Galaxy Formation in ΛCDM

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Constraints for galaxy formation theories

Initial Conditions: Planck cosmology

CMB + galaxy P(k) + Type Ia SNe →

Ω_Λ=0.72, Ω_m=0.28, Ω_b=0.046, H_0=70 km/s/Mpc, σ_8=0.82

Final Conditions: Low-z galaxy properties (including MW)

Integral Constraints:

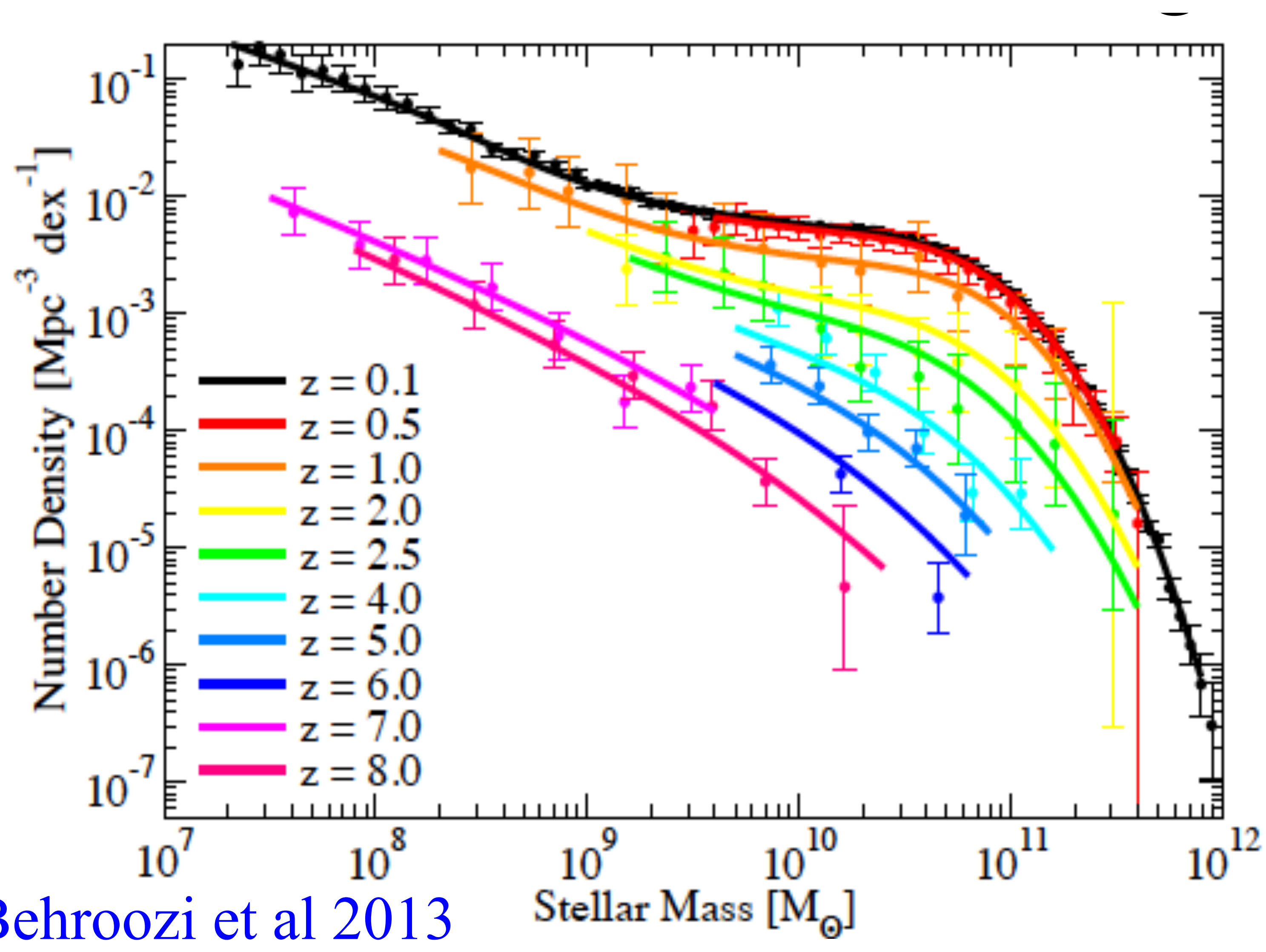
Star Formation Rate Density (SFRD) vs. redshift ($M_\odot$/yr/Mpc^3)

Stellar Mass Density (SMD) vs. redshift ($M_\odot$/Mpc^3)

SMD should = integrated SFRD: $\rho^*(t) = \int dt\, d\rho/dt$ (considering recycled fraction!)

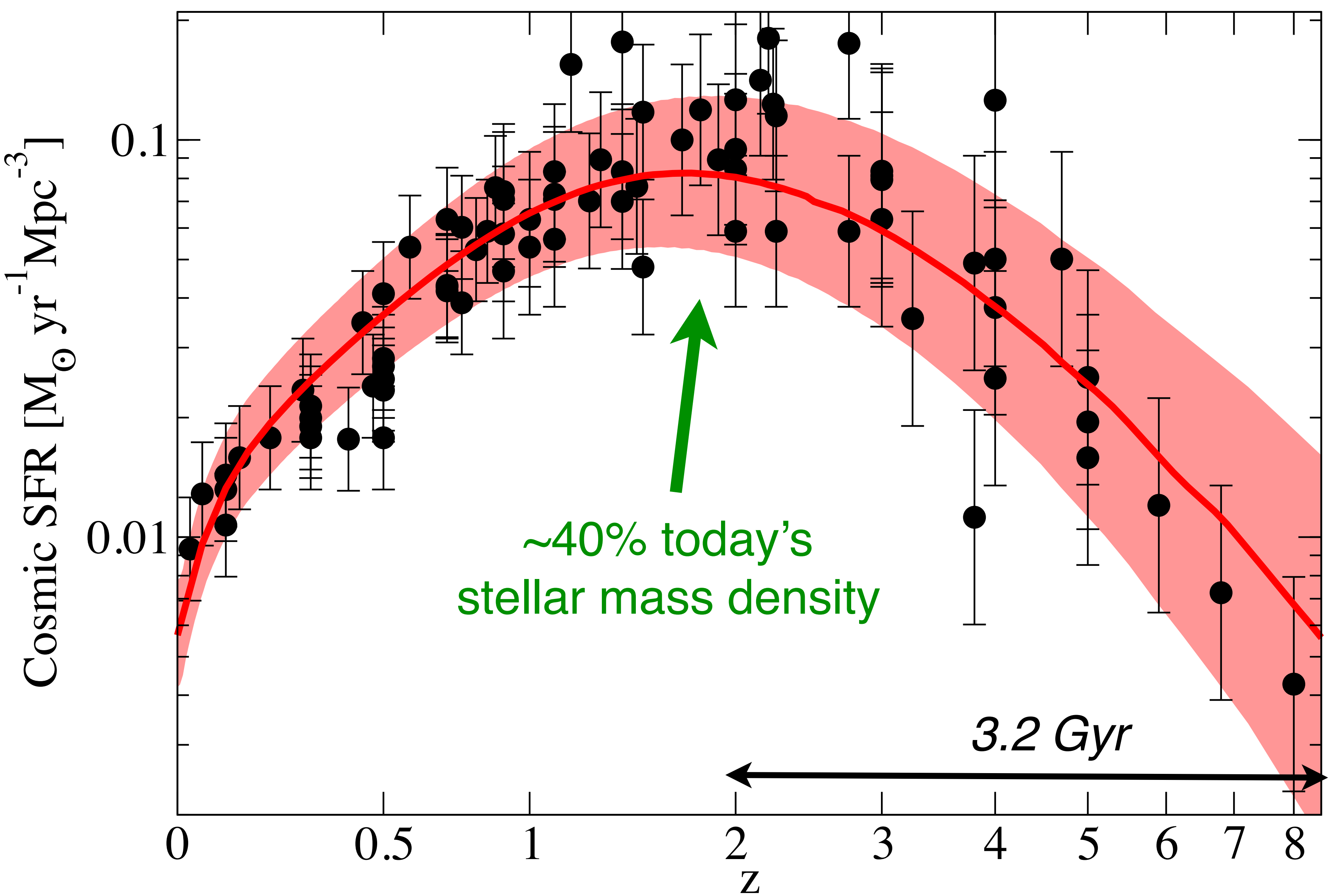
Extragalactic Background Light (EBL)

Integral Constraints



Behroozi et al 2013

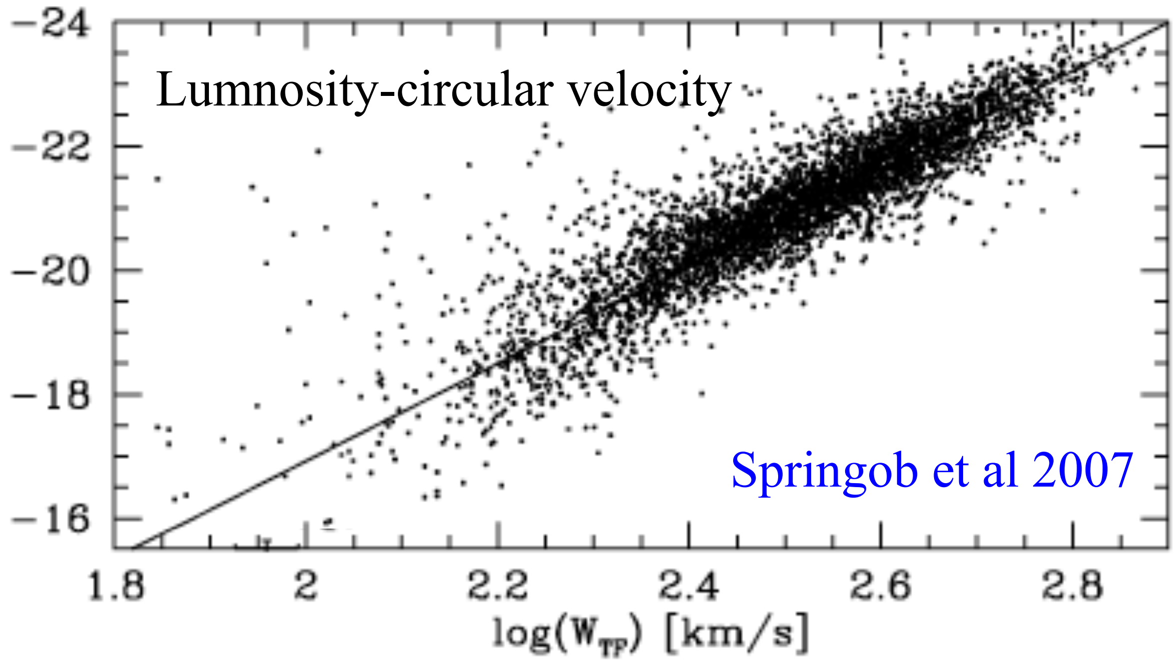
Integral Constraints (cont.)

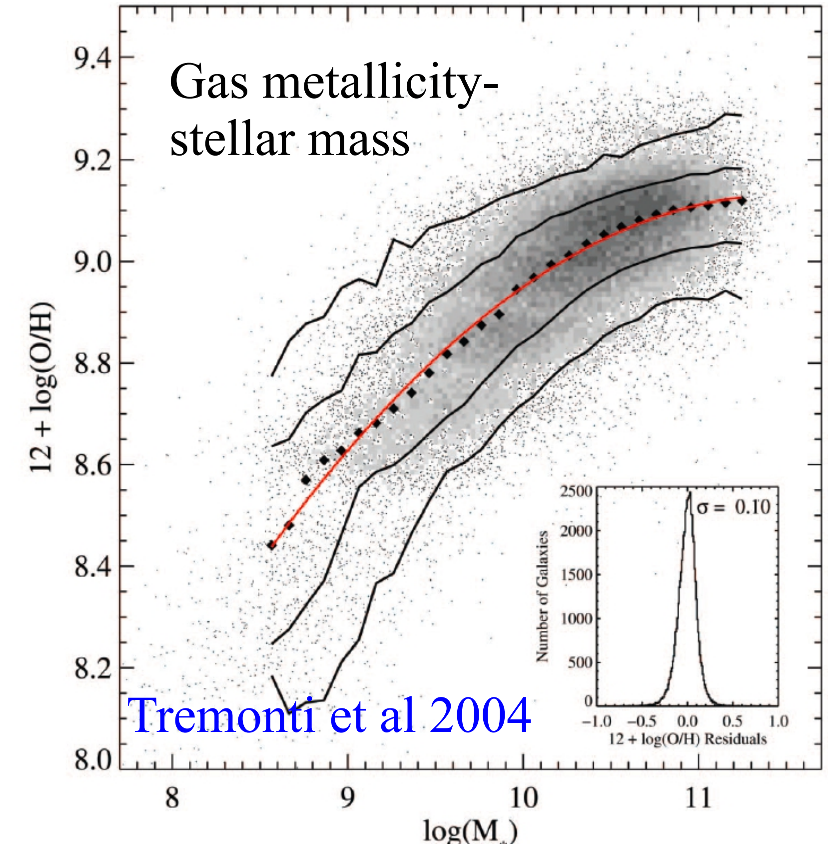


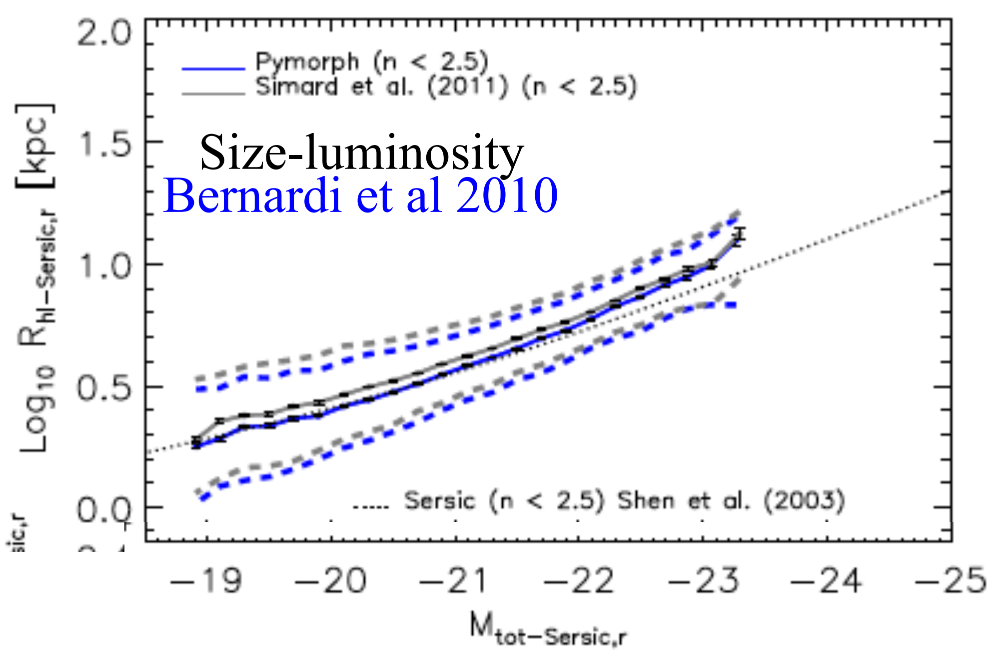
Behroozi et al. (2013); Madau & Dickinson (2014)

