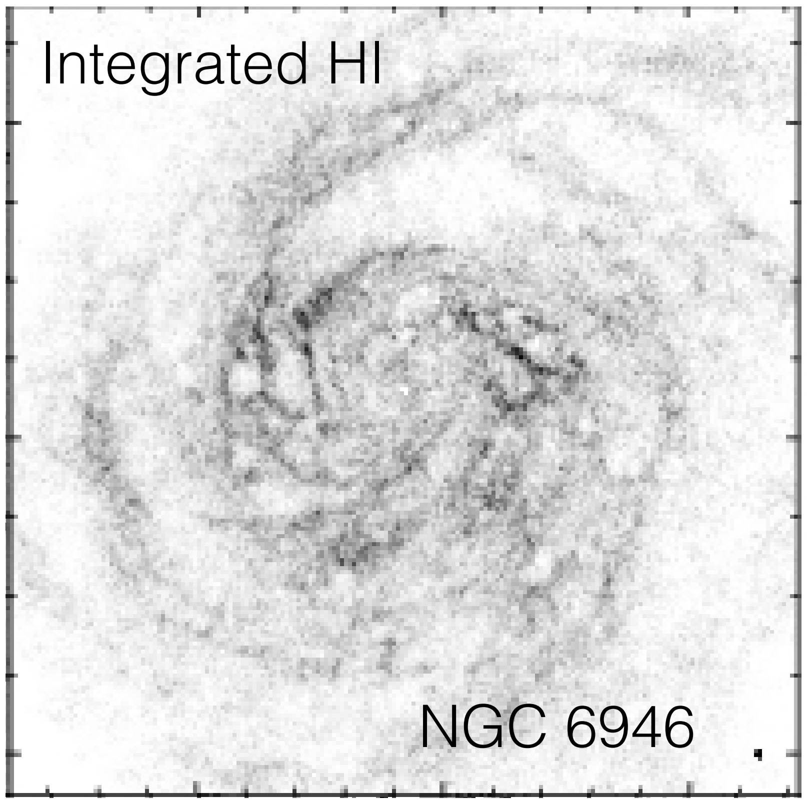
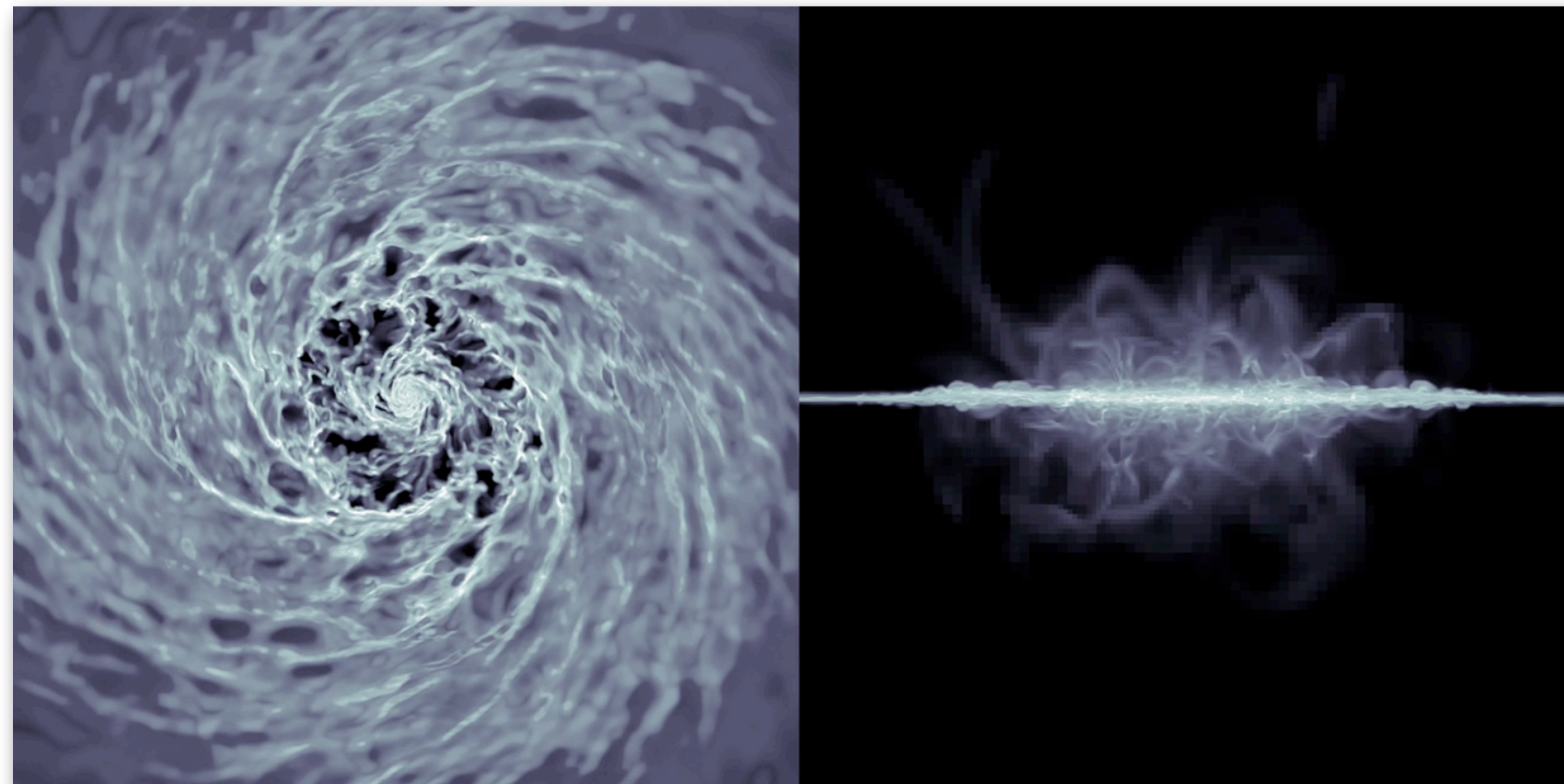
Shaping the interstellar medium with stellar feedback

Work in progress!



THINGS (Walter et al. 2008)

vs.



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+ Andrey Kravtsov, Nick Gnedin, Sam Leitner, Kearn Grisdale, Alessandro Romeo, Florent Renaud, Ramon Rey-Raposo, Justin Read …

Ringberg, 10/5 - 2016

Stellar feedback in cosmological simulations Agertz et al. (2013)

A stellar population/particle of mass m_*, +IMF, + M_{star}-Z-age relation (e.g. Bertelli et al. 1994), gives us a time resolved release of:

Energy: $$\dot{E}_{\rm tot} = \dot{E}_{\rm SN}(m_*, t, Z_*) + \dot{E}_{\rm wind}(m_*, t, Z_*)$$

Momentum: $$\dot{p}_{\rm tot} = \dot{p}_{\rm SN}(m_*, t, Z_*) + \dot{p}_{\rm wind}(m_*, t, Z_*) + \dot{p}_{\rm rad}(m_*, t, Z_{\rm gas})$$

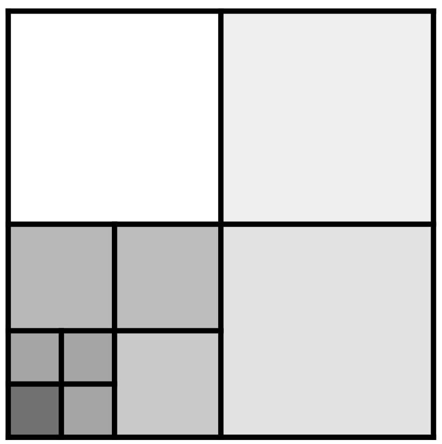
Mass loss: $$\dot{m}_{\rm tot} = \dot{m}_{\rm SN}(m_*, t, Z_*) + \dot{m}_{\rm winds}(m_*, t, Z_*)$$

Metals: $$\dot{m}_{Z,\rm tot} = \dot{m}_{Z,\rm SN}(m_*, t, Z_*) + \dot{m}_{Z,\rm winds}(m_*, t, Z_*)$$

All rates are calibrated on the stellar evolution code STARBURST99 (*Leitherer et al. 1999*). See also *Hopkins et al. (2012, 2014), Brook et al. (2012), Ceverino et al. (2013)*.

- All simulations performed using the Adaptive-Mesh-Refinement (AMR) code **RAMSES** (*Teyssier 2002*)

- Cosmic ray feedback (Booth et al. 2013) $+\dot{E}_{\rm CR}$



Momentum generation

The **initial** momentum injection rates from SNe, stellar winds and radiation pressure are roughly equal

$$\dot{p}_{\rm SNII} \sim \dot{p}_{\rm winds} \sim \frac{L_{\rm mech}}{v} \sim \frac{L_{\rm bol}}{c} \sim \dot{p}_{\rm rad}$$

- IR photon trapping? Warm/hot dust? Stability of feedback accelerated shells? (*Krumholz & Thompson 2013*)

$$\dot{p}_{\rm rad} = \tau \frac{L}{c}$$

- Supernovae explosions undergoing a successful adiabatic **Sedov-Taylor** phase, will also boost momentum (e.g. *Cioffi et al.1988, Blondin et al. 1998*)

$$p_{\rm ST} = M_{\rm ST} v_{\rm ST} \approx 2.6 \times 10^5 \, E_{51}^{16/17} n_0^{-2/17} M_\odot \, {\rm km \, s^{-1}} \longrightarrow p_{\rm ST} \sim 10 \, p_{\rm SNII}$$

- **The success of momentum generation depends on environment**, e.g. cooling in unresolved shocks. *Thornton et al. (1998), Cho & Kang (2008)* and *Krausse et al. (2013)* found that only 10-20% of thermal energy is converted into kinetic energy. A large number of studies just in the past year has studied momentum generation: *Martizzi et al. (2015), Kim & Ostriker (2015), Vasiliev et al. (2015), Simpson et al. (2015), Gatto et al. (2015), Walch et al. (2015), Haid et al. (2016) etc.*

Feedback energy injection/evolution

- Thermal feedback is inefficient in galaxy formation simulations; **the gas cooling time in dense gas is short.**

- Successful implementations of thermal feedback usually assume an extended period of **adiabatic evolution** (*Gerritsen 1997, Stinson et al. 2006, Governato et al. 2010, Agertz et al. 2011, Guedes et al. 2011*). Alternatively, one may find ways of depositing the energy outside of star forming regions (**runaway stars**, *Ceverino & Klypin 2010*), by enforcing large temperature jumps via **selective energy deposition** (*Dalla Vecchia & Schaye 2013*) or explicitly modeling **super bubbles.** *(Keller, Wadsley et al. 2014)*

- We evolve a fraction of the feedback energy using a second energy equation (Agertz et al. 2013, 2015). This field provides extra pressure to the gas. See also Teyssier et al. (2013), Birnboim et al. (2015).

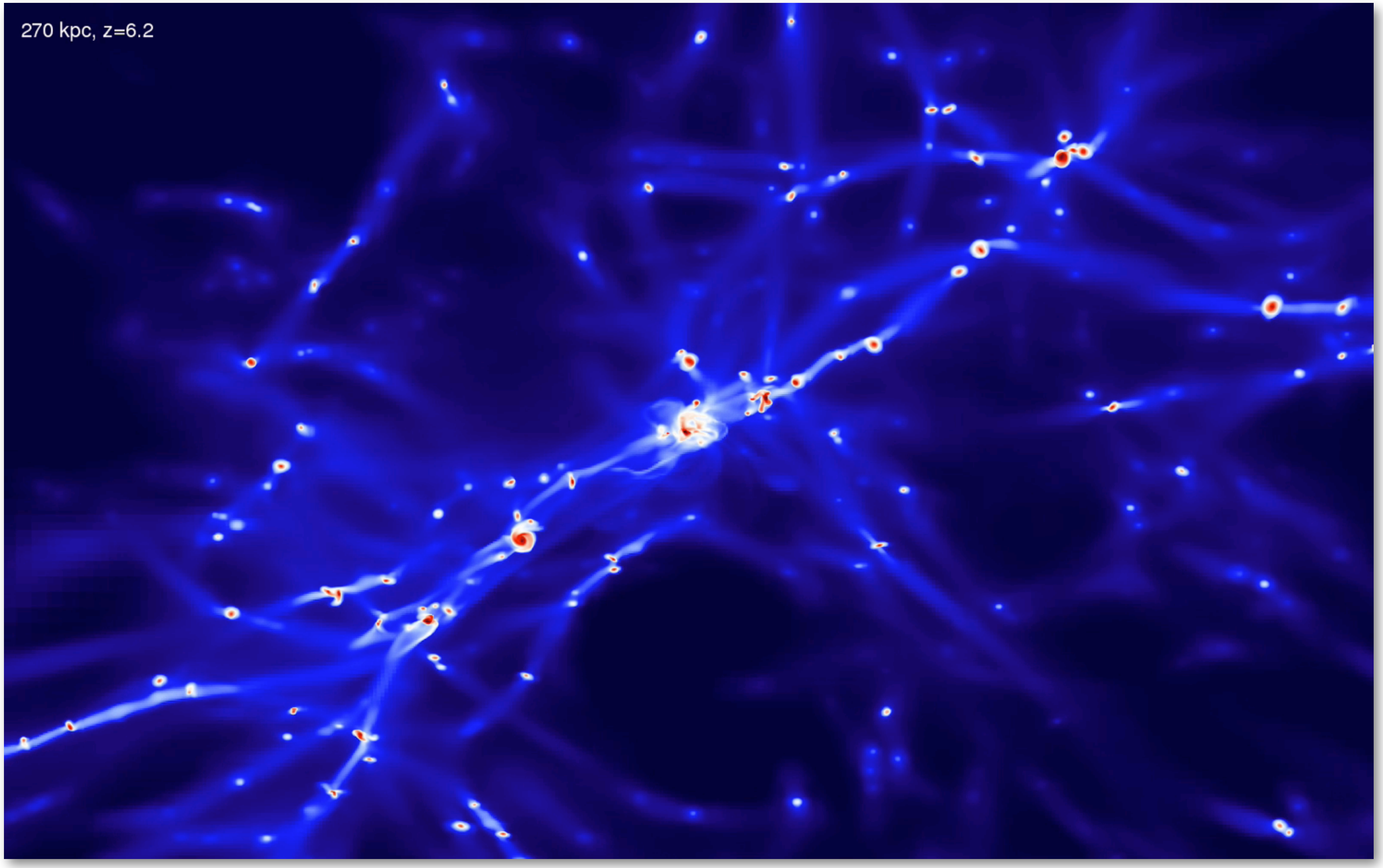
$$\frac{\partial}{\partial t}(E_{\rm fb}) + \nabla \cdot (E_{\rm fb} v_{\rm gas}) = -P_{\rm fb} \nabla \cdot v_{\rm gas} - \frac{E_{\rm fb}}{t_{\rm dis}}$$

$$t_{\rm dis} = 10\,{\rm Myr} \qquad f_{\rm fb} = 10\% - 50\%$$

Cosmological zoom-in simulations of galaxy formation

- Milky Way-like progenitor, $M_{200}=10^{12}\ M_{sun}$ at z=0.
- Force/hydro resolution: 50-100 pc.
- Accounts for energy and momentum feedback via radiation pressure, stellar winds and supernovae, as well as associated enrichment and mass loss processes.
- Star formation based on local abundance of H_2 (*Krumholz et al. 2009, Gnedin et al. 2009, Kuhlen et al. 2012, Christensen et al. 2014*).

$$\dot{\rho}_{\star} = f_{\mathrm{H}_2} \epsilon_{\mathrm{ff}} \frac{\rho_{\mathrm{gas}}}{t_{\mathrm{ff}}}$$



