Galaxy Formation and Feedback

Tiara Winter School 2012

Richard Bower

Bower, Benson, Crain 2011

Outline

From haloes to galaxies

Techniques

Sources of feedback

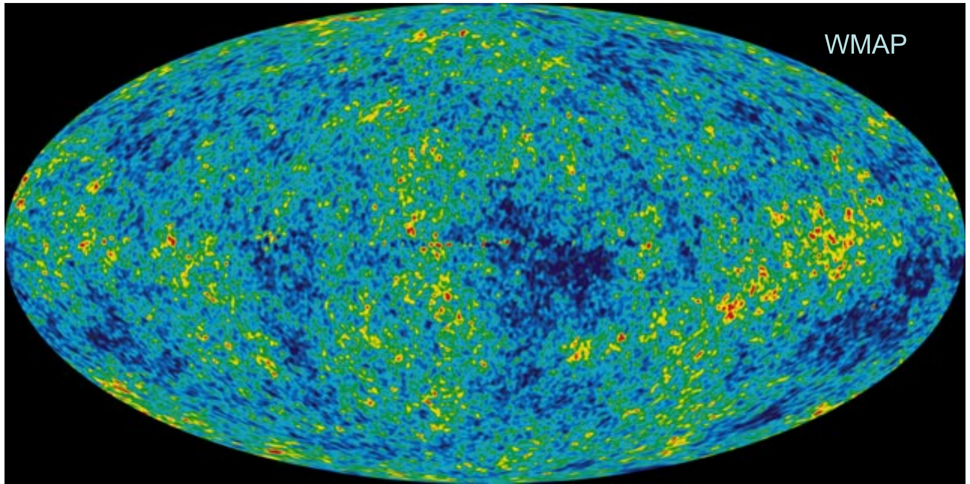
Exploring feedback

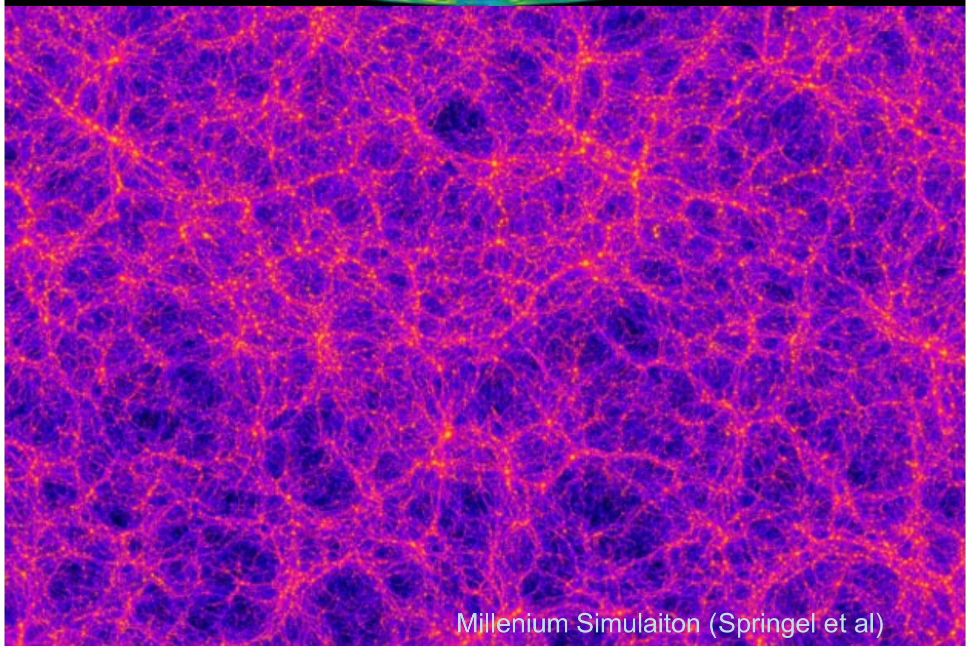
Part I

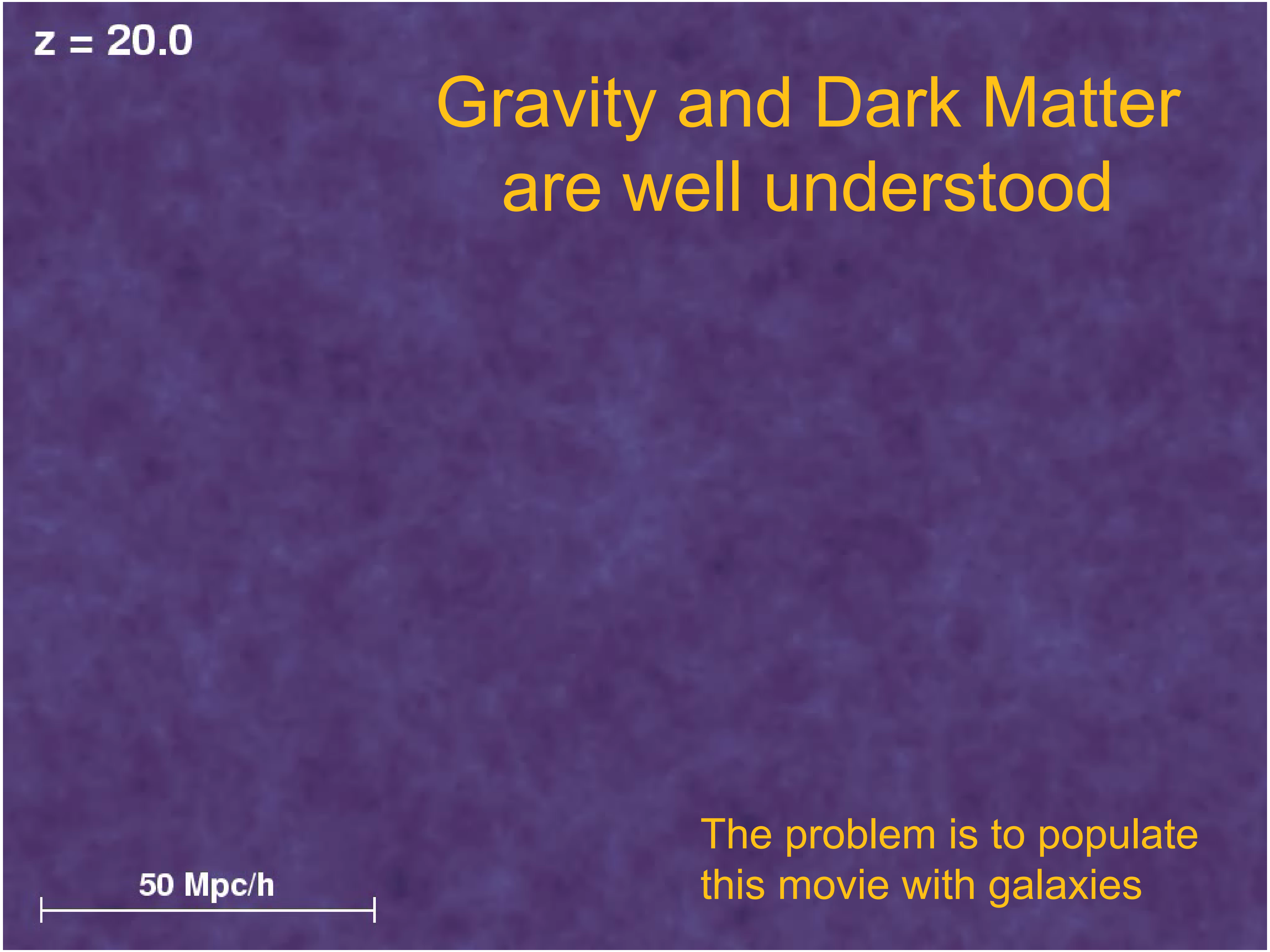
From the mass function of haloes
to that of galaxies

