銀河形成シミュレーションの現状と展望

Takashi Okamoto (NAOJ)

Talk plan

- 銀河形成シミュレーションの現状、
  SA model との関係
- 例えばこんな simulation
- AGN feedback
  - SA を眺めながらモデルを組んだ例
- 現在の simulation の問題点
- 展望？

現状

動く
セミアナ

「動く」ことによるメリット

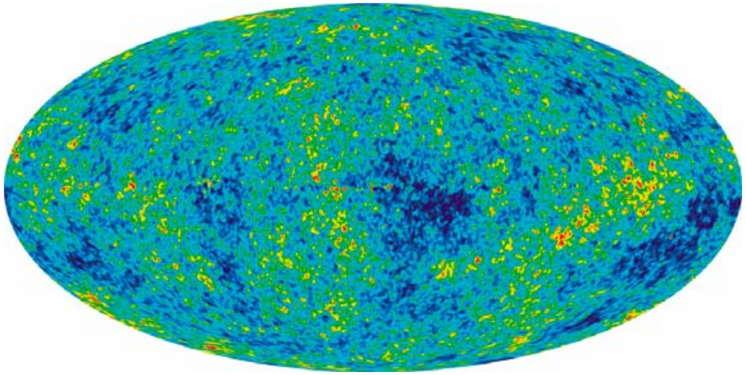
- Local physics
  - Multi-zone
- Dynamics
  - Gaining angular momentum through tidal field
  - Interactions
    - Tidal interaction
    - Mergers
  - Outflows
    - Fountains
    - Winds

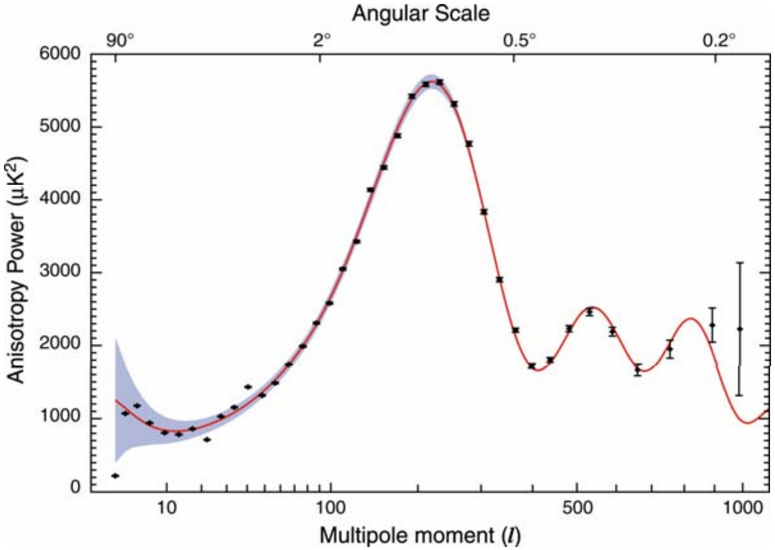
デメリット

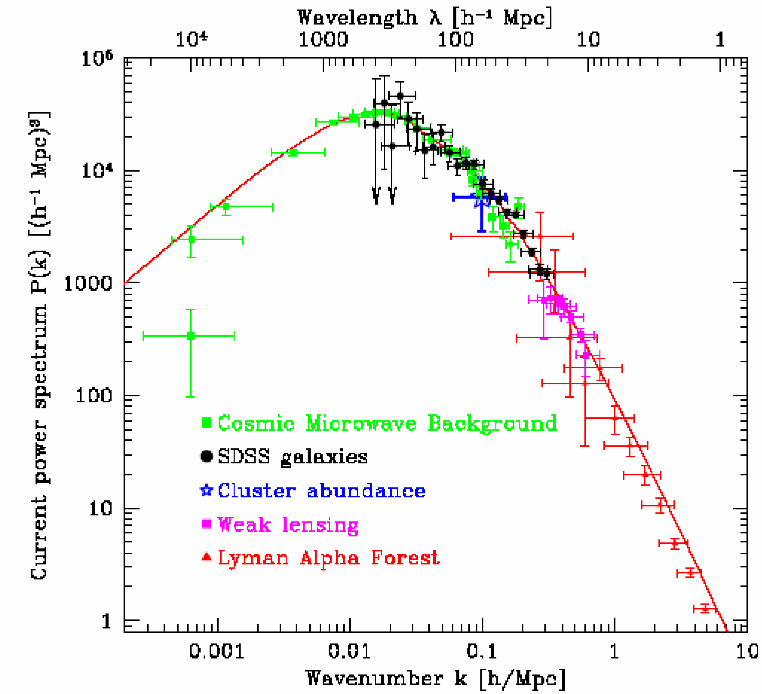
- Expensive
- Numerical effects
- SA model と同じくらいのパラメーター数
  - 「動く」せいで不定性は増す

The initial condition for galaxy formation

- Background cosmology
  - WMAP
  - LSS (2dF, SDSS)
  - Type Ia SNe



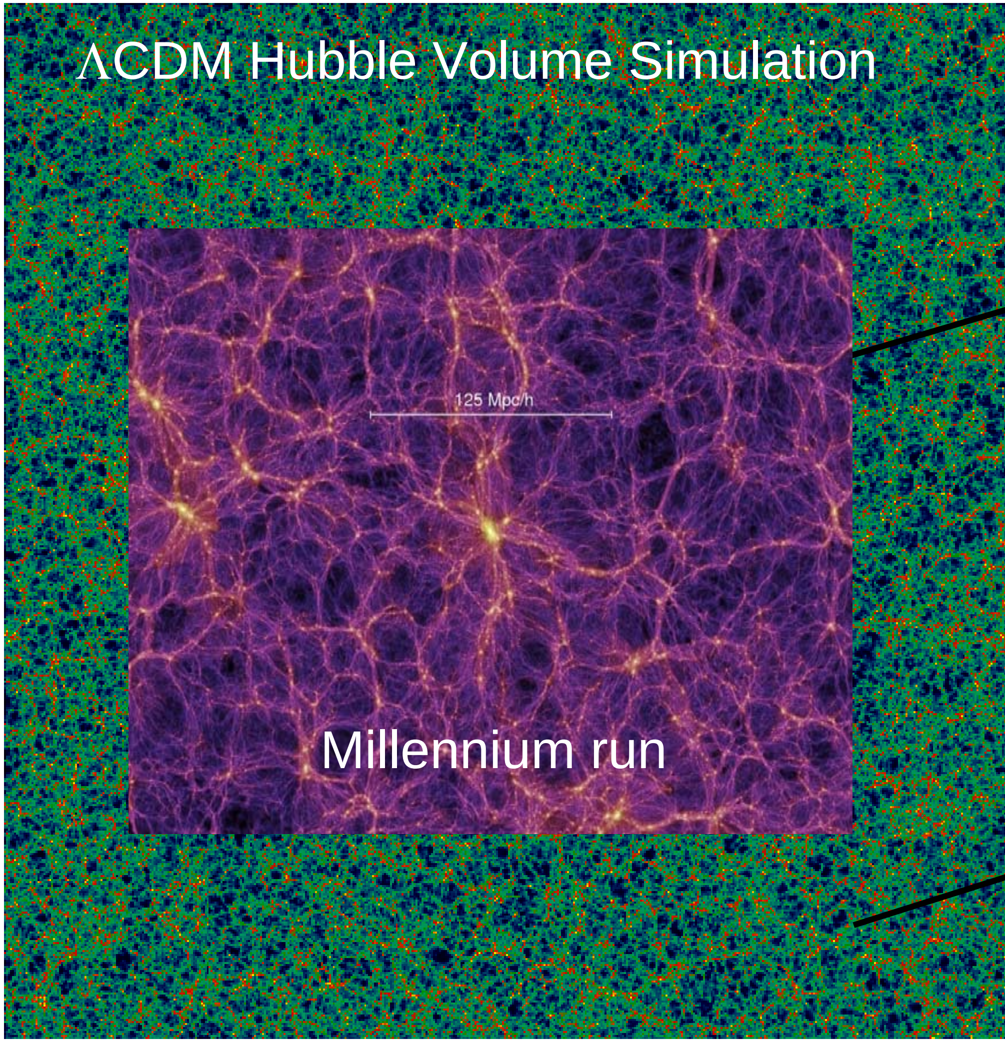




Tegmark et al. 2003

  - ΛCDM

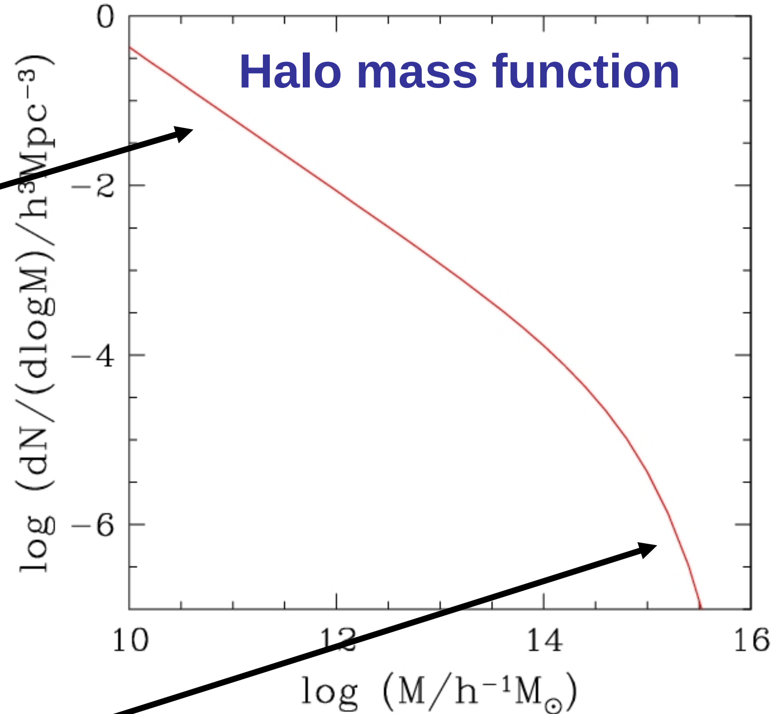
The abundance of dark halos



3000 Mpc/h

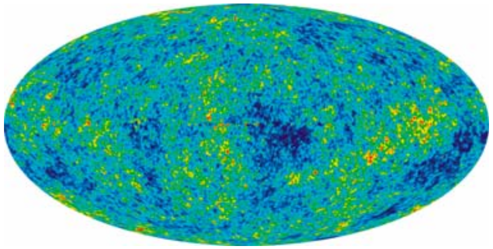
Virgo consortium

ΛCDM

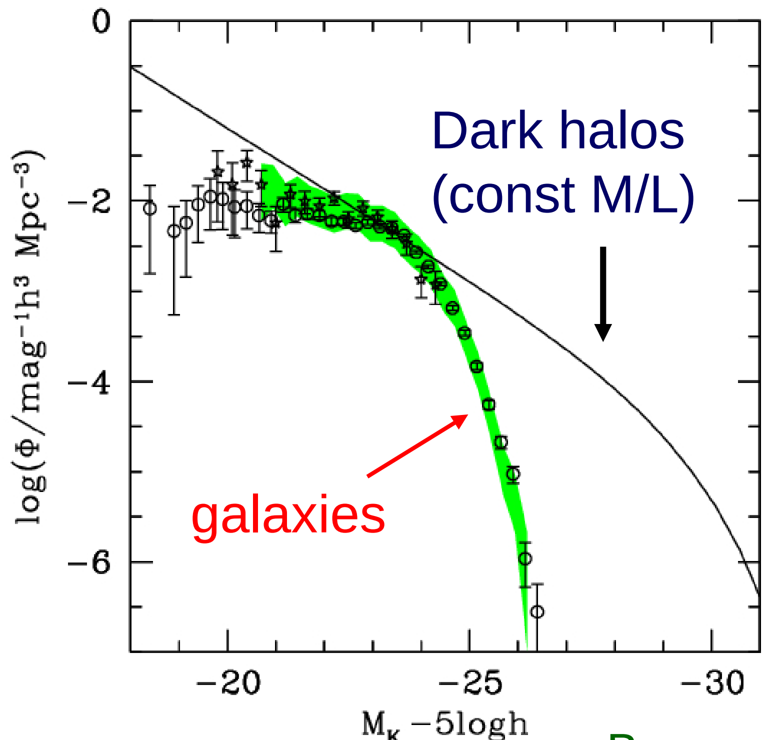


Jenkins+99

Galaxy formation



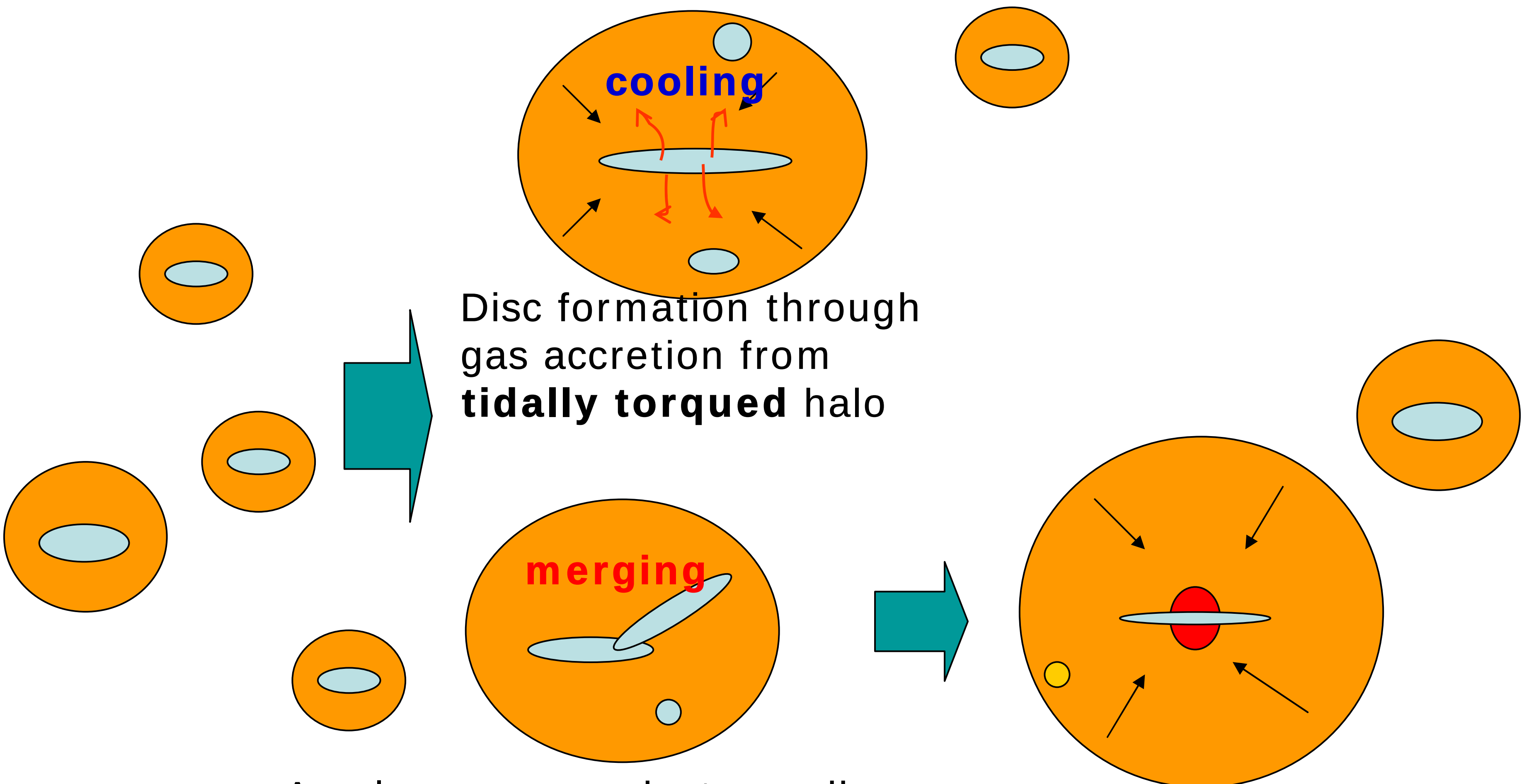
The galaxy luminosity function



Benson+03

Baryonic physics is very important!

A standard picture of galaxy formation



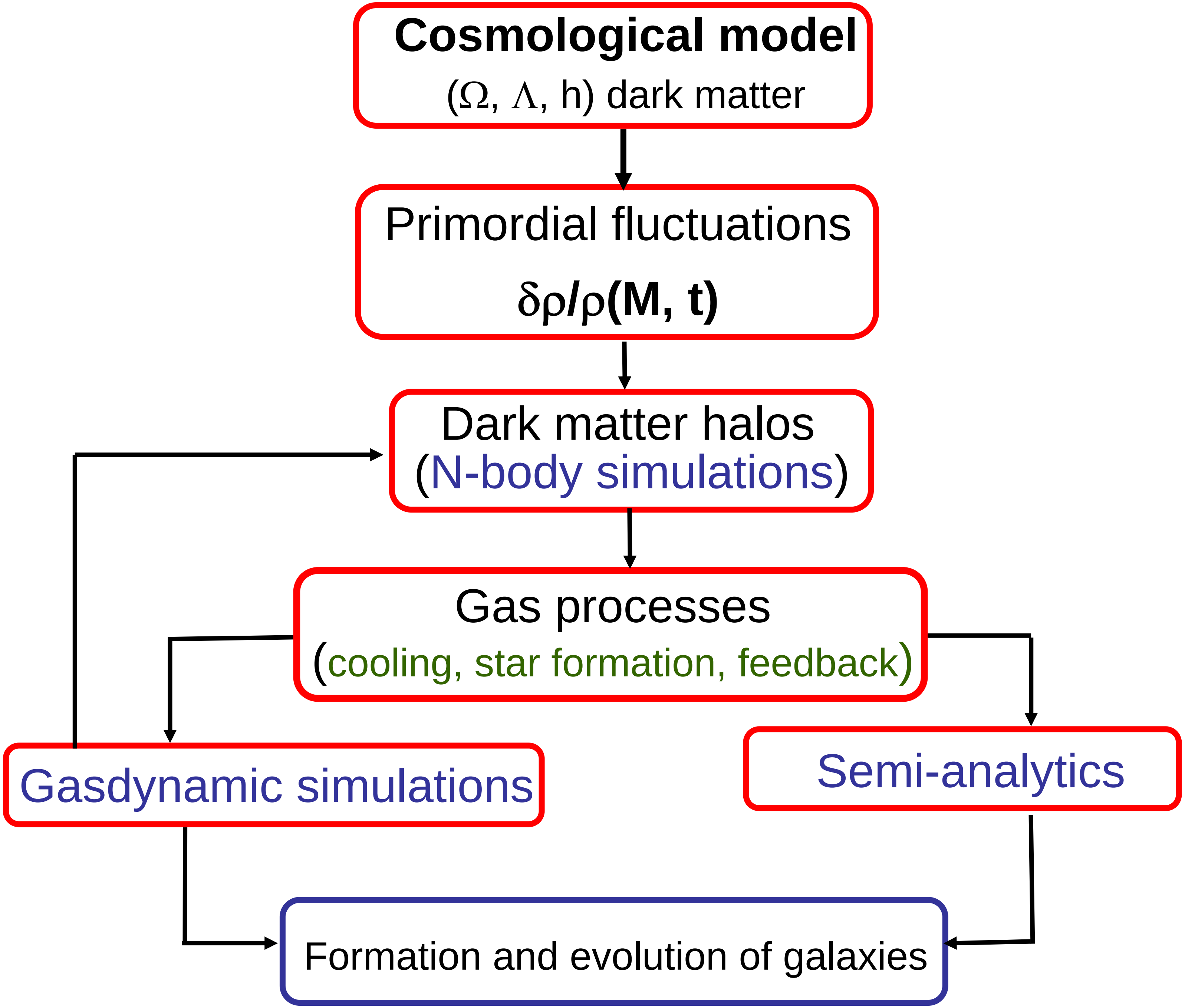
Disc formation through gas accretion from **tidally torqued** halo

A galaxy merger destroys discs and leads to bulge formation

Further cooling forms an additional disc.

