Star formation efficiency in halos of different mass and the role of feedback in galaxy formation

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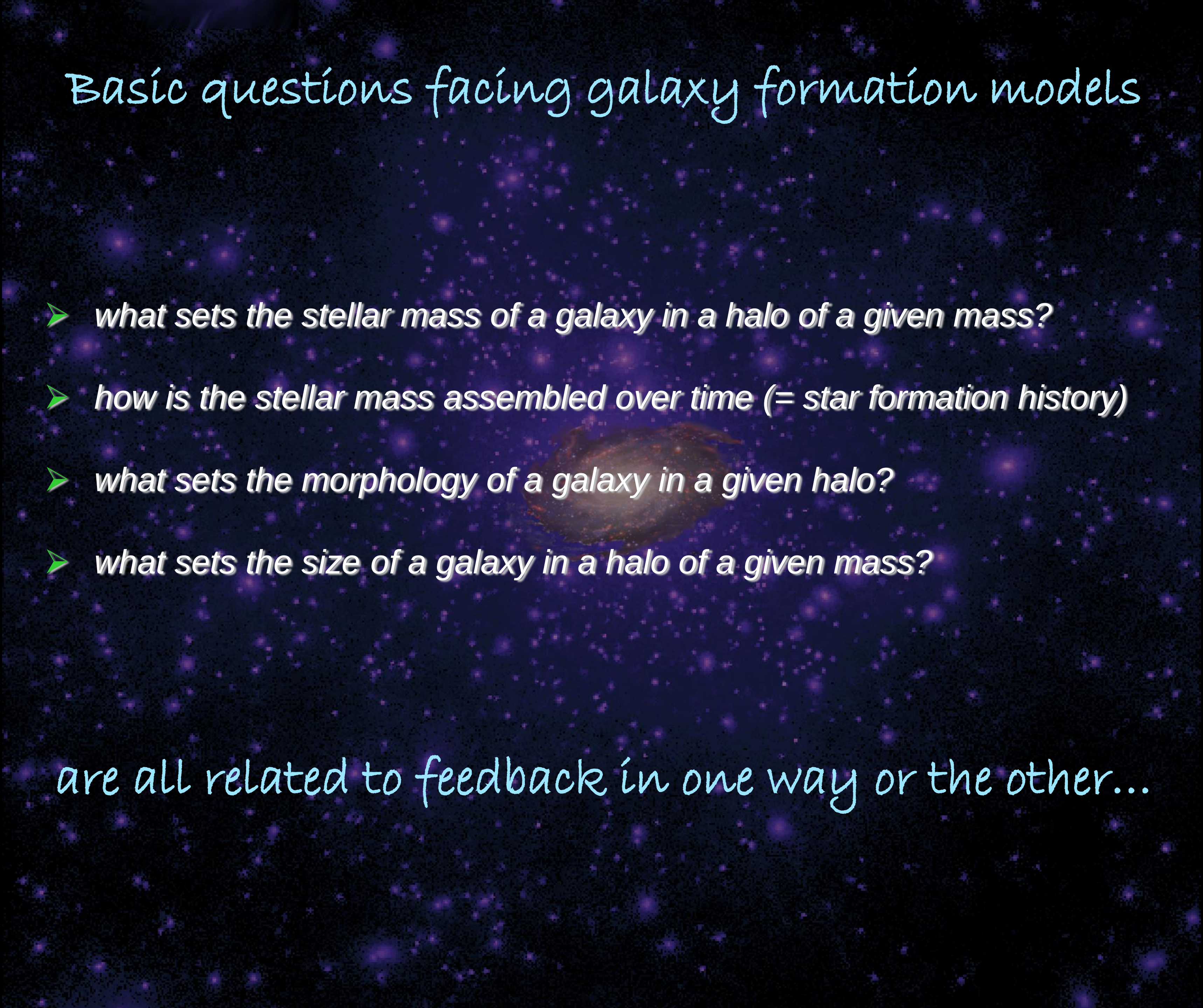
Fire Down Below: the impact of feedback on star and galaxy formation

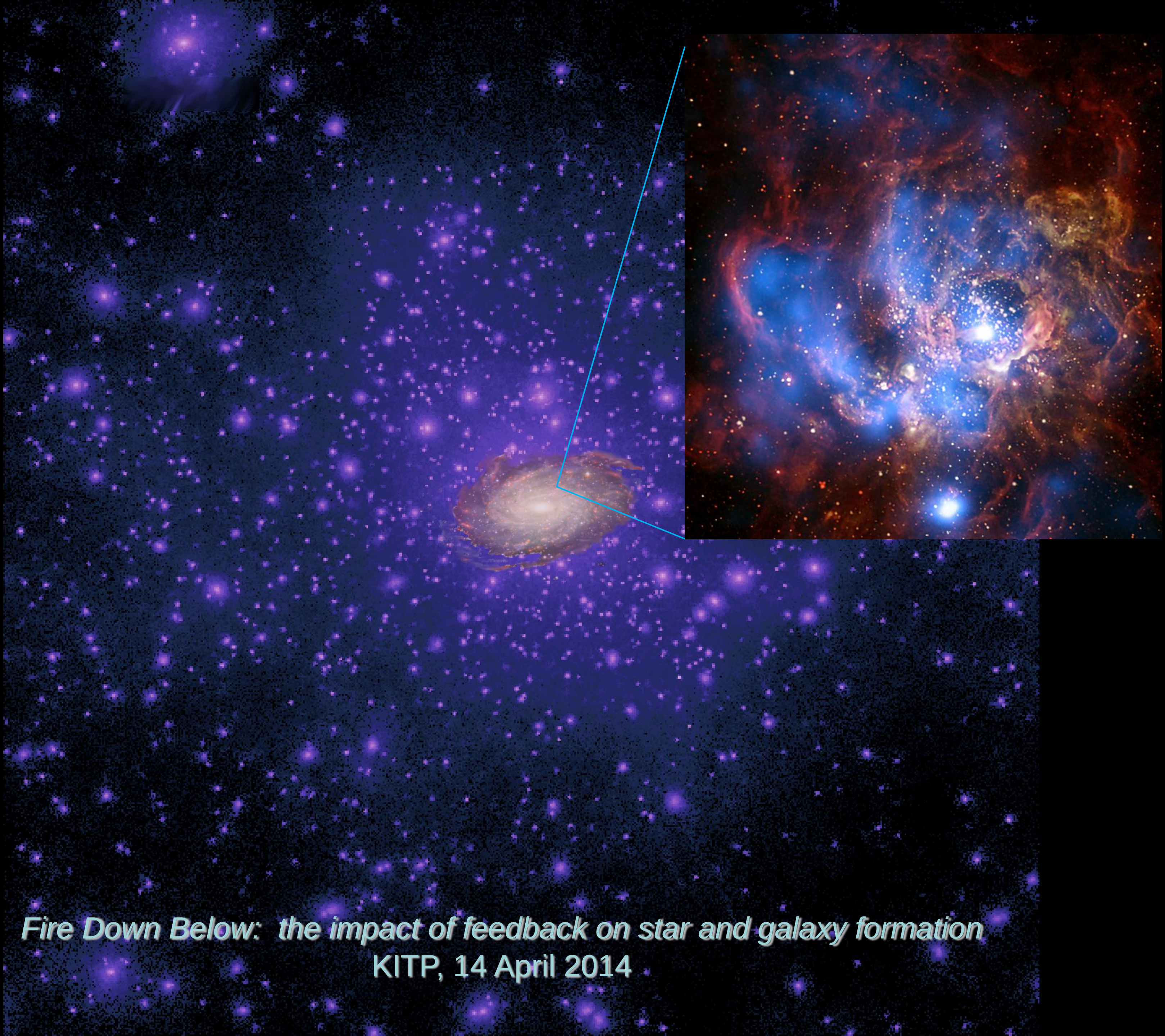
KITP, 14 April 2014

Basic questions facing galaxy formation models



- *what sets the stellar mass of a galaxy in a halo of a given mass?*
- *how is the stellar mass assembled over time (= star formation history)*
- *what sets the morphology of a galaxy in a given halo?*
- *what sets the size of a galaxy in a halo of a given mass?*

are all related to feedback in one way or the other...



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Dark matter distribution in CDM halos is approximately self-similar (halos of different mass look similar when rescaled to the same size)

z=0 dark matter distribution in a cluster-sized (3×10^{14} Msun) and
a Milky Way-sized (2×10^{12} Msun) objects formed in the ΛCDM universe
(brightness and color reflect log of the local matter density)

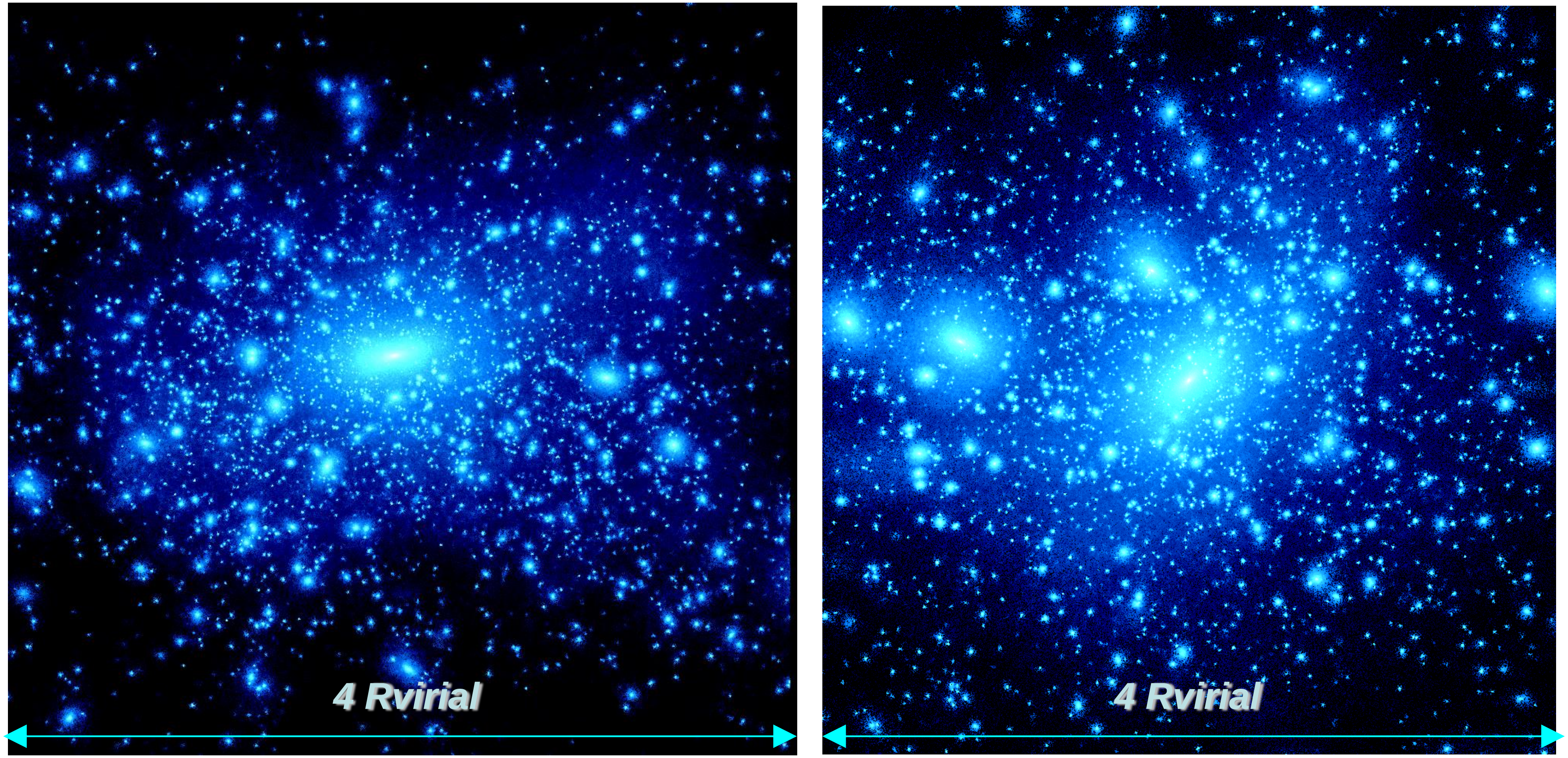
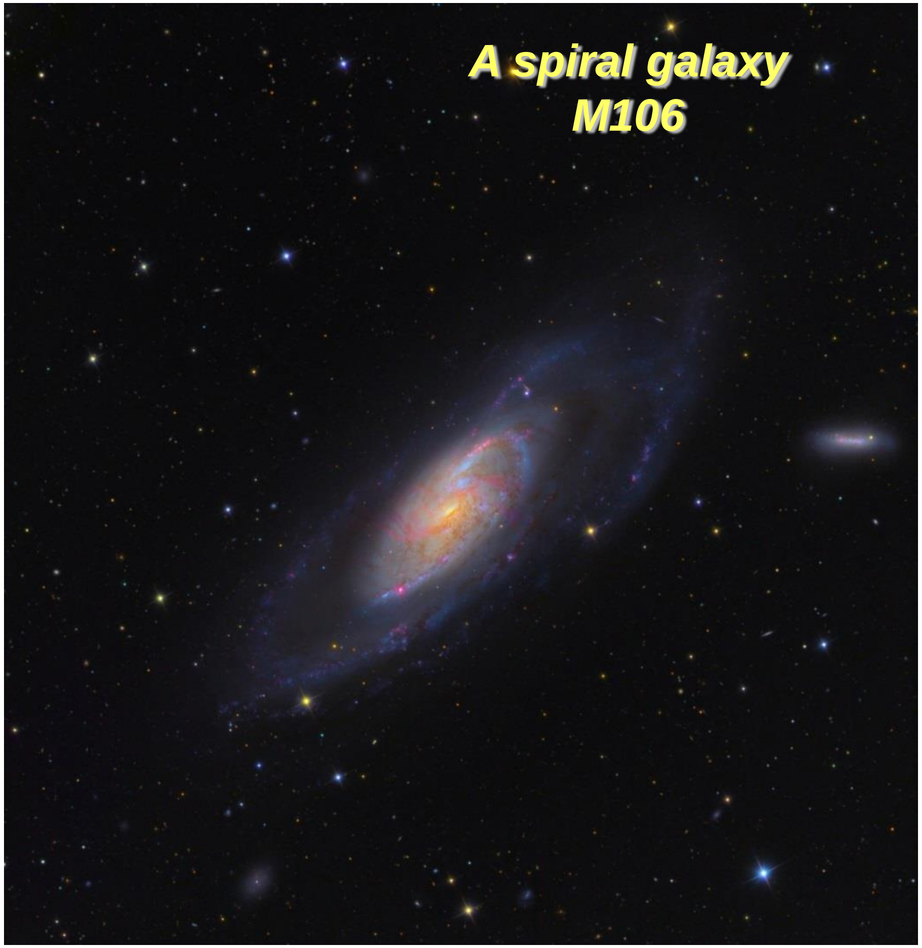