In the beginning…

- The big Bang+CDM model predicts that the universe is seeded with small density fluctuations.
- We can measure these in the CMB
- Gravitational Instability magnified the initial fluctuations to make non-linear structures:
  - The cosmic web
  - Dark matter haloes





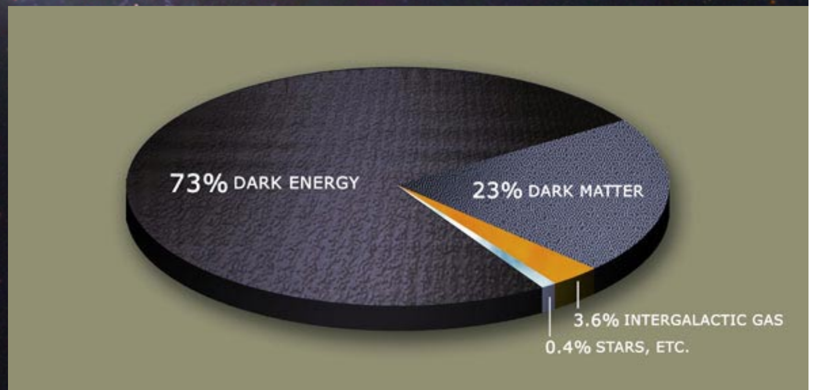


Gravity and Dark Matter are well understood

The problem is to populate this movie with galaxies

Filling the universe with light

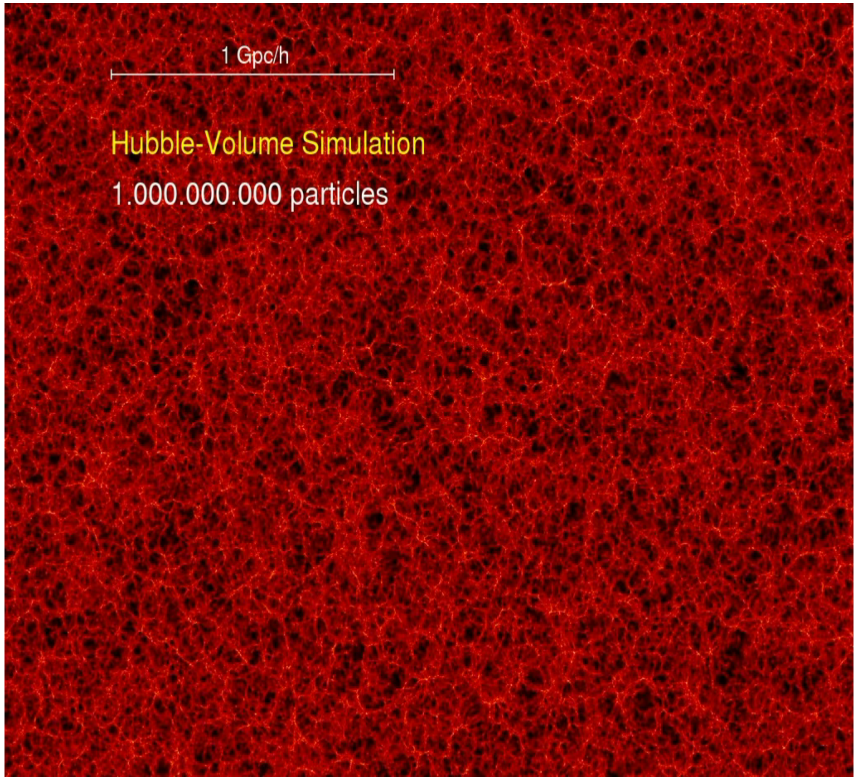
- But this is not directly observable…
- … we still need to populate this universe with galaxies!!!
- … and black holes
- … with some baryons left over to make the inter-galactic medium

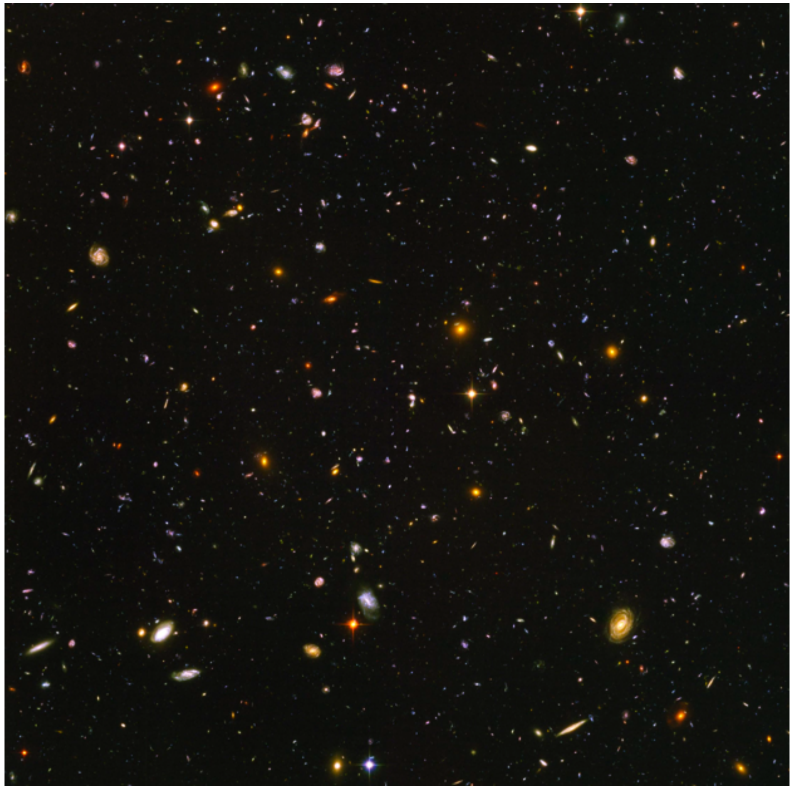


Most of the baryons are in the IGM!!!

We want to…

- Get from here (t=10^3 yr)
- ...to here (t=10^{10} yr)



