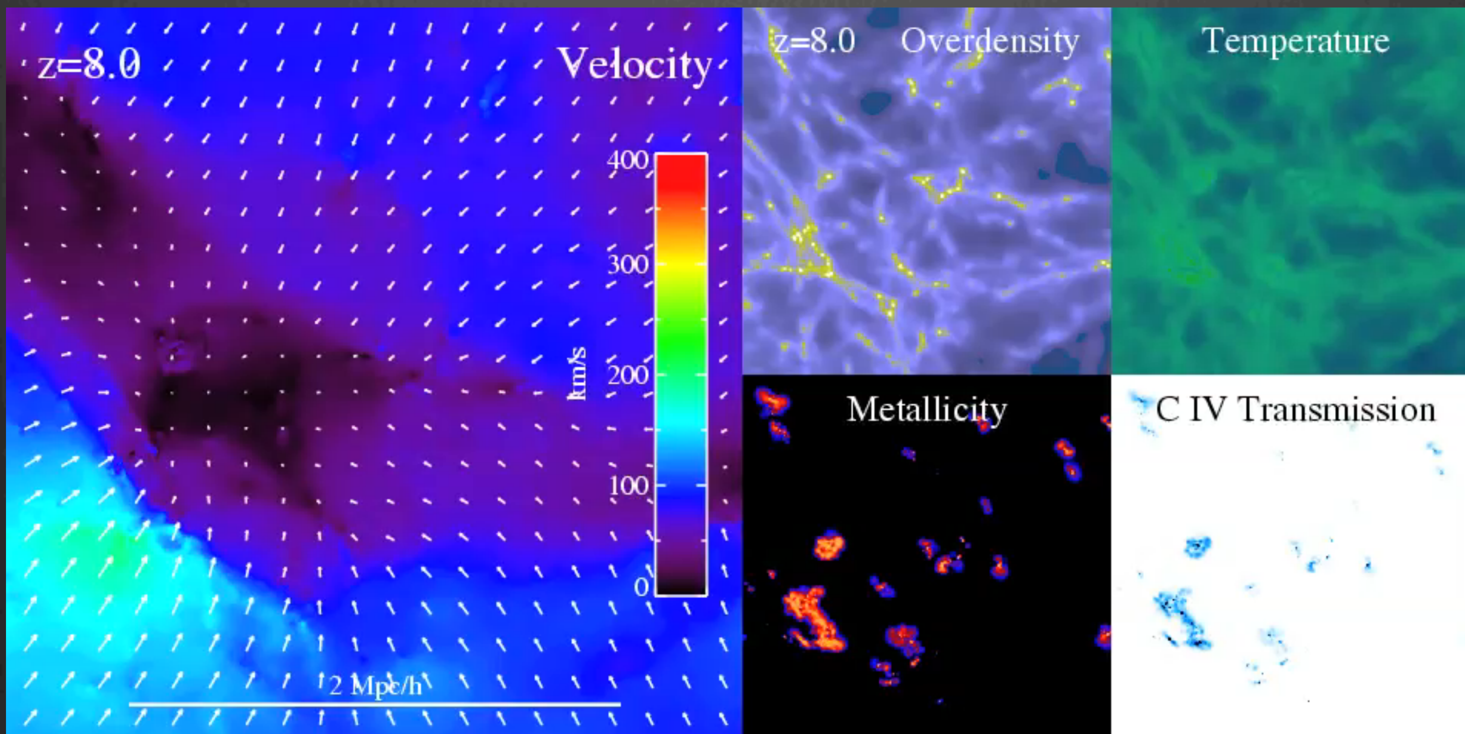
Constraining Inflows and Outflows From Galaxy Growth Across Cosmic Time



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with Sourav Mitra & Kristian Finlator

and R Somerville, B Oppenheimer, R Thompson

UNIVERSITY of the WESTERN CAPE

RESPICE PROSPICE

Includes:
Gravity
Gas (moving mesh)
Star formation
Photoionizing bkgd
Black hole growth
10-species chemistry
Type II SNe feedback
Type Ia SNe feedback
AGB stellar evol
AGN feedback

~6 billion cells
1 kpc resolution
100 Mpc volume

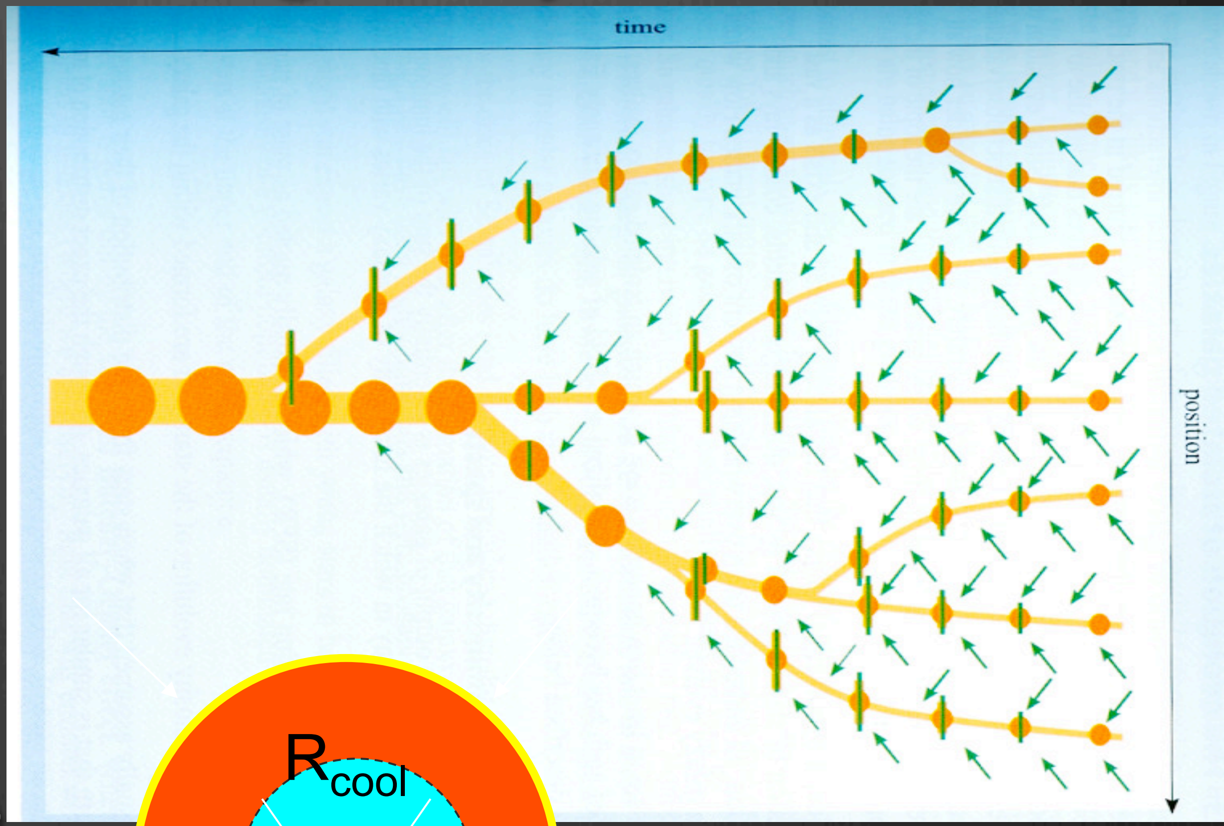
The Illustris Project: AREPO

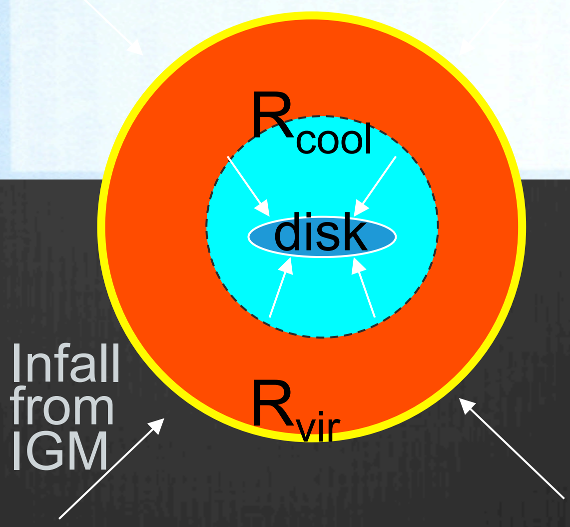
SAM cartoon of galaxy formation

Take N-body merger tree, add parameterized baryonic physics:

