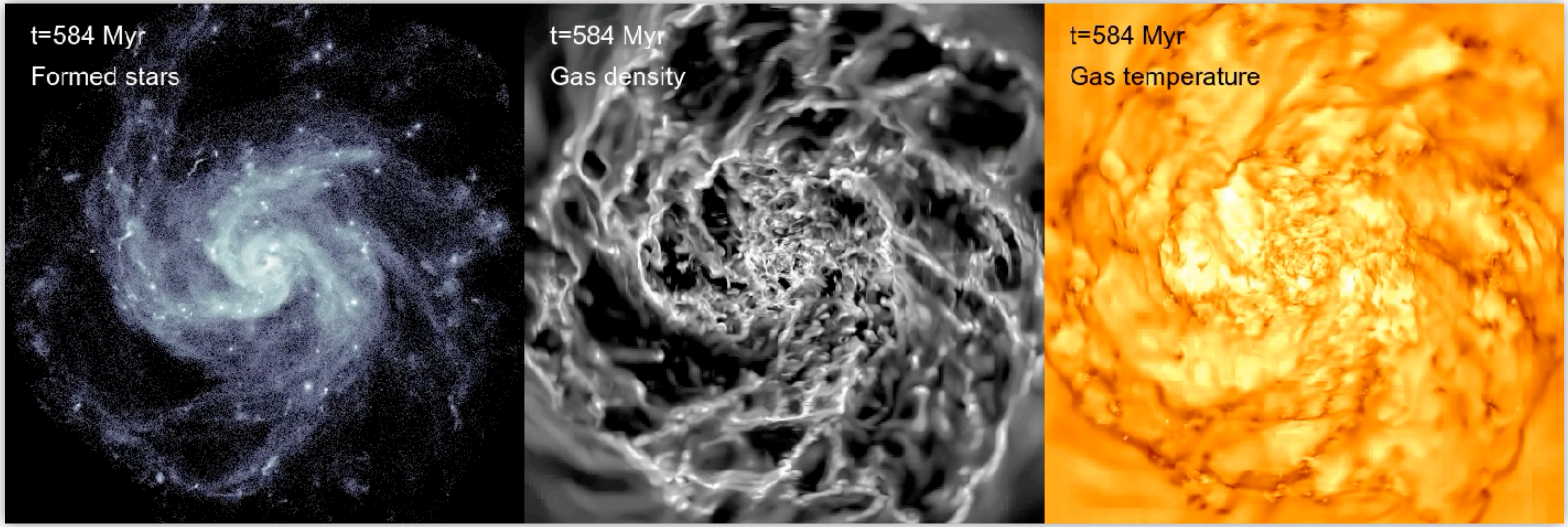
Turbulence in the interstellar medium - feedback and gravity

Oscar Agertz, Lund University
with Florent Renaud, Alessandro Romeo + a bunch of others

- What levels of turbulence can be driven in disc galaxies?
- Insights from cosmological simulations - the settling of turbulent discs

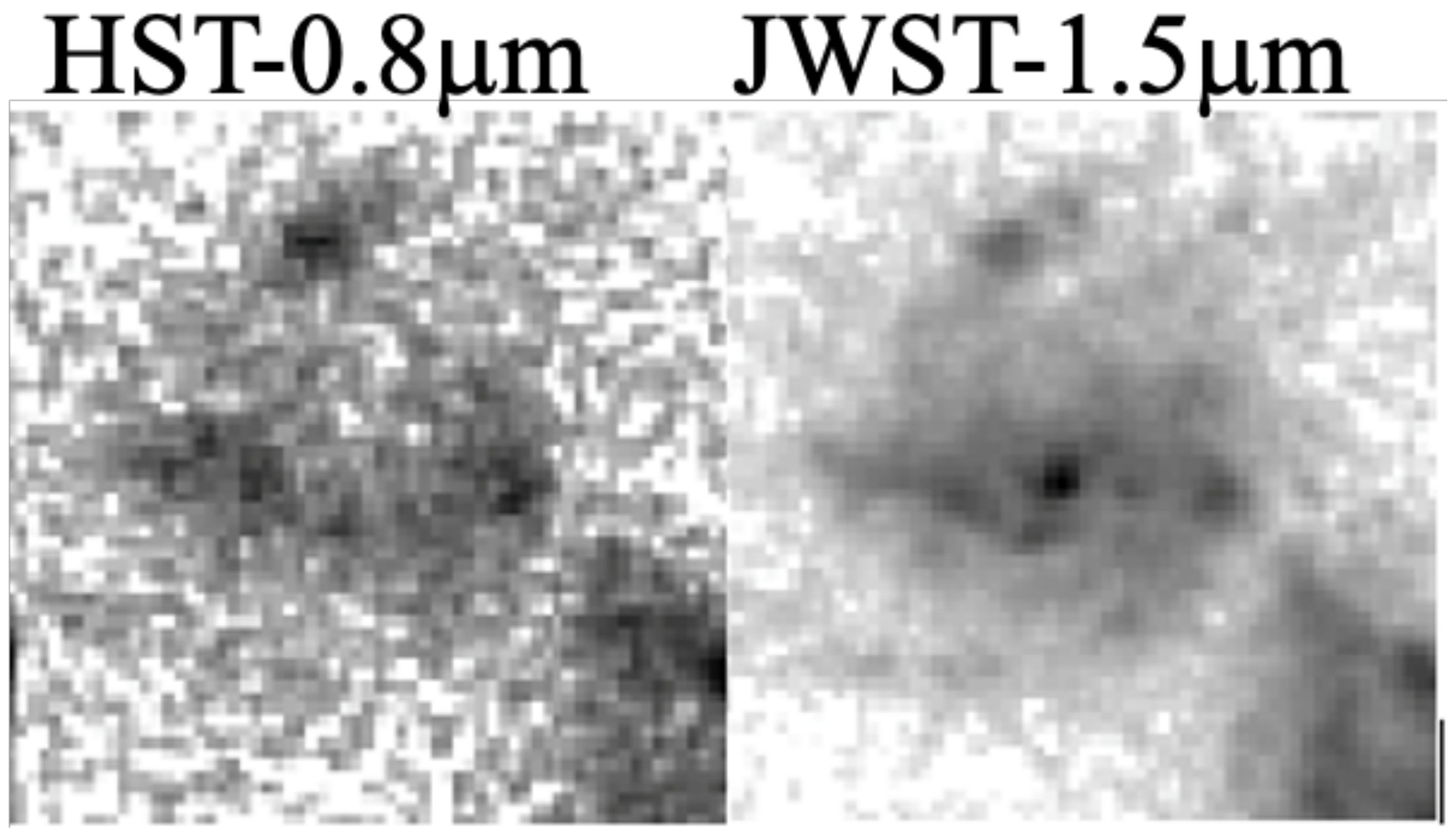
- Turbulence driven by gravity and feedback:
  - Injection scale of turbulence
  - Origins of molecular cloud properties



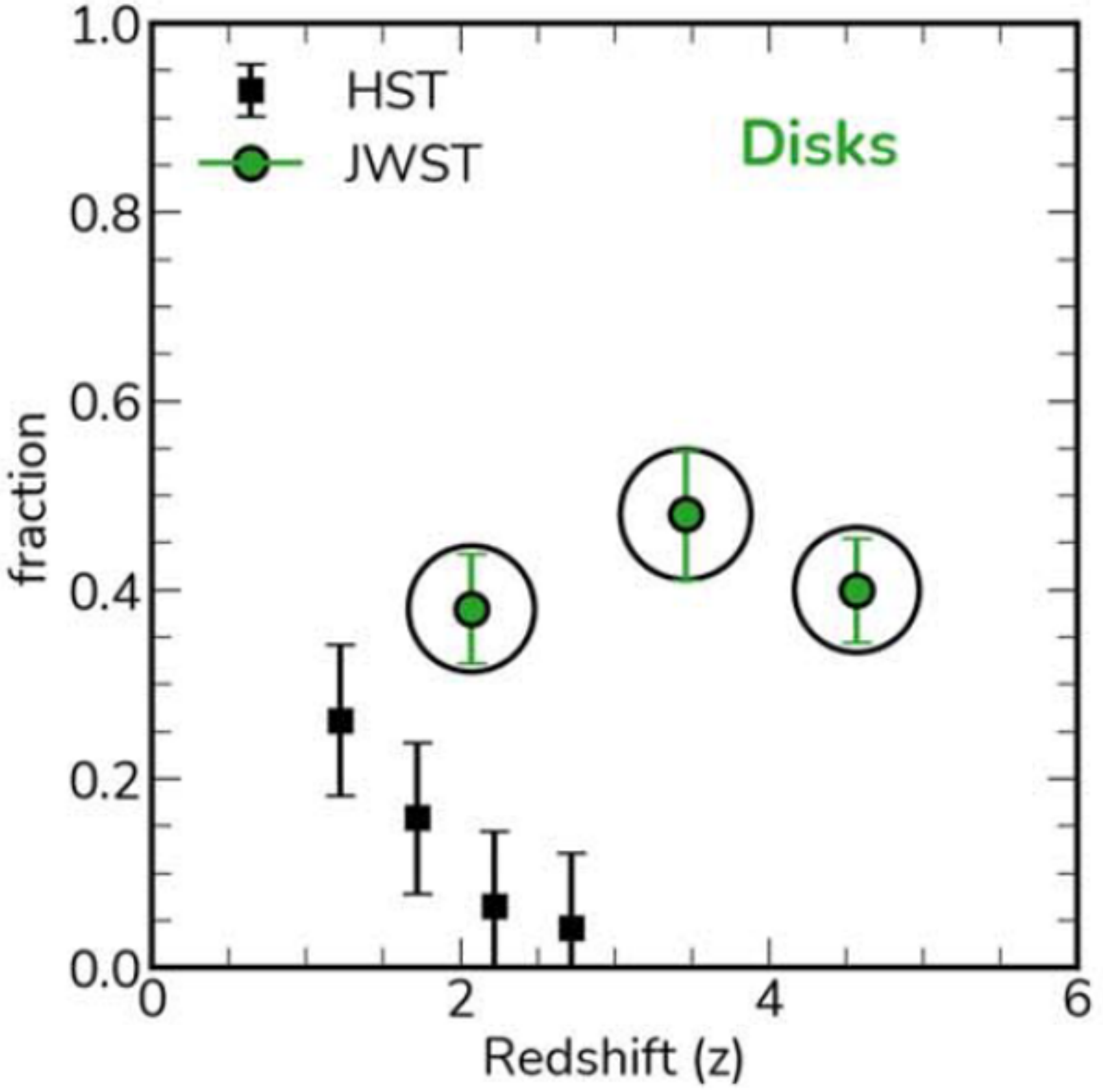
Marstrand, 11 June, 2025

Ongoing paradigm shift: disc galaxies form early

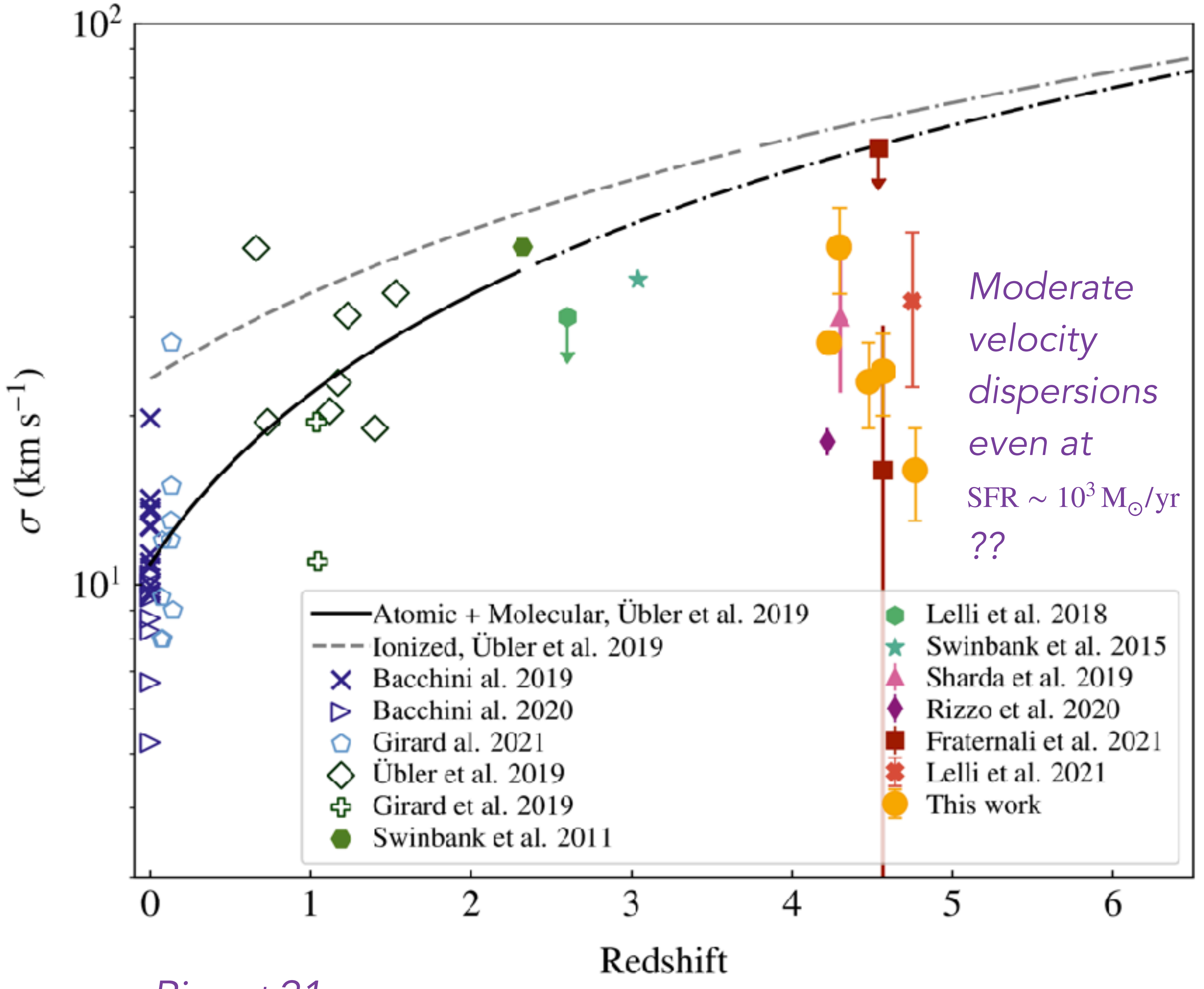
- **Hubble Space Telescope**
  Discs disappear past z~2
  (~10 Gyr lookback time)
- **JWST**
  Enormous increase in disc fractions!
  50% disc fraction even at z=4
  (~1.5 Gyr after the Big Bang))
- See also e.g. *Kartaltepe+23*
  (CEERS, discs up to z=9!)



Ferreira+23



High-redshift disc galaxies are more turbulent and gas-rich



Rizzo+21

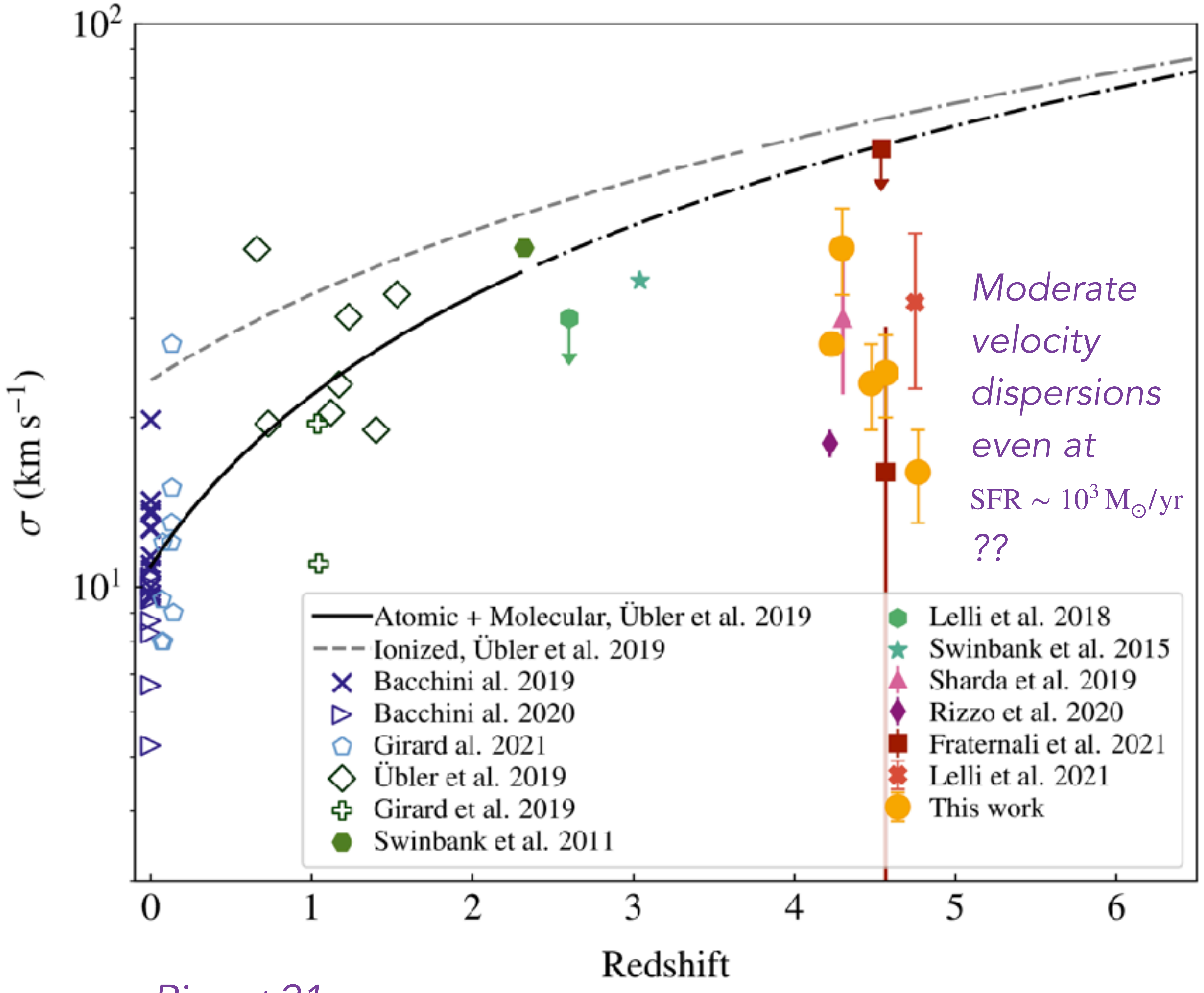
Many discs are kinematically cold!

v/σ as high as 10-20 up to $z \sim 3.5$ in cold gas tracers (ALMA: CO,CI,CII, *Rizzo+23*)

Jones+21, Rizzo+21, Lelli+21, Fraternali+21, Tsukui & Iguchi'21, Herrera-Camus+22,Roman-Oliveira+23, Parlanti+23, Pope+23; de Graaff et al. 2024; Parlanti et al. 2024

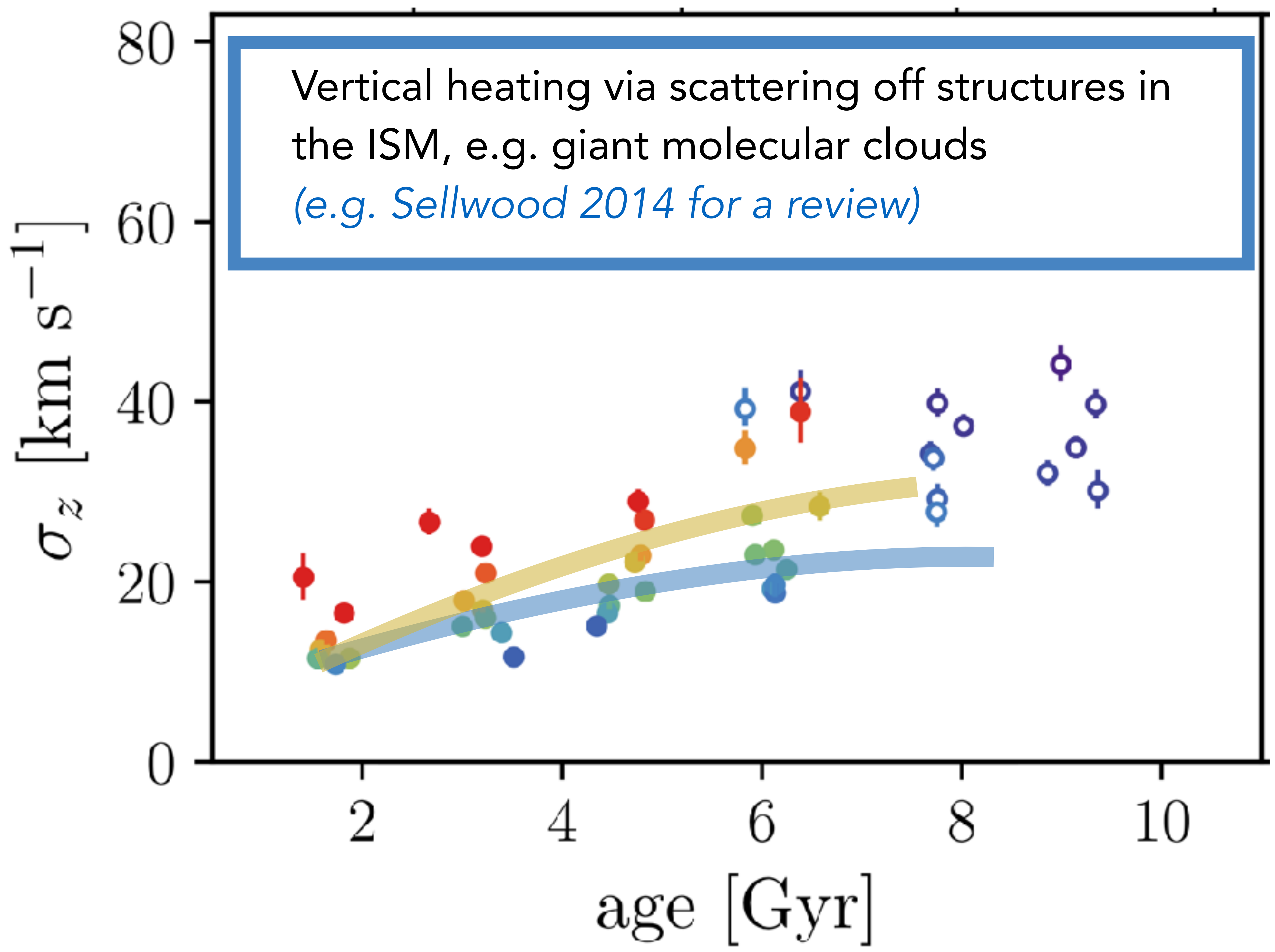
Is this a challenge to reproduce in simulations?