Local Constraints

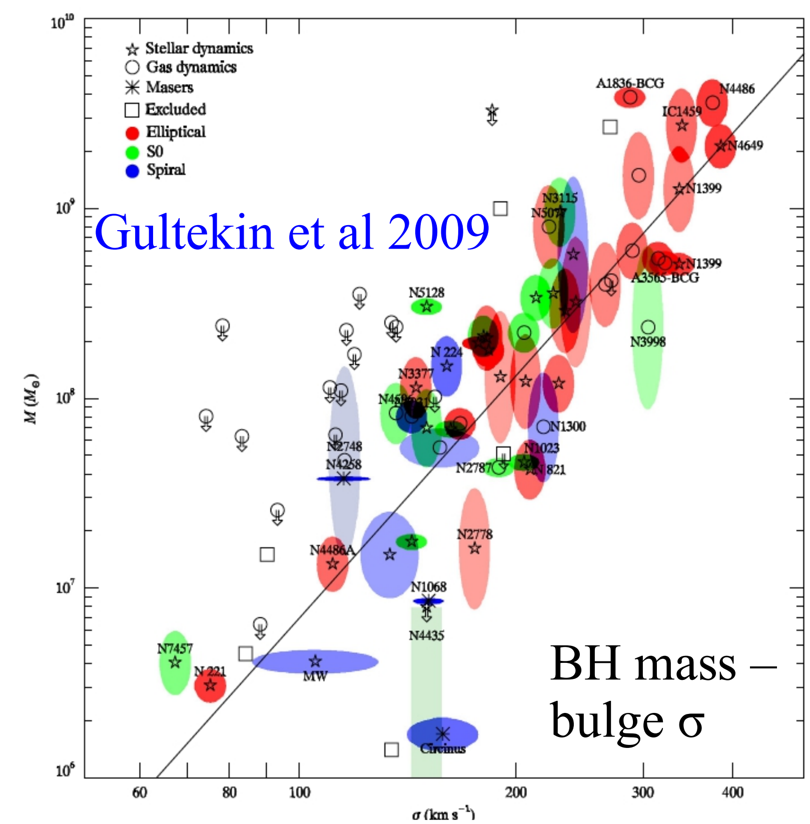
Scaling relations between global properties are well characterised at z ~ 0







...some are also measured at higher redshift



Galaxy formation models

All models use merger trees as a basis for dark matter treatment

Three main types of galaxy formation models

(see NASA online lecture on Galaxy Formation by Silk et al.)

Semi-analytical models (SAMs):

Describes growth of structures approximately with analytic techniques

Makes assumptions on physical processes in galaxies - *many free parameters tuned by hand*

Relatively inexpensive computationally

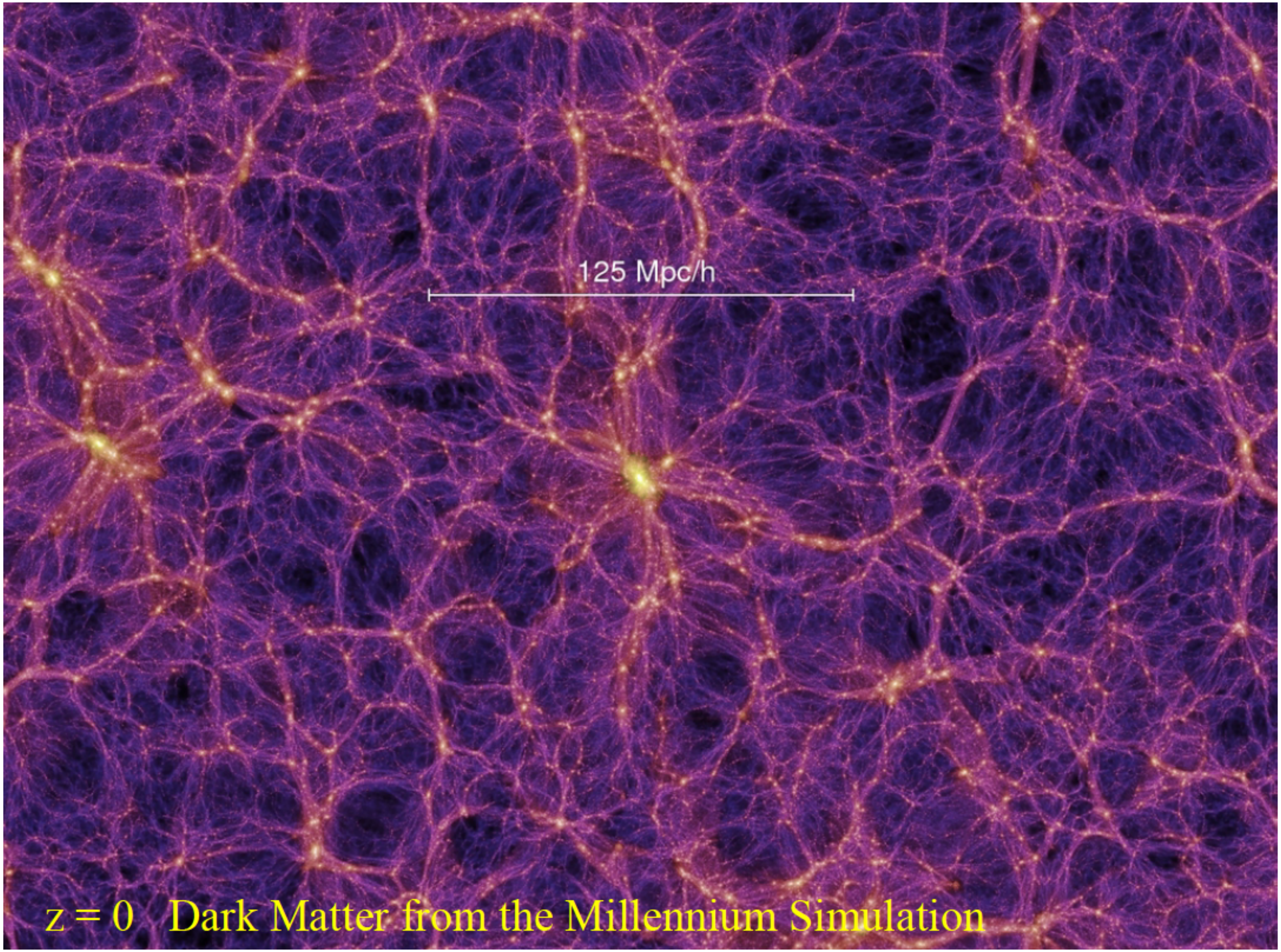
N-body and hydrodynamical simulations: computationally expensive

Equations of gravity and hydrodynamics are solved in consistent way

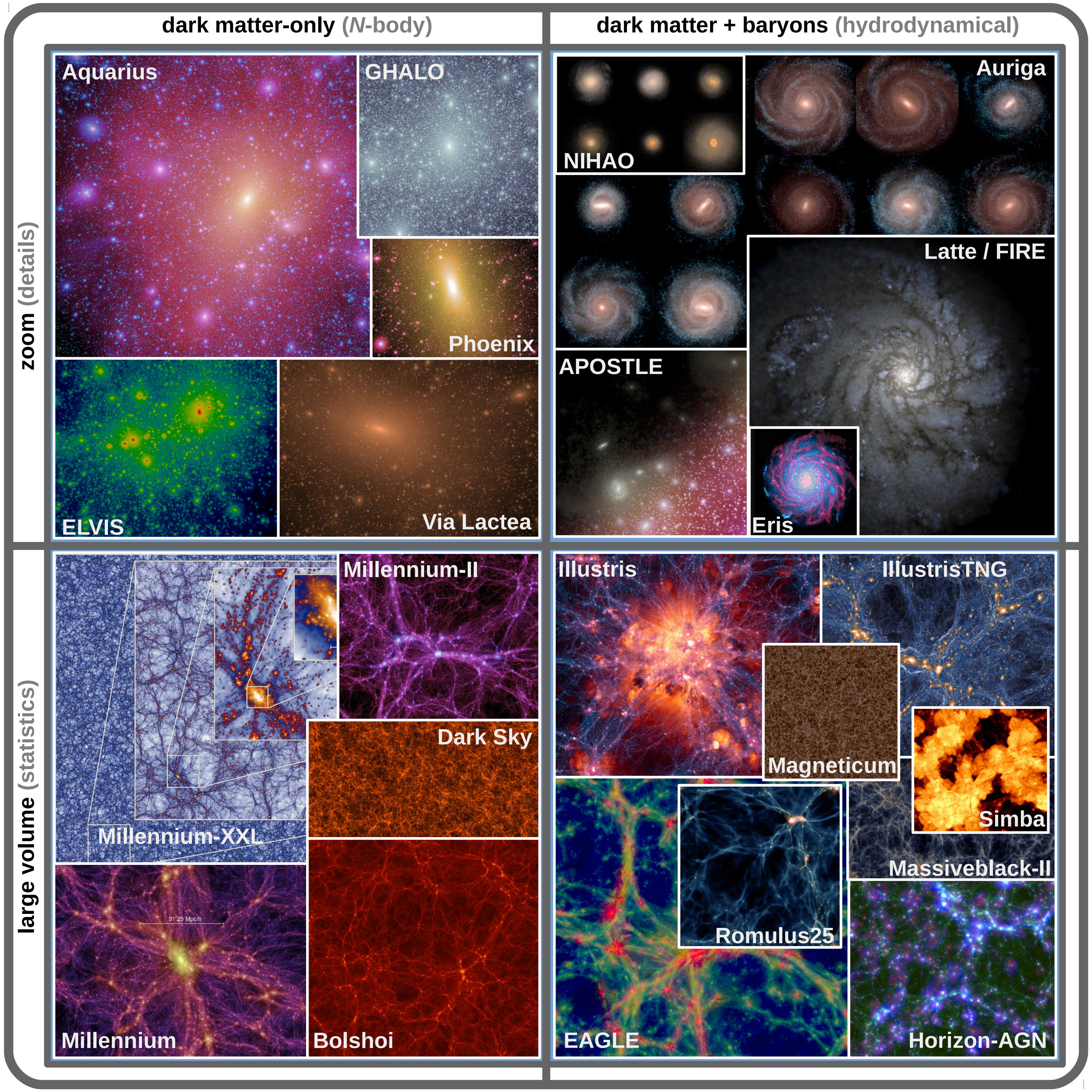
Pure dark matter simulations (**N-body**) work well at large scale, but baryonic physics necessary at small scales

Difficult to deal with all astronomical scales in a coherent fashion: physics below pc scale ("sub-grid" physics) introduced by hand (like SAMs) - **hybrid approach**

Some model varieties overcome this problem (**hydro models**): e.g. *smoothed particle hydrodynamics (SPH); adaptive mesh refinement (AMR)*

