



Ludwig Franz Benedict Biermann

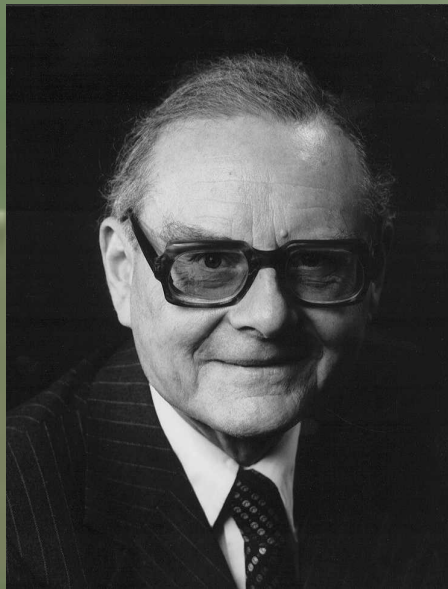
• (1907 – 1986)



Founding director Max Planck Institute for Astrophysics (1958)

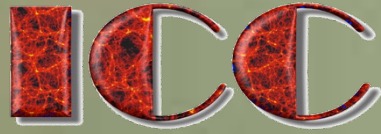


The vicissitudes of the cold dark matter model of cosmogony



Carlos S. Frenk
Institute for Computational Cosmology,
Durham





I. 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



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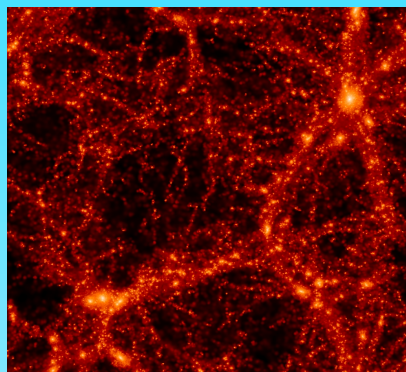
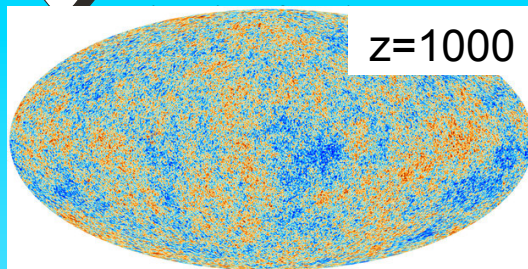
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Galaxy formation theory

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formation and evolution of galaxies

Should aim to explain the entire galaxy
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Basic ingredients



Cosmological model

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

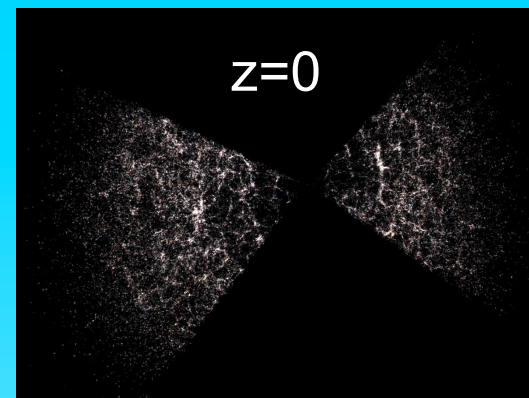
Primordial fluctuations

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

Dark matter halos
(N-body simulations)

Gas processes
(cooling, star formation, feedback)

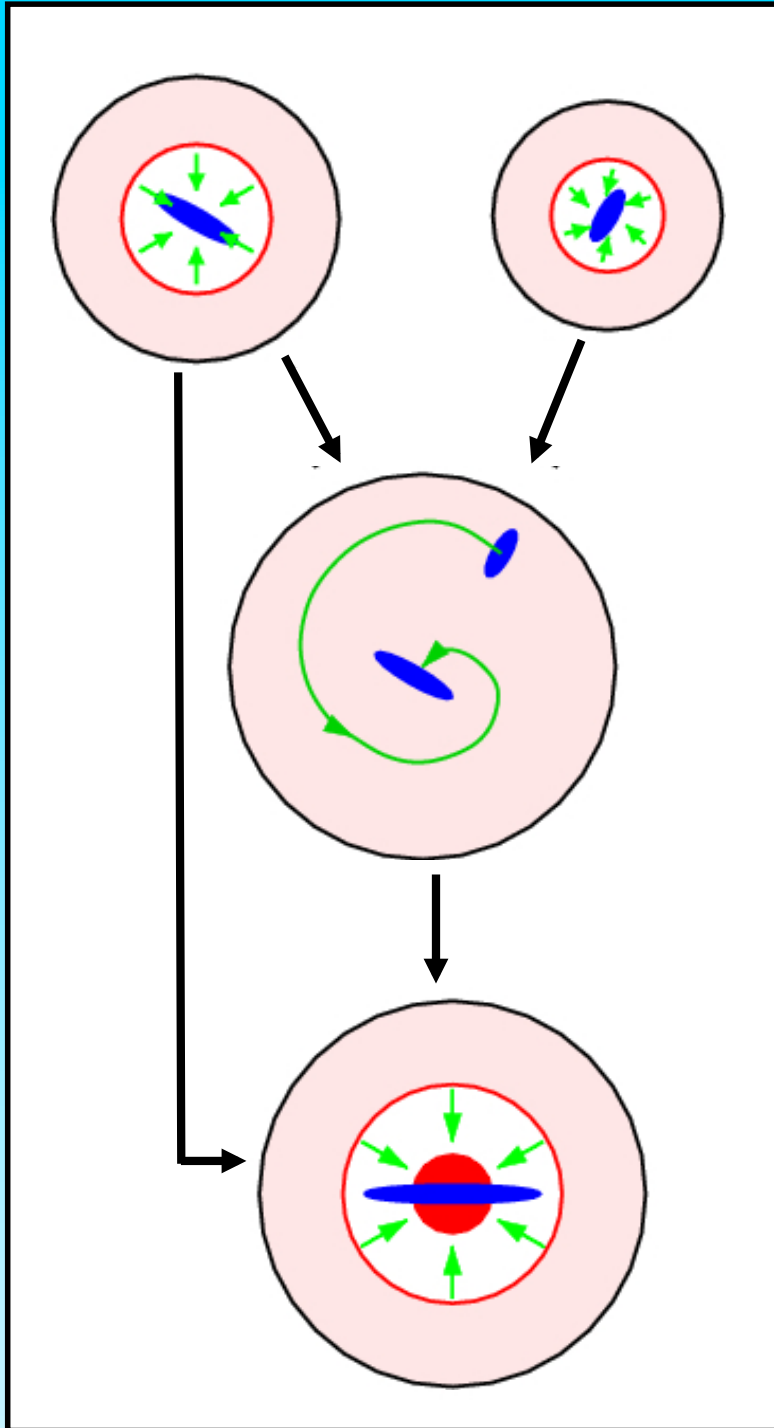
Formation and evolution of galaxies



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 $\rightarrow$ **starburst & BH growth**
- Major mergers: stellar disks $\rightarrow$ **spheroids**
- New **disk** may form by gas accretion

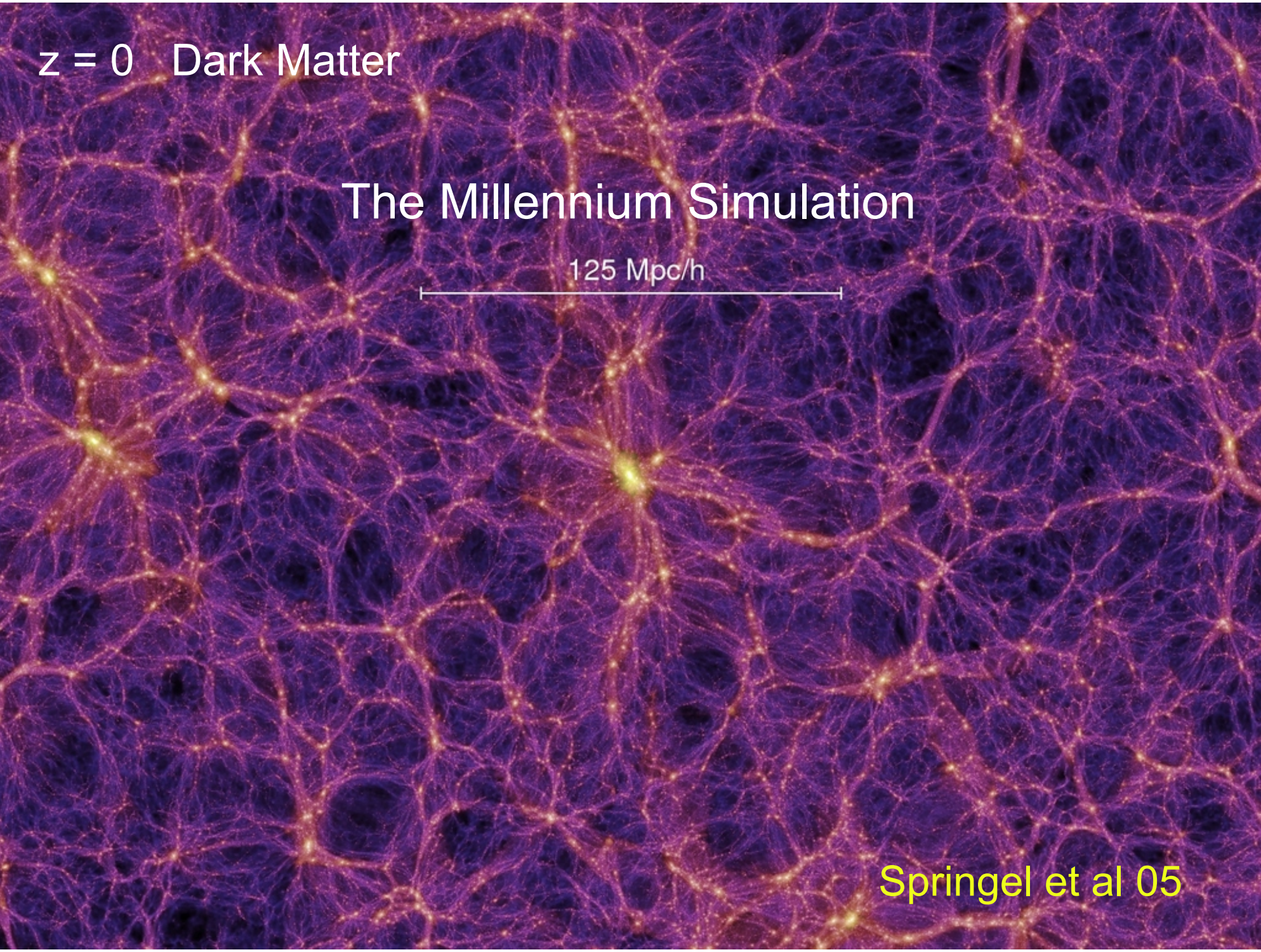
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-

$z = 0$ 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

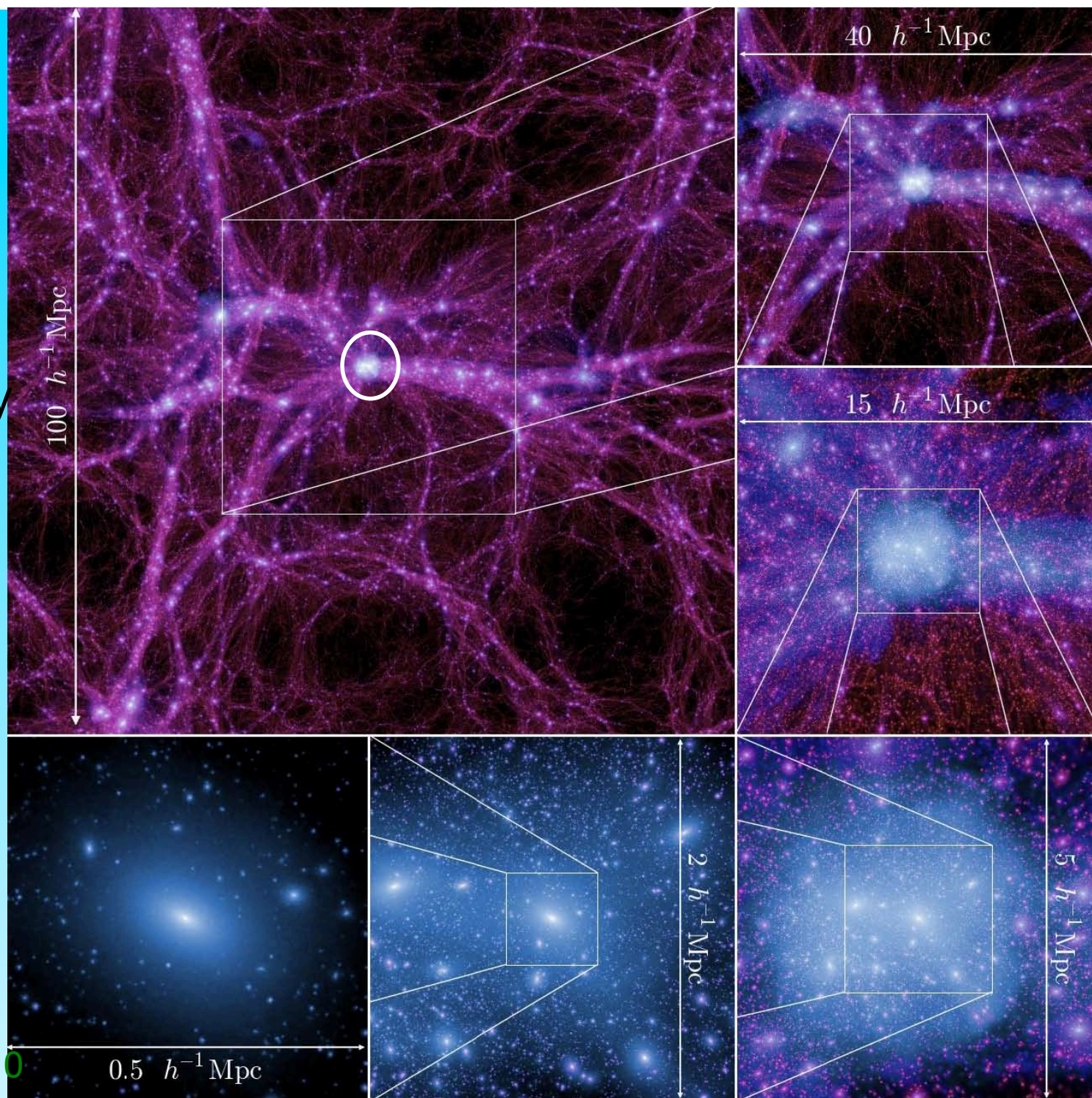
Same N

1/5 linear size



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

Boylan-Kolchin et al '10



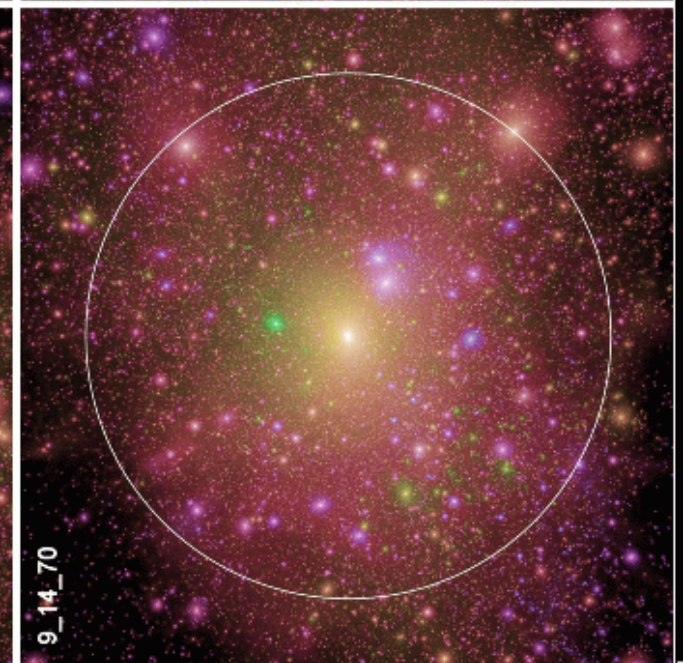
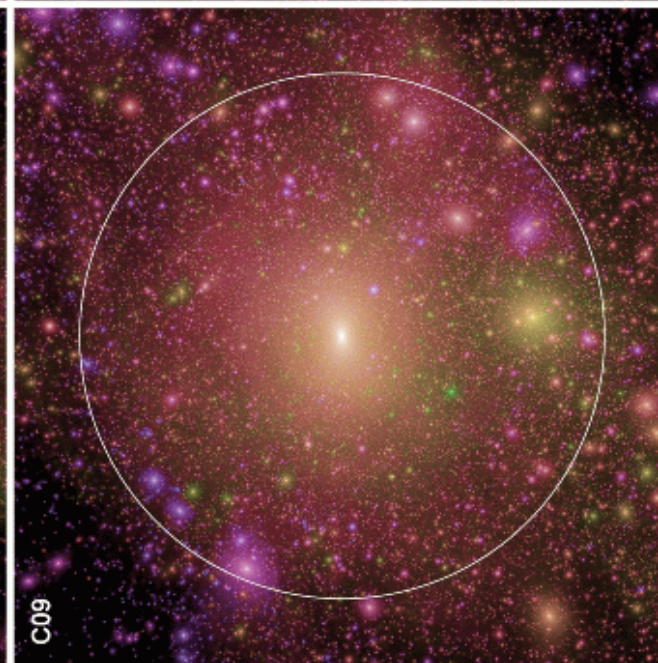
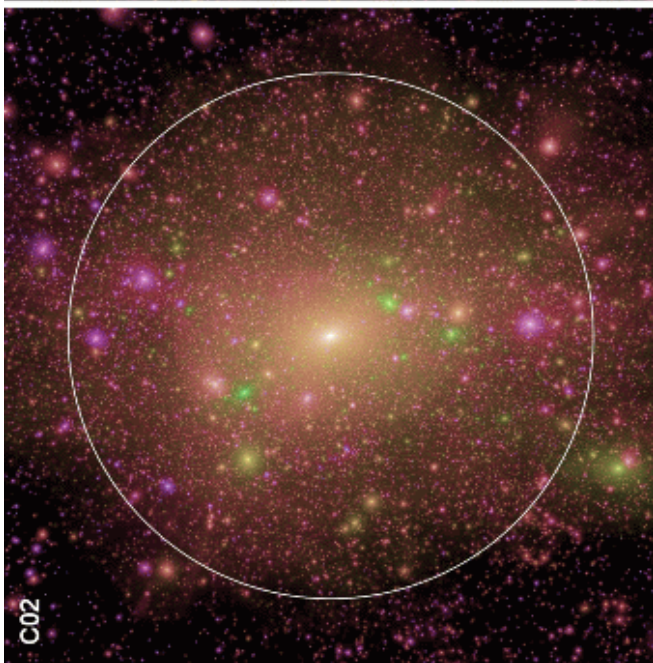
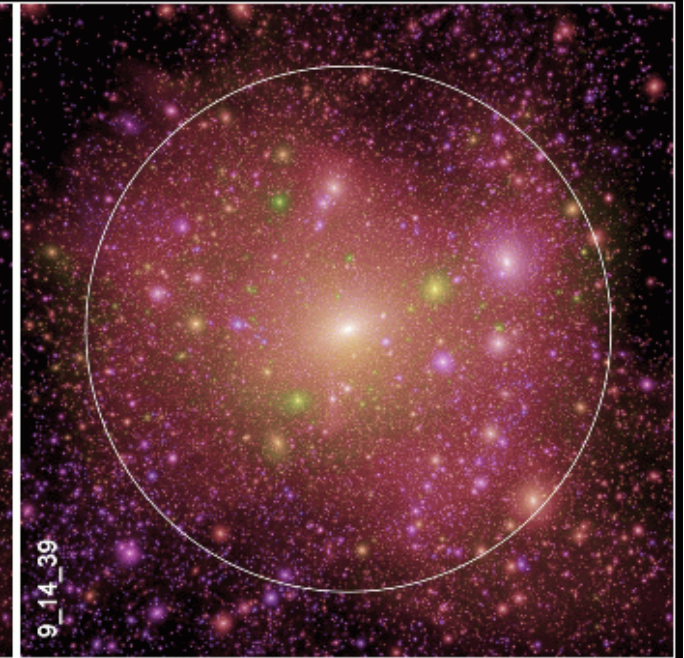
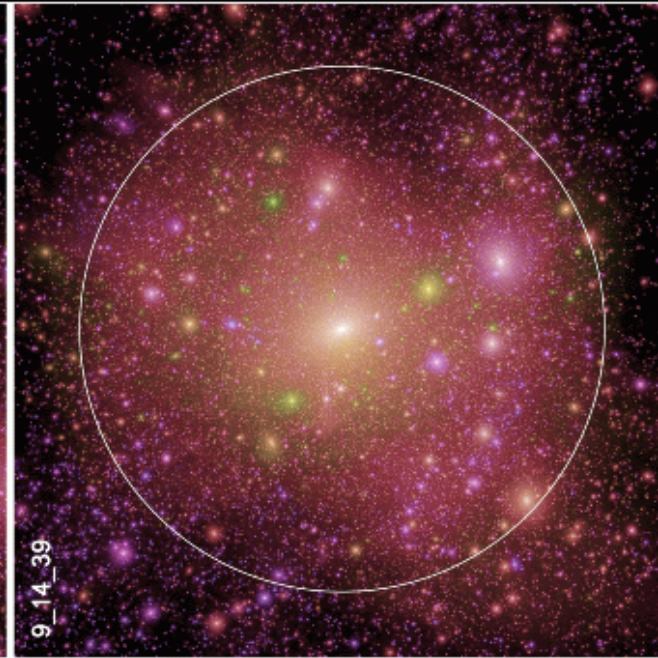
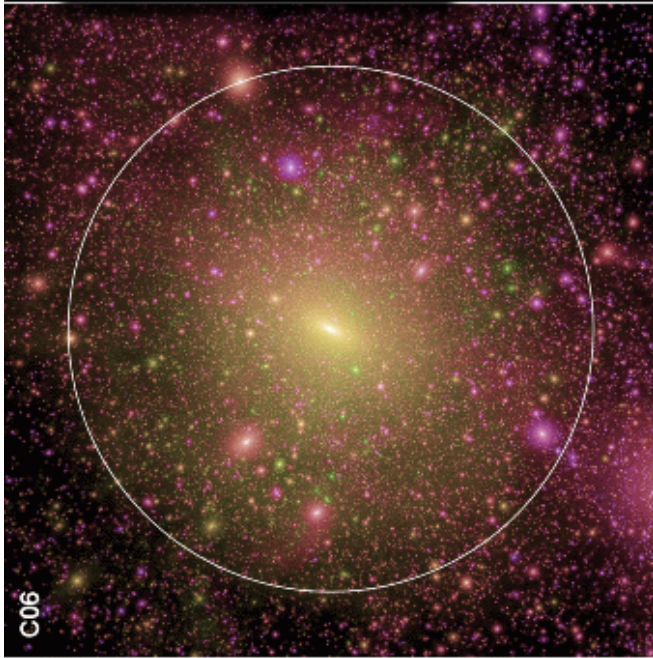
$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc

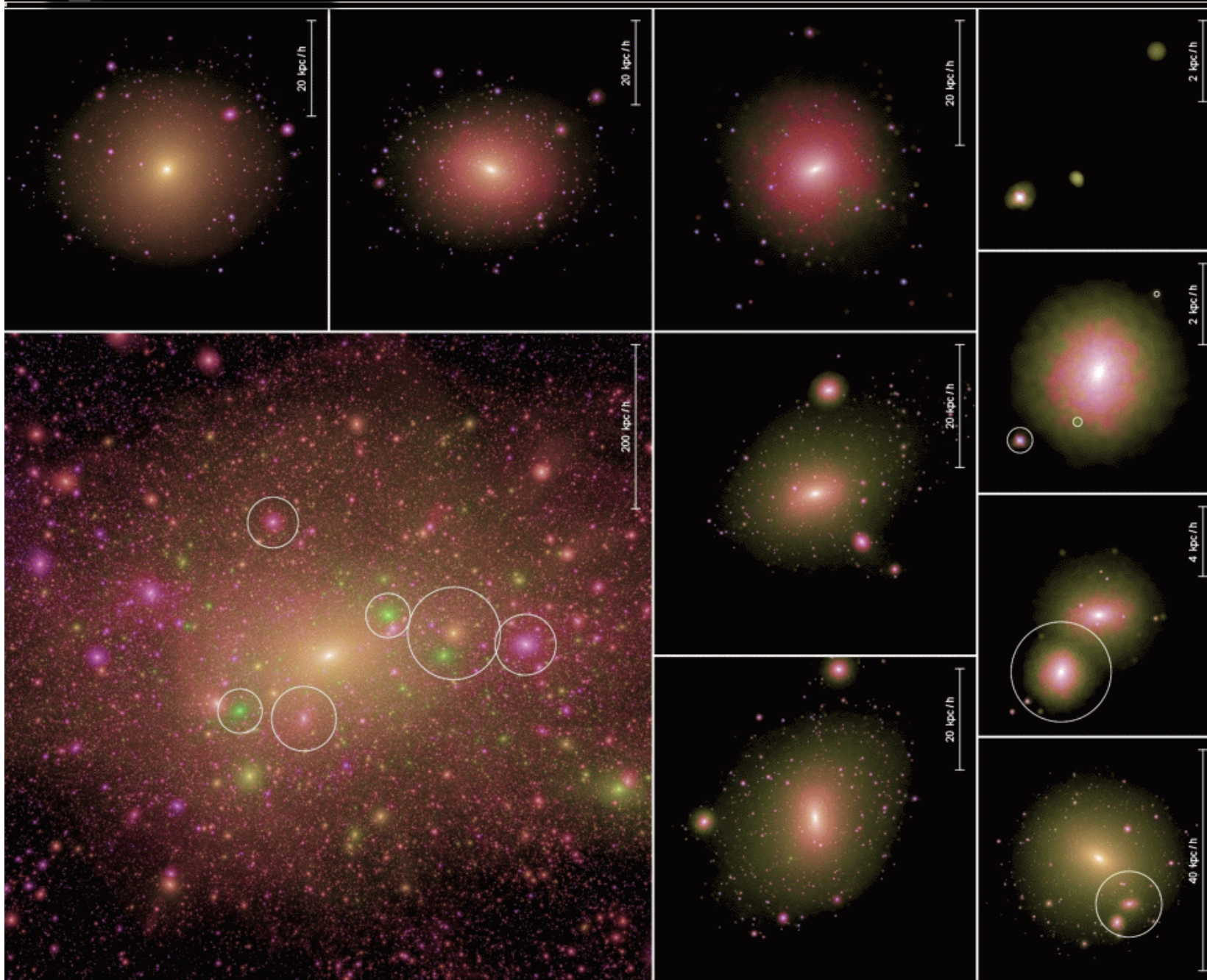
VIRG

Images of Aquarius galactic halos



VIRG

Substructures within substructures



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

The hierarchy clearly is **NOT self-similar** and is heavily dependent on the degree of tidal stripping of the subhalo