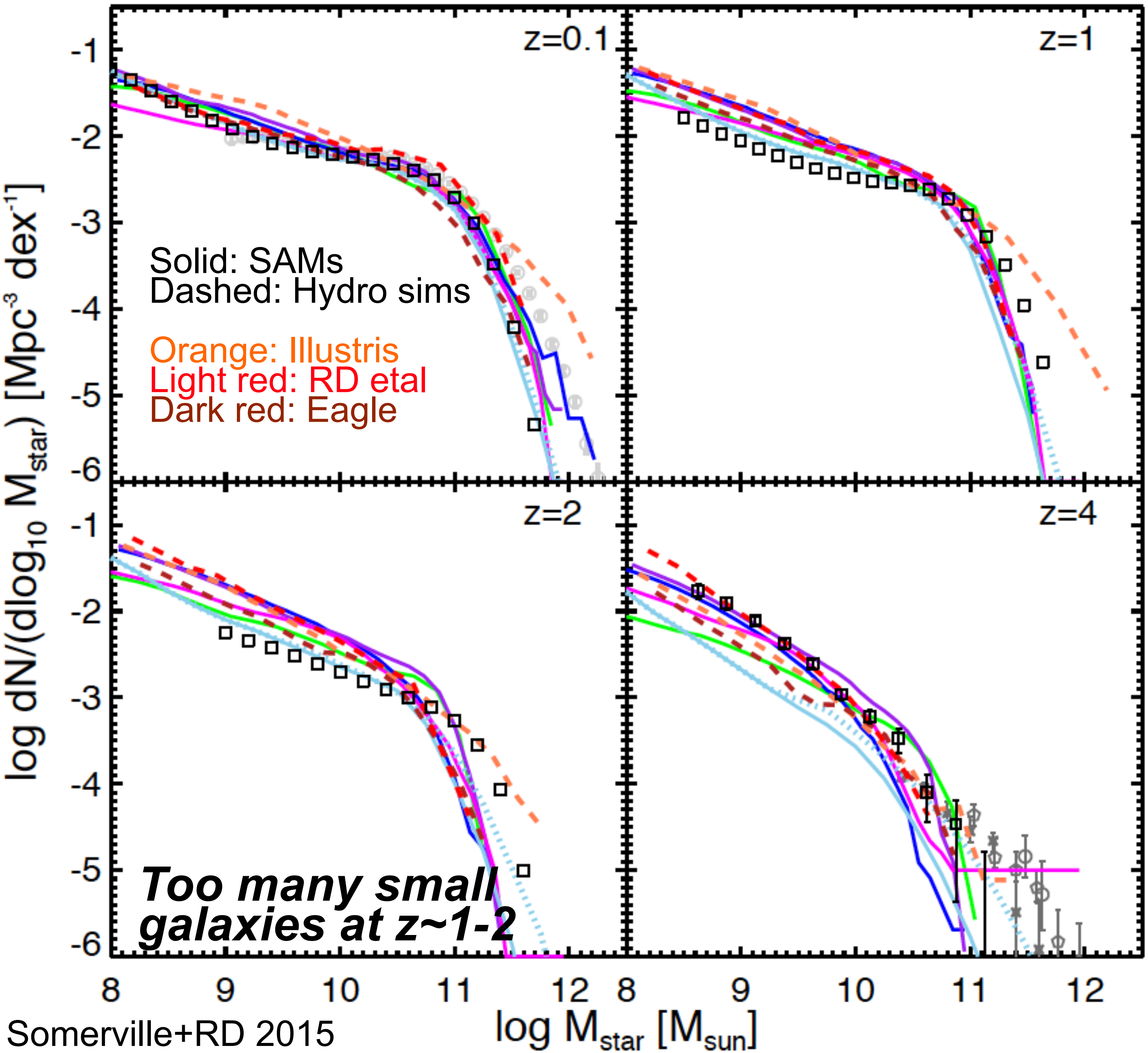
SFR, cooling, feedback, galaxy merging, …

Typically ~40-50 parameters, tuned to match z=0 data.



