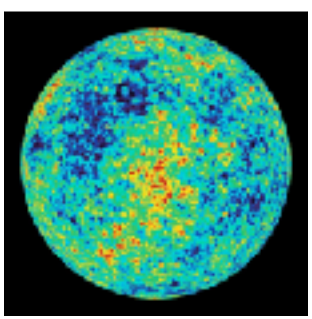
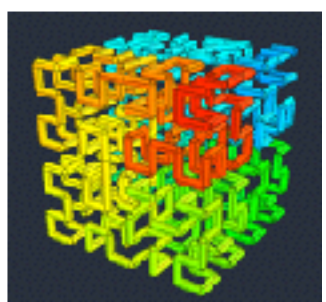
Bridging the scales between stars, black holes and galaxies

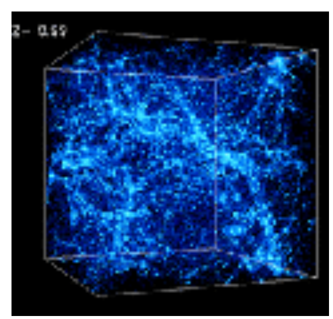
Romain Teyssier

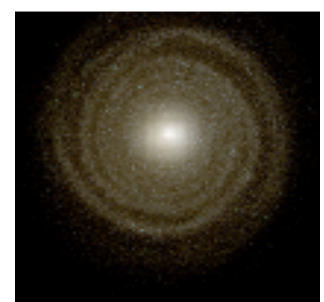
Elena Gavagnin, Michael Kretschmer, Pawel Biernacki

University of Zurich[UZH]









Outline

- Formation of a young star cluster in a turbulent molecular could with radiative feedback with Elena Gavagnin’s PhD thesis (MNRAS, 2017, 472, 4155)

- The effect of supernovae momentum feedback and new star formation recipe on properties of simulated galaxies with Michael Kretschmer’s first results (in preparation)

- The dynamics of supermassive black-holes in high-redshift galaxies: the case for nuclear star cluster co-evolution with Pawel Biernacki PhD thesis (MNRAS, 2017, 469, 295)

Observed young embedded star clusters

Arches

NGC 3603

Simulation of the birth and death of a star cluster

Initial conditions: fully developed turbulence in a spherical cloud of mass 20’000 solar masses and radius 5 pc.

Maximum spatial resolution 0.02 pc

Minimum spatial resolution 500 AU

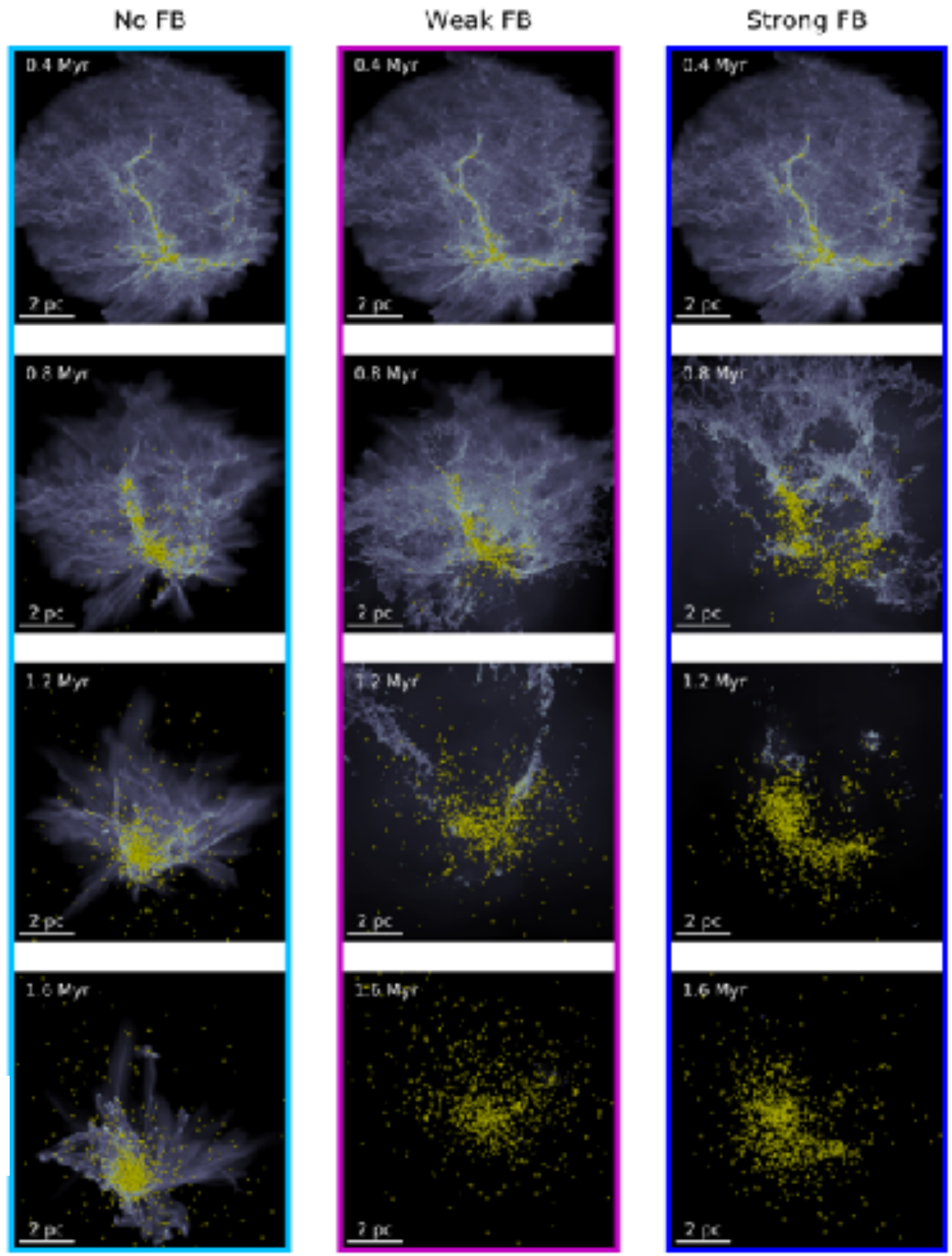
Mass resolution 0.003 solar masses

3 models with only UV radiation (strong, weak and none)

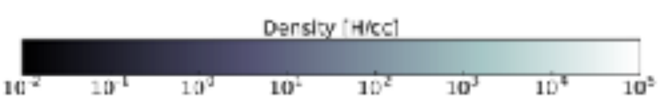
Sink particle algorithm based on clump finder.

Accretion rate based on Bondi model.

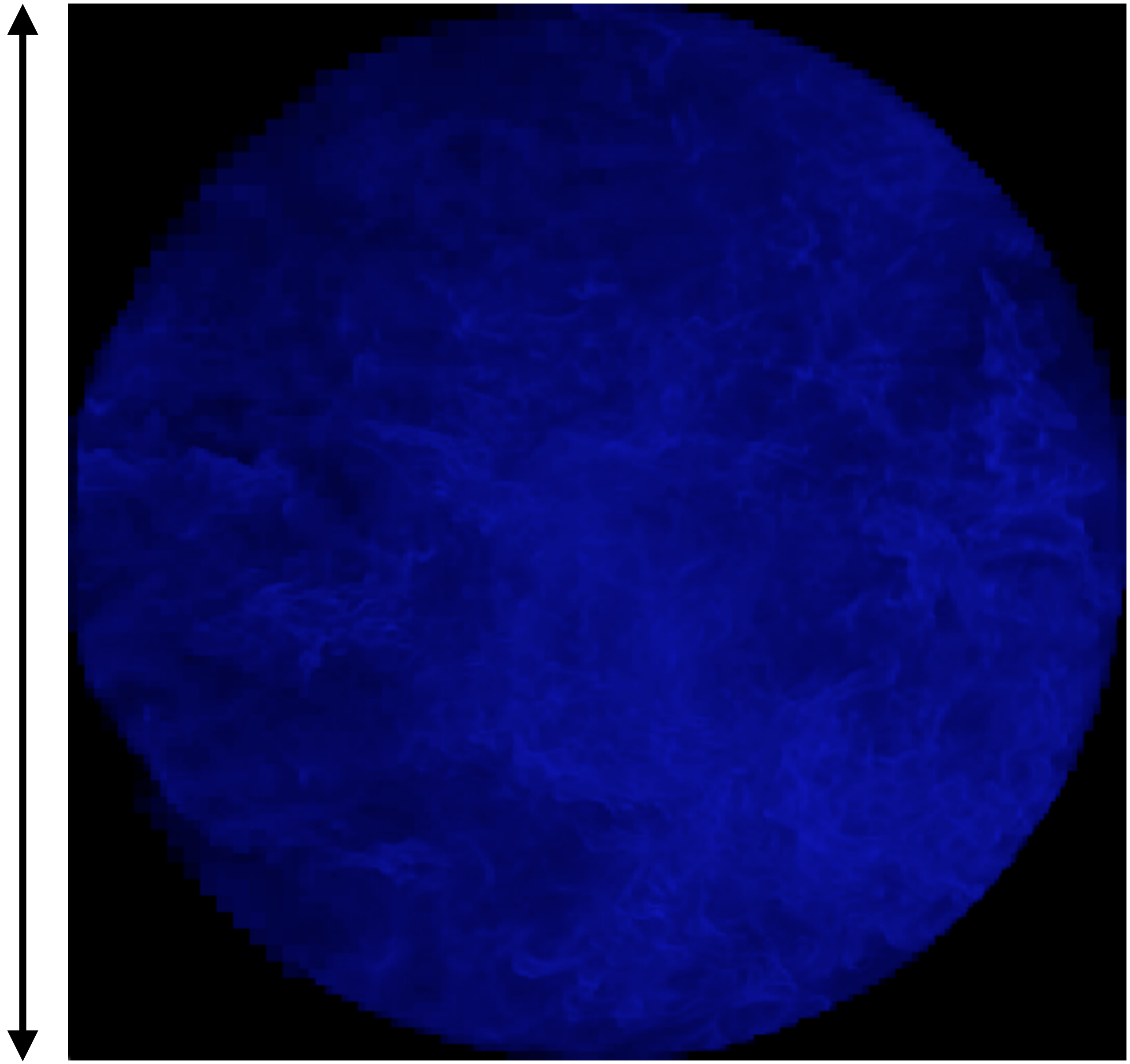
Direct gravity solver between sinks and between sinks and gas.



