Galaxy evolution: big questions

Carlos S. Frenk
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Big questions in galaxy evolution

A subjective choice!

The 7 questions of galaxy evolution

- Cosmic star formation history and growth of stellar mass?
- The first galaxies: how was the universe reionized?
- Galaxy assembly and origin of galaxy morphology?
- Gas and metals cycling in and out of galaxies?
- Growth of supermassive black holes?
- Role of feedback processes from supernovae and AGN?
- What is the IMF? Is it universal?

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Big problems in galaxy evolution

A subjective choice!

The three little pigs

- What is the star formation history of the Universe and the associated growth of stellar mass?
- How and when were galaxies assembled and what is the origin of the Hubble sequence?
- How was the Universe reionized and what is the connection between the first galaxies and today's galaxies?

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Big questions in galaxy evolution

When and how has a big question been 'answered' ?

When relevant data have been reliably (systematics-free) obtained

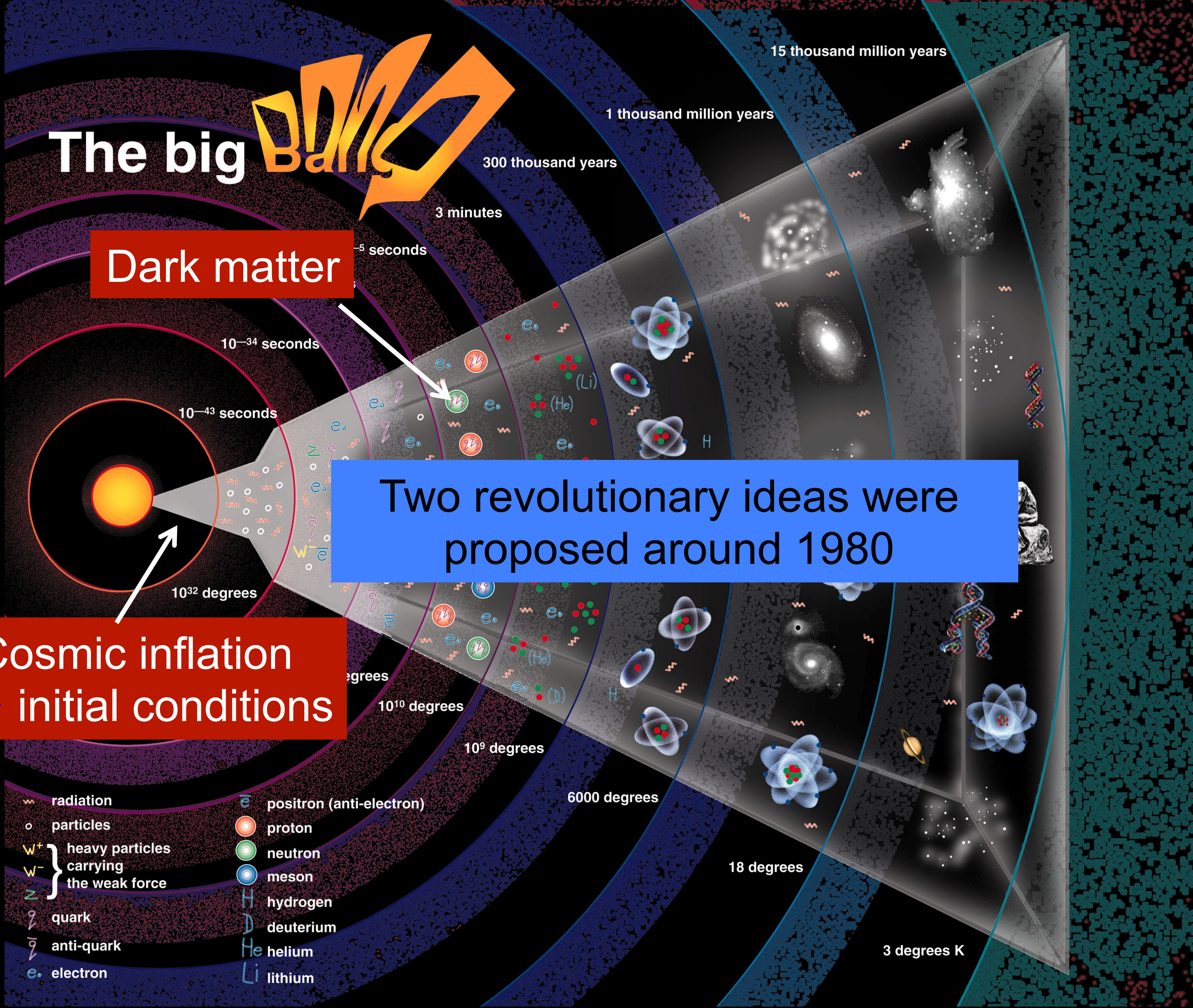
AND

we have a physics-based model that explains the data in a compelling way

Two revolutionary ideas were proposed around 1980

Dark matter

Cosmic inflation → initial conditions



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What do we think we know about galaxy formation and evolution?

- The initial conditions
- Main growth mechanism
- The evolution and distribution of dark matter
- A list of the main processes likely to be important

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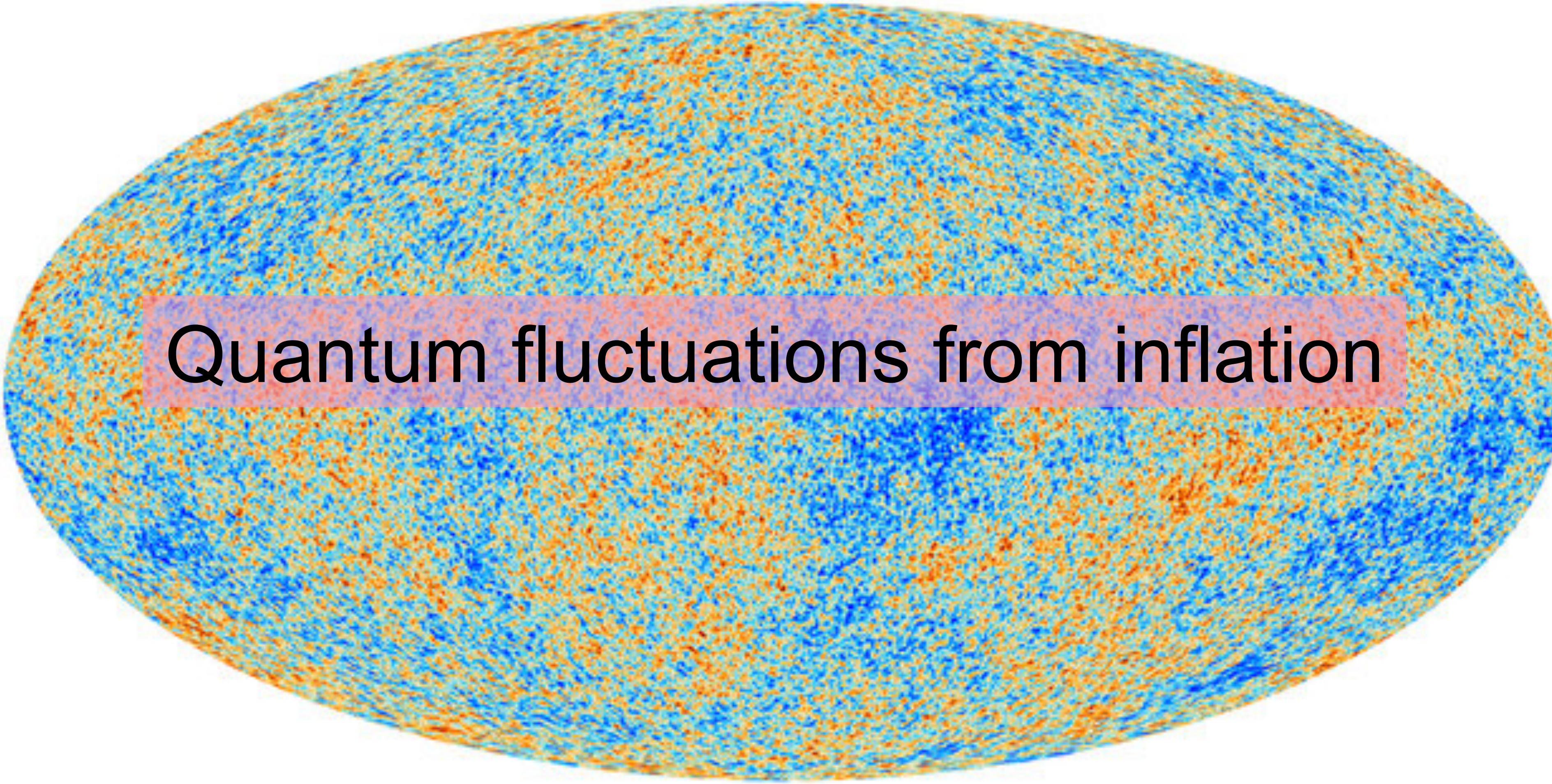
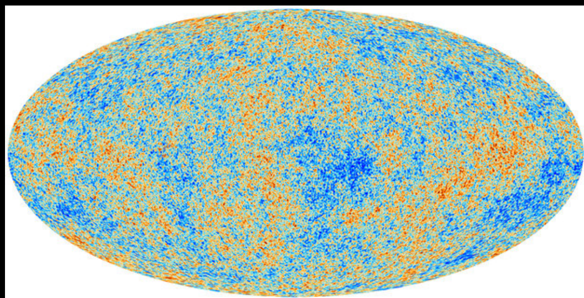
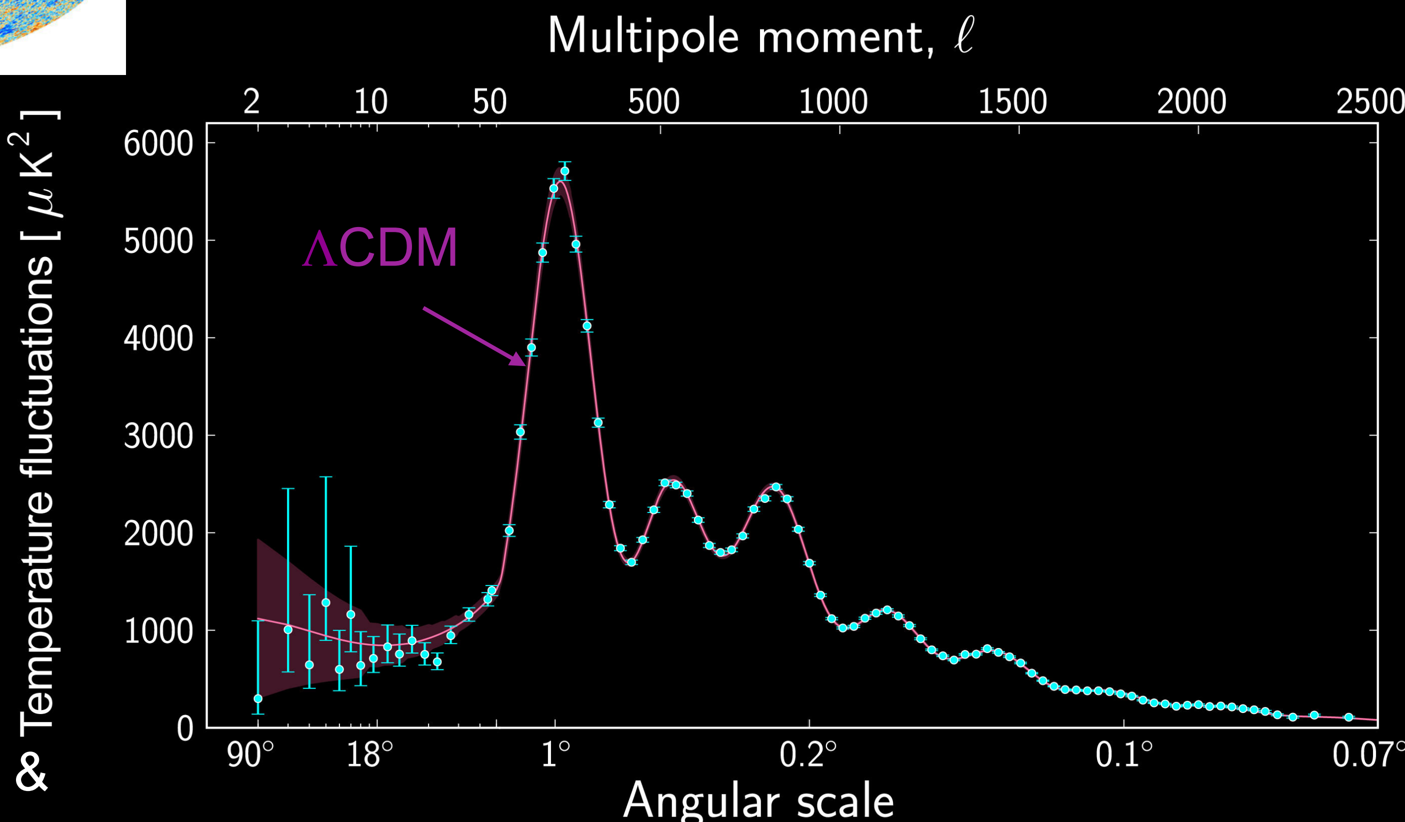
The initial conditions for galaxy formation



Planck temp anisotropies in CMB



Amplitude of fluctuations at z~ 1000



The data confirm the theoretical predictions (linear theory)

Peebles '82; Bond & Efstathiou '80s

Planck collaboration '13

Univer

The six parameters of minimal ΛCDM model

Parameter	Planck+WP Best fit	Planck+WP 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

A 40σ detection of non-baryonic dark matter using only z=1000 data!

Planck collaboration ‘13

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Growth mechanism

Primordial fluctuations grow by gravitational instability driven by dark matter

The formation of cosmic structure

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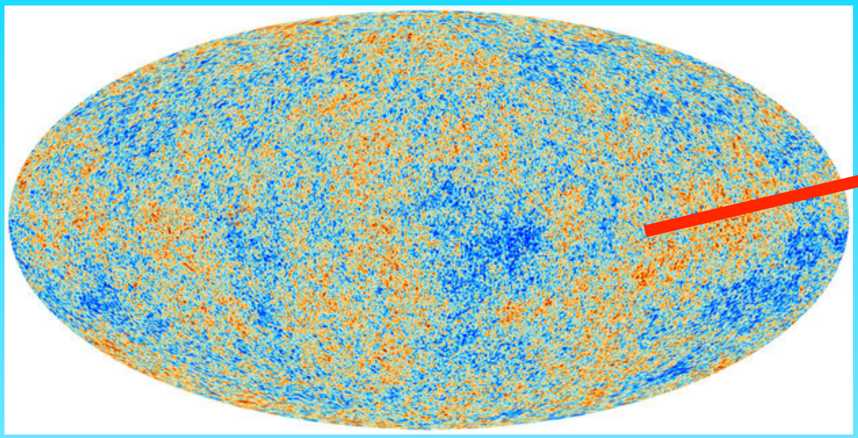
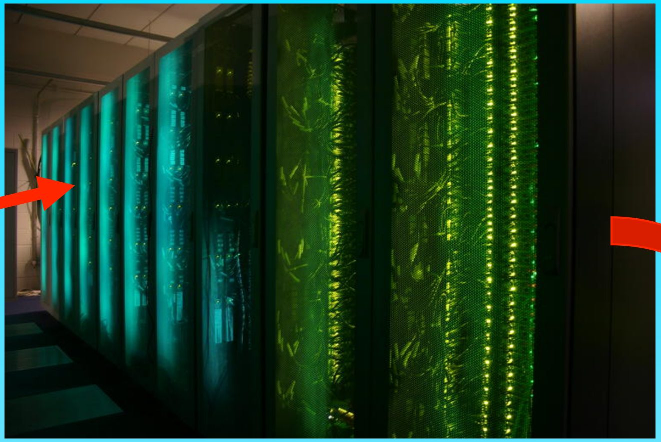
“Cosmology machine”

t=380,000 yrs $\delta\rho/\rho \sim 10^{-5}$





Simulations

Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today

t=13.8 billion yrs

$\delta\rho/\rho \sim 1-10^{6}$

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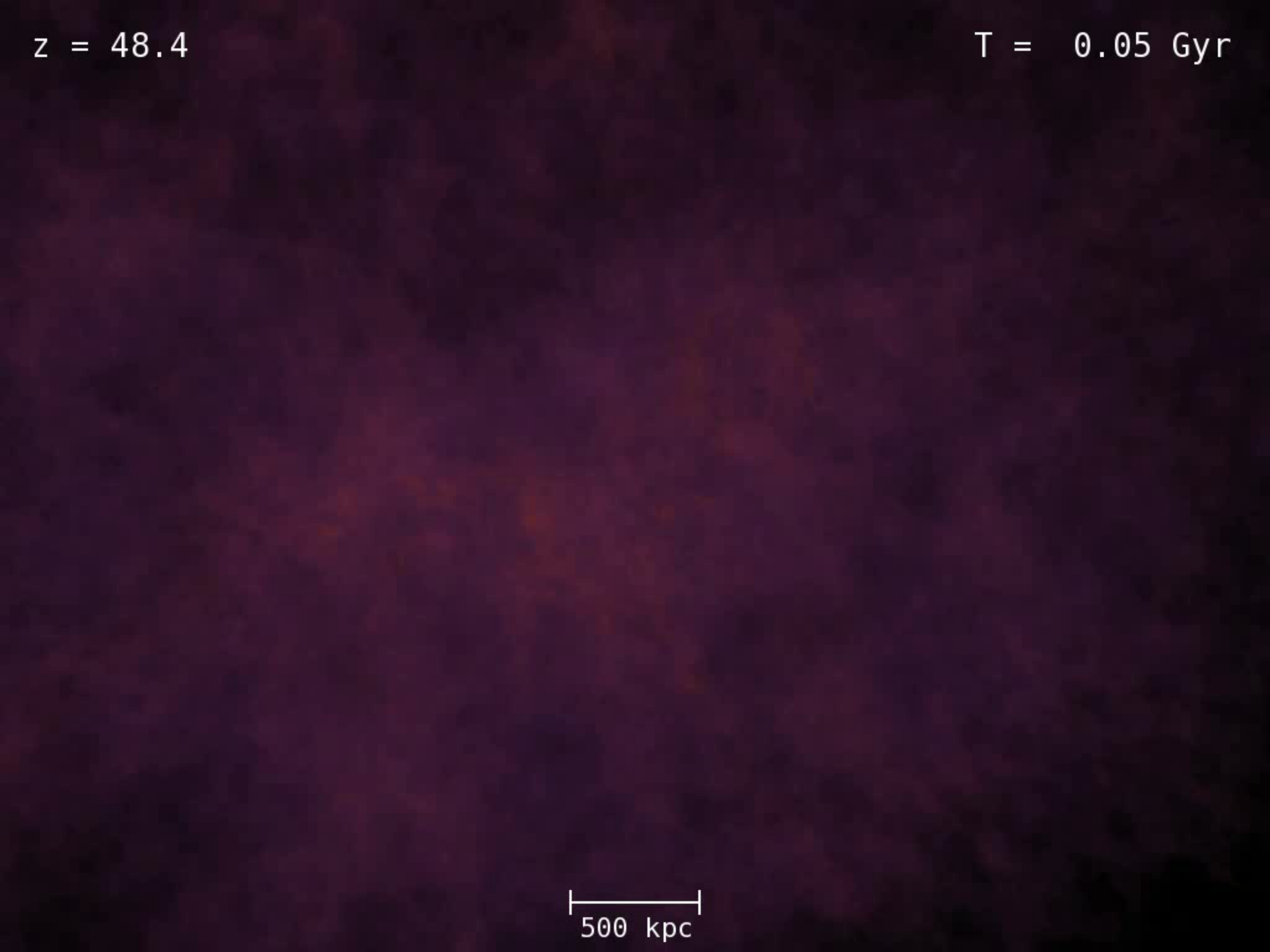
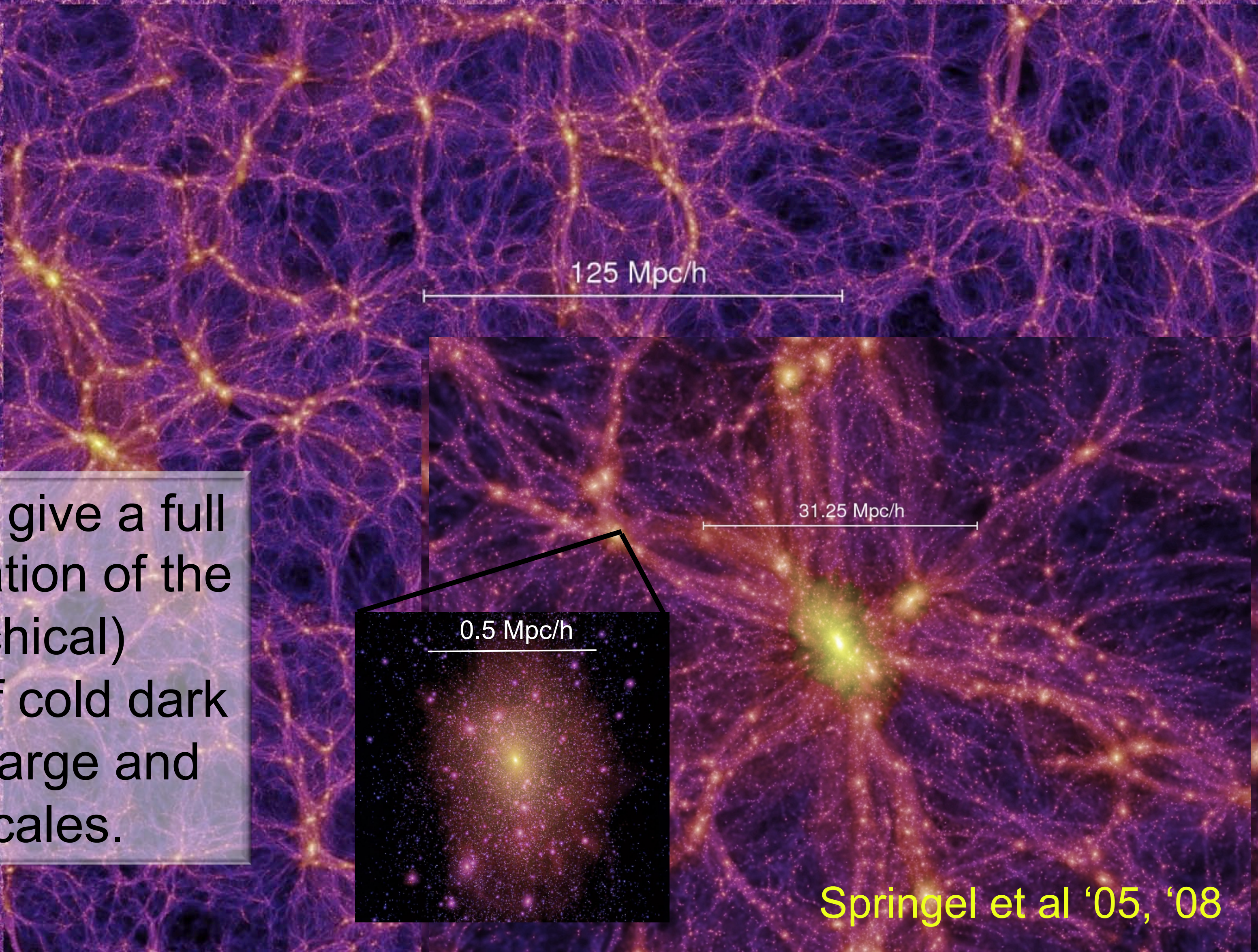

z = 48.4
T = 0.05 Gyr
500 kpc

Dark matter

The internal structure of halos and the large-scale distribution of cold dark matter are known

VIRGO

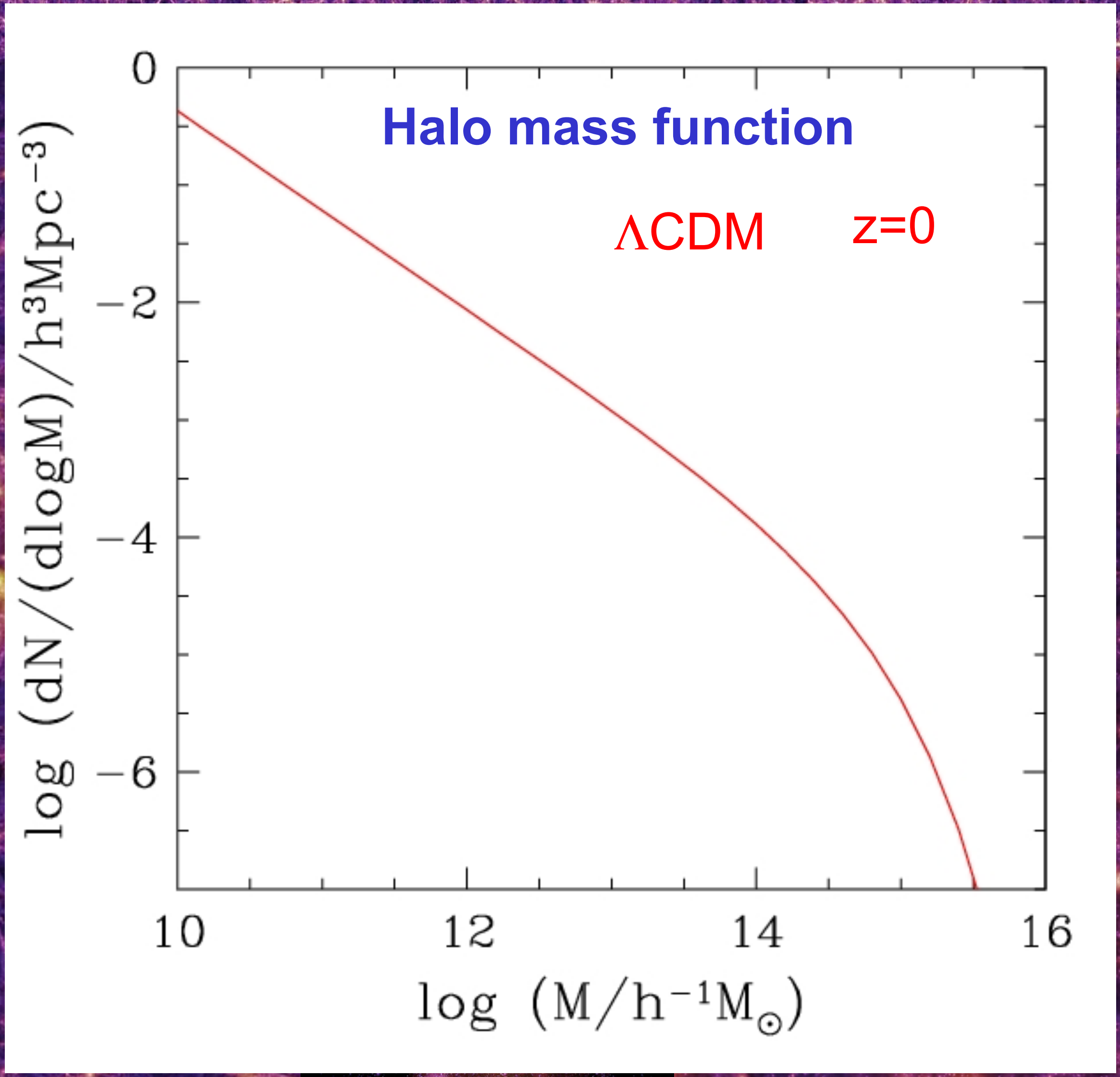
The Millennium/Aquarius simulation series



