Galaxy formation: Predictions from models

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Basic resolution requirements

- Convergence requires resolving the Jeans scales:

$$M_{\rm J} \approx 1\times10^7\,h^{-1}\,{\rm M}_\odot\,f_{\rm g}^{3/2}\left(\frac{n_{\rm H}}{10^{-1}\,{\rm cm}^{-3}}\right)^{-1/2}\left(\frac{T}{10^4\,{\rm K}}\right)^{3/2}$$

$$L_{\rm J} \approx 1.5\,h^{-1}\,{\rm kpc}\,f_{\rm g}^{1/2}\left(\frac{n_{\rm H}}{10^{-1}\,{\rm cm}^{-3}}\right)^{-1/2}\left(\frac{T}{10^4\,{\rm K}}\right)^{1/2}$$

- Resolving the warm phase requires:
  - Particle mass << 10^7 $M_\odot$
  - Spatial resolution << 1 kpc
- Resolving gas with n_H~10 cm^{-3} and T~10^2 K requires:
  - particle mass << 10^3 $M_\odot$
  - spatial resolution << 10 pc
  - Radiative transfer
  - Complex chemistry

Self-regulated galaxy formation

- Feedback too weak compared to accretion
  - Gas density increases
  - Star formation /BH growth rate increases
  - Feedback increases
- Feedback too strong compared to accretion
  - Gas density decreases
  - Star formation/BH growth rate decreases
  - Feedback decreases

Consequences of self-regulated GF

- Galaxies tend to a state of quasi-equilibrium (outflow ~ inflow), when averaged over suitable length and time scales
  - ➢ Existence of simple scaling relations
- Outflow reacts to inflow
  - ➢ Gas accretion drives galaxy evolution

Consequences of self-regulated GF

- M_* inversely proportional to efficiency of SF feedback
  - ➢ M_*-M_{halo} relation cannot be predicted unless the radiative losses in the ISM can be predicted
- M_{BH} inversely proportional to efficiency of AGN feedback
  - ➢ Normalisation of M_{BH}-M_* relation difficult to predict from first principles

➢ Feedback efficiencies need to be calibrated, e.g. to reproduce the observed $z = 0$ mass functions of galaxies and black holes

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The EAGLE project: simulating the evolution and assembly of galaxies and their environments

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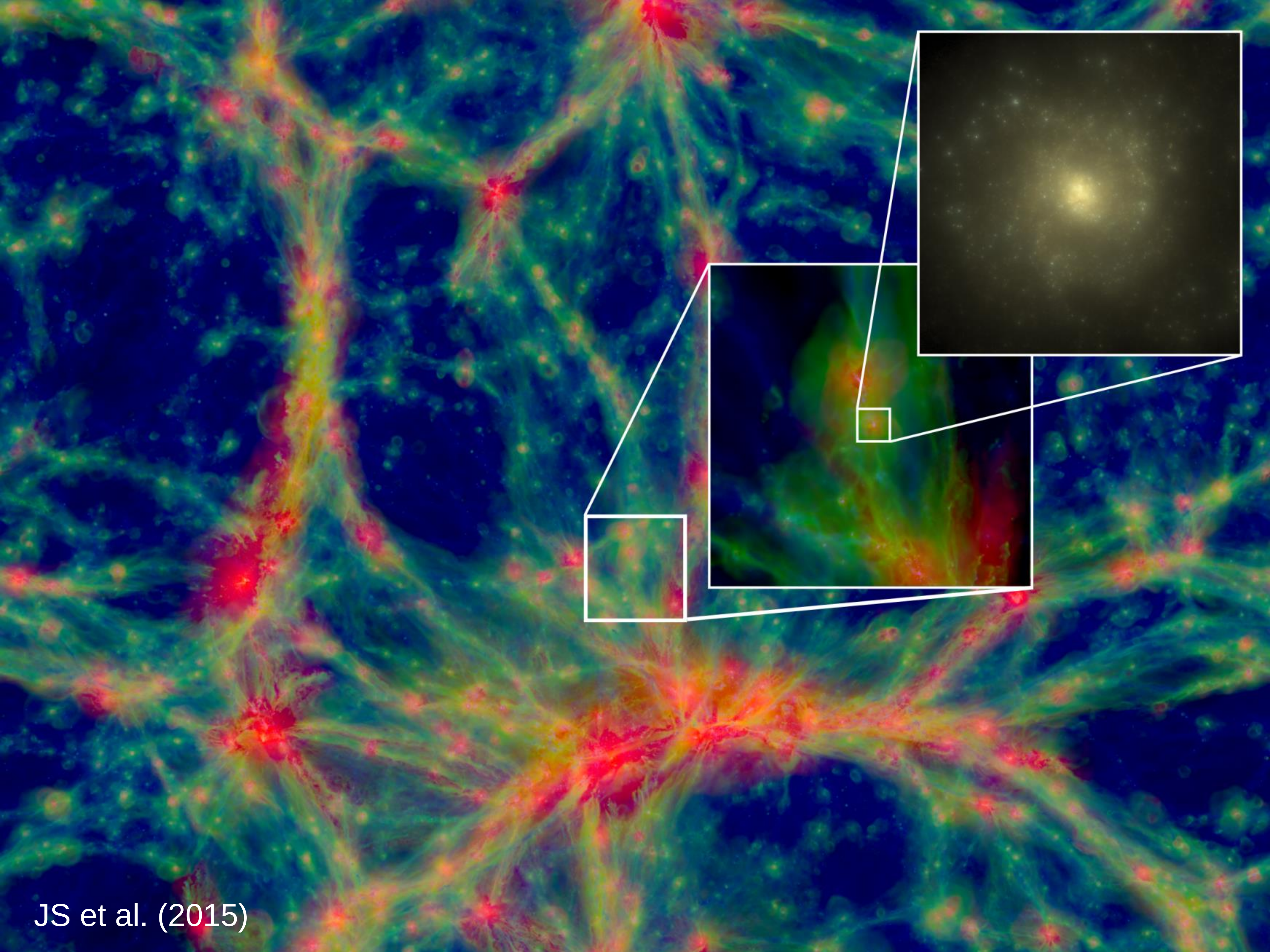
EAGLE:

Evolution and Assembly of GaLaxies and their Environments

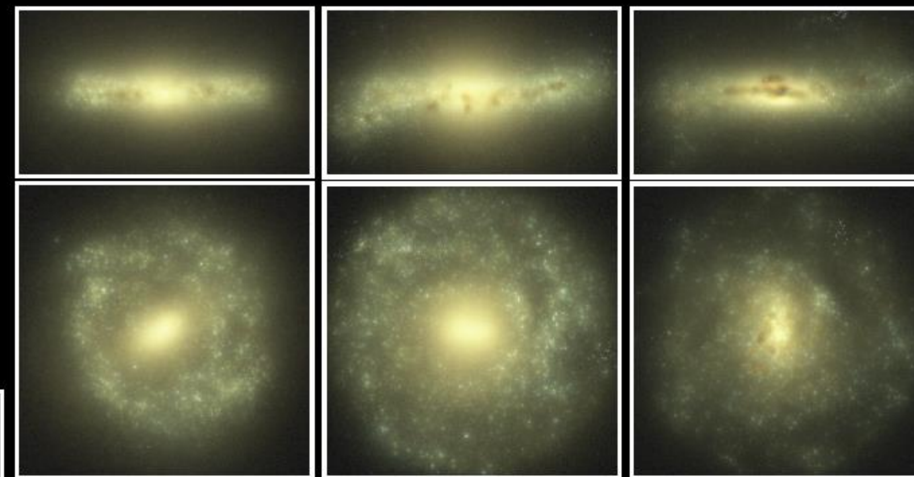
- Planck year 1 cosmology
- Volumes of 25 - 100 Mpc and zooms
- Up to 2×1504^3 (~7 billion) particles
- Particle mass 10^5 – 10^6 $M_\odot$ (smaller for zooms), resolves warm ISM
- Pressure-entropy SPH, time step limiter
- Includes feedback from stars and AGN (1 type each)
- Subgrid recipes depend only on local hydro quantities
- Winds develop naturally without predetermined mass loading or velocity
- Hydro and cooling never turned off
- Feedback efficiency calibrated to match $z = 0$ mass function and galaxy sizes
- Many different models, spin offs


JS et al. (2015)

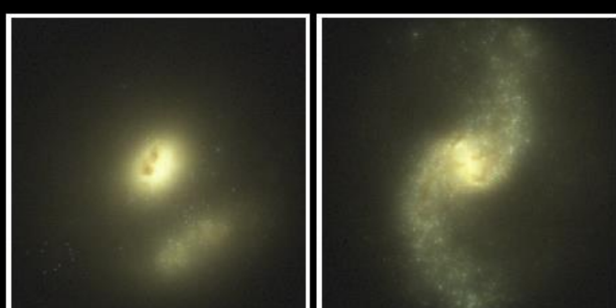
Images from u,g,r filters + dust

From JS et al. (2015)