High-redshift disc galaxies are more turbulent and gas-rich



Rizzo+21

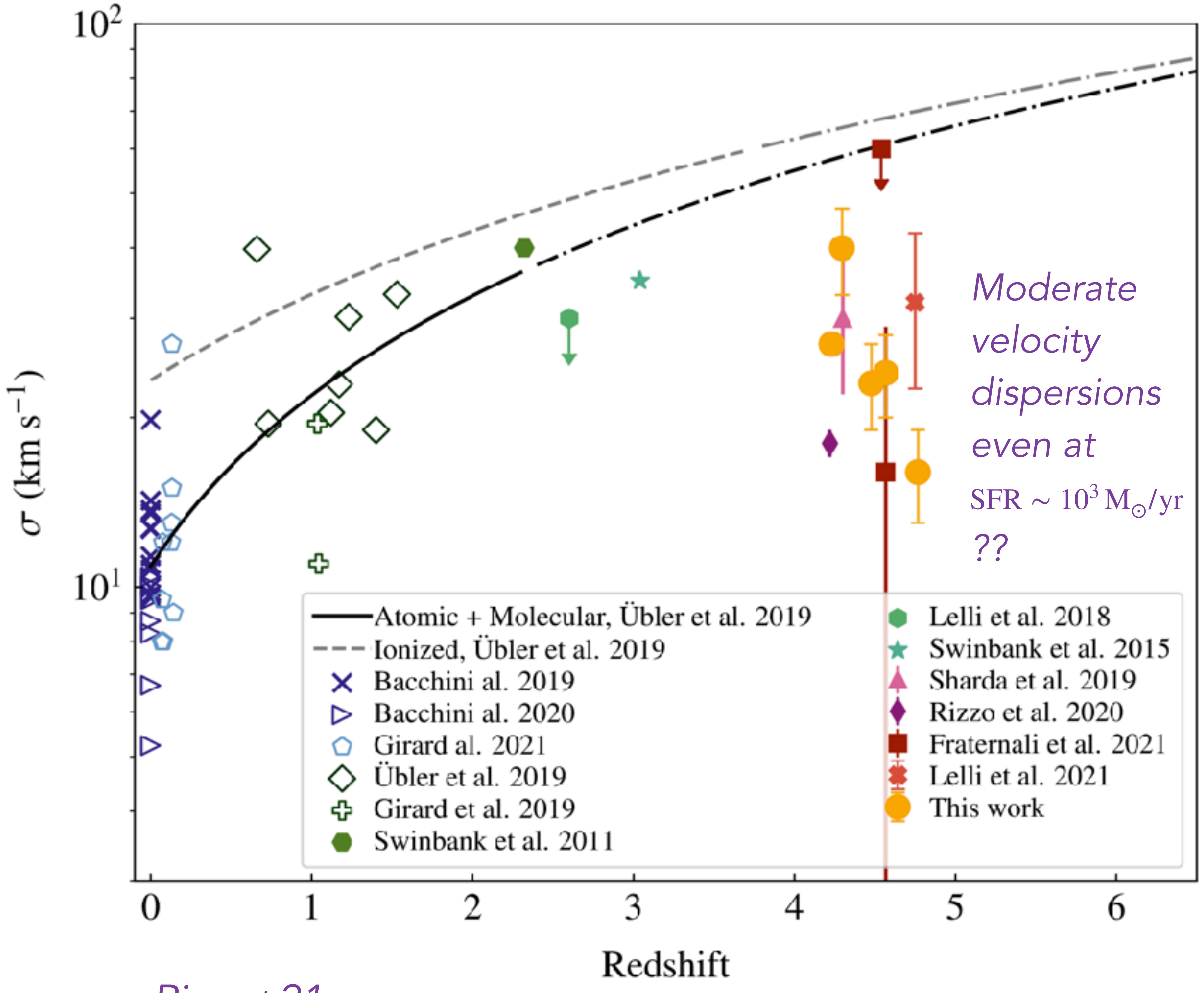
Milky Way, stellar age-velocity dispersion



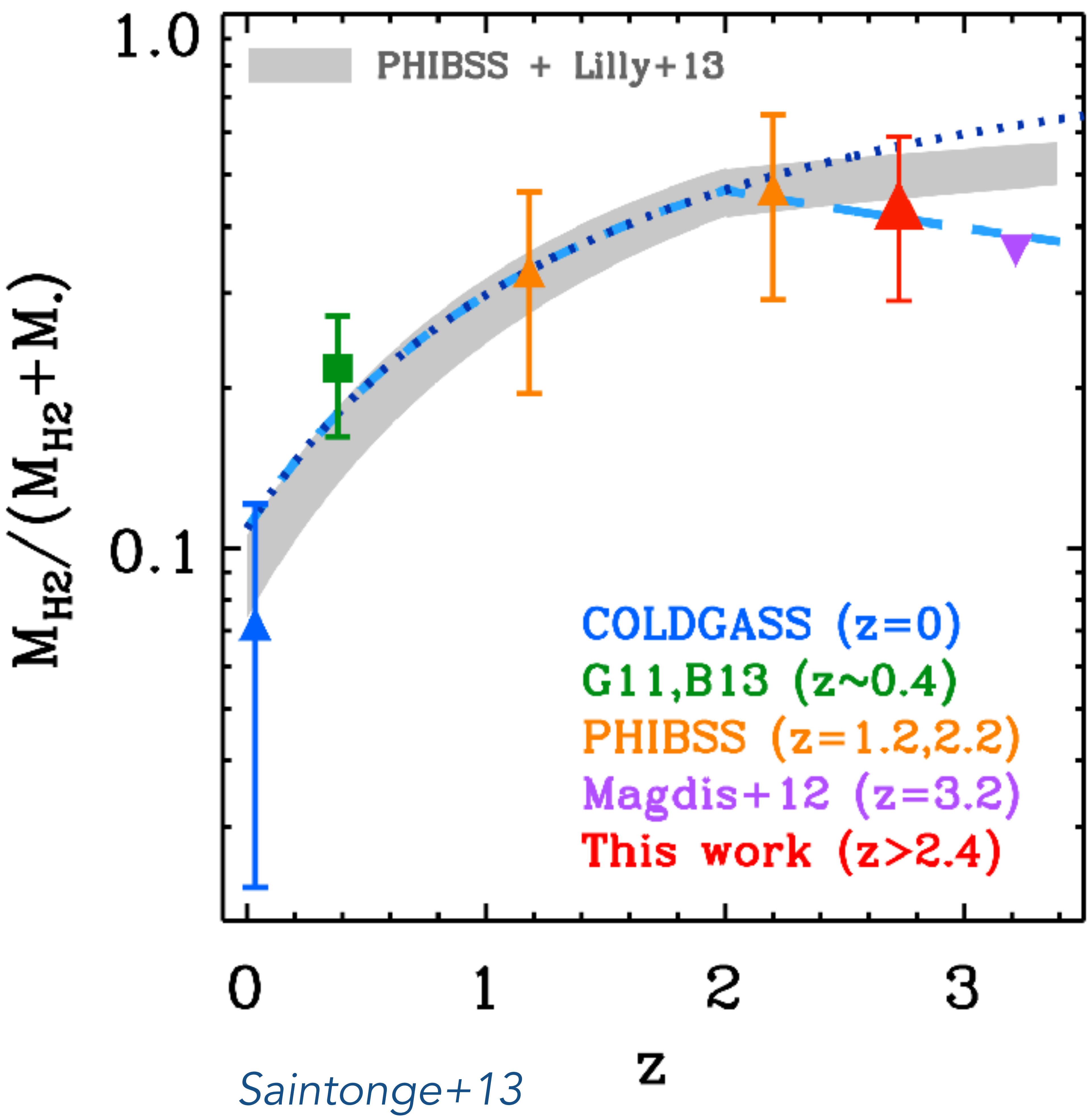
Vertical heating via scattering off structures in the ISM, e.g. giant molecular clouds
(e.g. Sellwood 2014 for a review)

Mackereth+19, using APOGEE and Gaia
(also Wielen 77, Nordström+04)

High-redshift disc galaxies are more turbulent and gas-rich



Rizzo+21



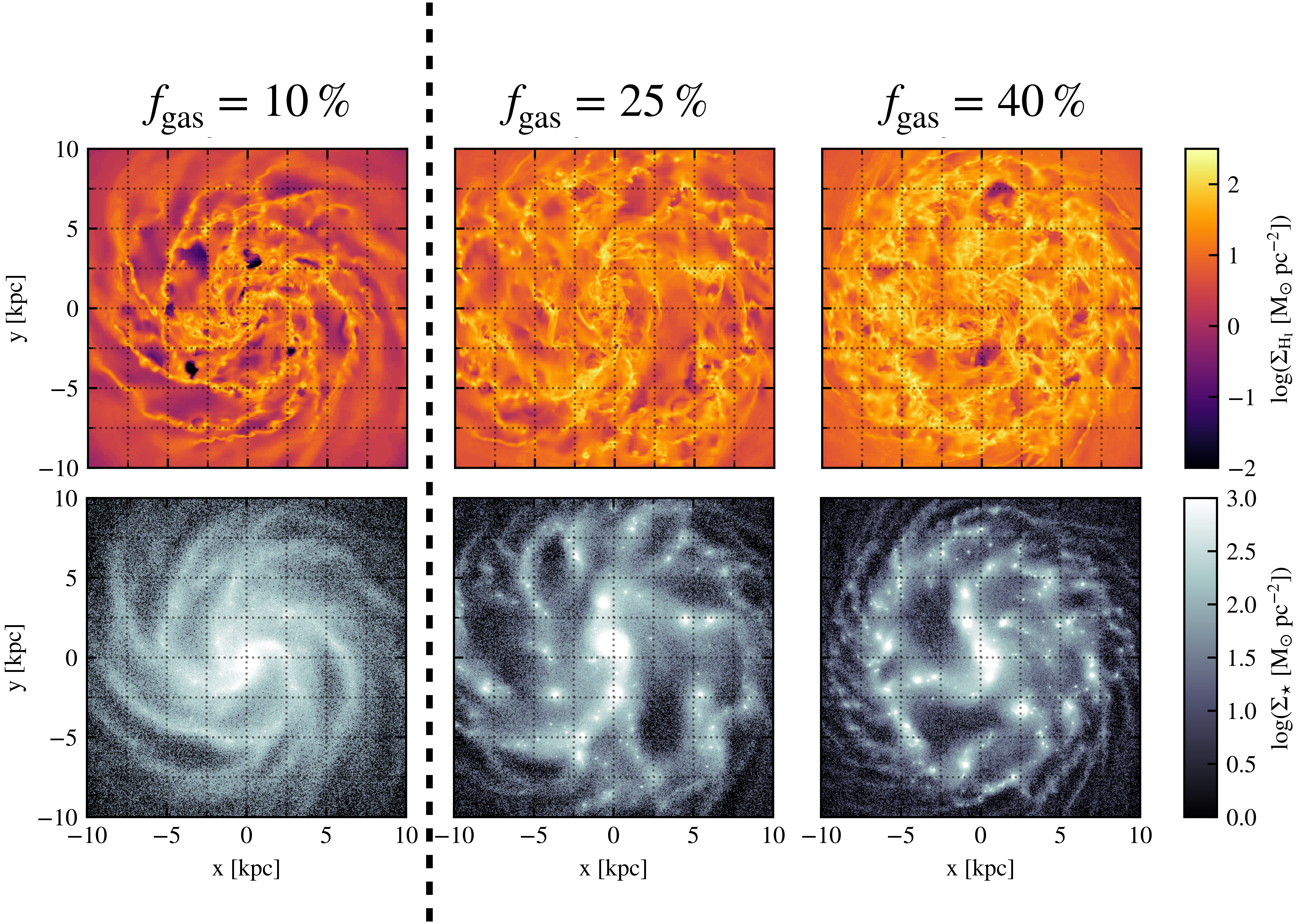
Saintonge+13

From giants clumps to clouds

Disc stability, fragmentation and turbulence properties of disc galaxies

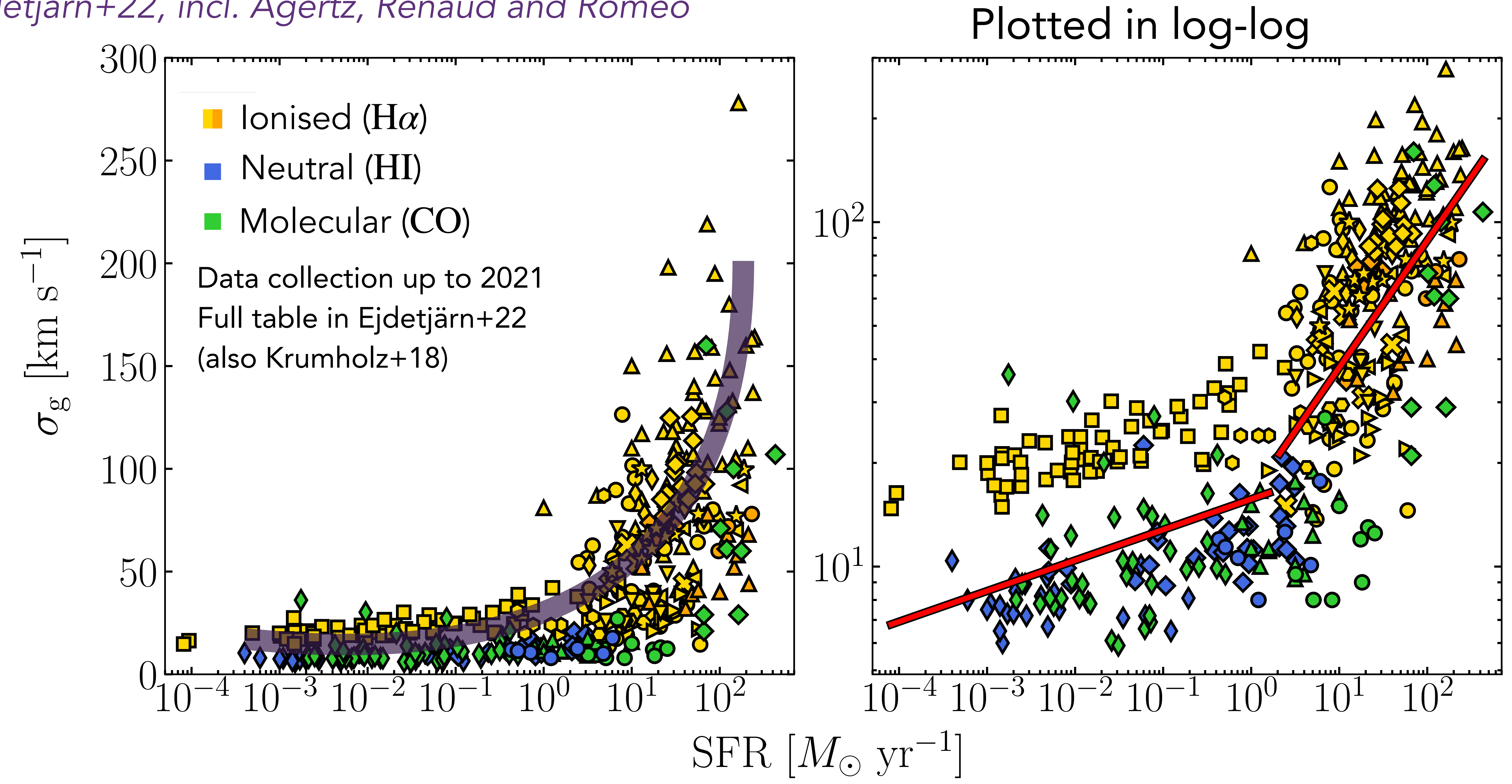
- Adaptive mesh refinement simulations (RAMSES, *Teyssier 2002*) of isolated galaxies
- Milky Way mass ($M_{\rm disc} = 5 \times 10^{10}$ M$_\odot$, $M_{200} = 10^{12}$ M$_\odot$).
- Disc mass kept fixed, but gas fraction increased from 10% to 70%.

1) Gravitational instabilities versus gas fraction *(Renaud+21)*
2) How does ISM turbulence map onto stellar kinematics *(van Donkelaar+22)*
3) Gravity versus stellar feedback as a driver of turbulence *(Ejdetjärn+22)*
4) Cloud scaling relations in gas-rich galaxies *(Renaud+24)*



Turbulence driving

Ejdetjärn+22, incl. Agertz, Renaud and Romeo



Analytical work relating feedback, gravity, disc stability and gas transport can broadly explain trends *(e.g. Krumholz & Burkhart'16, Krumholz+18)*

- Data is heterogenous
- High SFR data is mostly high redshift and mostly obtained from Hα.
- Beam smearing; - methods based on 2D modelling are biased towards higher values of σ_{gas} (see e.g. Di Teodoro & Fraternali'15)

Simple test:

Let's study how discs react to the absence or presence of feedback regulation

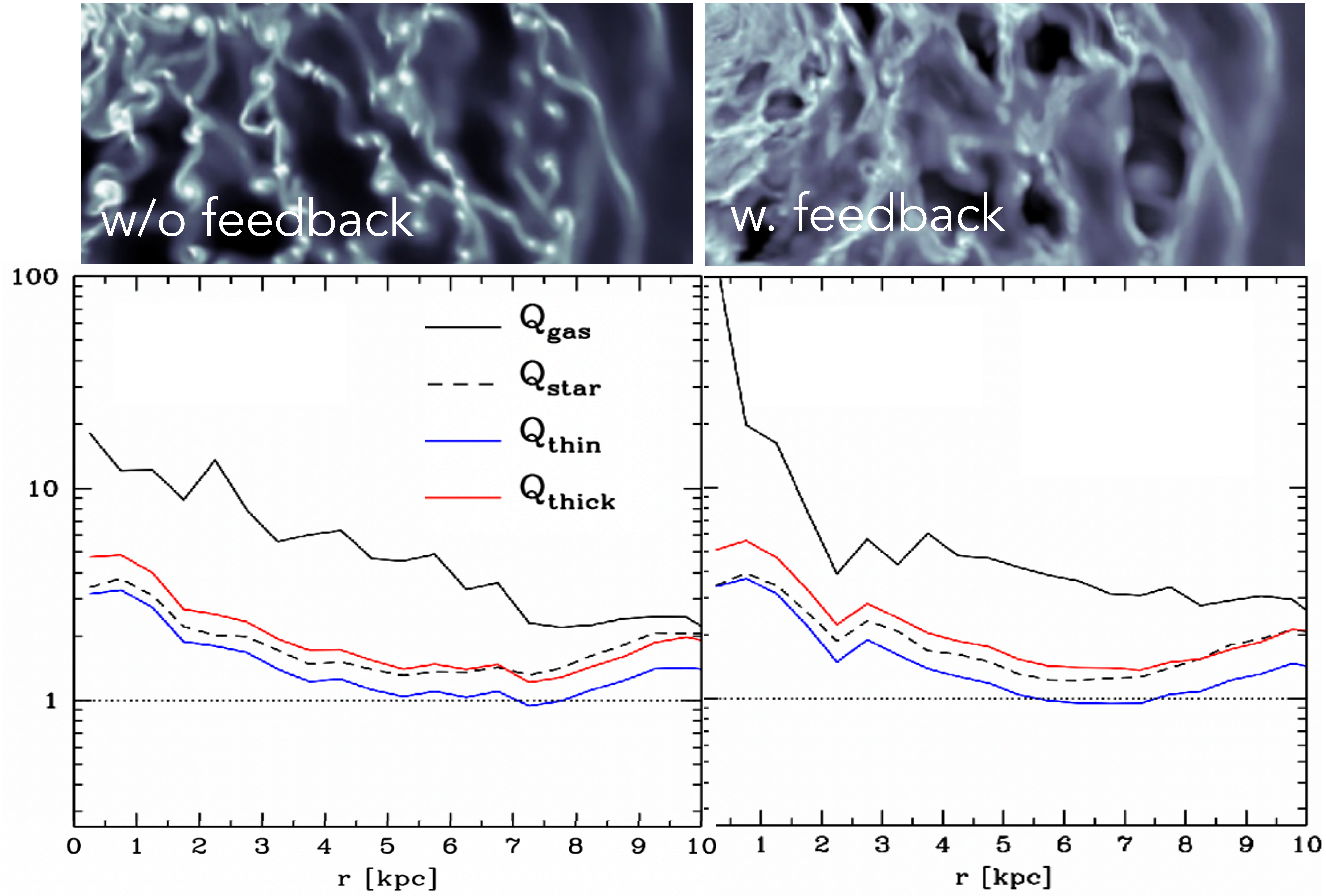
Ejdetjärn+22, incl. Agertz, Renaud and Romeo

Simulated discs self-regulate to $Q_{\rm tot} \sim$ few, regardless of turbulence driver

Agertz+15

$Q_{\rm gas} \sim 1$, which is commonly adopted in analytical models, is *inappropriate* for local Universe spirals!

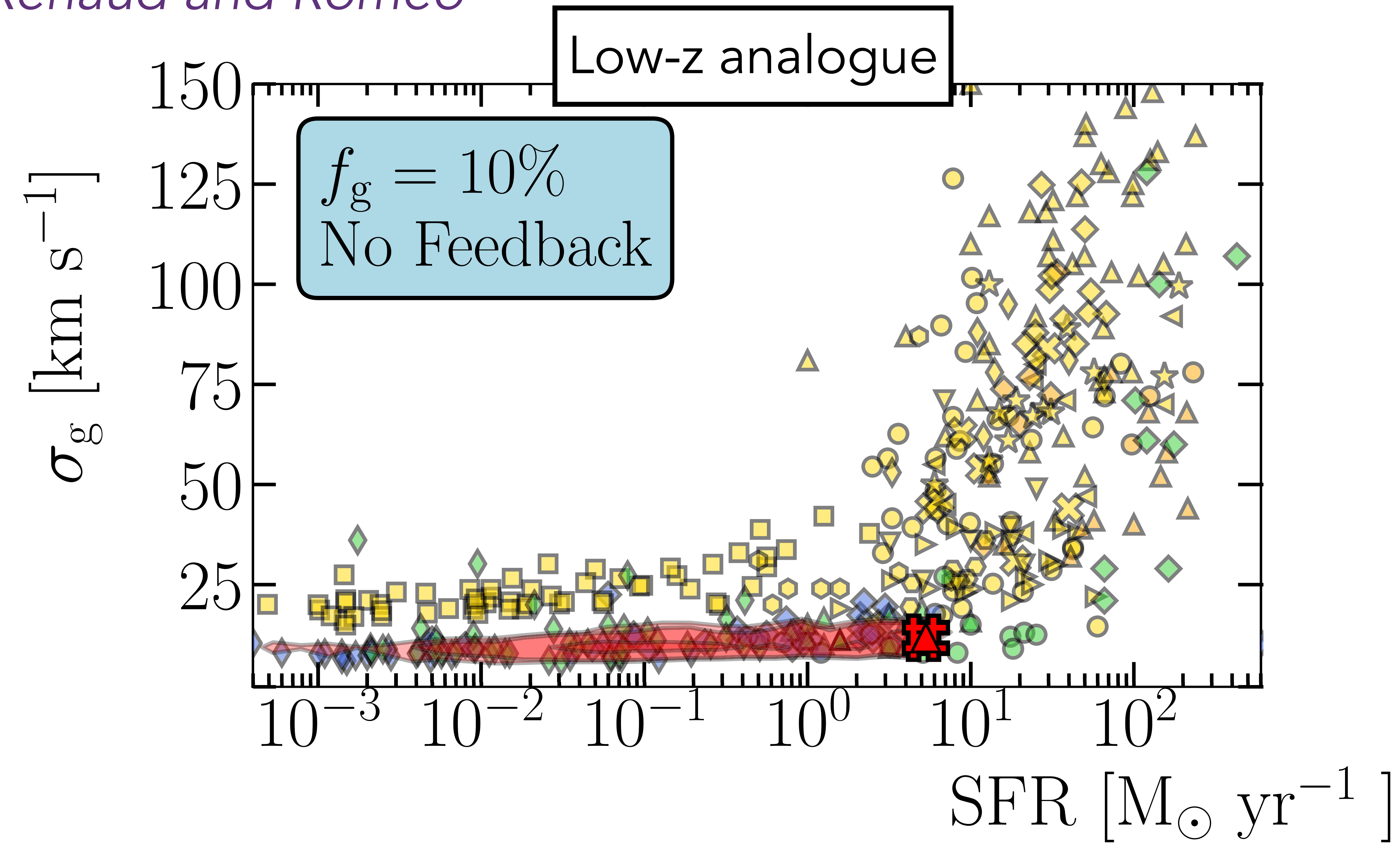
$Q_{\rm gas} \gg 1$ in observations *e.g. Elmegreen & Hunter'15, Romeo & Mogotsi'17*

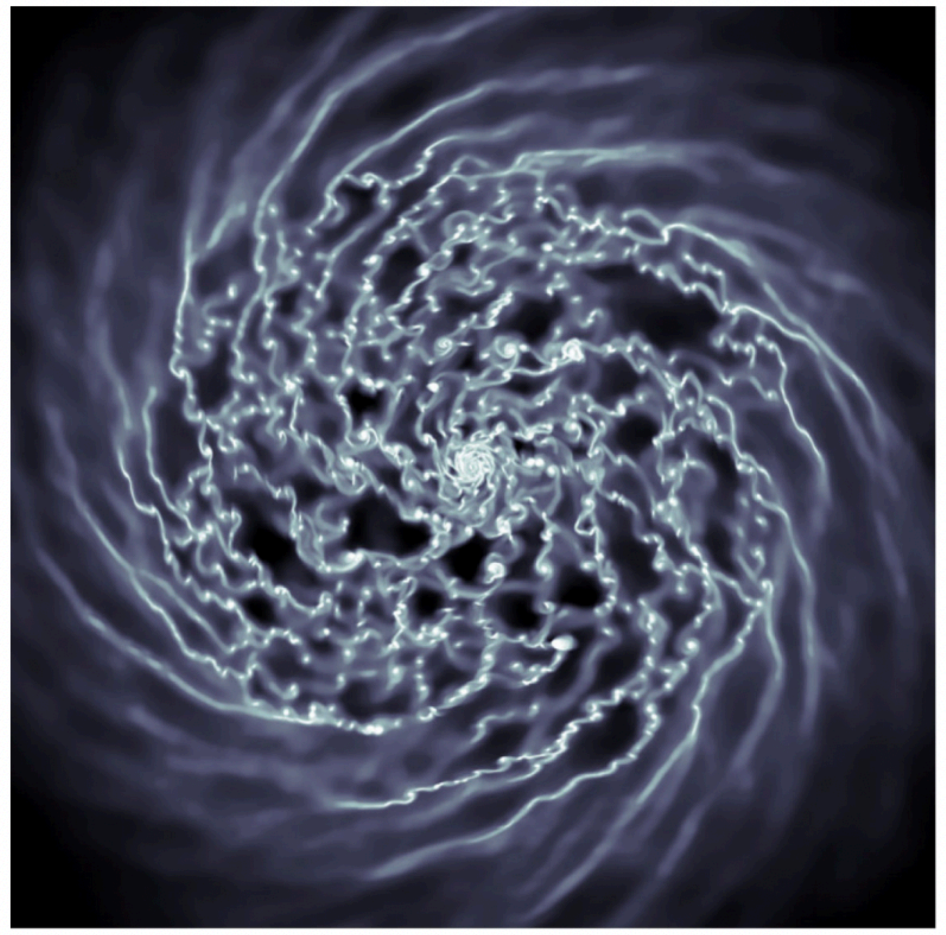


Gas velocity dispersion in simulated discs with different gas fractions and star formation rates

Ejdetjärn+22, incl. Agertz, Renaud and Romeo

- **Without feedback**, the disc fragments into long-lived clouds and irregular motions are driven by disc instabilities.