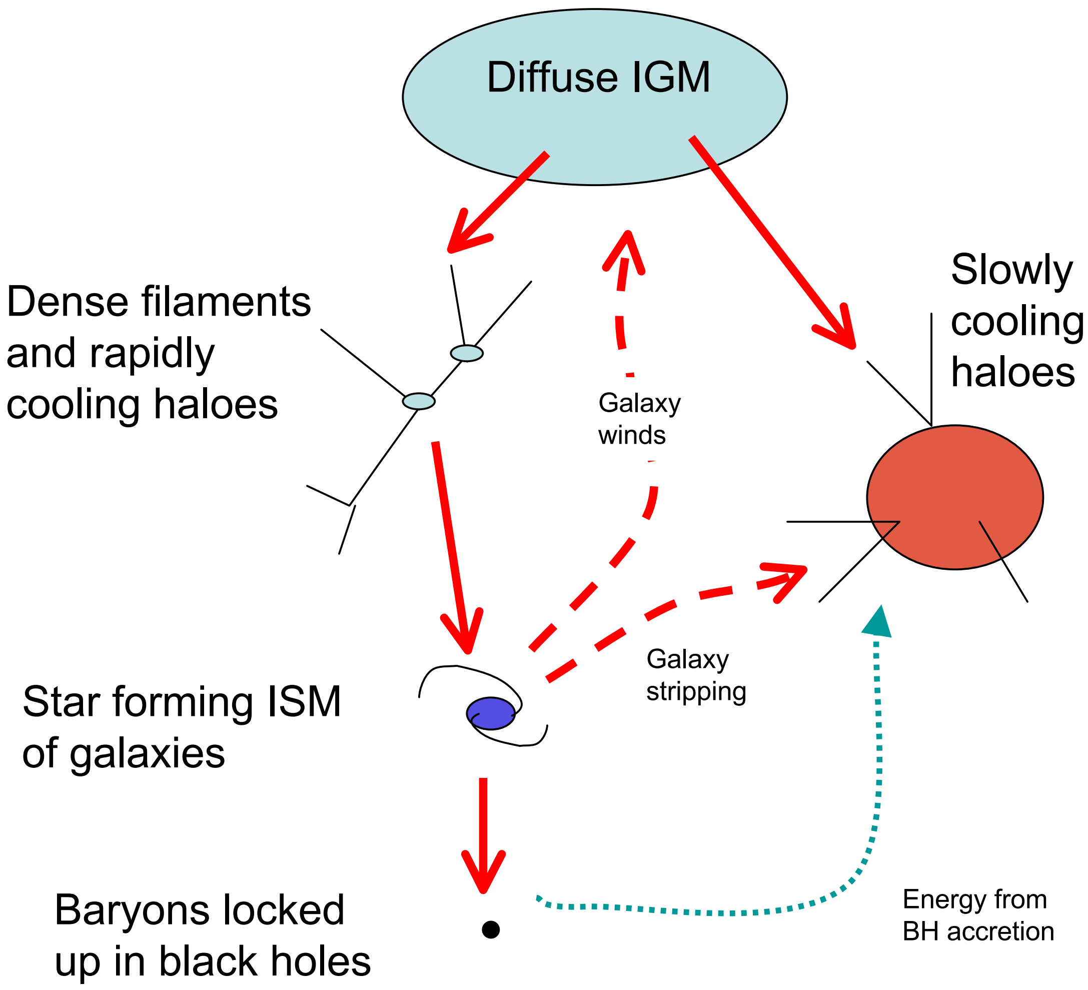


(and before…)

(and beyond…)

A recent history of Baryons

- Adiabatic expansion of universe
  - Too diffuse to cool
- Collapse into dense structures
  - Shock heating - raises entropy
  - Radiative cooling - lowers entropy
- Two regimes
  - Early low mass haloes, cooling dominates
  - Late, high mass haloes, heating dominates
    - followed by slow cooling
- The reality is much more complicated
  - Effect of metals; density gradients; anisotropy; feedback

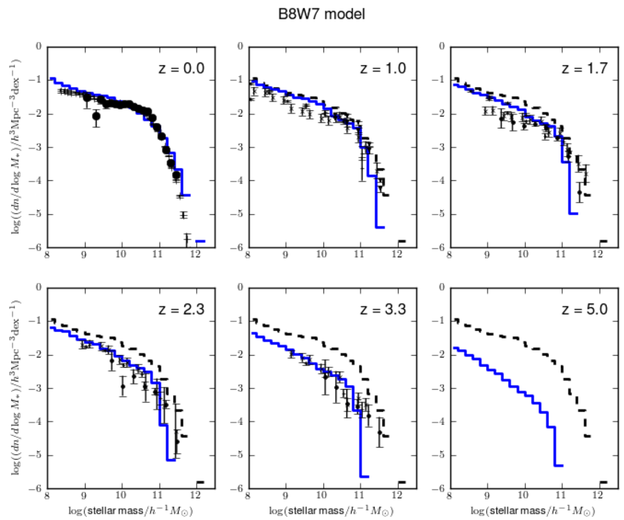


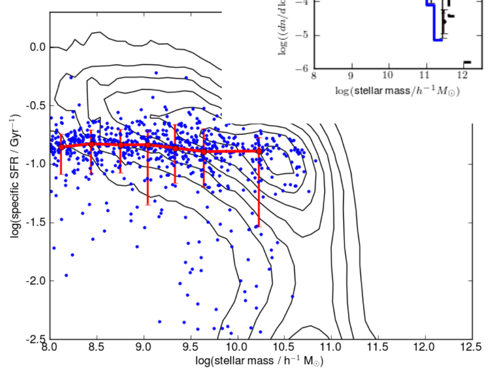
Part II

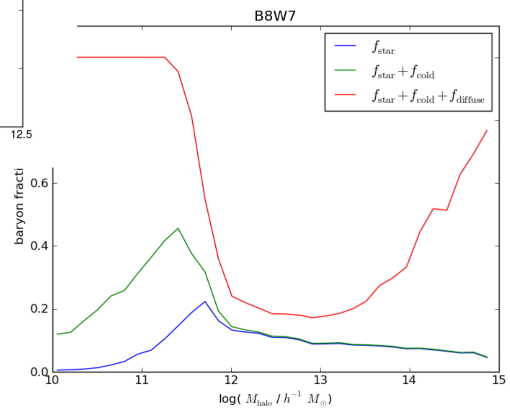
The Galaxy Formation Challenge

What are the key properties of galaxies?

- The stellar mass function
- The specific star formation rates of galaxies
- The history of star formation ("down sizing")
- The abundance of cold gas, warm gas and metals