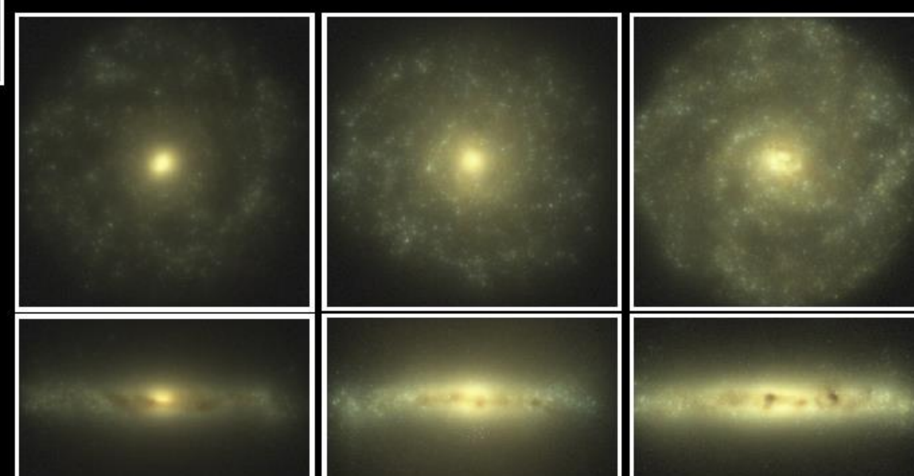
Barred discs



Ellipticals



Irregulars



Discs

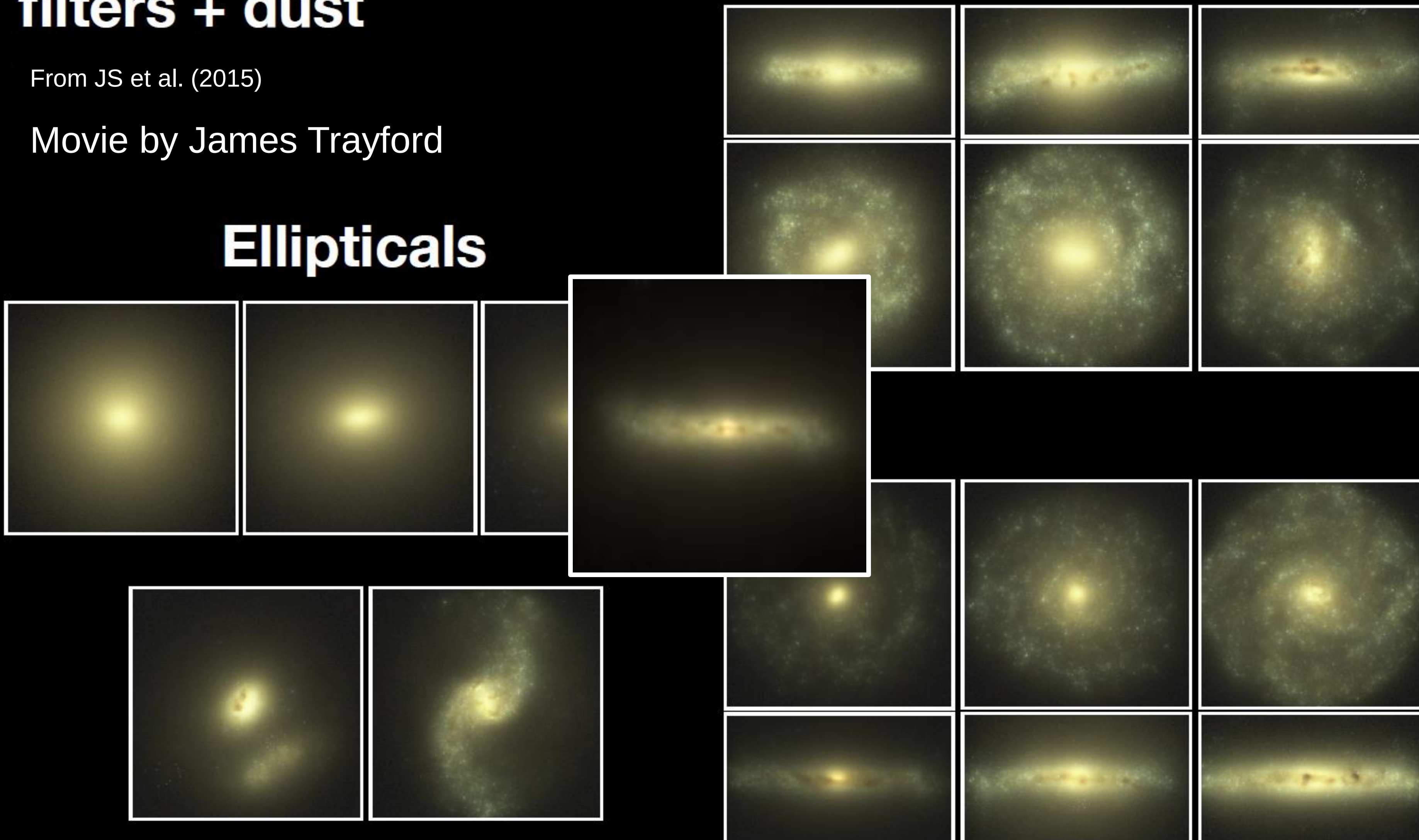
Images from u,g,r filters + dust

From JS et al. (2015)

