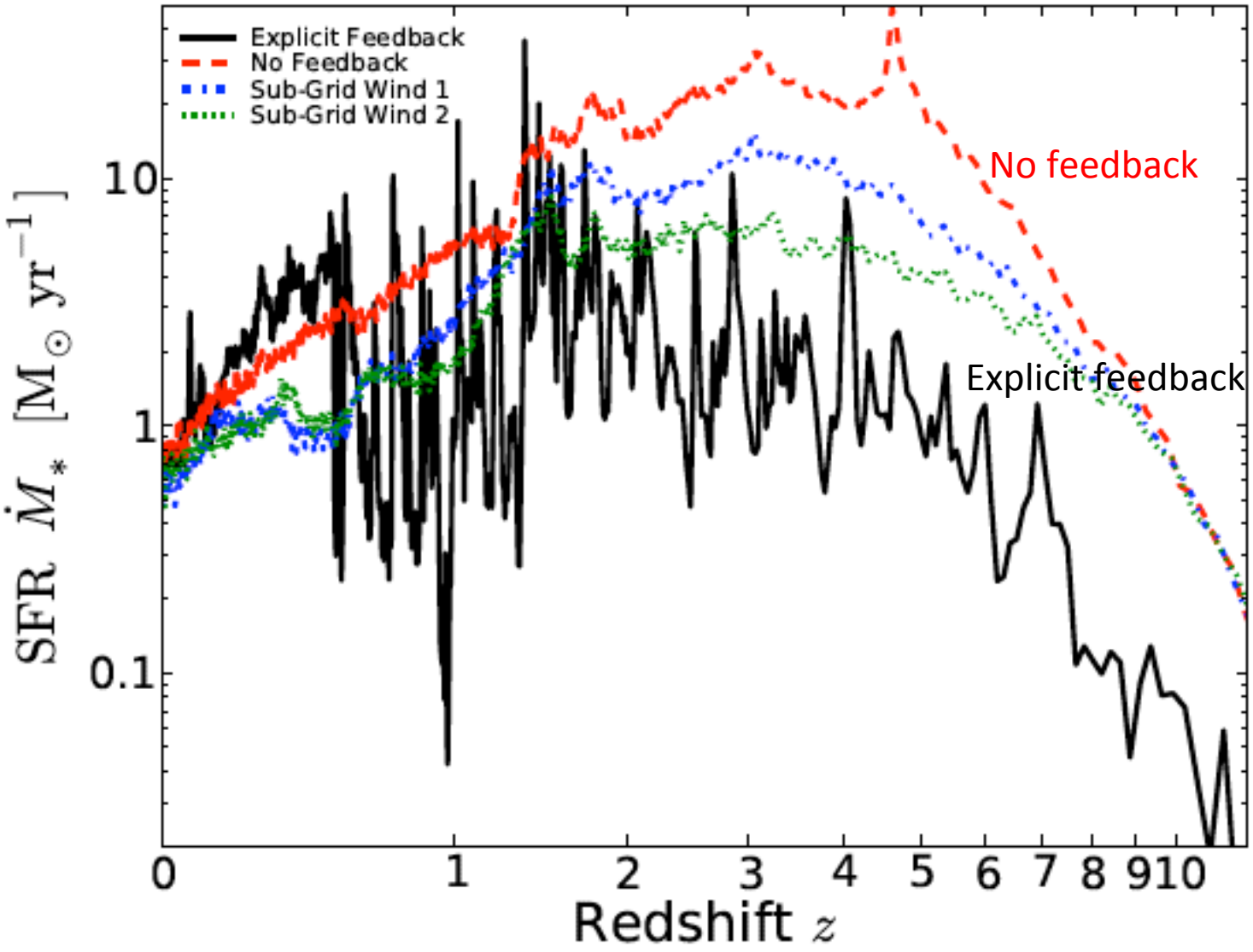
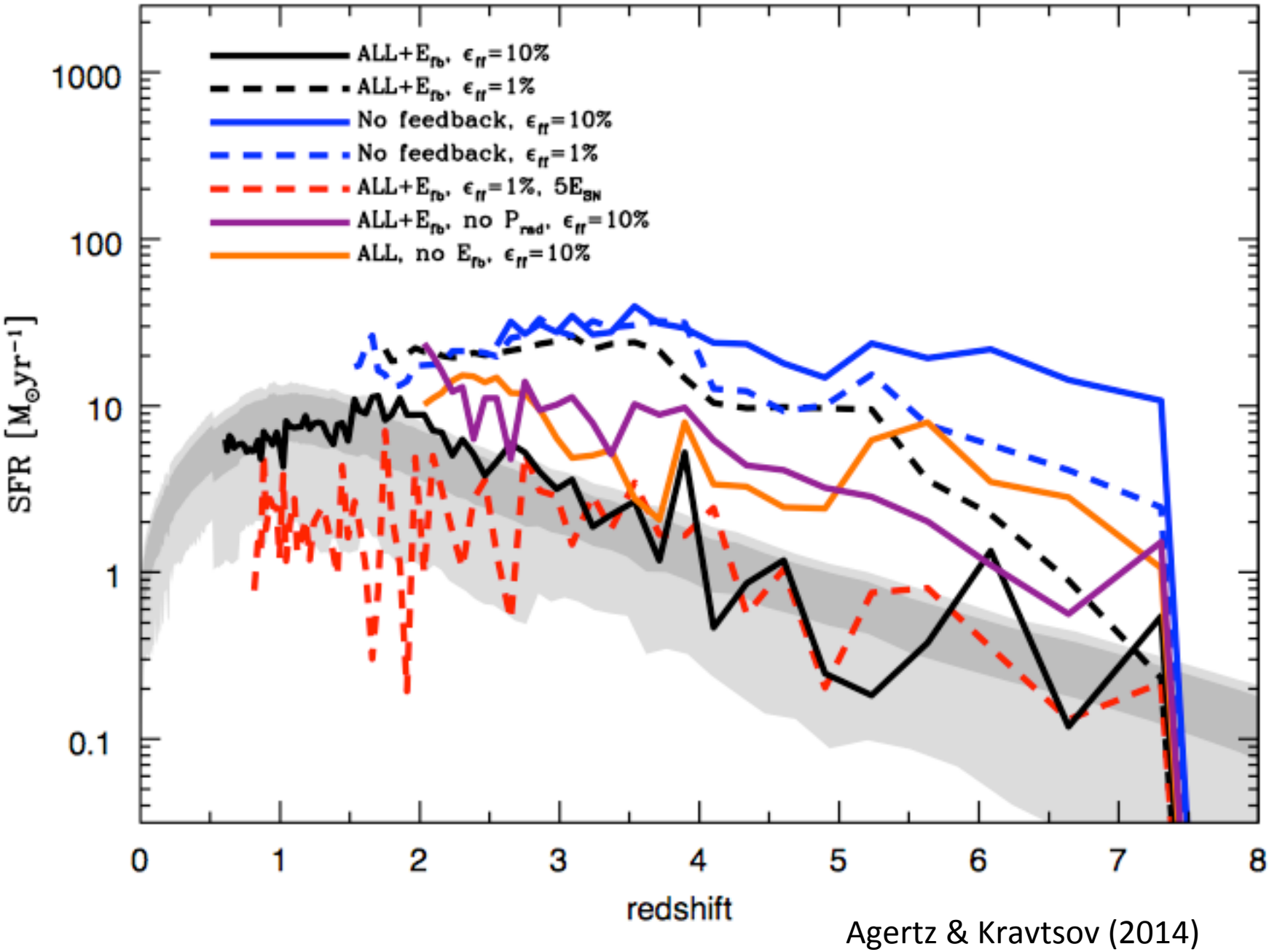
Regulating star formation with turbulence at high redshift

Adrianne Slyz, Julien Devriendt (University of Oxford),
Taysun Kimm (Princeton University)

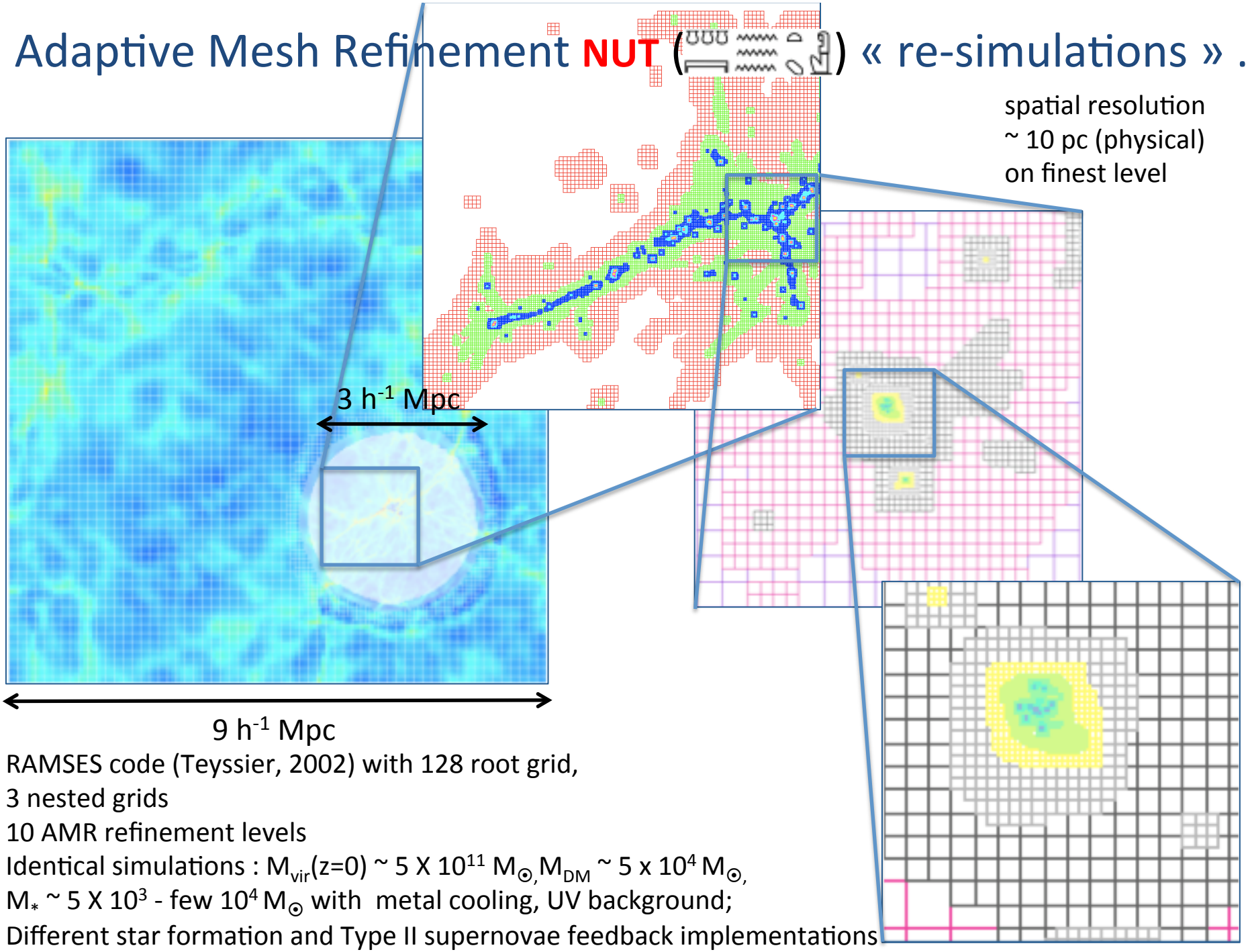


Hopkins et al. (2014)

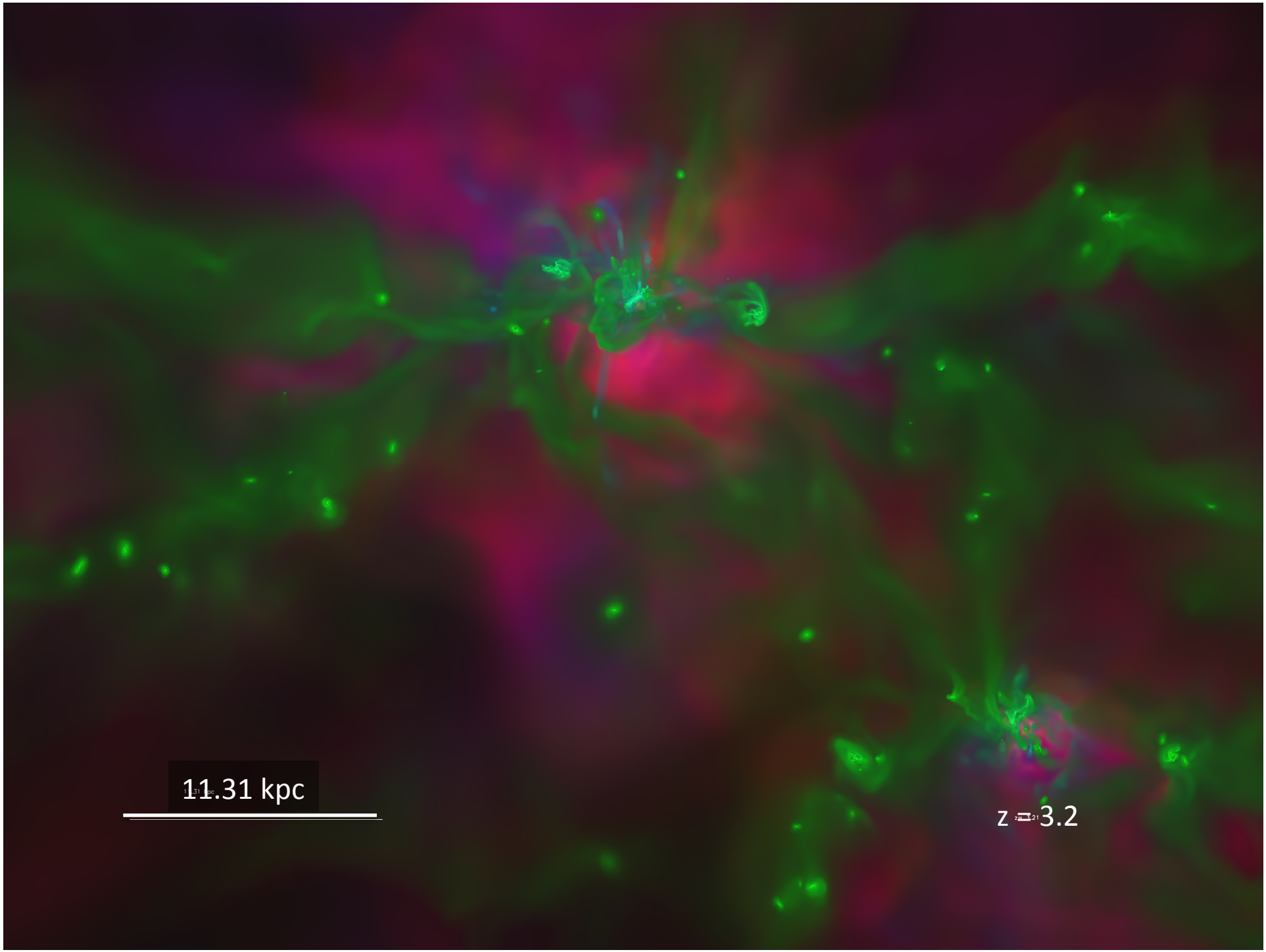


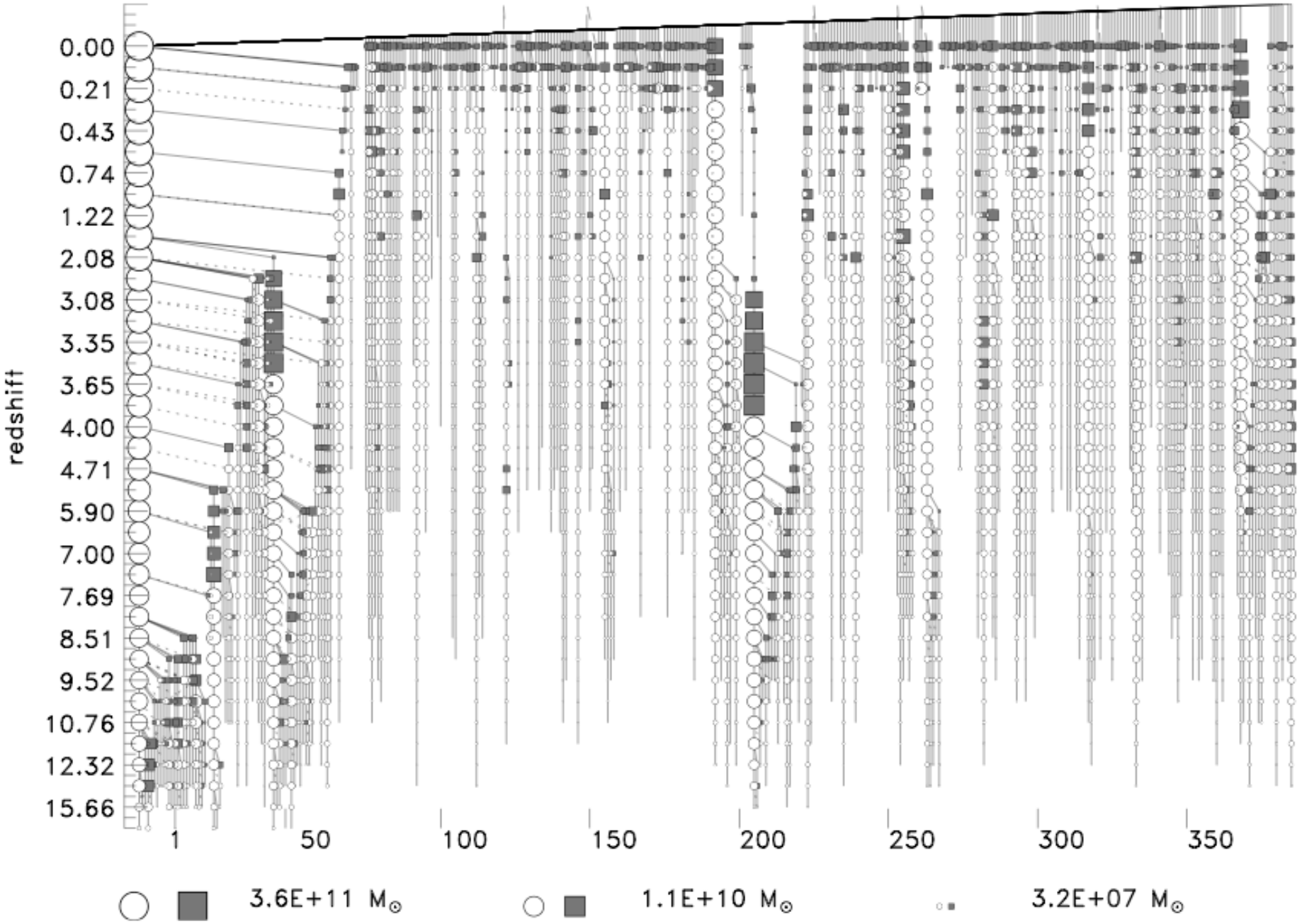
Agertz & Kravtsov (2014)

Adaptive Mesh Refinement NUT ( ) « re-simulations » …

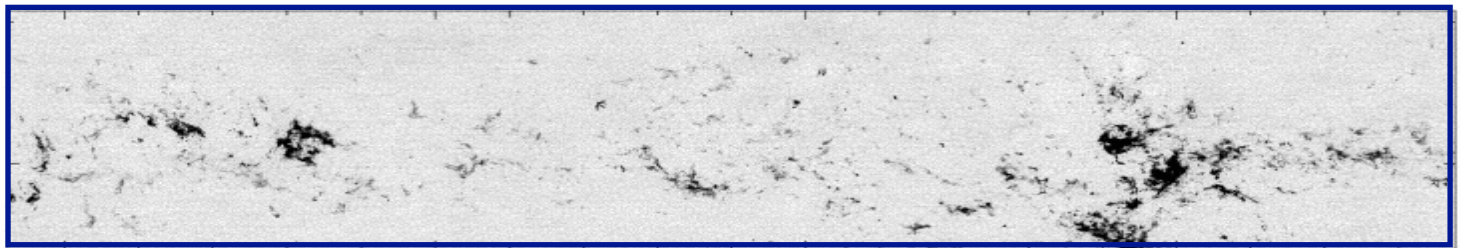


RAMSES code (Teyssier, 2002) with 128 root grid,
3 nested grids
10 AMR refinement levels
Identical simulations : $M_{vir}(z=0) \sim 5 \times 10^{11}\ M_{\odot}$, $M_{DM} \sim 5 \times 10^{4}\ M_{\odot}$,
$M_{*} \sim 5 \times 10^{3}$ - few $10^{4}\ M_{\odot}$ with metal cooling, UV background;
Different star formation and Type II supernovae feedback implementations


11.31 kpc
z = 3.2


redshift
0.00
0.21
0.43
0.74
1.22
2.08
3.08
3.35
3.65
4.00
4.71
5.90
7.00
7.69
8.51
9.52
10.76
12.32
15.66
1
50
100
150
200
250
300
350
3.6E+11 M⊙
1.1E+10 M⊙
3.2E+07 M⊙

Which gas should form stars in the simulations?



Heyer et al. 1998

(FCRAO CO survey)

if $\rho > \rho_0$

$$\dot{\rho}_* = \frac{\epsilon\,\rho}{t_{\rm ff}} \propto \rho^{3/2}$$

with $\epsilon = 0.01$

$\rho_0 = 400$ atoms/cm ^{3}

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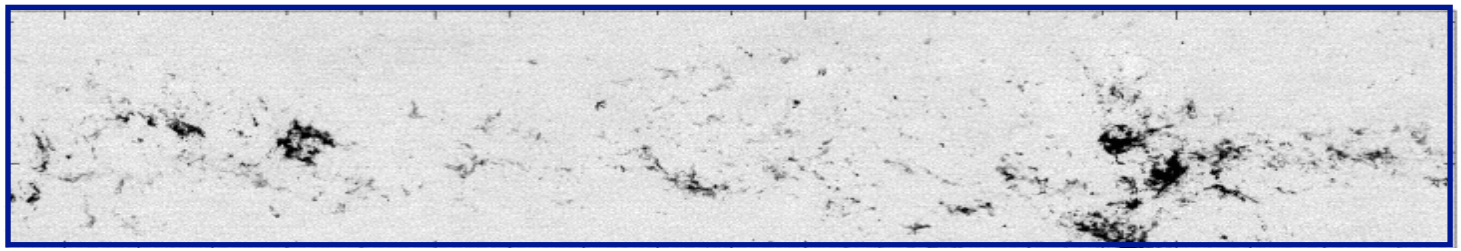


Heyer et al. 1998

(FCRAO CO survey)

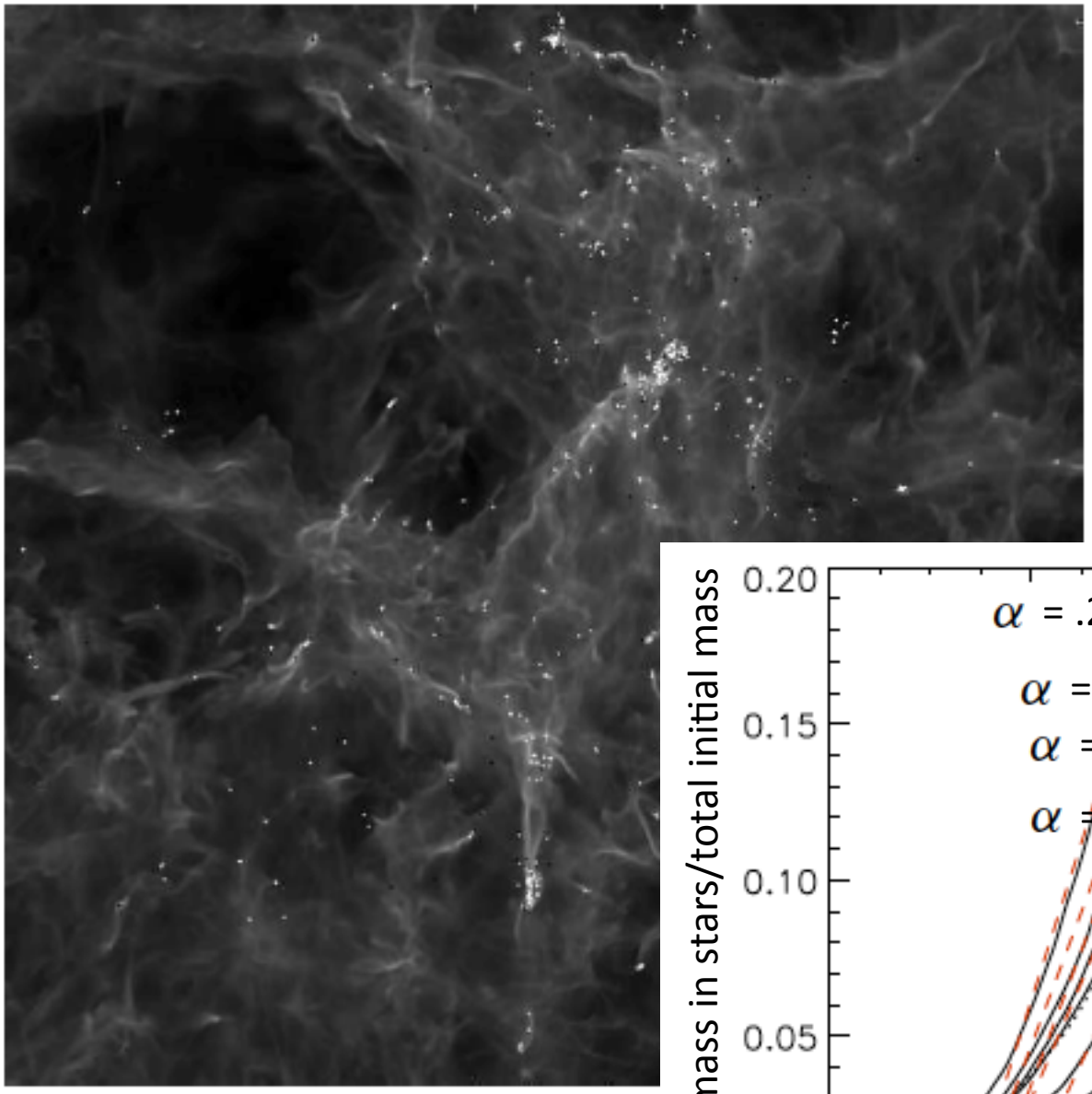
$$\sigma_{\rm eff}^2 + c_{\rm s}^2 < \beta\, G\, M$$

$$\alpha \equiv \sigma_{\rm eff}^2\, \delta r / \beta\, G\, M(<\delta r)$$

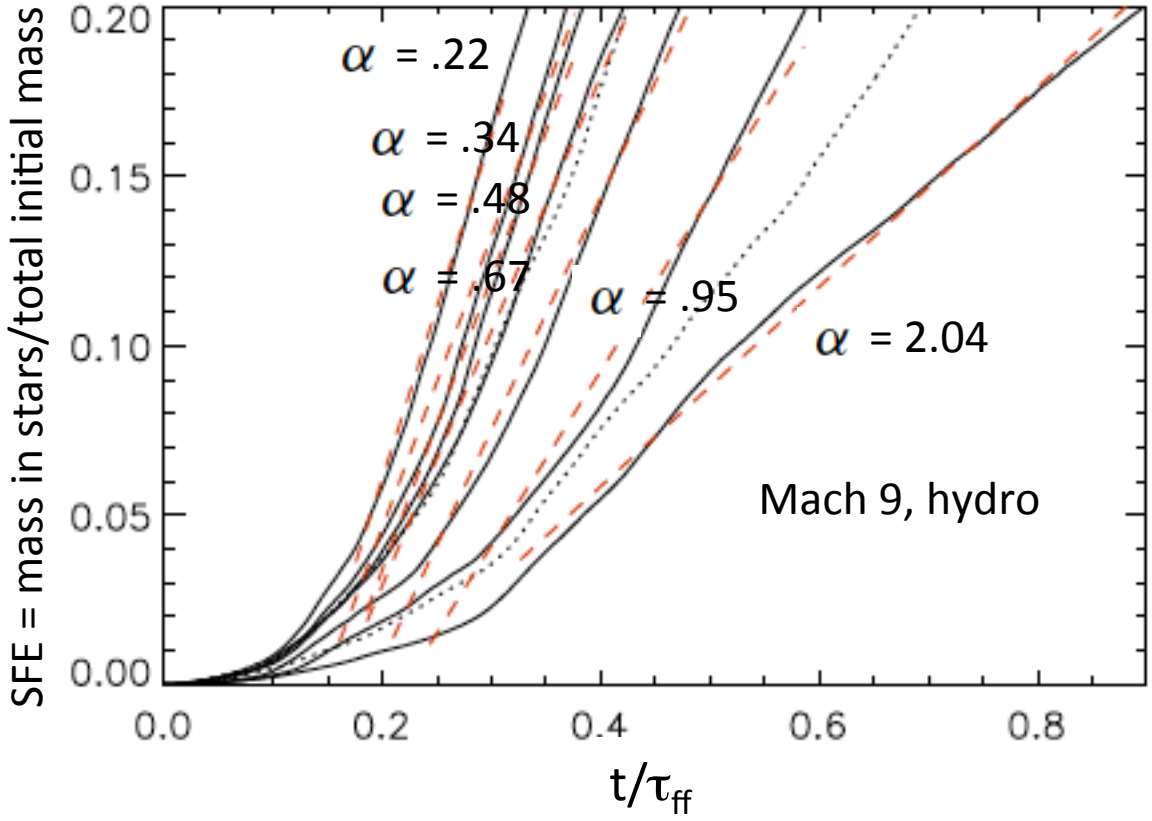
$$\alpha \equiv \beta' \frac{|\nabla \cdot \boldsymbol{v}|^2 + |\nabla \times \boldsymbol{v}|^2}{G\,\rho} < 1$$

$$\beta' \approx 1/2$$

Hopkins, Narayanan, Murray 2013

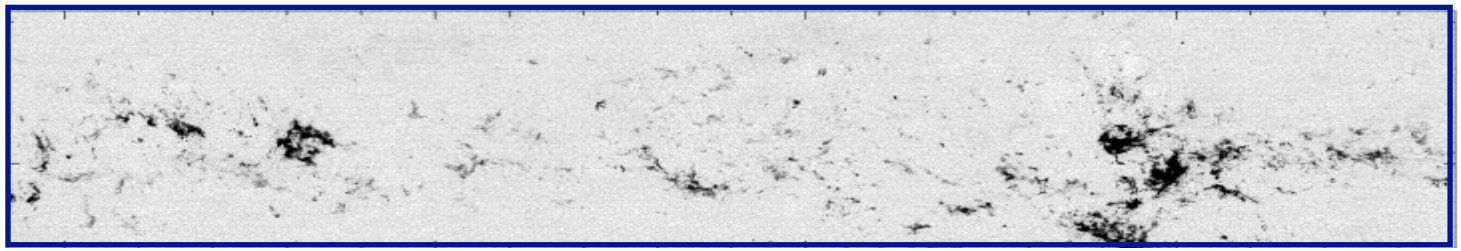


Star formation rate in high resolution driven supersonic turbulence simulations



Padoan & Nordlund 2011

Which gas should form stars in the simulations?



