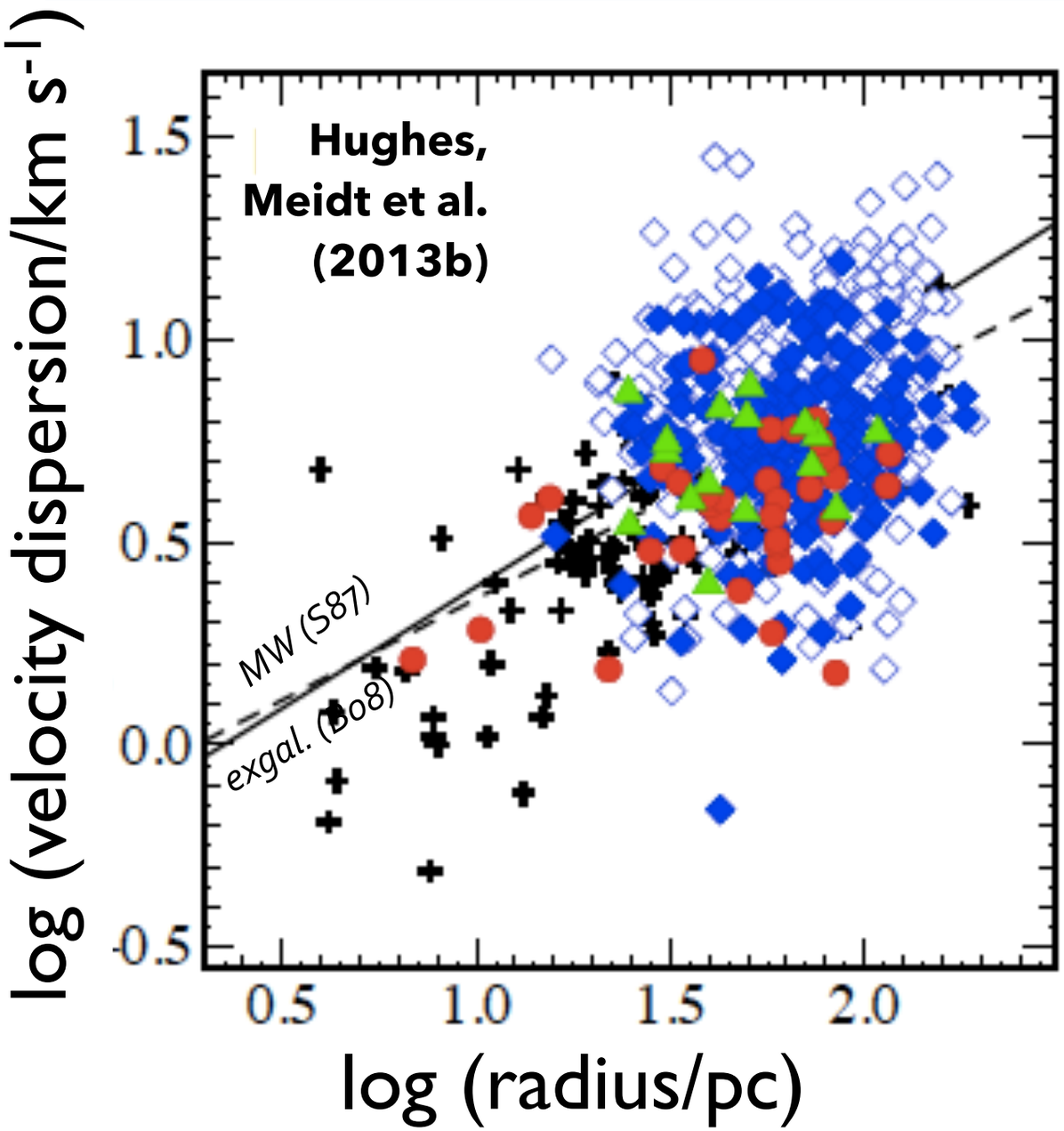
⇨

GMC properties are not universal

no universal free-fall time!