Movie by James Trayford

Barred discs

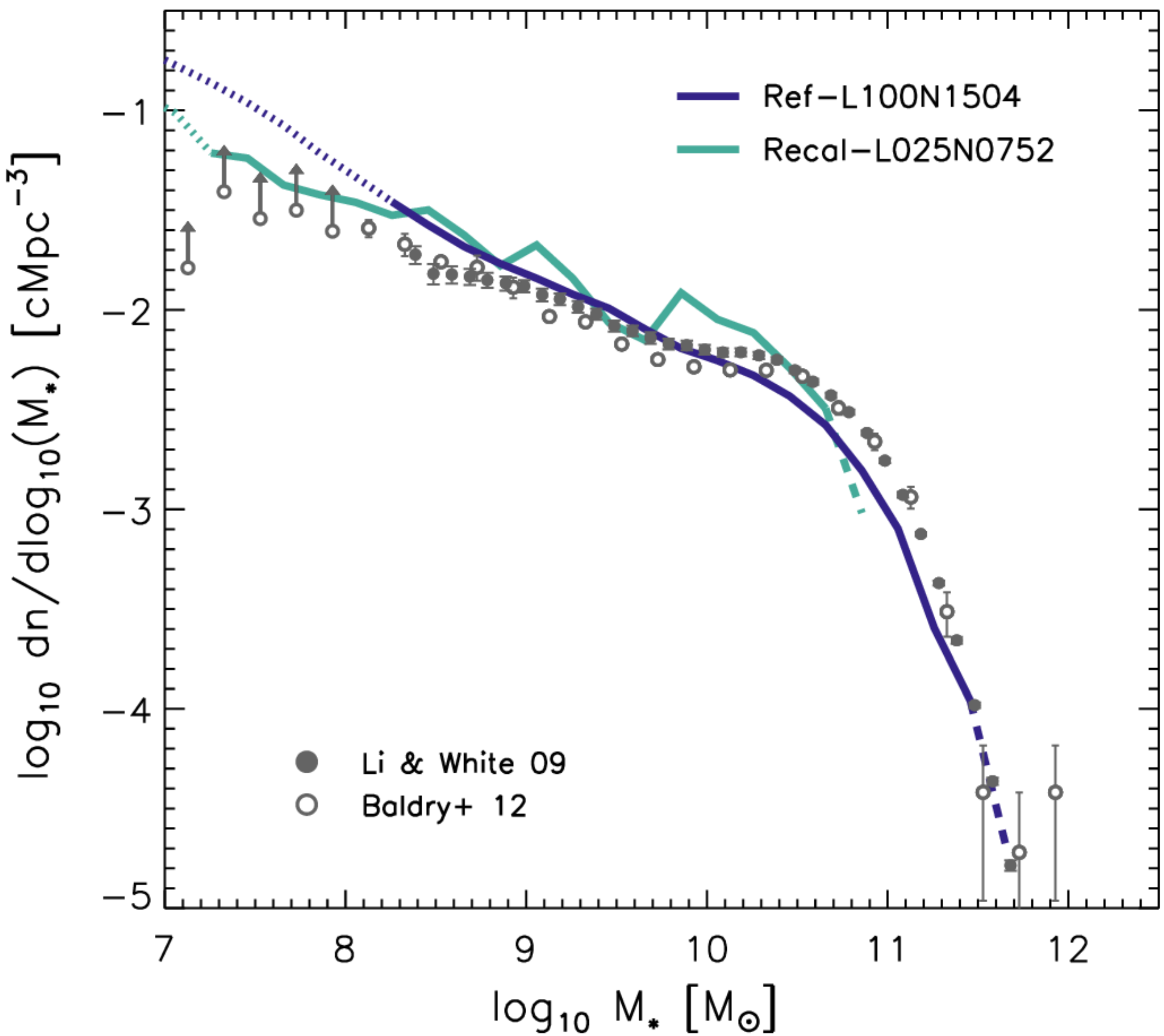
Ellipticals



Irregulars

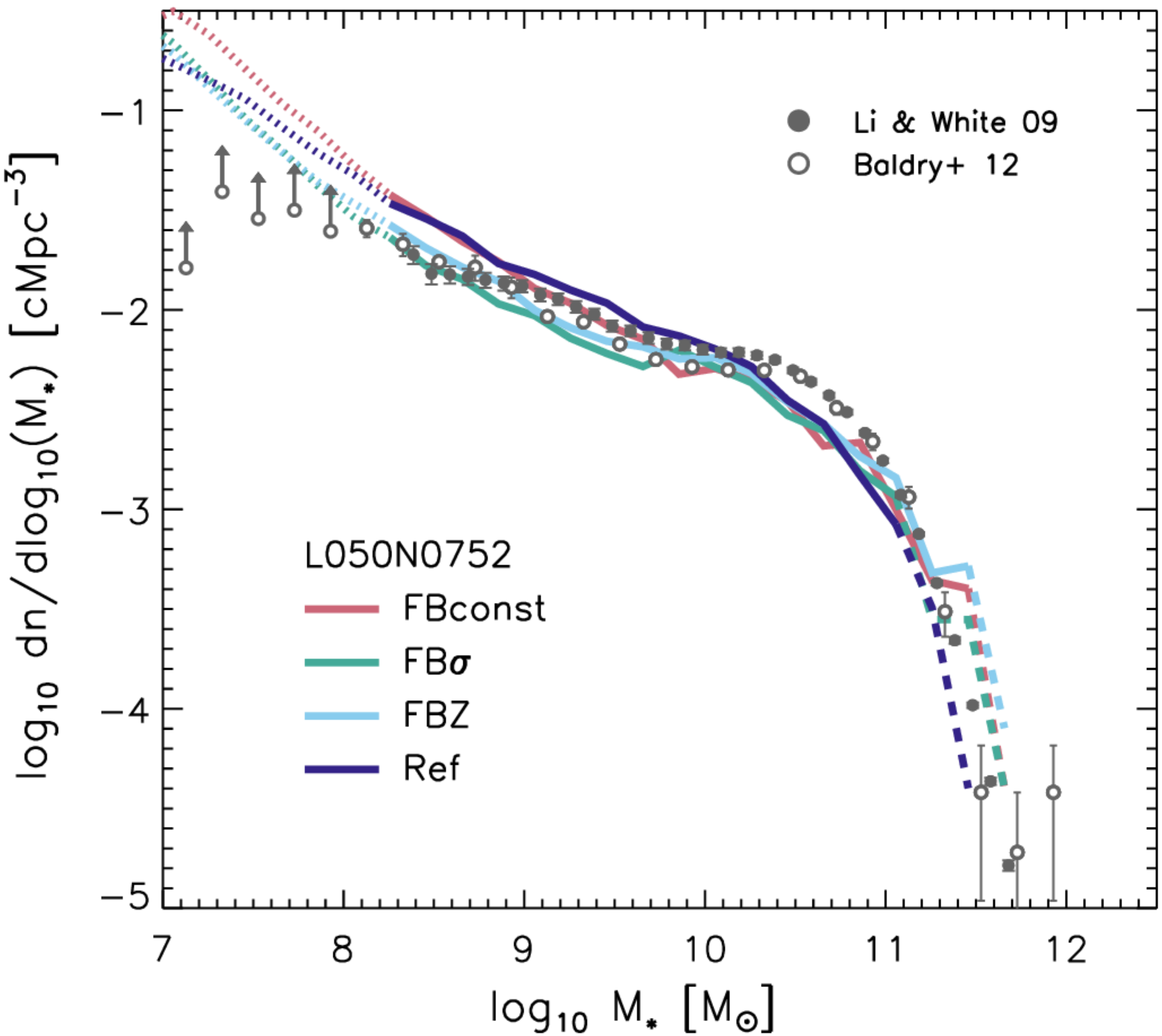
Discs

Galaxy mass function

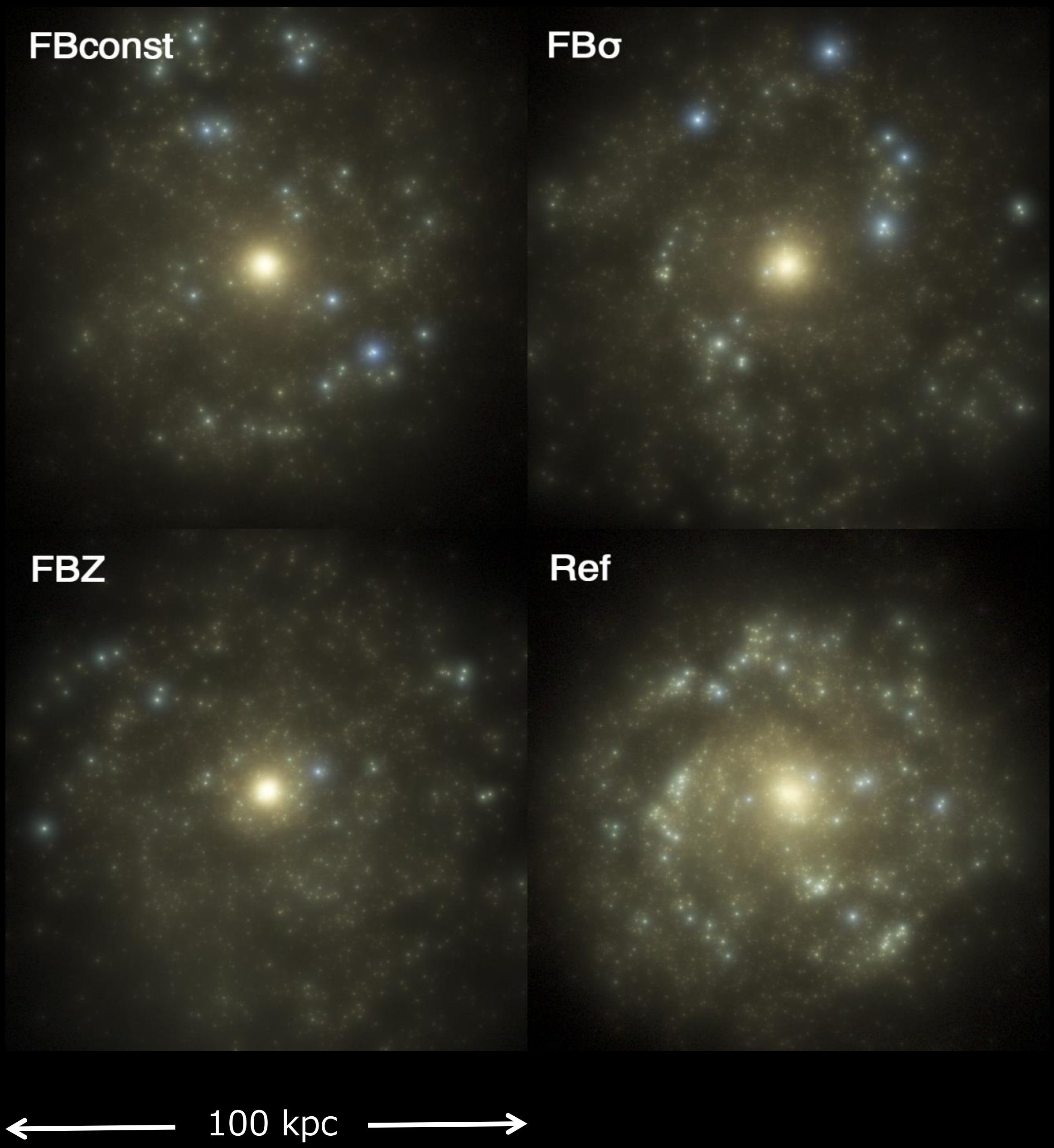


JS et al. (2015)

Many ways to fit the mass function



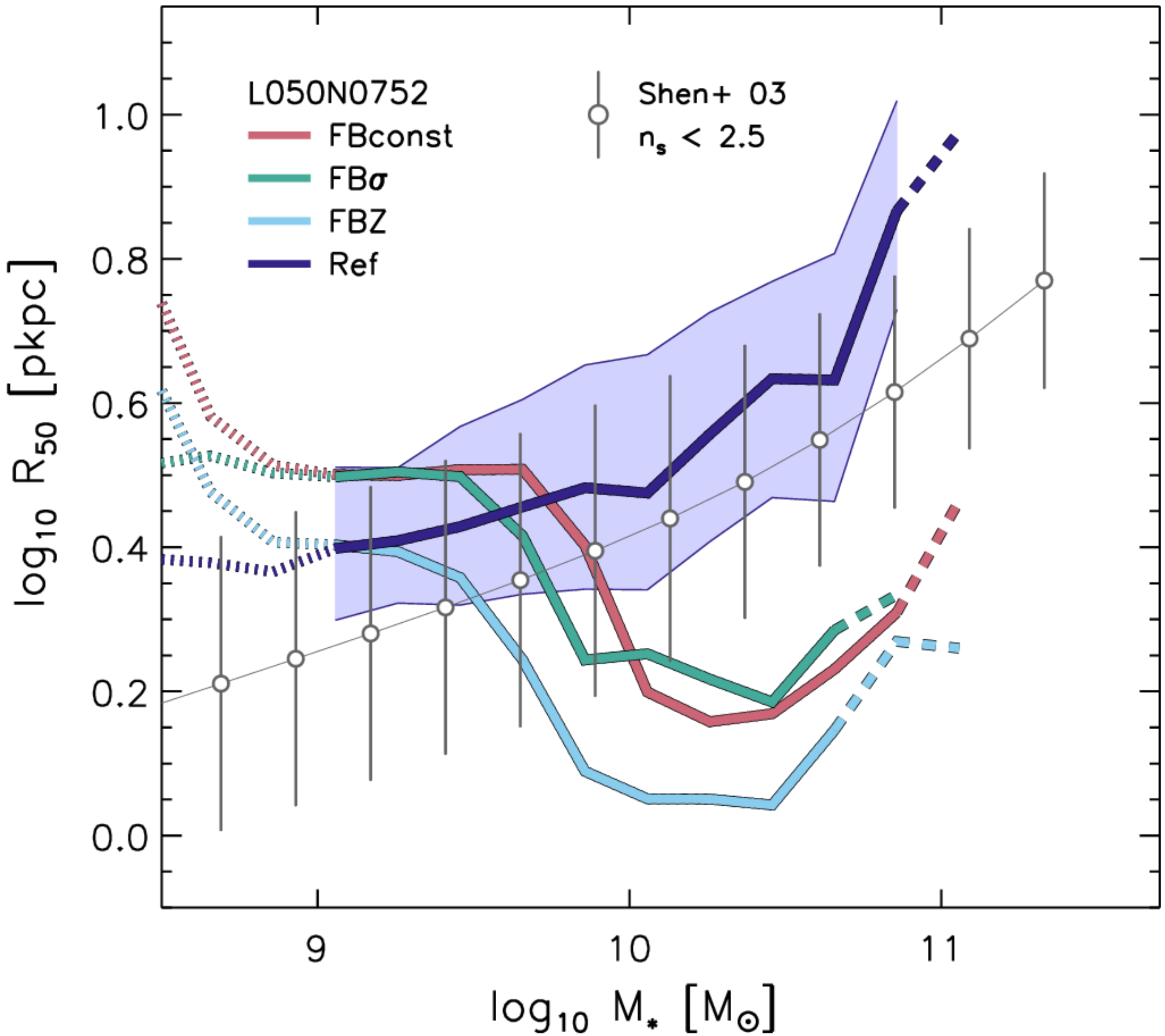
Crain, JS et al. (2015)



