Cosmological simulations of galaxy formation

Romain Teyssier

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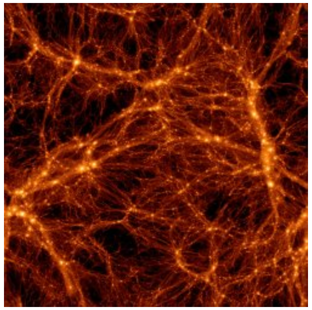
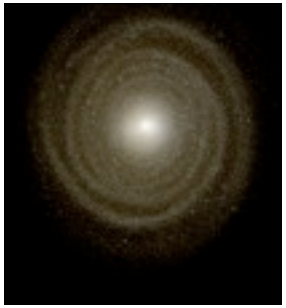
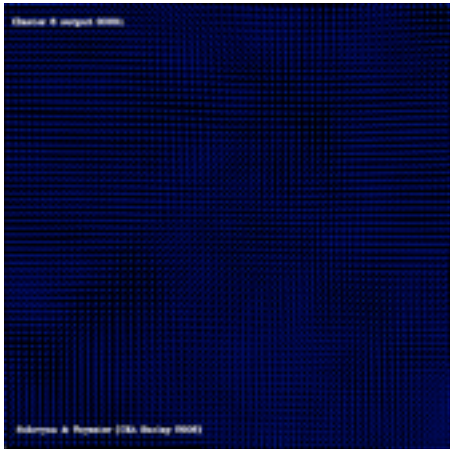




Galaxy formation for dummies

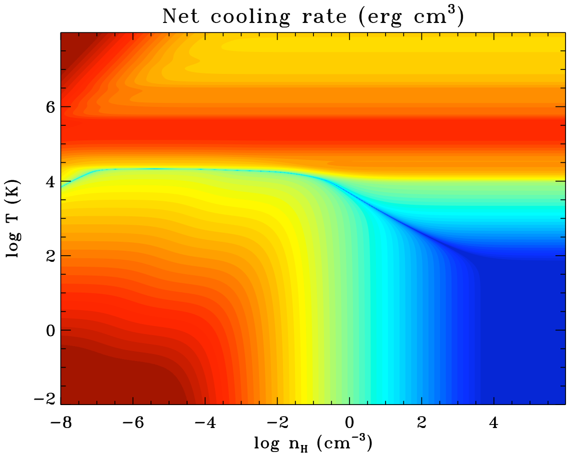
Formation of slowly rotating dark matter halos

- spin from tidal torques
- statistical Virial equilibrium



Hot gas settles in thermal equilibrium

$$\frac{3}{2}\frac{k_B T_{gas}}{\mu m_H} = \frac{1}{2}\frac{G M_{halo}}{R_{halo}}$$



Radiative cooling dissipates pressure support, dense gas discs settle into centrifugal equilibrium: radiative atomic physics sets the galaxy mass.

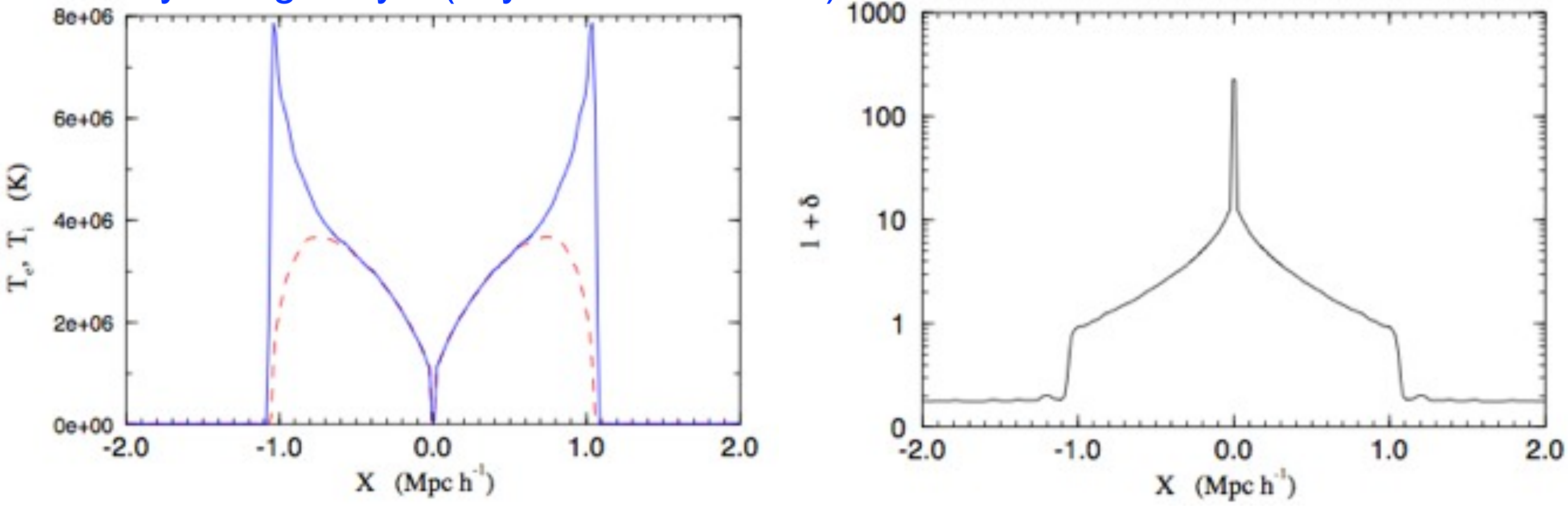
$$\mathcal{I}_0 = 13.6 \text{ eV} \qquad M_{\text{galaxies}} \simeq 10^{11} \ M_\odot$$

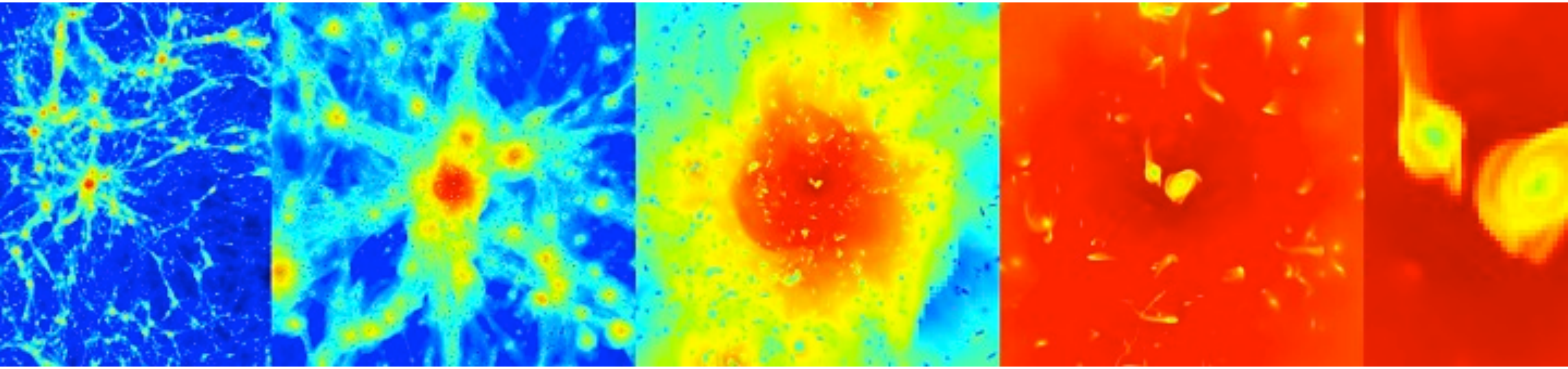
White and Rees (1978); Dekel and Silk (1986)

Disc galaxies form from quiescent gas accretion history, while elliptical galaxies form out of violent mergers.

From pancake collapse to the Cosmic Web

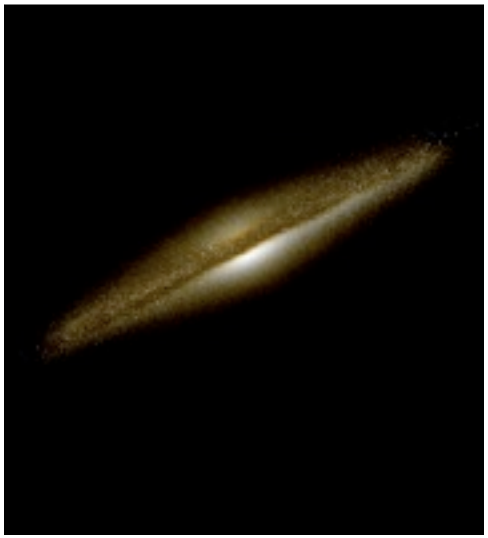
My first galaxy... (Teyssier et al. 1997)

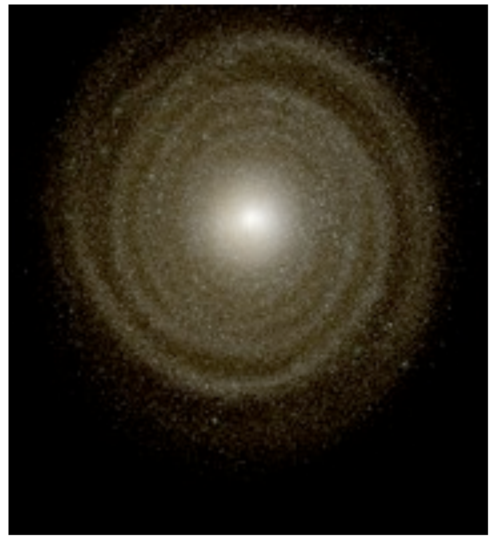




Mare Nostrum simulation (Ocvirk et al. 2008)

Modern galaxy formation simulations





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

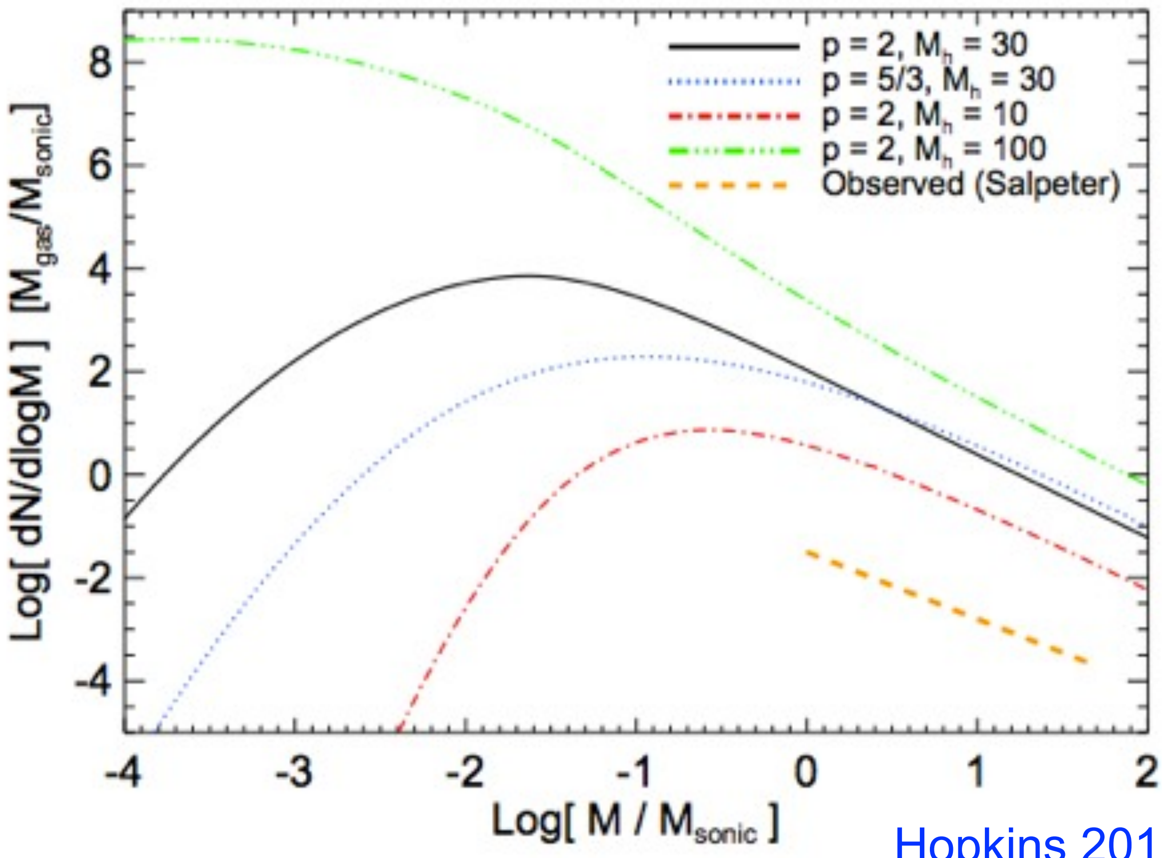
NGC4622 as seen from HST

Outline

- Impact of star formation recipe
- Impact of code type
- Modeling stellar thermal feedback
- Impact of feedback for dwarf galaxies
- Modeling stellar radiation feedback
- Modeling feedback from AGN
- Impact of feedback for massive galaxies

Star formation: what do we know ?

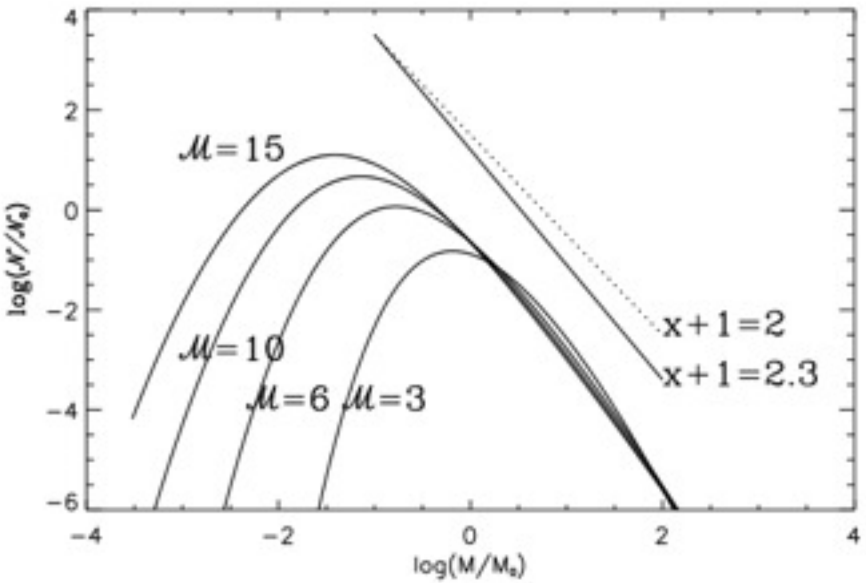
My favorite theory for star formation: gravo-turbulent fragmentation.
Turbulence in the ISM determines ultimately the mass spectrum of molecular cores (CMF) and stars therein (IMF) (Hennebelle & Chabrier 2008; Hopkins 2010)



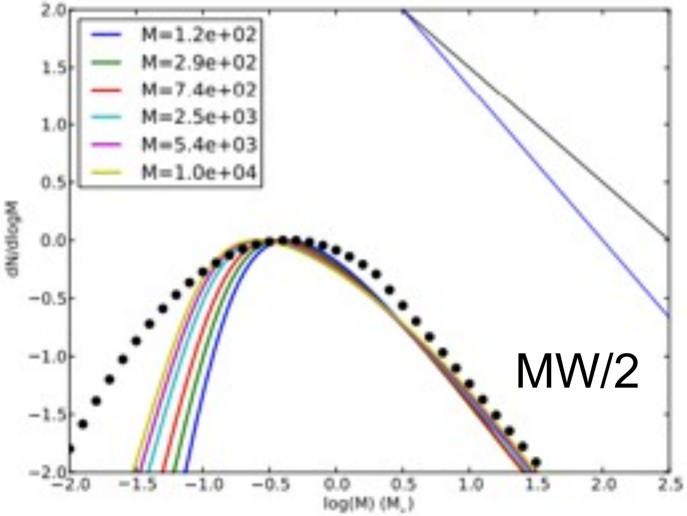
Hopkins 2010

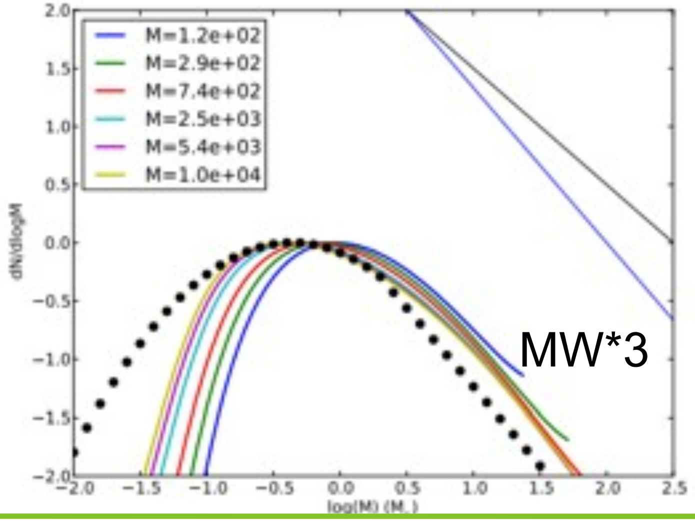
The IMF is (probably) not universal

In galaxy formation, we have a wide range of physical parameters for turbulence: various Mach number, various FUV and cosmic rays fluxes.



Effect of the Mach number
Hennebelle & Chabrier 2008



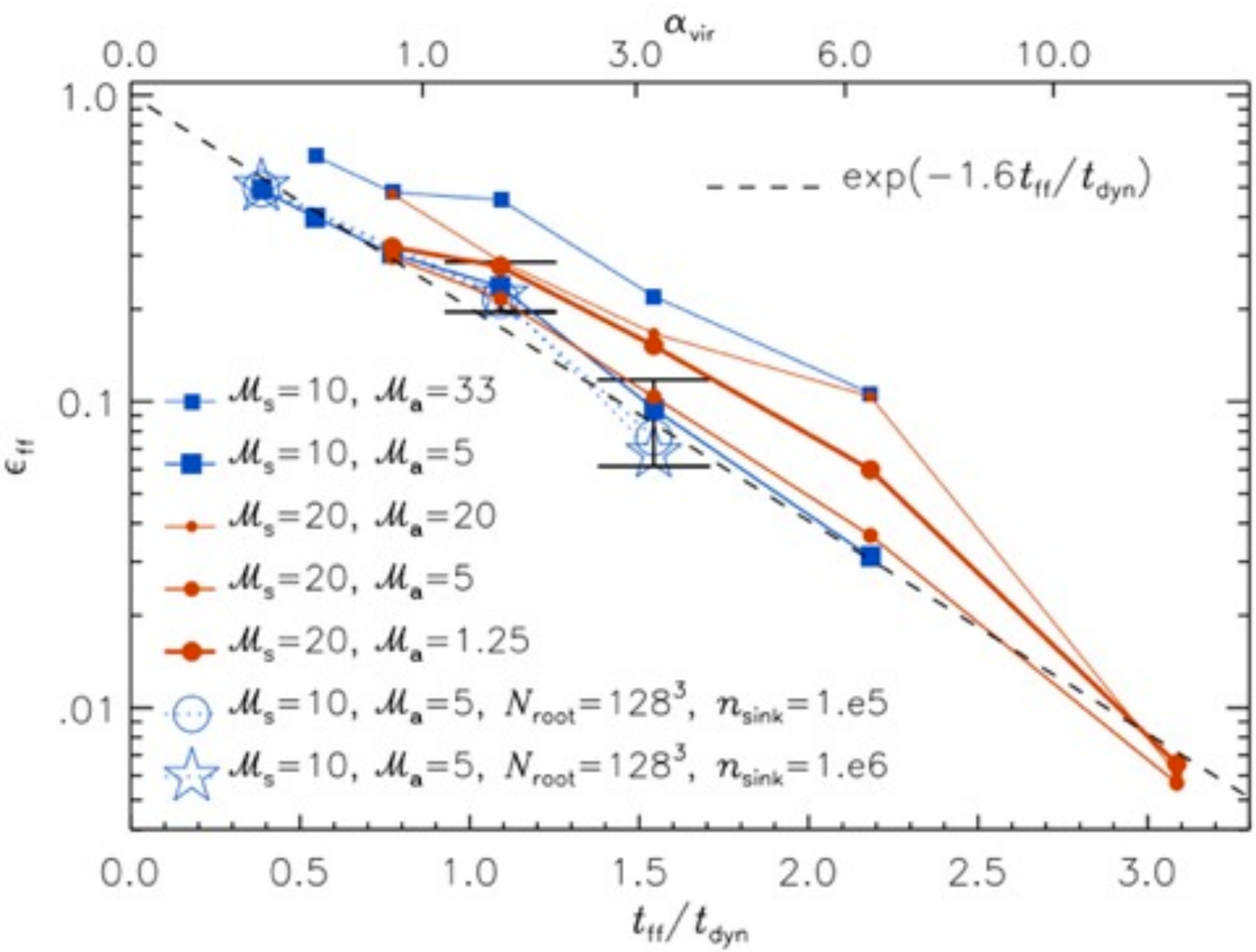


Effect of the CR flux
Hennebelle 2012

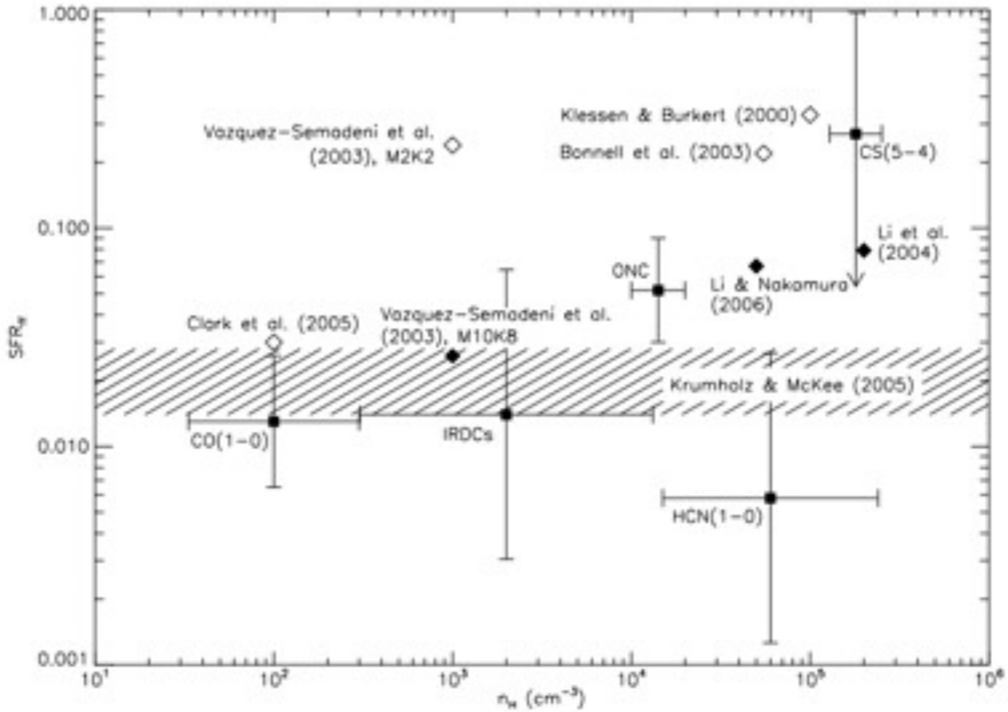
Star formation recipe

SFR per free-fall time parametrized by the *efficiency parameter* ε_{ff}

Magnetized gravito-turbulence simulations predict a rather simple law.
Padoan, Haugbolle & Nordlund (2012)