Two ways for studying galaxy formation in cosmological context

- Semi-analytic models
  - Halo formation histories (merger tree) from either the extended Press-Schechter theory or cosmological N-body simulations
  - Simple parameterized physics for baryons (SF, cooling, FB, etc.)
  - Fast! -> statistics
- Cosmological simulations (N-body + Hydro)
  - Including hydrodynamics
  - But still modelling is needed for sub-resolution physics (SF, FB, multiphase ISM, etc)
  - Computationally expensive


Cosmological model
(Ω, Λ, h) dark matter
Primordial fluctuations
δρ/ρ(M, t)
Dark matter halos
(N-body simulations)
Gas processes
(cooling, star formation, feedback)
Gasdynamic simulations
Semi-analytics
Formation and evolution of galaxies

Difficulties in cosmological simulations of galaxy formation

- Wide dynamical range
  - From large scale structure to the ISM
- Not well-understood processes
  - Star formation, supernova feedback, etc.
  - These processes operate well below numerical resolution of cosmological simulations
- Need large sample for verifying galaxy formation models

Roles of tidal field

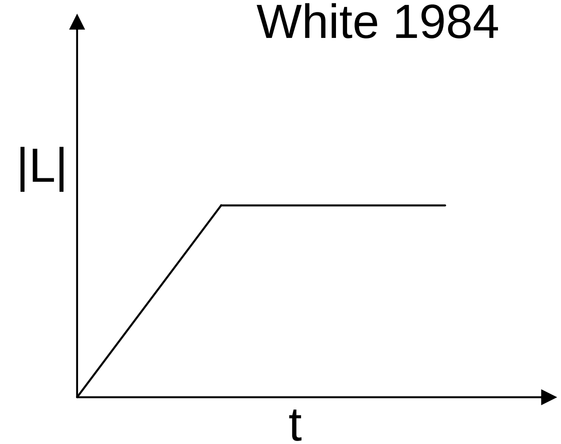
- Spin up proto-halos

$$\mathbf{r} = a(t)\mathbf{x}(t) \approx a(t)[\mathbf{q} - D(t)\nabla\Phi],$$

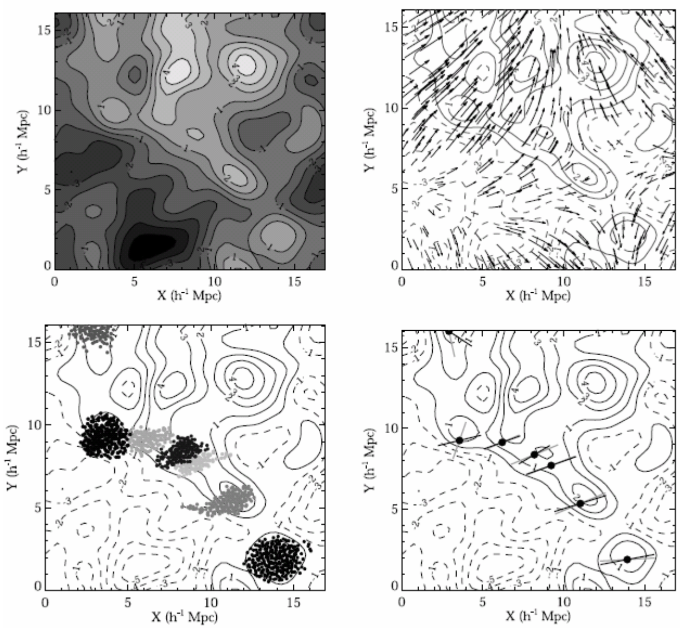
$$L_i(t) = a^2 \dot{D} \varepsilon_{ijk} \left.\frac{\partial^2 \Phi}{\partial q'_j \partial q'_l}\right|_{q'=0} \int_\Gamma q'_l q'_k d^3 q' = -a^2 \dot{D} \varepsilon_{ijk} \mathbf{T}_{jl} \mathbf{I}_{lk},$$

$$\text{where } T_{ij} = -\left.\frac{\partial^2 \Phi}{\partial q'_i \partial q'_j}\right|_{q'=0} \text{ and } I_{ij} = \int_\Gamma q'_i q'_j d^3 q'.$$

White 1984



- Accelerate/deaccelerate collapse of proto-halos



Porciani et al. 2002b

Angular momentum profile

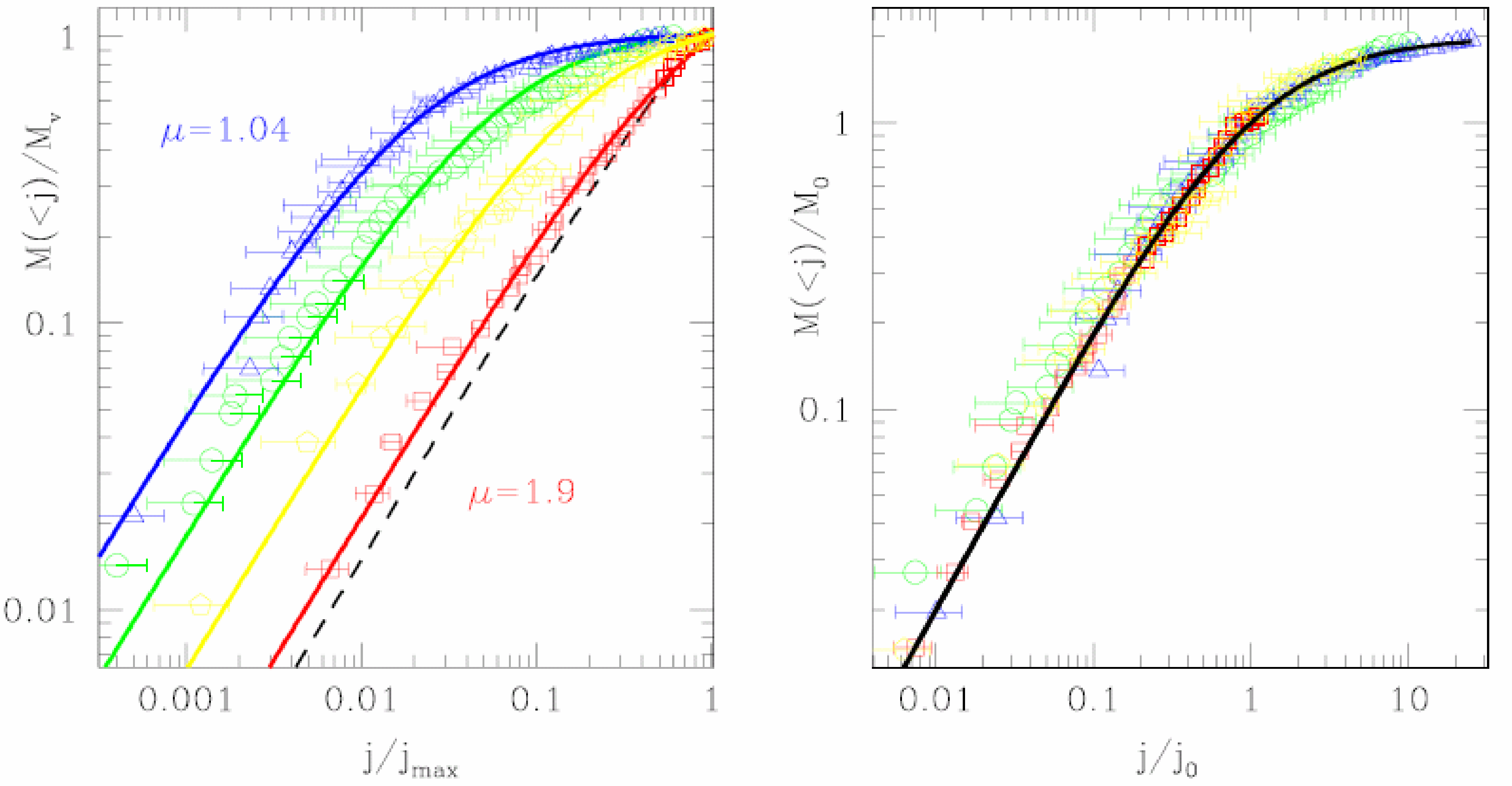
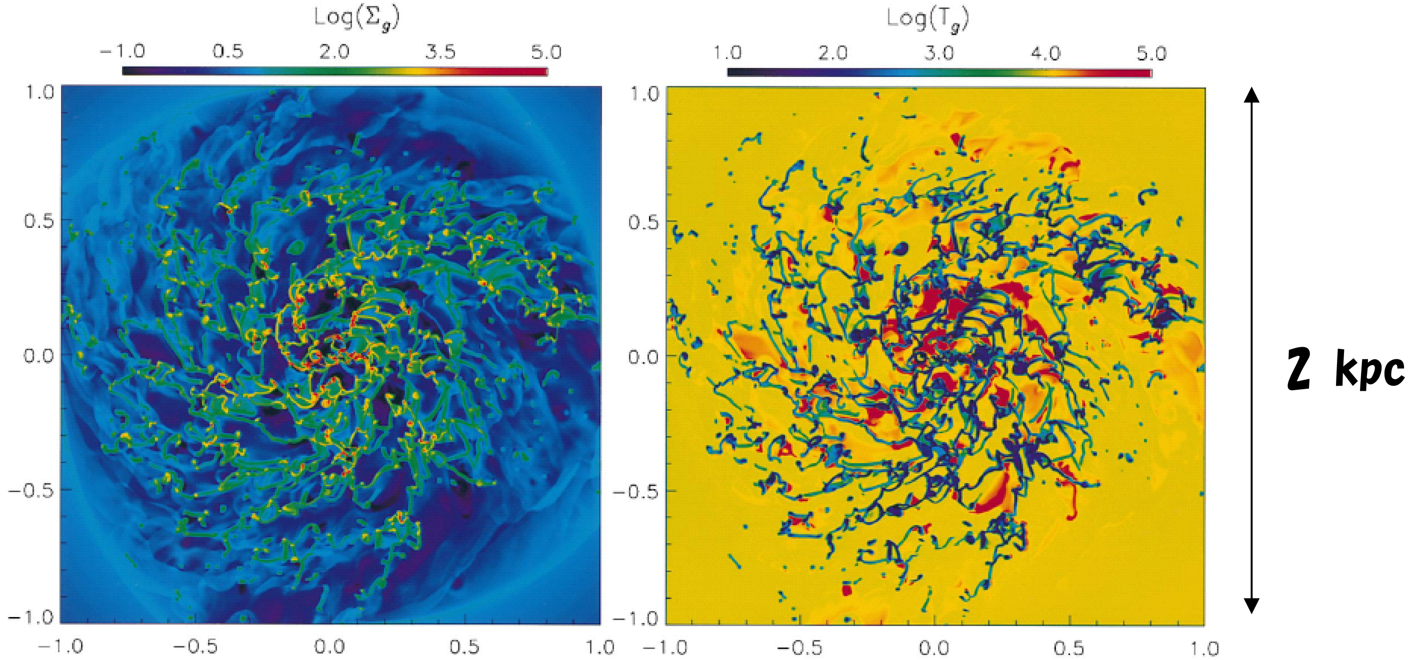


FIG. 4.— Mass distribution of specific angular momentum in four halos spanning a range of μ values from 1.04 to 1.9. Symbols and errors correspond to the ranked j measurements in cells, while the curves are the functional fits, $M(< j) = M_v \mu j/(j_0 + j)$. (a) All profiles are normalized to coincide at M_v, where $j = j_{max}$. The value of μ measures the relative extent of the power-law regime until it bends over. Shown for comparison is the distribution for a uniform sphere in solid-body rotation (dashed line). (b) All profiles are normalized to coincide at j_0 and on top of the universal profile (curve). The value of μ now correlates with the uppermost point, j_{max}/j_0, along the universal curve.

Bullock+02

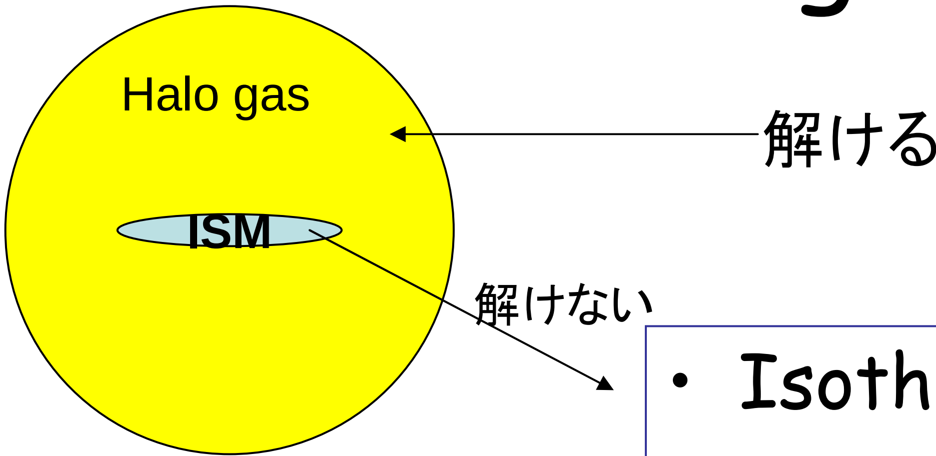
Interstellar medium

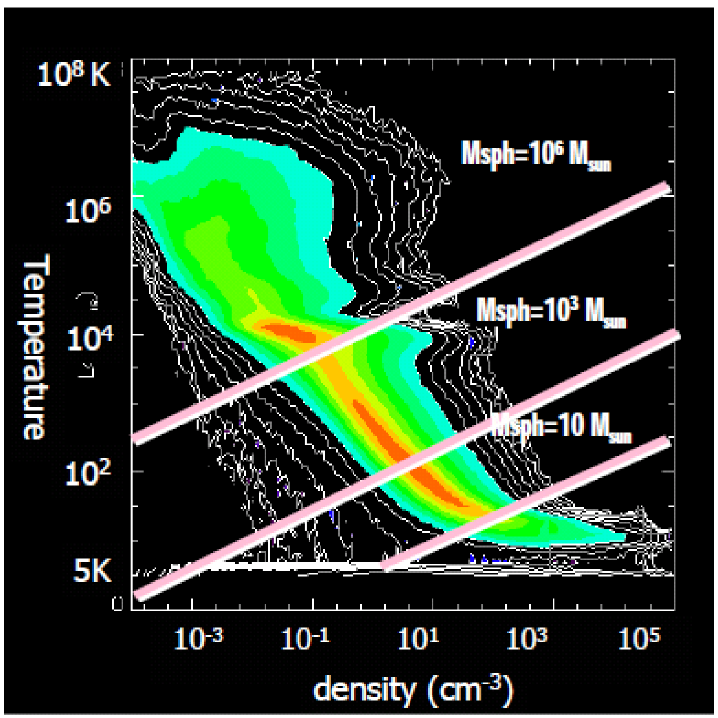


Wada & Norman 99

- The ISM has complicated multiphase structure.
- The box size of this **2D** simulation is comparable to the size of **one numerical element in typical high-resolution** cosmological simulations used to study galaxy formation.

Modeling the ISM





- Isothermal gals with $T = 10^4$K
  - Standard (many authors)
- Multiphase (2-phase) model
  - Springel & Hernquist (2003)
  - Okamoto et al. 2005
- Sticky particle
  - Booth, Theuns, & Okamoto 2006

Star formation & feedback in simulations

- Star formation

$$\rho_{\text{gas}} > \rho_{\text{th}},$$

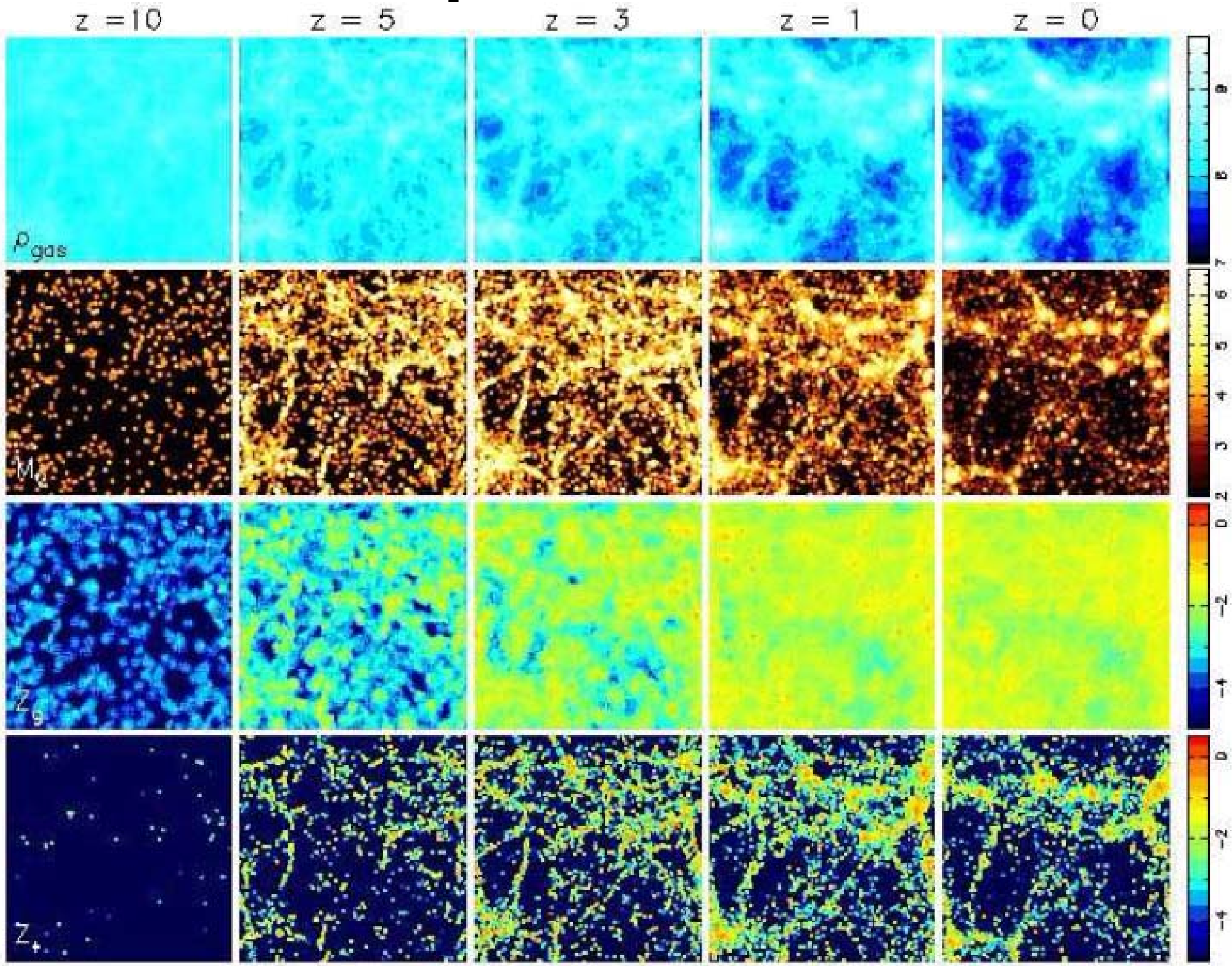
$$\dot{\rho}_* = C_* \frac{\rho_{\text{gas}}}{t_{\text{dyn}}(\rho_{\text{gas}})} \propto \rho_{\text{gas}}^{1.5}$$

  - Simulations of elliptical galaxies
    - Large C_* (~1) and strong feedback for halting SF (e.g. Kobayashi 2004; Kawata & Gibson 2005)
  - Simulations of disc galaxies
    - Small C_* (~0.03) and relatively weak feedback (e.g. Steinmetz & Navarro 1999; Thacker & Couchman 2001; Abadi et al. 2003a; Governato et al. 2004; Robertson et al. 2004)
  - Combined
    - Sommer-Larsen+03, Okamoto+05

Two kinds of cosmological simulations

- Box
  - Simulate whole periodic simulation box
  - Galaxy population
  - Intergalactic medium
  - Low resolution
- Zoom
  - Multi-resolution
  - Put high-resolution and gas particles into the region of interest.
  - **Single objects**
  - High resolution

An example of box-sim



Kobayashi+06

So far..

