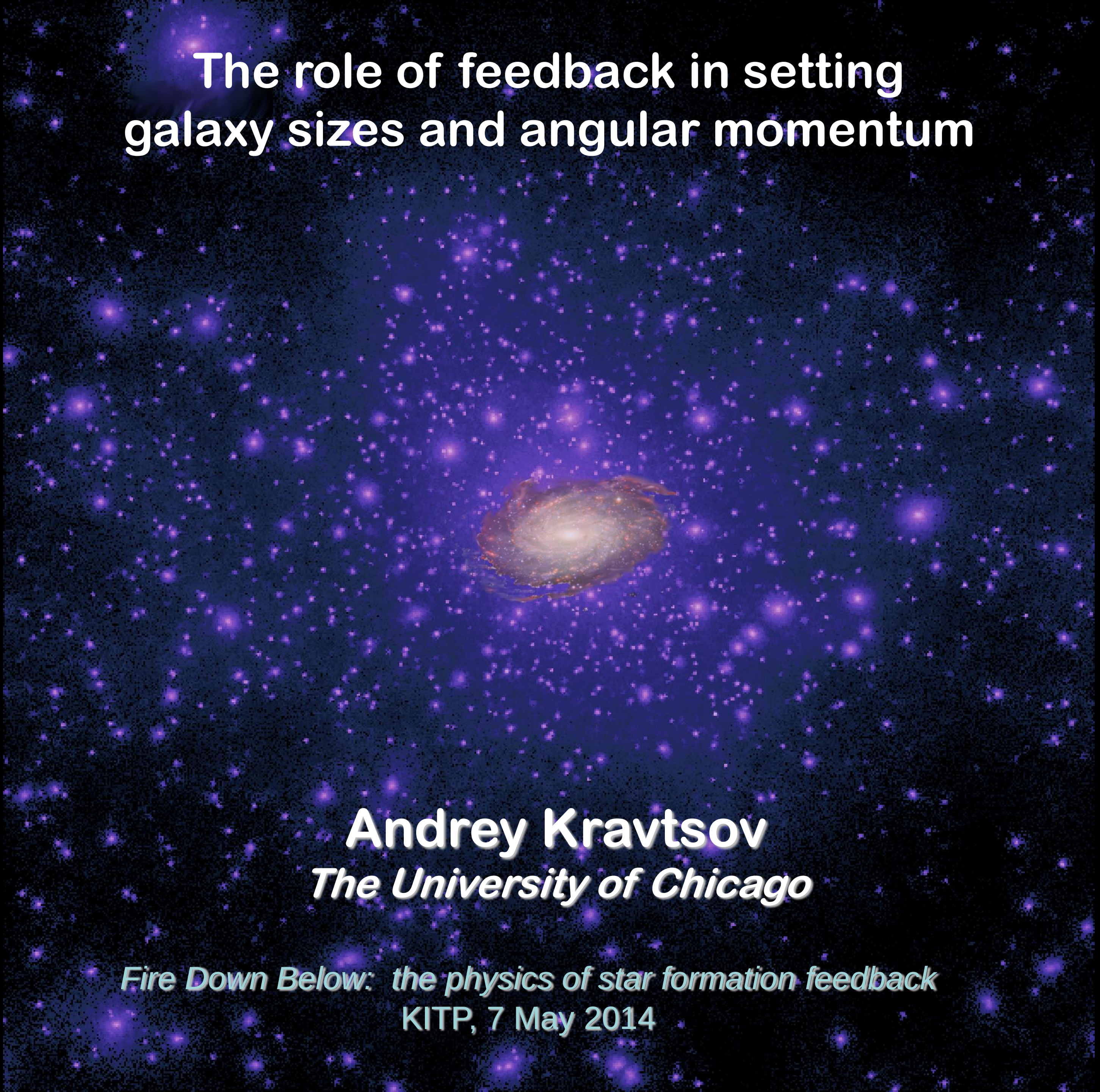
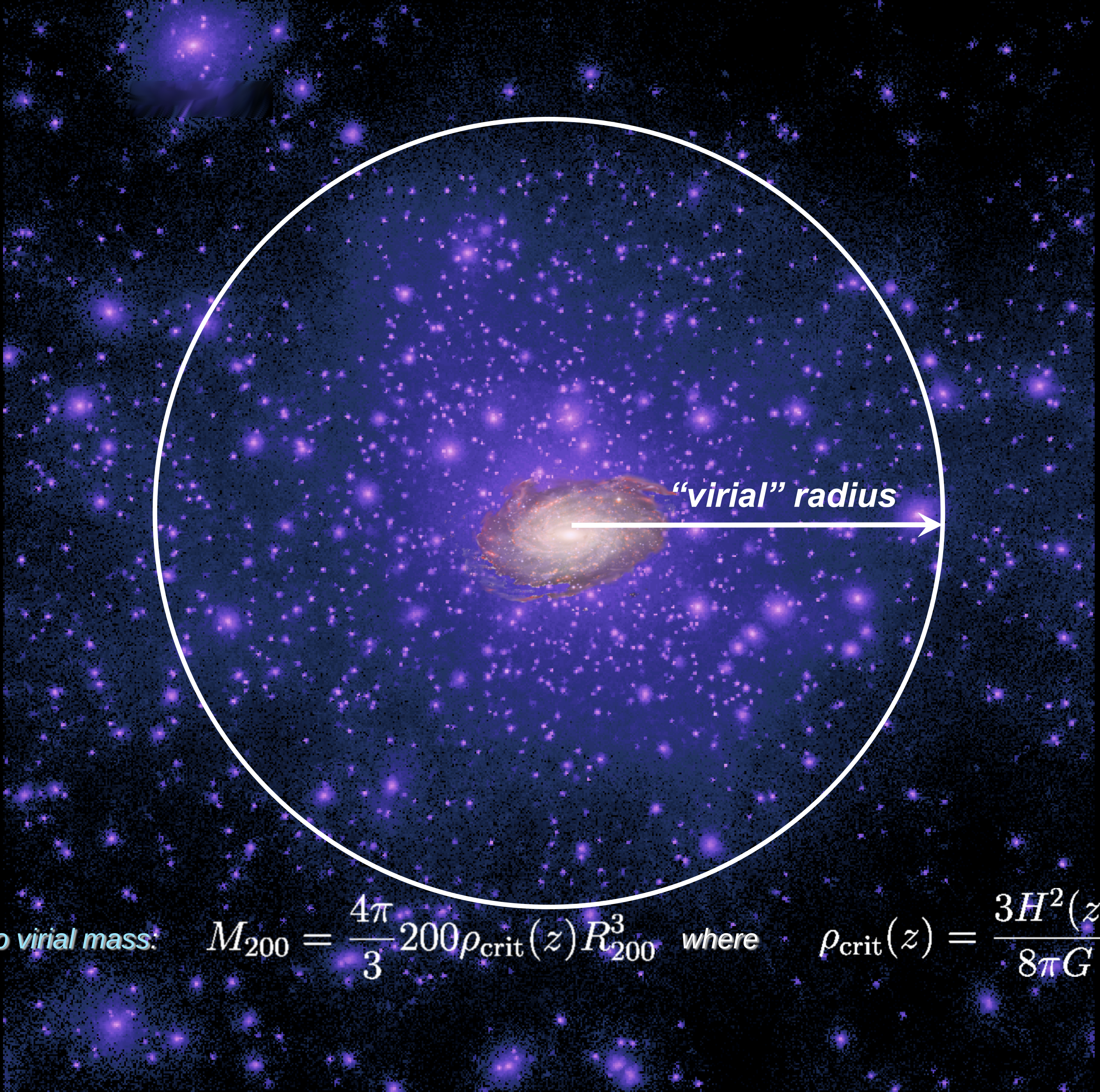
The role of feedback in setting galaxy sizes and angular momentum



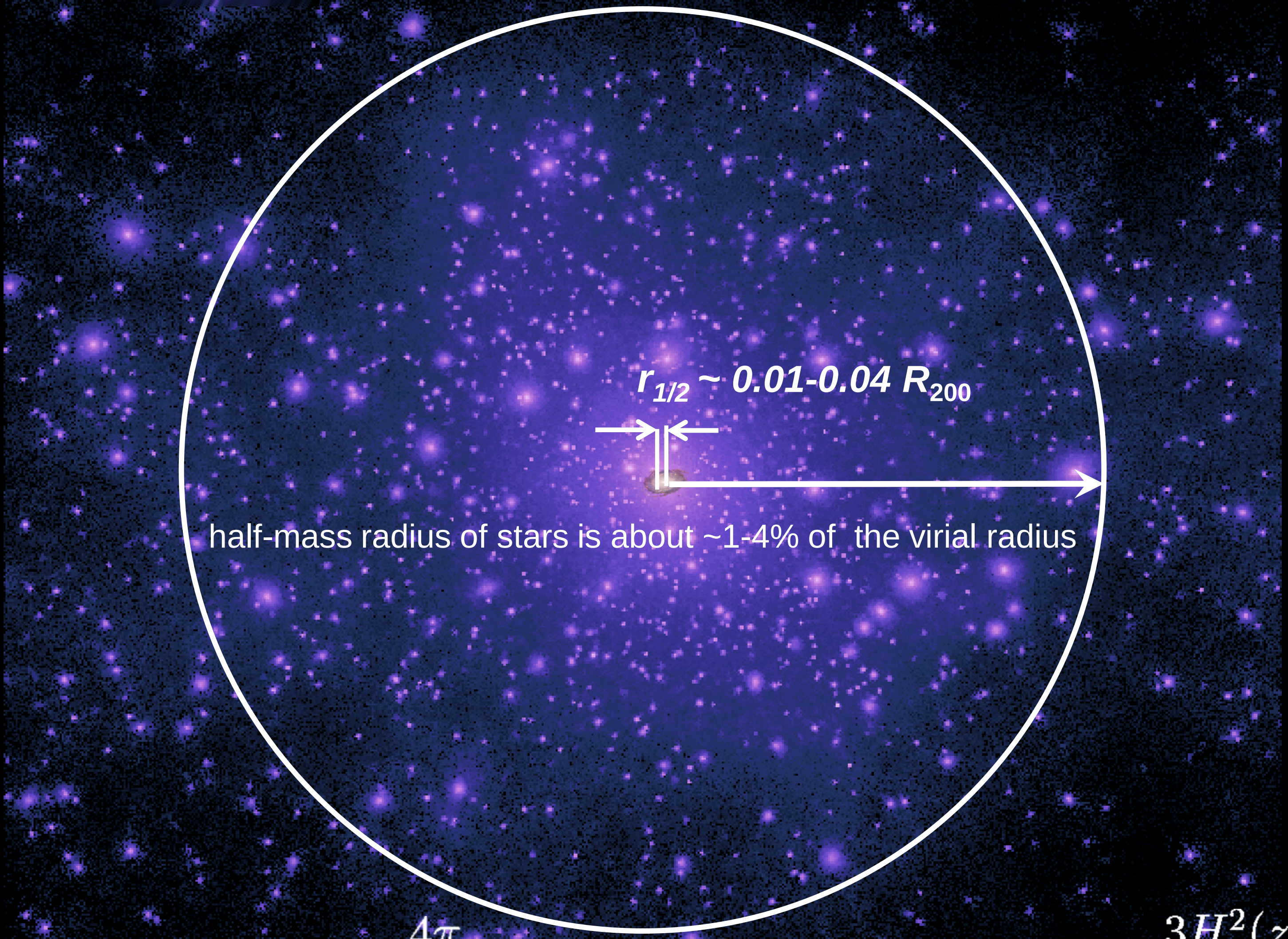
Andrey Kravtsov
The University of Chicago

Fire Down Below: the physics of star formation feedback
KITP, 7 May 2014



halo virial mass: $M_{200} = \frac{4\pi}{3} 200 \rho_{\rm crit}(z) R_{200}^3$ *where* $\rho_{\rm crit}(z) = \frac{3H^2(z)}{8\pi G}$

