L-Galaxies

Overview of physical modules and results

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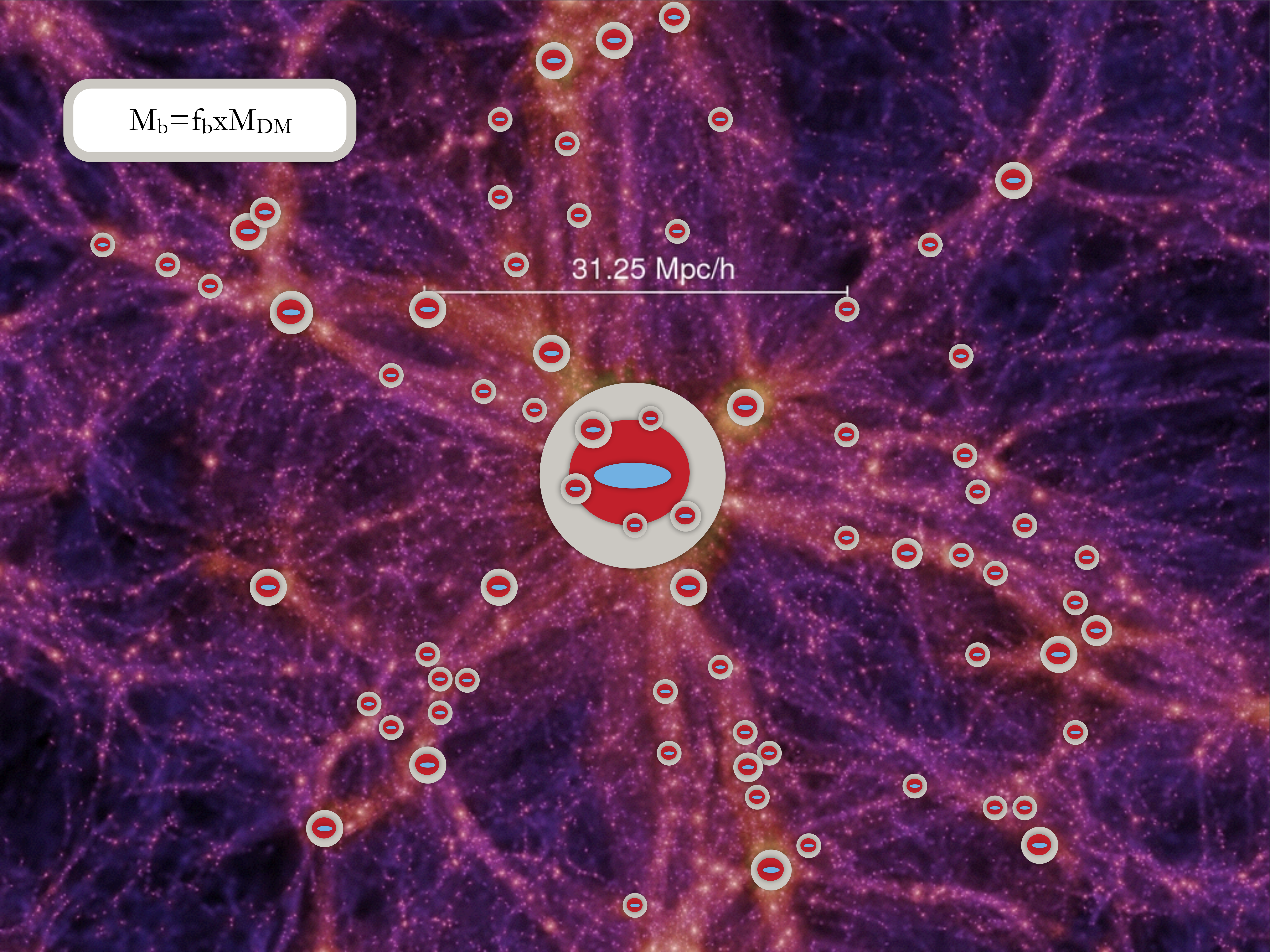
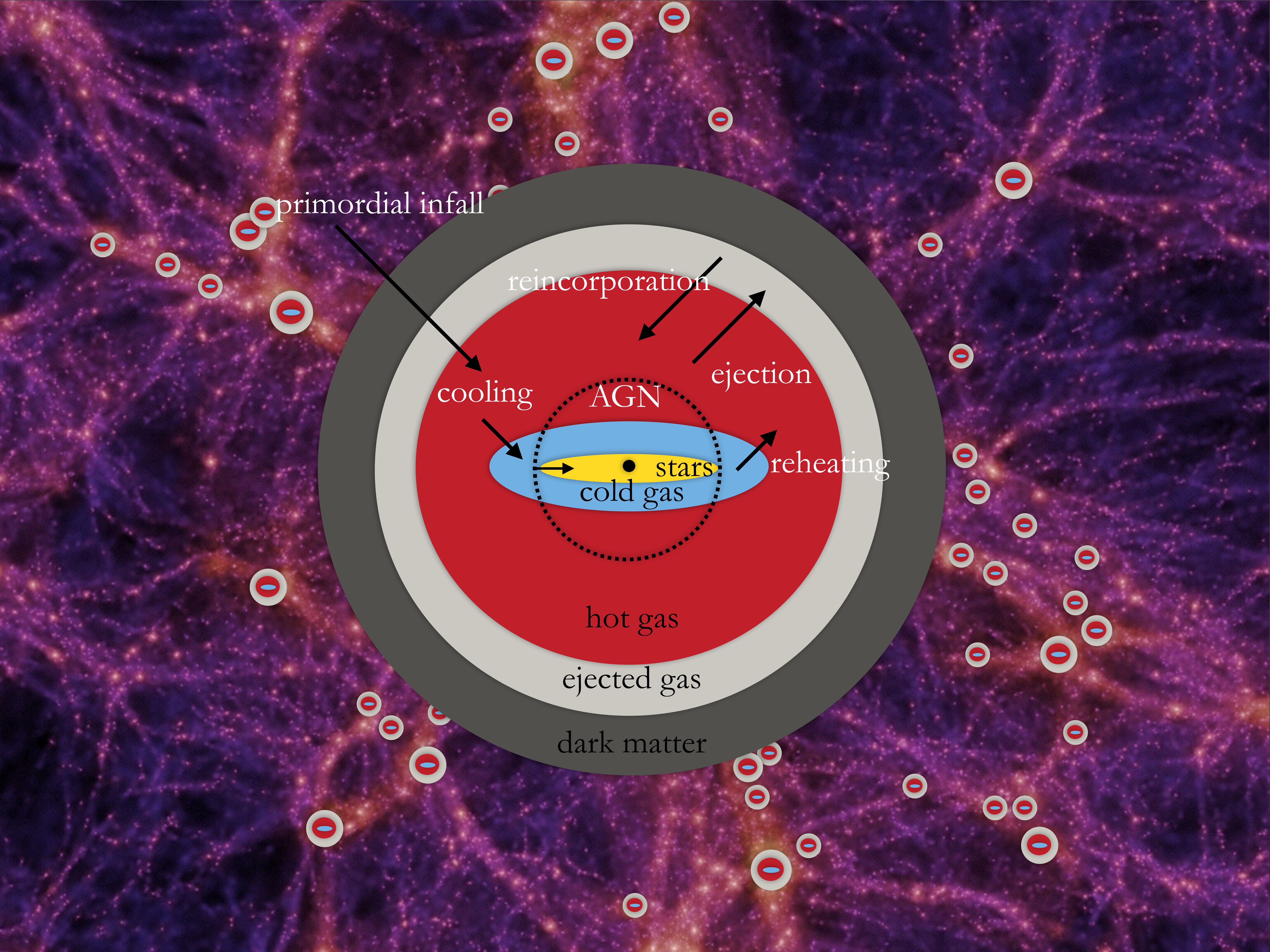
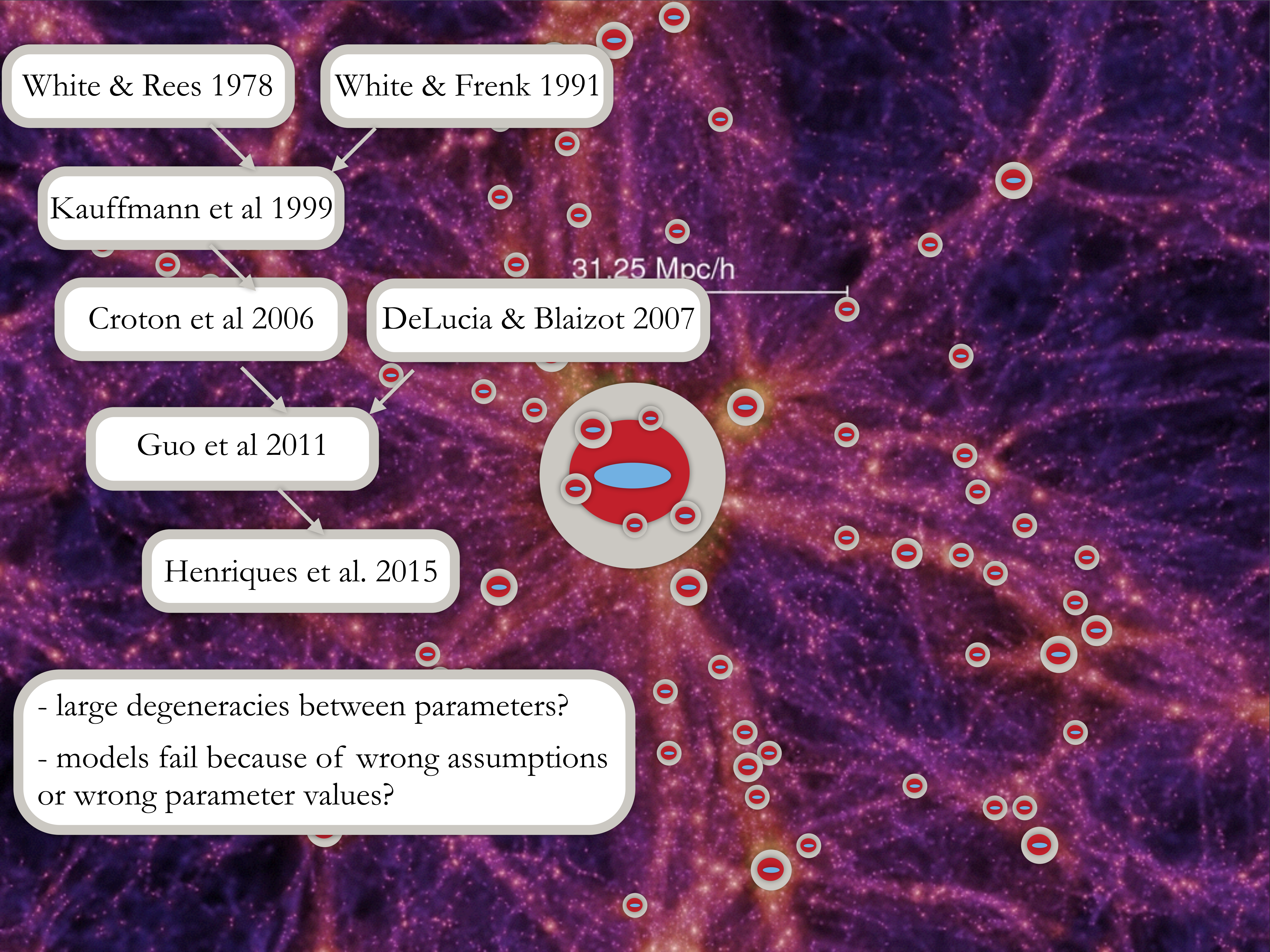
Raul Angulo, Scott Clay, Marcel Van Daalen, Qi Guo,
Gerard Lemson, Roderik Overzier, Volker Springel, Rob Yates

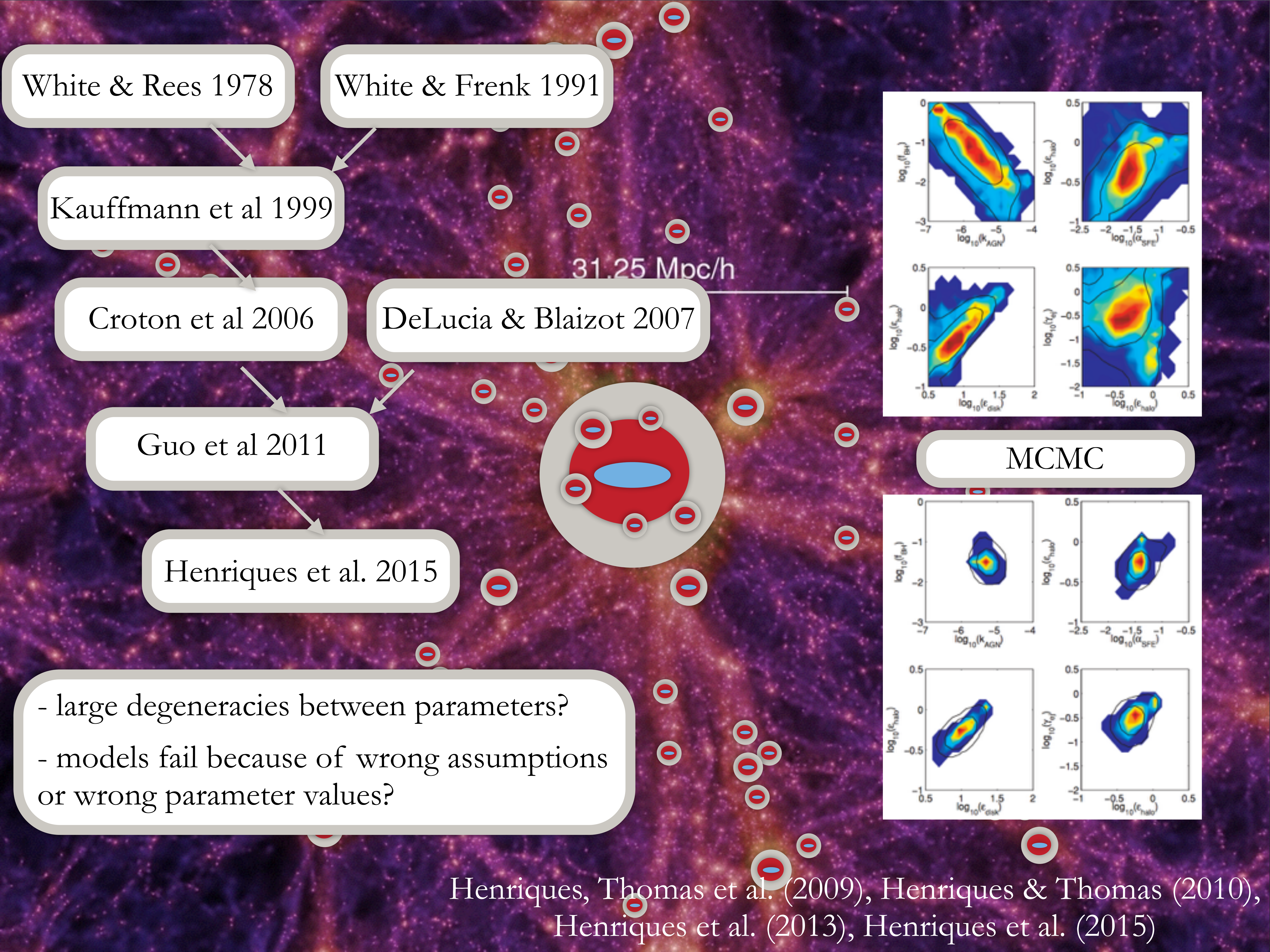
+ Gabriella De Lucia & Guinevere Kauffmann

Henriques et al. 2015; Guo et al. 2011, 2013; De Lucia & Blaizot 2007; Croton et al. 2006;
Springel et al. 2001, 2005; Kauffmann et al. 1993, 1999; White & Frenk 1991; White 1989;


Mb=fbxMDM
31.25 Mpc/h


primordial infall
reincorporation
ejection
cooling
AGN
reheating
stars
cold gas
hot gas
ejected gas
dark matter


White & Rees 1978
White & Frenk 1991
Kauffmann et al 1999
Croton et al 2006
DeLucia & Blaizot 2007
Guo et al 2011
Henriques et al. 2015
31.25 Mpc/h
- large degeneracies between parameters?
- models fail because of wrong assumptions or wrong parameter values?


White & Rees 1978
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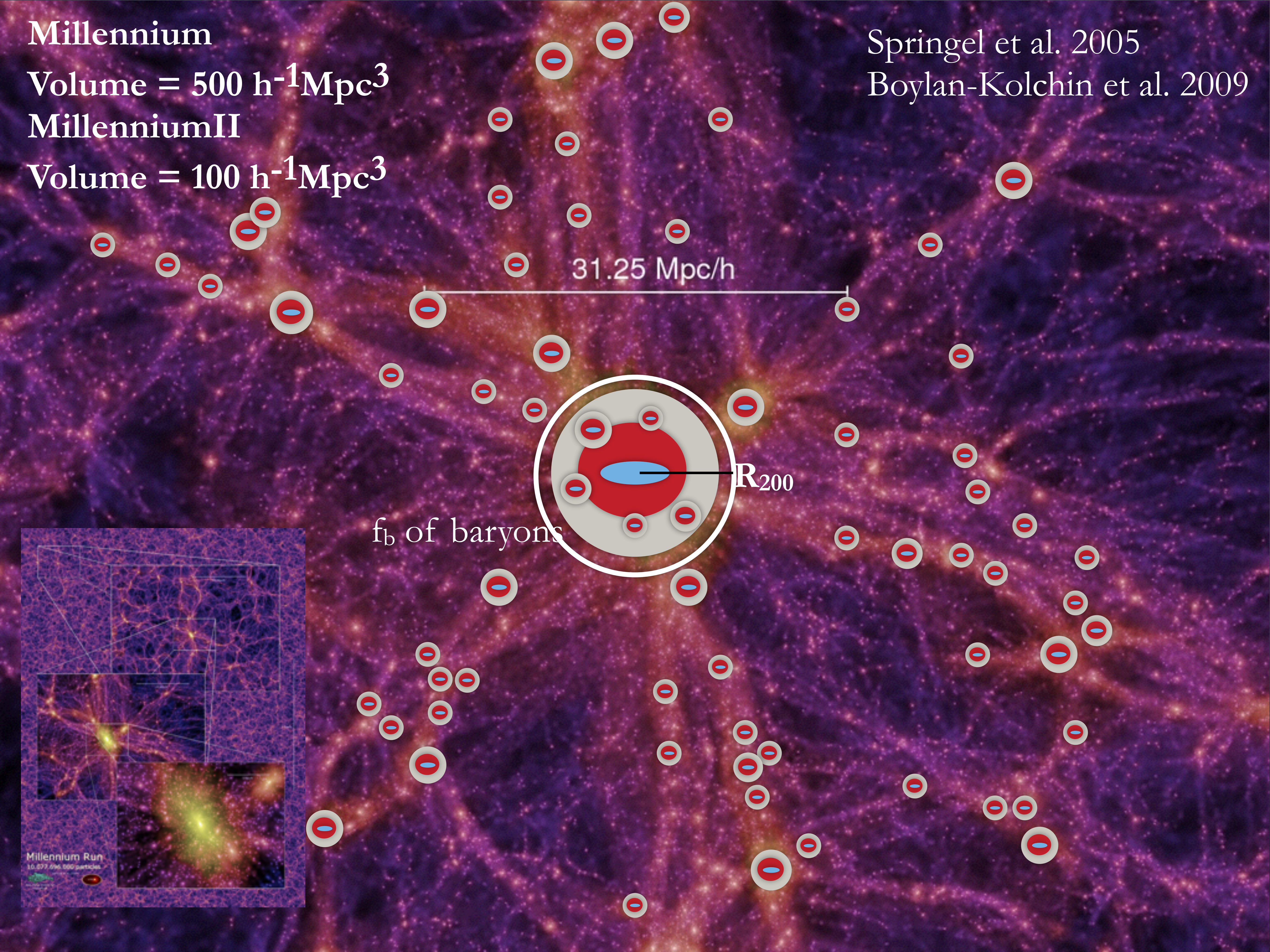
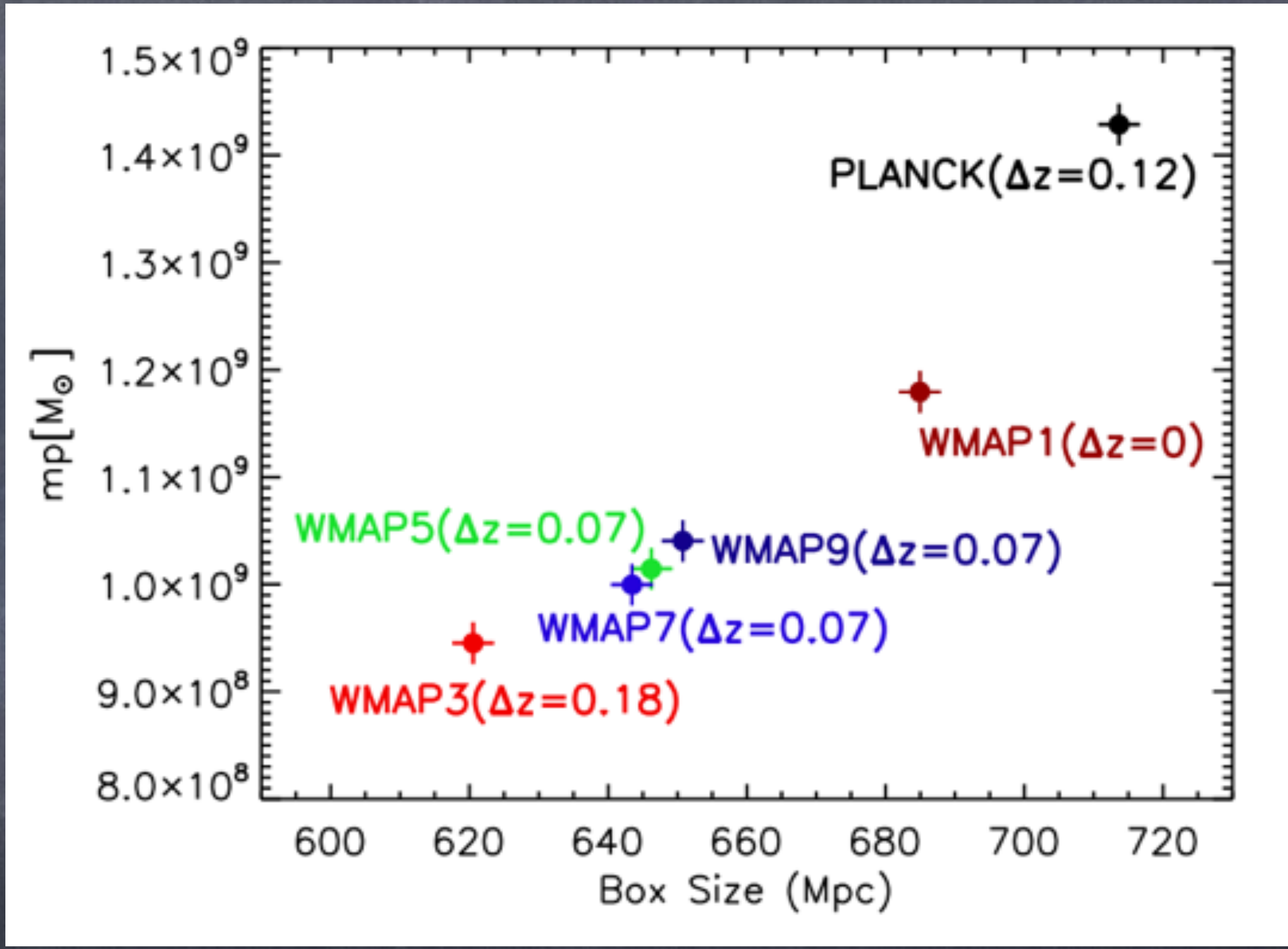
31.25 Mpc/h
MCMC
- large degeneracies between parameters?
- models fail because of wrong assumptions or wrong parameter values?
Henriques, Thomas et al. (2009), Henriques & Thomas (2010),
Henriques et al. (2013), Henriques et al. (2015)


Millennium
Volume = 500 $h^{-1}Mpc^3$
MillenniumII
Volume = 100 $h^{-1}Mpc^3$
Springel et al. 2005
Boylan-Kolchin et al. 2009
31.25 Mpc/h
R_{200}
f_b of baryons
Millennium Run

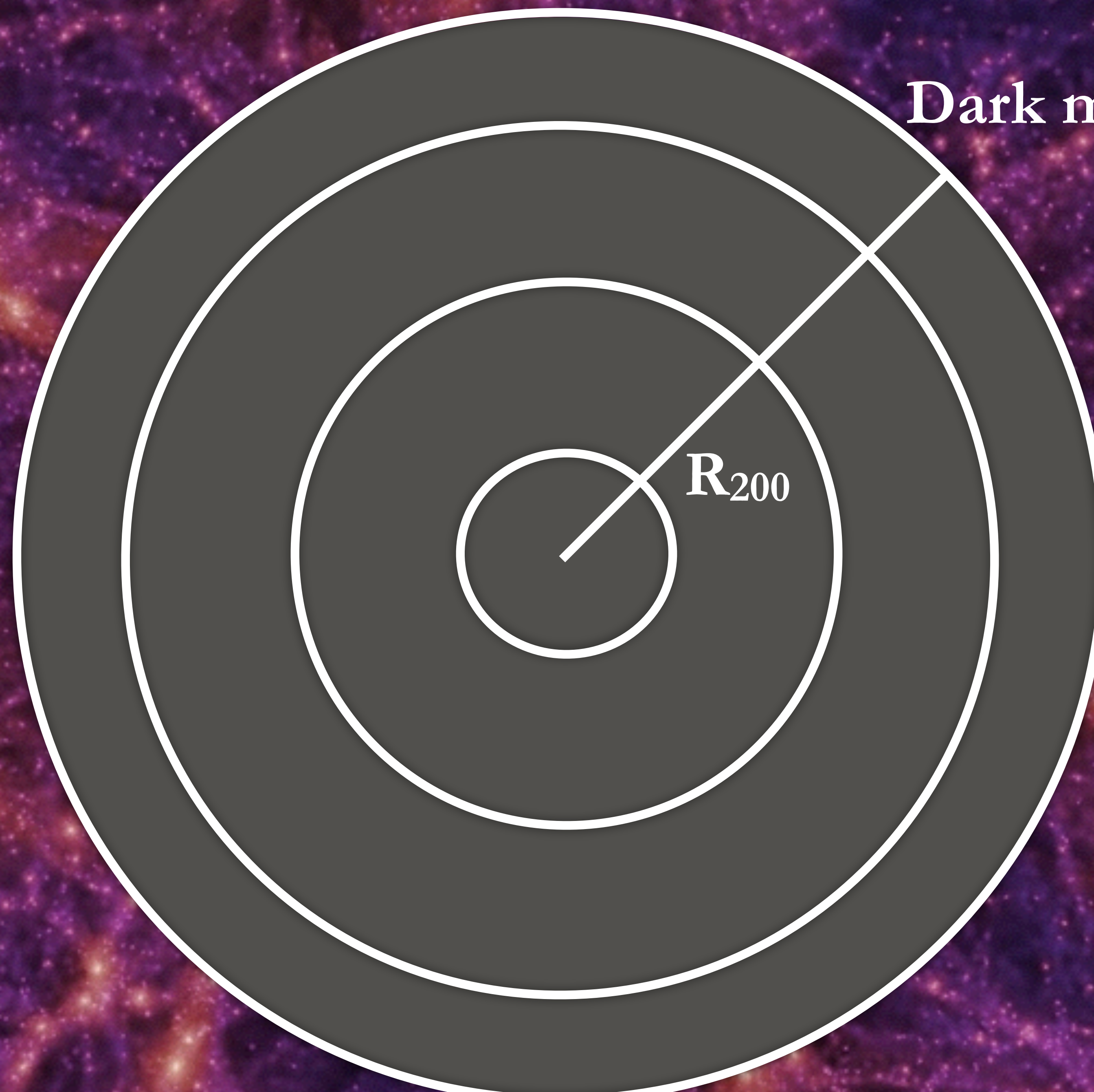
Cosmology

Particle mass, Box size and redshift are scaled to the recently published PLANCK cosmology following Angulo & White 2010

As shown in Wang et al. 2008 and Guo et al. 2013, it doesn't matter yet for galaxy formation.

