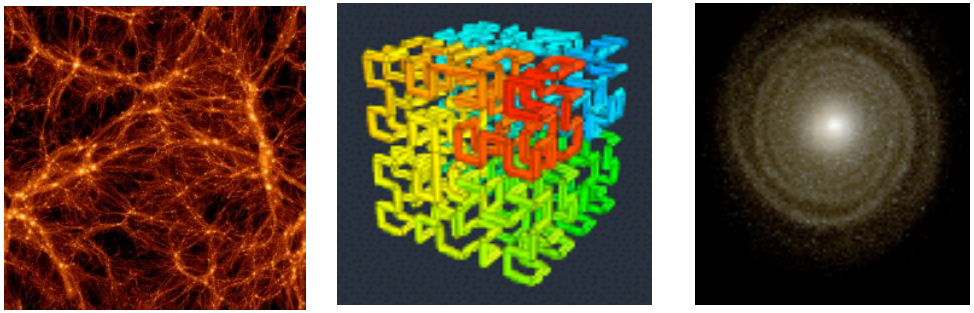
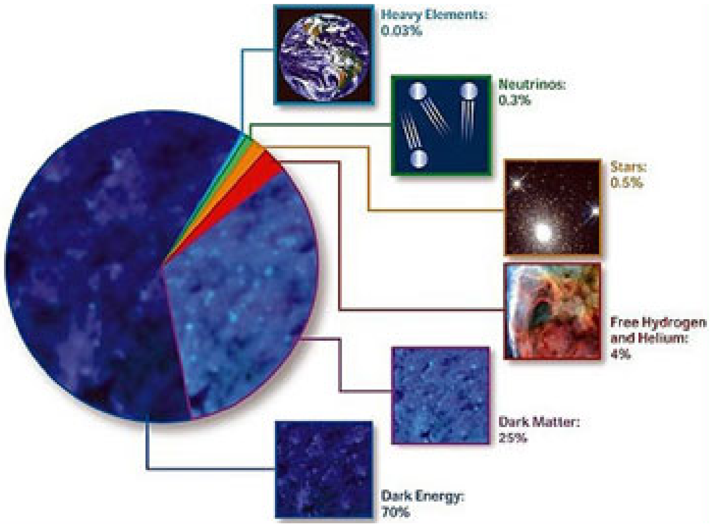
Galaxy formation

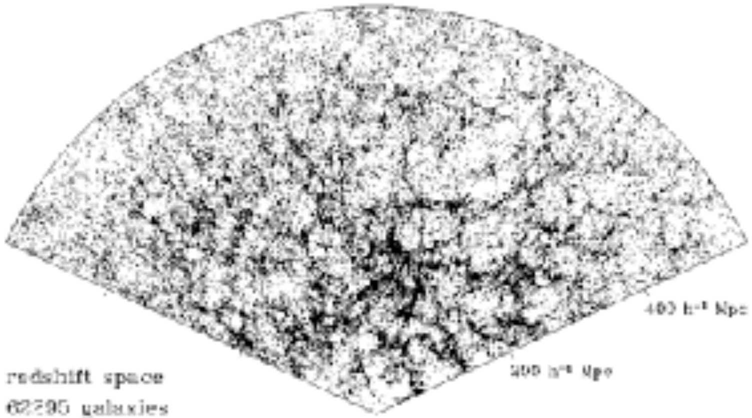
Romain Teyssier

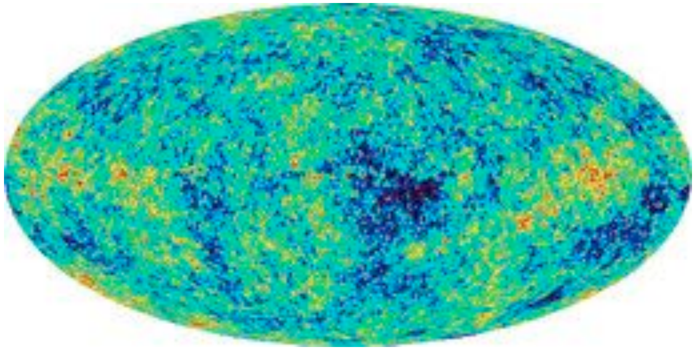
University of Zurich

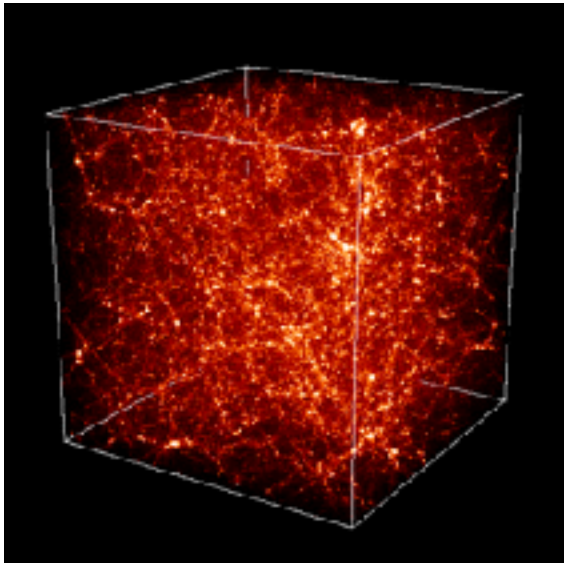


Cosmological simulations



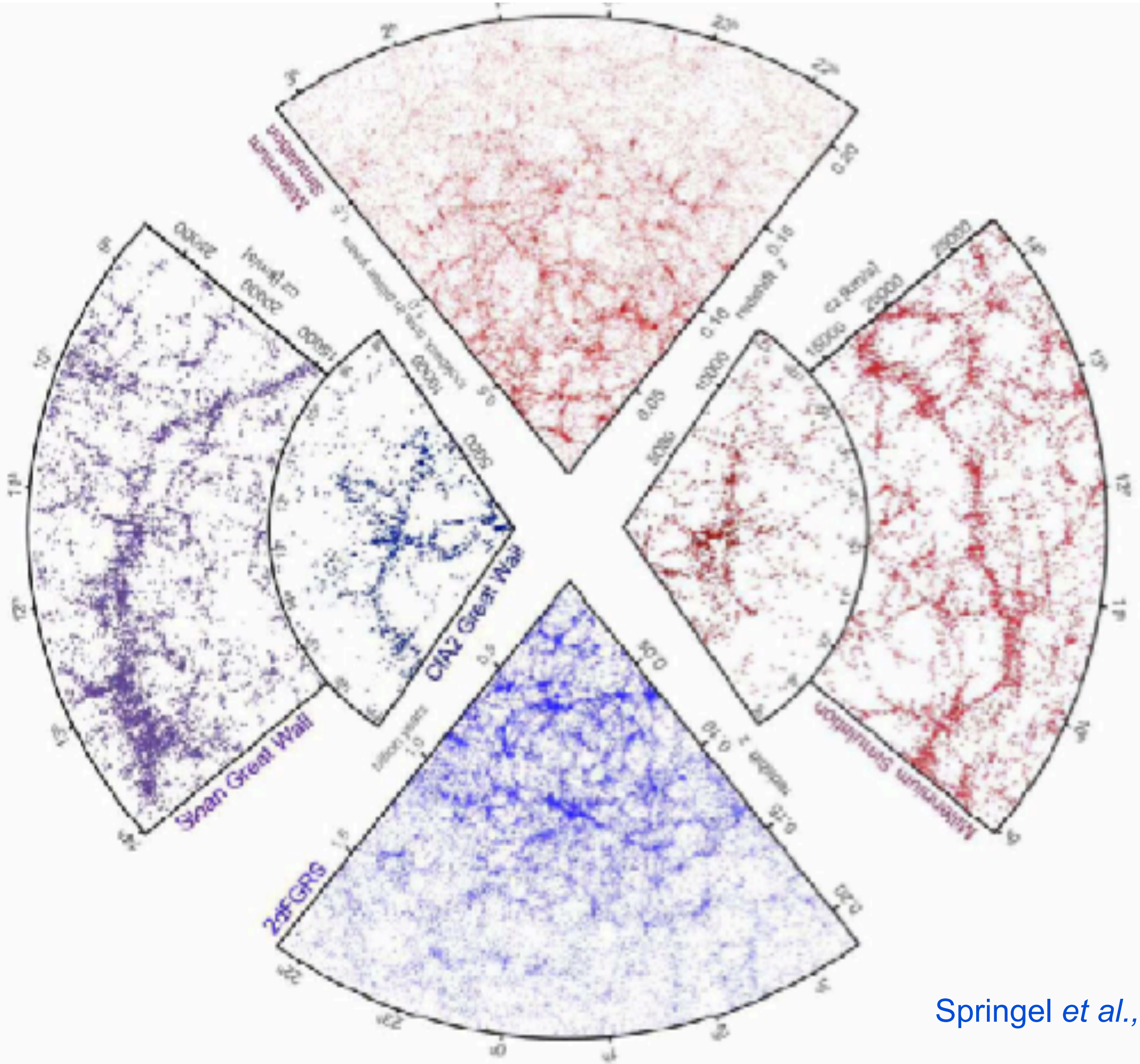






From Gaussian random fields to galaxies: non-linear dynamics of gravitational instability with N-body and hydrodynamics codes.

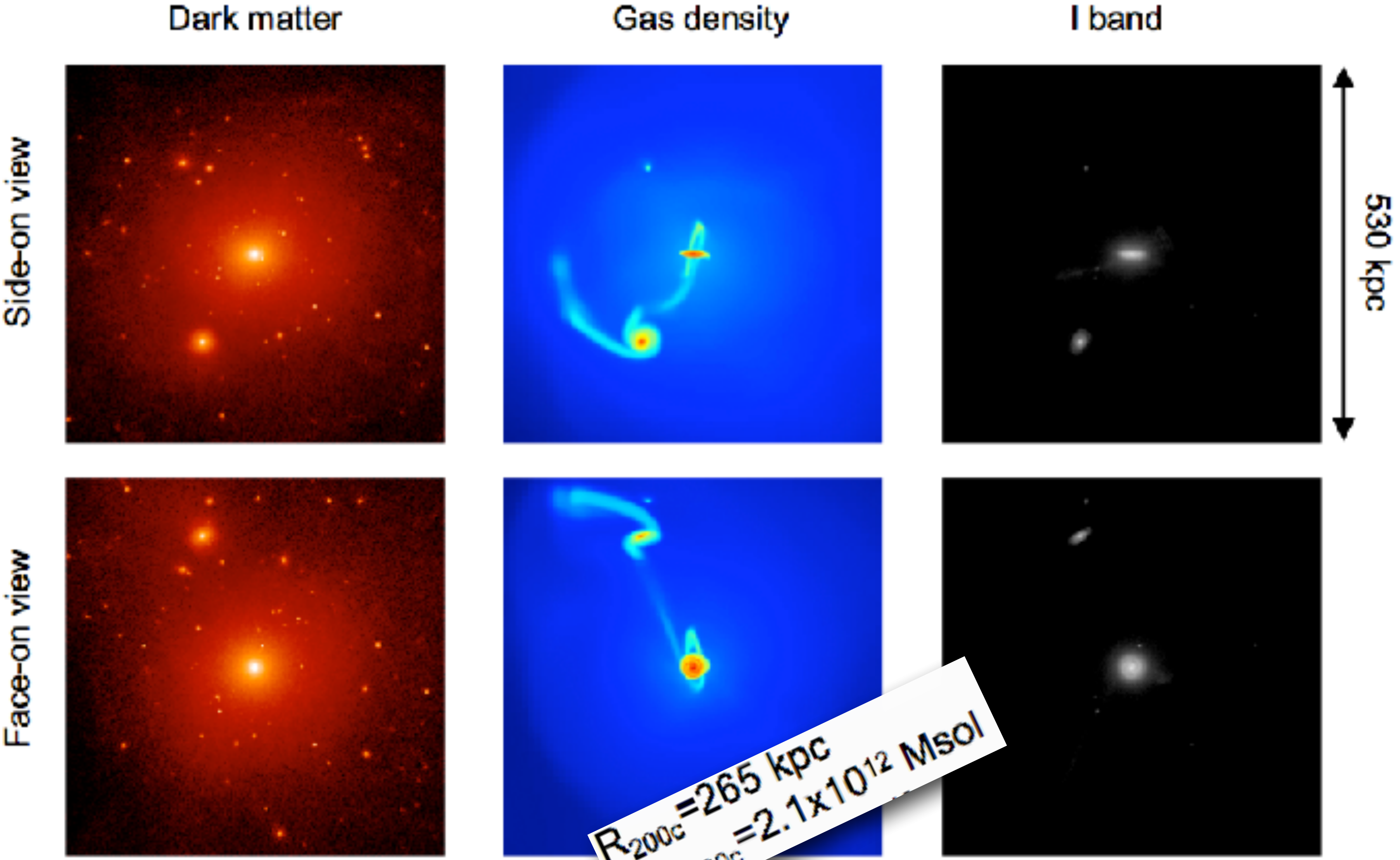
Cosmological simulations



Springel *et al.*, Nature, 2006

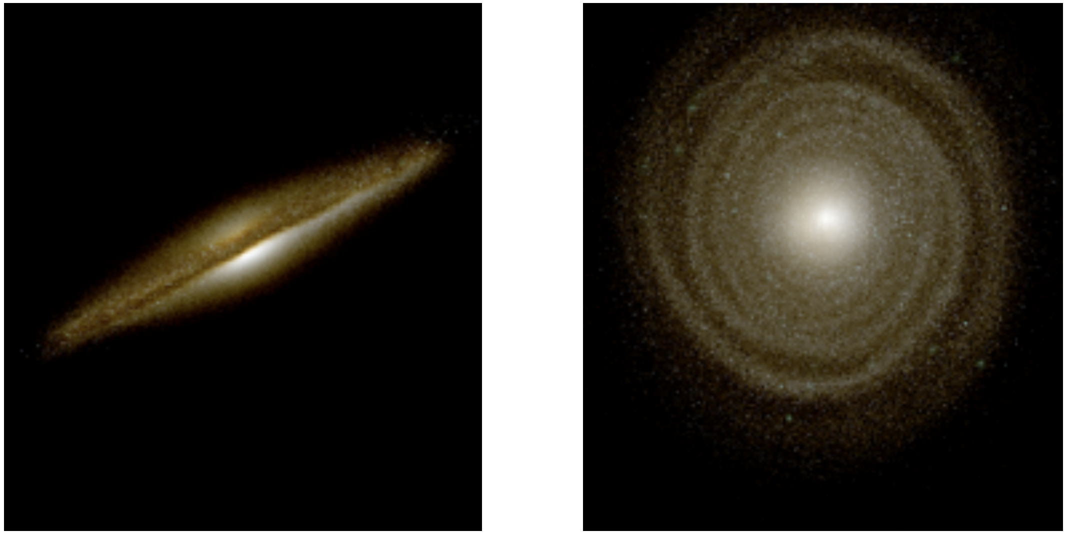
Galaxy formation simulations

The Aquila comparison project (Scannapieco *et al.* 2012)



R_{200c}=265 kpc
$M_{tot,200c}$=2.1x10^{12} Msol

Galaxy formation simulations

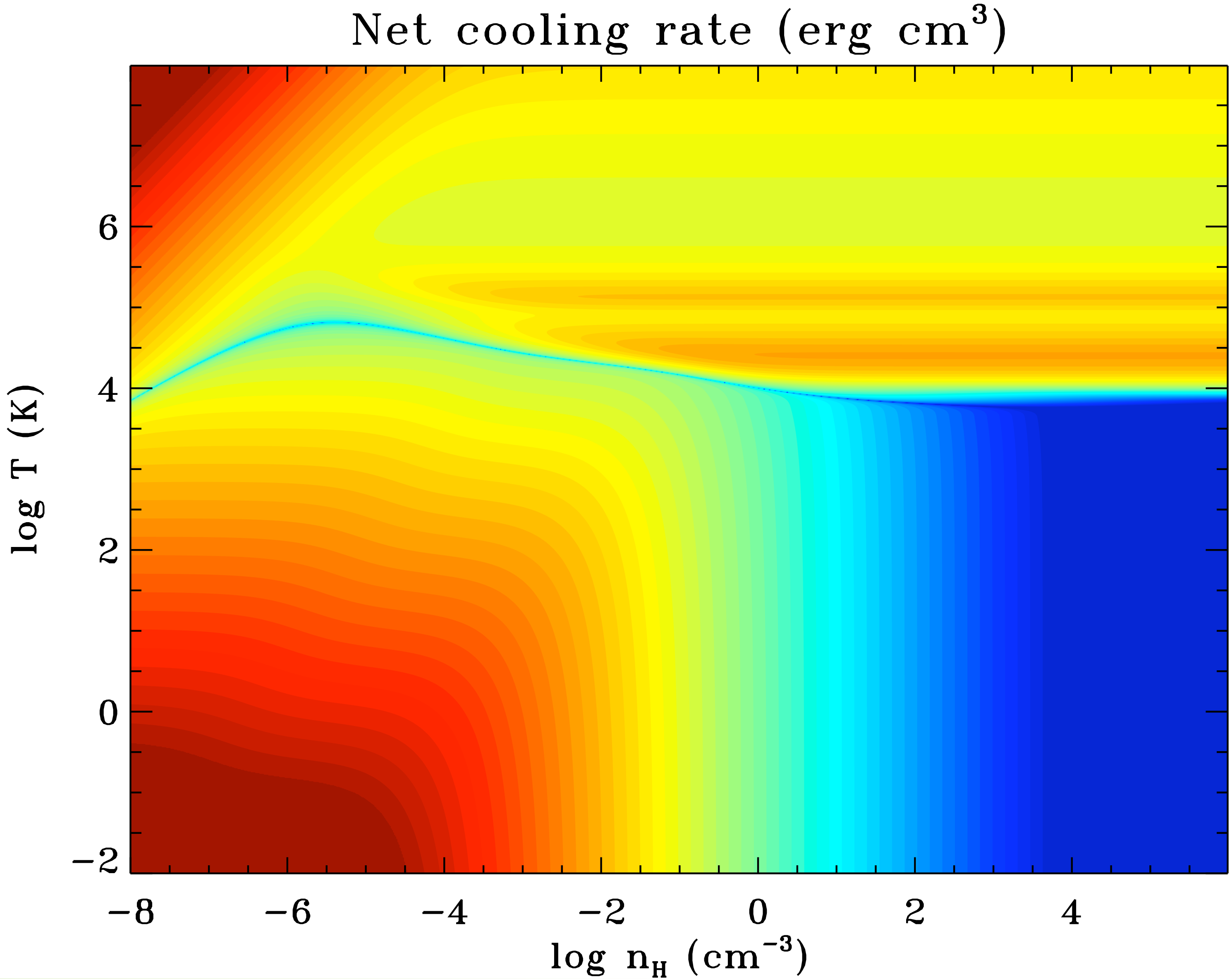


Mock gri SDSS composite image with dust absorption based on Draine opacity model.