$M_{200} = 10^{12}\ M_{\odot}$

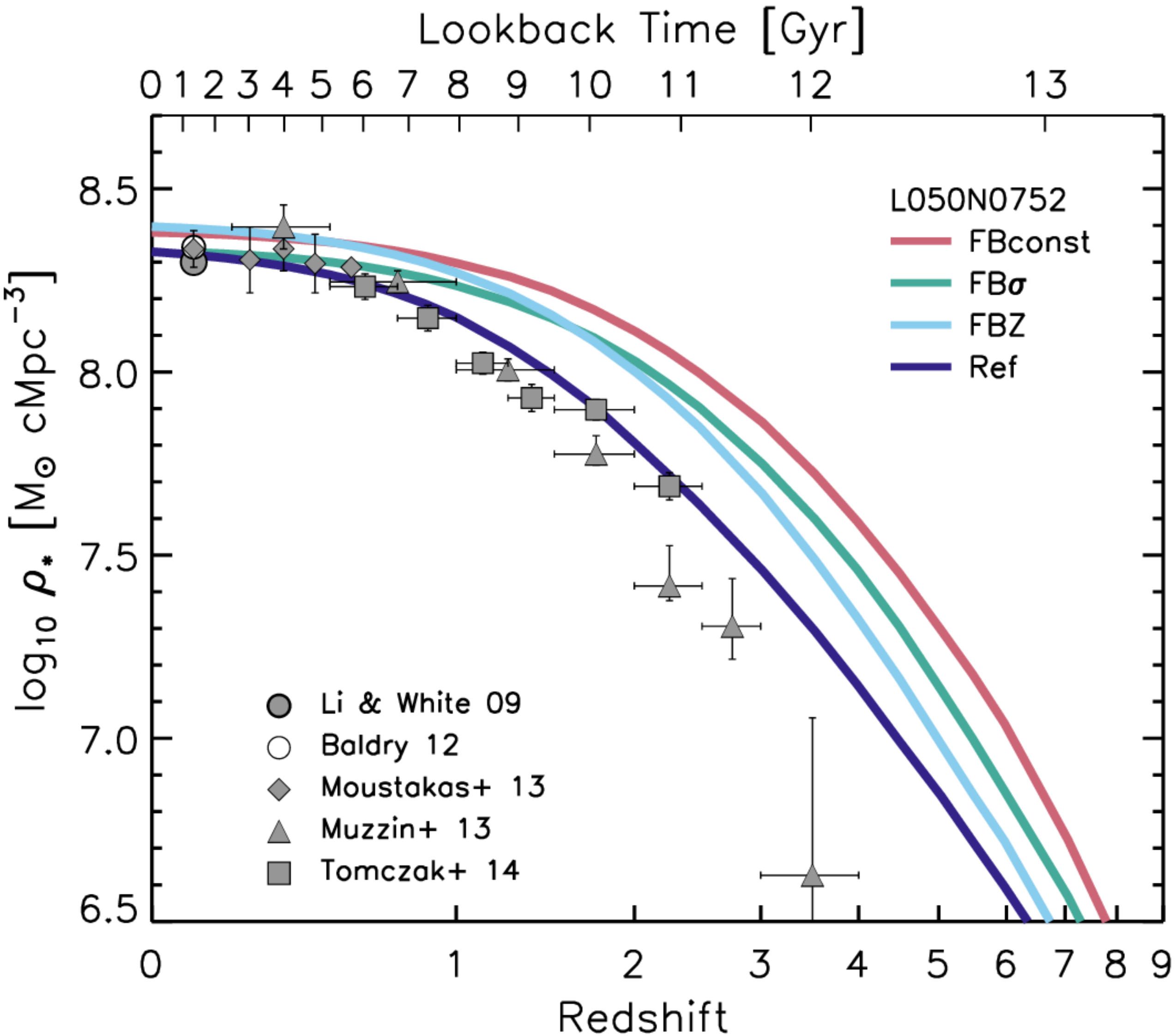
Crain, JS et al. (2015)

Sizes



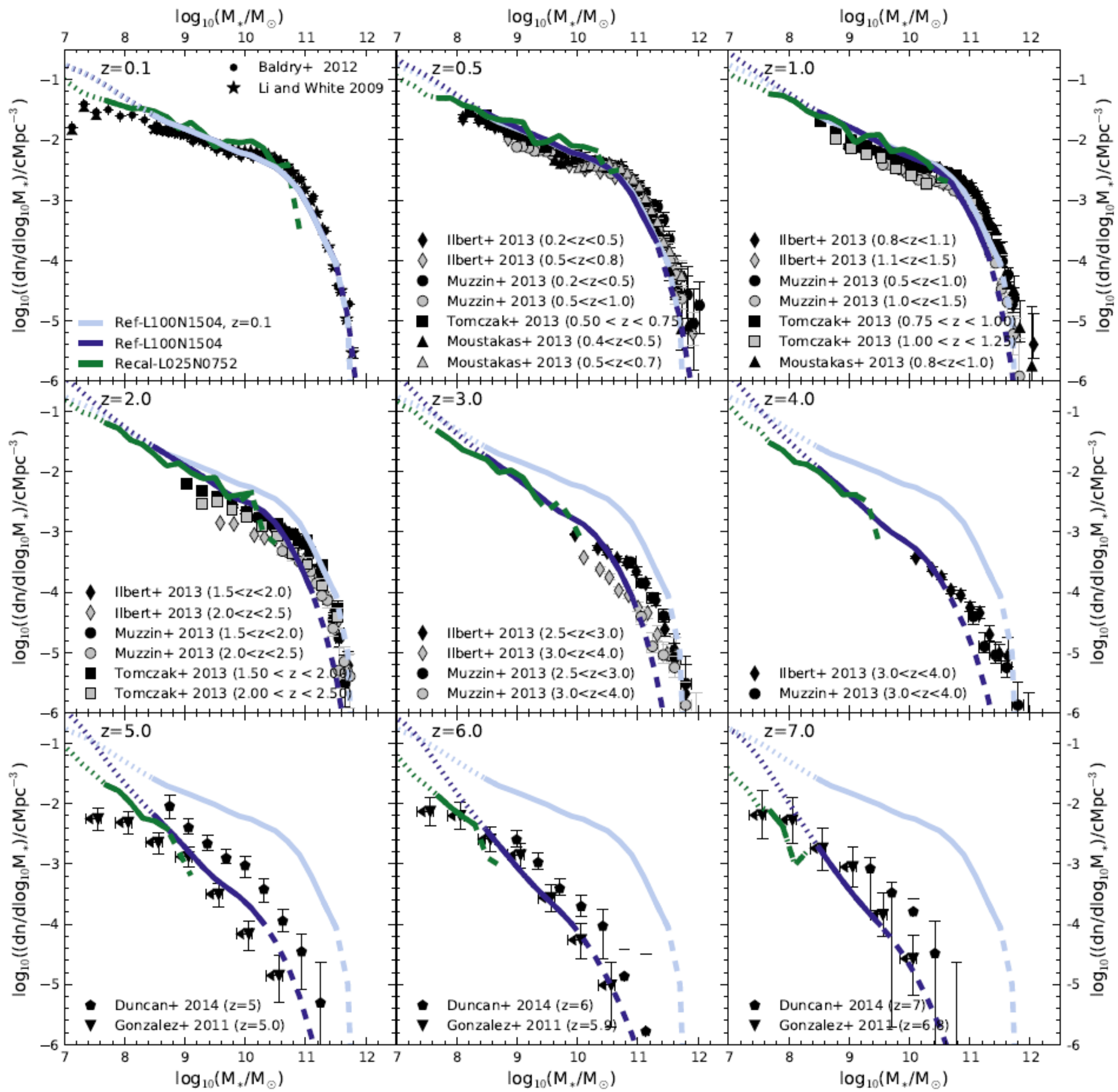
Crain, JS et al. (2015)