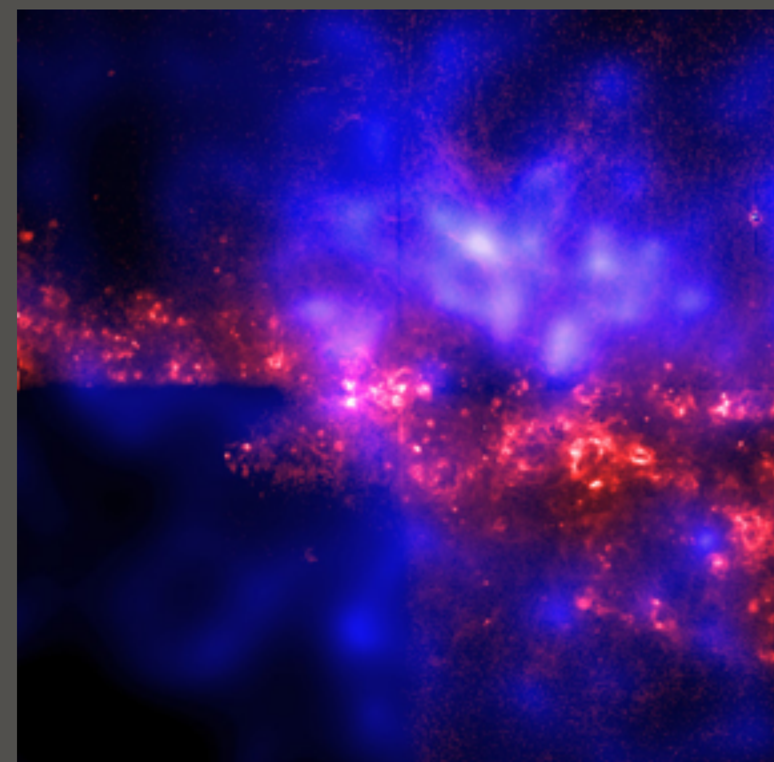


Dark matter halo mass



$$M_{200\mathrm{c}} = \frac{100}{G} H^2(z) R_{200\mathrm{c}}^3 = \frac{V_{200\mathrm{c}}^3}{10\, G H(z)}$$

primordial infall



dark matter

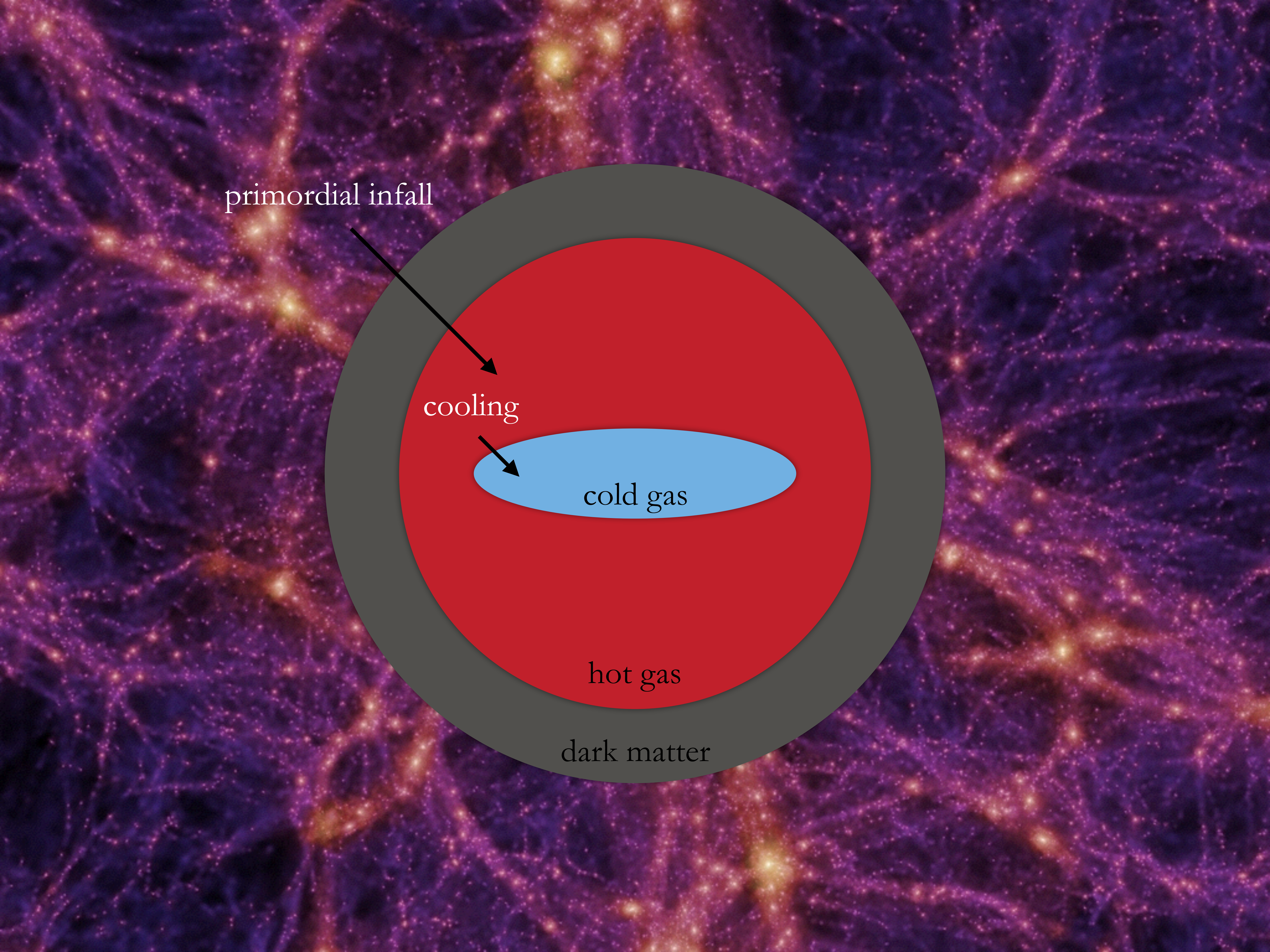
difuse gas phase

$$M_b = f_b \times M_{200c}$$

reionization

$$f_b(z, M_{200c}) = f_b^{\cos}\left(1 + (2^{\alpha/3} - 1)\left[\frac{M_{200c}}{M_F(z)}\right]^{-\alpha}\right)^{-3/\alpha}$$

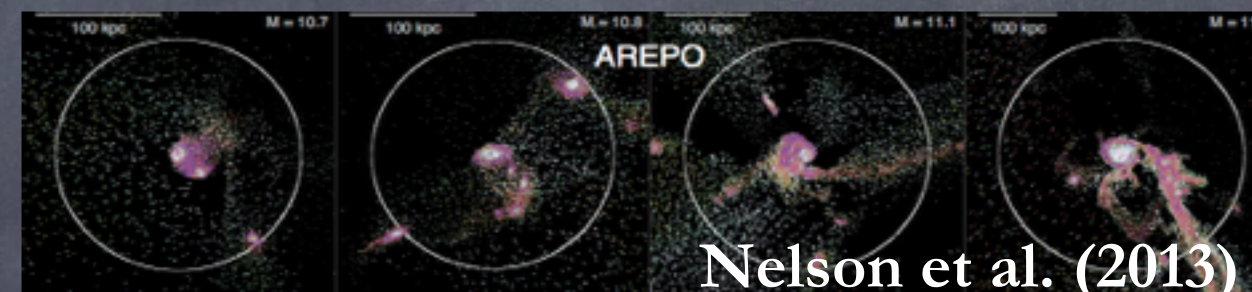
De lucia et al. 2004, Guo et al. 2011


primordial infall
cooling
cold gas
hot gas
dark matter

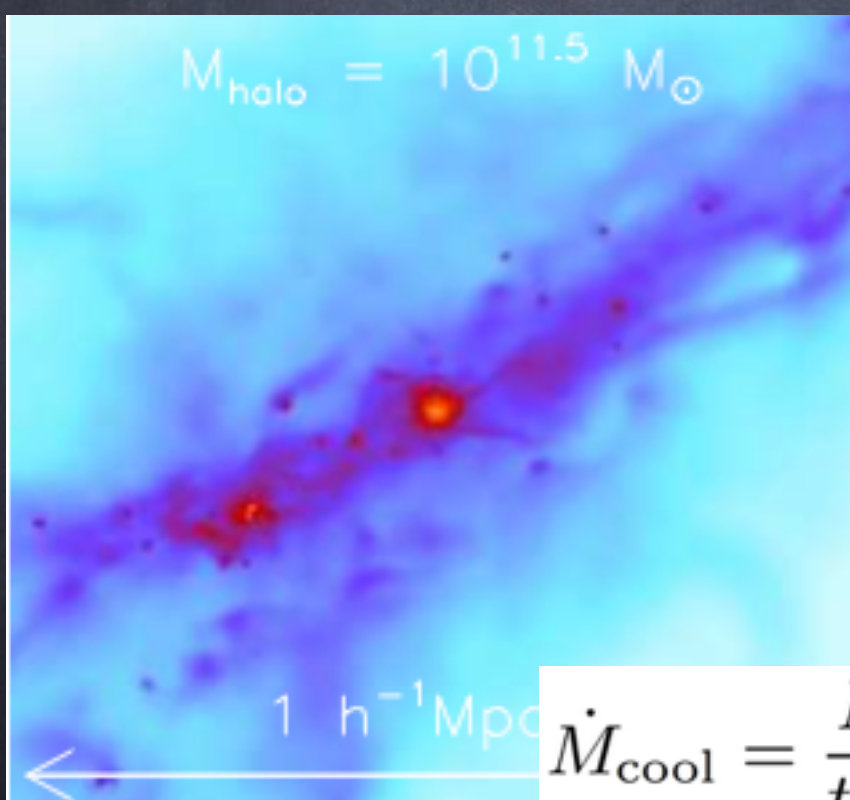
Gas Cooling – White & Frenk 91

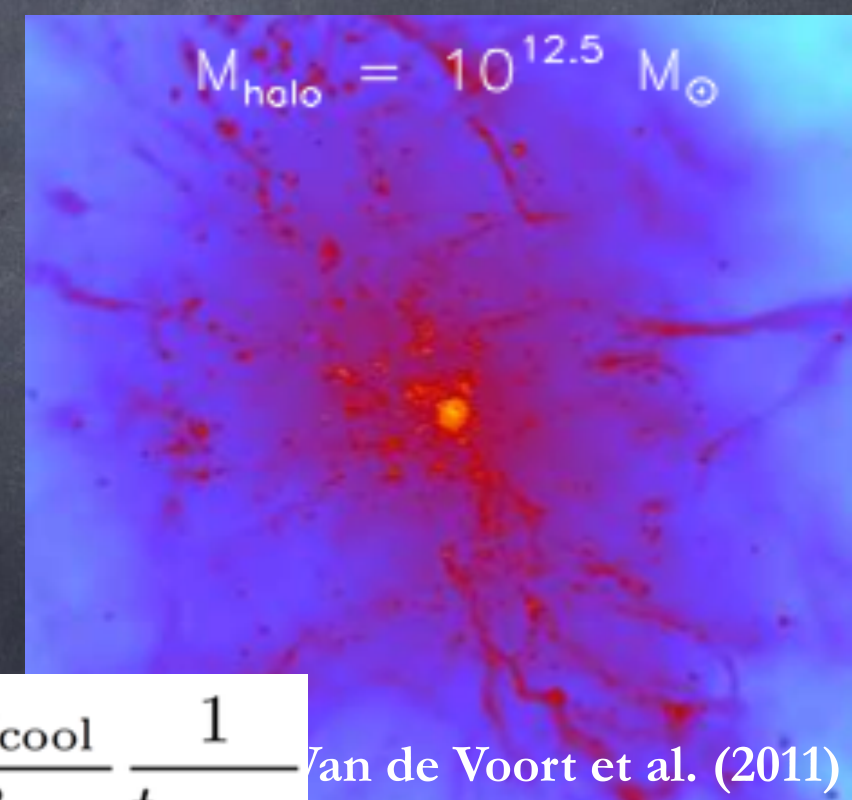
Either rapid (high-z, low-M) or through a quasi-static atmosphere (low-z, high-M)

$$t_{\rm cool}(r) = \frac{3\mu m_{\rm H} k T_{200c}}{2\rho_{\rm hot}(r)\Lambda(T_{\rm hot}, Z_{\rm hot})} \Longrightarrow r_{\rm cool} = \left[\frac{t_{\rm dyn,h} M_{\rm hot}\Lambda(T_{\rm hot}, Z_{\rm hot})}{6\pi\mu m_{\rm H} k T_{200c} R_{200c}}\right]^{\frac{1}{2}}$$



Nelson et al. (2013)





Van de Voort et al. (2011)

$r_{cool} > R_{200c}$

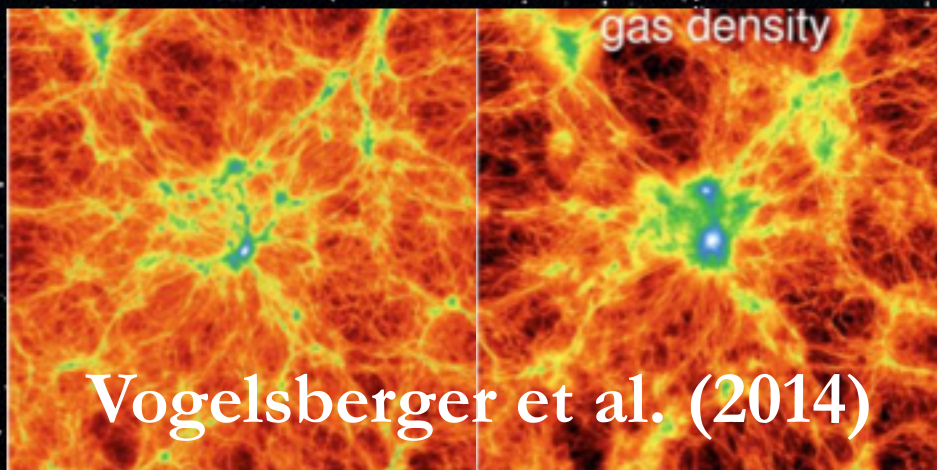
$$\dot{M}_{\rm cool} = \frac{M_{\rm hot}}{t_{\rm dyn,h}}$$

$r_{cool} < R_{200c}$

$$\dot{M}_{\rm cool} = M_{\rm hot}\frac{r_{\rm cool}}{R_{200c}}\frac{1}{t_{\rm dyn,h}}$$

Mass of Hot Gas that cools into the disk

Disk Formation



Vogelsberger et al. (2014)

Cooling brings angular momentum from halo

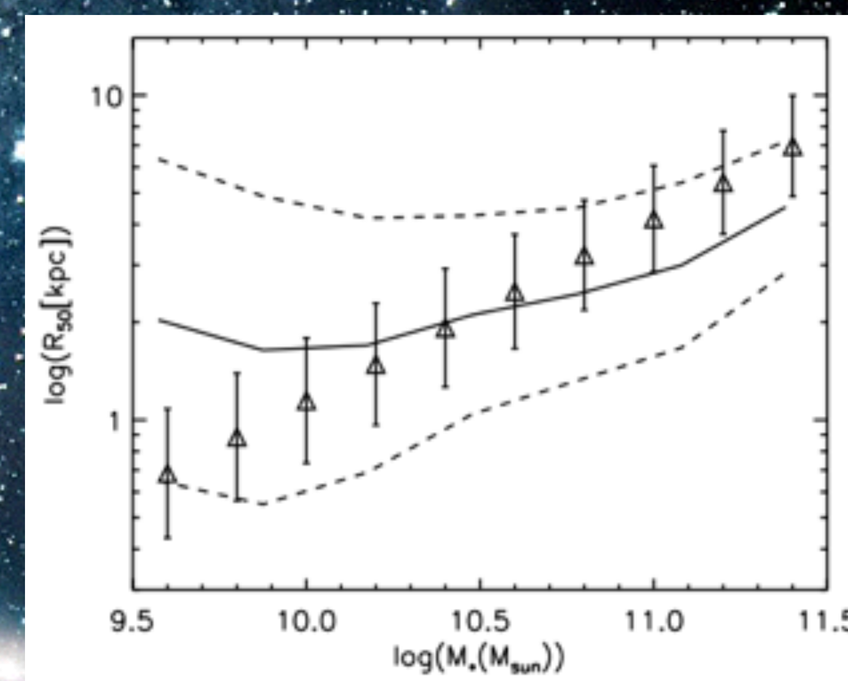
$$\Delta\vec{J}_{\rm gas} = \frac{\vec{J}_{\rm DM}}{M_{\rm DM}}\dot{M}_{\rm cool}\delta t - \frac{\vec{J}_{\rm gas}}{M_{\rm gas}}((1-{\rm R}_{\rm ret})\dot{\rm M}_{\star}\delta t + \Delta{\rm M}_{\rm reheat}) + \frac{\vec{J}_{\rm DM}}{M_{\rm DM}}M_{\rm sat,gas}, \qquad {\rm (S9)}$$

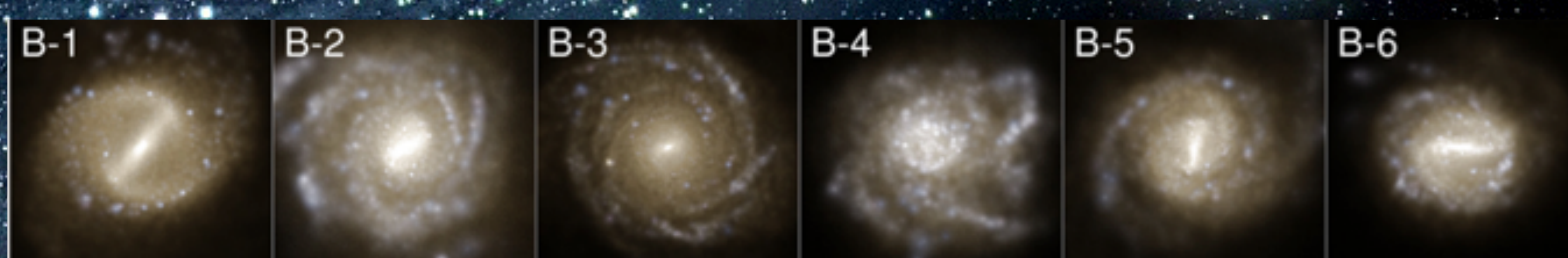
assuming a flat rotational curve

$$R_{\star} = \frac{J_{\star}/M_{\star,{\rm d}}}{2V_{\rm max}}$$

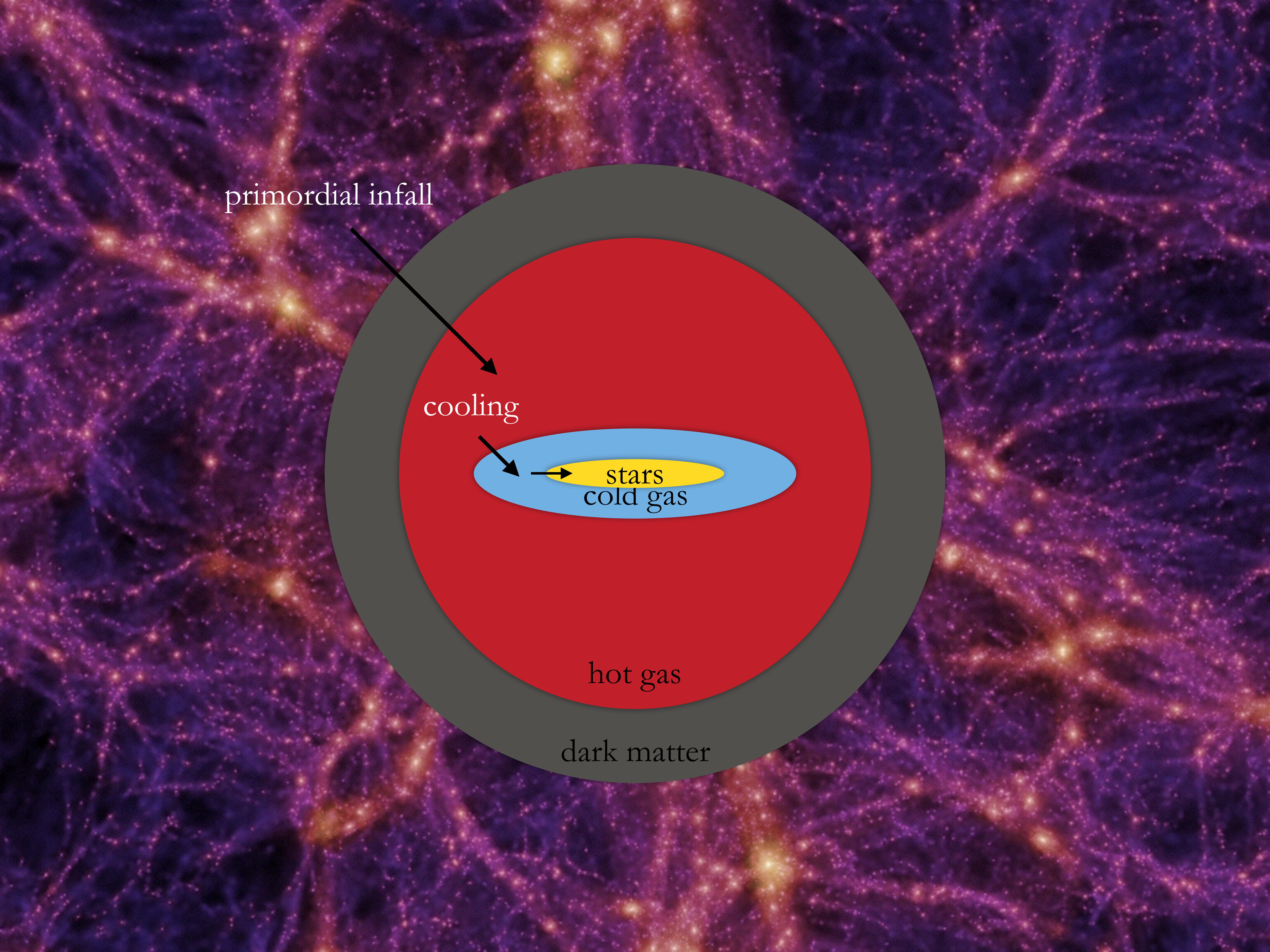
$$\Sigma_{\star}(R) = \Sigma_{\star,0}\exp(-R/R_{\star})$$

Kauffmann et al. 1999, Guo et al. 2011





Vogelsberger et al. (2014)


primordial infall
cooling
stars
cold gas
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Star Formation

Quiescent star formation ⟹ ~ 3% of gas converted into stars in $t_{dyn,disk}$

$$\Sigma_{\rm crit}(R) = \Sigma_{\rm SF} \left(\frac{V_{\rm vir}}{200\,{\rm km\,s^{-1}}}\right)\left(\frac{R}{\rm kpc}\right)^{-1}.$$