- Box simulations
  - Insufficient resolution
  - Insufficient box size
  - Gaining little insight into physical processes
  - Expensive
- 観測屋さんは喜ぶことも
- 将来的にはやらないといけない
  - 必要最小限の resolution を見極める必要あり

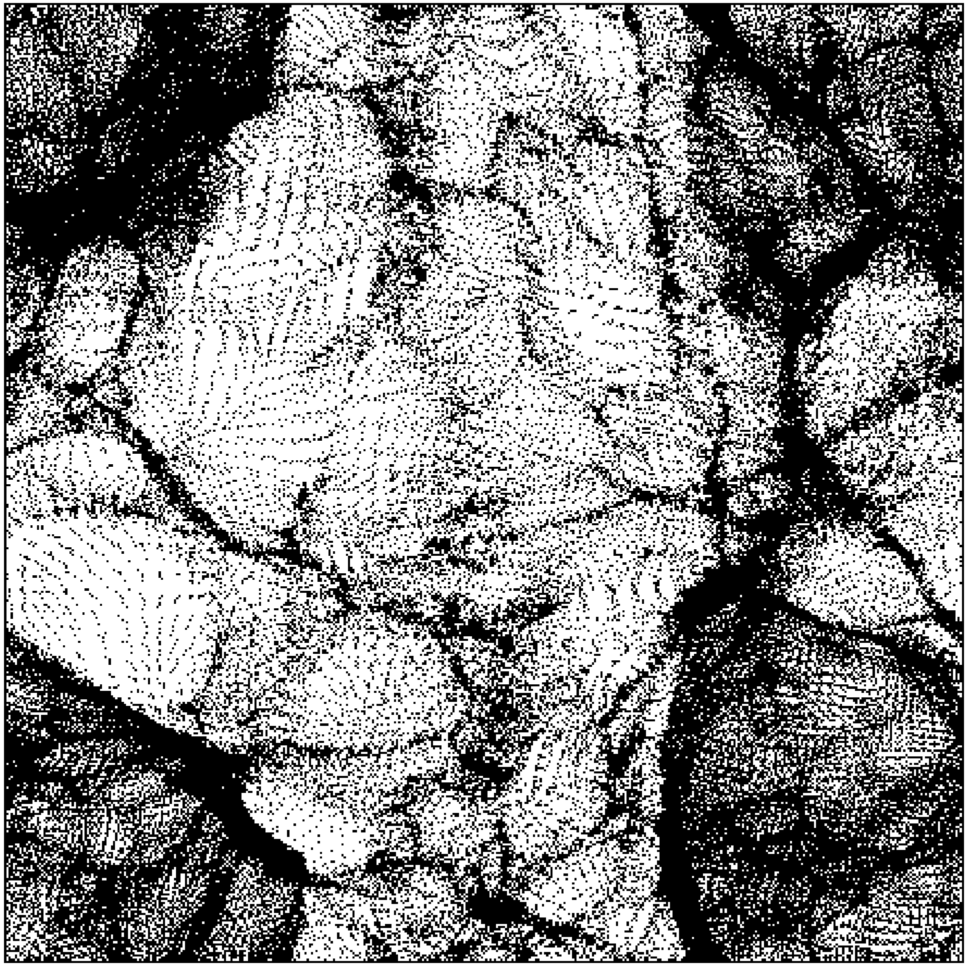
Zoom simulation

- 一つ一つ心を込めて
  - 比較的詳しく形成過程を見られる
  - 統計量が求まらない
  - 観測と比較できない
  - 初期条件？
  - モデルに制限がつかない
- モデルが固まって計算機が速くなったら box simulation に以降する必要あり

Simulations of single objects

(Zoom simulations)

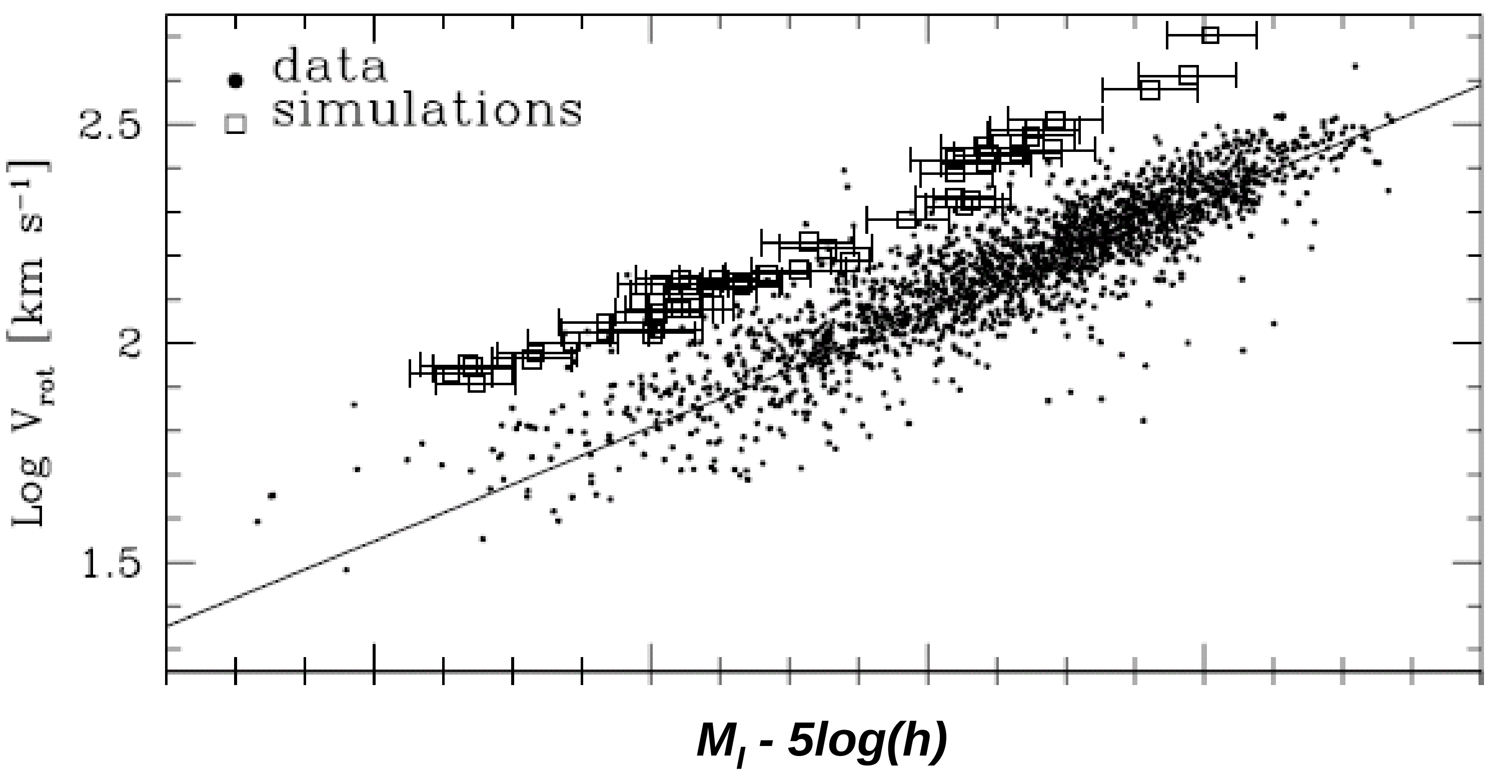
Initial conditions



Problems

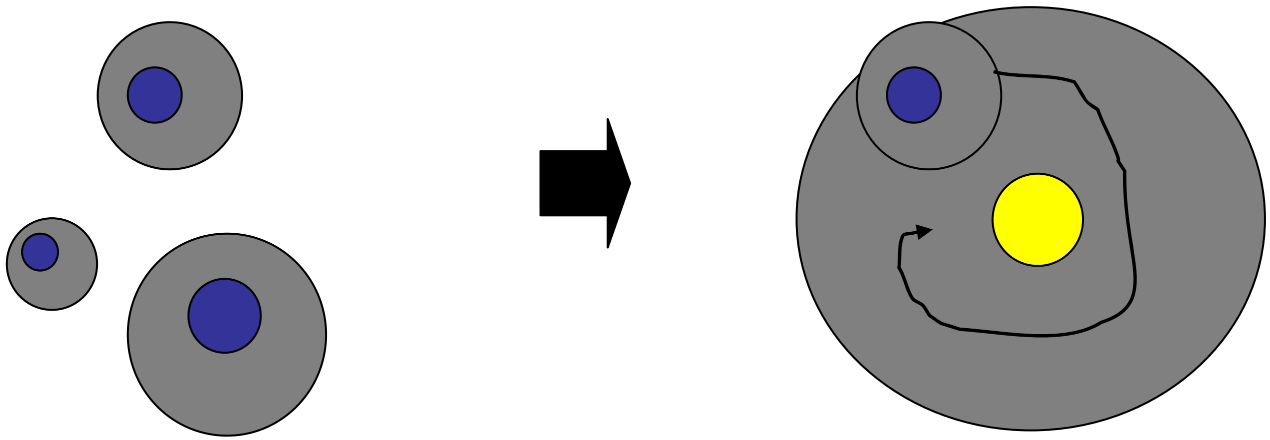
- Angular momentum problem
  - Simulations based on CDM produce too many **bulge-dominated** galaxies.
  - ~~Simulated discs are too small in CDM simulations.~~
- Satellite problem
  - CDM predicts too many sub-halos compared to observed satellite galaxies

Simulated Tully-Fisher relation



- Simulated galaxies in CDM have too compact.

Angular momentum problem

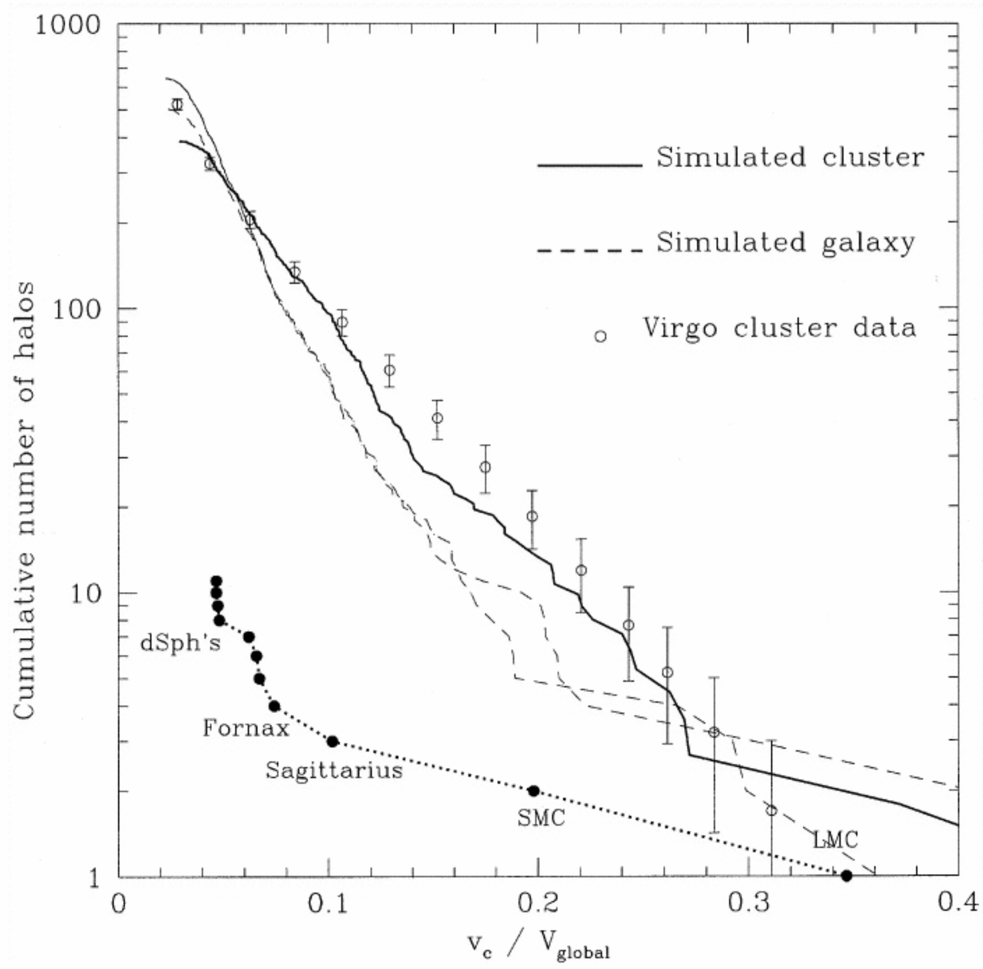


High cooling rate at high-z

Lose angular momentum!!

Cooled baryons loose their angular momenta through dynamical friction and spiral into the centre.

Satellite problem

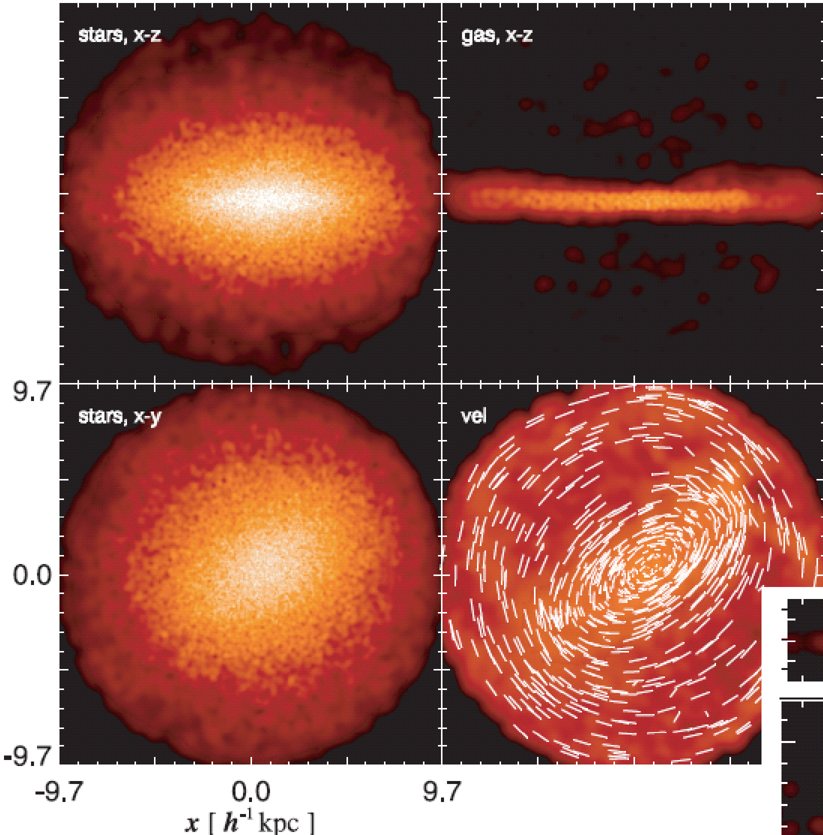


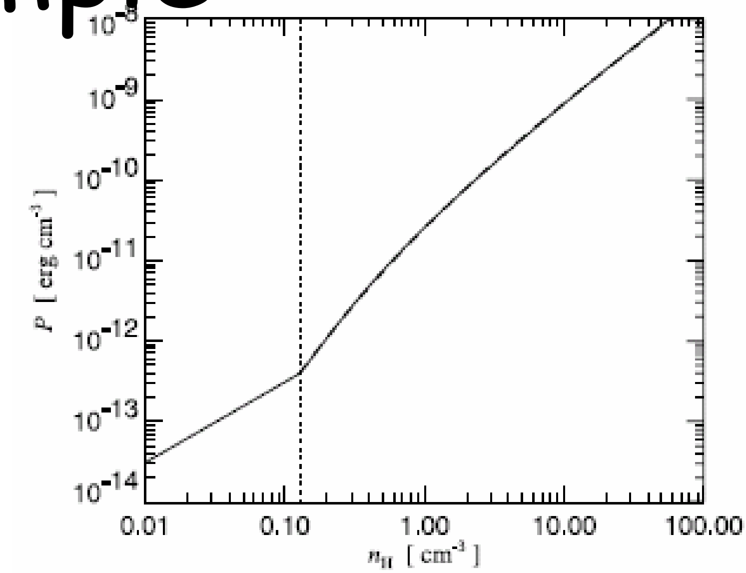
- Simulated galaxies have too many sub-halos.

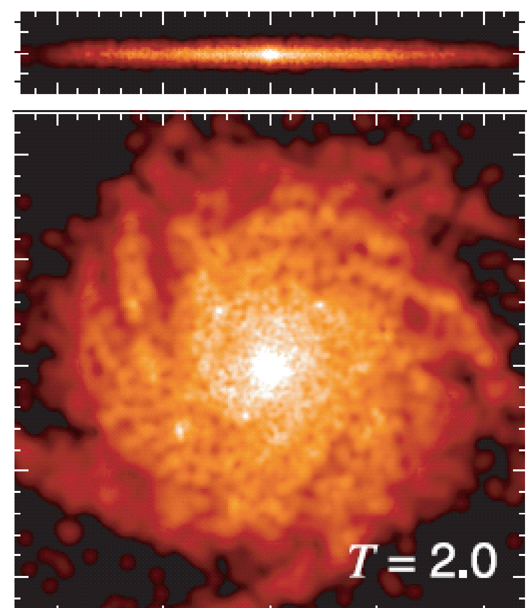
Some successes

- Sommer-Larsen et al. 2003
  - Using two distinct star formation modes
    - Early star formation - High star formation efficiency & very strong feedback
    - Late star formation – low star formation efficiency & no feedback
- Governato et al. 2004
  - Numerical resolution is matter.
- Robertson et al. 2004
  - Stiffer EQS for the ISM stabilises gas disc.
- Okamoto et al. 2005 (This talk)
  - Multi-phase ISM
  - Two distinct star formation modes – quiescent & bursts

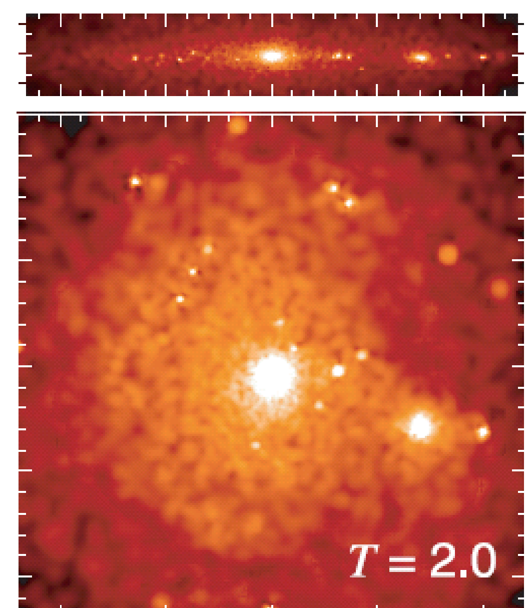
An example





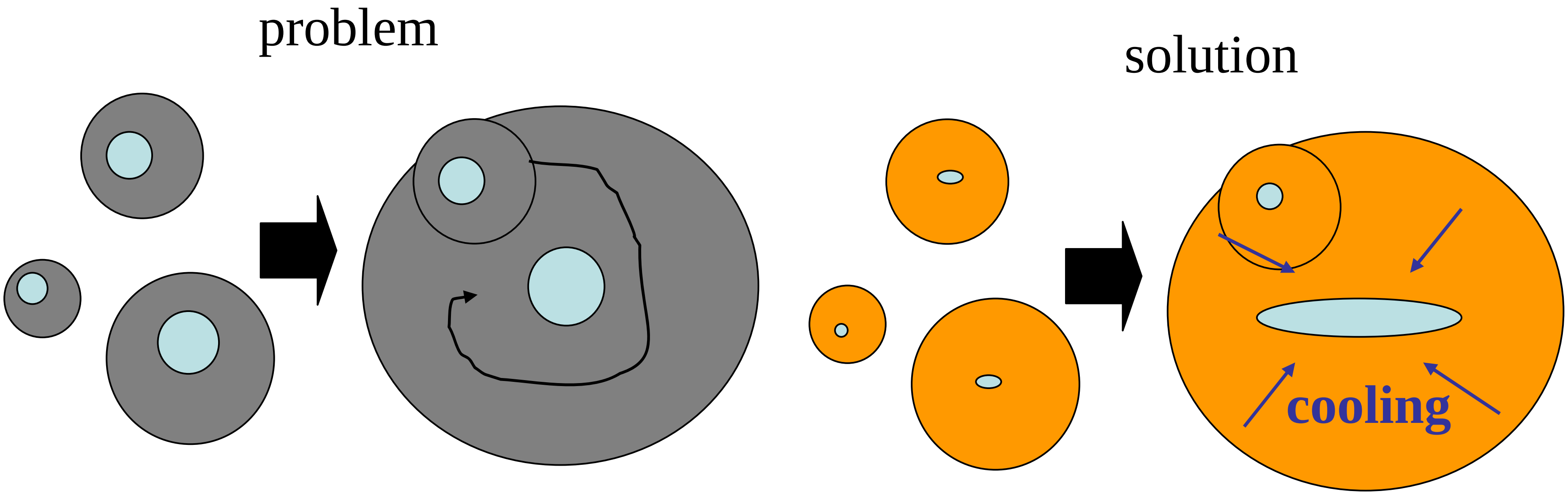


Multi-phase



Iso-thermal

Angular momentum problem



High cooling rate at high-z

Lose angular momentum!!

