Galaxy formation in a ΛCDM Universe

The semi-analytic approach

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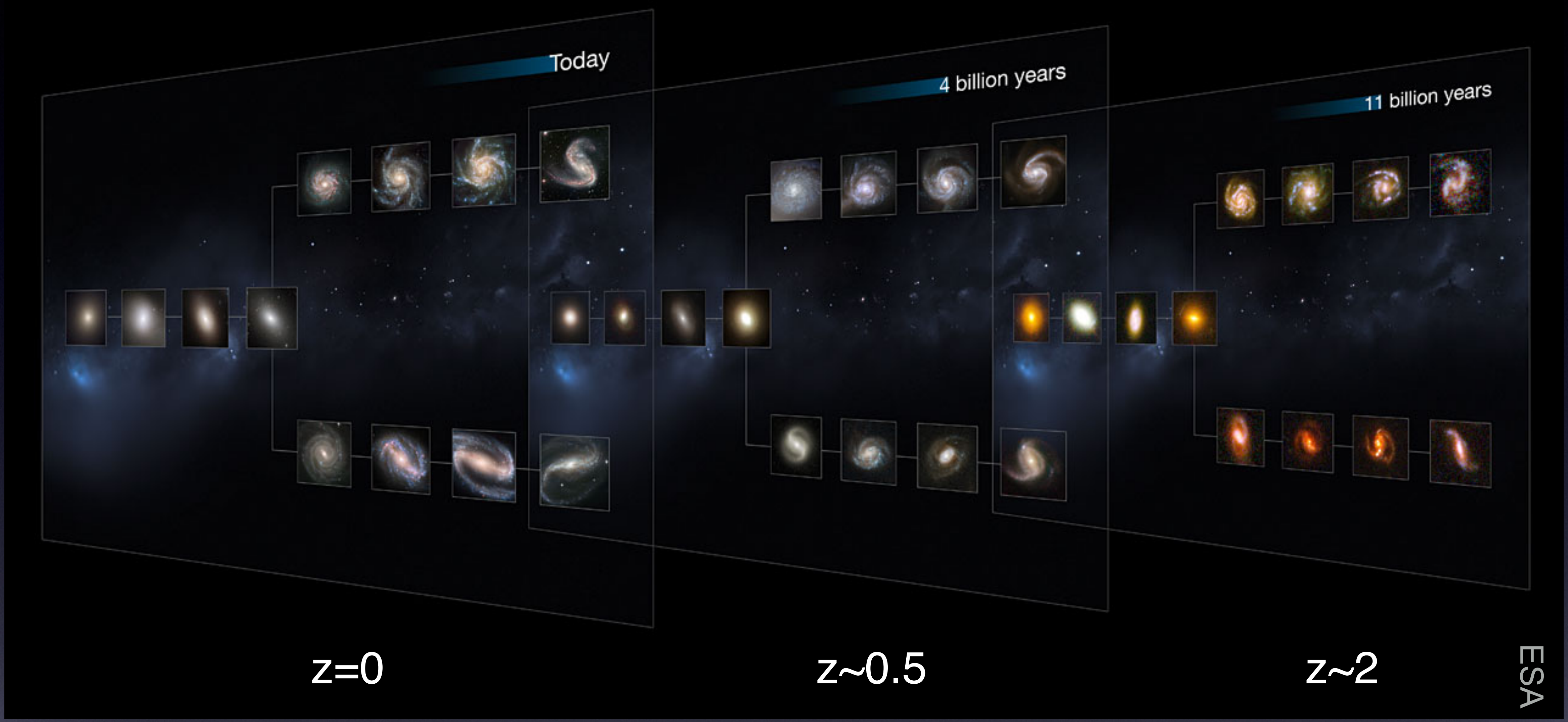
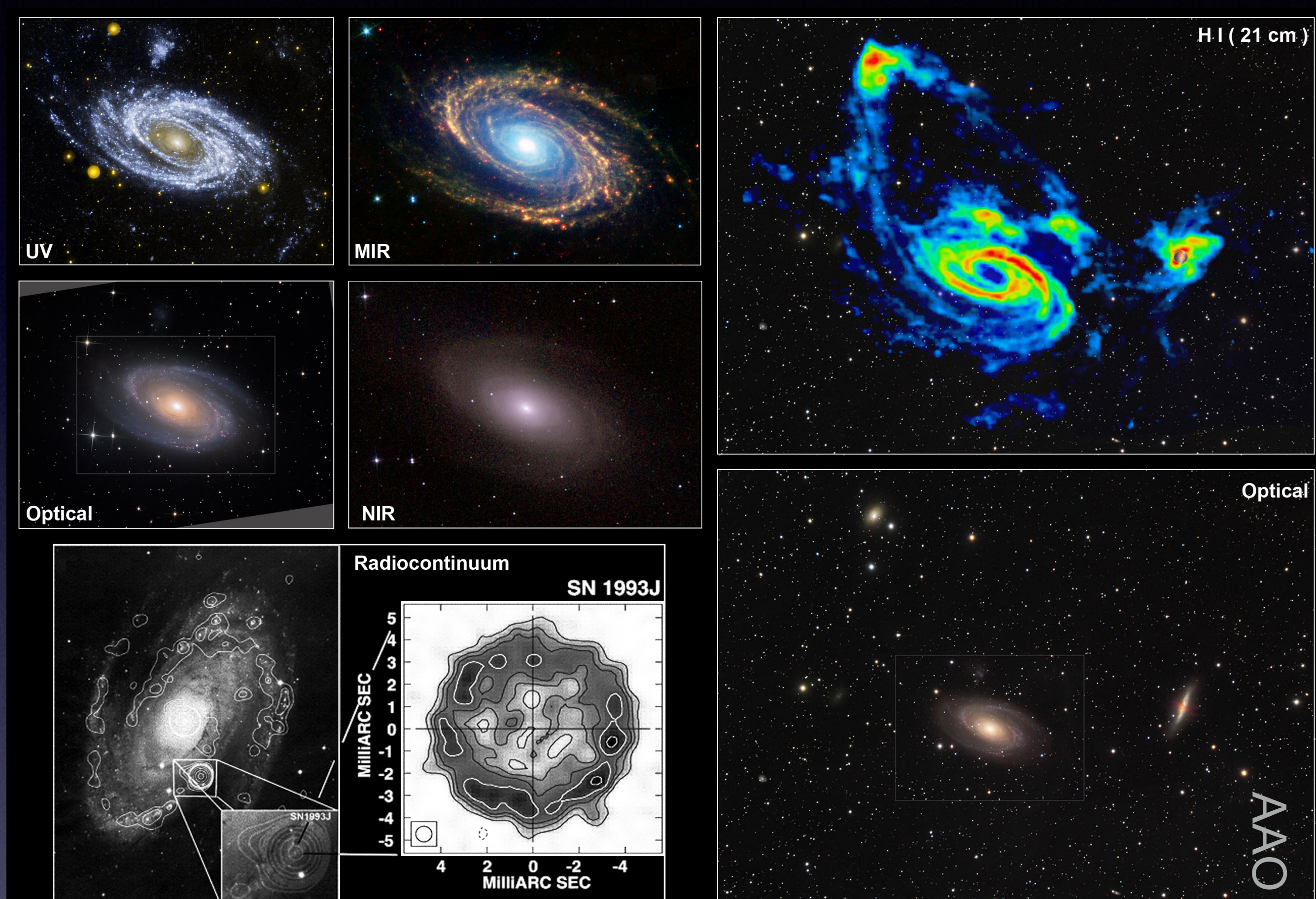
DarkSky simulation

INTRODUCTION



Wide diversity of properties (sizes, morphologies, structure, colours, etc) in the galaxy population

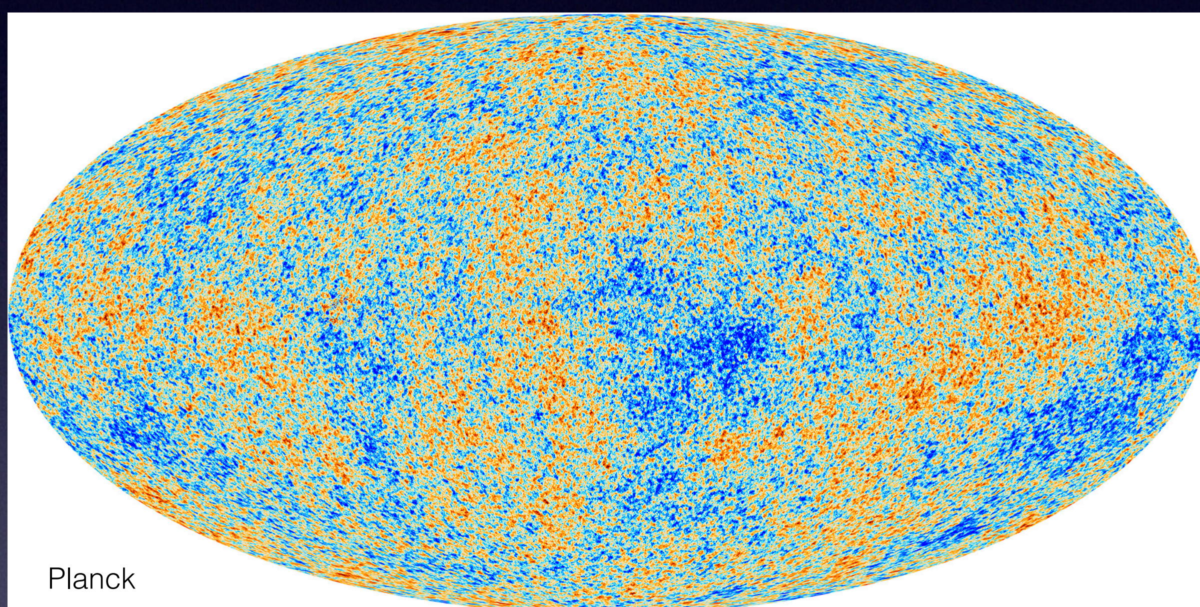
INTRODUCTION

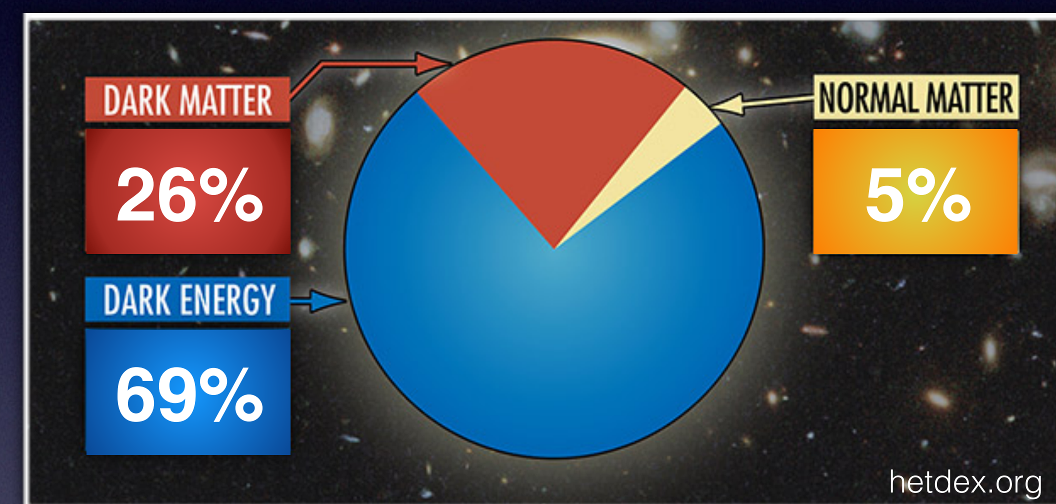


Galaxy formation is a complex process involving many physical mechanisms at once

INTRODUCTION

The semi-analytic technique is a way to (try to) model in a single framework all the physics that are relevant for galaxy formation within ΛCDM

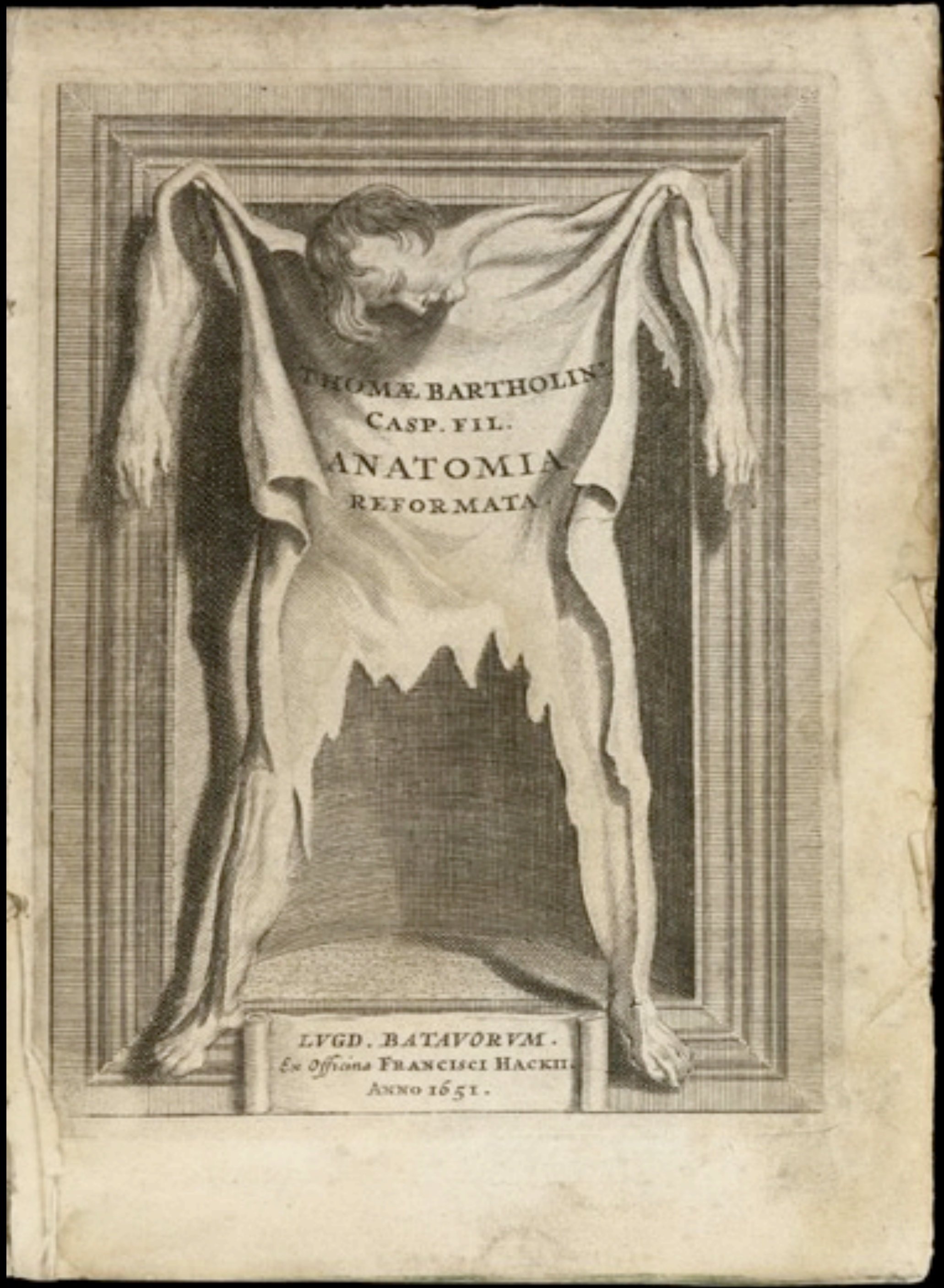




*=> **Hybrid approach** : Baryonic physics that govern galaxy formation are modelled "semi-analytically" as a post-processing step of DM cosmological simulations*

INTRODUCTION

The skeleton

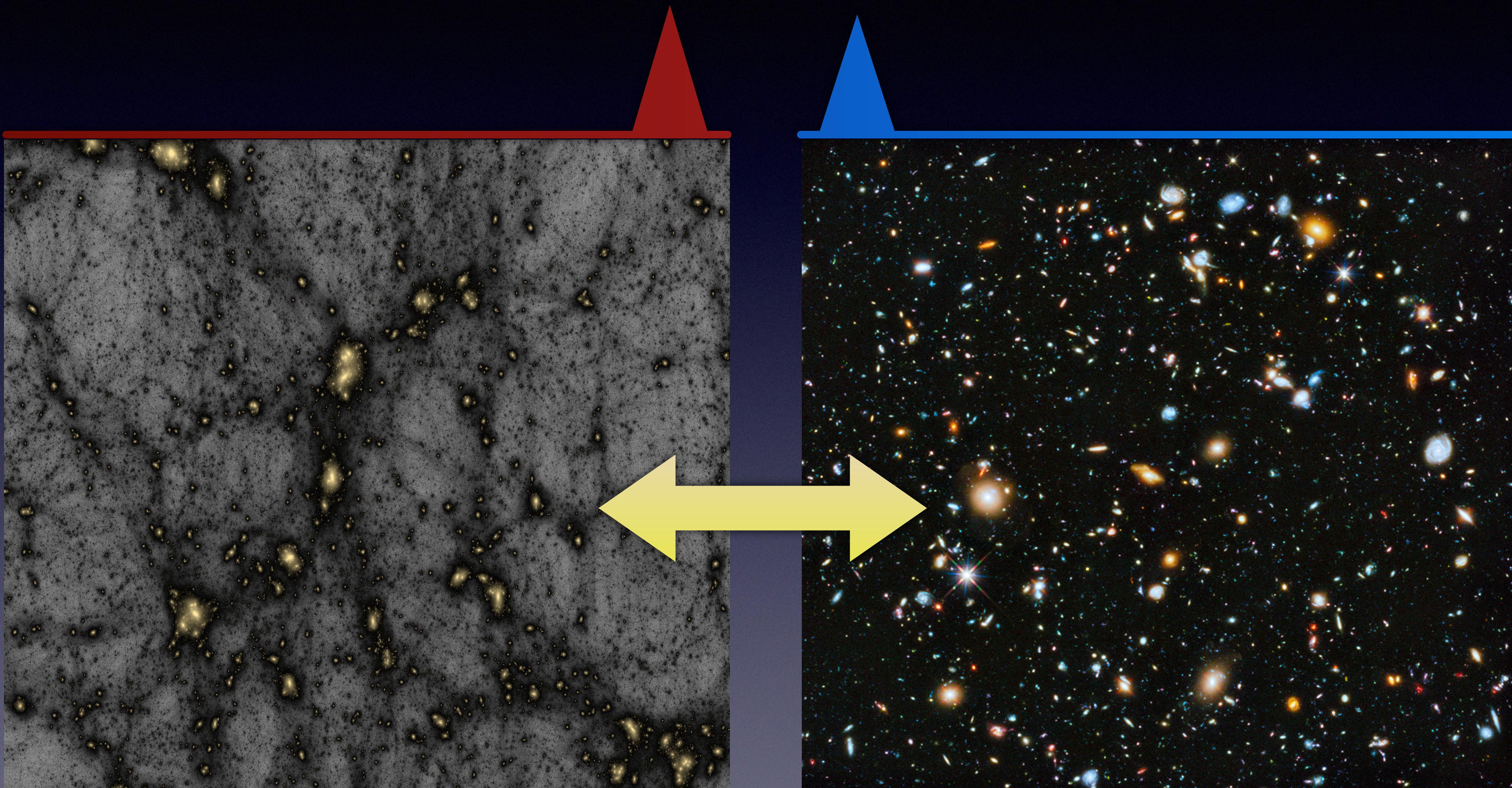


The flesh

slide by D. Croton

INTRODUCTION

How do you go from **this** to **that** ?



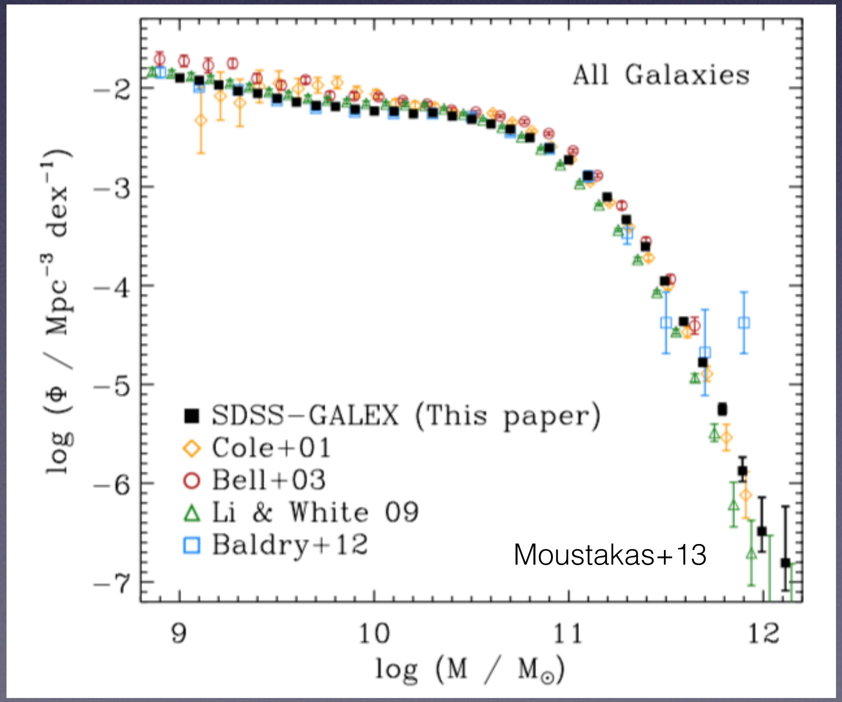
INTRODUCTION

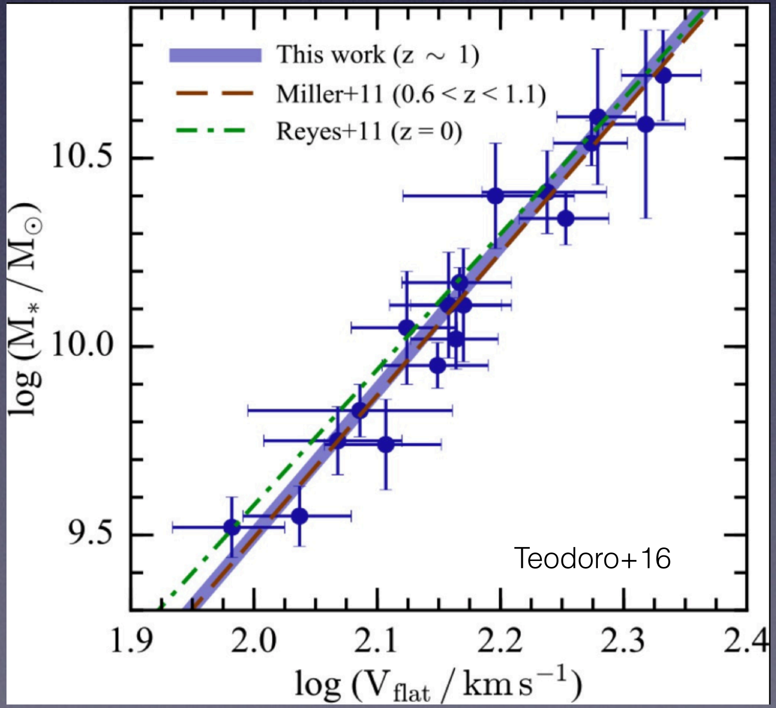
Baryonic physics modelled from :

- ✦ **First principles**
- ✦ **Physically-motivated prescriptions (e.g. from hydro simulations)**
- ✦ **Empirical laws from observations**

Large samples of virtual galaxies in cosmological volumes

Test/adjust the models by comparing with fundamental constraints from observations





INTRODUCTION

Pioneering ideas

Gas cooling regulates the galaxy mass that can form in a given DM halo

(Silk77, Binney77, Rees & Ostriker77)

Star formation needs to be **regulated**

(Silk&Dekel86, White & Frenk91, Efstathiou92, Thoul & Weinberg95, Binney & Tabor 95)

Galaxy formation as a **two-step process**
(White & Rees 1978)

- Disc formation due to **angular momentum conservation** (Fall & Efstathiou 1980, Mo et al. 1998)
- **Disc instabilities** and **mergers**

=> bars / stellar bulges
(Efstathiou 1982, Barnes 1988)

First SAMs in the early 90s **(White & Frenk 1991; Lacey & Silk 1991 ; Kauffmann, White & Guiderdoni 1993; Cole et al. 1994, Somerville & Primack 1999 etc)**

OUTLINE

- Cosmological simulations of dark matter
- Physics of galaxy formation in semi-analytic models
- High-redshift galaxies in GALICS
- How to generate mock observables from SAMs

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DARK MATTER SKELETON

To model galaxy formation in a ΛCDM Universe using the SA technique, we first need to describe the hierarchical growth of DM haloes:

(i) the **abundance** (i.e. the *halo mass function*) of DM halos at a given time,

(ii) their **formation histories** (i.e. the *merger trees*),

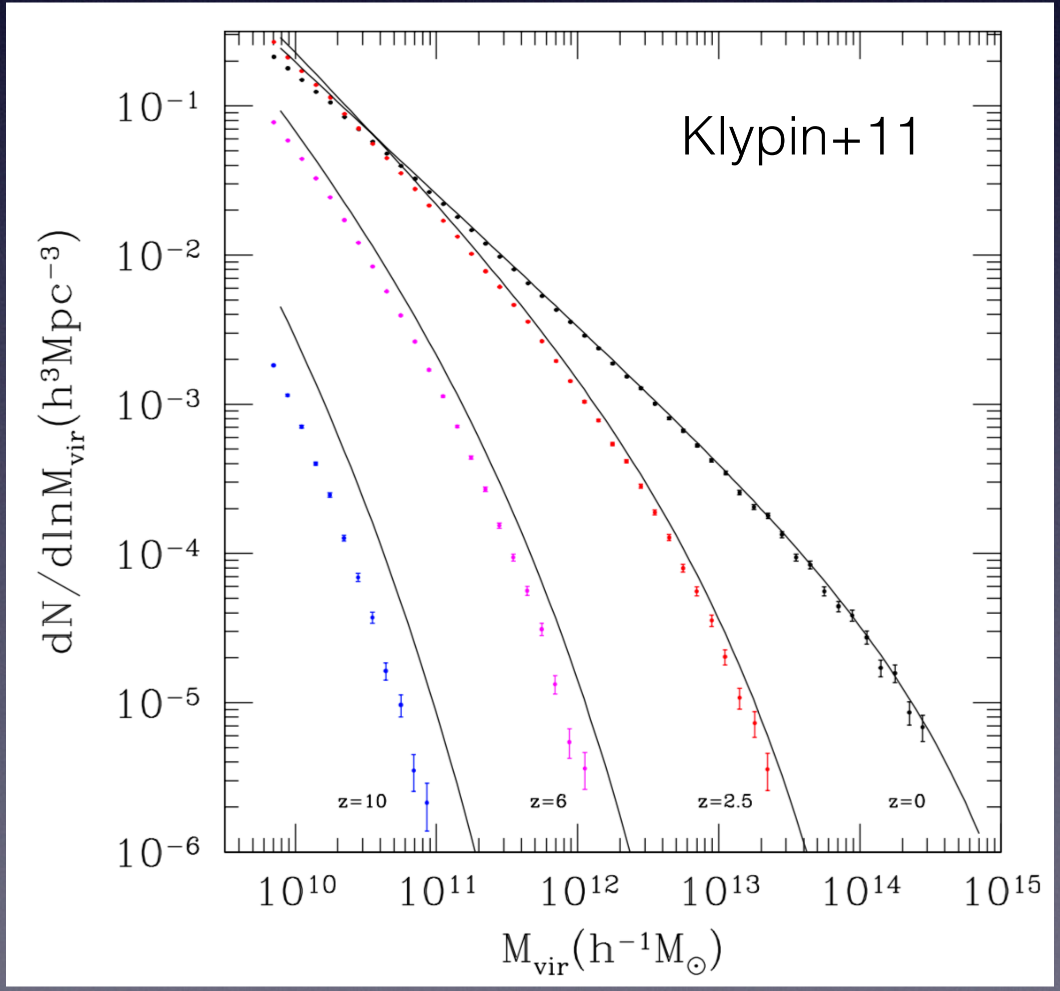
(iii) the **physical properties** of each individual halo.

✦ **Press-Schechter formalism (and its variants)**

Halo abundances estimated analytically.
Merger trees generated with a Monte-Carlo approach by sampling the distribution of progenitors using PS theory.