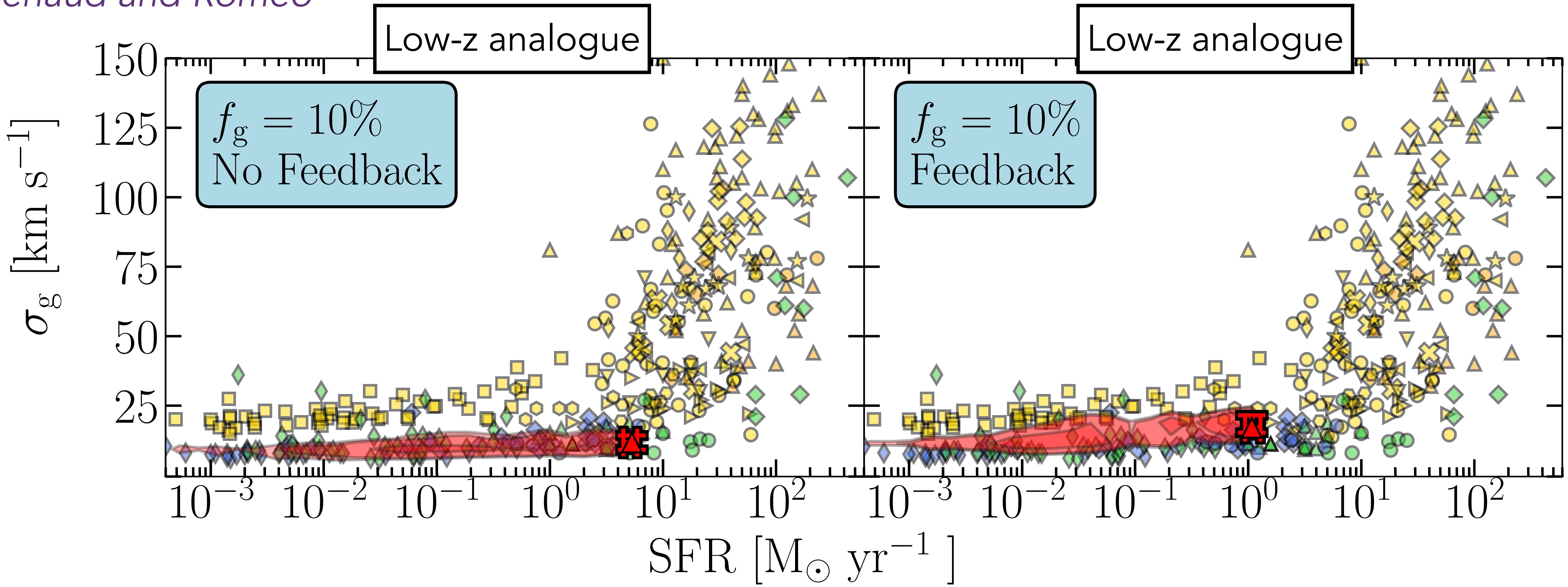


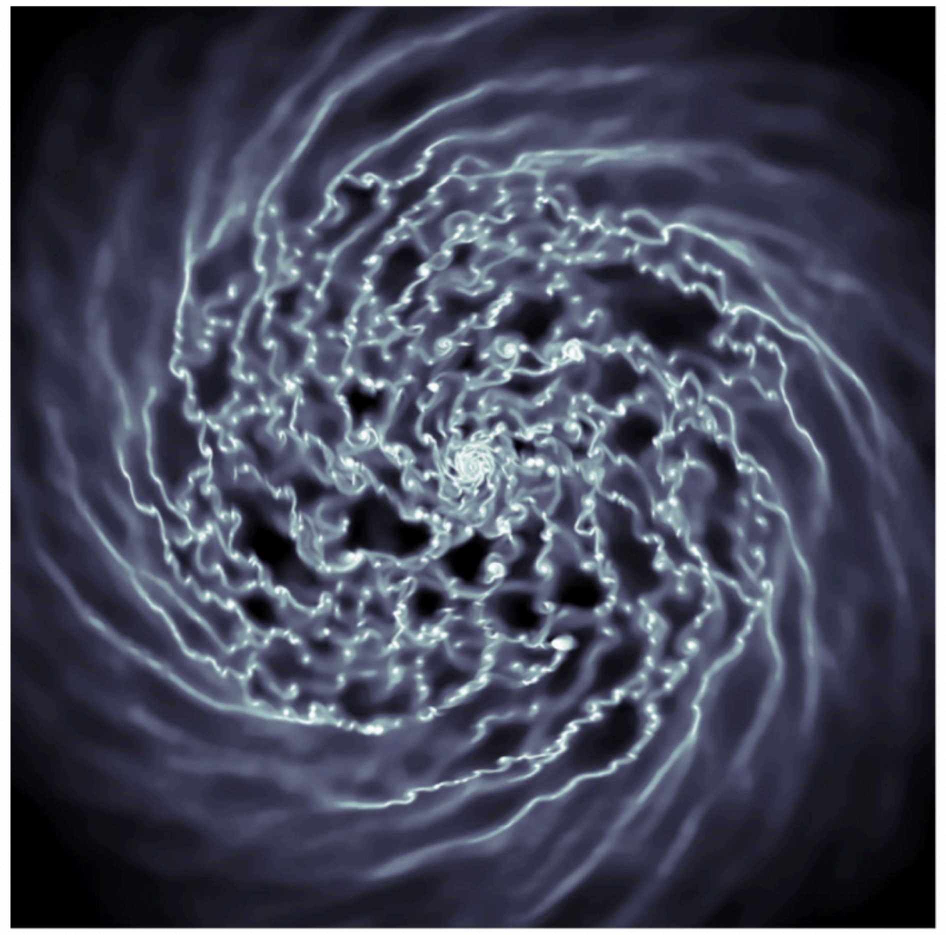
Gas velocity dispersion in simulated discs with different gas fractions and star formation rates

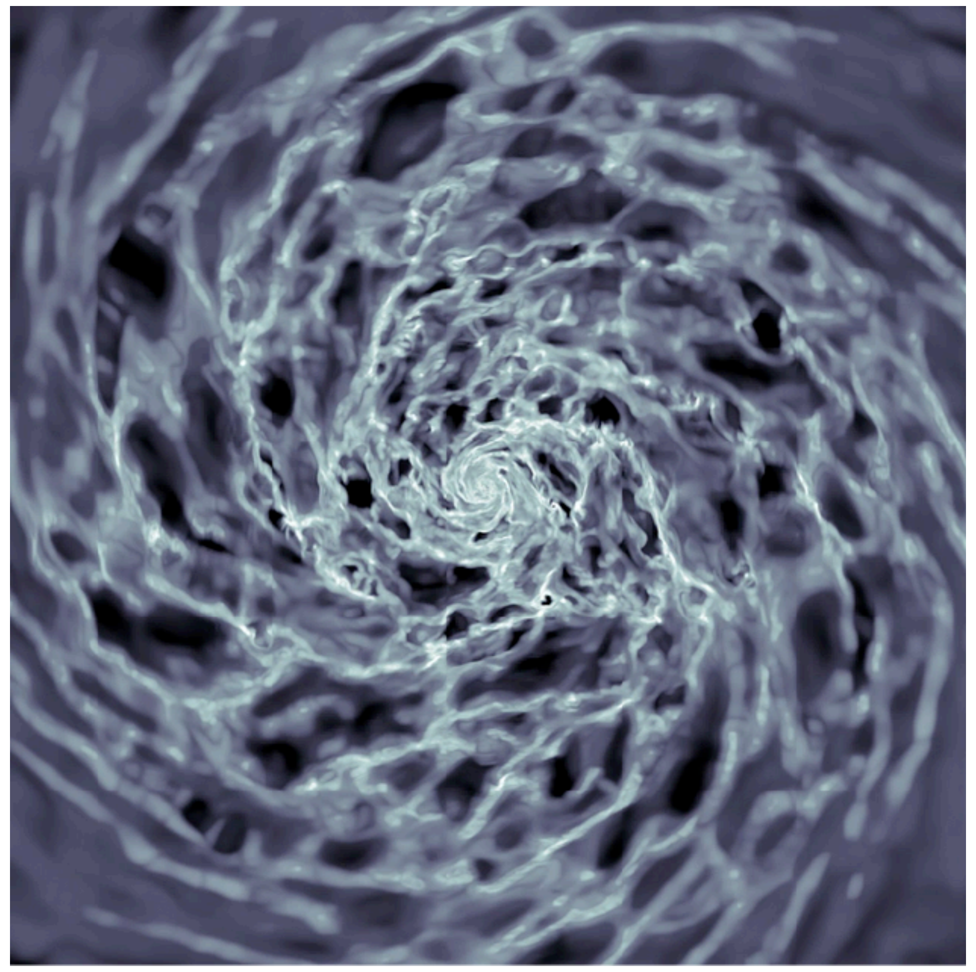
Ejdetjärn+22, incl. Agertz, Renaud and Romeo

- **Without feedback**, the disc fragments into long-lived clouds and irregular motions are driven by disc instabilities.

- **With feedback**, the disc reaches similar levels of σ_{gas}, although molecular clouds are now dispersed after a few free-fall times.







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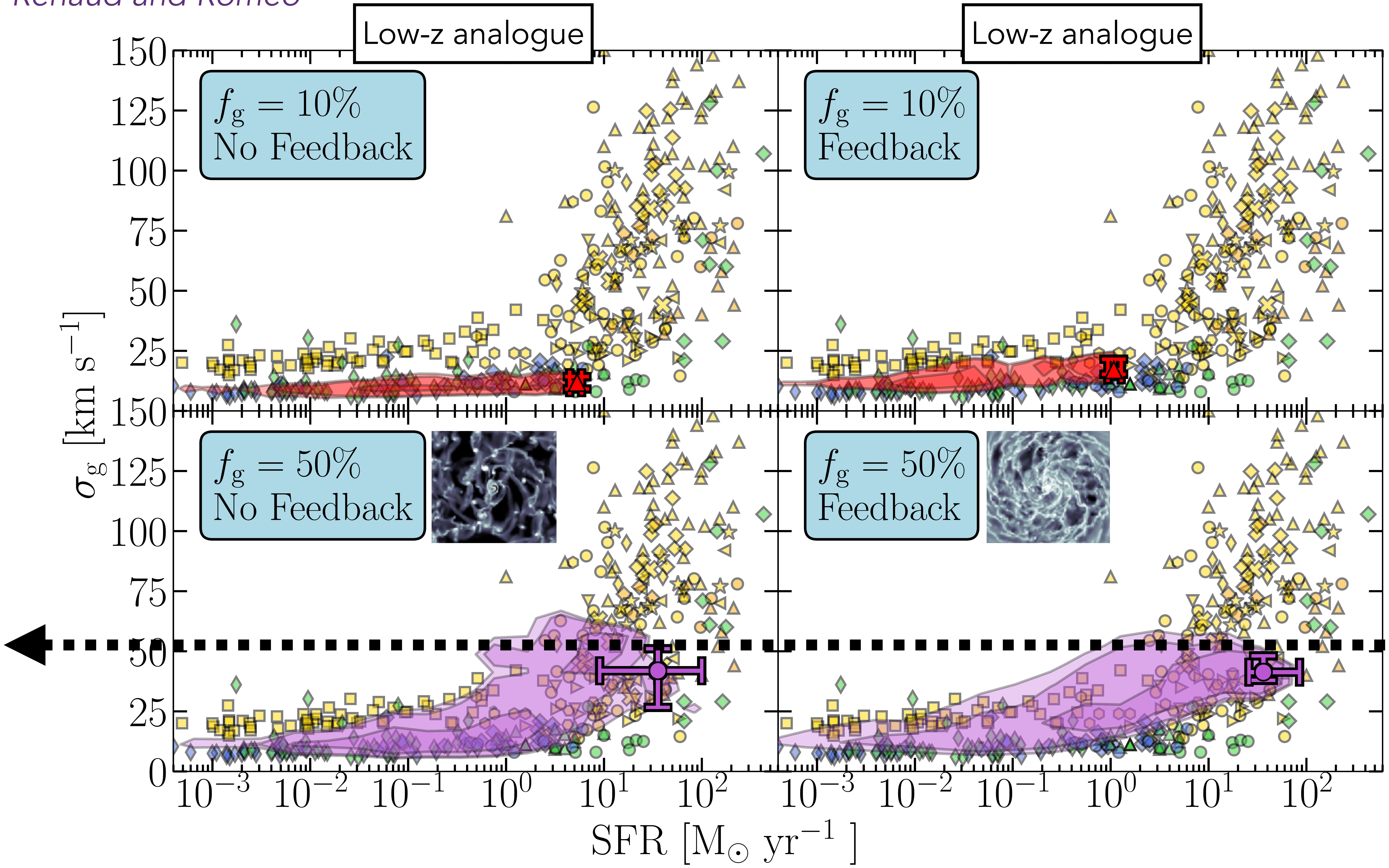
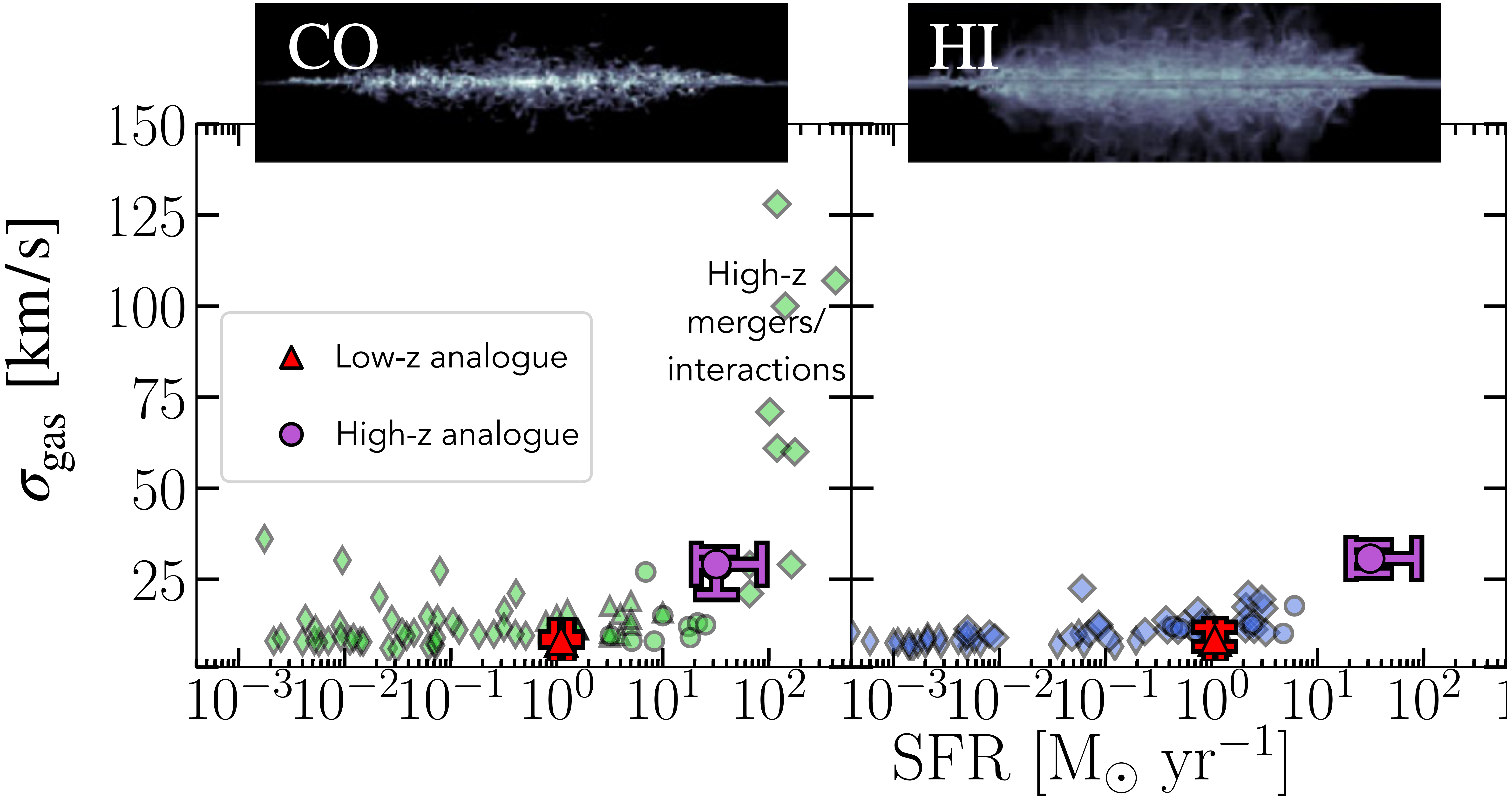


The simulations are unable to reproduce $\sigma_{gas} \gtrsim 50$ km/s.

(NB: $M_{vir} \sim 10^{12}$ M$_\odot$)

Disc turbulence levels in different gas phases

Ejdetjärn+22, incl. Agertz, Renaud and Romeo



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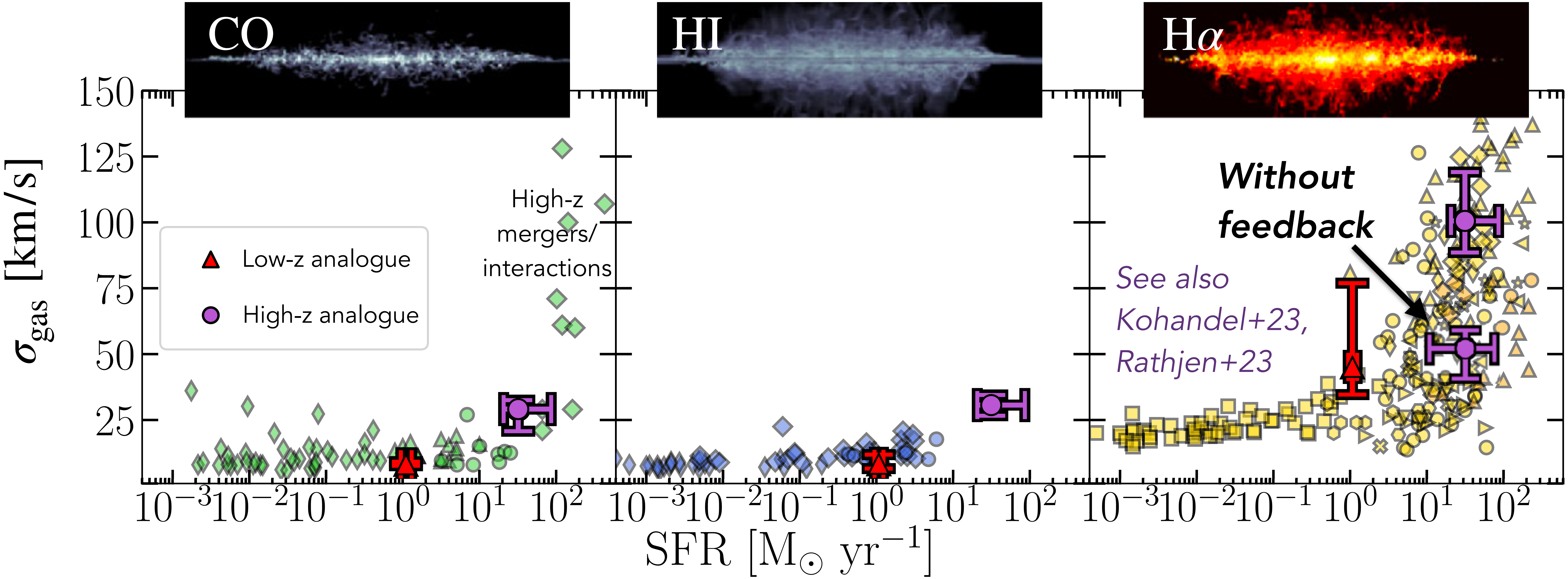
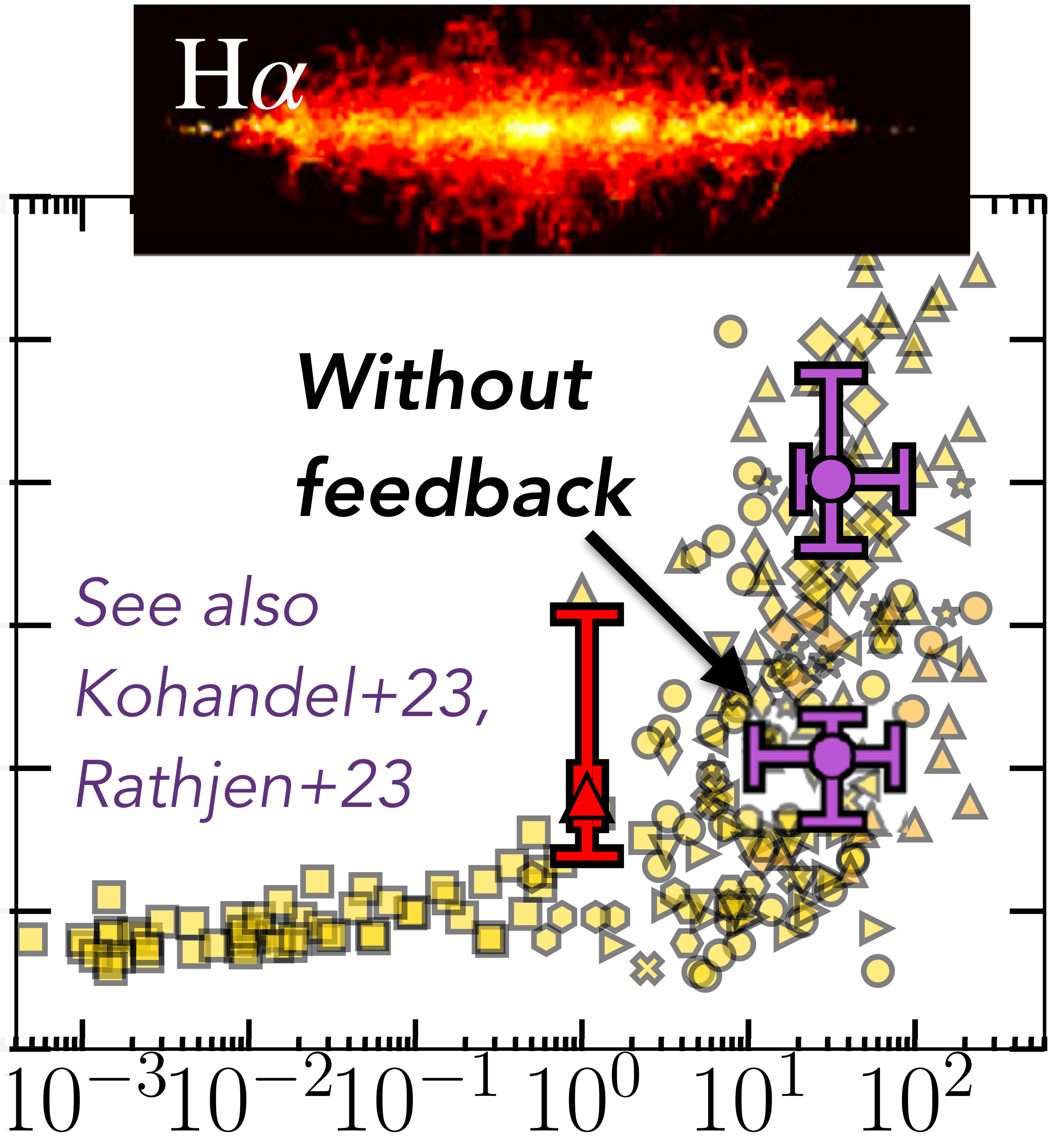


- Feedback powered turbulence levels in $\mathrm{H}\alpha$. But, this is only $\sim 10\,\%$ of the total turbulence energy budget *(in close agreement with inference from PHANGS-MUSE/HST data, Egorov+23)*
- A constant CO-$\mathrm{H}\alpha$ offset is observed in nearby and high-z galaxies *(Girard et al. 2021, Lenkić+24)*, which these simulations reproduce *(Ejdetjärn et al. in prep)*