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

Springel et al ‘05, ‘08

The Millennium/Aquarius simulation series

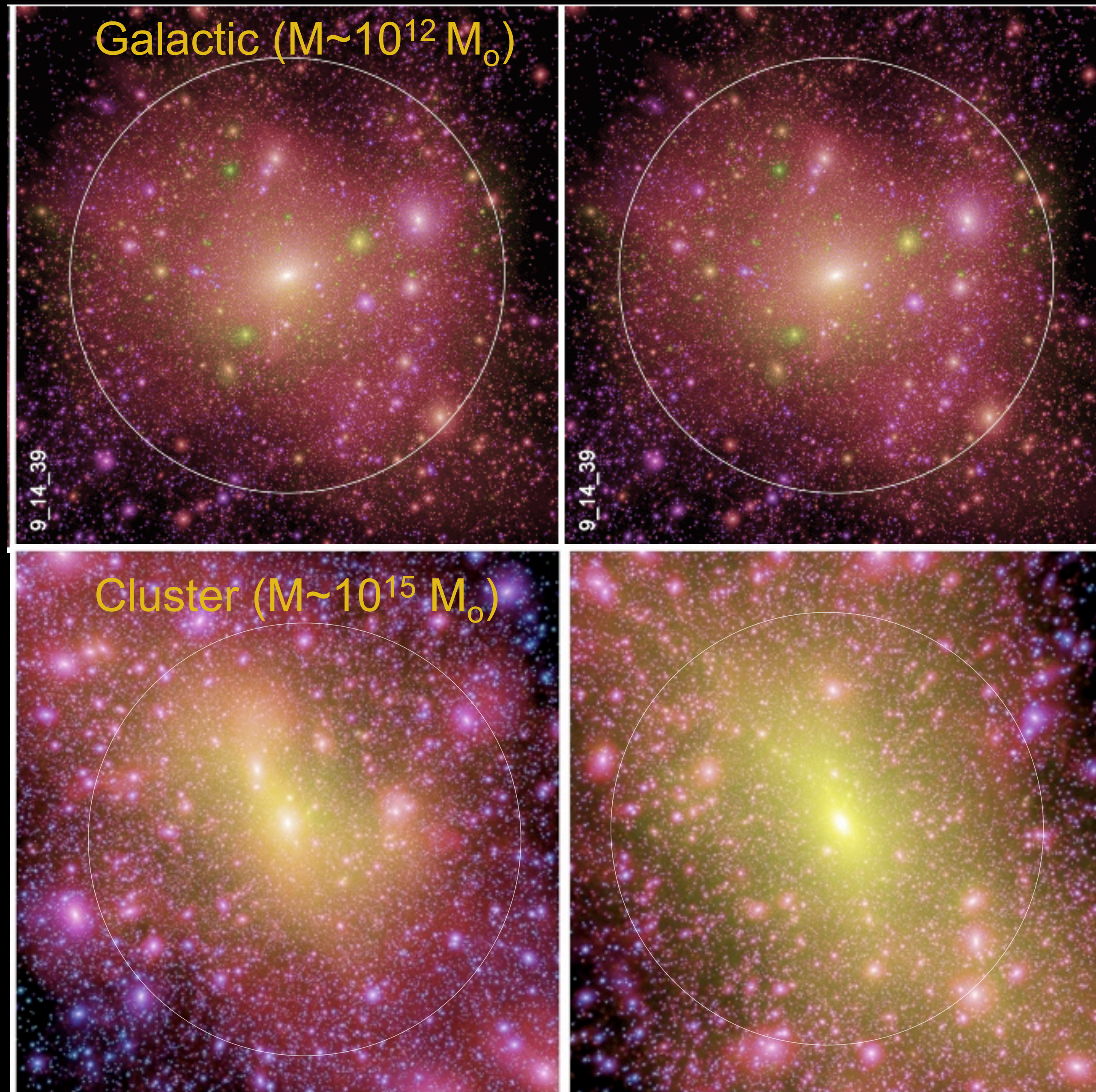


Springel et al '05, '08

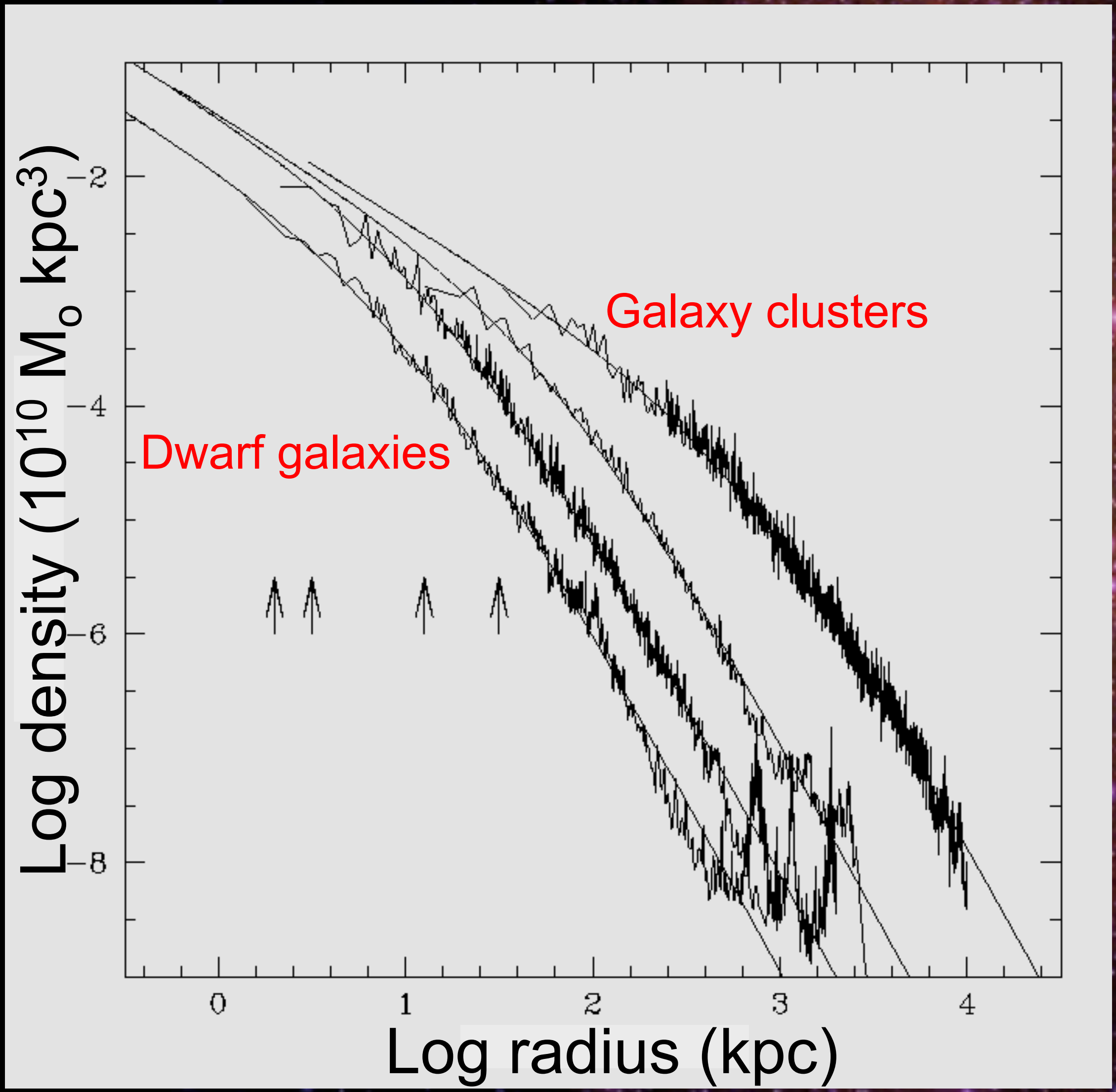
Aquarius (galactic) & Phoenix (cluster) halos

Self-similarity of CDM halos

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



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:

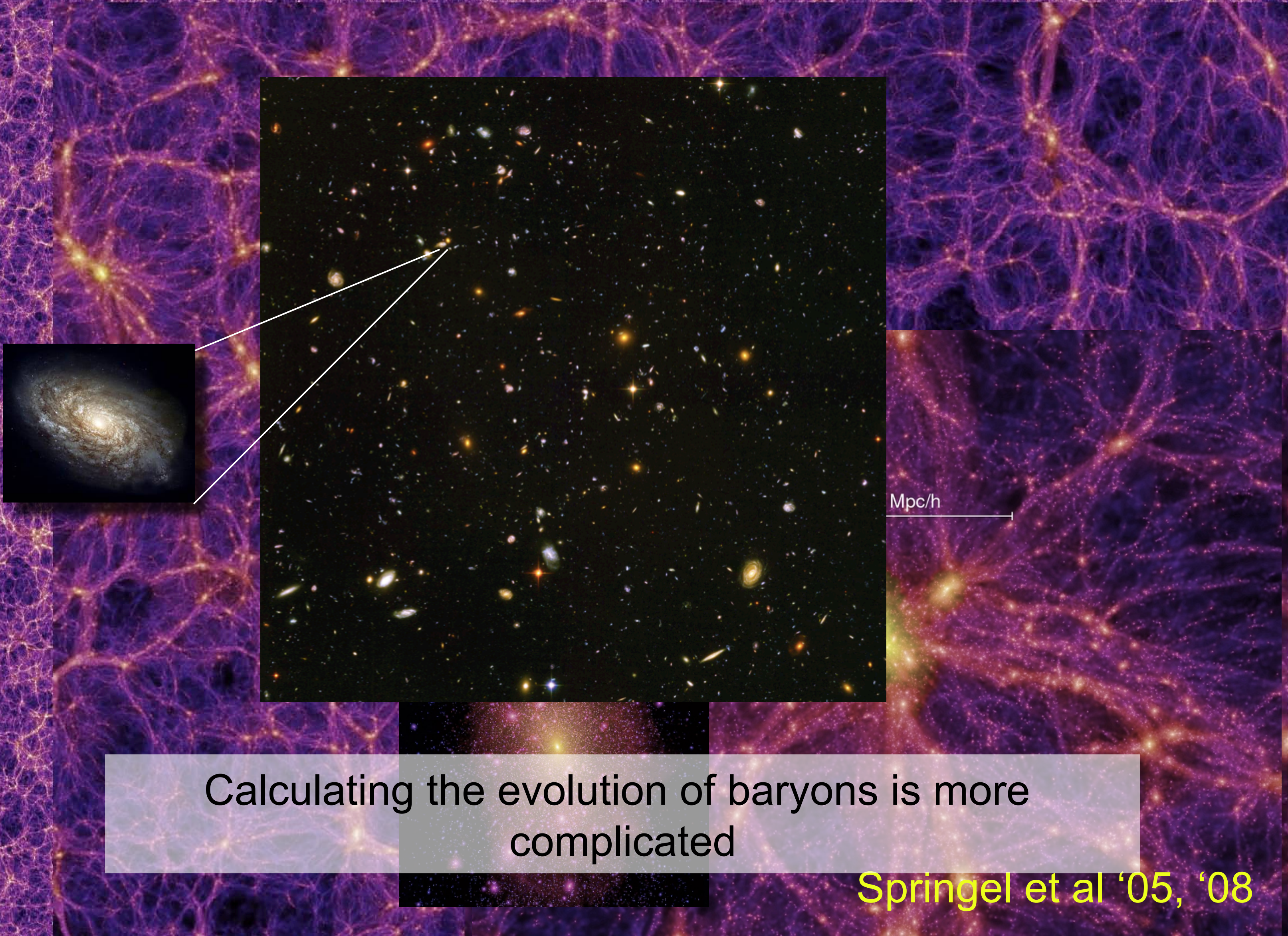
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White '97)

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

The Millennium/Aquarius simulation series

The (relatively) “easy” part of the problem



Calculating the evolution of baryons is more complicated

Springel et al ‘05, ‘08

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The main processes likely to be important in galaxy formation

- The 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 energy due to stellar evolution and SN
  - Formation of supermassive black holes and AGN feedback
  - Tidal and ram pressure stripping of gas
  - Tidal stripping and mergers of galaxies as their halos merge
  - Disk instabilities, secular evolution

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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

"Sub-grid physics"

+ Gas dynamics in full generality

- Limited dynamic range

- Expensive: cannot explore range of sub-grid models

Phenomenological model

- Approximate gas dynamics

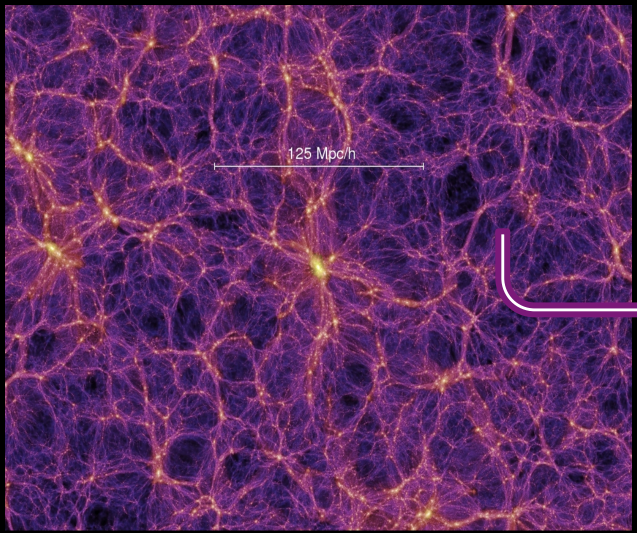
+ Unlimited dynamic range

+ Can easily explore different sub-grid models

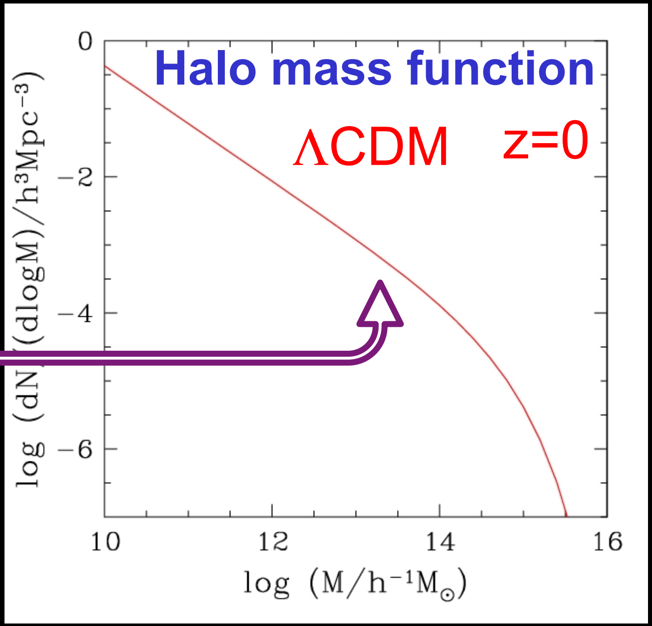
The goals of gal. population models

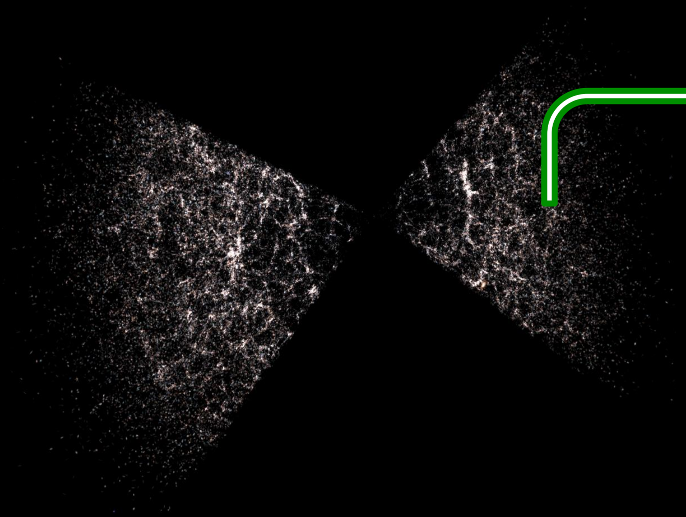
- Explore the statistics and interaction of the many processes affecting stars and gas within growing CDM structures
- Understand how the effects of these processes are reflected in the various observed population properties of galaxies and their evolution -- abundances, scaling relations, clustering
- 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 ΛCDM initial conditions

Abundance of gals & dark halos

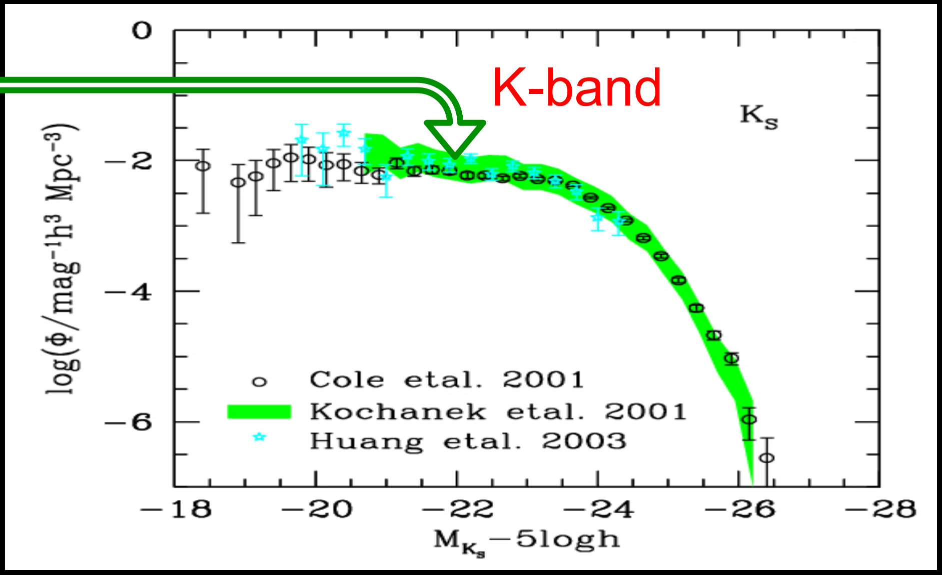


Millennium run





2dFGRS



The galaxy luminosity function

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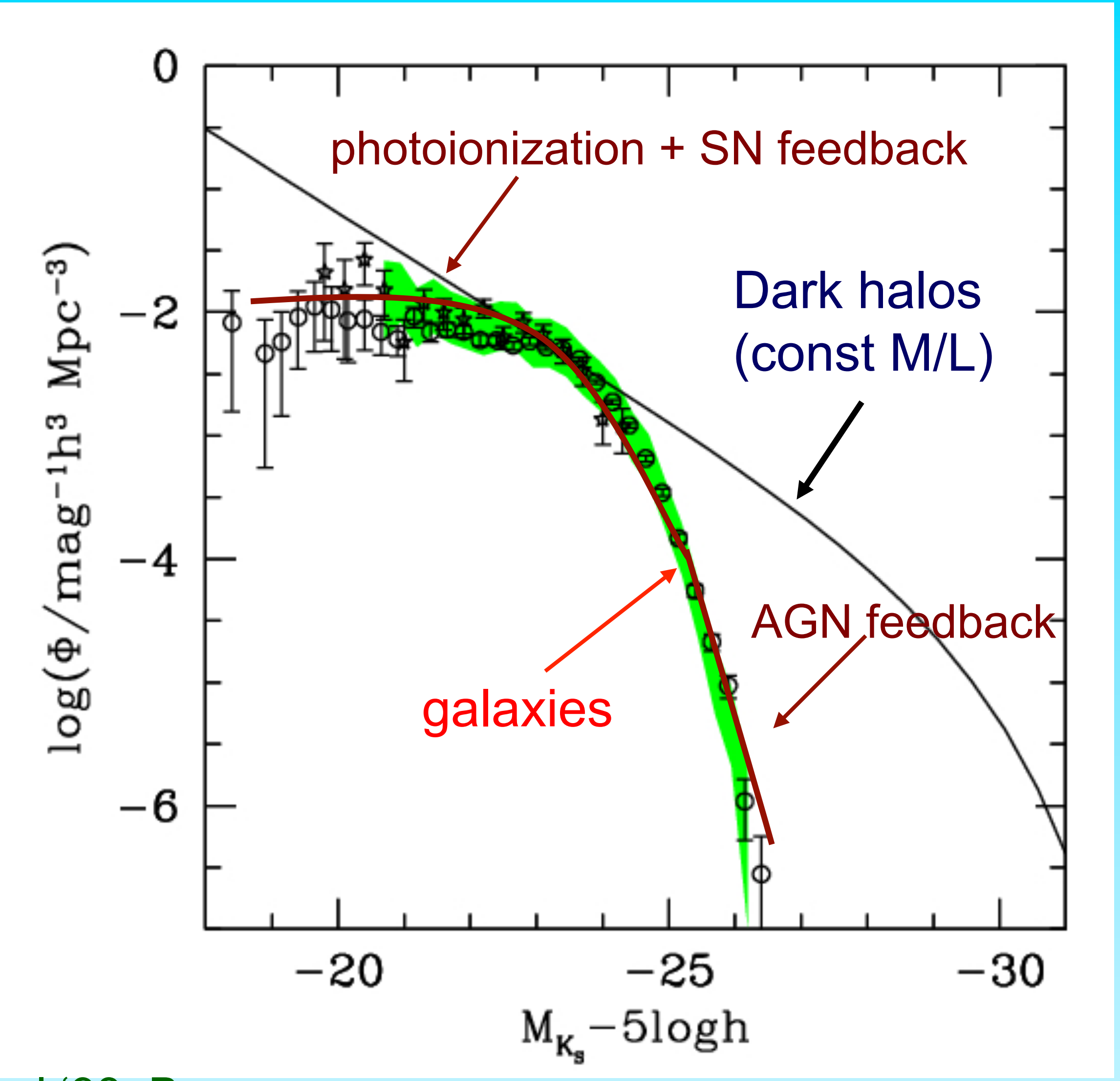
The halo mass function and the galaxy luminosity function have different shapes

⇨

Galaxy luminosity not just ∝ halo mass

Complicated variation of M/L with halo mass



White & Frenk ‘91; Kauffmann et al ‘93; Benson et al ’03; Croton et al ‘05; Bower et al. ’06

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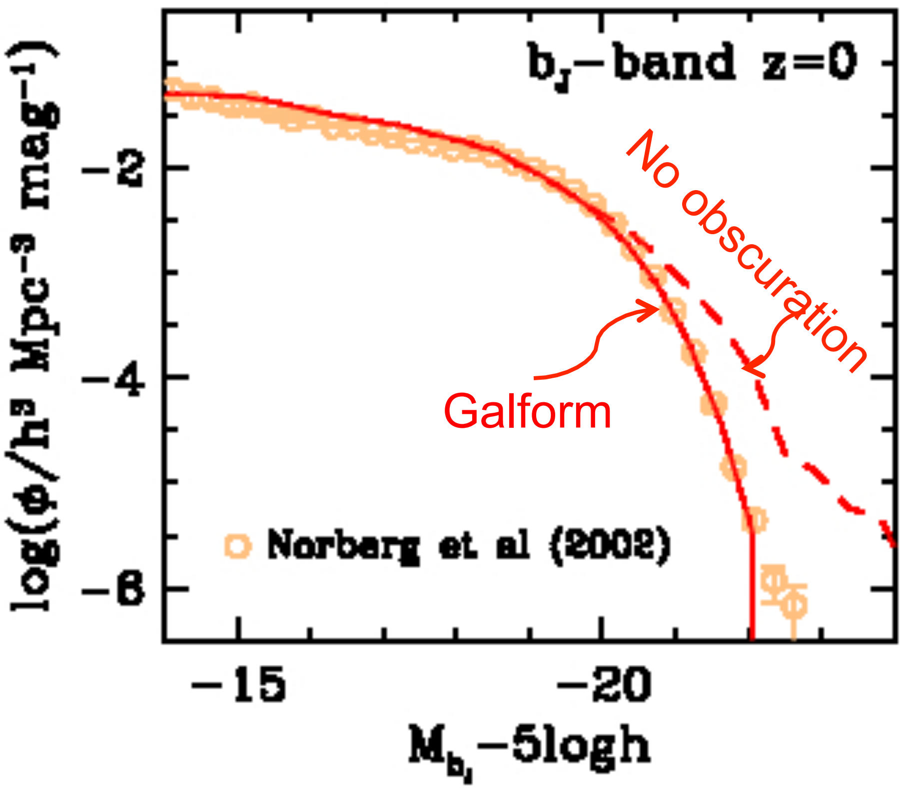
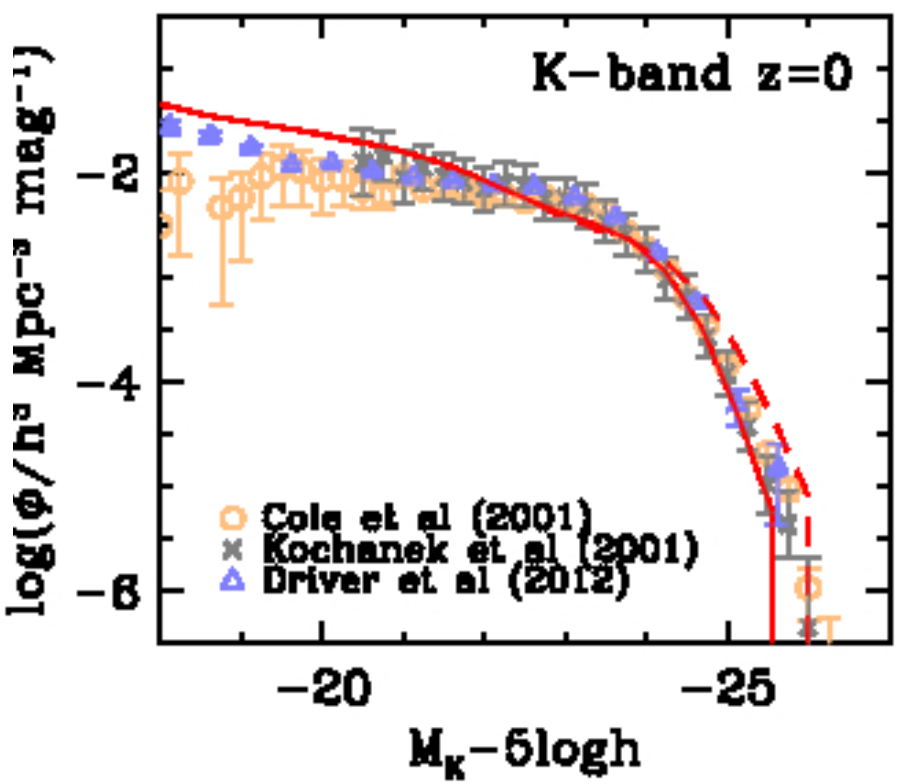
The galaxy luminosity function