✦ **Cosmological N-body simulations of DM**

=> information on the spatial distribution and dynamics of haloes
=> more accurate than PS formalisms
(e.g. Governato et al. 1999; Jenkins et al. 2001)

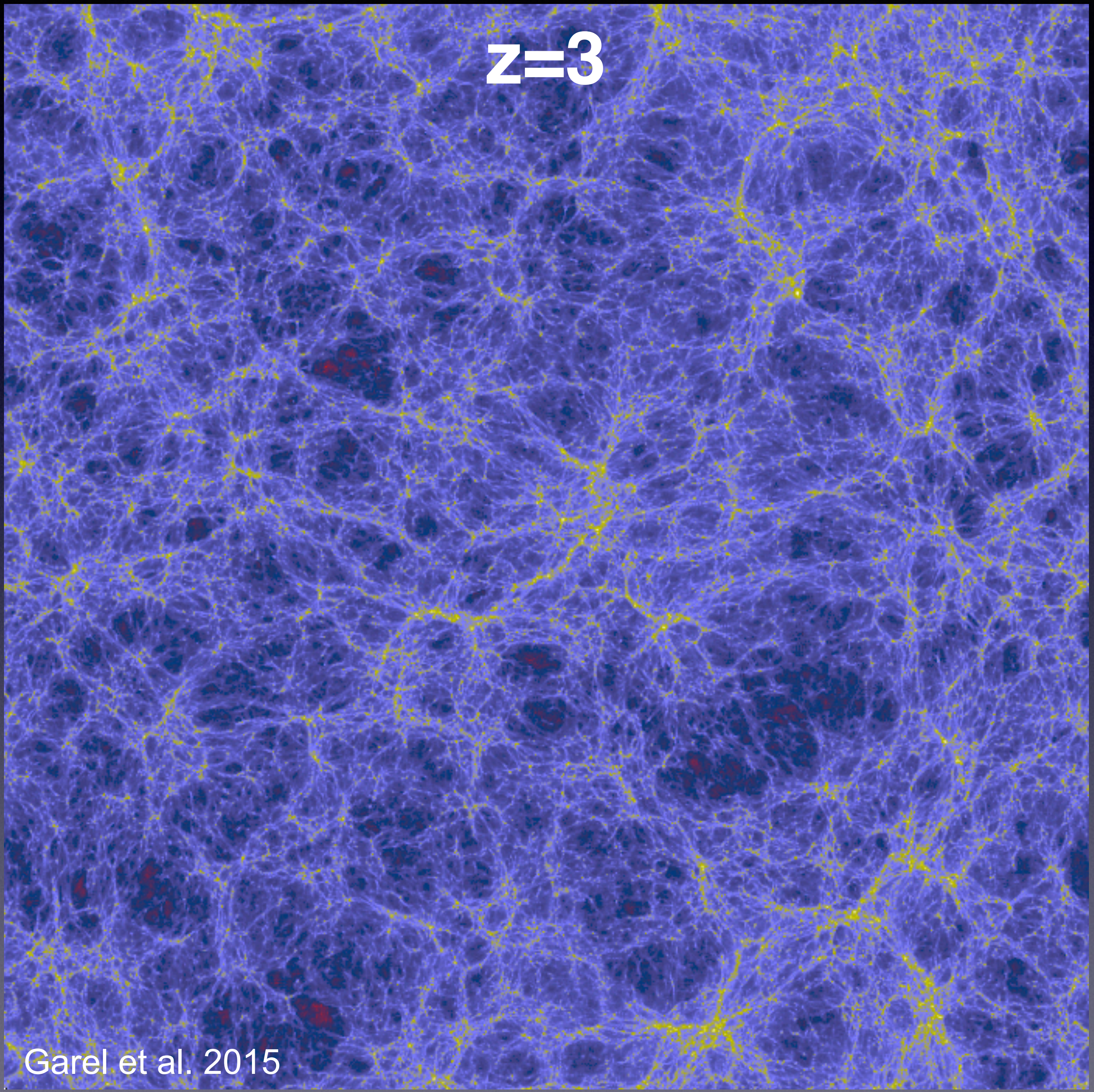


Cosmological N-body simulations

- DM "particles" used to sample the 3D density field in a representative volume (a box) of Universe
- Initial conditions set by cosmology
- Follow the dynamical evolution of collisionless DM particles (gravitational interactions only)

$$\mathrm{M_p} = \frac{\rho_0 V_\mathrm{b}}{N_\mathrm{p}}$$

$$\rho_0 = 2.7755 \times 10^{11} \Omega_\mathrm{m} \mathrm{h}^2 \mathrm{M}_\odot.\mathrm{Mpc}^{-3}$$



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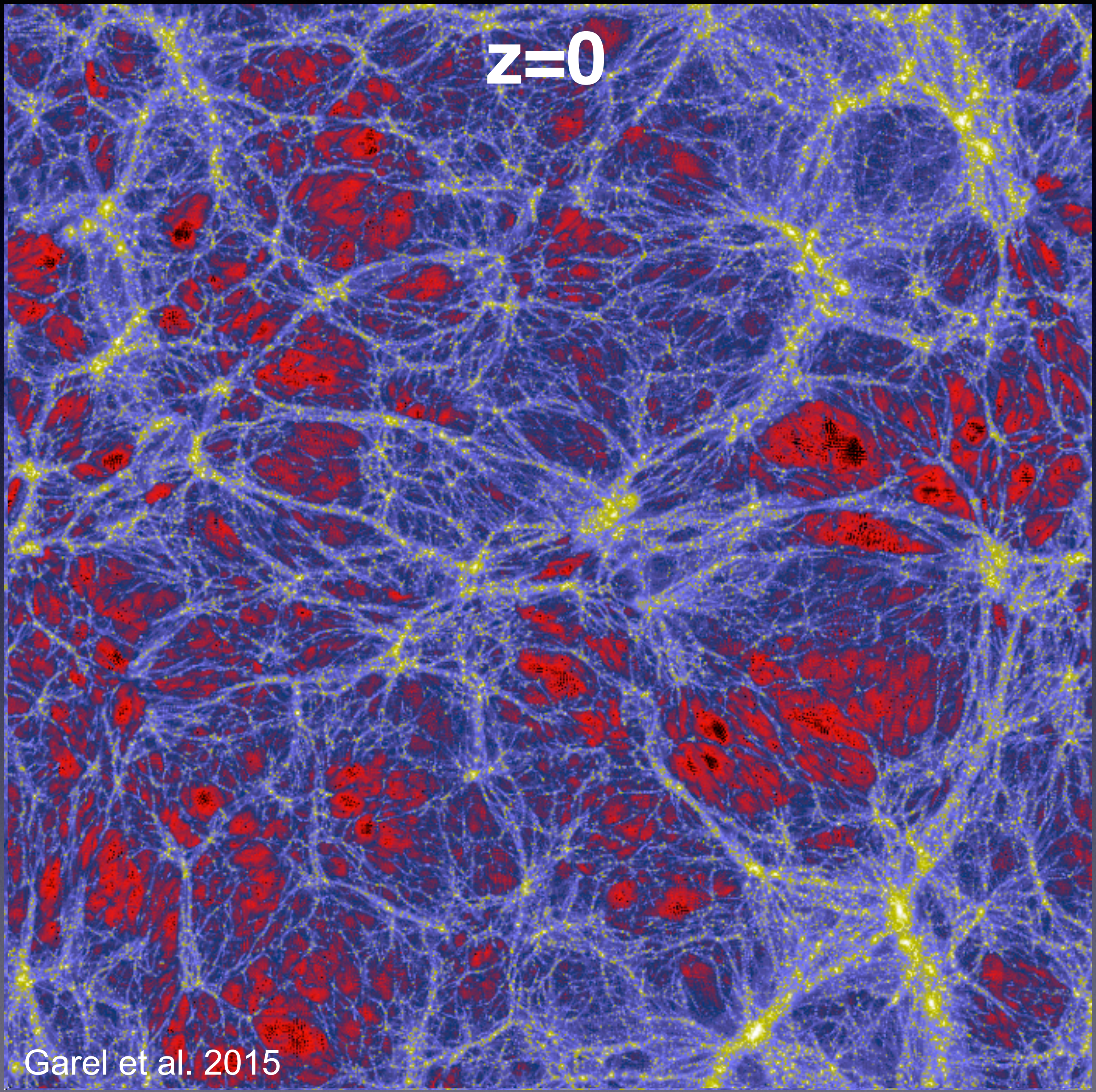


Cosmological N-body simulations

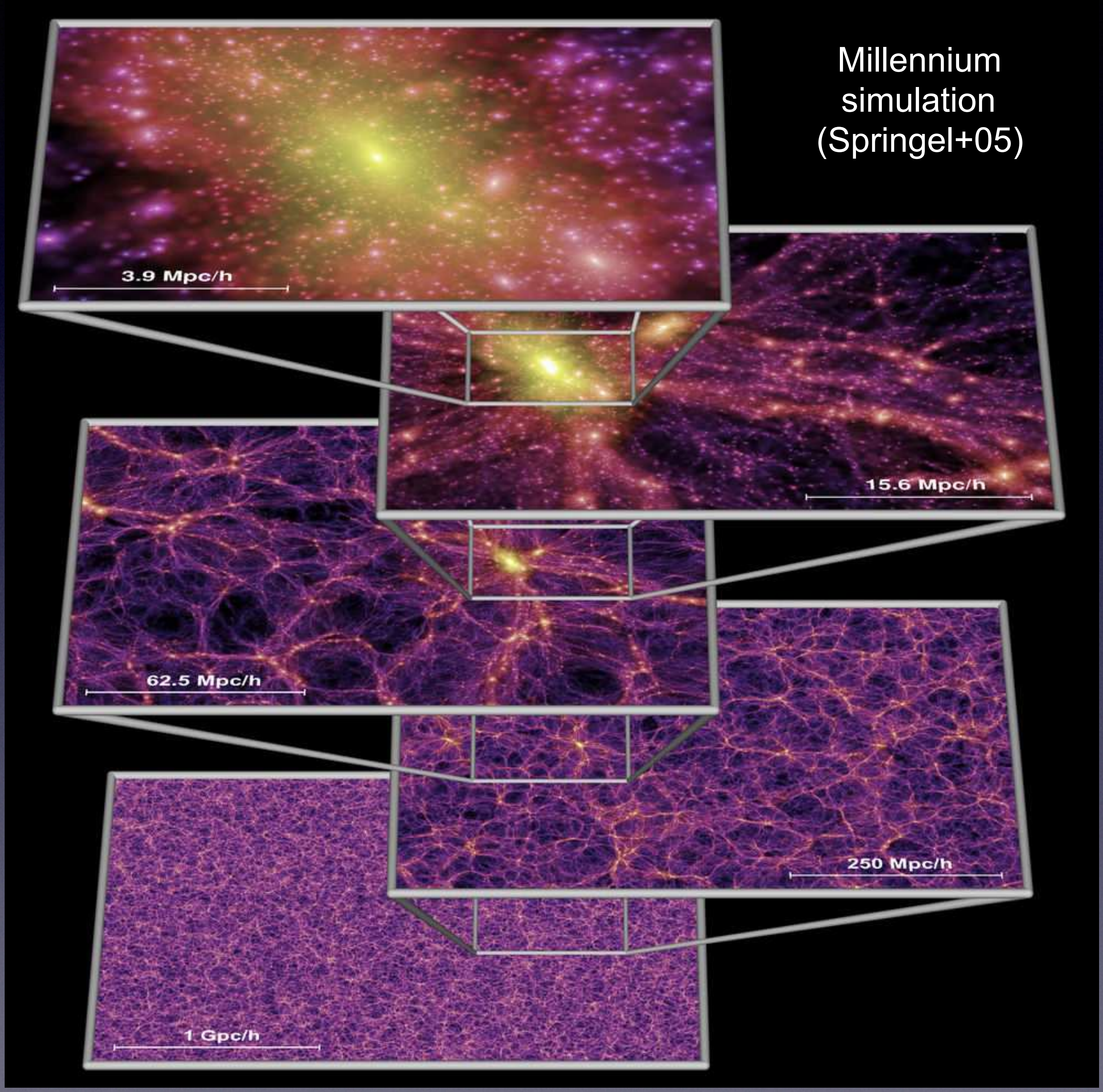
Cosmological simulations need to span a wide dynamic range.

Small particle mass

=> resolve low-mass haloes ($min(M_{halo}) = 20\text{-}100 \times M_p$) & internal structure

Large volume

=> include density fluctuations on large scales
=> enough statistics to get representative sample of haloes and rare (i.e. massive) objects in particular



HALO IDENTIFICATION

Several methods to identify DM halos:

- Friends-Of-Friends (FOF; Davies et al. 1985) algorithms link together all particles separated by less than a characteristic distance (the *linking length*)
- Another way is to use an overdensity threshold to identify density peaks, the i.e. haloes (e.g. Bertschinger & Gelb 1991)

Physical properties

Keep particles that are gravitationally bound
=> virial mass M_{vir}

R_{vir} is the radius of the spherical overdensity of mass M_{vir}

$$\Delta\rho = \frac{3M_{\rm vir}}{4\pi R_{\rm vir}^3}$$

"Spin" parameter

$$\lambda = \frac{|E|^{1/2} J}{G M_{\rm vir}^{5/2}}$$

HALO MASS FUNCTIONS

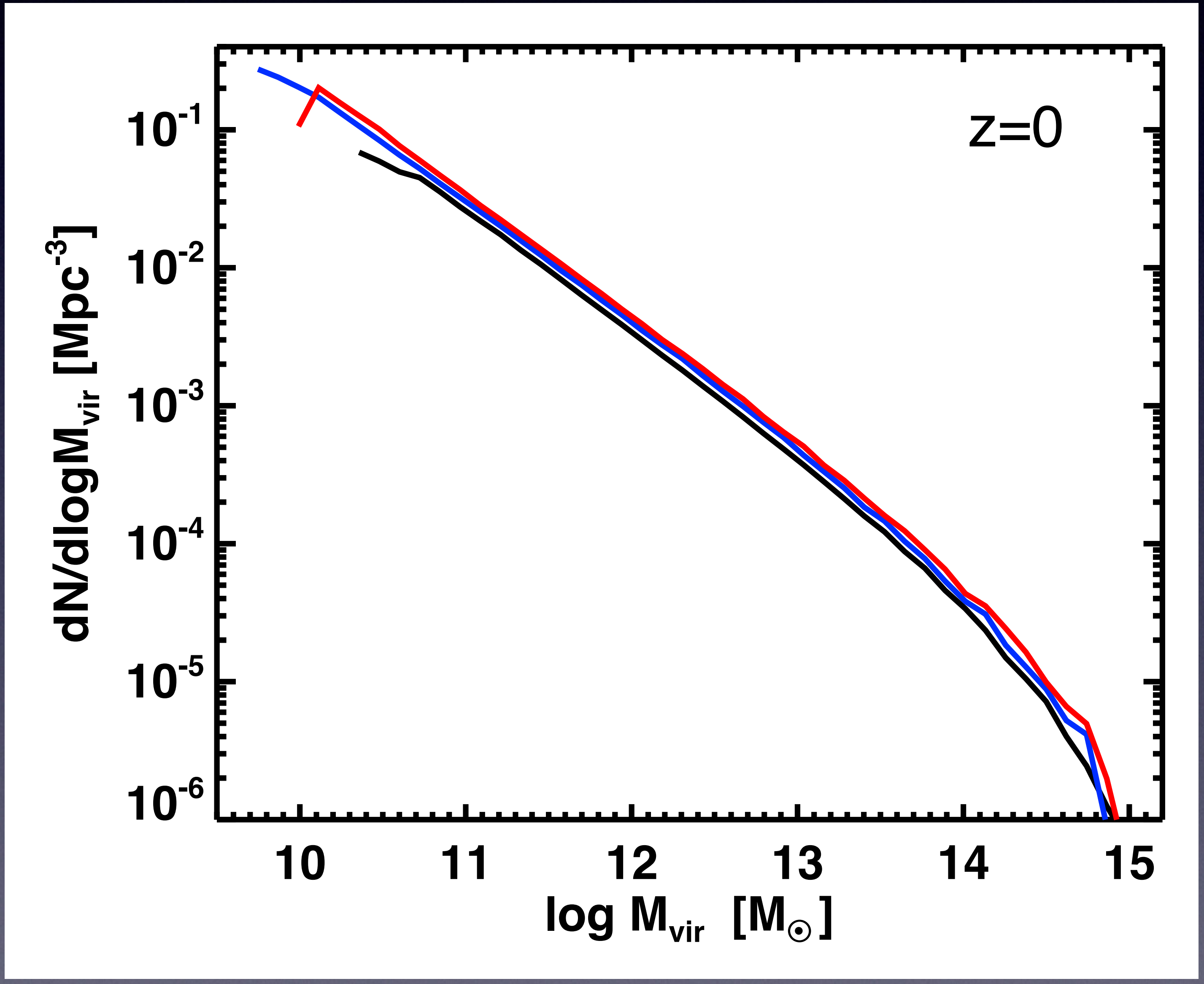
HMF for different cosmologies

Millennium (Springel+01) : WMAP-1

Bolshoi (Klypin+11) : WMAP-5

Bolshoi-Planck (Klypin+16): Planck

	h_{100}	Ω_Λ	Ω_m	σ_8	n
Millennium	0.73	0.75	0.25	0.90	1.0
Bolshoi	0.70	0.73	0.27	0.82	0.95
Bolshoi Pl.	0.68	0.69	0.31	0.82	0.96



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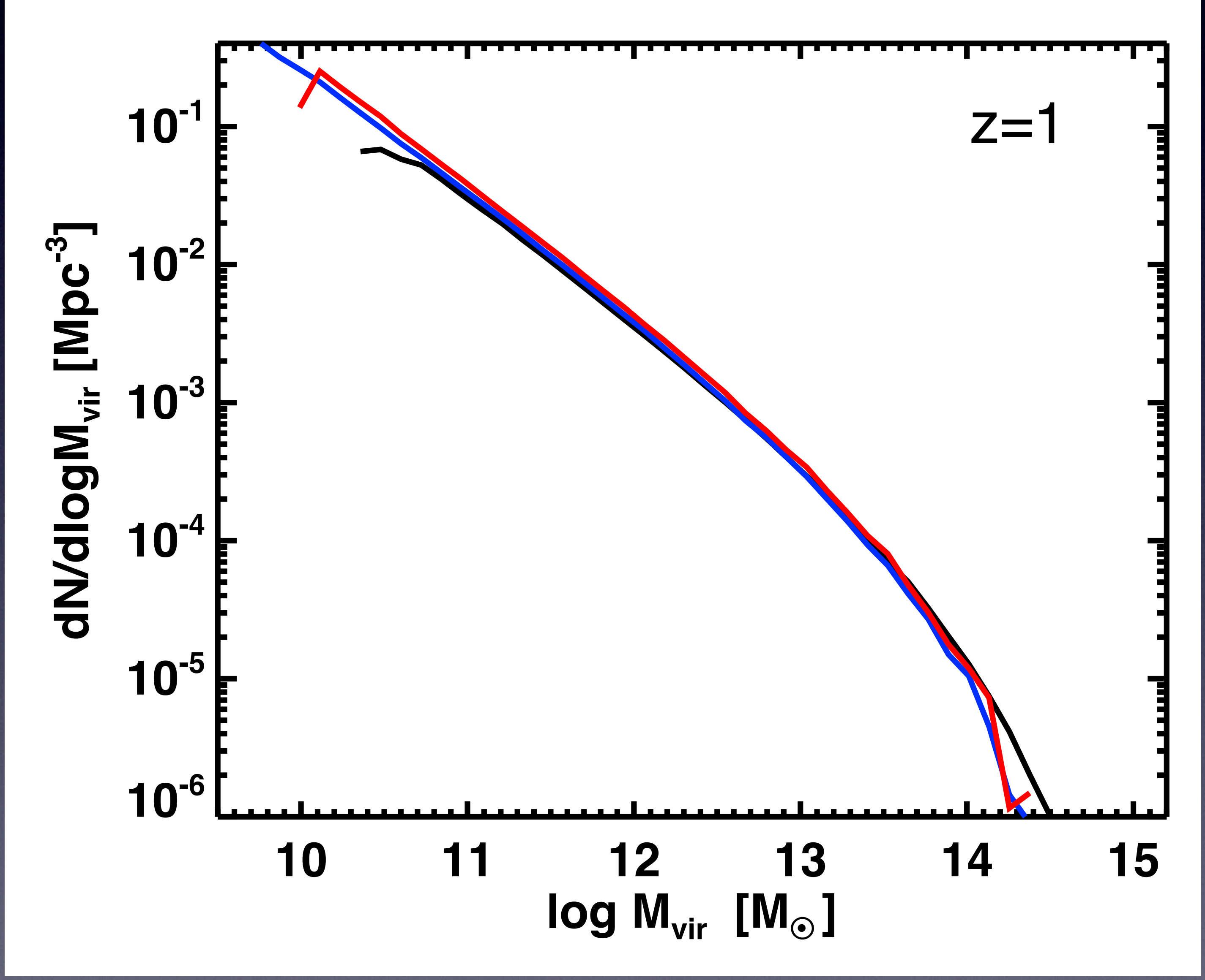

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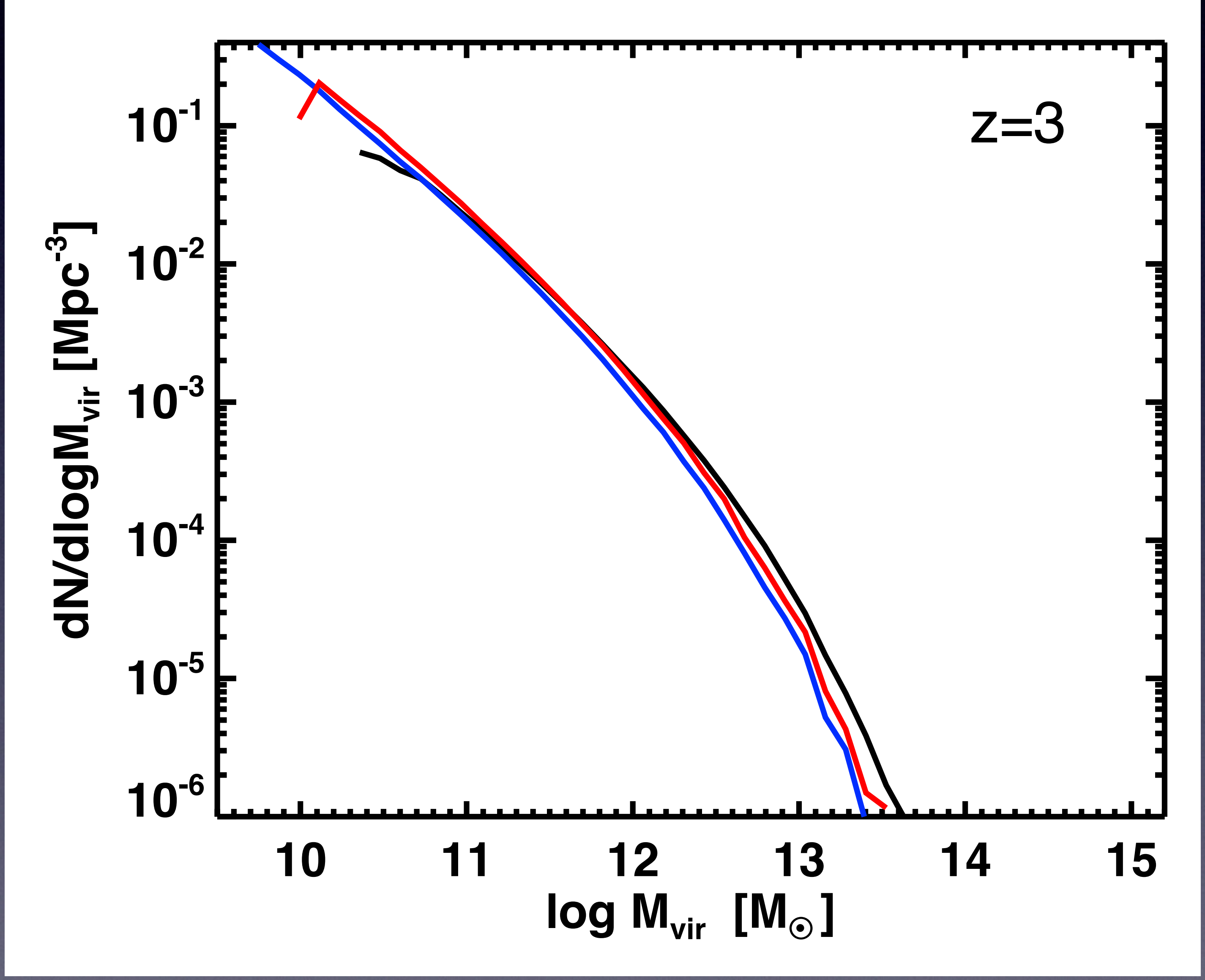

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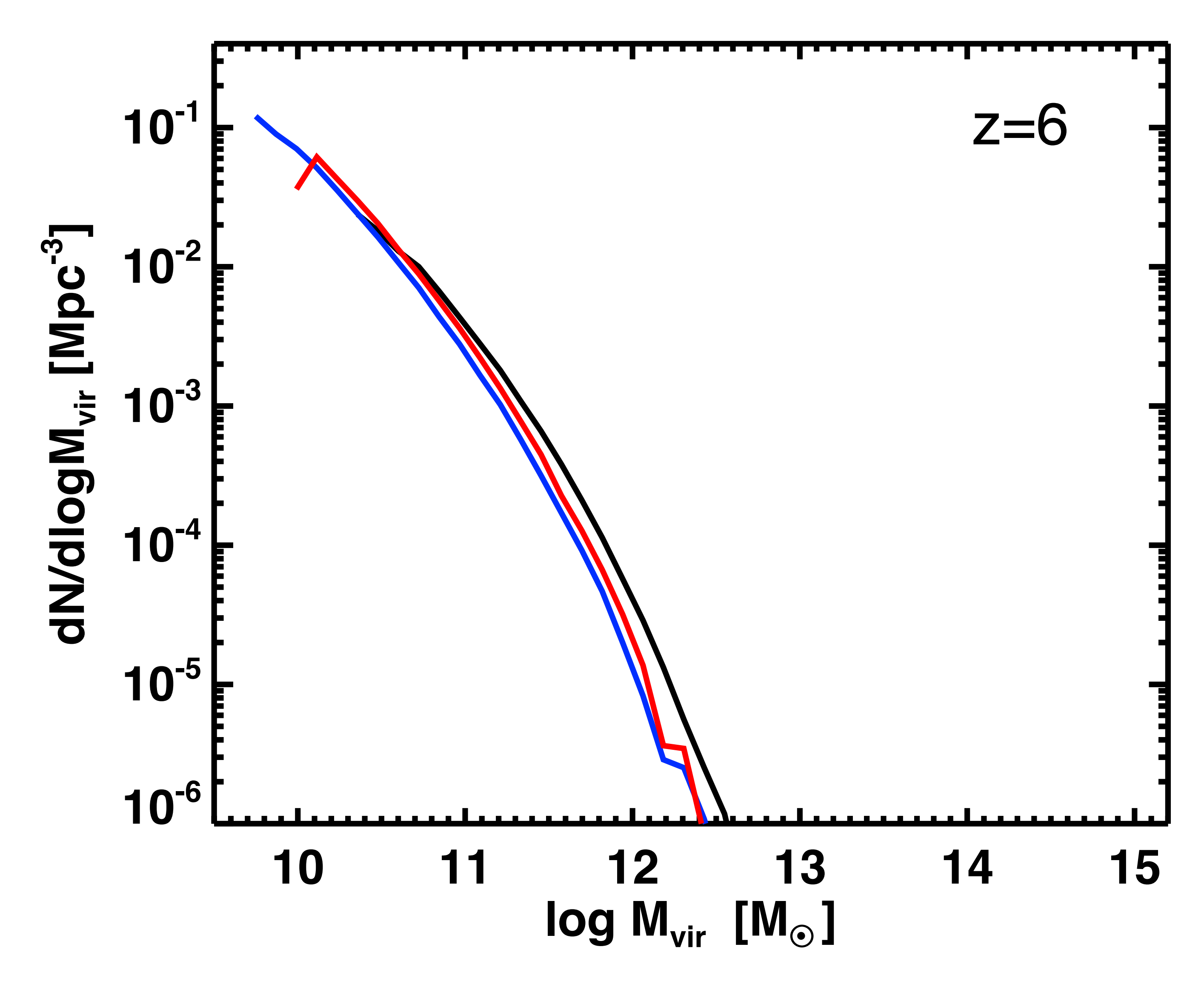

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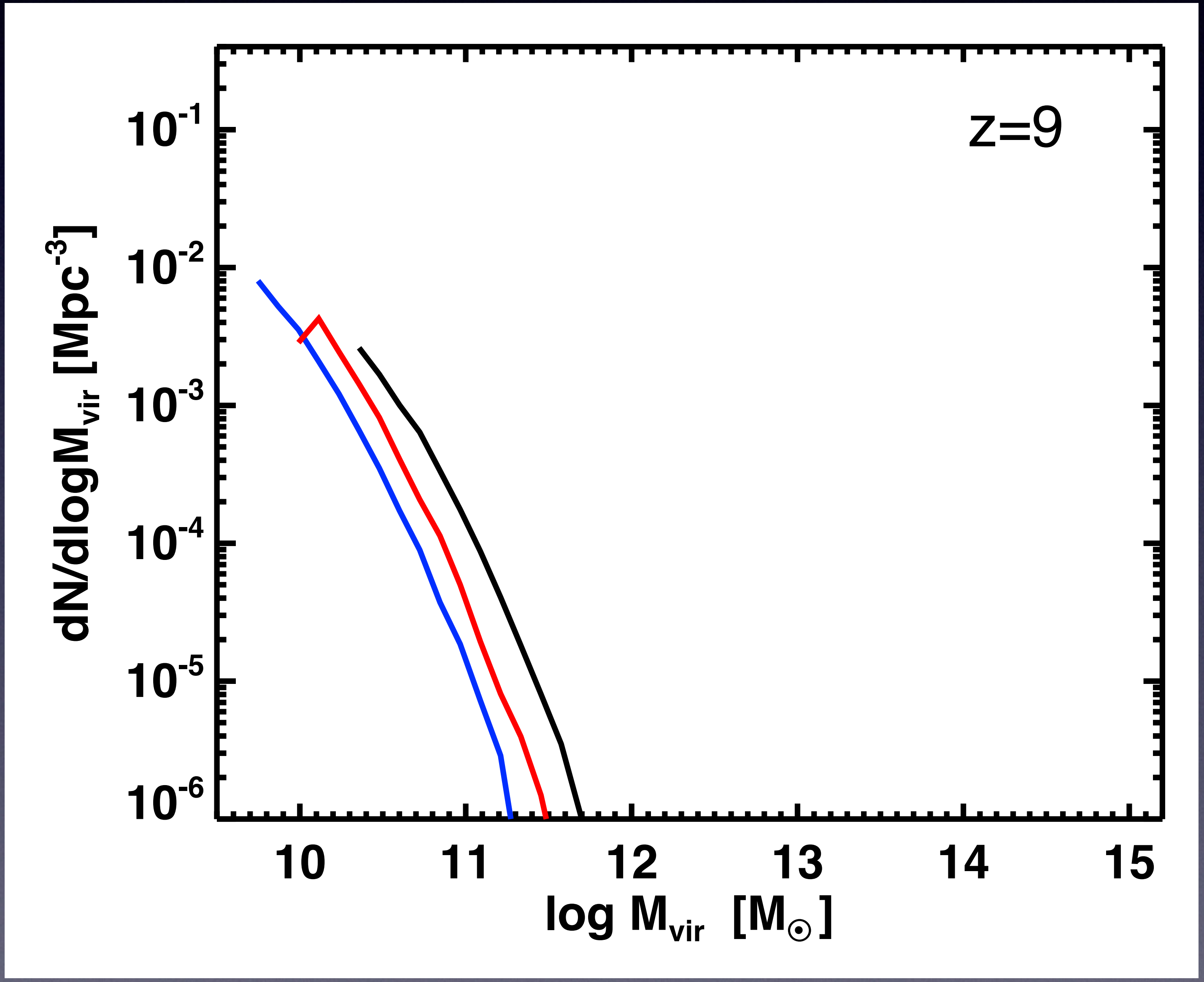