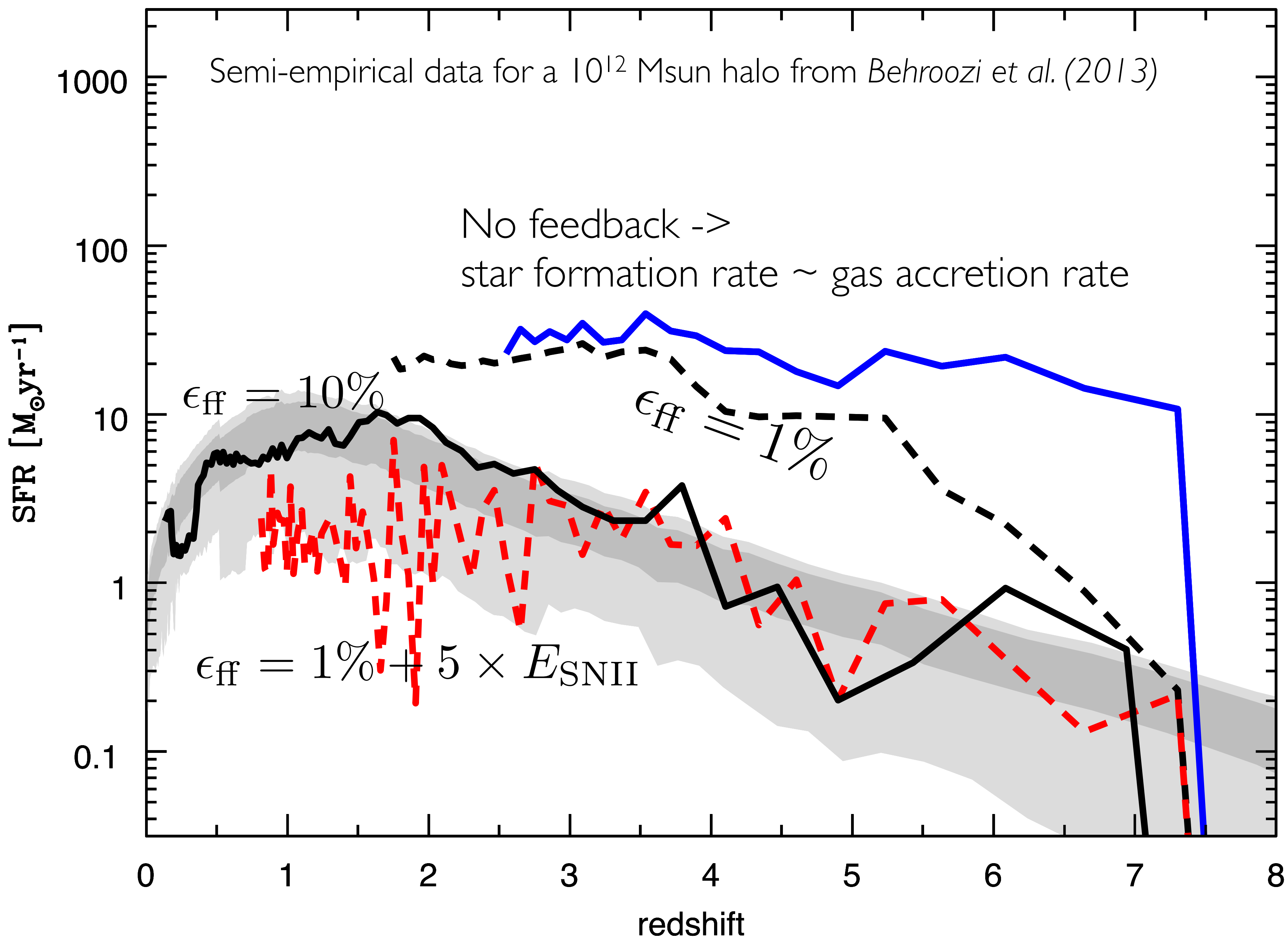
Agertz & Kravtsov (2015 & 2016)

Star formation histories

Star formation in Milky Way-like galaxies is expected to be highly suppressed for the first 3 billion years!

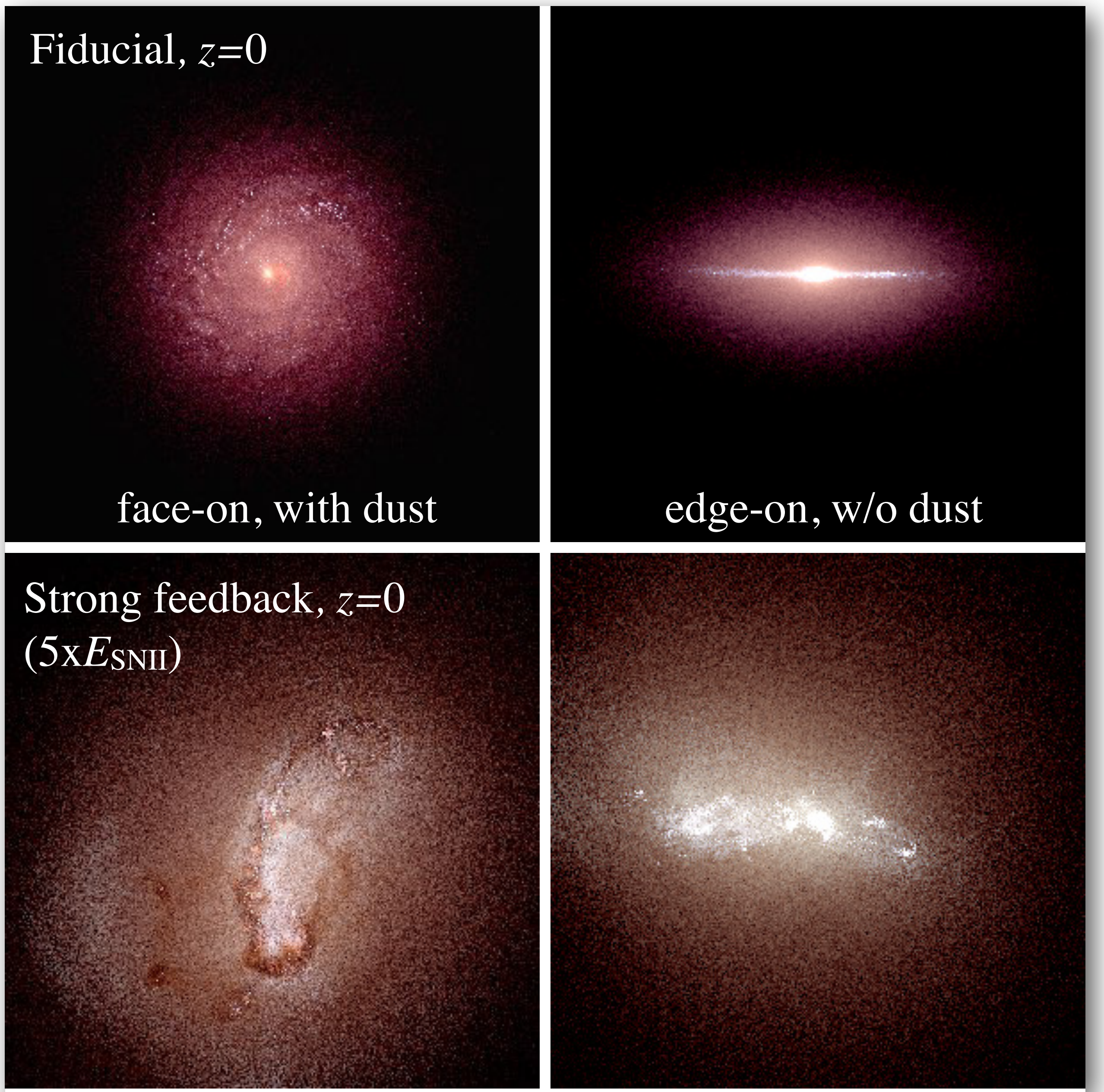
"Milky Way-like galaxies form ~90% of stellar mass after z~2.5"

Leitner (2012), Behroozi et al. (2013), van Dokkum et al. (2013)



Internal properties differ significantly!

SDSS mockups (g,r,i)
Agertz & Kravtsov (2016)

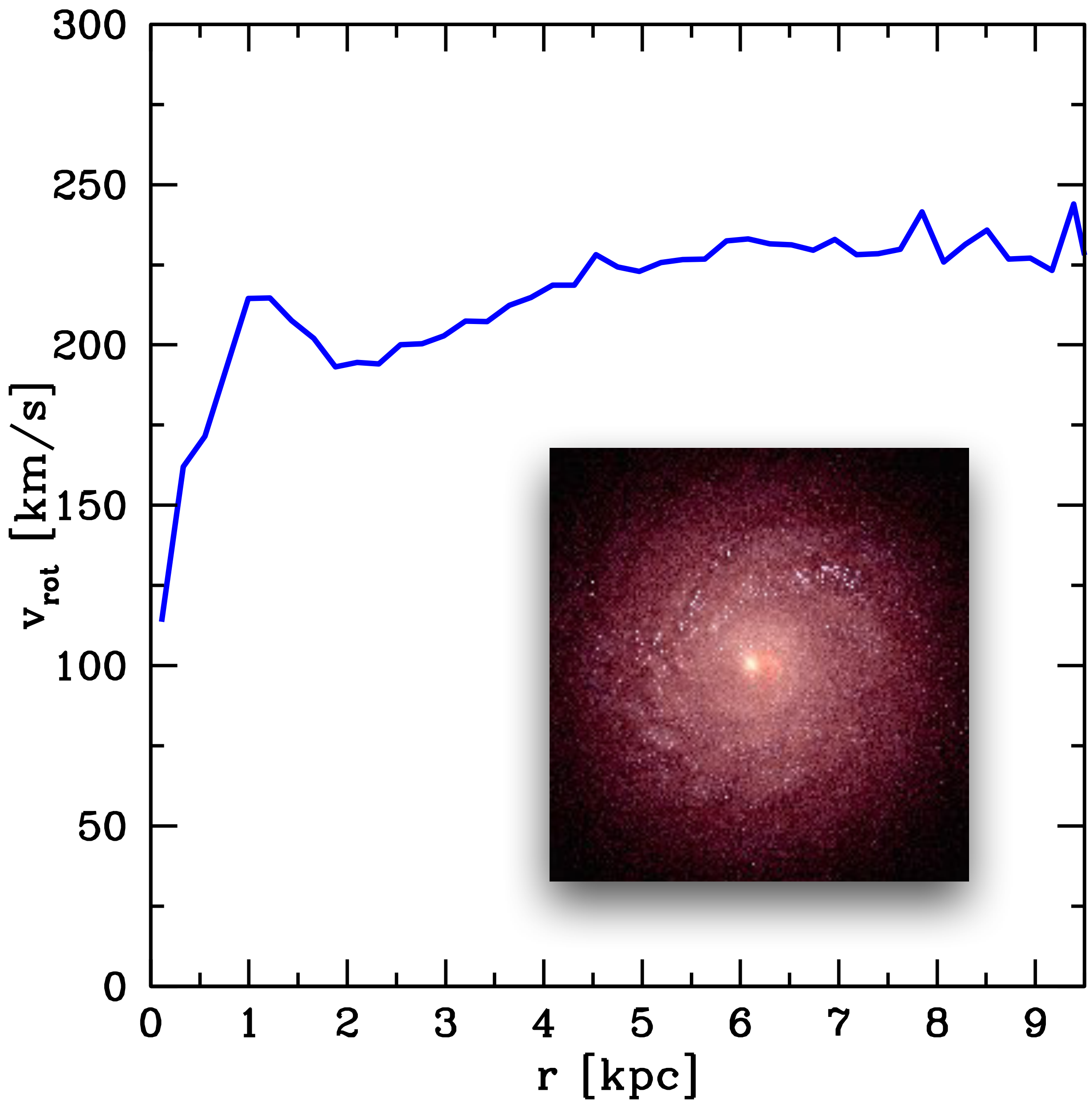


+

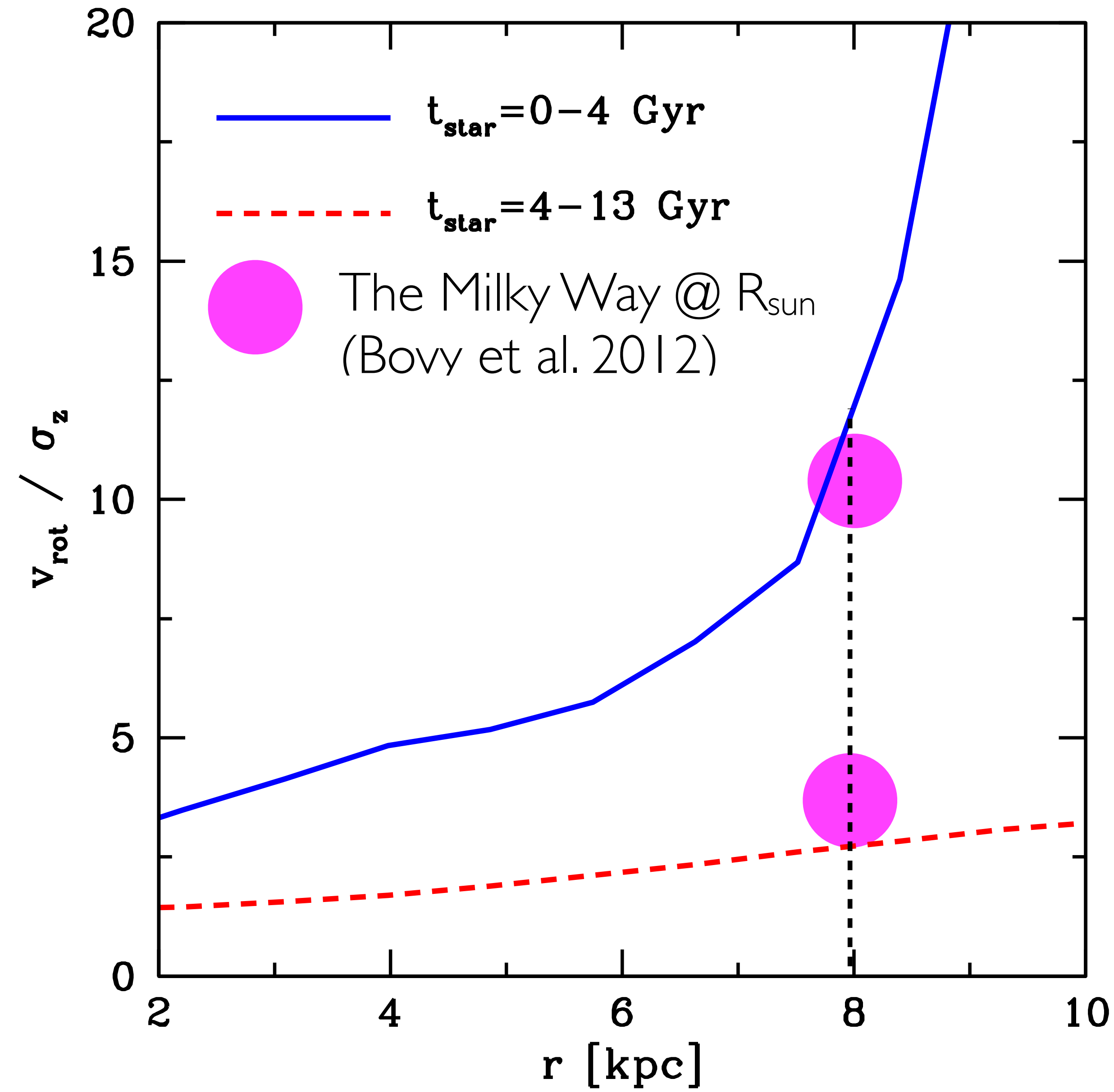
- Cosmic star formation histories
- Stellar mass - halo mass relation
- Stellar mass - gas metallicity relation + evolution
- Kennicutt-Schmidt relation
- Flat rotation curves
- M-$r_{1/2}$ relation
- Surface density of stars/gas vs local spirals

