Cosmic Evolution of Disk Instabilities

Florent Renaud
Strasbourg Observatory

with
Oscar Agertz
Alessandro Romeo

JWST + LENSING

Claeyssens et al. (2023)

GAS-RICH CLUMPY DISKS

Most of disk galaxies at cosmic noon ($z \sim 1-3$) host huge star forming gas clumps ($M_{\rm gas} \sim 10^{8-9}\,{\rm M_\odot}$, $M_\star \sim 10^7\,{\rm M_\odot}$)

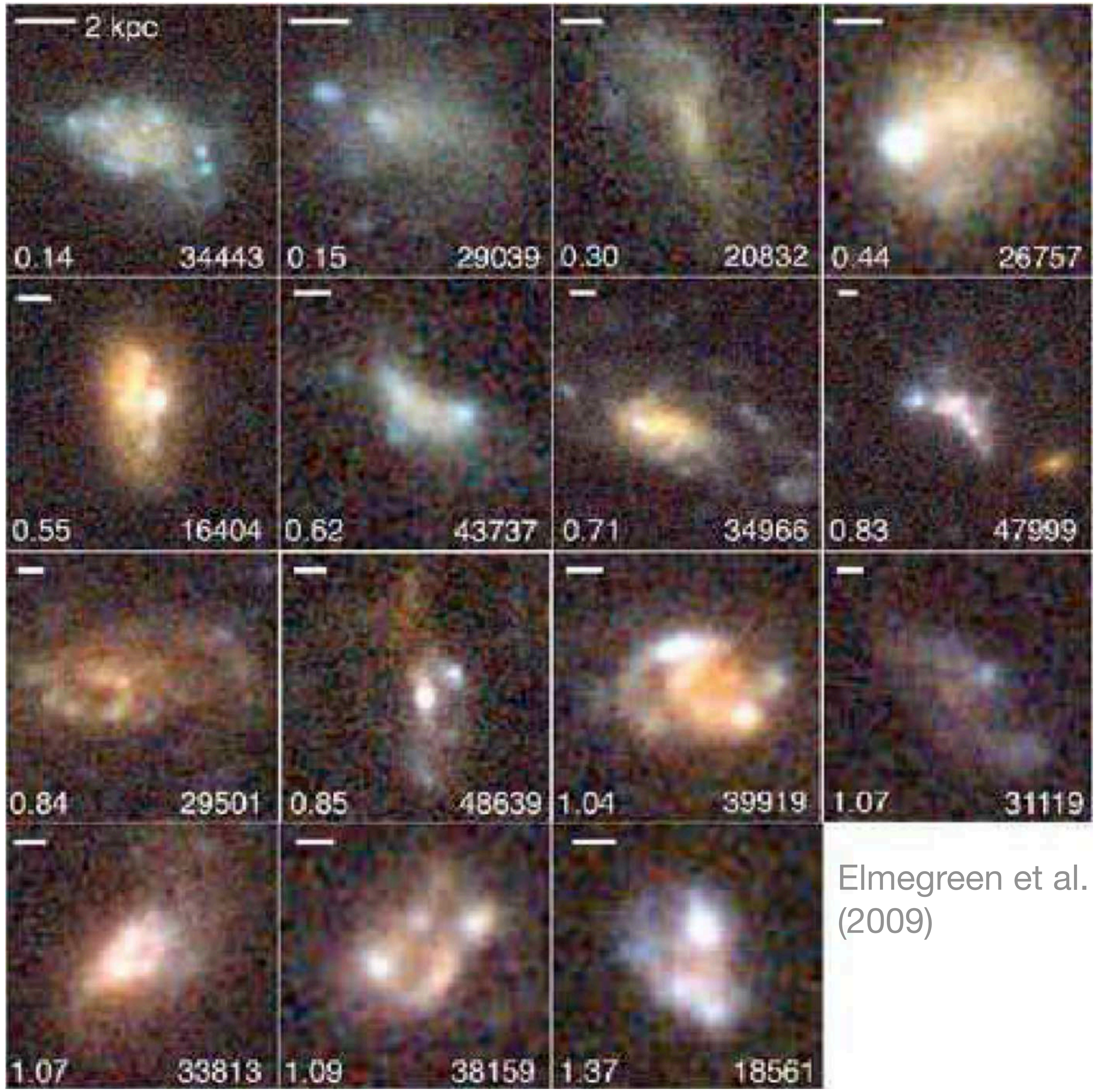
Guo et al. (2015), Sattari et al. (2023)

Clumps are found in galaxies with high gas fractions

$$f_{\rm gas} = \frac{M_{\rm gas}}{M_{\rm gas} + M_\star}$$

Clumps *could* play a role in the formation of

- thick disk (via turbulence injection)
  Krumholz et al. (2018), van Donkelaar et al. (2021), Ginzburg et al. (2022)
- bulge (via migration, *if clumps are long-lived*)
  Elmegreen et al. (2008), Agertz et al. (2009), Dekel et al. (2009)
- globular clusters
  Shapiro et al. (2008), Mandelker et al. (2017)



Elmegreen et al. (2009)

see also Wuyts et al. (2012), Tamburello et al. (2015), Zanella et al. (2015), Behrendt et al. (2019), Dessauges-Zavadsky et al. (2019), Huertas-Company (2020), Claeyssens et al. (2025), and many more...

DIFFERENT INSTABILITY REGIME IN GAS-RICH DISKS

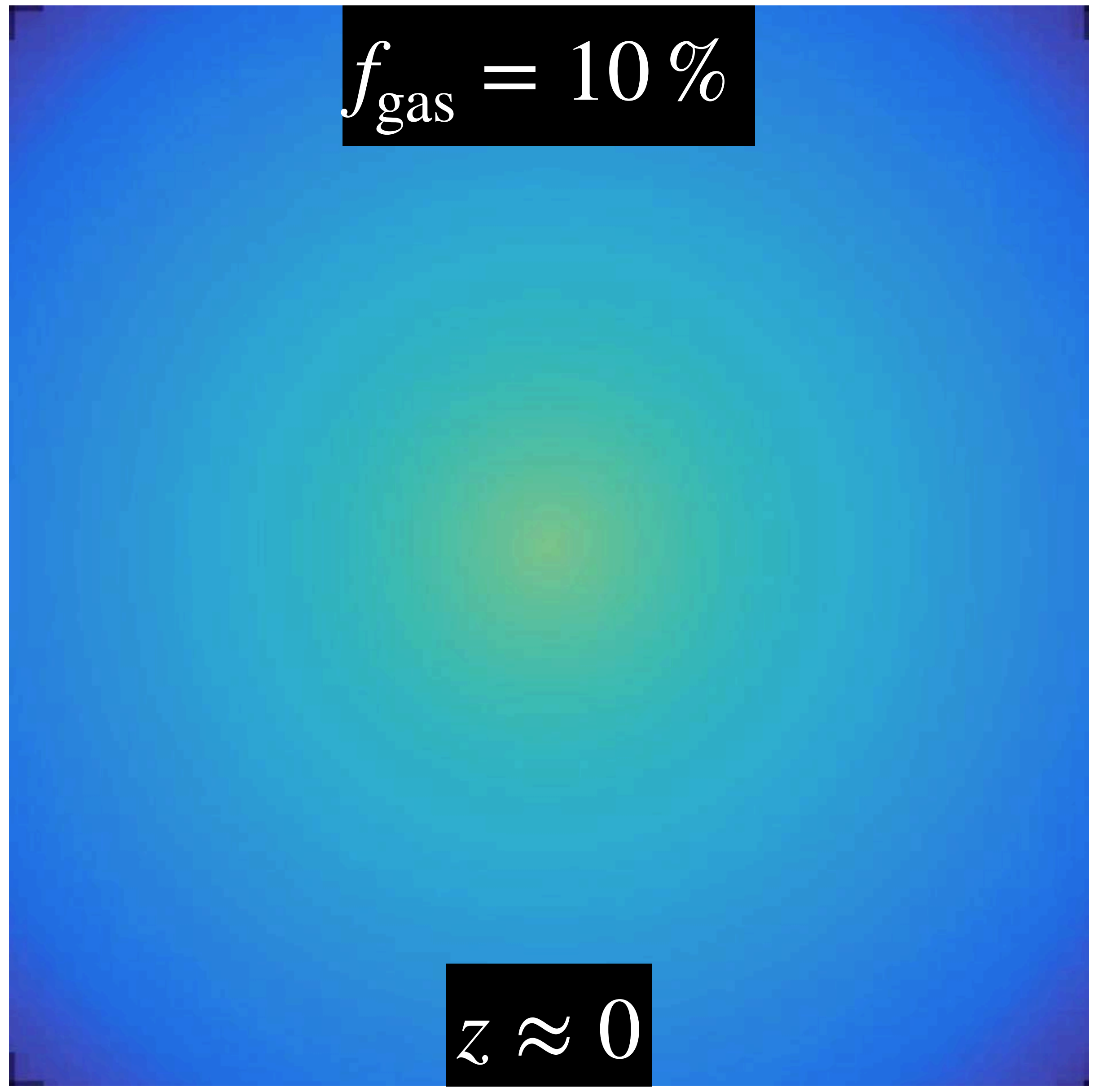
Renaud, Romeo & Agertz (2021)

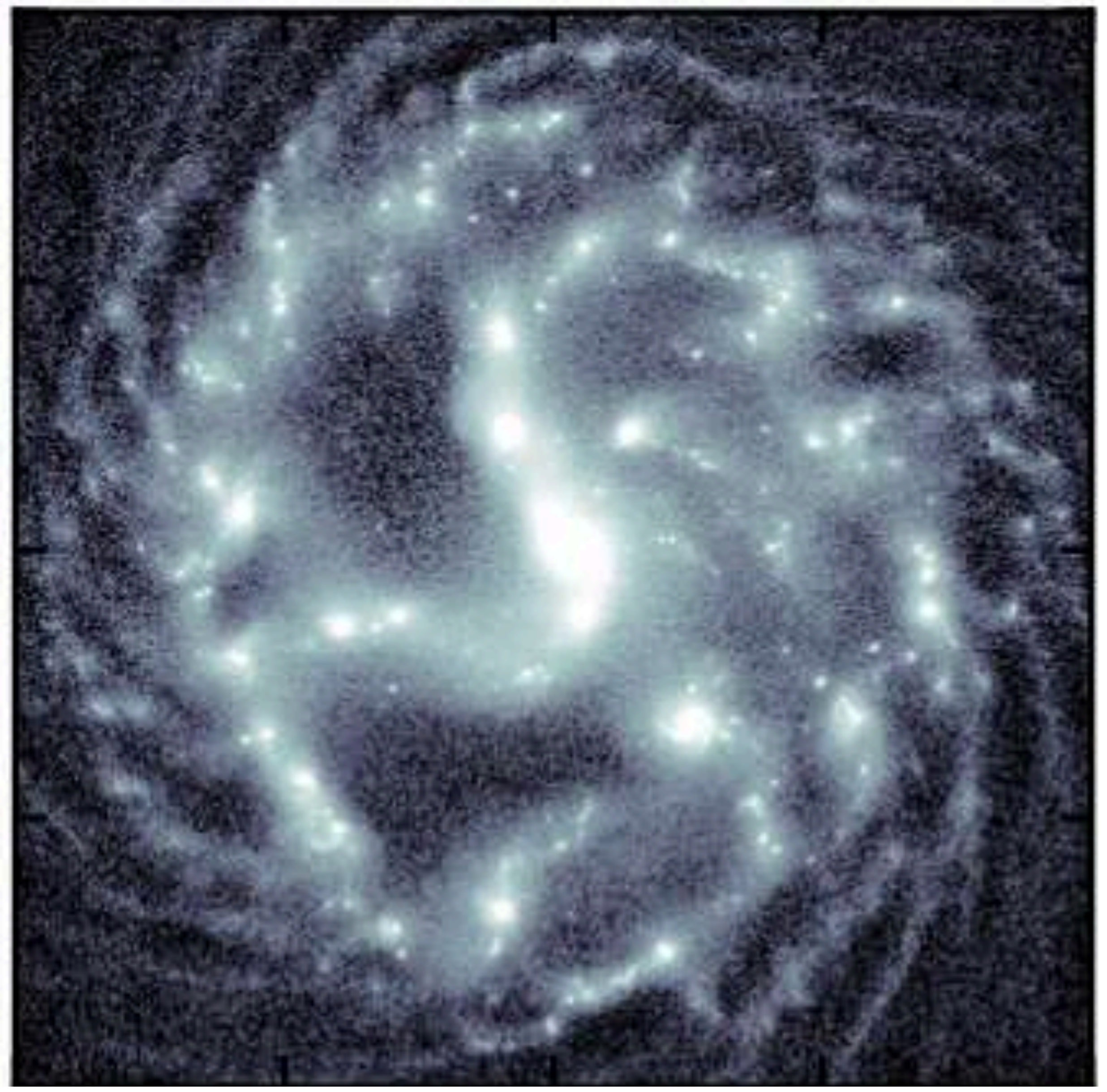
In gas-rich disks:
the molecular gas changes the instability regime

Transition from clump-driven to disk-driven (Toomre)
at $f_{\rm gas} \approx 20\,\%$
Renaud et al. (2021)

Violent disk instabilities
Noguchi (1999), Agertz et al. (2009), Dekel et al. (2009)

Favored by turbulent compression
in cosmo context
Ginsburg et al. (2025)





TRANSITION ALSO SEEN IN KINEMATICS

Gas rich (clumpy) disks provide a high velocity dispersion to young stars...