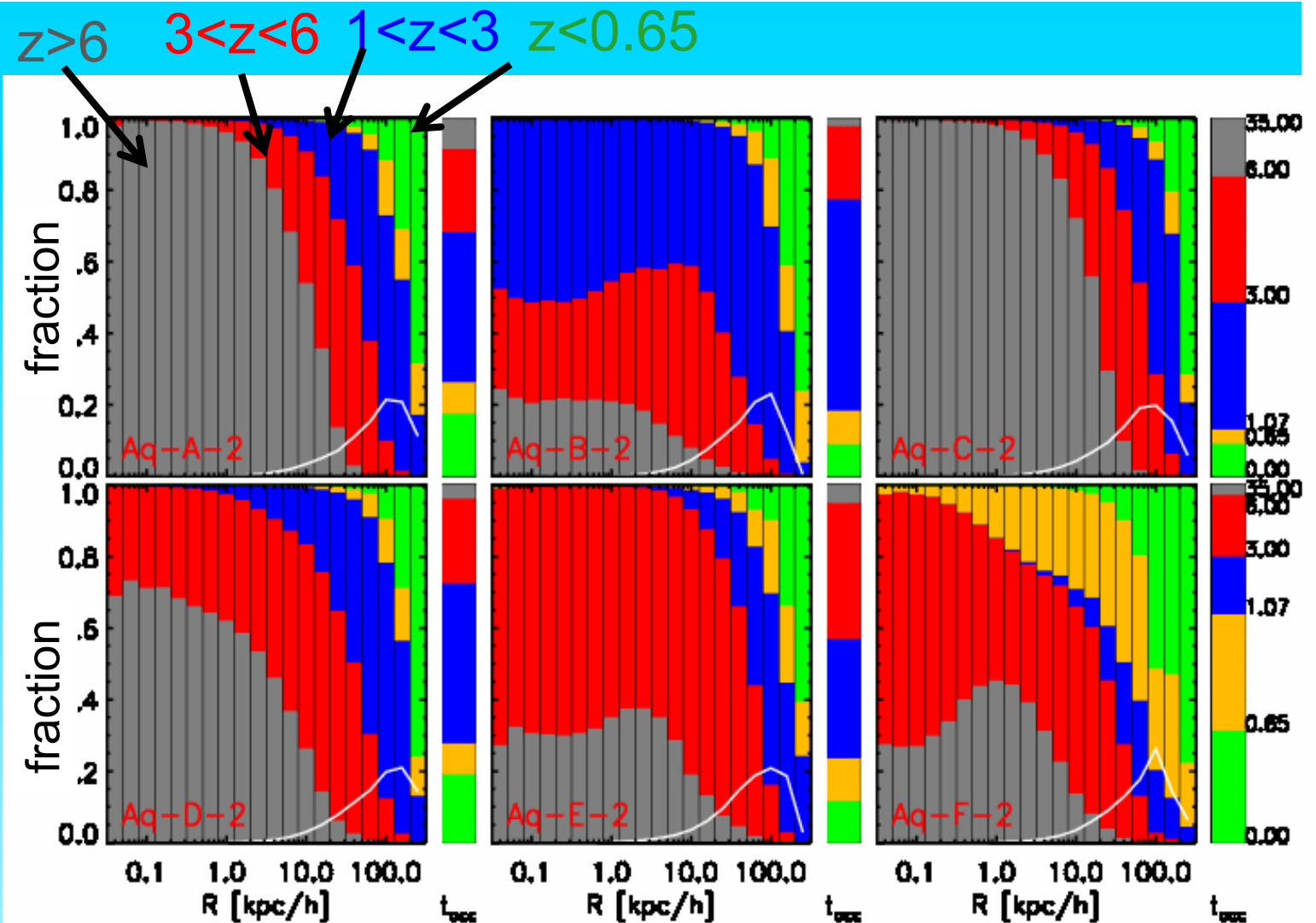


Dark matter halo assembly

DM halo assembly

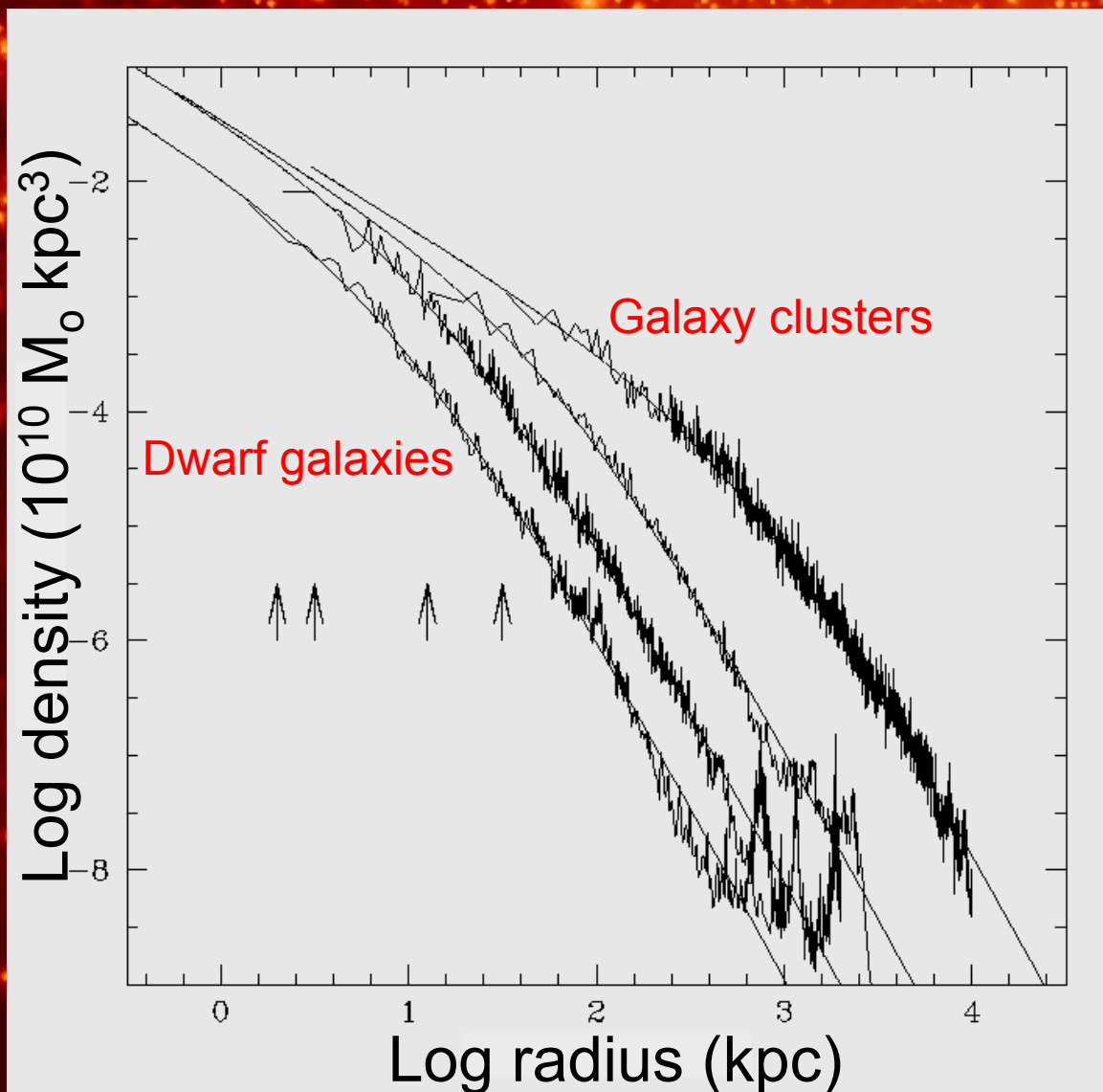
Aquarius halos

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

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or 'core' near the centre.

(Navarro, Frenk & White '97)

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

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



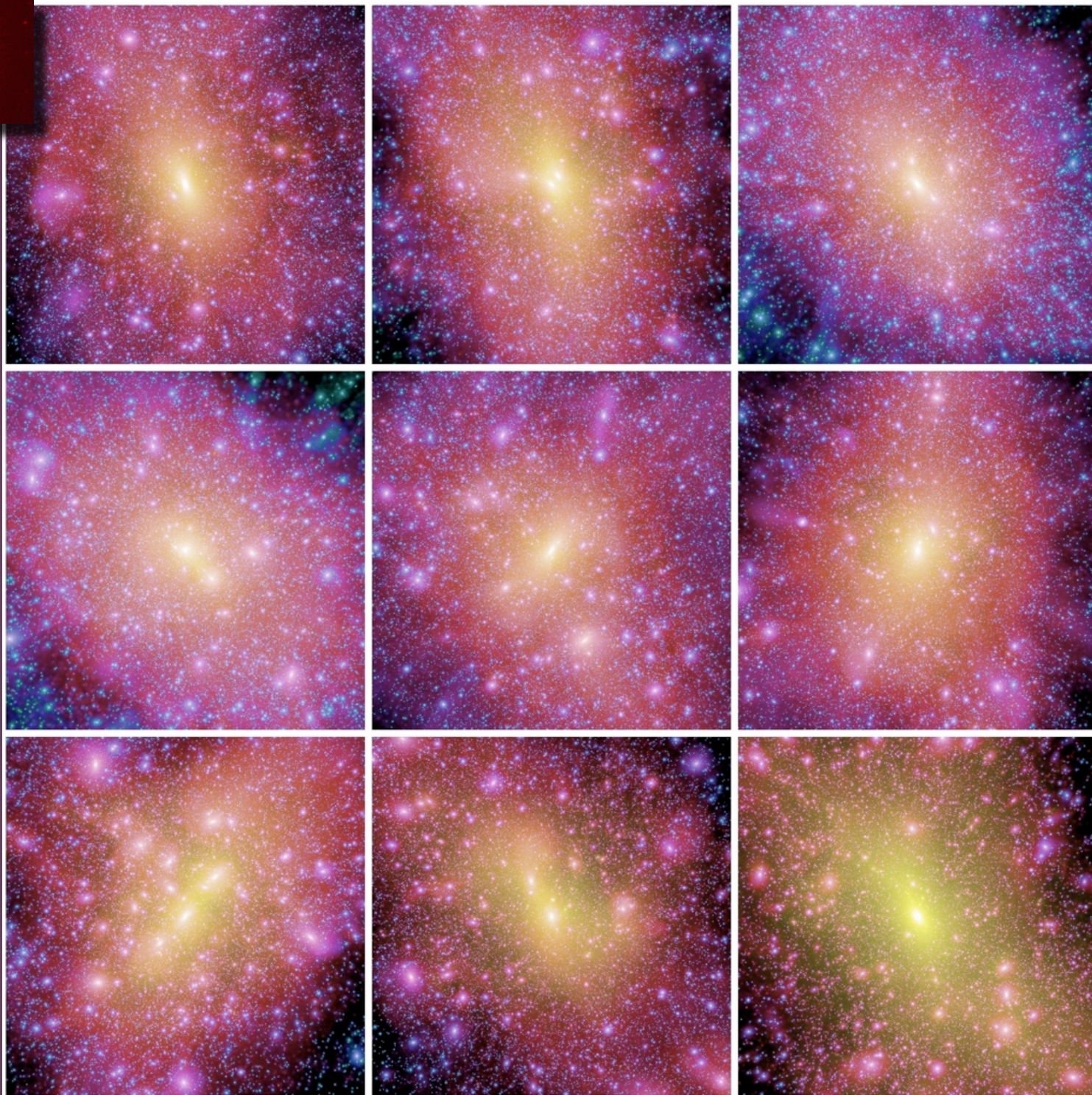
The “NFW” profile



© BT - musicolor.wordpress.com

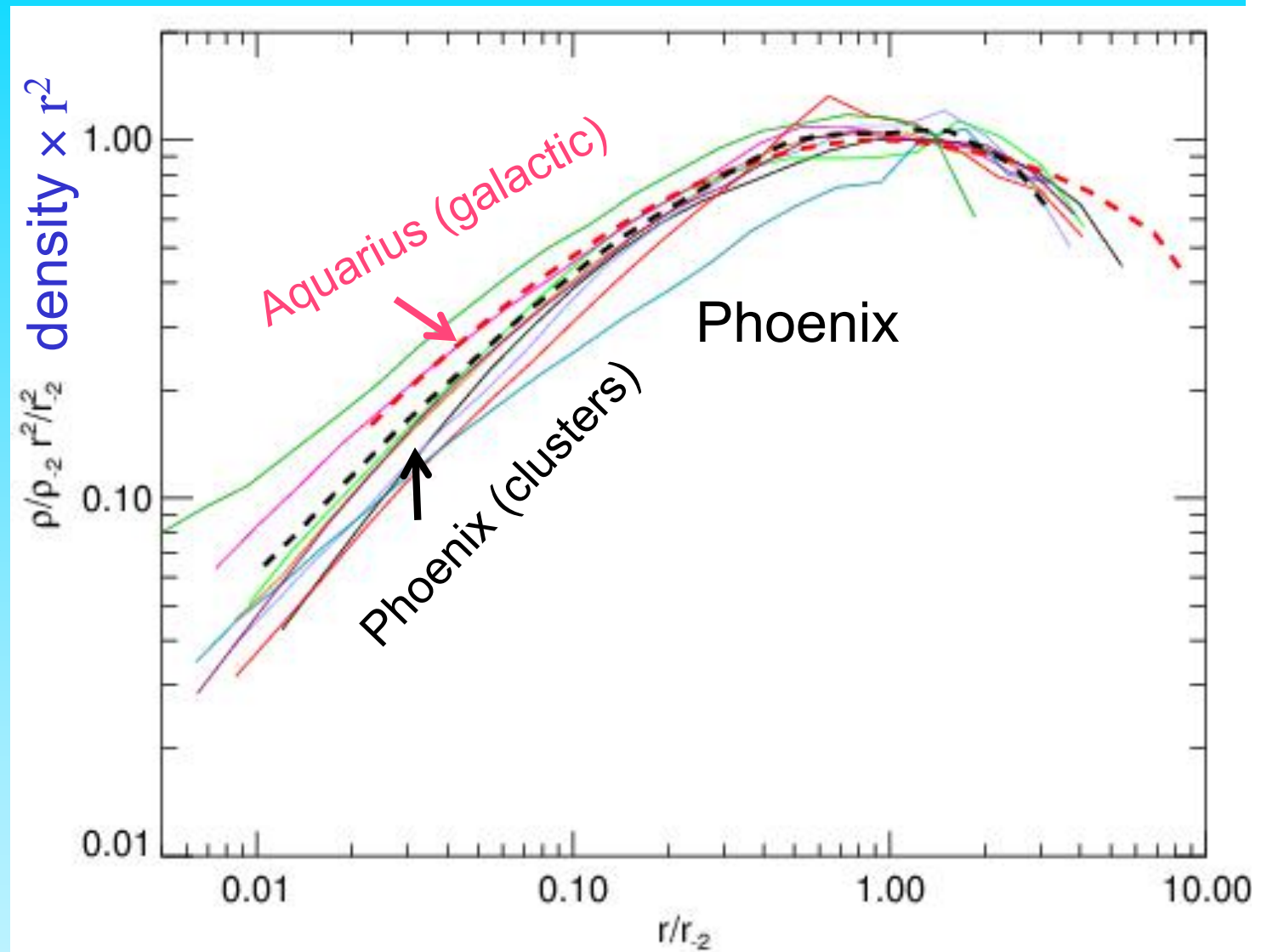
VIRGO

Phoenix cluster halos



Dark matter density profile $\rho(r)$

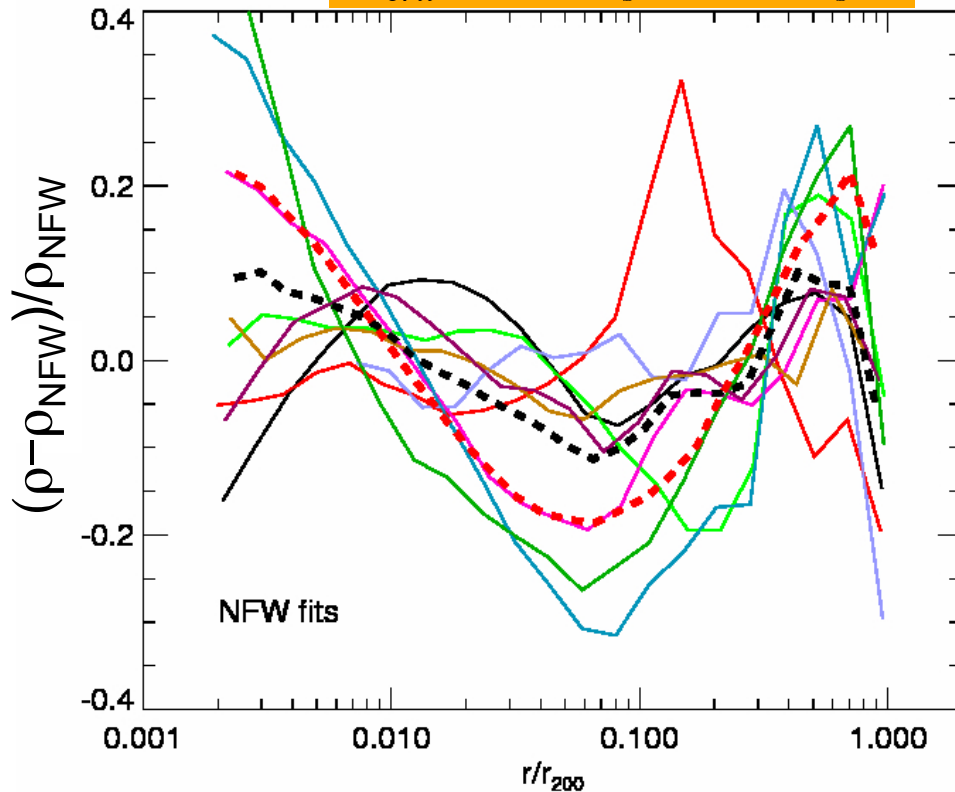
Density profile nearly **universal**, but there are small differences between galaxies & clusters



Deviations from NFW & Einasto forms

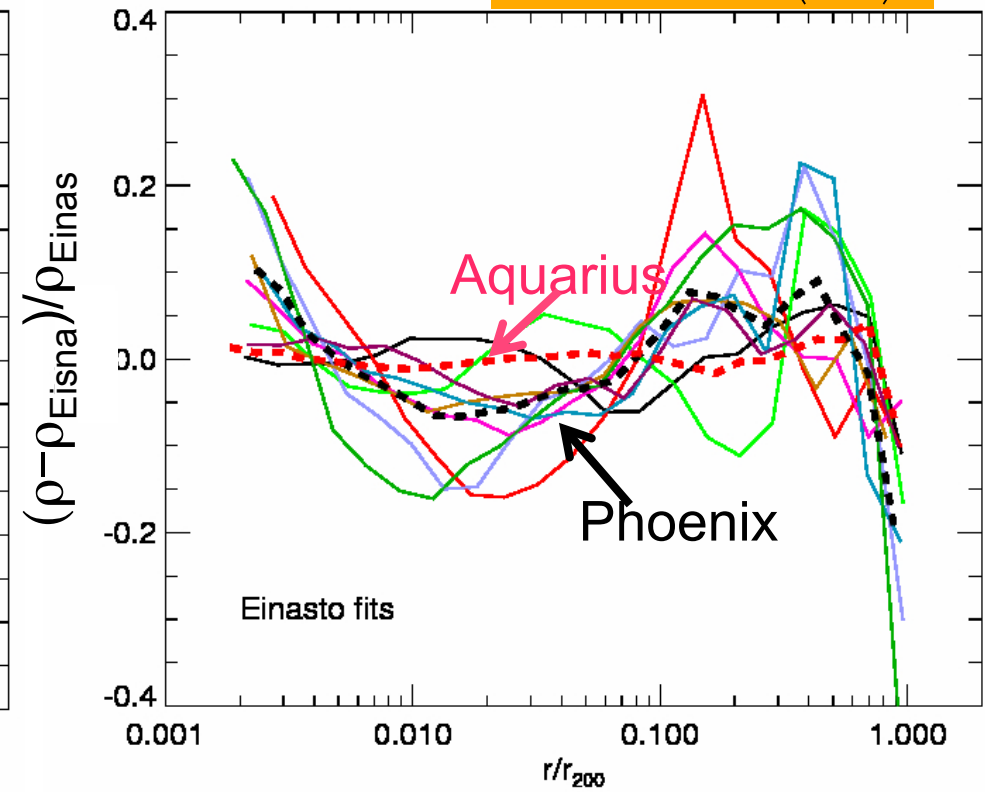
NFW

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



Einasto

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

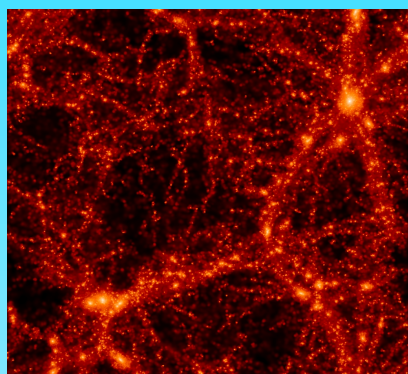
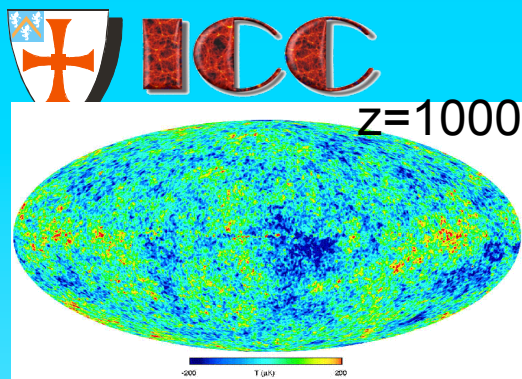


Galactic and cluster halos deviate from NFW by ~10-20%
and from Einasto by <~ 7%

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

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

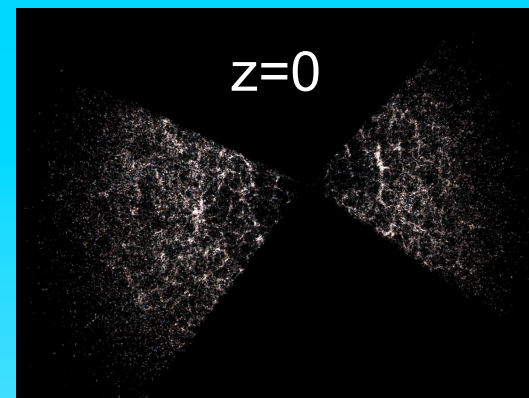
Dark matter halos
(N-body simulations)

Gas processes
(cooling, star formation, feedback)

Gasdynamic simulations

Semi-analytics

Formation and evolution of galaxies



Well understood

Semi-analytic modelling of galaxy formation

Galaxy formation in a CDM universe

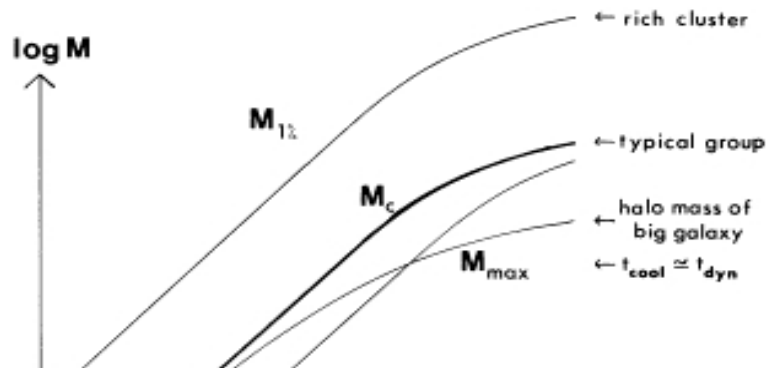
Mon. Not. R. astr. Soc. (1978) 183, 341–358

White & Rees '78

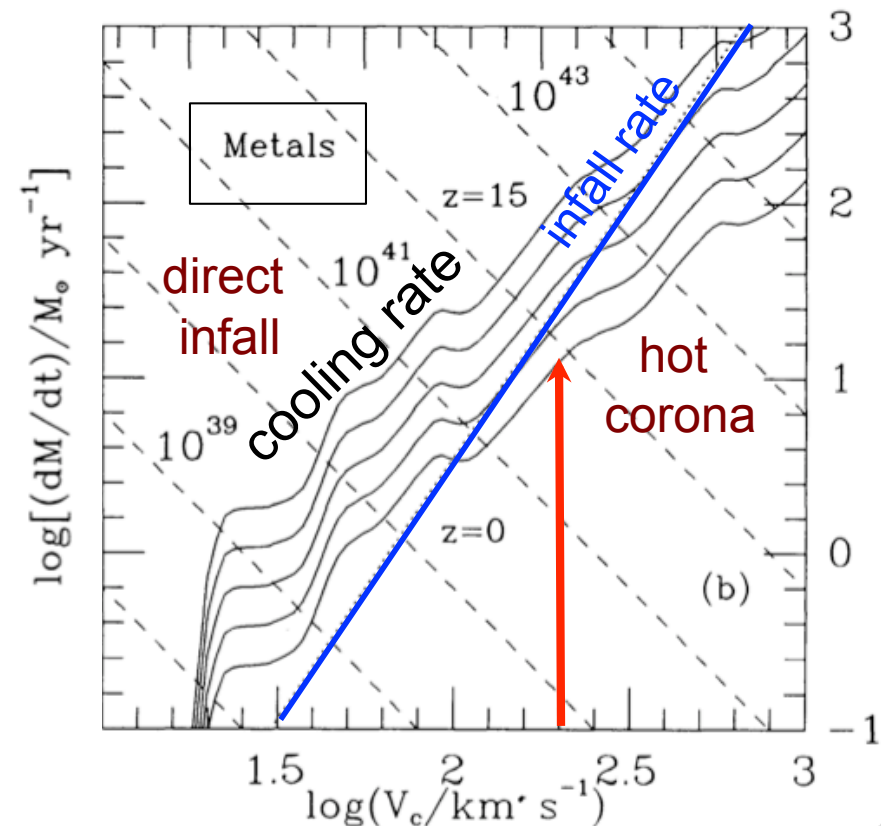
Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