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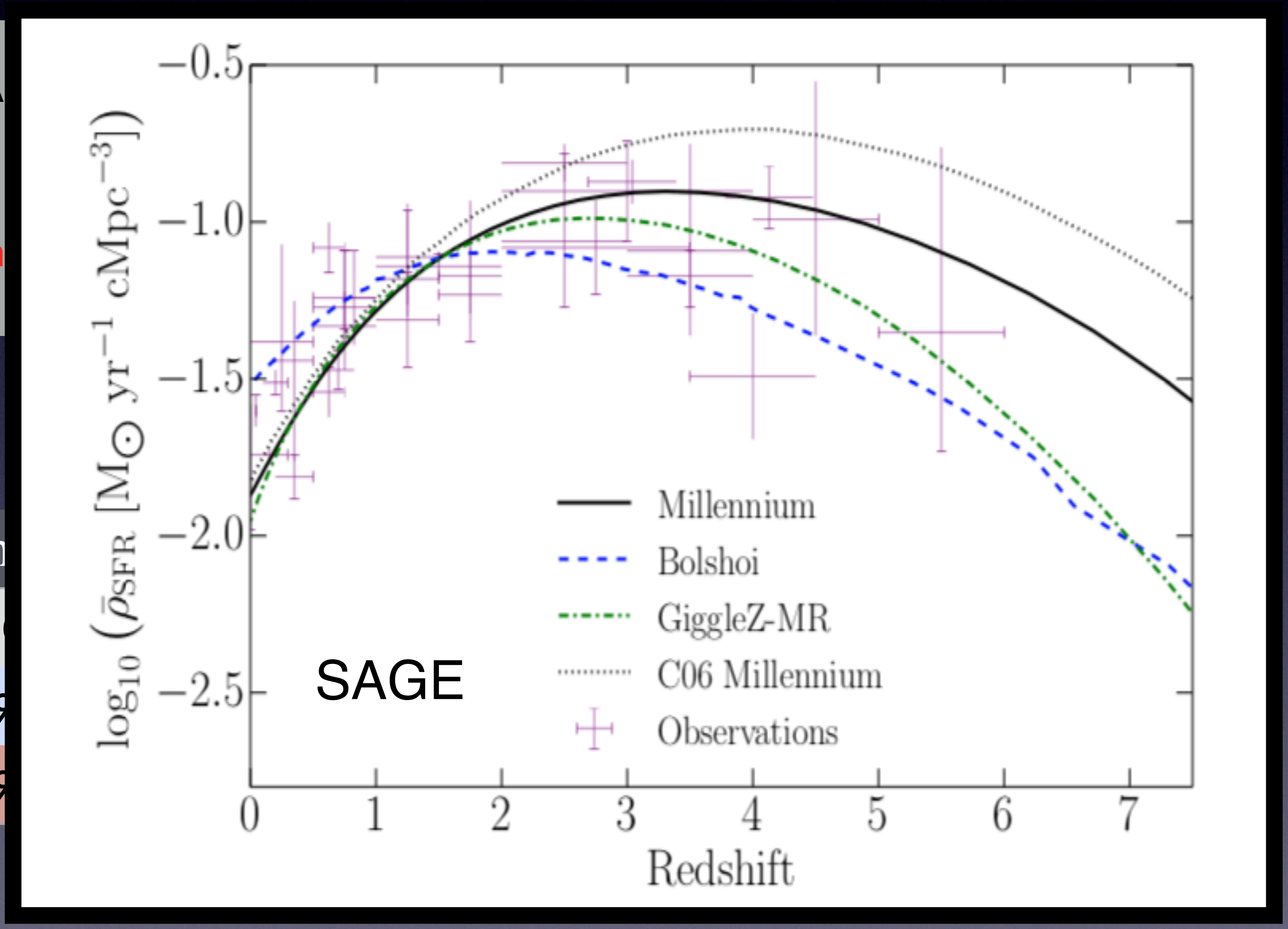


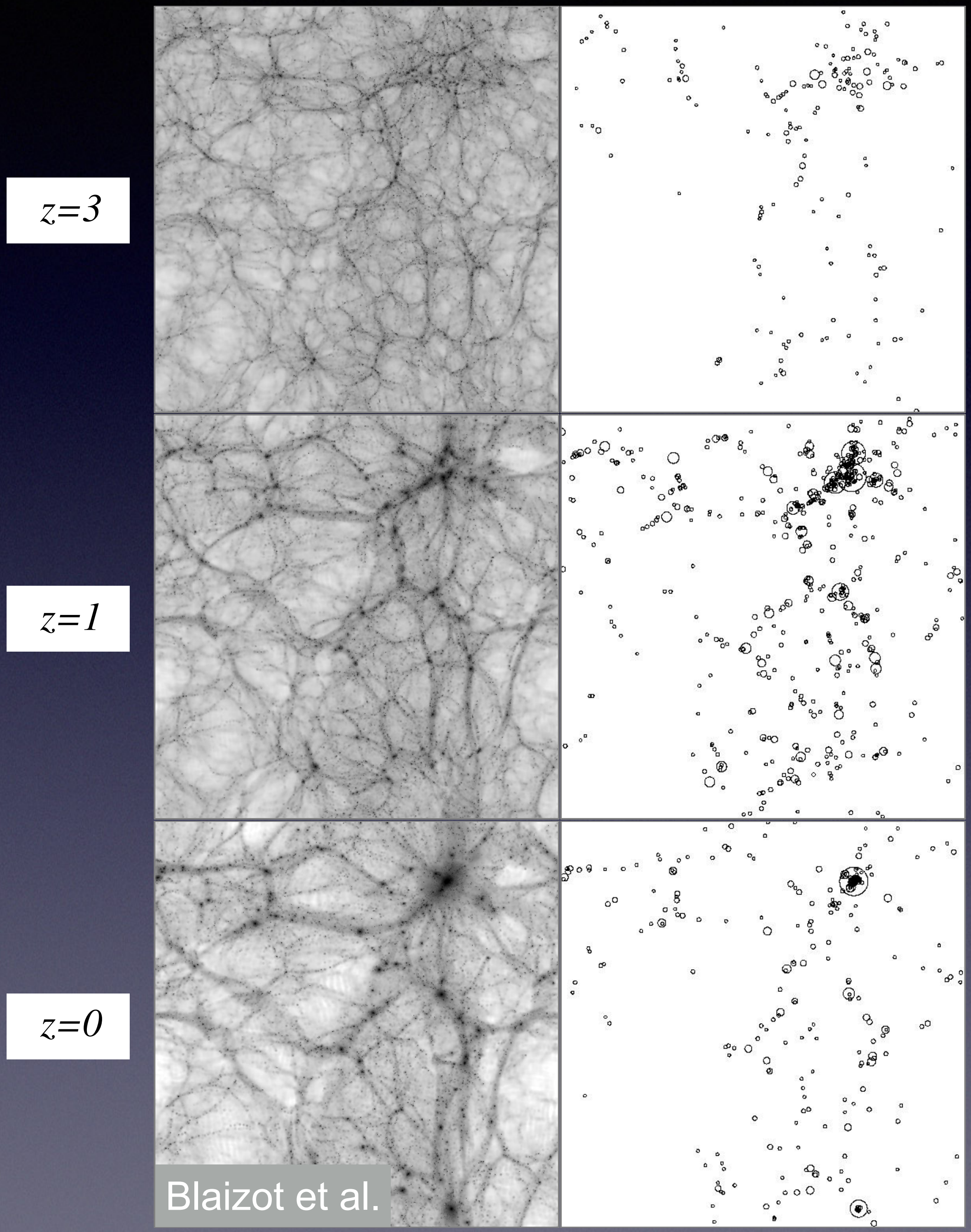
HALO MERGER TREES

Record the halo growth (mergers & diffuse accretion)

Link the haloes between snapshots

- *Identify progenitors in earlier snaphots & descendants in later snapshots*
- *Different methods to track progenitors & descendants (see Lee+14)*
- *Usually, a halo can have many progenitors but only one descendant*

All the DM information needed by SAMs is encoded in the merger trees



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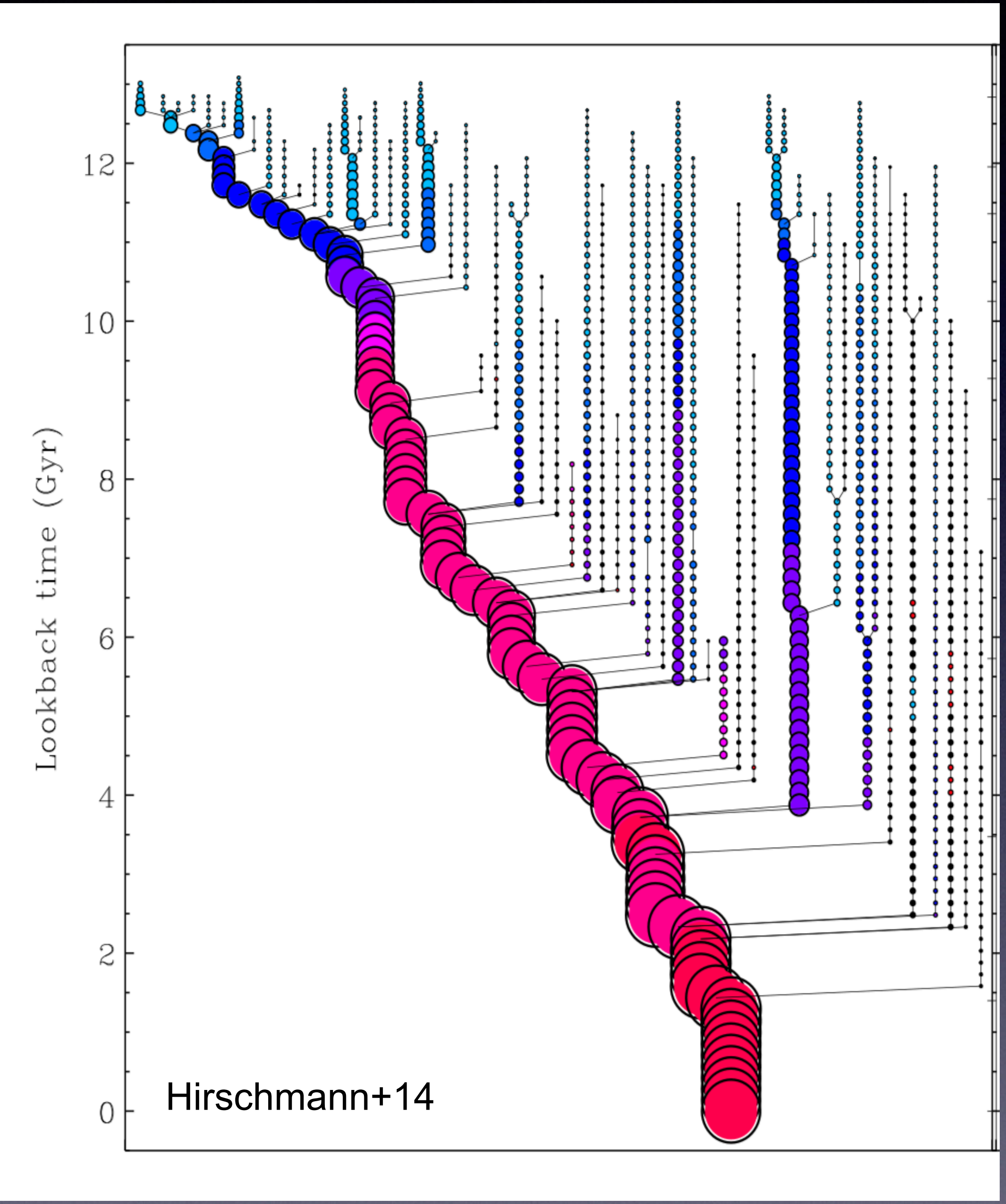

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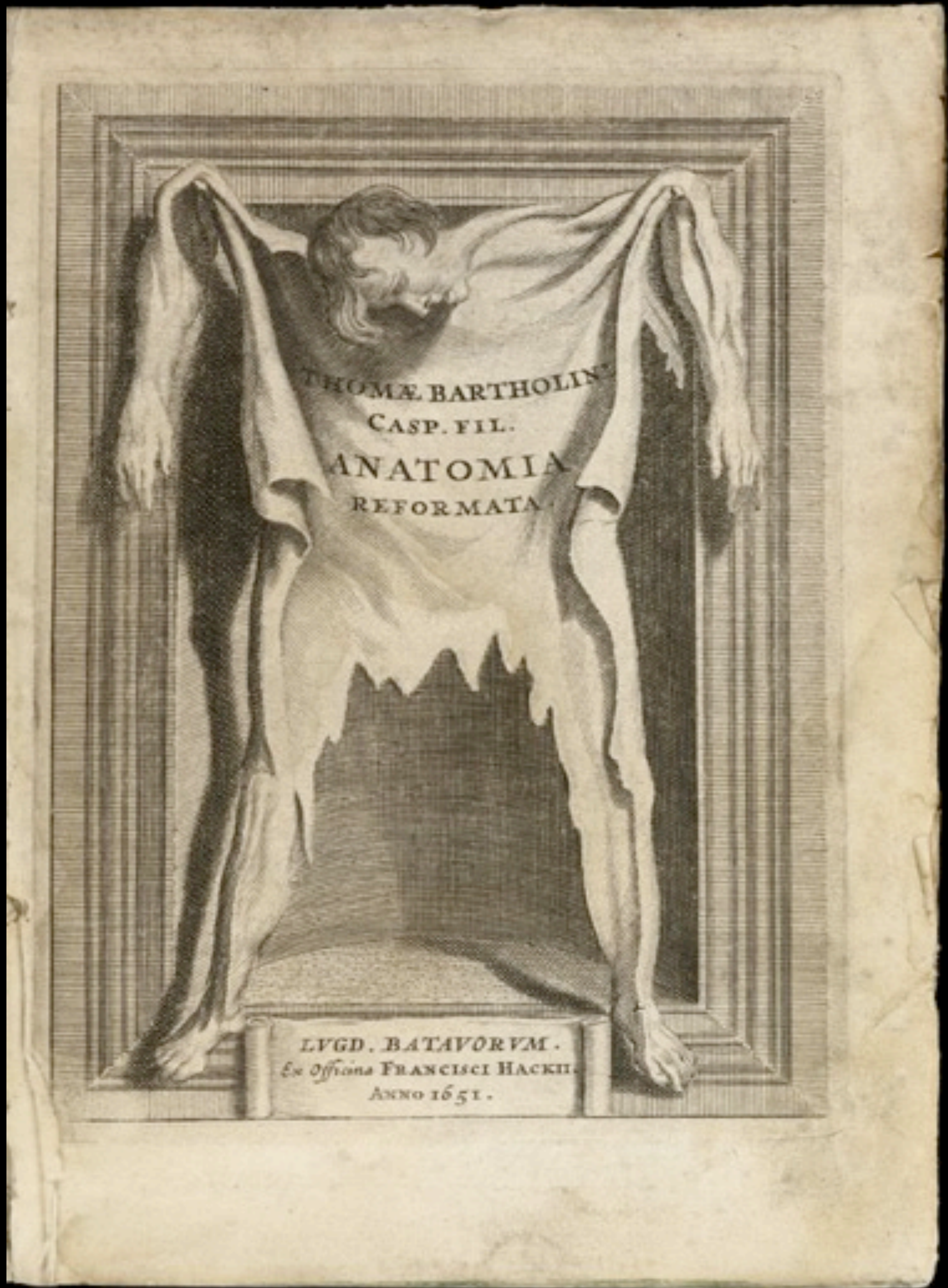
The skeleton



The flesh

OUTLINE

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- **Physics of galaxy formation in semi-analytic models**
- High-redshift galaxies in GALICS
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Schematic view of semi-analytic galaxies

Baryonic cycle described by a set of differential equations

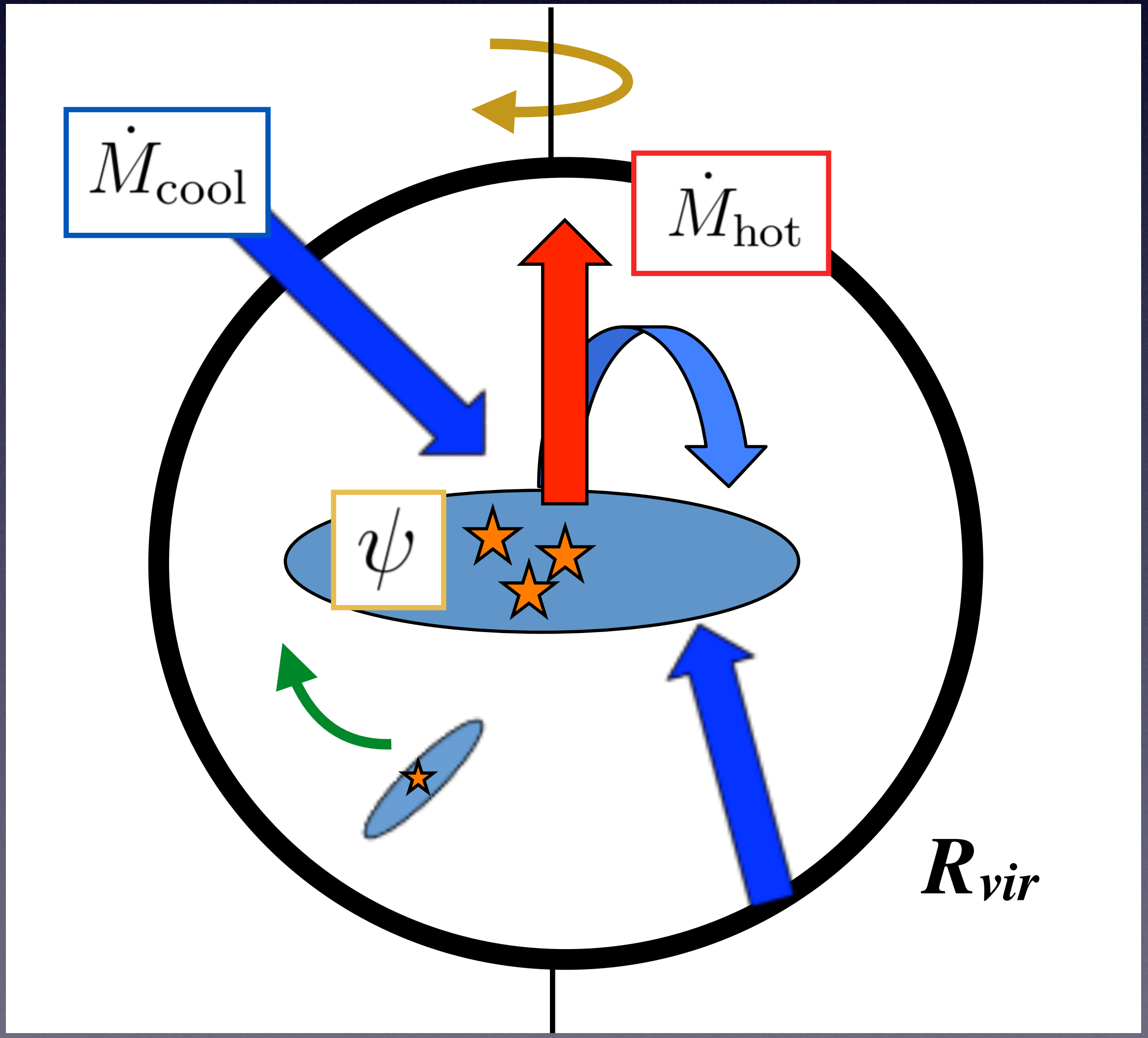
(solved numerically over substeps between each snapshot)

Baryonic content of a halo divided in several components/reservoirs:

- *Hot gas halo*
- *Cold gas disc*
- *Stellar disc*
- *Stellar bulge*
- *Intra-cluster stars etc*

Gas accretion onto the halo = $f_{\rm baryon}\frac{dM_{\rm DM}}{dt}$

$$\begin{aligned}
\psi &= \textit{star formation rate (SFR)} \\
\dot{M}_{\rm cold} &= \dot{M}_{\rm cool} - (1 - R + \beta)\psi \\
\dot{M}_{\rm hot} &= -\dot{M}_{\rm cool} + \beta\psi \\
\dot{M}_{\star}^{Z} &= (1 - R)Z_{\rm cold}\psi \\
\dot{M}_{\rm cold}^{Z} &= \dot{M}_{\rm cool}Z_{\rm hot} \\
&+ (p\,(1 - e) - (1 + \beta - R)Z_{\rm cold})\psi \\
\dot{M}_{\rm hot}^{Z} &= -\dot{M}_{\rm cool}Z_{\rm hot} + (p\,e + \beta Z_{\rm cold})\psi.
\end{aligned}$$



POPULAR SEMI-ANALYTIC MODELS

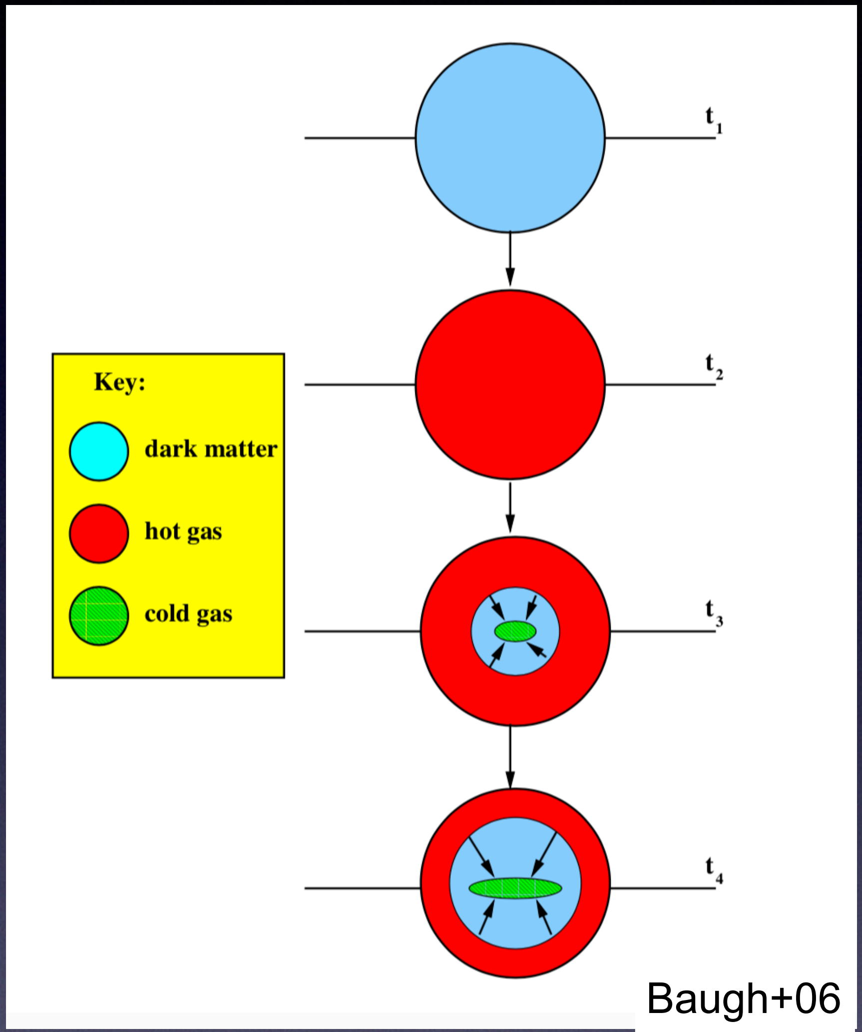
POPULAR SEMI-ANALYTIC MODELS

GAS COOLING (in SAGE)

Gas infalling into the halo is heated by shocks and settles into an isothermal sphere in hydrostatic equilibrium

$$\rho_g(r) = \frac{m_{\rm hot}}{4\pi R_{\rm vir} r^2}$$

Hot gas (excited state)
=> radiative cooling (de-excitation + photon emission)
=> pressure support drops
=> gas sinks to the center



Baugh+06

Cooling time

$$t_{\rm cool} = \frac{3}{2}\frac{\bar{\mu} m_{\rm p} kT}{\rho_g(r)\Lambda(T, Z)}$$

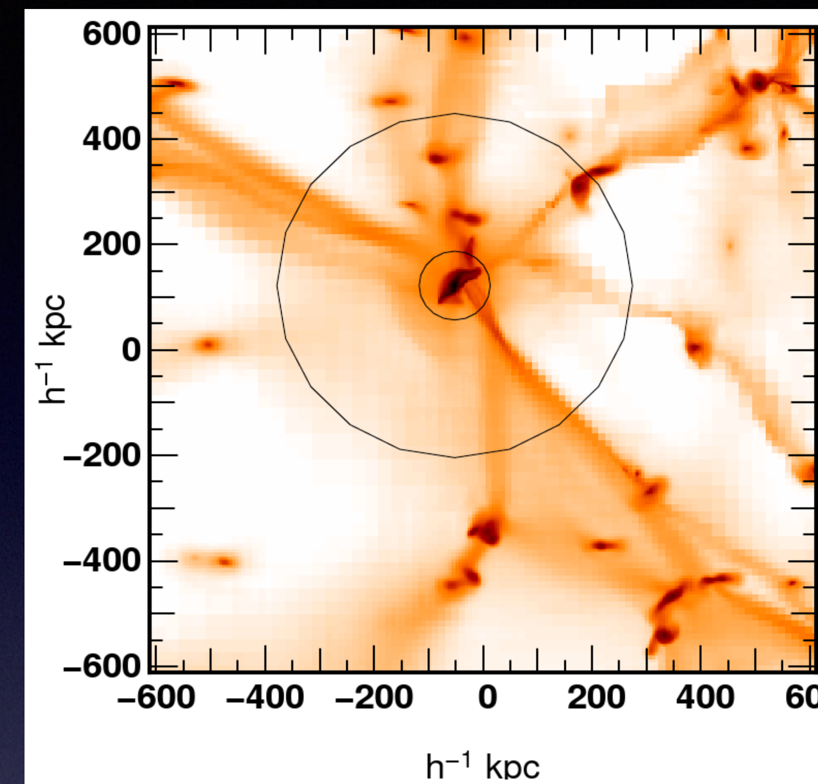
tcool < tdyn : rapid cooling

tcool > tdyn : less efficient cooling

$$\dot{m}_{\rm cool} = \frac{1}{2}\left(\frac{r_{\rm cool}}{R_{\rm vir}}\right)\left(\frac{m_{\rm hot}}{t_{\rm cool}}\right)$$

GAS COOLING (in GALICS)

Hydrodynamic simulations at high redshift

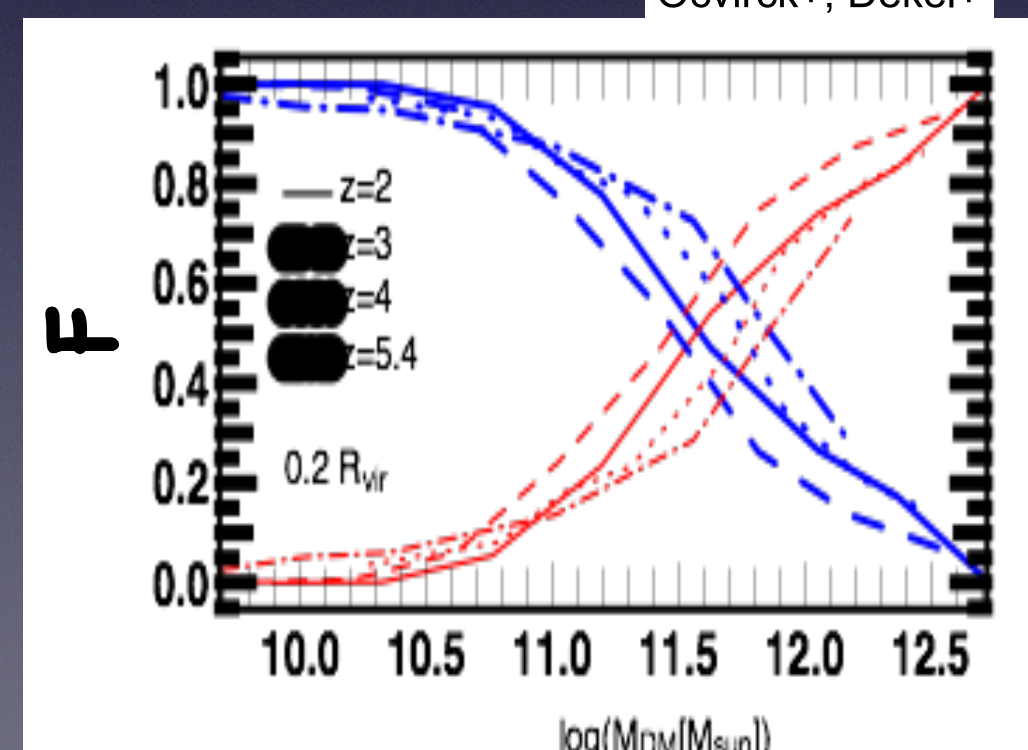


Ocvirck+, Dekel+

Gas may directly infall onto galaxy (as "cold filaments") without being heated

Fraction of "cold" gas able to infall:

$$F = \begin{cases} 1 & \text{if } M_h < M_{min} \\ (M_{max}-M_h)/(M_{max}-M_{min}) & \text{if } M_{min} < M_h < M_{max} \\ 0 & \text{if } M_h > M_{max} \end{cases}$$