...but only at $f_{\rm gas} \gtrsim 20\,\%$

After $f_{\rm gas} \approx 20\,\%$:

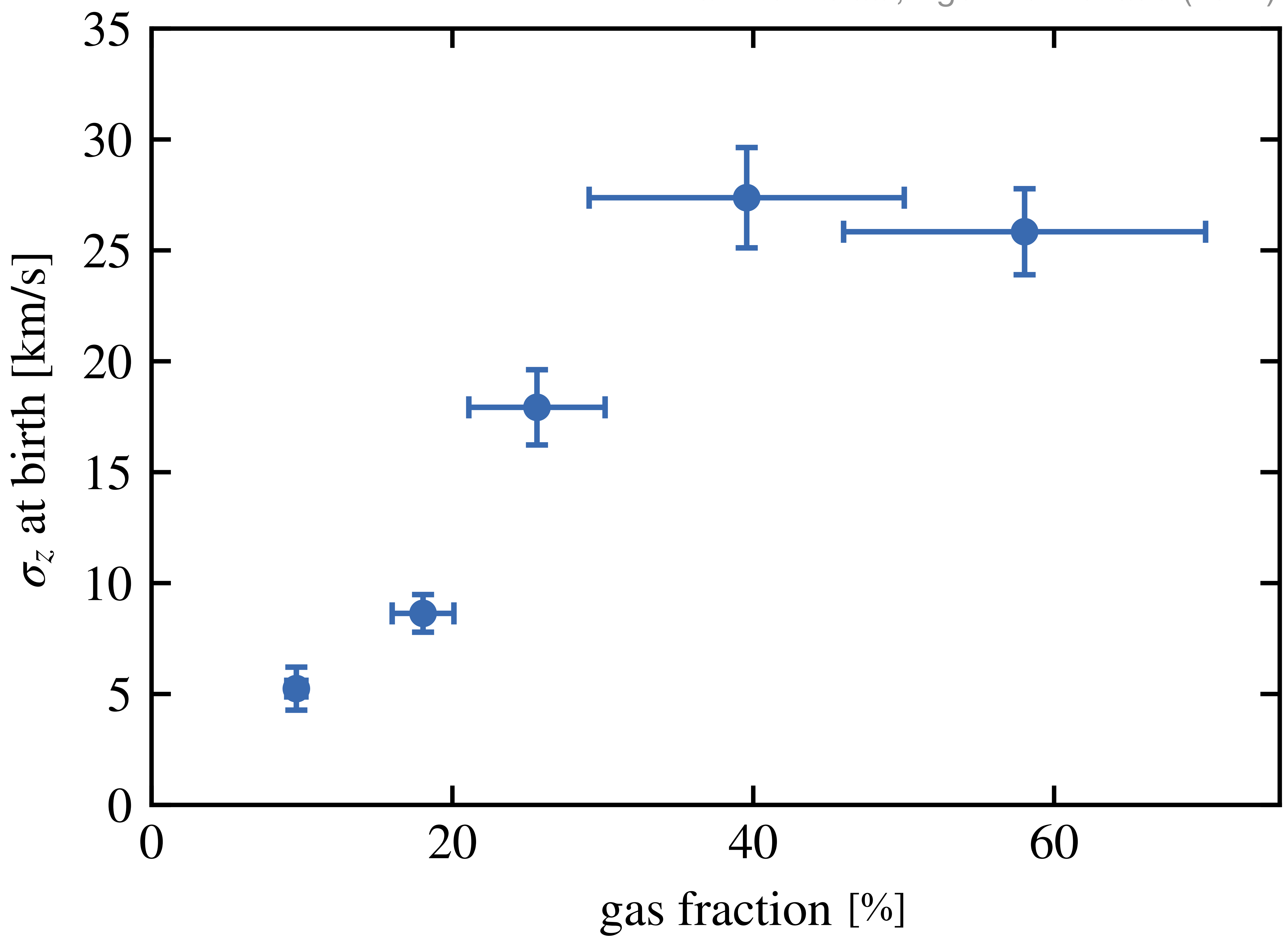
- less turbulence
- onset of disk instabilities (Toomre)
- low and slow star formation
- enrichment at low $[\alpha/{\rm Fe}]$

→ *High gas fraction = barrier against thin disk formation*

(very similar signature from mergers)

ask me about this!

van Donkelaar, Agertz & Renaud (2022)



Safronov-Toomre Q:

Safronov (1960), Toomre (1964)

$$Q = \frac{\kappa\sigma}{\pi G \Sigma} = \frac{\text{rotation \& pressure}}{\text{gravity}}$$

Romeo & Falstad (2013) parameter:

how different from the most unstable component

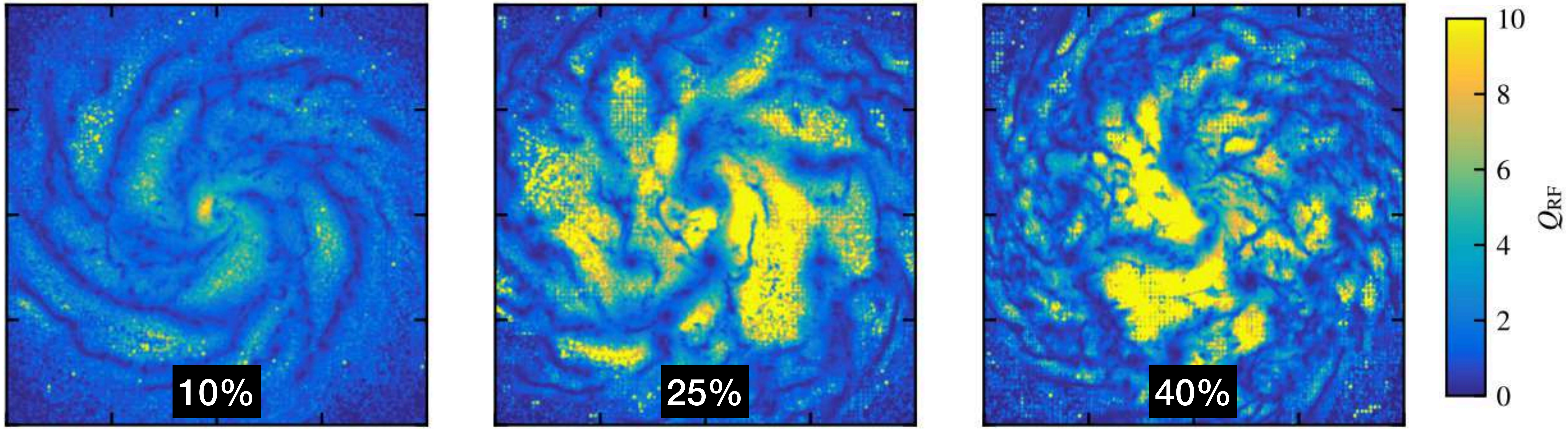
$$Q_{\rm RF} = \left(\sum_i \frac{1}{Q_i} \frac{W_i}{T_i} \right)^{-1}$$

$i \in \{\mathrm{HI}, \mathrm{H_2}, \star\}$

disk thickness

Requires the disk to be:

- ~~axisymmetric~~ → galaxies can have $Q \gg 1$ from non-axisymmetric perturbations
  Romeo & Mogotsi (2017)
- solved! ~~razor-thin~~
- solved! ~~mono-component~~ (100% stars *or* 100% gas)



Renaud, Romeo & Agertz (2021)

DRIVER OF INSTABILITIES

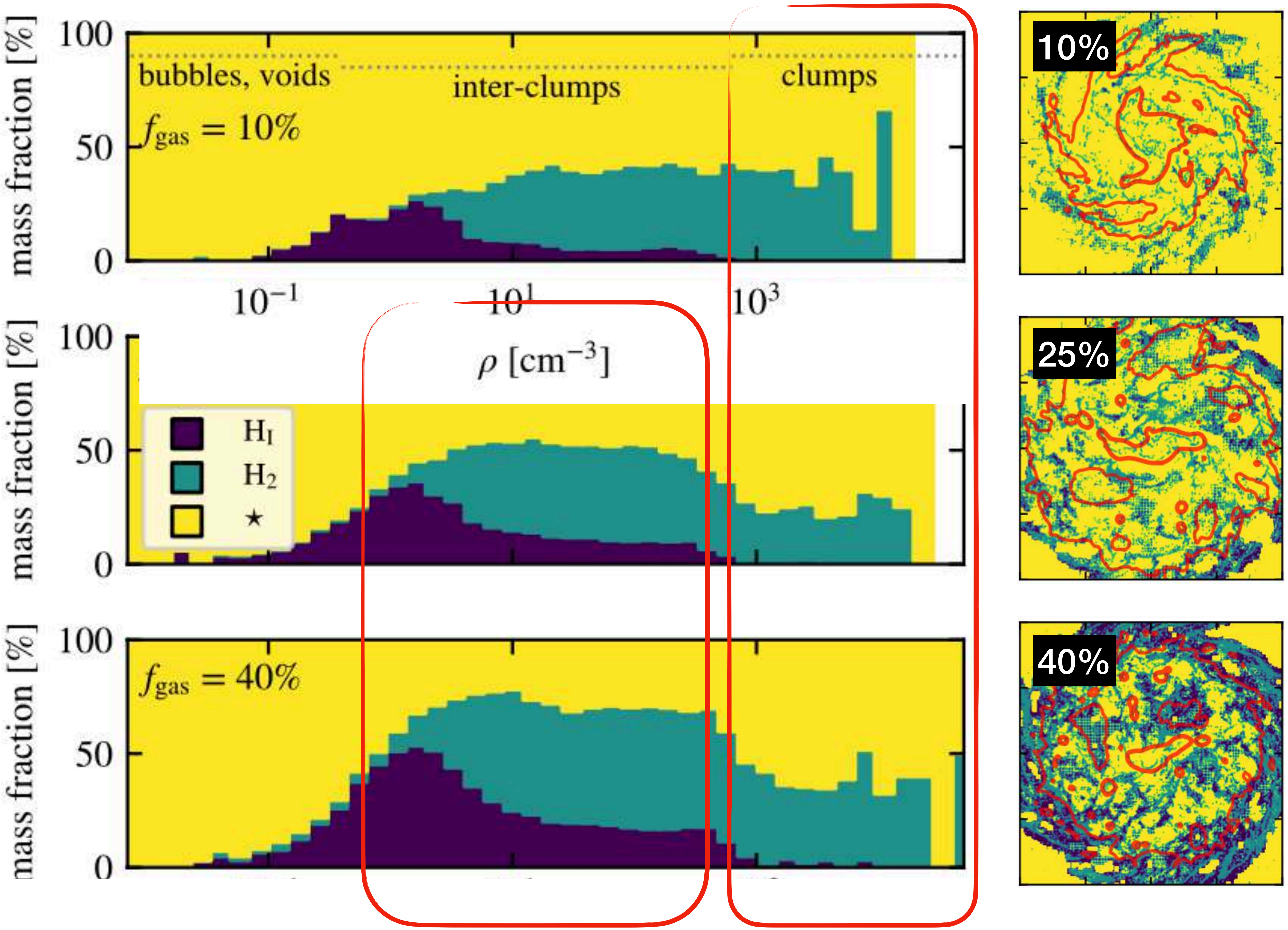
Gas takes the dominant role in the inter-clump medium
i.e. for the assembly of the clumps

The gaseous phase sets the formation of the clumps

Stars dominate *within* clumps

Stellar feedback increases the turbulence support
(but doesn't affect the stars much)

Renaud, Romeo & Agertz (2021)



DECOUPLING

Coupled instabilities in most regions (70-90%)

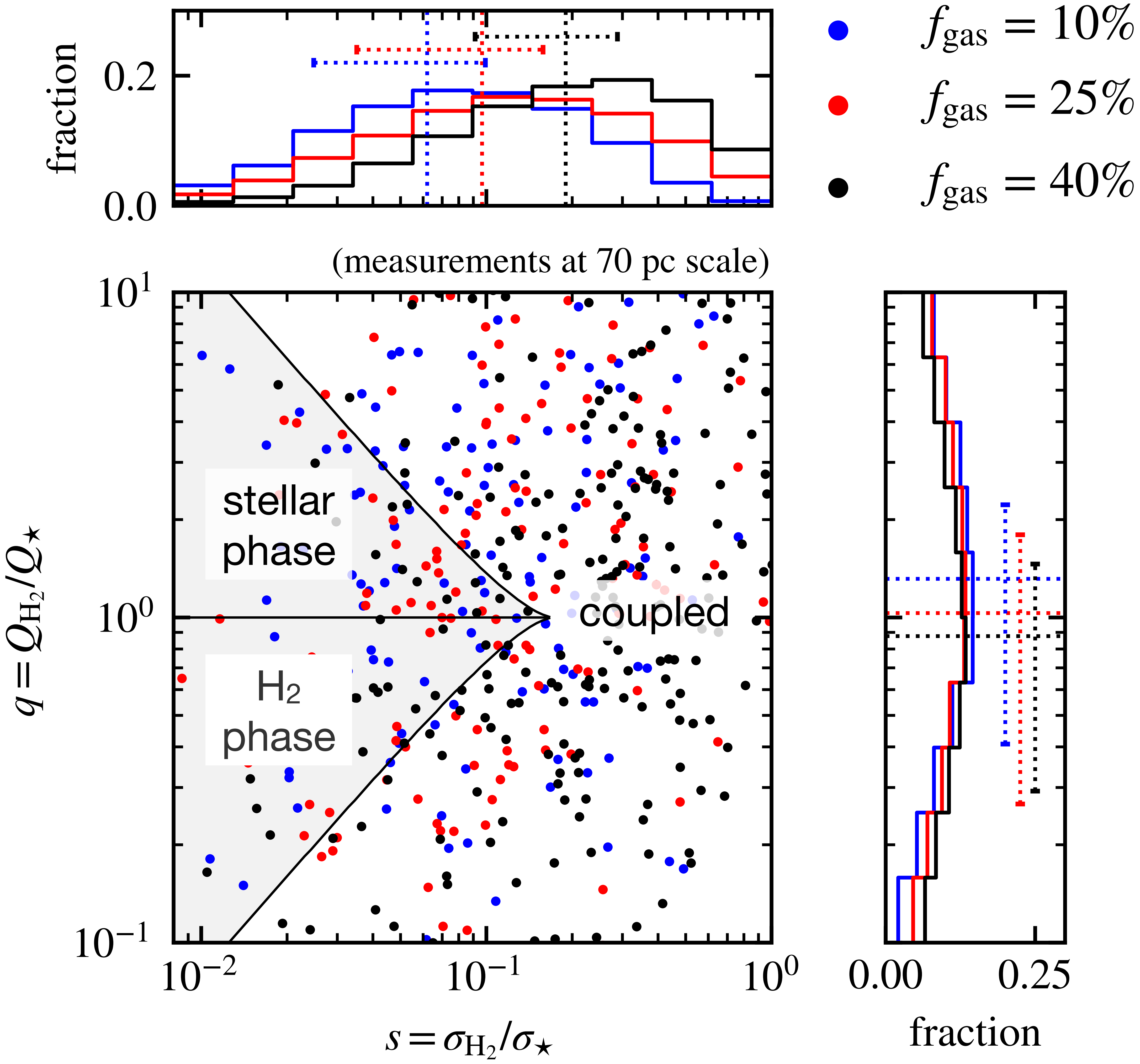
→ instabilities from one component affect the others

Decoupled regions:

- stronger **turbulence** (Mach number)
- more **stable** (Q_{RF})
- larger instability **scale** ($\lambda_{RF} = 2\pi\sigma_m/\kappa$)

Role of feedback in decoupling

$t_{\text{feedback}} \ll t_{\text{disk}}$



Renaud, Romeo & Agertz (2021)