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)

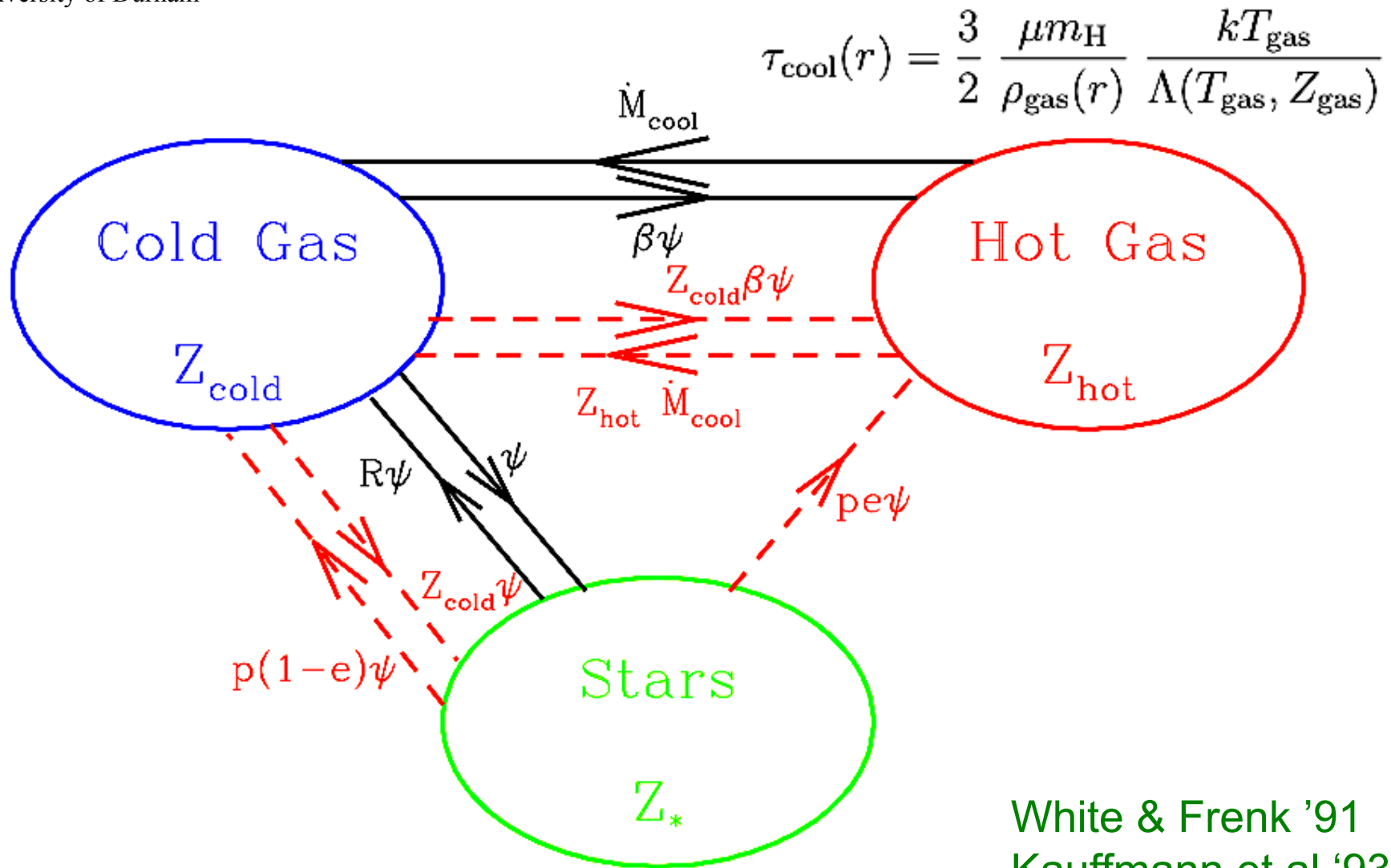


White & Rees calculated how gas cools and condenses into a

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:

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

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

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

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

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

$$\begin{aligned} \dot{M}_{\text{cold}}^Z &= \dot{M}_{\text{cool}}Z_{\text{hot}} \\ &+ (p(1 - e) - (1 + \beta - R)Z_{\text{cold}})\psi, \end{aligned}$$

Mass conservation

R = recycled fraction

ψ = star formation rate

Conservation of metals

β = SN feedback parameter

p = metal yield

e = fraction of metals ejected

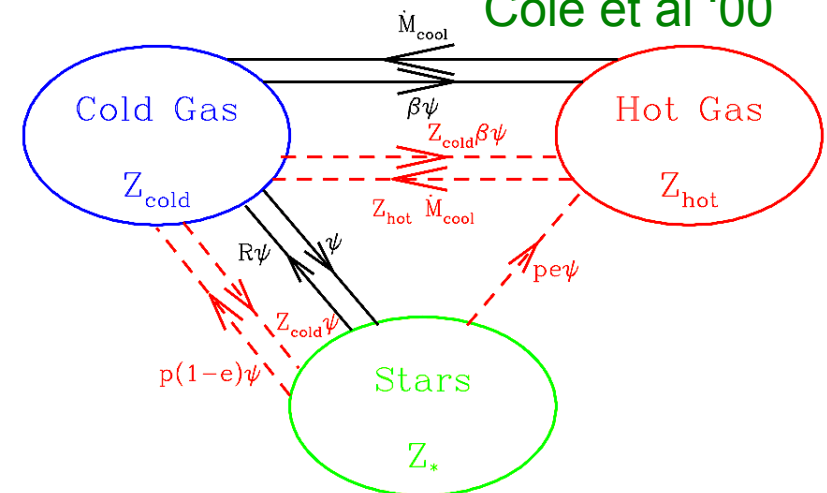
White & Frenk '91,
Kauffmann et al '93
Cole et al '00

SFR & mass ejection

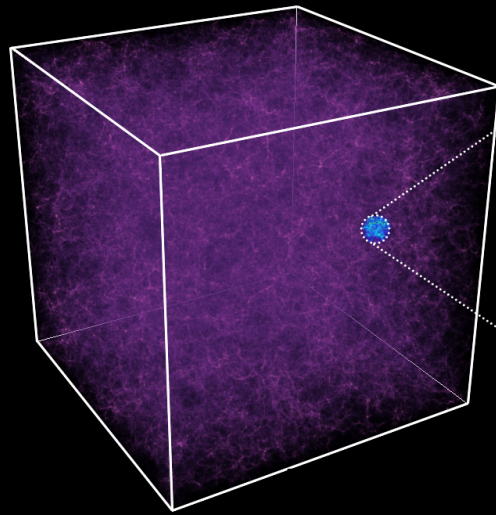
SFR $\psi = \frac{\dot{M}_{\text{cold}}}{\tau_*(r_{\text{disk}}, V_{\text{disk}})}$

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

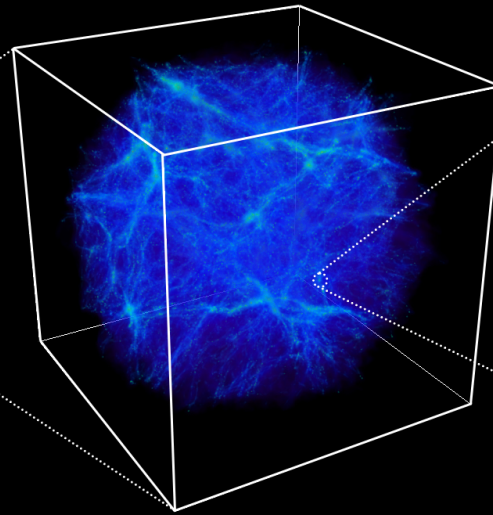
AGN feedback $\dot{M}_{\text{BH}} = f_{\text{BH}}\psi_{\text{burst}} + \frac{L_{\text{cool}}}{c^2 \epsilon_{\text{SMBH}}}$



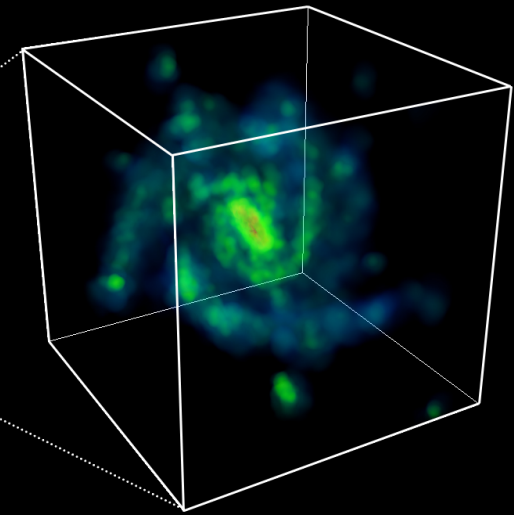
Hydrodynamic simulations



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)

X-ray coronae in simulations of disc galaxy formation

Robert A. Crain, Ian G. McCarthy, Carlos S. Frenk, Tom Theuns & Joop Schaye

[The main body of the document contains the abstract and the beginning of the introduction, which are mostly illegible due to the low contrast of the image.]

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

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“Subgrid physics”

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

Phenomenological model

- 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:

Hydrodynamical simulations

- Mostly used for individual examples (except e.g. OWLS/GIMIC)
- Ideal for asymmetric processes (e.g. accretion in filaments)
- Internal structure of galaxies

Semi-analytic model

- Used for galaxy populations (luminosity fns., scaling relations...)
- Can be applied at all redshifts
- Ideal for modelling complex processes (e.g. dust obsctn/emission)

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:

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

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

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

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

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$$\begin{aligned} \dot{M}_{\text{cold}}^Z &= \dot{M}_{\text{cool}}Z_{\text{hot}} \\ &+ (p(1 - e) - (1 + \beta - R)Z_{\text{cold}})\psi, \end{aligned}$$

R = recycled fraction

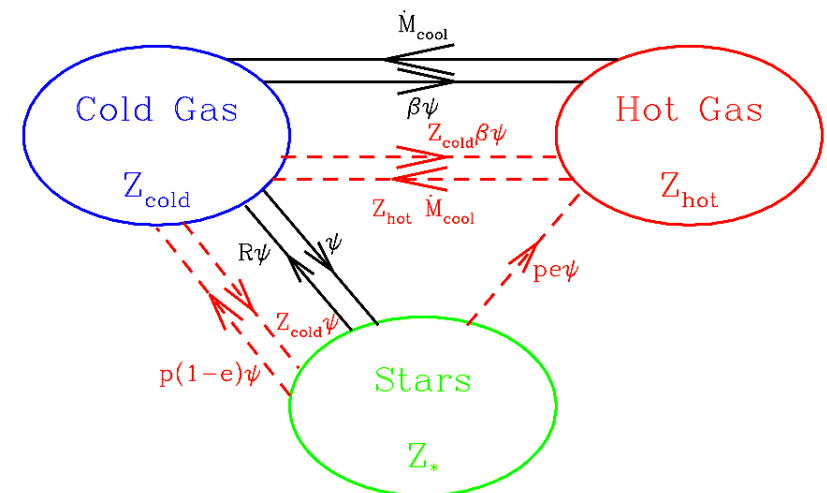
ψ = star formation rate

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

Semi-analytics

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

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_{BH} , T_{heat} , $\epsilon_{\text{rad}} \dots$

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

Galaxy formation models: successes and failures

Major successes:

- Dark matter assembly and halo properties
- The galaxy luminosity fn. in visible/near-IR and stellar mass fn.
- Galaxy clustering on large scales, e. g. BAO

(Some) partial successes:

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

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

Galaxy formation models: successes and failures

Major successes:

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Galaxy formation models: successes and failures

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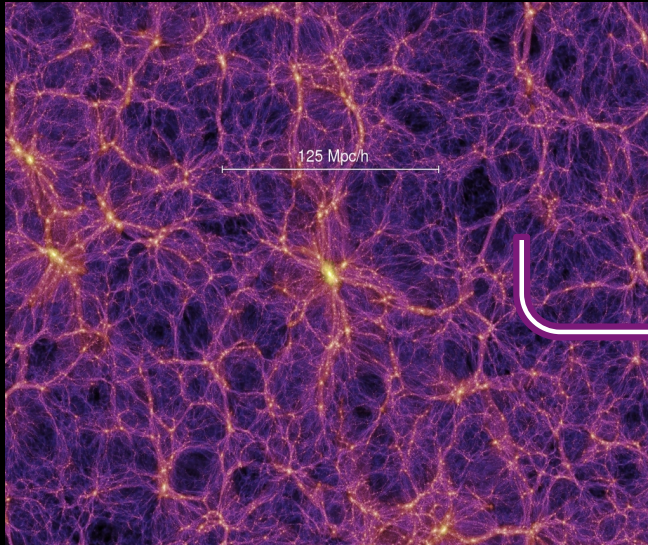
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(Some) partial successes:

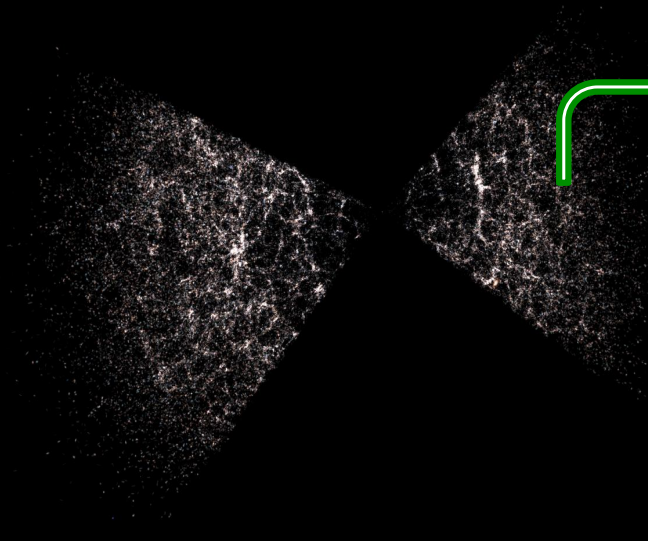
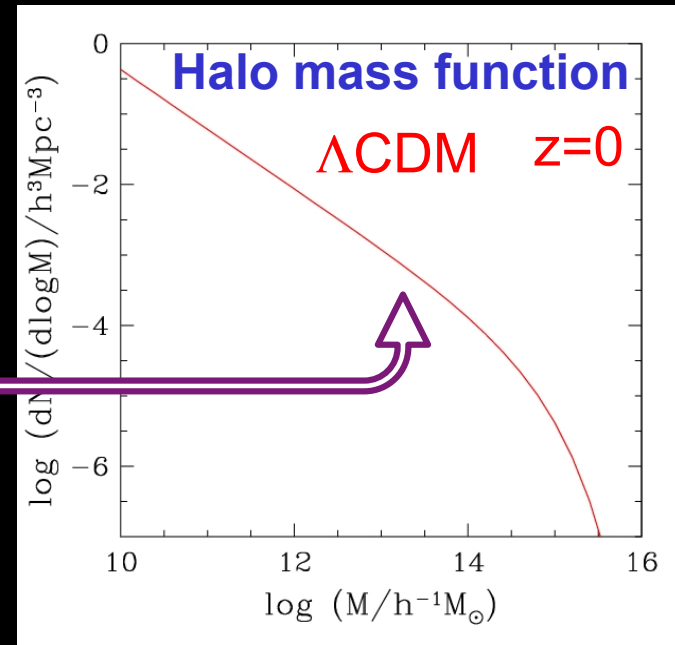
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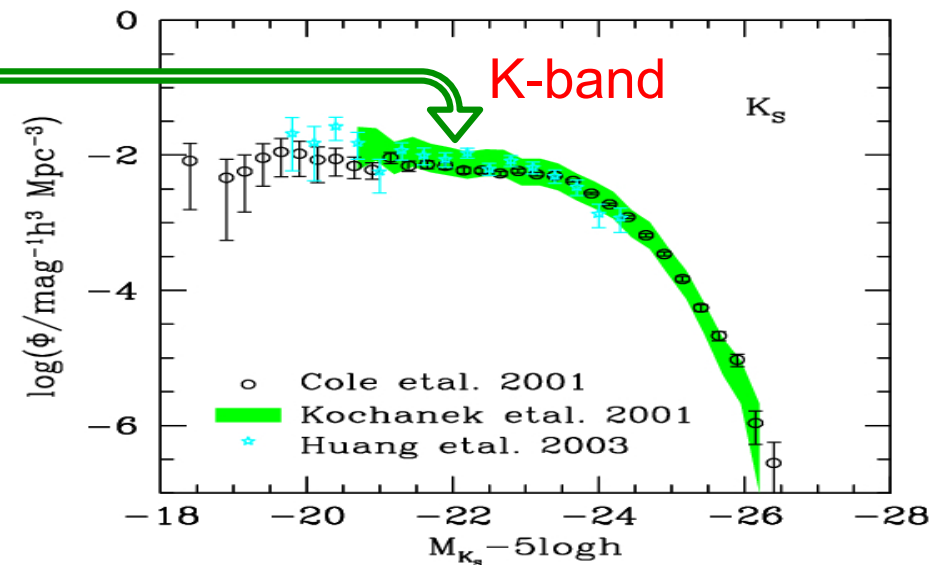
Abundance of gals & dark halos



Millennium run

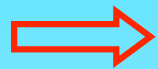


2dFGRS

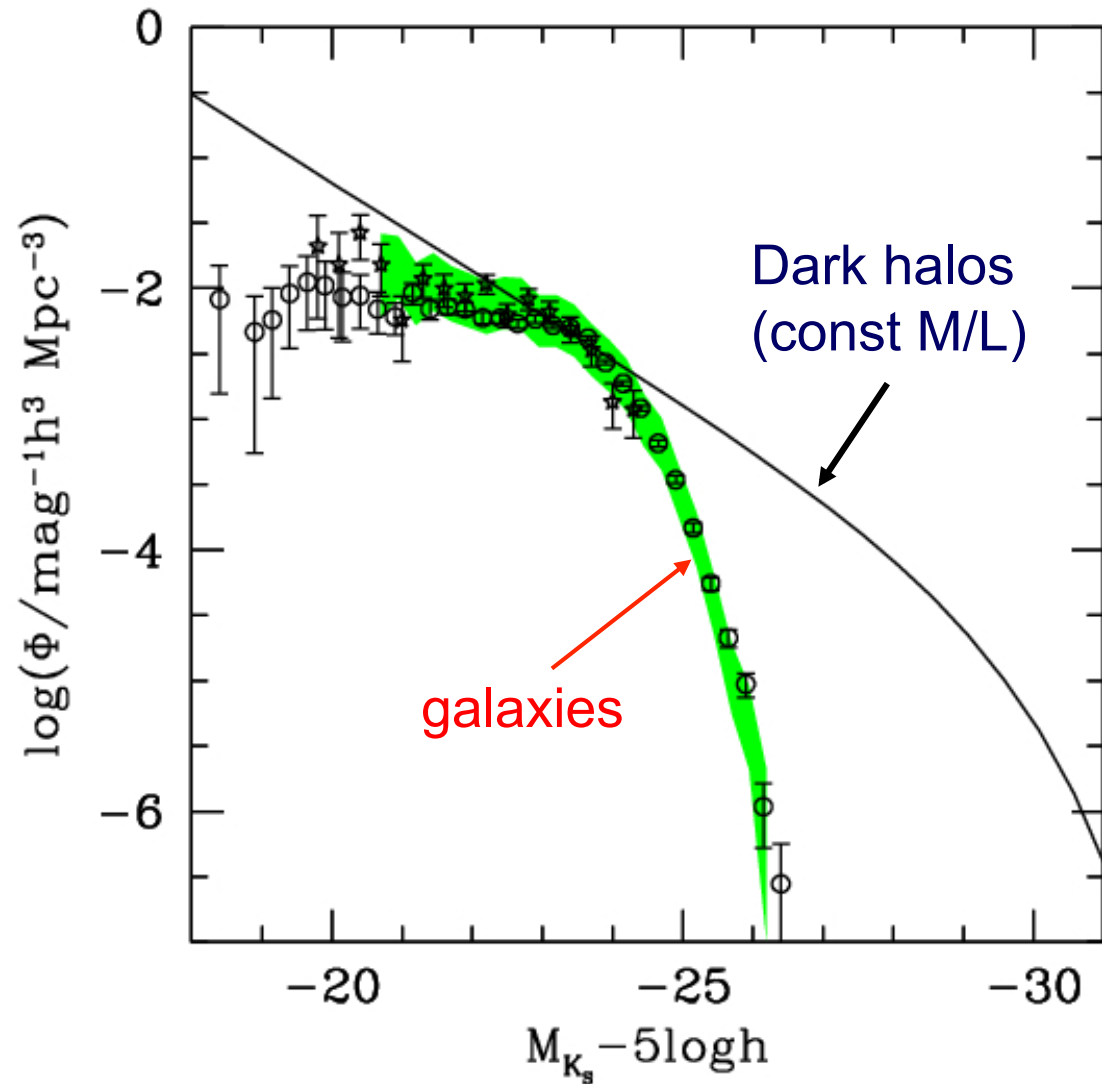


The galaxy luminosity function

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



Complicated variation of M/L with halo mass



Deconstructing the galaxy LF

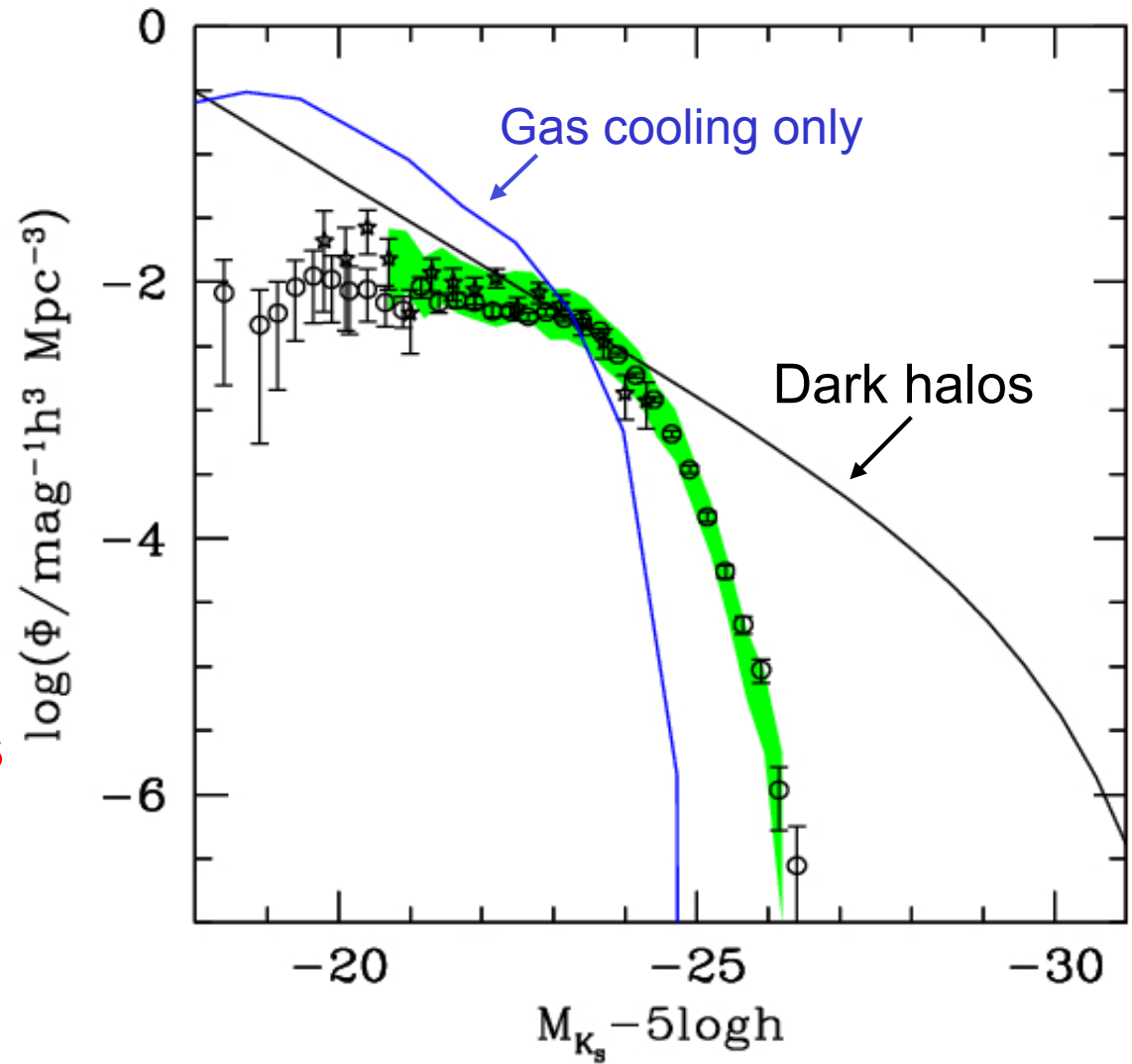
Gas cooling only



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

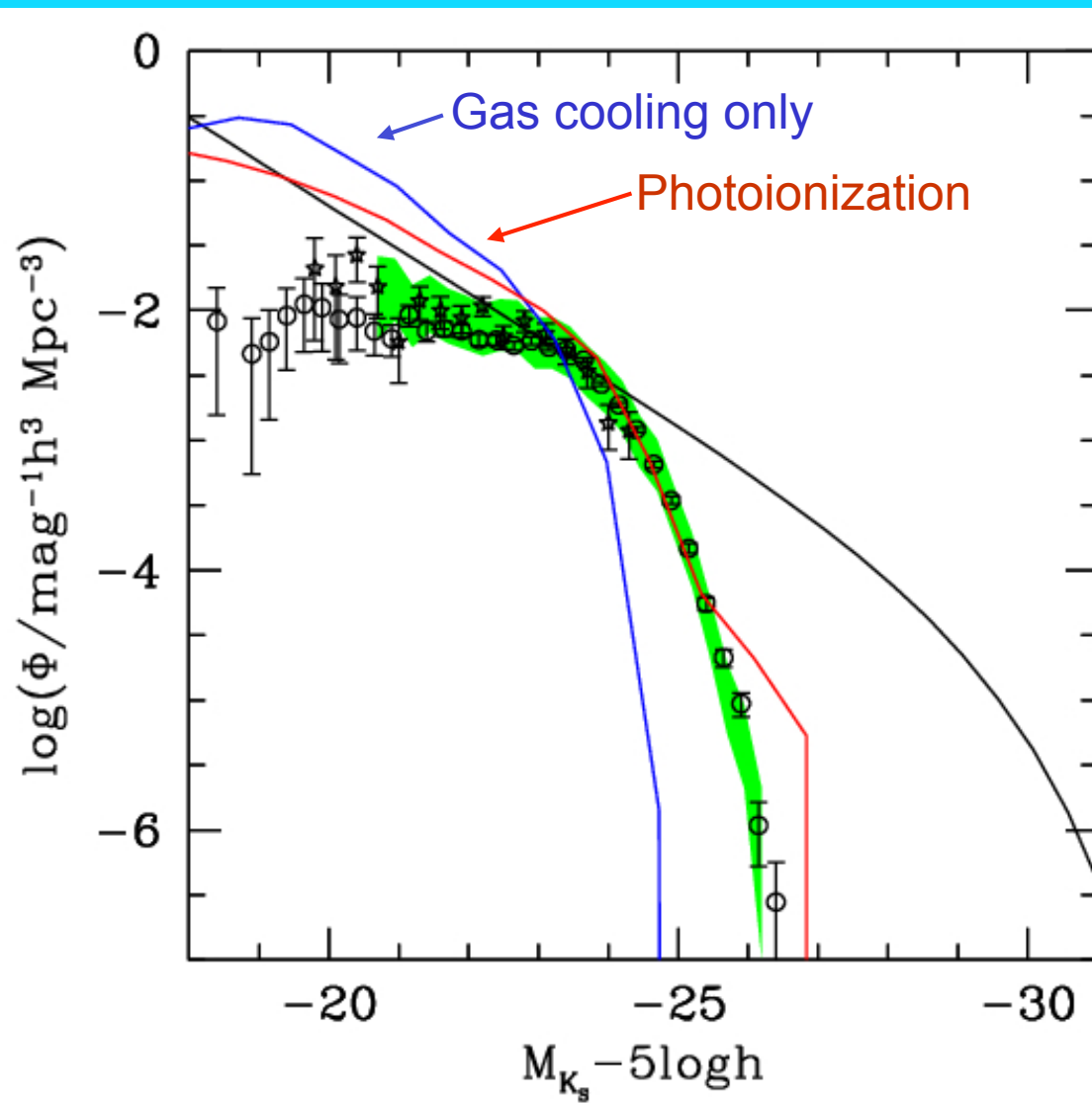
No energy injection, ie:

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:

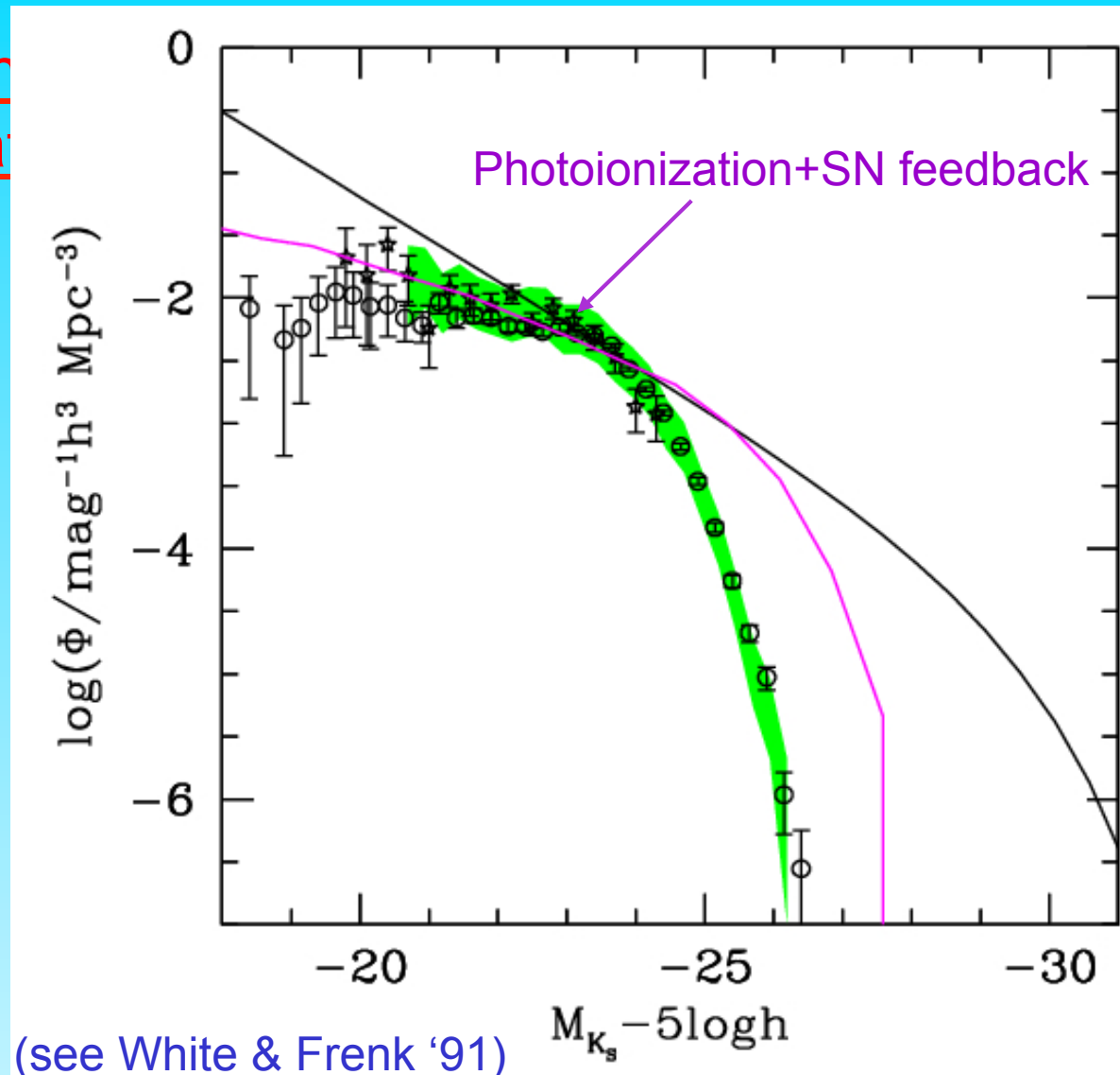
Can be explained by

- ✓ Reionization
- ✓ SNe feedback

Bright end:

→ Too many bright galaxies

Need to prevent too much gas cooling in large halos



(see White & Frenk '91)

Benson, Bower, Frenk, Lacey, Baugh & Cole '03

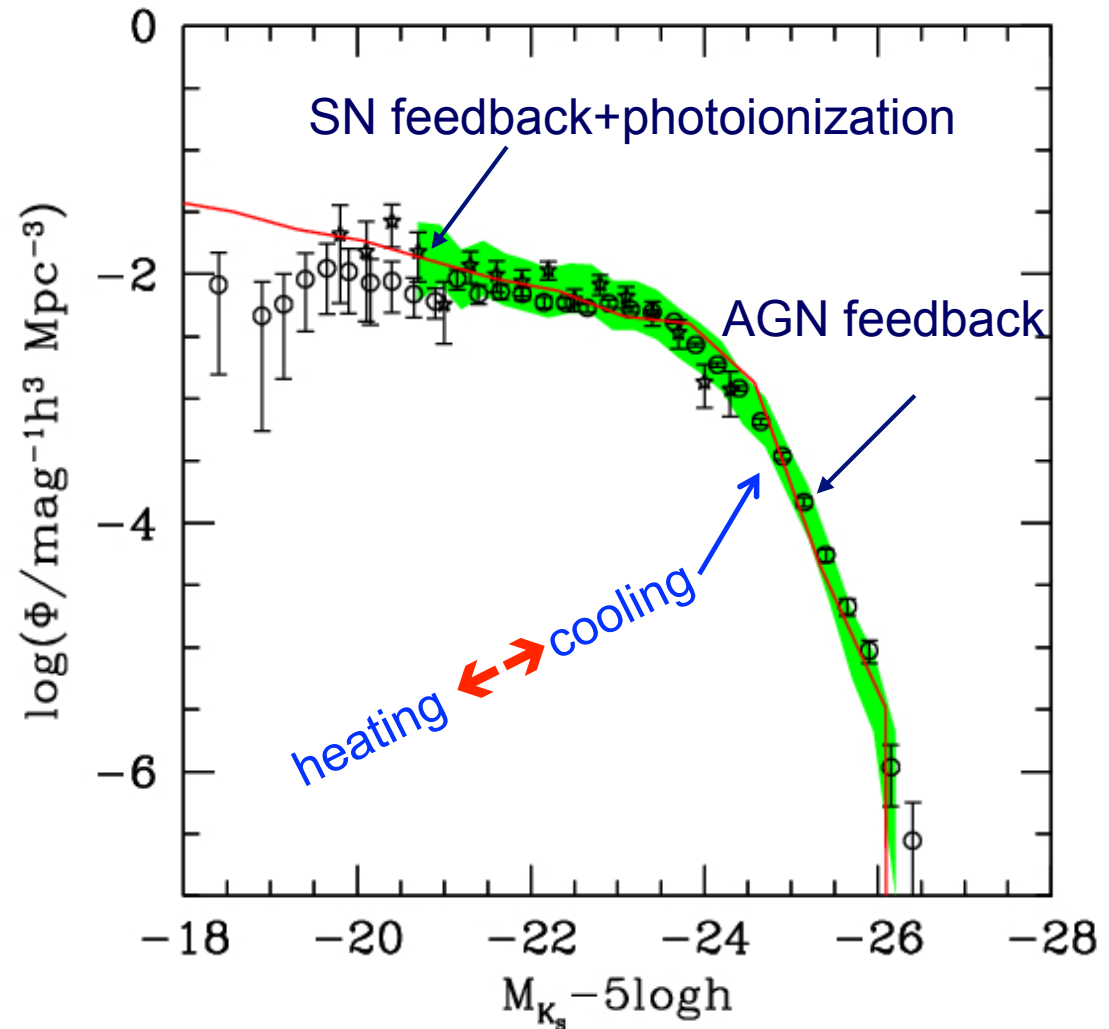
Deconstructing the galaxy LF

Faint end:

Photoionization +
reheating of cold
disk gas by SN

Bright end:

AGN feedback:
energy transported
by bubbles



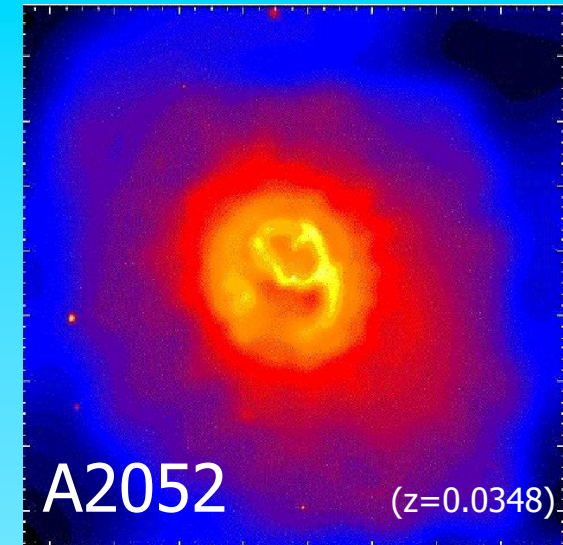
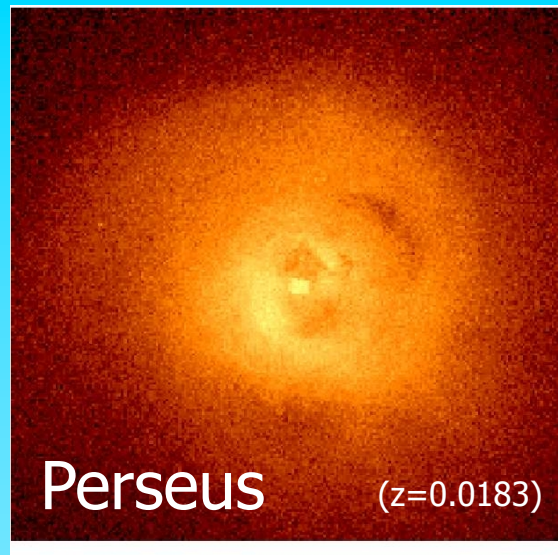
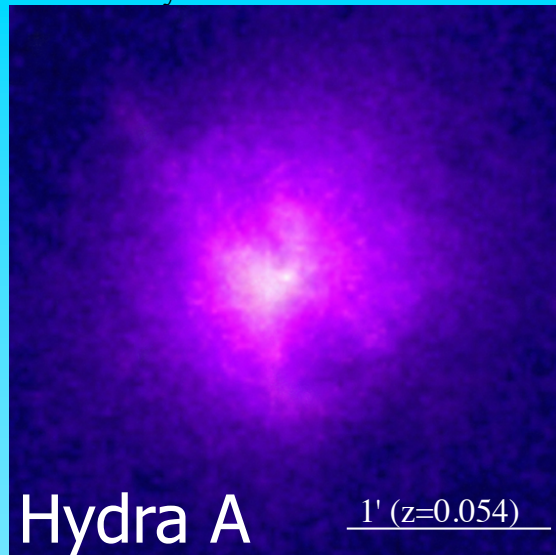
Croton et al '06, Bower et al '06

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

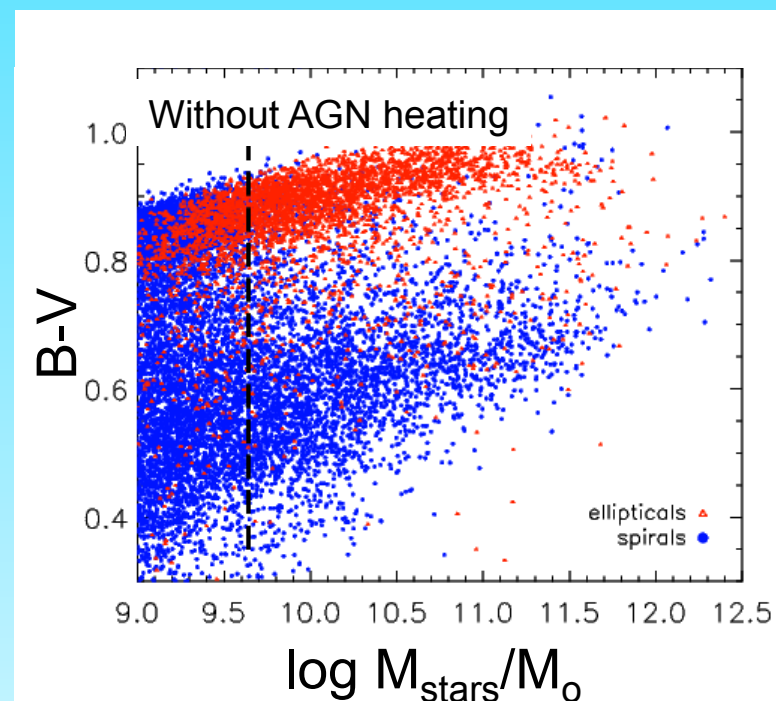
⇒ Gas should be cooling radiatively and flowing to the centre

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

⇒ Something must be heating the gas!

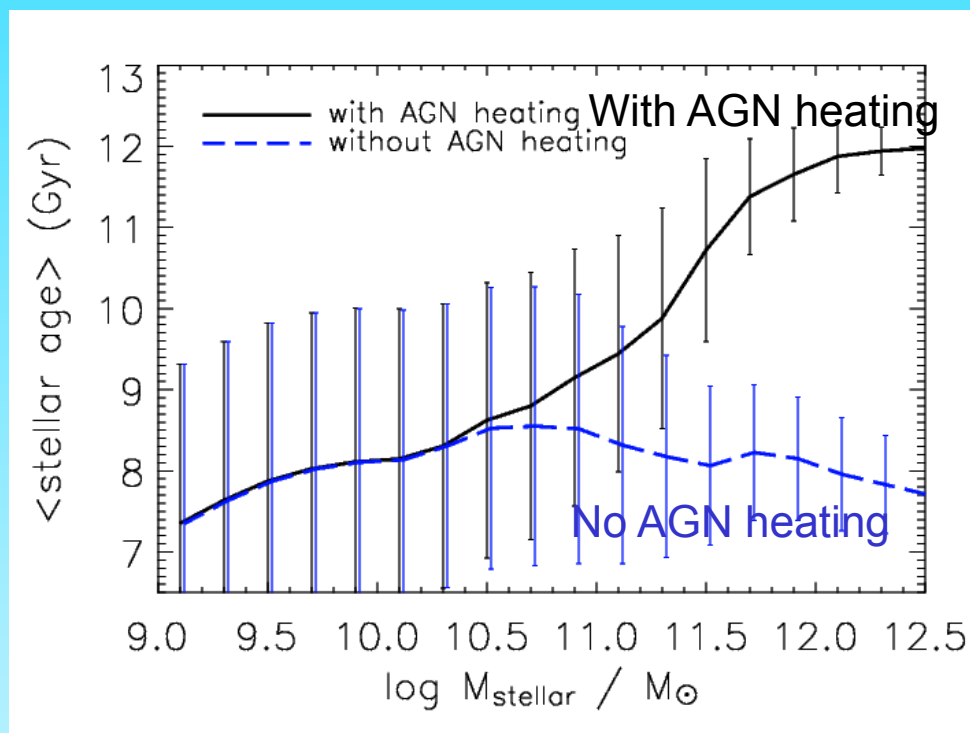
AGN feedback and the properties of ellipticals

The most massive
galaxies are red,
elliptical

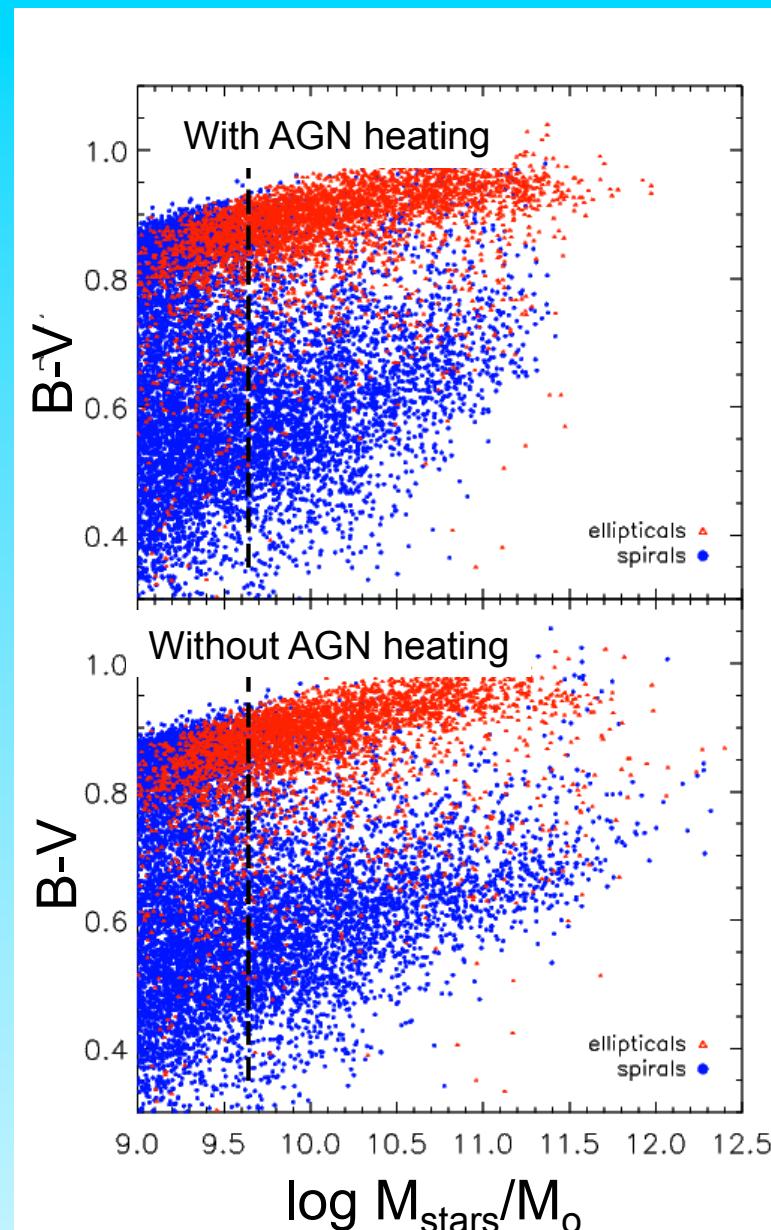


AGN feedback and the properties of ellipticals

The most massive galaxies are red, elliptical



and old!!



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)

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

Black holes and galaxy formation

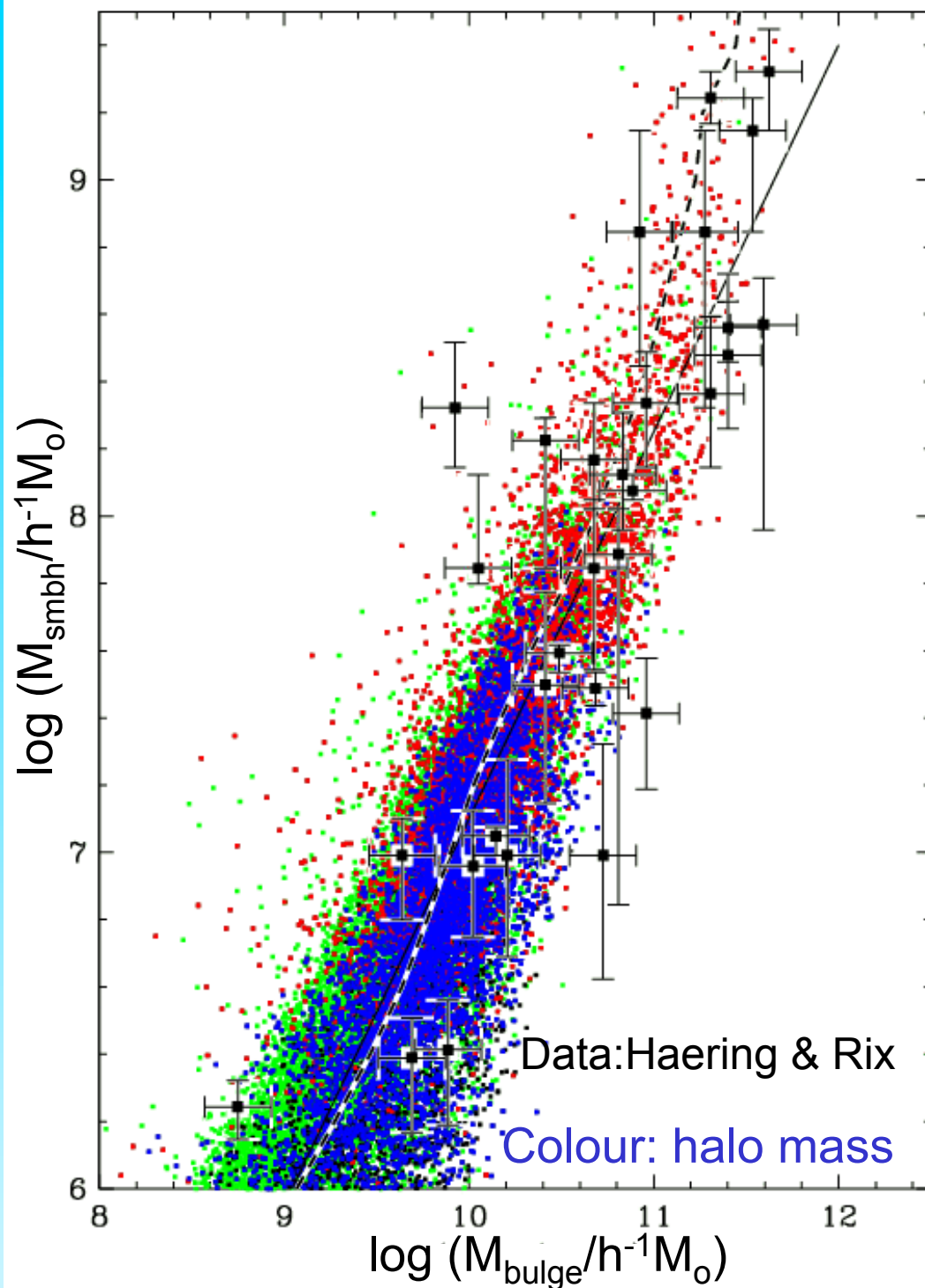
B-H mass vs bulge mass

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

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

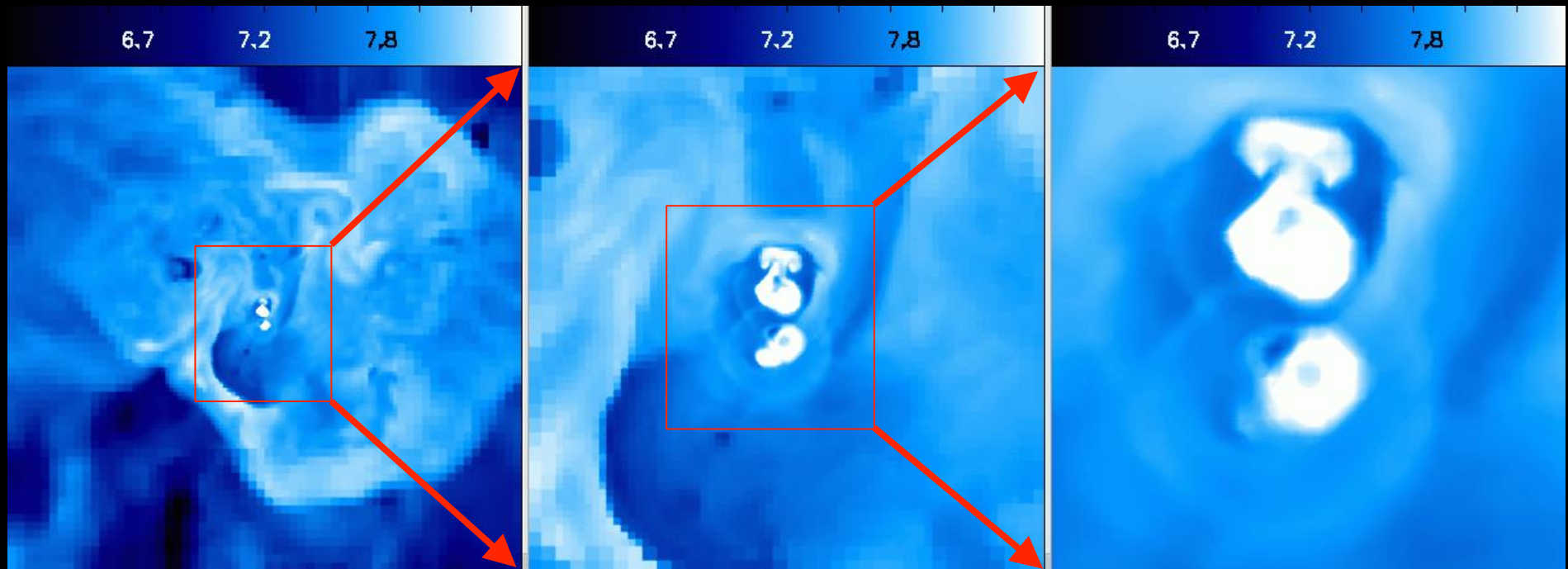
BH growth during feeding phase
steepens slope at large M

