AGN feedback and galaxy formation

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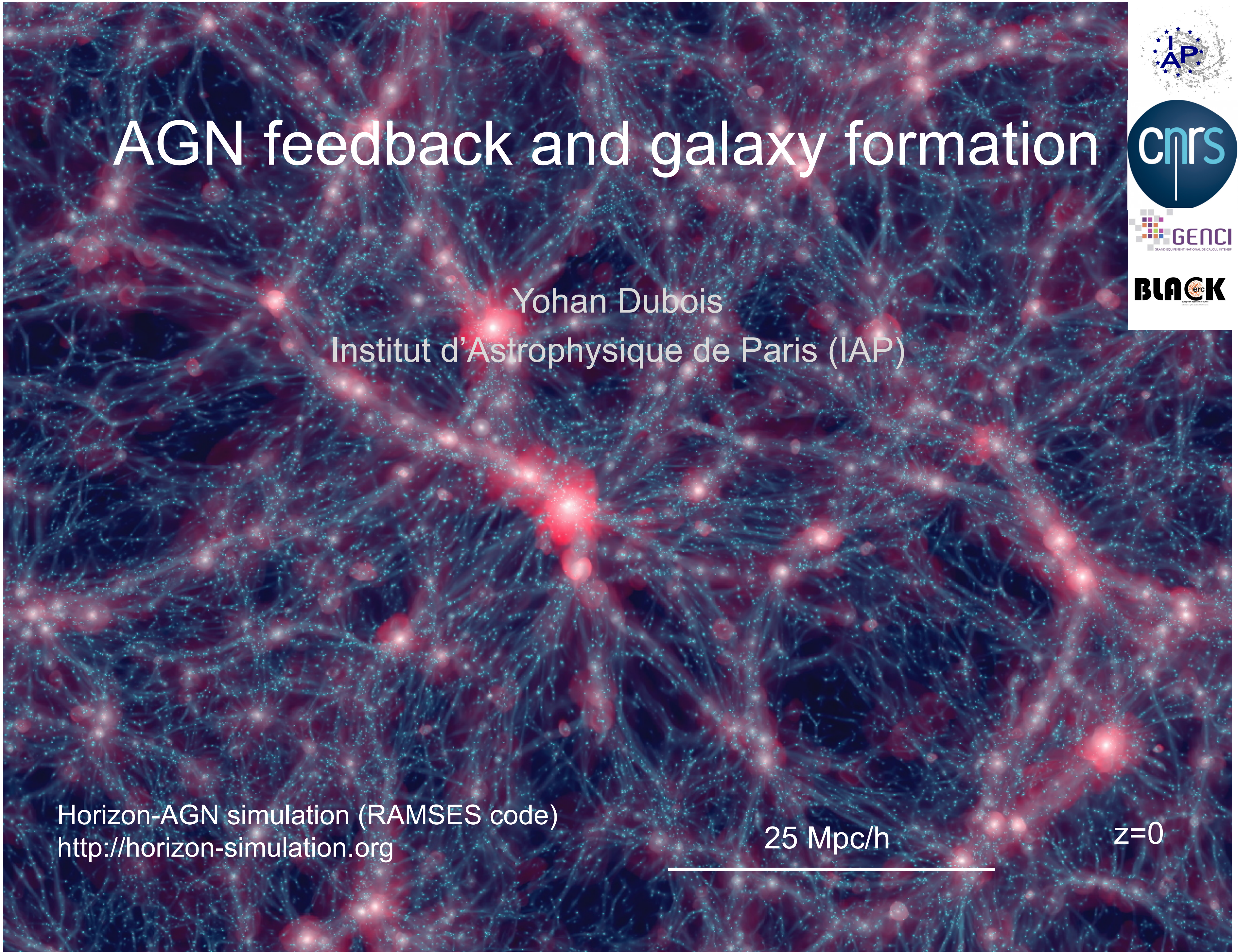
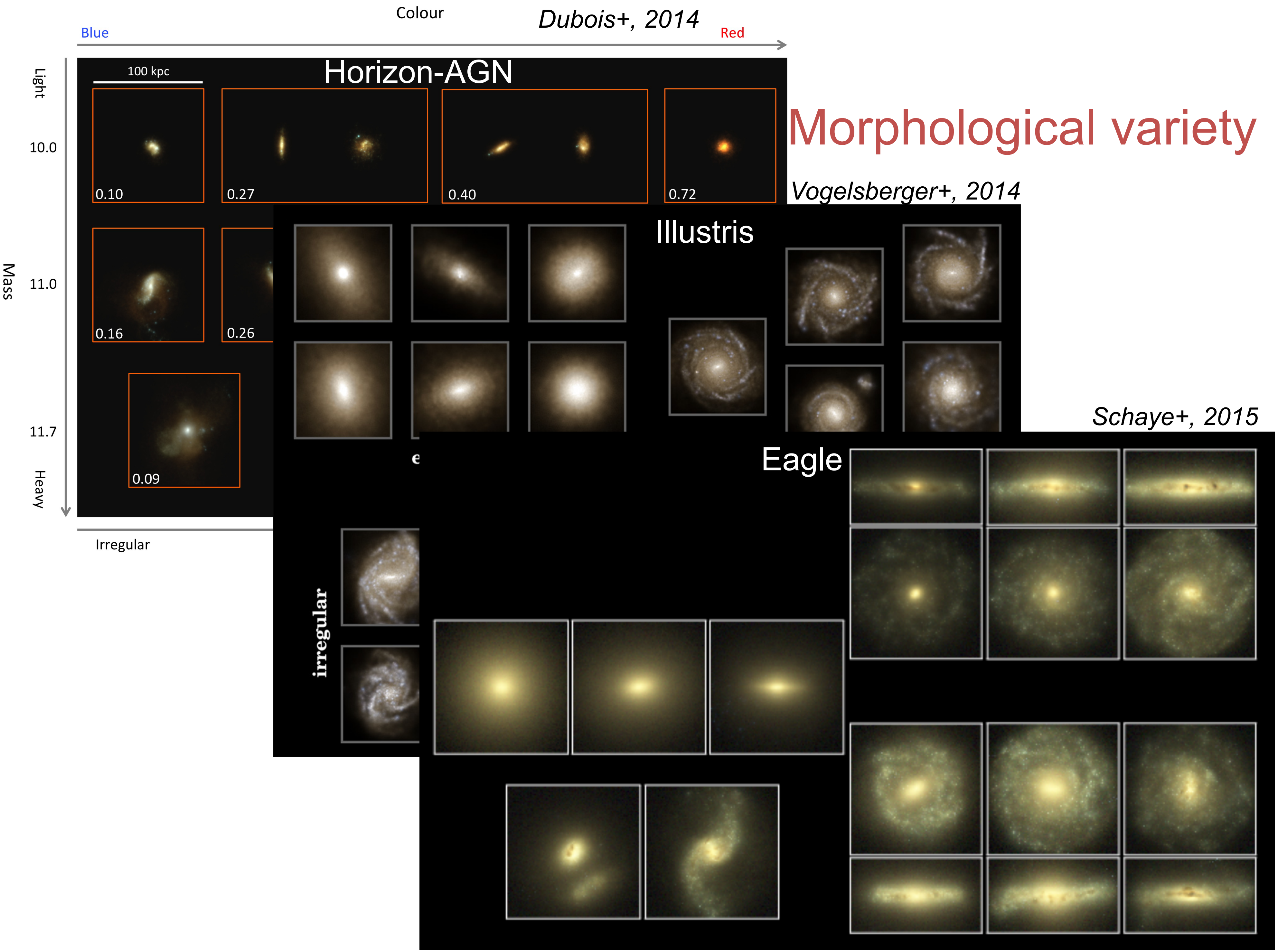


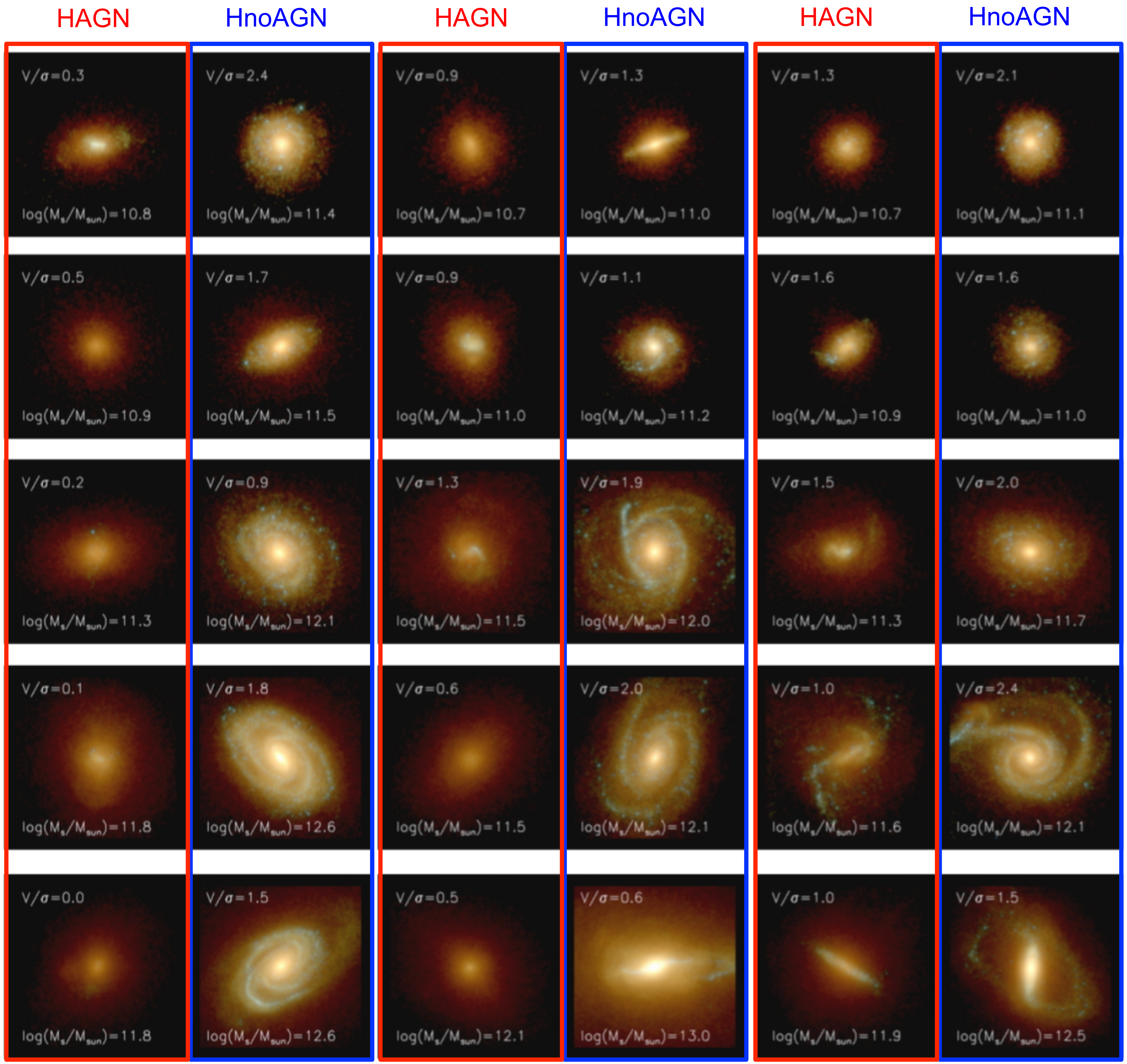
Morphological transformations and AGN feedback

1) What SMBHs do for morphology

2) What morphology does for SMBHs

Morphological variety

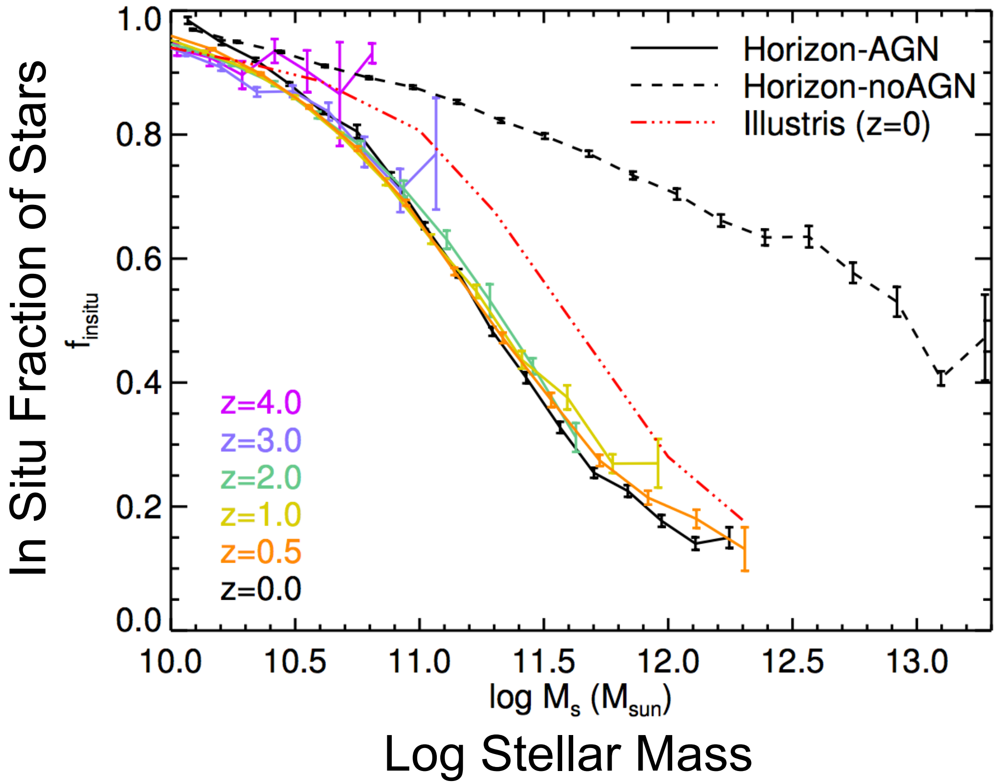


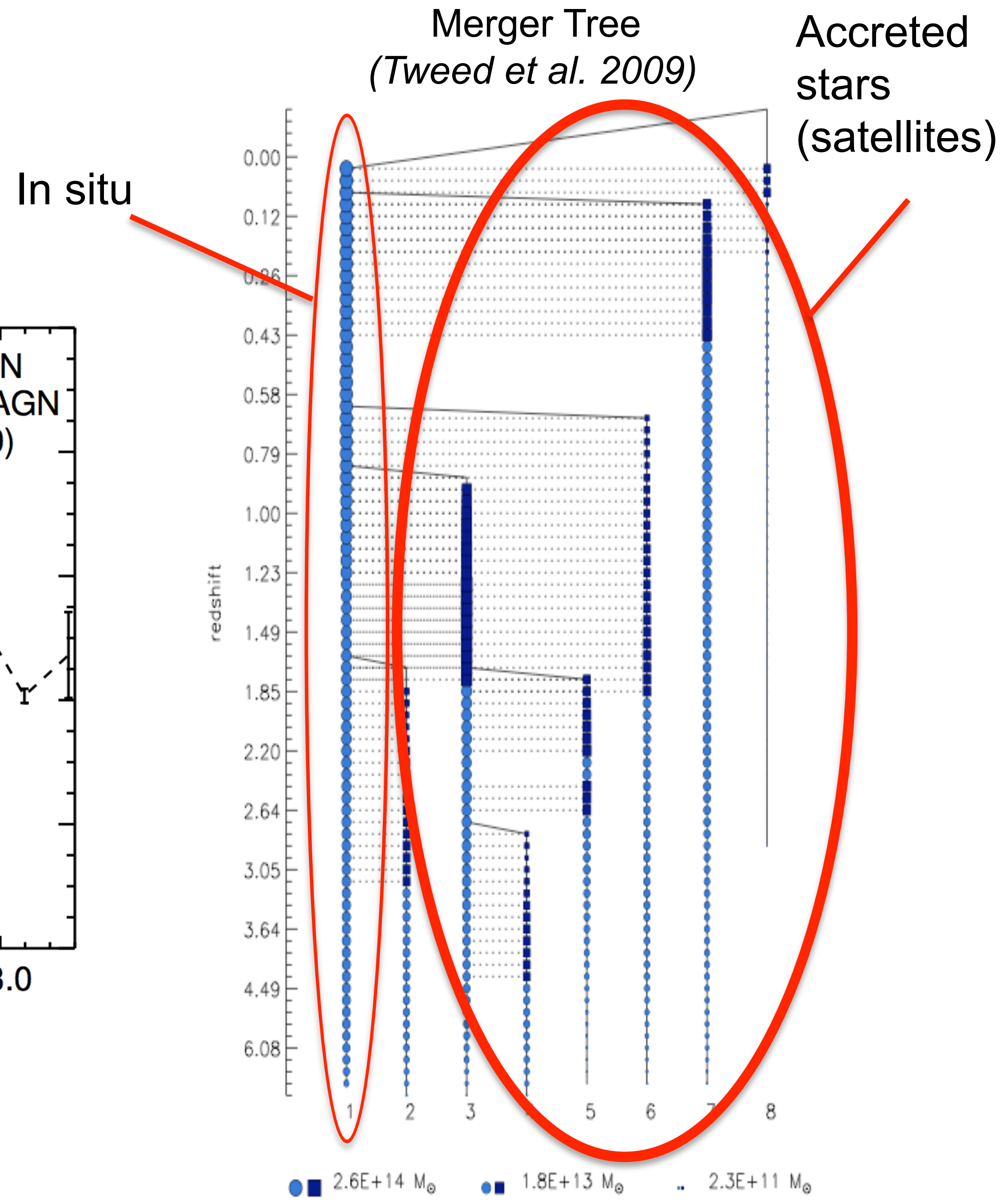


AGN feedback model:
- Bondi accretion rate
- Booth & Schaye 2009 boost
- Eddington limited
- Quasar (heating mode)
- Radio mode (biconical jet)