Gavagnin et al. (2017)



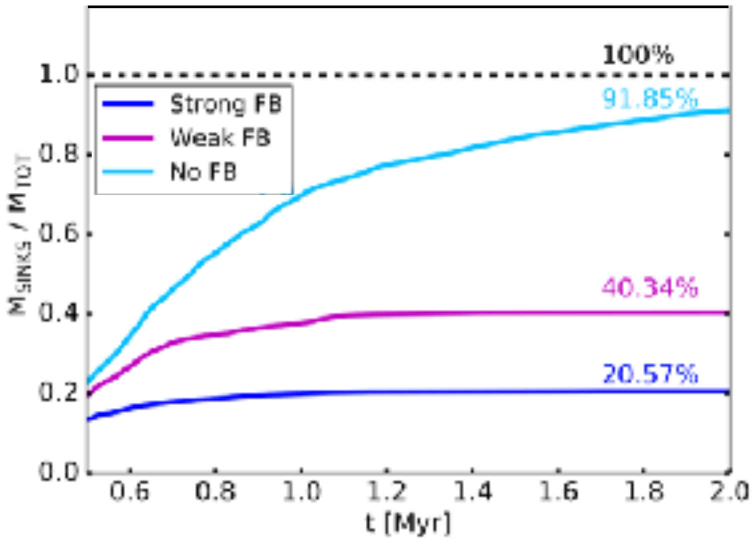
Star formation and radiation feedback



Gavagnin et al. (2017)

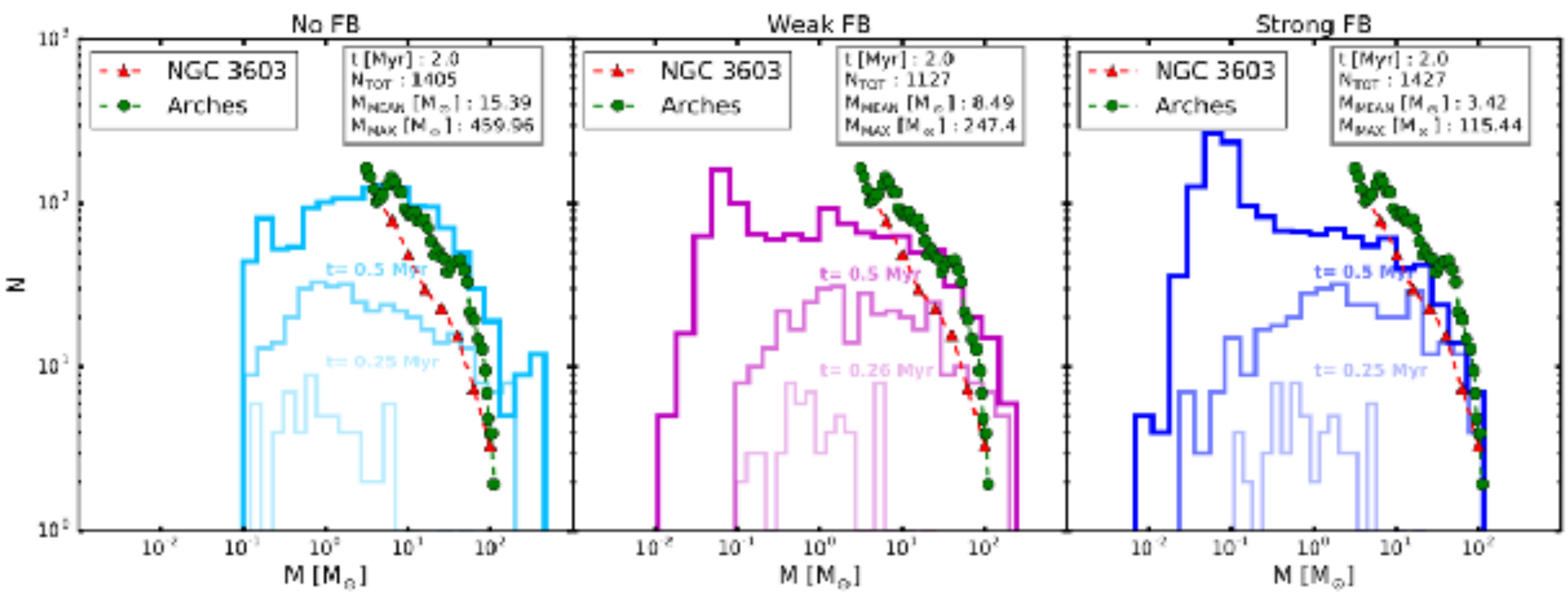
The role of feedback in shaping the star cluster

Gavagnin et al. (2017)



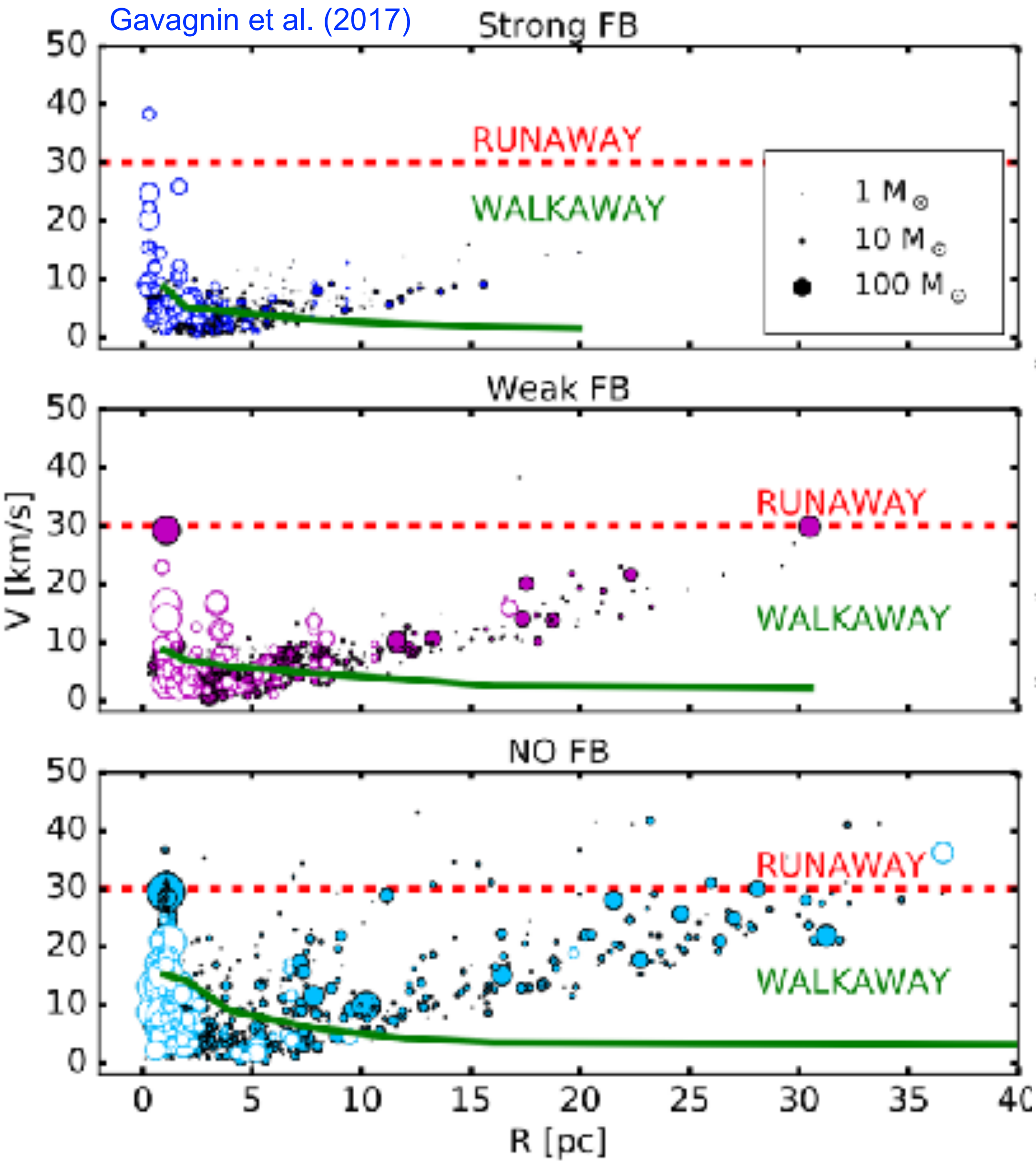
Radiation feedback regulates the cloud star formation efficiency.