Thin and thick disks at z=0 (Agertz & Kravtsov 2015)

Rotational velocity of young stars



Stellar rotational velocity/ vertical velocity dispersion

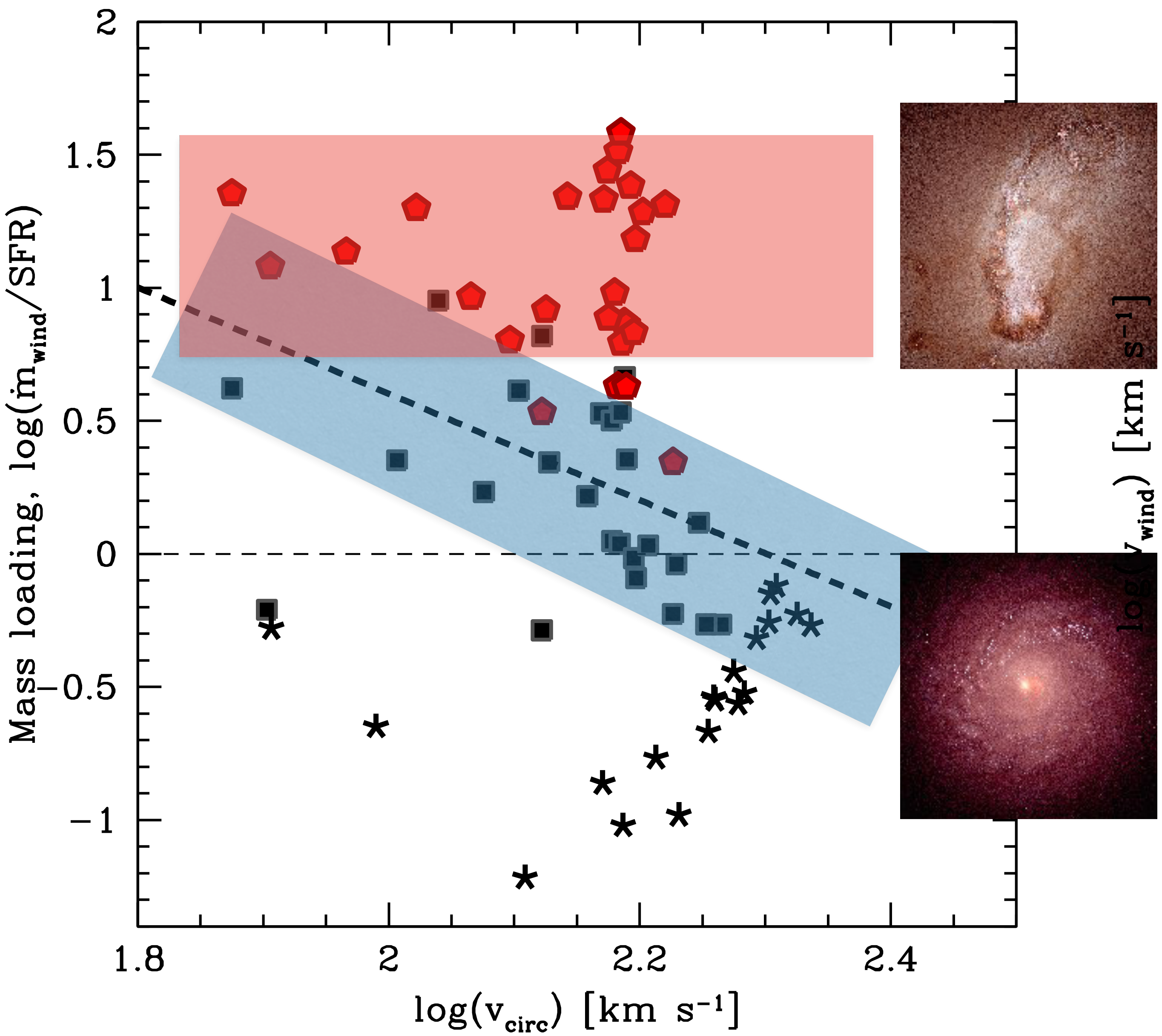


Appears when dx <50-100 pc. In the current model, only 1/3 of the disk mass is in a kinematically thin disk.

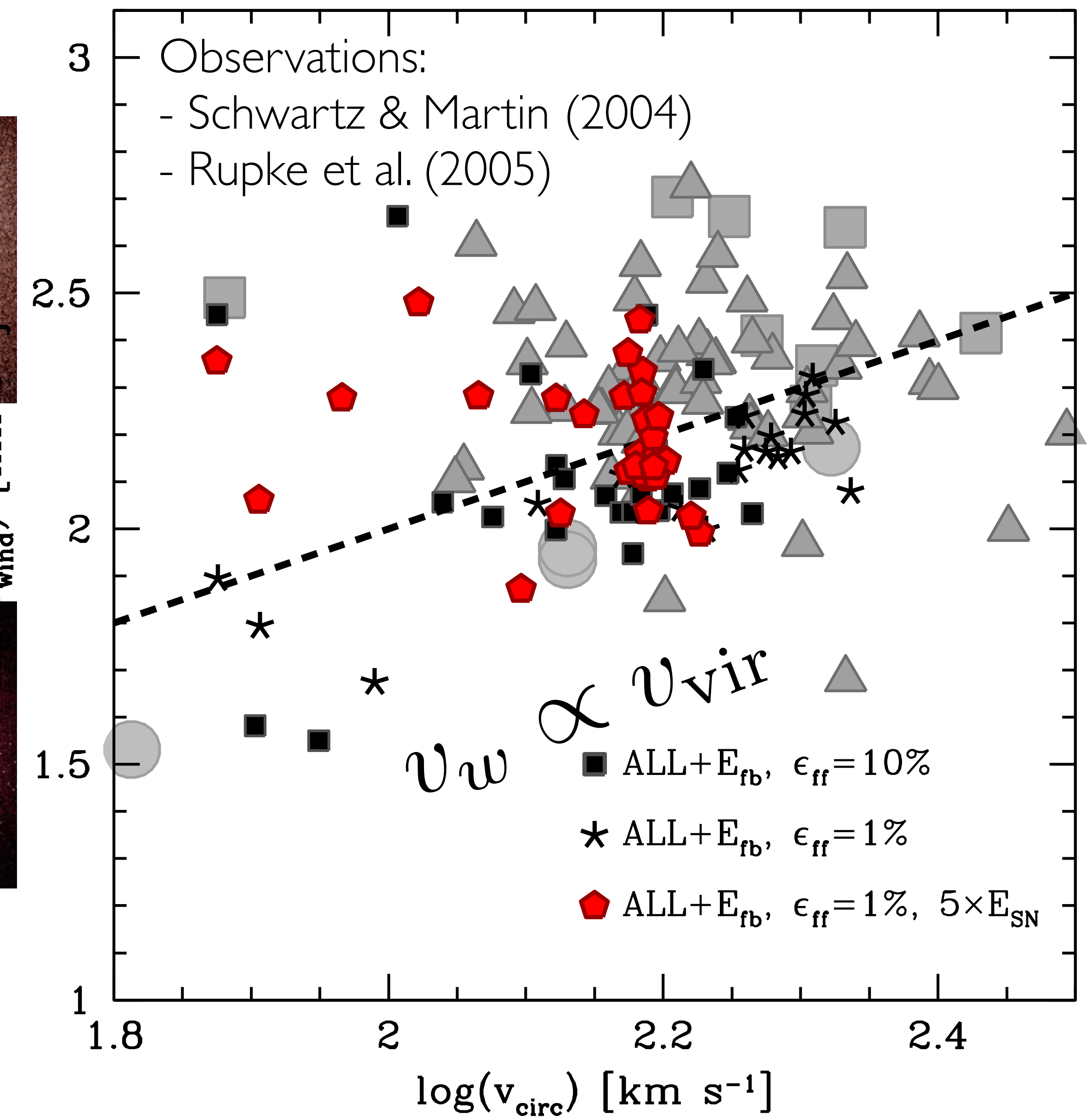
Galactic winds as emergent phenomena (not put in by hand!)

Mass-loading: $(\dot{m}_{\rm wind}/{\rm SFR}) - v_{\rm circ}$

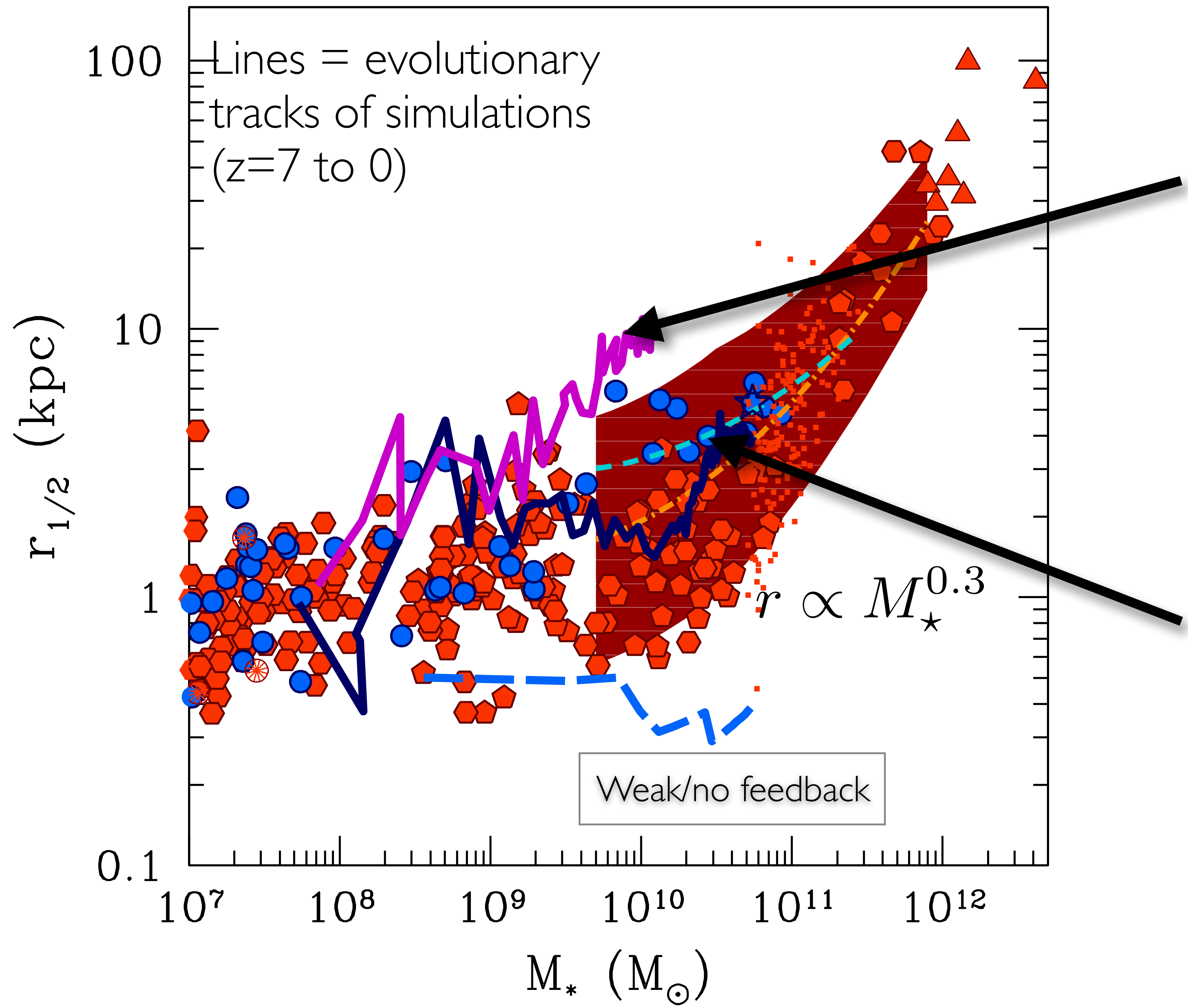
Measured at r=20 kpc for v>0



Wind velocities: $v_{\rm wind} - v_{\rm circ}$



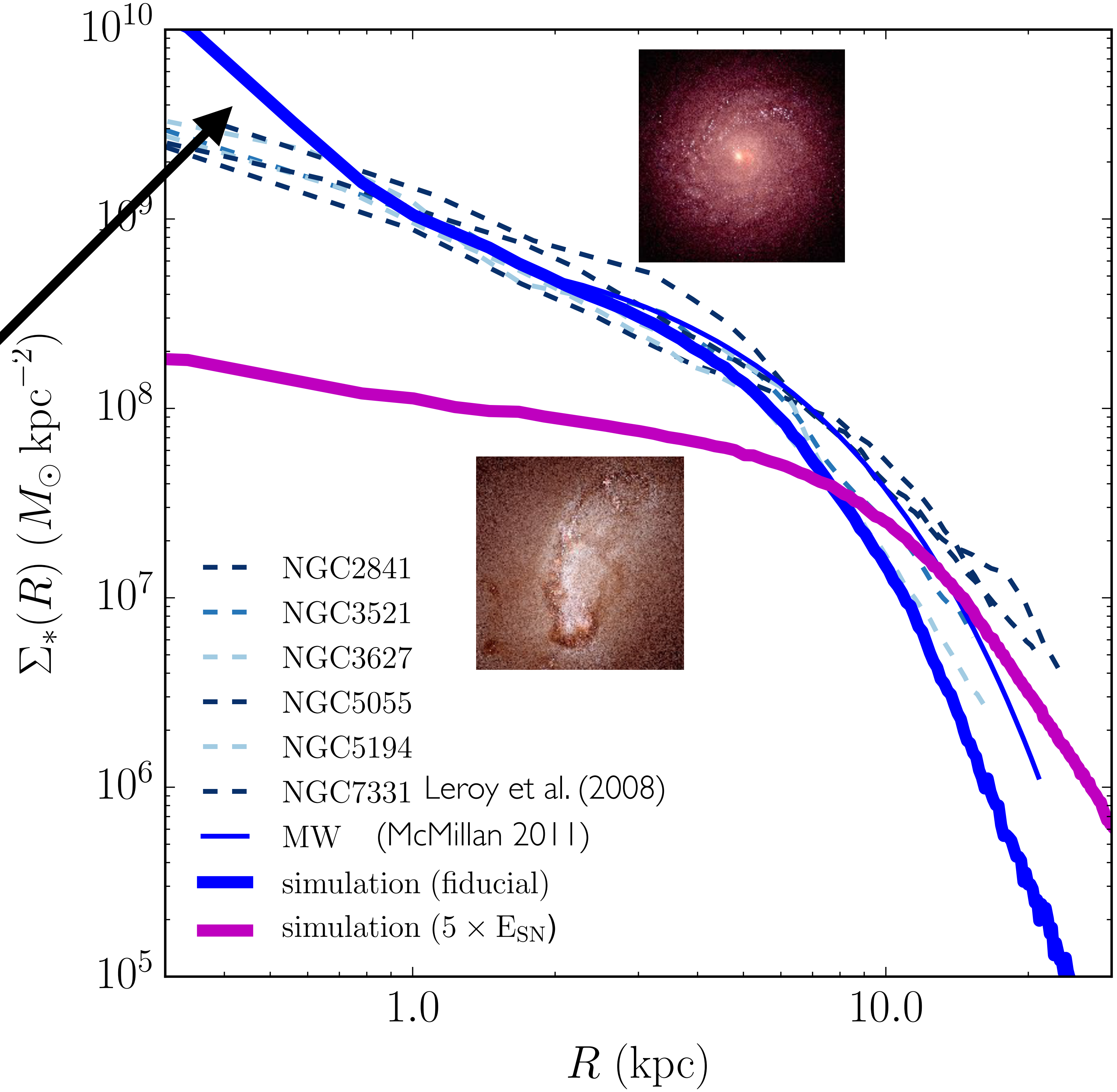
Galaxy sizes (Agertz & Kravtsov 2016)