STAR FORMATION

SAGE **Convert cold gas in disk into stars over $t_{dyn,disk}$**

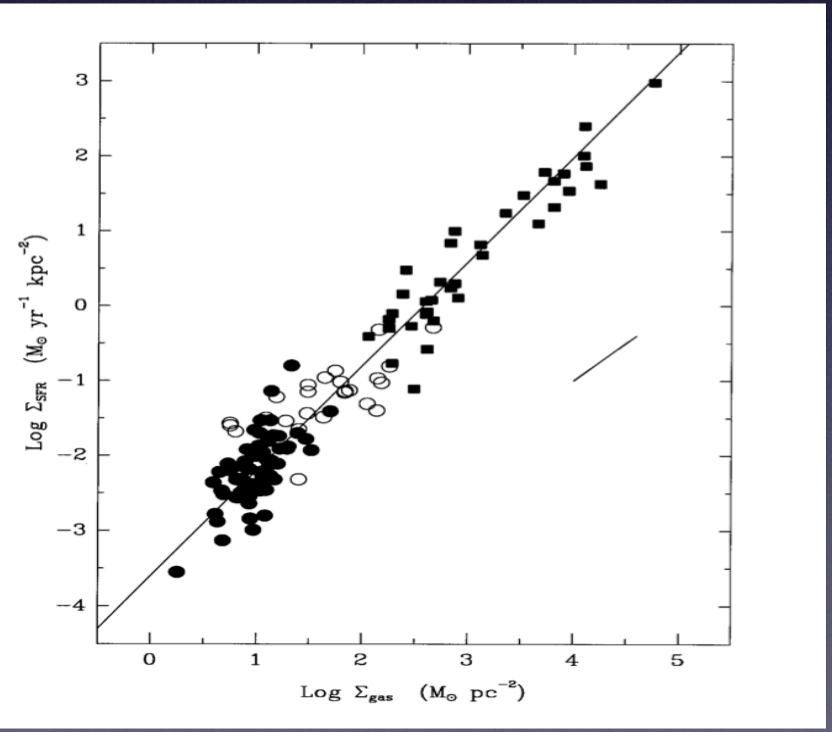
$$\dot{m}_* = \alpha_{SF} \frac{(m_{cold} - m_{crit})}{t_{dyn,disk}}$$

- Consider only unstable gas (above critical mass)
- Inefficient process (usually $\alpha_{SF} \sim$ 1-10%)

GALICS **Empirical SF law (Kennicutt)**

$$\Sigma_{SFR} = \epsilon \, \Sigma_{cold}^{1.4}$$

$\epsilon = \alpha_{SF} / \alpha_{SF,Kennicutt}$

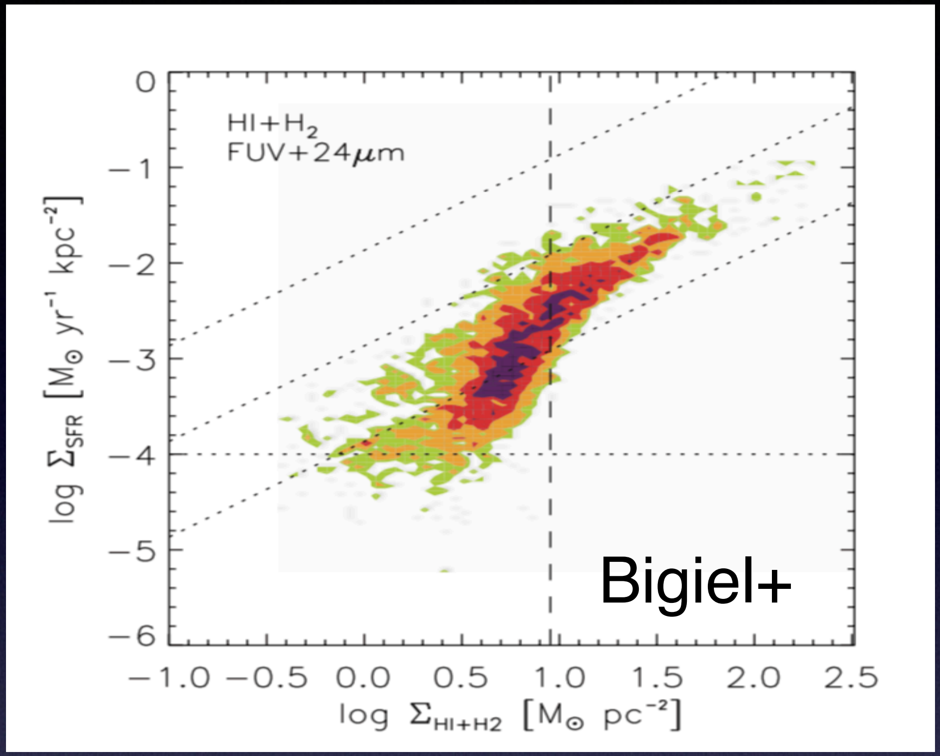


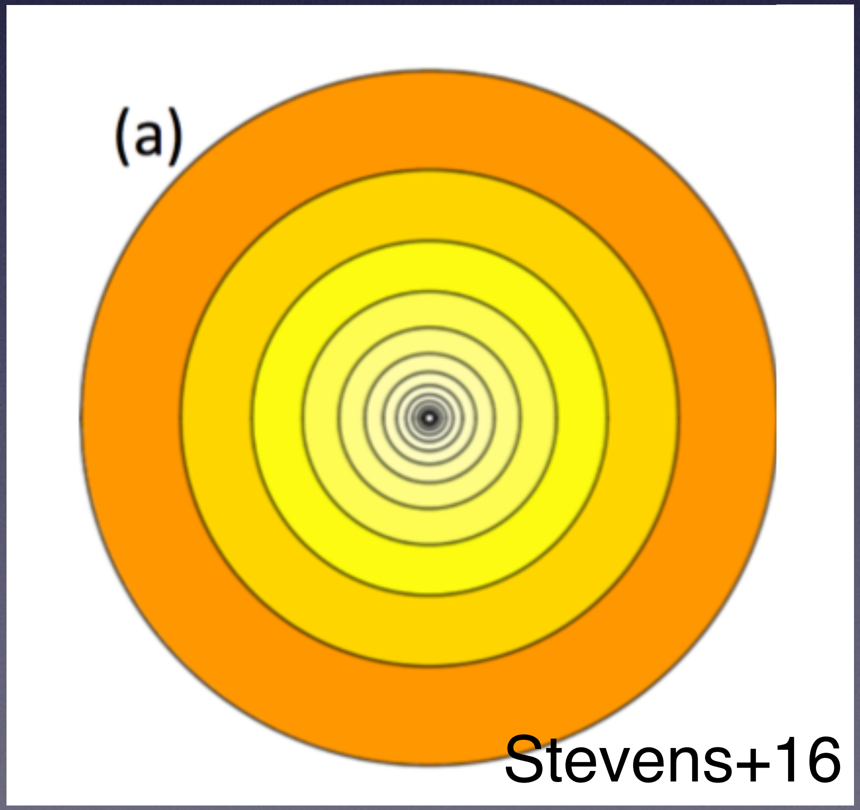
Here, the SFR is an integrated property as the prescriptions are applied to the full disk.

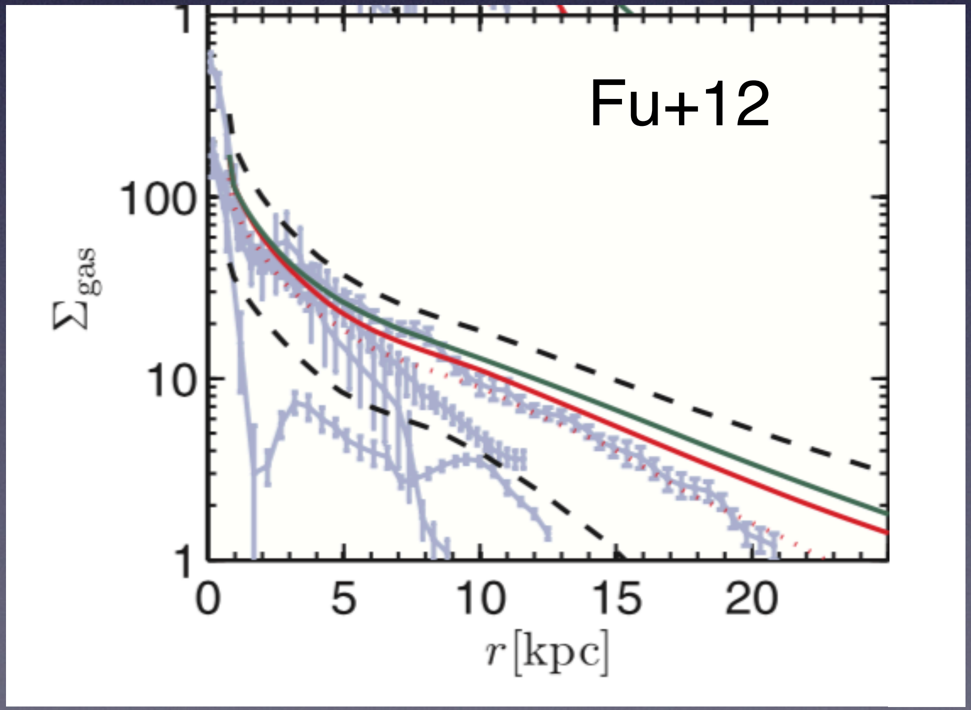
STAR FORMATION

New data can now resolve internal variation of SF (SFR vs. HI and H_2)

"disc decomposition" models







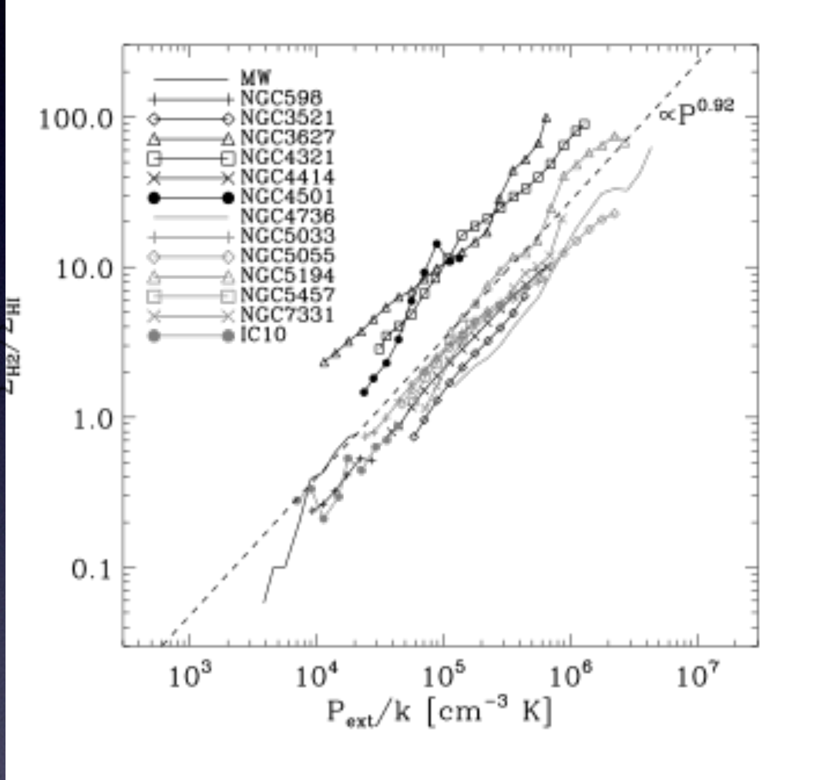
STAR FORMATION

$\Sigma_{SFR} \sim f_{H2}\, \Sigma_{cold}$ ($M_{cold} = M_{HI} + M_{H2}$)

✦ **Empirical law by Blitz & Rosolowski**

H2 cloud formation set by external pressure on disks

$$\frac{\Sigma(\mathrm{H_2})}{\Sigma(\mathrm{HI})} = \left(\frac{P_{\mathrm{ext}}}{P_0}\right)^{\alpha}$$



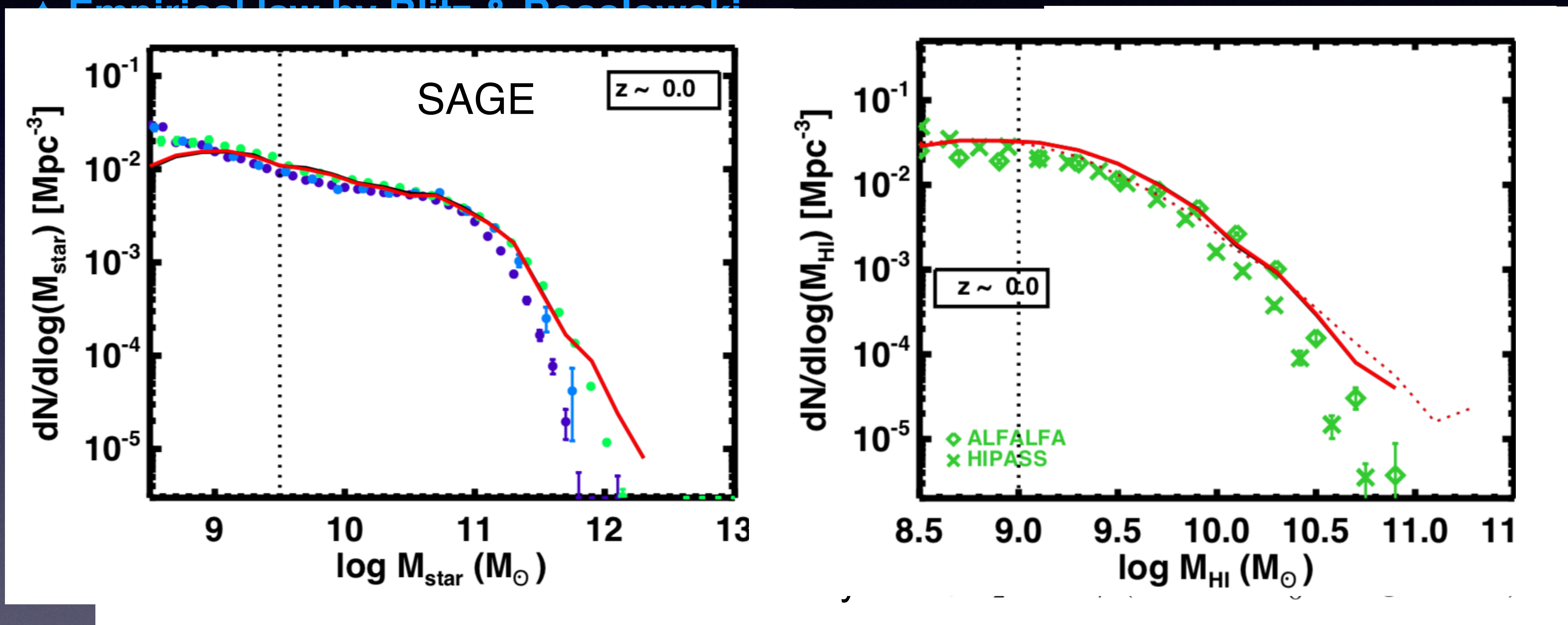
✦ **Theoretical law by Krumholz & McKee**

H_2 formation is function of gas metallicity Z : $f_{\mathrm{H_2}} \sim \Sigma/(\Sigma + 10 Z_0^{-1} M_{\odot}\ \mathrm{pc}^{-2})$

=> Very popular recipes : GALFORM, SAGE, L-GALAXIES, Santa Cruz etc
(predictions for HI and H_2 forthcoming surveys)

STAR FORMATION

$$\Sigma_{SFR} \sim f_{H2}\, \Sigma_{cold}$$ $(M_{cold} = M_{HI} + M_{H2})$



=> Very popular recipes : GALFORM, SAGE, L-GALAXIES, Santa Cruz etc

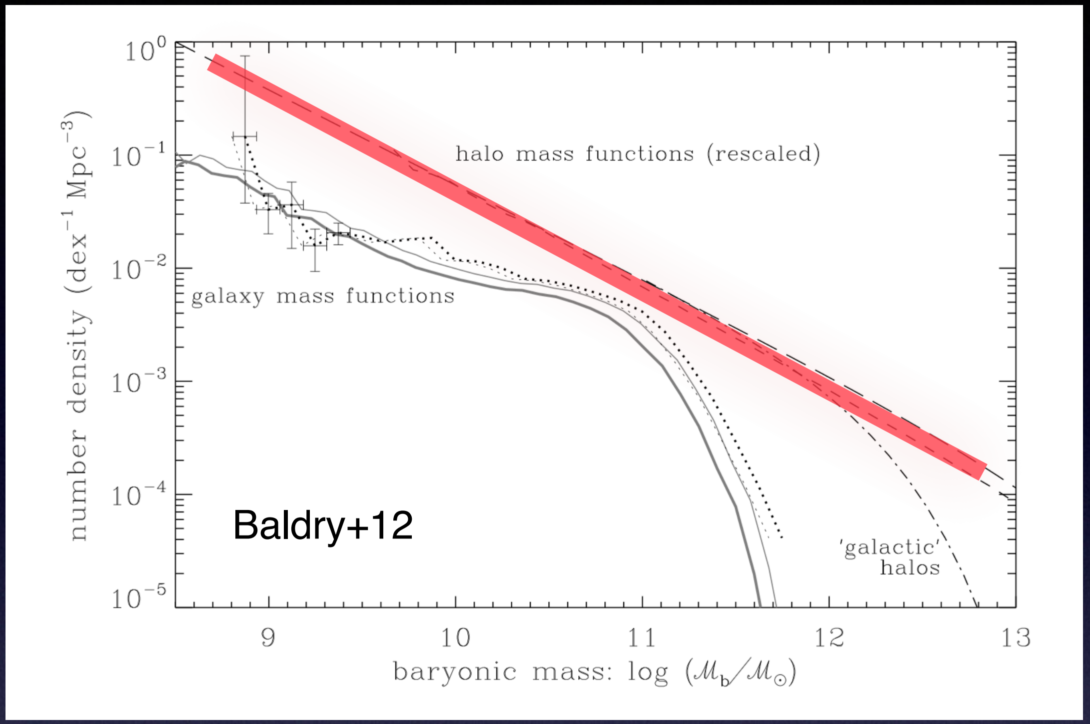
(predictions for HI and H_2 forthcoming surveys)

SUPERNOVA FEEDBACK

Shallow slope at low-mass end of SMF

=> need feedback mechanism to remove gas from low-mass galaxies

e.g. young stars exploding as supernovae can release lots of mechanical and radiative energy



From E conservation:

$$\dot{M}_{\rm out} = \frac{2\,\epsilon_{\rm SN} E_{\rm SN} \Psi_{\rm SN} {\rm SFR}}{v_{\rm esc}^2} \;, \quad v_{\rm esc}^2 \sim M_{gal}$$

Silk 2003

Many different modellings, e.g. in momentum-conserving winds, $\dot{M}_{out} \sim 1 / v_{esc}$

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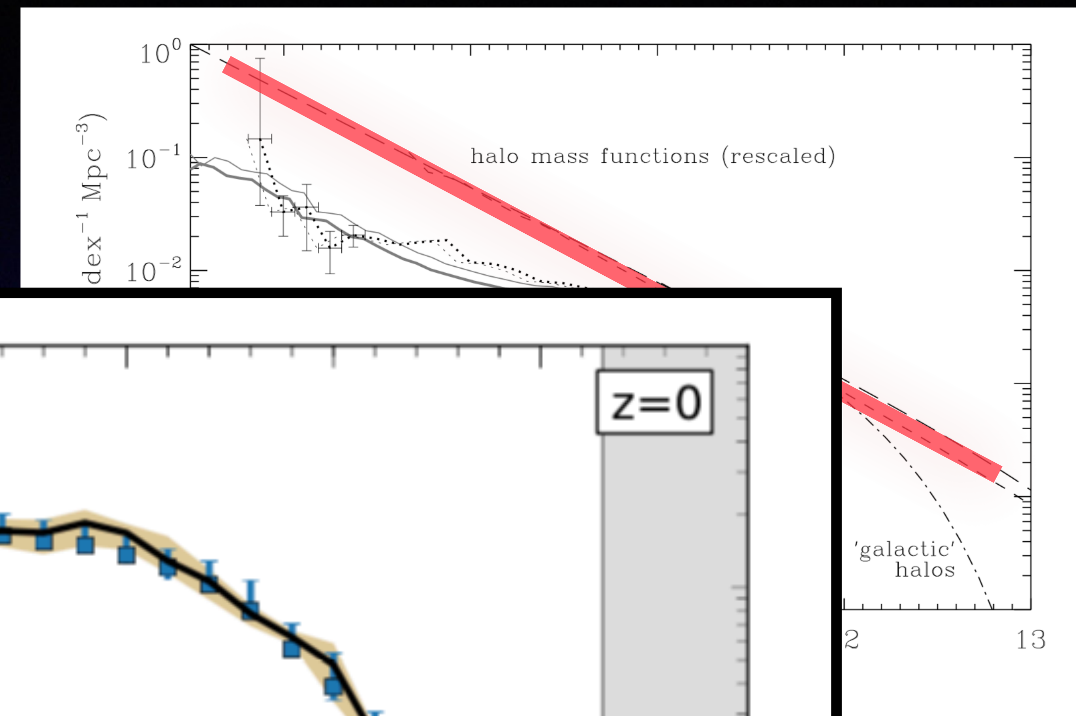
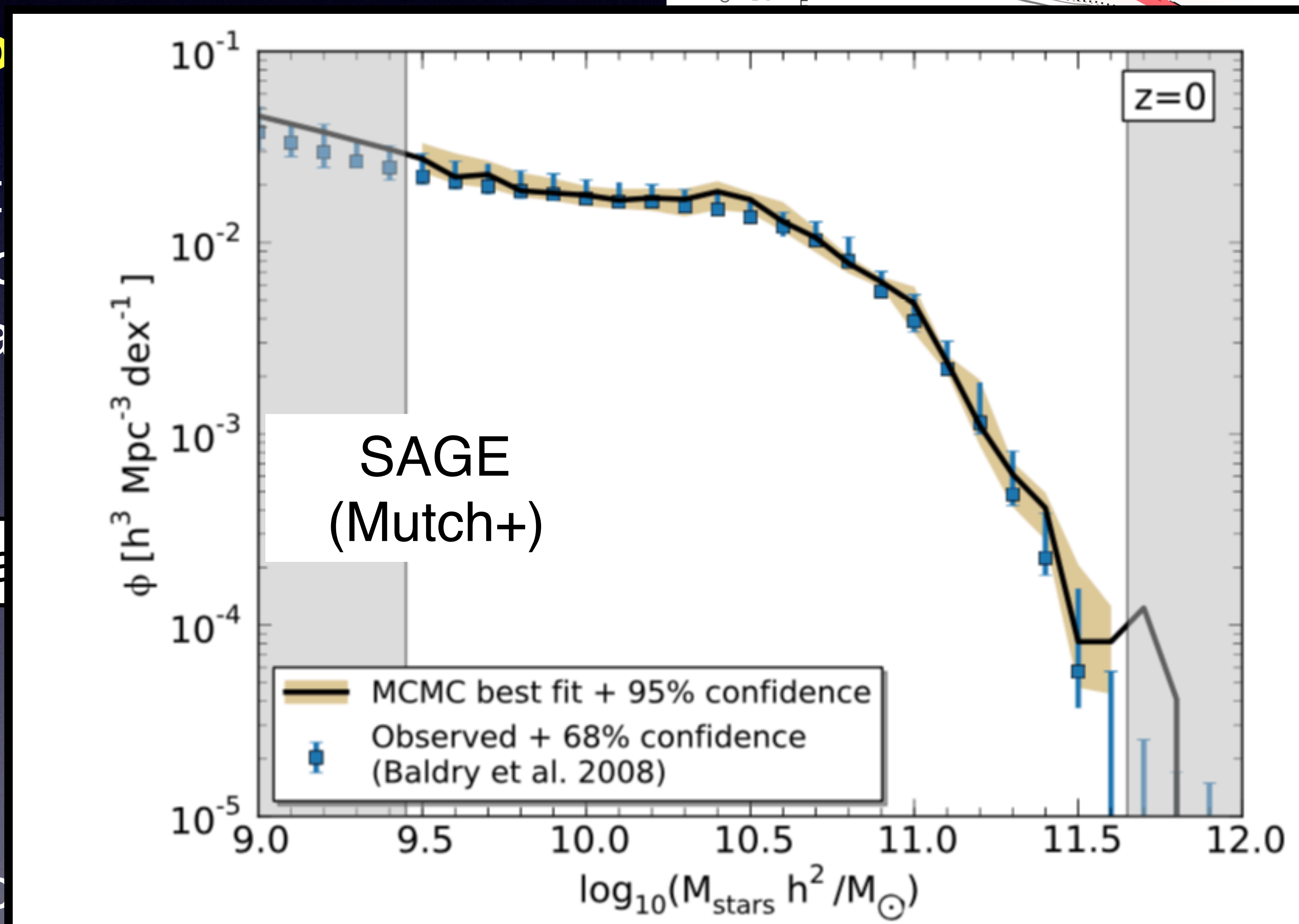




Many different mo ~ 1 / v_{esc}

PHOTO-HEATING "FEEDBACK"

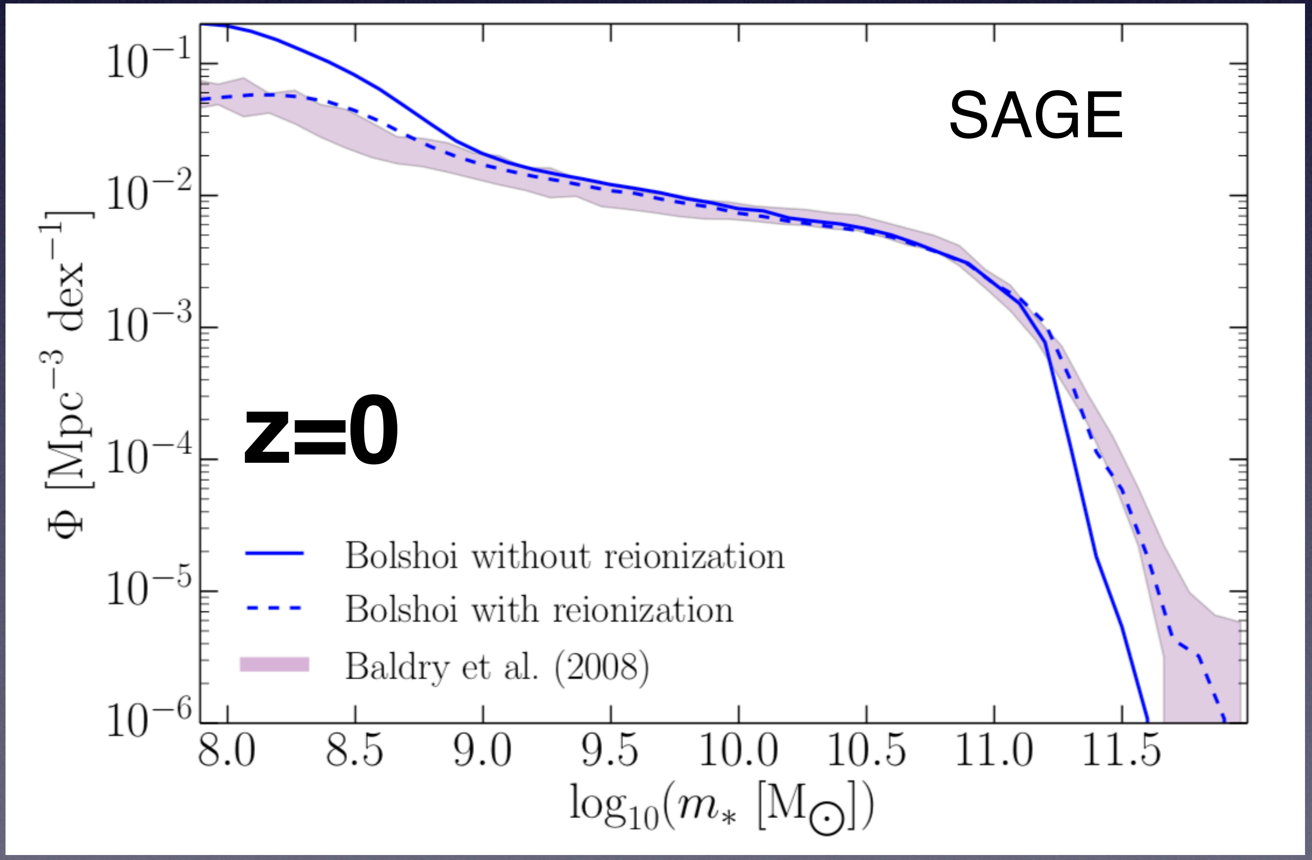
After reionisation, UV background can heat pre-galactic gas

=> No gas condensation in halos if $E_{therm} > |E_{grav}|$: **efficient at low M_{halo} !**

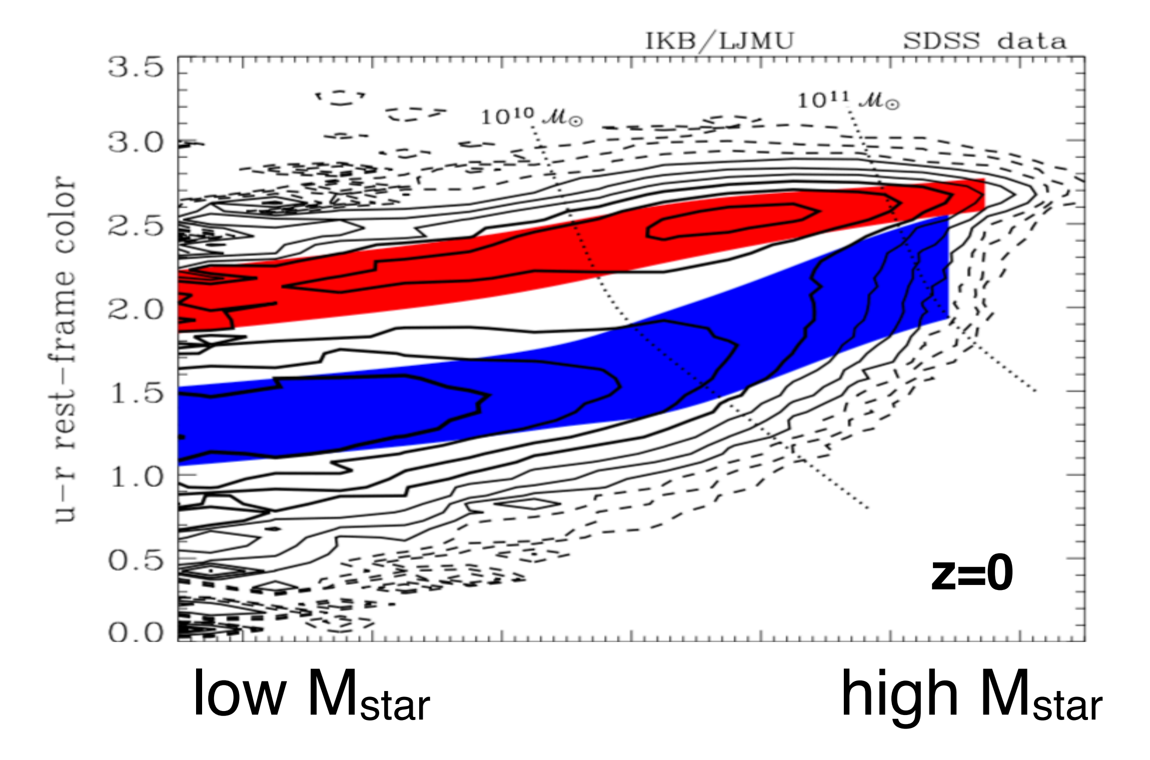
Prescriptions often used in SAM estimated from hydro. simulations