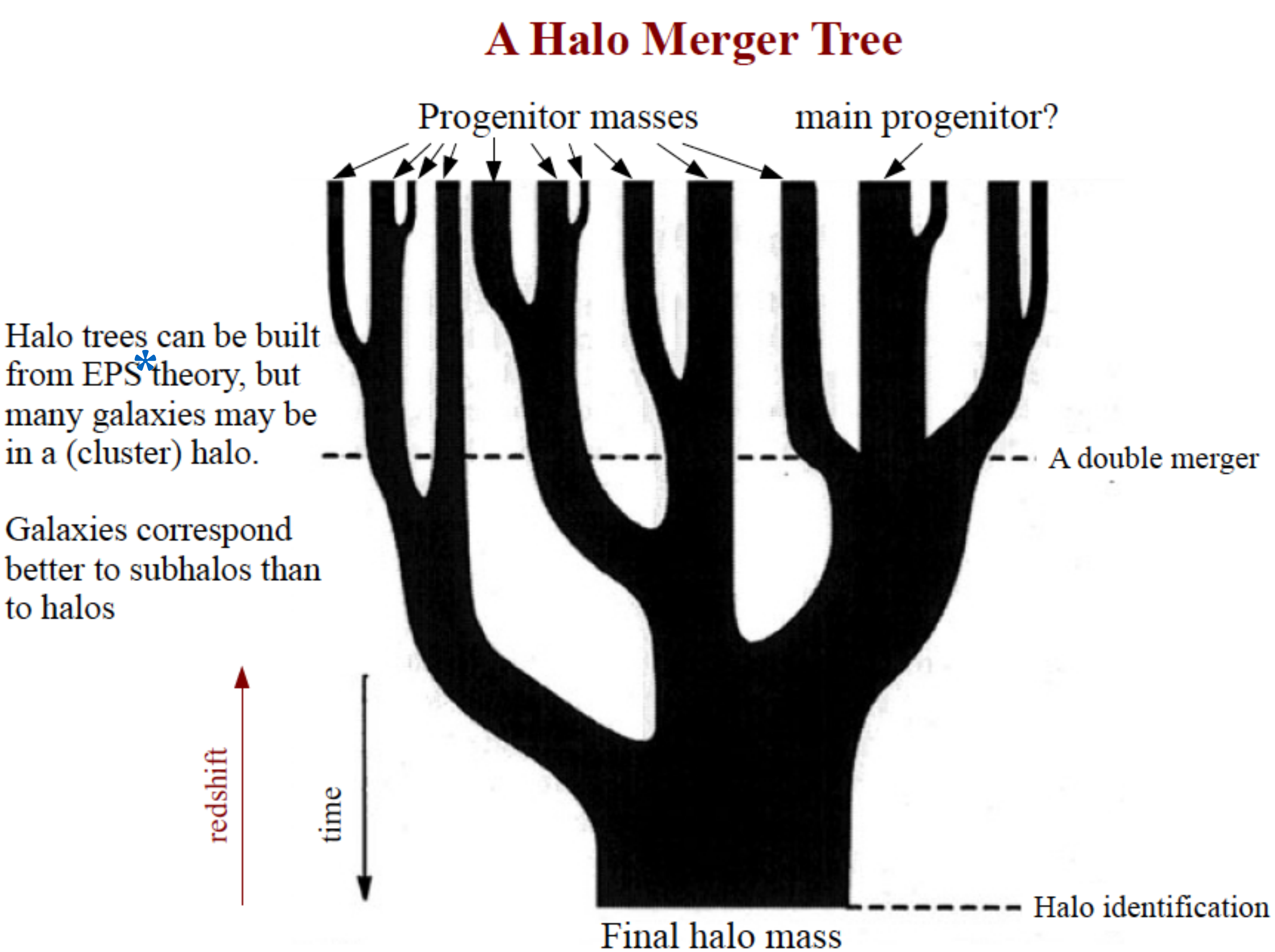

125 Mpc/h
z = 0   Dark Matter from the Millennium Simulation

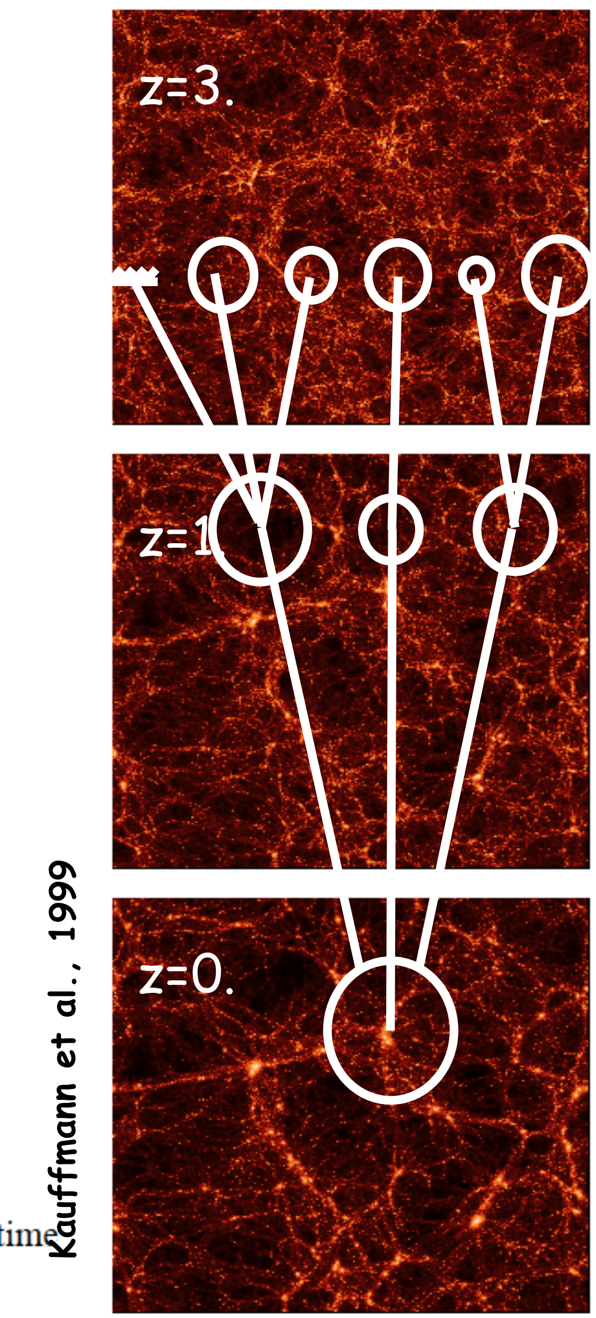
Overview of Cosmological Models



from Vogelsberger et al. (2020) review

Skeleton: dark matter halos





White & Frenk (1991), Baugh (2006)

* EPS= extended Press-Schechter

The halo mass function is derived from the initial (linear) density field.
Progenitors of any local DM halo can be traced at every redshift.

Key physical processes involved in galaxy formation

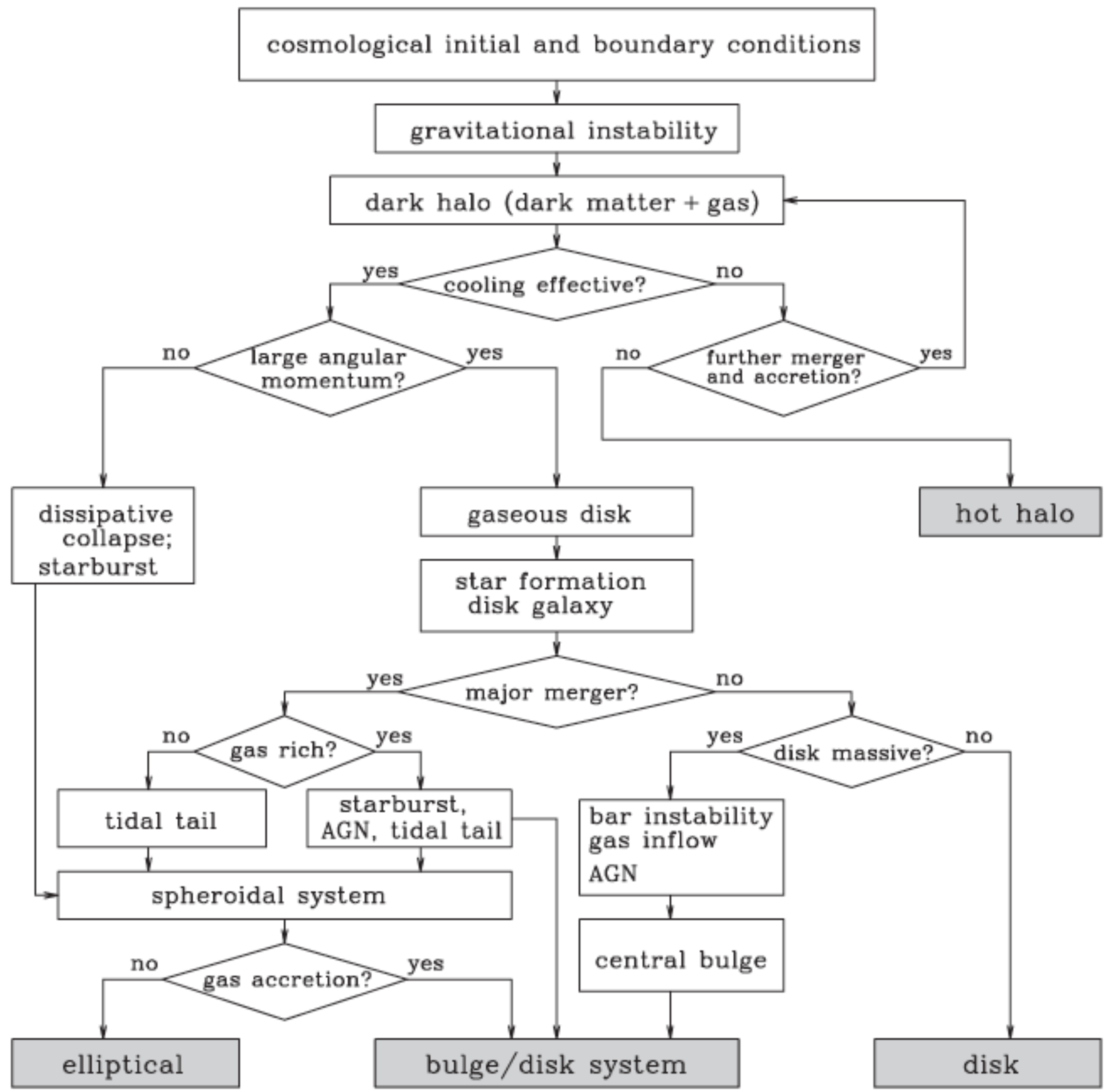
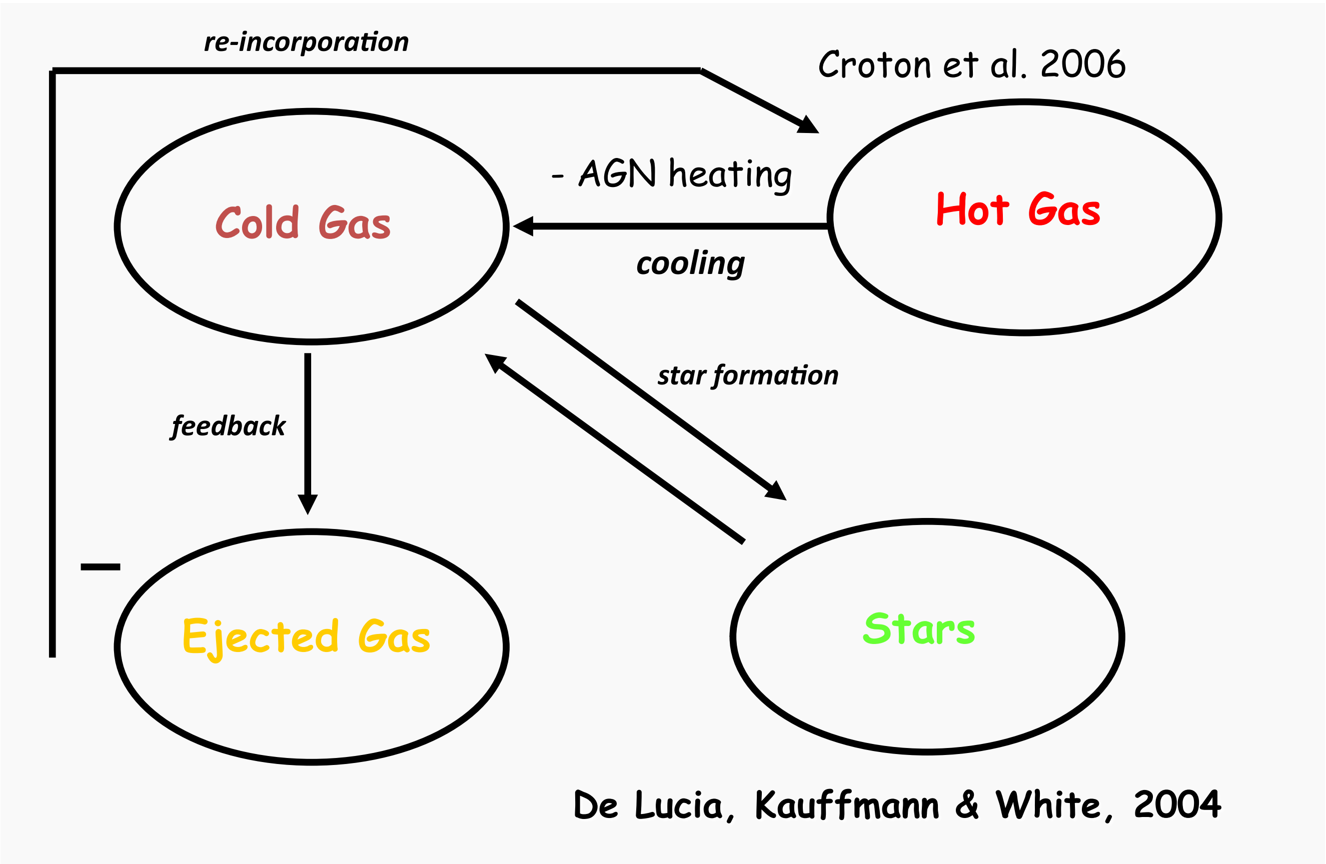


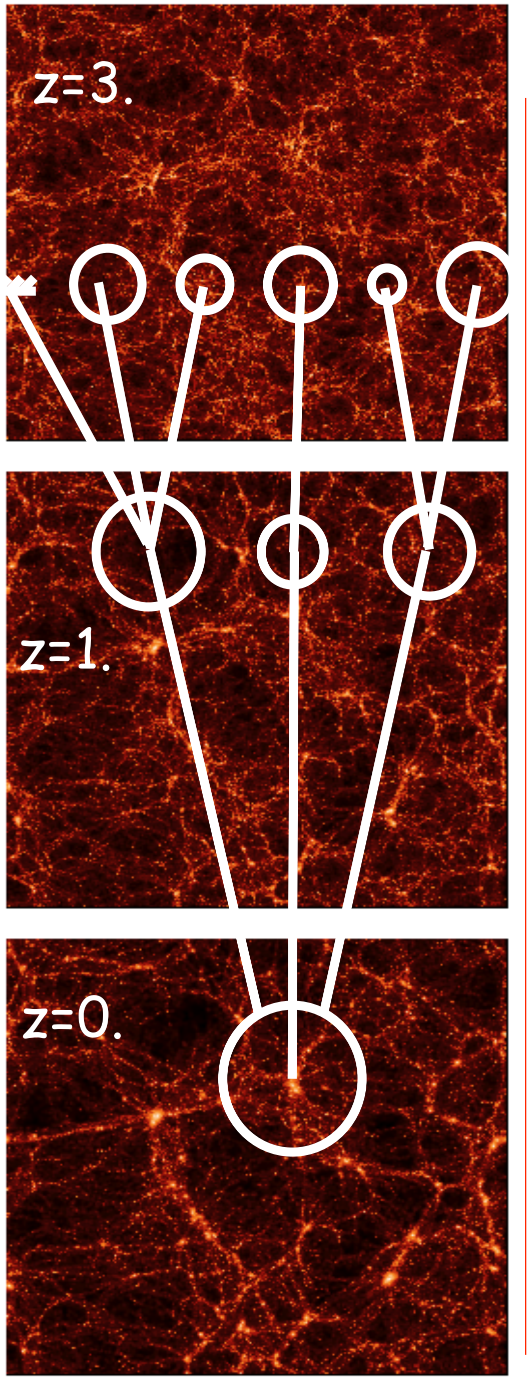
Fig. 1.1. A logic flow chart for galaxy formation. In the standard scenario, the initial and boundary conditions for galaxy formation are set by the cosmological framework. The paths leading to the formation of various galaxies are shown along with the relevant physical processes. Note, however, that processes do not separate as neatly as this figure suggests. For example, cold gas may not have the time to settle into a gaseous disk before a major merger takes place.

