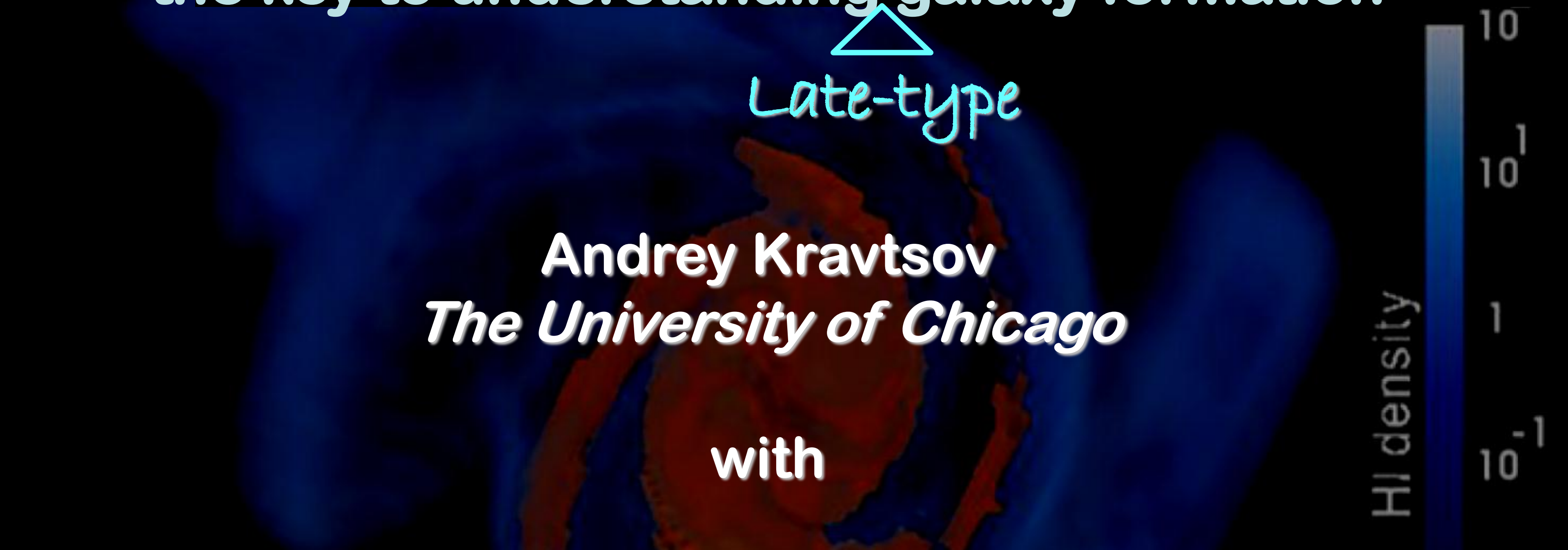
Star formation during the first three billion years: the key to understanding galaxy formation

Late-type



Andrey Kravtsov
The University of Chicago

with

Nick Gnedin
(Fermilab/U.Chicago)

Kostas Tassis
(JPL-> MPIfR)

Oscar Agertz
(KICP, U.Chicago)

Sam Leitner
(KICP, U.Chicago)

Denis Erkal
(U.Chicago)

Robert Feldmann
(Fermilab/KICP)

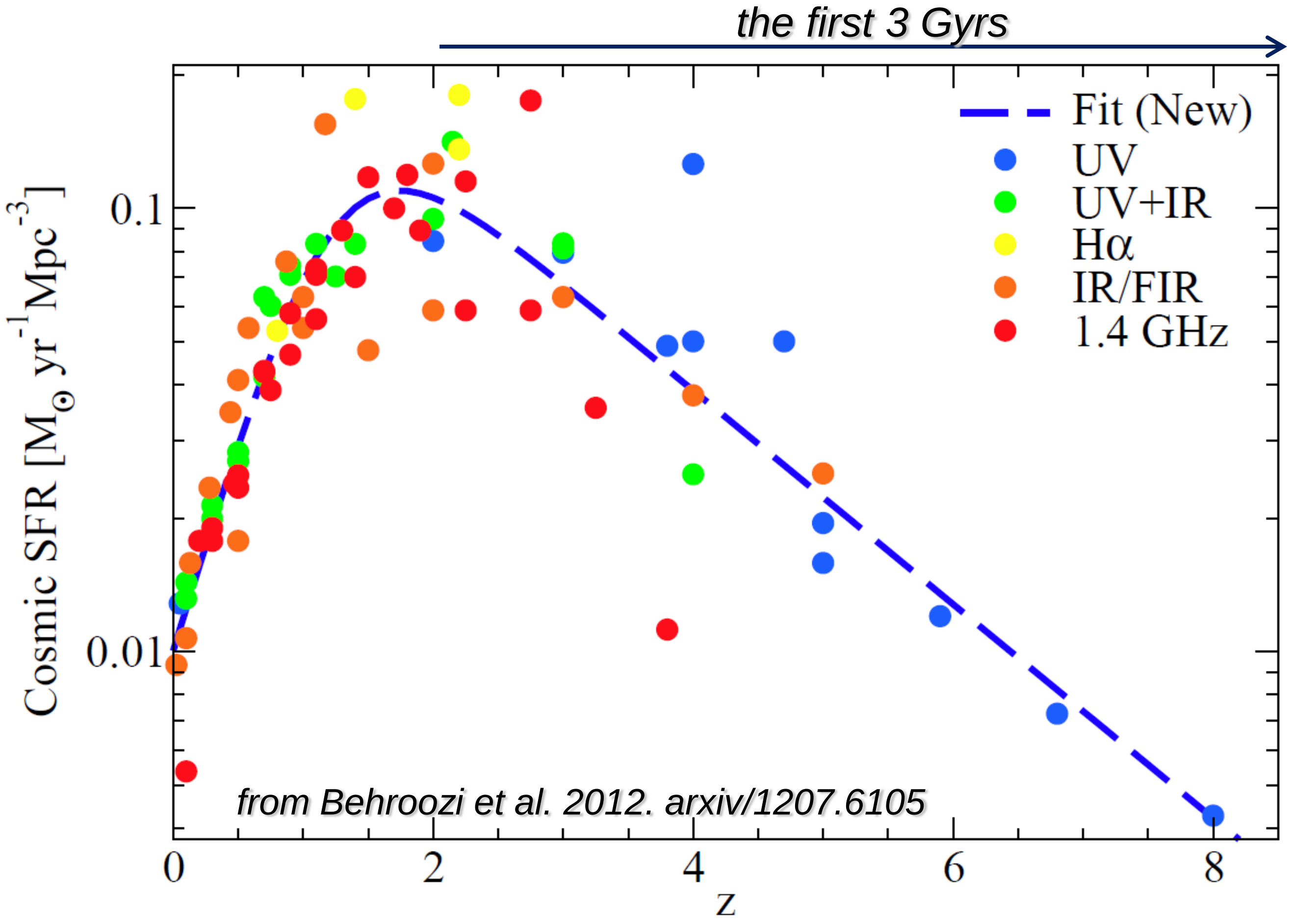
Galactic-scale star formation

observation meets theory

Cosmic-scale star formation

average star formation history in the universe from current observations

"The universe got tenure at z~2" – Hans-Walter Rix



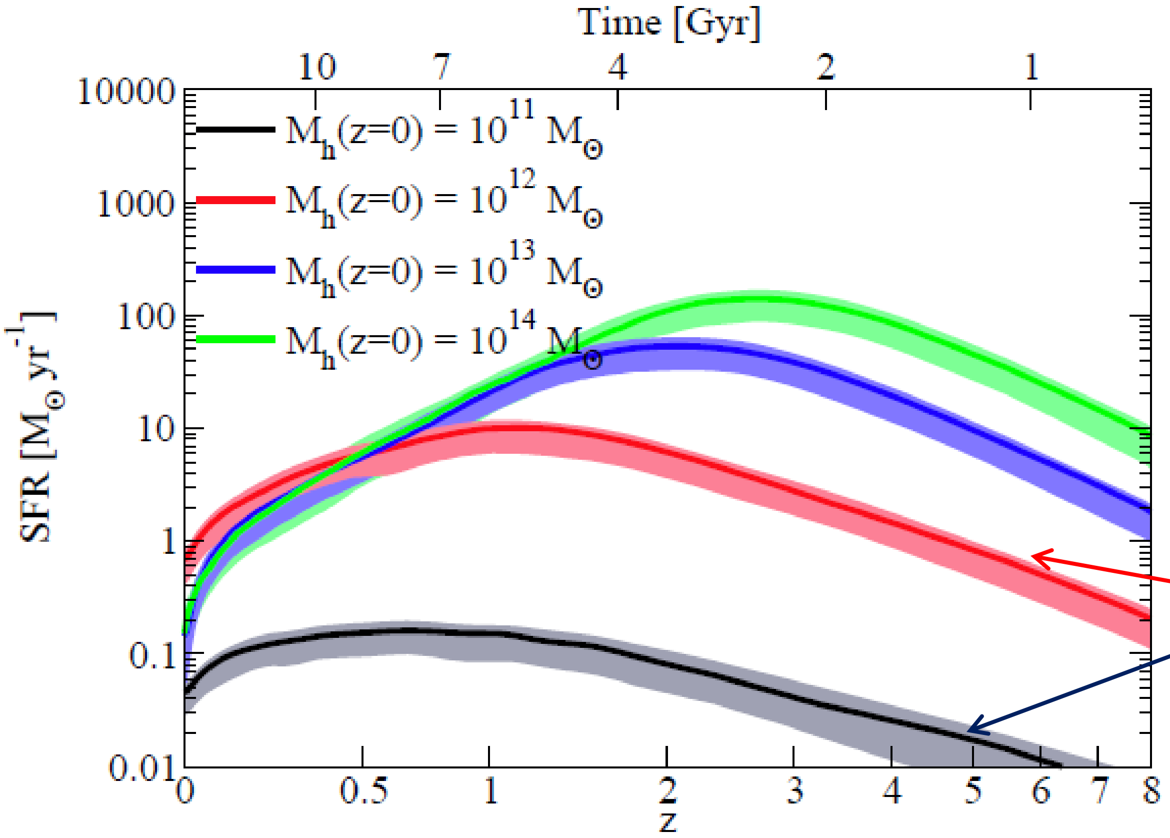
the first 3 Gyrs

from Behroozi et al. 2012. arxiv/1207.6105

However, upon closer examination… only massive galaxies tenured by z~2; late-type progenitors were still in the postdoc mode at that epoch

star formation histories of galaxies in halos of different final mass (at z=0) derived from abundance matching approach

Behroozi et al. arxiv/1207.6105 (cf. also Moster et al., arxiv/1205.5807)



Final stellar mass = integral over star formation history

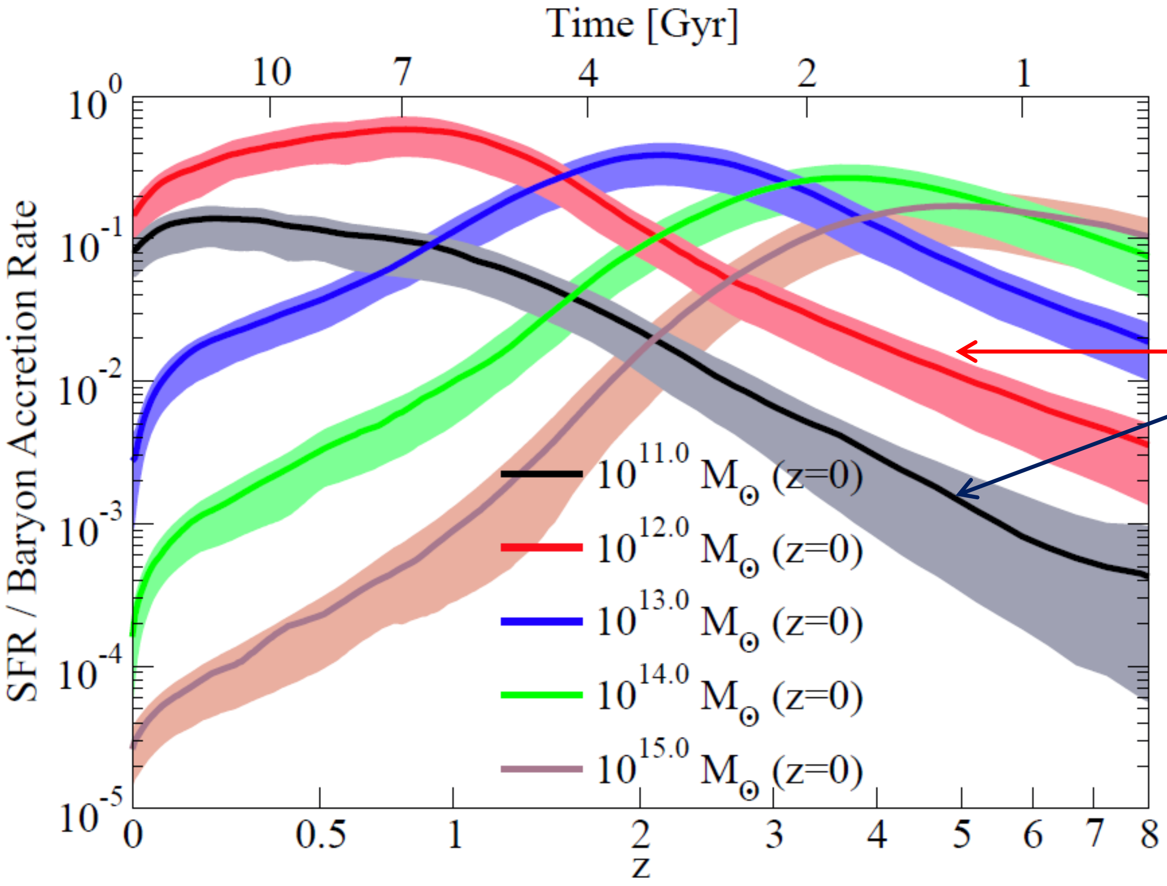
$$M_* = \int \dot{M}_*(t)dt$$

but SFH itself critically matters in setting galaxy properties, such as morphology

low star formation rates are expected in halos of mass <~10^{12} Msun (at z=0)

