# 宇宙論的銀河形成シミュレーションで探る遠方銀河の形態獲得プロセスと形成期銀河円盤の力学不安定性解析

井上 茂樹

カブリ数物連携宇宙研究機構 / 東京大学

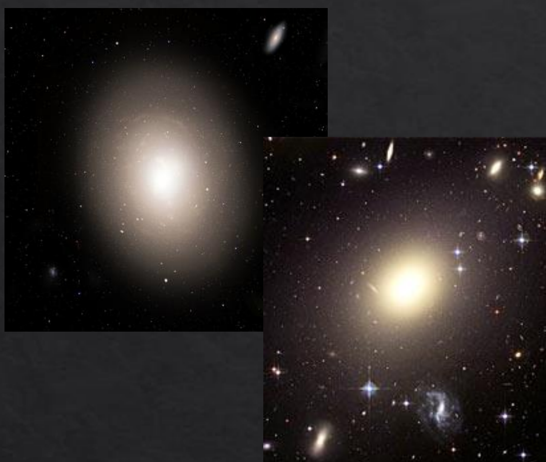
# CONTENTS

- Our previous studies (done in the Hebrew university of Jerusalem)
  - Formation of massive compact galaxies
  - Dynamical instability of high-z disc galaxies

# Compaction and quenching of high-z galaxies

Zolotov, Inoue et al. MNRAS, 450, 2327 (2015)

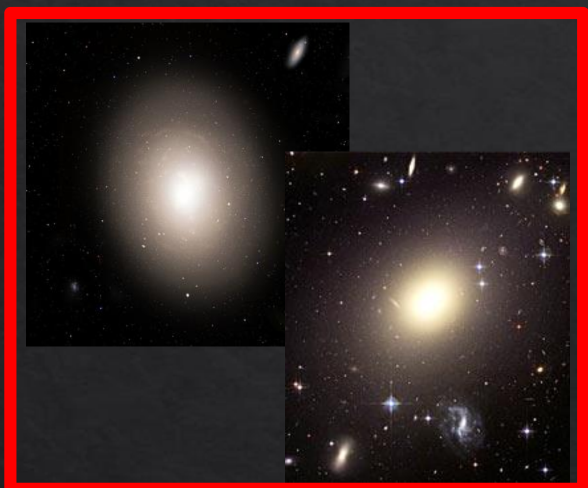
# Morphological acquisition of ellipticals



What is the beginning of morphological acquisition?

at z>2-3

# Morphological acquisition of ellipticals

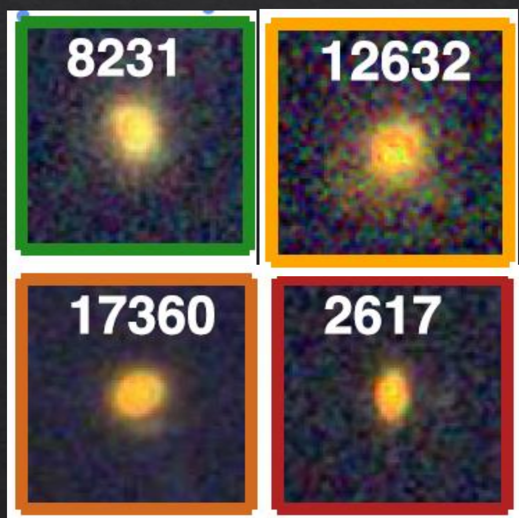


What is the beginning of morphological acquisition?

at z>2-3

# Morphological acquisition of ellipticals

We look into ellipticals in high-redshift.




Barro, Inoue et al. (2016)

$\sim 10^9$ yr

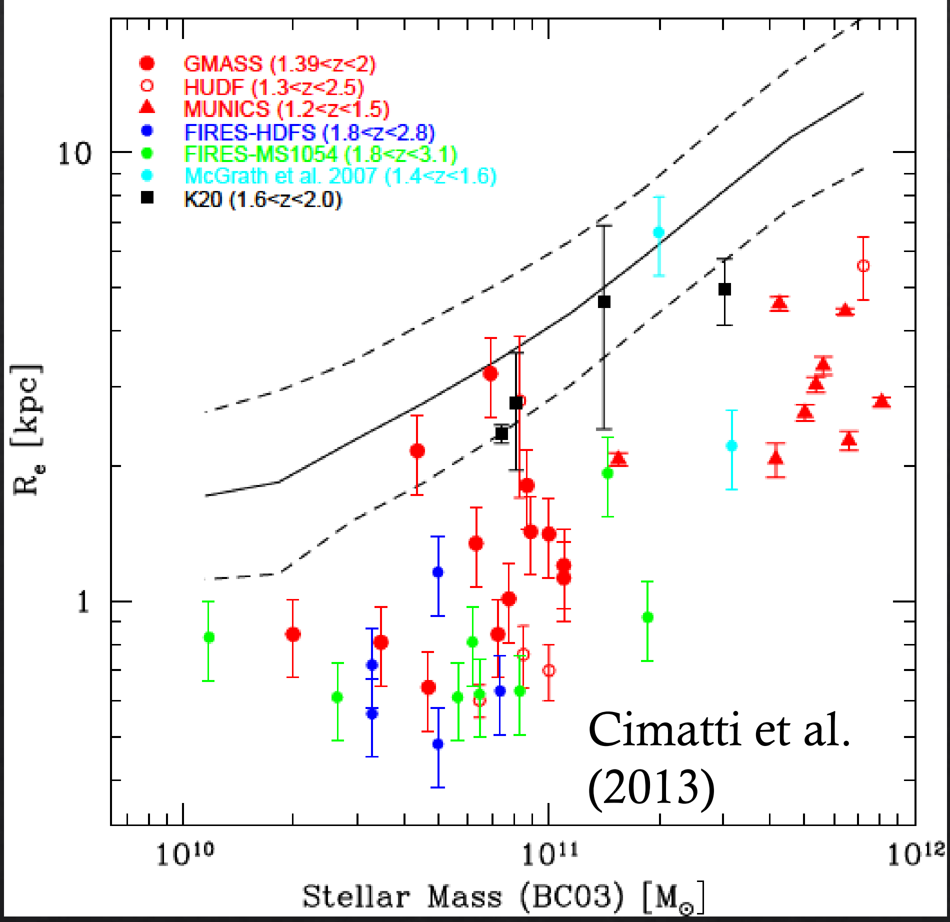
?

What is the beginning of morphological acquisition?

at z>2-3

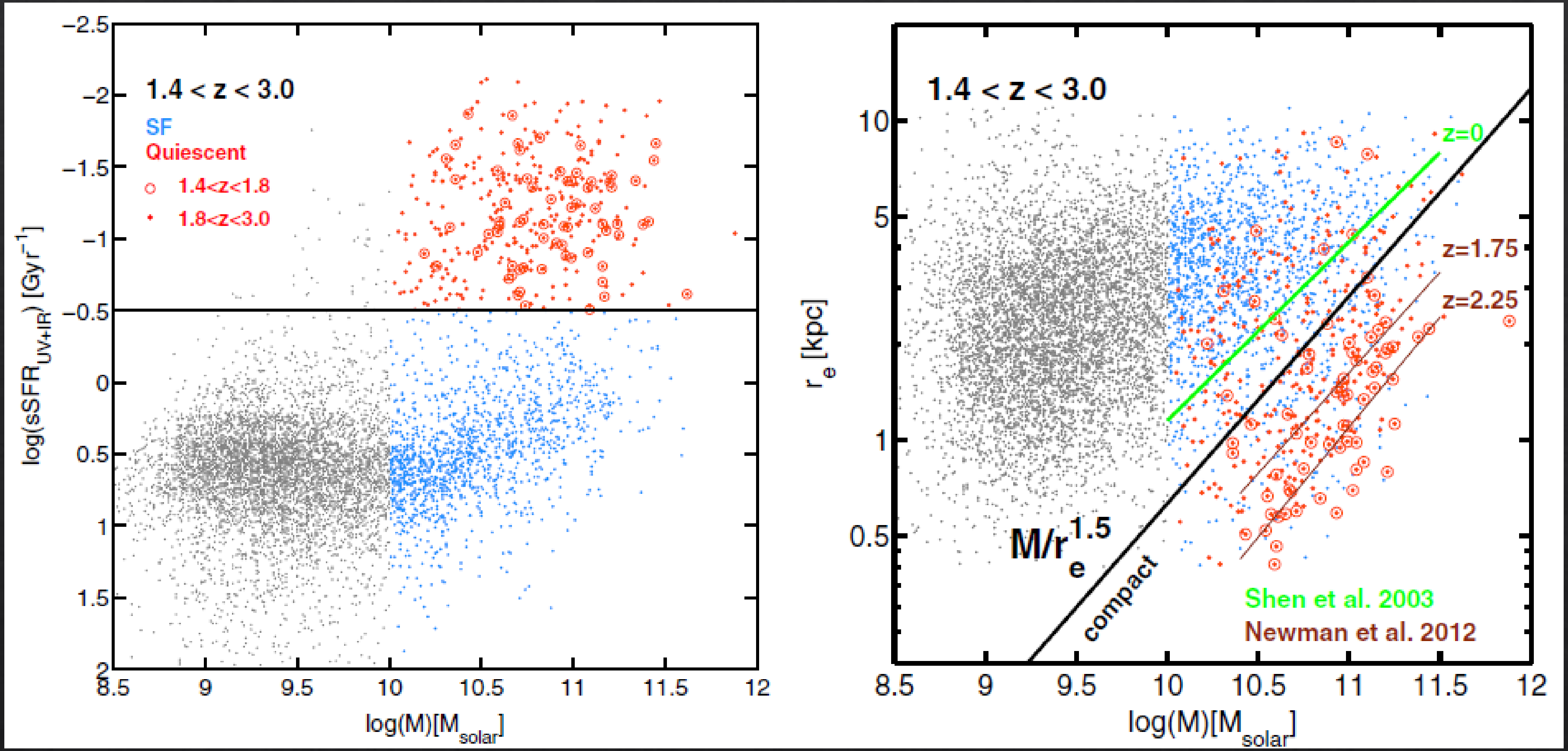
# Size evolution of elliptical galaxies

- High-z ellipticals are more compact than low-z ones.
  - What can enlarge them?
    - Dry minor mergers
  - How do they form?



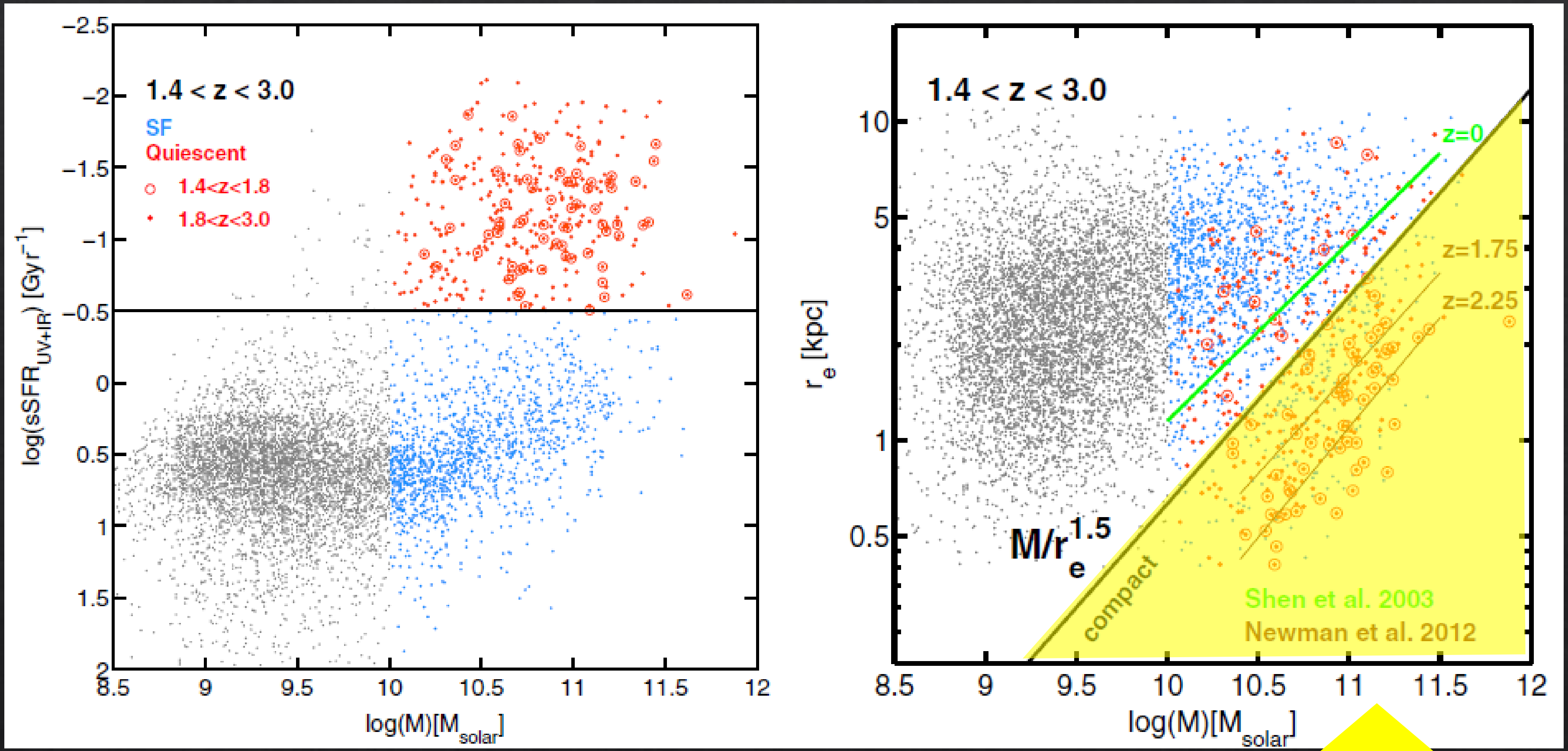
# Massive compact galaxies

Barro et al. (2013)



# Massive compact galaxies

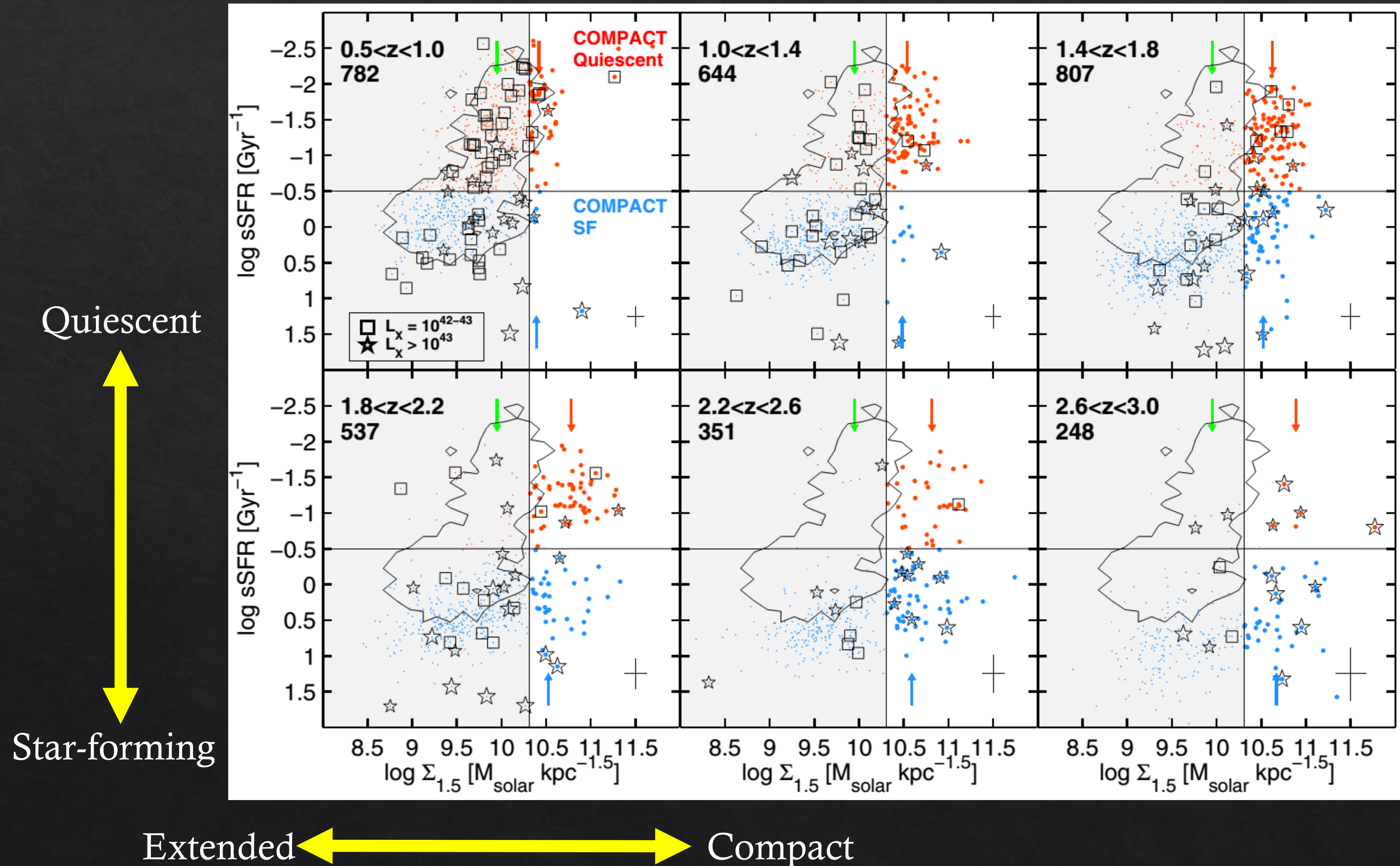
Barro et al. (2013)




- **Massive compact galaxies**
  - **Could be "seeds" of elliptical galaxies.**

# Evolution track of high-z massive galaxies

Barro et al. (2013)

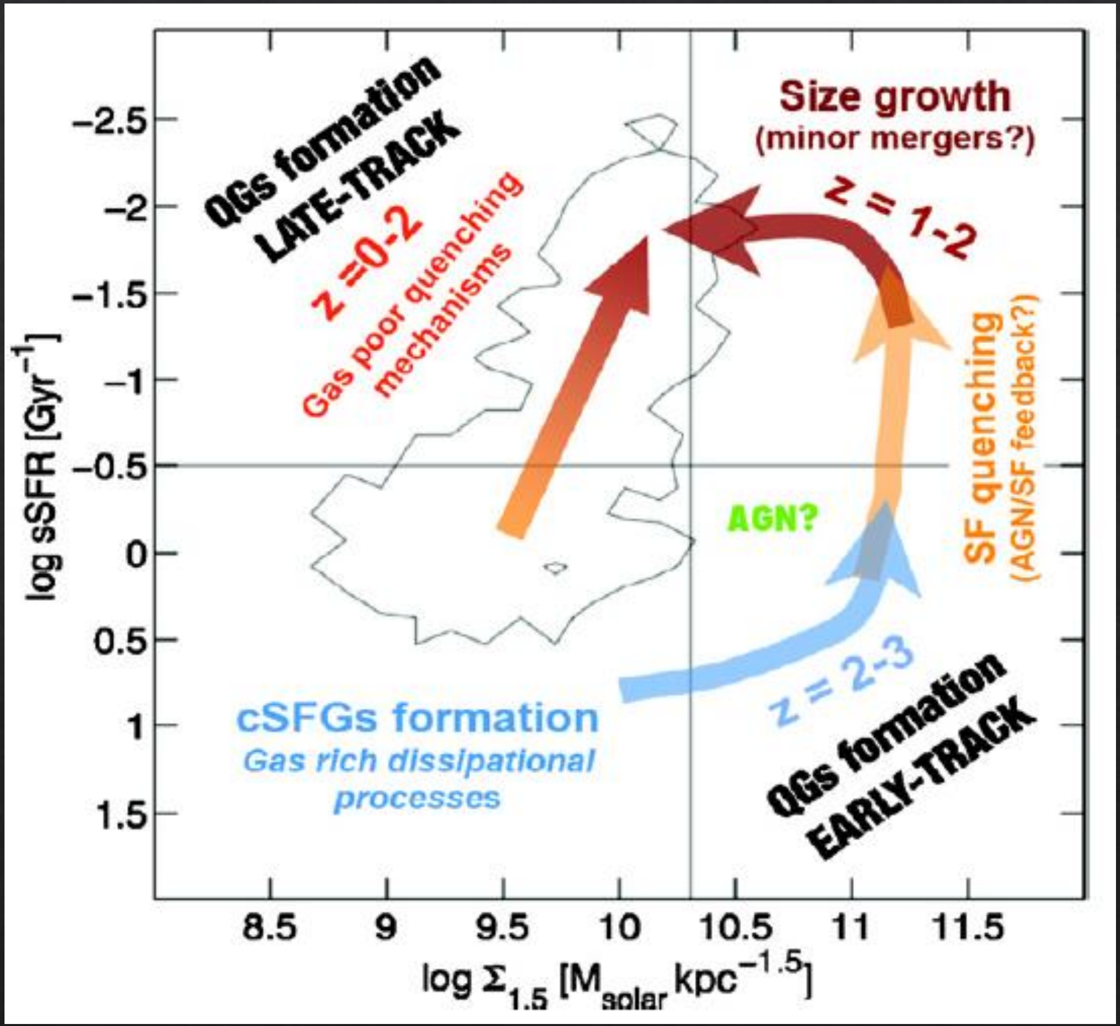


# Evolution track of high-z massive galaxies

Barro et al. (2013)