Disc turbulence levels in different gas phases

Ejdetjärn+22, incl. Agertz, Renaud and Romeo

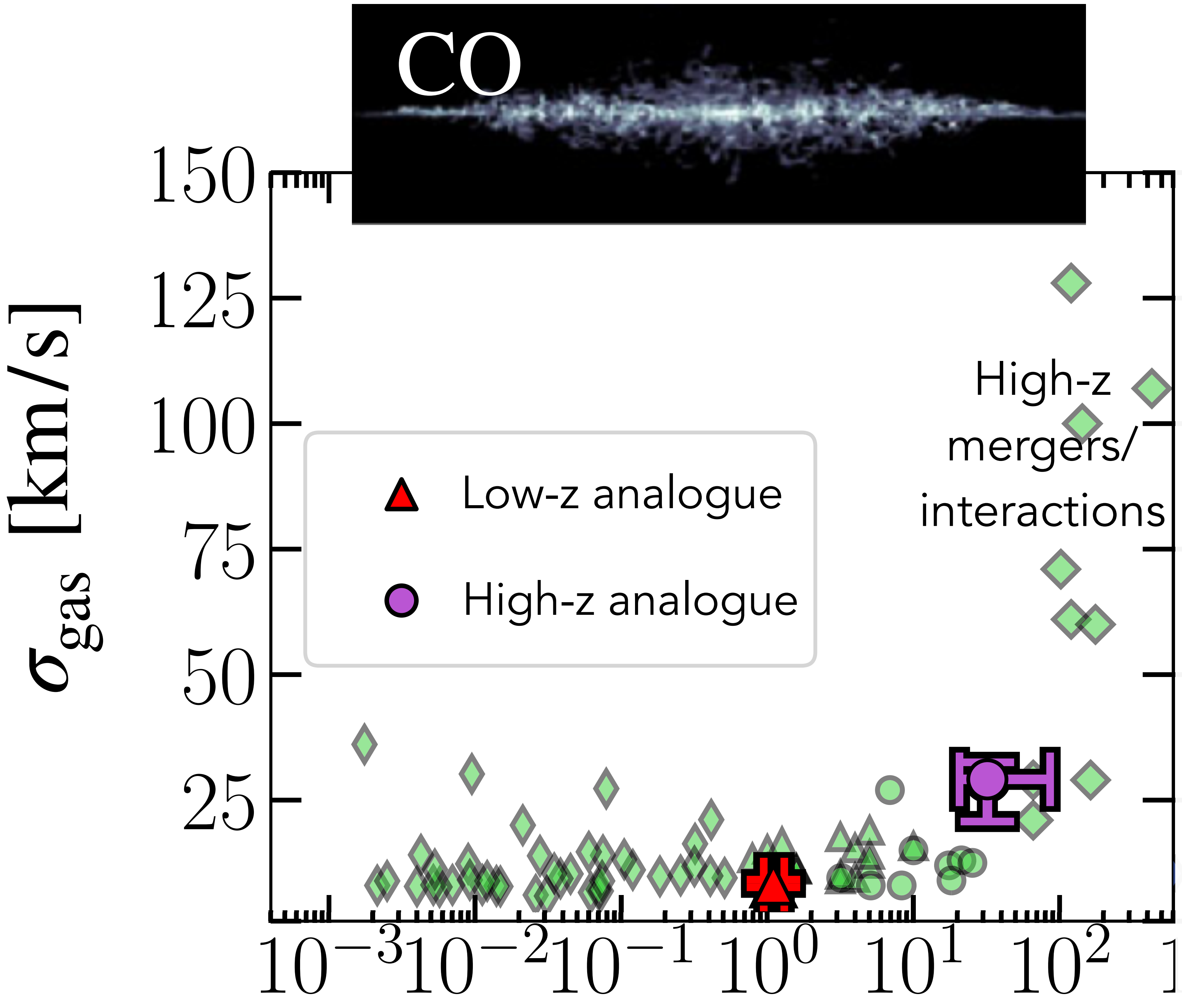
Caveat:
this depends on the amount of diffuse vs. dense Hα (*Ejdetjärn+24*).



- High feedback powered turbulence levels in Hα. But, this is only ~ 0 % of the total turbulence energy budget *(in close agreement with inference from PHANGS-MUSE/HST data, Egorov et al. 2023)*
- A constant CO-Hα offset is observed in nearby and high-z galaxies *(Girard et al. 2021, Lenkić+24)*, which these simulations reproduce *(also Ejdetjärn et al. in prep)*

Disc turbulence levels in different gas phases

(Ejdetjärn, Agertz et al. 2022)



Caveat for analytical models:

Absent mergers/interactions, the cold/dense ISM in high-z discs cannot be driven to turbulent velocity dispersions of $\sigma \gtrsim 40-50$ km/s.

Greater values are due to beam smearing/non-disc geometries (Di Teodoro & Fraternali'15)

- High feedback powered turbulence levels in Hα. But, this is only $\sim 10\,\%$ of the total turbulence energy budget *(in close agreement with inference from PHANGS-MUSE/HST data, Egorov et al. 2023)*
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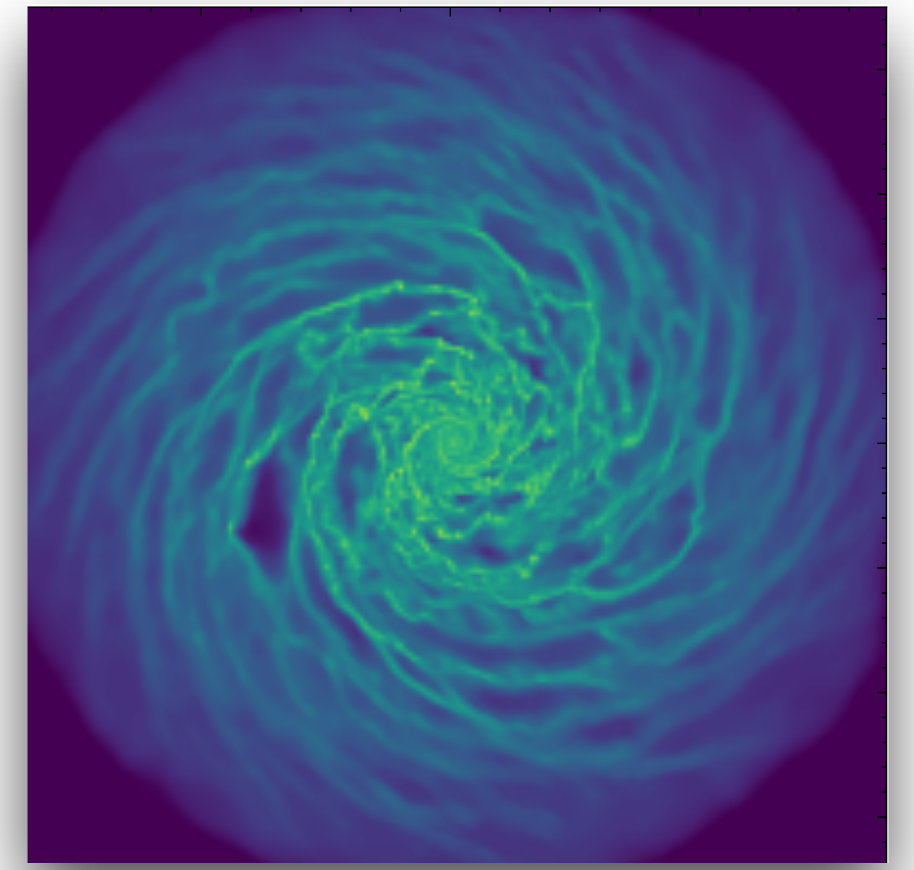
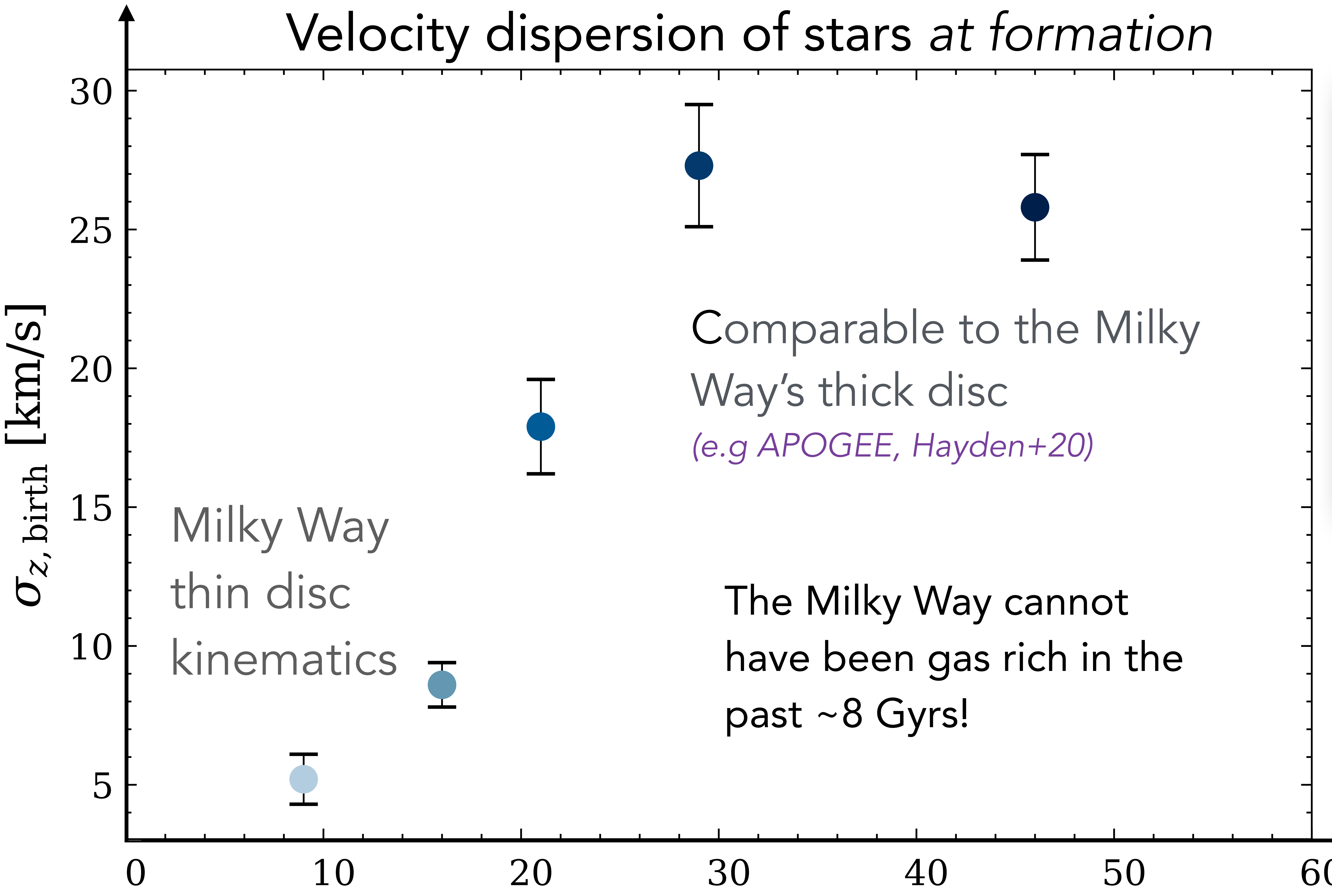
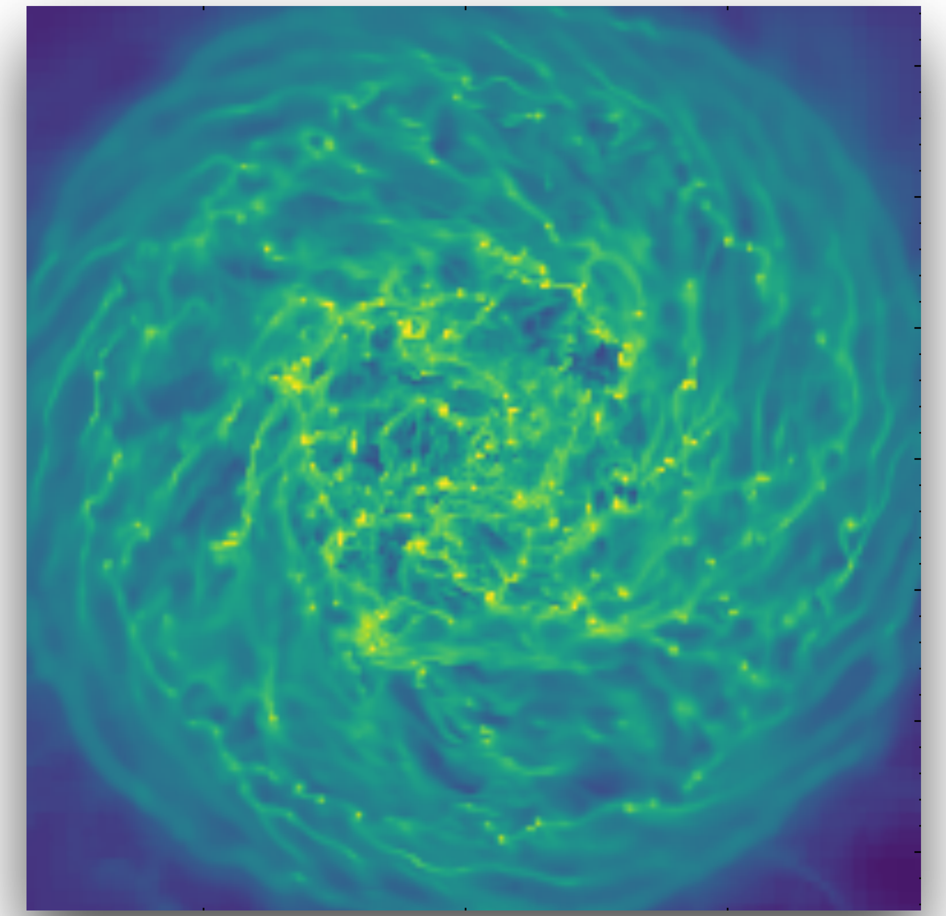
Connecting high-z ISM conditions to current day stellar discs

Molecular gas turbulence in gas rich, turbulent galaxies prevent thin disc formation

van Donkelaar, Agertz, Renaud'22







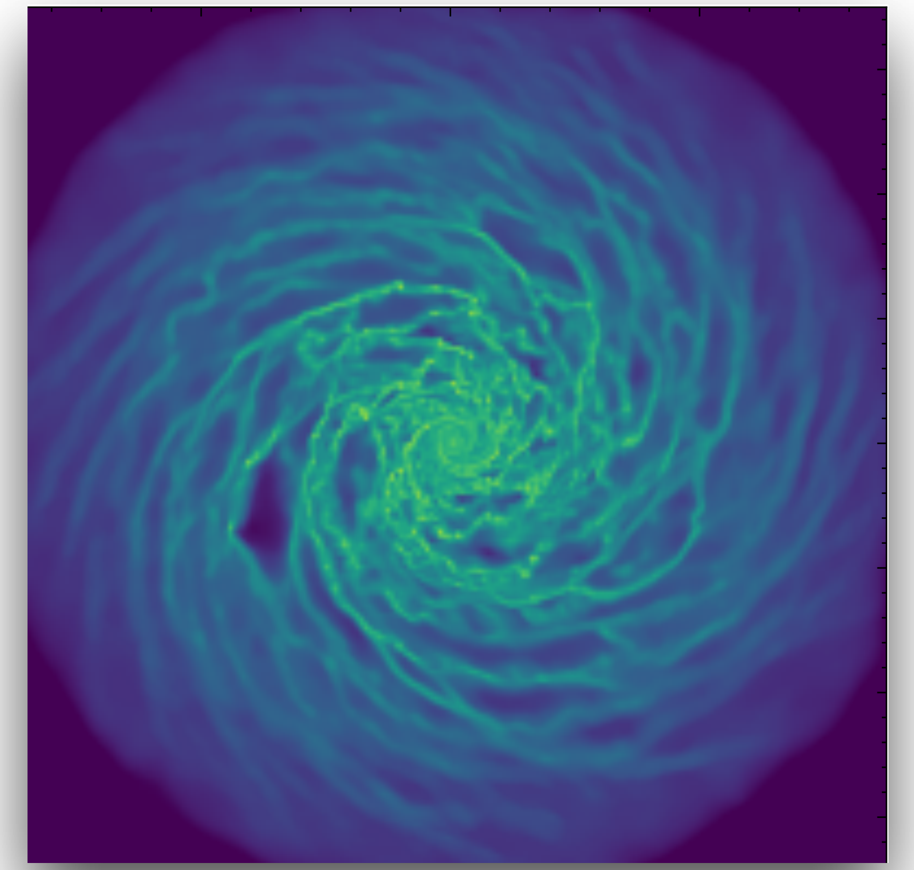
Local Universe conditions

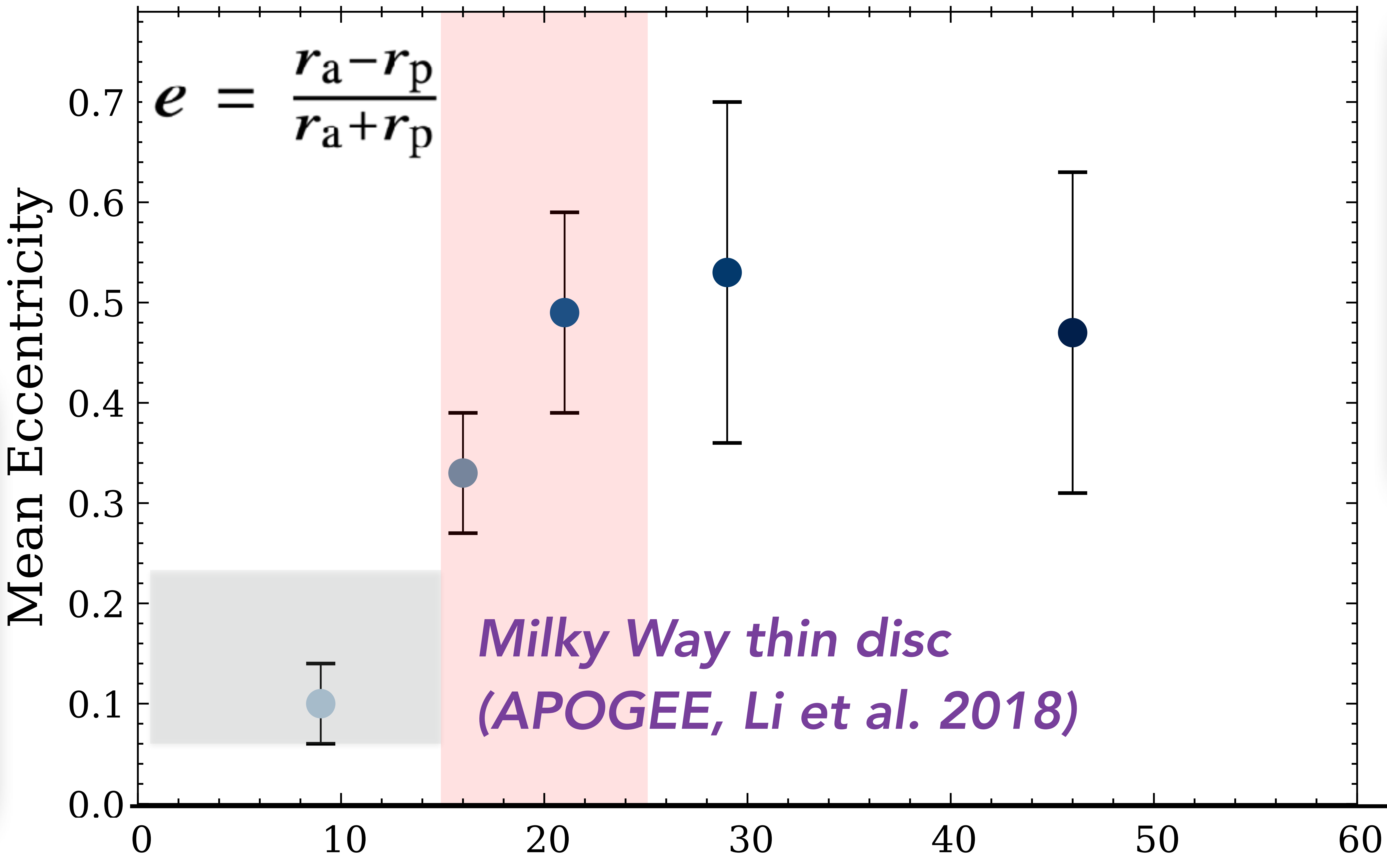
High redshift conditions

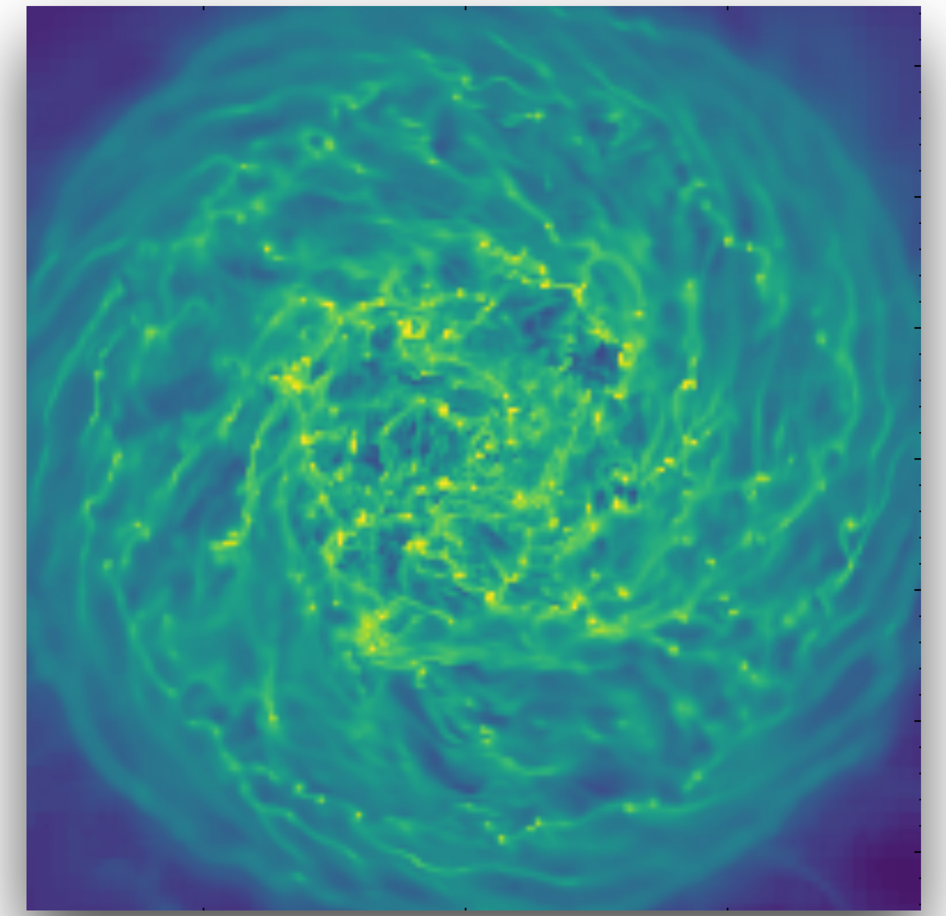
High redshift conditions lead to large orbital eccentricities

