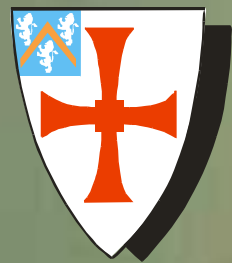


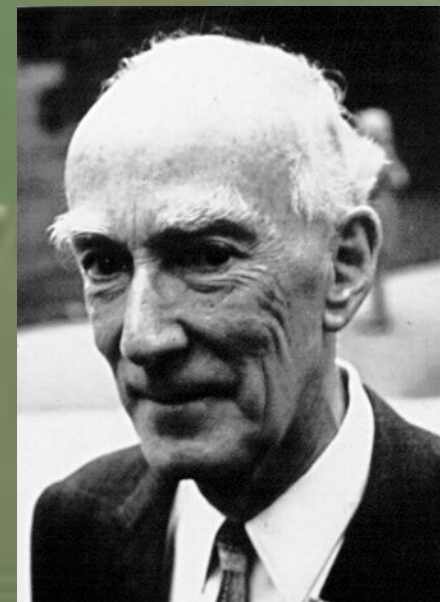


Jan Oort
(1990 – 1992)



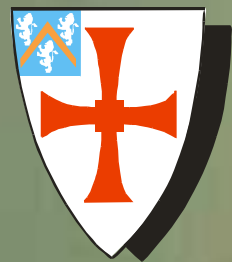


The vicissitudes of the cold dark matter model of cosmogony



Carlos S. Frenk
Institute for Computational Cosmology,
Durham





II. Galaxy formation models: myth and reality

Carlos S. Frenk
Institute for Computational Cosmology,
Durham



$z=5.7$

31.25 Mpc/h

$z=0$

31.25 Mpc/h

15.6 Mpc/h

Galaxy formation theory

Galaxy formation theory:
a physics-based model for the
formation and evolution of galaxies

Should aim to explain the entire galaxy
population at all epochs



$z=5.7$

31.25 Mpc/h

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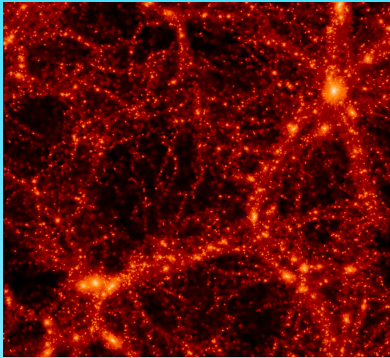
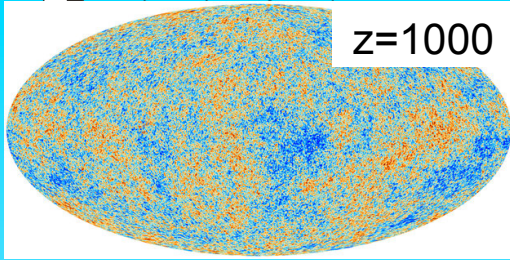
15.6 Mpc/h

Galaxy formation theory

Galaxy formation theory:
a physics-based model for the
formation and evolution of galaxies

Should aim to explain the entire galaxy
population at all epochs

Basic ingredients



Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$; dark matter

Primordial fluctuations

Λ CDM $\rightarrow \delta\rho/\rho(M, t)$

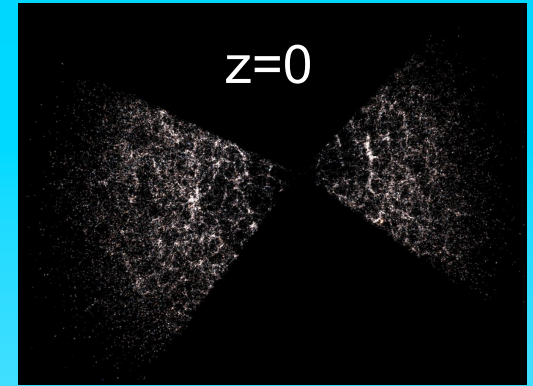
Dark matter halos

(N-body simulations)

Gas processes

(cooling, star formation, feedback)

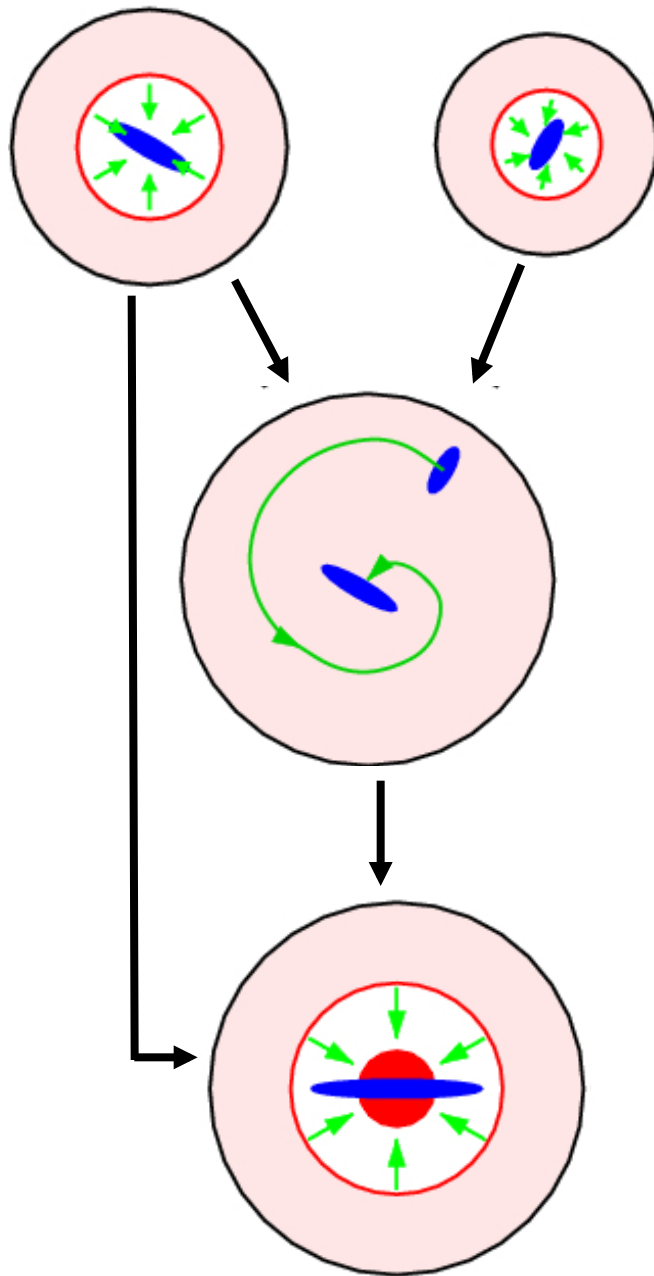
Formation and evolution of galaxies



Galaxy formation theory: what do we think we know?

- Cosmological parameters & expansion history of universe: Λ CDM
- Initial conditions for the formation of structure
- The identity of main astrophysical processes involved:
 - Gravity-driven hierarchical growth of dark matter halos
 - Cooling of (rotating gas) and condensation into DM halos
 - Star formation
 - Feedback from stellar processes: early reionization, SN
 - Central supermassive black hole formation and AGN feedback
 - Tidal and ram pressure stripping of gas
 - Tidal stripping and mergers of galaxies as their halos merge
 - Disk instabilities, secular evolution

Galaxy formation: the basics



- Infalling gas shock-heated to T_{vir}
- Gas cools radiatively onto central galaxy and forms **disk**, **conserving J**?
 $\rightarrow r_{\text{disk}} \sim \lambda_h r_{\text{cool}}$
- Stars form in disk
- And give rise to **feedback** effects
- Satellite sinks by **dynamical friction** and merges onto central galaxy
- Mergers $\rightarrow$ **starbursts**, **BH growth**
- Major mergers & disk instabilities: stellar disks $\rightarrow$ **spheroids**
- New **disk** may form by gas accretion

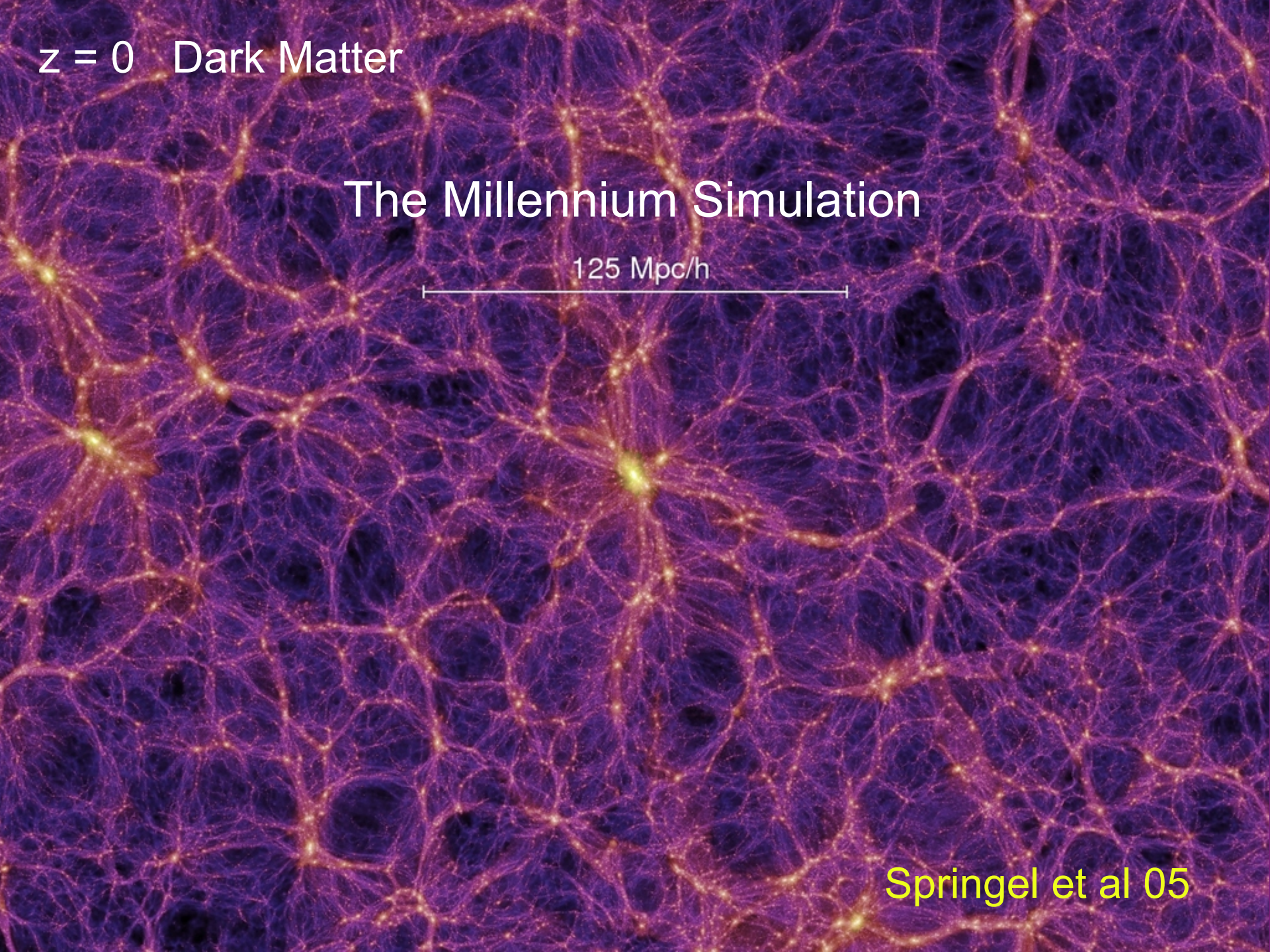
Galaxy formation theory: what do we think we know?

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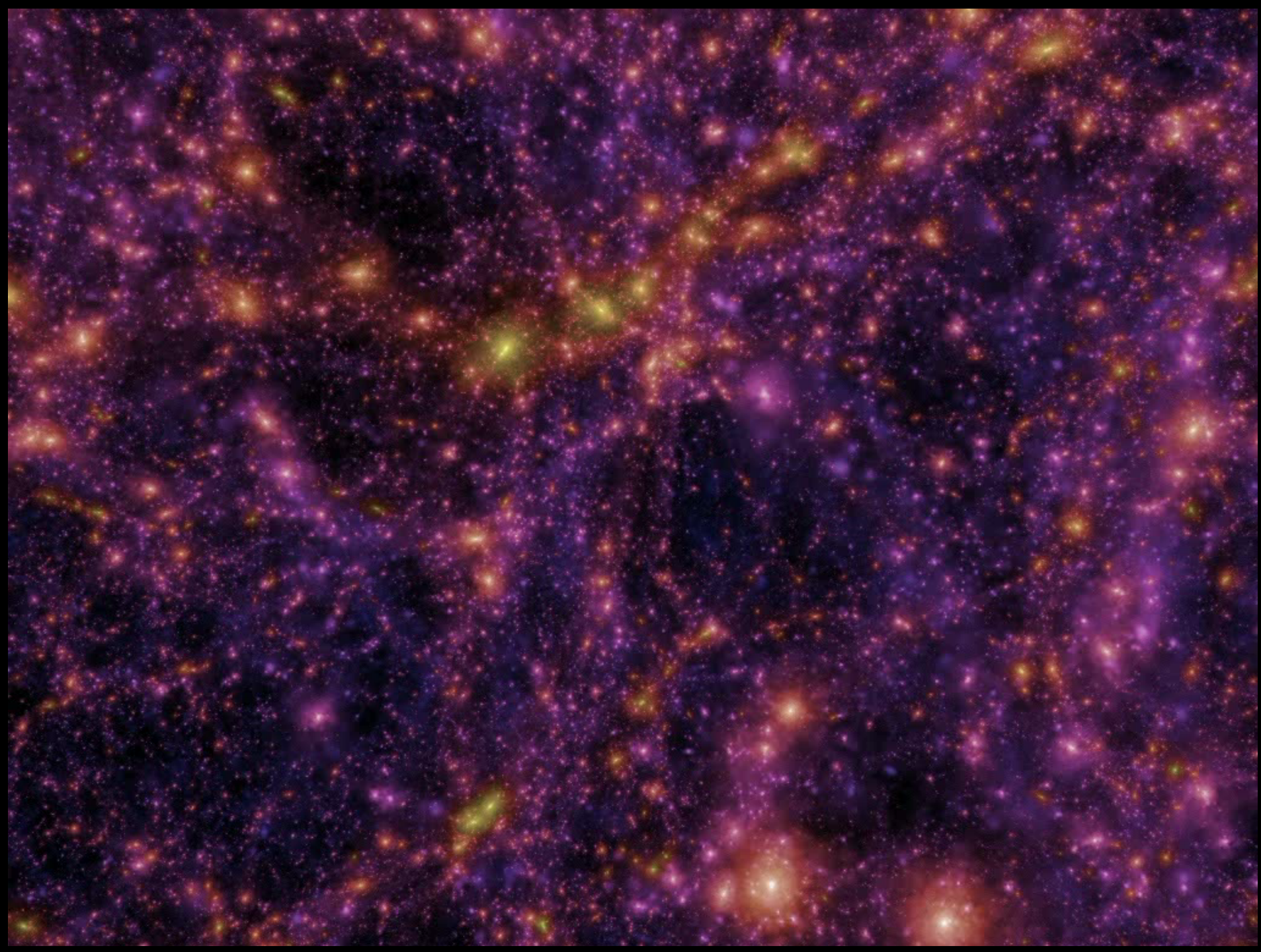
$z = 0$ Dark Matter

The Millennium Simulation

125 Mpc/h



Springel et al 05





Carlos Frenk

Liang Gao

Adrian Jenkins

Julio Navarro

Frazer Pearce

Joop Schaye

Volker Springel

Peter Thomas

Simon White

+ many students
and postdocs



UK, Germany, Netherlands, Canada,
China collaboration

Pictures, movies and simulation data

available at:

<http://www.mpa-garching.mpg.de/Virgo>

www.durham.ac.uk/virgo

Millennium-II (2008)

Same cosmology

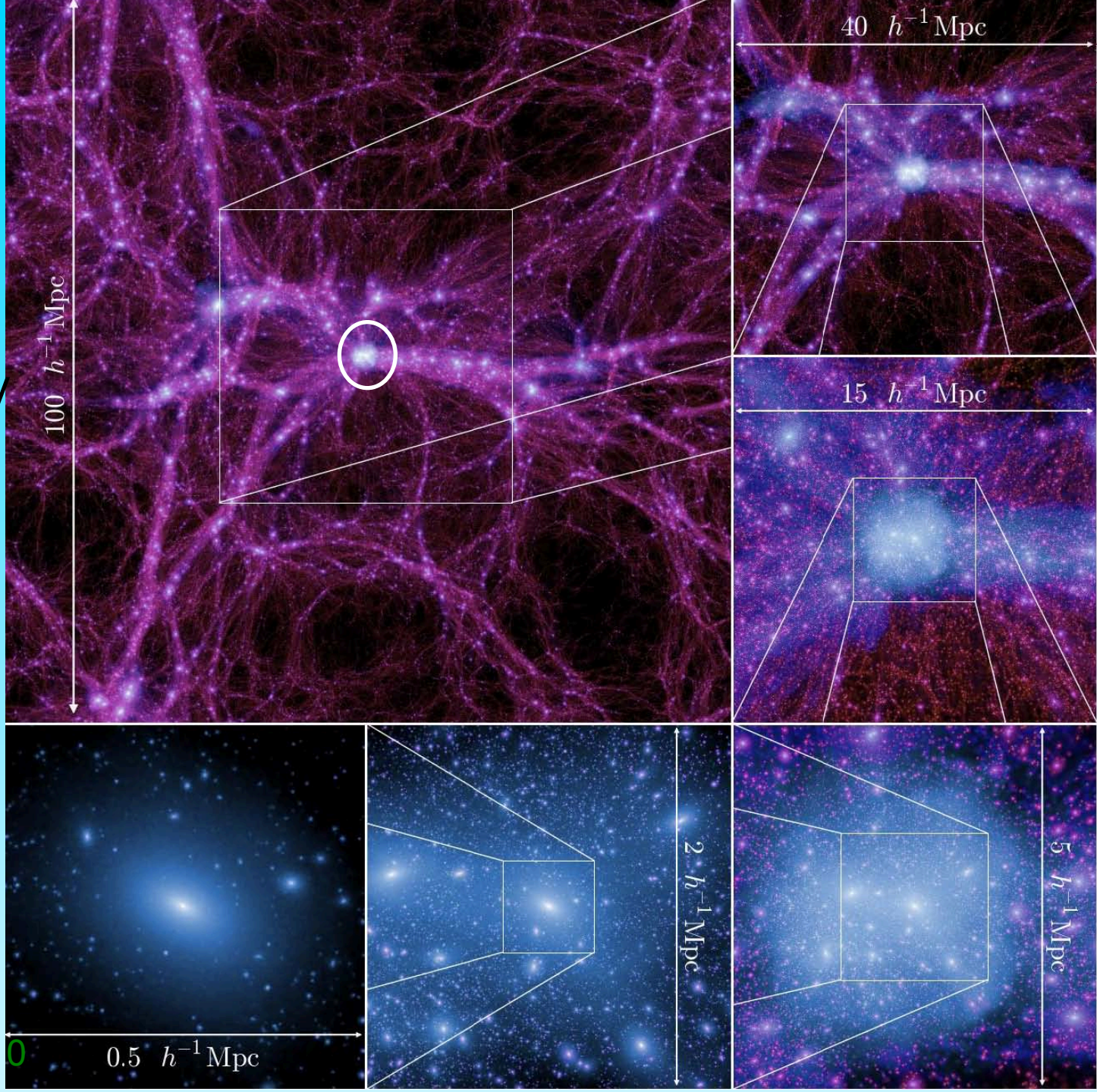
Same N

1/5 linear size



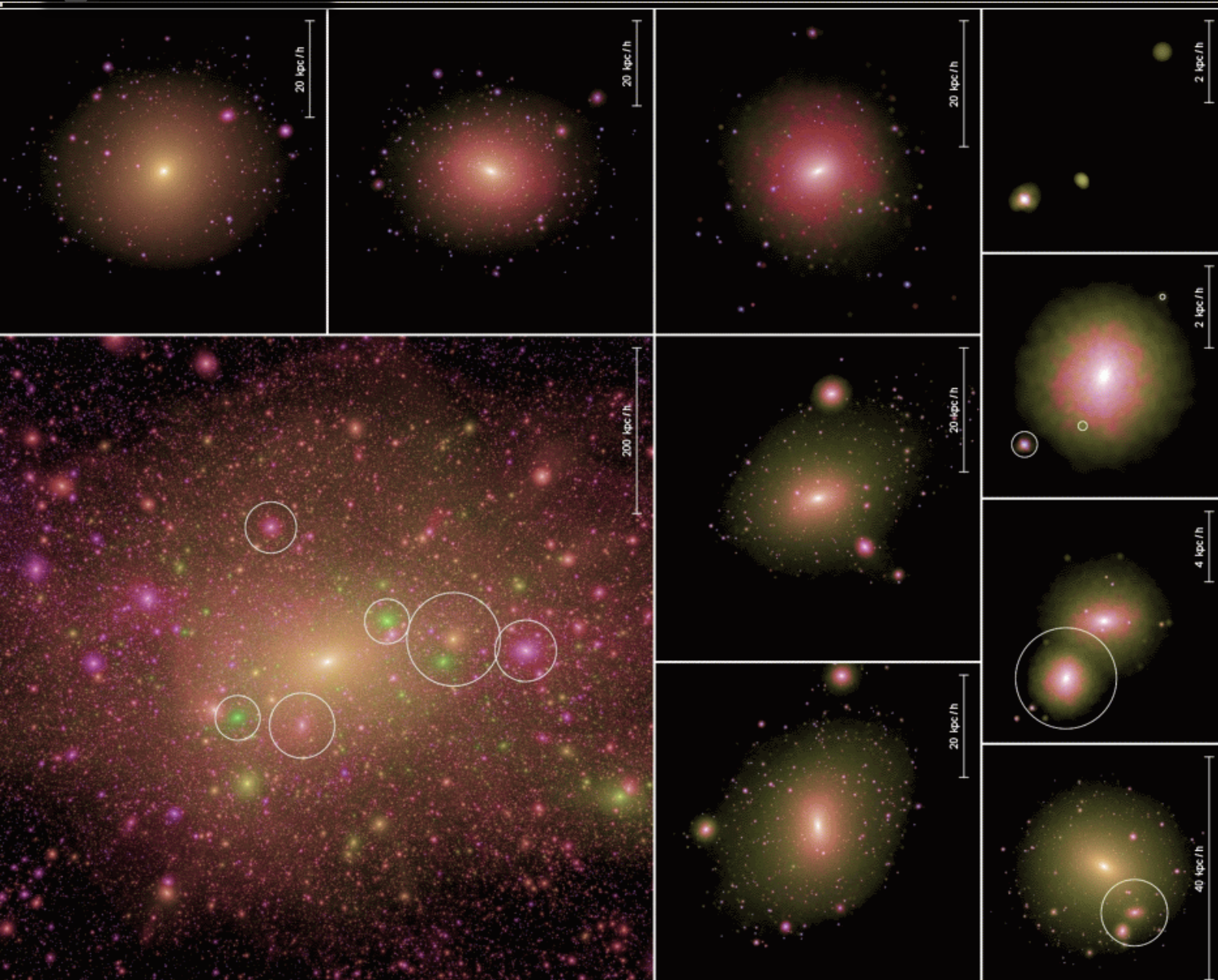
Resolves halos
of mass
 $M > 10^8 M_\odot$

Boylan-Kolchin et al '10



VIRGO

The Aquarius simulations of galactic halos



6 halos at
varying
resolution

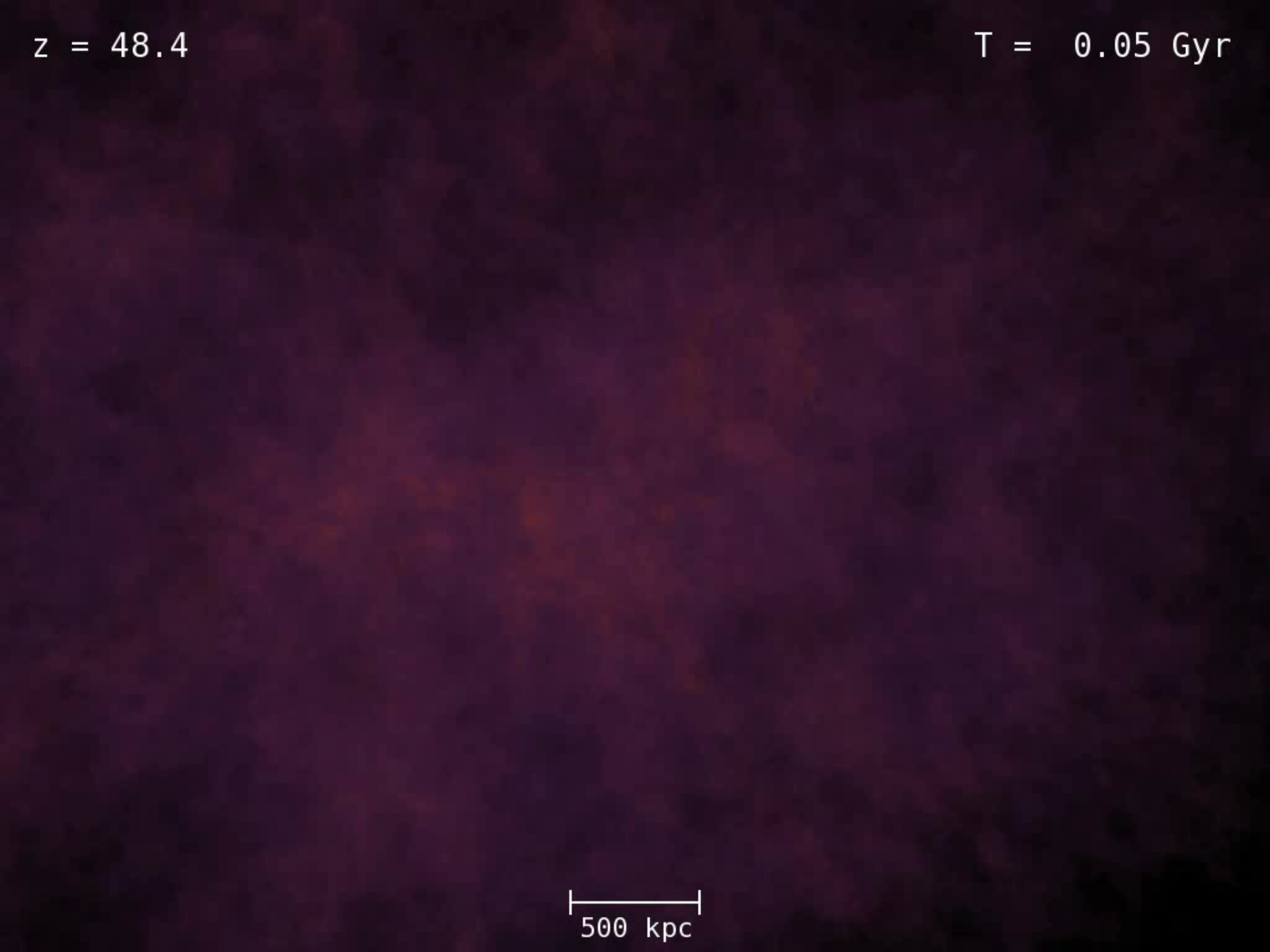
Best res:
 $m_p = 10^3 M_\odot$

There are
substructures
embedded
within other
structures.
We detect 4
generations

$z = 48.4$

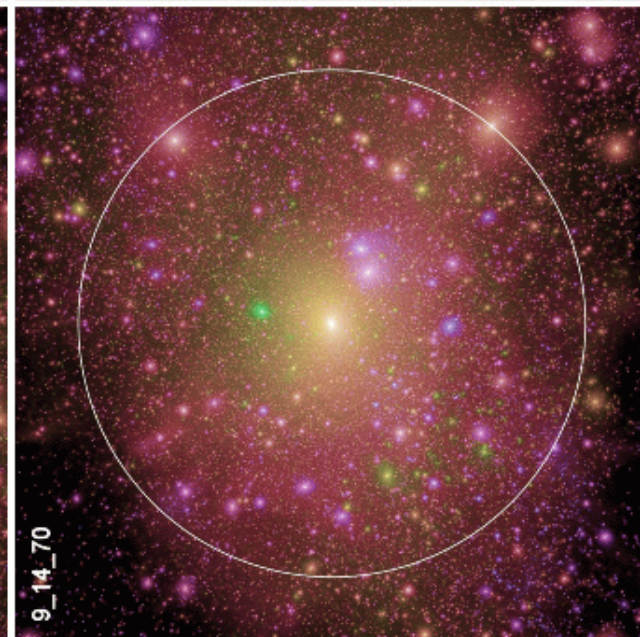
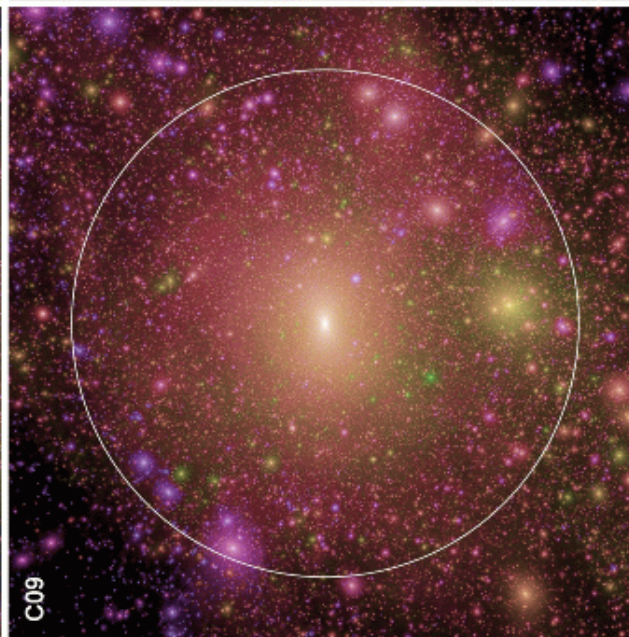
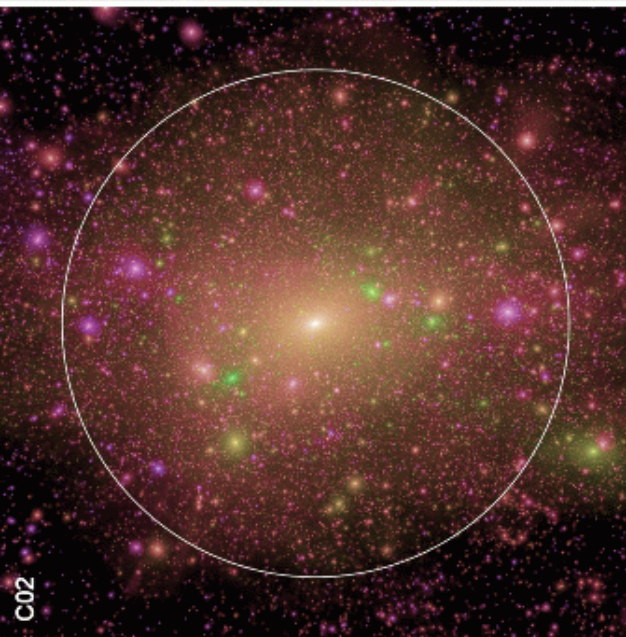
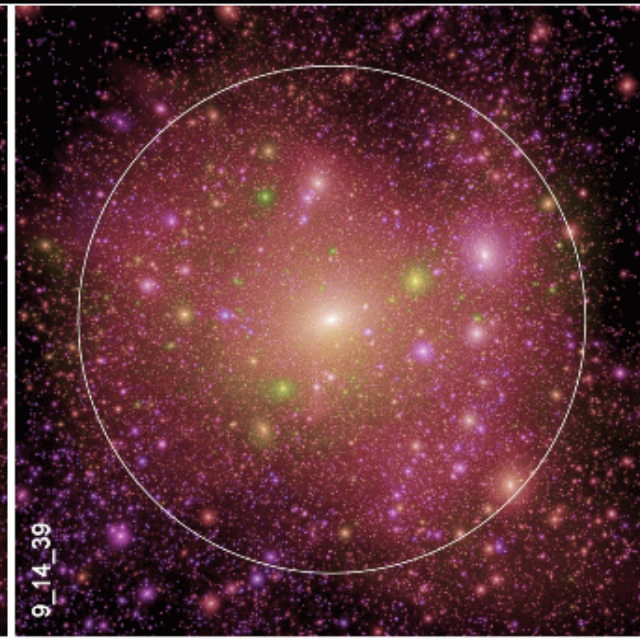
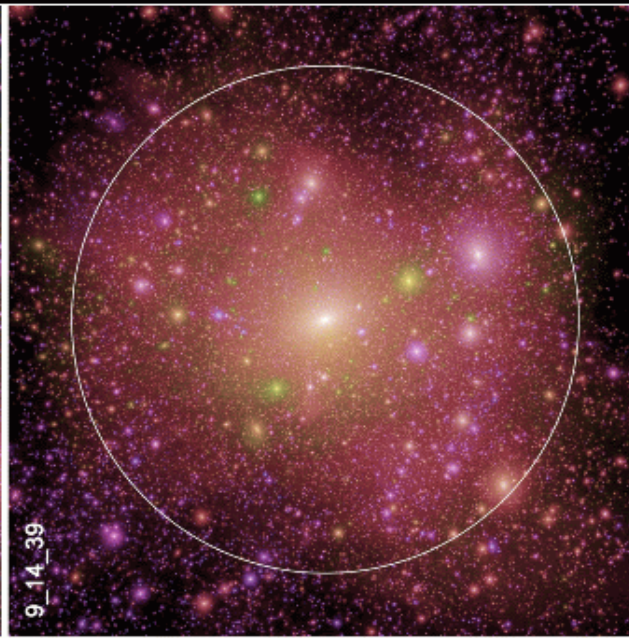
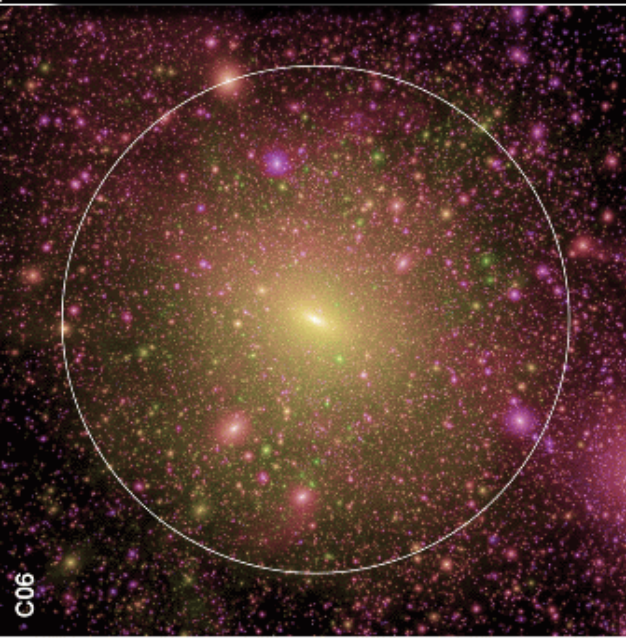
$T = 0.05 \text{ Gyr}$

500 kpc

A visualization of the cosmic structure at redshift $z = 48.4$. The image shows a complex network of dark, filamentary structures against a lighter, grainy background, representing the early stages of galaxy formation. The structures are primarily oriented vertically and horizontally, with some diagonal filaments. The overall appearance is that of a high-resolution simulation or observation of the universe at this early epoch.

VIRGO

Images of Aquarius galactic halos



VIRGO

The Millennium/Aquarius simulation series

Simulations give a full characterization of the (hierarchical) clustering of cold dark matter on large and small scales.

125 Mpc/h

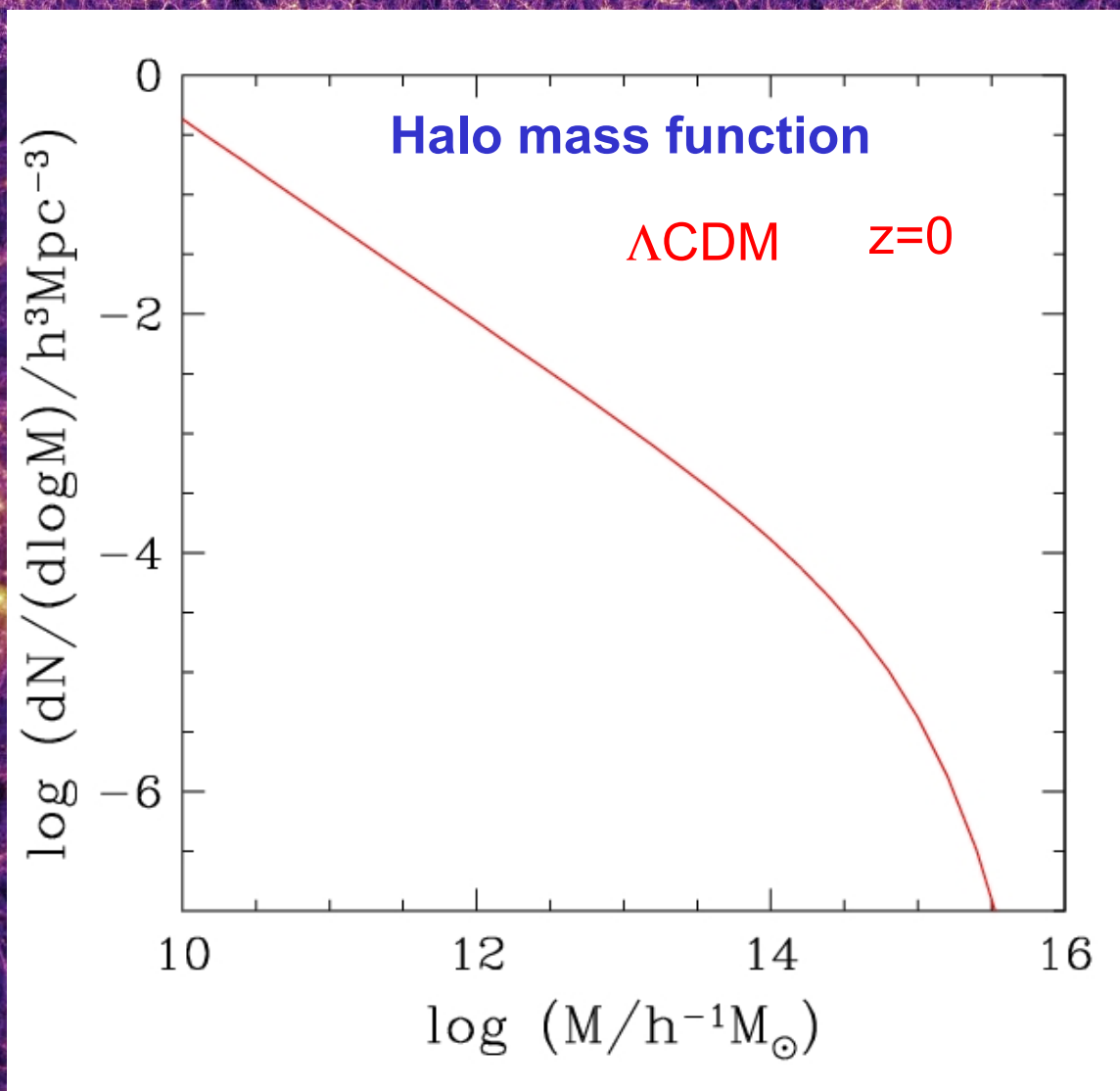
31.25 Mpc/h

0.5 Mpc/h

Springel et al '05, '08

VIRG

The Millennium/Aquarius simulation series



Springel et al '05, '08

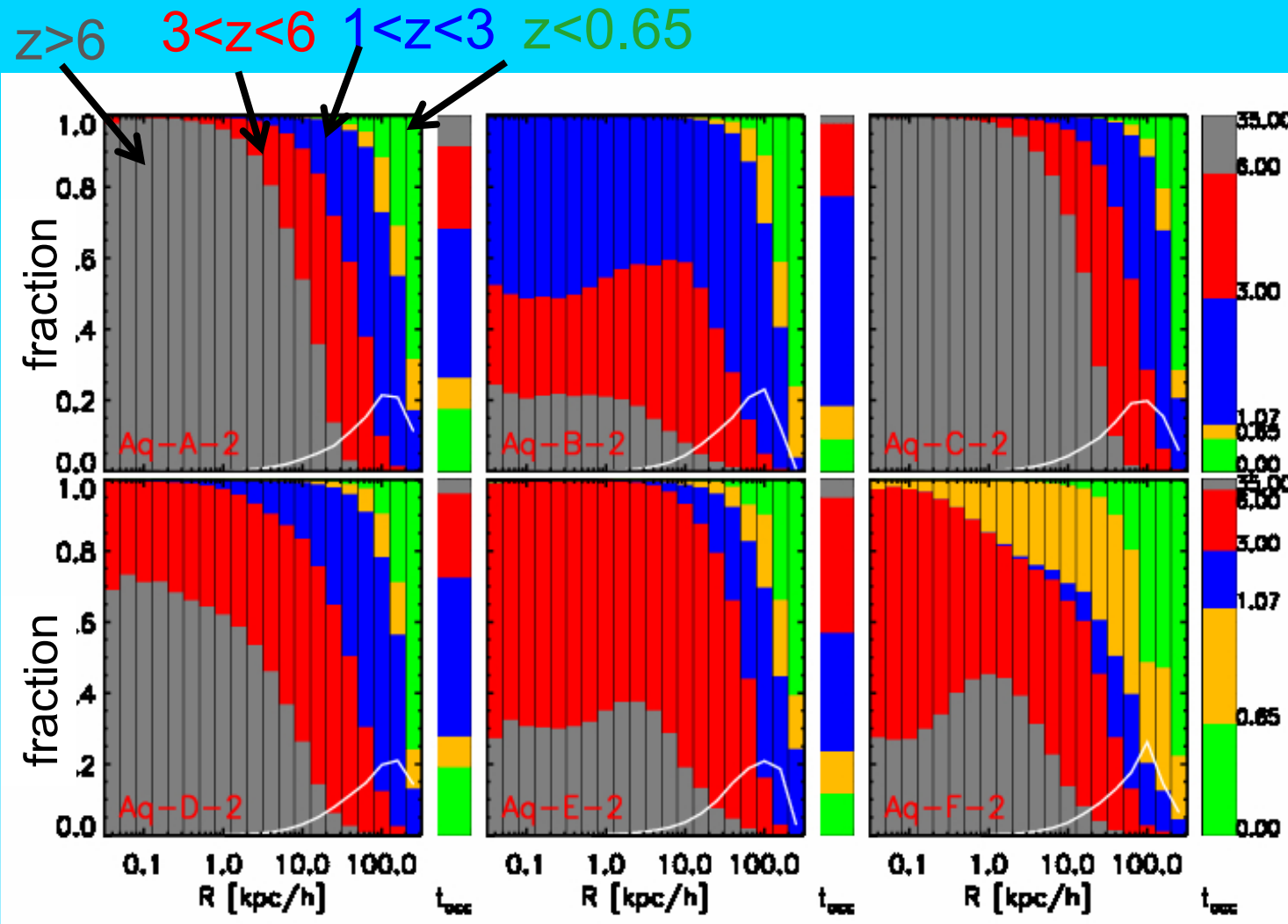


Dark matter halo assembly

DM halo assembly

Aquarius halos

Wang et al. '11



- DM halos form **inside out**; **inner** regions **stable** since early times
- Major mergers** ($m_2/m_1 > 0.1$) contribute **< 20%** to total **mass** growth