Keep them hot at high-z

Disc formation

Star formation & feedback in simulations

- Star formation

$$\rho_{\rm gas} > \rho_{\rm th},$$

$$\dot{\rho}_* = C_* \frac{\rho_{\rm gas}}{t_{\rm dyn}(\rho_{\rm gas})} \propto \rho_{\rm gas}^{1.5}$$

  - Simulations of elliptical galaxies
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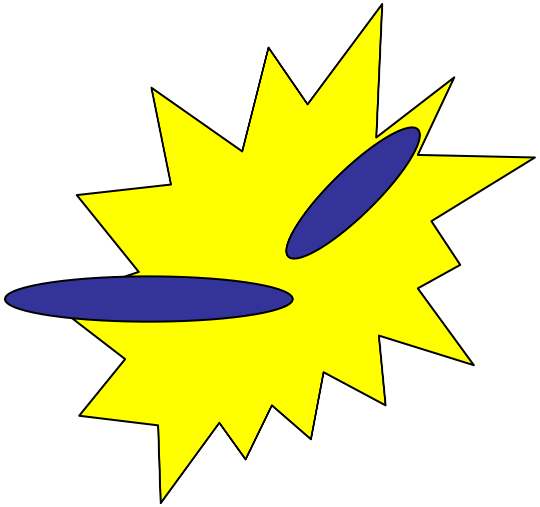
Two star formation modes

- Quiescent
  - Self-regulated star formation
  - Salpeter IMF
- Burst
  - High star formation efficiency
  - Top-heavy IMF
  - Trigger?

Top-heavy IMF in bursts?



- Recent version of GALFORM
  - More luminous
    high-z populations (*Baugh et al. 2005*)
  - More α–elements
    ICM and Es (*Nagashima et al. 2005a, b*)

Also more feedback energy for merging galaxies!!

Two star formation modes

- Quiescent
  - Self-regulated star formation
  - Salpeter IMF
- Burst
  - High star formation efficiency
  - Top-heavy IMF
  - Trigger?

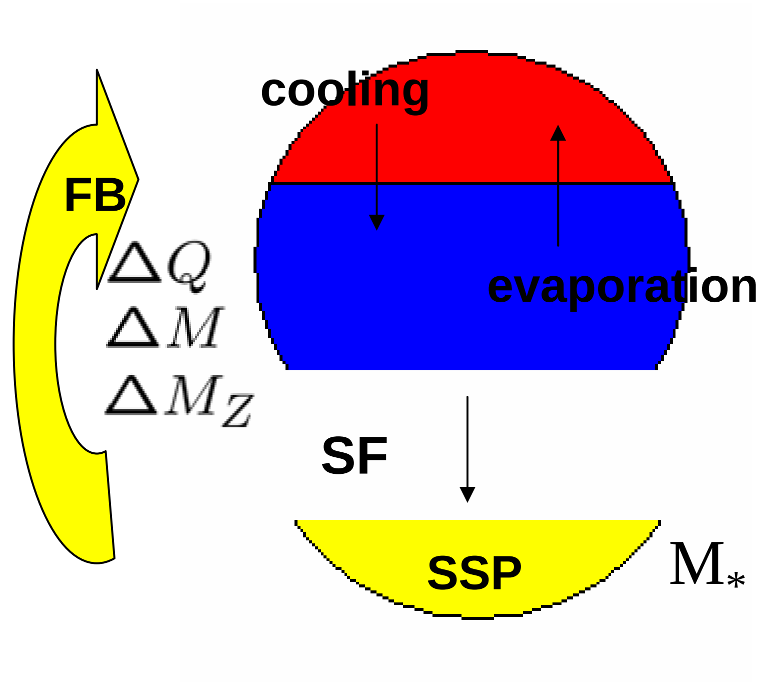
SF & FB

$$p_* = \frac{M_\mathrm{c}}{M_*}\left\{1 - \exp\left[-\frac{\Delta t}{t_*}\right]\right\}$$

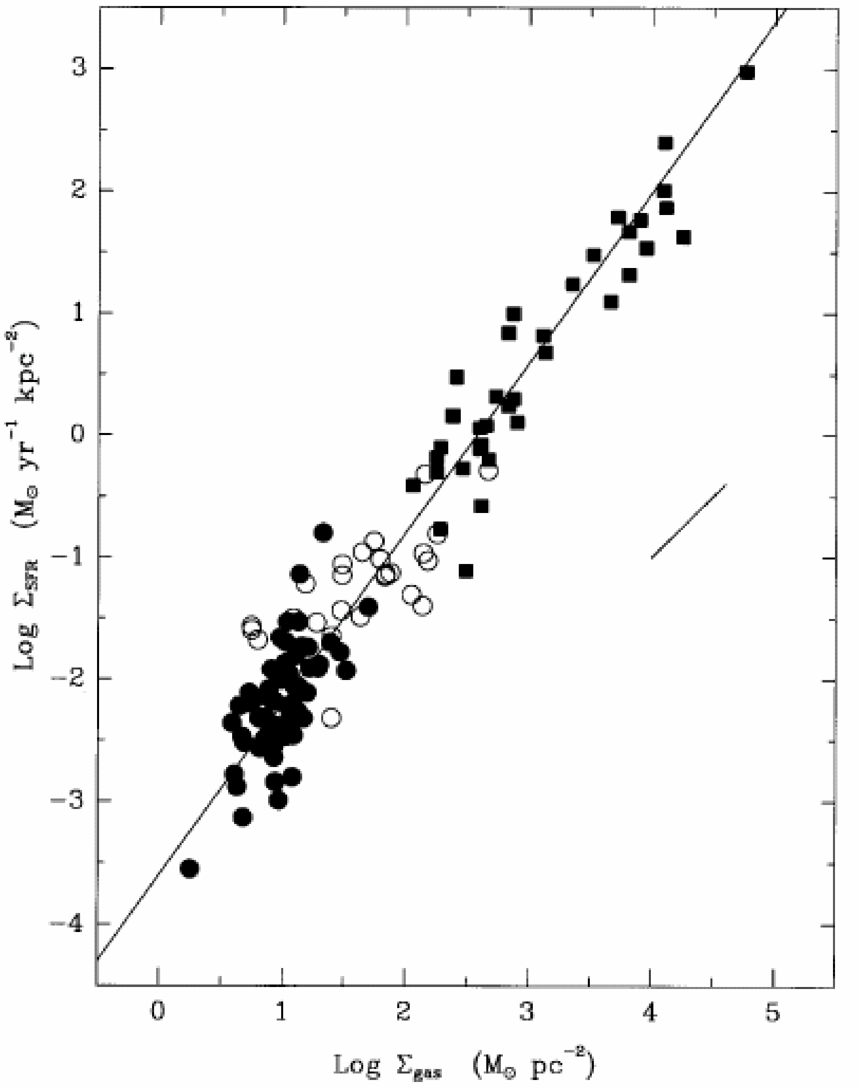
$$\Delta M_\mathrm{evp} = A\Delta Q_\mathrm{FB}/u_\mathrm{SN}$$

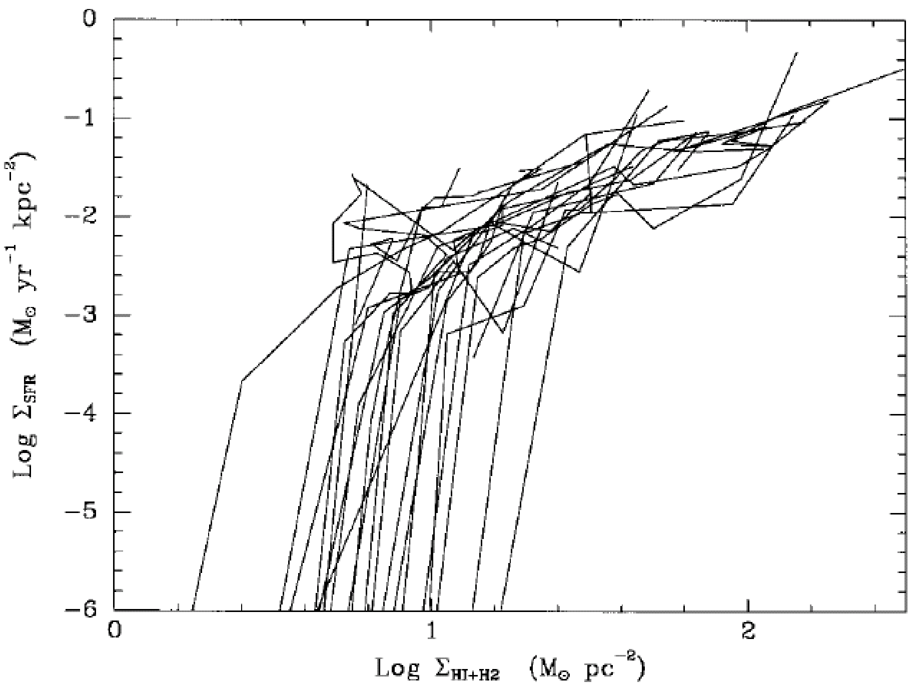
$$\Delta M_h = \Delta M_\mathrm{evp} - \frac{\Lambda_\mathrm{net}(\rho_h, Z)}{u_h - u_c}\frac{M_h}{\rho_h}\Delta t$$

$$\dot{u}_h = \frac{\Delta Q_\mathrm{FB} + \Delta M_\mathrm{evp}(u_h - u_c)}{M_h \Delta t}$$



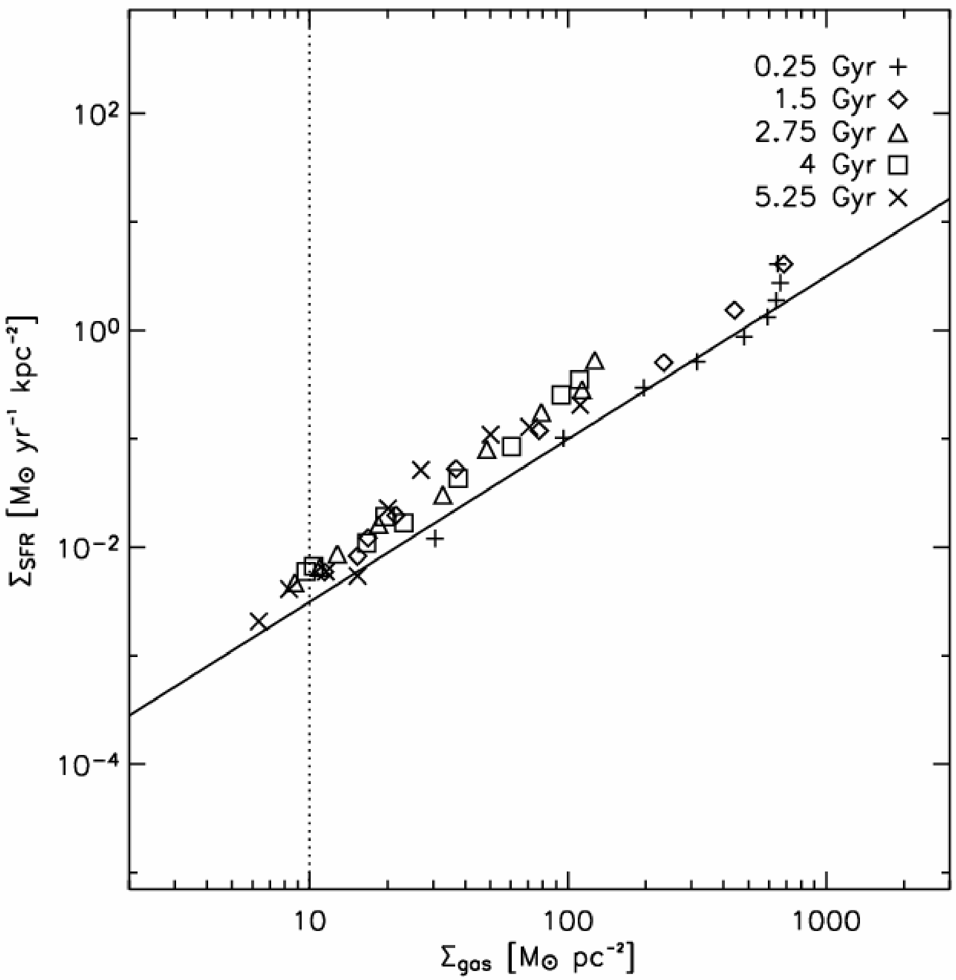
The Kennicutt law





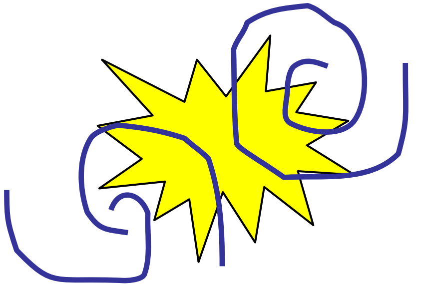
Kennicutt 98

The Kennicutt law

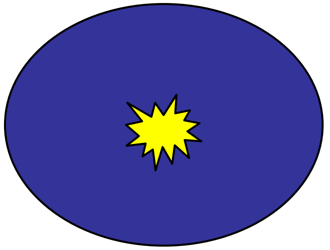


What triggers bursts?

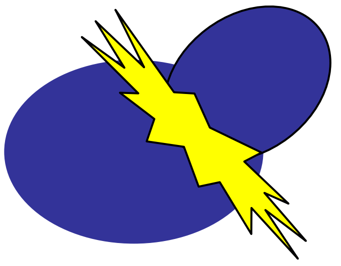
- In SA models
  - Merger



- In simulations
  - High density ($\rho > \rho_{burst}$)
    - Nuclear starbursts



  - Strong shock ($\dot{s} > \dot{s}_{burst}$)
    - Extended starbursts.



Simulations

ΛCDM:

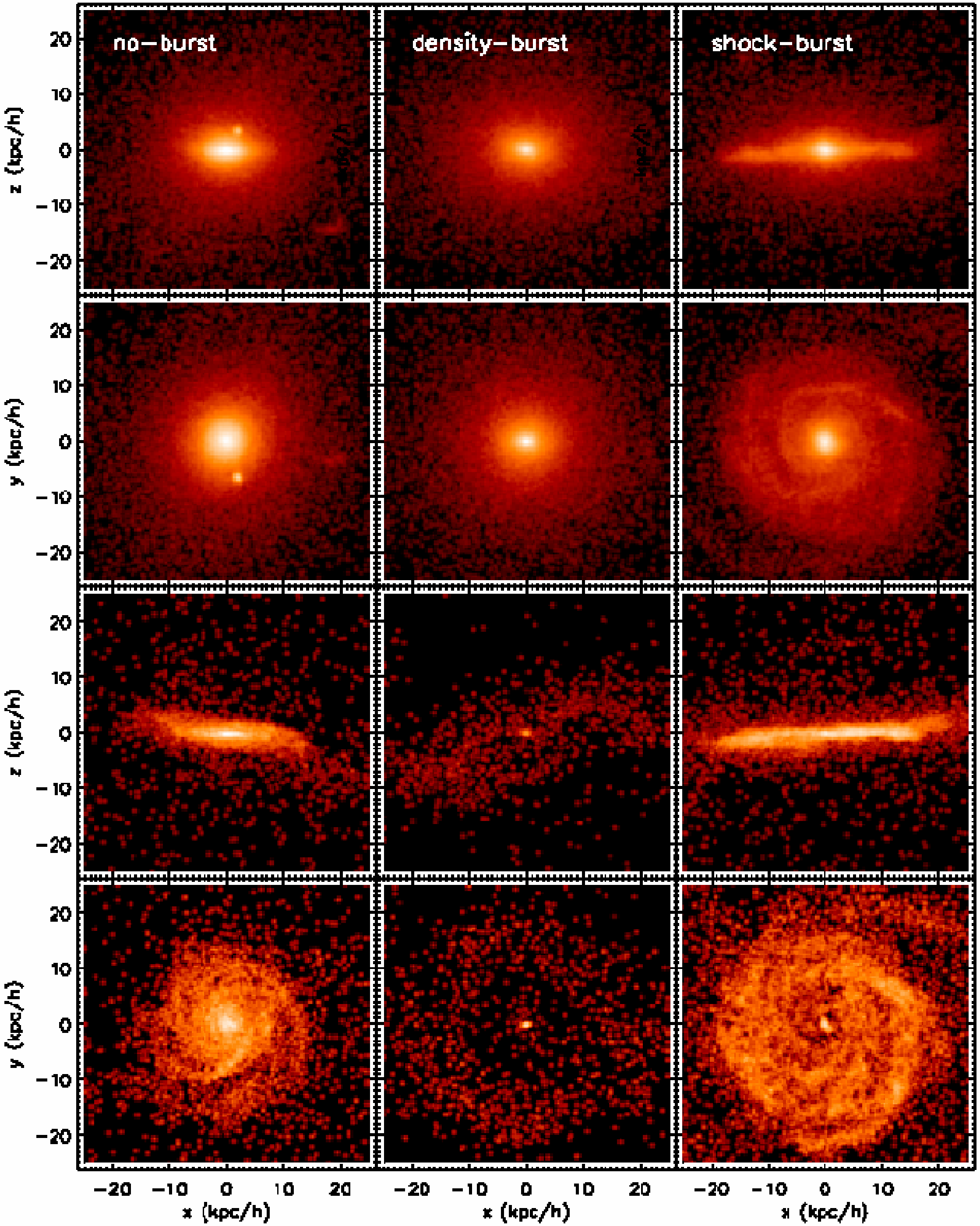
- Box-size L= 35.335 h^{-1} Mpc
- Halo with a quiet merger history.

3 models

- **No-burst (only quiescent SF)**
- **Density-induced burst**
- **Shock-induced burst**

Same initial conditions in all cases!

$50\ h^{-1}$ kpc



Stars: edge on

Stars: face on

Gas: edge on

Gas: edge on

Dynamical decomposition

- Abadi et al. 2003
  - Calculate the angular momentum of co-rotating circular orbit $J_c(E)$ for a given binding energy.
  - Define an orbital circularity, $J_z/J_c(E)$.
  - Decompose each galaxy into a spheroid and a disk assuming non-rotating spheroids.

Probability distribution of orbital circularity.