Turbulence sets the shape of the Initial Mass Function but feedback affects the high mass end.



The star cluster final dynamical state

Gavagnin et al. (2017)



	Strong	Weak	NF
2-body systems	68	35	41
3-body systems	10	15	5
>3 body systems	10	5	10
Tot multi-body syst	78	55	51
Stars in multi-body syst	192(13%)	143(13%)	152(11%)
with $M > 1 M_\odot$	132(32%)	111(21%)	130(12%)
with $M > 10 M_\odot$	72(56%)	80(40%)	95(24%)
Bound stars	761 (53%)	647 (57%)	901 (64%)
Unbound stars	666 (47%)	480 (43%)	504 (36%)
Runaway	1 (1‰)	3 (3‰)	31 (2%)
of which in multi syst	1	0	2
Walkaway	501(35%)	402 (36%)	493 (35%)
of which in multisyst	74(5%)	50 (4%)	33(2%)

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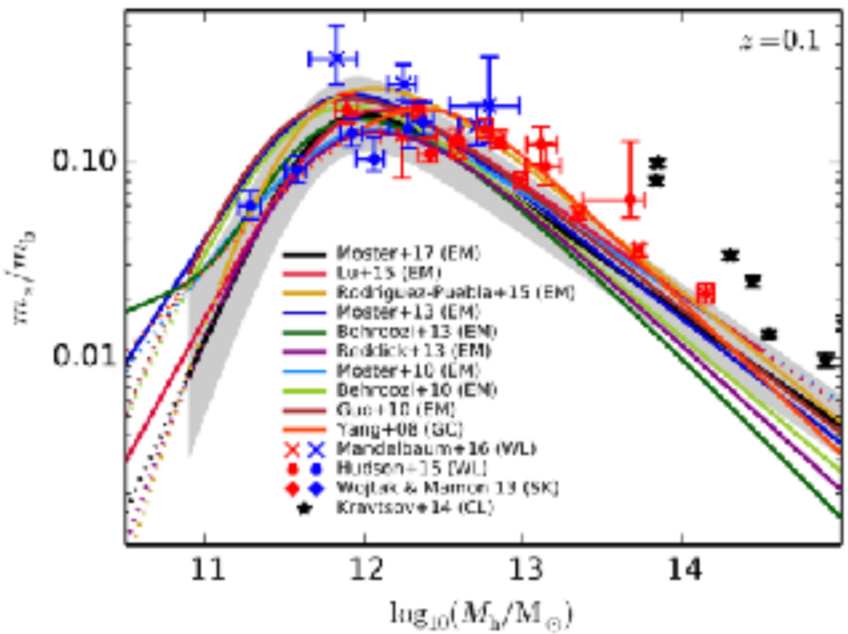
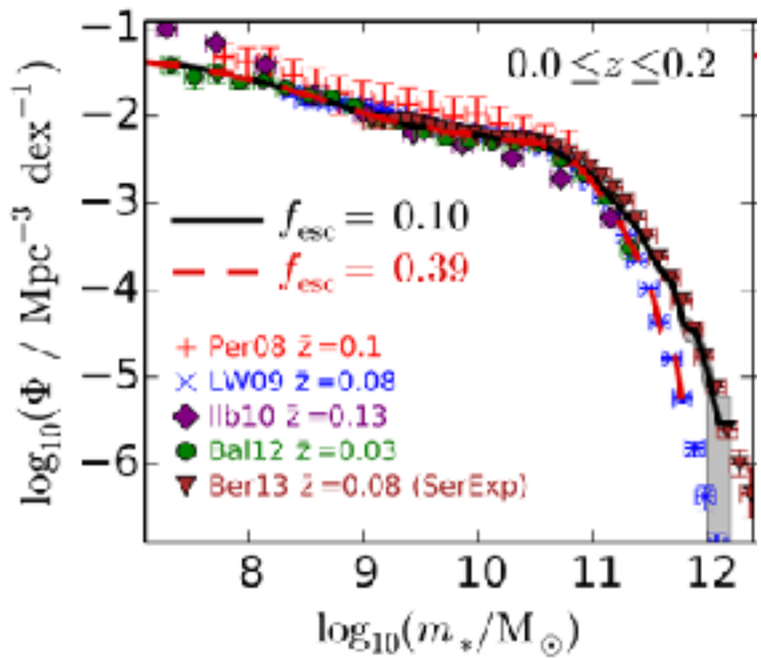
What do we know about galaxy formation ?

Moster et al. (2018)



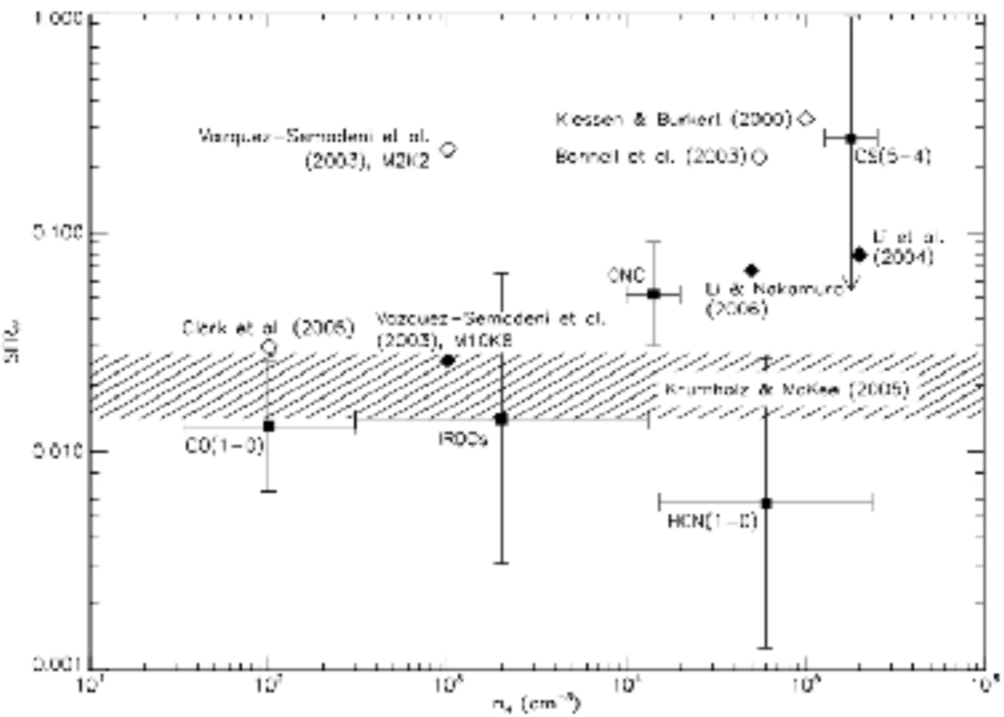


Conversion of baryons into stars is remarkably inefficient at all masses.

Stellar feedback regulates SF at low halo masses.

AGN feedback quenches star formation at high halo masses.