NGC4622 as seen from HST

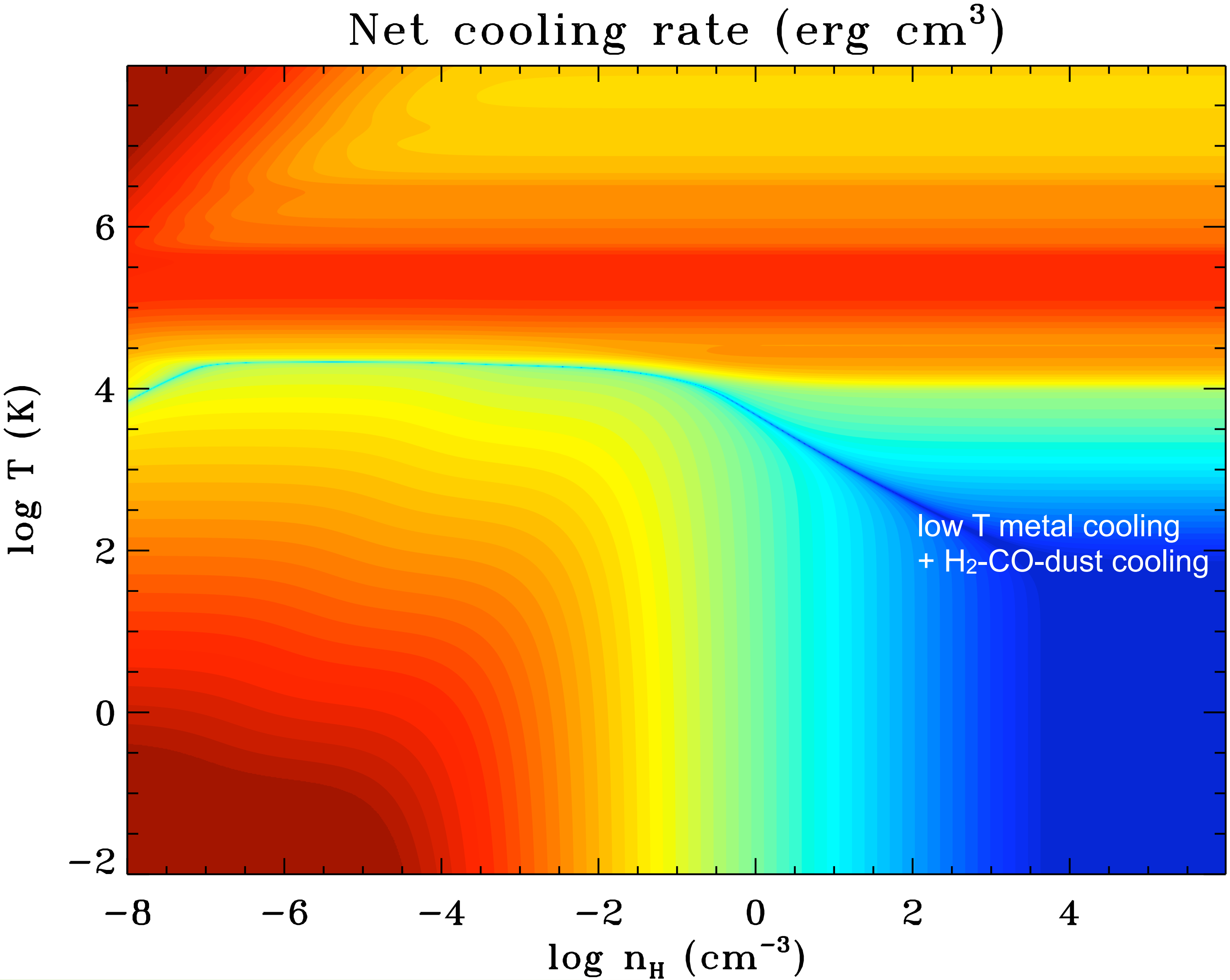
Cooling function for astrophysical plasmas

Photo-Ionization Equilibrium: depends on T and n



Cooling function for astrophysical plasmas

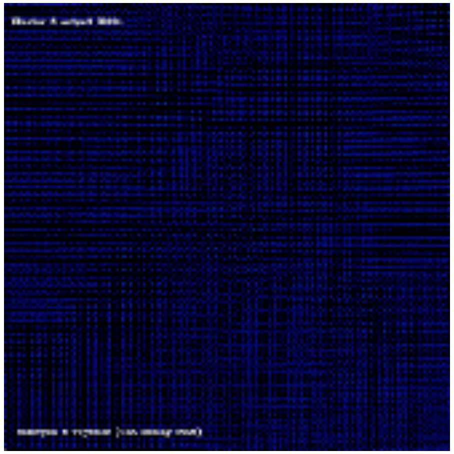
PIE including metals at solar level



Classical theory of galaxy formation

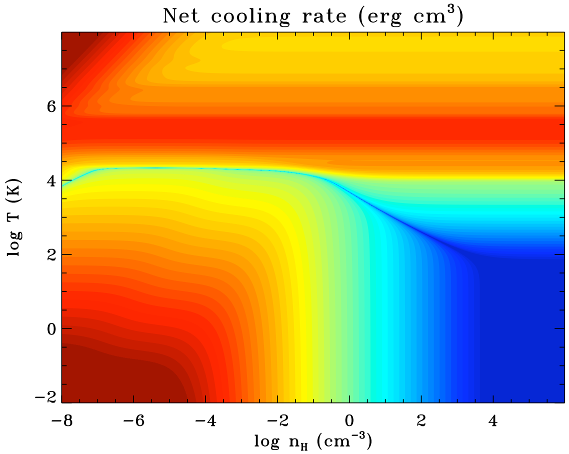
Formation of slowly rotating dark matter halos

- spin from tidal torques
- statistical Virial equilibrium



Hot gas settles in thermal equilibrium

$$\frac{3}{2}\frac{k_{\mathrm{B}}T_{gas}}{\mu m_{\mathrm{H}}} = \frac{1}{2}\frac{GM_{halo}}{R_{halo}}$$



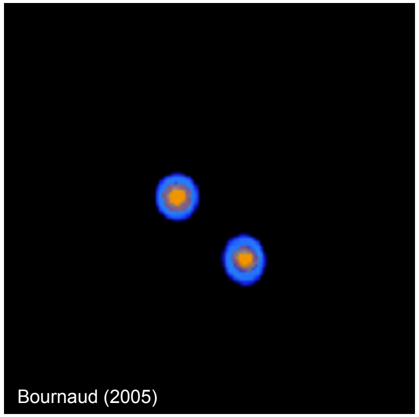
Radiative cooling dissipates pressure support

Dense gas disc settles into centrifugal equilibrium

Atomic physics sets typical galaxy masses

$$\mathcal{I}_0 = 13.6\ \mathrm{eV}$$

$$M_{\mathrm{galaxies}} \simeq 10^{11}\ M_{\odot}$$



Bournaud (2005)

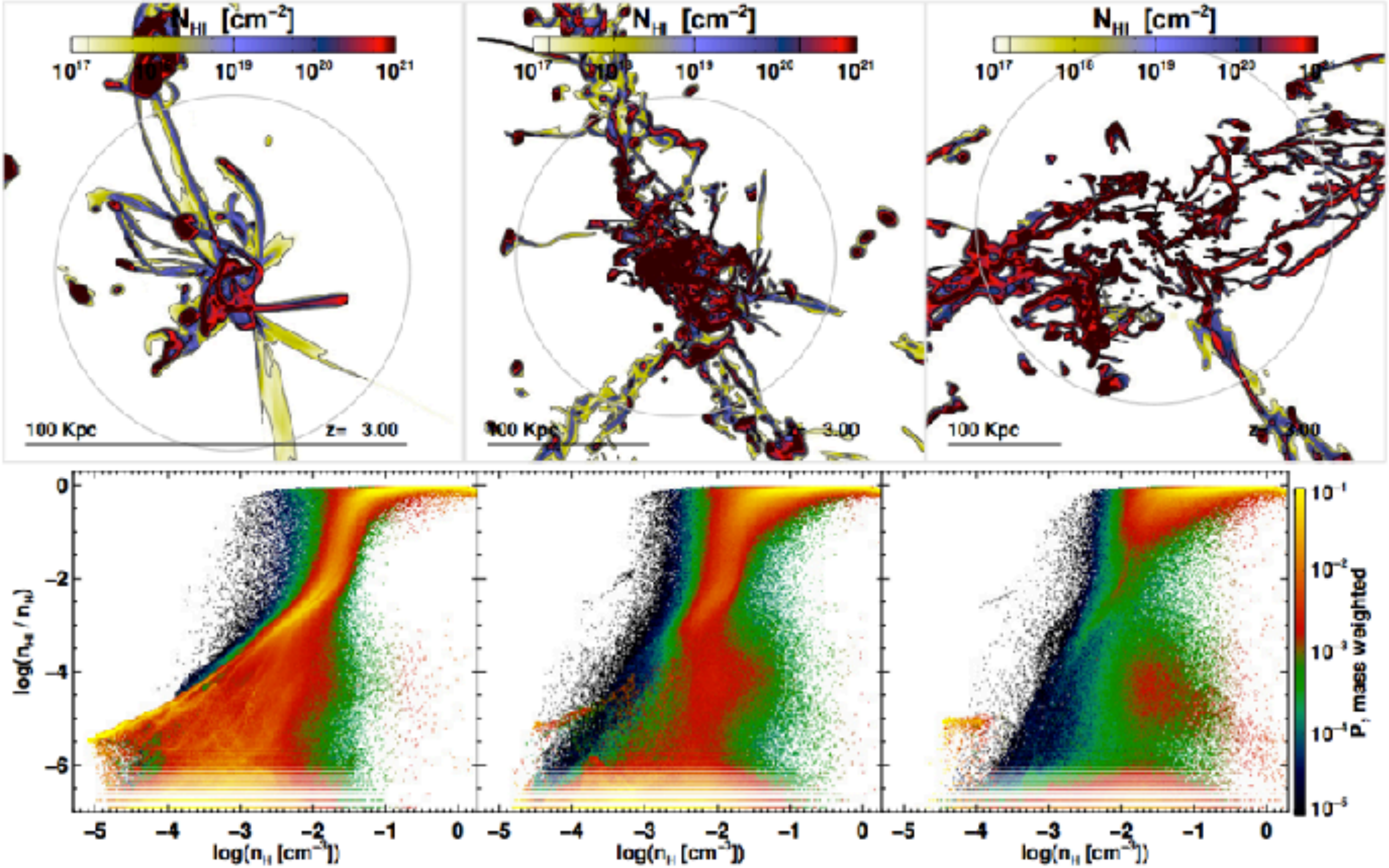
White and Rees (1978); Dekel and Silk (1986)

Discs form from quiescent gas accretion history

Ellipticals form out of violent mergers

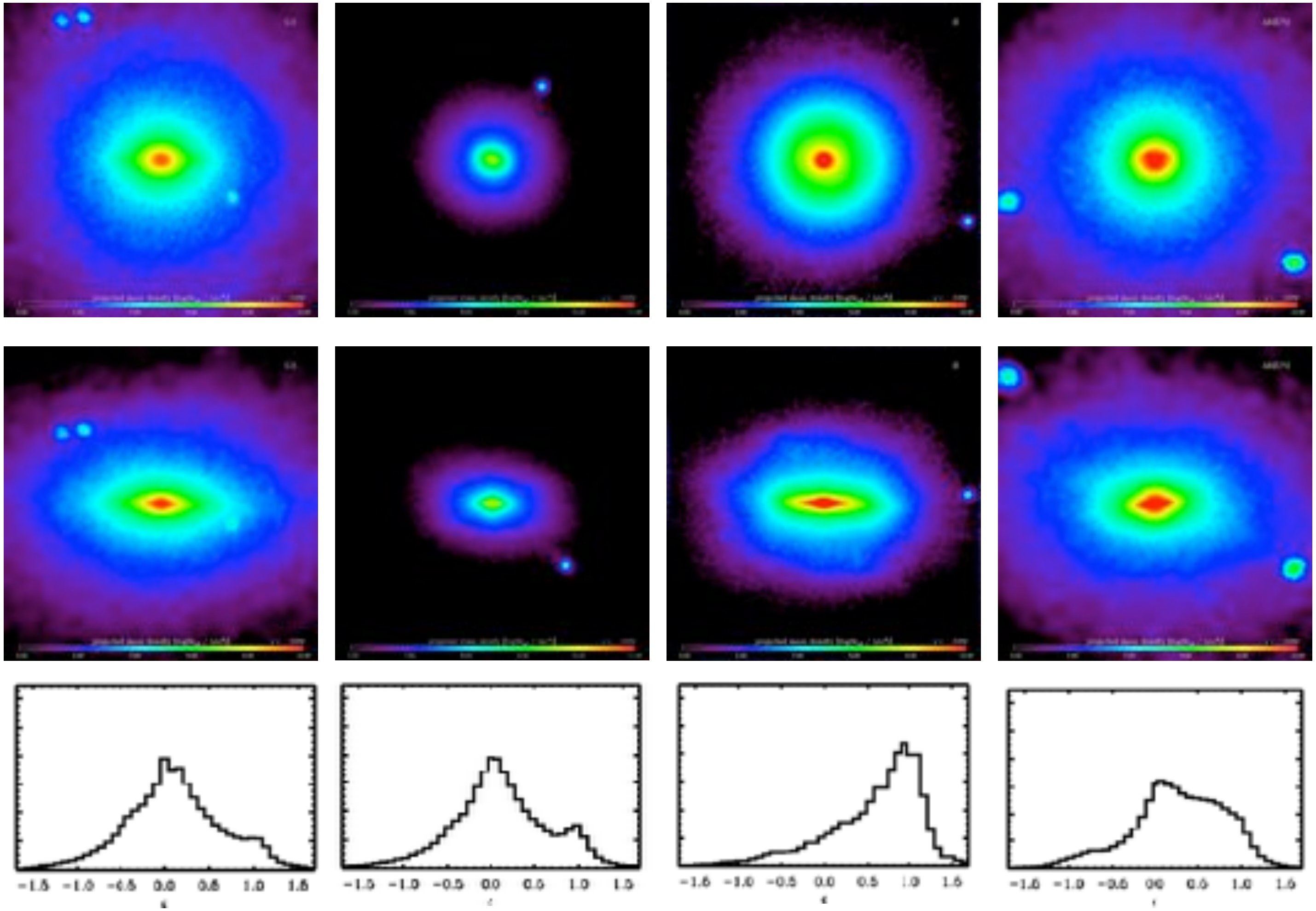
Modern theory of galaxy formation

Radiation hydrodynamics simulations from Rosdahl & Blaizot (2012)



Different codes, same physics, different morphologies...