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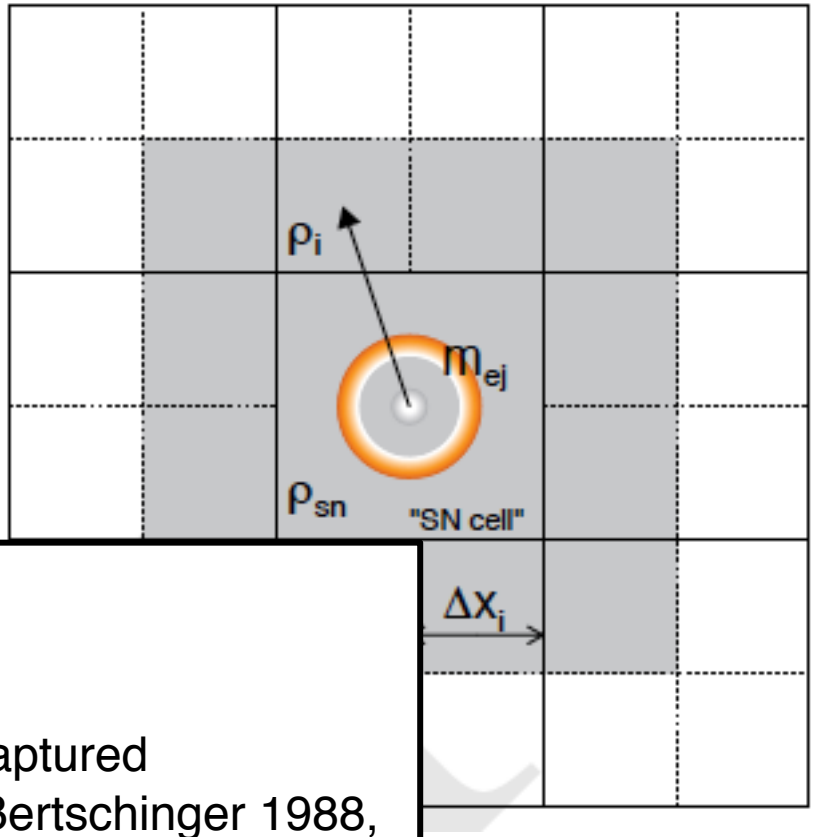
if $$\alpha \equiv \beta' \frac{|\nabla \cdot \boldsymbol{v}|^2 + |\nabla \times \boldsymbol{v}|^2}{G\,\rho} < 1$$

$$\dot{\rho}_* = \frac{\epsilon\,\rho}{t_{\rm ff}} \propto \rho^{3/2}$$

with $\epsilon = 1$

Hopkins, Narayanan, Murray 2013

Supernovae Feedback



If energy conserving phase is captured
→ Dubois & Teyssier 2008

If only momentum conserving phase is captured
→ Kimm & Cen (in prep), Cioffi, McKee, Bertschinger 1988, Kim, Kim, Ostriker 2011, Shetty & Ostriker 2012, Hopkins et al. 2014, Walch talk

Simulations

1. density threshold star formation, no SN feedback (No Fbk)

2. " , energy conserving SN fbk (ESN_Fbk)

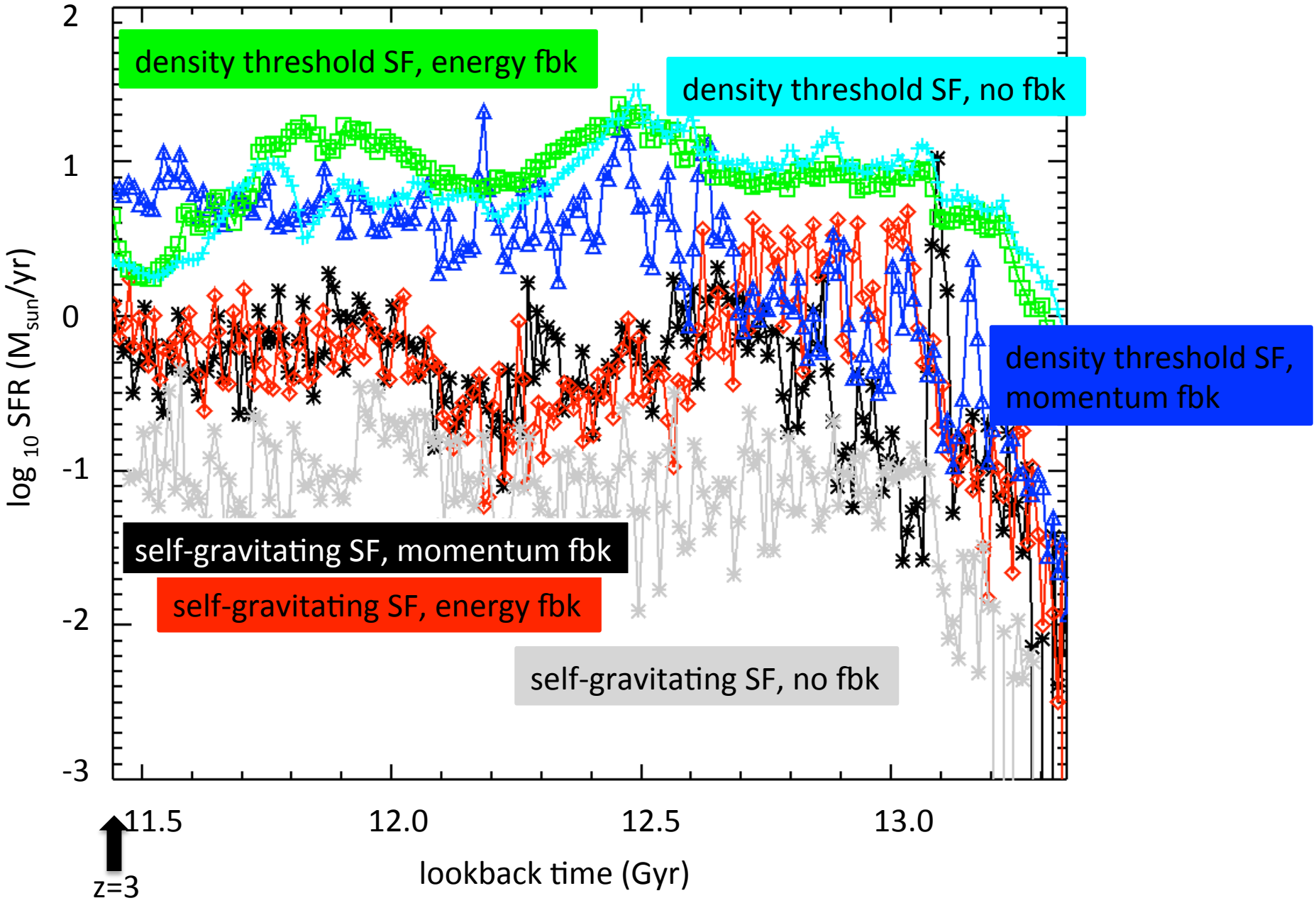
3. " , momentum conserving SN fbk (MSN_Fbk)

4. self-gravitating star formation, no SN feedback (No Fbk)

5. " , energy conserving SN fbk (ESN_Fbk)

6 " , momentum conserving SN fbk (MSN_Fbk)