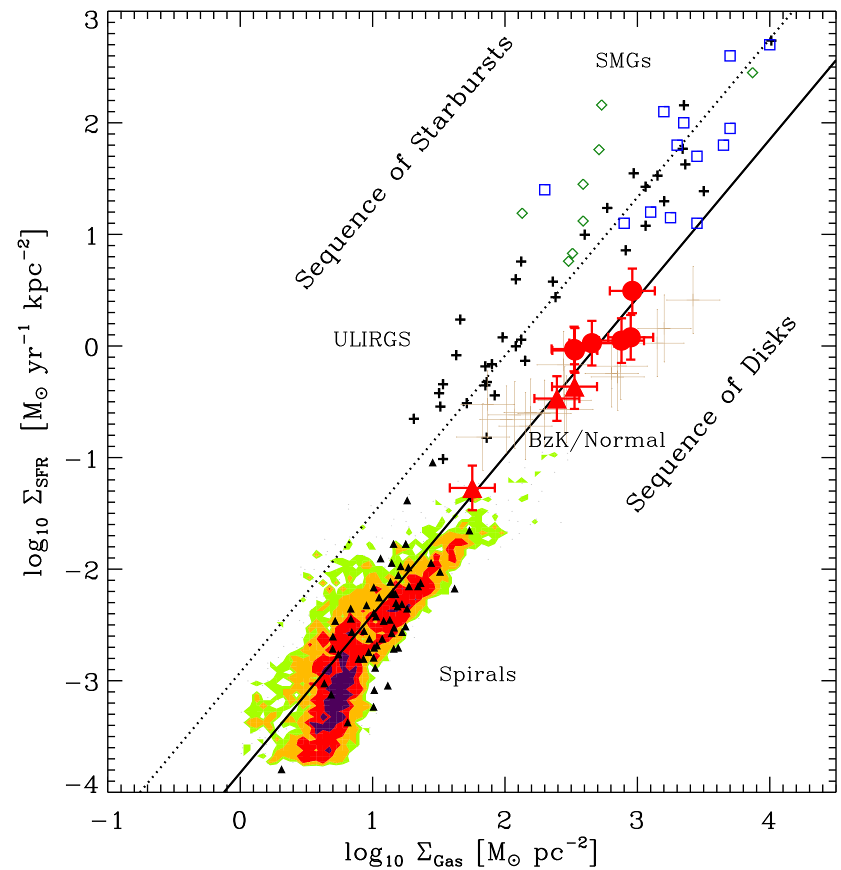
Old subgrid recipe for star formation



Schmidt law for star formation:

$$\dot{\rho}_* = \epsilon_* \frac{\rho_g}{t_{\rm ff}} \text{ for } \rho > \rho_*$$

Krumholz & Tan (2007)



Parameters are calibrated on the Kennicutt (1998) relation

$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{\rm M_\odot pc^{-2}} \right)^{1.4}$$

Daddi et al. (2010)

New subgrid recipe for star formation

1. Identify star forming cells
- self-shielding (Schaye 2004)
- cooling versus heating
- density thresholds for multi-phase ISM (Springel & Hernquist 2005)

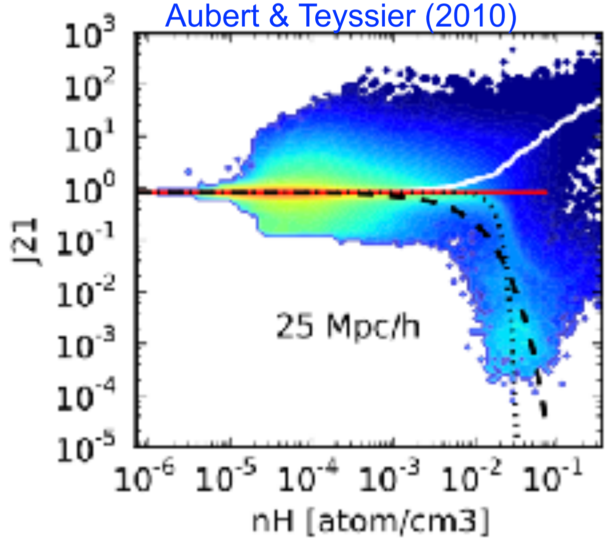
2. Compute star formation efficiency
- constant efficiency
- variable efficiency as a function of subgrid parameters

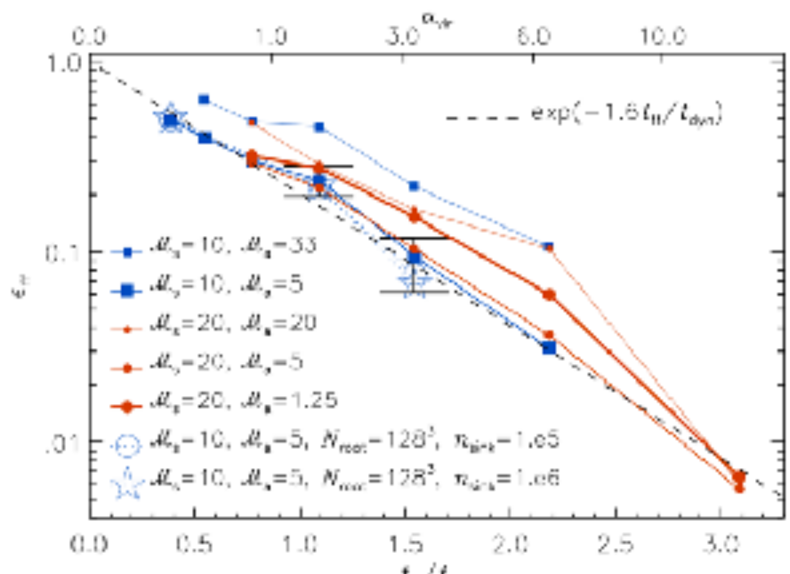
$$\dot{\rho}_* = \epsilon_{\rm ff} \frac{\rho_{\rm gas}}{t_{\rm ff}}$$

3. Spawn N star particles of fixed mass from a Poisson random process

Federrath & Klessen (2012), Hopkins et al. (2013), Schmid (2014), Perret et al. (2015), Trebitsch et al. (2017)

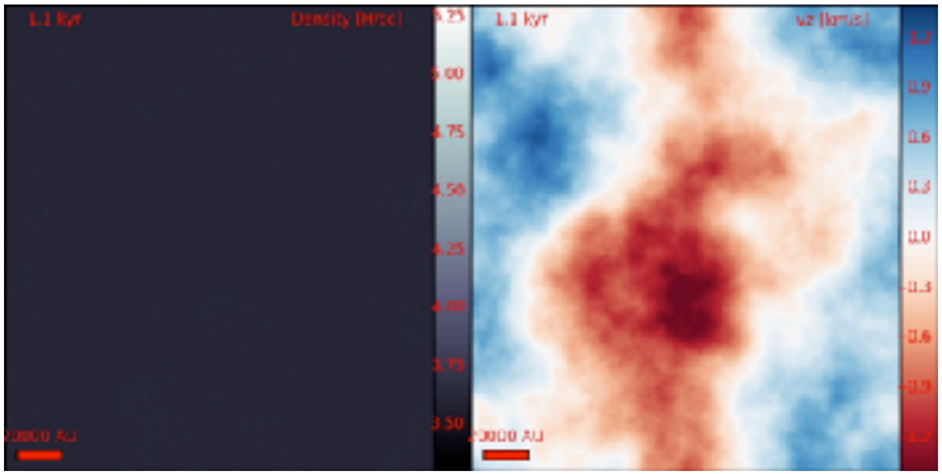
Aubert & Teyssier (2010)



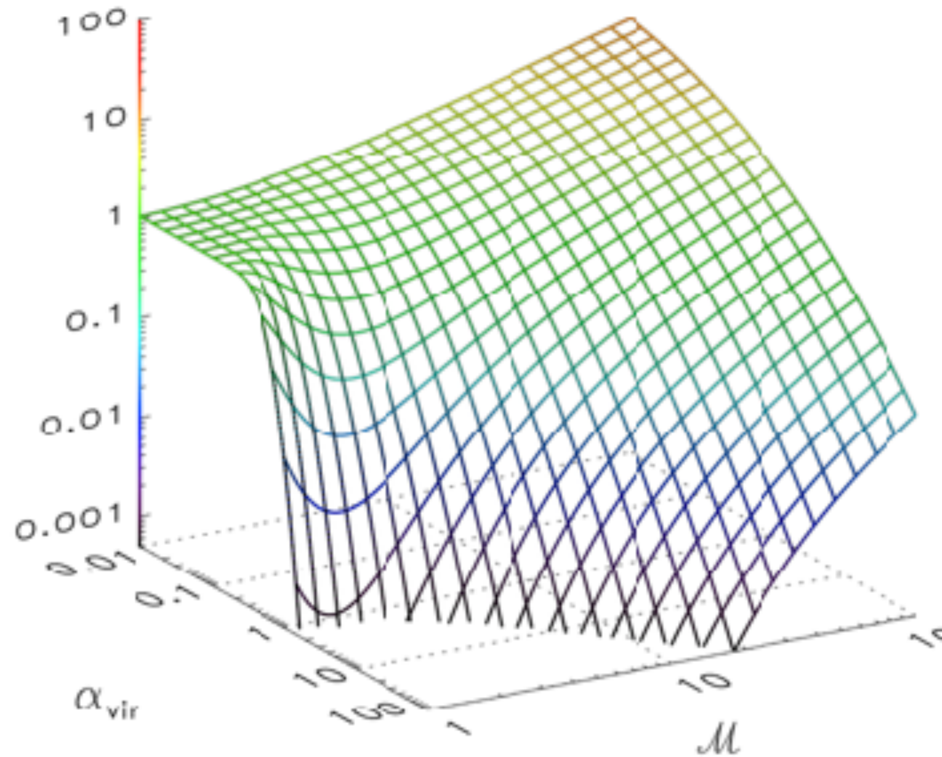


Padoan, Haugbolle & Nordlund (2012)