GADGET GASOLINE RAMSES AREPO



face-on

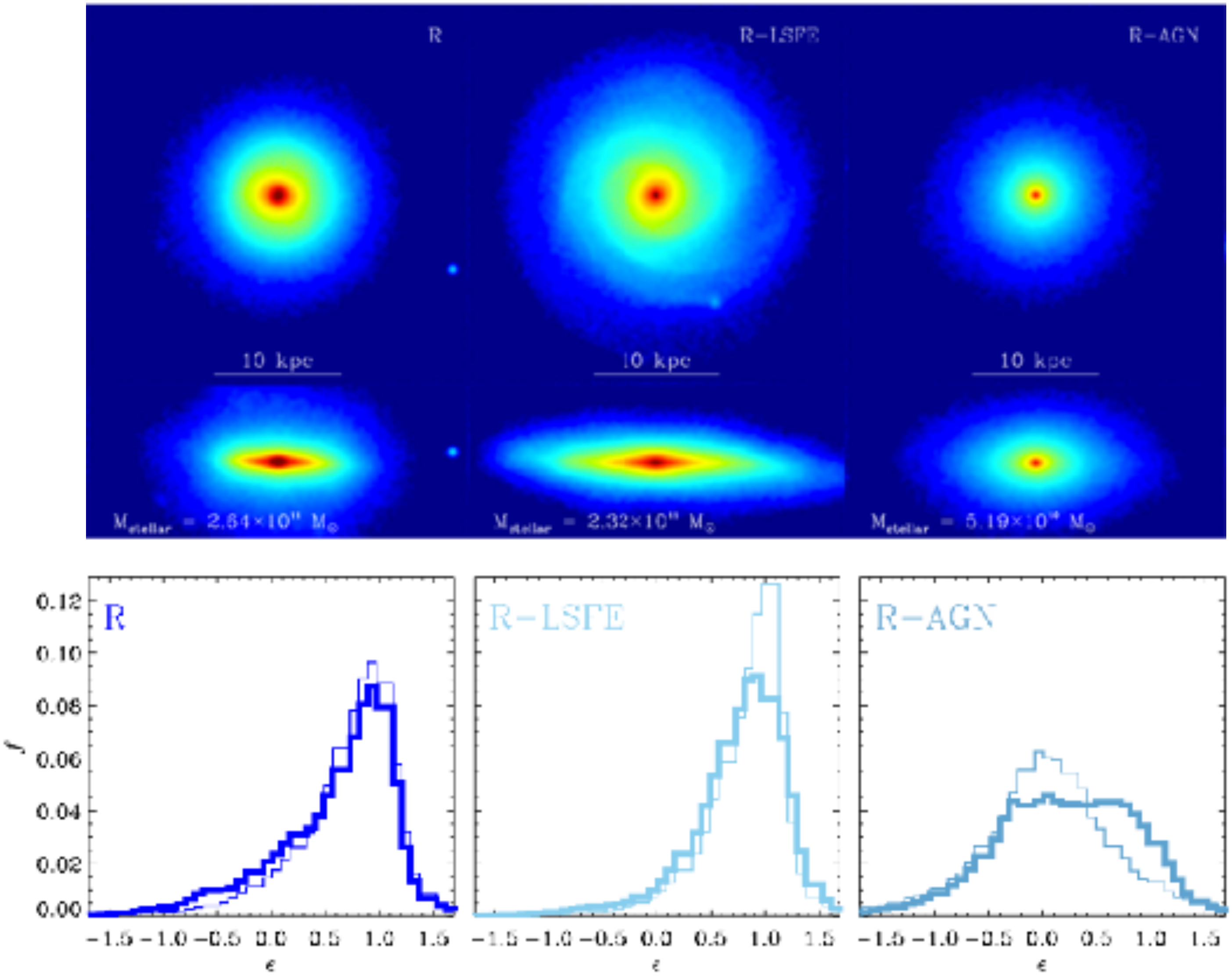
side-on

circularity

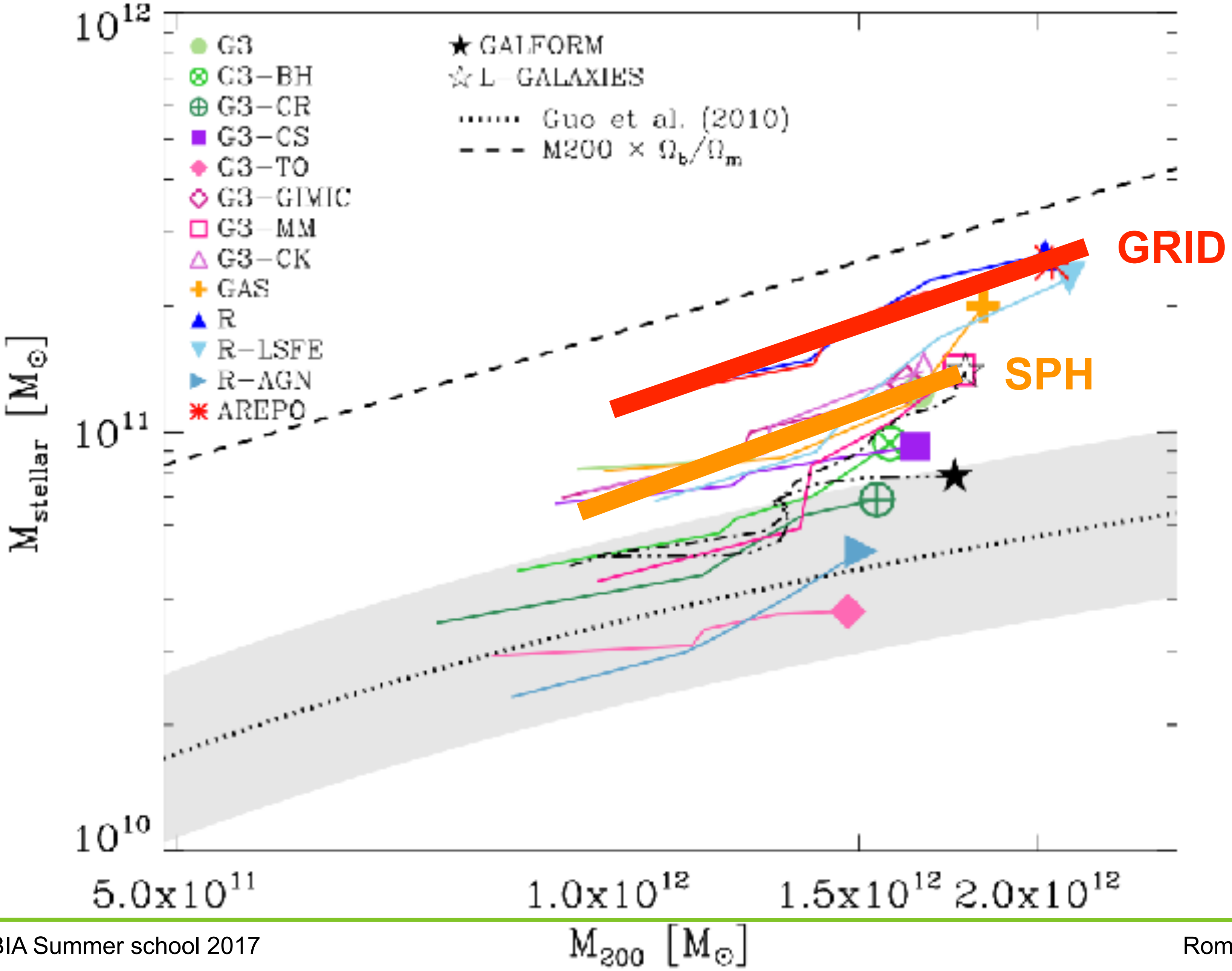
Low resolution runs

Same code, different subgrid models, different morphologies...

RAMSES



Feedback and SF matter more than code type.



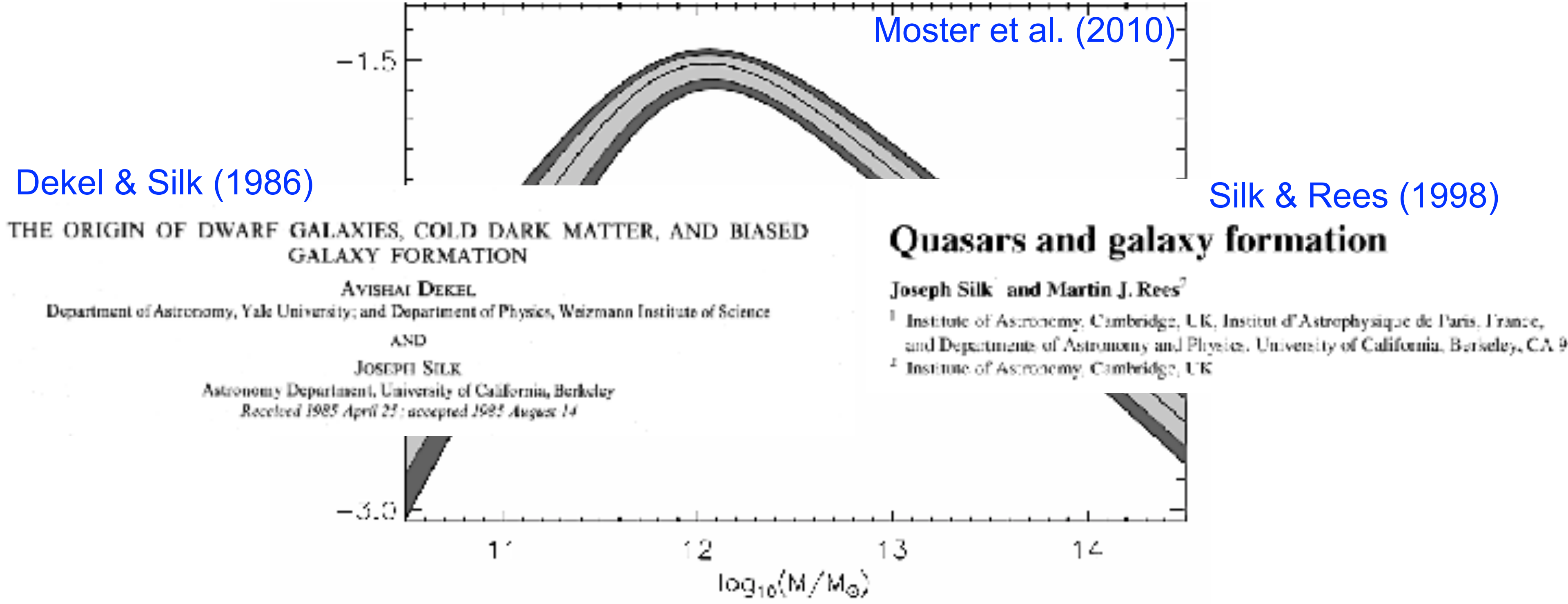
Feedback and star formation in galaxy formation

Very low efficiency of gas conversion into star.

Small mass galaxies are dominated by stellar feedback.

Large mass galaxies are governed by AGN feedback.

Stellar-to-halo mass ratio



THE ORIGIN OF DWARF GALAXIES, COLD DARK MATTER, AND BIASED GALAXY FORMATION

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Received 1985 April 25; accepted 1985 August 14

Quasars and galaxy formation

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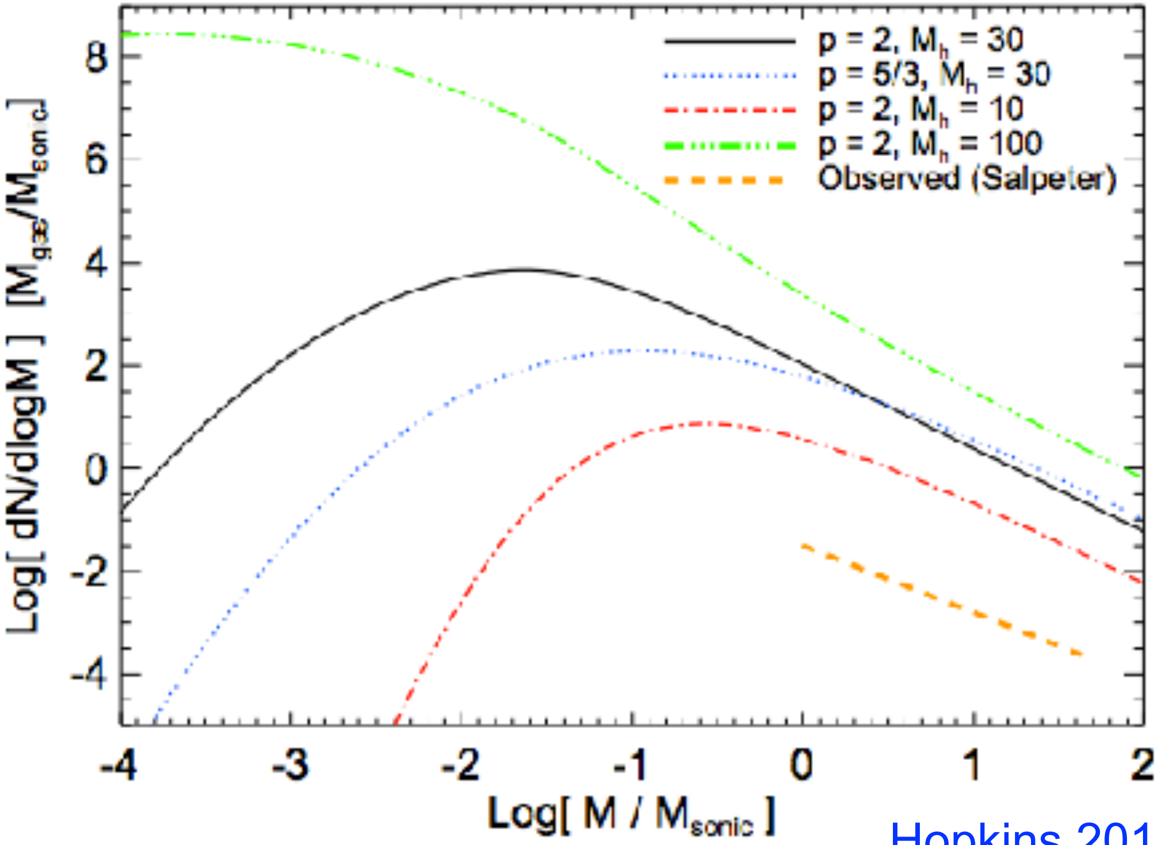
[2] Institute of Astronomy, Cambridge, UK

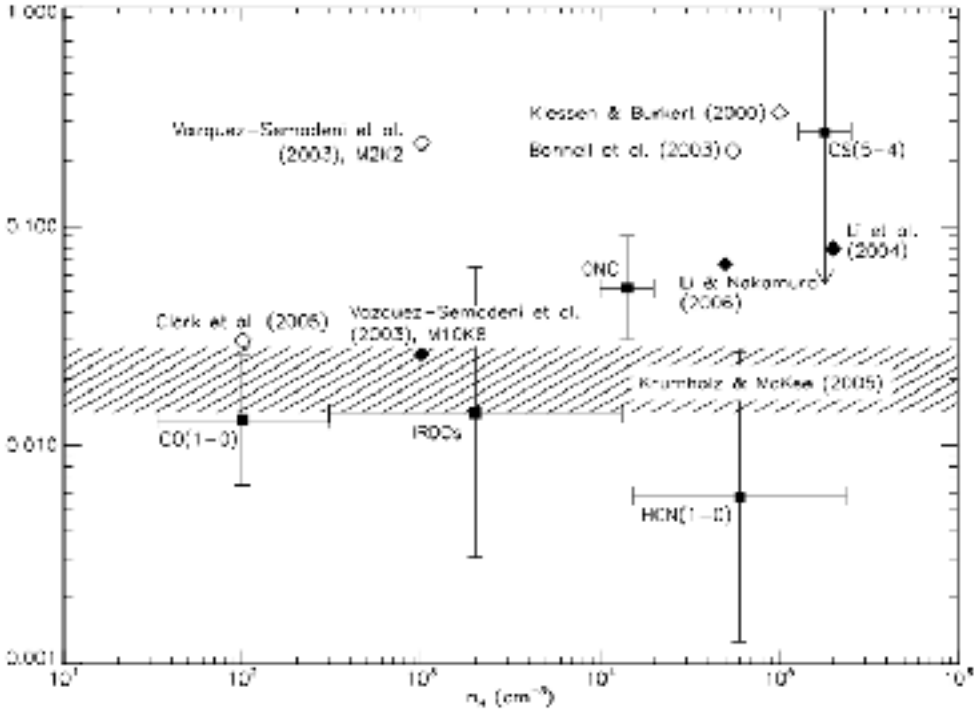
Star formation: what do we know ?

A popular theory for star formation: gravo-turbulent fragmentation.
Turbulence in the ISM determines ultimately the mass spectrum of molecular cores (CMF) and stars therein (IMF) (Hennebelle & Chabrier 2008; Hopkins 2010)



Hopkins 2010

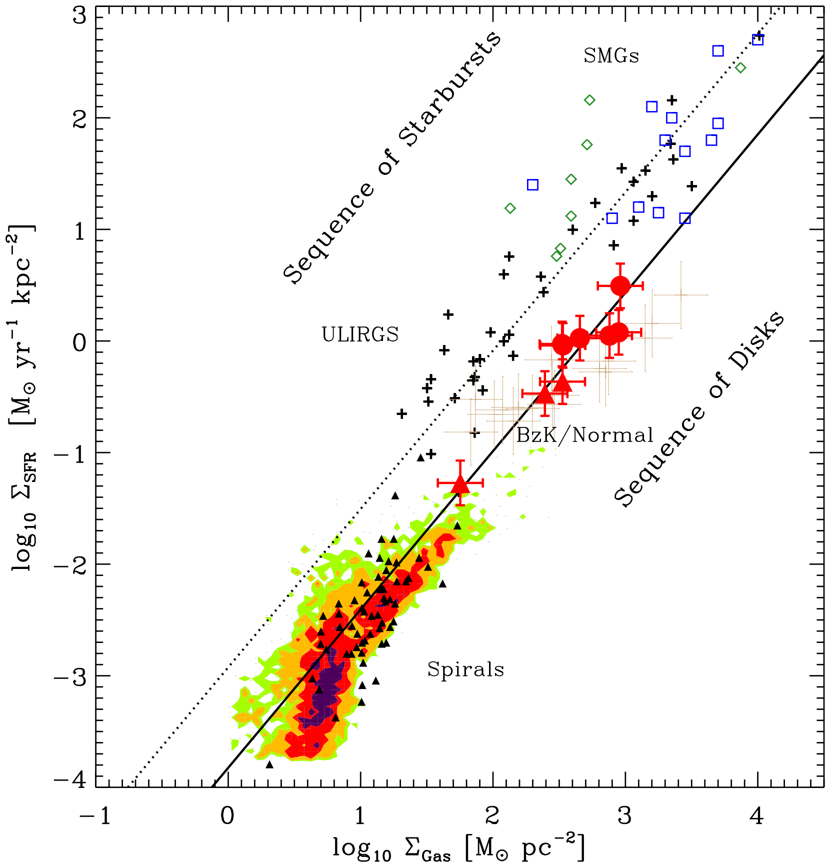
Old subgrid recipe for star formation



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

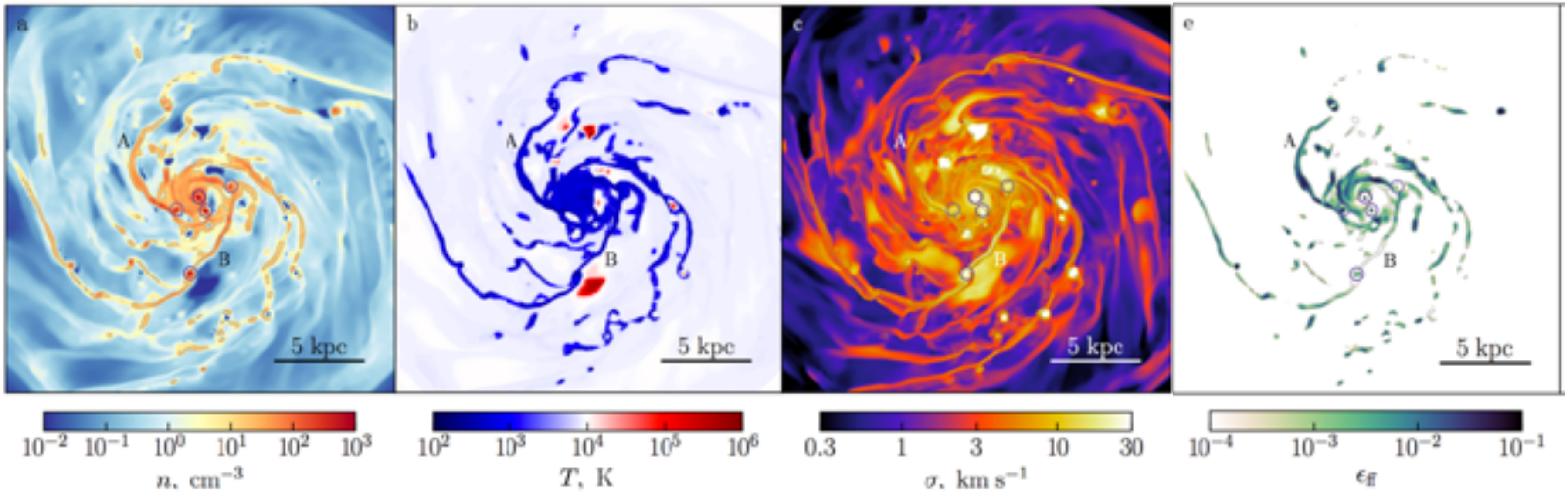
$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{{\rm M}_\odot {\rm pc}^{-2}} \right)^{1.4}$$

Daddi et al. (2010)

New subgrid recipe based on turbulent SF theory

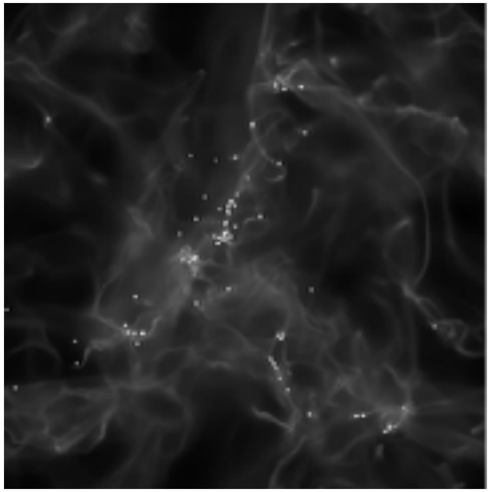
Isolated galaxy simulations with subgrid model for turbulent energy.