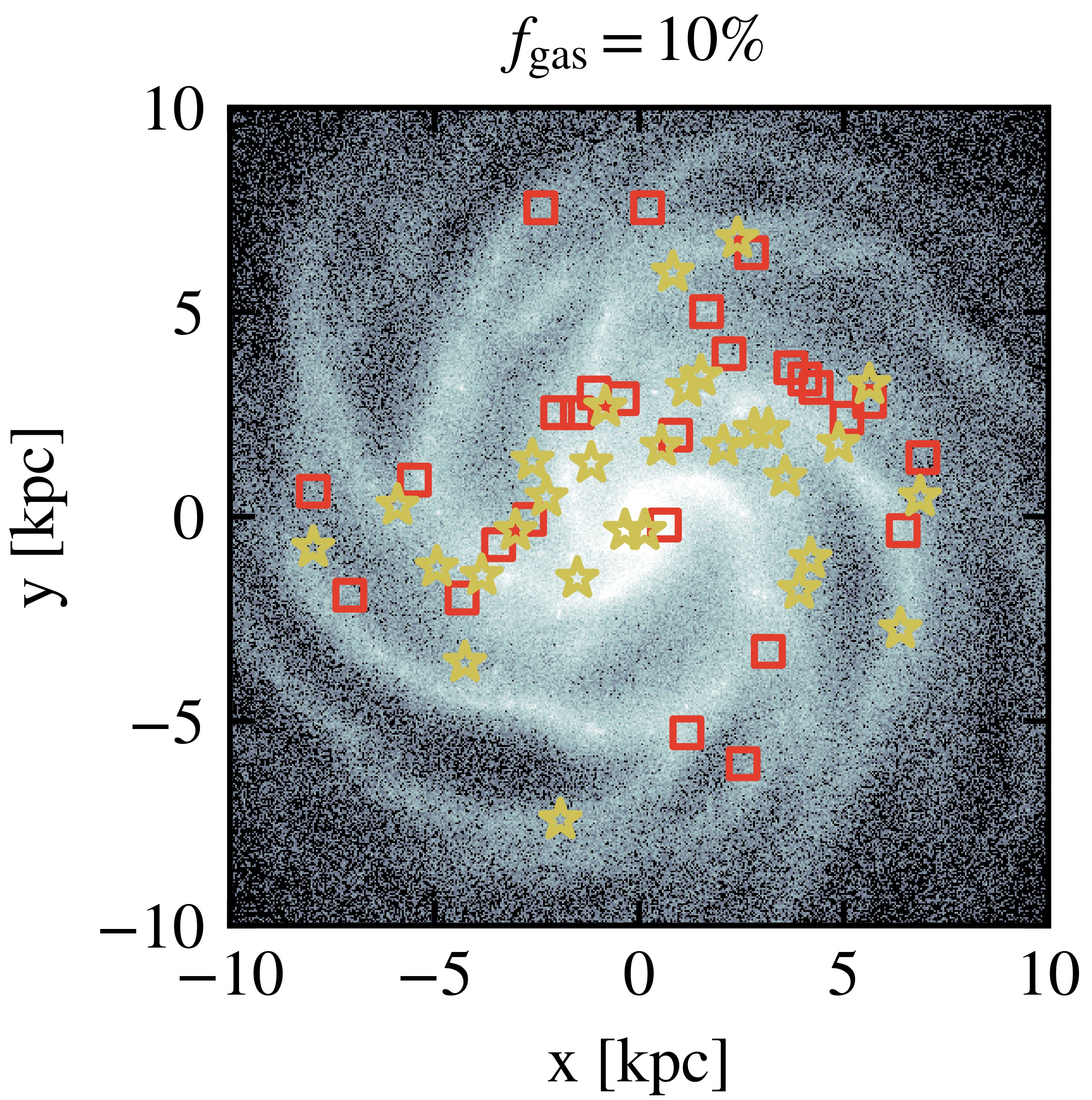
see also Romeo & Wiegert (2011), Romeo & Falstad (2013)

DECOUPLING FROM LARGE SCALE DYNAMICS

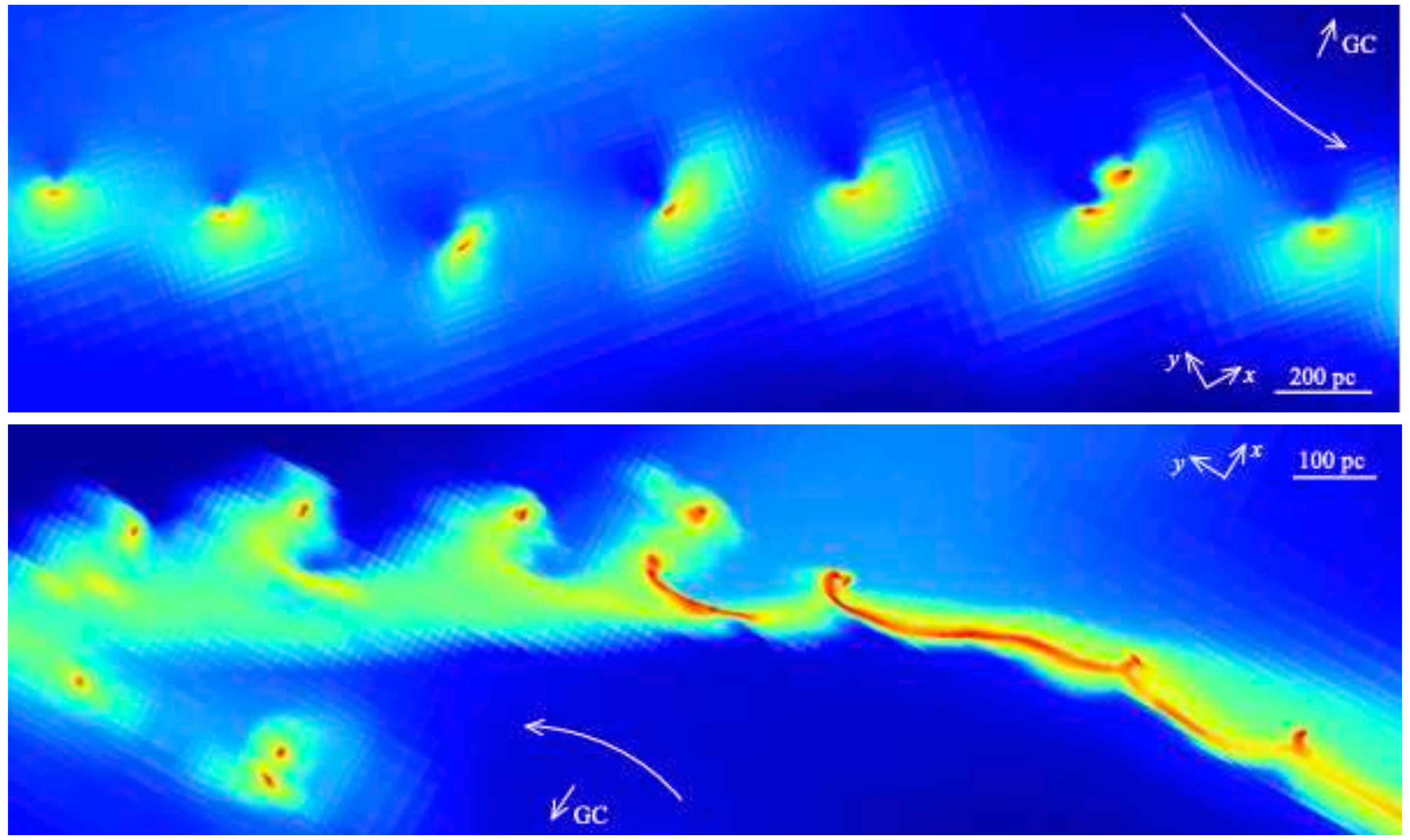
Decoupled instabilities driven by: ☆ stars □ H_2

(1% shown for clarity)

Renaud, Romeo & Agertz (2021)



Renaud et al. (2013, 2014)



- high pitch angle = fragmentation
  → *beads on a string*
- low pitch angle = KH instabilities
  → *spurs*

Decoupled regions at the edge of spirals or dense clumps

with high pitch angle → favors fragmentation in "beads on a string"

+ asymmetric drift = injection of feedback on the trailing side of spirals

See Eric's talk (Friday)

kpc-scale dynamics matters but the agent of decoupling is feedback

ISM PSD: WTF (INTERSTELLAR MEDIUM'S POWER SPECTRUM DENSITY: A WONDERFUL THEORETICAL FUNCTION)

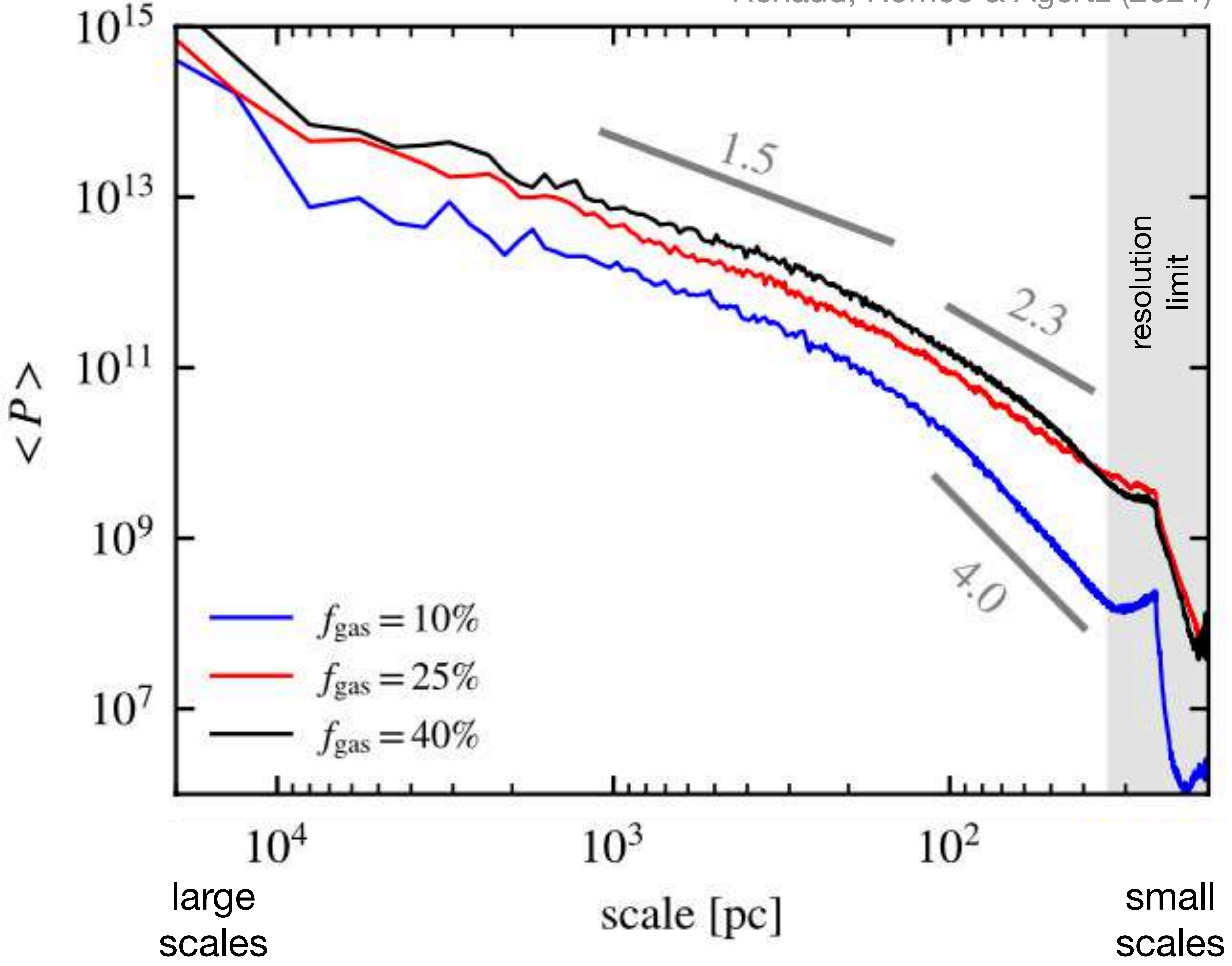
Change of slope at ~ 100 - 200 pc

Partly caused by the transition
from 2D to 3D turbulence
(i.e. within the disk scaleheight)
Dutta et al. (2009), Renaud et al. (2013)

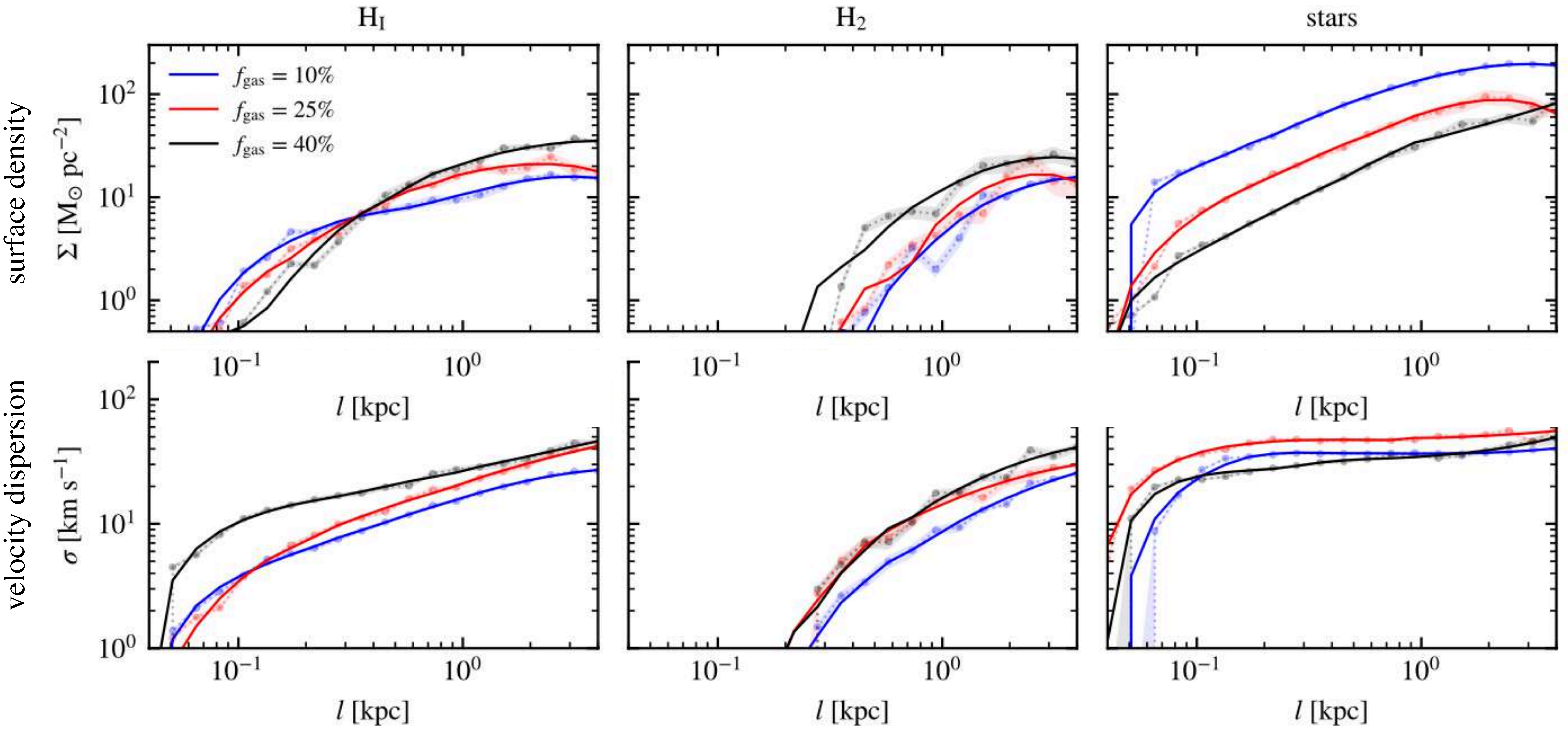
But divergence between the 3 cases...