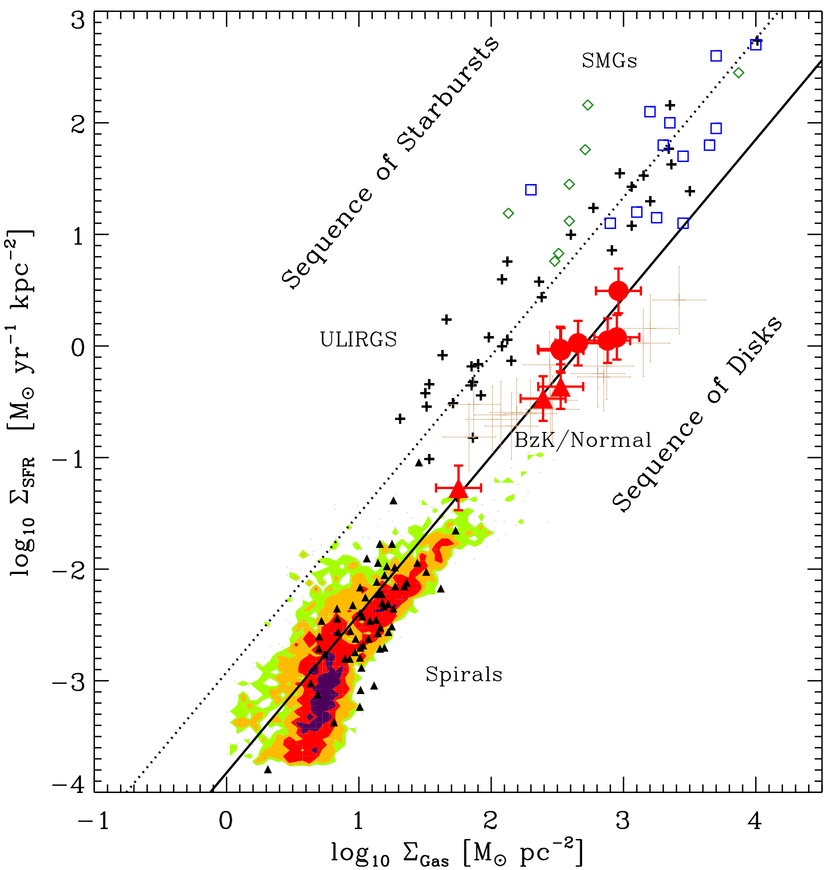
Star formation recipe



Schmidt law for star formation:

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

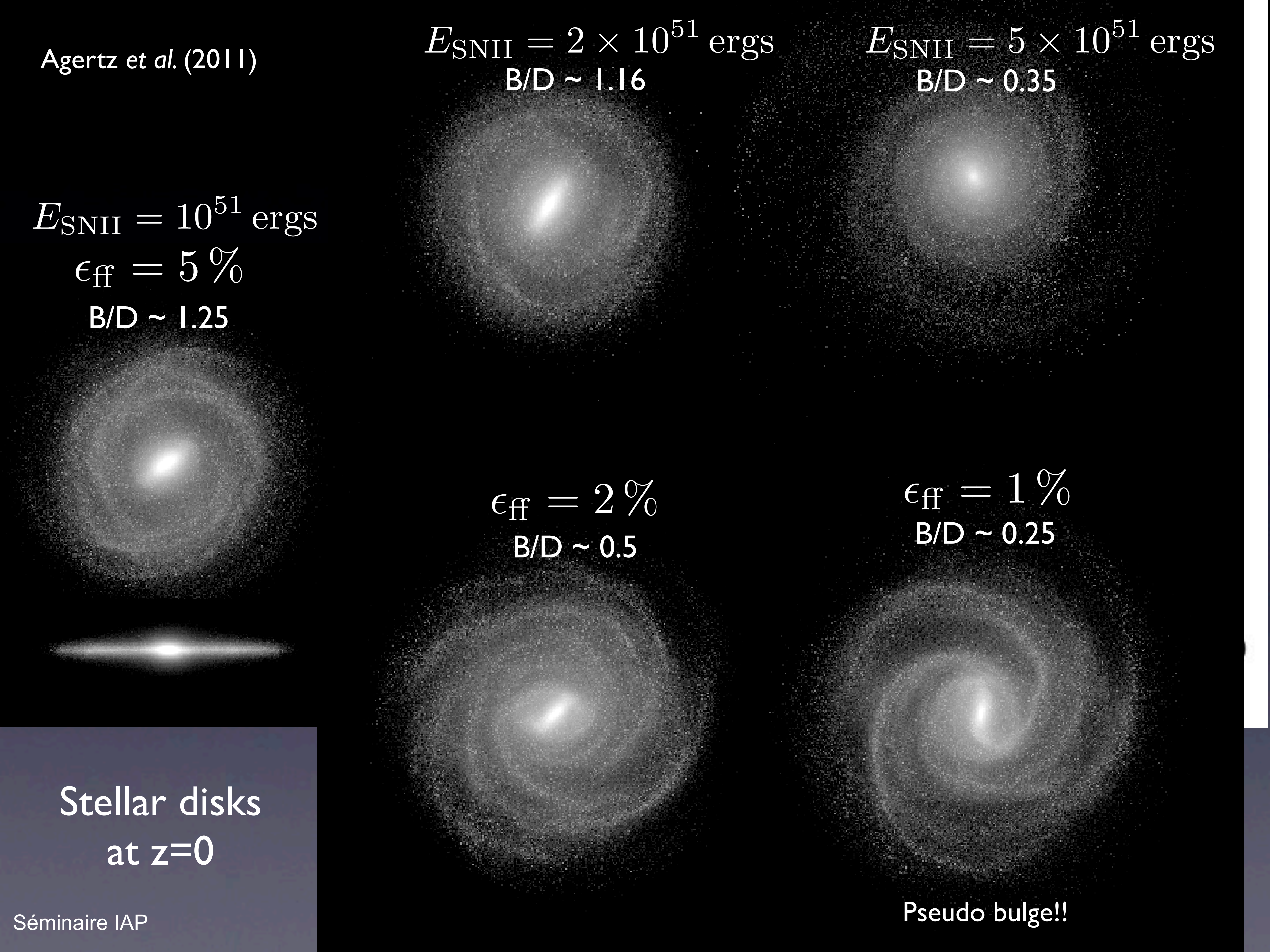
Krumholz & Tan (2007)



Parameters are calibrated on the Kennicutt (1998) relation

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

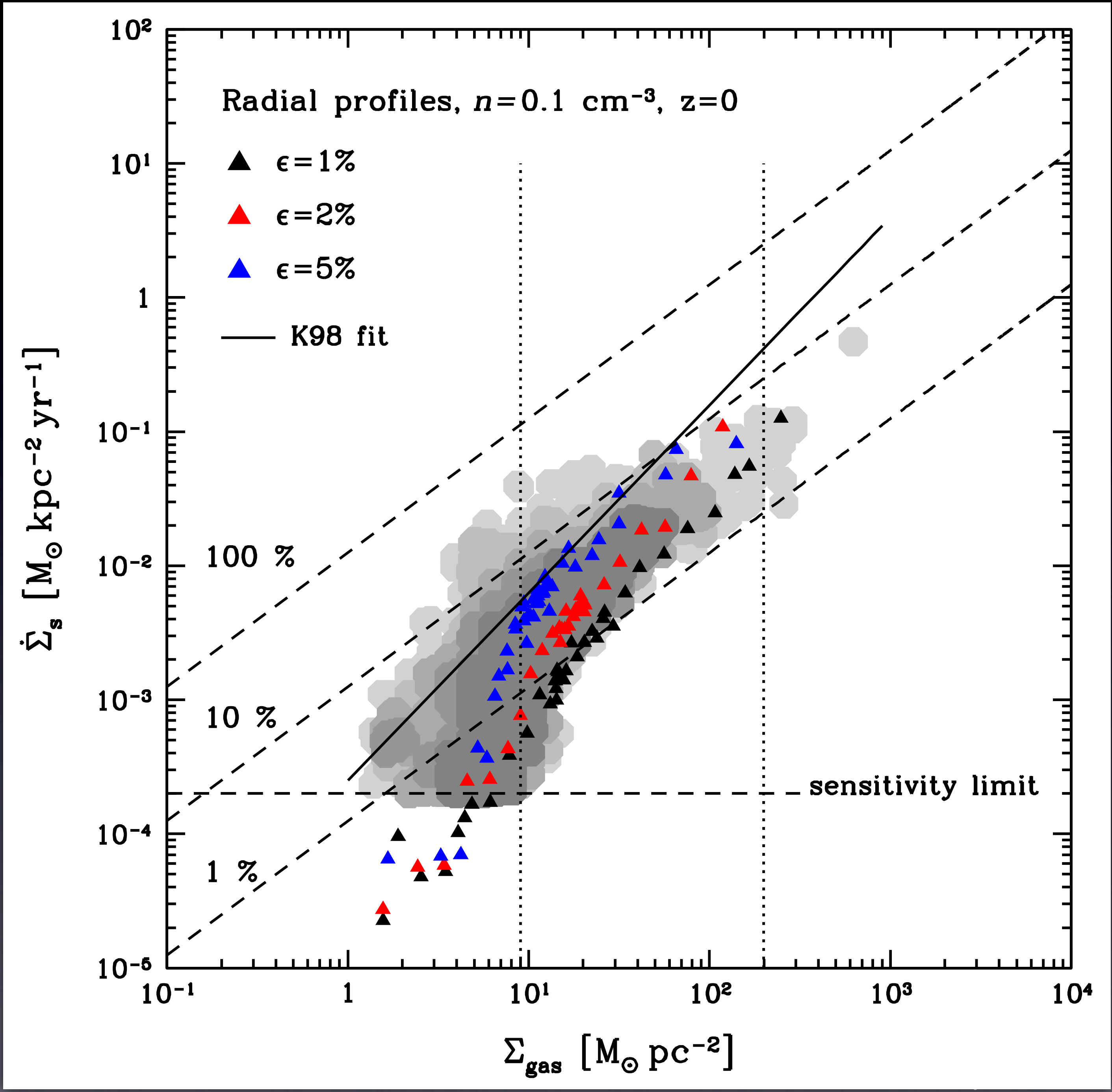
Daddi et al. (2010)


Agertz et al. (2011)
$E_{\mathrm{SNII}} = 2 \times 10^{51}$ ergs
B/D ~ 1.16
$E_{\mathrm{SNII}} = 5 \times 10^{51}$ ergs
B/D ~ 0.35
$E_{\mathrm{SNII}} = 10^{51}$ ergs
$\epsilon_{\mathrm{ff}} = 5\,\%$
B/D ~ 1.25
$\epsilon_{\mathrm{ff}} = 2\,\%$
B/D ~ 0.5
$\epsilon_{\mathrm{ff}} = 1\,\%$
B/D ~ 0.25
Pseudo bulge!!
Stellar disks
at z=0
Séminaire IAP

Agertz *et al.* (2011)

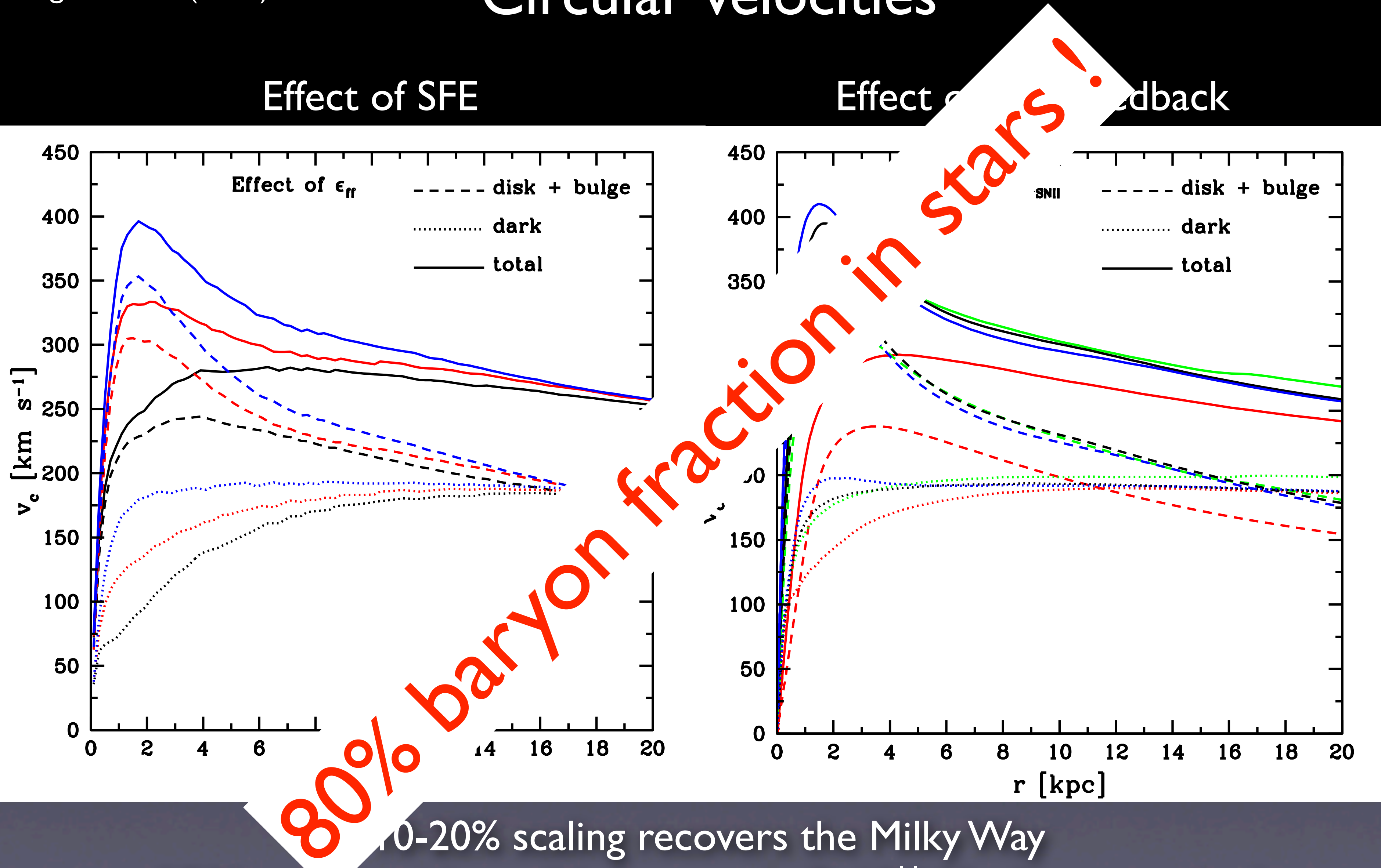
Observe simulated disks @ z=0

Kennicutt-Schmidt relation + THINGS data (Bigiel et al. 2008)



Agertz *et al.* (2011)

Circular velocities



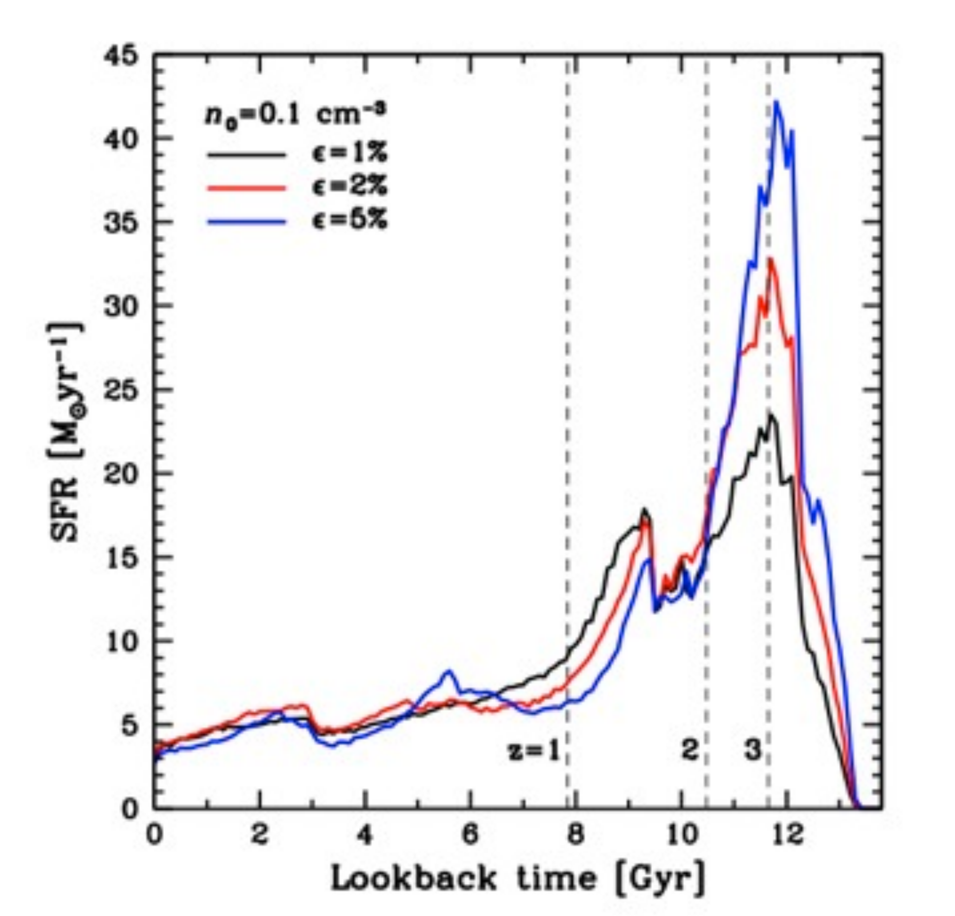
…10-20% scaling recovers the Milky Way

MW models with small halo mass (~ 7×10^{11} Msol) are required

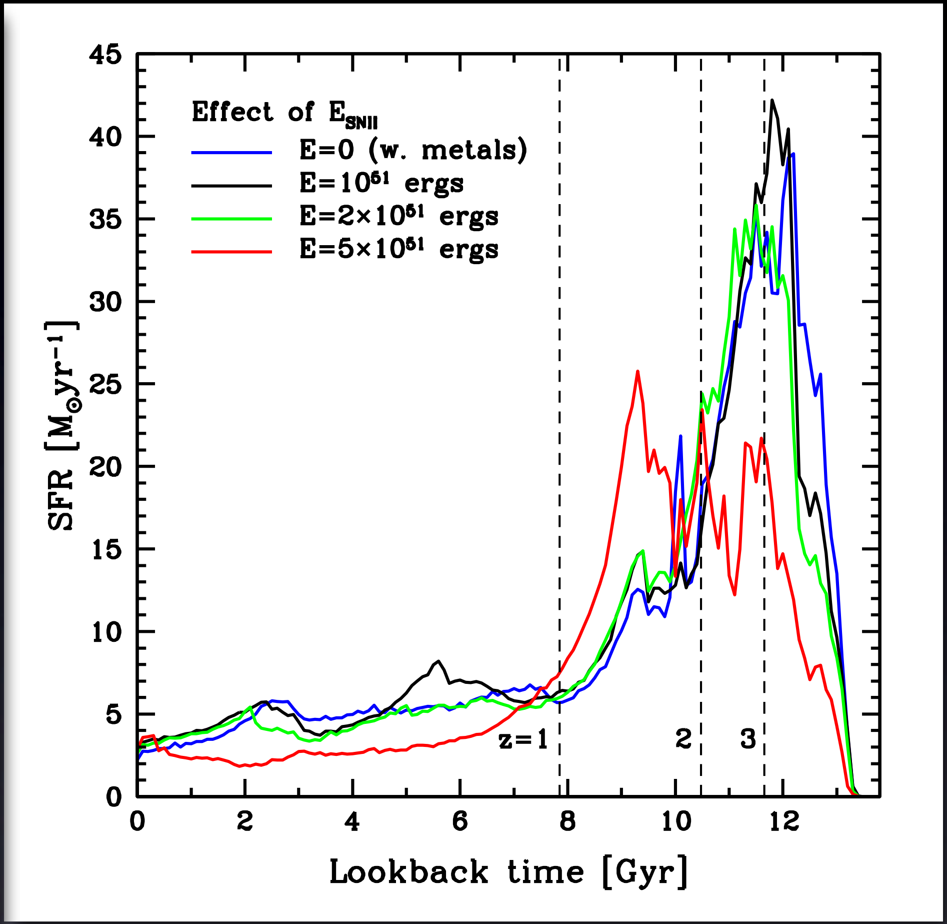
Agertz *et al.* (2011)