Quiescent

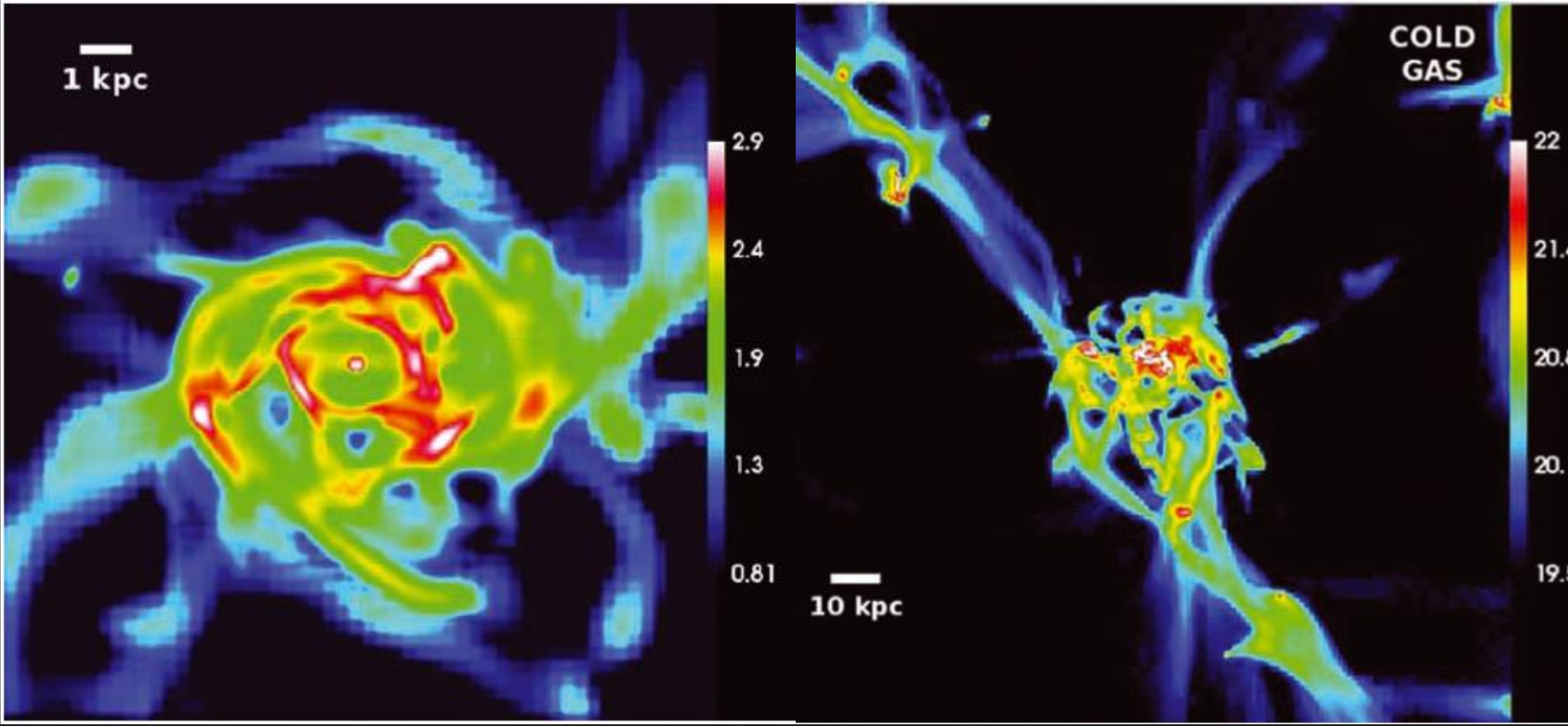
Star-forming




Extended

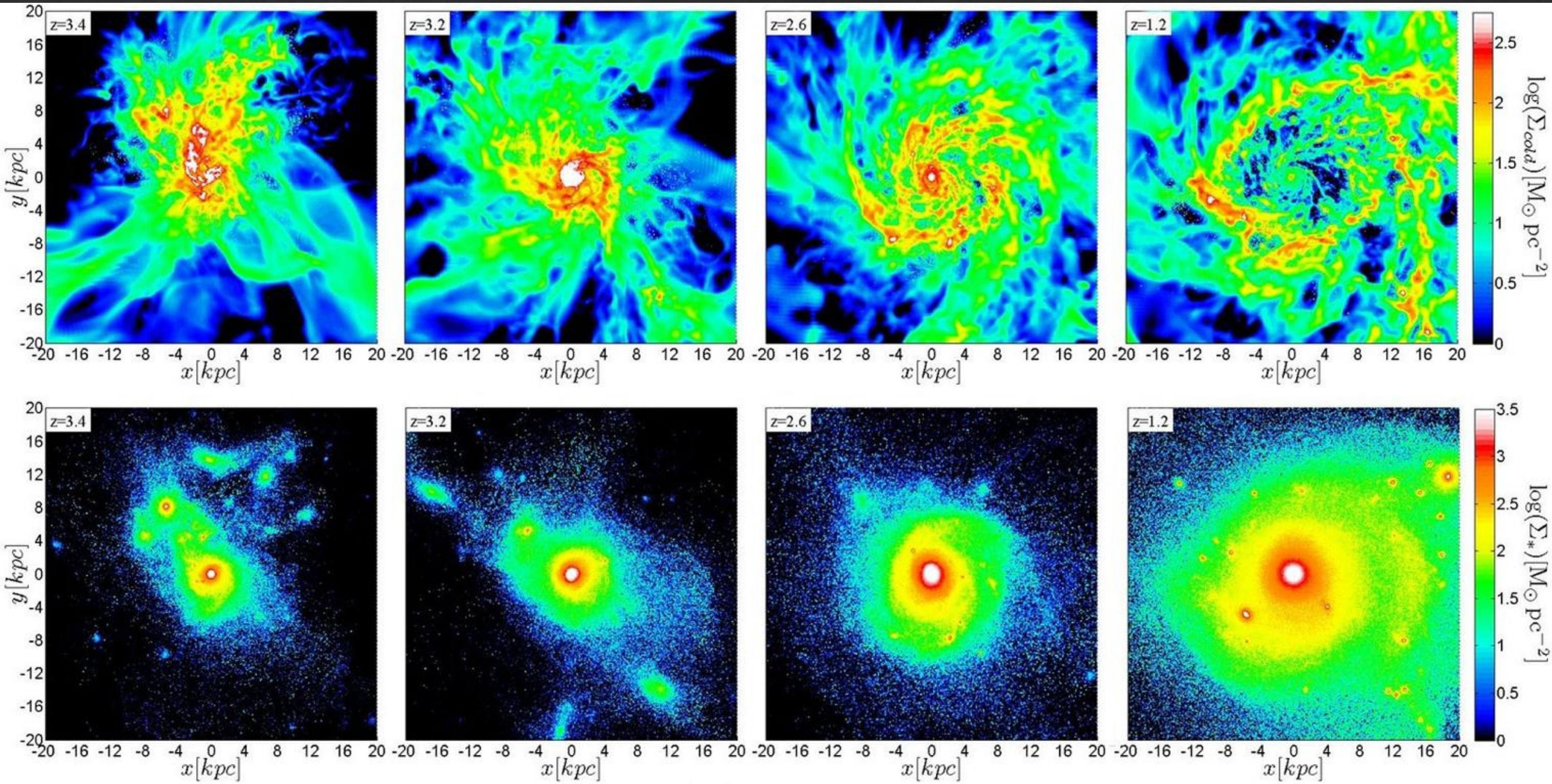
Compact

# Cosmological sims.



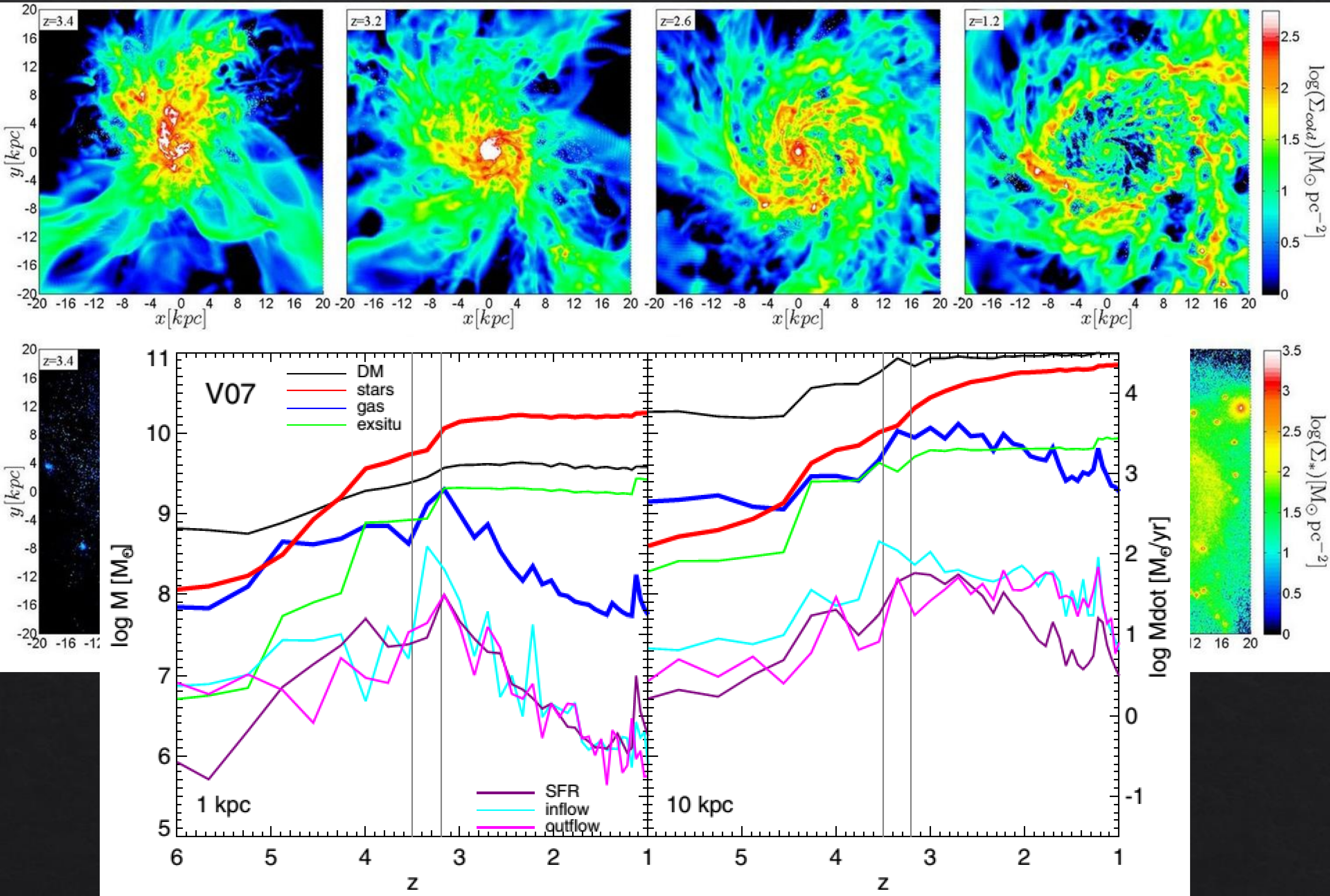

- Cosmological simulations
  - Ceverino et al. (2010, 2013) using ART code
    - 10pc-order resolution with radiation pressure.

# V07



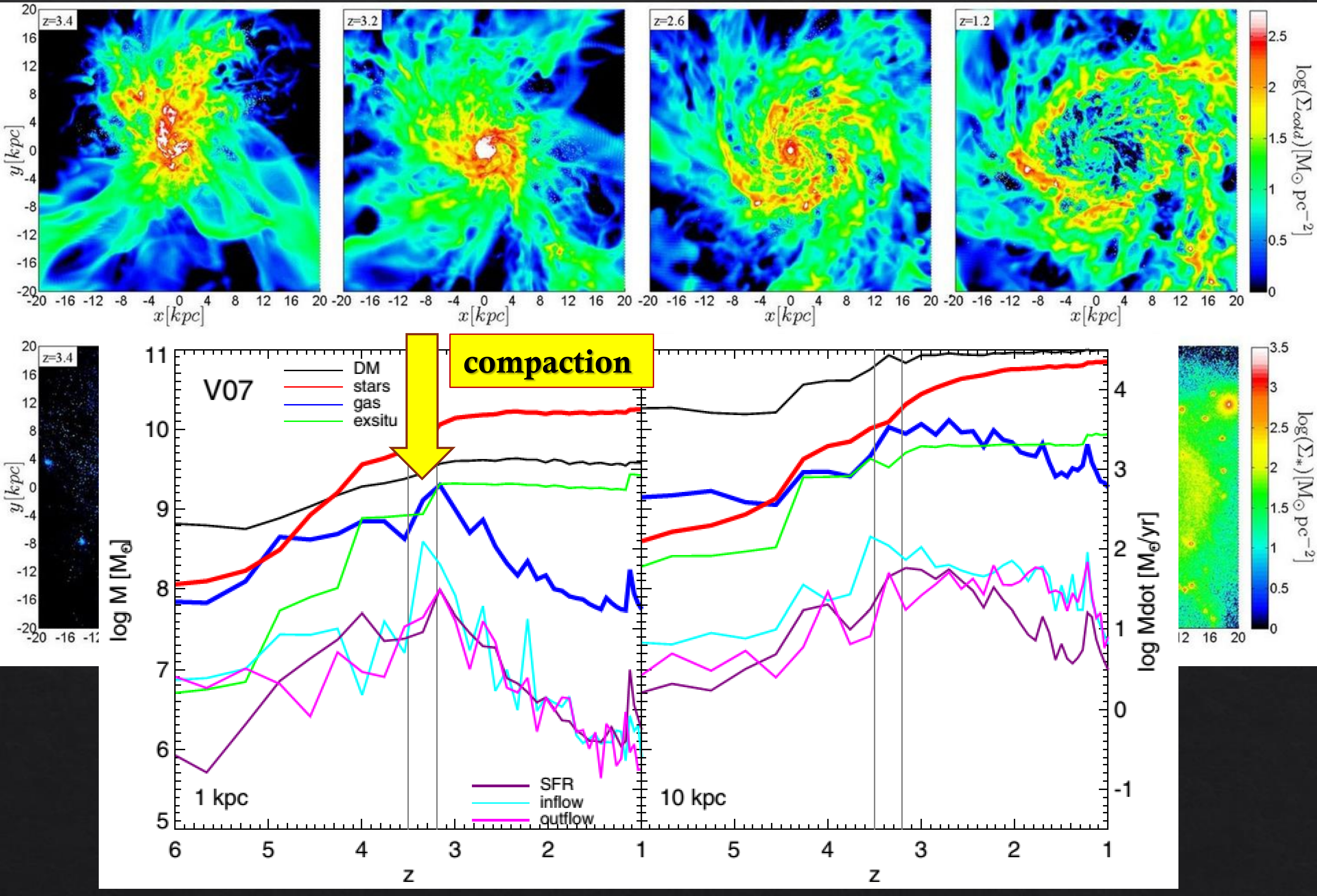
z=3.4
z=3.2
z=2.6
z=1.2
$\log(\Sigma_{cold})[M_\odot\, pc^{-2}]$
$\log(\Sigma_*)[M_\odot\, pc^{-2}]$
$x[kpc]$
$y[kpc]$

# V07



z=3.4
z=3.2
z=2.6
z=1.2
x[kpc]
y[kpc]
log(Σ_cold)[M_⊙ pc^-2]
log(Σ_*)[M_⊙ pc^-2]
V07
DM
stars
gas
exsitu
SFR
inflow
outflow
1 kpc
10 kpc
log M [M_⊙]
log Mdot [M_⊙/yr]
z

# V07



z=3.4
z=3.2
z=2.6
z=1.2
x[kpc]
y[kpc]
log(Σcold)[M⊙ pc−2]
log(Σ*)[M⊙ pc−2]
compaction
V07
DM
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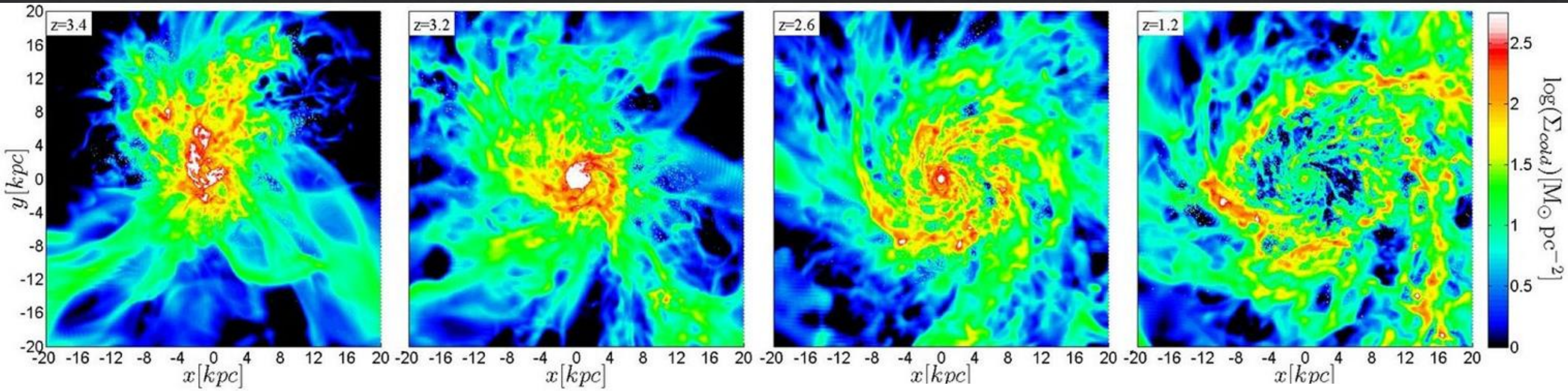
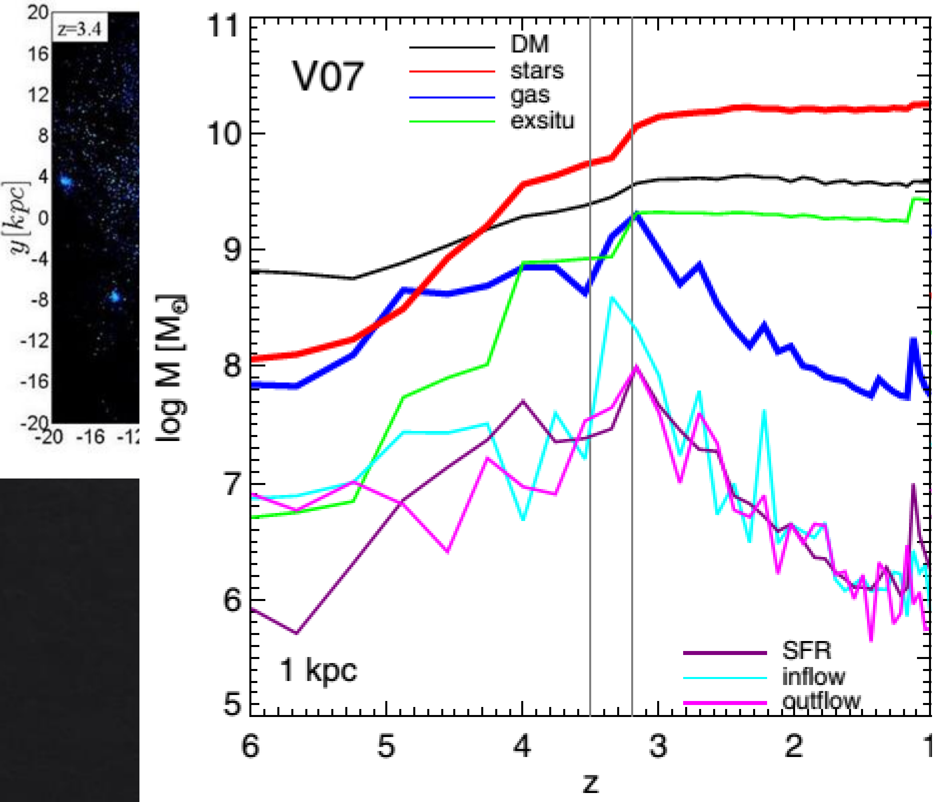
SFR
inflow
outflow
1 kpc
10 kpc
log M [M⊙]
log Mdot [M⊙/yr]
z

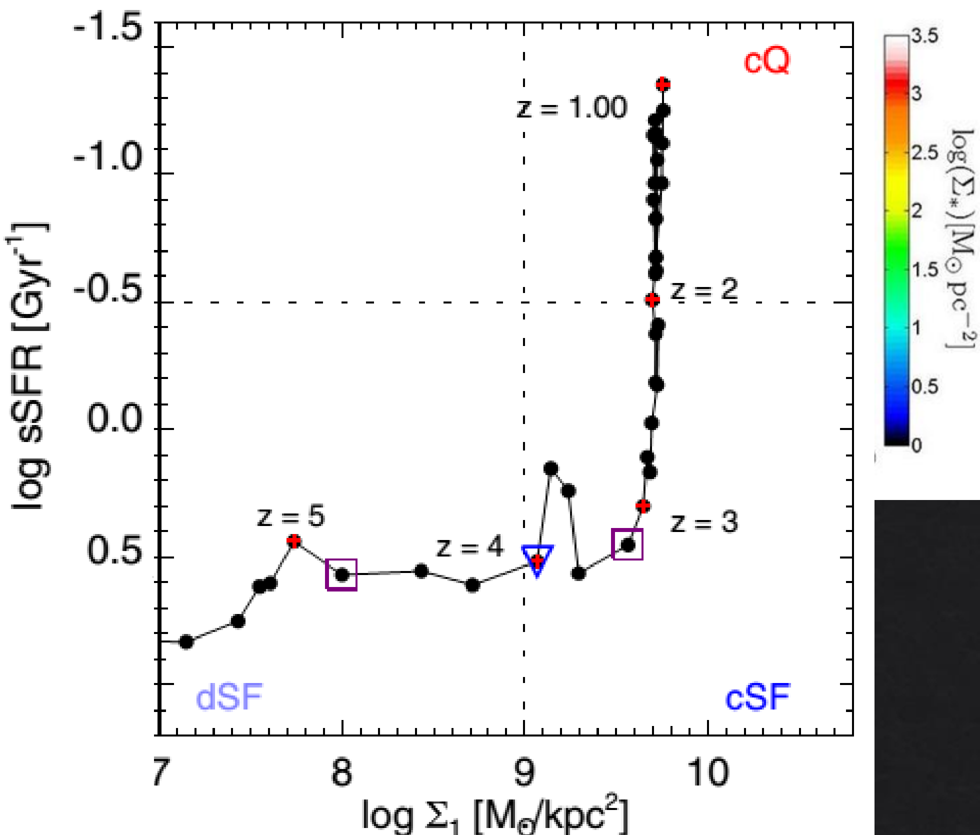
# V07



z=3.4
z=3.2
z=2.6
z=1.2
y[kpc]
x[kpc]
$\log(\Sigma_{cold})\,[M_\odot\,pc^{-2}]$

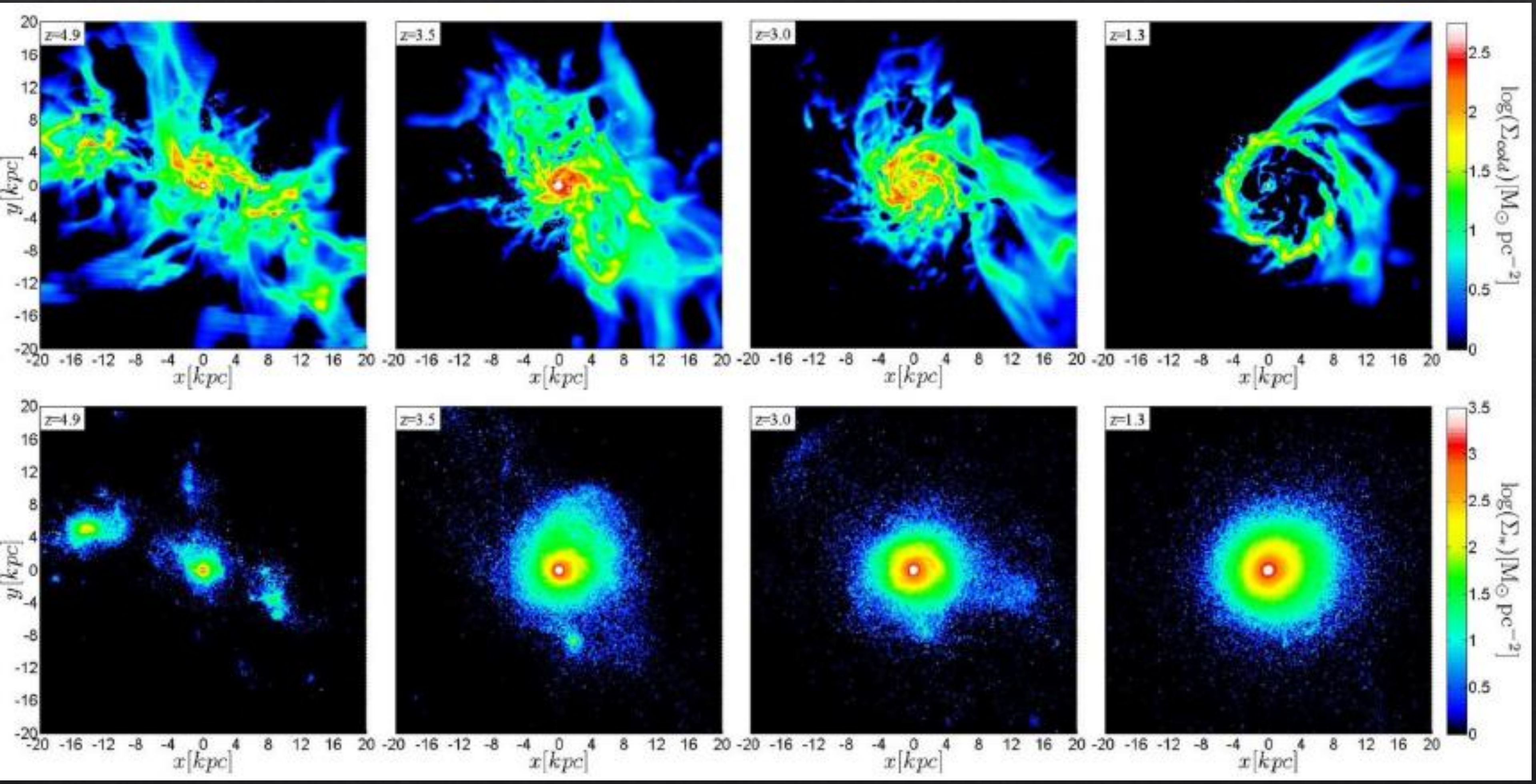



z=3.4
y[kpc]
V07
DM
stars
gas
exsitu
SFR
inflow
outflow
1 kpc
log M [$M_\odot$]
z

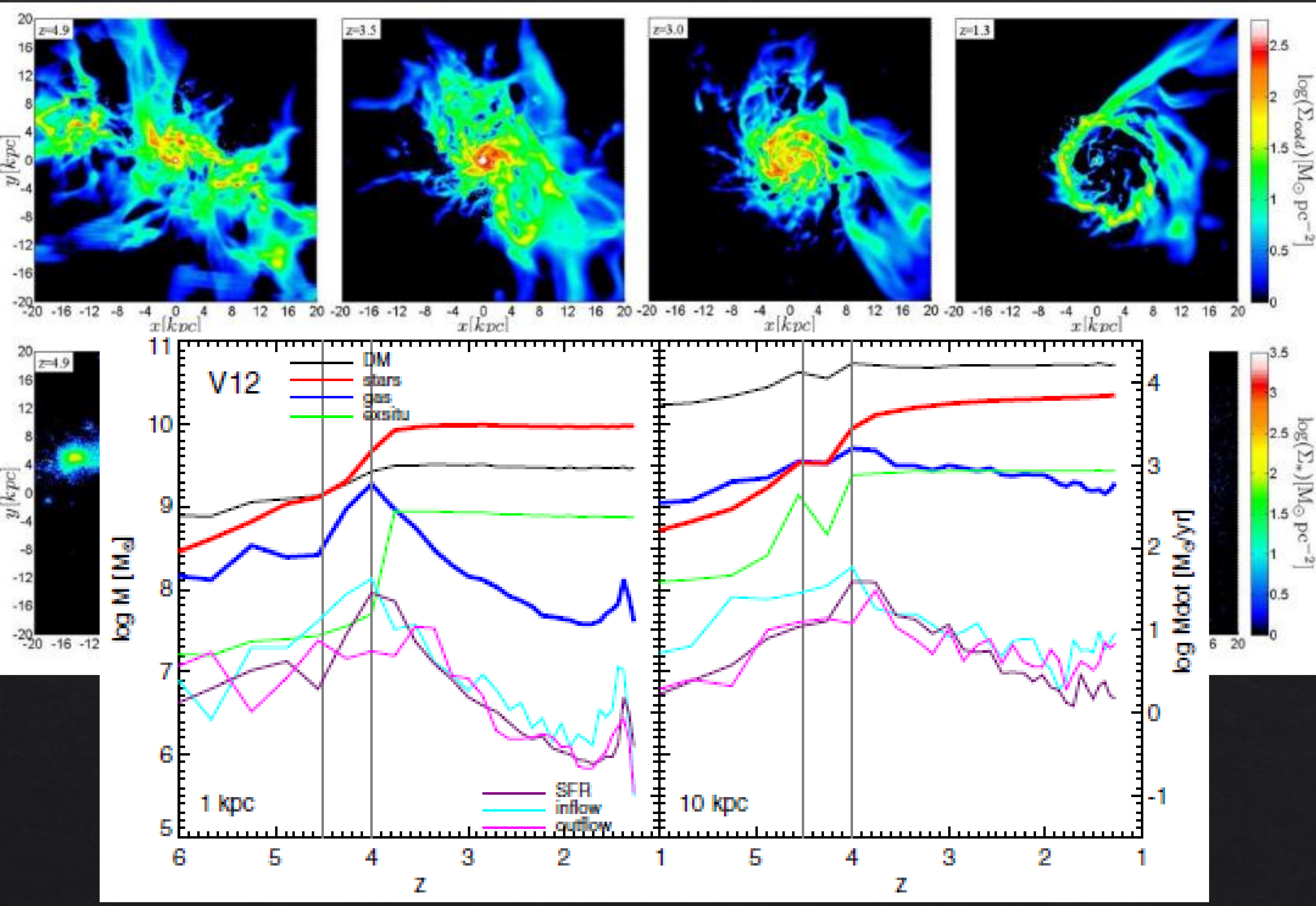
cQ
z = 1.00
z = 2
z = 3
z = 4
z = 5
dSF
cSF
log sSFR [$Gyr^{-1}$]
log $\Sigma_1$ [$M_\odot/kpc^2$]
$\log(\Sigma_*)\,[M_\odot\,pc^{-2}]$

# V12



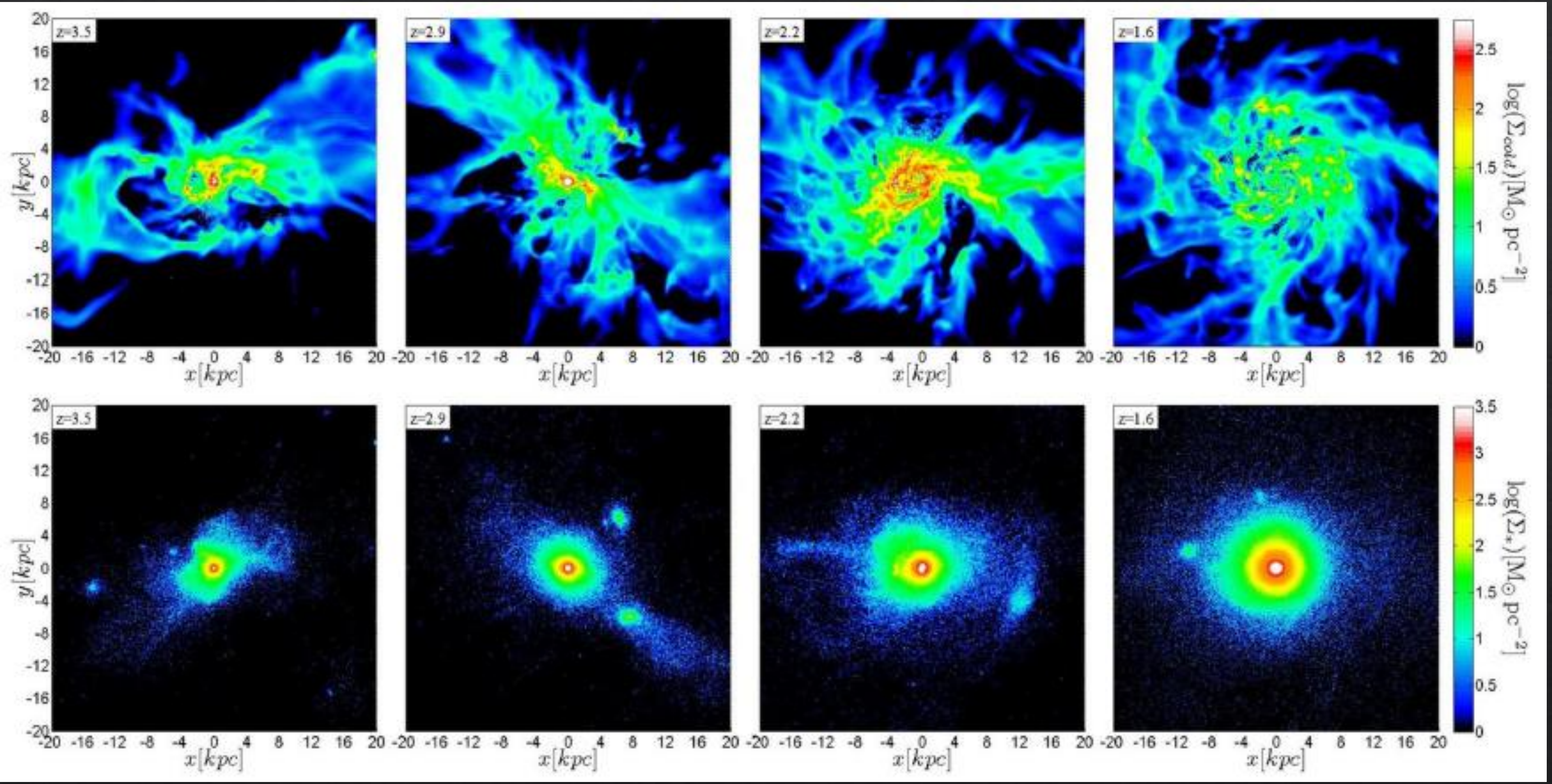
z=4.9
z=3.5
z=3.0
z=1.3
$x[kpc]$
$y[kpc]$
$\log(\Sigma_{cold})[\mathrm{M_\odot\,pc^{-2}}]$
$\log(\Sigma_*)[\mathrm{M_\odot\,pc^{-2}}]$