Evolution of the stellar density



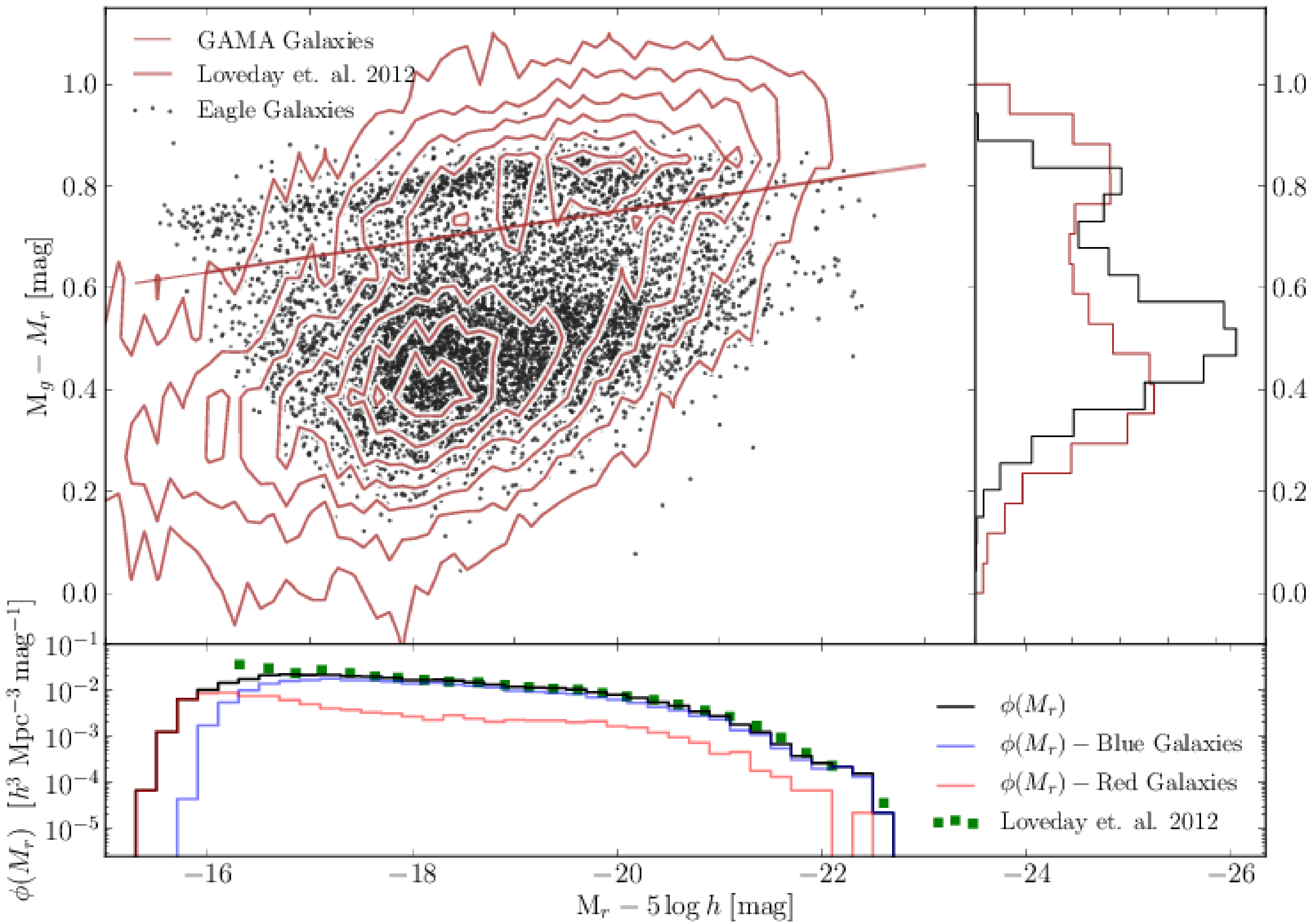
Crain, JS et al. (2015)

Evolution of the mass function



Furlong et al. (2015)

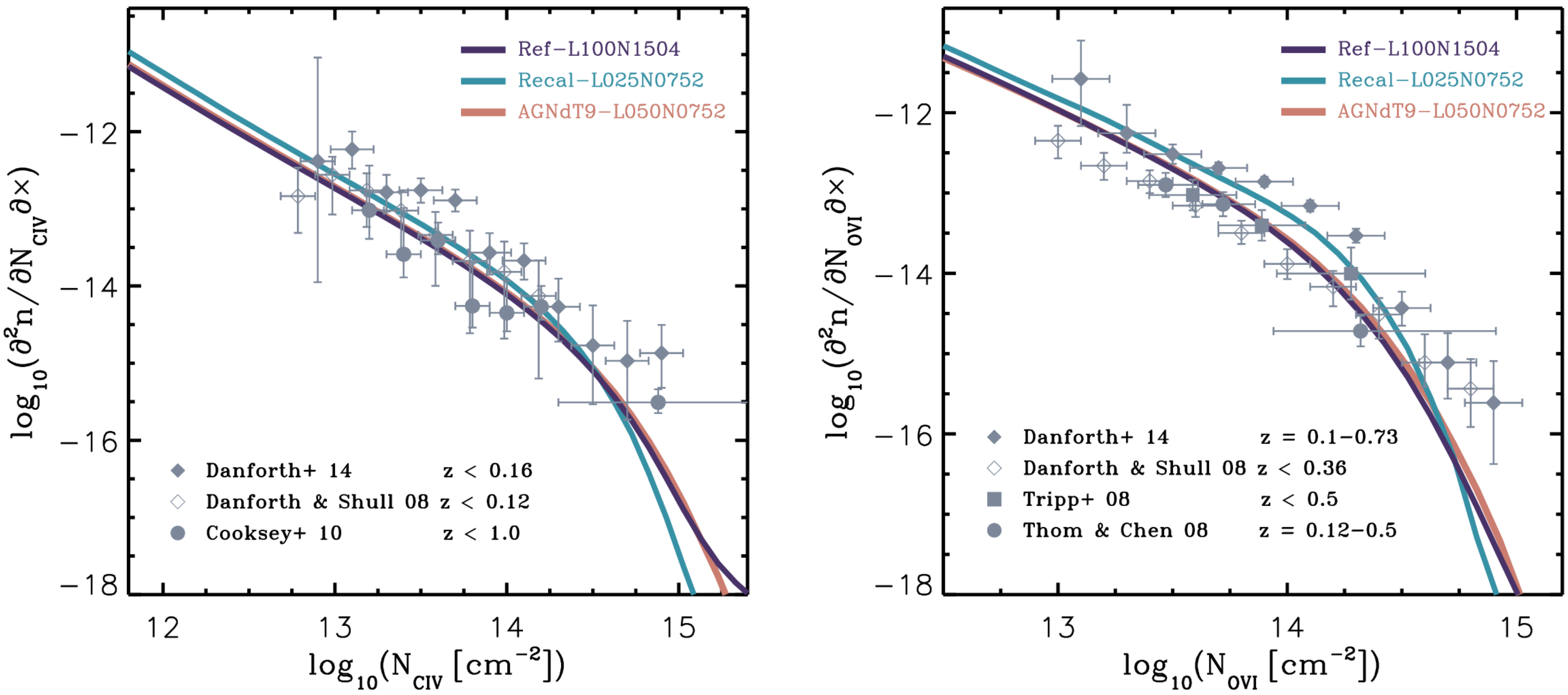
Colour-magnitude diagram: EAGLE vs GAMA



SPSS: Bruzual & Charlot ’93
Extinction: Charlot & Fall
Flux limit: GAMA

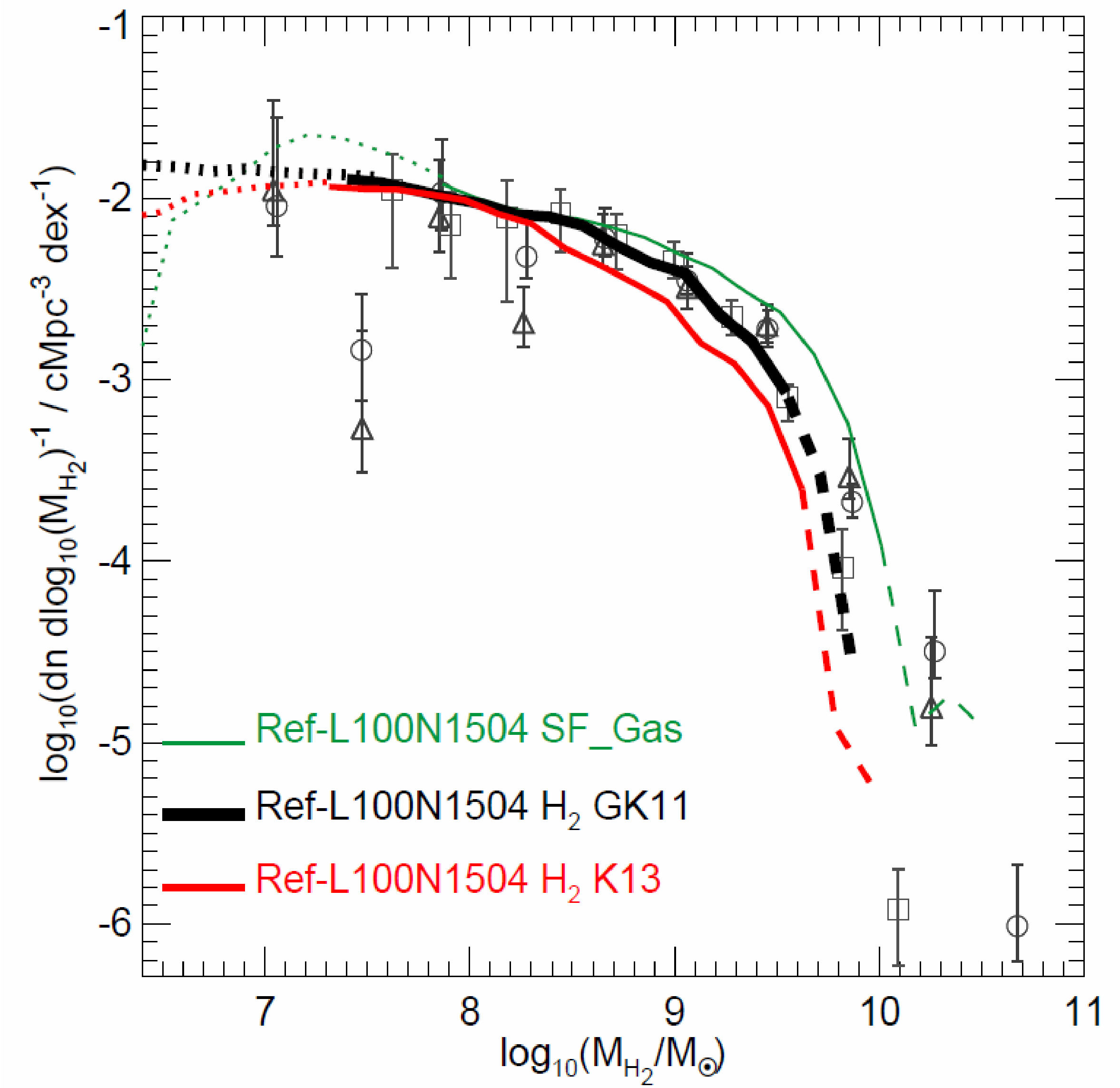
Trayford et al. (in prep)