Milky Way thin disc characteristics impossible for gas fractions > 20%

van Donkelaar, Agertz, Renaud'22





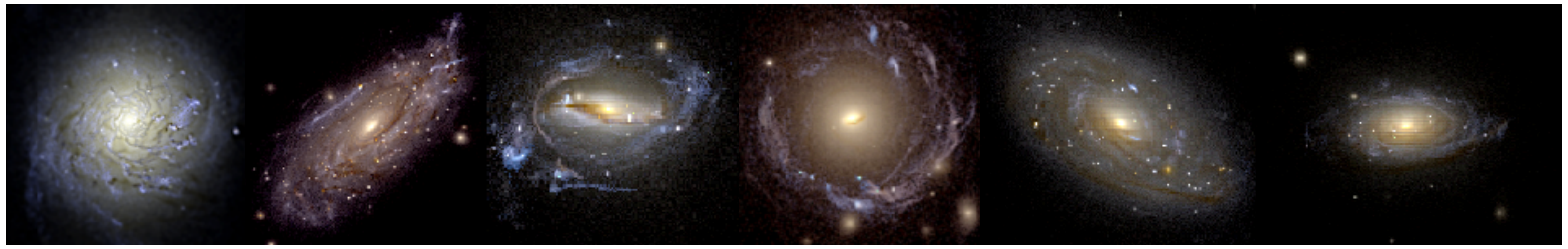


Local Universe conditions

High redshift conditions

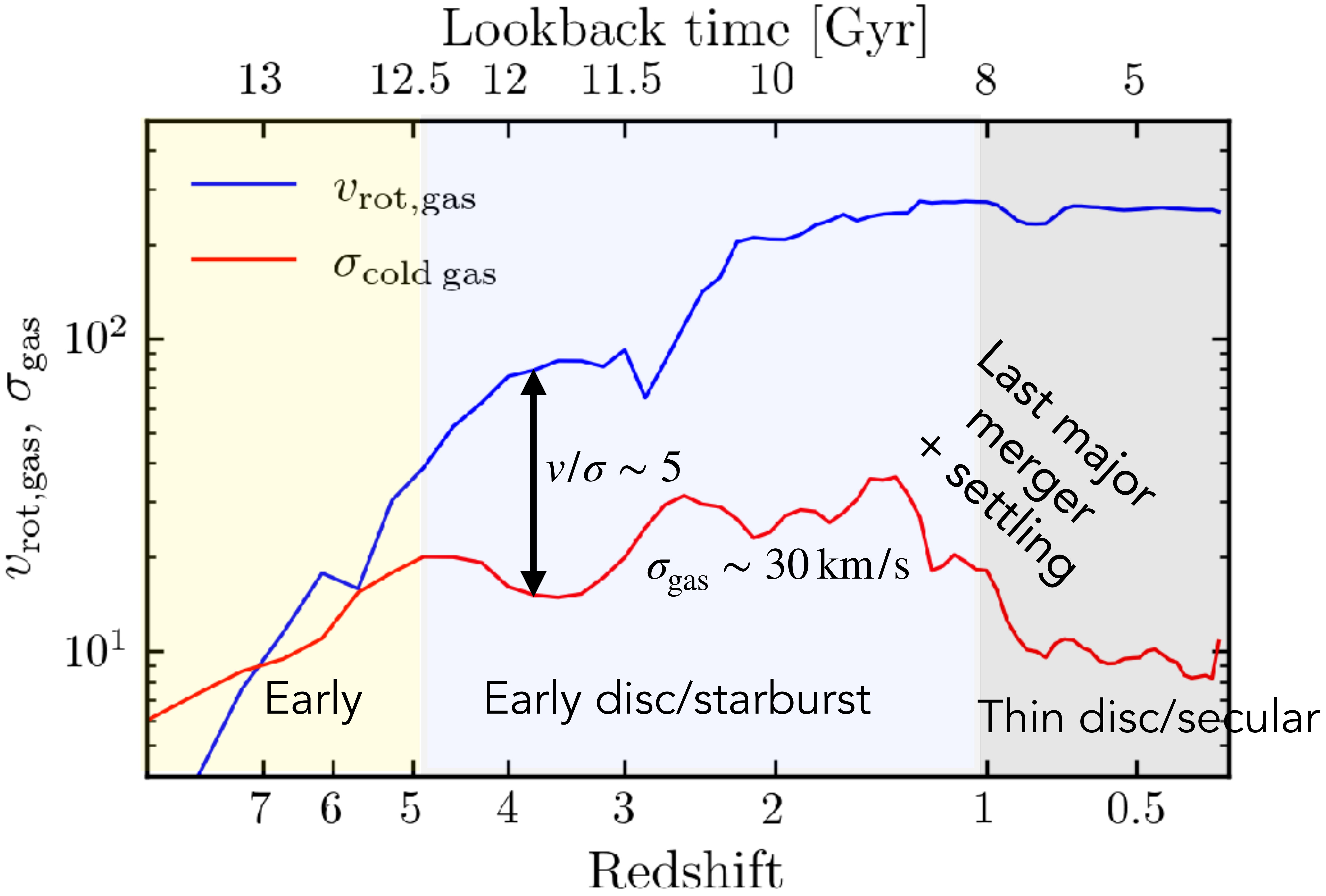
Insights from cosmological simulations

Disc formation in VINTERGATAN



Agertz+21, Renaud+21a,b, 22, Segovia Otero+22,25, Rey+23, Joshi+23,24, Nyhagen+in prep, Rufo Pastor+in prep

- Cosmological zoom simulations of $M_{200} = 10^{12}$ $M_\odot$ dark matter halos at z=0. Adaptive-mesh-refinement, Ramses *(Teyssier'02)*
- ***Segovia Otero+22:*** 3 phases can be identified (also from Milky Way stellar populations, e.g. *Belokurov & Kravtsov'22, Conroy+22, Rix+22)*

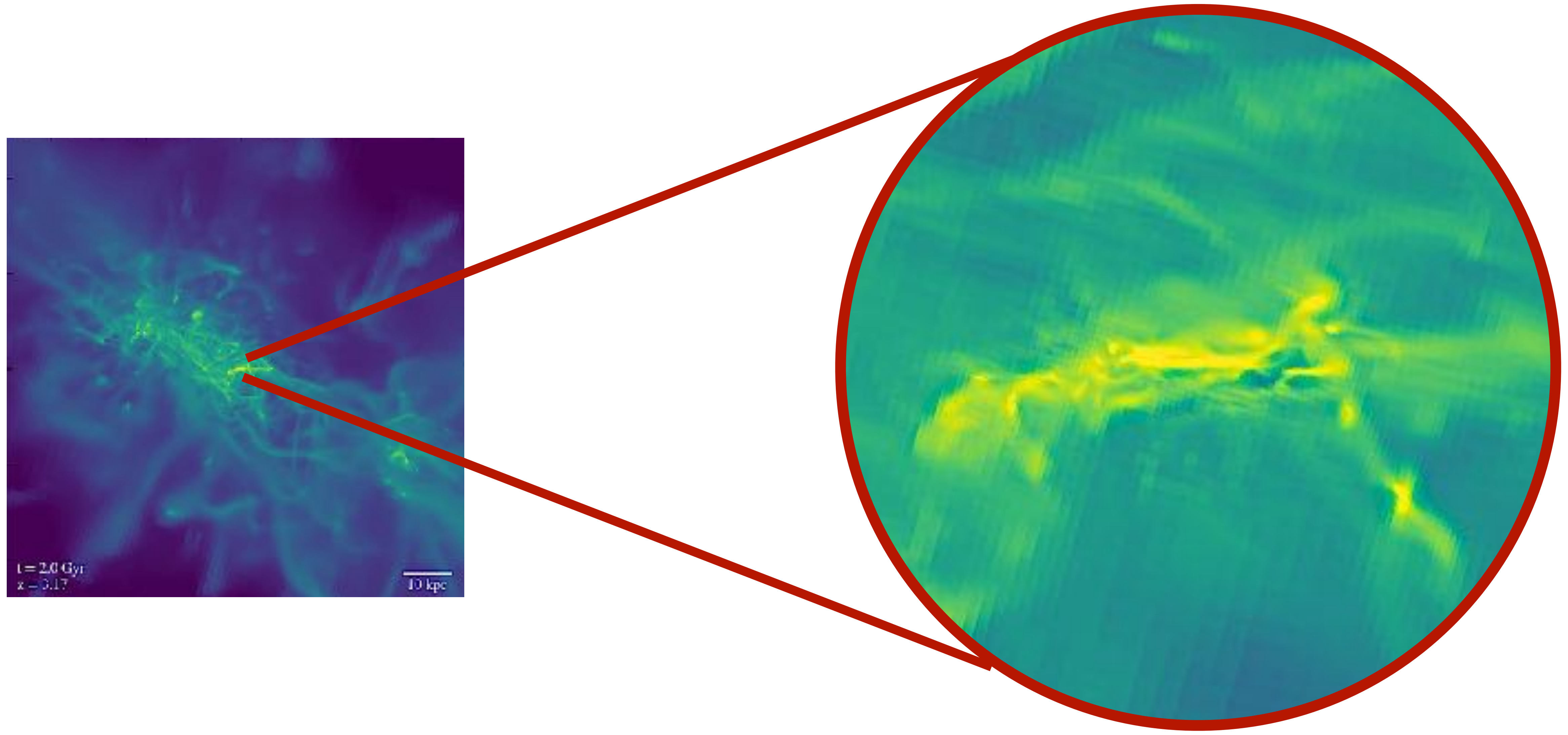


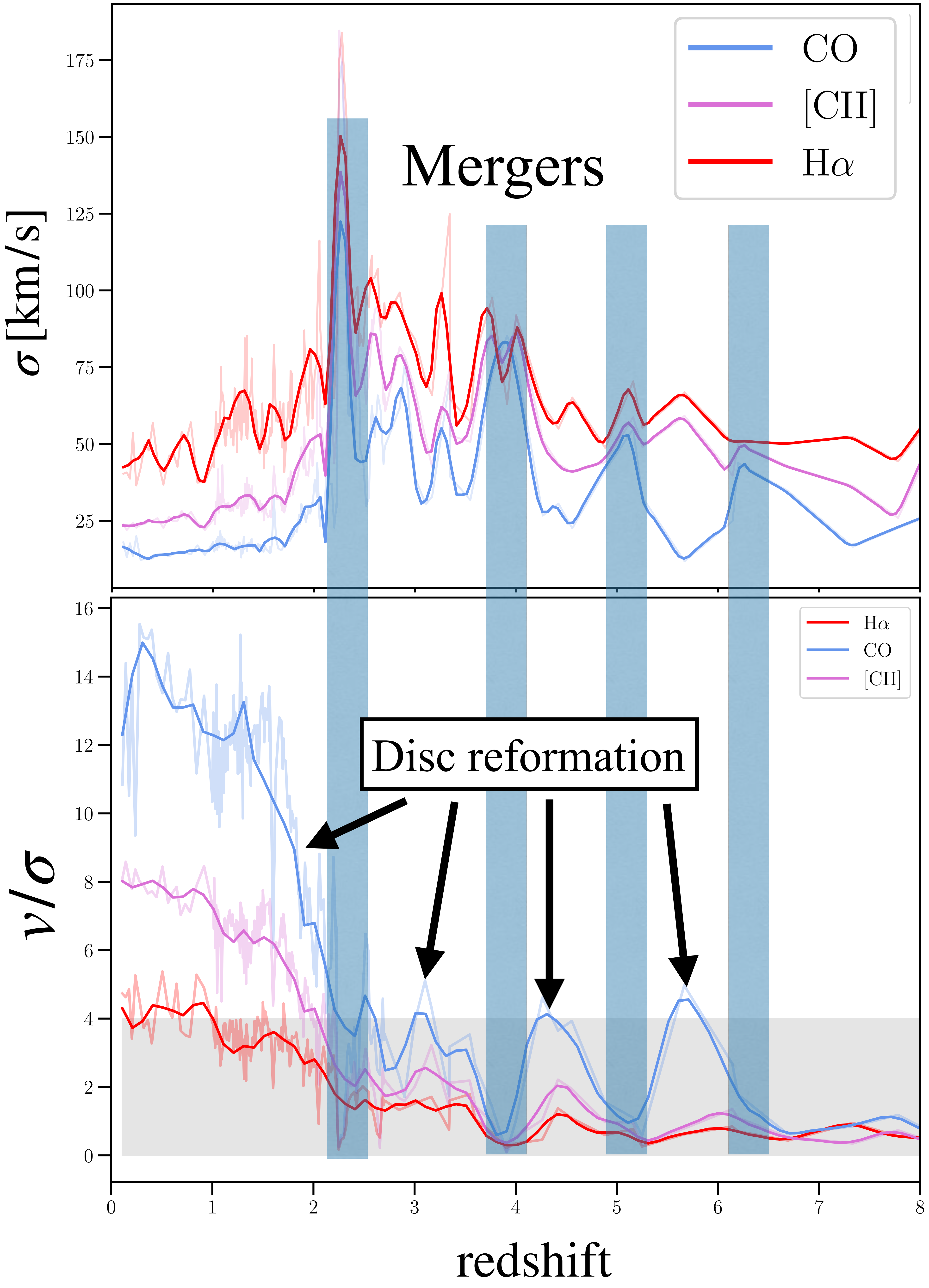
Interpreting observations (examples from preliminary work)

For discussion later?

Nyhagen, Agertz+in prep

- Low mass Milky Way progenitors: $M_{200} \sim 8 \times 10^{11}\ \mathrm{M}_\odot$
- Gas disc kinematics in different tracers
- Disc destruction and reformation



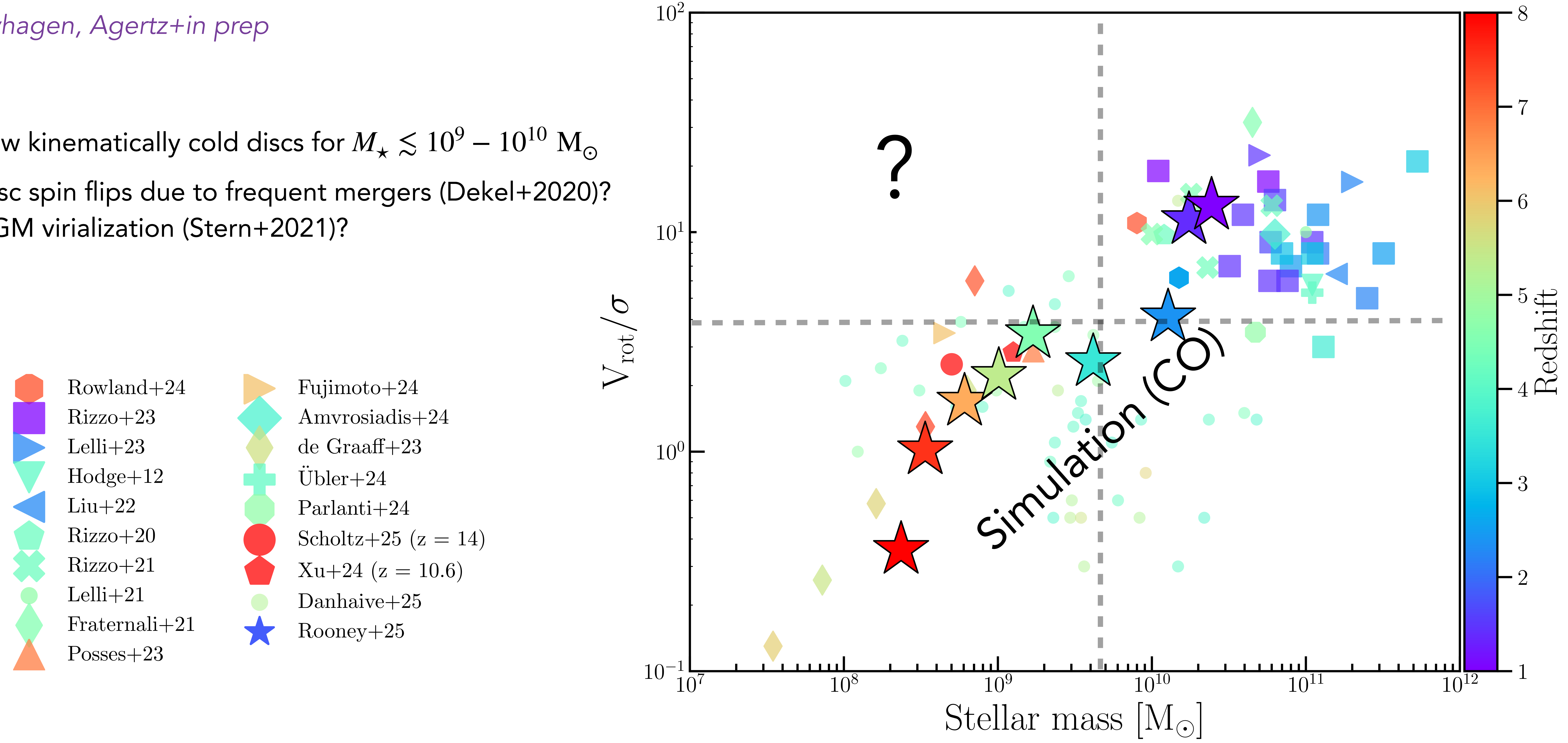


Interpreting observations (examples from preliminary work)

For discussion later?

Nyhagen, Agertz+in prep

- Few kinematically cold discs for $M_\star \lesssim 10^9 - 10^{10}$ $M_\odot$
- Disc spin flips due to frequent mergers (Dekel+2020)? CGM virialization (Stern+2021)?



Shaping the ISM

The roles of feedback and gravity

Simulated discs self-regulate to $Q_{\rm tot} \sim$ few, regardless of turbulence driver

Agertz+15

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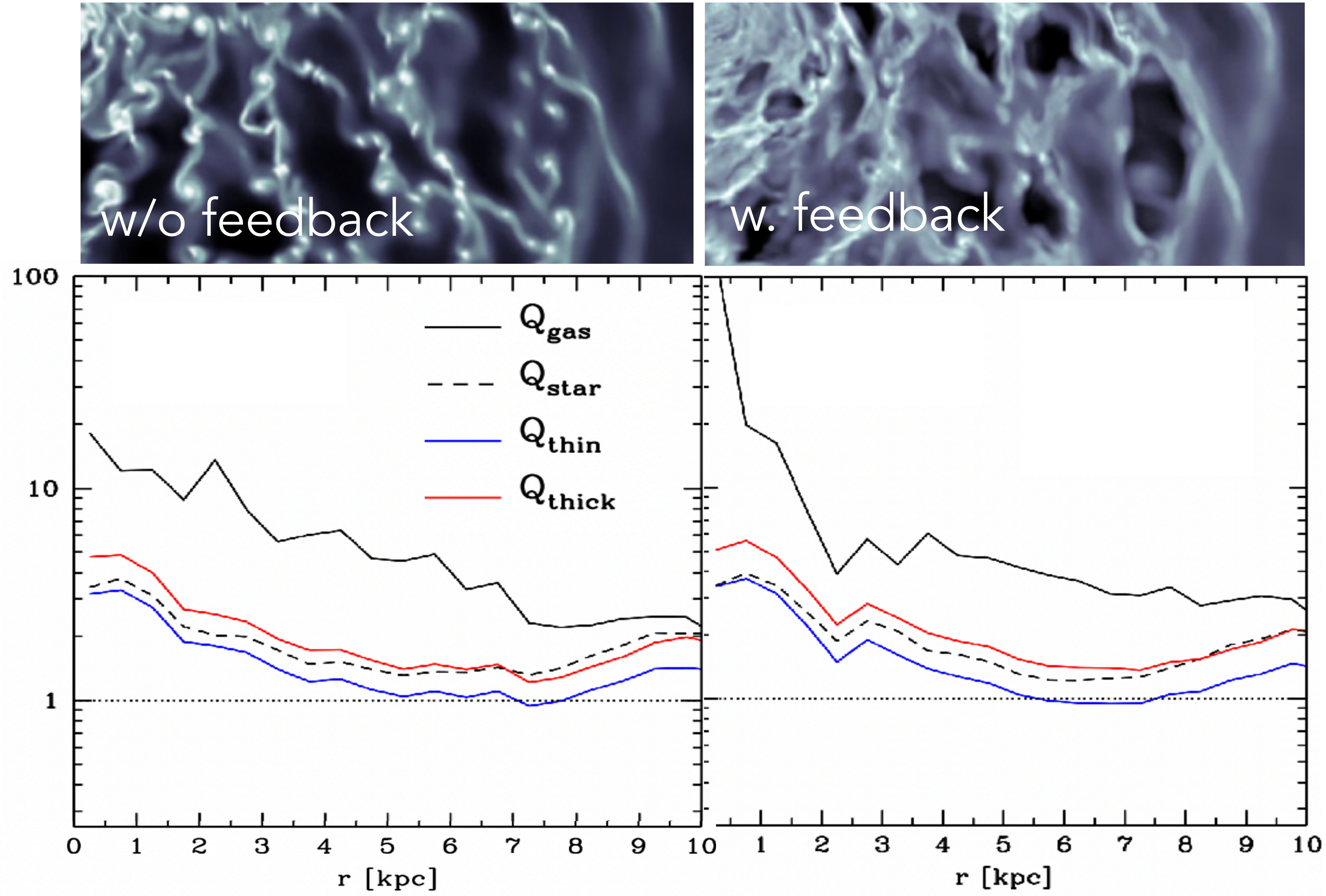


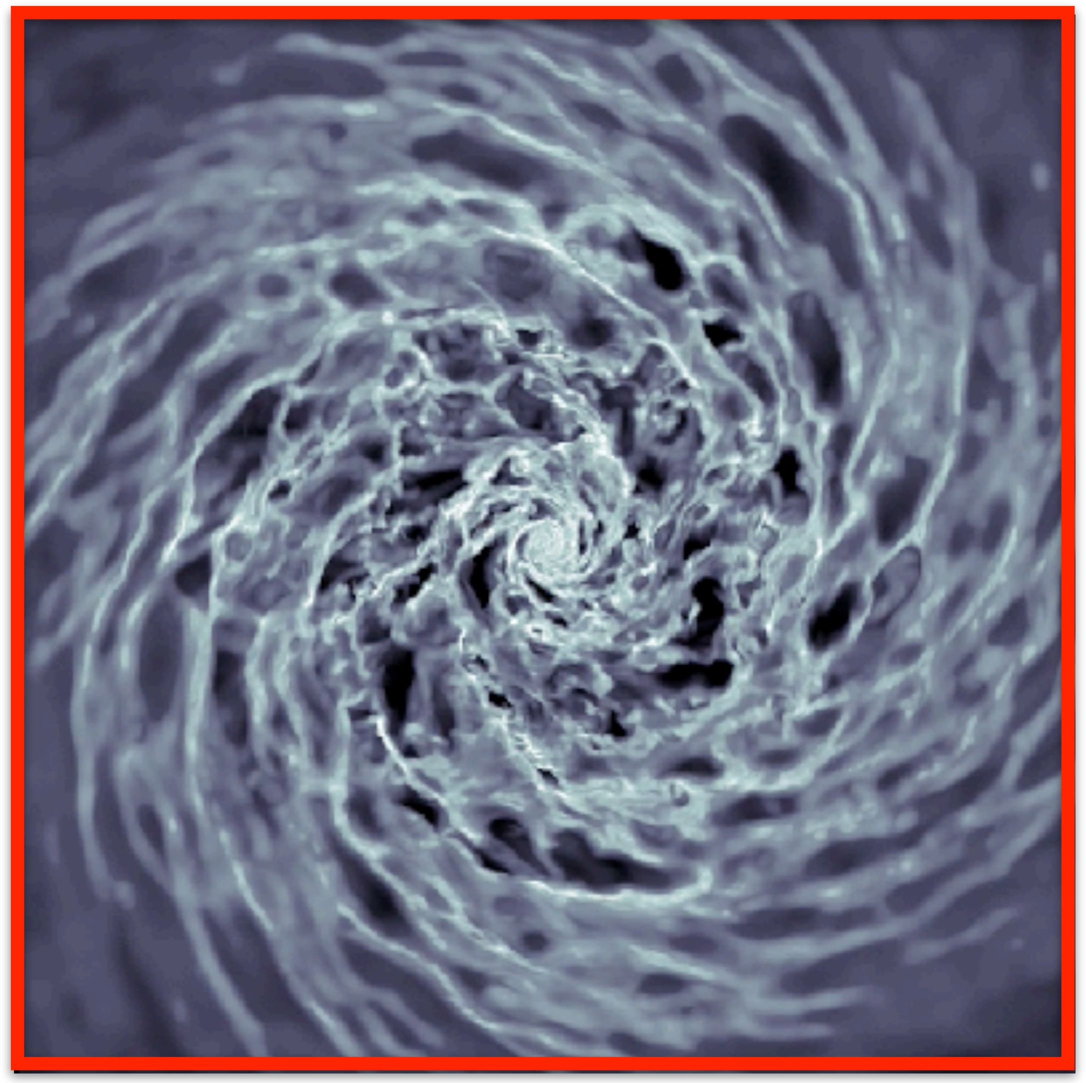
Shaping the ISM with gravity and feedback

