Origin and structure of massive clumps in high-z disk galaxies

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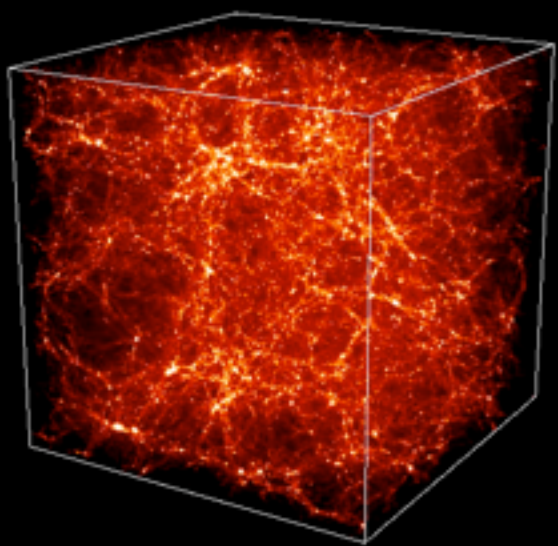
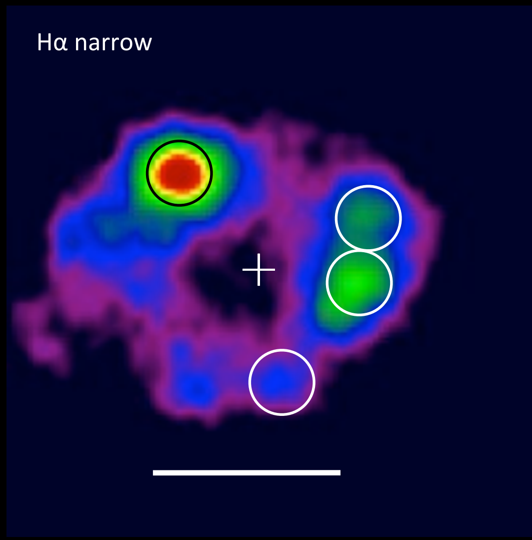
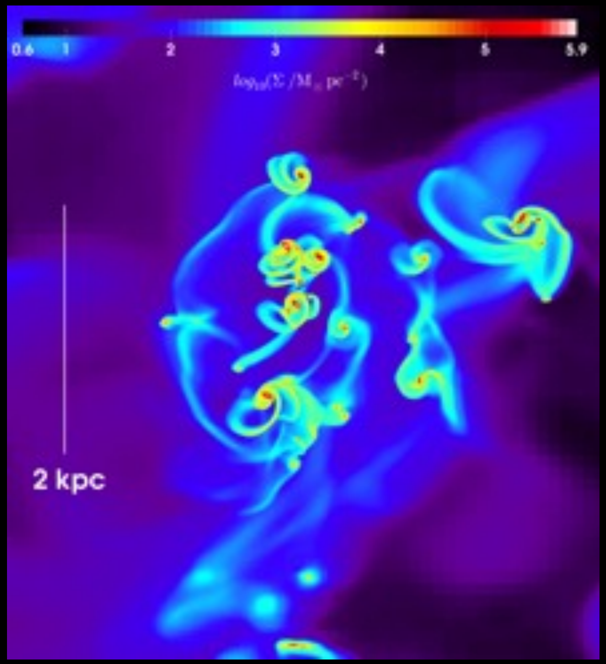
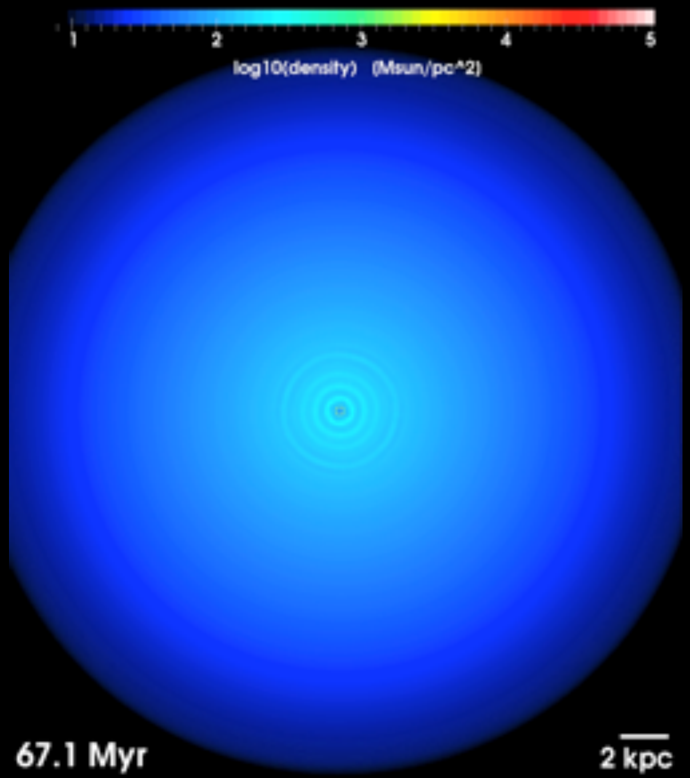
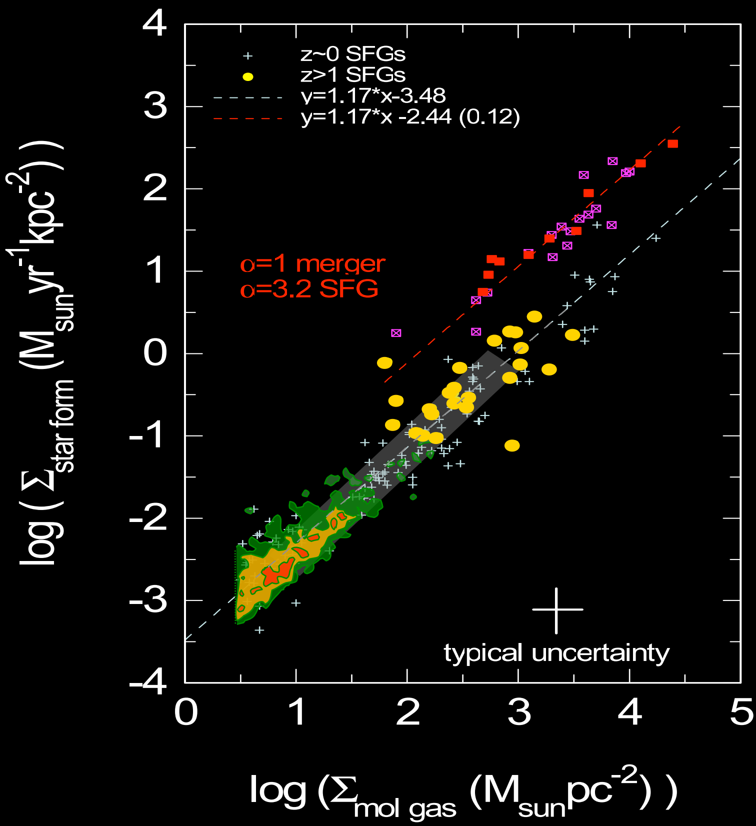
M. Behrendt, M. Schartmann,
R.Genzel, L. Tacconi, N. Förster-Schreiber,
A. Dekel, D. Ceverino + SINS





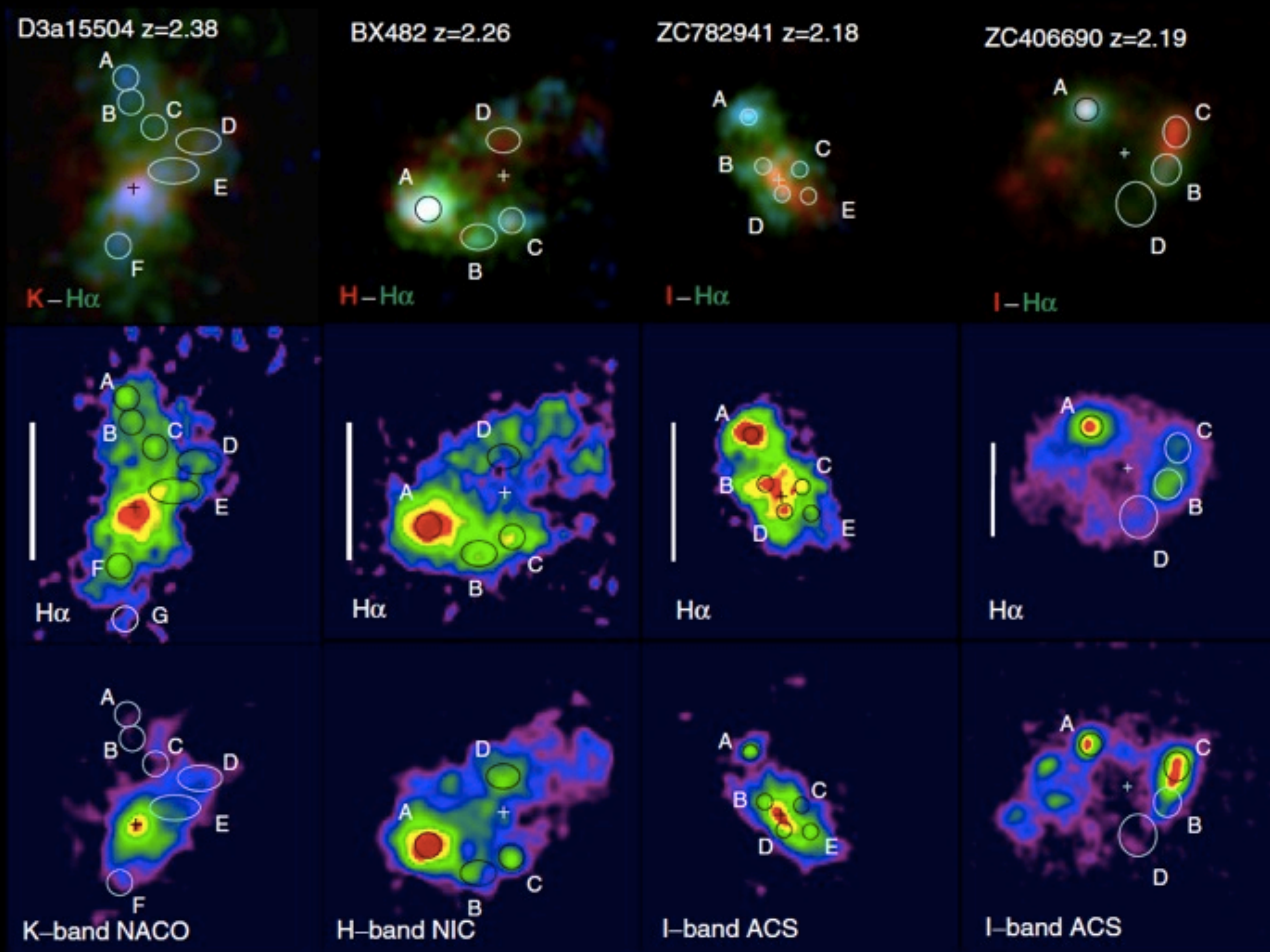


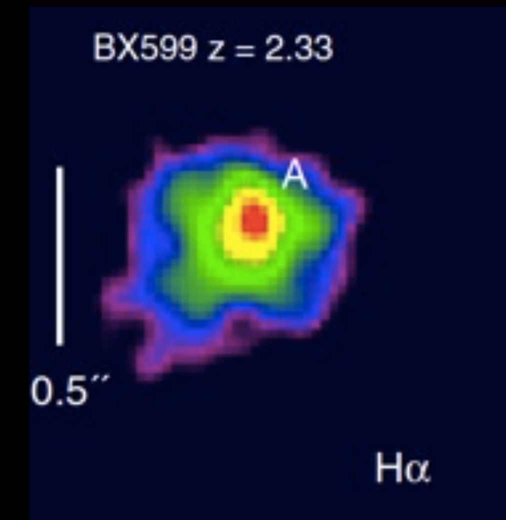




(see poster by Guang-Xing Li)

High-z, gas-rich, star-forming galaxies show kpc sized star-forming clumps





- structure + kinematics
- star formation + IMF
- outflow + mass loss
- nucleosynthesis

- globular clusters
- seed black holes
- bulge formation

(Elmegreen+04, 09, 13; Genzel+06,11; Förster-Schreiber+11, 09; Guo+ 12; Dekel & Krumholz 13; Zanella+ 15)

$$M_{clump} \approx 10^{7.5} - 10^{9.5} M_{\odot}$$

$$R_{clump} \approx 0.5 \text{ kpc - } 2 \text{ kpc}$$

Local Axisymmetric Instability

velocity dispersion

epicyclic frequency → $\propto \frac{V_{rot}}{R}$

$$Q_0 = \frac{\sigma\kappa}{\pi G \Sigma}$$

Toomre 1964

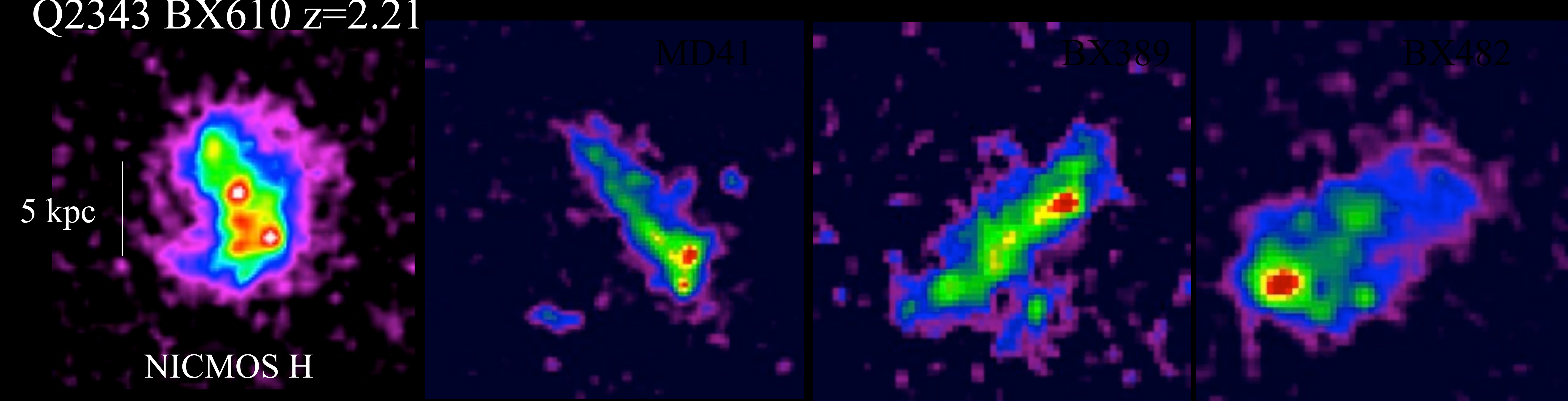
$$\begin{cases} Q_0 < 1 & \text{unstable} \\ Q_0 > 1 & \text{stable} \end{cases}$$

$$\delta \equiv M_{gas}/M_{dyn}$$

self-gravity → destabilizing

$$Q_0 = \frac{\sqrt{2}}{\delta}\frac{\sigma}{v_{rot}}$$

(e.g. Dekel+ 10,12,13,14)



Problems

- **Linear theory does not apply**
- **Do disks really stabilize for Q>1?**
- **σ does not depend on v_{rot}**
- **Most of the molecular mass is not in massive clumps**
- **Clumps should be fast rotating which is not observed.**
- **Clumps appear to not be virialized**