Bower et al 06



1

Buoyantly rising bubbles - temperature slice



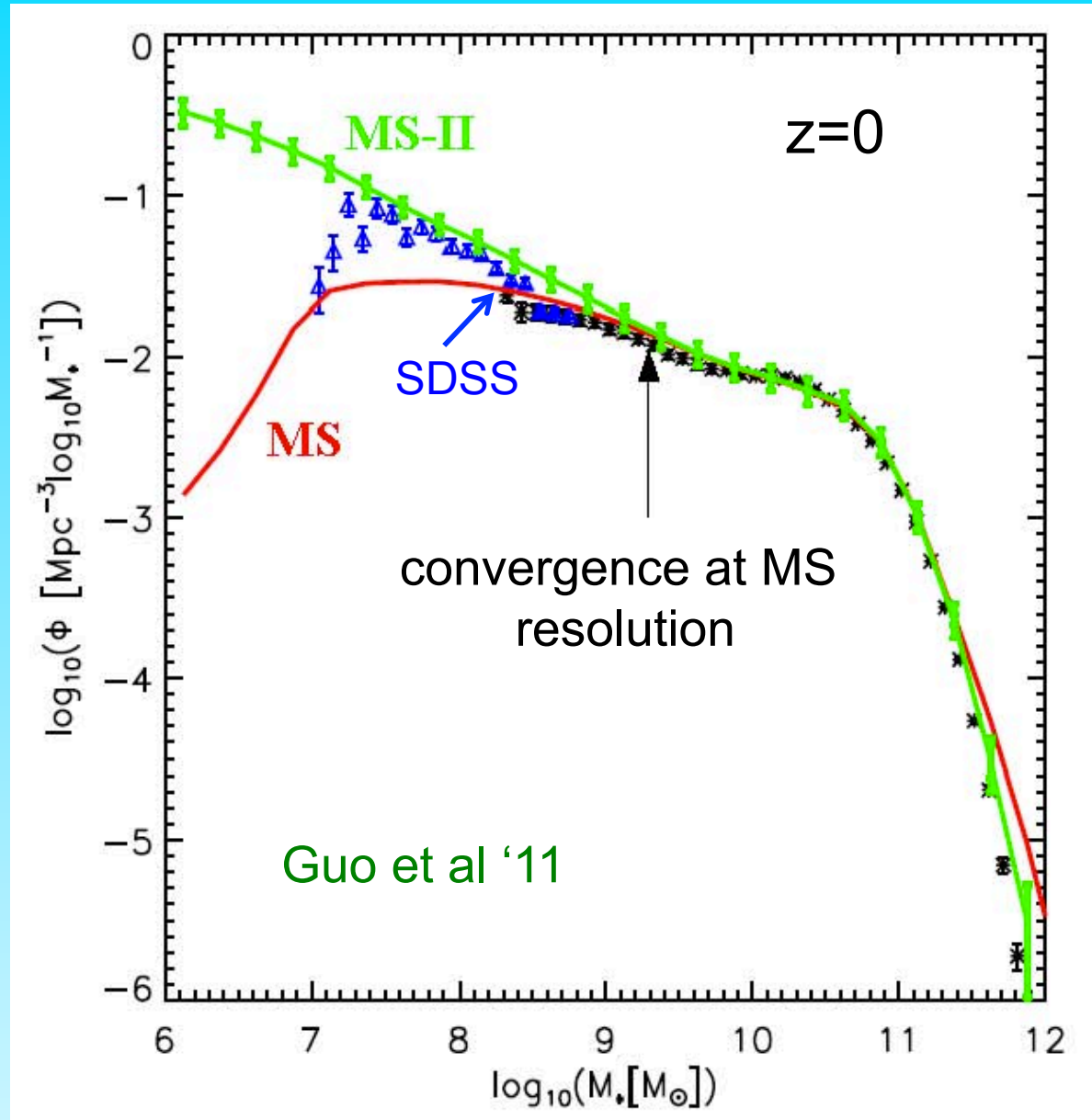
Brüggen, Ruszkowski & Hallman (2005)

The stellar mass function

Results for MS and
M-II converge

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

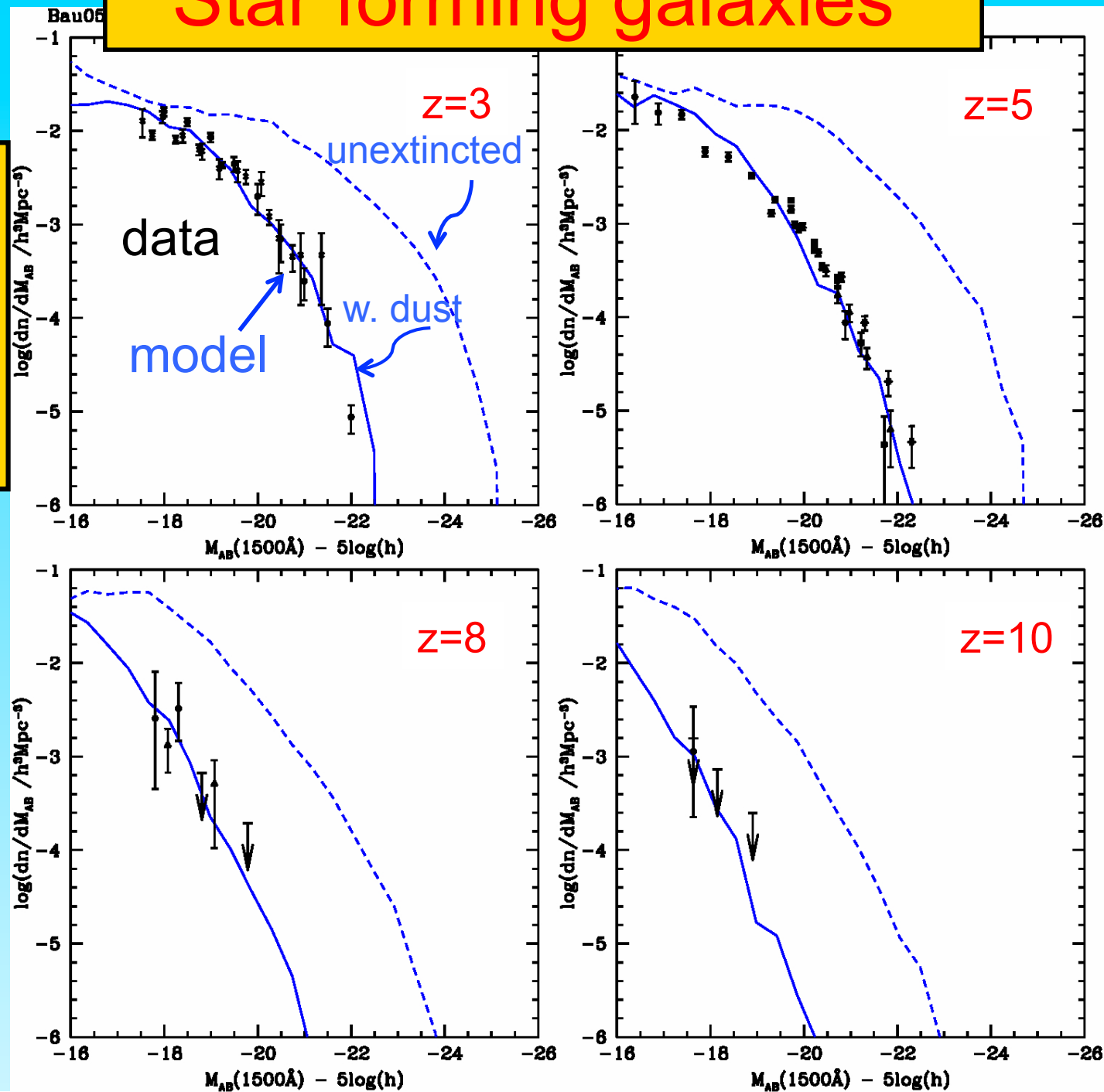
Guo et al. '11



Star forming galaxies

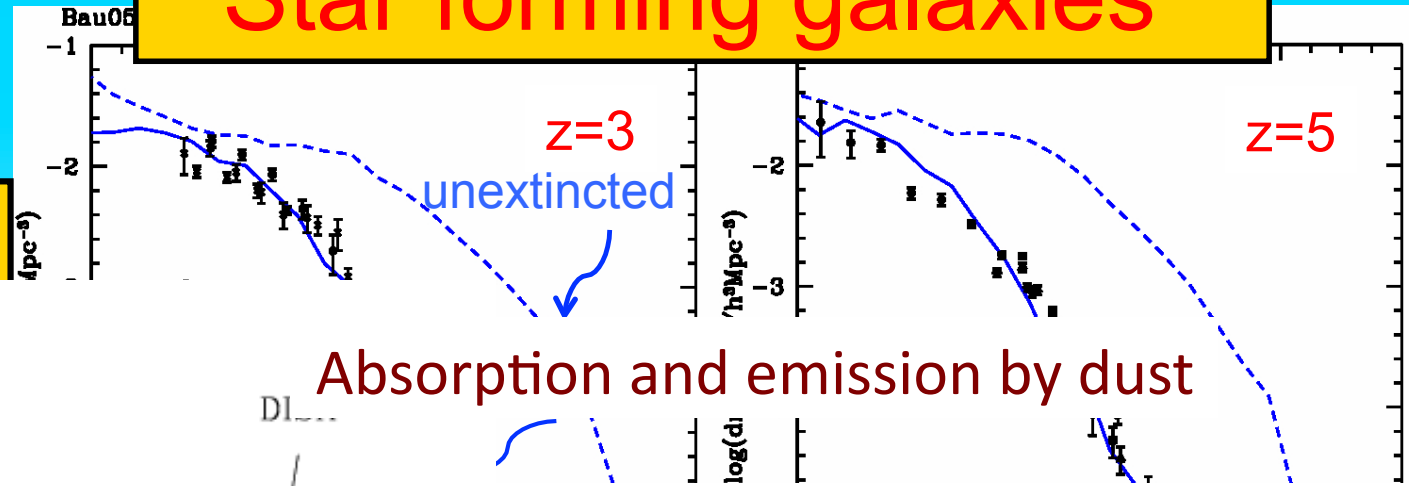
Evolution of Lyman-break galaxy lum. function

Lacey, Baugh, Frenk, Benson '11



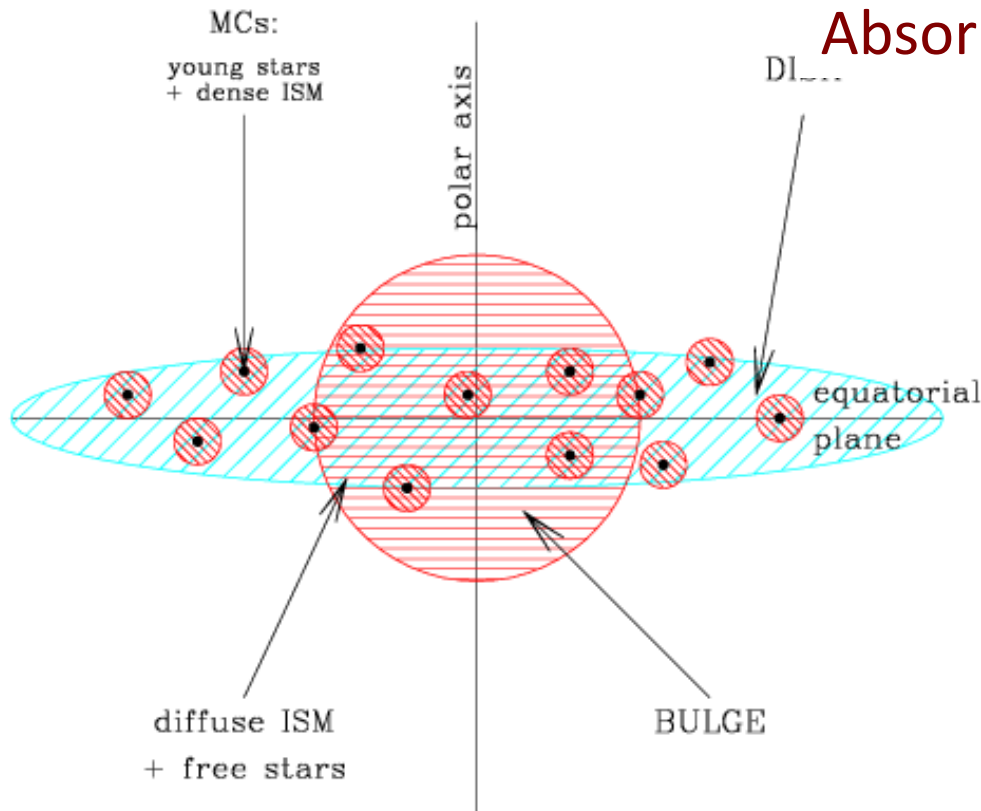
Star forming galaxies

Evolution of



Absorption and emission by dust

- 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

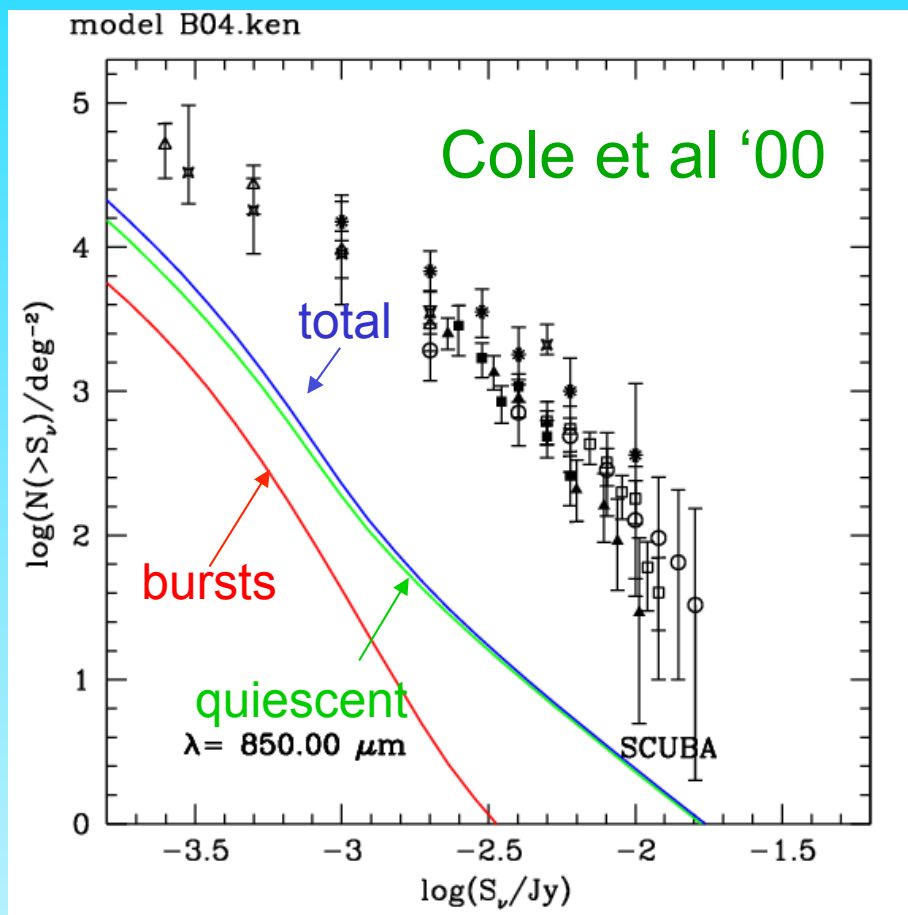


Granato, Lacey, Silva, Baugh,
Bressan, Cole & Frenk '00

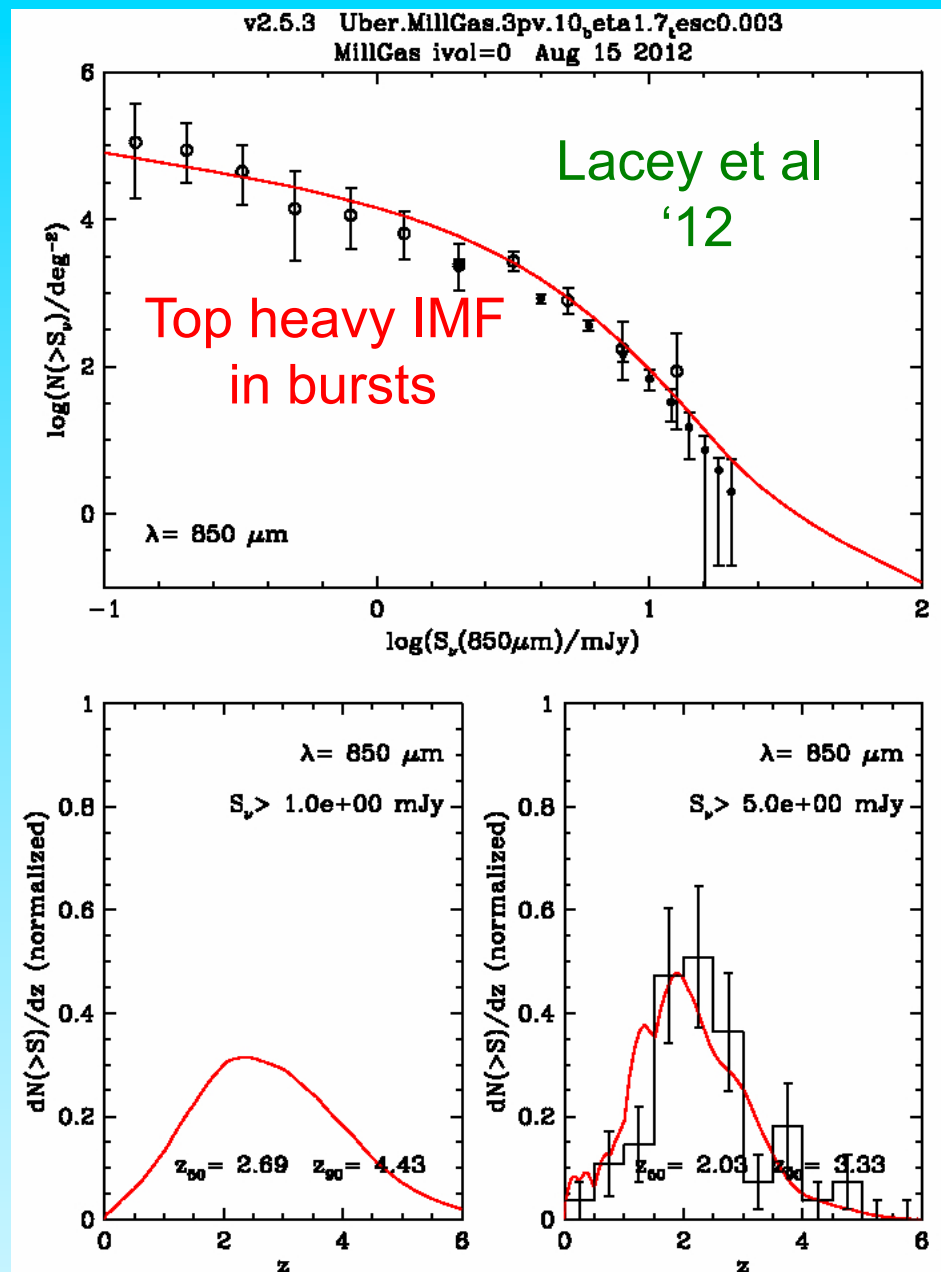


Sub-mm galaxies

Normal IMF



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



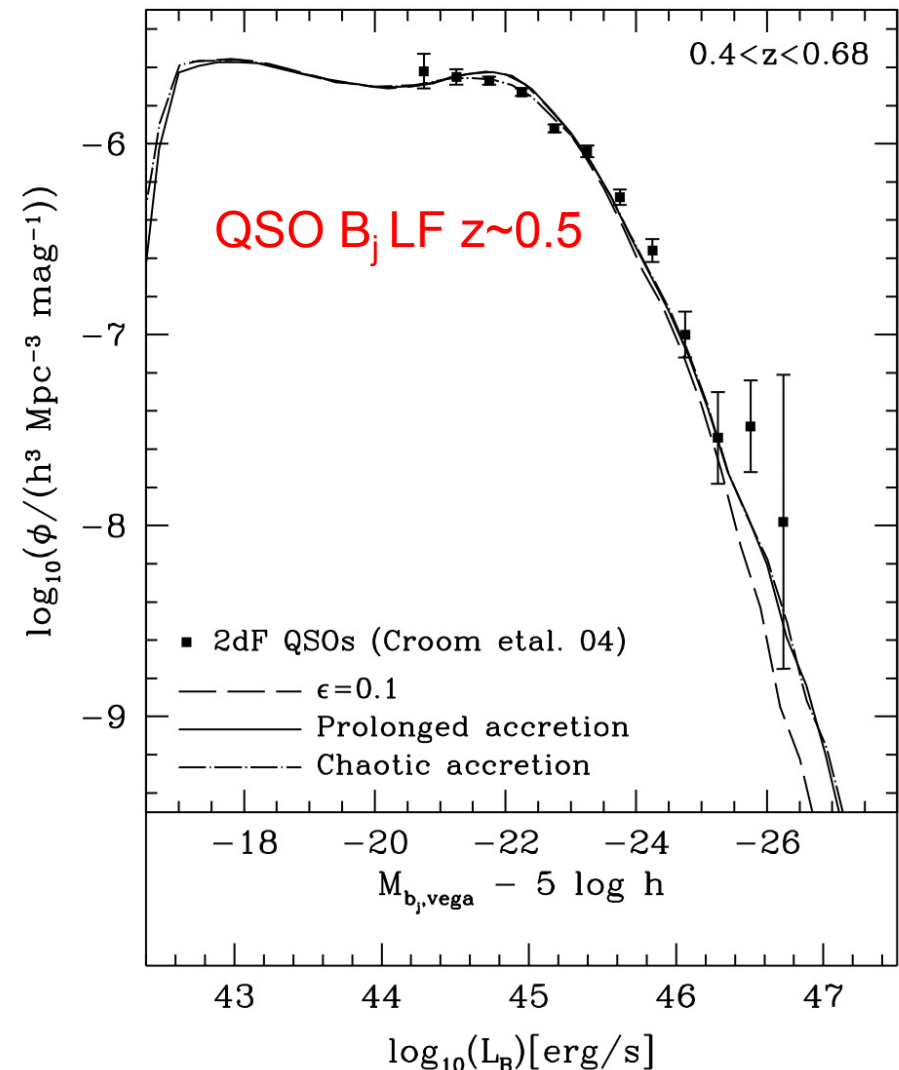
Semi-analytic modelling: the galaxy-QSO connection

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



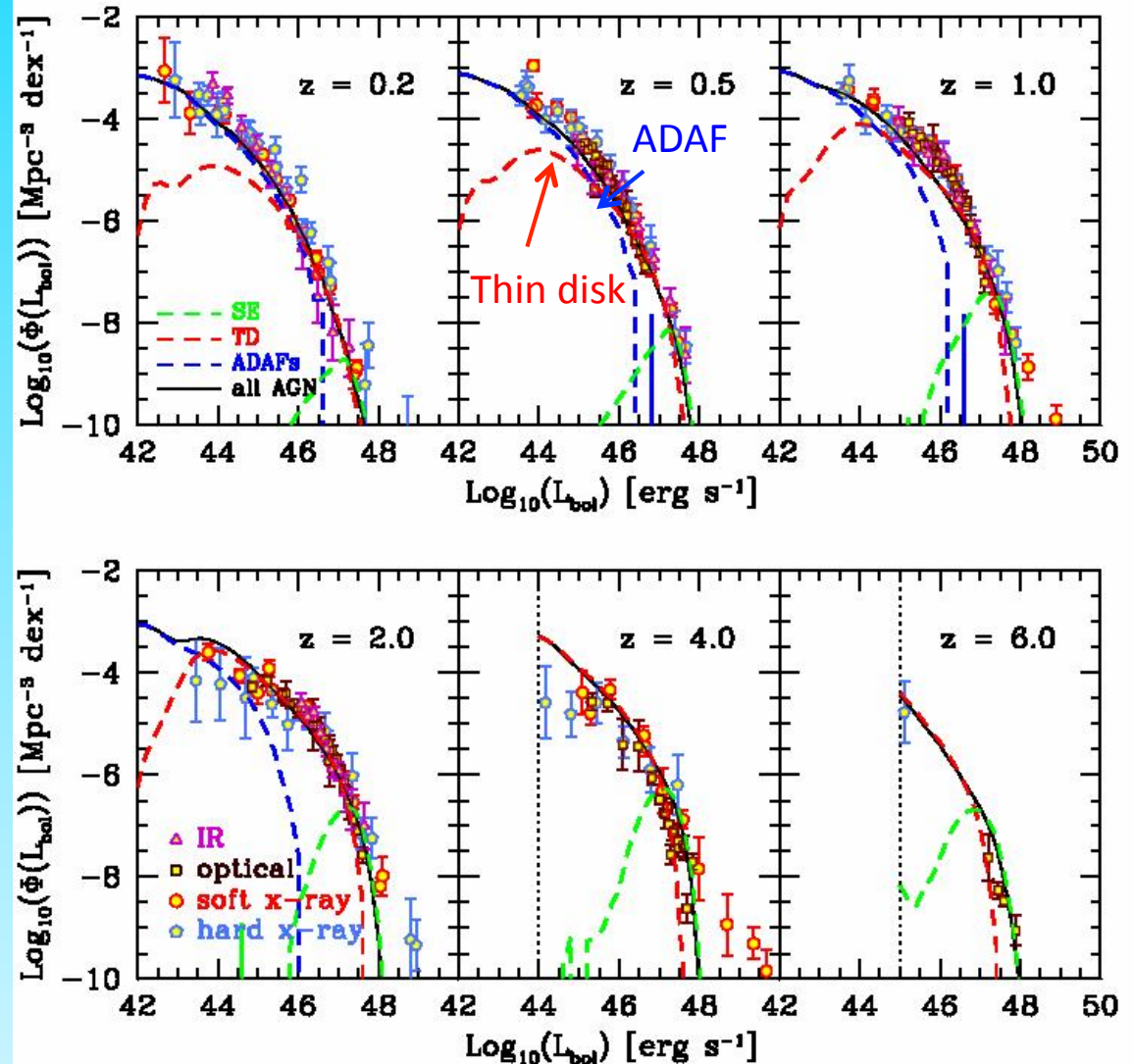
Semi-analytic modelling: the galaxy-QSO connection