Observational data from Misgeld & Hilker (2011), Leroy et al. (2008), Zhang et al. (2012), Bernardi et al. (2012). Szomoru et al. (2013)

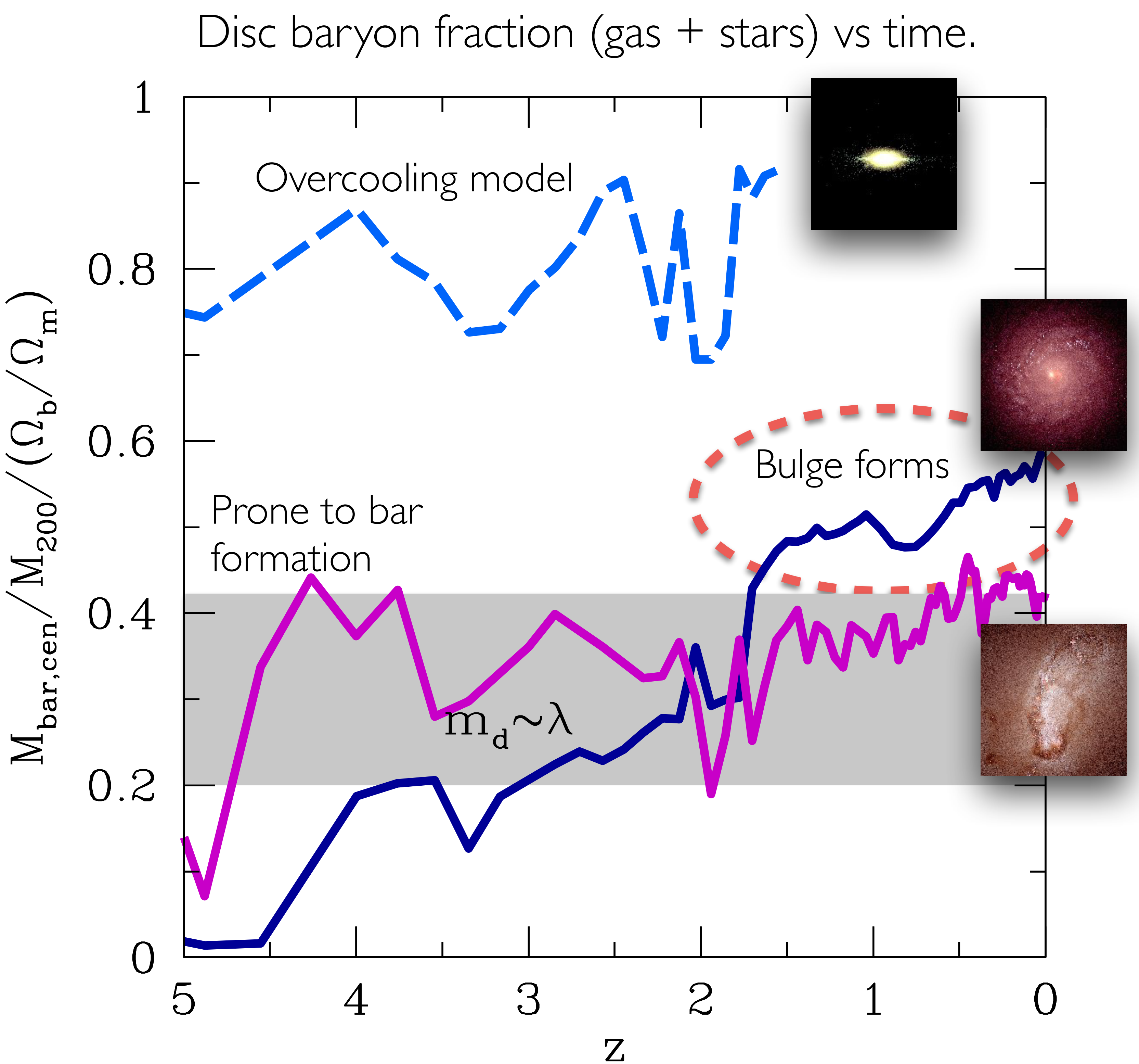
Surface density profiles (Agertz & Kravtsov 2016)

- Exponential stellar surface density profiles are recovered, with a normalization in agreement with local spirals
- The bulge component is prominent! This galaxy is roughly of Sa type.
- What drives the disc Hubble sequence?



(Agertz & Kravtsov 2016)

Disk instabilities/bars vs. feedback



Efstathiou, Lake & Negroponte (1982), Christodoulou et al. (1995), Mo, Mao & White (1998)

- Angular momentum loss occurs inside the discs due to instabilities (fragmentation, spiral arms and bars).
- The role of stellar feedback for the angular momentum content is two-fold:

1. expulsion of low-angular momentum gas from centers of galaxies (e.g. Brook et al 2009)
2. *maintain* of a low baryon fraction content via outflows in the disc to quench bar formation. This is 'easier' for low mass spirals.

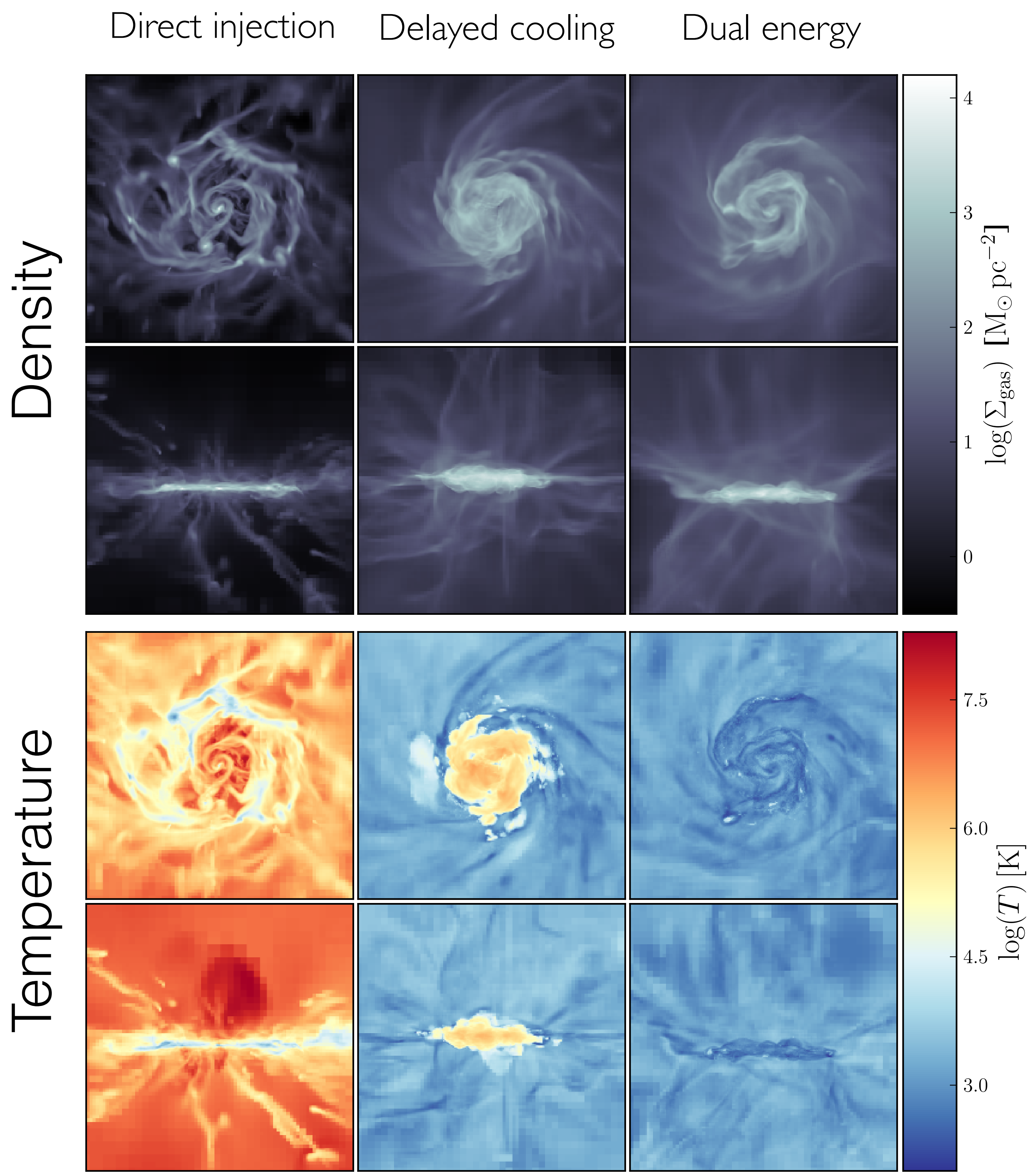
Coming back to the subgrid recipes…

$$\frac{\partial}{\partial t}(E_{\rm fb}) + \nabla \cdot (E_{\rm fb} v_{\rm gas}) = -P_{\rm fb} \nabla \cdot v_{\rm gas} - \frac{E_{\rm fb}}{t_{\rm dis}}$$

$$t_{\rm dis} = 10\,{\rm Myr}$$

$$f_{\rm fb} = 10\% - 50\%$$

- A bit unsatisfactory to have a free timescale and energy injection fraction to tune. A more proper subgrid model for these parameters would look like the Keller et al. (2014, 2016) super bubble model.
- Properties of ISM/CGM are sensitive to the implementation of thermal feedback.



Momentum generation from SNe

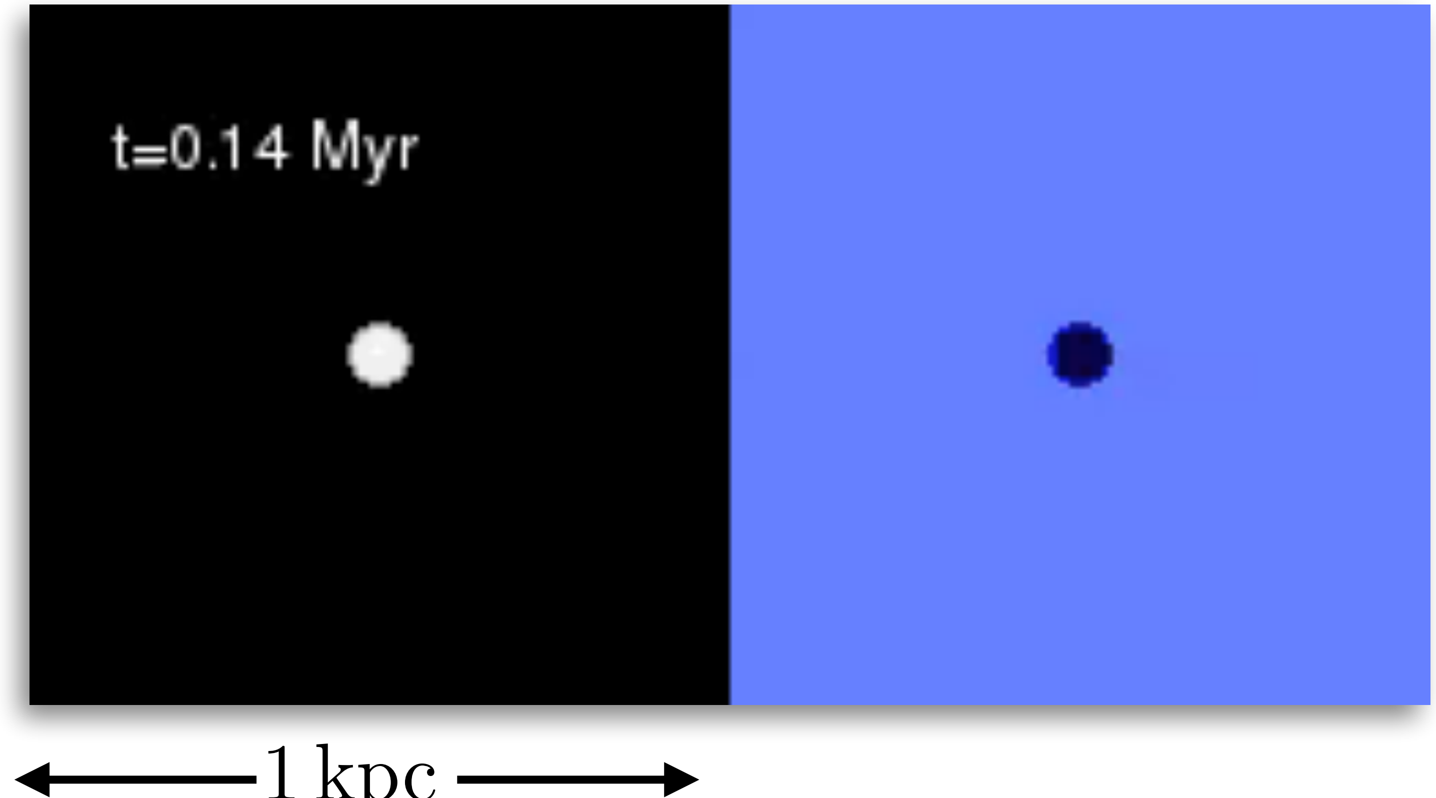
- A slew of studies just in the past year: *Martizzi et al. (2015), Kim & Ostriker (2015), Vasiliev et al. (2015), Simpon et al. (2015), Gatto et al. (2015), Walch et al. (2015), Haid et al. (2016) etc.*

- The total momentum that SNe inject into the interstellar medium depends on local density, turbulence properties etc, but doesn't change by more than a factor of ~ a few.

$$p_{\rm ST} \approx 2.6\times10^5\, E_{51}^{16/17} n_0^{-2/17} M_\odot {\rm km\,s^{-1}}$$