# V12



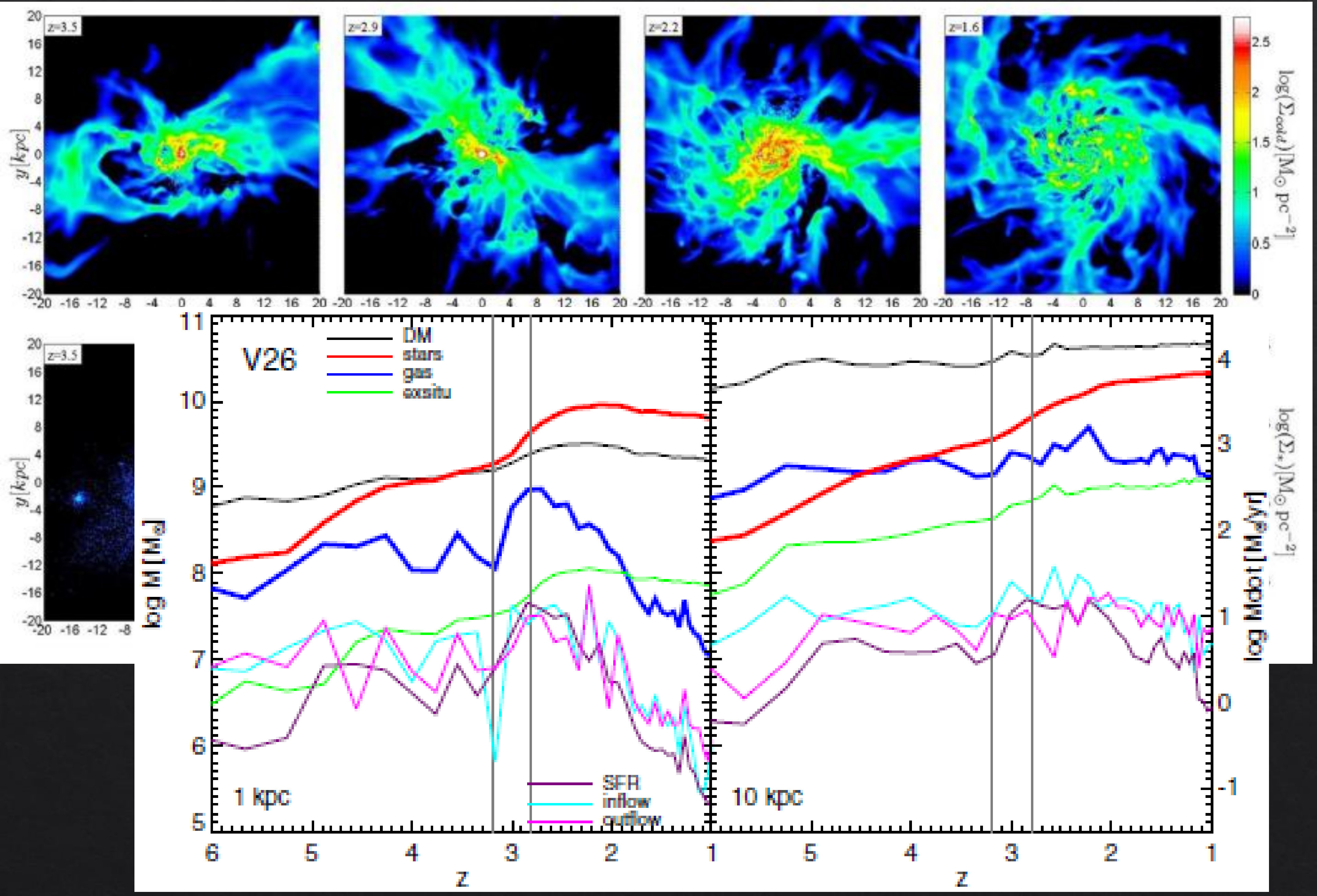
z=4.9
z=3.5
z=3.0
z=1.3
x[kpc]
y[kpc]
log(Σ_cold) [M⊙ pc⁻²]
log(Σ*) [M⊙ pc⁻²]
V12
DM
stars
gas
exsitu
SFR
inflow
outflow
1 kpc
10 kpc
log M [M⊙]
log Mdot [M⊙/yr]
z

# V26



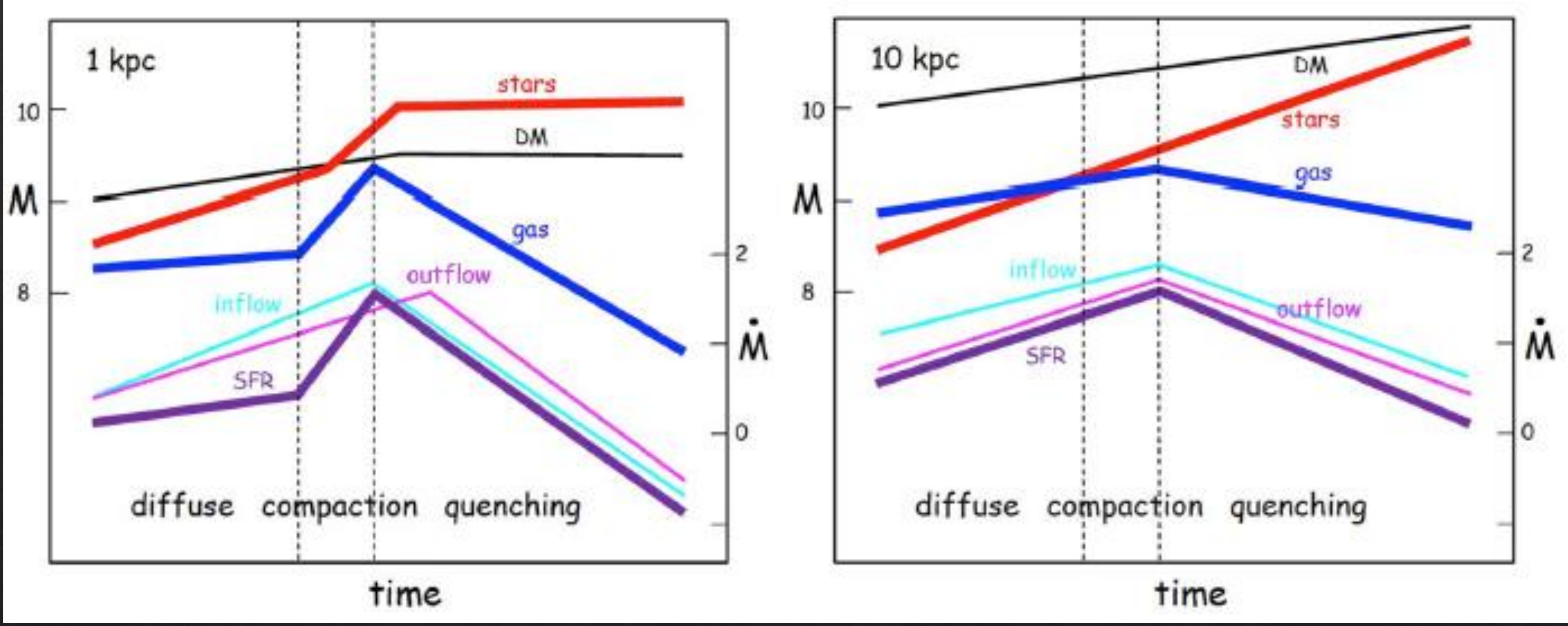
z=3.5
z=2.9
z=2.2
z=1.6
$y[kpc]$
$x[kpc]$
$\log(\Sigma_{cold})[M_\odot\,pc^{-2}]$
$\log(\Sigma_{*})[M_\odot\,pc^{-2}]$

# V26



z=3.5
z=2.9
z=2.2
z=1.6
y[kpc]
log(Σ_cold)[M⊙ pc^-2]
V26
DM
stars
gas
exsitu
log M [M⊙]
1 kpc
10 kpc
SFR
inflow
outflow
log Mdot [M⊙/yr]
log(Σ*)[M⊙ pc^-2]
z

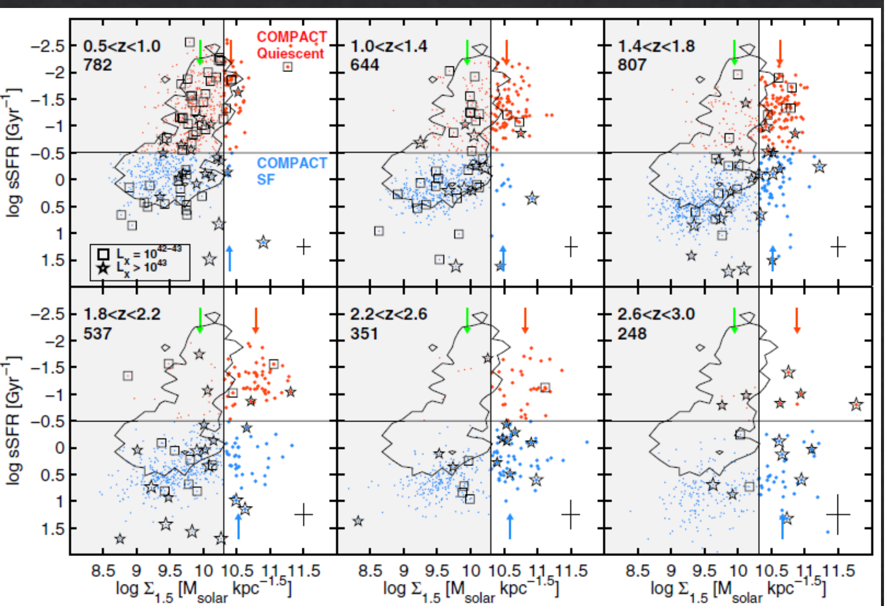
# Outline of the evolution

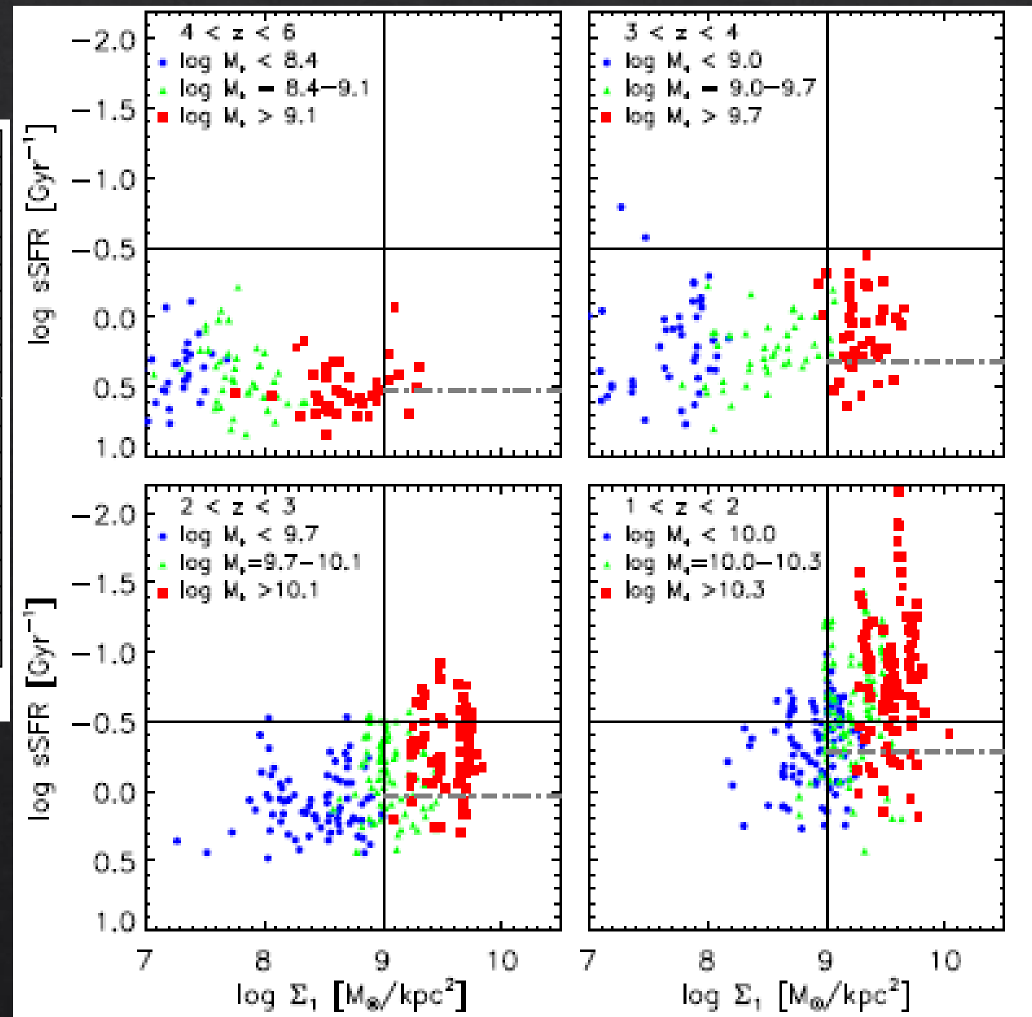



◈ MCGs go through **‘compaction’,** and then **‘quenching’.**

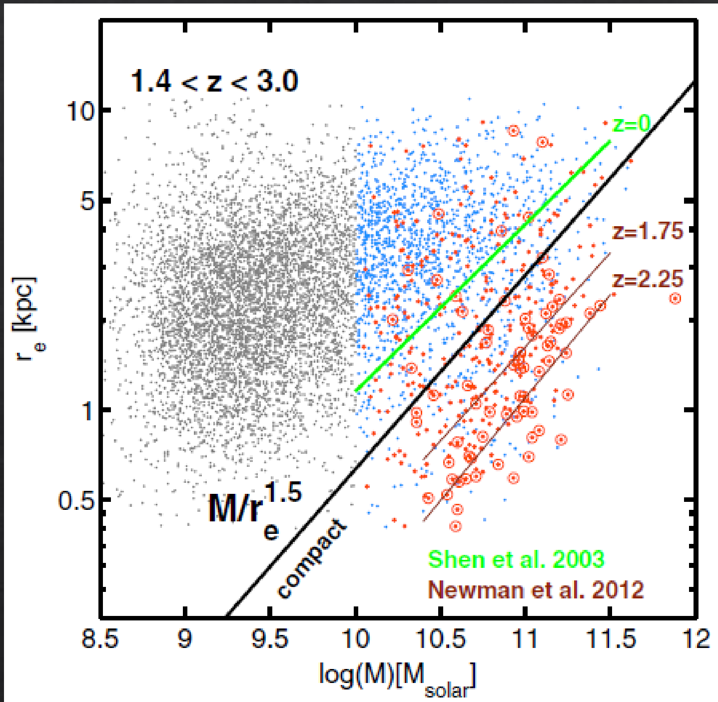
# The evolution track in the sims.

Barro et al. (2013)

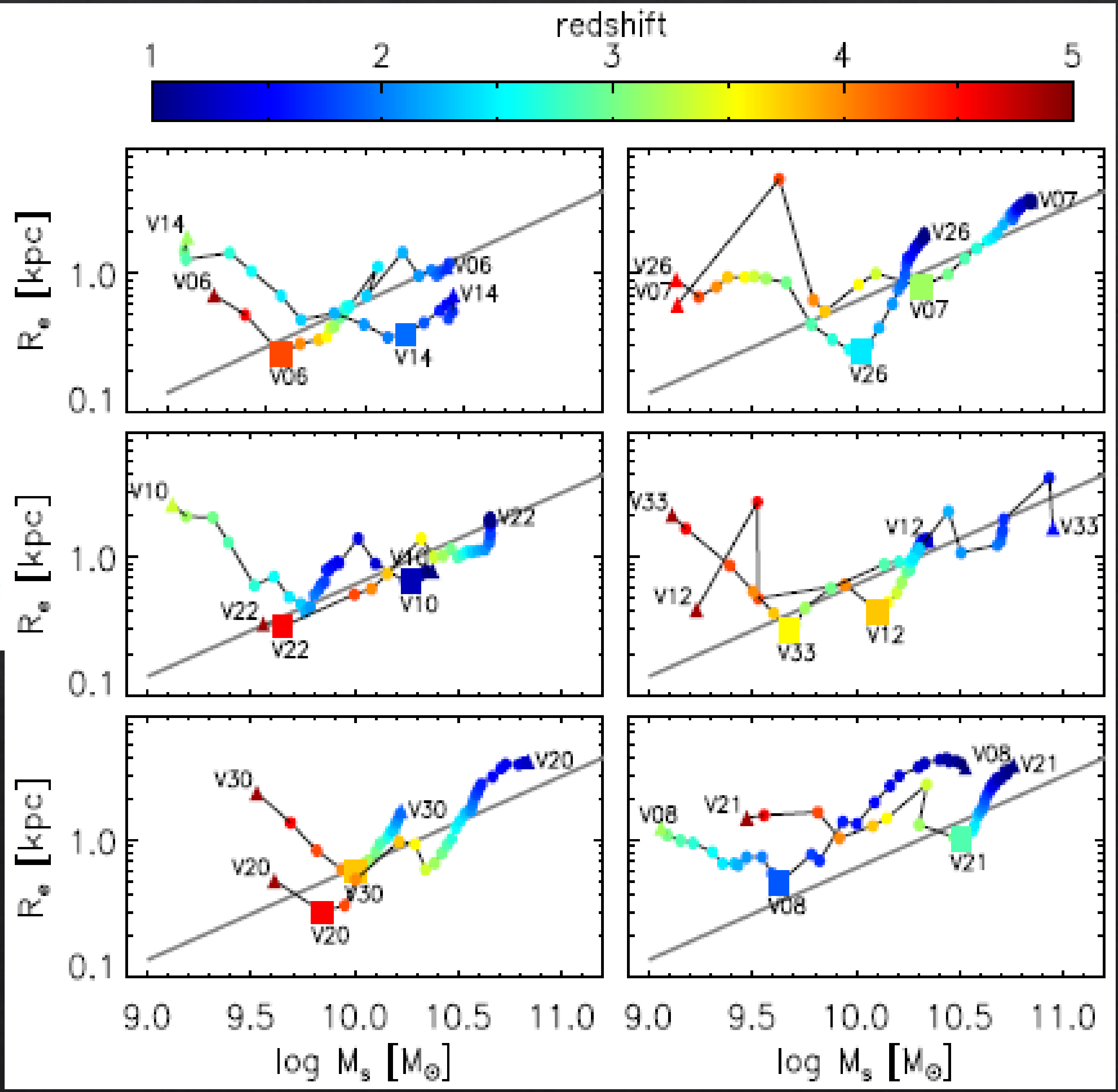


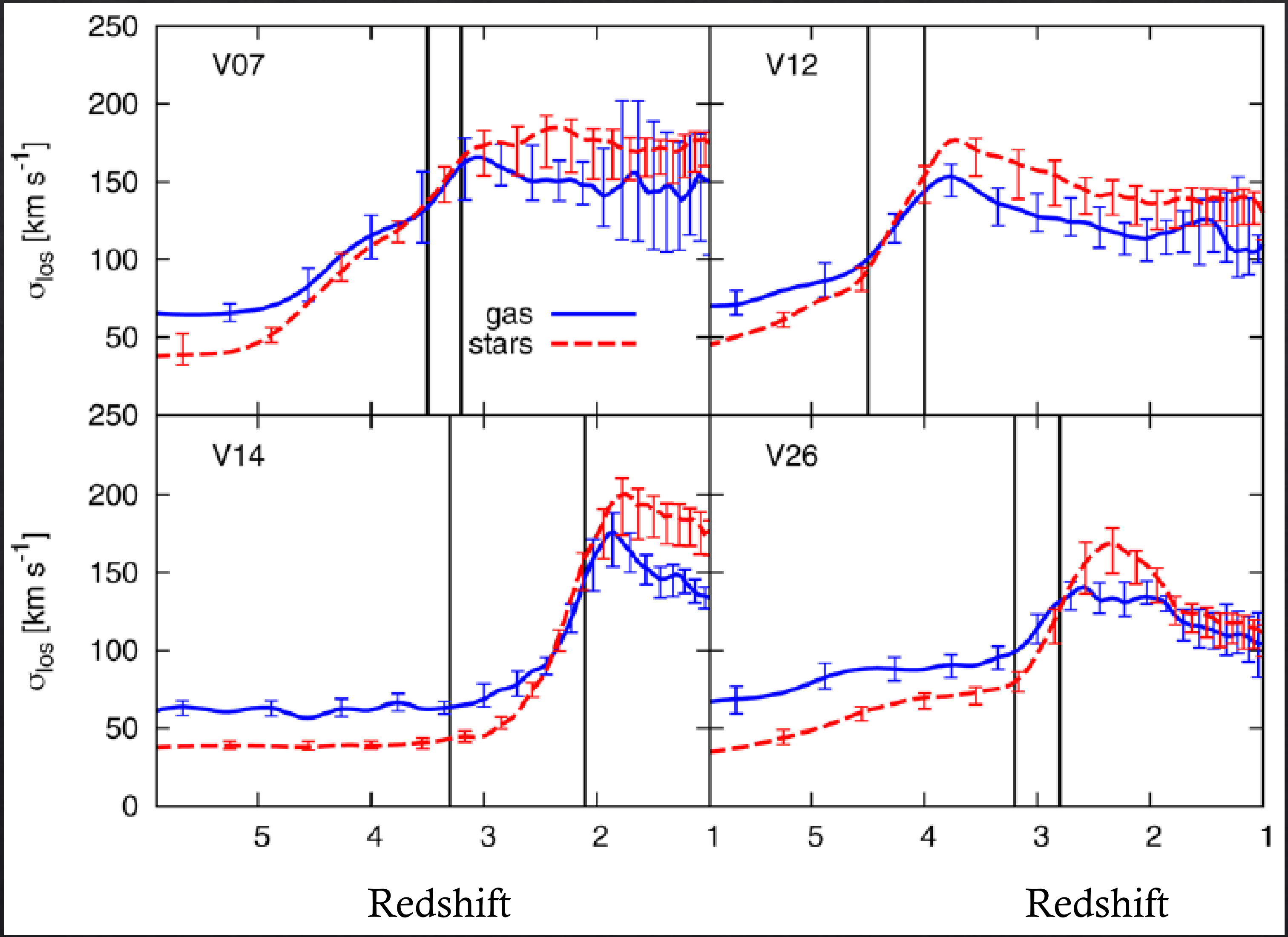
# Massiveness and compactness



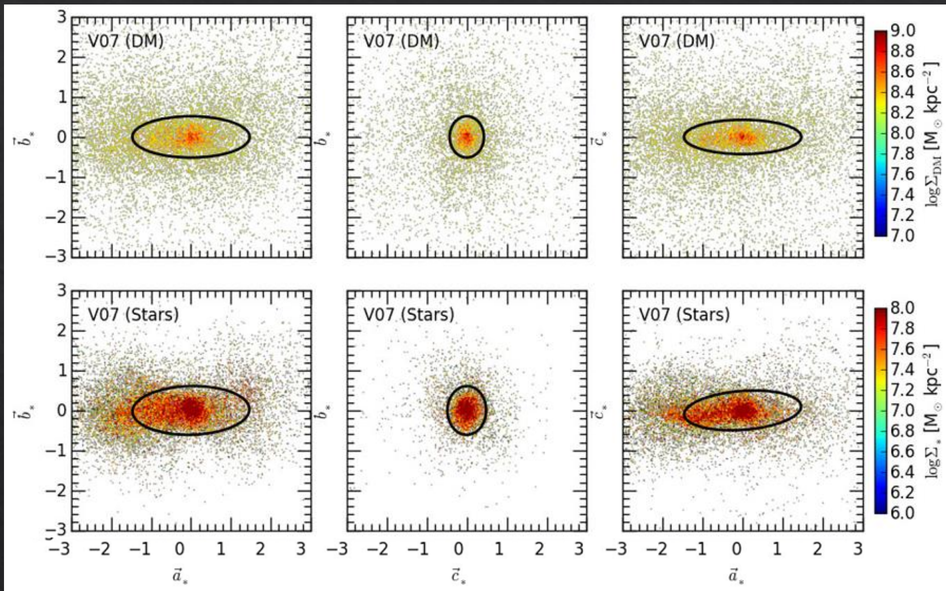

Barro et al. (2013)

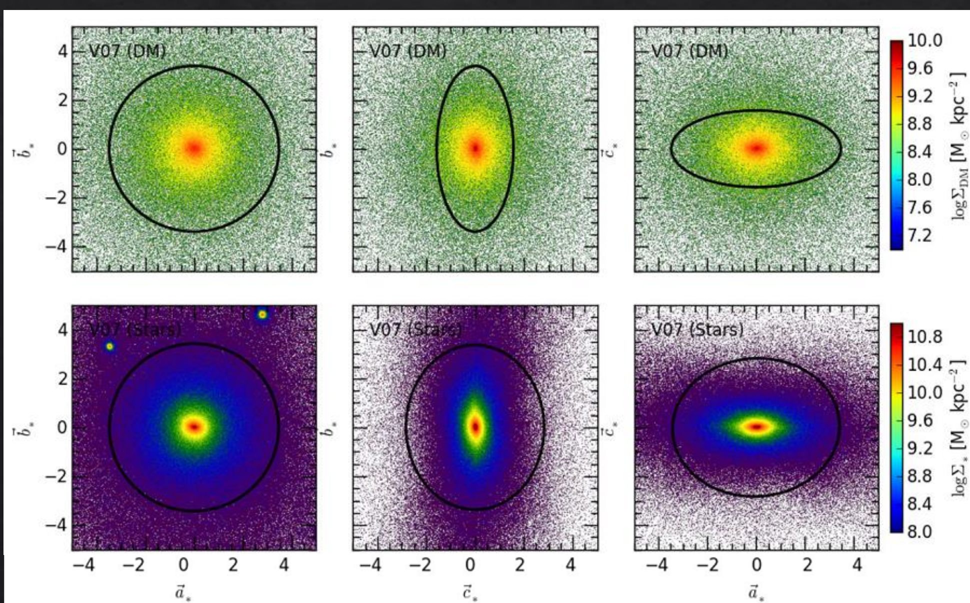


# Kinematics in compaction



# Shape transition between pre- and post-compaction




Tomassetti et al. (2016)