Star Formation Rates



density threshold SF, no fbk

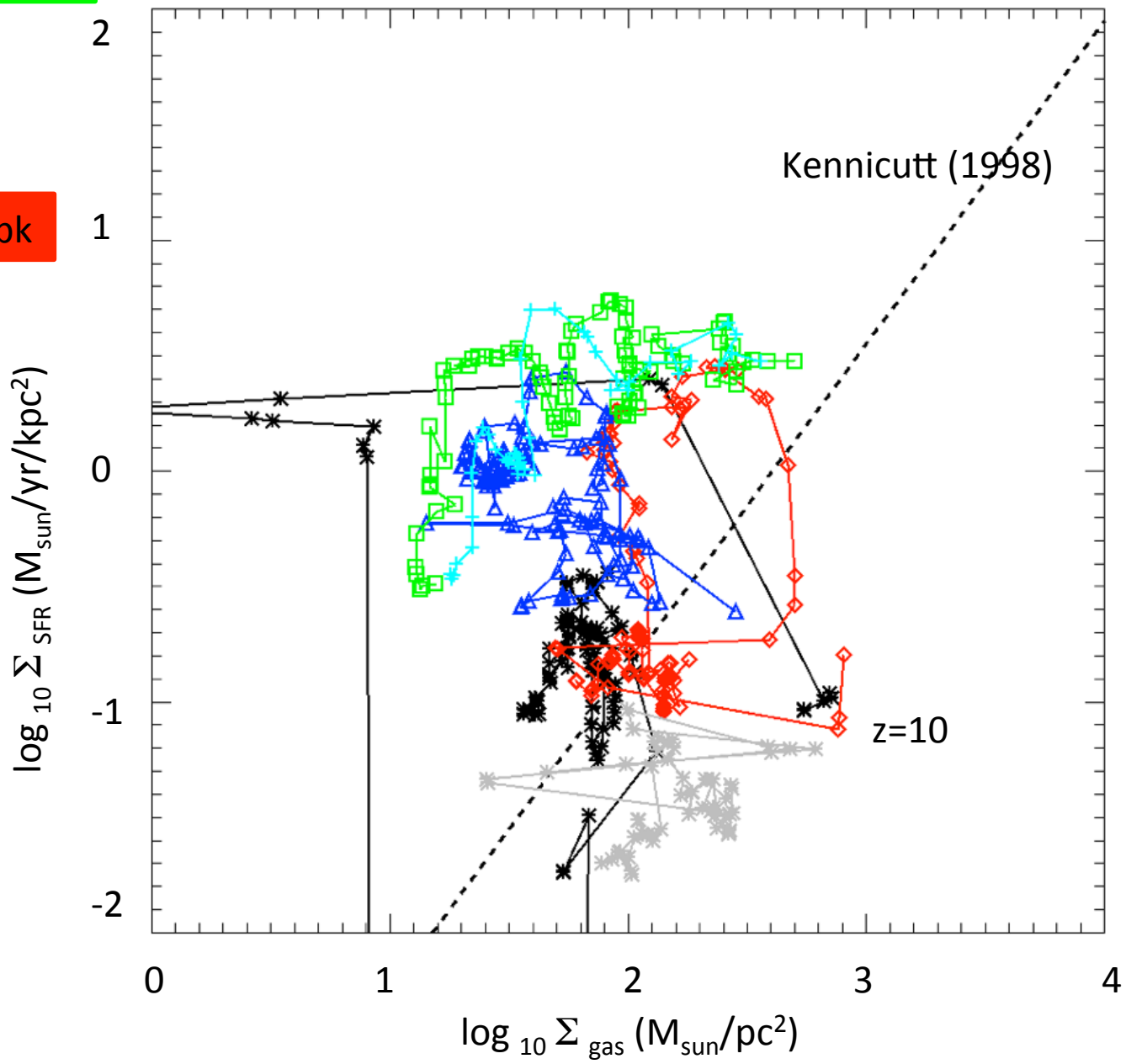
density threshold SF, energy fbk

density threshold SF, momentum fbk

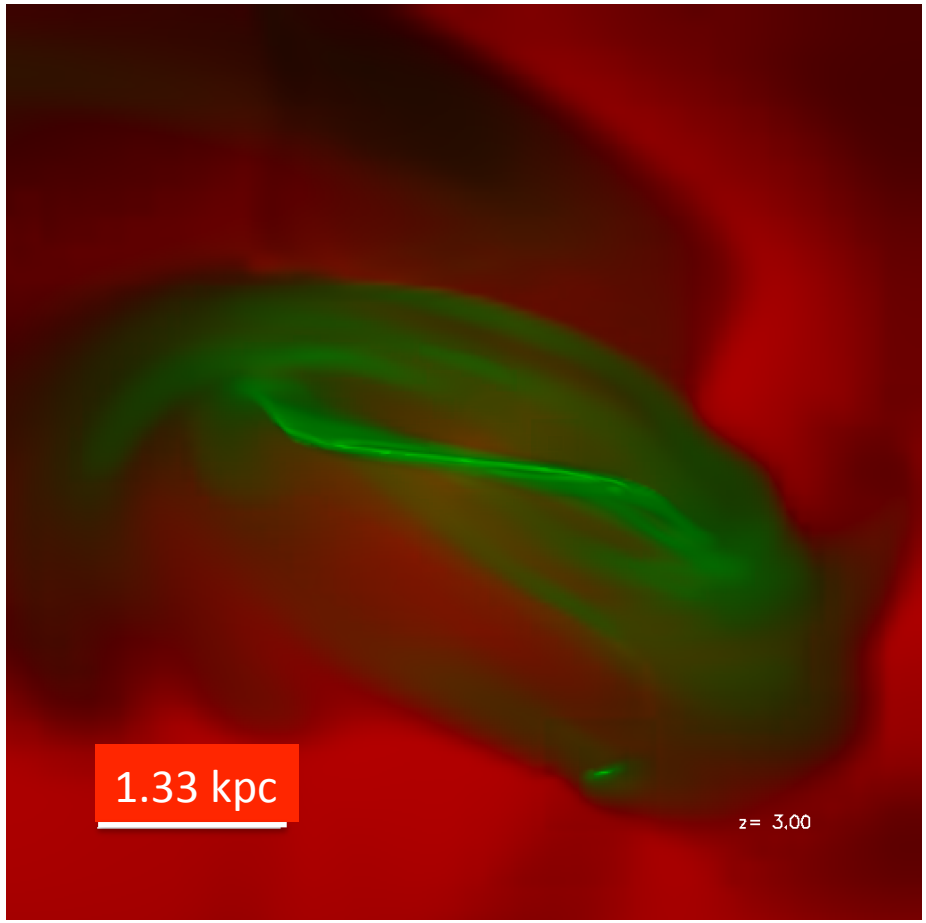
self-gravitating SF, no fbk

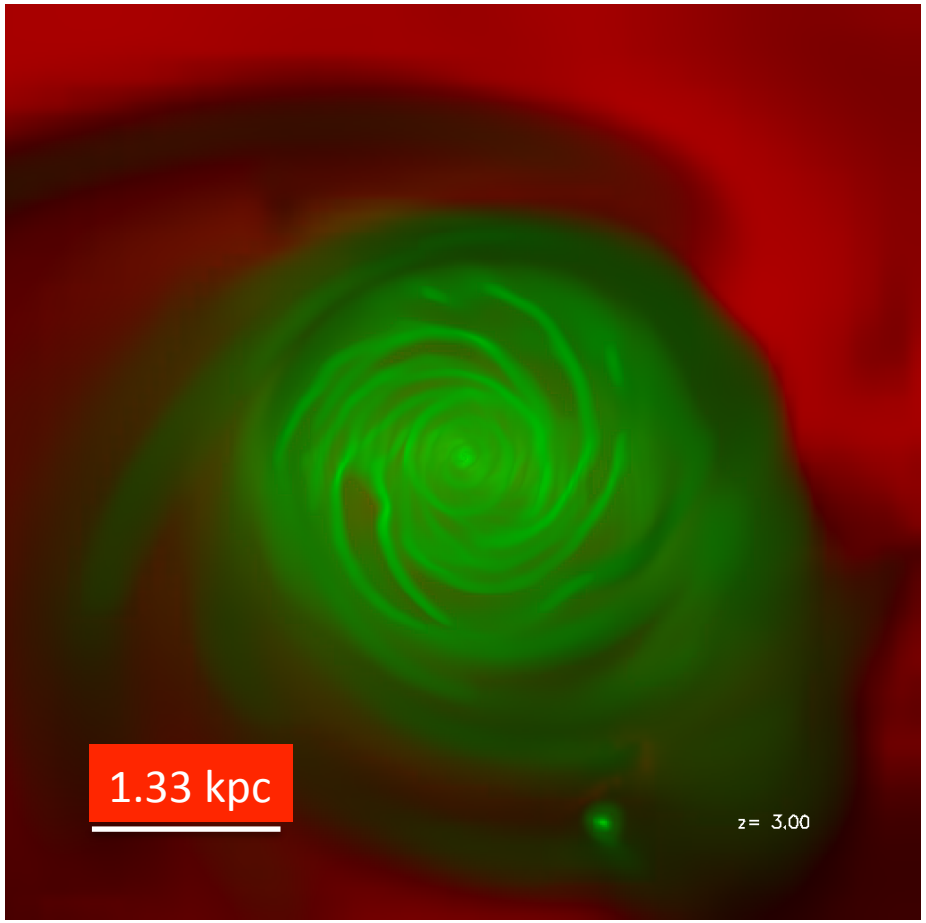
self-gravitating SF, energy fbk

self-gravitating SF, momentum fbk

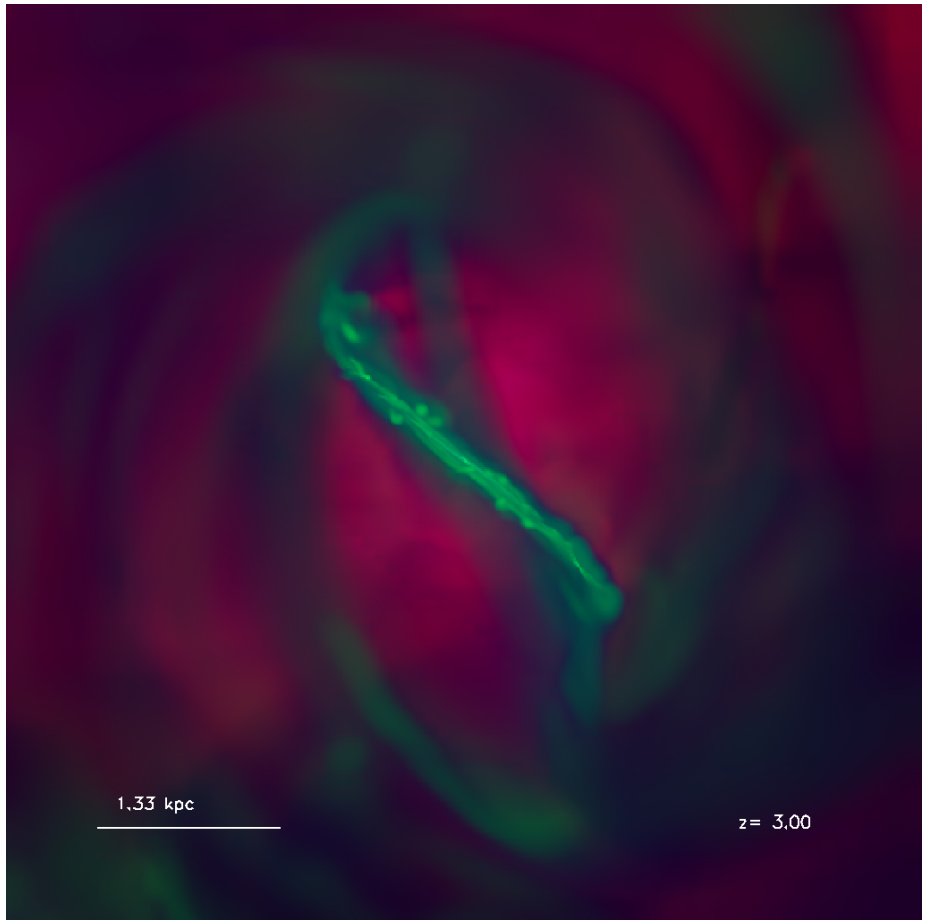


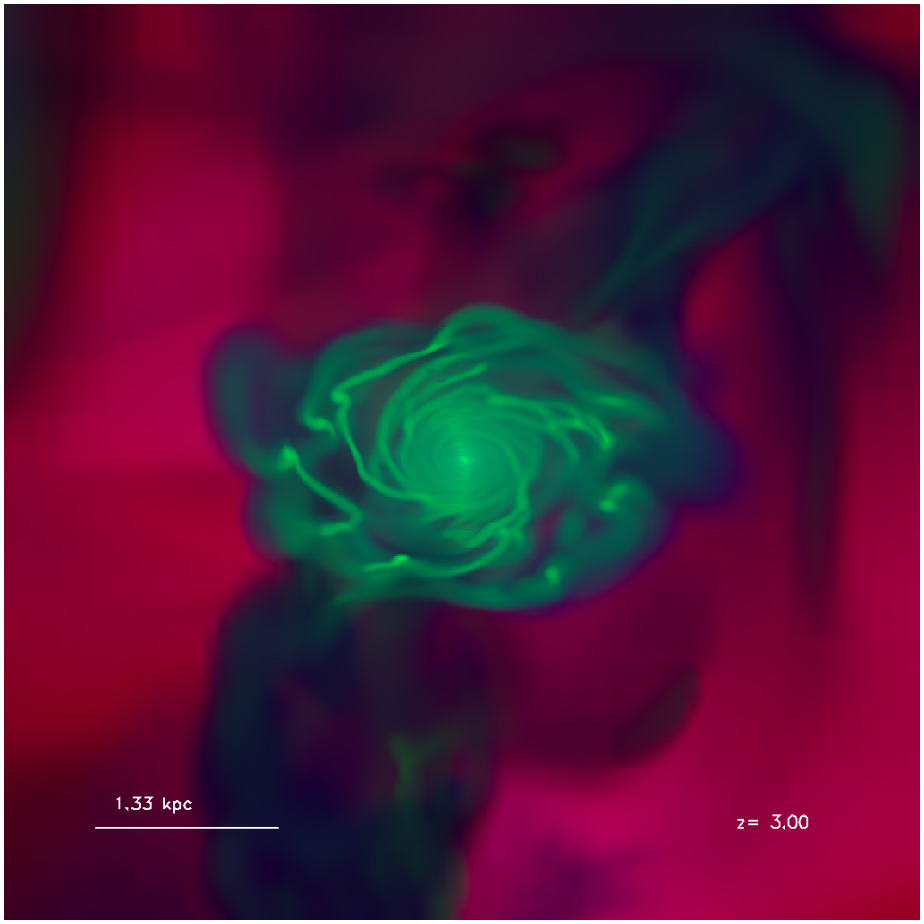
density threshold SF, no fbk



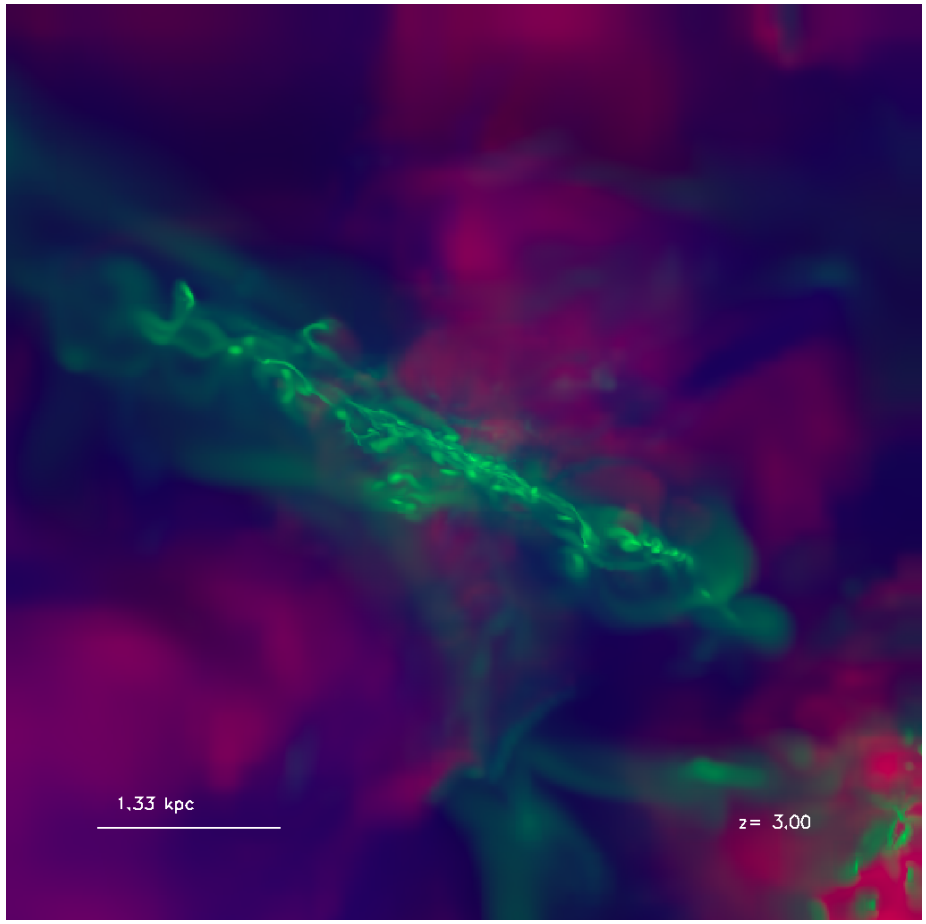


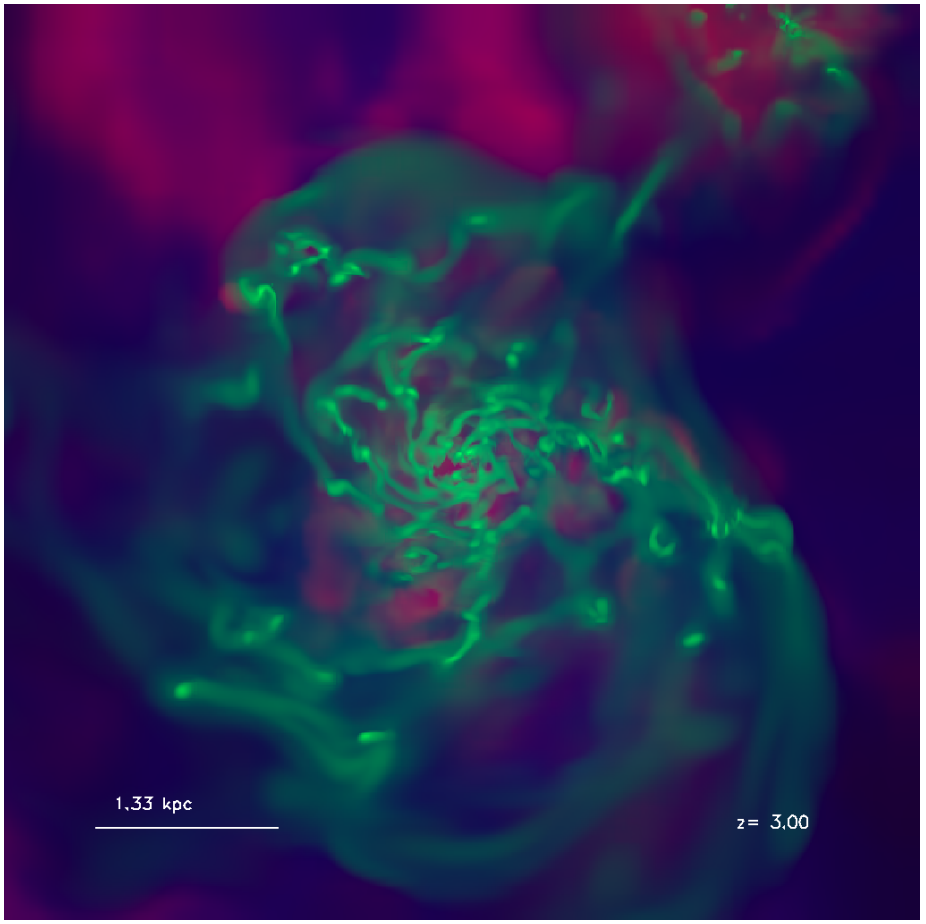
density threshold SF, energy fbk



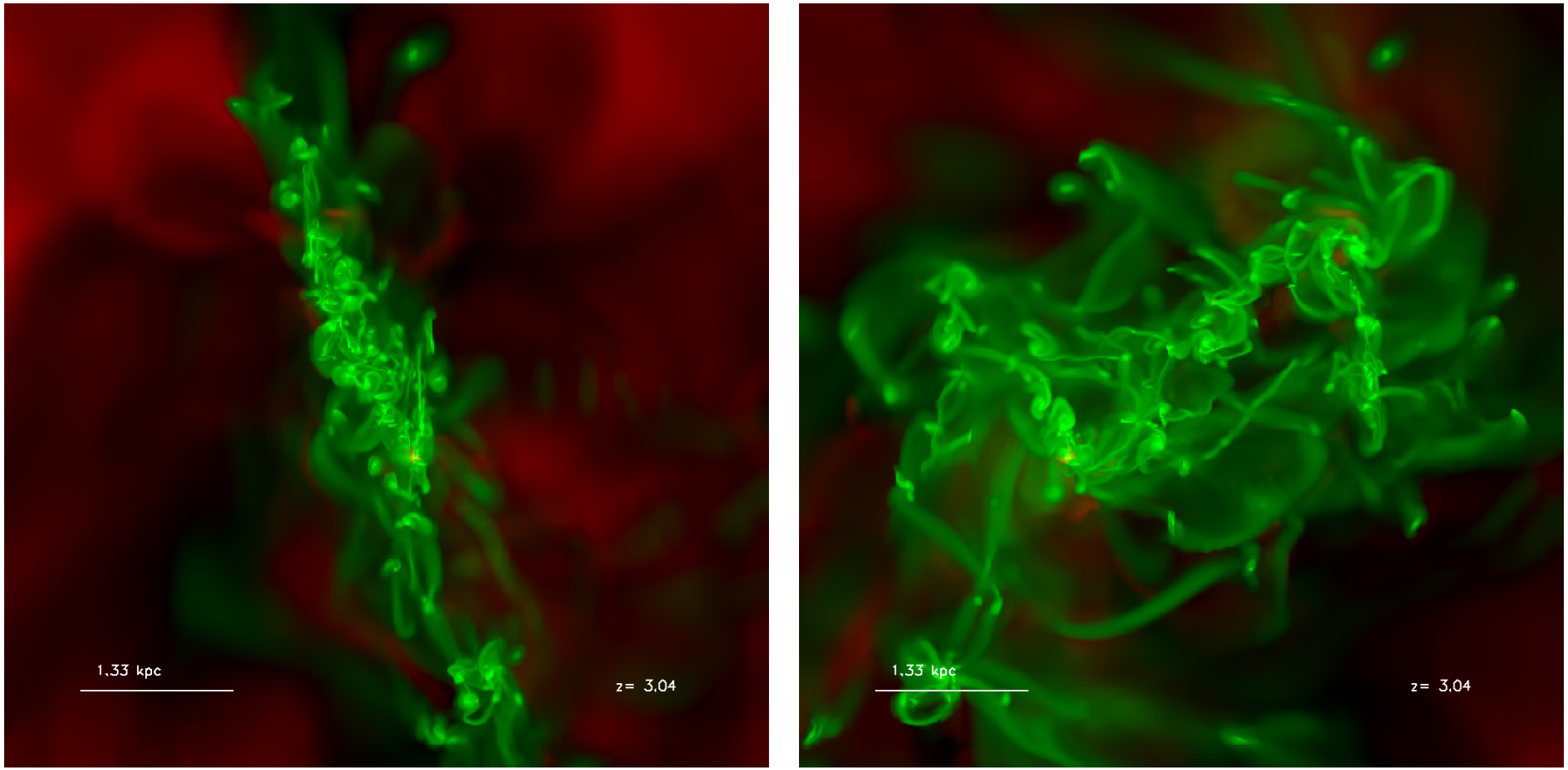


density threshold SF,
momentum fbk

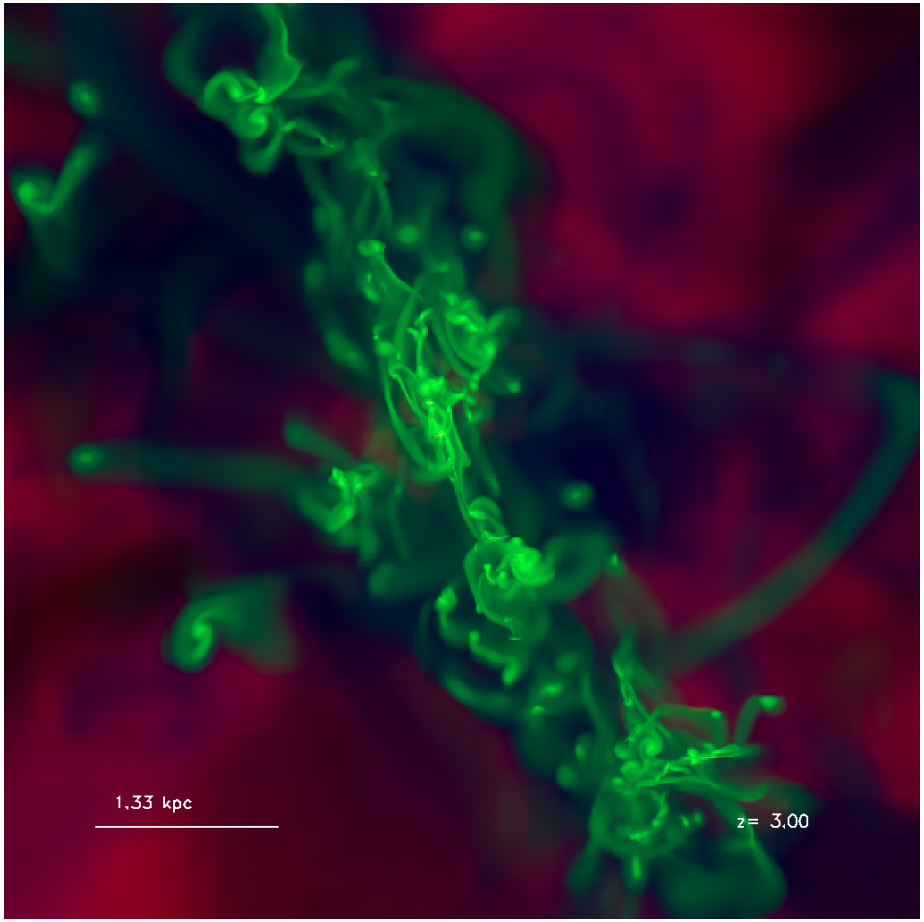


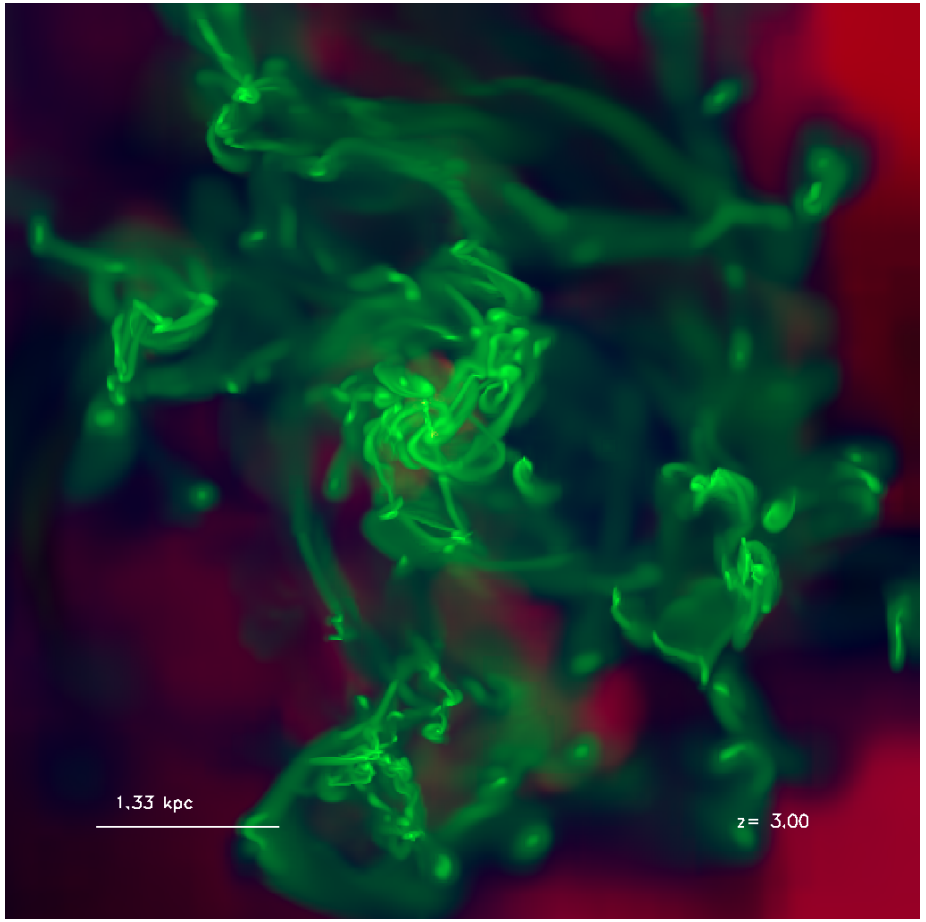


self-gravitating SF, no fbk

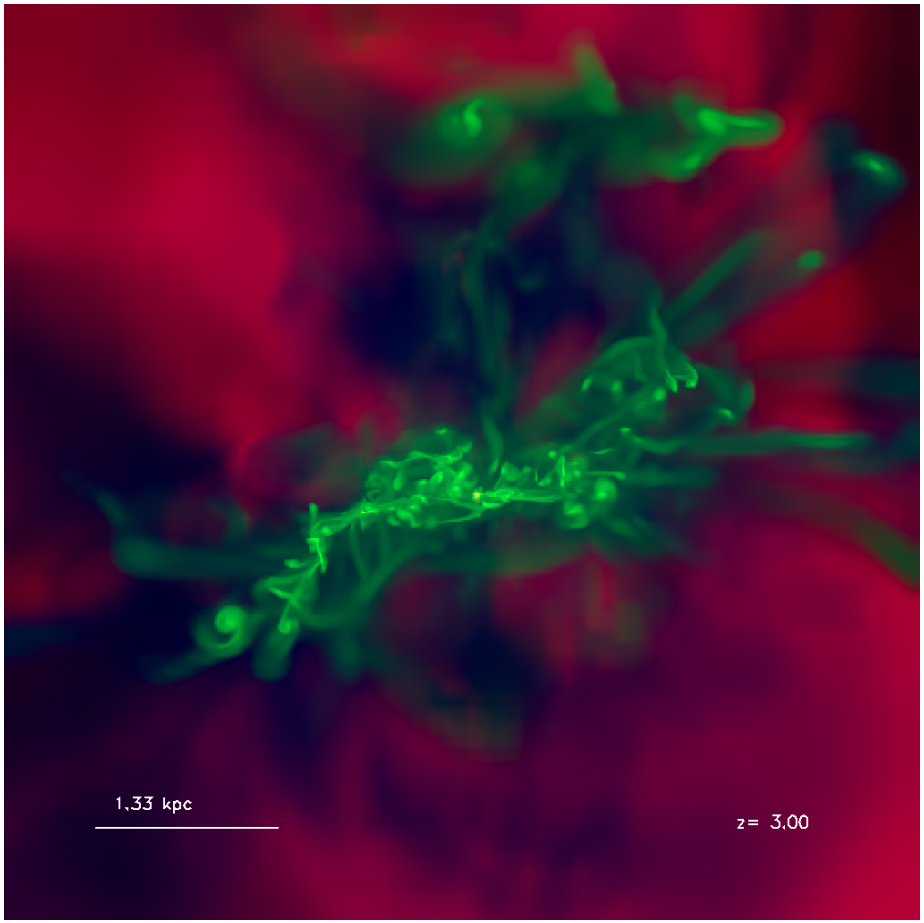


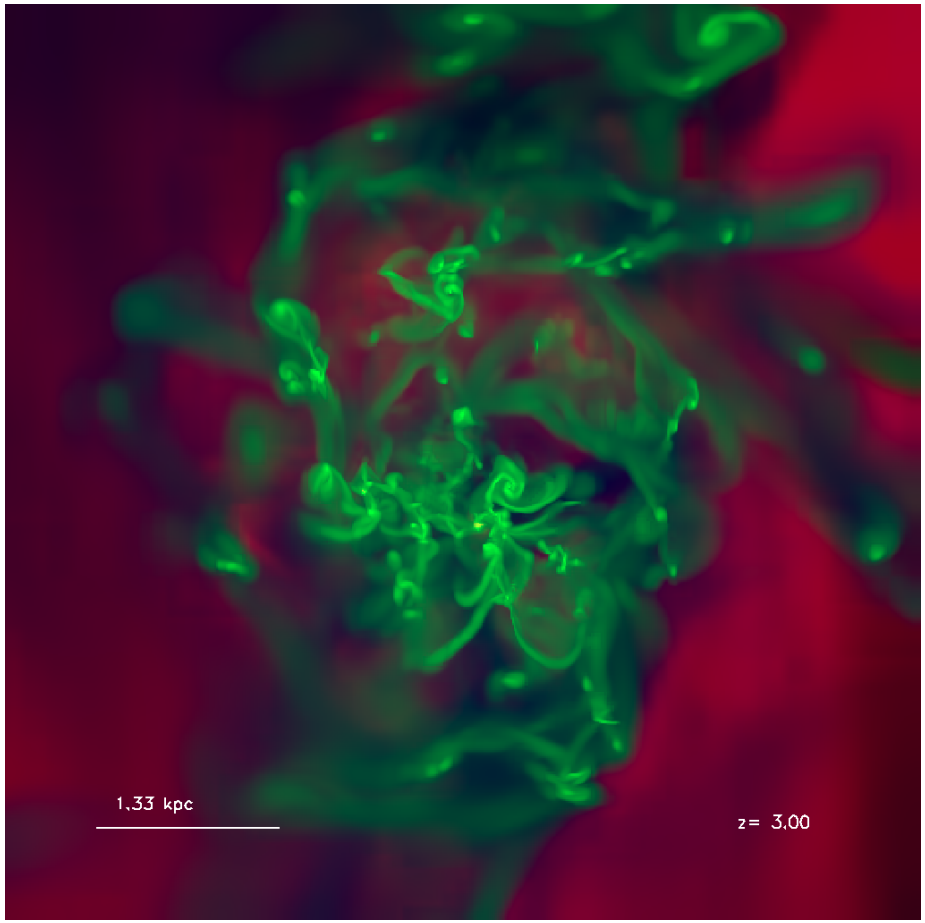
self-gravitating SF, energy fbk



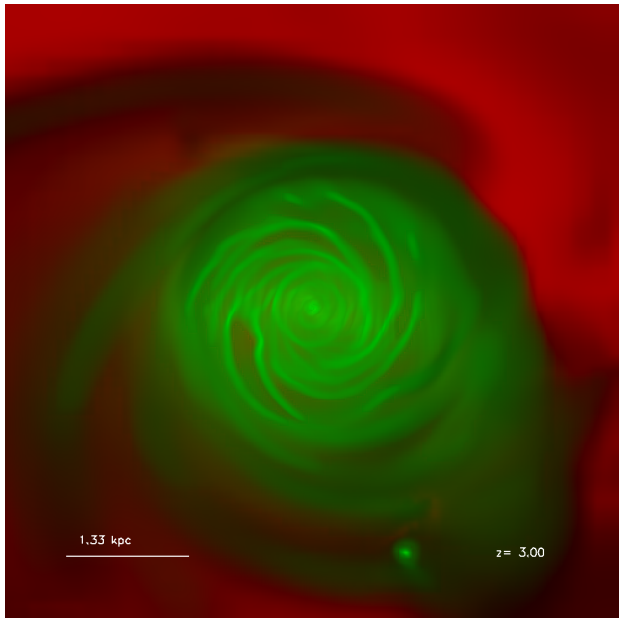


self-gravitating SF, momentum fbk

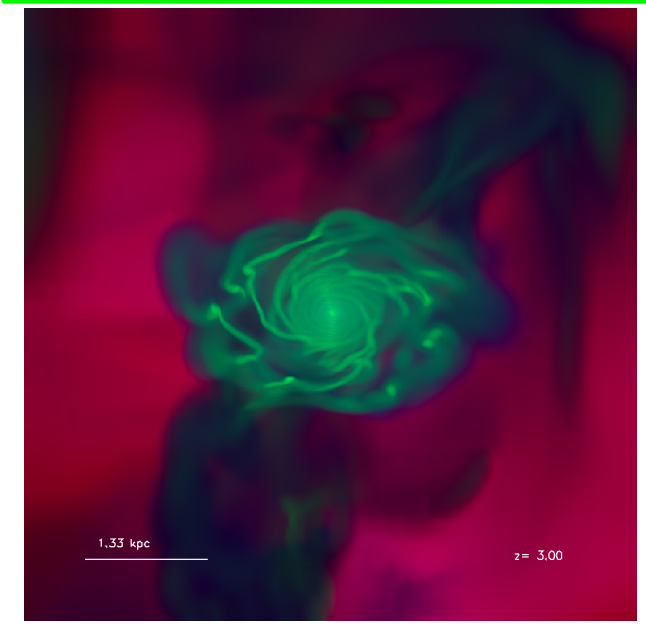




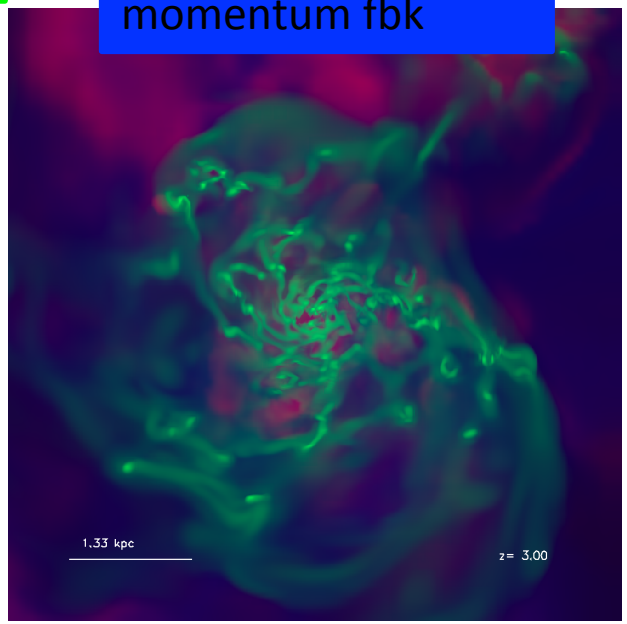
density threshold SF, no fbk



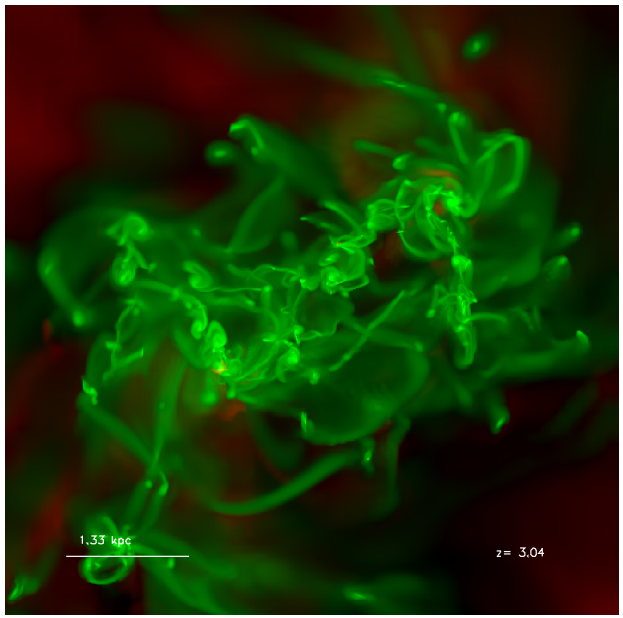
density threshold SF, energy fbk



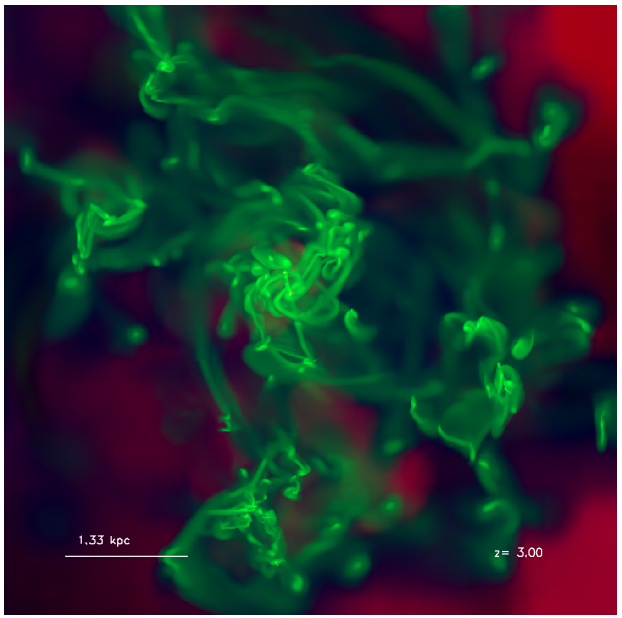
density threshold SF, momentum fbk



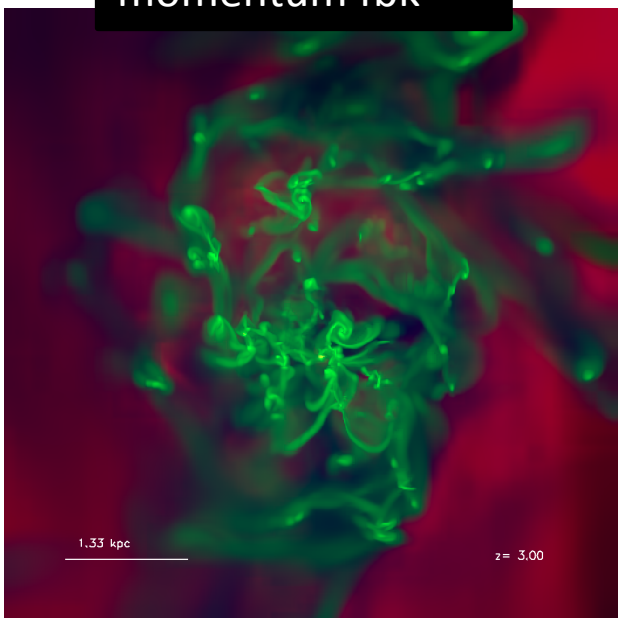
self-gravitating SF, no fbk



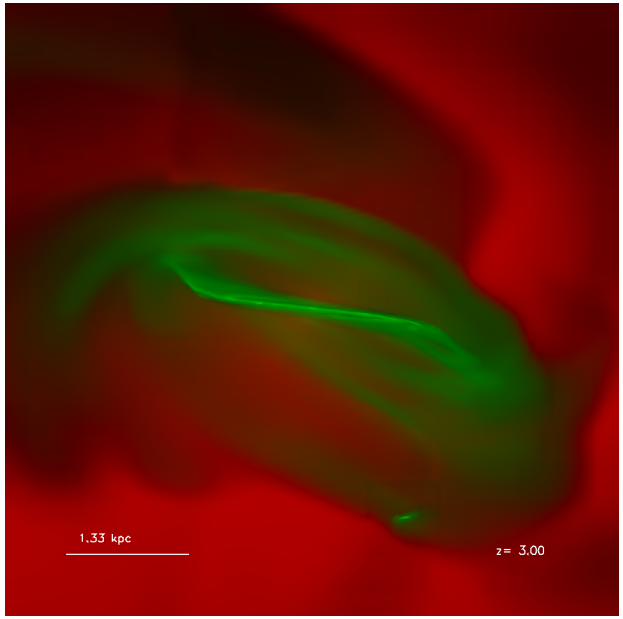
self-gravitating SF, energy fbk



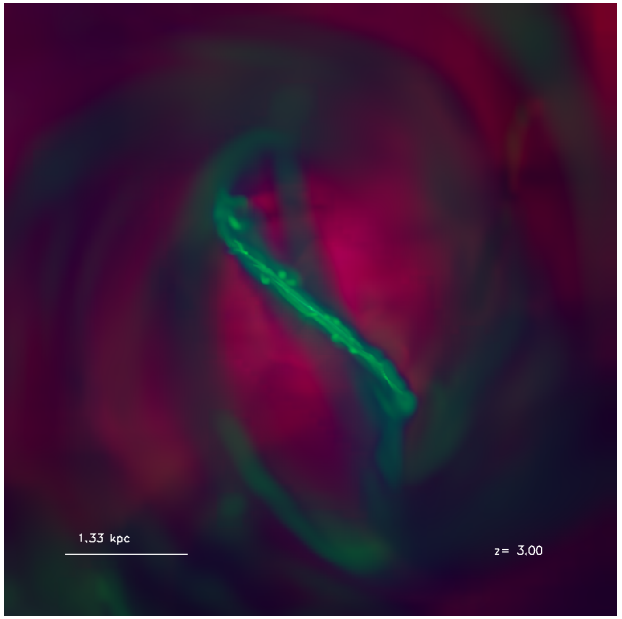
self-gravitating SF, momentum fbk



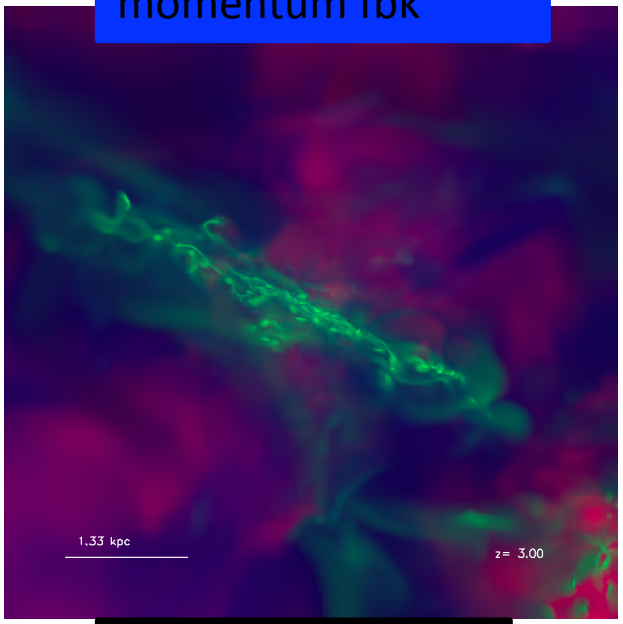
density threshold SF, no fbk



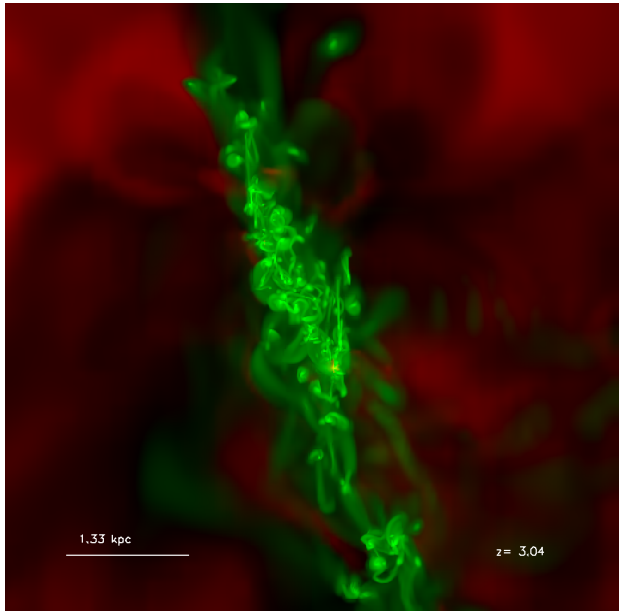
density threshold SF, energy fbk



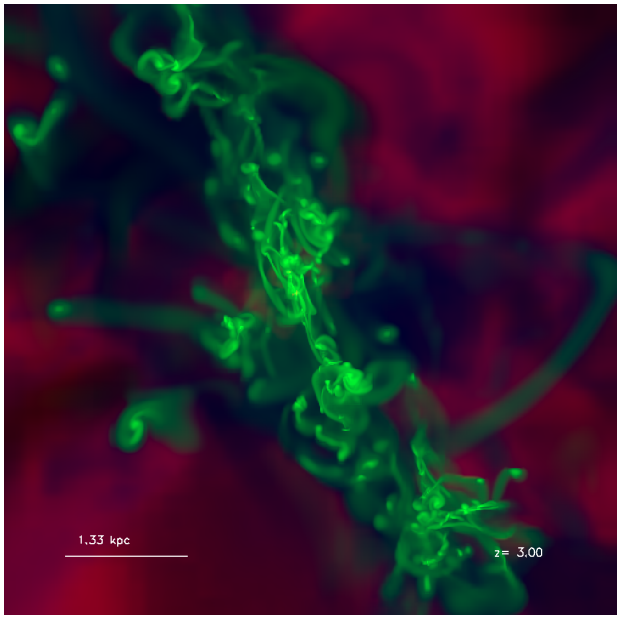
density threshold SF, momentum fbk



self-gravitating SF, no fbk



self-gravitating SF, energy fbk



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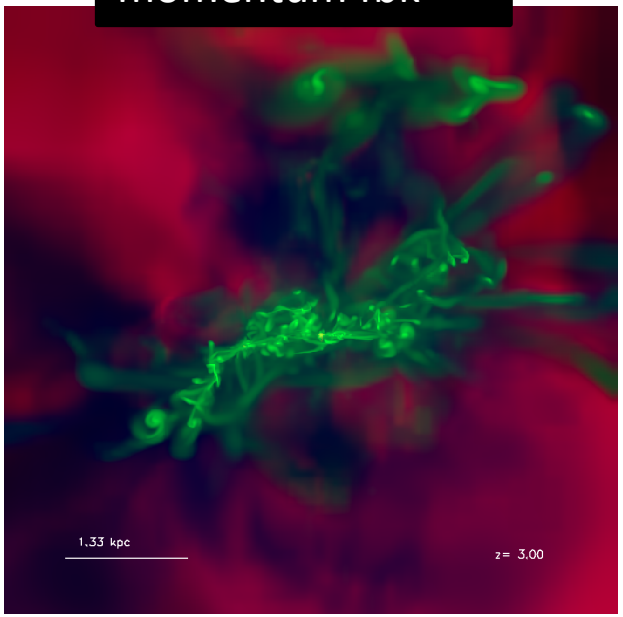


$$\omega^2 = 4\Omega^2 - 2\pi G\Sigma|k| + k^2 C_{\rm s}^2$$

$$\lambda_{\rm rot} = \pi^2 G\Sigma/\Omega^2$$

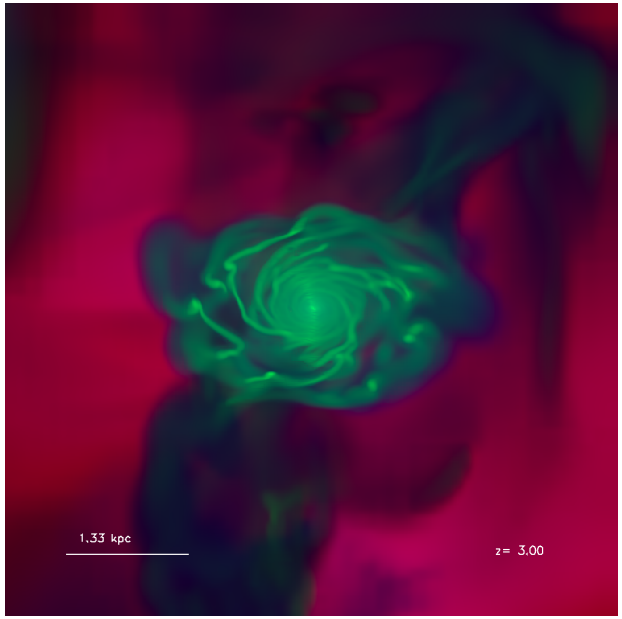
Toomre 1964

$$M_{\rm cl}^{\rm max} = \Sigma_{\rm gas} \left(\lambda_{\rm rot}/2\right)^2$$

$$M_{\rm cl}^{\rm max} = \frac{\pi^4 G^2 \Sigma_{\rm gas}^3}{4\Omega^4}$$

(see also Escala & Larson 2008)

density threshold SF, energy fbk



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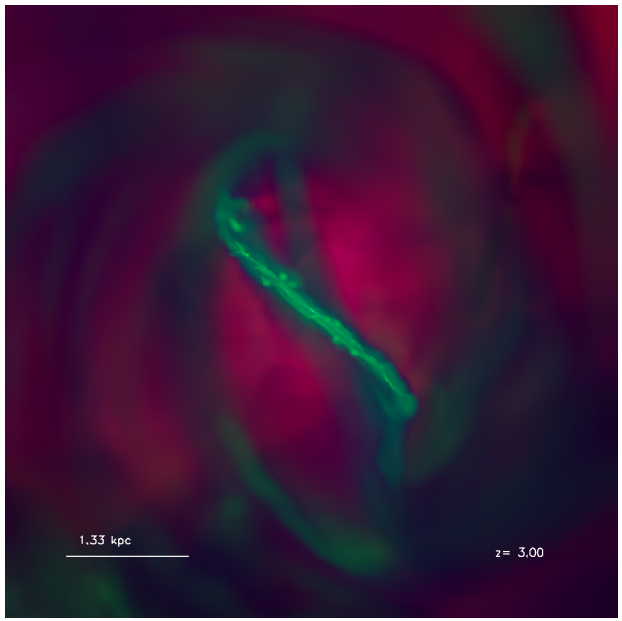
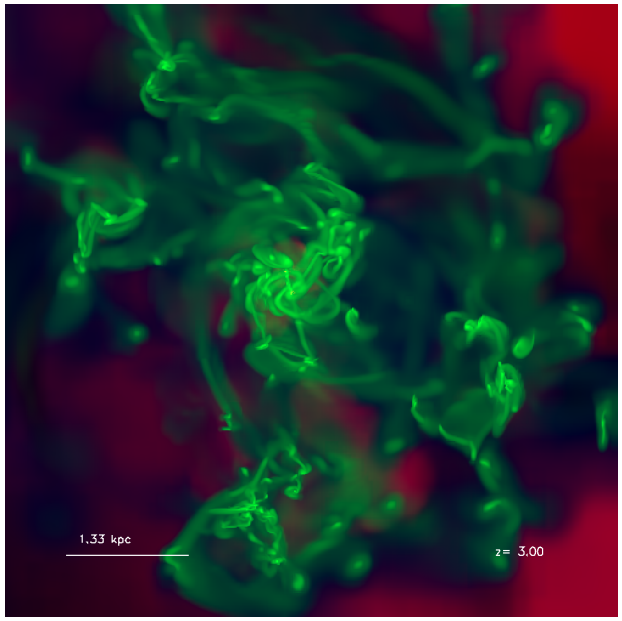


self-gravitating SF, energy fbk



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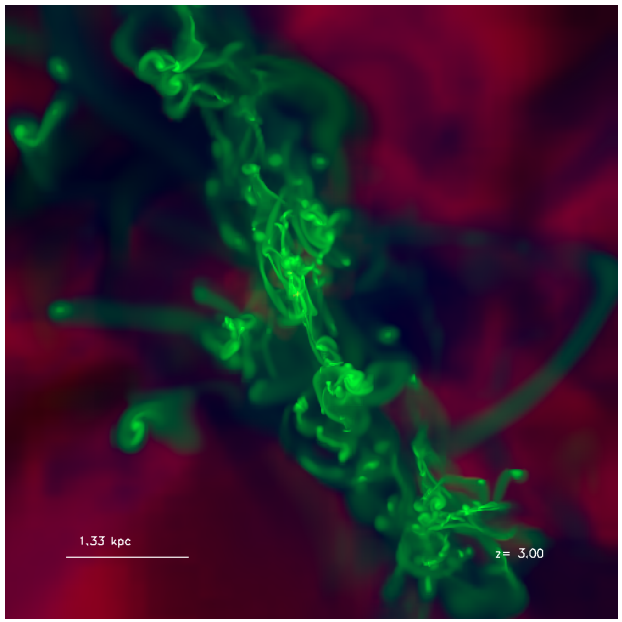