Violent disk instability

$$Q_0 = \frac{\sqrt{2}}{\delta}\left(\frac{\sigma}{v_{rot}}\right) \approx 1$$

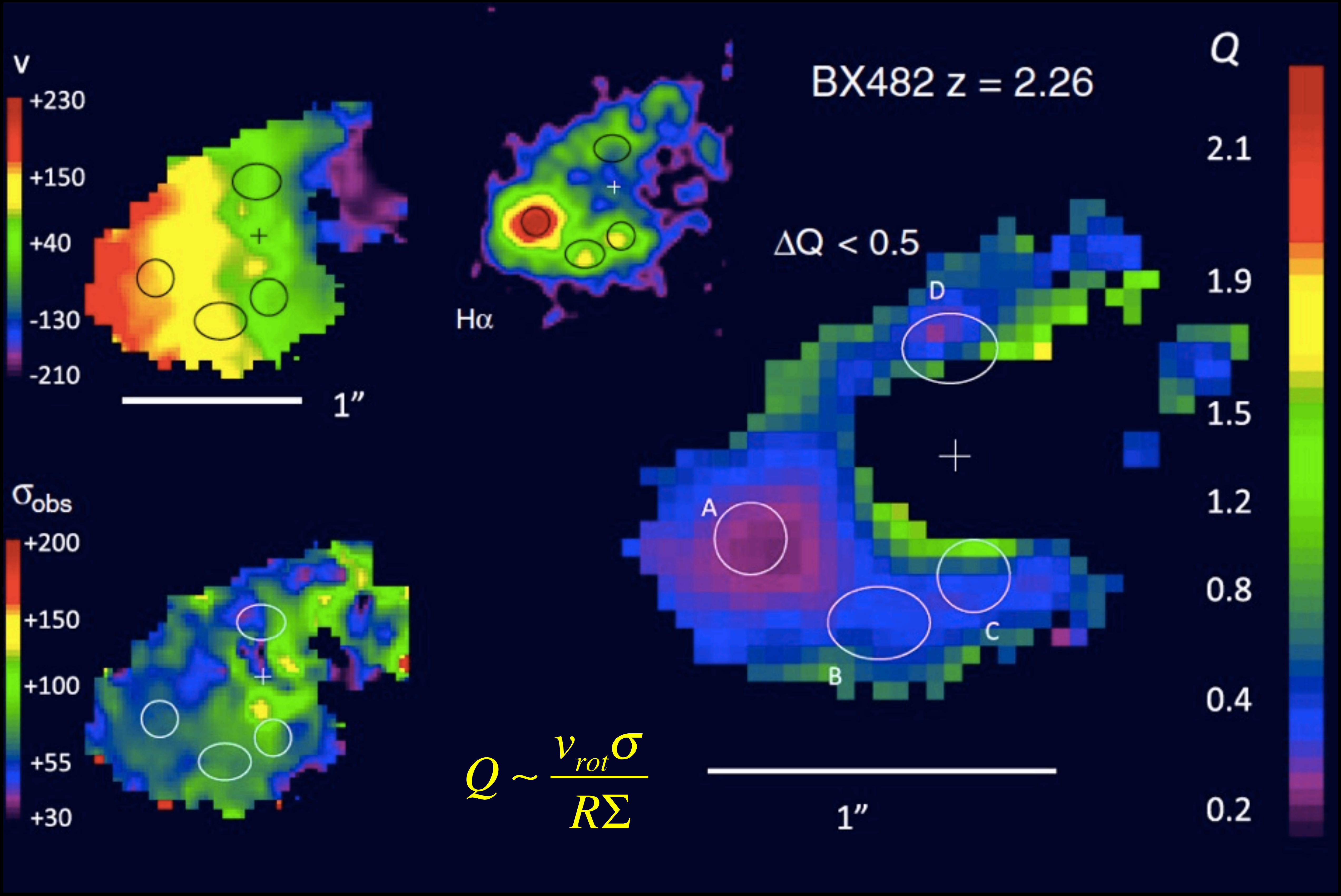
Tacconi+13 ↓ $\delta \equiv M_{gas} / M_{dyn} \approx 0.3$

$$\frac{\sigma}{v_{rot}} = \frac{\delta}{\sqrt{2}} \approx 0.2 \qquad \frac{\lambda}{R_{disk}} = \delta \approx 0.3$$

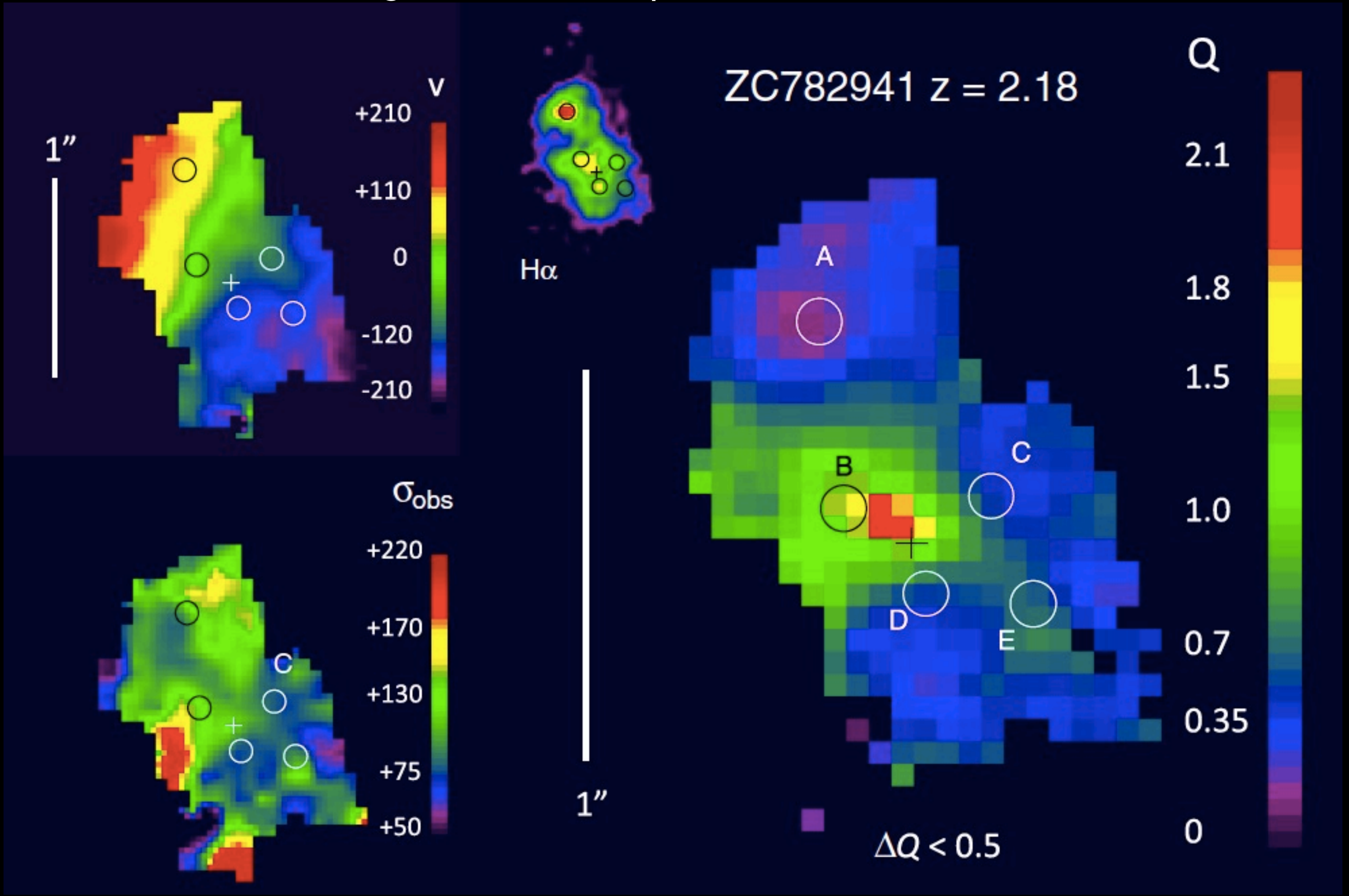
$$\frac{M_{clump}}{M_{disk}} \approx \delta^2 \approx 0.1$$

(Toomre 1964, Tacconi+ 10, Ceverino+ 10, Genzel+11, Behrendt+ 15; Tamburello+ 15)

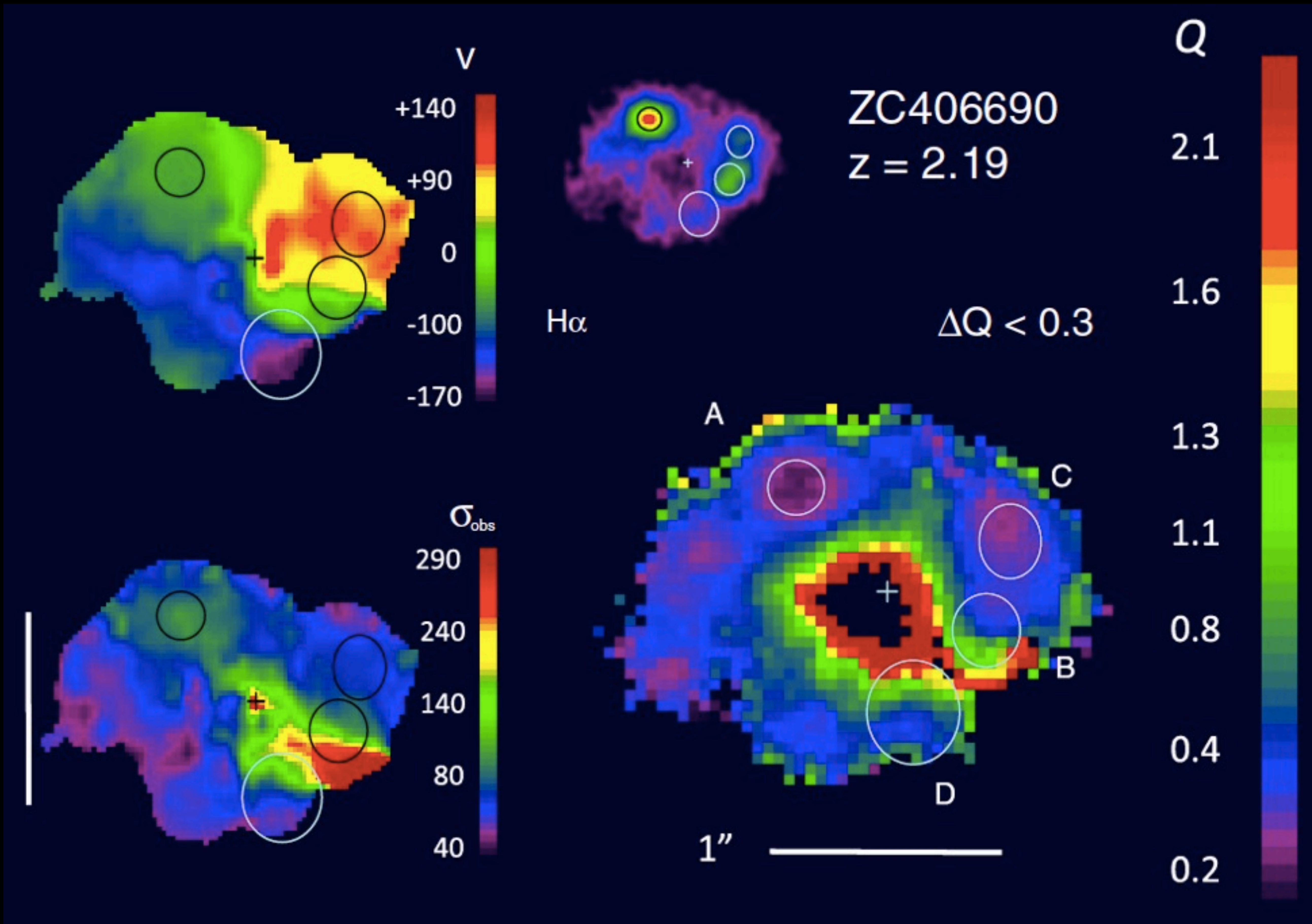
No signature of clumps in kinematical data



No signature of clumps in kinematical data

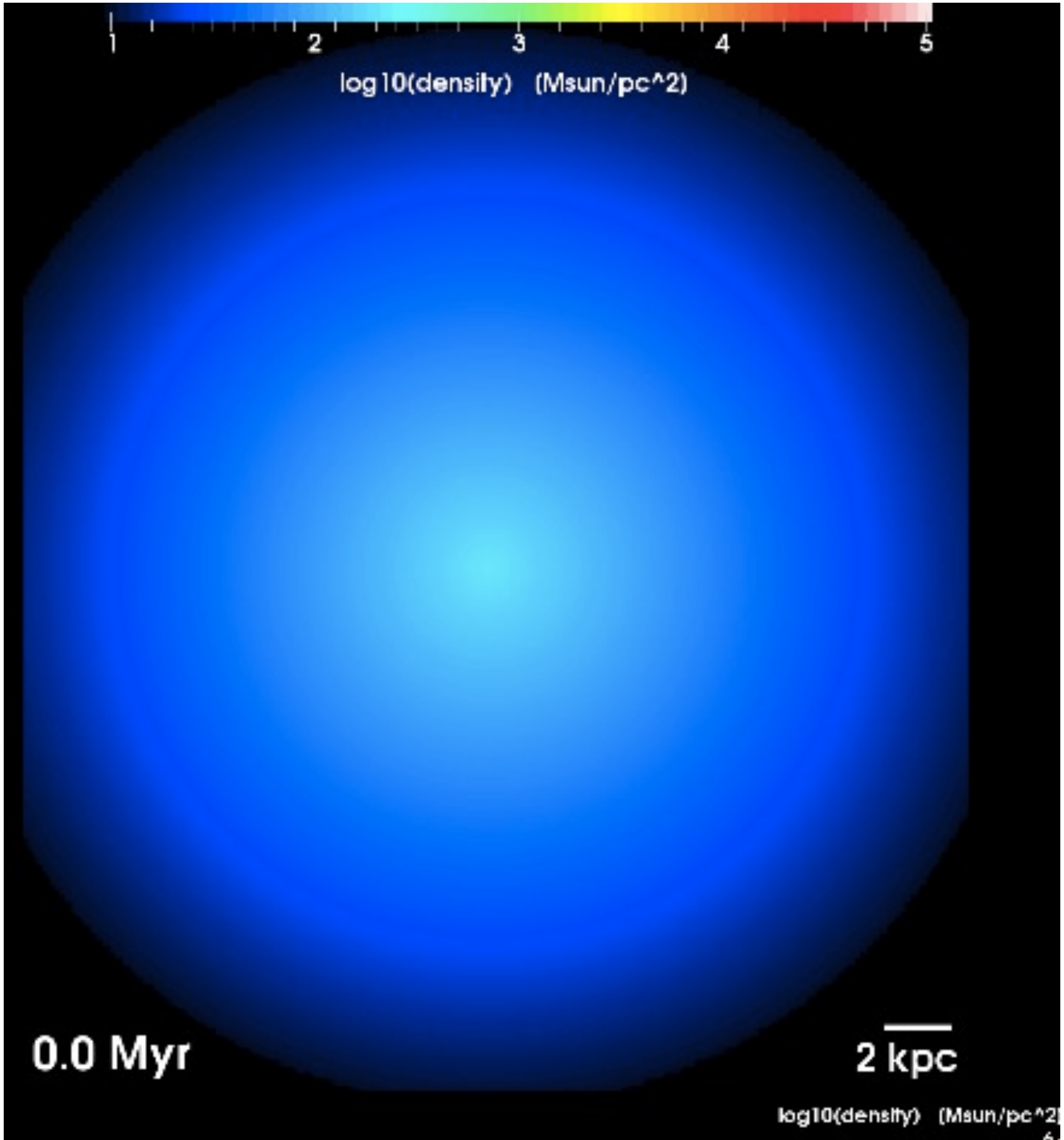


No signature of clumps in kinematical data



Unstable disk simulation

(Behrendt, Burkert & Schartmann, 15)