Star formation rate relative to baryon accretion rate of galaxy progenitors

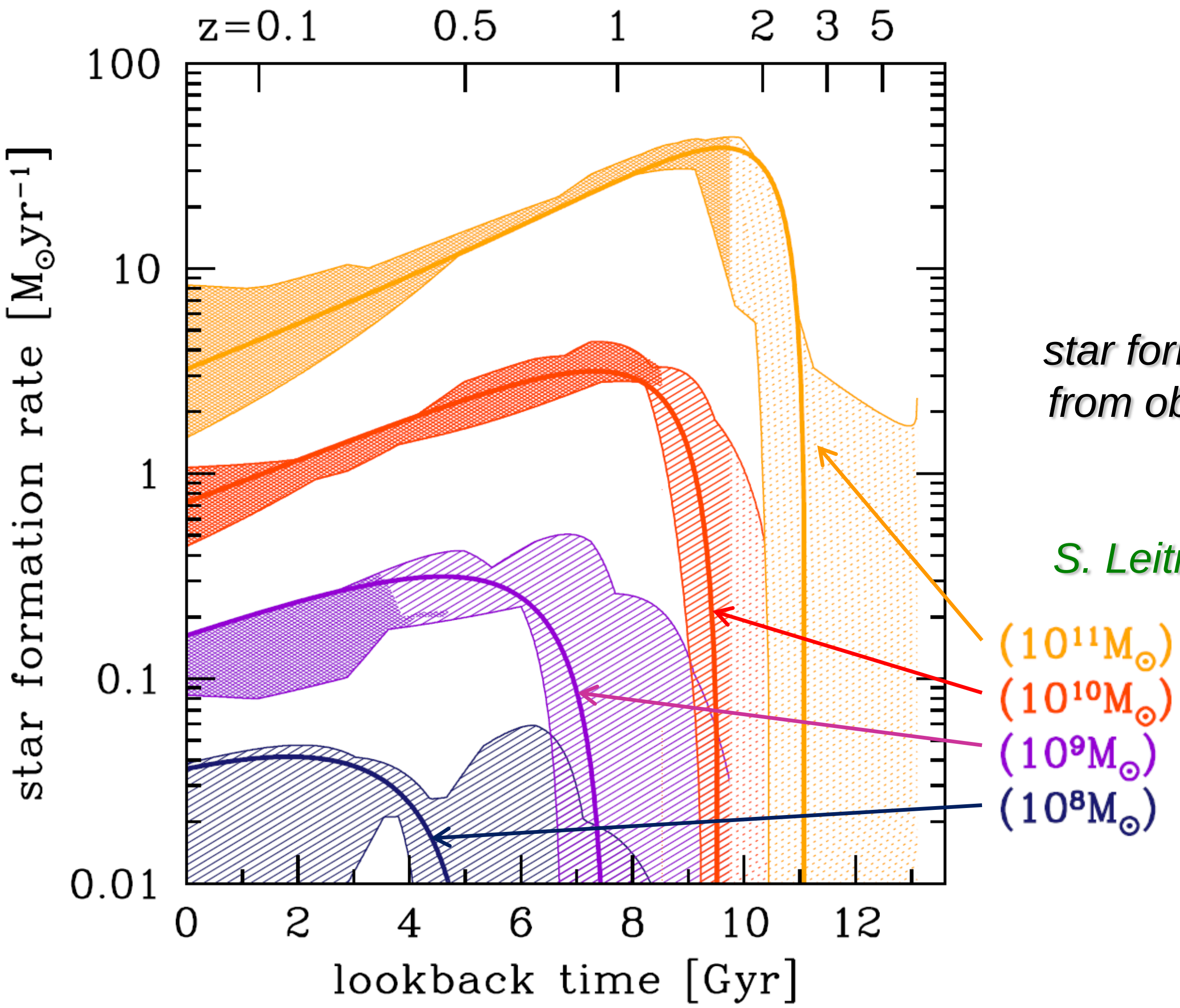
Galaxies forming in small mass halos convert only a small fraction of accreted gas mass into stars -> star formation at high z in such objects should be very inefficient (level of suppression comparable to early type galaxies at z~0)



low star formation rates are expected in halos of mass <~10^{12} Msun (at z=0)

Behroozi et al. 2012 arxiv/1207.6105

Observations indicate that spiral galaxies at low z form >80% of their stars at z<2



Sam Leitner
(U.Chicago)

star formation histories derived from observed evolution of the SFR-M relation*

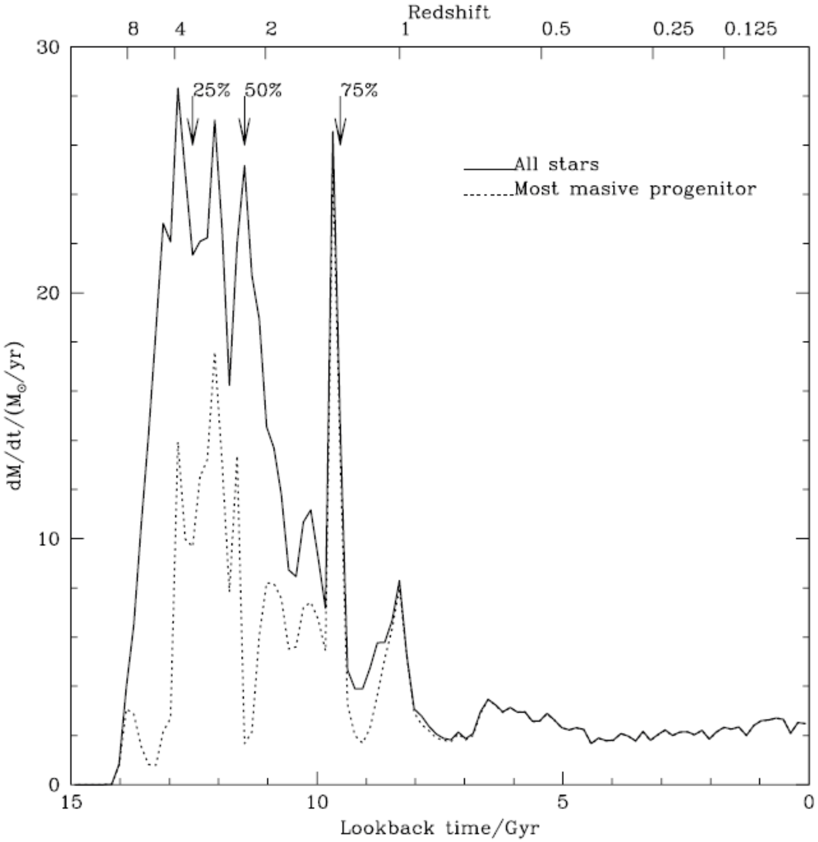
S. Leitner 2012, ApJ 745, 149

final (z=0) stellar masses of galaxies

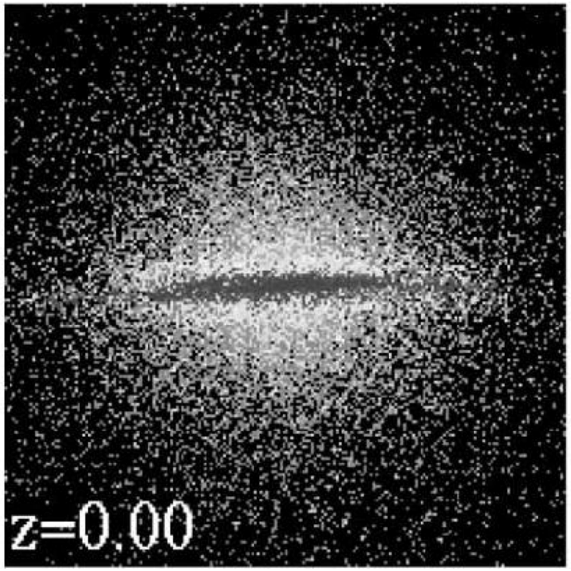
Star formation histories of galaxies in cosmological simulations typically exhibit high star formation rates at high z

this is the main reason galaxy formation simulations tend to produce mostly early-type like galaxies with massive spheroids

Star formation rate



lookback time in Gyrs



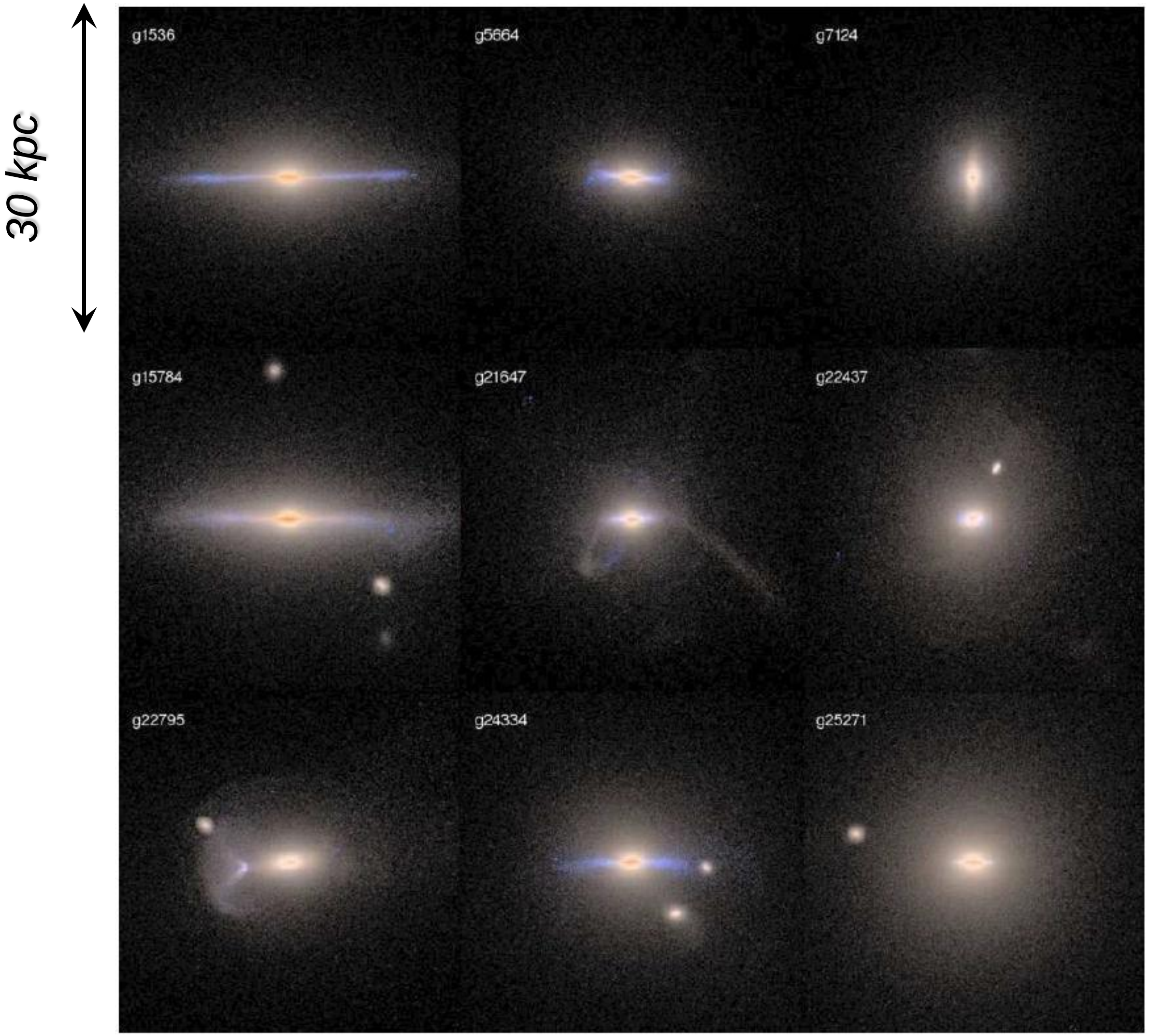
Abadi et al. 2003, ApJ 591, 499

Most of L<L* galaxies look like this...


NGC 253

composite R, G, B image
S. Mazlin et al.
Star Shadows Remote Observatory/PROMPT
CTIO

http://www.starshadows.com/gallery/display.cfm?imgID=319

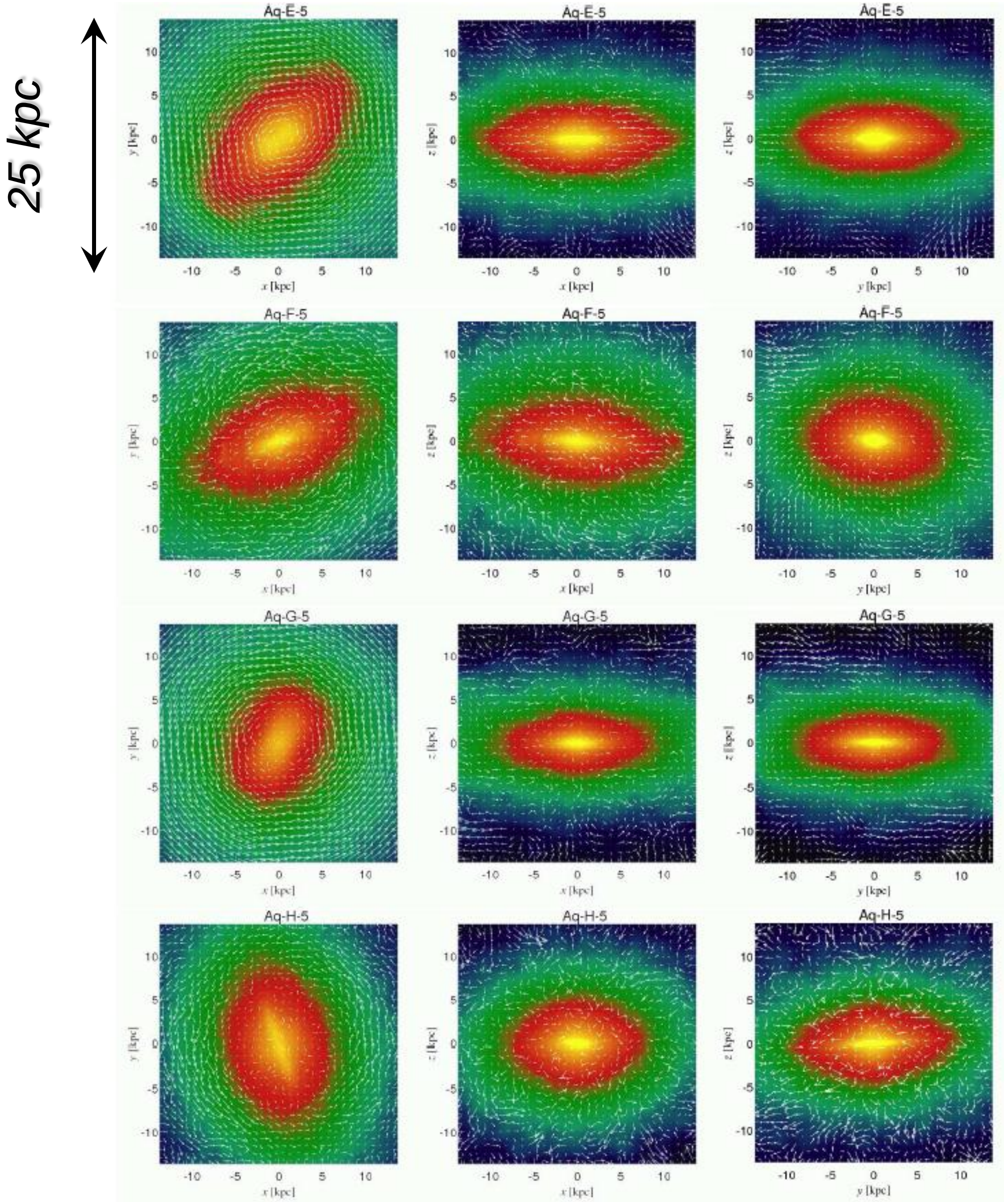


:

Stinson et al. 2010
MNRAS 408, 812
arXiv/1004.0675

projected stellar density for 9 different simulated galaxies of different stellar masses

color of stellar particles indicates their age (blue=young; reddish=old)

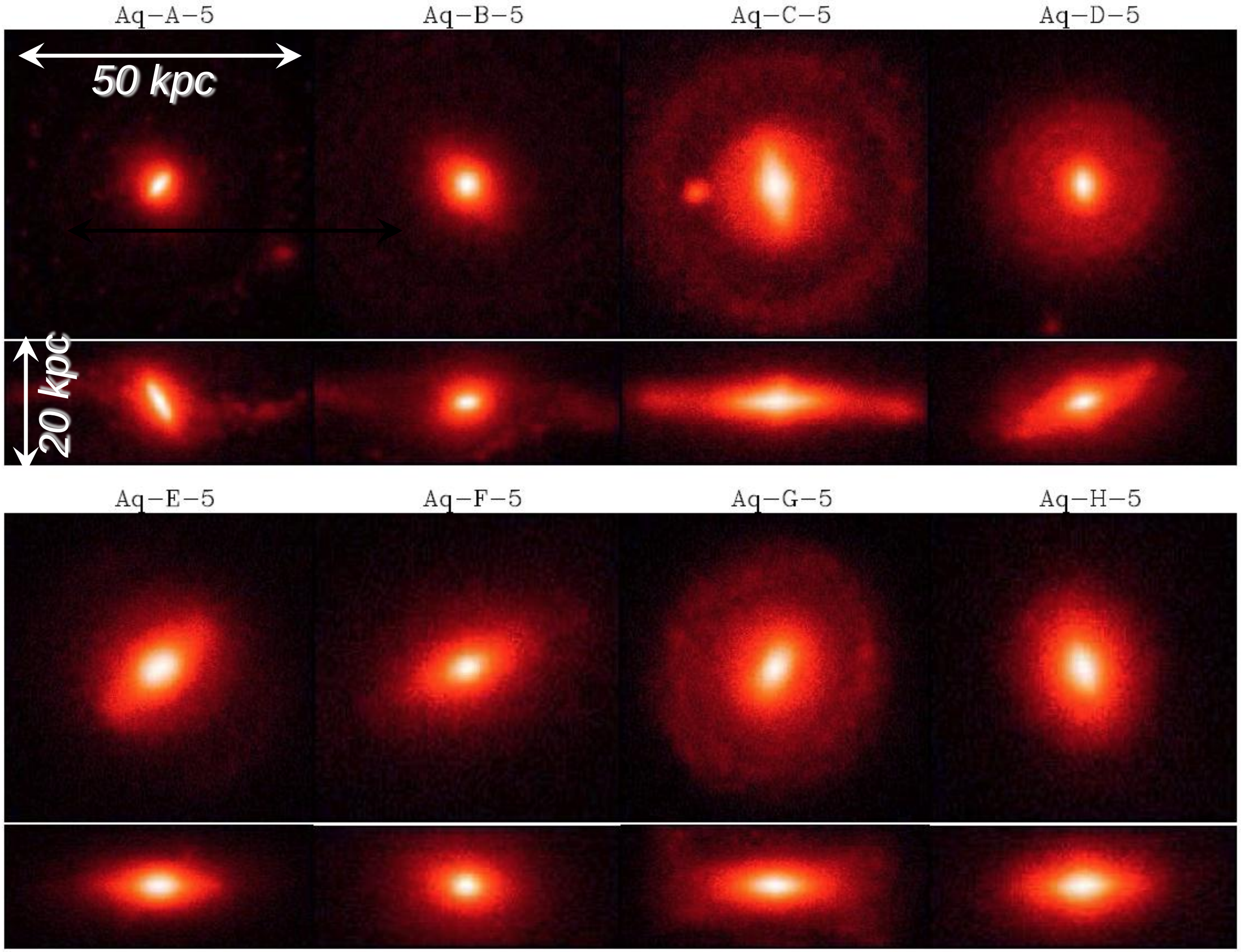


:

Scannapieco et al. 2009
MNRAS 396, 696

projected stellar density In three projections (rows) of four MW-sized simulated galaxies (columns)

the stars in the simulated galaxies are kinematically hot, which is reflected in prominent central spheroidal component and thick disk



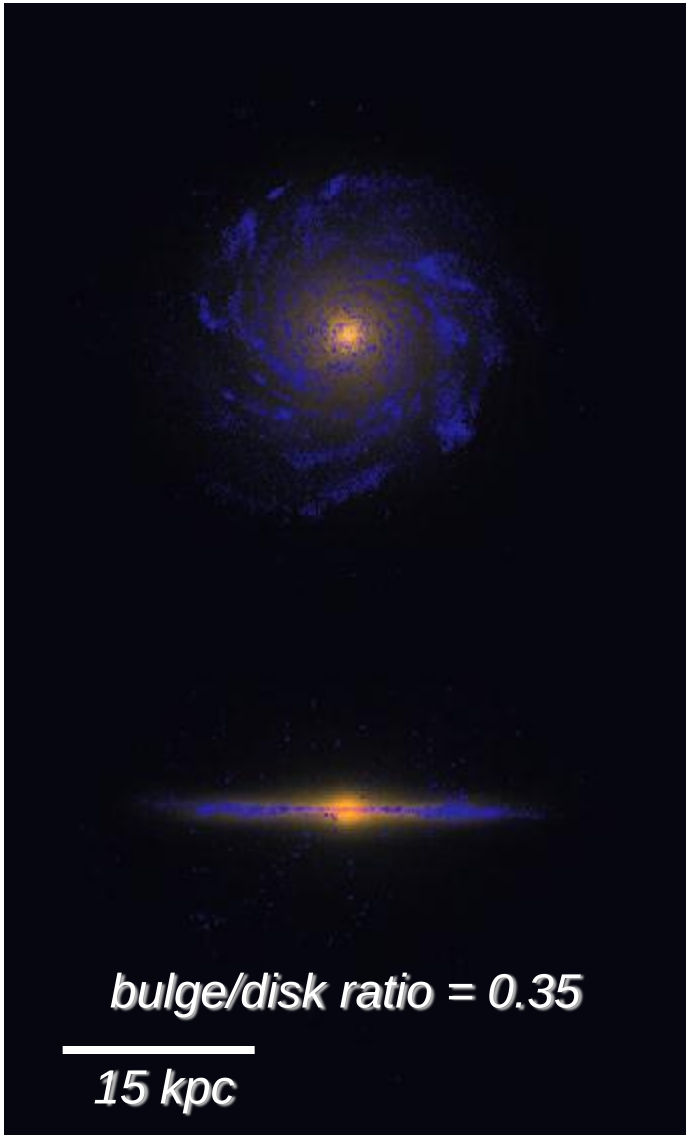
re-simulation of the Aquarius MW-sized halos

Scannapieco et al. 2011 MNRAS 417, 154

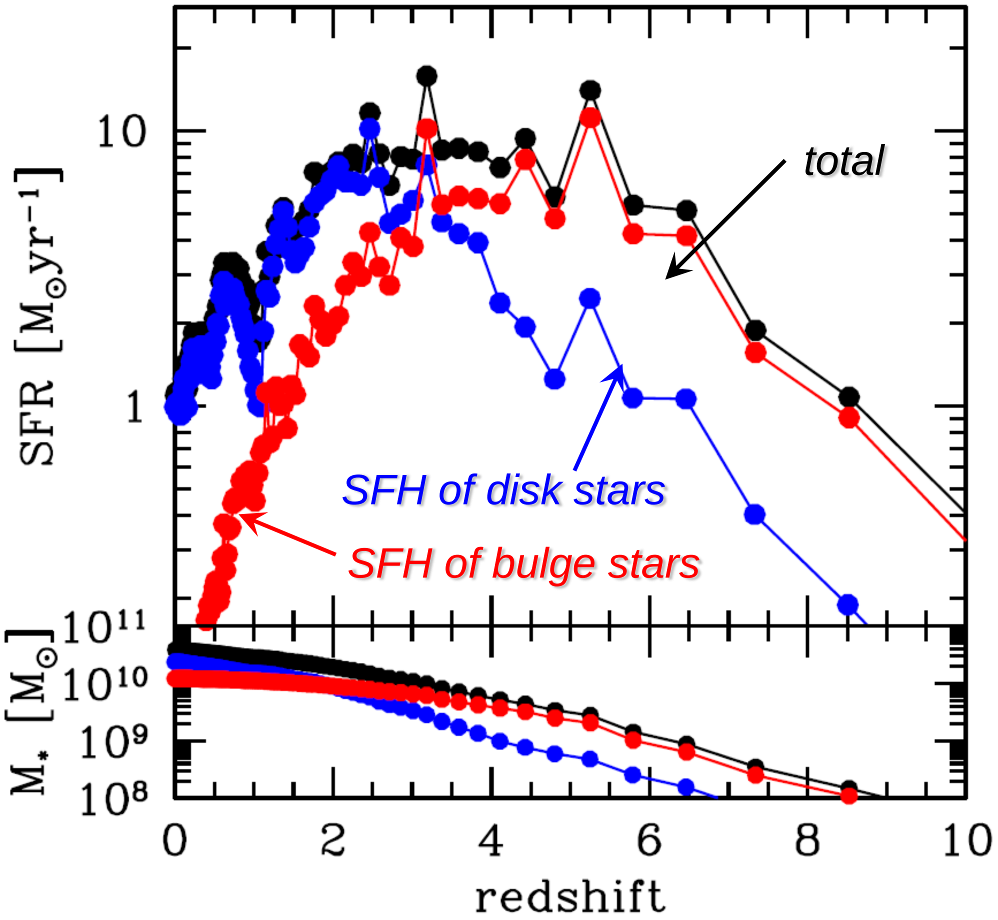
projected stellar surface density in i-band for 8 simulated galaxies (face-on and edge-on)

Fairly realistic MW-like galaxy produced in the Eris simulation

Guedes et al. 2011, ApJ 742, 76



Spheroidal component is largely built from stars formed at $z>2$

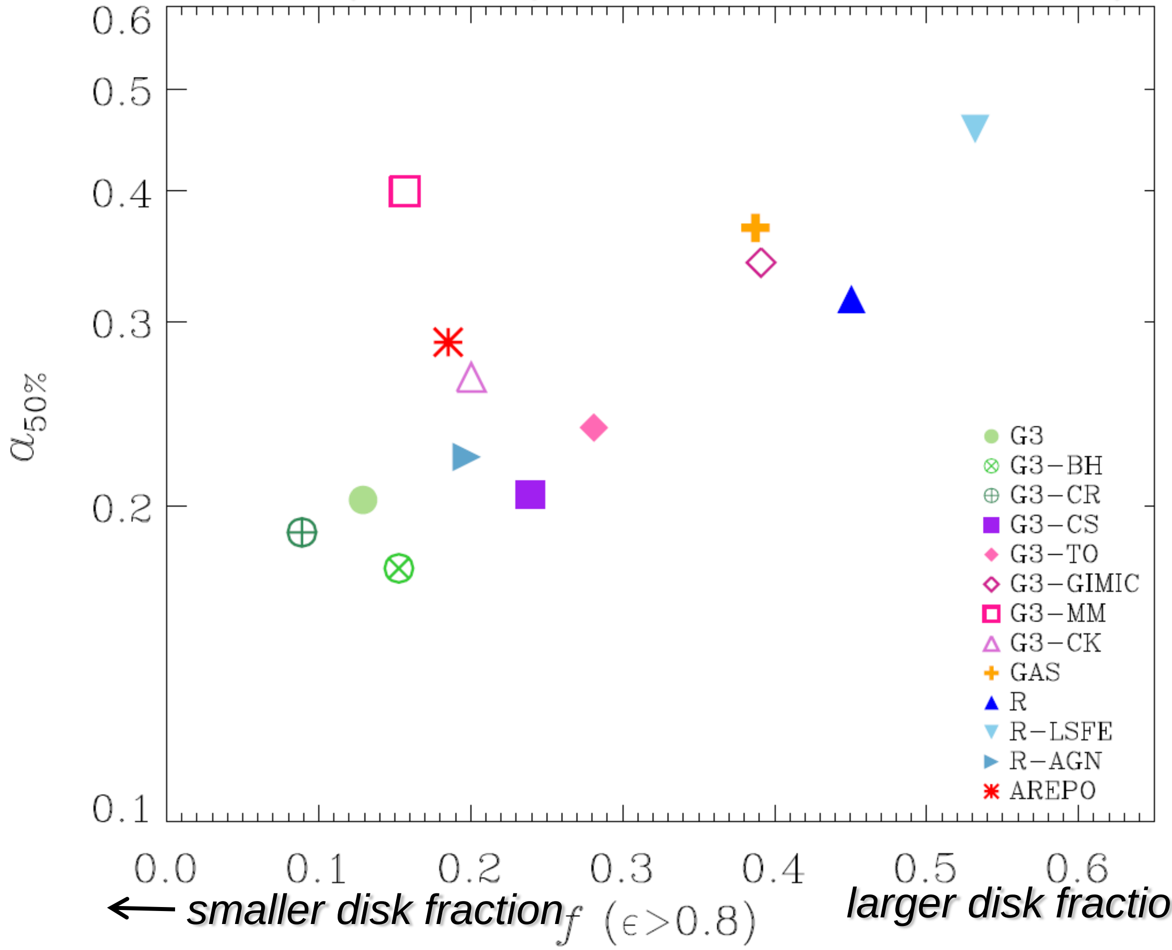


There is a distinct correlation between amount of early star formation and fraction of stars that end up in the disk

→ formation of "bulgeless" galaxies requires very inefficient star formation at $z>2$

comparison of galaxy formation simulations ("The Aquila project")

(C. Scannapieco et al. 2012, MNRAS 423, 726)



Expansion factor at which 50% of stars were formed

← smaller disk fraction

larger disk fraction →

fraction of stars in disk in simulated galaxy at z=0

Star formation at high z may be less efficient because galaxies have lower metallicities (and less dust) and higher interstellar FUV fluxes (smaller fraction of gas is shielded from FUV radiation)