New subgrid recipe for star formation



simulations from Tine Colman (UZH)



Federrath & Klessen (2012)

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{\left(s+\frac{1}{2}\sigma_s^2\right)^2}{2\sigma_s^2}\right)$$

$$\sigma_s^2 = \ln\left(1+b^2\mathcal{M}^2\right) \qquad \mathcal{M} = \frac{\sigma_t}{c_s}$$

$$\epsilon_{ff} = \exp\left(3/8\sigma_s^2\right)\left(1+\mathrm{erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right)$$

Different models for the critical density:
Krumholtz & McKee (2005)
Padoan & Nordlund (2011)
Hennebelle & Chabrier (2011)

$$\rho_{\rm crit} \propto \alpha_{\rm vir}\mathcal{M}^2 \qquad \alpha_{\rm vir} \simeq \frac{\sigma_t^2}{G\rho_0\ell^2}$$

Sub-Grid Scale (SGS) turbulence model

Turbulence subgrid model (Boussinesq approximation or eddy viscosity):

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u} + P\mathbb{I} + P_{\mathrm{T}}\mathbb{I}) = \rho \mathbf{g} + \nabla \cdot \mathbb{R}_{\mathrm{T}} \qquad K_{\mathrm{T}} = \frac{1}{2}\rho\sigma_{\mathrm{T}}^2$$

$$\frac{\partial K_{\mathrm{T}}}{\partial t} + \nabla \cdot (K_{\mathrm{T}}\mathbf{u}) = -P_{\mathrm{T}}\nabla \cdot \mathbf{u} + \mathbb{R}_{\mathrm{T}} : \nabla \mathbf{u} + \nabla \cdot \mathbf{Q}_{\mathrm{T}} - \frac{K_{\mathrm{T}}}{t_{\mathrm{diss}}} + \left(\dot{K}_{\mathrm{T}}\right)_{\mathrm{SN}}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{u}) = -P\nabla \cdot \mathbf{u} + \frac{K_{\mathrm{T}}}{t_{\mathrm{diss}}} + (\dot{e})_{\mathrm{SN}}$$

$$\mathbb{R}_{\mathrm{T}} = \rho\nu_{\mathrm{T}}\left(\nabla \mathbf{u} + \nabla \mathbf{u}^{\mathbf{T}} - \frac{2}{3}(\nabla \cdot \mathbf{u})\mathbb{I}\right) \qquad t_{\mathrm{diss}} = \frac{\ell}{\sigma_{\mathrm{T}}} \qquad \nu_{\mathrm{T}} = \ell\sigma_{\mathrm{T}}$$

$$\mathbf{Q}_{\mathrm{T}} = \rho\nu_{\mathrm{T}}\nabla\left(\frac{K_{\mathrm{T}}}{\rho}\right)$$

Star formation subgrid model:

$$\alpha_{\mathrm{vir}} = \frac{2K_{\mathrm{T}}}{V} = \frac{\sigma_{\mathrm{T}}^2}{G\rho\ell^2} \qquad \mathcal{M}_{\mathrm{T}} = \frac{\sigma_{\mathrm{T}}}{c_s} \qquad \epsilon_*\left(\alpha_{\mathrm{vir}}, \mathcal{M}_{\mathrm{T}}\right) \qquad \dot{\rho}_* = \epsilon_* \frac{\rho}{t_{ff}}$$

New feedback recipe for supernovae

Inspired from many on-going projects (Hopkins *et al.*, Kimm *et al.*, Agertz *et al.*, Schaye *et al.*, Springel *et al.*, Walch *et al.*, Hennebelle *et al.*, and more)

Minimum galaxy formation physics
– Momentum feedback for unresolved cooling radius (Martizzi *et al.* 2015)
– Thermal feedback with walkaway/runaway stars
– Individual supernovae (roughly 100-1000 explosions per stellar particle)
– Strömgren sphere heating at 20'000 K.

Implementing momentum feedback in RAMSES
– Use a non-thermal pressure variable to inject the momentum
– Modify the Riemann solver (similar to Agertz *et al.* 2013)
– Stochastic model for individual supernovae.

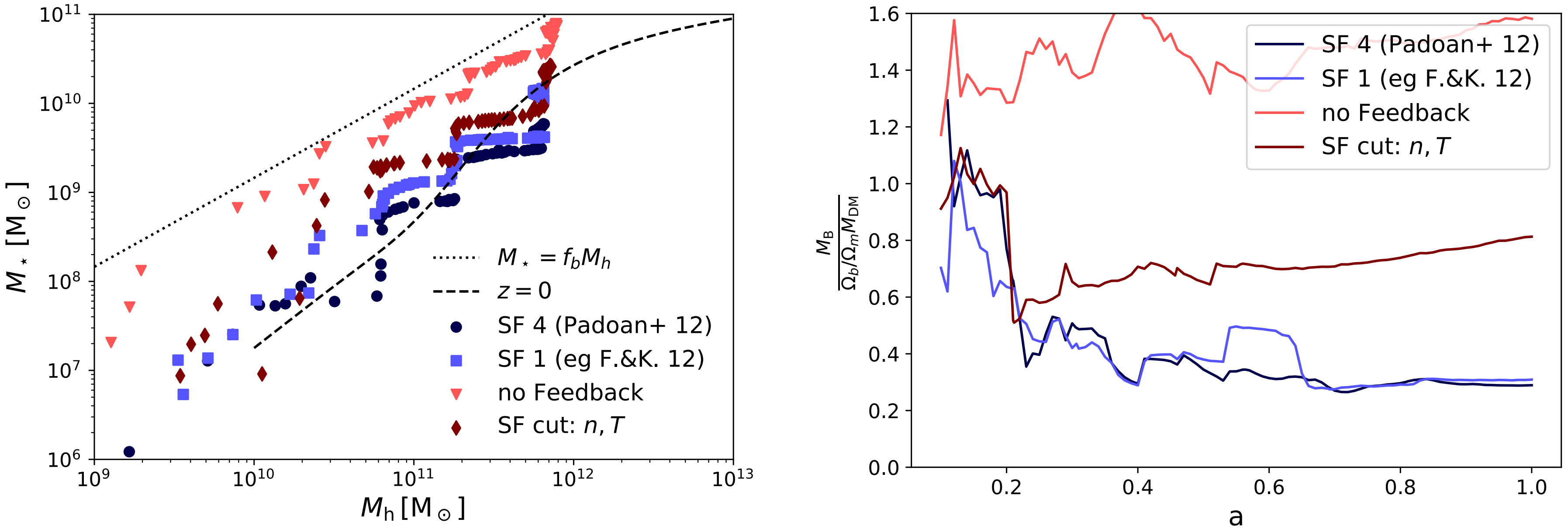
Problems with momentum feedback:
– very small small time steps (down to 500 years !)
– overestimate the momentum injection ?
– grid effects