Main Properties:

exponential surface density

$R_{disc} = 16\,kpc$

$h = 5.26\,kpc$

$T = 10^4 K$

$M_{disc} = 2.7 \times 10^{10} M_\odot$

$M_{DM} = 1.03 \times 10^{11} M_\odot$

AMR Refinement:

RAMSES

$N_J = 19$

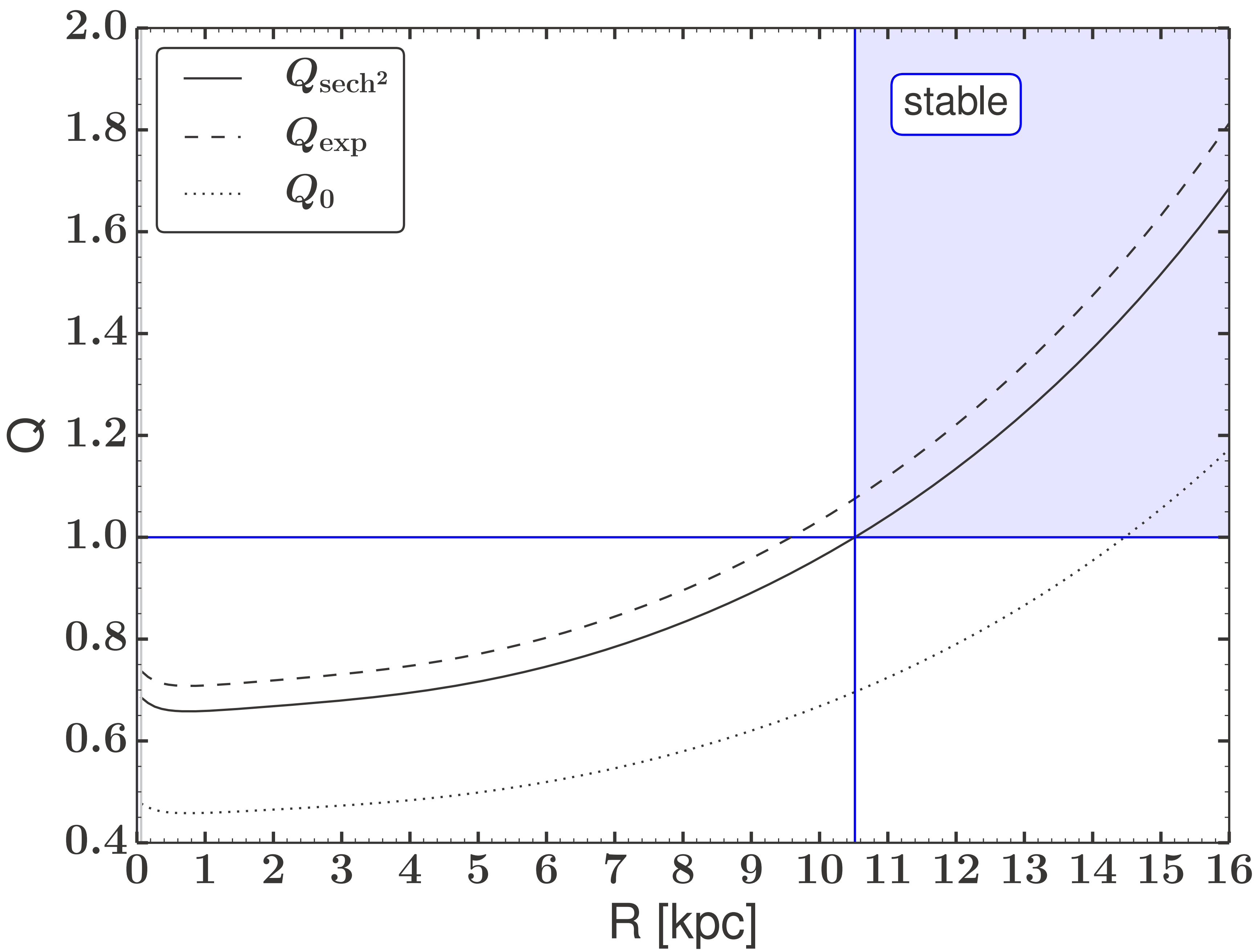
$\Delta_{\max} = 187.5\,pc$

$\Delta_{\min} = 2.9\,pc$

$\approx z_0, 5 \times resolved$

see also Bournaud+,14

Instability Parameter



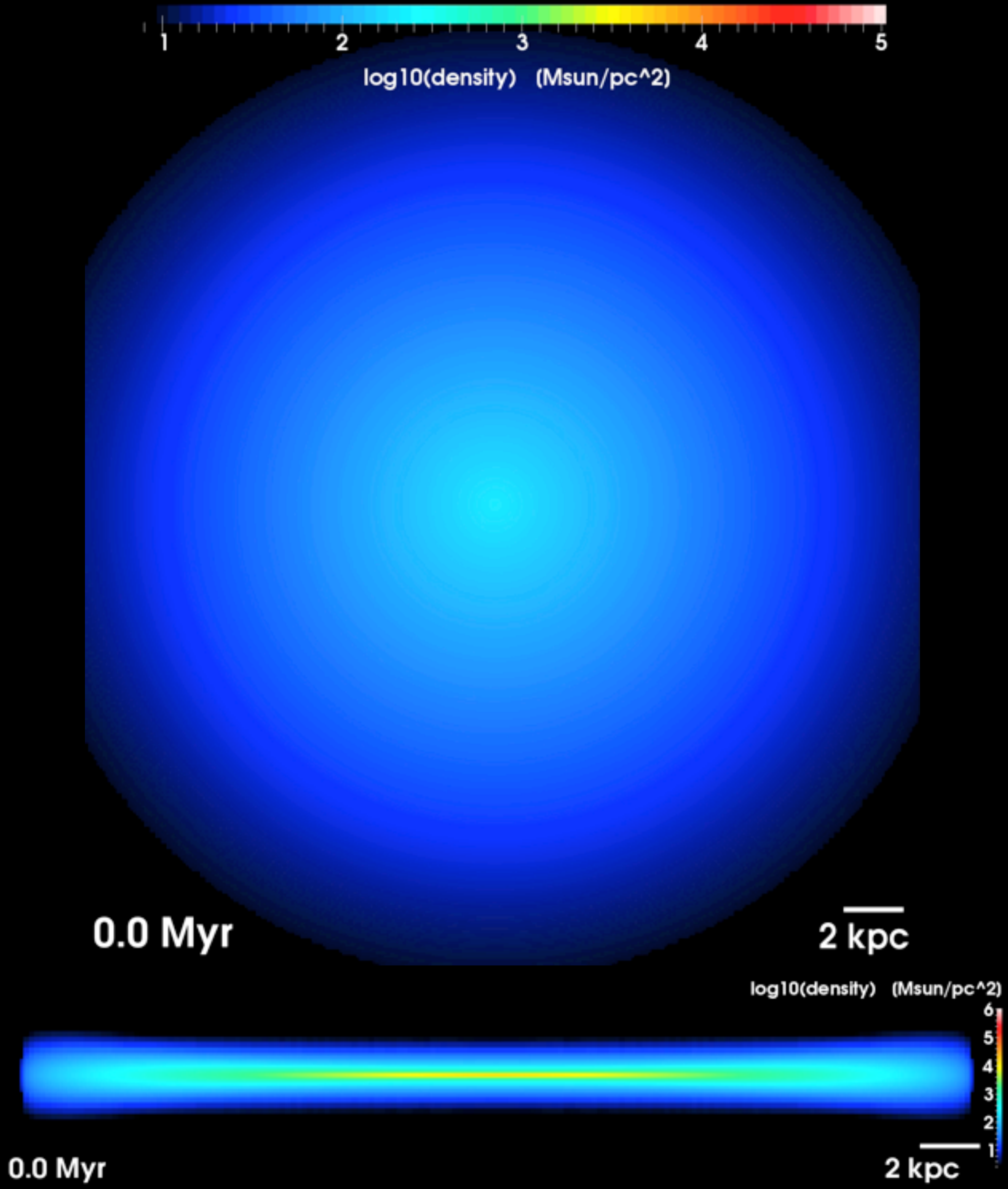
$$\tau = \frac{1}{\kappa}\frac{Q}{\sqrt{1-Q^2}} \xrightarrow{Q=1} \infty$$

$\delta = 0.3$

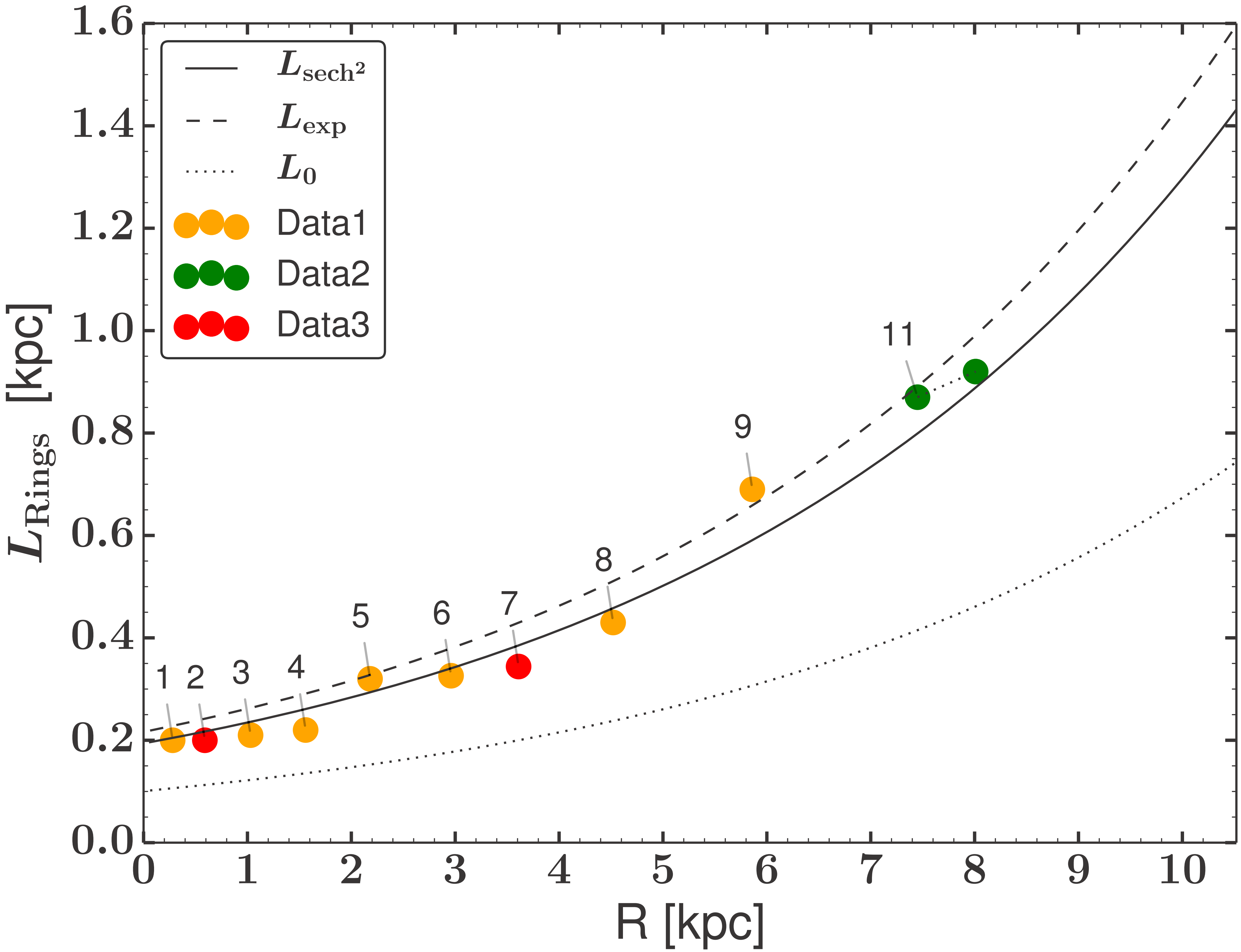
$M_{clump} \approx 1-3\cdot 10^9\, M_\odot$

$R_{clump} \approx 0.3\cdot R$

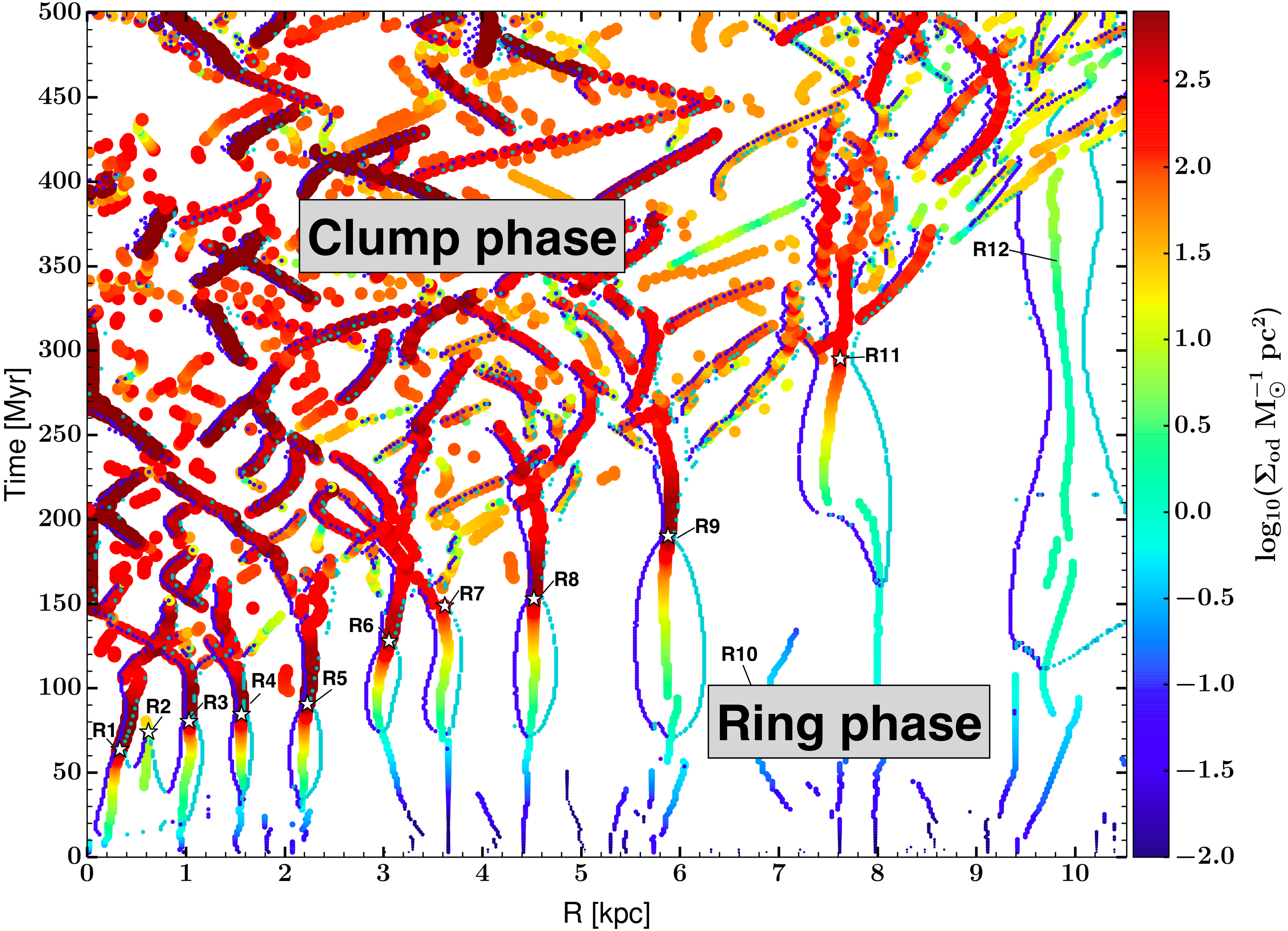
~ 10 Clumps


1
2
3
4
5
log10(density) (Msun/pc^2)
0.0 Myr
2 kpc
log10(density) (Msun/pc^2)
6
5
4
3
2
1
0.0 Myr
2 kpc