Dark matter halo structure

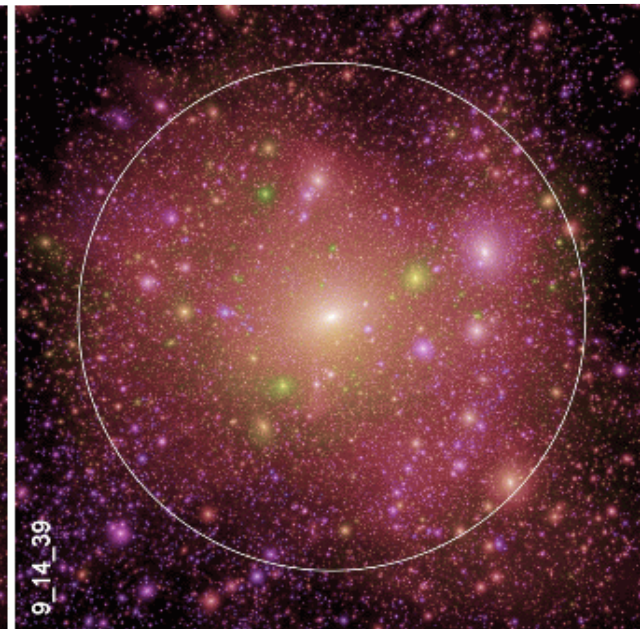
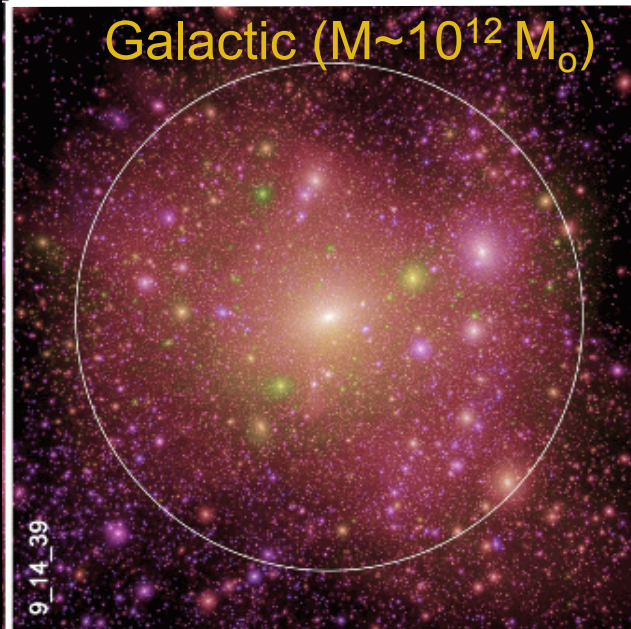
VIRGO

Aquarius (galactic) & Phoenix (cluster) halos

Self-similarity of CDM halos

The structure and
substructure of CDM
halos are
approximately self-
similar

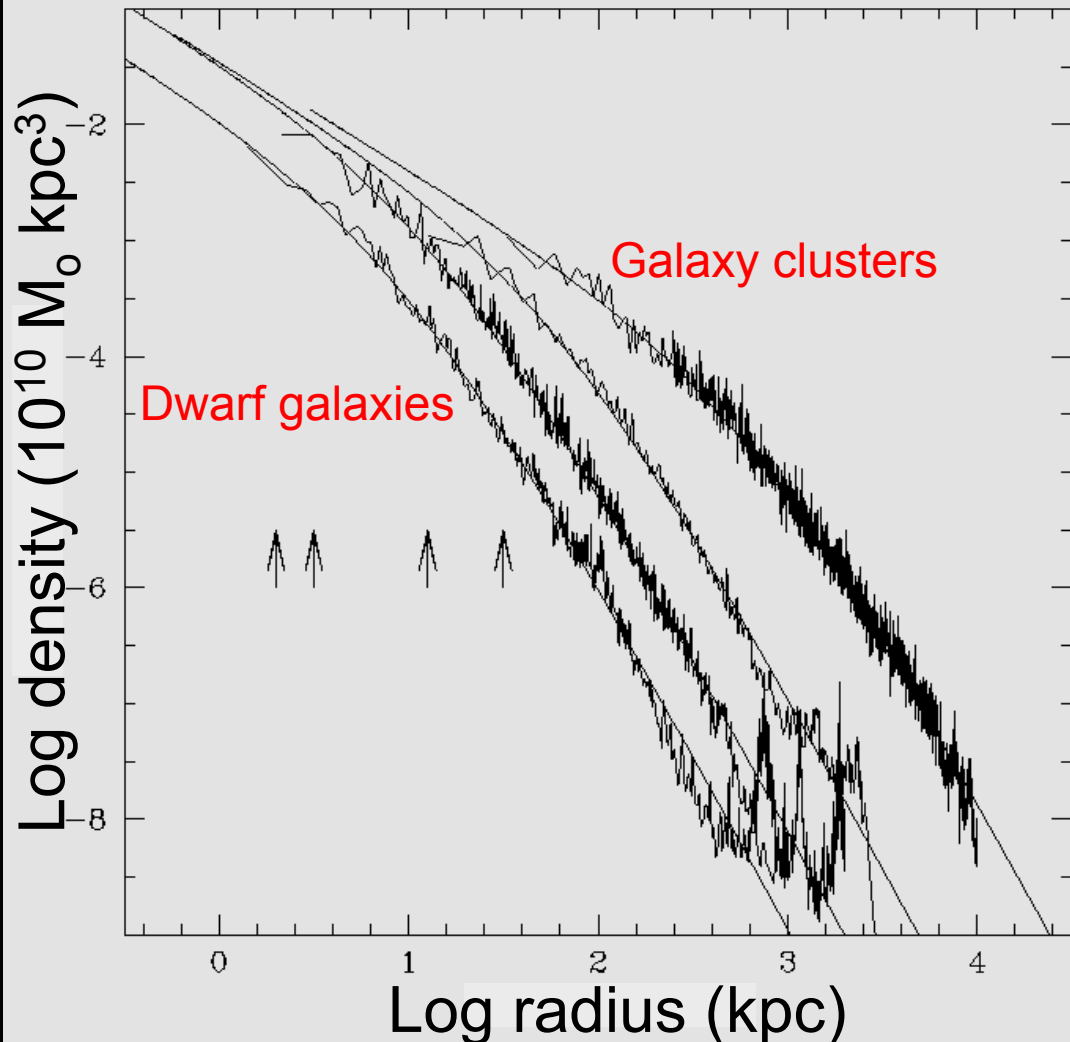
Galactic ($M \sim 10^{12} M_{\odot}$)



Cluster ($M \sim 10^{15} M_{\odot}$)



The Density Profile of Cold Dark Matter Halos



Shape of halo profiles
~independent of halo mass &
cosmological parameters

Density profiles are “cuspy”
no ‘core’ near the centre

Fitted by simple formula:

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White '97)

More massive halos and
halos that form earlier have
higher densities (bigger δ)



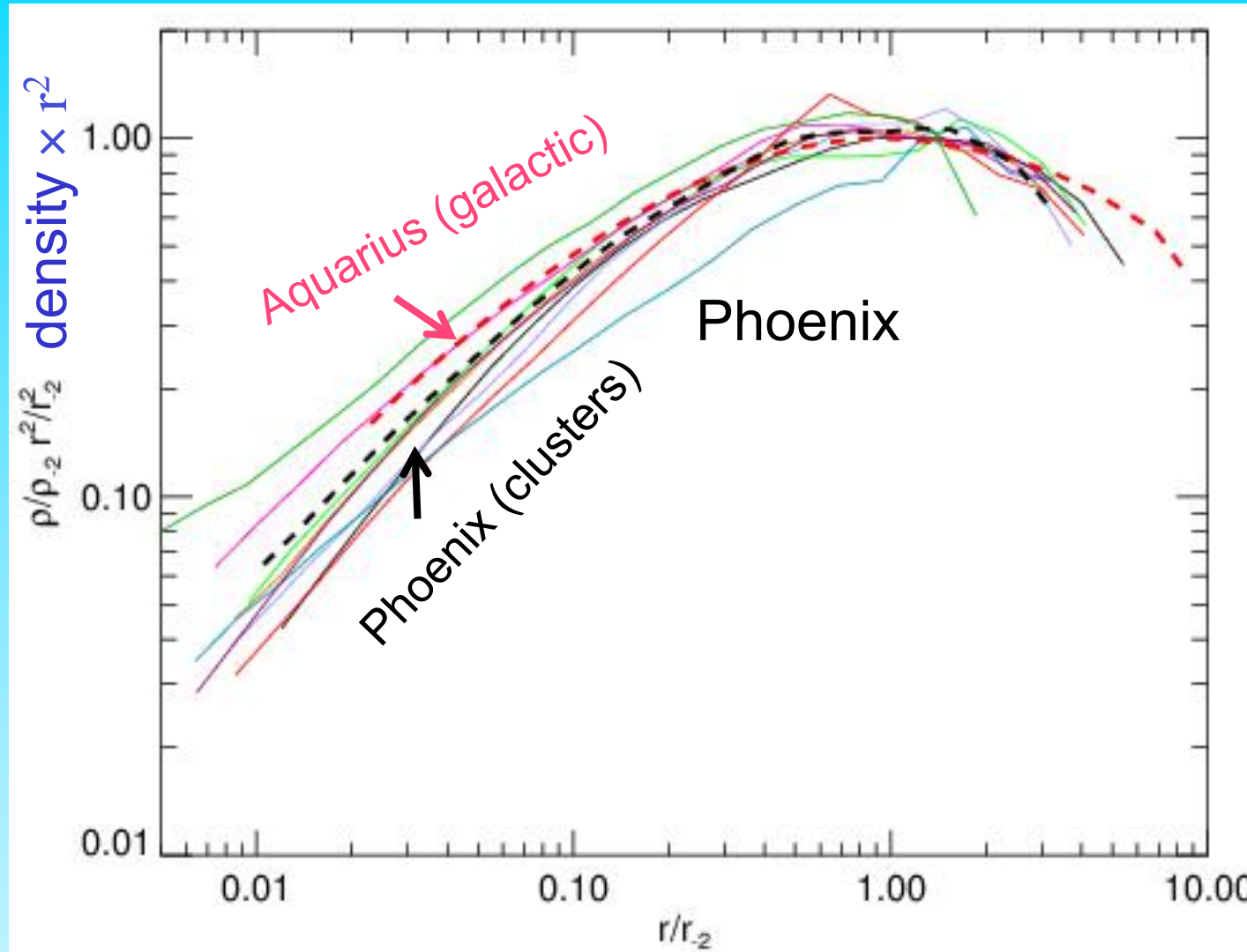
The “NFW” profile



© BT - musicolor.wordpress.com

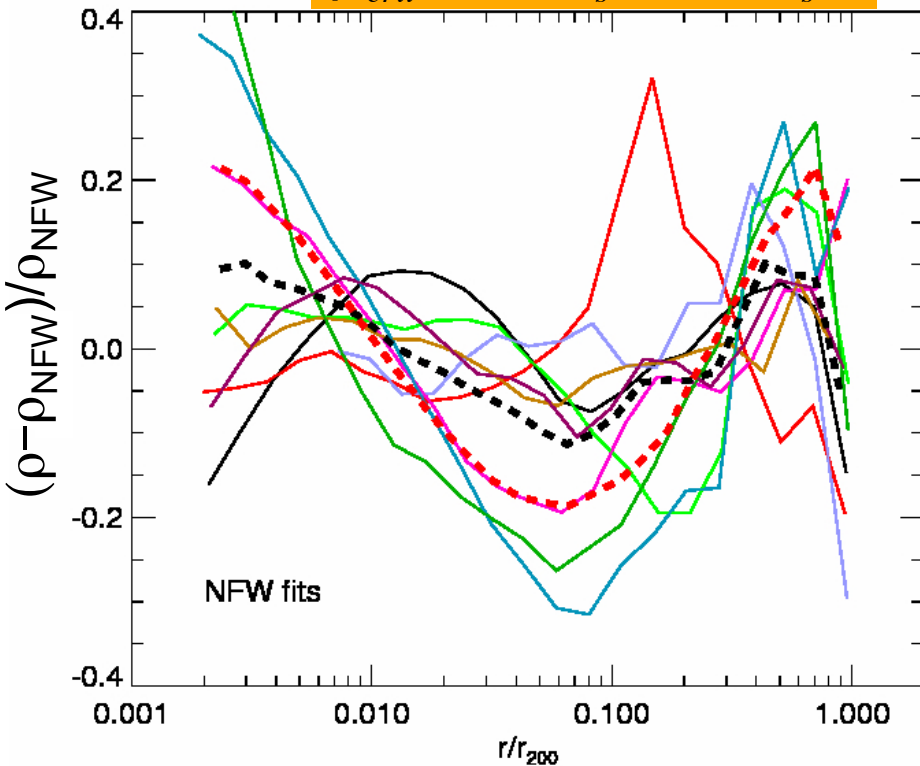
Dark matter density profile $\rho(r)$

Density profile nearly **universal**, but there are small differences between galaxies & clusters

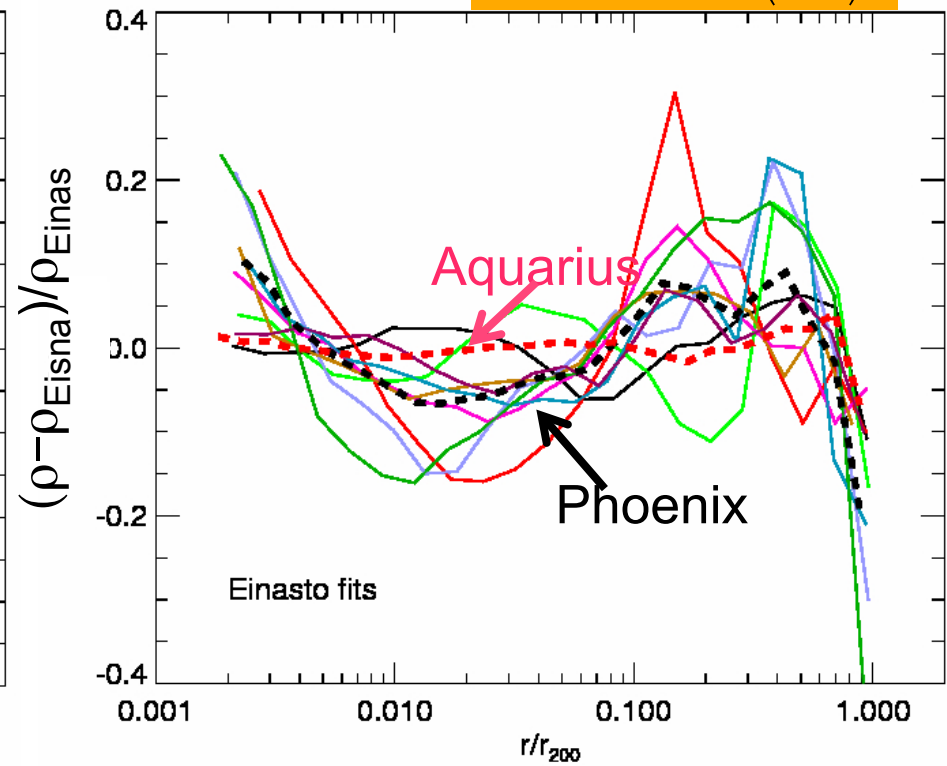


Deviations from NFW & Einasto forms

NFW
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$



Einasto
$$\frac{d \log \rho_\alpha}{d \log r} = -2 \left(\frac{r}{r_{-2}} \right)^\alpha$$

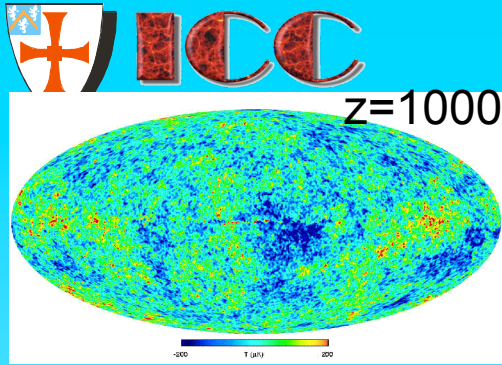


Galactic and cluster halos deviate from NFW by $\sim 10\text{-}20\%$
and from Einasto by $< \sim 7\%$

Navarro et al '04; Gao, Frenk, Jenkins, Springel & White '11

Galactic halos (without the galaxies)

- Halos are extended
 - Extend to ~ 10 times the 'visible' radius of galaxies and contain ~ 10 times the mass in the visible regions
- Halos are triaxial ellipsoids (not spherical)
 - more prolate than oblate
 - axial ratios greater than 2 are common
- Halos have nearly universal “cuspy” density profiles
 - $d \ln \rho / d \ln r = \gamma$ with $\gamma < -2.5$ at large r
 $\gamma \sim -1$ at small r
- Halos are clumpy
 - Substantial numbers of self-bound subhalos containing $\sim 10\%$ of the halo's mass



Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$; dark matter

Primordial fluctuations

$$\delta\rho/\rho(M, t)$$

Dark matter halos
(N-body simulations)

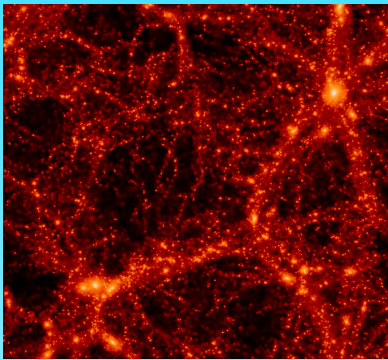
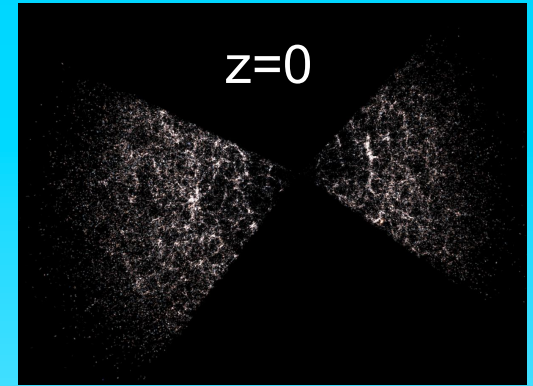
} Well understood

Gas processes
(cooling, star formation, feedback)

Gasdynamic simulations

Semi-analytics

Formation and evolution of galaxies



Semi-analytic modelling of galaxy formation

Galaxy formation in a CDM universe

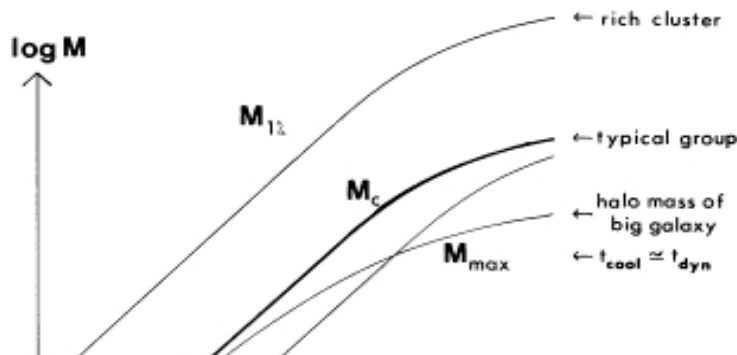
Mon. Not. R. astr. Soc. (1978) 183, 341–358

White & Rees '78

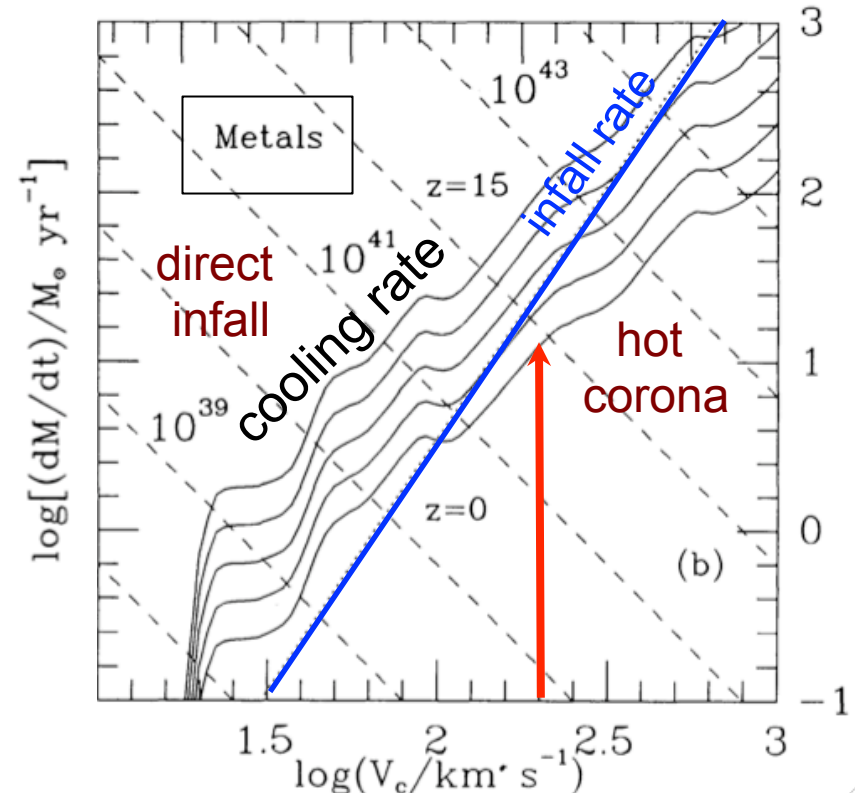
Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

S. D. M. White and M. J. Rees *Institute of Astronomy,
Madingley Road, Cambridge*

S. D. M. White and M. J. Rees



White & Frenk (1991)

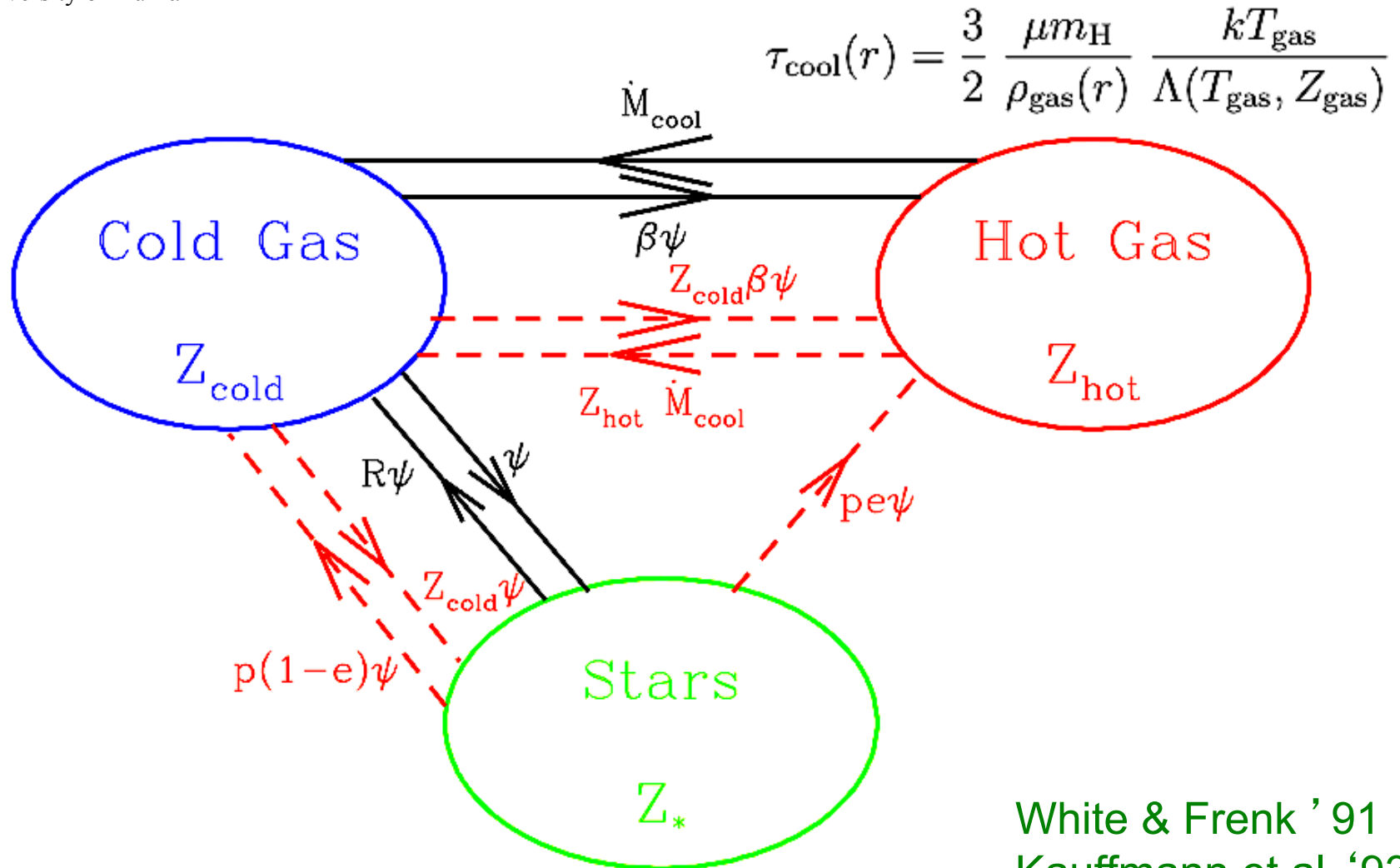


White & Rees calculated how gas cools and condenses into a

If $t_{\text{cool}} < t_{\text{dyn}}$ gas infalls directly (“cold flows”)

If $t_{\text{cool}} > t_{\text{dyn}}$ gas forms a hot corona and cools slowly

Evolution of baryons



White & Frenk '91
 Kauffmann et al '93
 Cole et al '94, '00

Evolution of baryons

Basic differential rate equations of Durham SA model:

$$\dot{M}_\star = (1 - R)\psi$$

$$\dot{M}_{\text{hot}} = -\dot{M}_{\text{cool}} + \beta\psi$$

$$\dot{M}_{\text{cold}} = \dot{M}_{\text{cool}} - (1 - R + \beta)\psi$$

$$\dot{M}_\star^Z = (1 - R)Z_{\text{cold}}\psi$$

$$\dot{M}_{\text{hot}}^Z = -\dot{M}_{\text{cool}}Z_{\text{hot}} + (pe + \beta Z_{\text{cold}})\psi$$

$$\dot{M}_{\text{cold}}^Z = \dot{M}_{\text{cool}}Z_{\text{hot}}$$

$$+ (p(1 - e) - (1 + \beta - R)Z_{\text{cold}})\psi,$$

Mass conservation

R = recycled fraction

ψ = star formation rate

Conservation of metals

β = SN feedback parameter

p = metal yield

e = fraction of metals ejected

White & Frenk '91,
Kauffmann et al '93
Cole et al '00

SFR & mass ejection

SFR

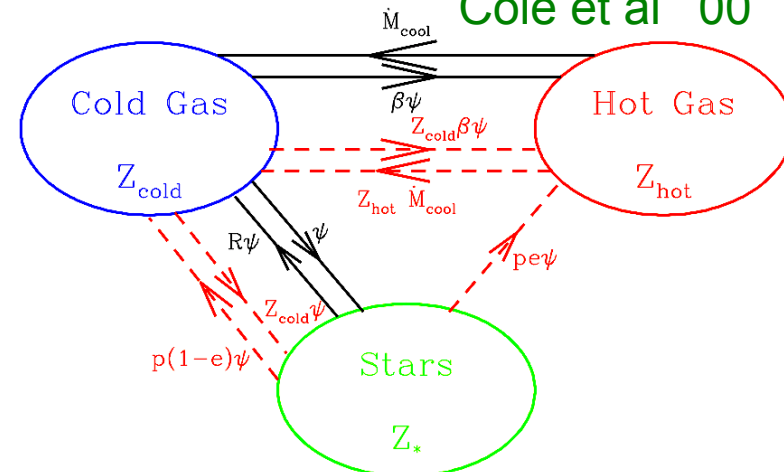
$$\psi = \frac{\dot{M}_{\text{cold}}}{\tau_\star(r_{\text{disk}}, V_{\text{disk}})}$$

SN
feedback

$$\dot{M}_{\text{eject}} = \beta(V_{\text{disk}})\psi$$

AGN
feedback

$$\dot{M}_{\text{BH}} = f_{\text{BH}}\psi_{\text{burst}} + \frac{L_{\text{cool}}}{c^2 \epsilon_{\text{SMBH}}}$$



Modelling galaxy formation

Gas dynamical processes

Flows - shocks - radiative cooling - heating

Hydrodynamical simulation



Solve hydro equations
numerically

Semi-analytic model



Assume spherical symmetry
& solve analytically

Astrophysical processes

- Star formation and SN feedback
- Production & mixing of metals
- Dust obscuration
- Galaxy mergers
- Reionization
- Evolution of stellar pops
- AGN feedback

Modelling galaxy formation

Gas dynamical processes

Flows - shocks - radiative cooling - heating

Hydrodynamical simulation



Solve hydro equations
numerically

Semi-analytic model



Assume spherical symmetry
& solve analytically

“Subgrid physics”

Phenomenological model

- Star formation and SN feedback
- Production & mixing of metals
- Dust obscuration
- Galaxy mergers

- Reionization
- Evolution of stellar pops
- AGN feedback

Modelling galaxy formation

Gas dynamical processes

Flows - shocks - radiative cooling - heating

Hydrodynamical simulation



Solve hydro equations
numerically

Semi-analytic model



Assume spherical symmetry
& solve analytically

“Subgrid physics”

- + Gas dynamics in full generality
- Limited dynamic range
- Expensive: cannot explore range of subgrid models

Phenomenological model

- Approximate gas dynamics
- + Unlimited dynamic range
- + Can easily explore different subgrid models

Modelling galaxy formation

Model baryonic processes:

Semi-analytic model

- Used for galaxy populations (luminosity fns., scaling relations...)
- Ideal for modelling complex processes (e.g. dust obsctn/emission)
- Can be applied in N-body simulations of very large volumes

Hydrodynamical simulations

- New generation → gas & gal. population in volume $\sim (100\text{Mpc})^3$
- Ideal for asymmetric processes (e.g. gas accretion in filaments)
- Internal structure of galaxies & clusters

Modelling galaxy formation: myth and reality

Three myths about semi-analytic modelling:

- It has loads of parameters
- You can tune the parameters to fit any observation you want
- The results are uninformative (“you don’t learn anything new”)

Three myths about cosmological gas simulations:

- They have few or no free parameters
- They solve the correct physics equations
- They give the truth

“Myth” (Oxford dictionary):
“a widely held but false belief or idea”

Evolution of baryons

Basic differential equations of Durham SA model:

$$\dot{M}_\star = (1 - R)\psi$$

$$\dot{M}_{\text{hot}} = -\dot{M}_{\text{cool}} + \beta\psi$$

$$\dot{M}_{\text{cold}} = \dot{M}_{\text{cool}} - (1 - R + \beta)\psi$$

$$\dot{M}_\star^Z = (1 - R)Z_{\text{cold}}\psi$$

$$\dot{M}_{\text{hot}}^Z = -\dot{M}_{\text{cool}}Z_{\text{hot}} + (pe + \beta Z_{\text{cold}})\psi$$

$$\dot{M}_{\text{cold}}^Z = \dot{M}_{\text{cool}}Z_{\text{hot}}$$

$$+ (p(1 - e) - (1 + \beta - R)Z_{\text{cold}})\psi,$$

R = recycled fraction

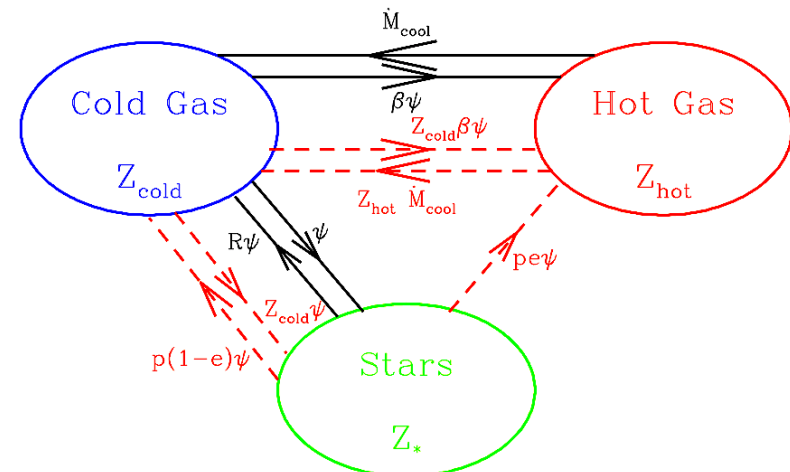
ψ = star formation rate

β = SN feedback parameter

p = metal yield

e = fraction of metals ejected

White & Frenk '91,
Kauffmann et al '93
Cole et al '00



Free parameters in SA models

White & Frenk '91; Kauffmann et al '93; Cole et al. '00

Semi-analytics

SFR & mass ejection

SFR $\psi = \frac{M_{\text{cold}}}{\tau_{\star}(r_{\text{disk}}, V_{\text{disk}})}$

SN feedback $\dot{M}_{\text{eject}} = \beta(V_{\text{disk}}) \psi$

AGN feedback $\dot{M}_{\text{BH}} = f_{\text{BH}} \psi_{\text{burst}} + \frac{L_{\text{cool}}}{c^2 \epsilon_{\text{SMBH}}}$

SFR timescale

$$\tau_{\star} \propto \tau_{\text{dyn,disk}} V_{\text{disk}}^{\alpha_{\star}}$$

SN feedback efficiency

$$\beta = (V_{\text{disk}}/V_{\text{hot}})^{-\alpha_{\text{hot}}}$$

AGN feedback efficiency

$$f_{\text{BH}}, \epsilon_{\text{SMBH}}$$

Basic SA model has 6 free parameters (plus IMF):

SFR: $\tau_0, \alpha_{\star}$; **SN feedback:** $\alpha_{\text{hot}}, V_{\text{hot}}$; **AGN feedback:** $f_{\text{BH}}, \epsilon_{\text{SMBH}}$

→ gives mass in stars, gas and metals at all times

To turn into observables, need extra modelling: dust, morphology...

Free parameters in simulations

“Subgrid physics” (i.e. rules for astrophysics below resolution)

Star formation: $\rho > \rho_{\text{th}}$; $T < T_{\text{th}}$ or $P = k\rho^\gamma$; ϵ_{SF}

SN feedback $\left\{ \begin{array}{l} - \text{kinetic } (\Delta t, \epsilon_{\text{SN}}, V_{\text{wind}}, \beta) \\ - \text{thermal } (\Delta t, \epsilon_{\text{SN}}, T_{\text{heat}}) \end{array} \right.$

AGN Feedback: $\dot{M}_{\text{BH}}, E_{\text{BH}}, T_{\text{heat}}, \epsilon_{\text{rad}} \dots$

Subgrid physics requires many assumption and parameters
and there are also numerical parameters

The goals of gal. population models

- Explore the statistics and interaction of the many **processes** affecting stars and gas within growing CDM structures
- Understand how the effects of these processes are reflected in the various observed population properties of galaxies and their evolution -- **abundances, scaling relations, clustering, etc**
- Allow **interpretation** of large observational surveys in terms of the rates, efficiencies and significance of these processes
- **NOT** to make a definitive *a priori* physical model for the formation of everything from linear Λ CDM initial conditions



Semi-analytical models (1991 -)

SA galaxy formation models: successes and failures

Major successes:

- The galaxy luminosity fn. in visible/near-IR and stellar mass fn.
- Evolution of galaxy luminosity function
- Galaxy formation – AGN connection; AGN phenomenology
- Galaxy clustering on large scales, e. g. BAO

(Some) partial successes:

- Scaling relations (TF; sizes; metallicities)
- History of cosmic star formation
- The galaxy luminosity fn in other bands (inc submm) & its evolution

SA galaxy formation models: successes and failures

Main failures:

- Environmental dependence of galaxy properties (e.g. colour)
- Galaxy clustering on small scales
- Galaxy morphology and sizes
- Effect of galaxy on DM halo
- Chemical abundance ratios

SA galaxy formation models: successes and failures

Major successes:

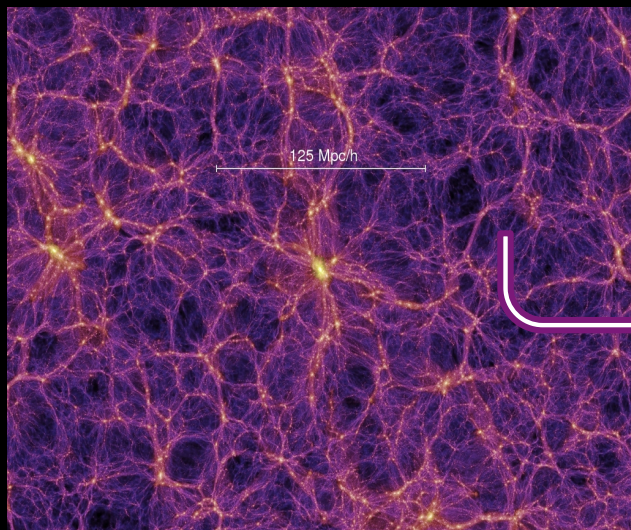
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(Some) partial successes:

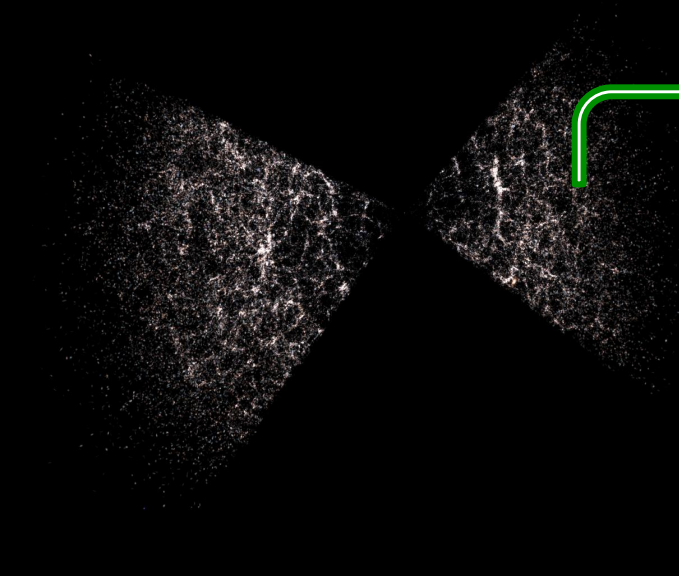
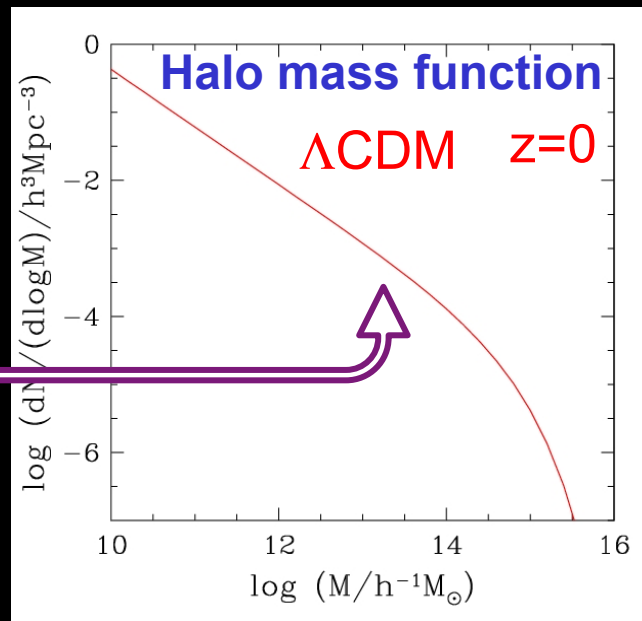
- Scaling relations (TF; sizes; metallicities)
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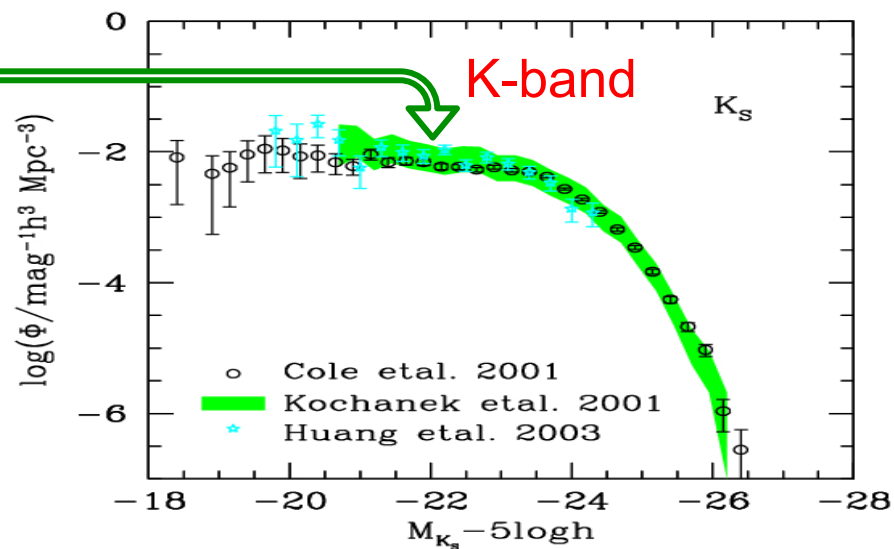
Abundance of gals & dark halos