scatter in KS relation

non-Universal cloud properties



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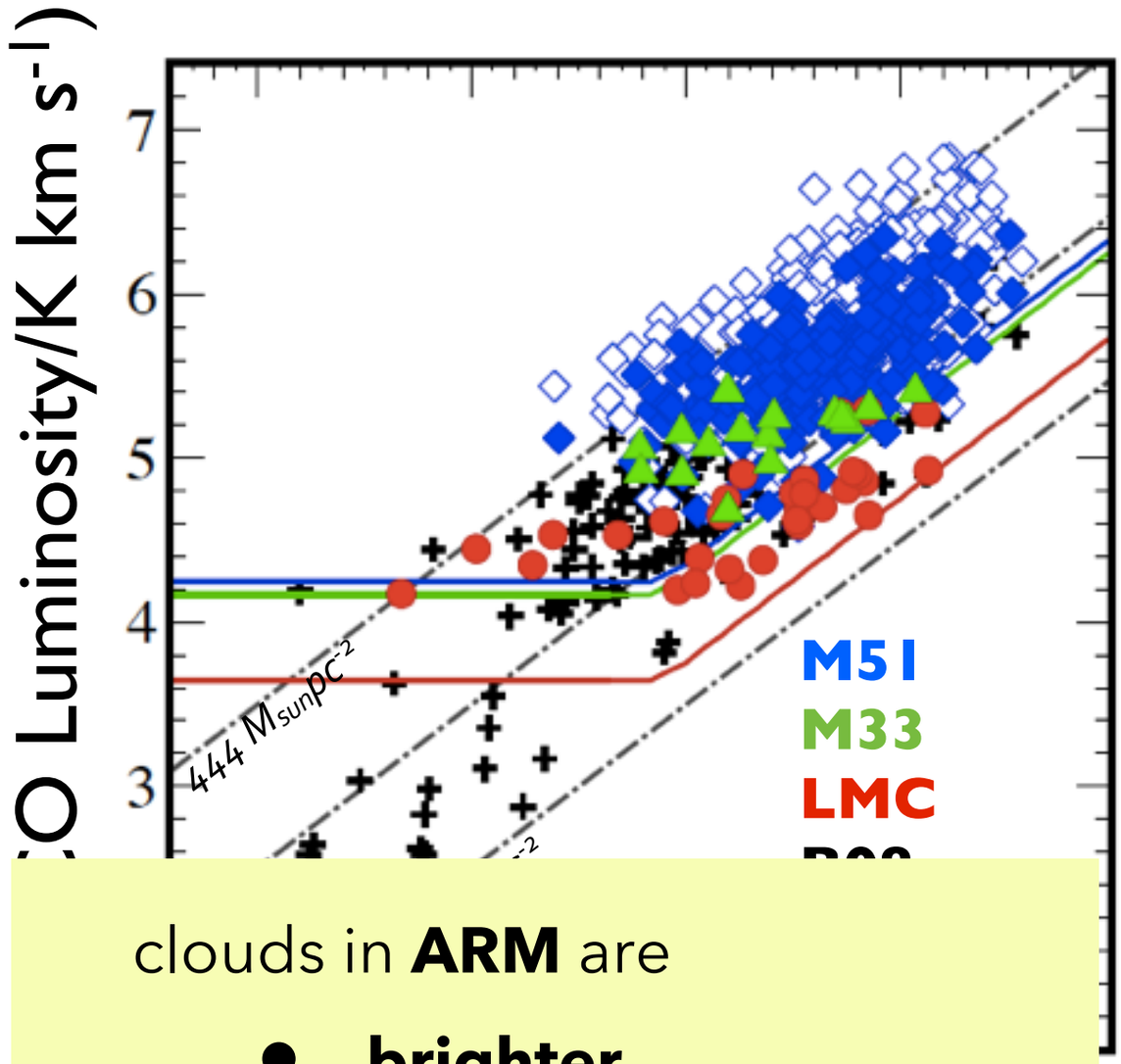
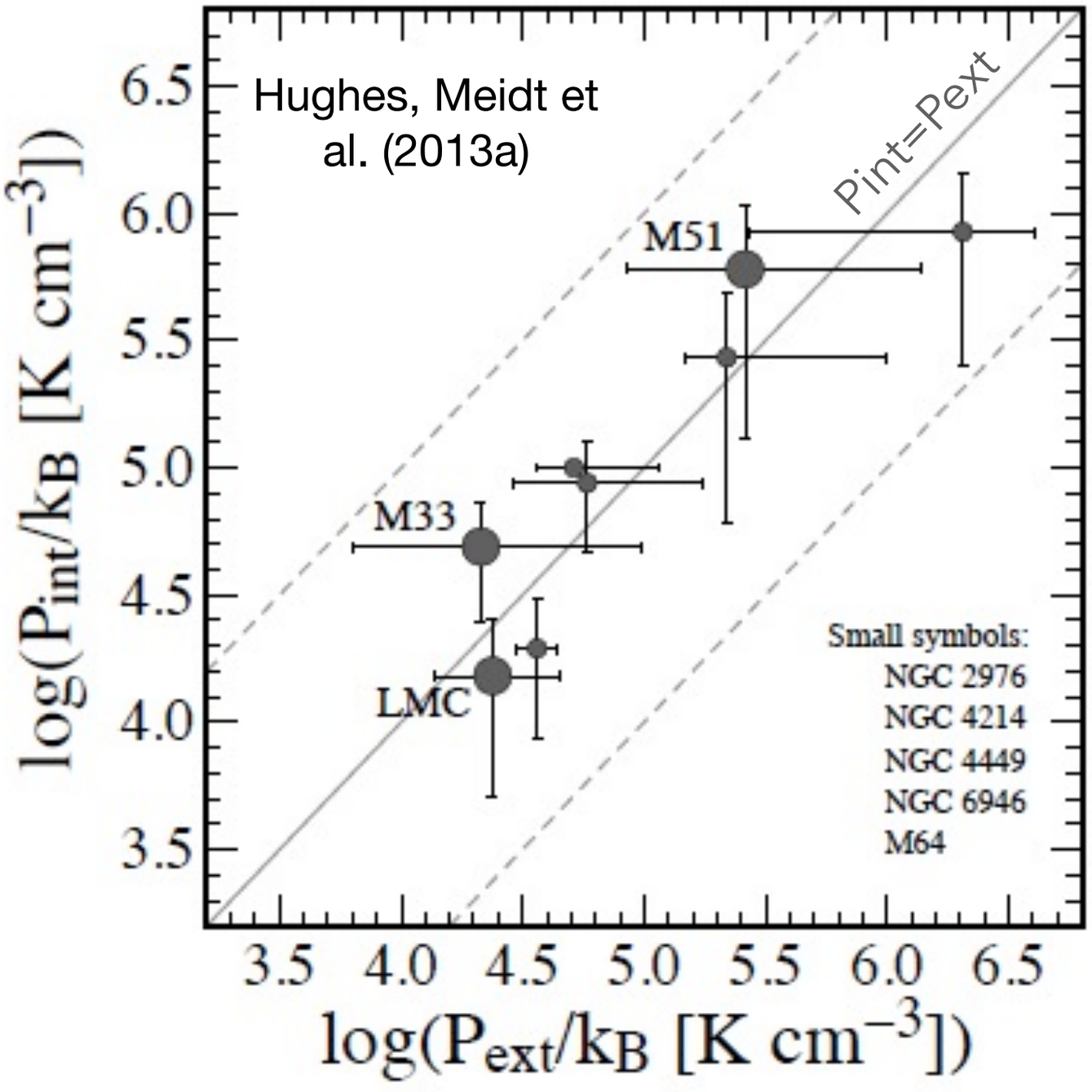