Intergalactic metals



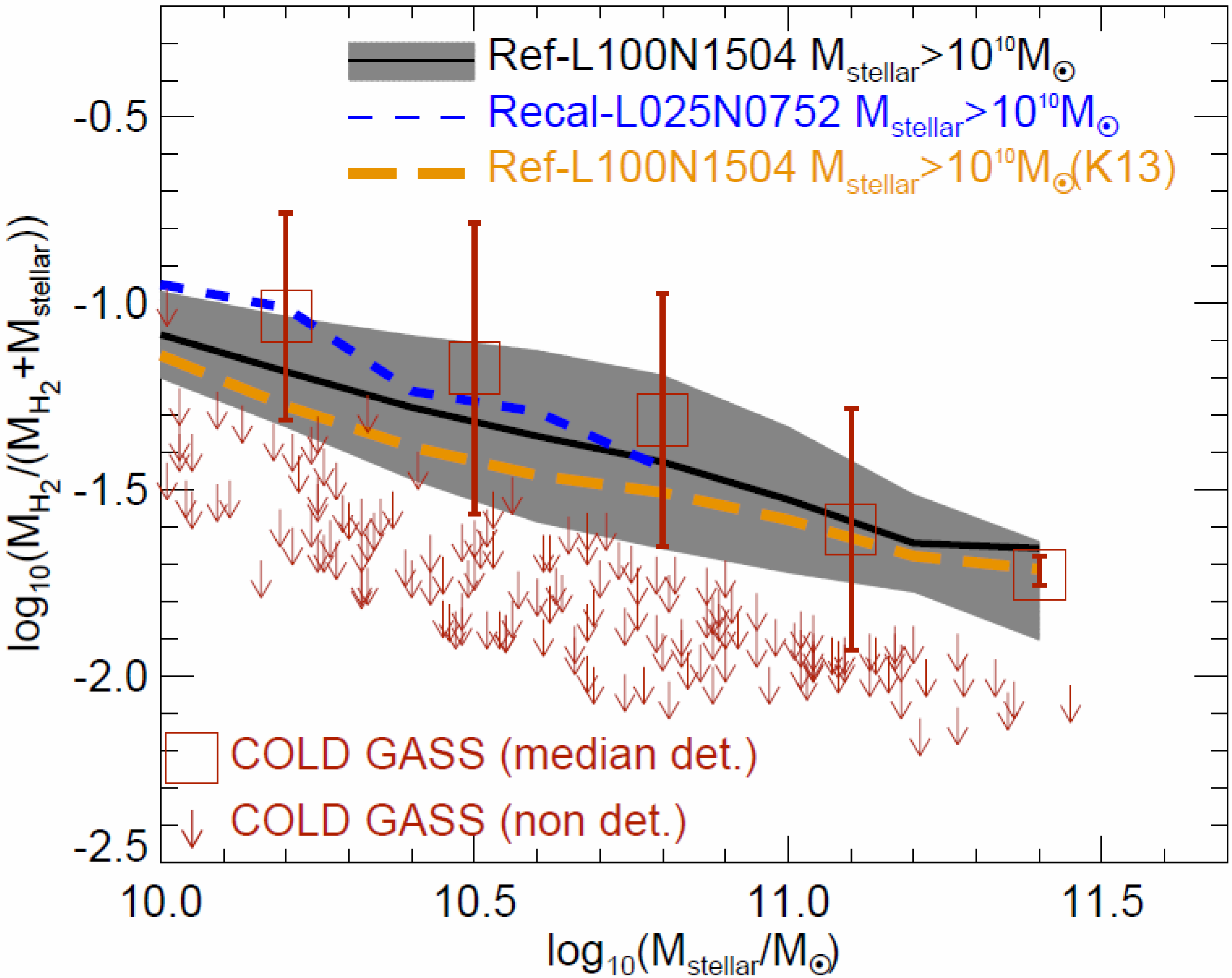
JS et al. (2015)

H_2 Mass function



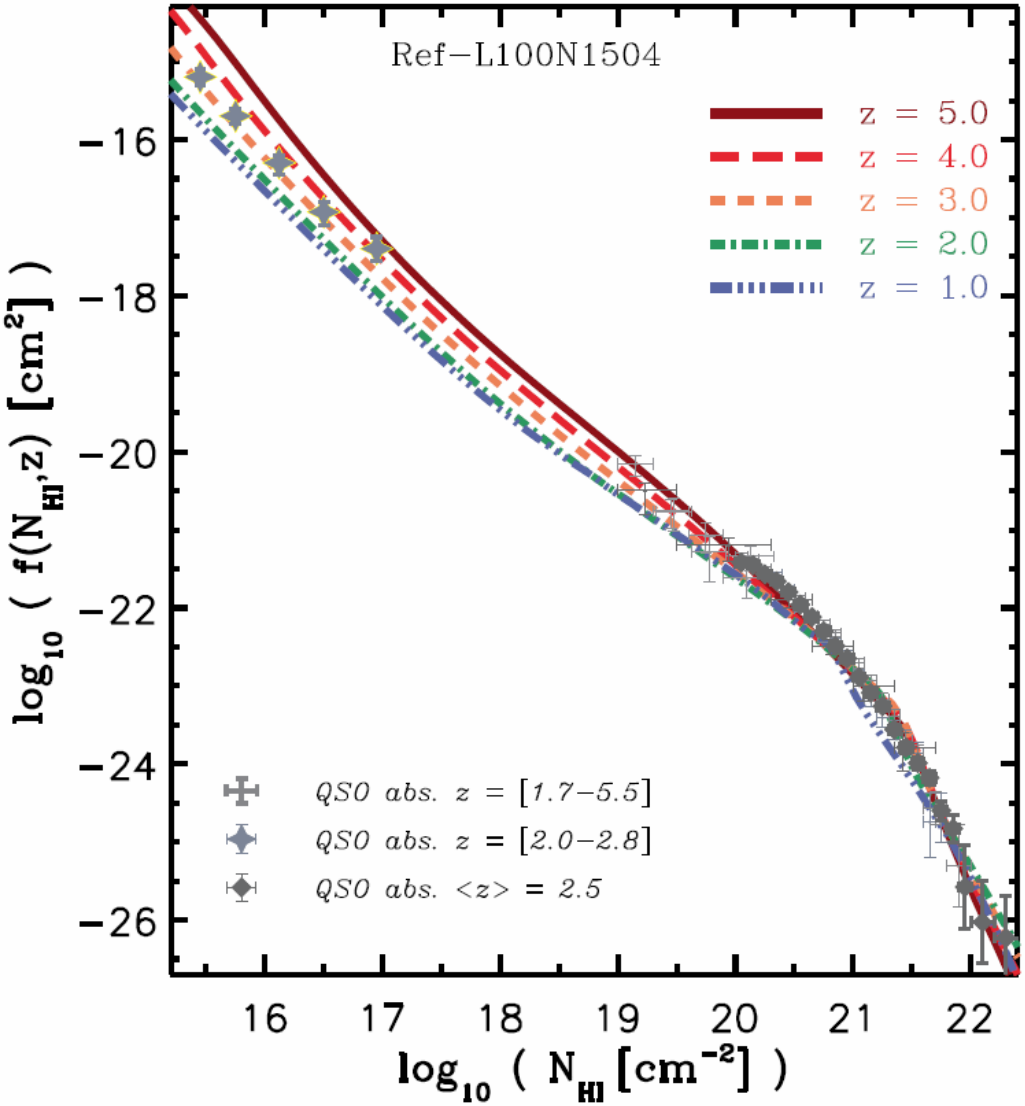
Lagos, Crain, JS et al. (in prep)