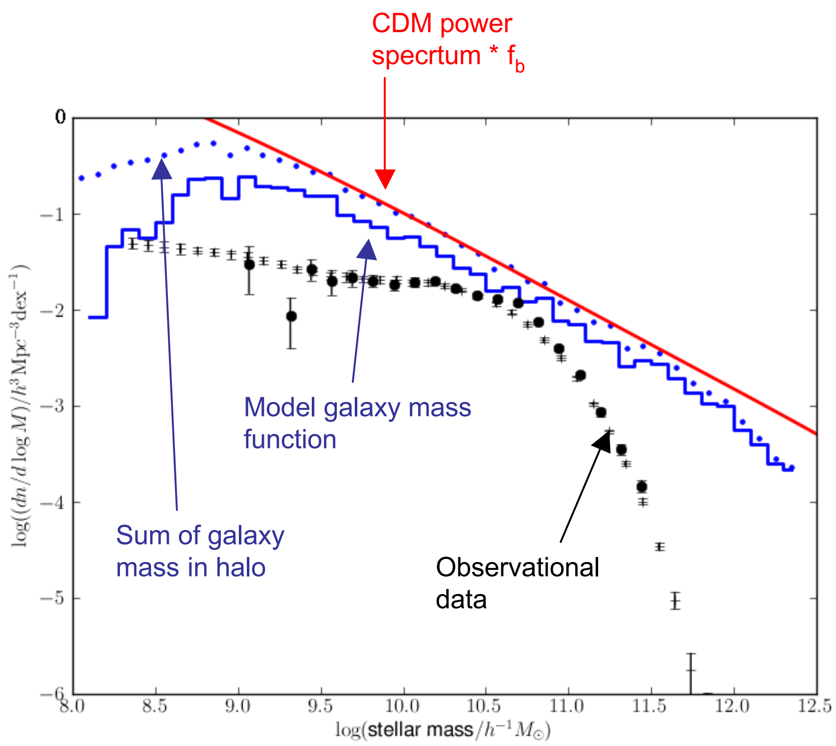






Comparing haloes and galaxies

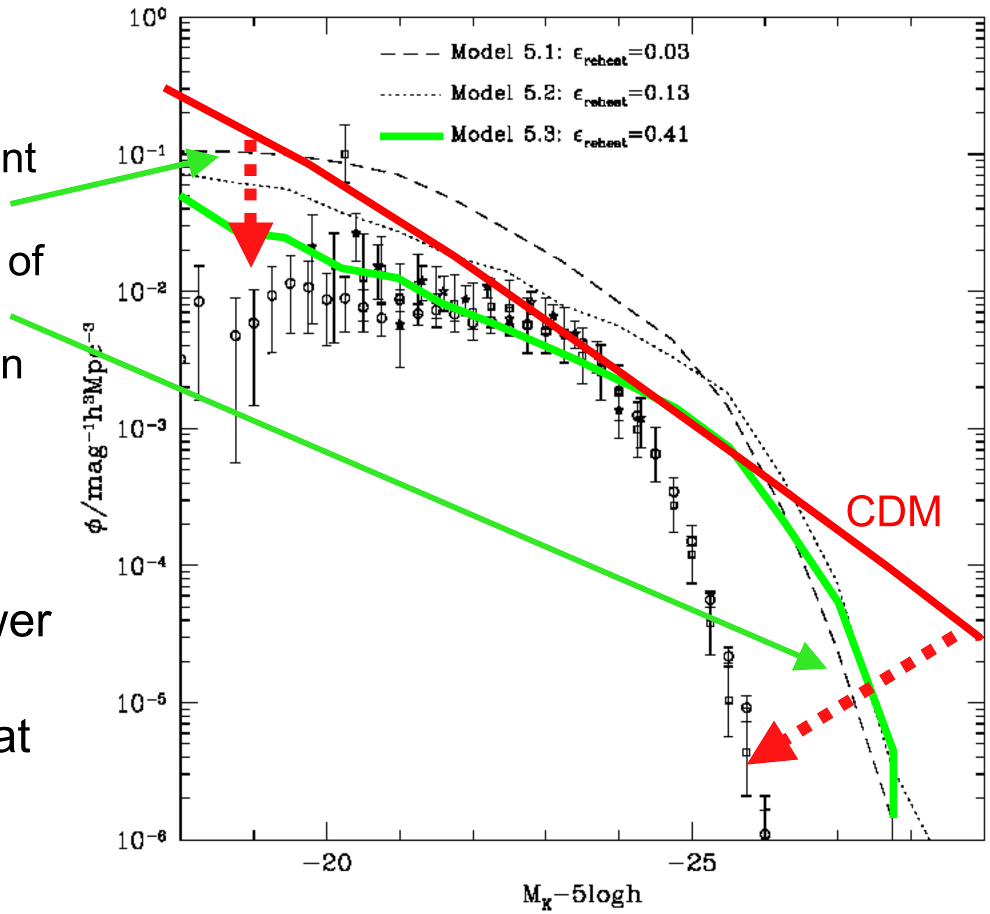
- WMAP => we know cosmological parameters well. We can robustly predict the halo mass function.
- Compare with the stellar mass function
  - Not 1 galaxy per halo
  - Need to allow for satellite haloes
- SHAM (sub-halo abundance matching)



Data from Bell et al 2003; Li & White 2009

Making the connection with galaxy formation

- The three problems of galaxy formation
  - Faint galaxies far less abundant than the CDM mass function
  - Sharp cut off at the bright end of the galaxy mass function
  - Lack of prolific star formation in central galaxies in clusters
  - Only 10% of the baryons condense into stars and cold gas
- Super-Novae may be the answer for faint galaxies?
- … but what creates the break at the bright end?



Benson et al 2003

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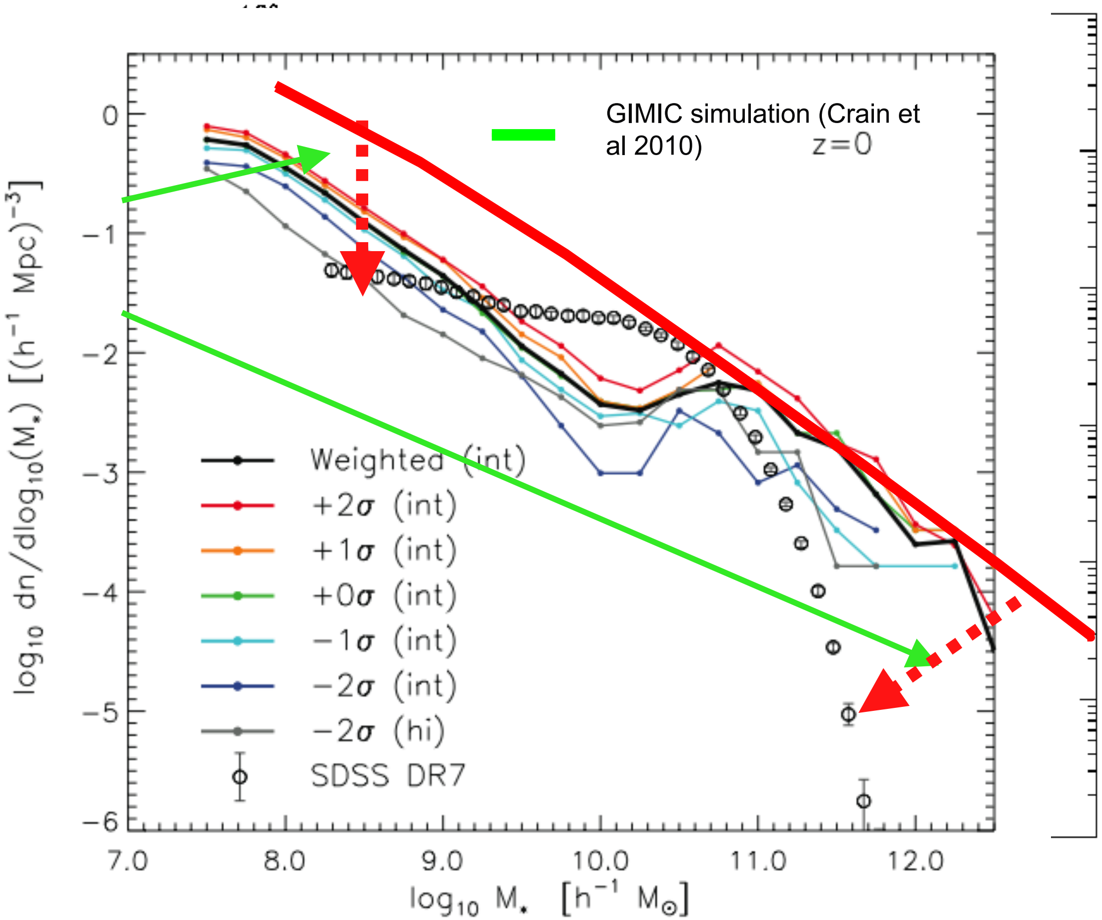


Part III

The techniques:

“semi-analytics” (aka Physics)

numerical simulation

How to solve the galaxy formation problem

- Numerical simulation
  - You know the equations, so solve them
    - SPH
    - AMR
  - Add cooling (OK), star formation (?), supernovae (?), black holes (?)
  - But…
    - Need utlra-high resolution
    - Don't actually know the equations
    - Current computers are far too slow