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





Lacey et al. '14

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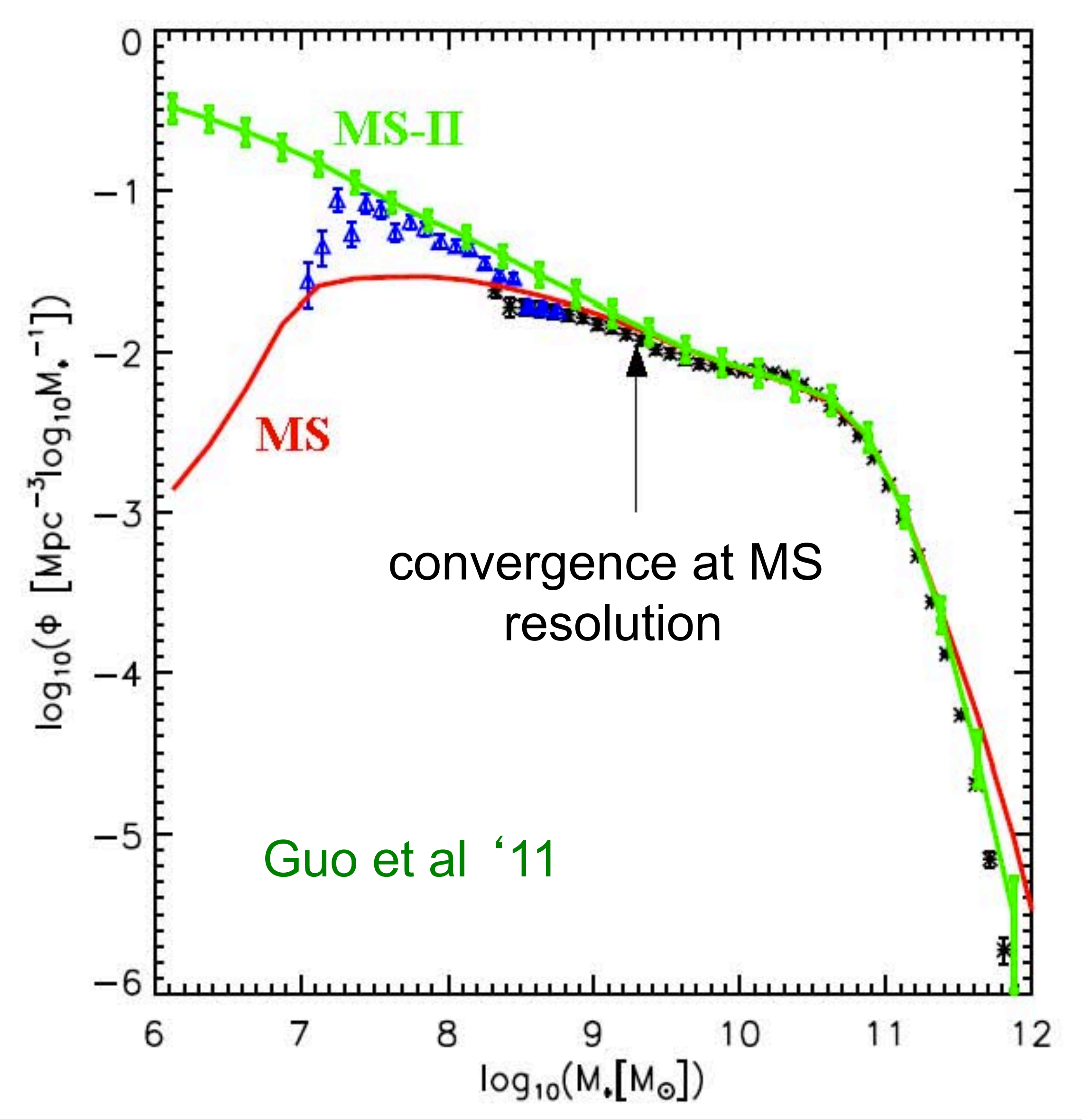
The stellar mass function

Results for MS and M-II converge

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

Guo et al. ‘11



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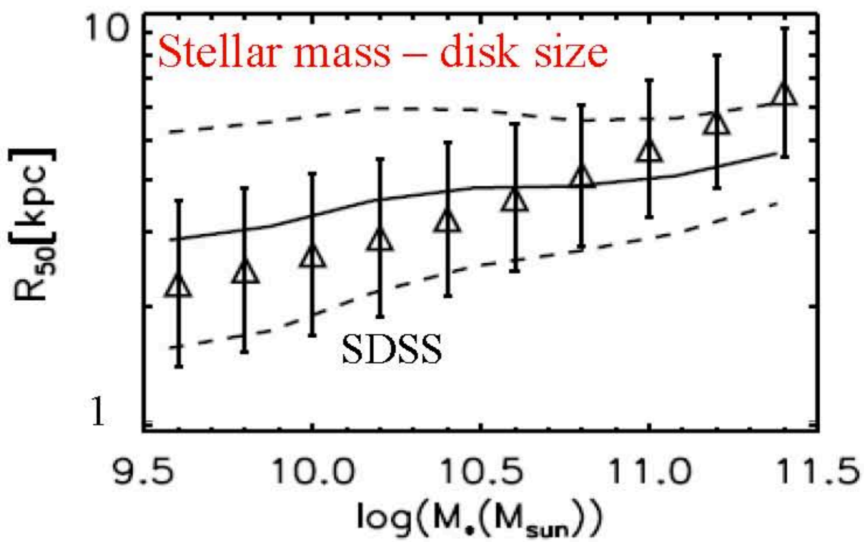
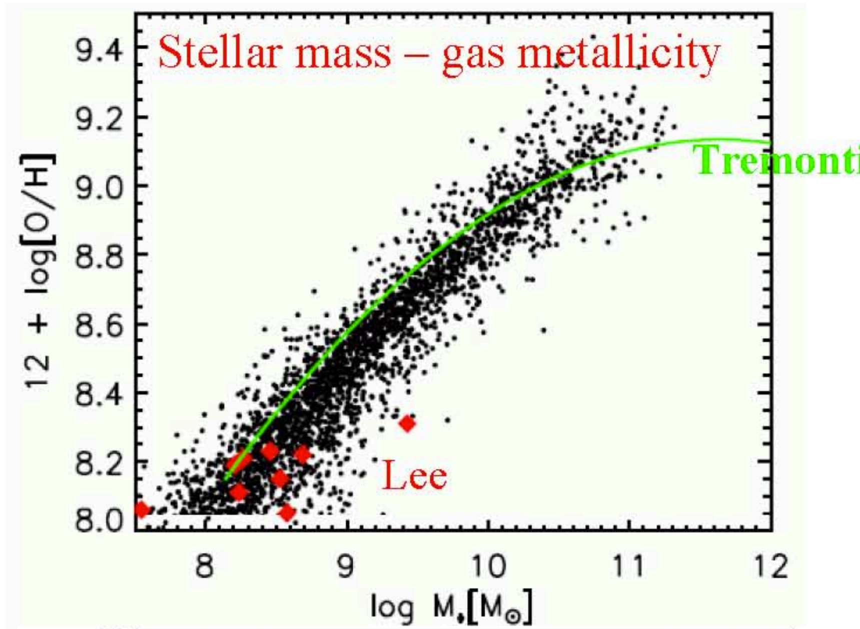
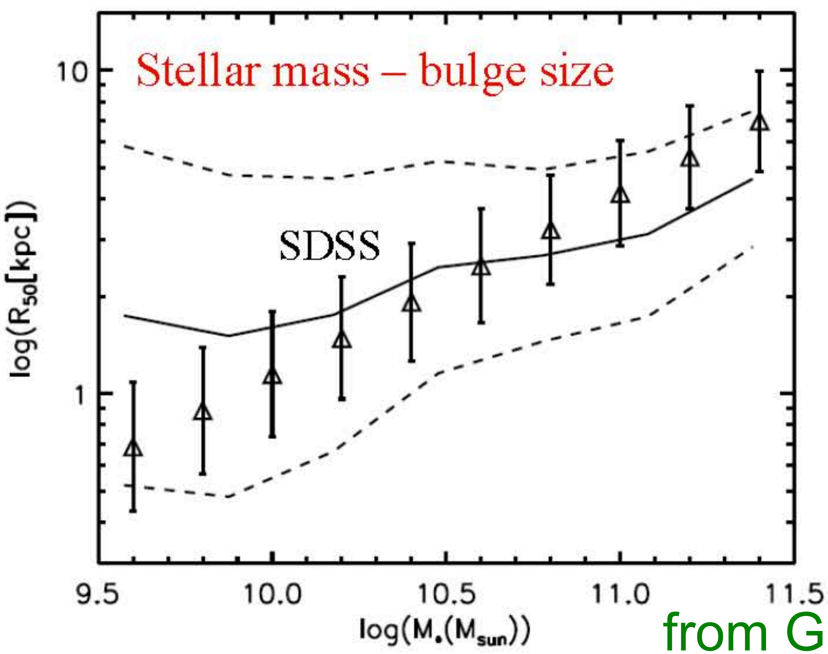
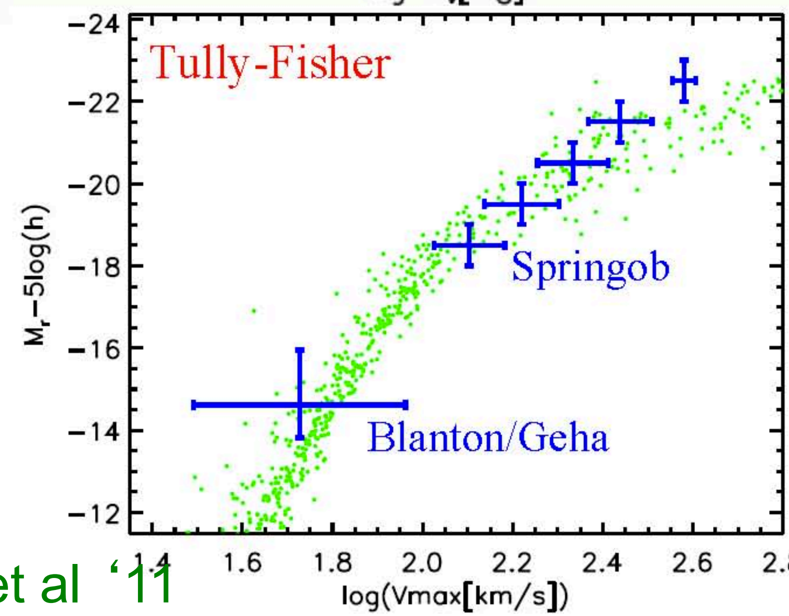
Basic galaxy properties









from Guo et al '11

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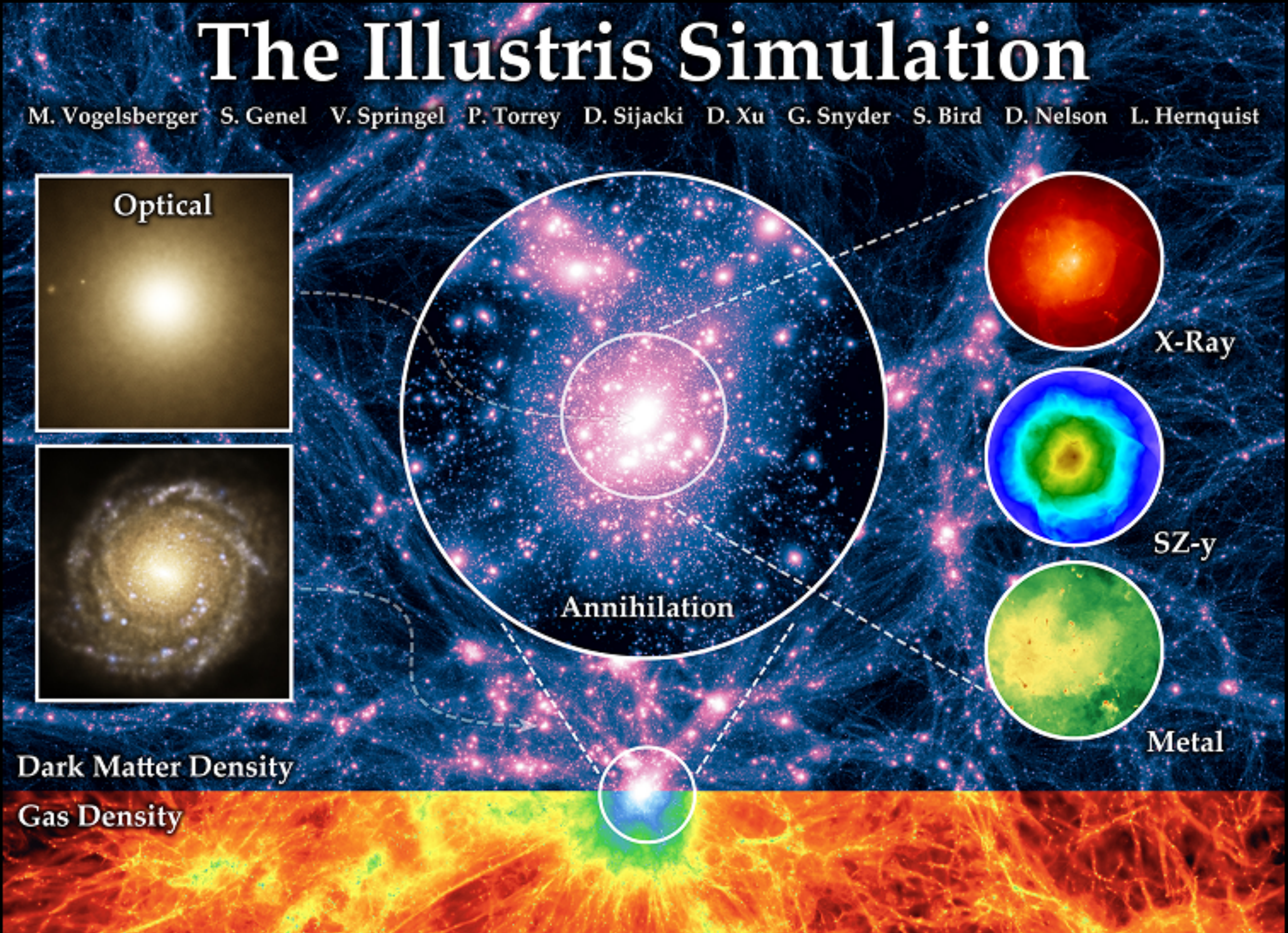
Gas simulations of galaxy populations

- New generation of gasdynamic simulations of cosmologically representative volumes (~100 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


The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
Annihilation
X-Ray
SZ-y
Metal
Dark Matter Density
Gas Density

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: Rob Crain, Joop Schaye.

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

+ Virgo Consortium

NAM 2014

Sub-grid schemes in EAGLE

(what's different about EAGLE?)

Star formation

$$\tau_* \propto P^{n_{KS}}$$

ISM turbulence

$$P_{ISM} \propto \rho^{\gamma}$$

Supernova feedback

$$p_{heat} = \frac{E_{SN}}{kT_{heat}} f(Z,\rho)$$

Metal enrichment and stellar mass loss

AGN accretion

$$\dot{m}_{BH} = \max\left(f(\rho, v_{\phi}), \dot{m}_{Edd}\right)$$

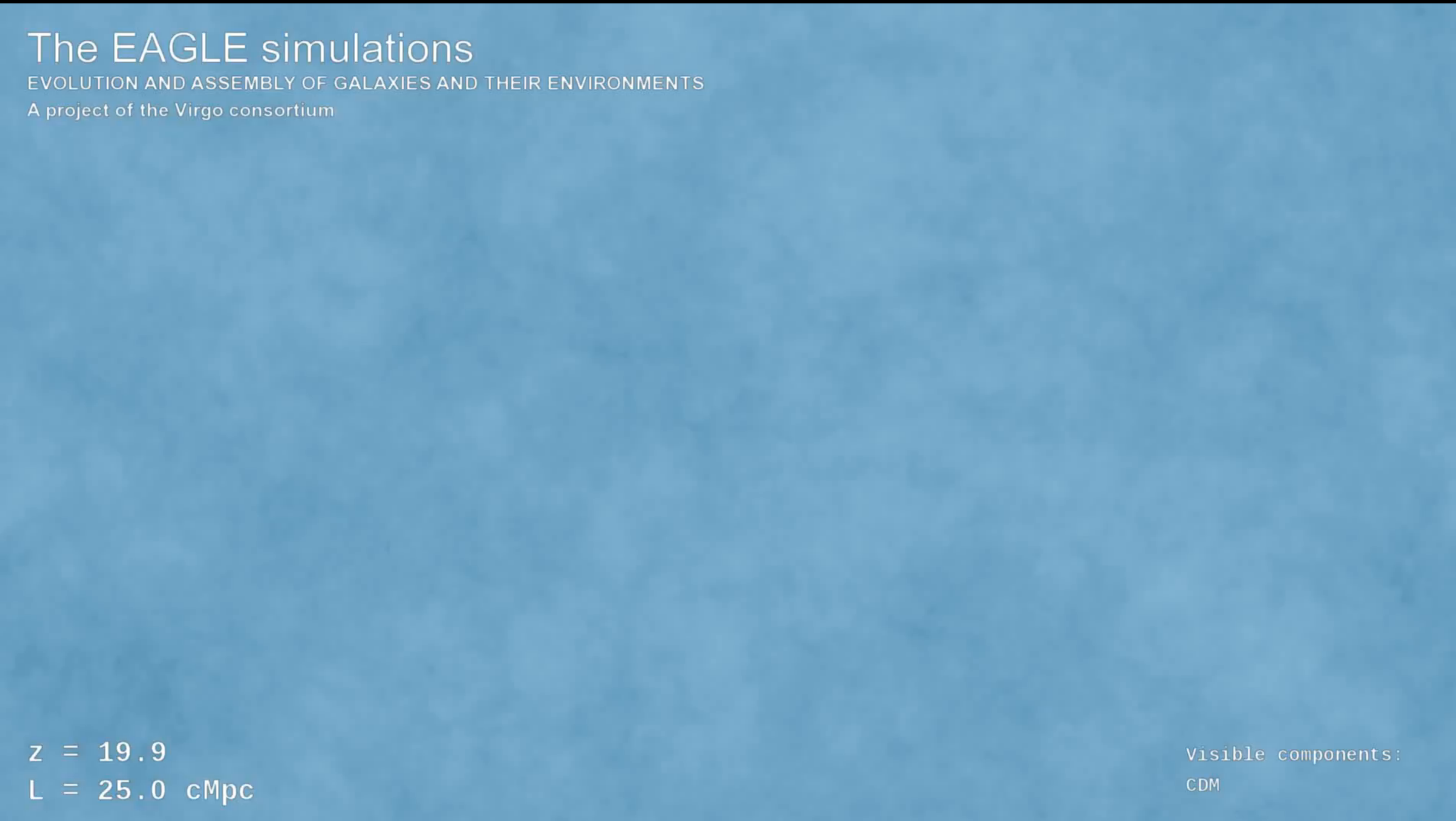
AGN feedback

$$p_{heat} = \frac{0.01\dot{m}c^2}{kT_{heat}}$$

Cooling and photo-ionisation

Subgrid physics with fully coupled hydrodynamics

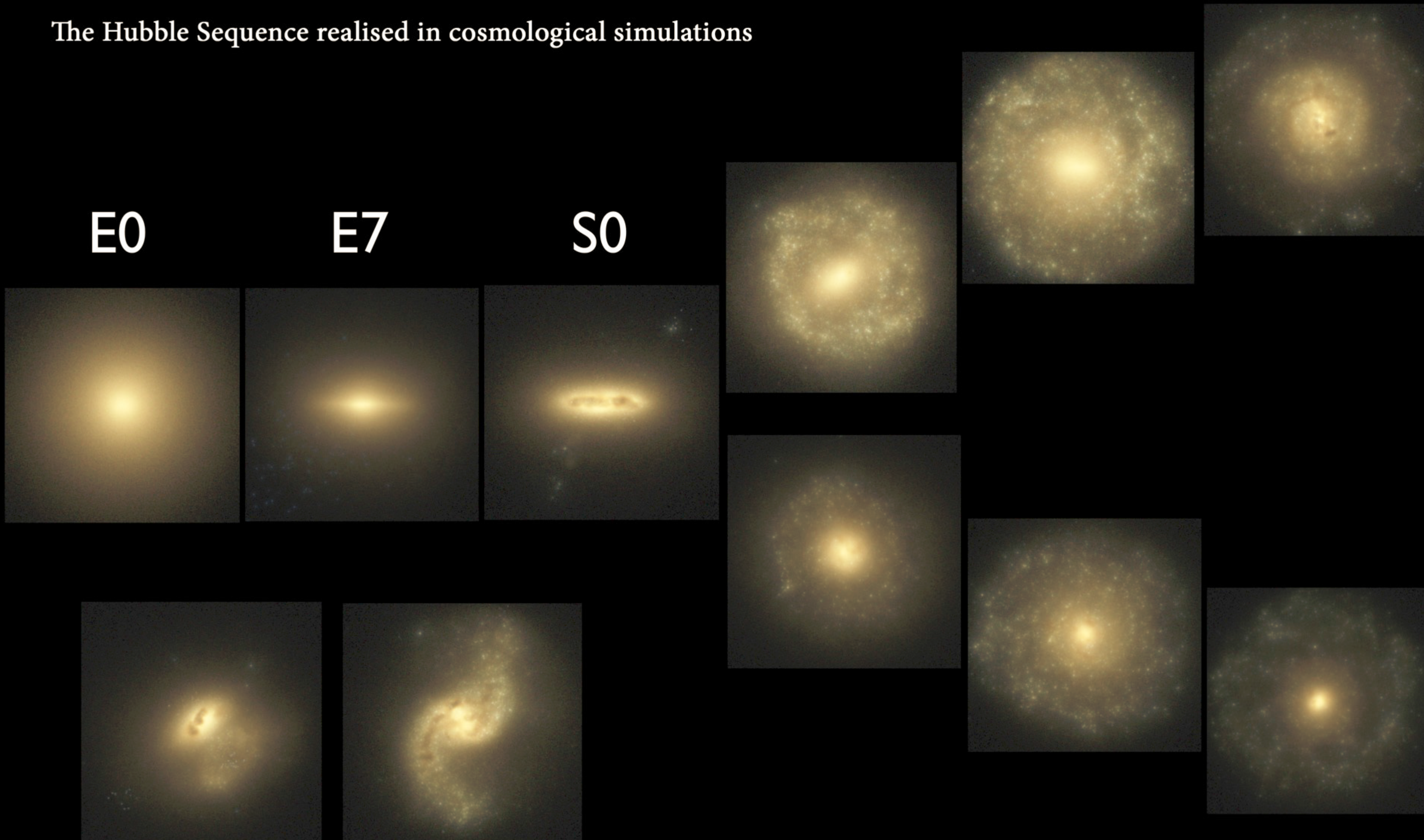
Dalla Vecchia & Schaye 2009, 2012; Roasas-Guevara et al 2014


The EAGLE simulations
EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS
A project of the Virgo consortium
z = 19.9
L = 25.0 cMpc
Visible components:
CDM

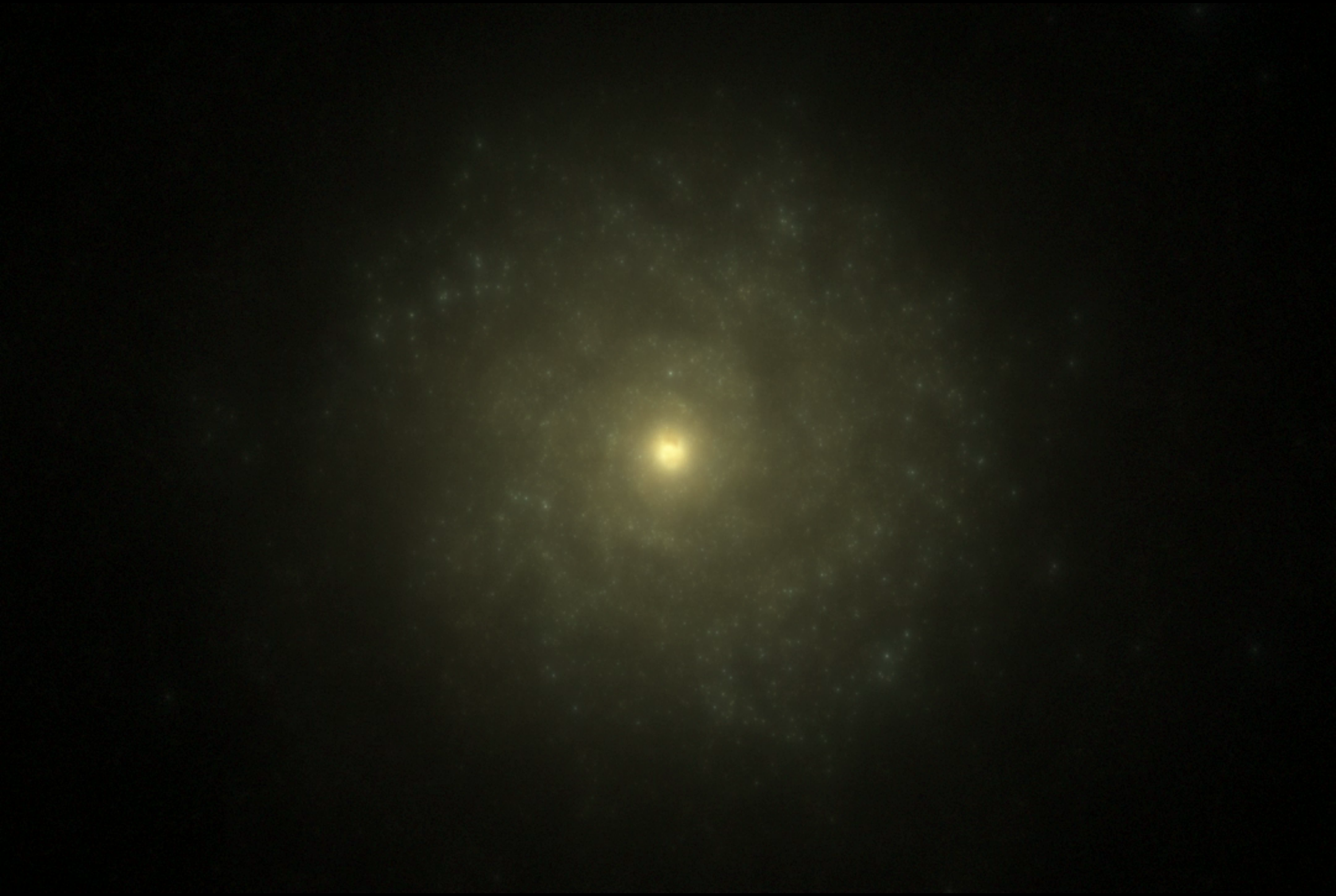
The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



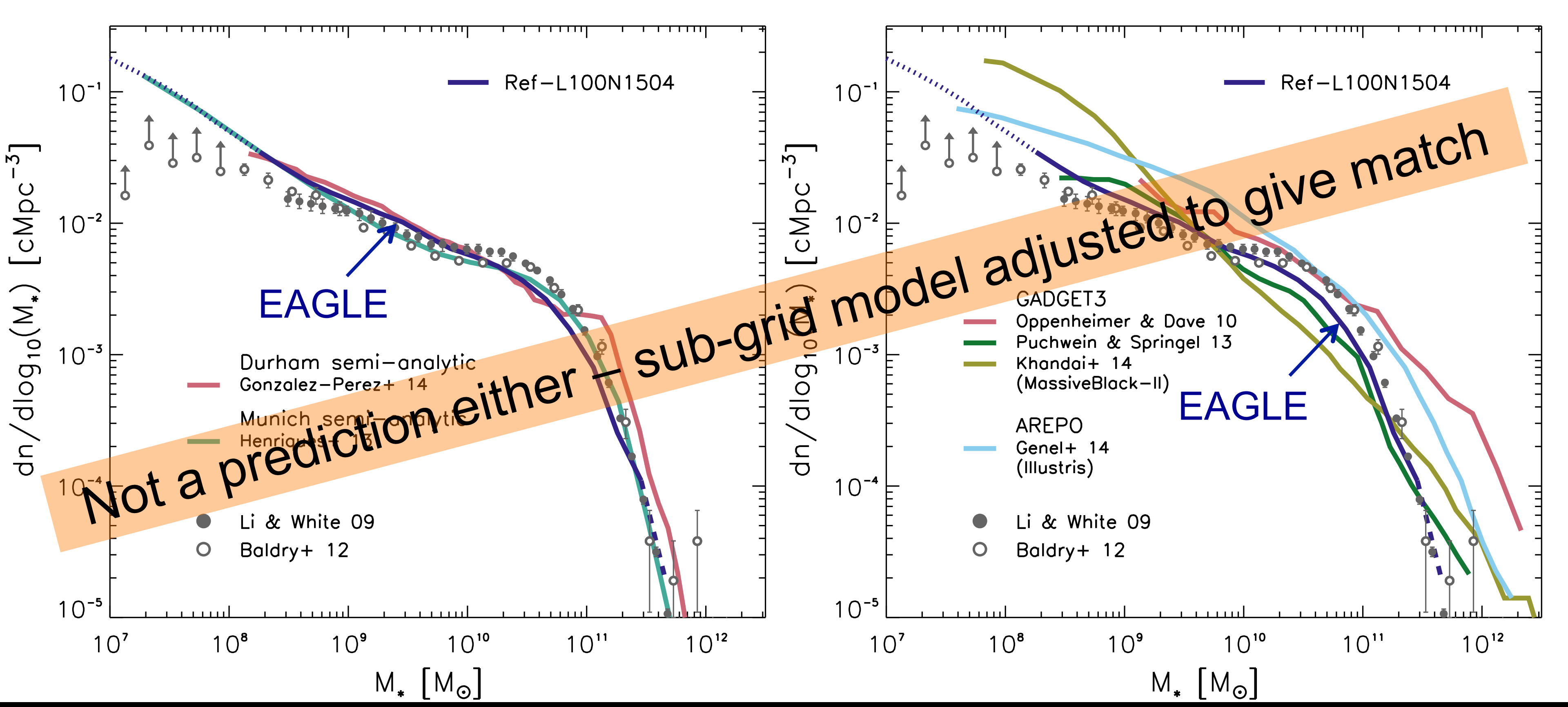
Trayford et al '14



Galaxy stellar mass function

Comparison to semi-analytic models

Comparison to other Hydro simulations



Big question 1

What is the star formation history of the Universe and the associated growth of stellar mass ?