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 *-burst mode

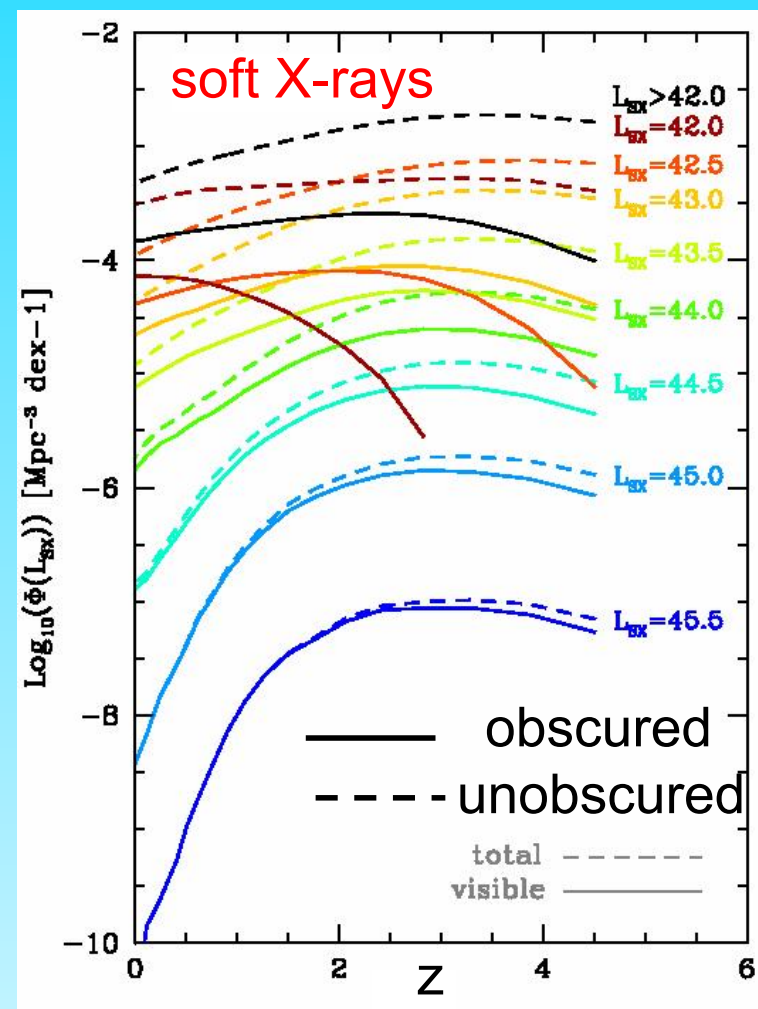
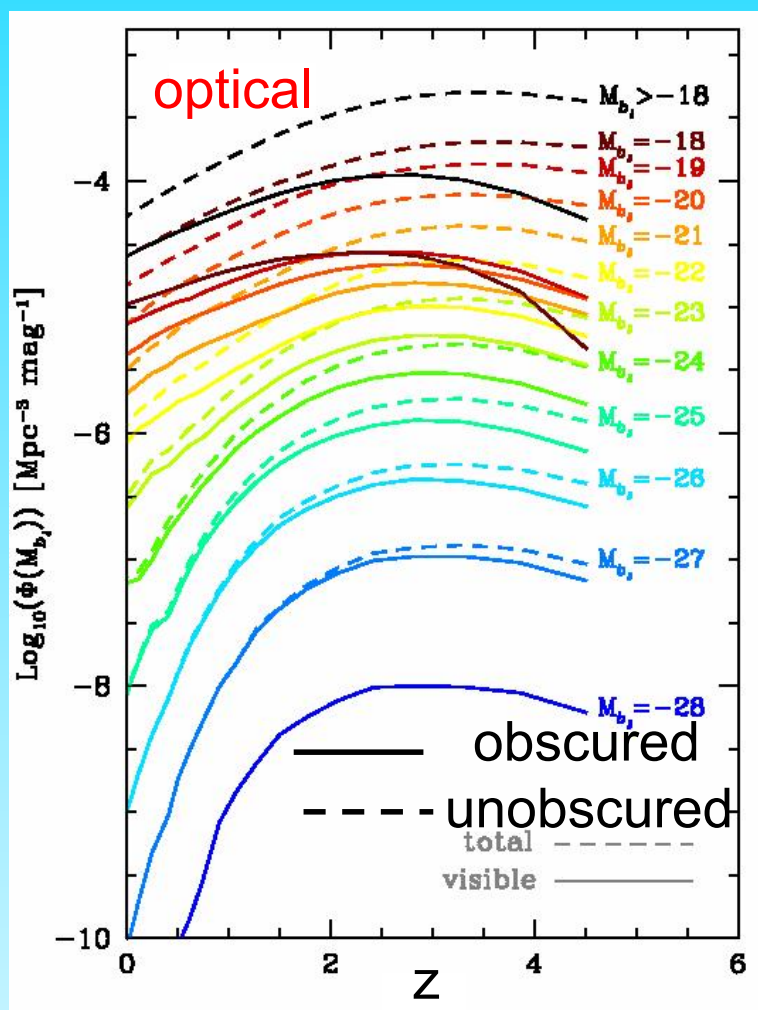
Fanidakis et al.12



AGN evolution: downsizing

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

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

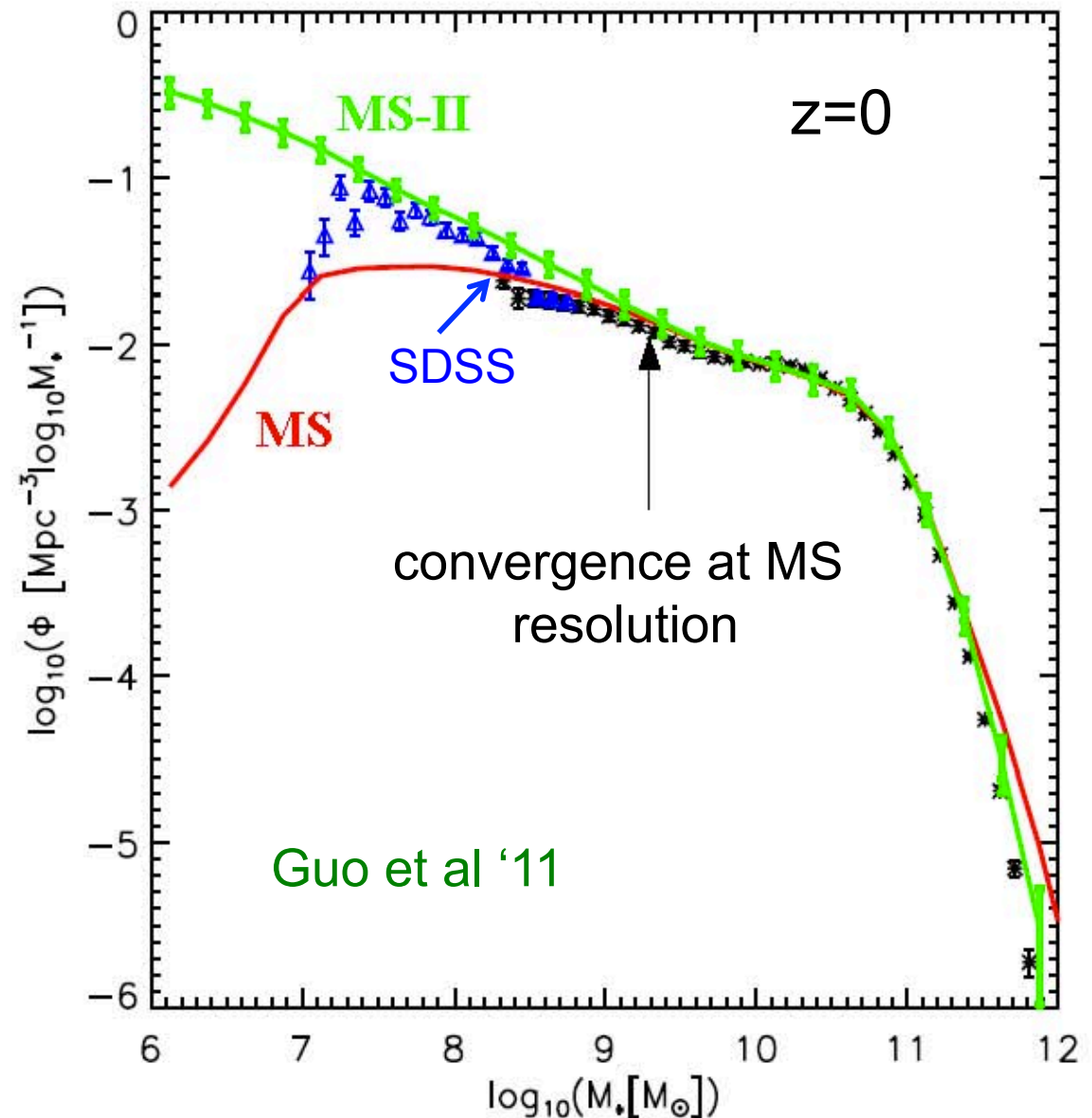


The stellar mass function

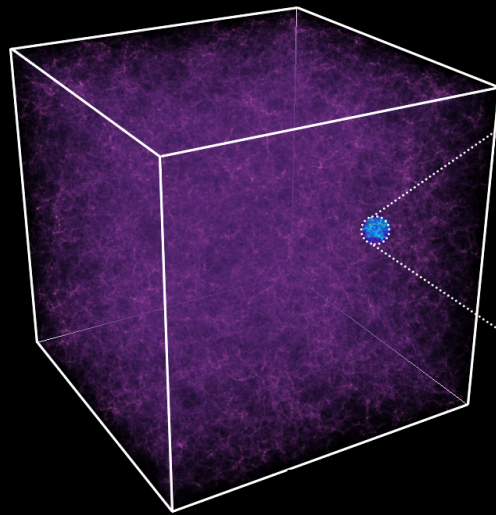
Results for MS and
M-II converge

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

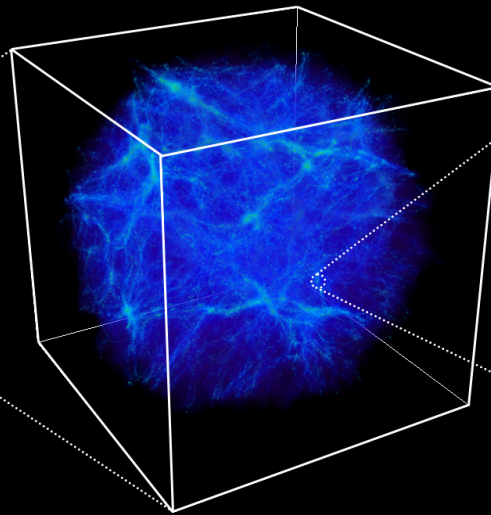
Guo et al. '11



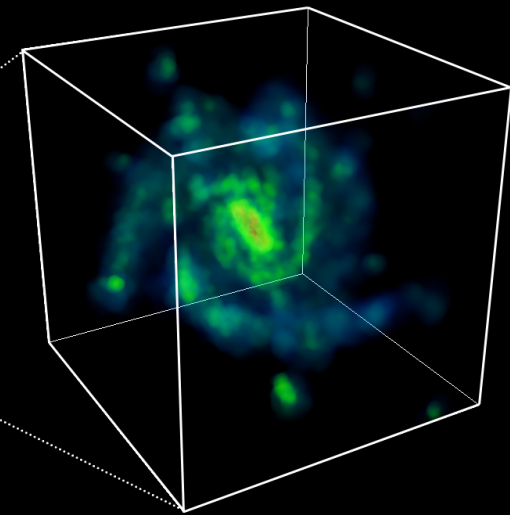
Galaxies-Intergalactic Medium Interaction Calculation



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 $z=0$

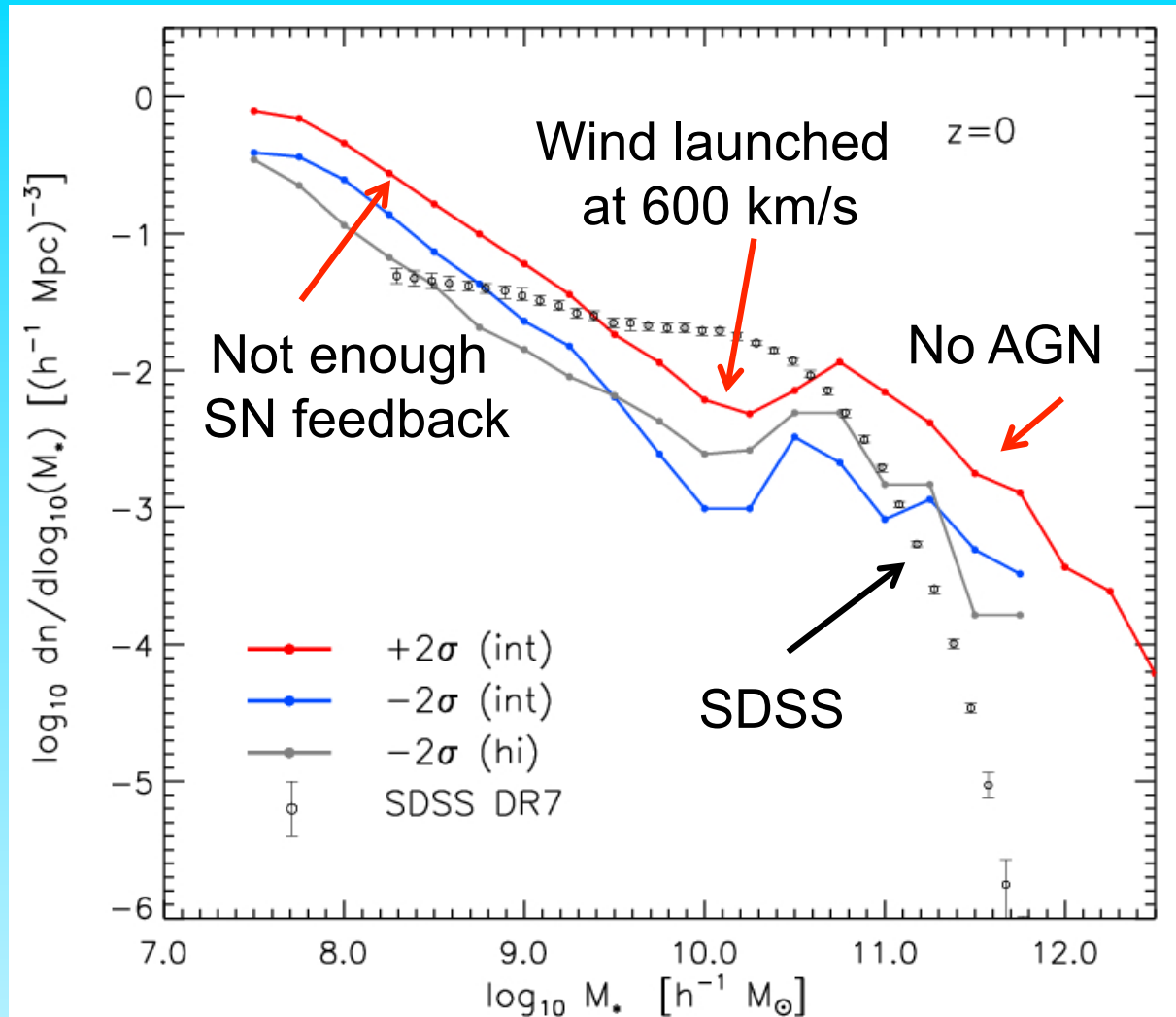
Crain et al. (2009)

The galaxy stellar mass function

Hydrodynamics

GIMIC project

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



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

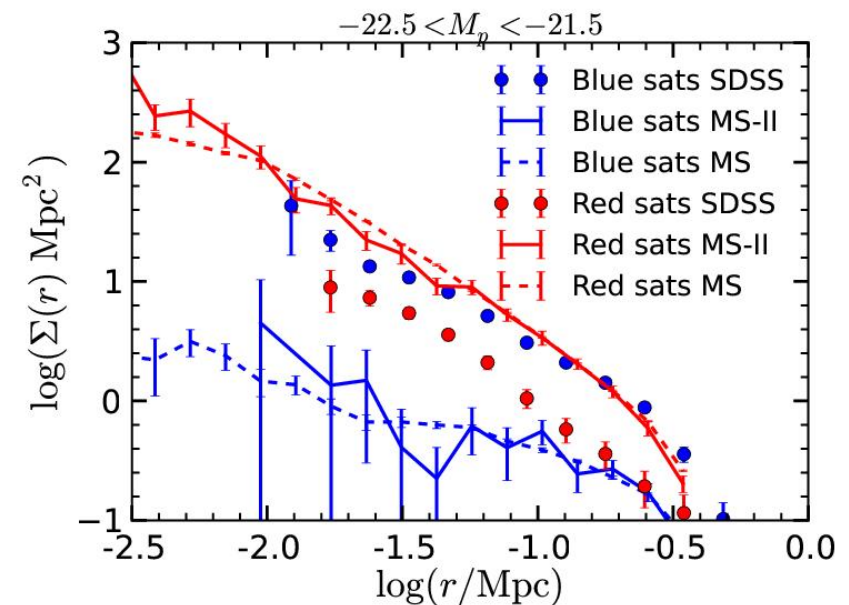
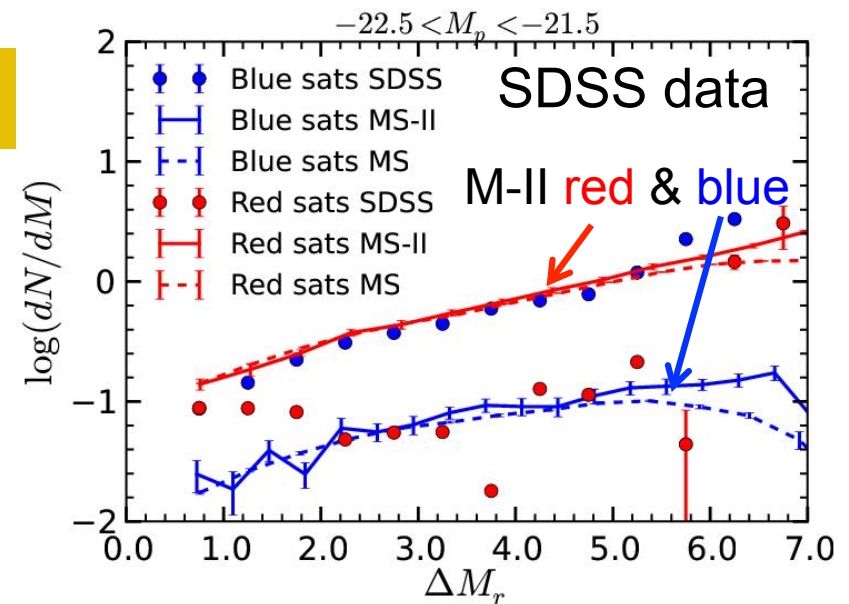
Satellites of Milky Way type galaxies

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

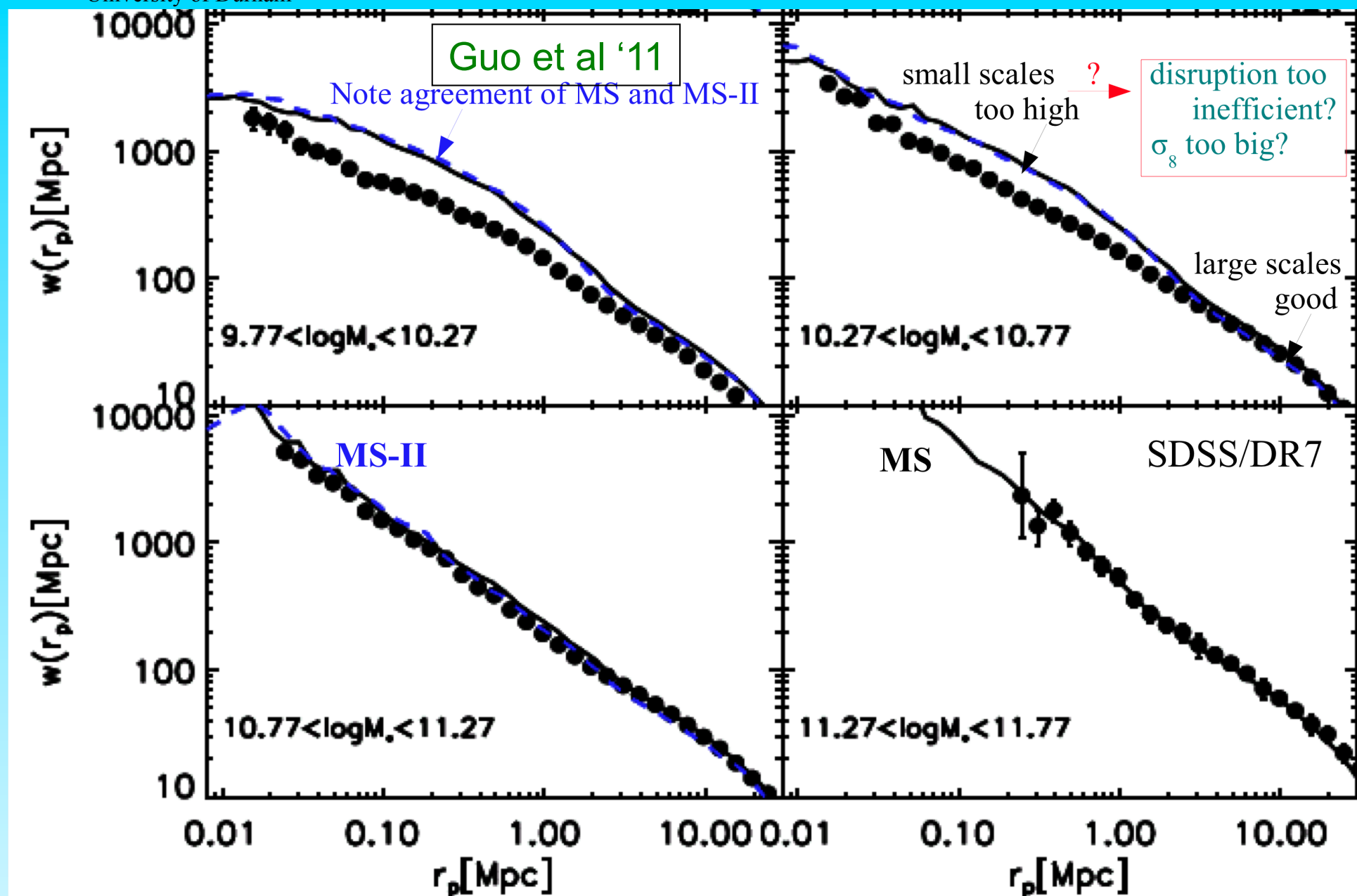
Models (Galform + Millennium-II)
fail completely!

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

Guo, Cole, Eke, Frenk '13



Mass-dependent galaxy clustering



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



Galaxy structure & morphology

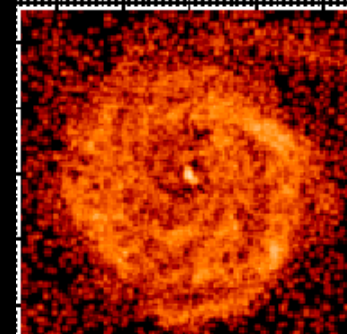
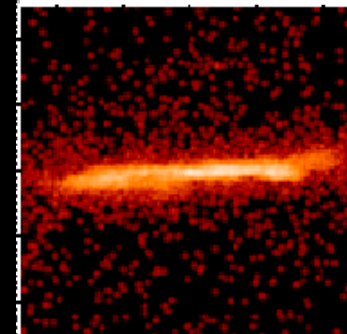
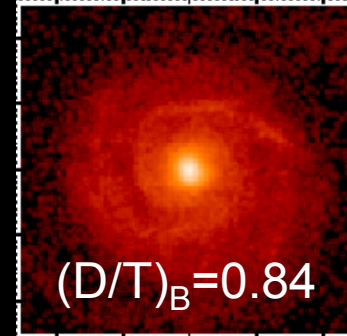
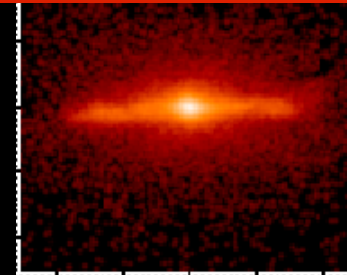
An ideal problem to tackle with cosmological simulations

?