Navier-Stokes Equations

$$\rho\left(\tfrac{\partial v}{\partial t} + v.\nabla v\right) = -\nabla P - \rho\nabla\phi + \mathrm{S}_{\mathrm{mom}}$$

$$\left(\tfrac{\partial \rho}{\partial t} + v.\nabla\rho\right) + \rho(\nabla.v) = S_{\mathrm{mass}}$$

$$\left(\tfrac{\partial(\rho e)}{\partial t} + v.\nabla(\rho e)\right) + \rho e(\nabla.v) = -\nabla(u.P) + S_{\mathrm{energy}}$$

SPH method

$$\rho_{\mathrm{i}} = \sum m_j W(r_{ij}, h)$$

$$P_i = K_i \rho_i^{\gamma}$$

$$\left.\frac{dv_i}{dt}\right|_{hydro} = -\sum m_j \left[\tfrac{P_i}{\rho_i^2}\nabla W_{ij}(h_i) + \tfrac{P_j}{\rho_j^2}\nabla W_{ij}(h_j)\right]$$

$$\left.\frac{dv_i}{dt}\right|_{visc} = -\sum m_j \Pi_{ij} v_{ij} \qquad \text{where } \Pi_{ij} \text{ is a viscosity}$$

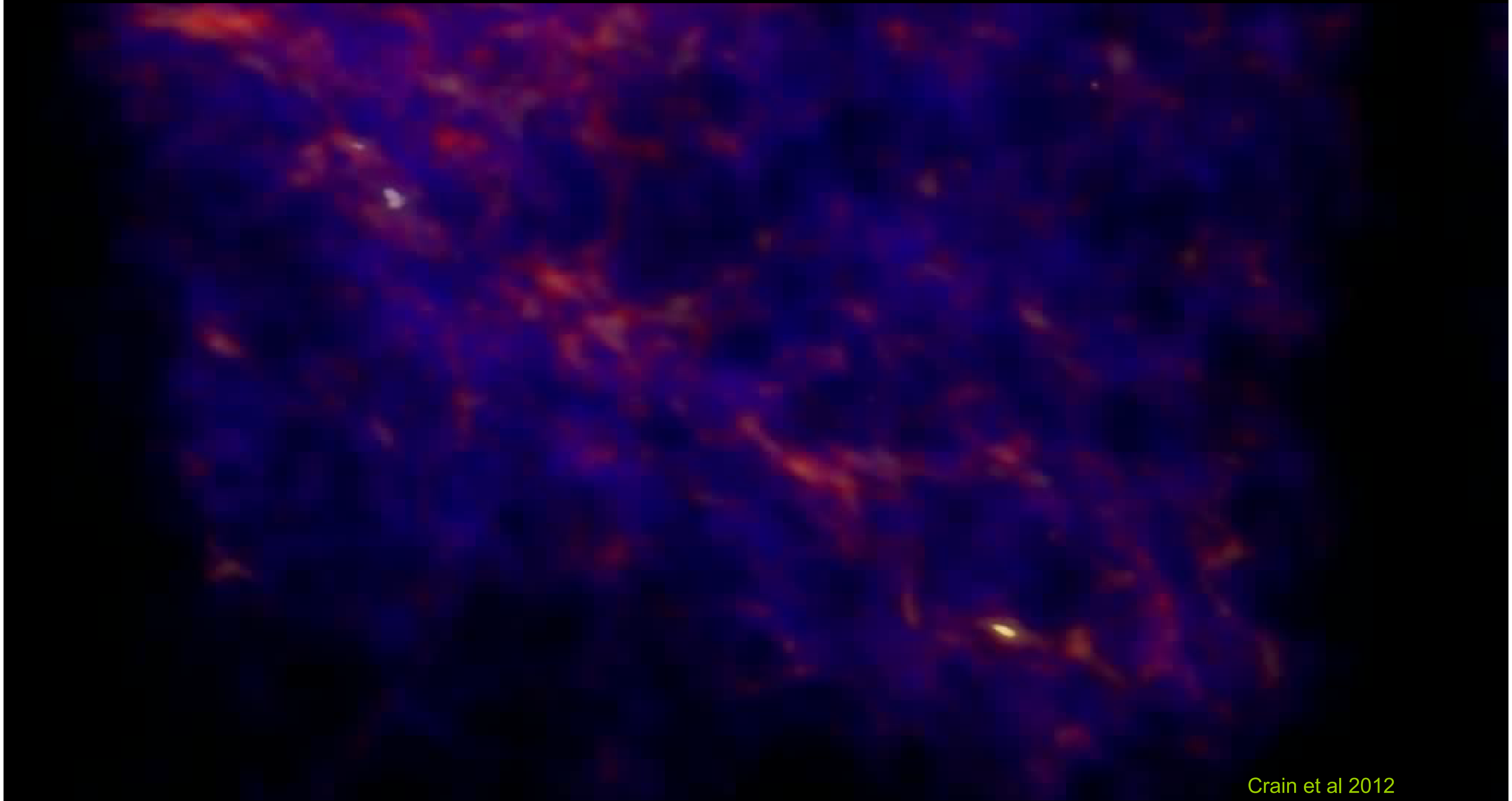
$$P_{visc} \approx \tfrac{1}{2}\rho^2 \Pi_{ij}$$

$$\frac{dK_i}{dt} = \tfrac{1}{2}\tfrac{\gamma-1}{\rho_i^{\gamma-1}} \sum m_j \Pi_{ij}(v_{ij} \cdot \nabla W_{ij})$$

Results depend much more on sub-grid assumptions than on numerical technique

Scannapieco et al 2011.

a galaxy formation simulation



Crain et al 2012
(GIMIC/OWLS)