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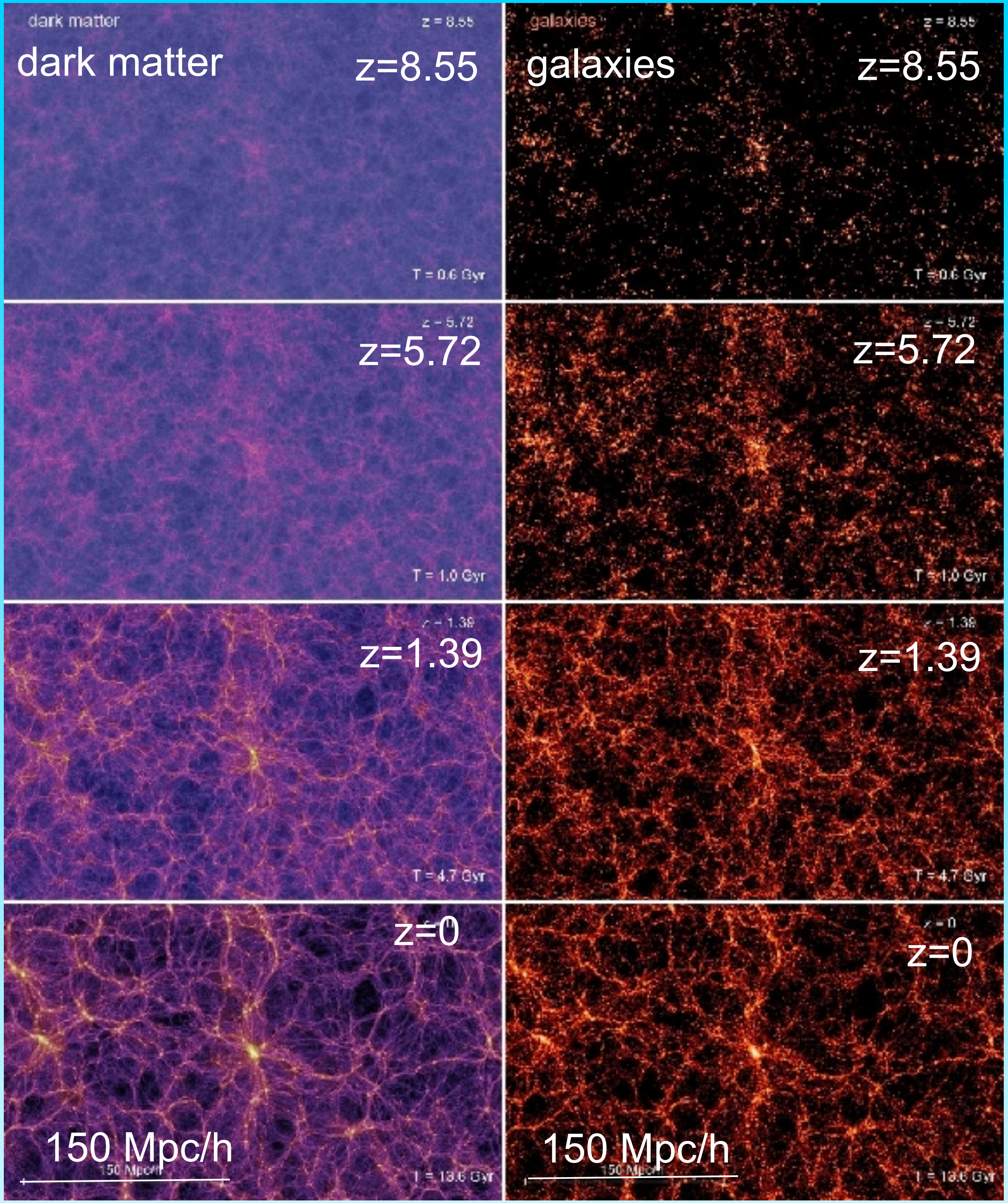
Millennium Simulation

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.

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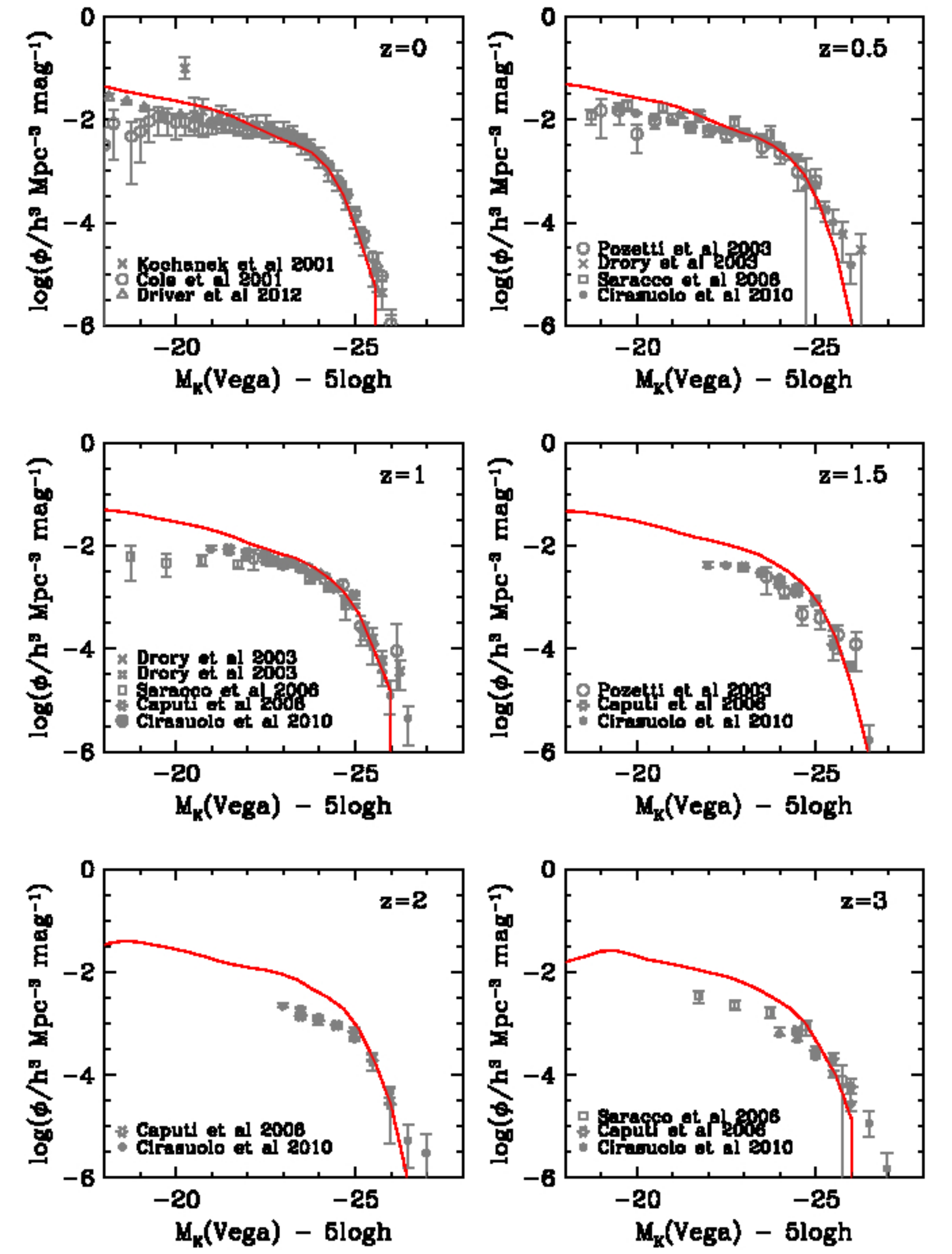
GALFORM

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



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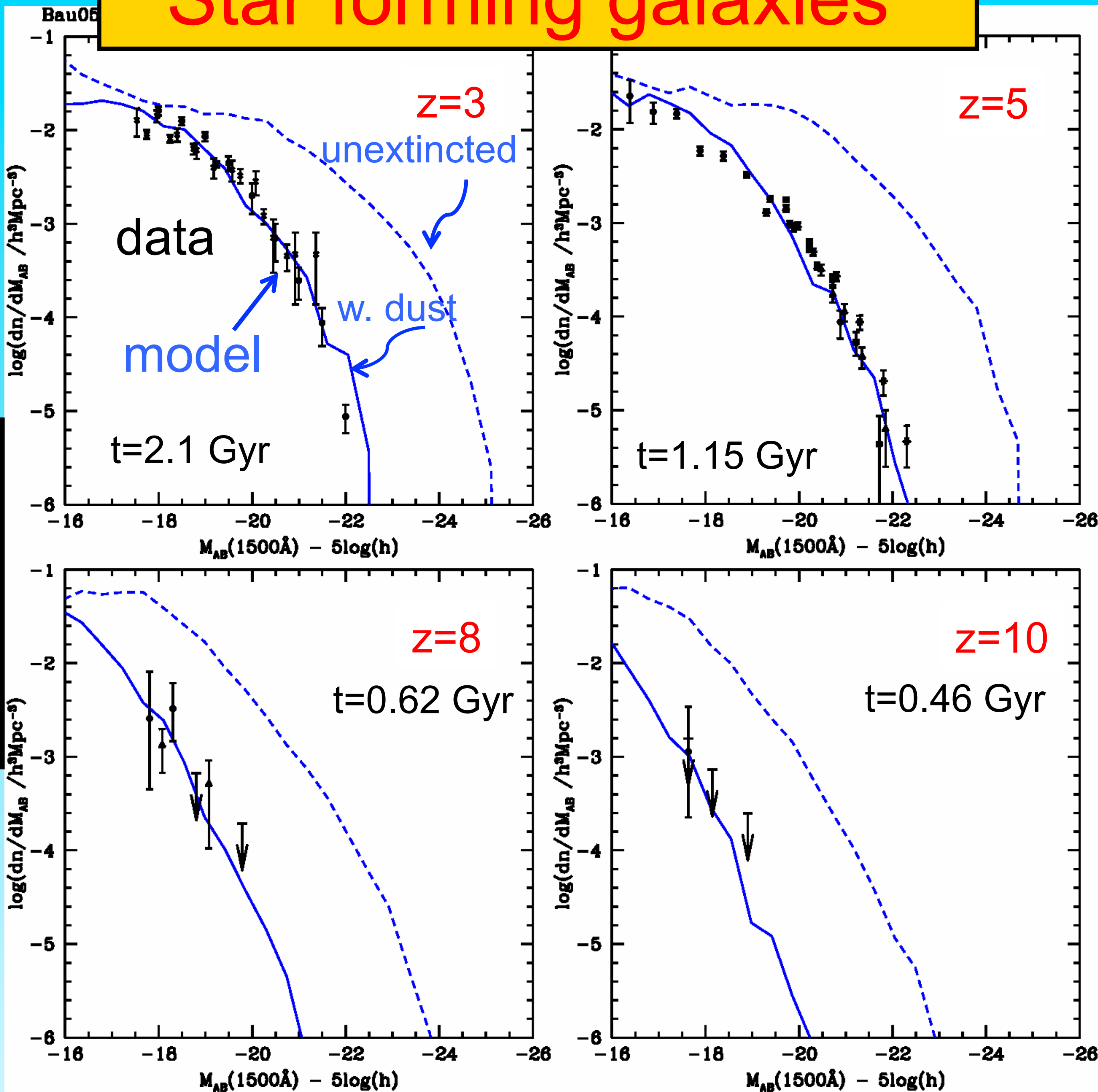
Star forming galaxies

GALFORM

Evolution of Lyman-break galaxy lum. function



Lacey, Baugh, Frenk, Benson ‘12

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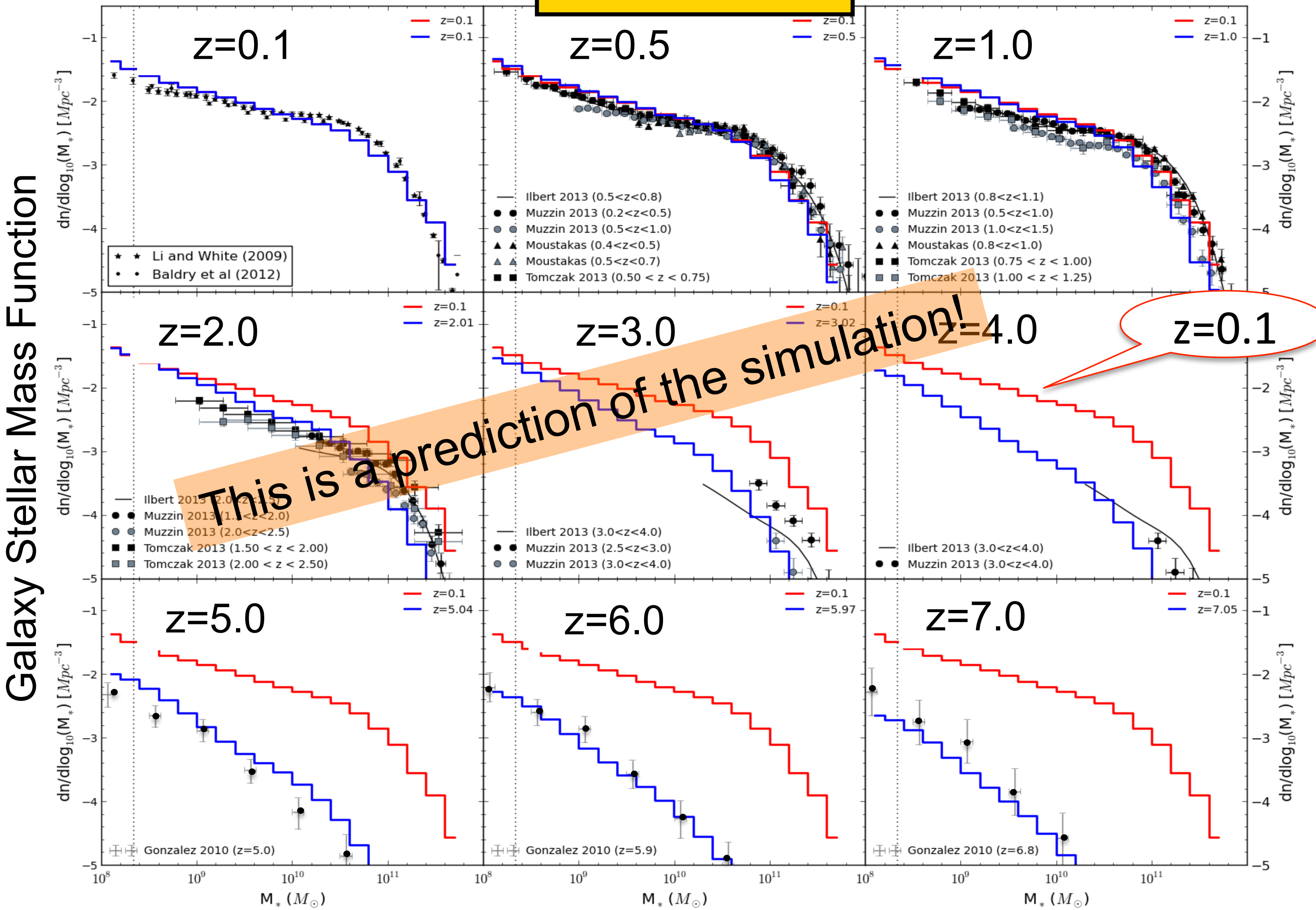
Evolution of the stellar mass fn.

EAGLE



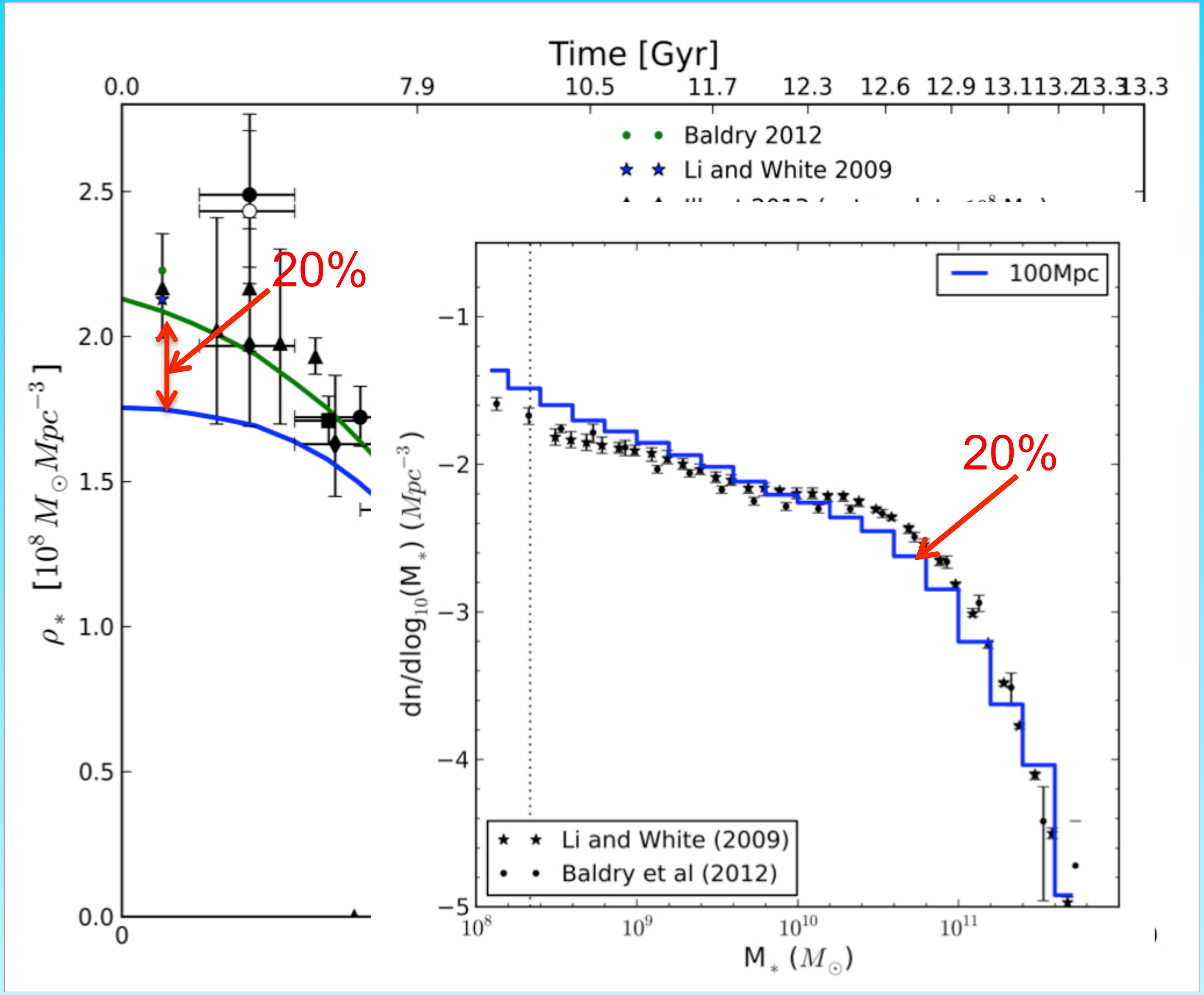
Evolution of stellar mass density

University of Durham

EAGLE

Stellar mass density formed by z

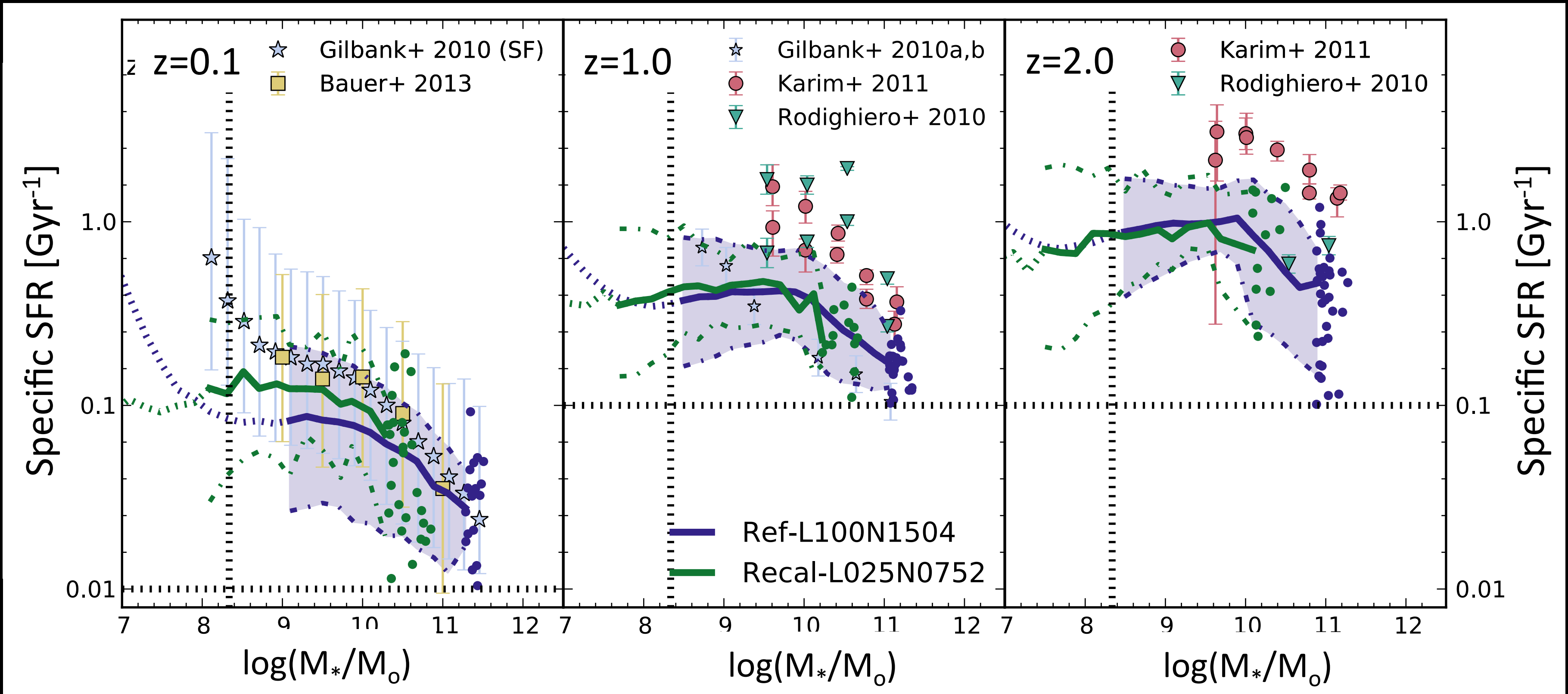
The model agrees with the data within 20%