Millennium run



2dFGRS

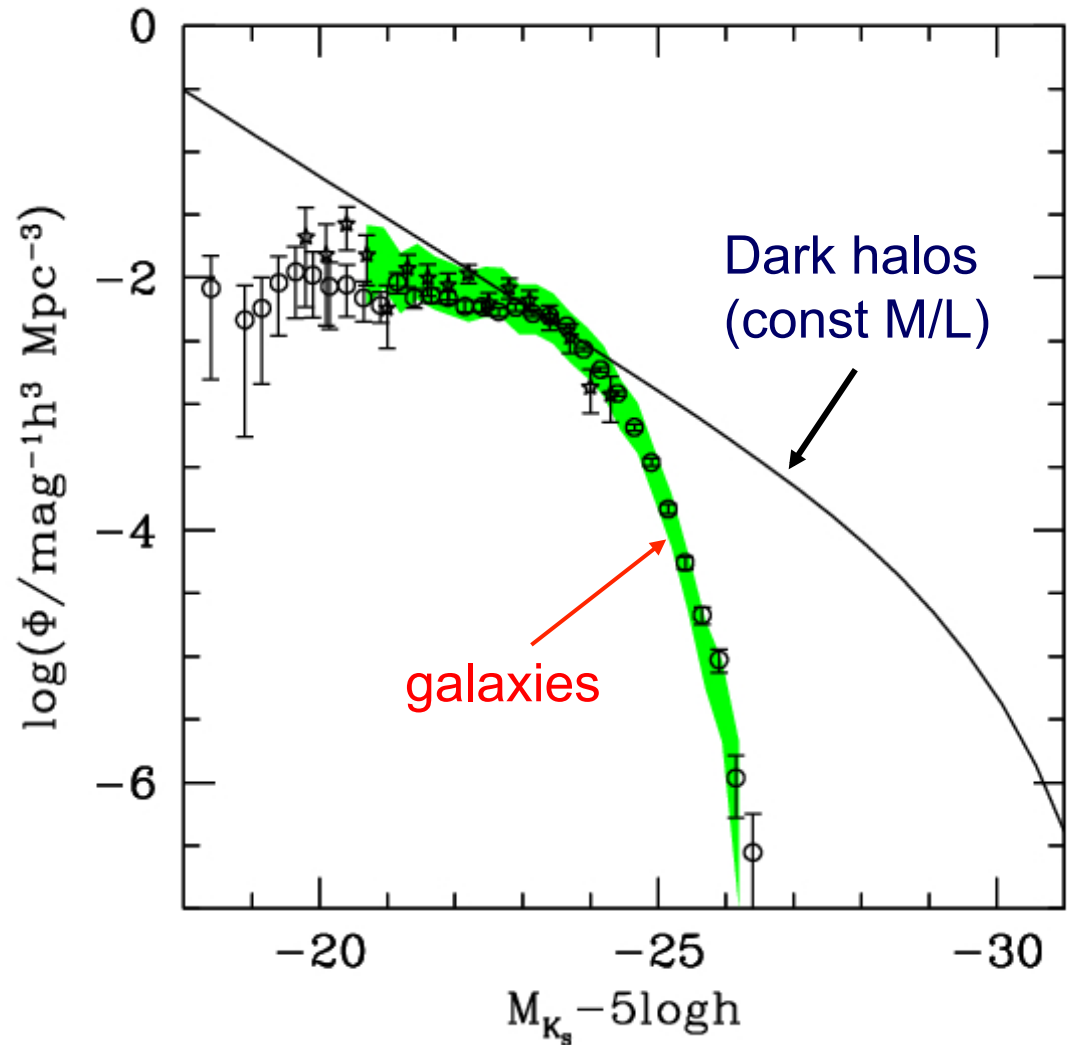


The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes

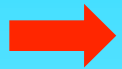


Complicated variation of M/L with halo mass



Deconstructing the galaxy LF

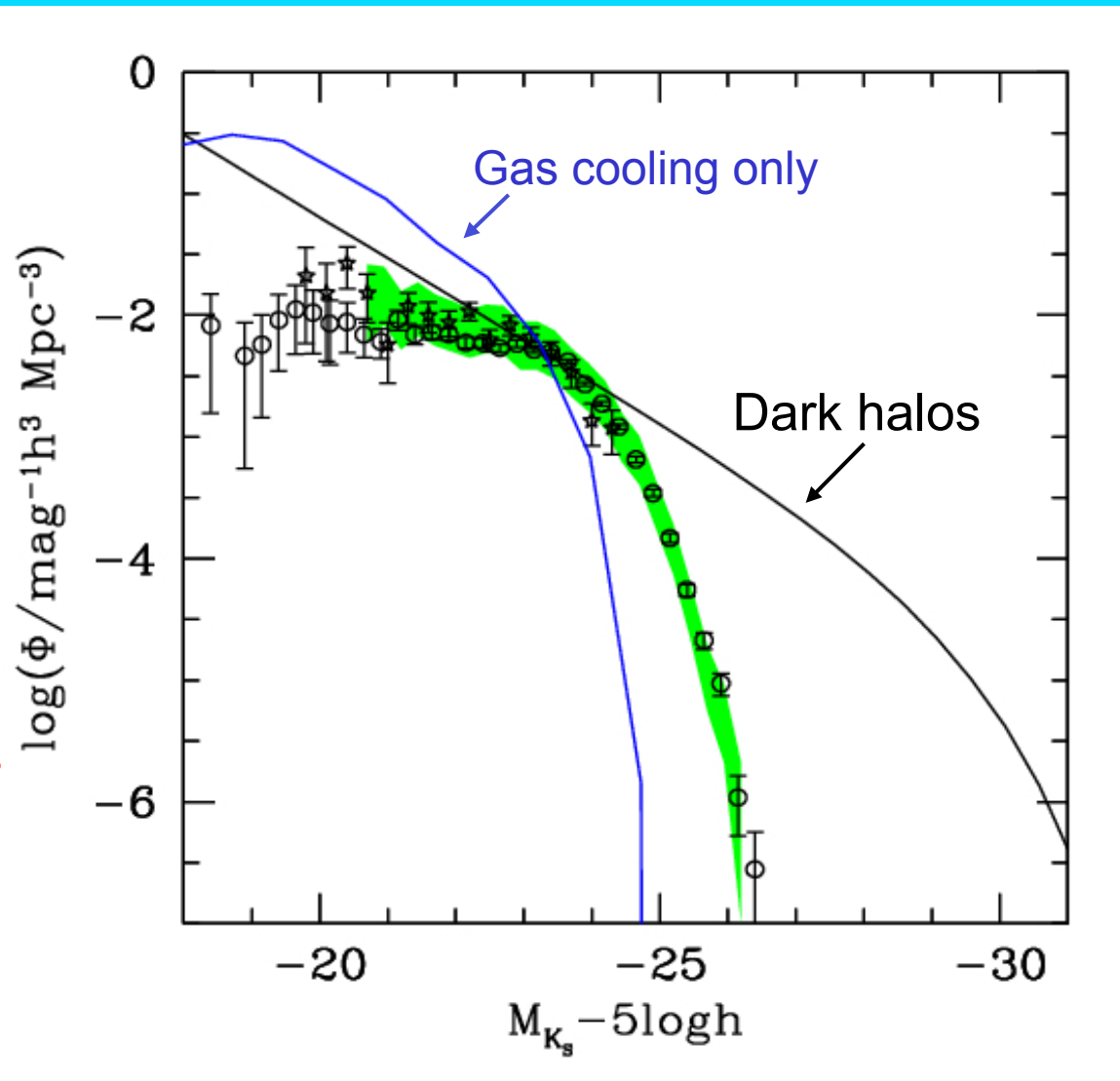
Gas cooling only



Gas cools in small halos
at early times ($t_{\text{cool}} \ll t_{\text{dyn}}$)



Faint end – too many gals
Bright end – too few gals



Deconstructing the galaxy LF

Cooling + photoionisation

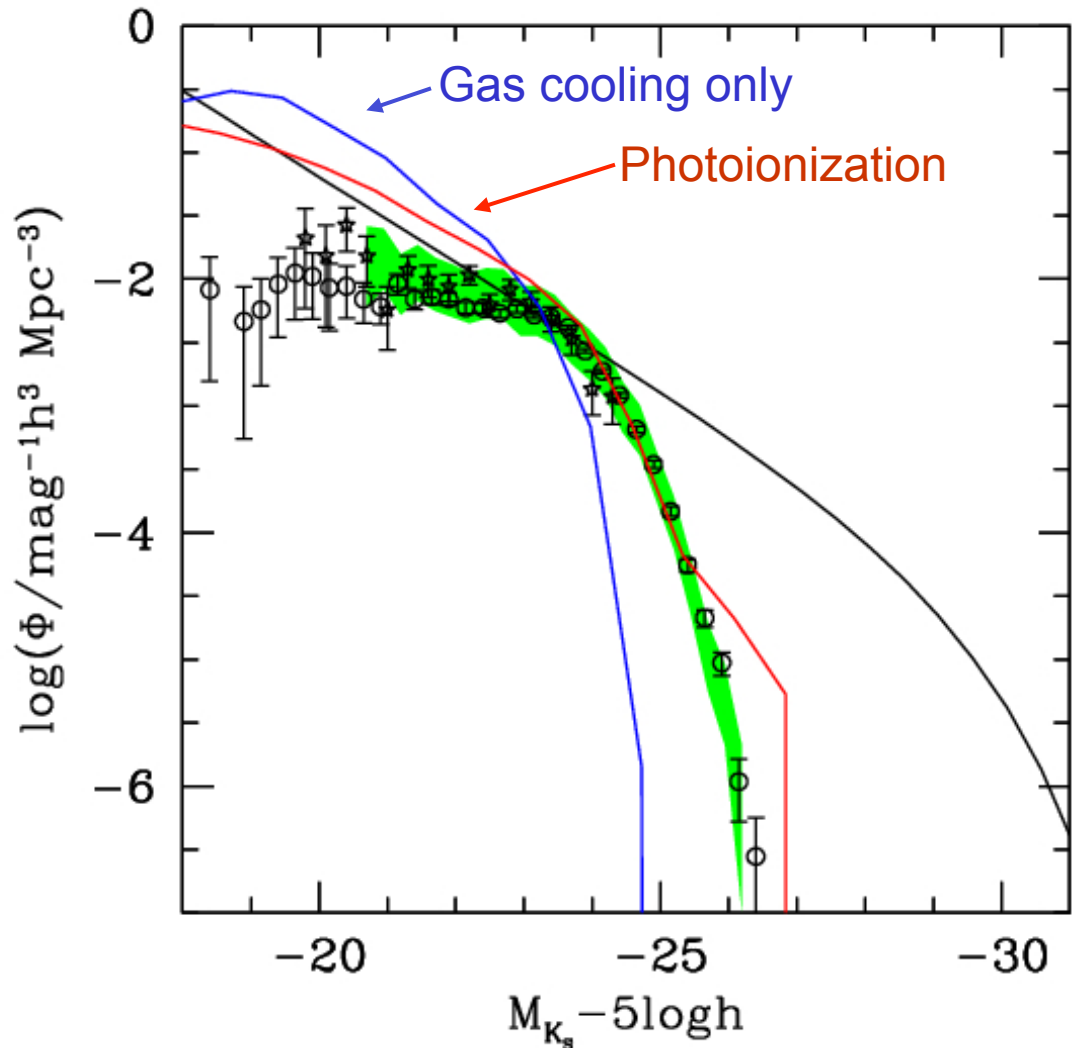
No energy injection, ie:

No SN feedback

Photoionization **flattens**
faint end, leaving enough
gas to make bright gals.

(Main effect: gas pressure)

Need additional
source(s) of feedback



Deconstructing the galaxy LF

Cooling + photoionisation
+energy feedback (reheat)

Faint end:

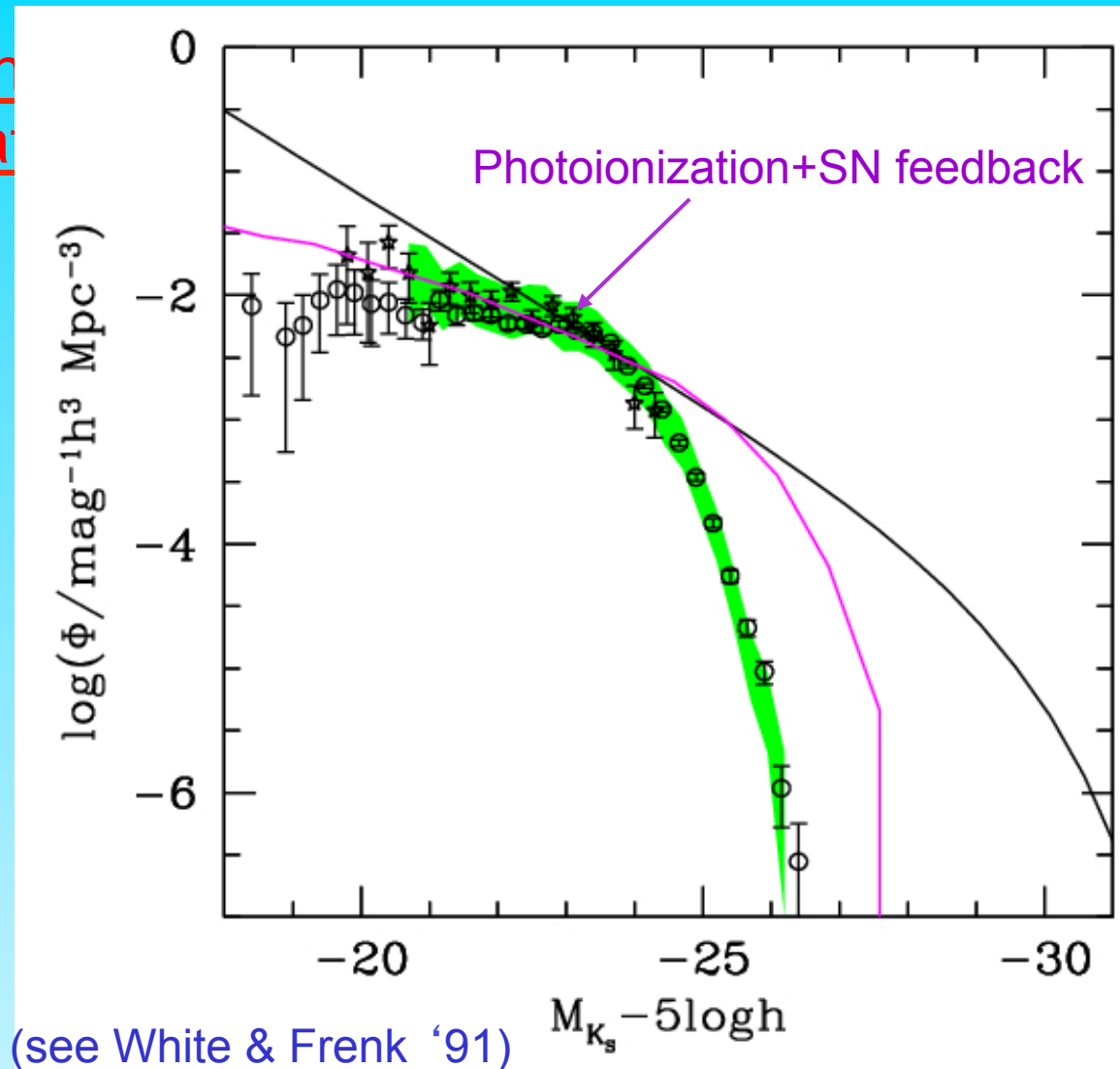
Can be explained by

- ✓ Reionization
- ✓ SNe feedback

Bright end:

→ Too many bright galaxies

Need to prevent too much gas cooling in large halos



(see White & Frenk '91)

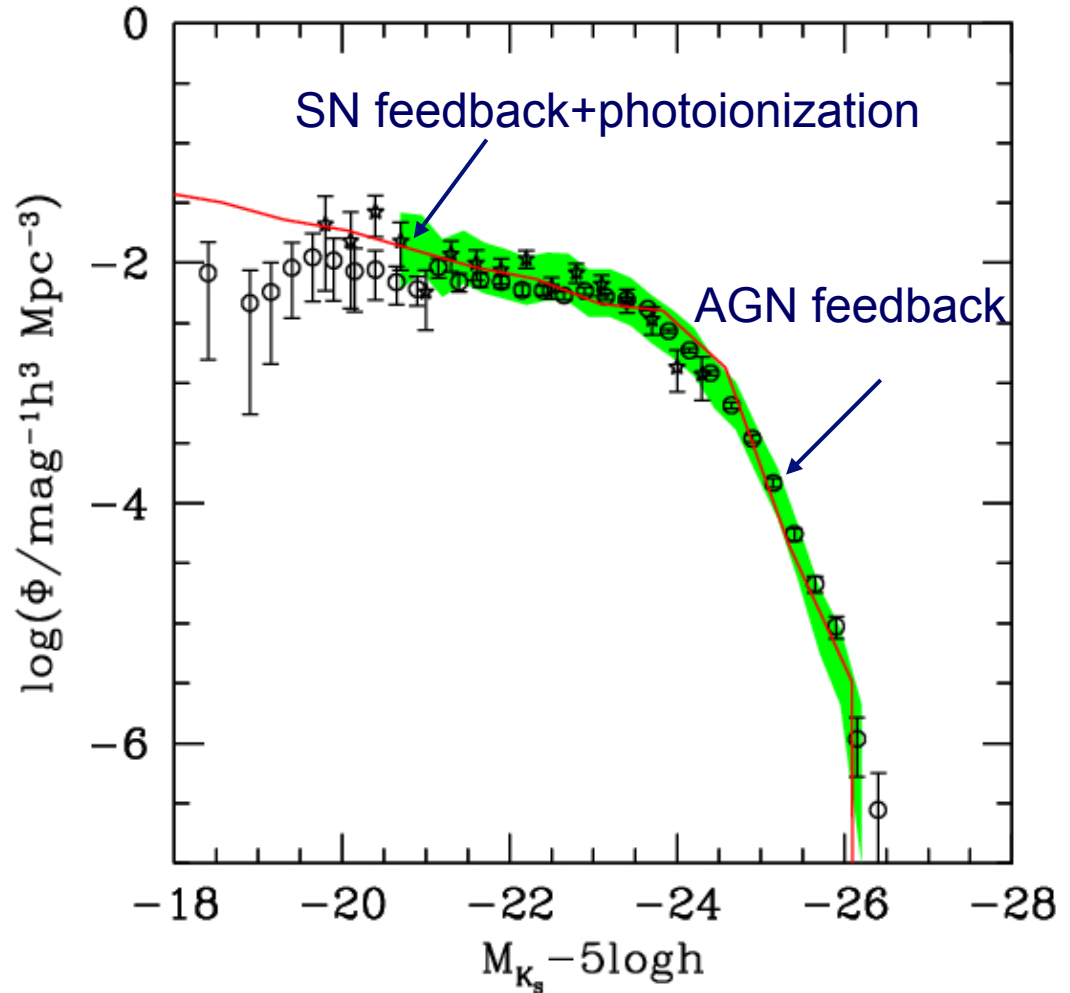
Deconstructing the galaxy LF

Faint end:

Photoionization +
reheating of cold
disk gas by SN

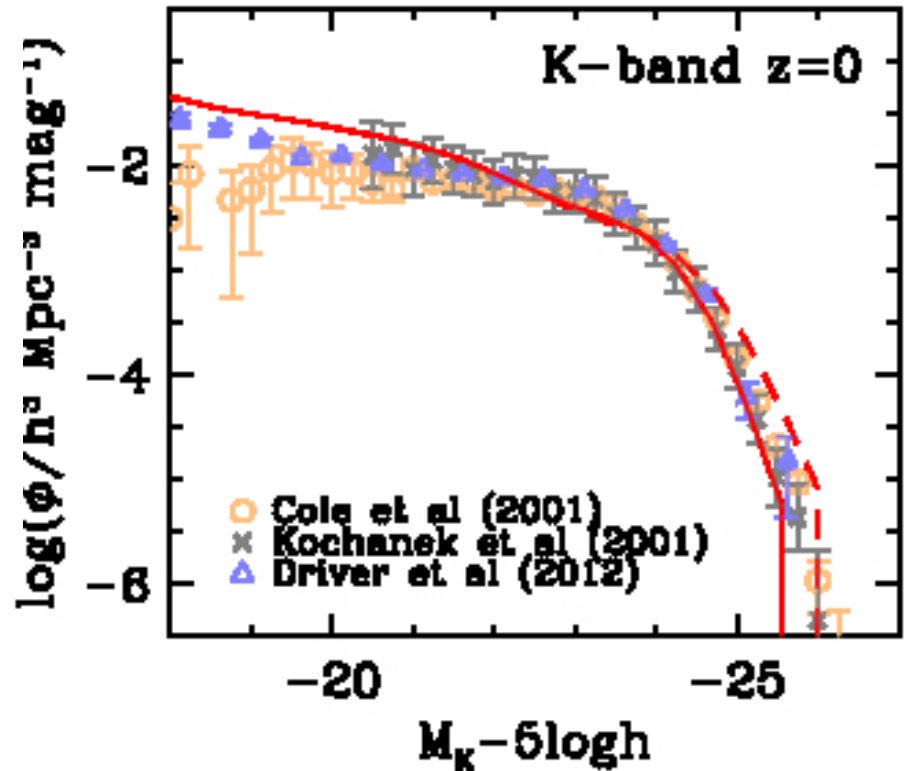
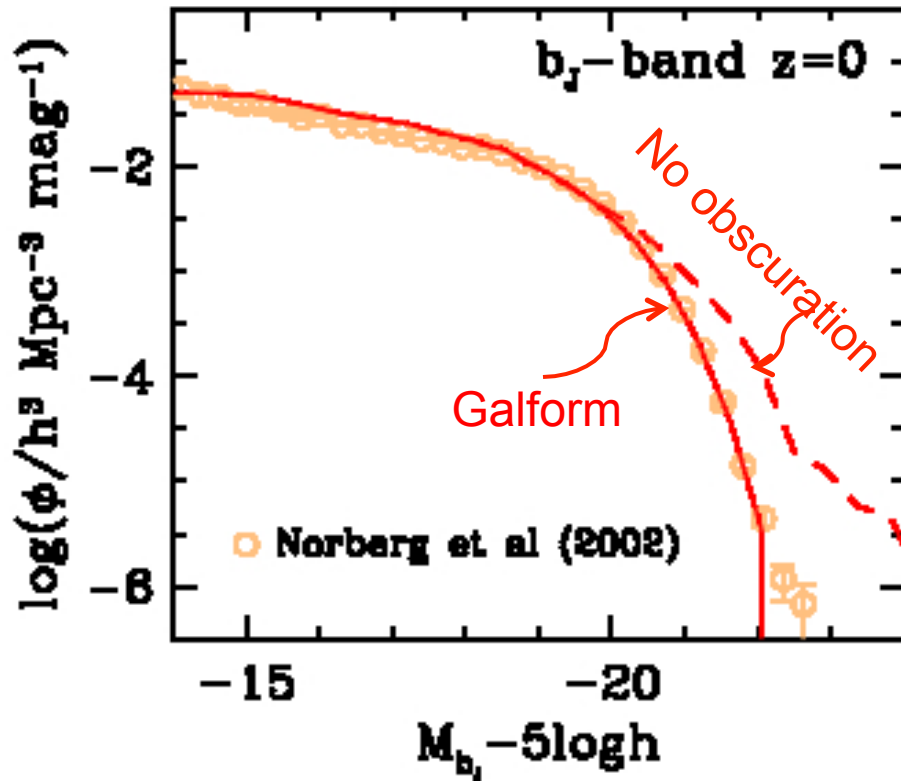
Bright end:

AGN feedback:
energy transported
by bubbles



The galaxy luminosity function

Not a “prediction” of the model – parameters adjusted to get this match!



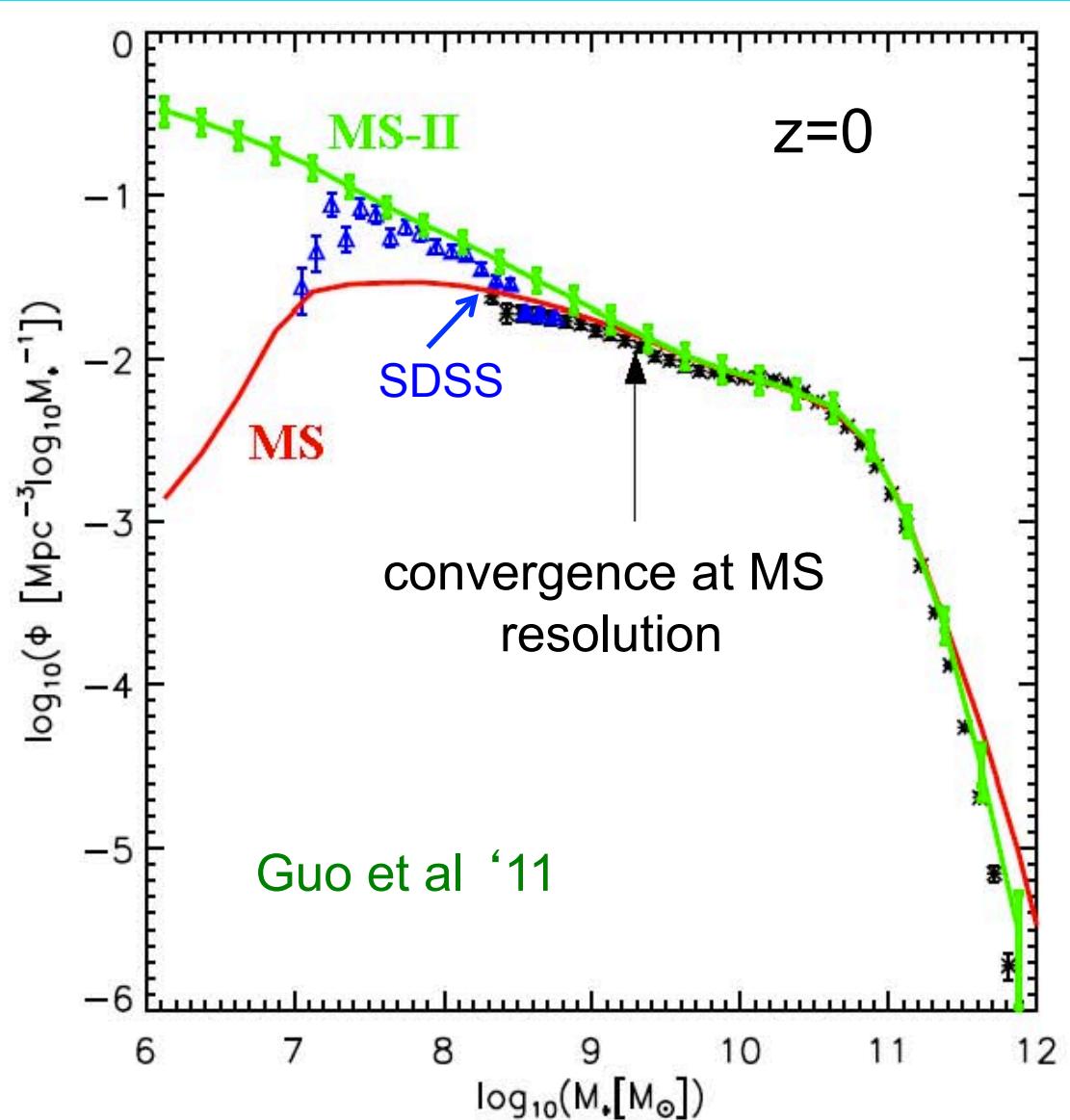
Lacey et al. '15

The stellar mass function

Results for MS and
M-II converge

Simulated mass function
fits the data over 5
decades in stellar mass!

Guo et al. '11



SA galaxy formation models: successes and failures

Major successes:

- The galaxy luminosity fn. in visible/near-IR and stellar mass fn.
- Evolution of galaxy luminosity function
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- Galaxy clustering on large scales, e. g. BAO

(Some) partial successes:

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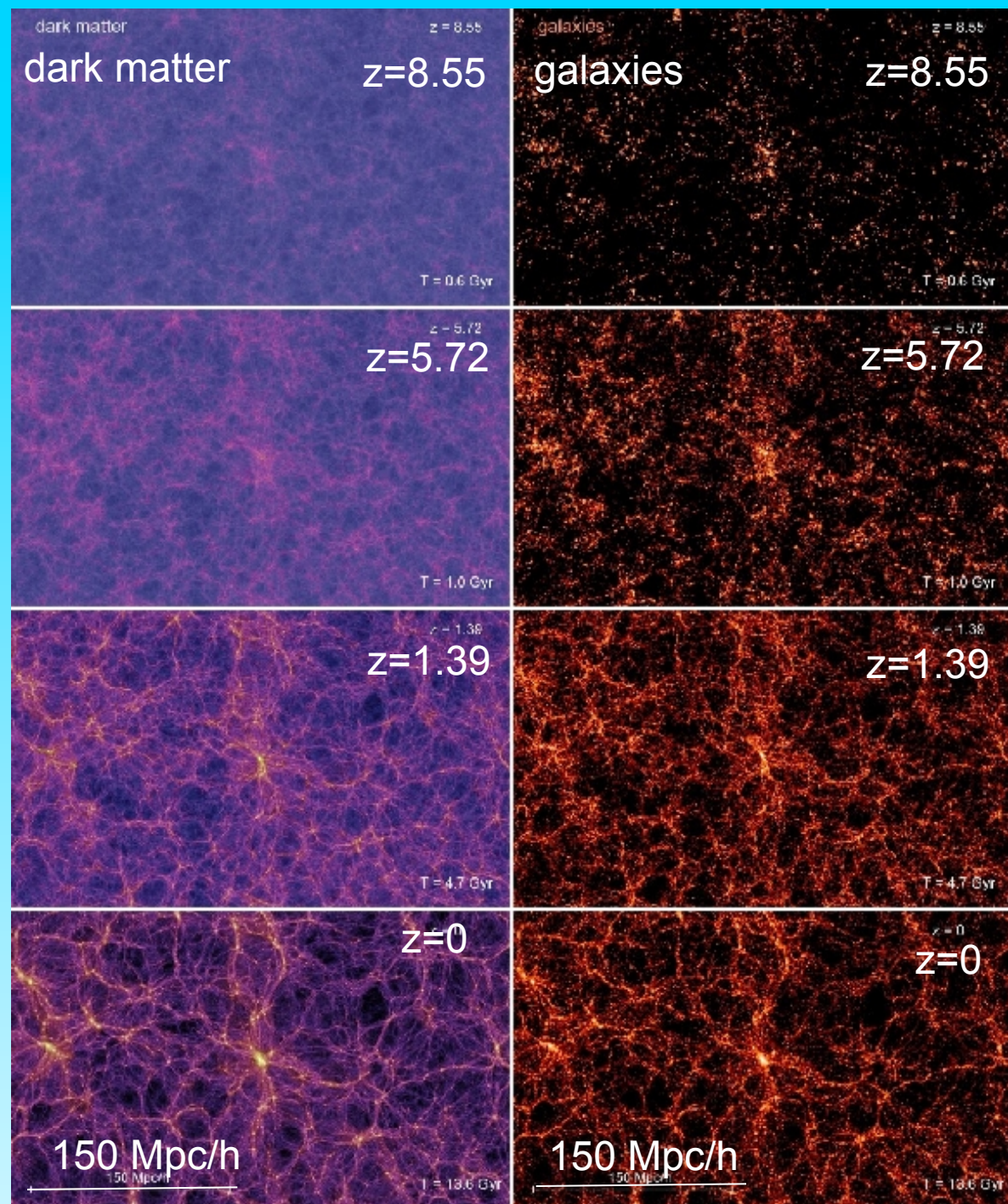
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Millennium Simulation

At early times, the **dark matter** is **smooth**, but the **galaxies** are already strongly **clustered**

Springel, Frenk & White
Nature, May/06



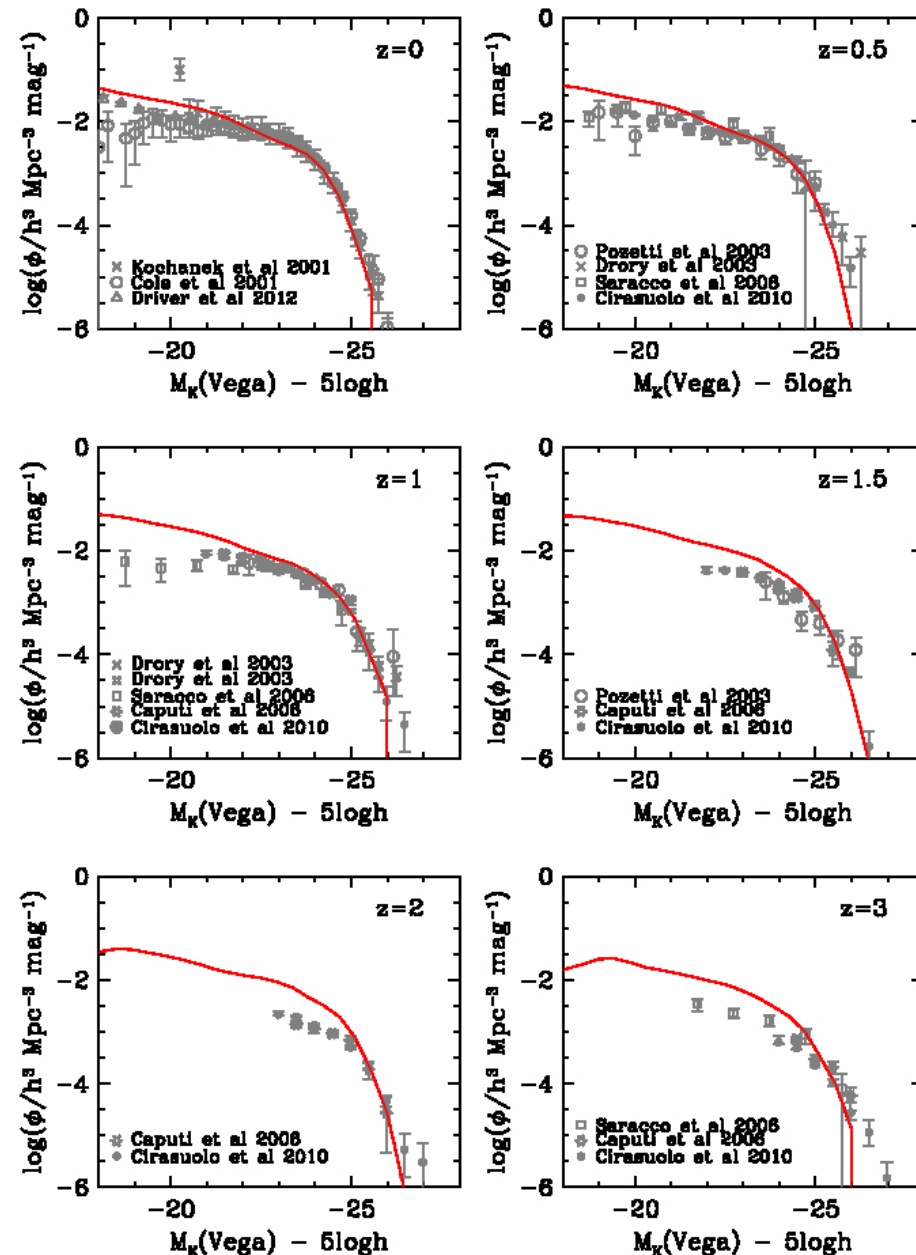
Evolution of the luminosity fn.

GALFORM

GALFORM gives excellent match to the evolution of the K-band galaxy luminosity function to $z=3$

This is a genuine prediction!

Lacey, Baugh, Frenk et al. '15



SA galaxy formation models: successes and failures

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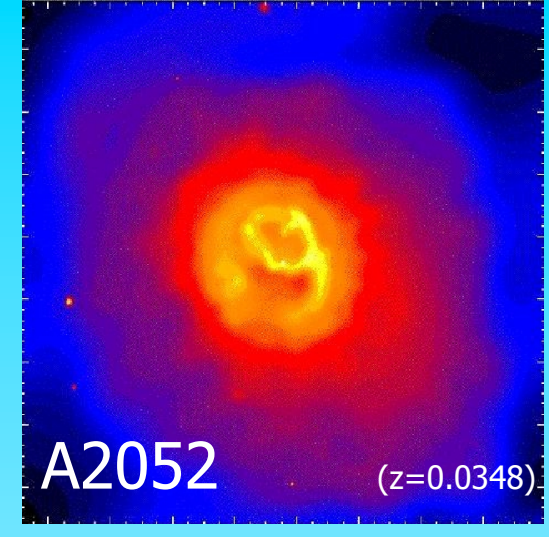
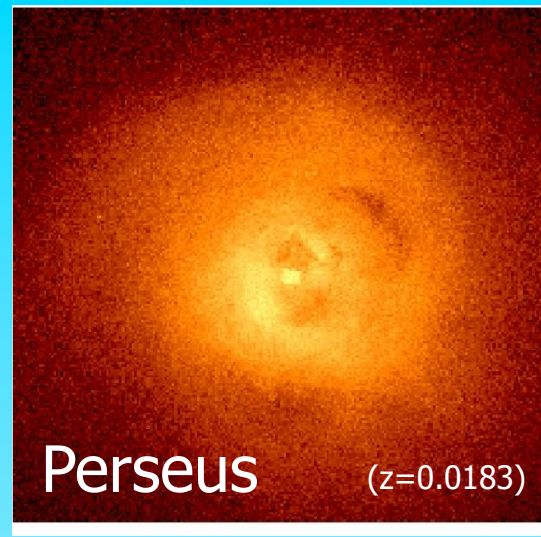
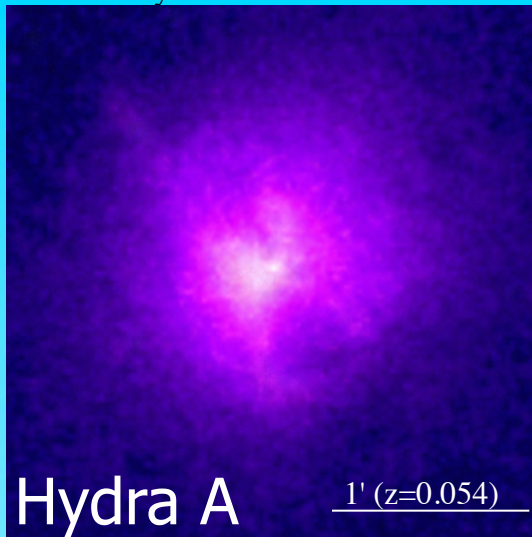
- Scaling relations (TF; sizes; metallicities)
- History of cosmic star formation
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AGN Feedback & gal formation

AGN feedback solves three major problems:

- Why is there a **bright cutoff** in the galaxy luminosity function?
- Why are there **no cooling flows** in clusters ?
- Why are the brightest galaxies **old, red** and **elliptical** ?
(The “**hierarchy**” problem)

Chandra Gallery of Cluster Cores



Cooling time of central gas $\ll$ age of cluster

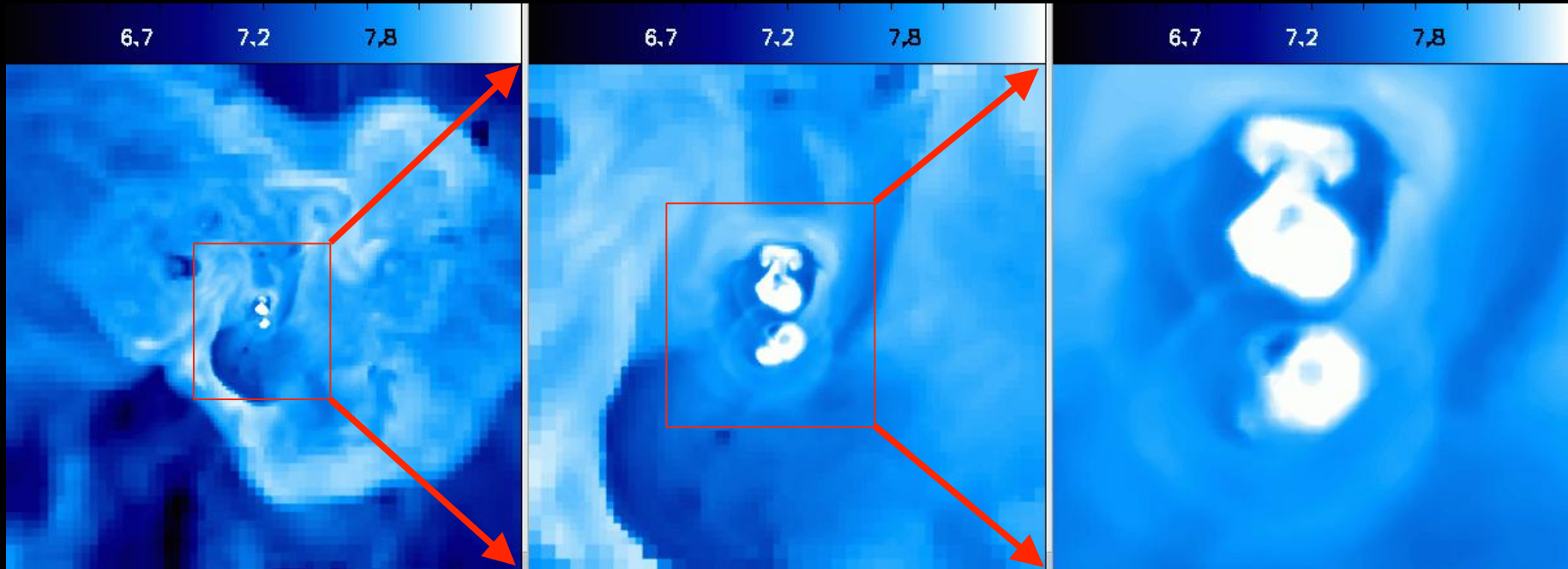
⇒ Gas should be cooling radiatively and flowing to the centre

No evidence for cooling flow -- “cluster cooling flow problem”

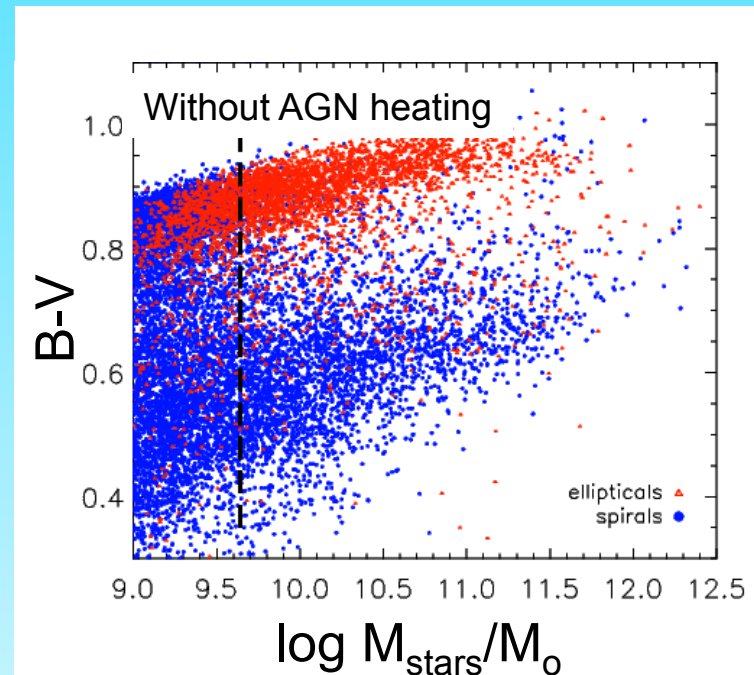
⇒ Something must be heating the gas!