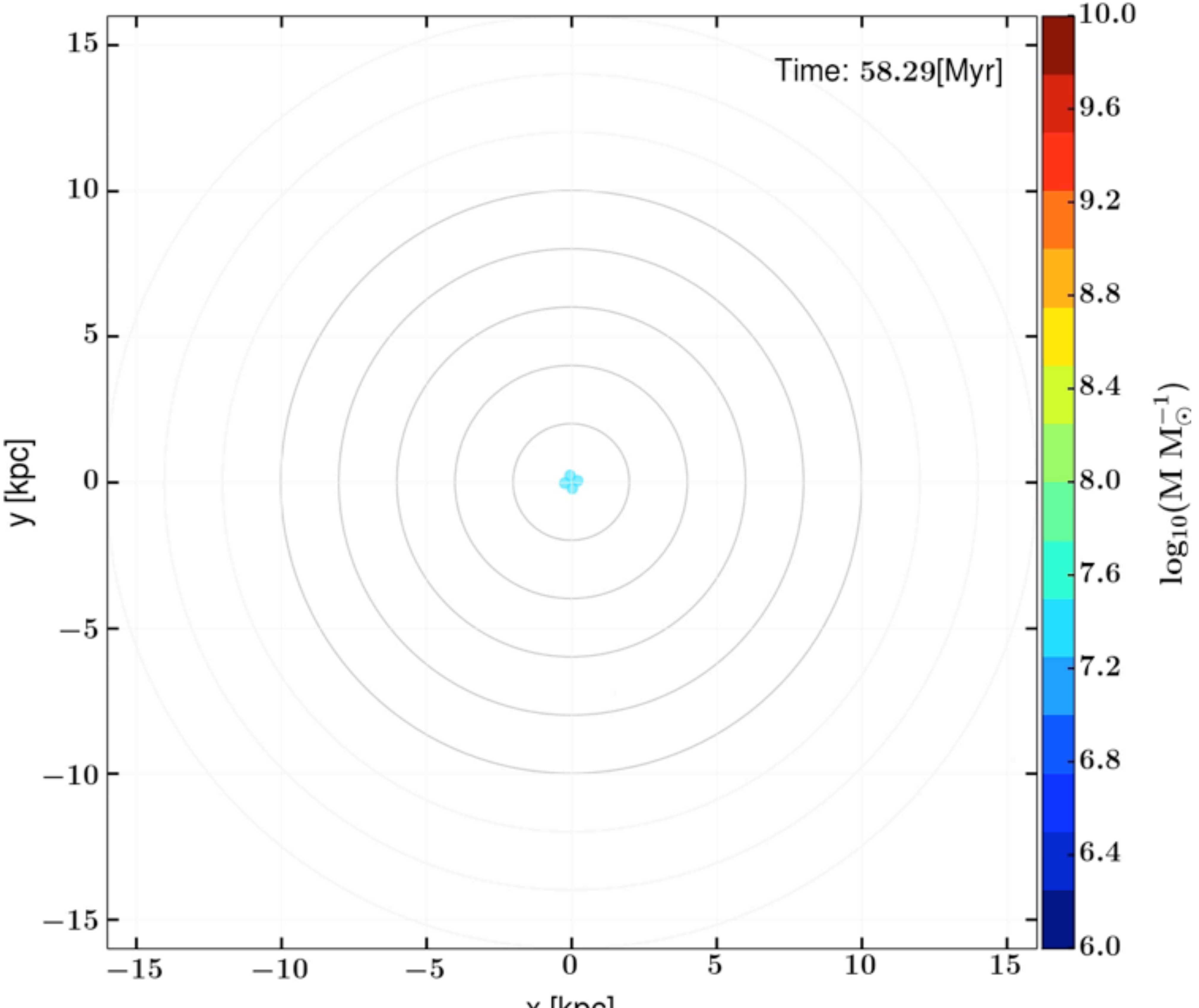
Ring Dimensions



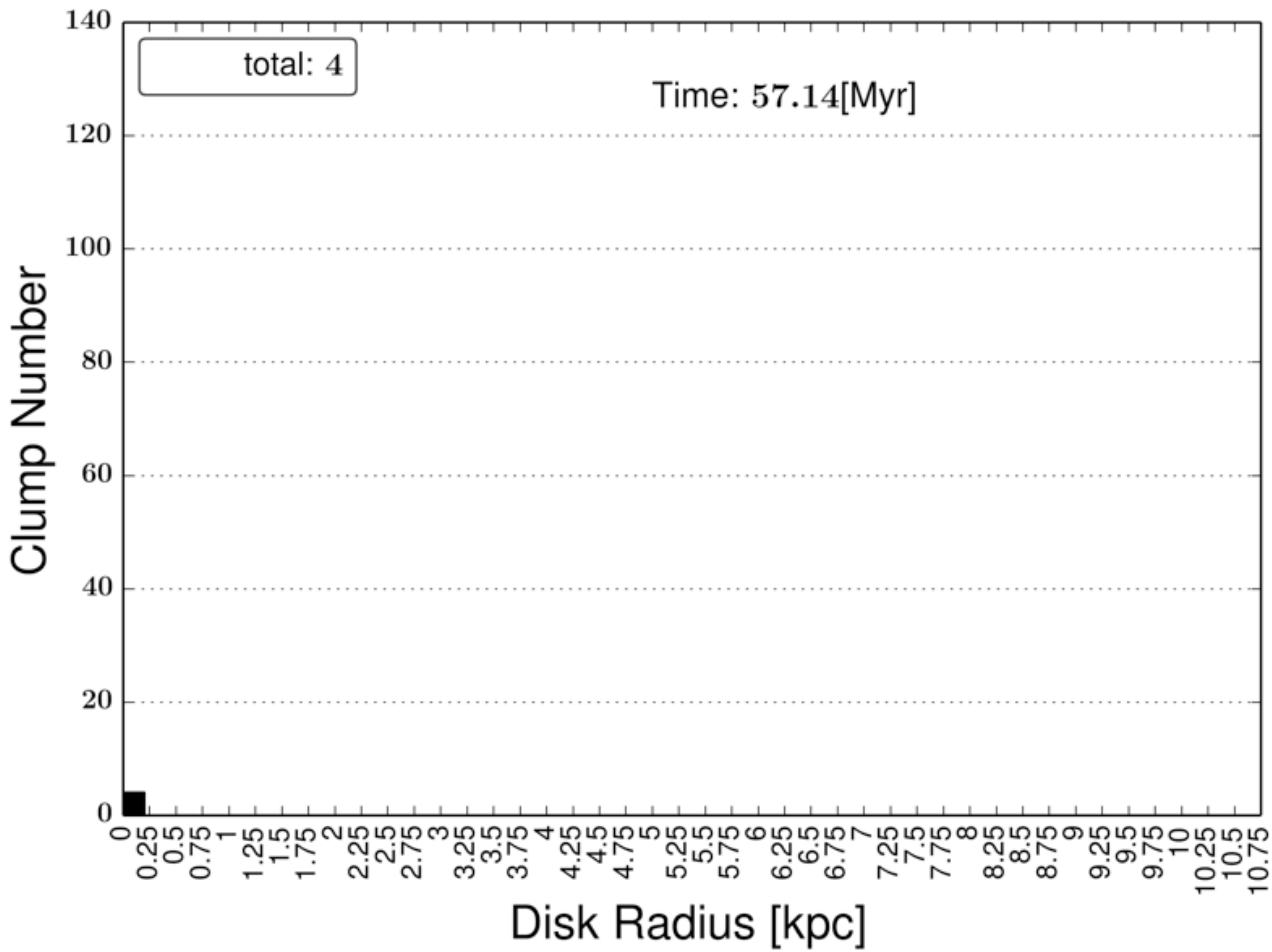
Relative Maxima

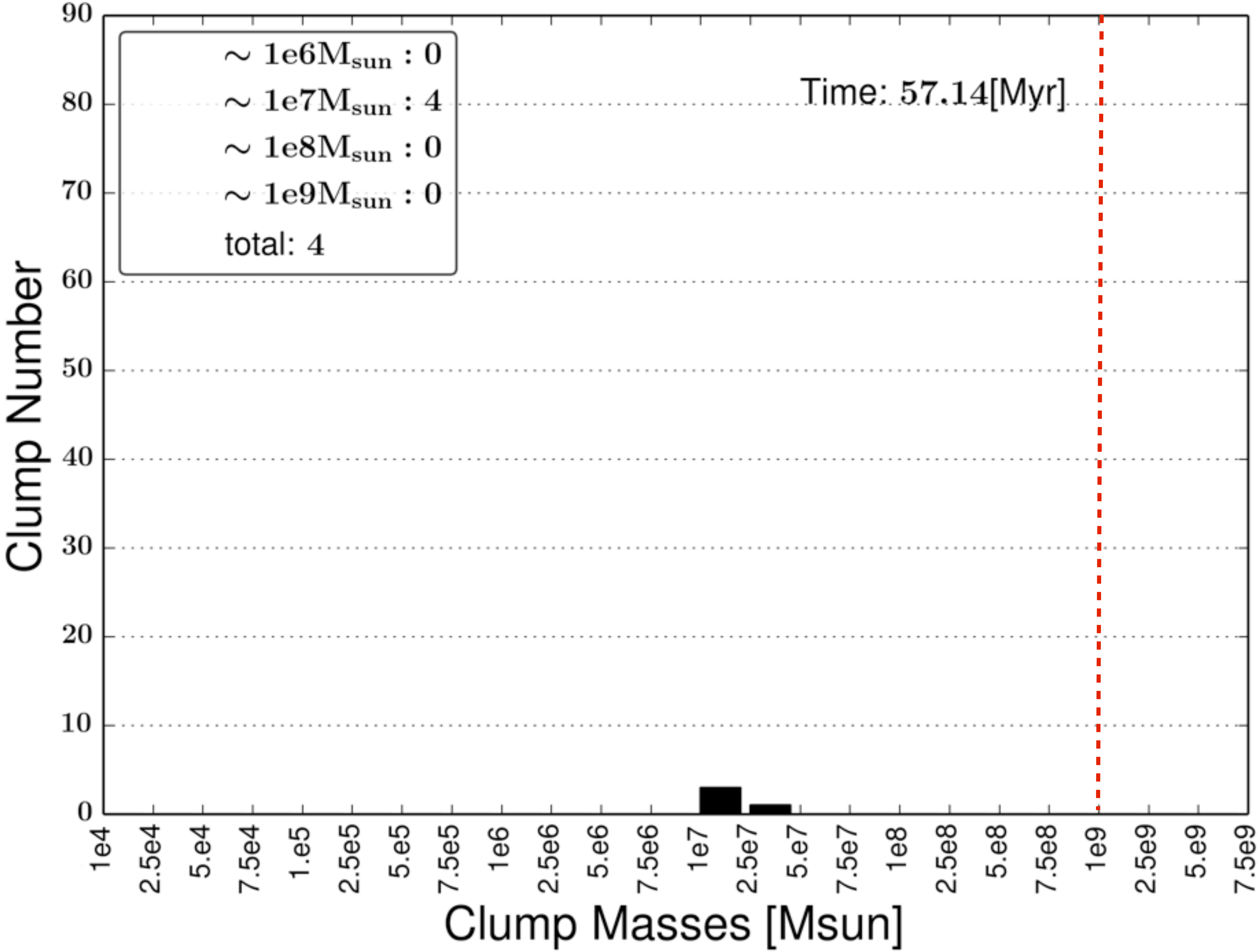


Physics of clump formation

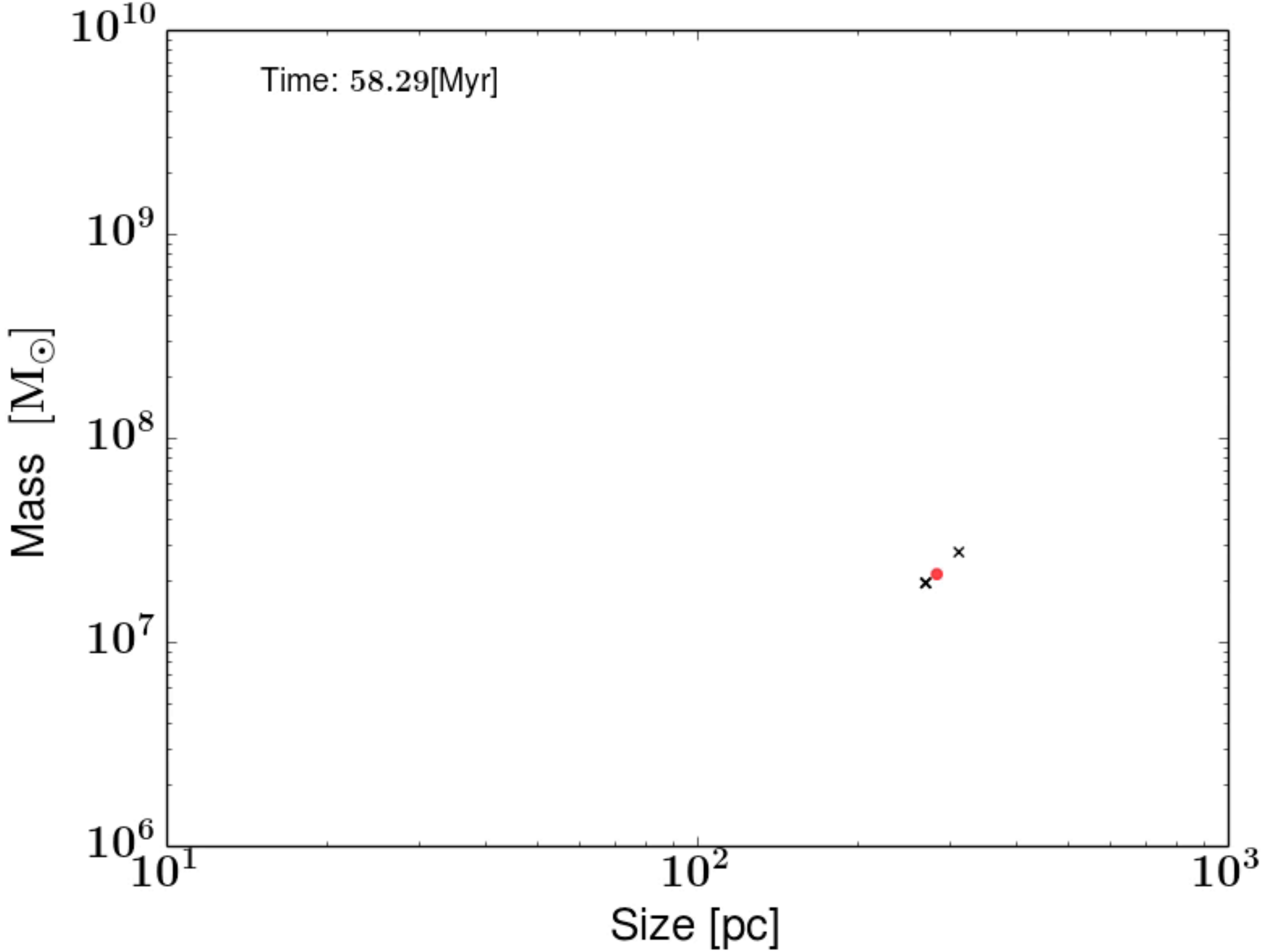


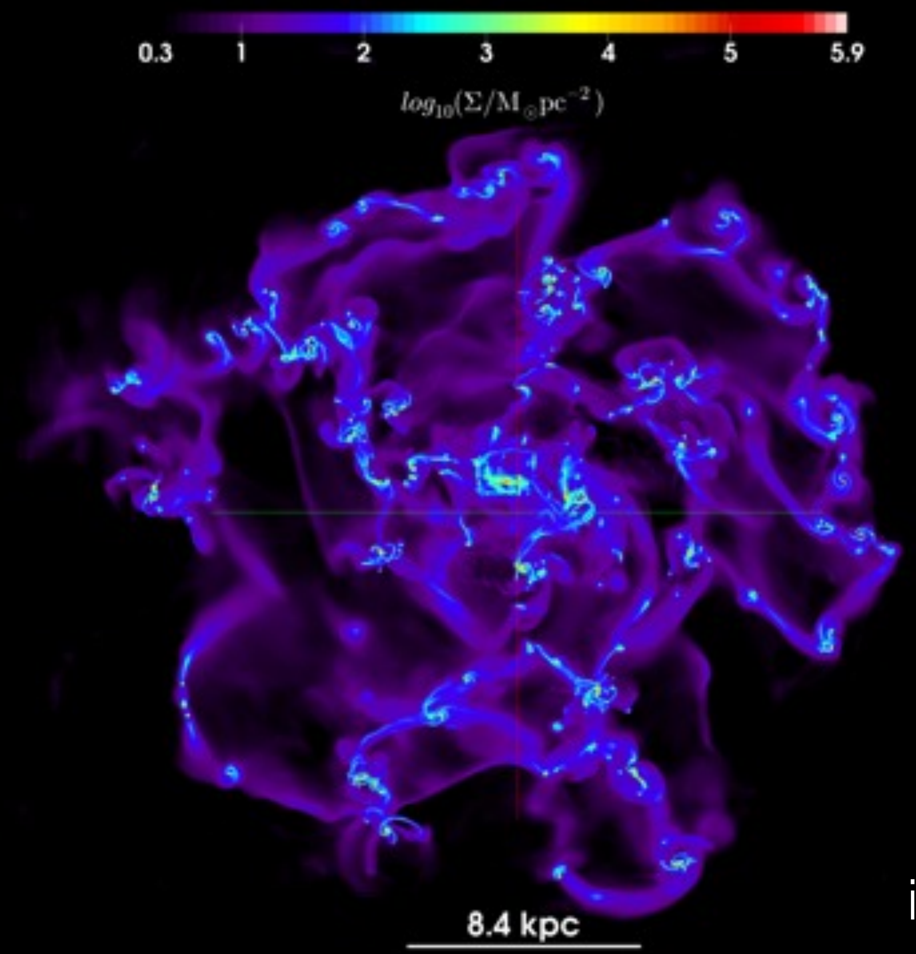
Physics of clump formation