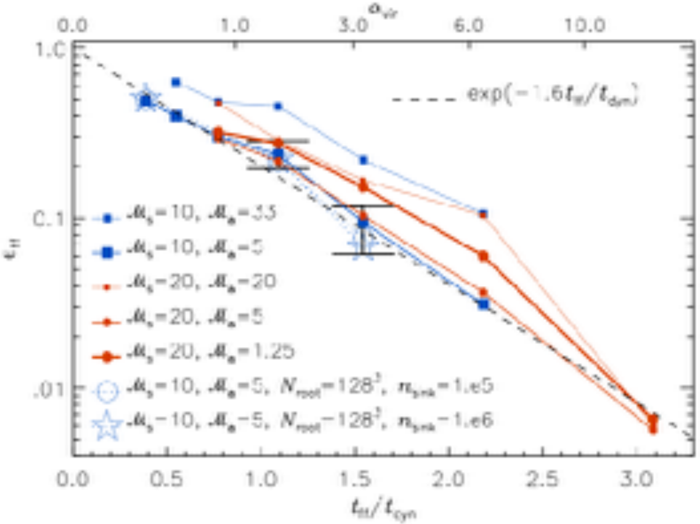
Semenov, Gnedin, Kravtsov 2016



Periodic box simulations with decaying turbulence and collapse into sink particles

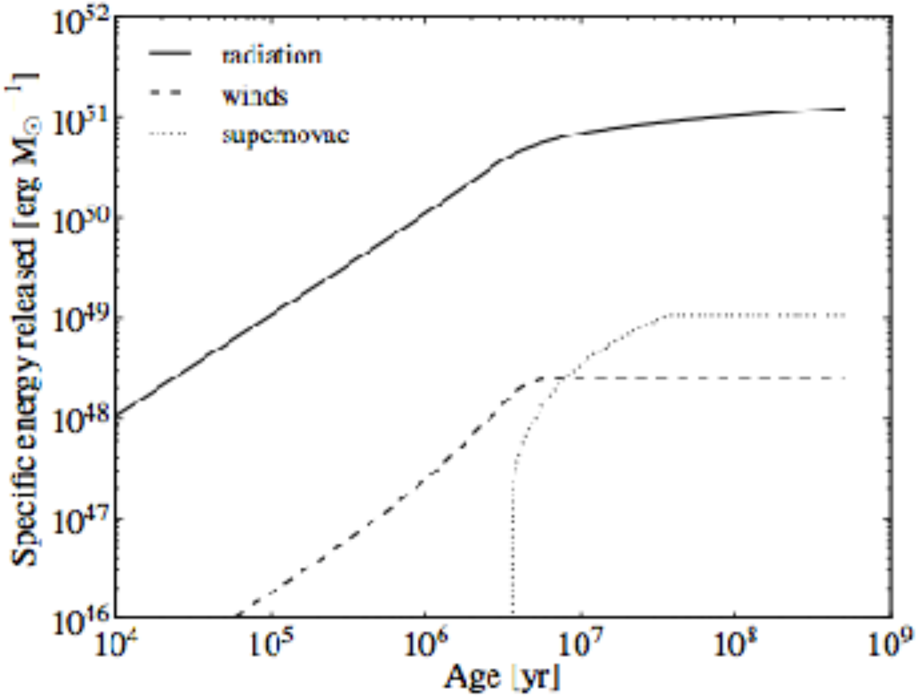
Padoan, Haugbolle, Nordlund 2012





Energy and momentum feedback from stars

Starburst99



After 10 Myr, 10 Msol stars have radiated:
- 10^{51} erg in supernovae & winds
- 10^{53} erg in radiation

UV radiation from stars:
- heats the gas to a few 10^4 K
- injects momentum

$$\Delta Q_{\rm rad} \simeq \frac{E}{c} = 2 \times 10^5~{\rm M_\odot km/s}$$

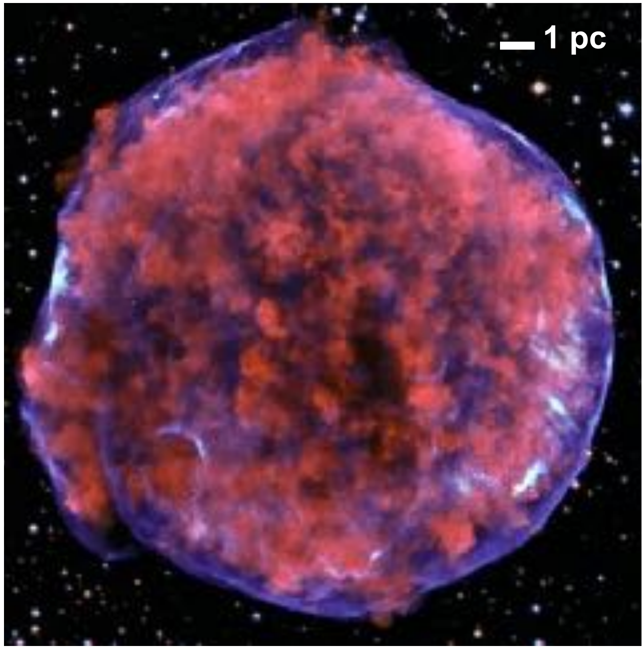
SN blast wave builds up momentum during the energy-conserving phase, until its reaches the cooling radius

$$r_{\rm cool} \simeq 3~{\rm pc} \left(\frac{n_{\rm H}}{100~{\rm H/cc}}\right)^{-0.5}$$

SN blast wave enters the momentum-conserving phase with terminal momentum

$$\Delta Q_{\rm max} \simeq \frac{E}{v_{\rm max}} = 1 \times 10^5~{\rm M_\odot km/s}$$

Stellar feedback with non-thermal energy



Chandra image of Tycho

Stellar winds, supernovae remnants are highly turbulent environment, filled with cosmic rays and magnetic field.

Thermal energy dissipates almost instantaneously through cooling. Non-thermal processes dissipate much more slowly.

Hanasz et al. 2009 ; Scannapieco & Brüggen 2010; Wadepuhl & Springel 2011 and others...

Here, we capture the non-thermal energy as:

$$\rho\frac{D\epsilon_{turb}}{Dt} = \dot{E}_{inj} - \frac{\rho\epsilon_{turb}}{t_{diss}} \qquad \epsilon_{turb} = \sigma_{turb}^2$$

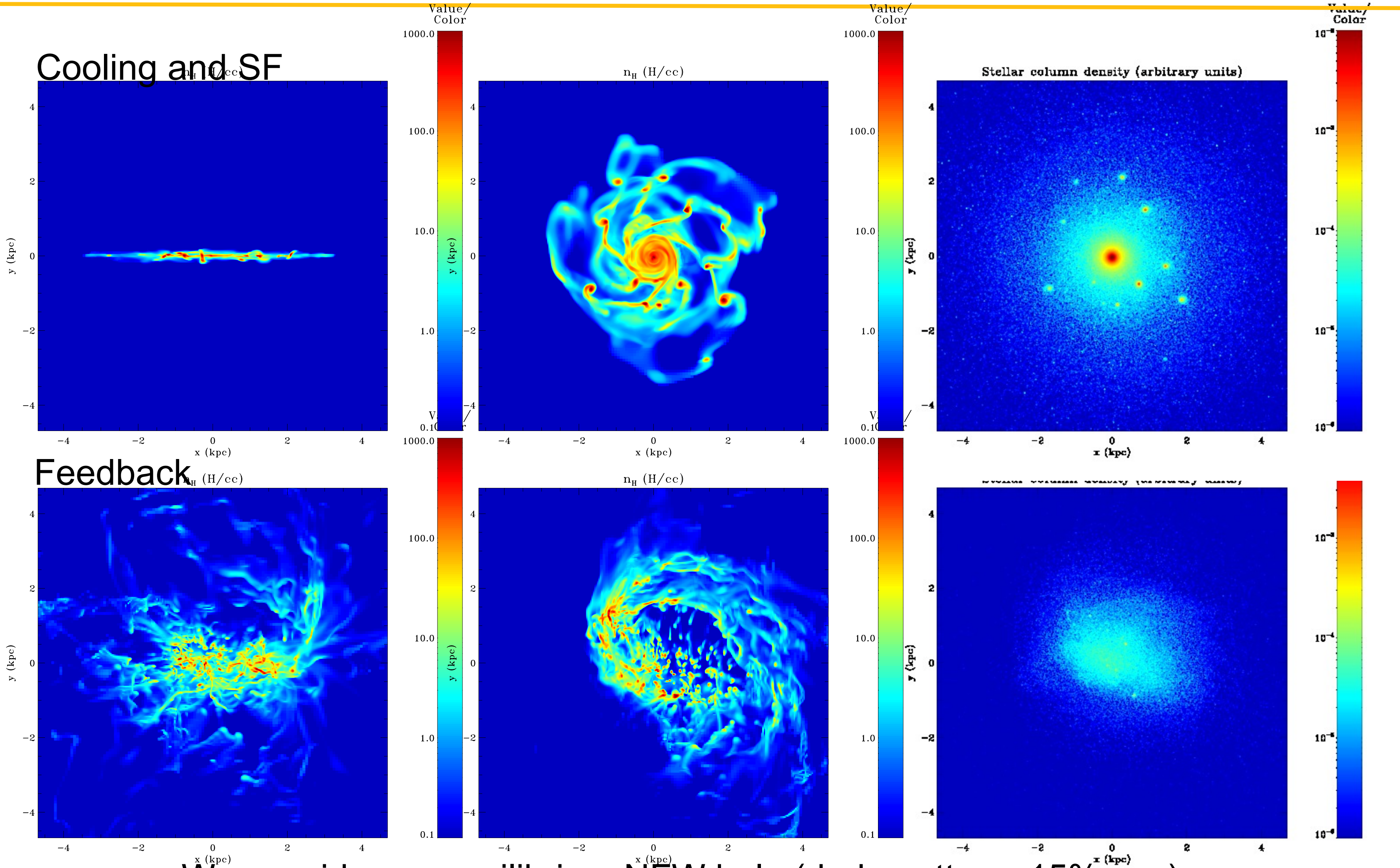
The total dynamical pressure is $P_{tot} = P_{thermal} + P_{turb}$

Maximal feedback scenario: $\dot{E}_{inj} = \dot{\rho}_* \eta_{SN} 10^{50}\ \mathrm{erg/M_\odot}$ $\qquad t_{diss} \simeq 10\ \mathrm{Myr}$

We mimic slow dissipation of non-thermal energy using delayed cooling for the thermal energy:

$$\rho\frac{D\epsilon_{thermal}}{Dt} = \dot{E}_{inj} - P_{thermal}\nabla\cdot\mathbf{v} - n_H^2\Lambda \quad \text{with} \quad \Lambda = 0 \text{ if } \sigma_{turb} > 10\ \mathrm{km/s}$$

Feedback in dwarf galaxies: a controlled experiment



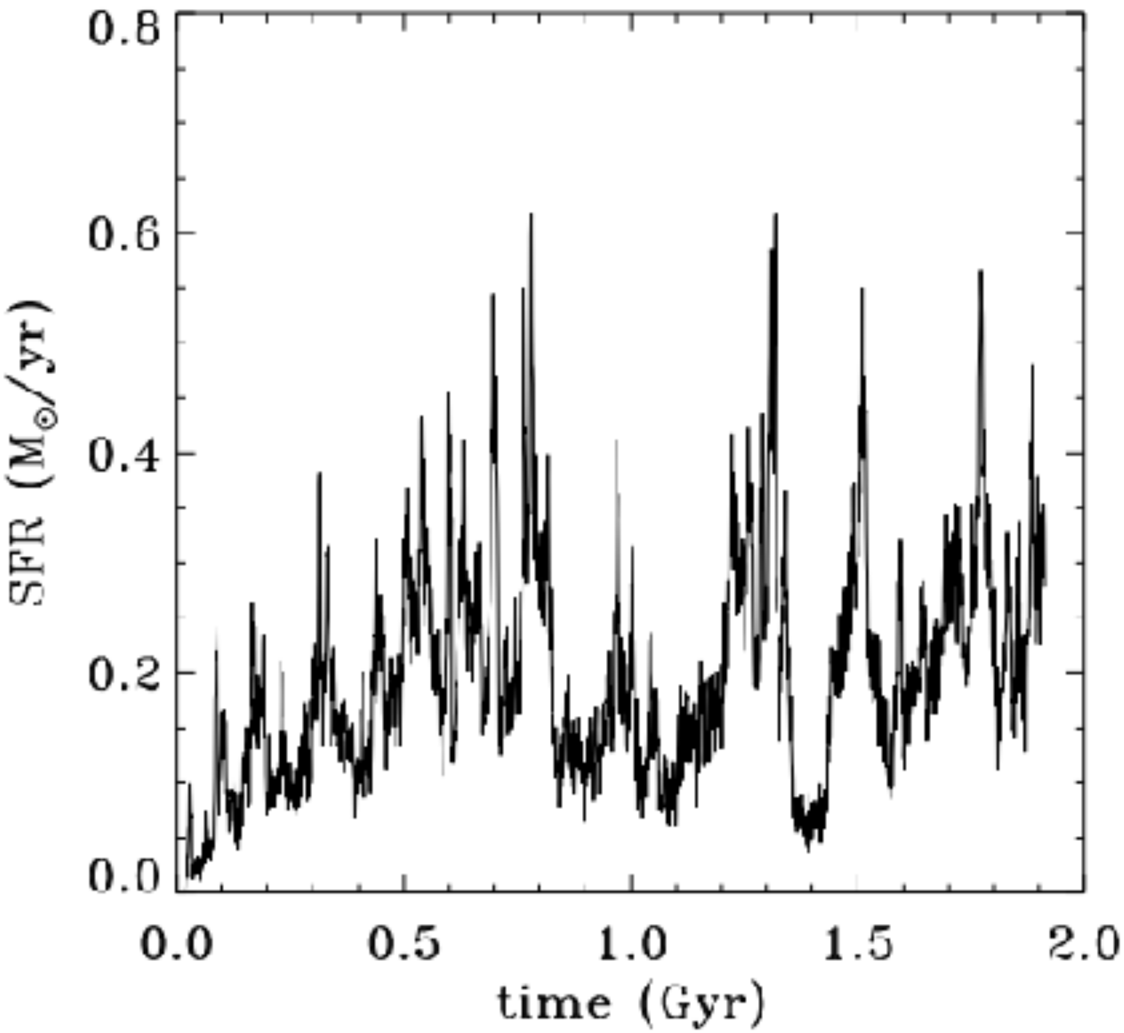
Cooling and SF

Feedback

We consider an equilibrium NFW halo (dark matter + 15% gas)

$N_{DM}=10^6$, Delta x=20 pc, V_{200}=35 km/s, $M_{200}=10^{10}$ M_{sol}

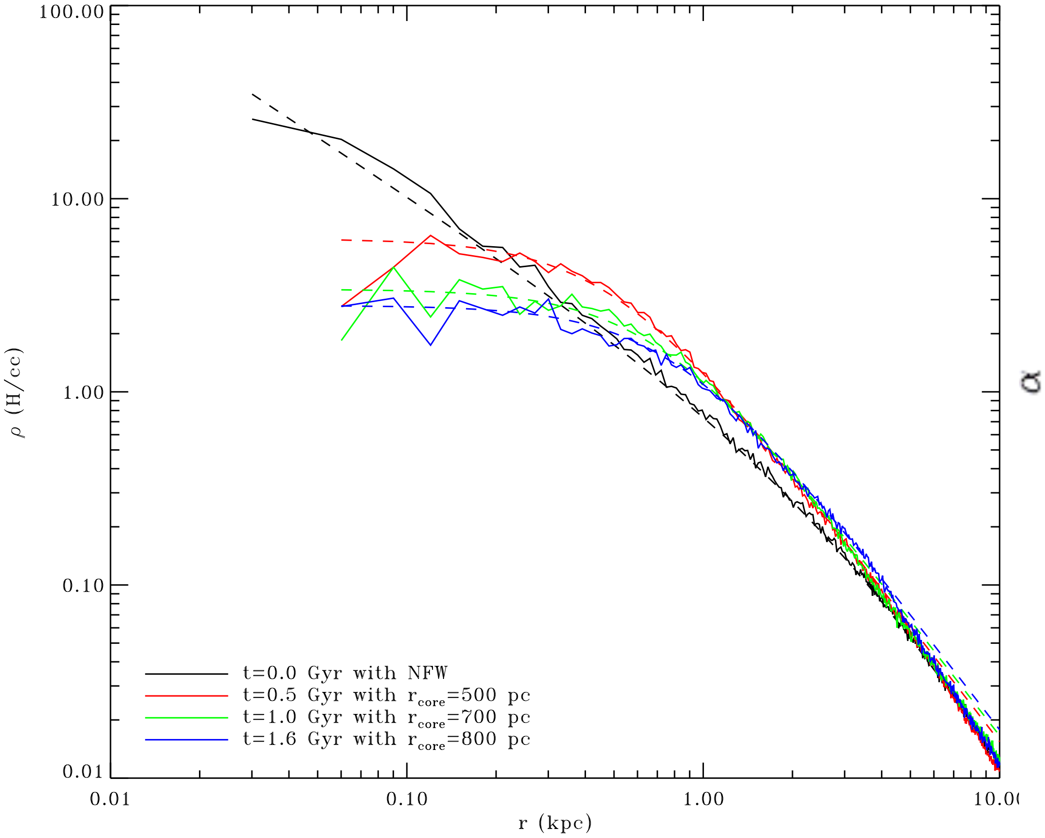
A Bursty Star Formation History

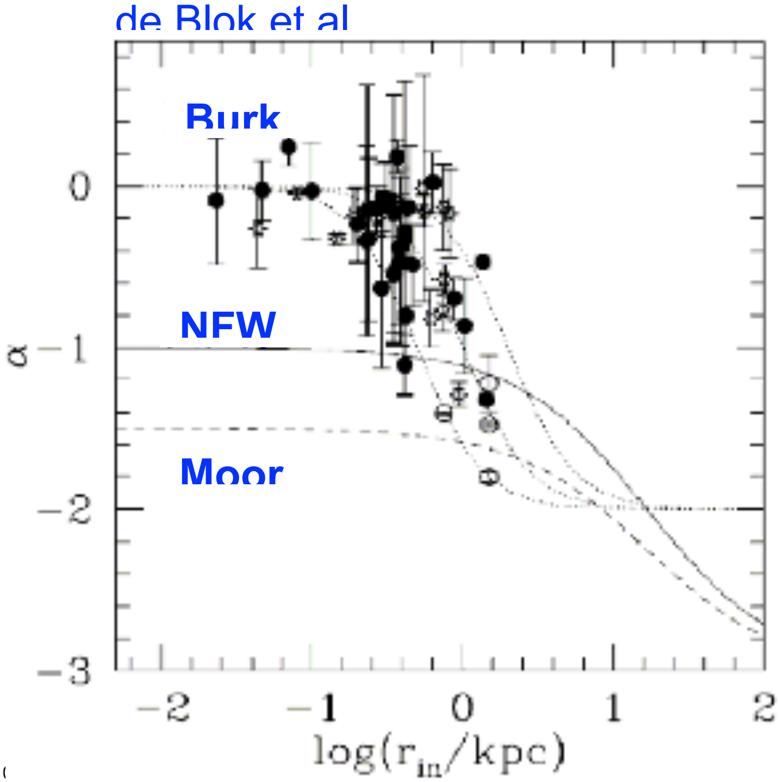


Dark matter cusp-to-core transformation

Excellent fit of the dark matter profile with a pseudo-isothermal profile

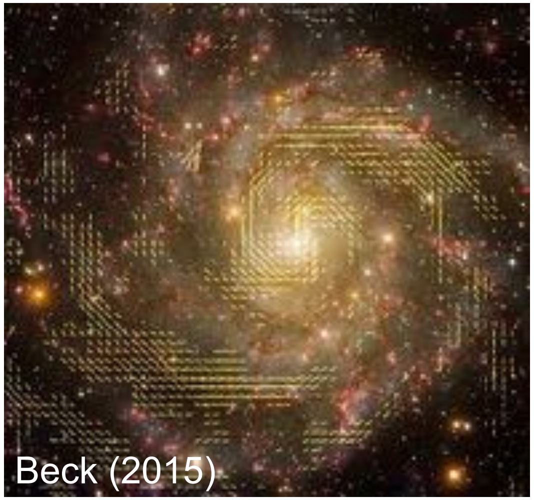
$$\rho \propto \frac{1}{1+(r/r_{core})^2}$$