Kennicutt 1998

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

Kauffmann et al. 1999, Fu et al. 2011, 2013, Henriques et al. 2014

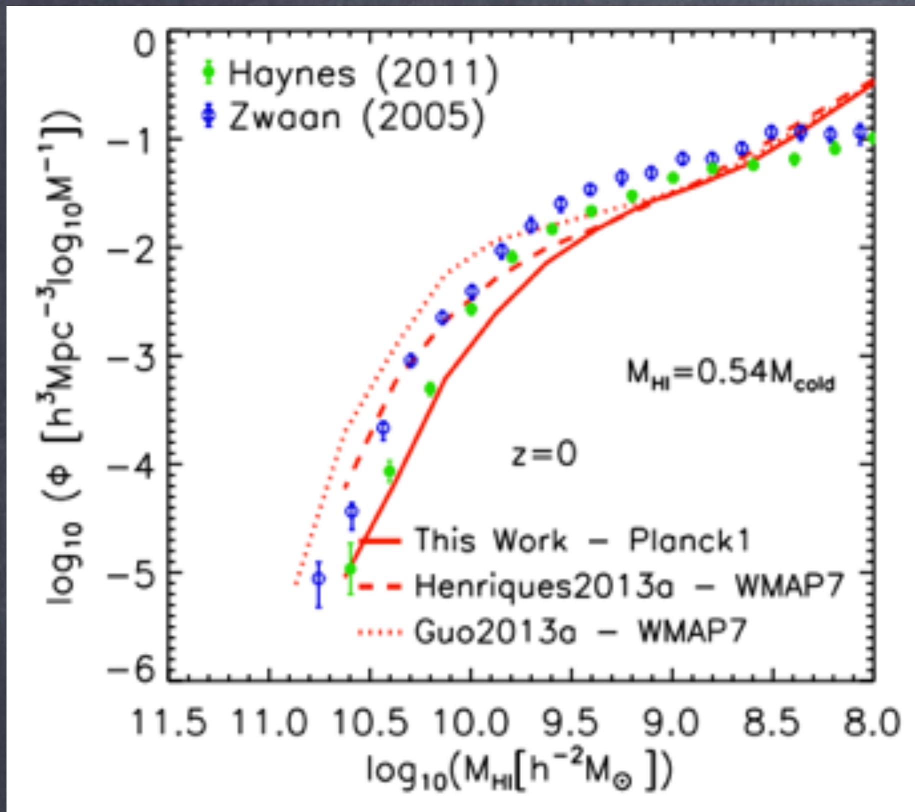
Violent star formation during mergers

$$m_{\star,\rm burst} = \alpha_{\rm SF,burst}\left(\frac{m_{\rm sat}}{m_{\rm central}}\right)^{\beta_{\rm SF,burst}} m_{\rm gas}.$$

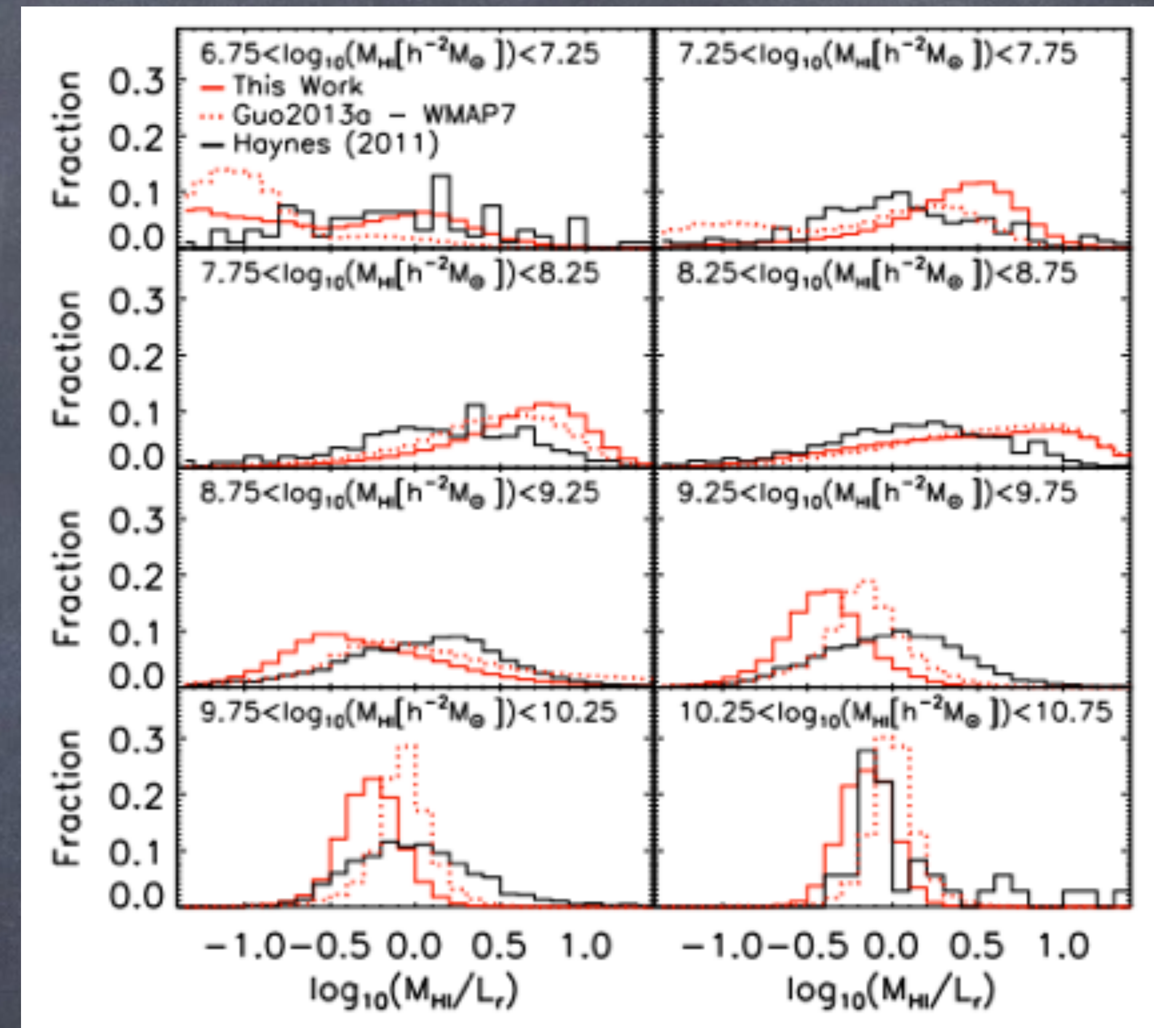
Mihos & Hernquist 1996

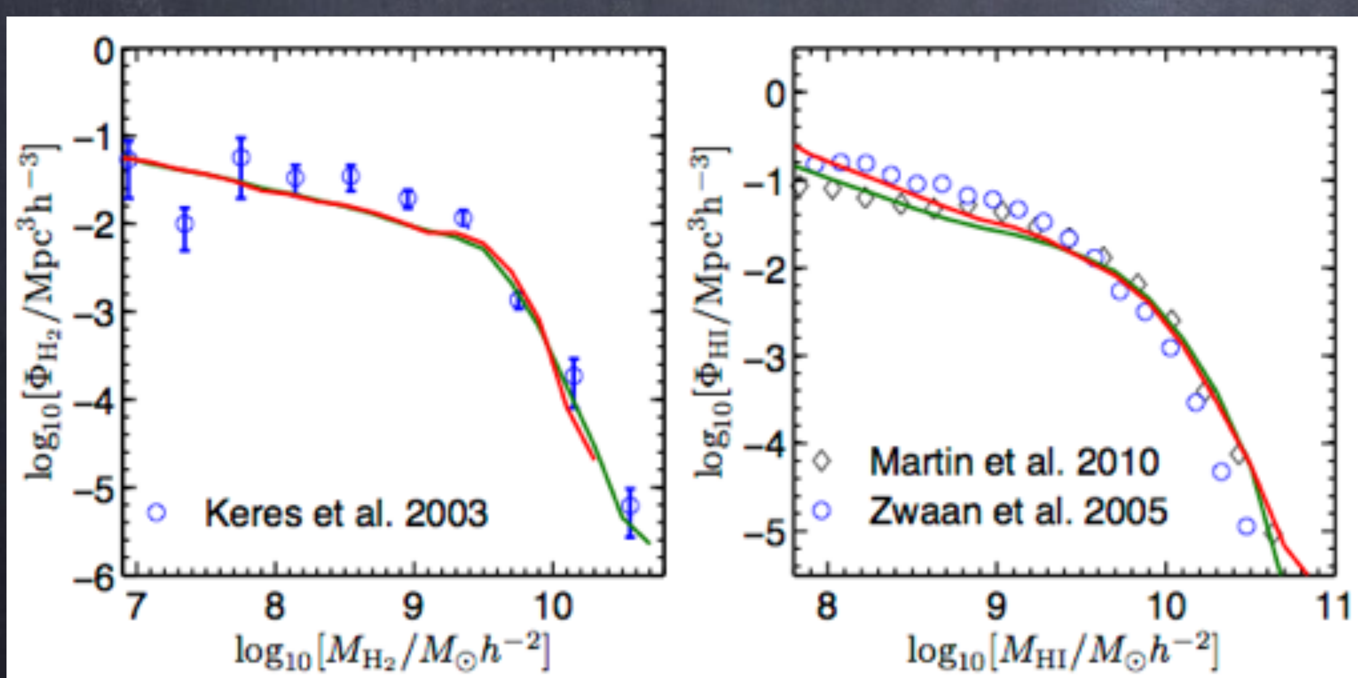
Gas Properties

HI mass function



Gas fractions

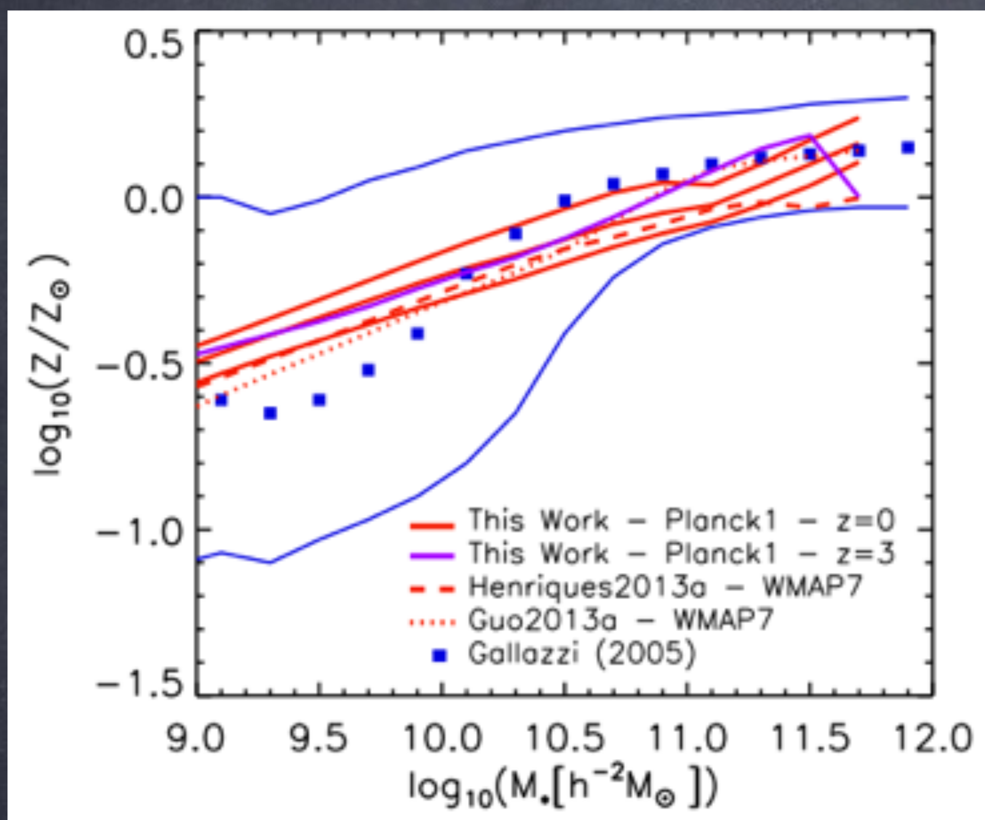




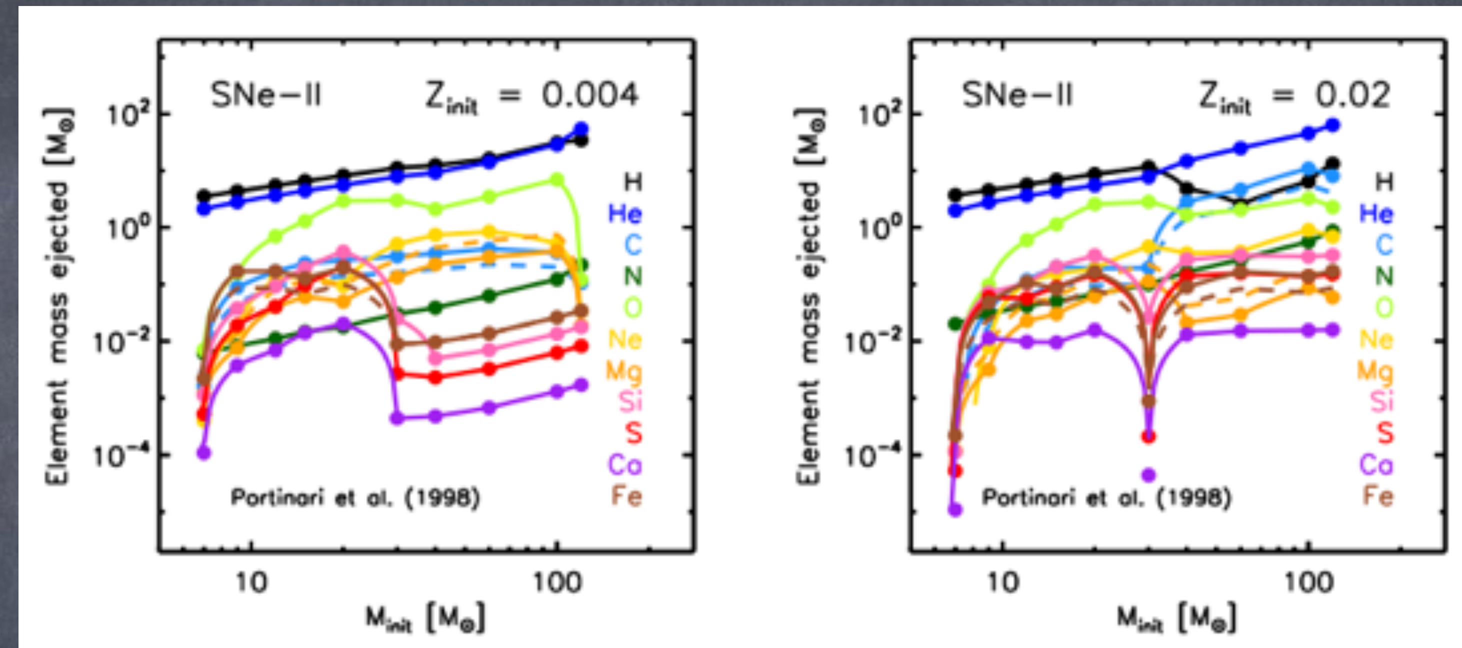
Fu et al. (2013) to be incorporated

Metal Enrichment

$M_{metals} = yM_*$



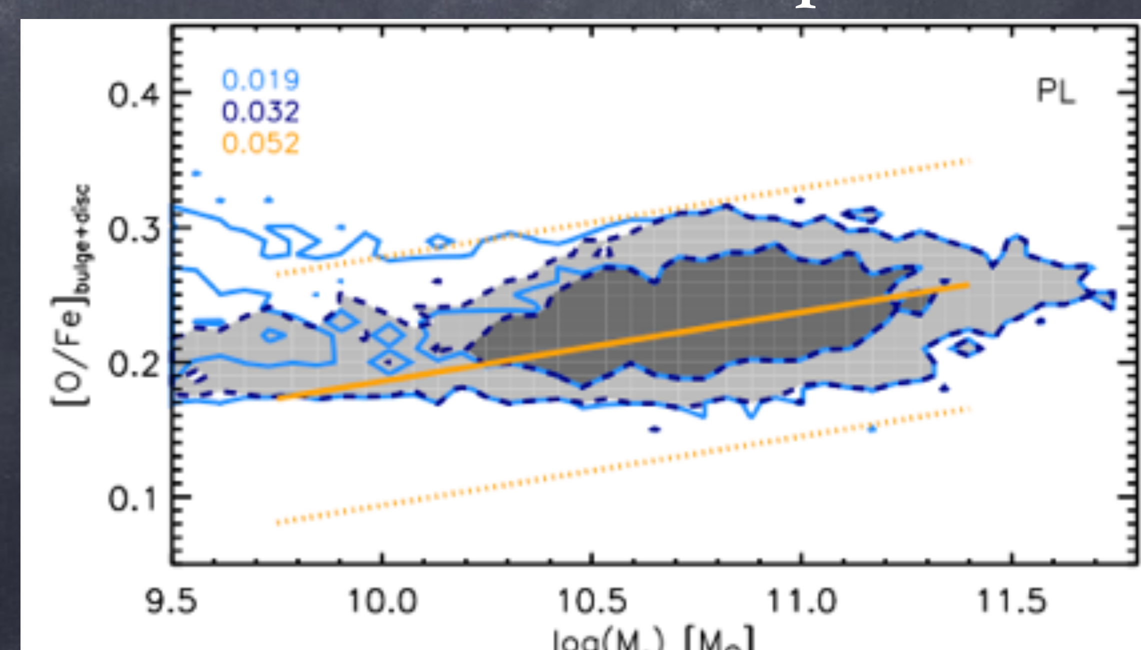
By default, the model assumes instantaneous recycling

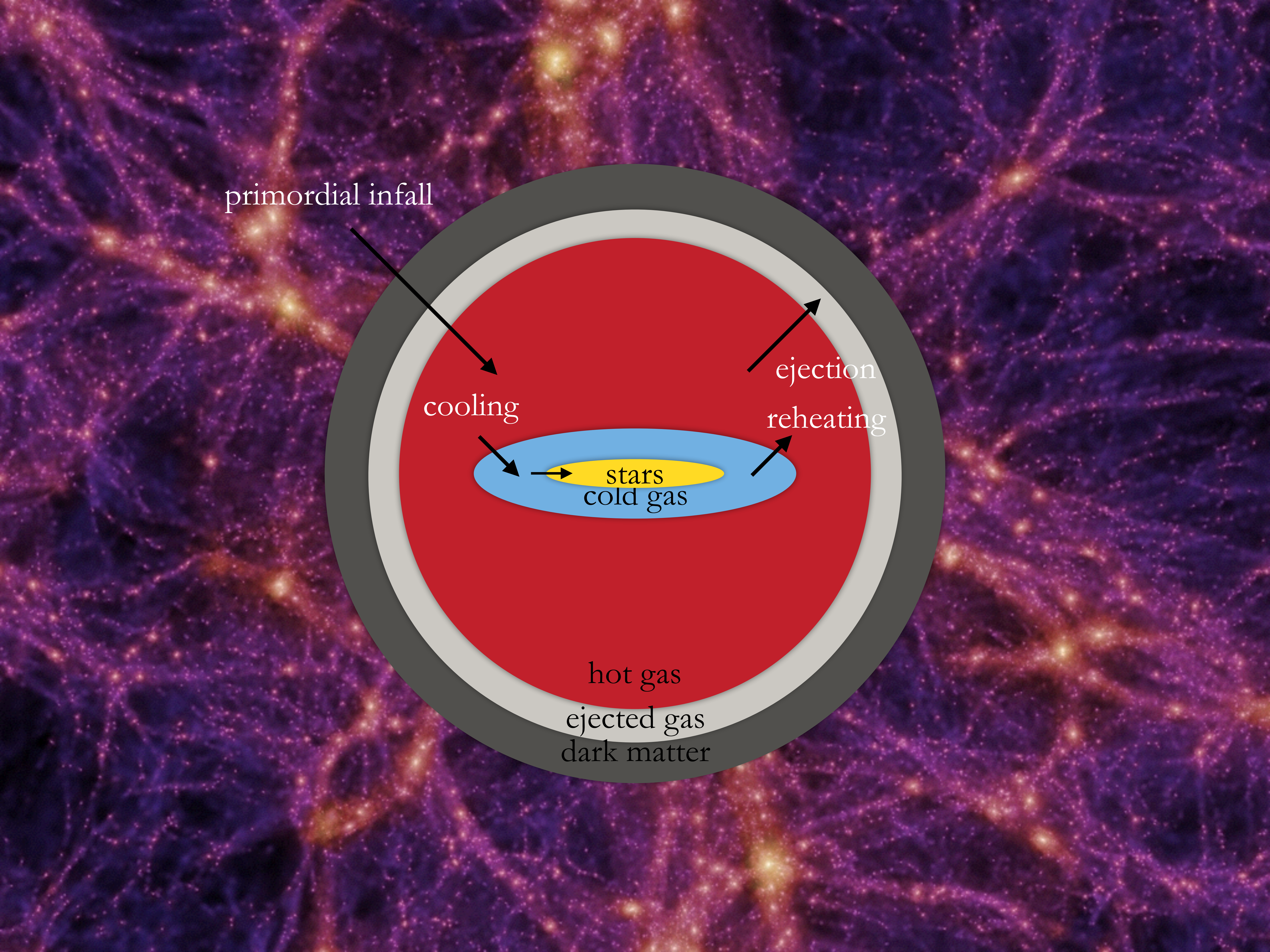


Yates et al. 2013

<u>Detailed chemical enrichment model:</u>

the mass of each element produced in stars of different masses (i.e. ages) and initial metallicities is computed.




primordial infall
ejection
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Supernova Feedback

SN energy available

$$\Delta E_{\rm SN} = \epsilon_{\rm halo} \times \frac{1}{2} \Delta m_{\star} V_{\rm SN}^2,$$

$$\epsilon_{\rm halo} = \eta \times \left[0.5 + \left(\frac{V_{\rm max}}{V_{\rm eject}} \right)^{-\beta_2} \right].$$

Energy used for reheating
(mass loading)

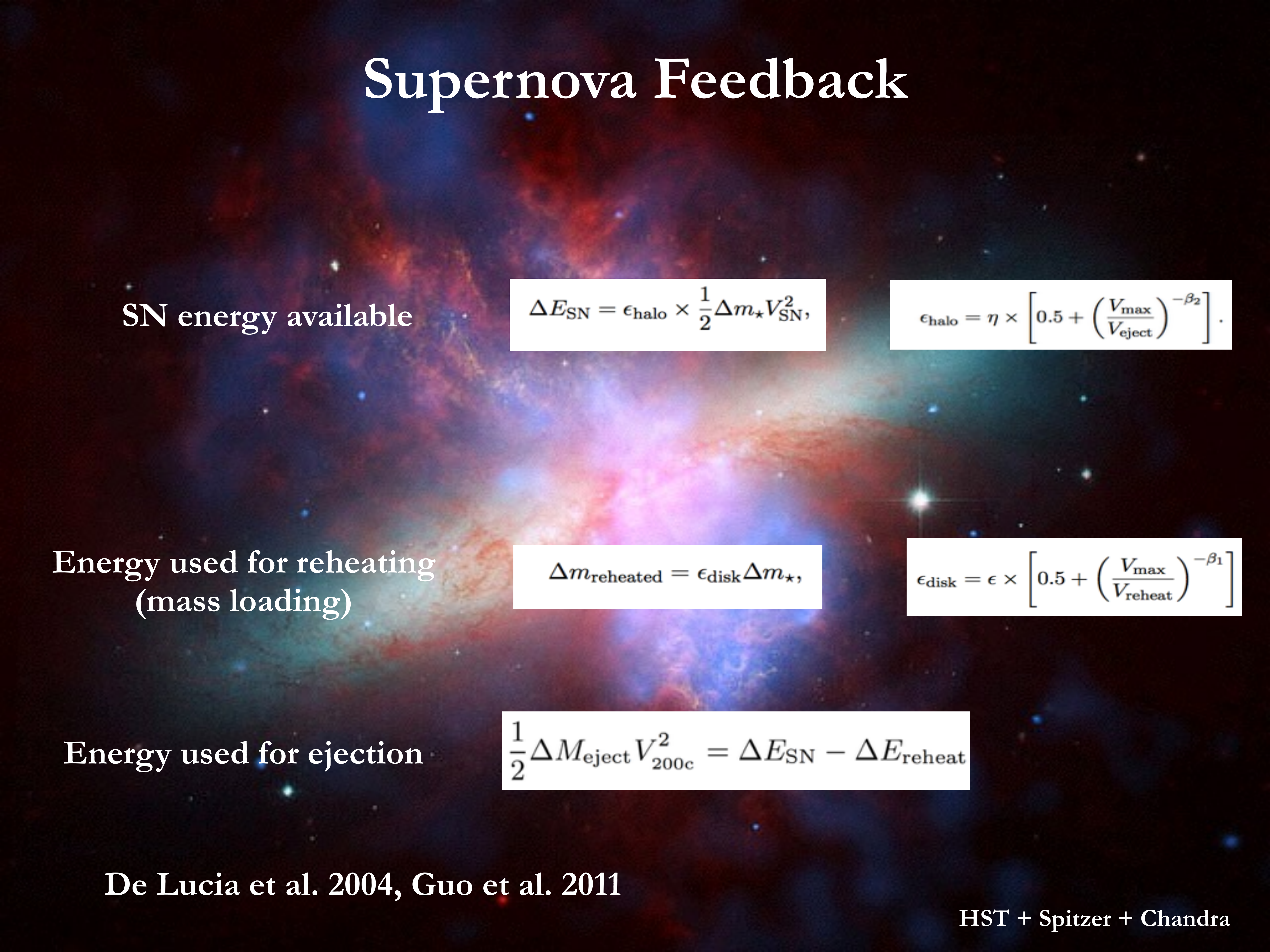
$$\Delta m_{\rm reheated} = \epsilon_{\rm disk} \Delta m_{\star},$$

$$\epsilon_{\rm disk} = \epsilon \times \left[0.5 + \left(\frac{V_{\rm max}}{V_{\rm reheat}} \right)^{-\beta_1} \right]$$