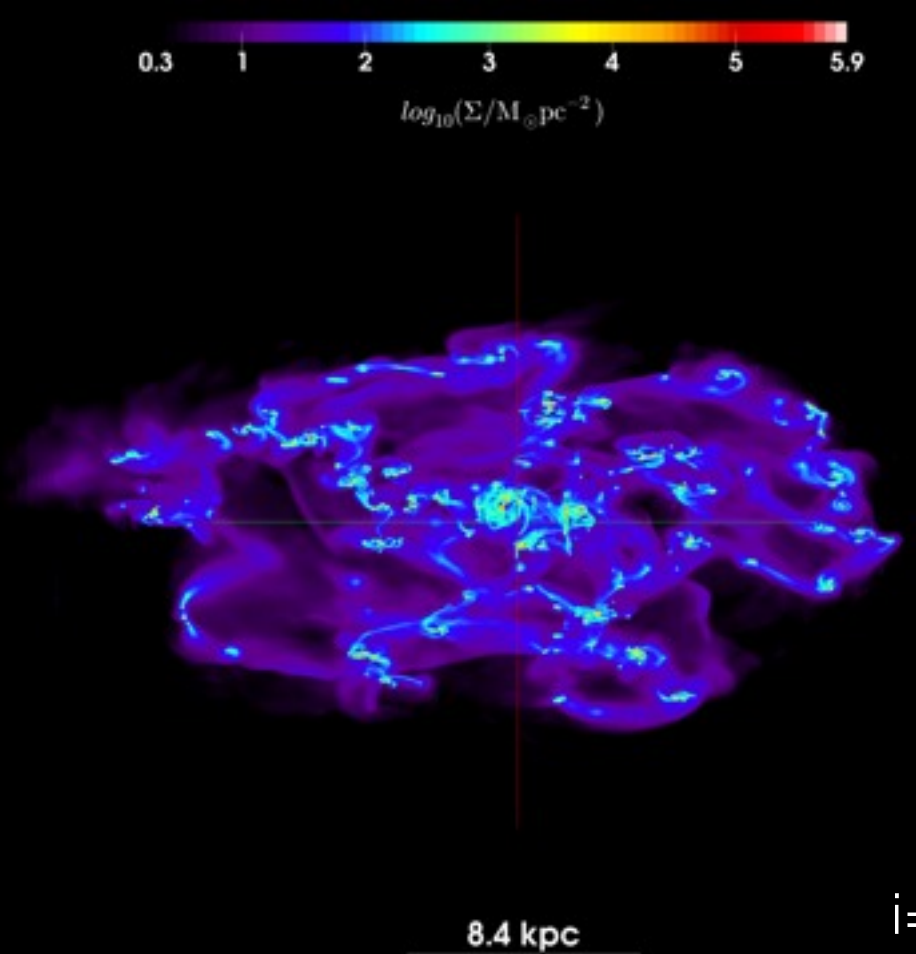
~ 1e6Msun : 0
~ 1e7Msun : 4
~ 1e8Msun : 0
~ 1e9Msun : 0
total: 4
Time: 57.14[Myr]
Clump Number
Clump Masses [Msun]
0
10
20
30
40
50
60
70
80
90
1e4
2.5e4
5.e4
7.5e4
1.e5
2.5e5
5.e5
7.5e5
1e6
2.5e6
5.e6
7.5e6
1e7
2.5e7
5.e7
7.5e7
1e8
2.5e8
5.e8
7.5e8
1e9
2.5e9
5.e9
7.5e9