I

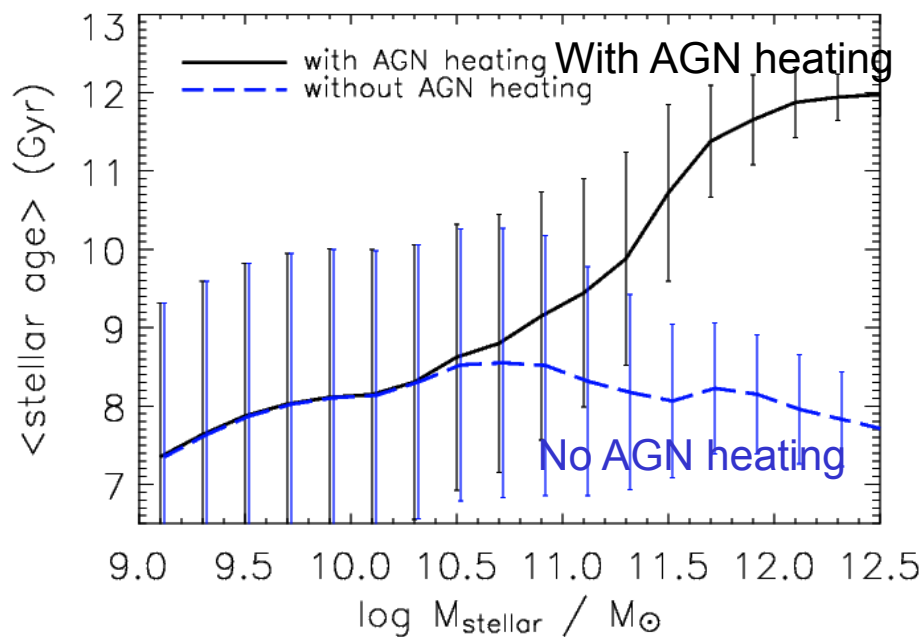
Buoyantly rising bubbles - temperature slice



The most massive
galaxies are red,
elliptical

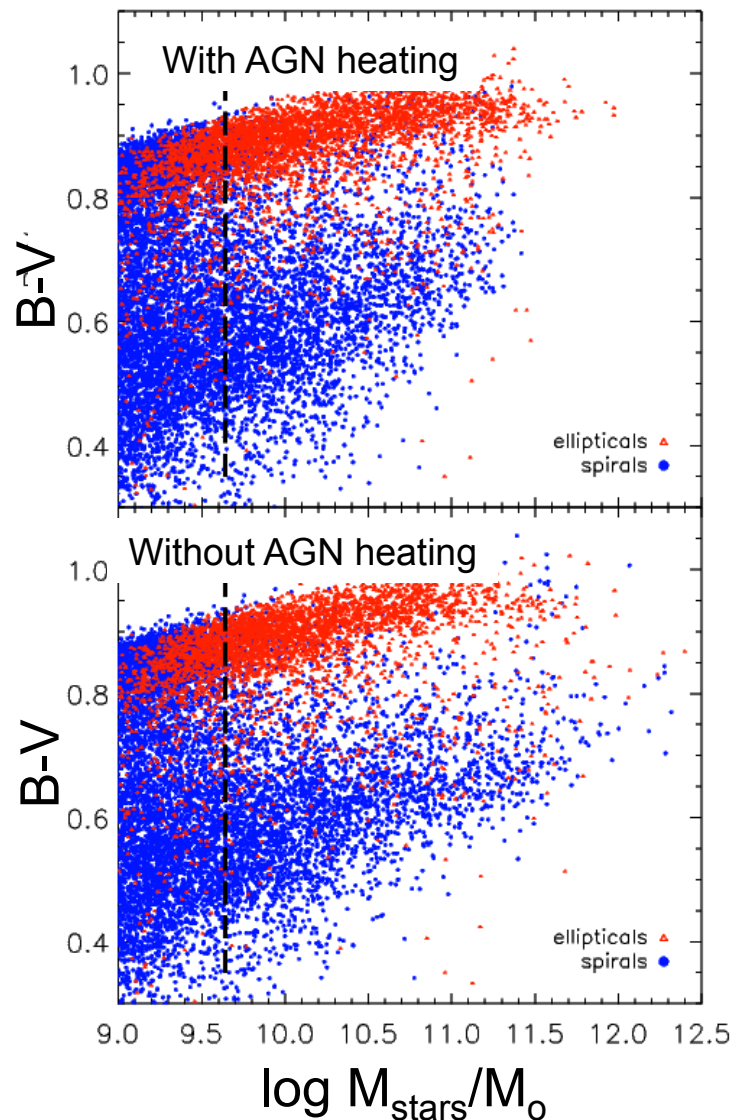


The most massive galaxies are red, elliptical



and old!!

Croton et al 05



AGN Feedback & gal formation

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- Why is there a **bright cutoff** in the galaxy luminosity function?
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- Why are the brightest galaxies **old, red** and **elliptical** ?
(The “**hierarchy**” problem)

... and as a bonus, automatically get the $M_{\text{BH}} - M_{\text{stellar}}$ relation!

Black holes and galaxy formation

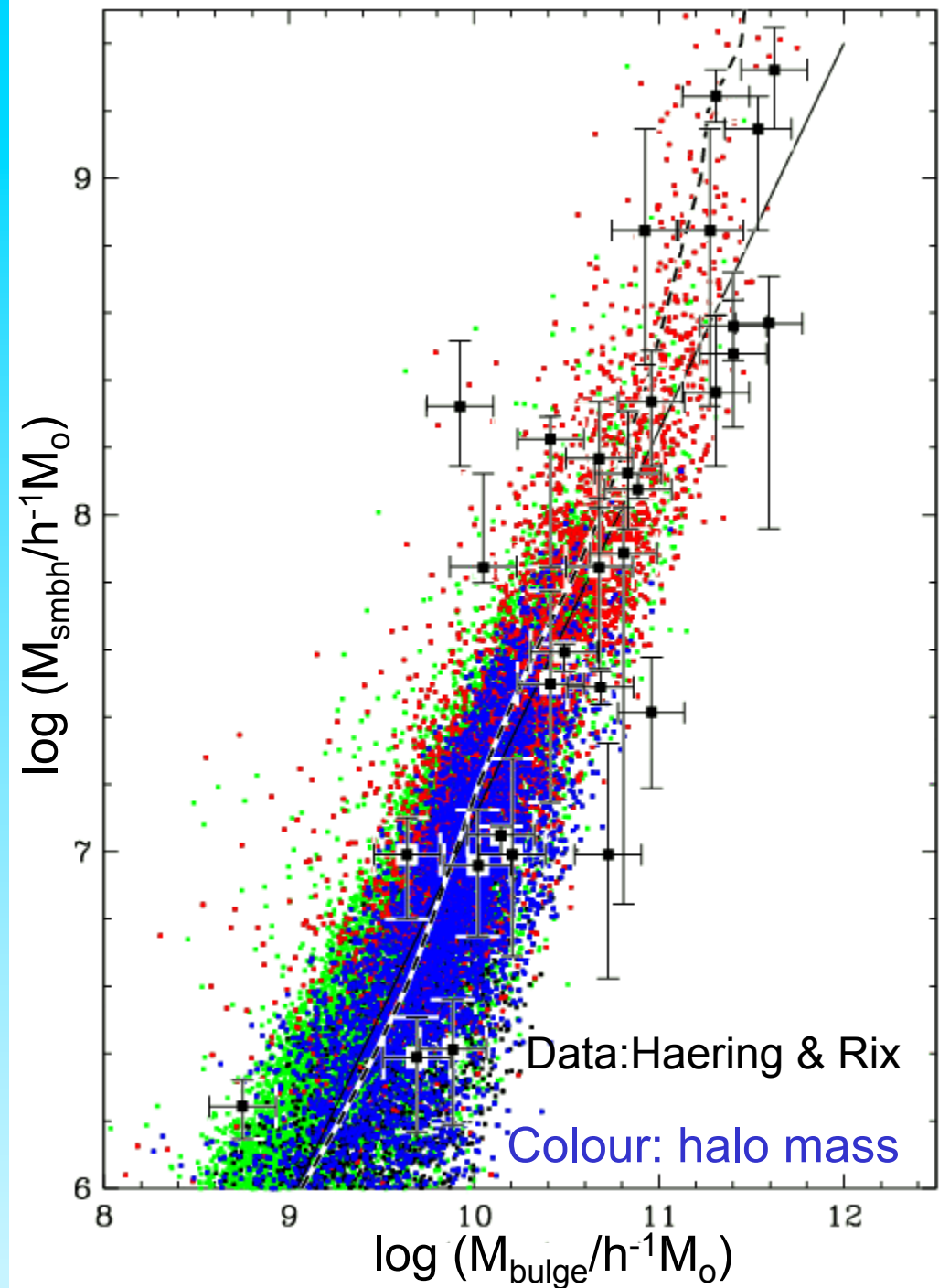
B-H mass vs bulge mass

Free parameter: fraction f_{BH}
of gas accreted by BH

f_{BH} fixes normalization;
slope and scatter are free

BH growth during feeding phase
steepens slope at large M

Bower et al 06



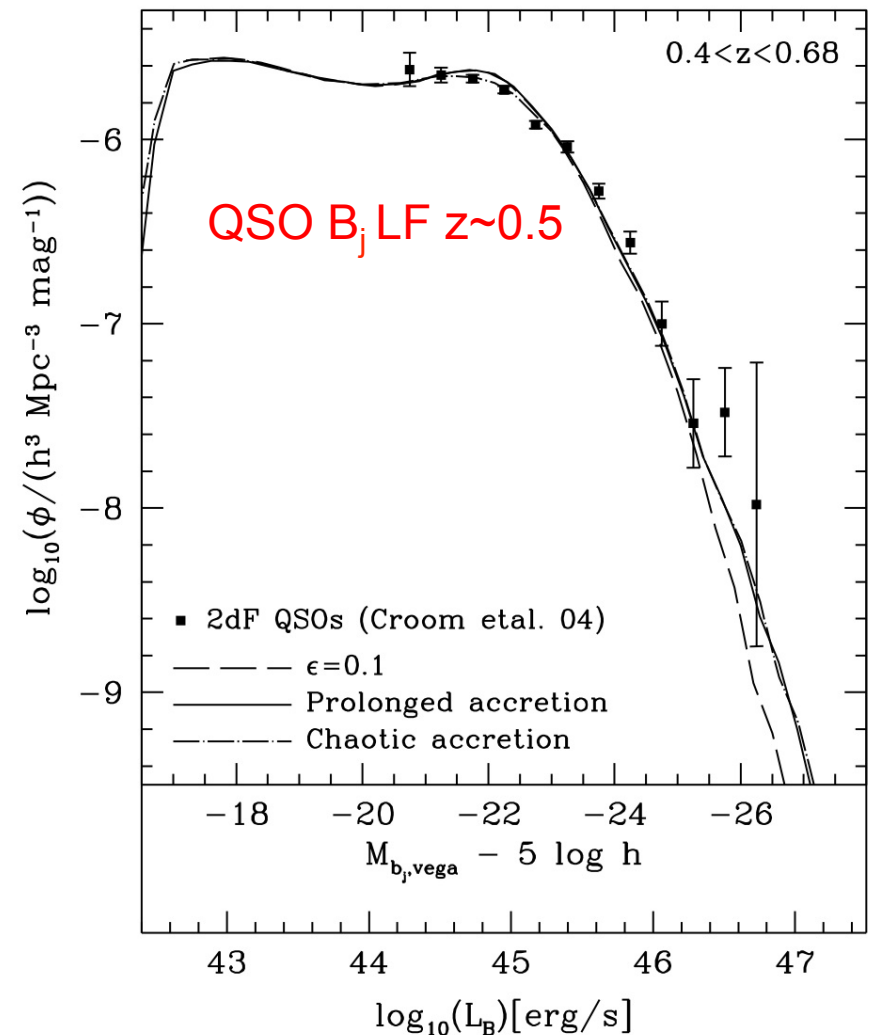
Semi-analytic modelling: the galaxy-QSO connection

With an extra layer of modelling, can calculate evolution of **black hole** mass, spin and mass accretion history

→ luminosity functions (LF) of **AGN** (optical, soft/hard X-rays, bolometric) for wide range of redshifts ($0 < z < 6$).

Fanidakis et al. '10, 12, 13a 13b

QSO luminosity function



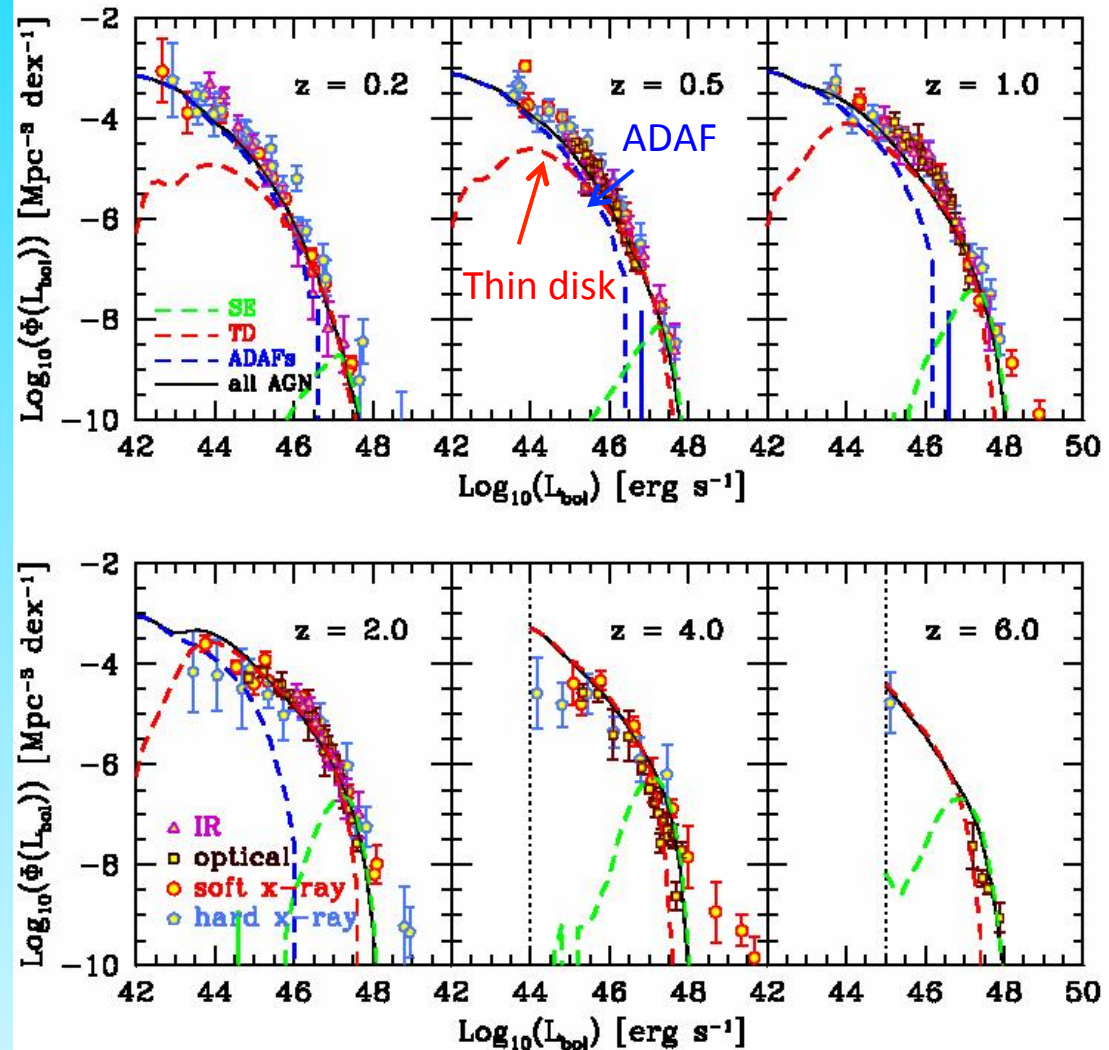
Semi-analytic modelling: the galaxy-QSO connection

Evolution of bolometric luminosity of AGN

Faint end: mainly AGN powered by **ADAFs** (massive BHs accreting in hot halo mode)

Bright end: mainly AGN powered by **thin disk** accretion in γ -burst mode

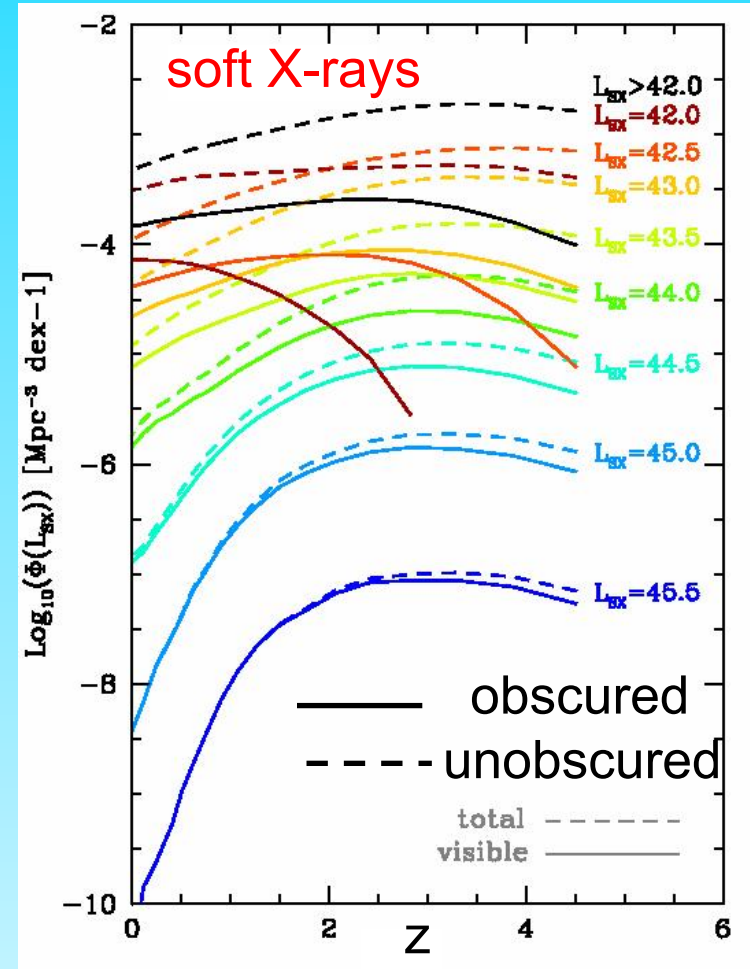
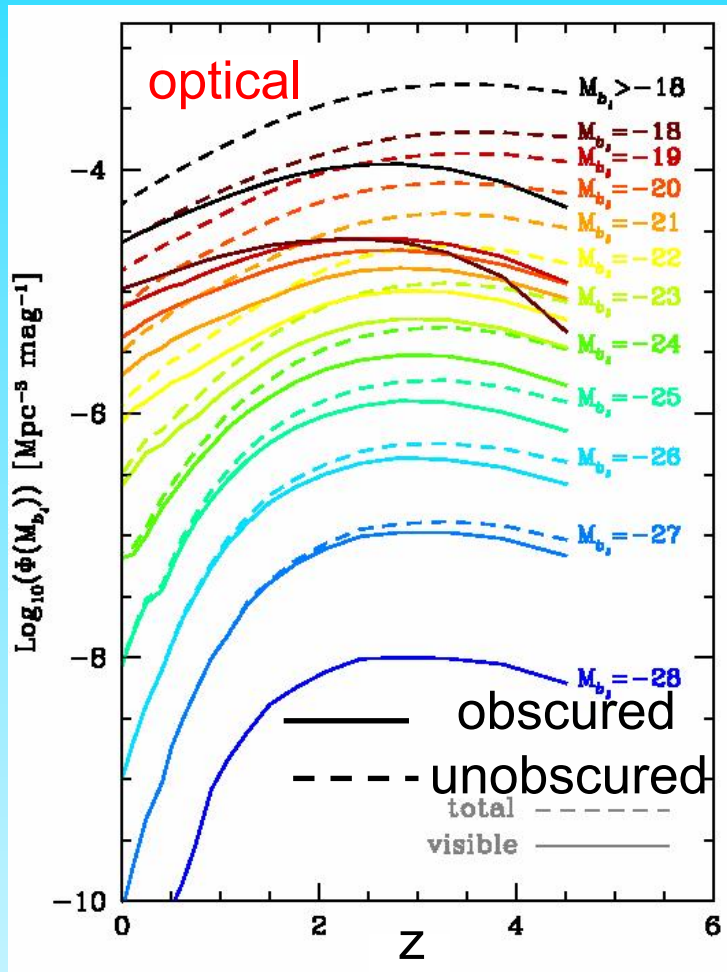
Fanidakis et al.12



AGN evolution: downsizing

comoving space density of AGN peaks at $z \sim 3$

Including obscuration $\rightarrow$ faint AGN peak at $z < 2$; bright at $z \sim 2-3$



SA galaxy formation models: successes and failures

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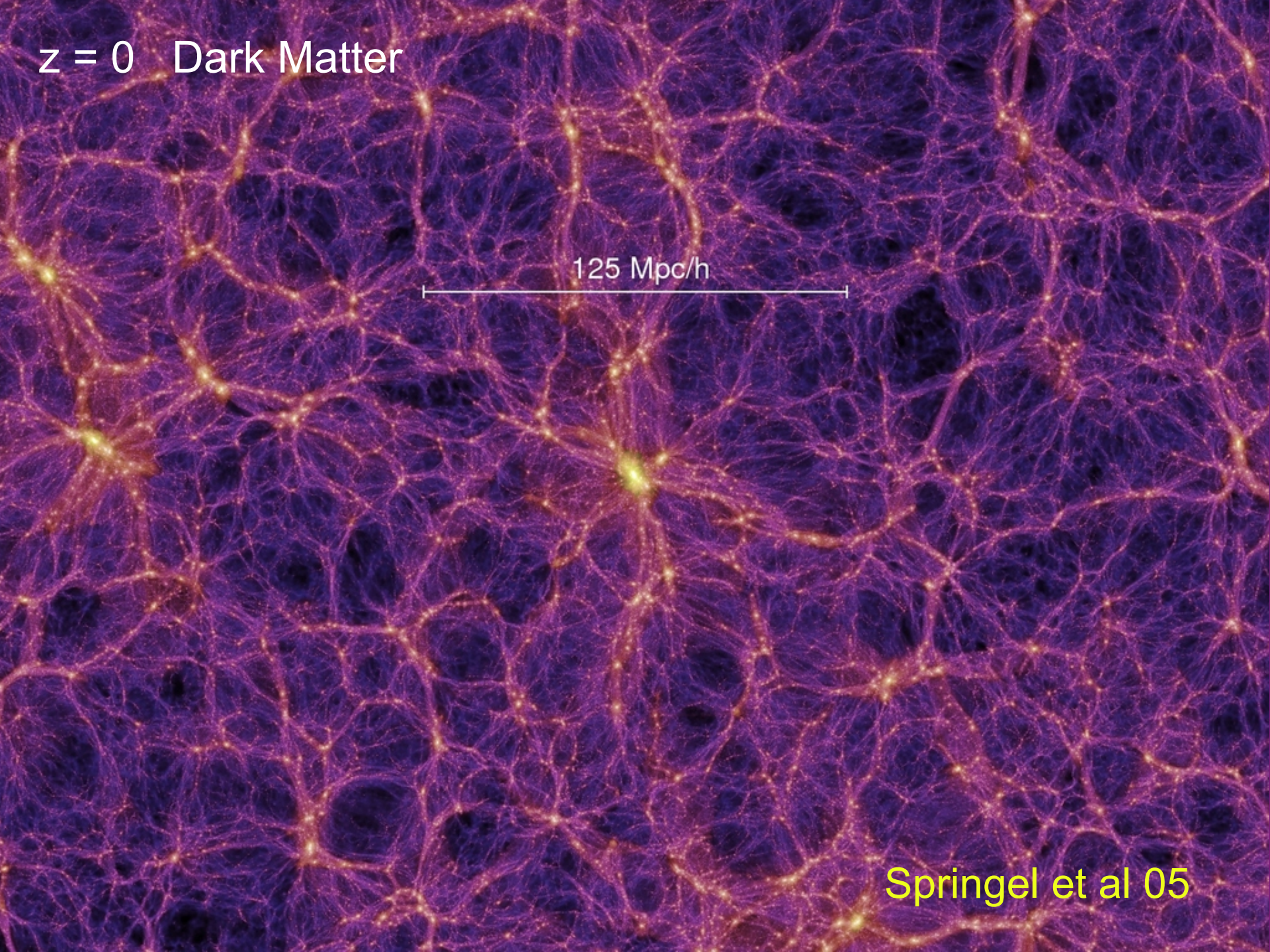
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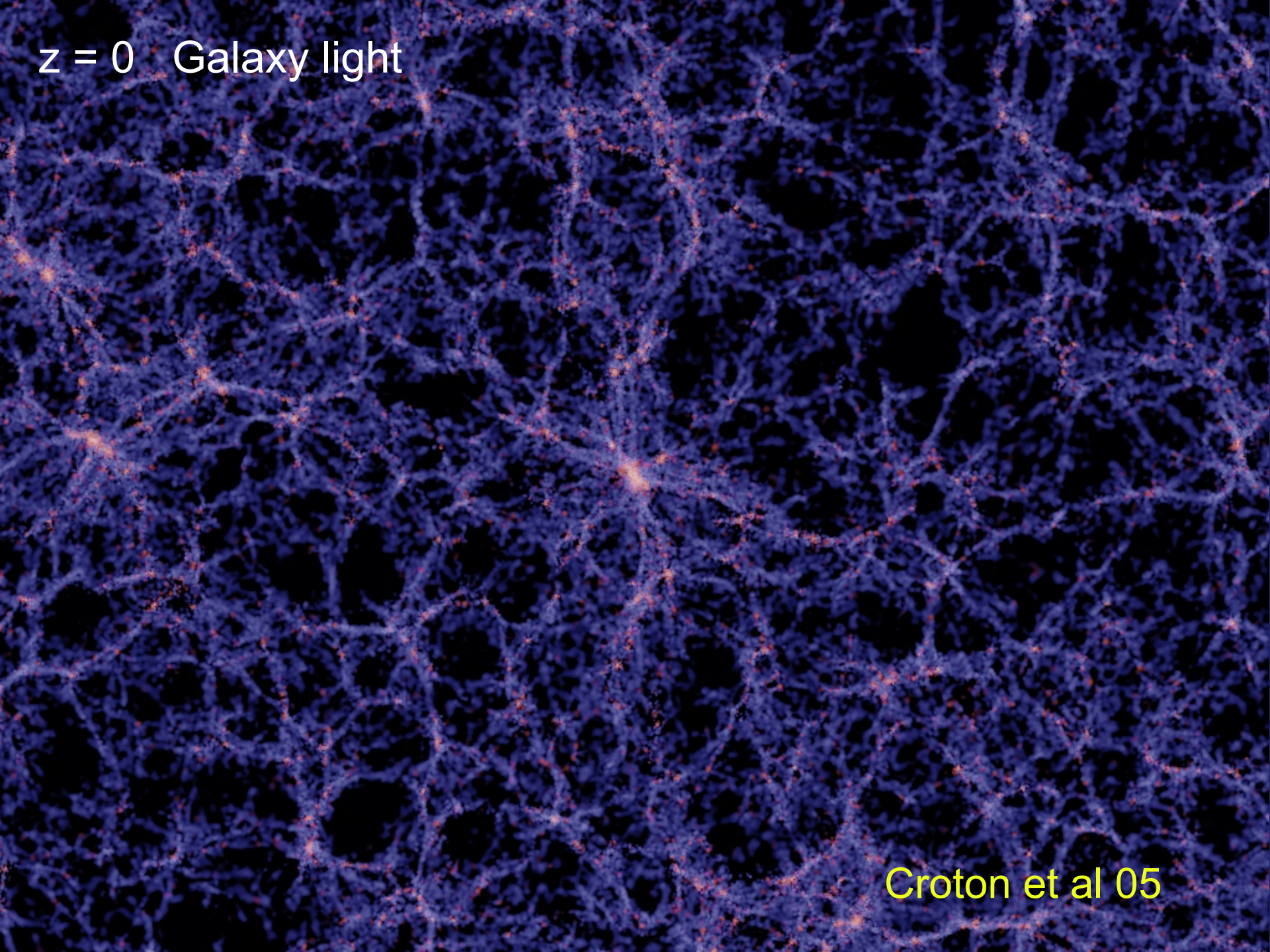
$z = 0$ Dark Matter

125 Mpc/h

A visualization of the dark matter distribution at redshift z=0. The image shows a complex, interconnected network of dark matter filaments and nodes, rendered in a purple-to-yellow color gradient. The filaments are thin and thread-like, while the nodes are denser and more luminous. A horizontal scale bar is positioned in the upper-middle part of the image, with the text '125 Mpc/h' above it. The overall structure is a 'cosmic web'.

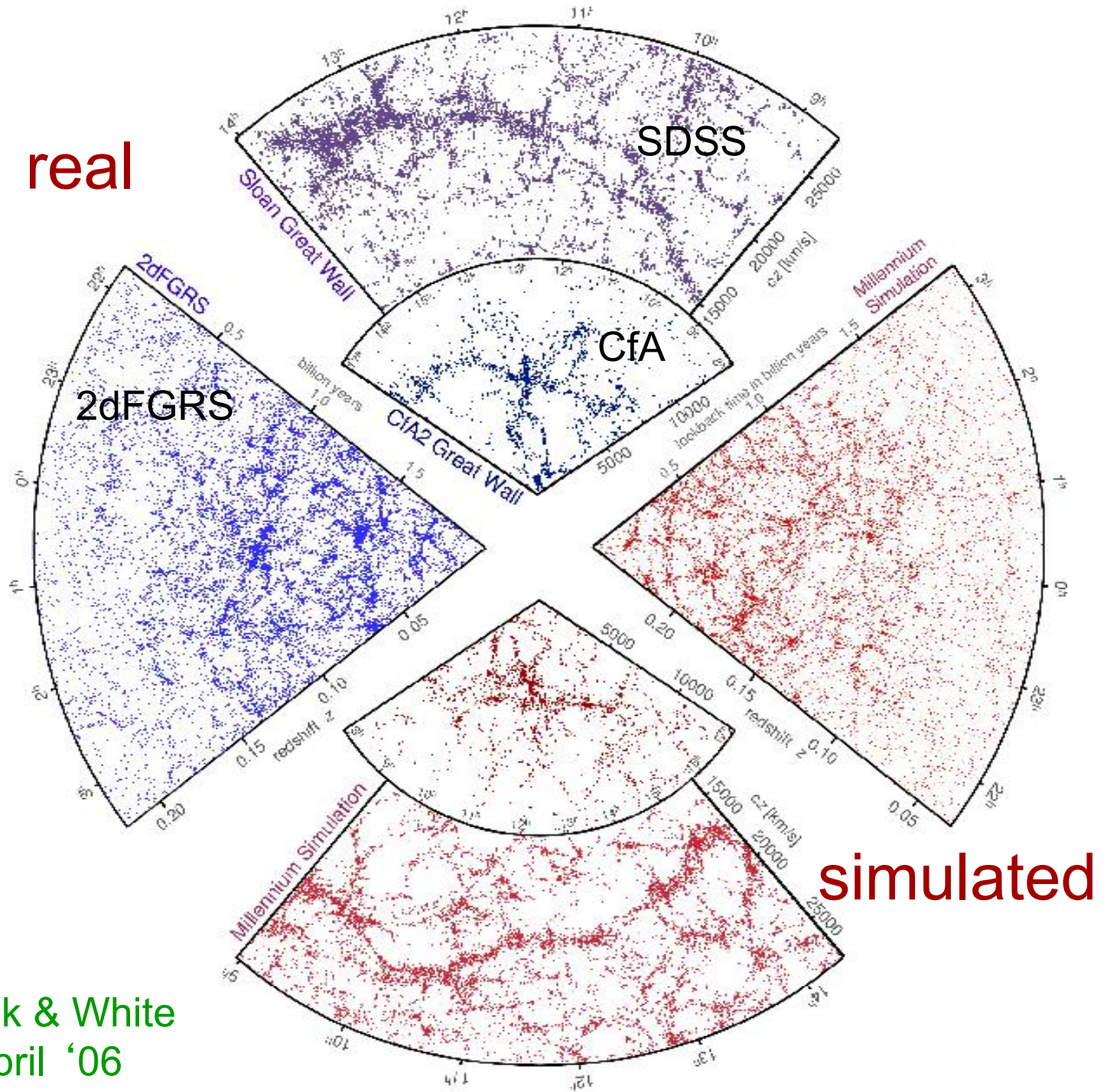
Springel et al 05

$z = 0$ Galaxy light

The image displays a complex, interconnected network of blue filaments and orange nodes, representing the distribution of galaxy light at redshift z=0. The filaments form a dense, web-like structure, with orange nodes marking the intersections and concentrations of light. The background is black, highlighting the intricate pattern of the cosmic web.

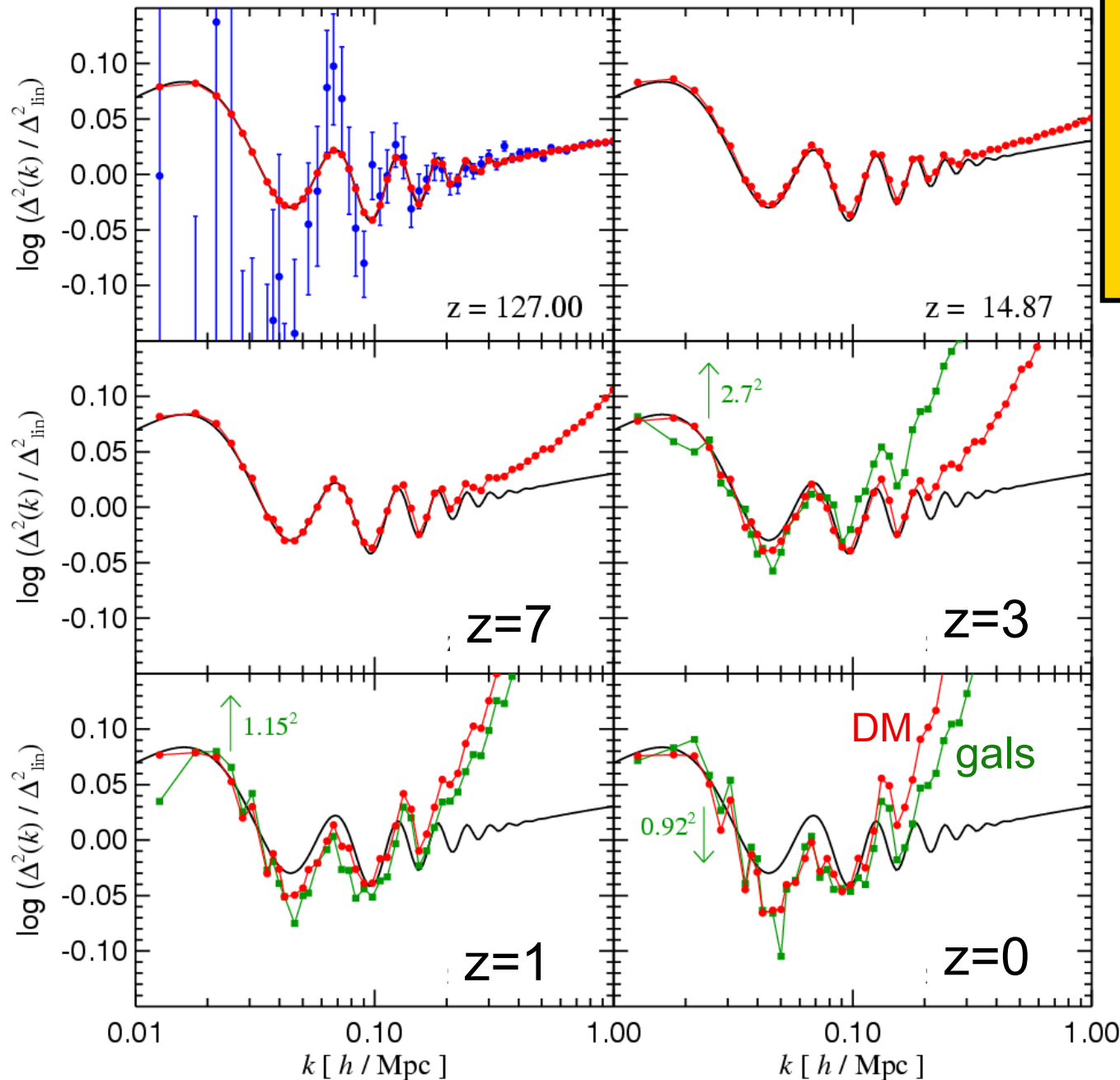
Croton et al 05

real



Springel, Frenk & White
Nature, April '06

Millennium simulation



Baryon
wiggles in
the galaxy
distribution

Power spectrum
from MS divided by
a baryon-free
 Λ CDM spectrum

Galaxy samples
matched to
plausible large
observational
surveys at given z

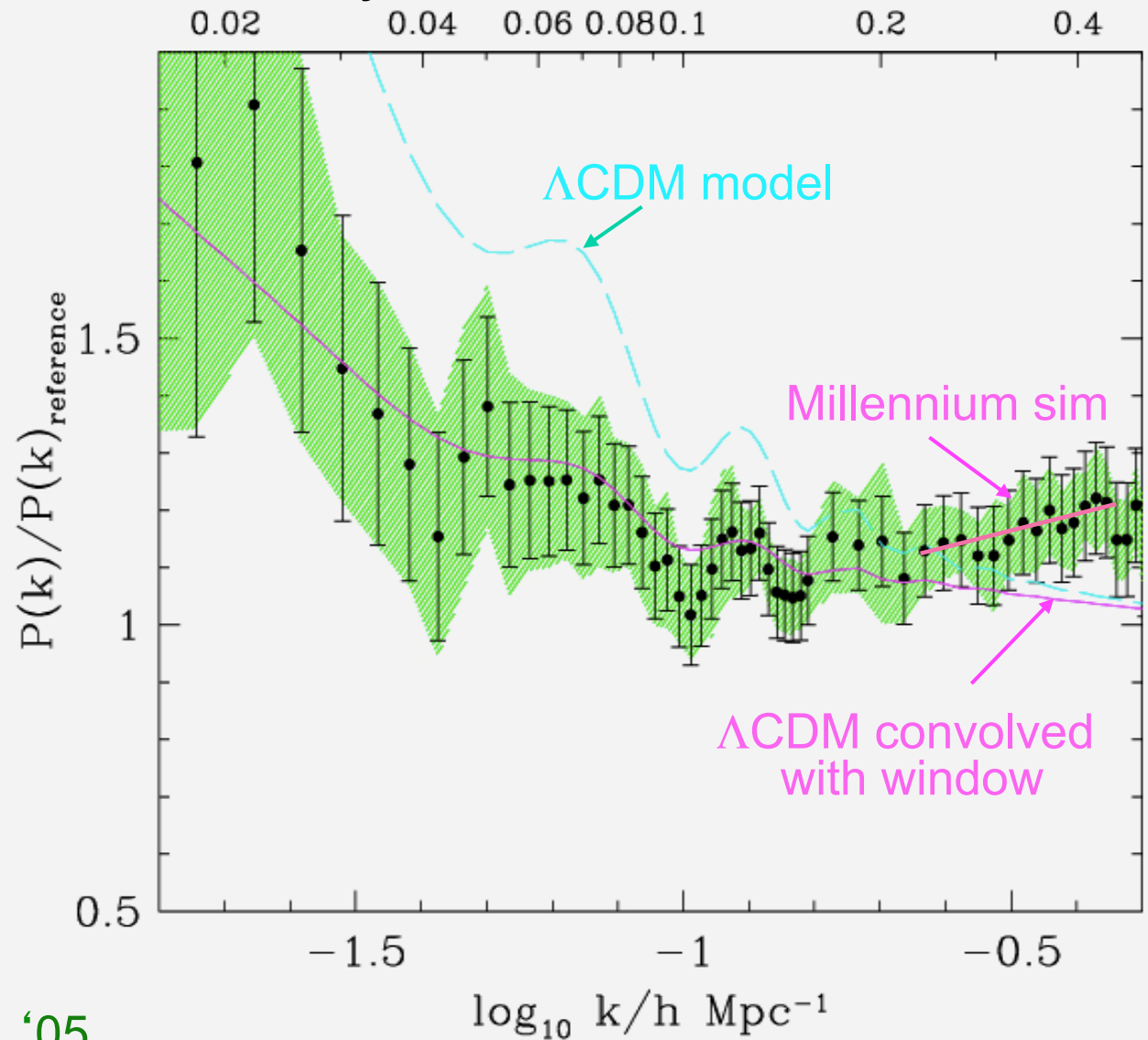
Springel et al 2005

Baryon acoustic oscillations in 2dFGRS

$$P(k) / P_{\text{ref}}(\Omega_{\text{baryon}}=0) k/h \text{ Mpc}^{-1}$$

220,000 redshifts

Baryon oscillations
conclusively detected
in 2dFGRS!!!