Dubois et al, 2016

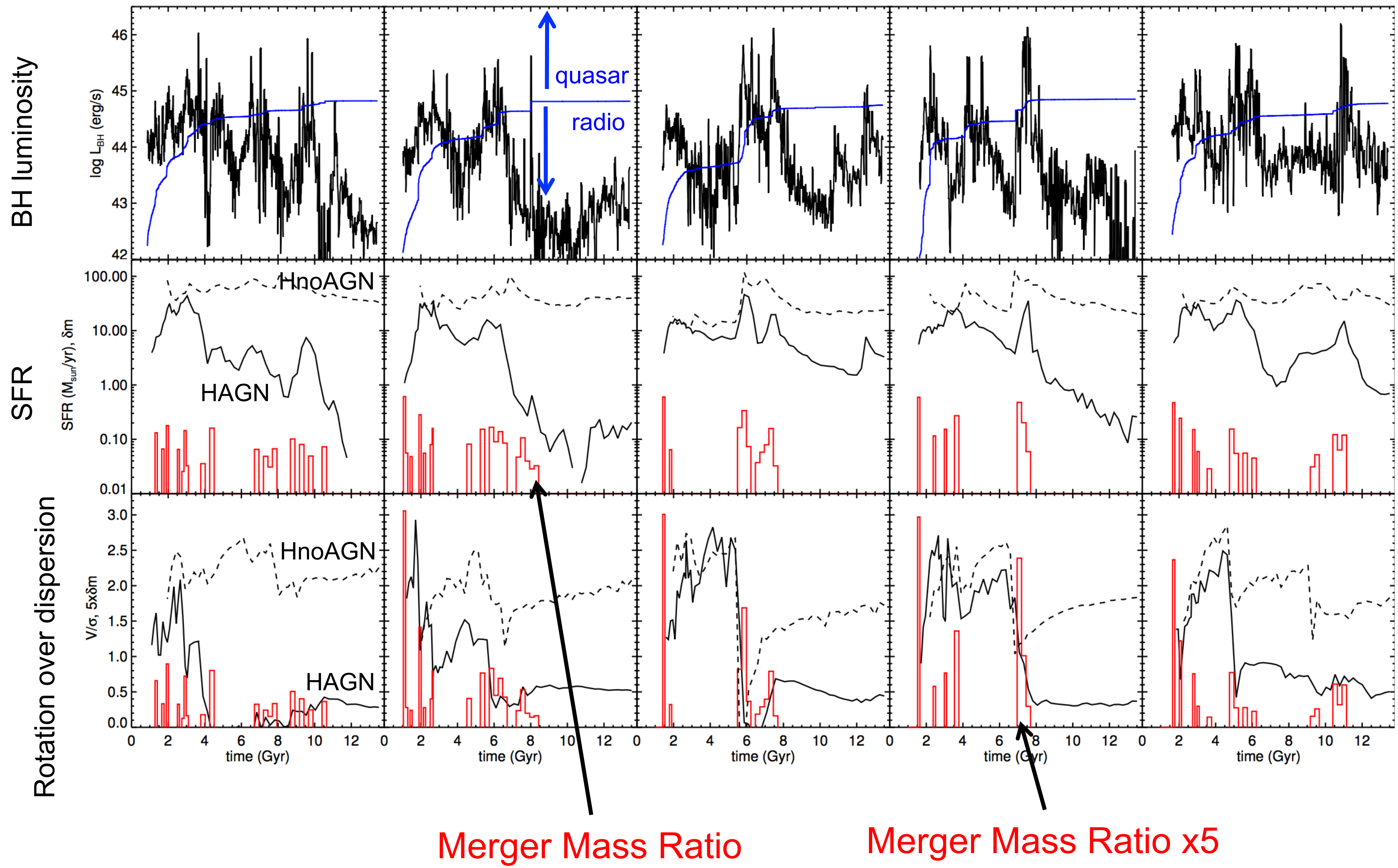
The origin of the stars



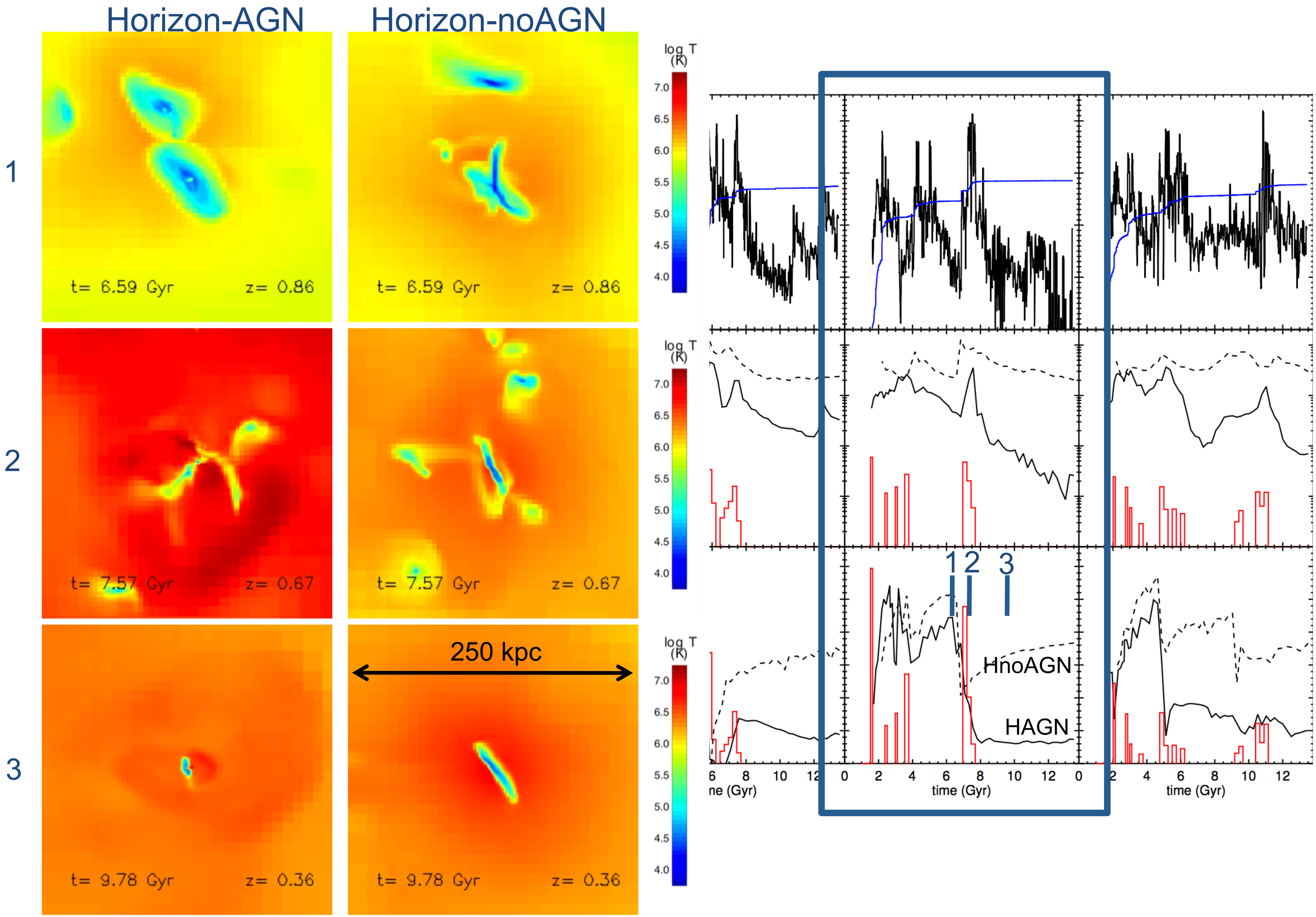


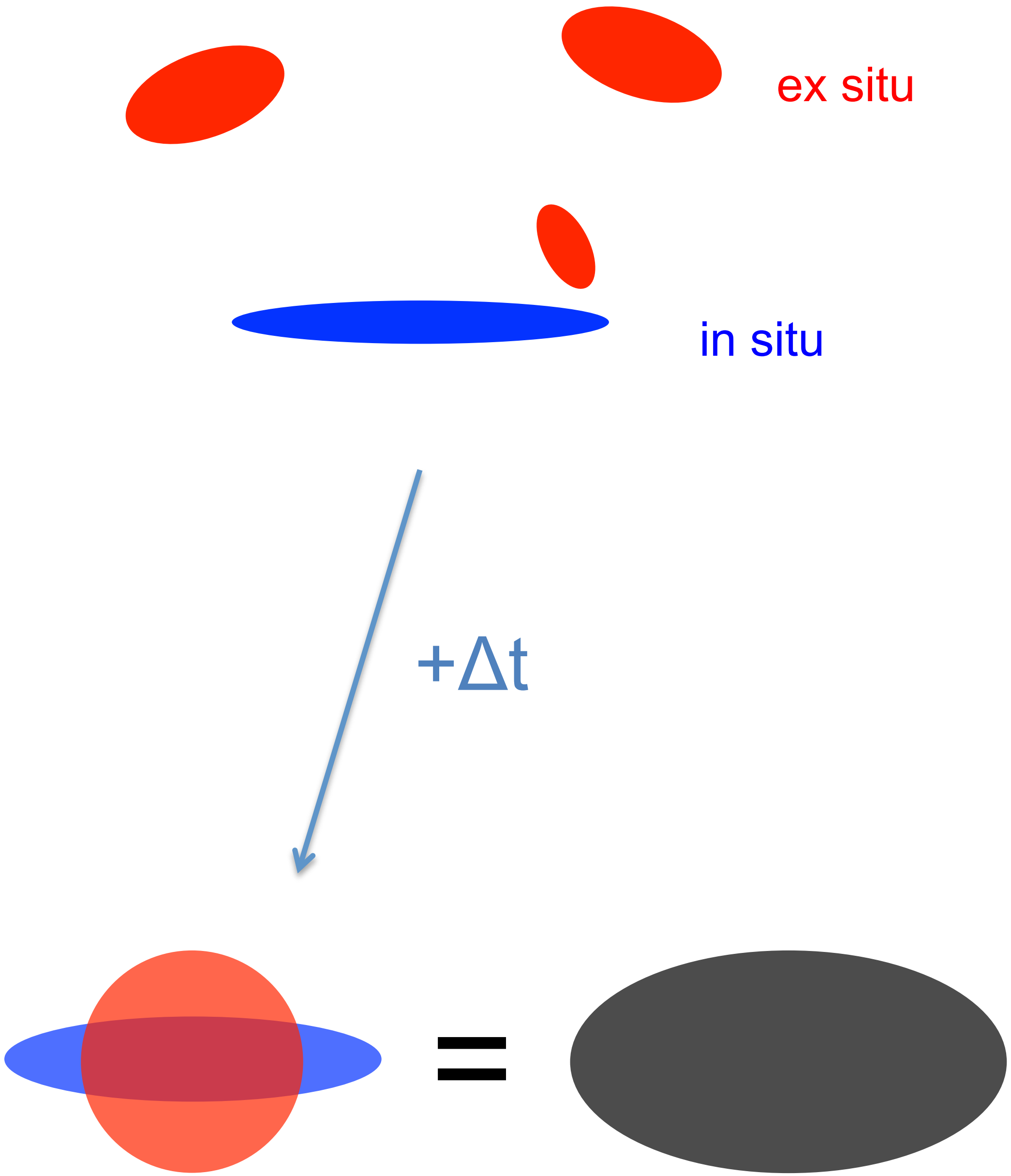
Dubois et al, 2016
See also Oser+ 2010; Lackner+ 2012; Dubois+ 2013; Rodriguez-Gomez+ 2016
Lee & Yi, 2013 (SAM)

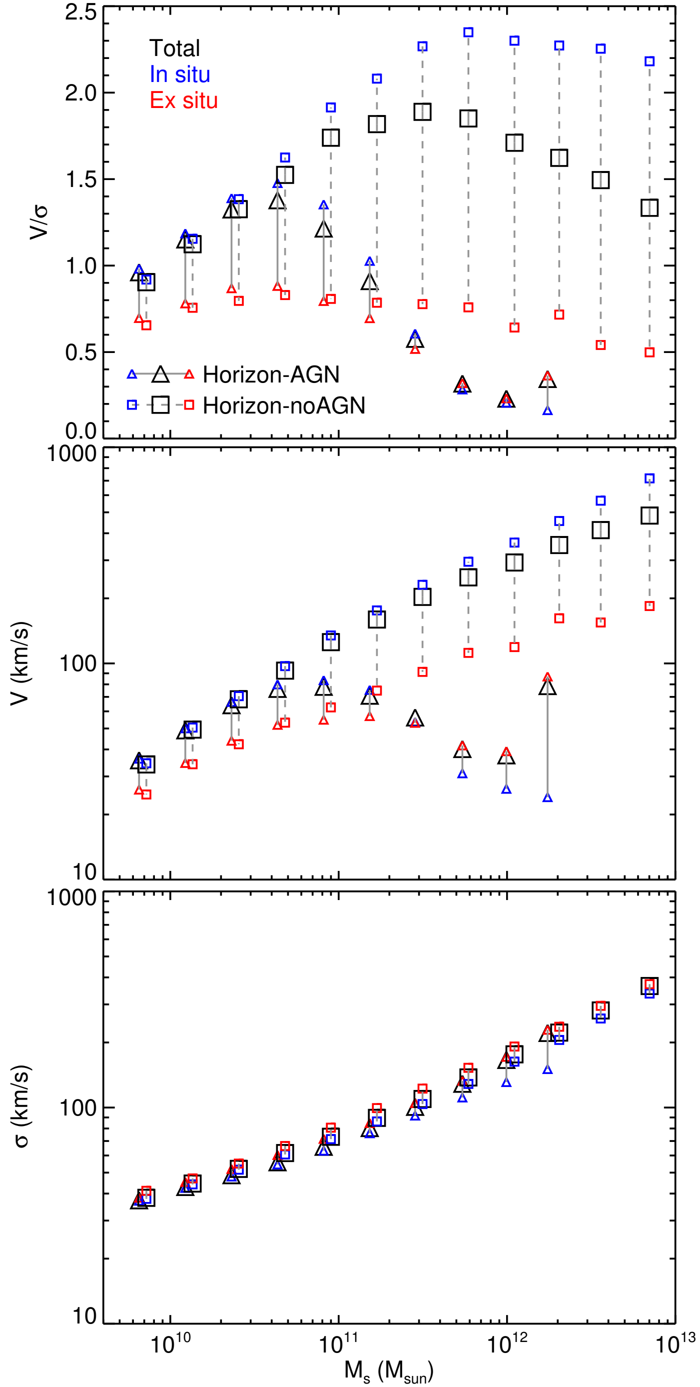
A few exemples of $2x10^{11}$ M_{sun} galaxies