Galaxy structure & morphology in cosmological simulations

Moderate f''_{back}

50 h^{-1} kpc



-20 -10 0 10 20
x (kpc/h)

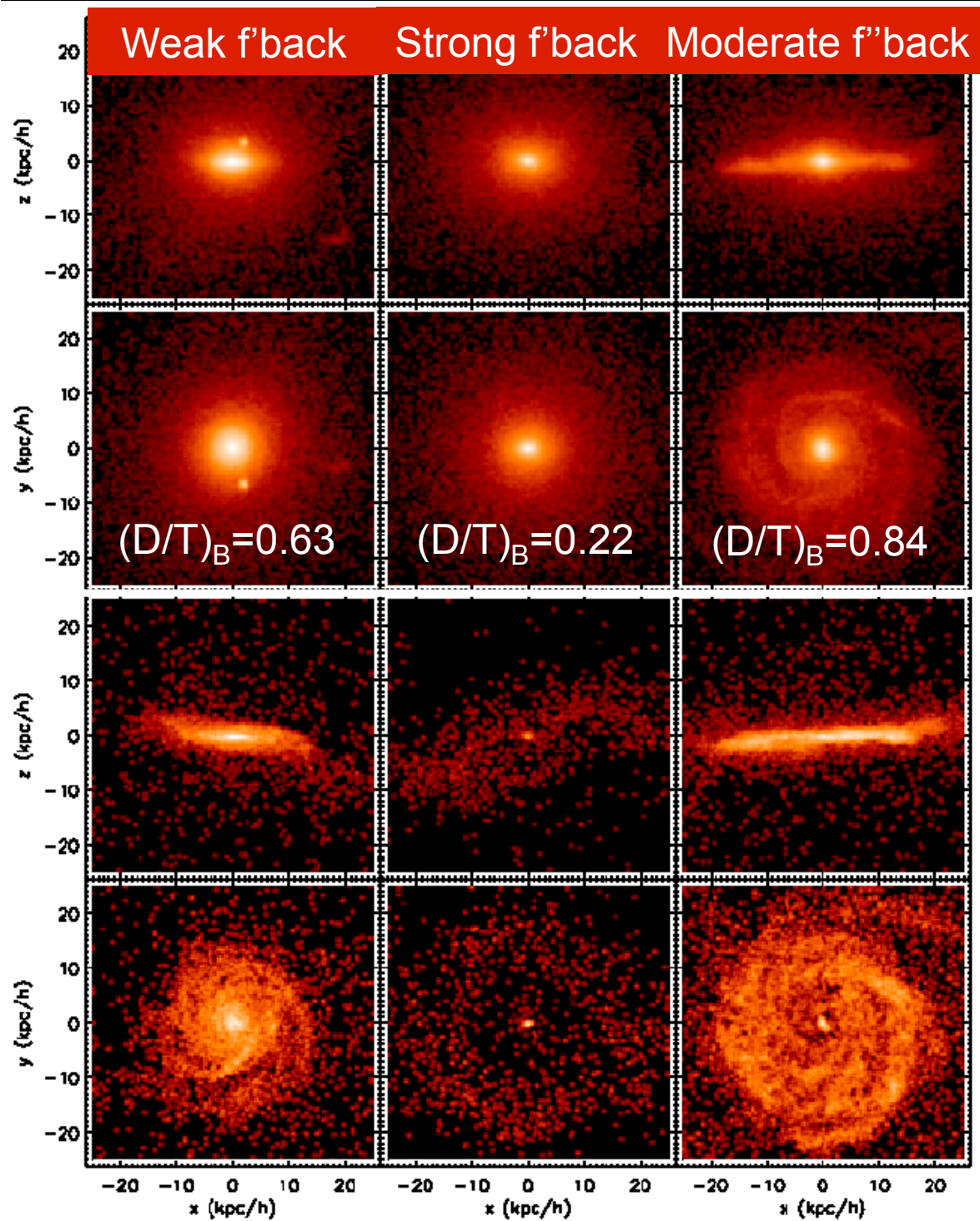
Stars

Gas:

Okamoto, Eke, Jenkins & Frenk 05

same dark matter halo!

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



Stars

Gas

Okamoto et al 05

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

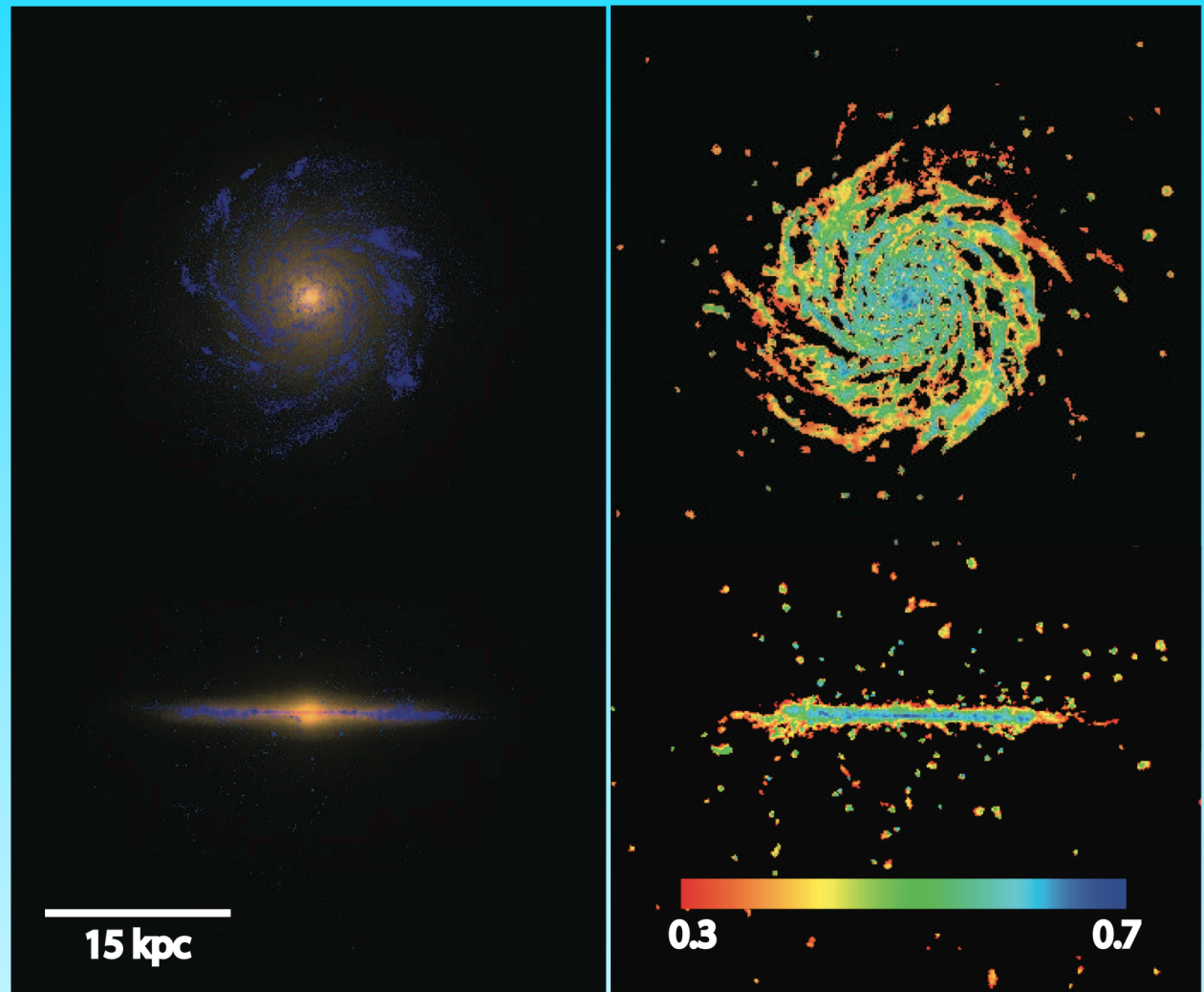
JAVIERA GUEDES^{1,3}, SIMONE CALLEGARI², PIERO MADAU¹, & LUCIO MAYER^{2,3}

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.”

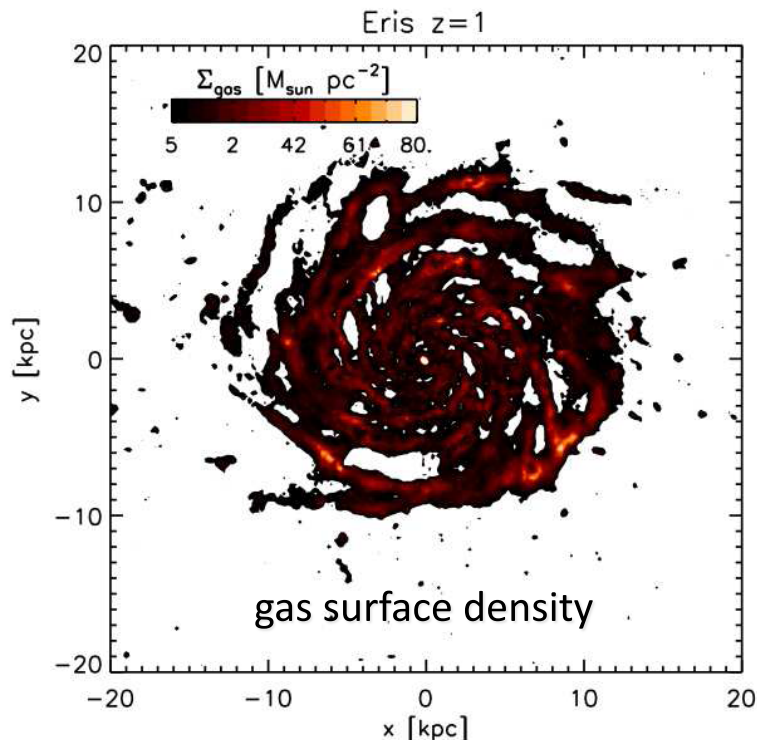


Galaxy structure & morphology

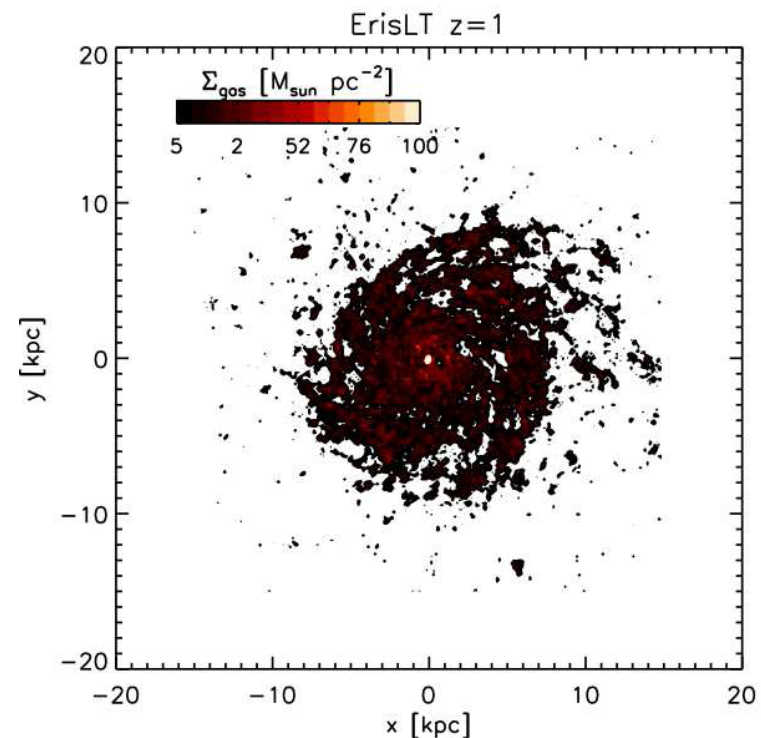
Results highly sensitive to adopted density threshold for star formation

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, little gas



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



What is the purpose of galaxy formation simulations?

Aquila comparison project: hydro simulation of an Aquarius halo

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	G3-CS	SPH	thermal	
(Scannapieco et al. '05, '06)				
Gadget3	G3-TO	SPH	thermal+kinetic	
(Okamoto et al. '10)				
Gadget3	G3-GIMIC	SPH	thermal+kinetic	
(Crain et al. '09)				
Gadget3	G3-MM	SPH	thermal	
Chiaki Kobayashi	G3-CK	SPH	thermal	
GASOLINE	GAS	SPH	thermal	
	R	AMR	thermal	
RAMSES	R-LSFE	AMR	thermal	Low SF efficiency
(Romain Teyssier)	R-AGN	AMR	thermal	BH
Arepo	Arepo	Moving mesh	thermal	

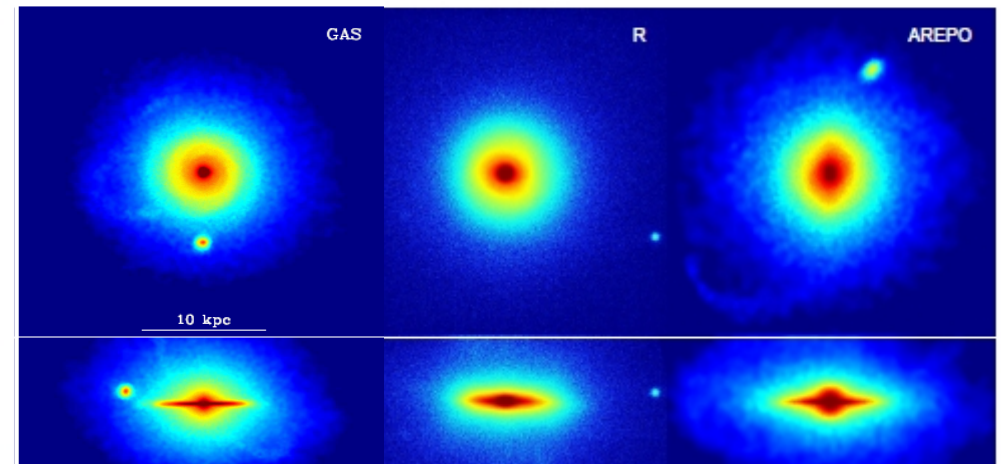
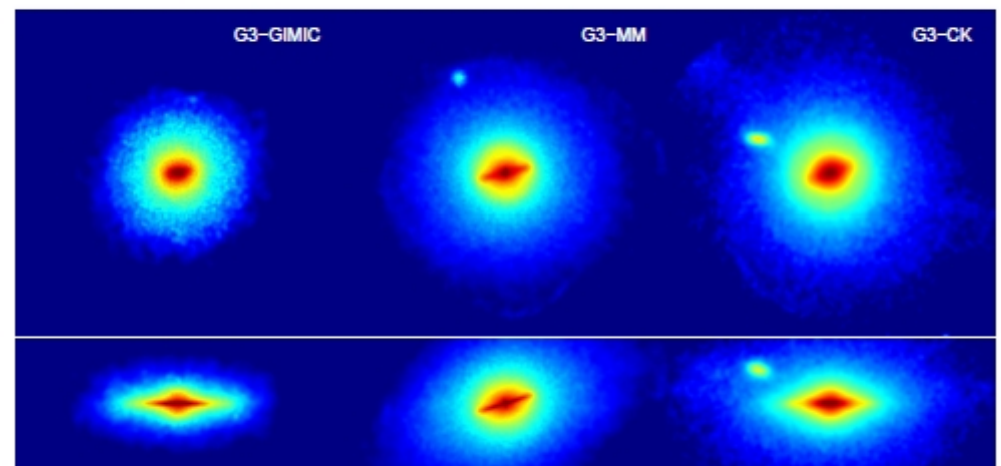
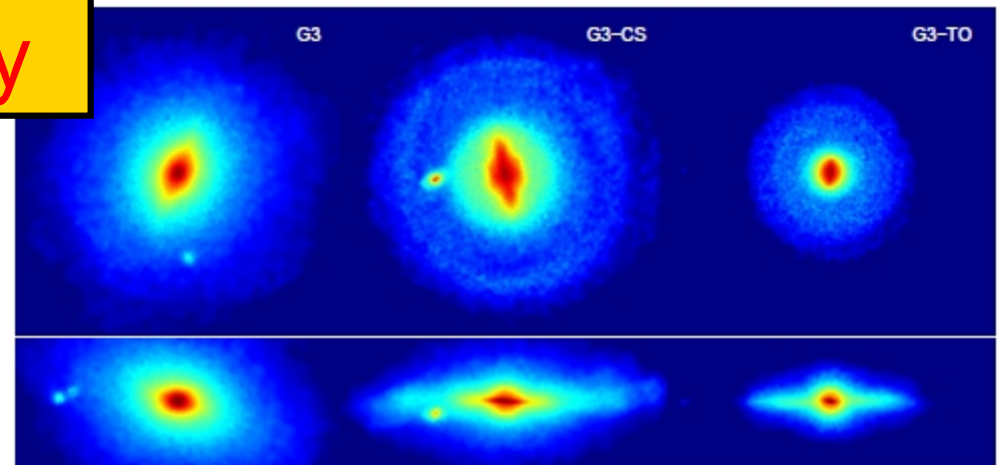
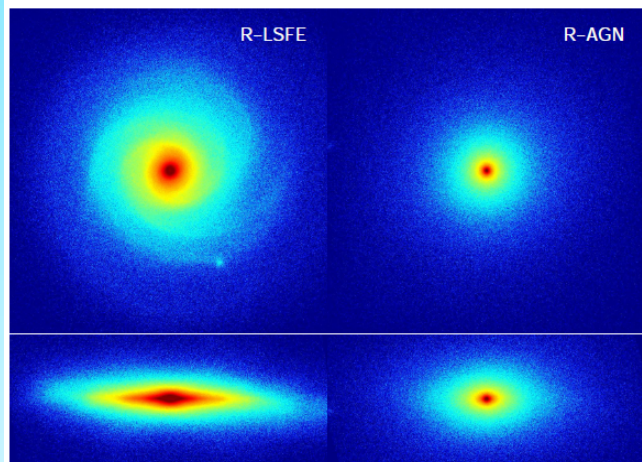
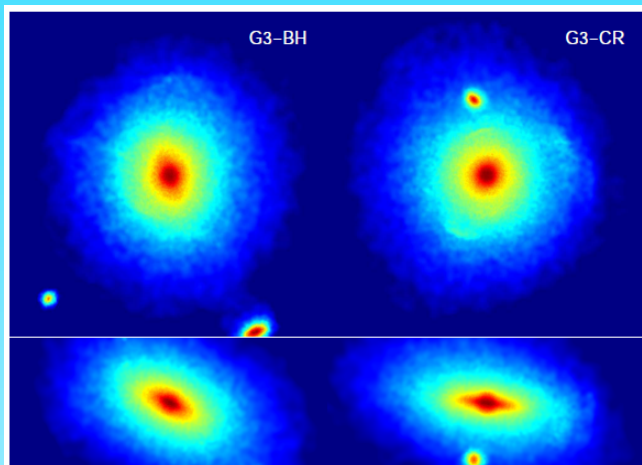
Scannapieco et al. 2012

Structure & morphology

- Most galaxies are multi-component: bulges, disks, bars.
- Strength of components varies from model to model.

face on

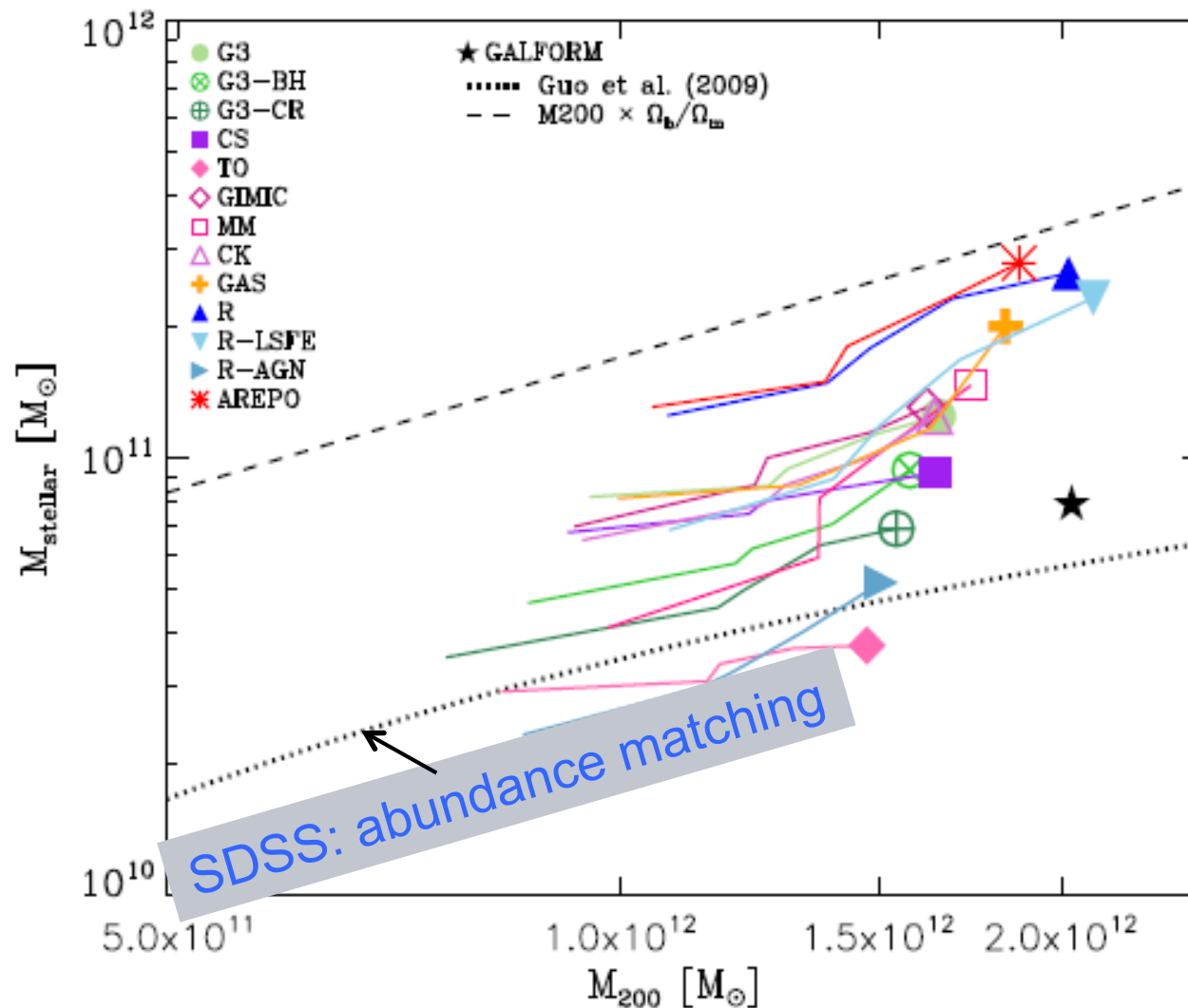
edge on



Stellar mass vs halo mass

● G3 □ G3-CS ■ G3-MM
⊕ G3-CR ◇ G3-TO △ G3-CK
⊗ G3-BH ◆ G3-GIMIC + GAS

▲ R ✱ AREPO
▼ R-LSFE
▶ R-AGN



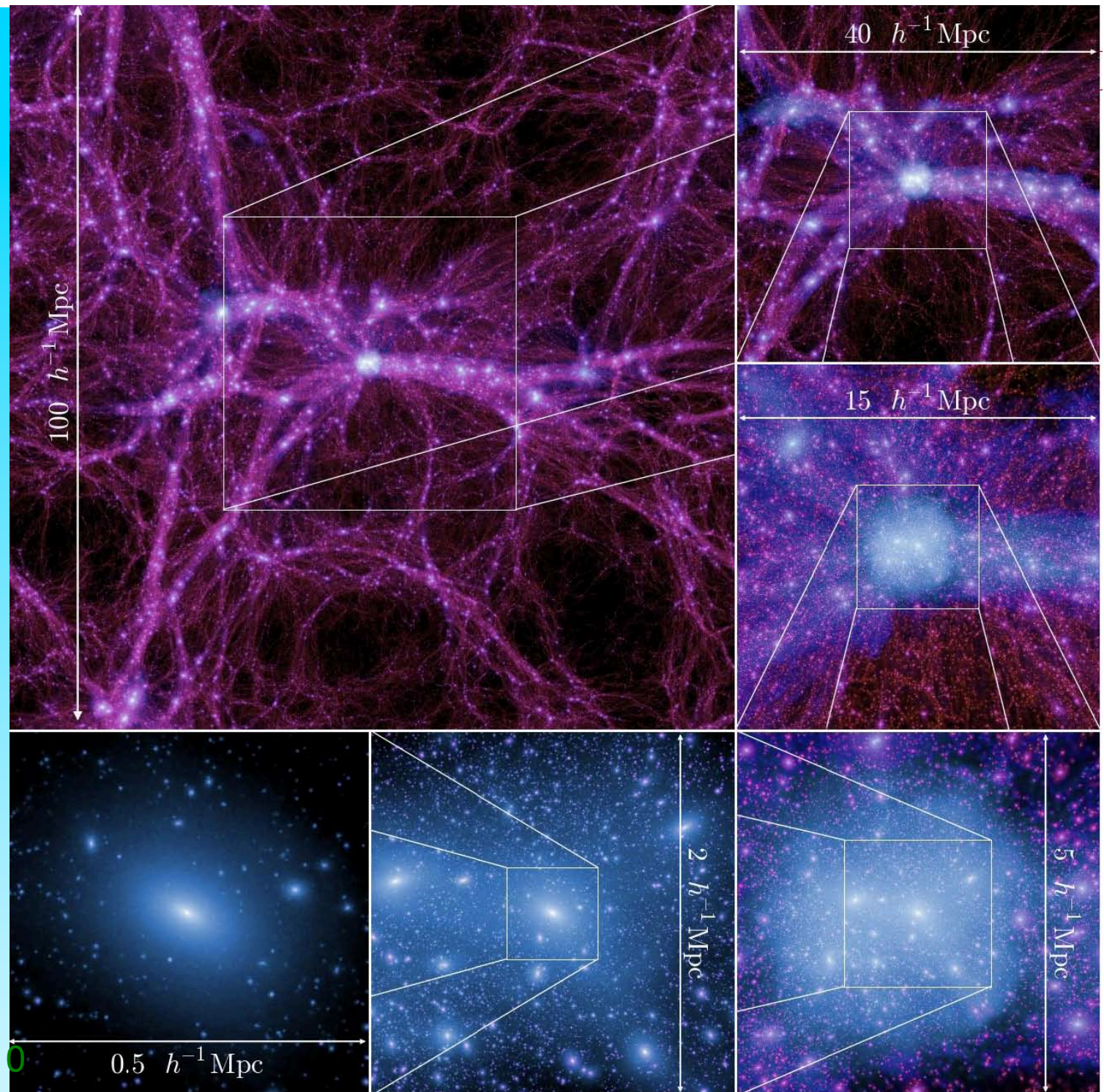
- Large spread in stellar masses
- Different feedback efficiency
- Evolution between $z=2$ and $z=0$ almost parallel to 1:1 relation