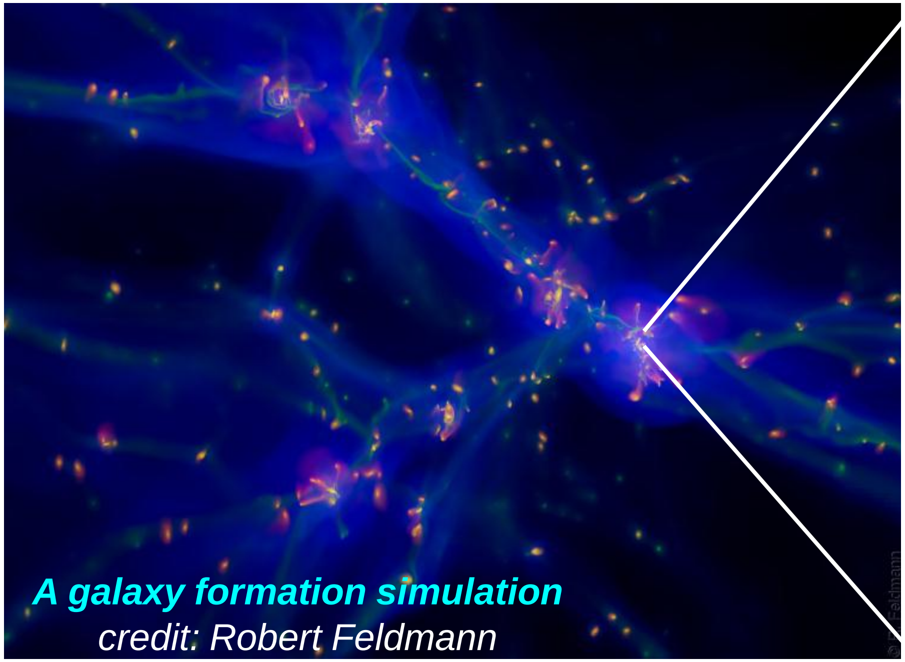
$$M_* = \int \dot{M}_*(t)\,dt \qquad\qquad \dot{M}_* = \int_{\mathrm{A_{disk}}} \dot{\Sigma}_* \, dA$$

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

↑

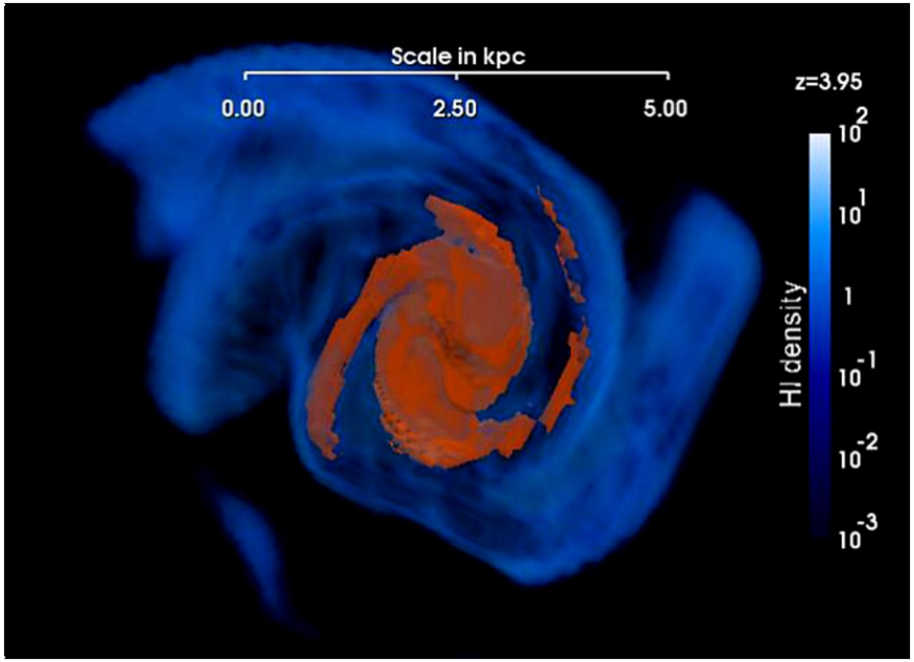
Kennicutt-Schmidt relation

Can we modulate star formation history simply by modulating gas consumption time scale? (i.e, without modifying Σgas)



A galaxy formation simulation

credit: Robert Feldmann



Gas consumption time is large in low-surface density and low-metallicity environments

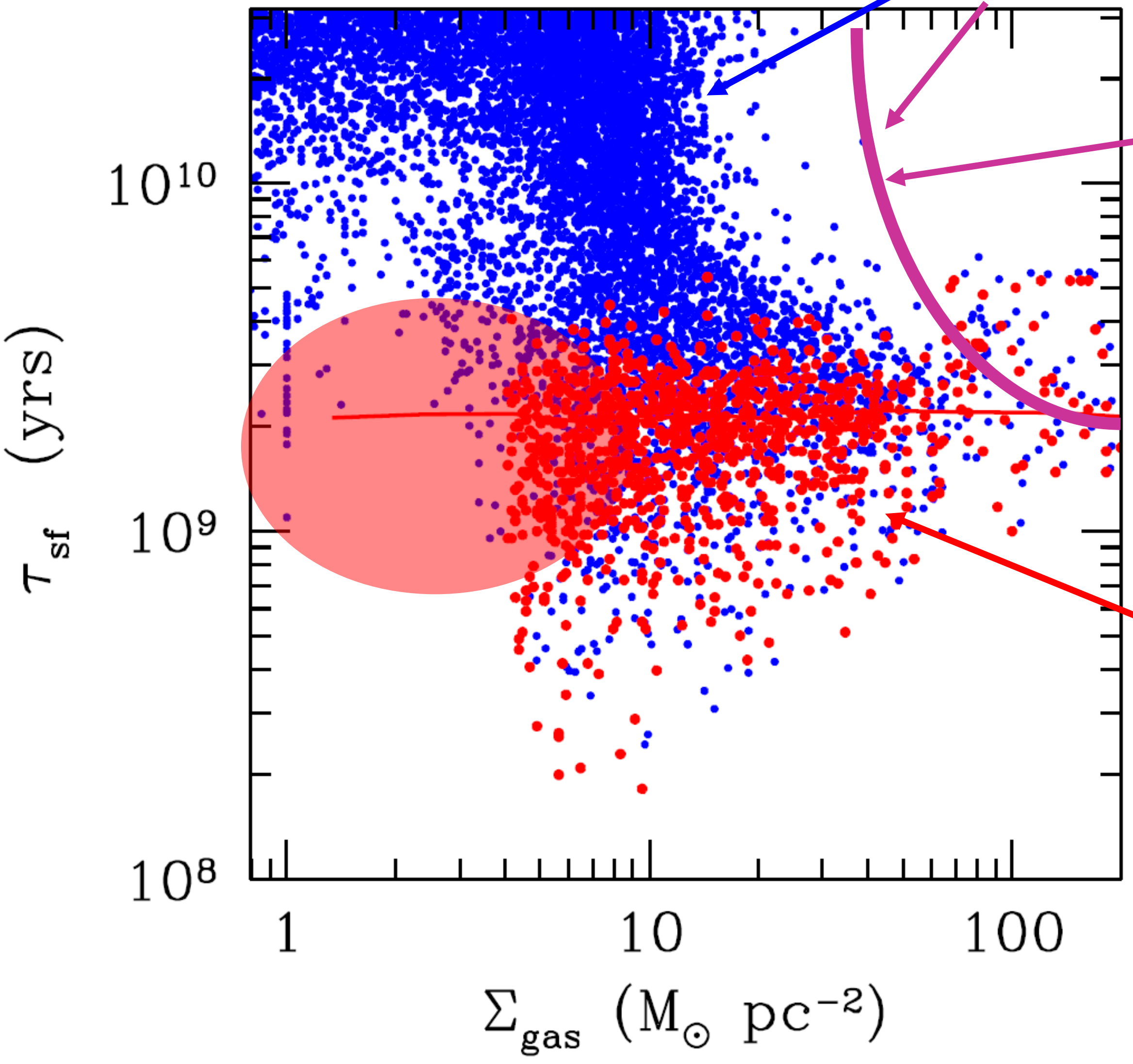
blue = *local galaxies*

Biegel et al. 2008, 2011

$$\tau_{\rm sf} = \frac{\Sigma_{\rm gas}}{\dot{\Sigma}_*}$$

Depletion time

(just another way of plotting the KS relation)



magenta = *low metallicity galaxies (high-z LBGs, DLAs, SMC)*

Wolfe & Chen '06
Rafelski et al '11
Bolatto et al. '11

red =

$$\tau_{\rm sf,H_2} = \frac{\Sigma_{\rm H_2}}{\dot{\Sigma}_*}$$

Bigiel et al '08, '11
Genzel et al. '10
Schruba et al. '12

Environmental dependence of star formation

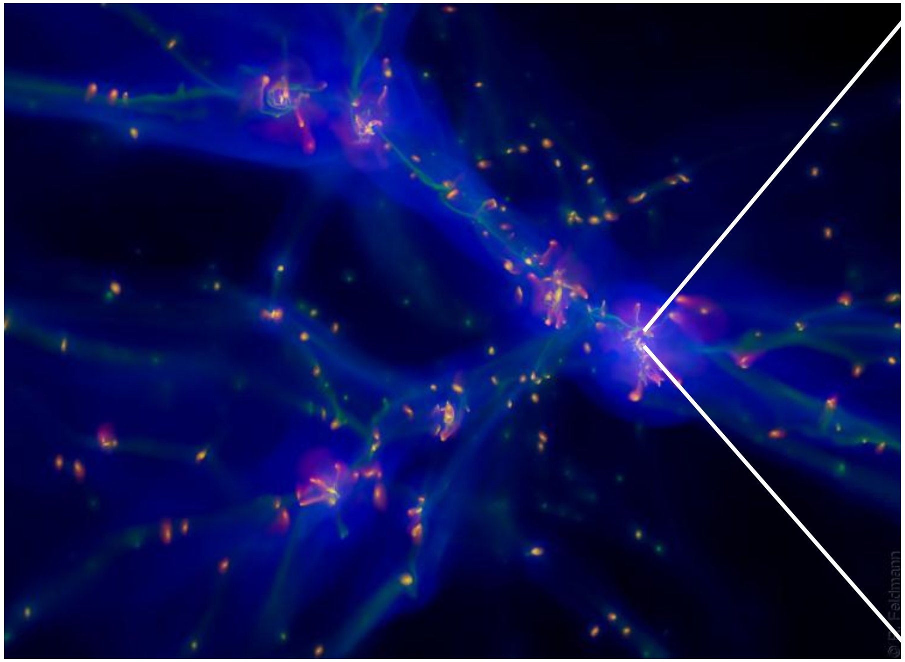
$$M_* = \int \dot{M}_*(t)\,dt \qquad \dot{M}_* = \int_{\mathrm{A_{disk}}} \dot{\Sigma}_*\,dA \quad = \int_{\mathrm{A_{disk}}} f_{\mathrm{H_2}}(\Sigma_{\mathrm{gas}})\,\frac{\Sigma_{\mathrm{gas}}}{\tau_{\mathrm{sf,H_2}}}\,dA$$

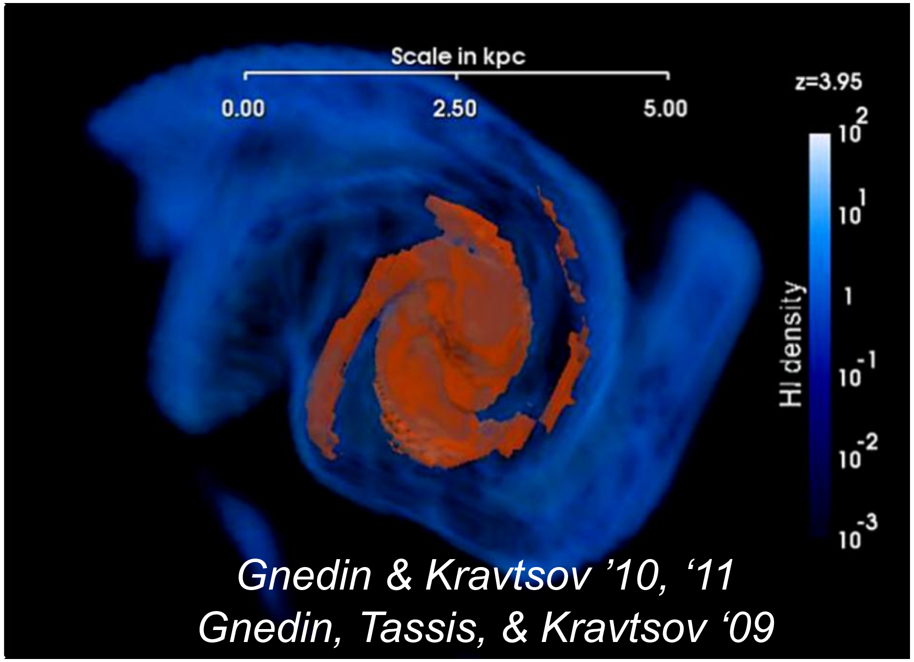
$$\uparrow$$

$$\dot{\Sigma}_* = \frac{\Sigma_{\mathrm{gas}}}{\tau_{\mathrm{sf}}} = \frac{\Sigma_{\mathrm{H_2}}}{\tau_{\mathrm{sf,H_2}}} = f_{\mathrm{H_2}}(\Sigma_{\mathrm{gas}})\,\frac{\Sigma_{\mathrm{gas}}}{\tau_{\mathrm{sf,H_2}}}$$

$$f_{\mathrm{H_2}} = f(Z, J_{\mathrm{UV}}, \Sigma_{\mathrm{gas}}, \ldots)$$

e.g., Elmegreen '93
Schaye '01

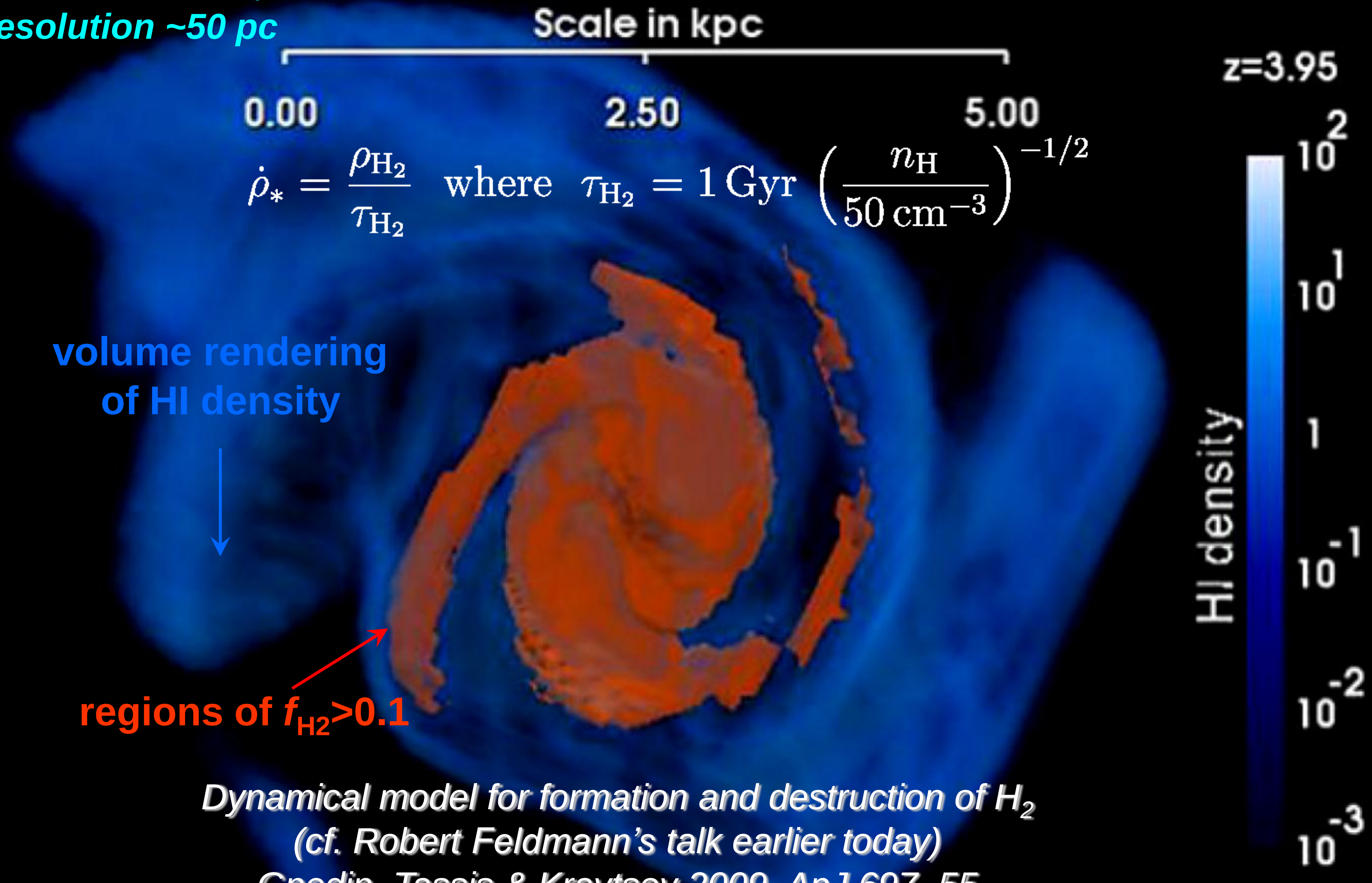




Gnedin & Kravtsov '10, '11
Gnedin, Tassis, & Kravtsov '09

ART simulation, resolution ~50 pc

$$\dot{\rho}_* = \frac{\rho_{H_2}}{\tau_{H_2}} \quad \text{where} \quad \tau_{H_2} = 1\,\mathrm{Gyr}\left(\frac{n_H}{50\,\mathrm{cm}^{-3}}\right)^{-1/2}$$