Transition between the galaxy-scale to cloud/clump-scale stability regime, depends on f_{gas}

Renaud, Romeo & Agertz (2021)



SCALE DEPENDENCE



Renaud, Romeo & Agertz (2021)

REGIMES OF INSTABILITY

Surface density:

$$\Sigma \approx \Sigma_0 \left(\frac{l}{l_0}\right)^a$$

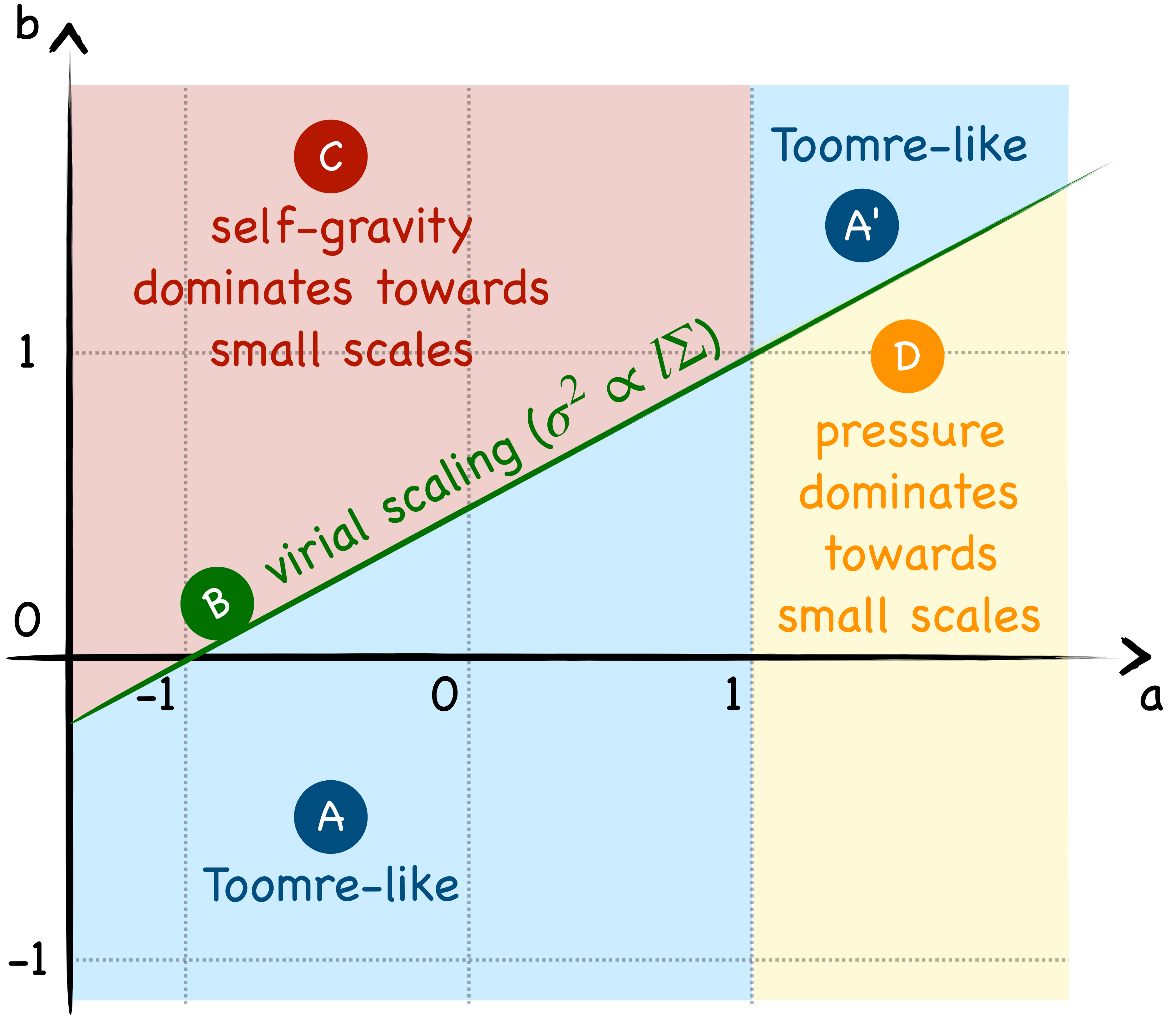
Velocity dispersion:

$$\sigma = \sigma_0 \left(\frac{l}{l_0}\right)^b$$

Dispersion equation:

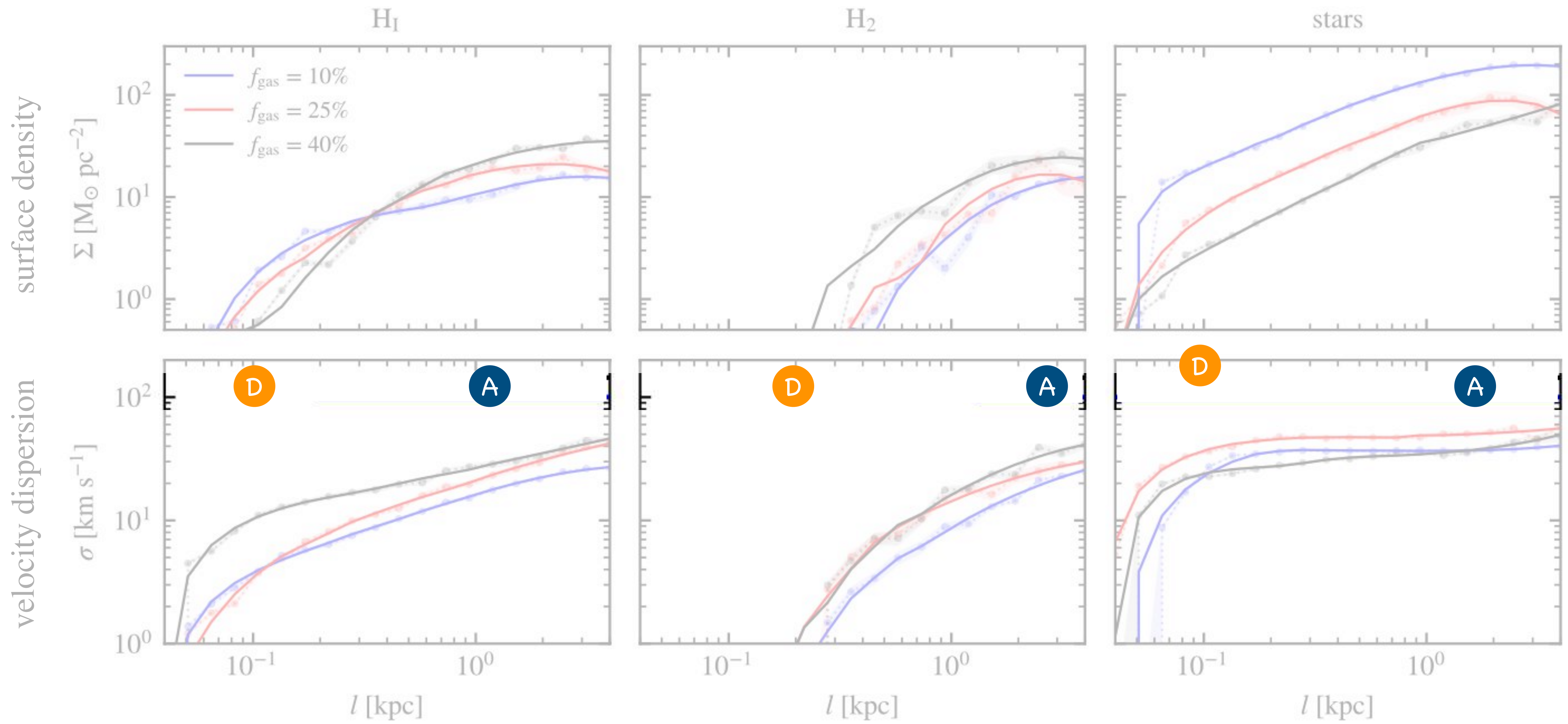
$$\omega^2 = \kappa^2 - 4\pi^2 G \Sigma_0 l_0^{-a} l^{a-1} + 4\pi^2 \sigma_0^2 l_0^{-2b} l^{2(b-1)}$$

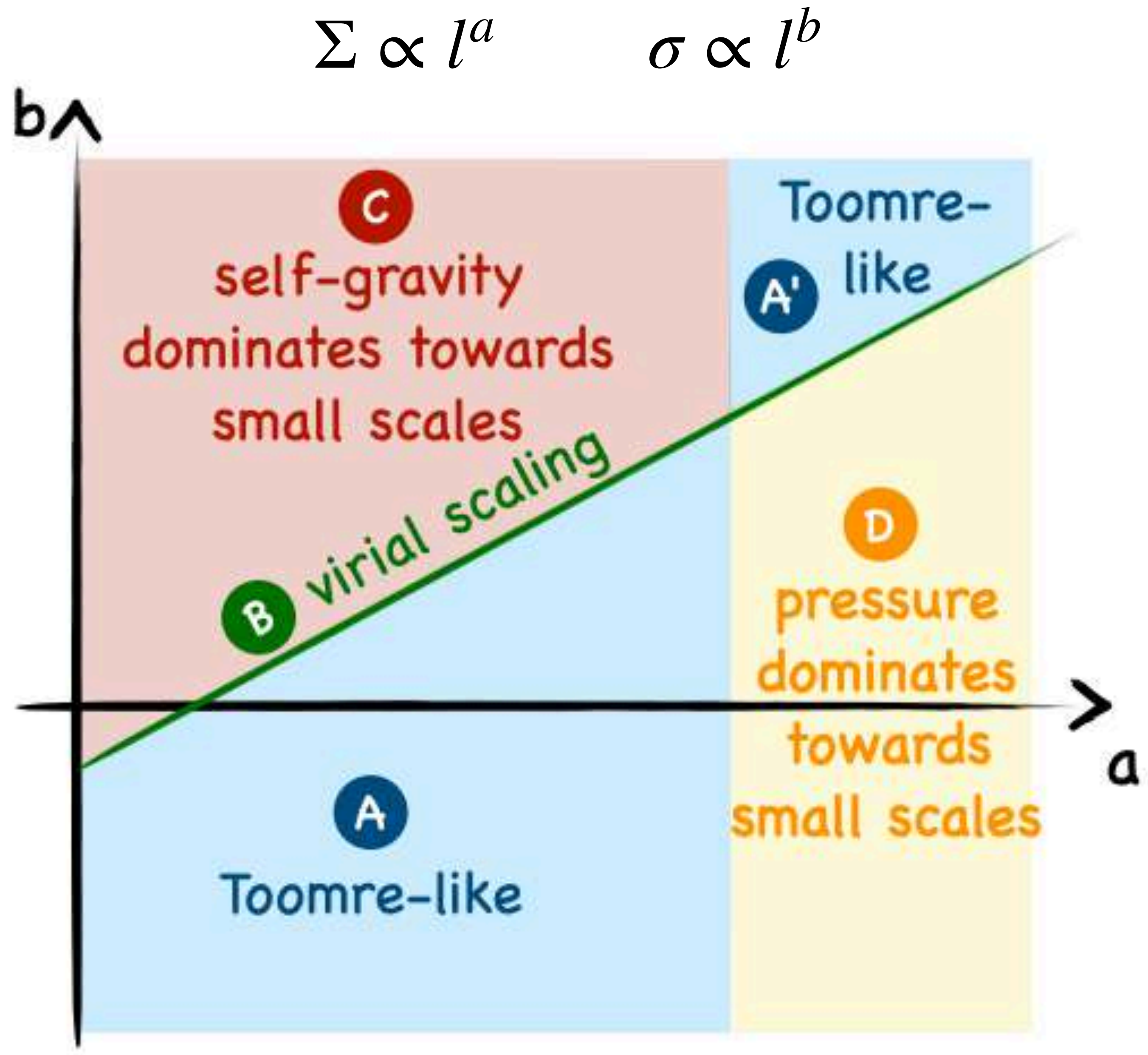
rotation gravity pressure



Renaud, Romeo & Agertz (2021)

TWO REGIMES OF INSTABILITIES





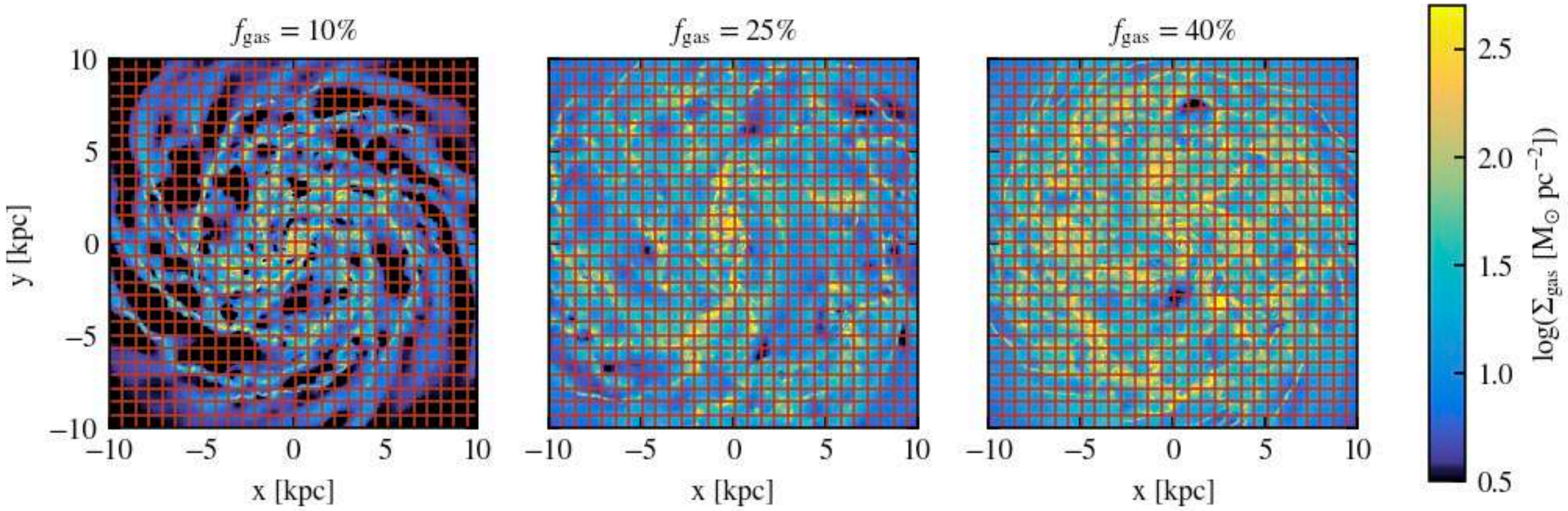
Disk-driven regime (A = Toomre-like) at large scales