fig. from Kravtsov ’09
(arXiv/0906.3295)

distribution of ordinary luminous matter in and around galaxy and galaxy cluster (manifestly not self-similar)

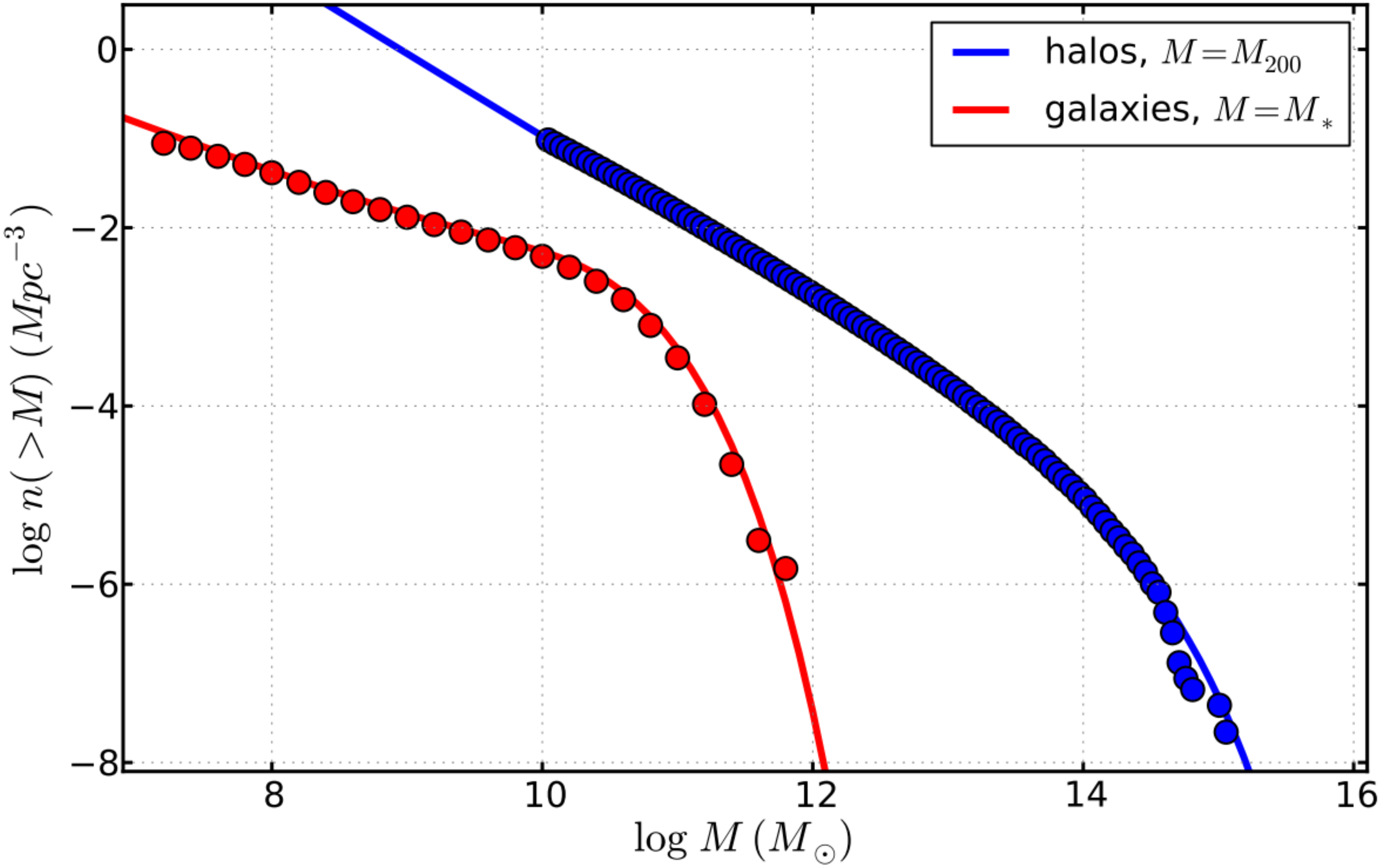


credit: Chandra XC/STScI

Stellar and halo mass functions

stellar and halo mass functions have qualitatively similar shapes, but are very different in detail.