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density threshold SF, no fbk

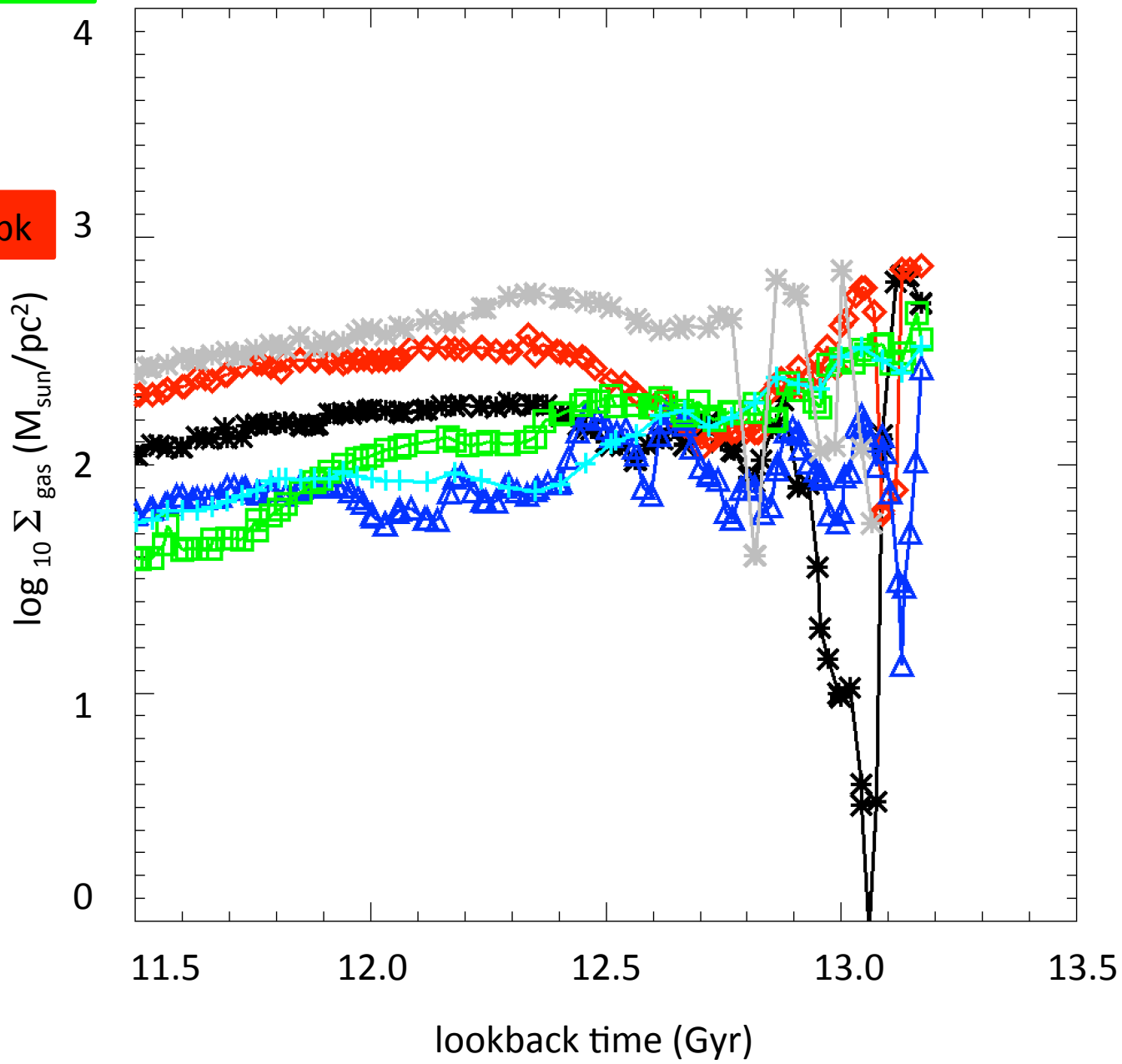
density threshold SF, energy fbk

density threshold SF, momentum fbk

self-gravitating SF, no fbk

self-gravitating SF, energy fbk

self-gravitating SF, momentum fbk



density threshold SF, no fbk

z=3

total v $_{circ}$ (DM + stars + gas)

gas v $_{rot}$

gas v $_{circ}$

mass weighted gas velocity dispersion

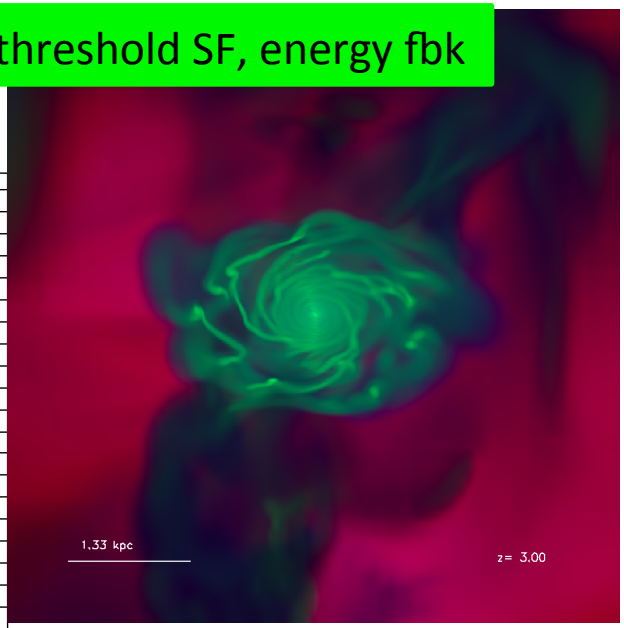
v (km/s)

0
100
200
300
400

0
0.5
1
1.5
2
2.5
3

R (kpc)

density threshold SF, energy fbk



z=3

total v $_{circ}$ (DM + stars + gas)

gas v $_{rot}$

gas v $_{circ}$

mass weighted gas velocity dispersion

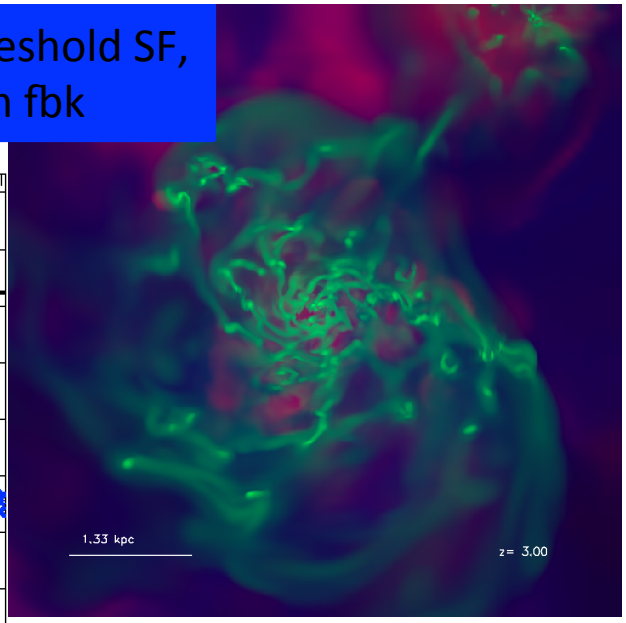
v (km/s)

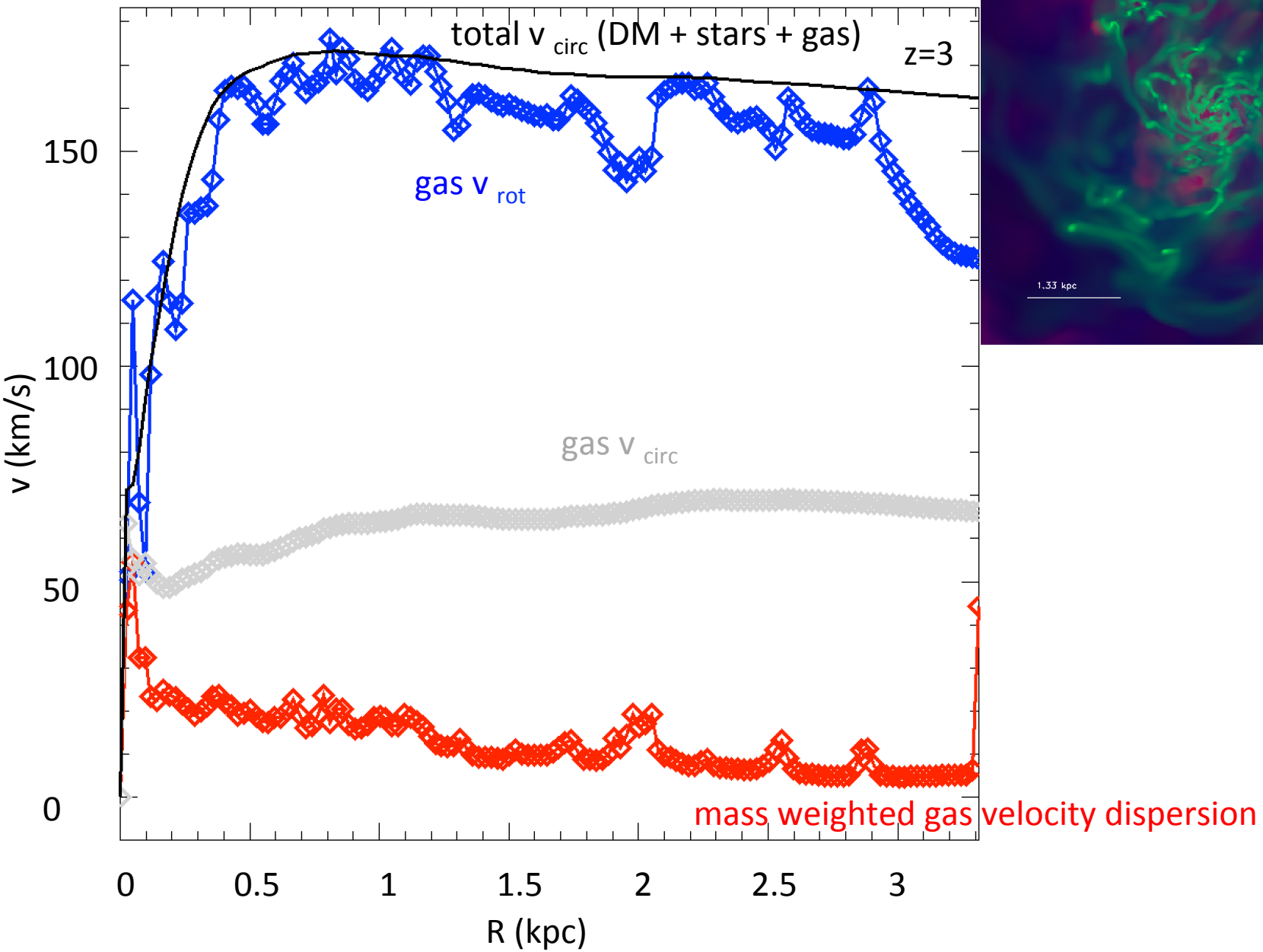
0
100
200
300
400

0
0.5
1
1.5
2
2.5
3

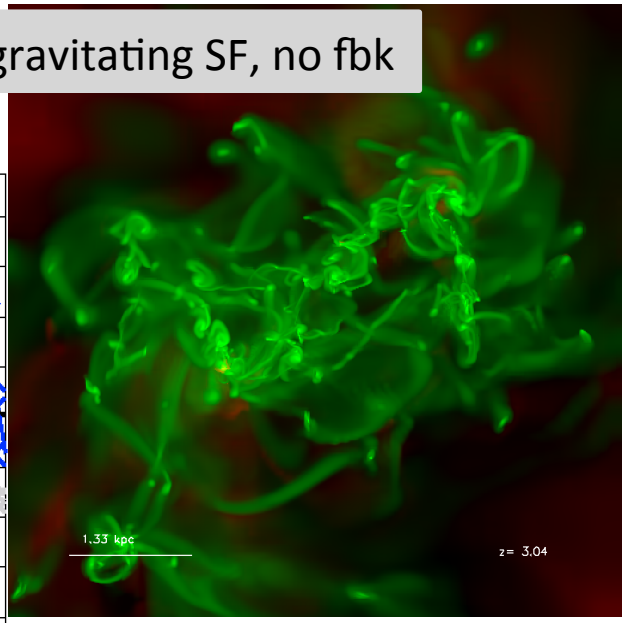
R (kpc)

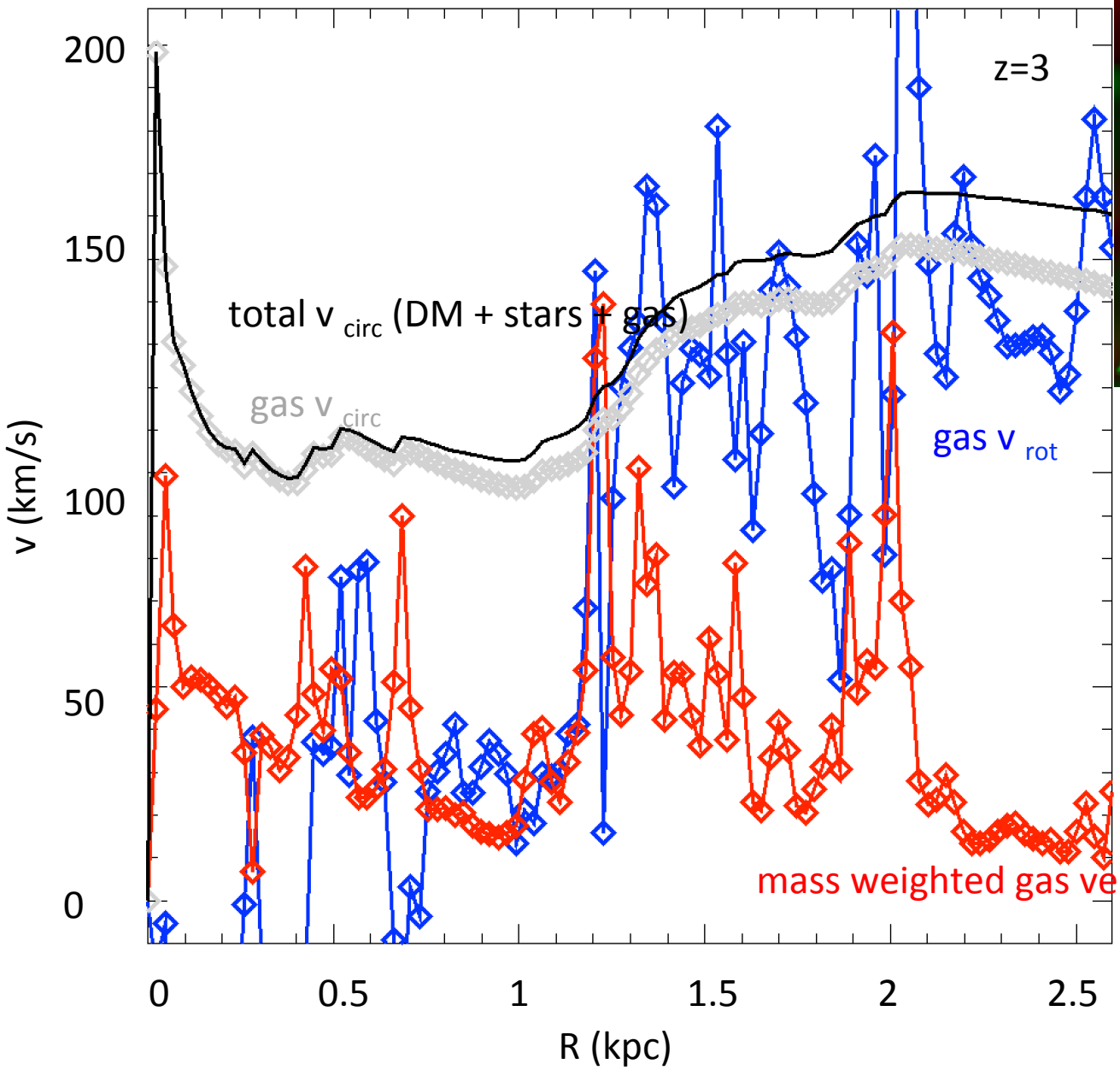
density threshold SF,
momentum fbk



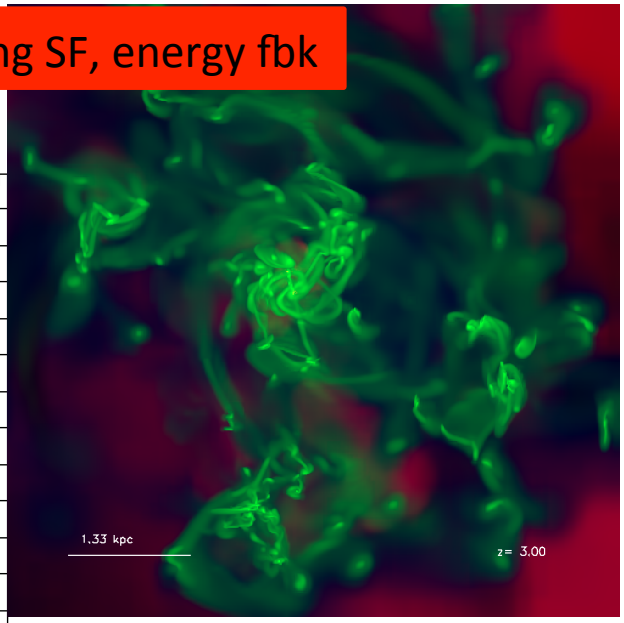


self-gravitating SF, no fbk





self-gravitating SF, energy fbk



z=3

total v circ (DM + stars + gas)

gas v circ

gas v rot

mass weighted gas velocity dispersion

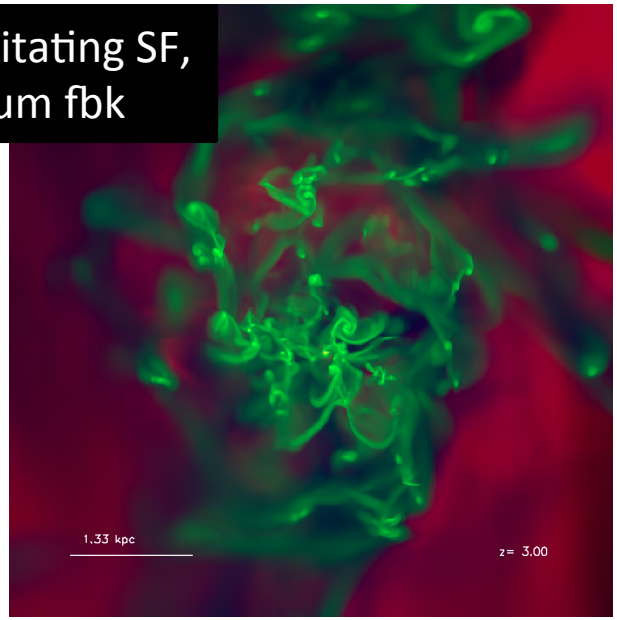
v (km/s)

0
50
100
150
200
250

0
0.5
1
1.5
2
2.5
3

R (kpc)

self-gravitating SF,
momentum fbk



z=3

total v $_{circ}$ (DM + stars + gas)

gas v $_{rot}$

gas v $_{circ}$

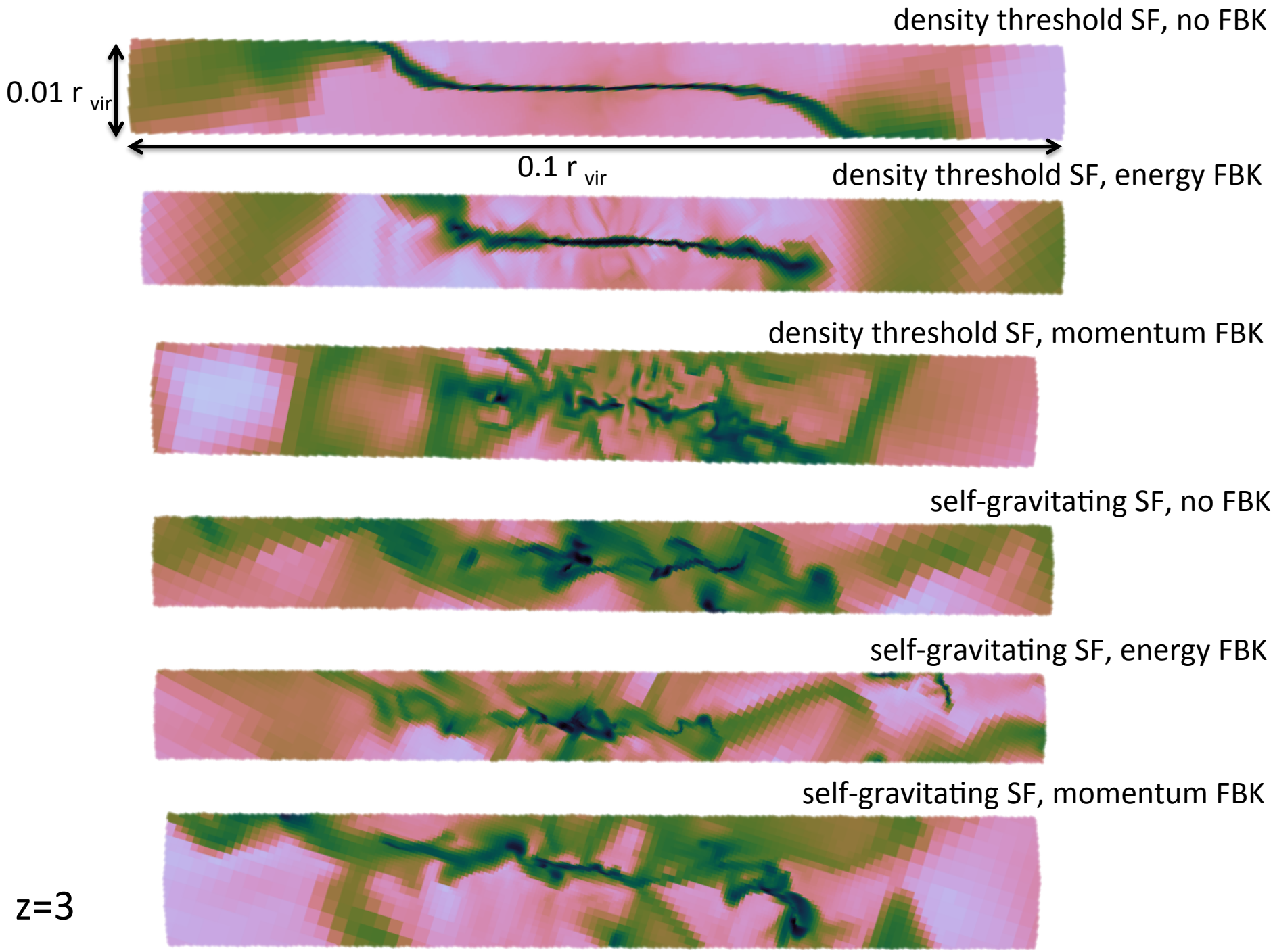
mass weighted gas velocity dispersion

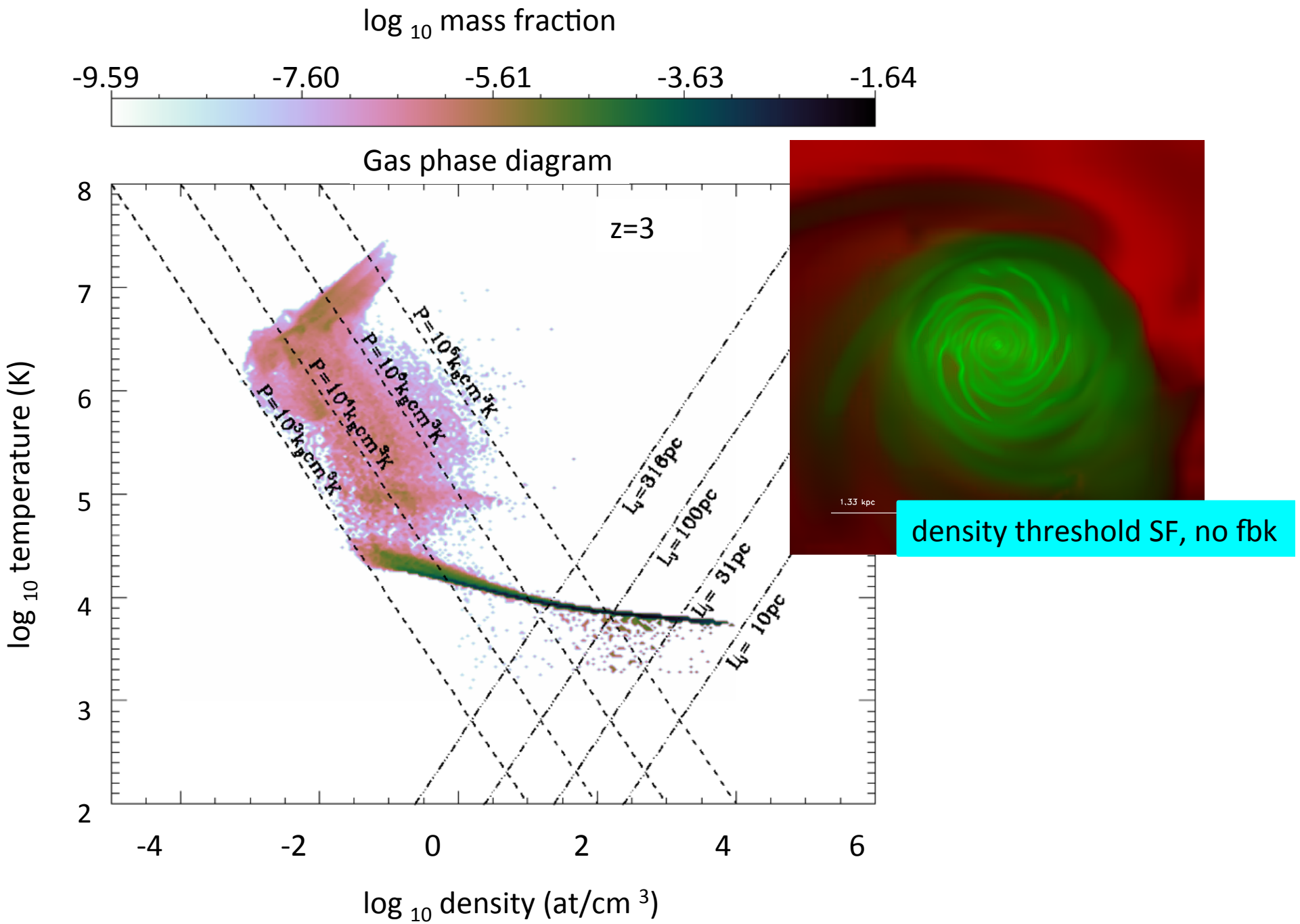
v (km/s)