Time: 58.29[Myr]
Mass [M⊙]
Size [pc]
10^10
10^9
10^8
10^7
10^6
10^1
10^2
10^3

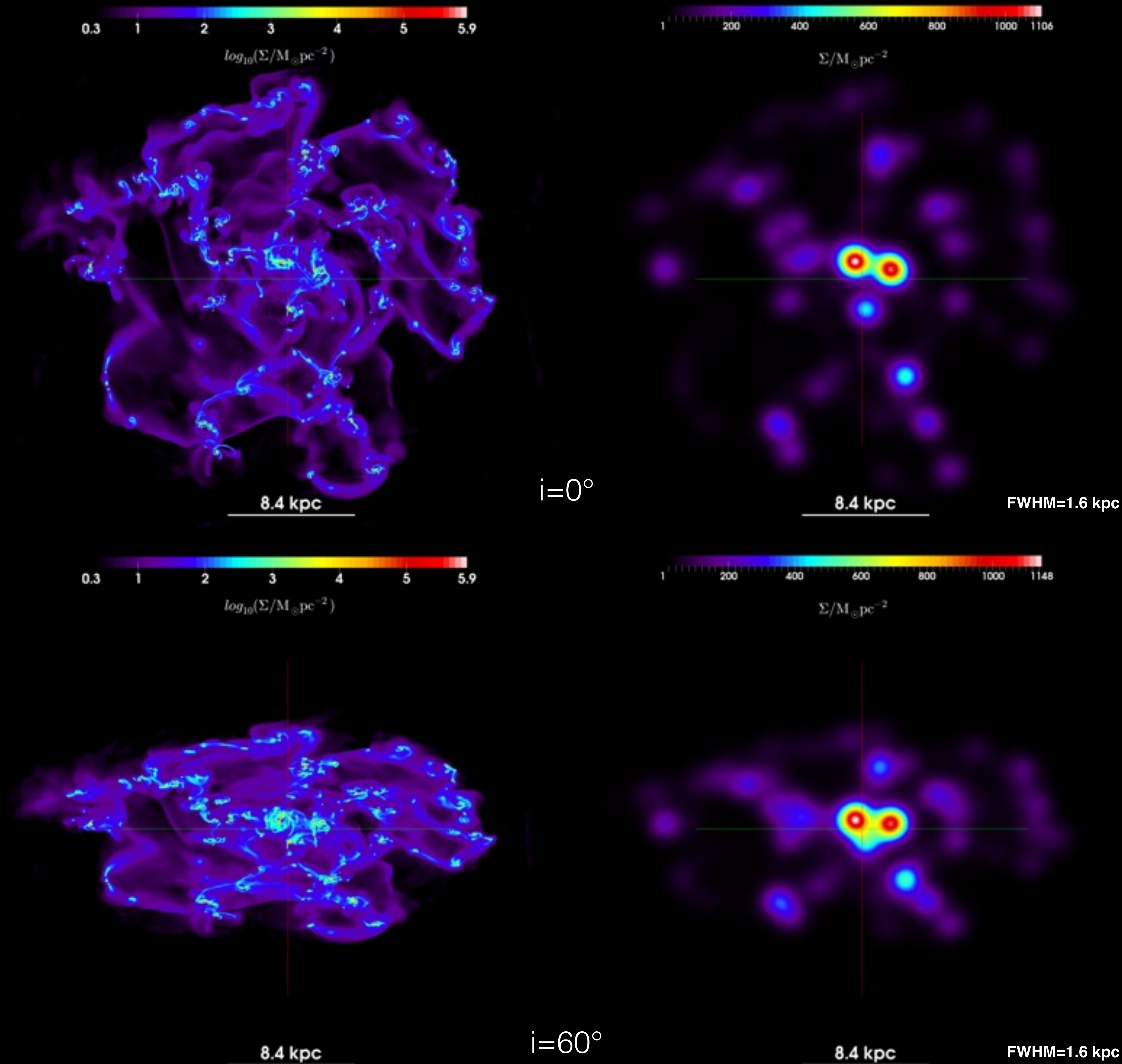


i=0°

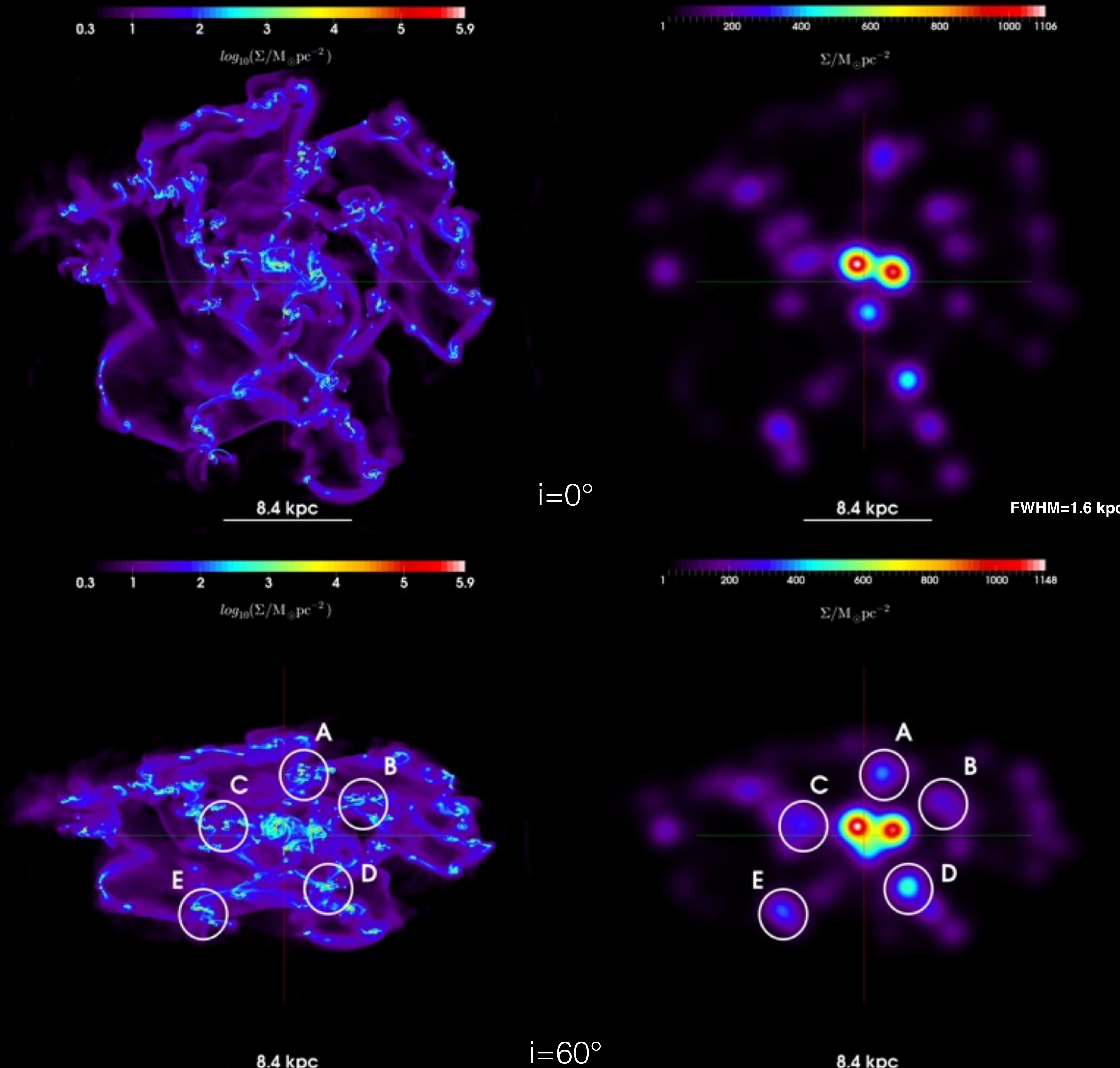
Surface Density



i=60°

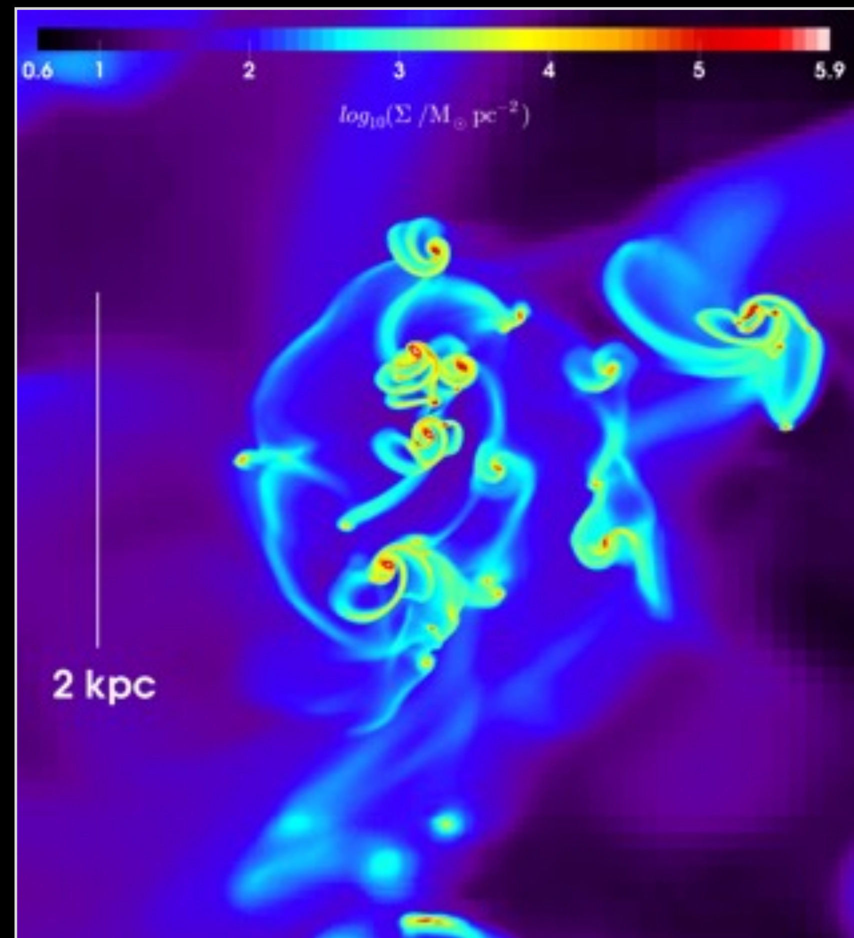


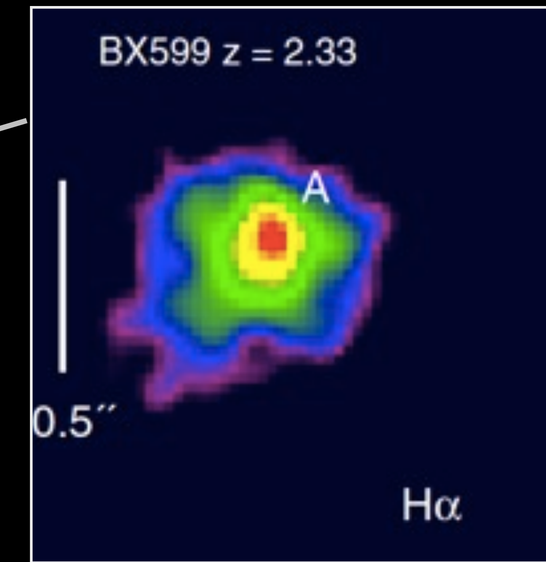
Surface Density

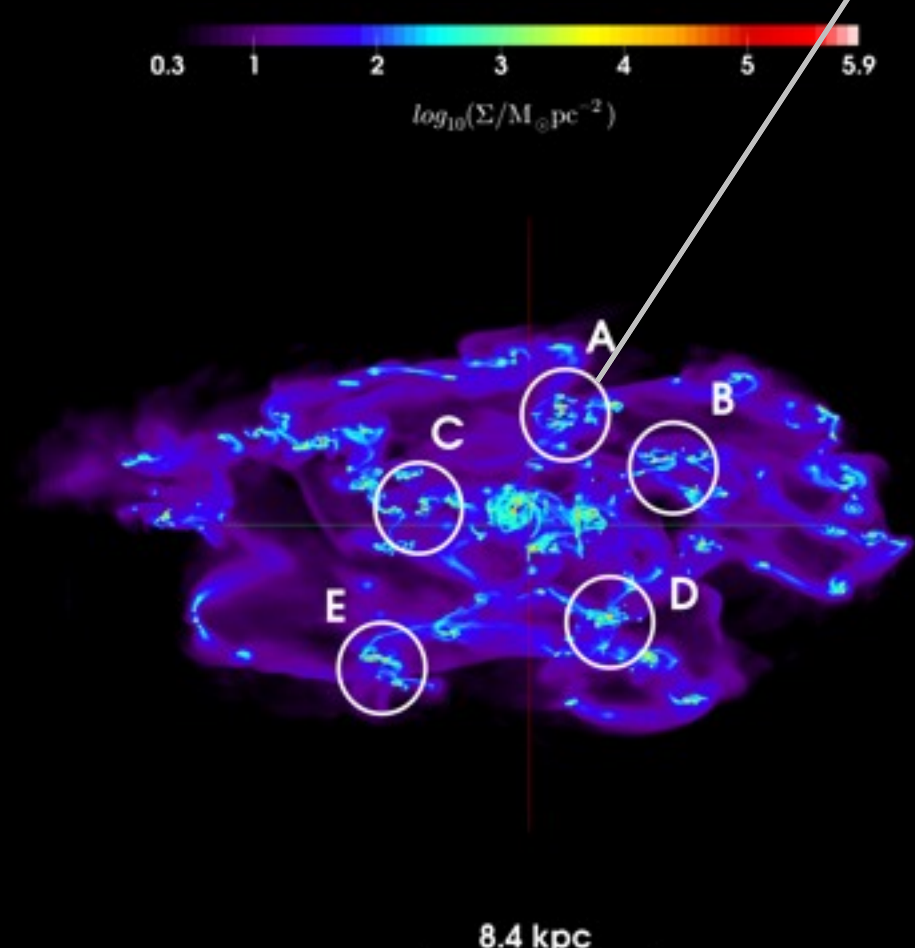


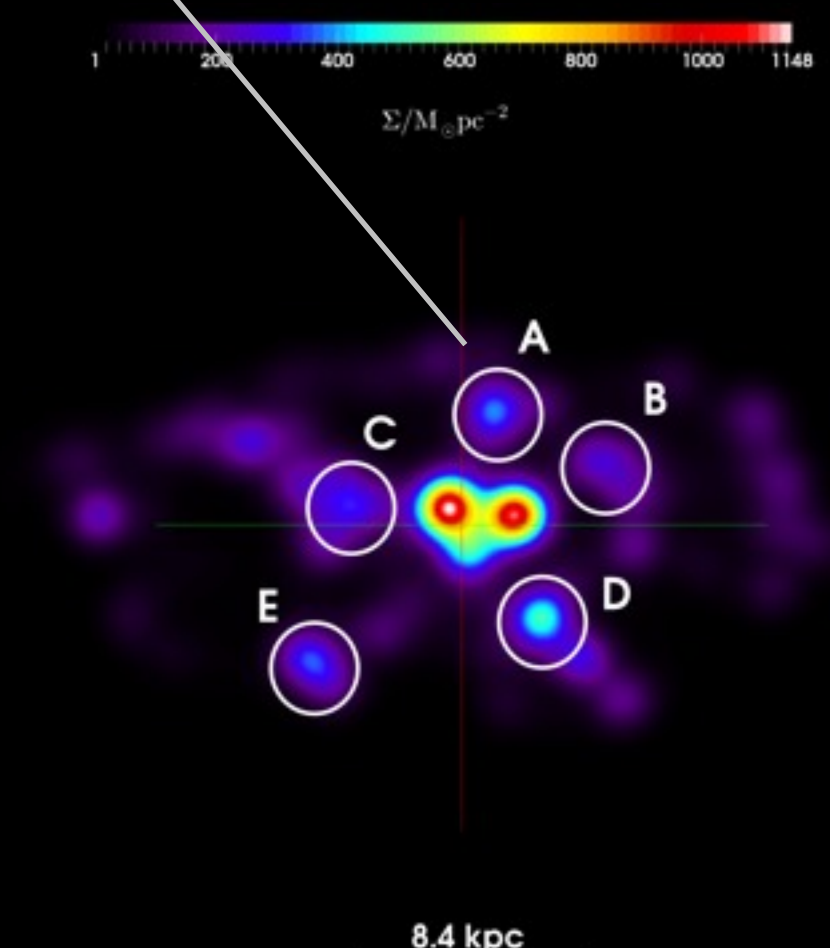
Surface Density

Surface Density

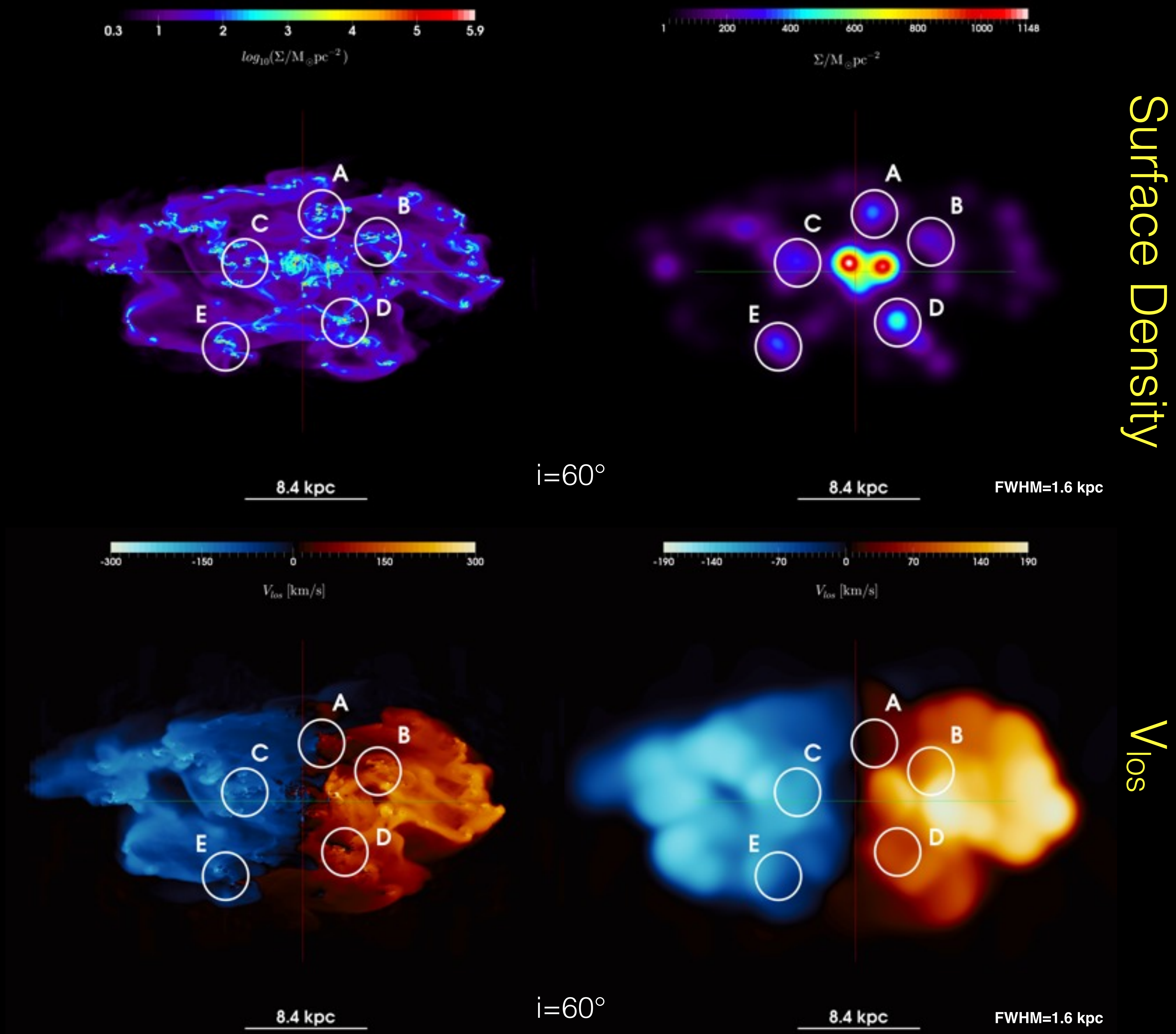




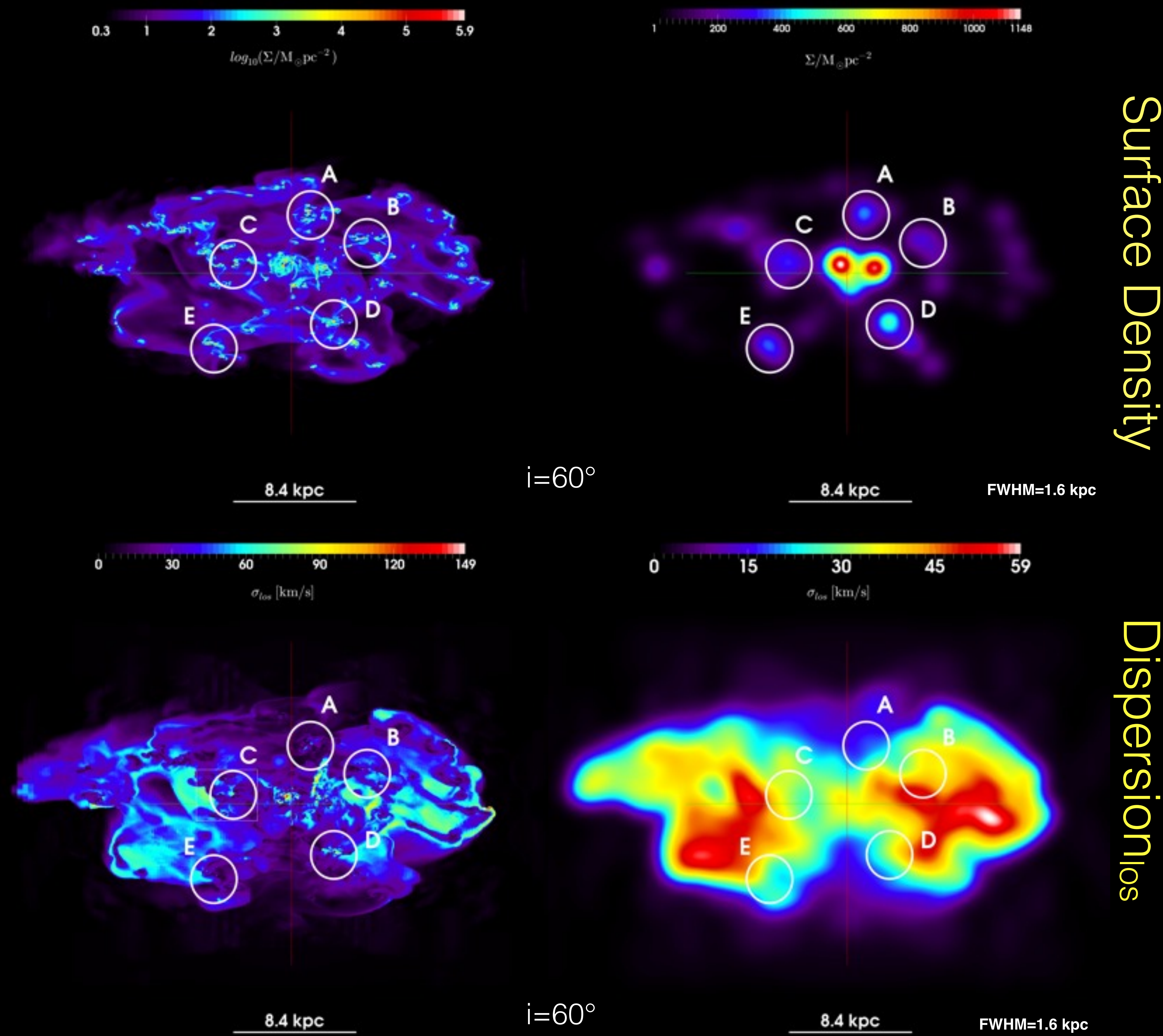


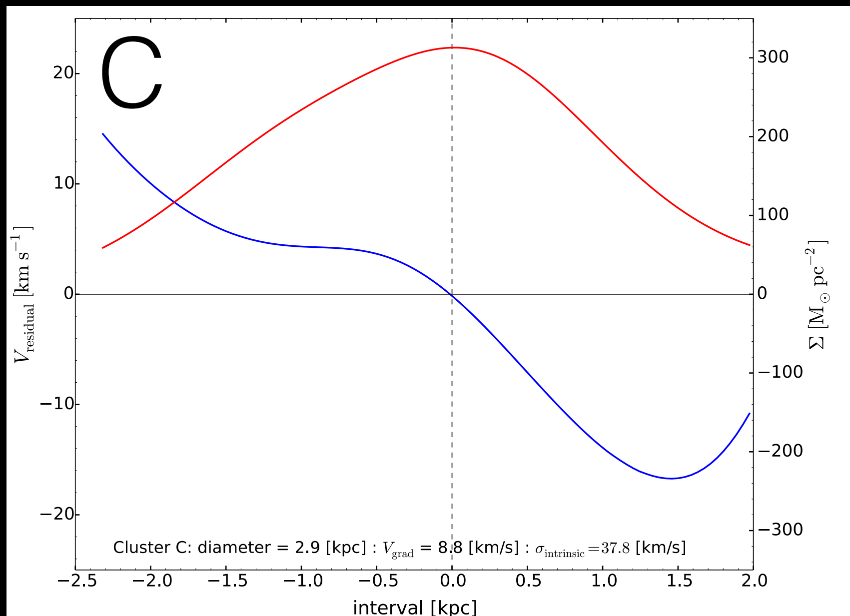


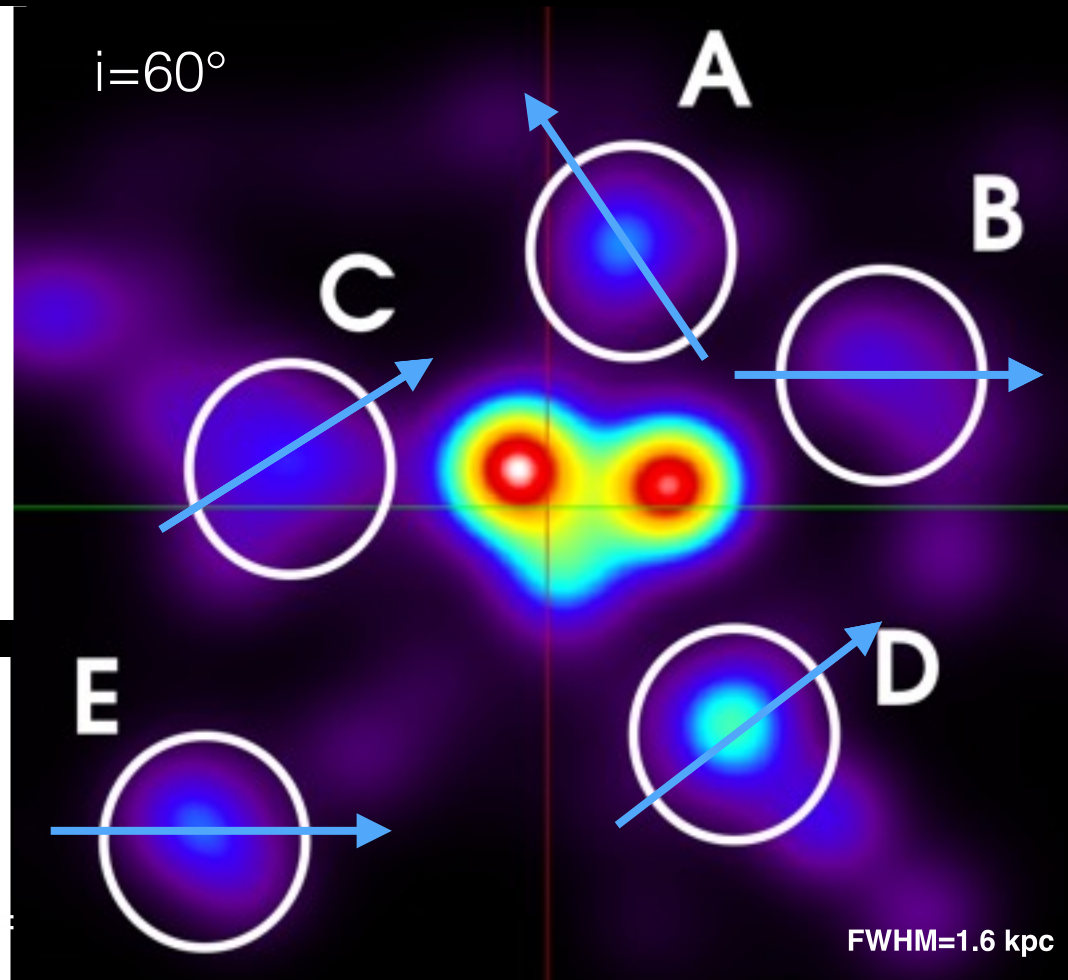