clouds in **ARM** are

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

compared to **inter-ARM**

the role of external pressure



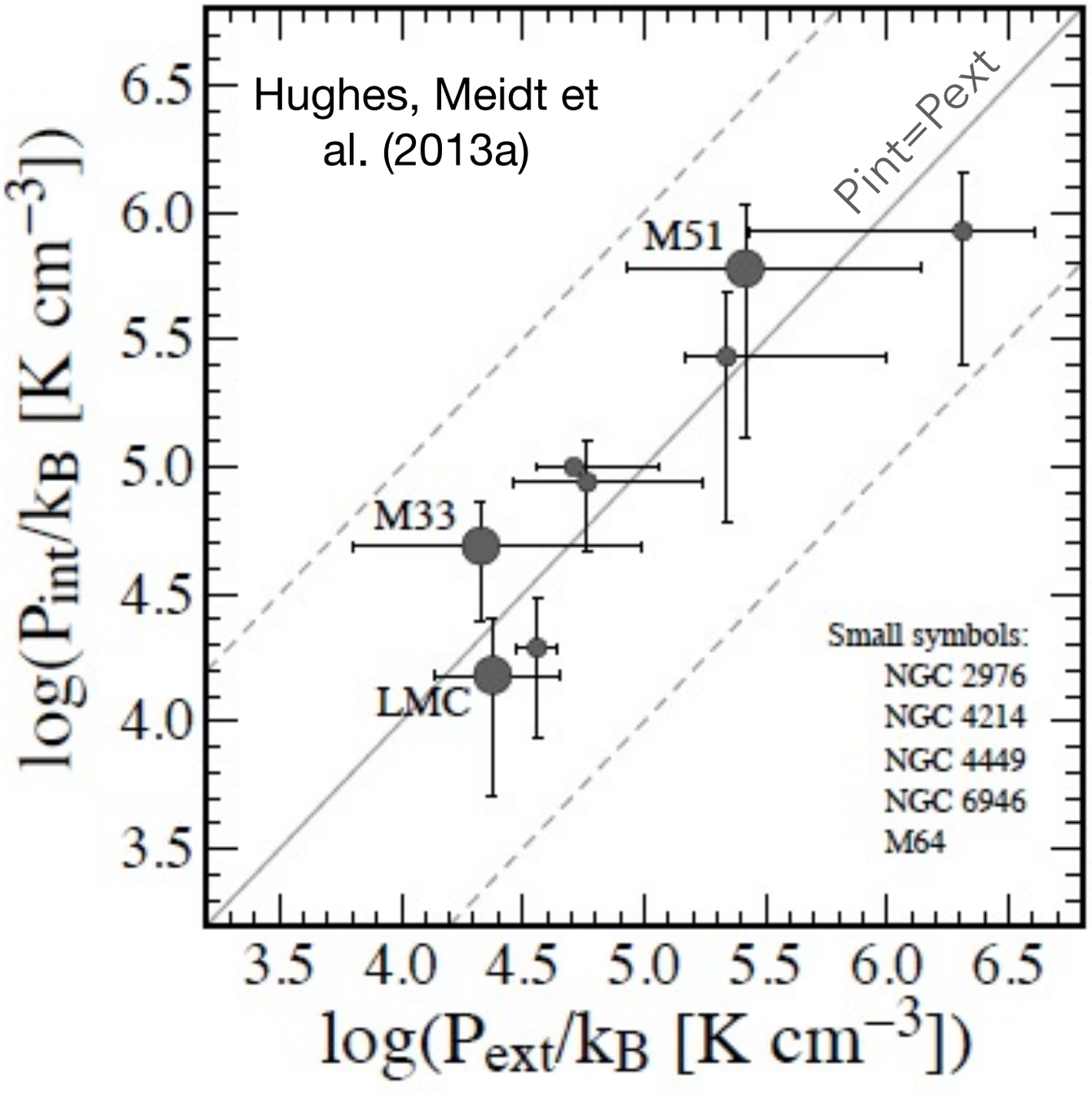
the role of external pressure

$$P_{int}=\rho\sigma^2$$

$$P_{ext}=G\Sigma_{gas}\left(\Sigma_{gas}+\frac{\sigma_{gas}}{\sigma_{stars}}\Sigma_{stars}\right)$$

Σ_{gas}: total ($HI+H_2$)