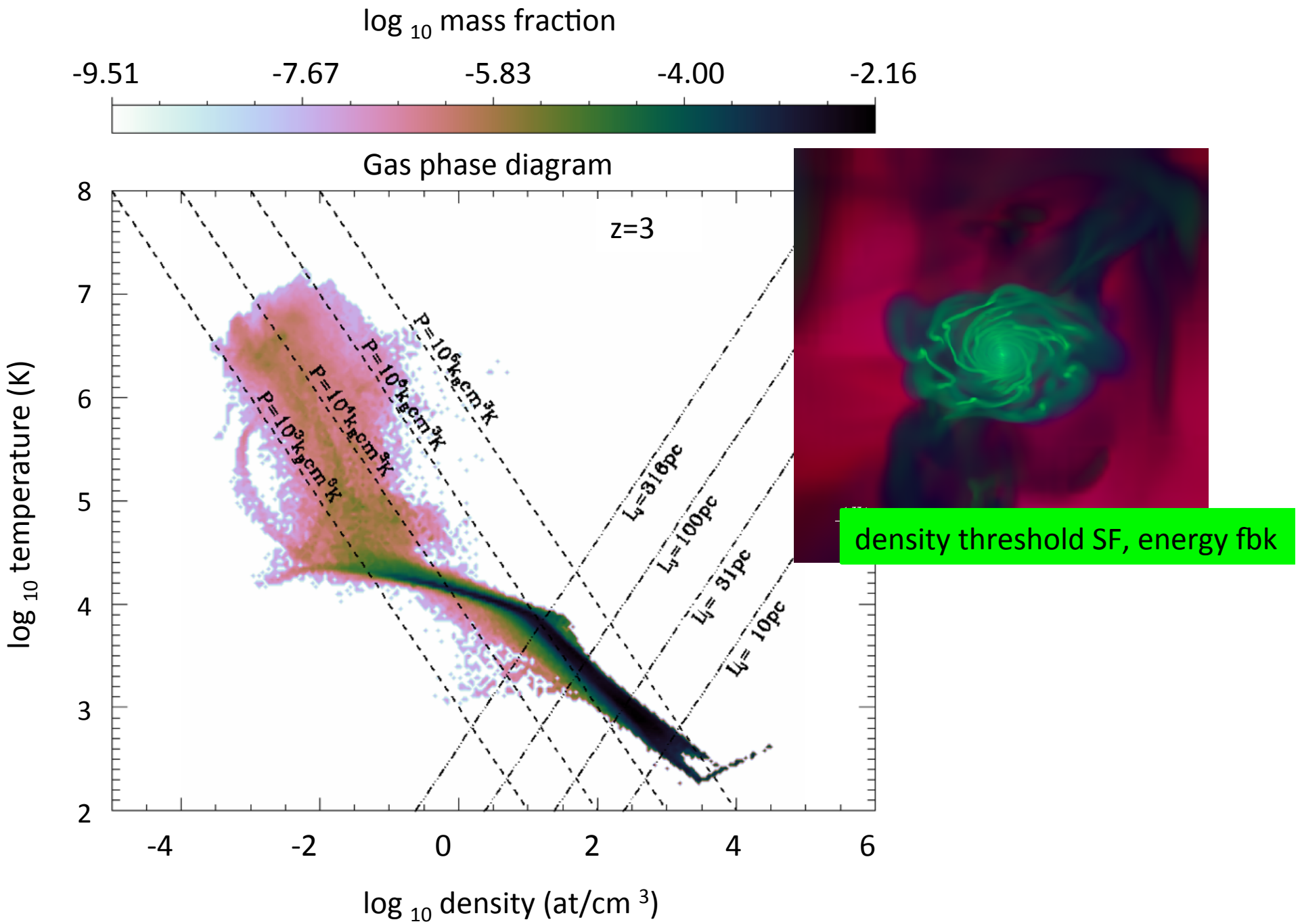
200
150
100
50
0

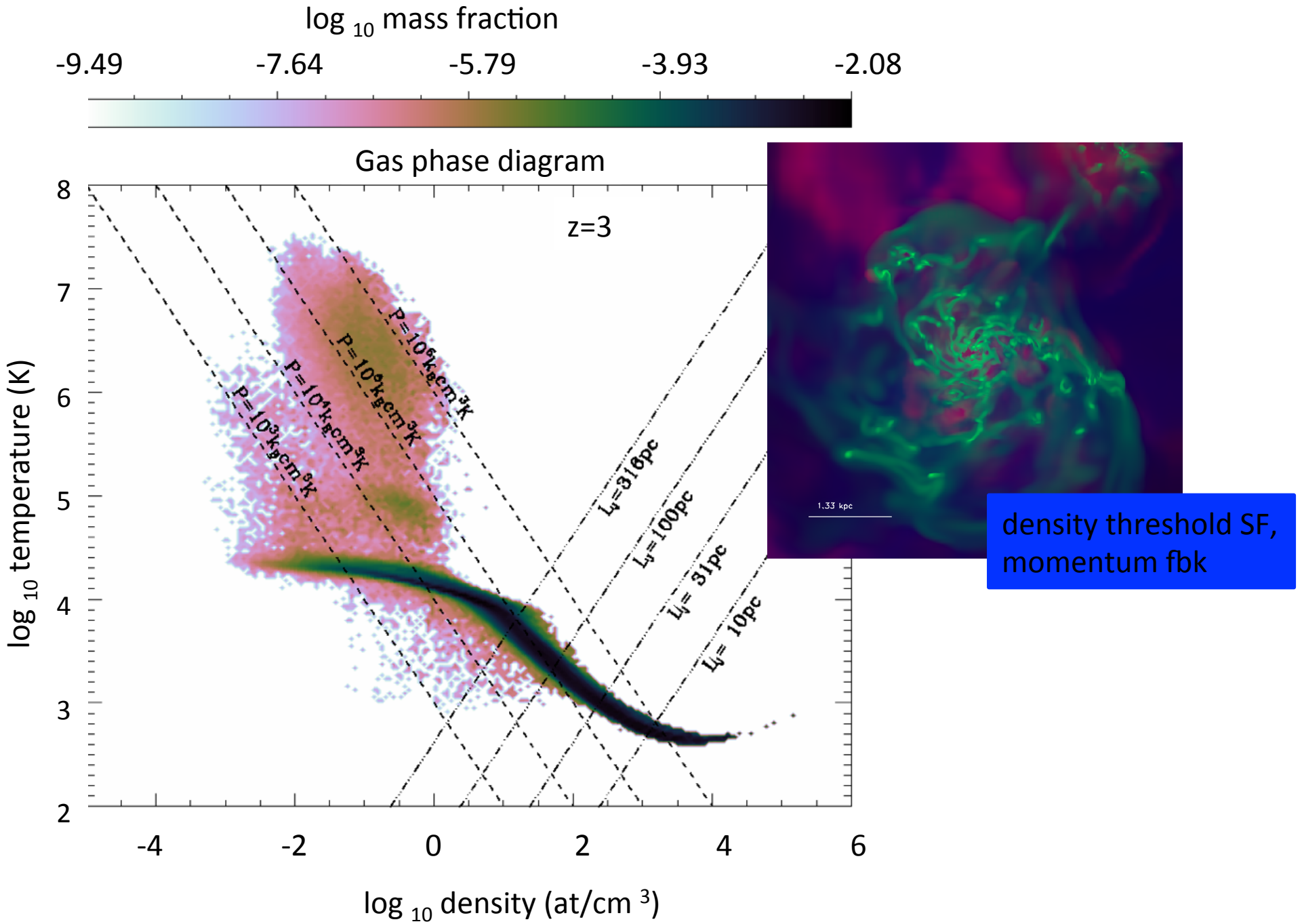
0
0.5
1
1.5
2
2.5

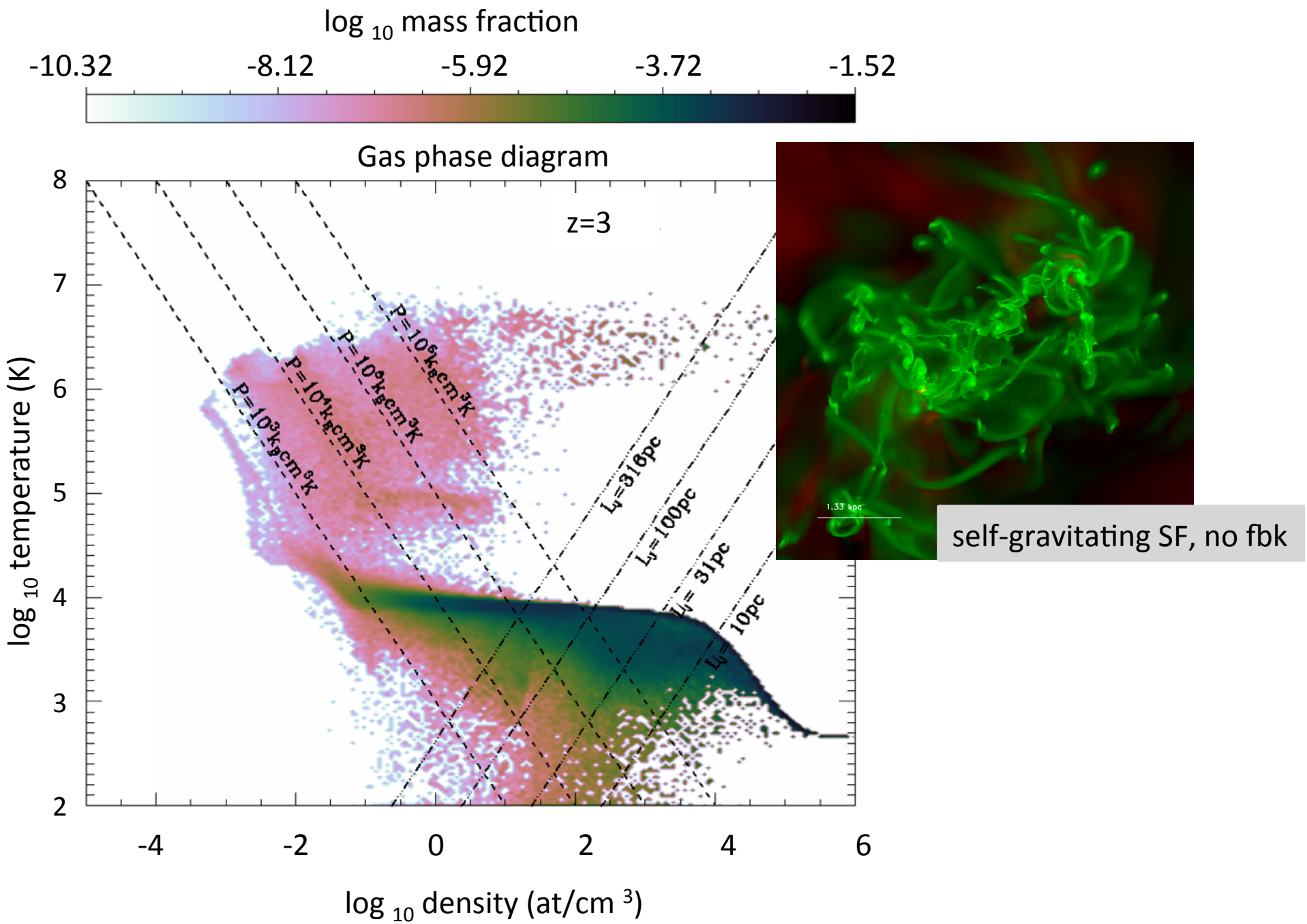
R (kpc)

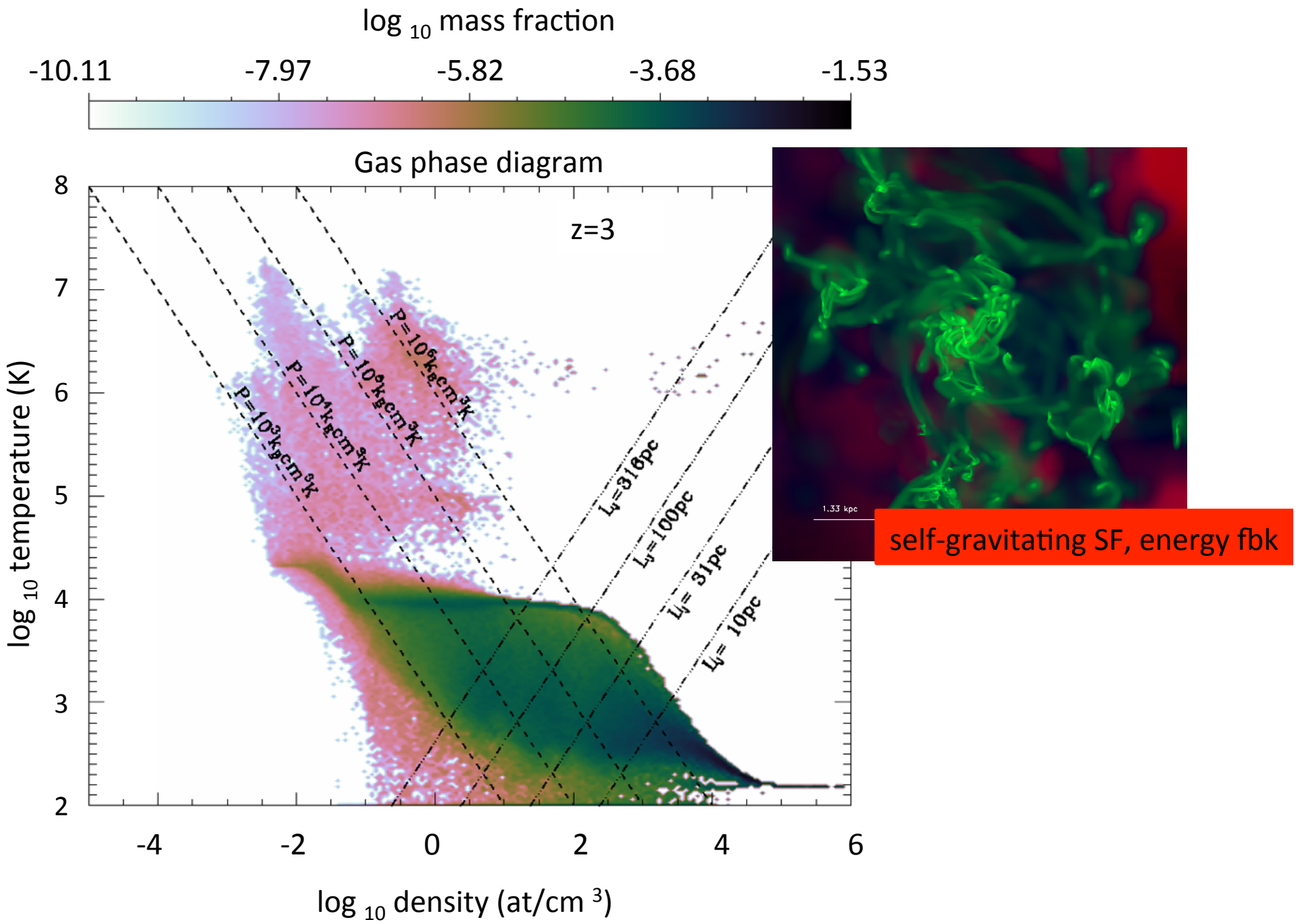

density threshold SF, no FBK
0.01 r vir
0.1 r vir
density threshold SF, energy FBK
density threshold SF, momentum FBK
self-gravitating SF, no FBK
self-gravitating SF, energy FBK
self-gravitating SF, momentum FBK
z=3

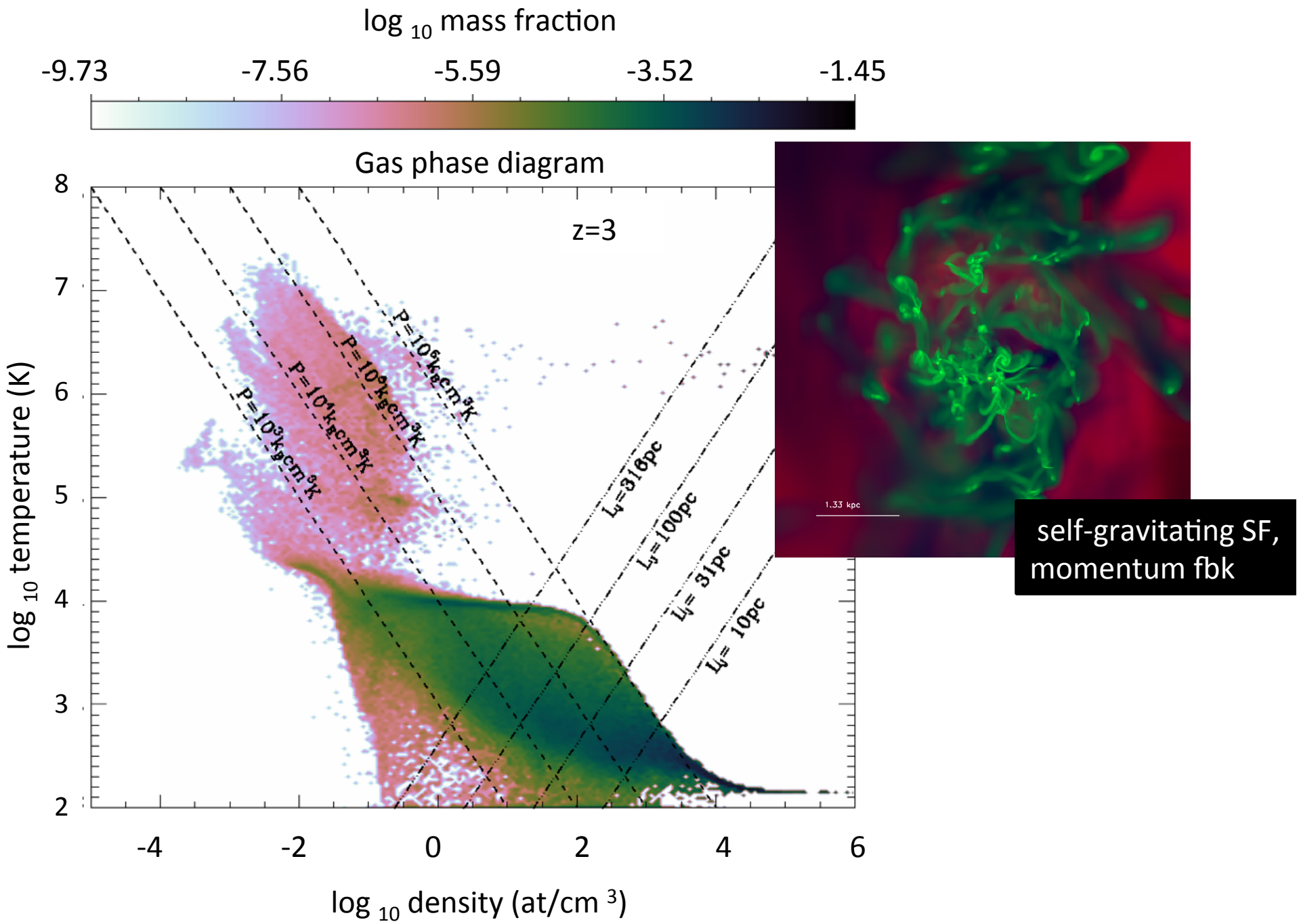

log 10 mass fraction
-9.59
-7.60
-5.61
-3.63
-1.64
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
L=316pc
L=100pc
L= 31pc
L= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
8
7
6
5
4
3
2
-4
-2
0
2
4
6
1.33 kpc
density threshold SF, no fbk

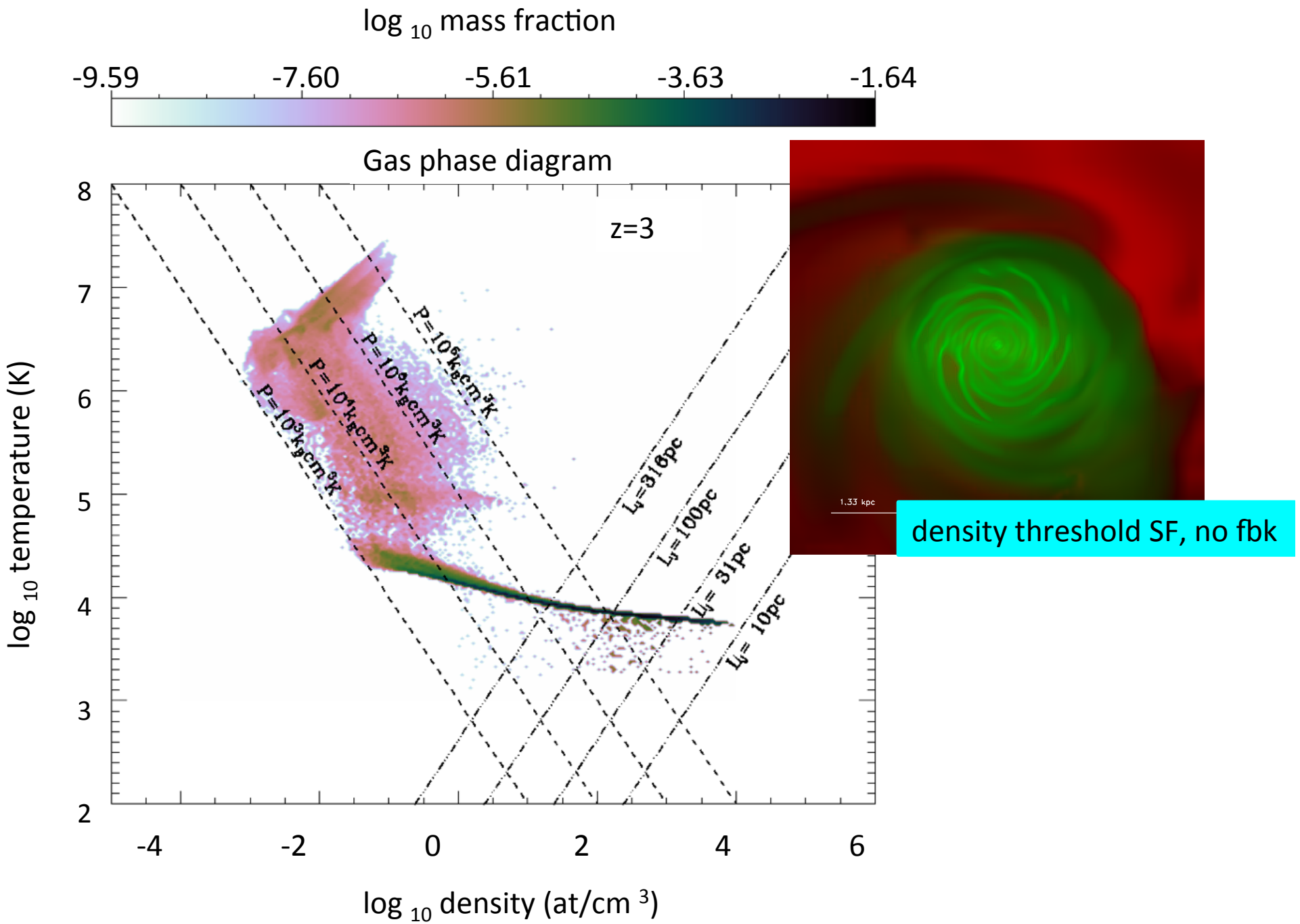

log 10 mass fraction
-9.51
-7.67
-5.83
-4.00
-2.16
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
L=316pc
L=100pc
L= 31pc
L= 10pc
log 10 temperature (K)
8
7
6
5
4
3
2
-4
-2
0
2
4
6
log 10 density (at/cm 3)
density threshold SF, energy fbk

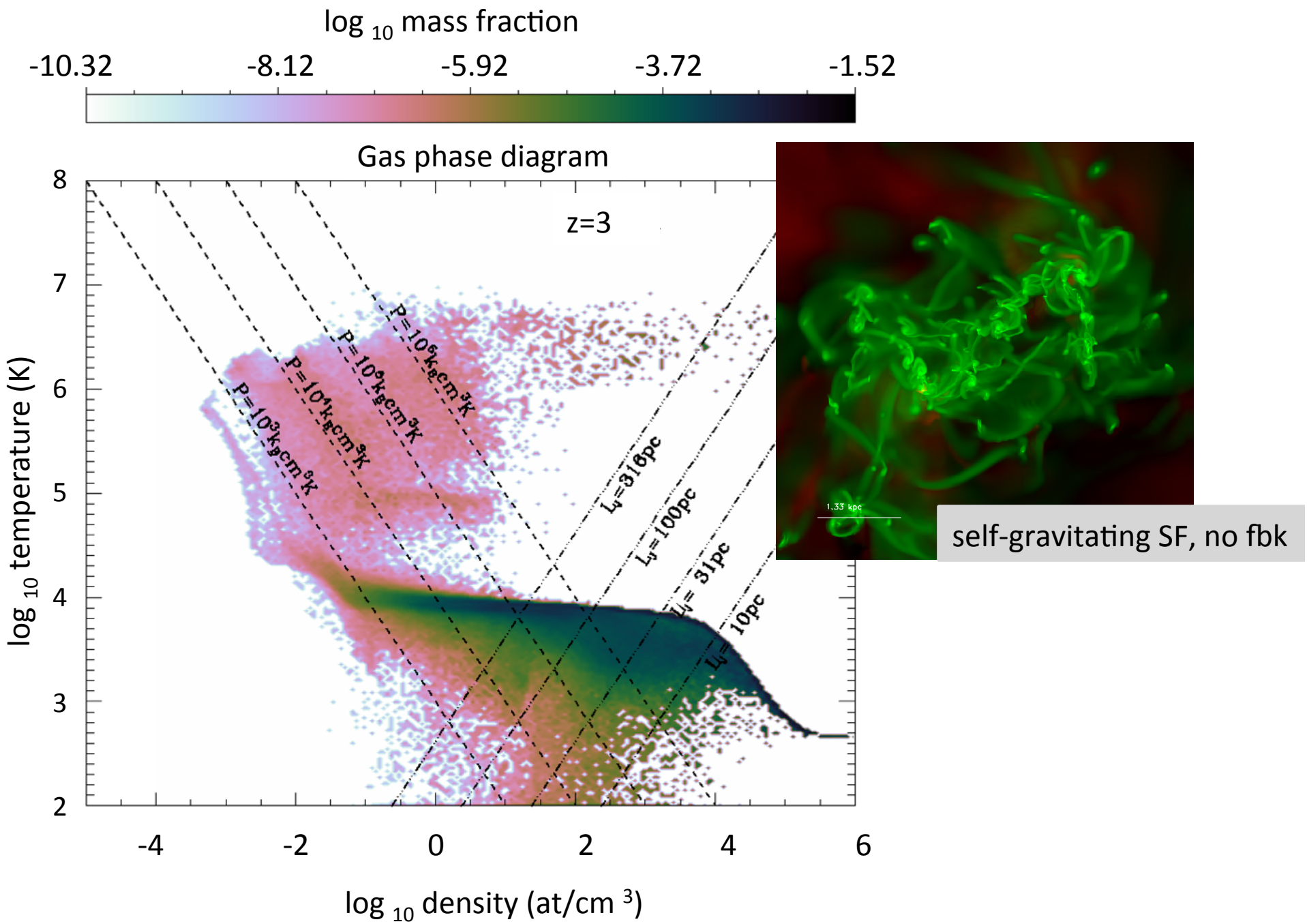

log 10 mass fraction
-9.49
-7.64
-5.79
-3.93
-2.08
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
Lj=316pc
Lj=100pc
Lj= 31pc
Lj= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
1.33 kpc
density threshold SF,
momentum fbk

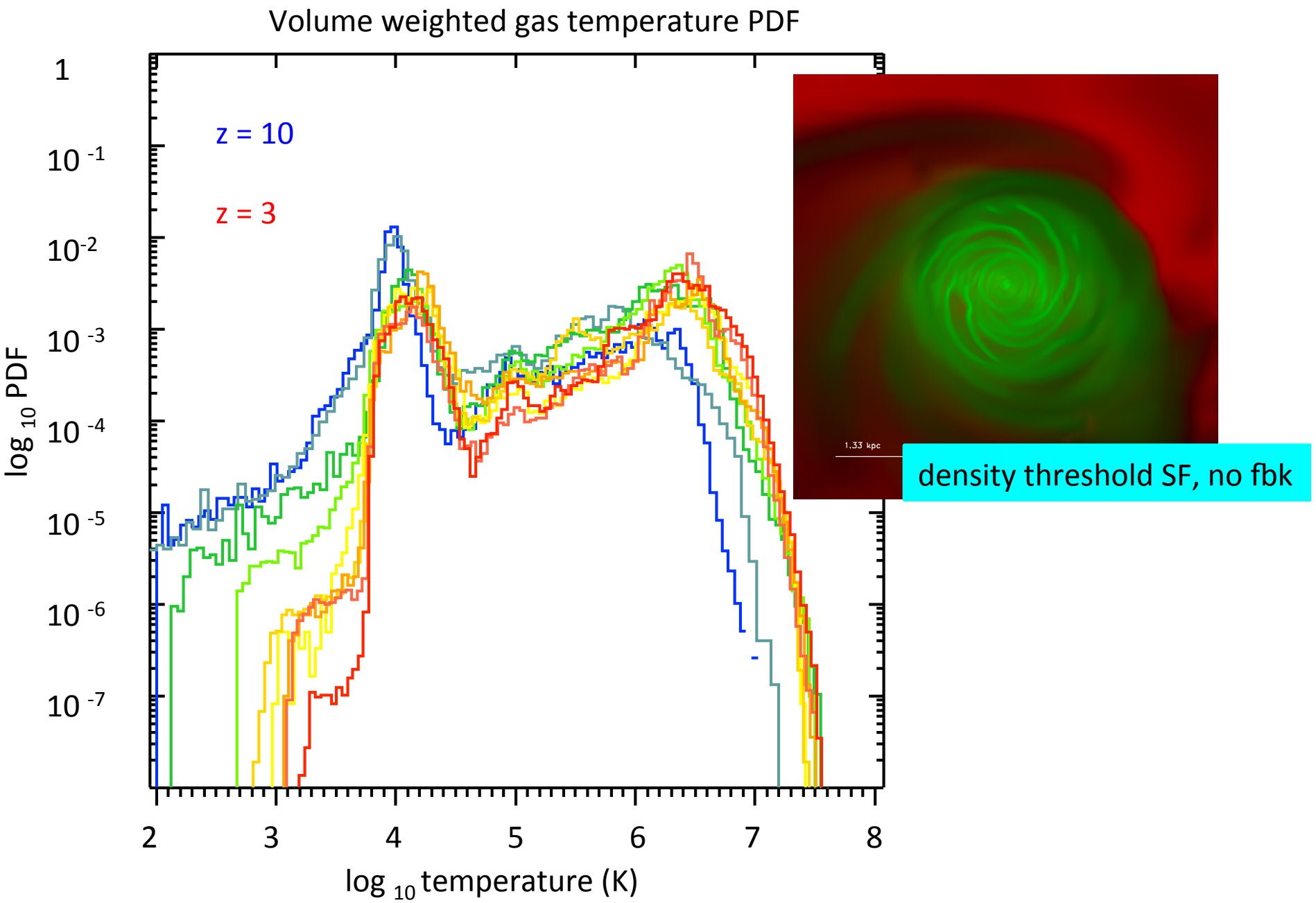

log 10 mass fraction
-10.32
-8.12
-5.92
-3.72
-1.52
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
L=316pc
L=100pc
L= 31pc
L= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
8
7
6
5
4
3
2
-4
-2
0
2
4
6
1.33 kpc
self-gravitating SF, no fbk