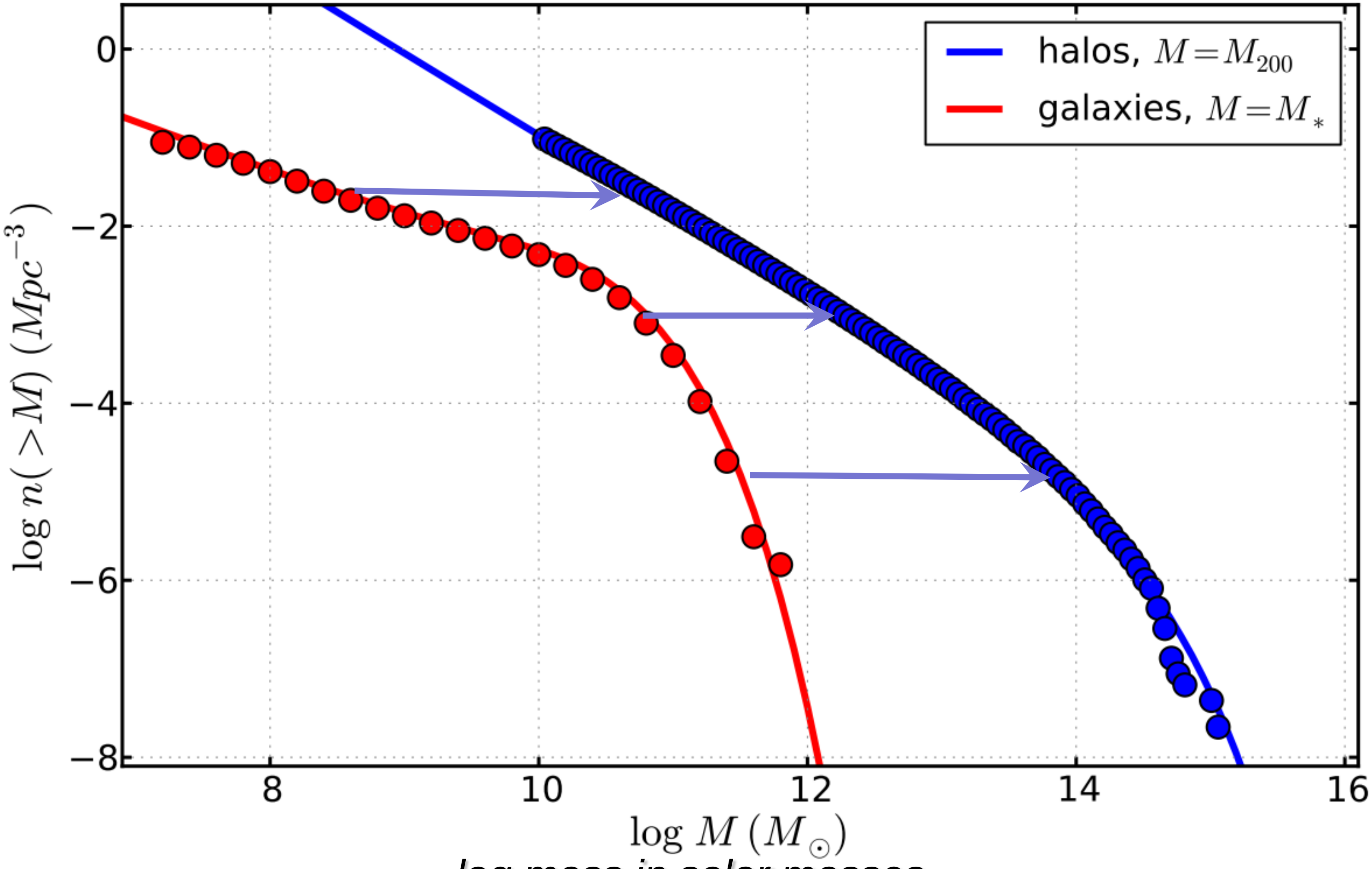
log space density



log mass in solar masses

Stellar mass of galaxies and total mass of halos

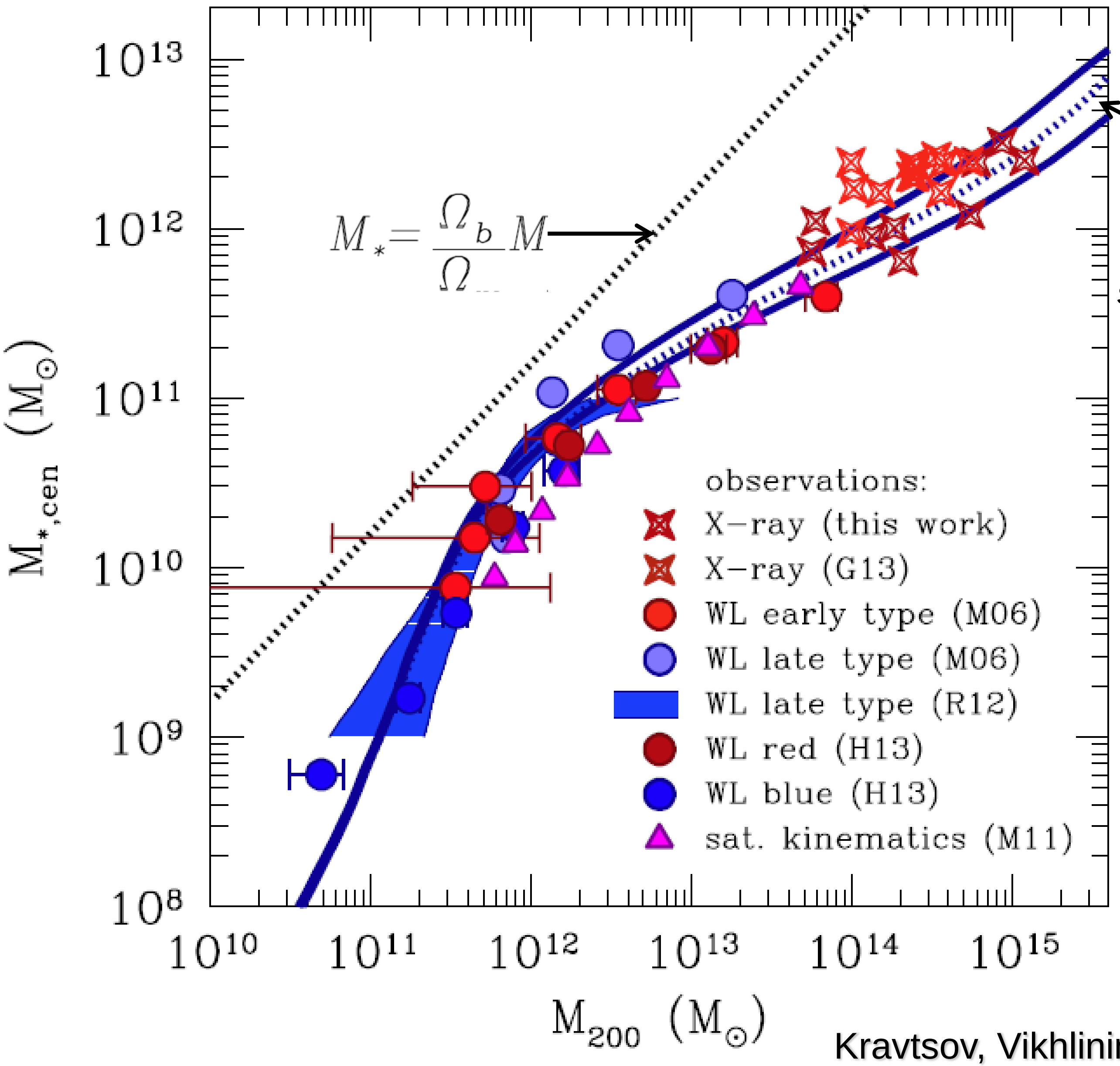
If we assume that galaxies form and live in dark matter halos, then comparison of the observed stellar mass function and predicted halo mass function (<u>the abundance matching</u>) implies that relation between galaxy stellar mass and "parent" halo mass is complicated, and is nonlinear



log space density

log mass in solar masses

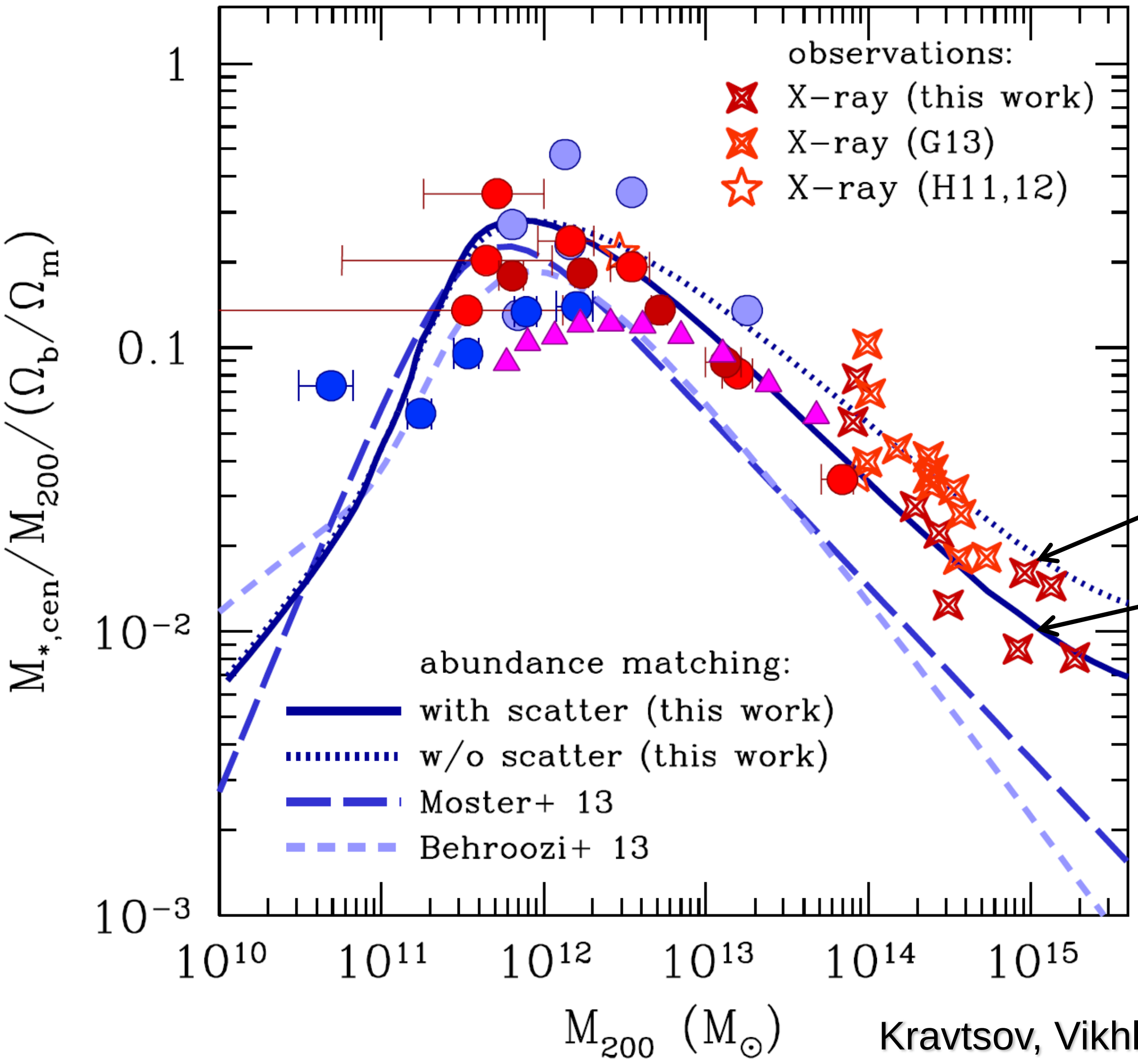
Stellar mass -halo mass relation



abundance matching using new stellar mass function of Bernardi et al. ‘13

Kravtsov, Vikhlinin, Meshsheryakov
arxiv/1401.7329

The low efficiency of star formation in halos: the key problem in galaxy formation



abundance matching using new stellar mass function of Bernardi et al. '13

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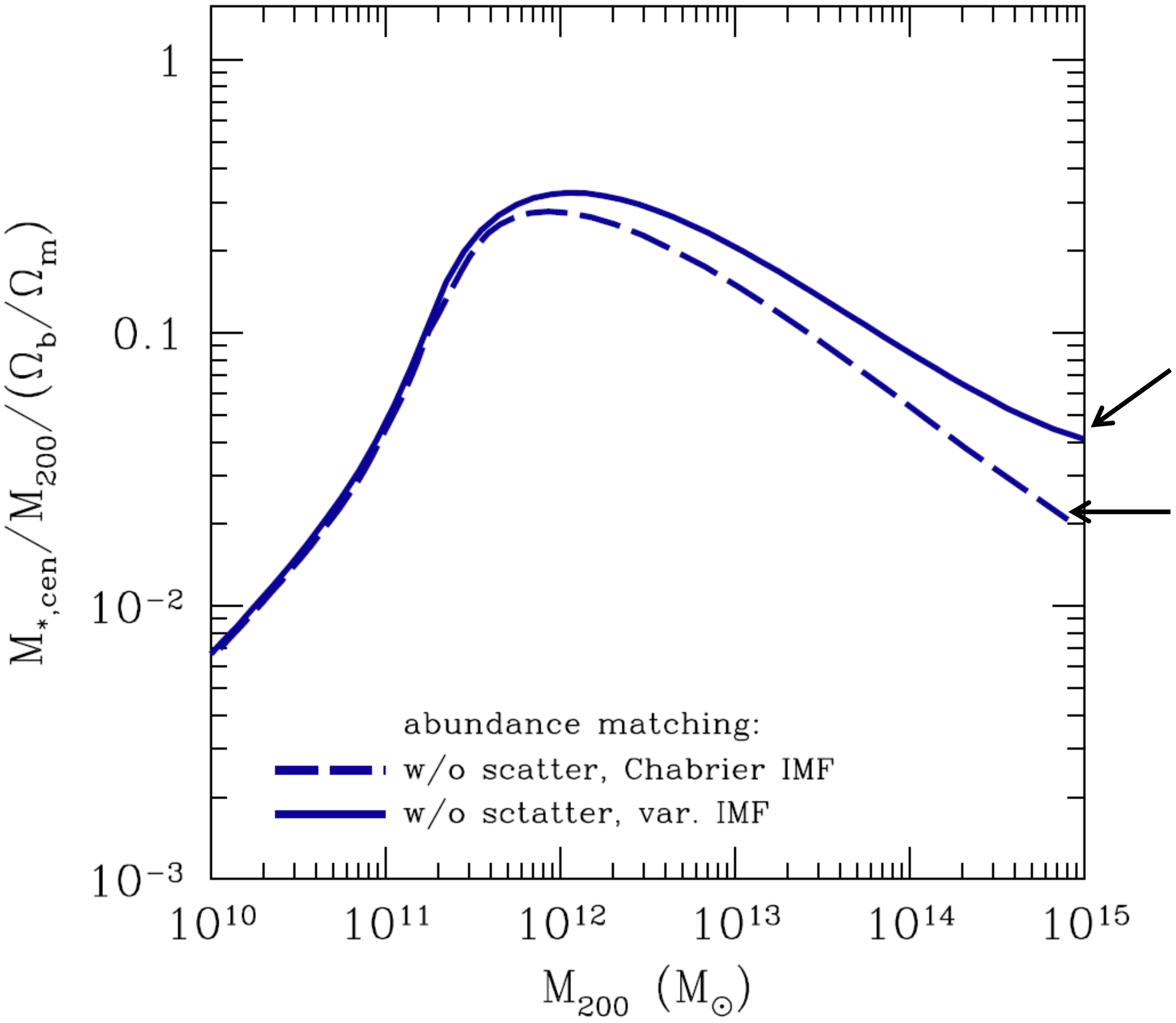
Effect of IMF