Energy used for ejection

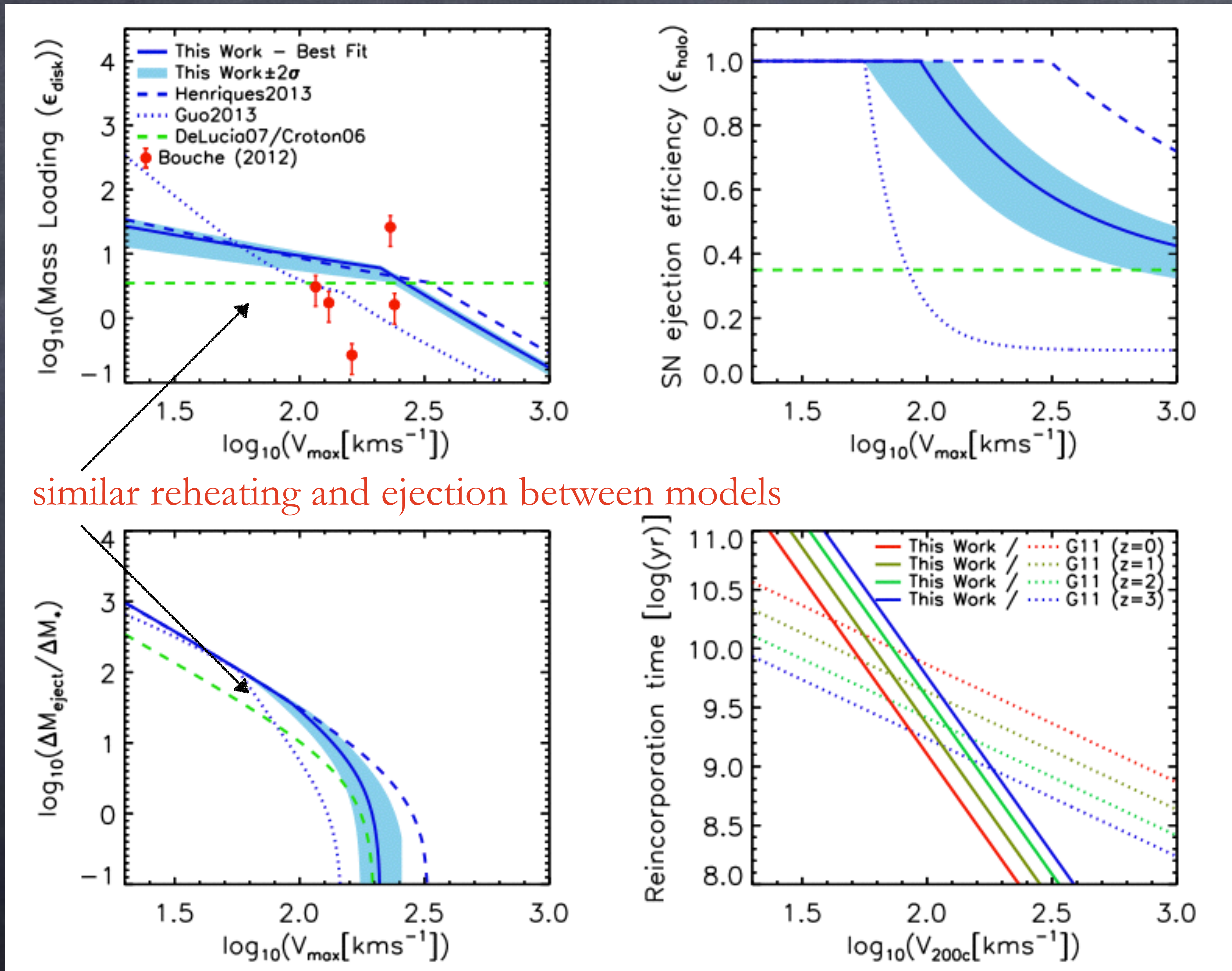
$$\frac{1}{2} \Delta M_{\rm eject} V_{\rm 200c}^2 = \Delta E_{\rm SN} - \Delta E_{\rm reheat}$$

De Lucia et al. 2004, Guo et al. 2011

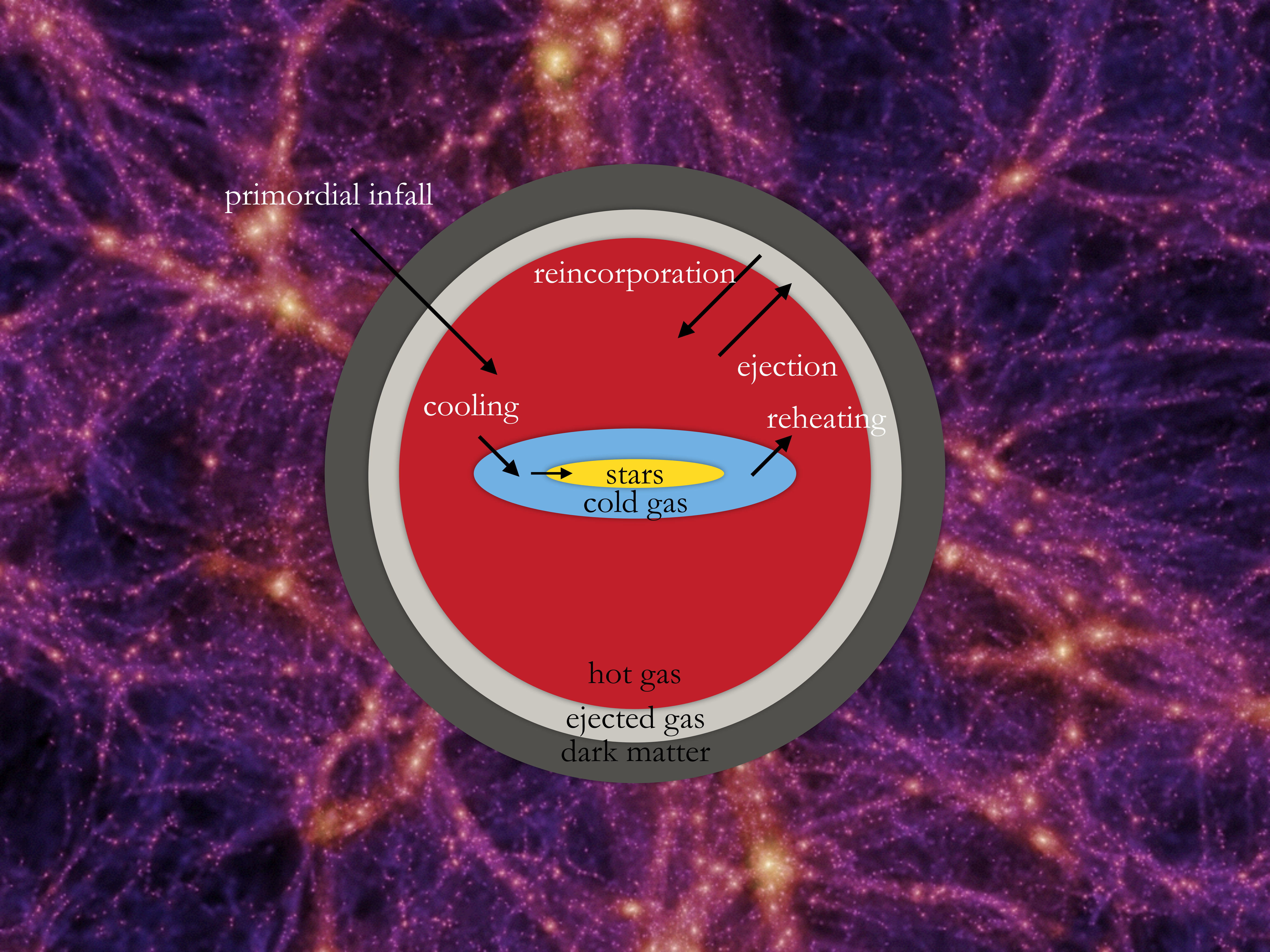


HST + Spitzer + Chandra

SN feedback



This Work – Best Fit
This Work±2σ
Henriques2013
Guo2013
DeLucia07/Croton06
Bouche (2012)
log10(Mass Loading (εdisk))
log10(Vmax[kms−1])
SN ejection efficiency (εhalo)
log10(Vmax[kms−1])
similar reheating and ejection between models
log10(ΔMeject/ΔM*)
log10(Vmax[kms−1])
This Work / G11 (z=0)
This Work / G11 (z=1)
This Work / G11 (z=2)
This Work / G11 (z=3)
Reincorporation time [log(yr)]
log10(V200c[kms−1])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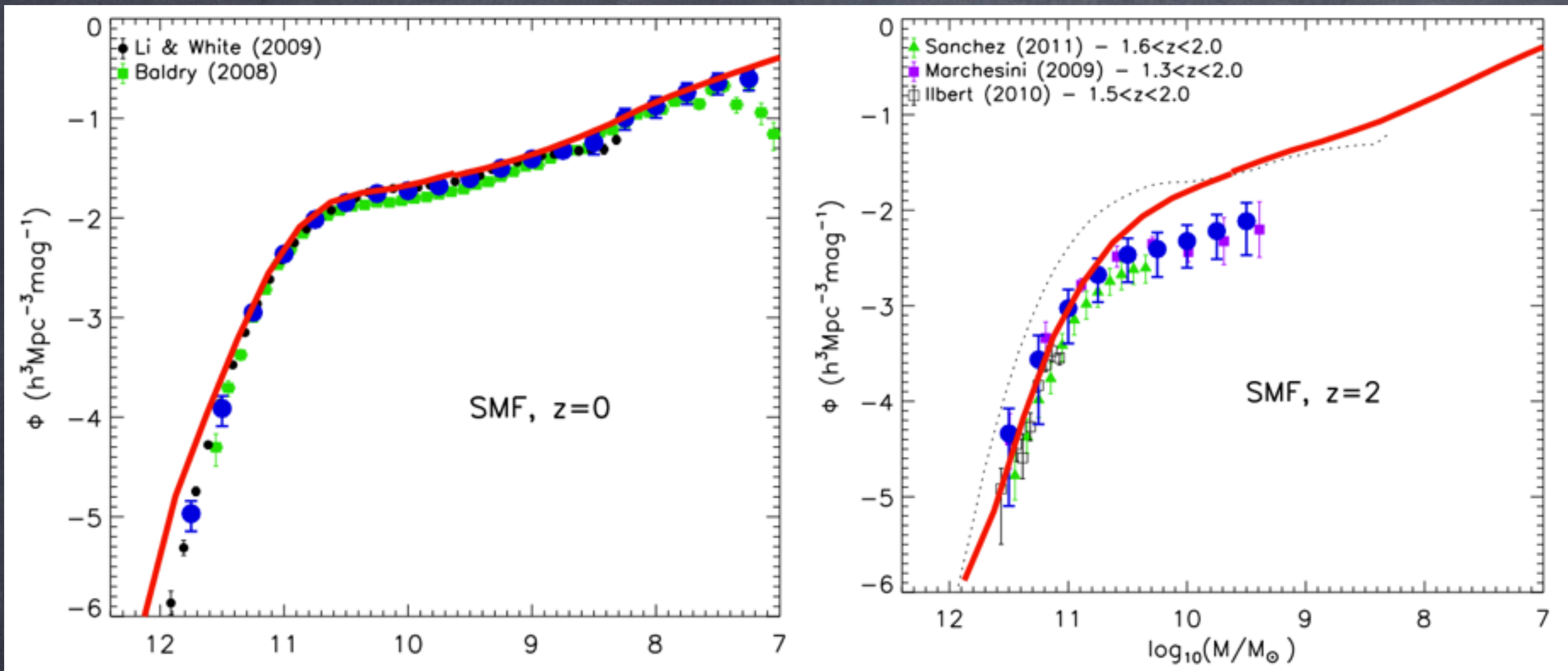
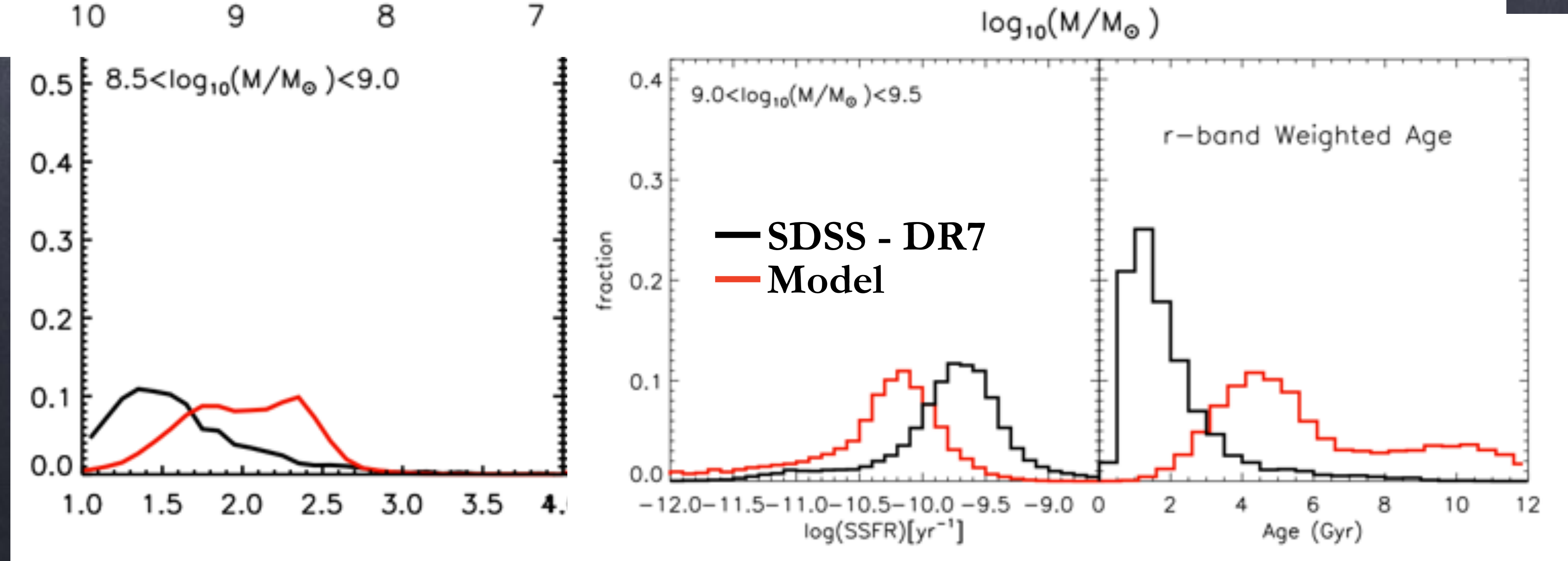
Guo2010/2013 model

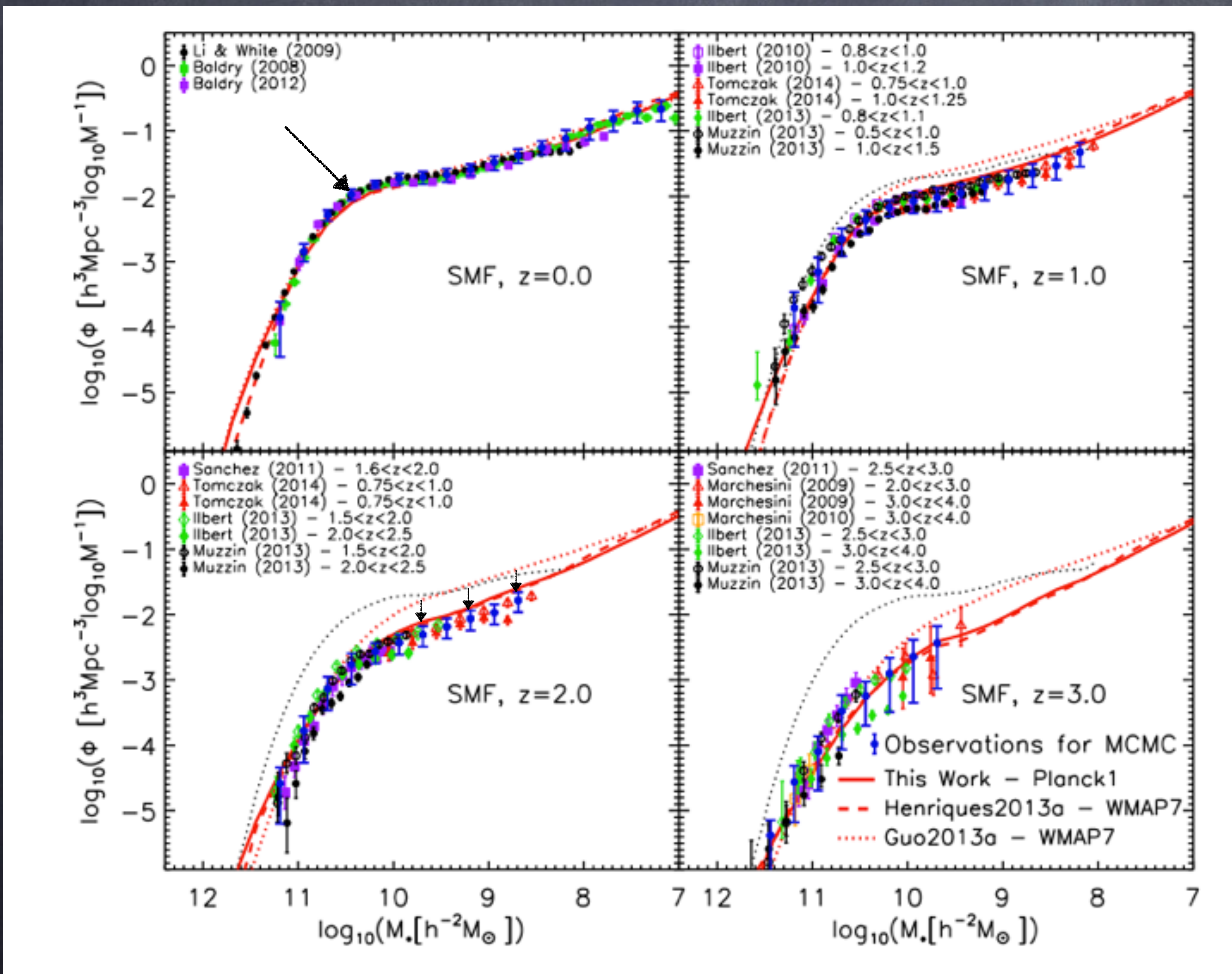
Excessive number of low mass galaxies forming at high-z





Gas Reincorporation

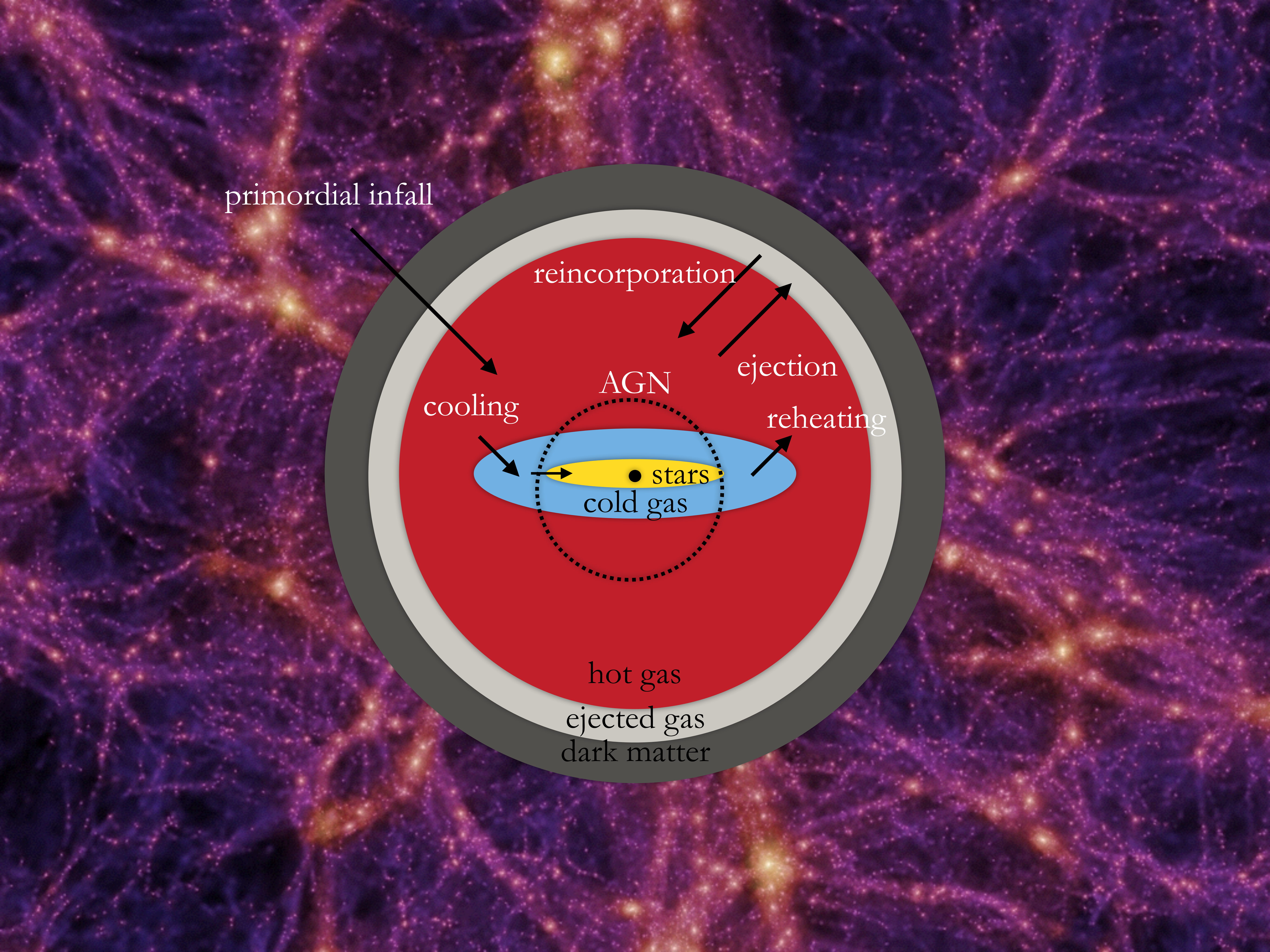
longer reincorporation time-scales for gas ejected by SN in low mass galaxies
lower number density at early times, stronger build up at later times



$$t_{\rm reinc} = -\gamma' \frac{10^{10}\,{\rm M}_\odot}{M_{\rm vir}},$$

<u>Henriques et al. 2013</u>
in agreement with
Oppenheimer & Dave
2008

hydro should correctly follow the gas flows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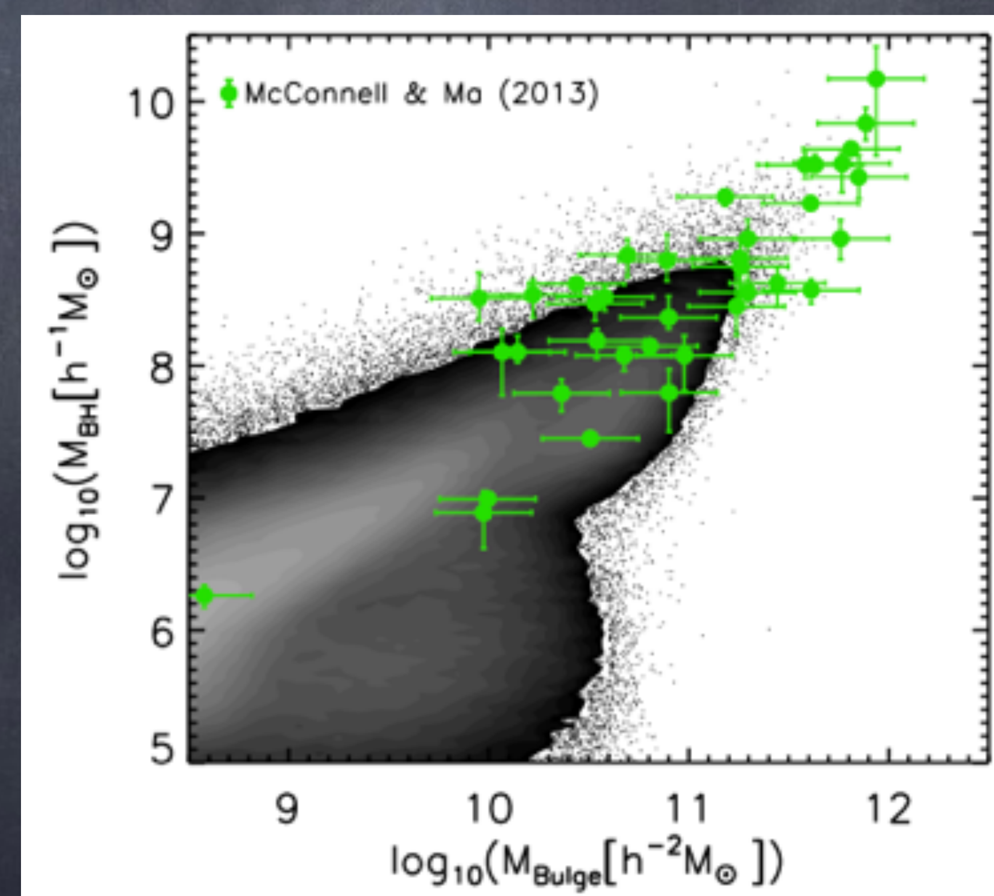
Black Hole Growth

Black Hole Growth During Mergers – Quasar (f_{BH})

BH growth during galaxy mergers both by merging with each other and by accretion of cold disk gas

$$\Delta m_{\rm BH,Q} = \frac{f_{\rm BH}(m_{\rm sat}/m_{\rm central})\, m_{\rm cold}}{1 + (V_{\rm BH}{\rm km\,s^{-1}}/V_{\rm vir})^2}.$$

Kauffmann & Haehnelt 2000



Black Hole Feedback

Quiescent Black Hole Accretion Rate – Radio (k_{AGN})

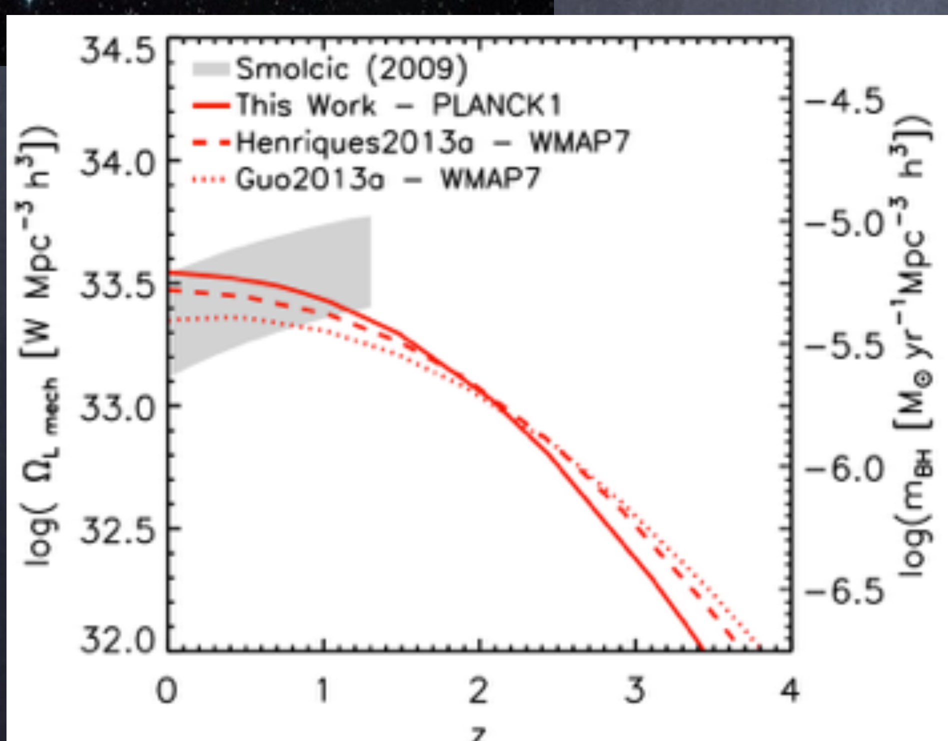
Hot gas accreted by the BH, once a static hot halo has formed around the host galaxy