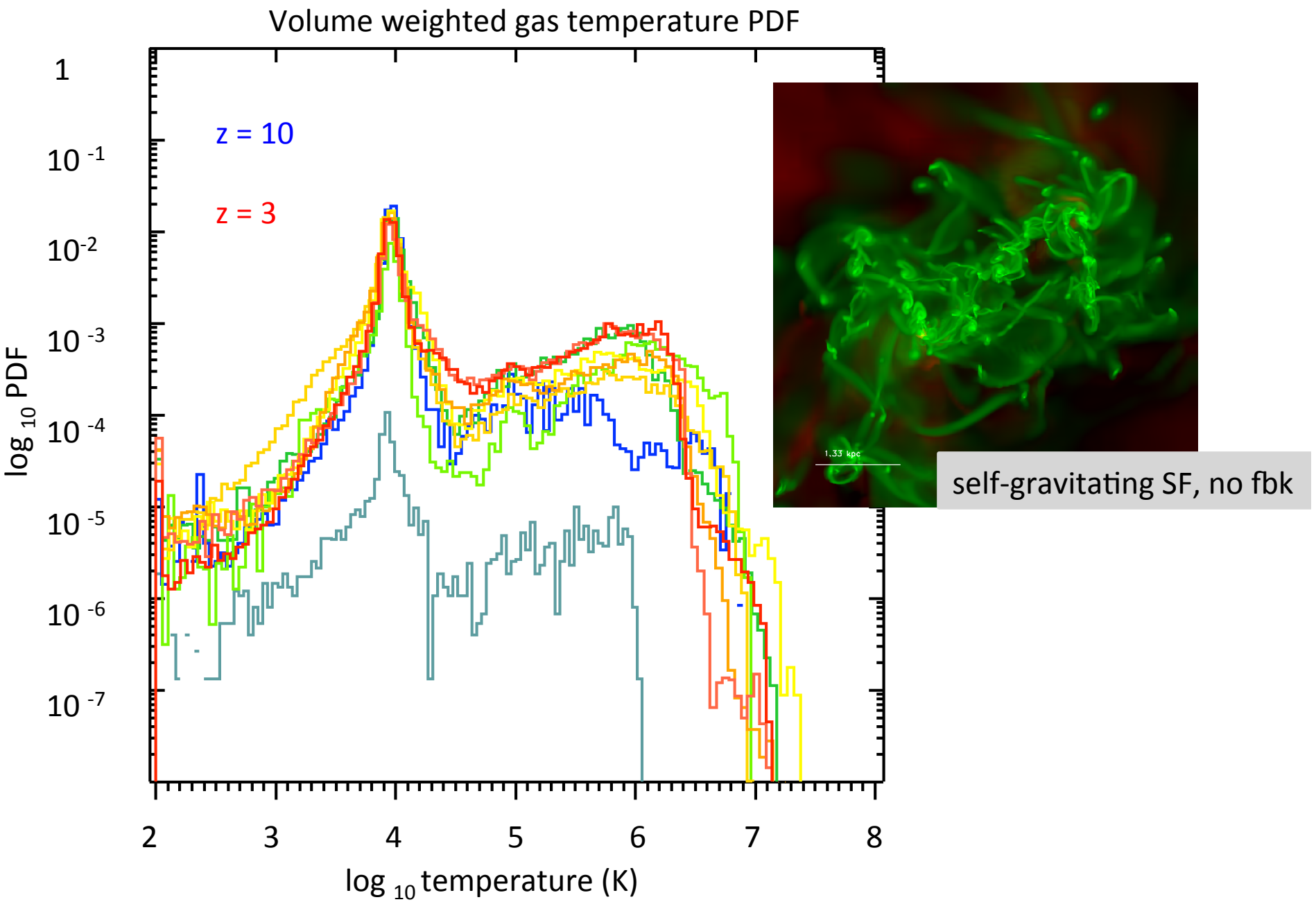

log 10 mass fraction
-10.11
-7.97
-5.82
-3.68
-1.53
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
Lj=316pc
Lj=100pc
Lj= 31pc
Lj= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
1.33 kpc
self-gravitating SF, energy fbk

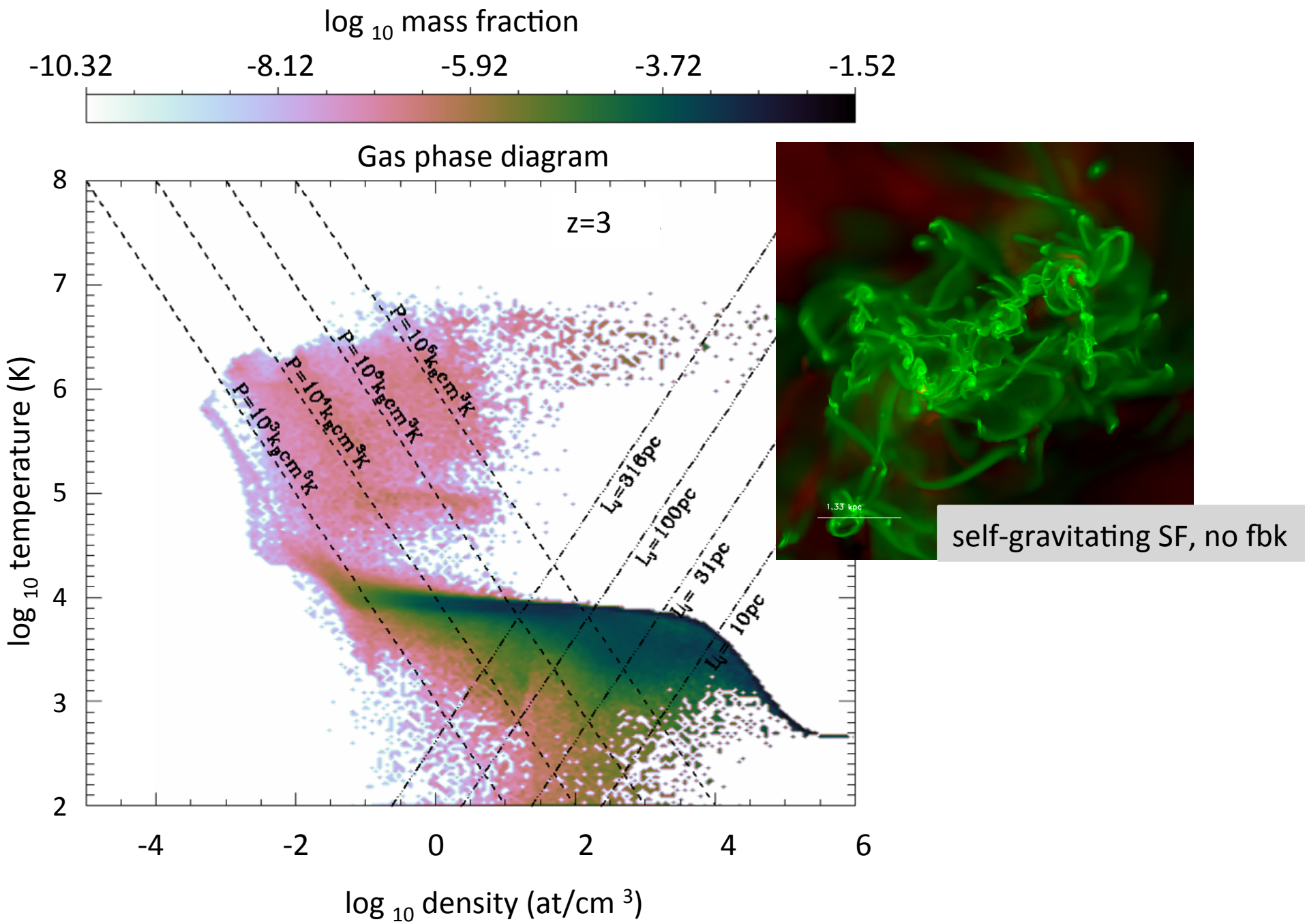

log 10 mass fraction
-9.73
-7.56
-5.59
-3.52
-1.45
Gas phase diagram
z=3
P=10⁶kgcm⁻³K
P=10⁵kgcm⁻³K
P=10⁴kgcm⁻³K
P=10³kgcm⁻³K
Lj=316pc
Lj=100pc
Lj= 31pc
Lj= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
8
7
6
5
4
3
2
-4
-2
0
2
4
6
1.33 kpc
self-gravitating SF,
momentum fbk

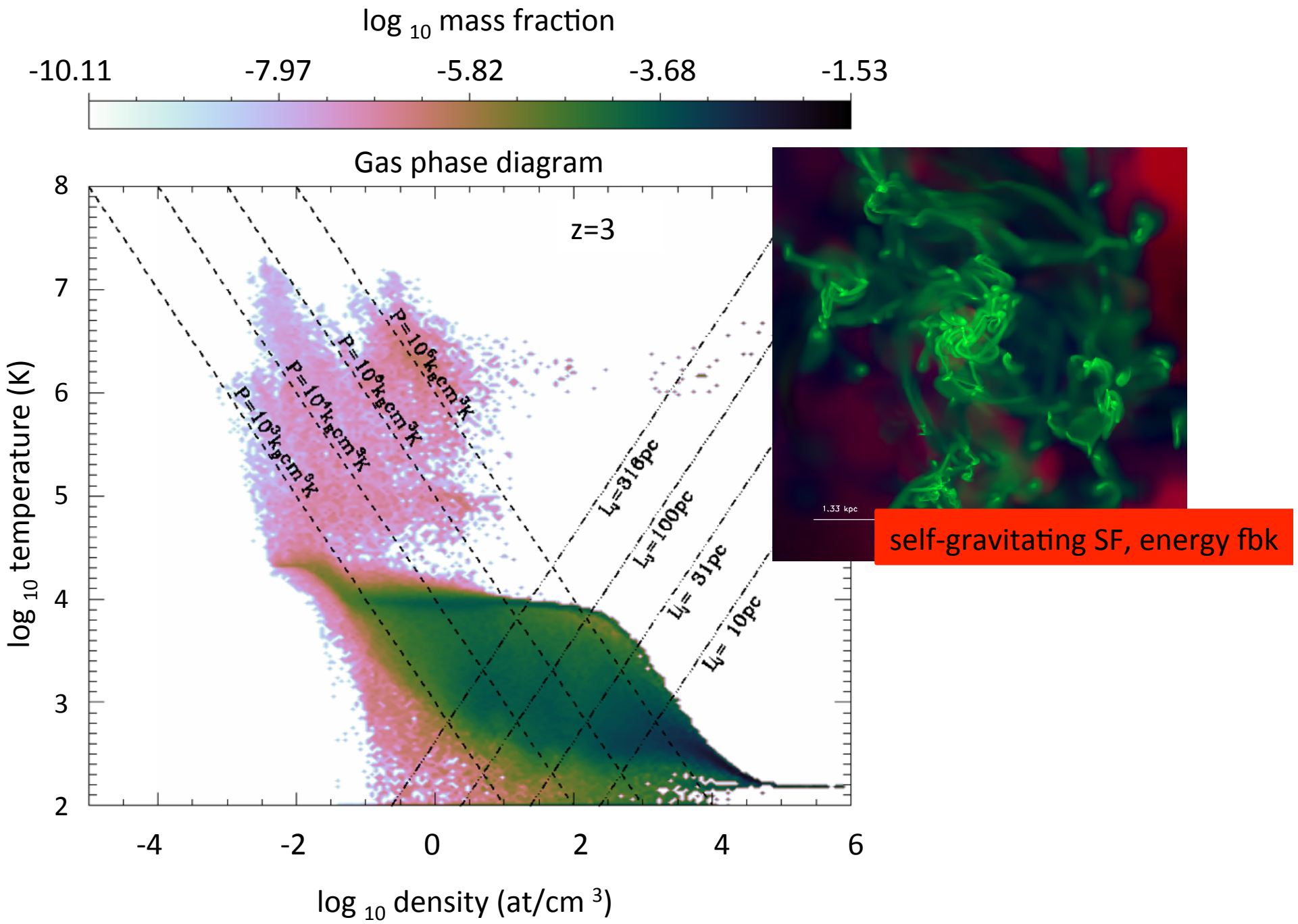

log 10 mass fraction
-9.59
-7.60
-5.61
-3.63
-1.64
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
L=316pc
L=100pc
L= 31pc
L= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
8
7
6
5
4
3
2
-4
-2
0
2
4
6
1.33 kpc
density threshold SF, no fbk

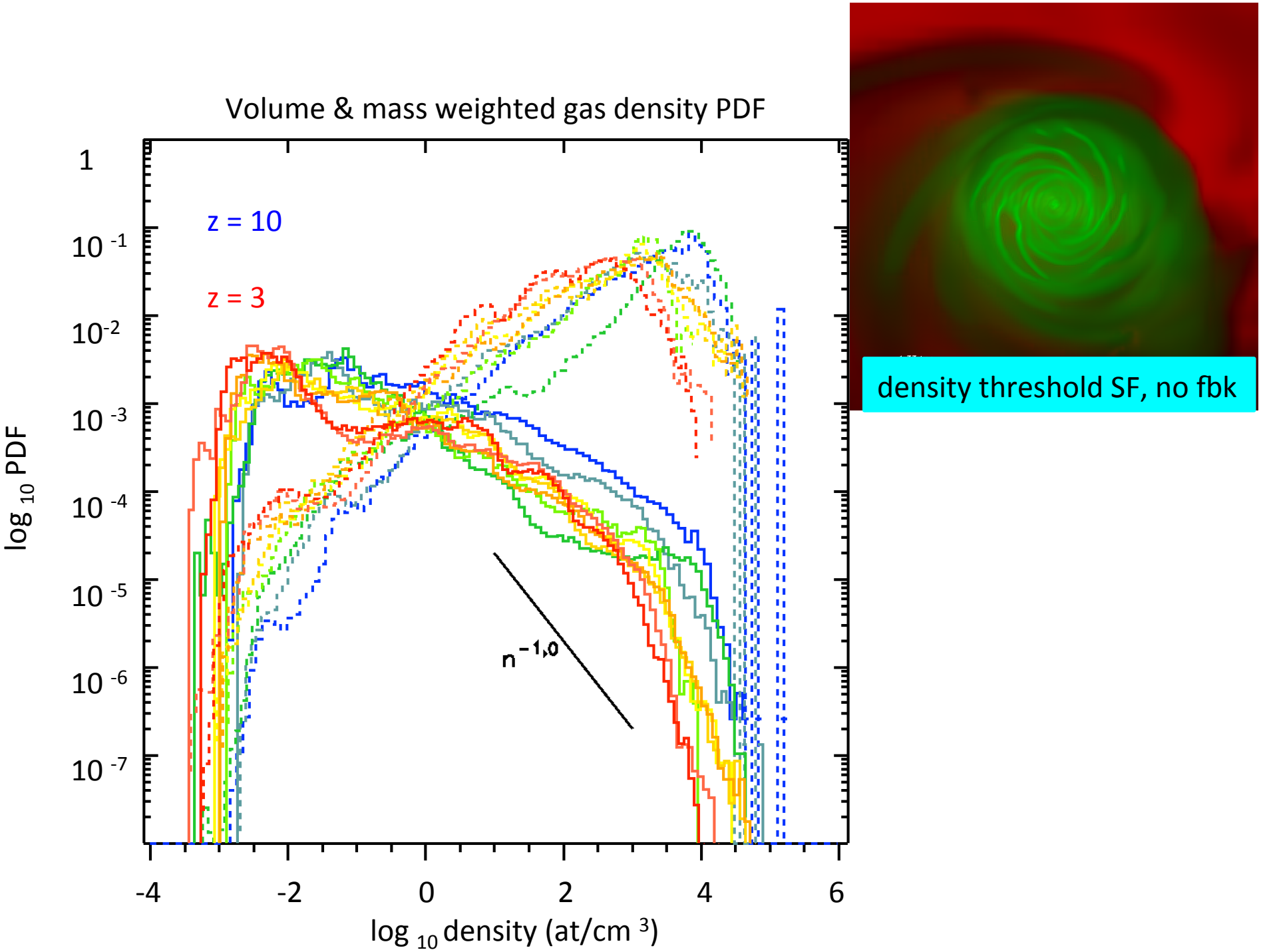

log 10 mass fraction
-10.32
-8.12
-5.92
-3.72
-1.52
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
L=316pc
L=100pc
L= 31pc
L= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
8
7
6
5
4
3
2
-4
-2
0
2
4
6
1.33 kpc
self-gravitating SF, no fbk

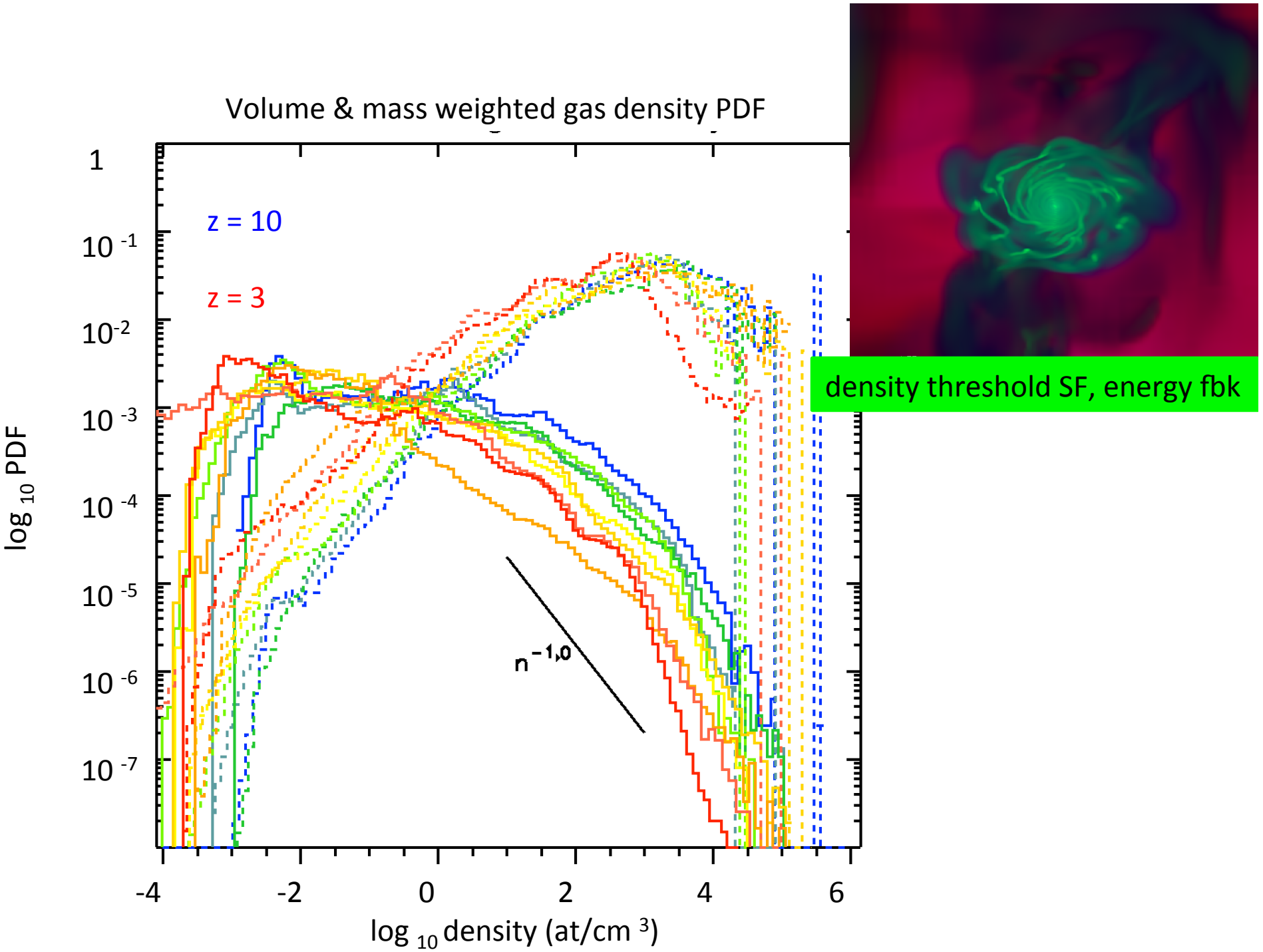

Volume weighted gas temperature PDF
z = 10
z = 3
log 10 PDF
log 10 temperature (K)
1
10 -1
10-2
10 -3
10 -4
10 -5
10 -6
10 -7
2
3
4
5
6
7
8
1.33 kpc
density threshold SF, no fbk

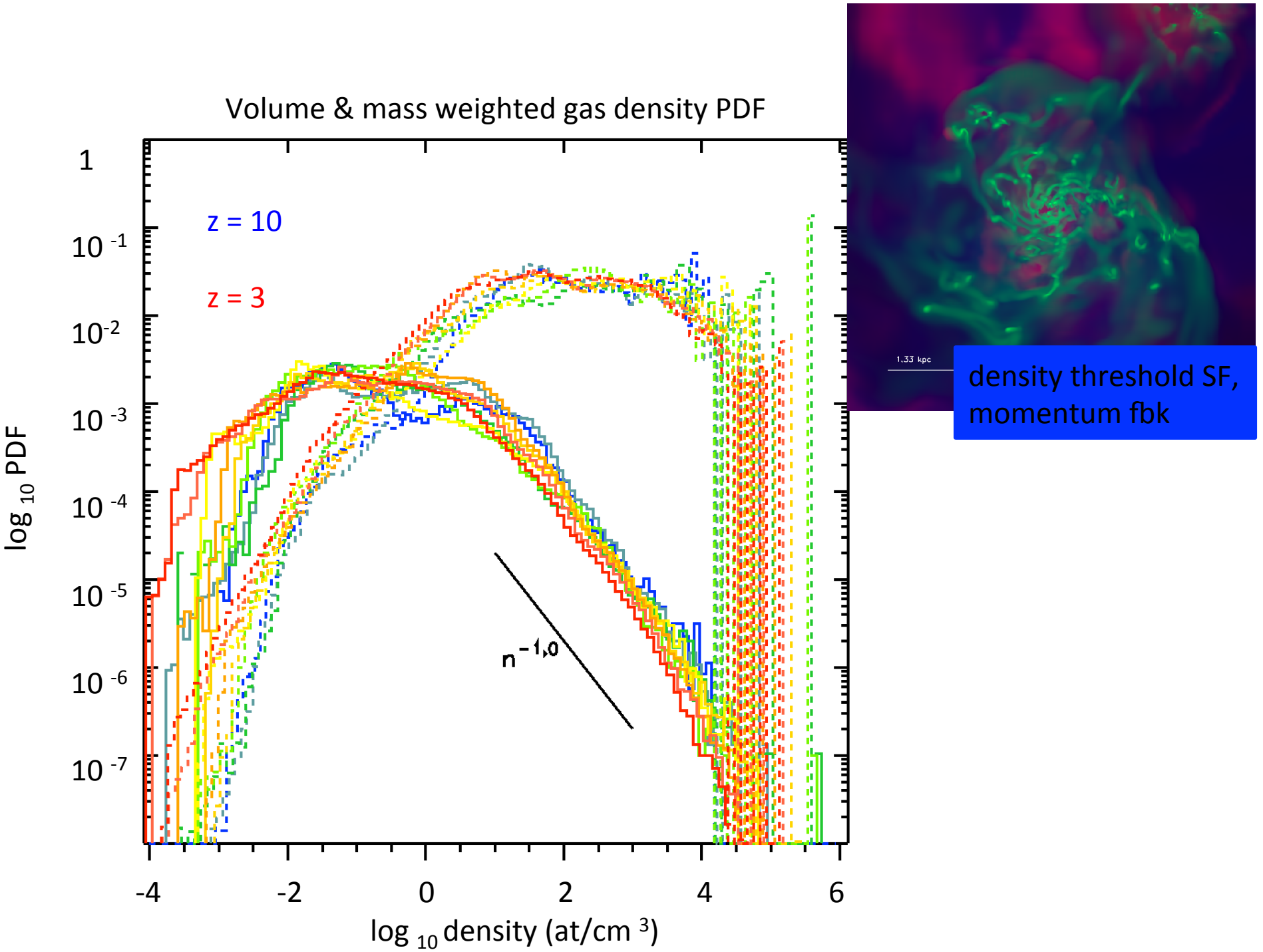

Volume weighted gas temperature PDF
z = 10
z = 3
log 10 PDF
log 10 temperature (K)
1
10 -1
10-2
10 -3
10 -4
10 -5
10 -6
10 -7
2
3
4
5
6
7
8
1.33 kpc
self-gravitating SF, no fbk


log 10 mass fraction
-10.32
-8.12
-5.92
-3.72
-1.52
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
L=316pc
L=100pc
L= 31pc
L= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
8
7
6
5
4
3
2
-4
-2
0
2
4
6
1.33 kpc
self-gravitating SF, no fbk

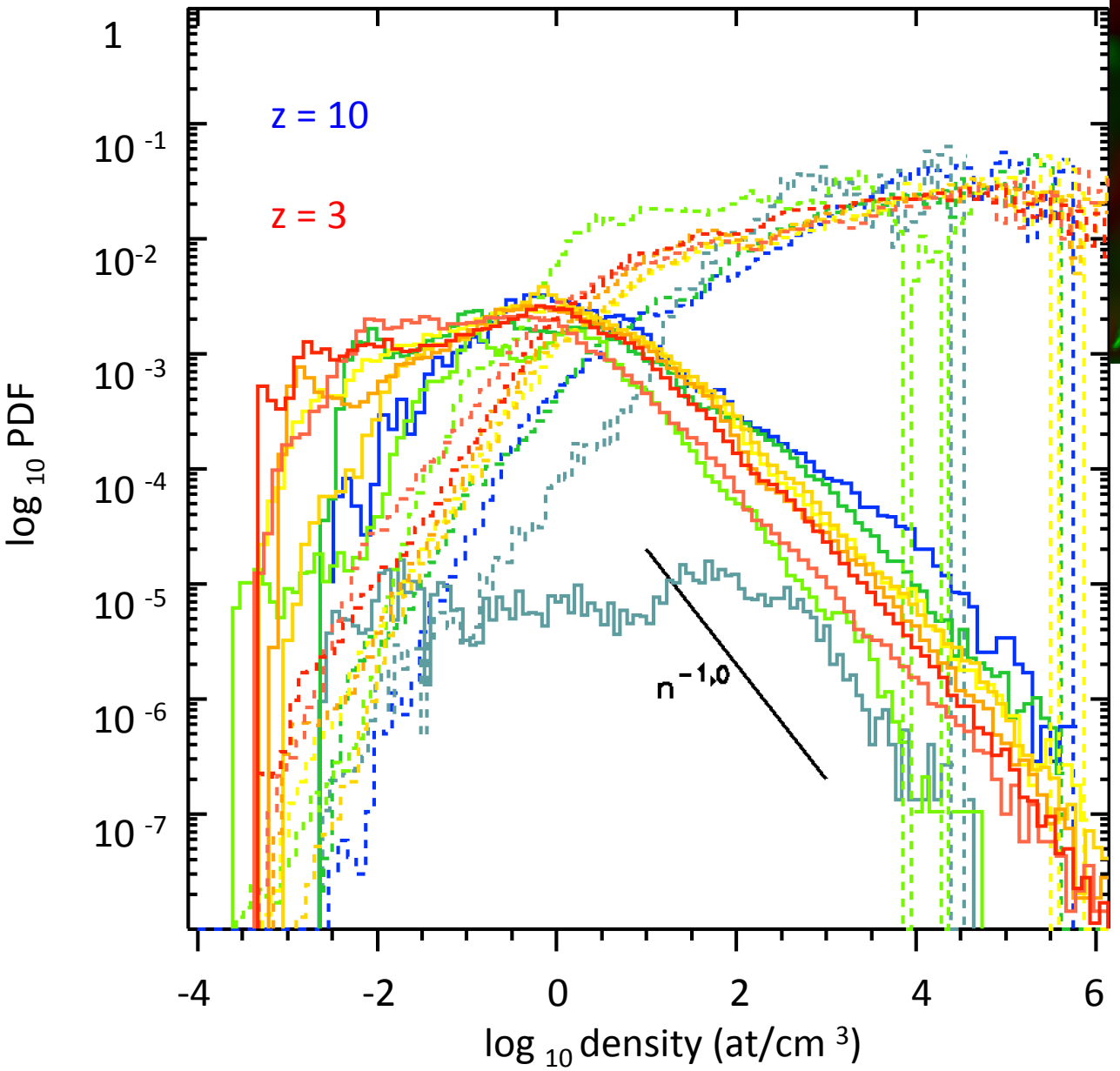

log 10 mass fraction
-10.11
-7.97
-5.82
-3.68
-1.53
Gas phase diagram
z=3
P=10⁶kgcm⁻¹K
P=10⁵kgcm⁻¹K
P=10⁴kgcm⁻¹K
P=10³kgcm⁻¹K
Lj=316pc
Lj=100pc
Lj= 31pc
Lj= 10pc
log 10 temperature (K)
log 10 density (at/cm 3)
1.33 kpc
self-gravitating SF, energy fbk


Volume & mass weighted gas density PDF
z = 10
z = 3
n^-1,0
log 10 PDF
log 10 density (at/cm 3)
1
10 -1
10-2
10 -3
10 -4
10 -5
10 -6
10 -7
-4
-2
0
2
4
6
density threshold SF, no fbk

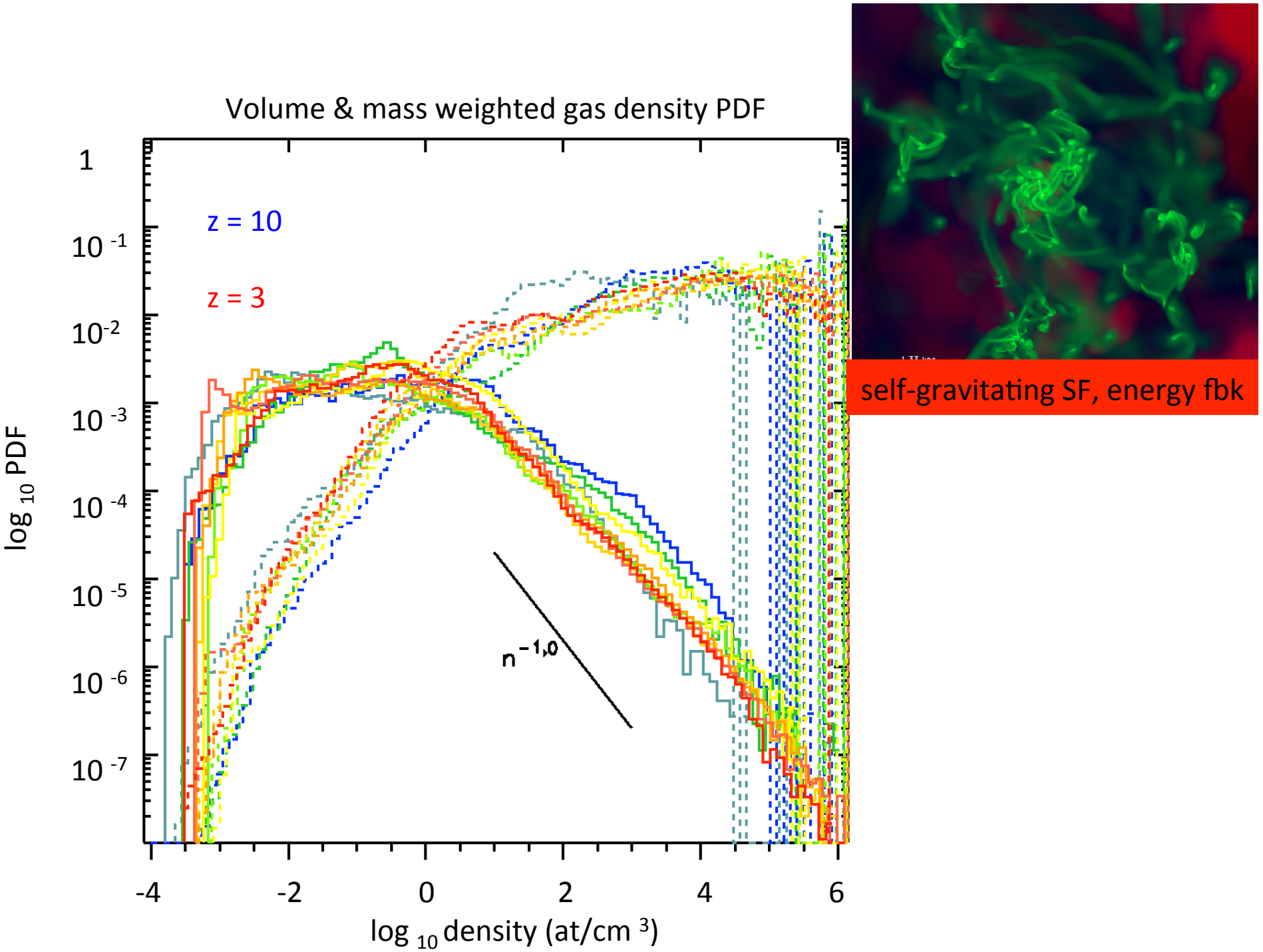

Volume & mass weighted gas density PDF
z = 10
z = 3
n^-1,0
log 10 PDF
log 10 density (at/cm 3)
1
10 -1
10-2
10 -3
10 -4
10 -5
10 -6
10 -7
-4
-2
0
2
4
6
density threshold SF, energy fbk