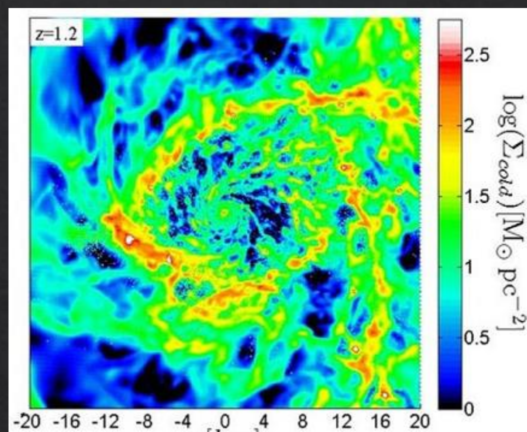
- Pre-compaction
  - DM dominates over stars.
  - DM is (intrinsically) prolate.
  - Stars follow the DM (prolate)

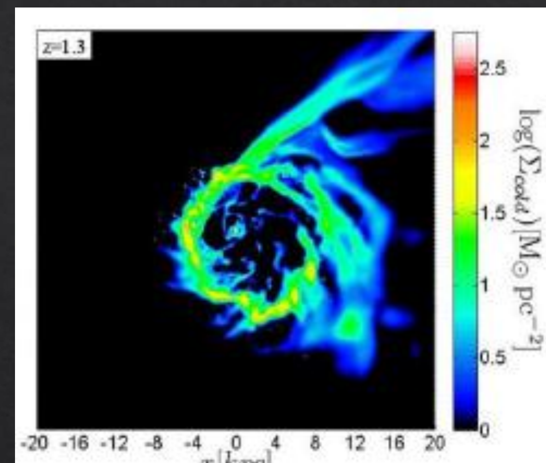
- Post-compaction
  - Stars dominate over DM.
  - Stars are generally oblate.
  - DM follows the stars (oblate)

# Remnant (evidence!) of the ‘compaction’ phenomenon

## Gas-ring structures around face-on MCGs

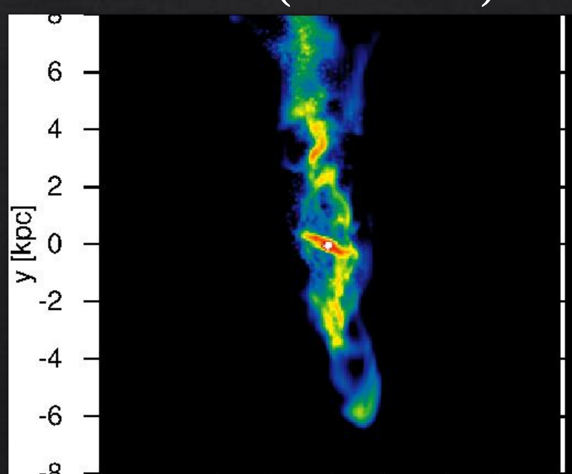
Remnant (evidence!) of the ‘compaction’ phenomenon

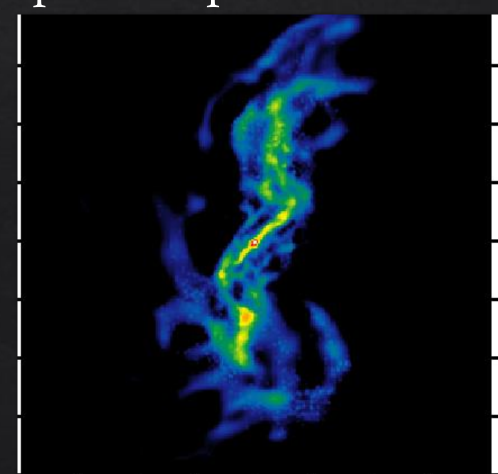



## Double disc structures around edge-on MCGs

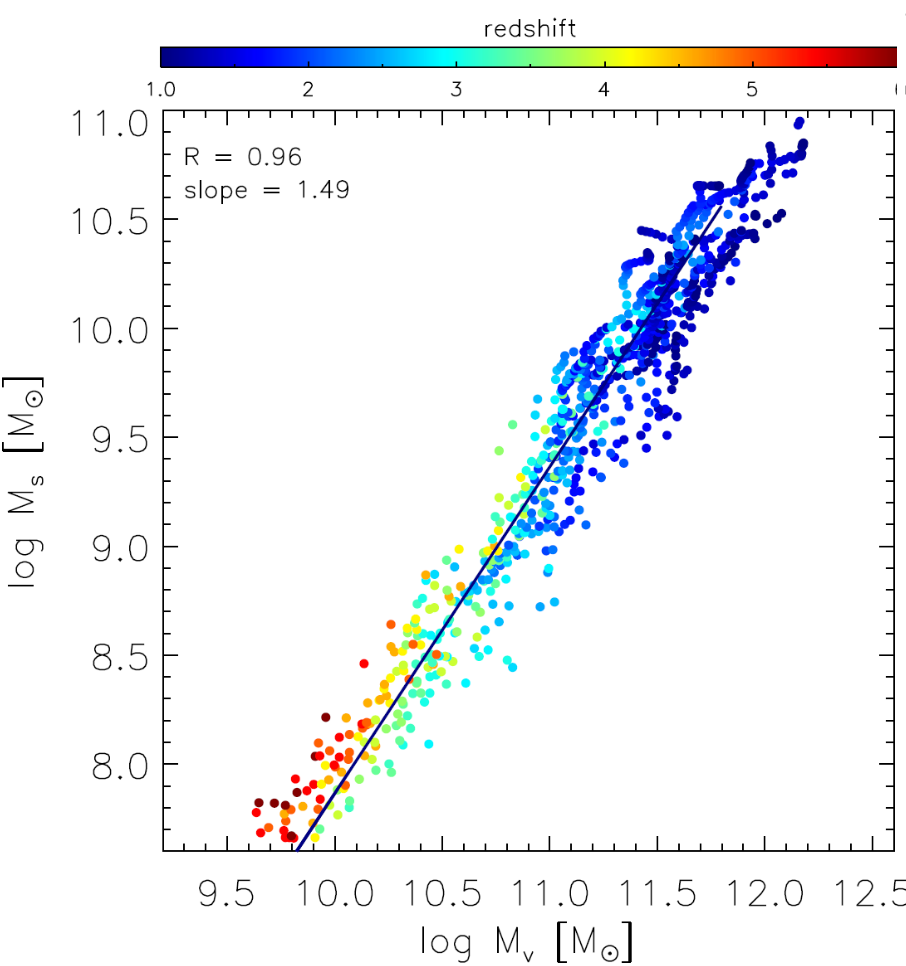
Remnant (evidence!) of the ‘compaction’ phenomenon

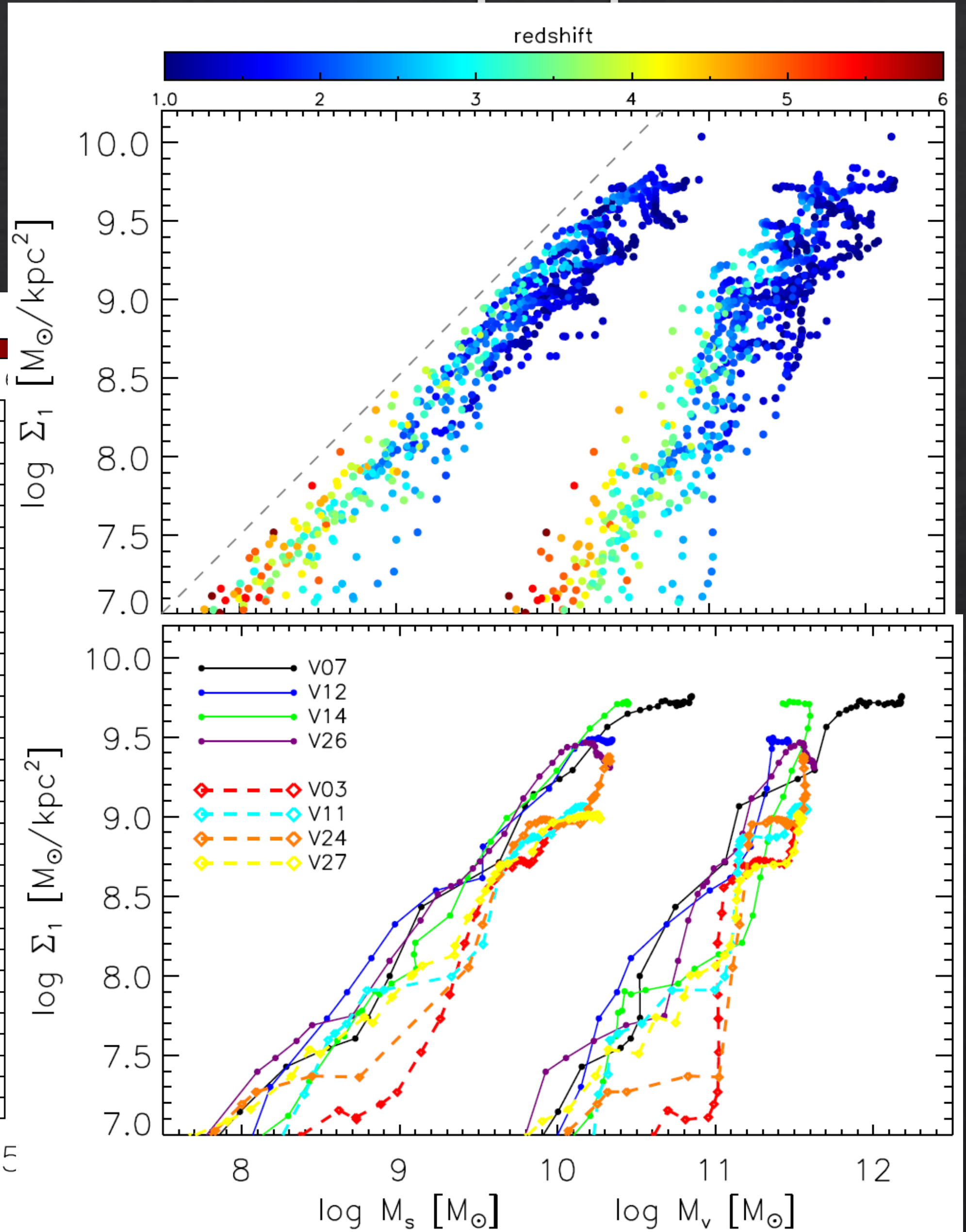


# Corelation & co-evolution of properties

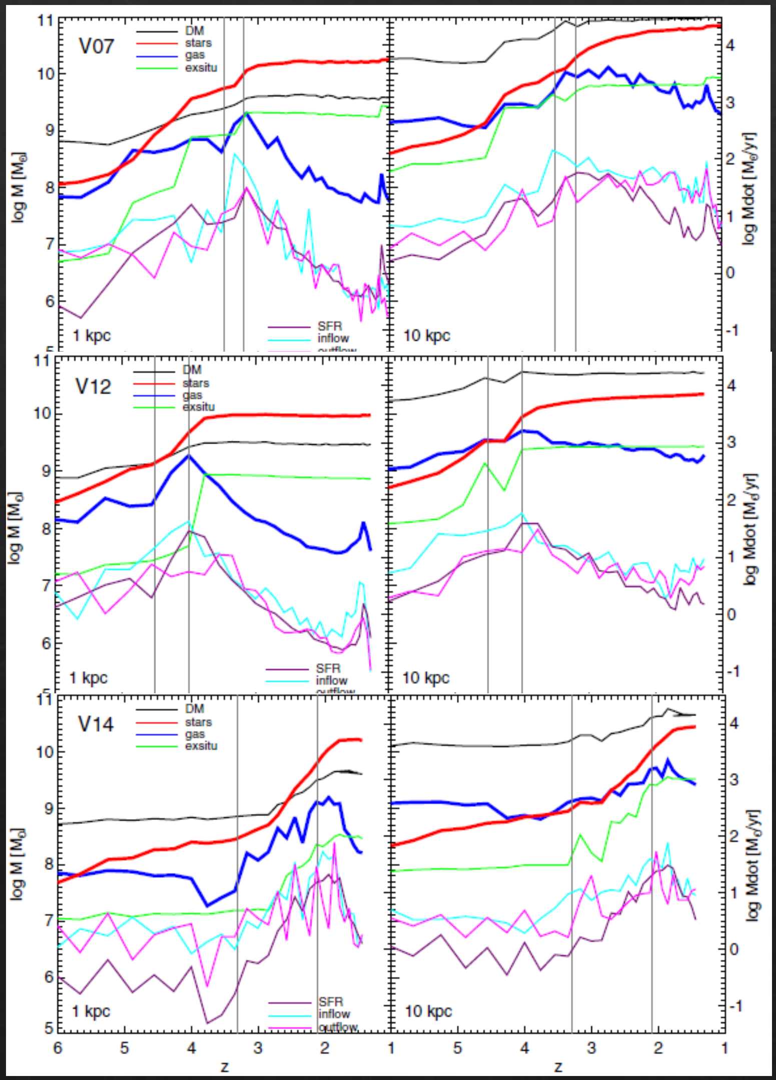
- $\Sigma_{vir} \propto {M_s}^{1.5}$
- $\Sigma_1 \propto M_s$
  - Why??



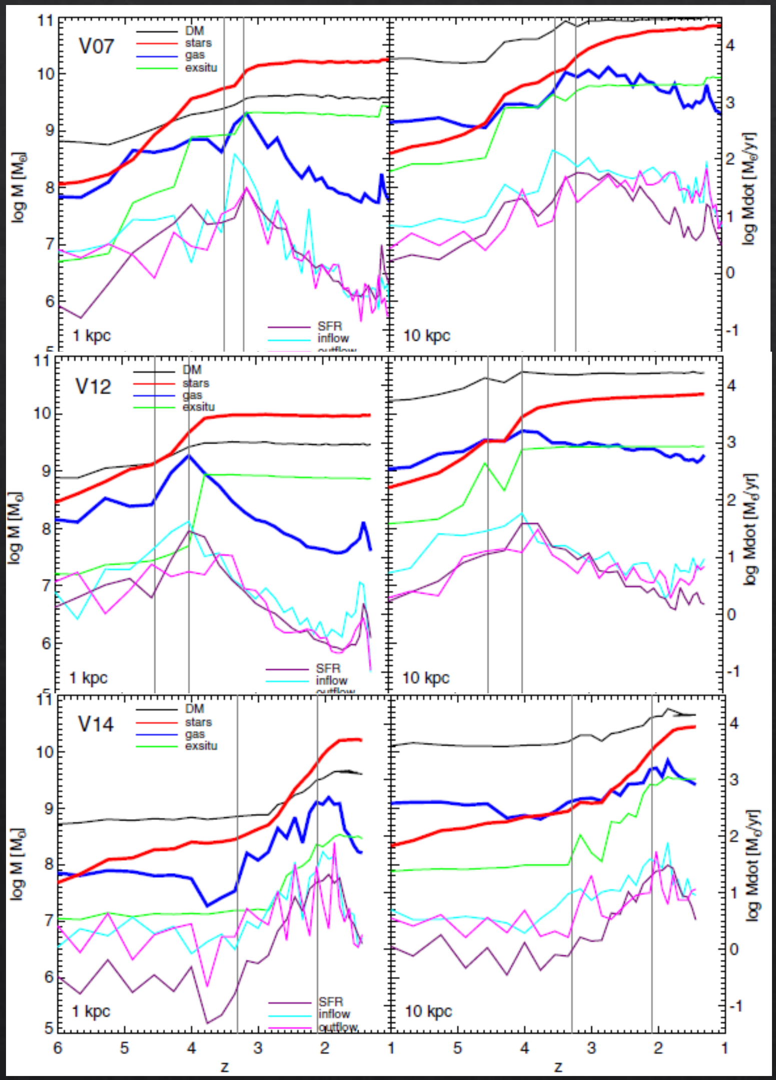
# The mechanism of ‘compaction’

- What is the trigger of compaction?
  - Mergers?
    - Minor mergers in compaction
    - But, not necessary
  - Domination of baryon?
    - $\Sigma_{stars} > \Sigma_{DM}$ in compaction
    - What is the physical meaning?



# The mechanism of 'quenching'

- What is the trigger of quenching?
  - Halo quenching
    - A halo grows enough to have a high virial temperature.
  - Morphological quenching
    - Potential becomes deep enough to stabilize a gas disc.
  - Gas consumption
    - Star-forming gas runs out.



# Summary

- Elliptical galaxies form from massive compact galaxies.
  - The formation of MCGs is **‘compaction’.**
  - Star-forming MCGs become quenched MCGs.

  - The mechanism of compaction is still an open issue.
    - Minor merger?
    - Intense gas accretion?
    - Gravitational dominance of baryon over DM?
  - The mechanism of quenching is another open issue.

# “Non-linear violent disc instability with high Toomre’s Q in high-redshift clumpy disc galaxies”

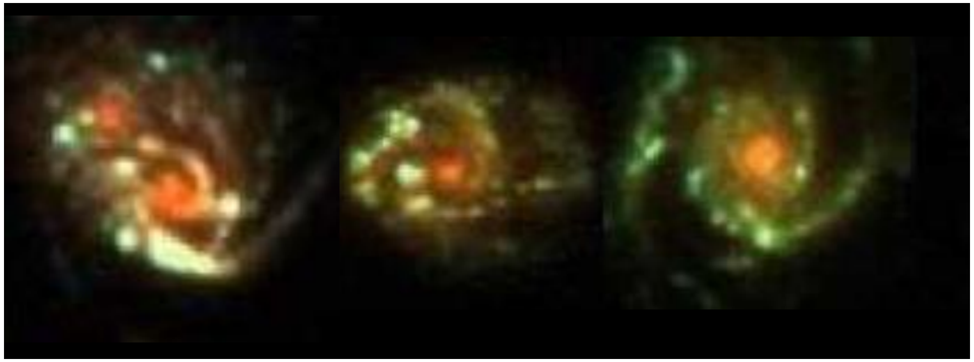
MNRAS, 456, 2052 (2016)

SI, Avishai Dekel, Nir Mandelker, Daniel Ceverino,
Frederic Bournaud, Joel Primack

# Clumpy galaxies

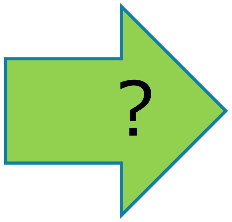
- Observed in the high-z universe（z > 1）
  – clump clusters / chain galaxies

in the high-z

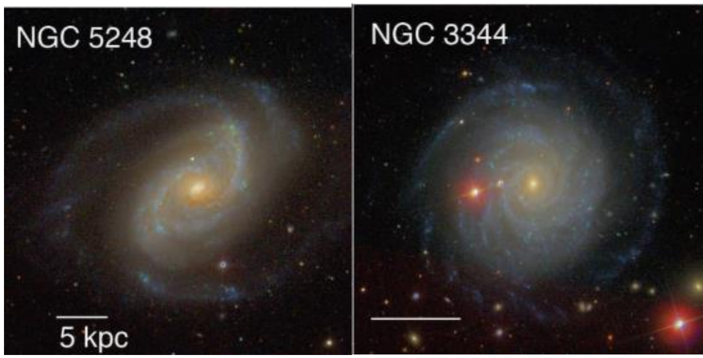


with HST　　Guo et al. (2014)

$\sim 10^9$ yr



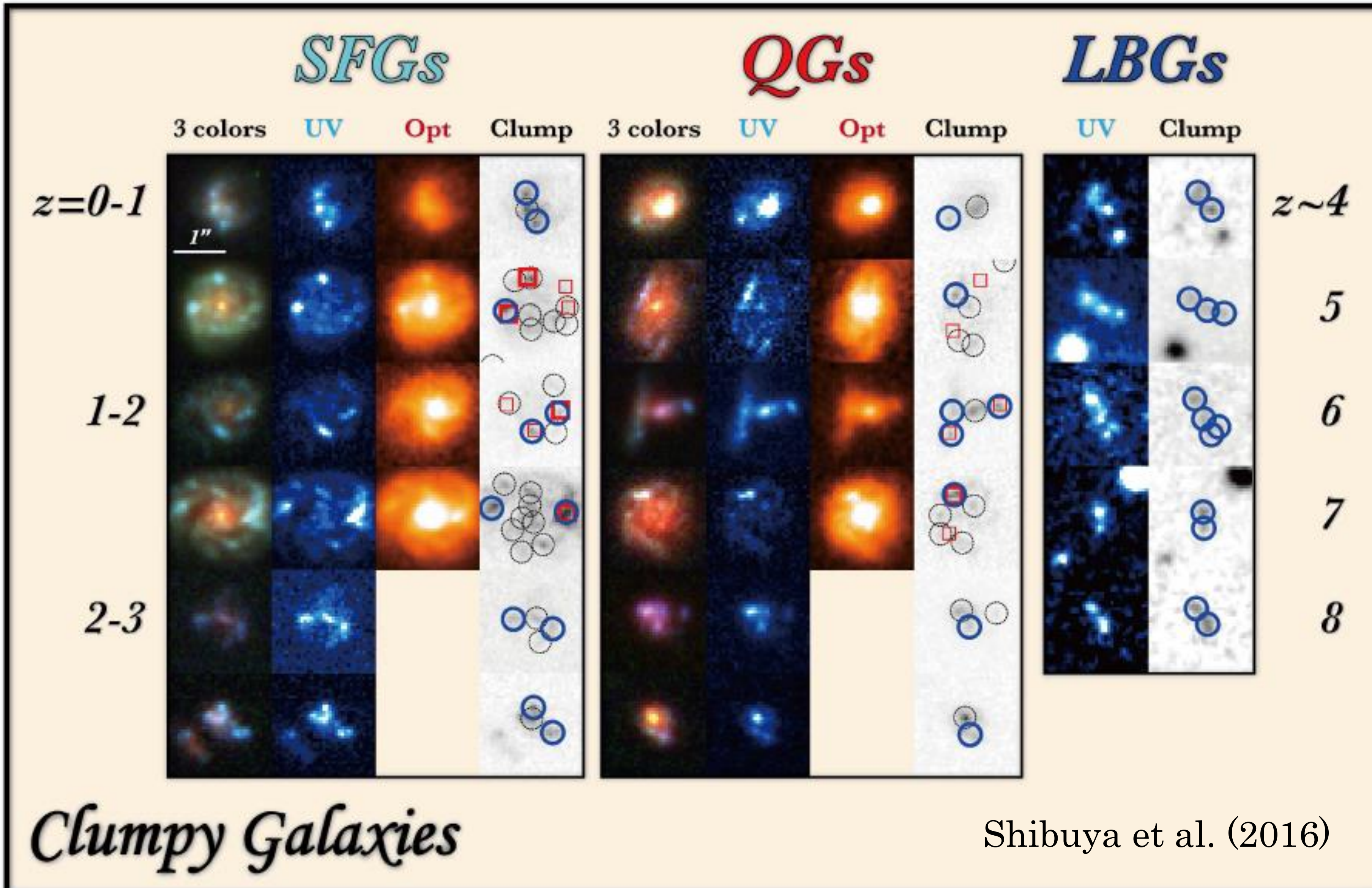

in the local universe




Elmegreen et al. (2013)

- \`Clumpy' galaxies are formation stages of disc galaxies.
  – \`Giant clumps' (~ $10^9$ $M_\odot$ at the largest)
  – Clumpy galaxies account for ~ 30-60 % in z=1-3
    - Tadaki+14, Murata+14, Livermore+15, Guo+15, Shibuya+16

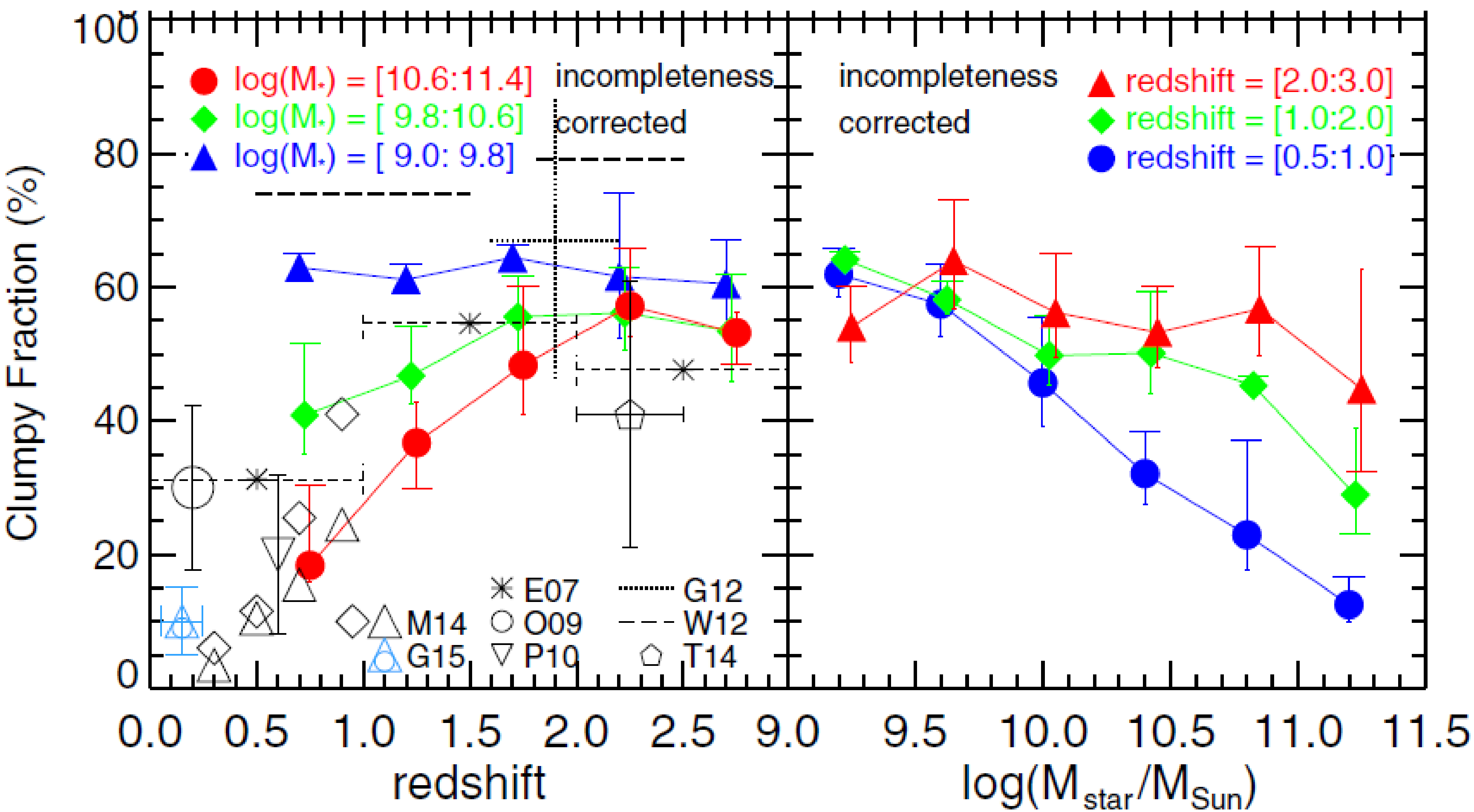
# Clumpy galaxies



# Clumpy fraction of galaxies

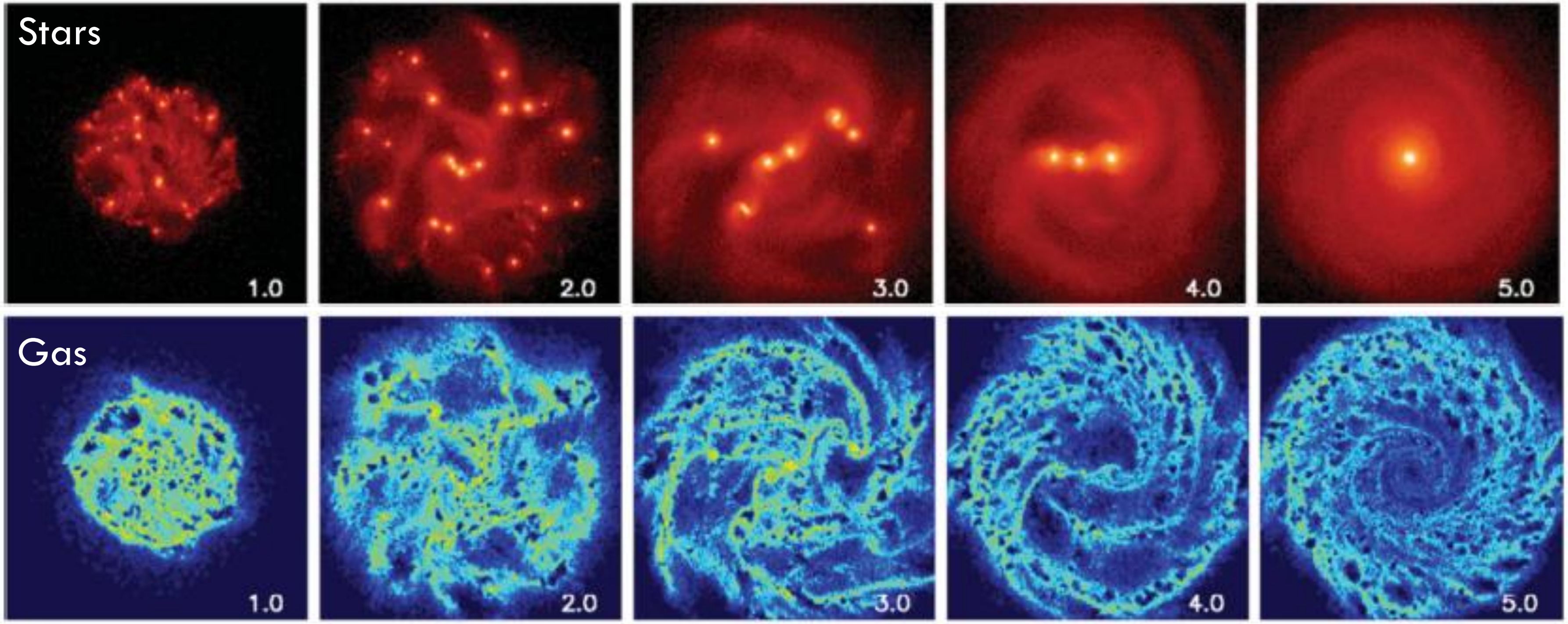
- Clumpy galaxies account for ~ 30-50 % in z=1-3
  - Tadaki+14, Livermore+15, Guo+15, Shibuya+16