If the IMF becomes progressively more bottom heavy for larger stellar mass, as indicated by observations, stellar fractions in massive halos drop significantly more slowly

stellar fraction (central galaxy) in units of the universal baryon fraction



varying IMF for spheroidal galaxies (more top-heavy for larger M)*

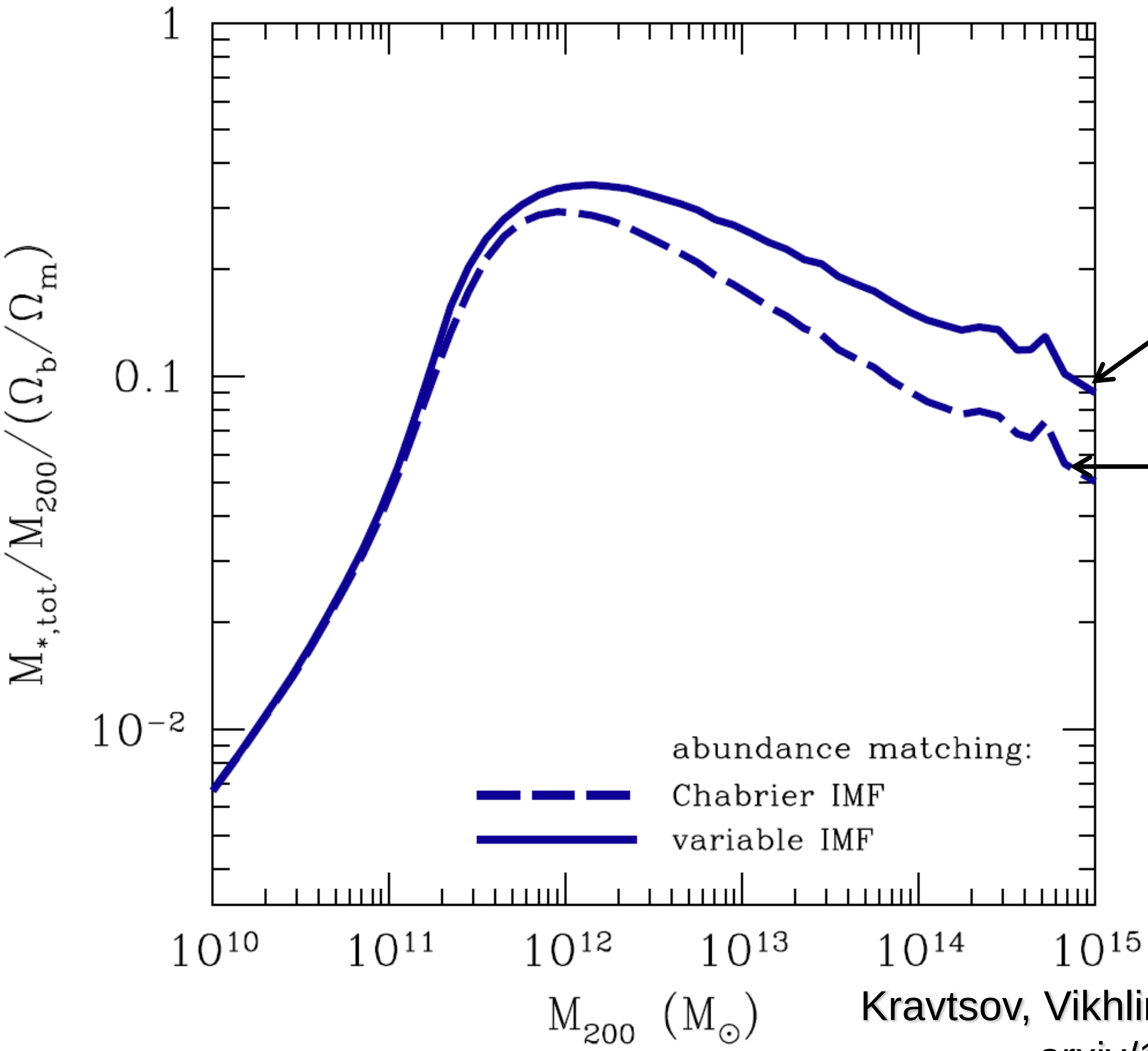
assuming constant Chabrier IMF

Kravtsov et al.
arxiv/1401.7329
(cf also
McGee et al.
arxiv/1311.5230)

Effect of IMF

total stellar fraction in massive clusters is only a factor of ~3-5 lower than in the Milky Way-sized halos, M_{halo}~10^{12} Msun

total
stellar fraction
(central galaxy
+
satellites)
in units of the
universal
baryon
fraction



varying IMF for
spheroidal galaxies
(more top-heavy for
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Kravtsov, Vikhlinin, Meshsheryakov
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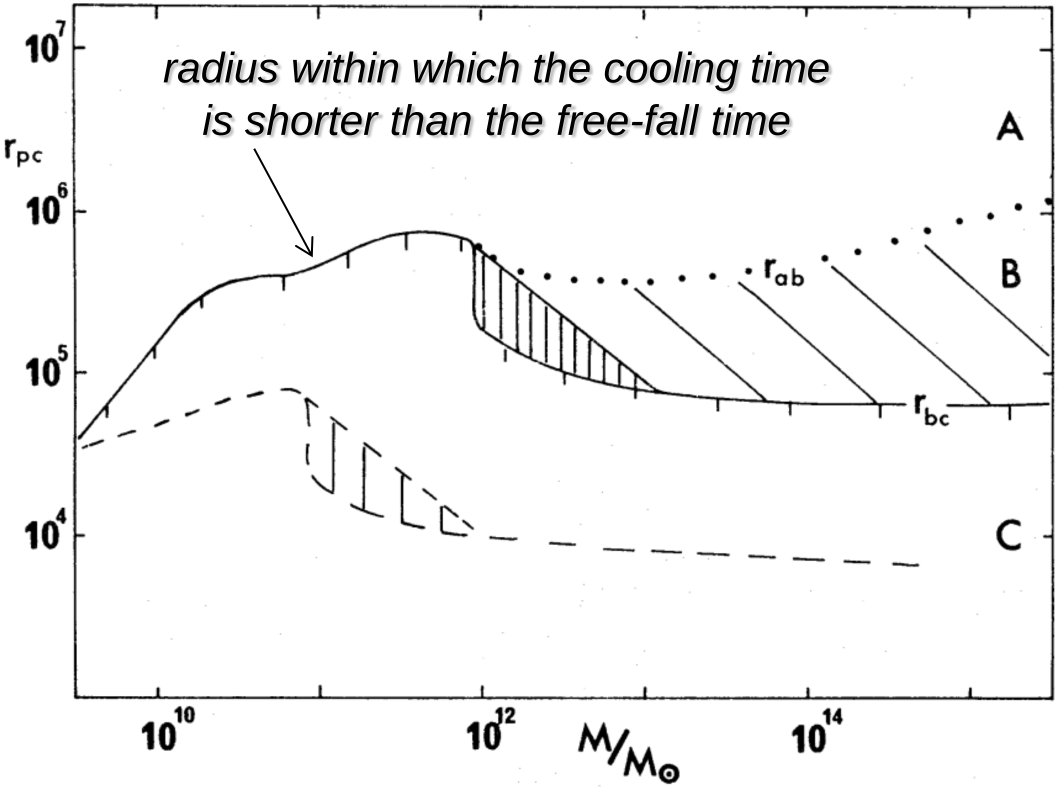
Characteristic galaxy mass

Ostriker & Rees (1977, also Silk 1977, White & Rees 1978, Blumenthal et al. 1984) have argued that there should be a characteristic halo mass of M_{halo}~10^{12} Msun, where galaxy formation should be most efficient, based on considering the cooling time in collapsing objects of different mass .

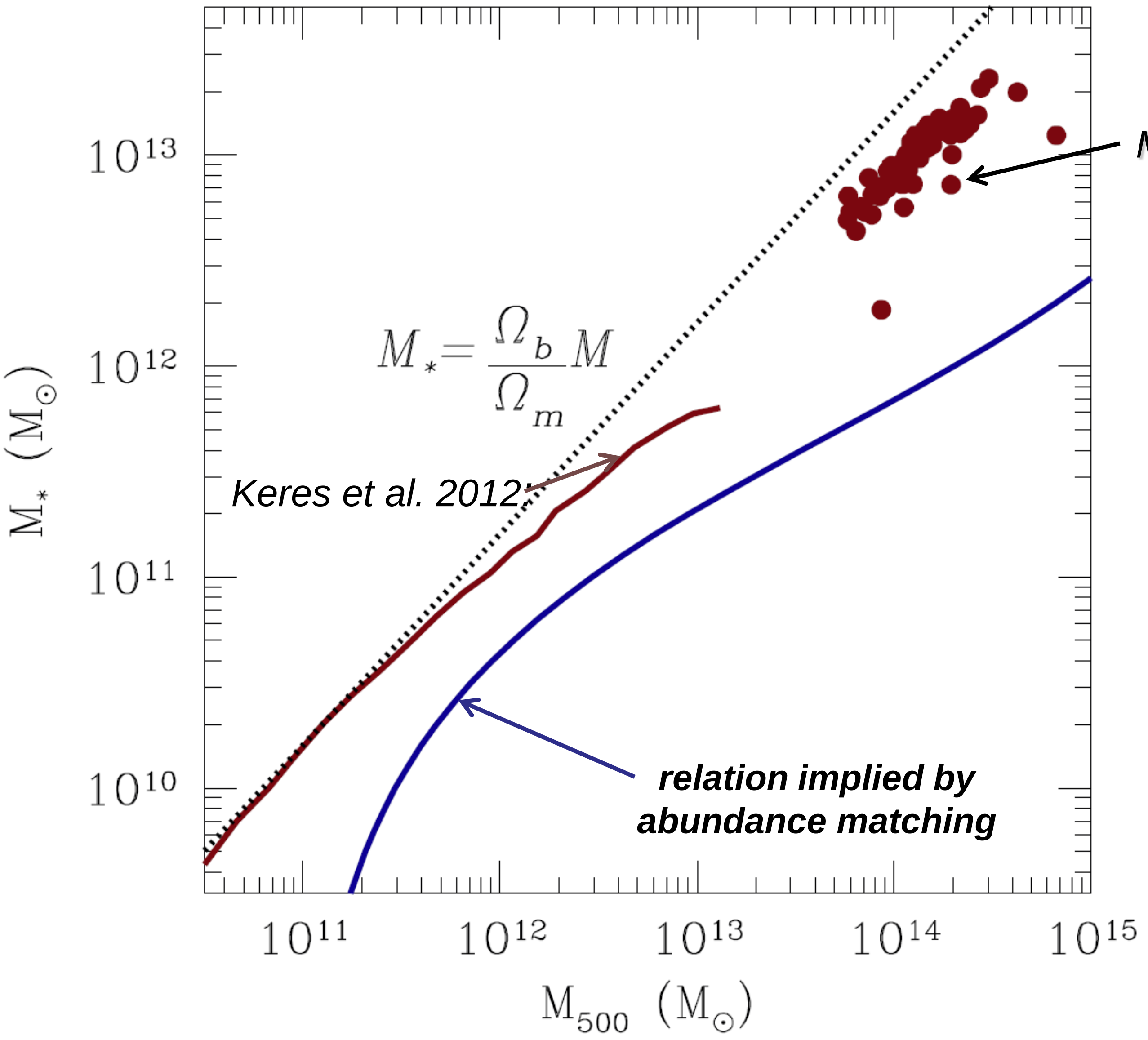


radius within which the cooling time is shorter than the free-fall time

radius
(parsecs)