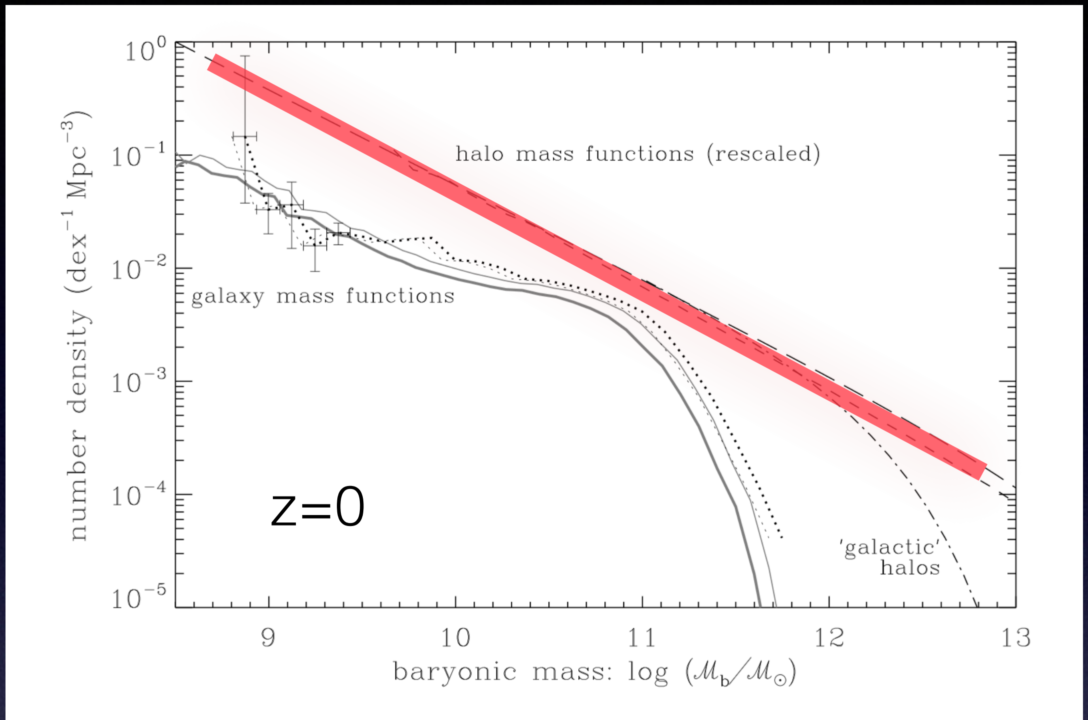
e.g. Okamoto+08 , Kravstov+, Ocvirk+15

$$f_b(z, M_{vir}) = f_b^{cos} \left(1 + (2^{\alpha/3} - 1)\left[\frac{M_{vir}}{M_F(z)}\right]^{-\alpha}\right)^{-3/\alpha}$$



AGN FEEDBACK





"Feedback" from AGN related to black hole growth and activity *(Kauffmann & Haehnelt 2000, Croton+06, Bower+06, Cattaneo+06 etc)*

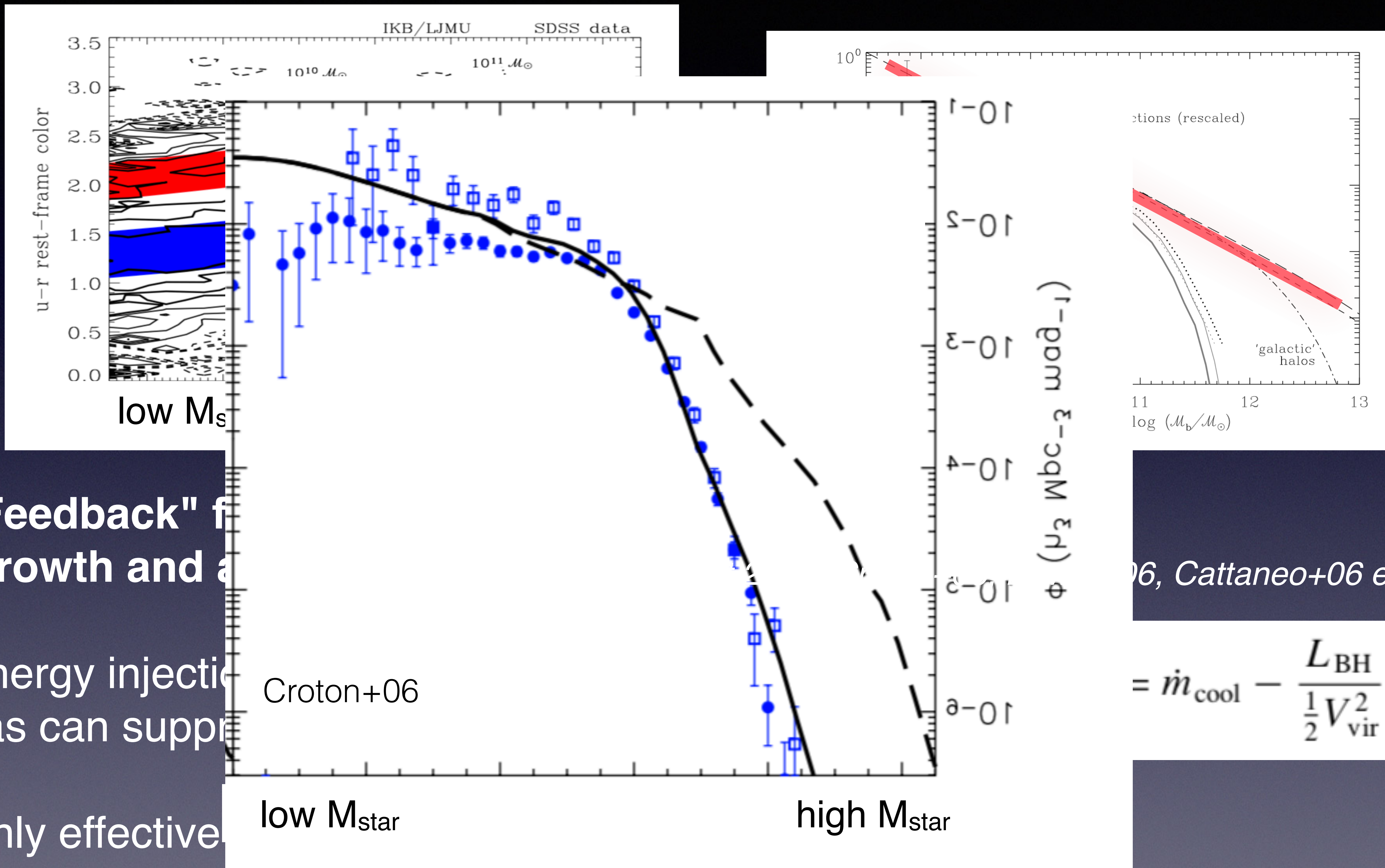
Energy injection (e.g. radio jets) in the surrounding gas can suppress the cooling flows

$$\dot{m}'_{\rm cool} = \dot{m}_{\rm cool} - \frac{L_{\rm BH}}{\frac{1}{2}V_{\rm vir}^2}$$

Only effective if tcool > tdyn (i.e. massive haloes)

AGN feedback does not require SF to be activated (unlike SN feedback)

AGN FEEDBACK



"Feedback" f
growth and a *6, Cattaneo+06 etc)*

Energy injecti
gas can suppr

$= \dot{m}_{\rm cool} - \frac{L_{\rm BH}}{\frac{1}{2}V_{\rm vir}^2}$

Only effective

AGN feedback does not require SF to be activated (unlike SN feedback)

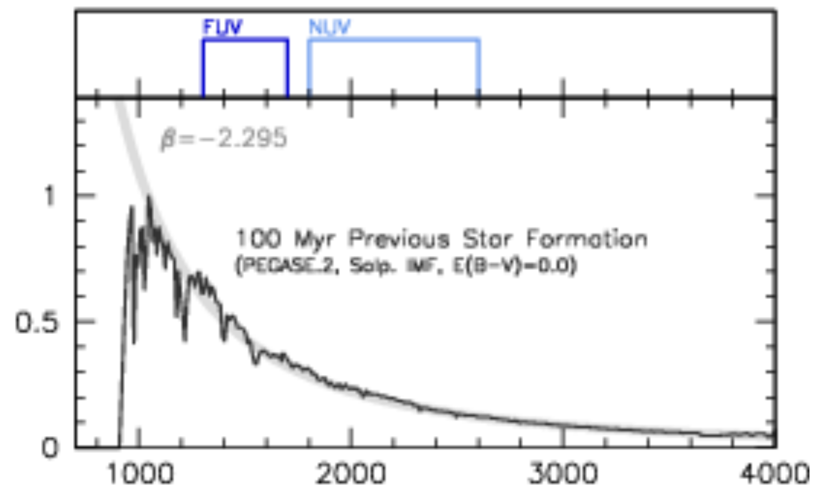
OUTLINE

- Cosmological simulations of dark matter
- Physics of galaxy formation in semi-analytic models
- **High-redshift galaxies in GALICS**
- How to generate mock observables from SAMs

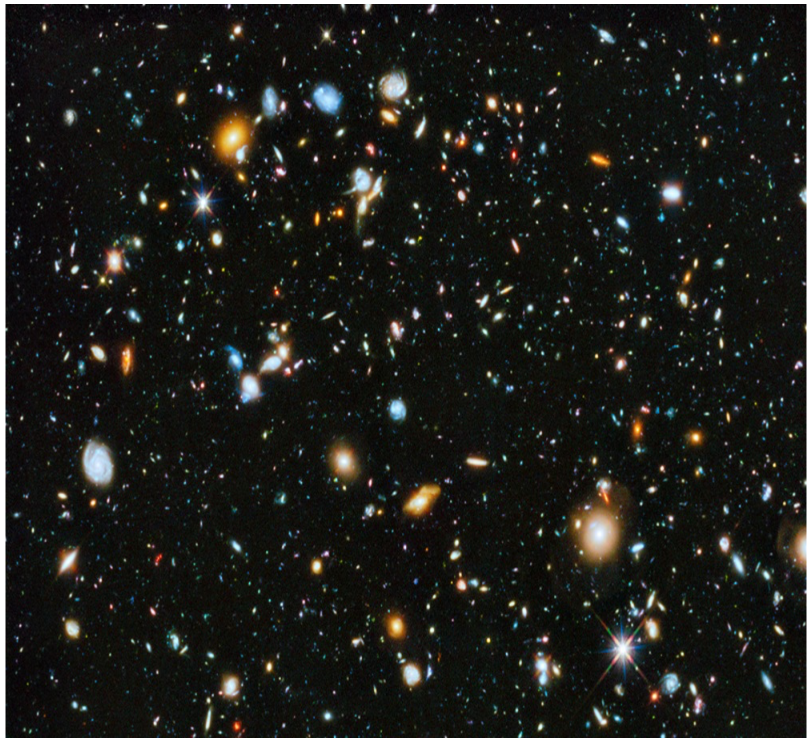
HIGH REDSHIFT GALAXIES IN GALICS

Distant star-forming galaxies detected from…

… strong stellar emission (Lyman-Break Galaxies)



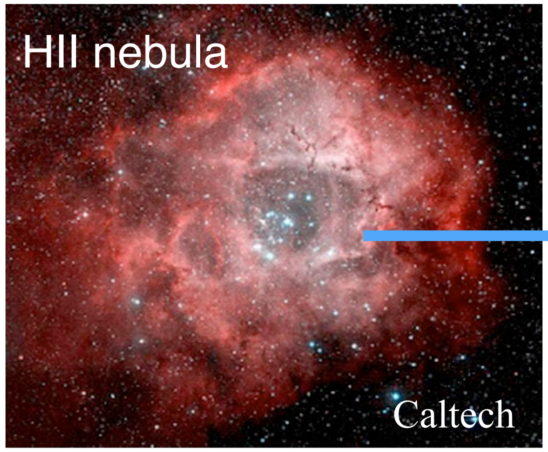
Hubble Ultra Deep Field

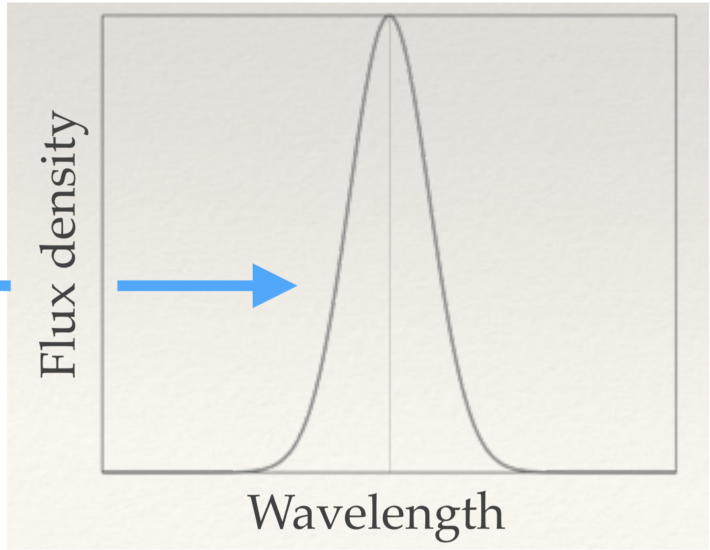


… Lyα emission line (Lyman-α Emitters)

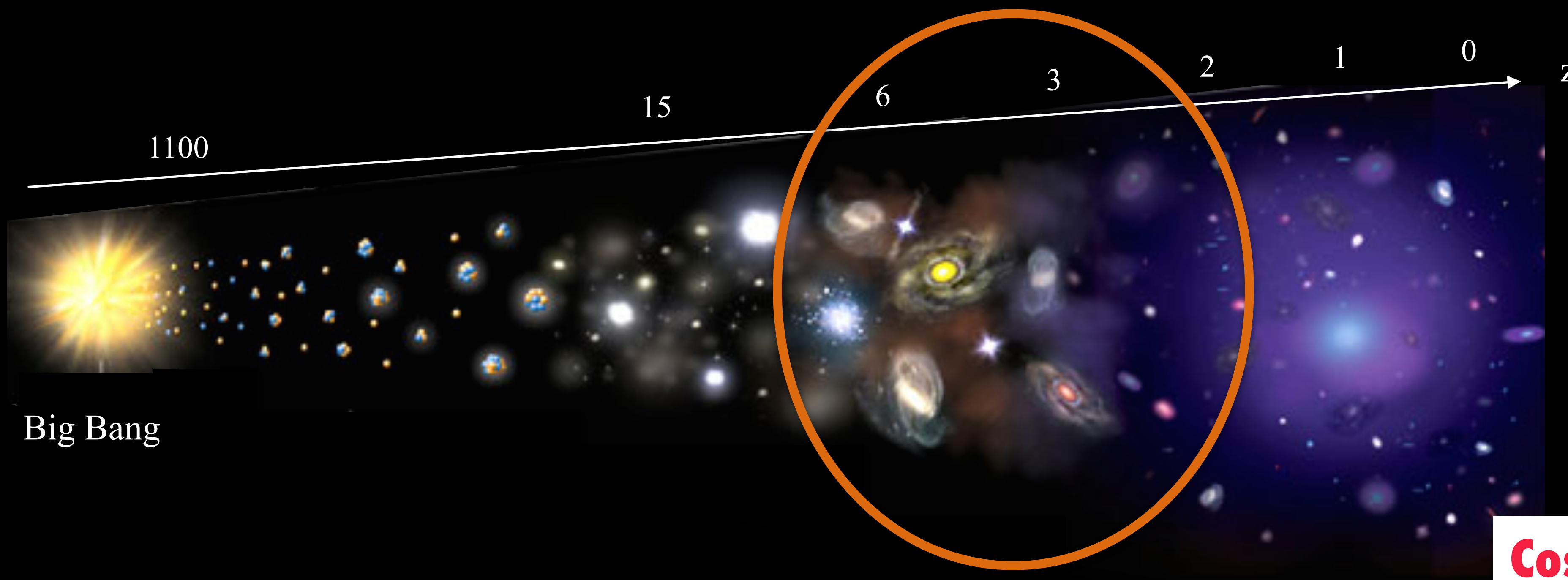
HI gas photoionised by young stars

~ 68% of ionising photons reprocessed into Lyα during recombination

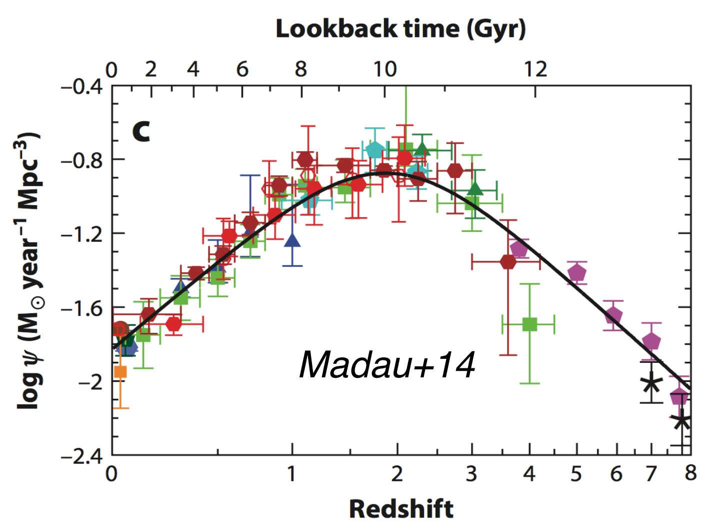




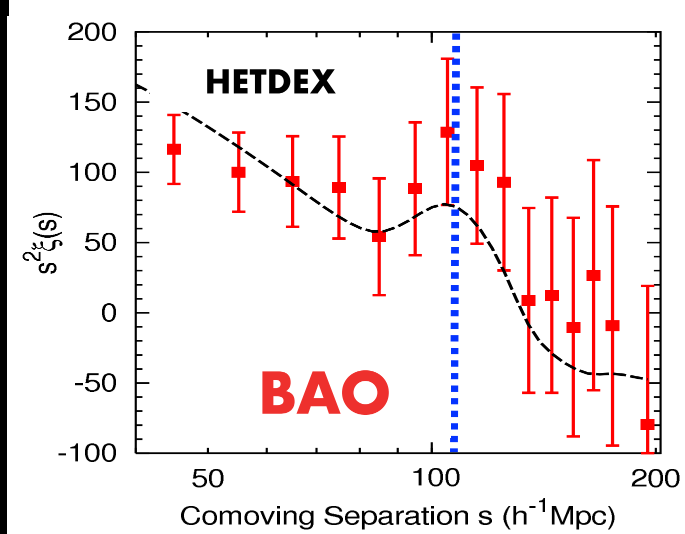
HIGH REDSHIFT GALAXIES IN GALICS



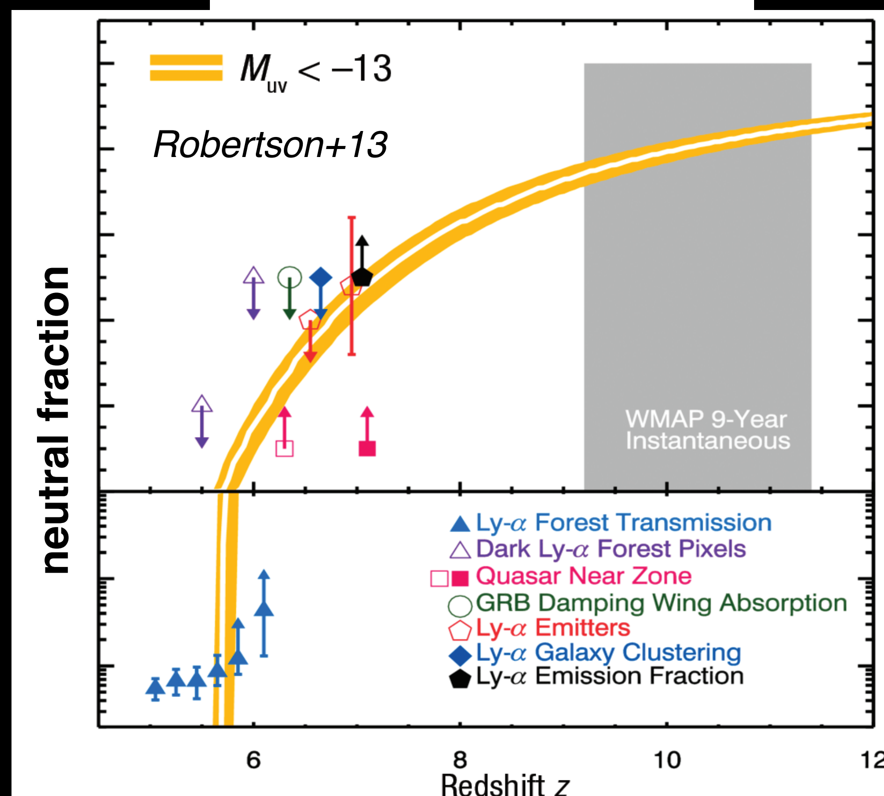
Build up of the galaxy population at early times



Cosmology



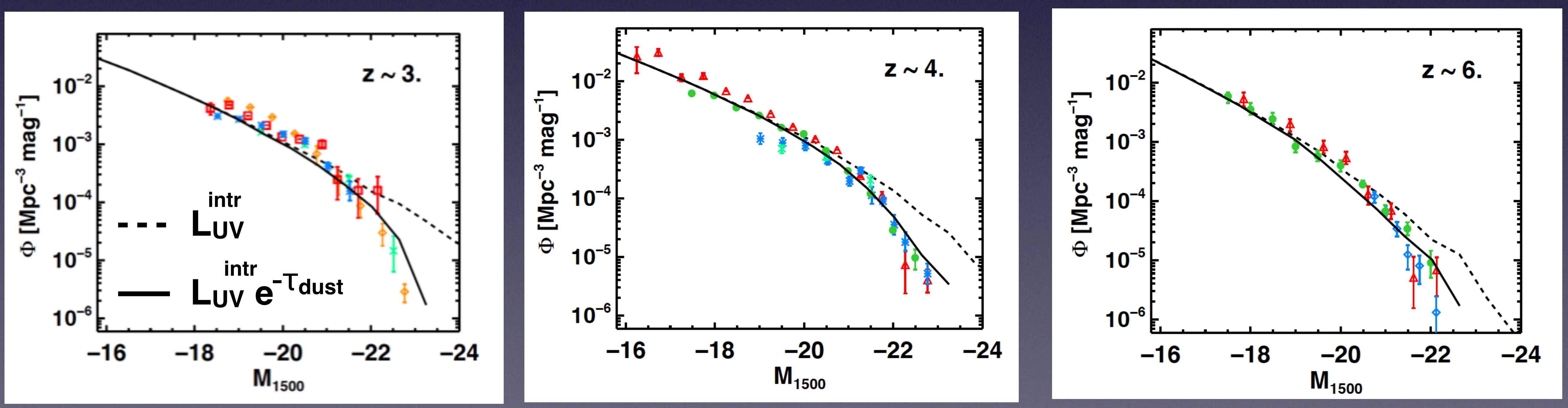
Cosmic reionisation



HIGH REDSHIFT GALAXIES IN GALICS

GALICS "adjusted" to reproduce LBG luminosity functions *(Garel+12,15,16)*

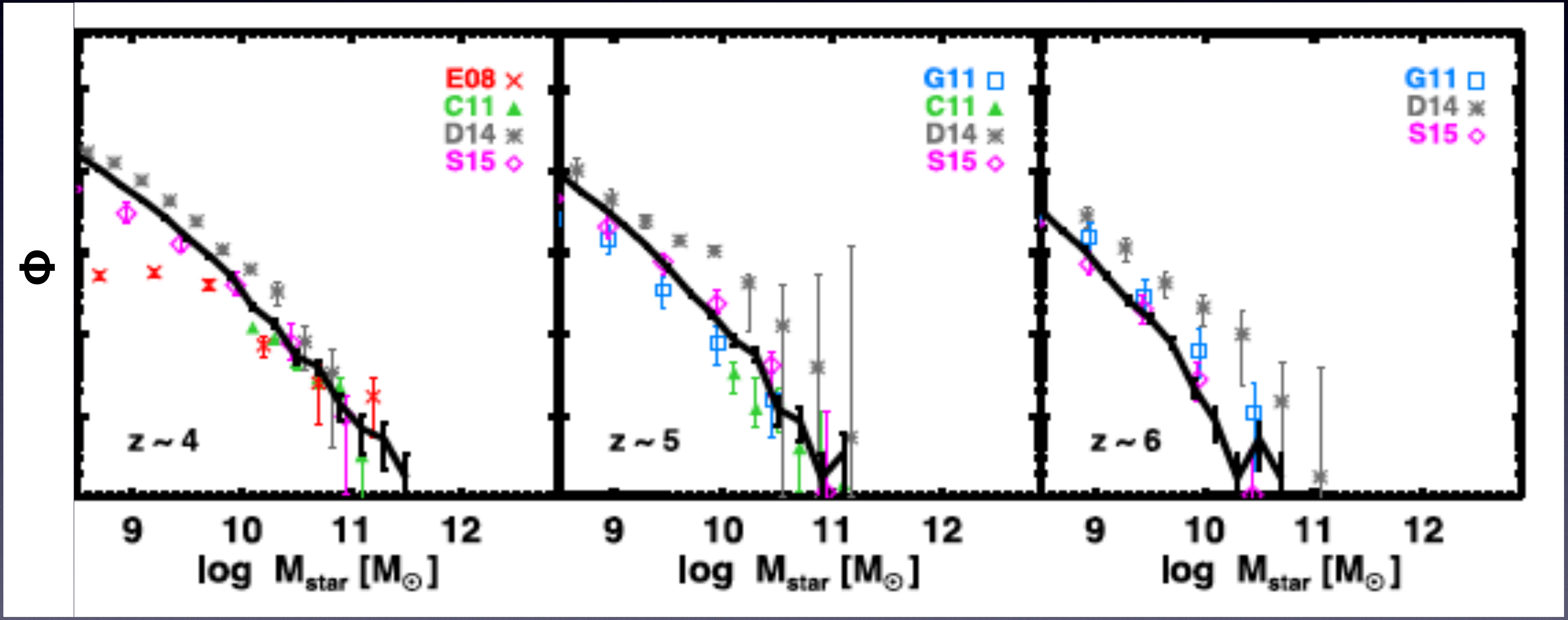
- *Cold accretion mode*
- *High SF efficiency*
- *Fast merging*
- *Gas reincorporation over short timescale*
- *Strong SN feedback*
- *Dust attenuation from Σ_{cold} and Z*
- *etc*



HIGH REDSHIFT GALAXIES IN GALICS

(Garel+12,15,16)

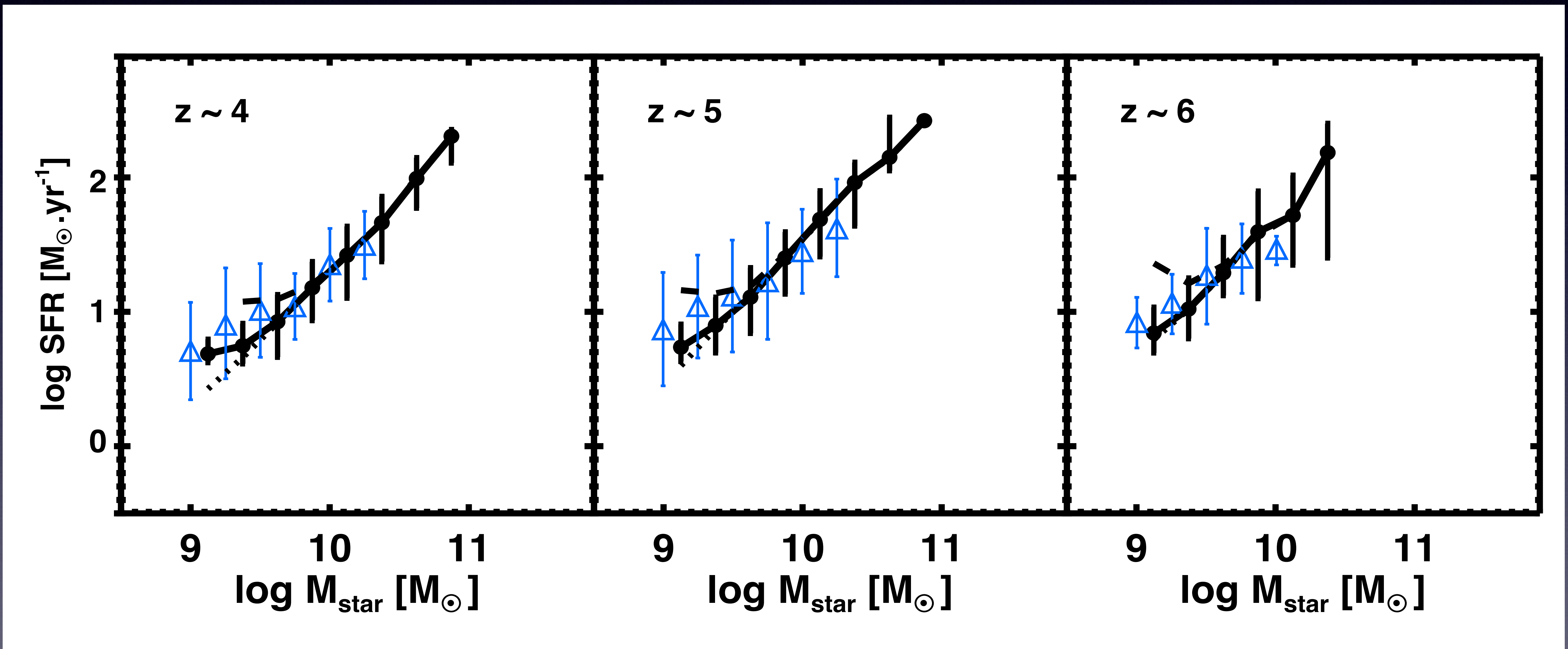
Stellar mass functions



HIGH REDSHIFT GALAXIES IN GALICS

(Garel+12,15,16)