Star formation histories

Effect of SFE

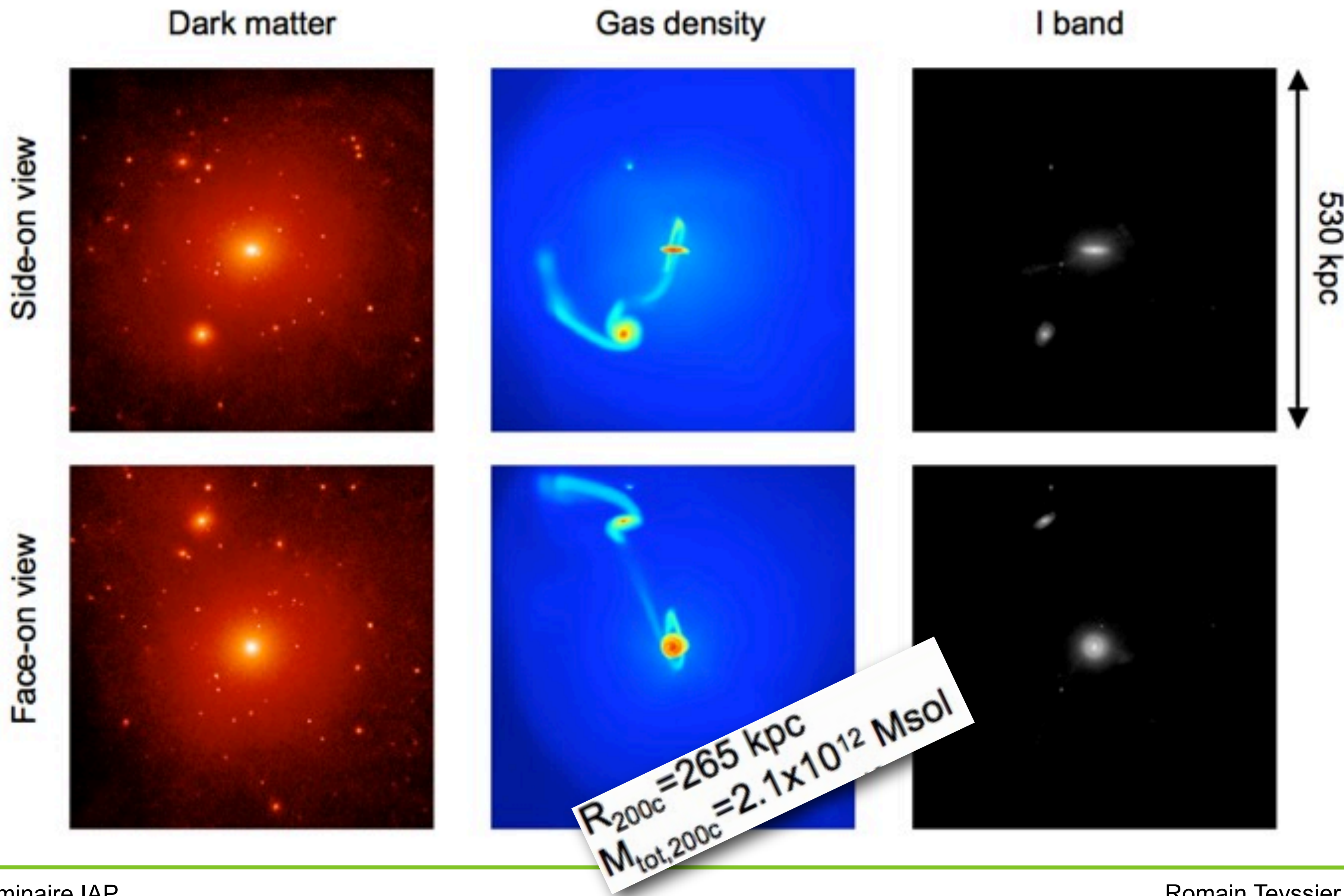


Effect of SNe feedback



The Aquila comparison project

Scannapieco *et al.* (2012) arxiv/1112.0315



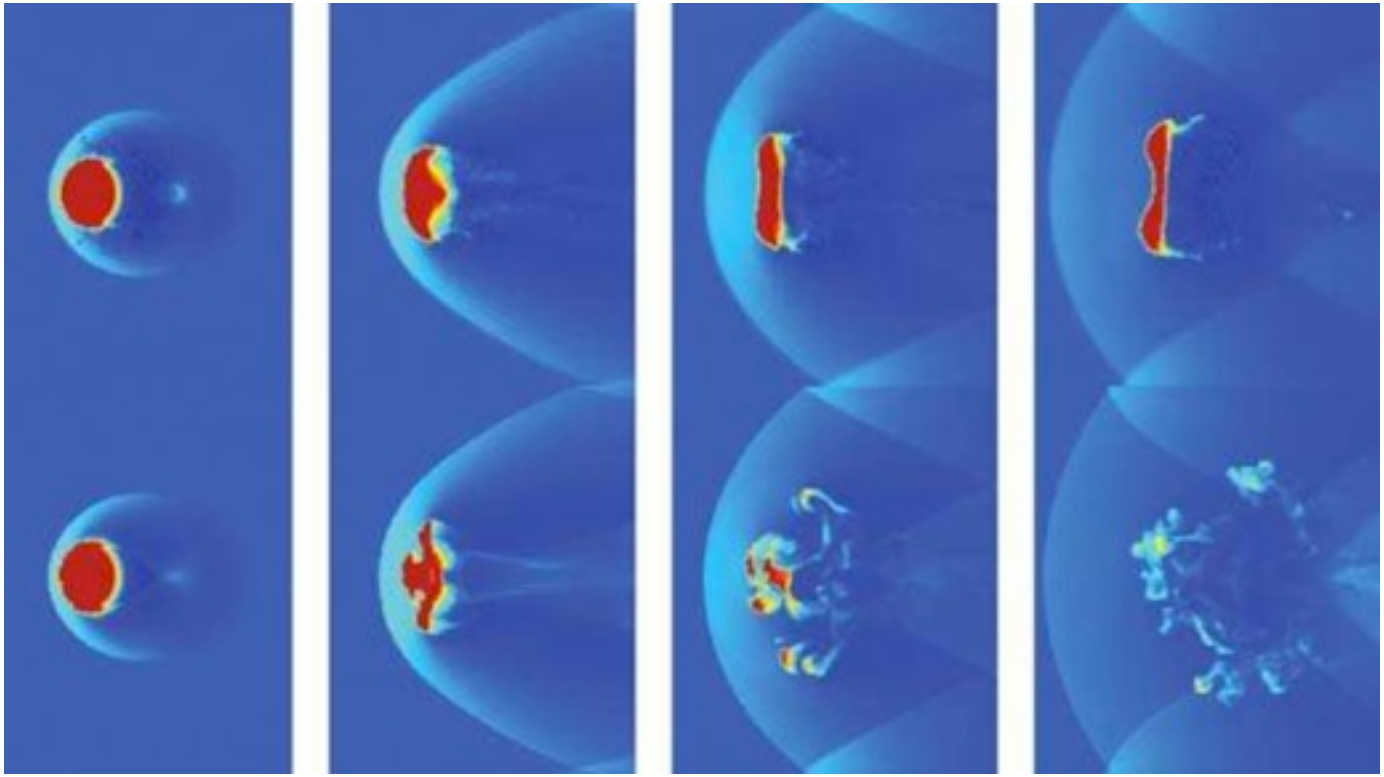
The Aquila project: varying codes and physics

TABLE 1
SUMMARY OF CODE CHARACTERISTICS AND IMPLEMENTED PHYSICS.

Code	Reference	Type	UV background z_{UV}	UV background spectrum	Cooling	Feedback
G3 (GADGET3)	[1]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-BH	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH
G3-CR	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH, CR
G3-CS	[2]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
G3-TO	[3]	SPH	9	[11]	metal-dependent [15]	SN (thermal+kinetic)
G3-GIMIC	[4]	SPH	9	[11]	metal-dependent [15]	SN (kinetic)
G3-MM	[5]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-CK	[6]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
GAS (GASOLINE)	[7]	SPH	10	[12]	metal-dependent [16]	SN (thermal)
R (RAMSES)	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-LSFE	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-AGN	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal), BH
Arepo	[9]	Moving Mesh	6	[10]	primordial [12]	SN (thermal)

NOTE. — [1] Springel et al. (2008); [2] Scannapieco et al. (2005); Scannapieco et al. (2006); [3] Okamoto et al. (2010); [4] Crain et al. (2009); [5] Murante et al. (2010); [6] Kobayashi (2007); [7] Stinson et al. (2006); [8] Teyssier (2002); Rasera & Teyssier (2006); Dubois & Teyssier (2008); [9] Springel (2010a); [10] Haardt & Madau (1996); [11] Haardt & Madau (2001); [12] Haardt & Madau (2005, private communication); [13] Katz et al. (1996); [14] Sutherland & Dopita (1993); [15] Wiersma et al. (2009a); [16] Shen et al (2010).

Galaxy formation codes: a few facts.



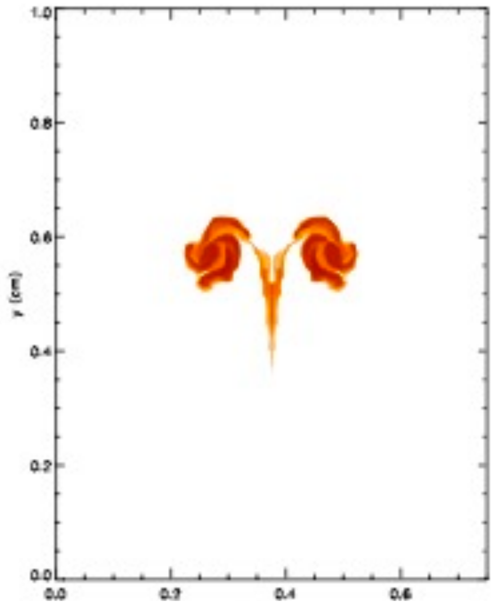
SPH (here GADGET2) cannot capture fluid instability correctly.

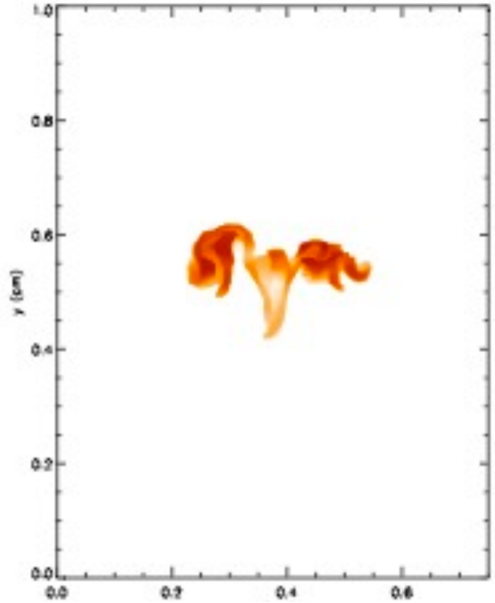
Blobs of gas survives for an artificial (infinite ?) long time to KH instability.

Agertz et al. (2007)

Galaxy formation codes: a few facts.

AMR

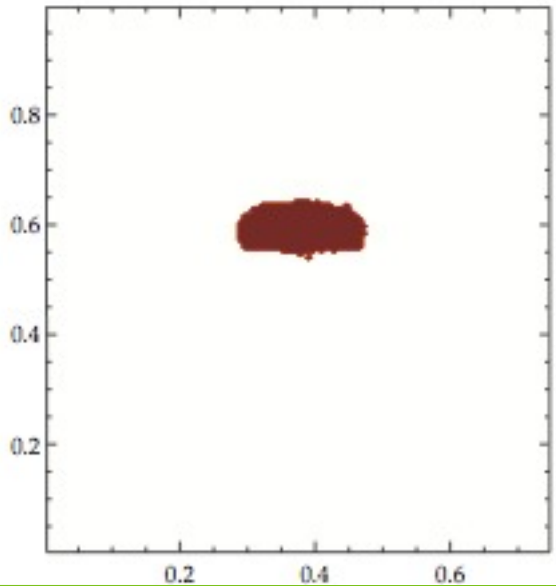


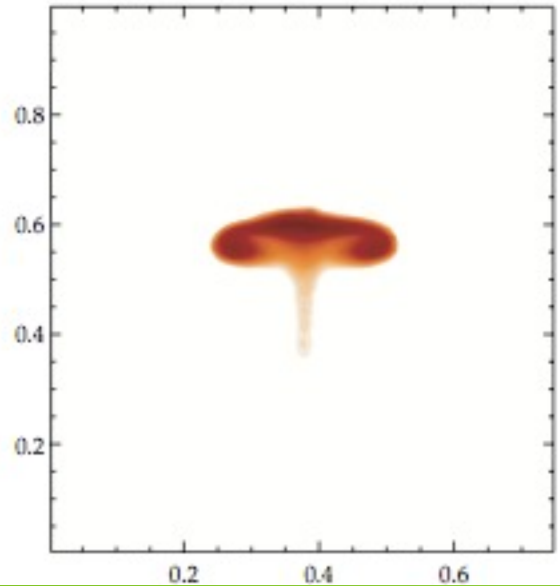


AMR with horizontal velocity: not strictly Galilean invariant

Wadsley et al. (2008), Price (2008)

standard SPH: strictly Galilean invariant





SPH with explicit entropy and mass diffusion

The Aquila project contenders

AREPO: moving mesh code (Springel 2010)

Lagrangian mesh points : Galilean invariance

Voronoï tessellation to define interfaces between finite volume elements. Based on the Godunov methodology: Riemann solver + slope limiter.

Feedback models similar to GADGET.

RAMSES: AMR Eulerian code (Teyssier 2002)

Different stellar feedback implementations, all inefficient at large halo masses.

AGN feedback model à la Booth & Schaye 2011

GASOLINE: standard SPH (Wadsley, Stadel & Quinn 2004)

Delayed cooling with blast wave model. Inefficient at large halo masses.

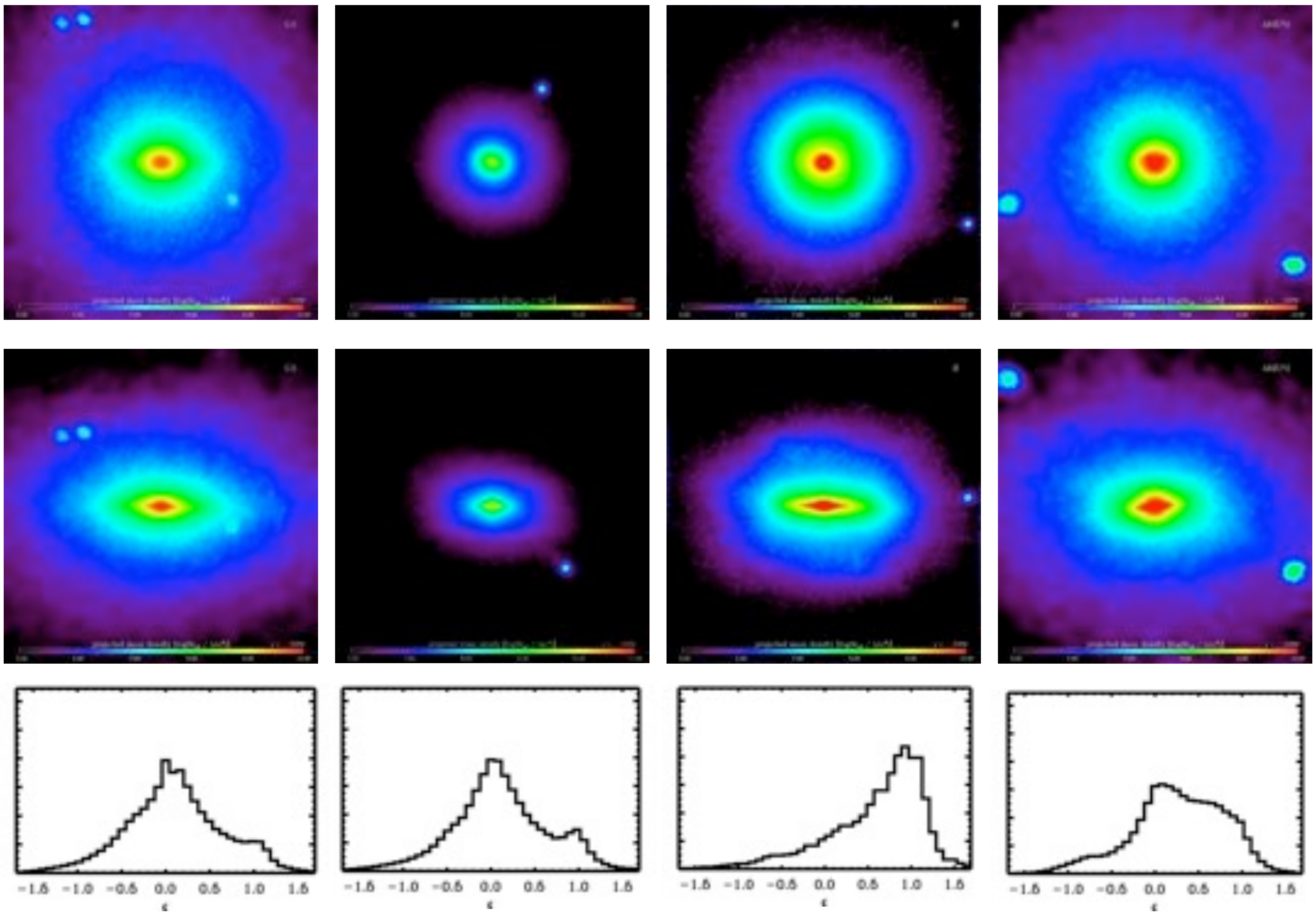
GADGET: standard SPH (Springel 2005)

Many different versions with various feedback recipe.

AGN feedback à la Sijacki et al.

Different codes, same physics, different morphologies...