Galaxy formation: the movie

No feedback but new SF model

Feedback but old SF model

Abundance matching test

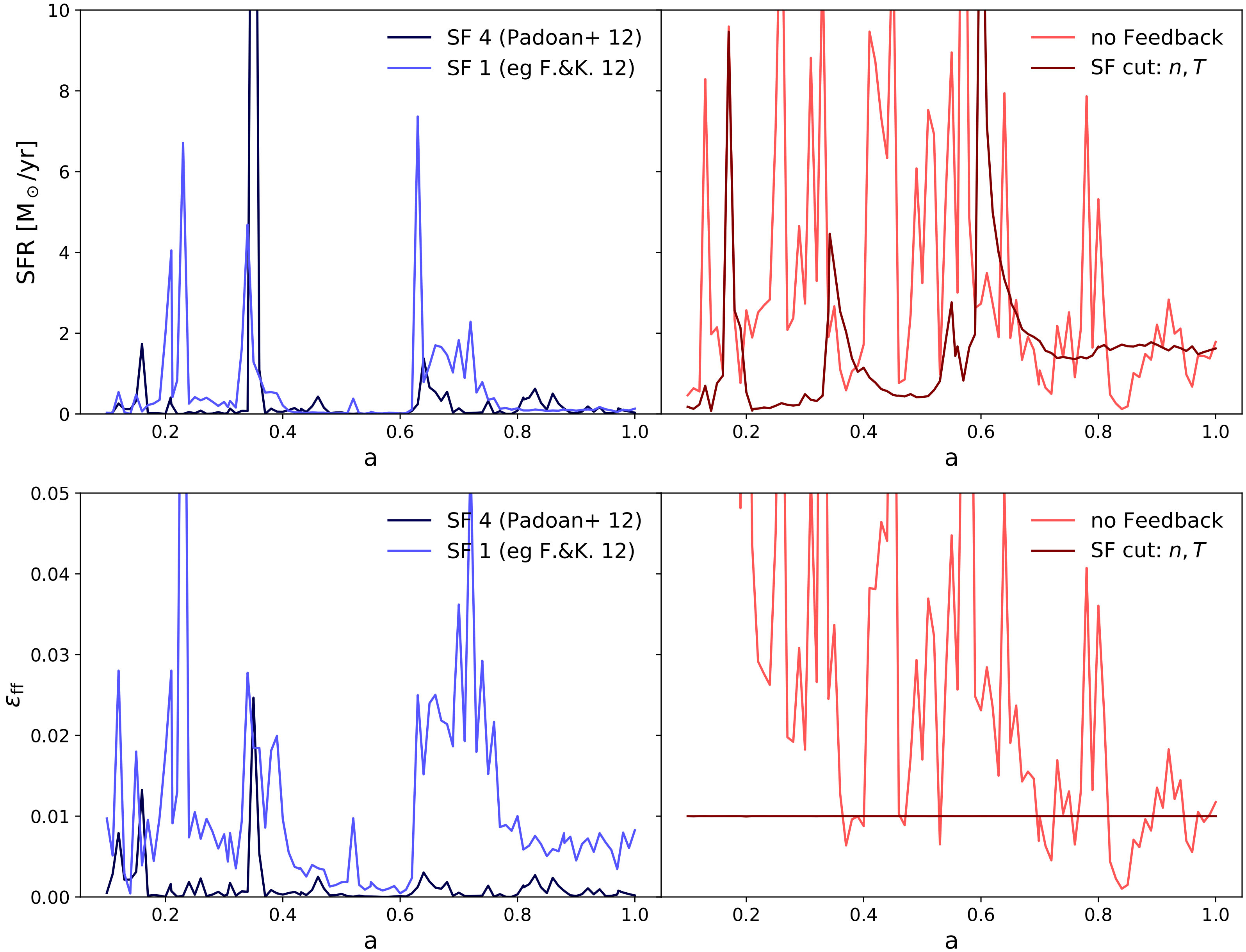


Strong stellar feedback removes baryons from the halo at high redshifts.

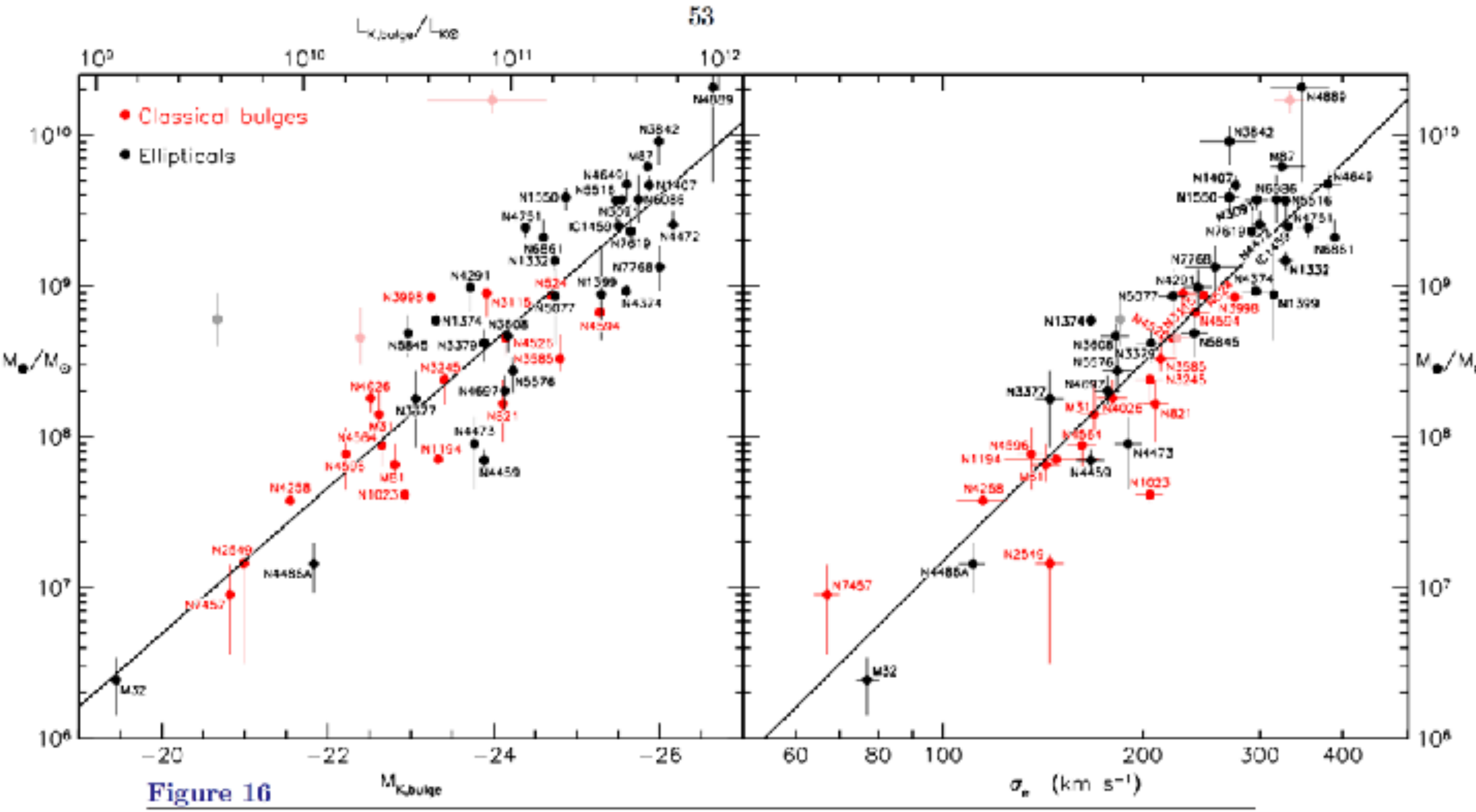
The adopted star formation model has an impact on the strength of stellar feedback.

In between merger events, lack of gas and low SFE quenches the galaxies.

Star formation is quenched after merger events



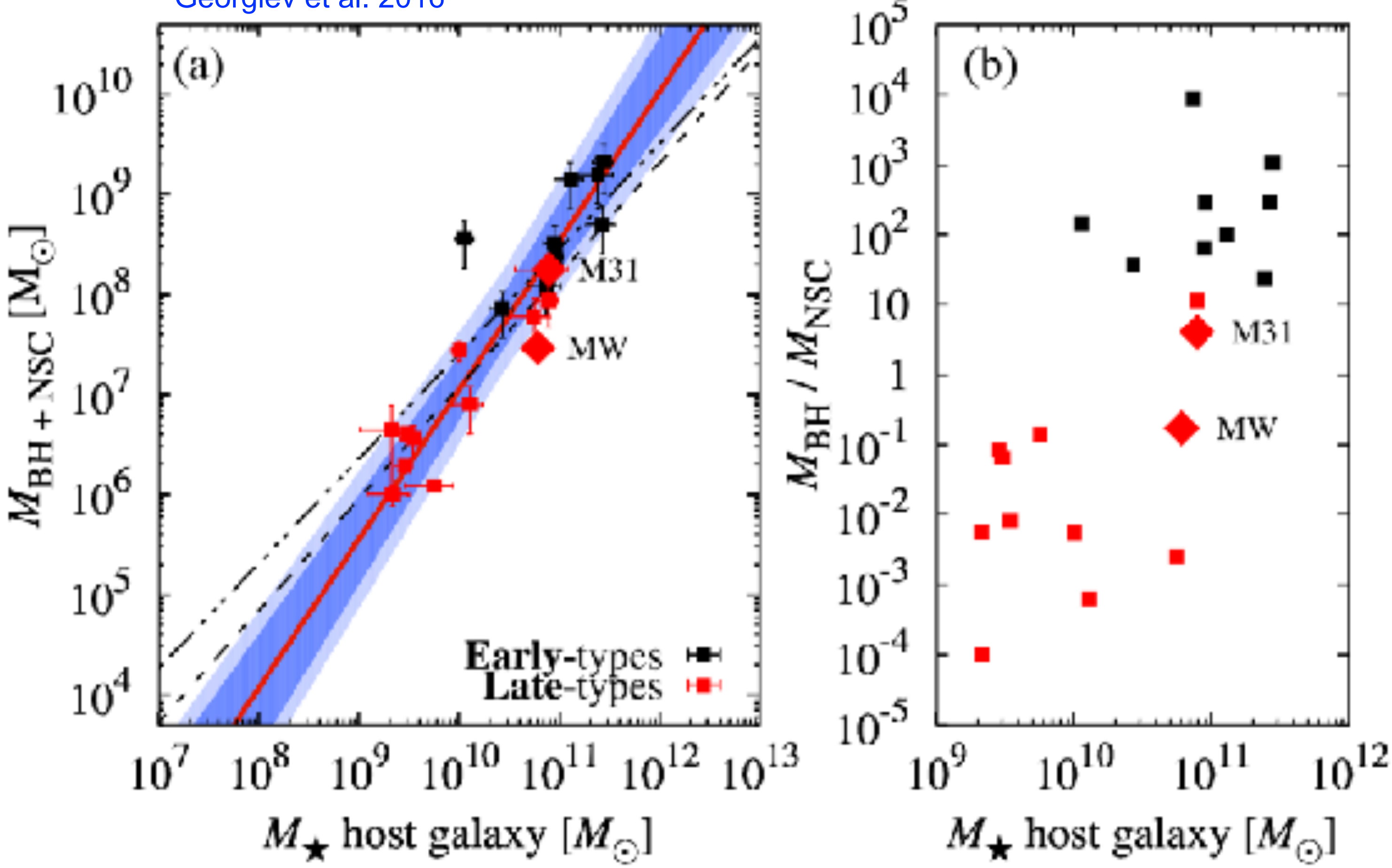
What do we know about supermassive black holes ?