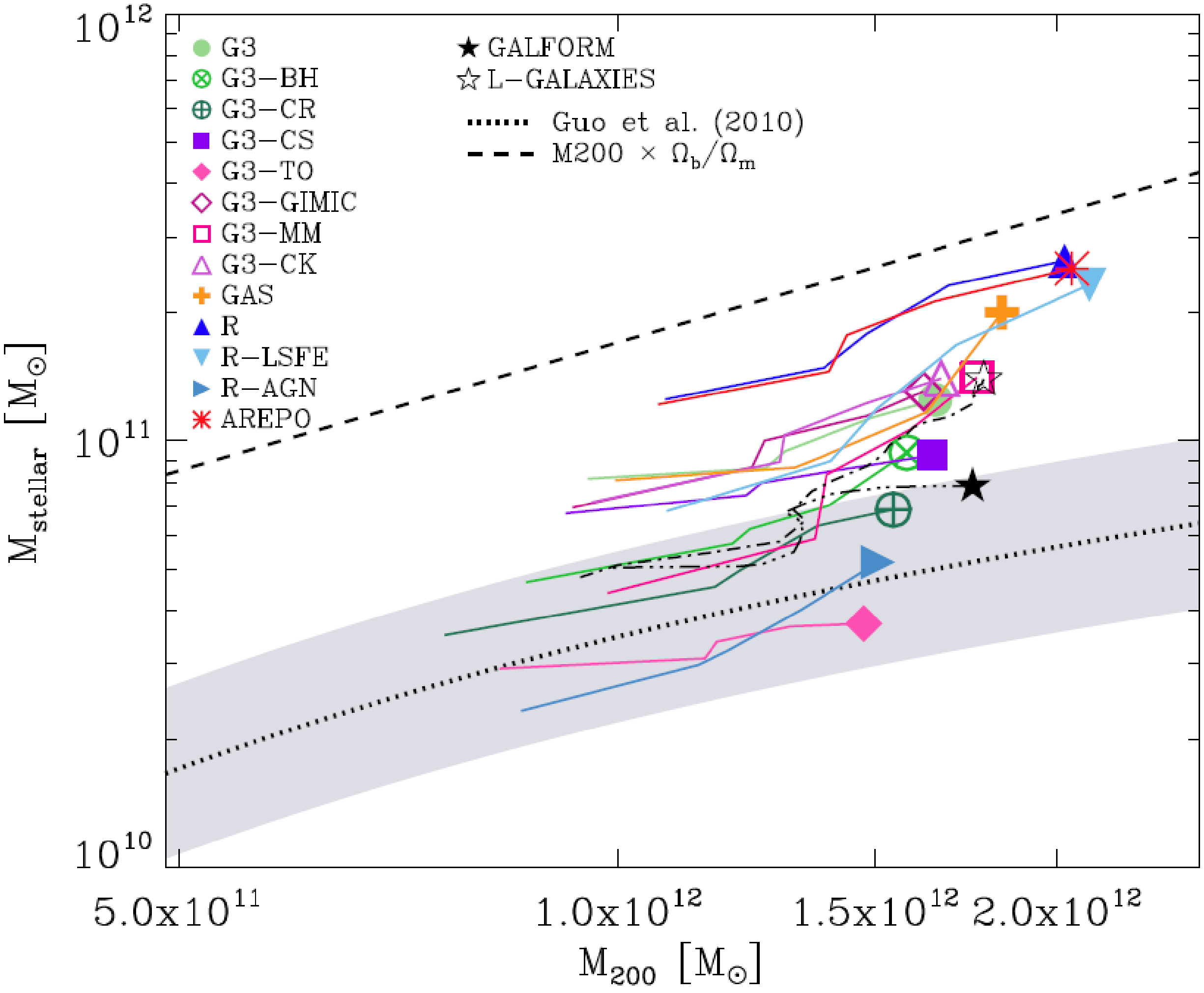
total mass of collapsing object
(solar masses)

Cosmological simulations including cooling only do not show a pronounced characteristic mass



Efficiency of star formation in a halo is sensitive to details of star formation and feedback implementation

Scannapieco et al. 2011
The Aquila simulation comparison project



$$M_* = \int \dot{M}_*(t)dt$$

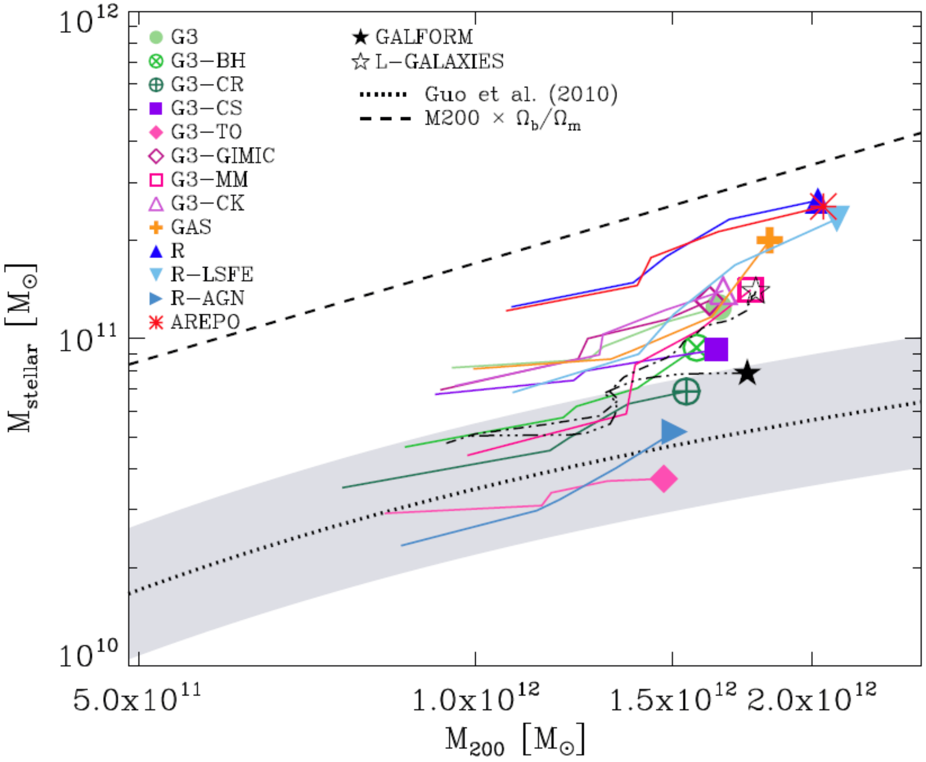
$$\dot{M}_* = \int_{A_{disk}} \dot{\Sigma}_* dA$$

$$\dot{\Sigma}_* = f(\Sigma_{gas,...}) = \frac{\Sigma_{gas}}{\tau_{sf}}$$

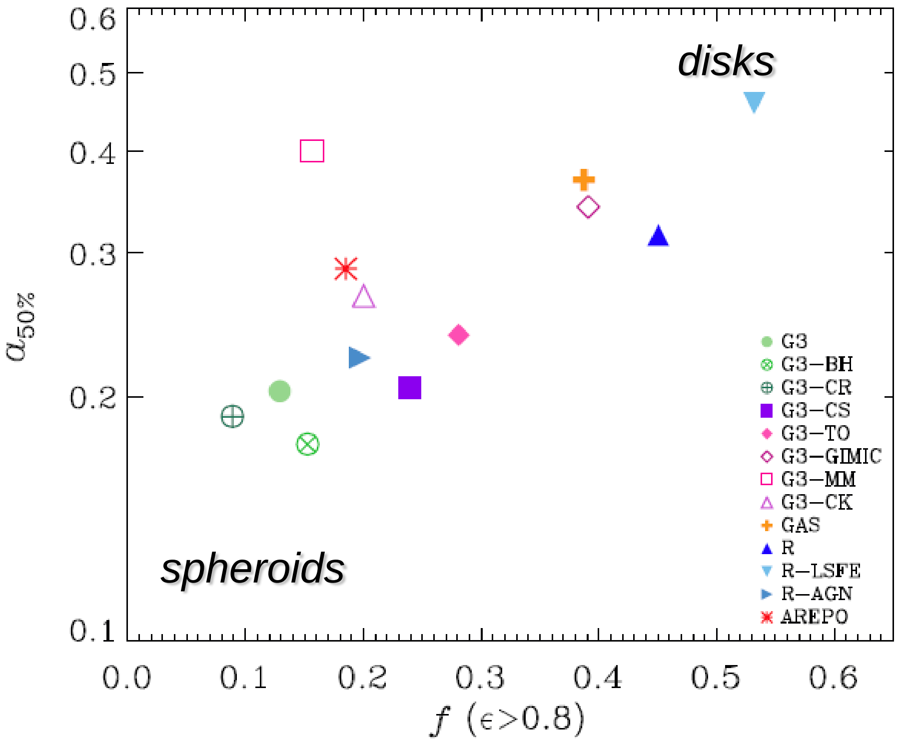
Morphology is relared to the star formation history

Scannapieco et al. 2011; cf. also Marinacci et al. 2013
The Aquila simulation comparison project

Galaxy tracks in M-Mhalo plane*



expansion factor by which 50% of the final galaxy formed and morphology



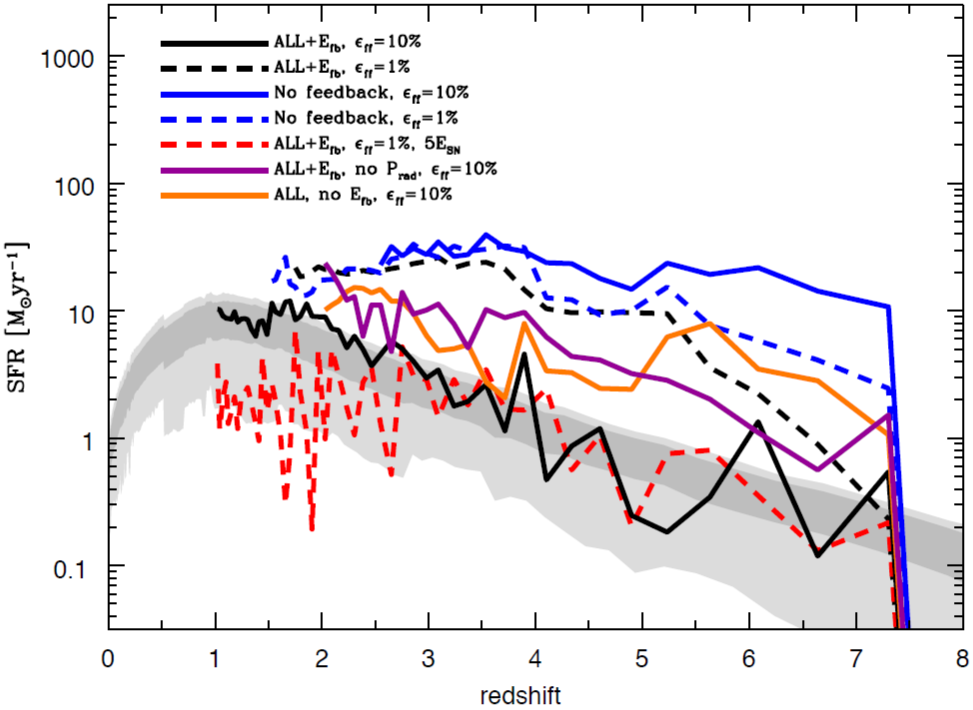
fraction of stars on circular orbits

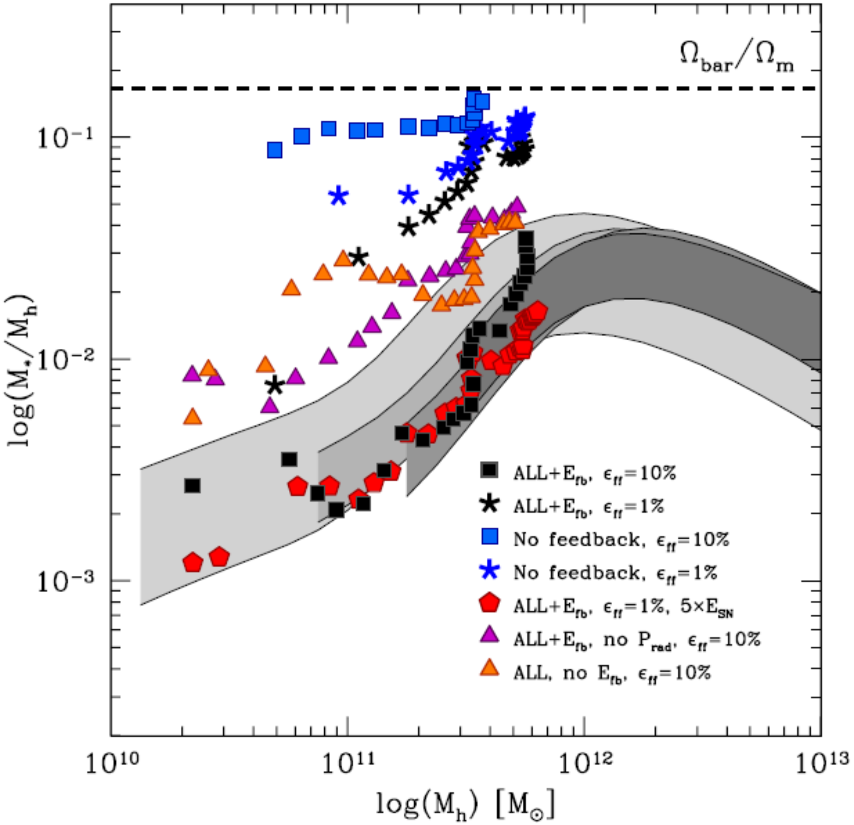
Modelling "early feedback" due to winds and radiation pressure helps in reproducing star formation histories and M*-M relation