Furlong et al. '15

Galaxy Formation in the Eagle Universe

- Specific star formation rates



Furlong et al. arXiv:1410.3485

Evolution of the SFR density

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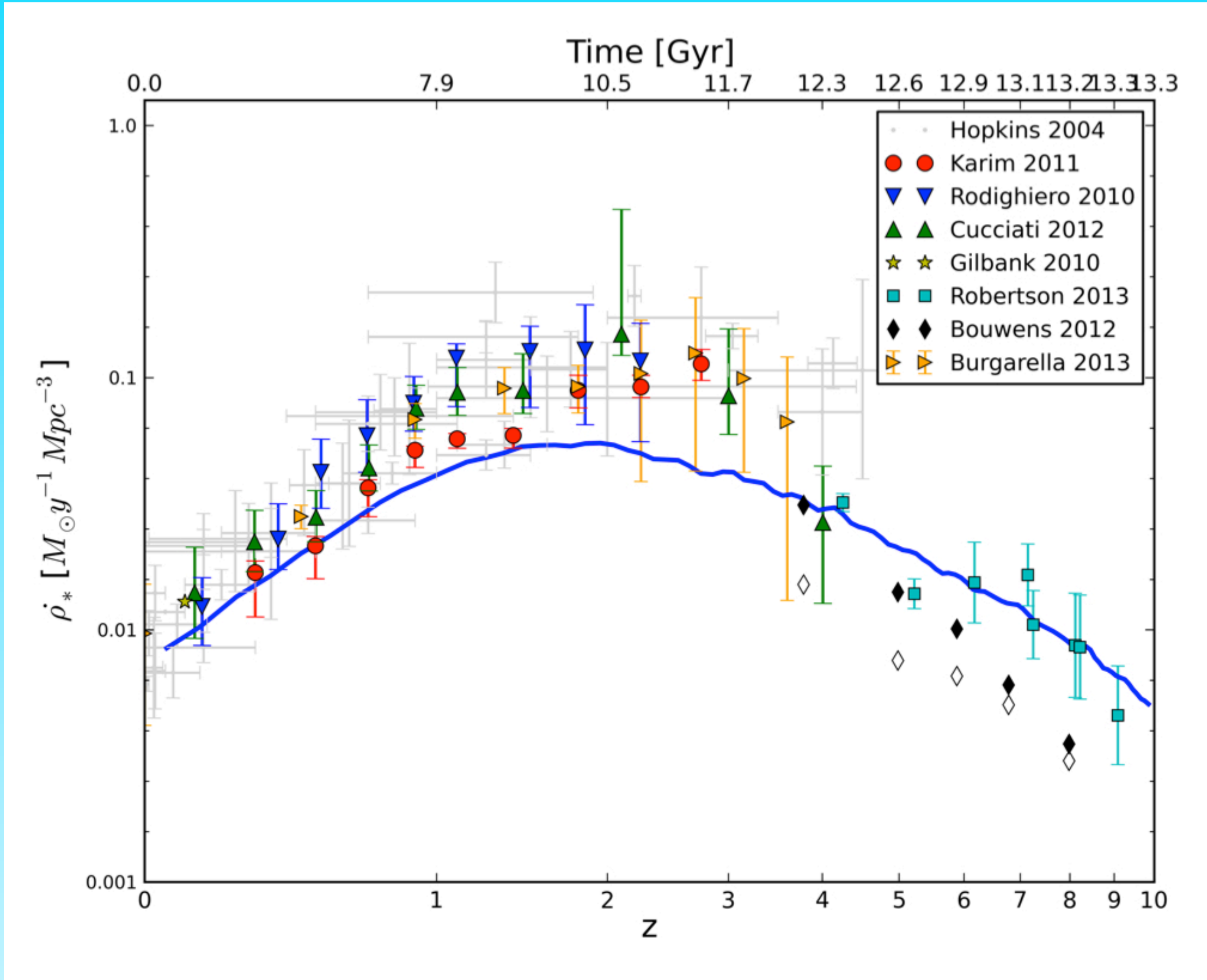
EAGLE

SFR density as a fn of z

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



Furlong et al. '15

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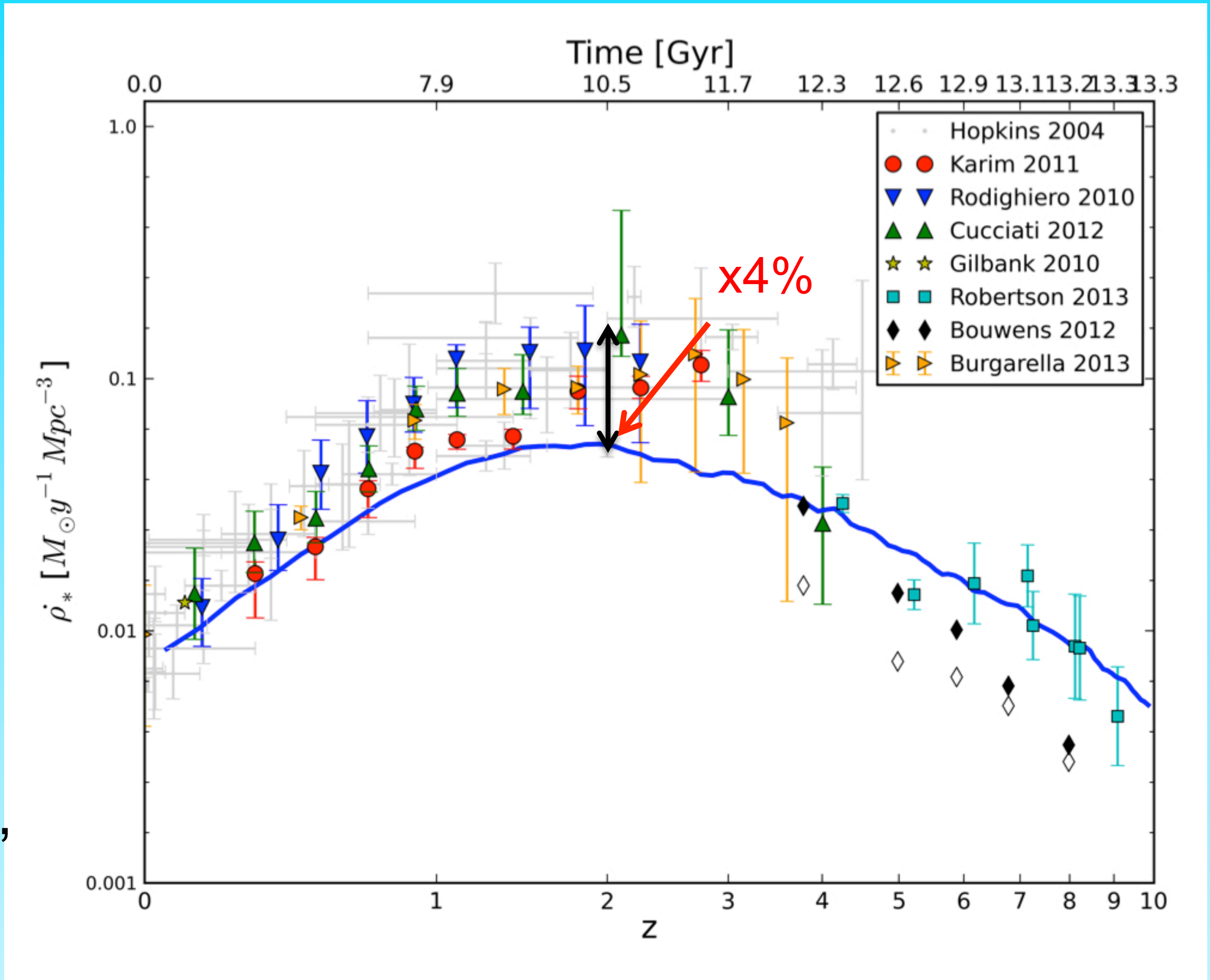
Evolution of the SFR density

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!



Furlong et al. ‘15

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Evolution of stellar mass density

University of Durham

EAGLE

Stellar mass density formed by z

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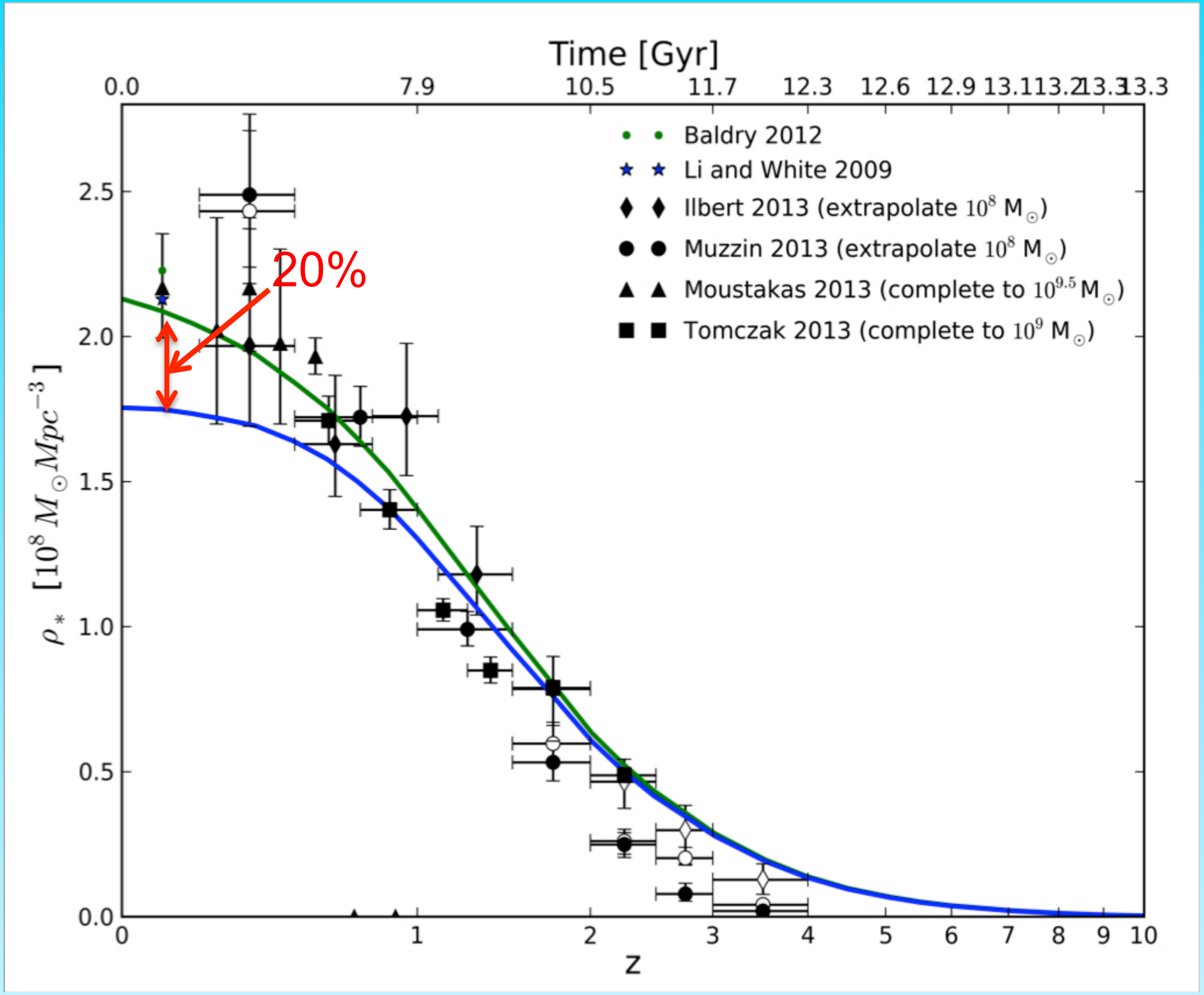

Furlong et al. '15

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Build-up of stellar populations

There appears to be an inconsistency between "measured" SFR(z) and M_* (z) in current data!

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Build-up of stellar mass: challenges for multiobject spect.

- Inconsistency between SFR(z) and $M_*(z)$ in data?
- Determine stellar mass fn reliably to high z
- Survey star-forming galaxies to higher z and fainter limits
- Differentiate between quiescent and starburst SF modes

Big question 2

How and when were galaxies assembled and what is the origin of the Hubble Sequence?

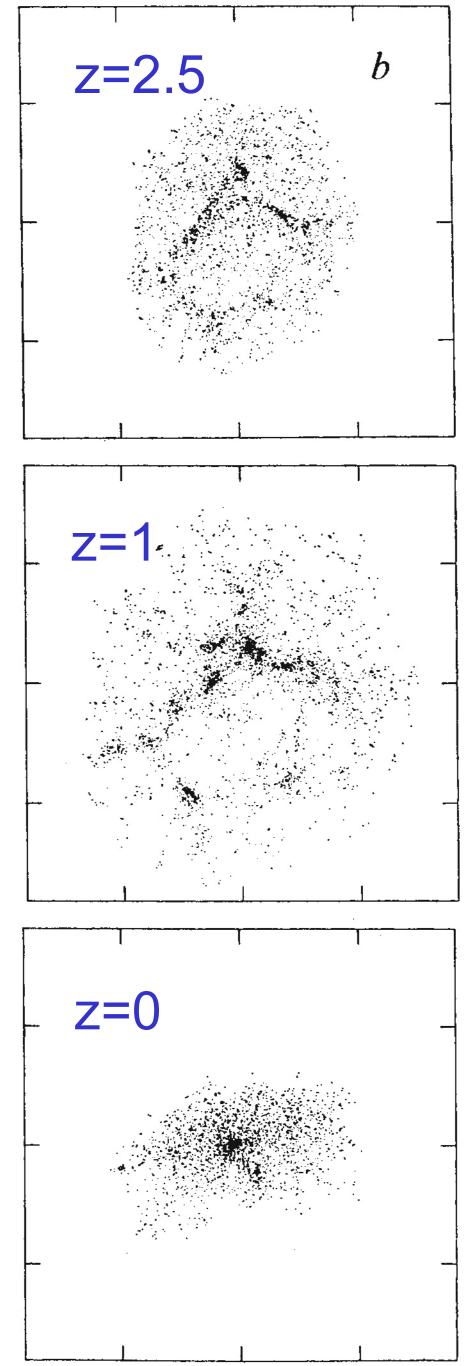
Relative role of in situ star formation, minor and major galaxy mergers, disk instabilities and environmental effects?

NATURE VOL. 317 17 OCTOBER 1985 — LETTERS TO NATURE

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) scales[9]. 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

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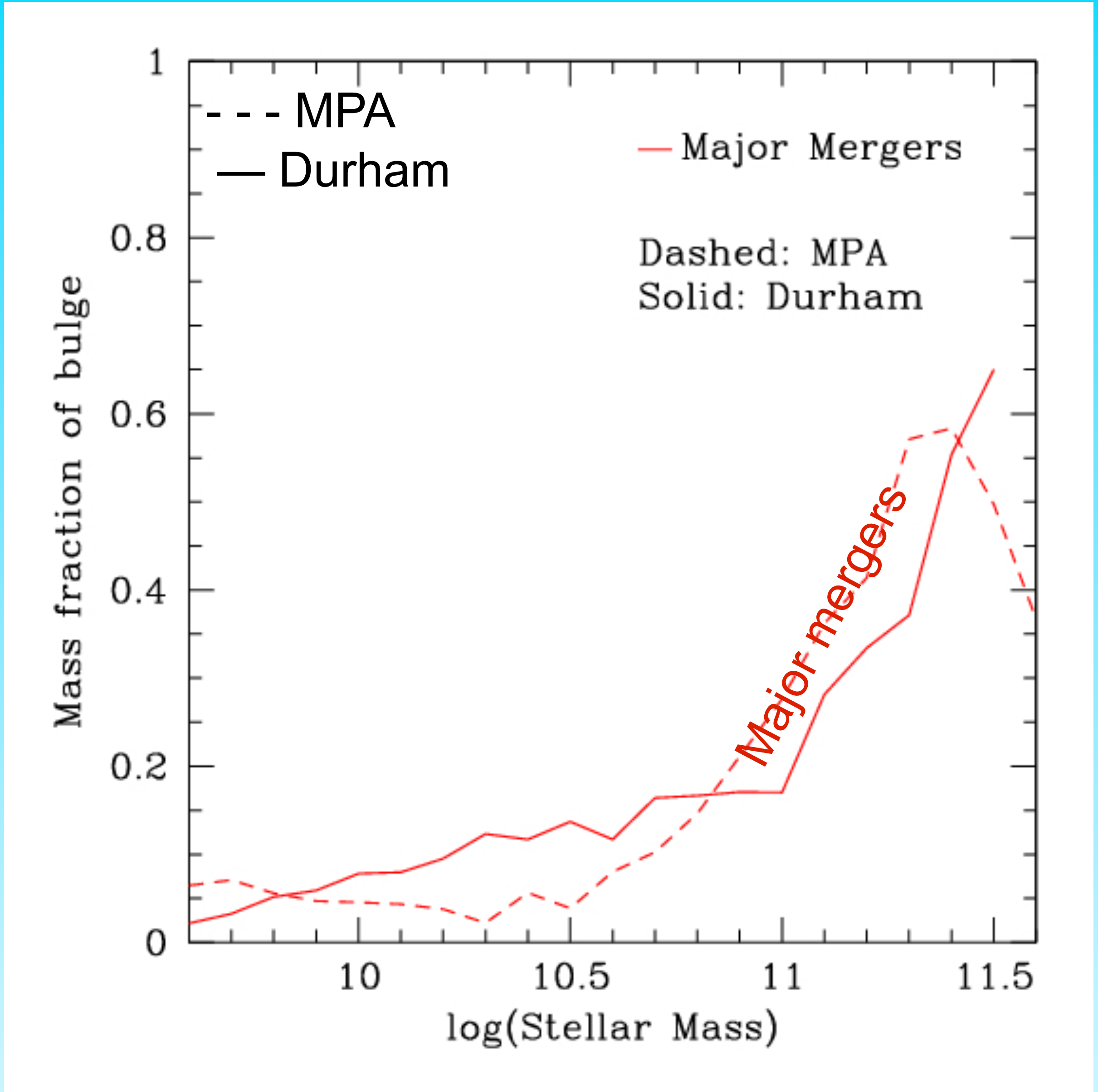
3 processes for making spheroids:

- 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

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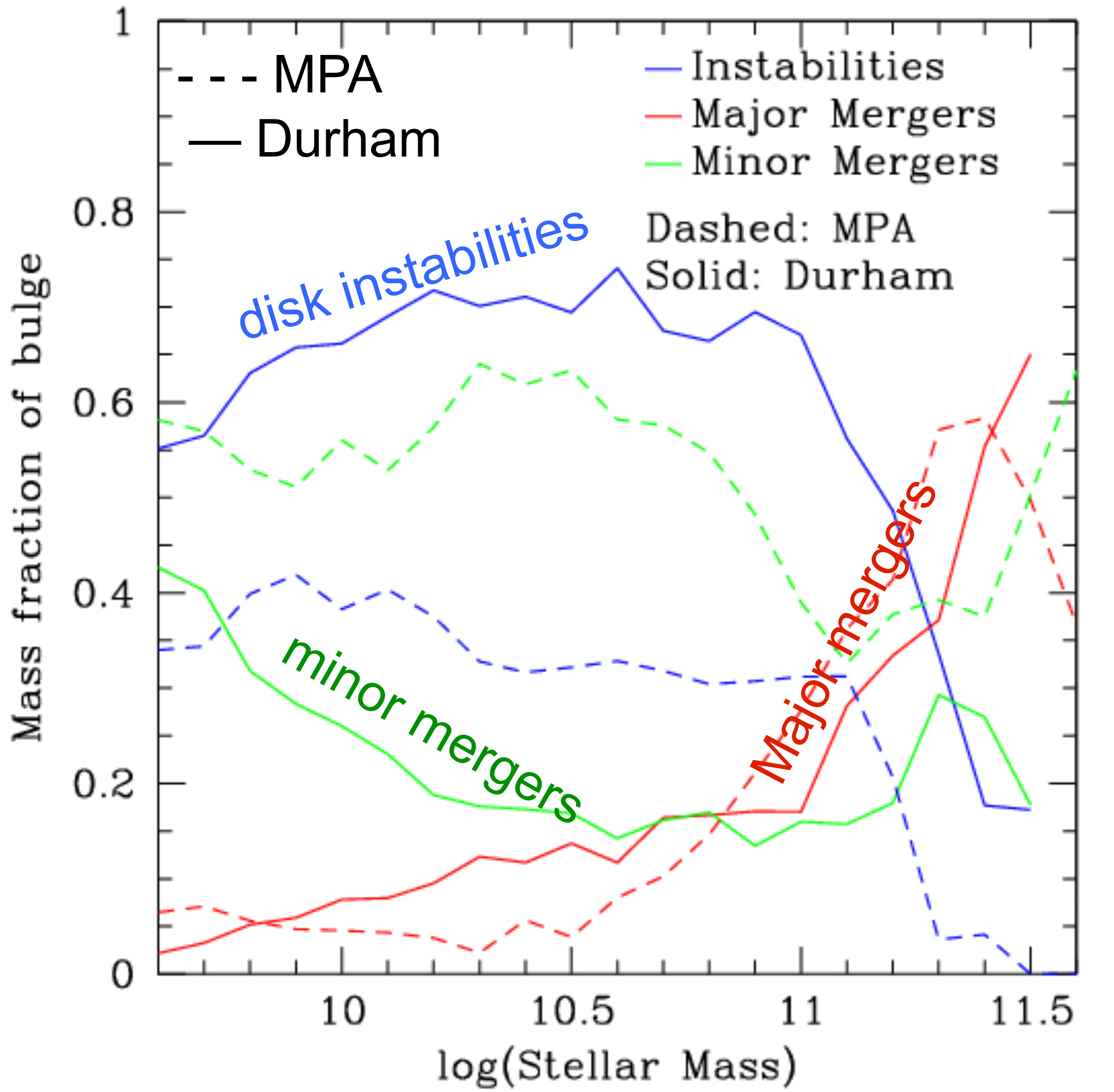
3 processes for making spheroids:

- 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



Size evolution of early-type galaxies

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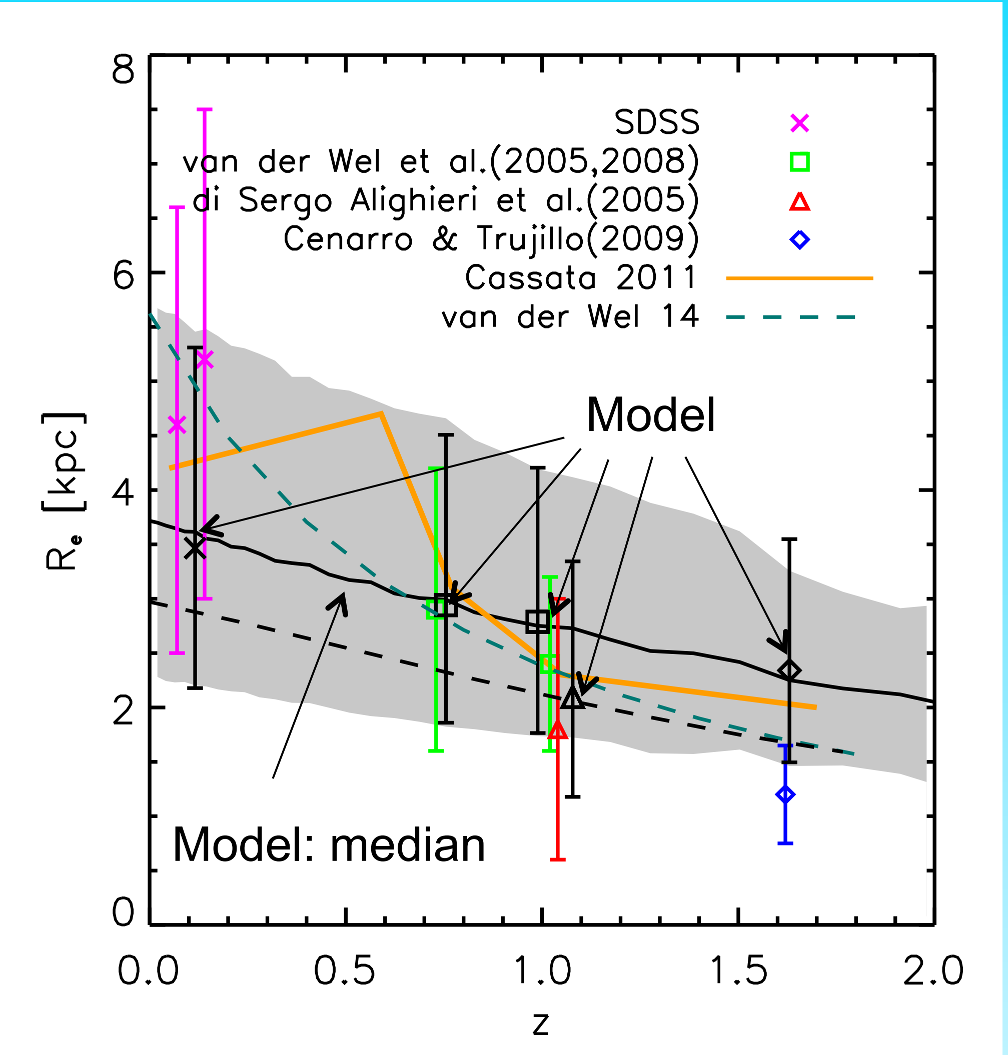
Early-type galaxies appear to grow in size by about x5 from z=1.5 to z=0!