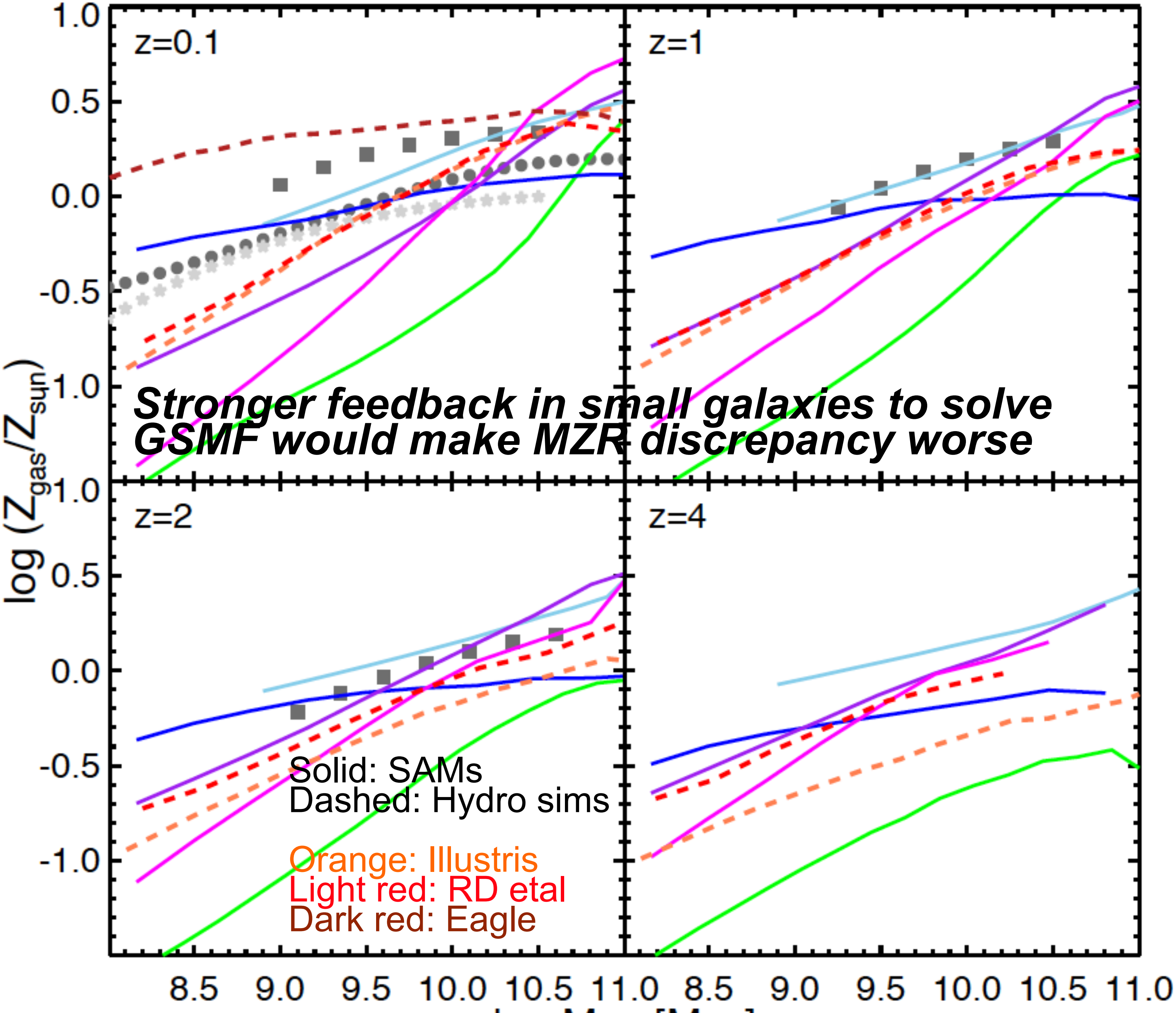


Galaxy Stellar Mass Function



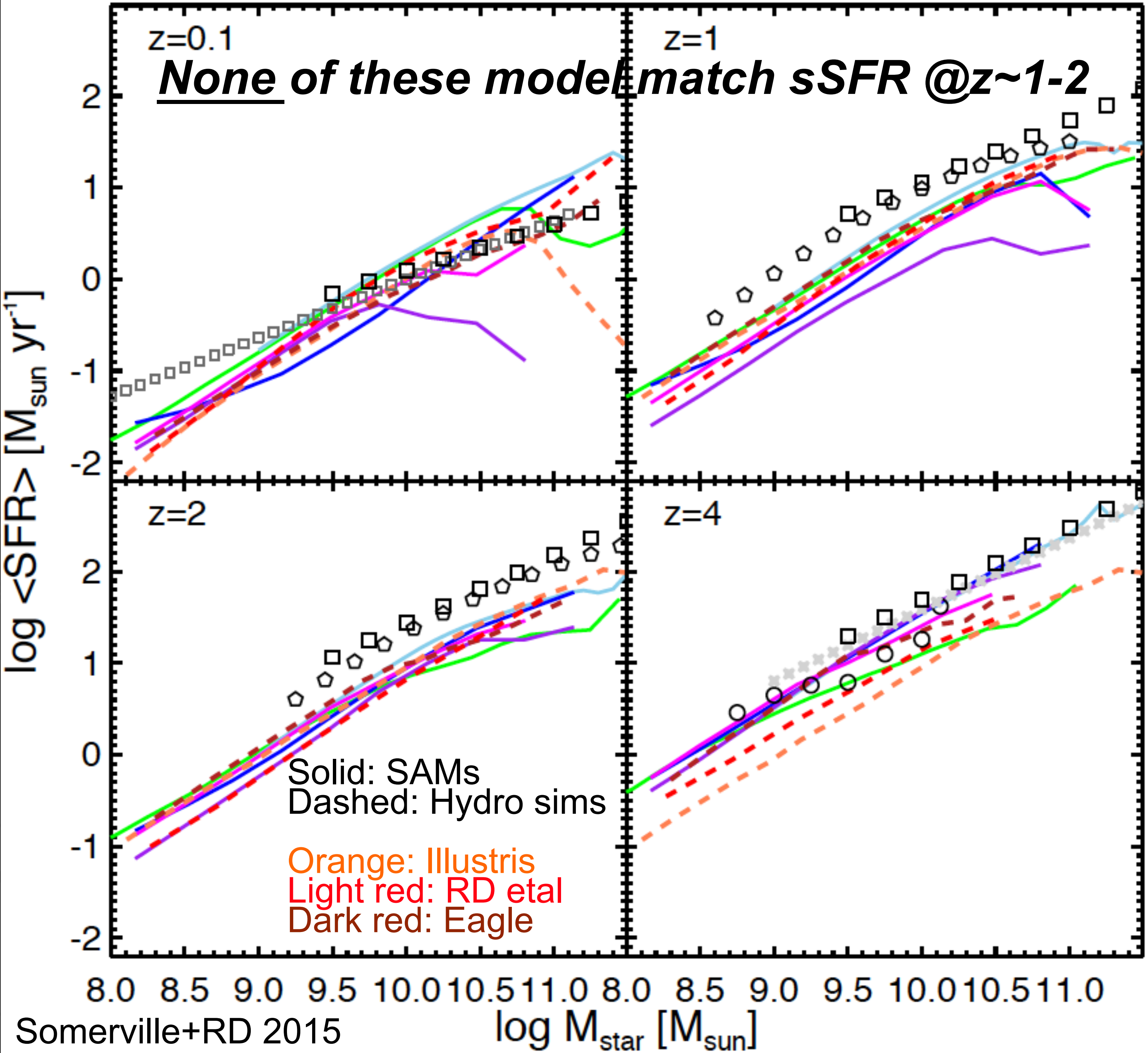
Somerville+RD 2015

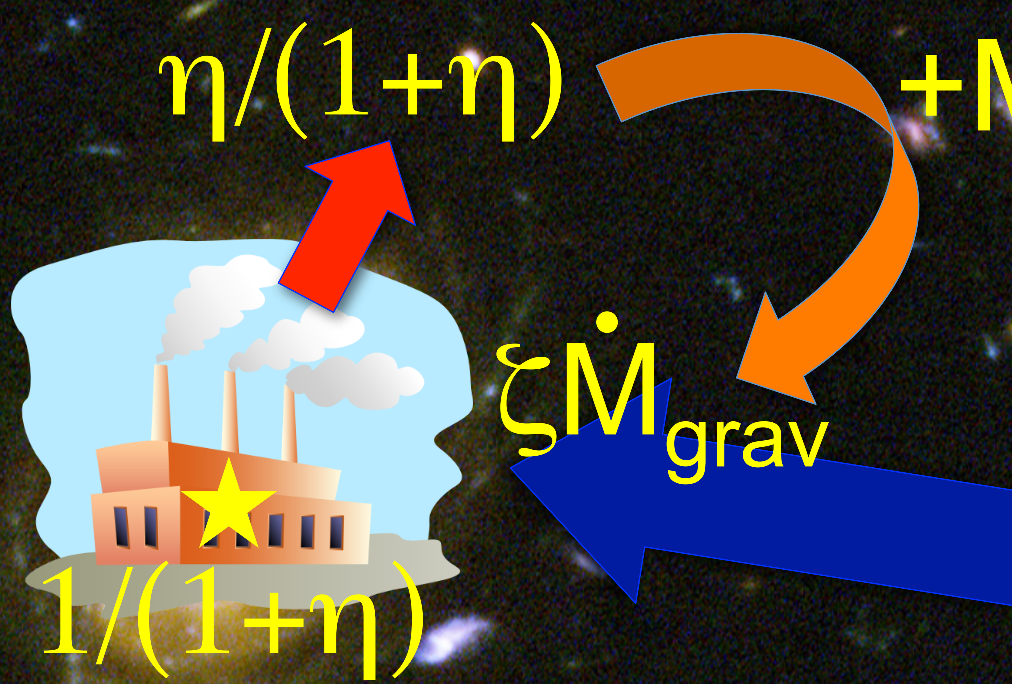
Mass-Metallicity Relation

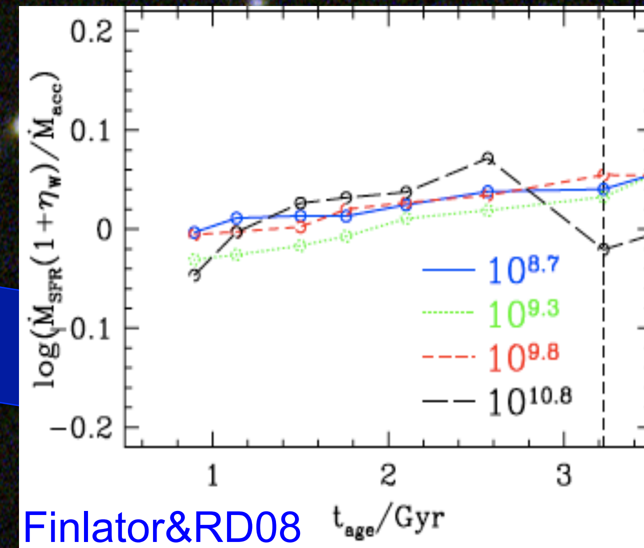


Somerville+RD 2015

Galaxy “Main Sequence”







(from IGM)

Equilibrium Model:

Inflow = SFR + Outflow + ~~dReservoir/dt~~

$$SFR = (\zeta\dot{M}_{grav}+\dot{M}_{recyc})/(1+\eta)$$

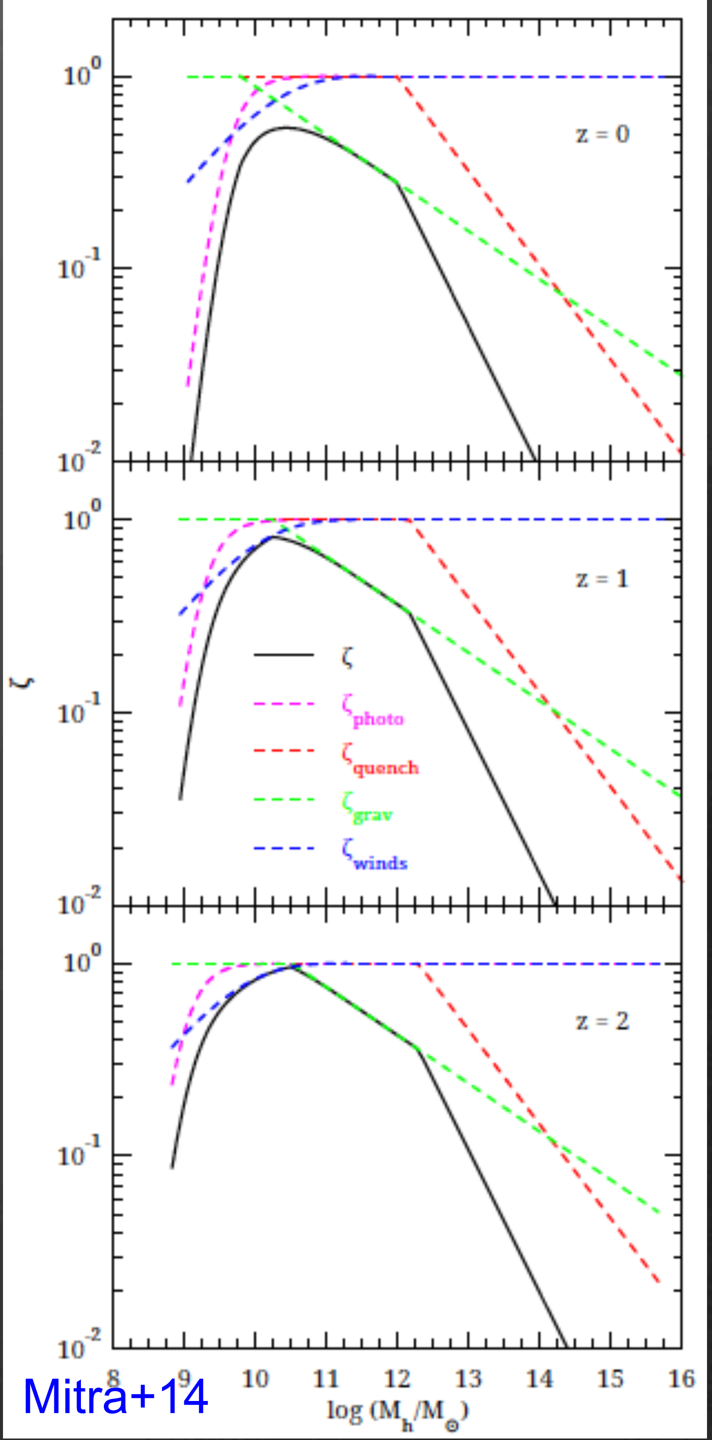
$$Z = y\ SFR/\zeta\dot{M}_{grav}$$

Finlator+08
Bouché+10
Davé+11,12
Lilly+13
Dekel+14

Baryon cycling parameters

- *Ejective feedback*
  η = Outflow/SFR
- *Preventive feedback*
  ζ (J_{UV}, AGN, …)
- *Wind recycling time*
  t_{rec} = time for outflow to return.