Real galaxies would look ~10 times smaller



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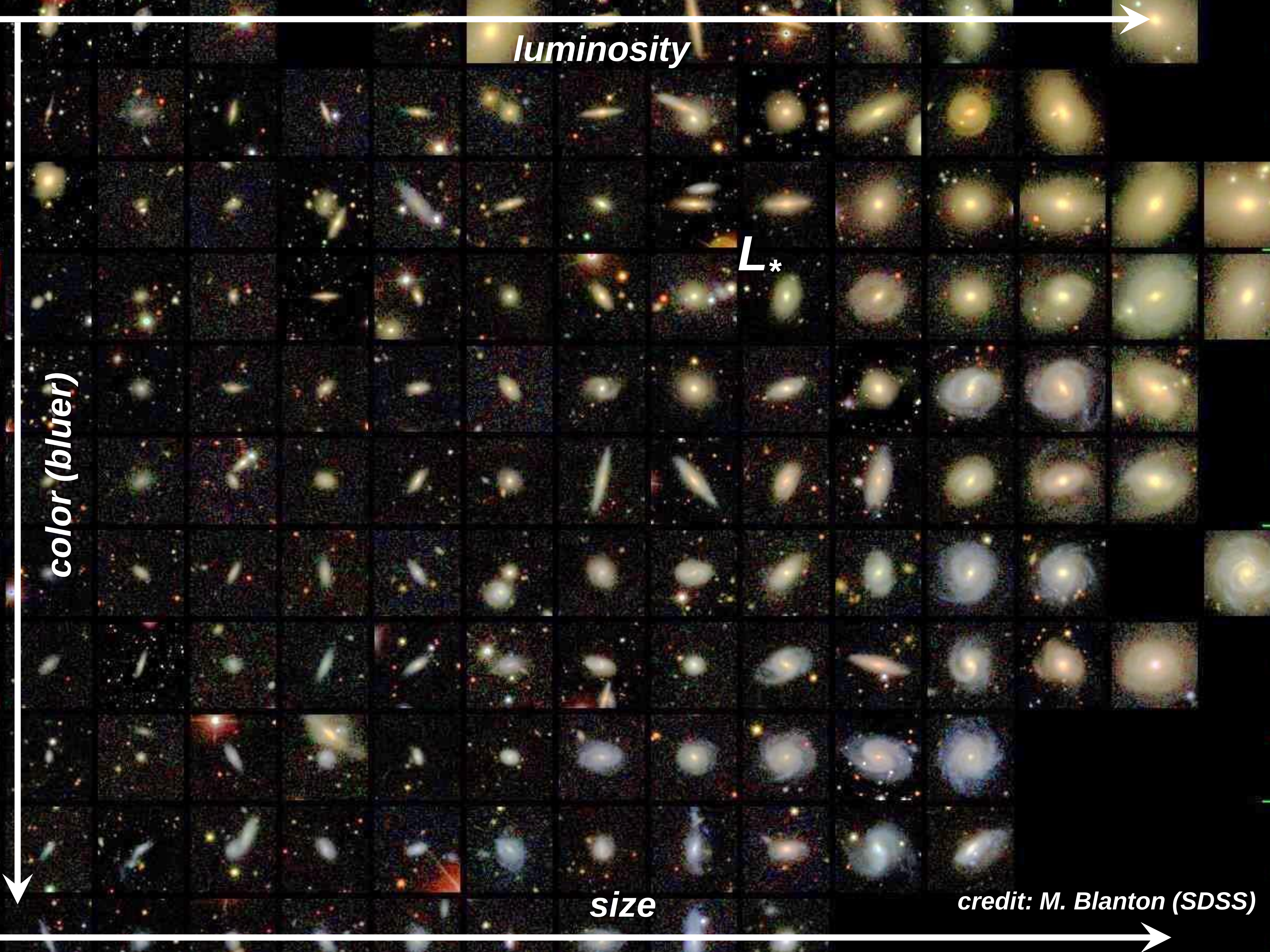
e.g., for the Milky Way: $M_{200,\rm MW} \approx 10^{12}\, M_\odot$

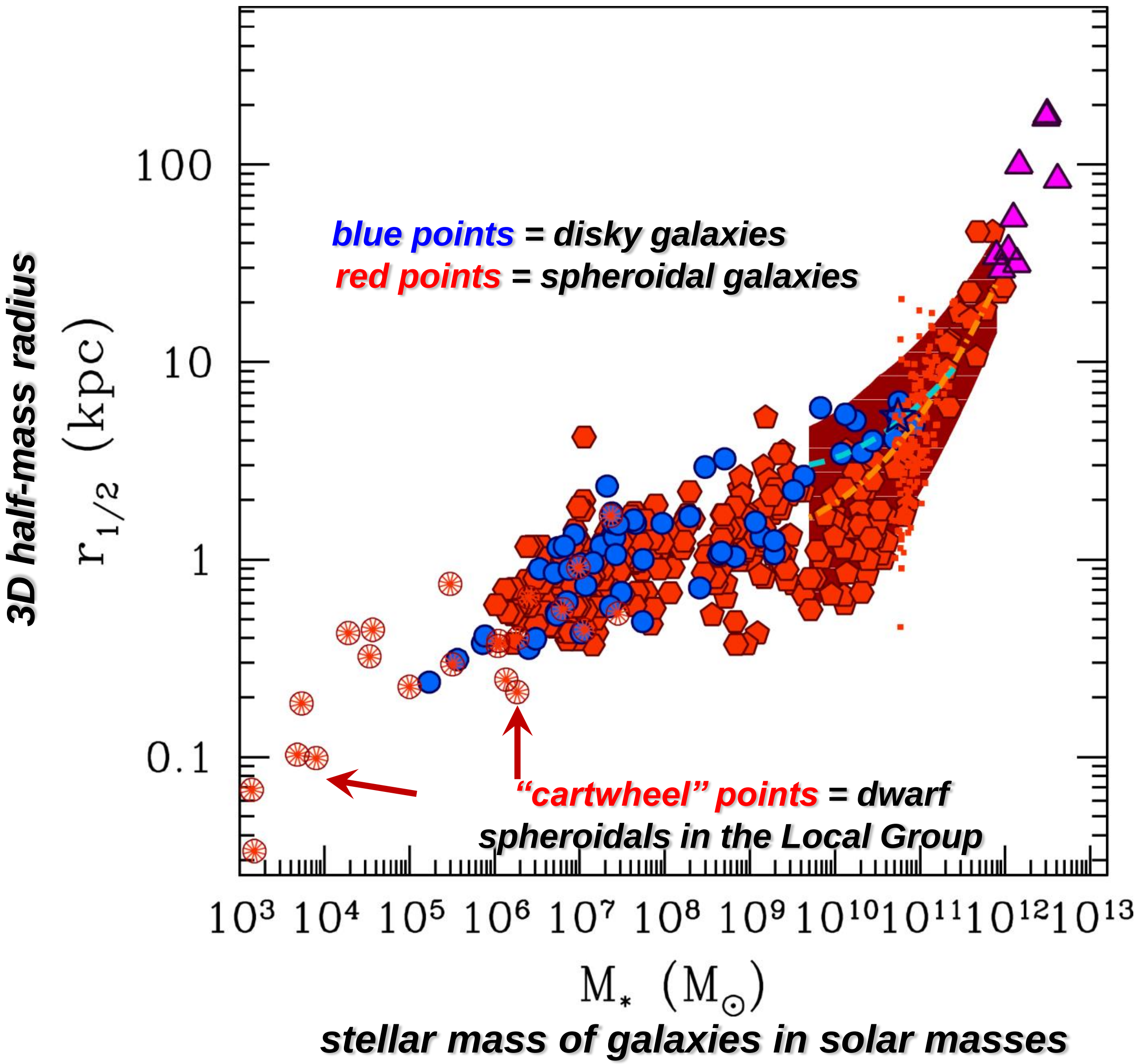
$R_{200} \approx 200\,{\rm kpc}$ → $r_{1/2} \approx 5\,{\rm kpc} \approx 0.025\, R_{200}$



luminosity
L_*
color (bluer)
size
credit: M. Blanton (SDSS)

Galaxy size-stellar mass correlation

correlation between size of stellar distribution in galaxies (half-mass radius) and stellar mass



Samples of galaxies chosen to cover a wide range of stellar masses and morphologies:

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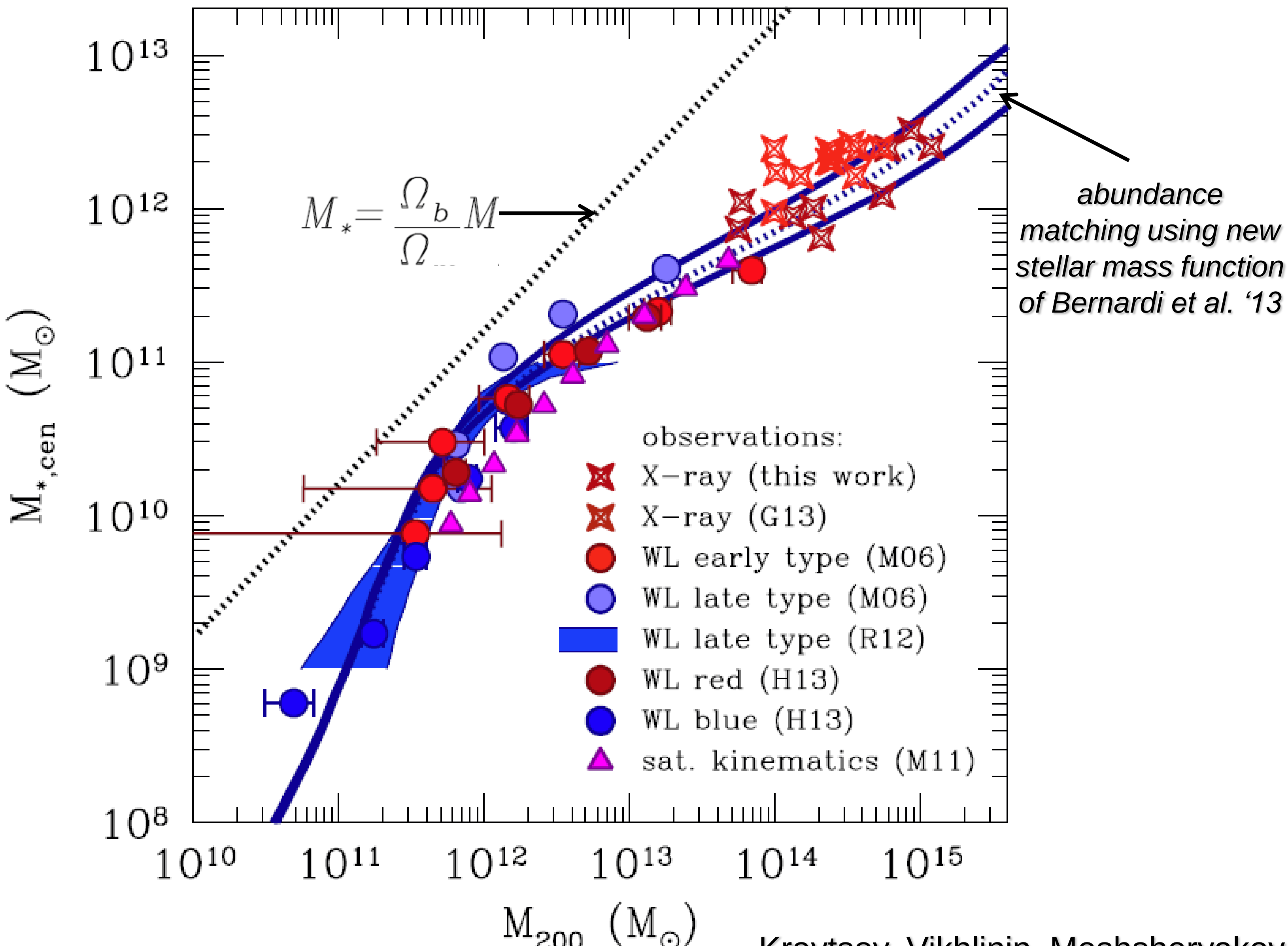
blue and orange lines are median relations for the late and early type galaxy samples of Bernardi et al.'12 and Szomoru et al. '12