Guo et al. (2015)



# Why are they clumpy?

- It has been proposed;
  - Galaxies are highly gas-rich (stream-fed) in their early formation stages.
  - Cold gas discs in the galaxies are **Toomre unstable** (Noguchi 1998, 1999).
  - **Clump formation is caused by 'Toomre instability'**




Inoue & Saitoh (2012)

# Toomre instability

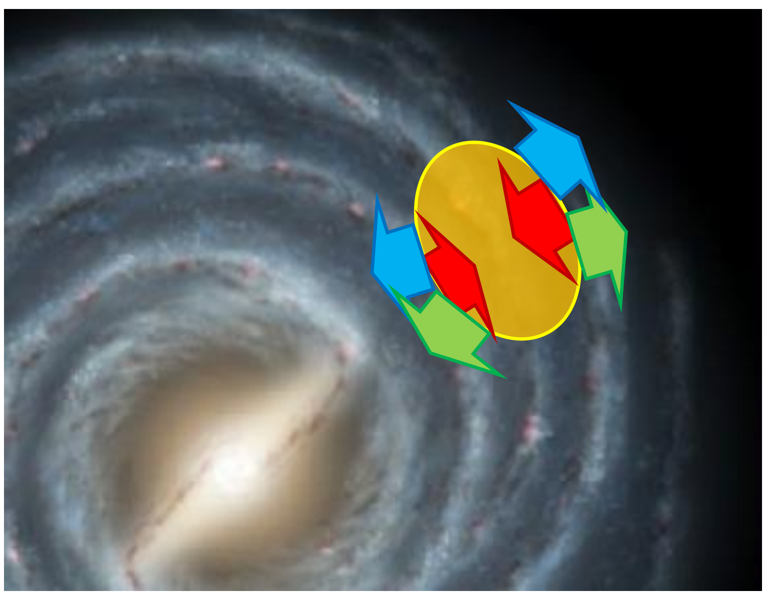
- From a **local** and **linear** perturbation theory for **axisymmetric** perturbations,

Velocity dispersion or sound speed (pressure)

Epicyclic frequency (Coriolis force)

<u>The stability condition</u>: $$Q \equiv \frac{\sigma\kappa}{\pi G \Sigma} > 1$$

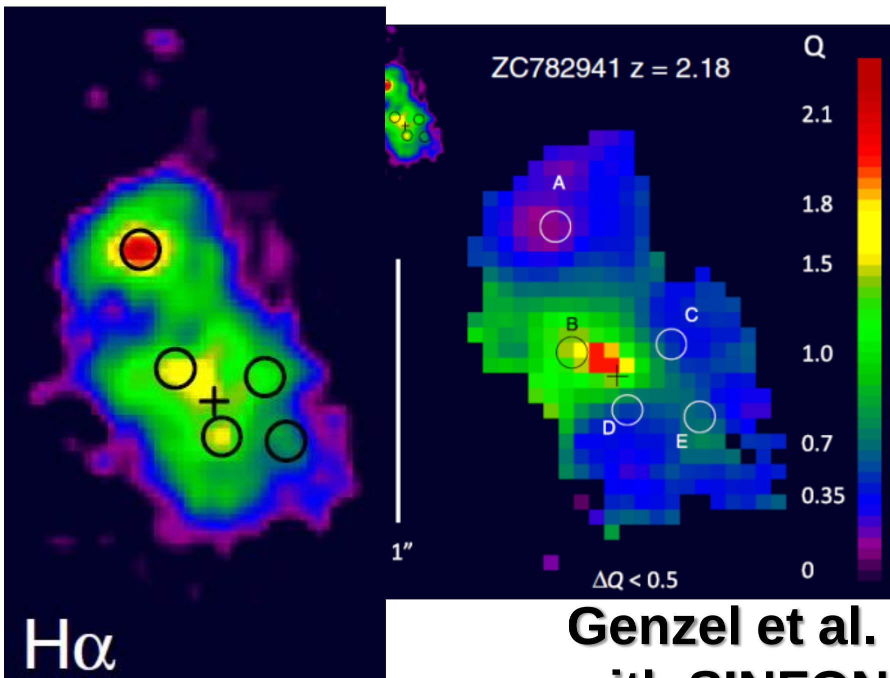
Surface density (self-gravity)

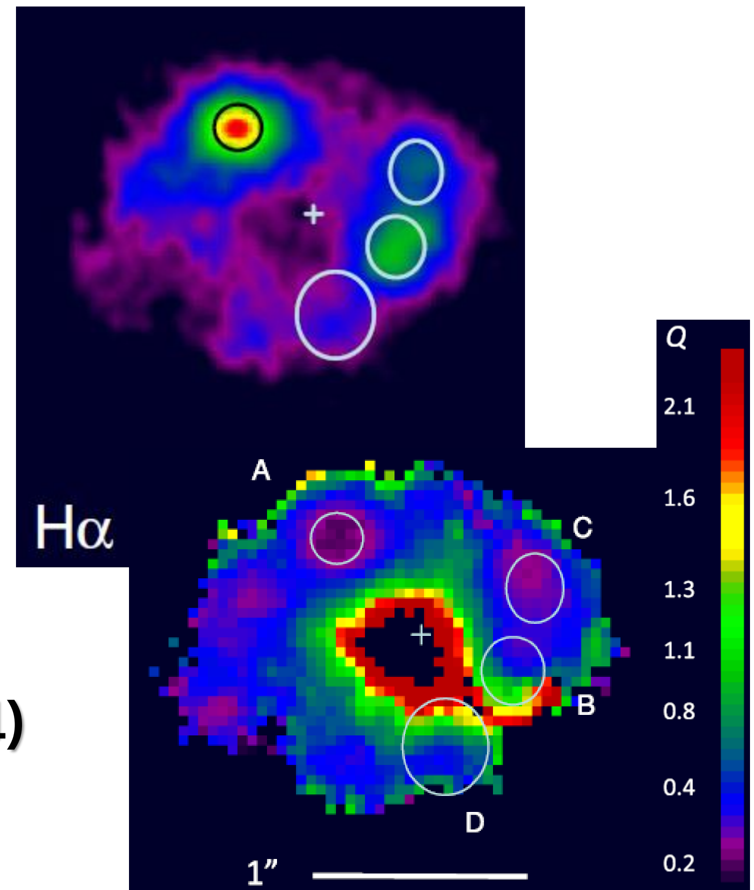


If Q<1, the local region is gravitationally unstable, going to collapse.

# Toomre instability

- From a **local** and **linear** perturbation theory for **axisymmetric** perturbations,
- In observations,




**Genzel et al. (2011) with SINFONI**

**Q $\leq$ 1 in observed clumpy discs.**

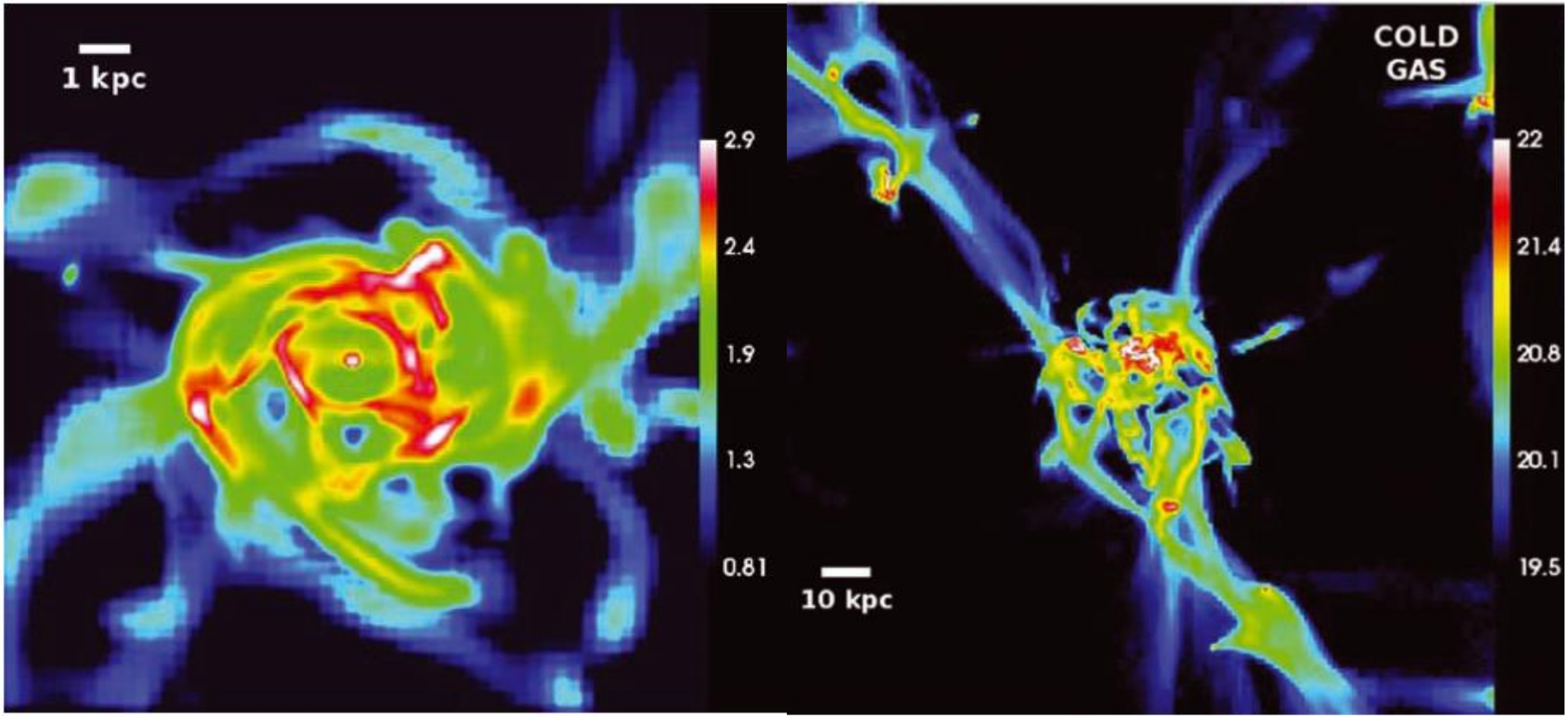
# Toomre instability

- From a **local** and **linear** perturbation theory for **axisymmetric** perturbations

- But, actually
  - **Global** effect may work for instability.
  - Perturbations may grow **non-linearly**.
  - Perturbations may be **non-axisymmetric**.

- **Galaxies in cosmological context may deviate from the "idealized" situation.**

# Toomre analysis in cosmological sims.



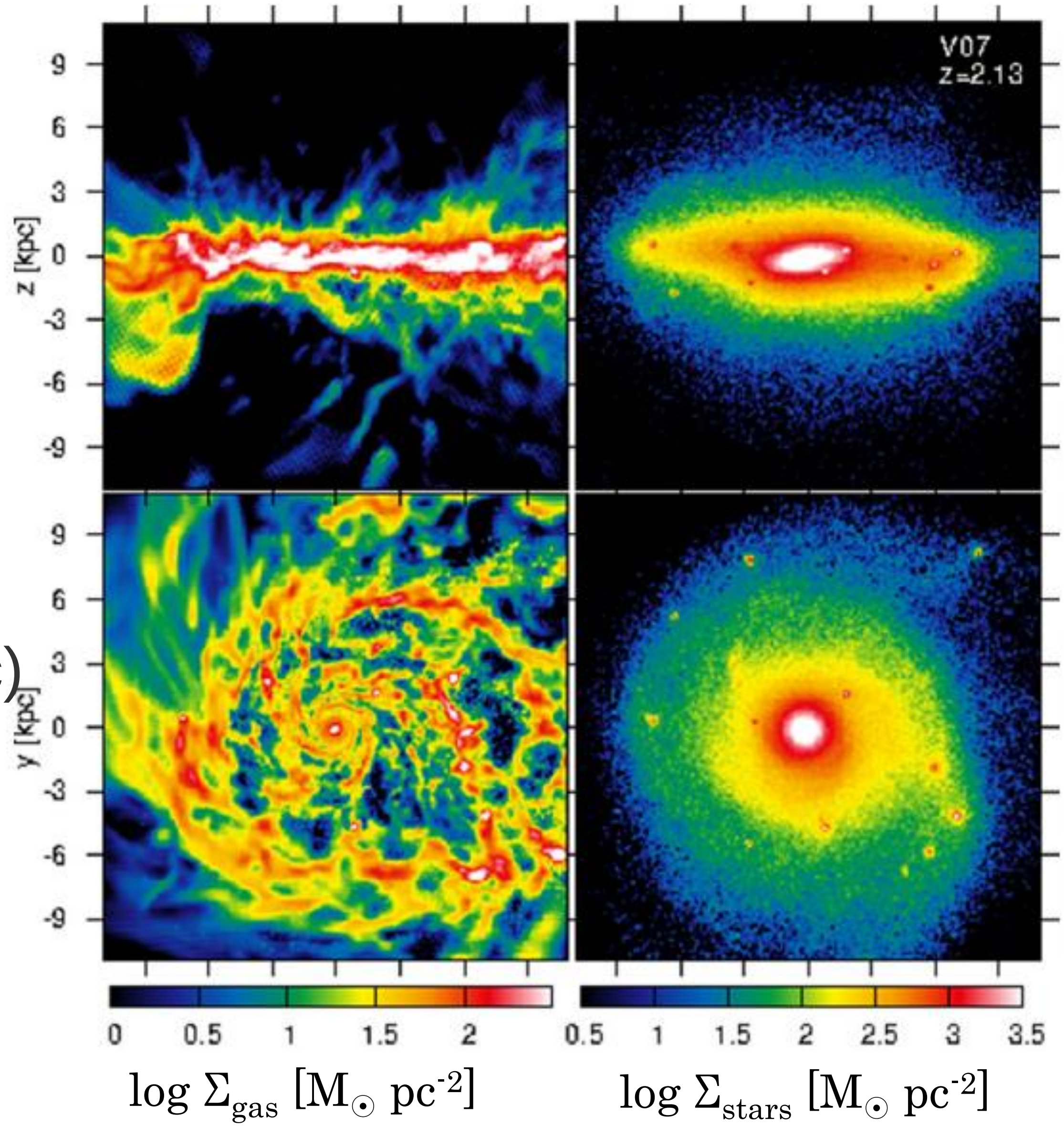

- Cosmological simulations
  - Ceverino et al. (2010, 2013) using ART code
    - 10pc-order resolution with radiation pressure.

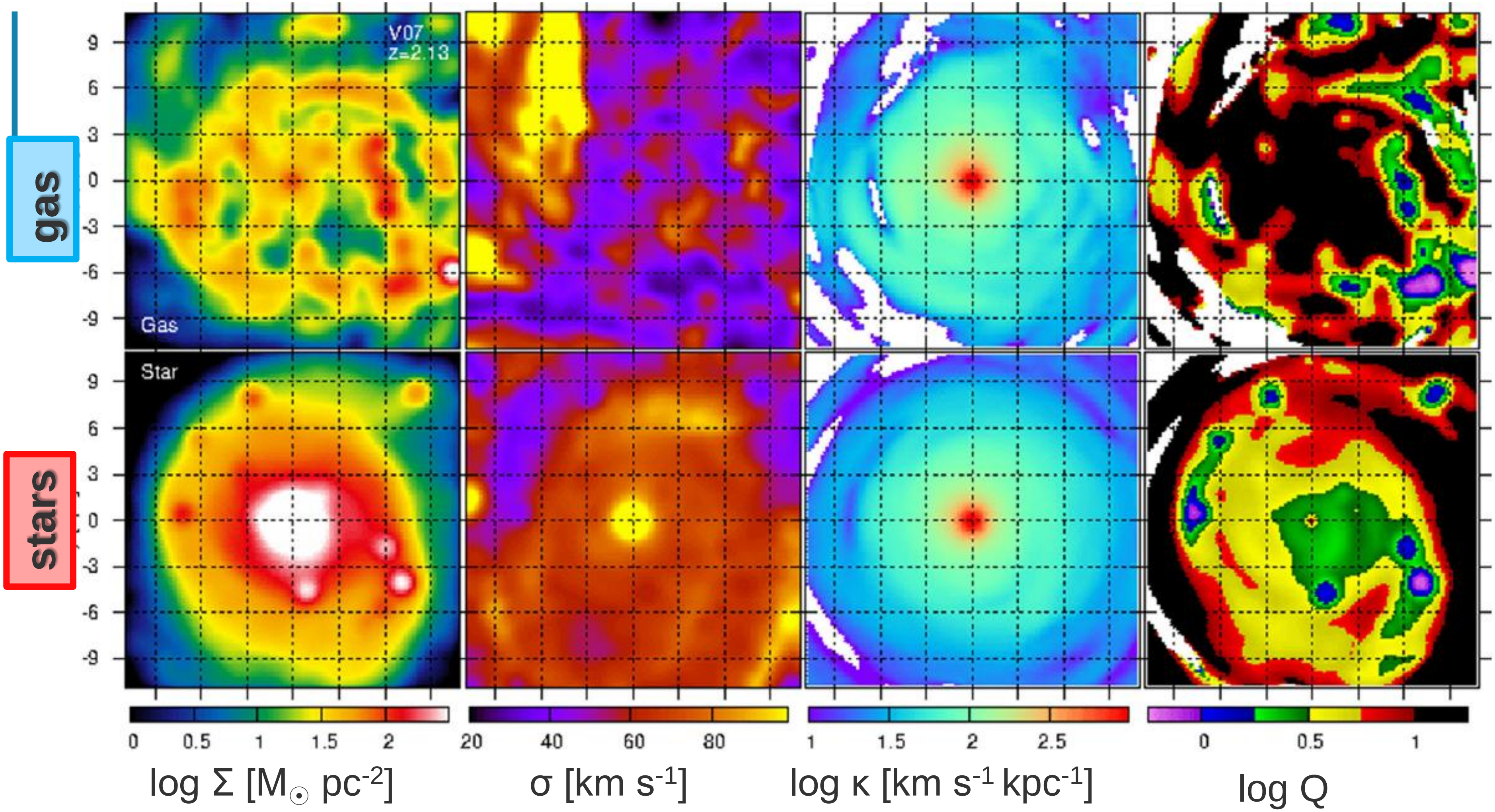
# How to measure $Q_{2comp}$

- **2-component model** (Romeo & Wiegert 2011)
  - $Q_{gas} = \frac{\kappa_{gas}\sigma_{gas}}{\pi G \Sigma_{gas}}$ , $Q_{star} = \frac{\kappa_{star}\sigma_{star}}{3.36 G \Sigma_{star}}$
  - $\begin{cases} {Q_{2comp}}^{-1} = W {Q_{gas}}^{-1} + {Q_{star}}^{-1} & (if \quad Q_{gas} > Q_{star}) \\ {Q_{2comp}}^{-1} = {Q_{gas}}^{-1} + W {Q_{star}}^{-1} & (if \quad Q_{gas} < Q_{star}) \end{cases}$
    - $W \equiv \frac{\sigma_{gas}\sigma_{star}}{{\sigma_{gas}}^2 + {\sigma_{star}}^2}$
  - $\sigma$ is velocity dispersion (not sound speed).
  - $\kappa$ is calculated from mean velocity fields of gas/star.
    - $\kappa \equiv \sqrt{2 \frac{<v_\phi>}{R} \left( \frac{d<v_\phi>}{dR} + \frac{<v_\phi>}{R} \right)}$
  - Young stars (age<100 Myr) are considered to be "gas "
  - Bulge stars are removed ; $j_z / j_{max} < 0.7$
  - Gaussian smoothing with **FWHM=1.2 kpc**
    - to focus on $M_{clump} = 10^{8-9}$ $M_\odot$
  - A razor-thin disc model (which gives lower limits)

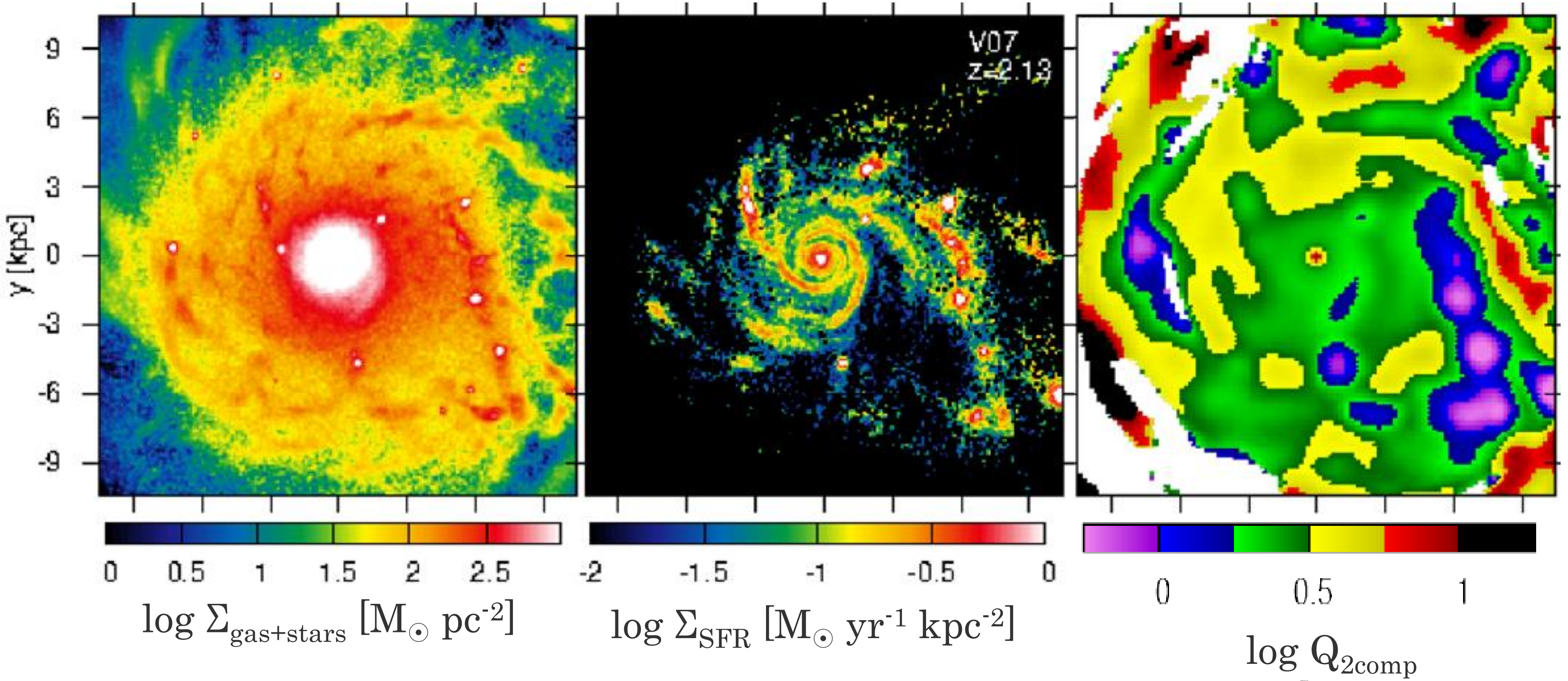
# Cosmological simulations

- V07
  - $z = 2.13$
  - $M_{vir} = 8.8 \times 10^{11}$ $M_\odot$
  - $M_{star} = 5.6 \times 10^{10}$ $M_\odot$
  - $f_{gas} = 0.18$
  - $B/T = 0.37$ (kinematic)
  - $SFR = 27.5$ $M_\odot$ yr$^{-1}$






**Purple** Q<1: linear instability
**Blue** Q=1-1.8: non-linear instability
**Green** Q=1.8-3: dissipative instability
**Yellow, Red, Black:** Q>3: stable state
**White:** imaginary κ (Q cannot be defined)

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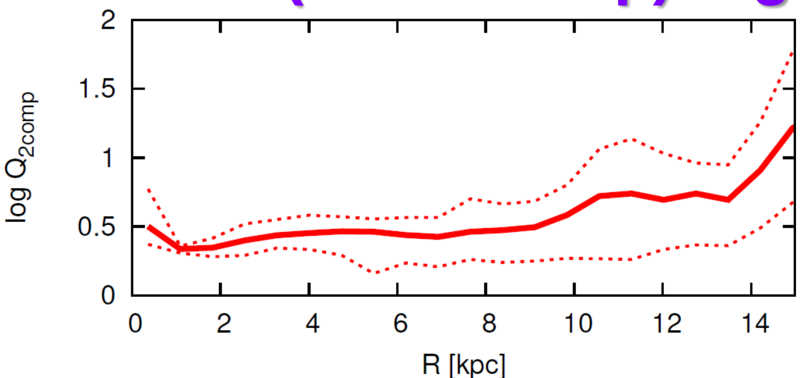