Model predicts very large scatter and strong selection effects

At hi-z gals small because halos are small; size growth in ETGs driven by minor mergers

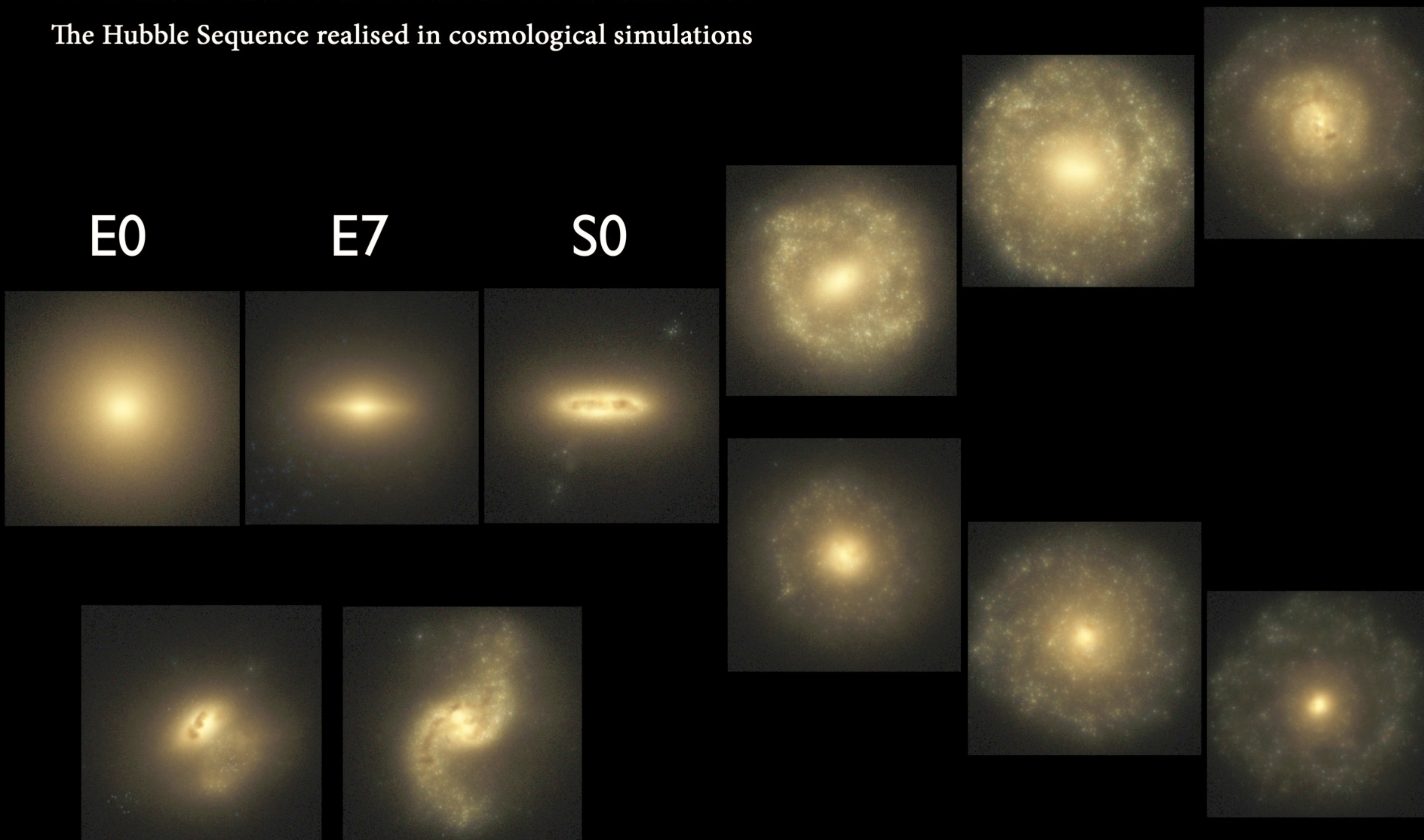


Xie et al. '15

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



Trayford et al '15

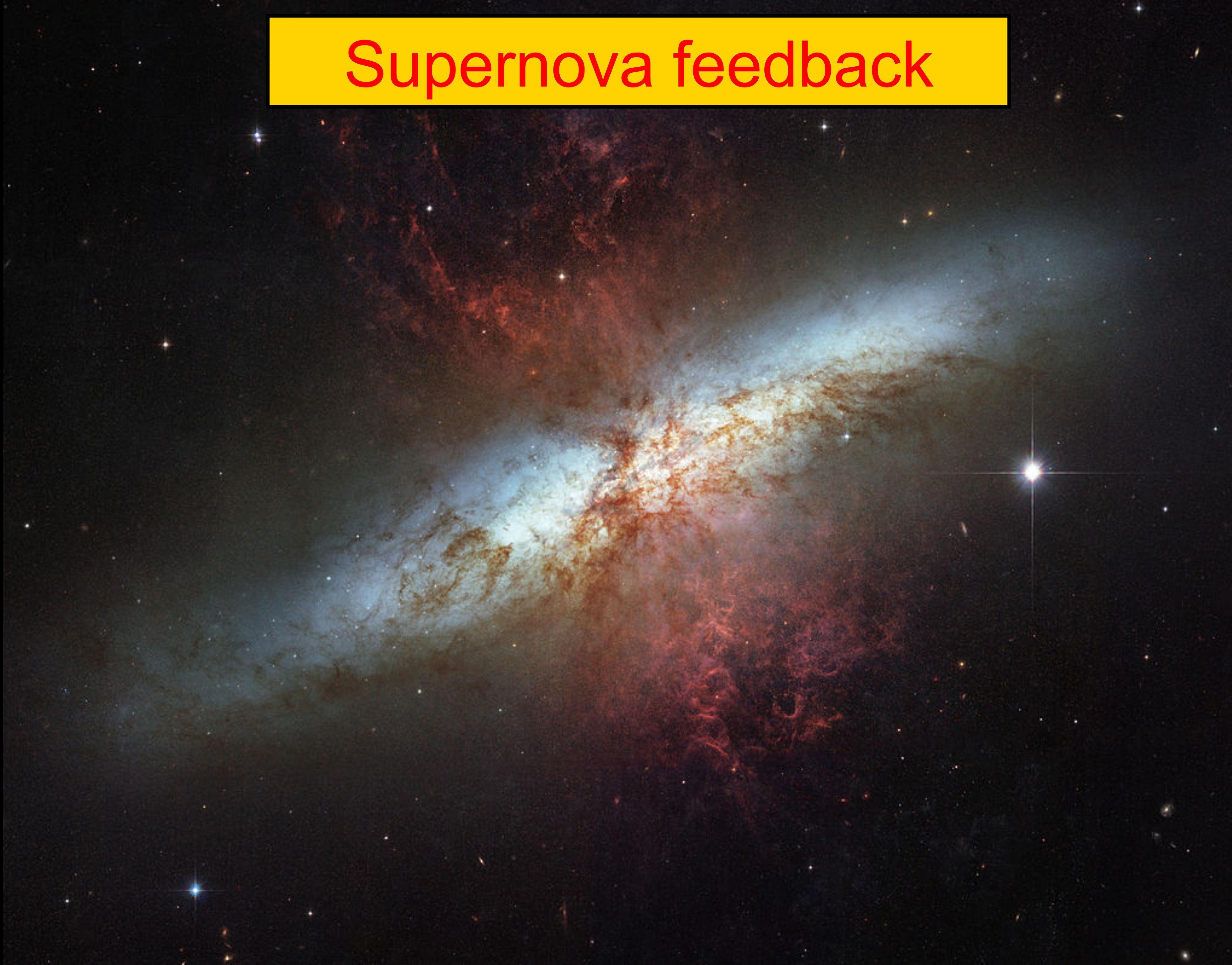
Galaxy assembly & morphology: challenges for multiobject spect.

- Measure galaxy sizes & structure to high-z → large imaging/ spectroscopic surveys with well-defined selection criteria
- Dynamical studies of galaxies at high-z
- Estimates of merger rates

Big question 3

How was the Universe reionized and what is the connection between the first and today's galaxies?

Supernova feedback



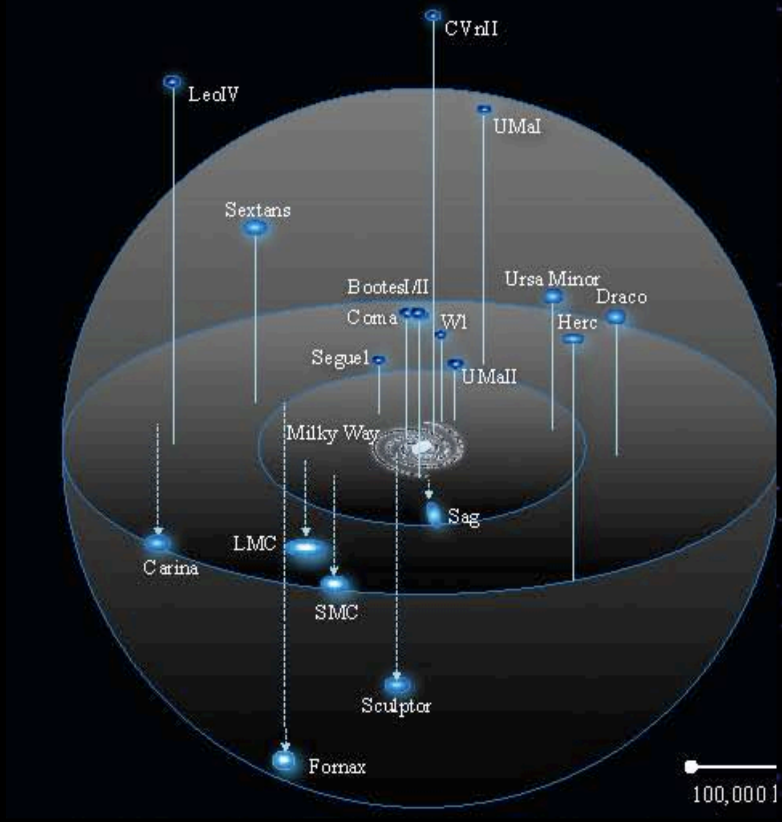
Supernova feedback

Supernova feedback plays a major role in:

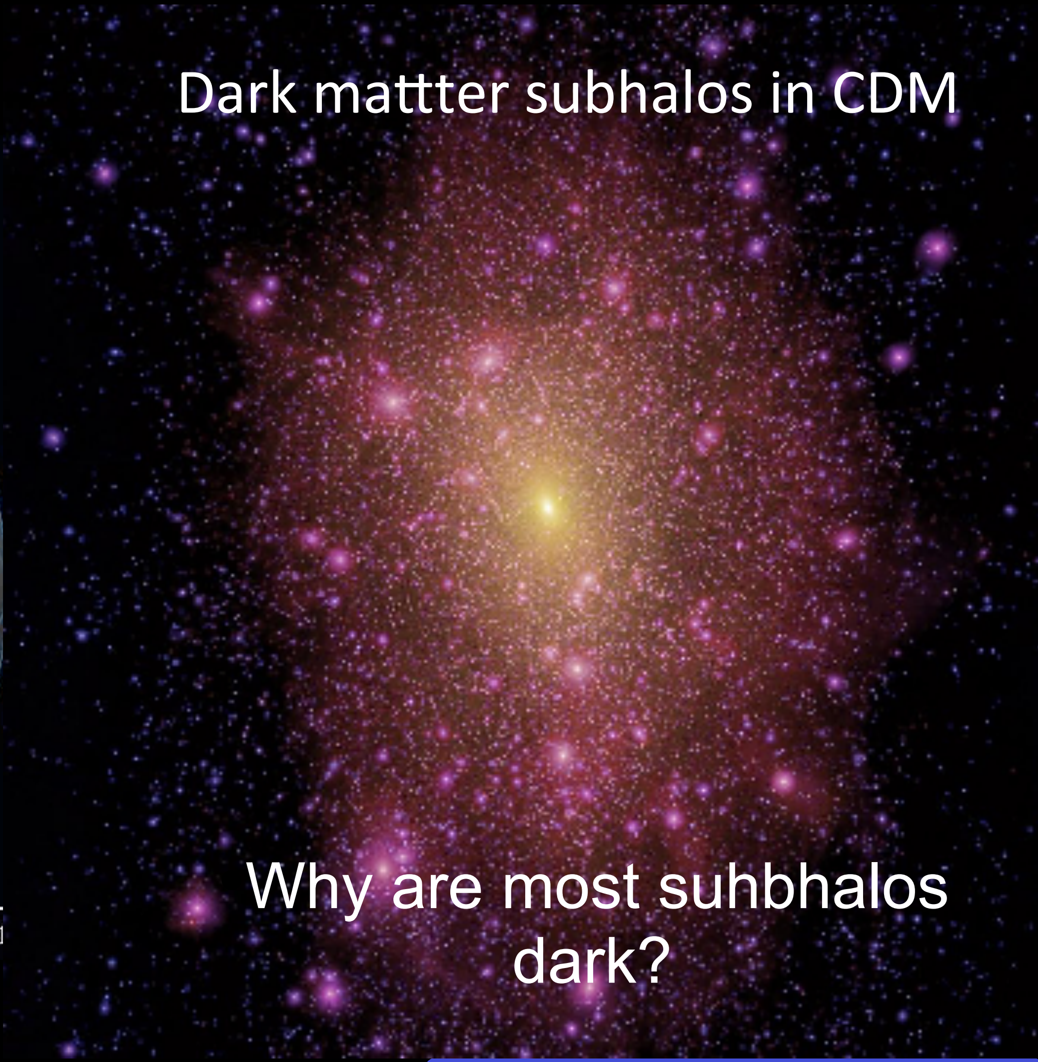
- The faint end of the galaxy luminosity function (MW satellites)
- The metallicity-luminosity relation
- Reionization of hydrogen at early times
- Galaxy sizes
- … and more

The “missing satellites” problem in CDM

The satellites of the MW



Dark matter subhalos in CDM

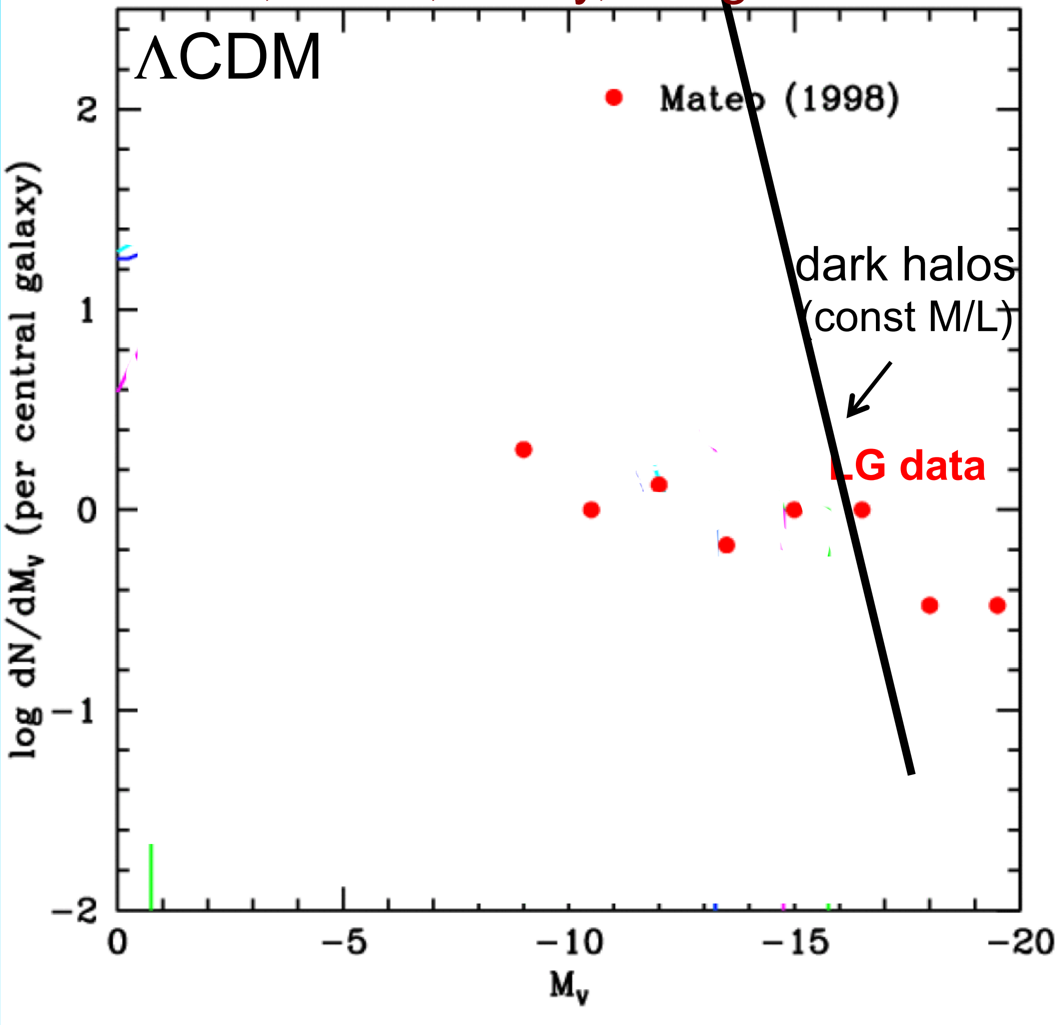


Why are most suhbhalos dark?

Luminosity Function of Local Group Satellites

University of Durham

Benson, Frenk, Lacey, Baugh & Cole '02



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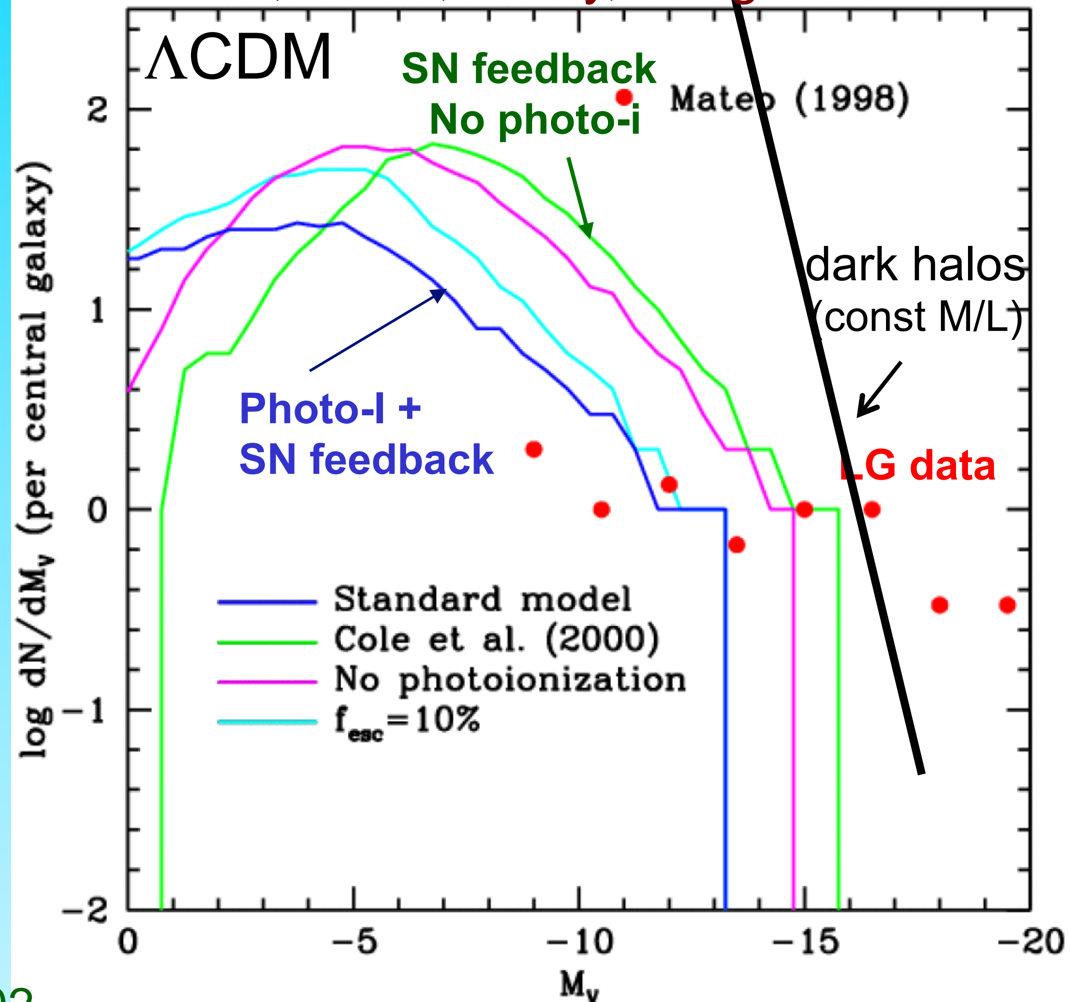
Luminosity Function of Local Group Satellites

- Photoionization inhibits the formation of satellites
- Abundance of satellies reduced by large factor!
- Median model gives correct abundance of sats brighter than M_V=-9, V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites

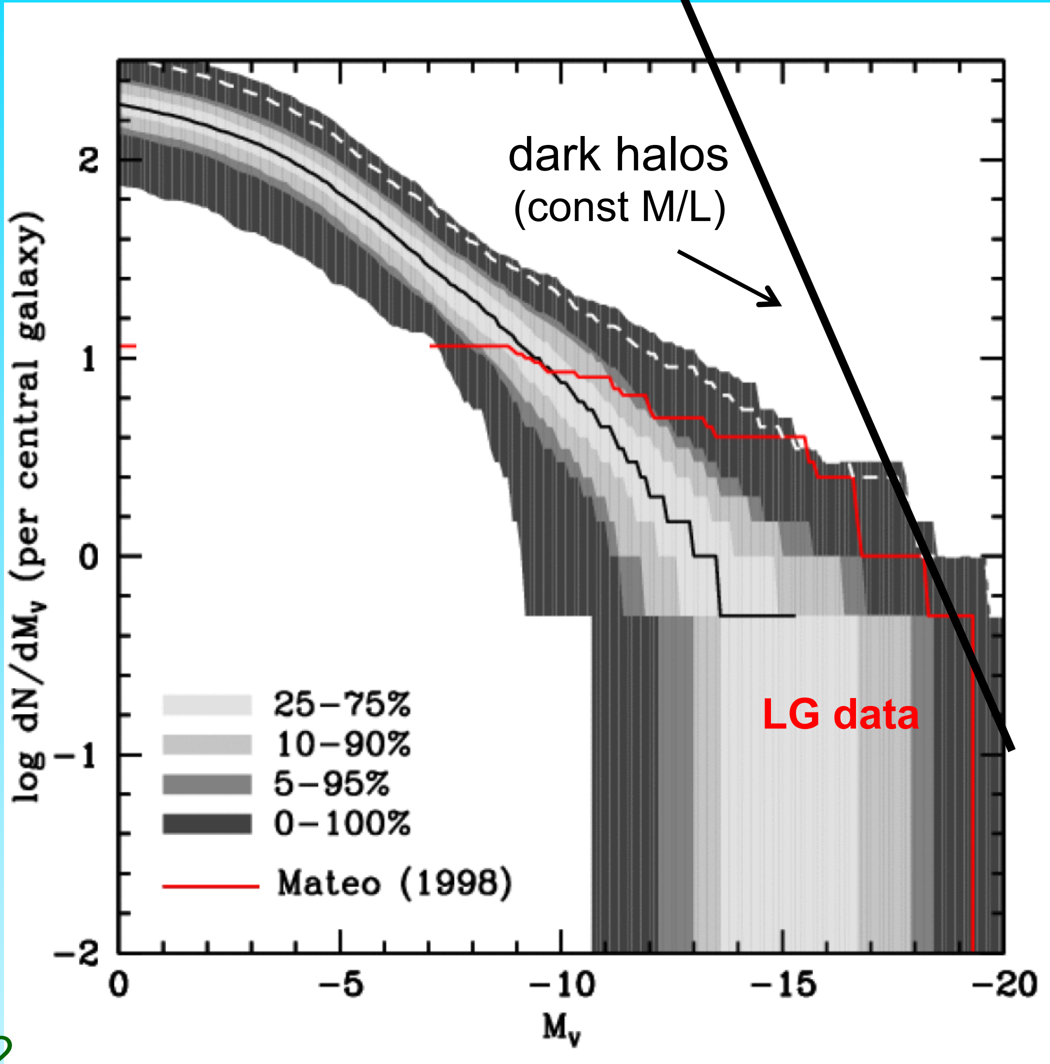
Benson, Frenk, Lacey, Baugh & Cole '02



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



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Luminosity Function of Local Group Satellites

University of Durham

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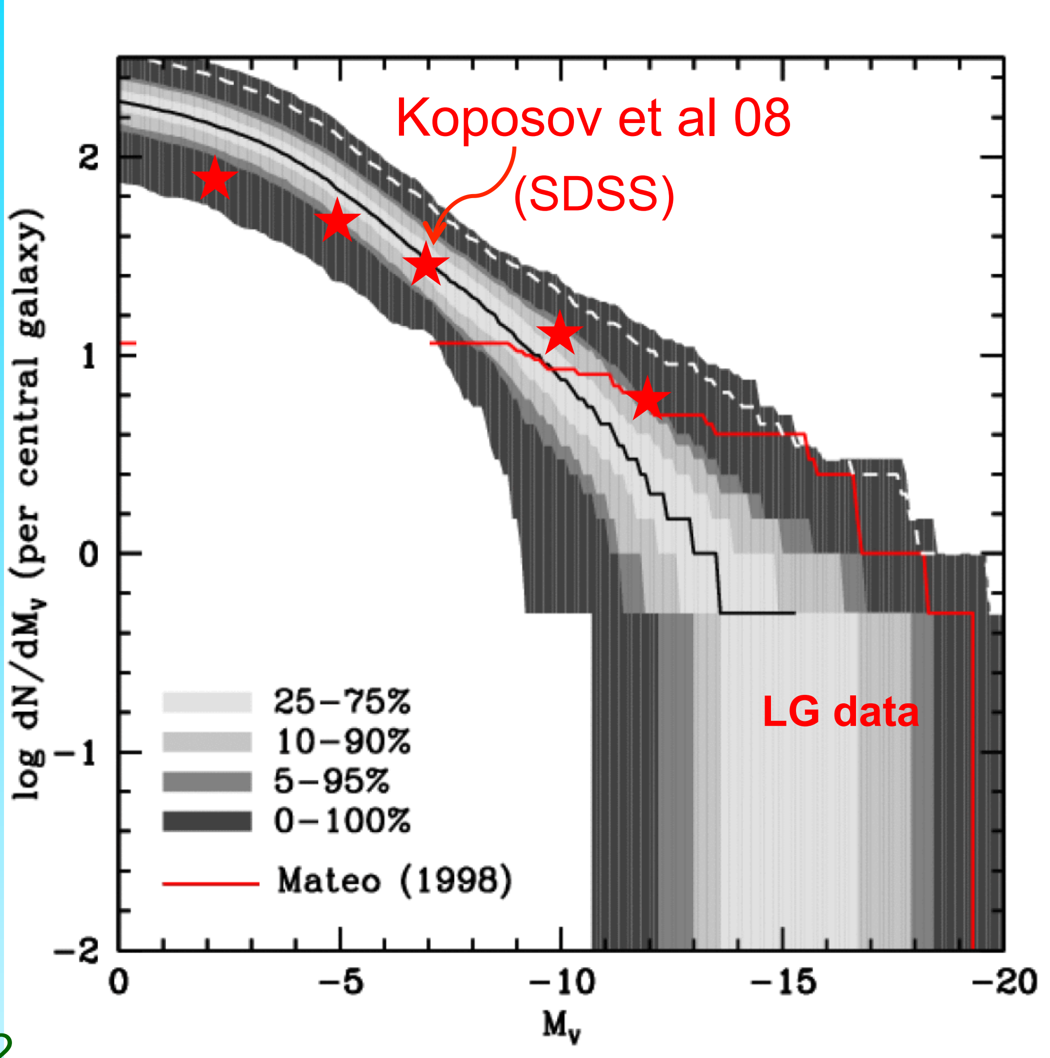