Σ_{stars}: from mass map



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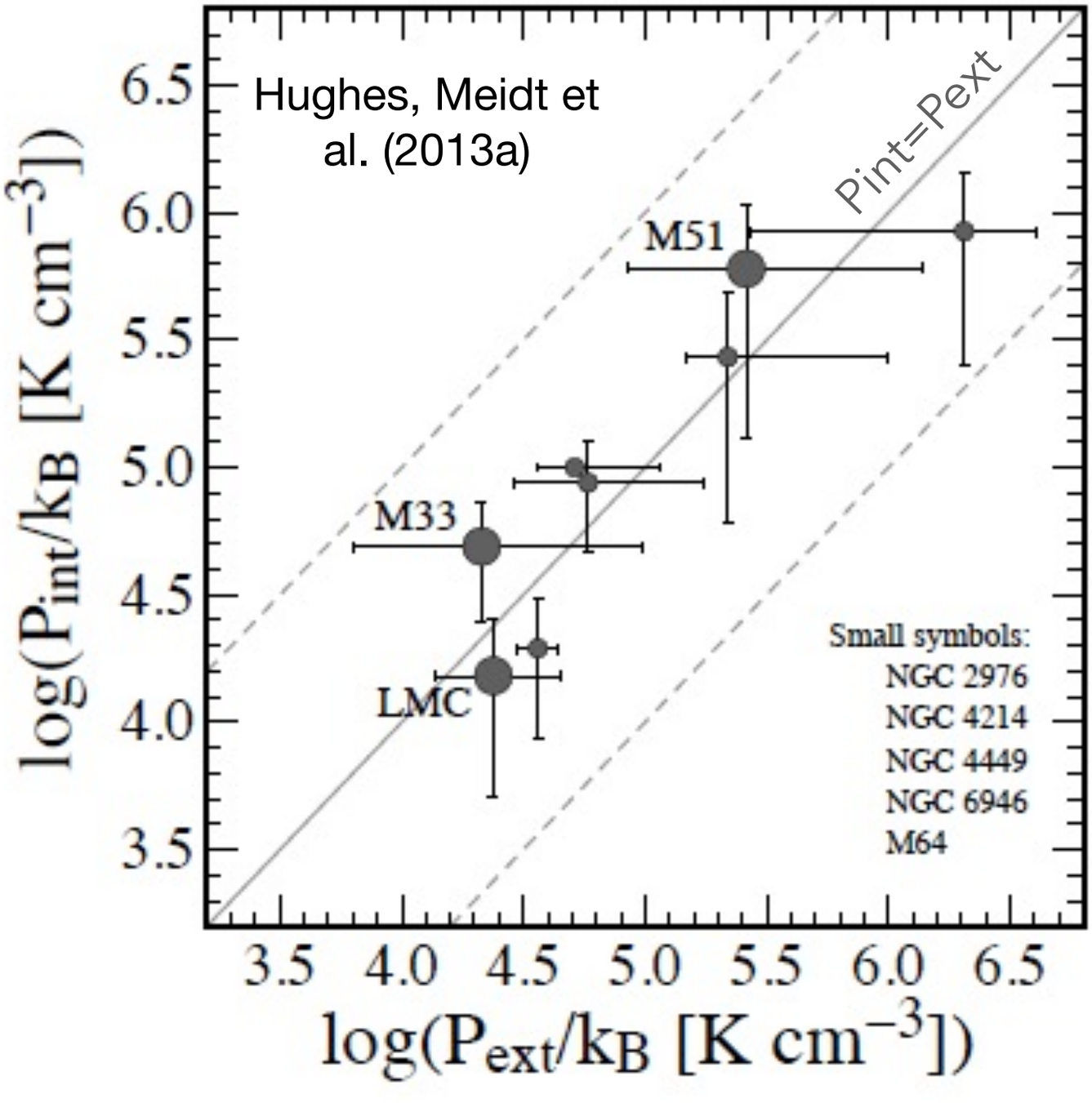
clouds coupled to surroundings



wrapping up

- clouds sensitive to environment, respond to local conditions

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revised view of local ISM pressure & dynamics

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- variations in dense gas fraction/SFE
- progress of SF across spiral arm (feedback!)

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dense gas + chemistry with ALMA!

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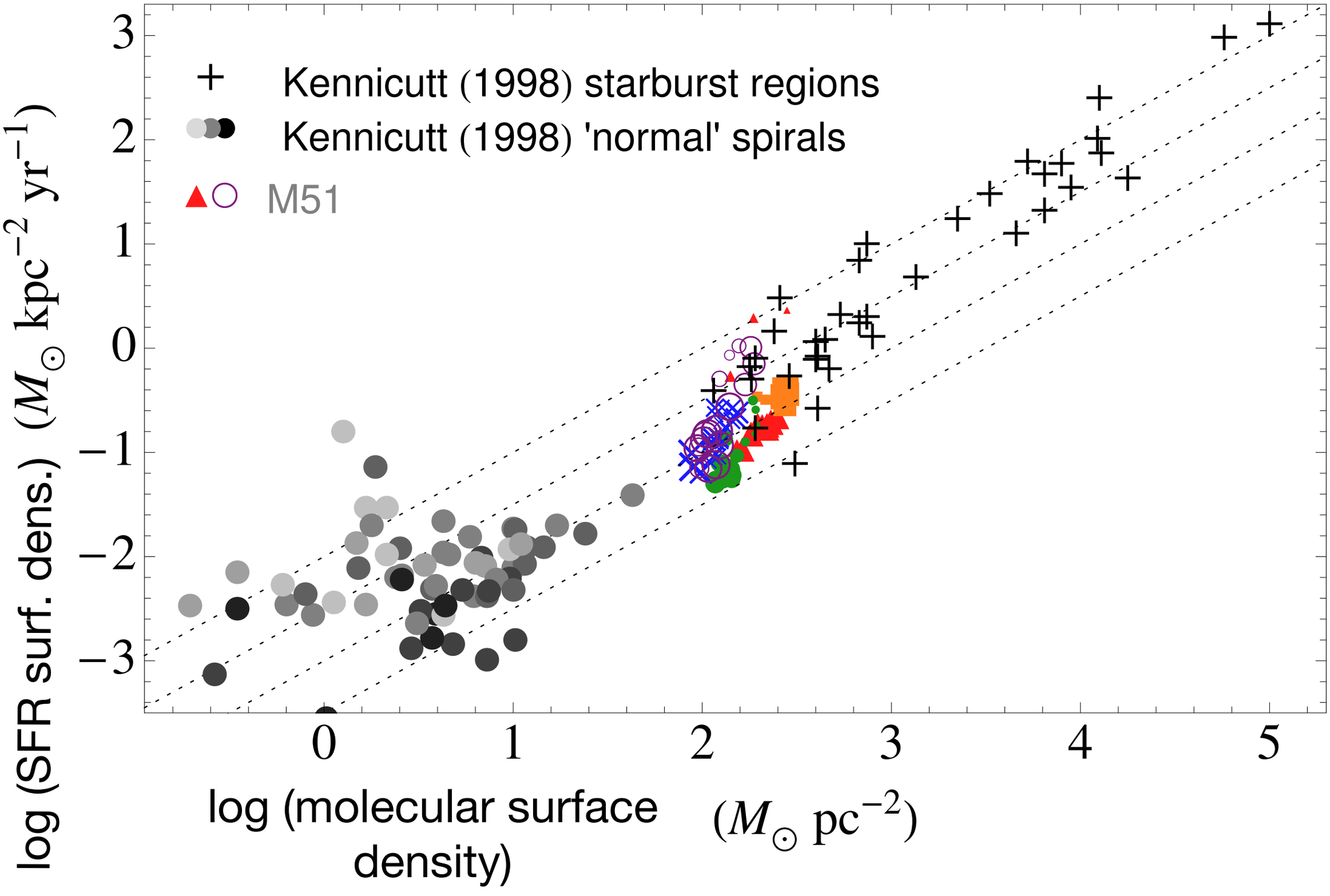
- clouds are dynamically evolving structures (sims: Dobbs & Pringle 2014)
- with short (20-30Myr) lifetimes (Kawamura et al. 2009 in LMC; Meidt et al. 2015 in M51)