SFR vs. Mstar

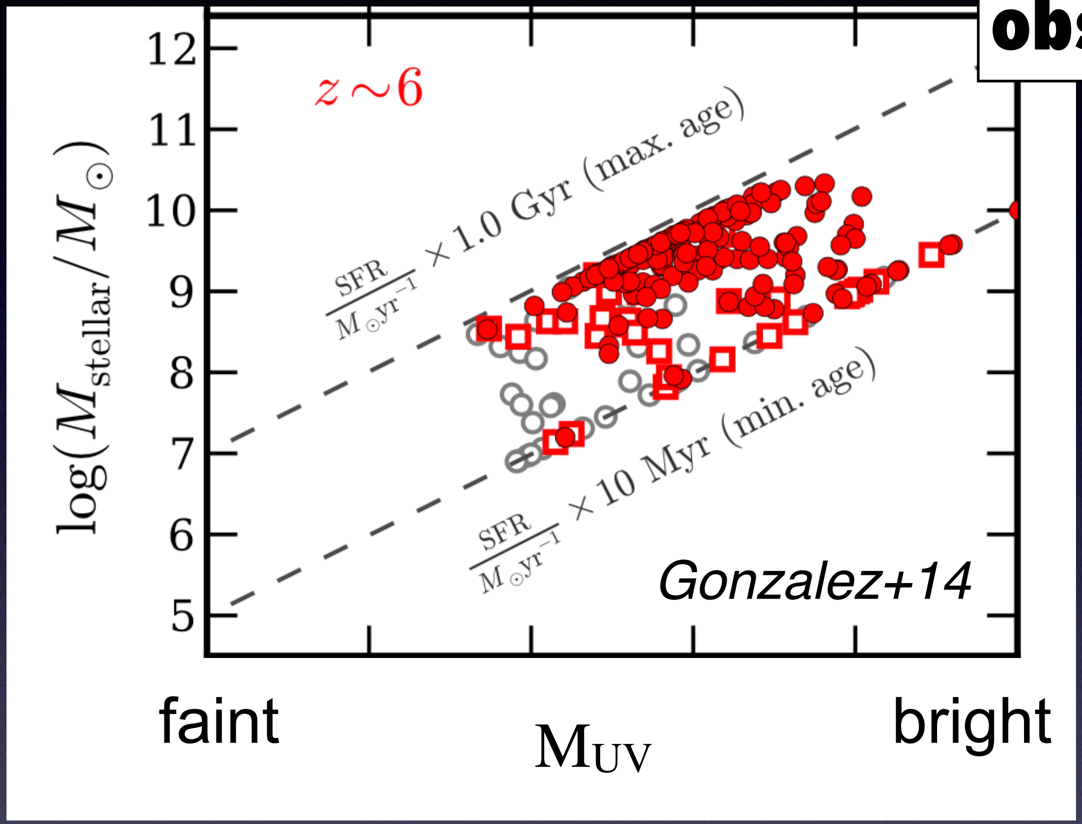


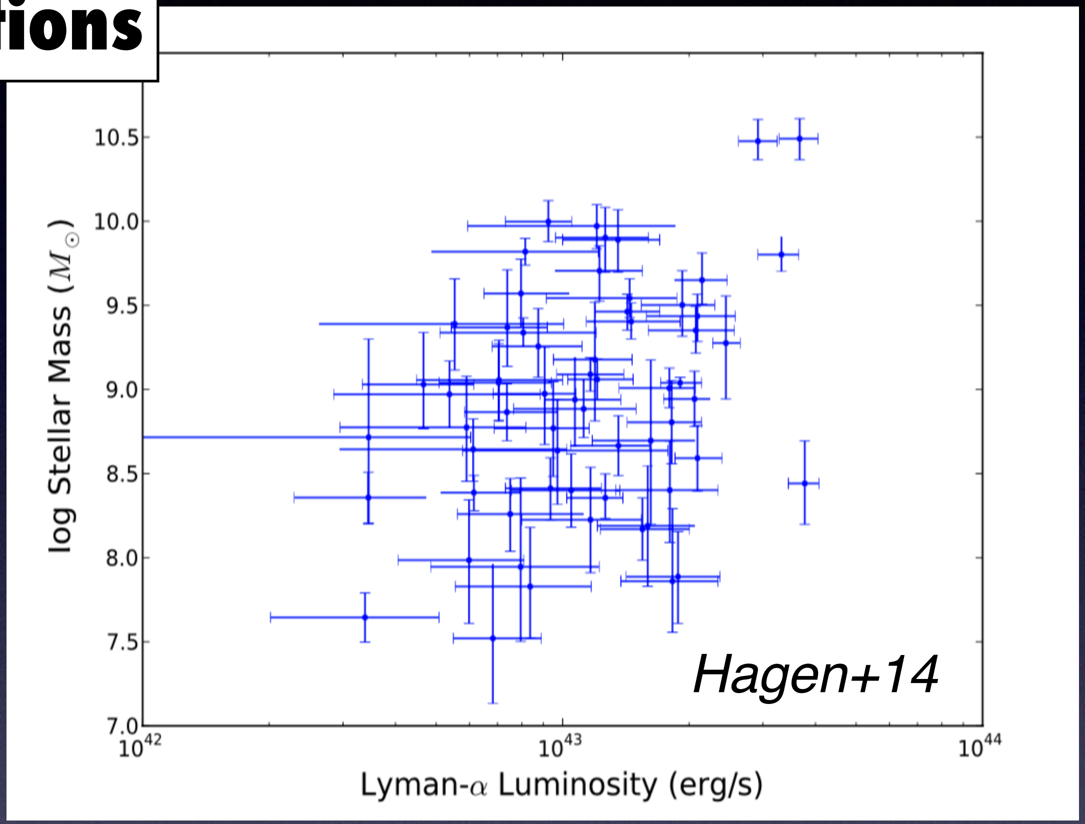
HIGH REDSHIFT GALAXIES IN GALICS

LBG

LAE

observations



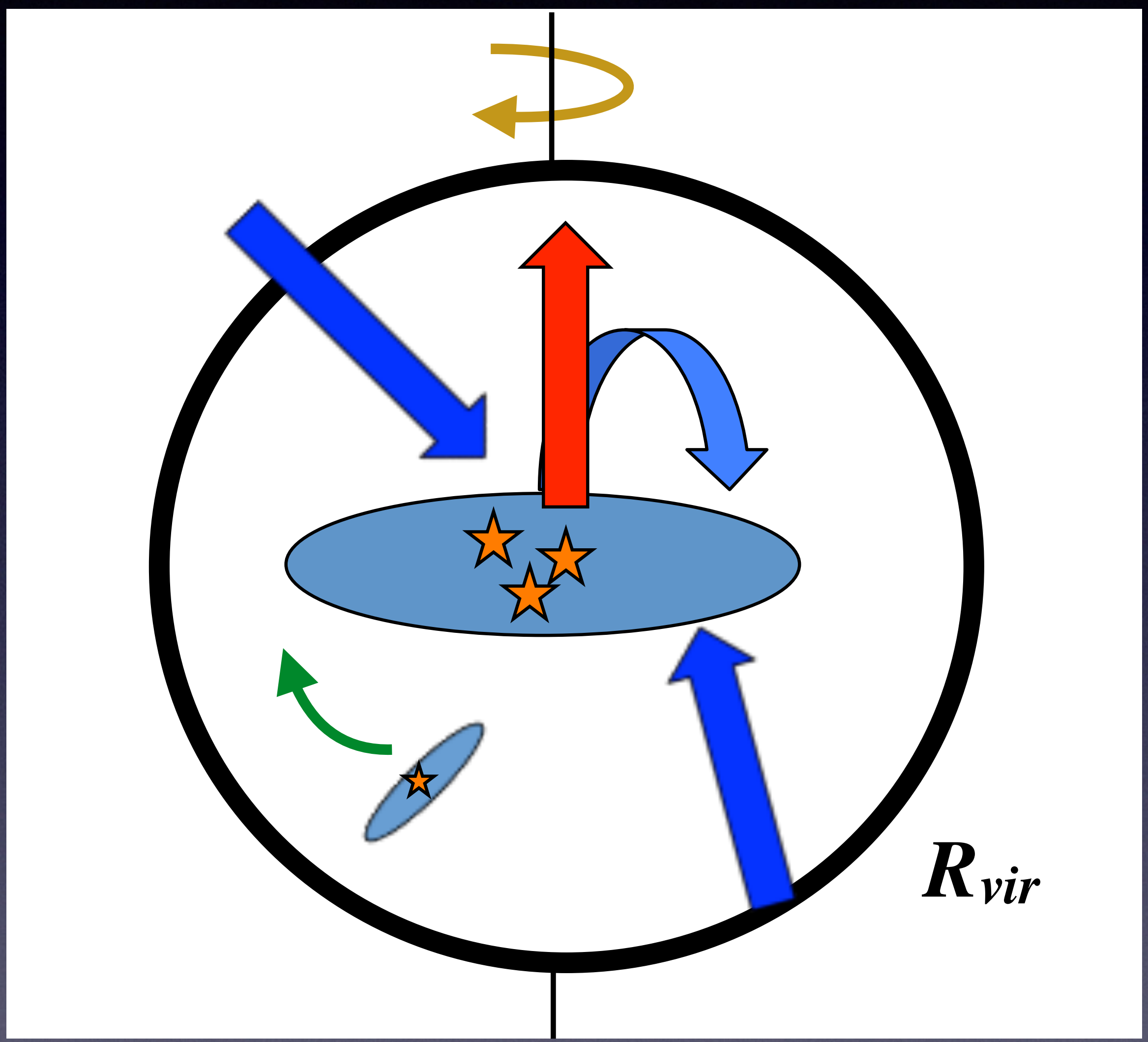


UV magnitude well correlated to M_{star} for LBGs

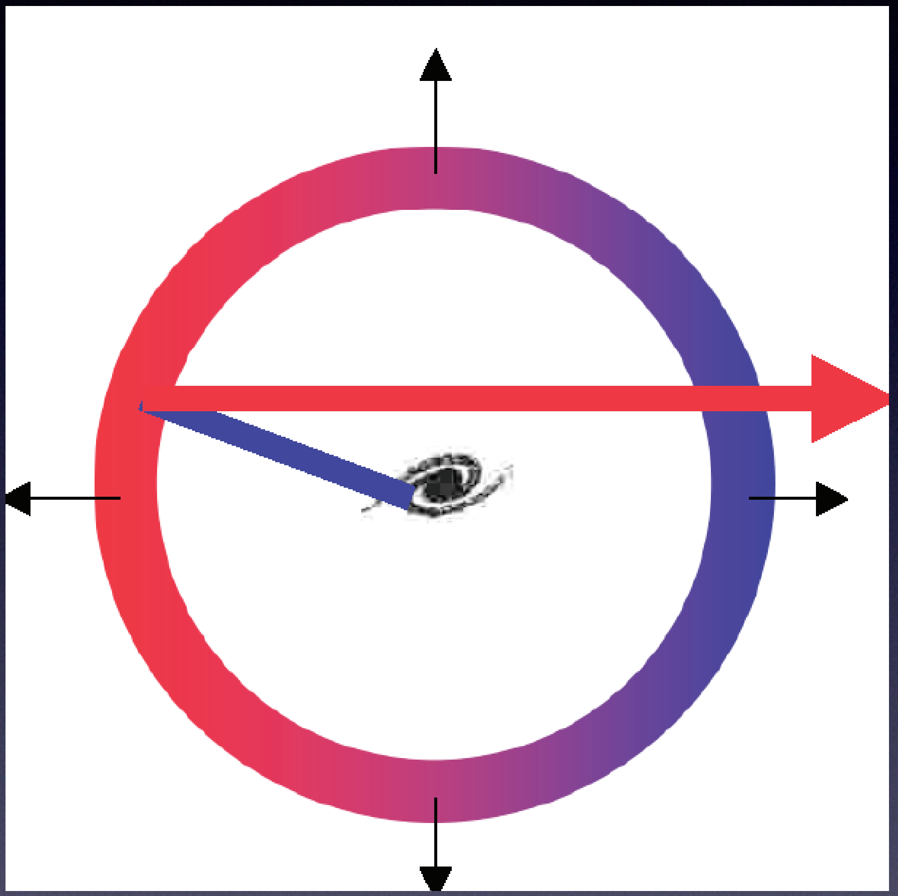
$L_{Ly\alpha}$ not a good tracer of M_{star}: complex radiation transfer of Lyα line in ISM/CGM/IGM **=> only a fraction fesc of Lyα photons escape galaxies**

HIGH REDSHIFT GALAXIES IN GALICS

Coupling of GALICS with simulations of Lya transfer



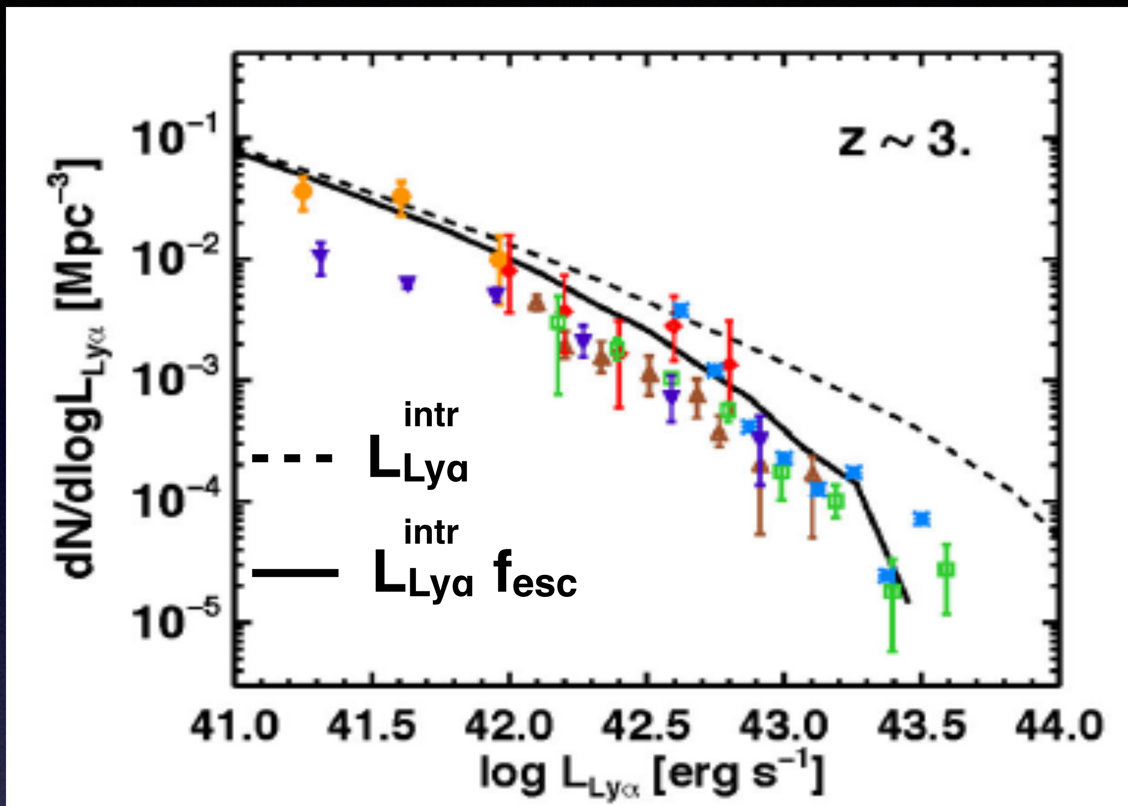
+

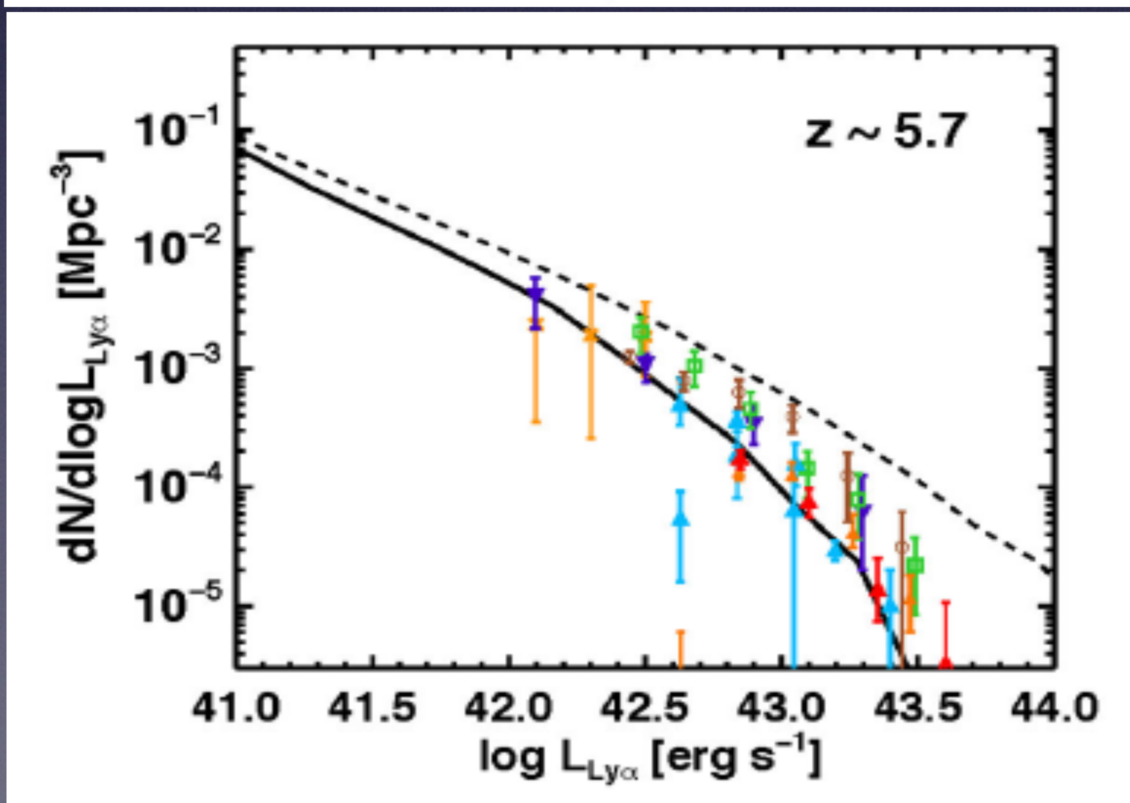


(Verhamme+06, Schaerer+11)

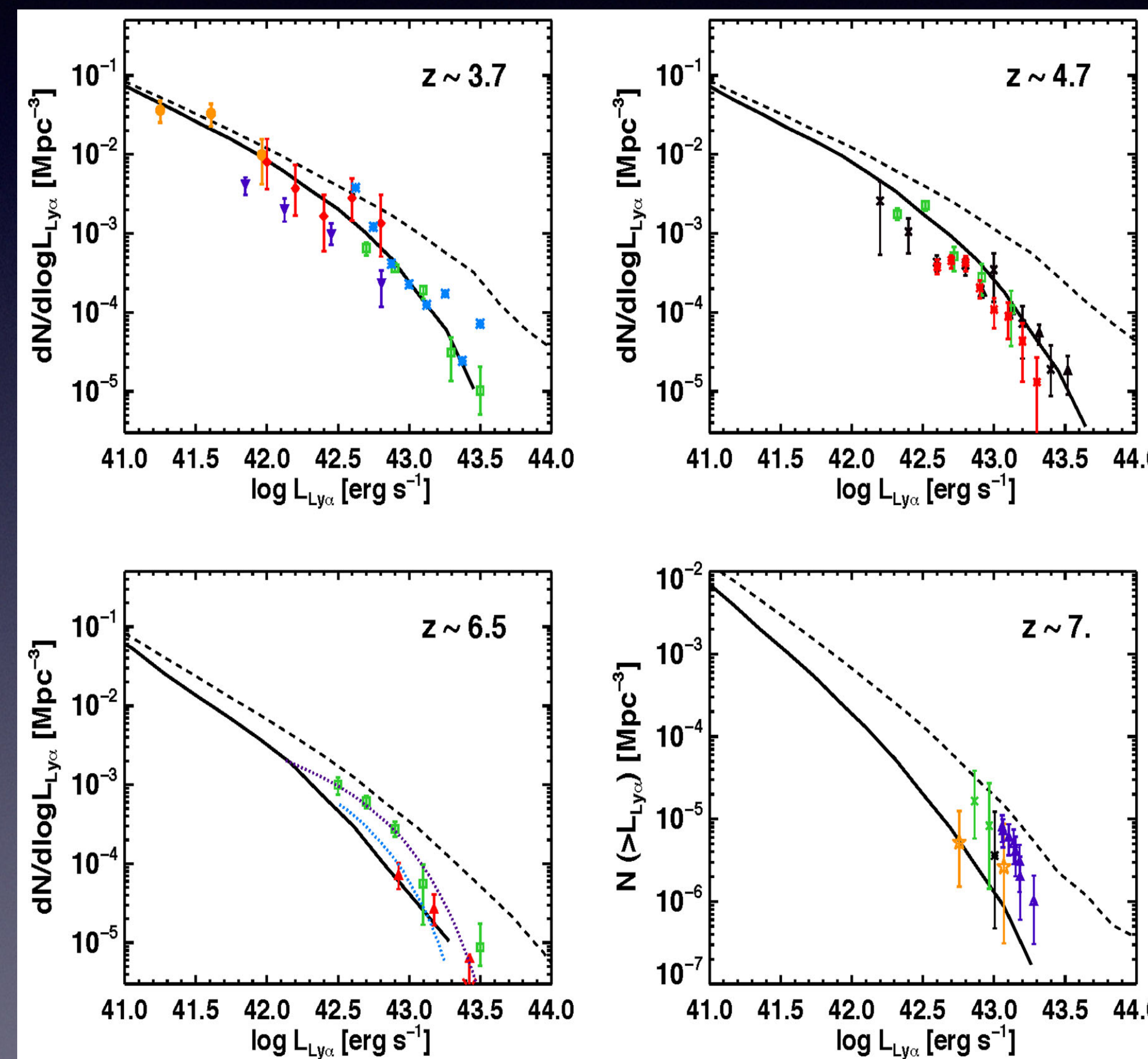
=> $L_{Ly\alpha}$ escape fraction

HIGH REDSHIFT GALAXIES IN GALICS

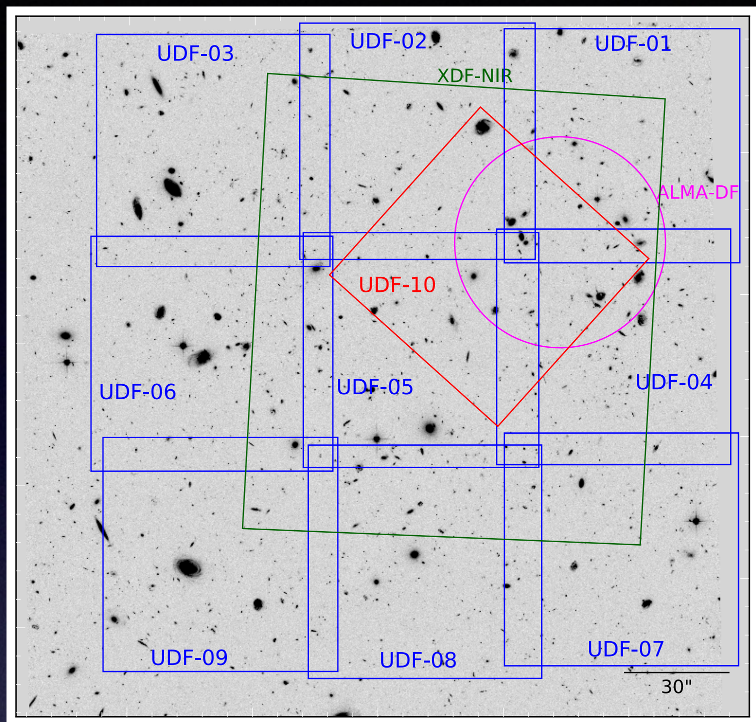




Lya luminosity functions

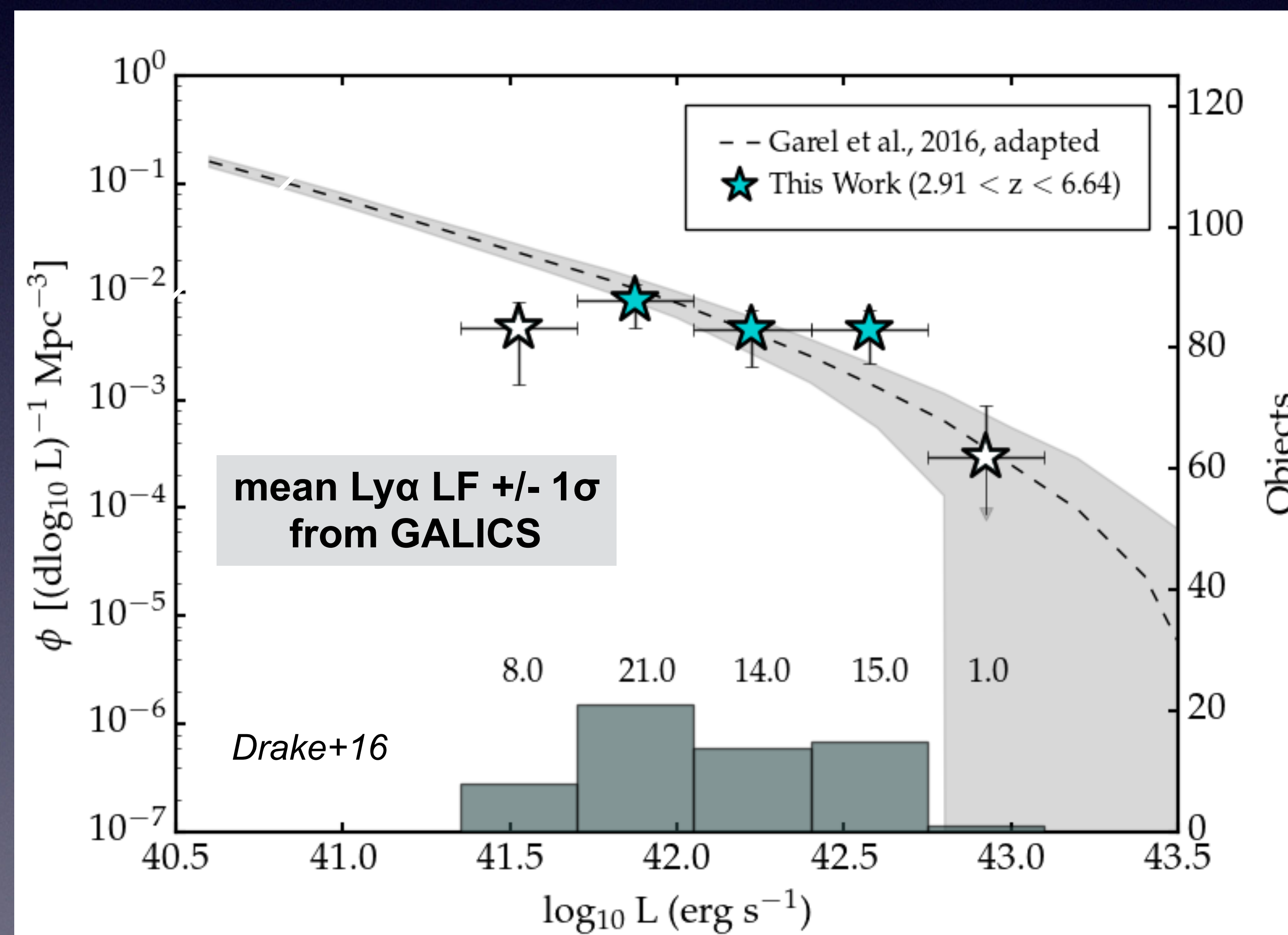


HIGH REDSHIFT GALAXIES IN GALICS



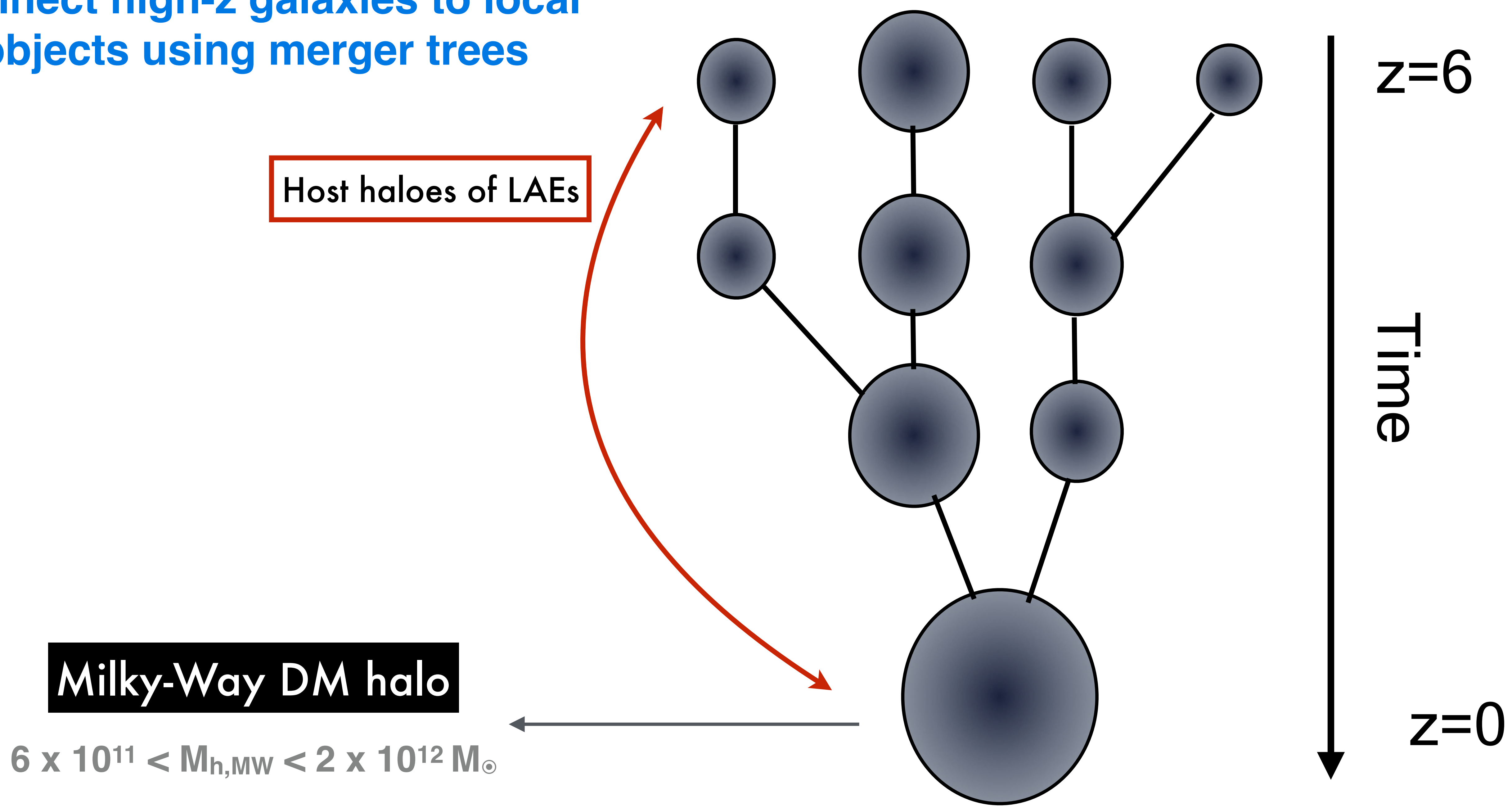
1'