Each depends on M_{halo}, z, …?



Parameterize, Bayesian MCMC

- Turns out we need 8 parameters (Bayesian evidence analysis shows that removing any more is not preferred):

Mitra+14

$$\eta = \left(\frac{M_h}{10^{\eta_1+\eta_2\sqrt{z}}}\right)^{\eta_3}$$

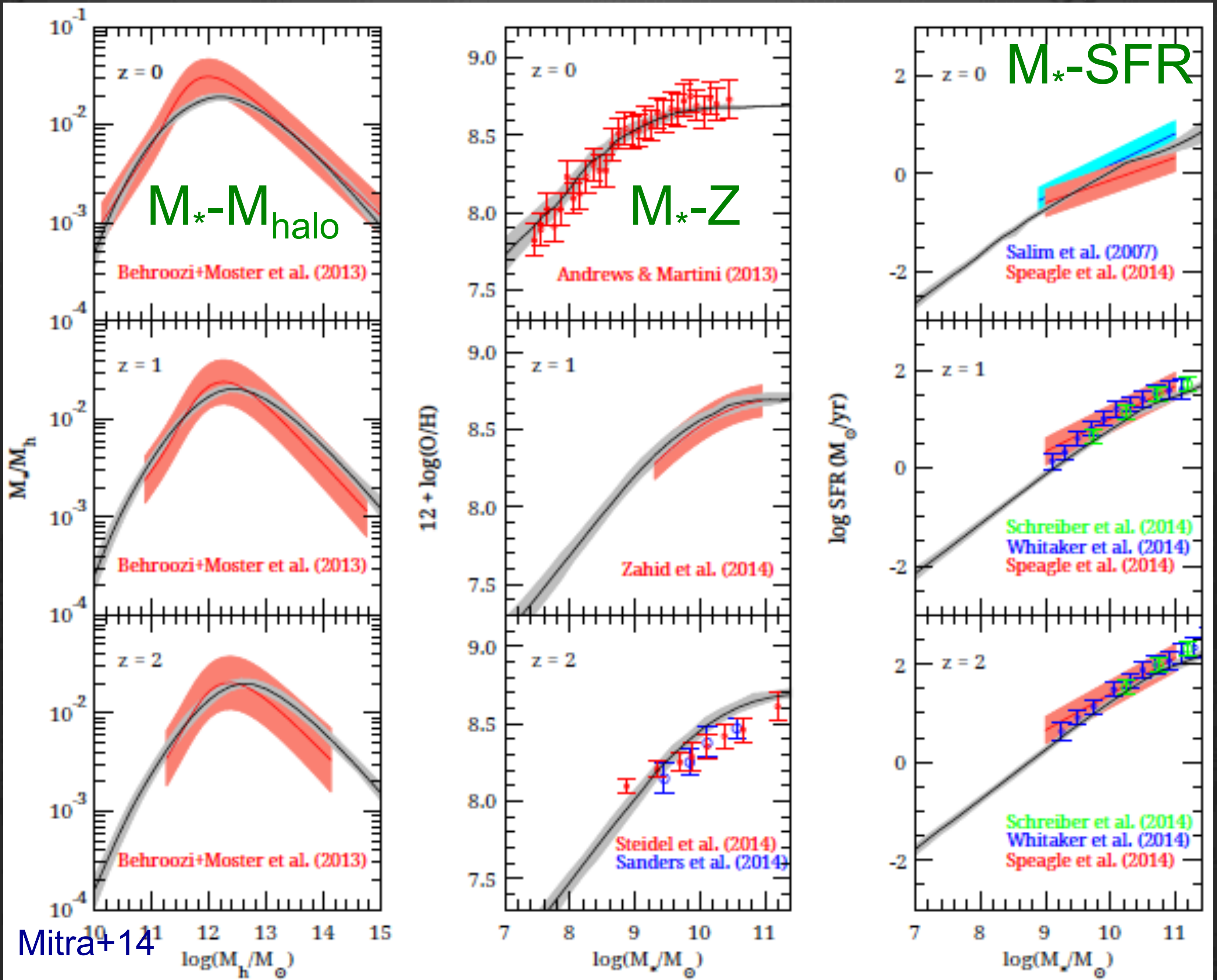
$$\zeta_{\rm quench} = {\rm MIN}\left[1, \left(\frac{M_h}{M_q}\right)^{\zeta_1}\right], \frac{M_q}{10^{12}M_\odot} = (0.96+\zeta_2 z).$$

$$t_{\rm rec} = \tau_1 \times 10^9 {\rm yr} \times (1+z)^{\tau_2}\left(\frac{M_h}{10^{12}}\right)^{\tau_3}$$

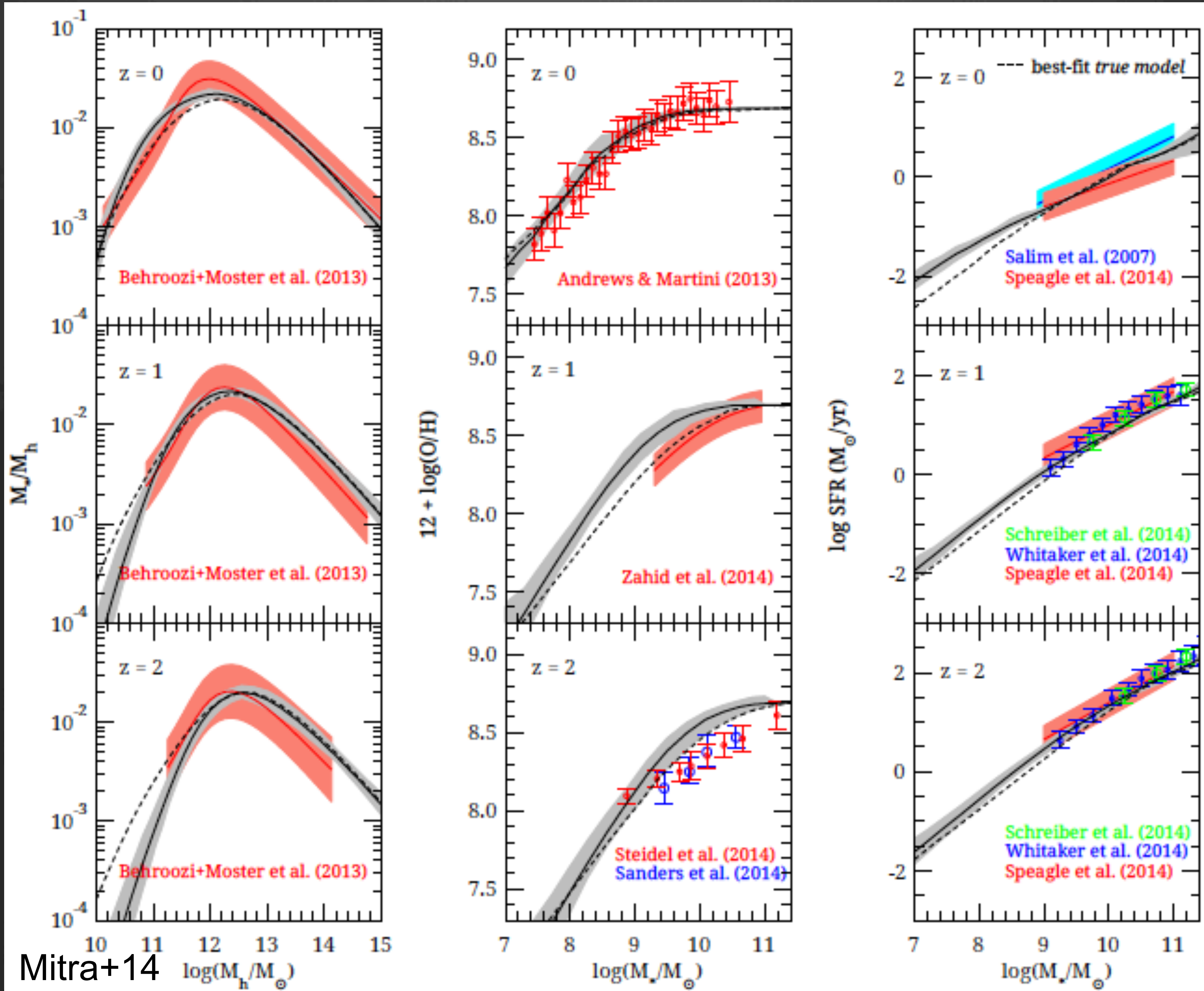
Observational Constraints

- M_*-M_{halo} (equivalent to GSMF, z=0-2): Inferred from GSMF(z~0-6) data, consistent w/SFR evol. [Behroozi+13, Moster+13].
- Mass-Metallicity relation: Now seen out to z~2 thanks to Keck/Mosfire. [Steidel+14,Sanders+14]
- SFR-M_* (z=0-2): Recent compilation with consistent calibrations from Speagle+14. [also Whitaker+14,Schreiber+14].