Murray et al. 2005, 2010; Hopkins et al. 2011a,b,c, 2013; Stinson et al. 2012
Trujillo-Gomez et al. 2013; Agertz & Kravtsov 2014

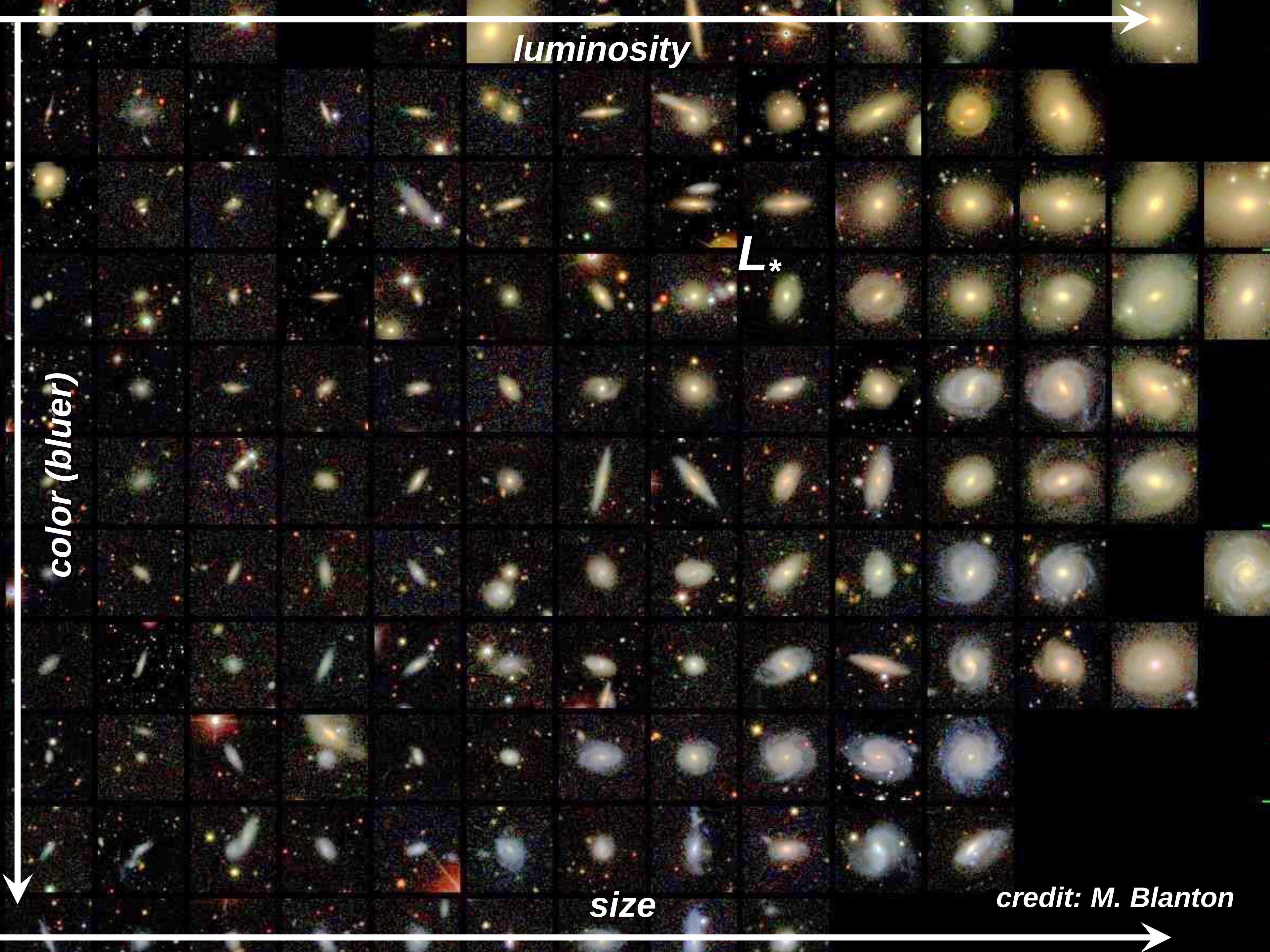
Oscar Agertz
(U.Chicago)

Star formation history of MW-sized progenitor and corresponding evolution in M*-M plane





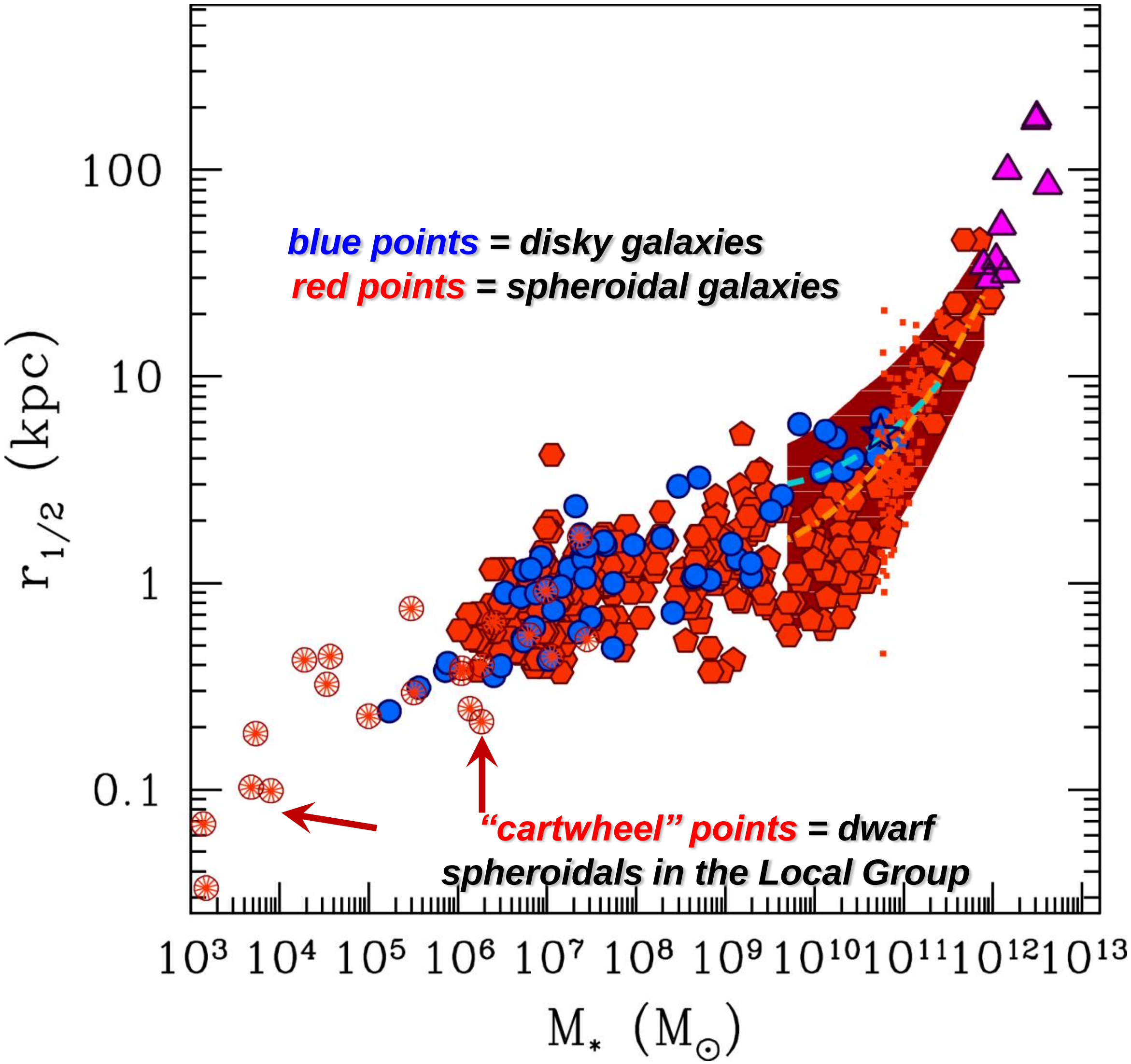
Agertz & Kravtsov 2014,
arxiv/1404. 2613



credit: M. Blanton

Galaxy size-stellar mass correlation

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



3D half-mass radius

blue points = disky galaxies
red points = spheroidal galaxies

"cartwheel" points = dwarf spheroidals in the Local Group

stellar mass of galaxies in solar masses

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

blue points = late type galaxies from the THINGS and LITTLE THINGS samples (Leroy et al. '09; Zhang et al. '12)

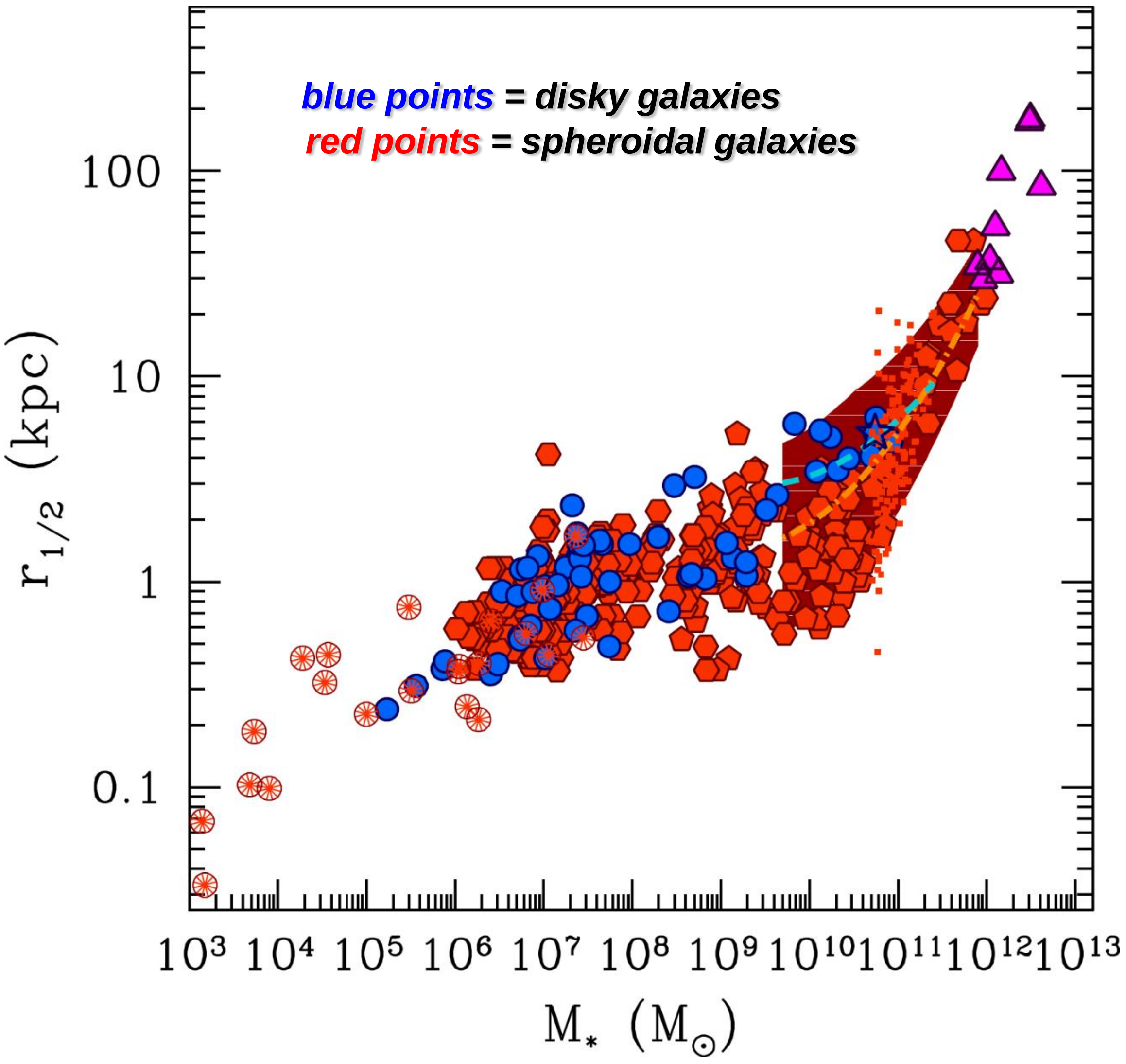
red points = spheroidal galaxies from different sources (Hilker & Misgeld '11; Szomoru et al. '12, etc.)