Modeling galaxies in ΛCDM

Hybrid approach

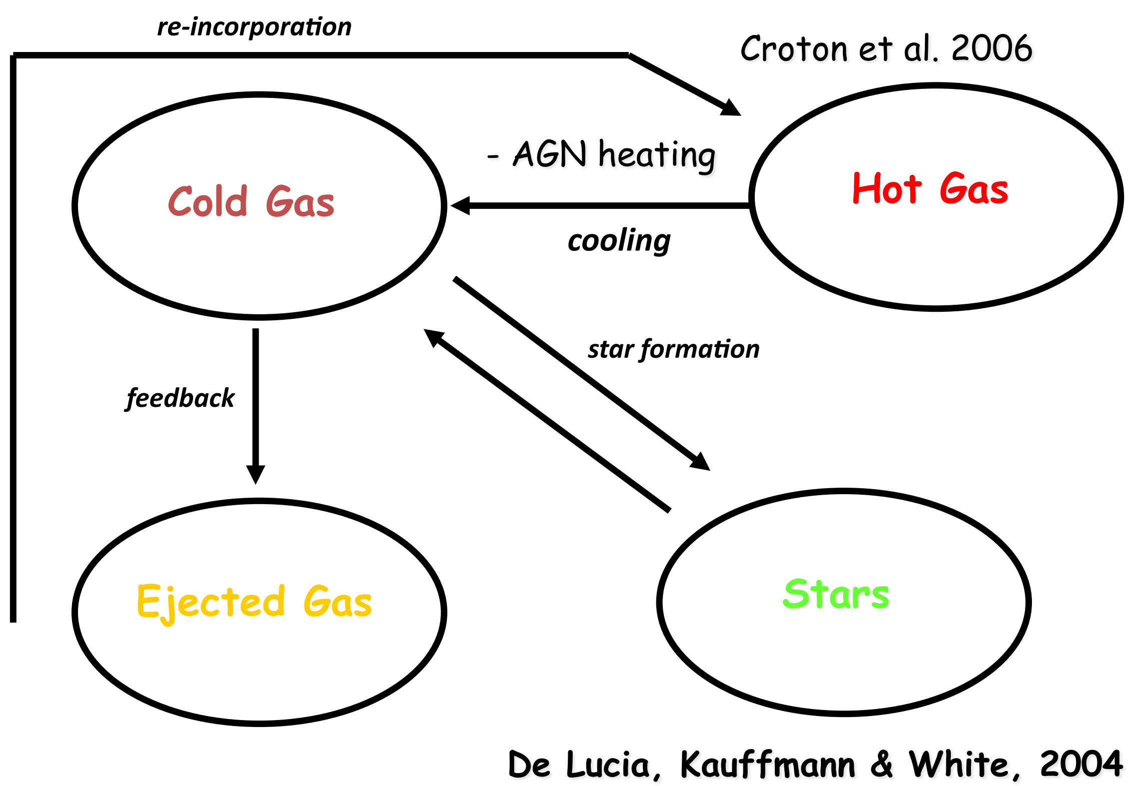
- high-resolution dark matter only simulation
- semi-analytic model to follow physics of baryons
  (simple, physically/observationally motivated prescriptions)

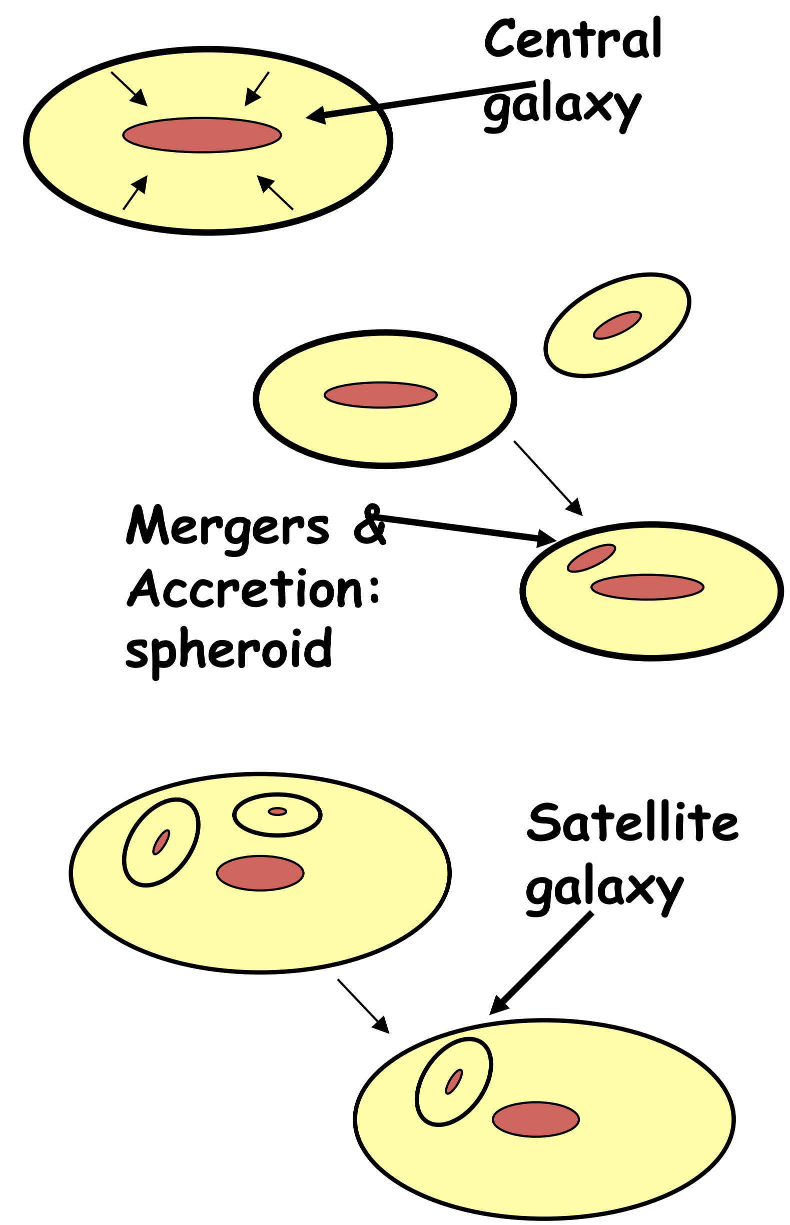




Kauffmann et al., 1999

How a SA model works





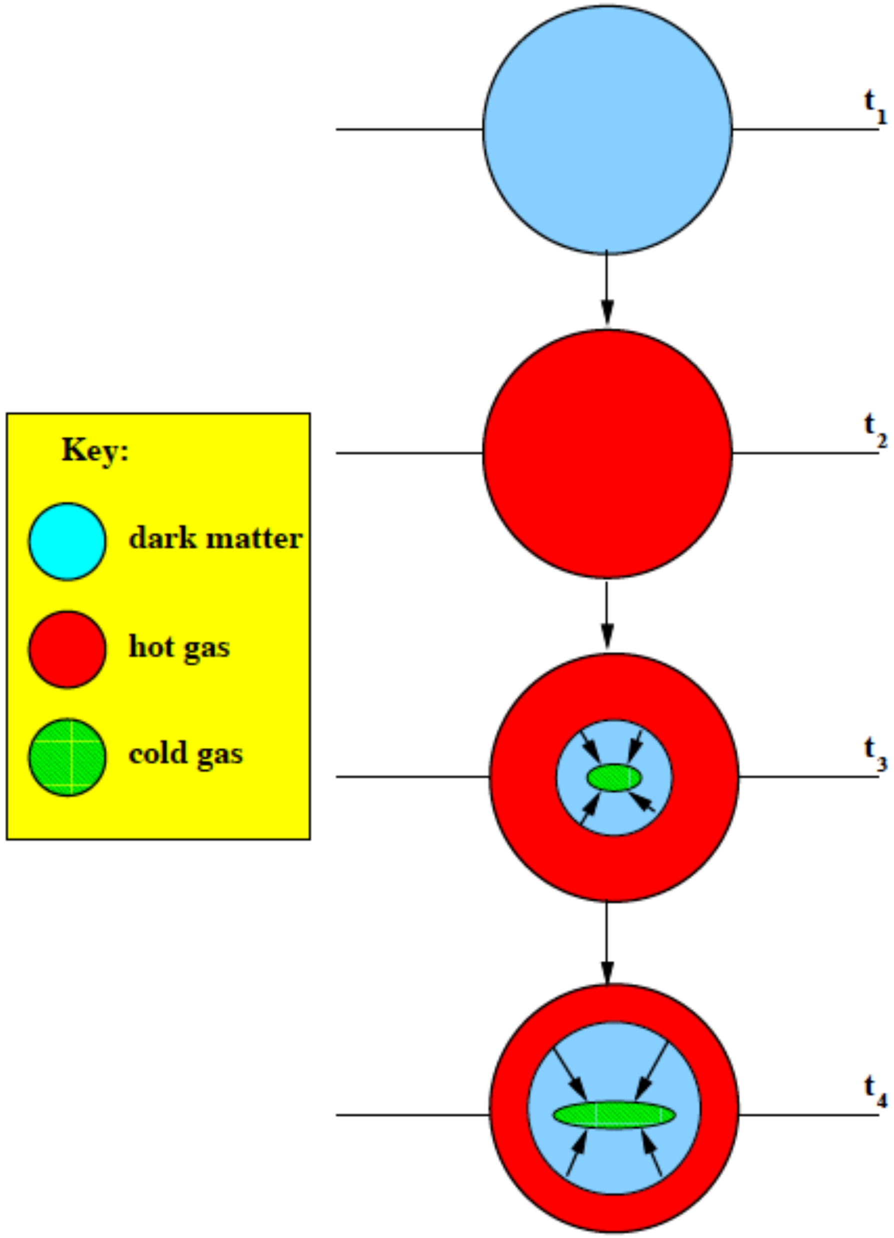
Each "box" is associated to a physical process
This is modelled by a (set of) equations/inequalities/criteria

De Lucia et al., 2004

Physical Processes in Galaxy Formation

Gas cooling

- At t_1: baryons fall into gravitational well of dark halo
  - If UV background is present, this may reduce the baryons that fall-in (especially for low mass halos)
- At t_2: Gas is heated by shocks as it falls, and attains the virial temperature of the halo
- At t_3: inner parts of hot halo cool and form a rotationally supported disk
- At t_4: cooling radius is larger, cold gas disk grows in size
- Meanwhile: halo grows in size, gets more gas, etc…



Gas cooling

- Gas feels gravitational pull by dark matter halo
- Fraction of gas initially is the baryon fraction Ω_b → $M_{gas} = f_b M_{halo}$

- Hot phase: gas shock heated to the virial temperature of the halo

$$T_{vir} = 1/2\ \mu/k\ m_H V^2_{vir}$$

$\mu = 1/1.71$ mean molecular mass of the gas, k Boltzmann constant, m_H mass of the H atom, V_{vir} virial velocity of halo

- The hot gas may be assumed to follow the density profile of the dark halo, be isothermal, or some other profile
  - This is important for cooling "recipe"

- The rate at which gas cools depends on T, chemical composition, and density
  - When it cools (see next slide), it looses pressure support, and sinks to the centre of a free-fall (dynamical) time and conserves some amount of angular momentum (from spinning halo) and hence forms a disk

Cooling function

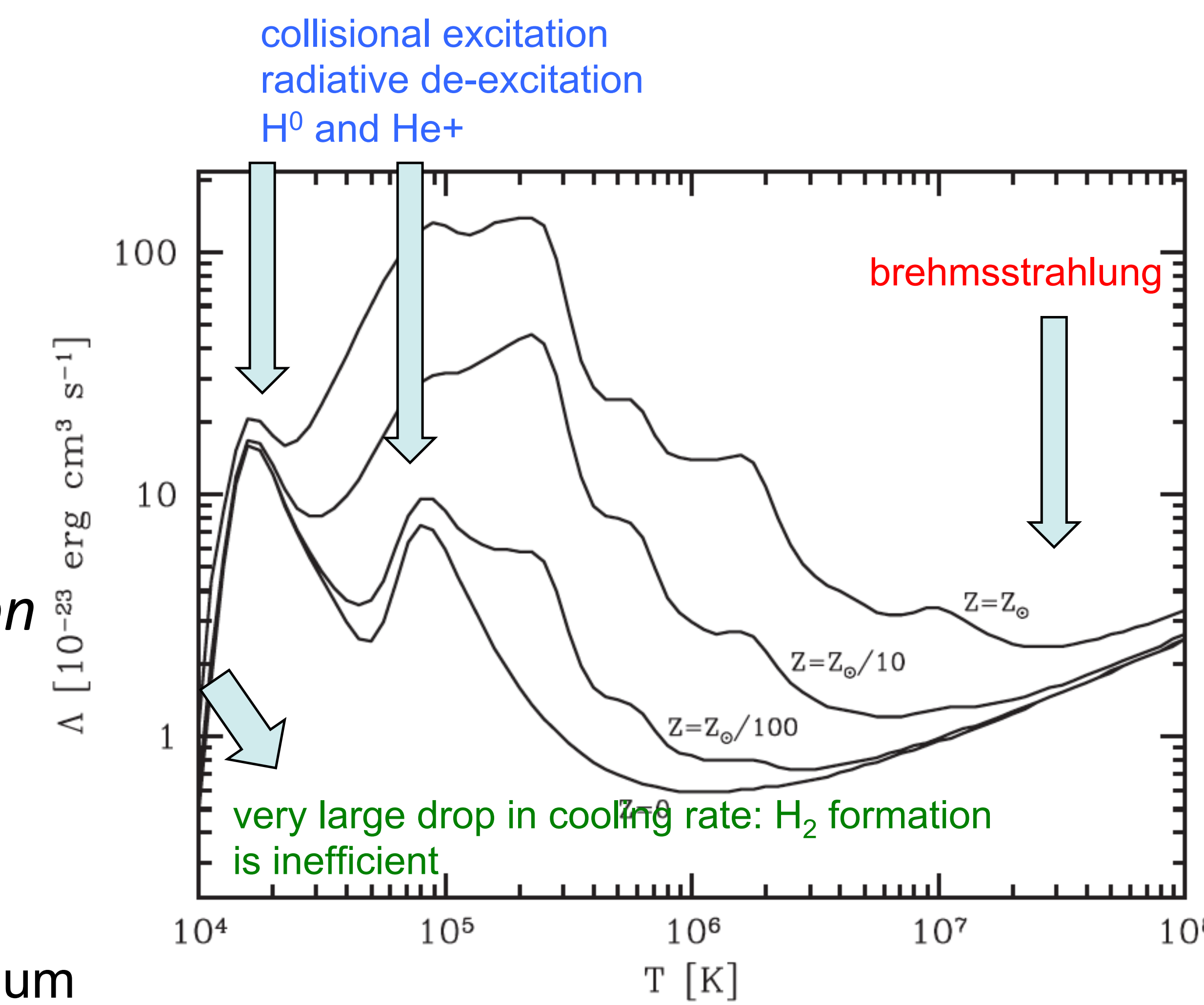
Radiative cooling: gas loses energy through radiation due to 2-body interactions