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

Millennium-II (2008)





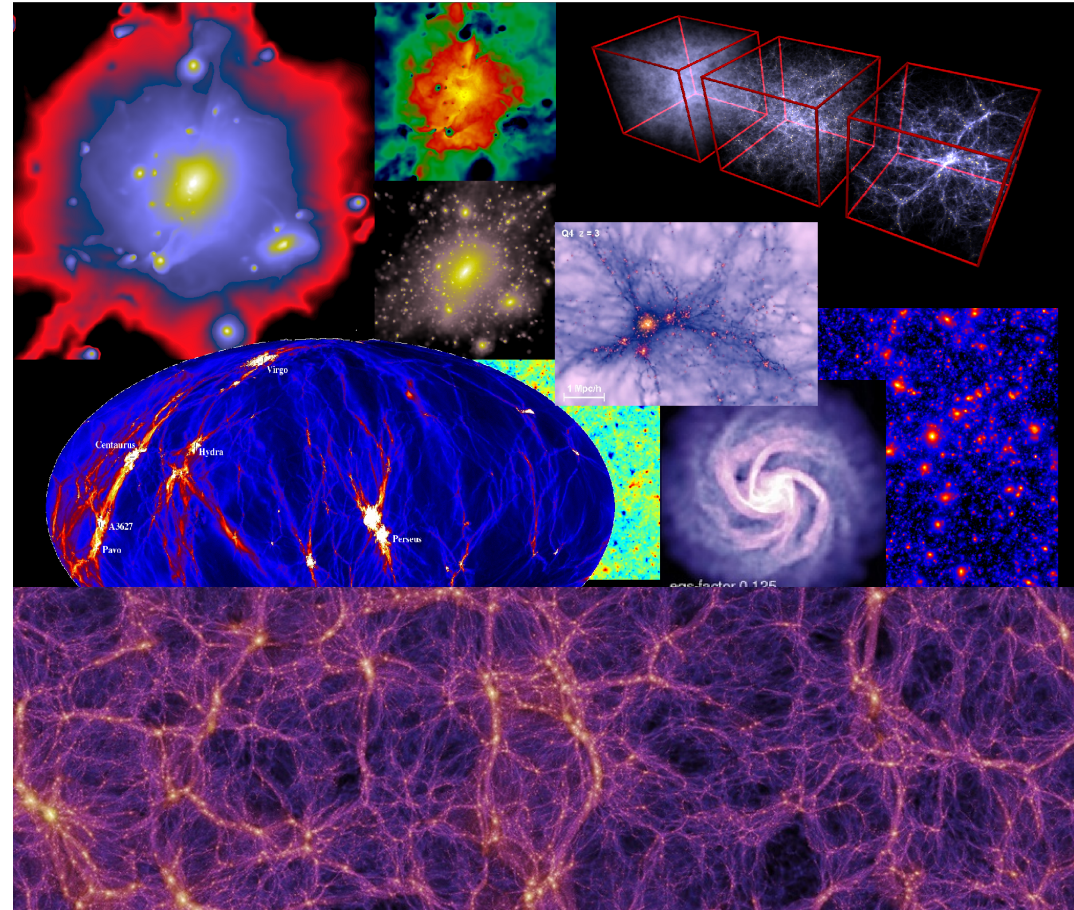
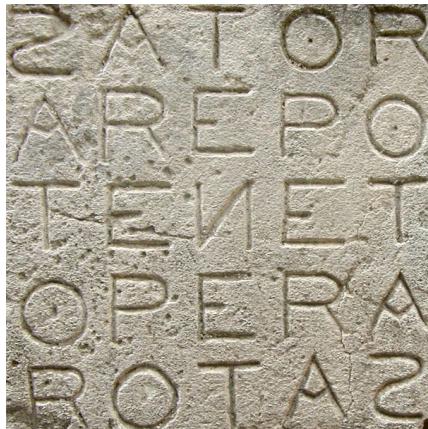
The next generation of galaxy formation simulations

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

Hydrodynamical simulations of galaxy formation

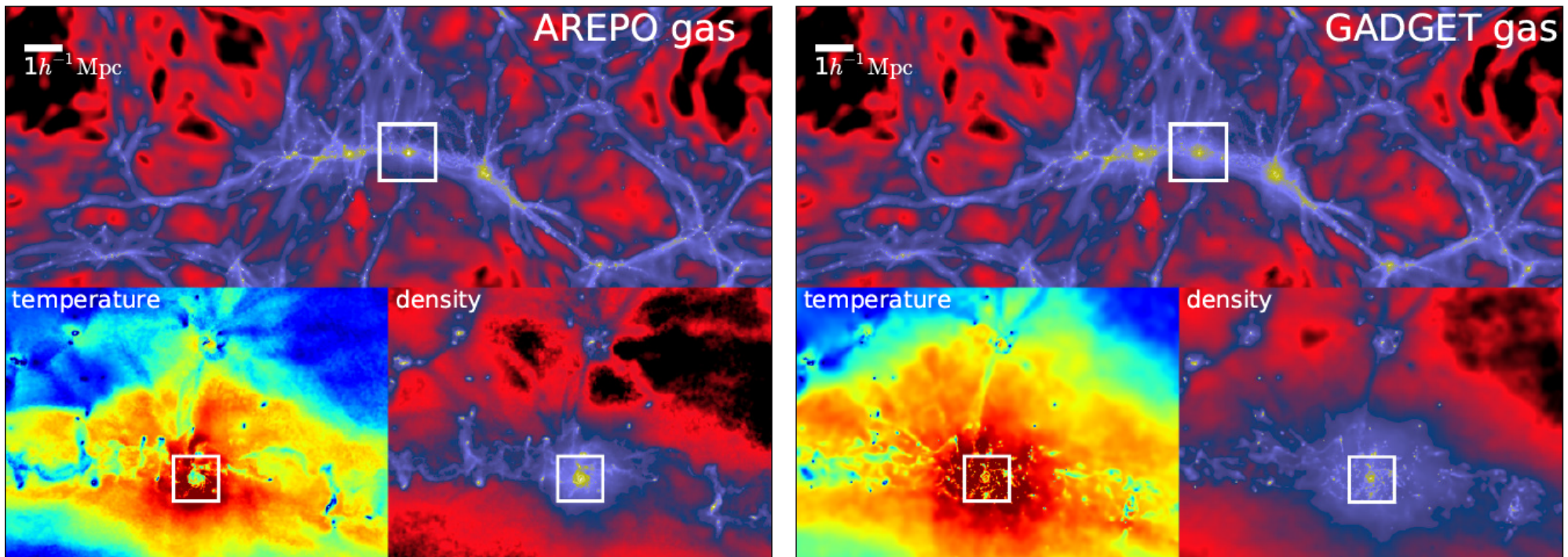
Volker Springel

- ▶ Moving-mesh technique: **Arepo**
- ▶ Turbulence, shocks, K-H instability ...
- ▶ MHD, cosmic rays

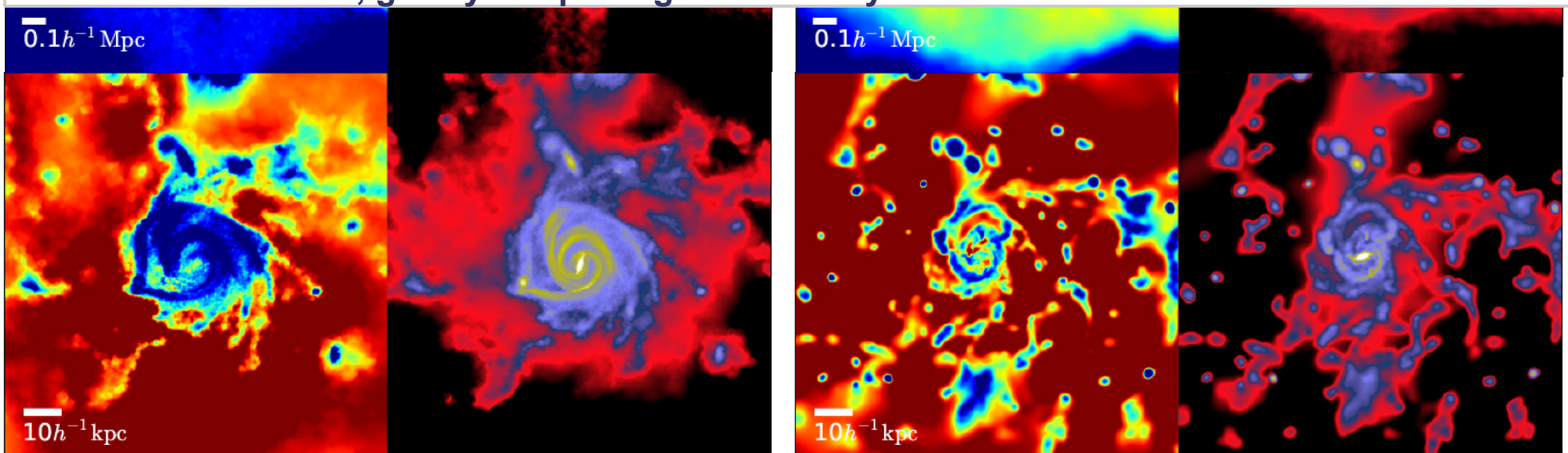


On large scales, the code produces similar results as standard SPH techniques

GAS AND TEMPERATURE FIELDS IN A COSMOLOGICAL HYDRODYNAMIC SIMULATION



But on small scales, galaxy morphologies look very different



Evolution and Assembly of GaLaxies and their Environments (EAGLE)

The marriage of semi-analytics and hydrodynamic simulations?



photography by
onique

The Eagle project

Schaye, Crain, Furlong,
Schaller, Bower, Theuns, Frenk

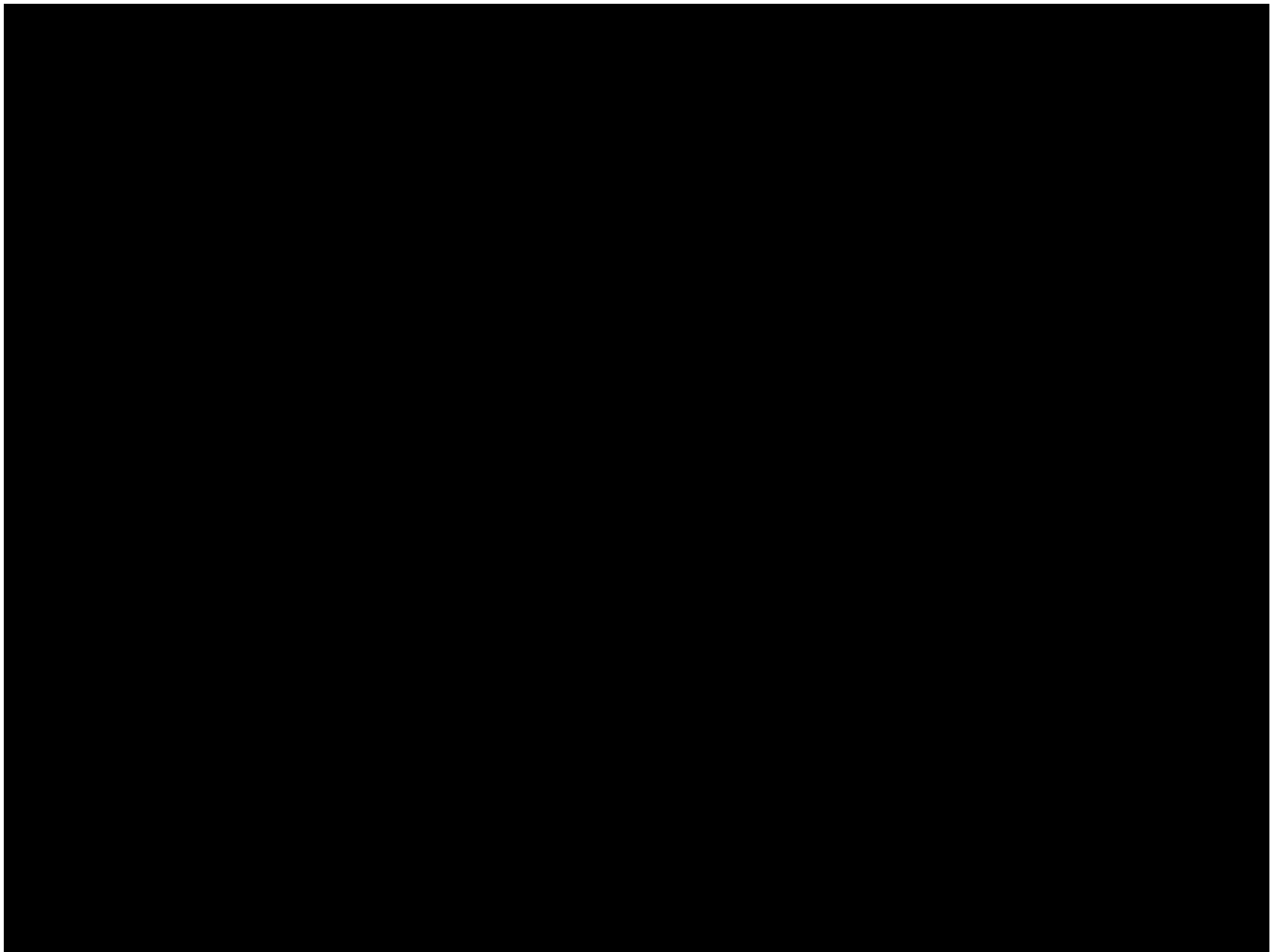
Goals:

- Simulate representative cosmological volume with baryons
- Compare to data
- Understand what works and why?

← This is the key!

Constraints:

- Match observed galaxy mass function
- Avoid unphysical solutions (e.g. decoupling feedback)

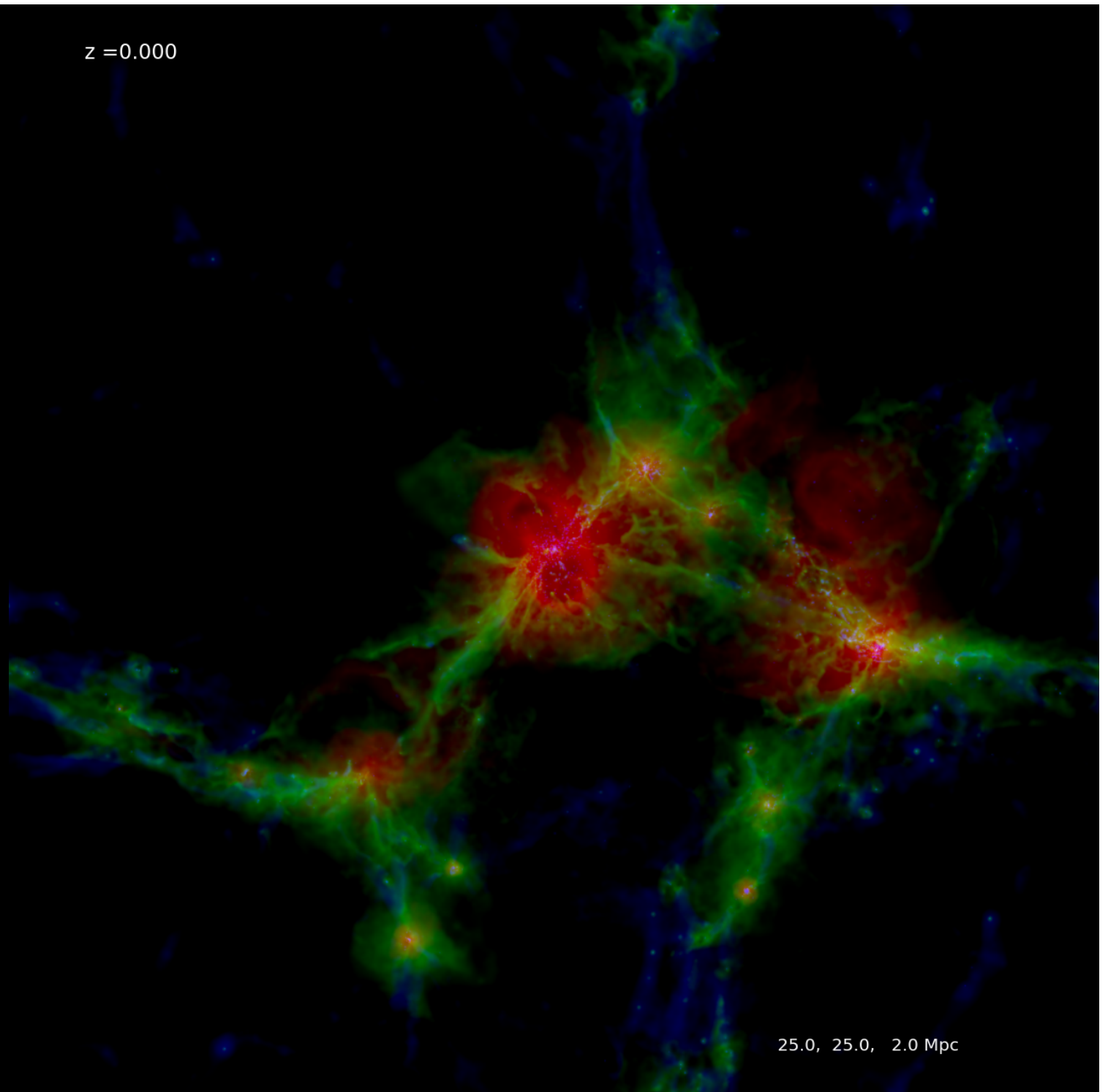


$z = 0.000$

Dissecting the effect of feedback

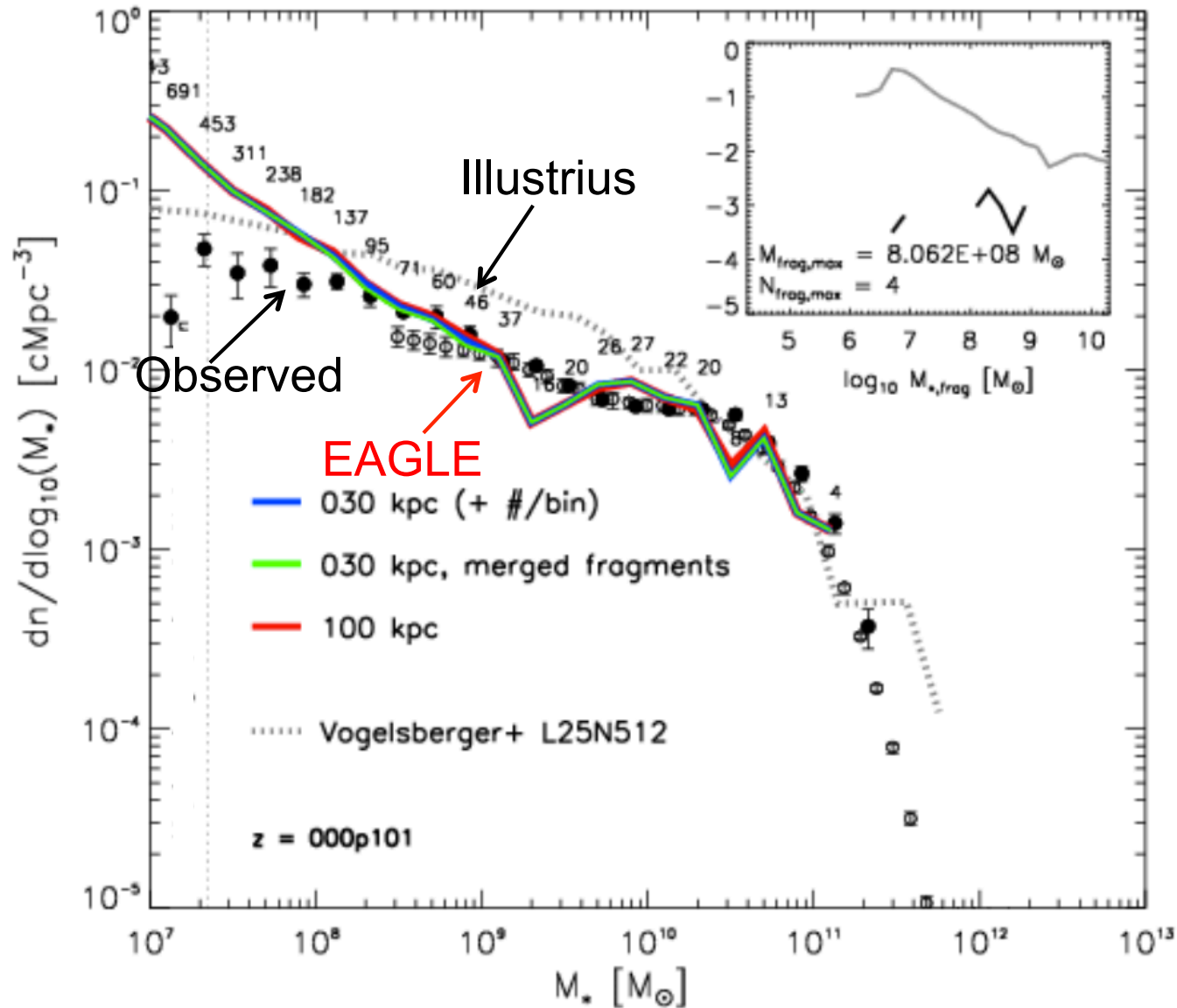
Taking
progressively
thinner slices
reveals holes and
loops in the
outflow.

Gas is much
more extended
than dark matter

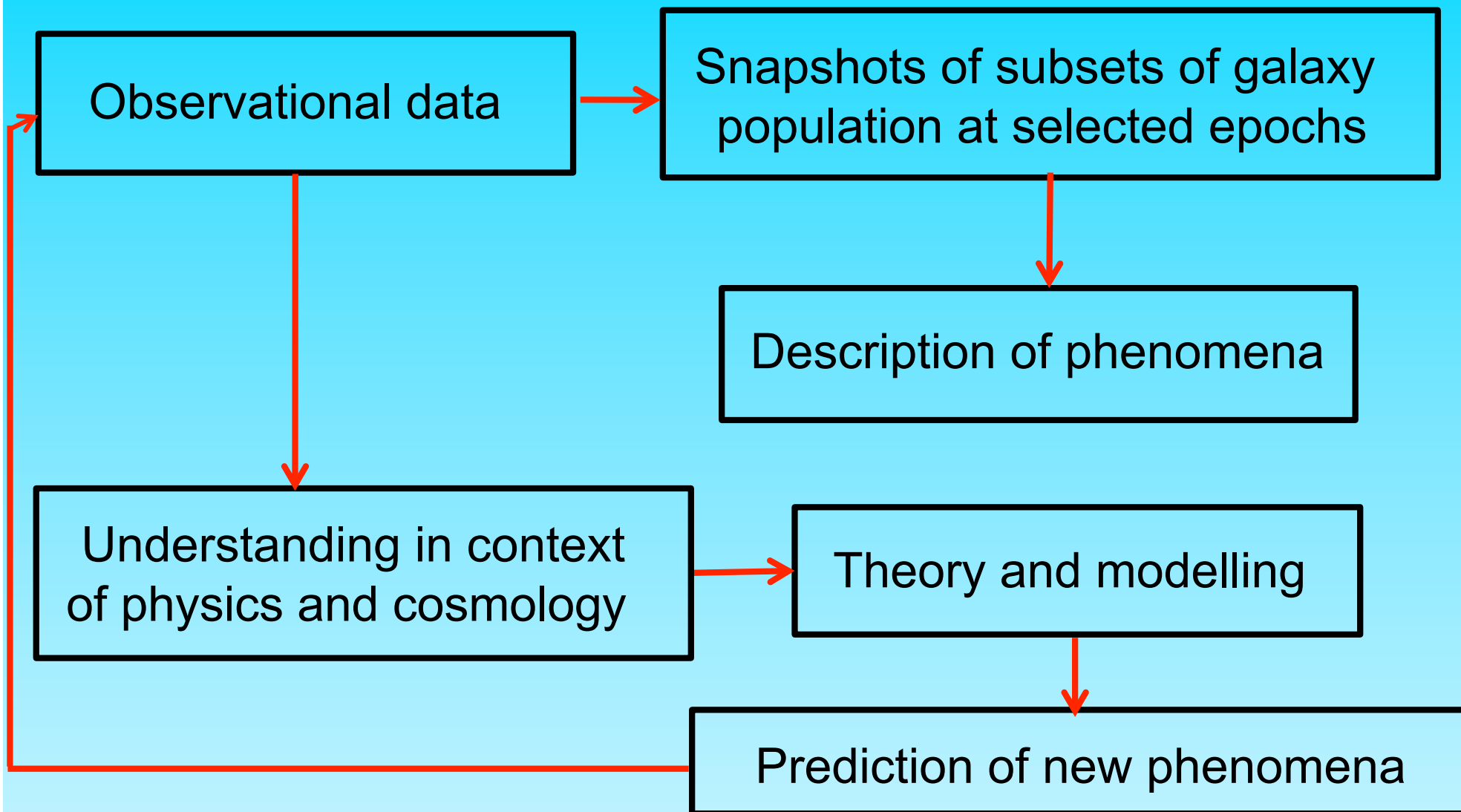


25.0, 25.0, 2.0 Mpc

New generation simulations: the stellar mass function



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

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

The Millennium Simulation (2005)

Springel et al 05

125 Mpc/h

566 papers making direct use of data from the MS (3/June/2013)

Most by authors unassociated with the consortium

Most based on the galaxy catalogues, particularly mock surveys

Conclusions

Main successes of galaxy formation theory over past 30 yrs:

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

Main failure of galaxy formation theory over past 30 yrs:

- Inability to explain the Hubble sequence of morphological types

Hydro simulations of galaxy formation: prospects

Hydrodynamics simulations

Main goals for next few years:

- improve hydrodynamics (“new” SPH; Ramses, Arepo)
- convert today’s “sub-grid physics” → resolved physics
 - Star formation
 - Feedback: reionization, SN, AGN ...
 - Tidal and ram pressure stripping of gas
 - Tidal stripping and mergers of galaxies as their halos merge
 - Disk instabilities, secular evolution
 - Magnetic fields, cosmic rays

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

Galaxy formation