magenta points = BCGs from Kravtsov, Vikhlinin & Mescheryakov '14

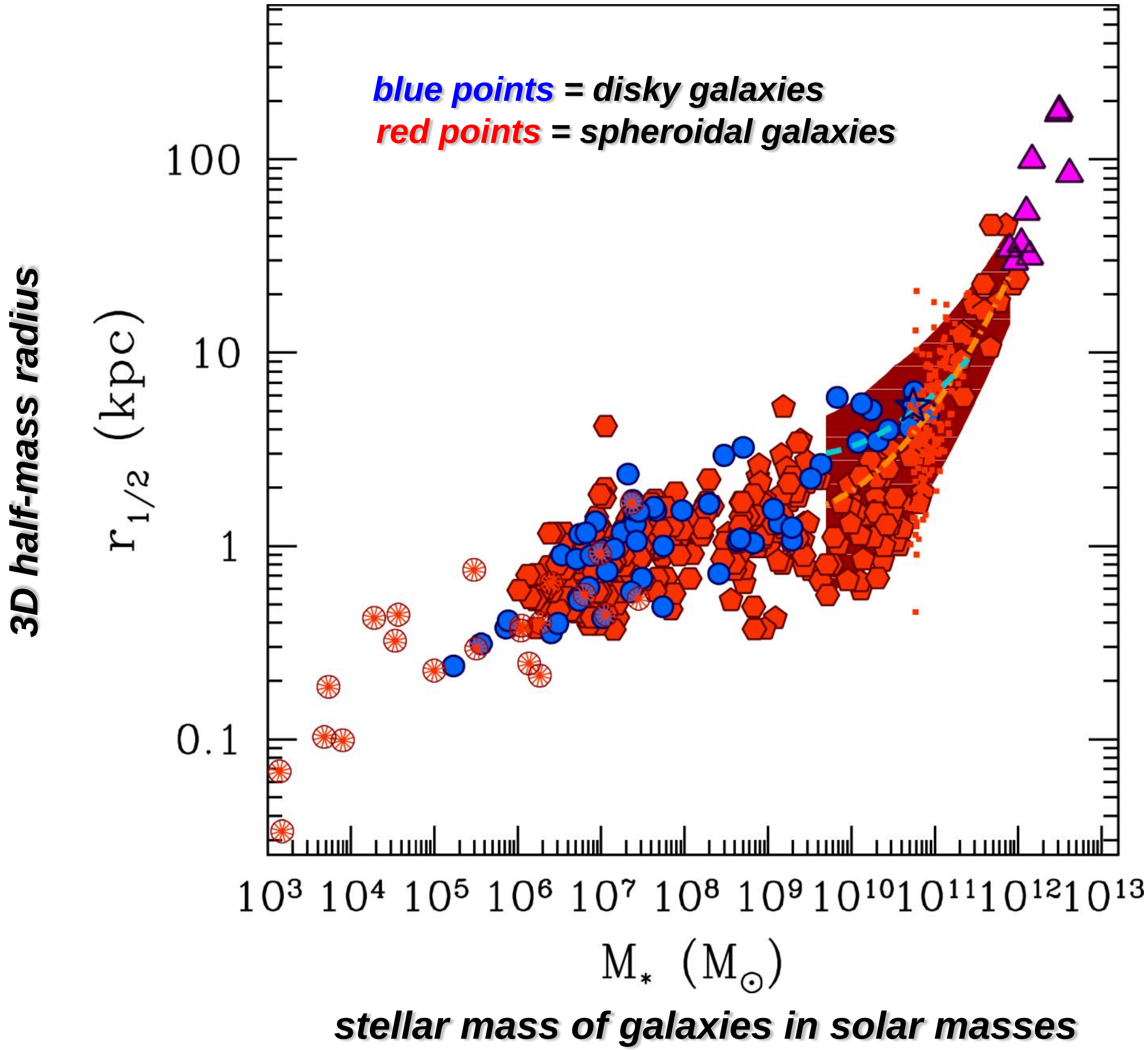
Kravtsov 2013, ApJL 764, 31
Kravtsov et al. 2014, arxiv/1401.7329

Stellar mass -halo mass relation



Kravtsov, Vikhlinin, Meshsheryakov
arxiv/1401.7329

How does the size of galaxies relate to the size of their parent halo?



abundance matching:

$$n(>M_*) = n(>M_{200})$$

↓

$M_* - M_{200}$ *relation*

↓

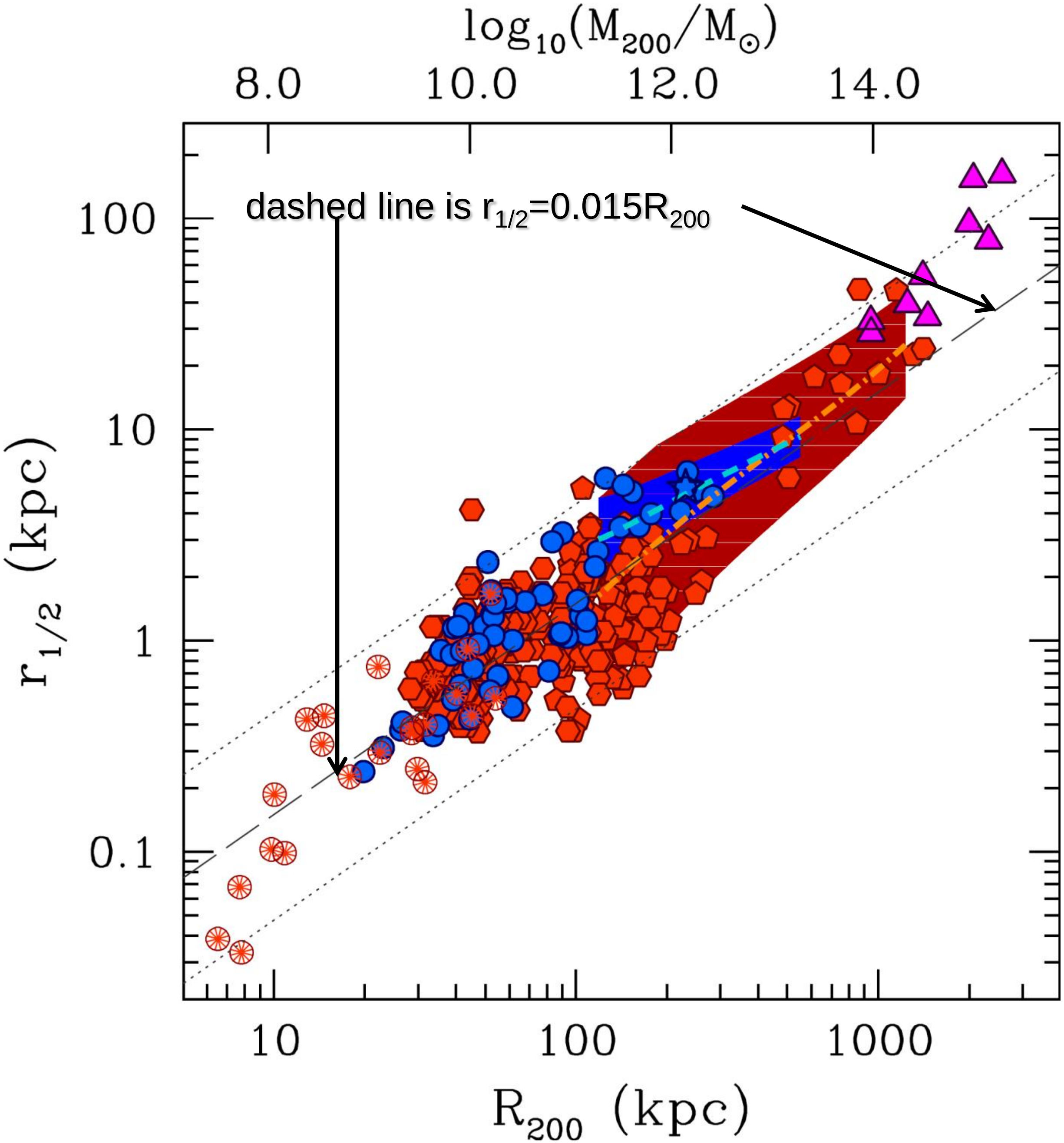
R_{200} *for a galaxy of a given* M_*

↓

$r_{1/2} - R_{200}$ *relation*

$$M_{200} = \frac{4\pi}{3}\Delta\rho_{\rm crit}R_{200}^3$$

Size-virial radius relation of galaxies



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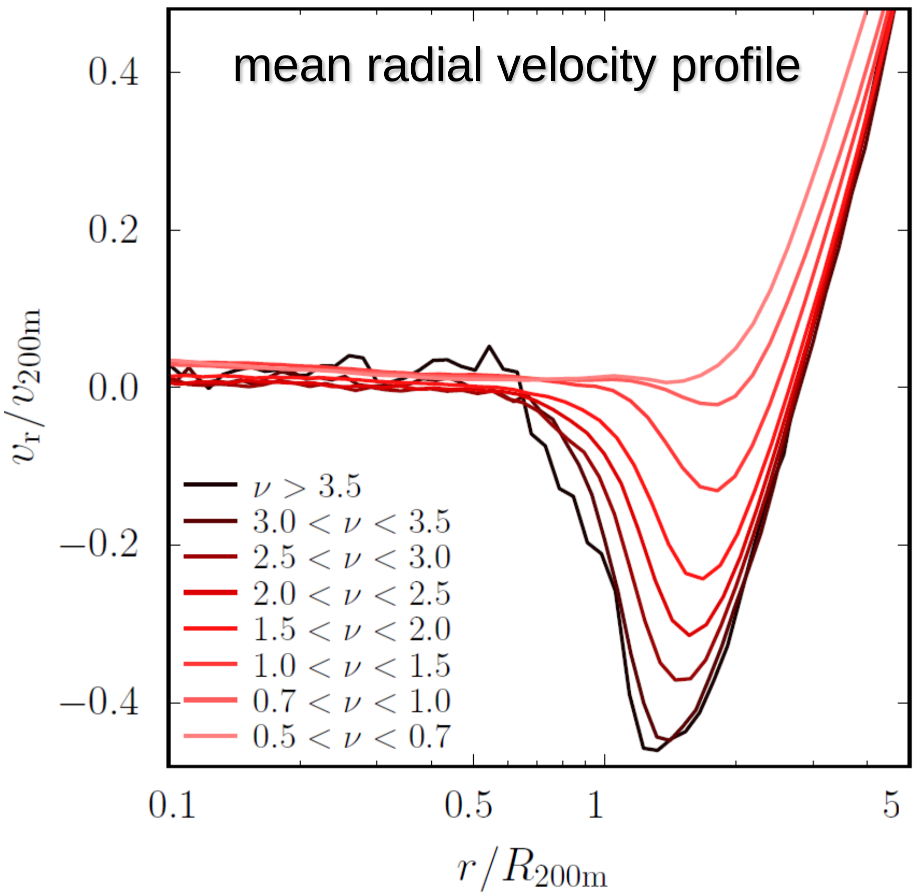
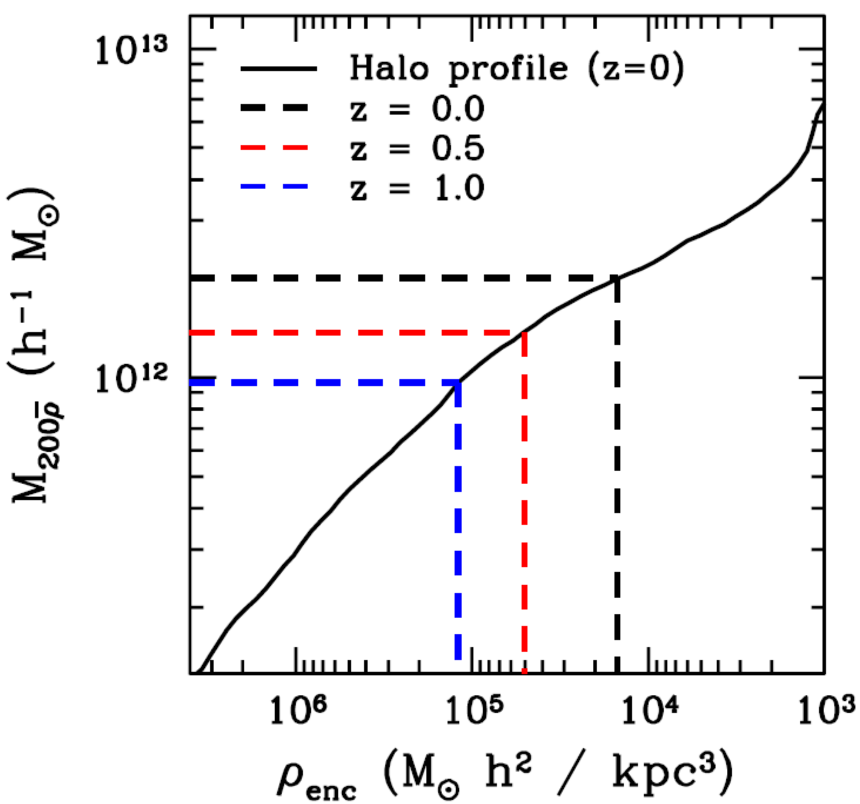
Pseudo-evolution of halo mass

- Mass can ("pseudo") evolve just due to its definition and changing reference density,
- even though the density profile does not evolve.

