Formation & evolution of galaxies & SMBHs

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Outline of lectures

1. Structure formation & assembly of dark halos
2. Gas cooling & angular momentum
3. Star formation & feedback
4. Galaxy mergers & morphologies
5. Cosmic evolution of galaxies
6. Formation of black holes
7. BH binaries & spin
8. Co-evolution of galaxies & AGN

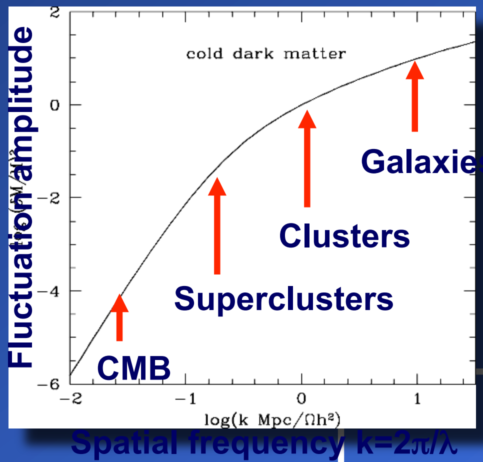
Lecture 2:

Gas cooling & angular momentum

Lecture 2 outline

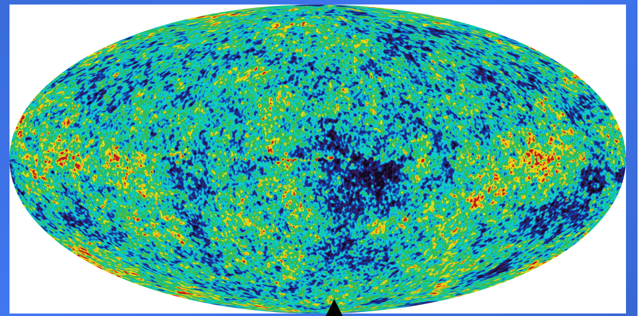
- Heating & cooling of gas
  - Shock-heating during structure formation
  - Radiative cooling
- Angular momentum & disk sizes
  - Tidal torques & angular momentum of halos
  - Disk sizes & angular momentum

Modelling galaxy formation



Cosmological model
(Ω, Λ, h) dark matter

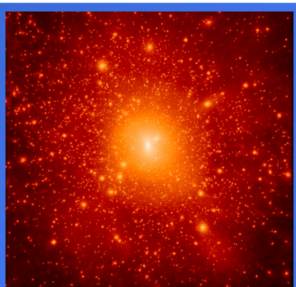
Primordial fluctuations
δρ/ρ(M, t)