Kormendy and Ho 2013

SMBH and NSC coevolution ?

Georgiev et al. 2016



NSC offers SMBH a protective habitat

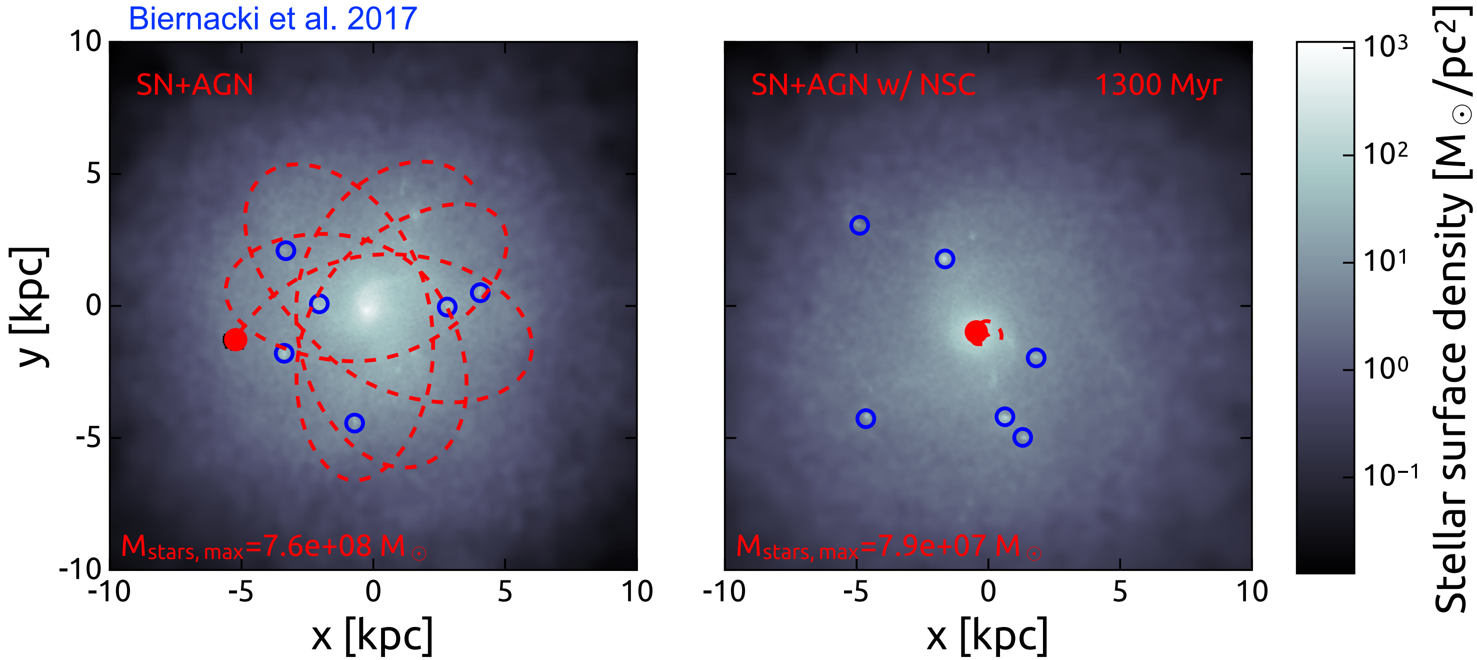
Dynamical friction will bring the SMBH towards the centre in time scale

$$t_{\rm drag} = \frac{1.65}{\ln \Lambda} \frac{R_{\rm orb}^2 \sigma}{G M_{\rm BH}} \simeq 2.7 \ {\rm Gyr} \frac{10^8 M_\odot}{M_{\rm BH}}$$

Massive clumps and star clusters will perturb the orbit of the SMBH.

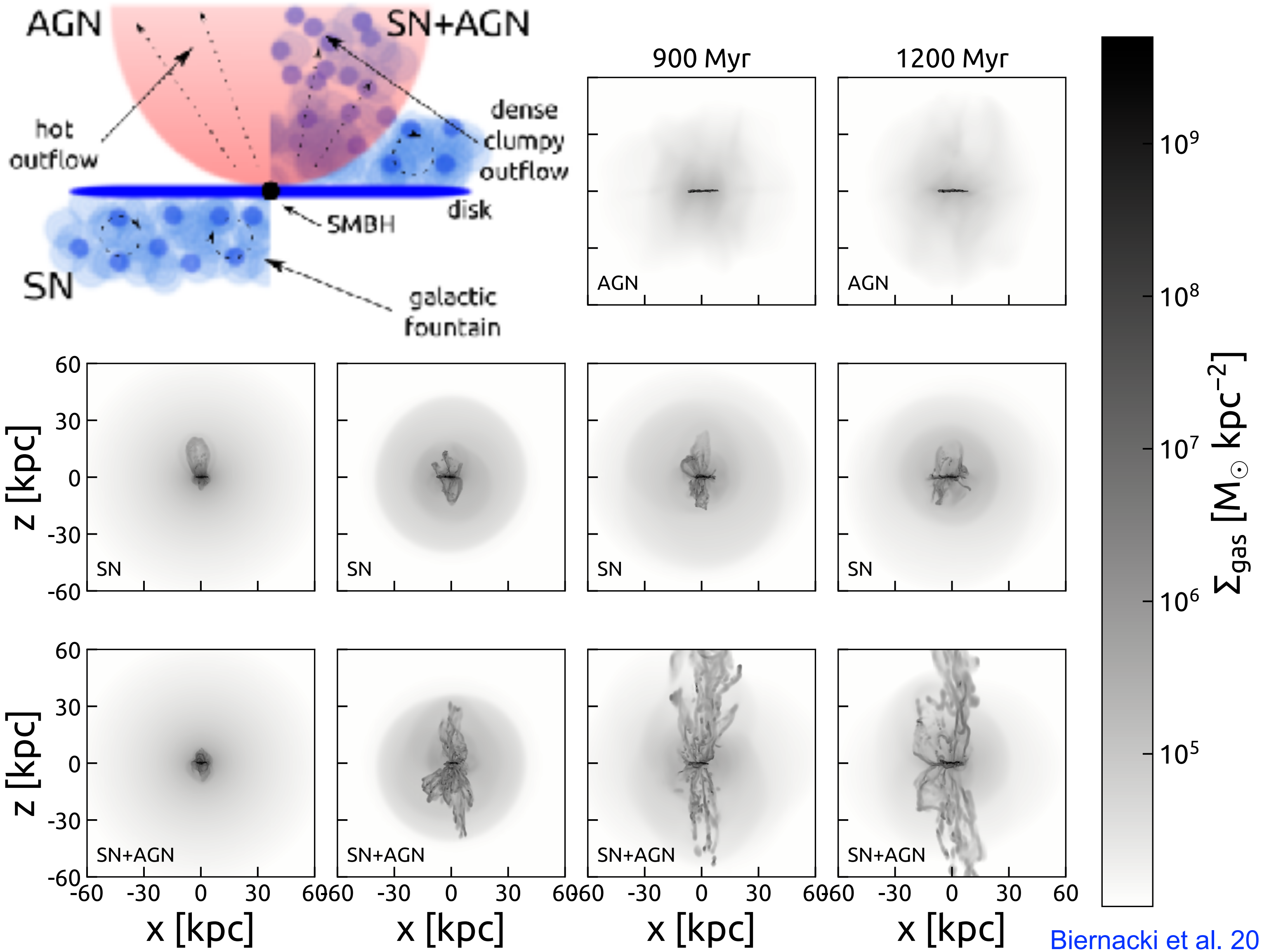
$$M_{\rm T} = \Sigma_{\rm gas} \pi \left(\frac{\lambda_{\rm T}}{2} \right)^2 \simeq 3 \times 10^8 M_\odot$$