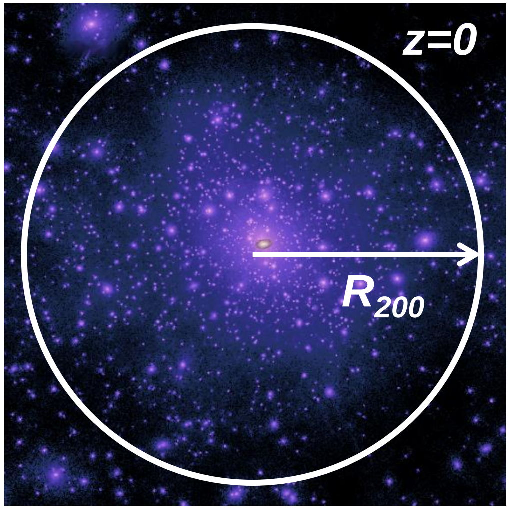
Diemand et al. 2007; Cuesta et al. 2008;
Diemer, More, Kravtsov 2013, ApJ 766, 25; Diemer & Kravtsov (arxiv/1401.1216)

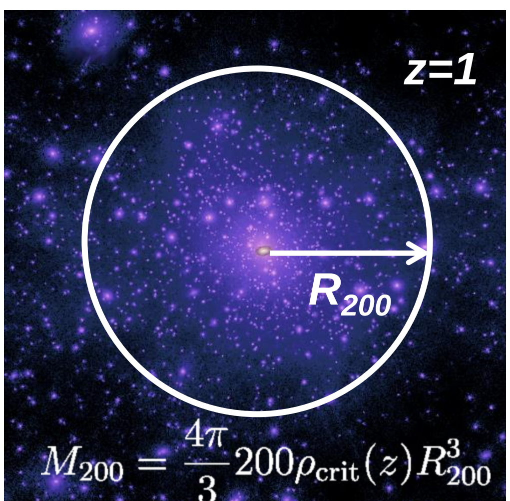


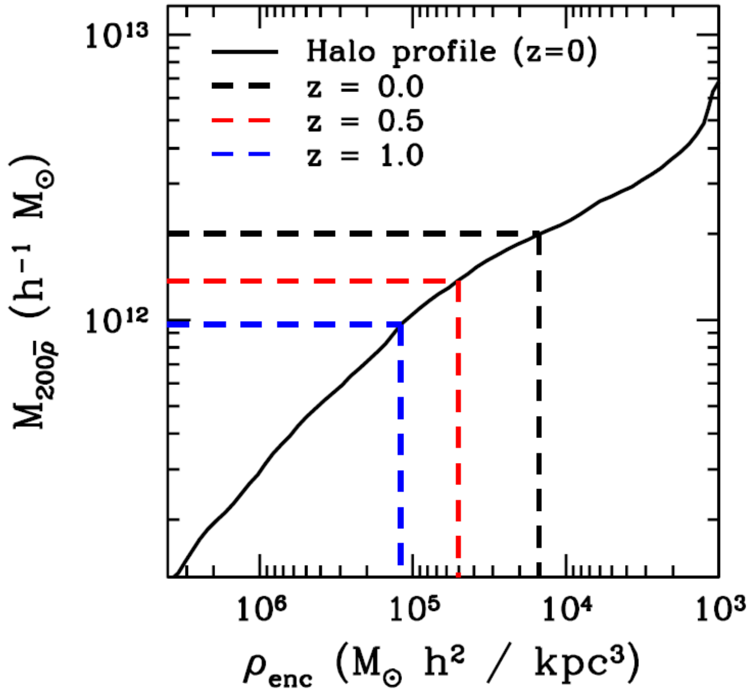


Need to account for pseudo-evolution of R_{200}

R_{200} will evolve just due to changing of ρ_{crit}, even if halo itself does not evolve. The size of course will not respond to such artificial evoltuon of halo radius. So R_{200} needs to be corrected.





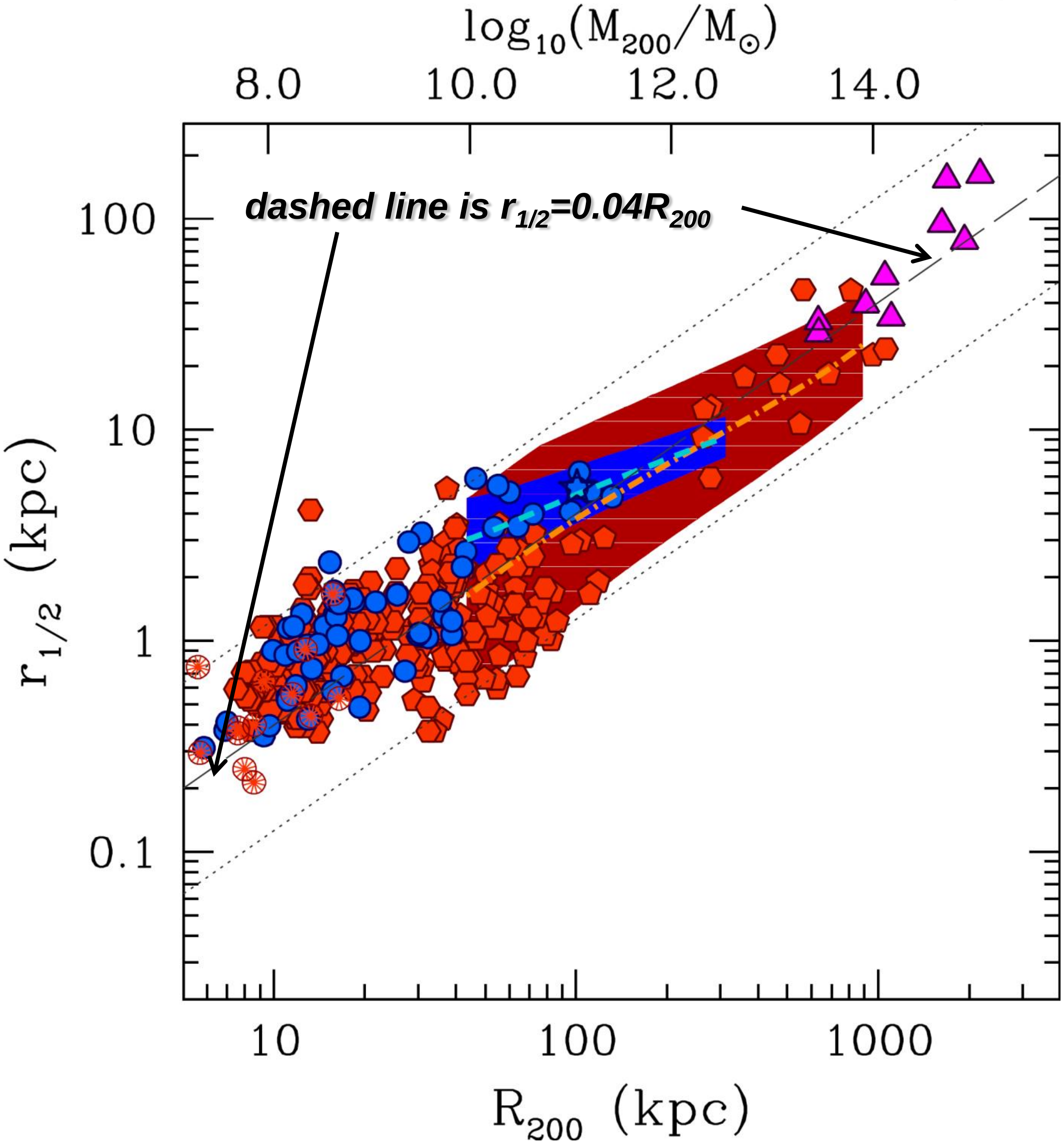


Diemer, More & Kravtsov 2013, ApJ 766, 25

also, Diemand et al. 2007; Cuesta et al. 2008

pseudo-evolution of R200 can be corrected using halo concentration (More, Diemer & Kravtsov, in prep.)

Size-virial relation of galaxies



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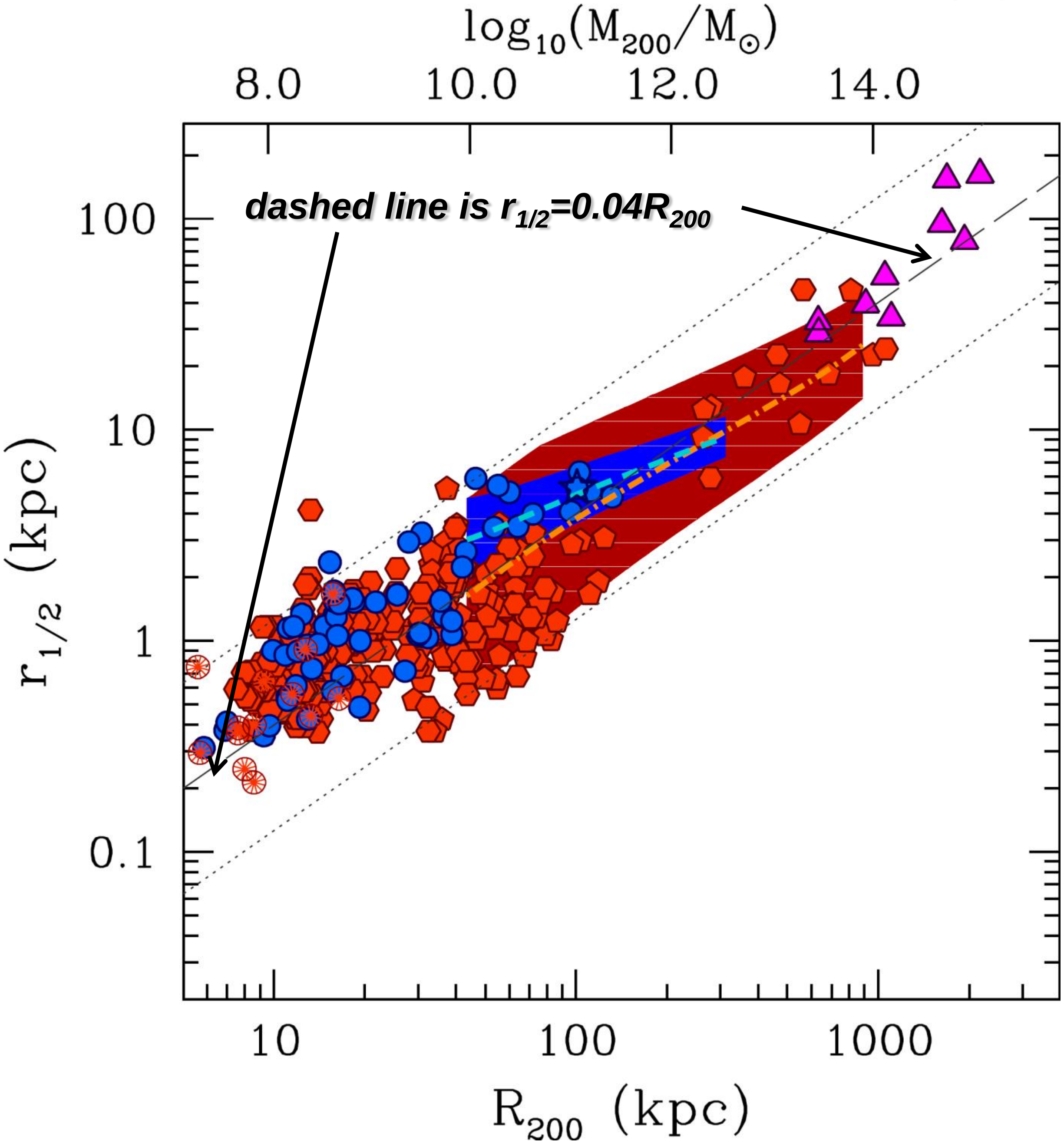

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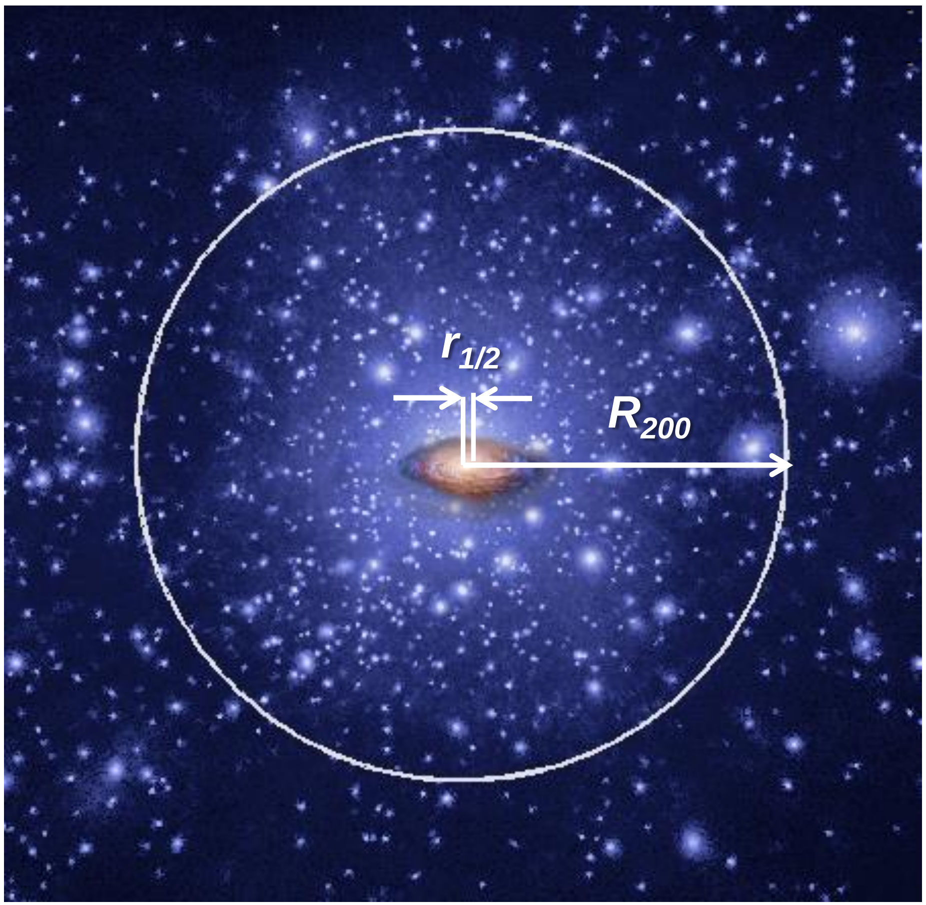
Angular momentum and sizes of galaxies

Fall & Efstathiou (1980, also Mo, Mao & White 1998) have proposed model, in which baryons and dark matter acquire similar specific angular momentum. As baryons cool and settle into central disk, the disk size is determined by the specific angular momentum.