Evolution of dark matter halos

Dynamics of cooling gas

N-body simulations



Star formation, feedback, evolution of stellar pops

- Gasdynamic simulations
- Semi-analytic modelling

Galaxy mergers

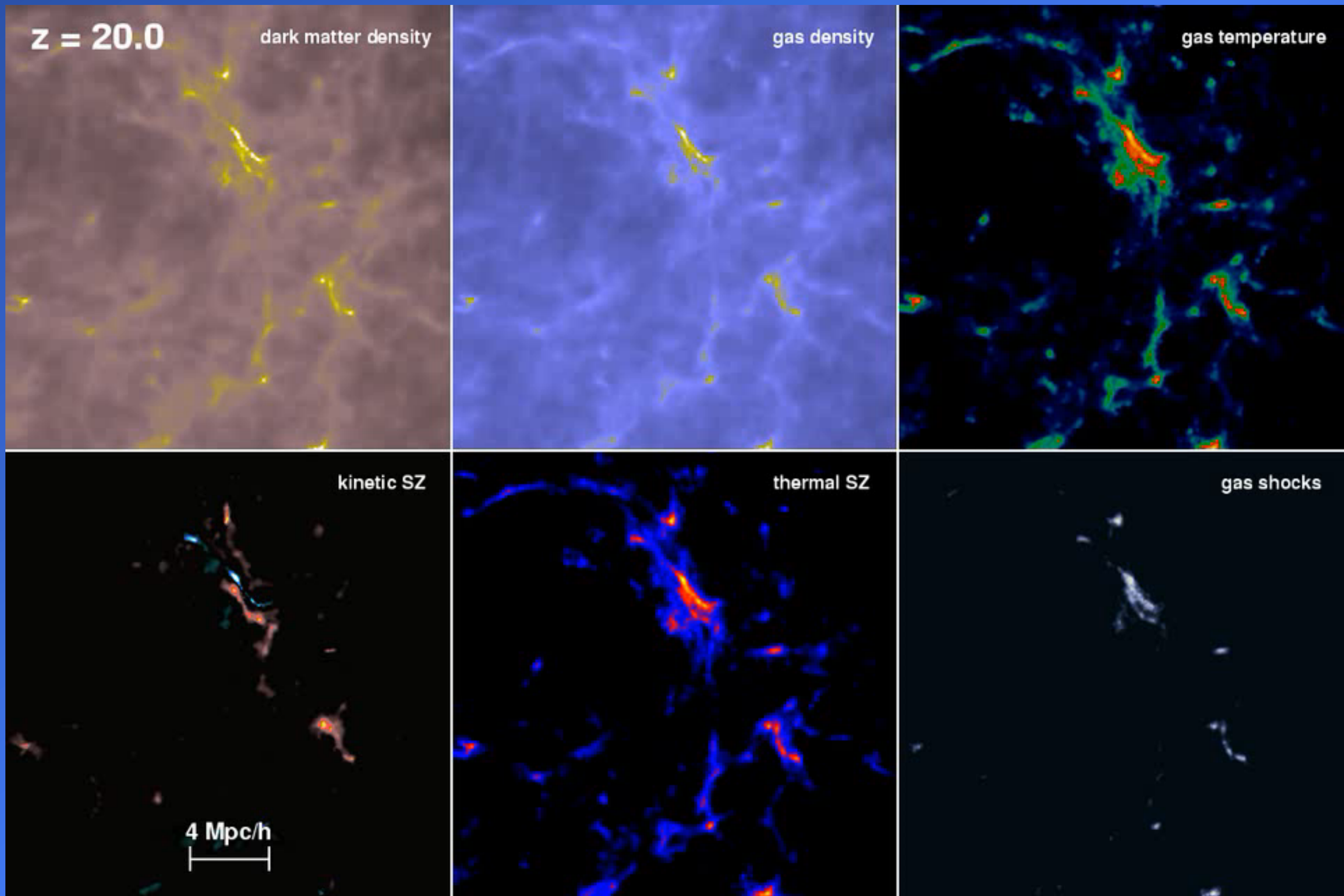
Formation and evolution of galaxies

Shock-heating of gas during structure formation

Shock heating during structure formation

- During collapse of structures, gravitational binding energy (negative of potential energy, PE) increases
- Gravitational PE released goes into kinetic energy (KE) of dark matter (DM) & baryons
- DM: collisionless - KE goes into internal KE of random motions in final object
- Gas: collisional - when gas streams collide supersonically, KE converted into thermal energy (TE) in shocks

Simulation of cluster formation including gas



Simulation by Volker Springel

Shock heating

- Shocks in both filaments & halos
- But most of shock-heating in halos, since these contain most of grav PE
- Gas follows DM quite closely up until shocks occur
- On cluster scales, $t_{cool} >> t_{dyn}$ so radiative cooling has little effect
- In this case, gas & DM have similar distribns even after shocking