A few exemples of $2x10^{11}$ M_{sun} galaxies




ex situ
in situ
+Δt
=

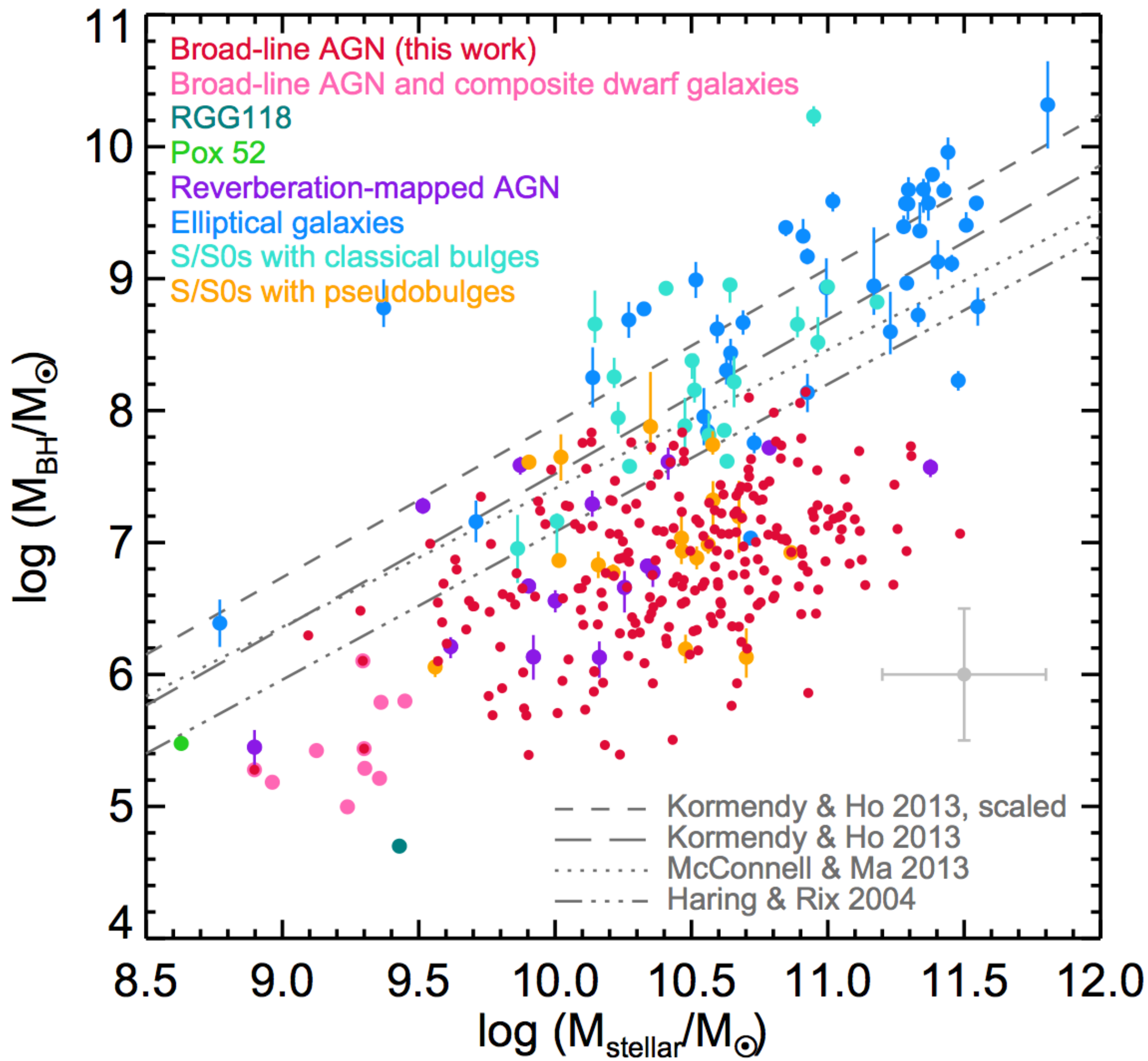

Total
In situ
Ex situ
Horizon-AGN
Horizon-noAGN
V/σ
V (km/s)
σ (km/s)
M_s (M_sun)
2.5
2.0
1.5
1.0
0.5
0.0
1000
100
10
10^10
10^11
10^12
10^13

Morphological transformations and AGN feedback

1) What SMBHs do for morphology

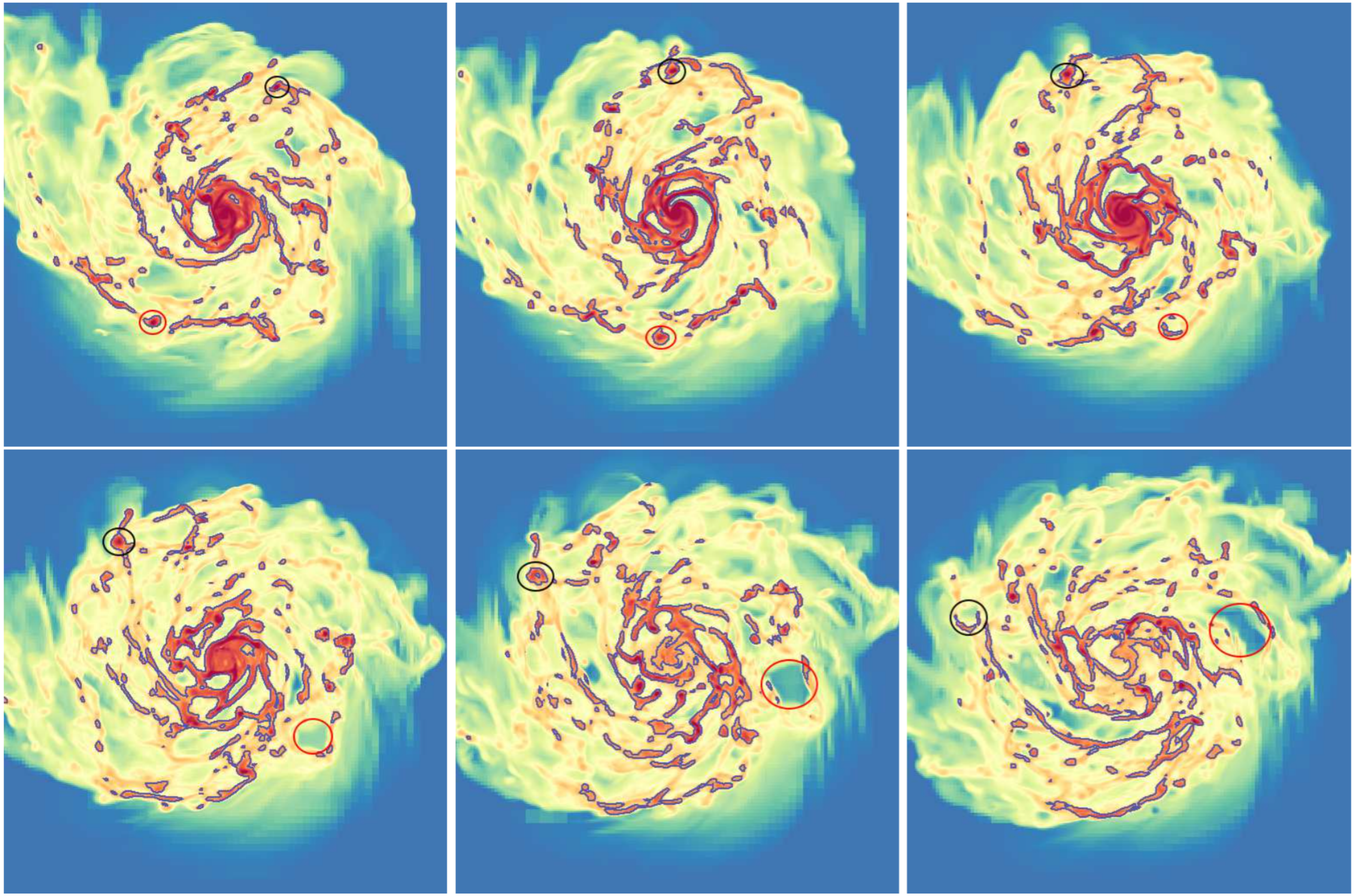
2) What morphology does for SMBHs

Puzzling observation fact



Reines & Volonteri, 2015

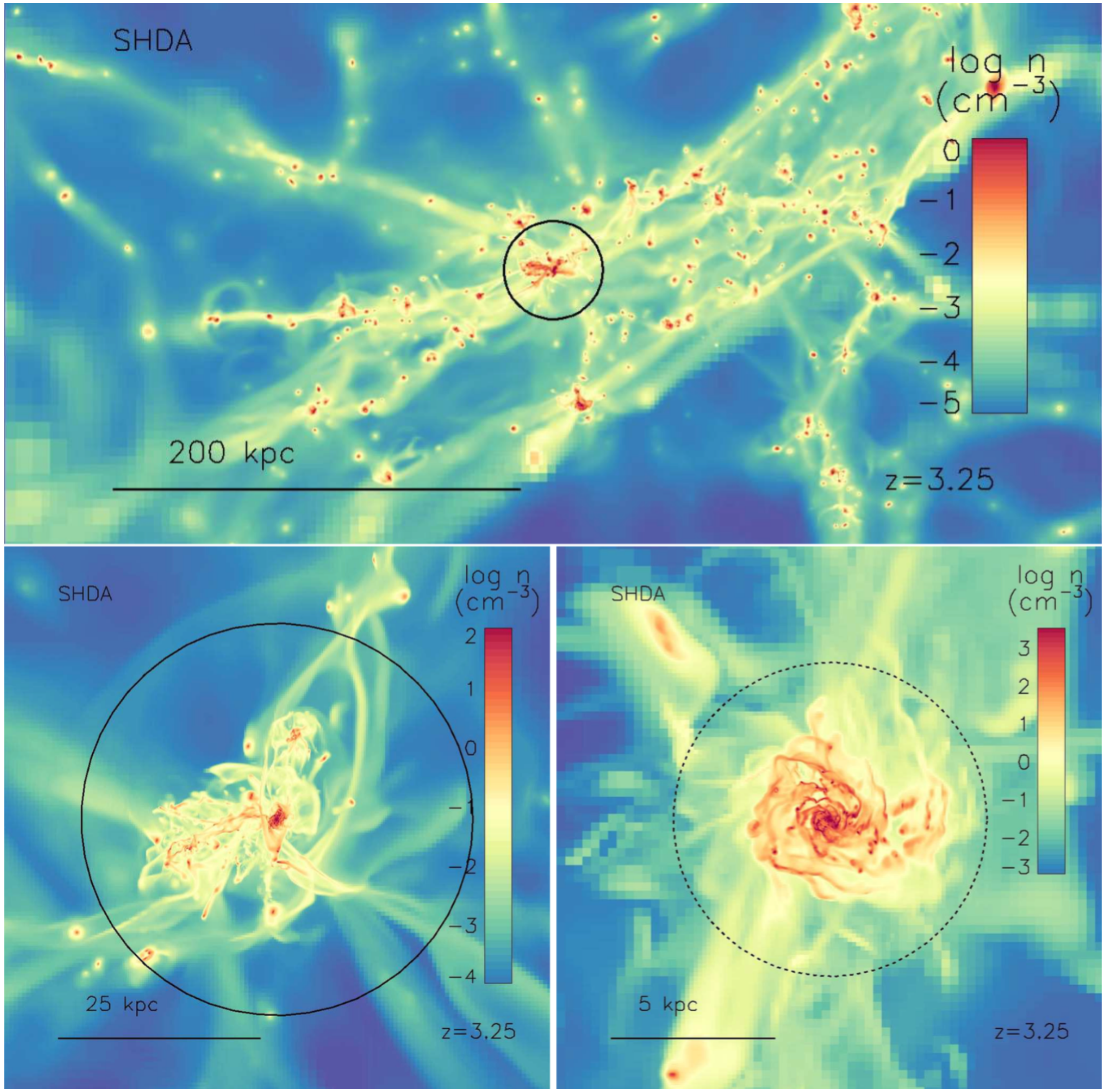
Does the SF clump destruction have any impact on BH growth?



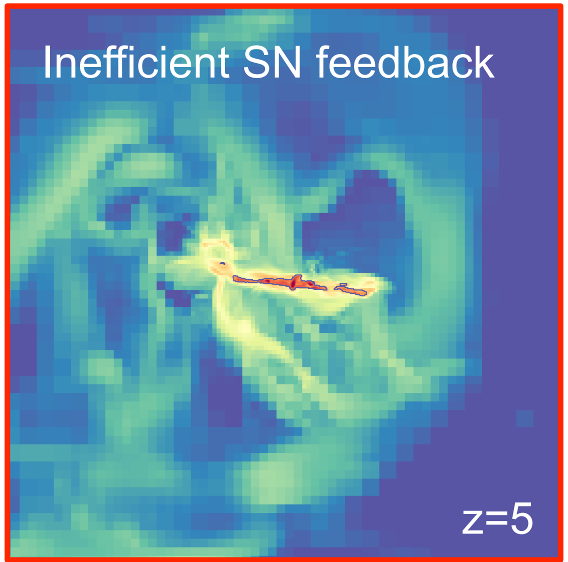
Dubois, Volonteri, Silk et al., 2014

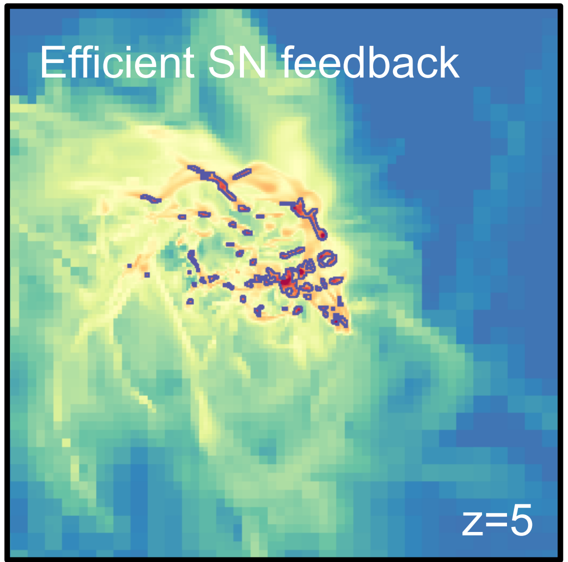
Cosmological zoom simulation

$M_h = 10^{12}\ M_{sun}$ @ z=2
$M_{DM,res} = 10^5\ M_{sun}$
dx=10 pc



BH growth delayed by efficient SN feedback





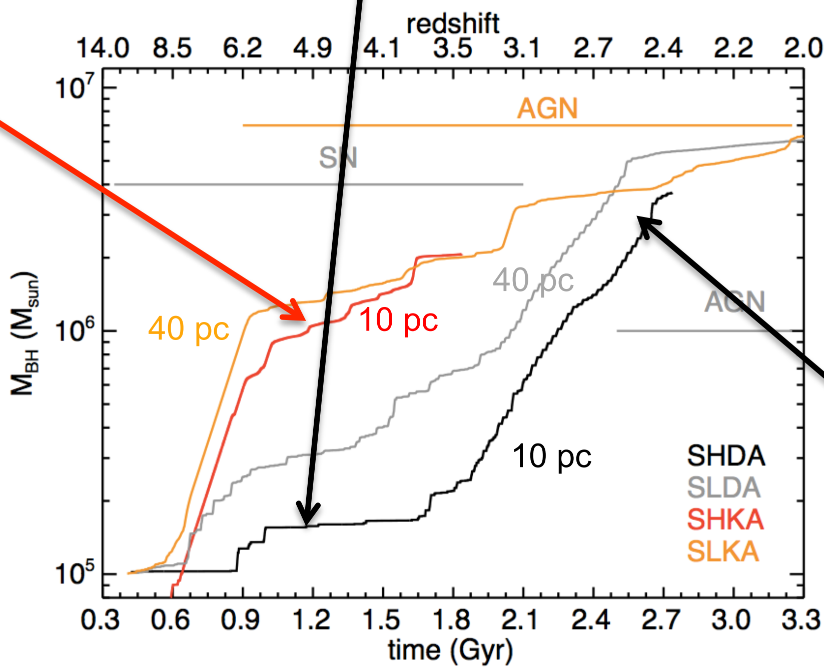
Bondi-capped-at-Eddington accretion rate
- AGN quasar heating $f_{Edd}>0.01$
- AGN radio jets $f_{Edd}<0.01$

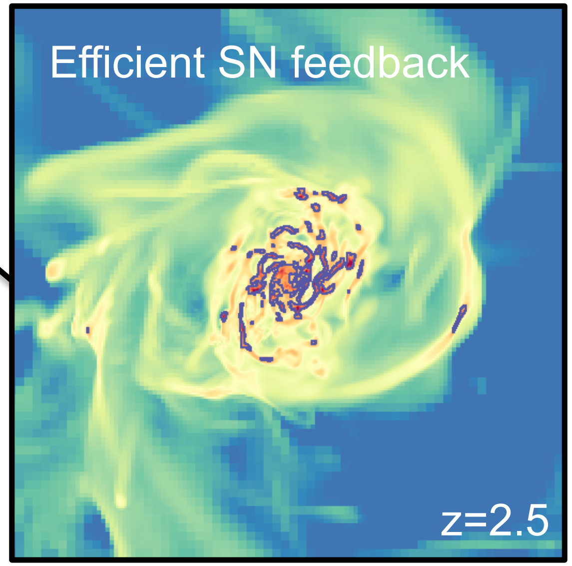
(Dubois et al, 2012)

& BH spin evolution with spin-dependent radiative efficiency (and Eddington accretion rate)
(Dubois et al, 2014)