Specific angular momentum of halo material can be parametrized as

$$j_{200} = \lambda V_{\rm circ}(R_{200}) R_{200} = \lambda \sqrt{\frac{GM_{200}}{R_{200}}} R_{200}$$
$$\propto \lambda R_{200}^2 \propto \lambda M_{200}^{2/3}$$

where

$$V_{\rm circ} \equiv \sqrt{\frac{GM(<R)}{R}}$$

is "circular" velocity - i.e., velocity required for rotational support against gravity

matter would attain rotational support when:

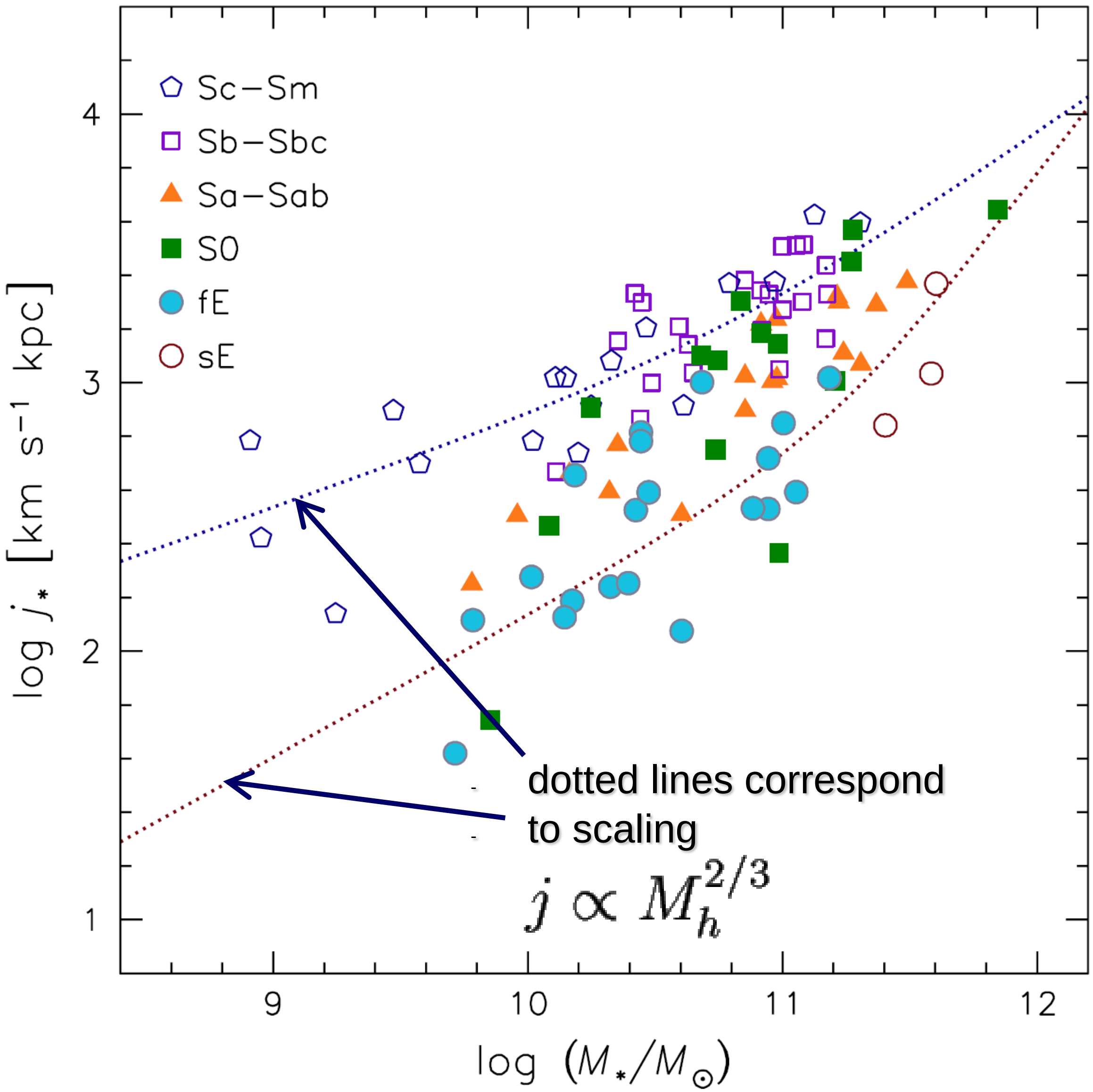
$$j = V_{\rm circ}(R) R = j_{200}$$

$$\rightarrow R = \lambda R_{200} \frac{V_{\rm circ}(R_{200})}{V_{\rm circ}(R)} \propto \lambda R_{200}$$

Simulations and tidal torque theory predict log-normal distribution of spins with typical values: $\lambda \approx 0.03 - 0.05$

Observed galaxies follow a similar trend

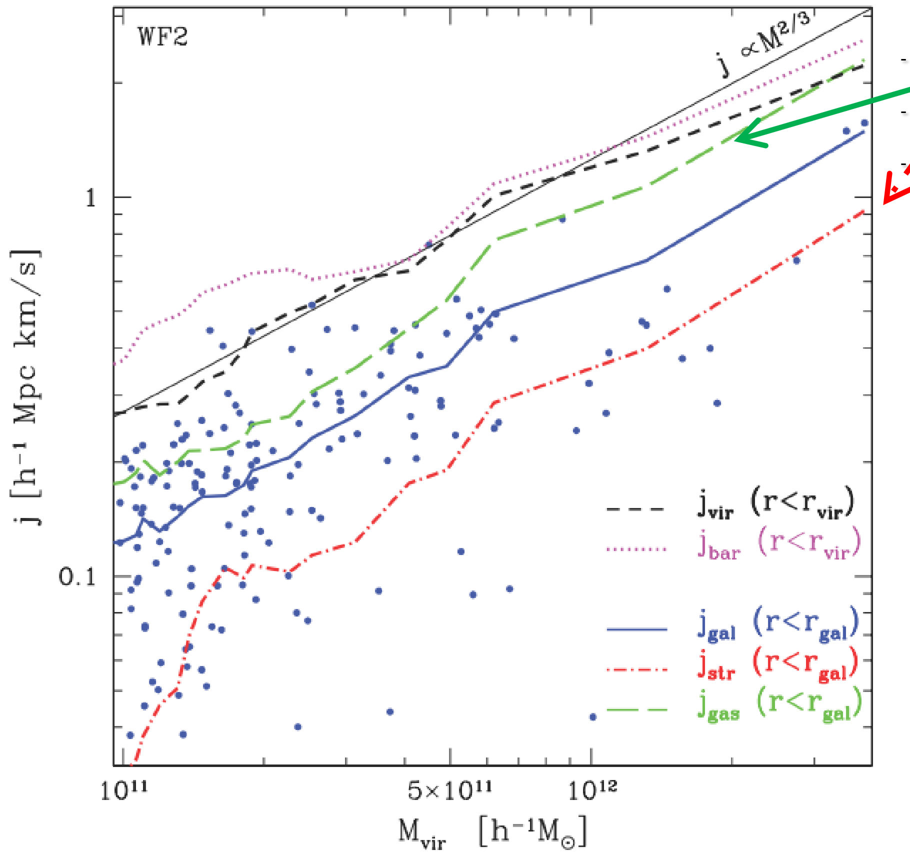
Fall & Romanowsky 2013, ApJL
cf. also Fall 1983; Romandowsky & Fall 2012, ApJ



Are such correlations seen in galaxy formation simulations?

results of recent galaxy formation simulations indicate that the answer is yes, if star formation in galaxy progenitors is strongly suppressed by feedback at high redshifts

Specific angular momentum of different components



virial mass of halos

Cold gas and stars in simulated galaxies follow the expected scaling:

$$j \propto M_h^{2/3}$$

Sales et al. 2010, MNRAS

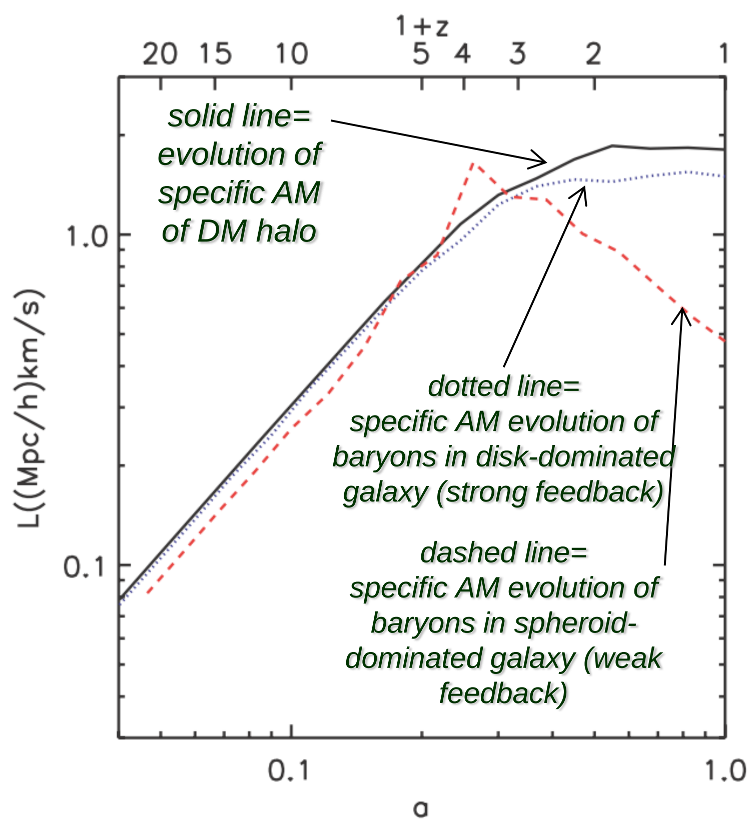
cf. also Zavala et al. 2008
Scannapieco et al. 2008