dense gas + chemistry with ALMA!

Are spirals really ‘normal’?



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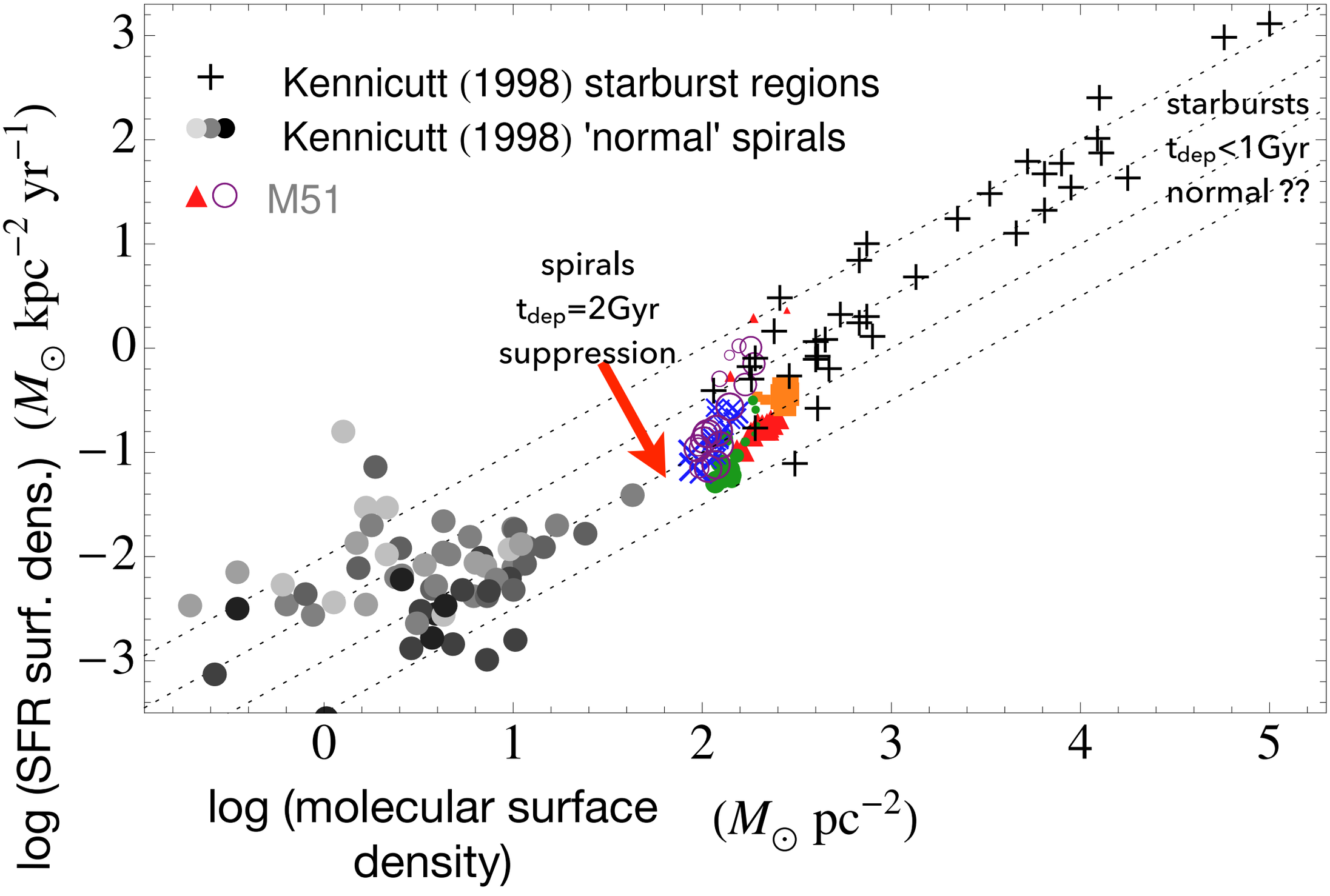