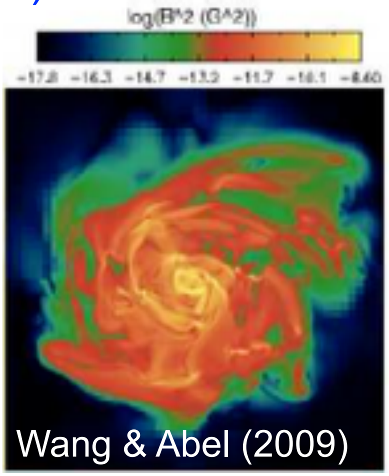


The origin of cosmic magnetic fields

- Biermann battery at the EoR sets the initial field around 10^{-20} G (Gnedin *et al.* 2000).
- Current magnetic fields in local galaxies reaches several 10^{-6} G (Beck 2015).
- High-redshift galaxies seems to have 10x larger fields, probably even increasing with increasing redshift (Bernet, Miniati & Lilly 2013)


Beck (2015)

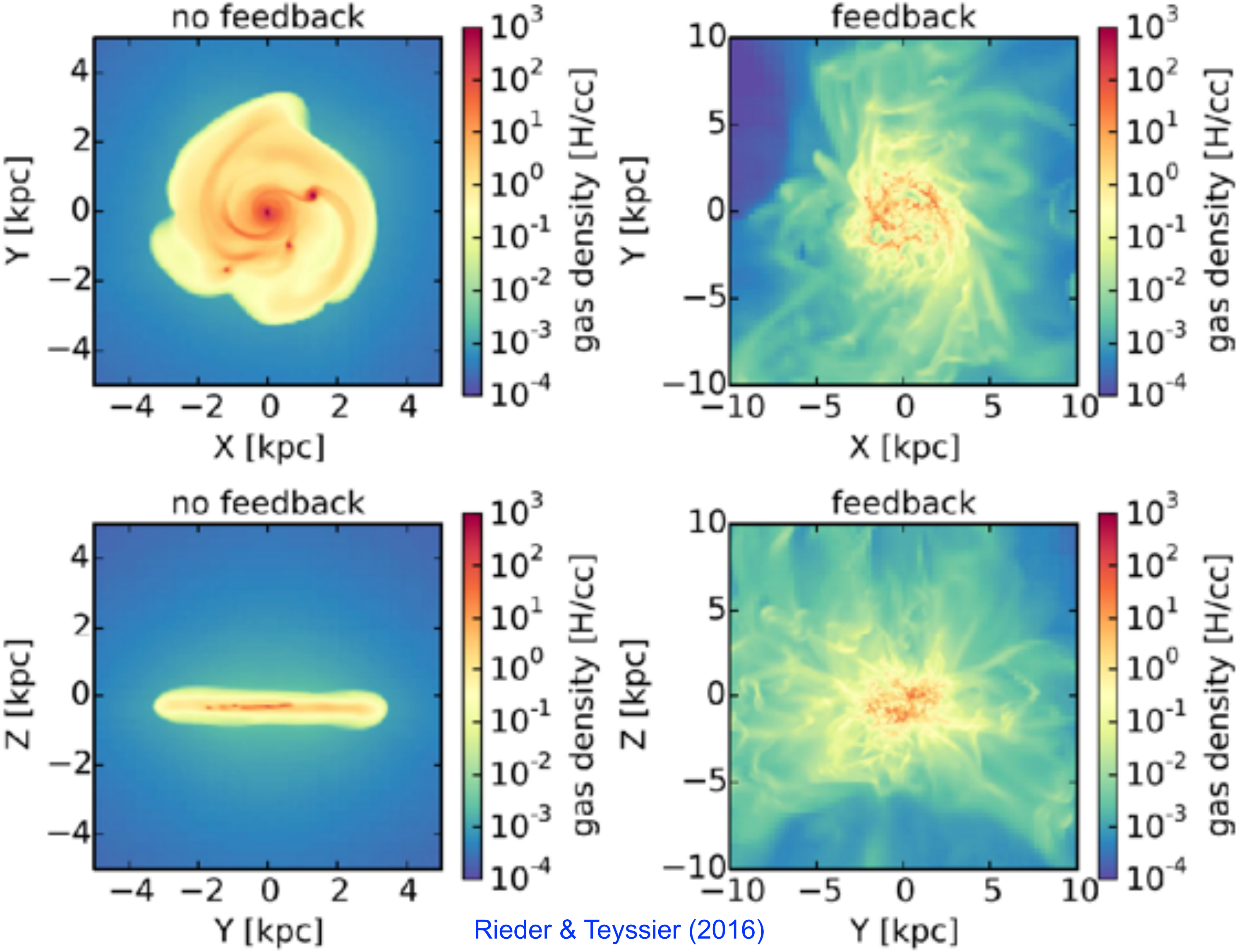
- Successful large-scale dynamos are slow with growth rate $\simeq 0.1\Omega$ up to Ω Hanasz *et al.* (2004), Pariev *et al.* (2007), Gressel *et al.* (2008)
- Early galaxy formation MHD simulations with no or weak feedback show moderate field amplification: Wang & Abel (2009), Dubois & Teyssier (2010)
- Recent simulations Beck *et al.* (2012), Pakmor & Springel (2013) or semi-analytical models Rodrigues *et al.* (2015) favour the scenario of a small scale dynamo at high redshift.



Wang & Abel (2009)

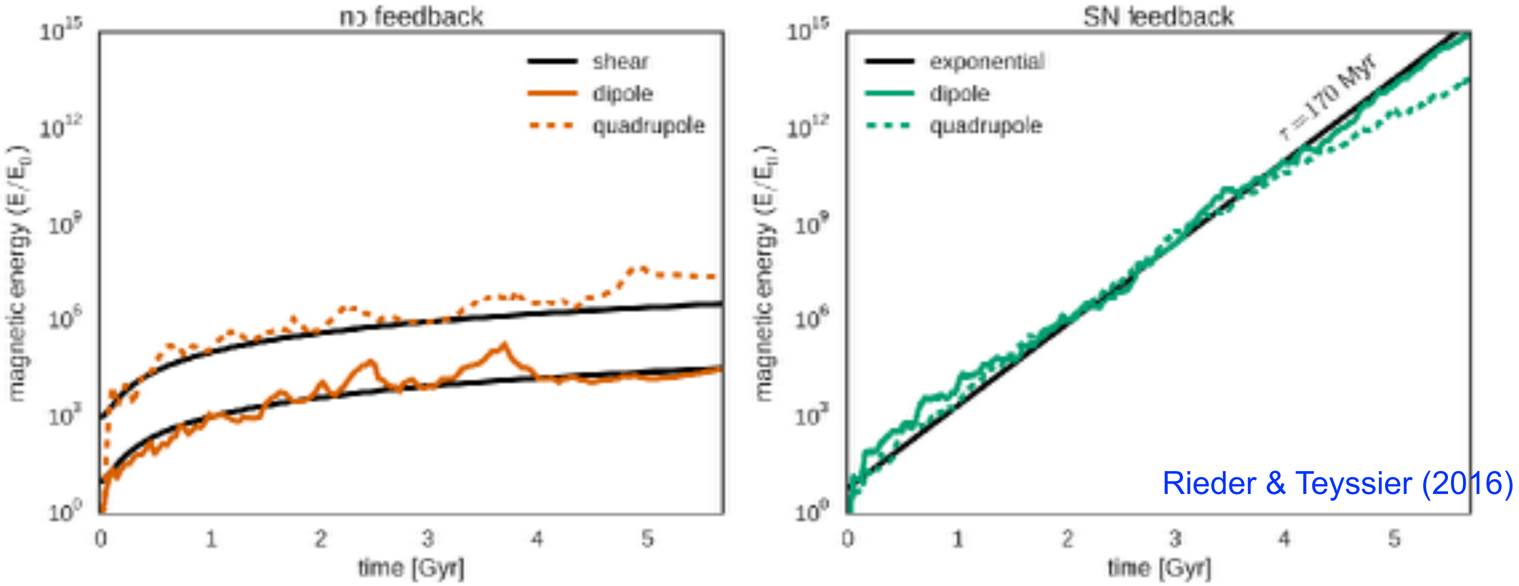
Turbulent dynamo in a dwarf galaxy

Cooling halo simulations

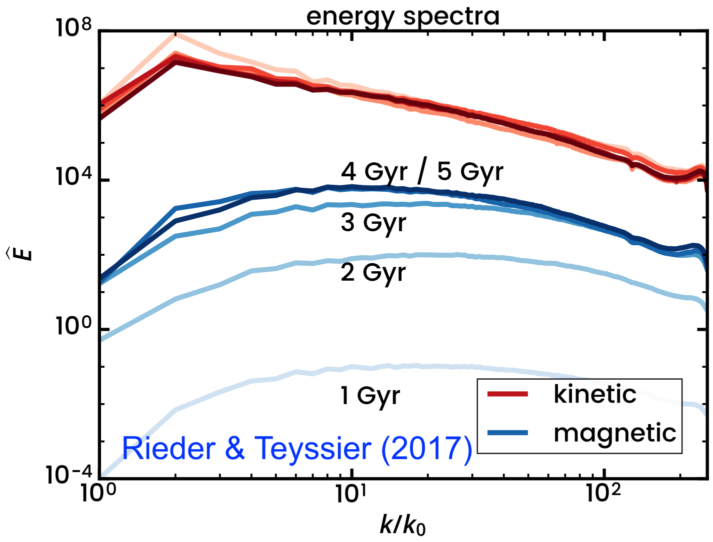


Rieder & Teyssier (2016)

Magnetic field generation in dwarf galaxies

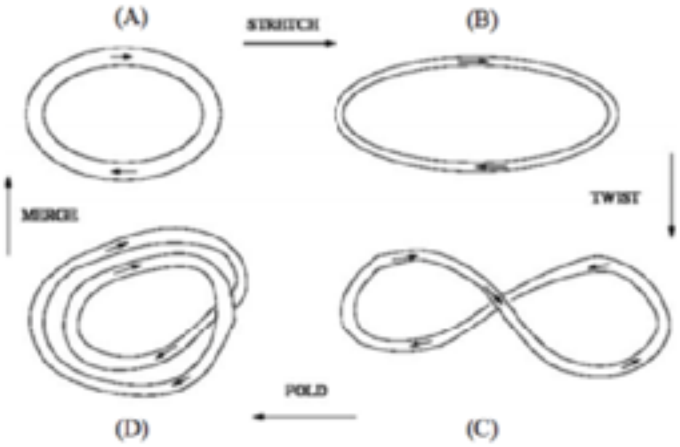


Rieder & Teyssier (2016)



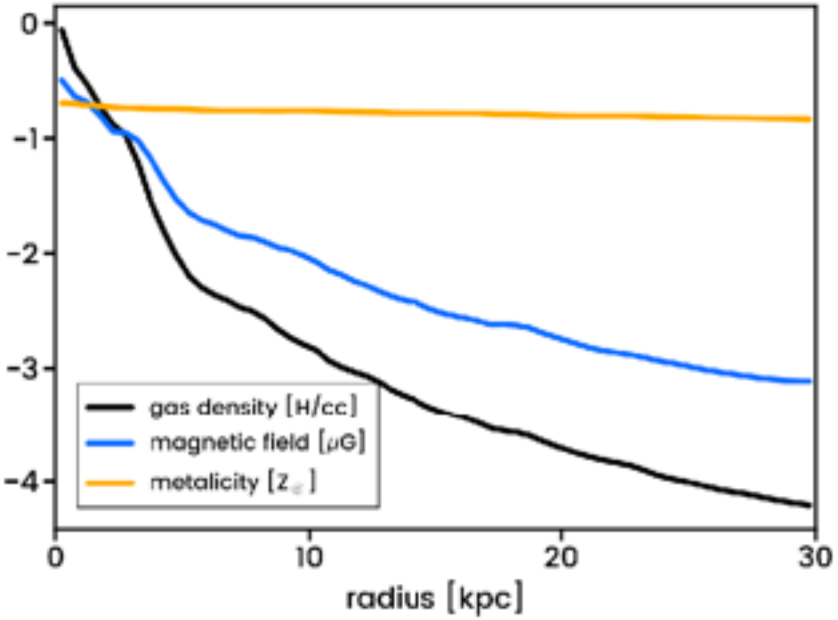
Rieder & Teyssier (2017)

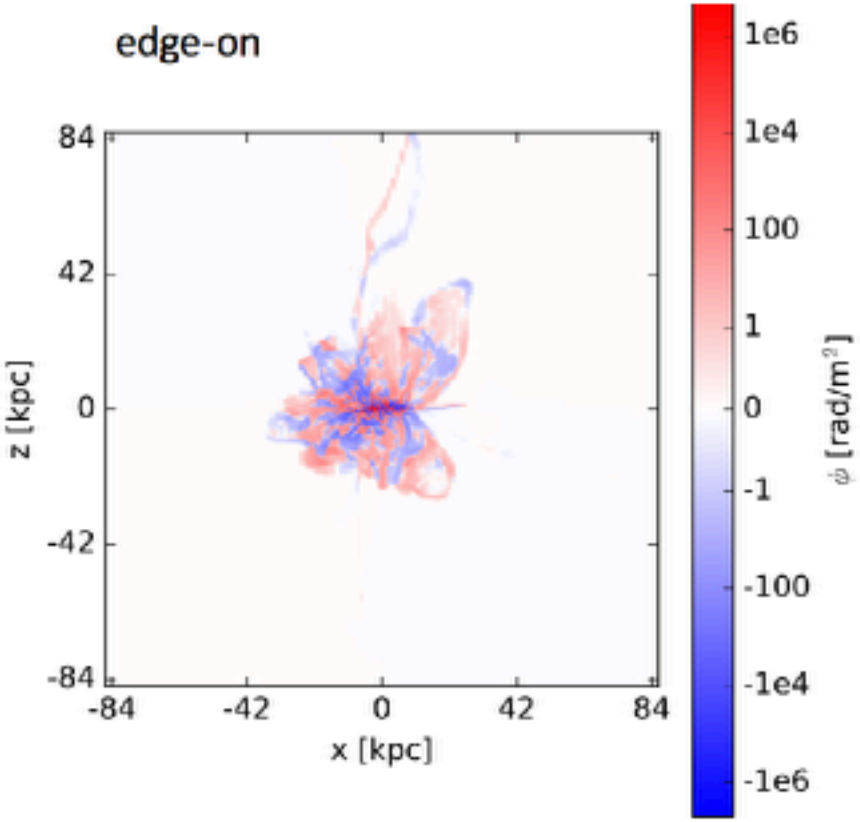
Stretch-twist-fold-merge mechanism



Observational signatures of the small-scale dynamo

Rieder & Teyssier 2017

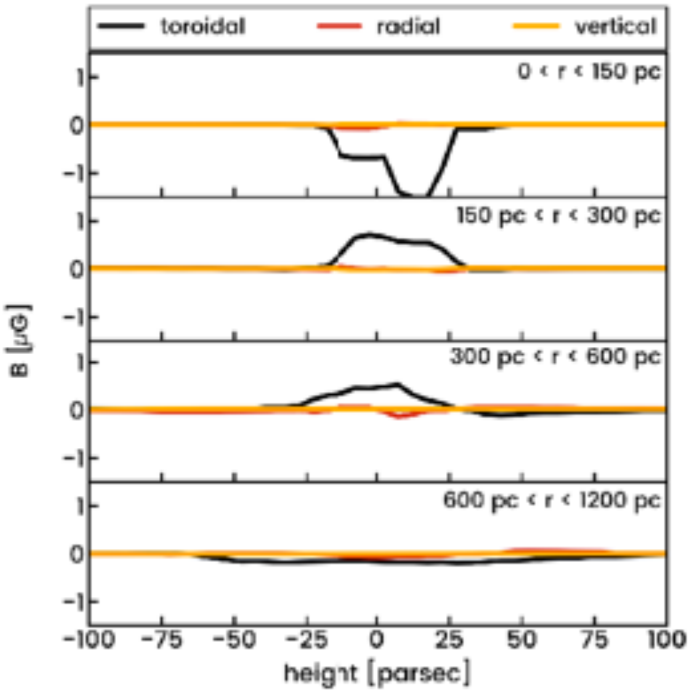


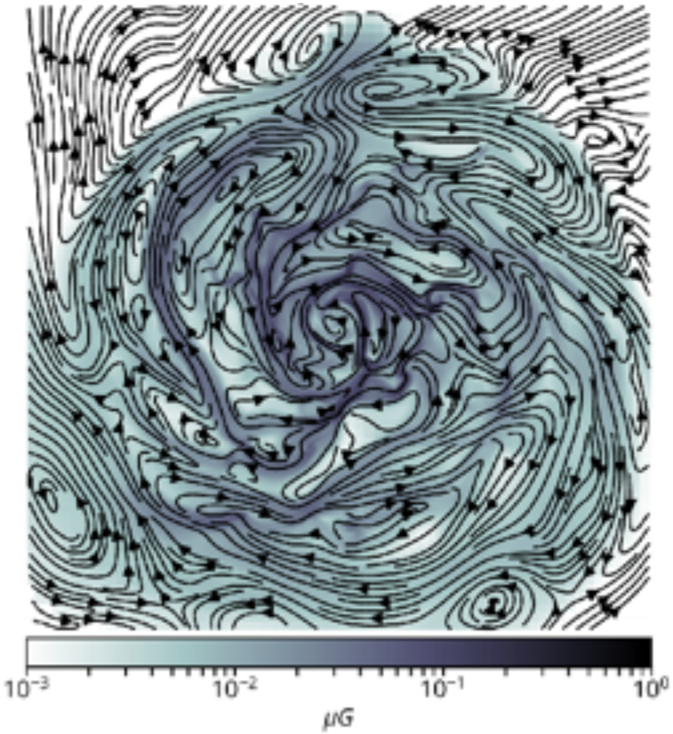


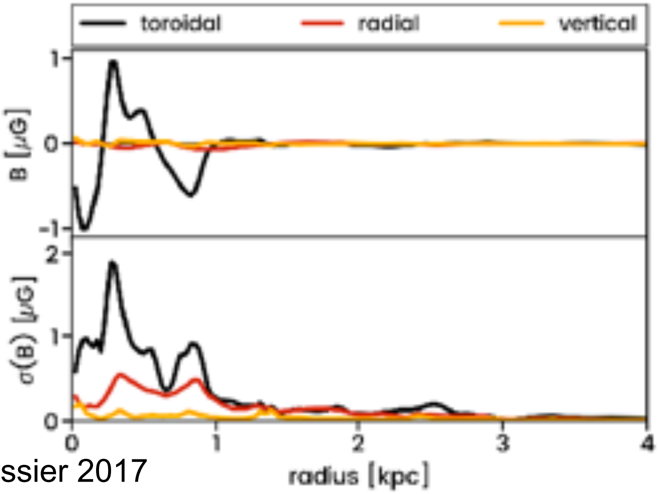
Simulation of a 10^{12} Msol halo with strong feedback and comparing to new VLA spectral data on 50 quasars with/without MgII absorption (Kwang Seong Kim and Simon Lilly, arxiv/1604.00028).