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 '13

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

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



3D half-mass radius

stellar mass of galaxies in solar masses

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

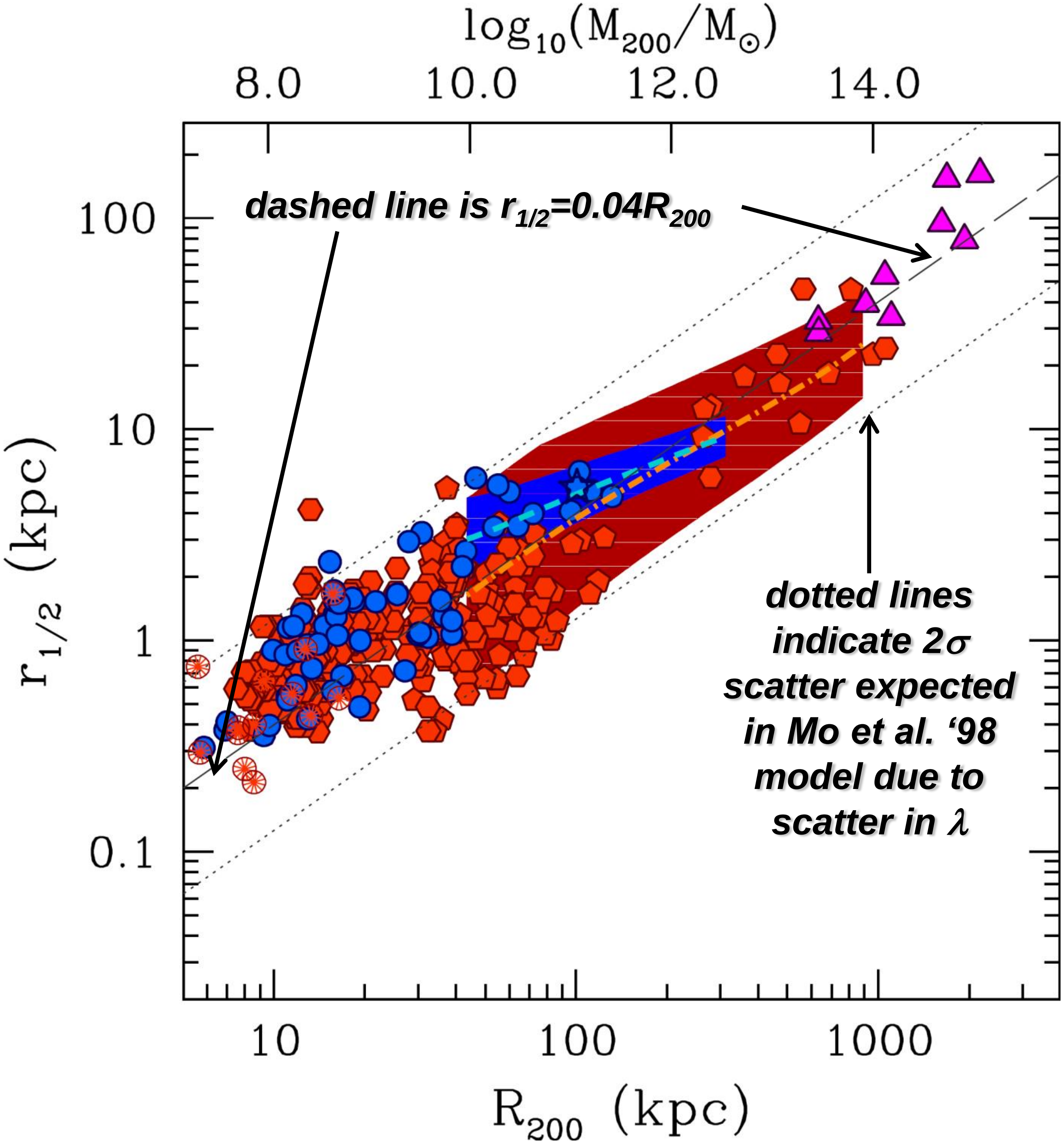
$$M_{200} = \frac{4\pi}{3}\Delta\rho_{\rm crit}R_{200}^3$$

↓

\+

pseudo-evolution correction

Size-virial relation of galaxies



dashed line is $r_{1/2}=0.04R_{200}$

dotted lines indicate 2σ scatter expected in Mo et al. '98 model due to scatter in λ

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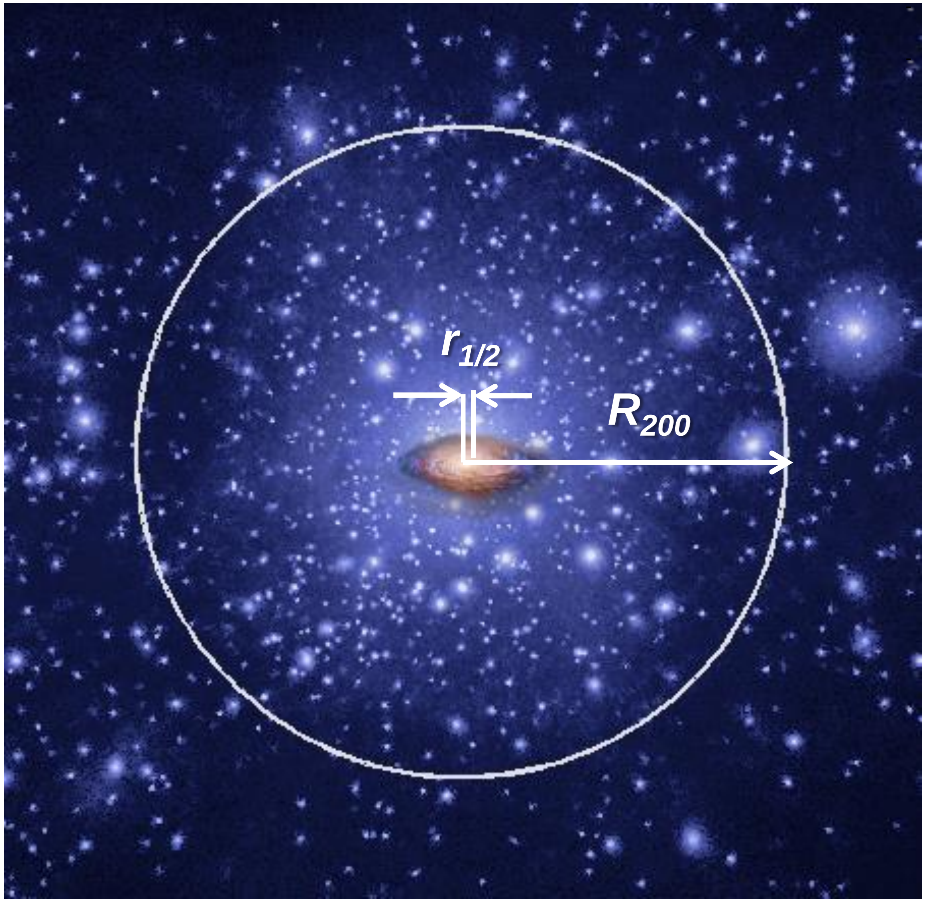
magenta points = BCGs from Mescheryakov & Vikhlinin '13 and Newman et al. '13

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

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:

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

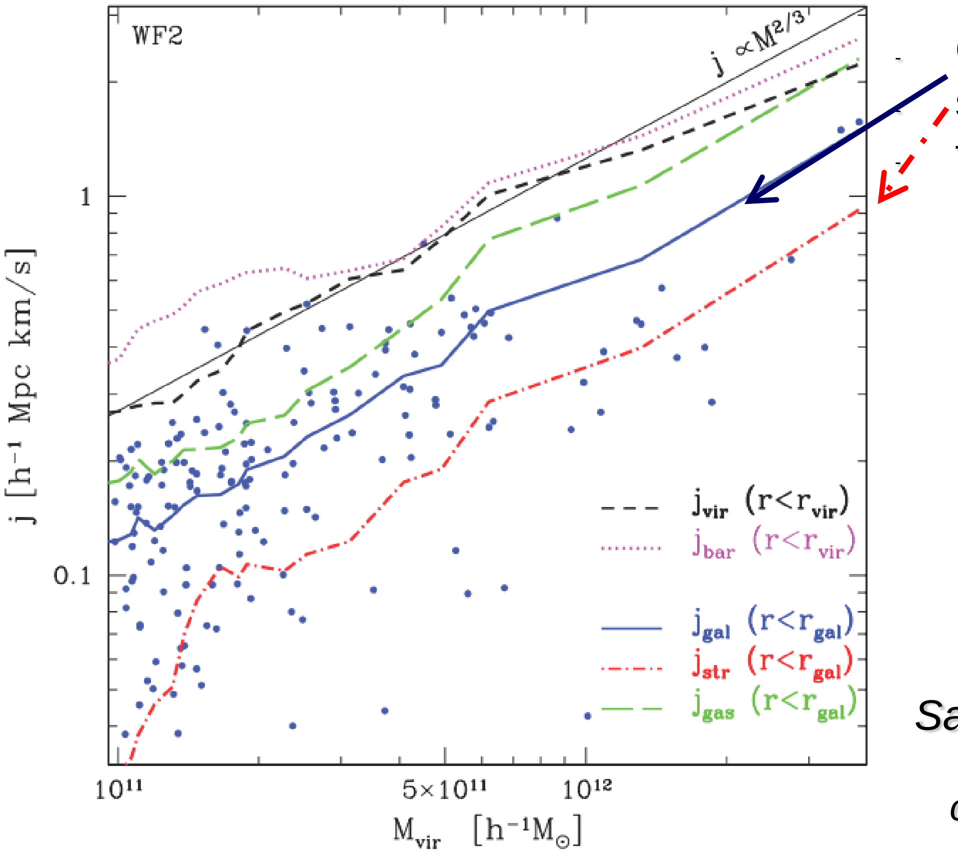
$$\rightarrow R = \lambda R_{200} \frac{V_{\rm circ}(R_{200})}{V_{\rm circ}(R)} \propto \lambda R_{200}$$

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

Galaxy formation is messy and complicated…
Is this simple picture supported by 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