- for T > 10^6 K gas is fully ionised, and the free electrons interact with nuclei and produce brehmsstrahlung/free-free emission
- At lower T: collisional ionization; recombination; collisional excitation
- The cooling rates due to these processes can be calculated, assuming the gas is optically thin to the emitted photons
- This is represented by a *cooling function*

$$\Lambda(T) \equiv \frac{\mathscr{C}}{n_{\rm H}^2},$$

$$\mathscr{C} = \int \varepsilon_{\rm ff}(\nu)\,{\rm d}\nu \approx 1.4\times 10^{-23} T_8^{1/2}\left(\frac{n_{\rm e}}{\rm cm^{-3}}\right)^2 {\rm erg\,s^{-1}\,cm^{-3}},$$

$\mathscr{C}$ = cooling rate



Plot assumes ionization equilibrium

Gas cooling: timescales

- The cooling time = thermal energy density of the gas/cooling rate

$$t_{\rm cool}(r) = \left(\frac{3}{2}\frac{\rho_{\rm gas} k T_{\rm vir}}{\mu m_{\rm H}}\right) / \left(\rho^2_{\rm gas}\Lambda(T_{\rm vir}, Z_{\rm gas})\right)$$

ρ_{gas} is the density of the gas (and function of *r*)

- Gas within r_{cool} (the radius at which $t_{cool}(r_{cool}) = t_{dyn} = R_{vir}/V_{vir} < t_H$) is allowed to cool

Virial radius r_vir is defined such that matter density inside is 100-200x critical density

- The rate of cooling is given by $\dot{m}_{\rm cool} = 4\pi\rho_{\rm g}(r_{\rm cool})r^2_{\rm cool}\dot{r}_{\rm cool}.$
- Most systems with $M_{vir} < 2\text{-}3\ 10^{11}\ M_{sun}$ have $r_{cool} \sim R_{vir}$ (very short cooling times), more massive systems sustain a hot halo $r_{cool} < R_{vir}$

- Gas heating can also happen
  - Photoionization in a radiation field/UV background (QSOs, massive stars), leads to IGM temperature $T \sim 10^4$ K, accretion onto halos with lower T_{vir} is suppressed.
  - Energy released by SN explosions, make gas more diffuse, thermal conduction, black hole accretion and jets….

Star formation

- Process is not well-understood, so use scalings/observationally motivated prescriptions:

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

- The m_{crit} corresponds to there being a surface density below which no SF is seen in galaxies

$$\Sigma_{crit}(R) = 120\left(\frac{V_{vir}}{200\ \mathrm{km\ s^{-1}}}\right)\left(\frac{R}{\mathrm{kpc}}\right)^{-1} \mathrm{M_\odot\ pc^{-2}}. \qquad m_{crit} = 3.8 \times 10^9\left(\frac{V_{vir}}{200\ \mathrm{km\ s^{-1}}}\right)\left(\frac{r_{disc}}{10\ \mathrm{kpc}}\right) \mathrm{M_\odot}$$

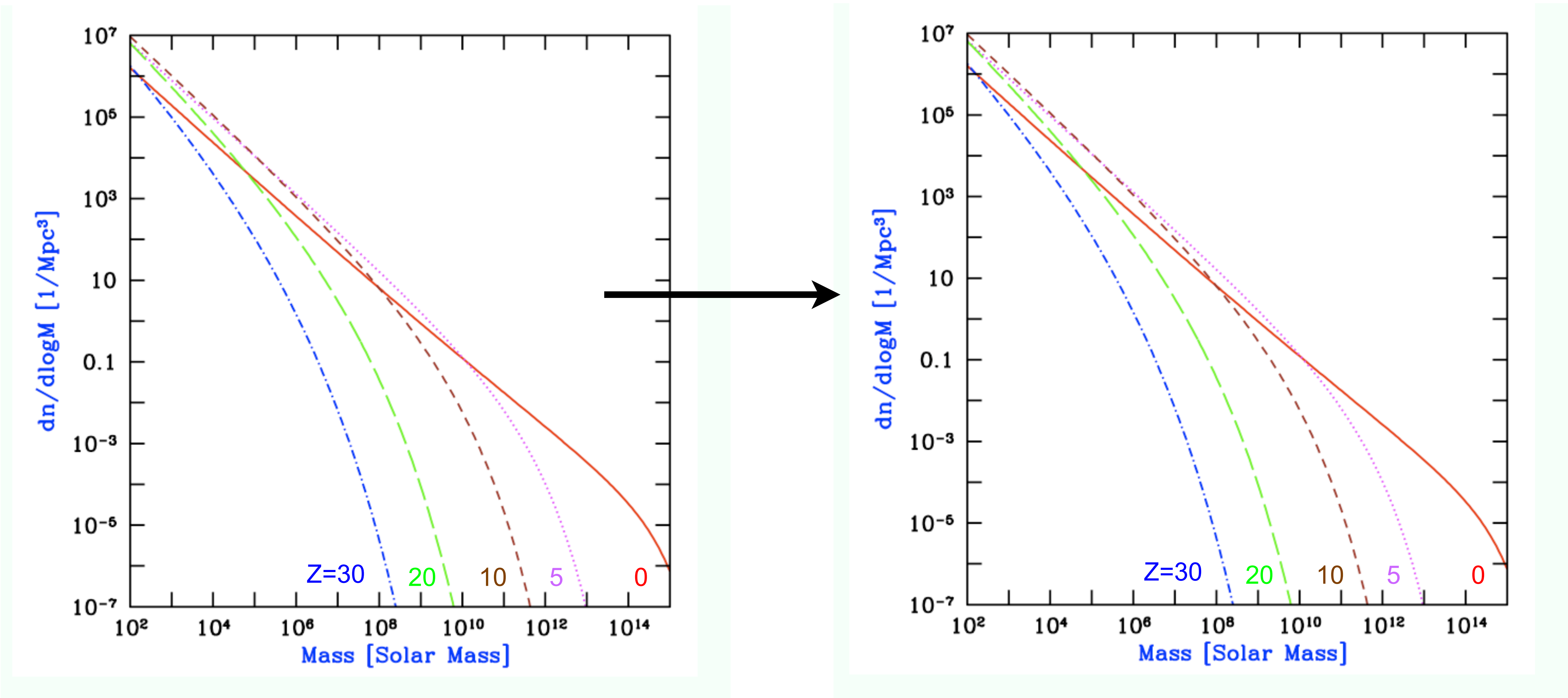
  - Disk scale-length is $r_s = (\lambda/\sqrt{2})R_{vir}$ (λ is halo spin parameter), and disk radius is $r_{disc} = 3r_s$

- α_{SF} is a **parameter** (efficiency): typical values are 5 – 15%

- Given a certain SFR, or mass in stars, need to establish how many stars of each mass are born: **choice of the IMF** (Salpeter, Kroupa, Scalo)
- Star formation occurs slowly in disks and otherwise in starbursts (e.g. mergers)

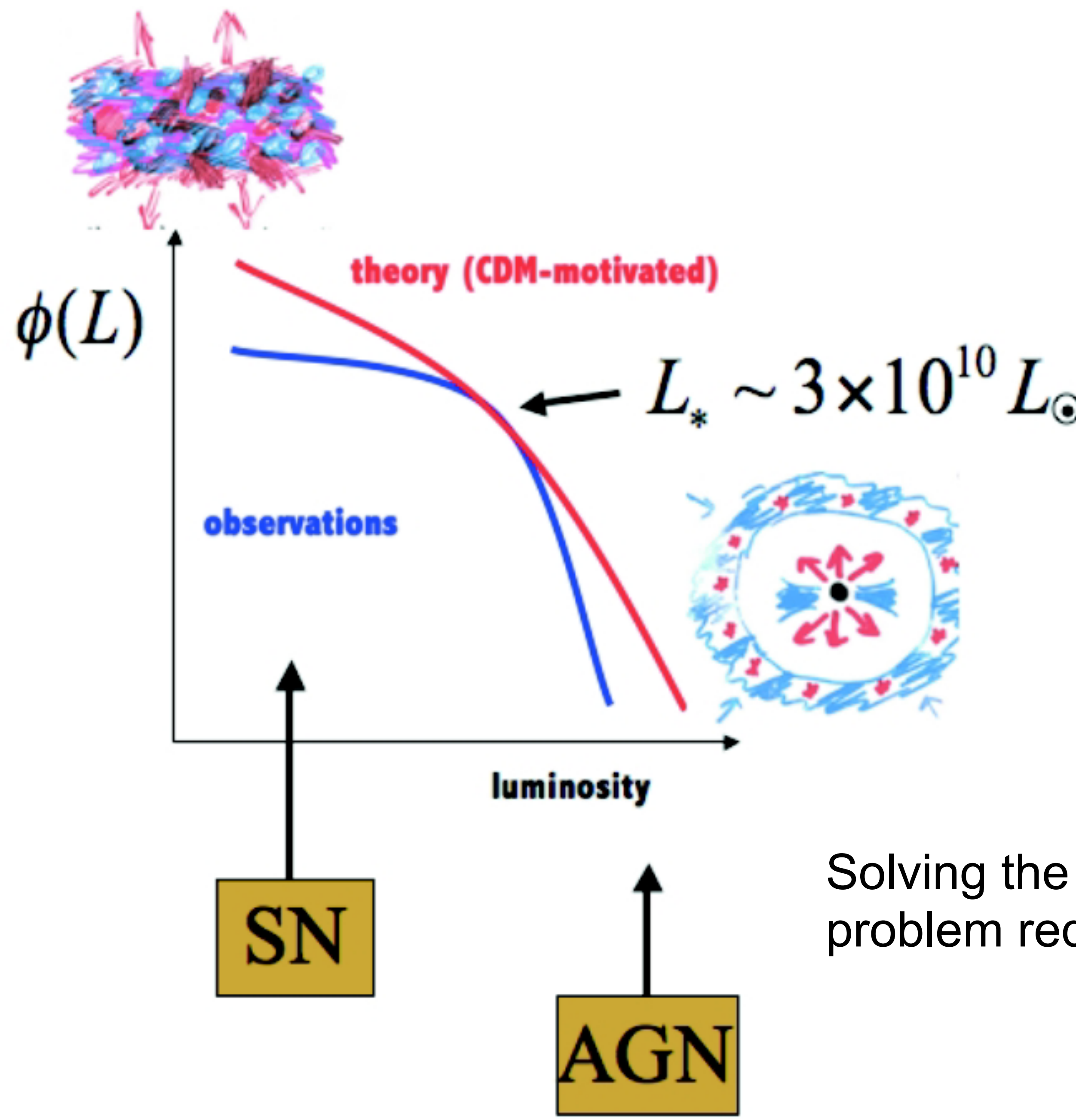
But only including gas cooling + star formation results in a problem..

If each halo had a constant gas to DM ratio and could form stars, what shape would this “luminosity function” (number of galaxies as function of luminosity) have?



Remember number of halos as function of mass = halo mass function

This is called the over-cooling problem - without feedback, galaxies produce too many stars



Solving the over-cooling problem requires feedback

http://arxiv.org/pdf/1102.0283v1.pdf - this is a very good review on feedback by Joe Silk

The picture with feedback

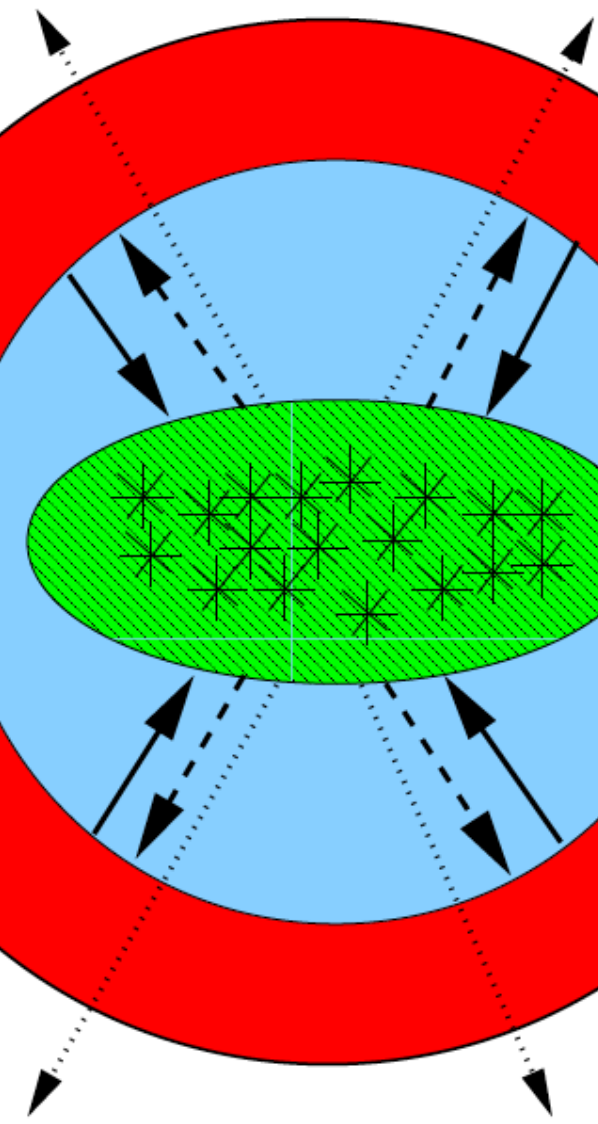


Figure 10. A schematic figure showing gas cooling from the hot halo (solid lines) and building up the reservoir of cold gas in the galactic disc. The cooled gas is turned into stars on a timescale set by the parameters of the model. Supernova explosions can reheat a fraction of the cooled gas and return it to the hot phase (dashed lines) or eject material from the halo altogether (dotted lines).