H_2 fraction



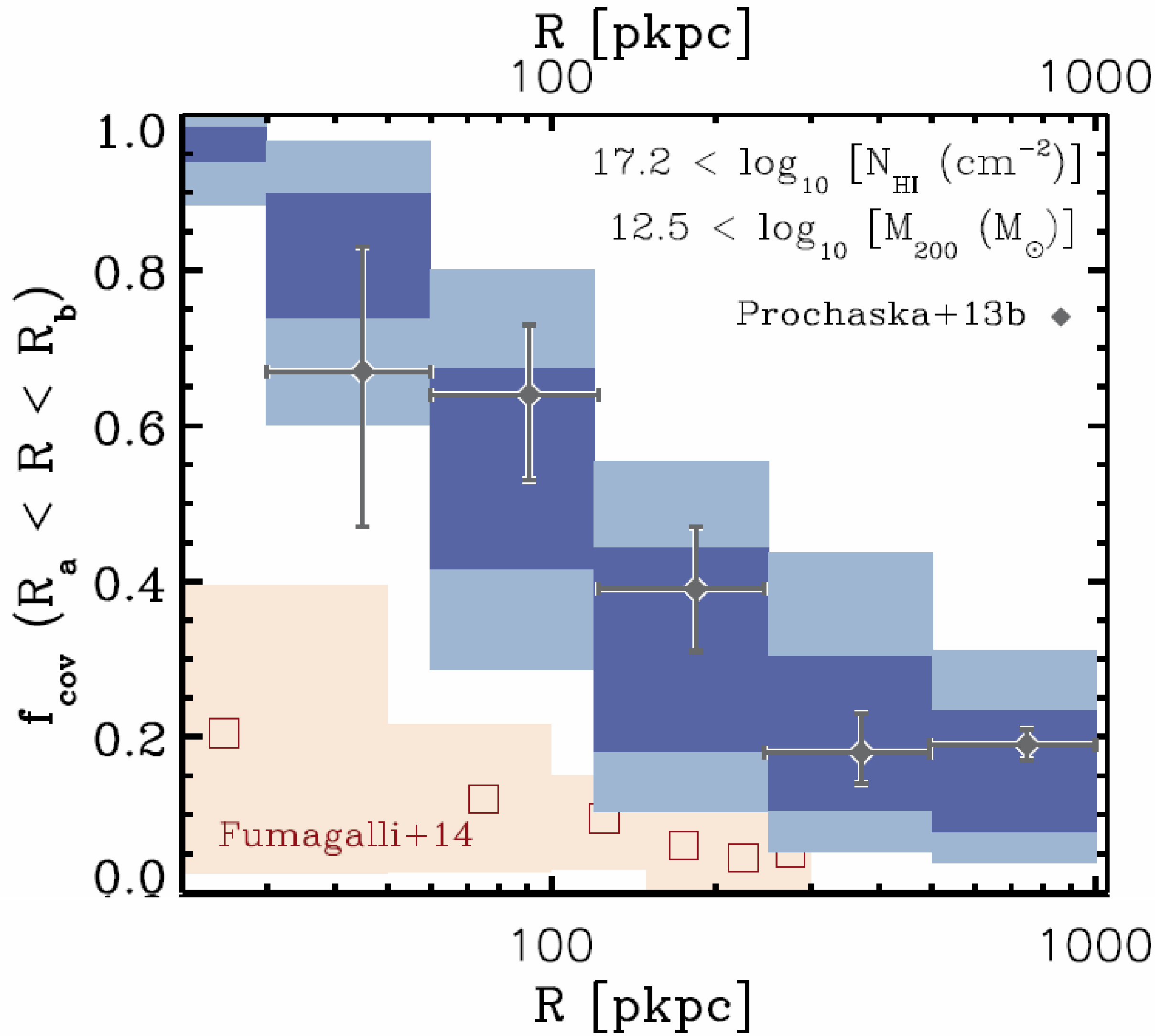
Lagos, Crain, JS et al. (in prep)

HI Column density distribution



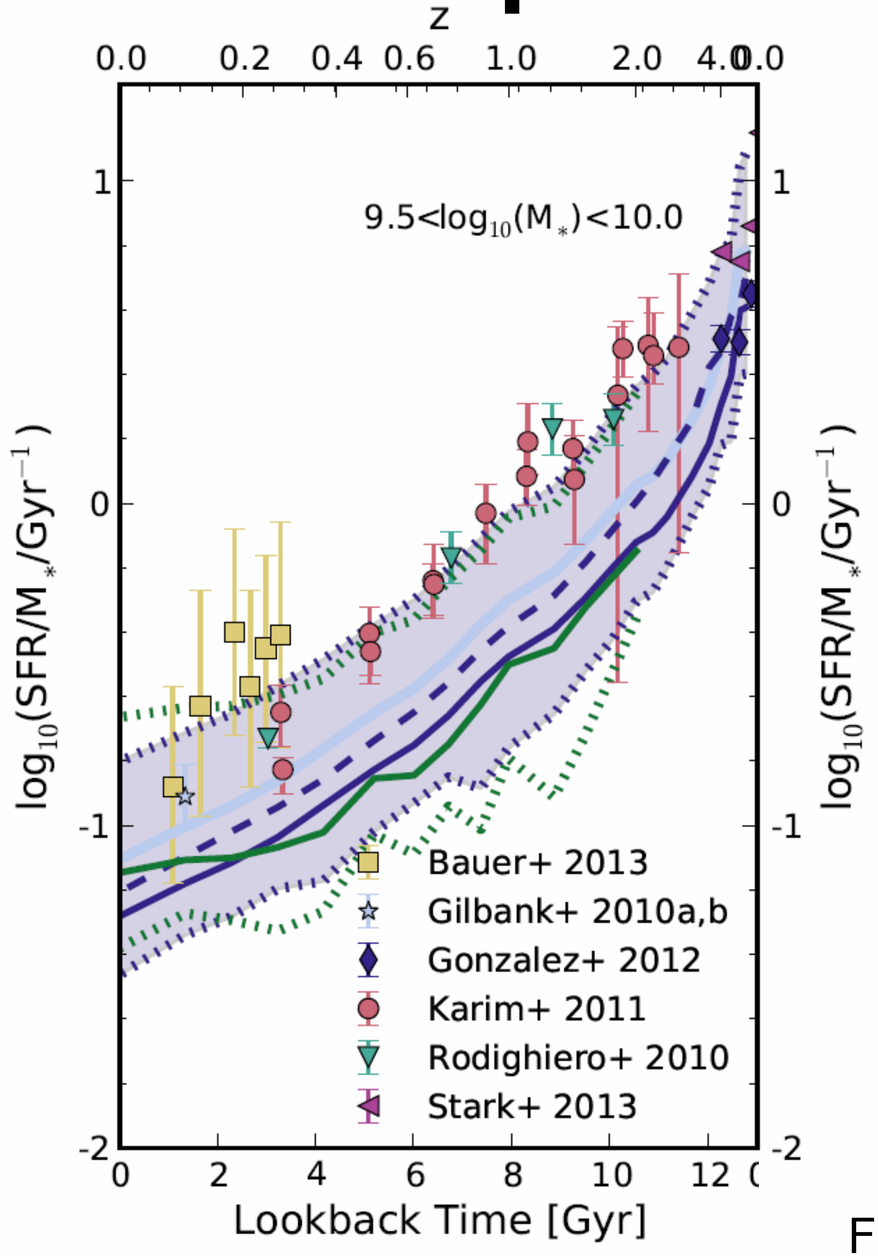
Rahmati, JS et al. (in prep)

HI LLS covering around bright z~2 quasars



Rahmati, JS et al. (in prep)

Evolution of specific SFR



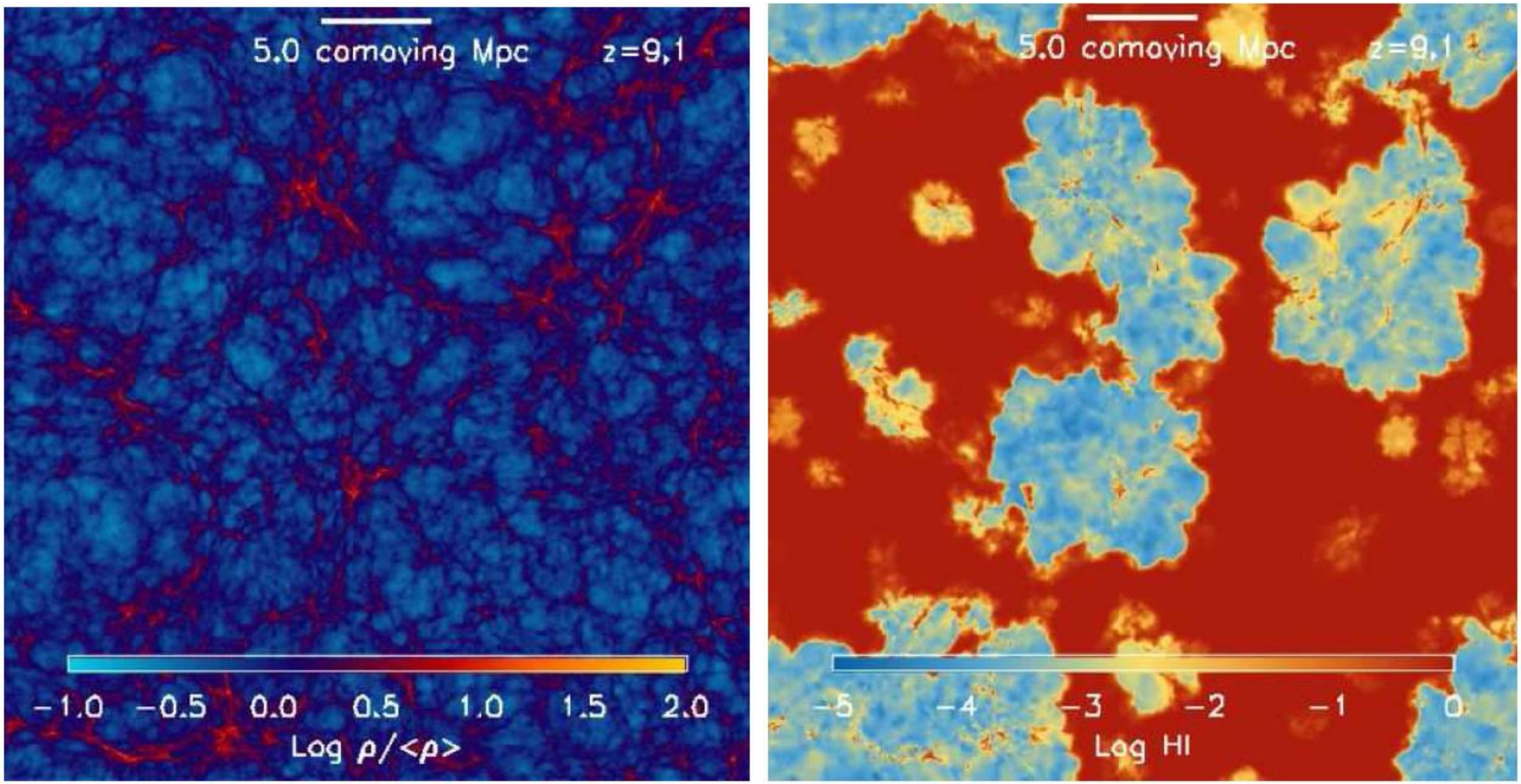
Furlong et al. (2015)