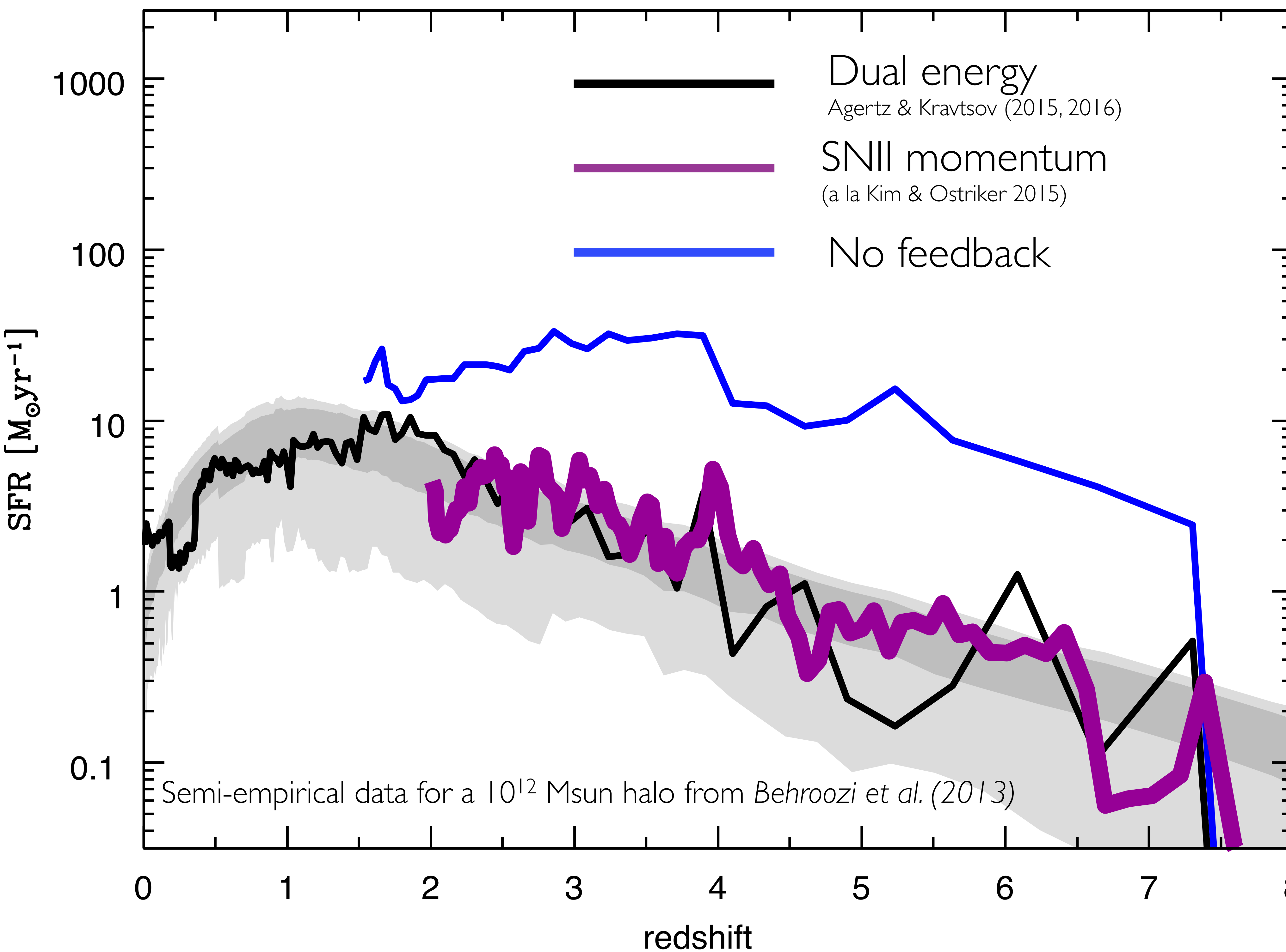
(Neglects CRs)

Test of Kim & Ostriker (2015) approach in a 10^6 M_{sun} cloud



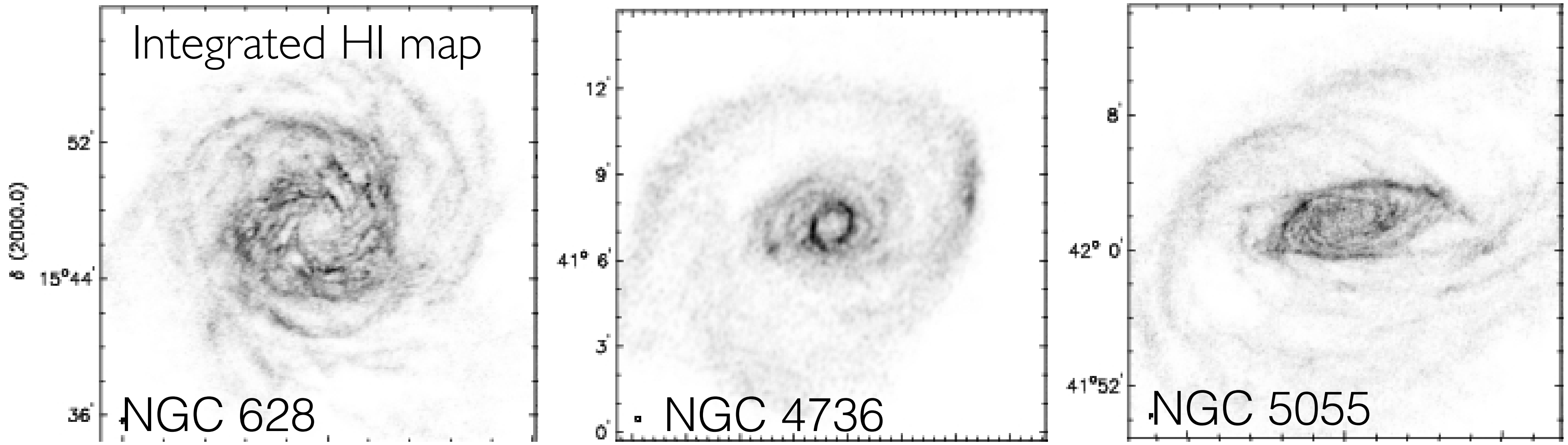
- Unresolved/embedded SNe are initialized in the momentum-conserving phase (<3 rcool)
- Resolved SNe (~98%) are initialized in the energy conserving phase

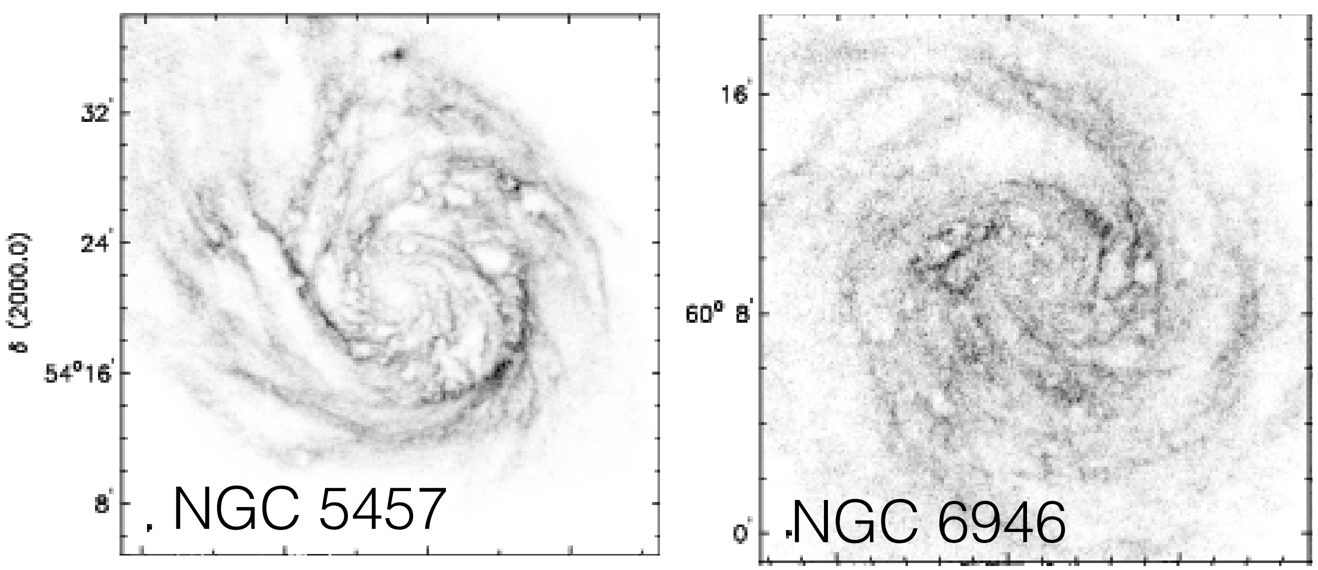
Star formation rates in cosmological simulations



see also Hopkins et al. (2014)

Can current feedback models reproduce the density and velocity structure of the cold ISM?



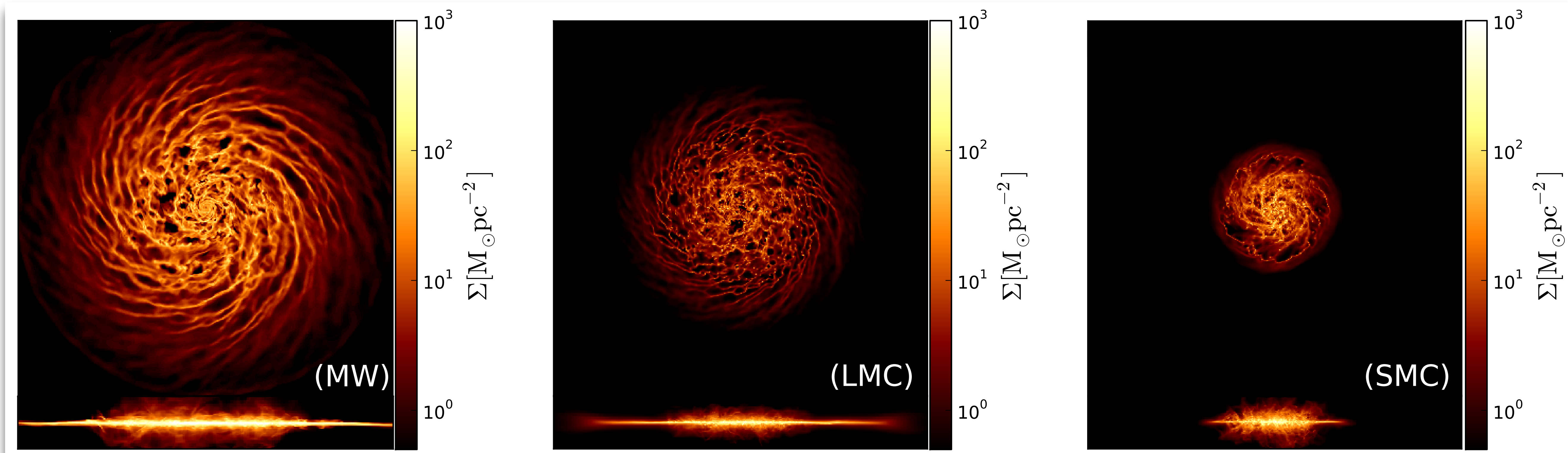


THINGS: THE H I NEARBY GALAXY SURVEY
Walter et al. (2008)
+
HERACLES: THE HERA CO LINE EXTRAGALACTIC SURVEY
Leroy et al. (2009)

Table 1. Summary of our analysed sample of galaxies from THINGS

Galaxy	Distance [Mpc]	Inclination [°]	$M_{\rm HI}$ [$10^8 M_\odot$]	$M_{\rm H_2}$ [$10^8 M_\odot$]	$M_\star$ [$10^8 M_\odot$]	Global SFR [$M_\odot {\rm yr}^{-1}$]	HI beam width [pc]	H_2 beam width [pc]
NGC 628	7.3	7	38.0	8.3	37.15	1.21	240	389
NGC 3521	10.7	73	80.2	26.5	602.56	3.34	425	570
NGC 4736	4.7	41	4.0	4.1	218.78	0.43	136	250
NGC 5055	10.1	59	91.0	36.2	575.44	2.42	263	538
NGC 5457	7.4	18	141.7	19.8	107.15	1.49	269	394
NGC 6946	5.9	33	41.5	32.0	91.20	4.76	173	314