Simple estimate of shock-heating in halo formation

- Halos in simulns found to be roughly in dynamical equilibrium at mean interior densities $M(<r_{vir})/(4\pi r_{vir}^3/3) > \rho_{vir}$
- given by spherical collapse model: $\rho_{vir}(z) \sim 100\ \rho_{av}(z)$
- defines characteristic radius r_{vir} for each halo
- characteristic circular velocity for halo V_{vir}

$$V^2_{vir} = GM(<r_{vir})/r_{vir}$$

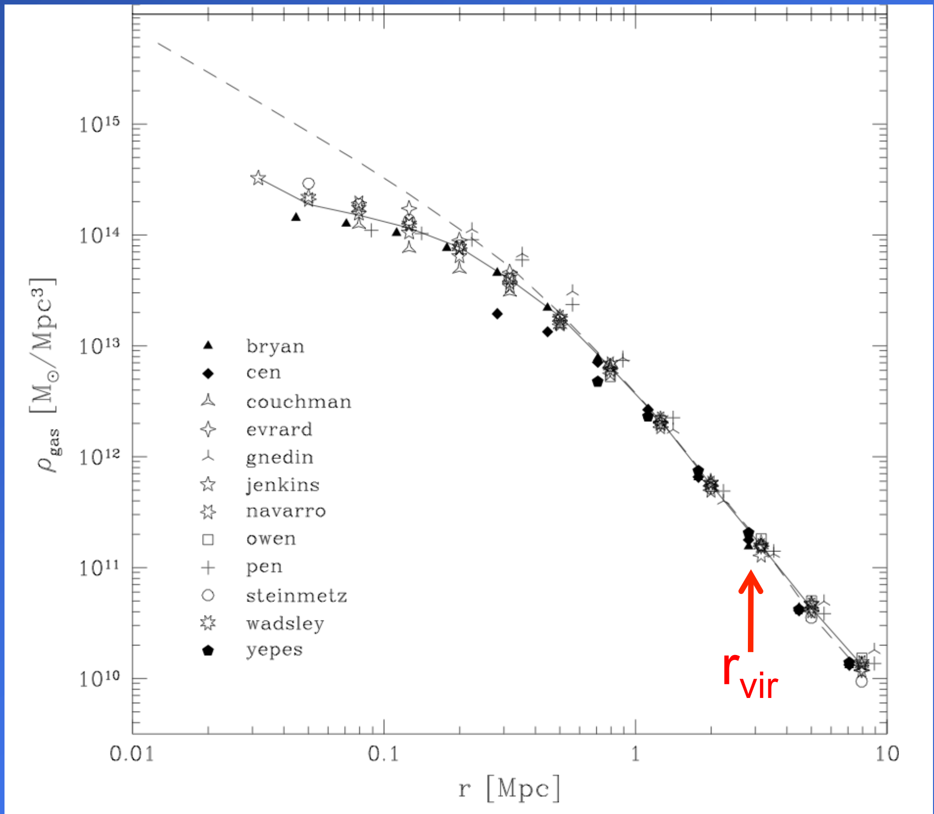
- Gas falling into halo releases grav PE per unit mass ~ $GM/r_{vir} = V^2_{vir}$
- This KE is thermalized in shock
- Thermal energy per unit mass is ~ $kT/\mu m_H$
- So if radiative cooling in shock negligible, gas in halos shock-heated to characteristic temperature T_{vir}