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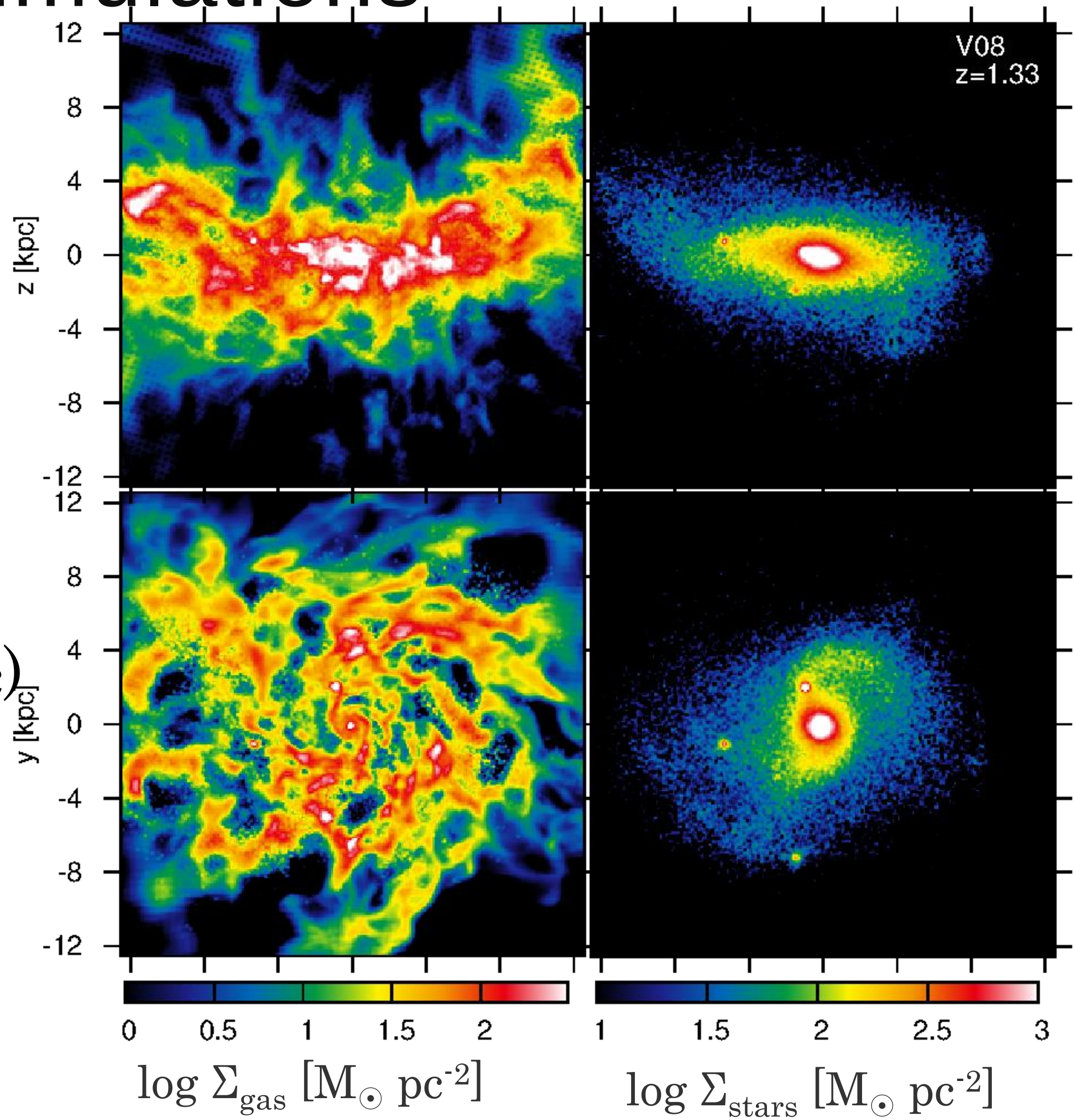
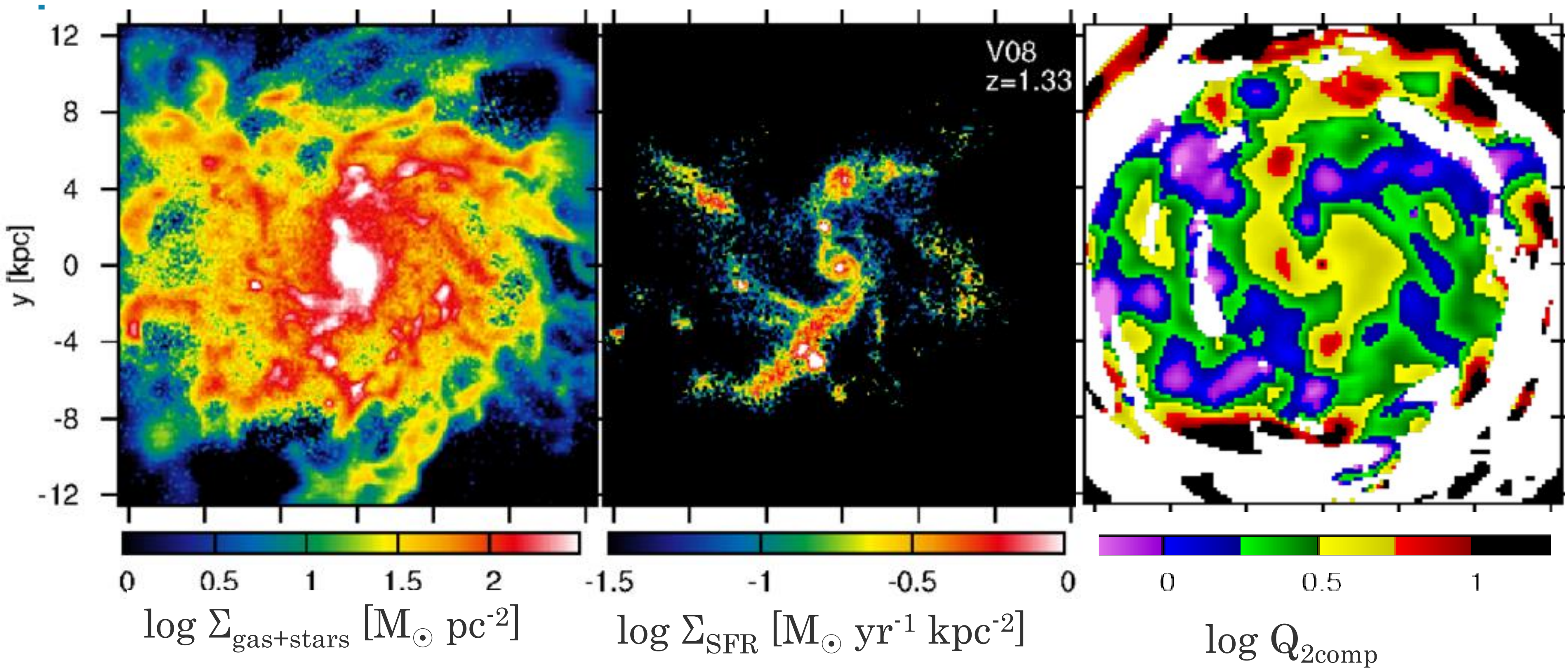
# Cosmological simulations

- V08
  - $z = 1.33$
  - $M_{vir} = 6.0 \times 10^{11}$ $M_\odot$
  - $M_{star} = 1.9 \times 10^{10}$ $M_\odot$
  - $f_{gas} = 0.42$
  - $B/T = 0.45$ (kinematic)
  - $SFR = 33.1$ $M_\odot$ $yr^{-1}$



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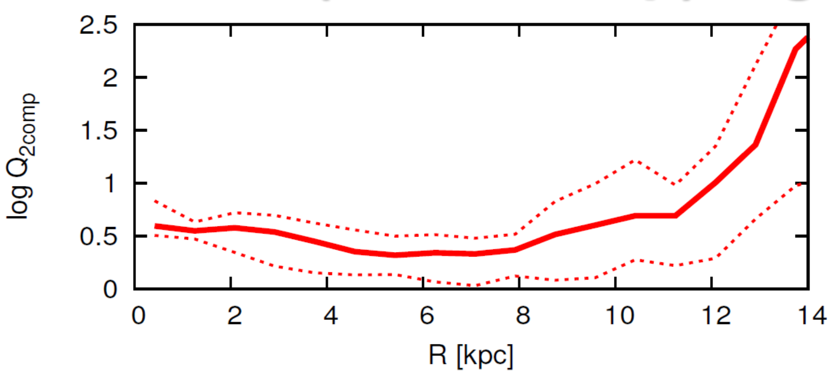


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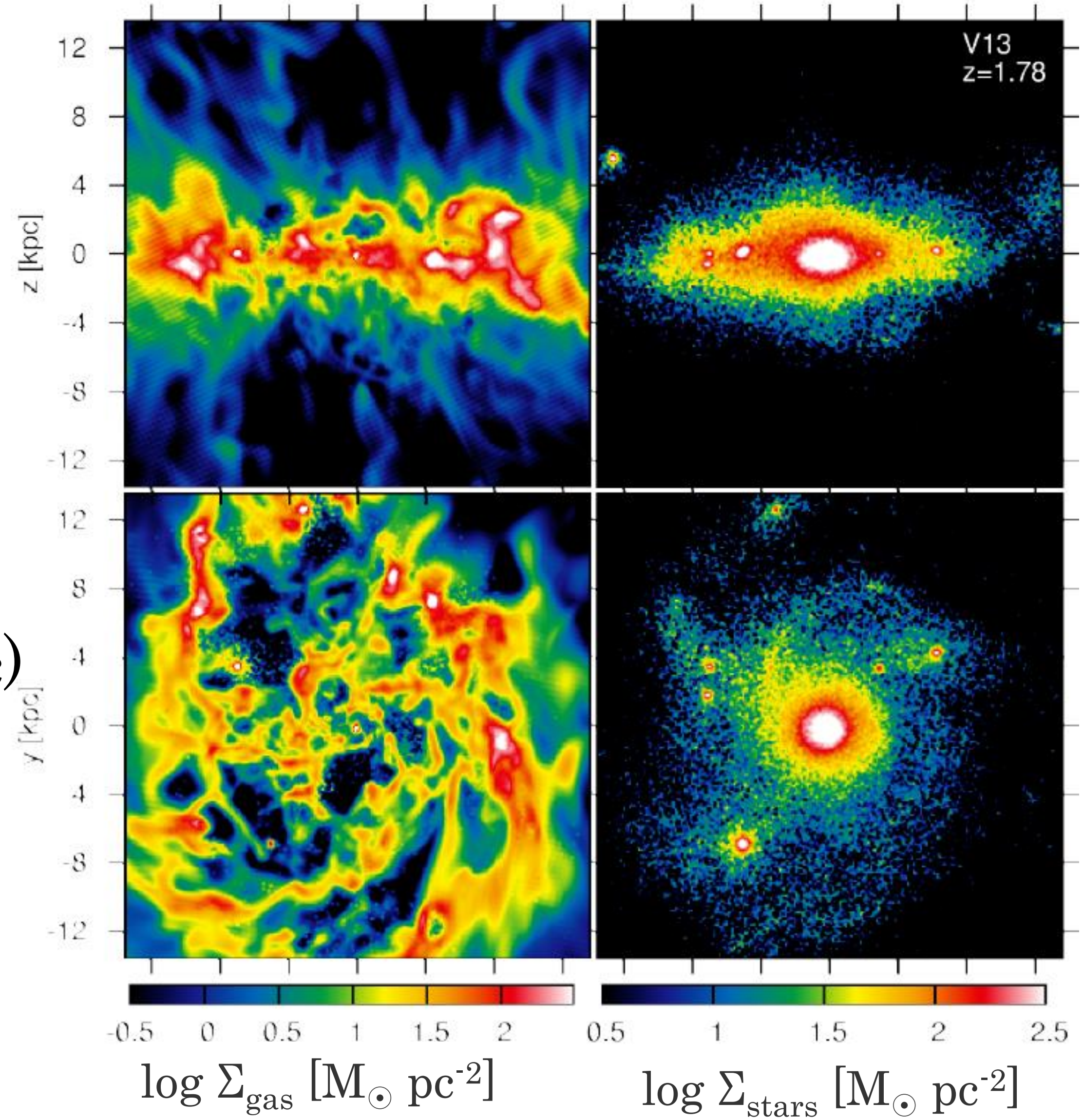
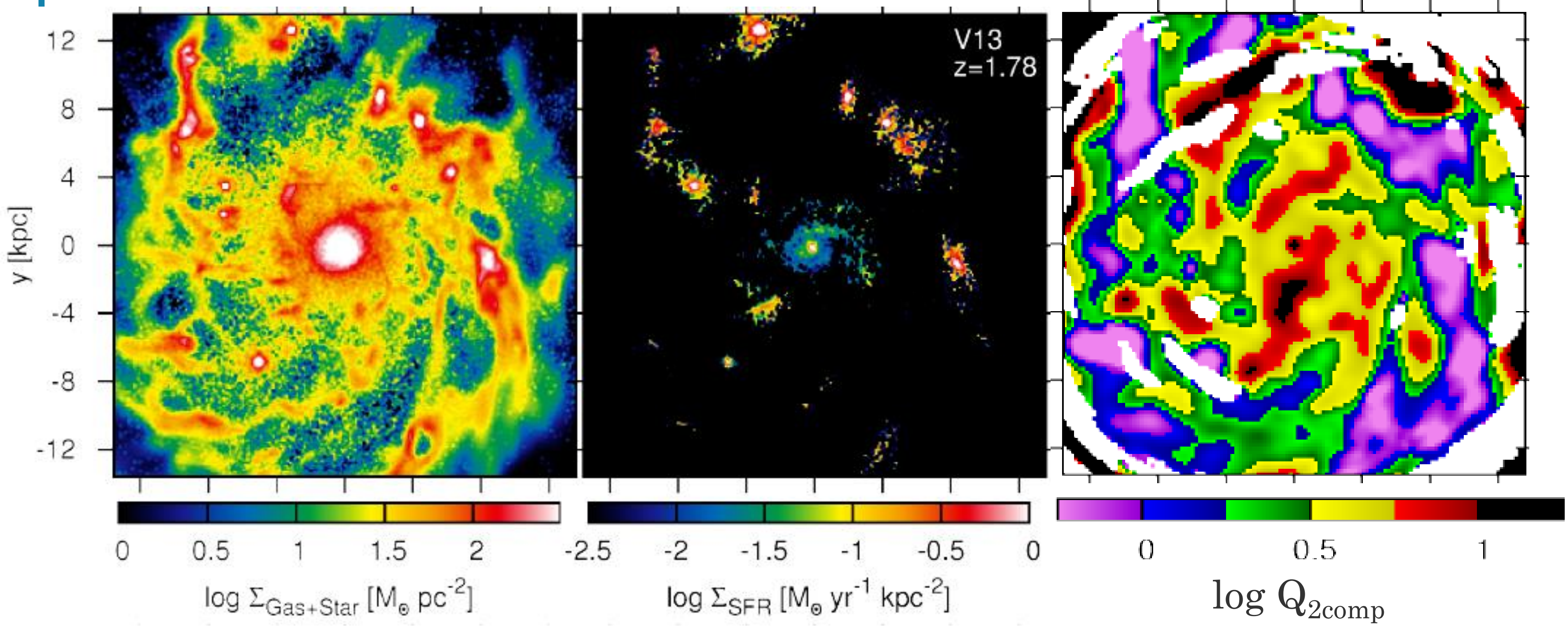
# Cosmological simulations

- V13
  - $z = 1.78$
  - $M_{vir} = 3.4 \times 10^{11}\ \mathrm{M}_{\odot}$
  - $M_{star} = 1.2 \times 10^{10}\ \mathrm{M}_{\odot}$
  - $f_{gas} = 0.40$
  - $B/T = 0.46$ (kinematic)
  - $SFR = 11.2\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$



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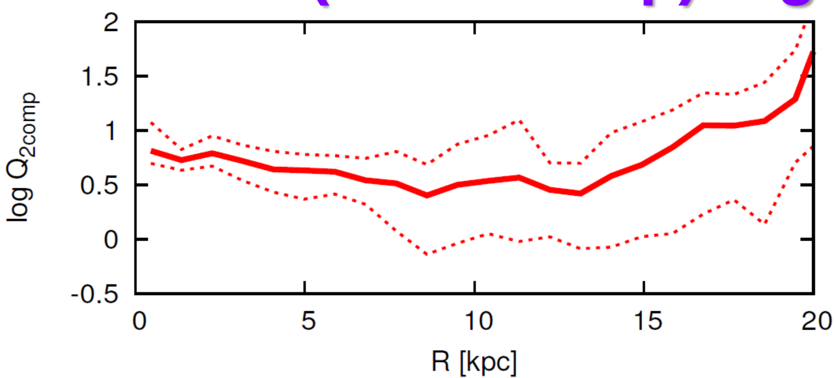


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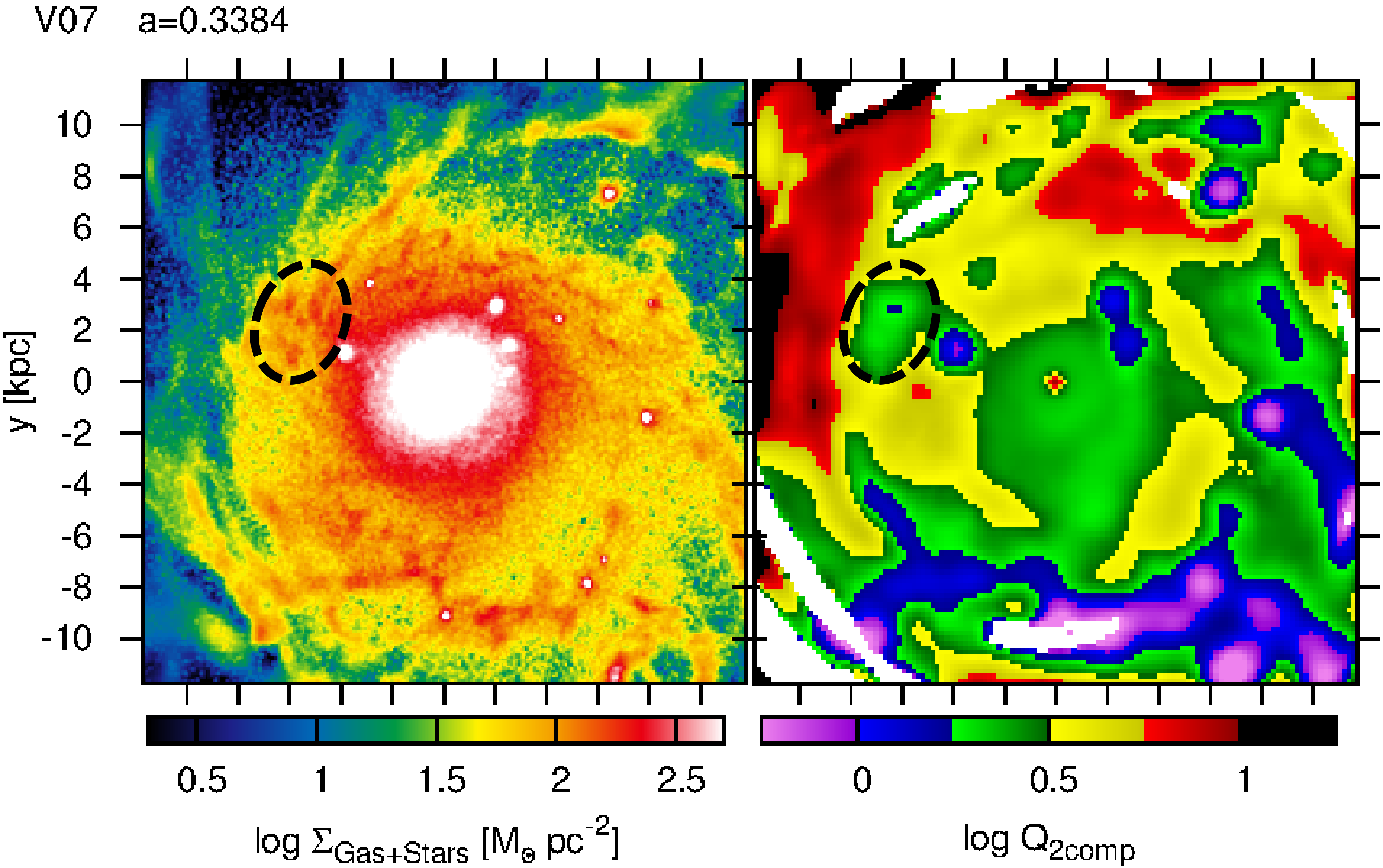
# Non-linear formation of clumps



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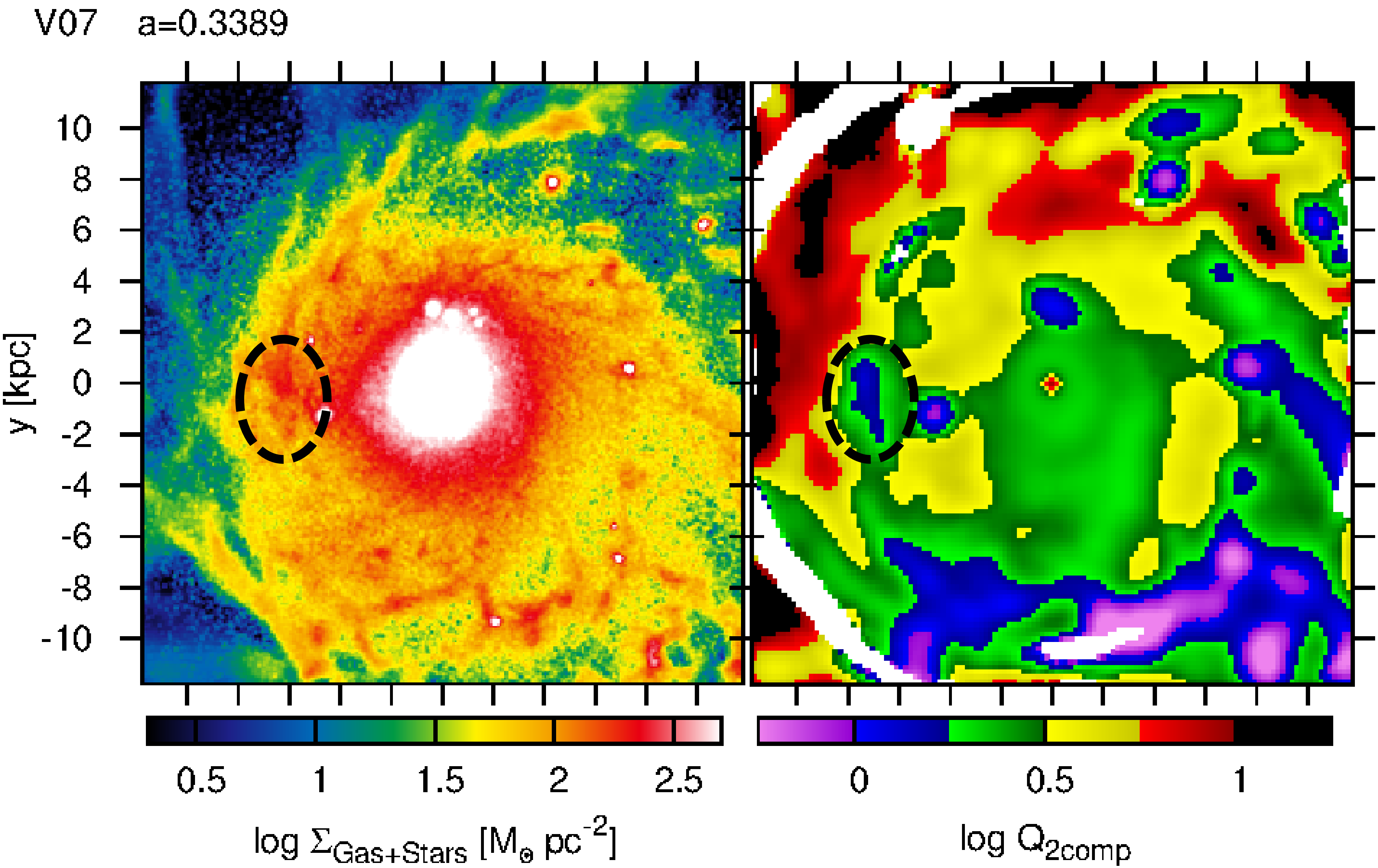

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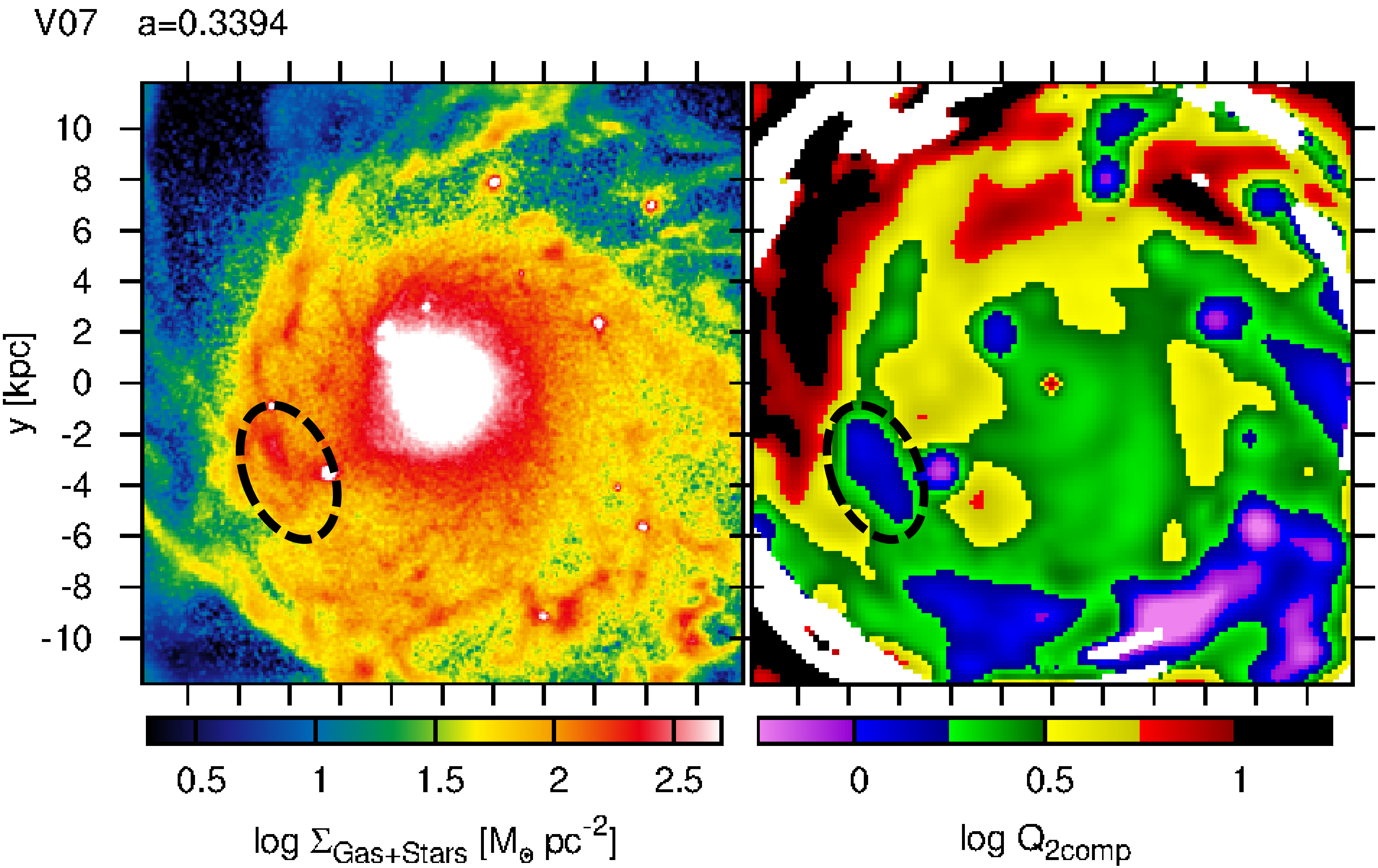