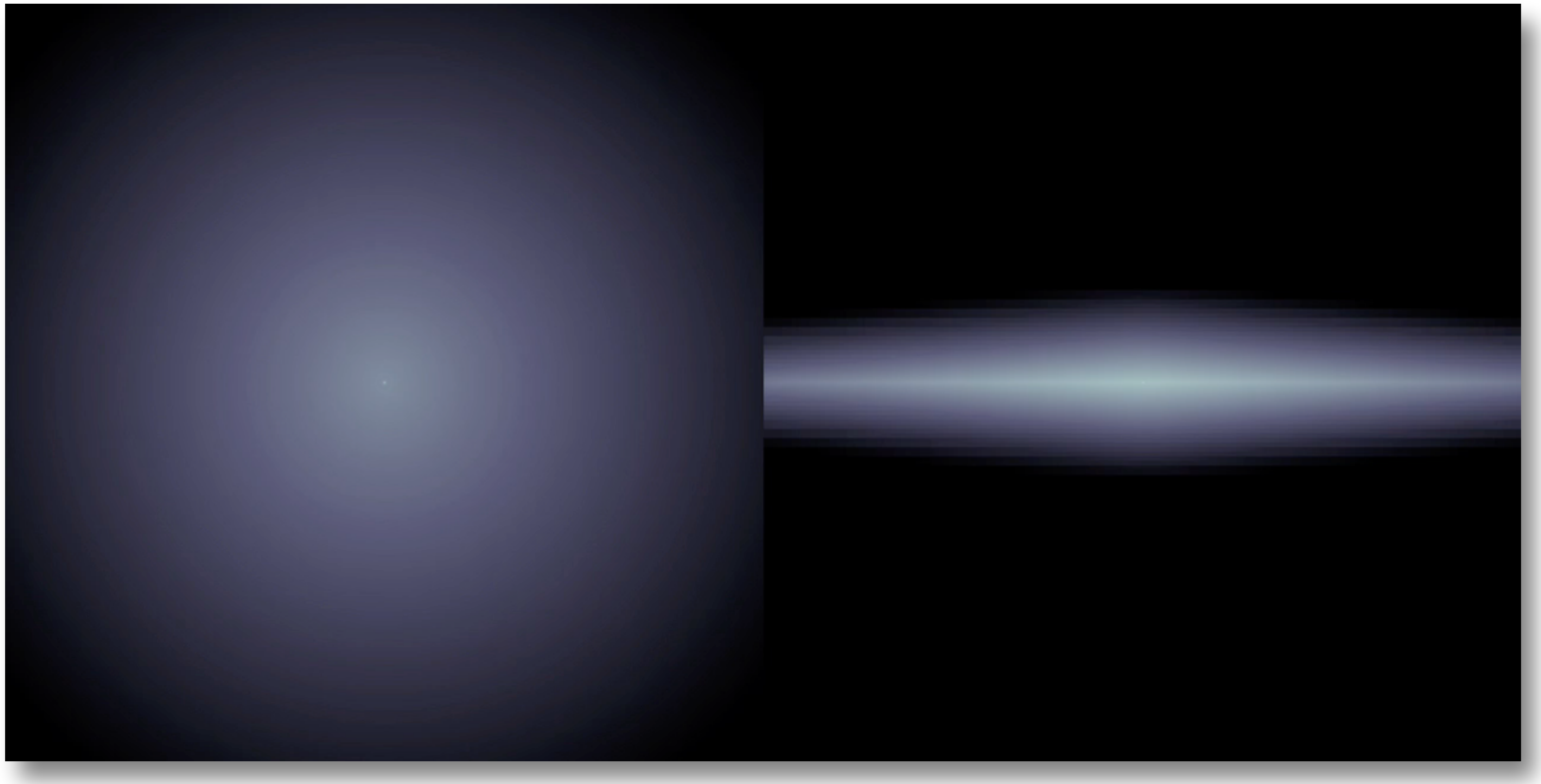
Galaxy simulations



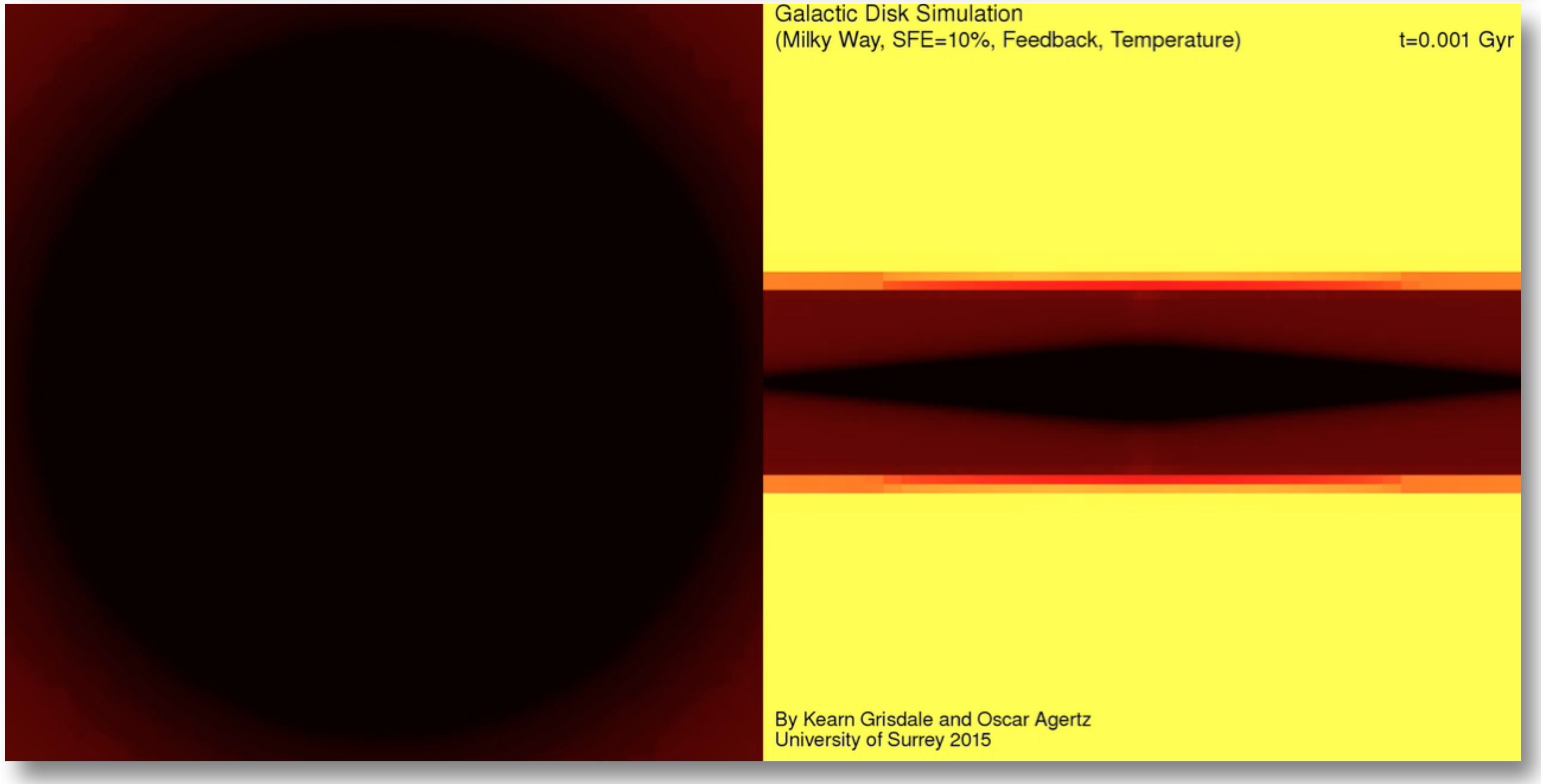
- Spatial resolution of a few parsec (tests with 2, 4 and 16 pc) (gas/star mass resolution ~1000/500 M_{sun})
- The galaxies are evolved with and without stellar feedback for 0.5 Gyr
- We compute surface density and kinetic energy power spectra (simulated data convolved with Gaussian, data is padded by 3x the domain etc)
- Molecular hydrogen model based on Krumholz, Mckee & Tomlinson (2009)

Galaxy simulations

Gas density

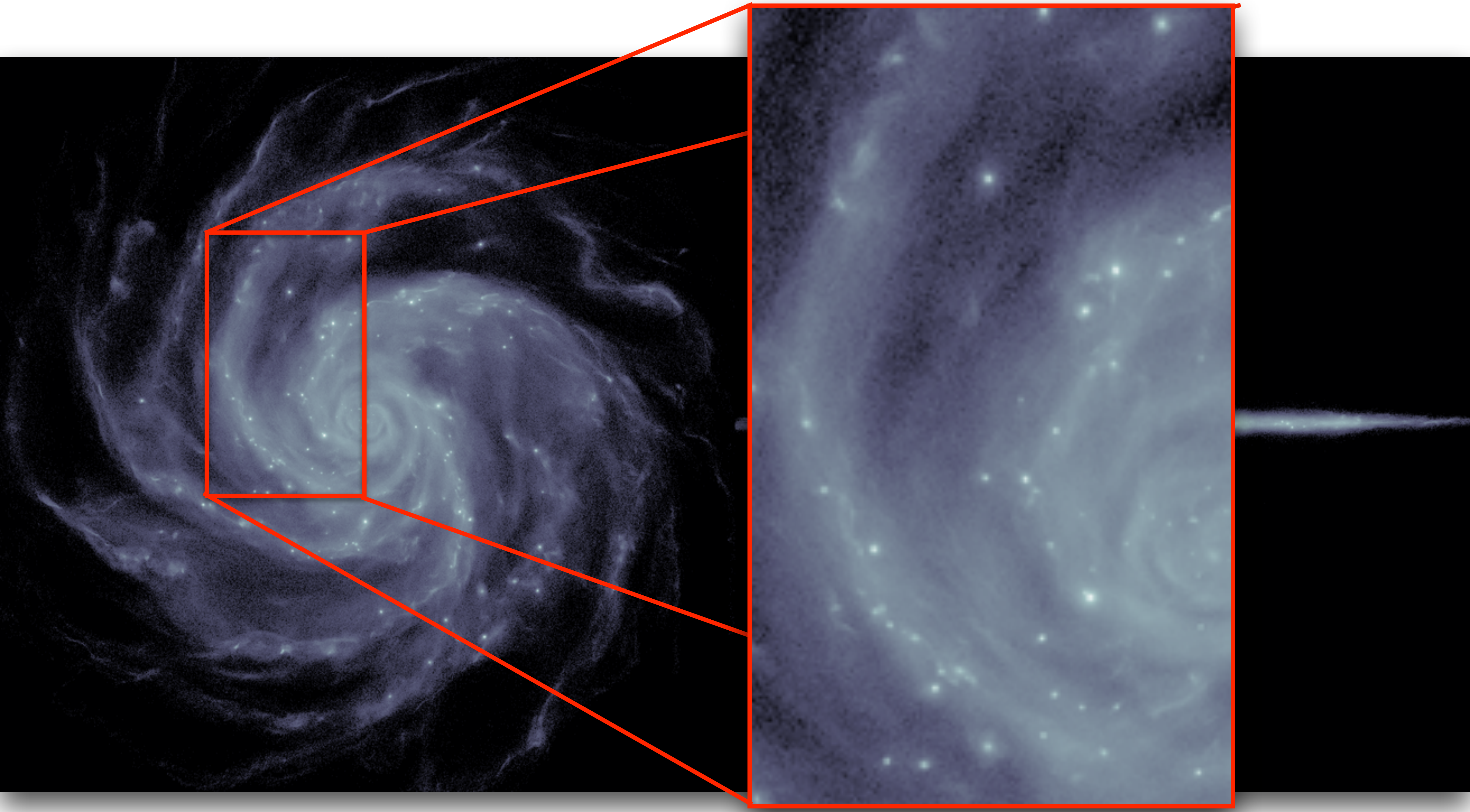


Gas temperature

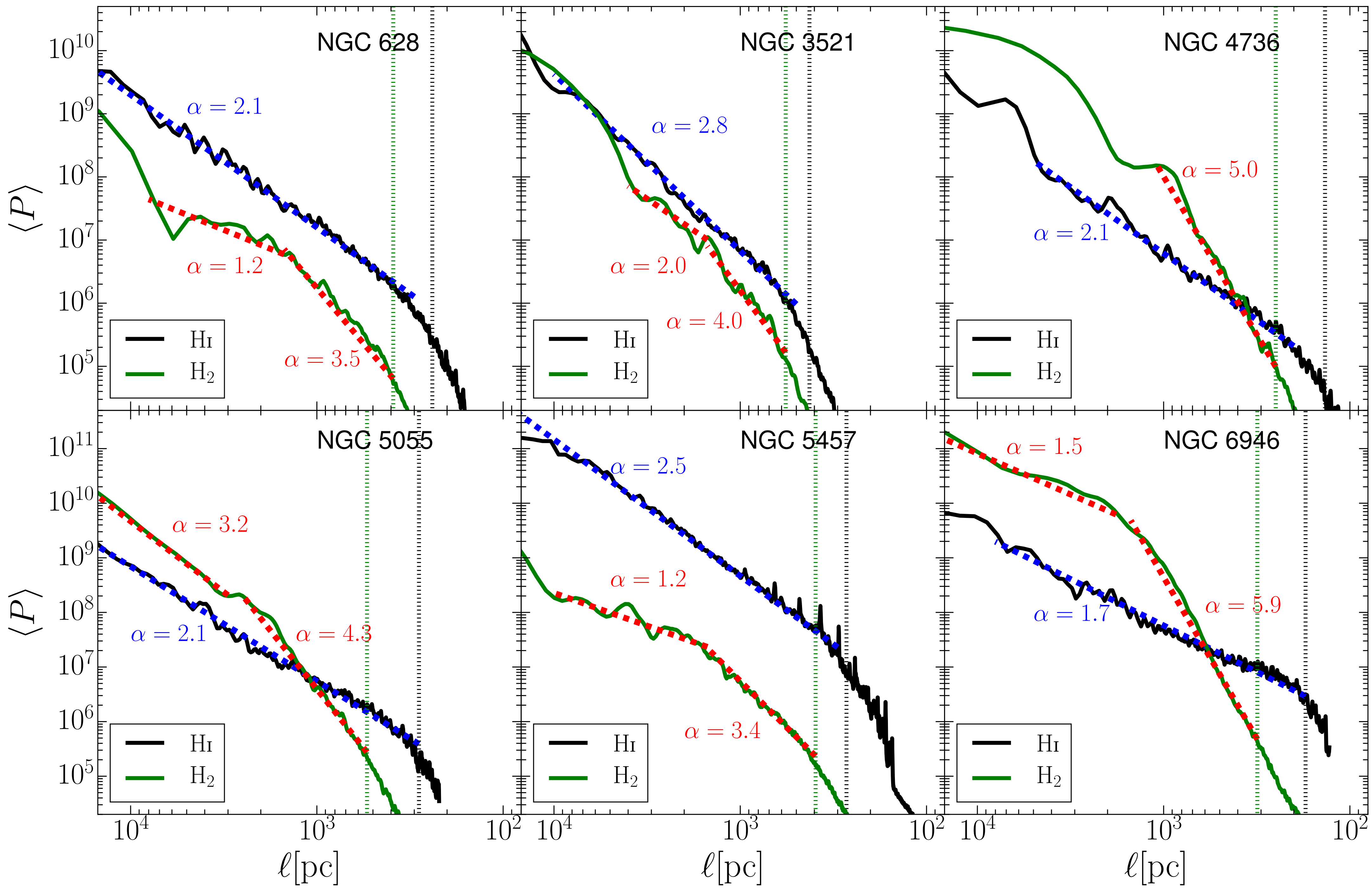


Grisdale, Agertz et al. (in prep)

Galaxy simulations



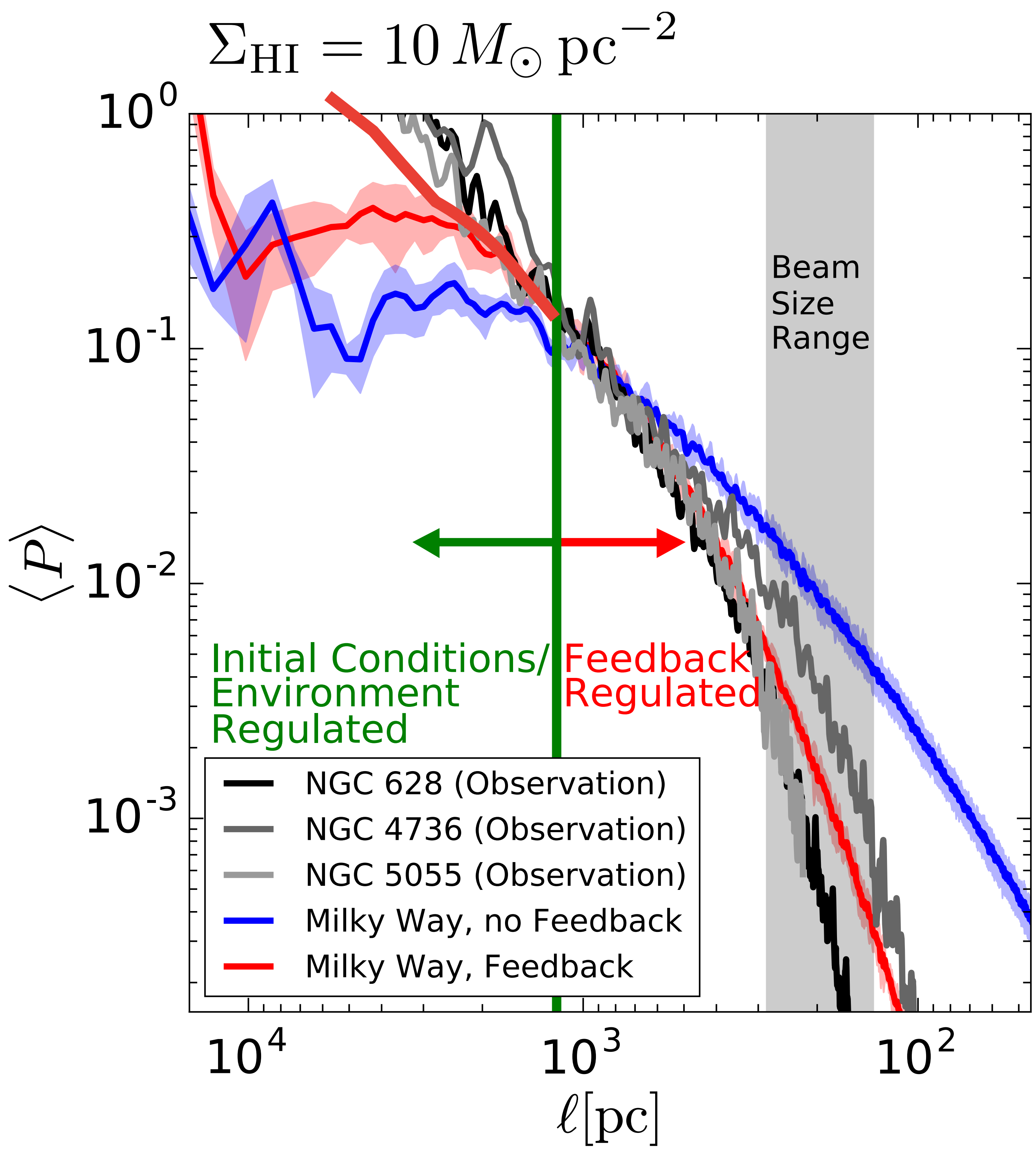
Observed surface density power spectra



see also e.g .Begum et al. 2006; Block et al. 2010; Bournaud et al. 2010; Pilkington et al. 2011, Combes et al. 2012; Dutta & Bharadwaj 2013; Dutta et al. 2008, 2009a,b, 2010, 2013; Elmegreen et al. 2001; Stanimirovic et al. 1999; Zhang et al. 2012, Walker et al. 2014