How to solve the galaxy formation problem

- Numerical simulation
  - You know the equations, so solve them
    - SPH
    - AMR
  - Add cooling (OK), star formation (?), supernovae (?), black holes (?)
  - But…
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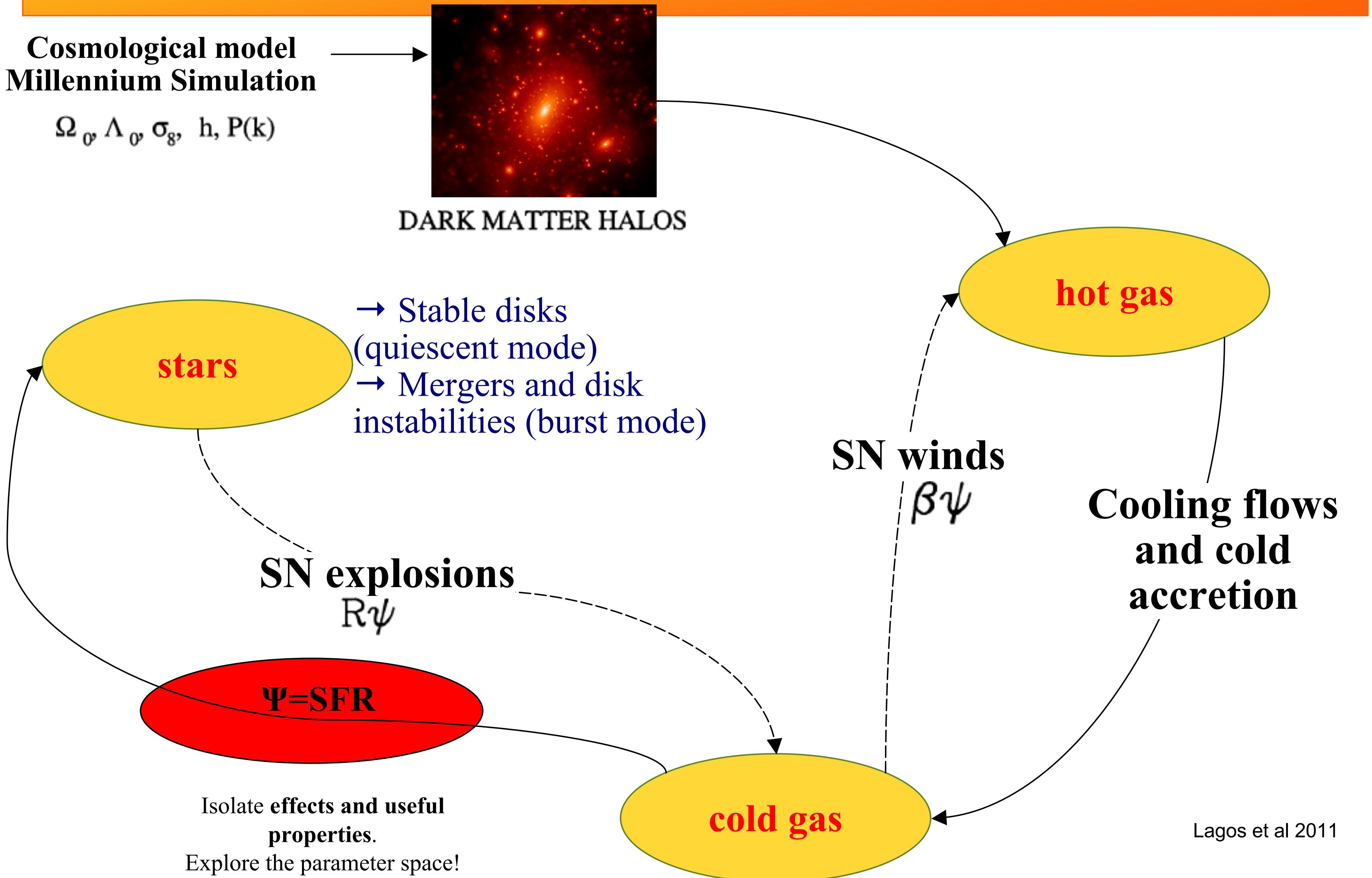
- "Semi-analytics"
  - Follow the spirit of the original papers…
  - Reduce the problem to a coupled set of non-linear differential equations
  - You "understand" the physics that's involved
  - Fast
    - Easy to see what happens if you change the assumptions
  - But…
    - only as good as the assumptions you make!

The GALFORM semi-analytic model
Cole et al. (2000)



Similar codes by Crotton et al 2006; Quo et al 2011

Parameters in the semi-analytic approach

- A subset of the equations in a typical semi-analytic model.
- Some equations simplified (eg., by assuming spherical symmetry)
- The “sub-grid” physics is described by uncertain parameters
  - These must be determined by comparison to observations
  - The choice of parameterisation should be justified using idealised simulations and physics

$$\frac{\mathrm{d}n}{\mathrm{d}\ln M_\mathrm{v}} = \sqrt{\frac{2}{\pi}}\frac{\Omega_0\rho_\mathrm{crit}}{M_\mathrm{v}}\left|\frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln M}\right| \times[1+1.047(\omega^{-2p})+0.6G_1+0.4G_2]A'\omega \times\exp\left(-\frac{1}{2}\omega^2-0.0325\frac{\omega^{2p}}{(n_\mathrm{eff}+3)^2}\right), \quad (3)$$

$$\dot{M}_{cool} = 4\pi r_{cool}^{\ 2}\rho(r_{cool})\frac{dr_{cool}}{dt}$$

$$t_\mathrm{cool}(t) = \frac{3k_\mathrm{B}T_\mathrm{v}(t)}{2\Lambda(t)n_\mathrm{H}}$$

$$\dot{M}_\star = \frac{M_\mathrm{gas}}{\tau_\star} - \dot{M}_\mathrm{R}$$

$$\dot{M}_\mathrm{gas} = -(1+\beta')\frac{M_\mathrm{gas}}{\tau_\star} + \dot{M}_\mathrm{R} + \dot{M}_\mathrm{infall}.$$

$$f_\mathrm{exp} = \exp\left(-\frac{\lambda_\phi V^2}{\langle e\rangle}\right),$$

$$\dot{M}_\mathrm{reheated} = (1-f_\mathrm{exp})\beta'\dot{M}_\star.$$

$$f_\mathrm{acc} = \exp\left(-\frac{V_\mathrm{max}^2}{\langle e\rangle}\right) - \exp\left(-\frac{V_\mathrm{v}^2}{\langle e\rangle}\right)$$

This is highly simplified - see Benson & Bower 2010 for a realistic version!

Parameters in the semi-analytic approach

- The "sub-grid" physics is described by uncertain parameters
  - These must be determined by comparison to observations
  - The choice of parameterisation should be justified using idealised simulations and physics

Parameter	Minimum	Maximum
h_0	0.6750	0.7270
Ω_b	0.04320	0.04920
Λ_0	0.7142	0.7278
σ_8	0.7650	0.8690
n_s	0.9320	0.9880
$V_{cut}/\mathrm{km\ s^{-1}}$	10.00	50.00
z_{cut}	5.000	13.00
$\log_{10}(\alpha_{cool})$	-1.523	0.4771
$\log_{10}(\alpha_{remove})$	-1.523	0.0000
$\log_{10}(a_{core})$	-2.000	-0.5229
$\log_{10}(\epsilon_\star)$	-3.523	-1.301
$\alpha_\star$	-4.000	1.000
$V_{hot,disk}/\mathrm{km\ s^{-1}}$	100.0	550.0
$V_{hot,burst}/\mathrm{km\ s^{-1}}$	100.0	550.0
α_{hot}	1.000	3.700
$\log_{10}(\lambda_{expel,disk})$	-1.523	1.000
$\log_{10}(\lambda_{expel,burst})$	-1.523	1.000
$\log_{10}(\epsilon_\bullet)$	-2.398	-1.000
$\log_{10}(\eta_\bullet)$	-3.000	-1.000
$\log_{10}(F_\bullet)$	-3.000	-1.523
$\log_{10}(\alpha_{reheat})$	-1.523	0.4771
$\log_{10}(f_{ellip})$	-2.000	-0.3010
$\log_{10}(f_{burst})$	-2.000	-0.3010
$\log_{10}(f_{gas,burst})$	-1.523	-0.3010
B/T_{burst}	0.0000	1.000
A_{ac}	0.7000	1.000
w_{ac}	0.7000	1.000
$\epsilon_{d,gas}$	0.7000	1.150
$\log_{10}(\epsilon_{strip})$	-2.000	0.0000