Feedback: many options/choices

- There are many prescriptions on feedback by SN (De Lucia et al. 2004)

$$\Delta M_{\rm reheat} = \frac{4}{3}\epsilon\frac{V_{\rm SN}^2}{V_{\rm vir}^2}\Delta M_*.$$

- In this case, the mass reheated depends also on the properties of the host halo, i.e. the amount of mass reheated per unit stellar mass formed is larger for a small galaxy than for a big galaxy
  - Feedback is more efficient/damaging for small galaxies like the dwarfs

- Feedback by AGN: energy released by accretion onto SMBH
  - very poorly constrained process
  - needed to model high-mass end of luminosity function (supression of cooling flow from hot halo for most massive galaxies)
  - to explain correlations between SMBH and host halo

Other processes

- Chemical evolution: return to the ISM of heavy elements synthesized in stars (winds, SNI, SNII)…
  - where to place it (hot, cold, ejected phases of the gas)
  - how much (not very well-known/constrained)

- Reionization: UV background heats gas, prevents further cooling in small halos
  - parametrization is global, but process is likely to be local (depending on nearby sources)

- Mergers and timescales
  - with N-body simulations, follow dark matter halos
  - Need prescription for merging or destruction timescale of stellar components of galaxies

The inclusion of "AGN feedback" helps to obtain better shape of LF, and also for ages of most massive galaxies

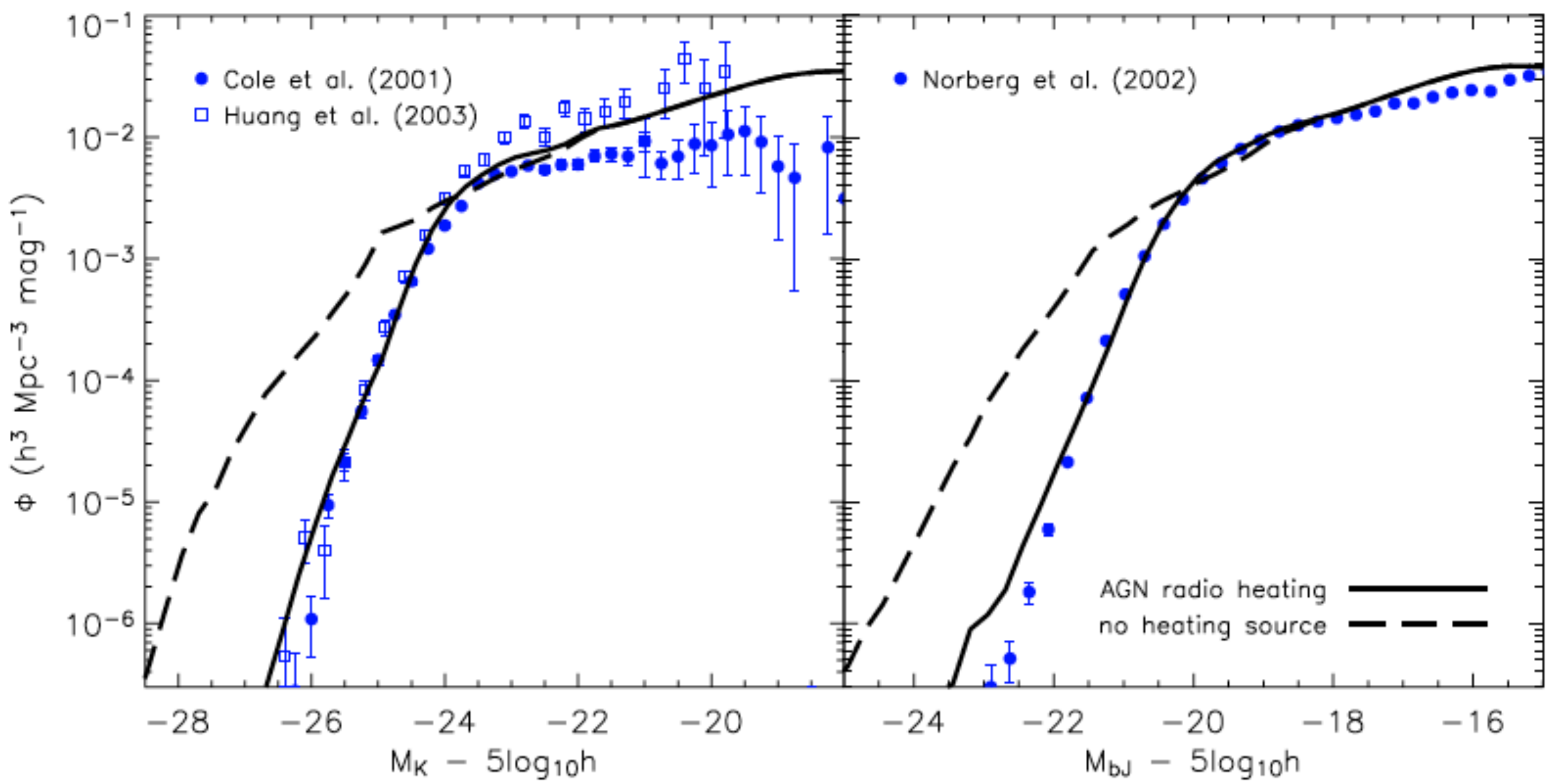


Figure 8. Galaxy luminosity functions in the K (left) and b_J (right) photometric bands, plotted with and without 'radio mode' feedback (solid and long-dashed lines respectively – see Section 3.4). Symbols indicate observational results as listed in each panel. As can be seen, the inclusion of AGN heating produces a good fit to the data in both colours. Without this heating source our model overpredicts the luminosities of massive galaxies by about two magnitudes and fails to reproduce the sharp bright-end cut-offs in the observed luminosity functions.

Croton et al. 2005

Linking galaxies and dark matter haloes

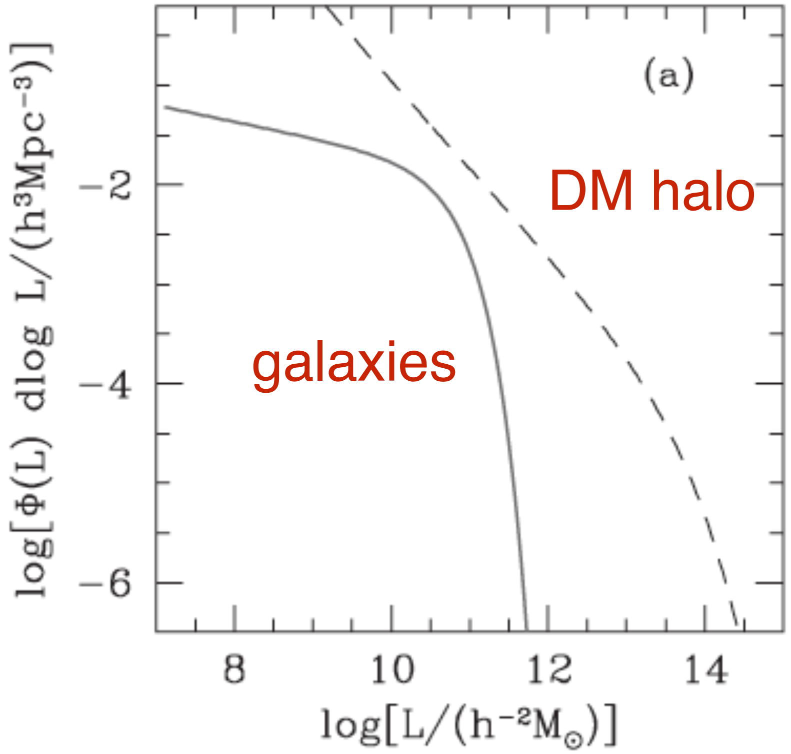
Linking halos to galaxies

- In current paradigm, galaxies are embedded in dark matter halos
- Since we understand/can predict the distribution of dark matter halos from first principles from simulations/EPS, we can attempt, in simple terms to see how we can link galaxies to dark matter halos (without the full SA modeling machinery)
- The simplest assumption is that the luminosity of a galaxy is directly proportional to the mass of its dark halo:

$$L = \frac{\varepsilon_{\rm SF}}{\Upsilon_\star} M_{\rm baryon} = \frac{\varepsilon_{\rm SF}}{\Upsilon_\star} \frac{\Omega_{\rm b,0}}{\Omega_{\rm m,0}} M.$$

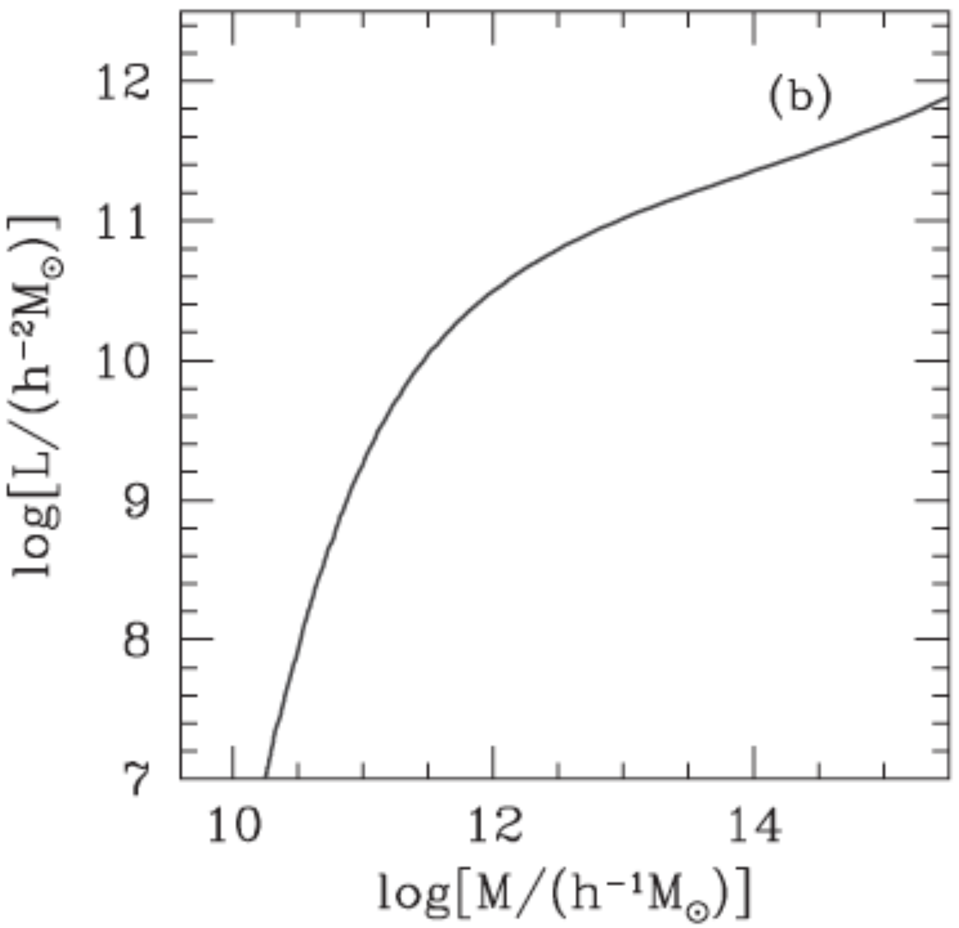
where ε_{SF} is a star formation efficiency,
Υ_* the stellar mass-to-light ratio of the population

The dashed curve shows the prediction for $\varepsilon_{SF} = \Upsilon_* = 1$ → it does not match the observed LF (solid)



- Let's assume there is a direct monotonic functional relation between L and M.
- The easiest is to solve for L as function of M such that $\int_L^\infty \phi(L')dL' = \int_M^\infty n(M')dM'$

Plot shows L is a function of mass, and since $L/M = \varepsilon_{SF}/\Upsilon_*$,
→ if we assume all galaxies have the same stellar populations (not quite correct, but a secondary effect), this implies that ε_{SF} *star-formation efficiency strongly depends on dark halo mass.*



•Very steep for low masses, and slower dependence at high mass end ("preferred" scale at M ~ 10^{12} Msun)
•Not so surprising given what we learned about star formation and feedback.