Equilibrium Model: MCMC constraints (χ^2~1.6)



Fit only to M_*-M_h, SFR-M_*, predict M_*-Z (χ^2~2.0)



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Parameter constraints

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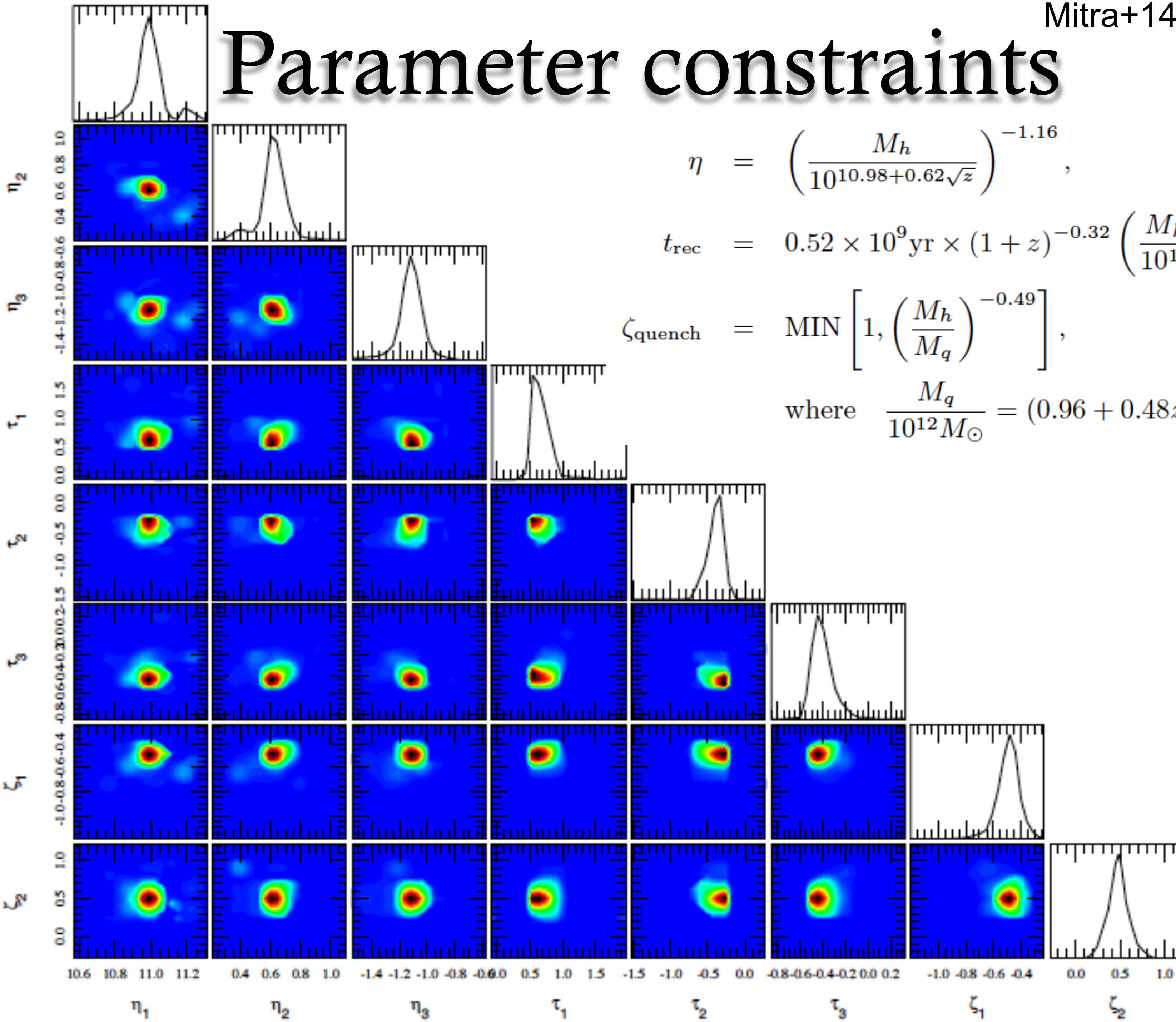


$$\eta = \left(\frac{M_h}{10^{10.98+0.62\sqrt{z}}}\right)^{-1.16},$$

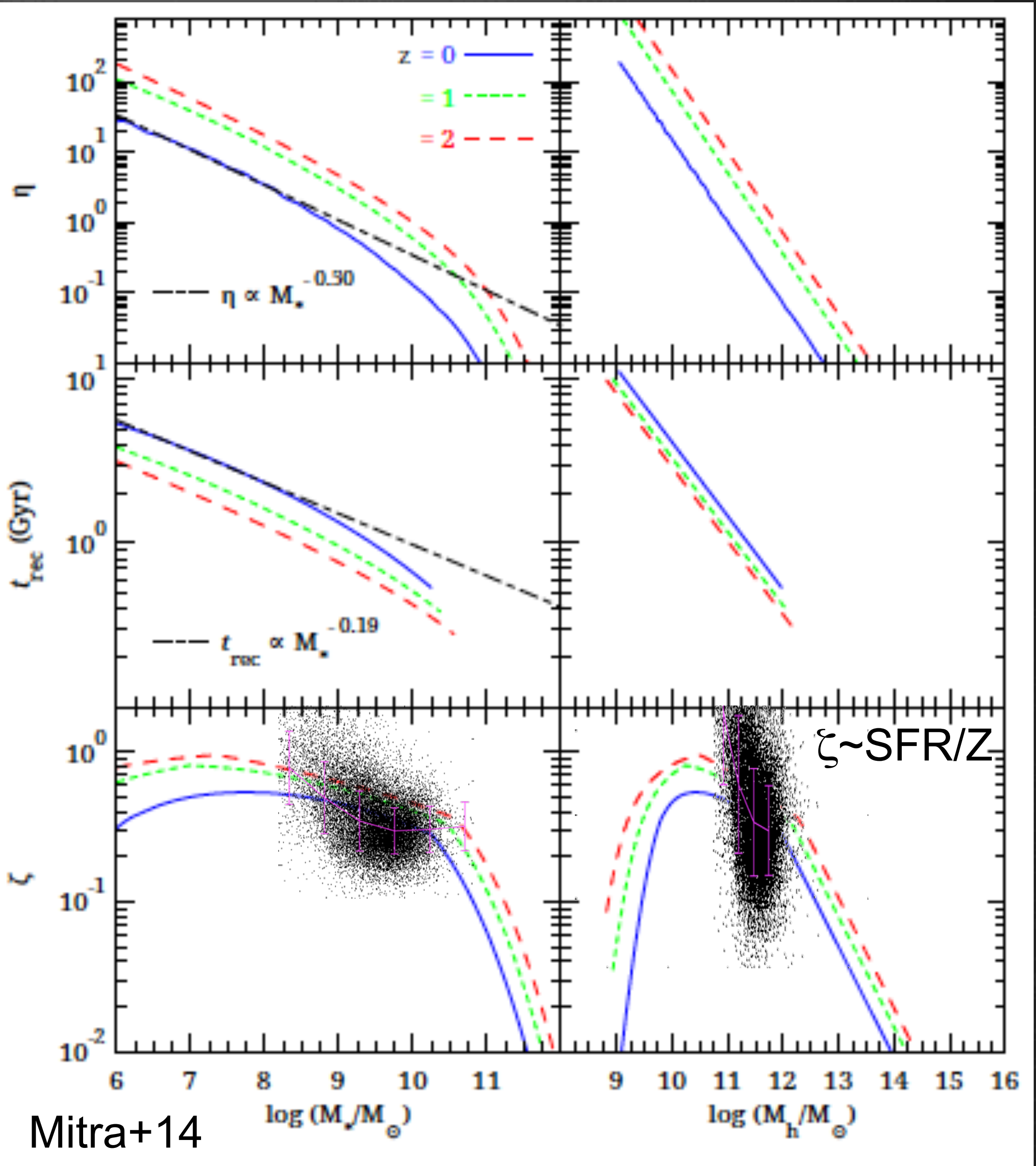
$$t_{\rm rec} = 0.52 \times 10^9 {\rm yr} \times (1+z)^{-0.32} \left(\frac{M_h}{10^{12}}\right)^{-0.45}$$