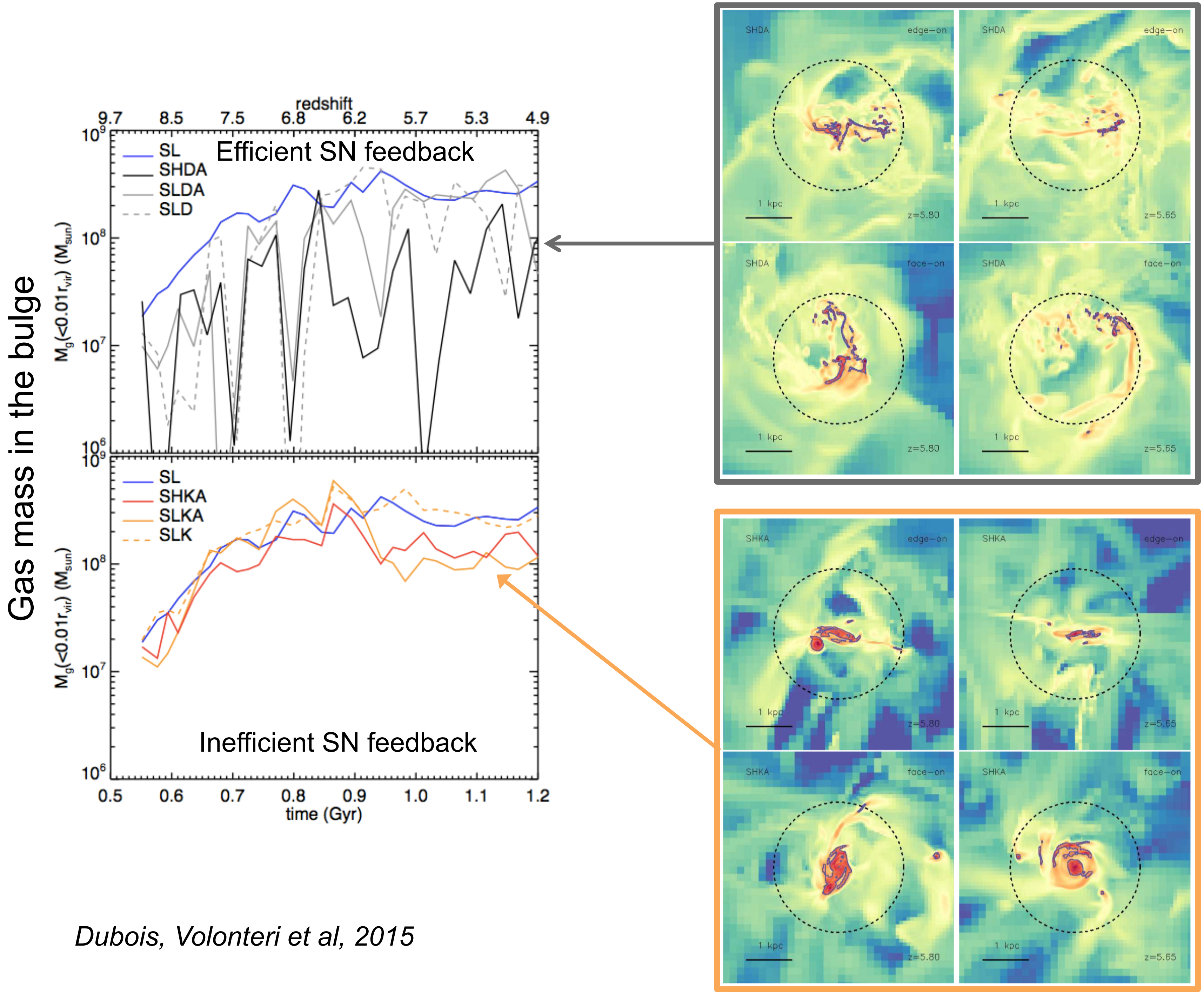
"Inefficient": kinetic blast wave model
(Dubois & Teyssier, 2008)

"Efficient": non-thermal component (CR, turbulence, magnetic fields) that delays gas cooling
(Teyssier, Pontzen, YD, Read, 2013)



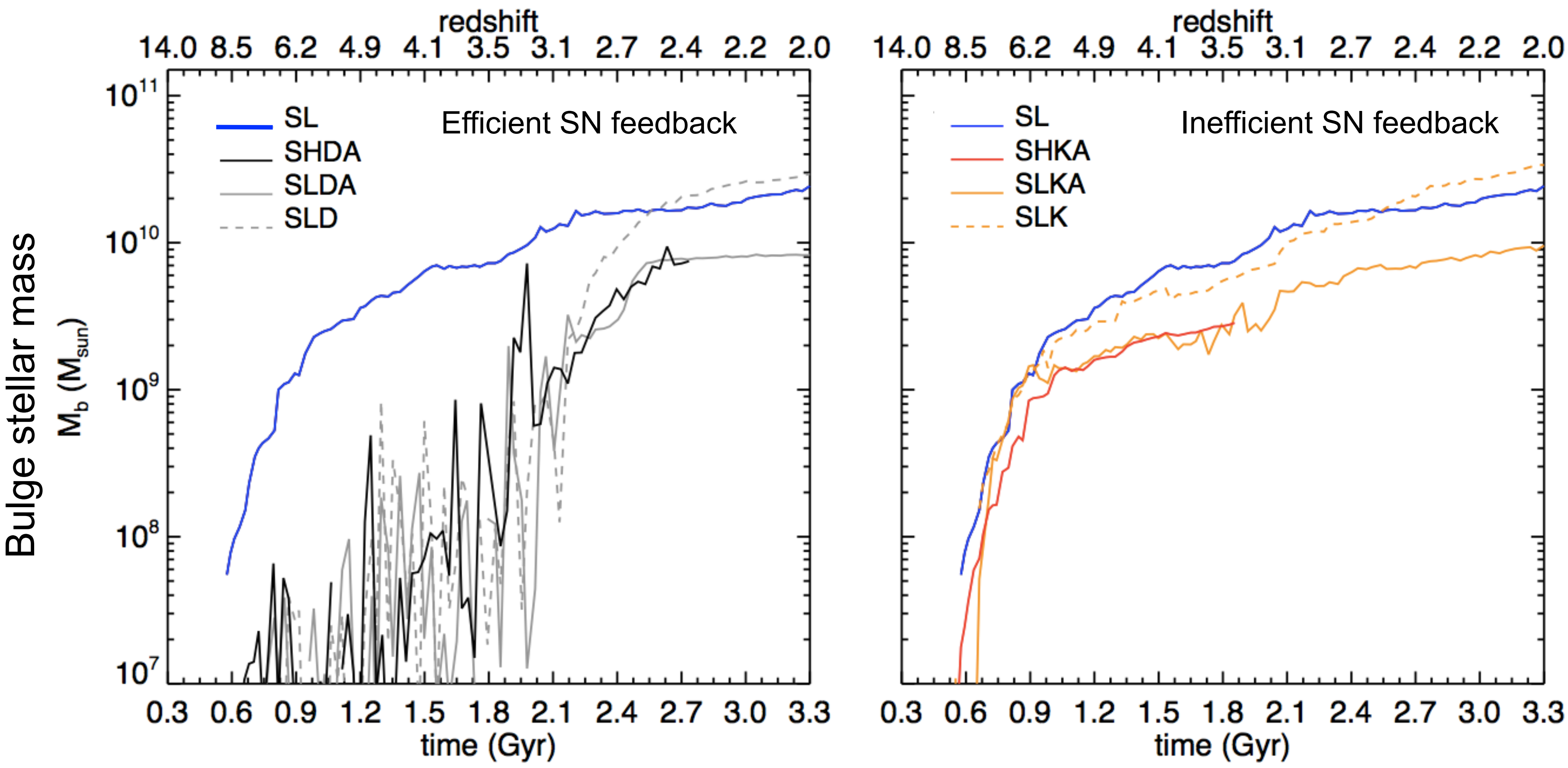


Dubois, Volonteri et al, 2015



Dubois, Volonteri et al, 2015

Efficient SN feedback delays bulge formation

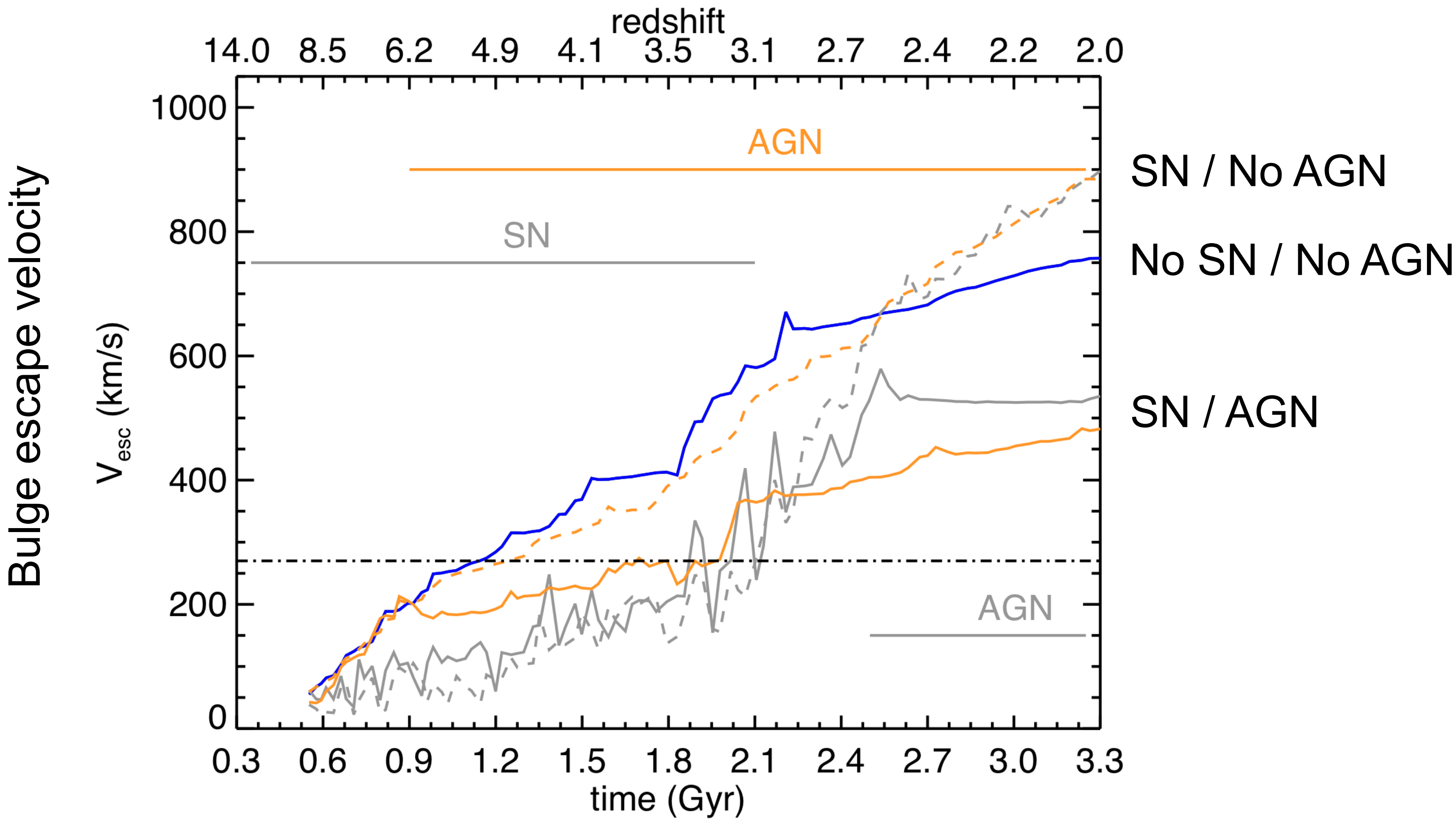


Dubois, Volonteri et al, 2015

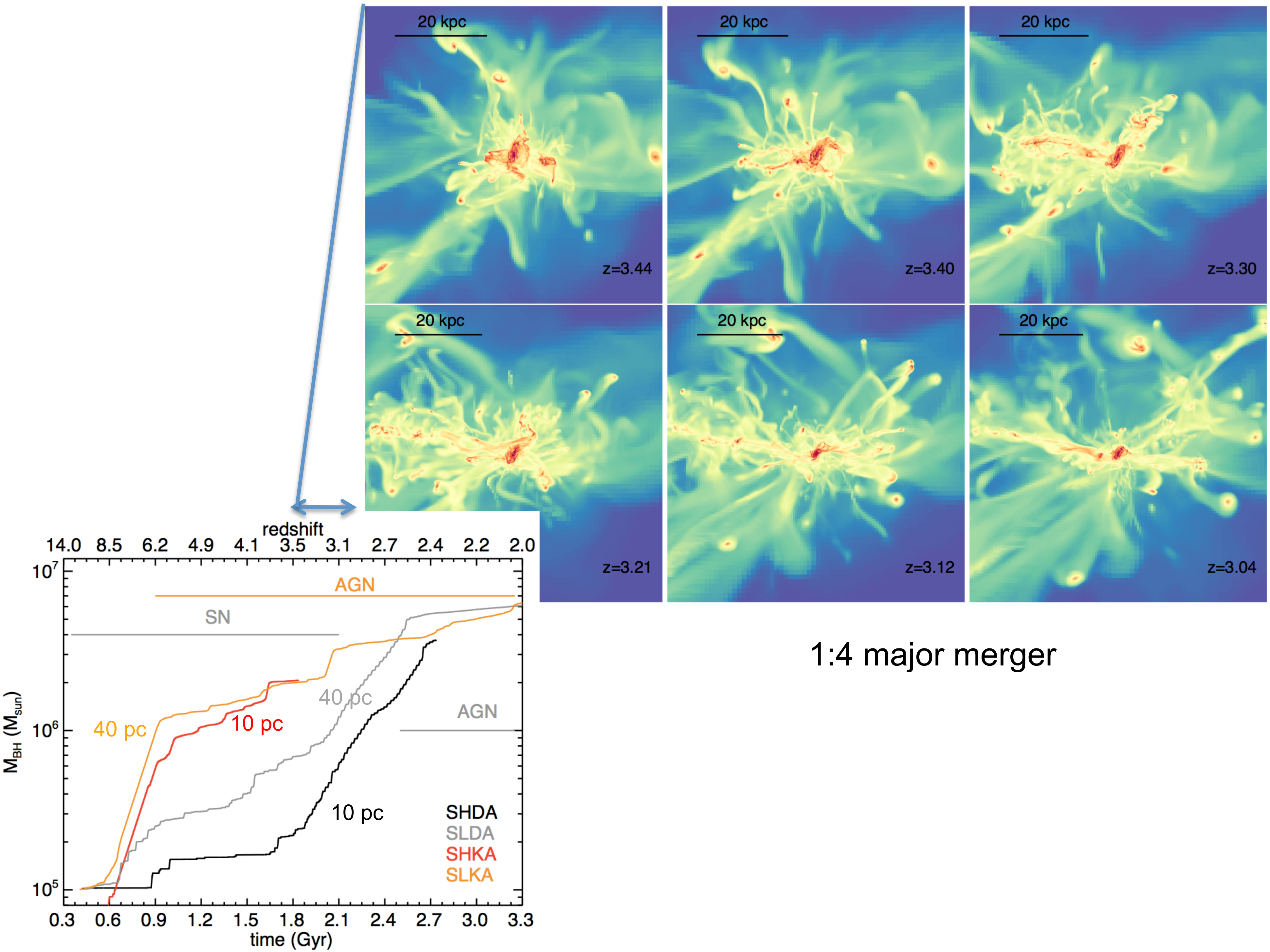
$$u_{\rm SN} = 1.2\sqrt{\frac{m_{\rm new,s}\eta_{\rm SN}e_{\rm SN}}{m_{\rm g}}} \simeq 270\sqrt{\frac{\eta_{\rm SN}}{0.1}}\sqrt{\frac{(m_{\rm new,s}/m_{\rm g})}{0.1}}\,{\rm km\,s^{-1}}$$