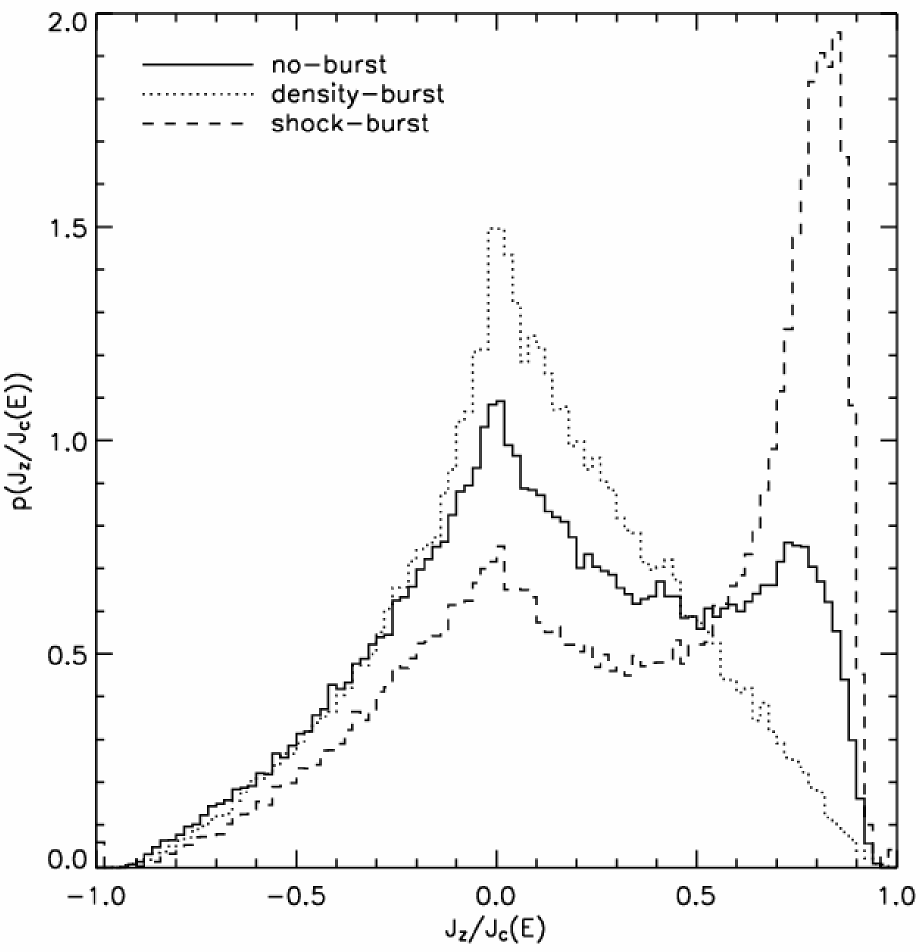


Table 3. Disc-to-total mass and luminosity ratios for simulated galaxies at $z = 0$.

	mass	*U*	*B*	*V*	*I*	*K*
no-burst	0.26	0.72	0.63	0.54	0.45	0.44
density-burst	0.21	0.22	0.22	0.22	0.21	0.20
shock-burst	0.48	0.86	0.84	0.80	0.72	0.66

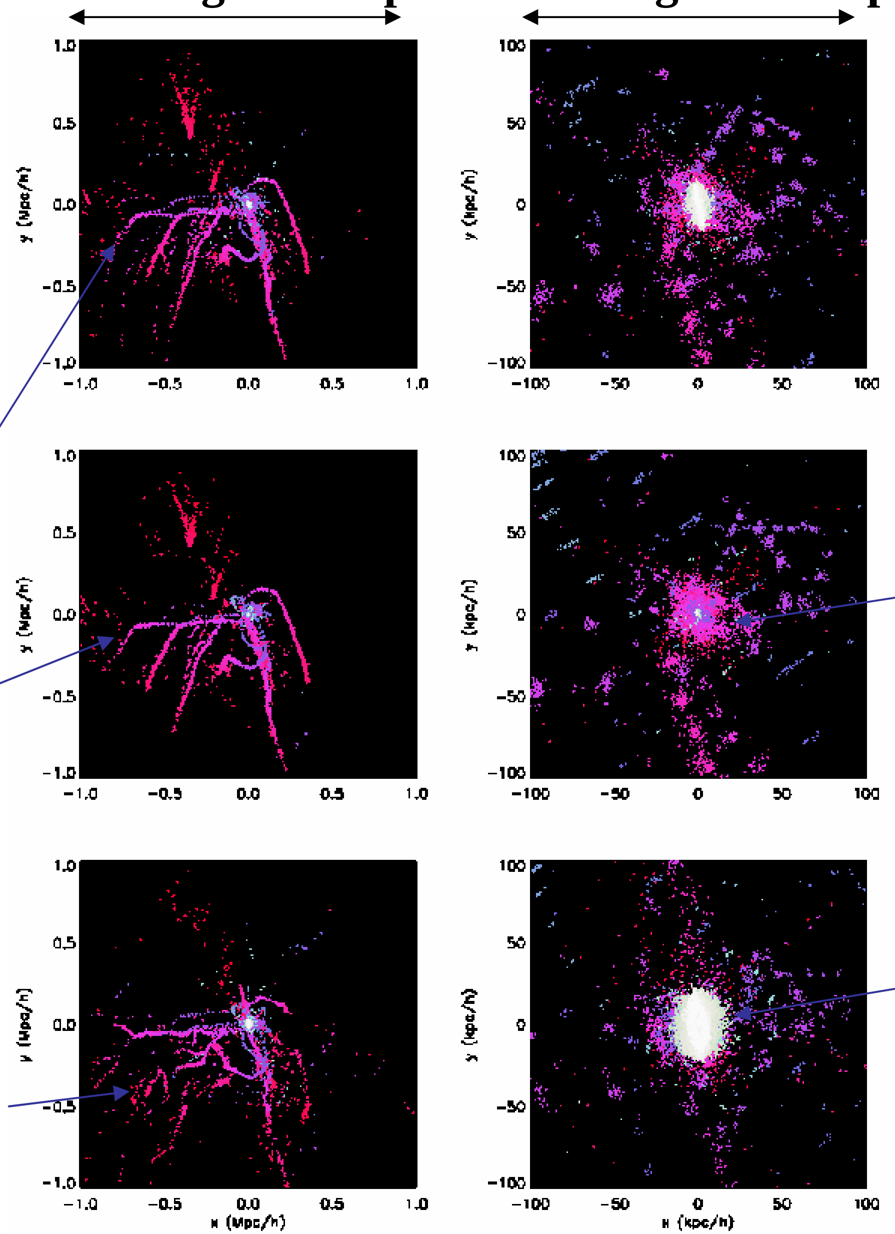
Birthplaces of stars

comoving 2 h^{-1} Mpc   comoving 200 h^{-1} kpc

no-burst

density-burst

shock-burst



Continuous trajectories

discontinuous!

Less SF

More SF

Star formation histories

No-burst

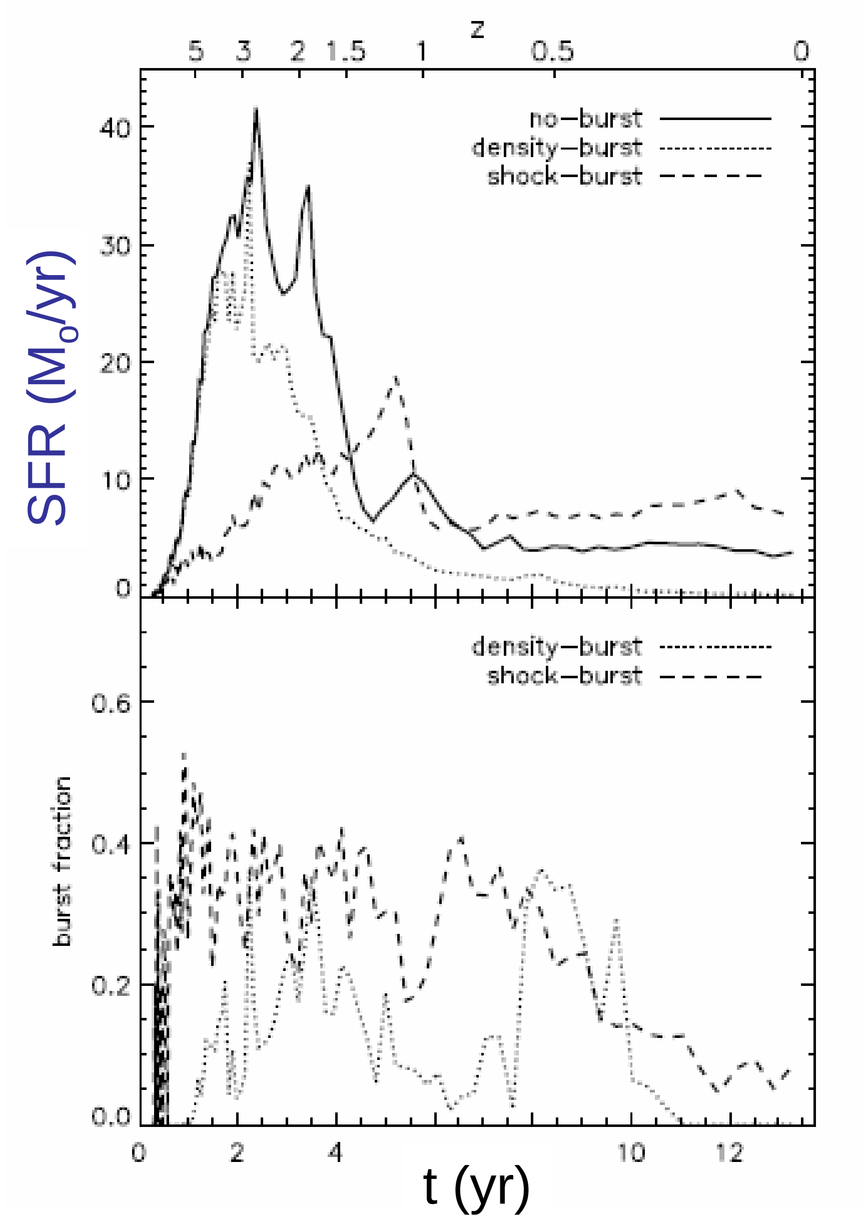
- SF peaks at high z and constant SFR at low-z forms a tiny disk.

Density-induced bursts

- Similar to no-burst model until gas density reaches threshold.
- Once bursts occur, SF strongly suppressed.
- Almost no SF after z = 0.5

Shock-induced bursts

- Burst fraction high at high-z → SF strongly suppressed.
- Burst fraction gradually ↘



Birthplaces of stars

Table 4. The ratio of stellar mass formed within a comoving $25h^{-1}$ kpc sphere from the centre of the main progenitor to the total stellar mass within $25h^{-1}$ kpc from the galactic centre at $z = 0$.

no-burst	density-burst	shock-burst
0.60	0.25	0.78

Galactic winds

No-burst

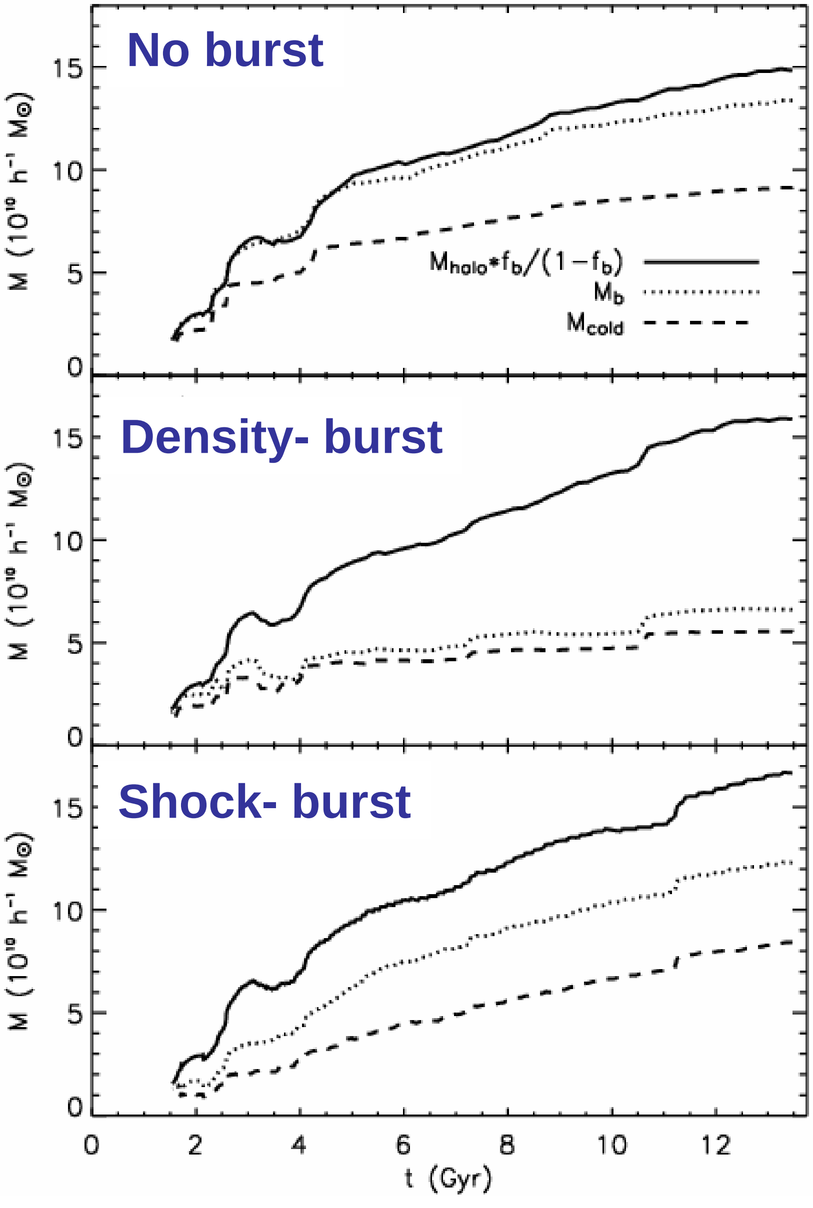
- Almost no gas lost
- Gal baryons: 2/3 cold, 1/3 hot

Density-induced bursts

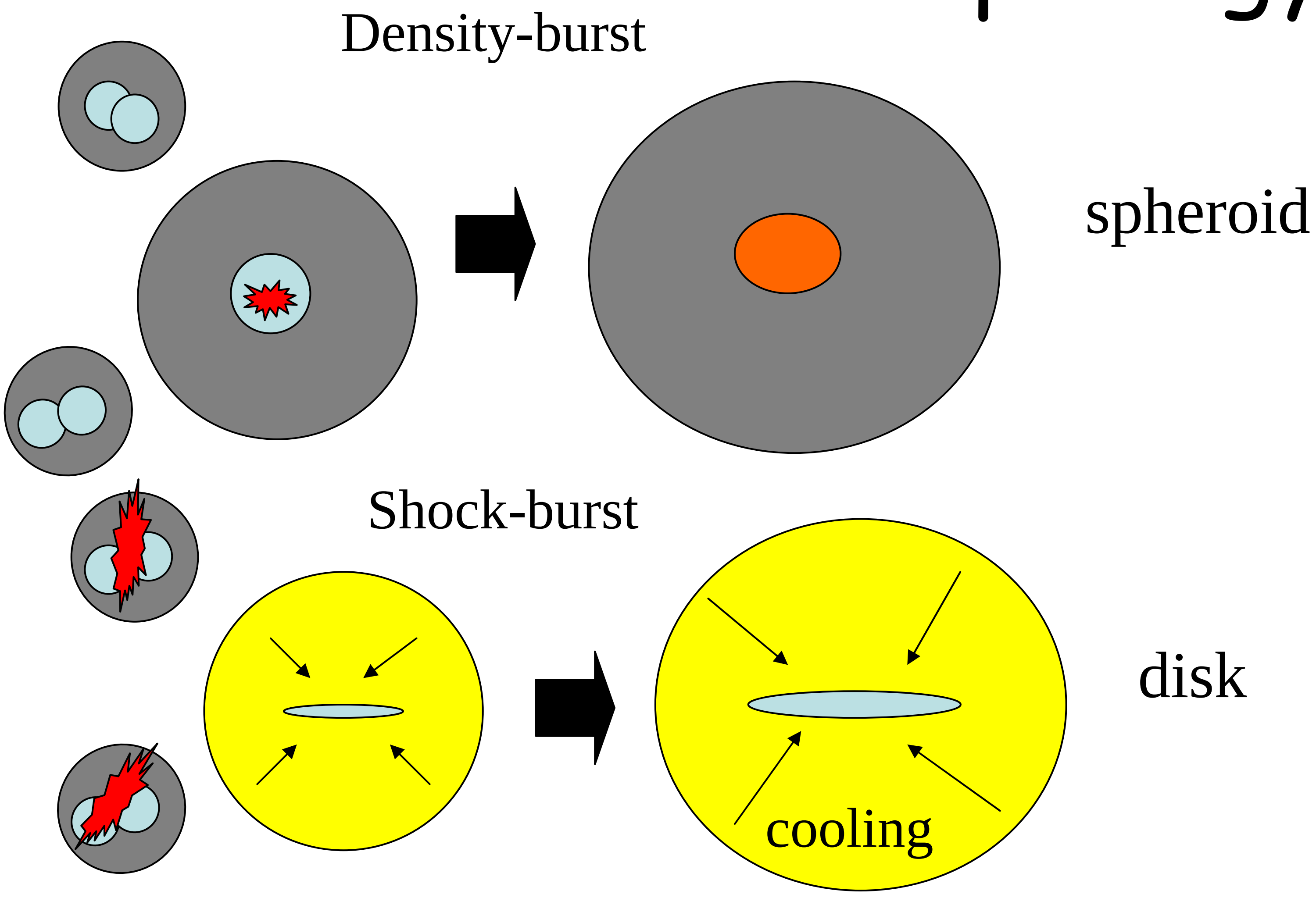
- 2/3 of gas lost in winds
- Gal baryons: all cold