Valid at all scales at low f_{gas} : structures are set by disk instabilities → spirals

At high f_{gas} only: transition to clump-driven (D) at a few 100 pc → ~~spirals~~ clumps

Renaud, Romeo & Agertz (2021)

EULERIAN APPROACH



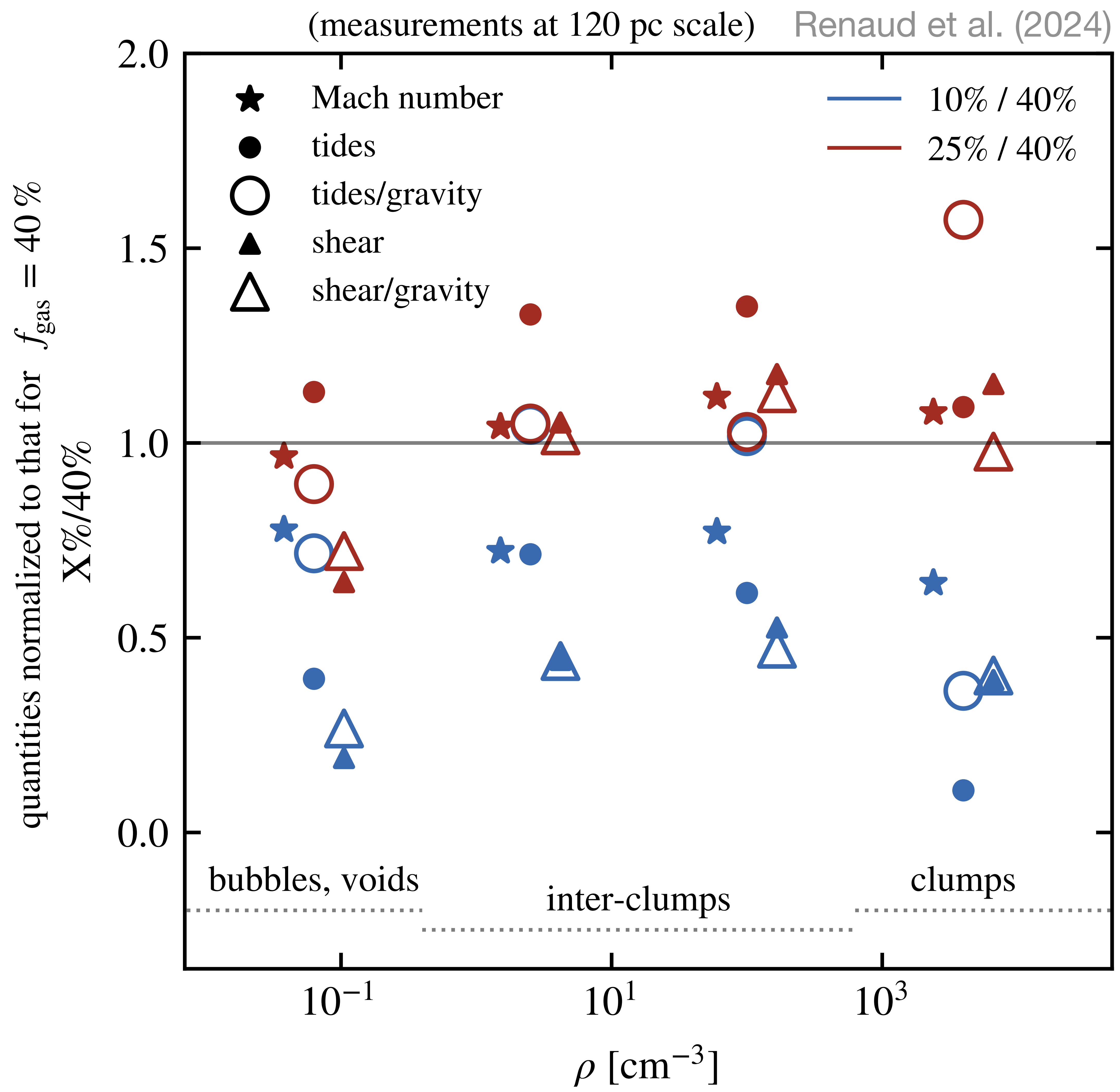
DISRUPTIVE MECHANISMS

Are differences amplified or mitigated by environmental effects around the clumps?

- **Turbulence**: higher in gas-rich disks, as observed (e.g., Föster Schreiber et al. 2009, Fisher et al. 2017)
- Same trends for **tides** and **shear** (but with stronger differences)
- Even when **normalized to self-gravity**

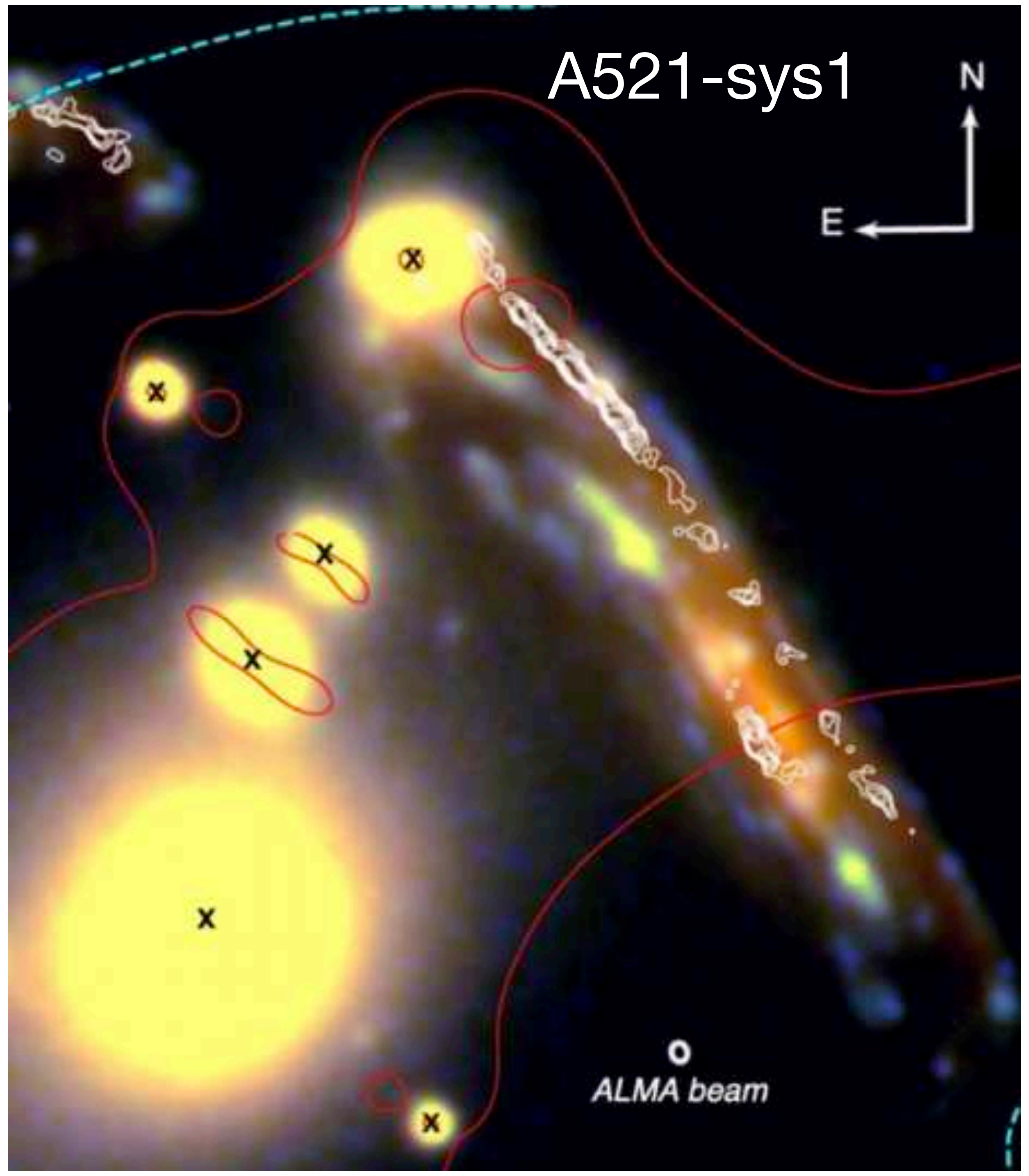
Again, many differences occur at $f_{\rm gas} \approx 20\,\%$

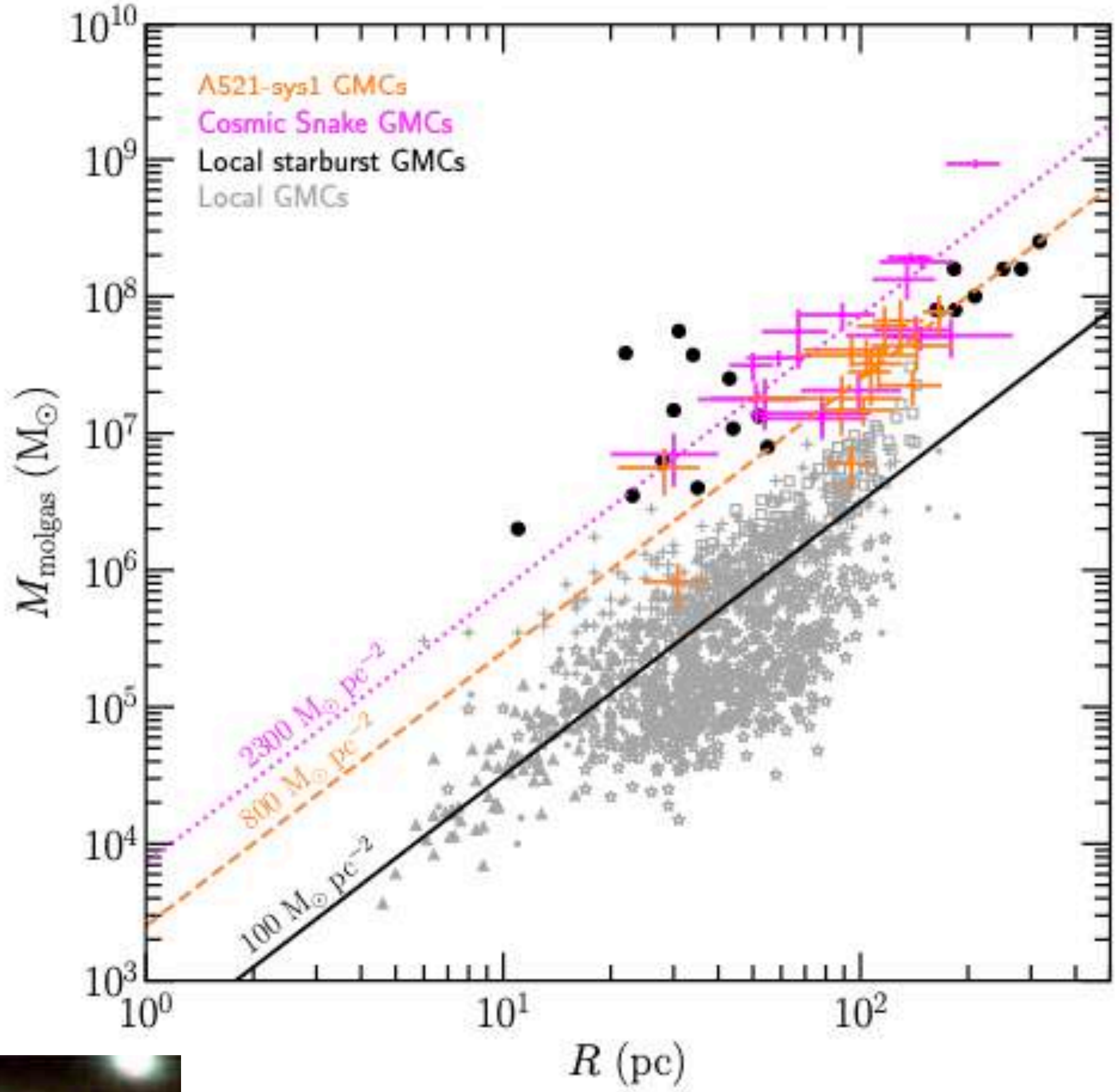
Stronger disruptive agents in gas-rich disks
→ short lifetimes for massive clumps??? *not so fast ...*