$$u_{\rm esc} = \sqrt{\frac{2Gm_{\rm cl}}{r_{\rm cl}}}$$ ~ 300 km s^{-1}

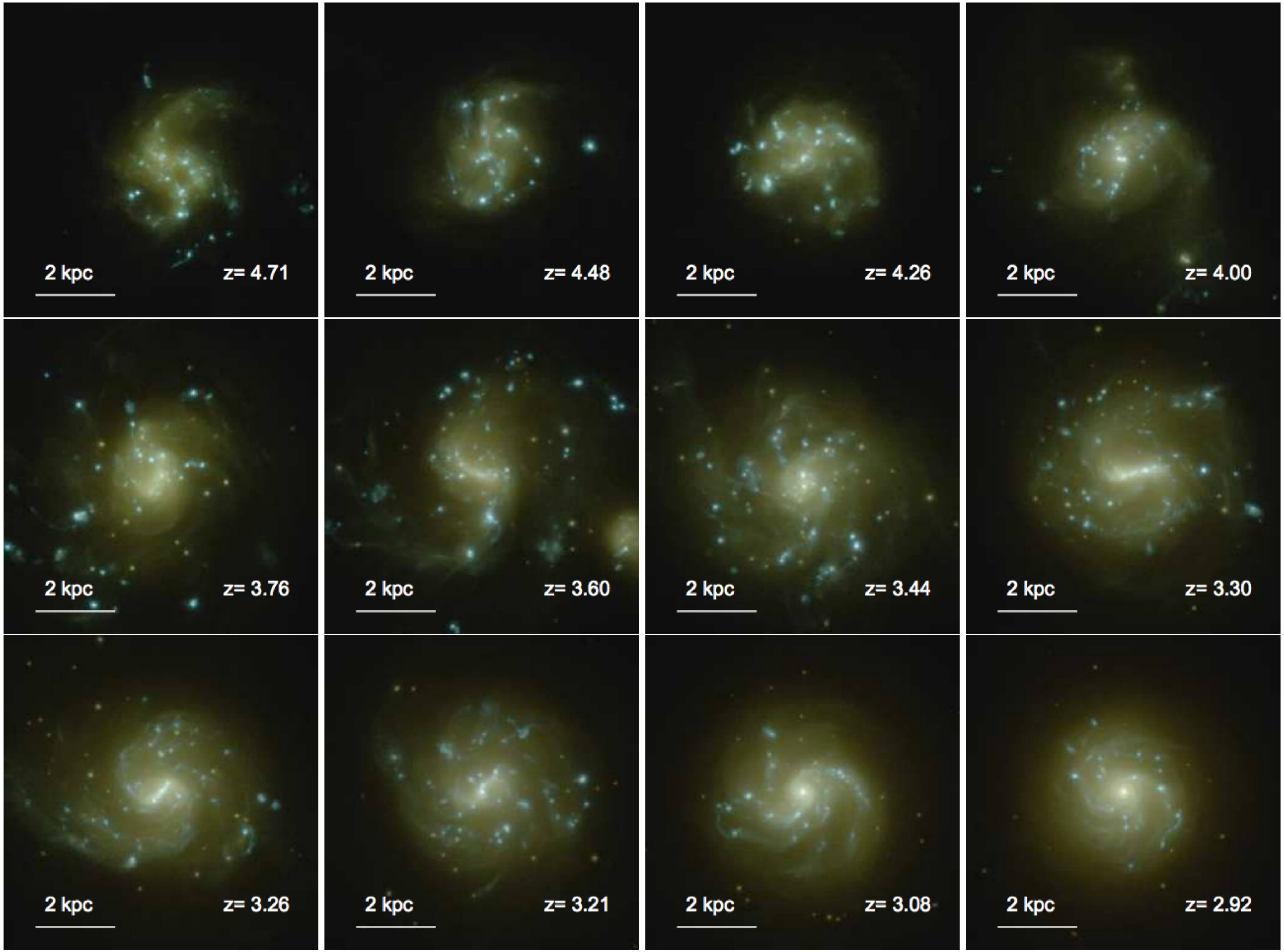
For $m_{cl}=10^9$ M_{sun} and r_{cl}=100 pc



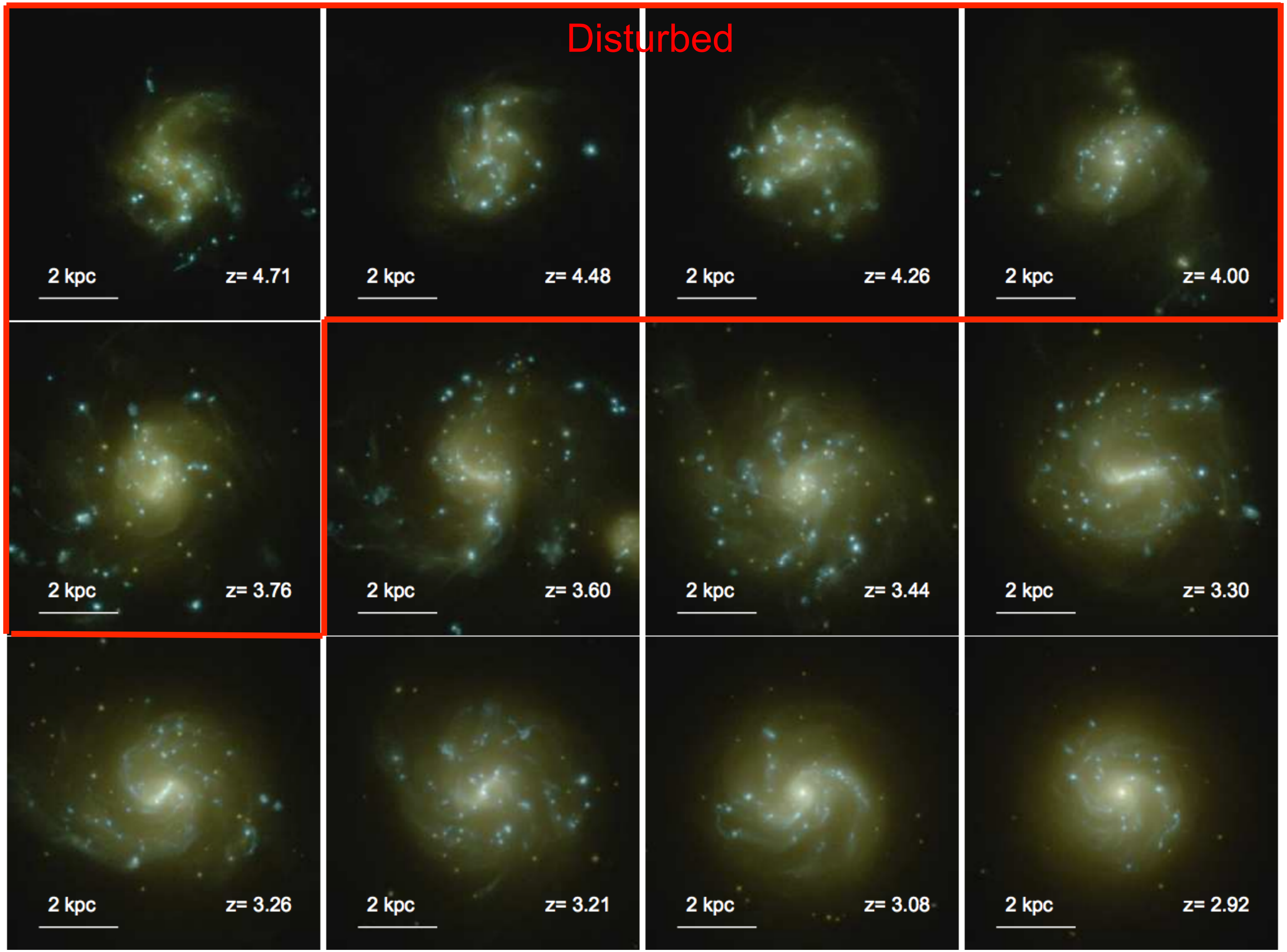
Dubois, Volonteri et al, 2015



1:4 major merger



2 kpc
z= 4.71
2 kpc
z= 4.48
2 kpc
z= 4.26
2 kpc
z= 4.00
2 kpc
z= 3.76
2 kpc
z= 3.60
2 kpc
z= 3.44
2 kpc
z= 3.30
2 kpc
z= 3.26
2 kpc
z= 3.21
2 kpc
z= 3.08
2 kpc
z= 2.92


Disturbed
2 kpc
z= 4.71
2 kpc
z= 4.48
2 kpc
z= 4.26
2 kpc
z= 4.00
2 kpc
z= 3.76
2 kpc
z= 3.60
2 kpc
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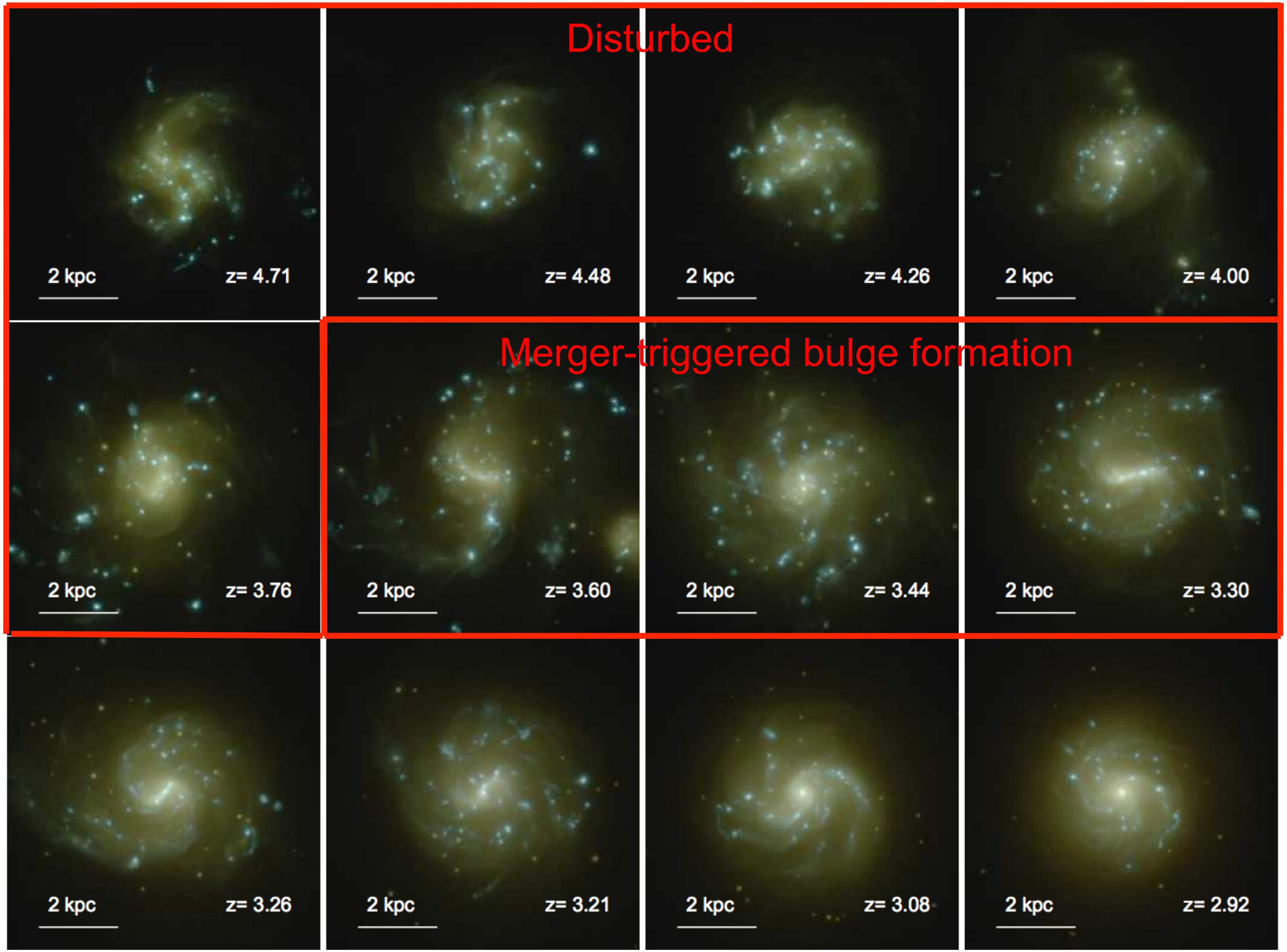
z= 2.92



Disturbed
2 kpc
z= 4.71
2 kpc
z= 4.48
2 kpc
z= 4.26
2 kpc
z= 4.00
Merger-triggered bulge formation
2 kpc
z= 3.76
2 kpc
z= 3.60
2 kpc
z= 3.44
2 kpc
z= 3.30
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z= 3.26
2 kpc
z= 3.21
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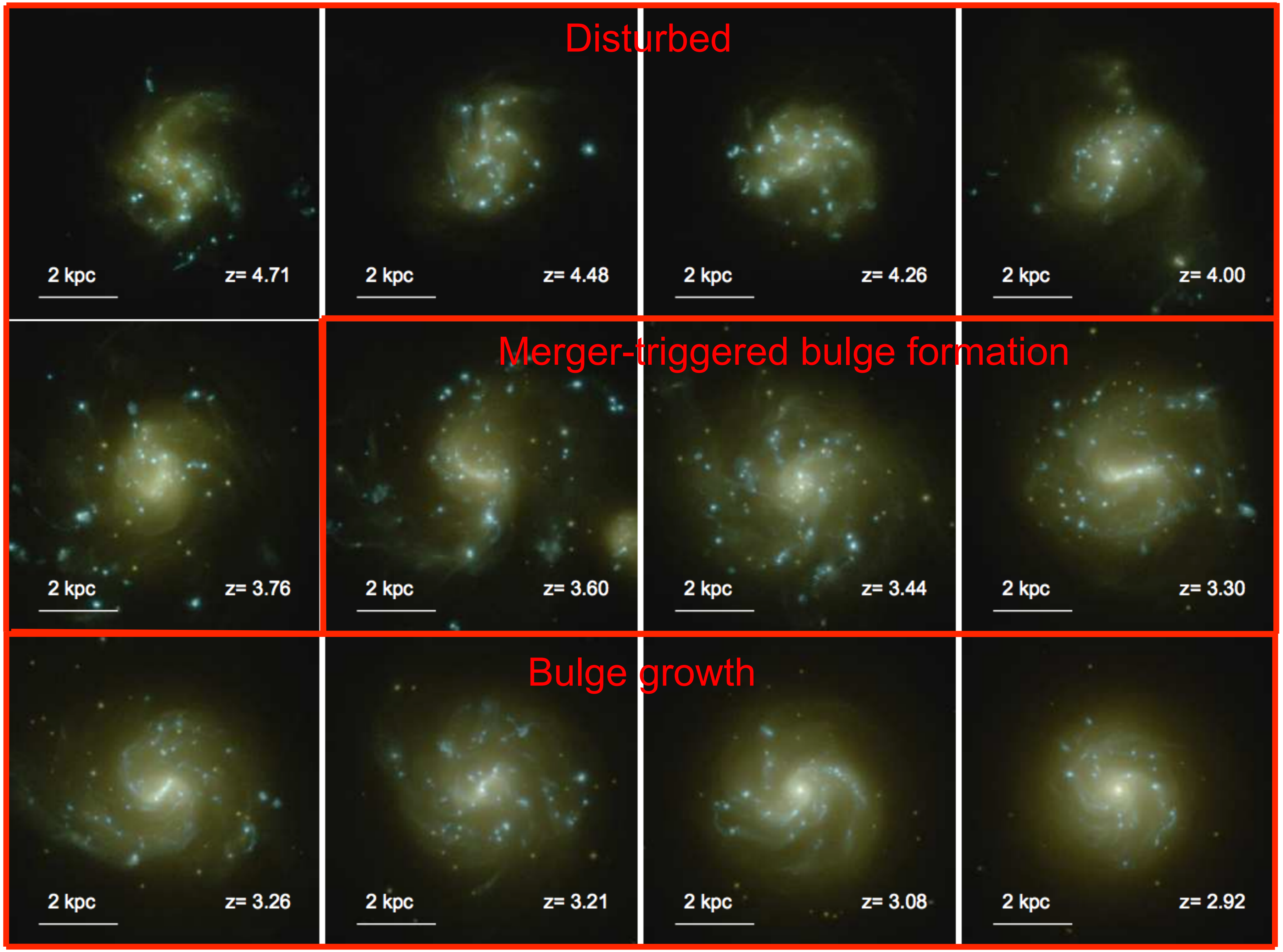
2 kpc
z= 2.92