Volume & mass weighted gas density PDF
z = 10
z = 3
n^-1,0
log 10 PDF
log 10 density (at/cm 3)
1
10 -1
10-2
10 -3
10 -4
10 -5
10 -6
10 -7
-4
-2
0
2
4
6
1.33 kpc
density threshold SF,
momentum fbk

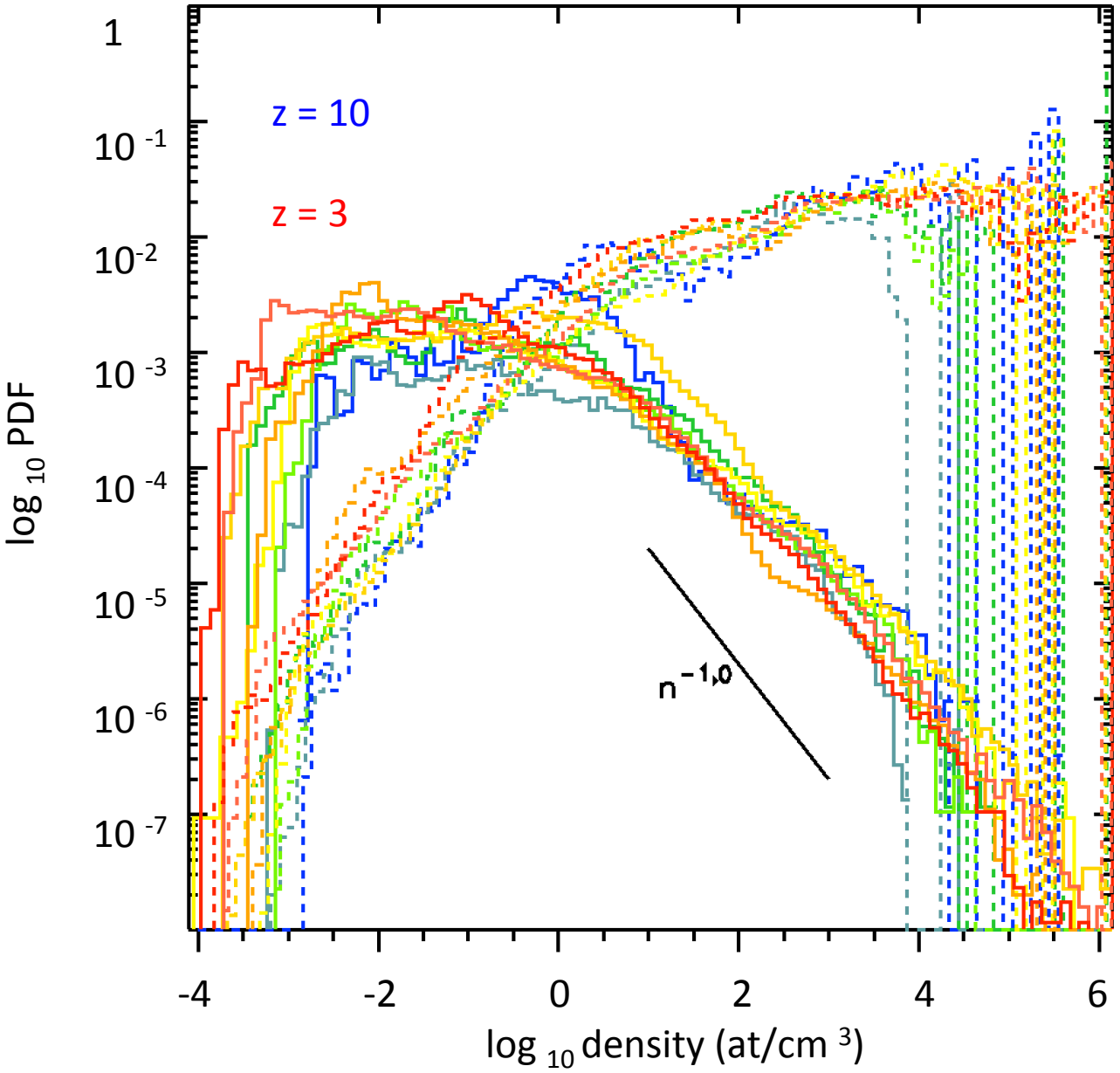
Volume & mass weighted gas density PDF

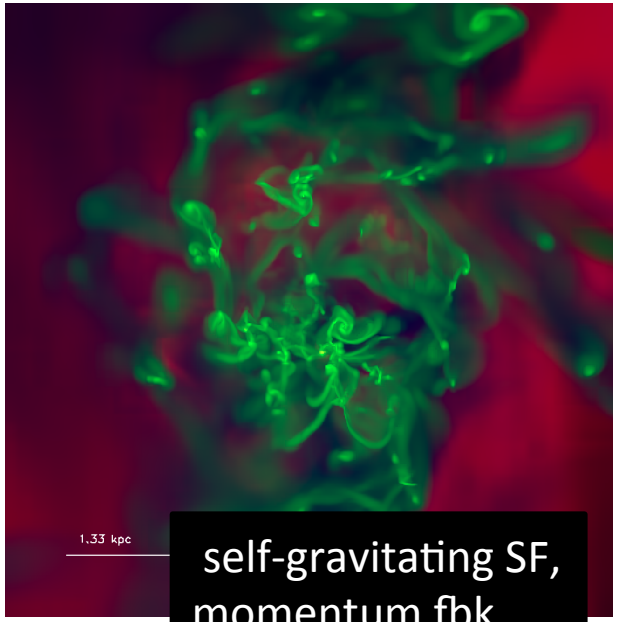


self-gravitating SF, no fbk

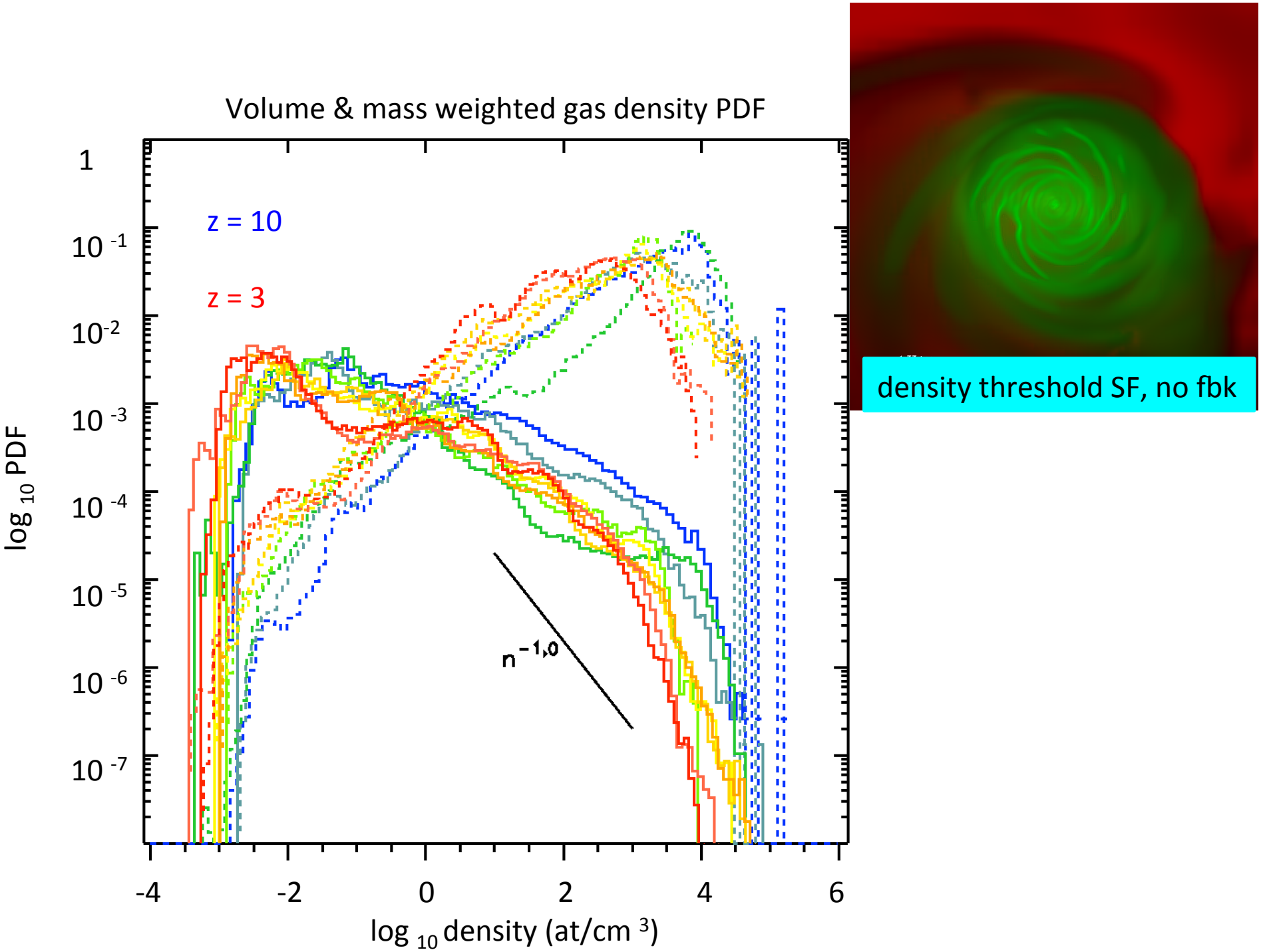

Volume & mass weighted gas density PDF
z = 10
z = 3
n^-1,0
log 10 PDF
log 10 density (at/cm 3)
1
10 -1
10-2
10 -3
10 -4
10 -5
10 -6
10 -7
-4
-2
0
2
4
6
self-gravitating SF, energy fbk

Volume & mass weighted gas density PDF

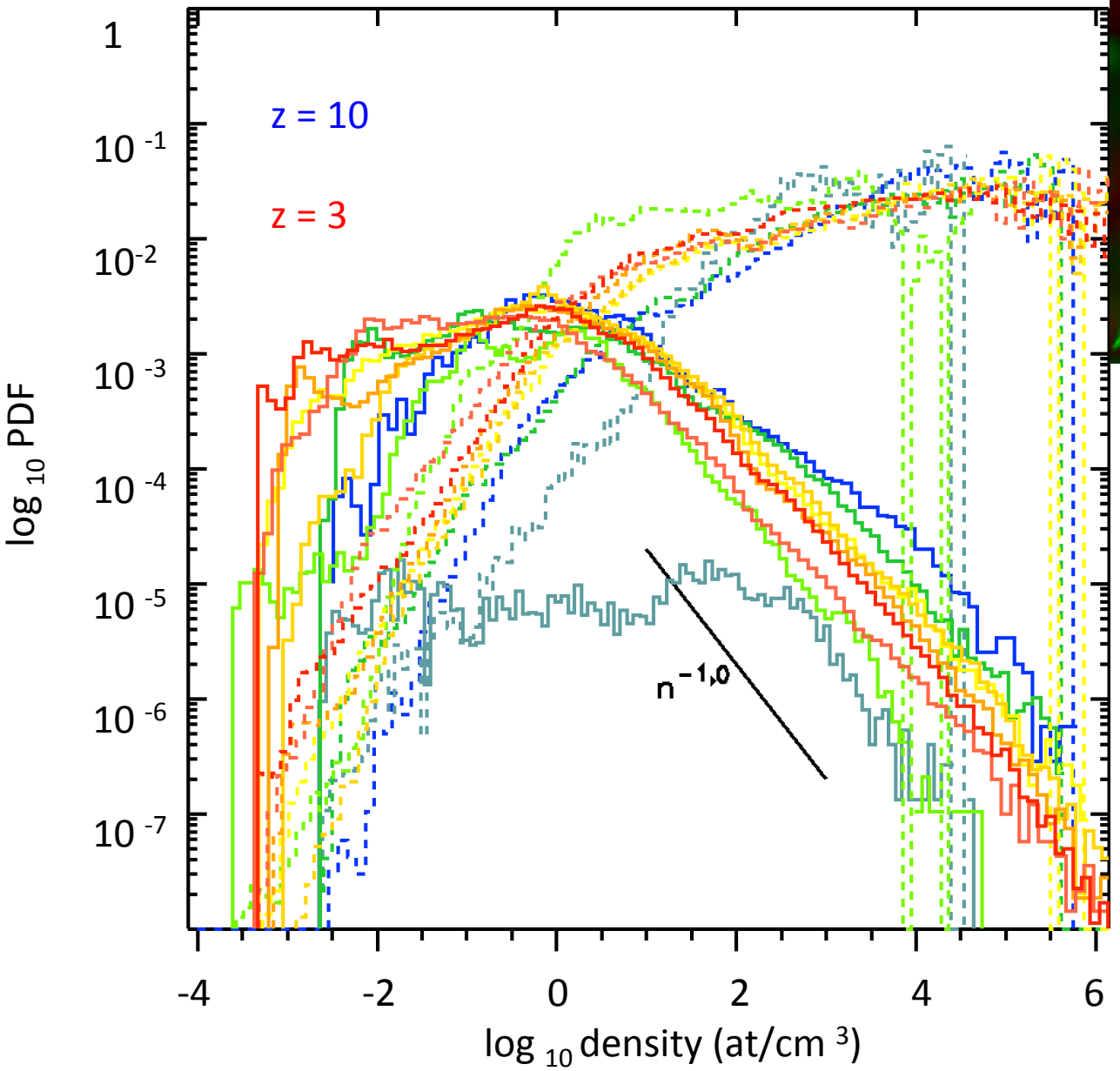




self-gravitating SF, momentum fbk

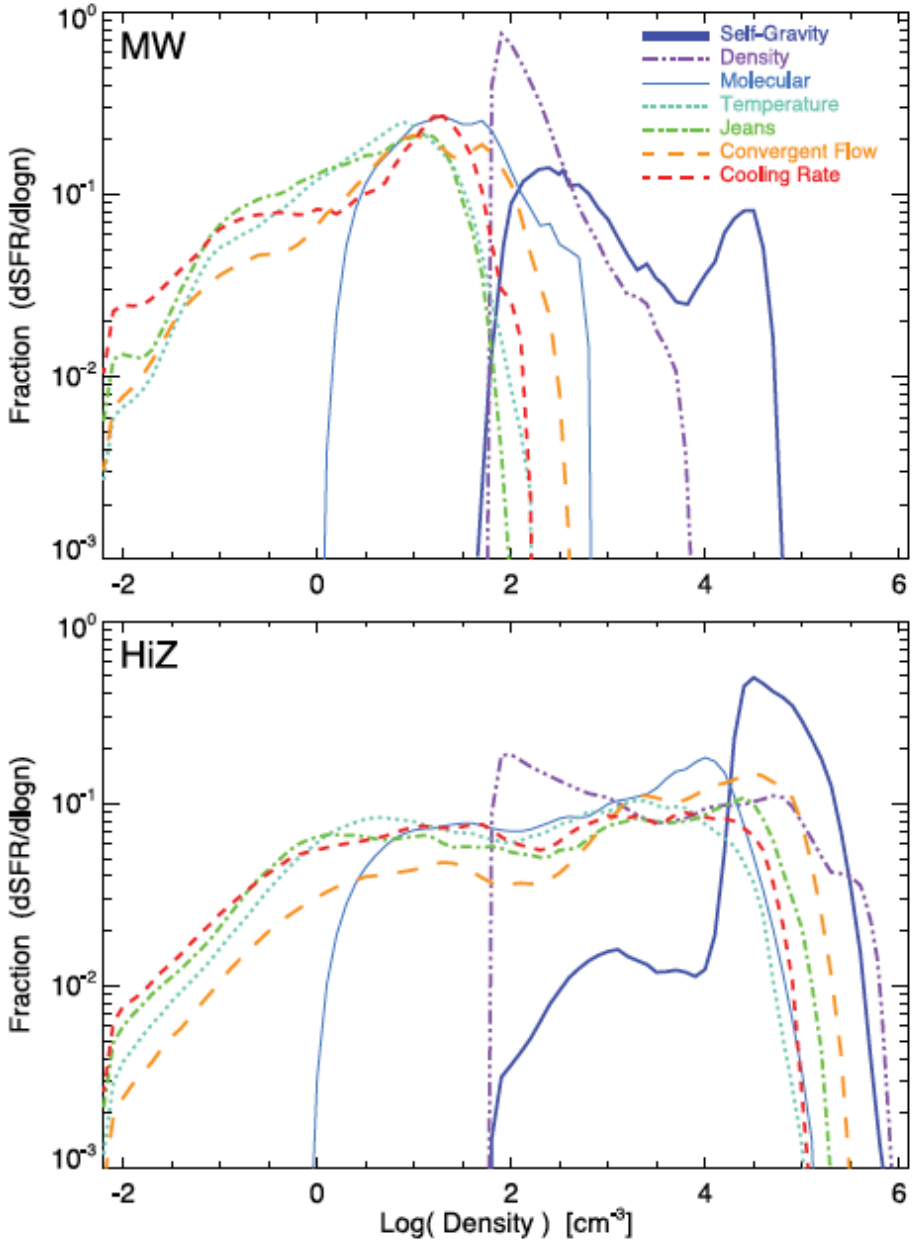

Volume & mass weighted gas density PDF
z = 10
z = 3
n^-1,0
log 10 PDF
log 10 density (at/cm 3)
1
10 -1
10-2
10 -3
10 -4
10 -5
10 -6
10 -7
-4
-2
0
2
4
6
density threshold SF, no fbk