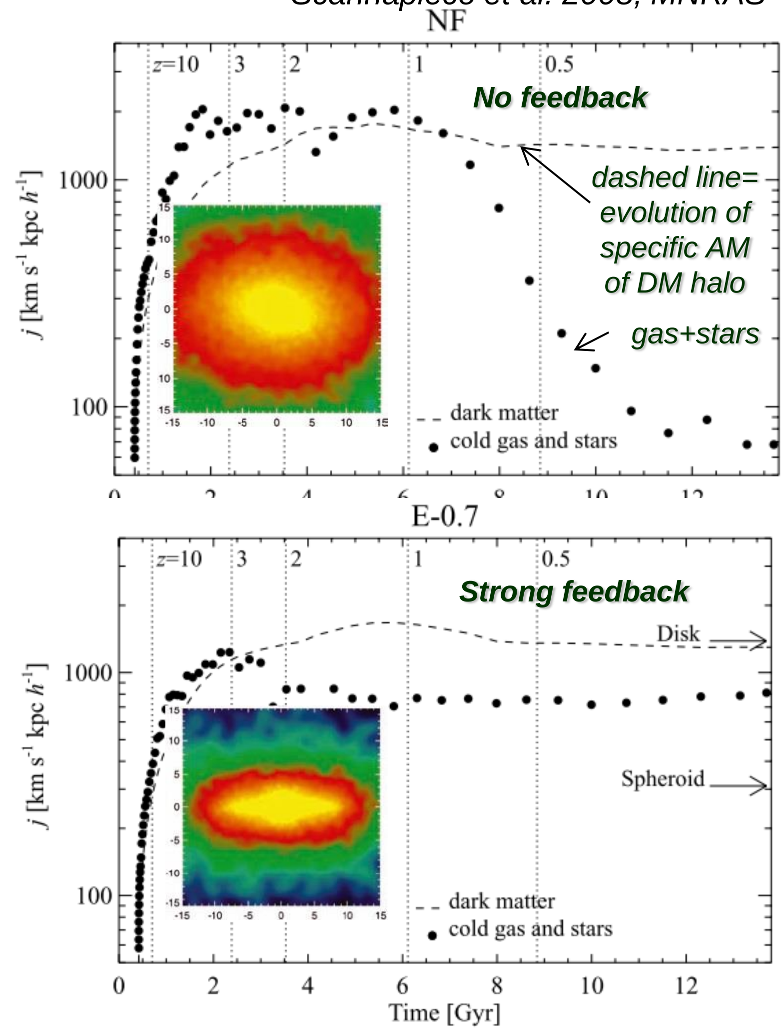
Efficient feedback appears to be crucial to preserve initial specific angular momentum of baryons

Results of recent galaxy formation simulations show that specific angular momentum acquired during collapse is approximately preserved, if star formation in galaxy progenitors is strongly suppressed at high redshifts

Scannapieco et al. 2008, MNRAS

Zavala et al. 2008, MNRAS

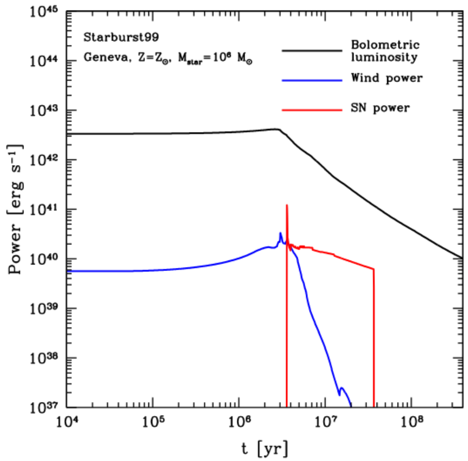




Modelling galaxy formation with improved recipes for star formation and feedback

Agertz & Kravtsov 2014 (cf. also Oscar's talk at the conference online)

Murray et al. 2005, 2010; Hopkins et al. 2011a,b,c, 2013; Stinson et al. 2012; Trujillo-Gomez et al. 2013;



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

Energy, momentum, mass and metals are injected in star forming regions in a time resolved manner + model for retaining SN energy in a separate variable (cf. Teyssier et al 2013)

→ *Star formation based on local density of molecular gas tracked in simulation using model of Krumholz, McKee & Tumlinson 2009.*

$$\dot{\rho}_* = f_{\rm H_2} \frac{\rho_{\rm g}}{t_{\rm SF}}$$

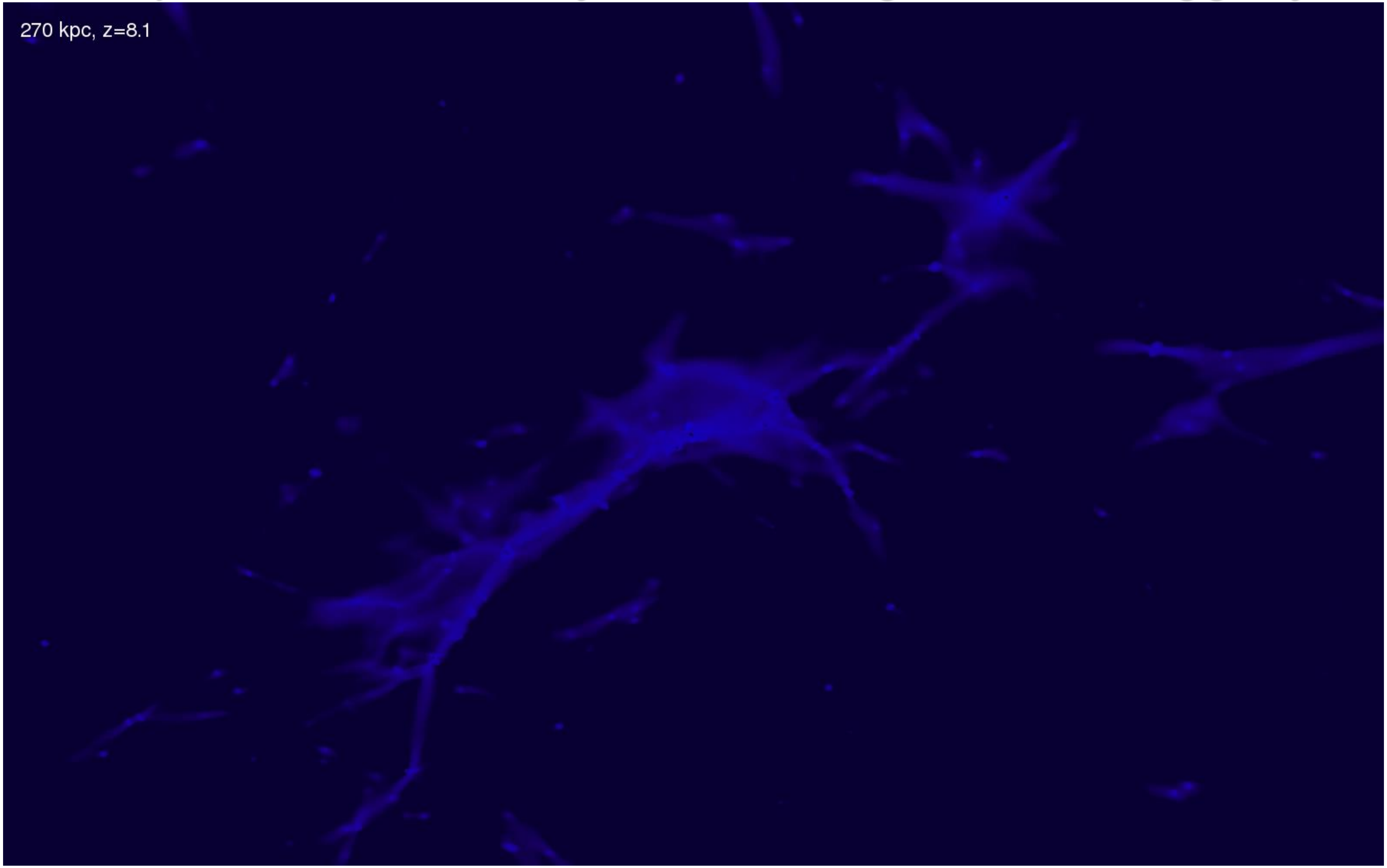
$$t_{\rm SF} = t_{\rm ff}/\epsilon_{\rm ff}$$

$$t_{\rm ff} = \sqrt{3\pi/32G\rho_{\rm g}}$$

→ *New subgrid model for stellar feedback that takes into account momentum injection due to radiation pressure and winds designed to work at ~50-100 pc scale (Agertz, Leitner, Kravtsov, Gnedin 2013, ApJ) and retention of "turbulent" energy due to SN feedback (cf. Springel 2003; Teyssier et al. 2013)*

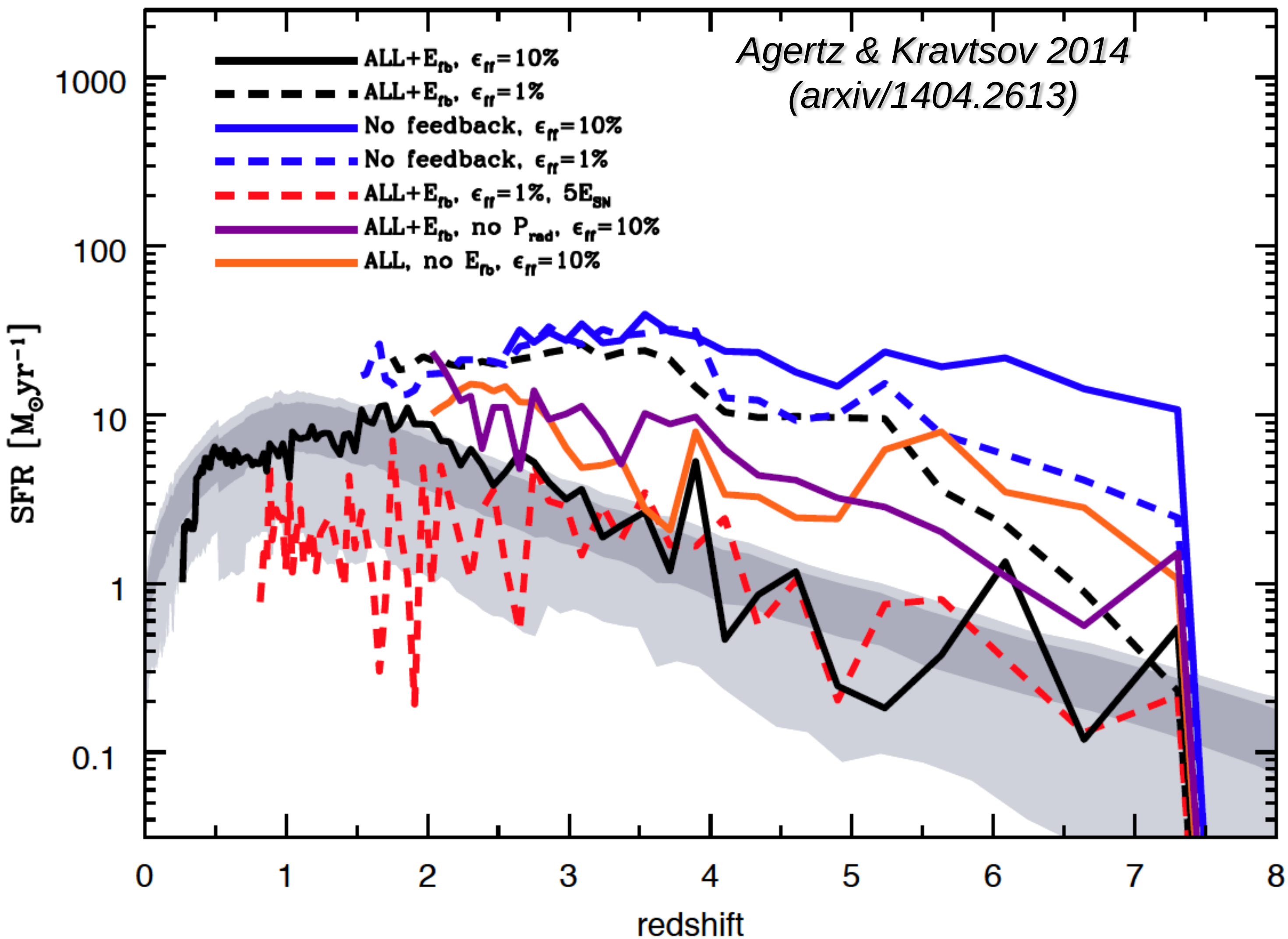
Galaxy formation simulation with (strong) feedback