GADGET GASOLINE RAMSES AREPO



face-on

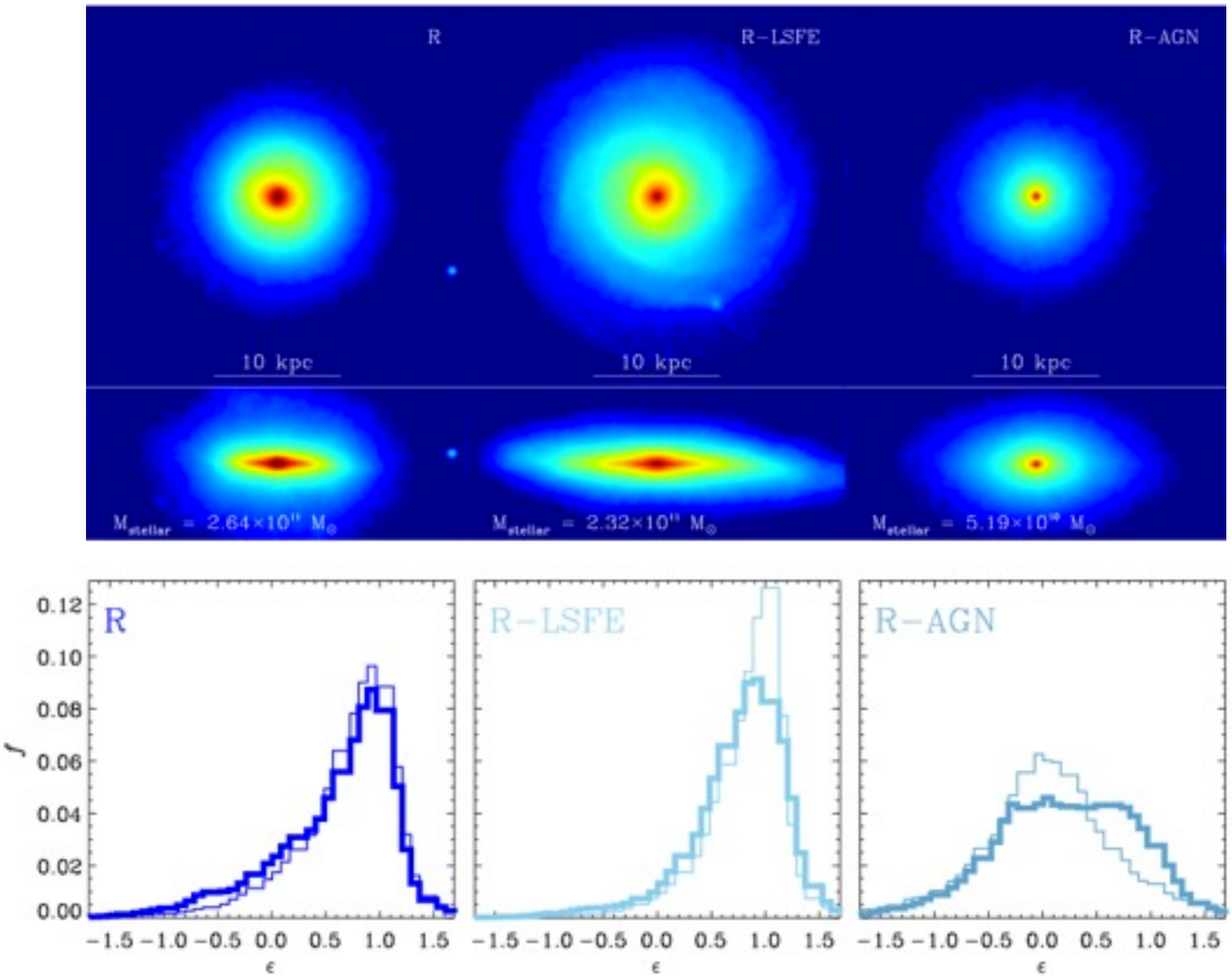
side-on

circularity

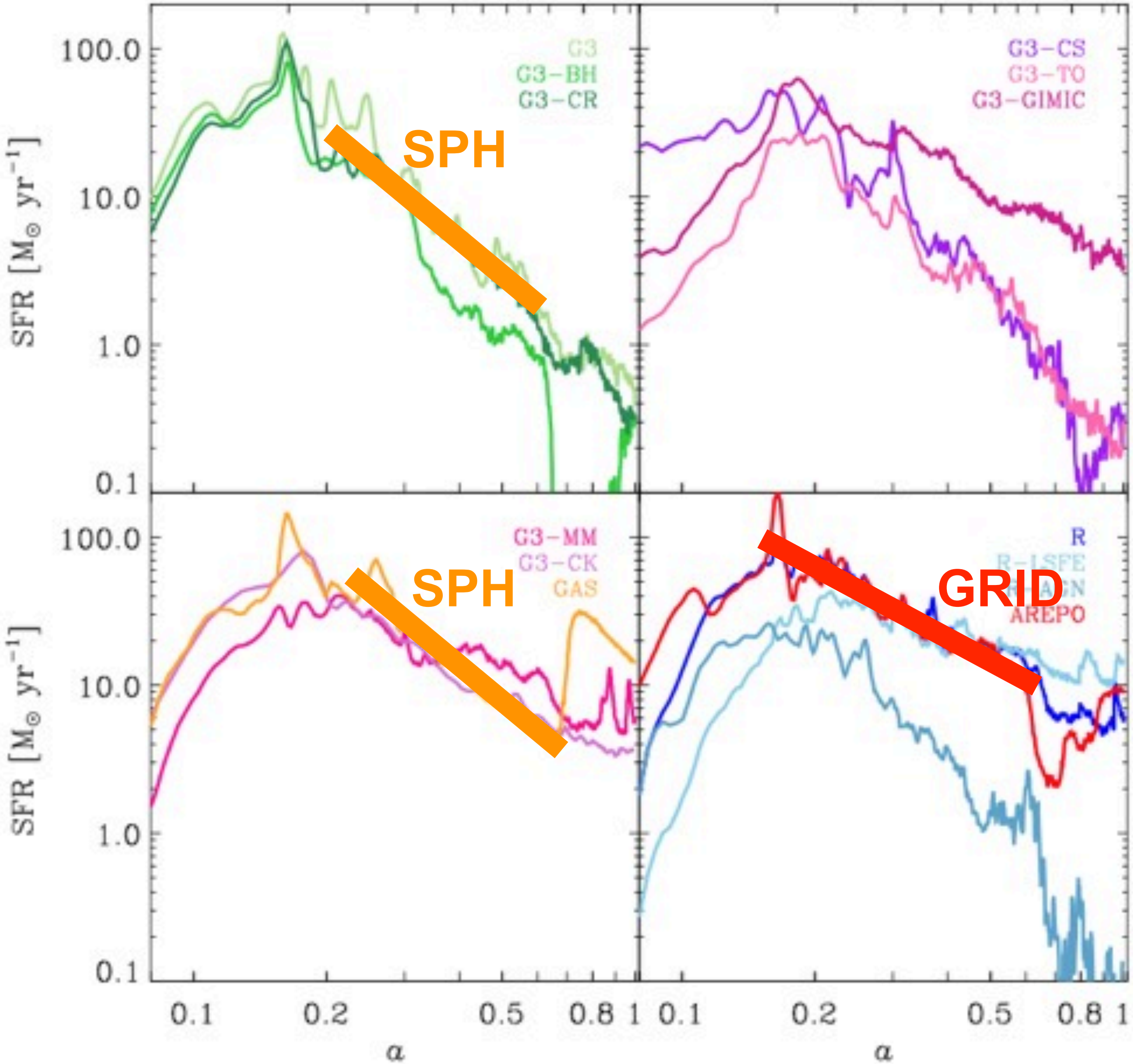
Low resolution runs

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

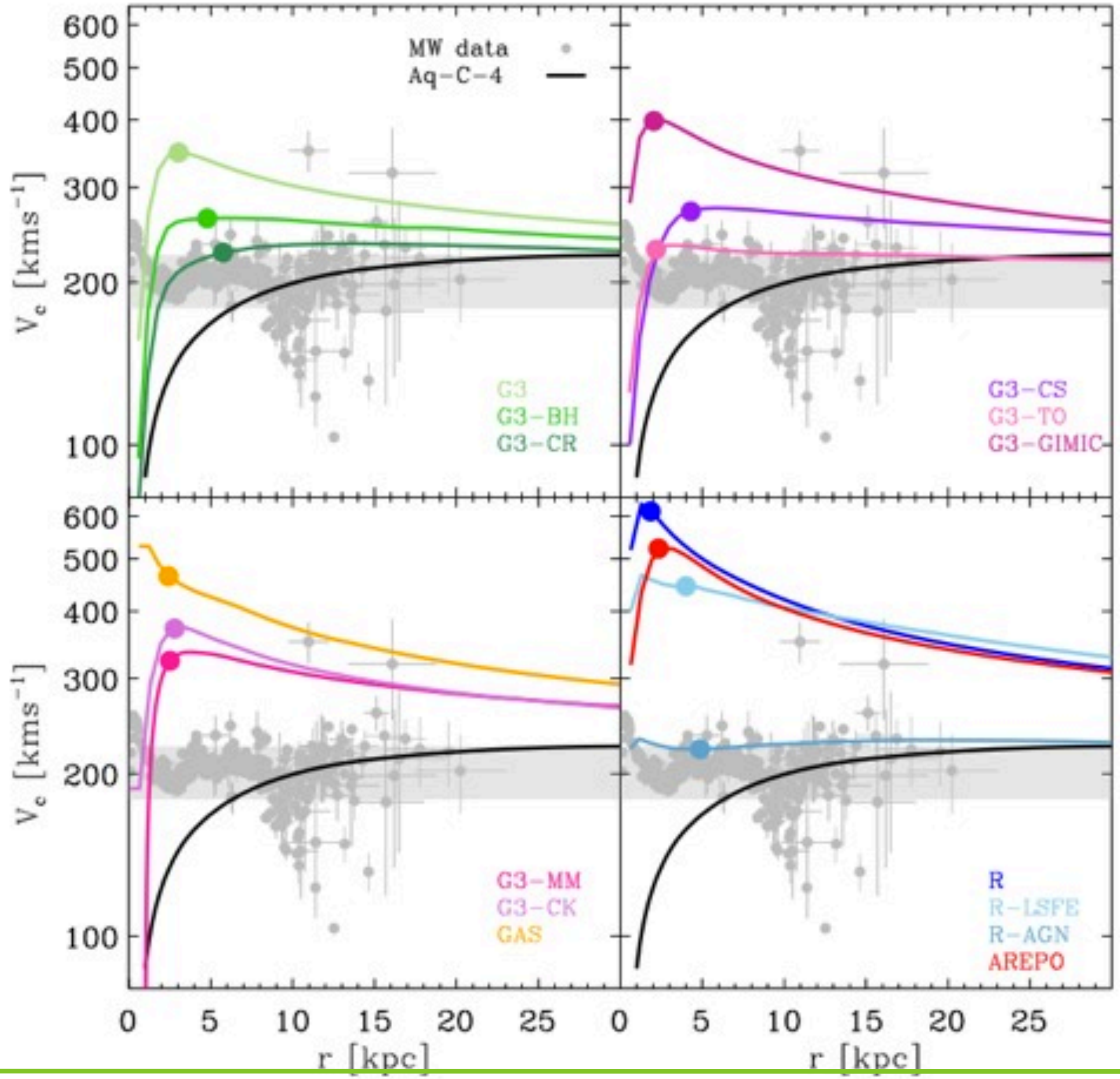
RAMSES



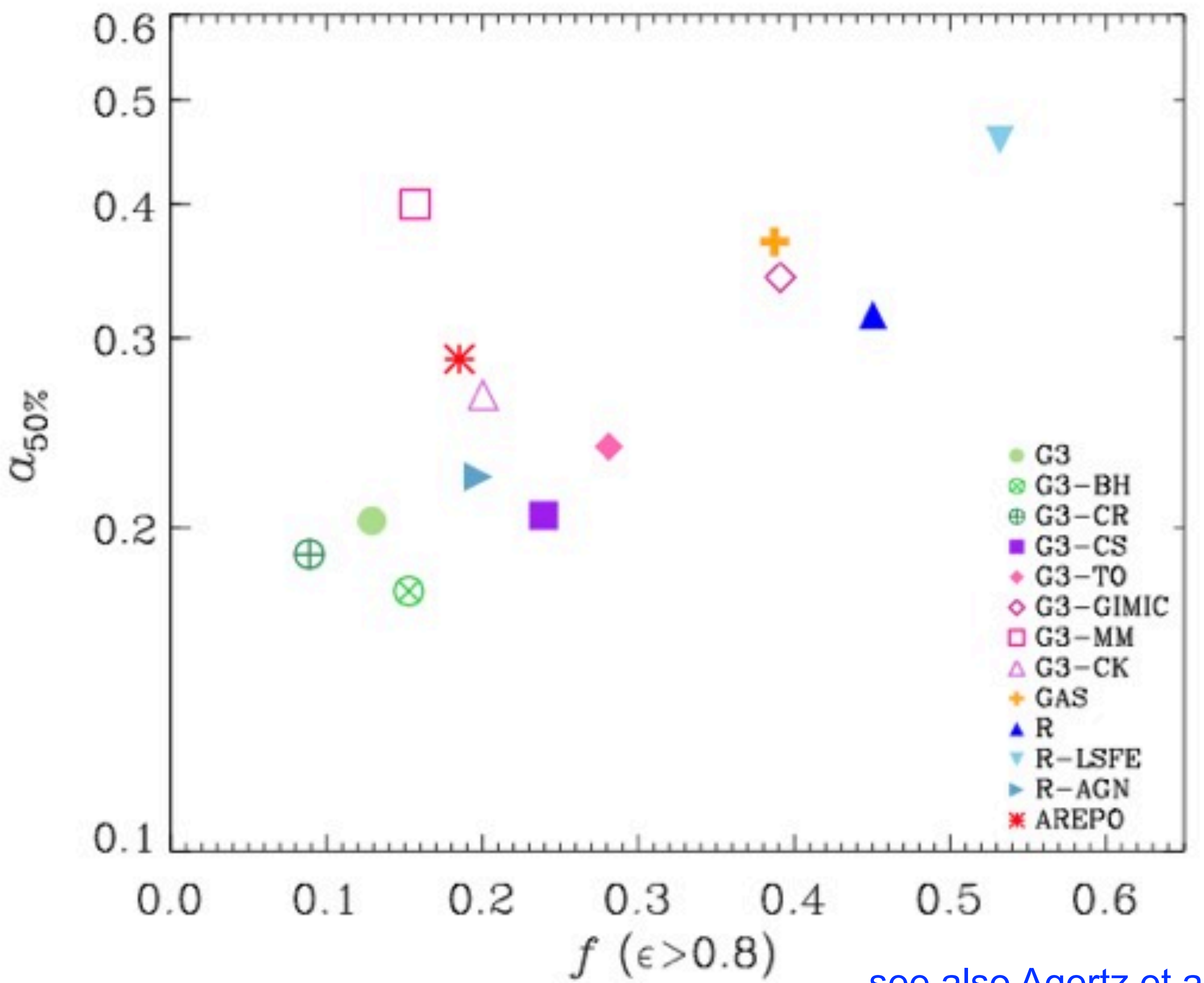
Stronger feedback, earlier star formation...



Stronger feedback, flatter rotation curves...

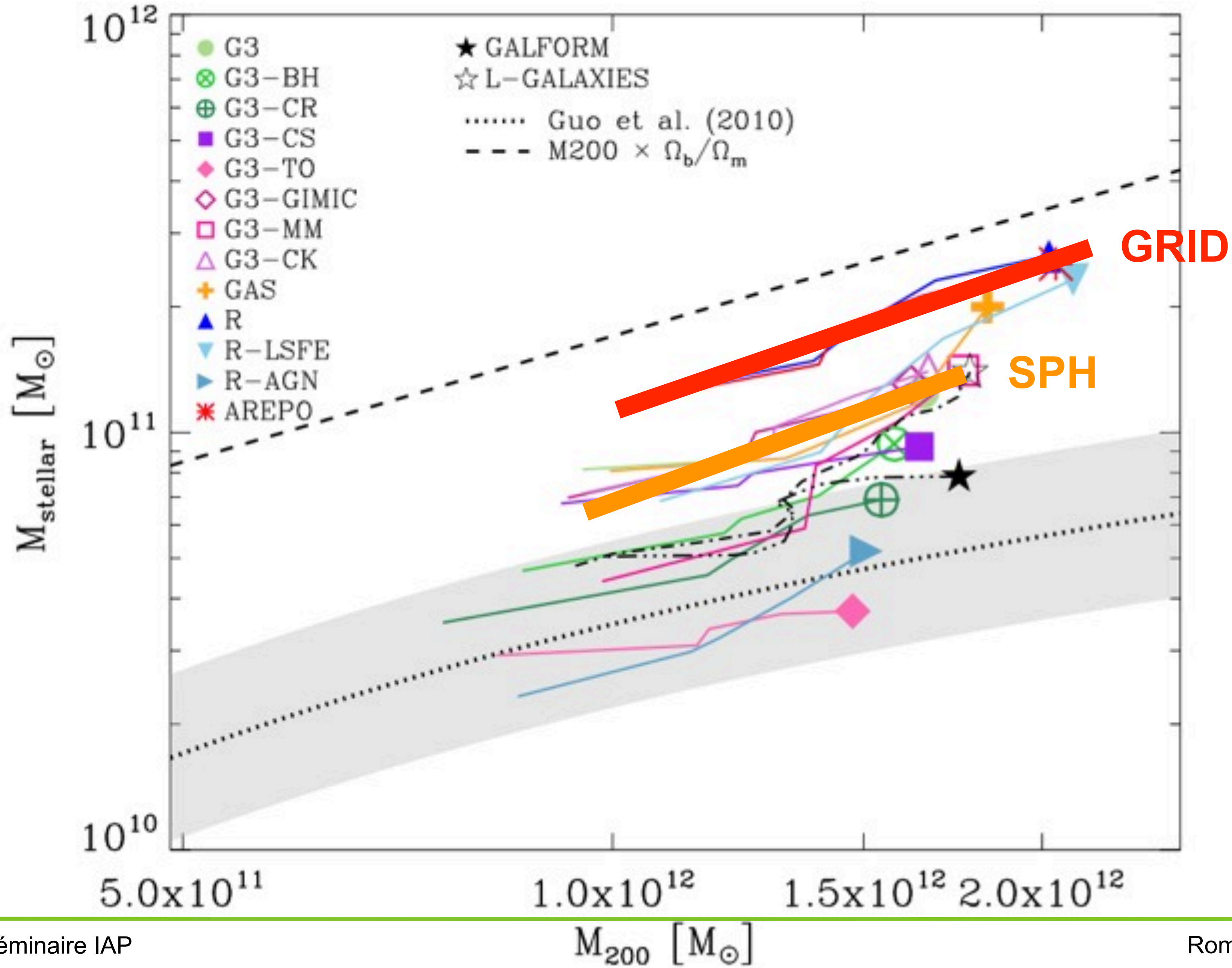


Disc mass correlates with median stellar age



see also Agertz et al. (2011)

Feedback and SF matter more than code type.



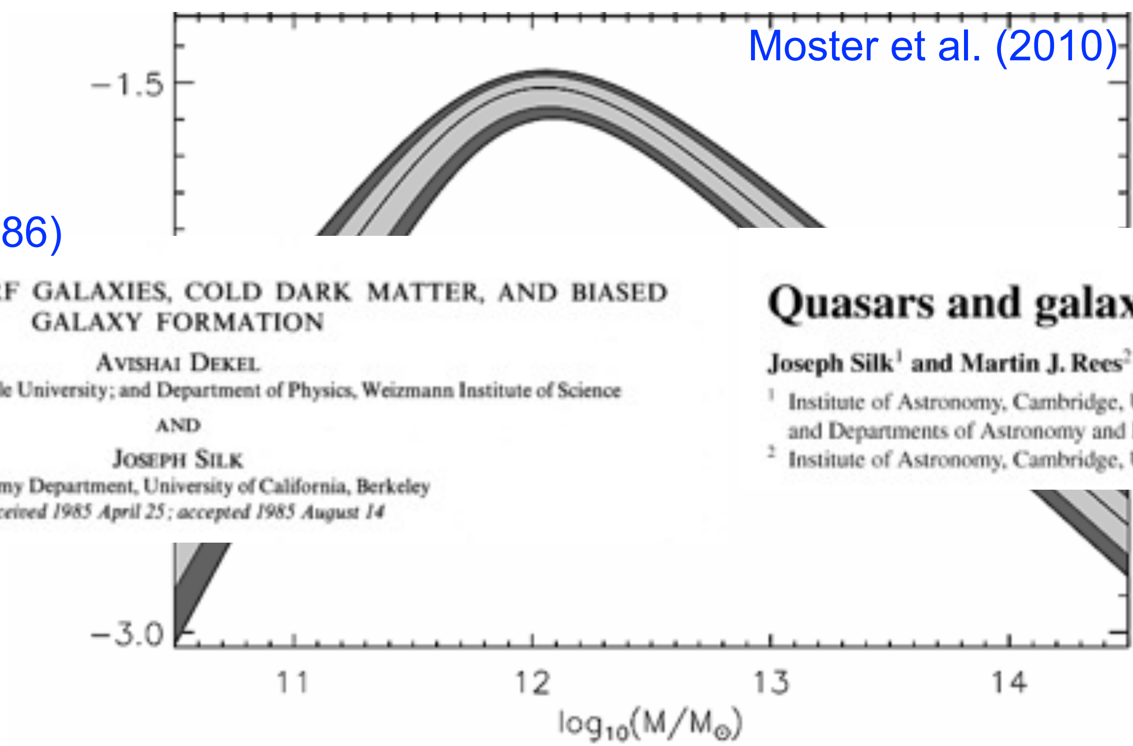
Feedback processes in galaxy formation

Small mass galaxies are dominated by stellar feedback

Large mass galaxies are governed by AGN feedback.

What about the Milky Way ?

Stellar-to-halo mass ratio



Dekel & Silk (1986)

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

AVISHAI DEKEL
Department of Astronomy, Yale University; and Department of Physics, Weizmann Institute of Science
AND
JOSEPH SILK
Astronomy Department, University of California, Berkeley

Received 1985 April 25; accepted 1985 August 14

Silk & Rees (1998)

Quasars and galaxy formation

Joseph Silk[1] and Martin J. Rees[2]
[1] Institute of Astronomy, Cambridge, UK, Institut d'Astrophysique de Paris, France, and Departments of Astronomy and Physics, University of California, Berkeley, CA 9
[2] Institute of Astronomy, Cambridge, UK

The problem with supernovae feedback

Consider a single molecular cloud of mass going supernova.

Most efficient case 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 $\displaystyle {\rm v}_{\rm Sedov} = \frac{2}{5}\sqrt{\frac{E_{\rm SN}}{M_{\rm gas}}} \simeq 90\ {\rm km/s}$

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

Cloud is destroyed but the gas remains within the galaxy $v_{\rm escape} \simeq 700\ {\rm km/s}$

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

$$M_{\rm wind} = \eta_{\rm wind} M_* \quad \text{with} \quad \eta_{\rm wind} < \frac{1}{\epsilon_*}$$

Mass-loading factor $\eta_{\rm wind} = 1$ gives only $\displaystyle {\rm v}_{\rm Sedov} = \frac{2}{5}\sqrt{\frac{E_{\rm SN}}{M_{\rm wind}}} \simeq 300\ {\rm km/s}$

Stellar feedback with delayed cooling

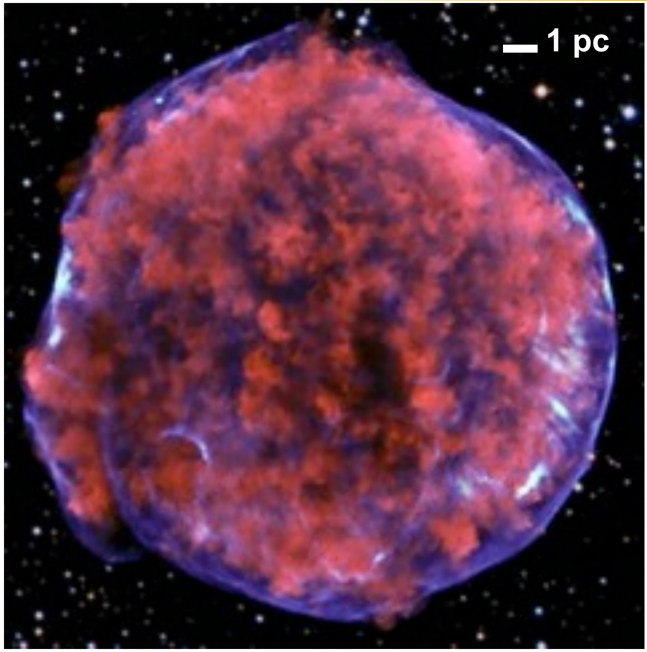
Stellar winds, supernovae remnants are highly turbulent environment, filled with cosmic rays and magnetic field.

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:

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



Chandra image of Tycho

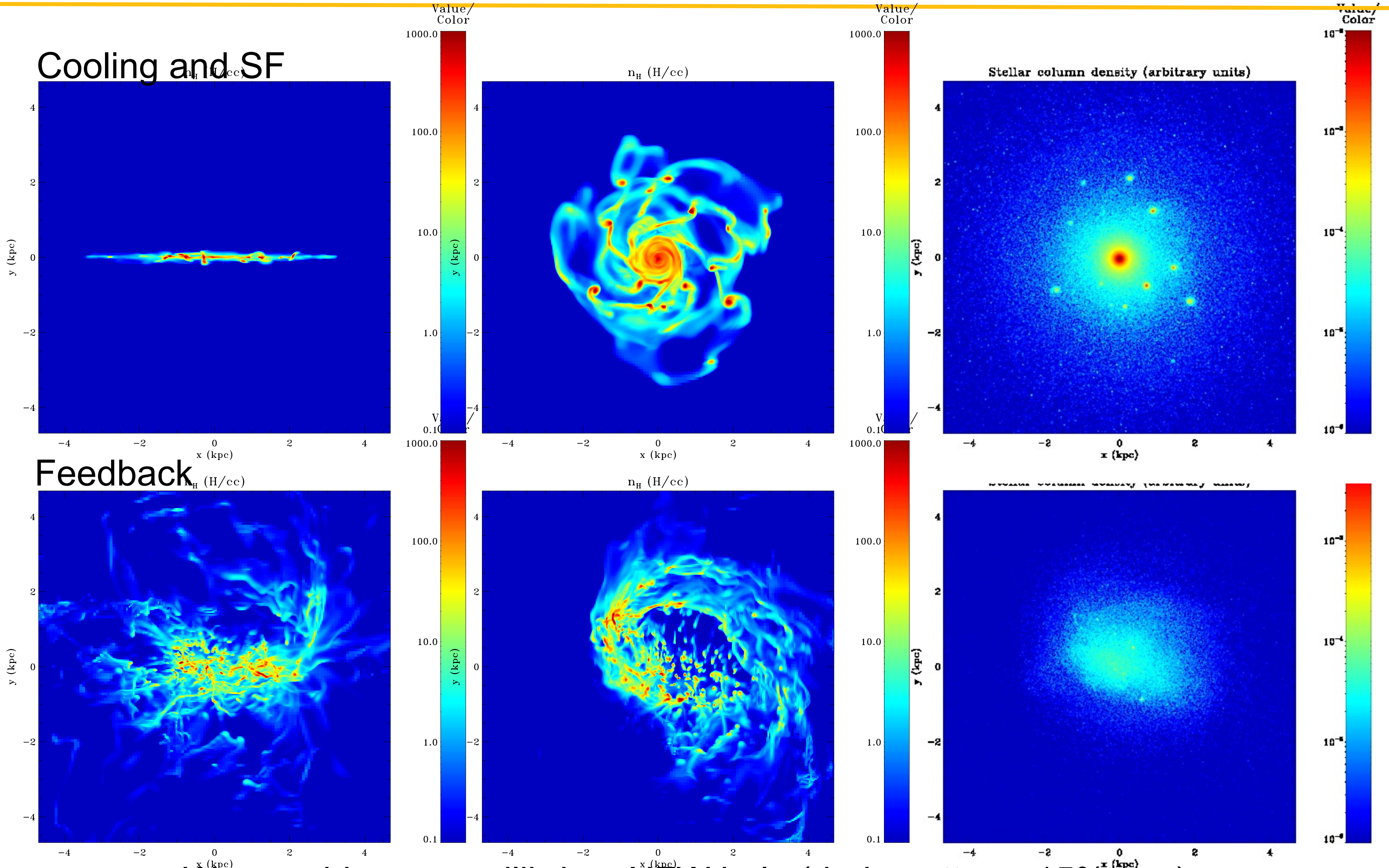
The total dynamical pressure is $P_{tot} = P_{thermal} + P_{turb}$