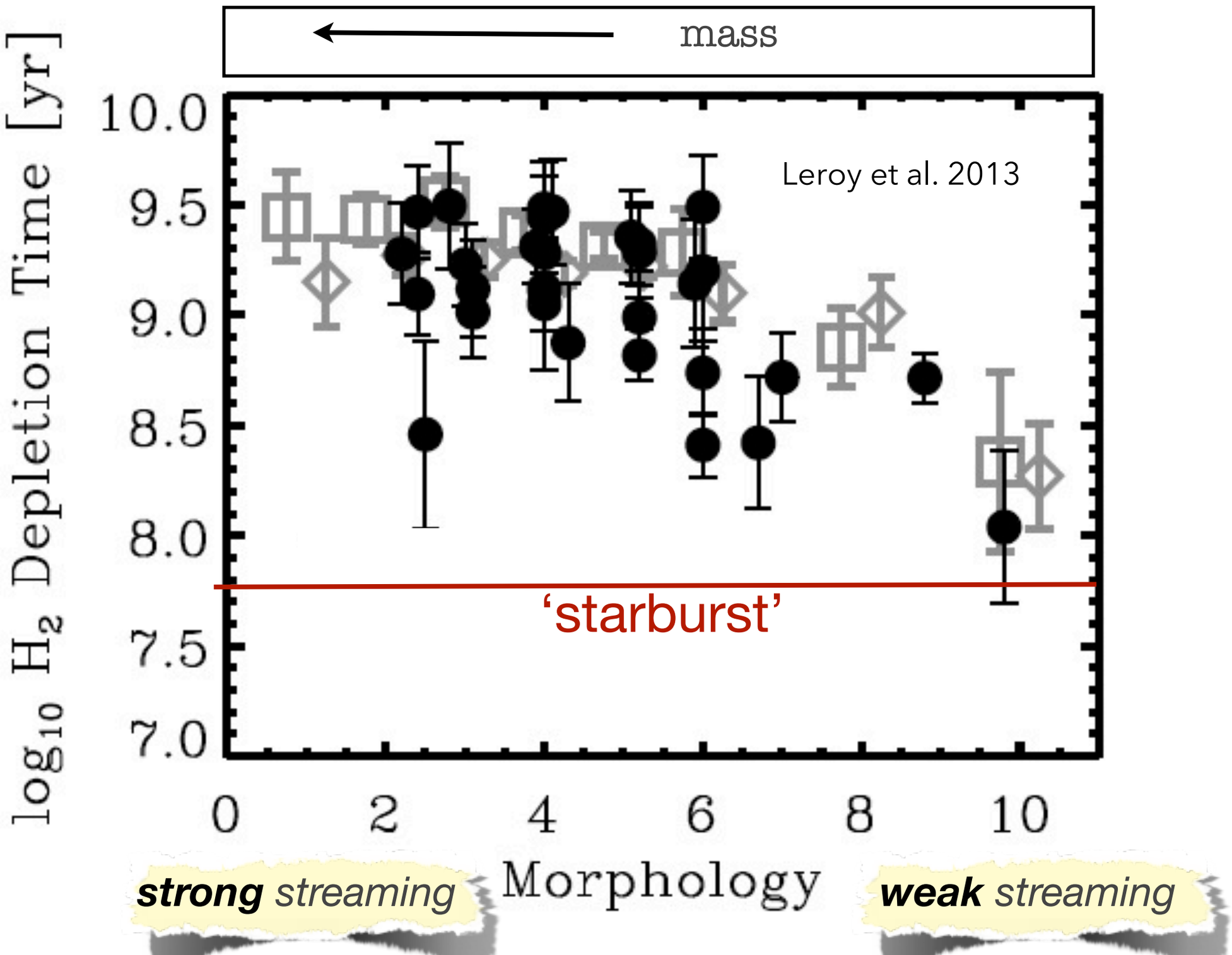
Take Away

- *clouds* are dynamic, evolving structures NOT decoupled from their environment
- *spiral arms* impact ISM structure/organization down to cloud-scales
- ***disk*** *gas flows/galaxy dynamics* impacts star formation