i=60°

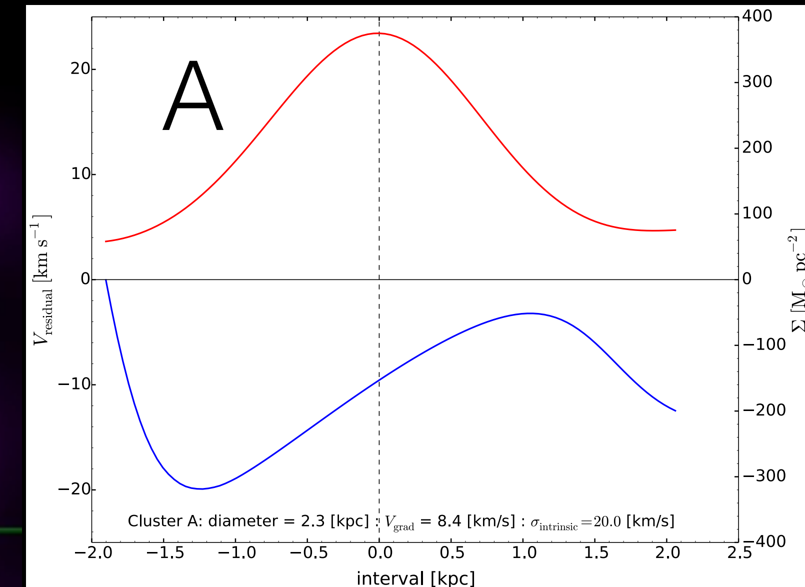


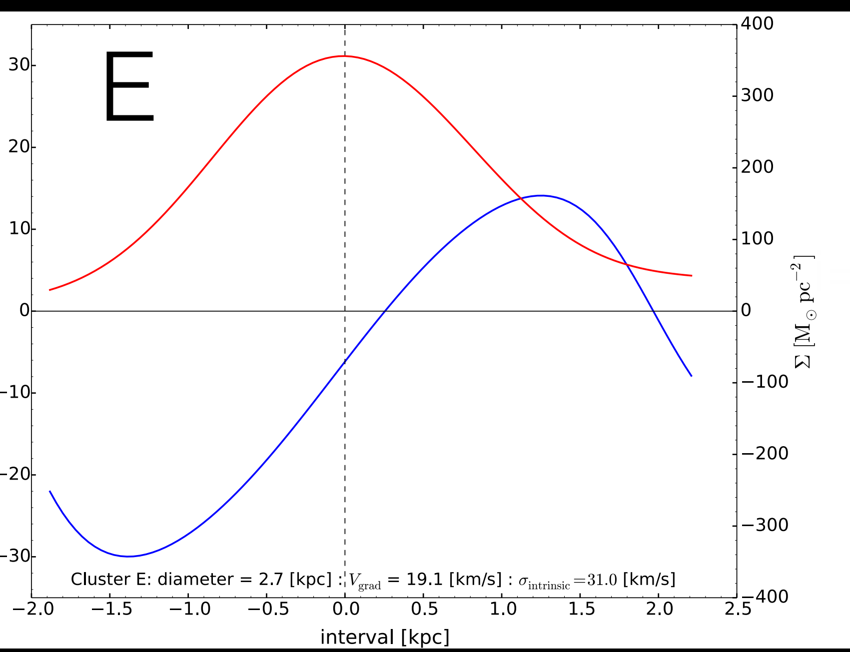
0.3 1 2 3 4 5 5.9
$log_{10}(\Sigma/M_\odot pc^{-2})$
1 200 400 600 800 1000 1148
$\Sigma/M_\odot pc^{-2}$
Surface Density
A
B
C
D
E
8.4 kpc
i=60°
FWHM=1.6 kpc
-300 -150 0 150 300
V_{los} [km/s]
-190 -140 -70 0 70 140 190
V_{los} [km/s]
V_{los}

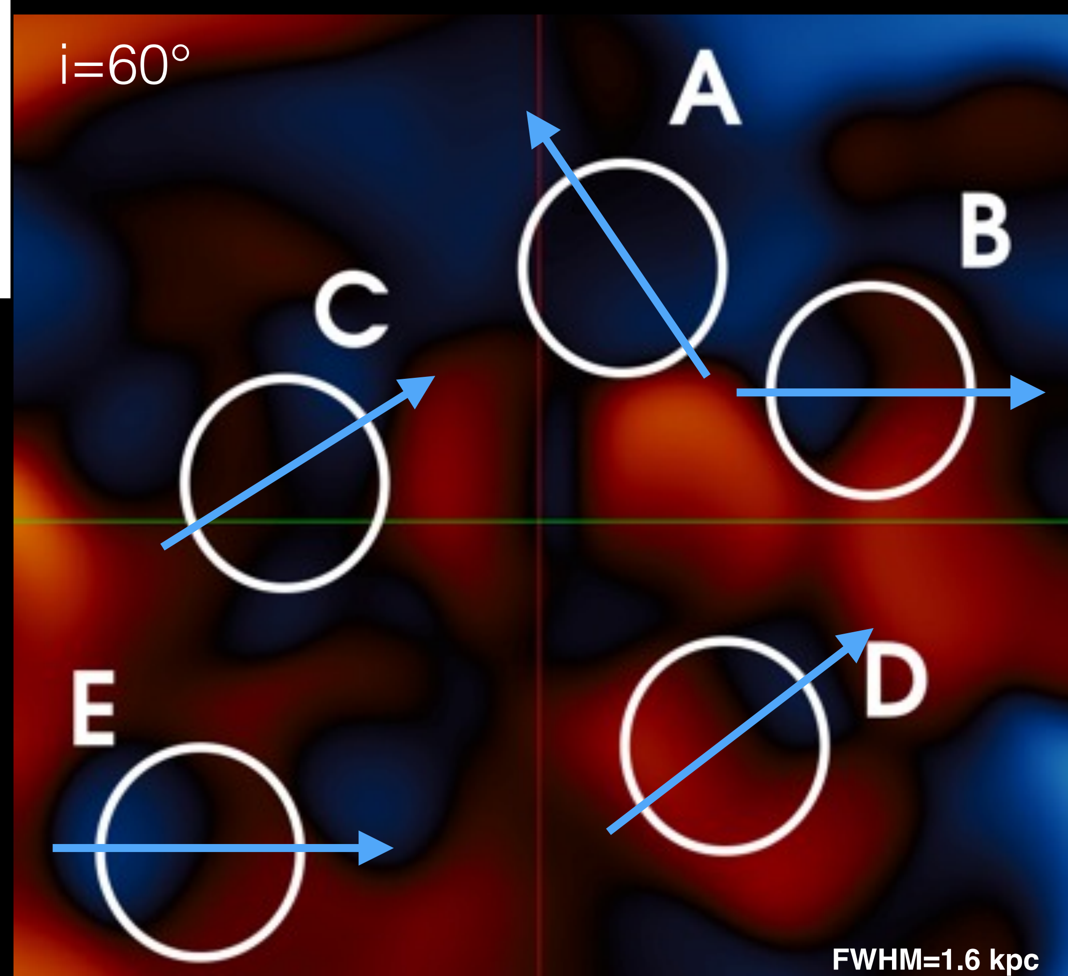

$log_{10}(\Sigma/M_\odot pc^{-2})$
$\Sigma/M_\odot pc^{-2}$
A
B
C
D
E
8.4 kpc
i=60°
FWHM=1.6 kpc
Surface Density
σ_{los} [km/s]
σ_{los} [km/s]
8.4 kpc
i=60°
FWHM=1.6 kpc
Dispersion$_{los}$