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



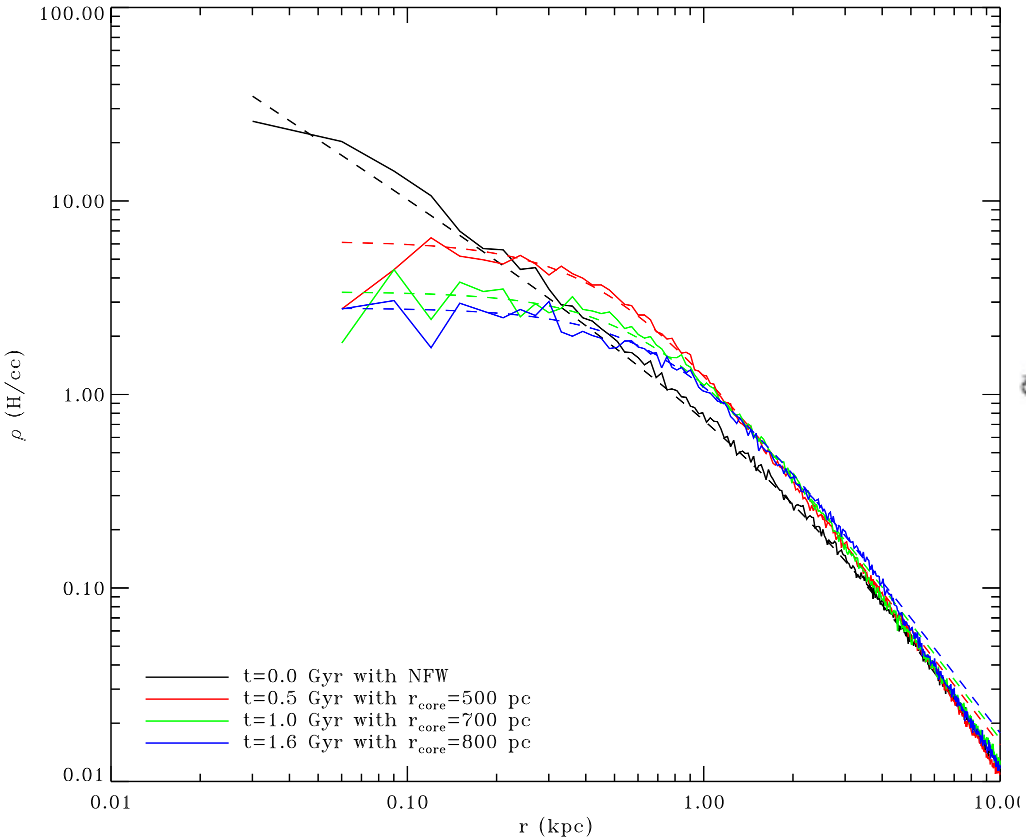
We consider an equilibrium NFW halo (dark matter + 15% gas)

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

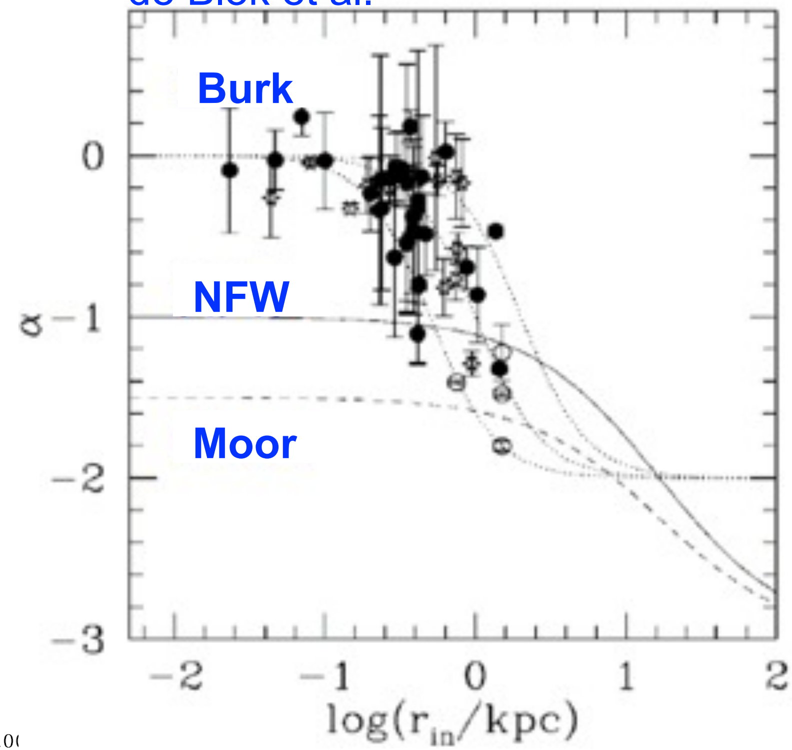
Dark matter cusp-to-core transformation

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

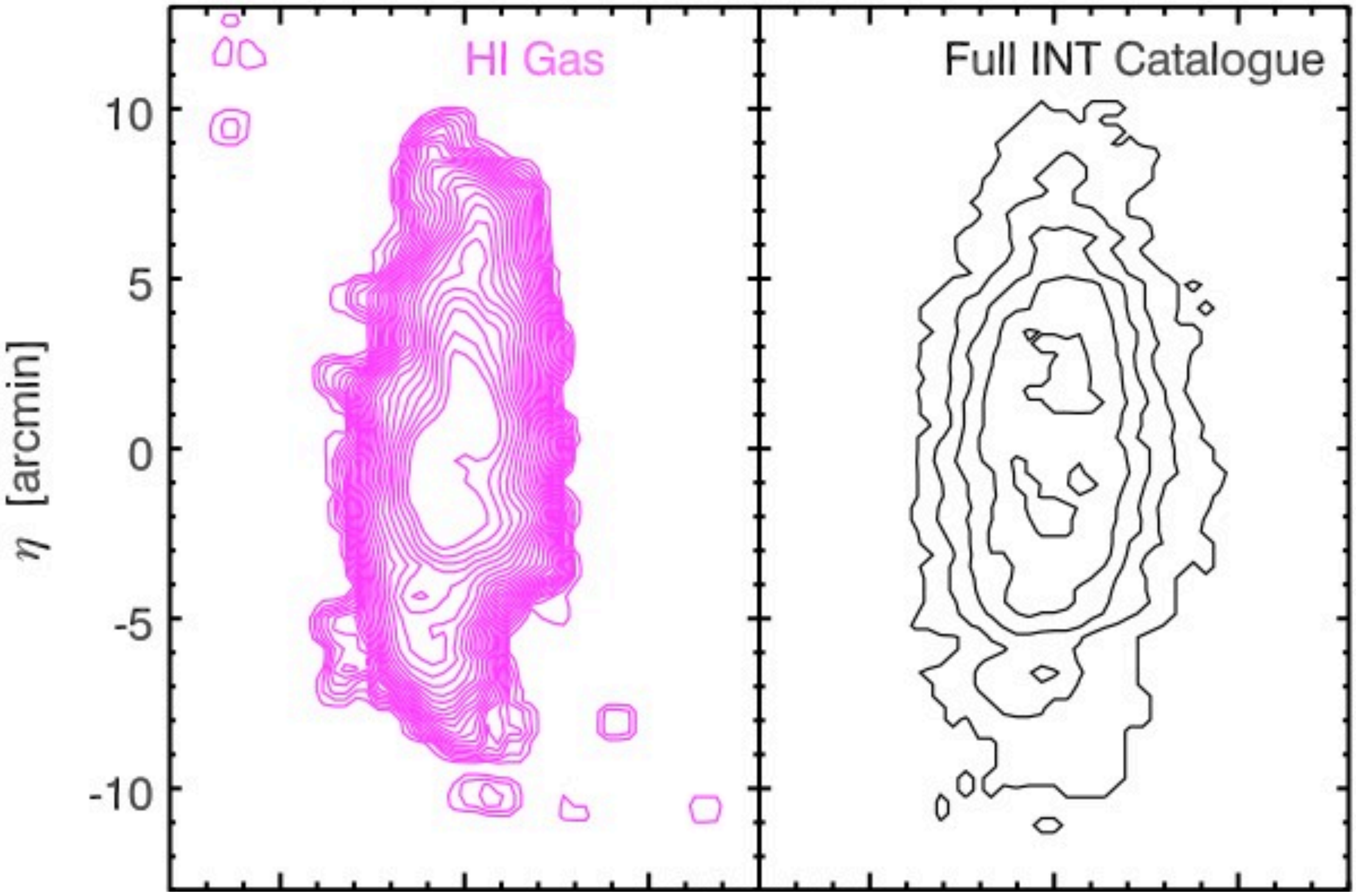
$$\rho \propto \frac{1}{1+(r/r_{core})^2}$$



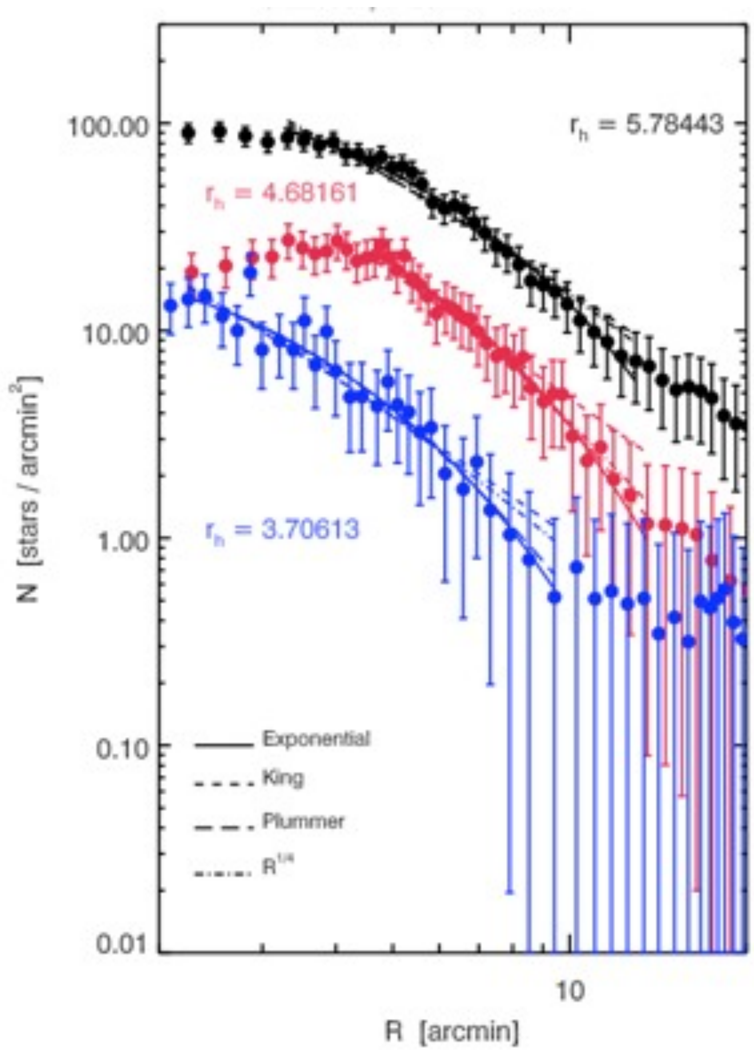
de Blok et al.

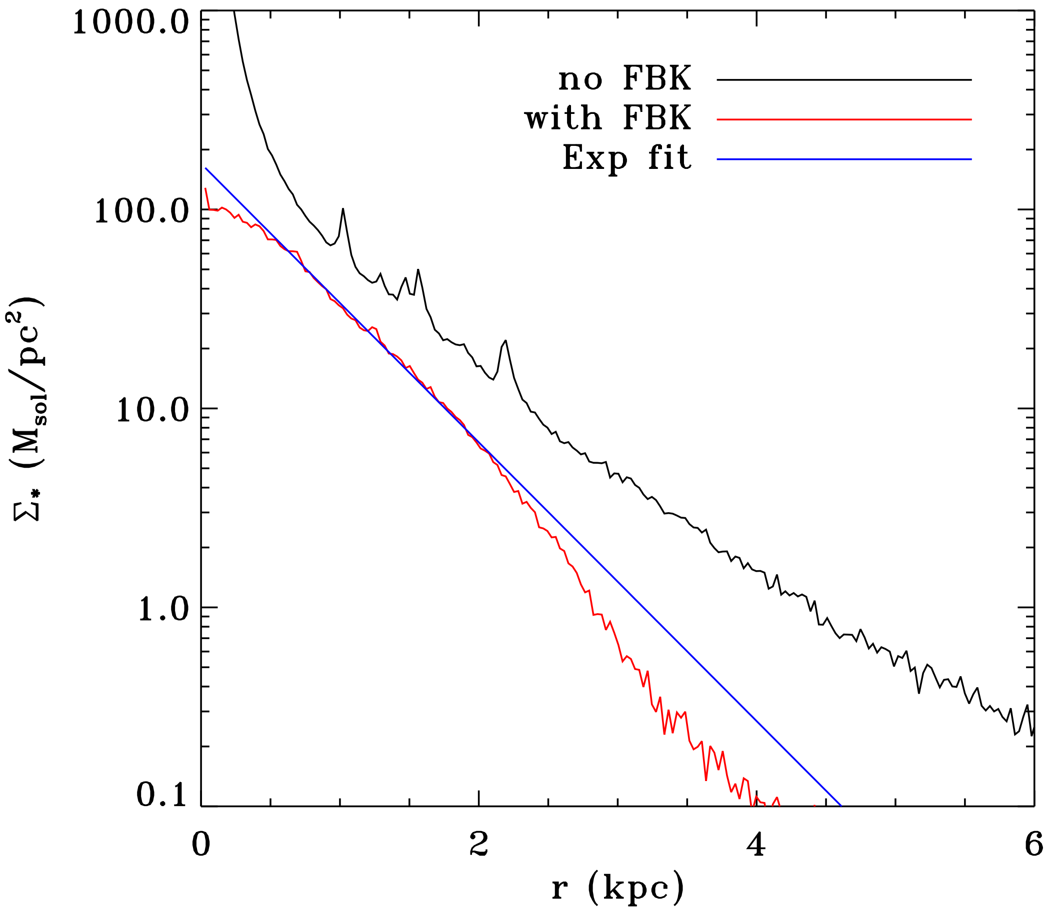


Comparison to WLM (Leaman et al. 2012)

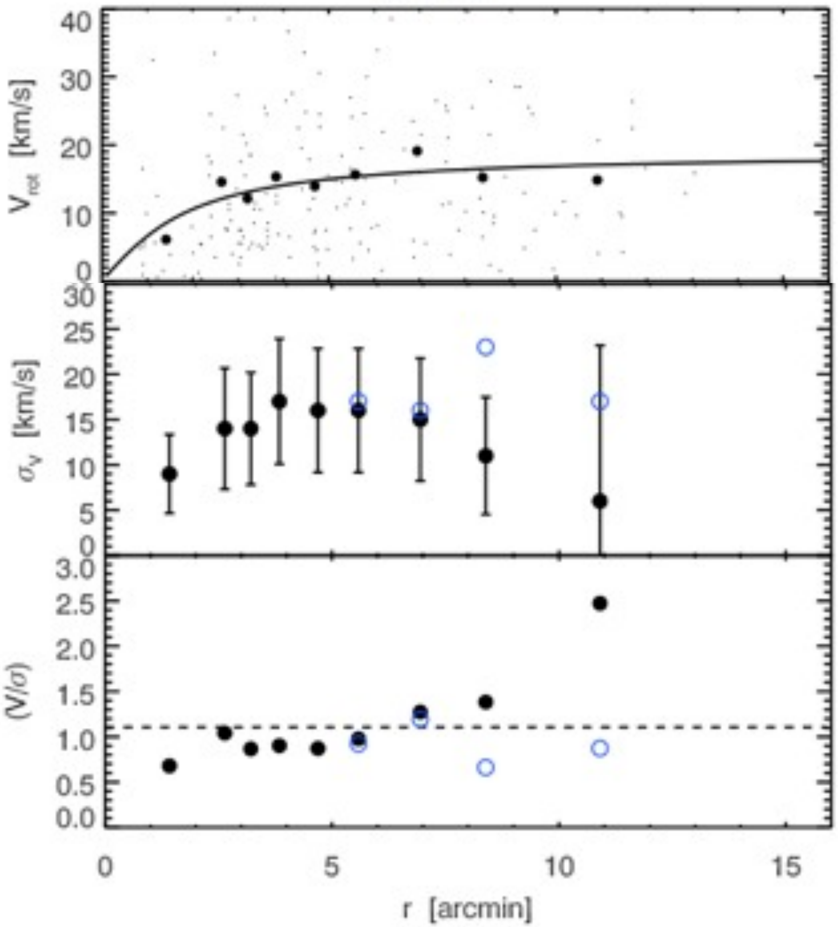


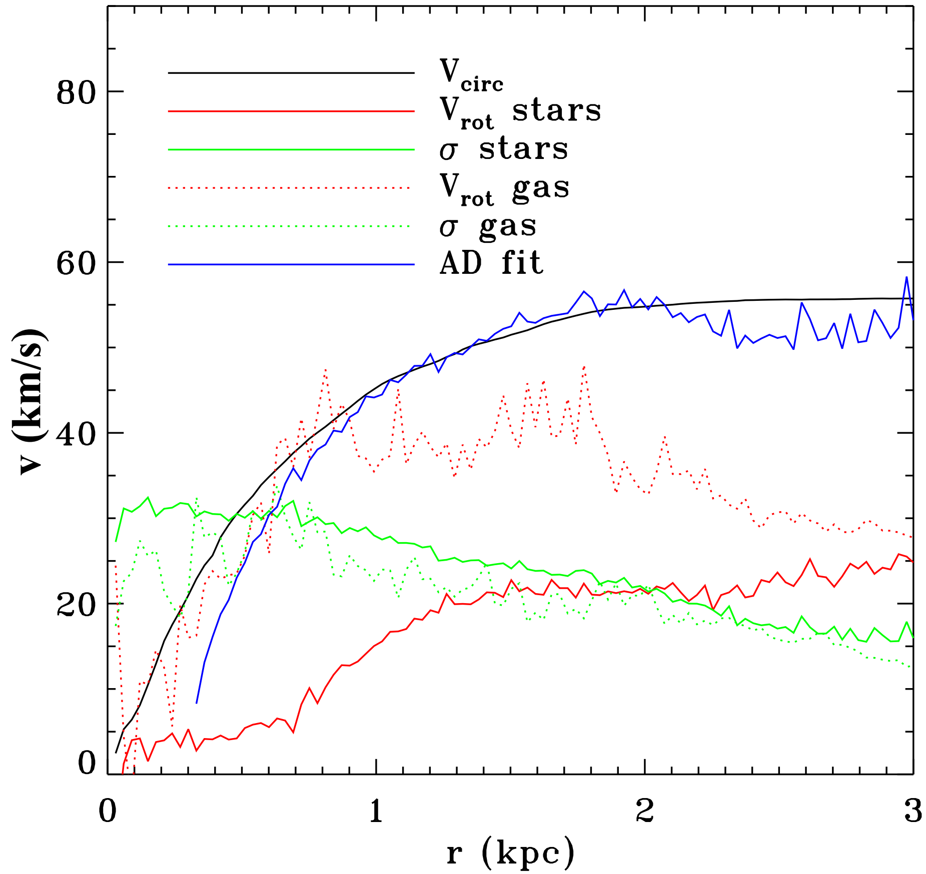
Stellar surface density: exponential with a core





A thick rotating disc





Still too many baryons in stars

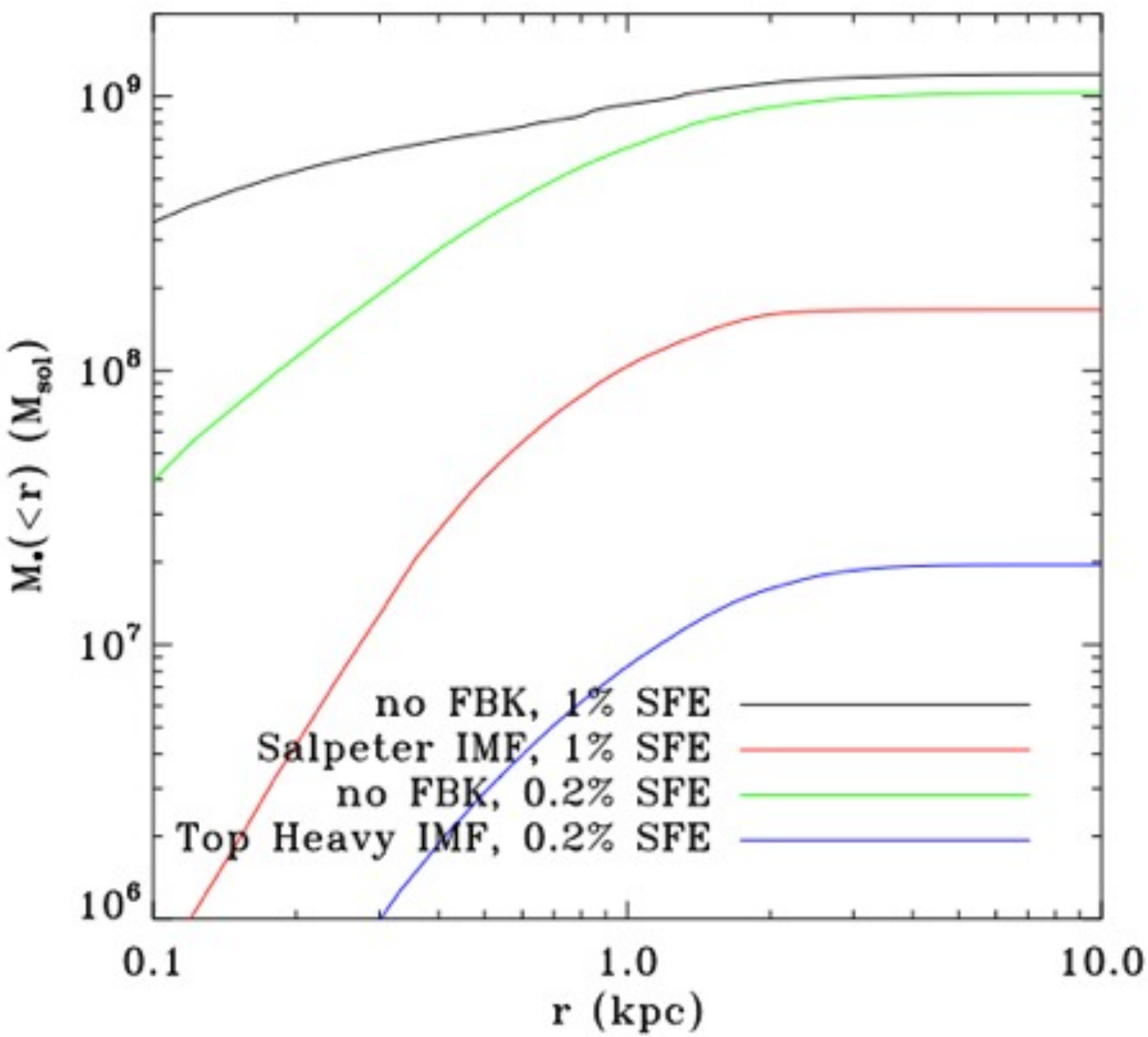
WLM lives in a 10^{10} Msol halo and formed 10^7 Msol of stars. We formed 10^8 Msol.

Solution ?