Shock-induced bursts

- 1/3 of gas lost in winds
- Gal baryons: 1/3 hot, 2/3 cold

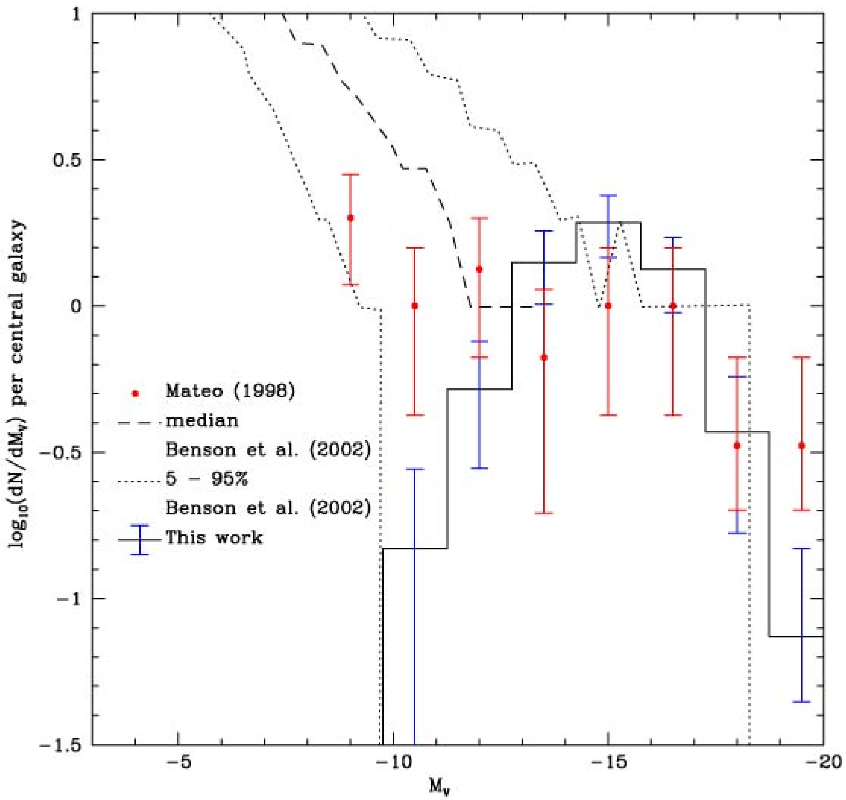


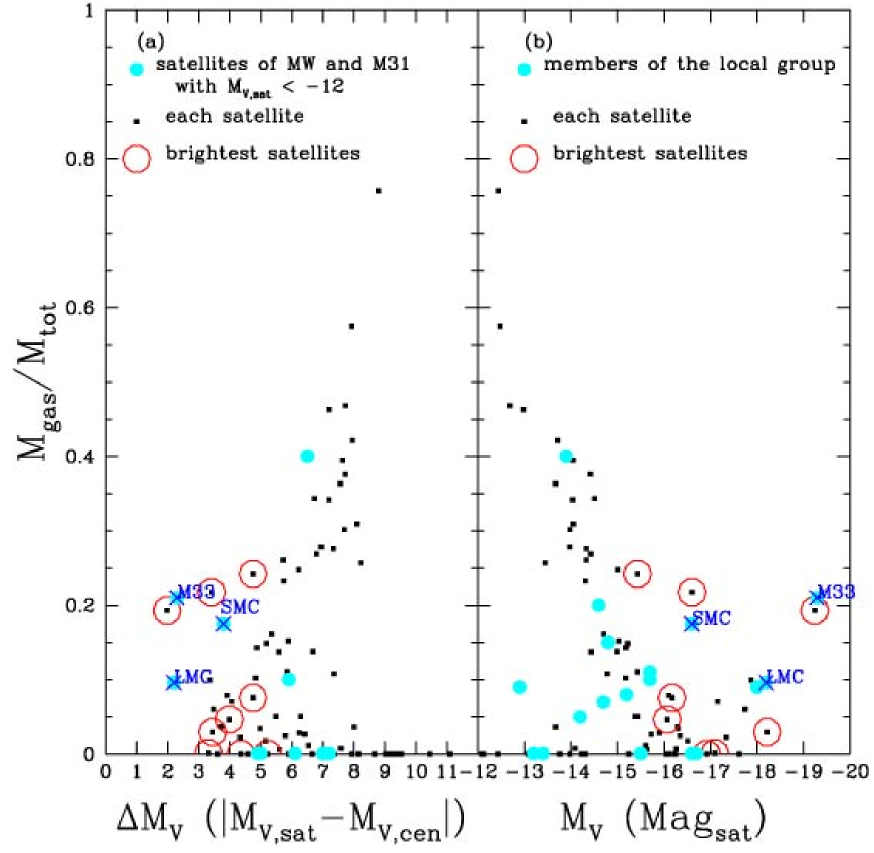
Feedback & morphology



SF & feedback strongly affect galaxy evolution

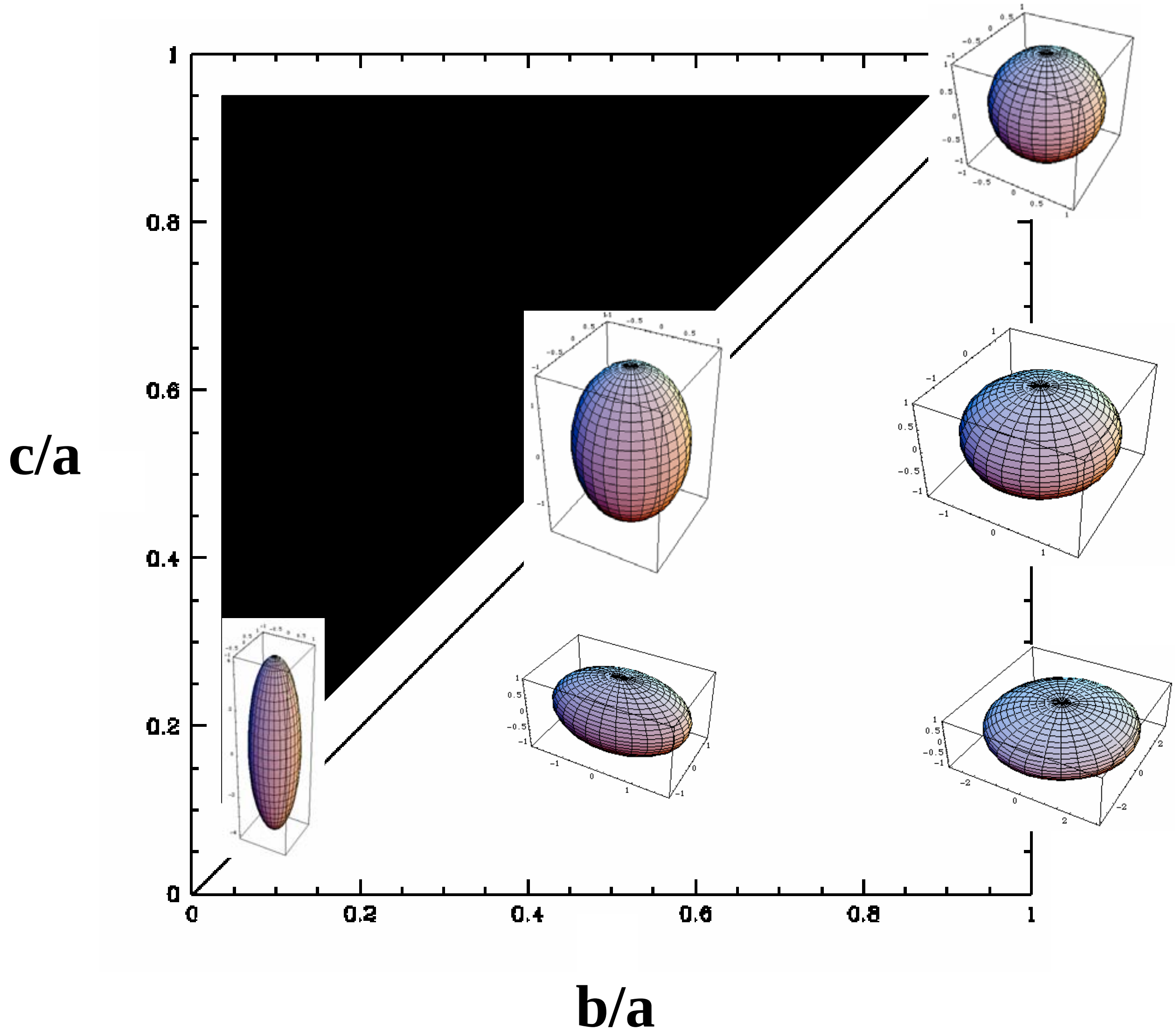
Simulated satellites



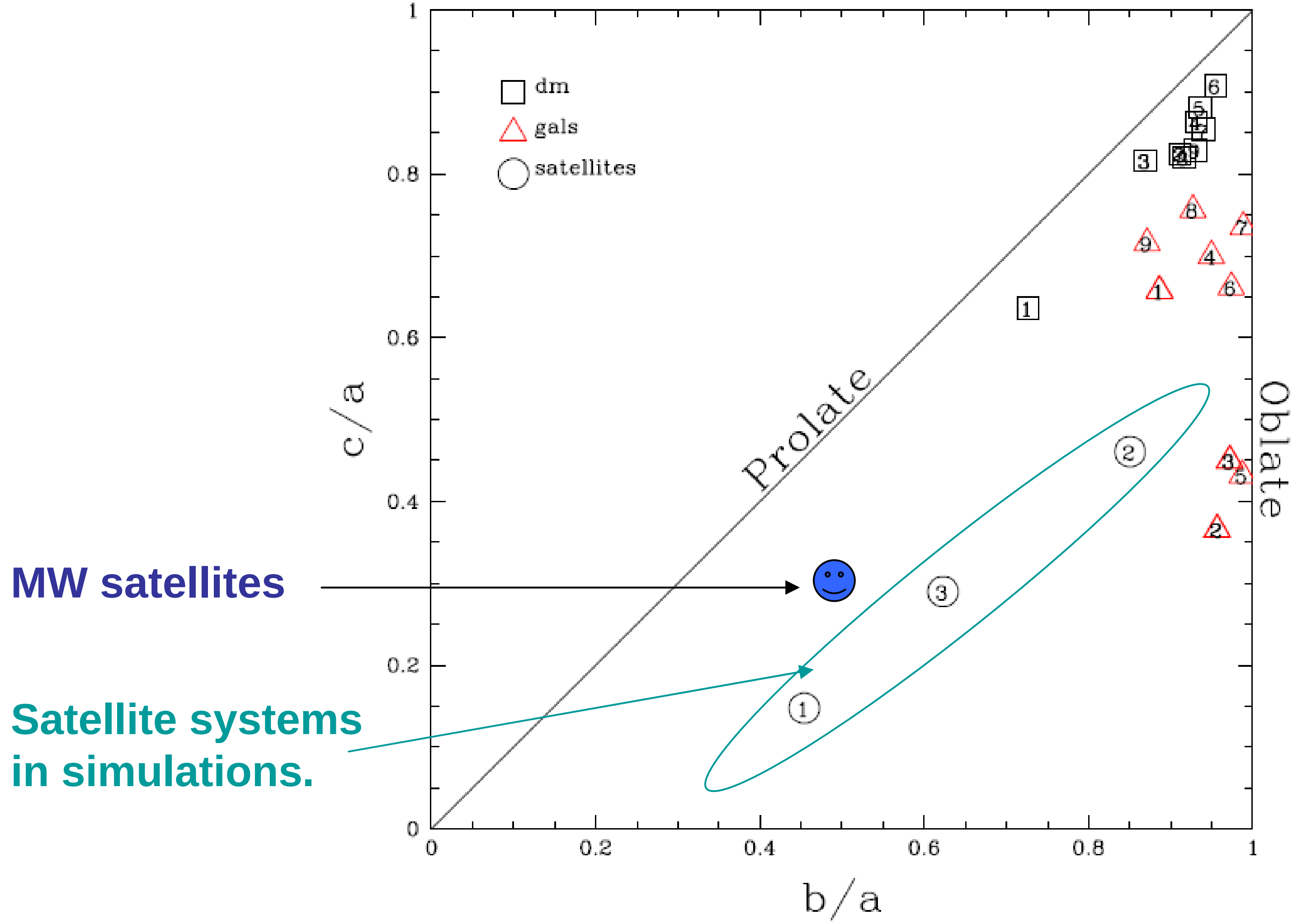


Libeskind & Okamoto et al. 2006

Flattening plots

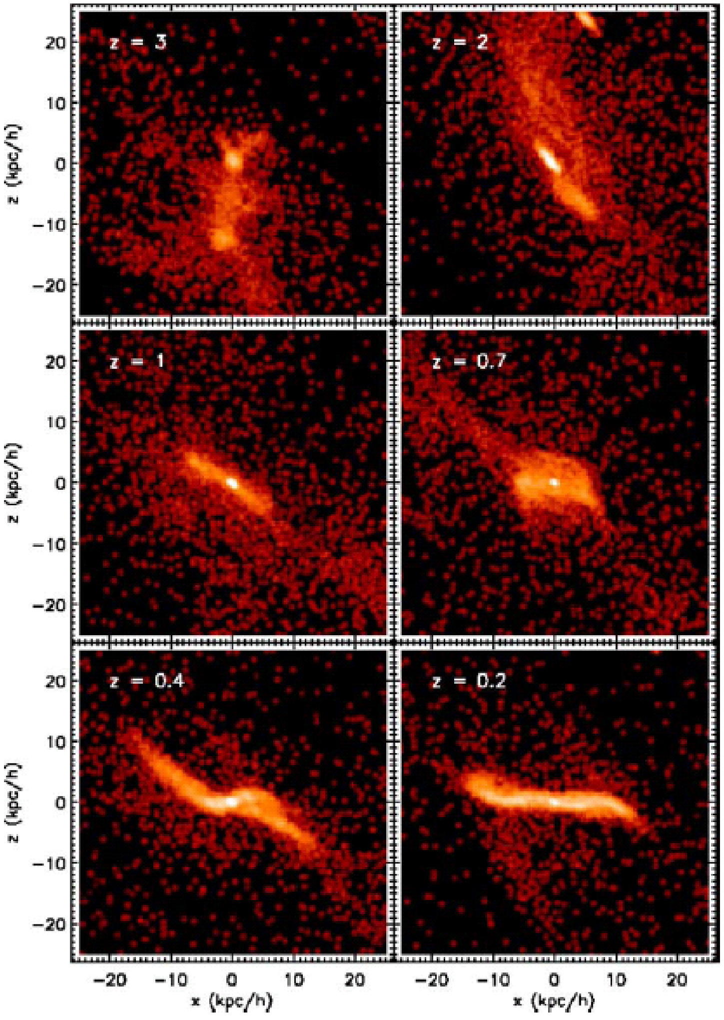


Shape of the satellite systems



Flattened satellite distribution is consistent with earlier studies by N-body and N-bod/SAM simulations (Libeskind et al. 2005, Zentner et al 2005, Kang et al 2005)

Orientation of a forming disc

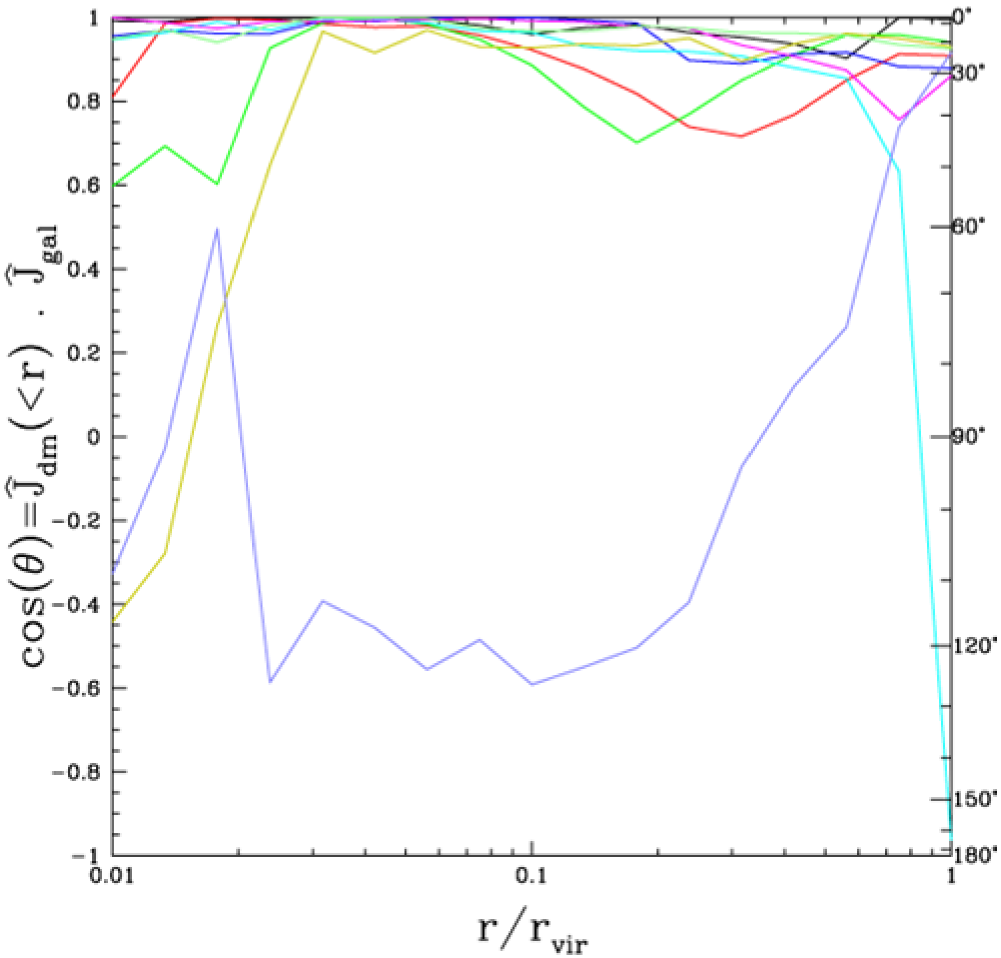


Fixed viewing angle (edge-on at z = 0)

Orientation of the disc can significantly change through its formation.

TakMono.avi

J-alignments



- J_{gal} is well aligned with J_{halo}

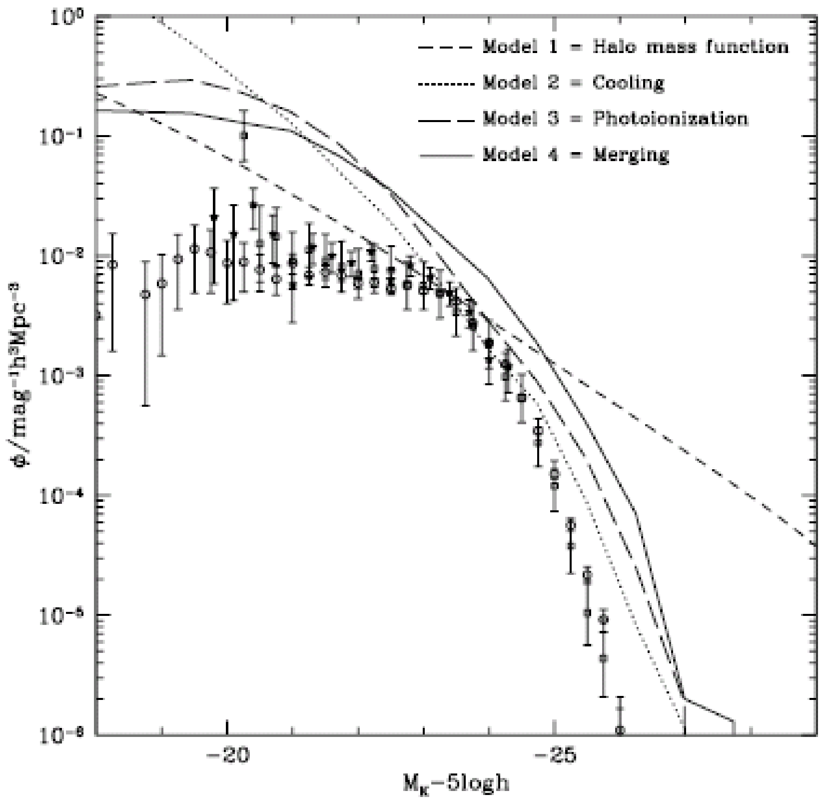
Summary

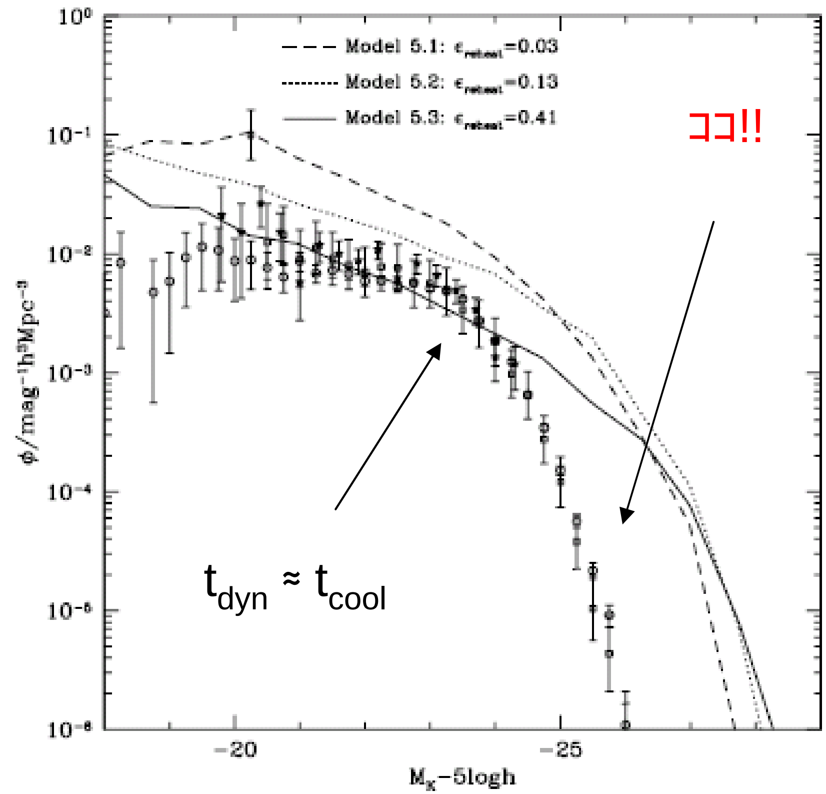
- The angular momentum problem can be avoided if starbursts are triggered by strong shocks and stars are born with a top-heavy IMF in the bursts.
- Results are too sensitive to assumed physics.
- We have to understand small scale physics and how to model it.
- The model that successfully produces a disc also explains LF of satellites.