Cole, Percival, Peacock,
Baugh, Frenk + 2dFGRS '05

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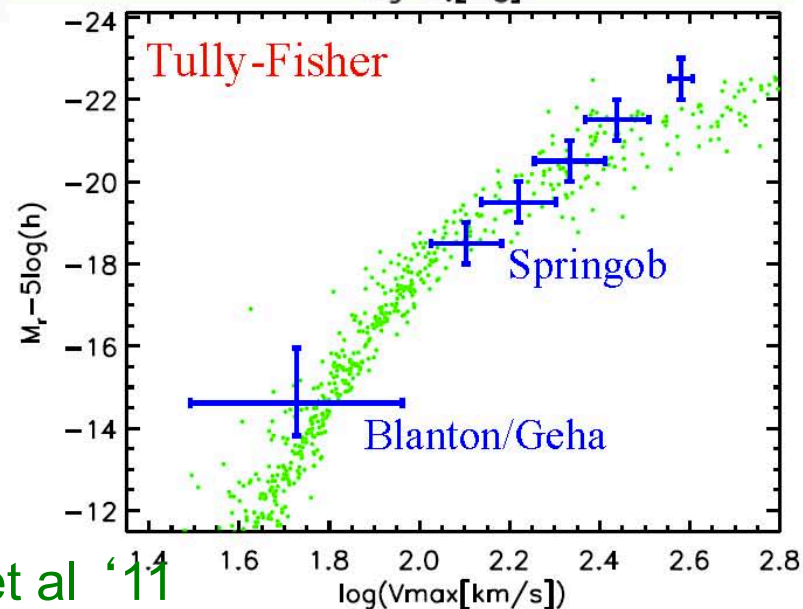
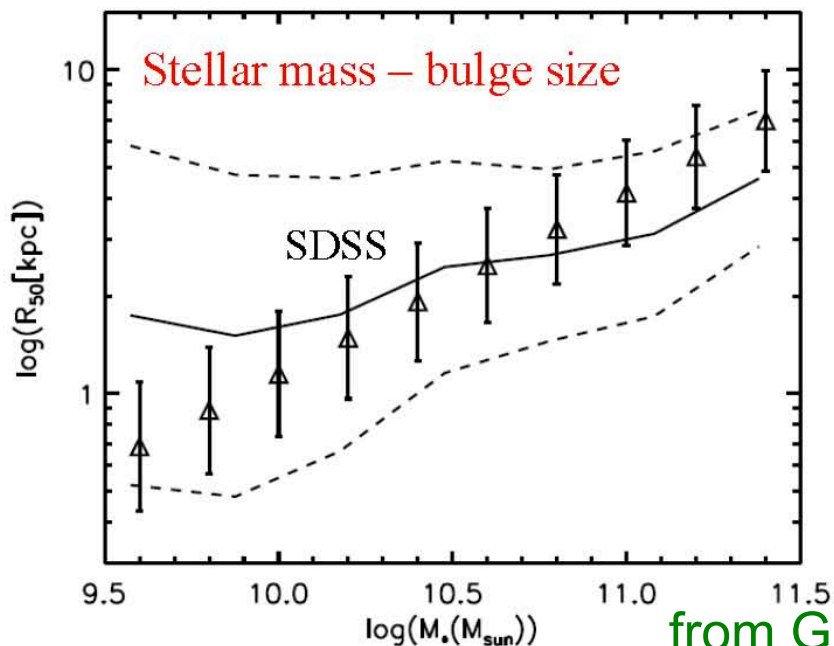
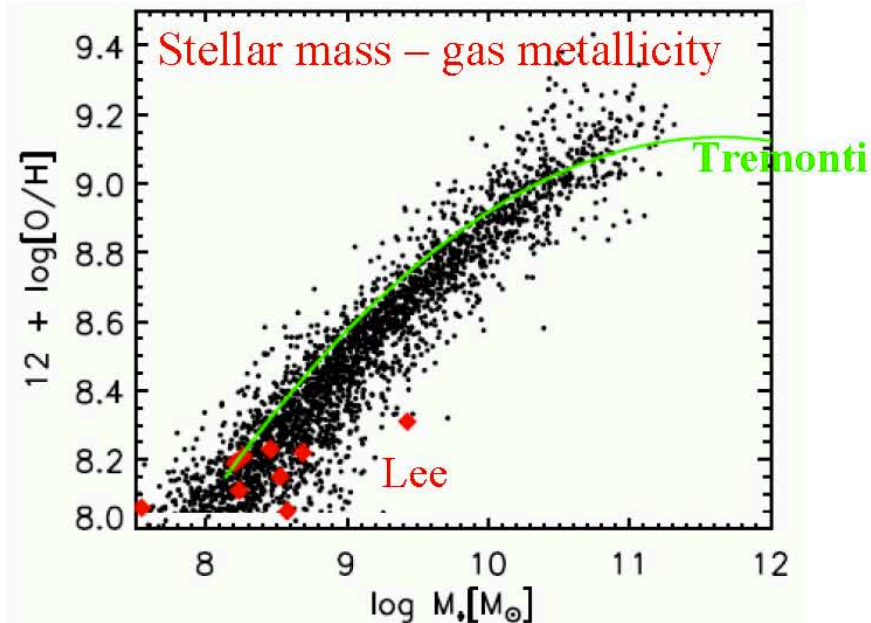
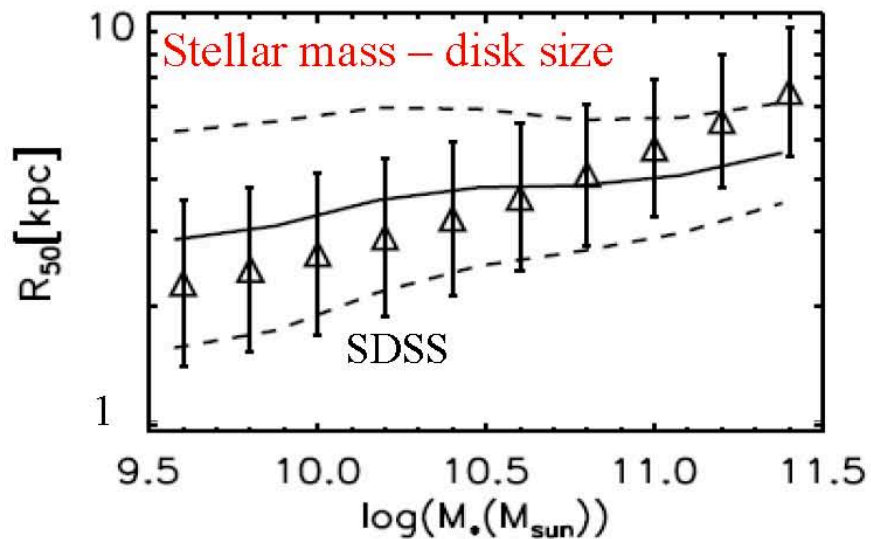
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Basic galaxy properties



from Guo et al '11

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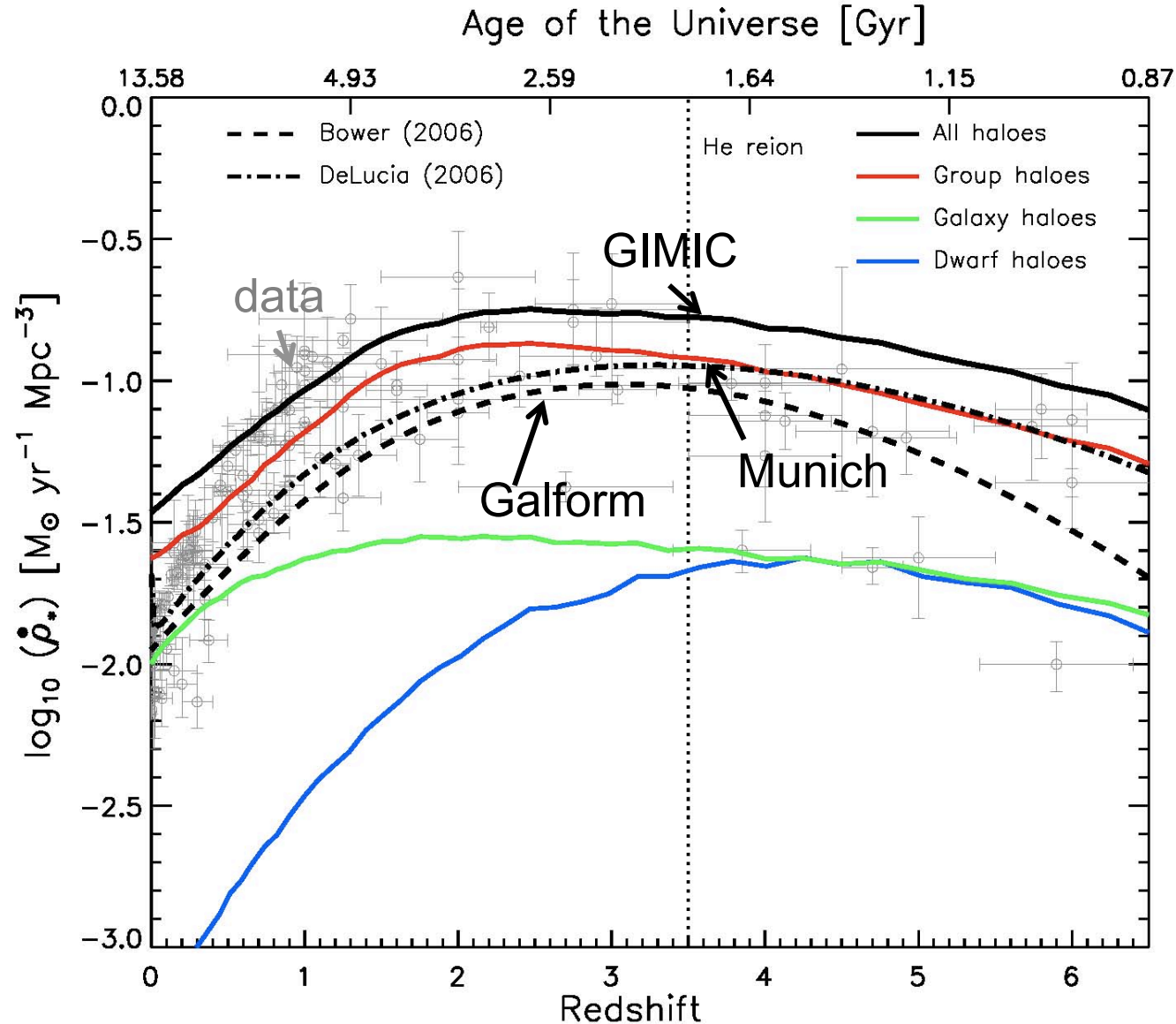
- Scaling relations (TF; sizes; metallicities)
- History of cosmic star formation
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The cosmic star formation rate

Sims & SA in rough agreement w data

Sims tuned to SFR

SA tuned to $z=0$ LF



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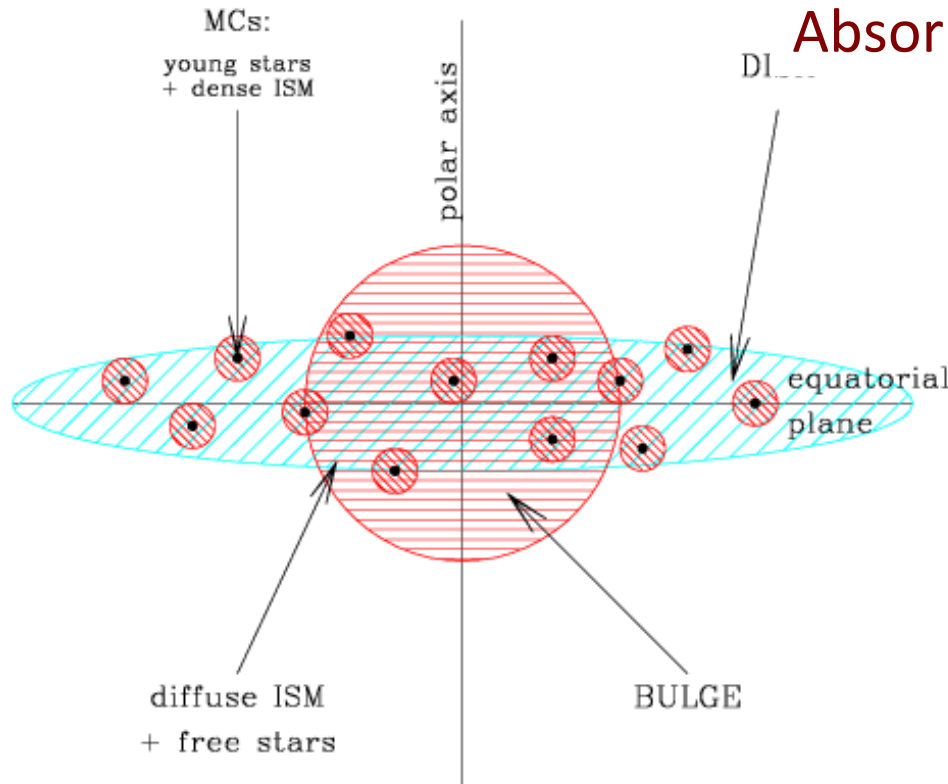
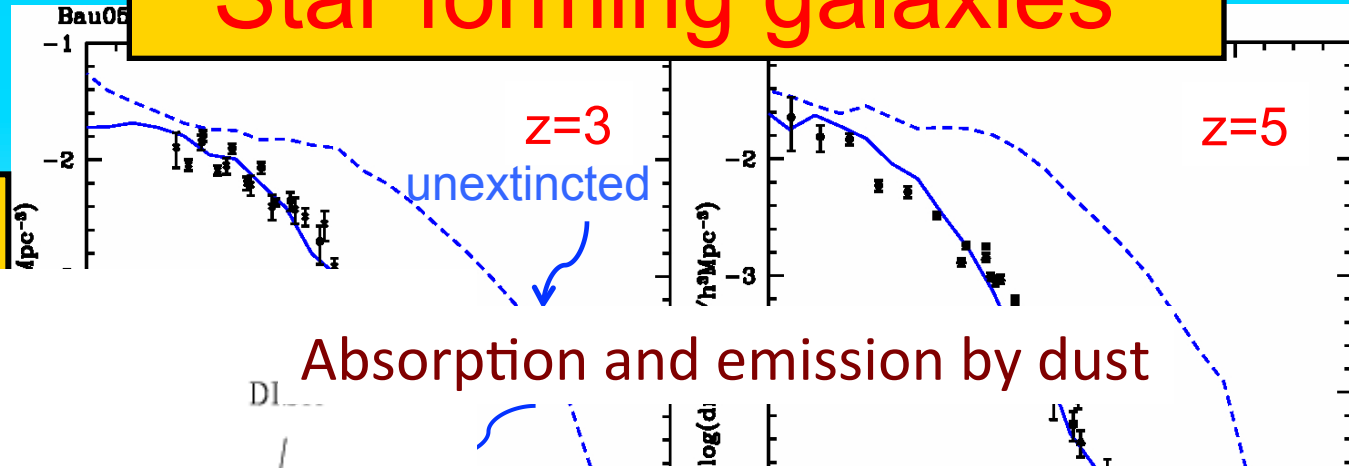
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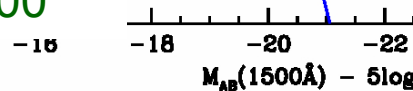
Star forming galaxies

Evolution of



- Dust in diffuse medium and molecular clouds
- Phys. dust grain model +PAHs
- Radiative transfer of starlight through clumpy dust medium
- Heating of dust grains → dust temp. distribution
- Grains with distri. of size/T → IR/submm emission

Granato, Lacey, Silva, Baugh,
Bressan, Cole & Frenk '00

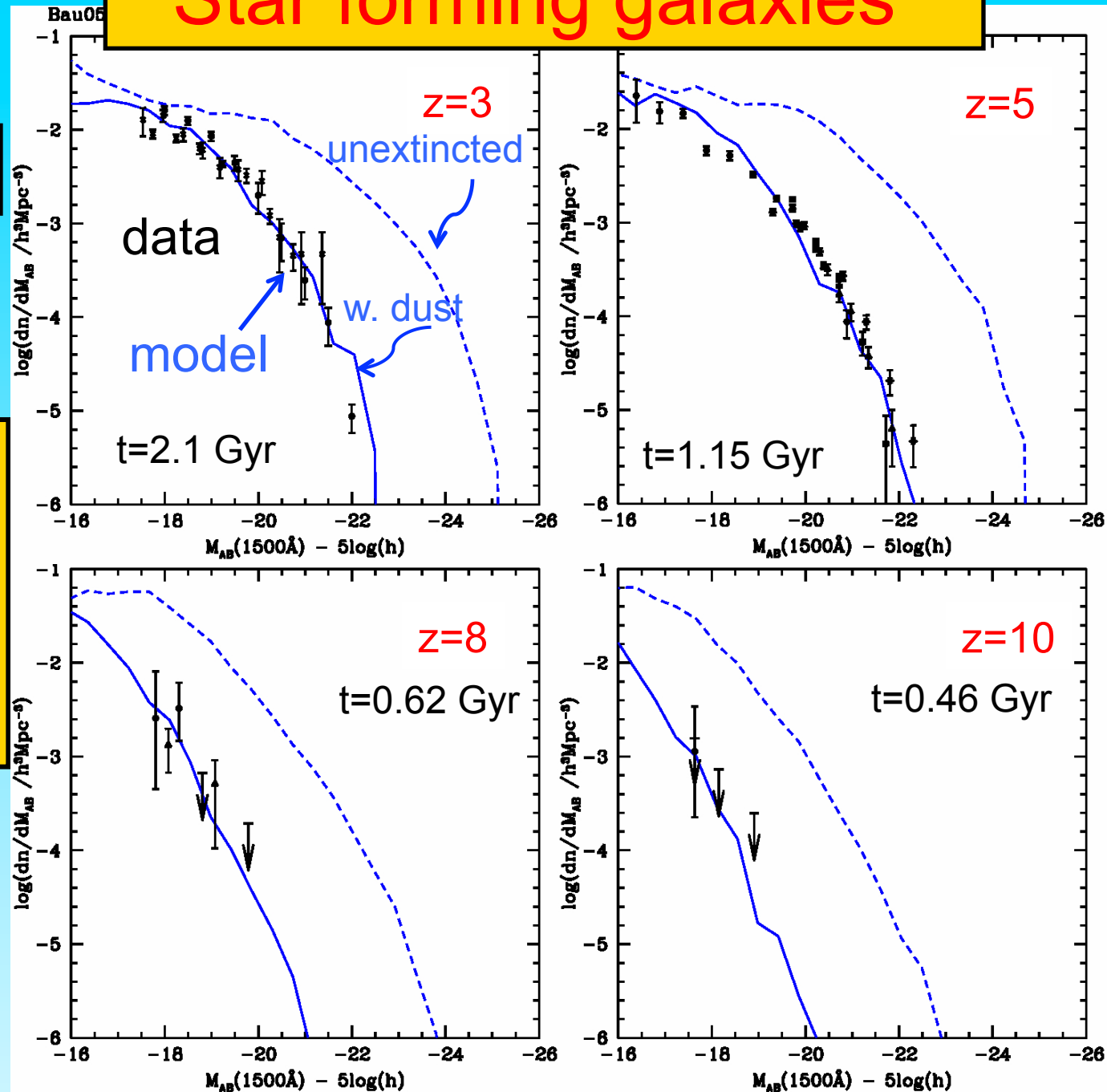


GALFORM

Star forming galaxies

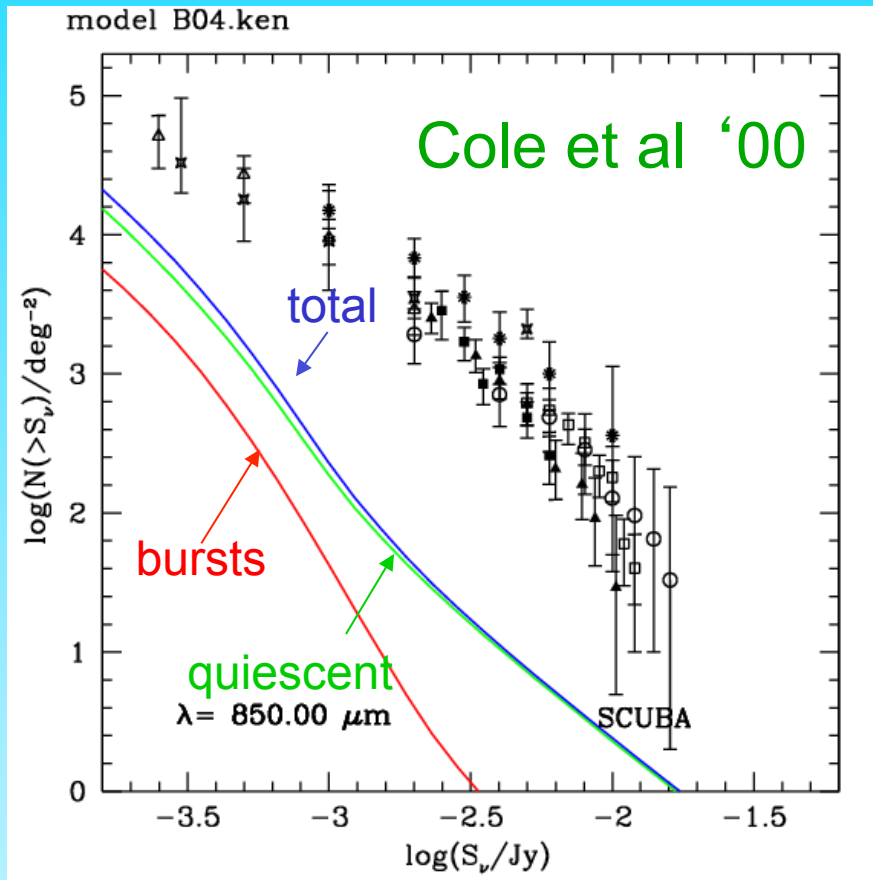
Evolution of Lyman-break galaxy lum. function

Lacey, Baugh,
Frenk, Benson '12

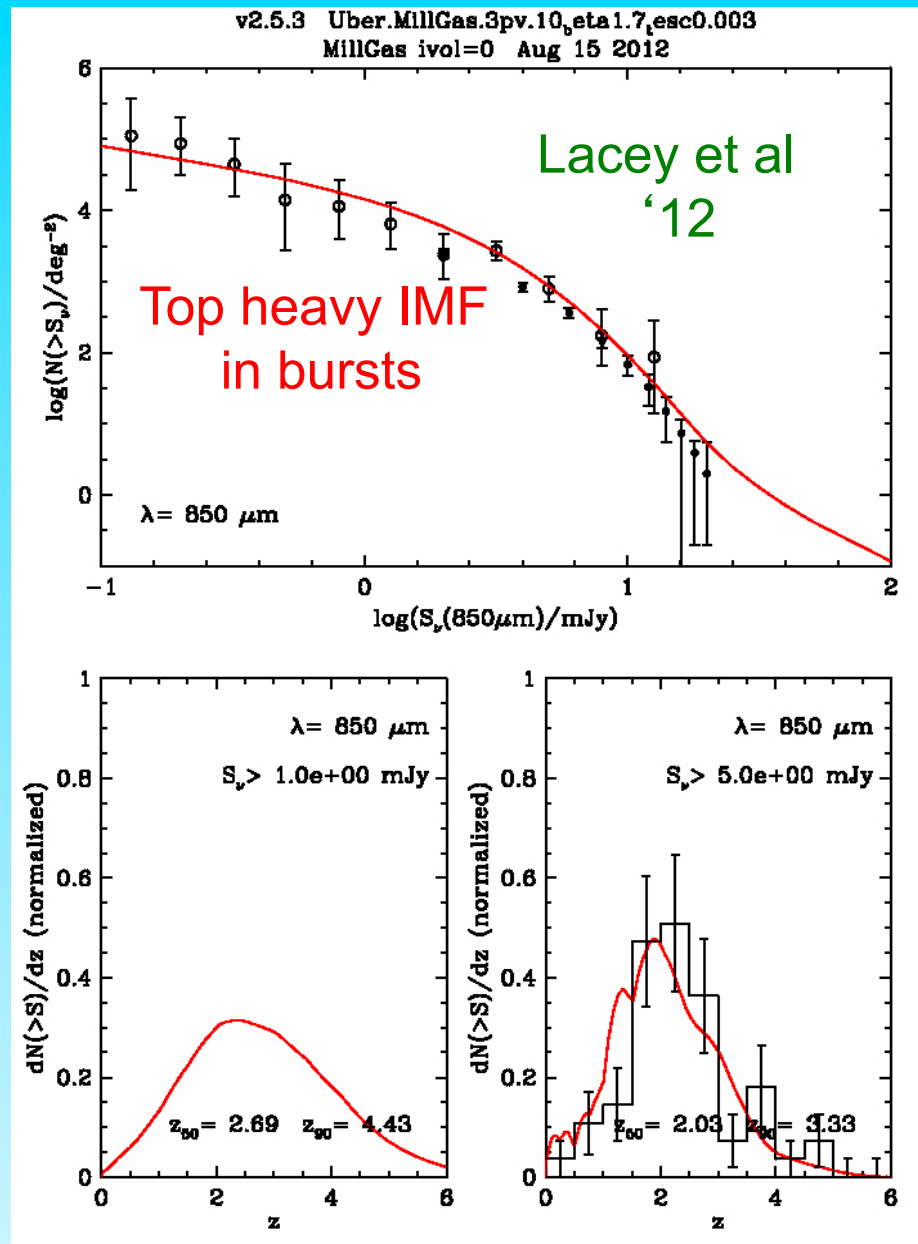


Sub-mm galaxies

Normal IMF



Sub-mm counts too low by factor ~ 30 for normal IMF



Galaxy formation models: successes and failures

Main failures:

- Environmental dependence of galaxy properties (e.g. colour)
- Galaxy clustering on small scales
- Galaxy morphology and sizes
- Effect of galaxy on DM halo
- Chemical abundance ratios

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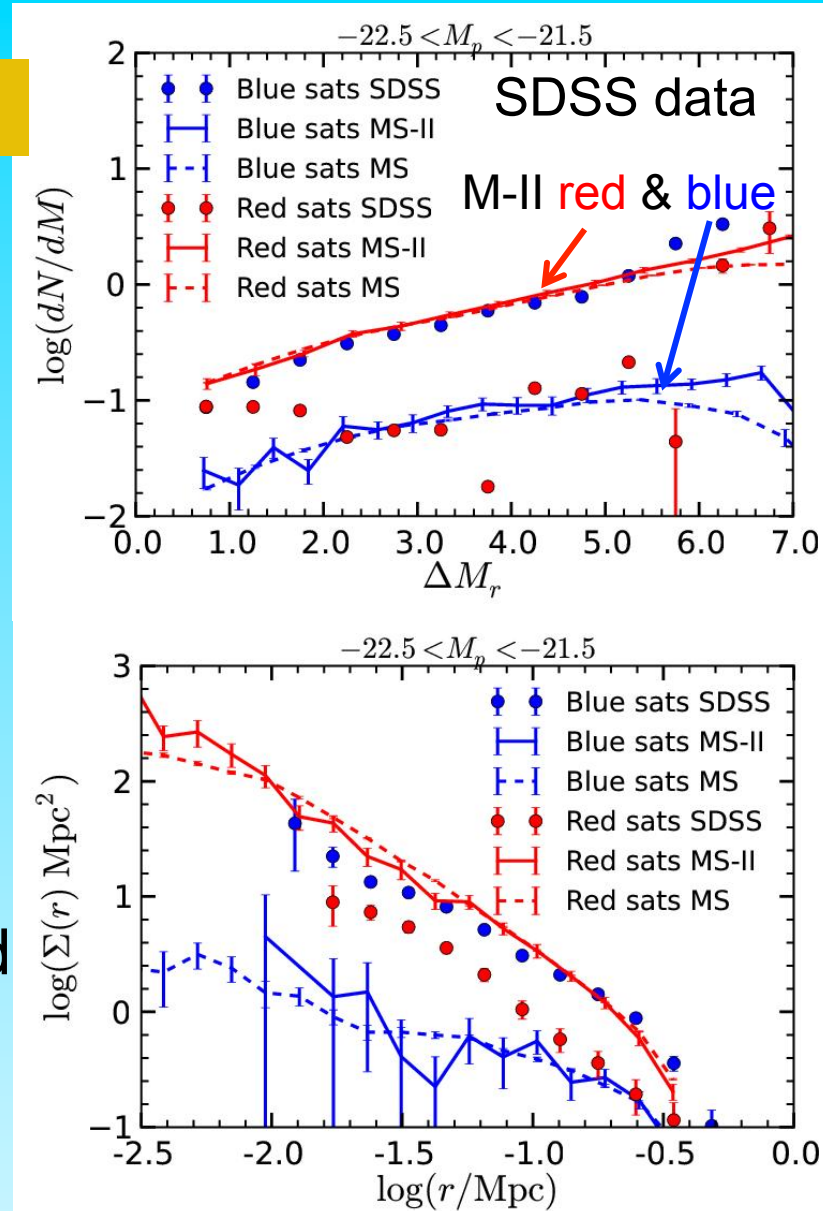
Satellites of Milky Way type galaxies

- Select MW-like primaries in SDSS
- Identify satellites (e.g. Fornax, LMC)
- Split sat sample into red/blue

Models (Galform + Millennium-II)
fail completely!

→ Important environmental effect(s) missing (tidal stripping of gas, induced star formation ...)?

Guo, Cole, Eke, Frenk '13

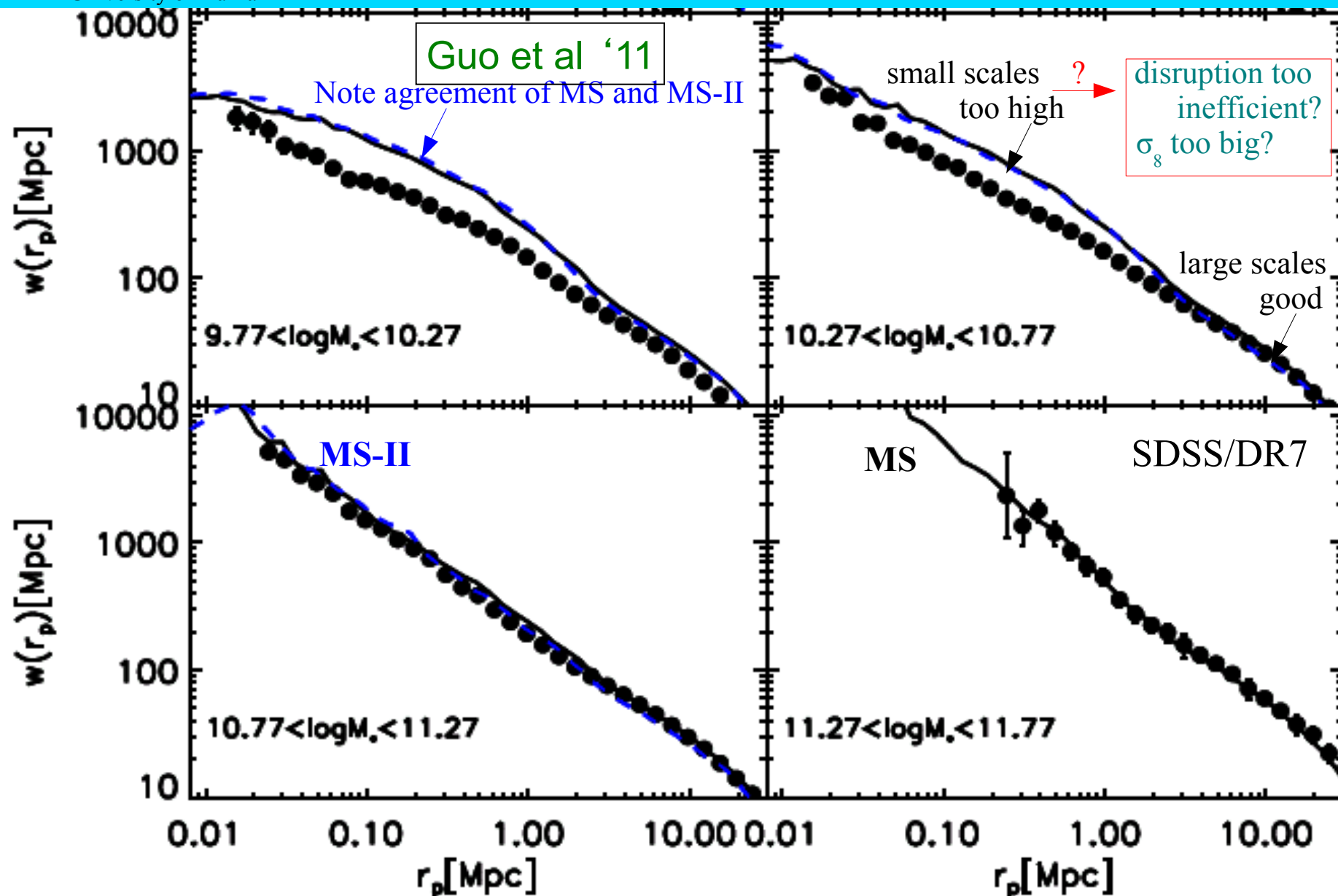


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Mass-dependent galaxy clustering





Hydrodynamic simulations (2005 -)



Hdrodynamic simulations

Numerical methods

- Smooth particle hydrodynamics (SPH; Gadget, Gasoline)
- Adaptive mesh refinement (Ramses, Enzo)
- Deformable mesh (Arepo)

Zooms

- Typically one galaxy at a time
- Calibrated to reproduce disk morphology or SF efficiency

Volumes

- Cosmological representative volumes ($\sim 100\text{Mpc}$)
- Calibrated to reproduce the galaxy luminsity function

Galaxy structure & morphology in cosmological simulations

Moderate f' ' back

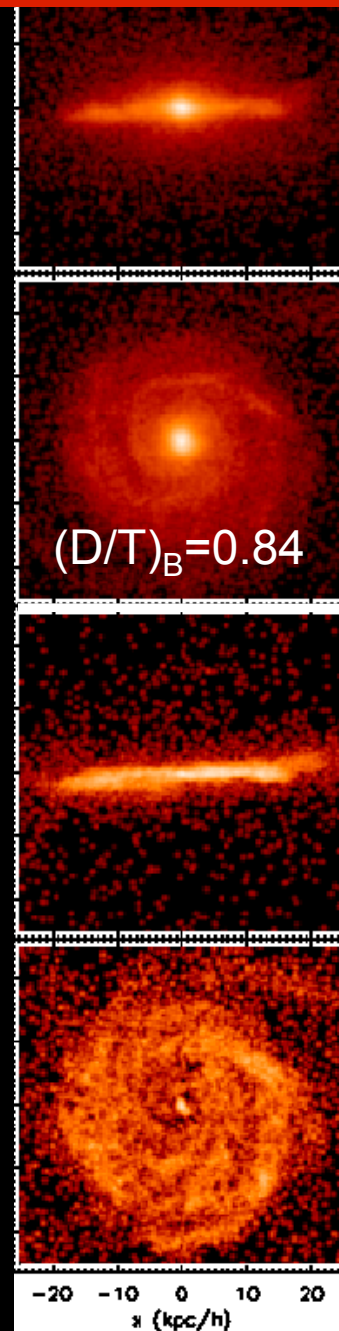
Stars

50 h^{-1} kpc

$(D/T)_B = 0.84$

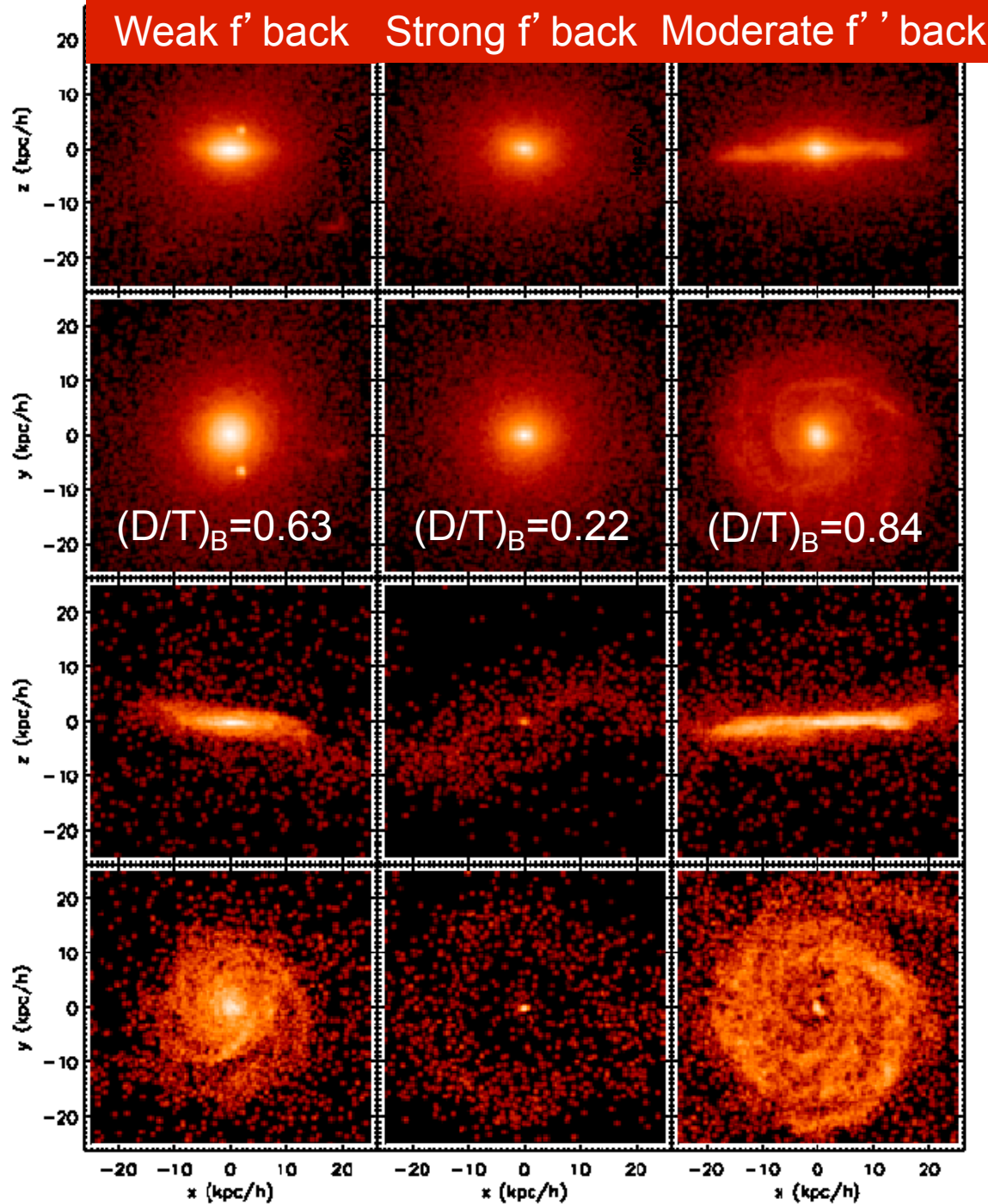
Gas:

Okamoto, Eke, Jenkins & Frenk 05



same dark matter halo!

$50 h^{-1} \text{ kpc}$



FORMING REALISTIC LATE-TYPE SPIRALS IN A Λ CDM UNIVERSE: THE ERIS SIMULATION

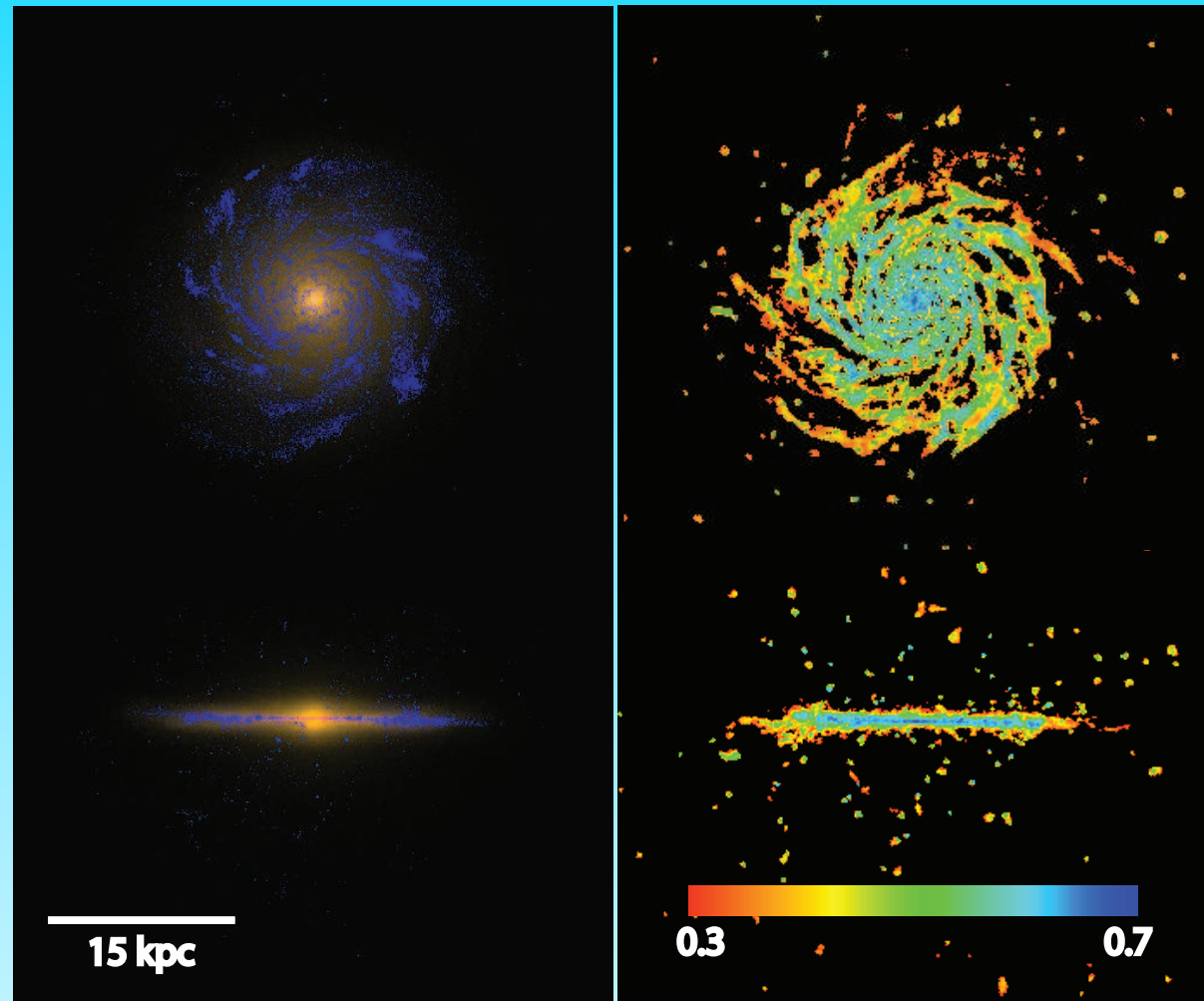
JAVIERA GUEDES^{1,3}, SIMONE CALLEGARI², PIERO MADAU¹, & LUCIO MAYER^{2,3}

accepted by the ApJ

2012

“... simulation in which a close analog of a Milky Way disk galaxy arises naturally”.

“... first cosmological hydrodynamic simulation in which the galaxy structural properties, the mass budget in the various components, ... are all consistent with a host of observational constraints.”