Biernacki et al. 2017



high-z clumpy galaxy

Combined effect of AGN and stellar feedback



Biernacki et al. 2018

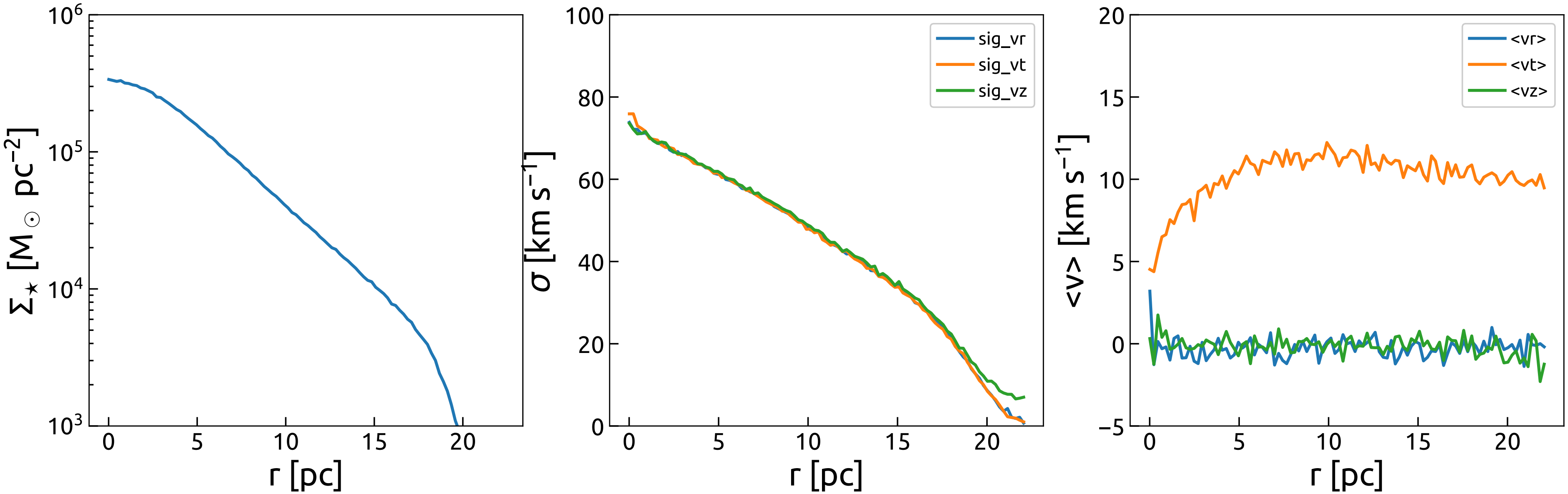
Feeding a SMBH with its host NSC

Numerical experiments: isolated nuclear star cluster (Plummer's sphere)

$$M_* = 5 \times 10^7 M_\odot \qquad r_{1/2} = 8 \text{ pc} \qquad M_{\rm BH} = 10^6 M_\odot$$

$$\frac{V}{\sigma} = \frac{1}{6} \qquad \dot{M}_{\rm wind} \simeq 6 \times 10^{-9} M_\odot/yr/M_\odot \qquad \dot{M}_{Edd} \simeq 0.02 M_\odot/yr$$

Thermal feedback based on local Bondi accretion rate $\Delta x \simeq 0.02$ pc
Gas injected by stellar wind from each individual star particle $N_* = 10^6$



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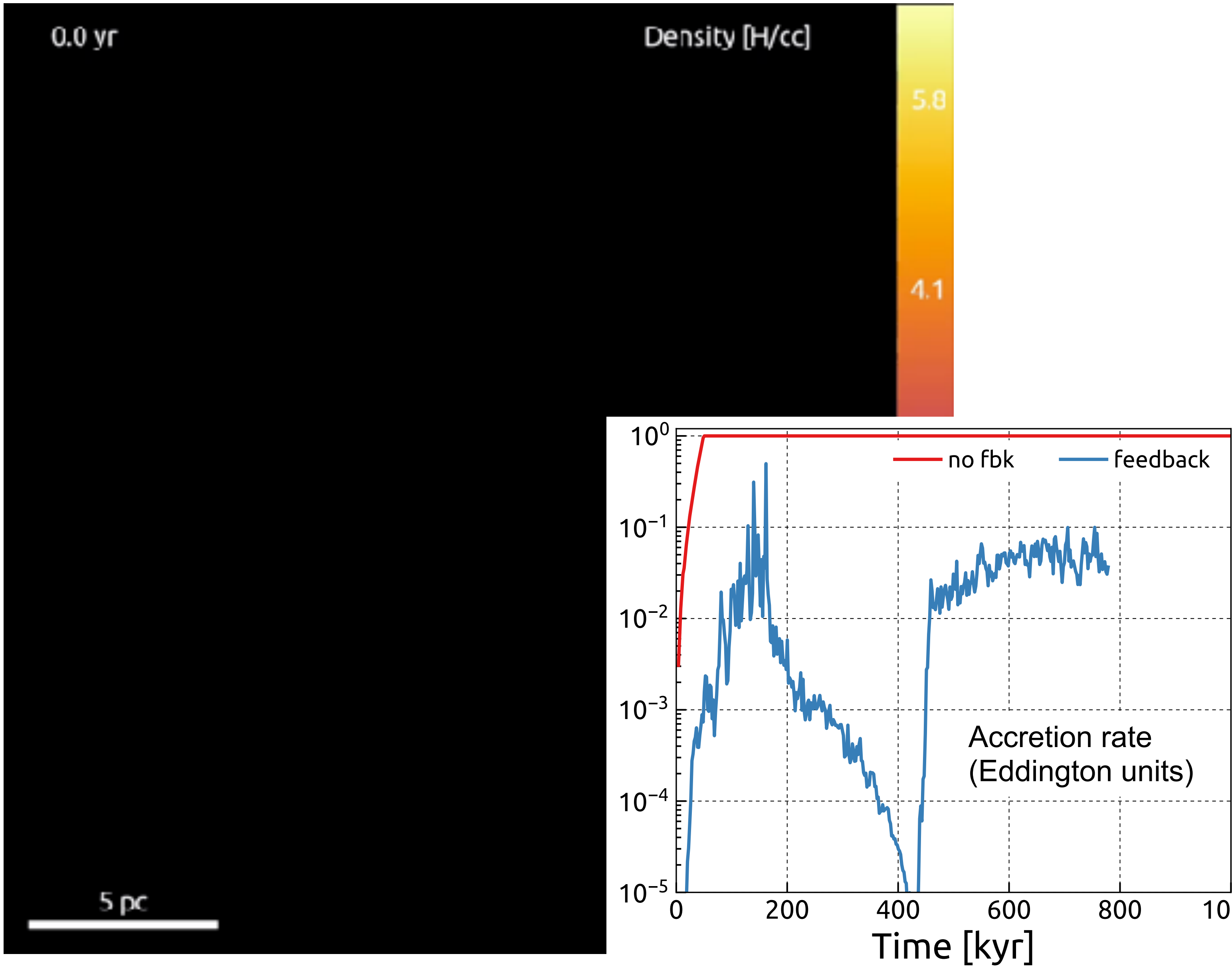
Feeding a SMBH with its host NSC



Conclusions

1. Star formation simulations within turbulent molecular clouds can provide detailed predictions on the star formation efficiency, stellar mass functions and star cluster properties: key output massive stars statistics, binarity and walkaways/runaways statistics

2. Galaxy formation models provide initial conditions for star formation models. New star formation subgrid recipe include more and more information from star formation models. Key resolved object in current and future galaxy formation simulations: star clusters

3. Supermassive black holes formation models are still unclear. One scenario could be intermediate black holes formation through stellar collisions within dense nuclear star clusters. Advantages: formation site, protective habitat against external perturbations, stellar winds as a reservoir of gas for sustained accretion and activity

Focus point in the theory of star and galaxy formation: star clusters !

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