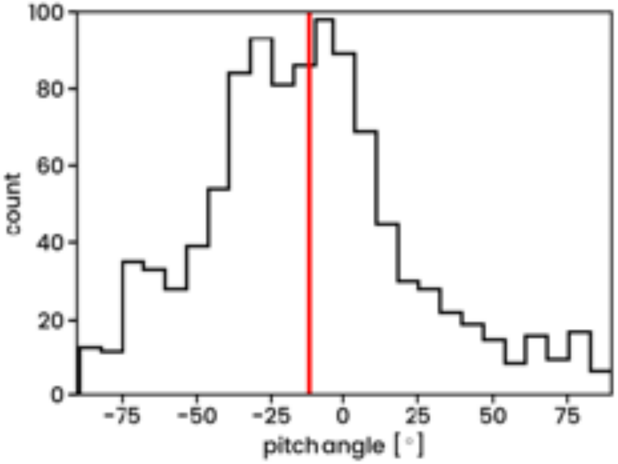
Saturated small scale dynamo within strong galactic winds compares favourably with observations at intermediate redshifts.

Transition to quiescence: final magnetic configuration



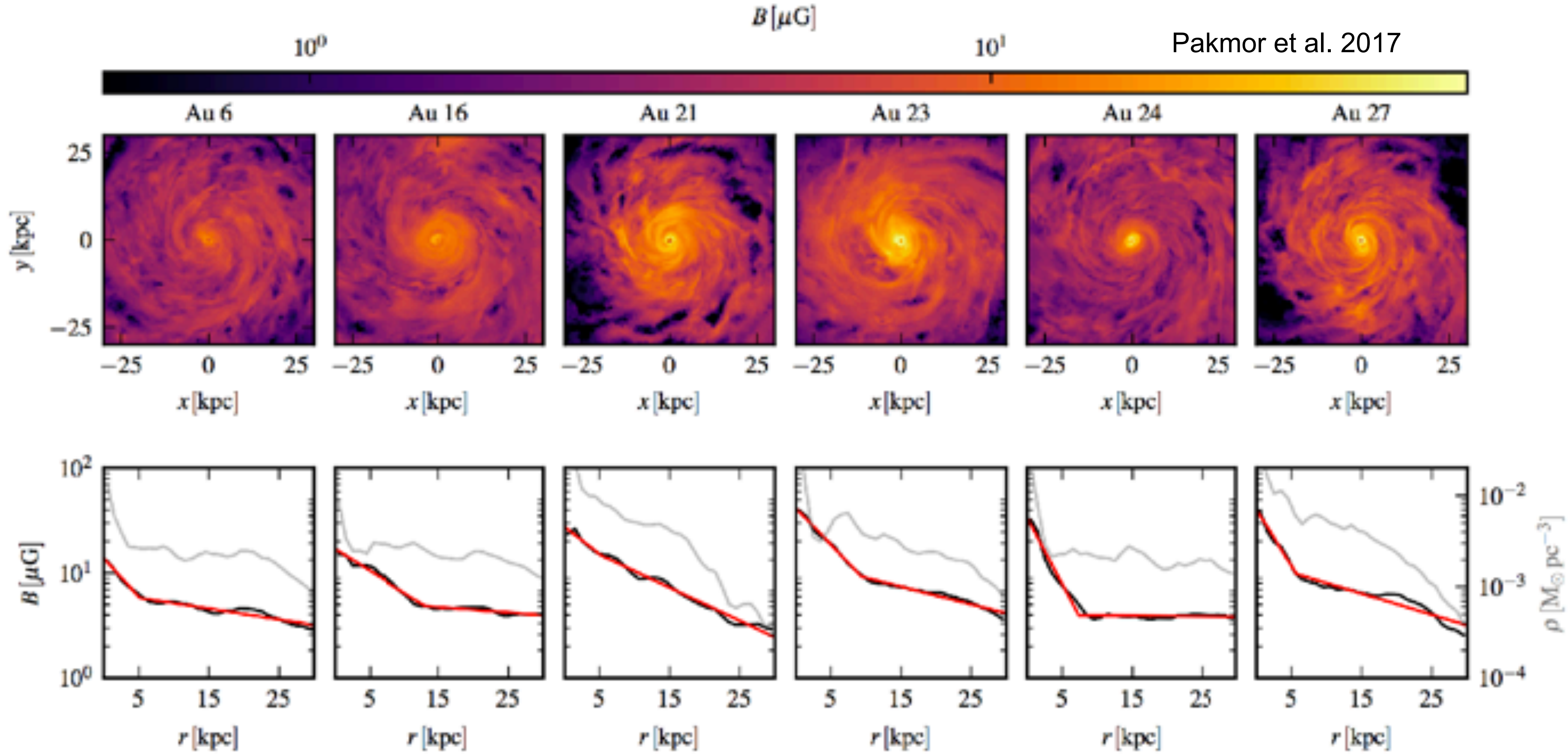






Rieder & Teyssier 2017

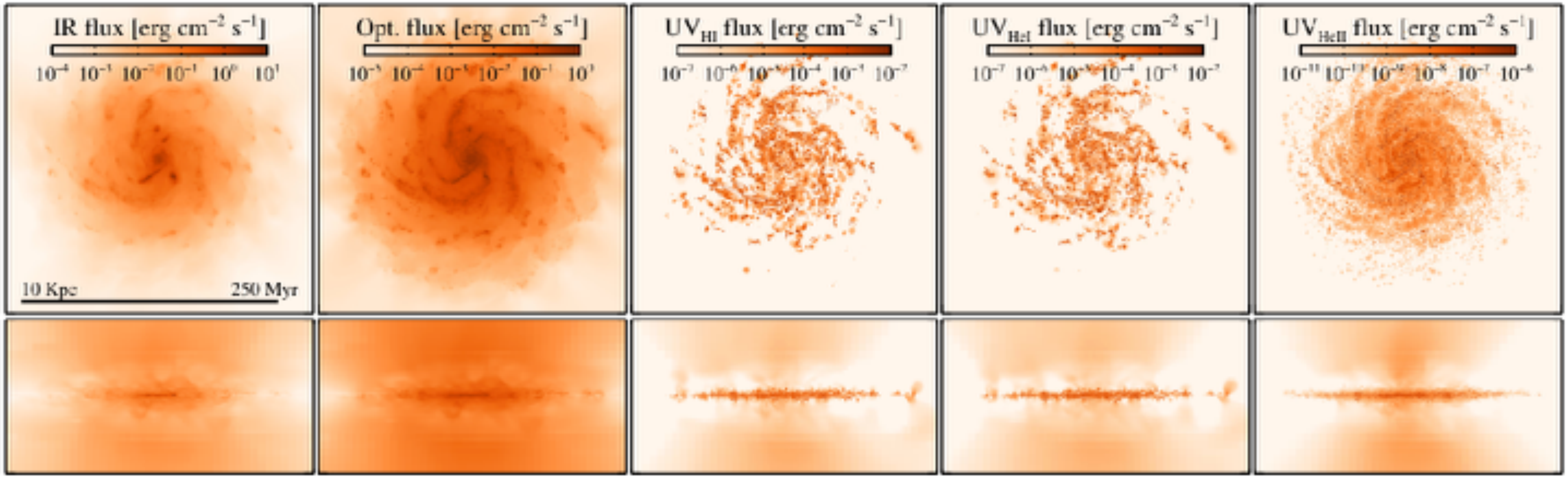
Cosmological MHD simulations



Pakmor et al. 2017

Galaxies that shine

Isolated galaxy with 5 different photons groups, photo-ionisation and dust absorption.



Rosdahl *et al.* (2015)

- 10^{11} solar masses halo
- 3×10^9 solar masses baryonic disk
- 50% gas fraction.

- 10^6 stellar and DM particles
- 18 pc resolution
- 0.1 solar metallicity

Feedback processes:

- thermal SN energy injection (no trick)
- radiation from the B&C (2003) SEDs.
- HI and dust opacities

Radiative processes:

- photo-ionisation heating
- direct pressure from UV
- IR pressure from dust scattering

The problem with supernovae feedback

Consider a single molecular cloud of mass $M_{\rm gas}$ going supernova.

Most efficient scenario is the adiabatic blast wave model (Sedov solution).

The total energy is just $E_{\rm SN} = \epsilon_{\rm SN} \epsilon_* M_{\rm gas} \dfrac{10^{51}}{10~{\rm M}_\odot}~{\rm erg}$

$\epsilon_* \simeq 10\%$

The cloud velocity is $v_{\rm Sedov} = \dfrac{2}{5}\sqrt{\dfrac{E_{\rm SN}}{M_{\rm gas}}} \simeq 90~{\rm km/s}$

$\epsilon_{\rm SN} \simeq 10\%$

The cloud is probably entirely destroyed but the gas remains within the galaxy. For the MW, the escape velocity is very high $v_{\rm escape} \simeq 700~{\rm km/s}$

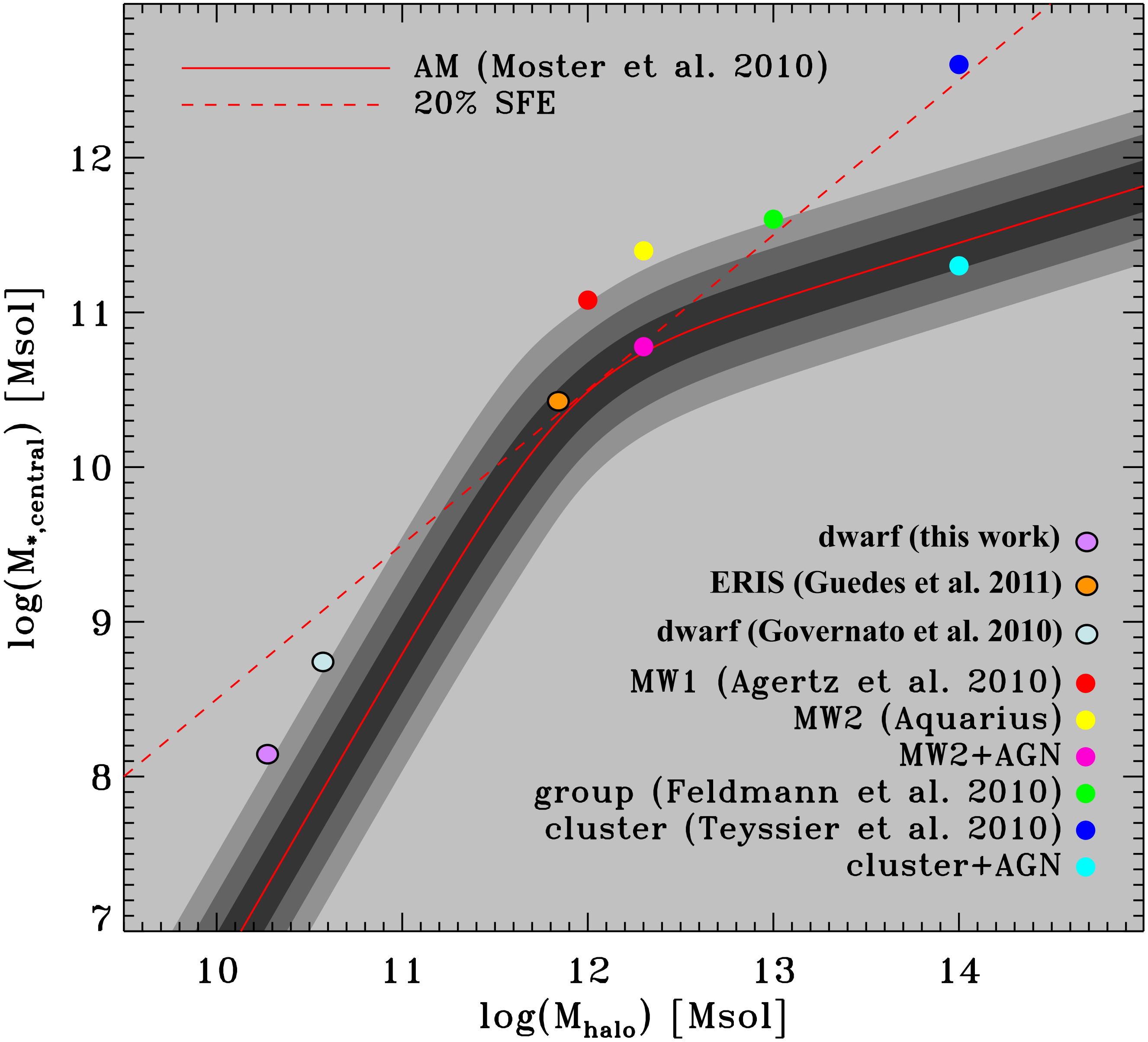
We can consider that only *a fraction* of the cloud is accelerated in a wind

$M_{\rm wind} = \eta_{\rm wind} M_*$ with $\eta_{\rm wind} < \dfrac{1}{\epsilon_*}$

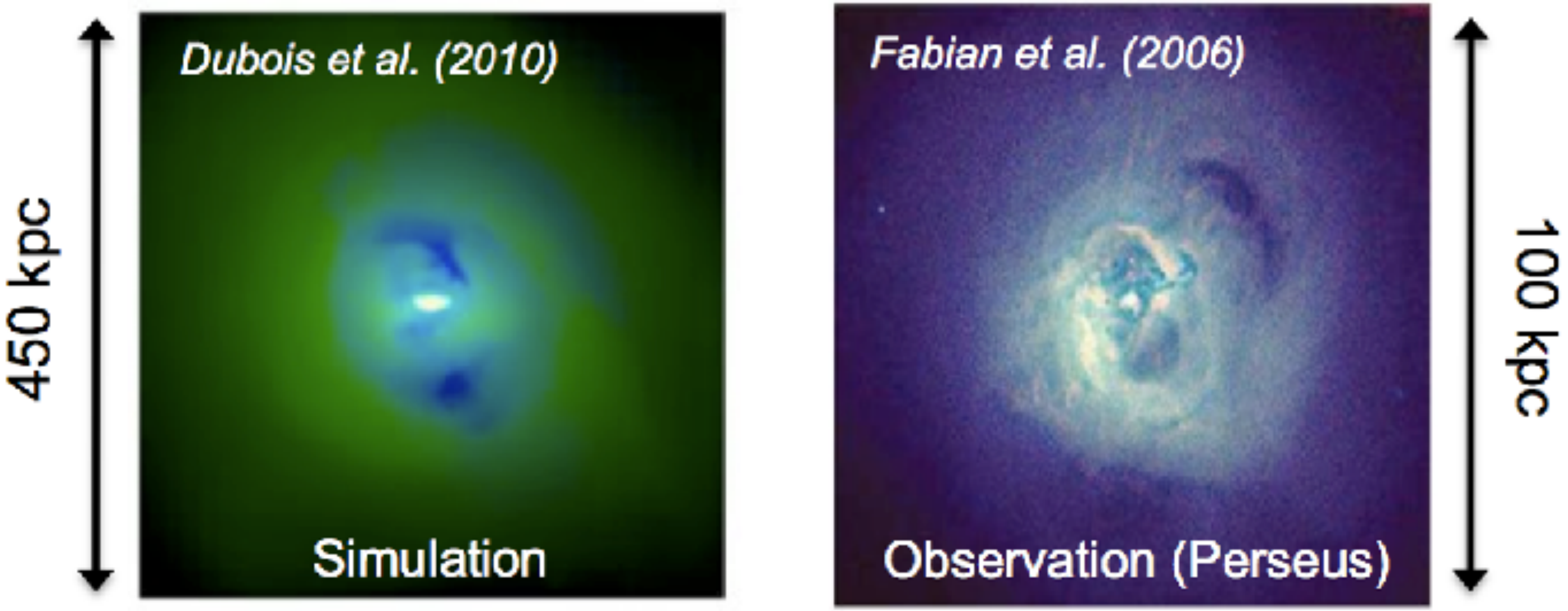
Mass-loading factor $\eta_{\rm wind} = 1$ gives only $v_{\rm Sedov} = \dfrac{2}{5}\sqrt{\dfrac{E_{\rm SN}}{M_{\rm wind}}} \simeq 300~{\rm km/s}$

Supernovae feedback hardly work for the MW, only for dwarf galaxies !