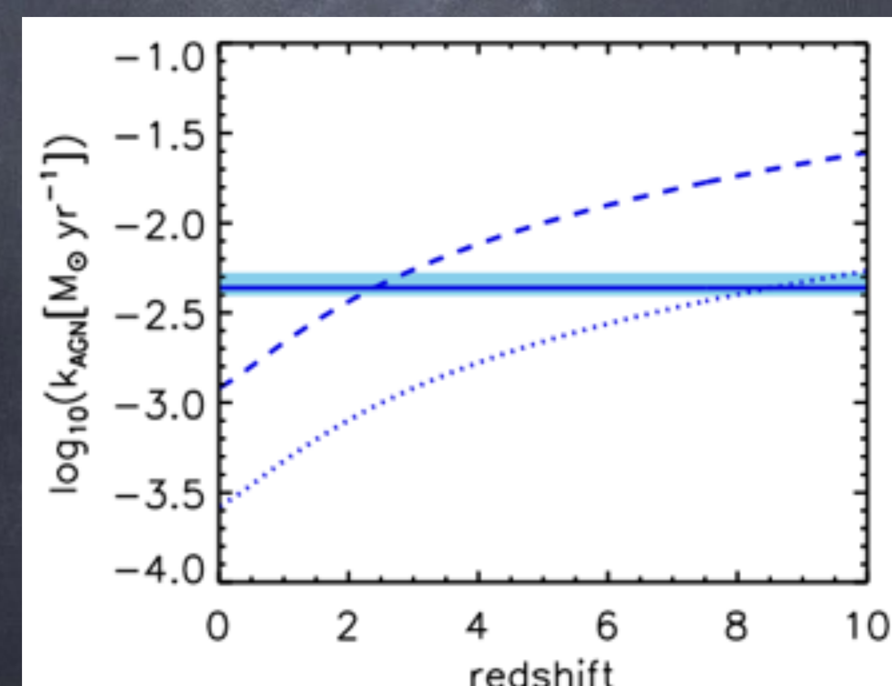
$$\dot{m}_{\rm BH,R} = k_{\rm AGN} \left(\frac{m_{\rm BH}}{10^8 \ {\rm M}_\odot} \right) \left(\frac{f_{\rm hot}}{0.1} \right) \left(\frac{V_{\rm vir}}{200 \, {\rm km \, s^{-1}}} \right)^3 , \quad \text{(A11)}$$

Croton et al. 2006

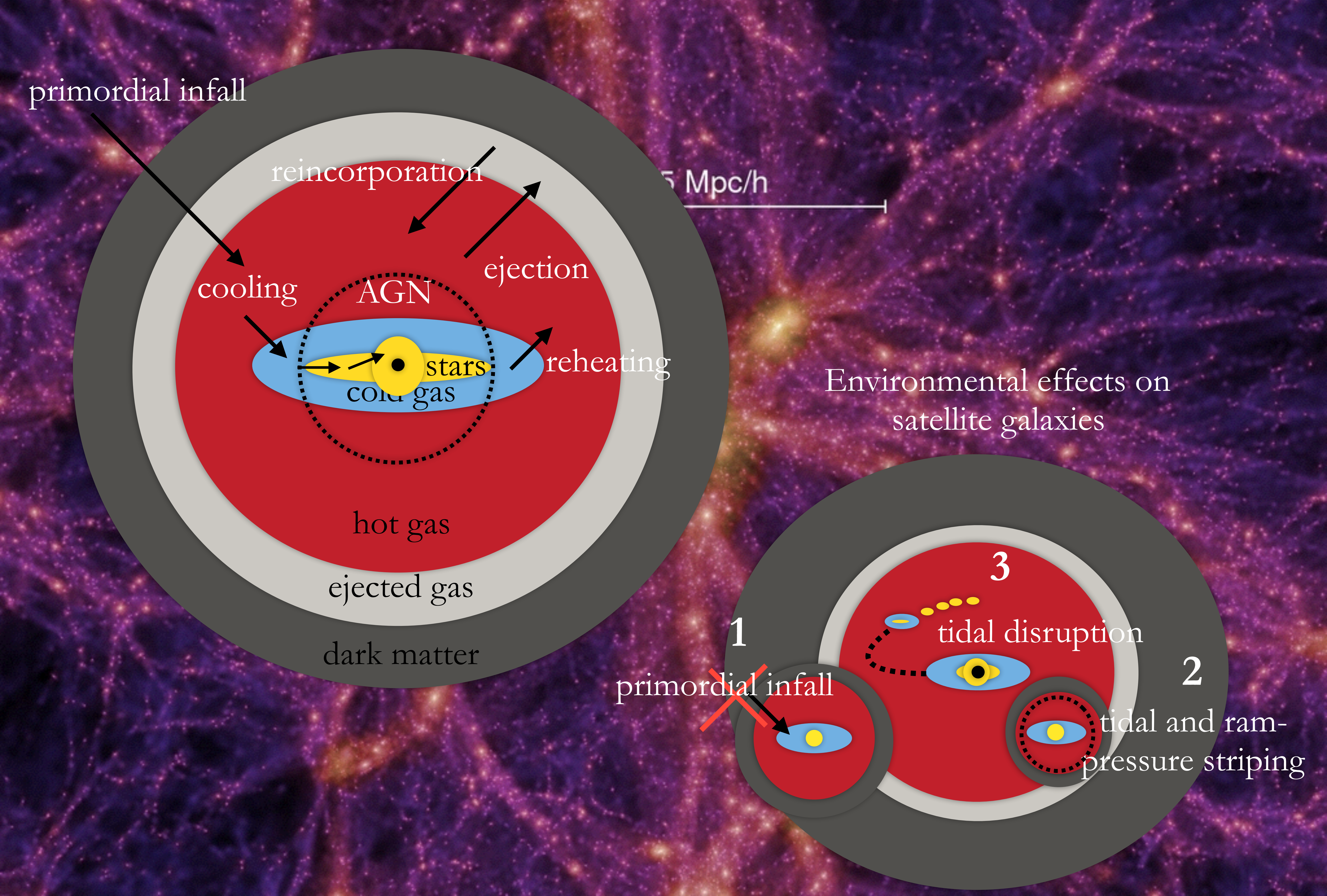
Henriques et al 2015

$$\dot{M}_{\rm BH} = k_{\rm AGN} \left(\frac{M_{\rm hot}}{10^{11}/{\rm h \, M_\odot}} \right) \left(\frac{M_{\rm BH}}{10^8/{\rm h \, M_\odot}} \right) .$$



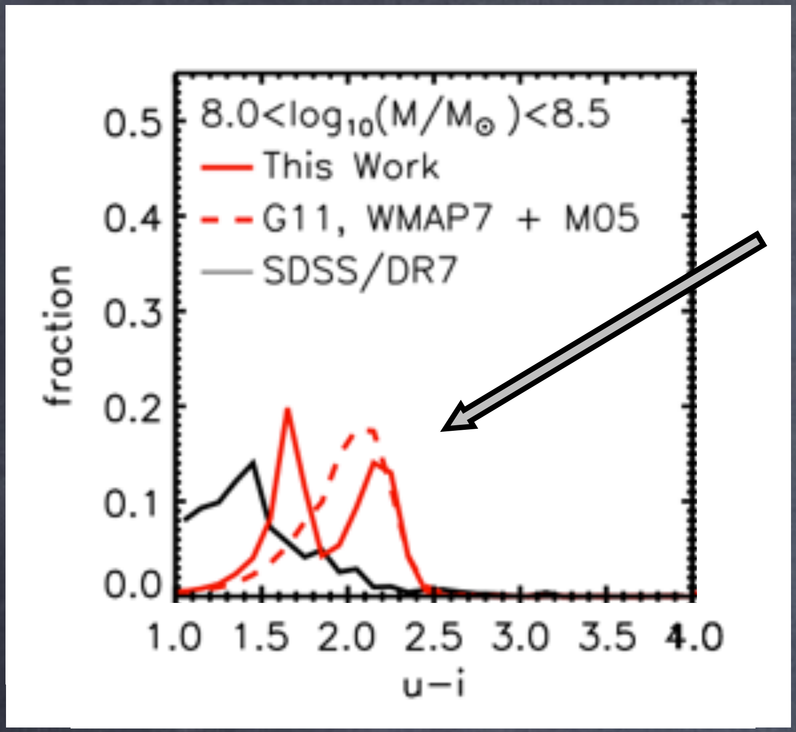


Environmental Effects



SF threshold and ram-pressure stripping

Henriques et al. 2013

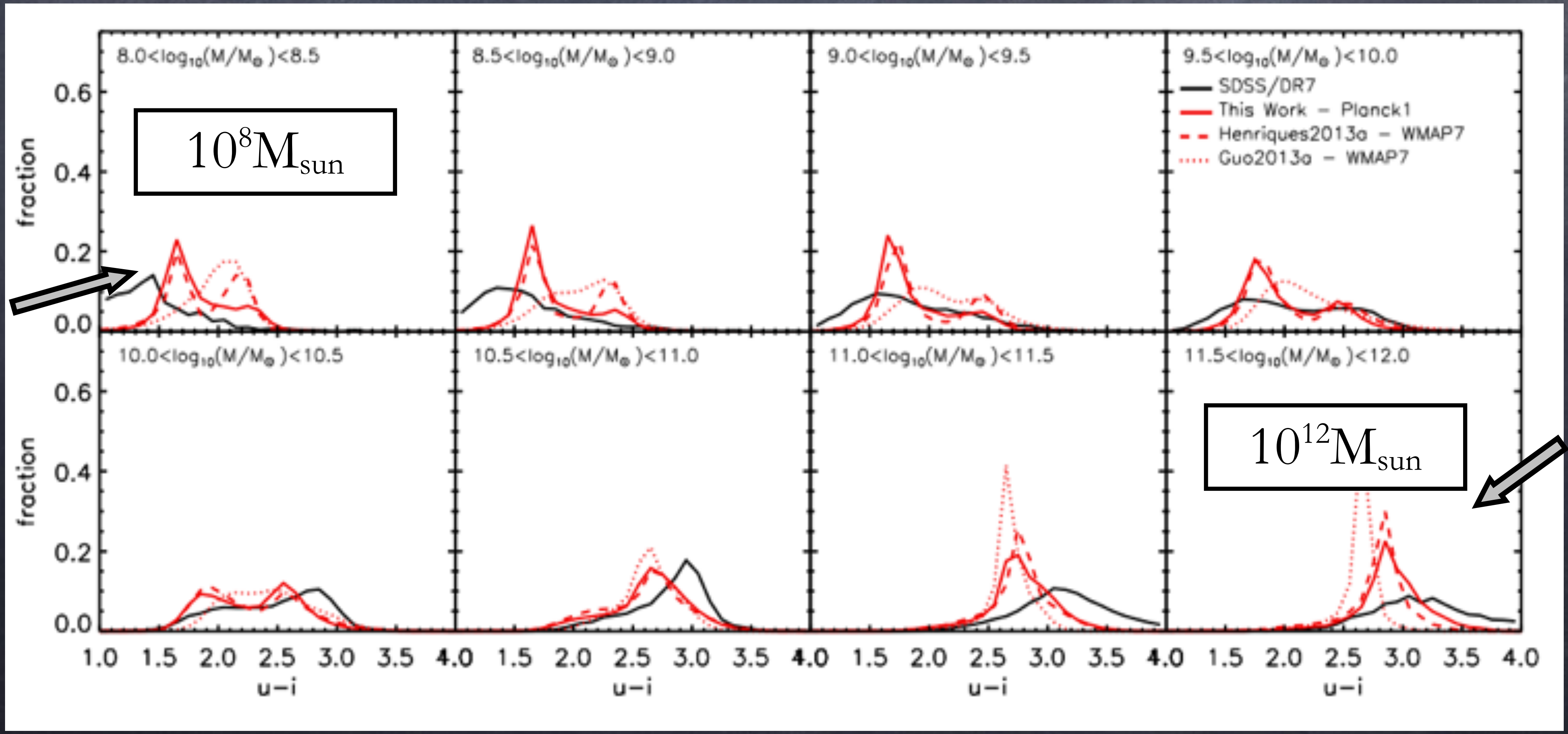


despite the later build up a population of low mass red satellites remained at z=0

→ lower the cold gas surface density threshold for SF

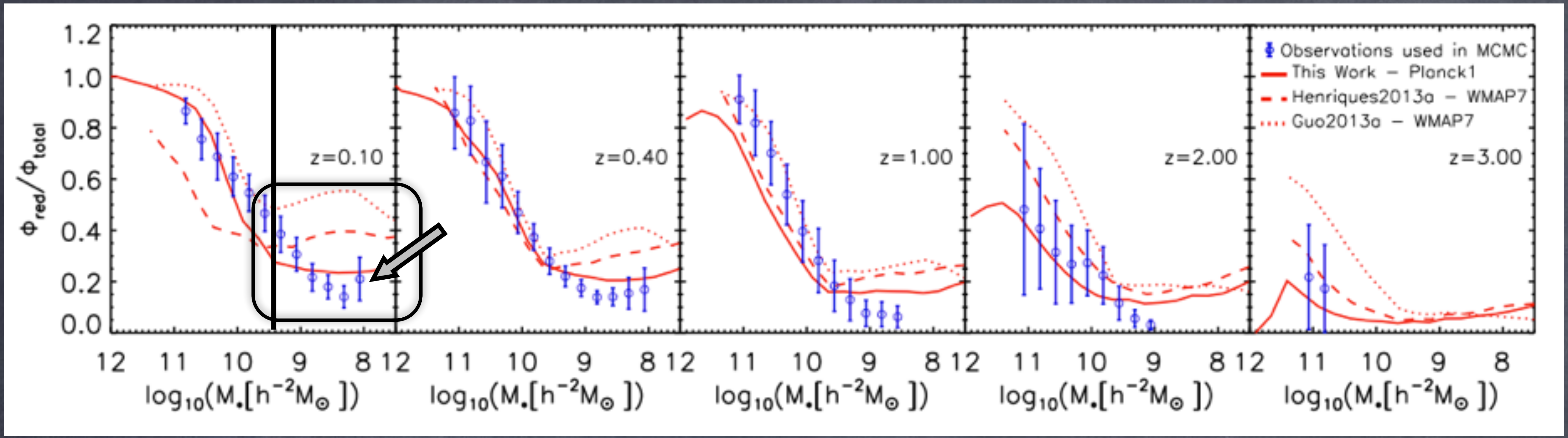
→ only include ram-pressure only in clusters ($M_{vir}>10^{14}$)

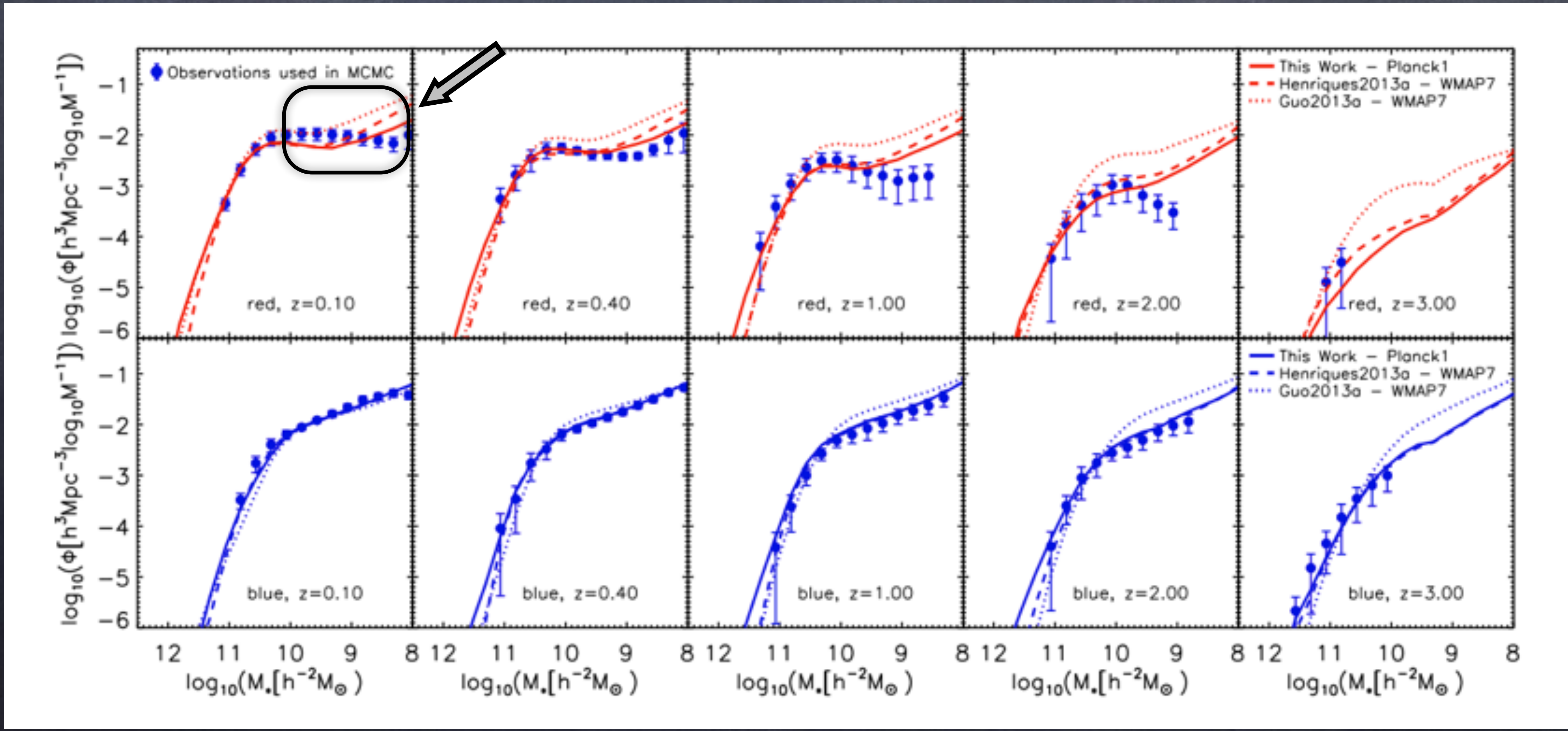
low mass galaxies are blue



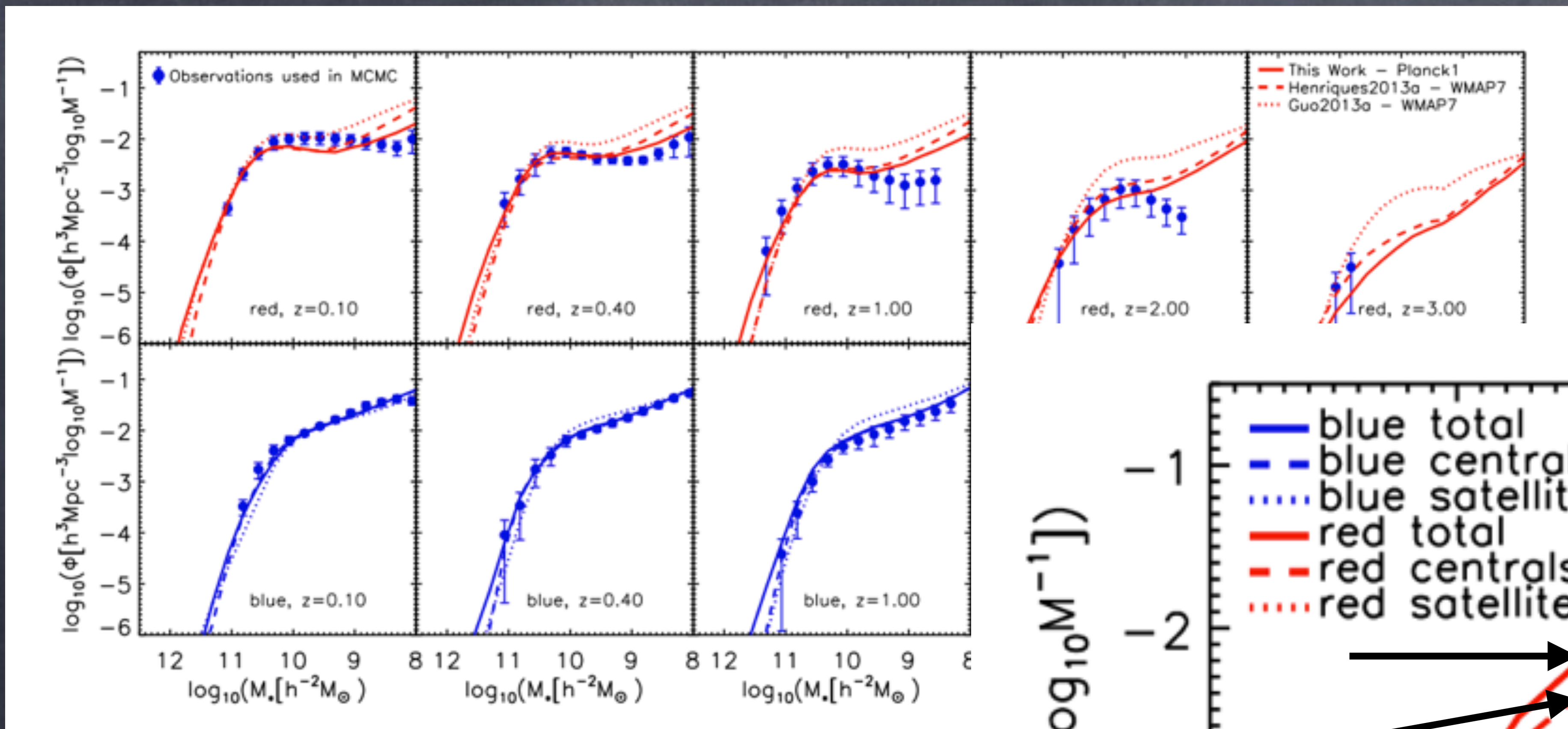
massive galaxies are red

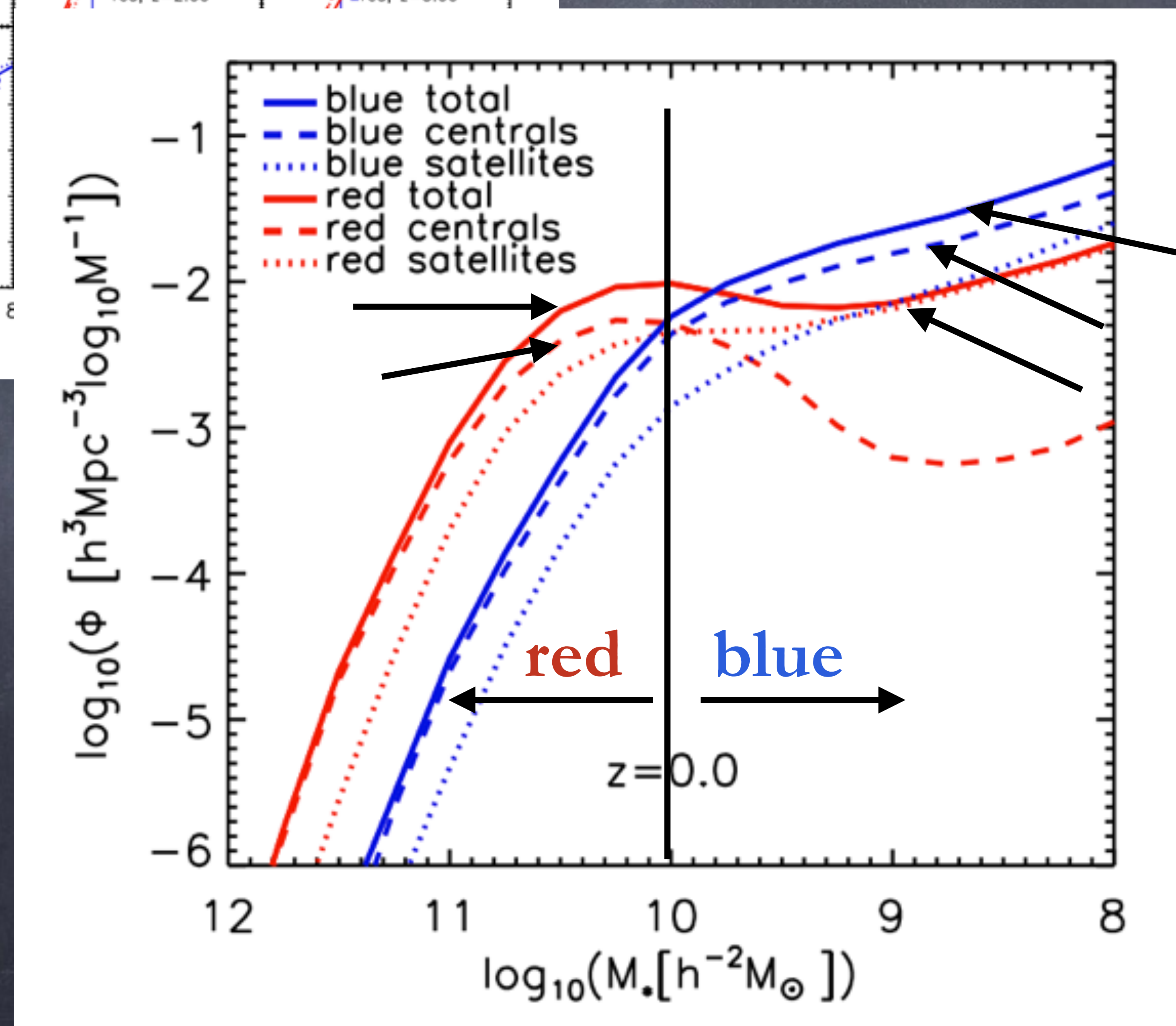
Stellar Mass Function by Colour





Stellar Mass Function by Colour





most massive galaxies are red

most low mass galaxies are blue

centrals dominate everywhere

red high mass centrals (AGN),
blue low mass centrals

low mass red galaxies are satellites

Mergers

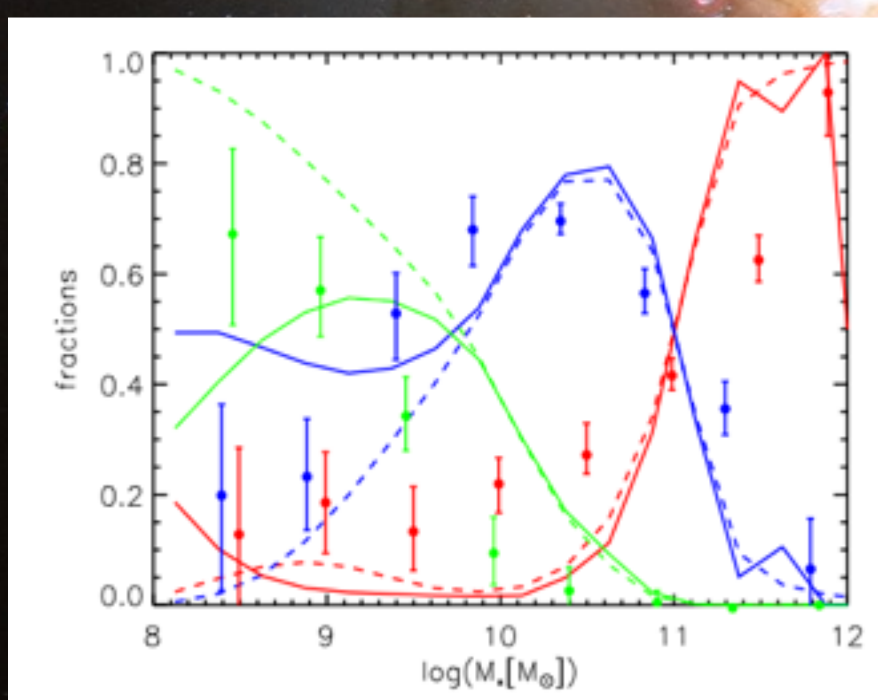
burst of star formation ⟹

$$M_{\star,\mathrm{burst}} = \alpha_{\mathrm{SF,burst}} \left(\frac{M_1}{M_2}\right)^{\beta_{\mathrm{SF,burst}}} M_{\mathrm{cold}}$$