volume rendering of HI density

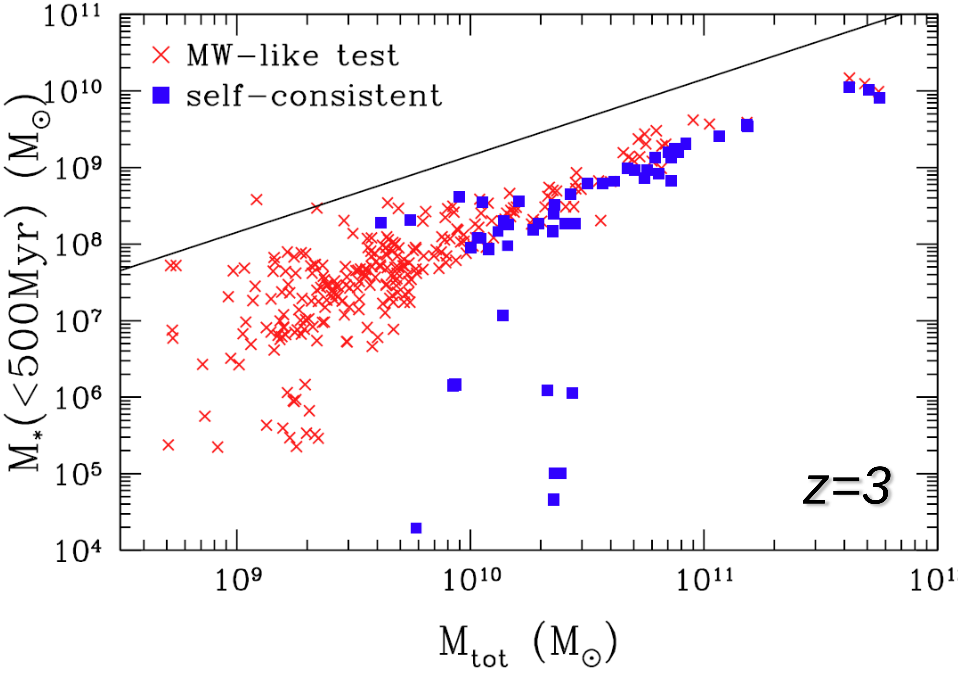
regions of f_{H2}>0.1

Dynamical model for formation and destruction of H_2
(cf. Robert Feldmann's talk earlier today)
Gnedin, Tassis & Kravtsov 2009, ApJ 697, 55
Gnedin & Kravtsov 2011, ApJ 728, 88
Gnedin & Kravtsov 2010, ApJ 714, 287

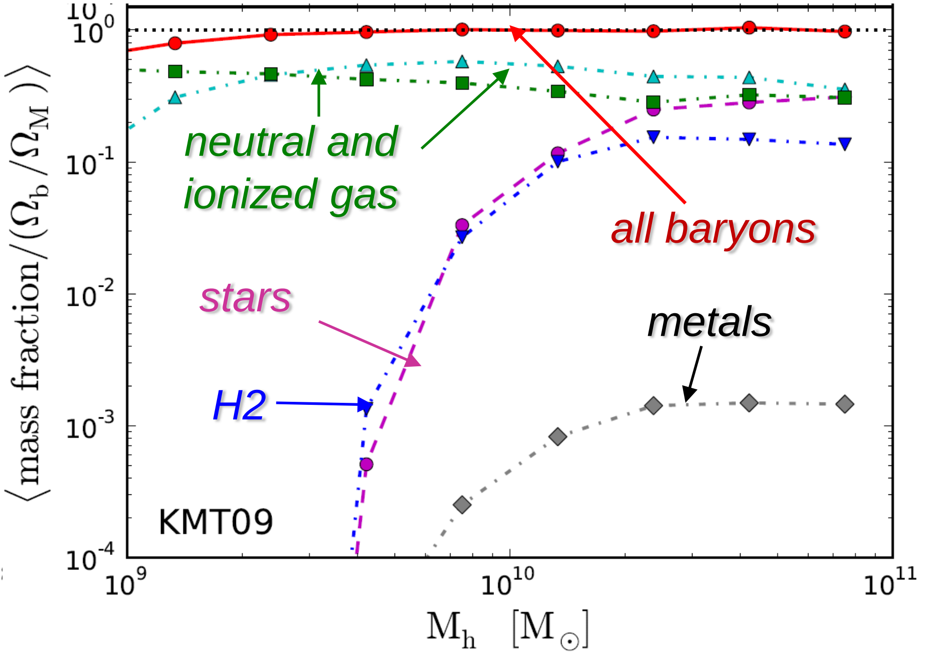
inefficiency of gas conversion into stars in low-metallicity, high-redshift small-mass galaxies

→ *suppresses star formation in halos of $M_h < 10^{10}$ Msun at high z*

Gnedin & Kravtsov 2010, ApJ 714, 287



Kuhlen et al. 2011 arXiv/1105.2376

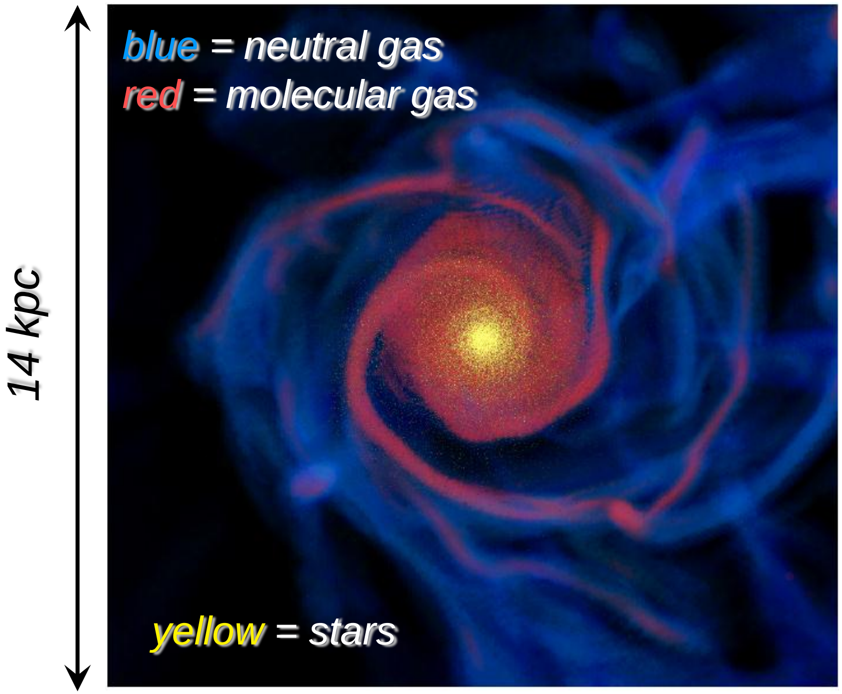


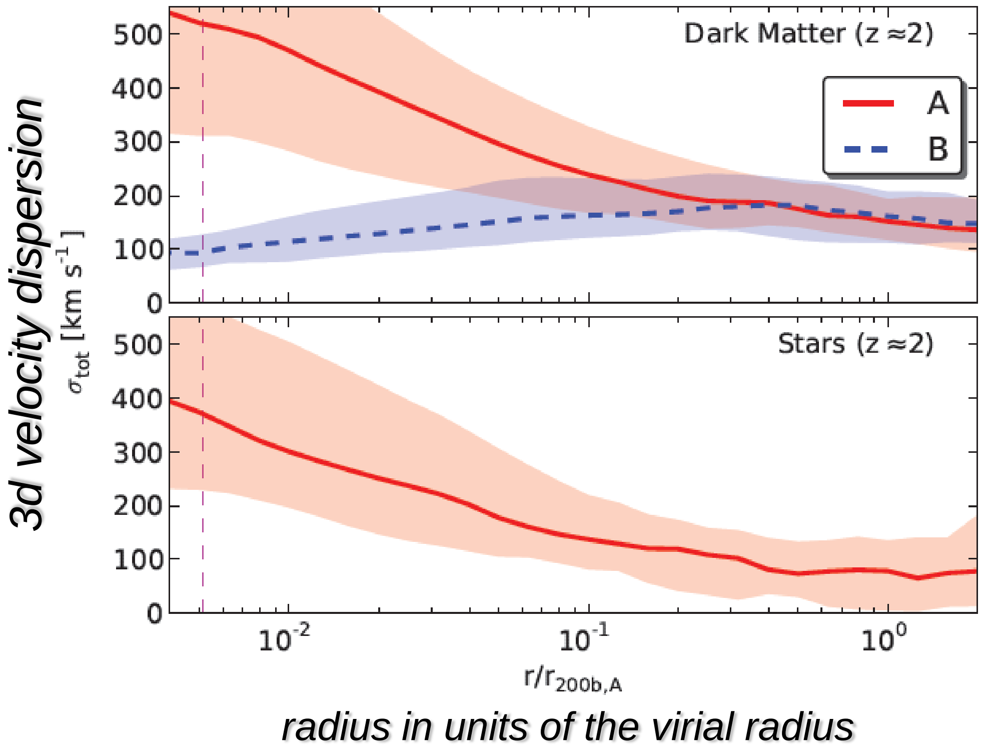
Inefficient star formation by itself will not solve problems such as baryon concentration problem

(baryon distribution is too concentrated towards the center)

ART code simulations of a MW-sized object with peak resolution of 80 pc (physical) within the disk, molecular hydrogen chemistry and 3d radiative transfer

Zemp, O. Gnedin, N. Gnedin, Kravtsov 2012, ApJ 748, 54



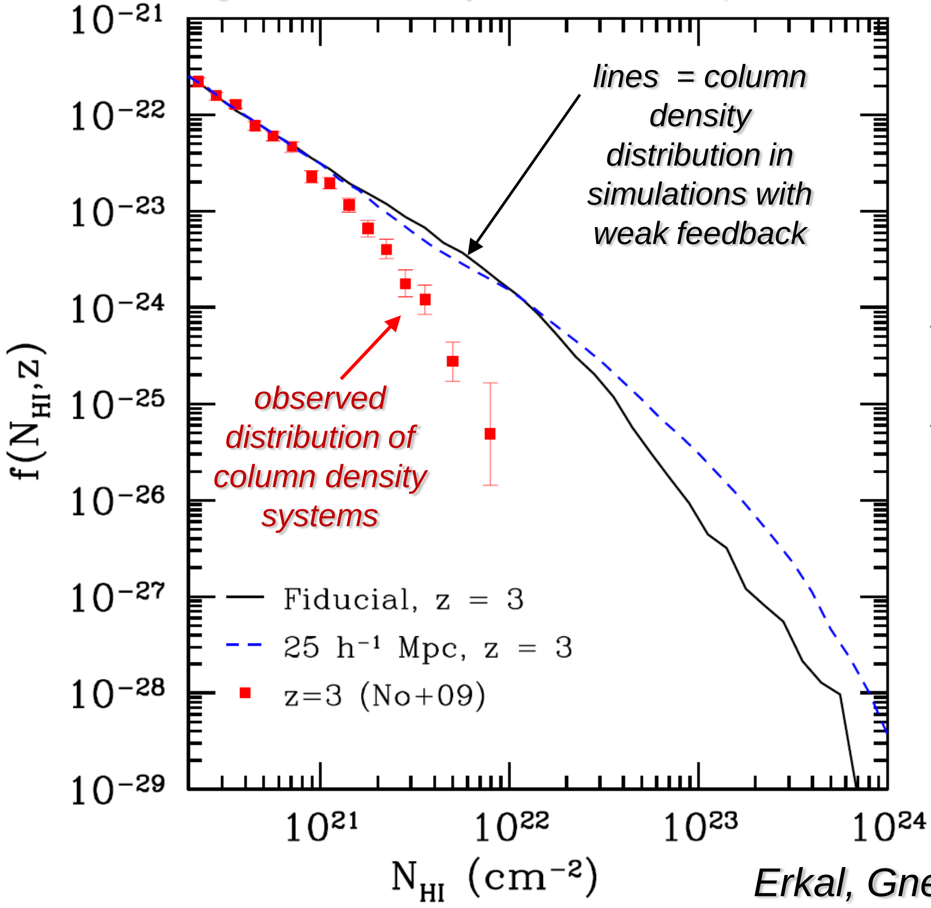


Our simulations fail to reproduce the high column density tail of the DLA NHI distribution

- even though they include H_2 physics, radiative transfer, etc.
- The culprit is the dense central concentration of gas in gaseous disks (ubiquitous in simulations with inefficient feedback)