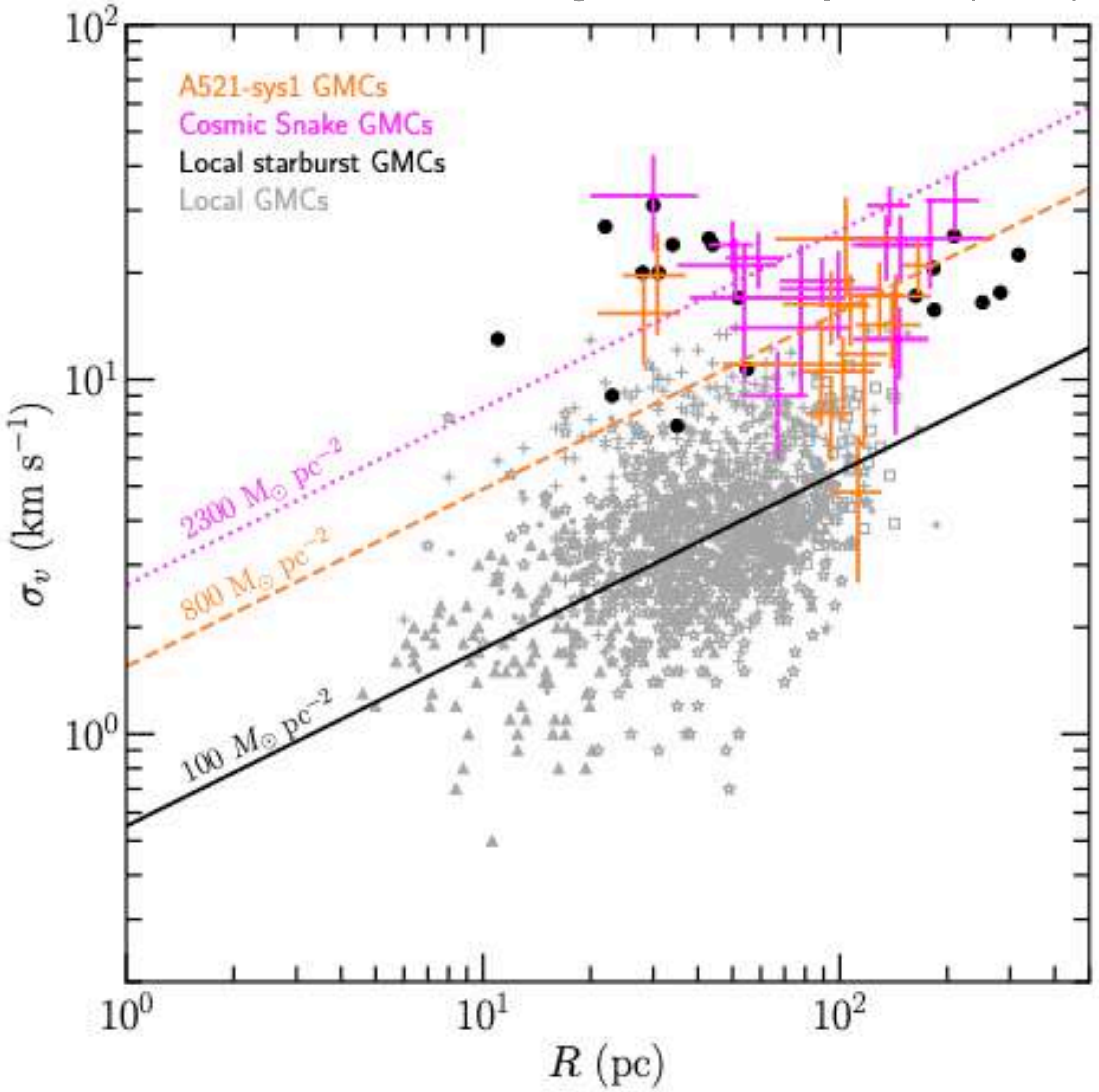


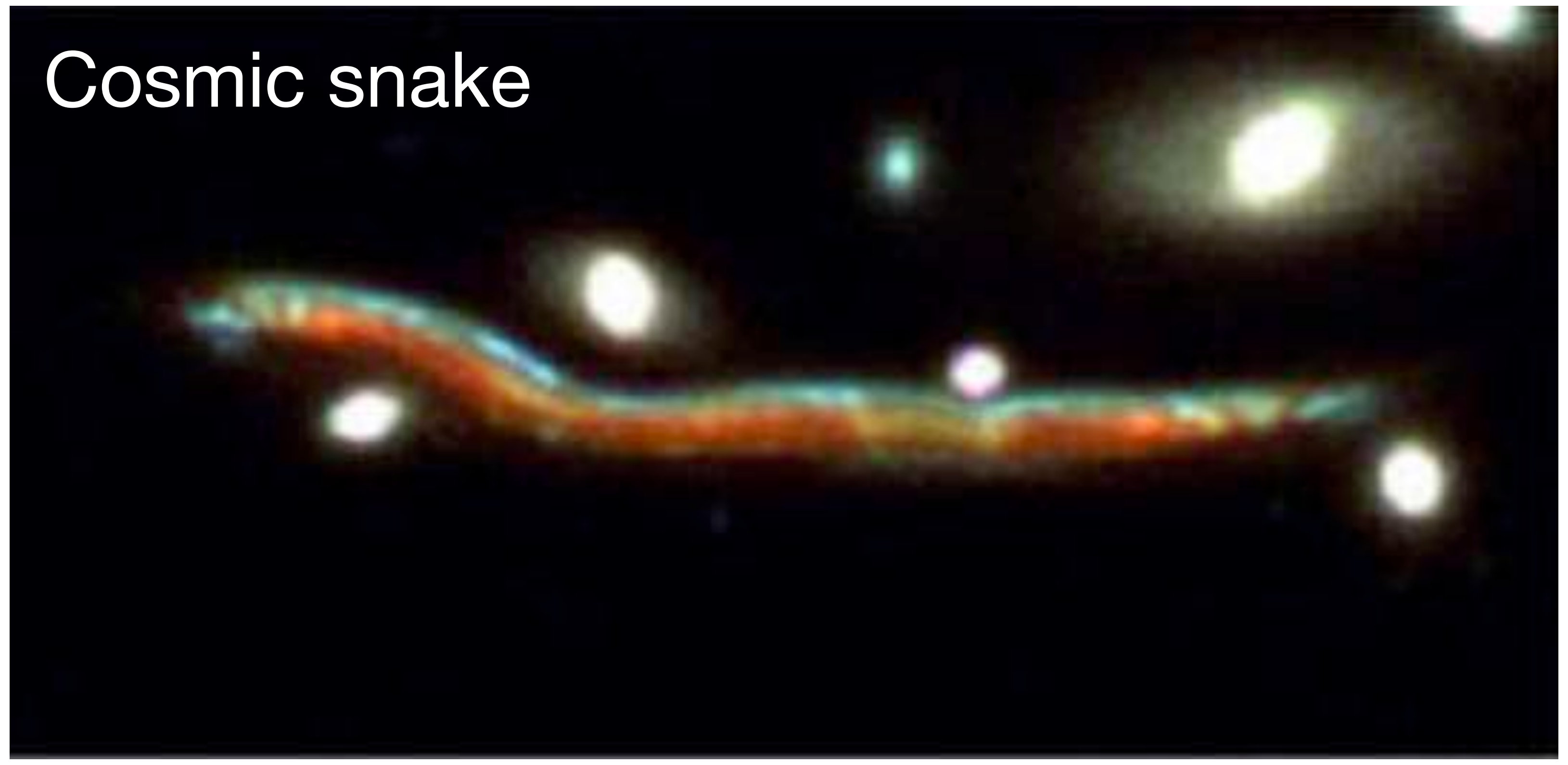
OBSERVED CLOUD SCALING RELATIONS AT z~1

Dessauges-Zavadsky et al. (2023)









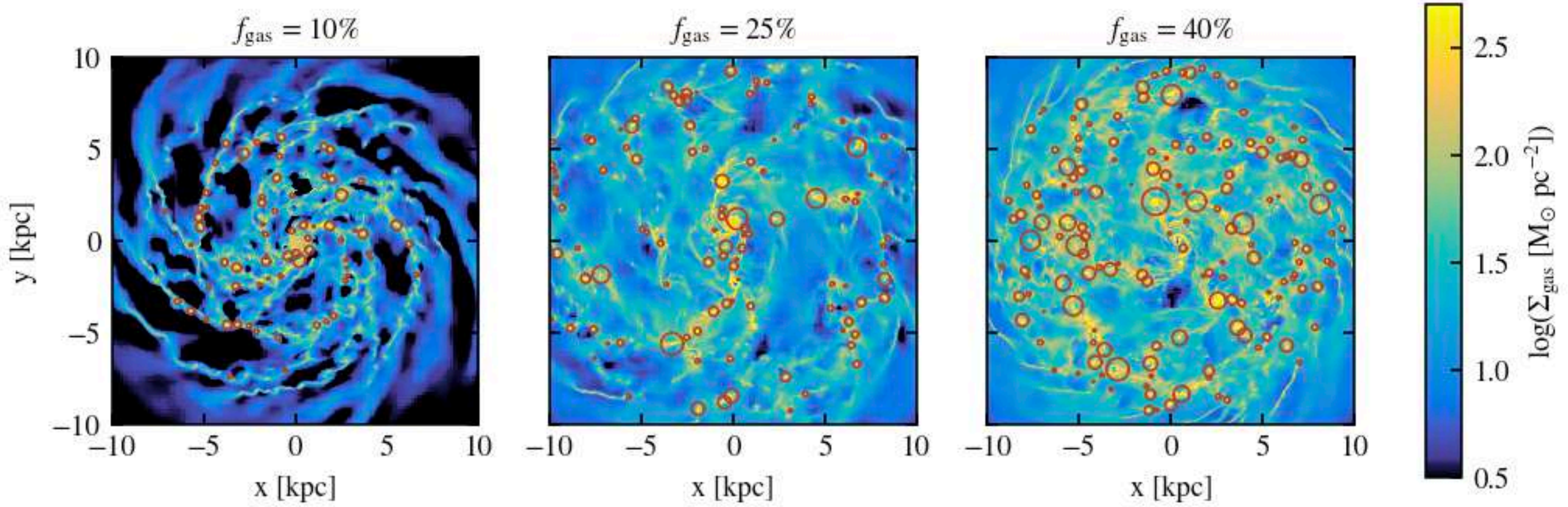
Feedback is essential to regulate ISM structures and scaling relations

Grisdale, Agertz, Romeo & Renaud (2018)

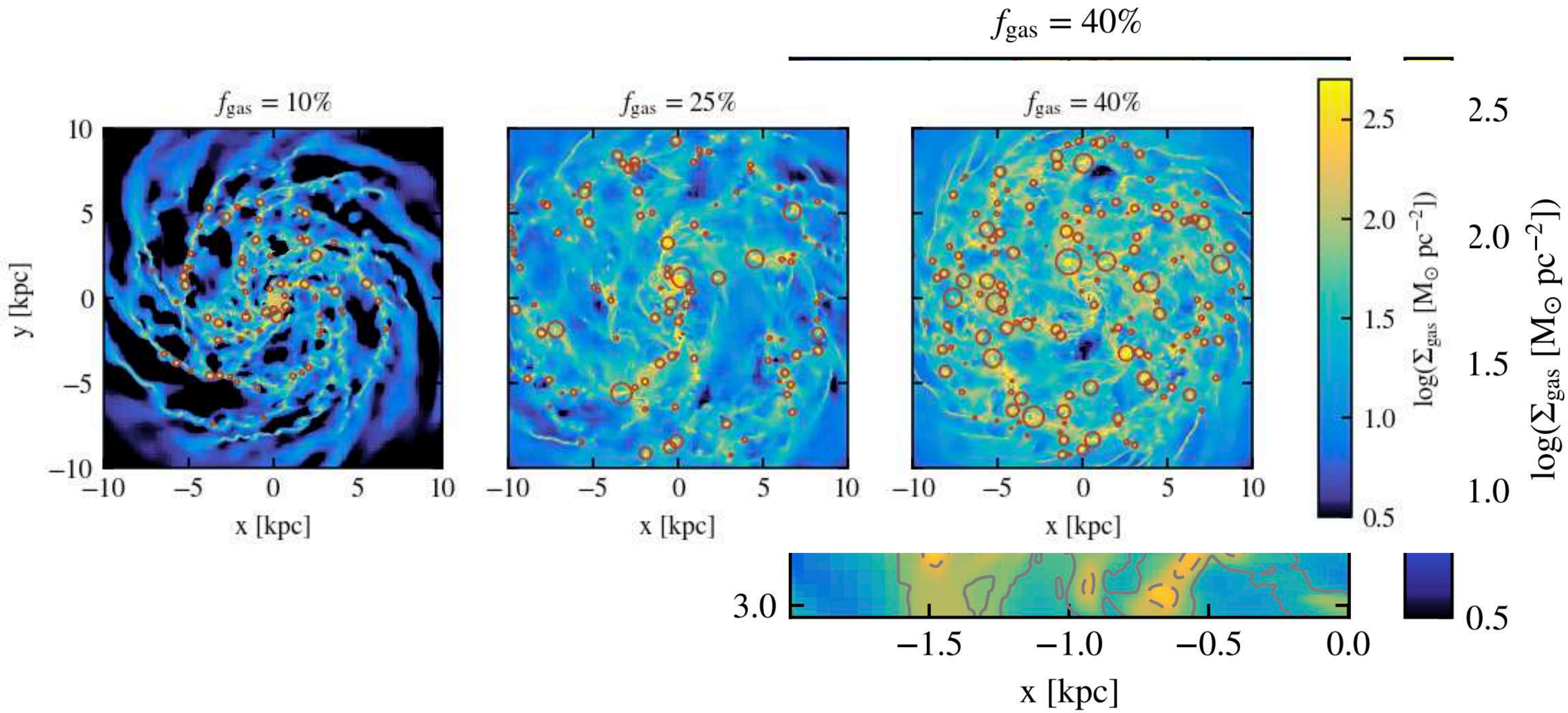
Clouds at z~1 are offset above the z=0 scaling relations

e.g., Larson (1981), Heyer et al. (2009), Miville-Deschenes et al. (2017)

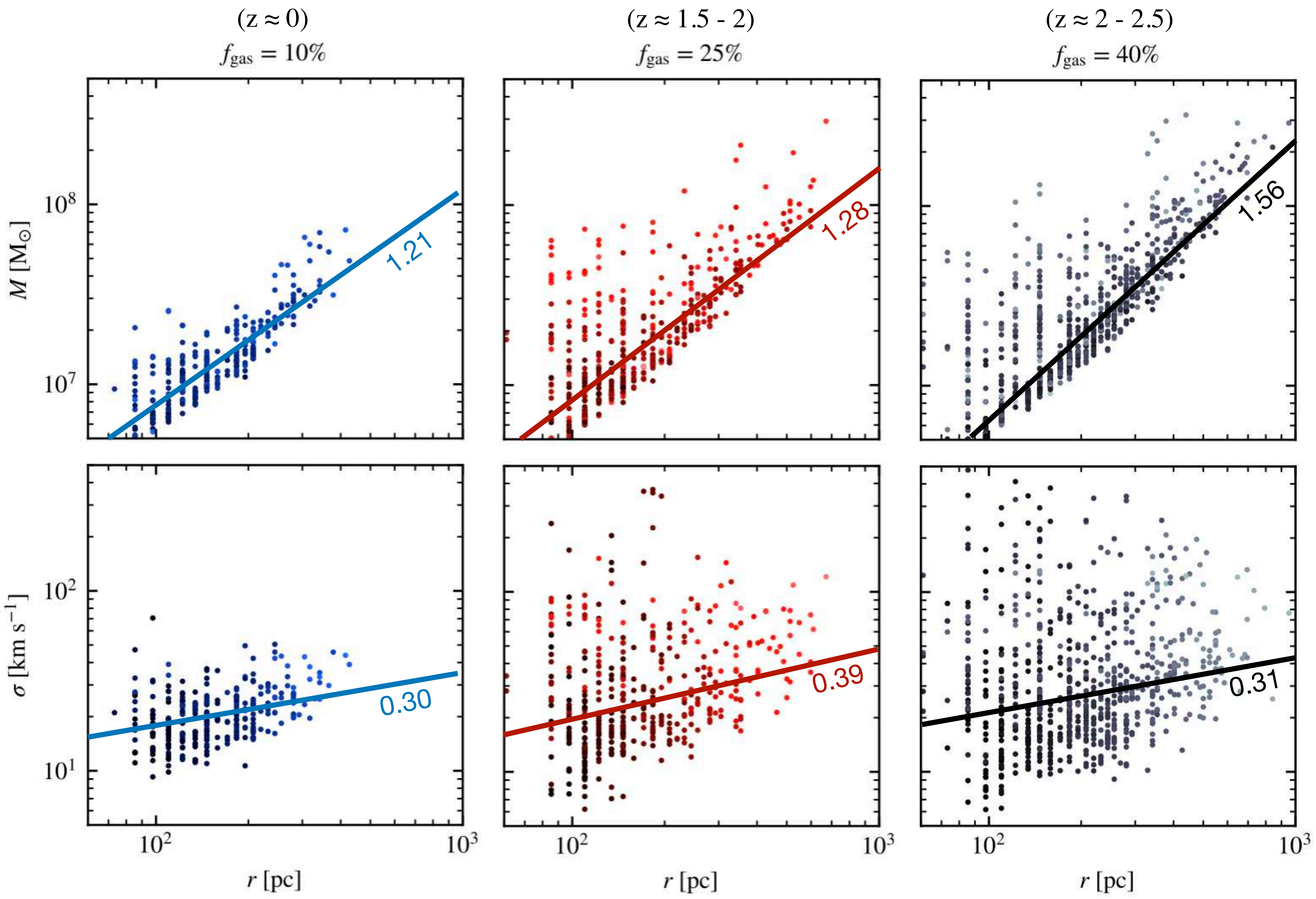
LAGRANGIAN APPROACH: CLUMP IDENTIFICATION