Constraints from abundance matching

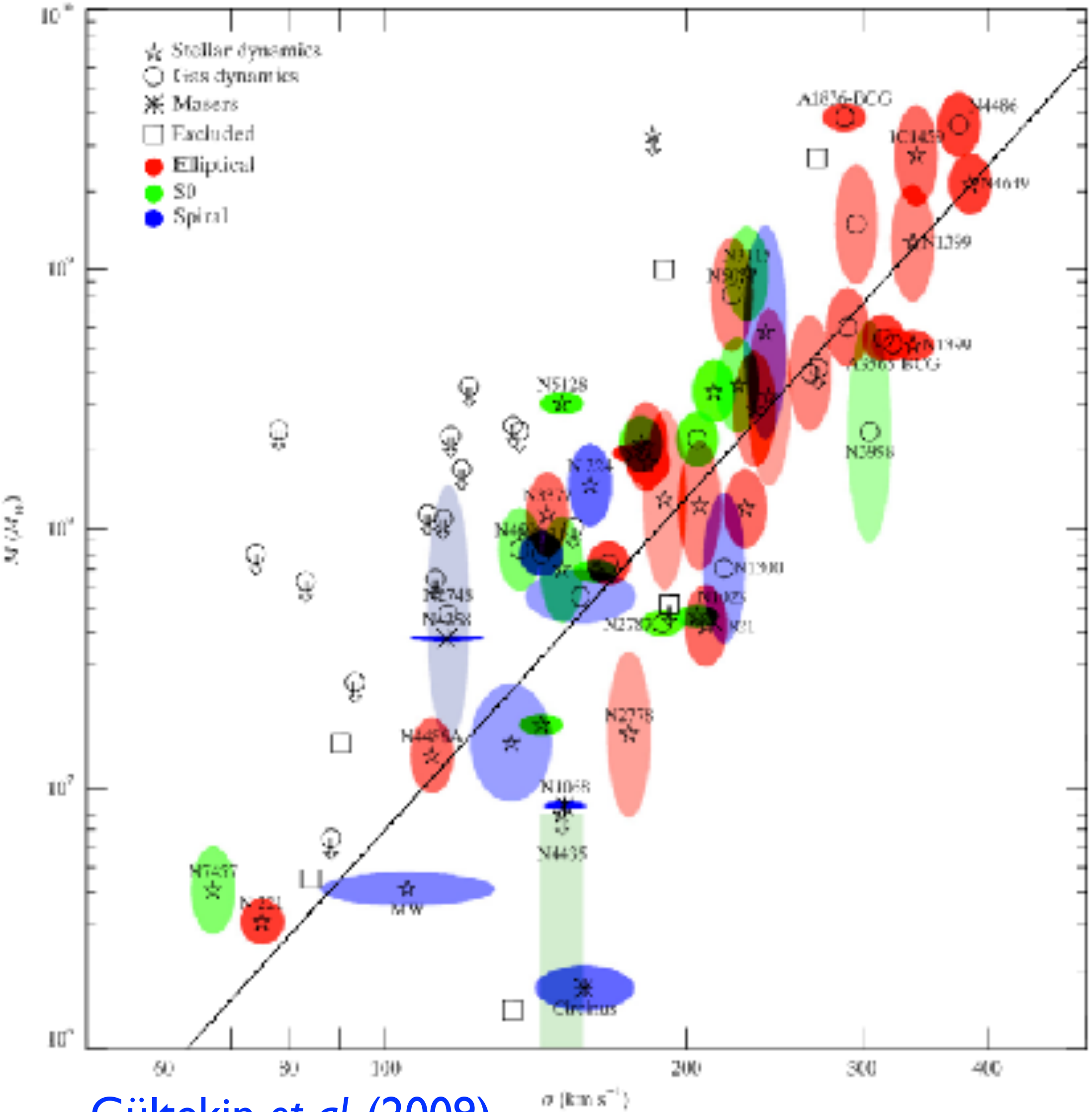


Feedback in massive galaxies: supermassive black holes



X-ray (3 bands)

Feedback in massive galaxies: supermassive black holes



Gültekin *et al.* (2009)

A simple model for SMBH growth and feedback

Numerical implementation in cosmological simulations: Sijacki et al. 2007; Booth & Schaye 2010 and many others. Constantly improving.

In high density regions with stellar 3D velocity dispersion > 100 km/s, we create a seed BH of mass 10^5 M_{sol}.

Accretion is governed by 2 regimes:

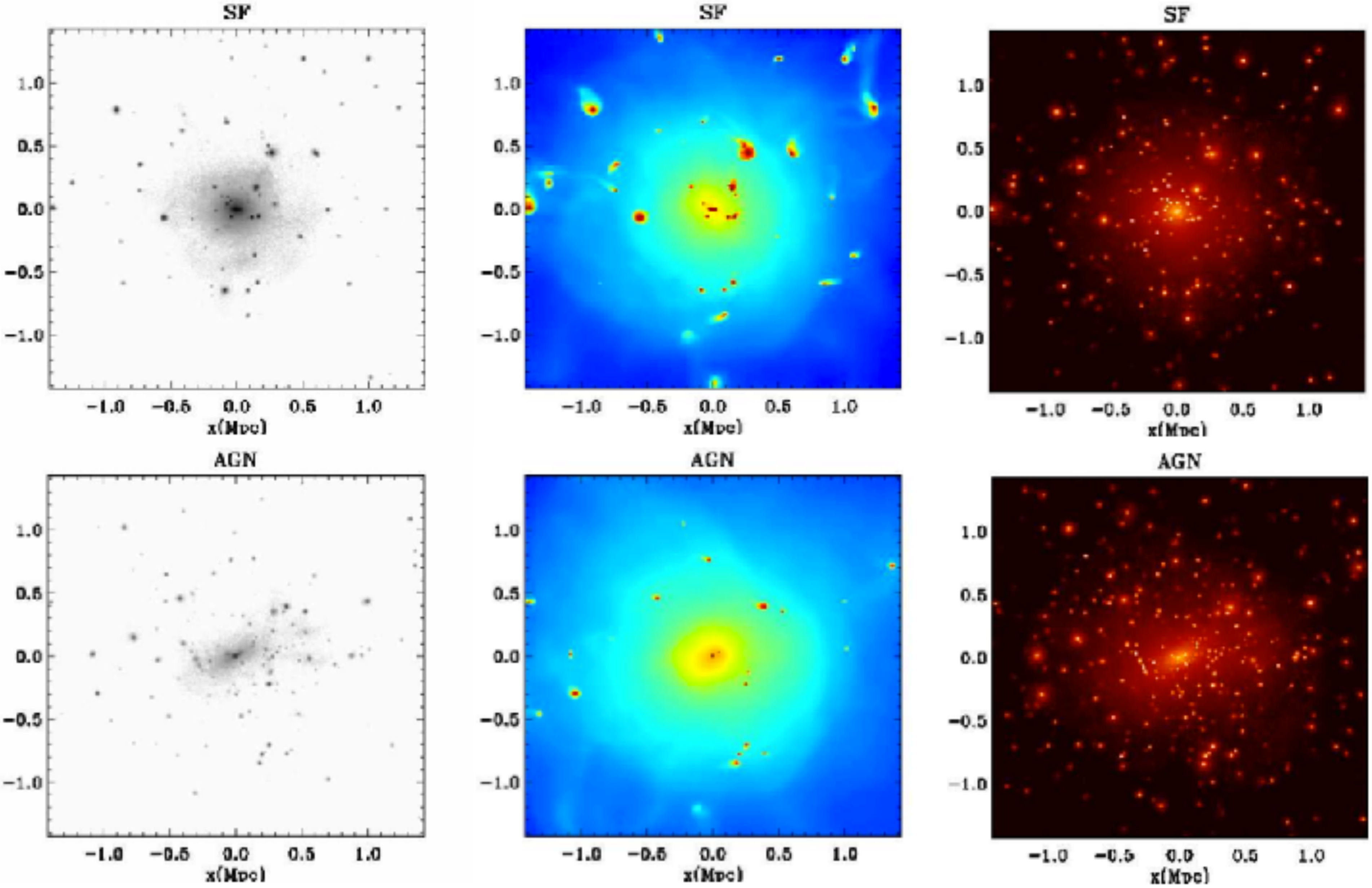
Bondi-Hoyle regime $$\dot{M}_{\rm BH} = \alpha_{\rm boost} \frac{4\pi {\rm G}^2 M_{\rm BH}^2 \rho}{(c_{\rm s}^2 + u^2)^{3/2}}$$

Eddington-limited $$\dot{M}_{\rm ED} = \frac{4\pi {\rm G} M_{\rm BH} m_{\rm p}}{\epsilon_r \sigma_{\rm T} c}$$

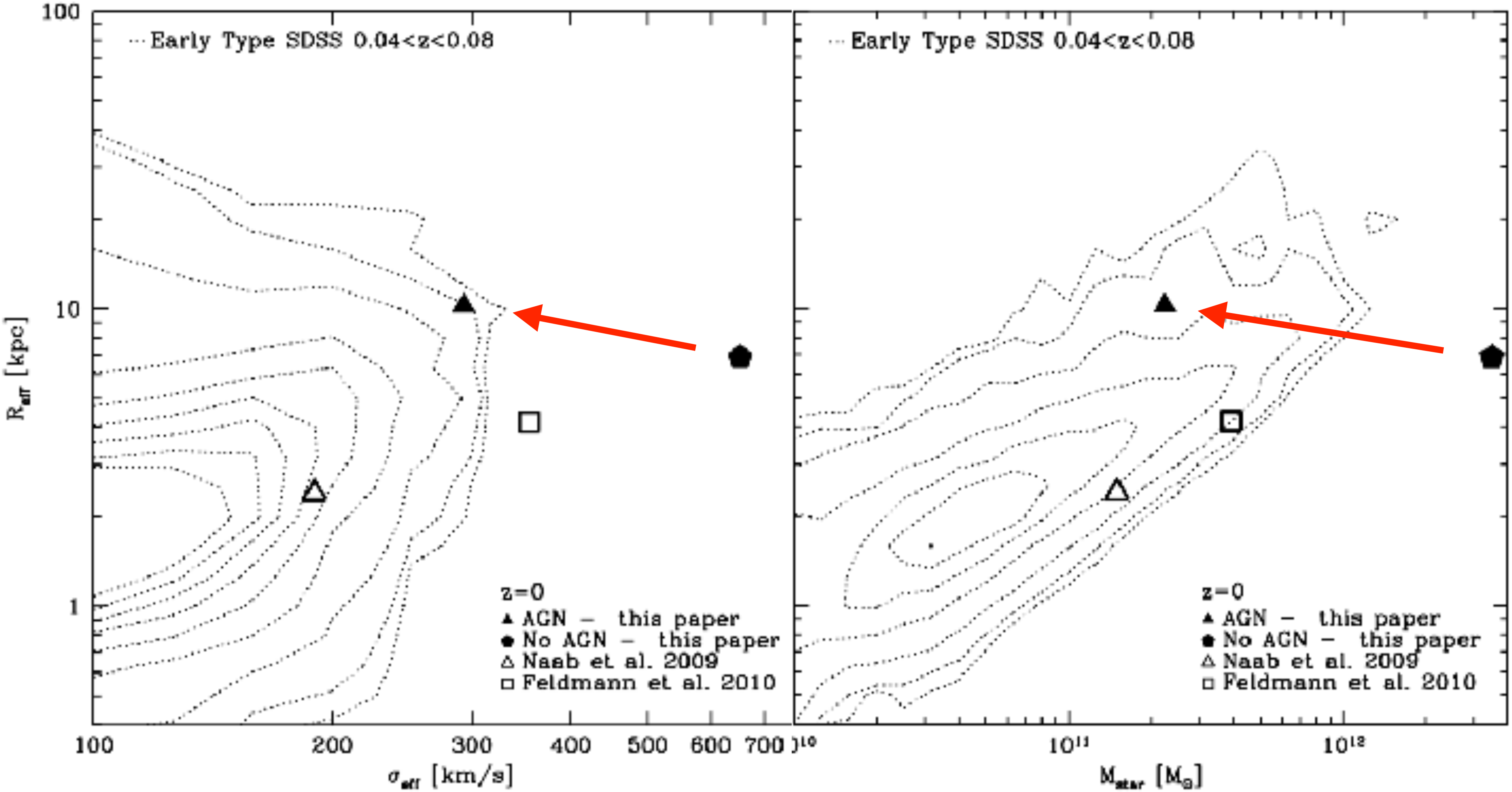
Feedback performed using a thermal dump $$\Delta E = \epsilon_c \epsilon_{\rm r} \dot{M}_{\rm acc} c^2 \Delta t.$$

Free parameter epsilon_c and alpha_boost calibrated on the M_BH-sigma and M_star-M_halo relations.

Galaxy formation on cluster scales



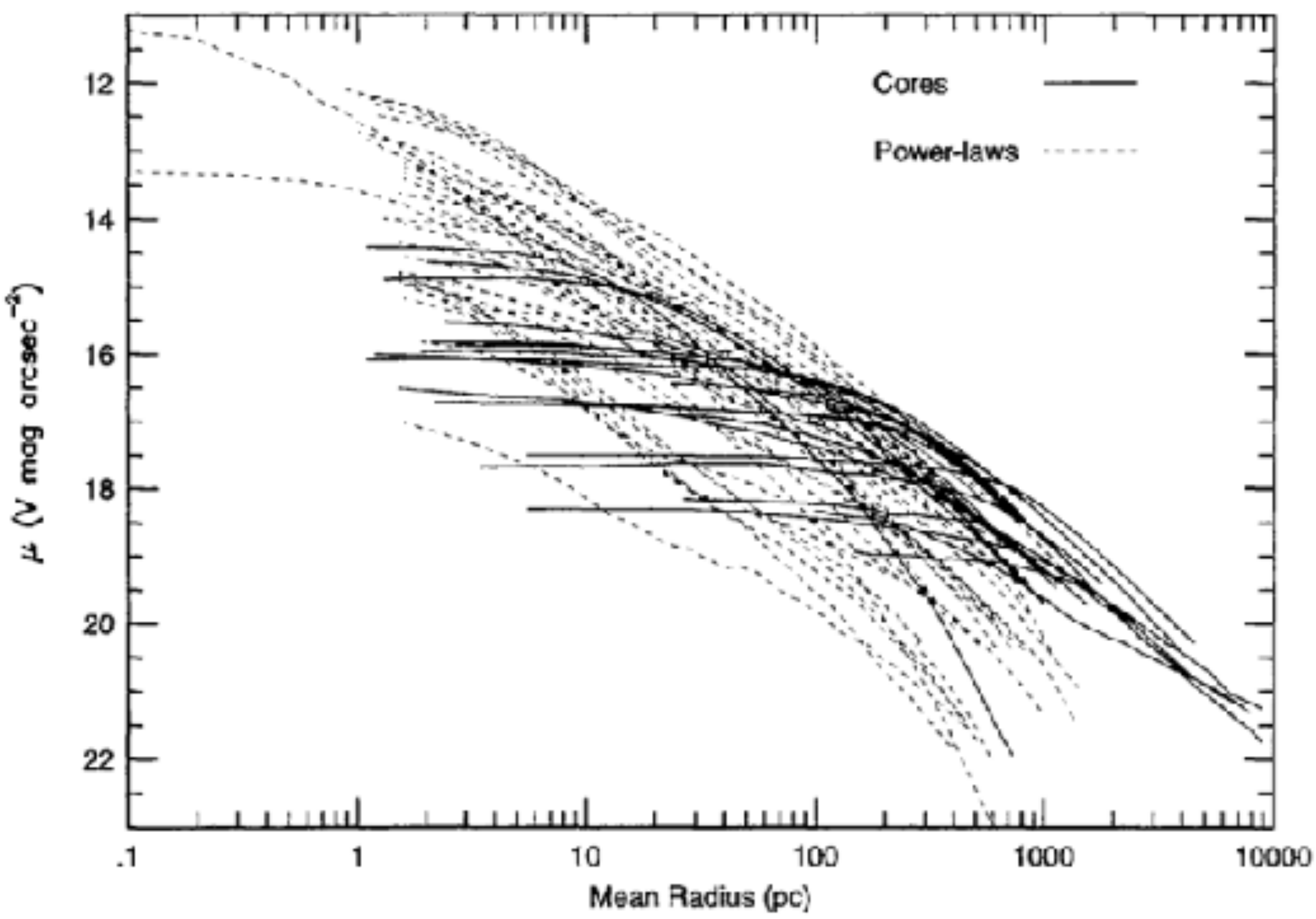
AGN feedback modifies the BCG properties



Booth & Schaye 10; Teyssier+10; Sembolini+11; Dubois+10,11; Martizzi+11

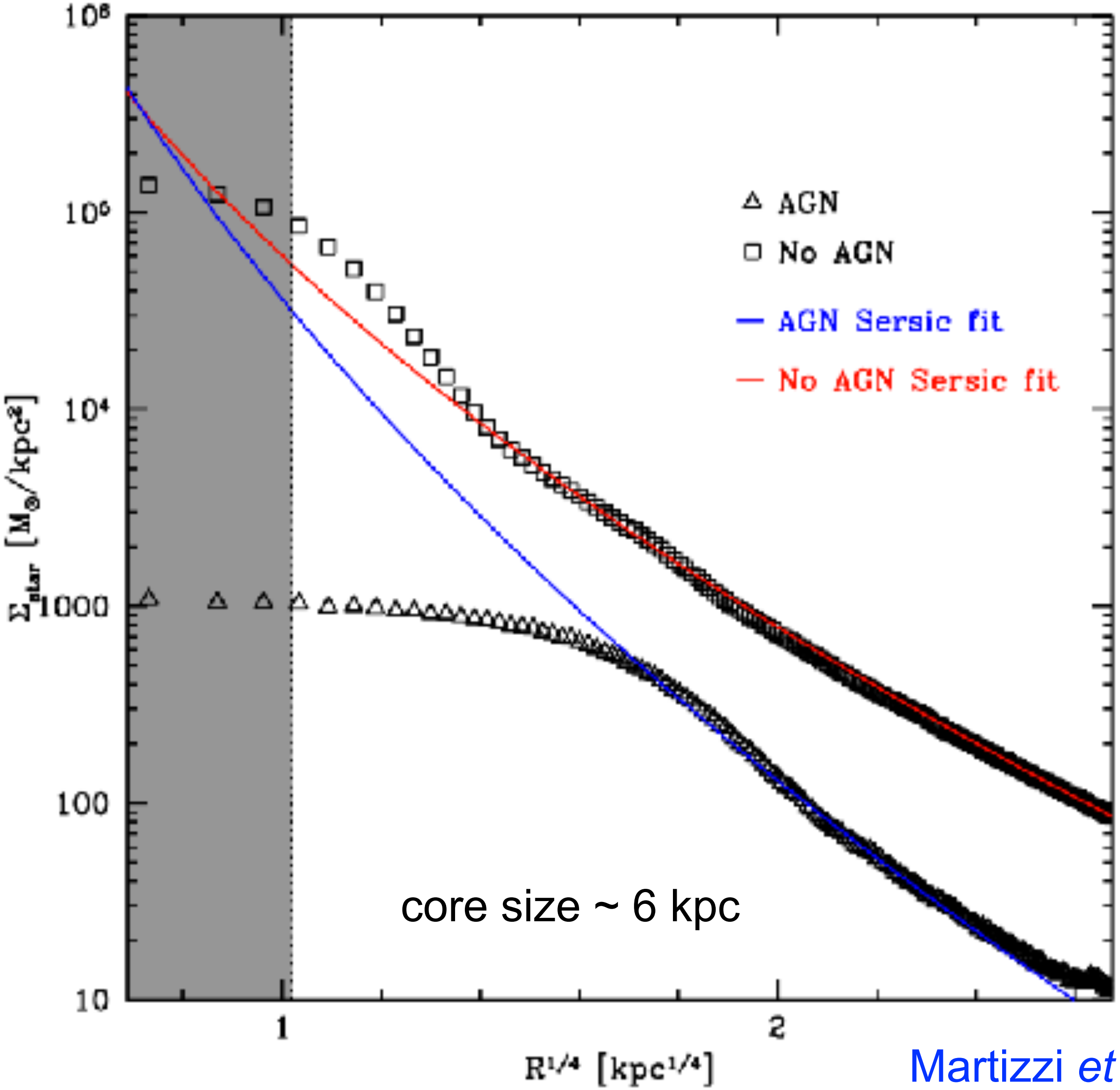
A dichotomy in the structure of elliptical galaxies