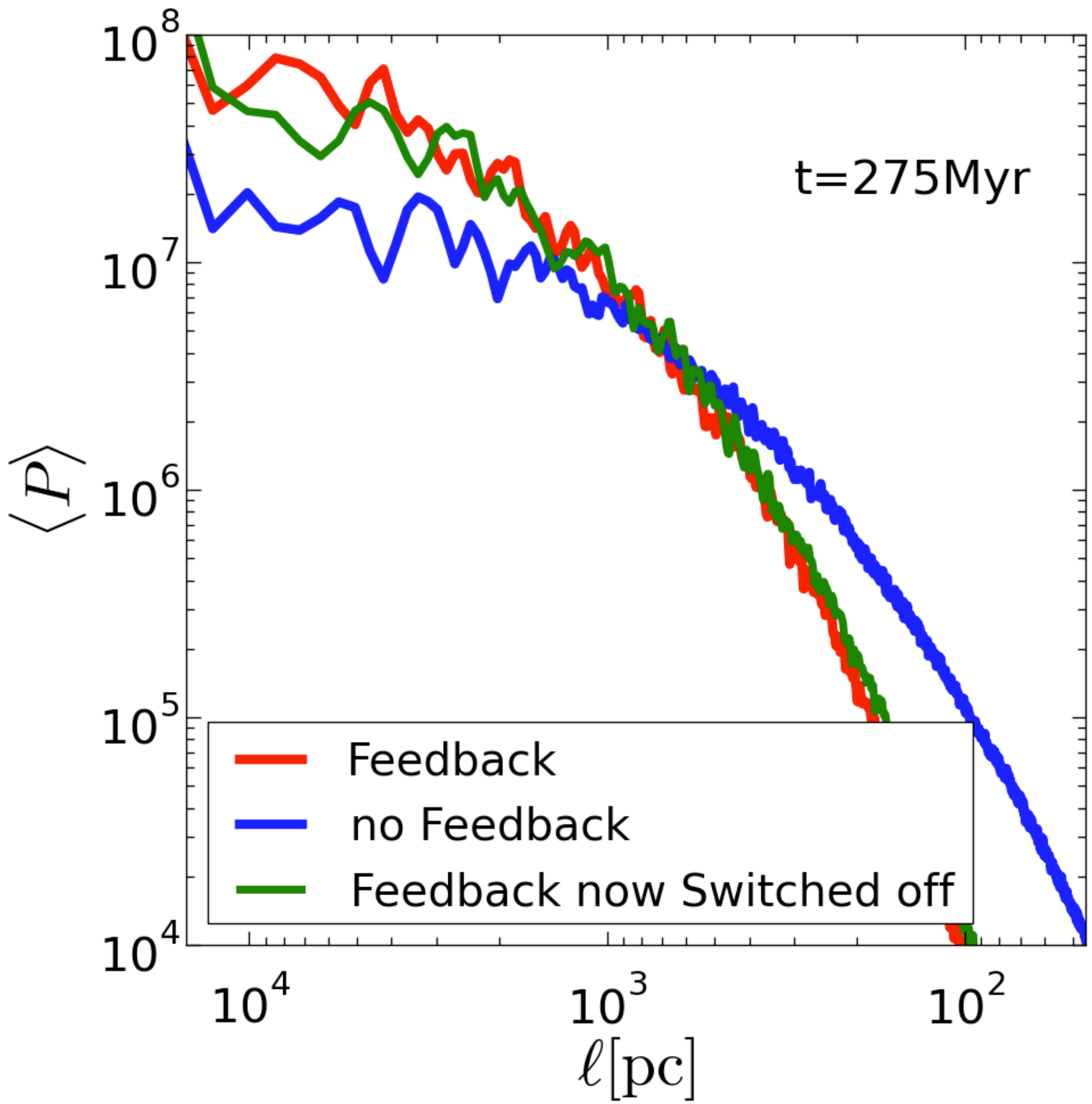
Simulated surface density power spectra

- Small scales (< 1kpc) are feedback regulated.
- Large scales are sensitive to the initial conditions. Adding an extended diffuse HI distribution brings large scale P(K) closer to observations.
- However, galaxies such as NGC 6946 have a higher fraction of dense HI gas and may fit the no feedback case better.



Simulated surface density power spectra

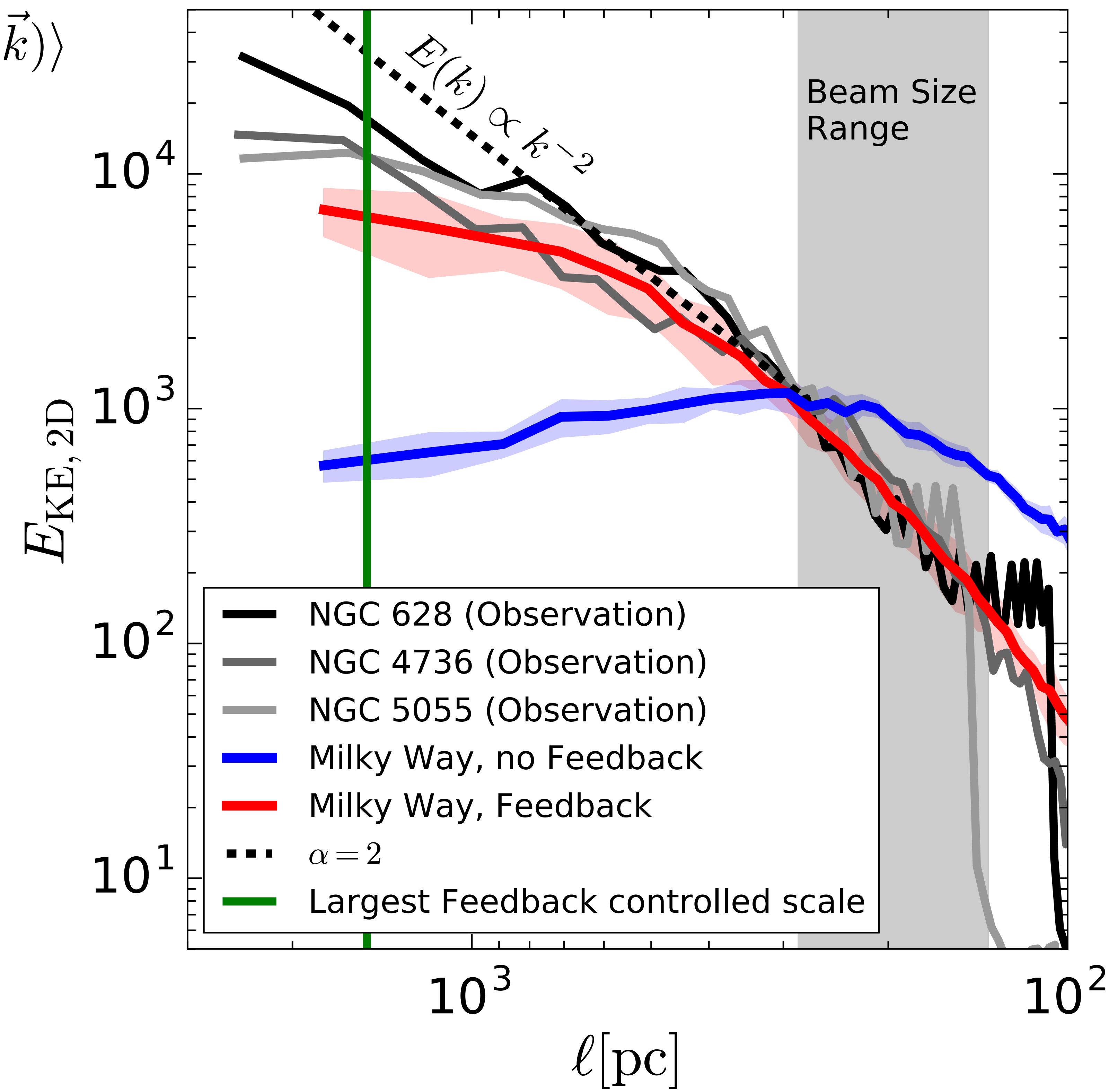
- Turning on/off feedback shifts feedback driven result closer to non-driven result on small scales (cloud formation)



Kinetic energy spectra of HI field

$$E(k) = \pi(2k)^{(D-1)}\langle P_w(\vec{k})\rangle$$

$$w = \sqrt{\Sigma} v_{\mathrm{los,HI}}$$



- Feedback driven simulation in good agreement with local spirals
- Weak/no feedback models underestimates large scale power
- In progress: sensitivity to star formation recipes, variations in feedback models (incl. RT, cosmic rays) etc.

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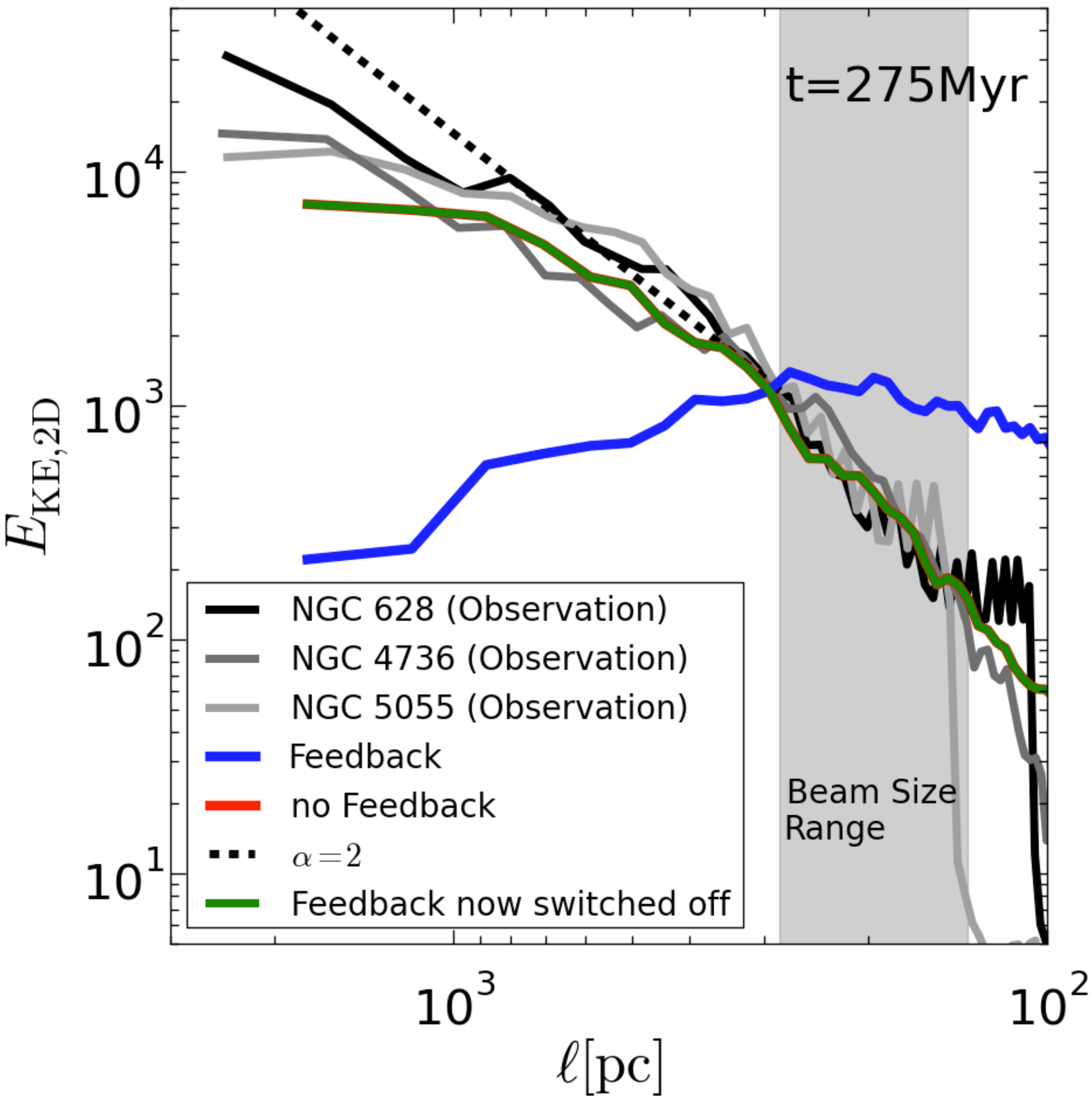
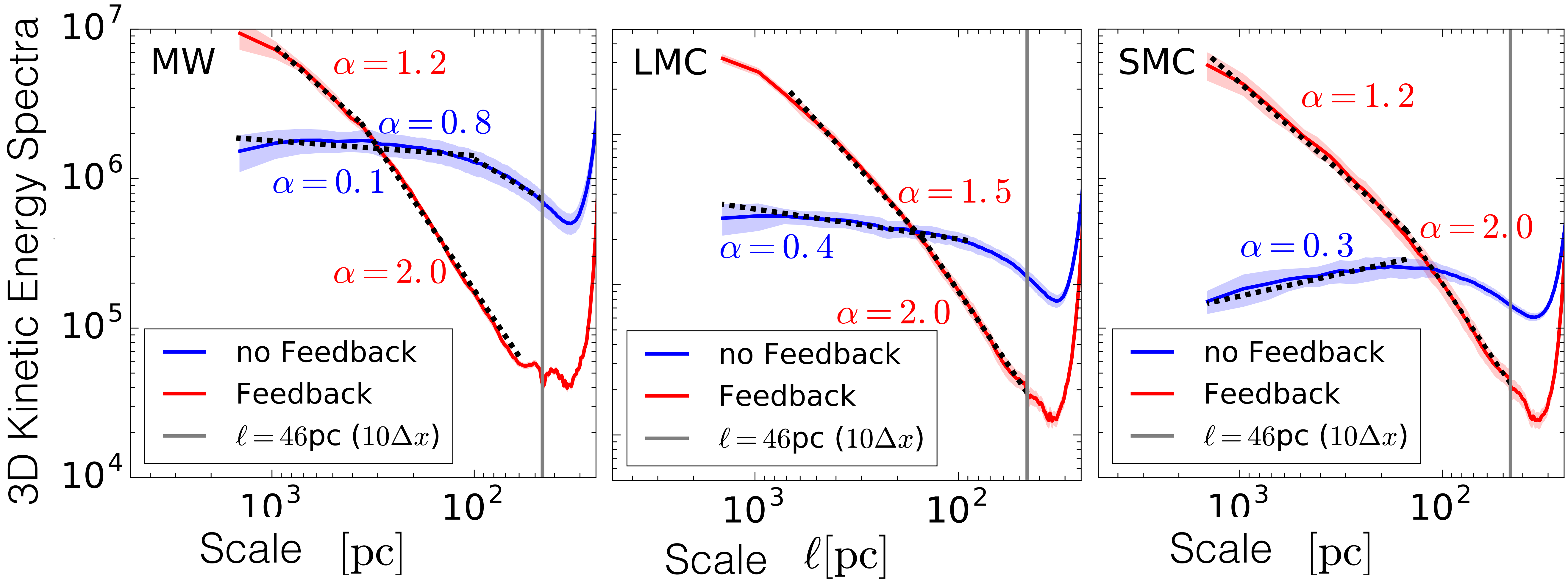