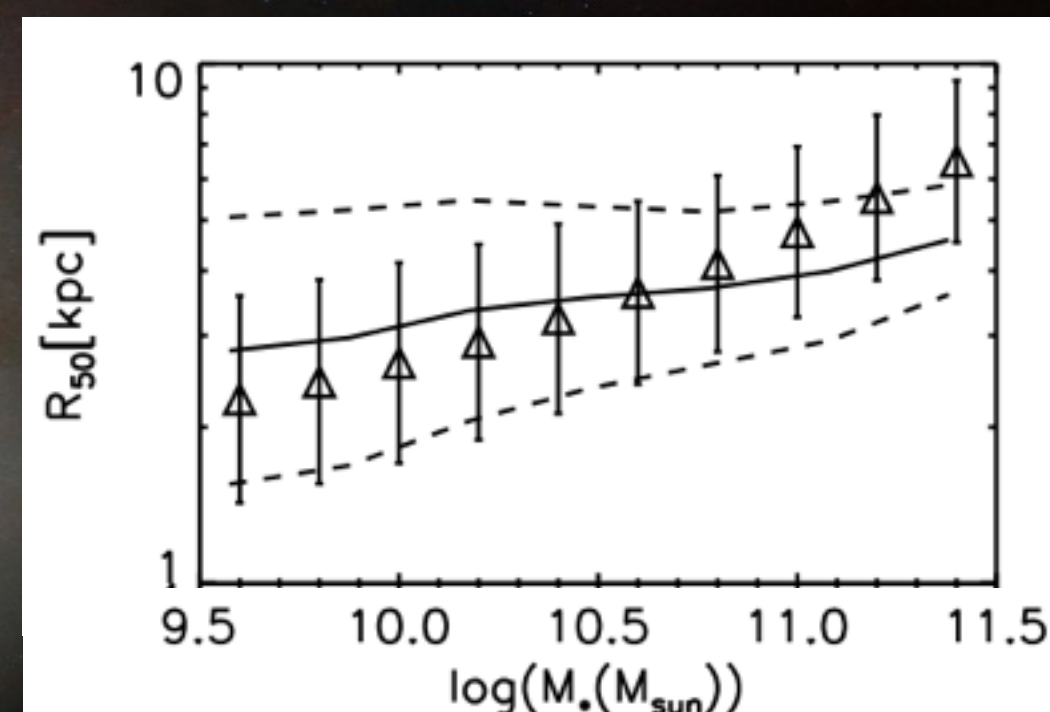
formation of a bulge ⟹

$$\frac{GM^2_{\mathrm{new,bulge}}}{R_{\mathrm{new,bulge}}} = \frac{GM_1^2}{R_1} + \frac{GM_2^2}{R_2} + 2\alpha_{\mathrm{inter}} \frac{GM_1 M_2}{R_1 + R_2}$$

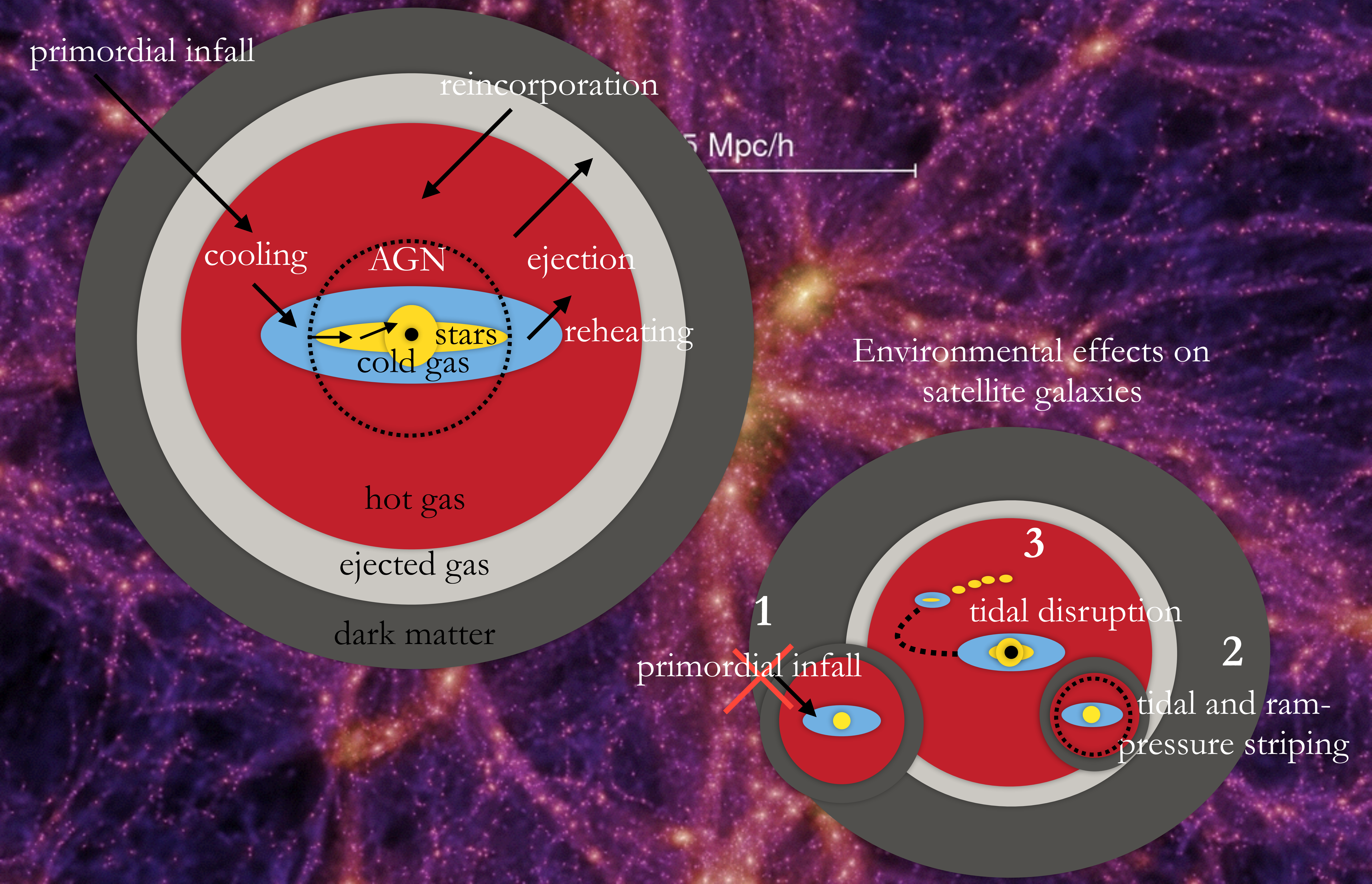
morphologies



bulge sizes

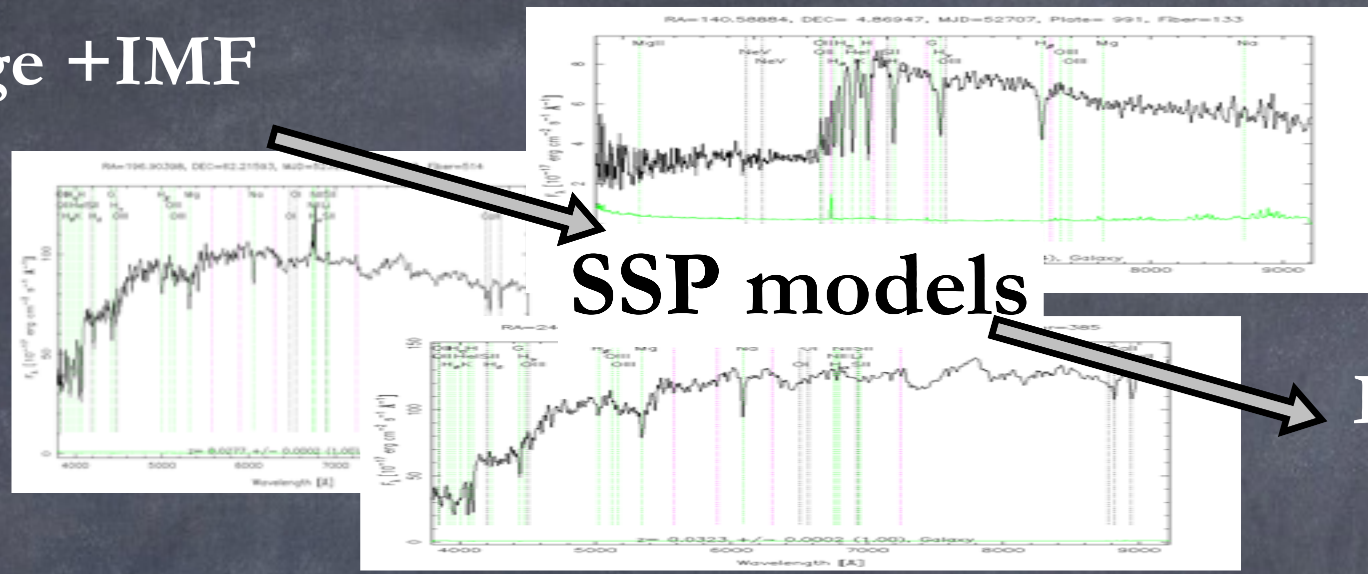


Model of Galaxy Formation



Emission Properties

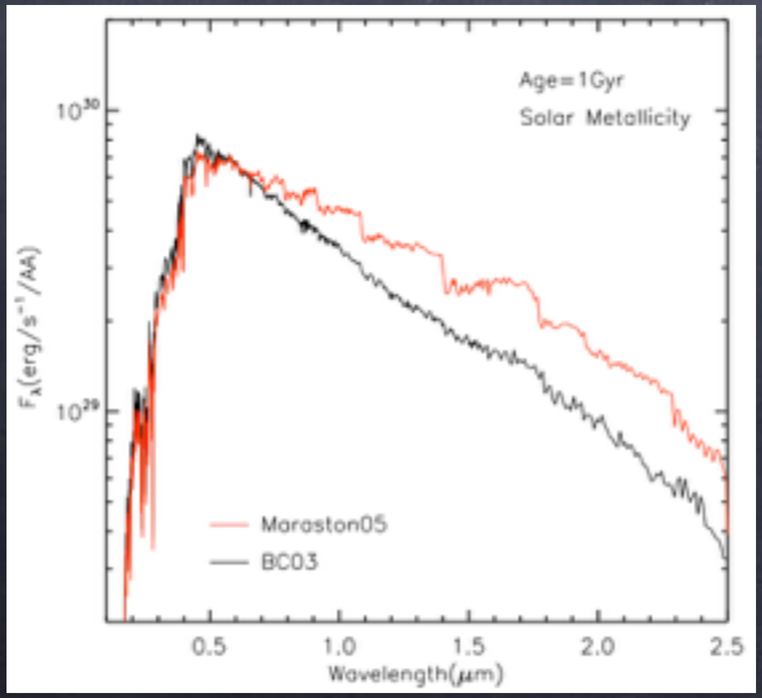
Metallicity + Age +IMF

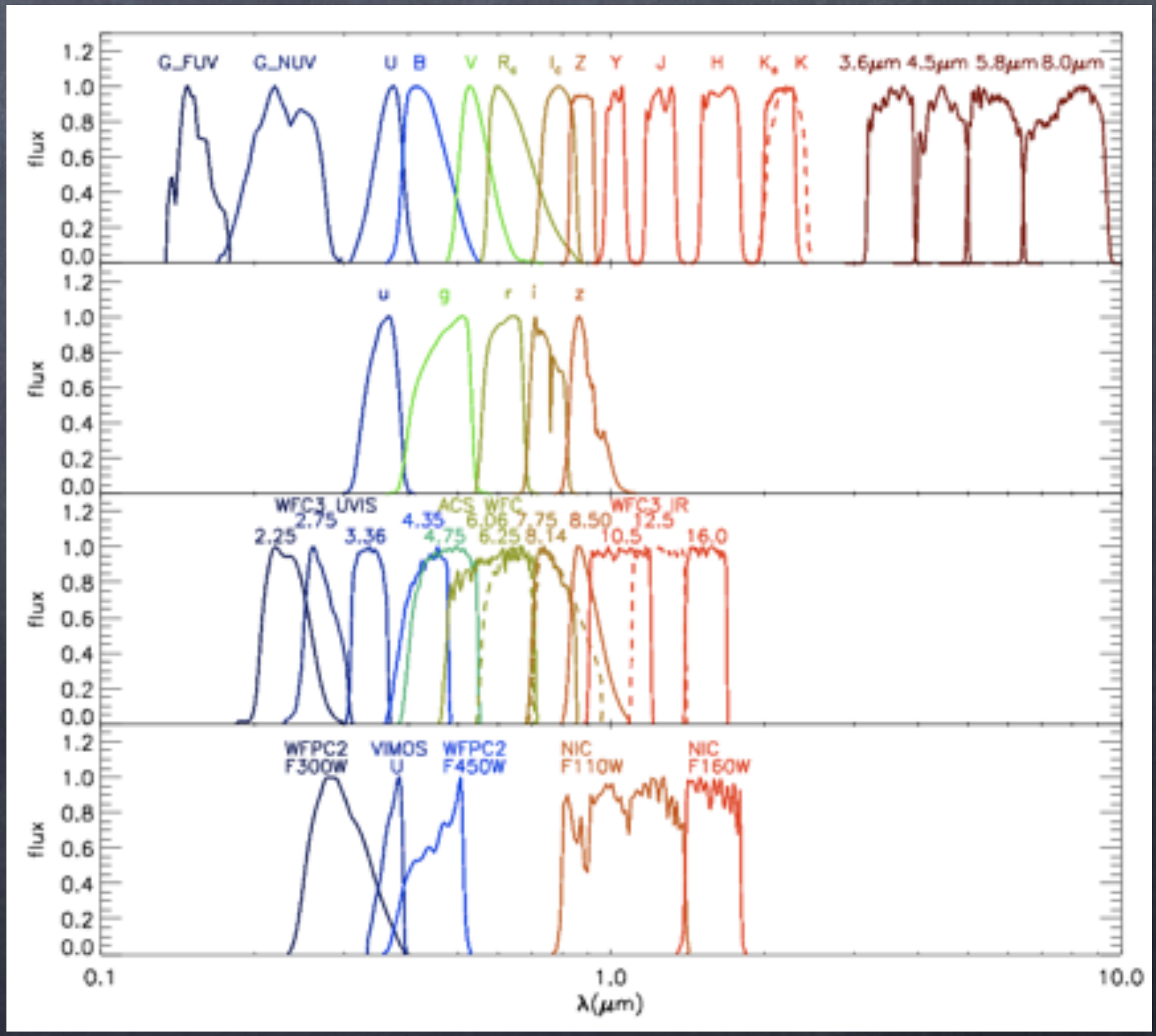


SSP models

Luminosity of a stellar population

Chabrier IMF + BC03 or M05 or CB07





Henriques et al. 2011, 2012

Dust Model

Optical depth of ISM dust

$$\tau_\lambda^{ISM} = \left(\frac{A_\lambda}{A_v}\right)_{Z_\odot} (1+z)^{-0.4} \left(\frac{Z_{\rm gas}}{Z_\odot}\right)^s \left(\frac{\langle N_H \rangle}{2.1\times 10^{21} {\rm atoms\,cm^{-2}}}\right)$$

$$\langle N_H \rangle = \frac{M_{\rm cold}}{1.4\, m_p \pi (a R_{\rm D})^2} {\rm atoms\,cm}^{-2}$$

Optical depth of dust in molecular clouds

$$\tau_\lambda^{BC} = \tau_\lambda^{\rm ISM} \left(\frac{1}{\mu} - 1\right) \left(\frac{\lambda}{5500\text{Å}}\right)^{-0.7}$$

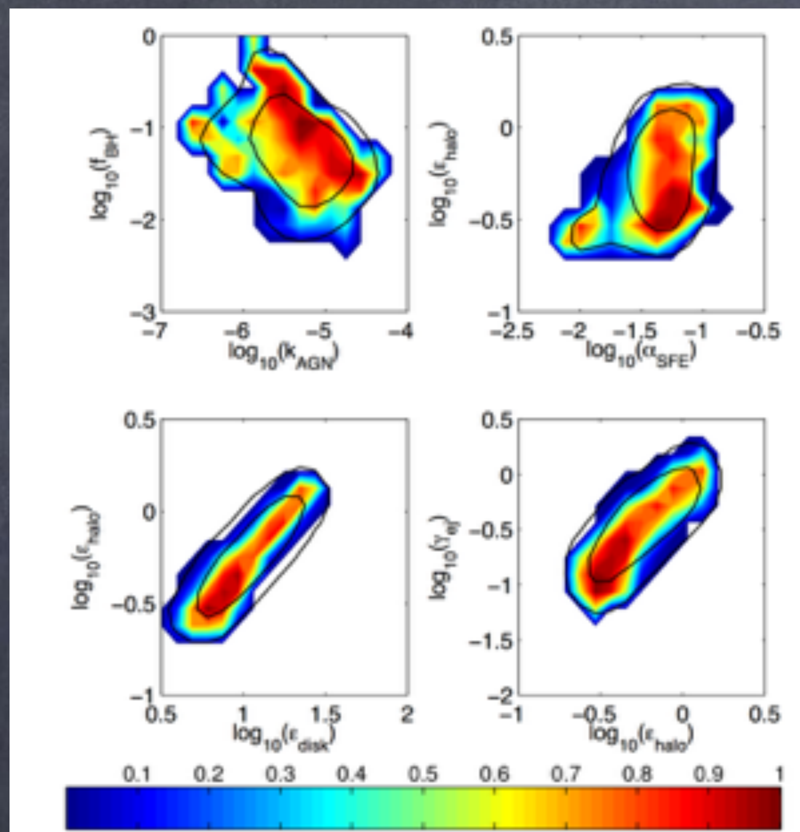
Extinction law:

$$A_\lambda = -2.5 \log \left(\frac{1 - \exp^{-\tau_\lambda \sec\theta}}{\tau_\lambda \sec\theta}\right)$$

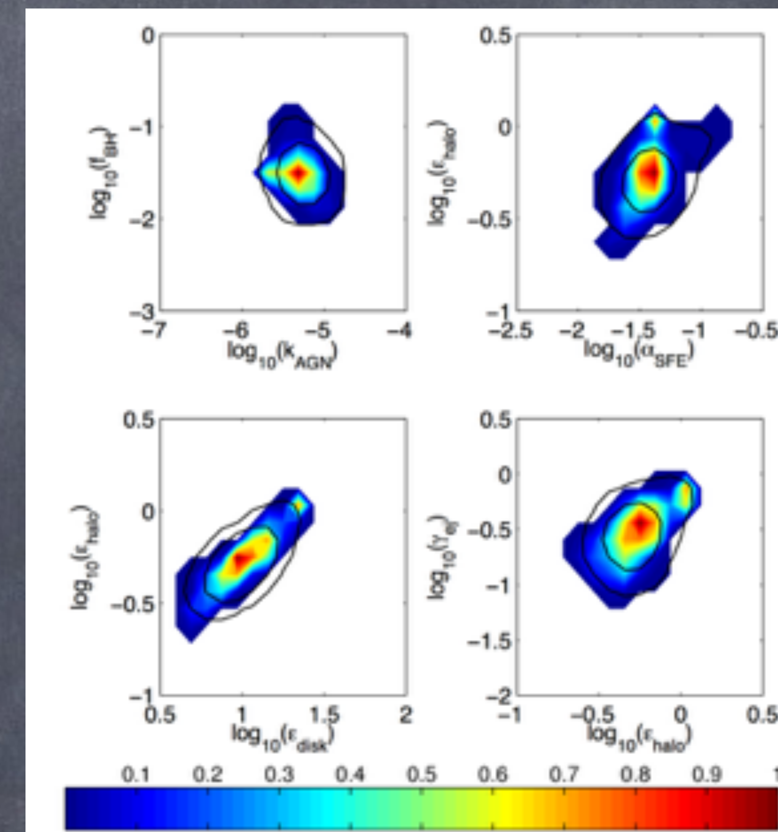
De Lucia & Blaizot 2007

MCMC

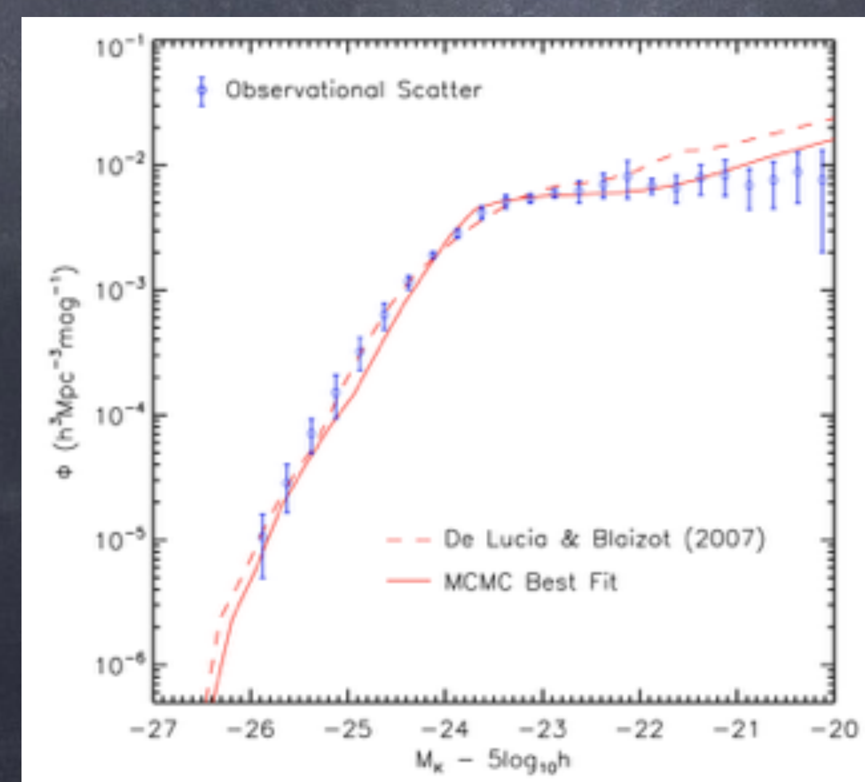
Only SMF as a constraint



SMF + colour + BHBM

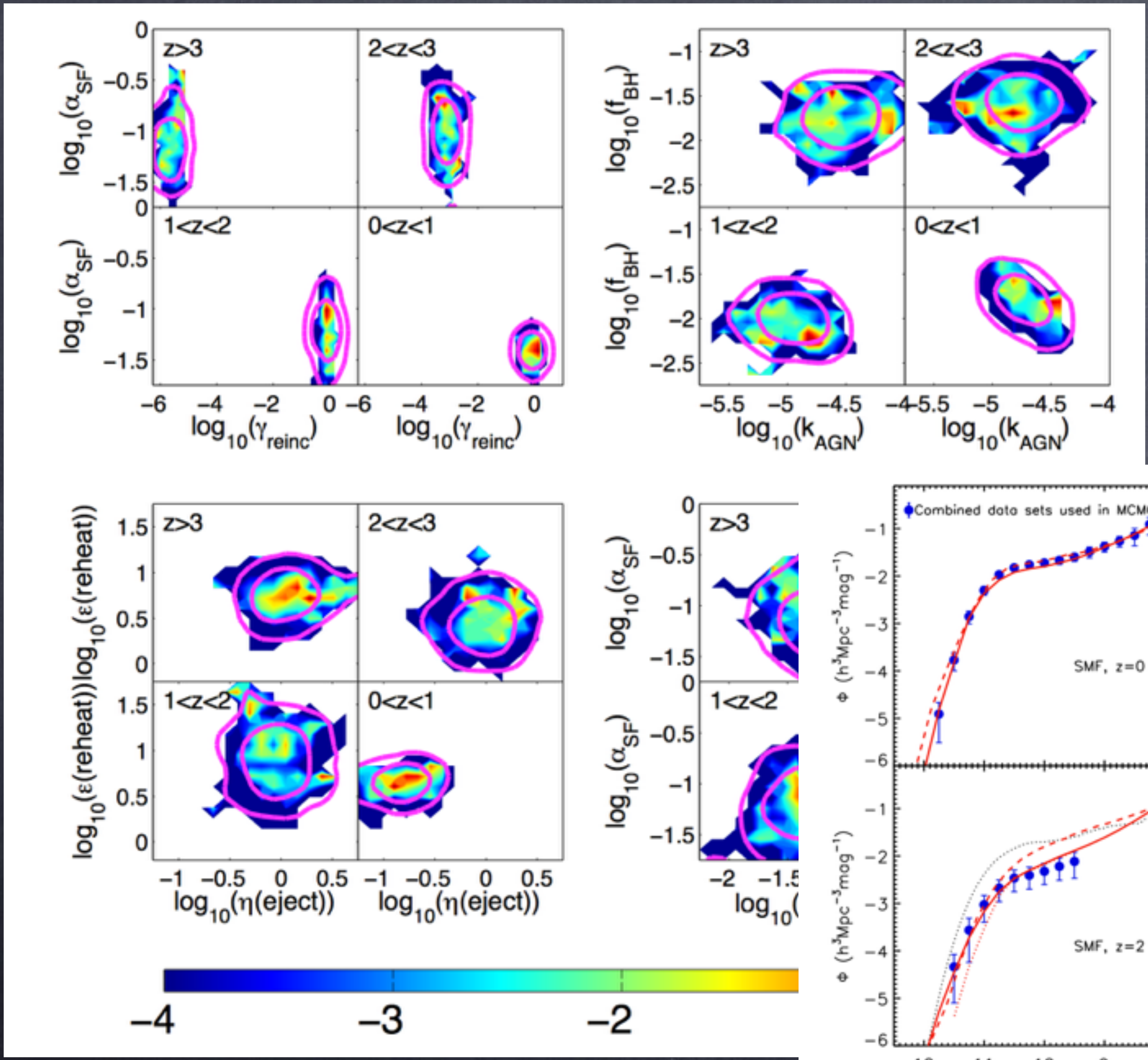


no degeneracies!!