•For example, take a galaxy where SF is enough to make SN blow the rest of the gas out of the halo (dwarf scale): $\varepsilon_{SF} \sim V_c^2 \rightarrow L \sim M V_c^2 = M^{5/3}$

•In massive galaxies, 3 processes affect the shape: radiative cooling longer than Hubble time; AGN feedback input energy; growth via mergers may be slow because timescales are longer

Abundance matching techniques

- Prescription is to assign most massive halos (from a simulation) to most massive galaxies (from an observed dataset), and assume that the relation is *monotonic*

$$n_g(> M_{\mathrm{star},i}) = n_h(> M_{\mathrm{vir},i}),$$

- This allows one to construct a stellar mass – halo mass relationship
  - care is required with satellites, whose mass should be that at infall

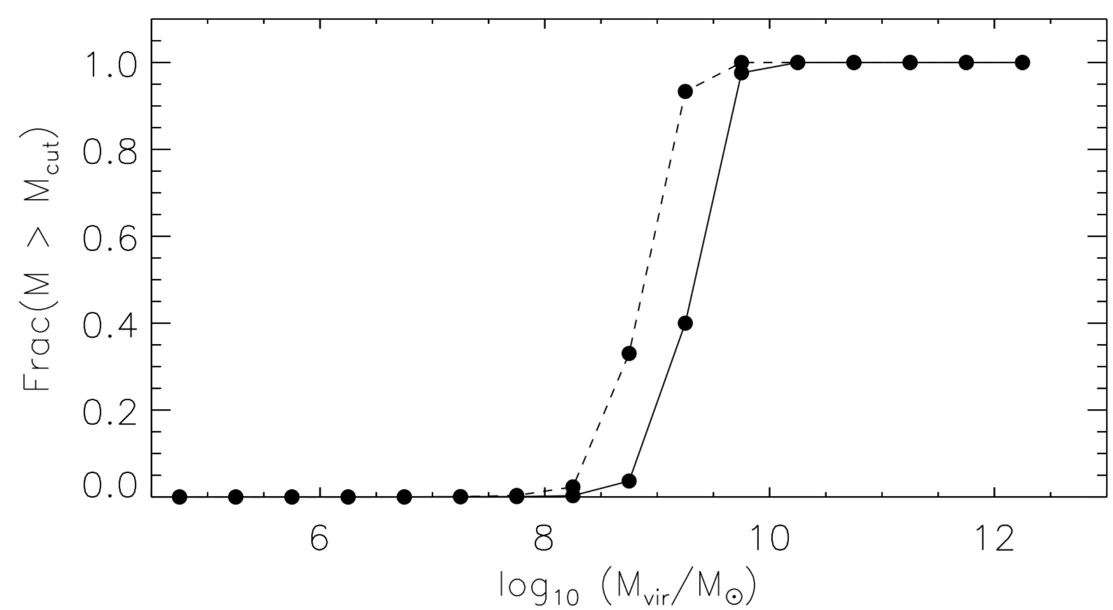
- Since more massive halos are most clustered, the result is that brighter galaxies are more clustered in agreement with observations (Zehavi et al. 2005)
- Prescription also works in reproducing mass-to-light ratios, clustering measurements and counts of pairs (and properties), galaxy-galaxy lensing, relation between SMBH mass and circular velocity of host, e.g. Vale & Ostriker (2004); Conroy et al. (2006)
- If one can obtain how this varies with time (by calibration with surveys), then many properties of galaxies can be studied as function of time

Abundance matching at faint end

- At the faint end there are large uncertainties
  - observationally the faint end slope is more poorly determined
- Not clear that the assumption that there is a monotonic relation between M^* and M_{DM} holds, i.e. there can be scales below which galaxy formation is selective in which halos can host a stellar component
  - reionization, HI cooling, backgrounds whose intensity vary with redshift…

•SA model coupled to a high-resolution DM only simulation, shows that below a certain mass $M_{DM} \sim 10^{10}$, a lower fraction of halos are expected to host galaxies (this ensures a good fit to the LF, HI mass function)
•Similar results are found in simulations (Sawala et al. 2015)
•Which halos these are depends on their assembly history…

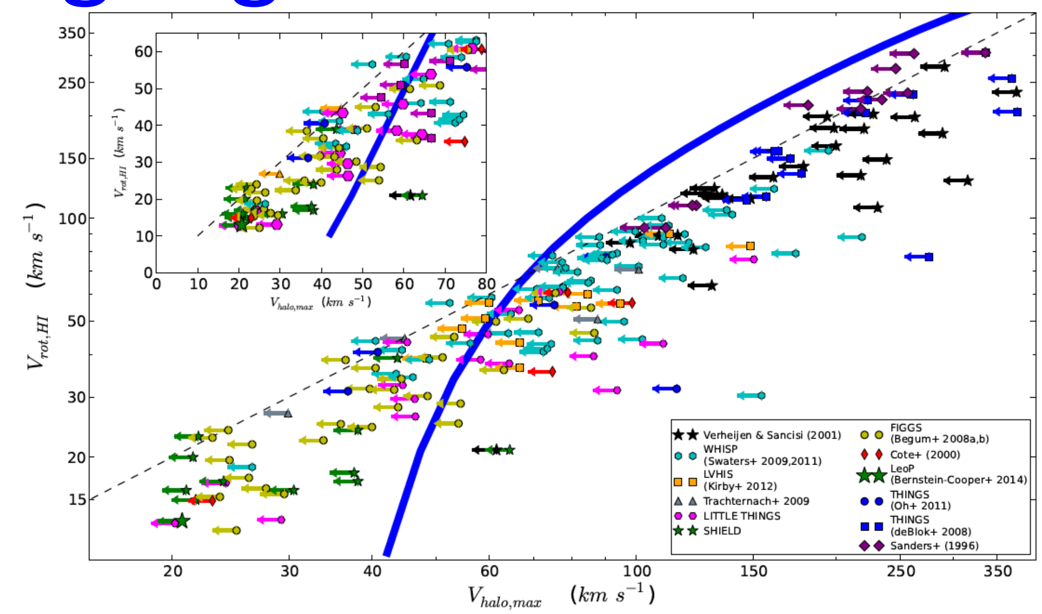
Yaryura et al. 2015



Abundance matching: are the right halos assigned to the right galaxies?

- Observations: galaxies of v_{rot} ~ 20-30 km/s in halos of V_{max} ~ 20 – 40 km/s (fit to rot. curve)
- Simple (in velocity) abundance matching predicts host halos of V_{max} ~ 50 km/s
  → *mismatch of cosmological model?*

Problem: Abundance matching fails because history matters/thresholds

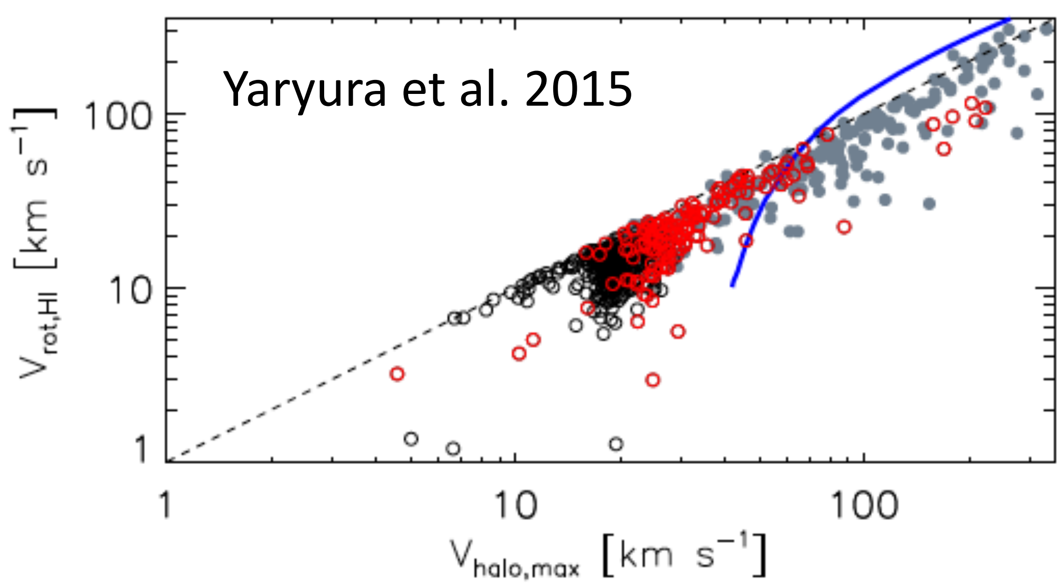


Papastergis et al. 2014

If one uses SA model:

- 50% of halos with M_{vir} ~ $10^{9.5}$ M_{sun} are dark
- full prescription for SF, feedback, gas cooling etc, makes SA model select more concentrated halos (collapsed earlier) to hos dwarf galaxies

→ Model (red) and observations (grey) in agreement



Hydrodynamical Simulations

Hydrodynamical simulations

- Backbone: cosmological model
- Initially gas and dark matter follow similar distributions
- Gravity: affecting both components
- Hydrodynamics: to model
  - cooling + heating
  - star formation
  - feedback (winds, SN explosions, AGN)
  - …

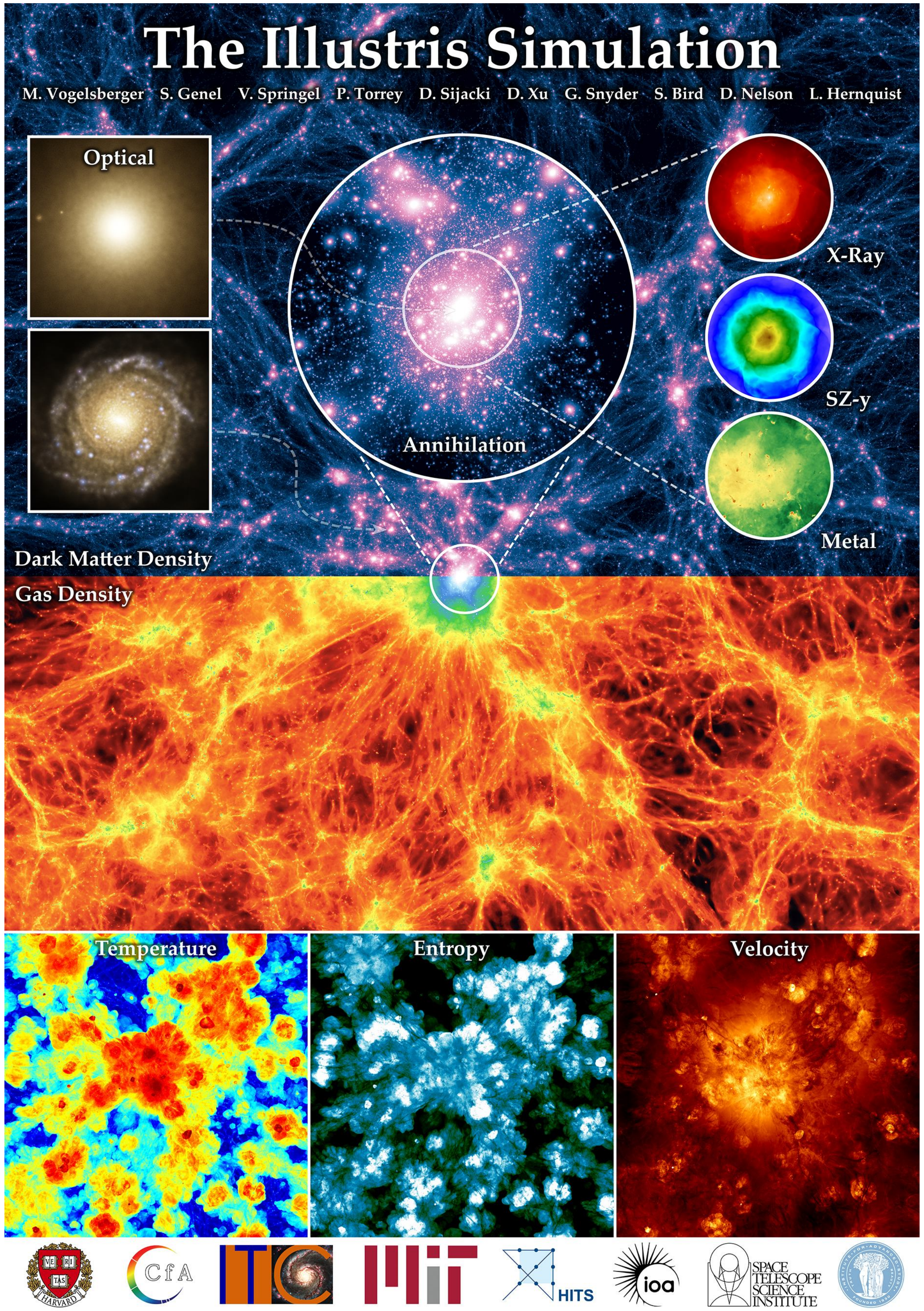
- Issues/limitations: poor understanding of all the physics in detail + numerical implementation (resolution from smallest to largest scales)
- Physics on scales below the numerical resolution are modeled as recipes, i.e the “subgrid” processes are represented in a coarse-way
  - For example, star formation within a fluid element is modeled as a Schmidt law, i.e. the rate of star formation is proportional to the local volume density of the gas, and does not take into account the details of processes happening on molecular cloud scales

- Feedback is modeled through injection of energy (kicks, momentum, energy) to the particles following different prescriptions (Governato et al. 2010, Vogelsberger et al. 2014, Schaye et al. 2014)… None of these actually model the SN explosion and evolution of the remnant
- something similar for AGN feedback