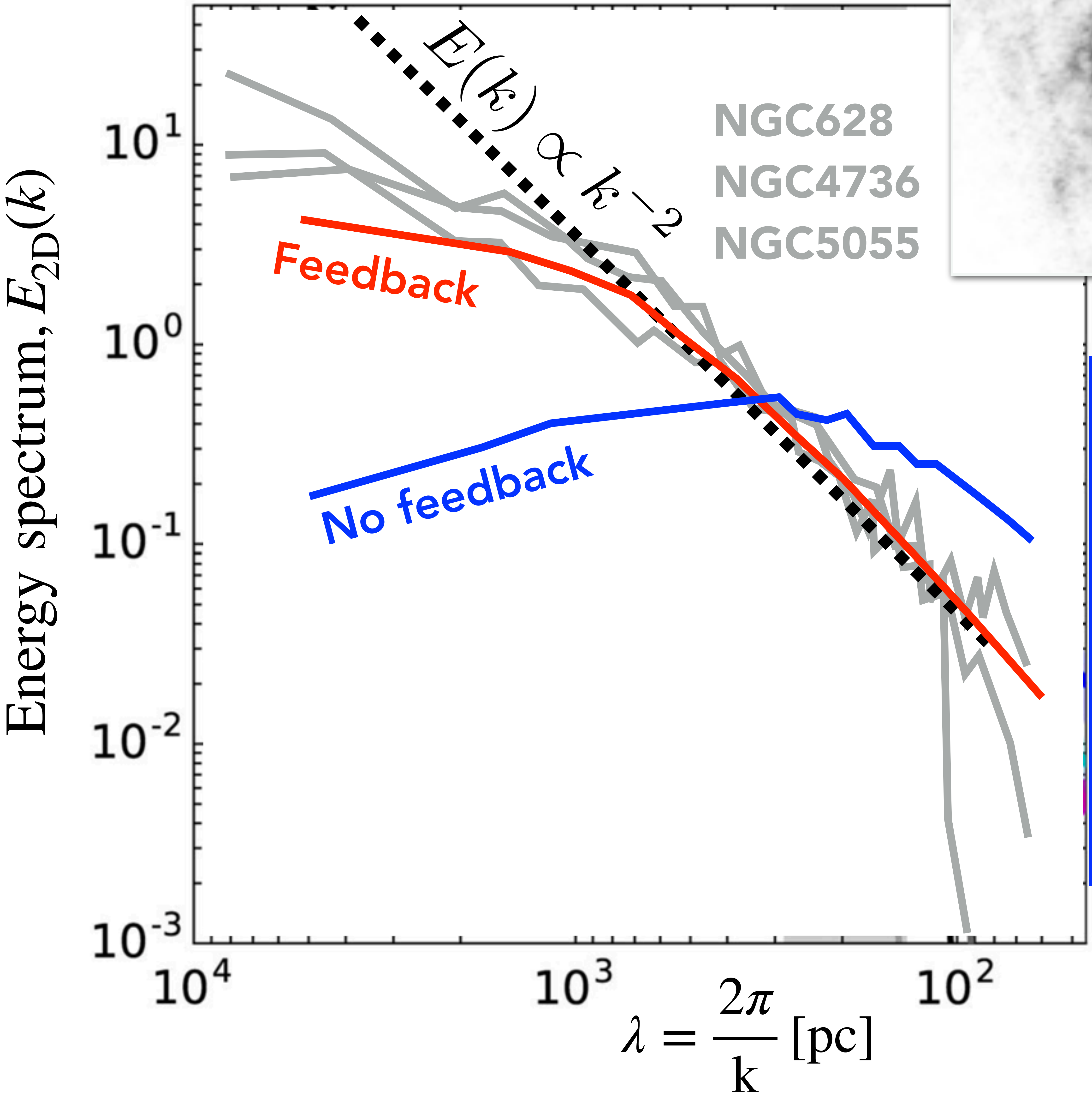
Kinetic energy spectrum of neutral hydrogen

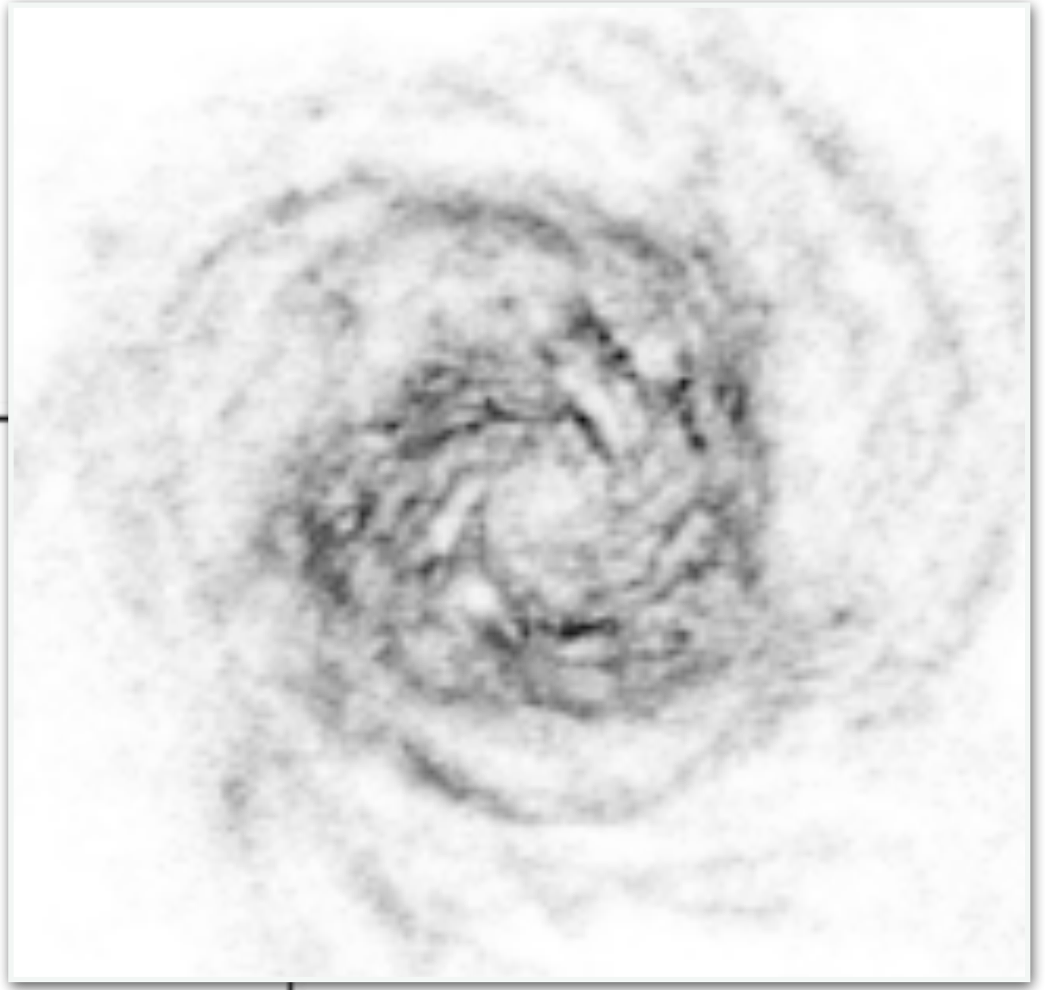
Grisdale+17 with Agertz, Renaud and Romeo

$$E(k) = \pi(2k)^{D-1}\langle P_w(\mathbf{k})\rangle$$

$$w = \sqrt{\Sigma_{\rm HI}}\sigma_{\rm los,HI}$$

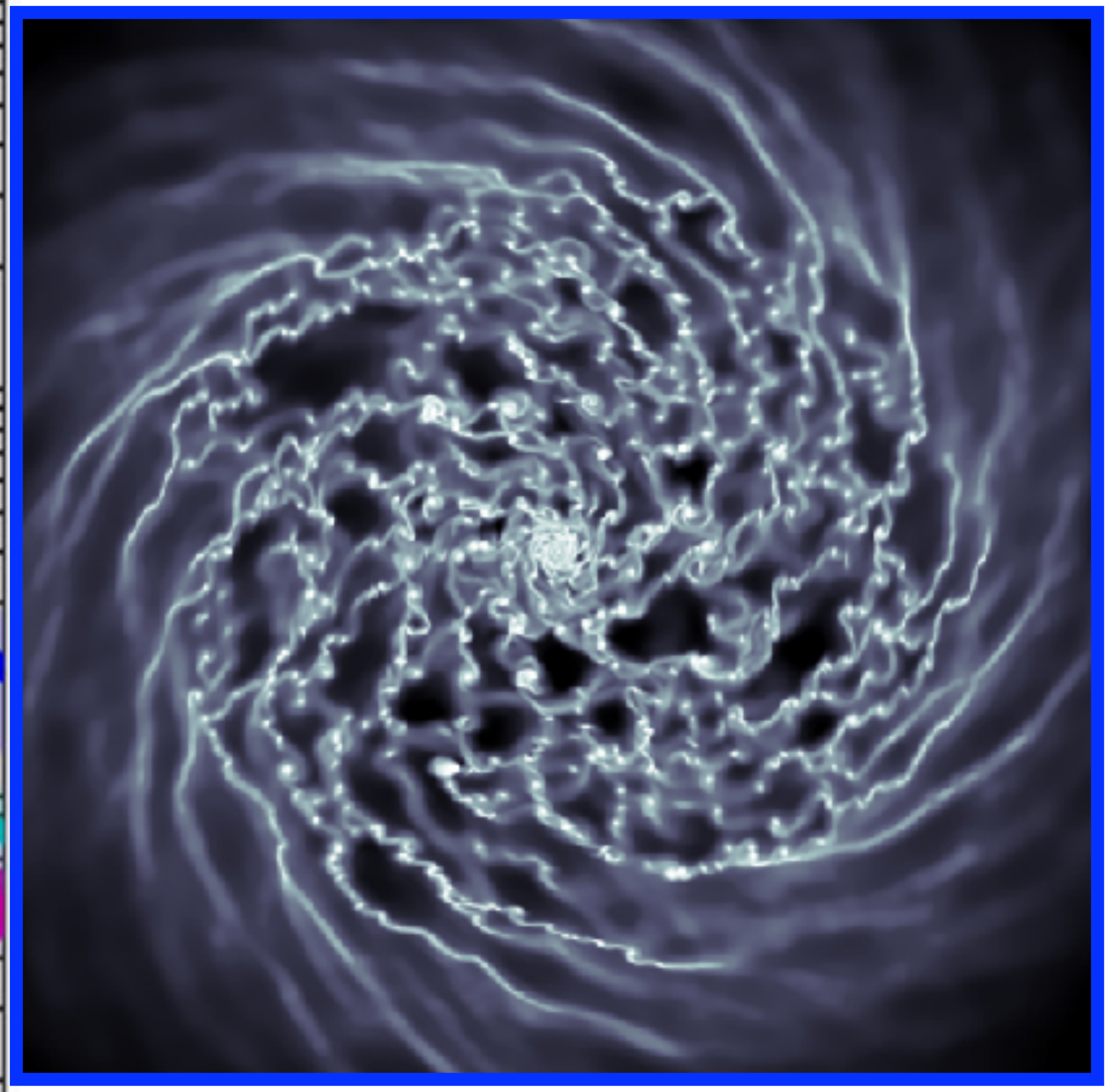






THINGS survey

Walter'08



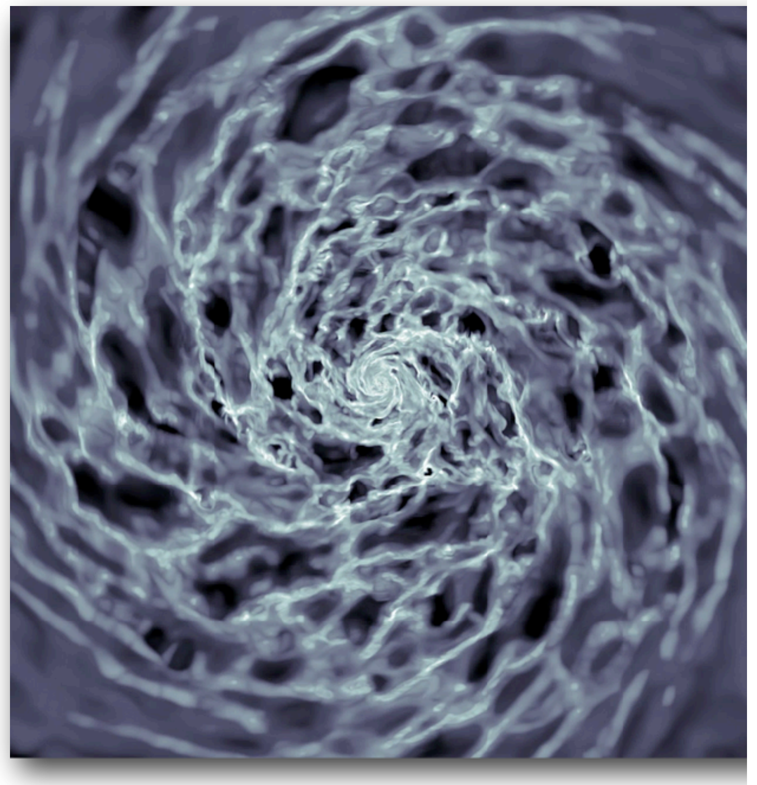
On what scale is ISM turbulence injected?

Agertz et al. (in prep for quite a while now…)

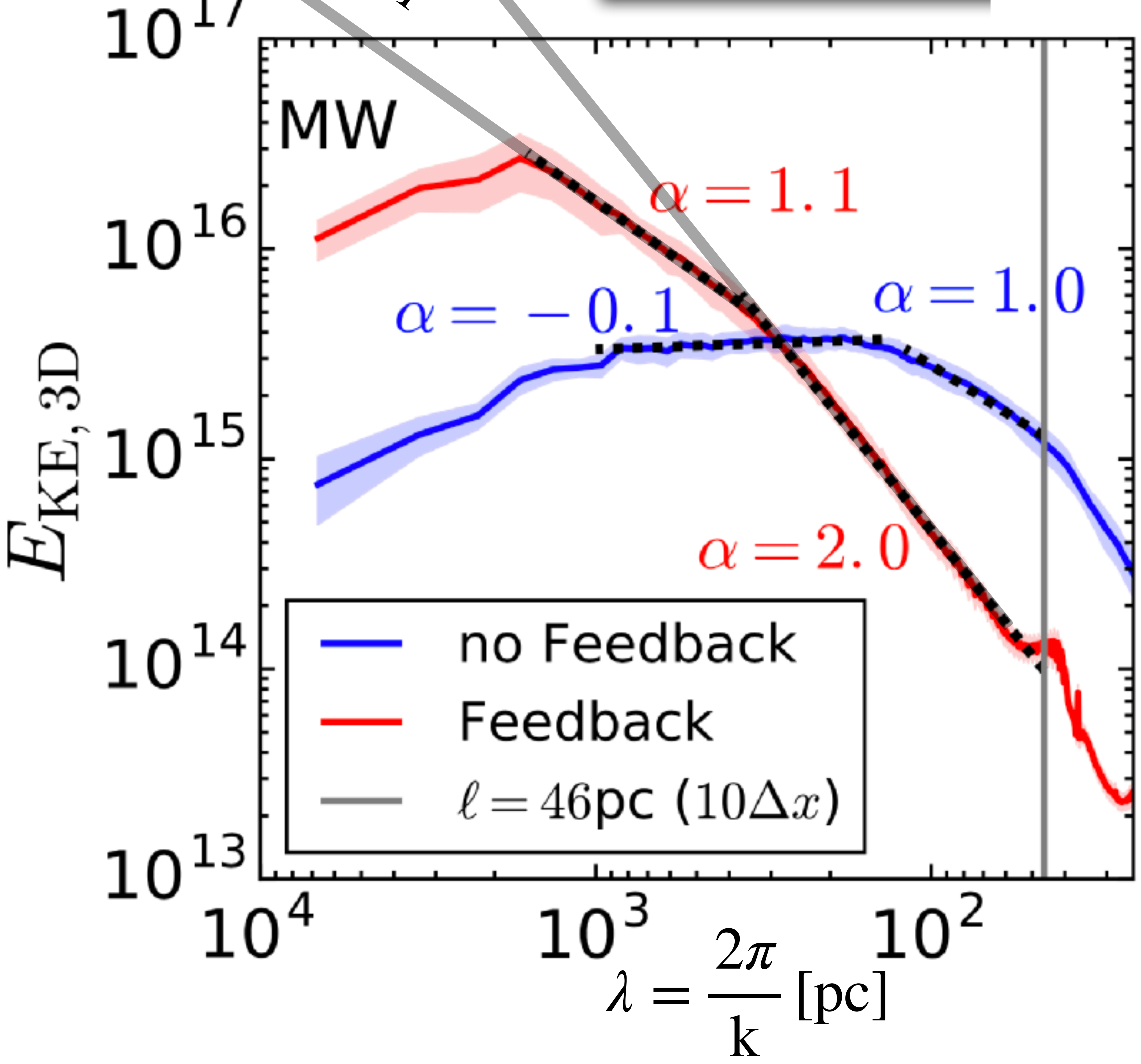
- Supersonic turbulence scaling up to disc thickness. Stellar feedback is essential to sustain this.

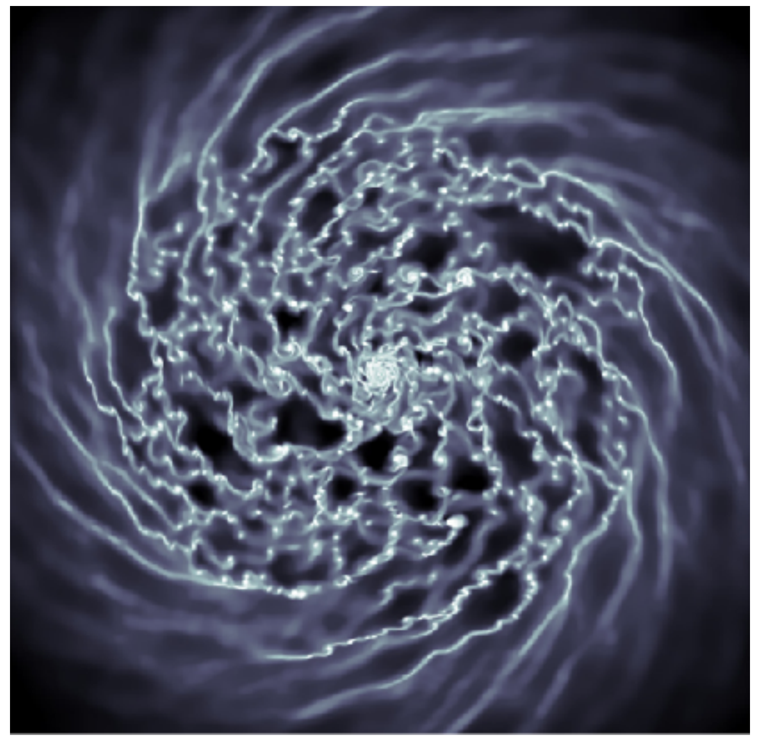
$$L_{\rm drive} \equiv \frac{2\pi \int k^{-1} E(k)\, {\rm d}k}{\int E(k)\, {\rm d}k}$$

Joung, Mac Low & Bryan'09
Padoan+16



$E(k) = \pi(2k)^{D-1}\langle P_w(\mathbf{k})\rangle$
with $w = \sqrt{\rho}\mathbf{v}$





Grisdale+17 with Agertz, Renaud and Romeo

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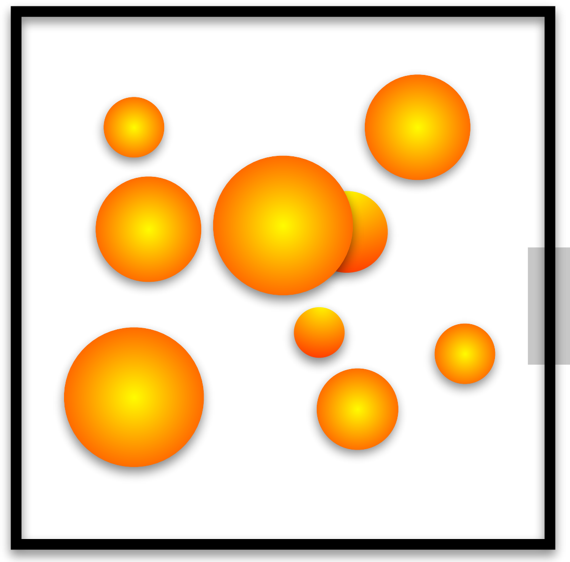
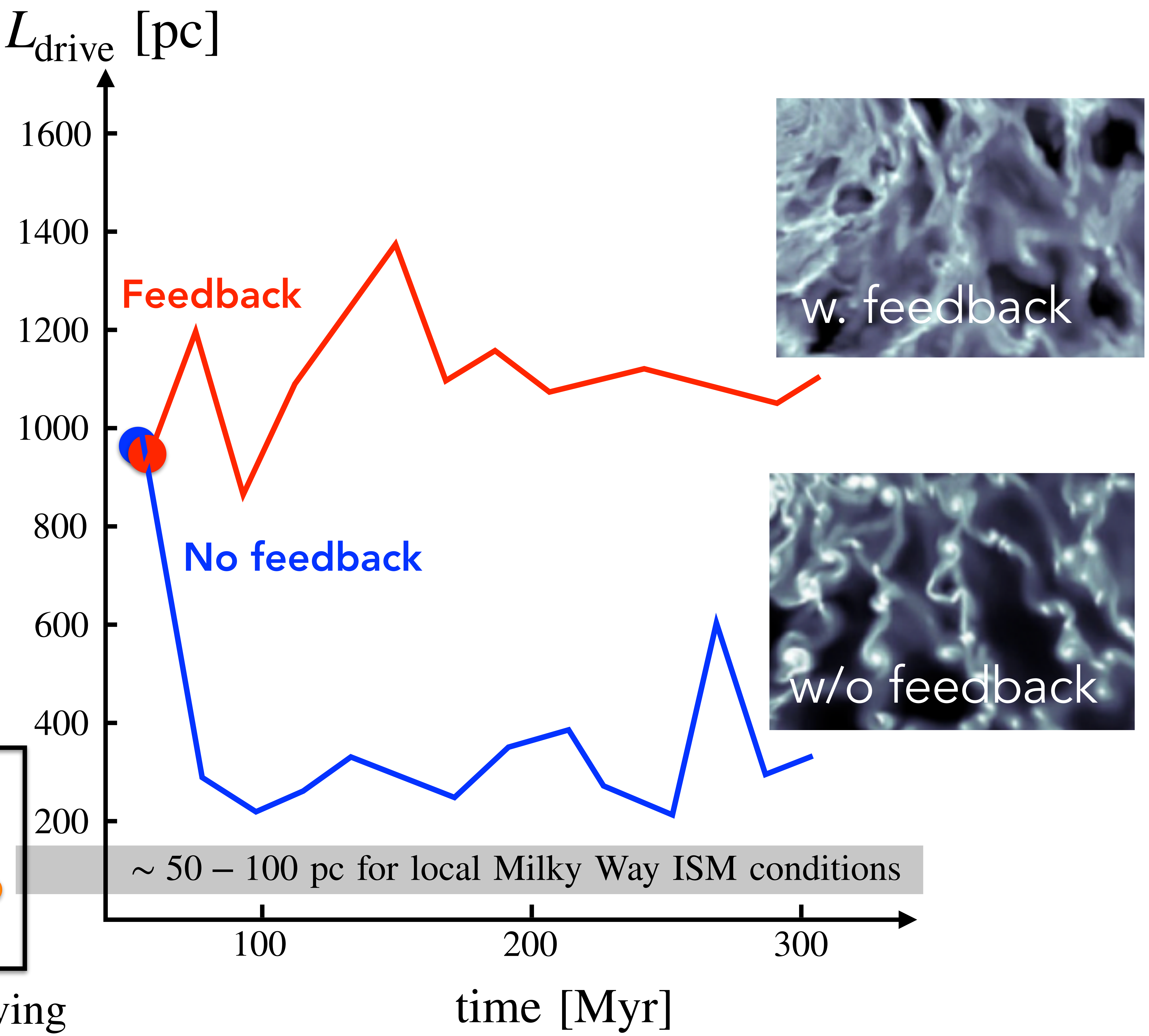
Joung, Mac Low & Bryan'09
Padoan+16

- Stellar feedback allows for a (counterintuitively?) large driving scale. Feedback redistributes gas from small to large scales where the driving occurs (gravity/shear).
- Large-scale coupling between gas and stars is crucial; disc instabilities are set by the stellar component in Milky Way conditions (e.g. Romeo & Mogotsi'17)