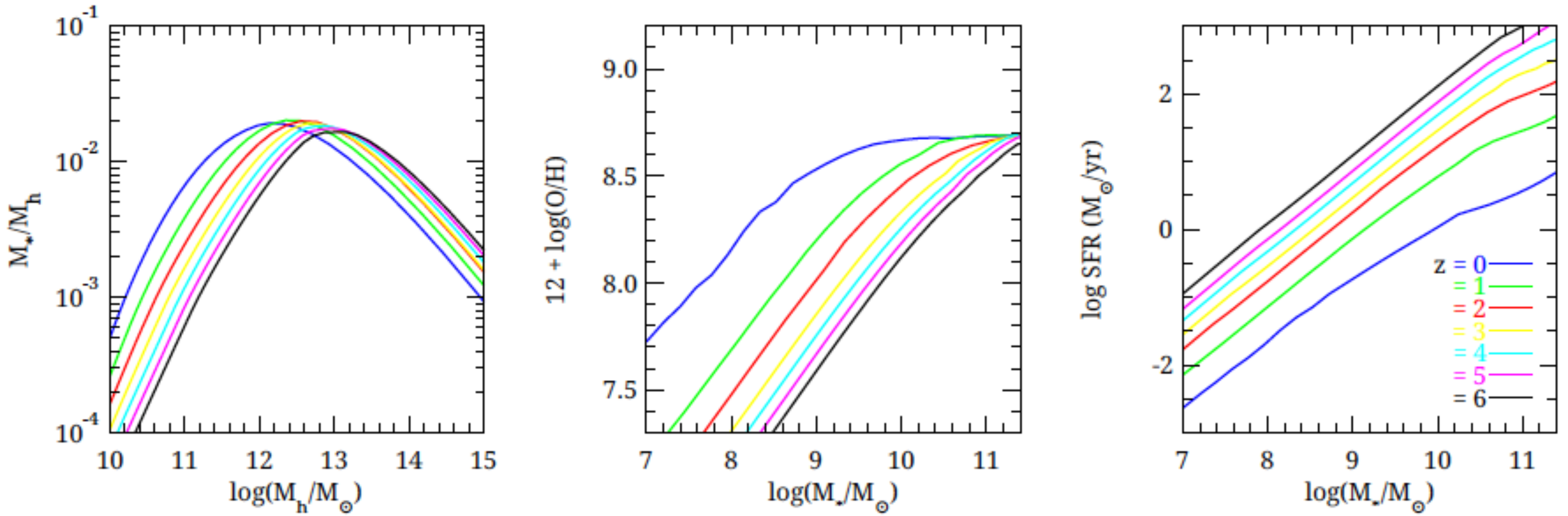
$$\zeta_{\rm quench} = {\rm MIN}\left[1, \left(\frac{M_h}{M_q}\right)^{-0.49}\right],$$

$$\text{where} \quad \frac{M_q}{10^{12} M_\odot} = (0.96 + 0.48z).$$

Outflows stronger in low-mass galaxies

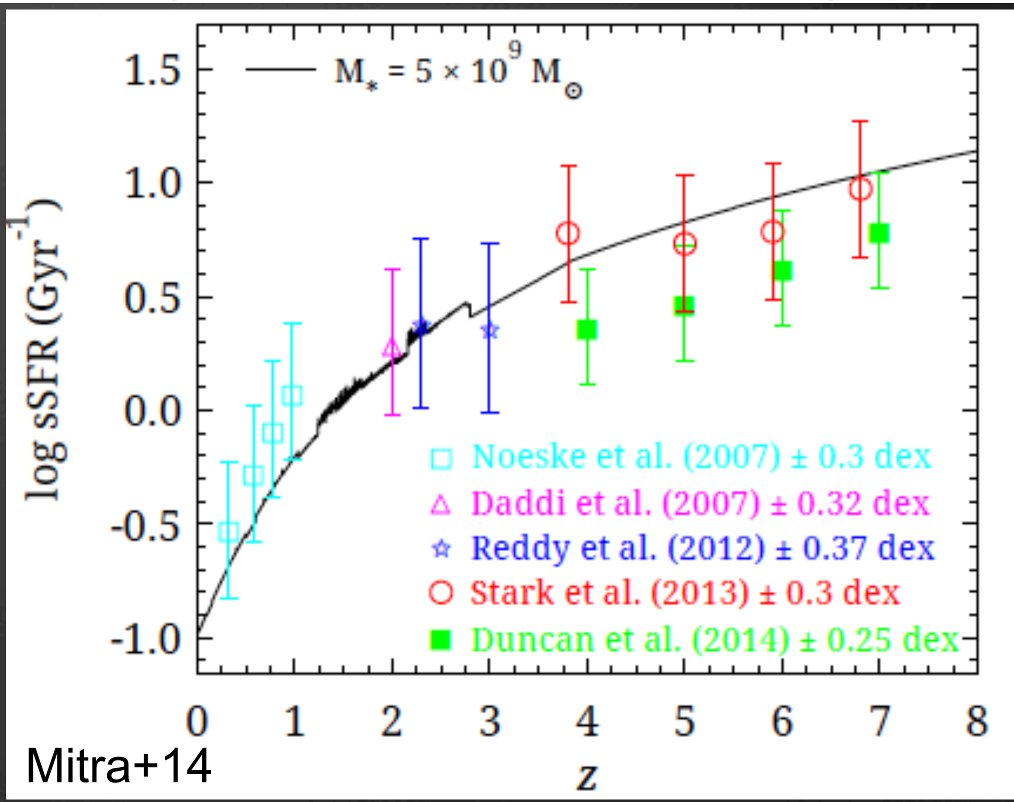
- $\eta \sim M_h^{-1.2} \sim M_*^{-0.3}$
- Stronger at hi-z
- FIRE (Muratov+15): $\eta \sim M_*^{-0.35}$, amplitude like at z~2
- $t_{rec} \sim M_h^{-0.45} \sim M_*^{-0.2}$
- Opp,RD+08, 10 best-fit hydro sims: $t_{rec} \sim M_h^{-0.5}$





Evolution of scaling relations

Can now fit sSFR(z) at z~2!



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Intuition from the Equilibrium Model

- Stellar and metal growth limited by ~~cooling rate and conversion of gas into stars~~

  ejective and preventive feedback
- Metal & gas content reflects ~~"evolutionary state"~~

  gas supply vs. consumption rate
- Mergers ~~drive galaxy evolution~~

  are subdominant to cold streams for fueling
- Galaxies & IGM ~~evolve independently~~

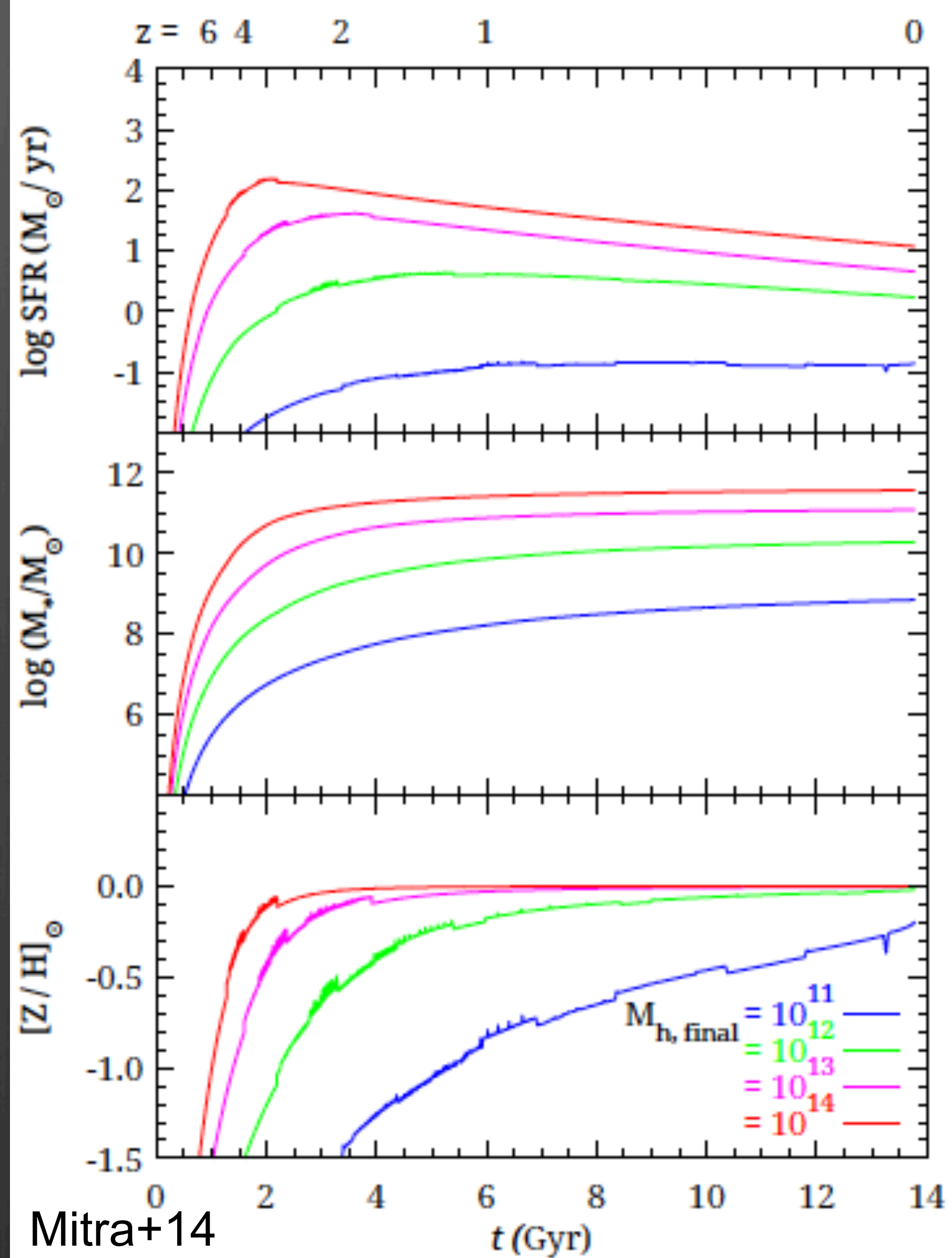
  are connected by baryon cycling

Summary

- Despite advances, modern SAMs and simulations still have difficulty matching z~0-2 data.
- The equilibrium model provides a new, simple, and robust approach to phenomenological galaxy formation, based on the simulation-motivated framework of baryon cycling.
- This model is able to fit key data across cosmic time with reasonable baryon cycling parameters, in which
  - small galaxies eject a larger fraction of accreted gas
  - recycling is more rapid in high-mass galaxies
  - quenching at a mass that evolves modestly upwards with z

What is it good for?