Predictions for MUSE surveys in the HUDF



Assess effect of cosmic variance using SAMs

Connect high-z galaxies to local objects using merger trees

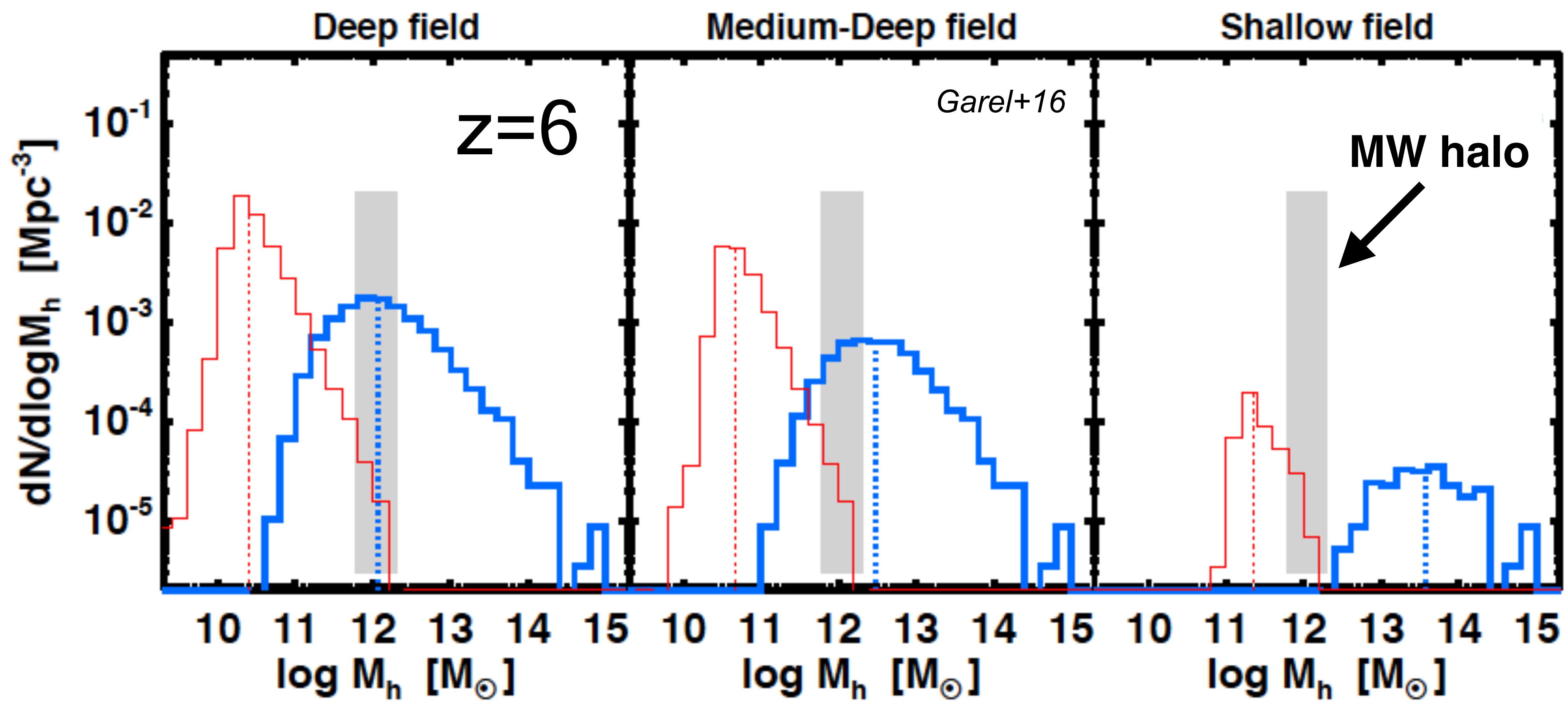


HIGH REDSHIFT GALAXIES IN GALICS

The host haloes of LAEs and their descendants

Mass distribution of the host haloes of z ~ 6 LAEs in MUSE surveys

Mass distribution of their descendants at z = 0

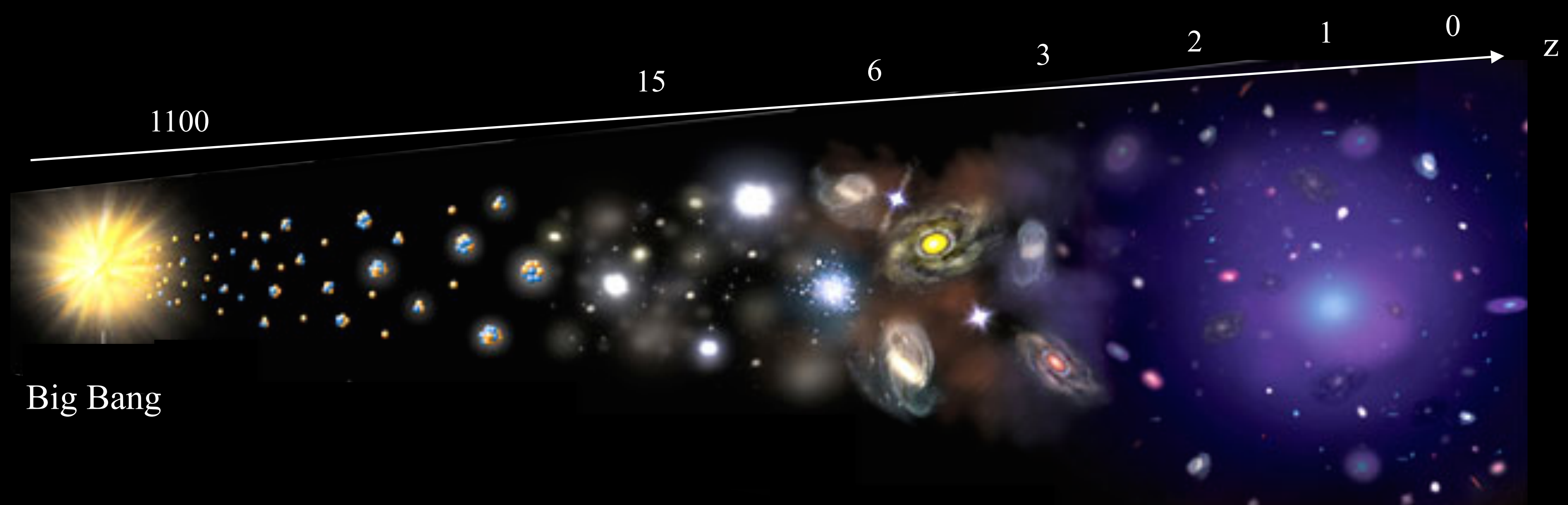


Bright LAEs at z=6 —> group/cluster galaxy haloes at z=0

Faint LAEs at z=6 —> L* galaxy haloes at z=0

HIGH REDSHIFT GALAXIES IN GALICS

Lyα as a tracer of reionisation ?



Test I

Strong evolution of the Lyα LF at z~6-7 due IGM attenuation?

Test II

Large ionised bubbles around massive haloes (inside-out scenario)

=> visible LAEs more "clustered" at EoR (*clustering boost*)

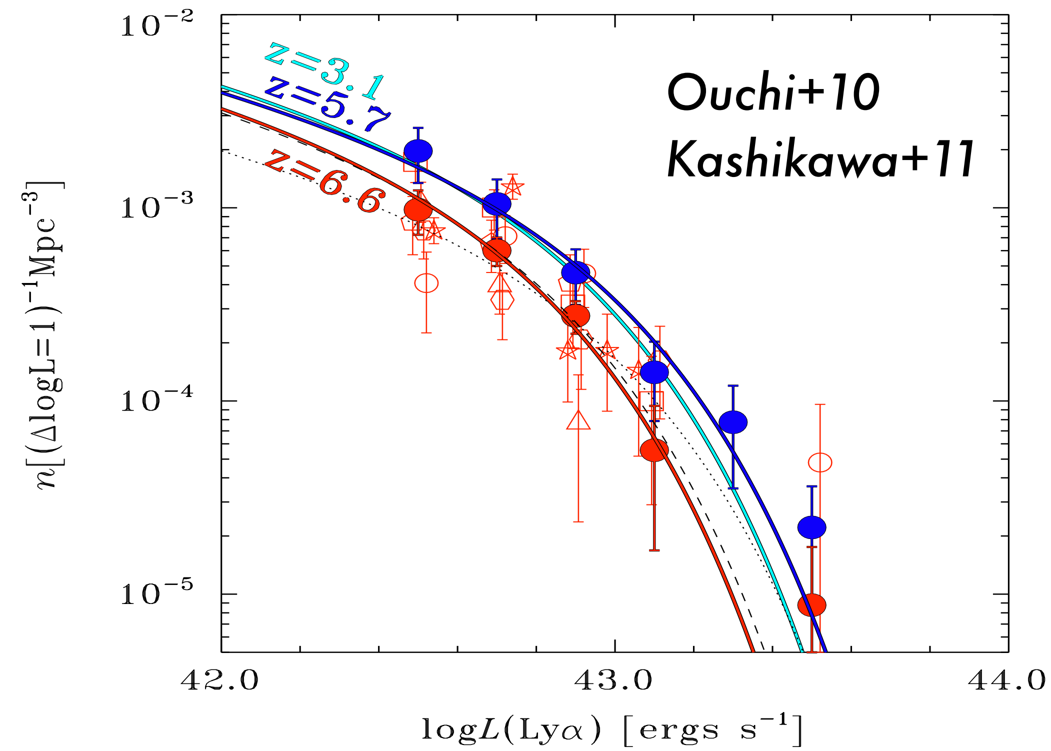
No Lyα attenuation by IGM during in EoR in GALICS : **part of intrinsic evolution?**

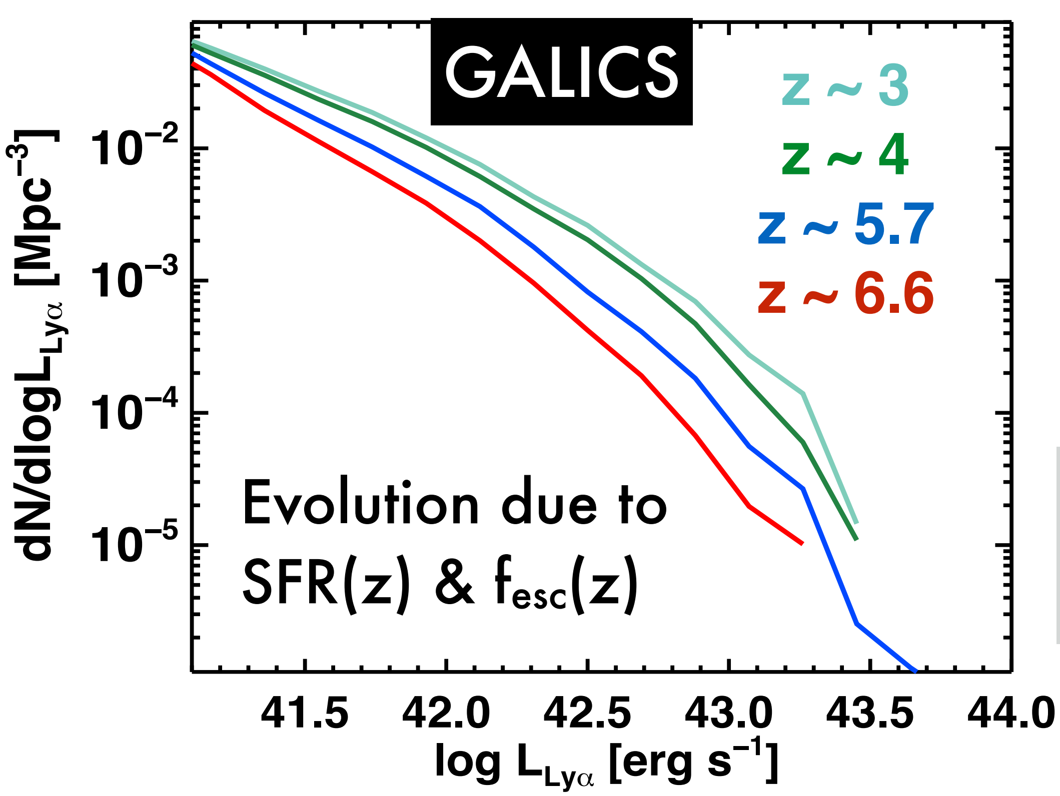
Lya LF evolution

=> **no apparent evolution** (3 < z < 5.7)

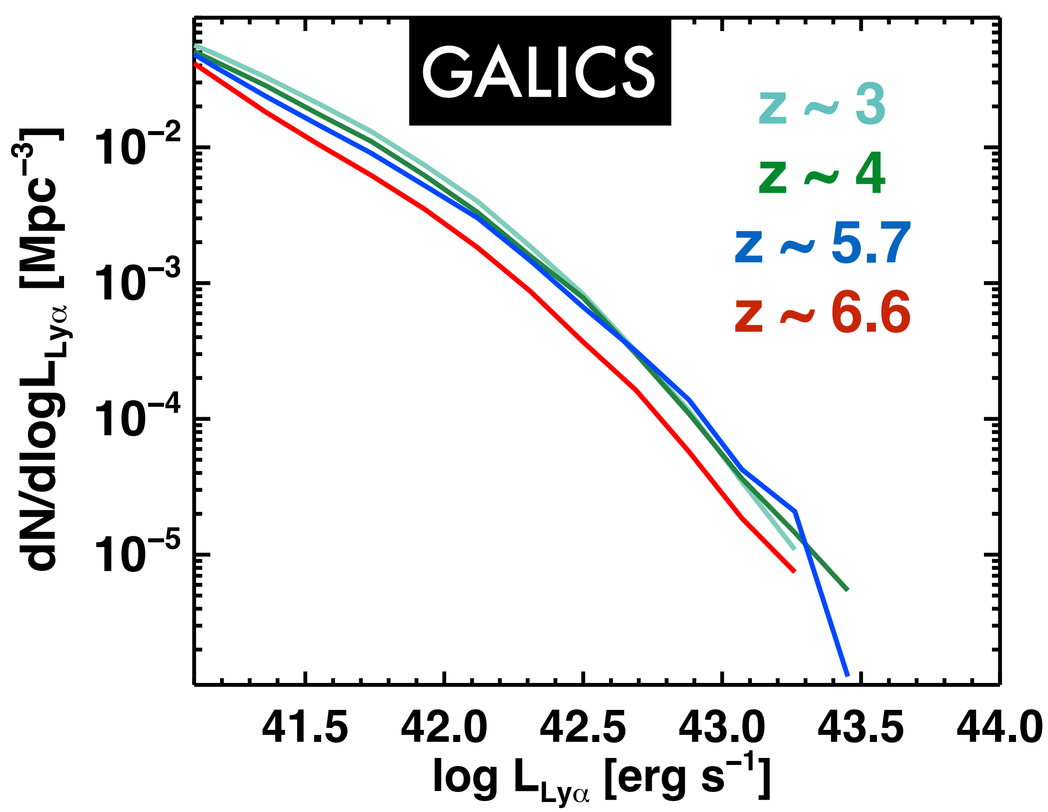
=> **L* decrease by ~ 30%** (5.7 < z < 6.6)

=> $\bar{x}_{\rm HI} \simeq$ 0.4 at z=6.6 if due to IGM only





+ w/ selection
(≃ Lyα EW cuts)



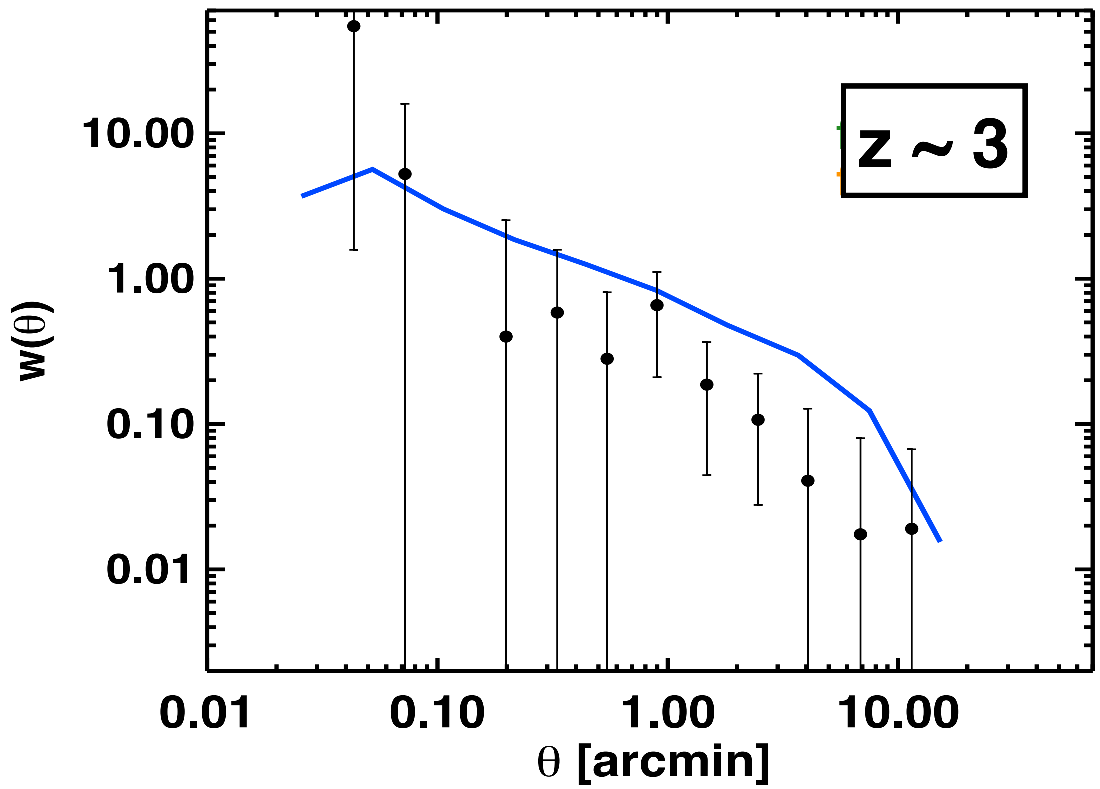
HIGH REDSHIFT GALAXIES IN GALICS

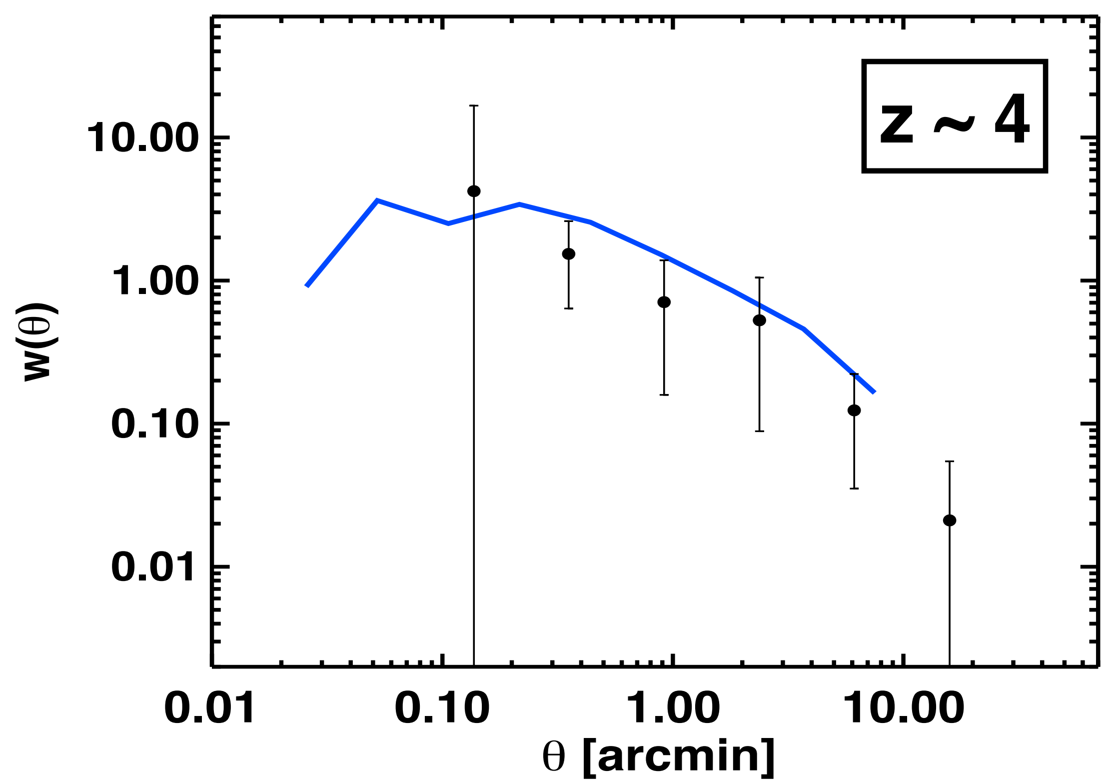
Angular correlation functions (ACF)

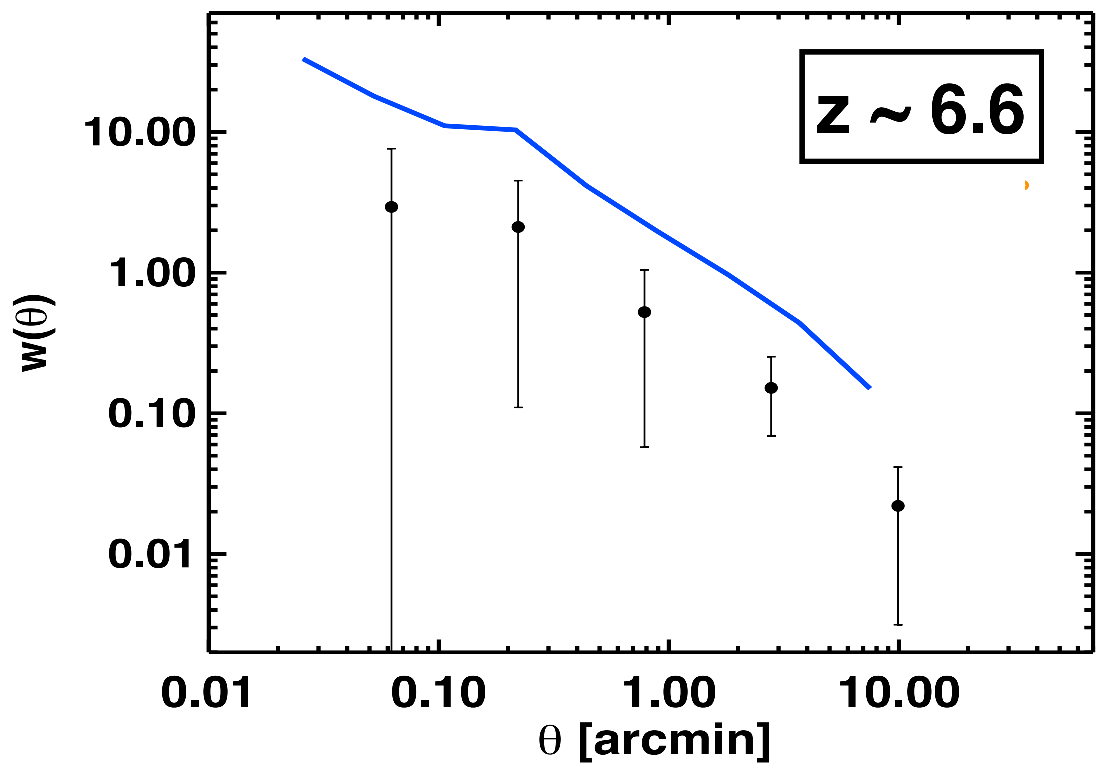
Comparison of GALICS with LAE data

Mean ACF from 1000 realizations
(= simulation seen from 1000 l.o.s.)

Lyα emitters too clustered in model
(host halos too massive?)