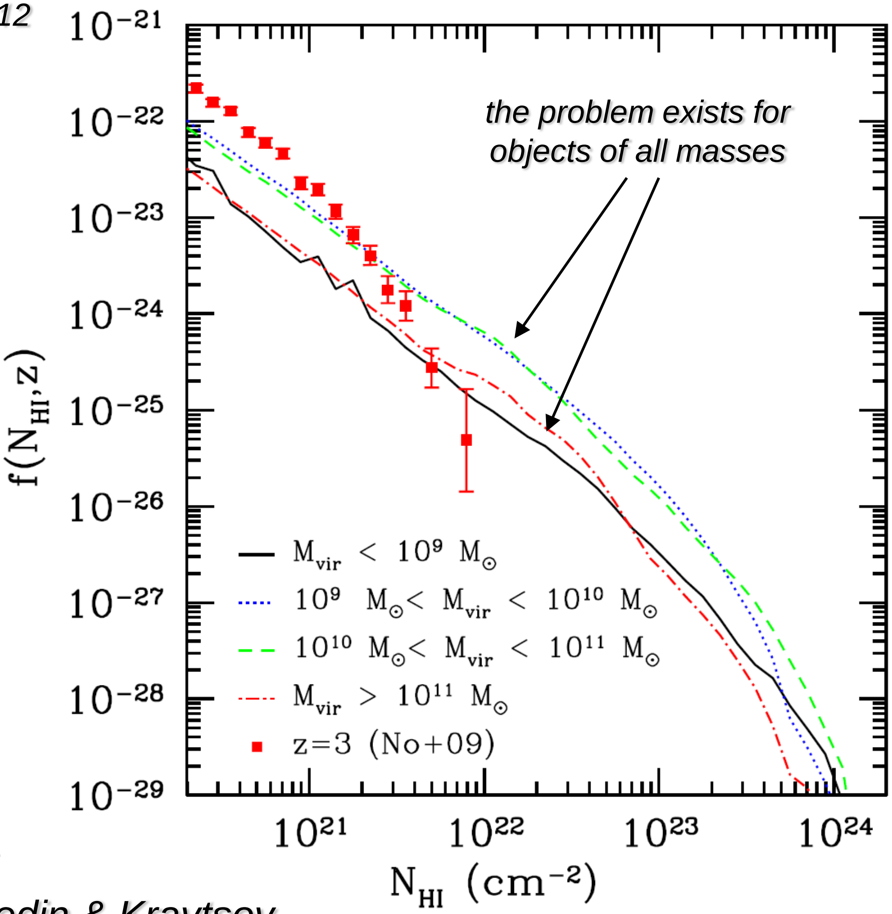
e.g., Hummels & Bryan 2012; Scannapieco et al. 2012

Denis Erkal
(U.Chicago)



lines = column density distribution in simulations with weak feedback

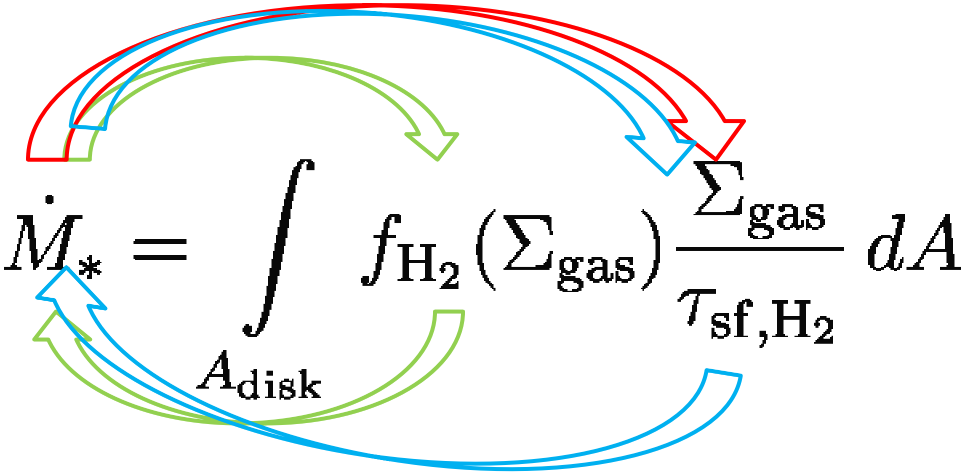
observed distribution of column density systems



the problem exists for objects of all masses

Erkal, Gnedin & Kravtsov
2012, ApJ submitted (arXiv/1201.3653)

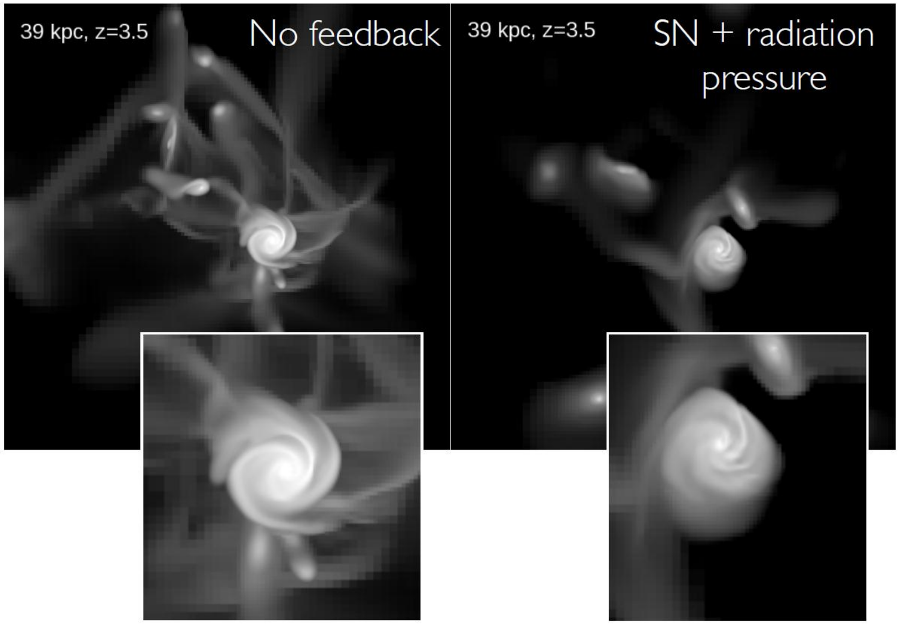
Need to model the star formation-feedback loop fully and correctly



$$\dot{M}_* = \int_{A_{\mathrm{disk}}} f_{\mathrm{H}_2}(\Sigma_{\mathrm{gas}}) \frac{\Sigma_{\mathrm{gas}}}{\tau_{\mathrm{sf},\mathrm{H}_2}} \, dA$$

In addition to correctly modelling gas consumption time scale, we need to model structure of gaseous disk (Σgas), which is very likely modified by feedback.

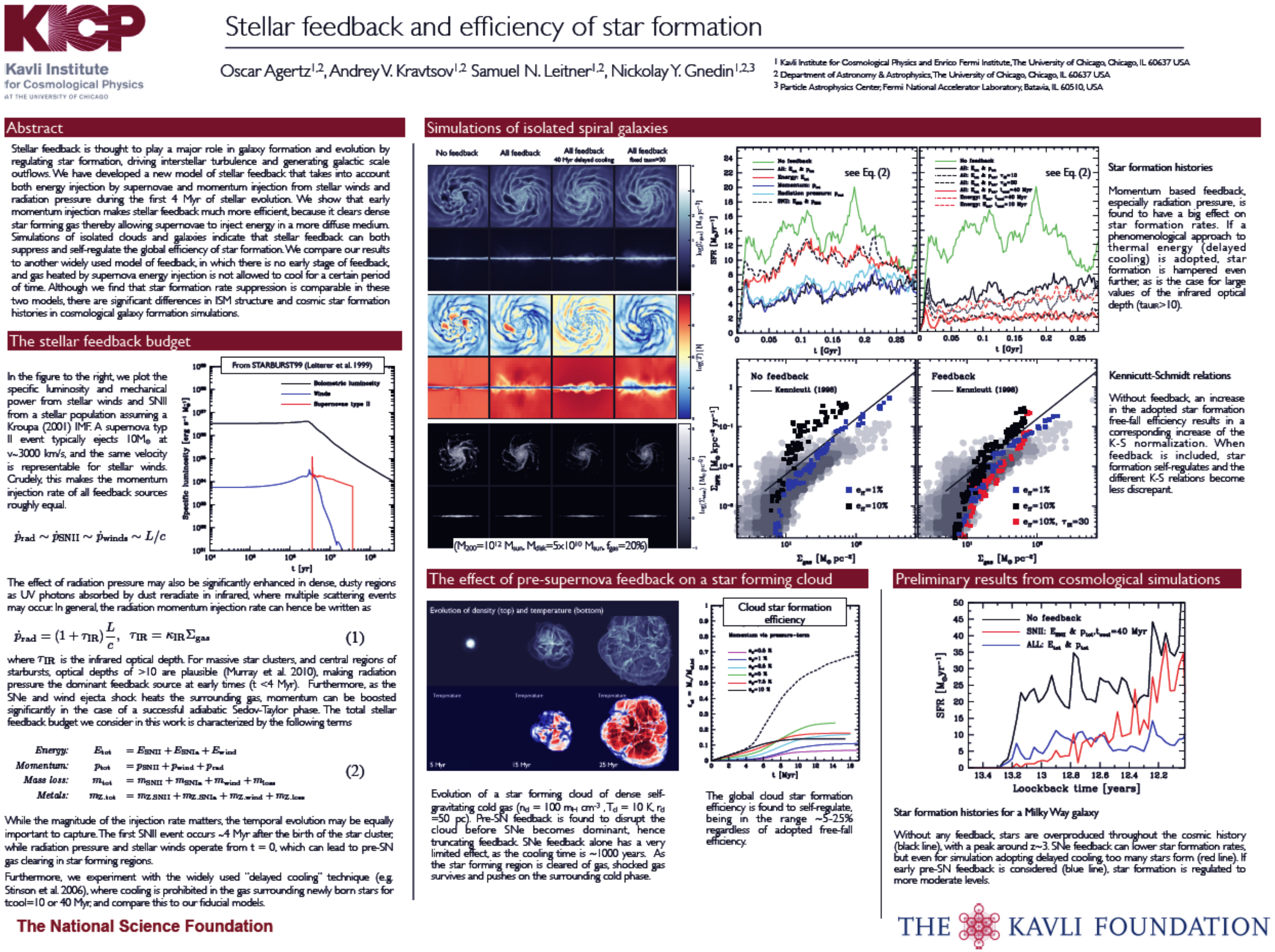
Challenge going forward is to figure out the correct balance of star formation efficiency (should be quite low on average) and seeming requirement that feedback should be efficient



O. Agertz

New subgrid model for stellar feedback which takes into account momentum injection due to radiation pressure and winds during early stages (< 4 Myr) of stellar evolution (Agertz, Kravtsov, Leitner & Gnedin 2012, in prep.)

see Oscar Agertz's poster for more details:



Kavli Institute for Cosmological Physics at the University of Chicago

Stellar feedback and efficiency of star formation

Oscar Agertz[1,2], Andrey V. Kravtsov[1,2] Samuel N. Leitner[1,2], Nickolay Y. Gnedin[1,2,3]

[1] Kavli Institute for Cosmological Physics and Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637 USA
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[3] Particle Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Abstract

Stellar feedback is thought to play a major role in galaxy formation and evolution by regulating star formation, driving interstellar turbulence and generating galactic scale outflows. We have developed a new model of stellar feedback that takes into account both energy injection by supernovae and momentum injection from stellar winds and radiation pressure during the first 4 Myr of stellar evolution. We show that early momentum injection makes stellar feedback much more efficient, because it clears dense star forming gas thereby allowing supernovae to inject energy in a more diffuse medium. Simulations of isolated clouds and galaxies indicate that stellar feedback can both suppress and self-regulate the global efficiency of star formation. We compare our results to another widely used model of feedback, in which there is no early stage of feedback, and gas heated by supernova energy injection is not allowed to cool for a certain period of time. Although we find that star formation rate suppression is comparable in these two models, there are significant differences in ISM structure and cosmic star formation histories in cosmological galaxy formation simulations.

The stellar feedback budget

In the figure to the right, we plot the specific luminosity and mechanical power from stellar winds and SNII from a stellar population assuming a Kroupa (2001) IMF. A supernova typ II event typically ejects $10 M_\odot$ at v~3000 km/s, and the same velocity is representable for stellar winds. Crudely, this makes the momentum injection rate of all feedback sources roughly equal.

$$\dot{p}_{\rm rad} \sim \dot{p}_{\rm SNII} \sim \dot{p}_{\rm winds} \sim L/c$$

The effect of radiation pressure may also be significantly enhanced in dense, dusty regions as UV photons absorbed by dust reradiate in infrared, where multiple scattering events may occur. In general, the radiation momentum injection rate can hence be written as

$$\dot{p}_{\rm rad} = (1+\tau_{\rm IR})\frac{L}{c}, \quad \tau_{\rm IR} = \kappa_{\rm IR}\Sigma_{\rm gas} \qquad (1)$$

where $\tau_{\rm IR}$ is the infrared optical depth. For massive star clusters, and central regions of starbursts, optical depths of >10 are plausible (Murray et al. 2010), making radiation pressure the dominant feedback source at early times (t <4 Myr). Furthermore, as the SNe and wind ejecta shock heats the surrounding gas, momentum can be boosted significantly in the case of a successful adiabatic Sedov-Taylor phase. The total stellar feedback budget we consider in this work is characterized by the following terms

$$\begin{aligned}
\textit{Energy:} \quad & E_{\rm tot} = E_{\rm SNII} + E_{\rm SNIa} + E_{\rm wind} \\
\textit{Momentum:} \quad & p_{\rm tot} = p_{\rm SNII} + p_{\rm wind} + p_{\rm rad} \\
\textit{Mass loss:} \quad & m_{\rm tot} = m_{\rm SNII} + m_{\rm SNIa} + m_{\rm wind} + m_{\rm loss} \\
\textit{Metals:} \quad & m_{\rm Z,tot} = m_{\rm Z,SNII} + m_{\rm Z,SNIa} + m_{\rm Z,wind} + m_{\rm Z,loss}
\end{aligned} \qquad (2)$$

While the magnitude of the injection rate matters, the temporal evolution may be equally important to capture. The first SNII event occurs ~4 Myr after the birth of the star cluster, while radiation pressure and stellar winds operate from t = 0, which can lead to pre-SN gas clearing in star forming regions.

Furthermore, we experiment with the widely used "delayed cooling" technique (e.g. Stinson et al. 2006), where cooling is prohibited in the gas surrounding newly born stars for tcool=10 or 40 Myr, and compare this to our fiducial models.

Simulations of isolated spiral galaxies

Star formation histories

Momentum based feedback, especially radiation pressure, is found to have a big effect on star formation rates. If a phenomenological approach to thermal energy (delayed cooling) is adopted, star formation is hampered even further, as is the case for large values of the infrared optical depth ($\tau_{\rm IR}$>10).

Kennicutt-Schmidt relations

Without feedback, an increase in the adopted star formation free-fall efficiency results in a corresponding increase of the K-S normalization. When feedback is included, star formation self-regulates and the different K-S relations become less discrepant.