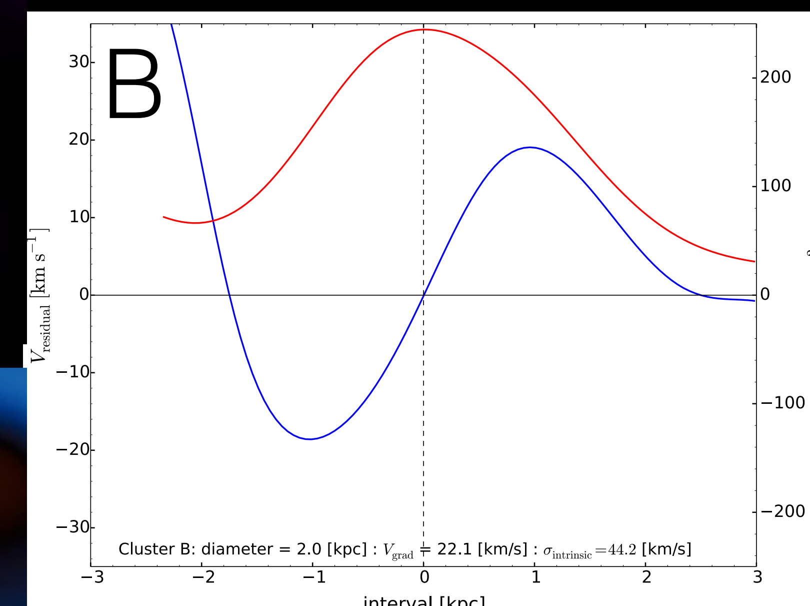


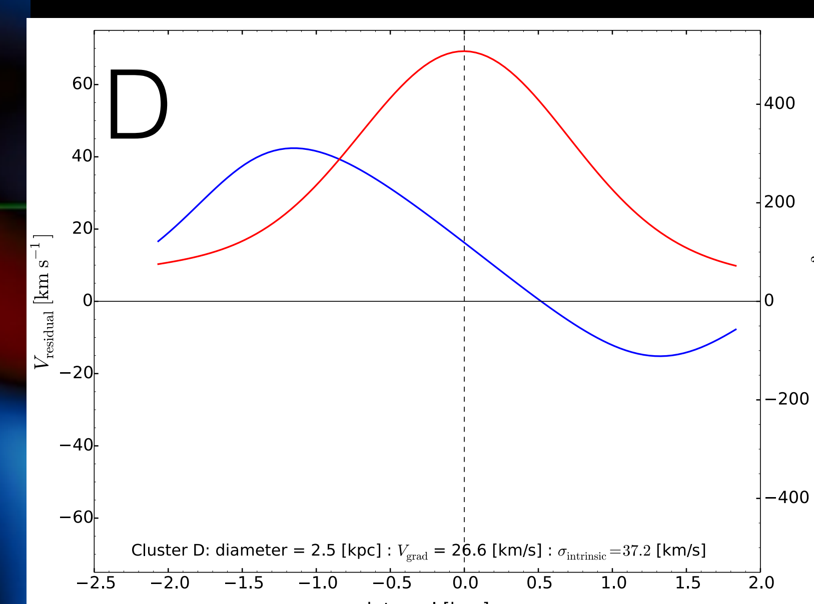








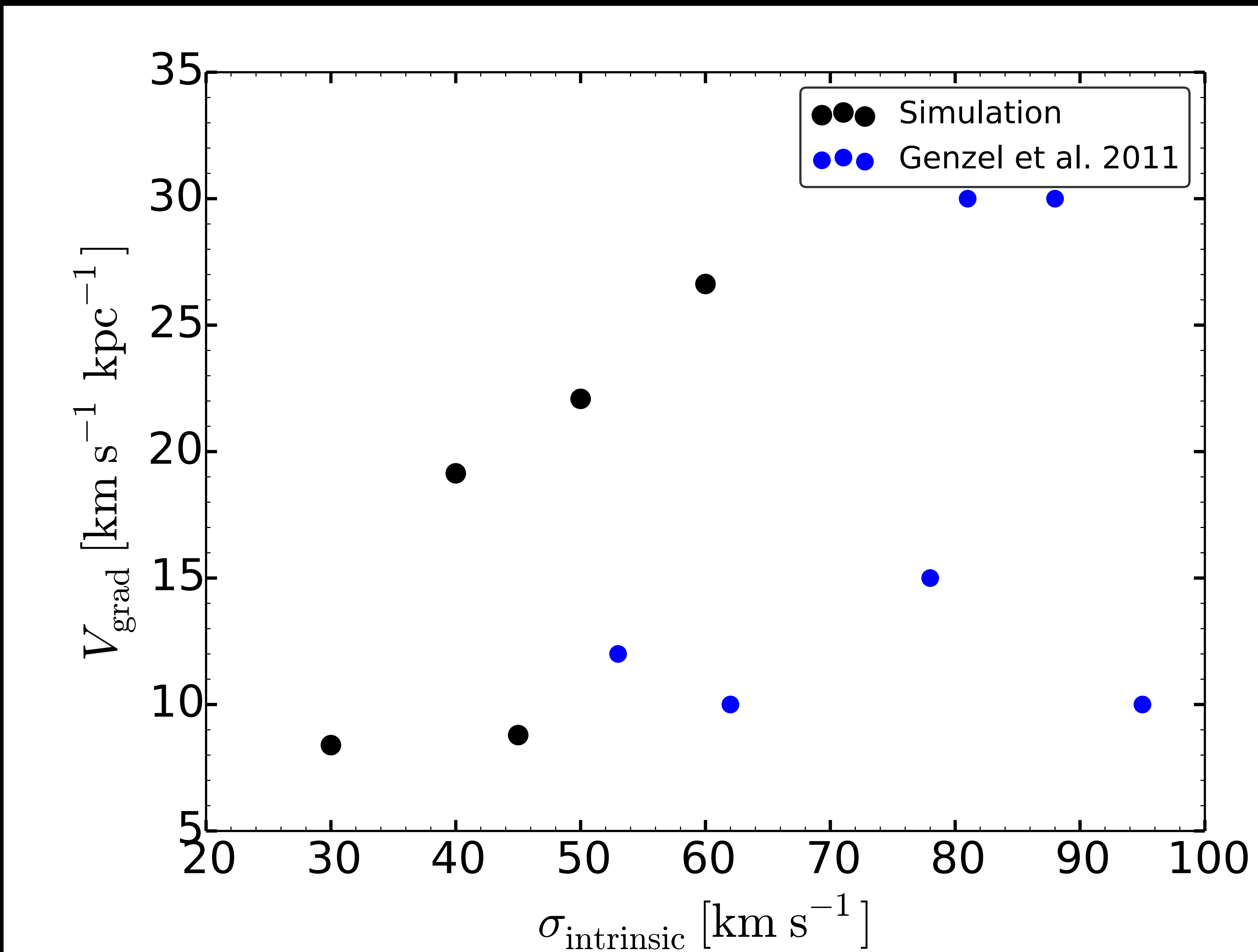




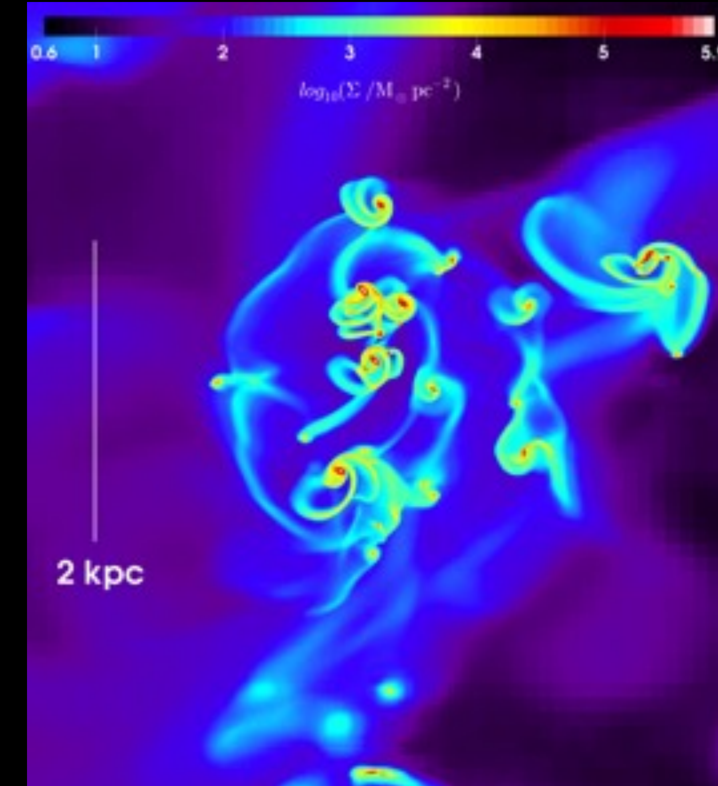
Diameter:
2-3 kpc

V_{grad}:
8-27 km/s/kpc

$\sigma_{intrinsic}$:
20-50 km/s

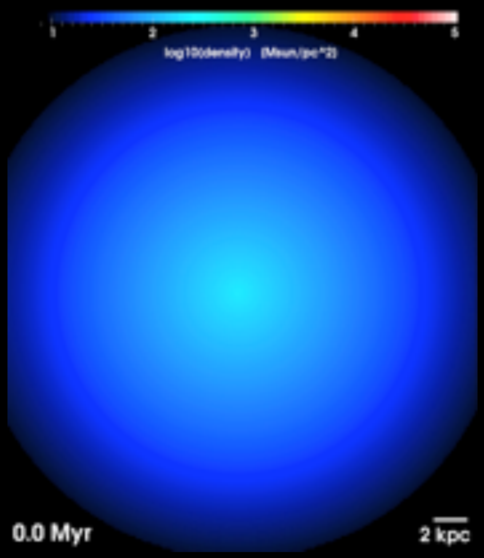


35
30
25
20
15
10
5
20
30
40
50
60
70
80
90
100
$V_{\rm grad}$ [km s^{-1} kpc^{-1}]
$\sigma_{\rm intrinsic}$ [km s^{-1}]
Simulation
Genzel et al. 2011



0.6
1
2
3
4
5
5.9
2 kpc

FWHM=1.6 kpc



Conclusions

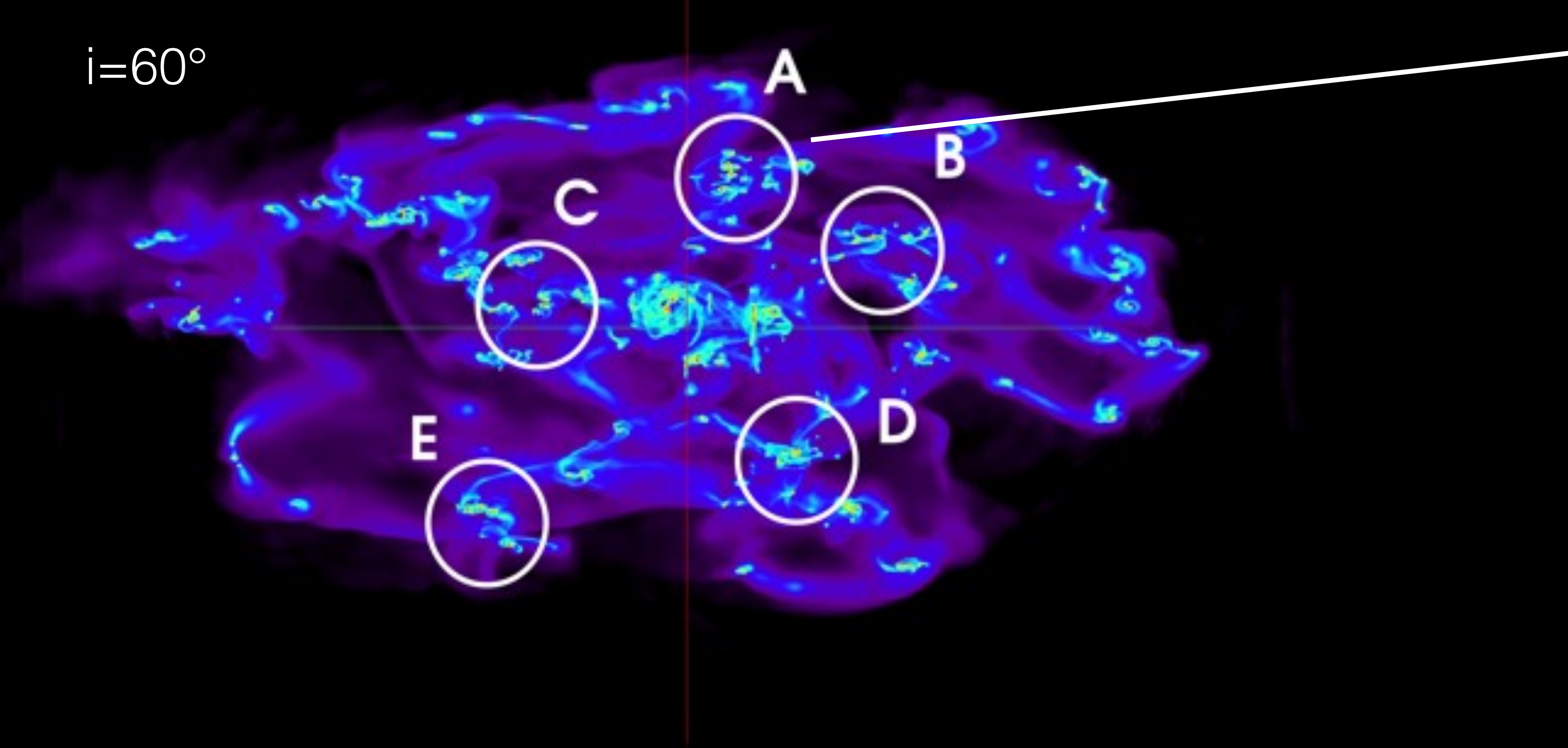
Toomre theory correctly predicts the growth of ring-like structures in unstable disks.

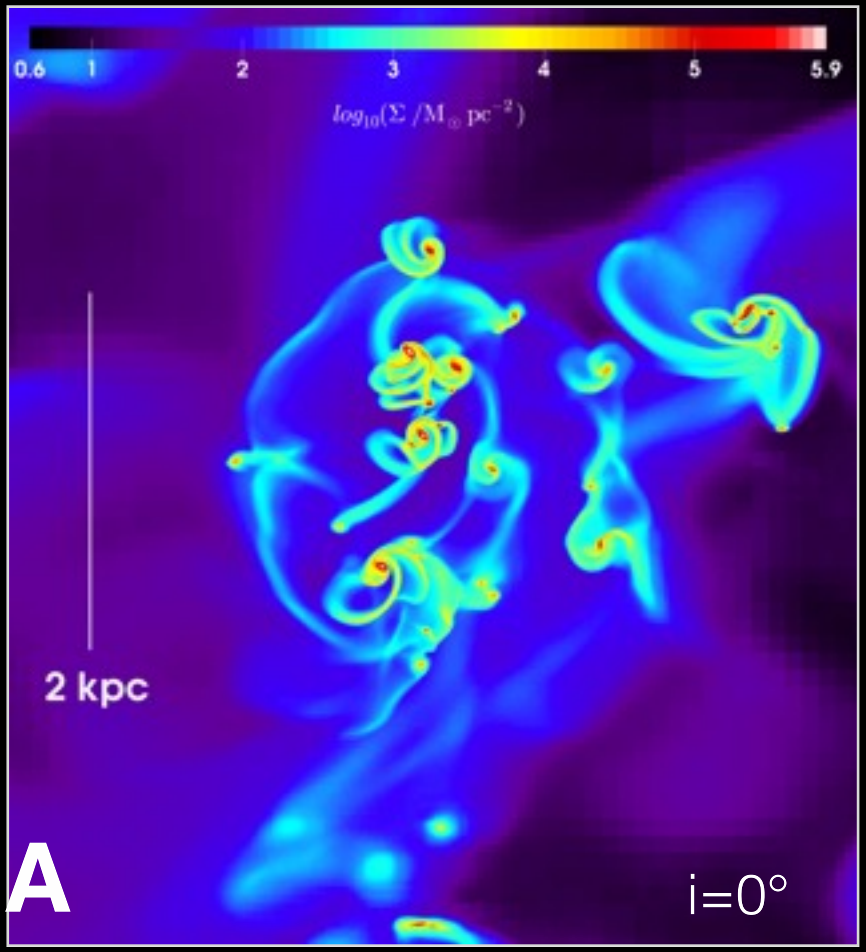
The fragmentation of the rings into **clumps**, the initial clump properties and their subsequent evolution **cannot be determined using linear Toomre theory**.

Clumps initially are **small** despite Q=0.5 however they later on grow by **merging** and are **disrupted** by violent encounters.

Clumps organise themselves into **massive clusters** that show properties very similar to observed massive **„clumps“ in high-z galaxies.**

Eventually a **self-regulated** time-independent **clump- and cluster mass distribution is** established.





The structure of massiv „clumps“ is more complex than usually assumed

- High dispersion due to subclump irregular motion
- Stellar feedback and star formation processes should be strongly affected by to substructure (Dekel & Krumholz 13)
- Globular cluster and seed black hole formation could be very different
- Infall physics of clusters and bulge formation depends on cluster properties