Benson, Frenk, Lacey, Baugh & Cole '02
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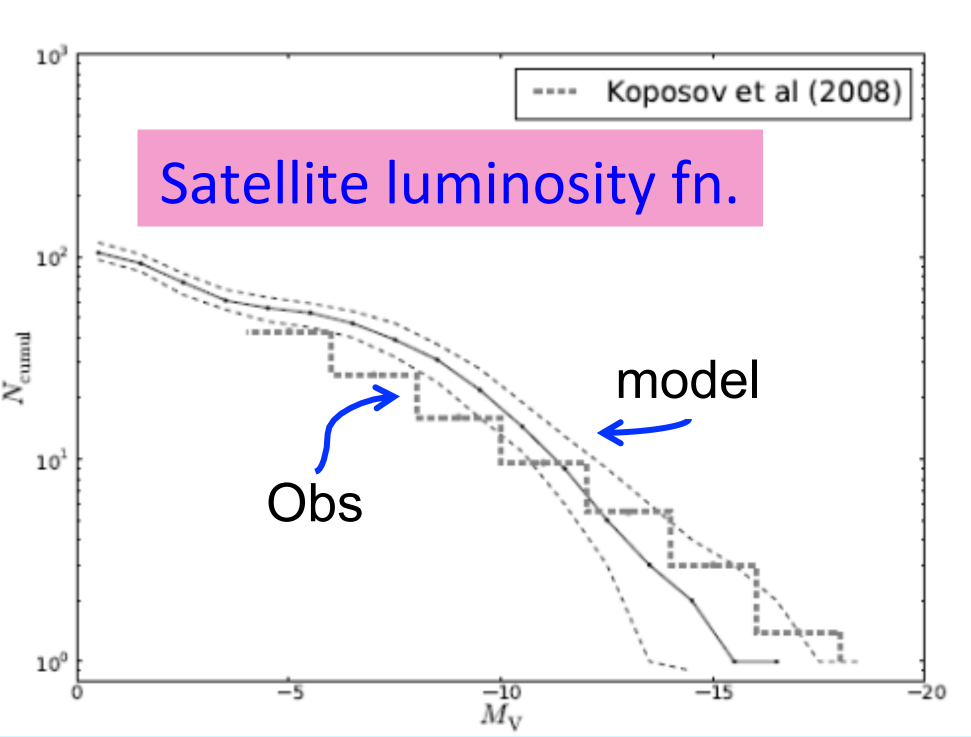
Supernova feedback

University of Durham

In GALFORM

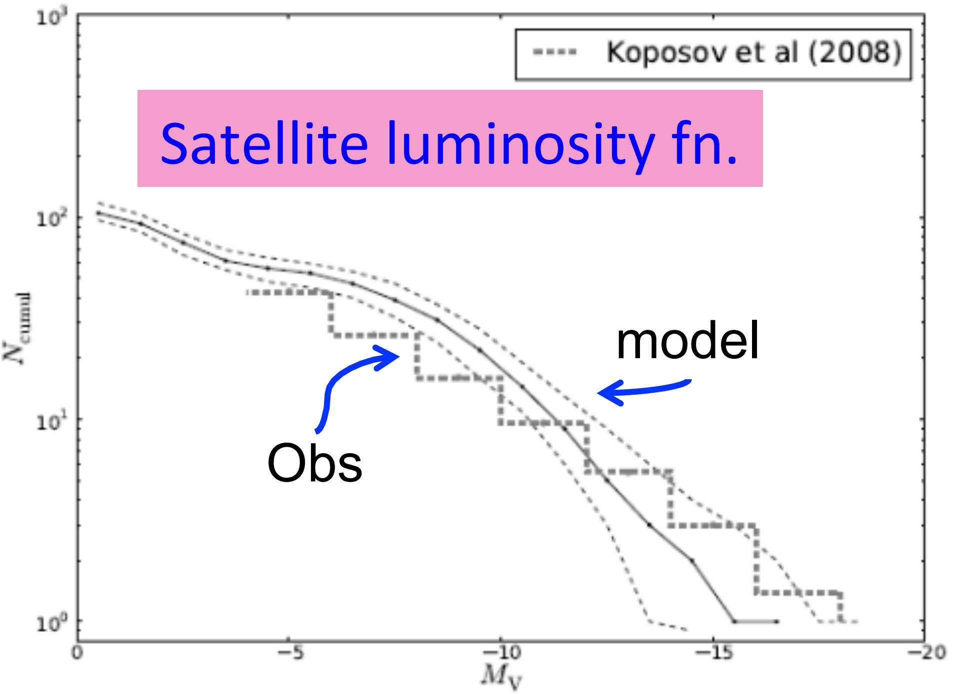
Hou, Frenk, Lacey et al. '15

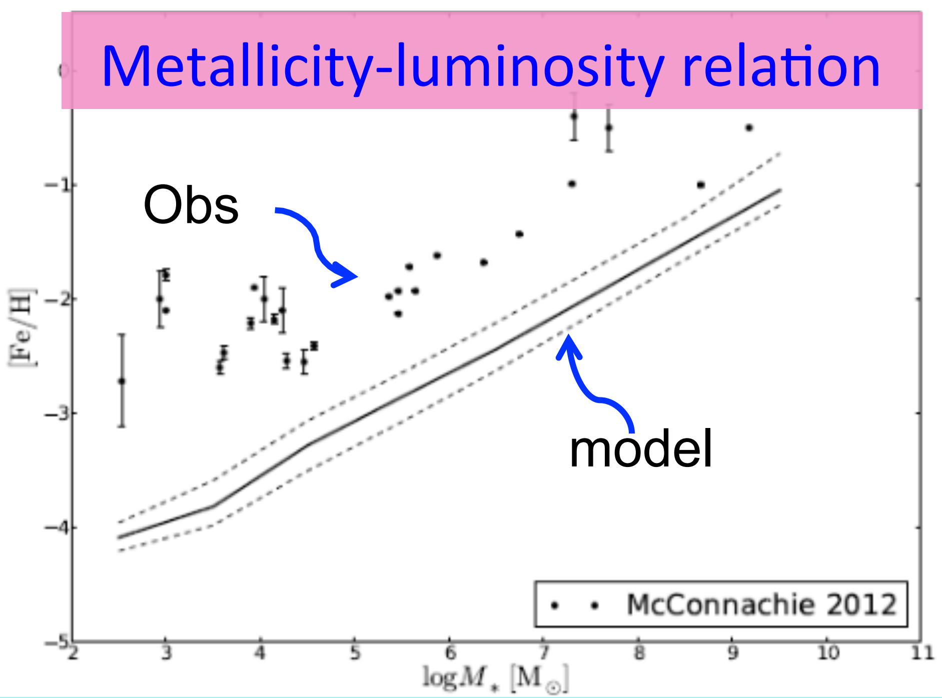


Supernova feedback

In GALFORM

Hou, Frenk, Lacey et al. '15





Standard feeback galform model → correct satellite LF

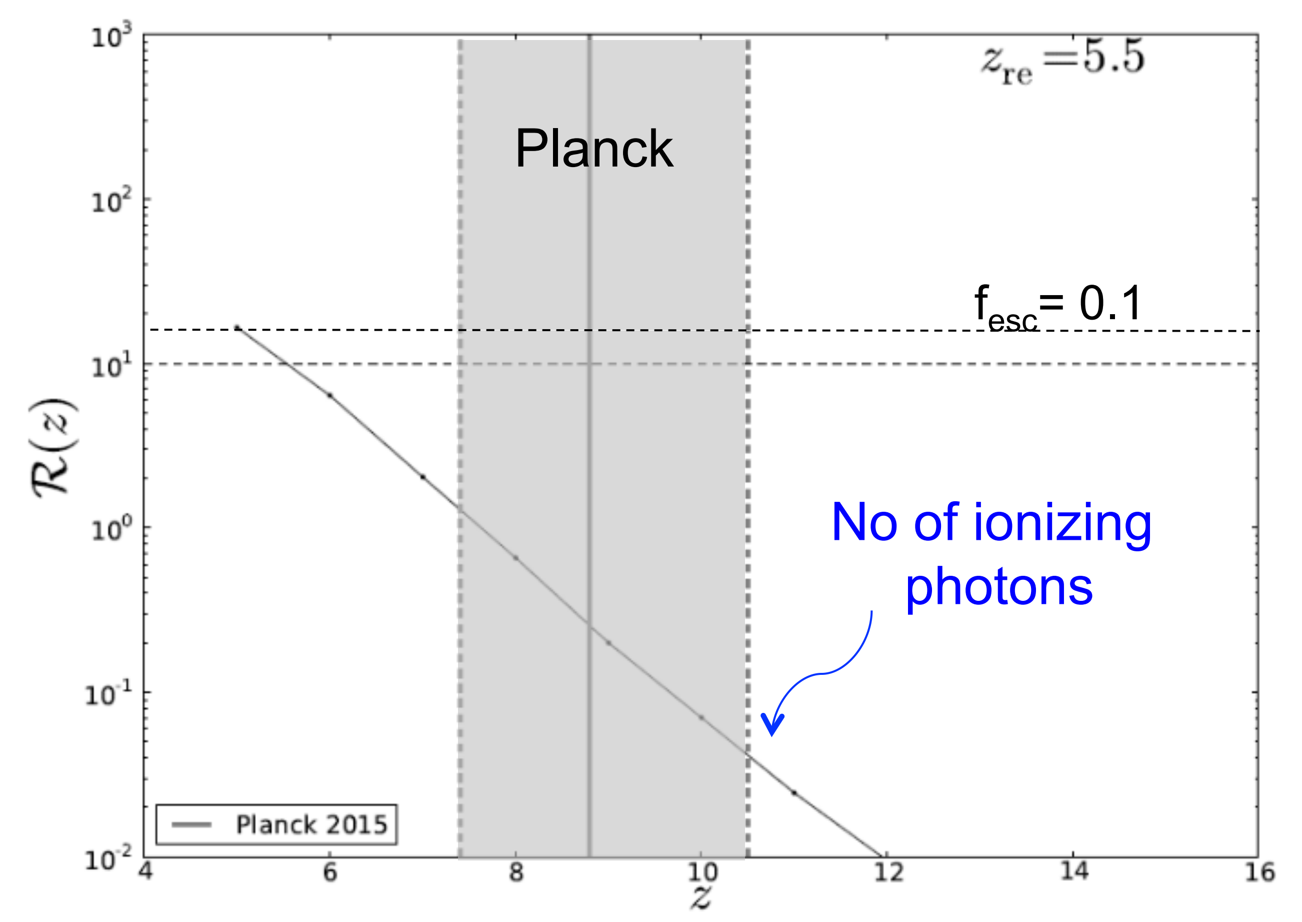
wrong metallicity-lum reln!

Supernova feedback

University of Durham

$$\mathcal{R}(z) = \frac{\text{no. of ionization photons emitted by redshift } z}{\text{No. of H atoms}}$$

$$\mathcal{R}(z) = \frac{1+N_{rec}}{f_{esc}} \approx \frac{2}{f_{esc}}$$



In GALFORM

Institute for Computational Cosmology

Supernova feedback

SN feedback must be:

• To match the Milky Way satellite luminosty fn	STRONG
• For galaxies to reionize the Universe at z~10	WEAK
• To get the [Fe/H] vs L relation for MW satellites	WEAK

University of Durham

Supernova feedback

In GALFORM

SFR & mass ejection

SFR

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

SN feedback

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

SN feedback efficiency

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

V_{disk} = disk circ vel.

V_{hot}, α_{hot} free parameters

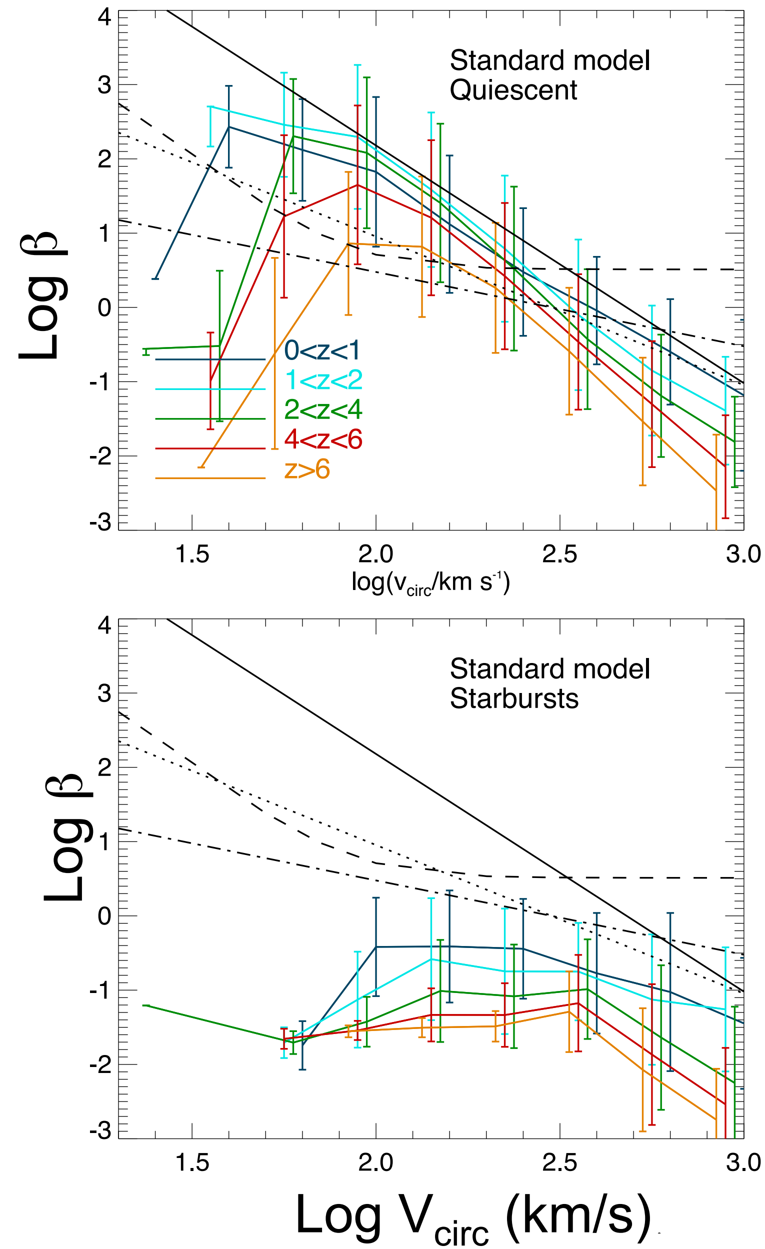
GALFORM

University of Durham

Dynamical model of SN feedback: evolution of pressurised bubbles in multiphase ISM

→ Efficiency β depends on redshift, is different for quiescent and burst SF and saturates for V<80km/s

Lagos et al '13



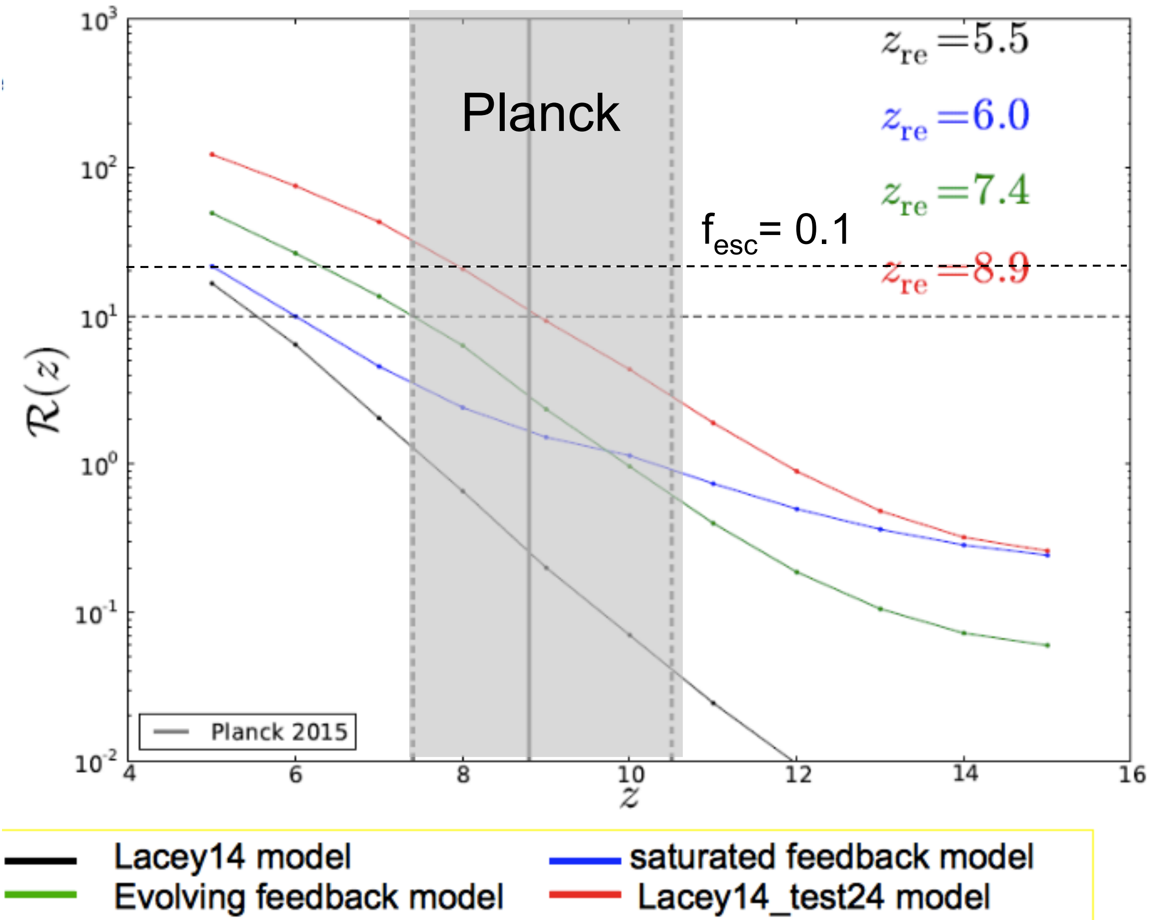
Reionization in GALFORM

University of Durham

$$\mathcal{R}(z) = \frac{\text{no. of ionization photons emitted by redshift z}}{\text{No. of H atoms}}$$

Modify SN feedback in GALFORM to mimic Lagos et al '13 model

Can reionize Universe at z=9!



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SN feedback in GALFORM

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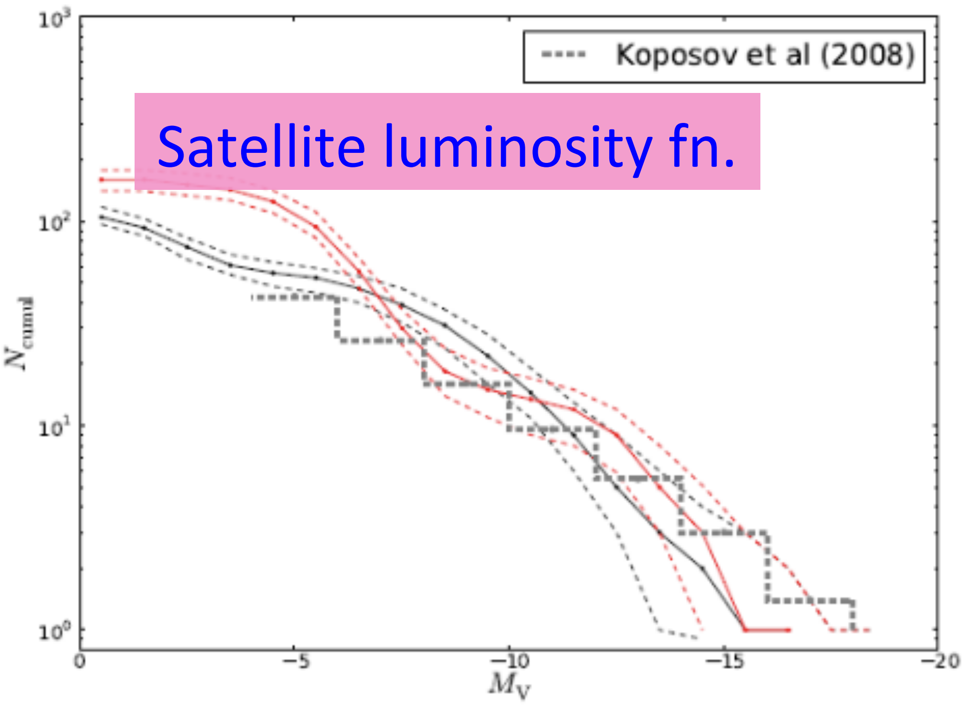
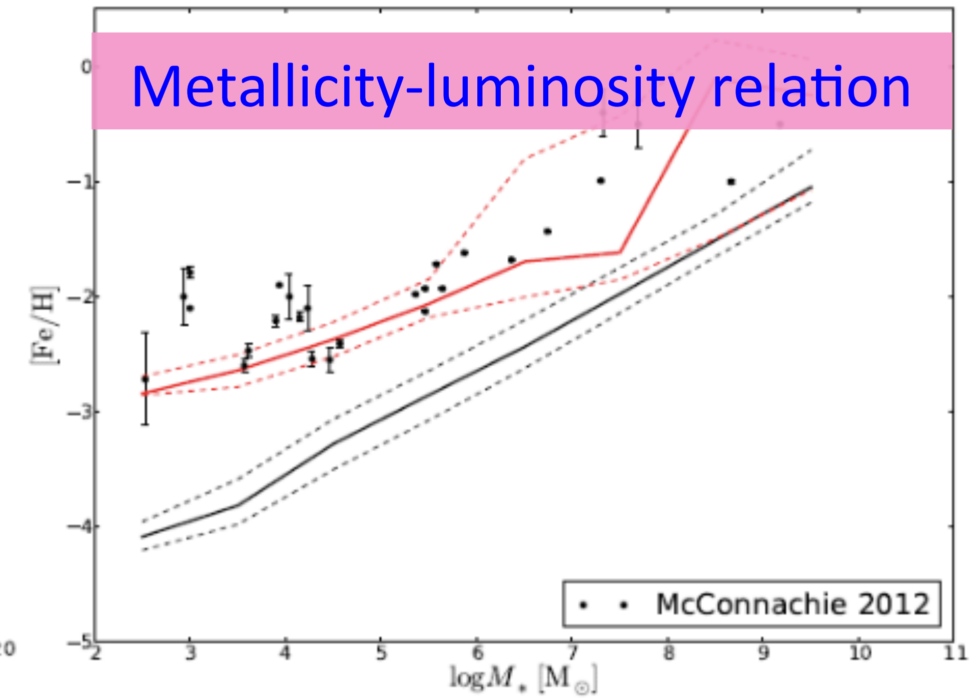
Need SN feedback efficiency to be low at high-z and high at low-z





Complex z-dependent feeback → galform model

correct satellite LF

correct metallicity-lum reln!