Disturbed
2 kpc
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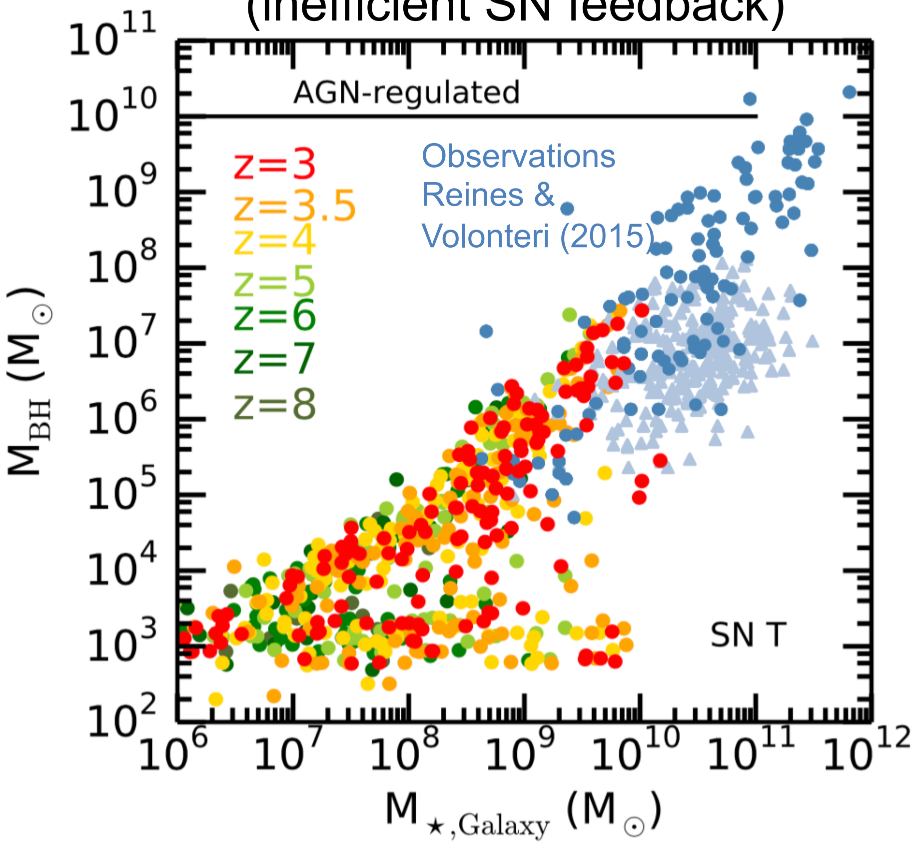
z= 4.00
Merger-triggered bulge formation
2 kpc
z= 3.76
2 kpc
z= 3.60
2 kpc
z= 3.44
2 kpc
z= 3.30
Bulge growth
2 kpc
z= 3.26
2 kpc
z= 3.21
2 kpc
z= 3.08
2 kpc
z= 2.92

Confirmed in a statistical sense

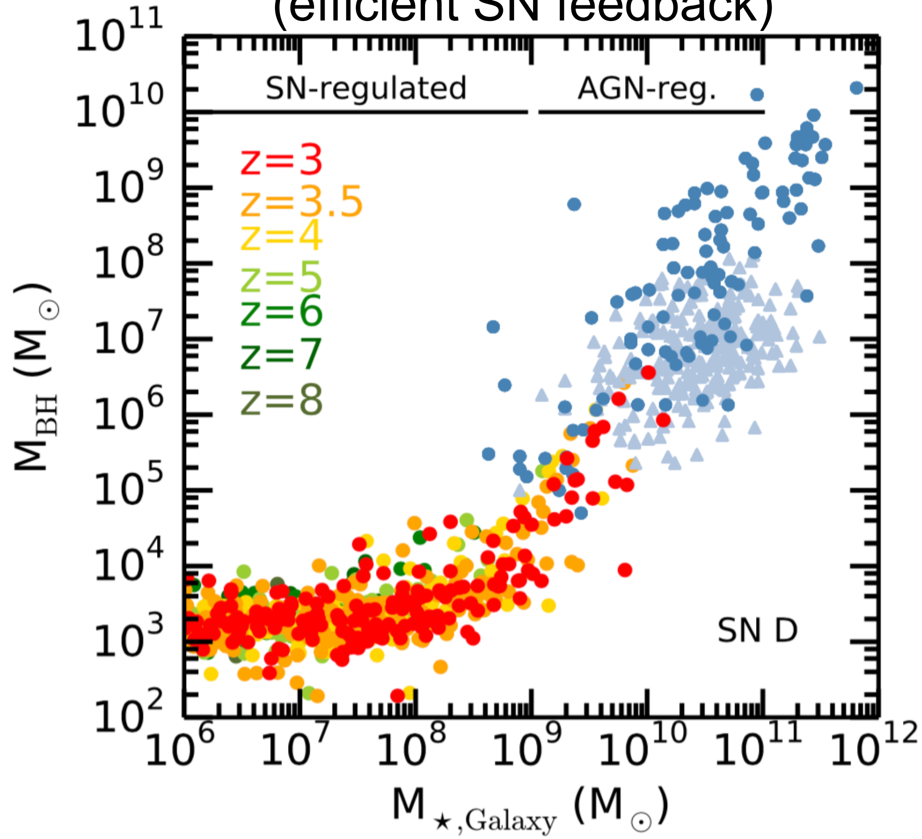
10 Mpc box with 80 pc spatial resolution
Using pop III BH seeding

Non-delayed cooling
(inefficient SN feedback)



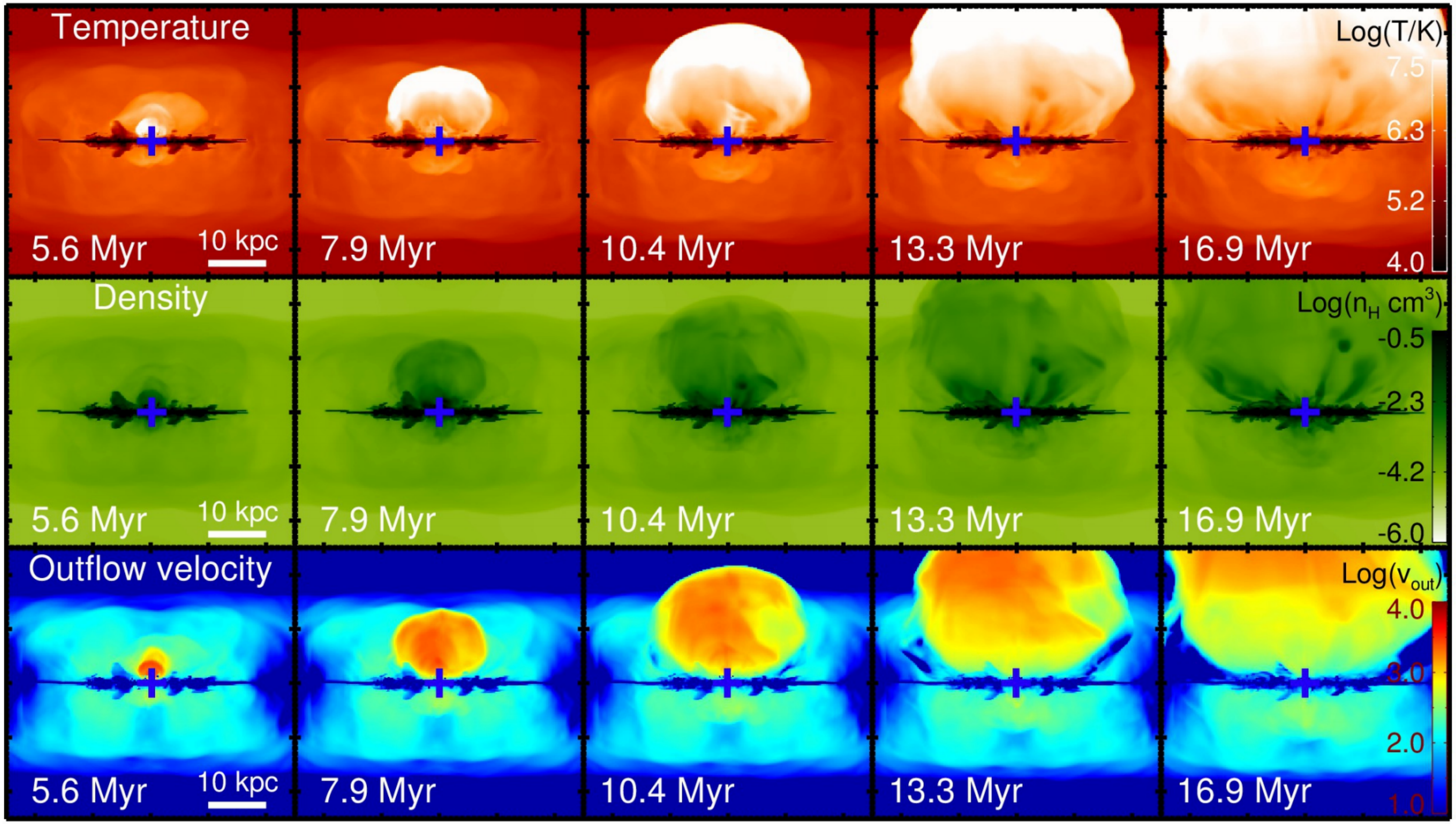
Habouzit, Volonteri, YD, sub.

Delayed cooling
(efficient SN feedback)



<u>Results also confirmed in:</u>
Bower et al, 2016 (EAGLE)
Prieto, Escala, Volonteri, YD, 2017 (z=6 halos)
Biernacki, Teyssier & Bleuler, arXiv (isolated disc simulations)

Quasar mode AGN do not destroy discs



Gabor & Bournaud, 2014

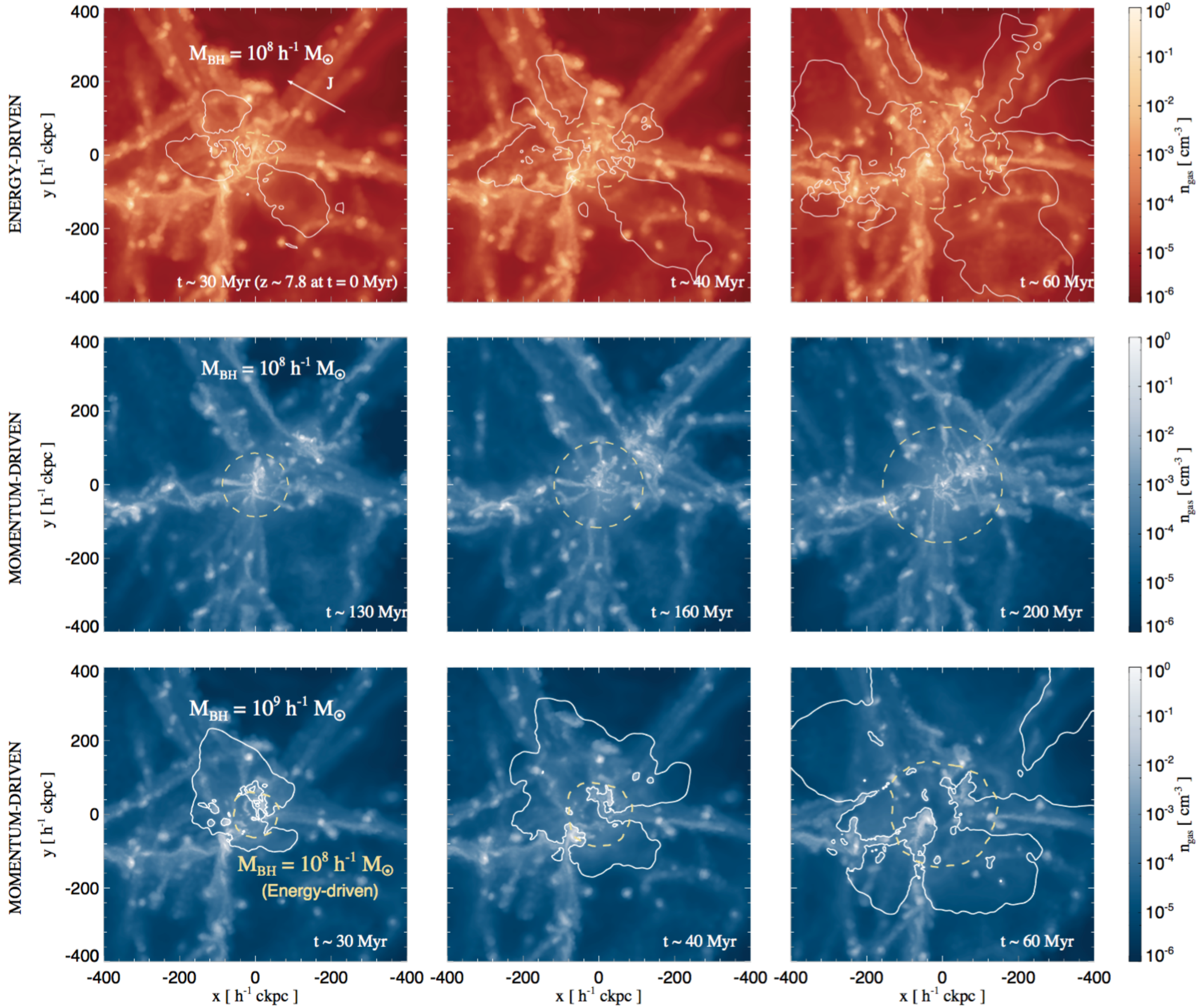
Inefficient momentum-driven winds (not RT simulations)

$M_{BH}=10^8\ M_{sun}$

$M_{BH}=10^8\ M_{sun}$
$dp/dt=L/c$

$M_{BH}=10^9\ M_{sun}$
$dp/dt=L/c$

($M_{BH}=10^8\ M_{sun}$
$dp/dt=10xL/c$)



Costa, Sijacki, Haehnelt, 2014

Radiation hydrodynamics

•Uses moment method with M1 closure to solve radiative transfer in RAMSES
(Rosdahl et al, 2013, Rosdahl & Teyssier 2015)
•Solving non-equilibrium evolution of ionisation fractions of H and He

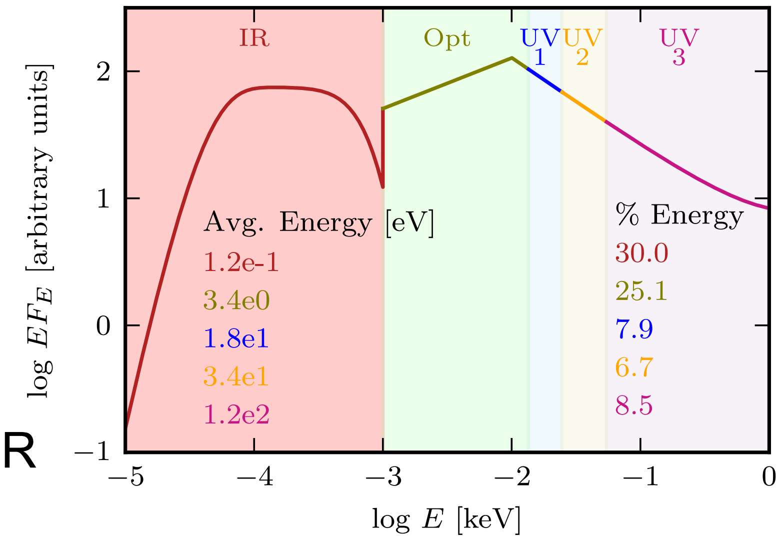
•Radiation Pressure + diffusion of multi-scattering IR radiation included

•Dust opacities $\kappa_{\rm D,UV} = 1000\,{\rm g\,cm^{-2}}$
$\kappa_{\rm D,IR} = 10\,{\rm g\,cm^{-2}}$
$\kappa_{\rm D} = 0 \text{ if } {\rm T} > 10^5\,{\rm K}$

•Solar metallicity with all metals in dust content
•Two AGN luminosities 10^{46} erg/s & 10^{43} erg/s

•Reduced speed of light approximation c_{red}=0.2 c
(Gnedin & Abel 2001)