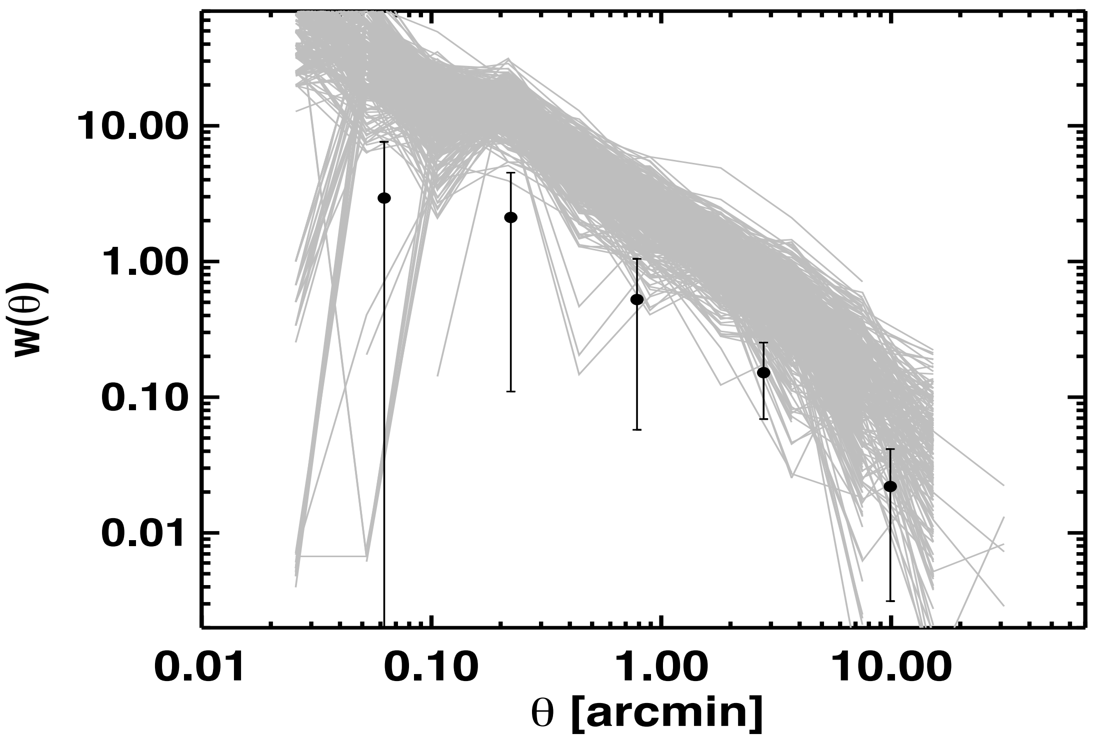




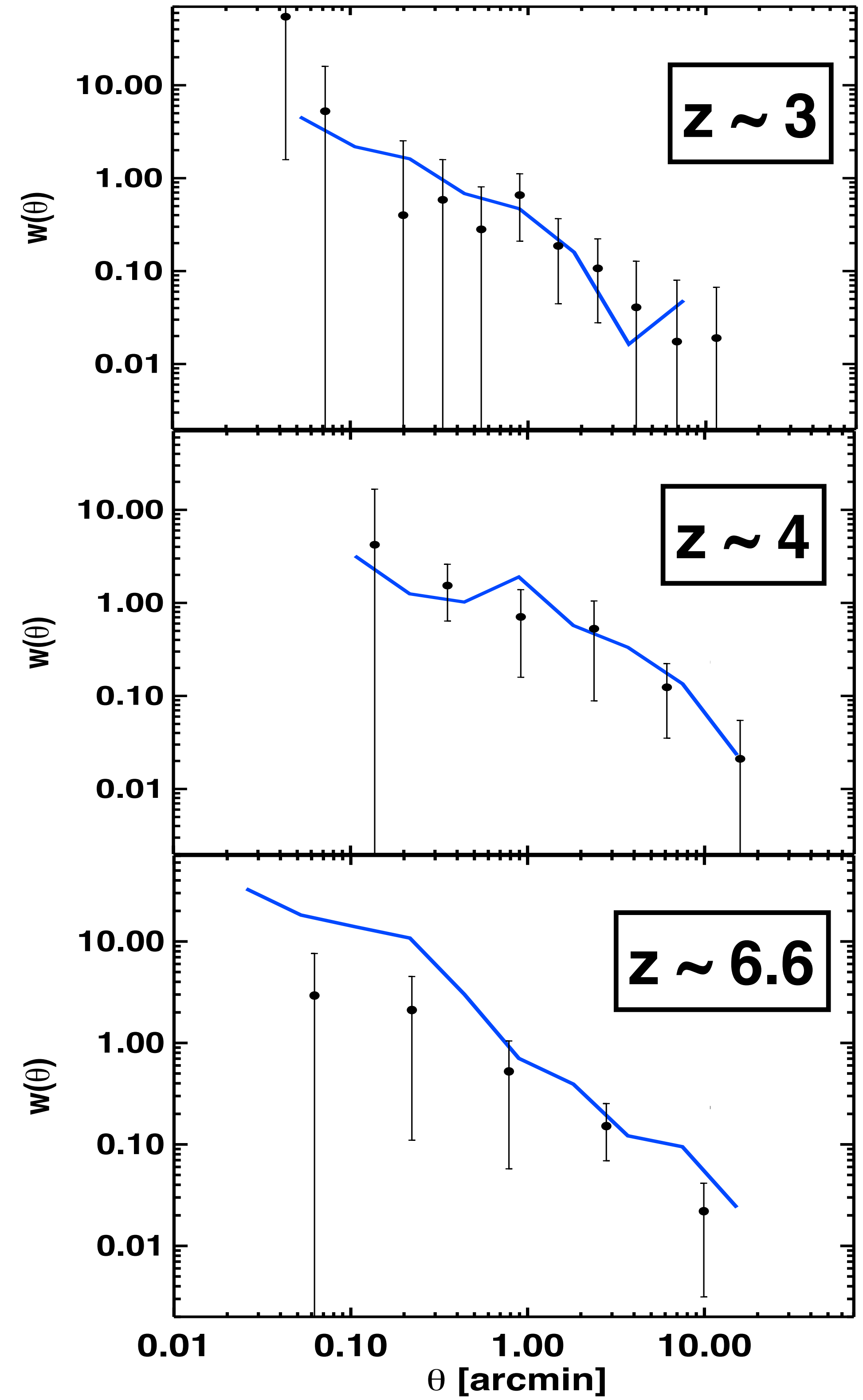


HIGH REDSHIFT GALAXIES IN GALICS

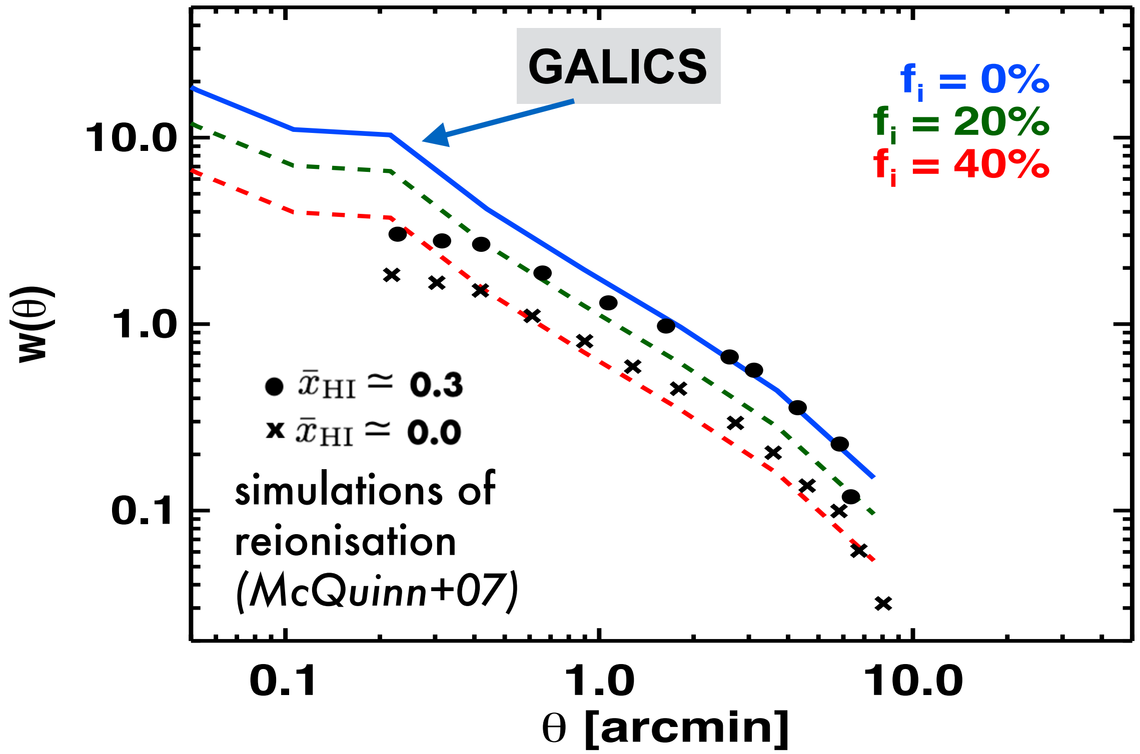
Strong variance between different realizations



Individual realizations

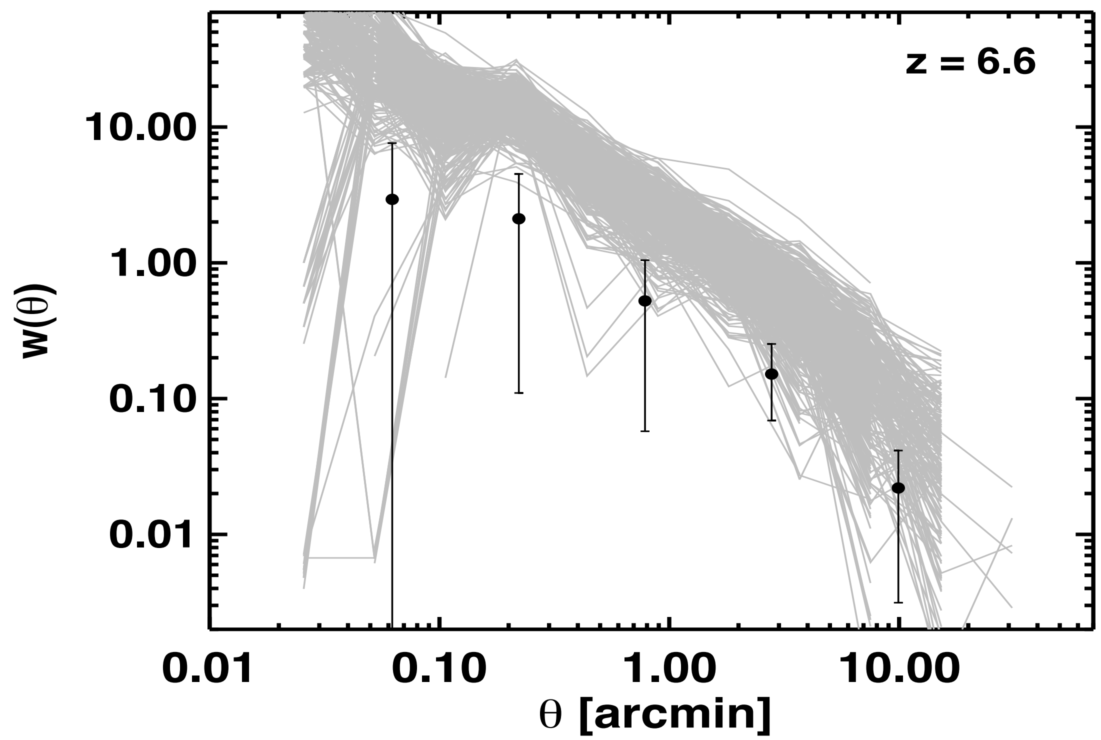


HIGH REDSHIFT GALAXIES IN GALICS



- ACF measurement from photometric surveys
- Fraction of low-z interlopers $f_i \simeq$ 0-40%
  Ouchi+10, Kashikawa+11, Hu+10

→ Add interlopers as randomly distributed sources in GALICS



Need to carefully account for intrinsic evolution, f_i and CV to use Lyα as *reionisation tests*

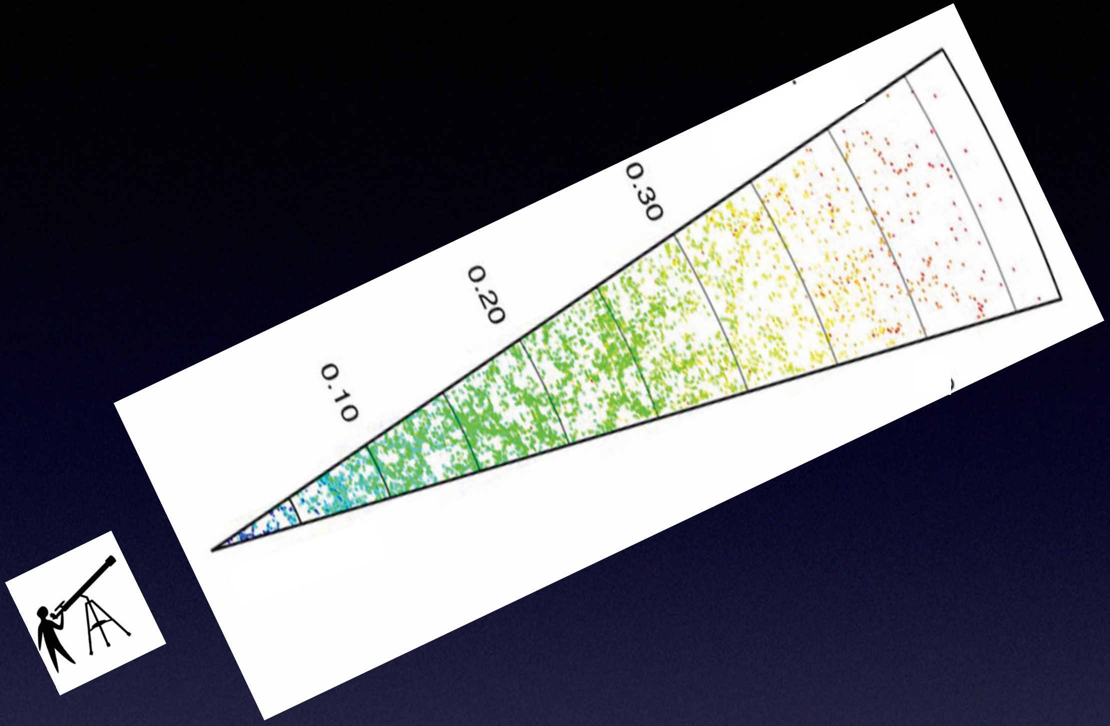
OUTLINE

- ✦ Cosmological simulations of dark matter
- ✦ Physics of galaxy formation in semi-analytic models
- ✦ High-redshift galaxies in GALICS
- ✦ **How to generate mock observables from SAMs**

MOCK LIGHTCONES

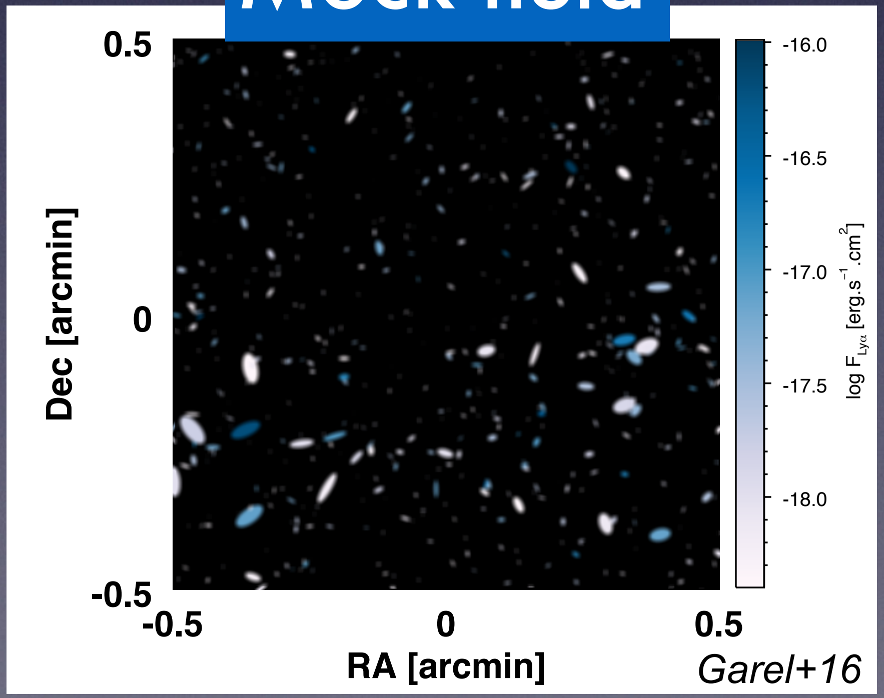
Raw output from SAMs are in "box frame"
(comoving positions, absolute magnitudes etc)

"Lightcone" built from the different snapshots
(e.g. Blaizot+06, Merson+13, Bernyk+16)



→ **mimic "observational selection**

Mock field



Observed field

TAO

Theoretical Astrophysical Observatory

Centre for Astrophysics and Supercomputing - Swinburne University of Technology

Bernyk et al. 2016

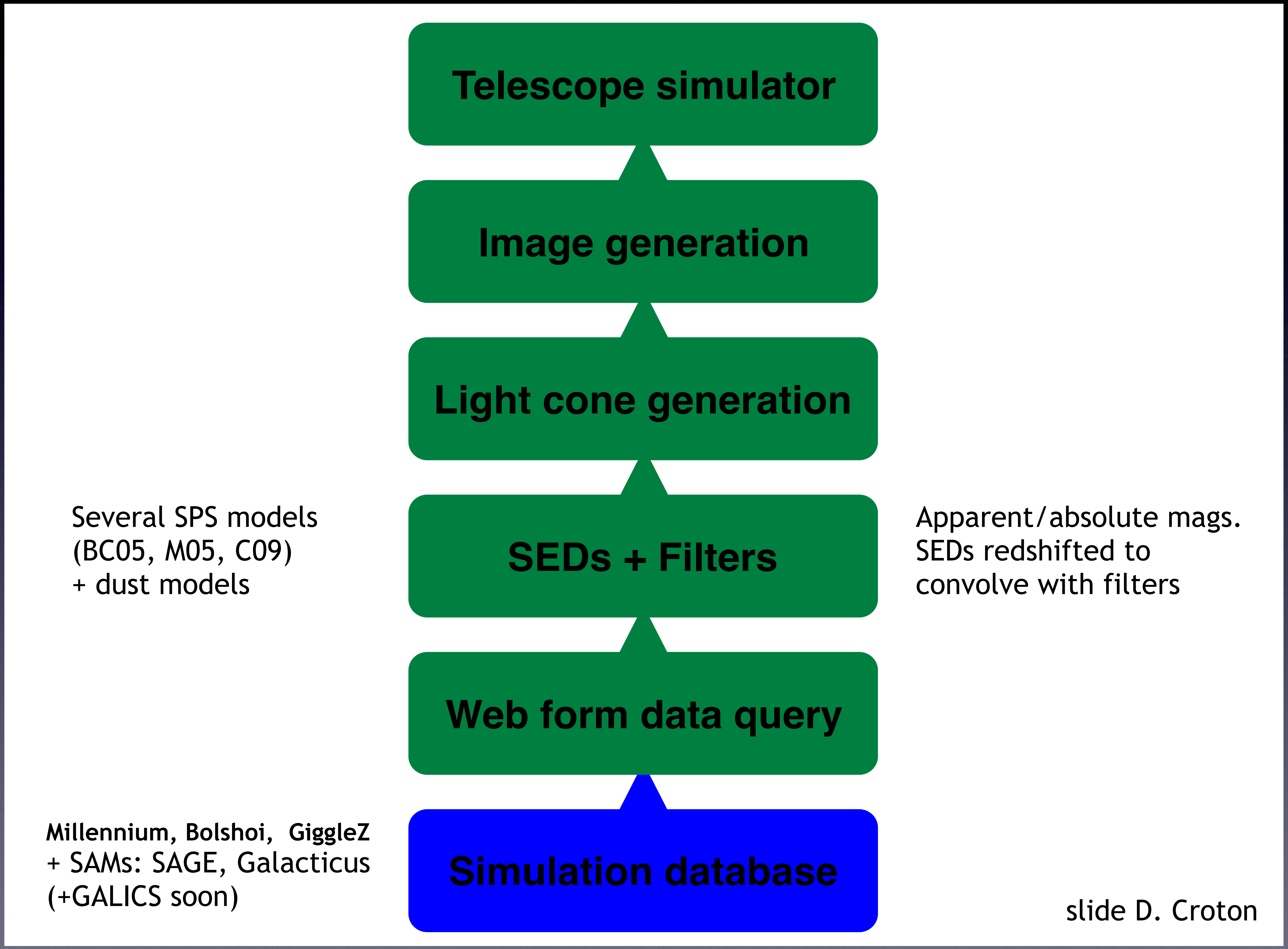
Darren Croton

Swinburne University of Technology

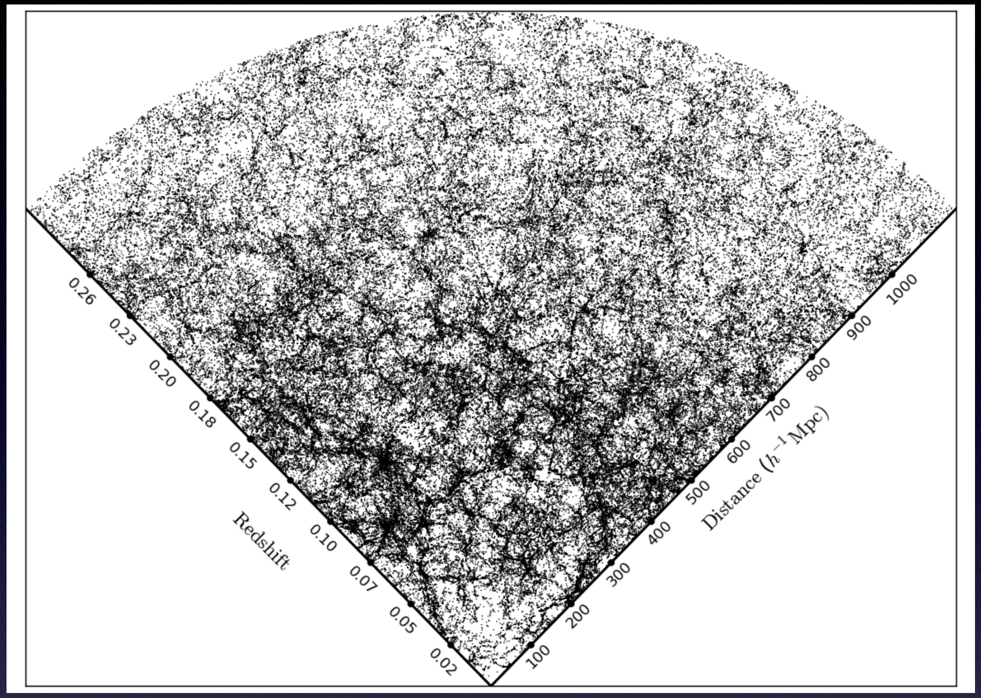
Science Team: Max Bernyk, Darren Croton, Thibault Garel, Simon Mutch, Greg Poole, Chiara Tonini.

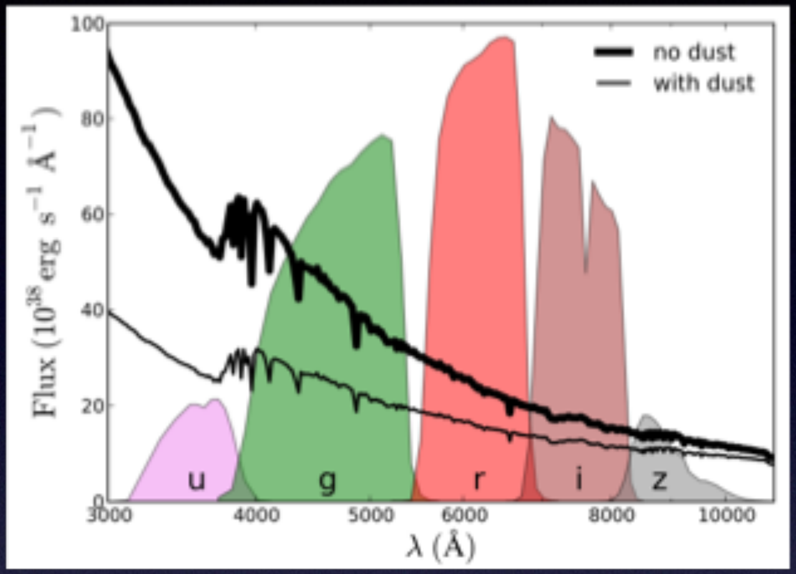
Technical Team: Alistair Grant, Amr Hassan, Luke Hodkinson.

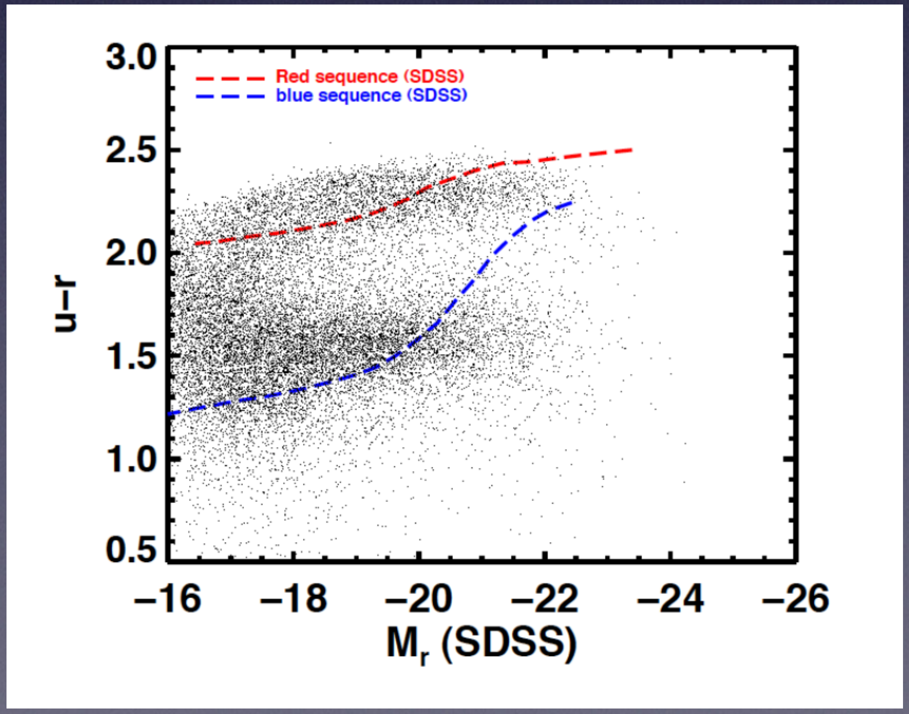
TAO

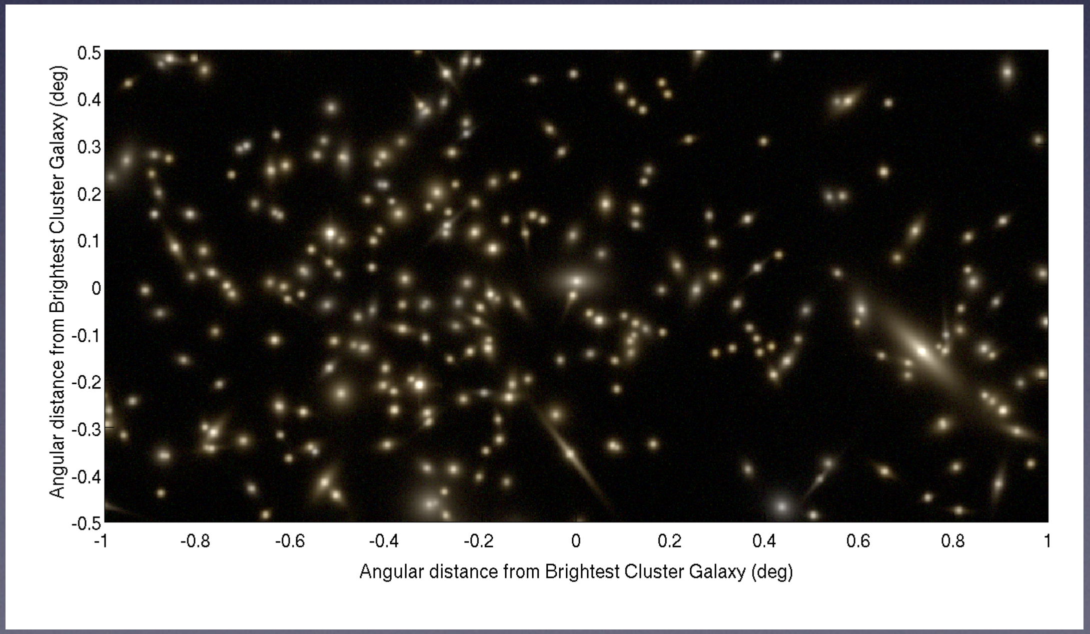

Telescope simulator
Image generation
Light cone generation
Several SPS models
(BC05, M05, C09)
+ dust models
SEDs + Filters
Apparent/absolute mags.
SEDs redshifted to
convolve with filters
Web form data query
Millennium, Bolshoi, GiggleZ
+ SAMs: SAGE, Galacticus
(+GALICS soon)
Simulation database
slide D. Croton

TAO


Redshift
Distance (h^{-1} Mpc)

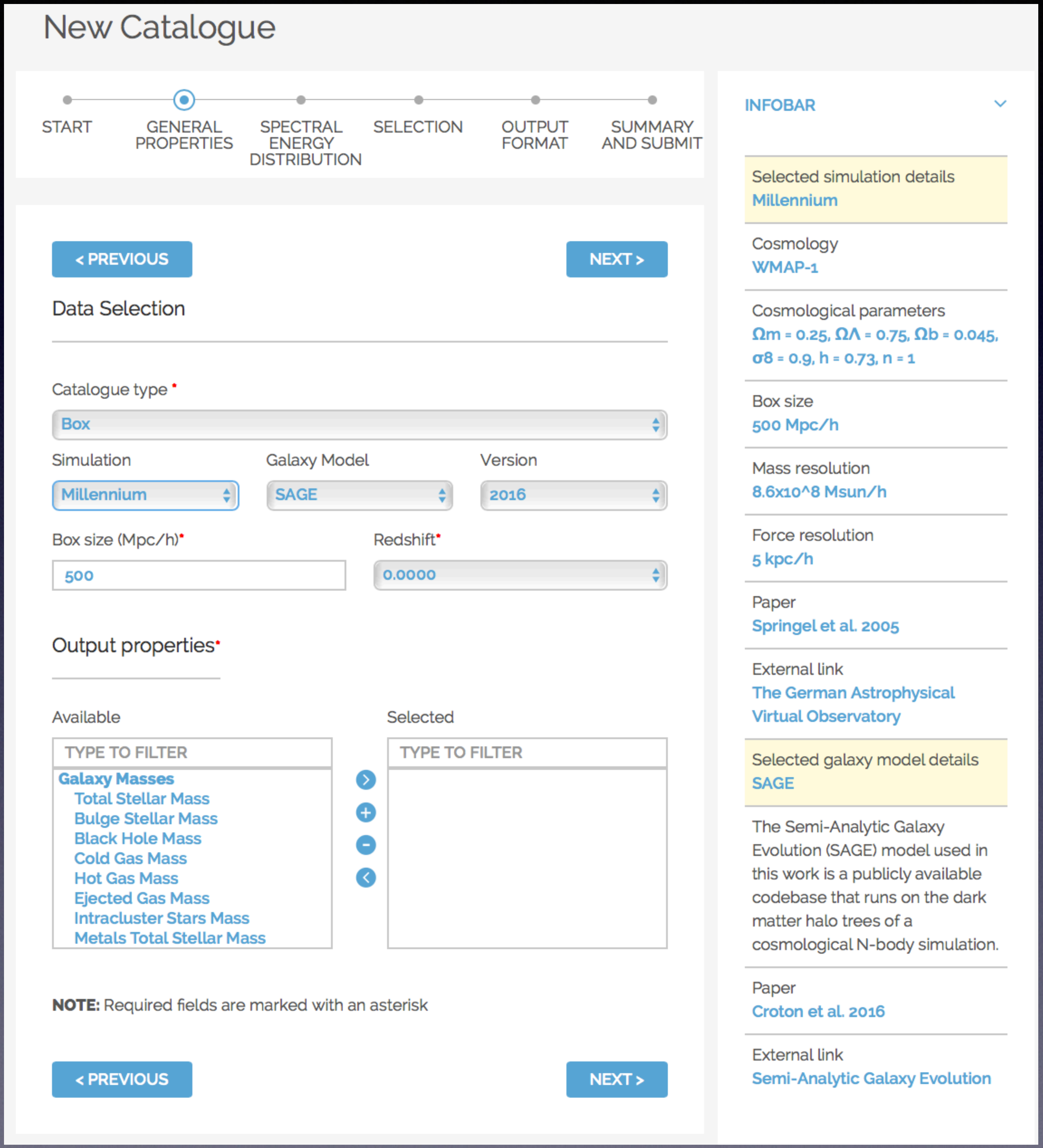

no dust
with dust
Flux (10^{38} erg s^{-1} Å^{-1})
u
g
r
i
z
λ (Å)


Red sequence (SDSS)
blue sequence (SDSS)
u–r
M_r (SDSS)


Angular distance from Brightest Cluster Galaxy (deg)
Angular distance from Brightest Cluster Galaxy (deg)

TAO

https://tao.asvo.org.au/tao/



CONCLUDING REMARKS

- SAMs are a very powerful/flexible tool to study galaxy formation & test different physical models
- Computationally cheap (wrt. hydro simulations…)
- Mock observables widely used to interpret observations & make predictions for extragalactic surveys
- Successful at reproducing many observations… but not all…