LAGRANGIAN APPROACH: CLUMP IDENTIFICATION



UNIVERSAL SCALING RELATIONS + OUTLIERS

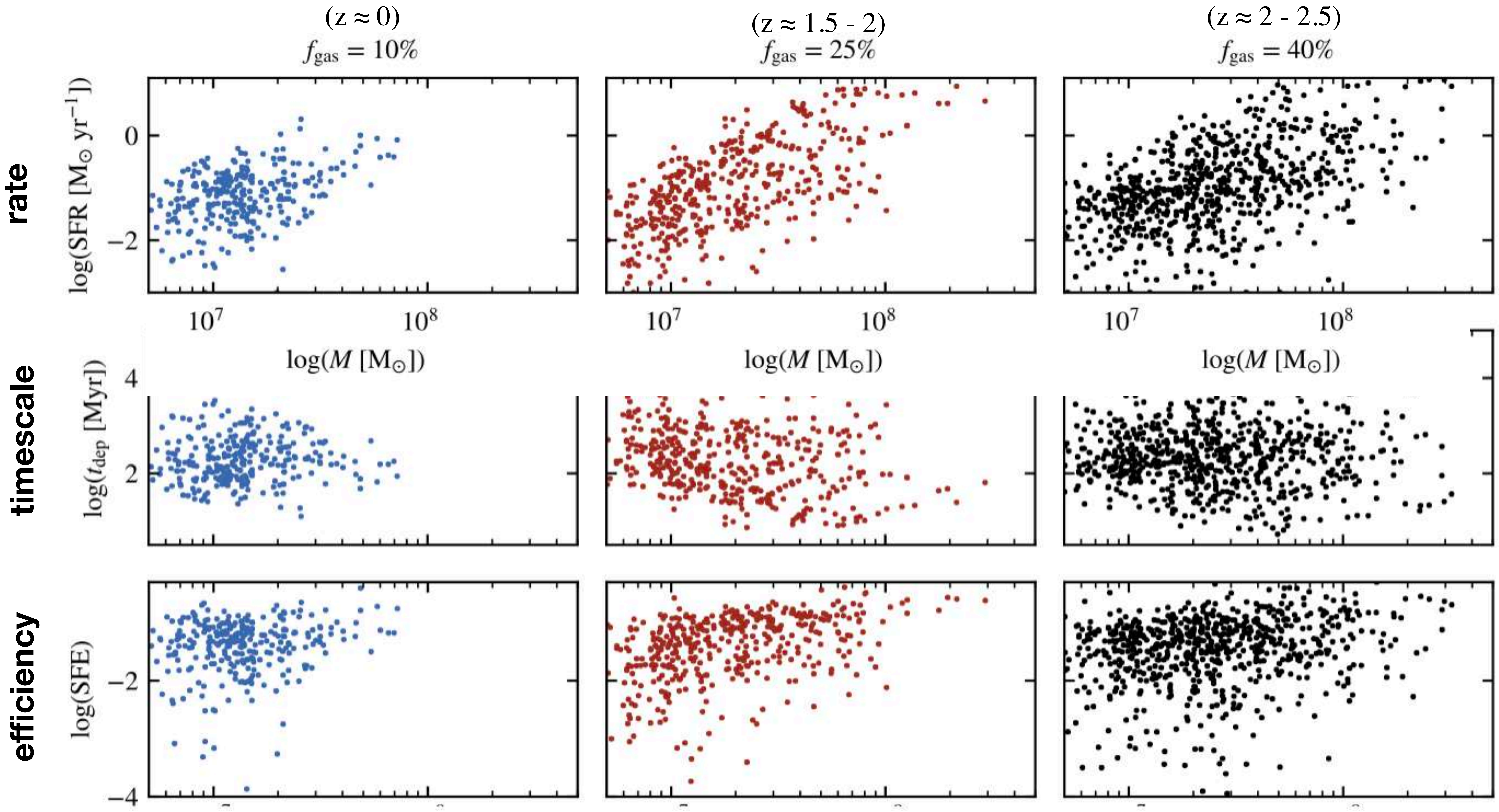


Clumps in gas-rich (high-*z*) disks follow Larson's-like scaling relations

... but with increased range and scatter

Renaud et al. (2024)

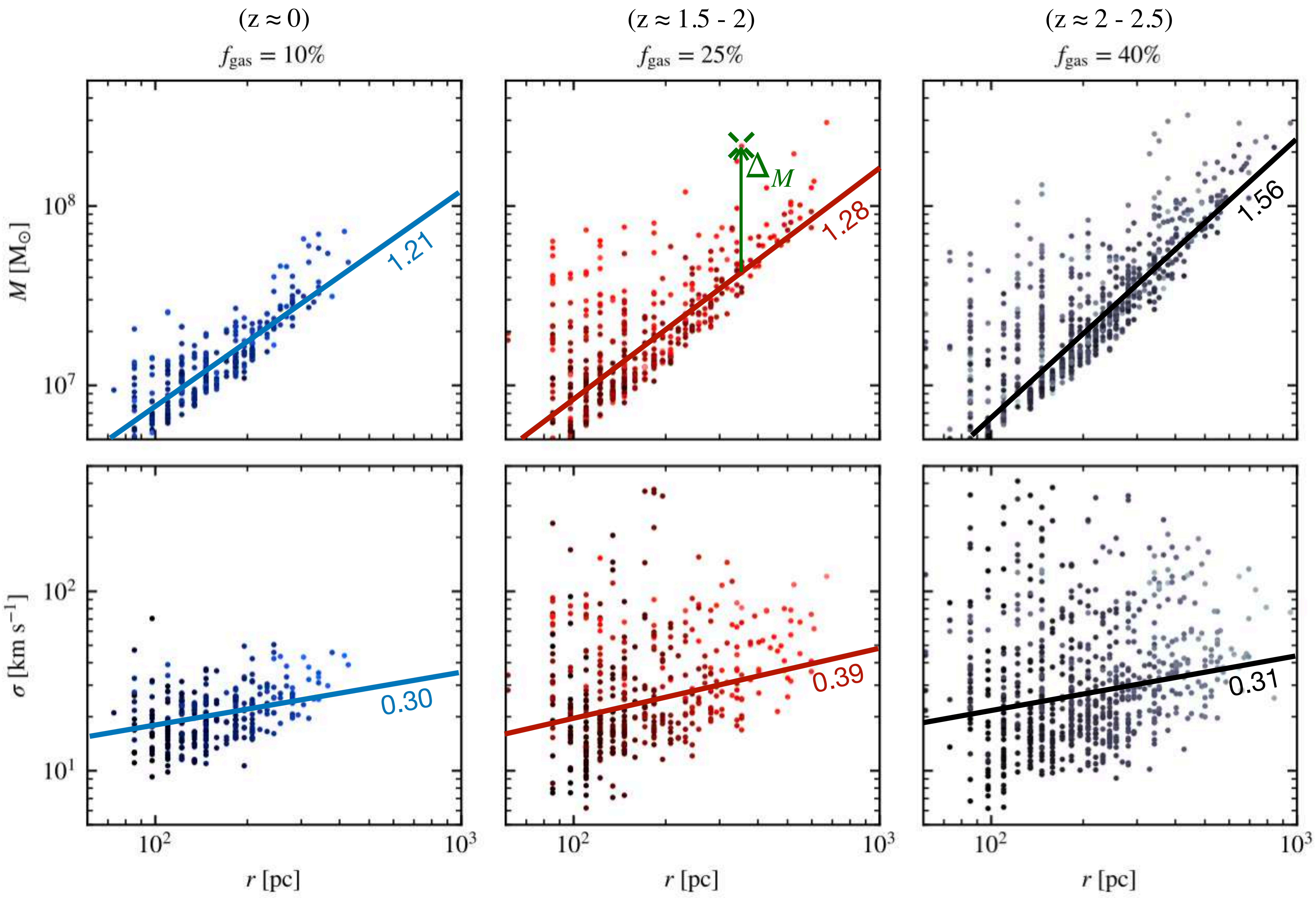
STAR FORMATION IS INDEPENDENT OF THE CLUMP MASS



No strong (if any) relation between the star formation indicators and clump mass

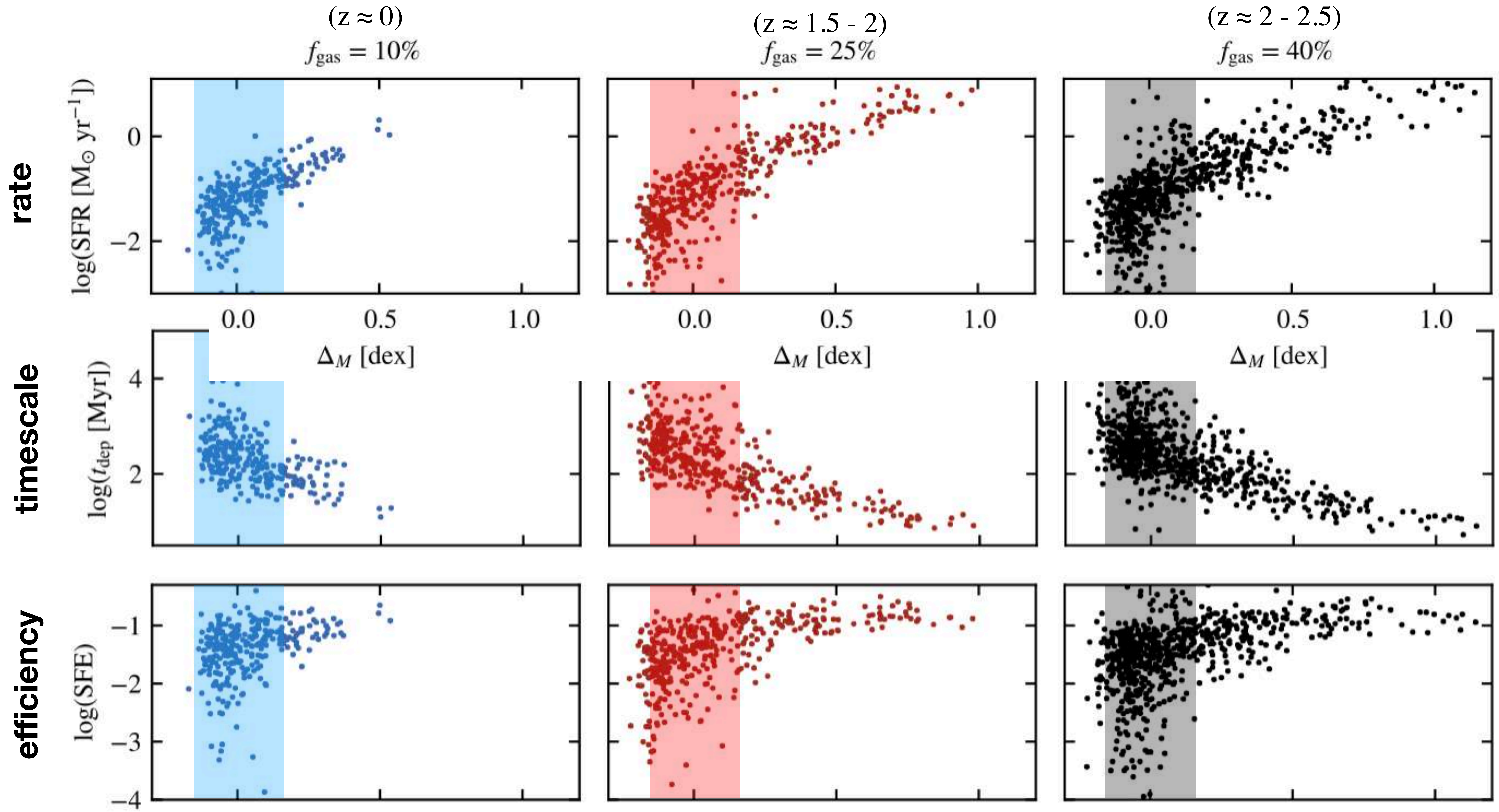
Renaud et al. (2024)

UNIVERSAL SCALING RELATIONS + OUTLIERS



Renaud et al. (2024)

DIFFERENT REGIMES OF STAR FORMATION IN EXTREME CLUMPS



Renaud et al. (2024)

Clumps with an *excess* of mass (for their size) have:

- high SFRs / low SFRs
- short depletion times / long depletion times
- high SFEs / low SFEs