5 photon groups



Sazonov+ 2004

Big Caveat:
No gravity
No cooling
No SF

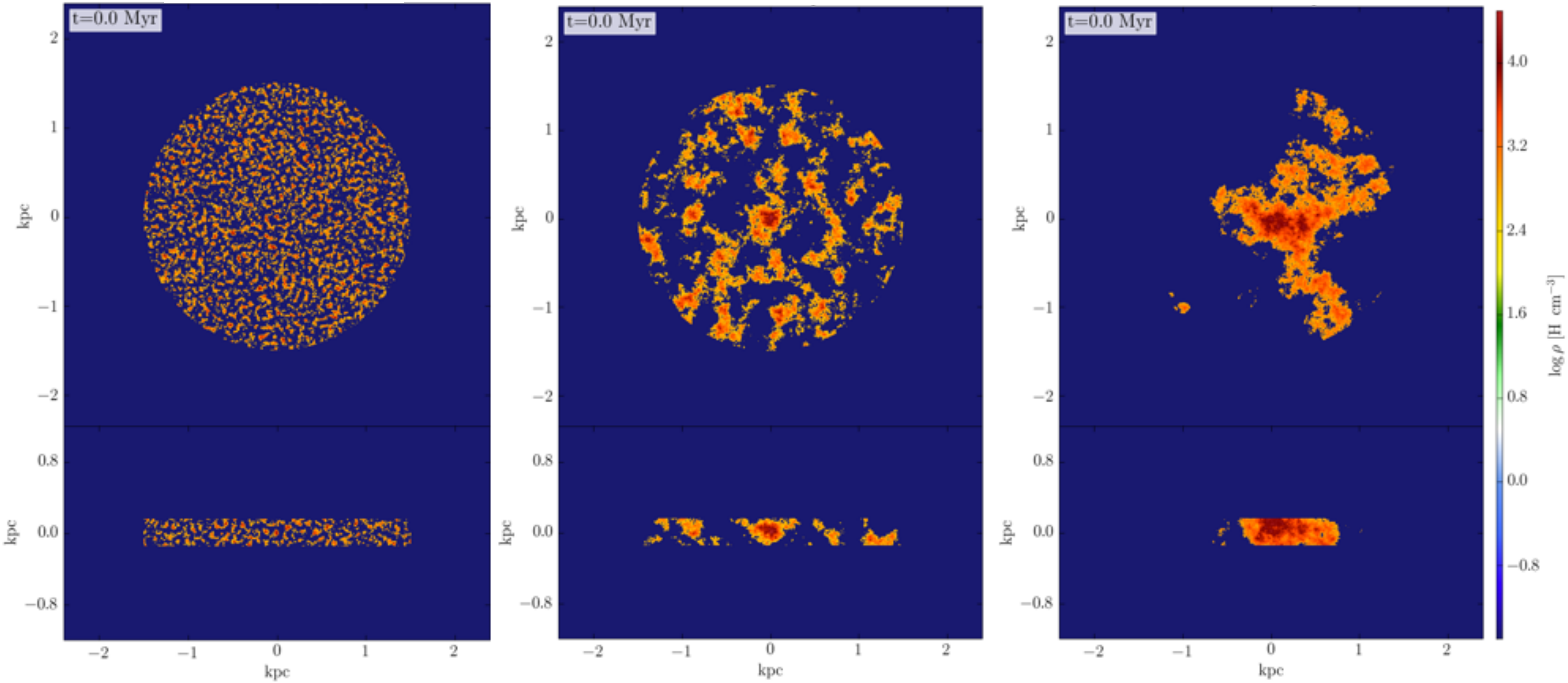
Bieri, YD, Rosdahl+, 2017

Shining a quasar in a multiphase medium

Log Normal pdf for gas density
Power spectrum $k^{-5/3}$ (and different cloud size)
ICs from Wagner & Bicknell (2011)

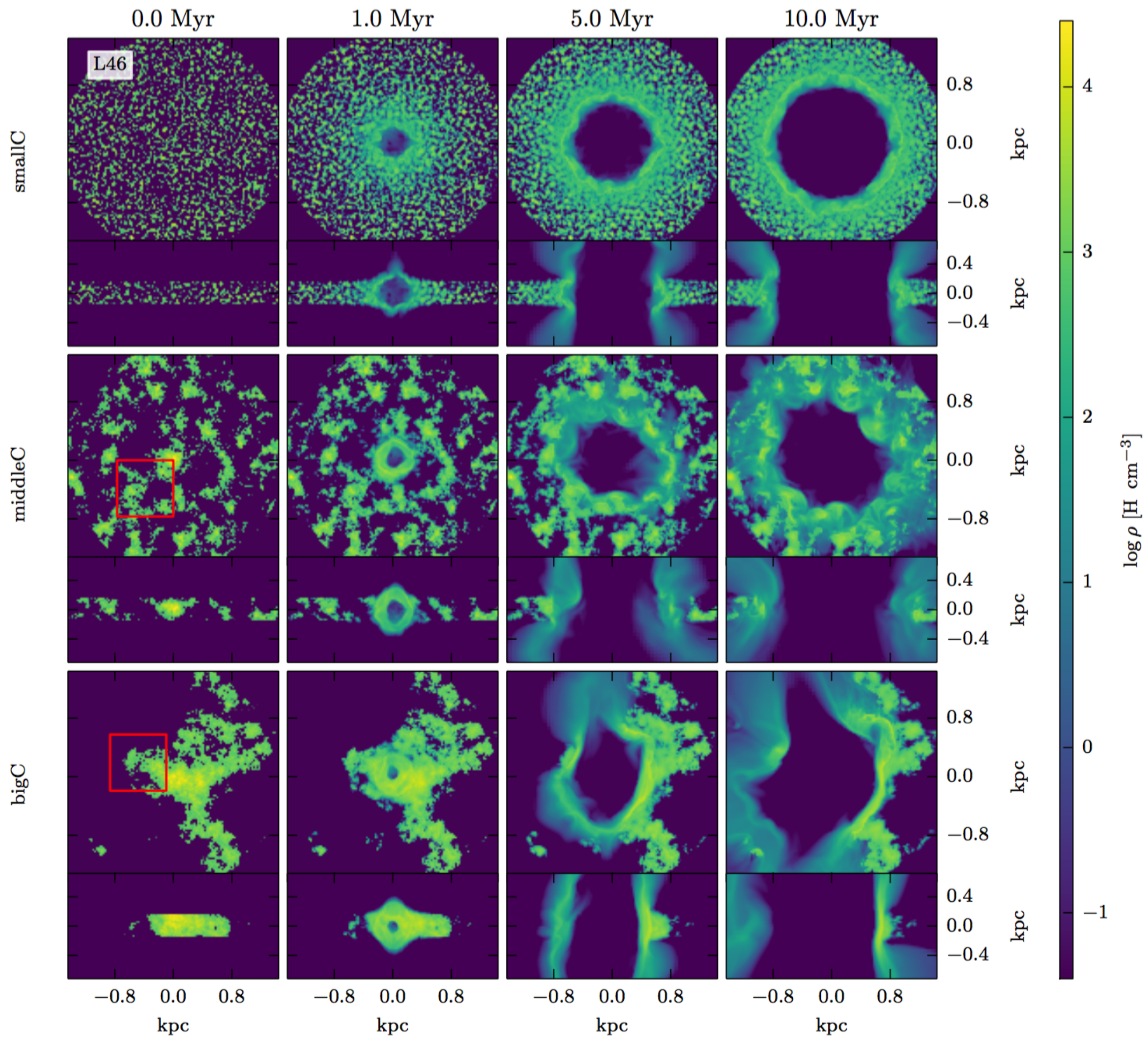
Galaxy mass is 2.10^{10} M_{sun}
With 100% gas (no DM, no stars)
Resolution is 5 pc in clouds