large-area gas dynamics
+ cloud properties

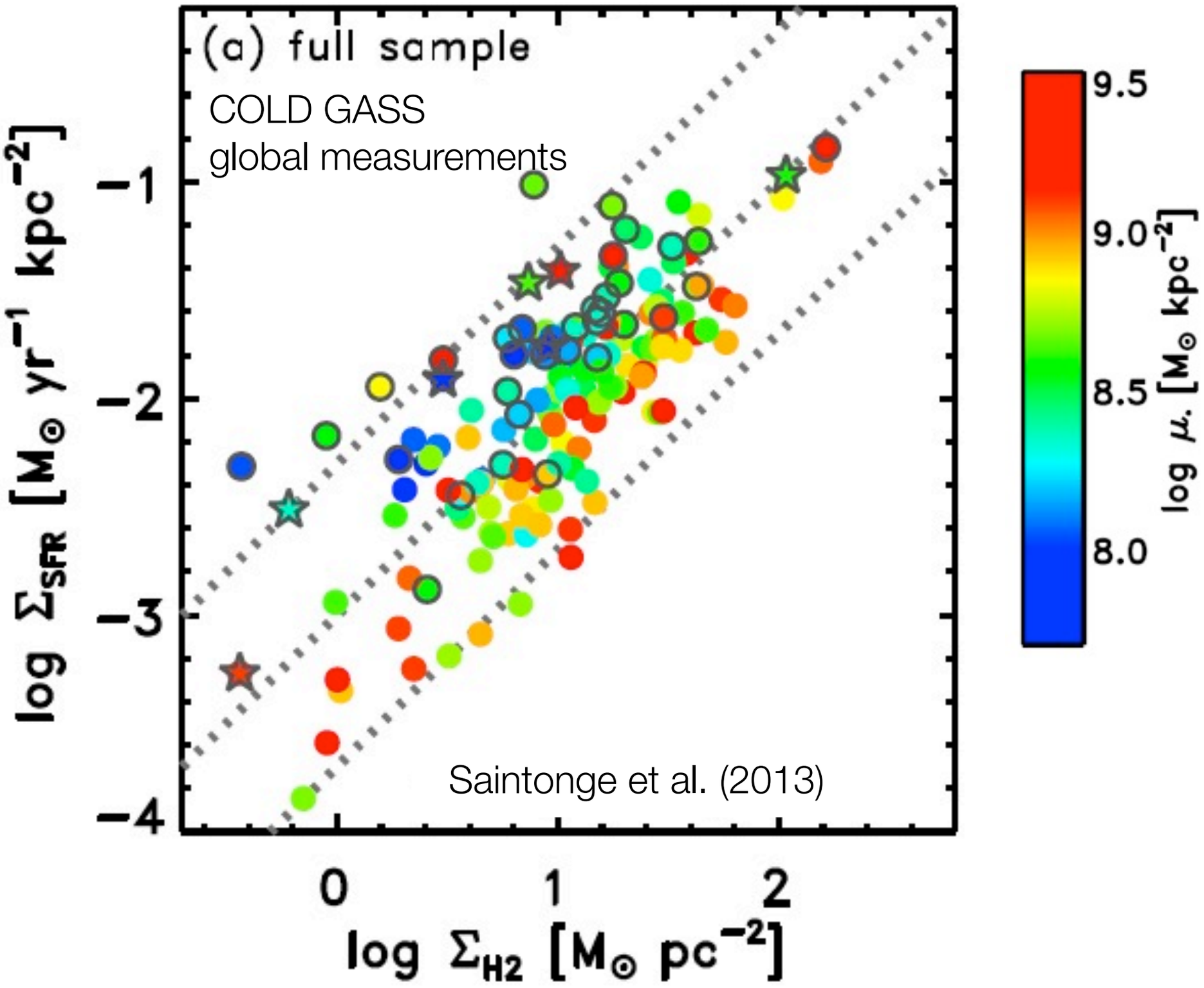
depletion time variations

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

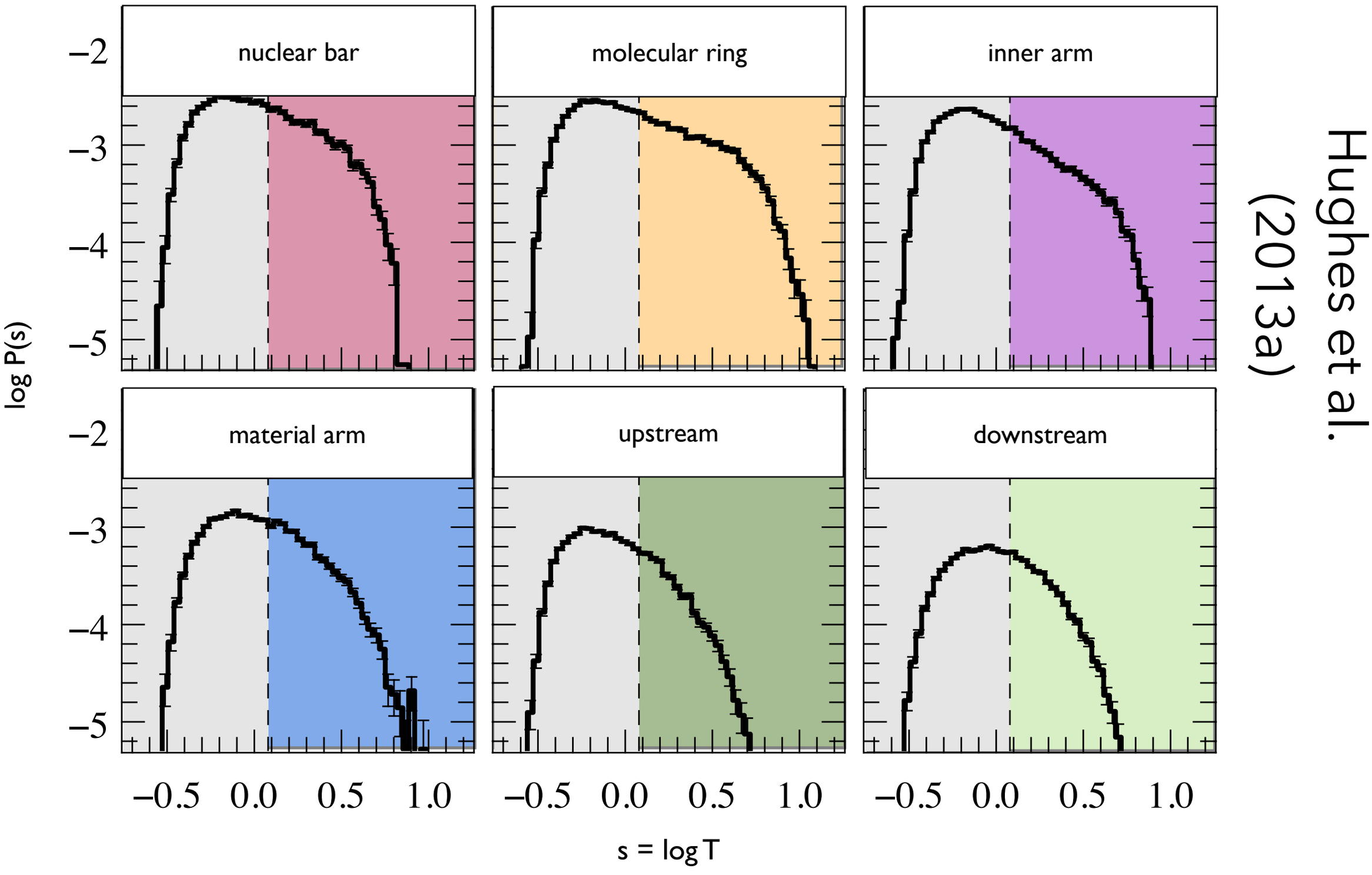


fraction of `active' (collapsing) clouds changing?