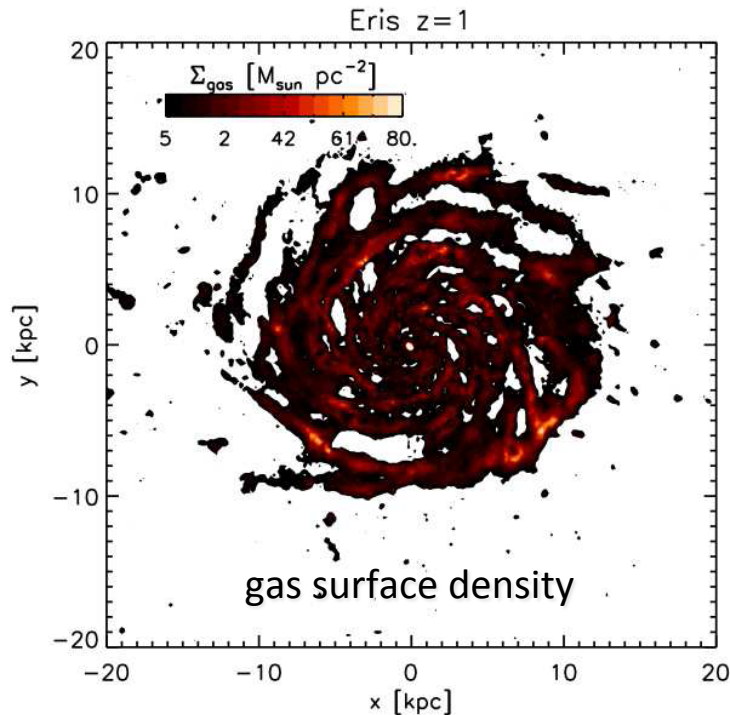


Galaxy structure & morphology

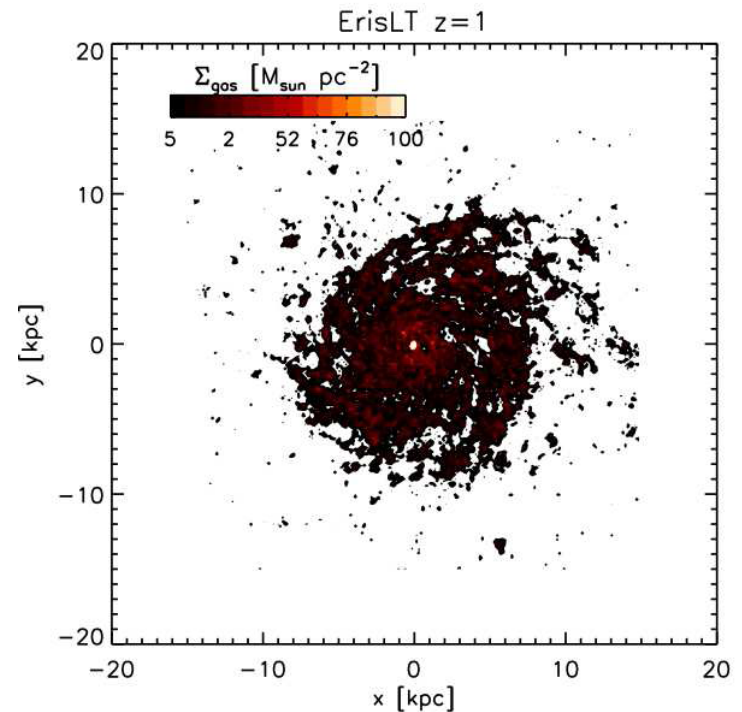
Results highly sensitive to adopted density threshold for star formation

Cold gas distribution in two Eris simulations from identical initial conditions
(Guedes et al. 2012; also Governato et al. 2011, Nature)

This simulation forms stars at densities $n > 5 \text{ cm}^{-3}$ → realistic gas disk



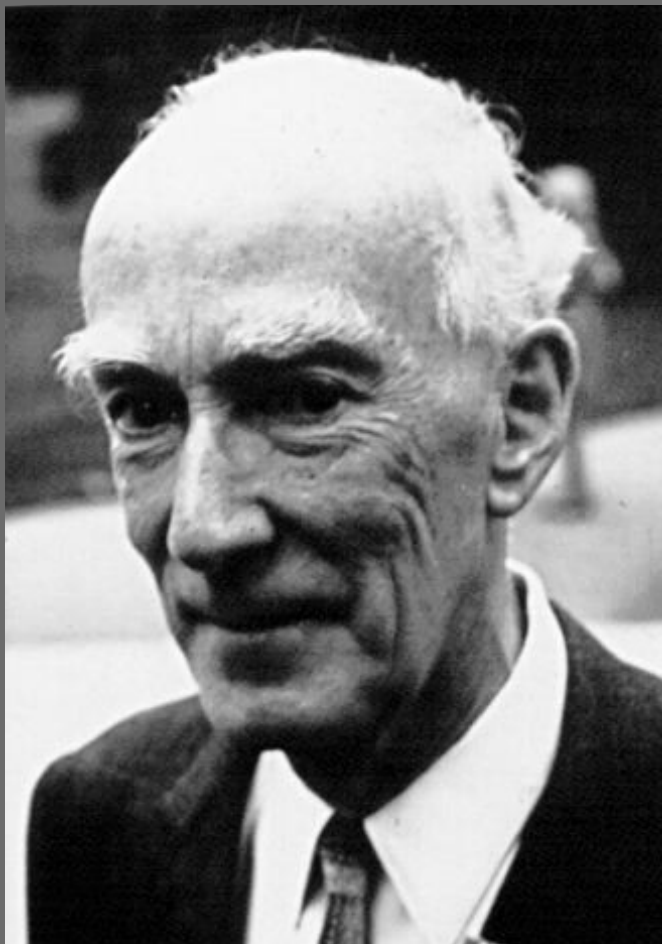
This simulation forms stars at densities $n > 0.1 \text{ cm}^{-3}$ → small disk,



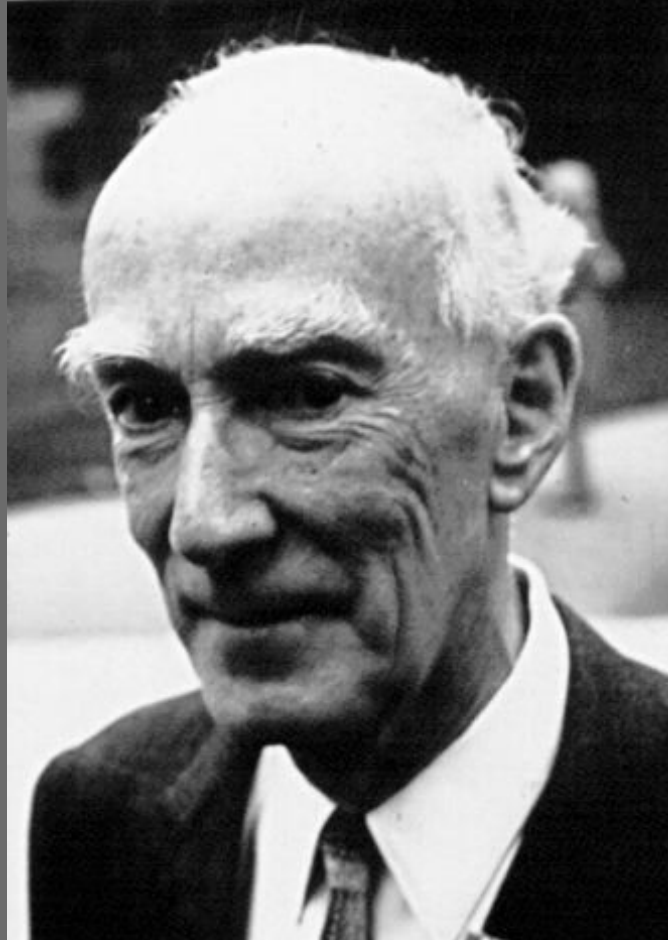
Need a better physical model for star formation in galaxy formation simulations!



What is the purpose of galaxy formation simulations?



It is NOT to produce a realistic looking galaxy in a computer



But to understand physical processes
responsible for galaxy properties

Aquila comparison project: hydro simulation of an Aquarius halo

Single MW-size halo; different codes; different feedback schemes

Scannapieco et al. '12

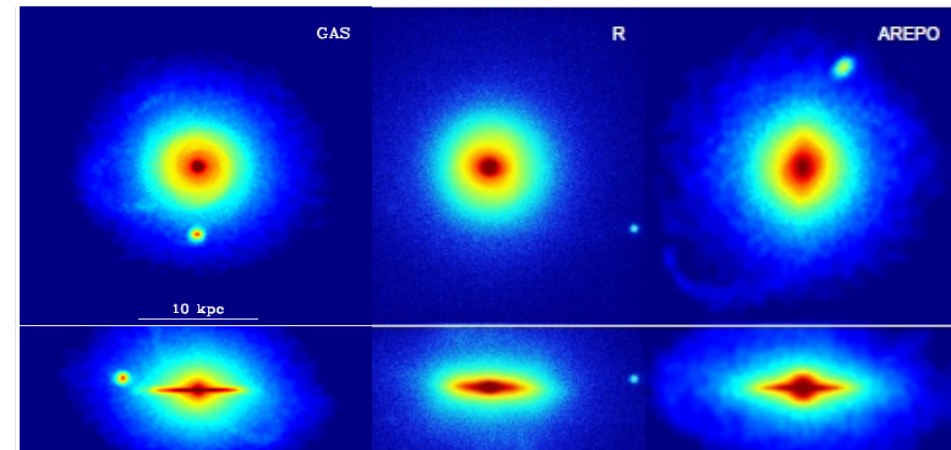
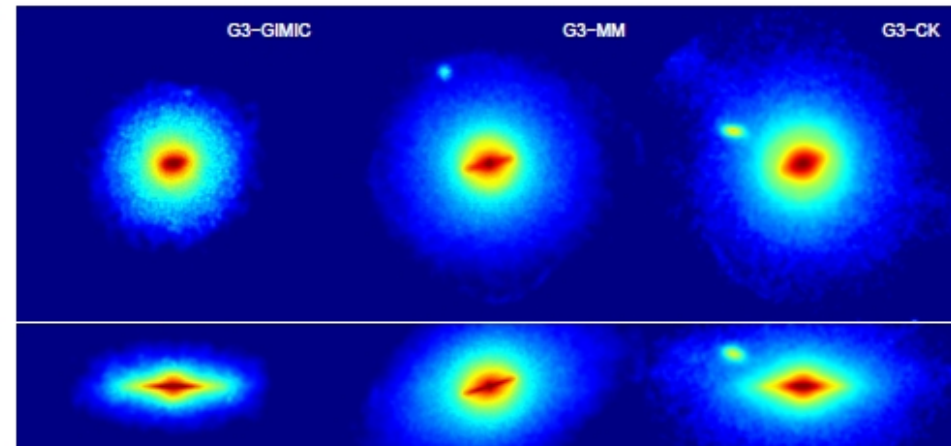
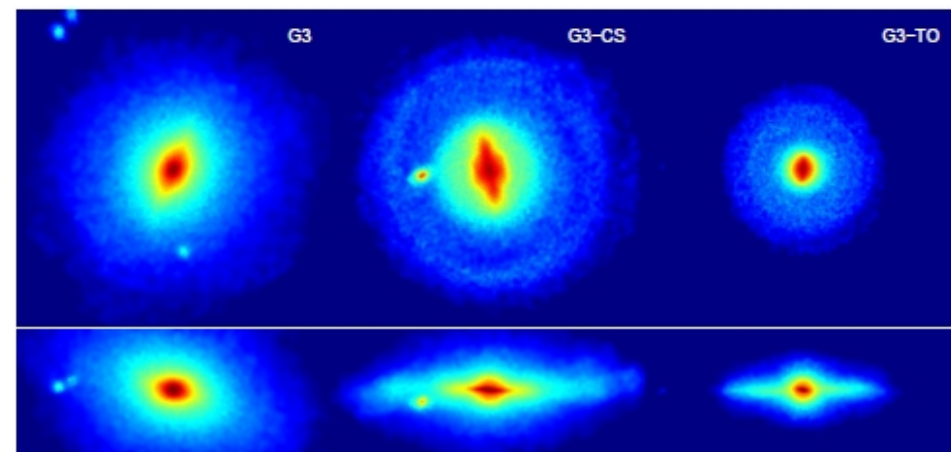
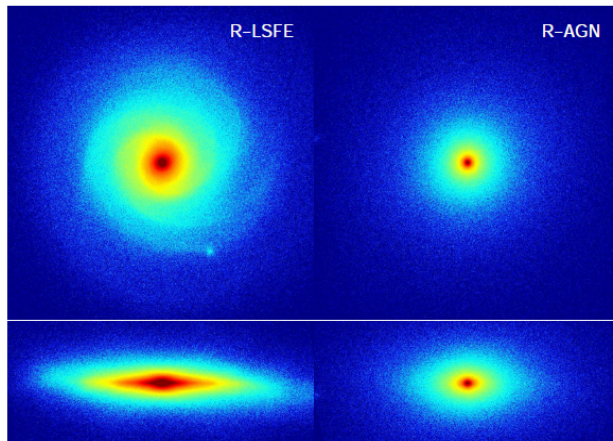
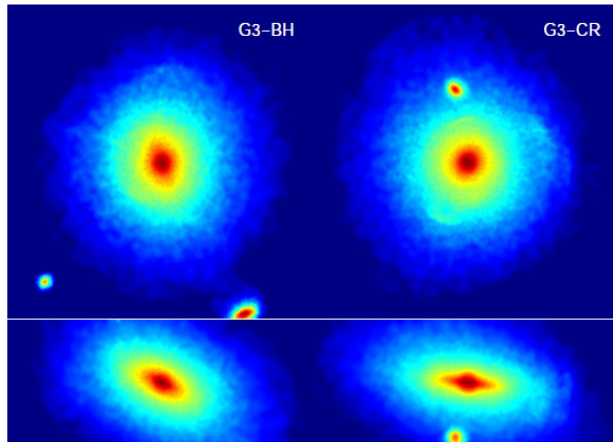
Code	name	type	Feedback (SN)	other
Gadget3	G3	SPH	thermal	
(Springel & Hernquist '02,'03)	G3-BH	SPH	thermal	Black holes (BH)
	G3-CR	SPH	thermal	BH + cosmic rays
Gadget3 (Scannapieco et al. '05, '06)	G3-CS	SPH	thermal	
Gadget3 (Okamoto et al. '10)	G3-TO	SPH	thermal+kinetic	
Gadget3 (Crain et al. '09)	G3-GIMIC	SPH	thermal+kinetic	
Gadget3	G3-MM	SPH	thermal	
Chiaki Kobayashi	G3-CK	SPH	thermal	
GASOLINE	GAS	SPH	thermal	
	R	AMR	thermal	
RAMSES (Romain Teyssier)	R-LSFE	AMR	thermal	Low SF efficiency
	R-AGN	AMR	thermal	BH
Arepo	Arepo	Moving mesh	thermal	

Individual galaxies

- Most galaxies are multi-component: bulges, disks, bars.
- Strength of components varies from model to model.
- Most (all?) fail to match observations

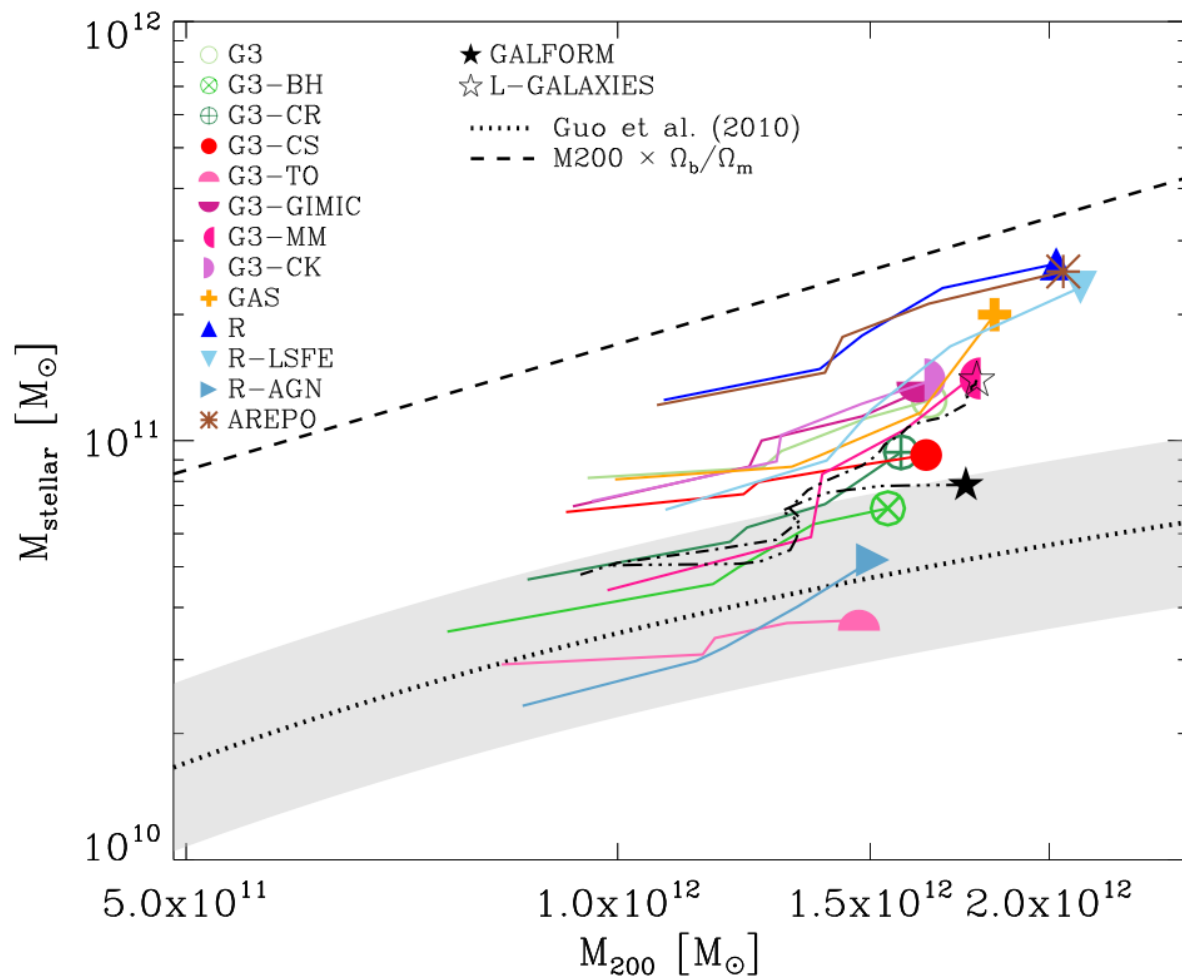
face on

edge on



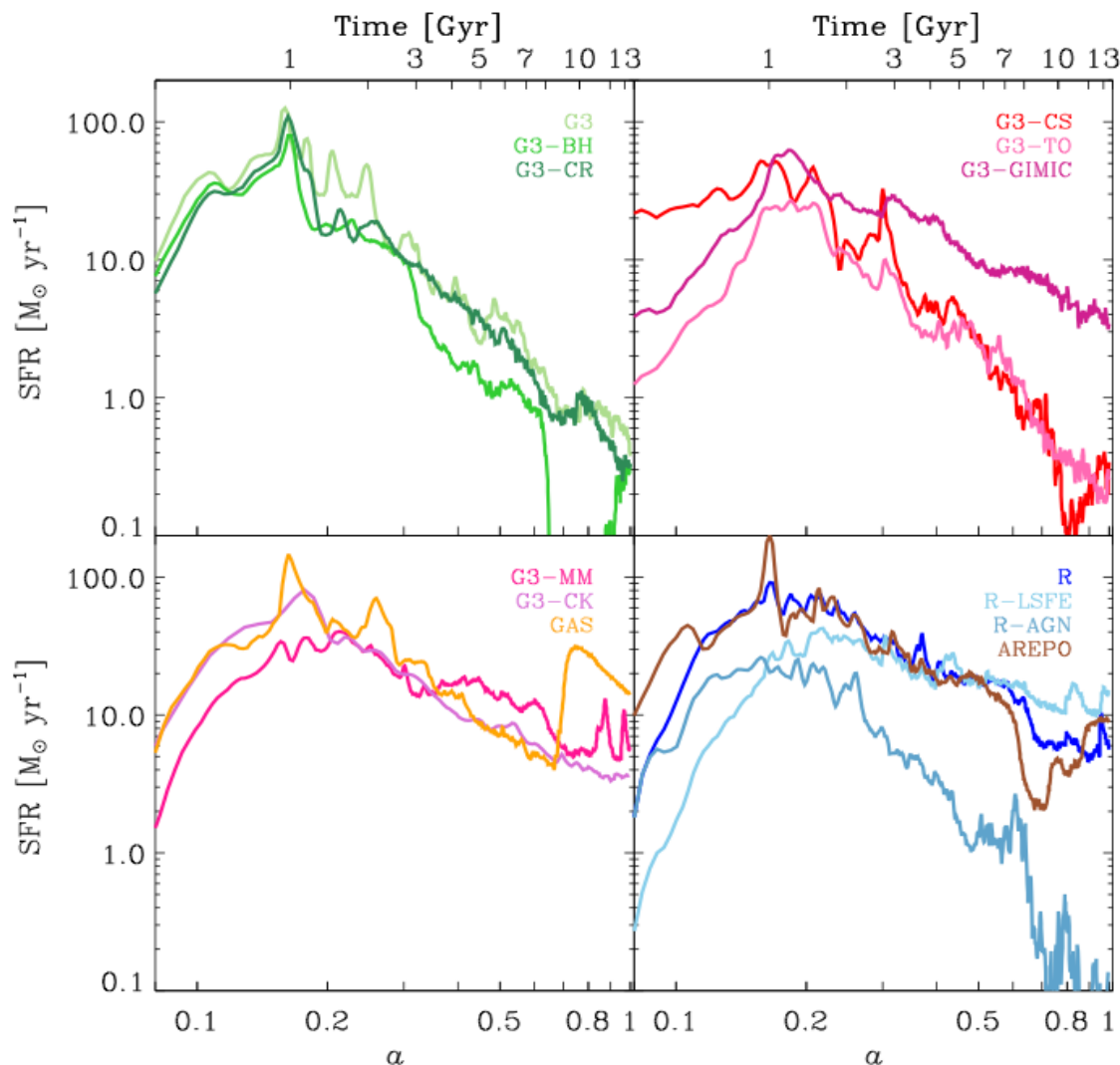
The Aquila project: M_* - M_{halo}

- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a “Milky Way-like” galaxy.
- Simulated galaxies that curtailed the early onset of star formation did best.



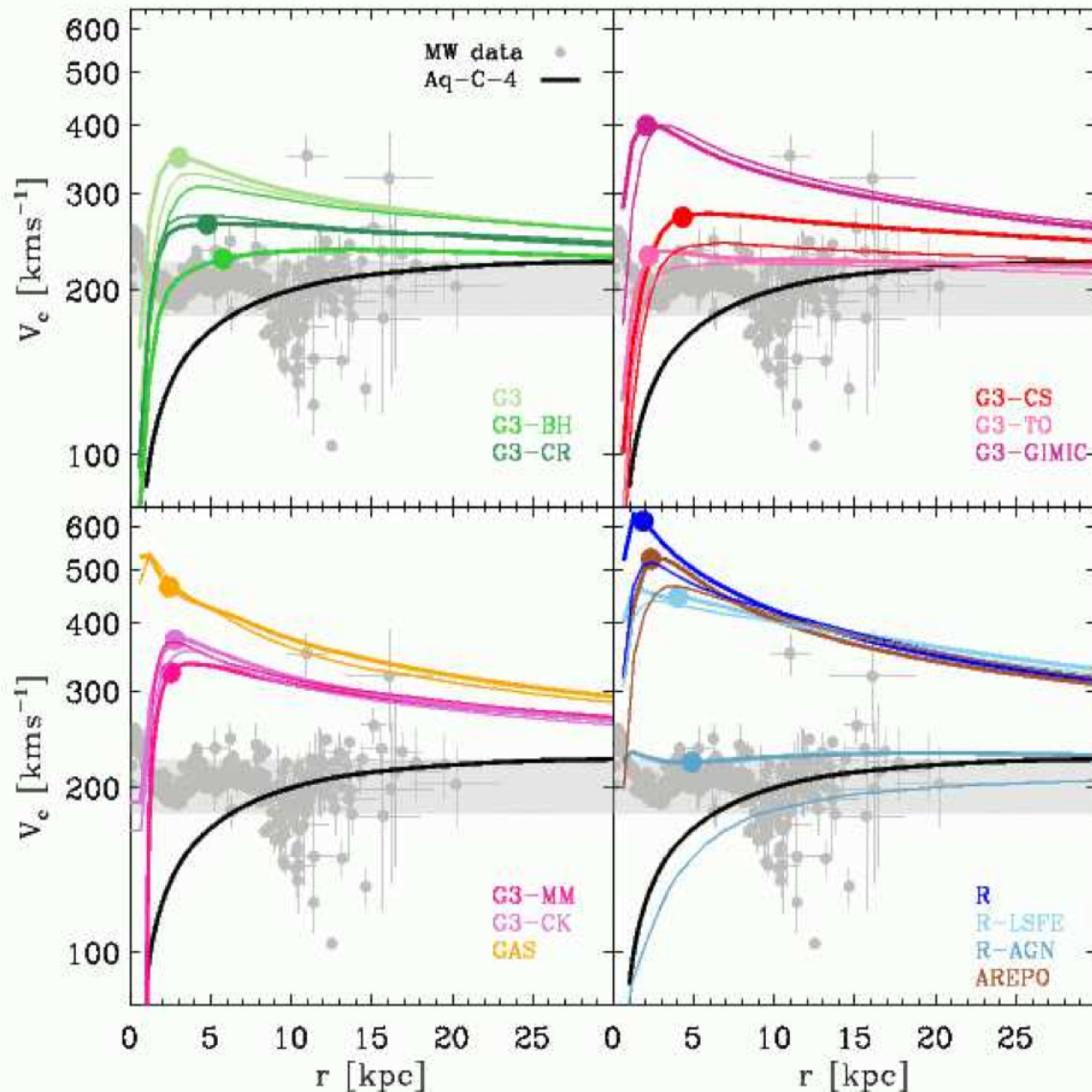
The Aquila project: SF rates

- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a “Milky Way-like” galaxy.
- Simulated galaxies that curtailed the early onset of star formation did best.



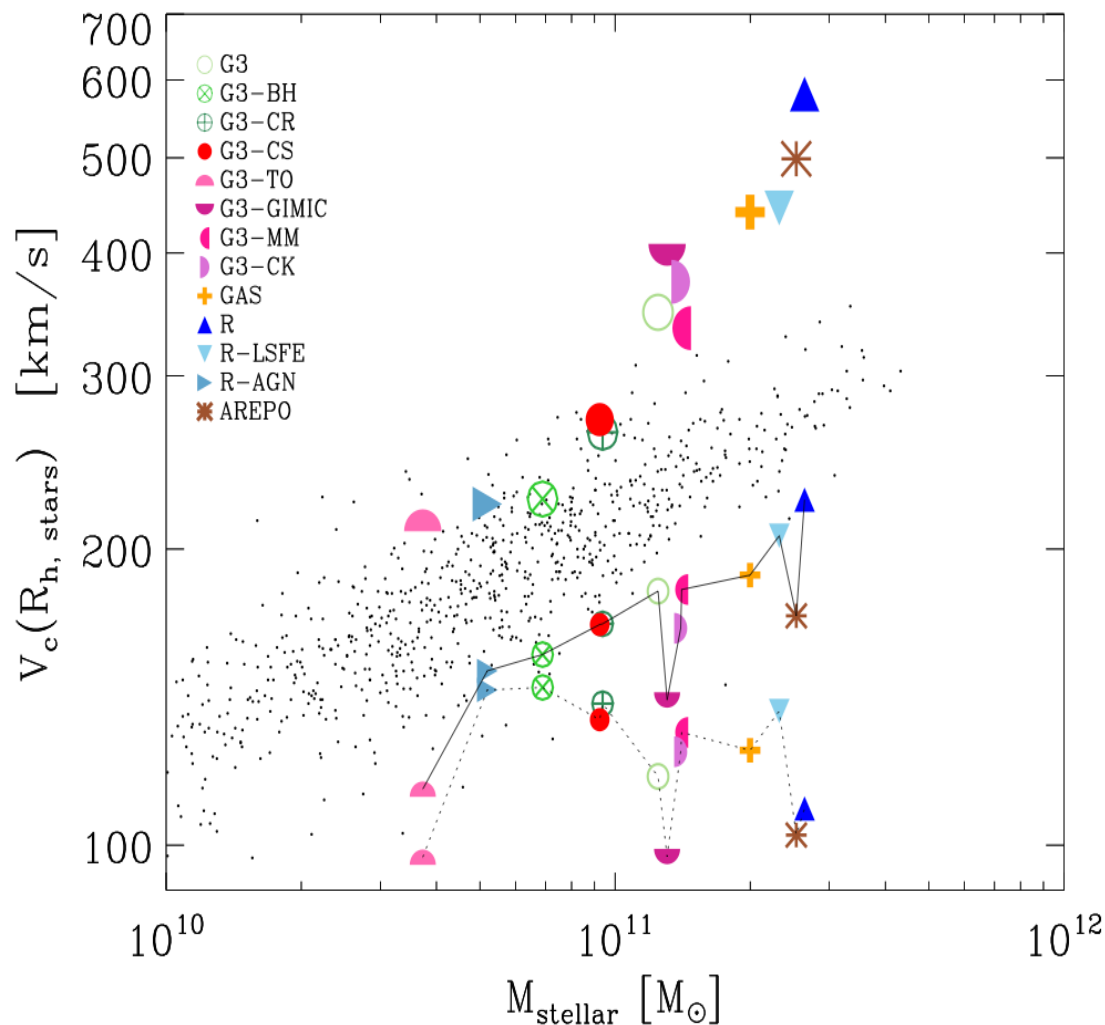
The Aquila project: rotation curves

- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a “Milky Way-like” galaxy.
- Simulated galaxies that curtailed the early onset of star formation did best.



The Aquila project: Tully-Fisher reln

- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a “Milky Way-like” galaxy.
- Simulated galaxies that curtailed the early onset of star formation did best.

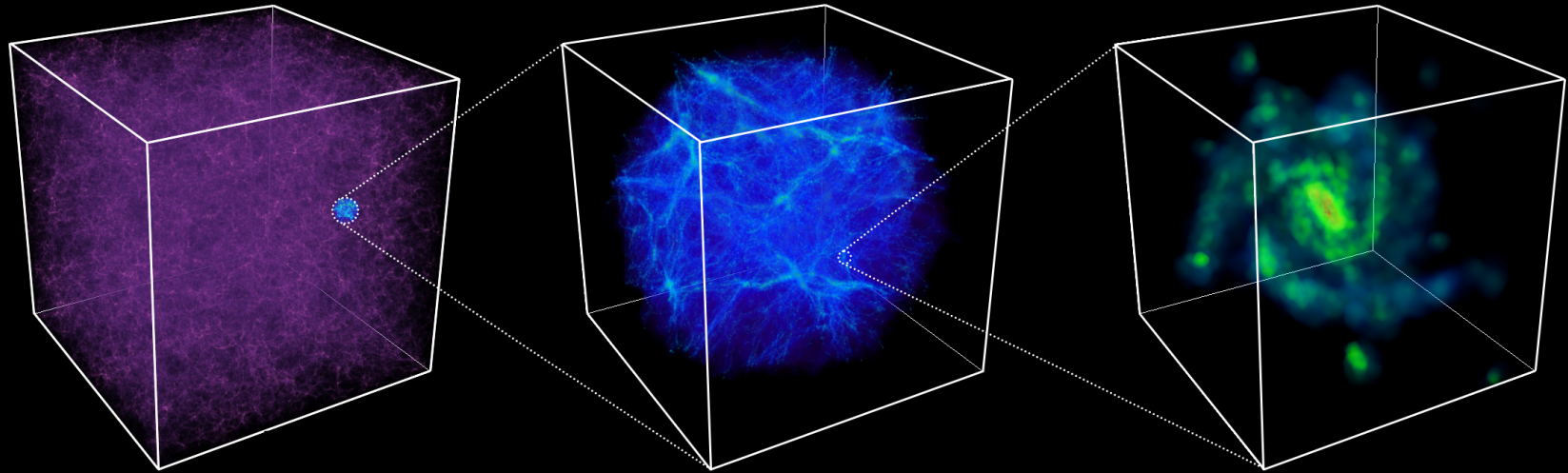


Hydro simulations of galaxy formation

- Need a better understanding of “subgrid” models and their effects
- Ultimately, replace “subgrid” models by resolved calculations (higher resolution)

→ Goal of new generation of hydro simulations

Galaxies-Intergalactic Medium Interaction Calculation



Millennium Simulation
 $L = 500 \text{ Mpc}/h$

GIMIC region (1 of 5)
 $r \sim 20 \text{ Mpc}/h$

GIMIC galaxy
 $\varepsilon = 500 \text{ pc}/h$

- ▶ “Resimulation” of 5 regions from the Millennium simulation including baryons
- ▶ Covering whole range of environments (voids $\rightarrow$ clusters)
- ▶ OWLS code: SPH, cooling, SF, feedback, chemodynamics
- ▶ $m_{\text{gas}} \sim 10^6 M_{\text{sun}}/h$, L^* galaxies resolved with 10^5 particles
- ▶ Runs to $z=0$

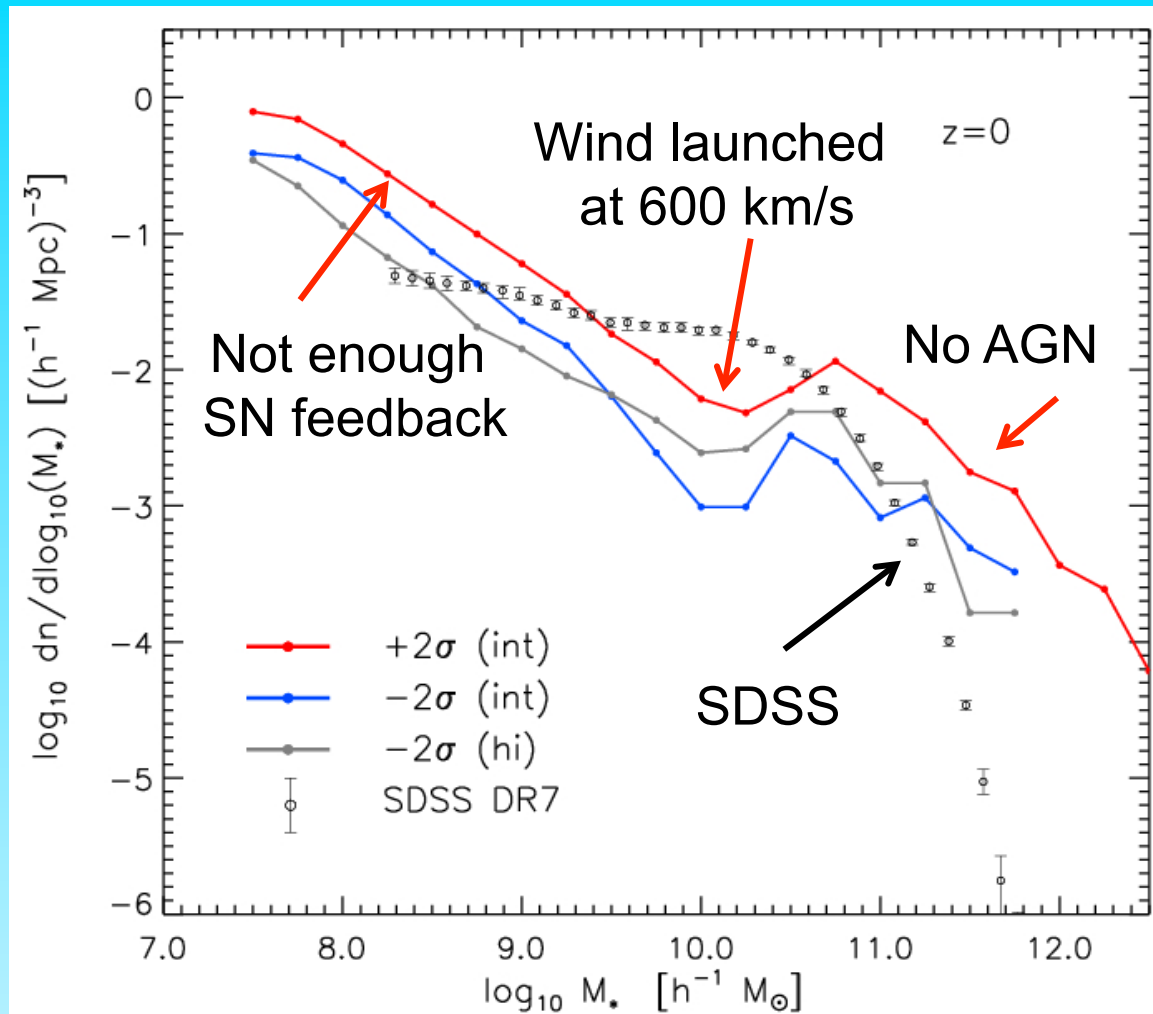
Crain et al. (2009)

The galaxy stellar mass function

Hydrodynamics

GIMIC project

SPH hi res resimulations of 5 regions from the Millennium run with full baryonic physics





The next generation of galaxy formation simulations

- “Illustris” – Arepo (moving mesh) (Springel, Vogelsberger, ...)
- “Evolution and Assembly of GaLaxies and their Environments (EAGLE)” – Anarchy (pressure-entropy SPH) (Virgo)

The goals of gal. population models

- Explore the statistics and interaction of the many **processes** affecting star and gas within growing CDM structures
- Understand how the effects of these processes are reflected in the various observed population properties of galaxies and their evolution -- **abundances, scaling relations, clustering**
- Allow **interpretation of** large observational surveys in terms of the rates, efficiencies and significance of these processes
- **NOT** to make a definitive *a priori* physical model for the formation of everything from linear Λ CDM initial conditions

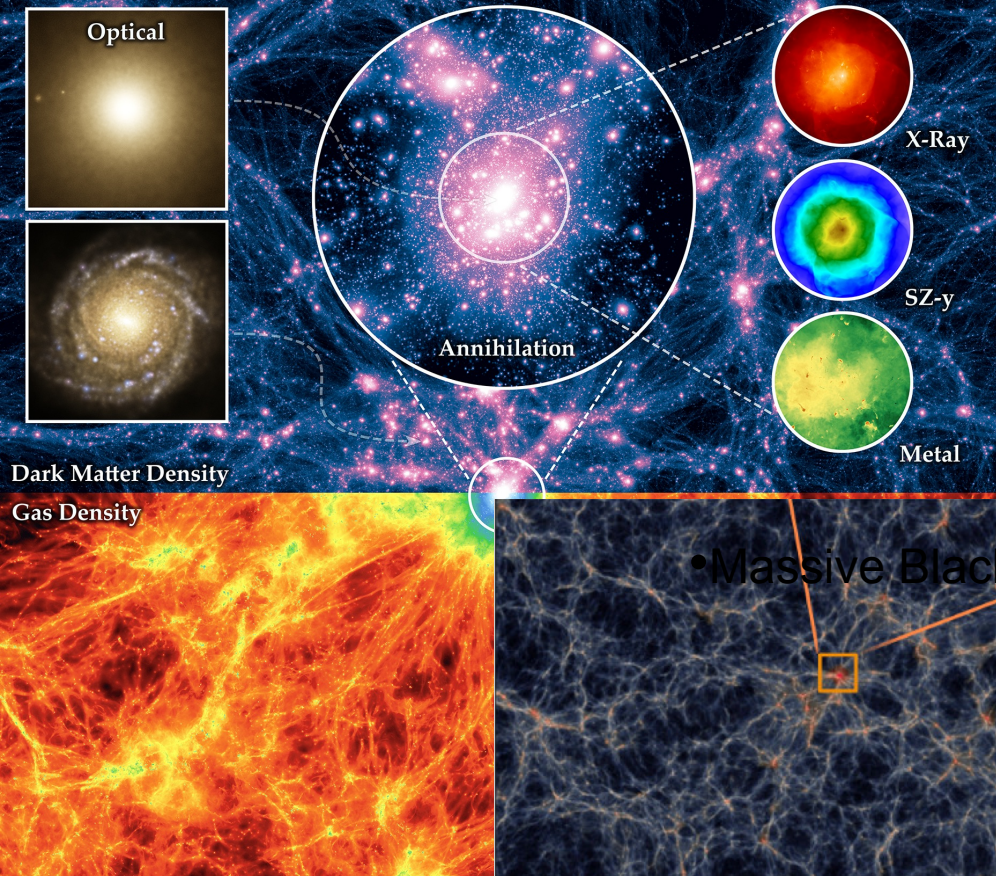
Gas simulations of galaxy populations

- New generation of gasdynamic simulations of cosmologically representative volumes ($\sim 100 \text{ Mpc}^3$) produce realistic galaxies
- Slower, much less resolution/volume than semianalytics but do not assume spherical symmetry and follow evol. of gas in detail

Galaxy Population Simulations

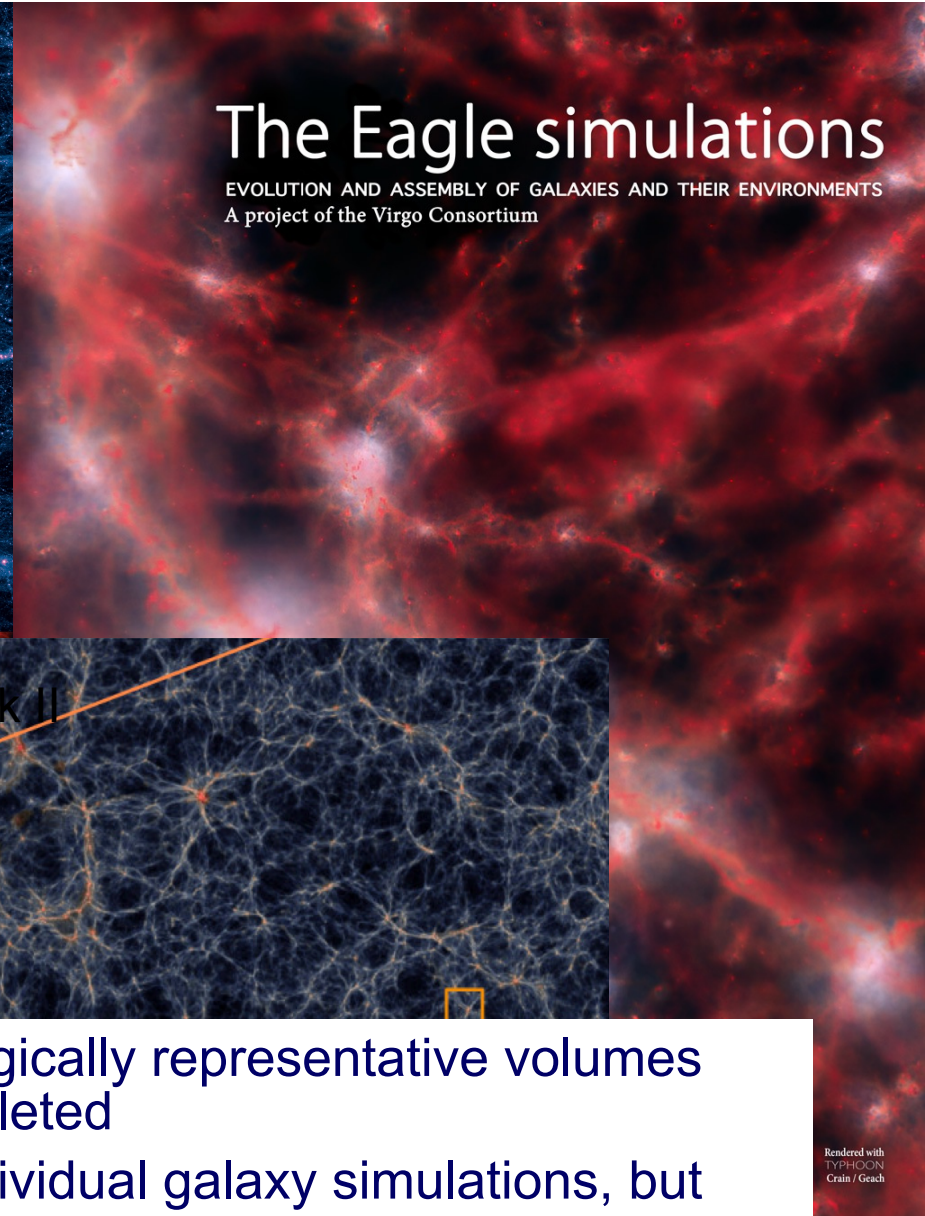
The Illustris Simulation

M. Vogelsberger · S. Genel · V. Springel · P. Torrey · D. Sijacki · D. Xu · G. Snyder · S. Bird · D. Nelson · L. Hernquist



The Eagle simulations

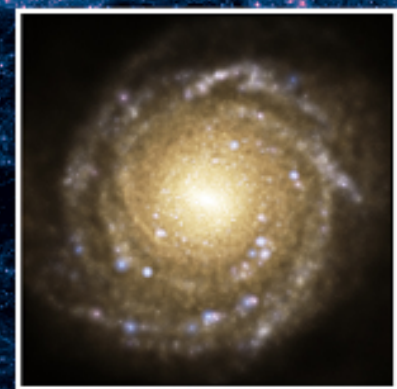
EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS
A project of the Virgo Consortium



- Three large simulation suites of cosmologically representative volumes (~100 Mpc box) have recently been completed
- Resolution (per galaxy) is worse than individual galaxy simulations, but agreement with observation is quite good

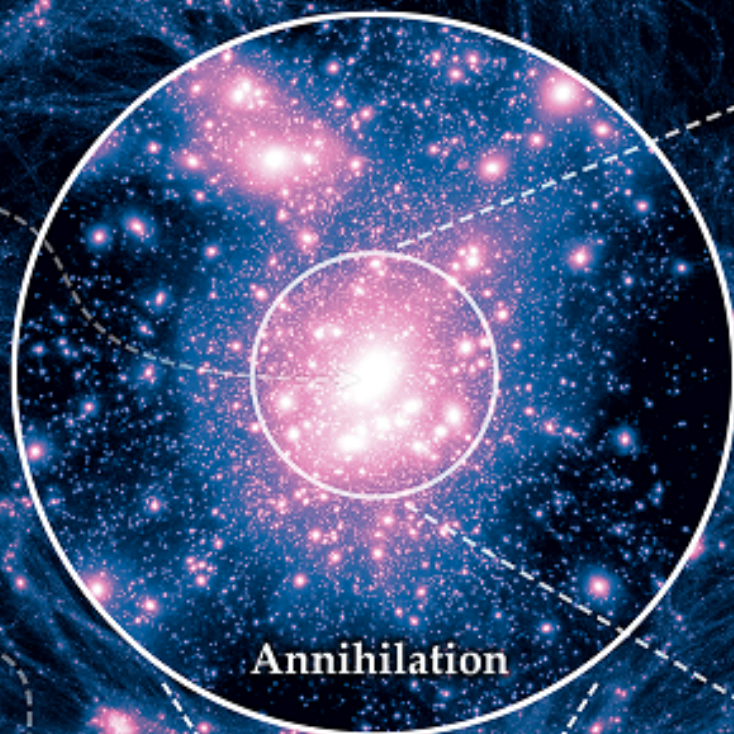
The Illustris Simulation

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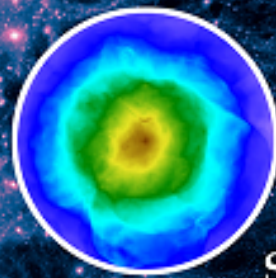


Dark Matter Density

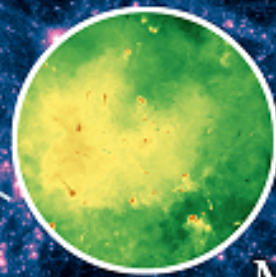
Gas Density



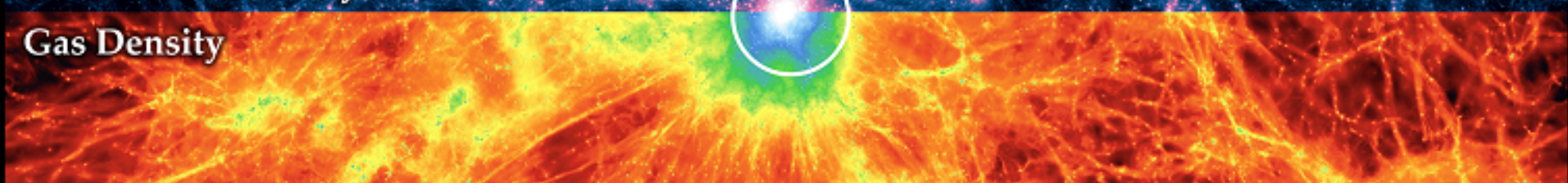
X-Ray



SZ-y



Metal



The VIRGO logo is located in the top left corner. It consists of the word "VIRGO" in white, sans-serif capital letters, positioned to the left of a bright, glowing orange and yellow light source, possibly representing a galaxy or a star, set against a dark red background.