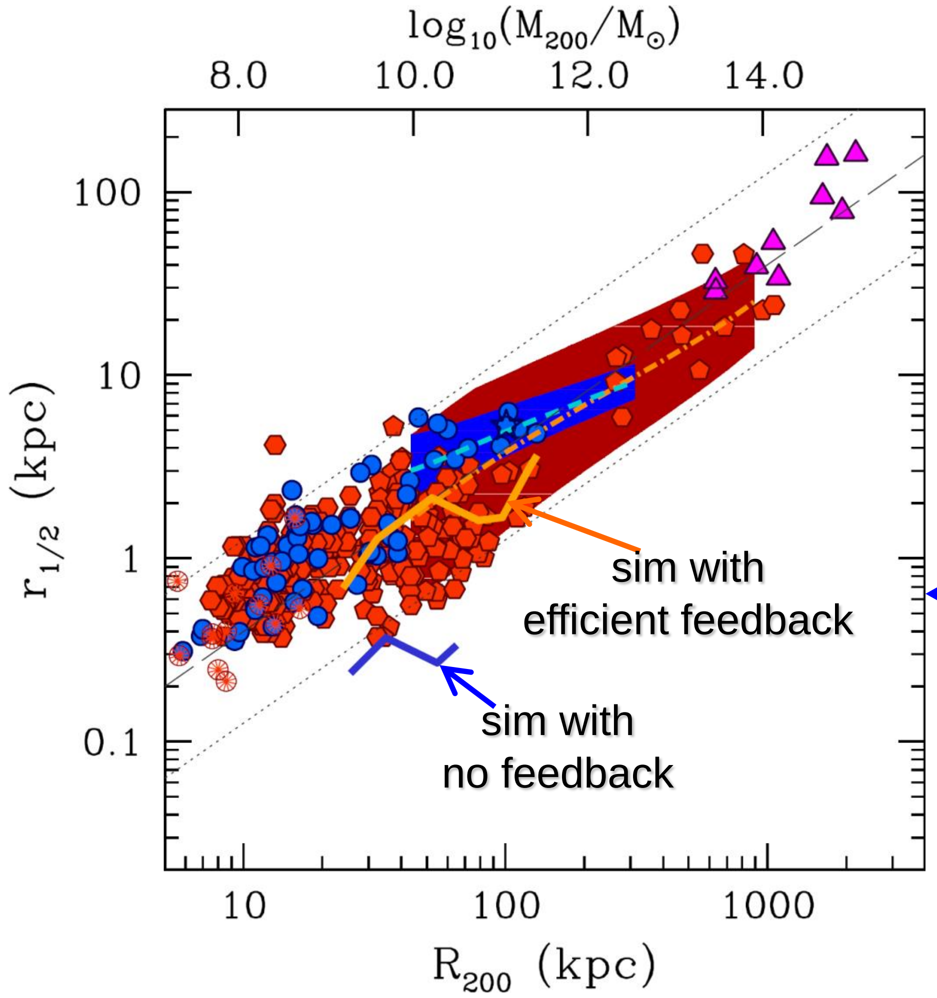
Cold gas and stars in simulated galaxies follow the expected scaling:

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

Sales et al. 2010, MNRAS

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

Size-virial radius relation



sim with
efficient feedback

sim with
no feedback

Galaxy formation simulations show that such linear relation does arise, if stellar feedback is sufficiently efficient (Zavala et al. ‘08; Scannapieco et al. ‘08; Sales et al. ’10)

evolution of $r_{1/2}$-R_{200} relation of the main progenitor of a MW-sized galaxy in galaxy formation simulations (Agertz & Kravtsov, in prep.)

summary

- star formation efficiency in halos is low and requires feedback to explain it

  For high mass halos stellar mass is not as low as previously thought, so less feedback is needed

- Halo properties, such as morphology are sensitive to star formation history and how efficient feedback was at high redshifts

  Early feedback due to winds and radiation pressure along with molecular hydrogen dependence on metallicity help to suppress star formation at high z

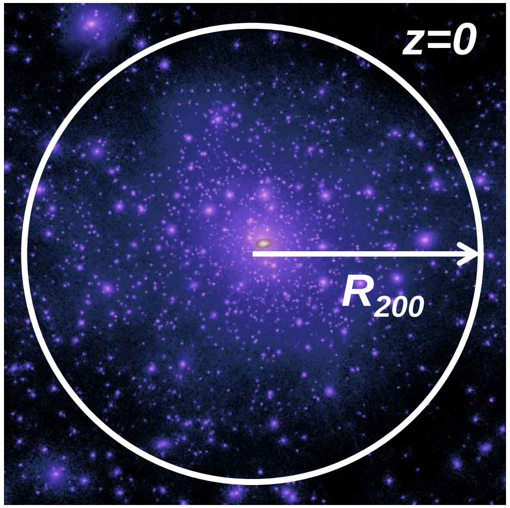
- galaxy sizes scale linearly with halo radius, as expected if they are set largely by the angular momentum baryons acquire during collapse

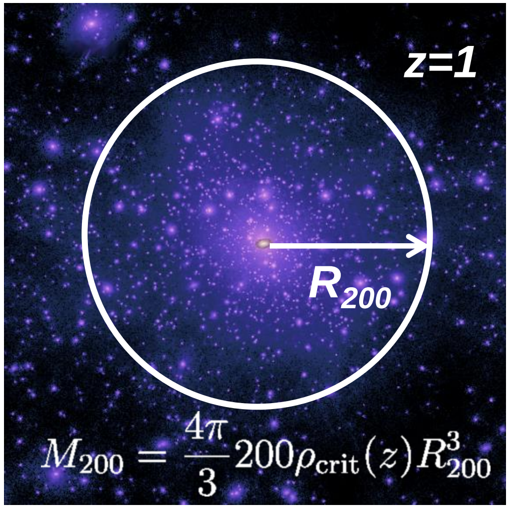
  simulations appear to reproduce this, if feedback is sufficiently efficient in suppressing star formation

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

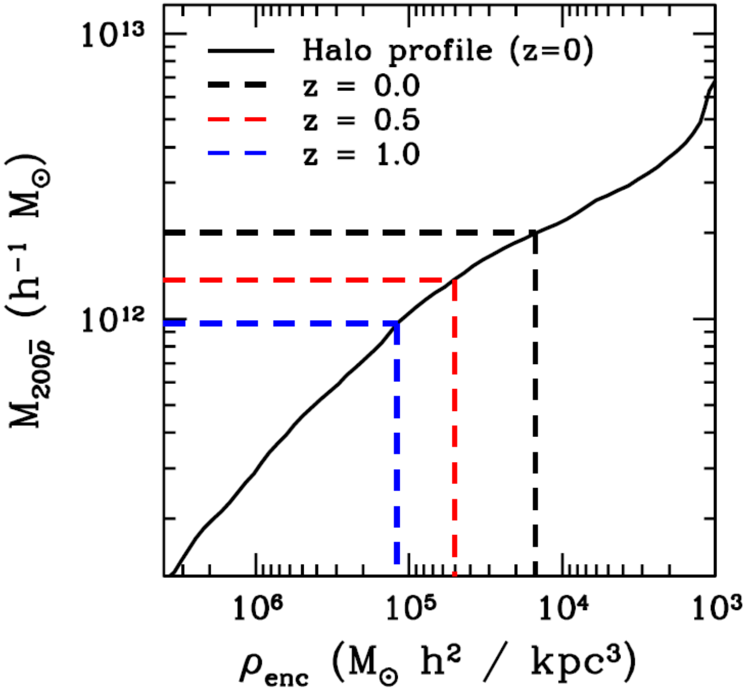
Need to account for pseudo-evolution of R_{200}

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.





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



Diemer et al. 2013, ApJ 766, 25

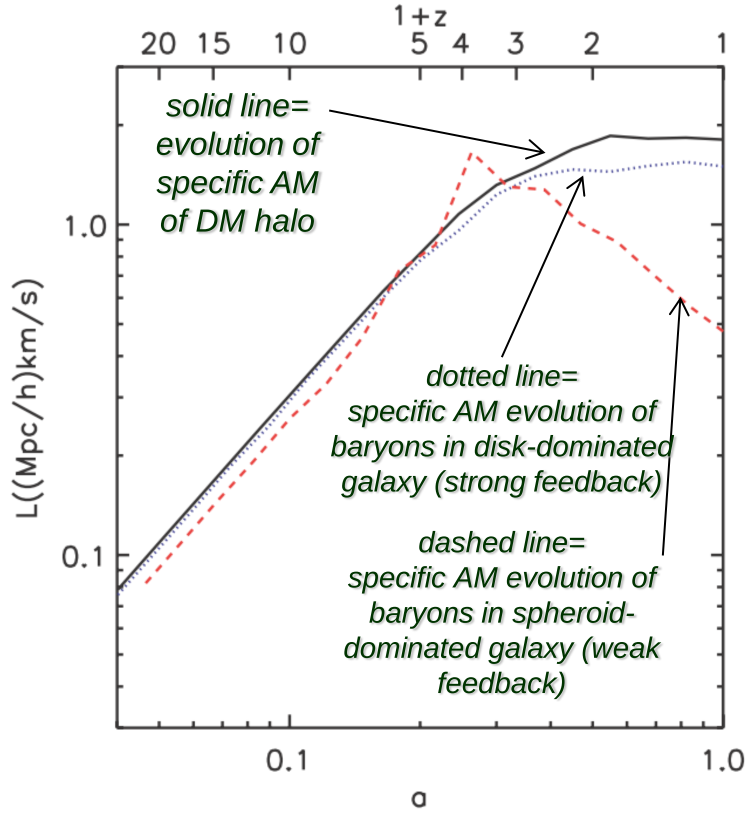
also, Diemand et al. 2007; Cuesta et al. 2008

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

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

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

Zavala et al. 2008, MNRAS

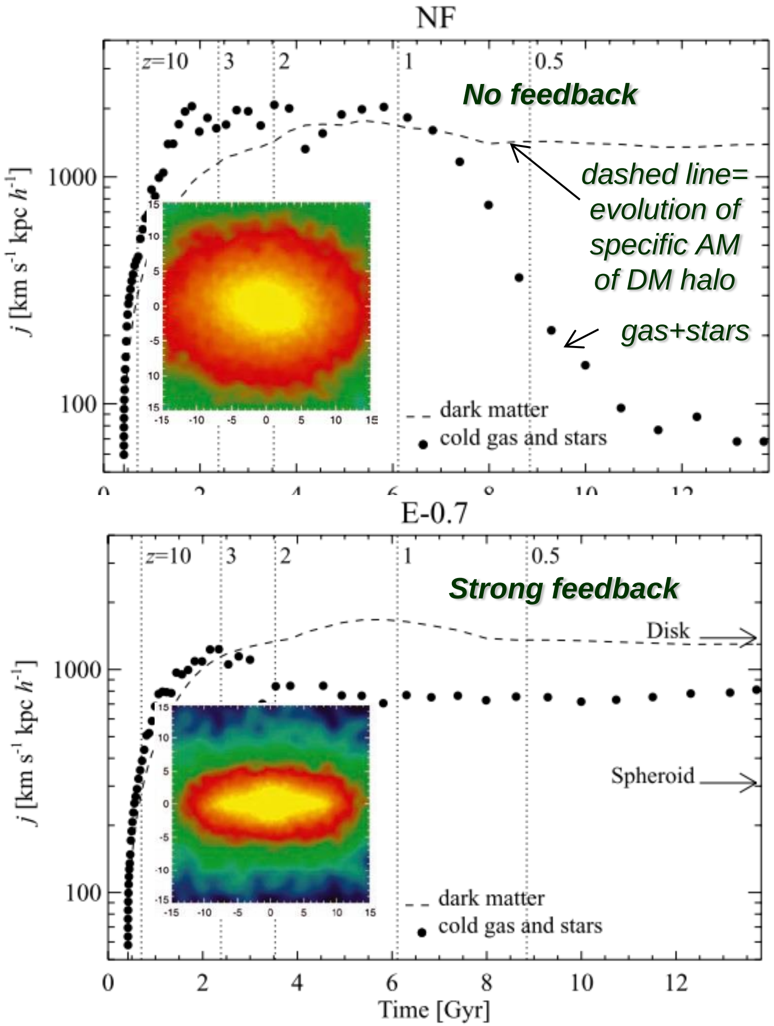


solid line= evolution of specific AM of DM halo

dotted line= specific AM evolution of baryons in disk-dominated galaxy (strong feedback)

dashed line= specific AM evolution of baryons in spheroid-dominated galaxy (weak feedback)

Scannapieco et al. 2008, MNRAS



No feedback

dashed line= evolution of specific AM of DM halo

gas+stars

Strong feedback