3D energy spectra



$$E_{\rm kin} = 4\pi k^2 \langle P_w(\vec{k}) \rangle$$
$$w = \sqrt{\rho} v$$

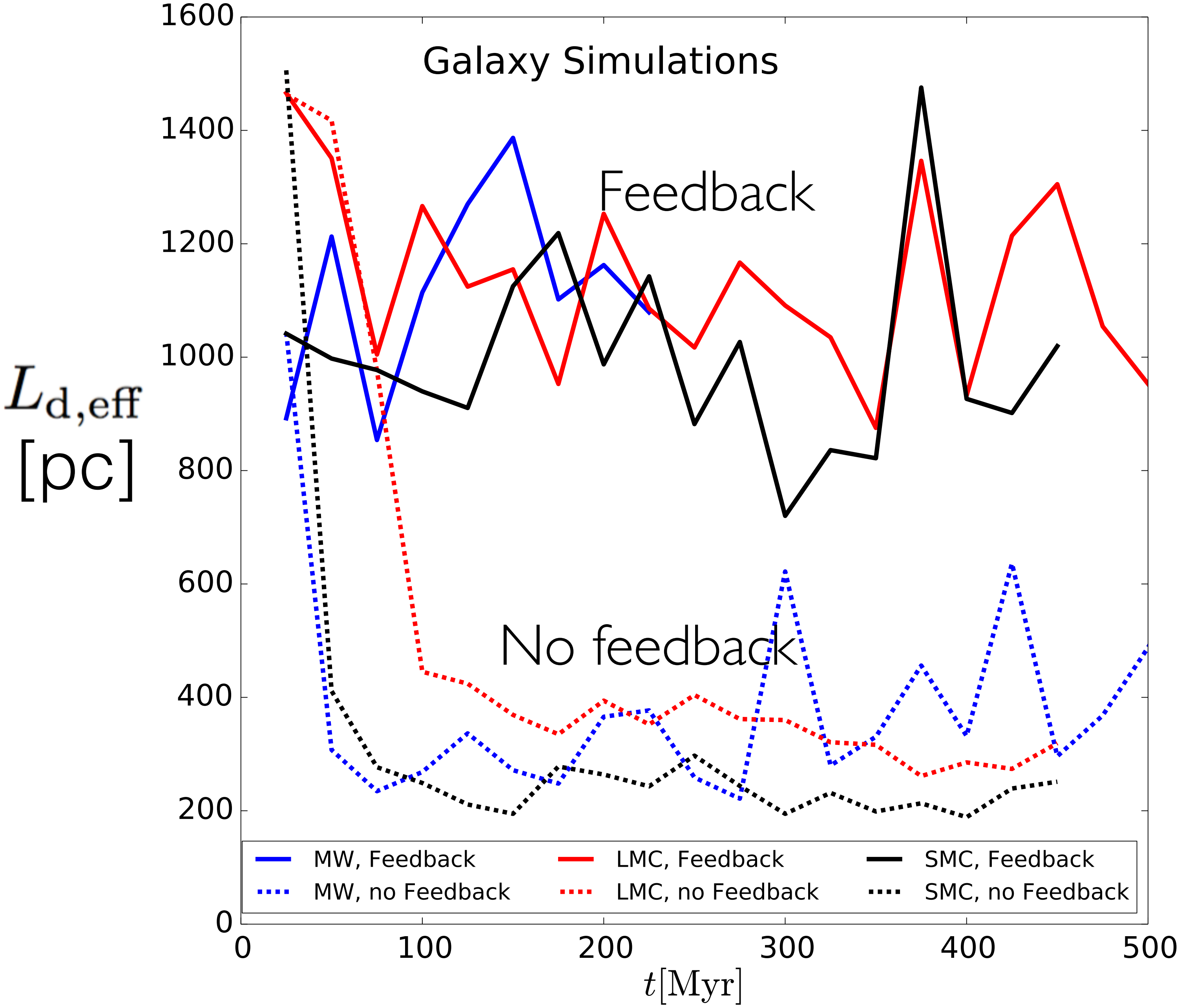
- Burgers like turbulence on scales < disc thickness. $E(k) \propto k^{-2}$
- Stellar feedback is necessary to sustain this. Large scale driving only fails as gas is trapped in dense clouds.

Effective driving scale of turbulence

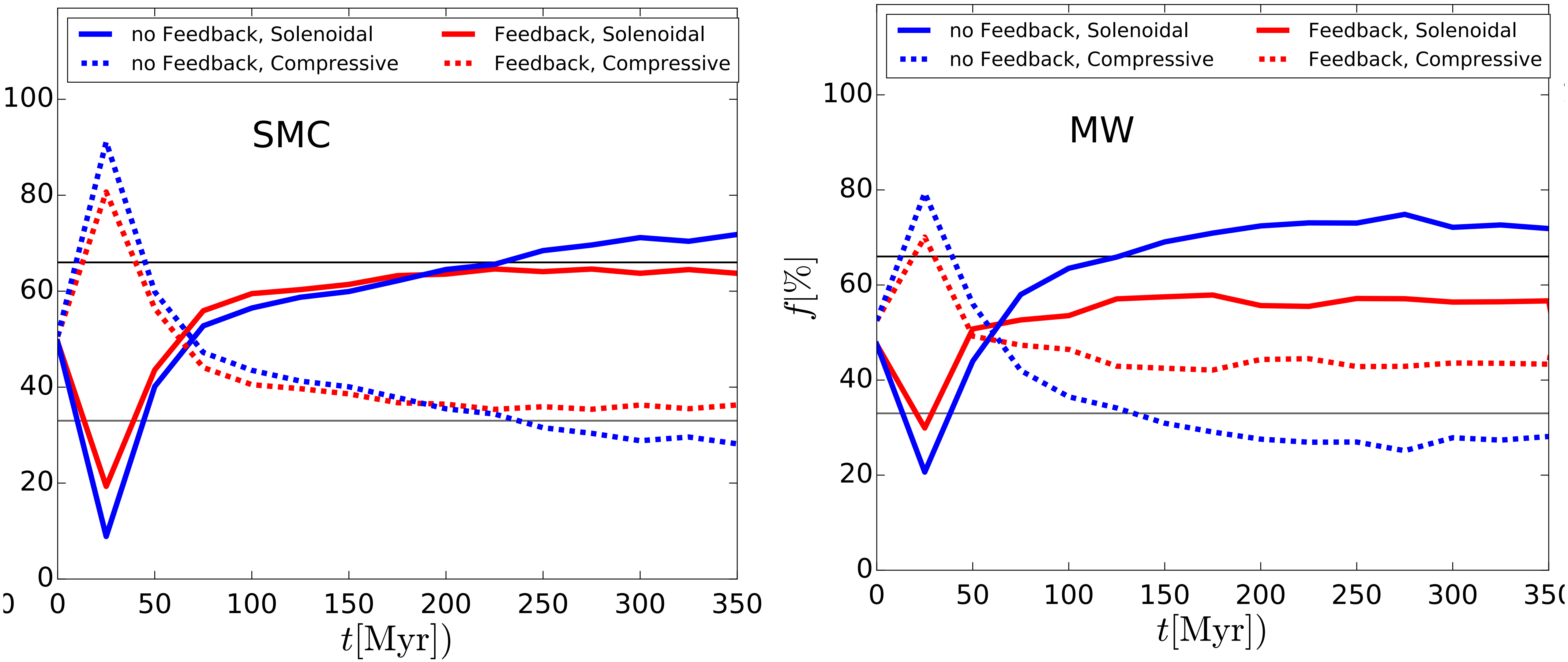
$$L_{\mathrm{d,eff}} \equiv \frac{2\pi \int k^{-1} E_k \, dk}{\int E_k \, dk}$$

e.g. Joung, Mac Low & Bryan (2009)

- Stellar feedback yields large effective driving scales (~1 kpc)
- Without feedback, L_d~ few 100 pc (cloud-cloud interactions?)

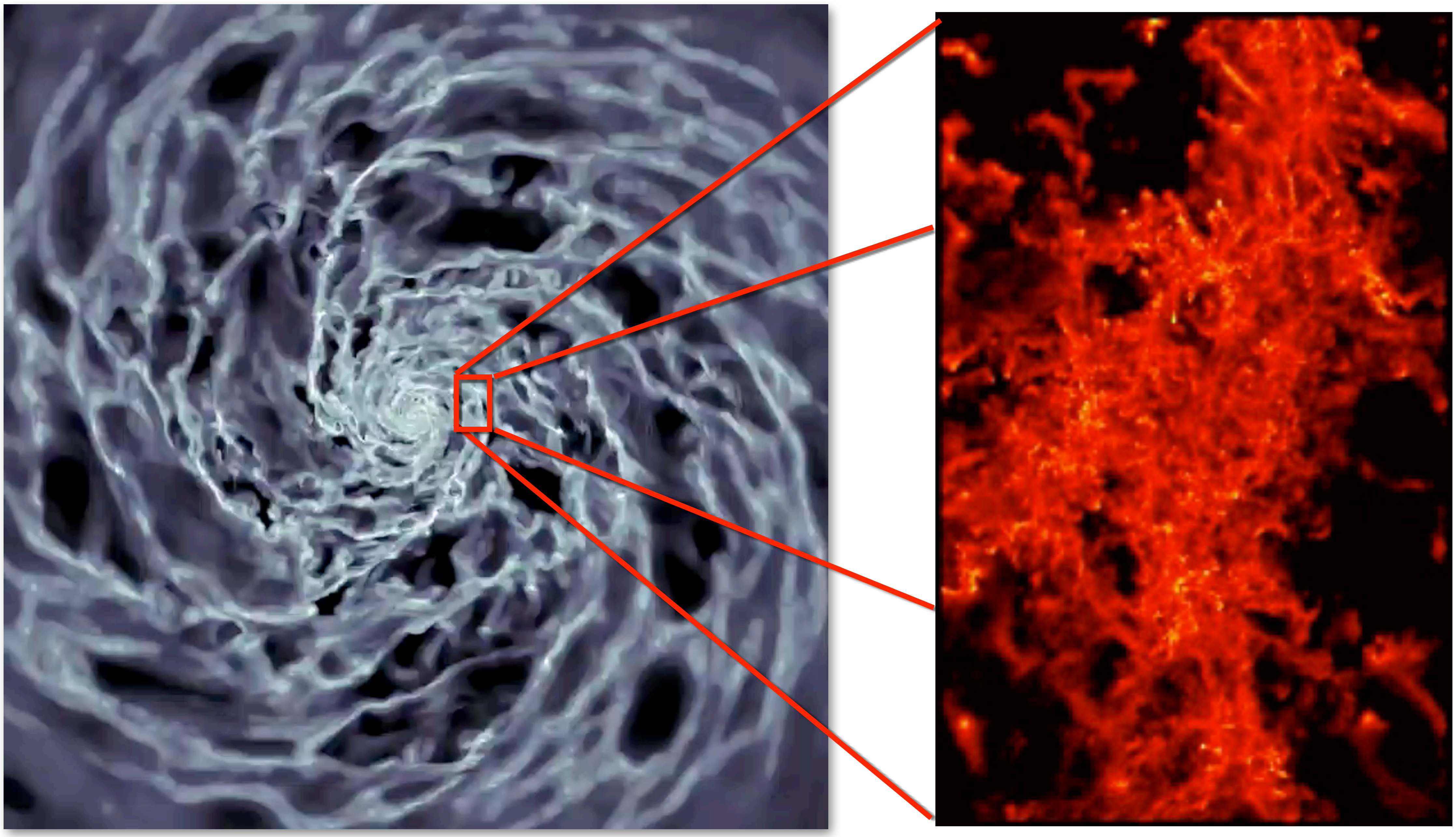


Vortical vs. solenoidal modes

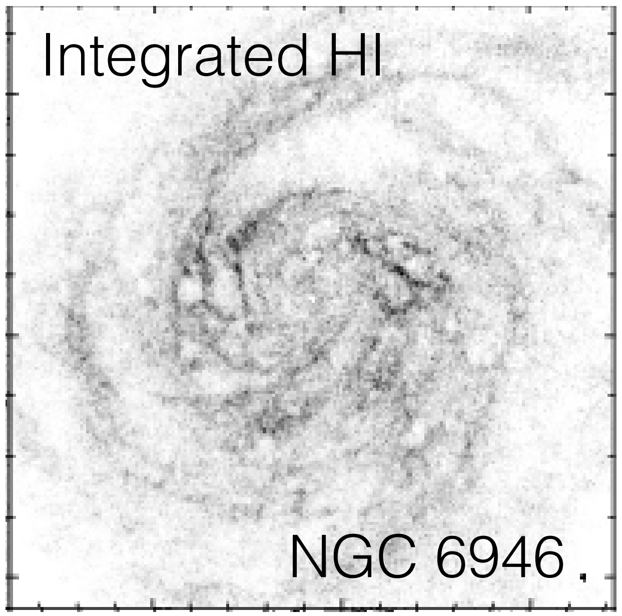


Next step: zooming in on star formation

Rey-Raposo, Agertz et al. (in prep)

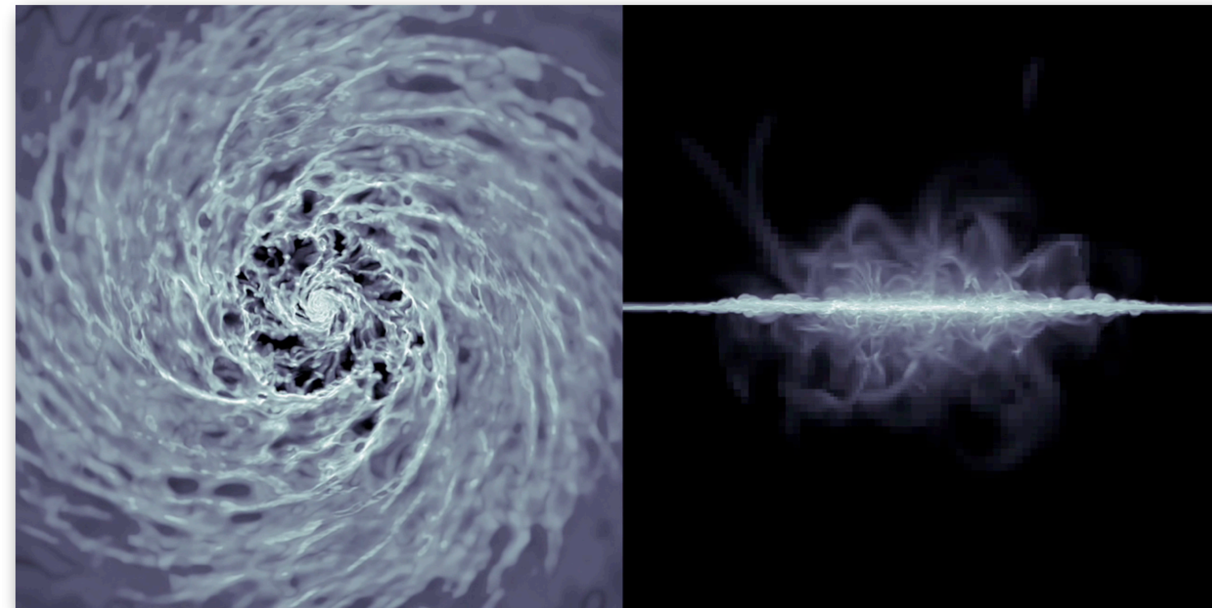


Conclusions



THINGS (Walter et al. 2008)

vs.



- Modern feedback models are able/designed to reproduce global properties of galaxies vs. redshift (stellar mass, disc sizes, metal content etc), but should also be tested against internal (ISM) properties

- Feedback (here a la Kim & Ostriker 2015) is necessary to match the observed density and energy structure of the ISM.

- Large scale (kpc) galactic driving of turbulence might dominate (large driving scale), but is sustained by stellar feedback via GMC dissolution/gas recycling.