VIRGO

The “Evolution and assembly of galaxies and their environment” (**EAGLE**) simulation project

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins

Leiden: Joop Schaye (PI), Rob Crain

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth...

+ **Virgo Consortium**
NAM 2014

The DiRAC logo is located in the bottom left corner. It features the word "DiRAC" in a stylized, italicized font, with a wavy line underneath it, all enclosed within a white rectangular box.

DiRAC

The ICC logo is located in the bottom center. It consists of the letters "ICC" in a bold, sans-serif font, with the full name "Institute for Computational Cosmology" written in smaller text below it.

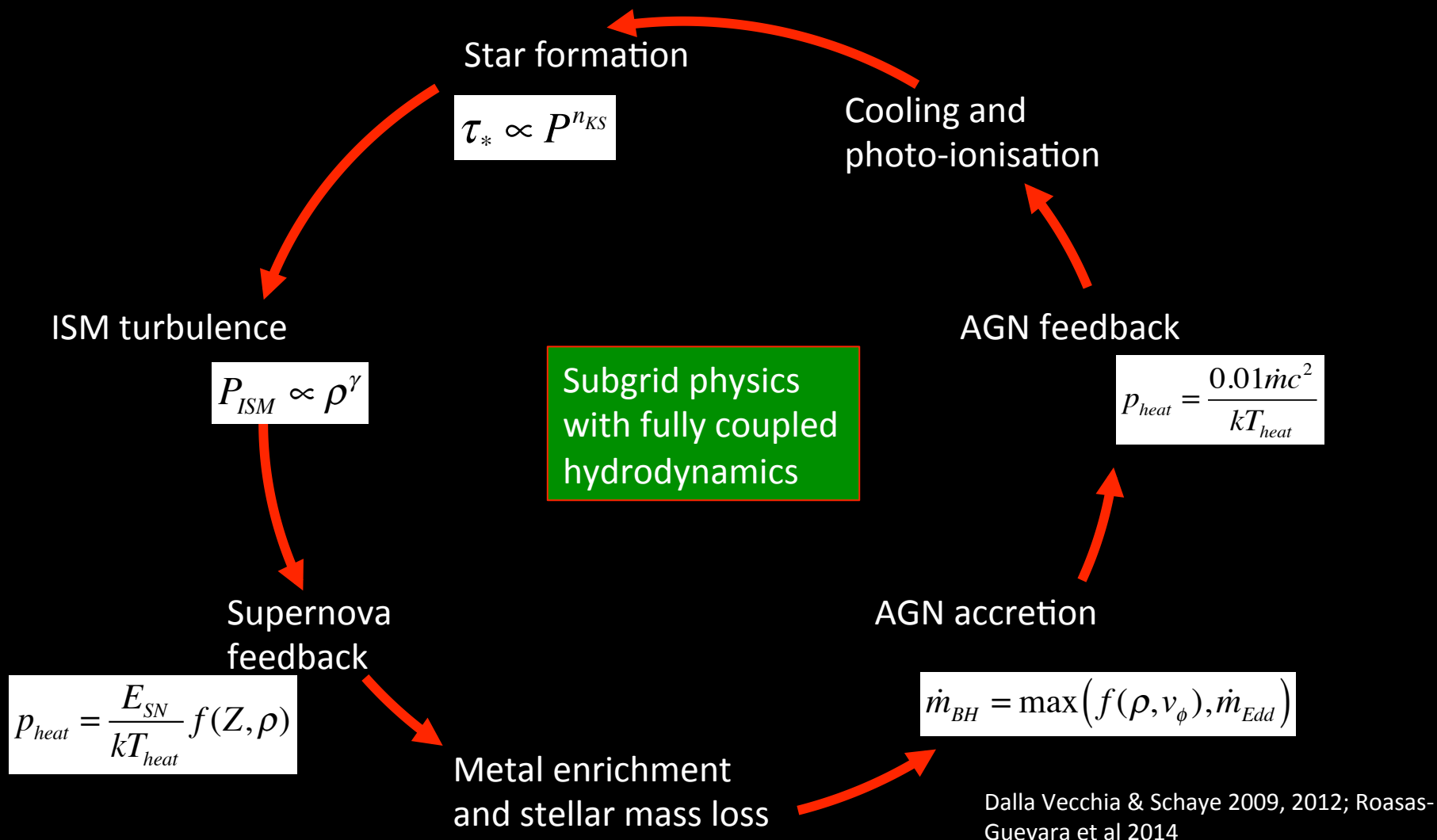
ICC

Institute for
Computational Cosmology

The PRACE logo is located in the bottom right corner. It features the word "PRACE" in a bold, sans-serif font, surrounded by a circular arrangement of stars, all within a blue rectangular box.

PRACE

Sub-grid schemes in EAGLE



The EAGLE simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

A project of the Virgo consortium

$z = 19.9$

$L = 25.0 \text{ cMpc}$

Visible components:

CDM

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

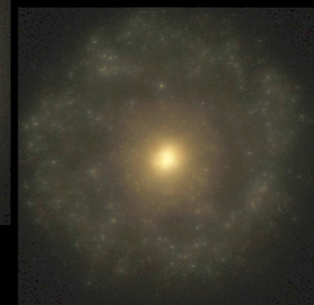
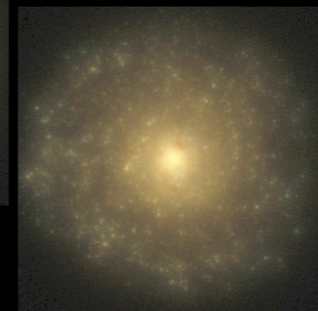
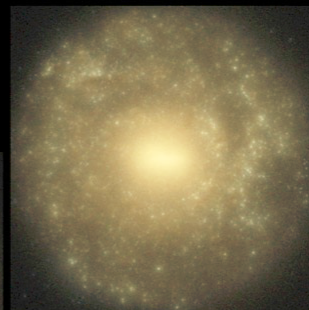
The Hubble Sequence realised in cosmological simulations

SB

E0

E7

S0



S

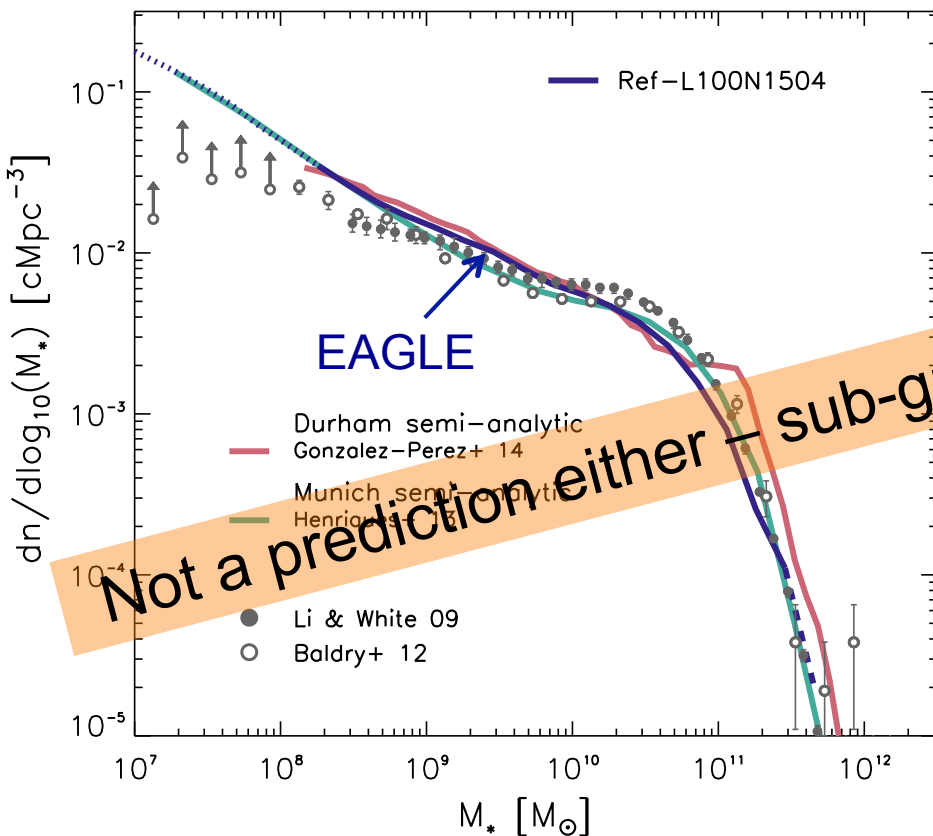
Irr



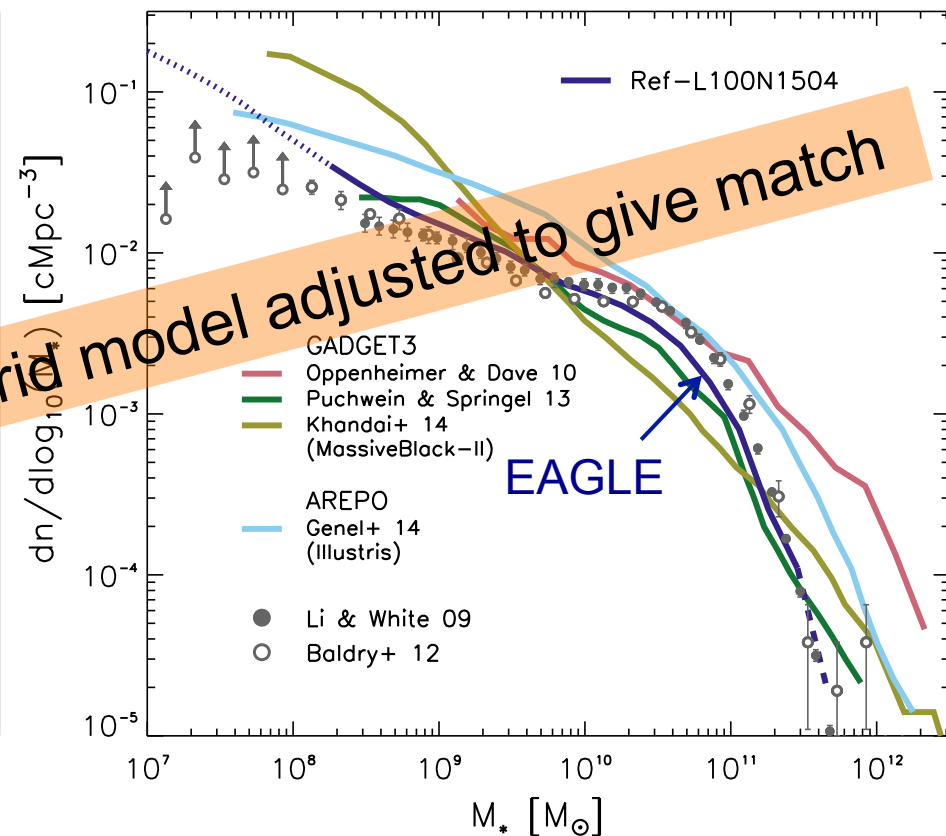
Trayford et al '14

Galaxy stellar mass function

Comparison to semi-analytic models

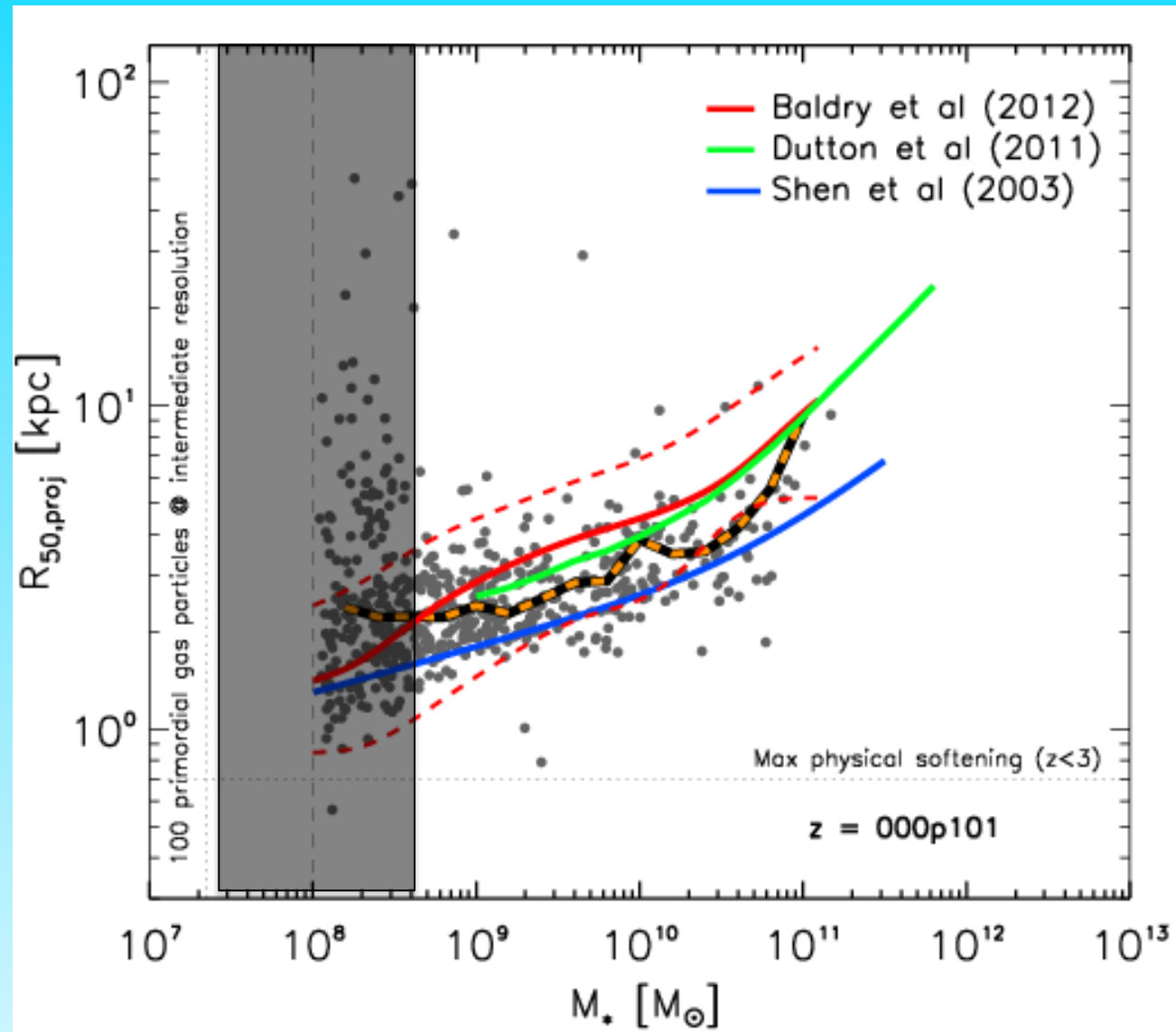


Comparison to other Hydro simulations



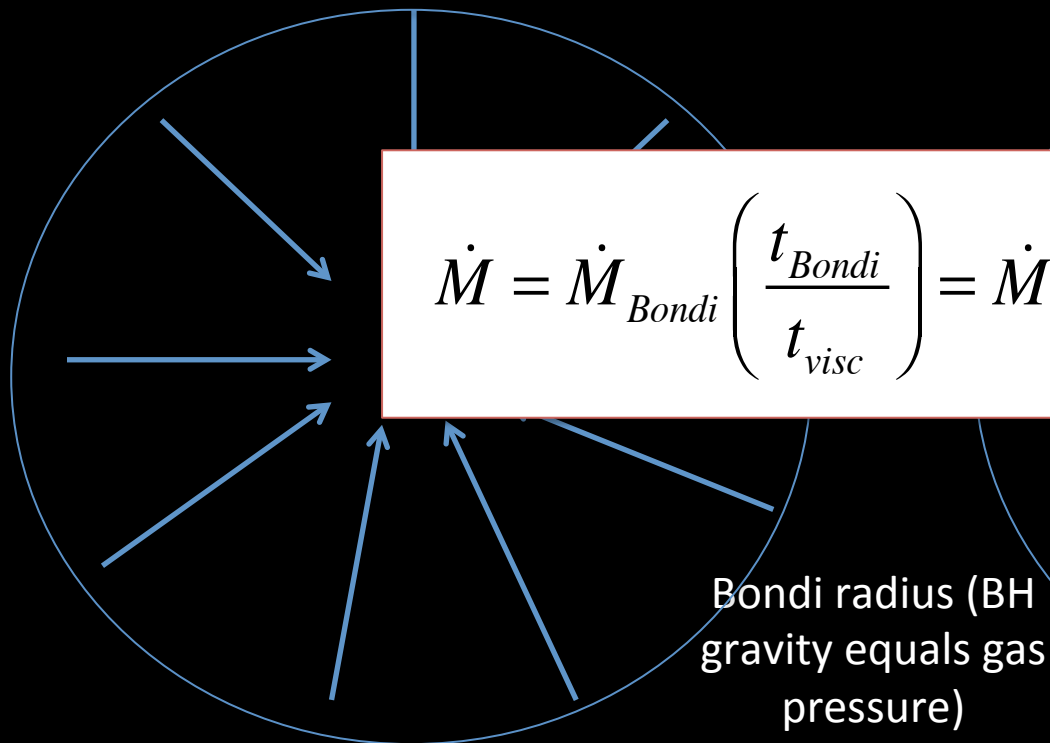
The size vs stellar mass relation in EAGLE

SN feedback model
adjusted to give
acceptable sizes



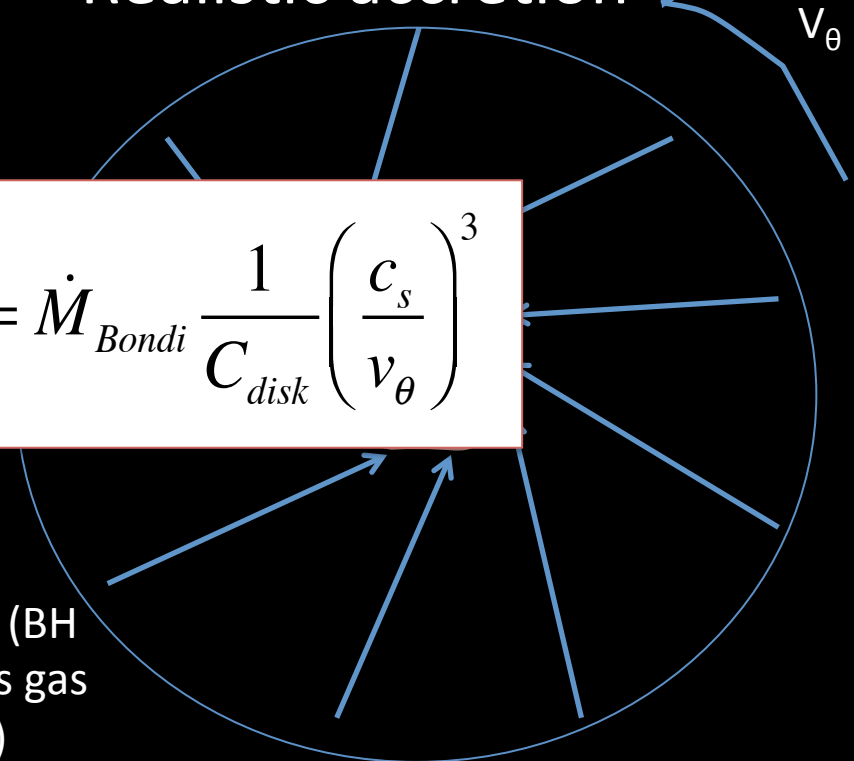
The black hole growth in EAGLE

- Bondi accretion



Material crossing the Bondi radius free-falls into the black hole

- Realistic accretion



Accreting material forms a disk at r_{circ} .
It then flows into the black hole on the
viscous timescale of the disk

$$\dot{M} = \dot{M}_{\text{Bondi}} \left(\frac{t_{\text{Bondi}}}{t_{\text{visc}}} \right) = \dot{M}_{\text{Bondi}} \frac{1}{C_{\text{disk}}} \left(\frac{c_s}{v_\theta} \right)^3$$

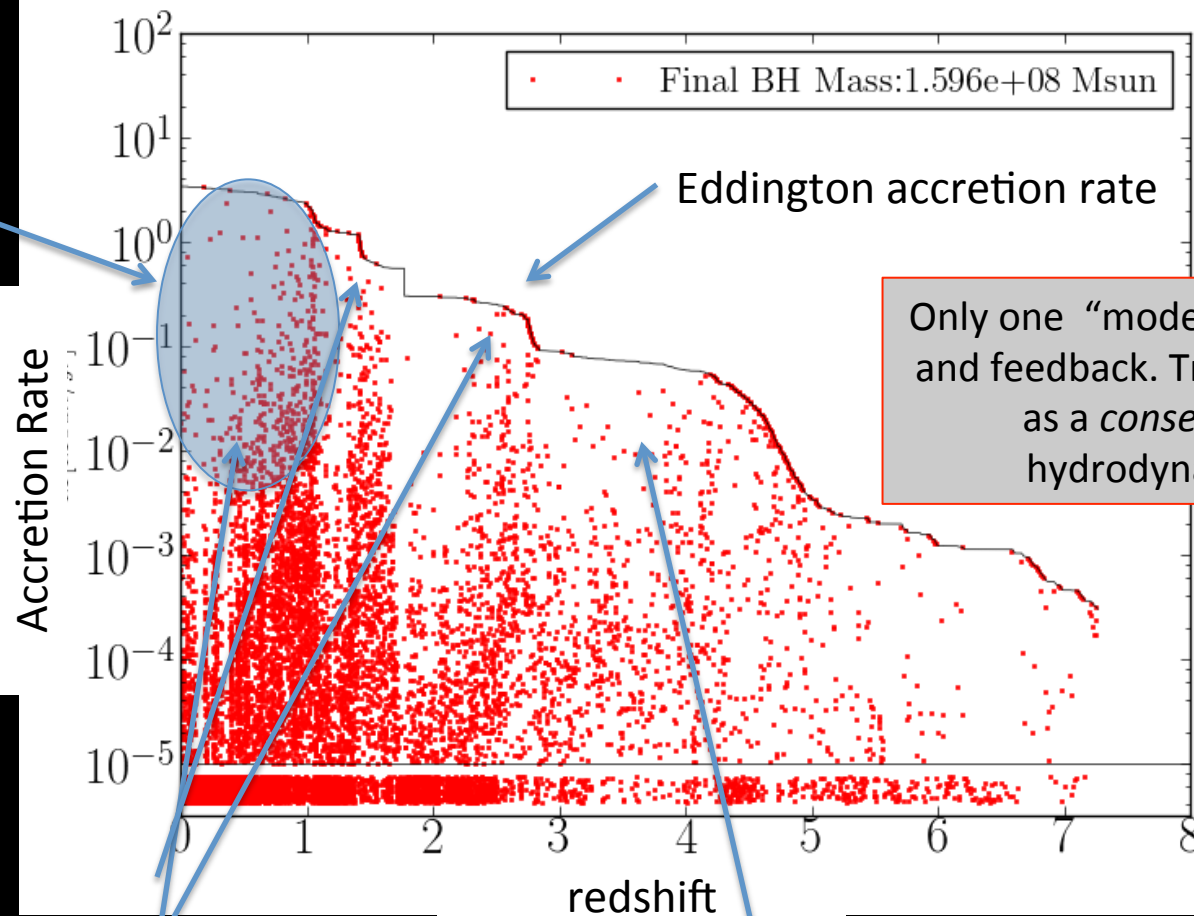
Implementing AGN feedback

- Outline of stochastic heating model
 - Avoids spurious cooling due to lack of resolution
 - Always heat gas to a fixed temperature, but with a probability that is dependent accretion rate
 - NO MODE – heating rate is the same whether accretion is close to Eddington limit or not.

The life of one black hole...

Frequent moderate accretion events

- But not often reaching Eddington
- Ideal accretion rates for generating radio jets



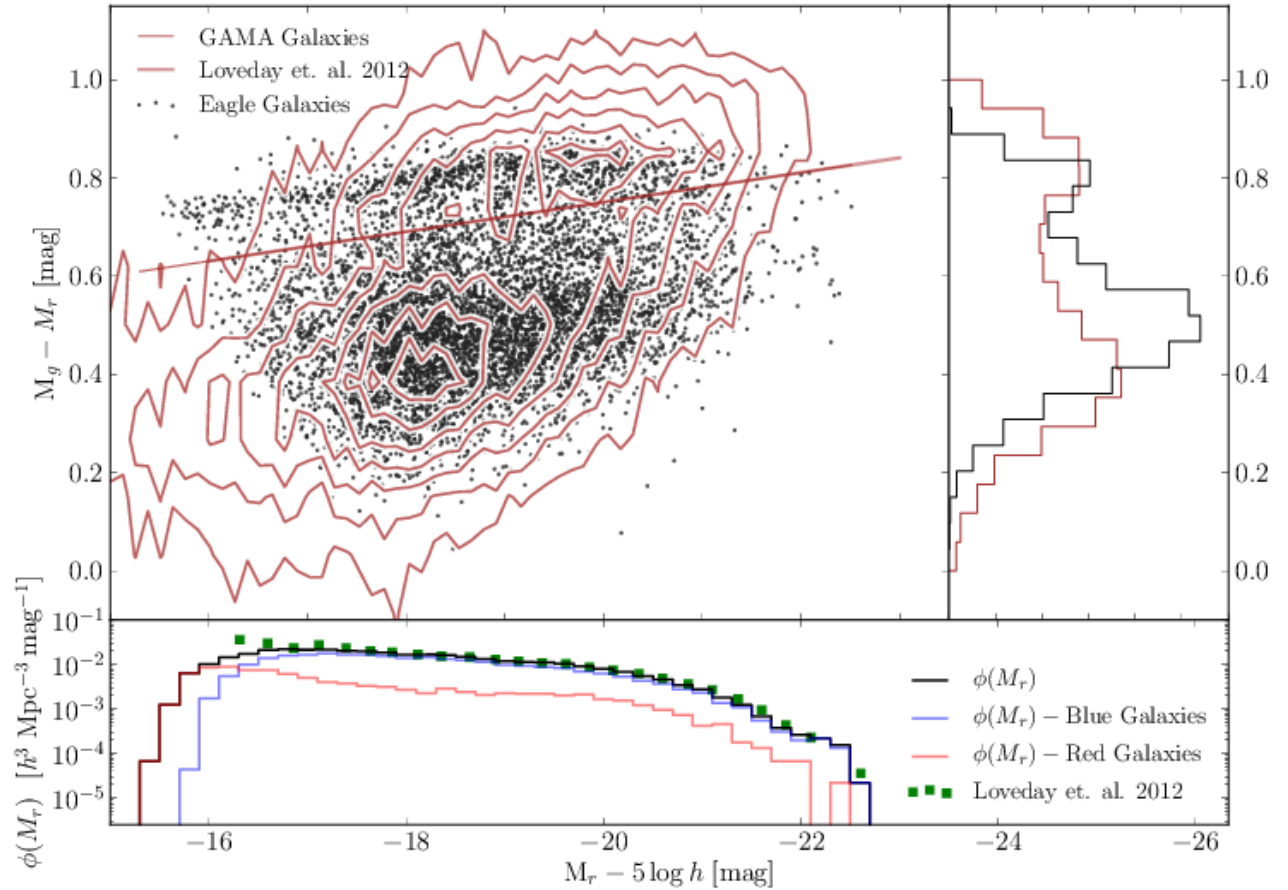
Only one “mode” of accretion and feedback. Trends emerge as a *consequence* hydrodynamics!!

Eddington-limited (quasar-like) accretion events

Long periods without significant accretion

The colour-mag reln in EAGLE

Good agreement
with GAMA data

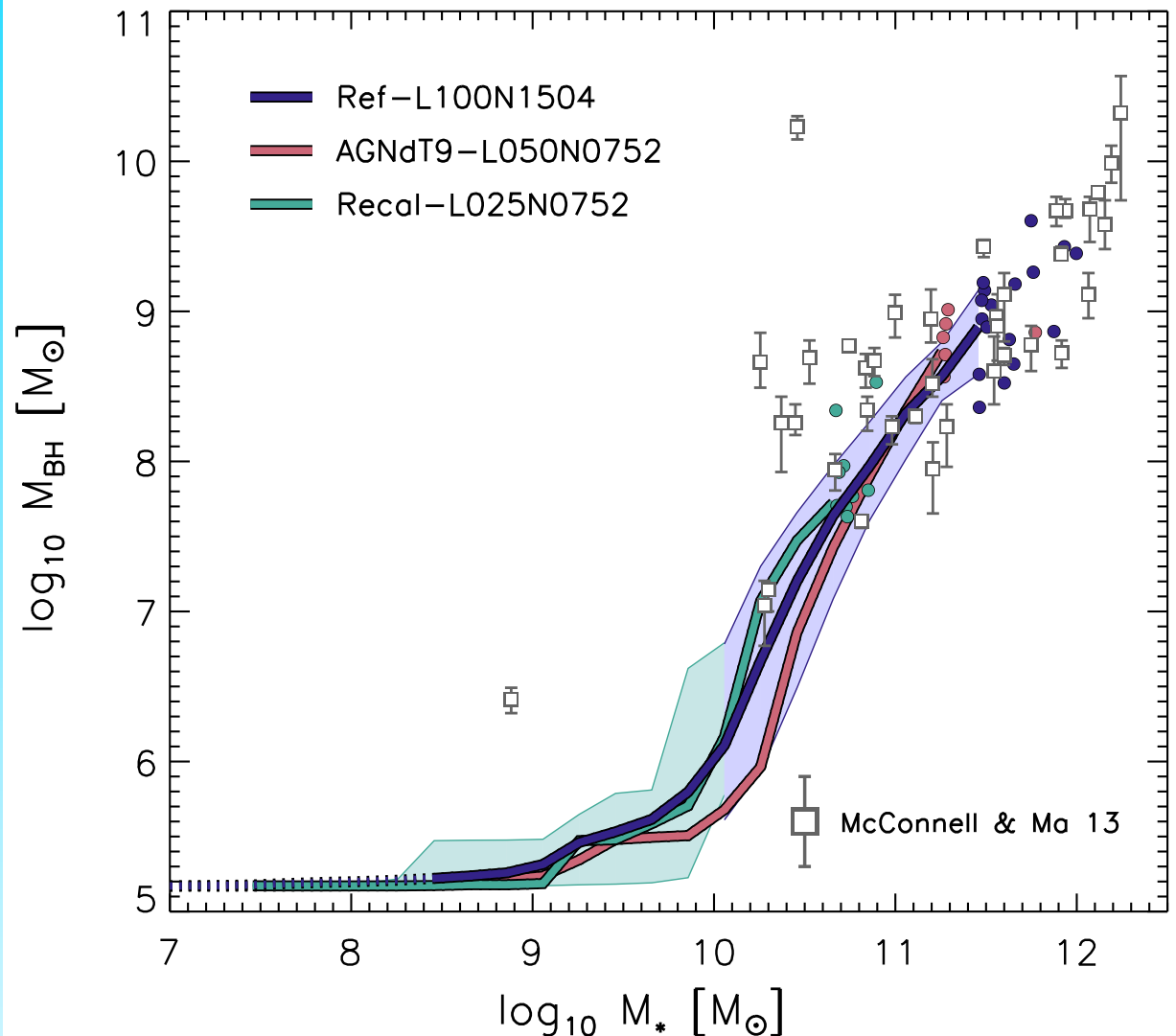


Trayford et al '15

The black hole mass vs stellar mass relation in EAGLE

Normalization fixed
by assumed
efficiency of AGN
feedback

Schaye et al. '15



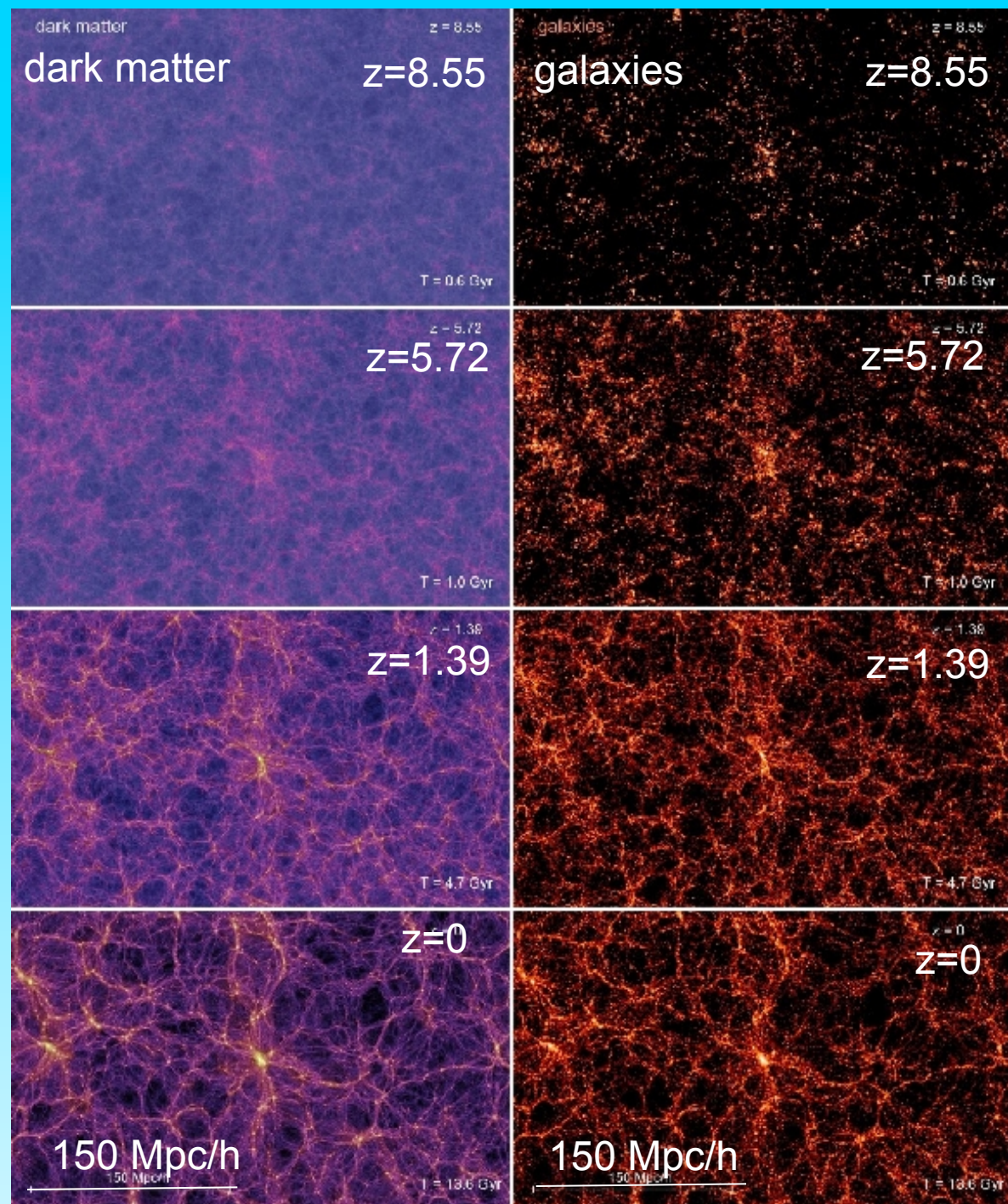


The build up of stellar populations over cosmic time

Millennium Simulation

At early times, the **dark matter** is **smooth**, but the **galaxies** are already strongly **clustered**

Springel, Frenk & White
Nature, May/06



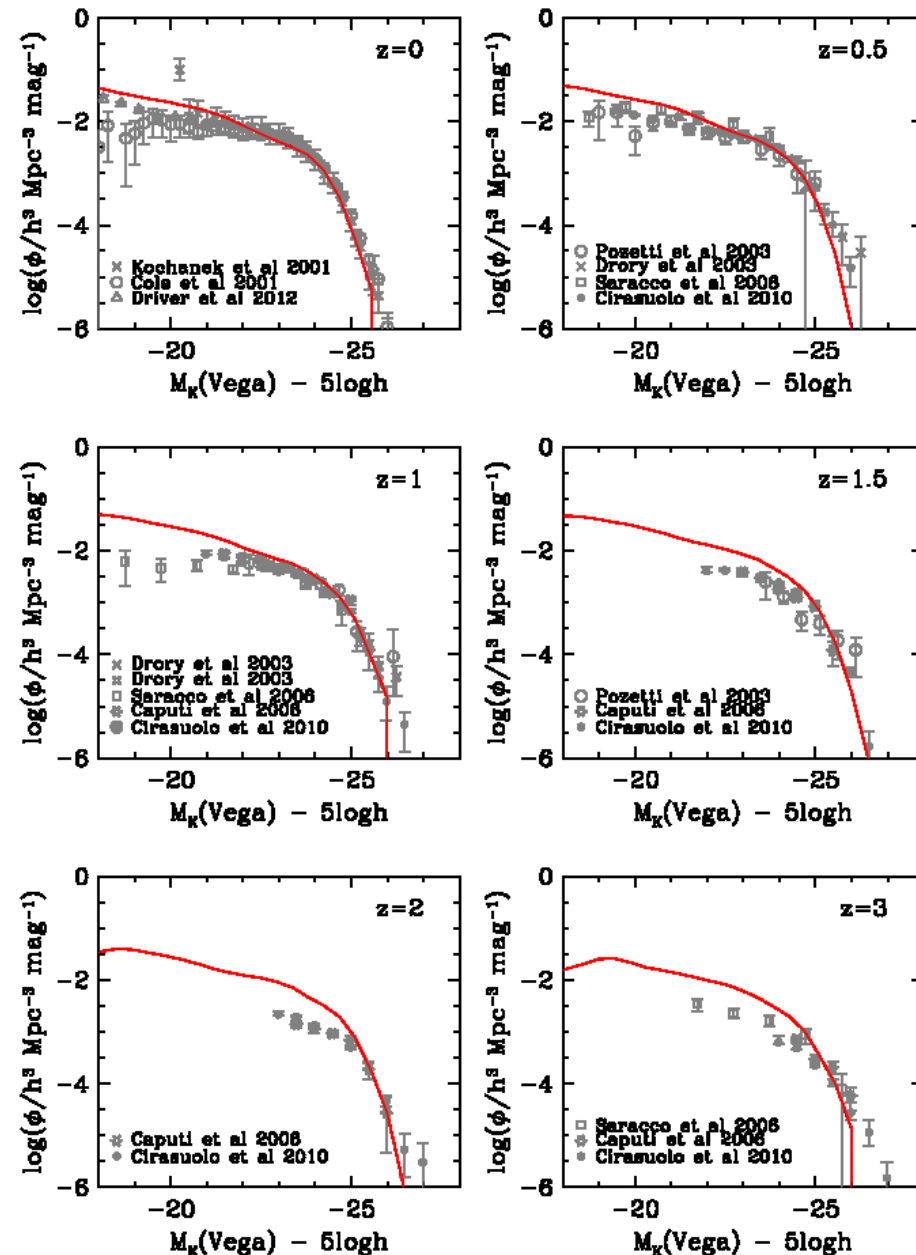
Evolution of the luminosity fn.