Need of AGN feedback

(BH → galaxy)

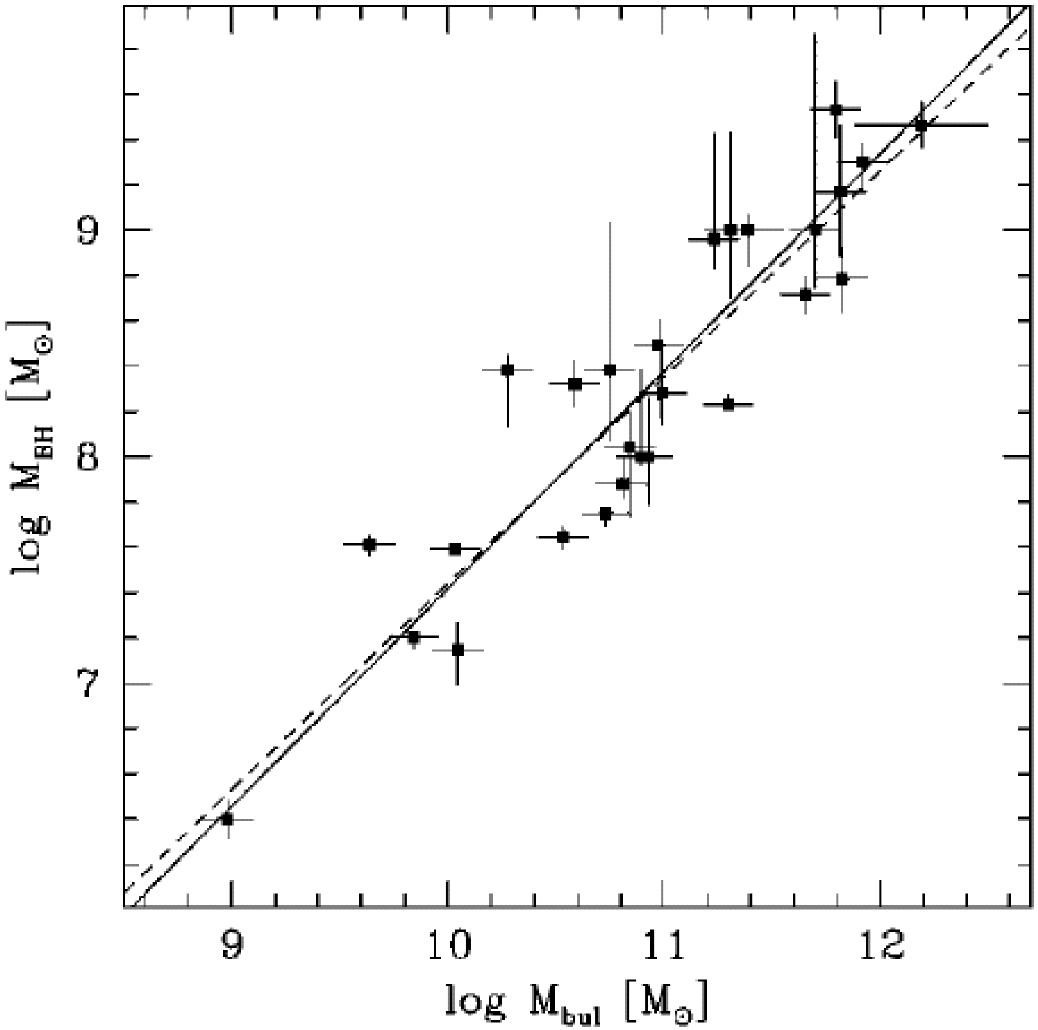
- Luminosity function of galaxies





Benson et al. 03

Magorrian (M_{BH}-M_{bulge}) relation



Marconi & Hunt 03

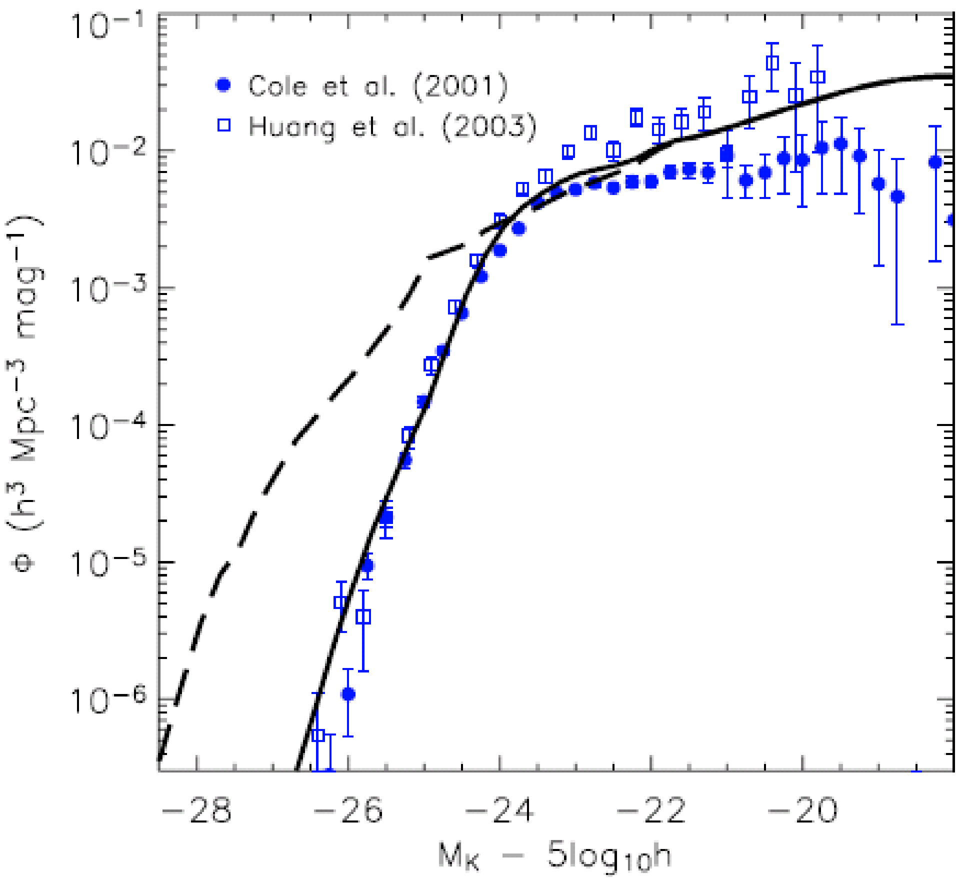
$dM_{bulge}/dt \propto dM_{BH}/dt$?

Galaxy → BH

Growth of BH and AGN feedback

- The Maggorian relation
  - $\mathrm{d}M_{BH}/\mathrm{d}t \propto SFR$ at galactic centre
- If $L_{\mathrm{FB}} \propto \mathrm{d}M_{\mathrm{BH}}/\mathrm{d}t$
  - No characteristic mass scale appears.

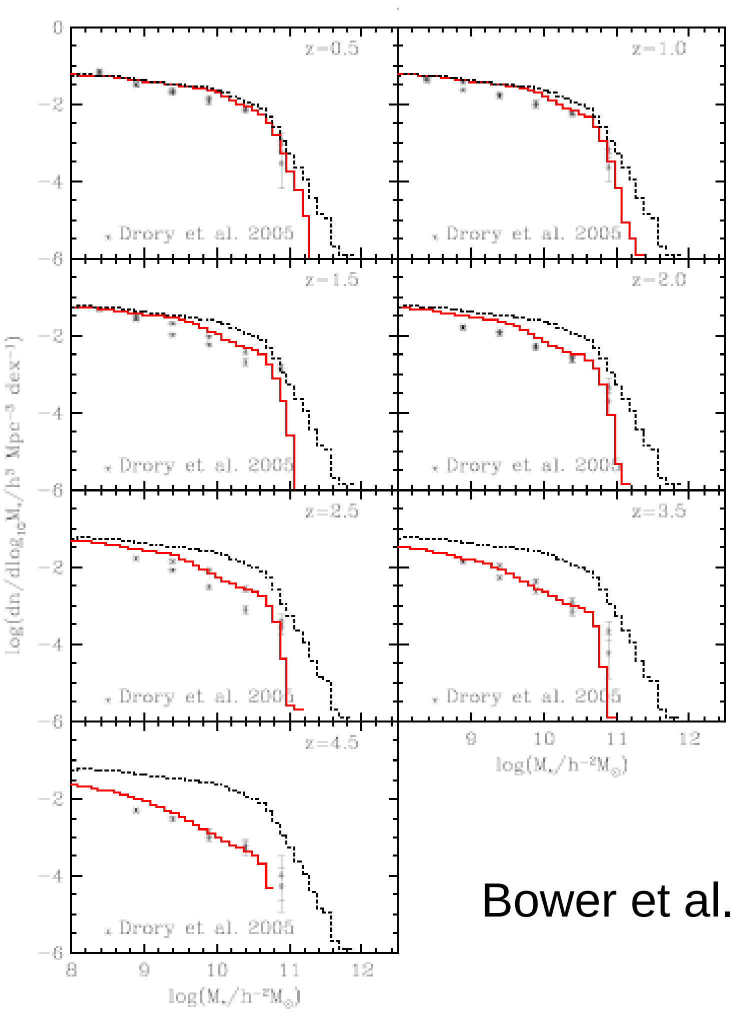
AGN feedback – local luminosity functions



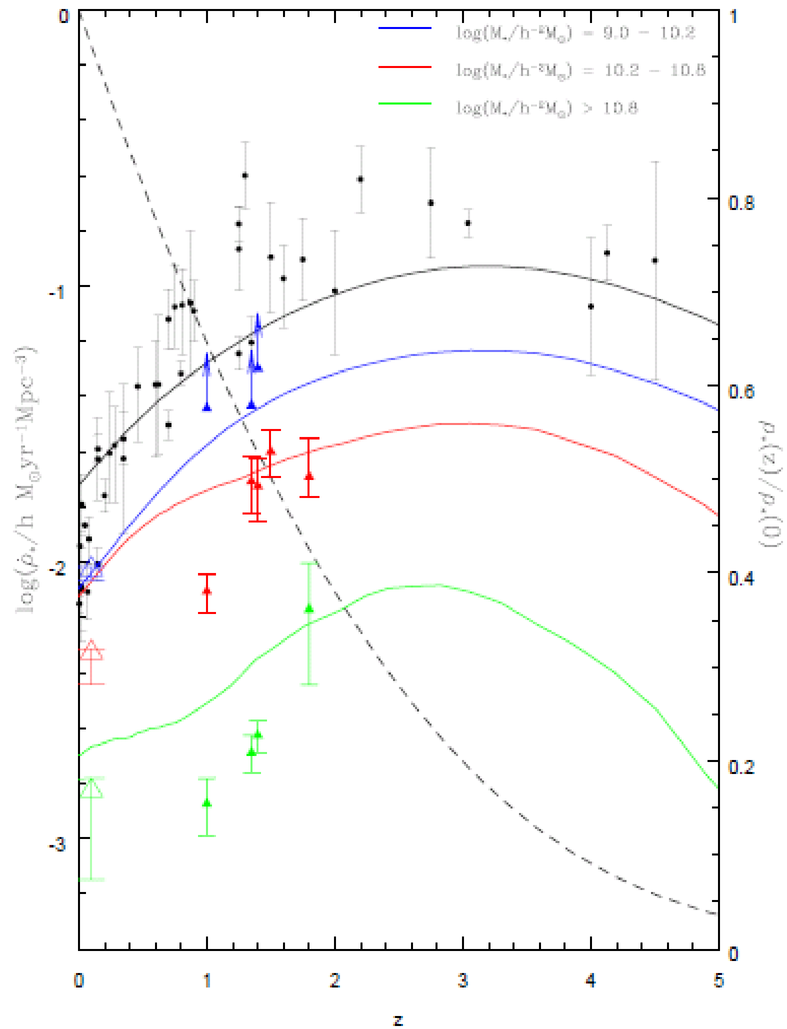
Croton et al. 2005

- $L_{FB} \propto M_{BH} M_{hot} t_H$
  - Feedback energy ejection rate is proportional to the product of the total mass of hot gas and the black hole mass (just a model!! no physics behind)

AGN feedback – down sizing



Bower et al. 06



What we can learn from semi-analytic models?

- If AGN feedback is preferentially effective in large halos where tcool > tdyn, the model can explain
  - Luminosity function
  - Cooling flow
  - Down sizing
- SNe feedback alone can account for the faint end of the luminosity functions

Simulations

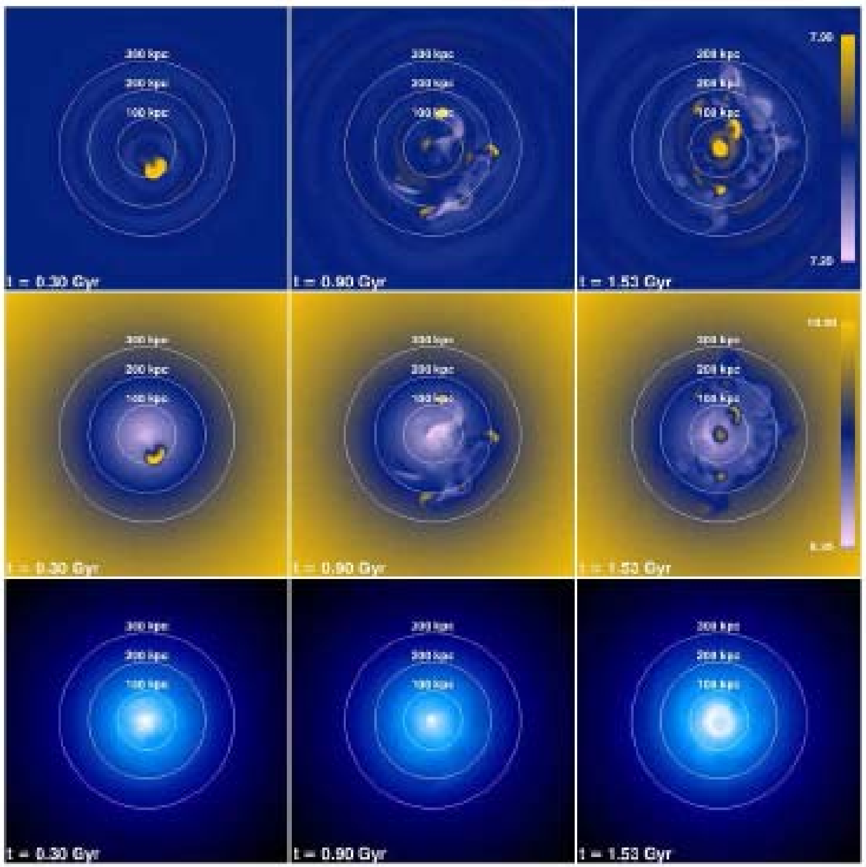
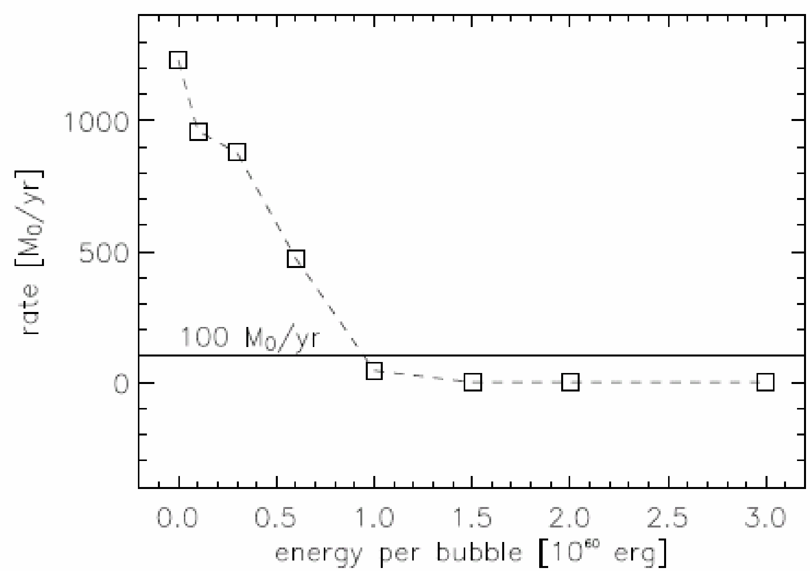


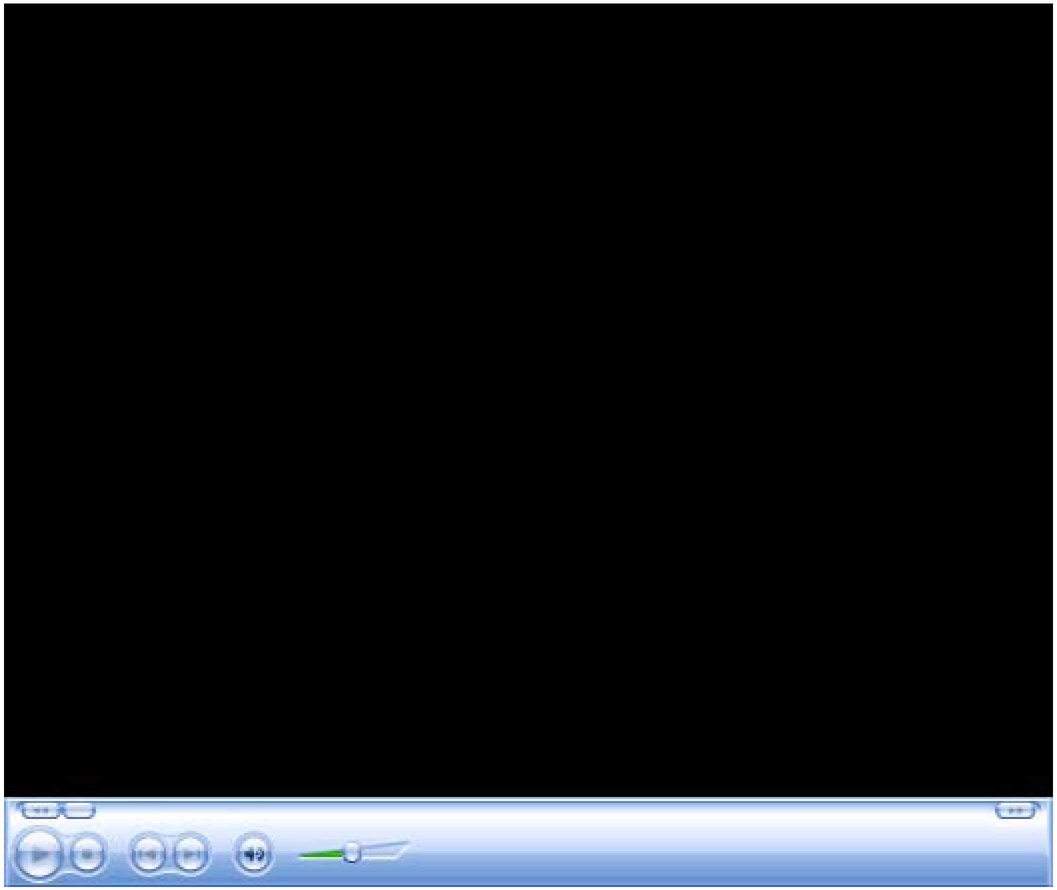
Figure 4. The time evolution (from left to right) of simulation S2.0. From top to bottom, the quantities shown are the temperature [K] and entropy [ergs $g^{-2/3}$ cm^2] on the x-y plane crossing the centre. In the bottom row we show the approximate bolometric emissivity $\rho^2 T^{1/2}$ projected through the simulation volume. The temperature distribution reveals the presence of sound waves propagating through the ICM. The sound waves are almost concentric and regular, a consequence of the periodic energy injection events near the cluster centre.

Cluster scale



Dalla Vecchia et al. 2004

Galaxy scale



$$L_{FB} \propto \dot{M}c^2$$

This model doesn't have a typical mass above which cooling is suppressed.