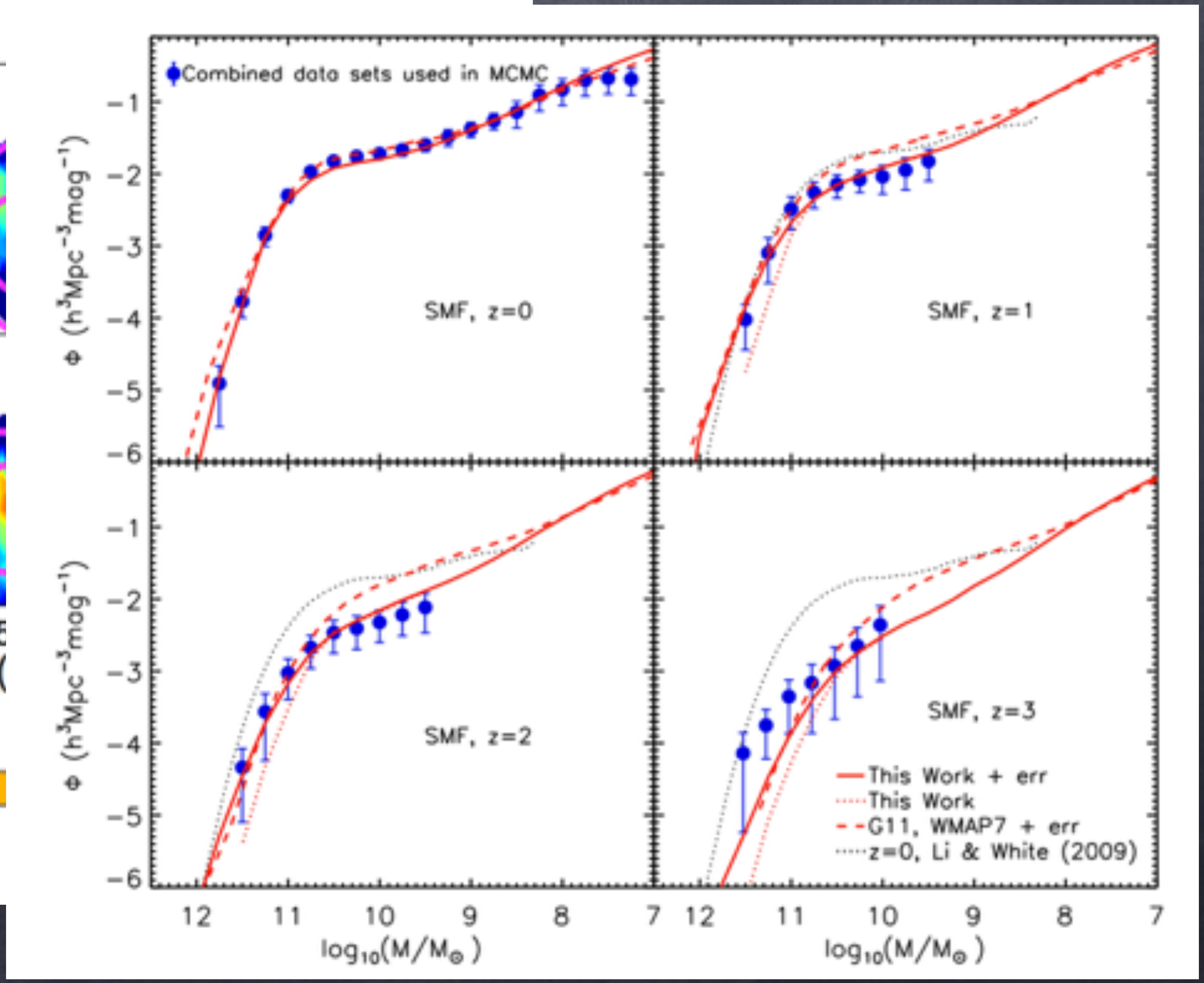


Simply fully sampling the parameter space, better agreement with observations can be found

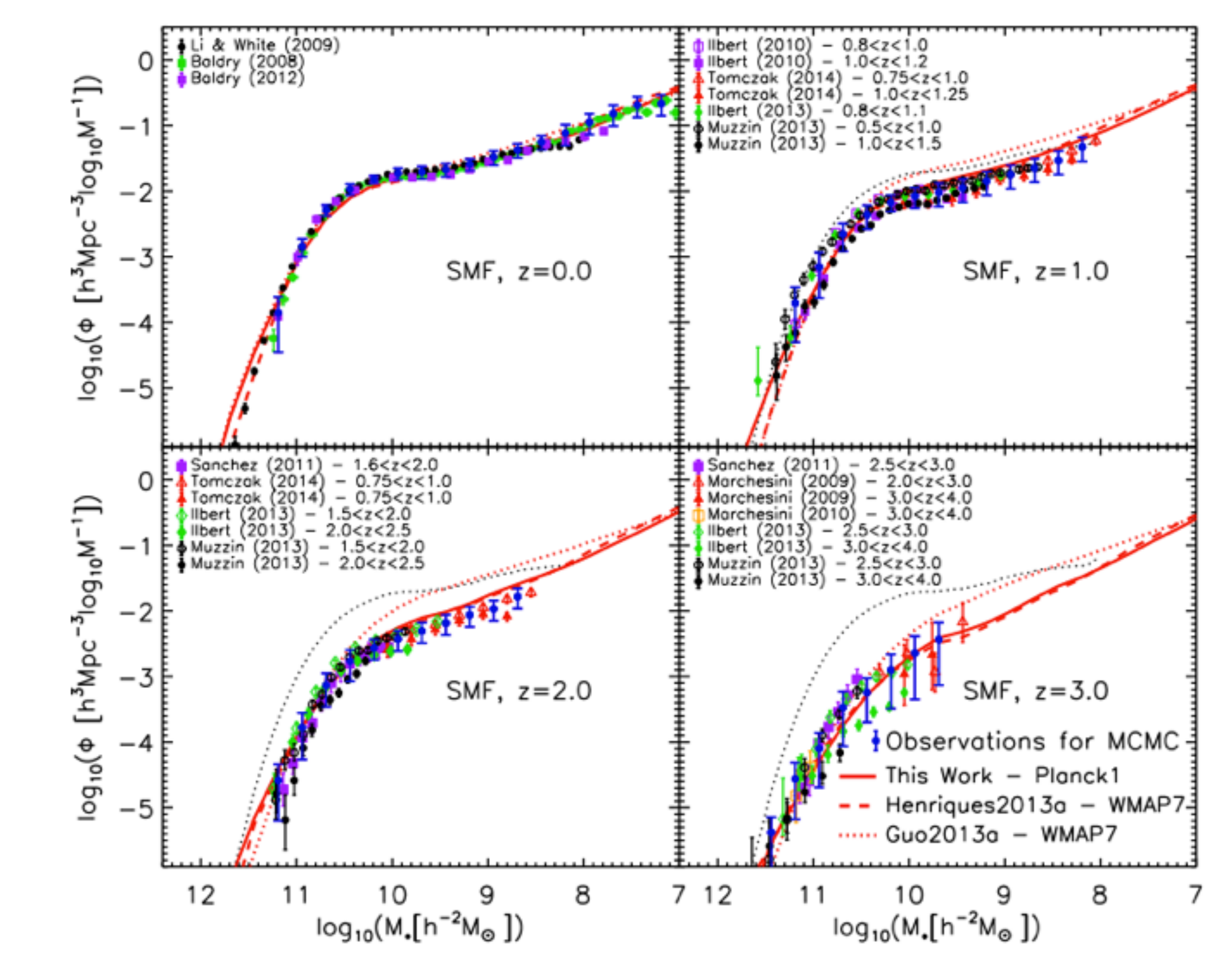
MCMC

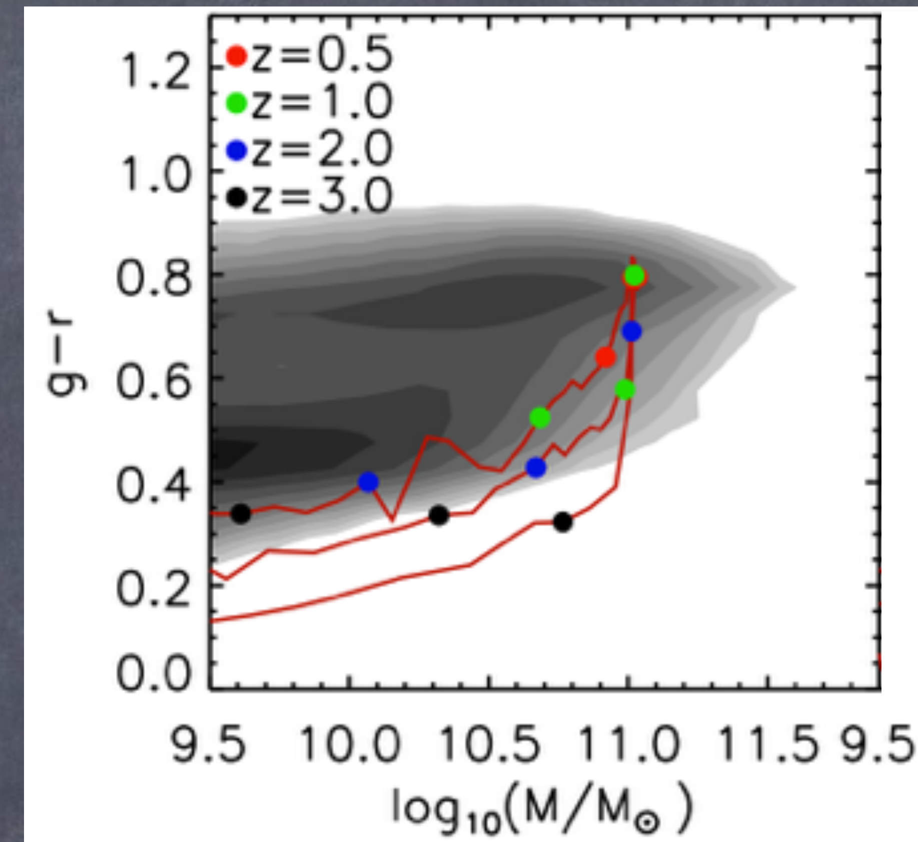


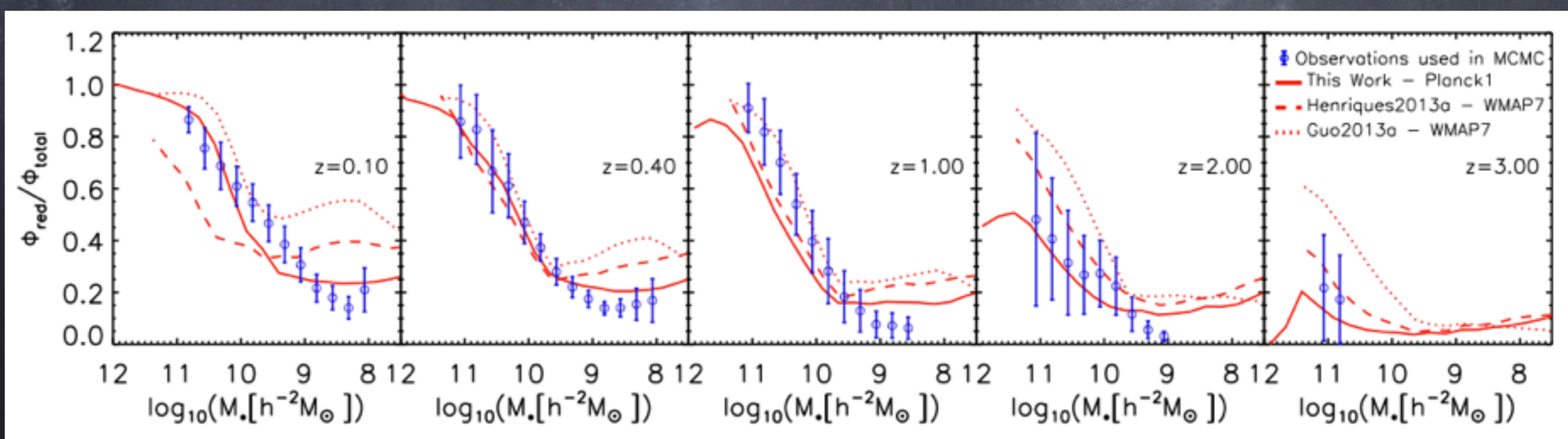
z>3
2<z<3
1<z<2
0<z<1
log10(αSF)
log10(γreinc)
log10(fBH)
log10(kAGN)
log10(ε(reheat))
log10(η(eject))
−4
−3
−2



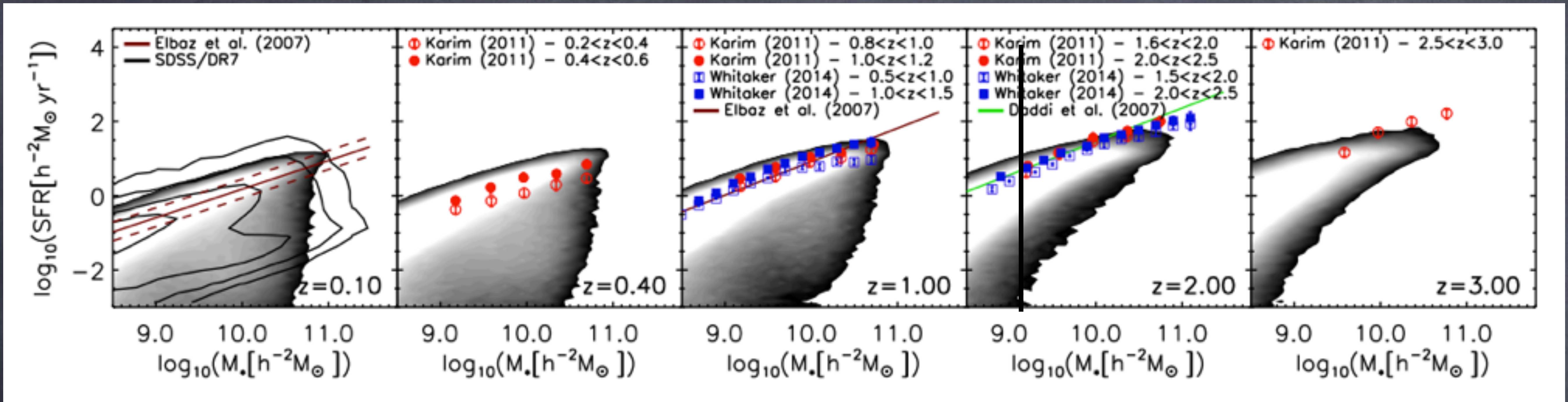
Combined data sets used in MCMC
SMF, z=0
SMF, z=1
SMF, z=2
SMF, z=3
This Work + err
This Work
G11, WMAP7 + err
z=0, Li & White (2009)
Φ (h³Mpc⁻³mag⁻¹)
log10(M/M⊙)

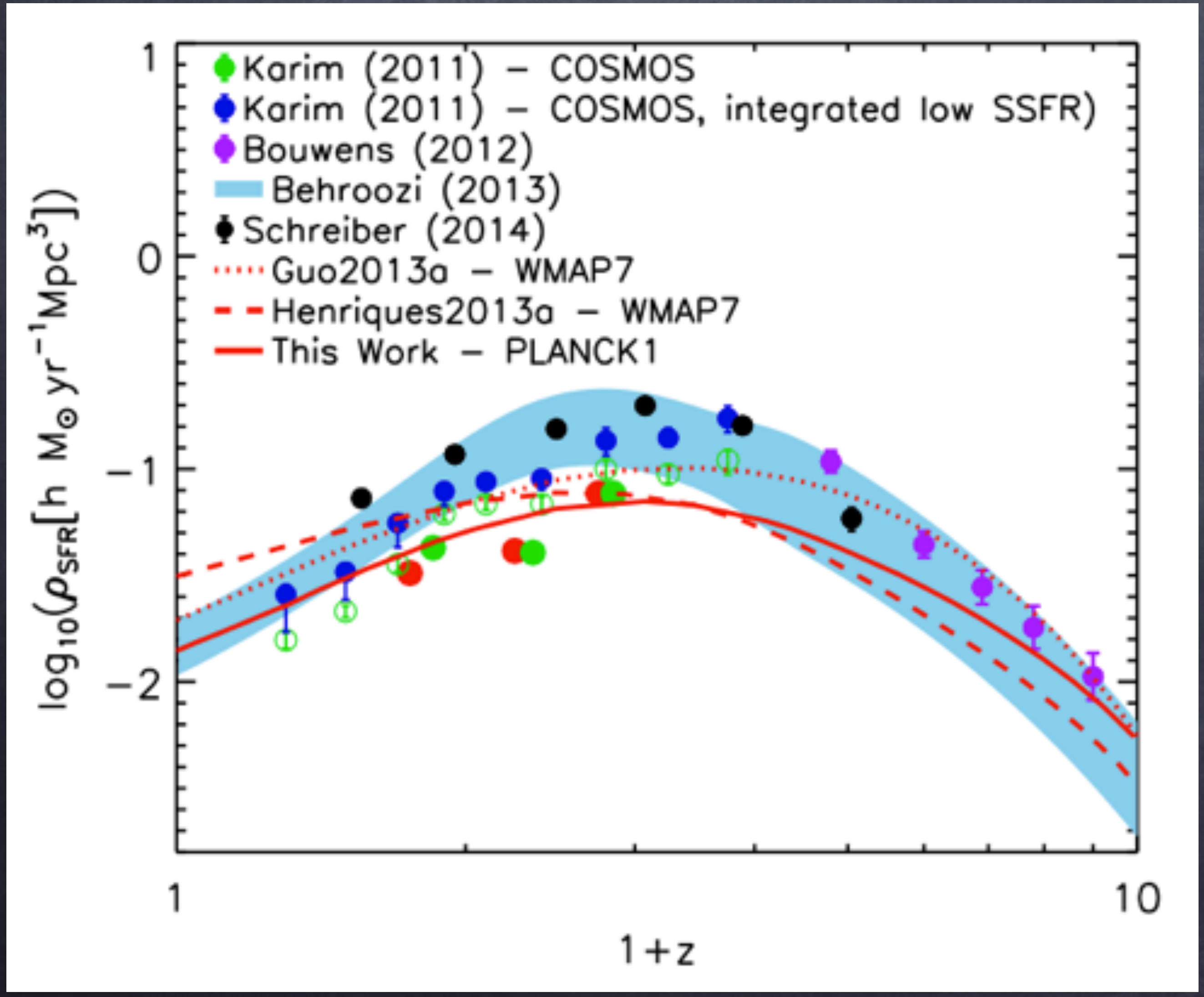

Li & White (2009)
Baldry (2008)
Baldry (2012)
SMF, z=0.0
Ilbert (2010) – 0.8<z<1.0
Ilbert (2010) – 1.0<z<1.2
Tomczak (2014) – 0.75<z<1.0
Tomczak (2014) – 1.0<z<1.25
Ilbert (2013) – 0.8<z<1.1
Muzzin (2013) – 0.5<z<1.0
Muzzin (2013) – 1.0<z<1.5
SMF, z=1.0
Sanchez (2011) – 1.6<z<2.0
Tomczak (2014) – 0.75<z<1.0
Tomczak (2014) – 0.75<z<1.0
Ilbert (2013) – 1.5<z<2.0
Ilbert (2013) – 2.0<z<2.5
Muzzin (2013) – 1.5<z<2.0
Muzzin (2013) – 2.0<z<2.5
SMF, z=2.0
Sanchez (2011) – 2.5<z<3.0
Marchesini (2009) – 2.0<z<3.0
Marchesini (2009) – 3.0<z<4.0
Marchesini (2010) – 3.0<z<4.0
Ilbert (2013) – 2.5<z<3.0
Ilbert (2013) – 3.0<z<4.0
Muzzin (2013) – 2.5<z<3.0
Muzzin (2013) – 3.0<z<4.0
SMF, z=3.0
Observations for MCMC
This Work – Planck1
Henriques2013a – WMAP7
Guo2013a – WMAP7
log10(Φ [h^3Mpc^-3log10M^-1])
log10(M*[h^-2M⊙])


z=0.5
z=1.0
z=2.0
z=3.0
g−r
log10(M/M⊙)


Φred/Φtotal
z=0.10
z=0.40
z=1.00
z=2.00
z=3.00
Observations used in MCMC
This Work – Planck1
Henriques2013a – WMAP7
Guo2013a – WMAP7
log10(M*[h^-2M⊙])