Temperature distribution of baryonic matter in a region around forming galaxy

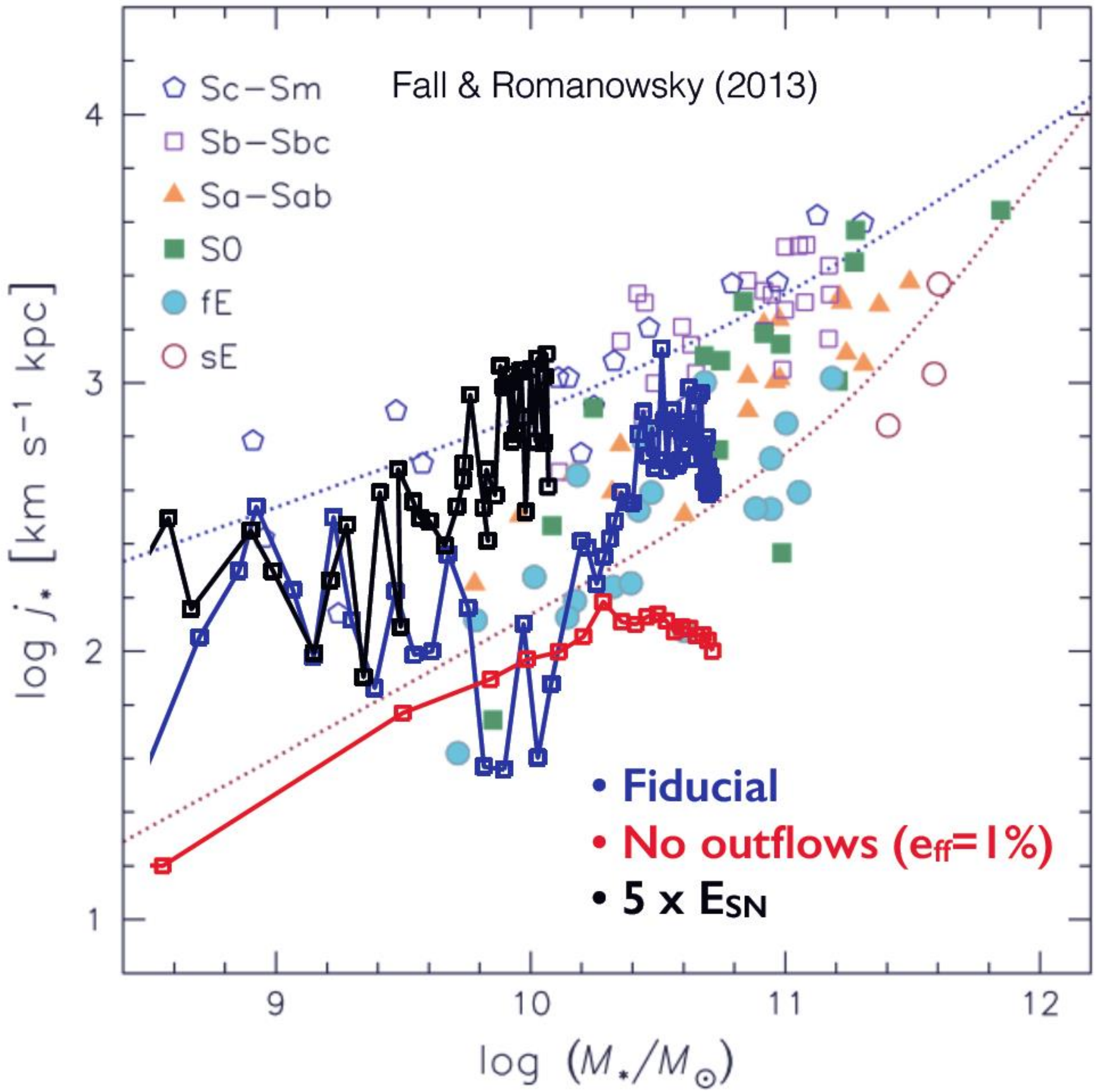


Agertz & Kravtsov
arxiv/1404.2613

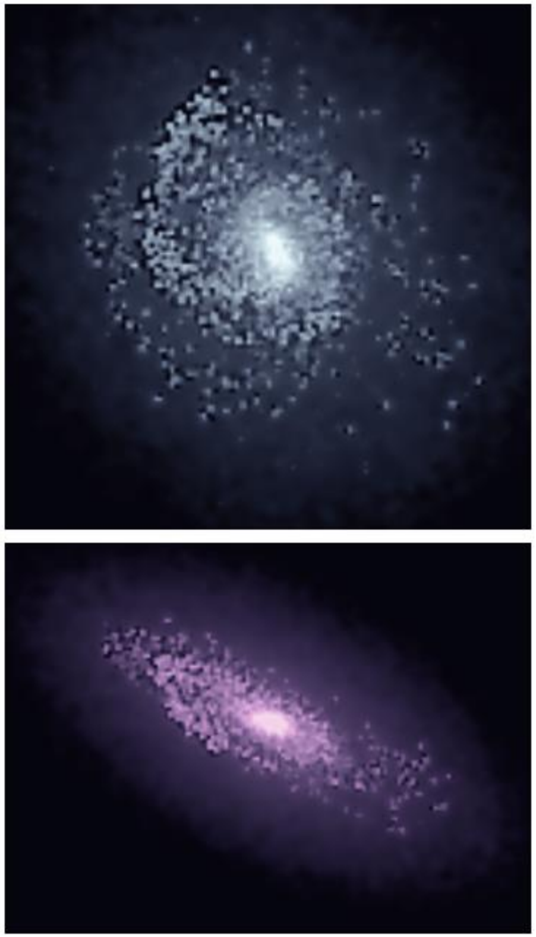
simulations of galaxy formation in a Milky Way sized halo with different parameters of star formation and feedback