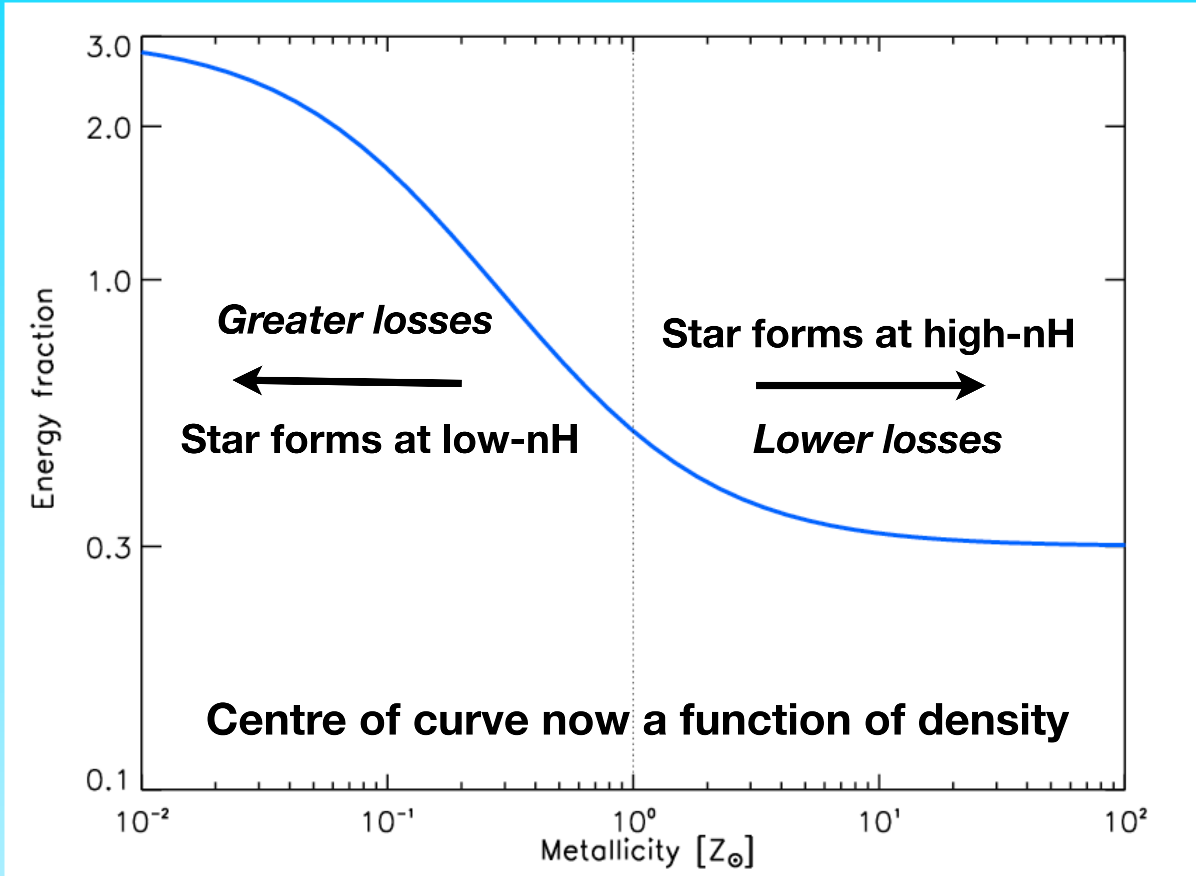
correct reionization z

Supernova feedback

In EAGLE

Feedback depends on metallicity and scales with gas density

Needed to account for galaxy stellar mass fn and galaxy sizes at z=0



VIRGO

EAGLE full hydro simulations

Local Group

Sawala et al ‘14

VIRGO

Far fewer satellite galaxies than CDM halos

EAGLE full hydro simulations

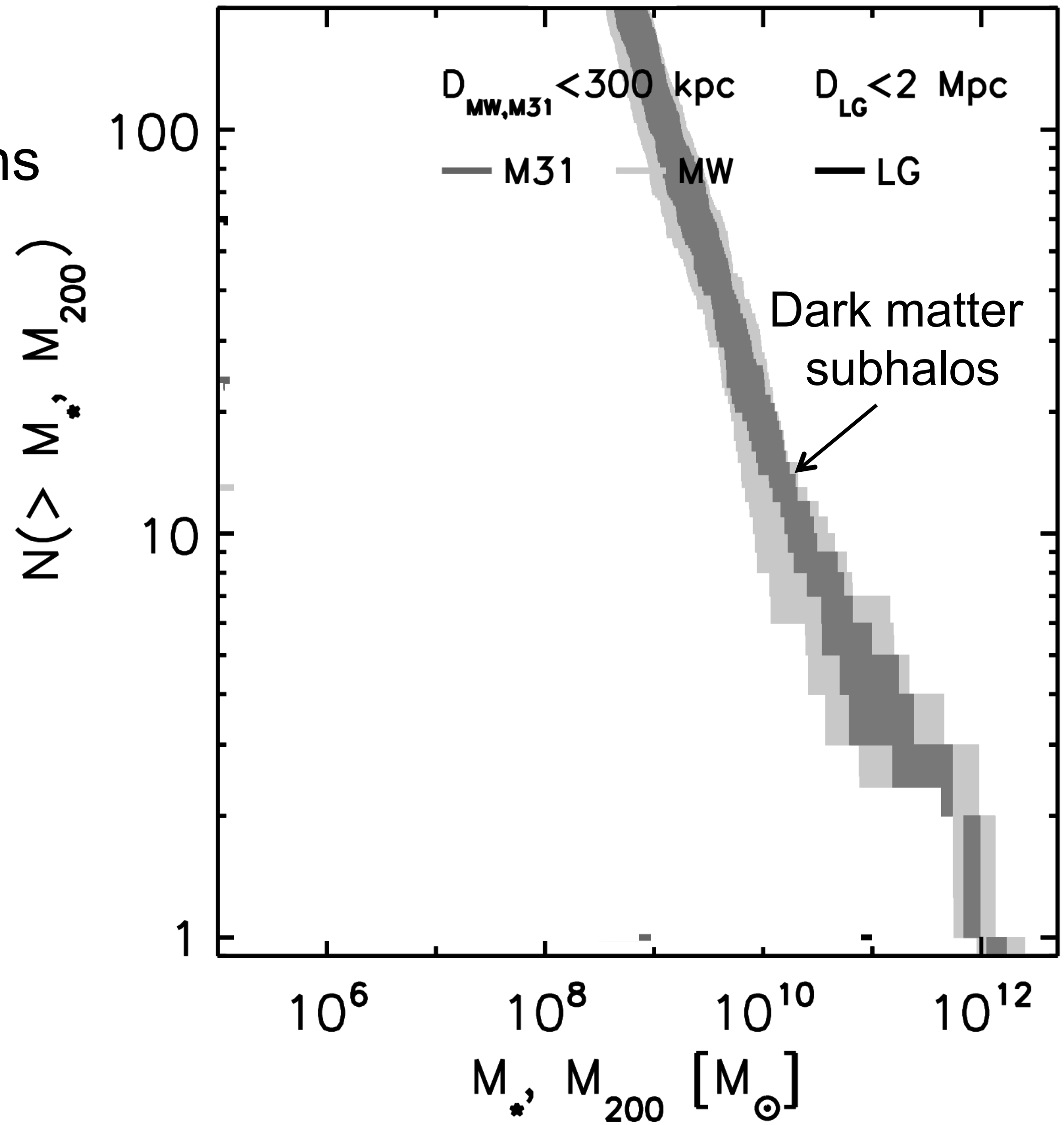
Local Group

Sawala et al ‘14

EAGLE Local Group simulation

University of Durham

Subhalo mass functions

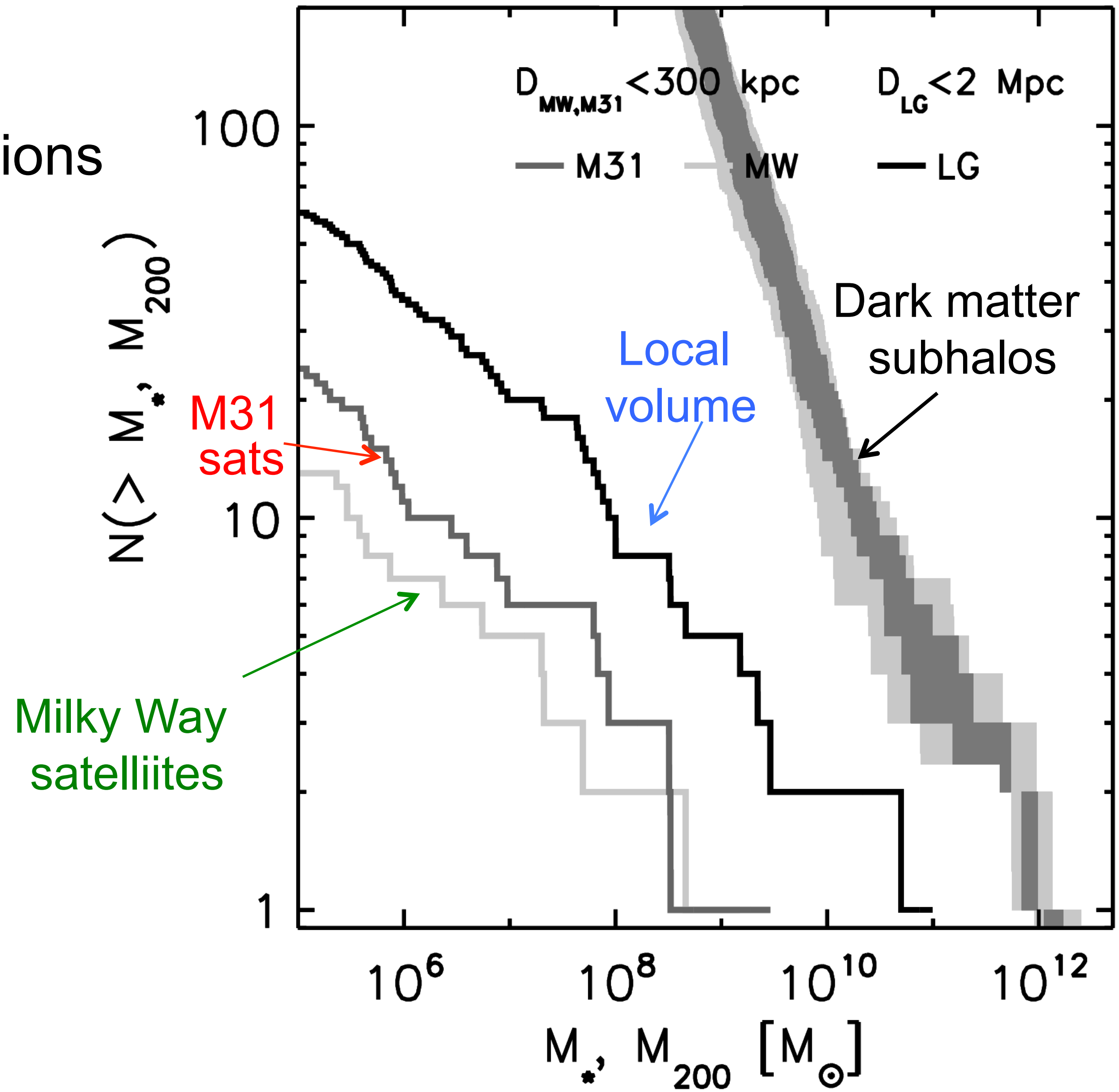


Sawala et al '14

ICC University of Durham

EAGLE Local Group simulation

Stellar mass functions



Sawala et al '14

EAGLE Local Group simulation

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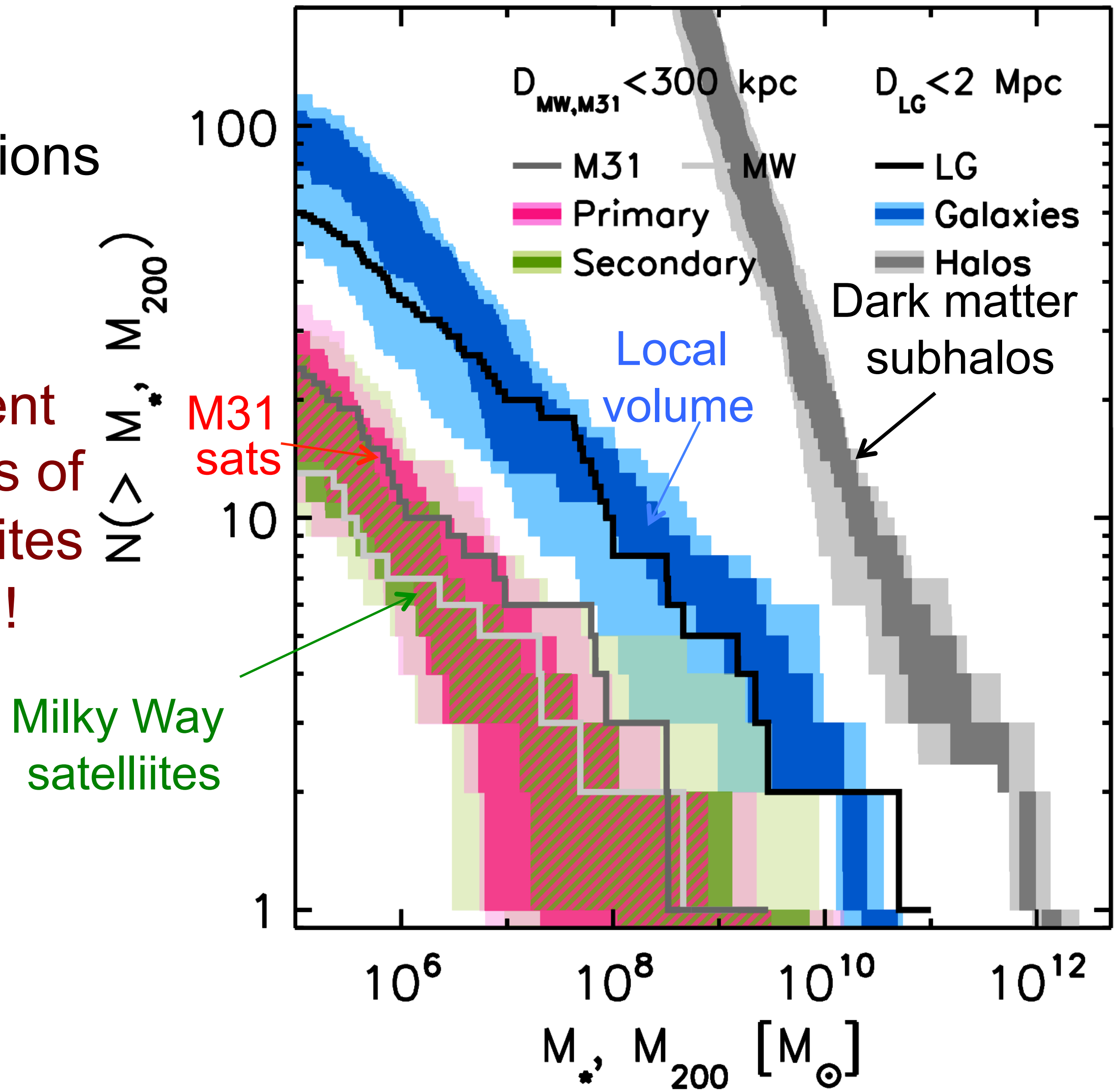
Stellar mass functions

Excellent agreement with stellar mass fns of MW and M31 satellites and field dwarfs !



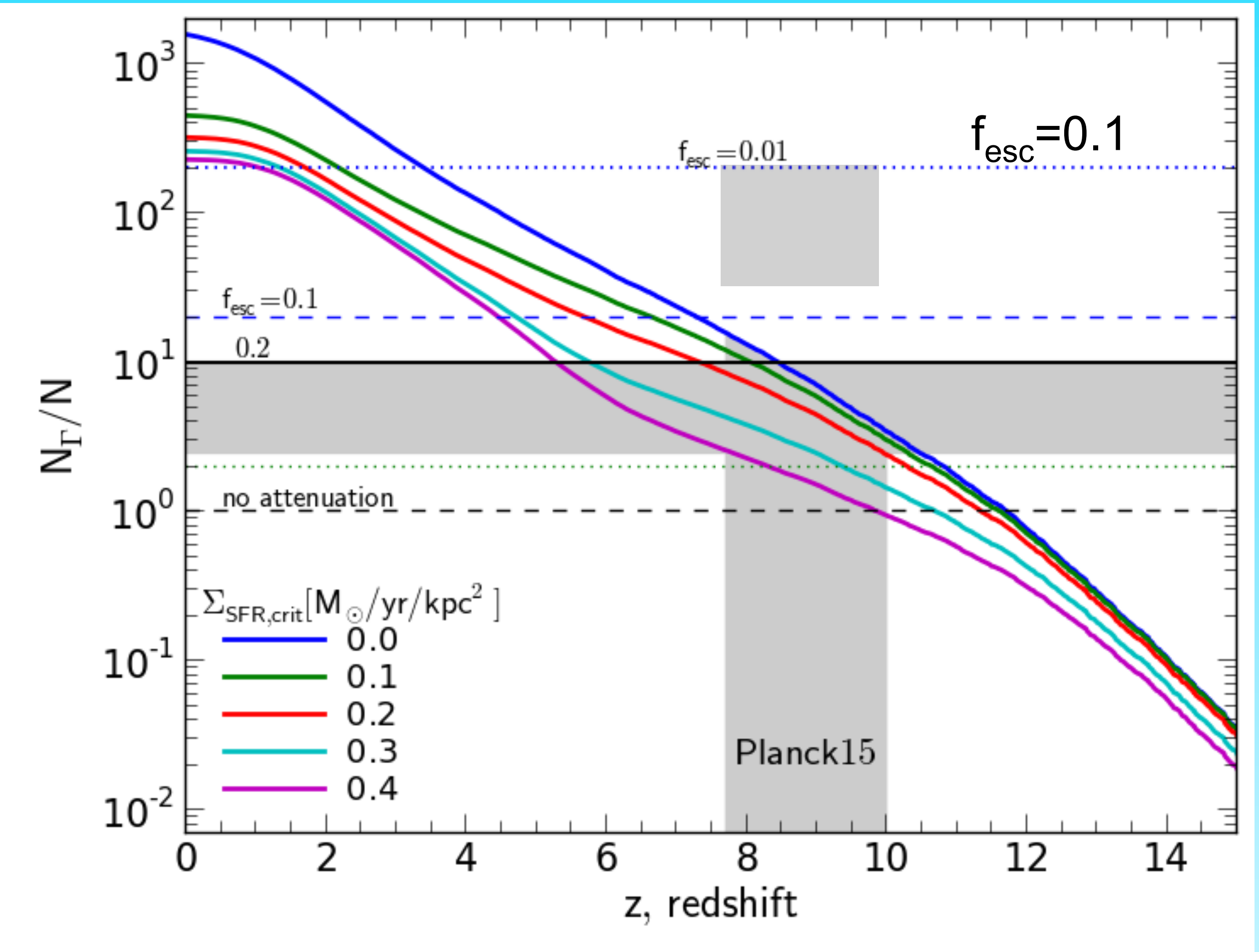
Sawala et al ‘14

Reionization in Eagle

University of Durham

$$\mathcal{R}(z) = \frac{\text{no. of ionization photons emitted by redshift } z}{\text{No. of H atoms}}$$

Need: $f_{esc} > 0.2$



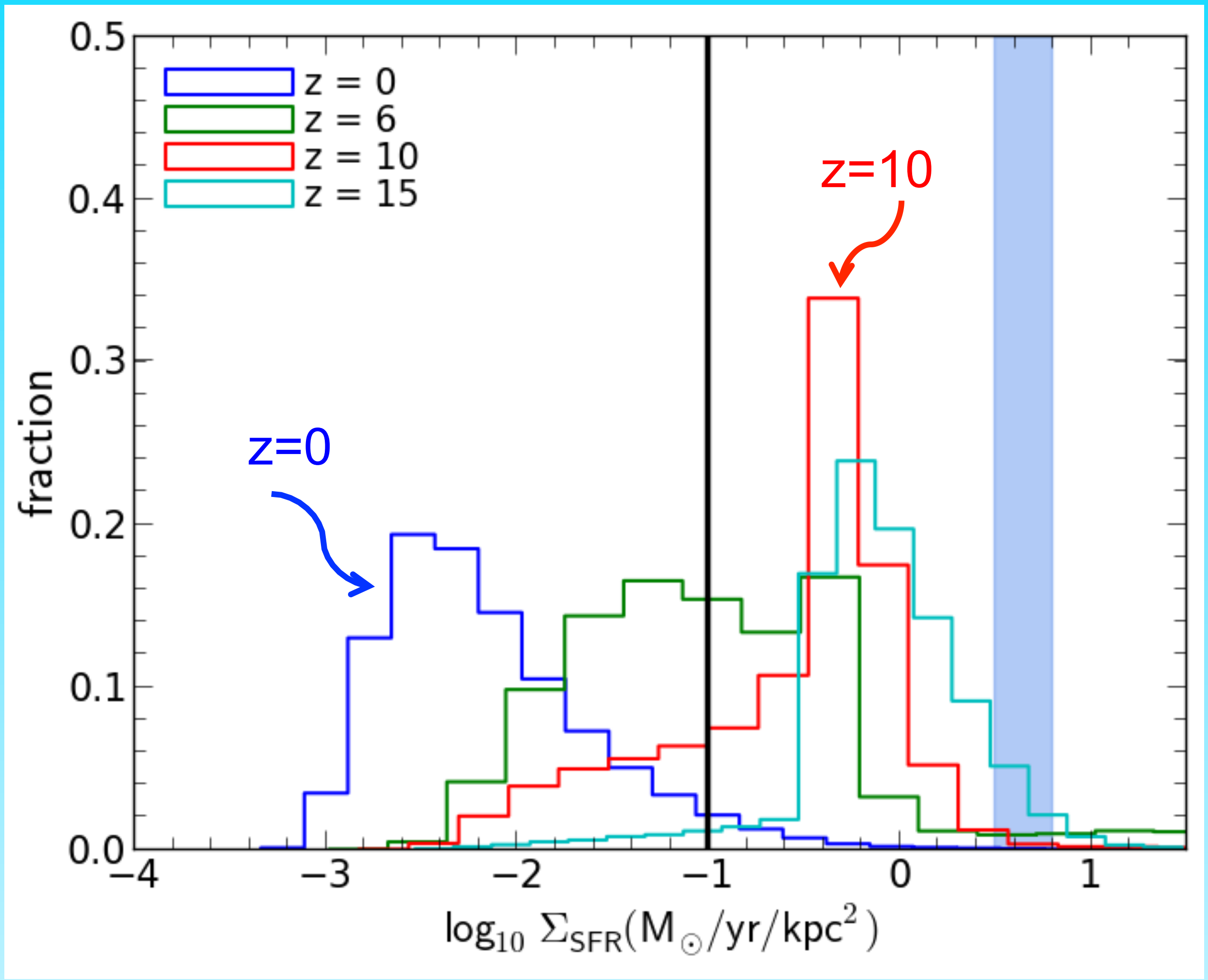
Sharma et al ‘15

Reionization in Eagle

University of Durham

At high-z, galaxies are bursty and have large SFR density

→ high escape fraction?



Sharma et al '15

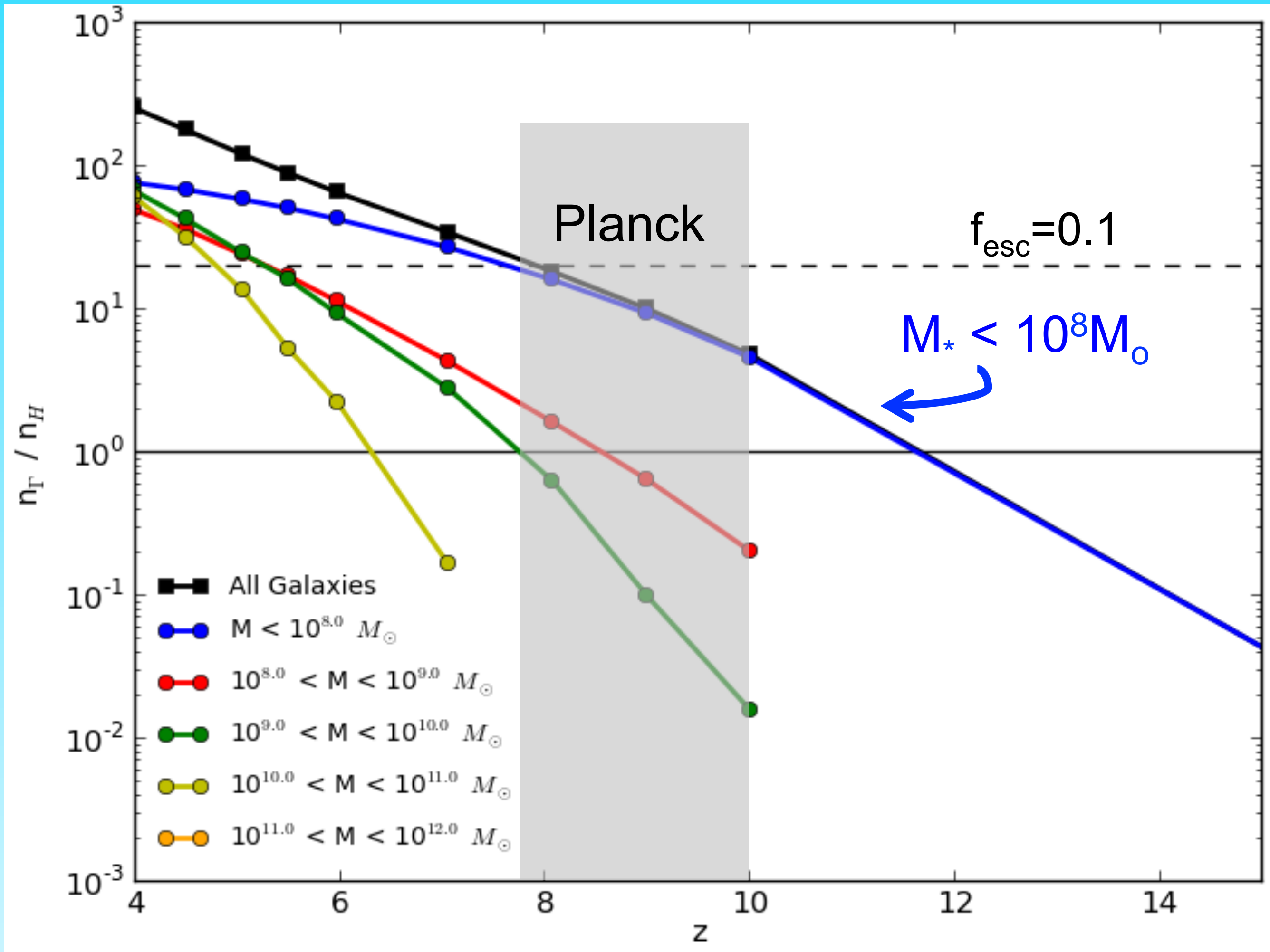
Reionization in Eagle

University of Durham

$$\mathcal{R}(z) = \frac{\text{no. of ionization photons emitted by redshift } z}{\text{No. of H atoms}}$$

Reionization at z~8 by galaxies of $M_* < 10^8 M_o$ or V_c~100 km/s

These would have M_{AB}(1500A) ~ −14 or m_{AB} ~32



Furlong et al. '15

SN Feedback in EAGLE

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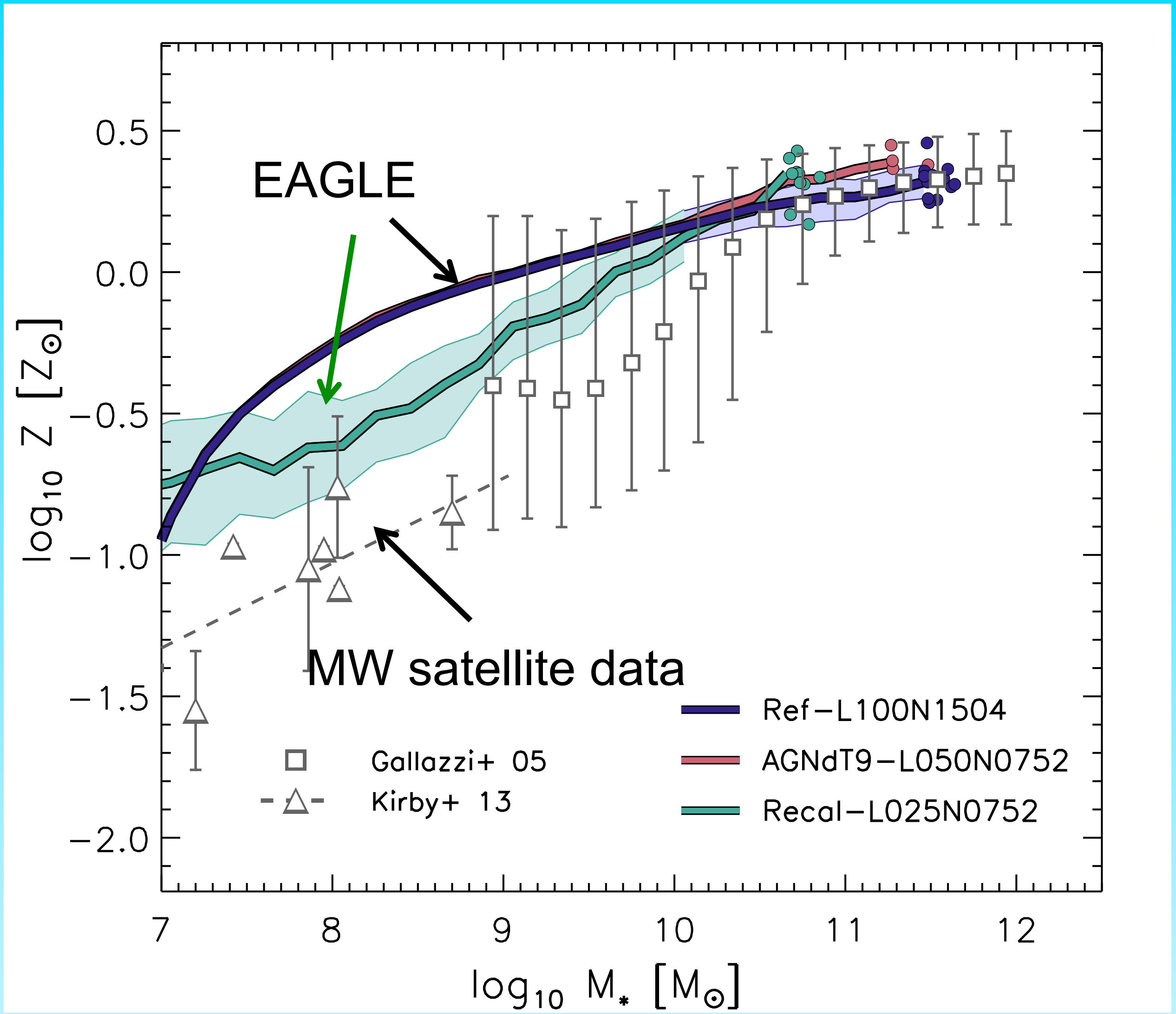
Metallicity-stellar mass relation

Not quite right!

Eagle: metal and density-dependent feeback →



correct satellite LF

correct reionization

wrong metallicity-lum reln!

SN feedback: challenges for multiobject spectroscopy

- At low z:
  - Field galaxy luminosity function to fainter limits
  - Satellite luminosity functions for external galaxies
  - Metallicities of faint galaxies
  - Escape fraction of ionizing photons
- At high z:
  - Luminosity function of star-forming galaxies
  - Escape fraction of ionizing photons

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Big questions in galaxy evolution

A subjective choice!

The 7 questions of galaxy evolution

- Cosmic star formation history and growth of stellar mass?
- The first galaxies: how was the universe reionized?
- Galaxy assembly and origin of galaxy morphology?
- Gas and metals cycling in and out of galaxies?
- Growth of supermassive black holes?
- Role of feedback processes from supernovae and AGN?
- What is the IMF? Is it universal?

Together with physics-based modelling, the next generation of multiobject spectrographs should answer at least some of the questions