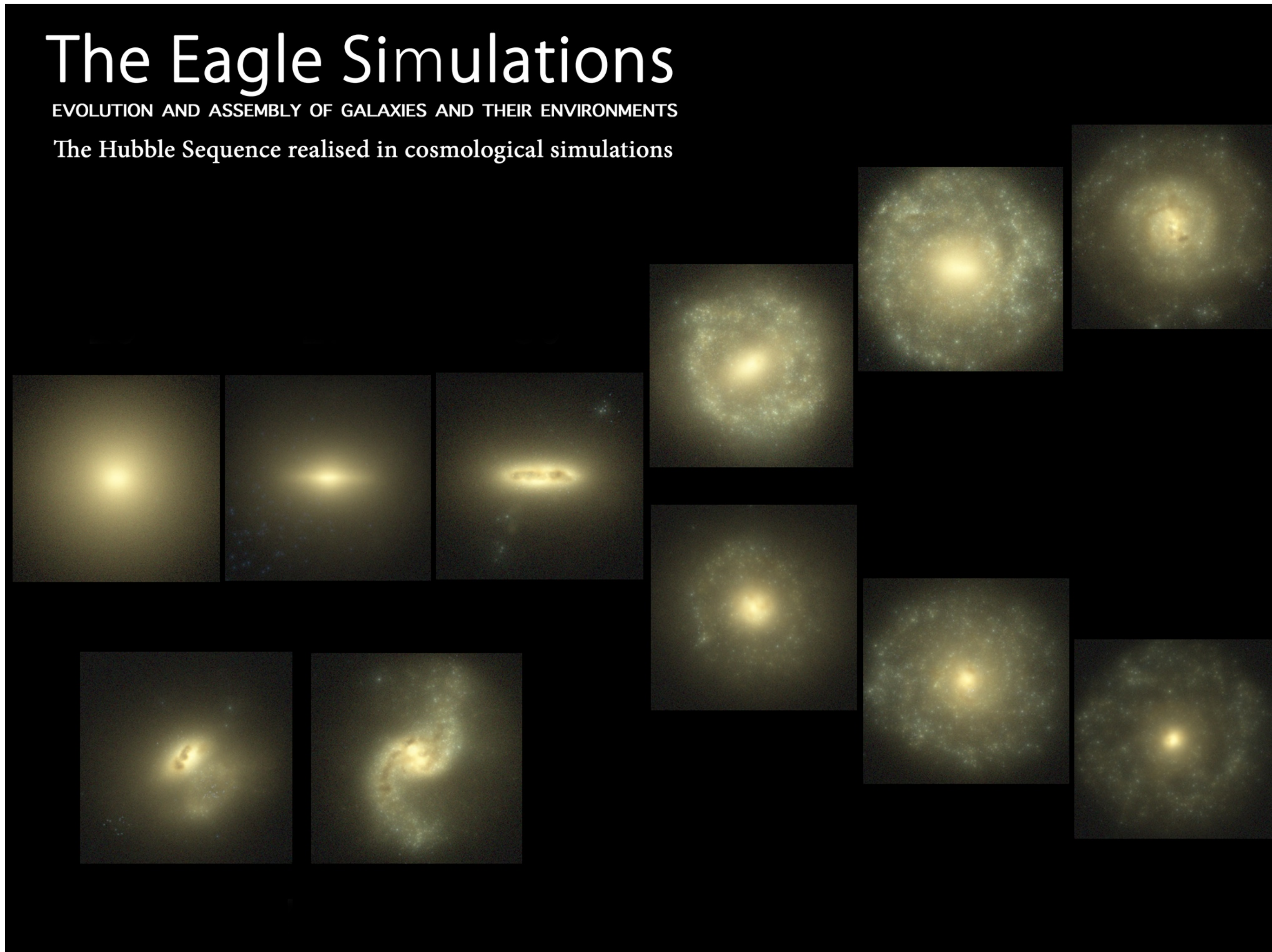
- However, hydrosimulations have advantages compared to SA models as well
  - the formation and evolution of dark matter halos is followed in detail and accurately
  - the coupling between baryons and dark matter is modeled automatically (without the need for recipes to describe how dark matter behaves when a disk forms, etc)
  - cooling is modeled fully, beyond spherical symmetry or quasi-static equilibrium
  - the impact of SN or winds can be modeled directly onto the different gas phases, without simplifications of the physics
  - inhomogeneities in star formation, ISM, gas phases are taking into account
  - timescales for mergers and destruction of galaxies via tides are all naturally incorporated (without recipes, just via integration of the equations of motions)
  - impact of environment (i.e. reionization, gas stripping when a galaxy falls into a cluster) directly incorporated
  - …

Cosmological hydro-simulations

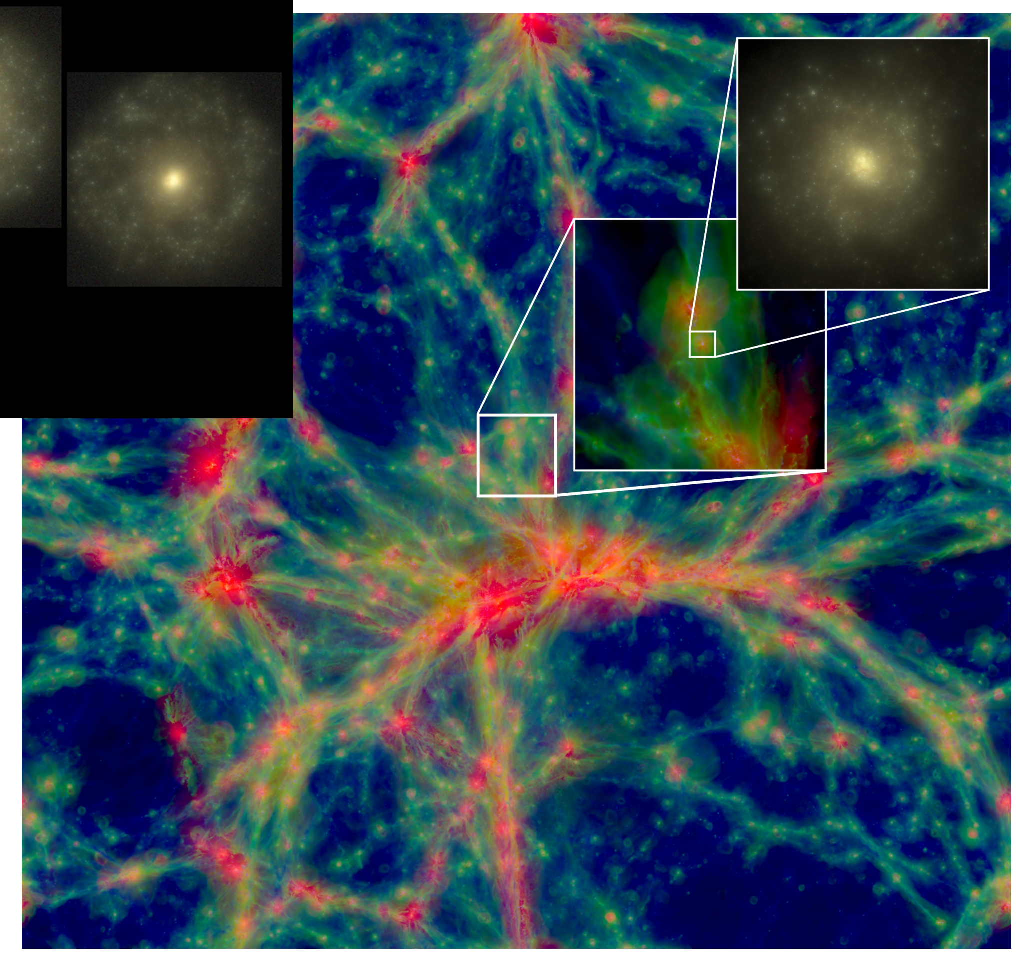
- The main compromise is between box size (volume to be simulated) and spatial resolution
  - in large volumes used to study the galaxy population, but galaxies are poorly resolved, i.e. internal structure is not reliably modeled
  - in small volumes, internal structure is resolved but products might depend on choice of initial conditions, and the effect of the environment cannot be well-addressed.
- To derive the properties of galaxies, i.e color, luminosities, one uses SFH from the simulations, and these translate into L and colors using stellar population codes
  - recall that stars are not individually modeled, in the best simulations to date (Vogelsberger et al. 2014++) the baryonic mass per particle is ~ 1.3 x 10^6 M_{sun}, → at best it could be argued this represents a "star cluster" <u>Update:</u> resolution reaches 10^3 - 10^4 Msun
- Catalogues can be produced to study sizes, mass growth histories, SFR, etc as function of environment, and time.



http://www.illustris-project.org/



Eagle: PI Schaye and the Virgo consortium



http://eagle.strw.leidenuniv.nl/
for movies, pictures and more information

Summary of Galaxy Formation Simulations

Table 2: Recent structure and galaxy formation simulations

simulation	volume	method[a]	mass resolution[b]	spatial resolution[c]	primary reference
	[Mpc^3]		[M$_\odot$]	[kpc]	
dark matter-only					
Millennium	685^3	TreePM	$1.2\times10^9/-$	$6.85/-$	Springel et al. (2005b)[368]
Millennium-2	137^3	TreePM	$9.4\times10^6/-$	$1.37/-$	Boylan-Kolchin et al. (2009)[369]
Horizon 4π	2740^3	PM/ML	$7.7\times10^9/-$	$10.41/-$	Teyssier et al. (2009)[370]
Bolshoi	357^3	PM/ML	$1.9\times10^8/-$	$1.43/-$	Klypin et al. (2011)[371]
Full Universe Run	29167^3	PM/ML	$1.4\times10^{12}/-$	$55.6/-$	Alimi et al. (2012)[372]
Millennium-XXL	4110^3	TreePM	$8.5\times10^9/-$	$13.7/-$	Angulo et al. (2012)[82]
MultiDark	1429^3	PM/ML	$1.2\times10^{10}/-$	$10/-$	Prada et al. (2012)[373]
Dark Sky	11628^3	Tree/FM	$5.7\times10^{10}/-$	$53.49/-$	Skillman et al. (2014)[54]
ν^2GC	1647^3	TreePM	$3.2\times10^8/-$	$6.28/-$	Ishiyama et al. (2015)[374]
Q Continuum	1300^3	TreePM/P^{3}M	$1.5\times10^8/-$	$2.82/-$	Heitmann et al. (2015)[84]
OuterRim	4225^3	TreePM/P^{3}M	$2.6\times10^9/-$	$6.0/-$	Habib et al. (2016)[46]
EuclidFlagship	20000^3	Tree/FM	$10^9/-$	$5/-$	Potter et al. (2017)[47]
Aquarius	zoom	TreePM	$1.7\times10^3/-$	$0.02/-$	Springel et al. (2008)[104]
Via Lactea II	zoom	Tree	$4.1\times10^3/-$	$0.04/-$	Diemand et al. (2008)[375]
GHALO	zoom	Tree	$1.0\times10^3/-$	$0.06/-$	Stadel et al. (2009)[376]
CLUES	zoom	TreePM	$3.4\times10^5/-$	$0.21/-$	Libeskind et al. (2010)[377]
Phoenix	zoom	TreePM	$8.7\times10^5/-$	$0.21/-$	Gao et al. (2012)[105]
ELVIS	zoom	TreePM	$1.9\times10^5/-$	$0.14/-$	Garrison-Kimmel et al. (2014)[378]
COCO	zoom	TreePM	$1.6\times10^5/-$	$0.33/-$	Hellwing et al. (2016)[379]
+ baryons					
Illustris	107^3	TreePM+MMFV	$6.7\times10^6/1.3\times10^6$	$1.42/0.71$	Vogelsberger et al. (2014)[149]
Horizon-AGN	142^3	PM/ML+AMR	$8.0\times10^7/1.0\times10^7$	$1.0/1.0$	Dubois et al. (2014)[380]
EAGLE	100^3	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	$0.7/0.7$	Schaye et al. (2015)[124]
MassiveBlack-2	143^3	TreePM+SPH	$1.6\times10^7/3.2\times10^6$	$2.64/2.64$	Khandai et al. (2015)[381]
Bluetides[d]	574^3	TreePM+SPH	$1.7\times10^7/3.4\times10^6$	$0.24/0.24$	Feng et al. (2016)[382]
Magneticum	68^3	TreePM+SPH	$5.3\times10^7/1.1\times10^7$	$1.4/0.7$-1.4	Bocquet et al. (2016)[85]
MUFASA	74^3	TreePM+MLFM	$9.6\times10^7/1.8\times10^7$	$0.74/0.74$	Daveé et al. (2016)[383]
BAHAMAS	571^3	TreePM+SPH	$5.5\times10^9/1.1\times10^9$	$0.25/0.25$	McCarthy et al. (2017)[384]
Romulus25	25^3	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	$0.25/0.25$	Tremmel et al. (2017)[385]
IllustrisTNG[e]	111^3	TreePM+MMFV	$7.5\times10^6/1.4\times10^6$	$0.74/0.19$	Springel et al. (2018)[87]
Simba[f]	147^3	TreePM+MLFM	$1.4\times10^8/2.7\times10^7$	$0.74/0.74$	Davé et al. (2019)[182]
Eris	zoom	Tree+SPH	$9.8\times10^4/2\times10^4$	$0.12/0.12$	Guedes et al. (2011)[349]
VELA	zoom	PM/ML + AMR	$8.3\times10^4/1.9\times10^5$	$0.03/0.03$[g]	Ceverino et al. (2014)[386]
NIHAO	zoom	Tree+SPH	$3.4\times10^3/6.2\times10^2$	$0.12/0.05$	Wang et al. (2015)[125]
APOSTLE	zoom	TreePM+SPH	$5.0\times10^4/1.0\times10^4$	$0.13/0.13$	Sawala et al. (2016)[387]
Latte/FIRE	zoom	TreePM+MLFM	$3.5\times10^4/7.1\times10^3$	$0.02/0.001$	Wetzel et al. (2016)[352]
Auriga	zoom	TreePM+MMFV	$4.0\times10^4/6.0\times10^3$	$0.18/0.18$[h]	Grand et al. (2017)[297]
MACSIS	zoom	TreePM+SPH	$6.4\times10^9/1.2\times10^9$	$5.77/5.77$	Barnes et al. (2017)[388]
Cluster-EAGLE	zoom	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	$0.7/0.7$	Barnes et al. (2017)[126]
The Three Hundred Project	zoom	TreePM+SPH	$1.9\times10^9/3.5\times10^8$	$9.59/9.59$	Cui et al. (2018)[389]
FABLE	zoom	TreePM+MMFV	$8.1\times10^7/1.5\times10^7$	$4.15/4.15$	Henden et al. (2018)[390]
RomulusC	zoom	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	$0.25/0.25$	Tremmel et al. (2019)[391]

[a] PM: particle-mesh; TreePM: tree + PM; FM: fast multipole; P^{3}M: particle-particle-particle-mesh; ML: multilevel; SPH: smoothed particle hydrodynamics; AMR: adaptive-mesh-refinement; MMFV: moving-mesh finite volume; MLFM: mesh-free finite mass

[b] highest resolution quoted (dark matter/gas)

[c] for particle based codes, the minimum softening length is reported; for mesh codes, the minimum cell size is quoted (dark matter/gas)

[d] final redshift $z = 8$; spatial resolution is in physical units at that redshift

[e] IllustrisTNG consists of three main simulations: TNG50, TNG100, TNG300; numbers are quoted for TNG100

[f] numbers for largest volume simulation quoted

[g] in physical units at $z = 3$

[h] for baryons the minimum physical softening is reported

from Vogelsberger et al. (2020) review

State-of-the-art but several problems

- We do not yet have a predictive model of galaxy formation ←
- Simulations without SN and AGN feedback overpredict the number of (very) small galaxies and of very massive galaxies
- Massive galaxies are too blue (too much cooling and hence present-day SF).
- Supernovae feedback implementation is critical
  - Energy can be quickly absorbed and radiated away (Katz 1992, Ferrara & Mac-Low 1999) as young massive stars that explode as SN do it in dense environments with cold gas
  - Cooling can be switched off temporarily (Gerritsen & Icke 1997; Thacker & Couchman 2000)
  - need to take into account a multi-phase ISM (Springel & Hernquist 2003)

- Prescriptions are somewhat ad-hoc → results need to be taken with caution
- Efforts into testing the different prescriptions/implementations (e.g. EAGLE)