Star Formation Rates

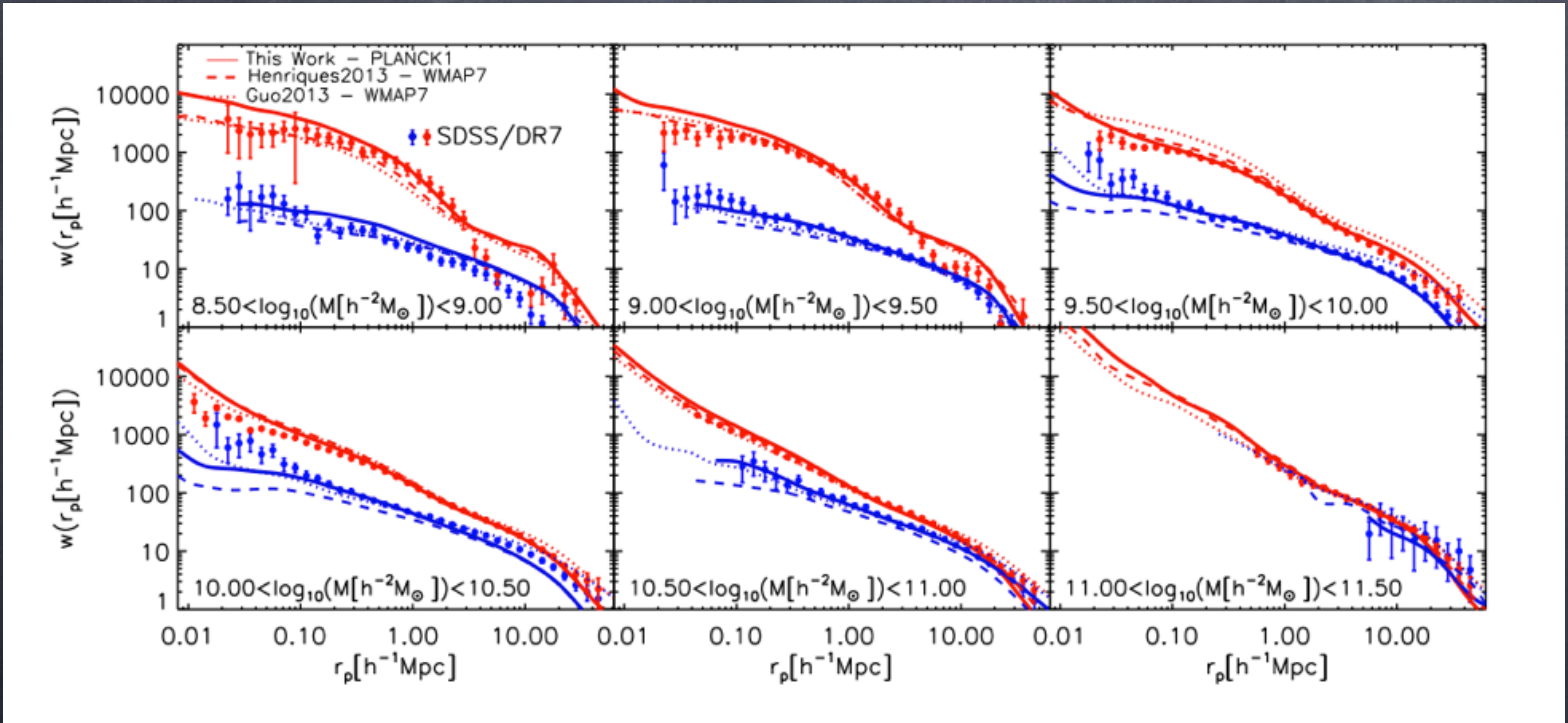


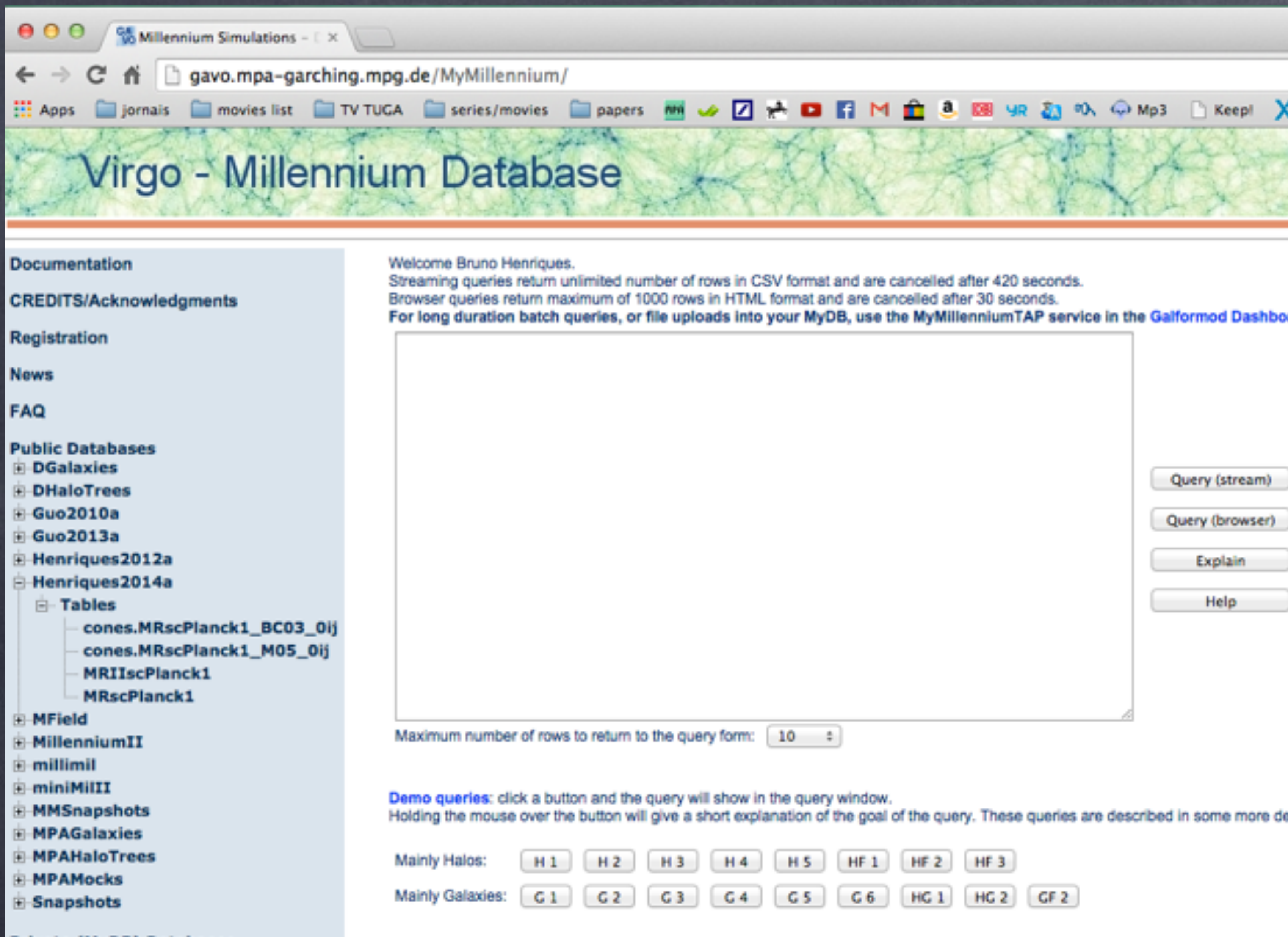


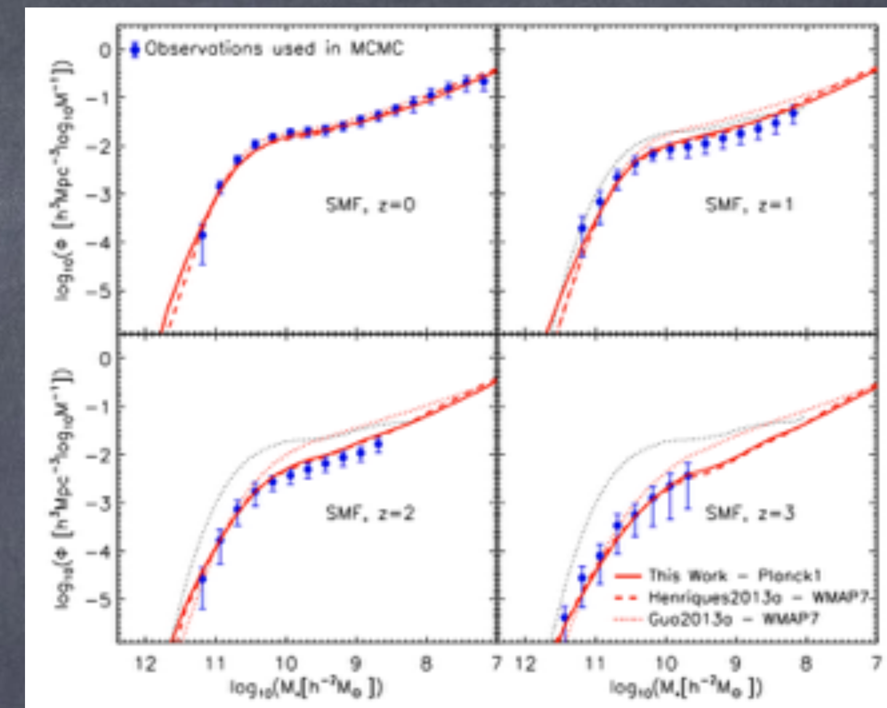
decrease in the normalisation of the main sequence due to a reduction in cosmic accretion

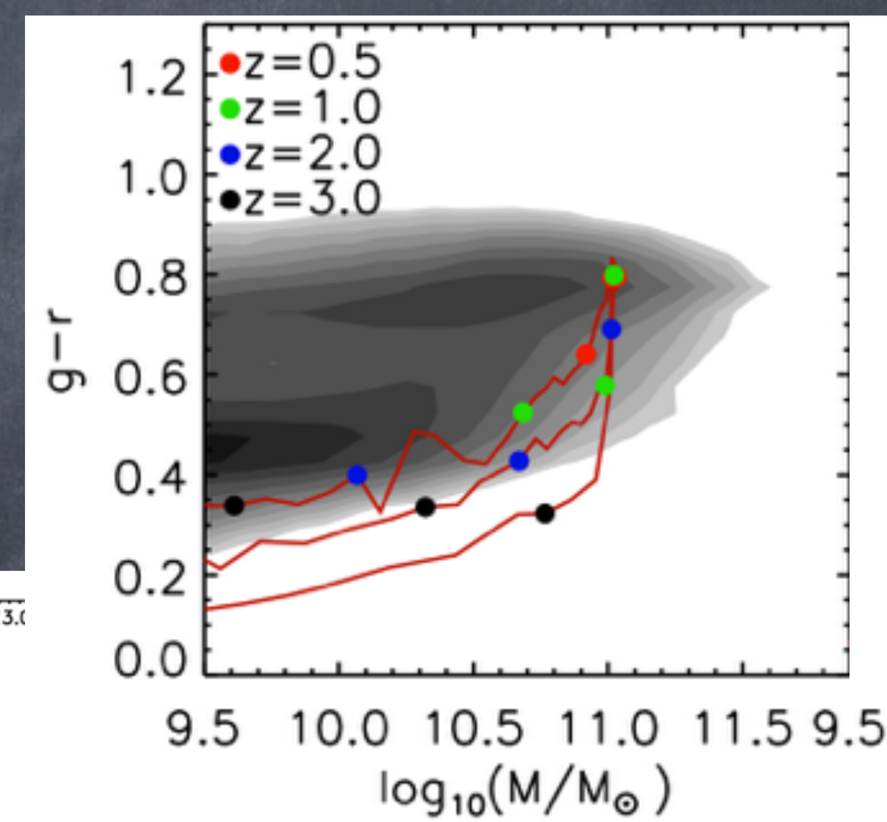
overall SFRD reduced due to a population of quenched objectes at z<2

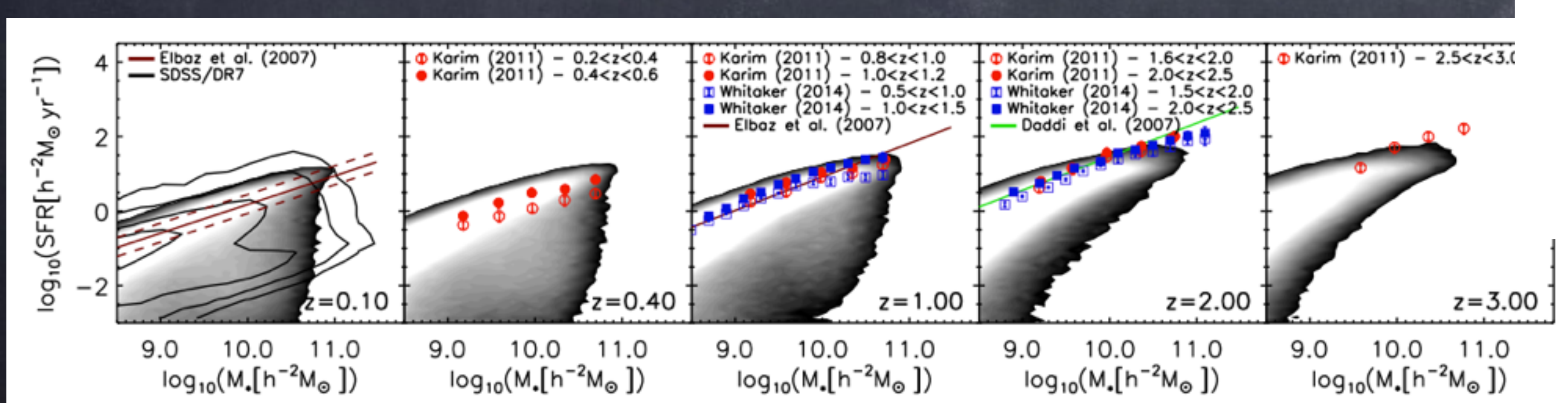
Clustering as a function of colour

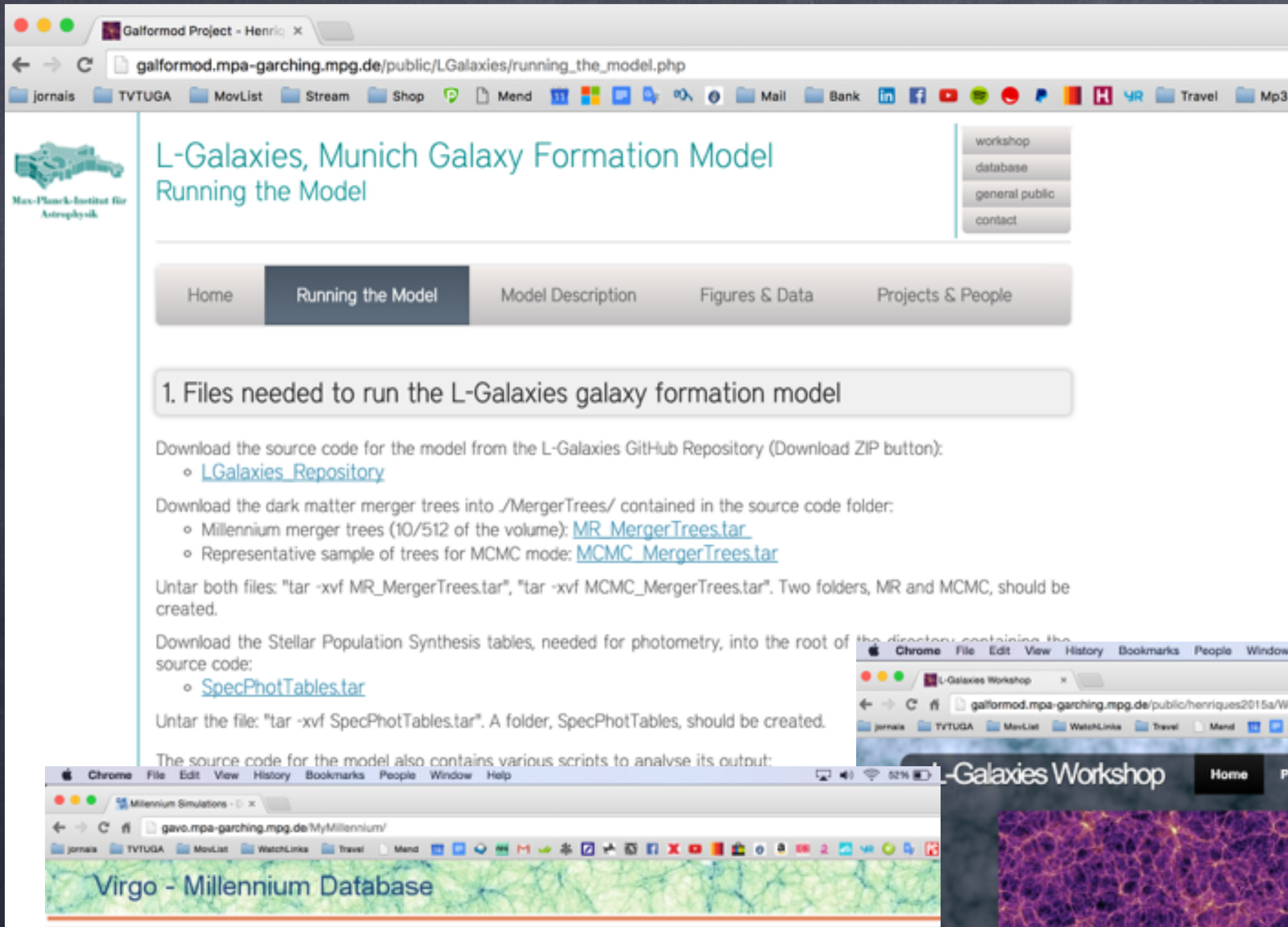



Millennium Simulations
gavo.mpa-garching.mpg.de/MyMillennium/
Apps
jornais
movies list
TV TUGA
series/movies
papers
Mp3
Keep!
Virgo - Millennium Database
Documentation
CREDITS/Acknowledgments
Registration
News
FAQ
Public Databases
DGalaxies
DHaloTrees
Guo2010a
Guo2013a
Henriques2012a
Henriques2014a
Tables
cones.MRscPlanck1_BC03_0ij
cones.MRscPlanck1_M05_0ij
MRIIscPlanck1
MRscPlanck1
MField
MillenniumII
millimil
miniMilII
MMSnapshots
MPAGalaxies
MPAHaloTrees
MPAMocks
Snapshots
Welcome Bruno Henriques.
Streaming queries return unlimited number of rows in CSV format and are cancelled after 420 seconds.
Browser queries return maximum of 1000 rows in HTML format and are cancelled after 30 seconds.
For long duration batch queries, or file uploads into your MyDB, use the MyMillenniumTAP service in the Galformod Dashboa
Query (stream)
Query (browser)
Explain
Help
Maximum number of rows to return to the query form: 10
Demo queries: click a button and the query will show in the query window.
Holding the mouse over the button will give a short explanation of the goal of the query. These queries are described in some more det
Mainly Halos: H 1 H 2 H 3 H 4 H 5 HF 1 HF 2 HF 3
Mainly Galaxies: G 1 G 2 G 3 G 4 G 5 G 6 HG 1 HG 2 GF 2

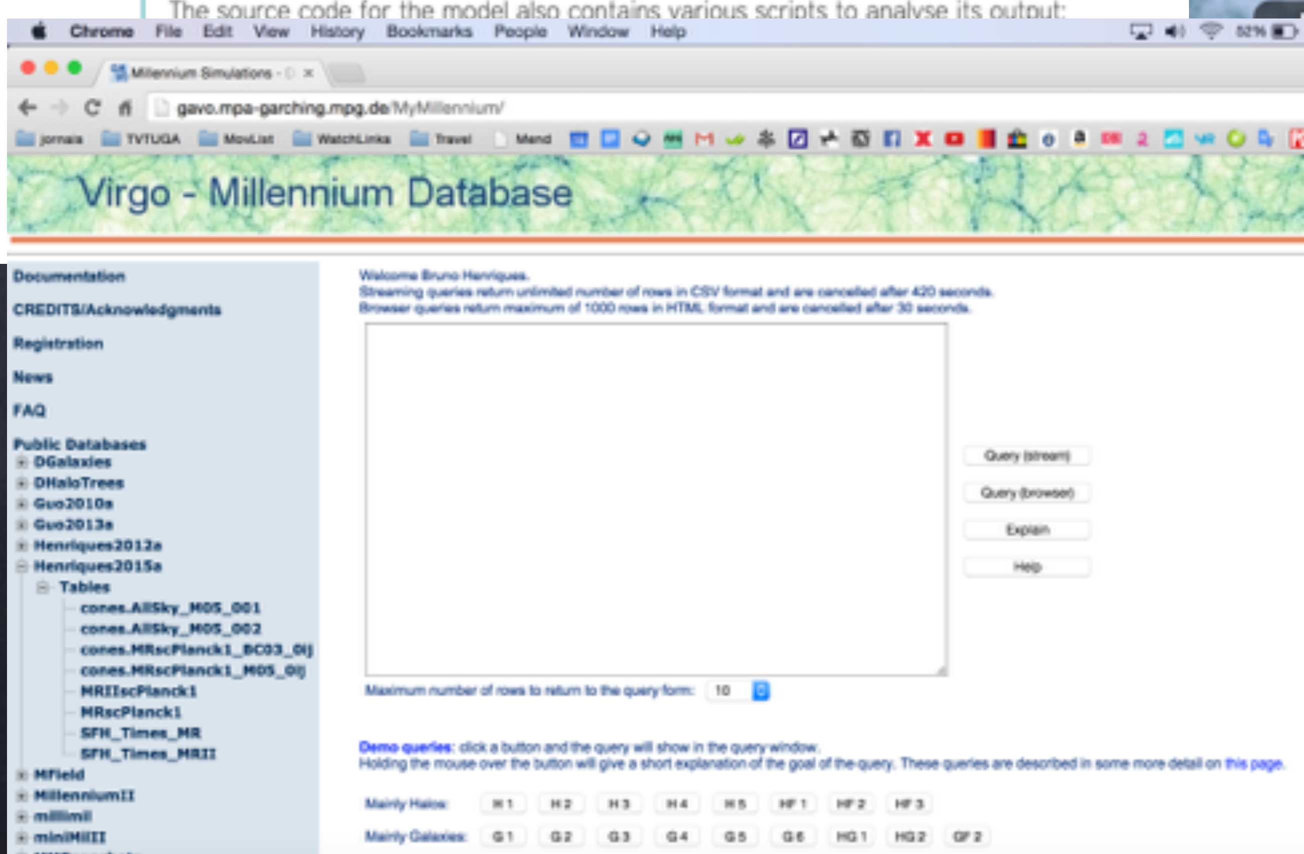

Observations used in MCMC
SMF, z=0
SMF, z=1
SMF, z=2
SMF, z=3
This Work – Planck1
Henriques2013a – WMAP7
Guo2013a – WMAP7
$\log_{10}(\Phi\ [h^3\mathrm{Mpc}^{-3}\log_{10}M^{-1}])$
$\log_{10}(M_*[h^{-2}M_\odot])$


z=0.5
z=1.0
z=2.0
z=3.0
g−r
$\log_{10}(M/M_\odot)$


Elbaz et al. (2007)
SDSS/DR7
Karim (2011) – 0.2<z<0.4
Karim (2011) – 0.4<z<0.6
Karim (2011) – 0.8<z<1.0
Karim (2011) – 1.0<z<1.2
Whitaker (2014) – 0.5<z<1.0
Whitaker (2014) – 1.0<z<1.5
Elbaz et al. (2007)
Karim (2011) – 1.6<z<2.0
Karim (2011) – 2.0<z<2.5
Whitaker (2014) – 1.5<z<2.0
Whitaker (2014) – 2.0<z<2.5
Daddi et al. (2007)
Karim (2011) – 2.5<z<3.0
z=0.10
z=0.40
z=1.00
z=2.00
z=3.00
$\log_{10}(\mathrm{SFR}[h^{-2}M_\odot\ \mathrm{yr}^{-1}])$
$\log_{10}(M_*[h^{-2}M_\odot])$



galformod.mpa-garching.mpg.de/public/LGalaxies/running_the_model.php
Max-Planck-Institut für Astrophysik
L-Galaxies, Munich Galaxy Formation Model
Running the Model
workshop
database
general public
contact
Home
Running the Model
Model Description
Figures & Data
Projects & People
1. Files needed to run the L-Galaxies galaxy formation model
Download the source code for the model from the L-Galaxies GitHub Repository (Download ZIP button):
LGalaxies_Repository
Download the dark matter merger trees into ./MergerTrees/ contained in the source code folder:
Millennium merger trees (10/512 of the volume): MR_MergerTrees.tar
Representative sample of trees for MCMC mode: MCMC_MergerTrees.tar
Untar both files: "tar -xvf MR_MergerTrees.tar", "tar -xvf MCMC_MergerTrees.tar". Two folders, MR and MCMC, should be created.
Download the Stellar Population Synthesis tables, needed for photometry, into the root of
source code:
SpecPhotTables.tar
Untar the file: "tar -xvf SpecPhotTables.tar". A folder, SpecPhotTables, should be created.



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Virgo - Millennium Database
Documentation
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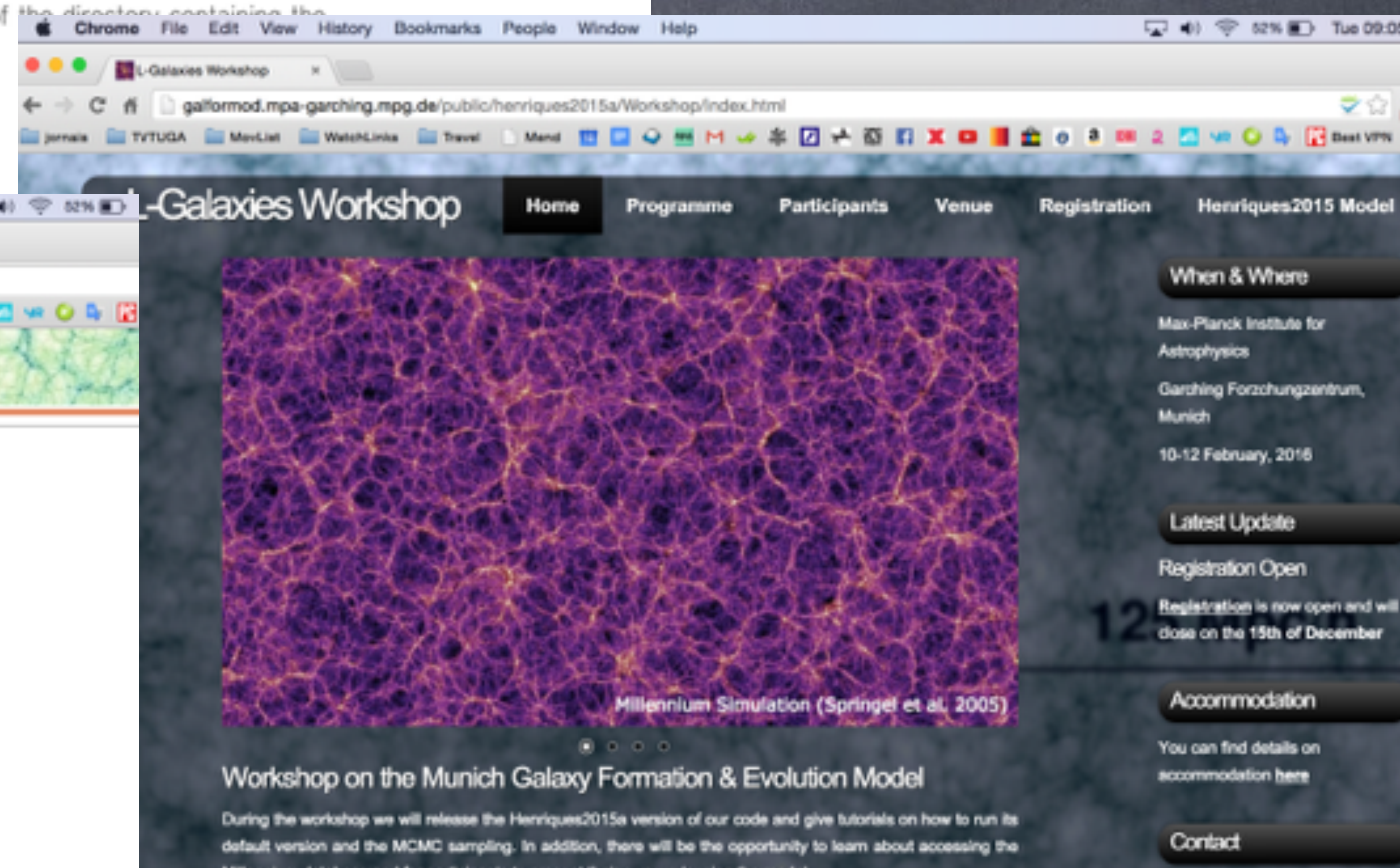
Public Databases
DGalaxies
DHaloTrees
Guo2010a
Guo2013a
Henriques2012a
Henriques2015a
Tables
MField
MillenniumII
millimil
miniMillI
MMSnapshots
Query (stream)
Query (browser)
Explain
Help



galformod.mpa-garching.mpg.de/public/henriques2015a/Workshop/index.html
L-Galaxies Workshop
Home
Programme
Participants
Venue
Registration
Henriques2015 Model
When & Where
Max-Planck Institute for Astrophysics
Garching Forschungzentrum, Munich
10-12 February, 2016
Latest Update
Registration Open
Accommodation
Contact
Millennium Simulation (Springel et al. 2005)
Workshop on the Munich Galaxy Formation & Evolution Model