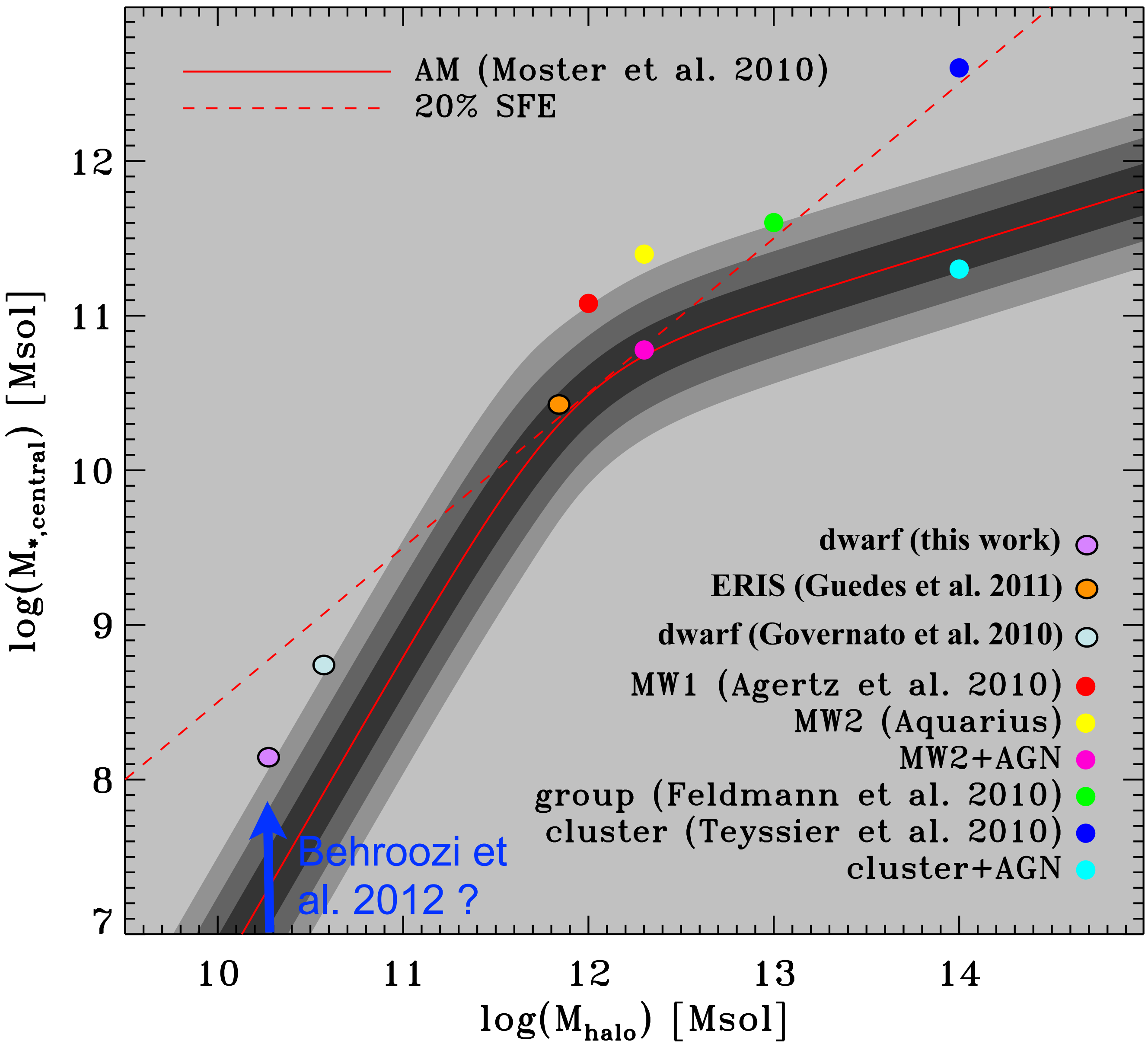
Lower the SF efficiency by 10 (Krumholz & Dekel 2011; Padoan et al. 2012)

AND

Use a top-heavy IMF and boost the mass fraction in massive star by 10 (Hennebelle et al. 2012; Marks et al. 2012)

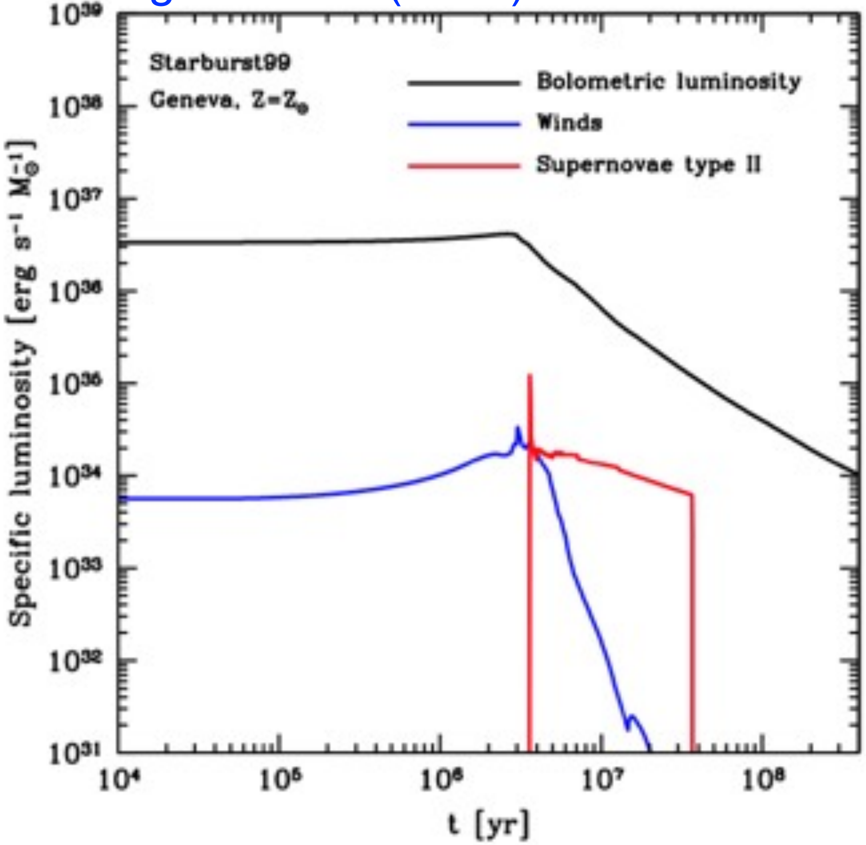


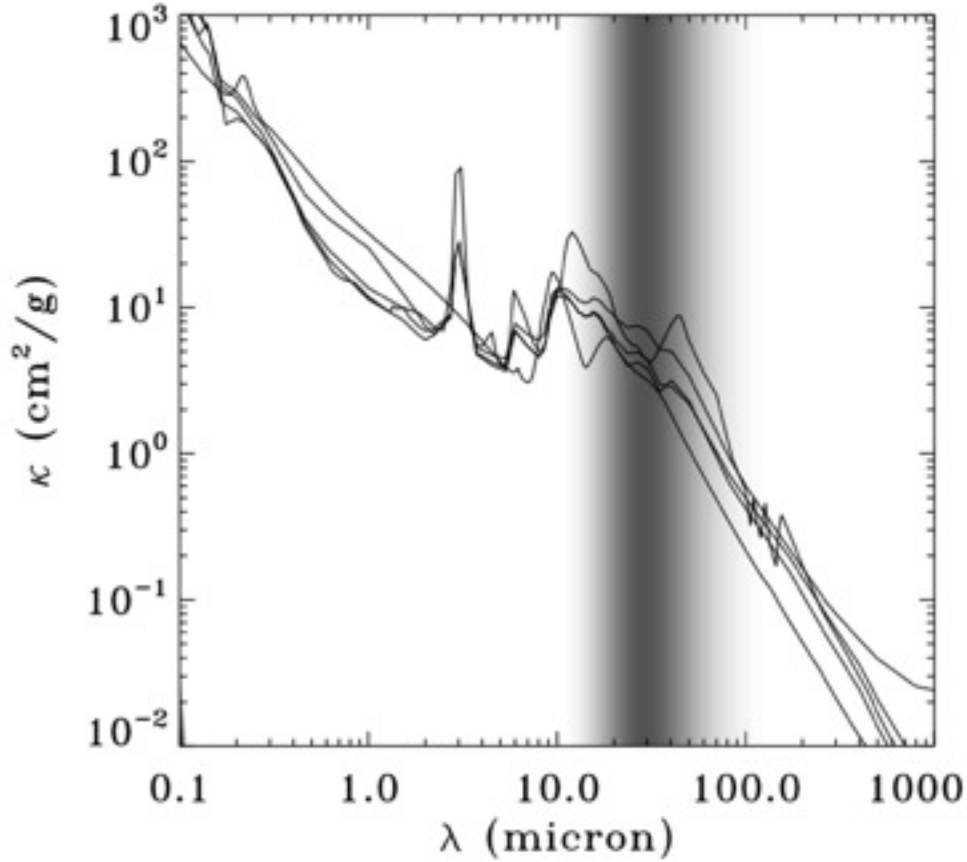
Constraints from abundance matching



Radiative feedback from stars

Agertz at al. (2012)





After 10 Myr, stars have radiated:

- 10^{51} erg in supernovae & winds
- 10^{53} erg in radiation

UV radiation is transformed into IR radiation that slowly diffuses out of high column density regions

$$\kappa_{\rm IR} \simeq 5 \pm 5 \ {\rm cm}^2/{\rm g}$$

Momentum-driven radiation feedback

Murray et al. (2005) proposed that momentum-driven radiation flows explains why molecular clouds are dispersing so fast. Murray et al. (2010) have shown that a fair fraction of the radiated energy can be transferred into gas momentum.

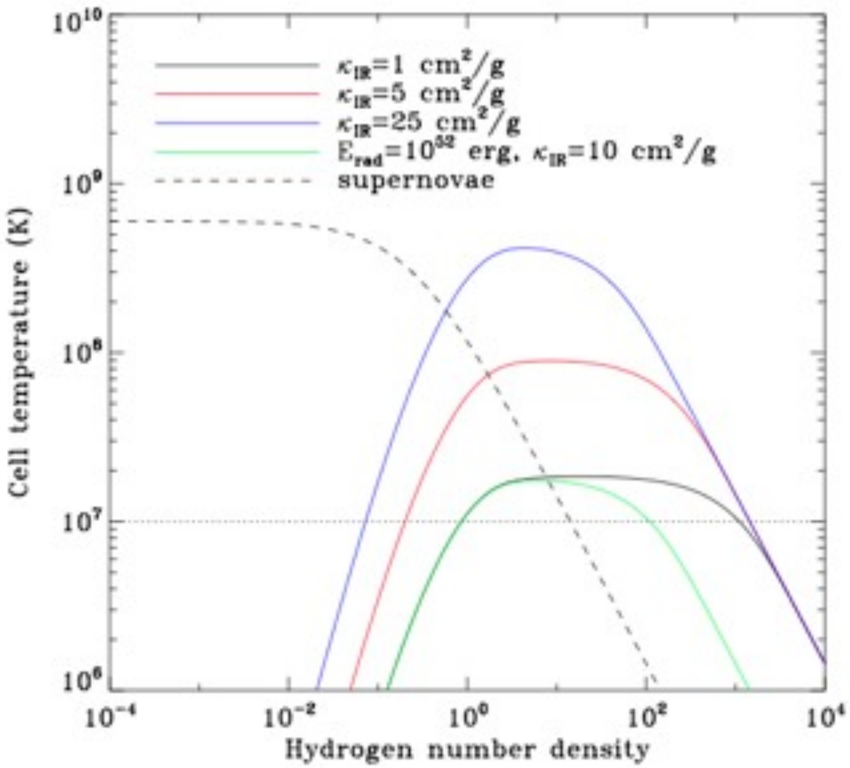
We propose here a simple model for IR radiation energy trapping. See other implementations by Hopkins et al. (2012) and Stinson et al. (2012)

$$E_{\rm abs} = 10^{53}\left(1 - \exp^{-\tau_{IR}}\right)\ {\rm erg}$$

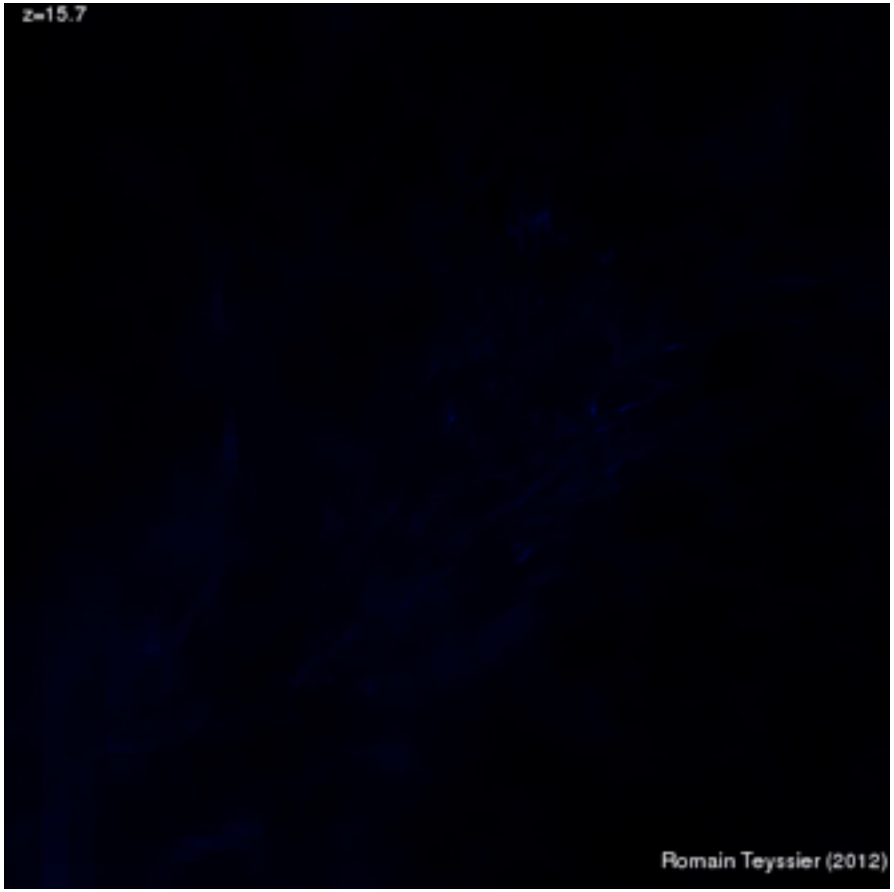
where the IR optical depth is computed using a local column density

$$\tau_{\rm IR} = \kappa_{\rm IR}\frac{Z}{Z_\odot}\rho_{\rm gas}\Delta x$$

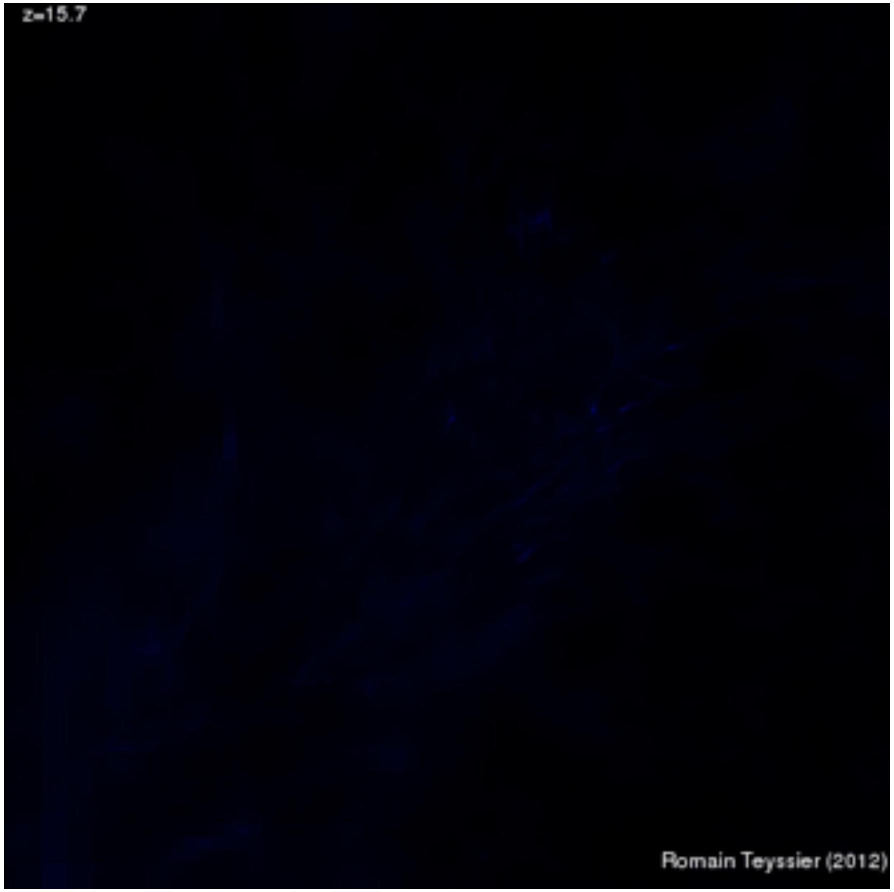
This energy is deposited in the non-thermal pressure component to maximize the conversion efficiency into momentum.