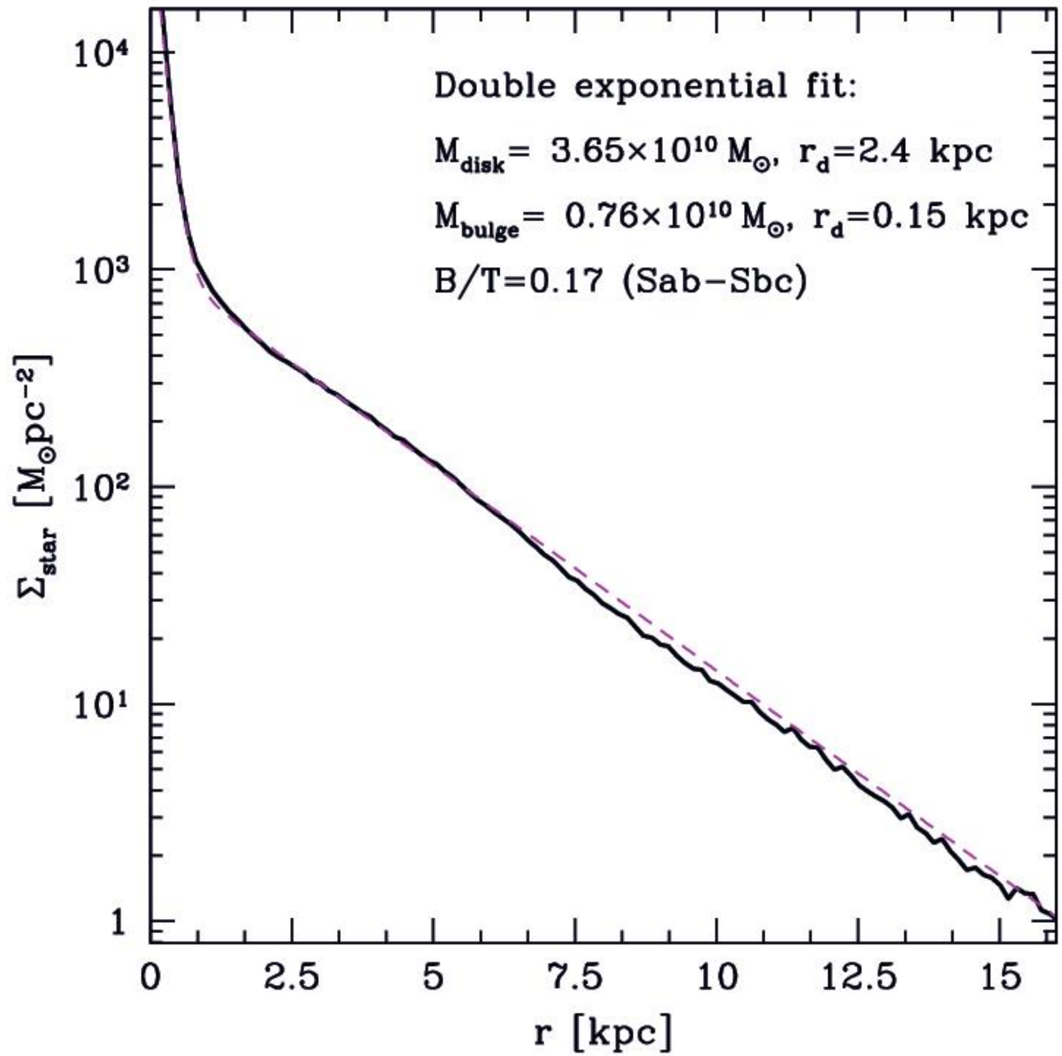
specific angular momentum evolution



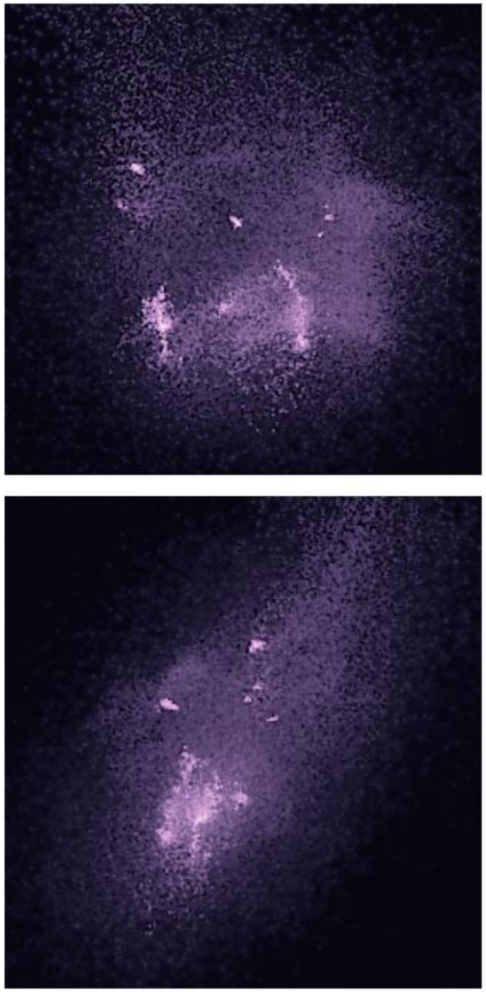
fiducial simulation at z=0.2



Luminosity weighted stellar densities



5xESN simulation at z=0.85



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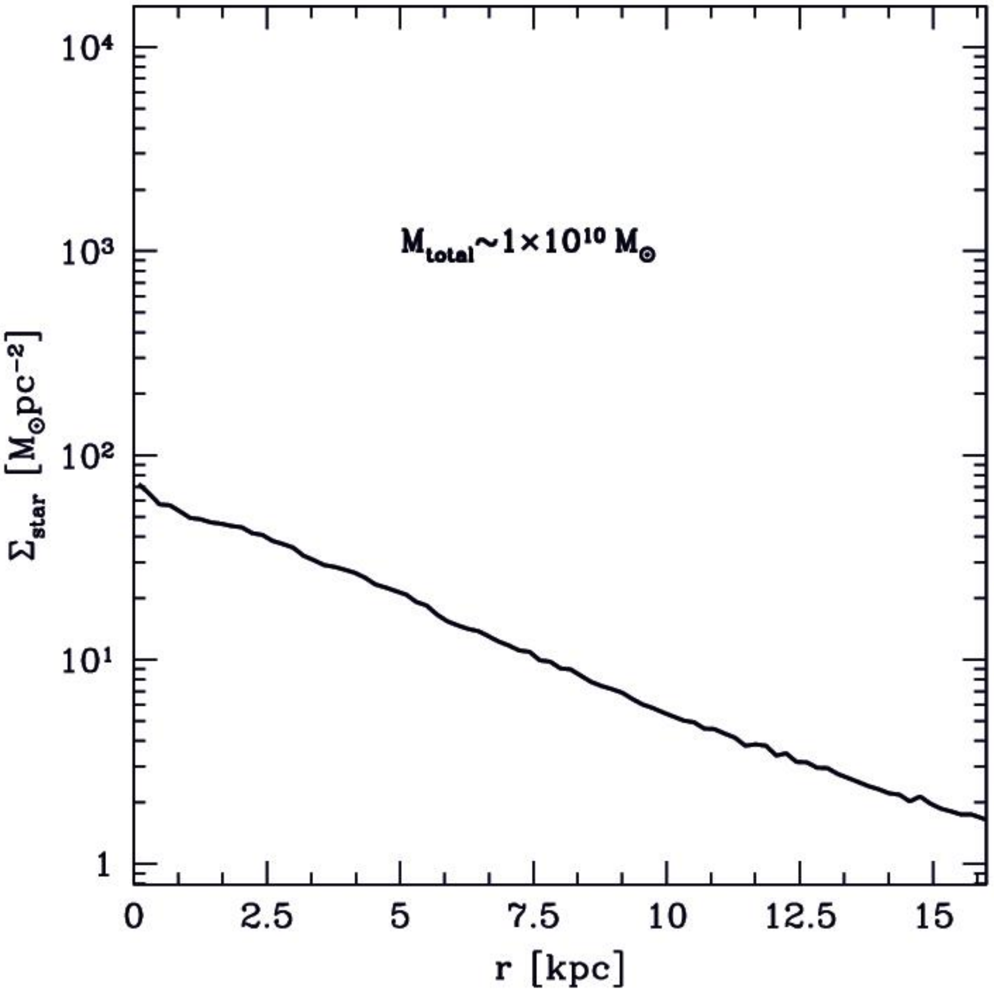
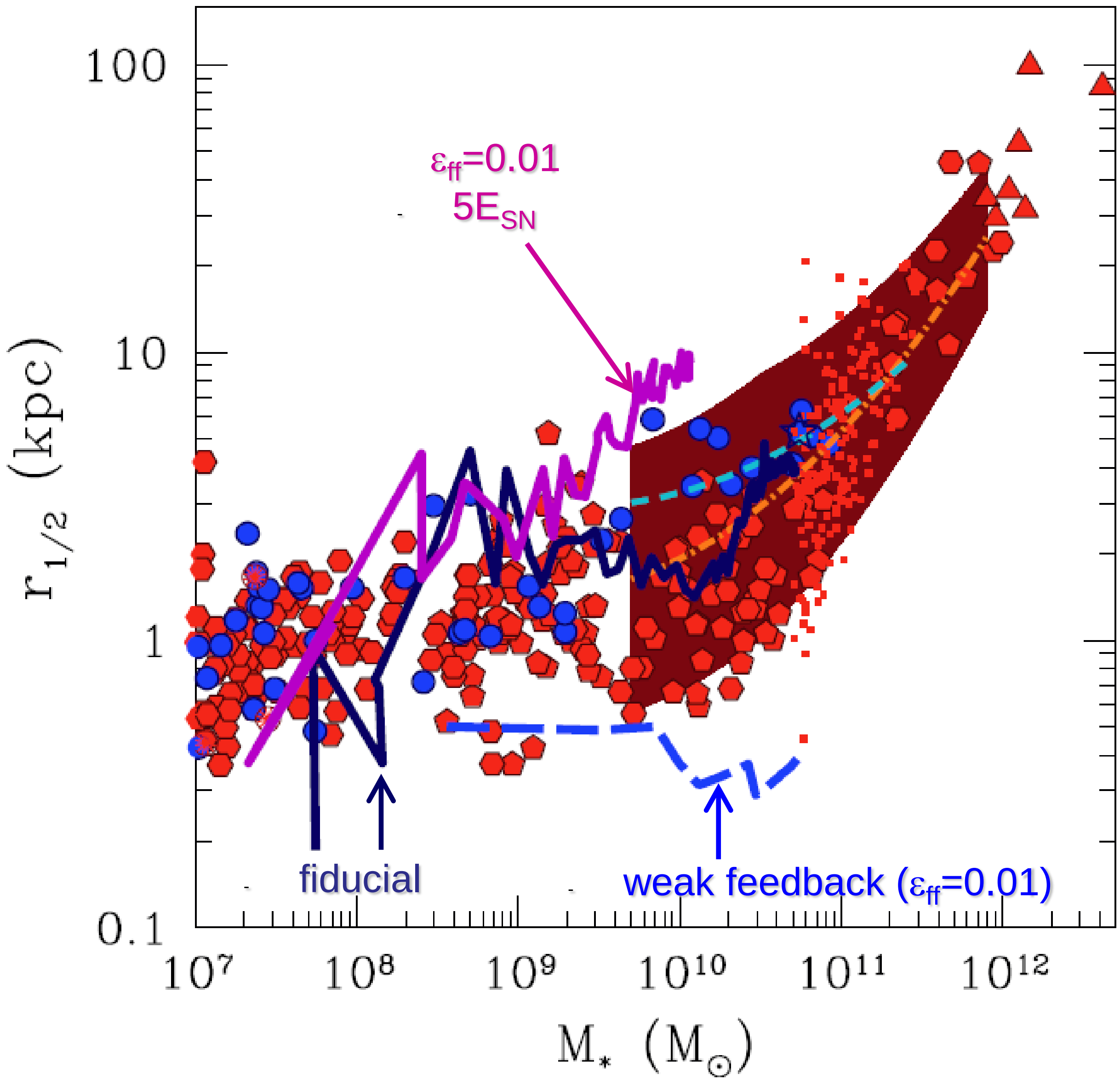


size-stellar mass relation



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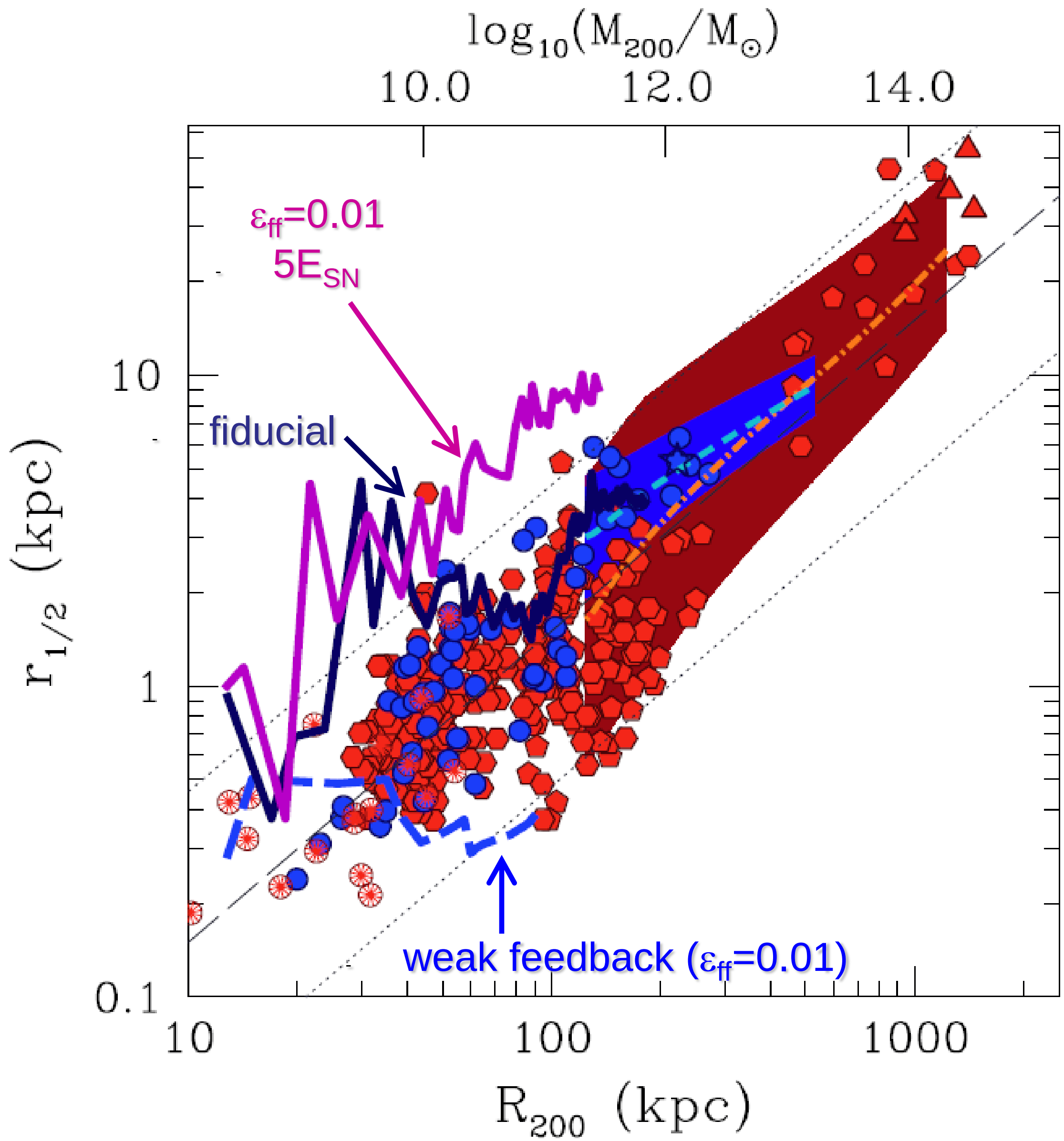
Agertz & Kravtsov 2014 in prep.

size-virial radius relation



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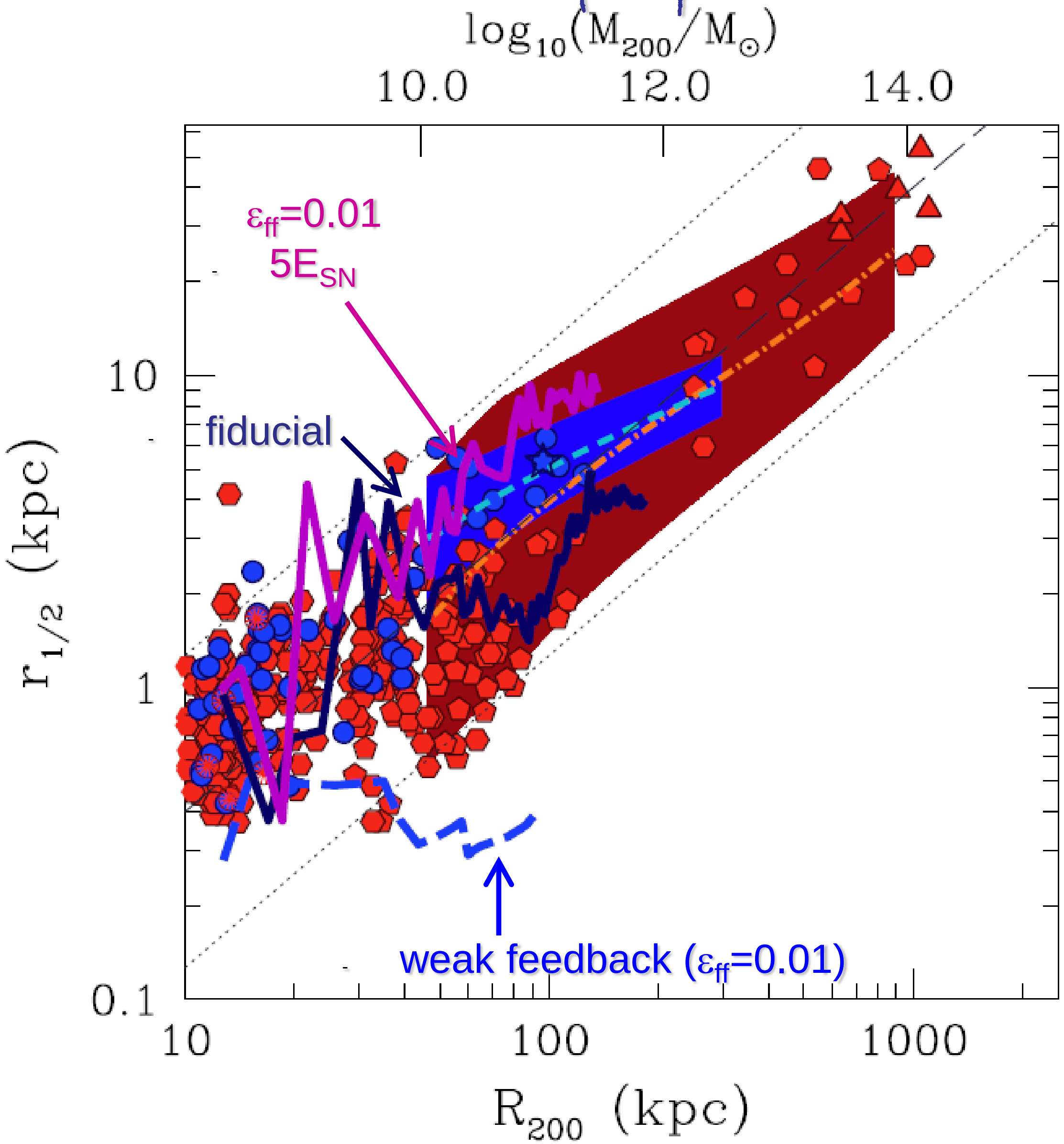
size-virial radius relation corrected for pseudo-evolution of R_{200}



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conclusions

- *scaling of galaxy sizes with virial radius is consistent with the simple scenario in which sizes are set by angular momentum of baryons acquired during collapse. This is true for both disk and spheroidal galaxies!*

- *stellar feedback plays a key role in allowing galaxies to retain large fraction of angular momentum acquired during collapse*

- *simulations with efficient feedback simultaneously reproduce star formation history, stellar-mass halo mass relation, size-virial radius scaling, and angular momentum of observed galaxies. Some details do depend on how feedback is implemented.*

Kravtsov 2013, ApJL 764, 31
Kravtsov et al. 2014, arxiv/1401.7329
Agertz & Kravtsov 1404.2613