The effect of pre-supernova feedback on a star forming cloud

Evolution of a star forming cloud of dense self-gravitating cold gas ($n_{\rm cl}$ = 100 $m_{\rm H}$ cm^{-3}, $T_{\rm cl}$ = 10 K, $r_{\rm cl}$ =50 pc). Pre-SN feedback is found to disrupt the cloud before SNe becomes dominant, hence truncating feedback. SNe feedback alone has a very limited effect, as the cooling time is ~1000 years. As the star forming region is cleared of gas, shocked gas survives and pushes on the surrounding cold phase.

The global cloud star formation efficiency is found to self-regulate, being in the range ~5-25% regardless of adopted free-fall efficiency.

Preliminary results from cosmological simulations

Star formation histories for a Milky Way galaxy

Without any feedback, stars are overproduced throughout the cosmic history (black line), with a peak around z~3. SNe feedback can lower star formation rates, but even for simulation adopting delayed cooling, too many stars form (red line). If early pre-SN feedback is considered (blue line), star formation is regulated to more moderate levels.

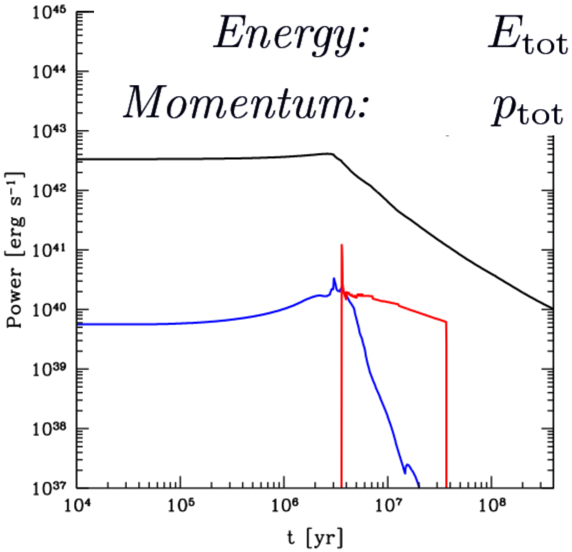
The National Science Foundation

THE KAVLI FOUNDATION

Oscar Agertz
(U.Chicago)

Importance of early, pre-supernovae stellar feedback

(Agertz et al. '12, see also, Murray et al. 2005, 2010; Hopkins et al. 2011a,b,c,d; Stinson et al. 2012, arxiv/1208.0002)



Energy: $$E_{\mathrm{tot}} = E_{\mathrm{SNII}} + E_{\mathrm{SNIa}} + E_{\mathrm{wind}}$$

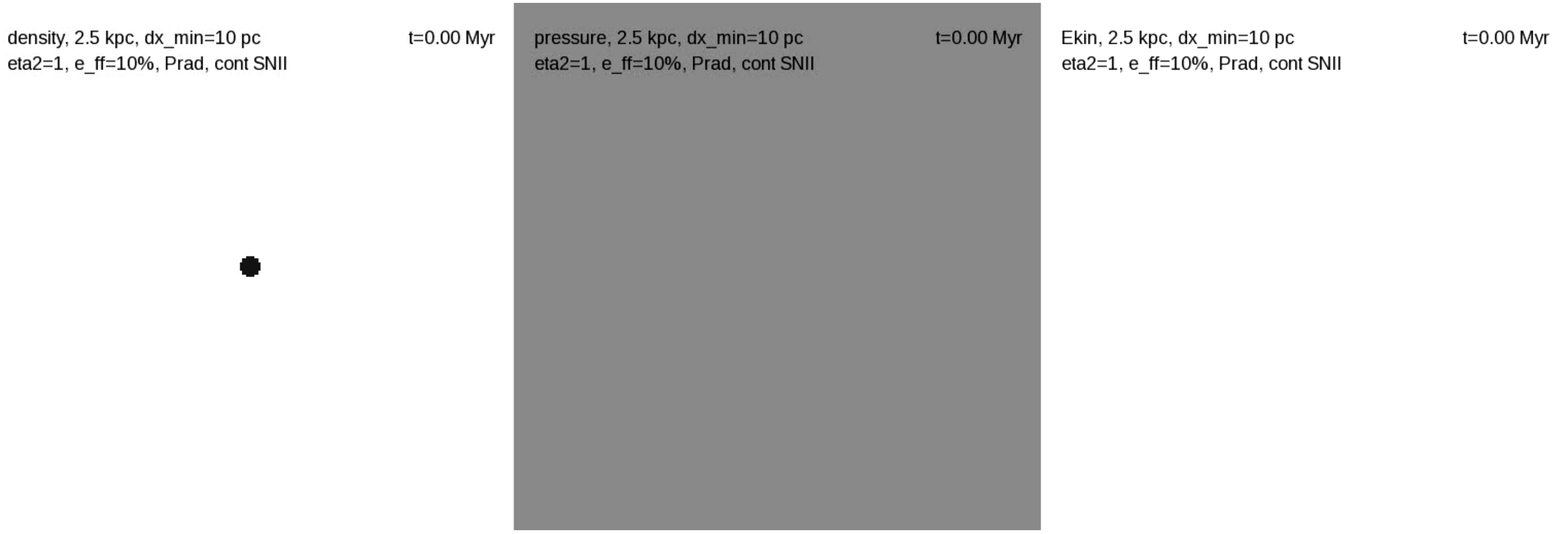
Momentum: $$p_{\mathrm{tot}} = p_{\mathrm{SNII}} + p_{\mathrm{wind}} + p_{\mathrm{rad}}$$

these three are comparable and radiation pressure may even dominate in high-density regions of young embedded clusters

$$\dot{p}_{\mathrm{rad}} = (1+\tau_{\mathrm{IR}})\frac{L}{c}, \quad \tau_{\mathrm{IR}} = \kappa_{\mathrm{IR}}\Sigma_{\mathrm{gas}}$$

NGC 602 (young star cluster in the SMC)

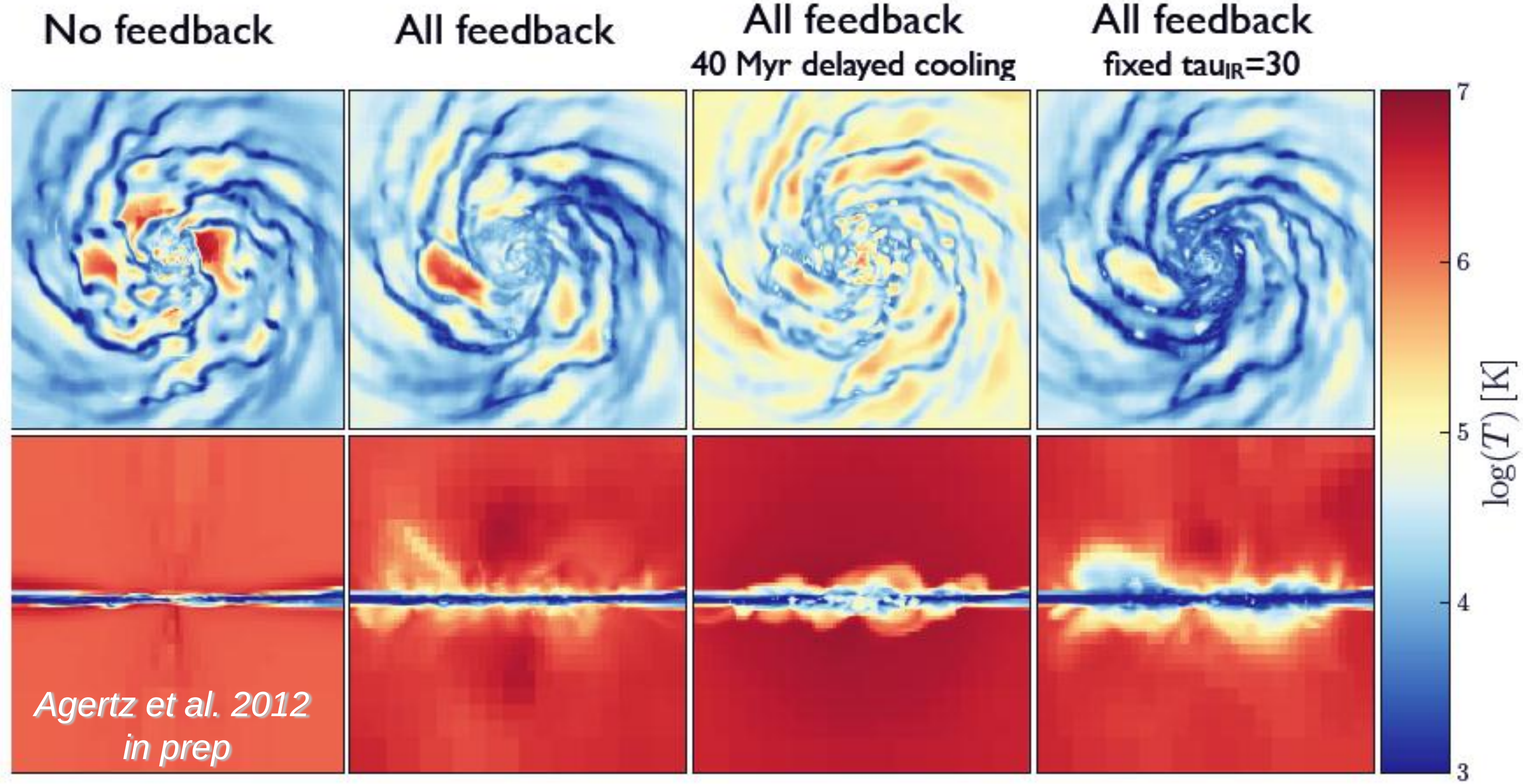
Idealized spherical cloud simulation with early momentum injection and subsequent supernova enerhy injection:



Early momentum injection generally makes stellar feedback much more efficient in disrupting star forming clouds and re-distributing gas within the disk

(cf. also, Hopkins et al. 2011a,b,c,d; Hummels & Bryan 2011)

temperature maps in simulations of isolated MW-sized disk

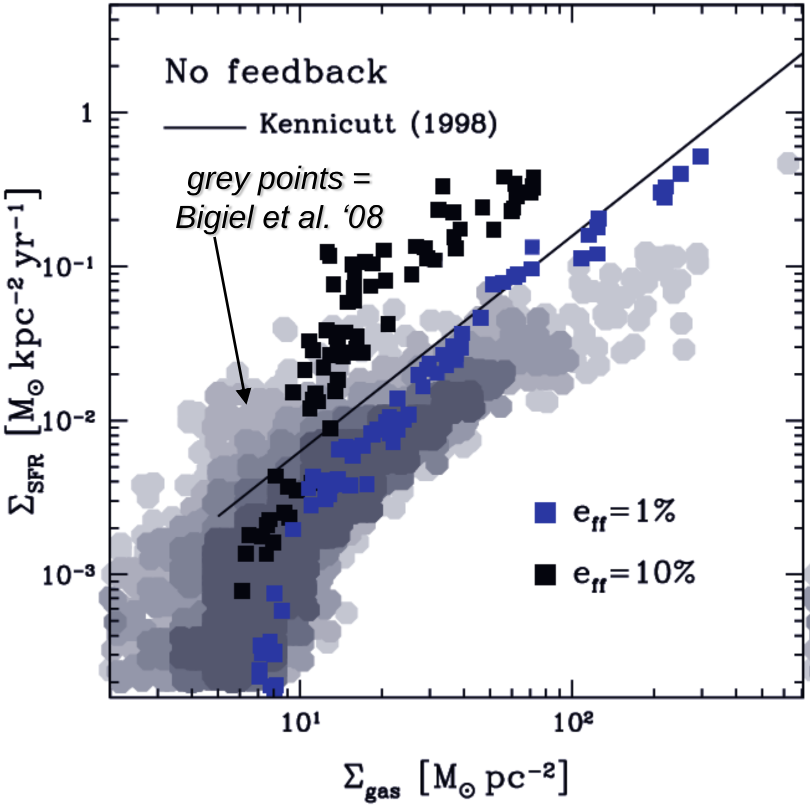


Agertz et al. 2012 in prep

Efficient feedback tends to self-regulate star formation efficiency (i.e., normalization of the Kennicutt-Schmidt relation)

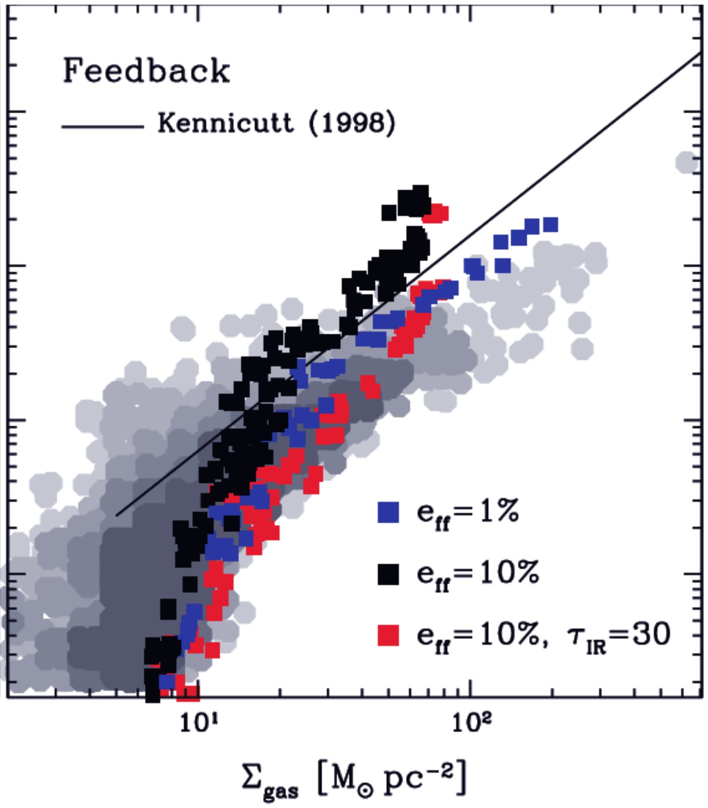
(Agertz et al. ‘12, in prep; cf. also, Hopkins et al. 2011; Dobbs et al. 2011)