Preliminary results

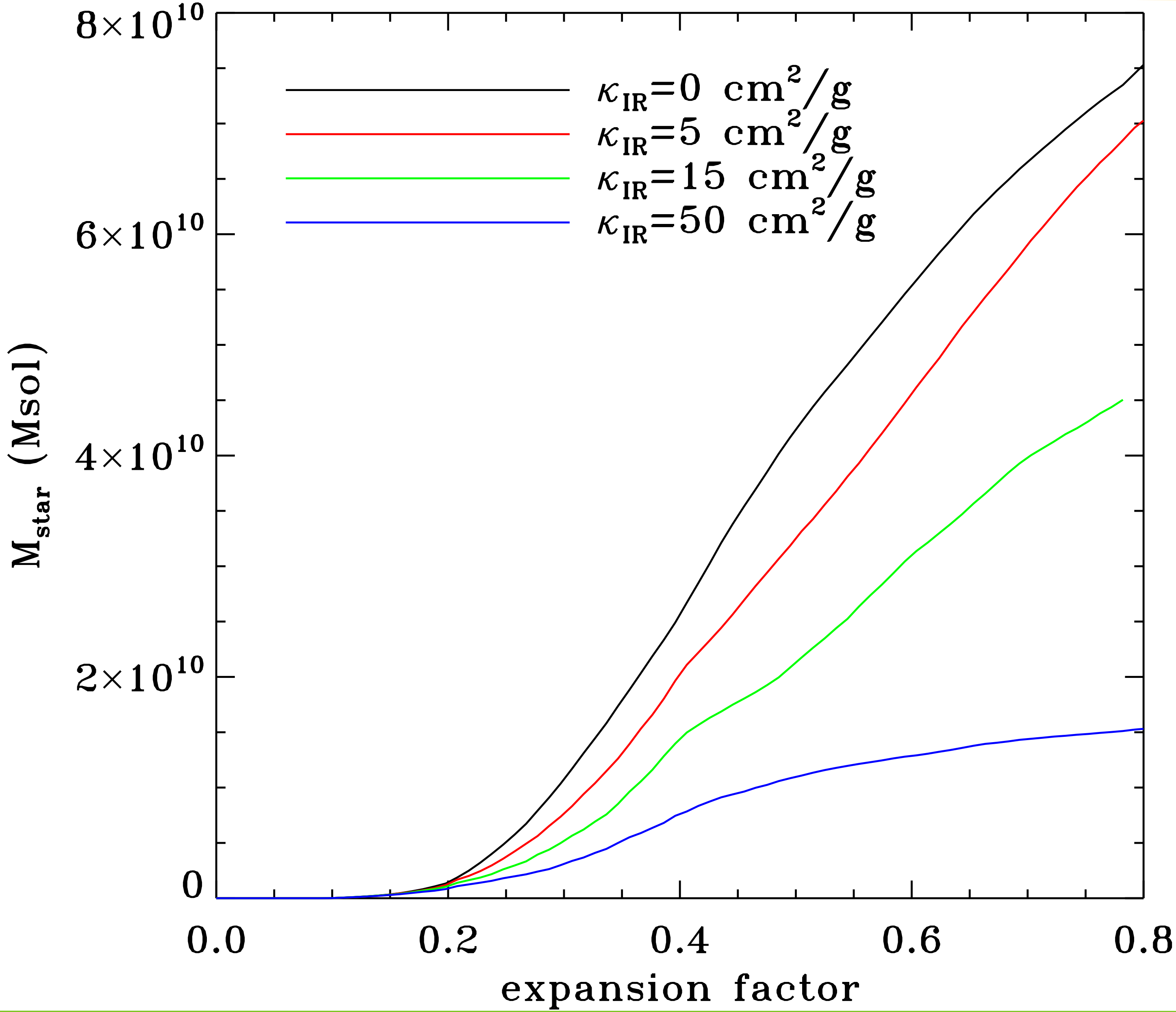


$$\kappa_{\rm IR} = 15 \ {\rm cm}^2/g$$

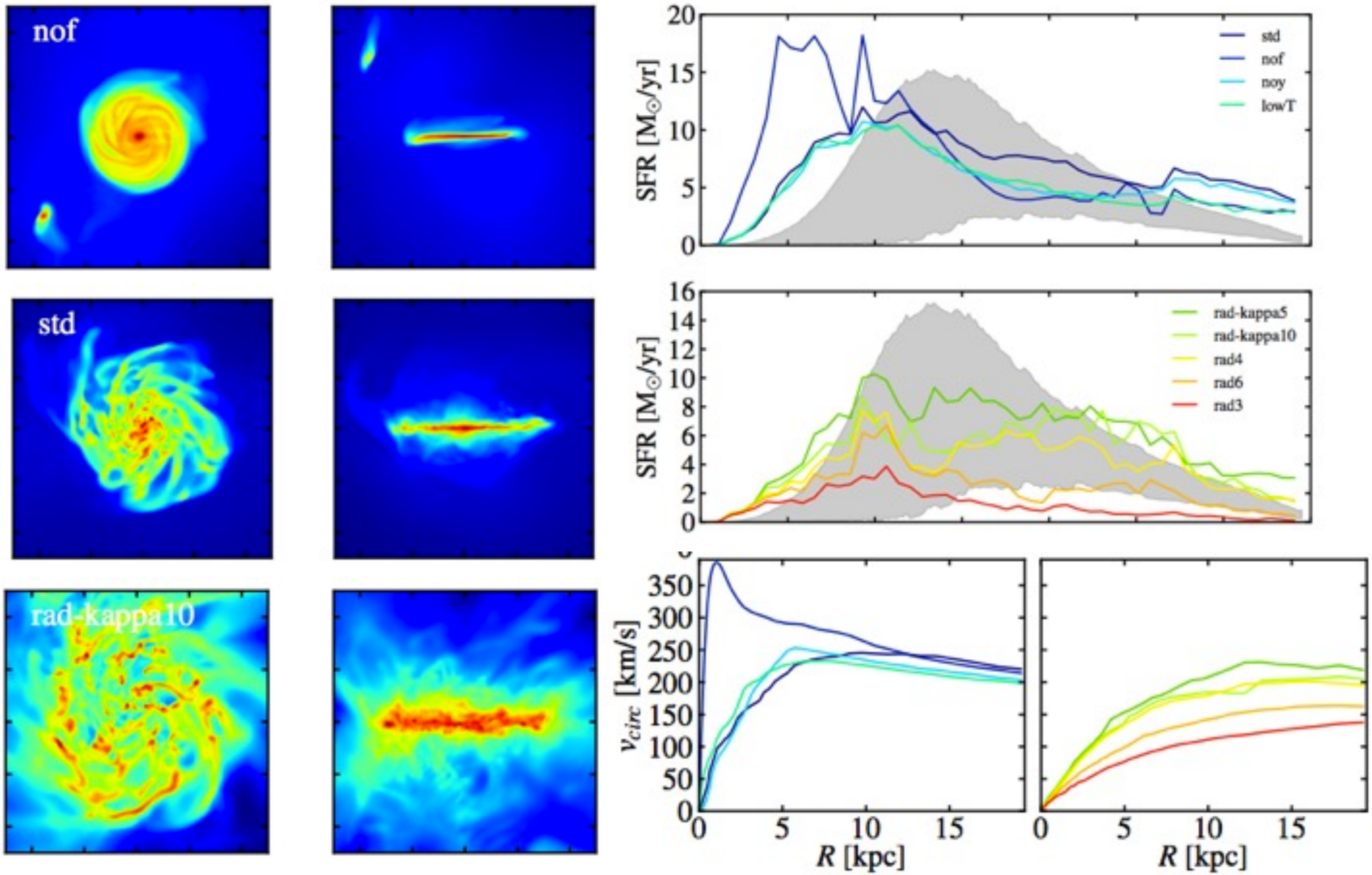


$$\kappa_{\rm IR} = 0 \ {\rm cm}^2/g$$

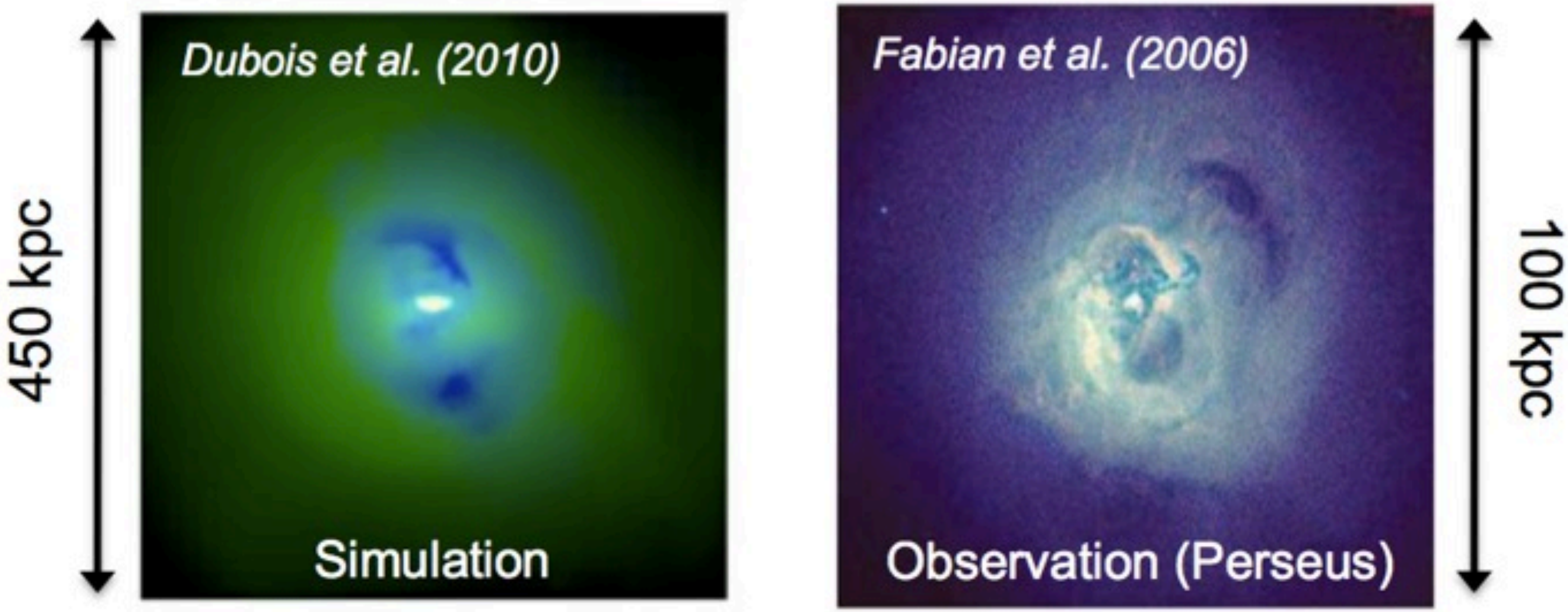
Preliminary results



Preliminary results

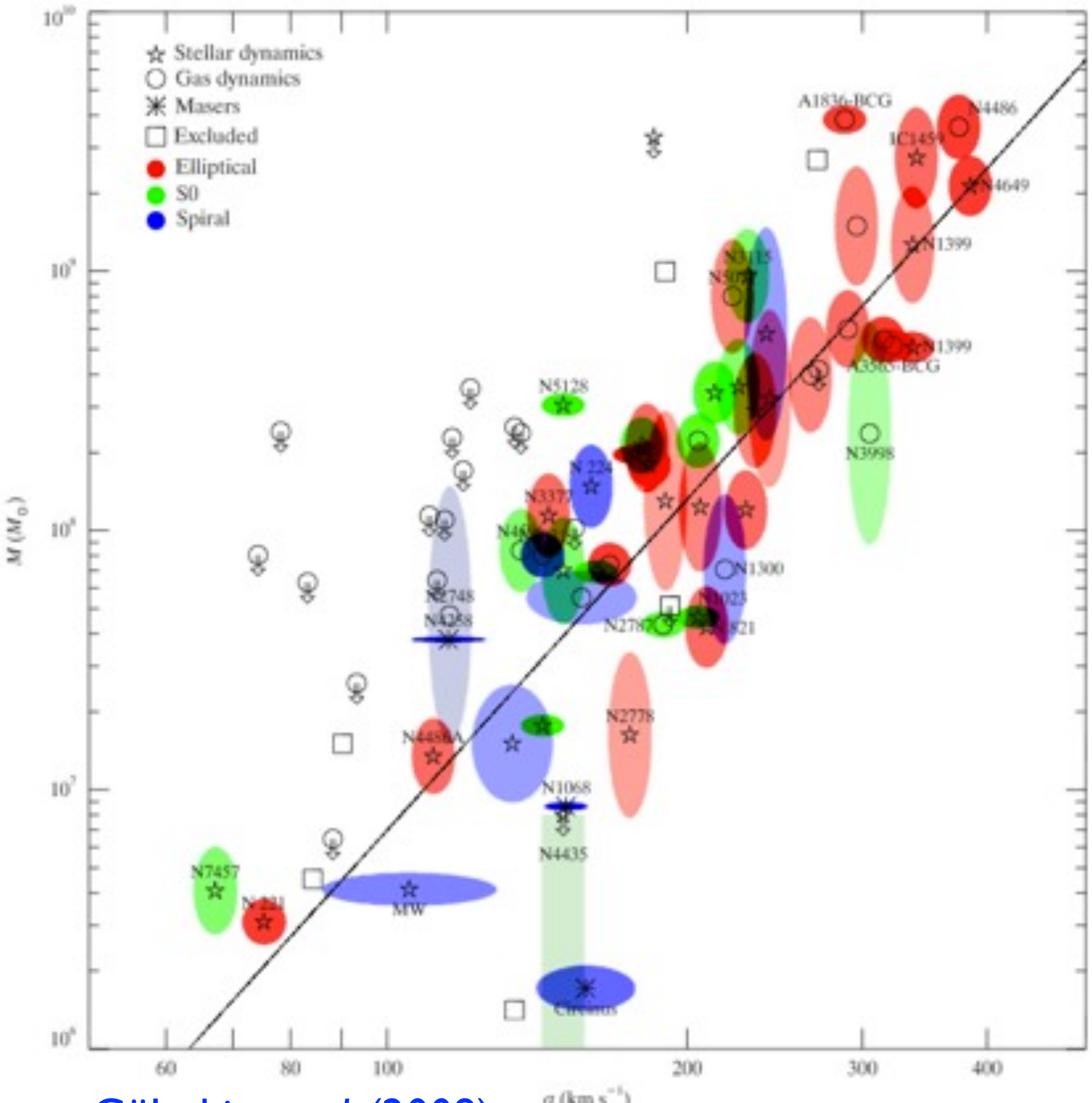


Feedback in massive galaxies: supermassive black holes



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 $$\dot{M}_{\rm BH} = \alpha_{\rm boost} \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2 + u^2)^{3/2}}$$

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

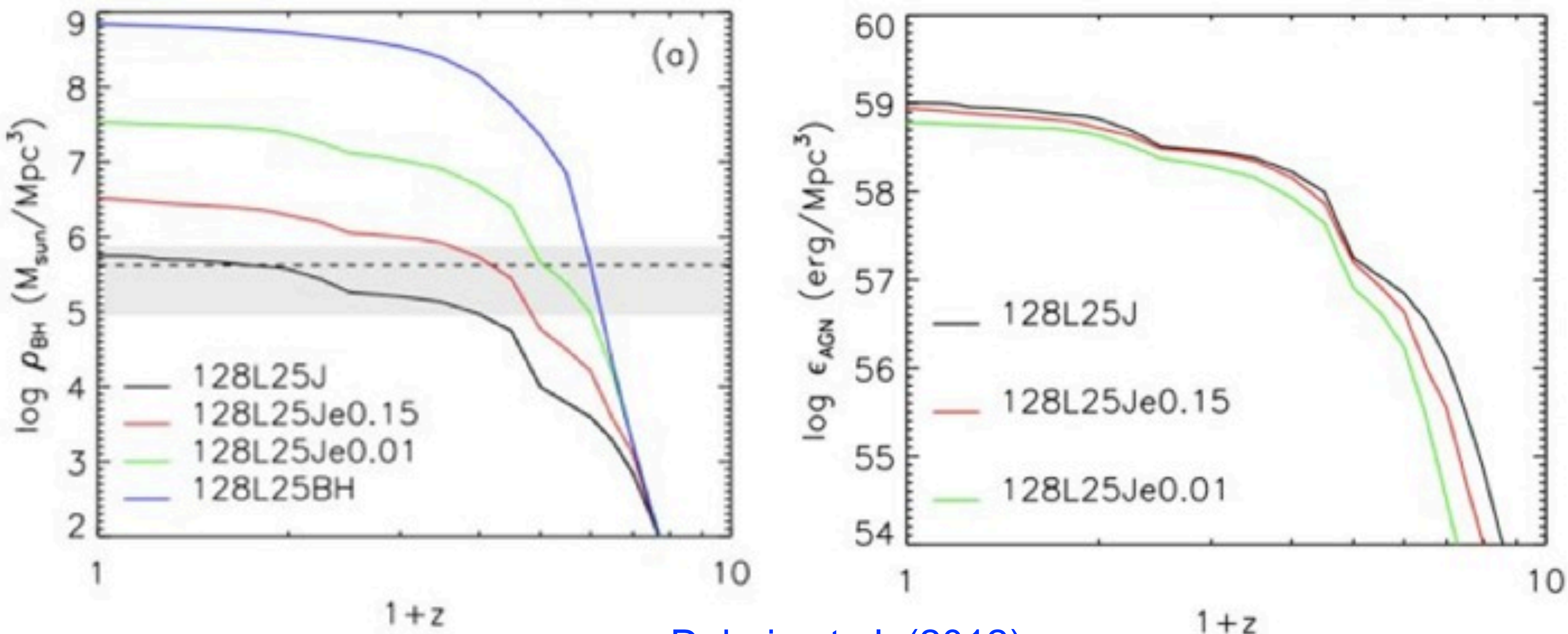
Feedback performed using a thermal dump $$\Delta E = \epsilon_c \epsilon_r \dot{M}_{\rm acc} c^2 \Delta t.$$

with following trick to avoid overcooling: $$E_{\rm AGN} > \frac{3}{2} m_{\rm gas} k_B T_{\rm min} \qquad T_{\rm min} = 10^7 \ {\rm K}$$

Free parameter ε_c calibrated on the M-σ relation.

AGN feedback: calibrating the coupling efficiency

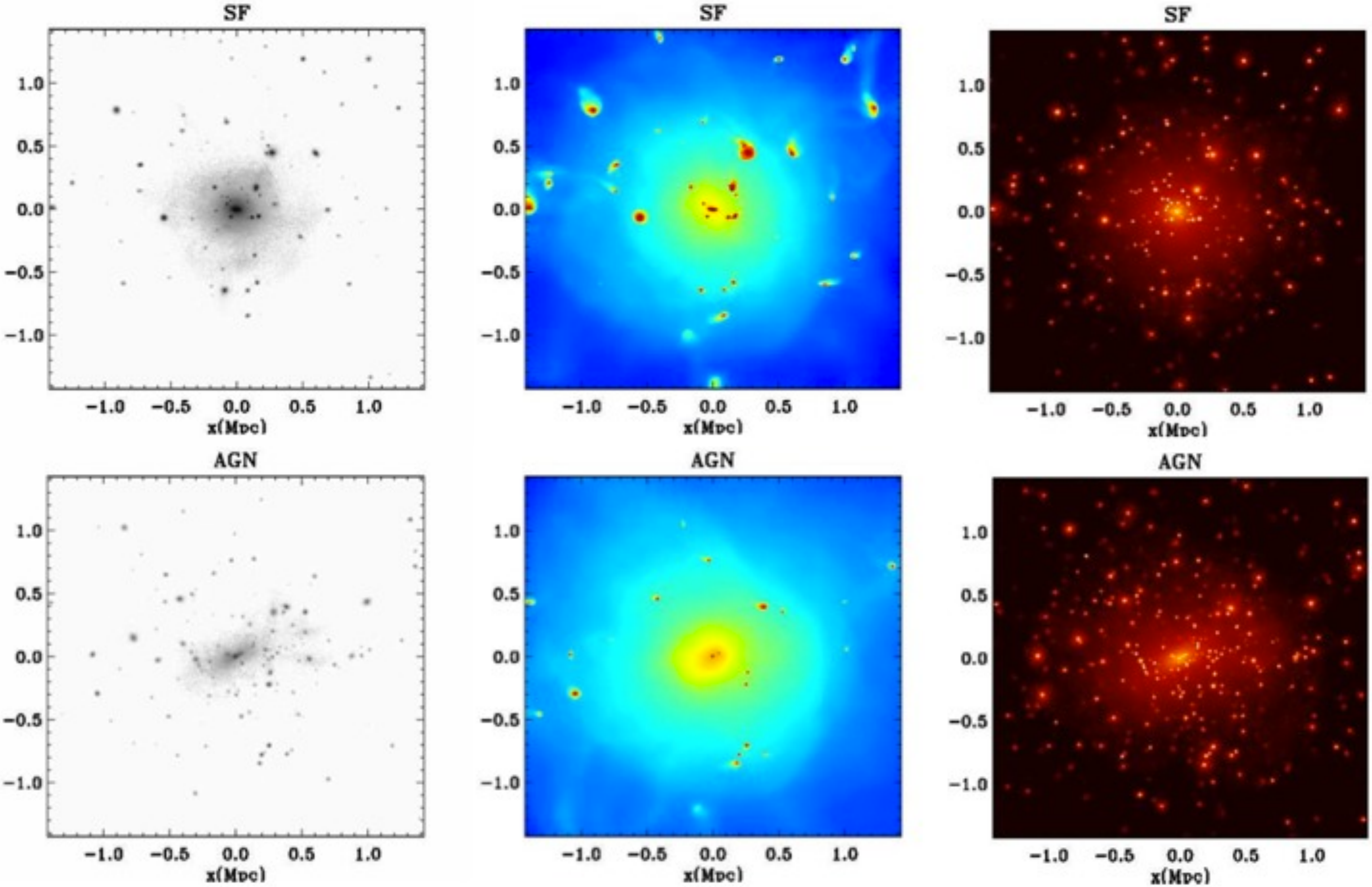
$$\Delta E = \epsilon_c \epsilon_r \dot{M}_{acc} c^2 \Delta t.$$



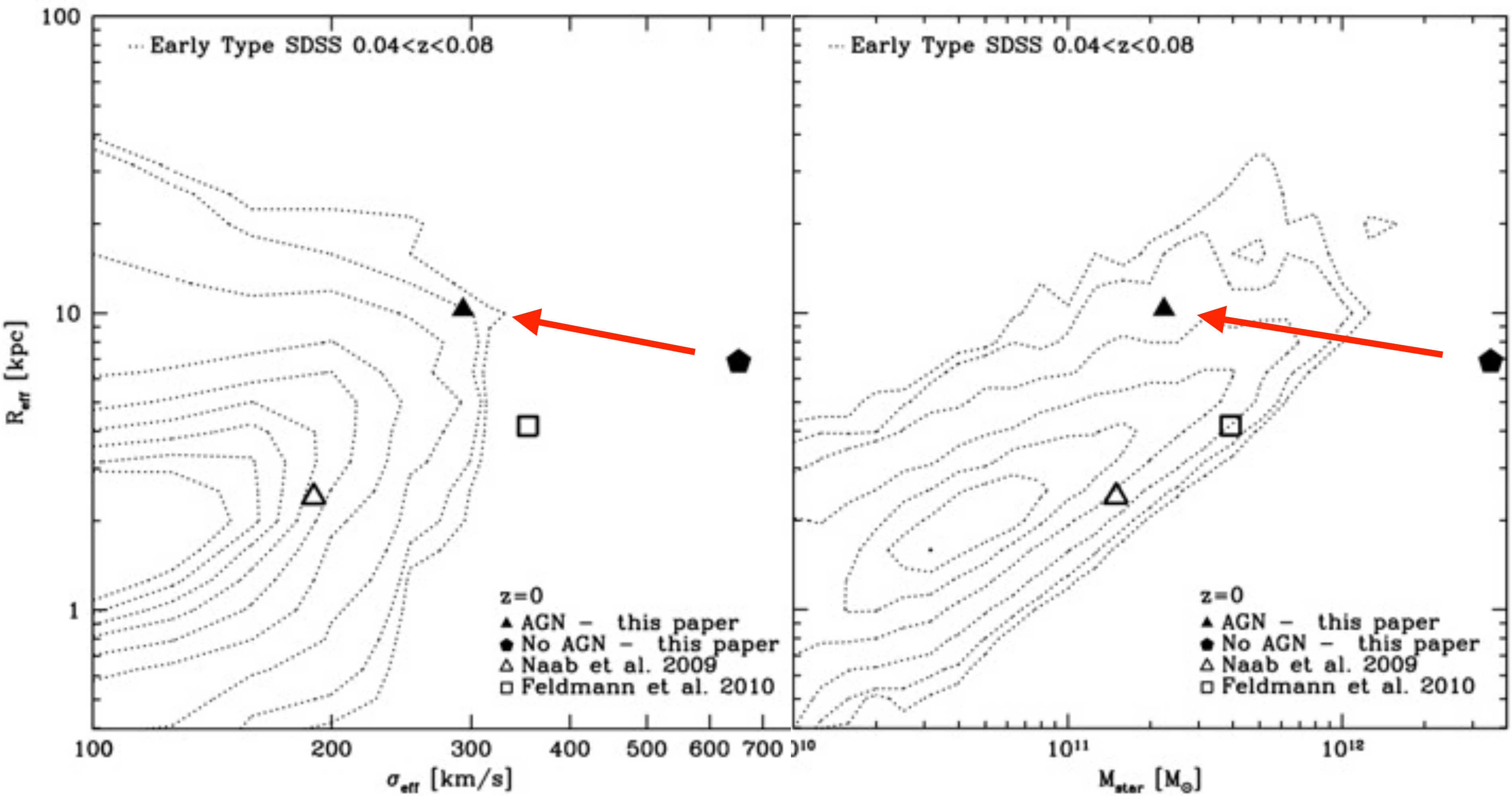
Dubois at al. (2012)