Volume & mass weighted gas density PDF



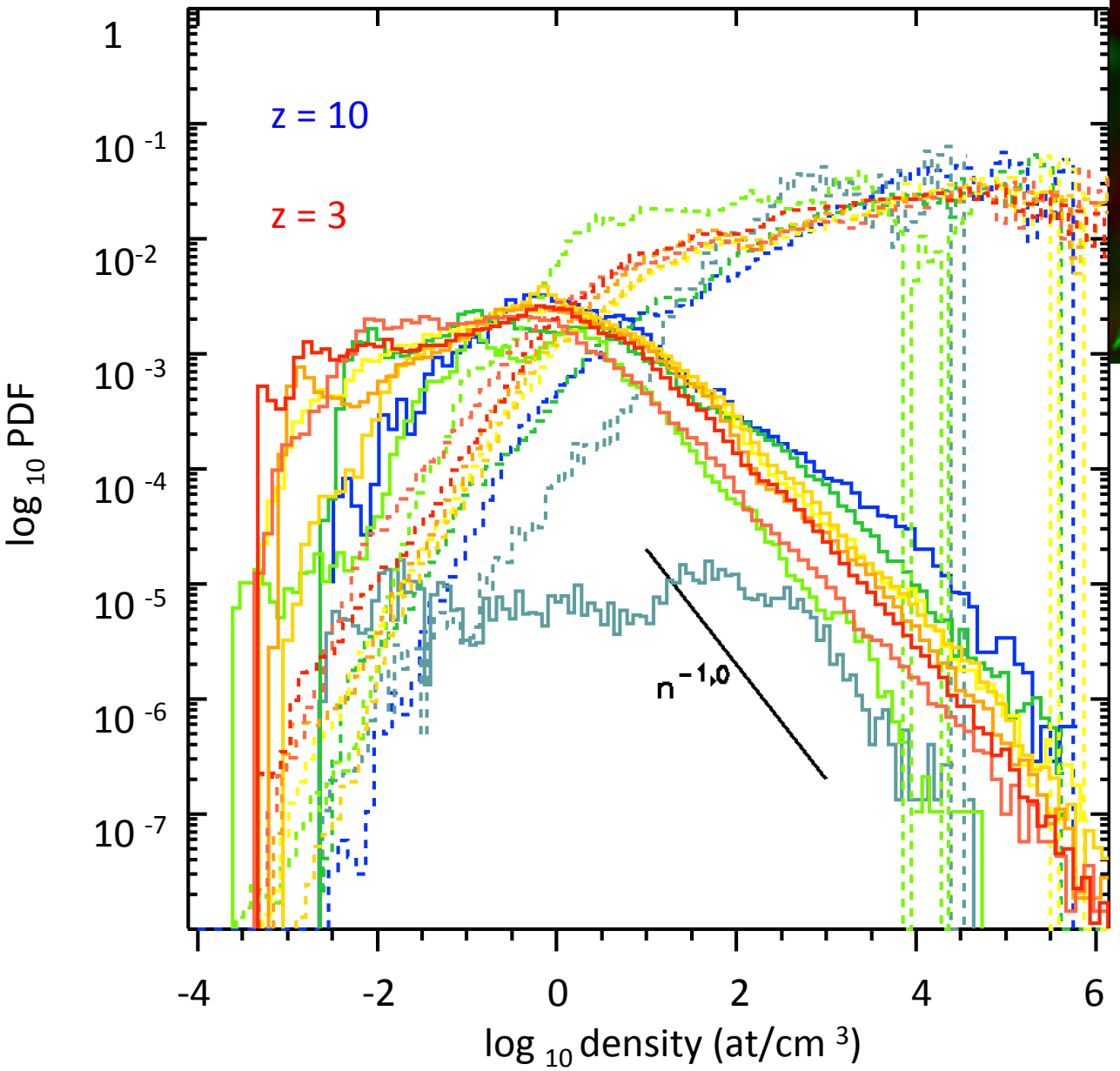
self-gravitating SF, no fbk

SFR weighted density distribution for different star formation prescriptions

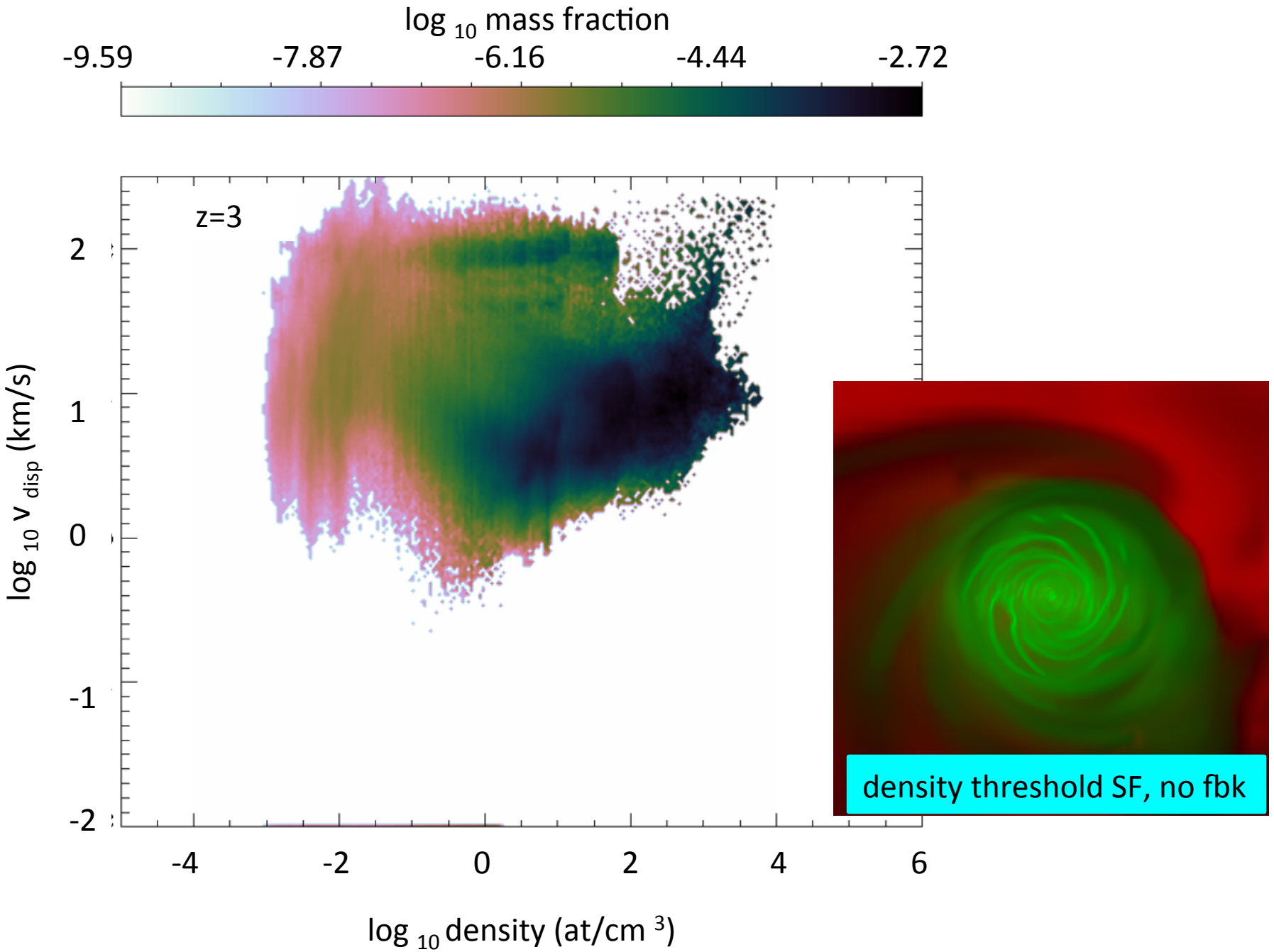


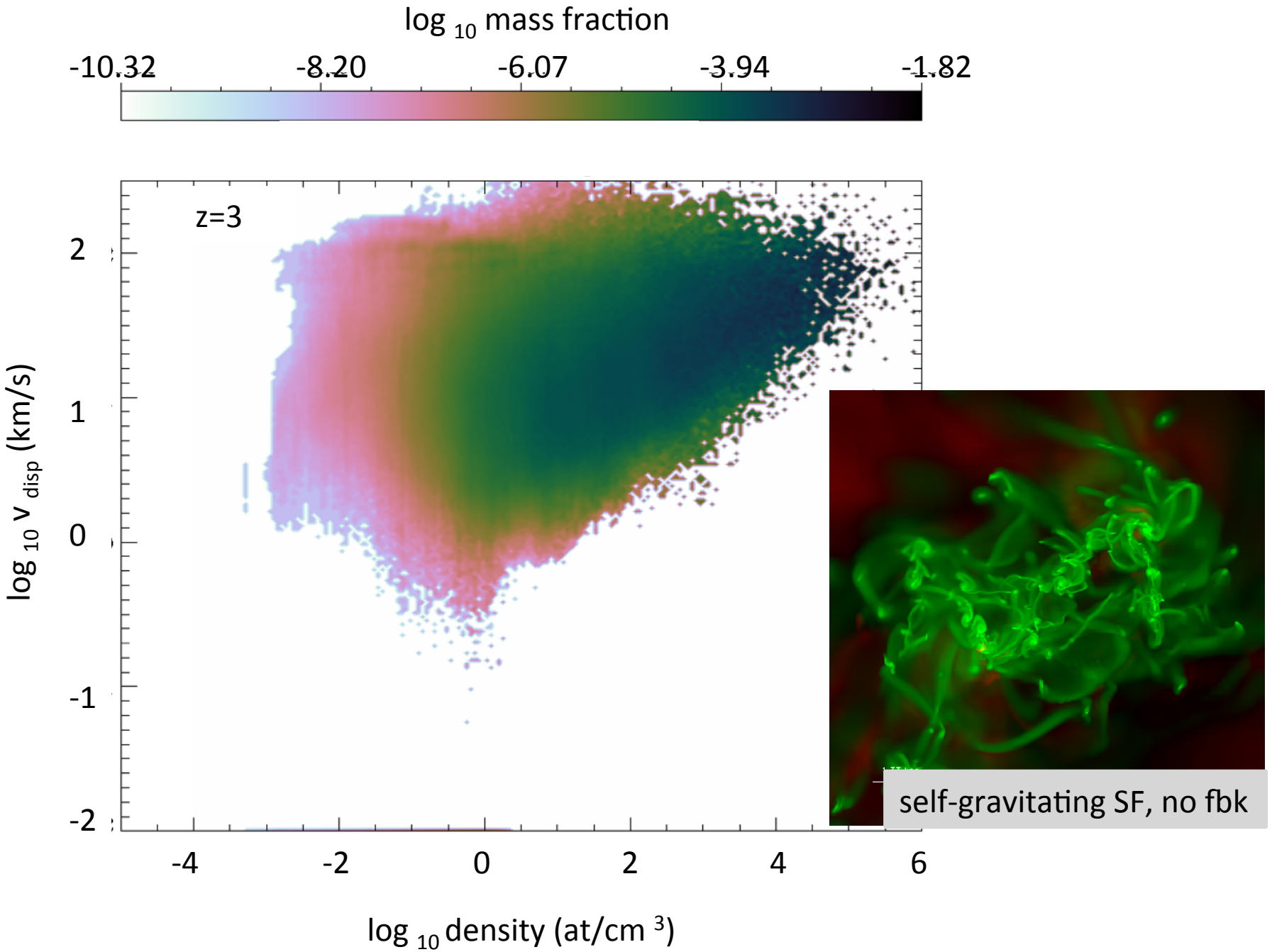
Hopkins et al. 2013

Volume & mass weighted gas density PDF

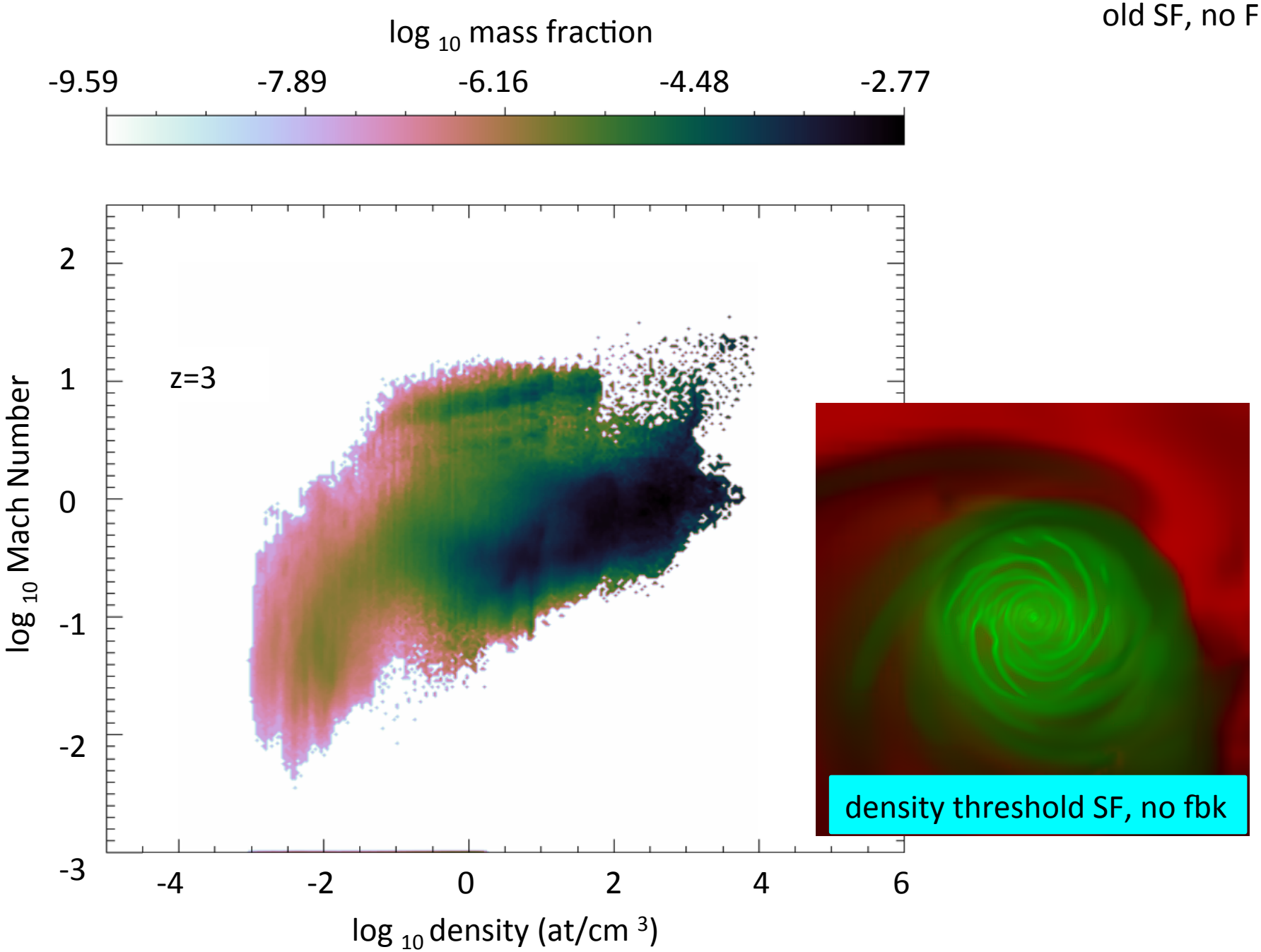


self-gravitating SF, no fbk

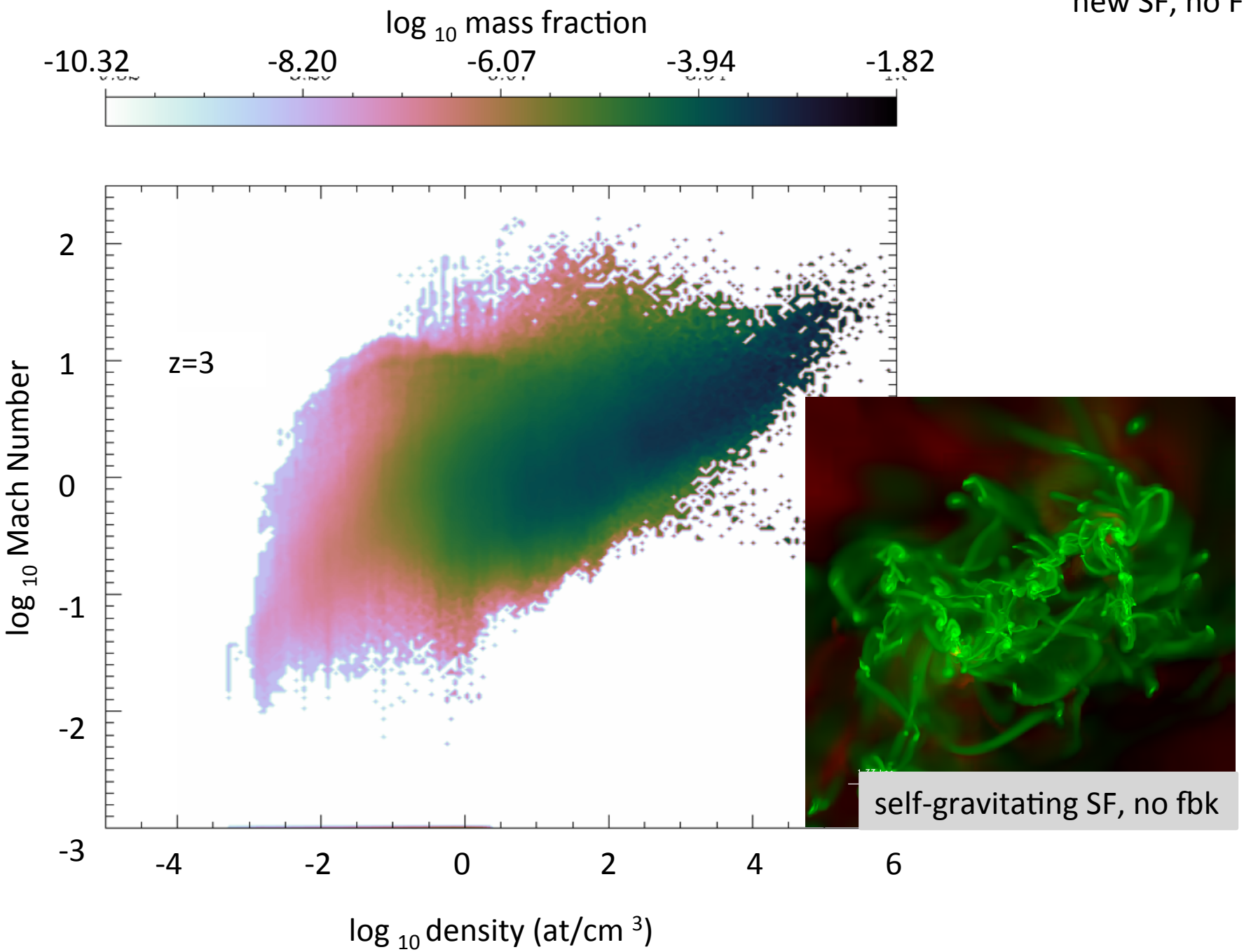

log 10 mass fraction
-9.59
-7.87
-6.16
-4.44
-2.72
z=3
log 10 v disp (km/s)
2
1
0
-1
-2
-4
-2
0
2
4
6
log 10 density (at/cm 3)
density threshold SF, no fbk


log 10 mass fraction
-10.32
-8.20
-6.07
-3.94
-1.82
z=3
log 10 v disp (km/s)
2
1
0
-1
-2
-4
-2
0
2
4
6
log 10 density (at/cm 3)
self-gravitating SF, no fbk

old SF, no FBK


log 10 mass fraction
-9.59
-7.89
-6.16
-4.48
-2.77
z=3
log 10 Mach Number
2
1
0
-1
-2
-3
-4
-2
0
2
4
6
log 10 density (at/cm 3)
density threshold SF, no fbk

new SF, no FBK


log 10 mass fraction
-10.32
-8.20
-6.07
-3.94
-1.82
z=3
log 10 Mach Number
2
1
0
-1
-2
-3
-4
-2
0
2
4
6
log 10 density (at/cm 3)
self-gravitating SF, no fbk

density threshold SF, no fbk

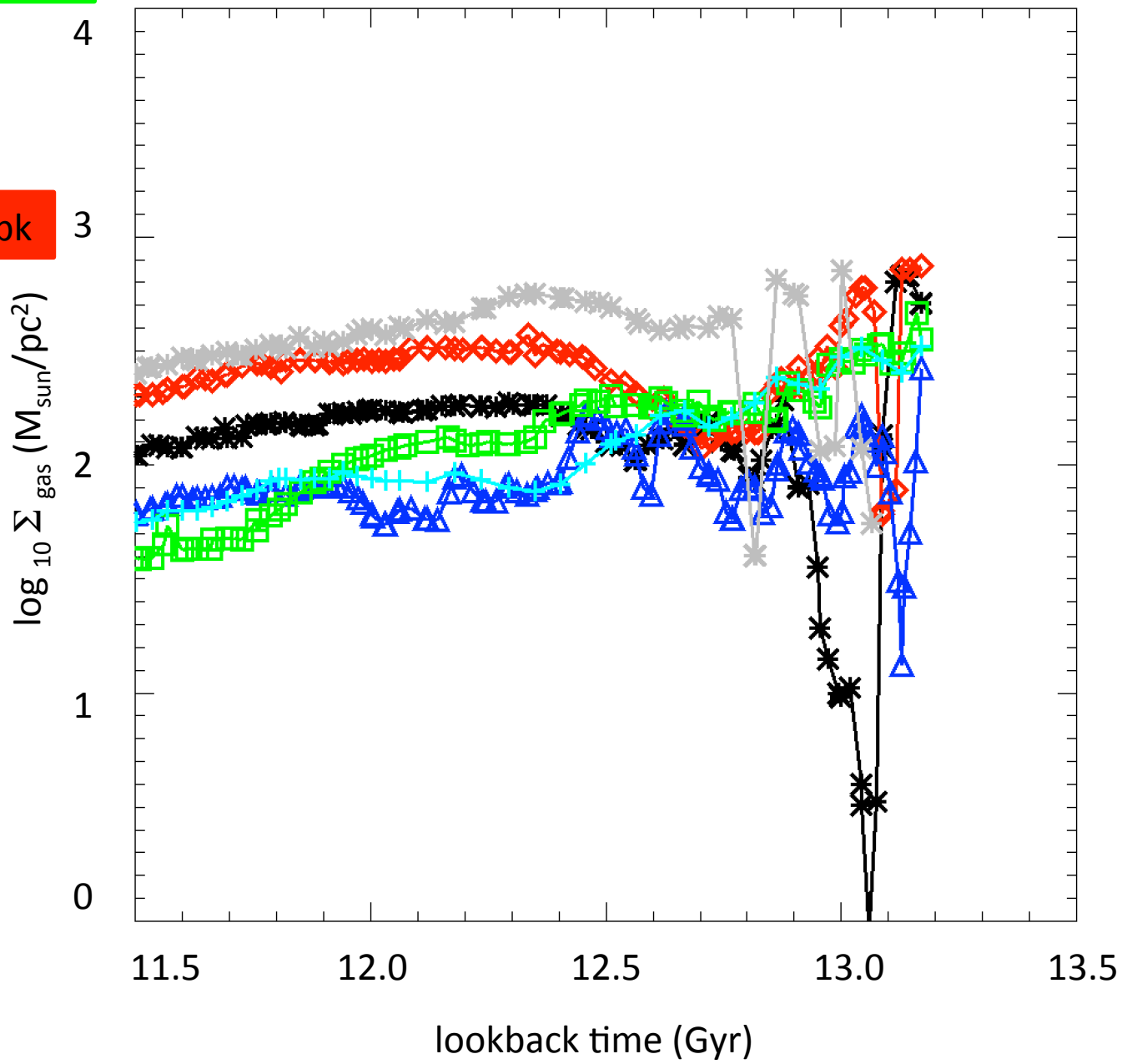
density threshold SF, energy fbk

density threshold SF, momentum fbk

self-gravitating SF, no fbk

self-gravitating SF, energy fbk

self-gravitating SF, momentum fbk



density threshold SF, no fbk

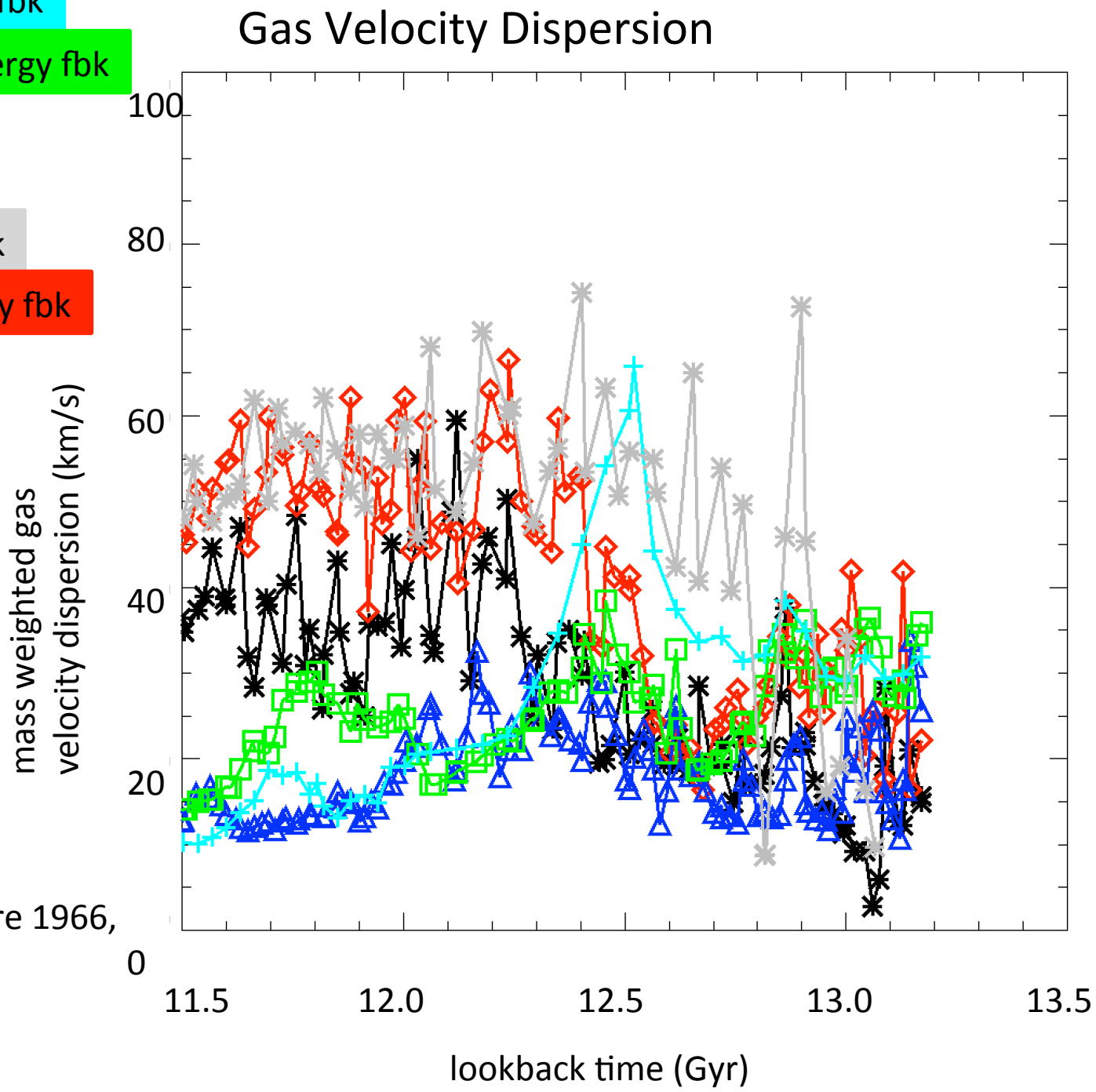
density threshold SF, energy fbk

density threshold SF, momentum fbk

self-gravitating SF, no fbk

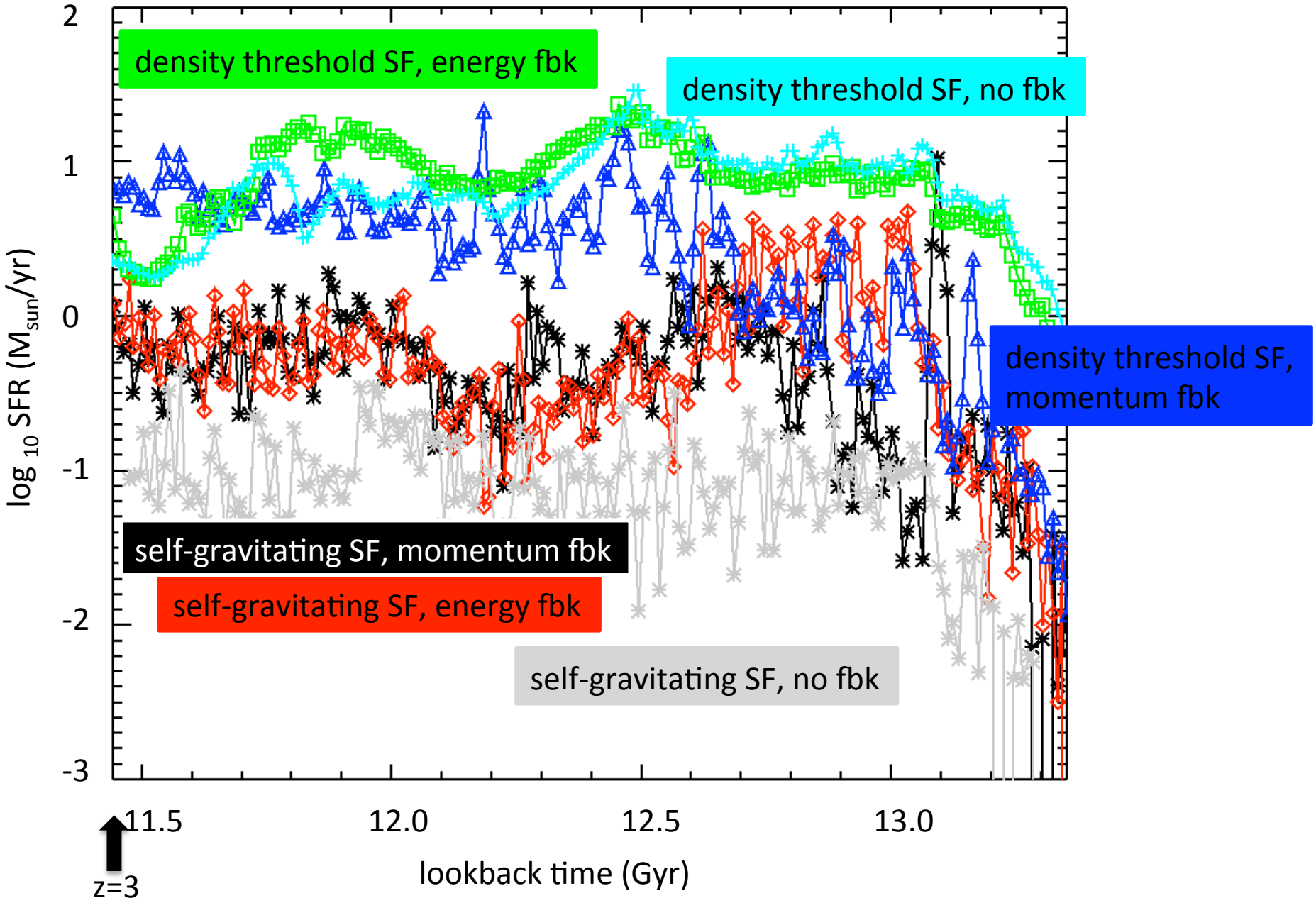
self-gravitating SF, energy fbk

self-gravitating SF, momentum fbk



(see also Julian & Toomre 1966,
Kimm et al 2002,
Kim & Ostriker 2007)

Star Formation Rates



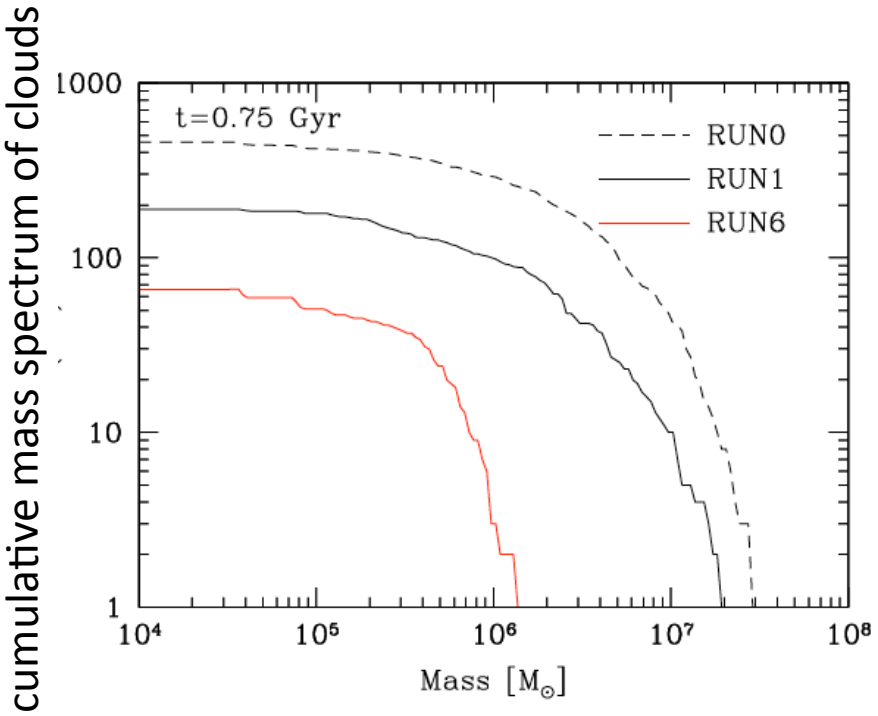
higher gas surface density

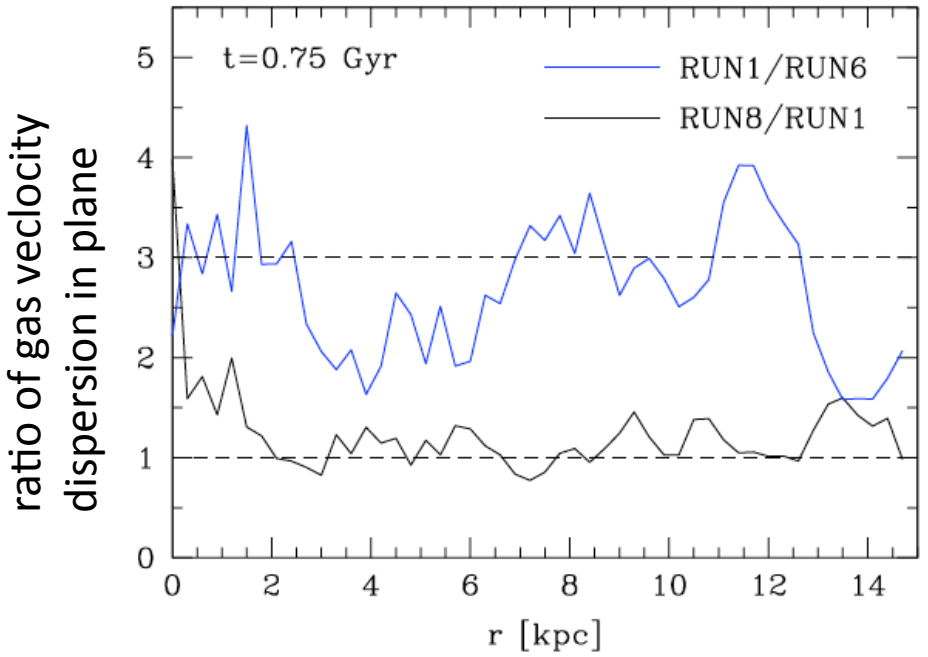
larger dense structures

higher gas velocity dispersions

less star formation

Changing surface density in isolated disk simulations (Agertz et al. 2009)





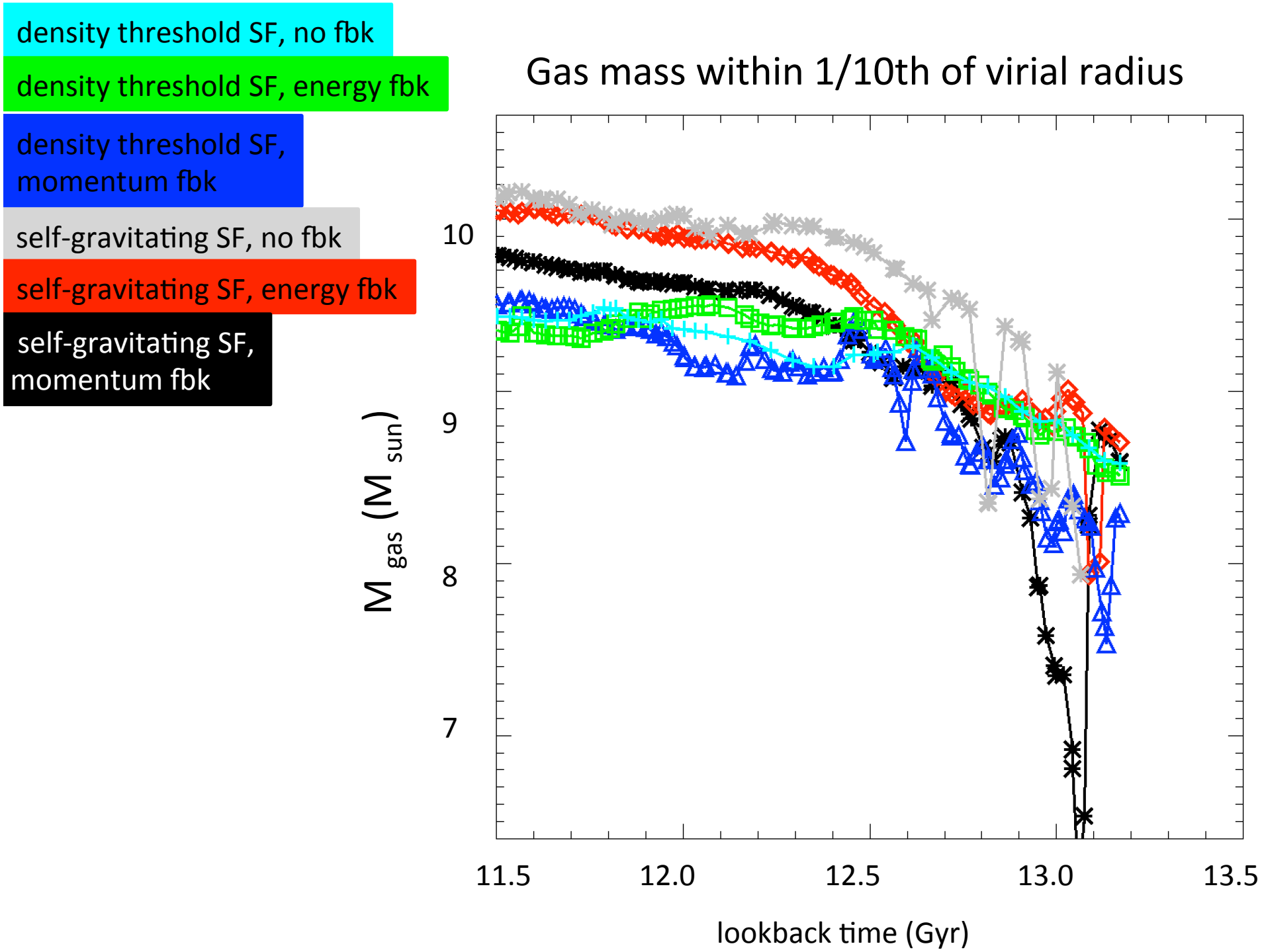
RUN6 has 1/3 gas mass of RUN 1, so 1/3 surface density (isolated disk)

$$M_{\rm cl}^{\rm max} = \frac{\pi^4 G^2 \Sigma_{\rm gas}^3}{4\Omega^4}$$

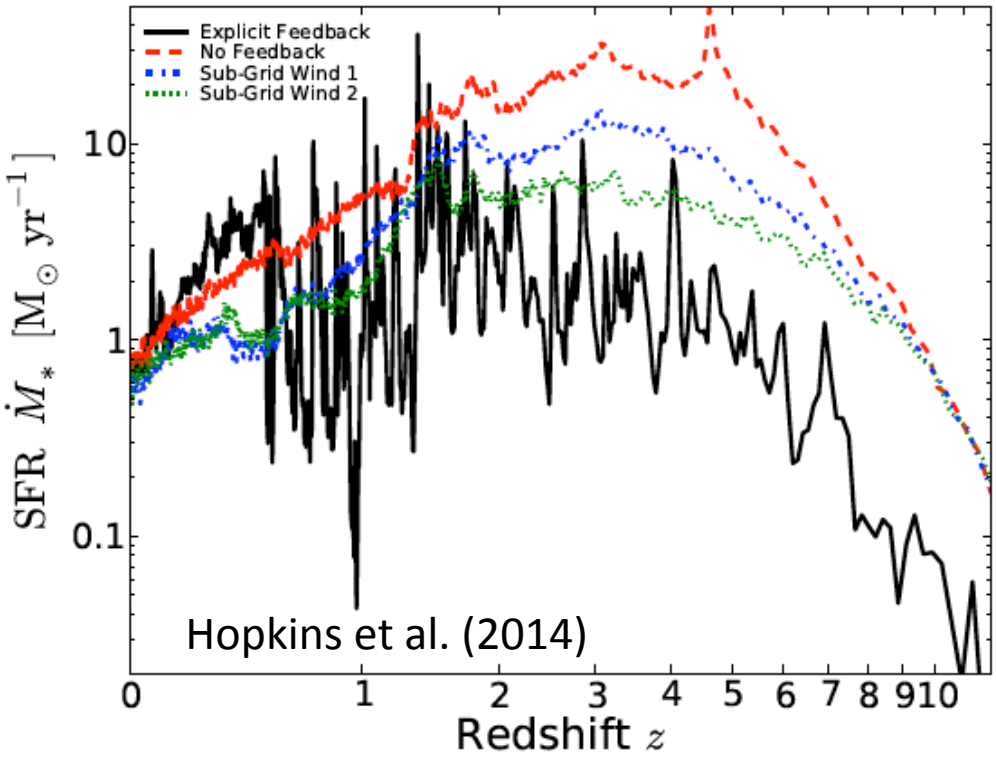
27 times smaller largest cloud masses
(Escala & Larson 2008)

$$\sigma_{xy} \approx 0.94 (G M_{\rm cl} \kappa)^{1/3}$$

3 times lower gas velocity dispersion
In plane of disk (Gammie et al. 1991)


density threshold SF, no fbk
density threshold SF, energy fbk
density threshold SF, momentum fbk
self-gravitating SF, no fbk
self-gravitating SF, energy fbk
self-gravitating SF, momentum fbk
Gas mass within 1/10th of virial radius
M gas (M sun)
10
9
8
7
11.5
12.0
12.5
13.0
13.5
lookback time (Gyr)

Seems possible to drive turbulence in gas rich galaxies
by self-gravity and shear and for this to suppress star formation



Hopkins et al. (2014)

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