Pure SN driving



Shaping the molecular cloud populations

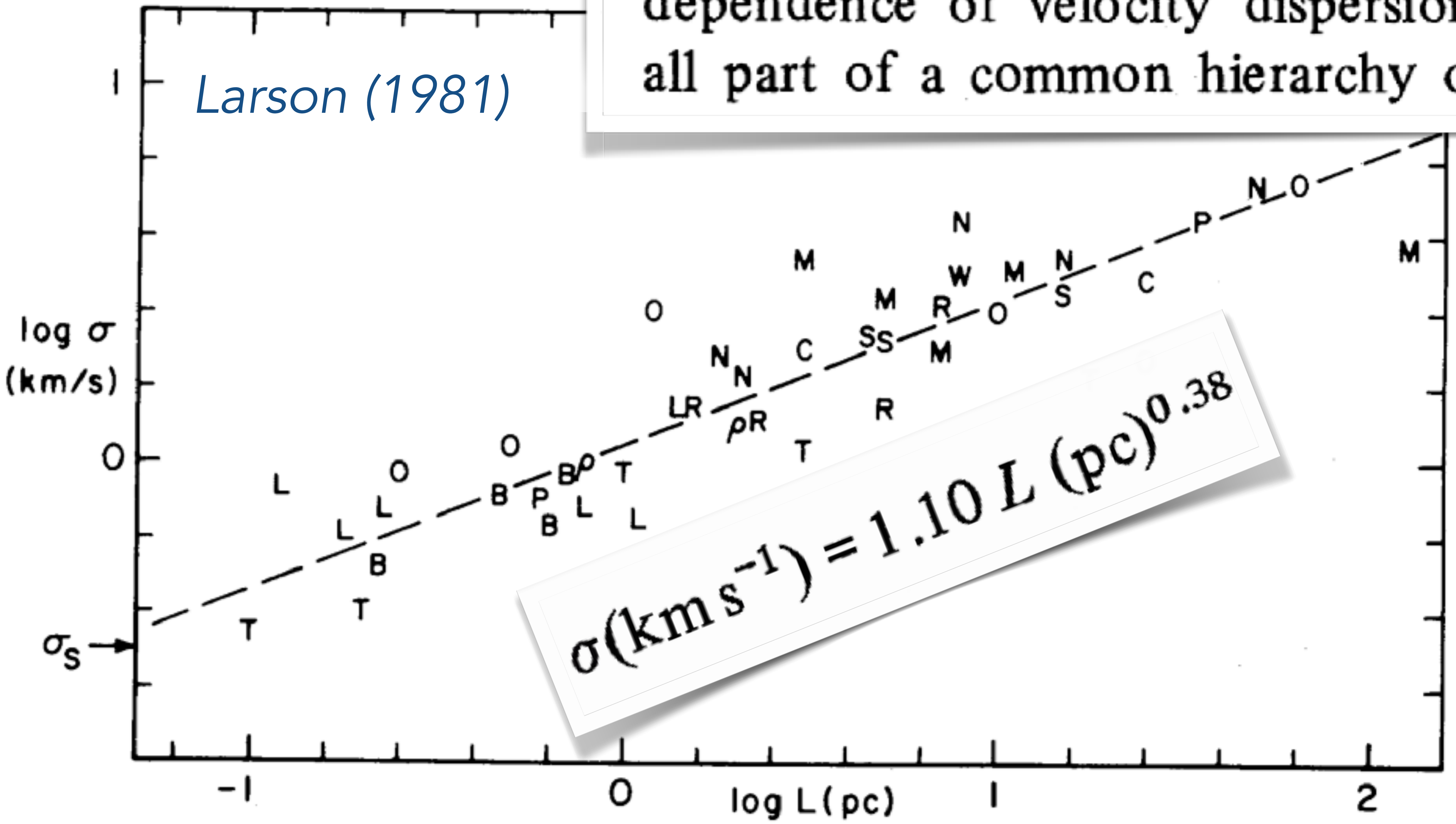
The roles of feedback and gravity

Giant Molecular Clouds (GMCs) and their turbulent structure

Turbulence and star formation in molecular clouds

Richard B. Larson *Yale University Observatory, Box 6666, New Haven, Connecticut 06511, USA*

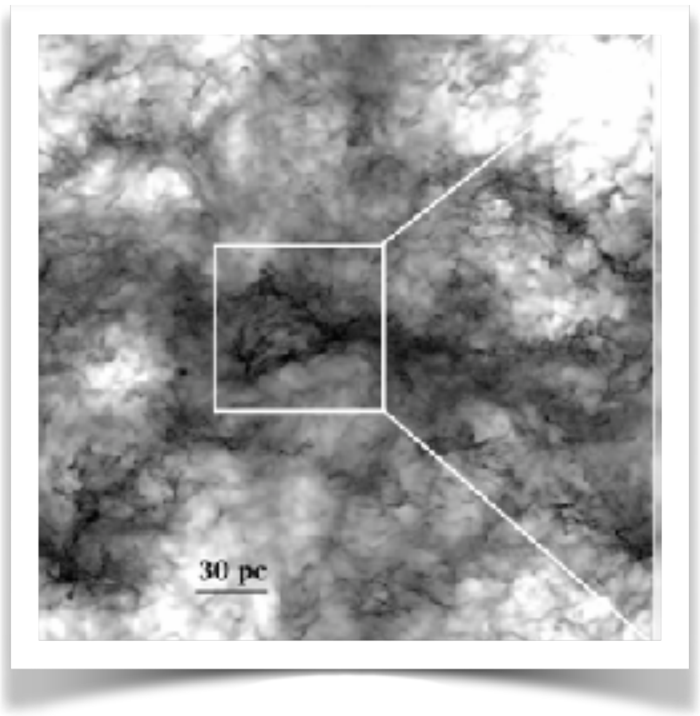
" The fact that nearly all of the regions studied show approximately the same power-law dependence of velocity dispersion on region size suggests that the observed motions are all part of a common hierarchy of interstellar turbulent motions "



$$\sigma(\mathrm{km\,s^{-1}}) = 1.10\, L\,(\mathrm{pc})^{0.38}$$

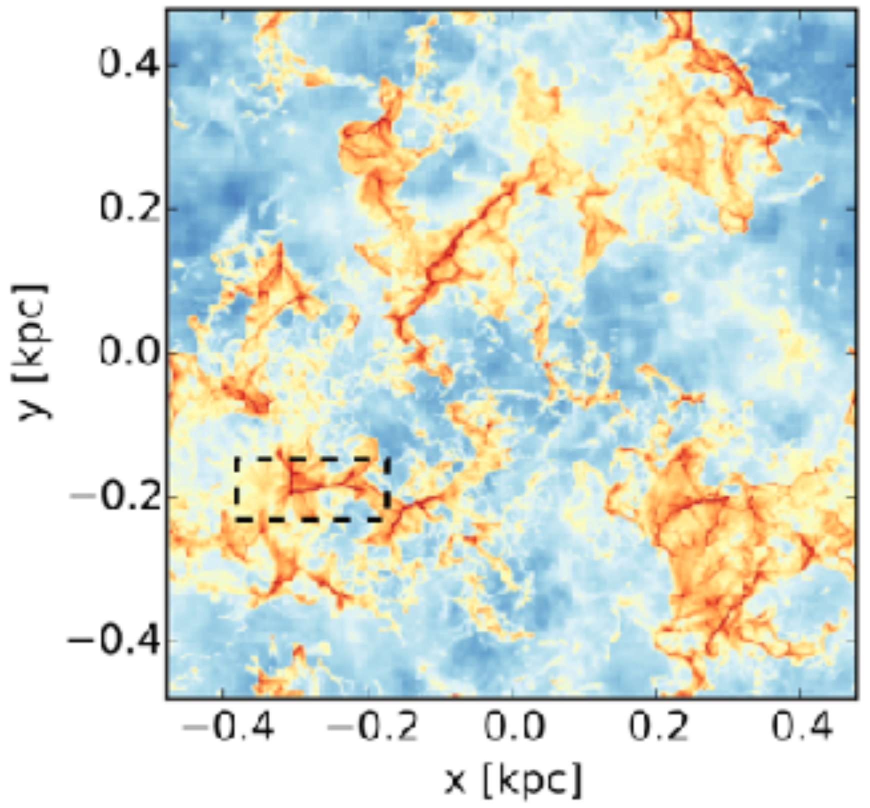
Solomon+87, Heyer+09, Roman-Duval+10, Rice+16, Miville-Deschenes, Murray & Lee'17

Giant Molecular Clouds (GMCs) and their turbulent structure



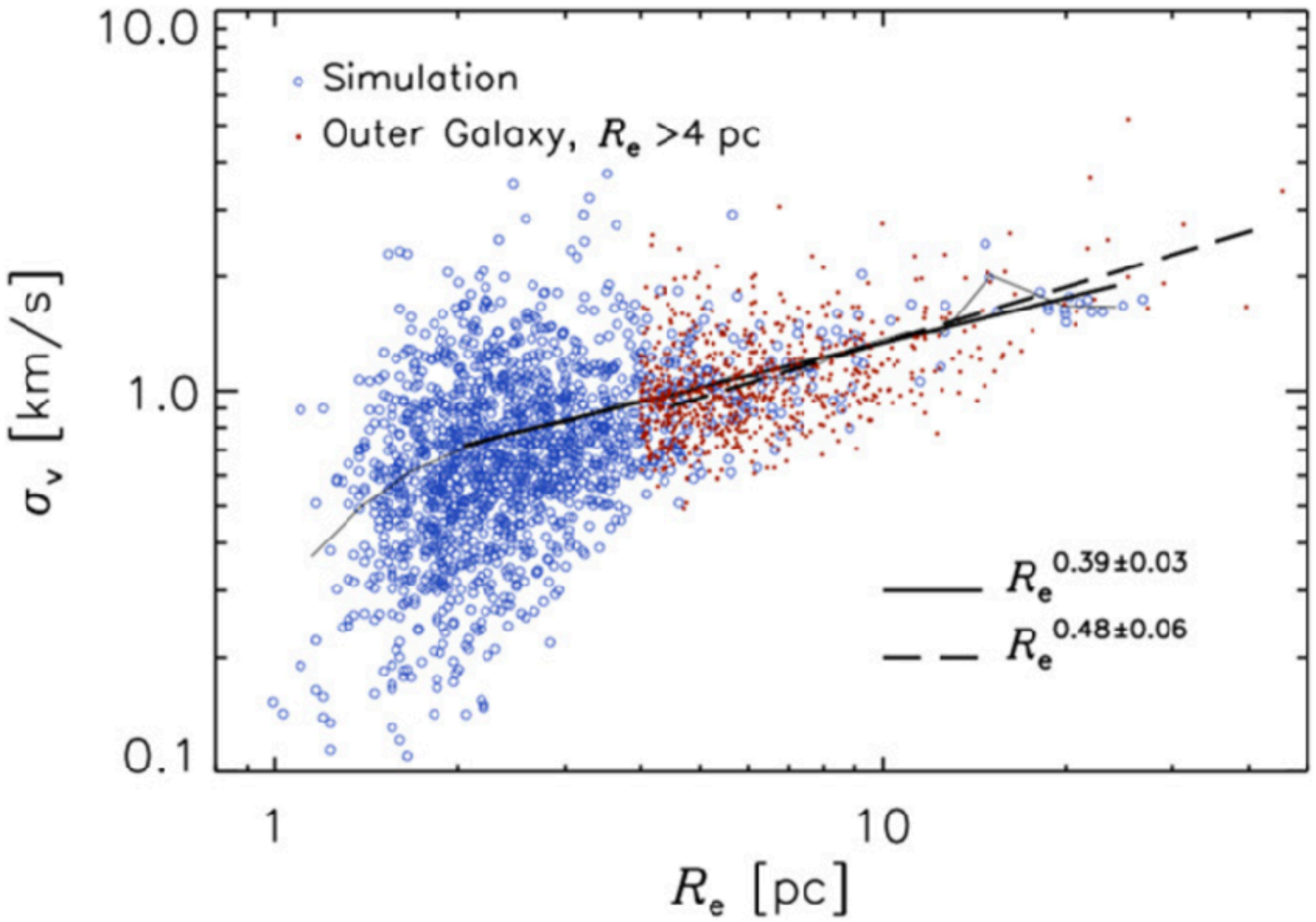
"Supernova driven hydrodynamical turbulence drives scaling relations"

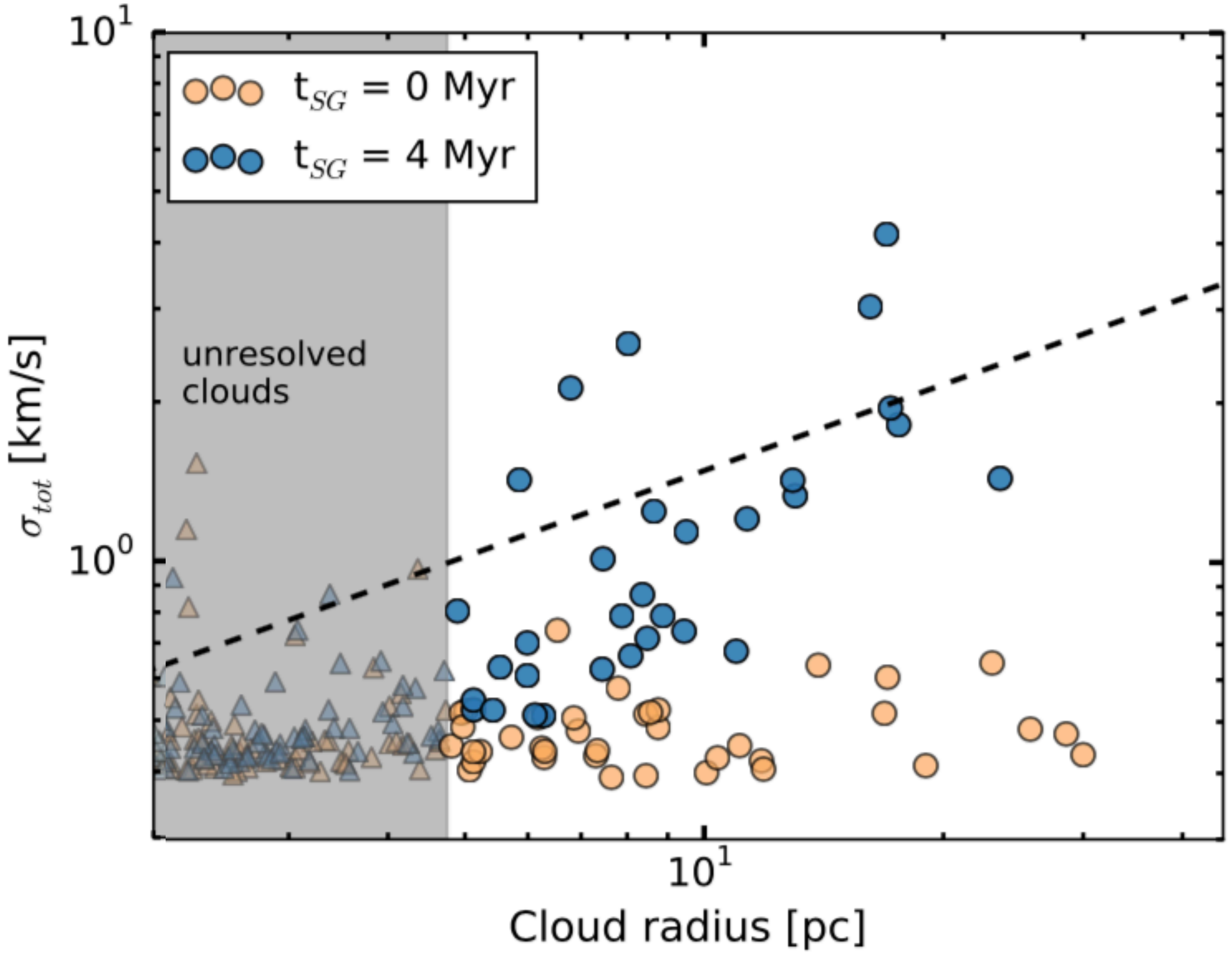
Padoan+16



"Supernova explosions alone do not drive enough turbulent motions - gas self-gravity is needed"

Ibáñez-Mejía, Mac Low+16
(also Ballesteros-Paredes+11)



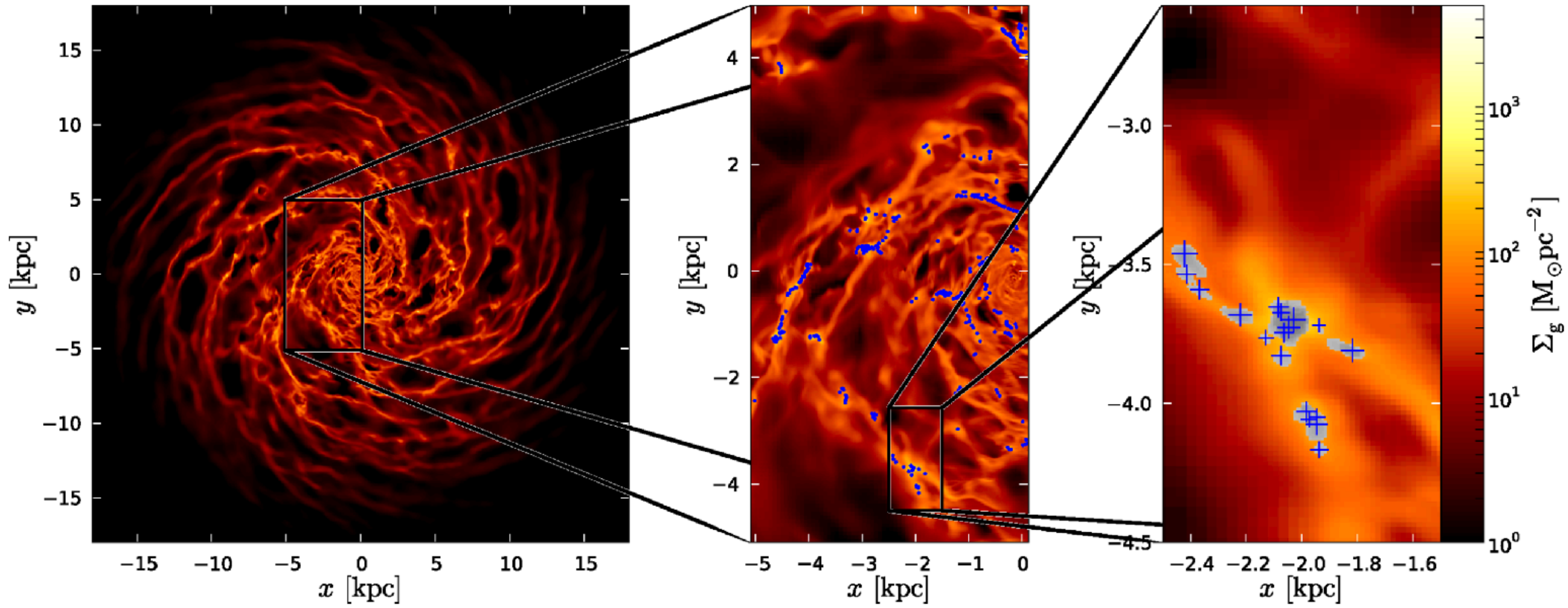


Turbulent cascade and molecular cloud formation
(Gravitational instabilities and stellar feedback in tandem)

Grisdale+18, incl. Agertz, Renaud & Romeo

Keep things simple: CLUMPFIND (Williams et al. 1994).

(2D contours, $C_{\mathrm{min}} = 10\ \mathrm{M_\odot pc^{-2}}$, molecular gas for densities $> 100\ \mathrm{cm^{-3}}$)



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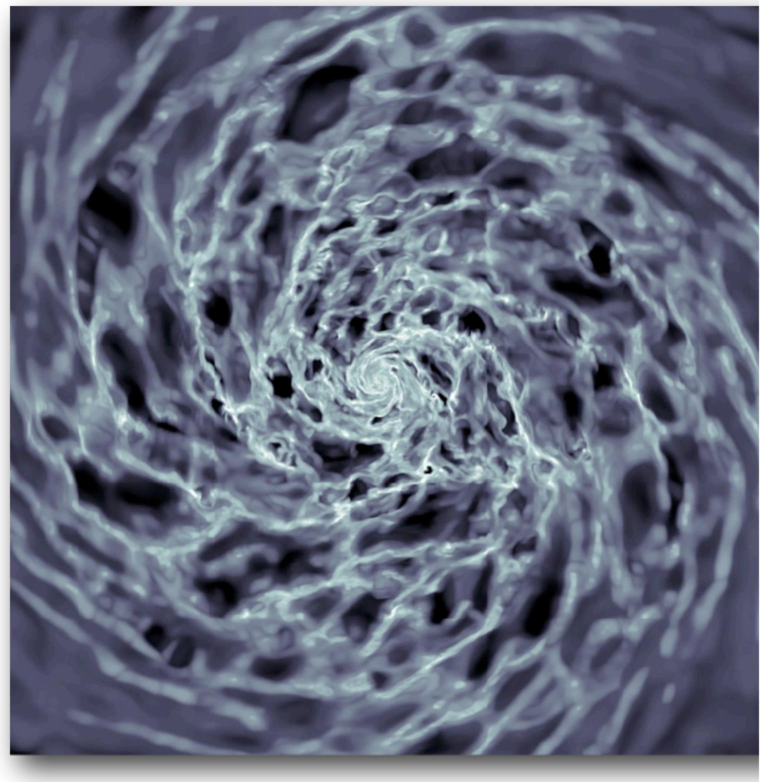
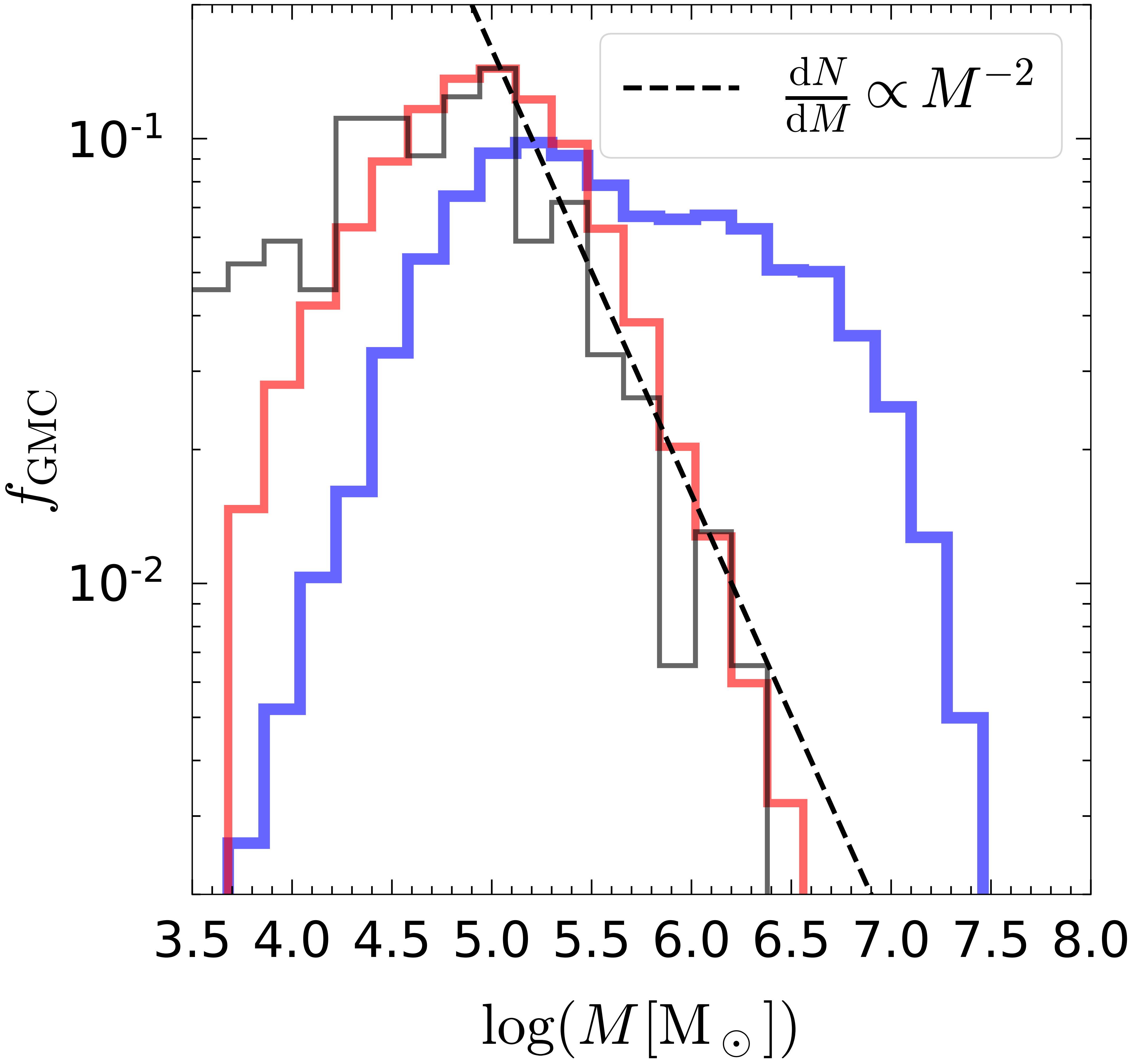
(Gravitational instabilities and stellar feedback in tandem)