BHs deposit the same energy / independant of the AGN efficiency

Galaxy formation on cluster scales

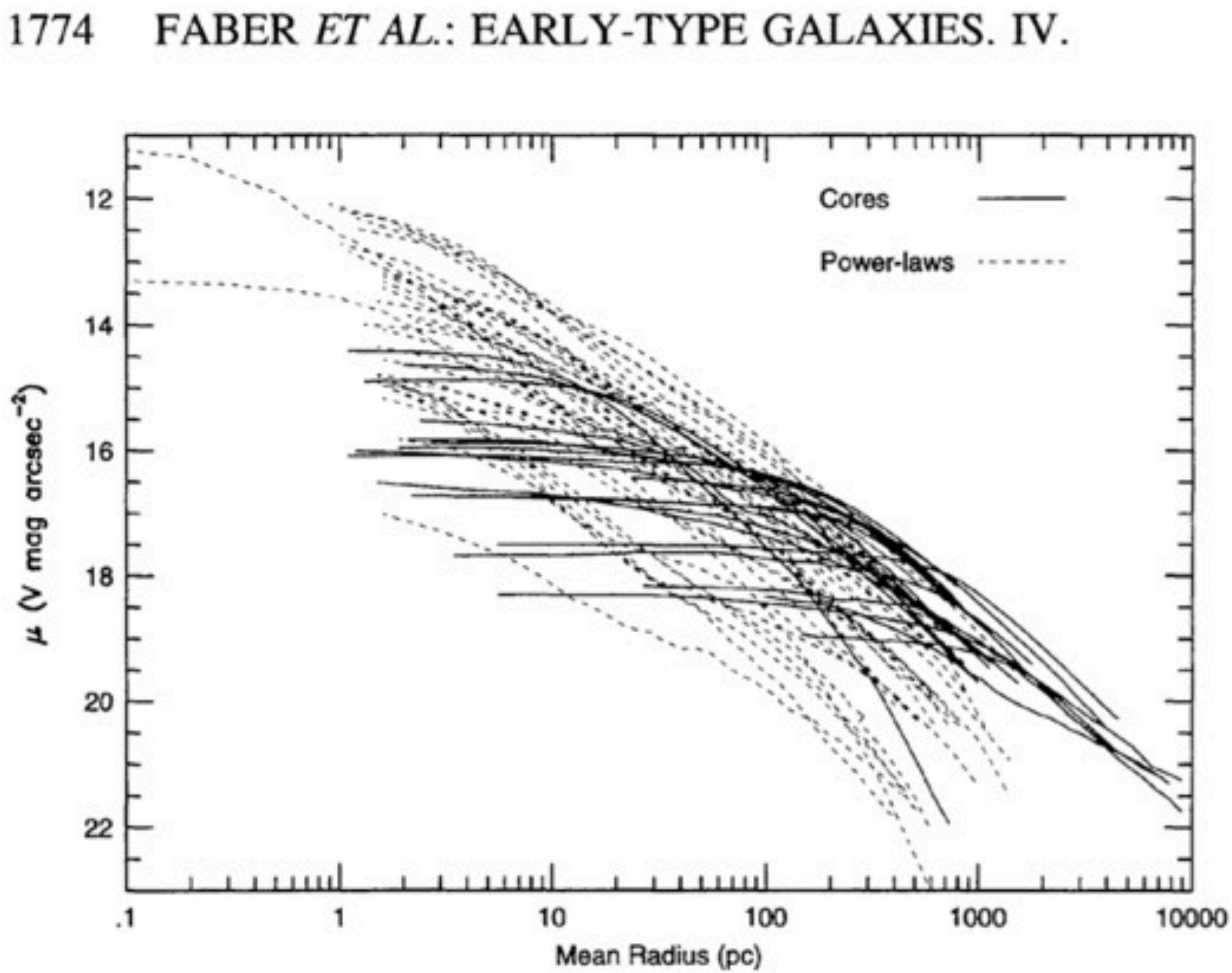


AGN feedback modifies the BCG properties



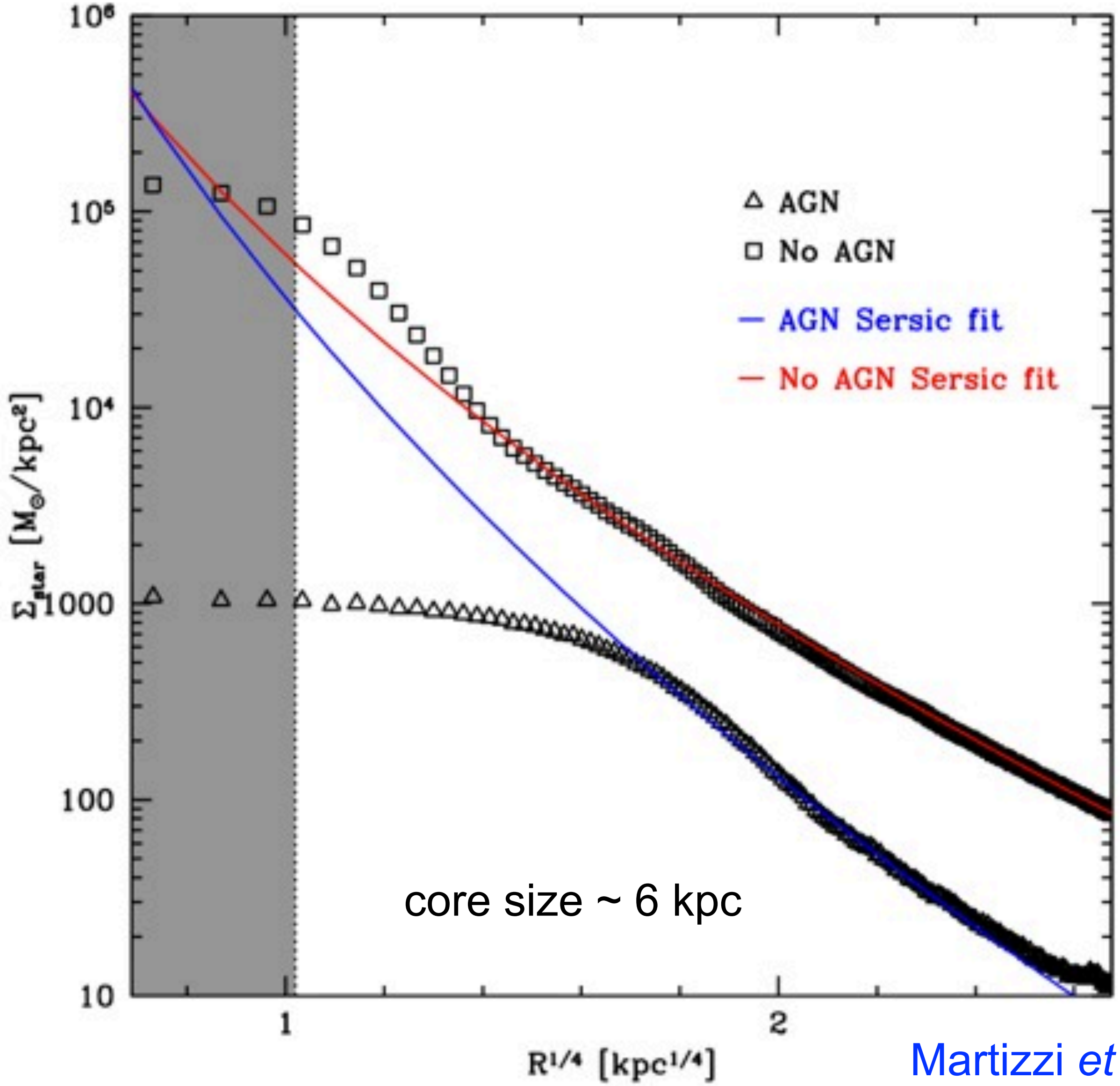
Booth & Schaye 10; Teyssier+10; Sembolini+11; Dubois+10,11; Martizzi+11

A dichotomy in the structure of elliptical galaxies



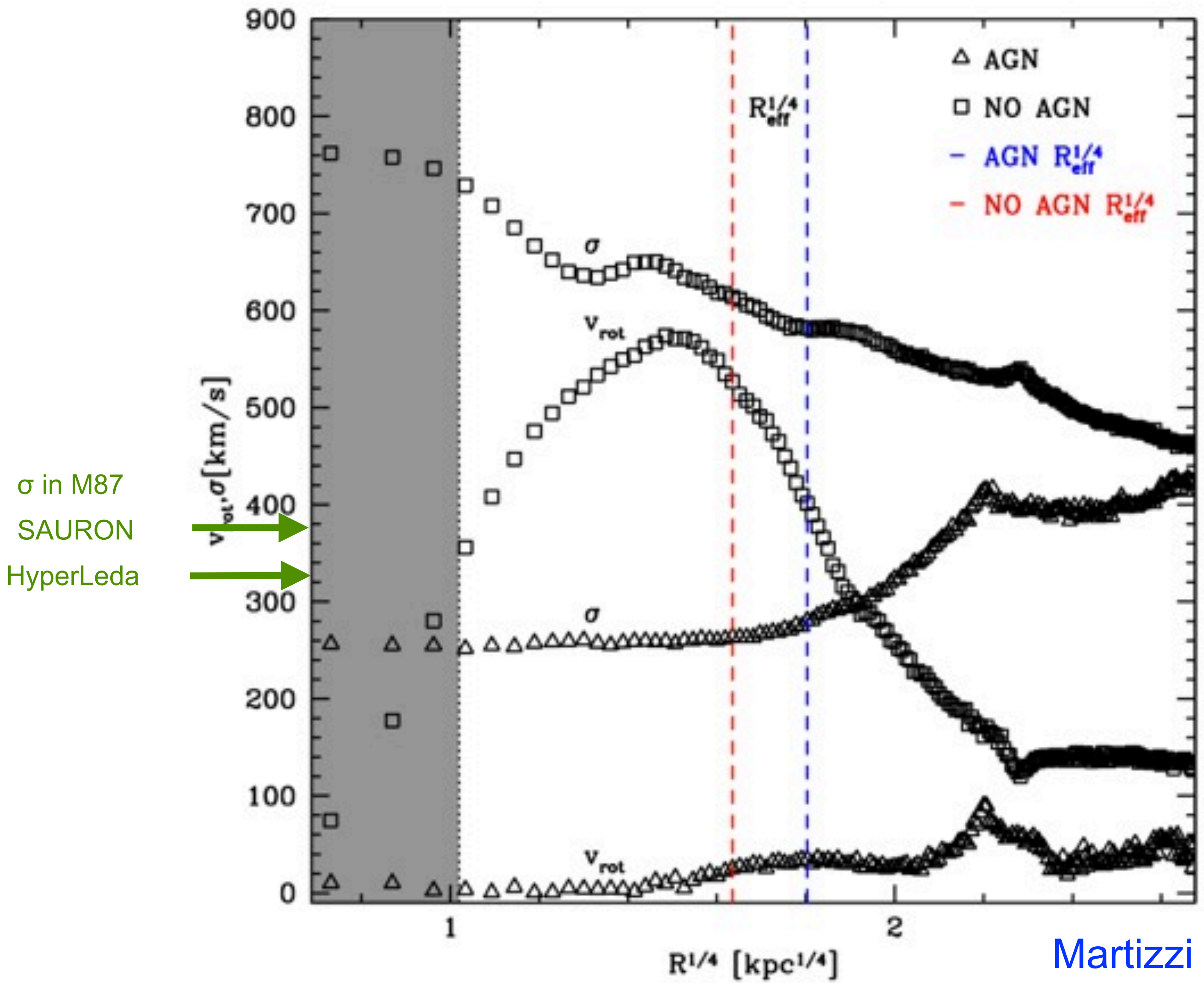
Faber et al. 1997

Structural properties of the BCG



Martizzi *et al.* 2011

Kinematic properties of the BCG

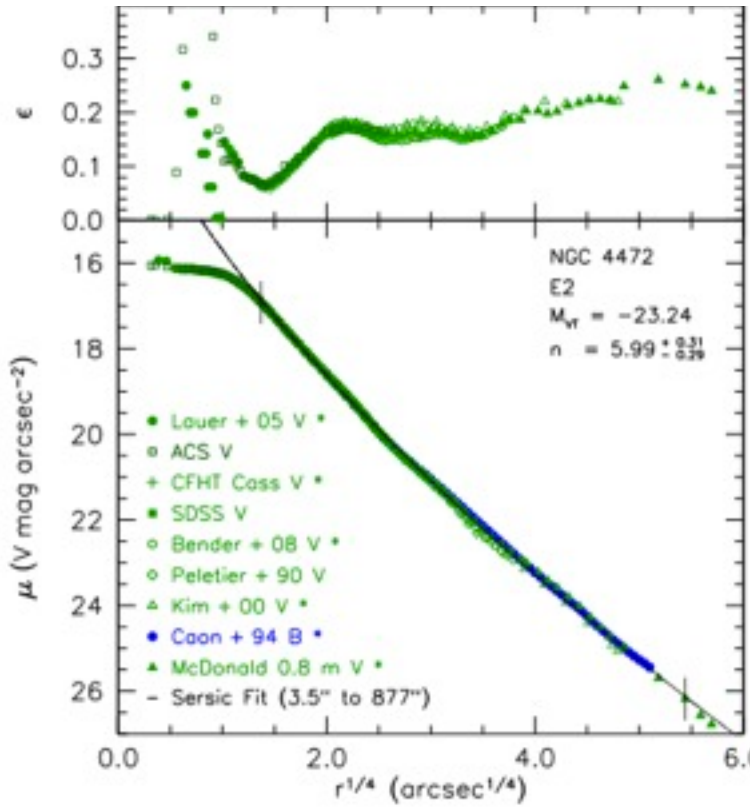


Martizzi *et al.* 2011

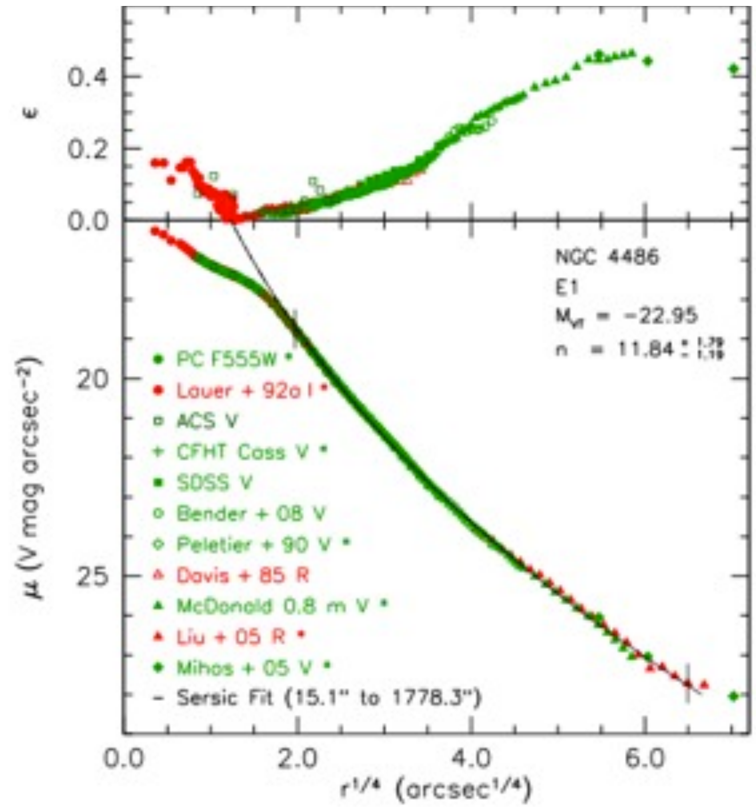
A stellar core in massive elliptical galaxies

Core elliptical: light deficit, low ellipticity, slow rotator

Kormendy *et al.* 2009



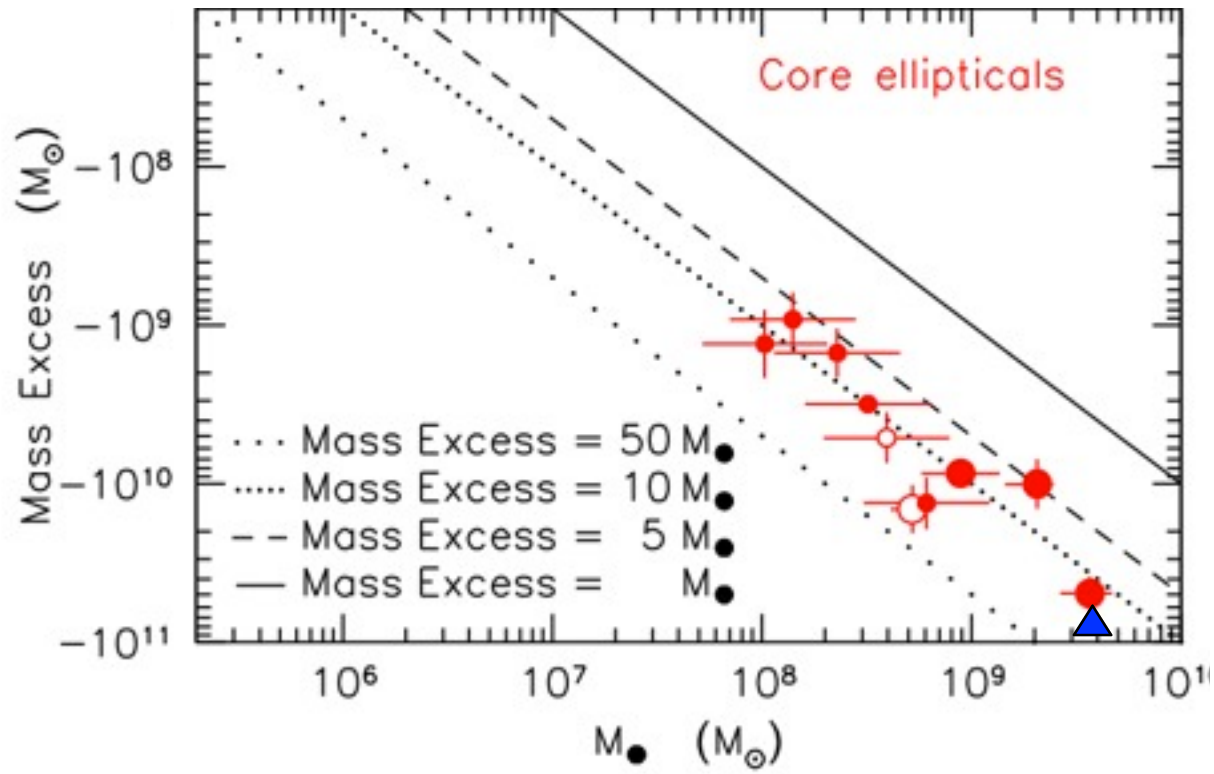
core size ~ 0.5 kpc



core size ~ 3 kpc

Large mass deficit in the core

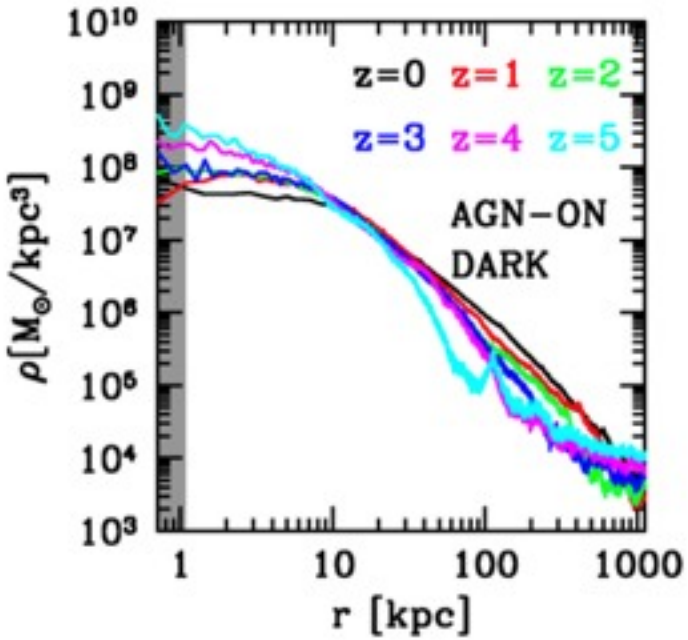
From the Sersic fit, we infer a mass deficit $M_{def}=10^{11}$ M_{sol} or $M_{def}/M_\bullet=20$.

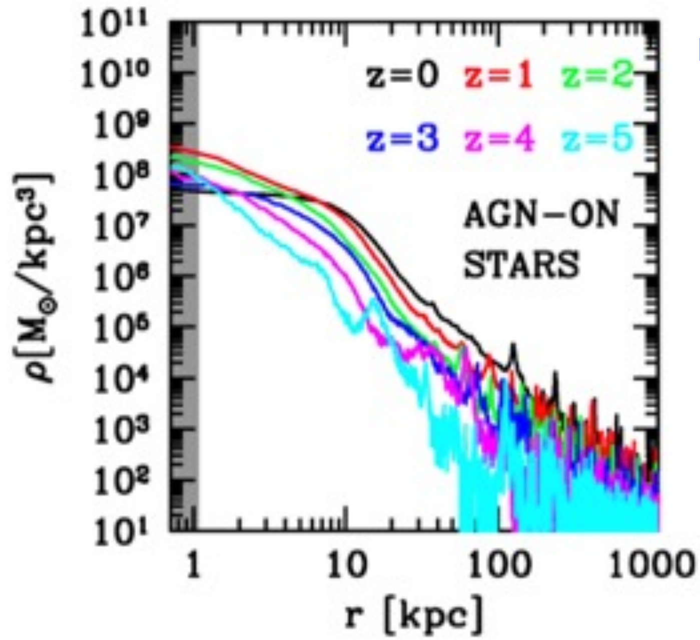


Kormendy *et al.* 2009

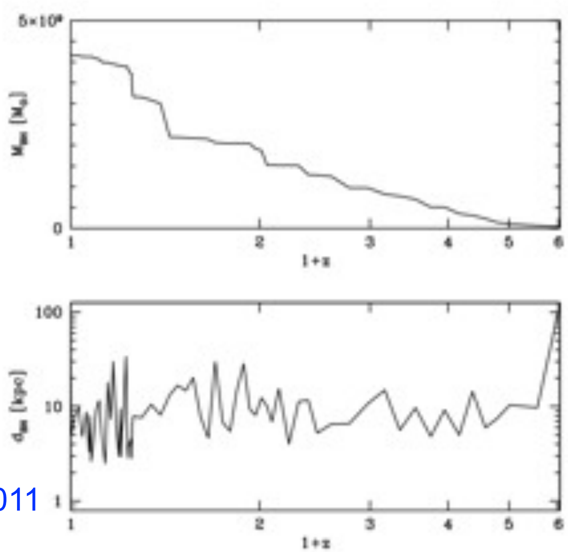
Martizzi *et al.* 2011

Origin of stellar and dark matter cores in clusters





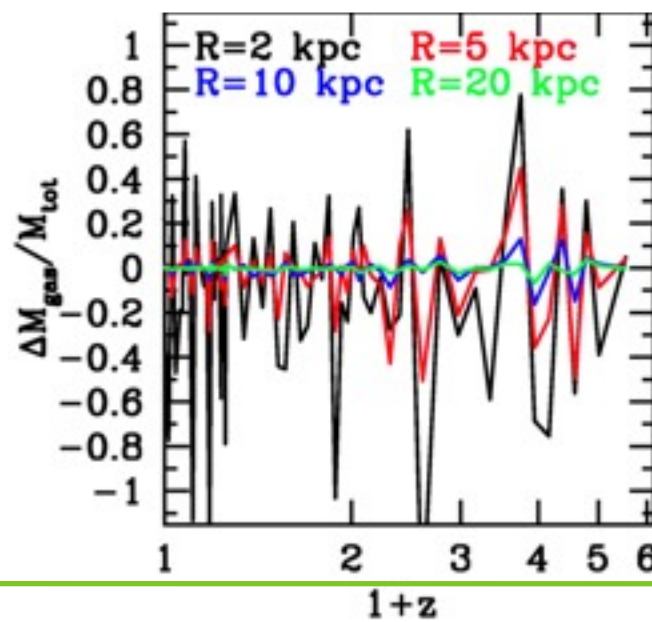
Martizzi *et al.* 2012



$M_{def}/M_{\bullet} \approx$ 1 to 5

Goerdt *et al.* 2010

Kulkarni & Loeb 2011



$\Delta\Phi/\Phi$=100%

Peirani et al. 2008

Conclusion

A new stellar feedback scheme in RAMSES based on non-thermal processes and implemented as a delayed-cooling scheme.

Dwarf (10^{10} M_{sol}) cooling halo simulations give rise to a cusp-core dark matter profile transition, due to large potential fluctuations within the core.

Kinematic analysis reveals a thick, rotating, exponential disk, in striking agreement with an observed, quasi-isolated dwarf WLM.

Radiative feedback of IR radiation on dust play a major role for MW-like galaxies. It probably sets the starting point of AGN feedback.

The Booth & Schaye AGN feedback model has been implemented in RAMSES and used in a 10^{14} M_{sol} halo cosmological simulation.

This brings the massive central galaxy properties in agreement with observations (no more overcooling).

Kinematics analysis reveals a massive, slowly rotating elliptical galaxy with a cored Sersic profile.

AGN feedback (high z) and SMBH friction (low z) give rise to the formation of a dark matter and a stellar core (or broken power law) of similar sizes.