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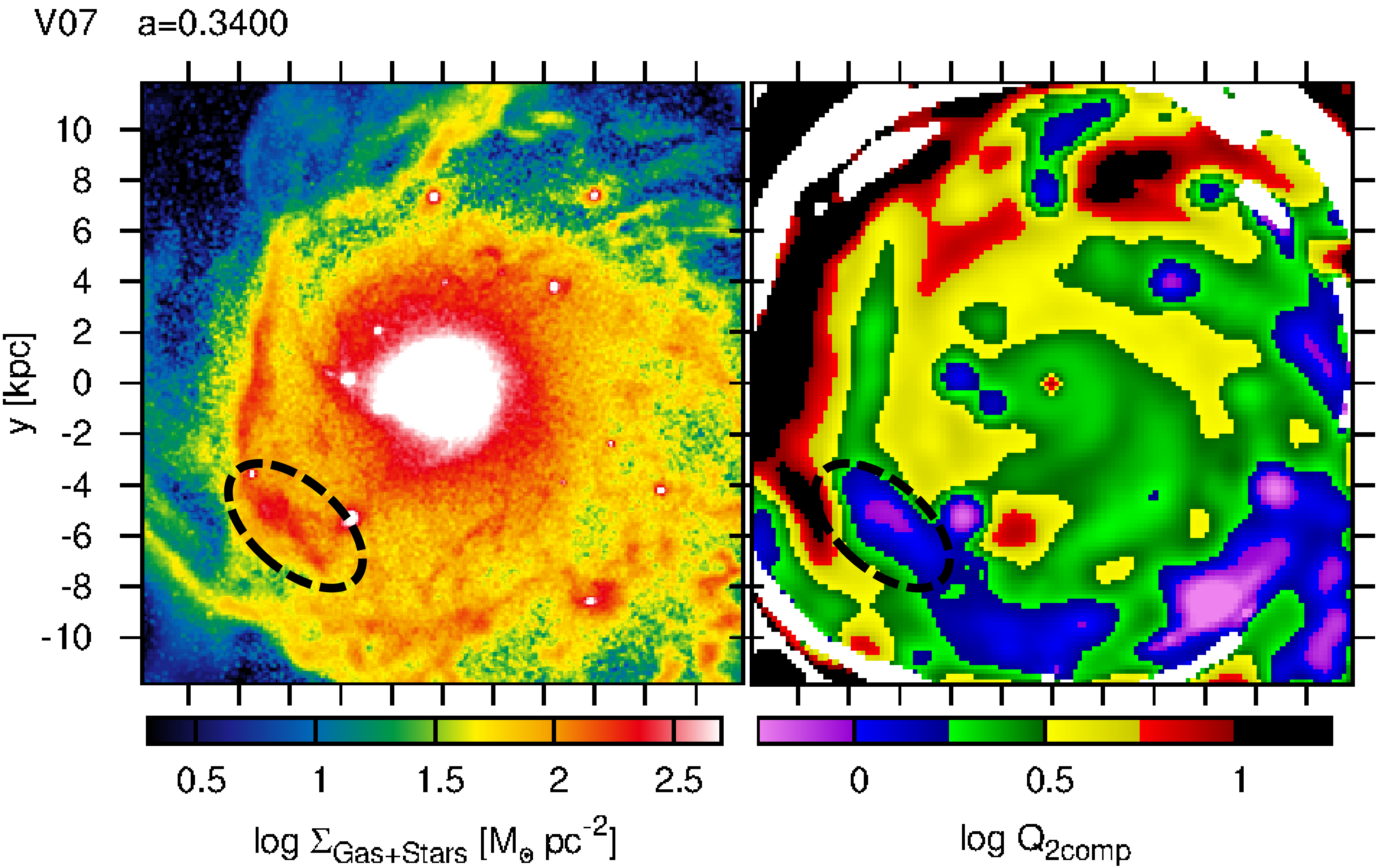

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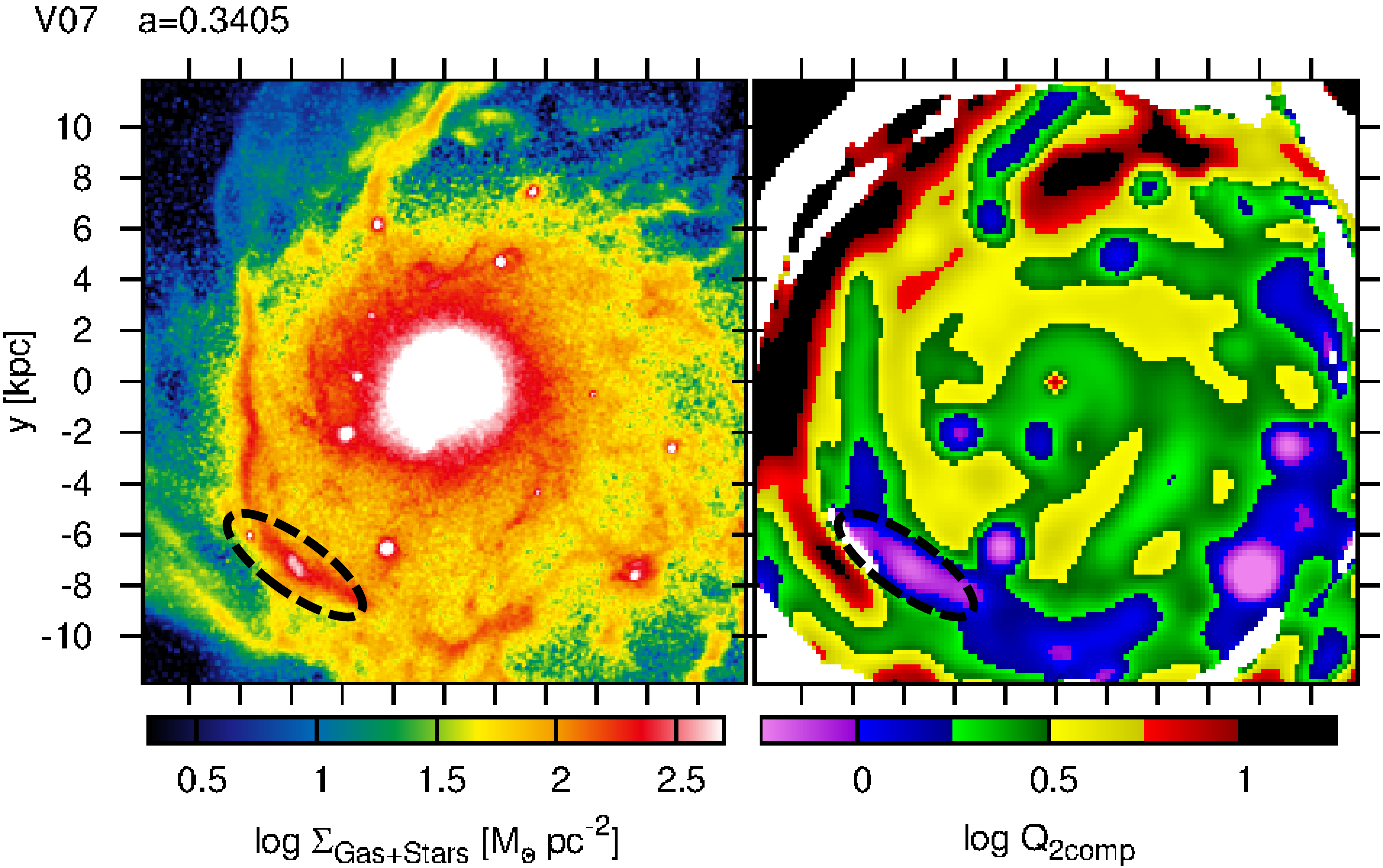

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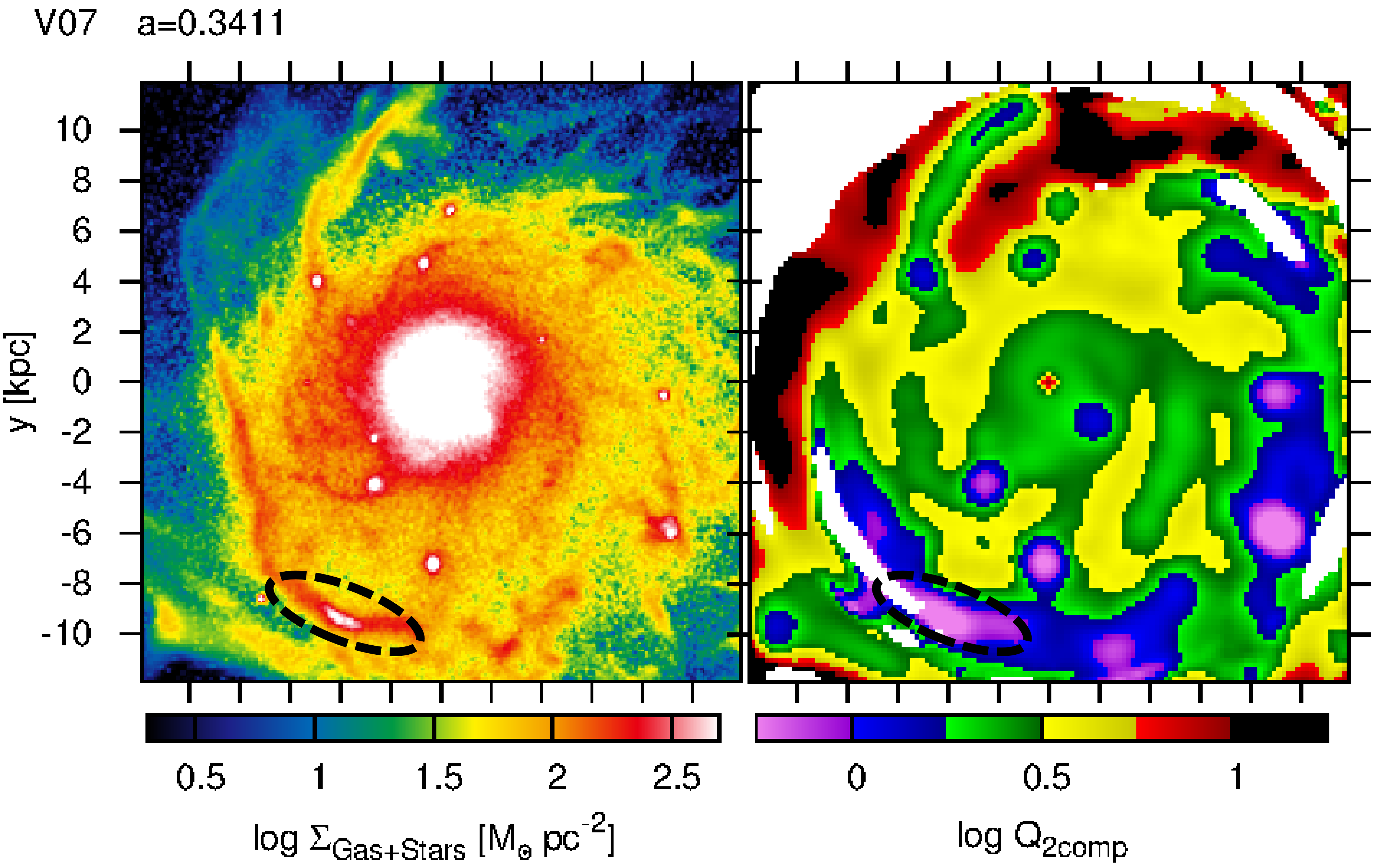

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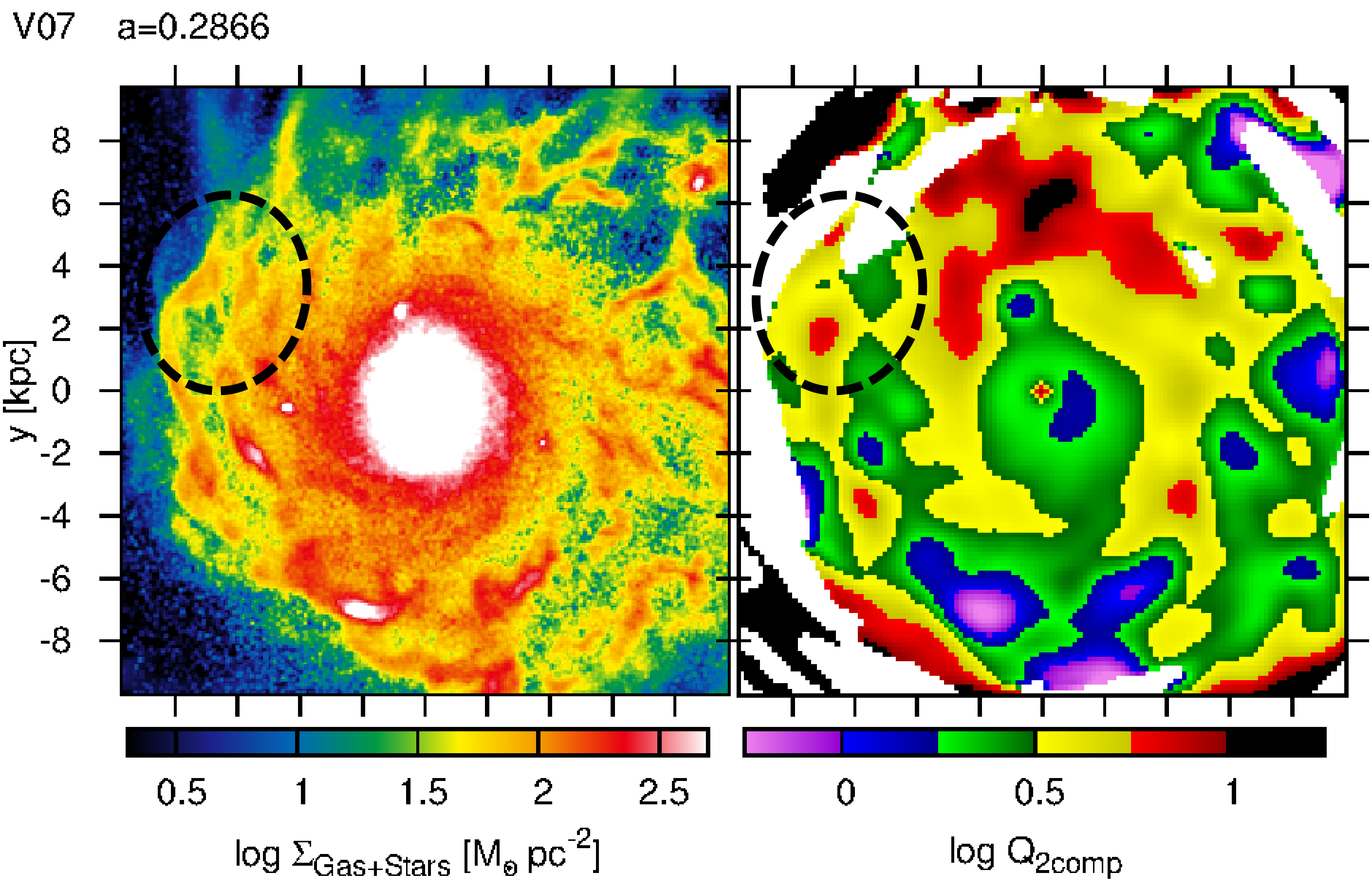

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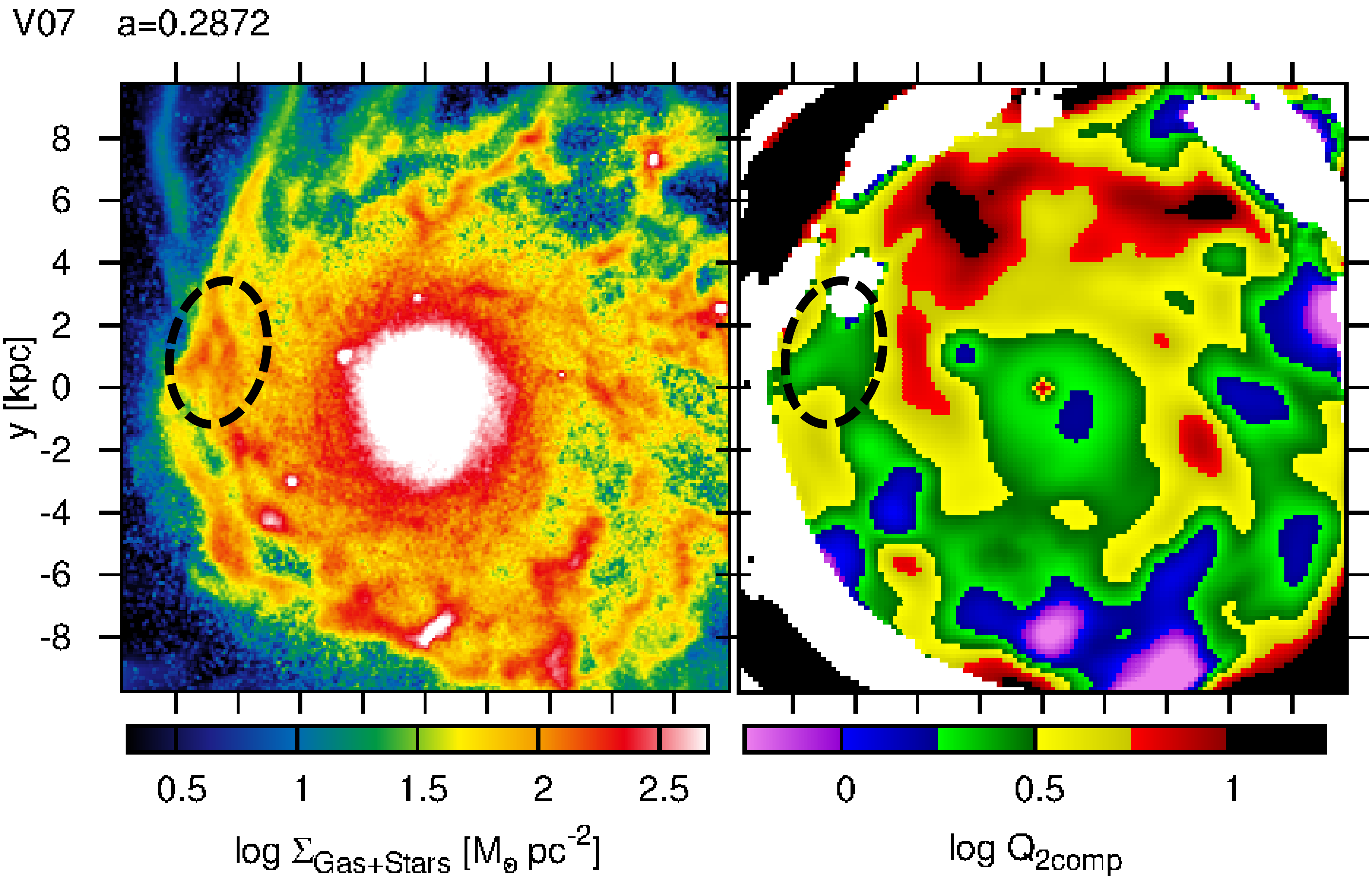

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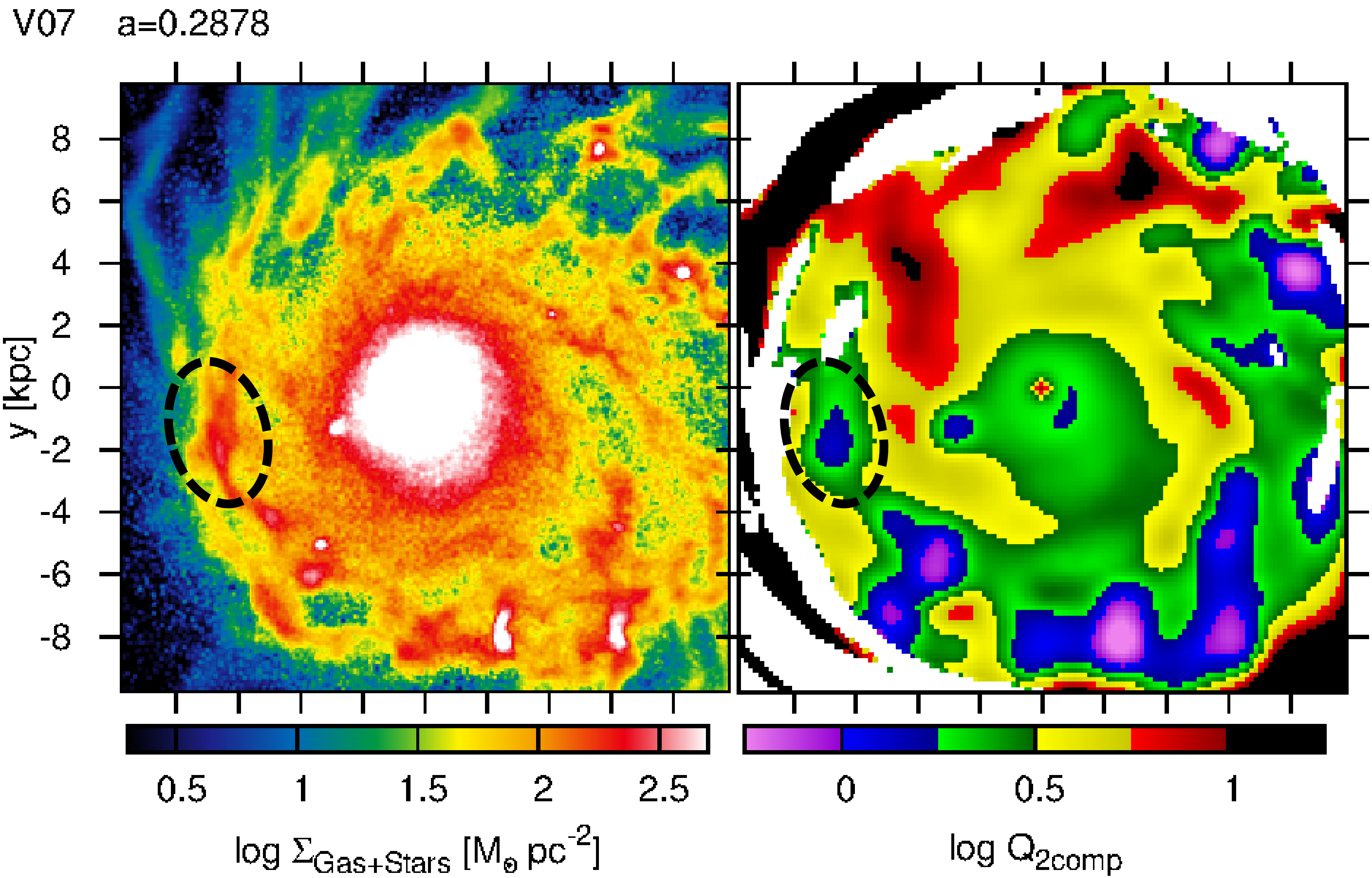

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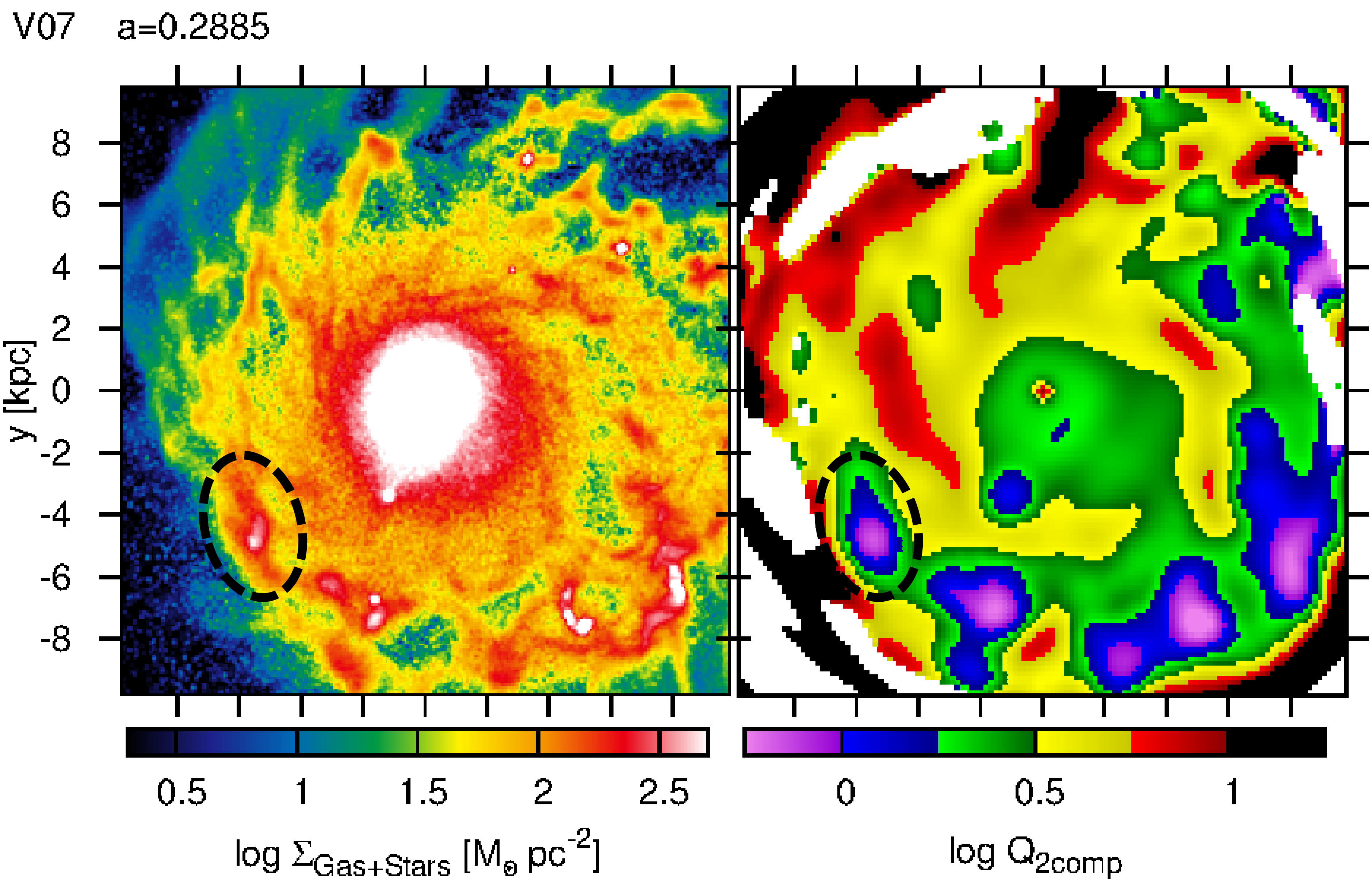