Small clouds | Medium clouds | Large clouds

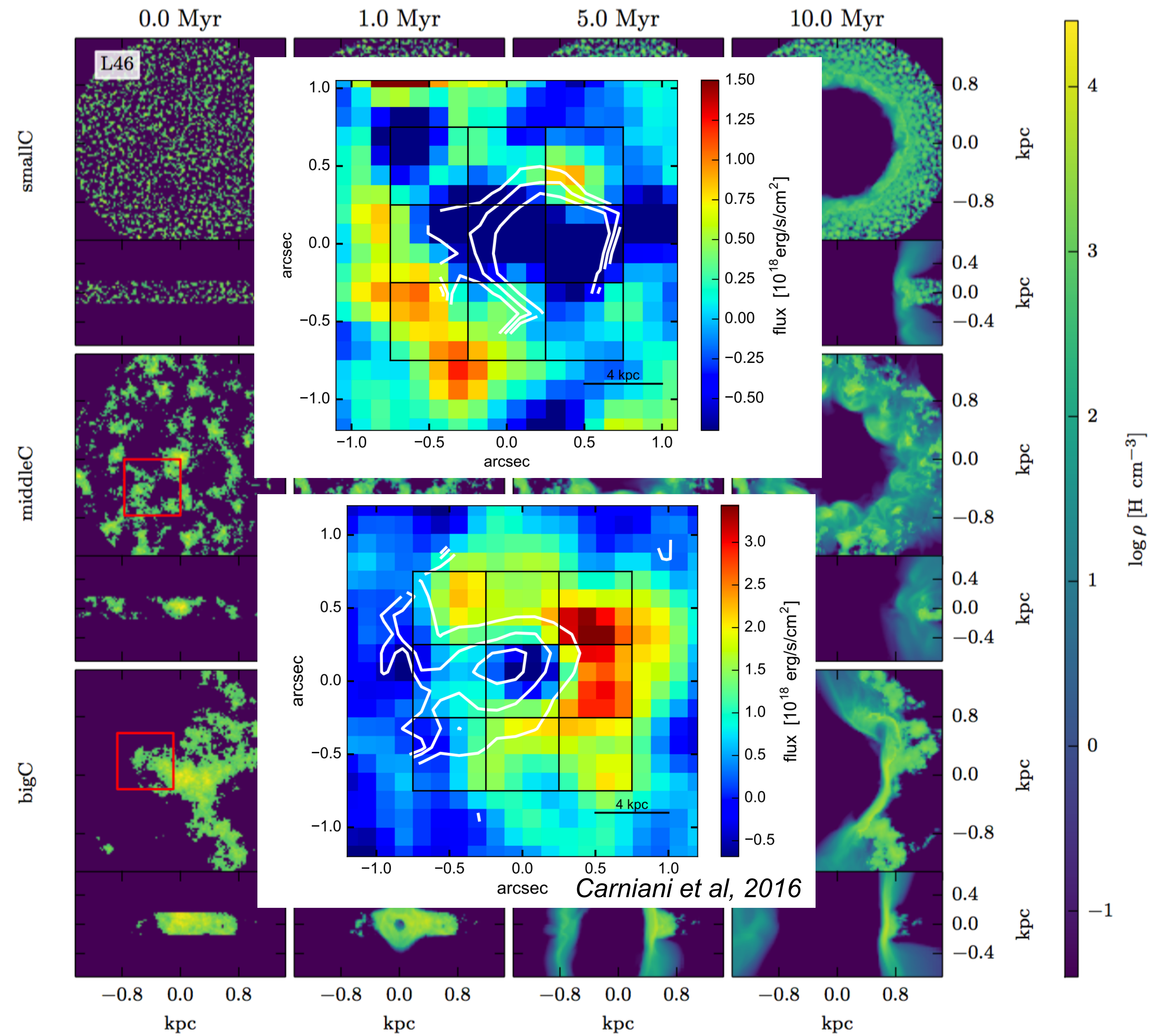


L_{cloud}=50 pc | L_{cloud}=300 pc | L_{cloud}=1 kpc

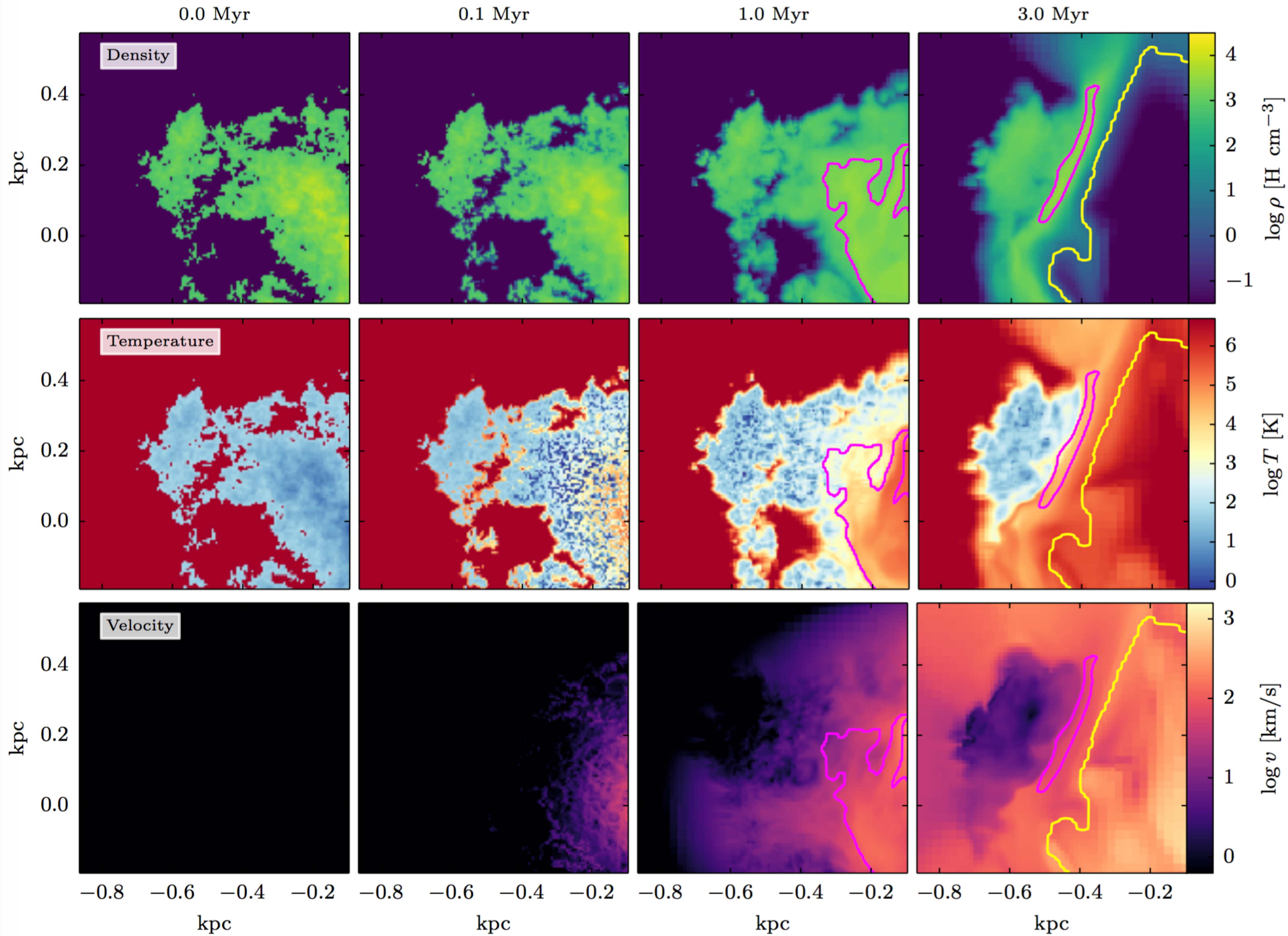
Bieri, YD, Rosdahl+, 2017



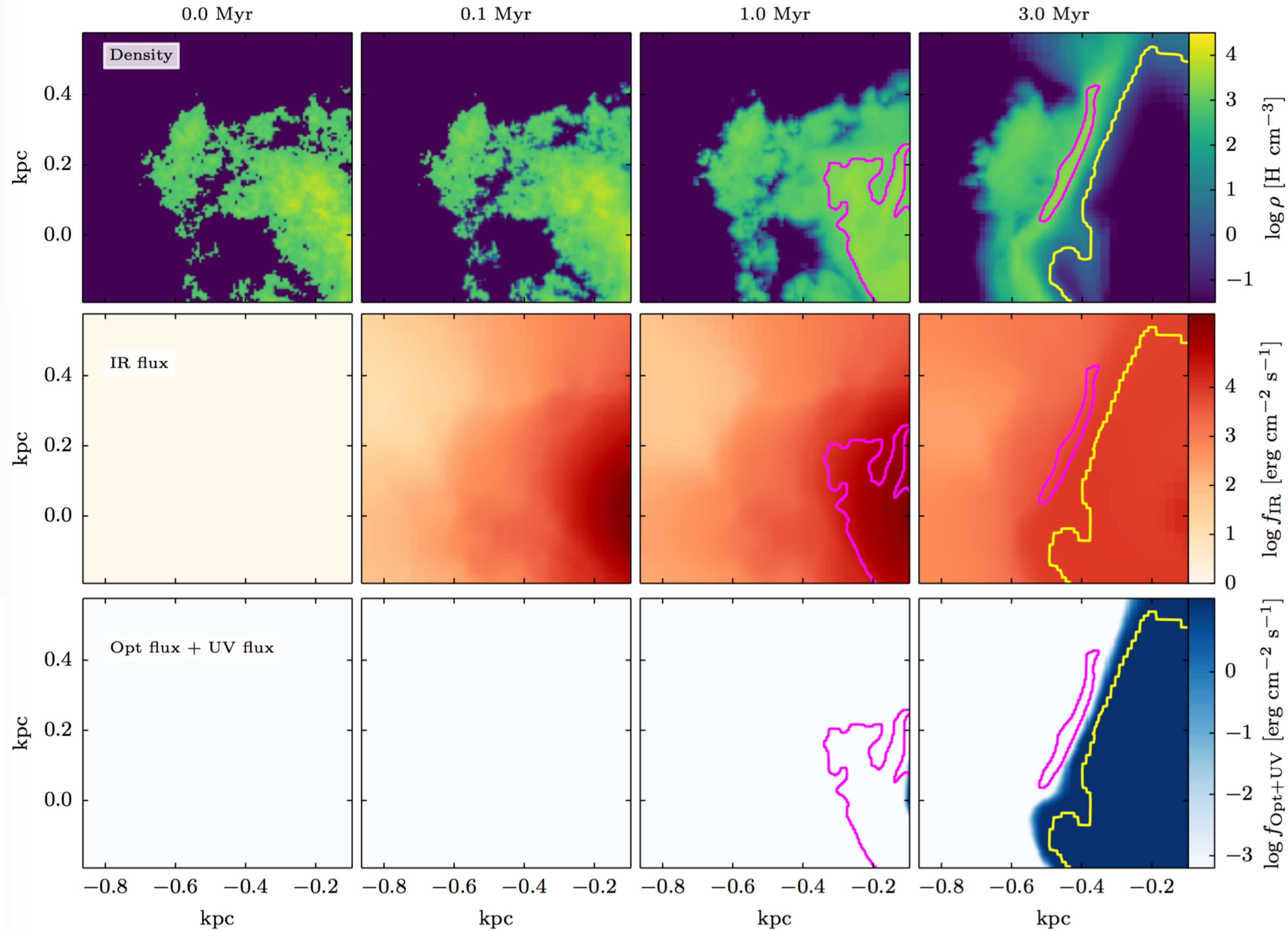
Bieri, YD, Rosdahl+, 2017



Bieri, YD, Rosdahl+, 2017



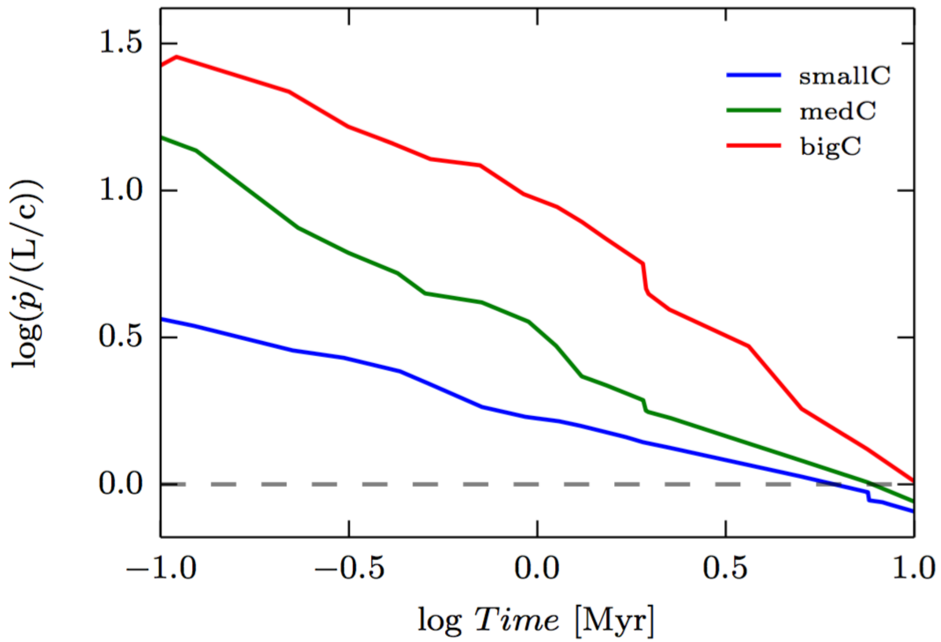
0.0 Myr
0.1 Myr
1.0 Myr
3.0 Myr
Density
Temperature
Velocity
kpc
0.4
0.2
0.0
−0.8
−0.6
−0.4
−0.2
$\log \rho$ [H cm^{-3}]
$\log T$ [K]
$\log v$ [km/s]

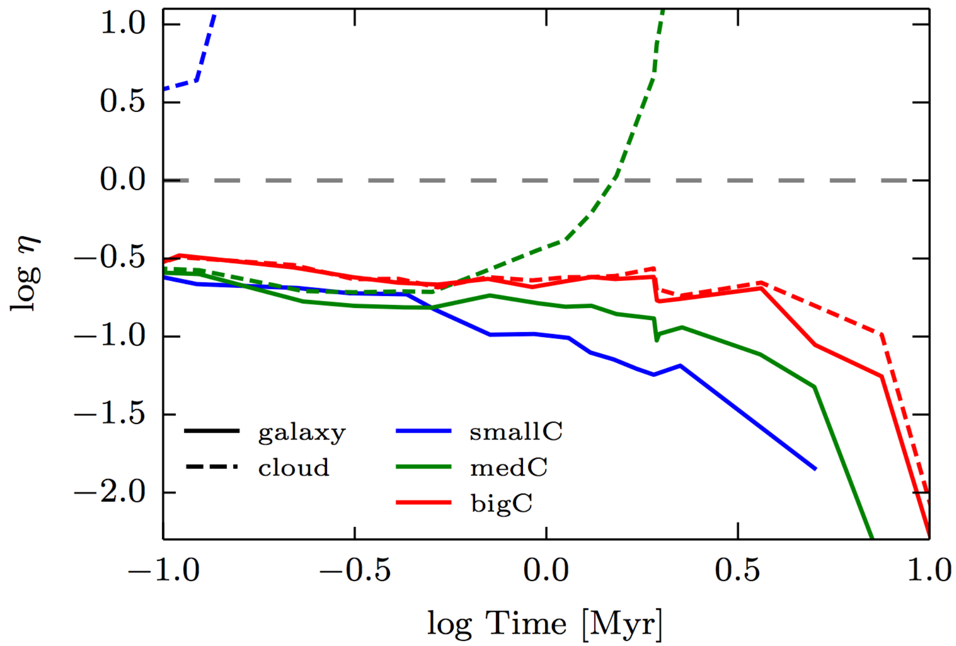


0.0 Myr
0.1 Myr
1.0 Myr
3.0 Myr
Density
IR flux
Opt flux + UV flux
kpc
0.4
0.2
0.0
−0.8
−0.6
−0.4
−0.2
log ρ [H cm^−3]
log f_IR [erg cm^−2 s^−1]
log f_Opt+UV [erg cm^−2 s^−1]

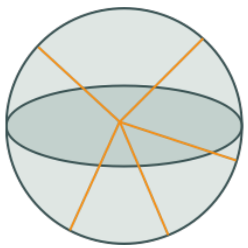
Mechanical advantage

$$\dot{p} = (1 + \eta\tau_{\mathrm{IR}})\frac{L}{c}$$



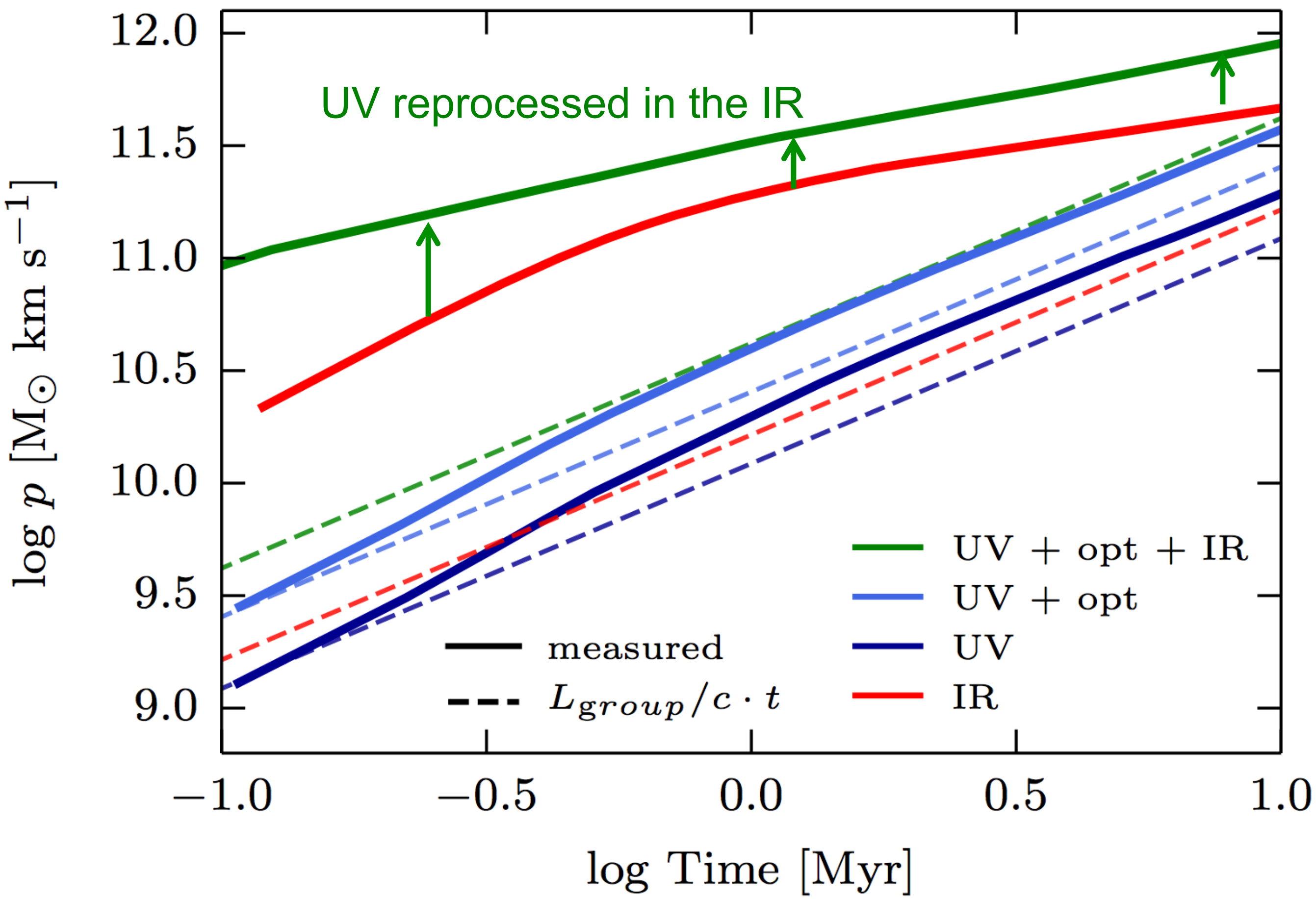


500 rays are cast to measure τ_{IR}



Bieri, YD, Rosdahl+, 2017

Mechanical advantage considering different groups



The uncertainties in dust-gas coupling

- Dust grains receive IR momentum kicks
- This momentum has to be transfered to the gas to regulate the galaxy gas content
- Two problems:

1) Gas particles scatter on dust grains

⟶ dynamical friction and momentum transfer

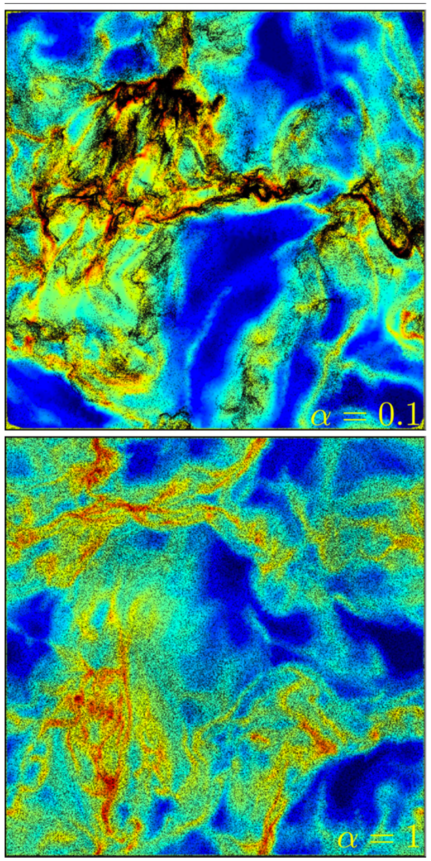
$$t_{\rm stop} \simeq \frac{\tilde{\rho}_{\rm D} a_{\rm D}}{\rho_{\rm gas} c_{\rm s}} \qquad t_{\rm stop} \simeq 1\,{\rm Myr}$$

$$\tilde{\rho}_{\rm D} = 3\,{\rm g\,cm^{-3}}$$
$$a_{\rm D} = 0.1\,\mu{\rm m}$$
$$\rho_{\rm gas} = 1\,{\rm cm^{-3}}$$
$$c_{\rm s} = 3\,{\rm km\,s^{-1}}$$

$$t_{\rm cross} \simeq 0.1\,{\rm Myr}$$

$$u_{\rm D} = 100\,{\rm km\,s^{-1}}$$
$$r_{\rm cloud} = 10\,{\rm pc}$$

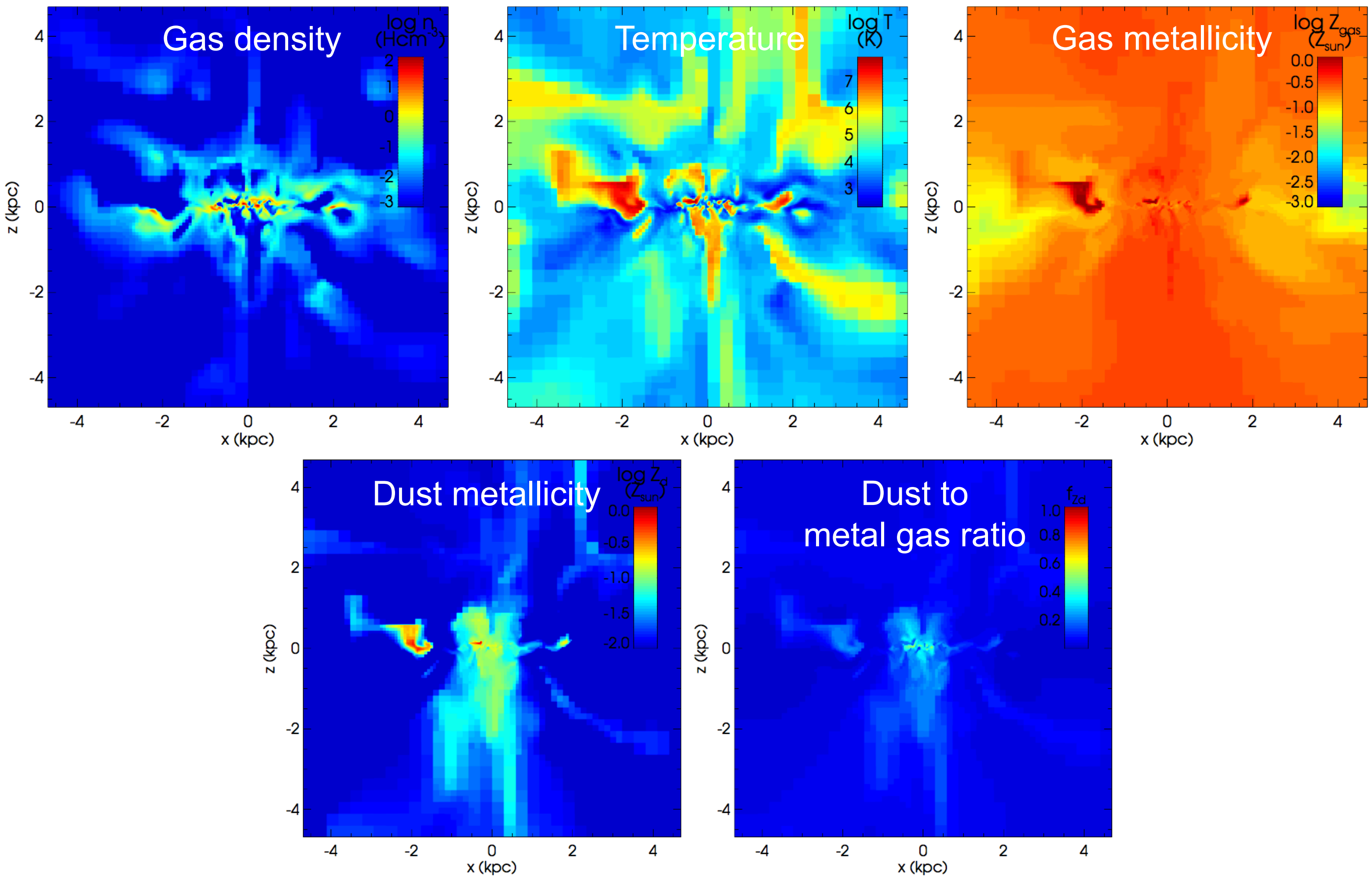
2) Dust can be destroyed at high temperatures ($T>10^6$ K) by thermal sputtering, and in SN explosions (inertial sputtering)



Hopkins & Lee, 2015

Including dust processing (work in progress)

- Dust destruction through thermal sputtering and SN shock destruction
- Dust growth at low temperatures
- Dust is a passive scalar (i.e. dust is glued to gas motions)



Summary

- AGN feedback controls the formation of ellipticals by freezing the morphological transformation due to mergers
- BH growth at high redshift:
  - SN feedback can suppress BH growth in high-redshift low-mass galaxies $M_{bulge}<10^9\ M_{sun}$ (or $V_{esc}<270$ km/s)
  - Burst of AGN activity triggered by wet mergers associated with bulge formation
- Quasar mode with photons only:
  - Can drive winds because of IR multi-scattering
    - Though fewer scatters than theoretically inferred
  - Destroys the disc
    - Need to be confirmed in more realistic set-up