$$kT_{vir} = \tfrac{1}{2}\mu m_H V^2_{vir}$$

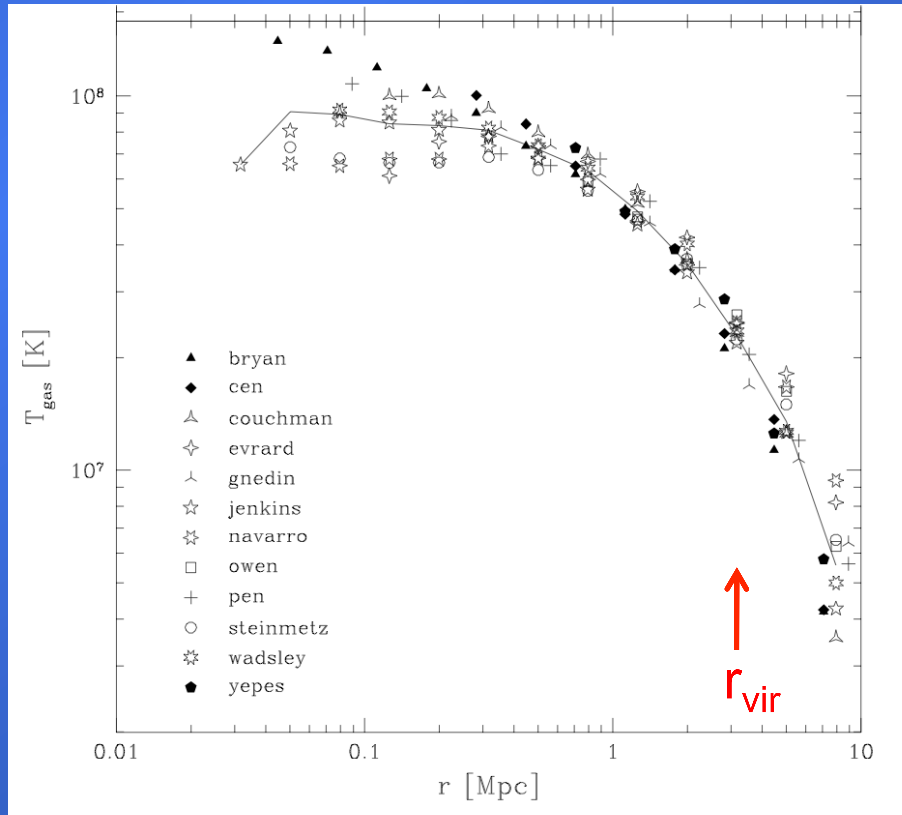
- Gas at this temp is supported against further collapse in halo by its thermal pressure