1774 FABER *ET AL.*: EARLY-TYPE GALAXIES. IV.



Faber et al. 1997

Structural properties of the BCG



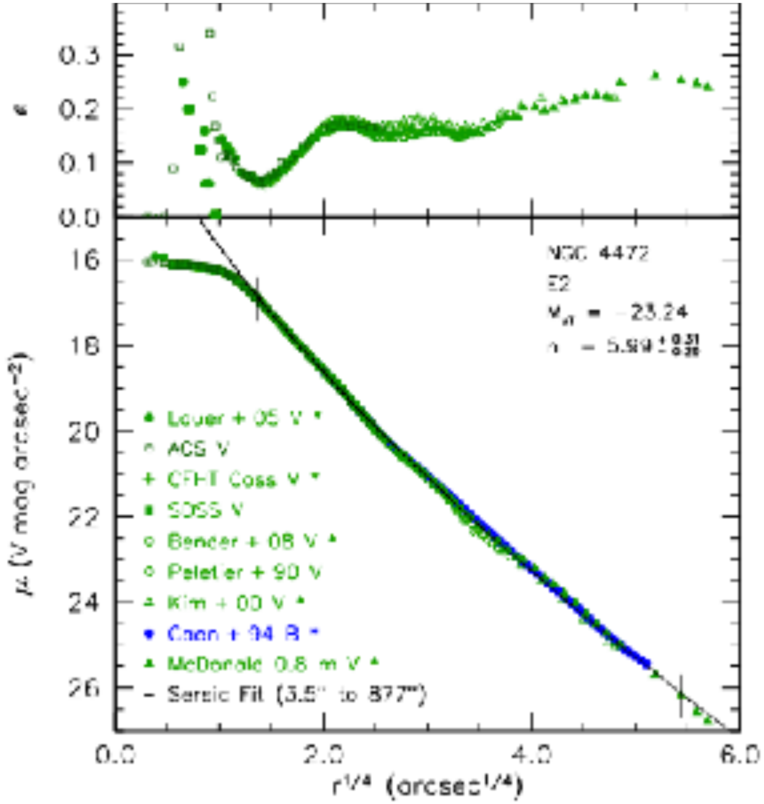
core size ~ 6 kpc

Martizzi *et al.* 2011

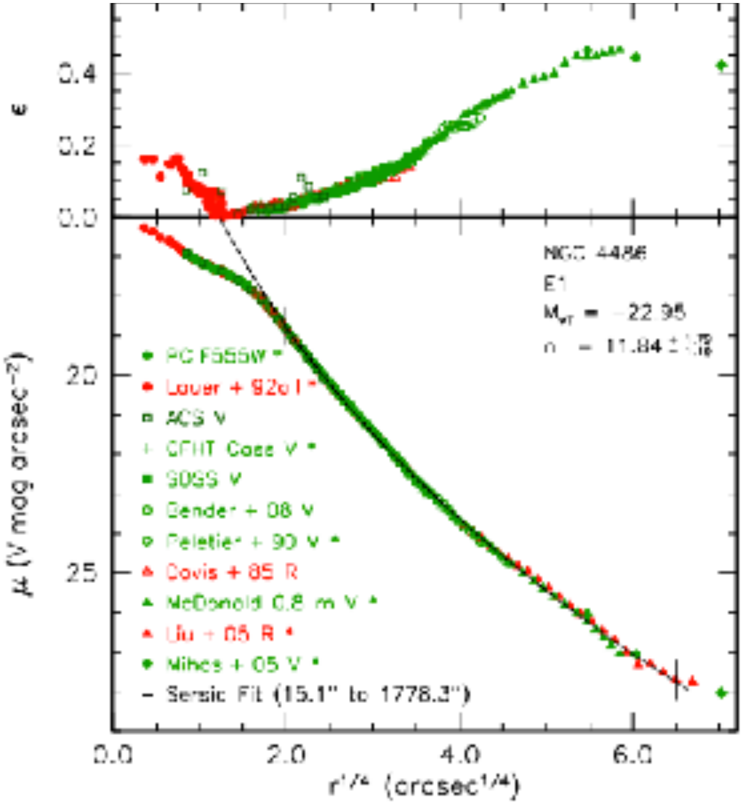
A stellar core in massive elliptical galaxies

Core elliptical: light deficit, low ellipticity, slow rotator

Kormendy *et al.* 2009

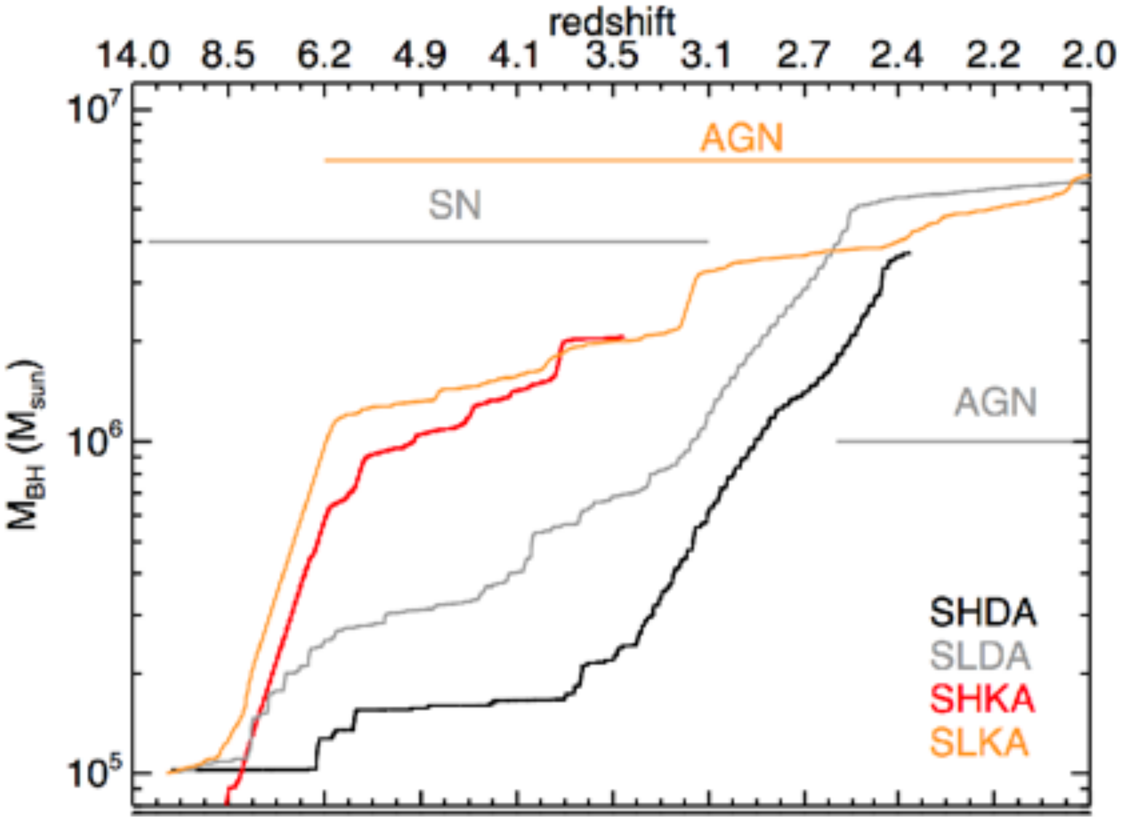


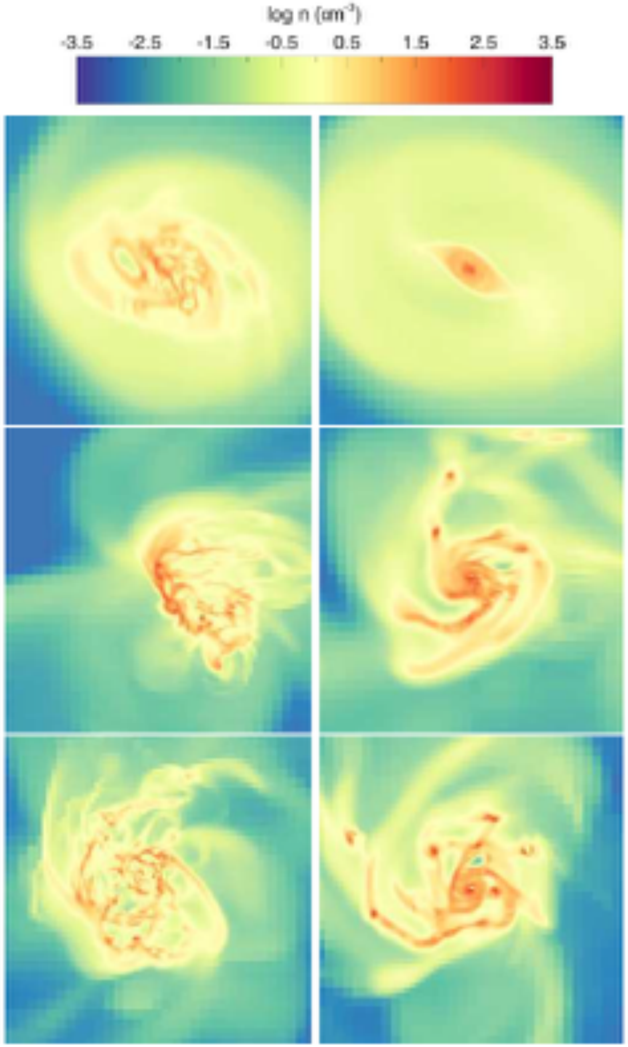
core size ~ 0.5 kpc



core size ~ 3 kpc

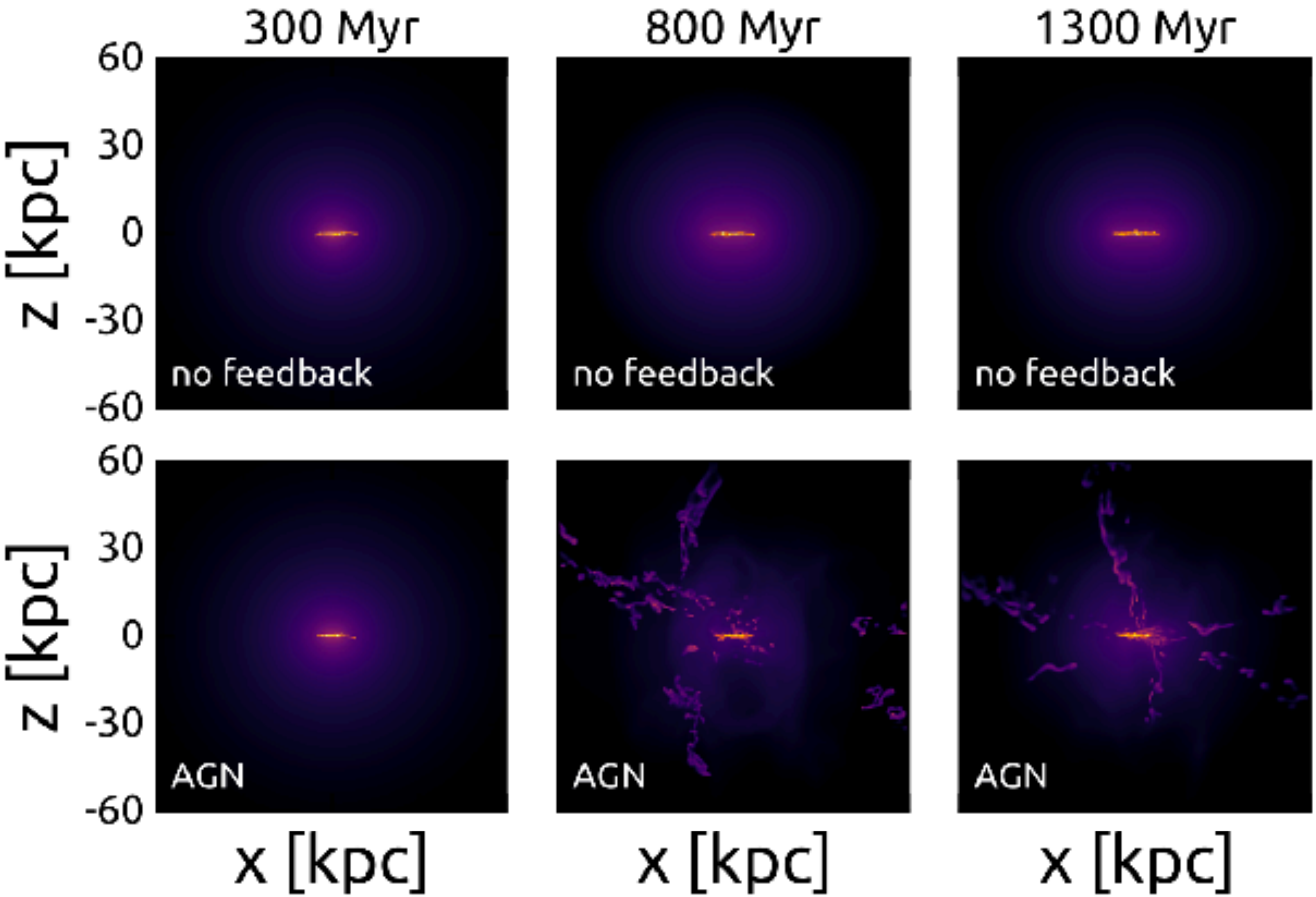
SN feedback limits SMBH growth



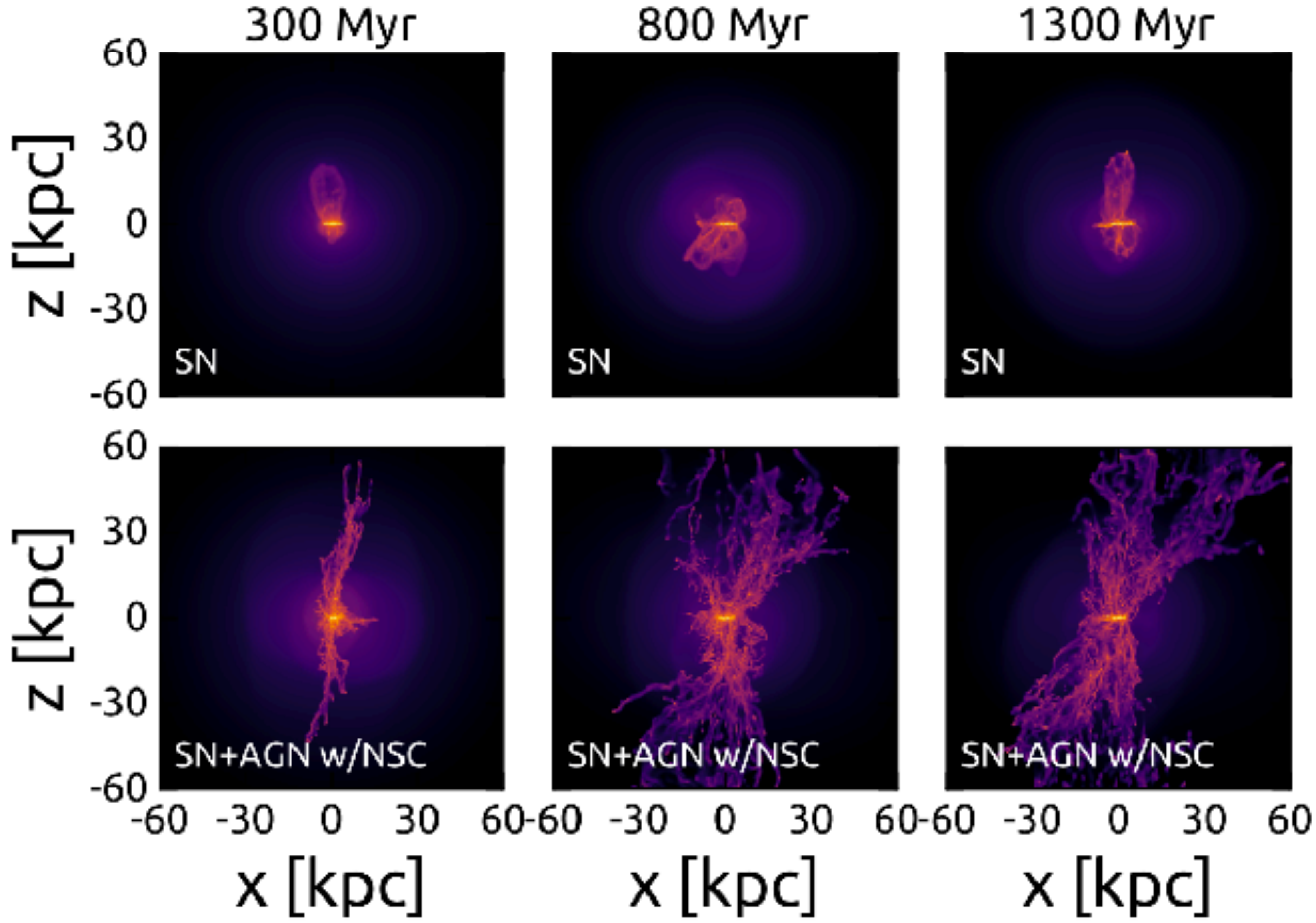


Dubois et al. 2015

Combined SN/AGN feedback to launch massive outflows



Combined SN/AGN feedback to launch massive outflows



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