- Get SFR and Z histories for given M*,z.
- Serve as input into cosmological sims that include feedback.
- Make predictions for evolution to higher z.
- Populate N-body with "average" galaxies.
- New framework for understanding galaxy formation



Mitra+14

Modeling a concordant galaxy population: Status

- Simulations, despite many advances, still can't match basic demographics of (M*, Z, SFR, HI) at z=0 let alone at high-z. Improvements still be "trial and error". *How much farther can we take this?*
- SAMs now employ MCMC etc, but even using 20+ parameters can't match all properties. *Is the basic framework flawed?*

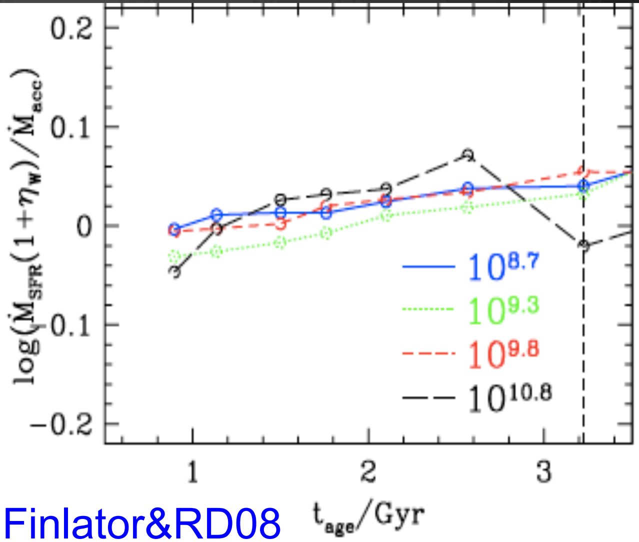
Need a simple, robust parameterization that we can easily match to data and that captures insights from simulation.

Equilibrium Relations

Inflow = SFR + Outflow + ~~dReservoir/dt~~

RD+12

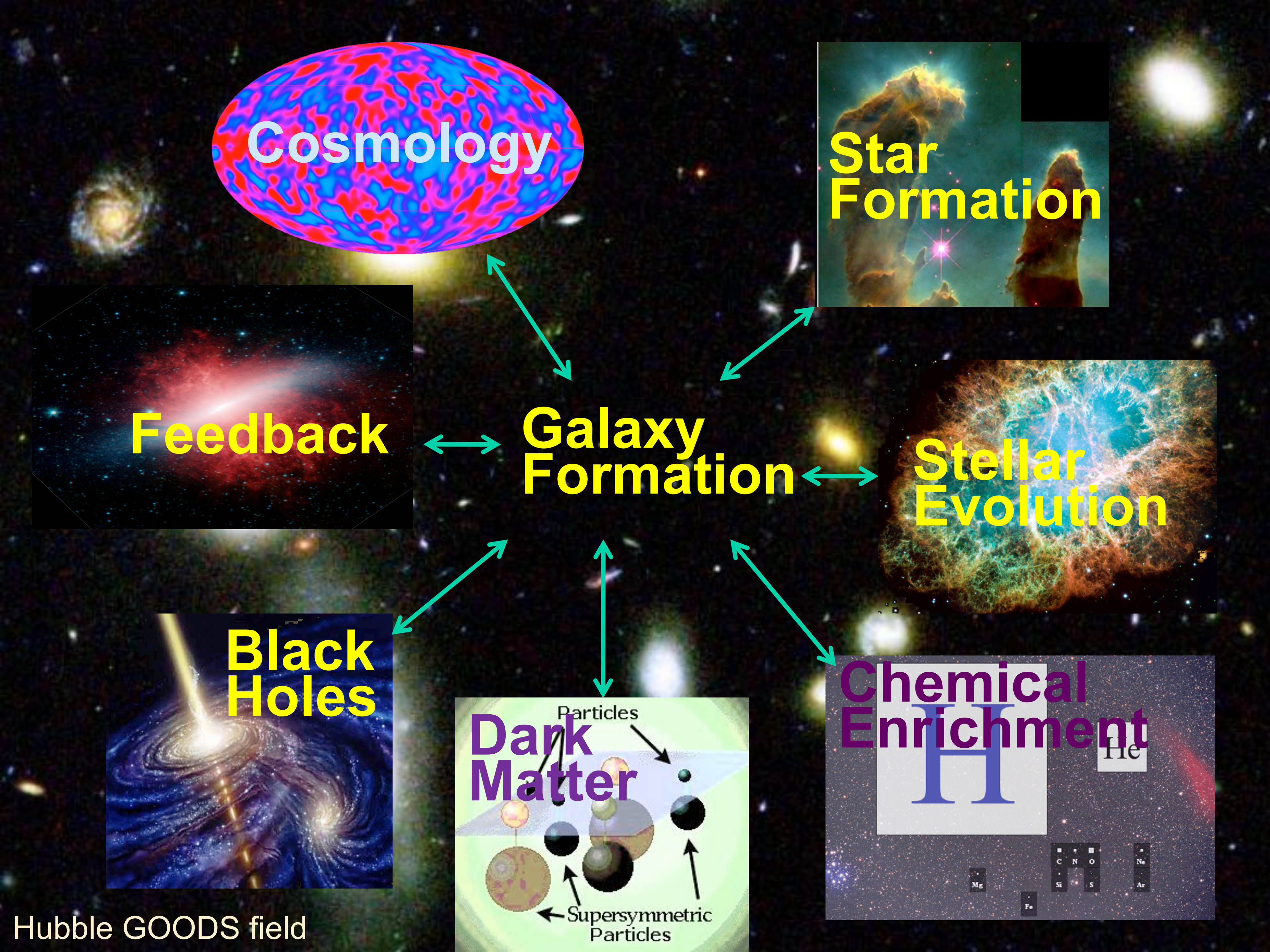
- $SFR = (\zeta\, \dot{M}_{grav} + \dot{M}_{recyc})/(1+\eta)$
- $Z = y\ SFR\ /\ \zeta\, \dot{M}_{grav}$
- $f_{gas} = (1 + (t_{dep}\ sSFR)^{-1})^{-1}$