Di Matteo et al. 2005

Motivation

- Construct a physically motivated, self-consistent AGN feedback model which efficiently shut off cooling solely in massive halos.
- No cosmological simulations with evolving BHs and AGN feedback.
- Study roles of BHs in galaxy formation and vise versa.
- Make predictions

Mass accretion on to central BHs

- Radiation drag model by Kawakatu & Umemura 2002

$$\dot{M} = \eta_{\rm drag} \frac{L_{\rm SFR}(t)}{c^2}(1 - e^{-\tau_{\rm SFR}(t)}),$$

$$\text{where } \tau_{SFR} \approx \frac{3\chi_d}{4\pi}\frac{M_{\rm cloud}}{r_{\rm SFR}^2} \text{ and}$$

$$\chi_{\rm d} = 300\,{\rm cm}^2{\rm g}^{-1}(\alpha_{\rm d}/0.1\mu{\rm m})^{-1}(\rho_{\rm s}/{\rm g\,cm}^{-3})\,(Z/0.3Z_{\rm sun})$$

- Roughly speaking,
  - Magorrian relation $\dot{M} \propto \dot{M}_{SF}$
  - If $L_{FB} \propto dM/dt$, $L_{FB} \propto$ SFR

AGN feedback

- In order to have strong feedback in large halo where $t_{cool} > t_{dyn}$, here we consider two modes of accretion.
  - $\dot{M} > \dot{M}_{crit} \approx 0.01–0.1 \dot{M}_{Edd}$
    Radiatively efficient thin accretion flow
  - $\dot{M} < \dot{M}_{crit}$
    Radiatively inefficient thick accretion flow
- Only the latter associates with radio jets (e.g. Narayan & Quataert 05)

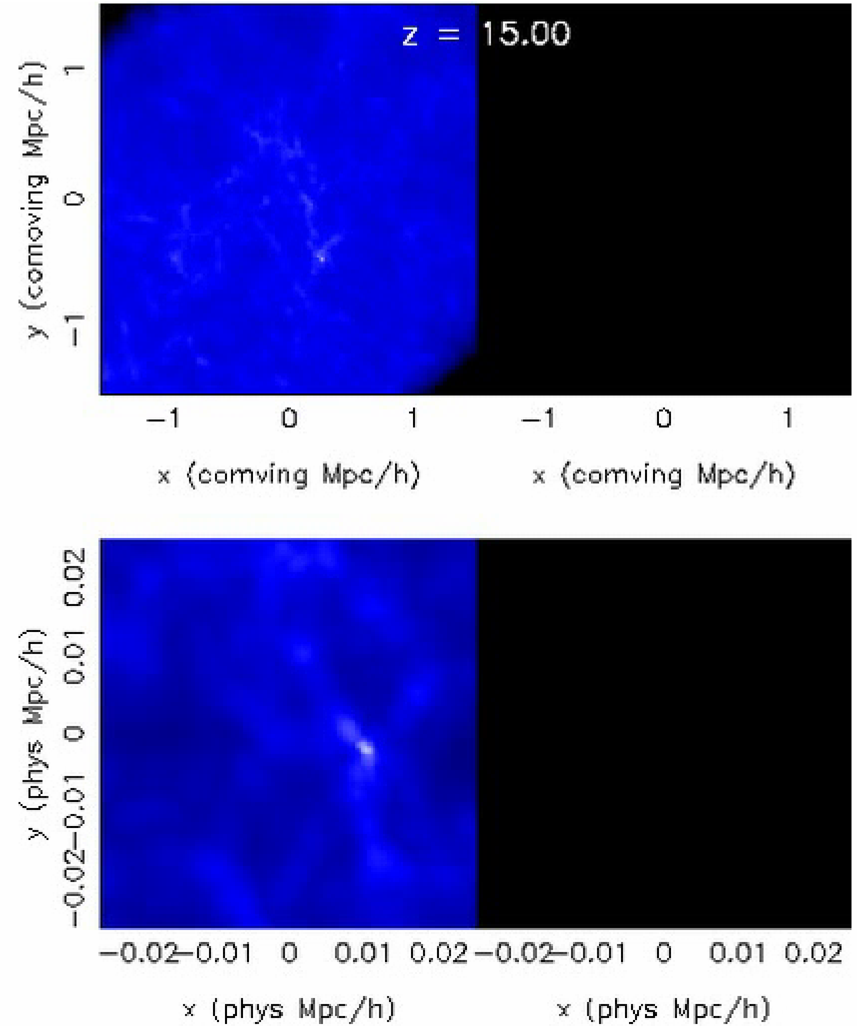
$$L_{\mathrm{FB}}^{\mathrm{Thin}} \approx 5 \times 10^{-5} \dot{M} c^2,$$

$$L_{\mathrm{FB}}^{\mathrm{Thick}} \approx 2.5 \times 10^{-1} \dot{M} c^2$$ (Meier 2001)

Simulation

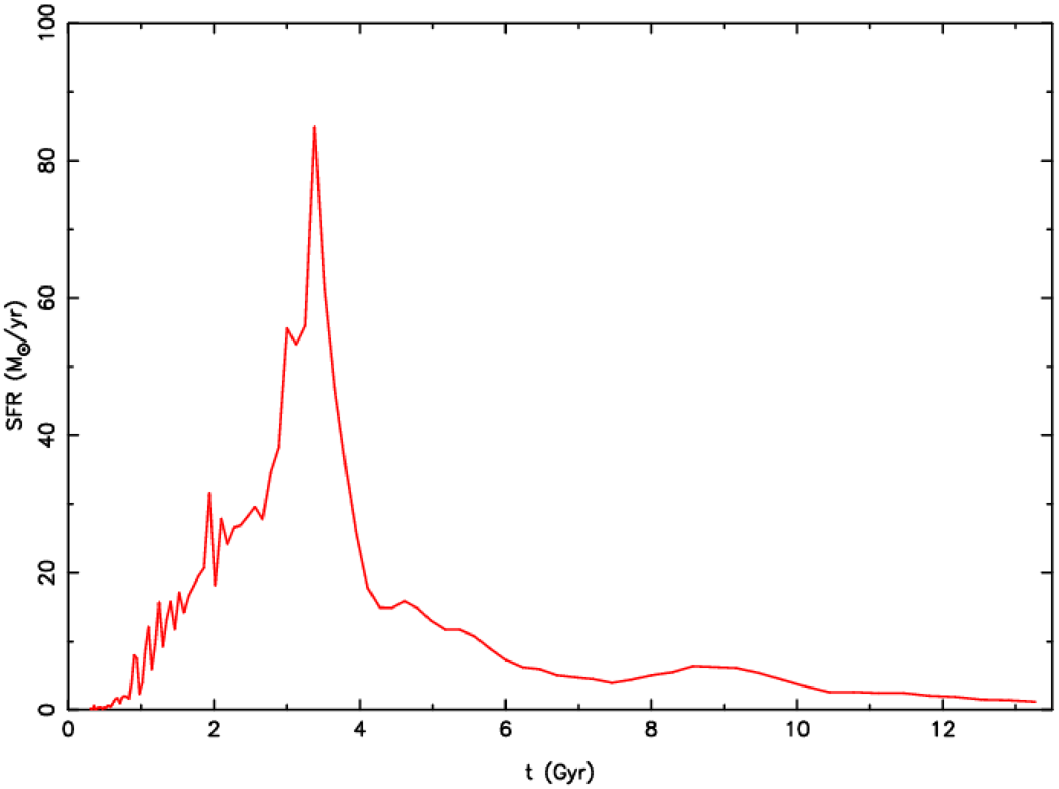
- ΛCDM
- 35.325 h^{-1}Mpc periodic box
- Target halo
  - $M_{vir} \sim 2 \times 10^{12}\ h^{-1}\ M_{sun}$
  - $z_{major} \sim 1$
  - $z_{half} \sim 1.5$
- UV background
- Type Ia & II SNe
- Metallicity dependent radiative cooling

Results



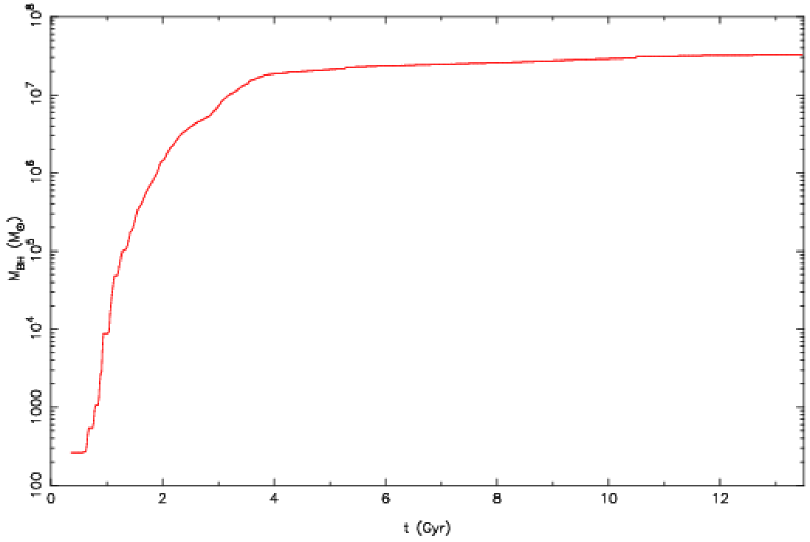
z = 15.00
y (comoving Mpc/h)
−1
0
1
−1
0
1
−1
0
1
x (comving Mpc/h)
x (comving Mpc/h)
y (phys Mpc/h)
−0.02
−0.01
0
0.01
0.02
−0.02
−0.01
0
0.01
0.02
−0.02
−0.01
0
0.01
0.02
x (phys Mpc/h)
x (phys Mpc/h)

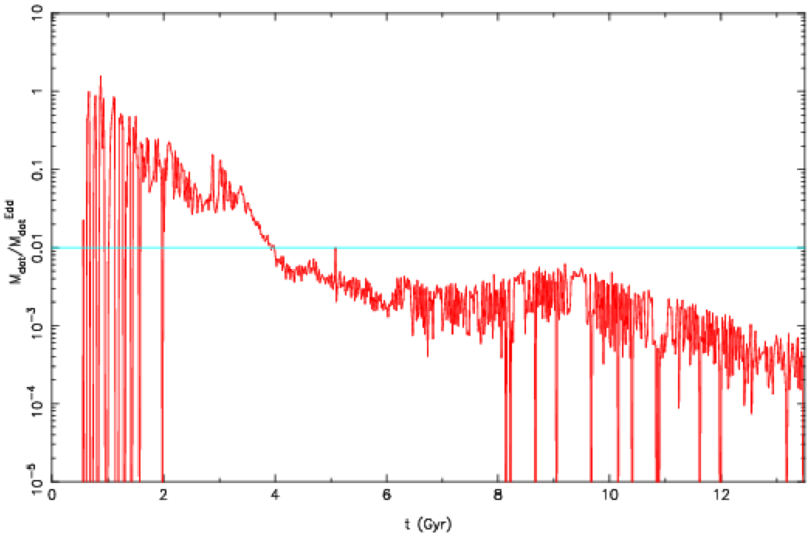
SFR



Peaked at z = 2.

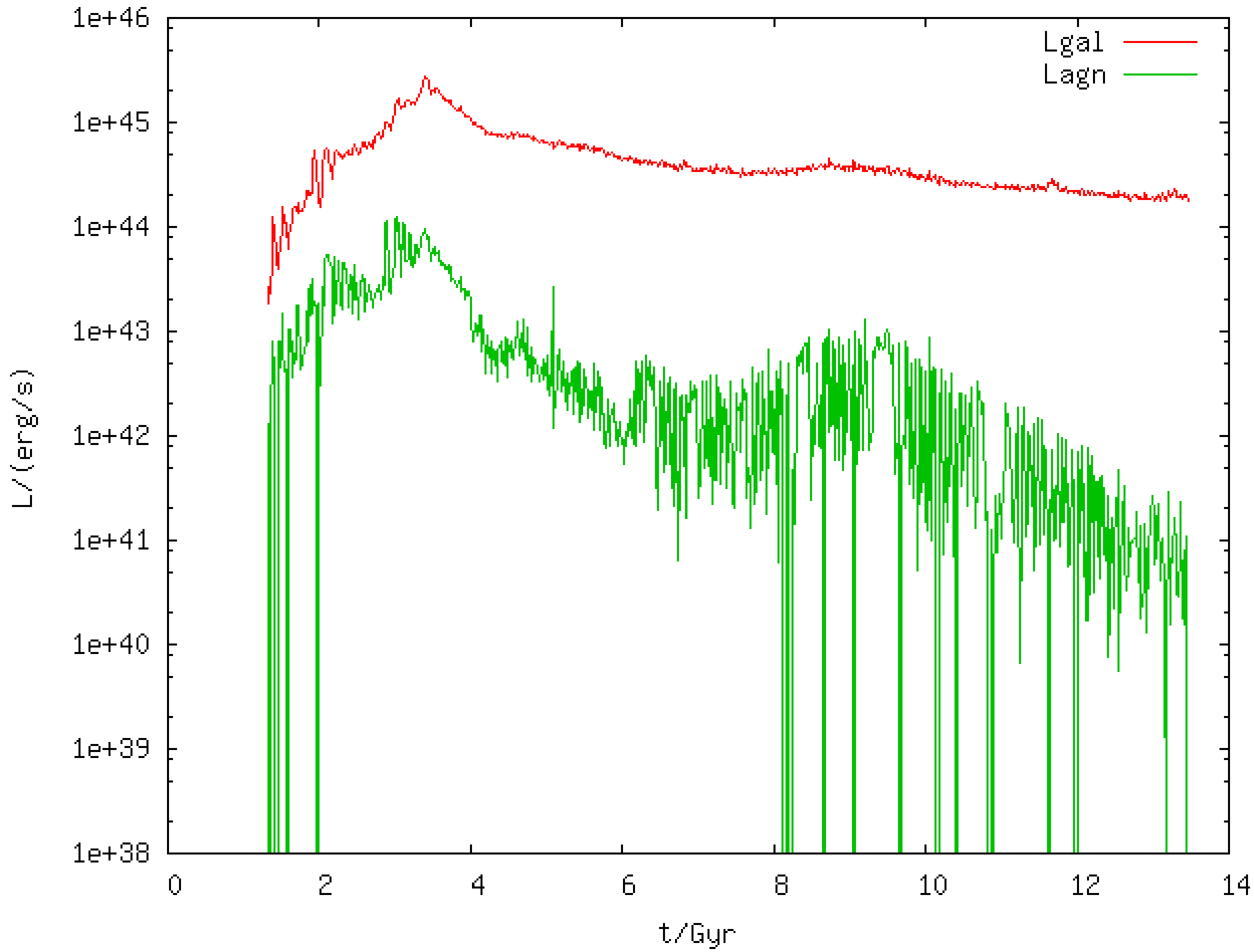
BH evolution



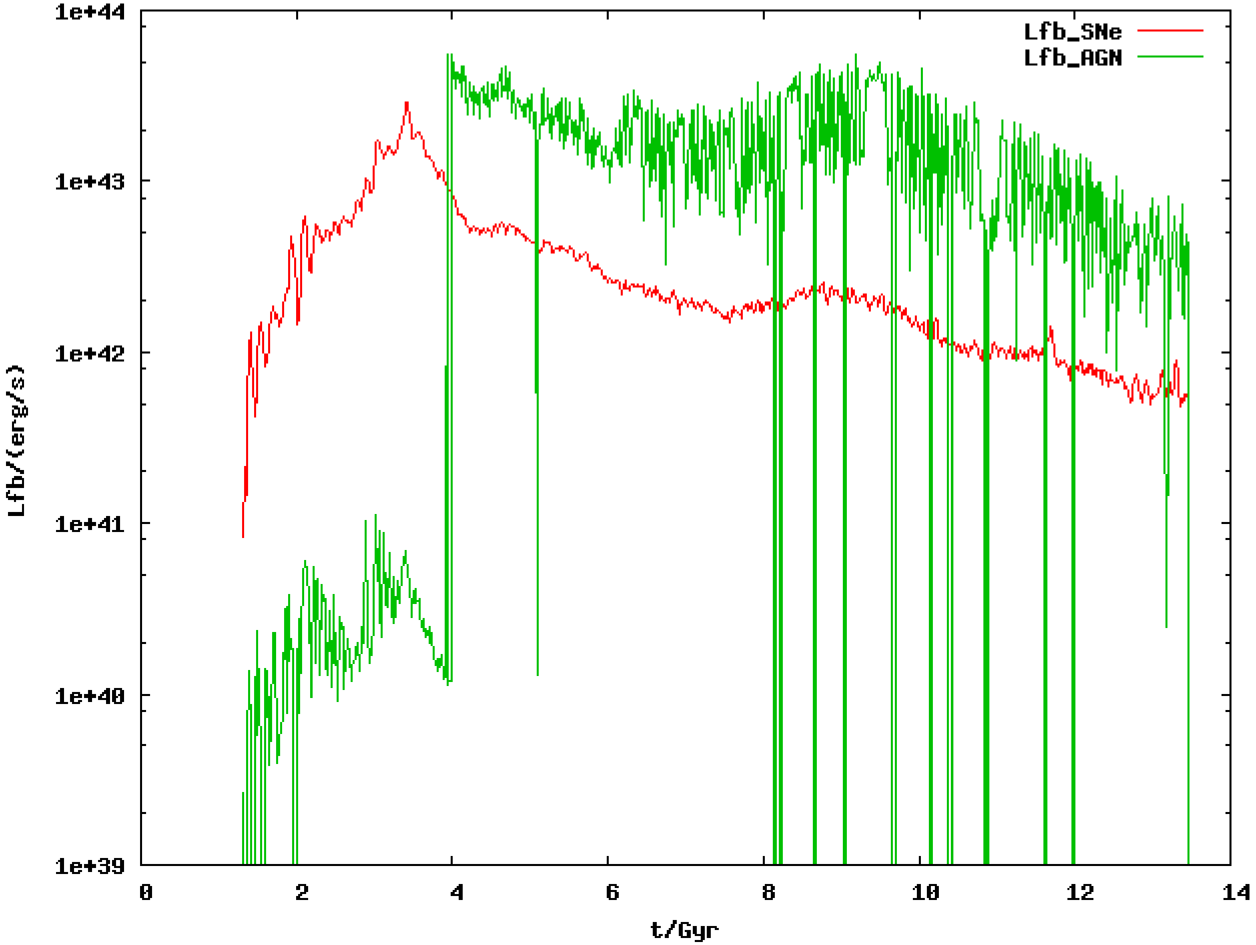


- The BH mass roughly agrees with that inferred from the Magorrian relation.
- The accretion mode changes after the star burst. phase.

Relative importance of the AGN
1. Bolometric luminosities



Relative importance of the AGN
1. Feedback energy



Summary

- Code is almost ready.
  - Almost…
- By assuming two modes of accretion flow
  - The AGN becomes a dominant source of feedback after the starburst phase.
  - The AGN is luminous only in the starburst phase.
- Future work
  - Groups and clusters
  - Slim disc at $\dot{M} > \dot{M}_{\mathrm{Edd}}$?
  - Effects of radiation

数値シミュレーションの最大の不定性

- Feedback
  - Cooling function が温度の関数なので、同じ E_{FB} を与えてもそれを空間的・時間的にどう配分するかで結果が大きく変わる
    - 小さな質量を加熱→高温→strong FB
    - 同様に instantaneous FB の方がまじめに星の寿命を計算して少しずつ熱を注入するよりずっと強い FB の効果

展望

- Higher resolution
  - 天の川プロジェクト？
- Better code
  - さよなら SPH
- More physics
  - Conduction
  - Radiation
  - Magnetic field
- よりよい理解につながるのか？
- まあほどほどに

個人的には…

- 星形成のモデルはなんであれ、観測 (Kennicutt law) を再現できる程度のもので十分
- ISM からどのくらいのガスがどのくらいの速度でハローに逃げるかが一番大事。
  - High-resolution の simulation で調べられるかも？
- 本当に星形成のモードが複数あるのか？あるならどんな物理で切り替わるのか？
  - 分子雲形成入りの high-resolution の simulation
    - 銀河をまわしたりぶつけたりて M_{H2}/M_{gas} と local の物理量の関係を見てみるとか…