More discussion of parameters and fitting them in Bower et al 2010

The equations of galaxy formation

- Reduce equation set to a minumum
- Use cosmology as driving term

efficiency

cold gas reservoir

SFR

$$\dot{M}_* = \varepsilon_* M_g$$

$$\dot{M}_g = \gamma \dot{M}_{in} - (1+\beta)\dot{M}_*$$

Feedback - suppression of inflow

Cosmology - halo growth rate

Feedback - mass expelled by star formation

The equations of galaxy formation

- Reduce equation set to a minimum
- Use cosmology as driving term

$$\dot{M}_* = \varepsilon_* M_g$$

$$\dot{M}_g = \gamma \dot{M}_{in} - (1+\beta)\dot{M}_*$$

$$\beta = \beta_0 M_h^{-0.5}$$

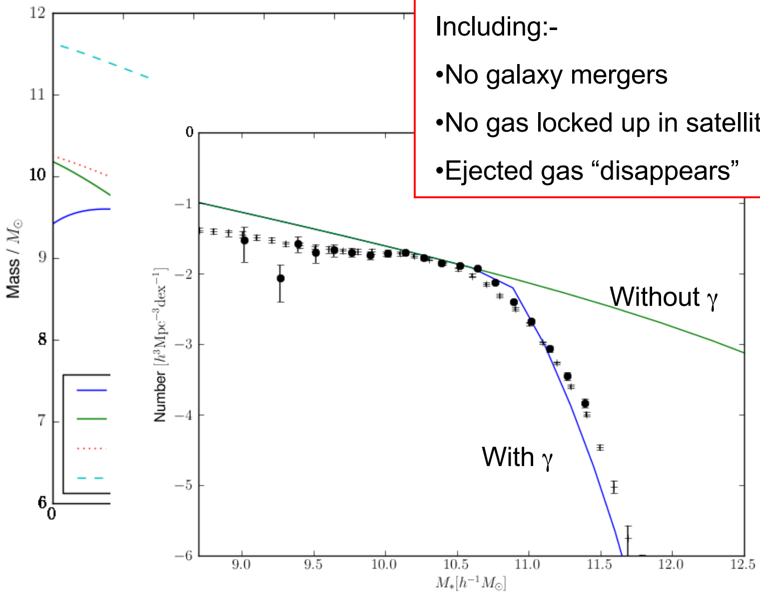
$$\gamma = \min\left(1, \left(\frac{M_h}{3.10^{12}}\right)^{-1}\right)$$

$$\dot{M}_{in} = \frac{\Omega_b}{\Omega_m} 34 \left(\frac{M_h}{10^{12}}\right)^{1.14} (1+z)^{2.4}$$

WARING!!!! Many assumptions!

Including:-

- No galaxy mergers
- No gas locked up in satellites
- Ejected gas “disappears”



(eg Neistein et al 2008)

Part IV

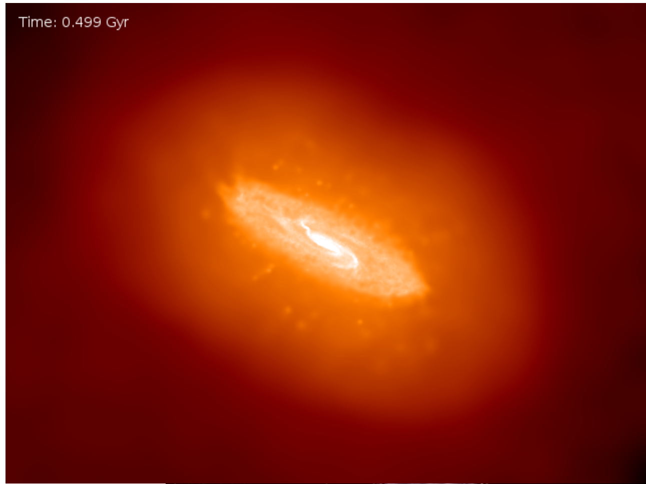
Sources of feedback

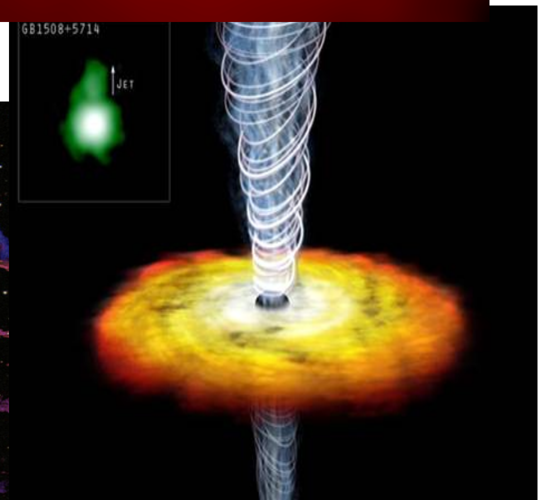
Sources of Feedback

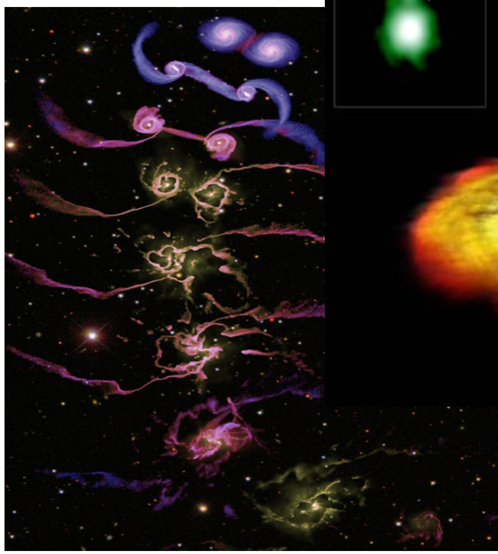
Low energy

High energy

- Reionisation
- Stellar winds and radiation pressure
- Supernovae
- Quasars
- Radio Jets
- Conduction