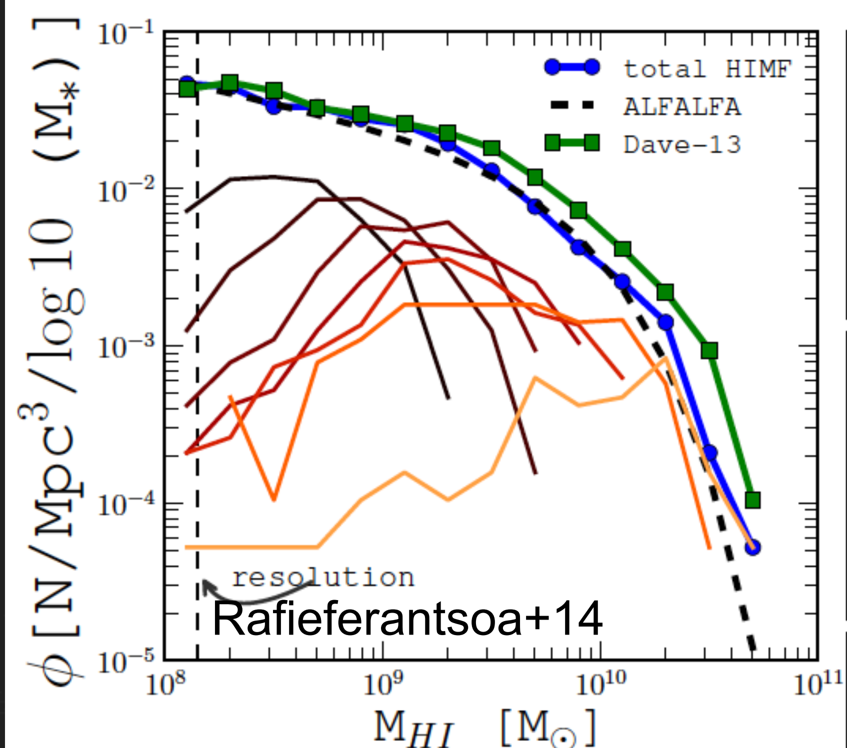


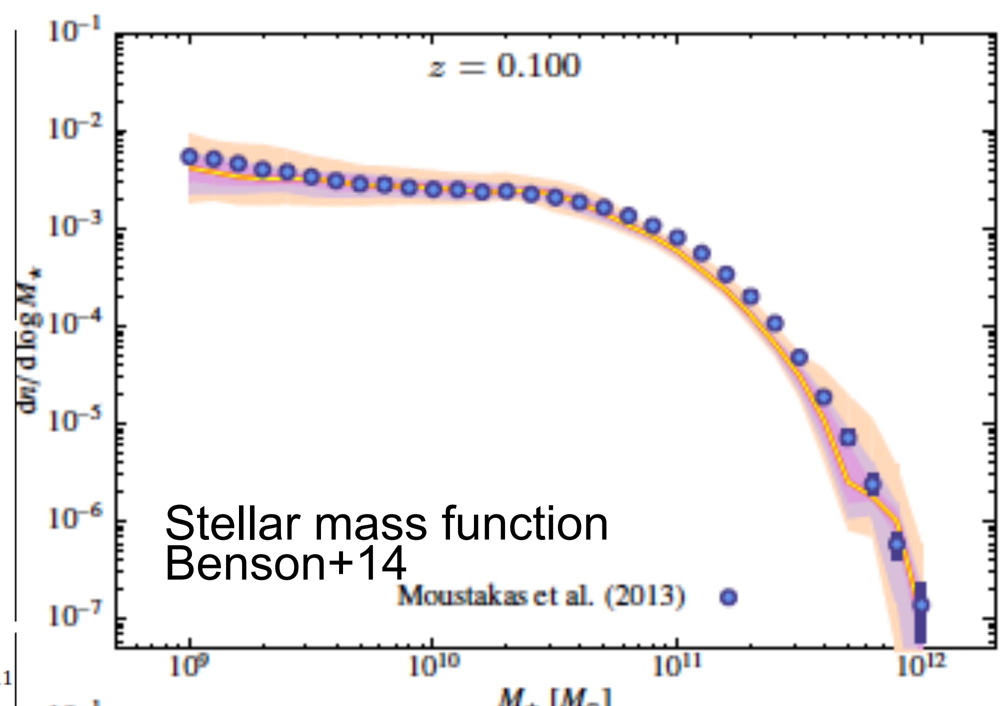
Finlator&RD08

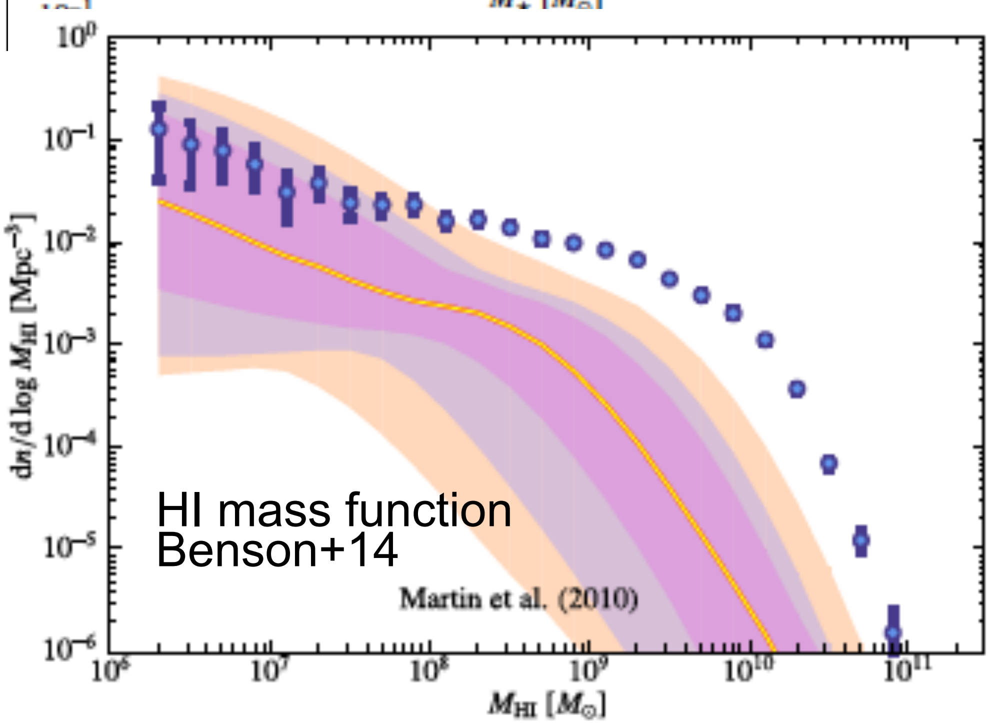
where e.g.

$\dot{M}_{grav} \sim f_b\ M_{halo}^{\ 1.1}\ (1+z)^{2.25}$ [Dekel+09]


Cosmology
Star Formation
Feedback
Galaxy Formation
Stellar Evolution
Black Holes
Dark Matter
Particles
Supersymmetric Particles
Chemical Enrichment
H
He
Hubble GOODS field

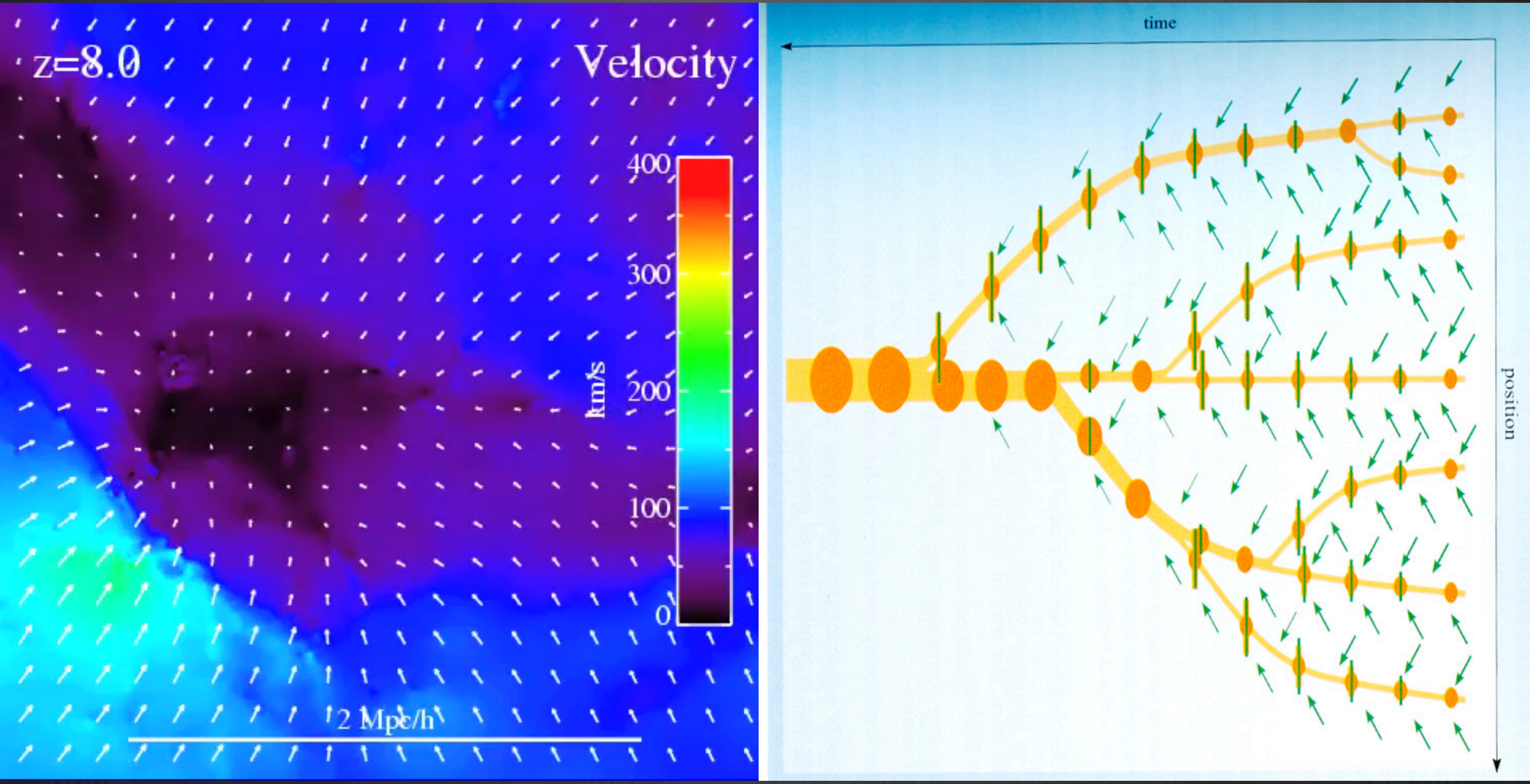






- Benson+14: “highly simplified” SAM, “only” 25 parameters. Full MCMC!
- Fits GSMF to z~1, but badly fails HIMF

Hydro Sims: "Baryon Cycling"



The cycle of inflows, outflows, and re-accretion governs the growth and evolution of galaxies.

What's left to be done?

- LOTS!
- Consider *scatter*: Fluctuations in gravitational inflow rate, plus(?) excursions via major mergers.
- Include *gas* (HI, H_2): Compare/constrain to data
- Model *satellites*: Affected by stripping processes.
- Examine *environment*: Formation time bias, …
- Compare with hydro simulations w/same parameters
- Implement into full N-body simulations.