GALFORM

GALFORM gives excellent match to the evolution of the K-band galaxy luminosity function to $z=3$

This is a genuine prediction!

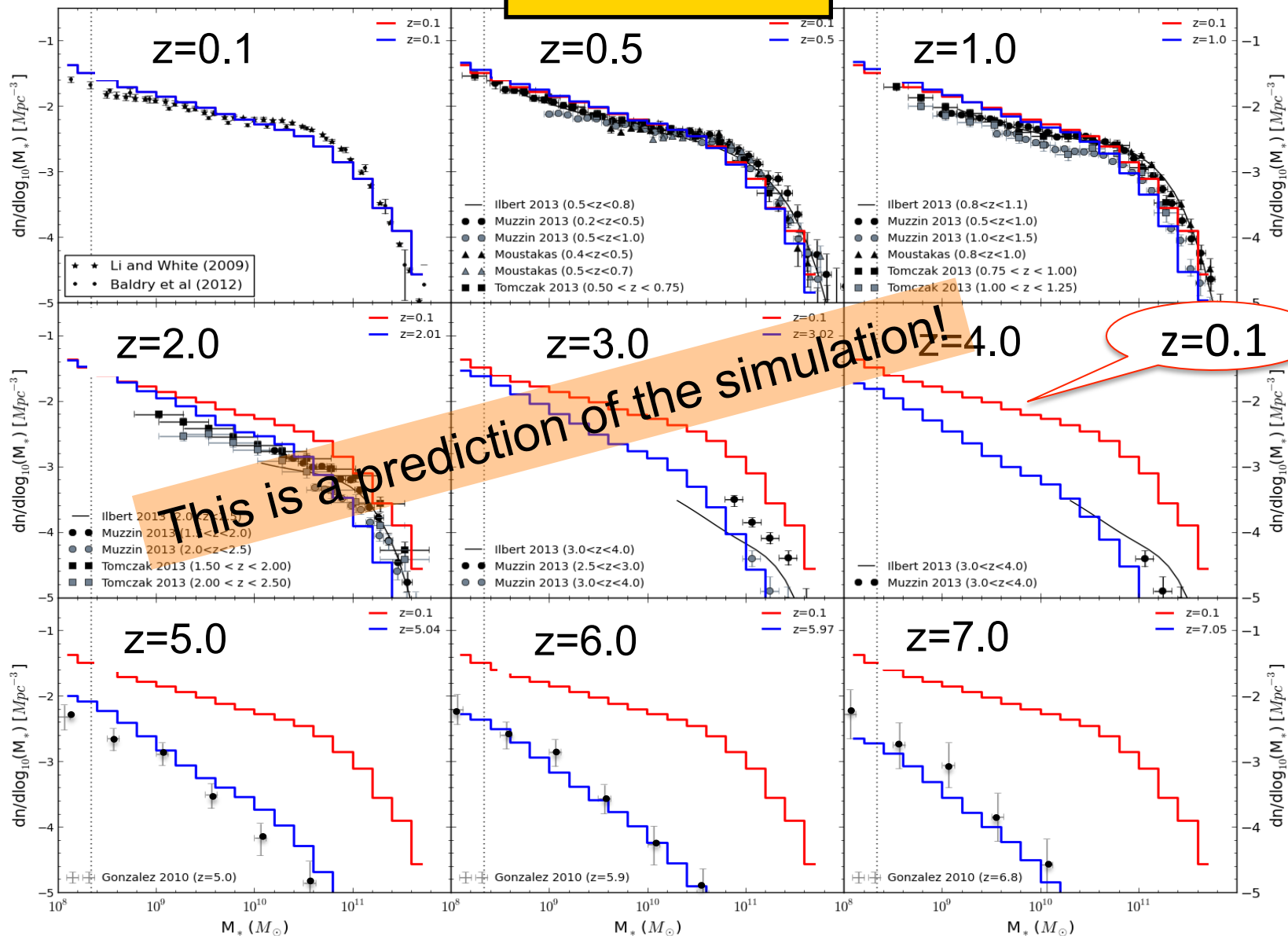
Lacey, Baugh, Frenk et al. '15



Evolution of the stellar mass fn.

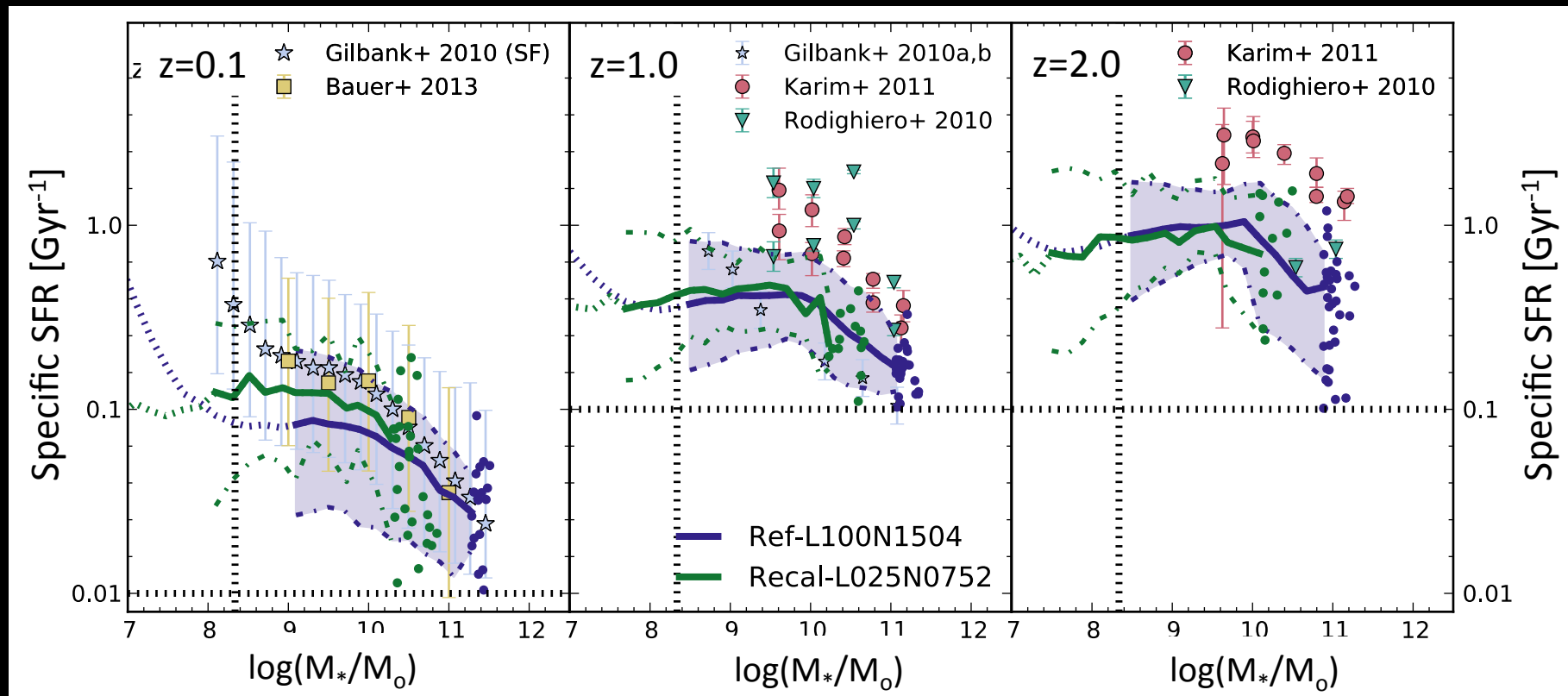
EAGLE

Galaxy Stellar Mass Function



Galaxy Formation in the Eagle Universe

- Specific star formation rates

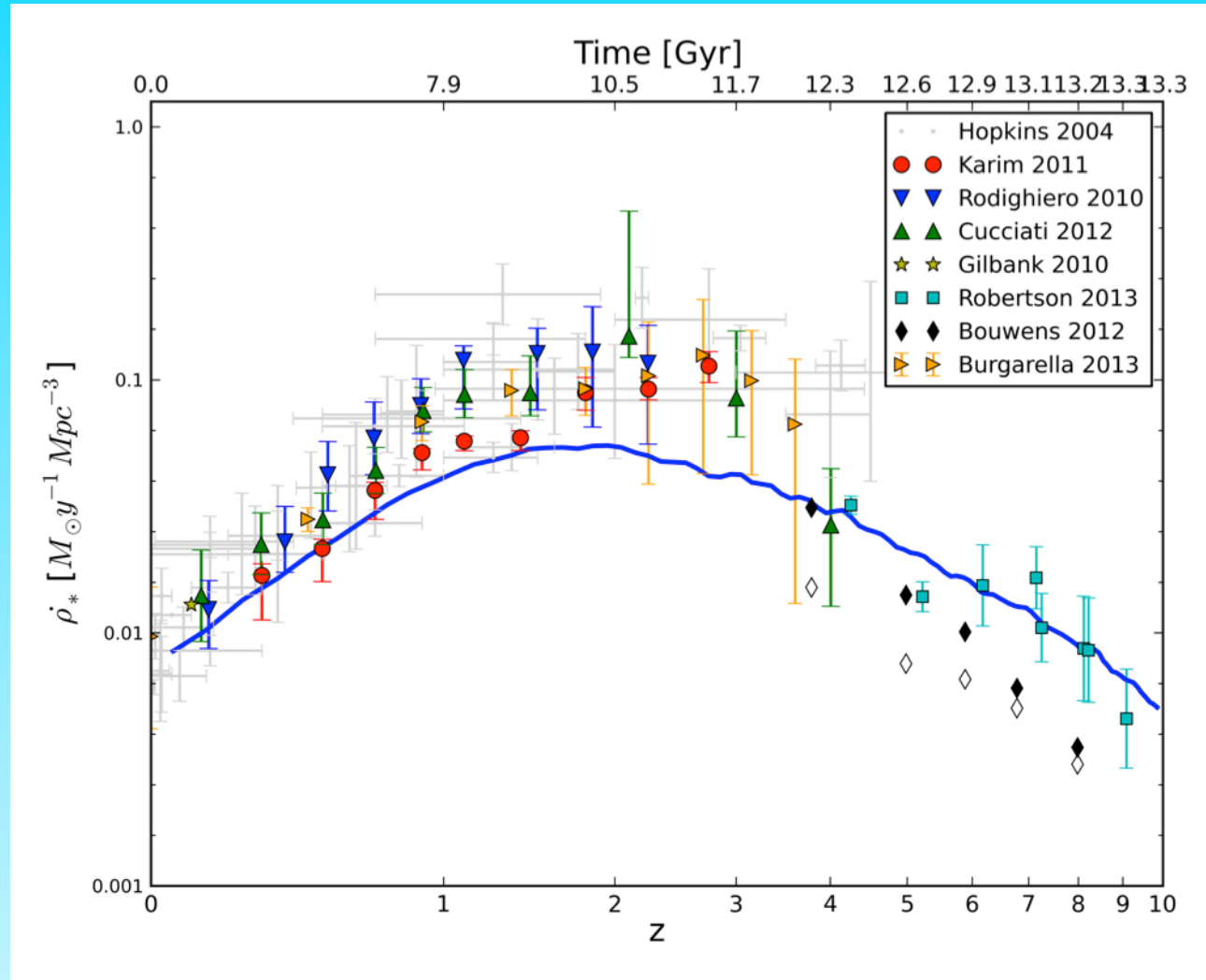


Evolution of the SFR density

EAGLE

SFR density as a
fn of z

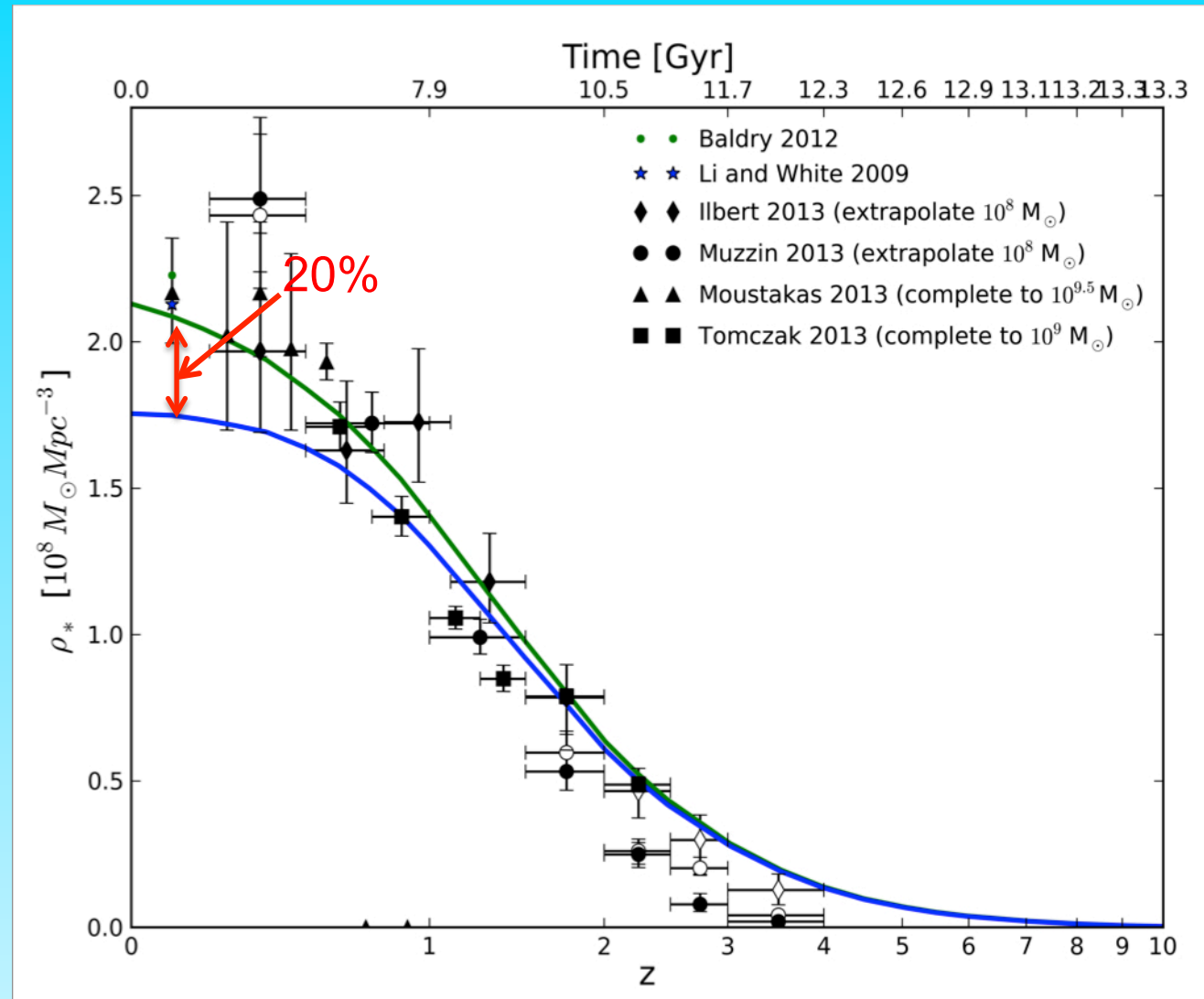
The model lies
below the data by
> x2 at most z



EAGLE

Stellar mass
density formed by z

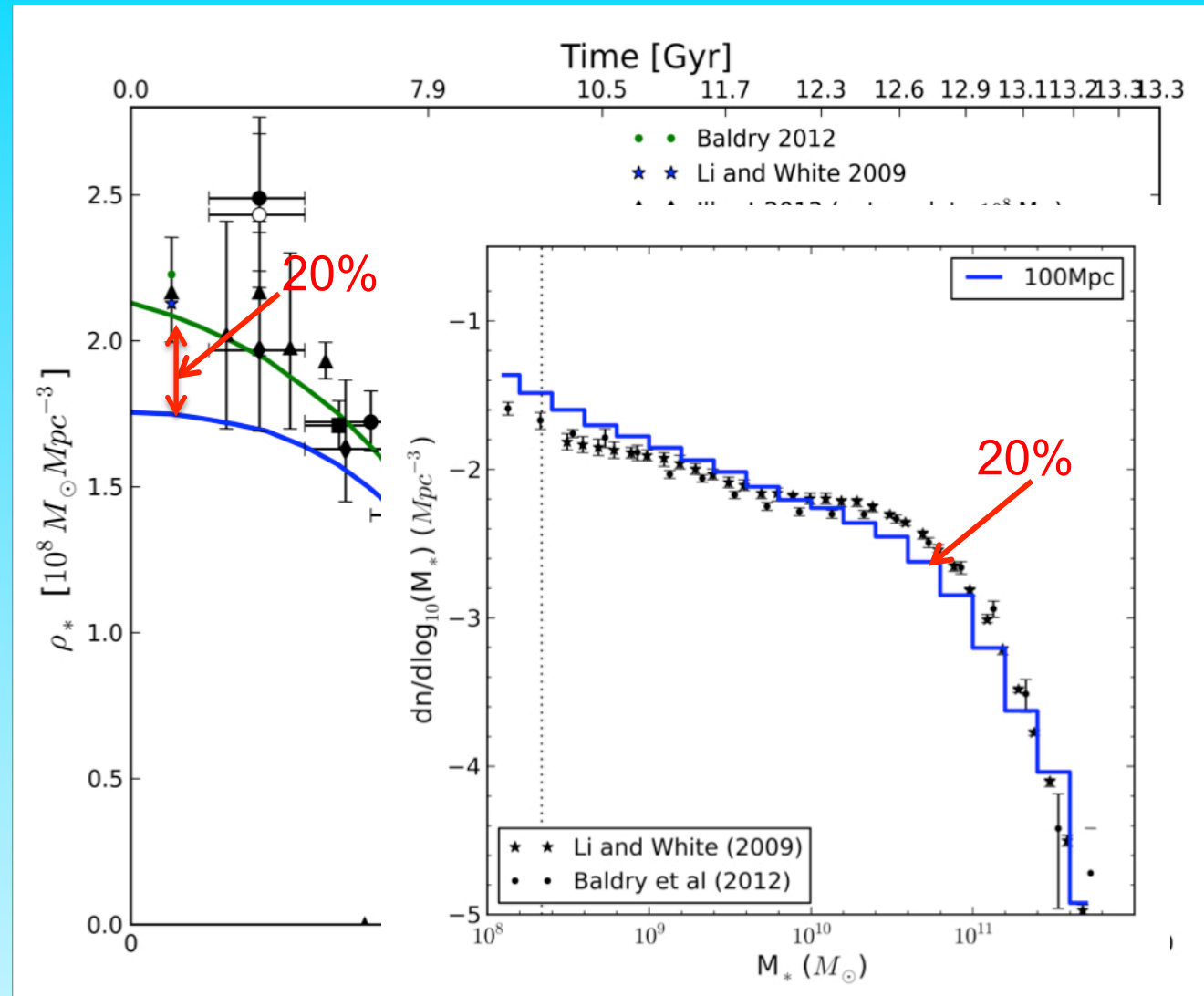
The model
agrees with the
data within 20%



EAGLE

Stellar mass density formed by z

The model agrees with the data within 20%



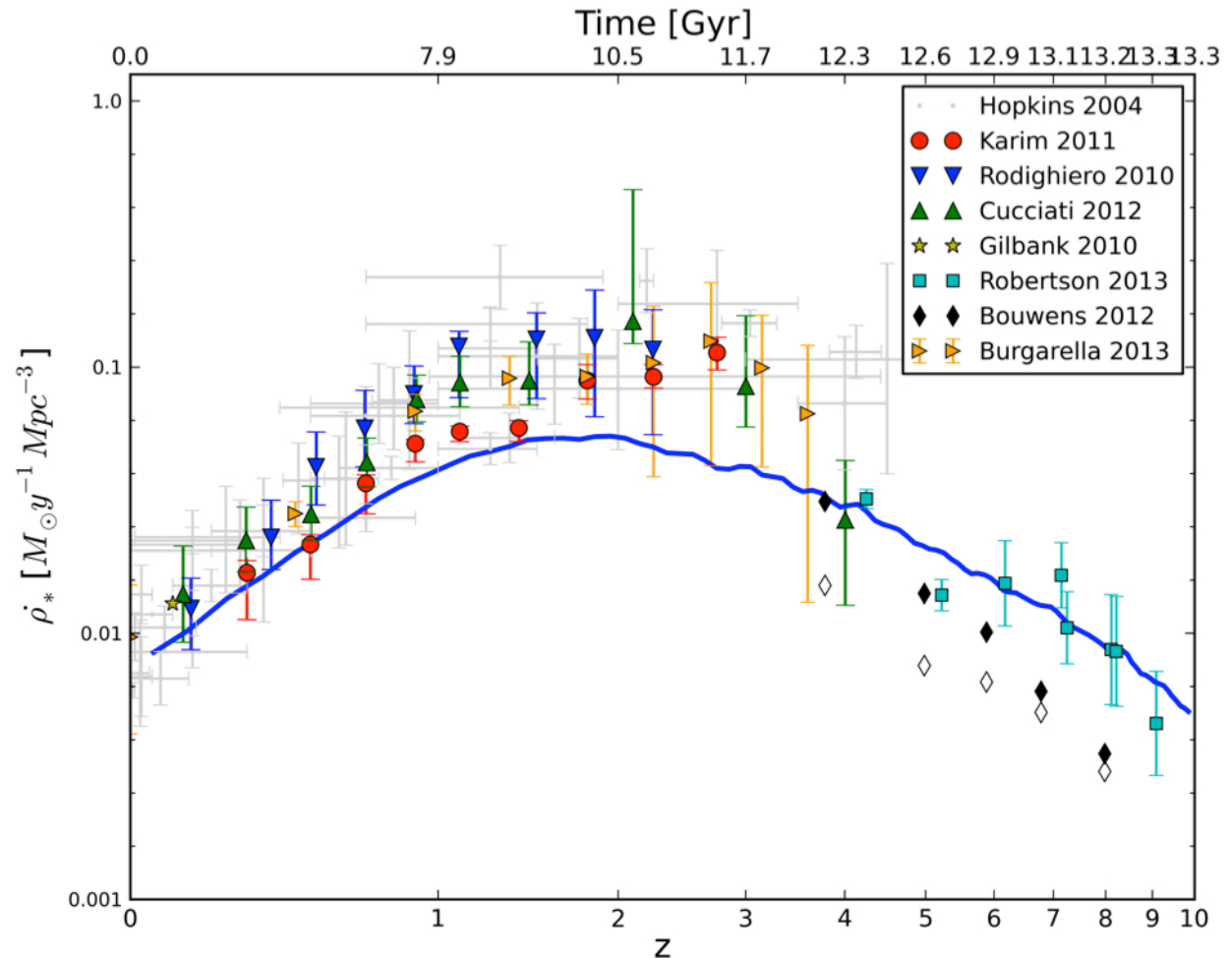
Evolution of the SFR density

EAGLE

SFR density as a
fn of z

The model lies
below the data by
> x2 at most z

But it matches (to
20%) the “measured”
stellar mass at all z !



There appears to be an inconsistency between
“measured” $\text{SFR}(z)$ and $M_*(z)$ in current data!



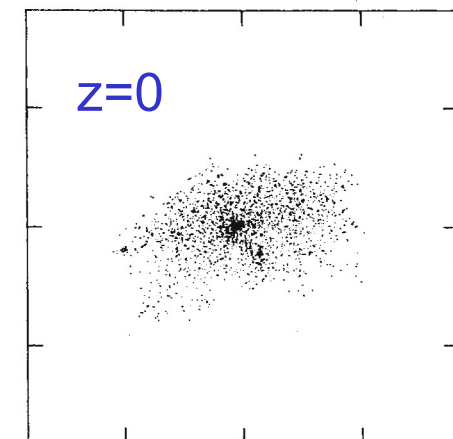
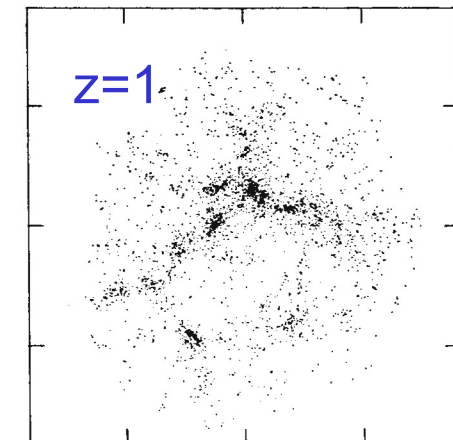
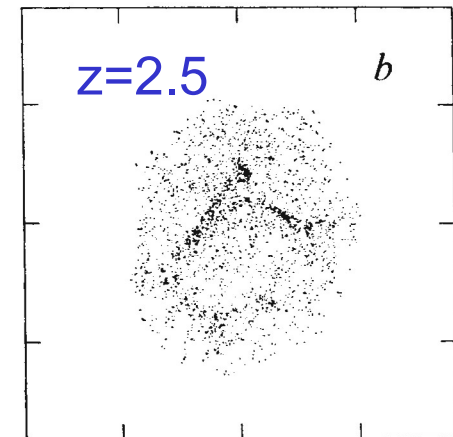
Galaxy assembly and the origin of the Hubble Sequence?

Relative role of in situ star formation, minor and major galaxy mergers and disk instabilities ?

Cold dark matter, the structure of galactic haloes and the origin of the Hubble sequence

Carlos S. Frenk*, Simon D. M. White†, George Efstathiou‡ & Marc Davis§

A popular theory for galaxy formation holds that the Universe is dominated by exotic particles such as axions, photinos or gravitinos (collectively known as cold dark matter, CDM)^{1–3}. This hypothesis can reconcile the aesthetically pleasing idea of a flat universe with the standard theory of primordial nucleosynthesis and with upper limits on anisotropies in the cosmic microwave background^{4–6}. The resulting model is consistent with the observed dynamics of galaxy clustering only if galaxy formation is biased towards high-density regions^{7,8}. We have shown that such a biased model successfully matches the distribution of galaxies on megaparsec (Mpc) scales⁹. If it is to be viable, it must also account for the structure of individual galaxies and their haloes. Here we describe a simulation of a flat CDM universe which can resolve structures of comparable scale to the luminous parts of galaxies. We find that such a universe produces objects with the abundance and characteristic properties inferred for galaxy haloes. Our results imply that merging plays an important part in galaxy formation and suggest a possible explanation for the Hubble sequence.



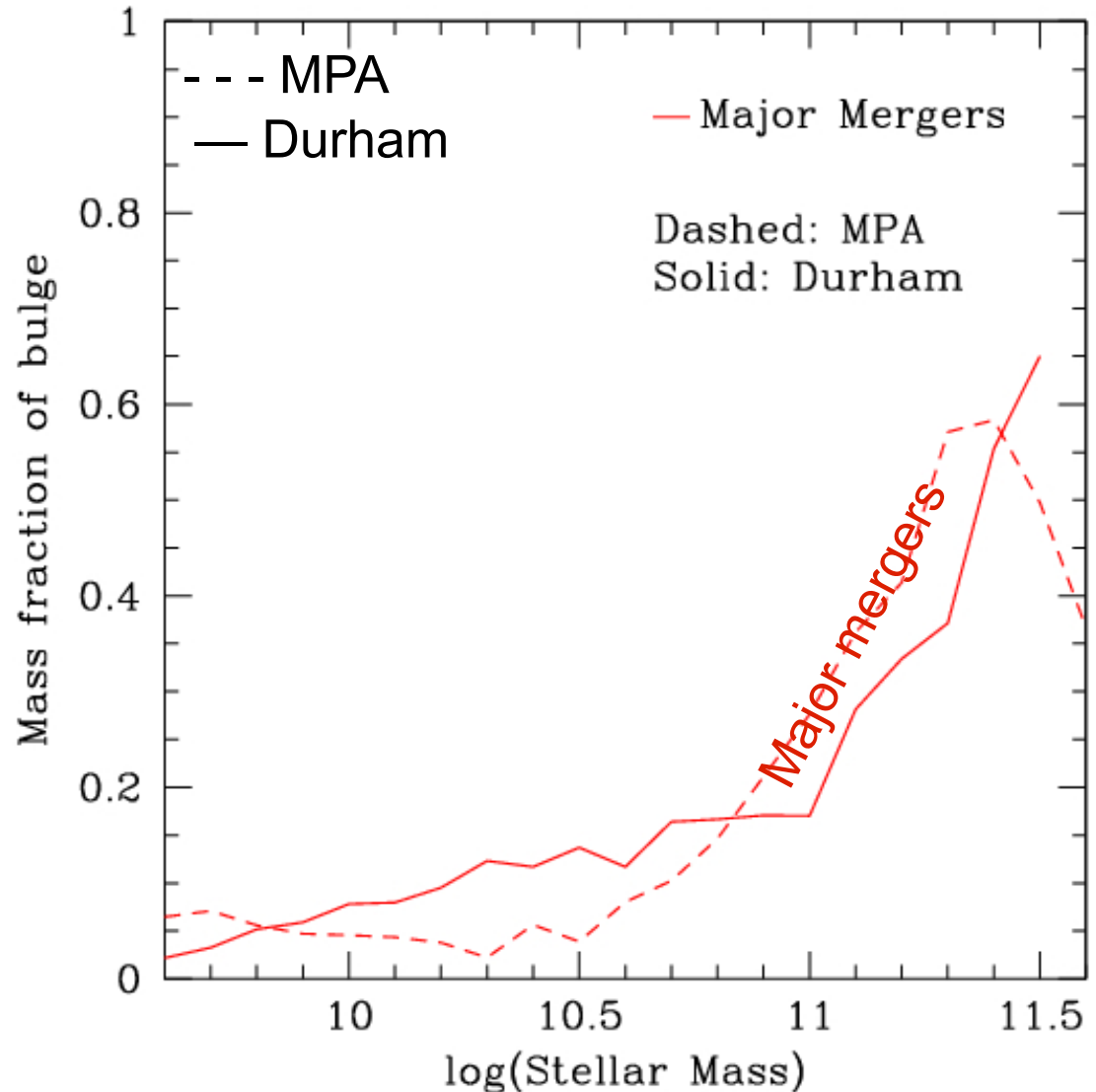
The formation of spheroids: ellipticals & bulges

3 processes for making spheroids:

- Major mergers
- Minor mergers
- Disk instabilities

Average fraction of
spheroid stars form
by each process

Parry, Eke & Frenk '08



The formation of spheroids: ellipticals & bulges

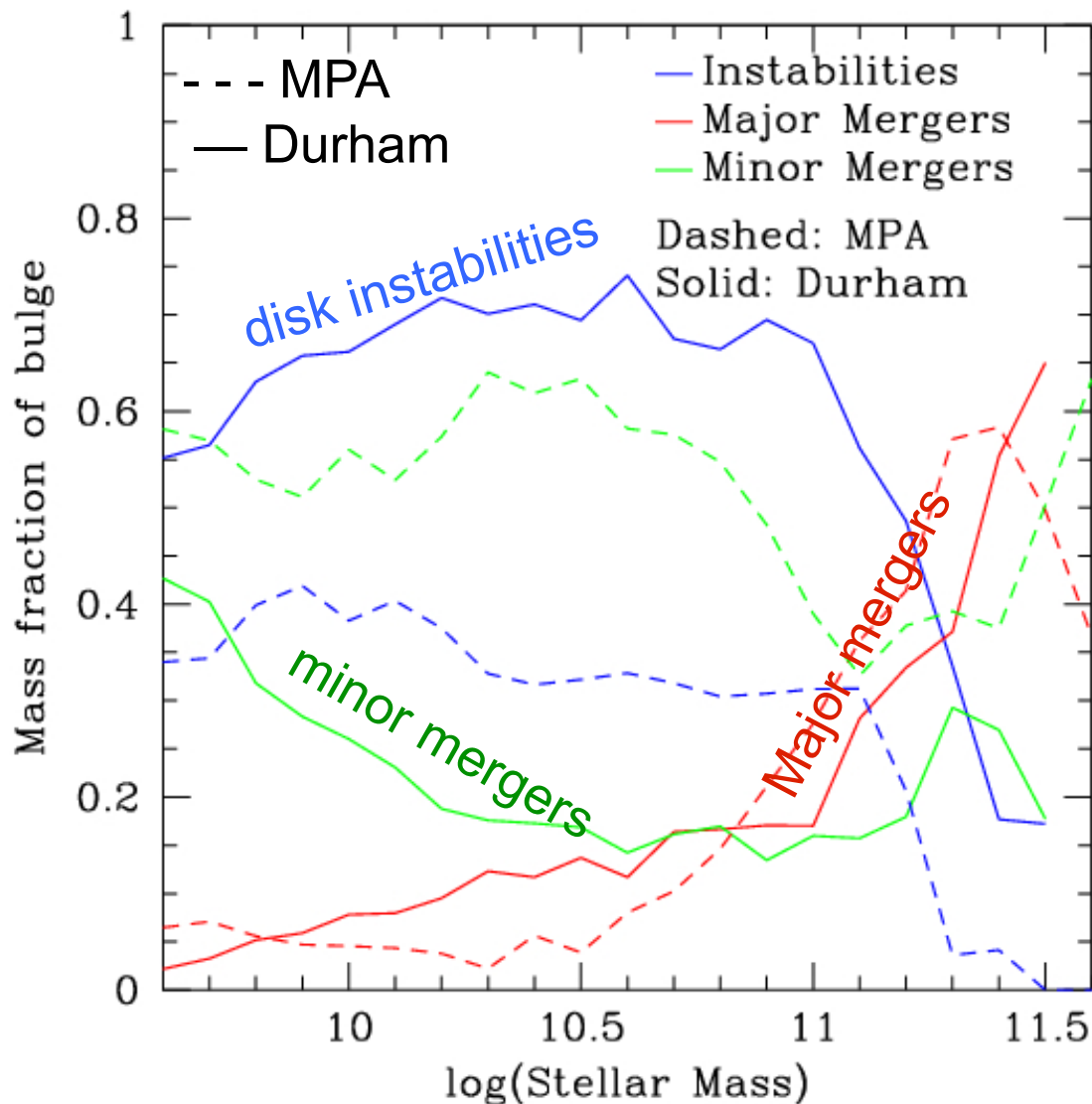
3 processes for making spheroids:

- Major mergers
- Minor mergers
- Disk instabilities

Average fraction of
spheroid stars form
by each process

Major mergers only
dominant for bright
spheroids

Parry, Eke & Frenk '08



The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

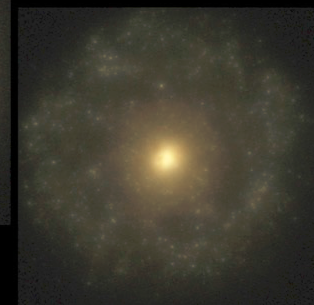
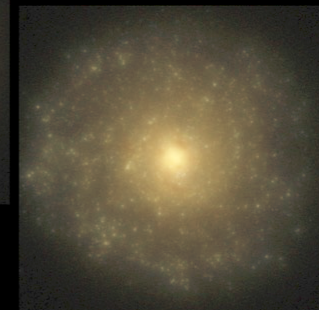
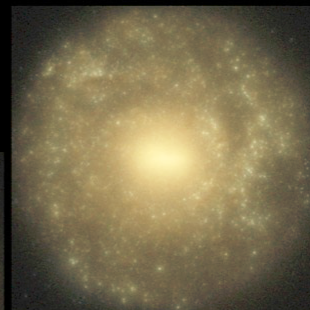
The Hubble Sequence realised in cosmological simulations

E0

E7

S0

SB

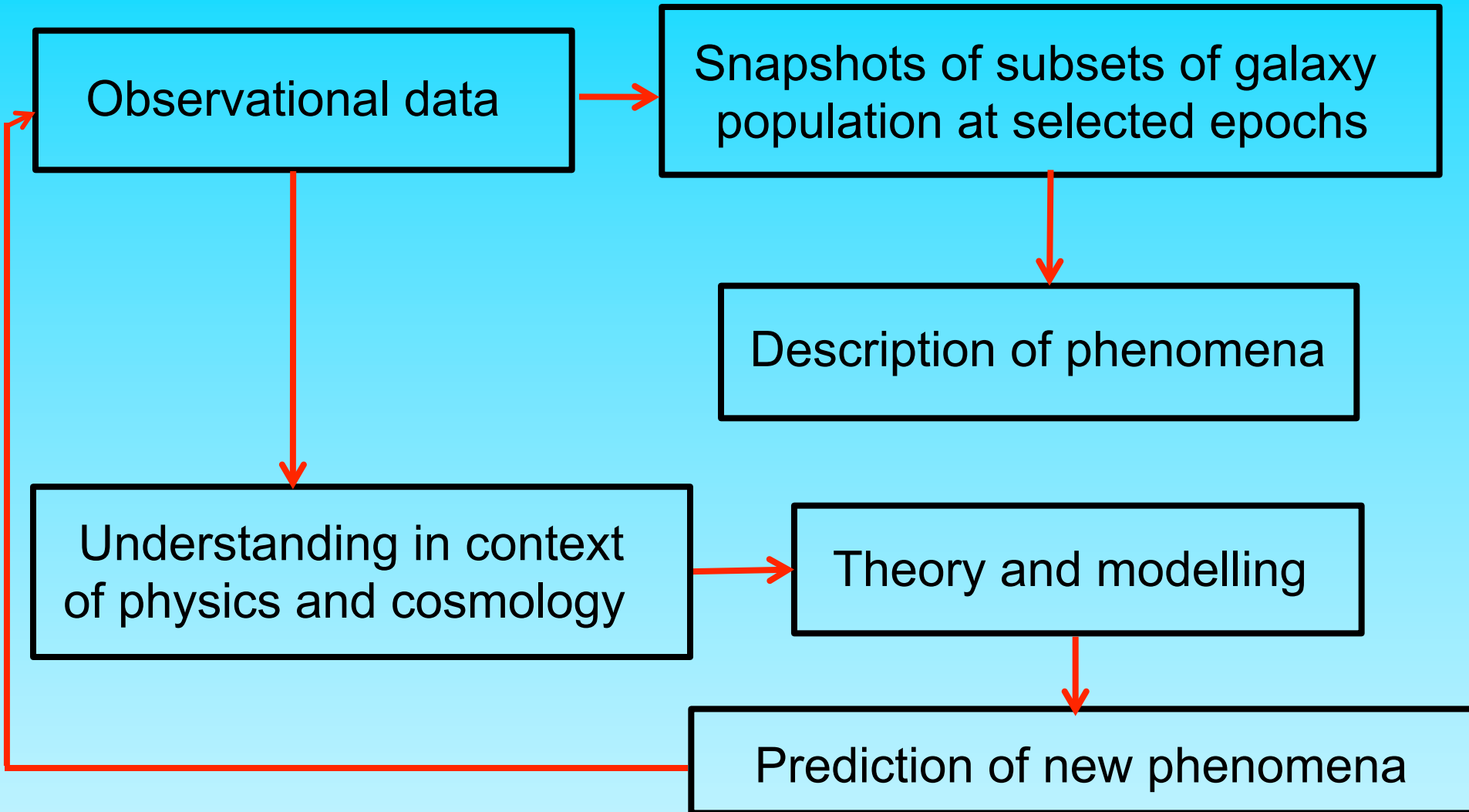


Irr

S

Trayford et al '14

Conclusions



Conclusions

Main successes in galaxy formation theory over past 30 yrs:

- Plausible explanation of evolution of dark matter distribution → contributed to widespread acceptance of Λ CDM
- Identification of main physical processes that determine **galaxy luminosity function** → how DM halos are populated by galaxies
- Plausible explanation for build-up and assembly of galaxies

These have come mostly from a combination of N-body simulations and theory realized through semi-analytic models

Modelling massive galaxies: prospects

Semi-analytic modelling

Keep improving astrophysics modelling

- Star formation – IMF
- Interstellar medium: molecular clouds, coupling of SN energy
- Metal production and diffusion
- Black hole formation & AGN
 - accretion disks
 - BH spin
 - Jet generation
 - Magnetic fields
 - BH-BH mergers, gravity waves

Conclusions

Hydrodynamic simulations have now achieved comparable sophistication to semi-analytic models

Results so far generally confirm earlier conclusions from SA models, but open up new theoretical possibilities:

- Gaseous phenomena: outflows, inflows, CGM, ICM
- Internal structure (morphology?) of galaxies and clusters

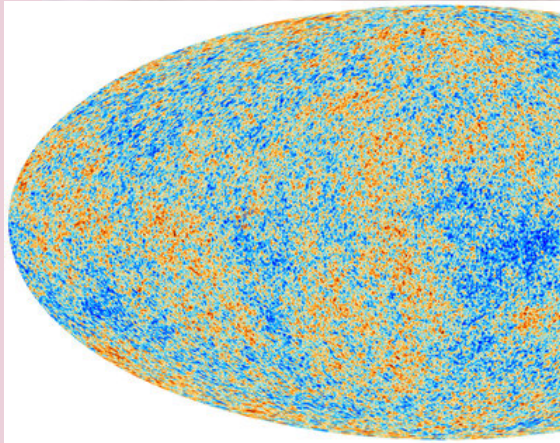
Hydro simulations of galaxy formation: prospects

Hydrodynamics simulations

Main goals for next few years:

- improve hydrodynamics
- convert today's "sub-grid physics" → resolved physics
 - Multiphase ISM
 - Star formation
 - Feedback: reionization, SN, AGN ...
 - Tidal and ram pressure stripping of gas
 - Disk instabilities, secular evolution
 - Magnetic fields, cosmic rays

Galaxy formation



Hydro simulations of galaxy formation: prospects

Hydrodynamics simulations

- already exists
- in progress
- don't hold your breath

- Better resolution
 - purely a technological issue
 - as resolution increases “new physics” are uncovered
 - is numerical “convergence” achievable or (desirable)?
- Better physics
 - Hydrodyn.: turbulence, fluid instabilities – Arepo (Springel)
 - Gas cooling – HI (Kravtsov)
 - Radiative transfer – (several groups)
 - Magnetic fields, cosmic rays – (Pfrommer, Springel)

Hydro simulations of galaxy formation: prospects

Hydrodynamics simulations

- Better astrophysics

- Star formation – IMF
- Interstellar medium: molecular clouds, coupling of SN energy
- Metal production and diffusion
- Black hole formation & AGN
 - accretion disks
 - BH spin
 - Jet generation
 - Magnetic fields
 - BH-BH mergers, gravity waves

■ already exists

■ in progress

■ don't hold your breath