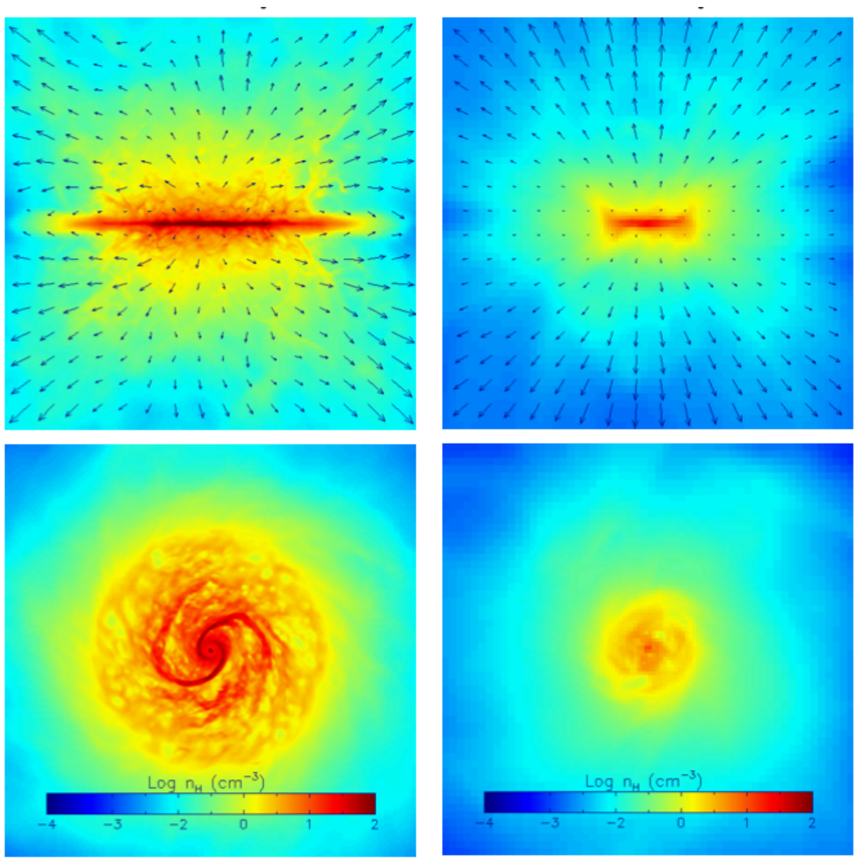






Sources of feedback

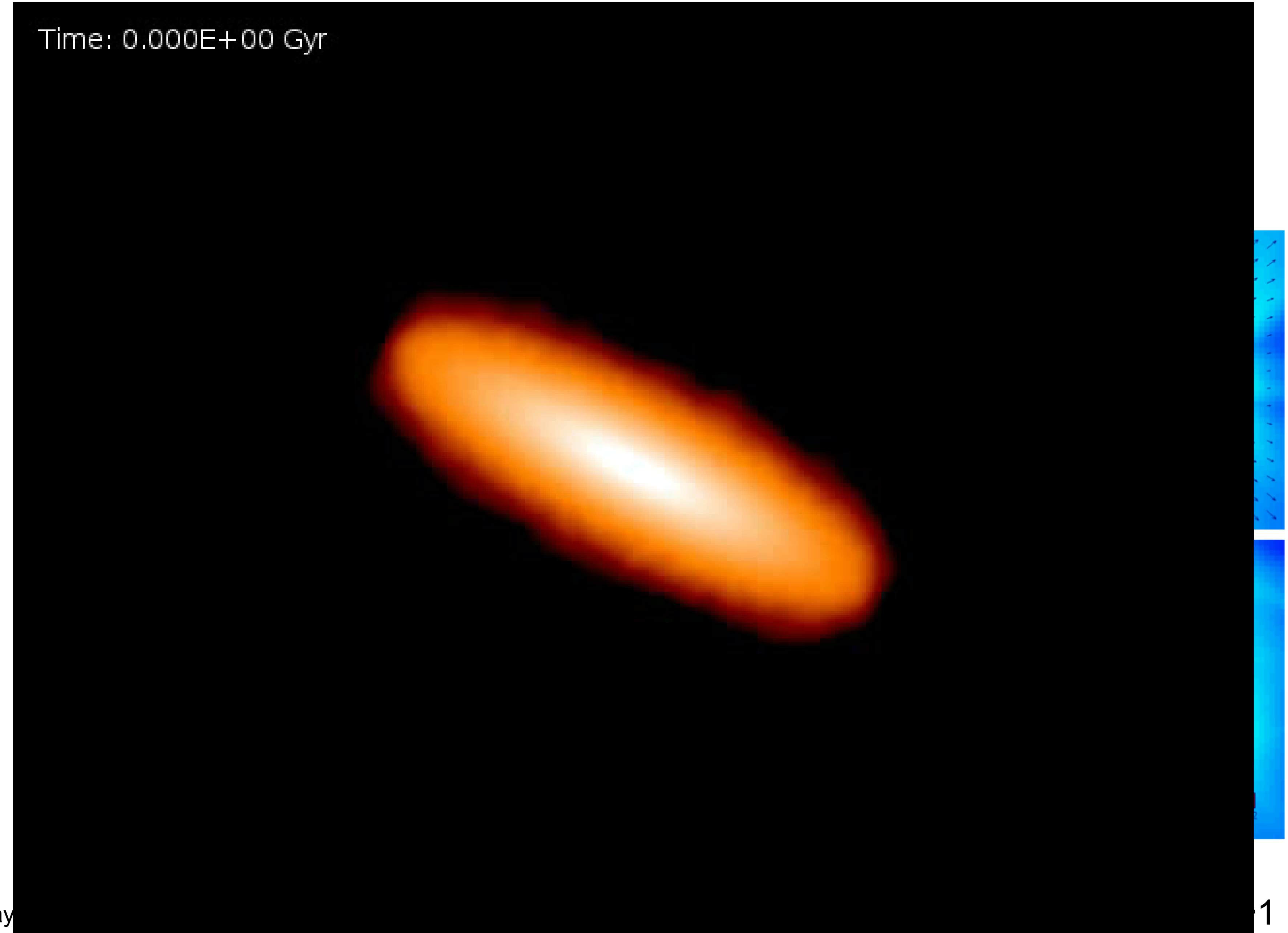
- Re-ionisation
  - Only effective below 30 km/s.
  - Explains rarity of faintest MW satellites
- Supernovae
  - Very important - for regulating galaxies
  - Generate the galactic fountain and regulate star formation
  - Do starbursts drive “superwinds”?
    - Velocity offsets common in high-z galaxies
    - Let’s look at the evidence
- Conduction and galaxy stirring, cosmic rays?
    - may be important in the hottest systems



MW galaxy $\beta_{0.2}$~0.1
Dwarf galaxy $\beta_{0.2}$~1

Schaye & Dalla Vecchia 2008, Mitchel et al 2010

Schay
Vecchia 2008, Mitchel
et al 2010



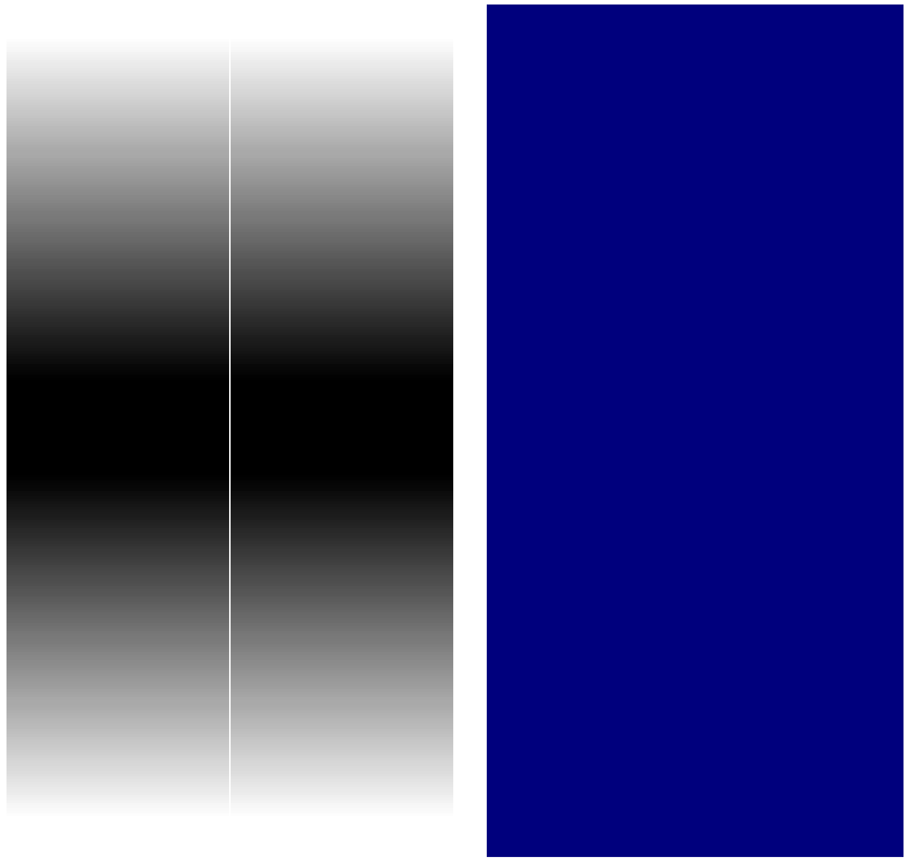
Schay
Vecchia 2008, Mitchel
et al 2010

Supernova Feedback

- It's complicated!
  - Multiphase ISM
  - Porosity of the ISM
  - Direct simulation requires sufficient resolution to avoid artificial cooling of supernova ejecta
- These simulations give:

$$\beta = 22\left(\frac{\Sigma_g}{1M_0pc^{-2}}\right)^{-0.7} f_g^{\;0.5}$$

Rather weaker than required by observations!



Simulating feedback at 1pc resolution!!! (Creasey et al 2012)

Part IV

Exploring feedback