Radiation-hydrodynmical simulations of reionisation

If the multiphase ISM is unresolved, then we need to:

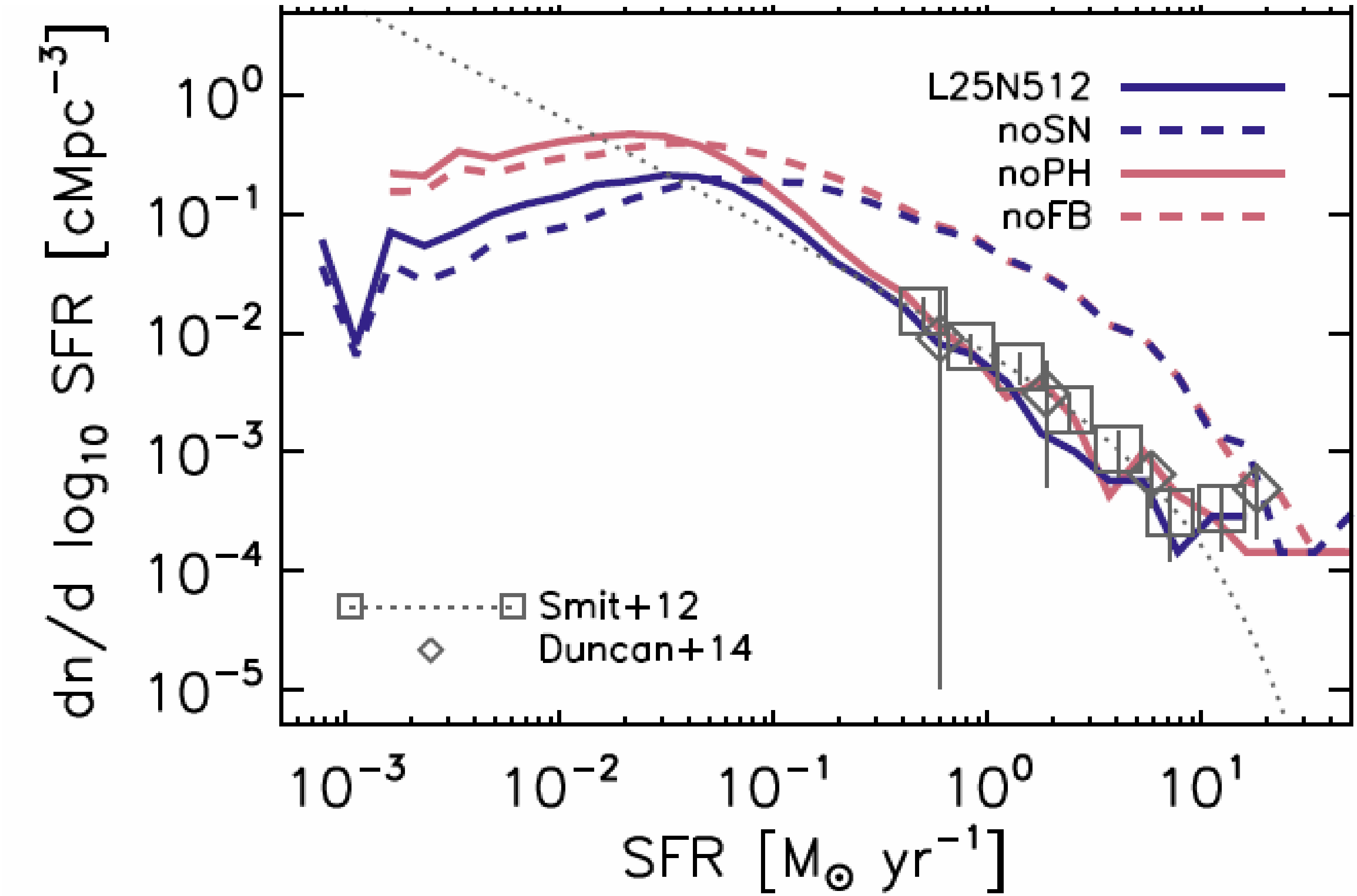
- Calibrate subgrid stellar feedback to fit luminosity function (not done here; f_{th}=1)
- Calibrate subgrid escape fraction to desired reionisation history (not done here; $f_{esc,subgrid}$=1)

Radiation-hydro simulations of reionisation



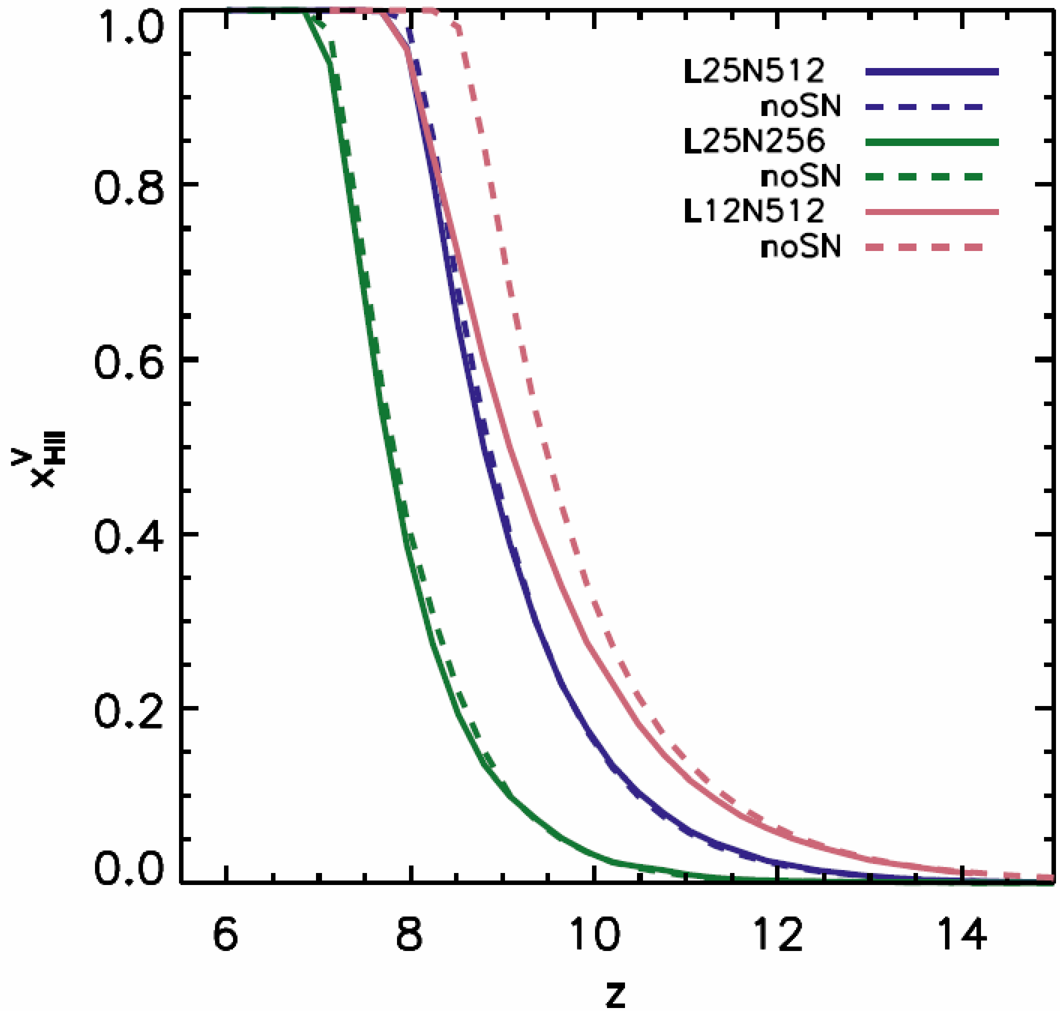
Pawlik, JS & Dalla Vecchia (2015)

Effects of supernovae and photoheating



Pawlik, JS & Dalla Vecchia (2015)

Effects of supernovae on reionisation



Pawlik, JS & Dalla Vecchia (2015)

Cosmological Hydro

- Galaxy formation is self-regulated. Cosmological accretion drives the evolution. Feedback is critical.
- Cosmological simulations cannot predict stellar and black hole masses, they need to be calibrated.
- Cosmological radiation-hydro simulations cannot predict the reionization history, they need calibration.
- There are many ways to get the $z=0$ galaxy mass function, but predictions for other observables vary.
- Many observations of galaxies and the IGM are reproduced once the $z=0$ mass function and sizes match the data.
- Simple, natural feedback recipes suffice.
- EAGLE rivals semi-analytic models in terms of reproducing galaxy observables.