depletion time variations

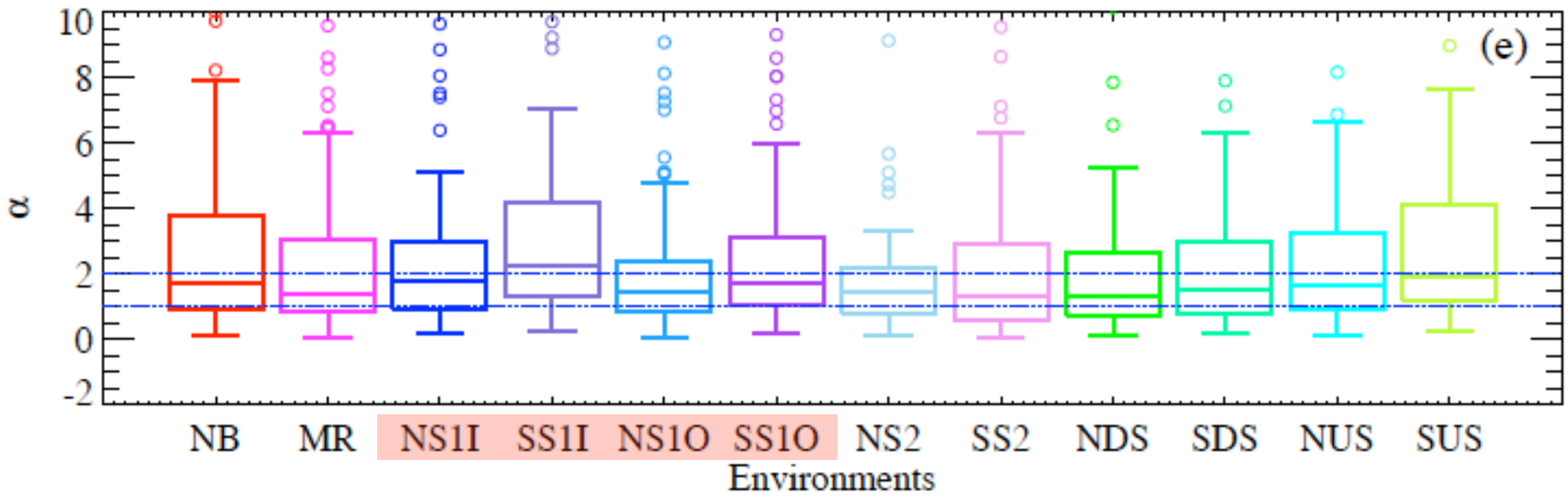


CO brightness PDFs in M51



Hughes et al. (2013a)

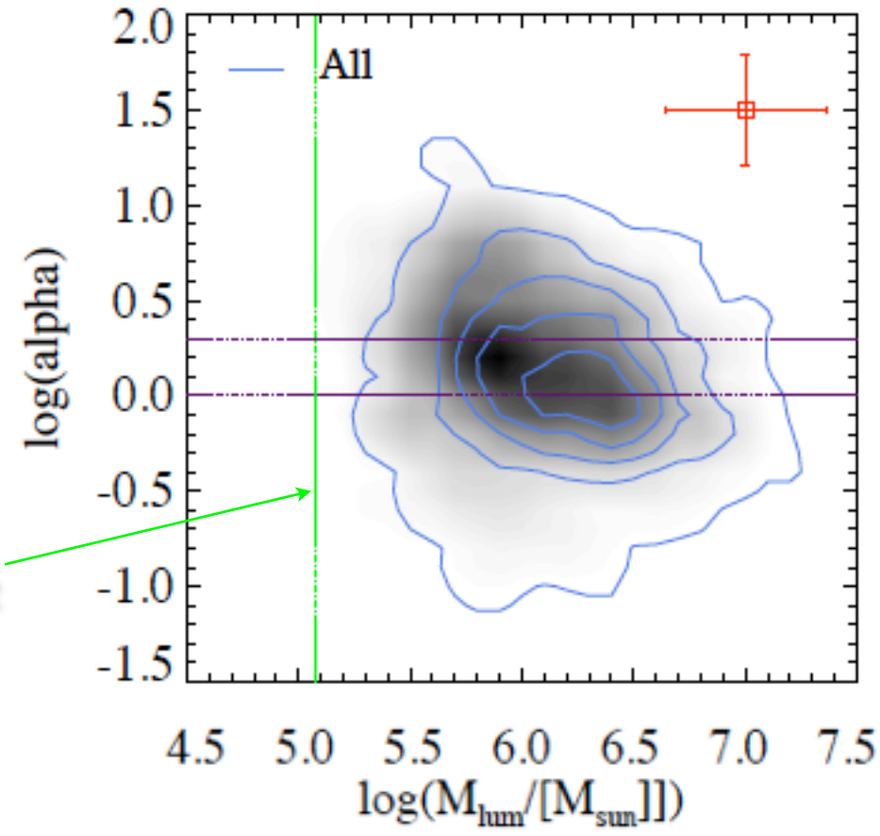
self-gravitating clouds??



] self-gravitating limit

(Bertoldi & McKee 1992)

$$\alpha = \frac{5\sigma_v^2 R}{M_{lum} G} = 1.12 \frac{M_{vir}}{M_{lum}}$$



sensitivity limit