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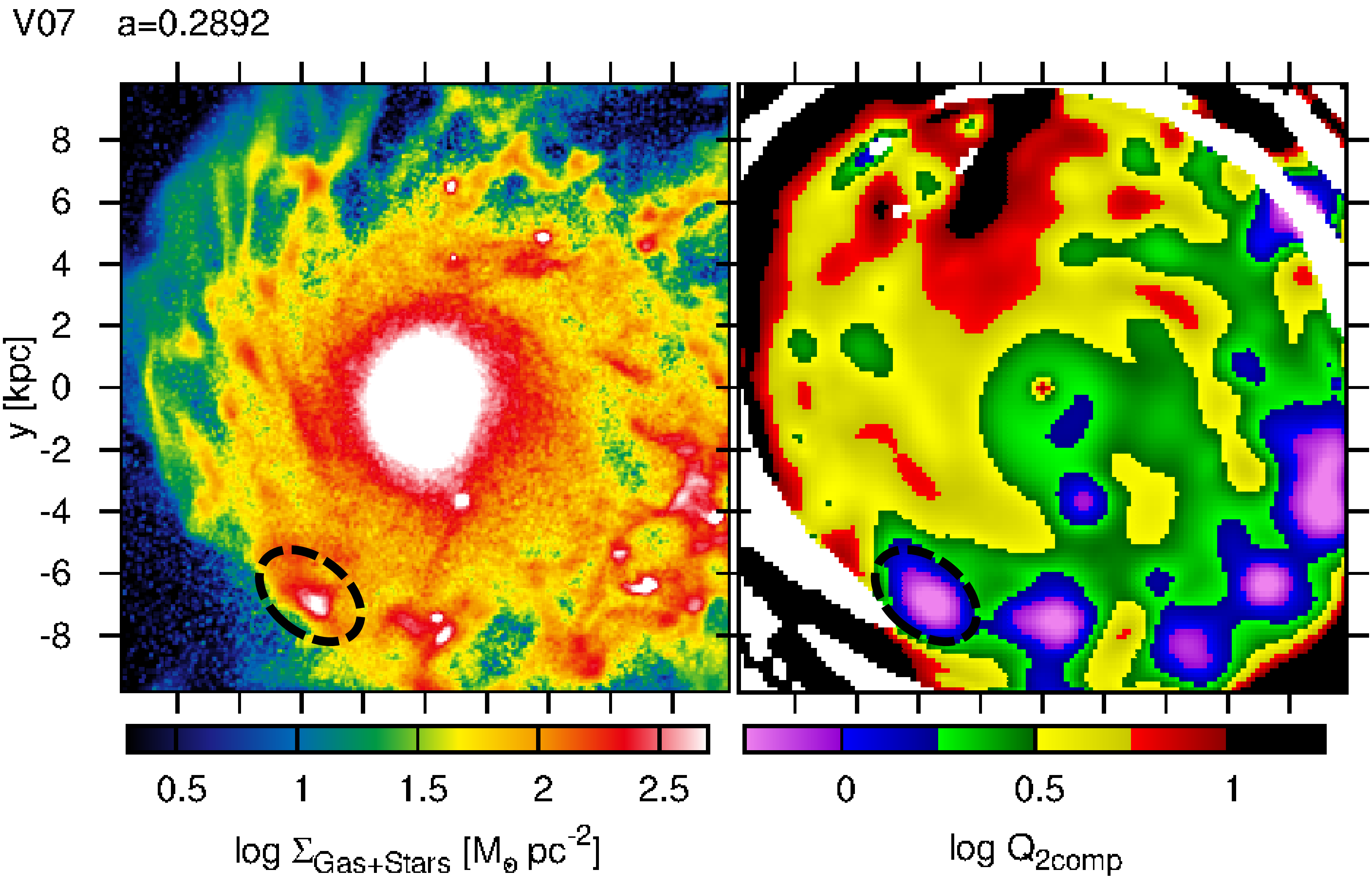
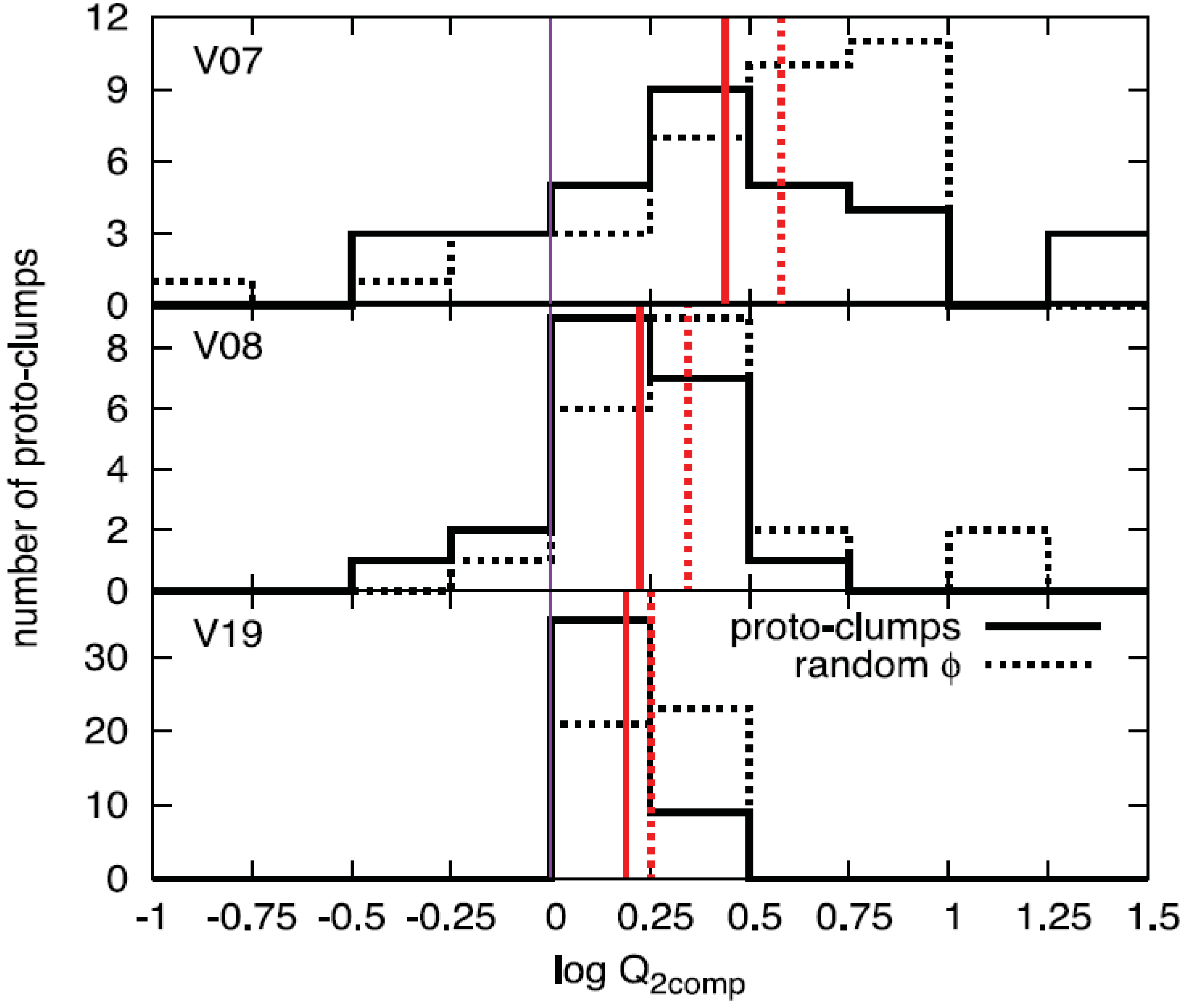


# Non-linear formation of clumps

- Distributions of Q on proto-clumps.
  - The initial masses $M_{clump} > 10^8\ M_\odot$

**Clump detection scheme (Mandelker+ 2014)**

We trace clumps back in time and space, and then we look into proto-clumps which are detected for the first time.



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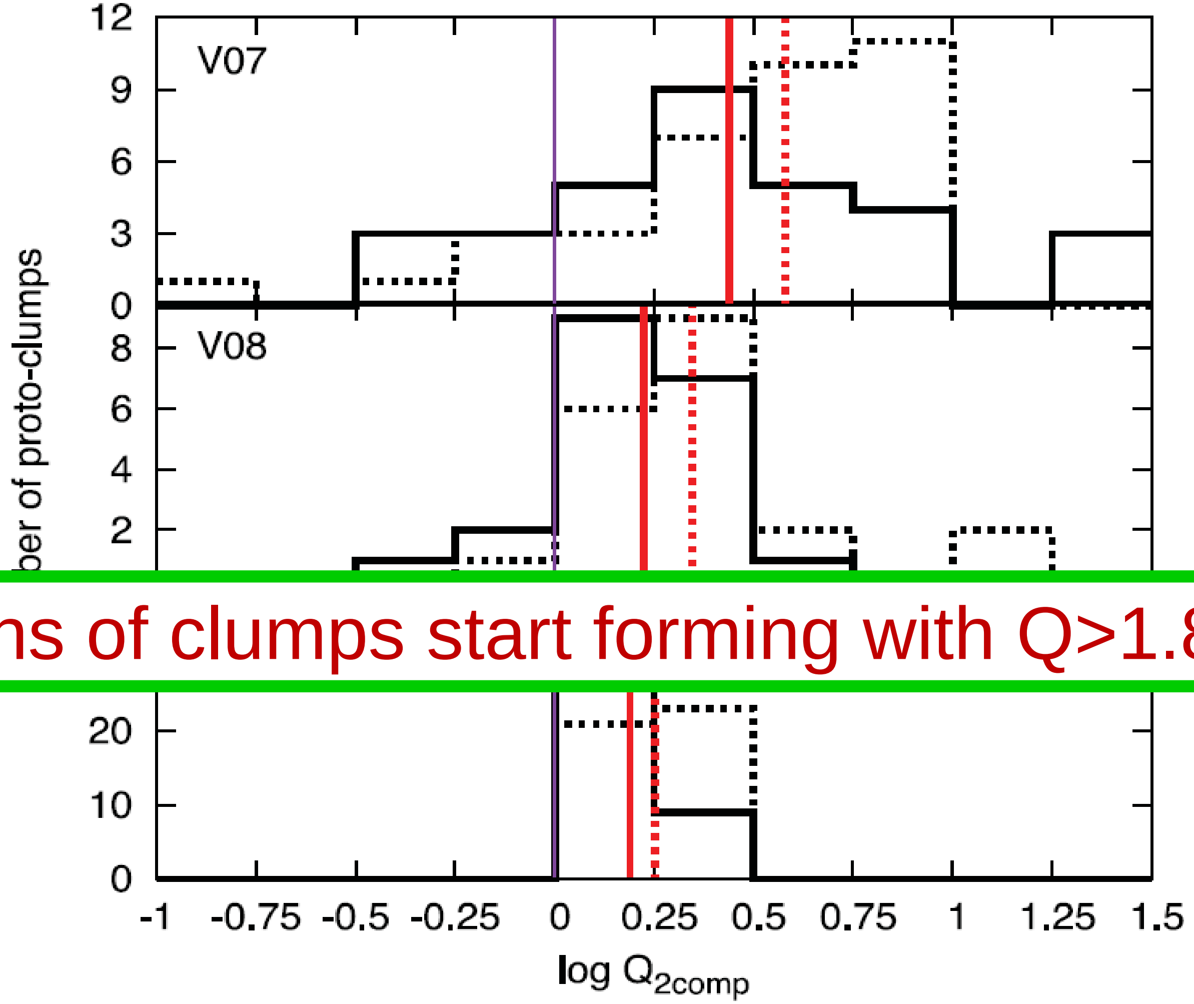


Significant fractions of clumps start forming with Q>1.8

# How do giant clumps form?

- Non-perturbative scenarios
  - Gas dissipation
    - $Q_{crit} = 2 - 3$ if gas cooling is rapid. *(Elmegreen 2011)*

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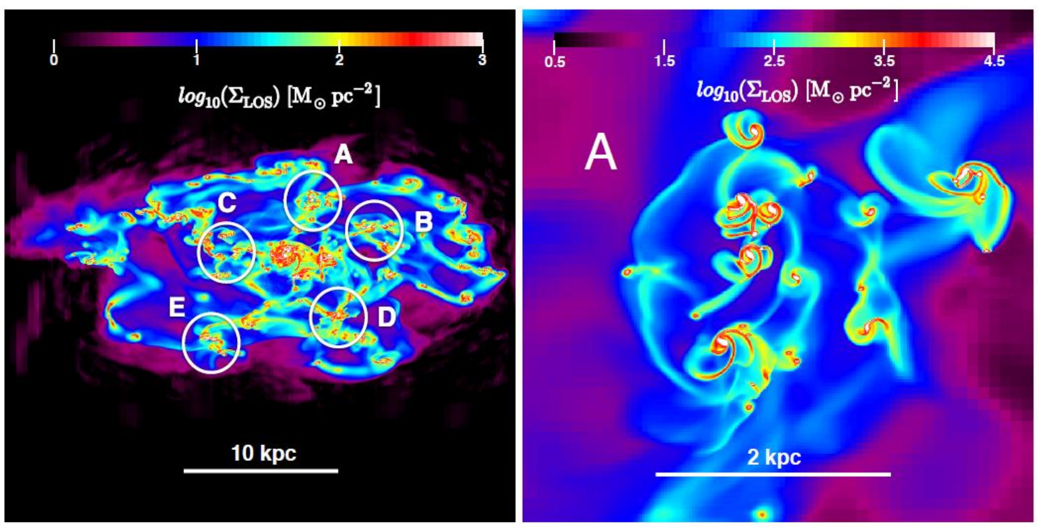
  - Small-scale formation and growth following
    - Q can be <1 on small scale *(e.g. Romeo et al 2010)*
      - Q-measurement can depend on physical scales, e.g. Larson low
      - We applied the Gaussian smoothing with FWHM=1.2 kpc




(a) Gas surface density (b) Zoom onto cluster A

A giant clump may form by mergers of small clumps. (Behrendt et al. 2015)

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  - Small-scale formation and growth following
    - Q can be <1 on small scale *(e.g. Romeo et al 2010)*
  - Non-axisymmetric perturbation
    - Rossby wave instability *(Lovelace & Hohlfeld 1978)*
      - A ring structure can break up into clumps
    - $m \neq 0$ perturbations *(Griv & Gedalin 2012)*
      - unstable up to $Q \cong 2$.

# How do giant clumps form?

- Perturbative scenarios
  - Minor mergers
    - Satellite accretion can disturb a disc.
  - Pre-existing clumps
    - Clumps also disturb a disc and stimulate formation of other clumps.

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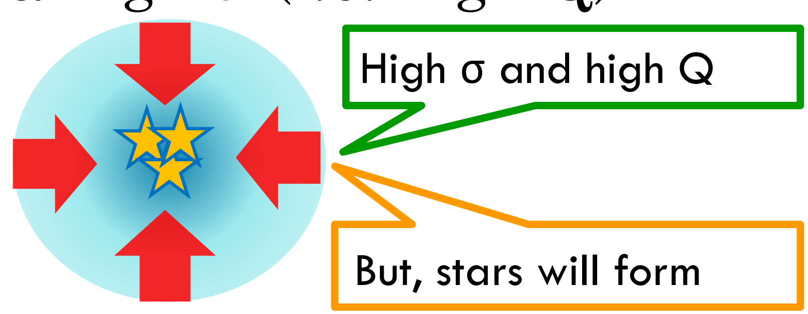
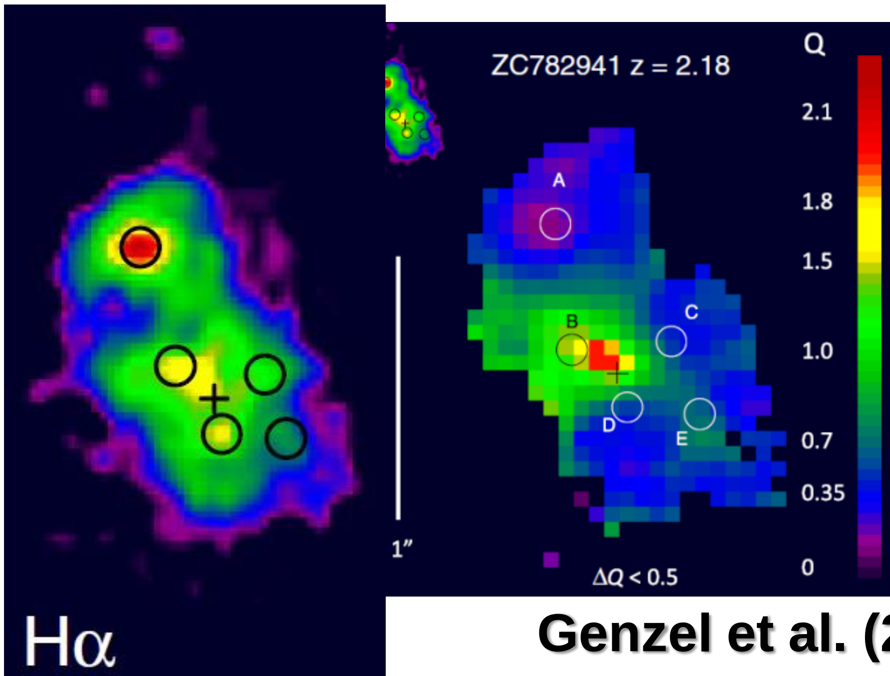
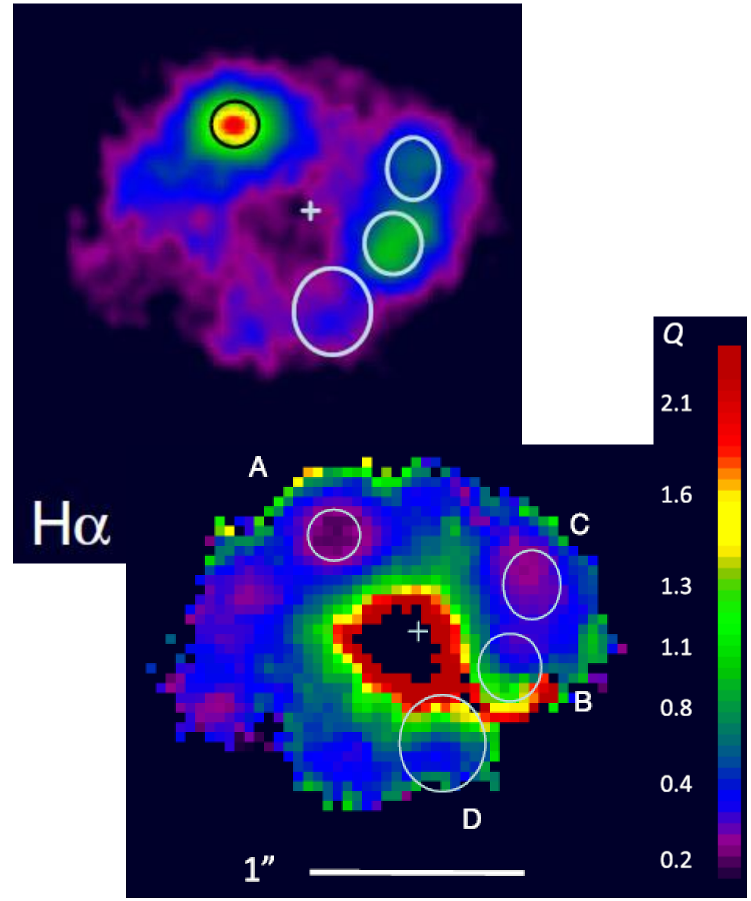
  - Cold stream flowing in a disc
    - Streams can join a disc with slow or counter rotation.
  - Compressive turbulence
    - Compressing gas can indicate a high $\sigma$ (i.e. high Q)
      - But a clump will form there



# Toomre instability

- In observations,



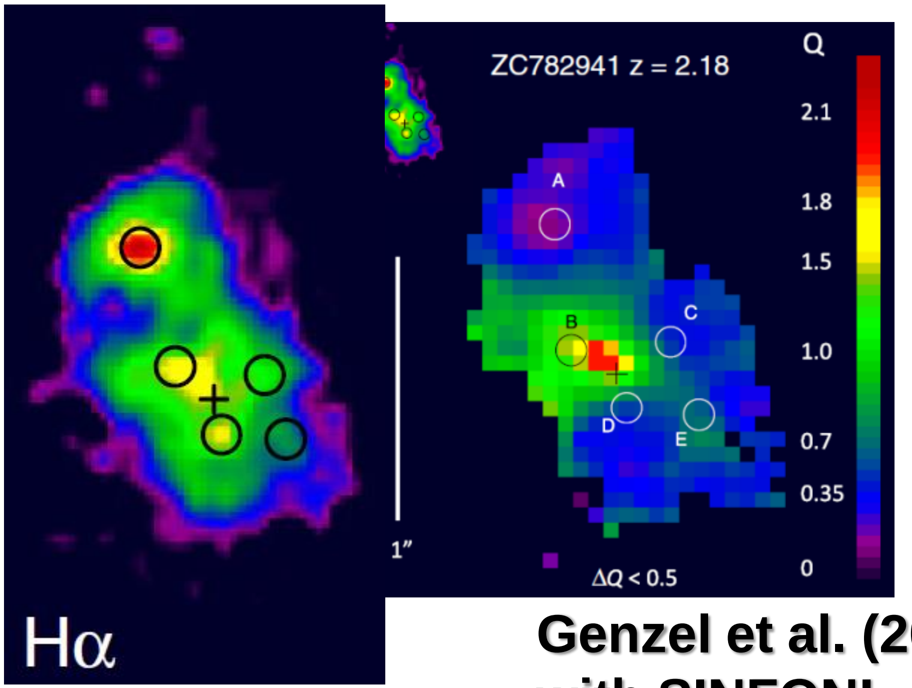

**Genzel et al. (2011) with SINFONI**

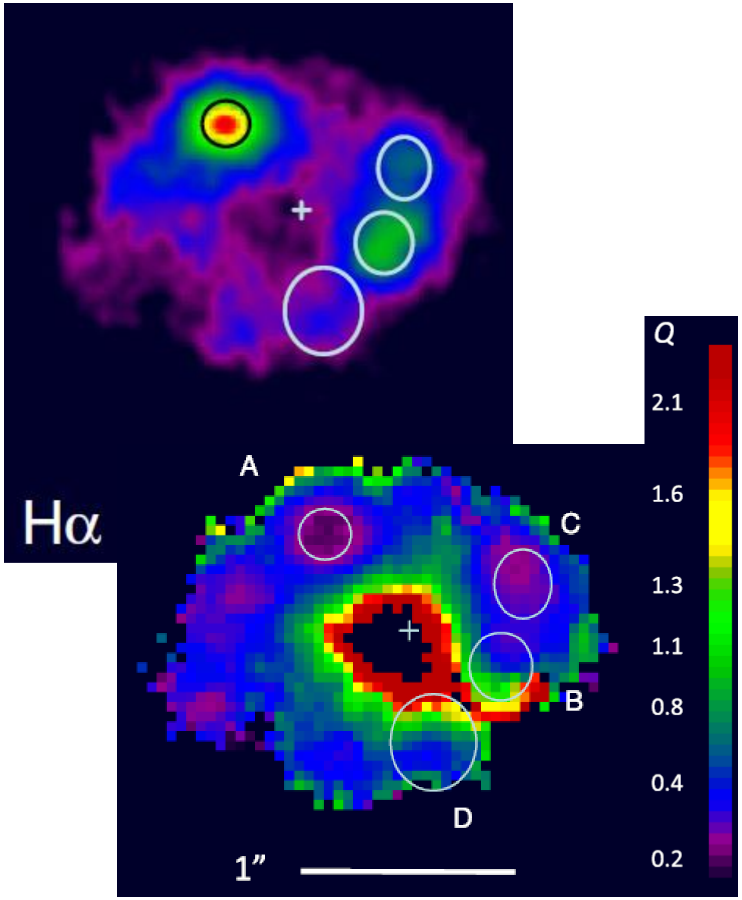
**Q ≤ 1 in the observations.**
**Q > 1 in our simulations.**

But, an unstable state cannot last long…

# Toomre instability

- In observations,



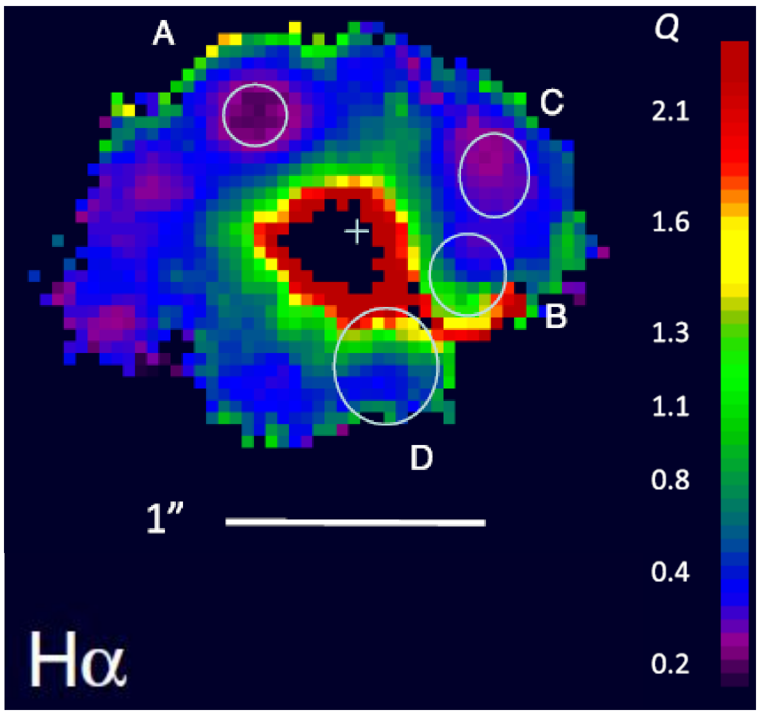




**Genzel et al. (2011) with SINFONI**

- Gas density may be overestimated in their observations?
- There are a lot of unresolved clumps smeared in discs? (Fisher et al. 2016)

# Obs. vs. sims.

- Toomre Q of gas component.
  - Too low in the obs.

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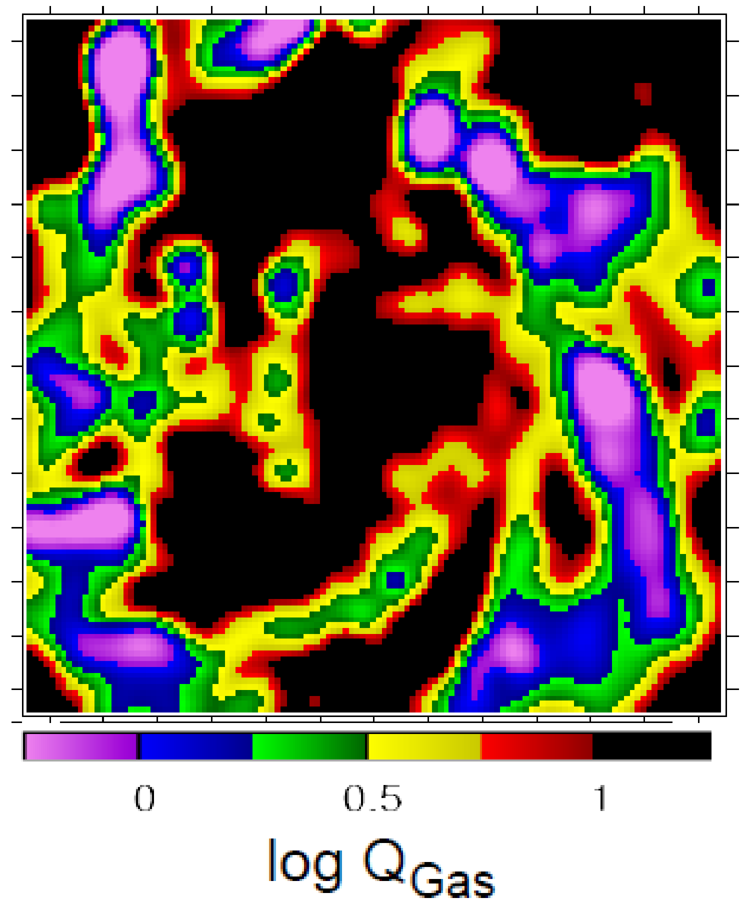

# Summary

- **Q>2-3 in disc (inter-clump) regions,**
- **Q<1 inside/around giant clumps.**

- **Formation of new clumps can start with Q>2-3.**

- **Clump formation is NOT NECESSARILY due to the (standard) Toomre instability.**

- Maybe induced by other mechanisms.
  - minor mergers, pre-existing clumps, cold streams, etc..

- There is tension between our sims and obs.
  - Gas density may be overestimated in observations?