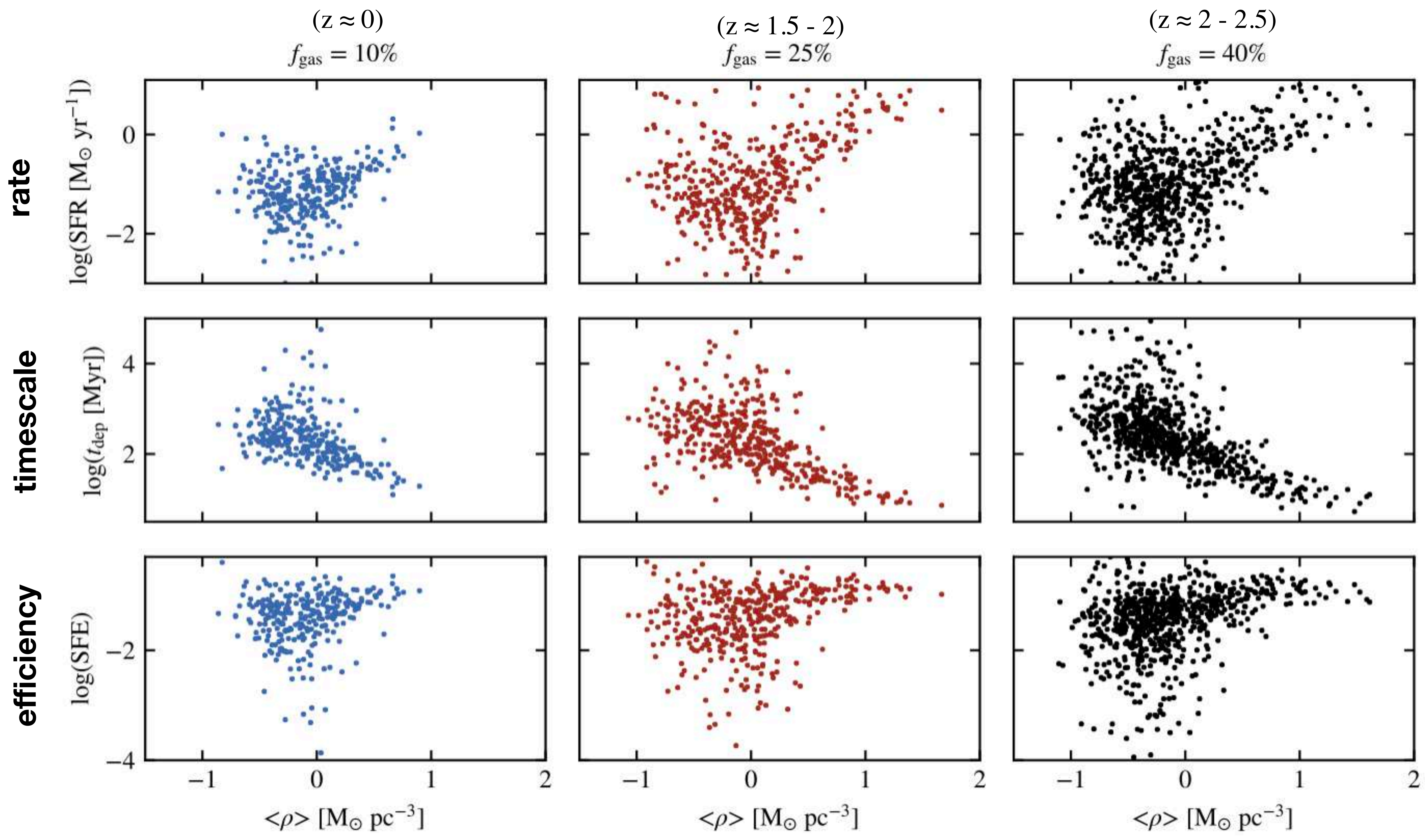
Large scatters for "normal" clumps ($\Delta_M \approx 0$)

as in e.g., Grisdale et al. (2019)
Miville-Dechenes et al. (2017)

More in Alvaro's talk (Wednesday pm)

Tighter relations for outliers

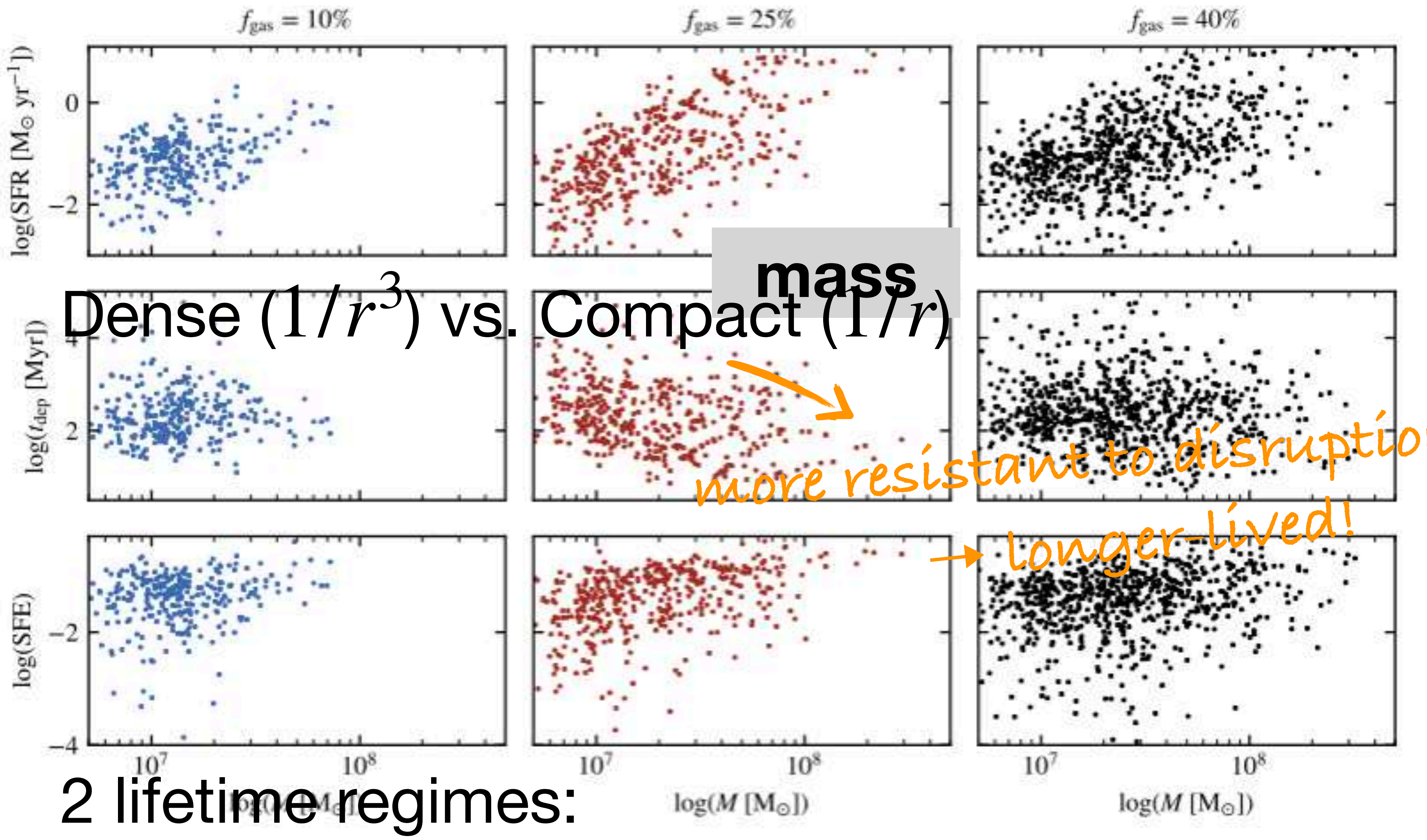
NOT JUST A DENSITY EFFECT



Weaker correlations with the density than with the excess mass!

Renaud et al. (2024)

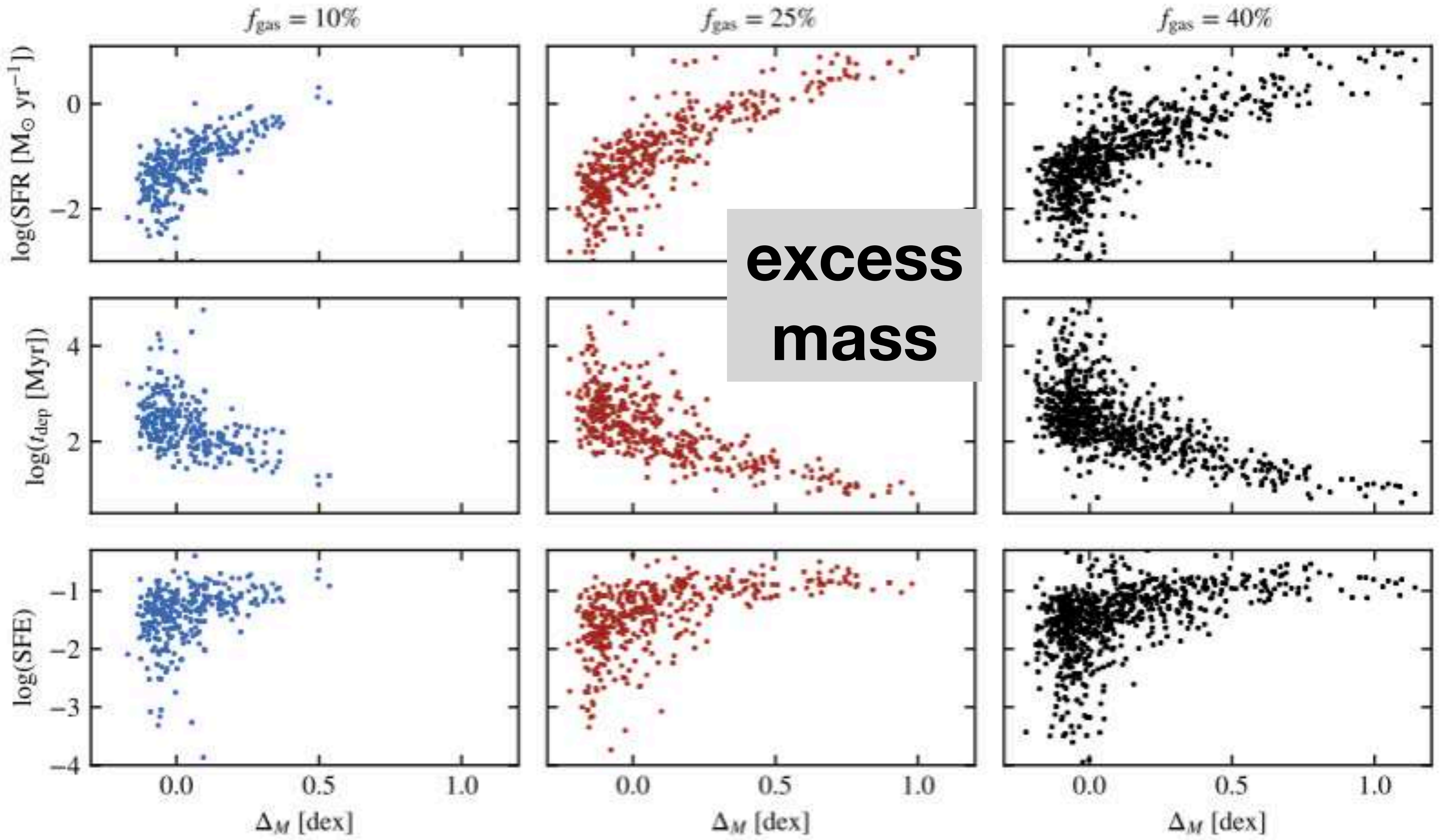
DIFFERENT REGIMES OF STAR FORMATION IN EXTREME CLUMPS

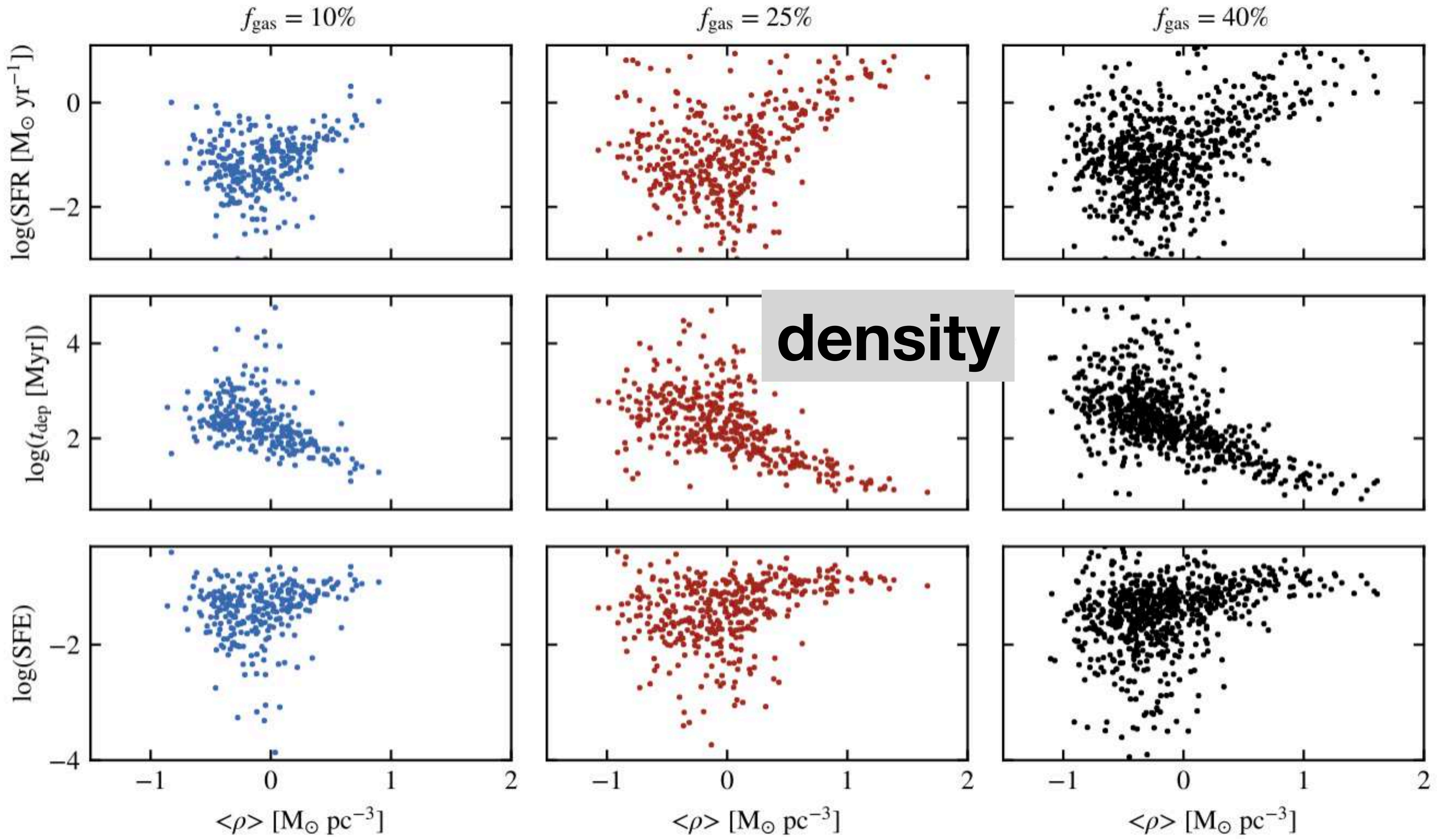


Dense ($1/r^3$) vs. Compact ($1/r$)

2 lifetime regimes:

Dekel et al. (2023)





short	long
normal clumps found at all f_{gas}	outlier clumps only at high f_{gas}

Florent Renaud | Strasbourg Observatory / CNRS
florent.renaud@astro.unistra.fr

Conclusions

Observational ***hints of evolving regimes*** for star cluster formation

Different regime of instability in gas-rich disks ($f_{\rm gas} \gtrsim 20\,\%$) → clumpy morphology

Clumps act as a ***barrier against thin disk*** formation (similarly to mergers)

Universal scaling relations for clumps at all gas fractions, but ...

Higher scatter in gas-rich disks → ***universality + more outliers***

Clumps with an excess mass form ***more*** stars, ***faster***, and ***more efficiently***

More disruptive environments in gas-rich galaxies, but ...

Extreme clumps are ***more compact*** than average → more resistant to disruption

Universal population of clouds + **extreme outliers**
at all gas fraction — only in gas-rich disks

You can watch my simulation movies here: **youtube.com/@florent.renaud**

You can download them here:

https://people.astro.unistra.fr/f.renaud/movies.php

Feel free to use them, as long as you cite the source 😉