Grisdale+18 with Agertz, Renaud and Romeo



$$\frac{dN}{dM}$$



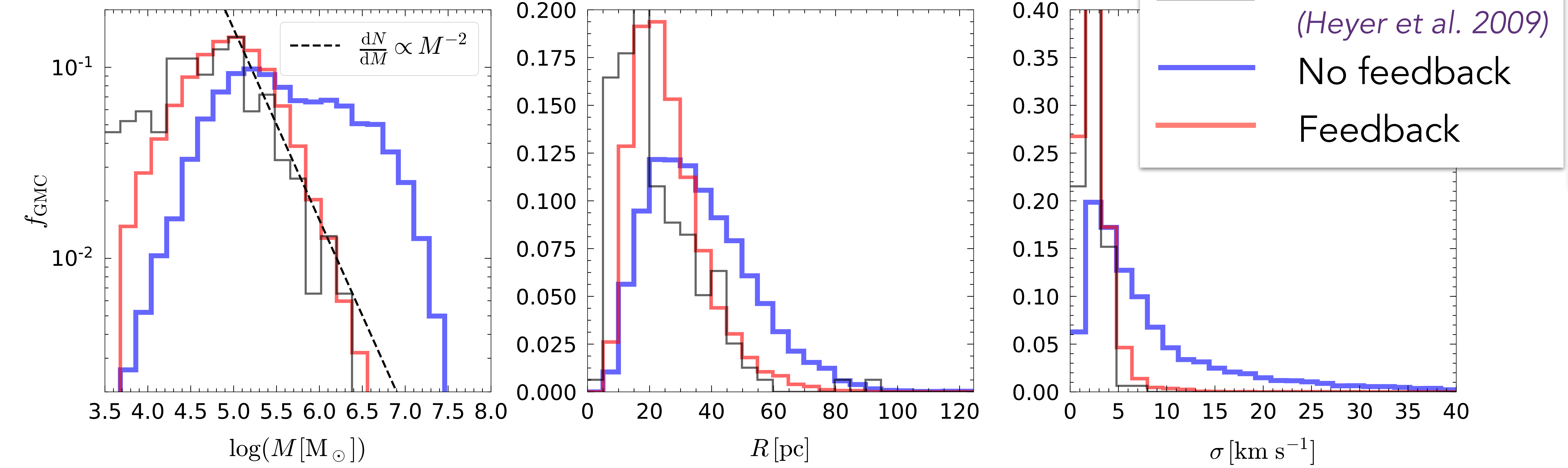
The Milky Way (Heyer et al. 2009)

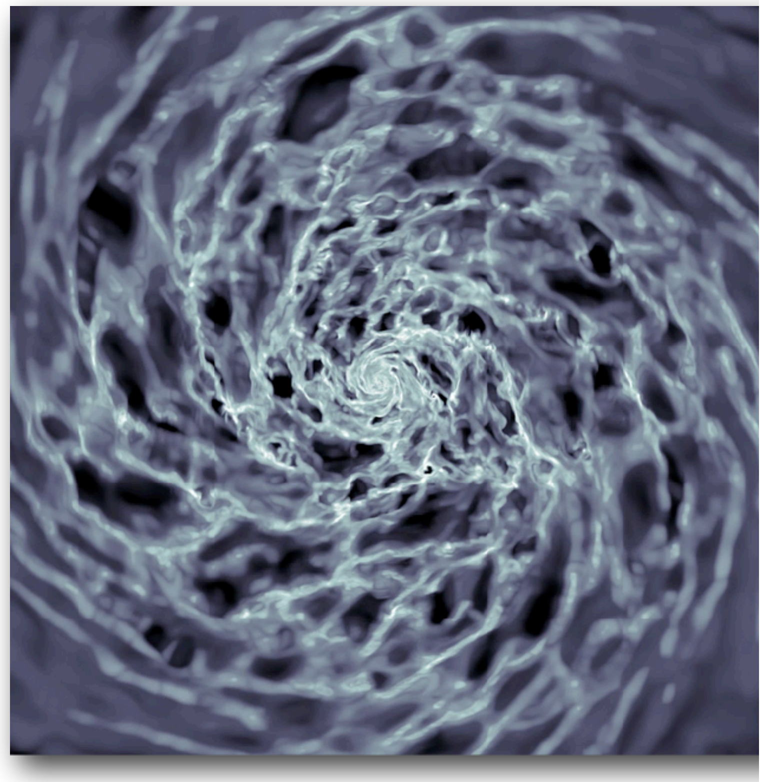
No feedback

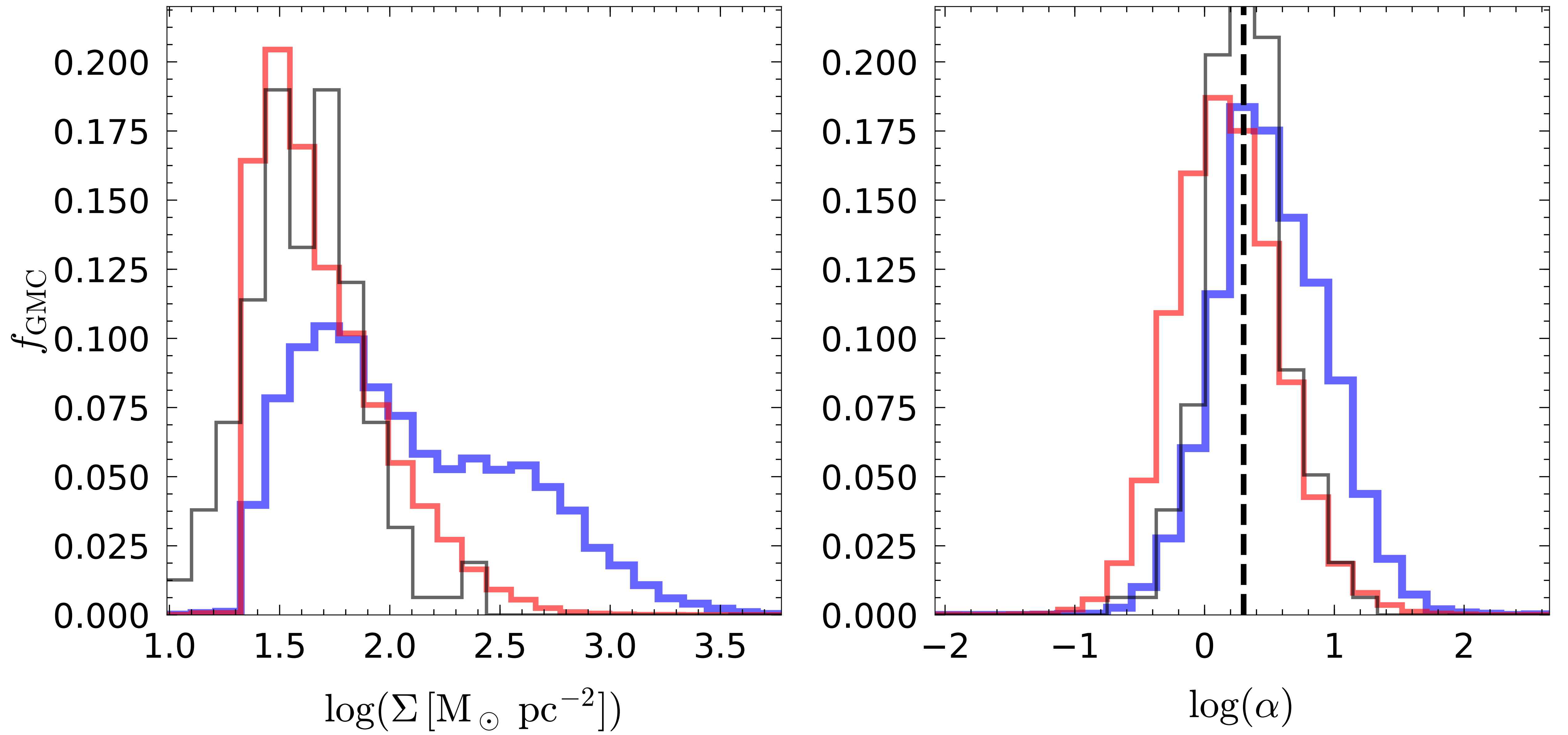
Feedback

Distribution of GMC properties: close match to the Milky Way

Grisdale+18 with Agertz, Renaud and Romeo







- Properties arise when turbulence spectrum is "realistic" ($E(k) \propto k^{-2}$) and is set by feedback + gravity + shear.
- Stellar feedback keeps GMC lifetimes to ~a few Myr up to 10s Myr, drives small scale turbulence, and recycles gas back to large scales.
- Leads to GMC masses, sizes and velocity dispersions in line with Milky Way observations (see also Ward+16, Hopkins'15 for analytical arguments, Grudic+18)

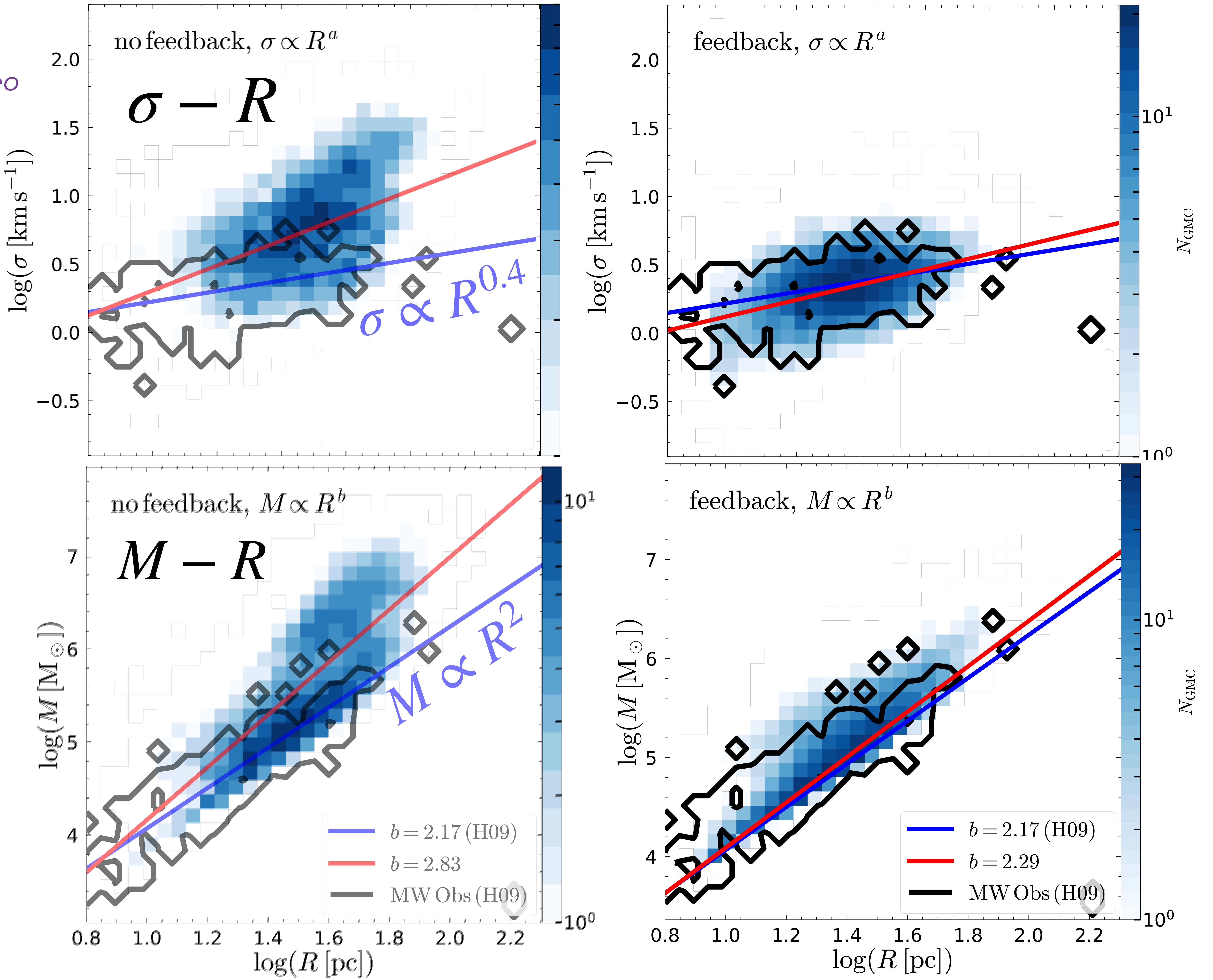
(Larson's) GMC scaling relations

Grisdale+18 with Agertz, Renaud and Romeo

The Milky Way (CO, Heyer et al. 2009)

Fit to observations

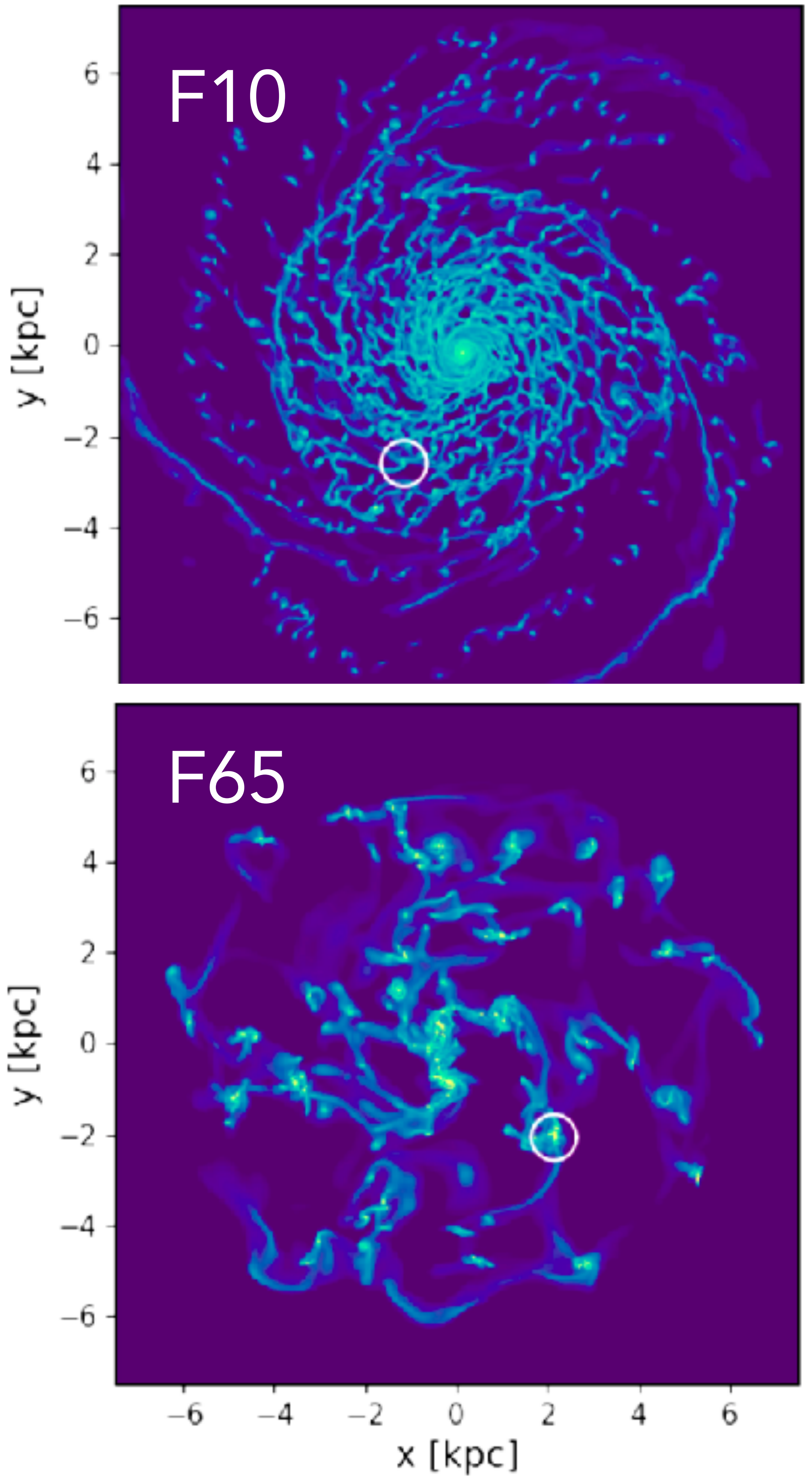
Fit to simulation



- Stellar feedback allows for a ***maintained*** large-small scale coupling with a realistic turbulence spectrum. The structure and lifetimes (few to 10s Myrs) of GMCs is an outcome of this process.
- Surprising(!?) result: these (hydrodynamical) simulations have a spatial resolution of 4 parsecs. They clearly ***do not resolve*** the internal structure of GMCs. Are the CO-traced scaling relations an outcome of large-scale cascade?

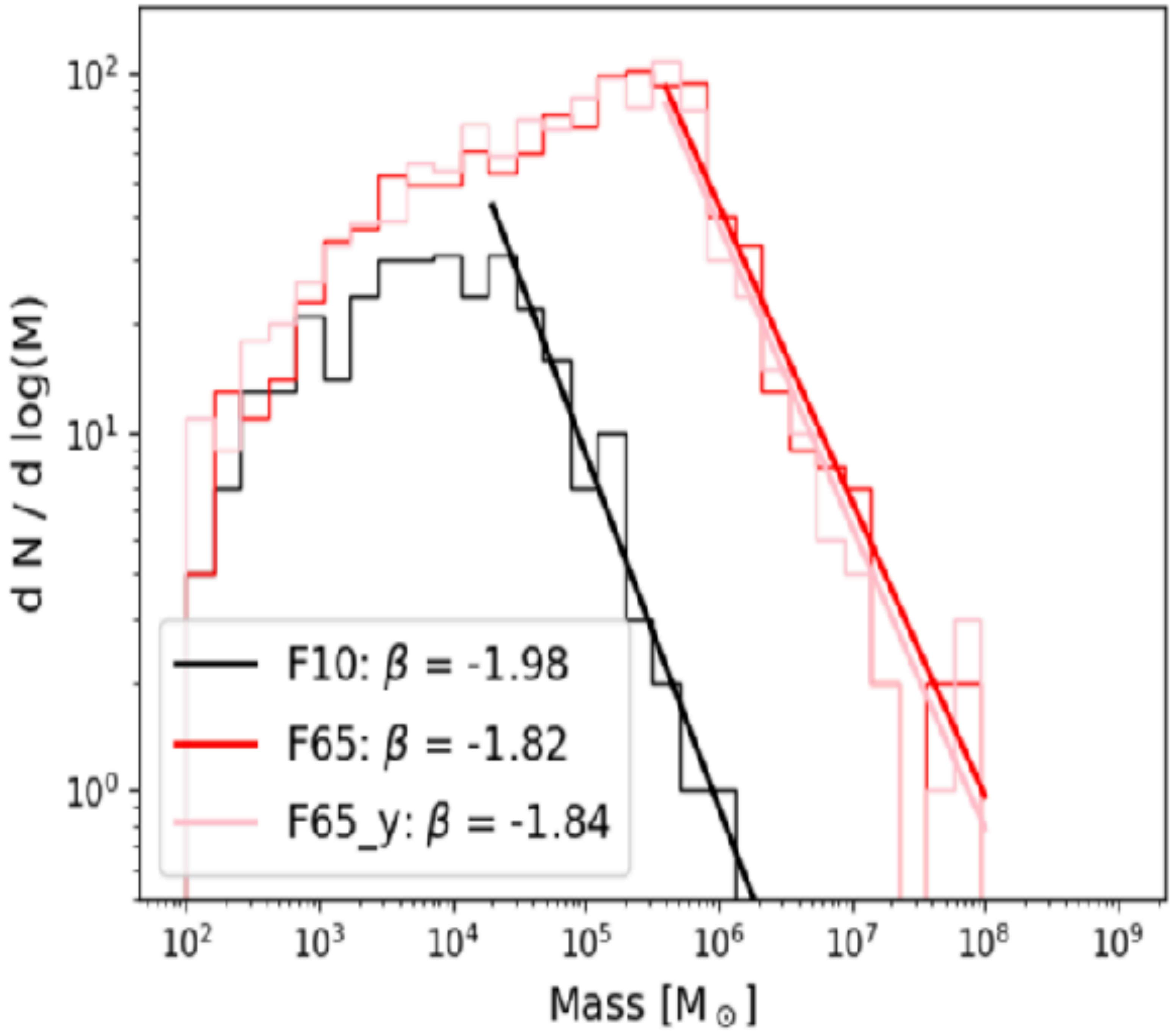
Gravity ***or*** feedback? Gravity ***and*** feedback? Gravity ***then*** feedback?

Isothermal ISM,
gravity, no feedback
Fensch+23



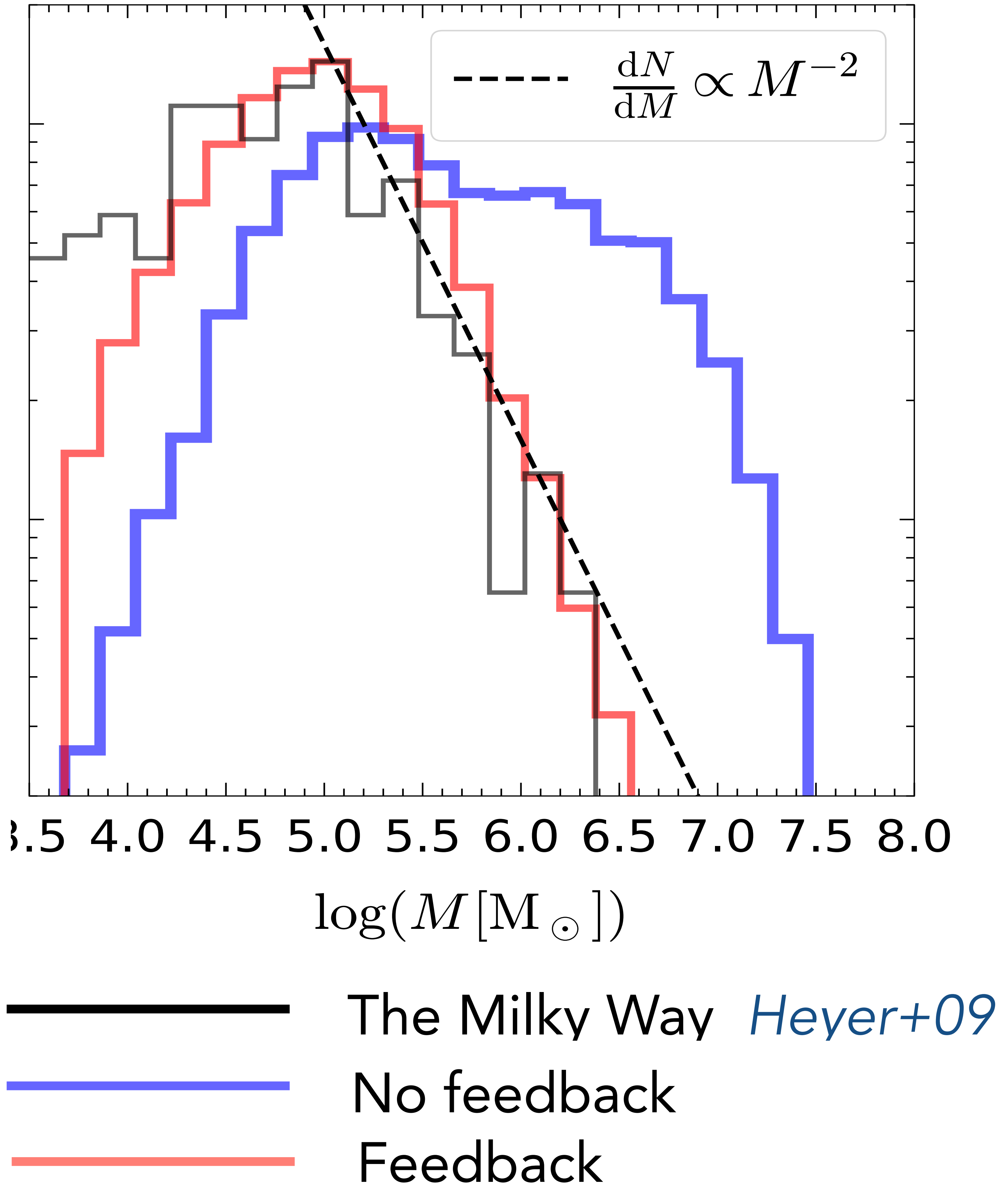
Run for 10 Myr,
i.e. "one cascade"

Gravity is enough
Fensch+23



Run for 100s of Myrs,
i.e. "many cascades"

Feedback is required
Grisdale+18 with Agertz, Renaud and Romeo



Summary

Turbulence driving in discs

- Turbulence in the cold ISM (e.g. CO) in high-z discs cannot be driven to $\sigma \gtrsim 50 \ \mathrm{km/s}$, except during mergers. Cosmological simulations of Milky Way progenitors confirm this.
- Warm gas tracers, e.g. $\mathrm{H}\alpha$, traces more diffuse gas, and feature greater σ.

Turbulence driven by gravity and feedback:

- The driving scale of turbulence is on large kpc-scales, but only when feedback "resets the cycle"
- Origins of molecular cloud properties: gravity alone can do it, but feedback "resets the cycle"