weak feedback:
linear dependence of KS normalization
on assumed SF efficiency

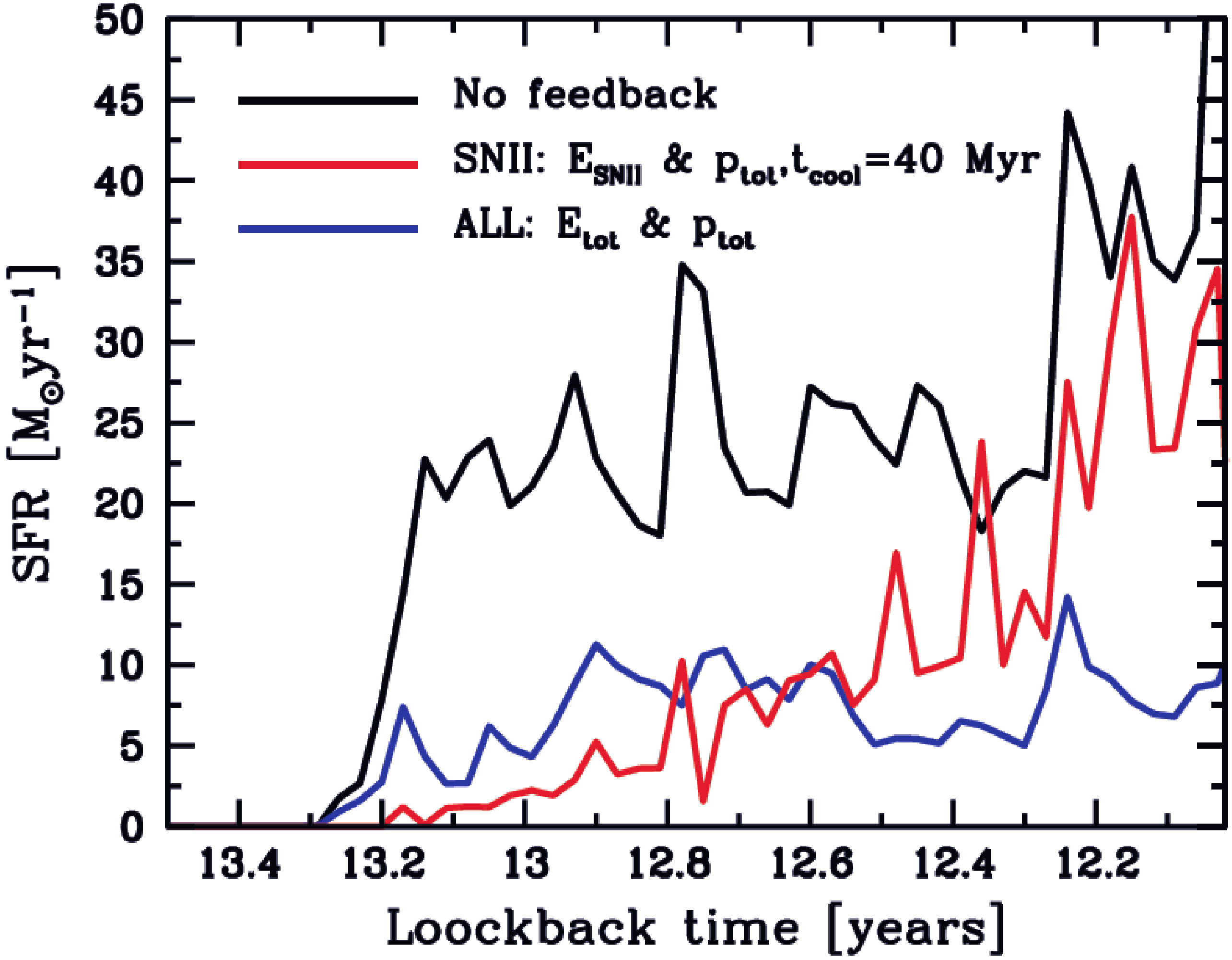


grey points = Bigiel et al. ‘08

strong feedback:
much weaker dependency
on assumed SF efficiency



Preliminary results from cosmological simulations indicate that Early stellar feedback can help to significantly reduce star formation at high z



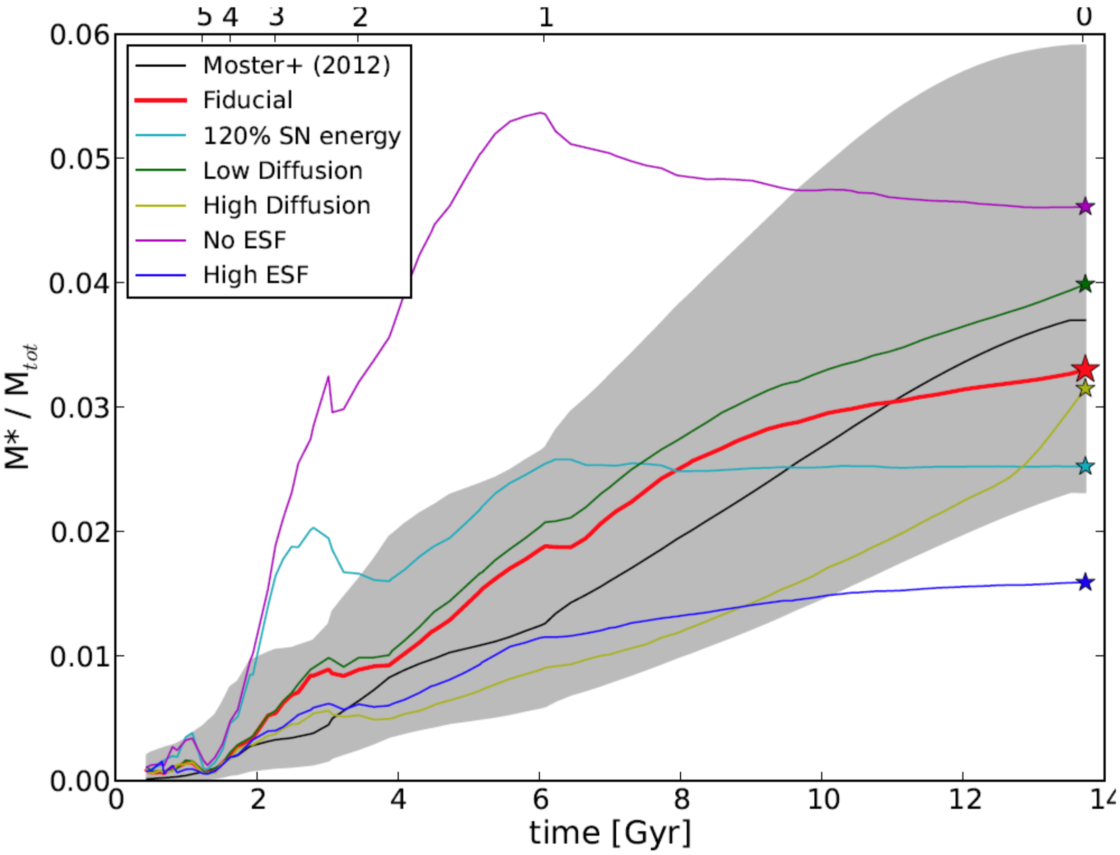
Agertz et al. '12
In prep.

Preliminary results from cosmological simulations indicate that Early stellar feedback can help to significantly reduce star formation at high z

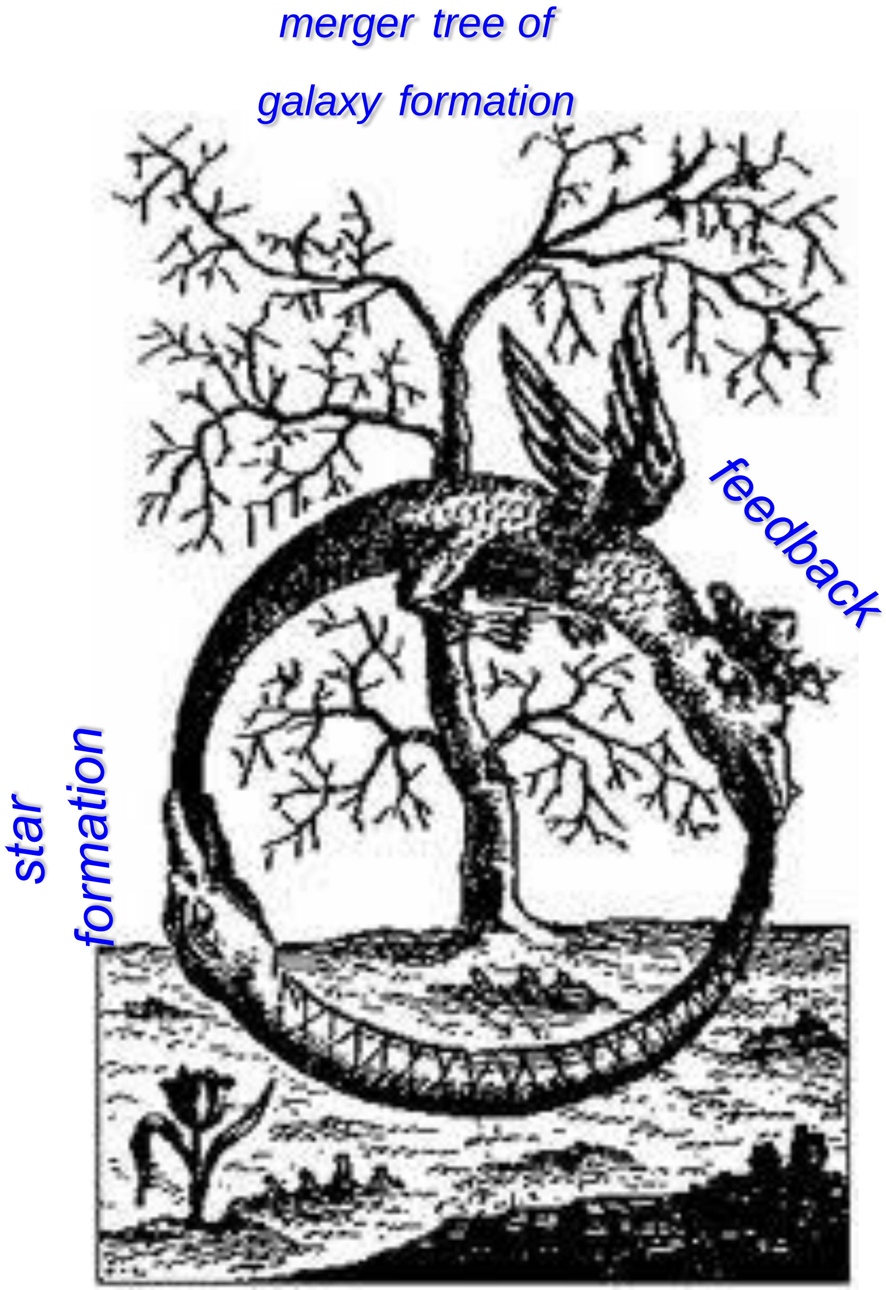
(Stinson et al. ‘12, arxiv/1208.0002 = today)

buildup of stellar mass (relative to total halo mass) in galaxy formation simulations with different feedback prescriptions/parameters

galaxy stellar mass/
current parent halo mass



summary



the Cosmic Ouroboros: star formation, feedback and the merger Tree of Galaxy Formation

- *Galaxy morphology is very sensitive to star formation history during the first 3 Gyrs of evolution of the universe (z>~2). Star formation should be highly suppressed to form late type disk galaxies.*

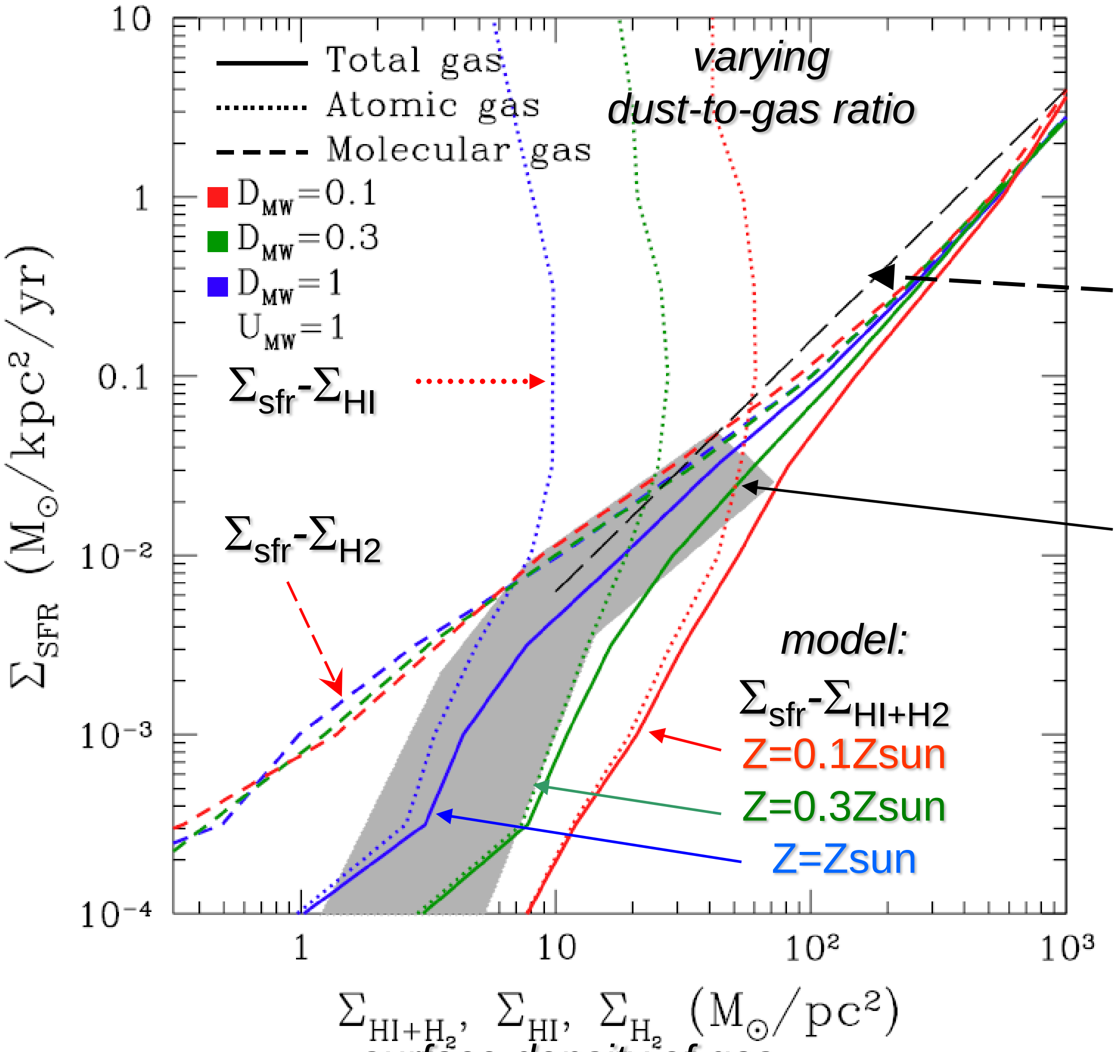
- *At the same time, stellar feedback should be very efficient to redistribute gas in the forming disks and drive outflows.*

- *Lots of progress in understanding what was missing in simulations of galaxy formation. The challenge going forward is to figure out details of the star formation-feedback loop*

  (in particular how to reconcile inefficiency of star formation required by observations and basic physical considerations AND need for strong and efficient stellar feedback)

Sensitivity of the Schmidt-Kennicutt relation to varying dust-to-gas ratio

test models simulated to z=3 but with different fixed dust-to-gas ratios and interstellar UV fluxes show that the main difference is gas metallicity



surface density of star formation rate measured in 500 pc patches

varying dust-to-gas ratio

Σ_{sfr}-Σ_{HI}

Σ_{sfr}-Σ_{H2}

observed: Kennicutt 1998 fit

observed: Bigiel et al. 2008 (gray band)

model:

Σ_{sfr}-Σ_{HI+H2}

Z=0.1Zsun

Z=0.3Zsun

Z=Zsun

Gnedin & Kravtsov 2010, ApJ 728, 88

surface density of gas