Density & temperature profiles of simulated cluster

gas density



gas temperature

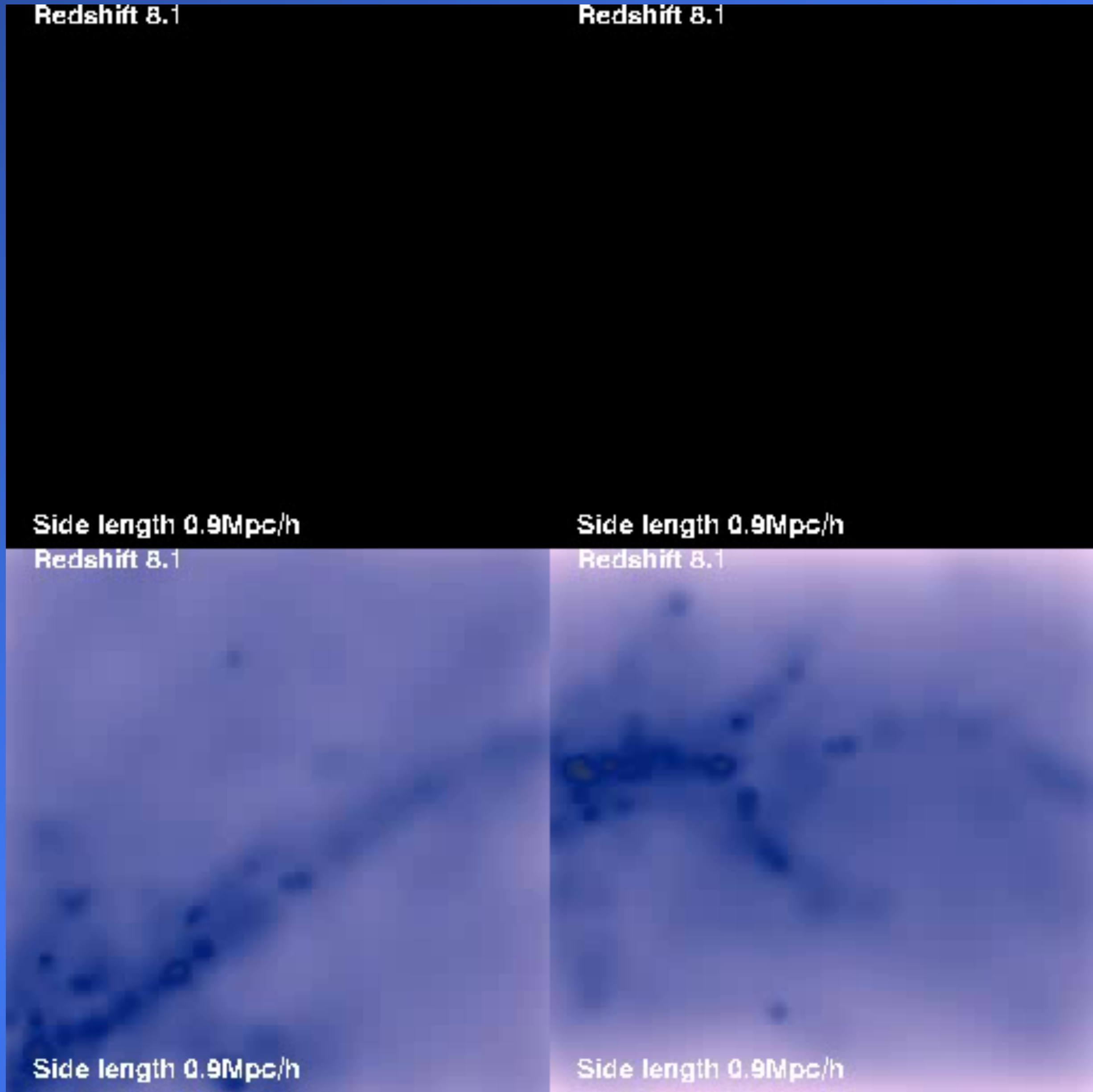


Radiative cooling of gas in halos

Importance of radiative cooling to galaxy formation

- Radiative cooling is CRITICAL!!
- In absence of cooling, gas has similar distribution to DM
- To form stars, gas must be able to dissipate thermal energy and undergo gravitational collapse in halos to become self-gravitating
- Without radiative cooling, gas cannot become self-gravitating, since pressure supported against collapse & mean density dominated by DM by factor ~10
- So radiative cooling an essential step in galaxy formation

Simulation of disk galaxy formation



stars

gas

Simulation by Takashi Okamoto

Role of radiative cooling in galaxy formation

- In galaxy size halos, radiative cooling of gas IS important, $t_{cool} < t_{Hub}$
- Dissipation of thermal energy allows gas to sink towards centre of halo
- Gas ends up in disk of radius $r_{gal} \sim 10$ kpc
- very different from DM in sphere of radius $r_{vir} \sim 100$ kpc

Radiative cooling

- In general, define radiative cooling rate per unit volume $\Lambda(n,T,Z)$
  - depends on atomic number density (n), temperature (T) & metallicity (Z)
- And radiative cooling timescale

$$t_{cool}(n,T,Z) = \frac{\frac{3}{2}nkT}{\Lambda(n,T,Z)}$$

- Radiative cooling rate depends on atomic & molecular processes

Radiative cooling processes in low-density gas (1)

- Compton cooling
  - Free electrons cool off CMB photons
  - 1-body, $\Lambda \propto n_e (T-T_{CMB}) U_{CMB}$
  - Cooling time t_{comp} independent of gas density & temperature (for $T >> T_{CMB}$)
  - $t_{comp} \propto 1/U_{CMB} \propto 1/(1+z)^4$
  - Only important at high-z, when $t_{comp} < t_H = 1/H$ i.e. $z>6$

Radiative cooling processes in low-density gas (2)

- Atomic
  - 2-body, $\Lambda \propto n^2 L(T)$
  - Collisional excitation of atomic levels
  - Recombination
  - Bremsstrahlung
  - In primordial gas, only H & He
  - In chemically enriched gas, cooling by metal ions (especially O, Fe) important
  - Metals dominate cooling for $Z > 0.1\, Z_{o}$

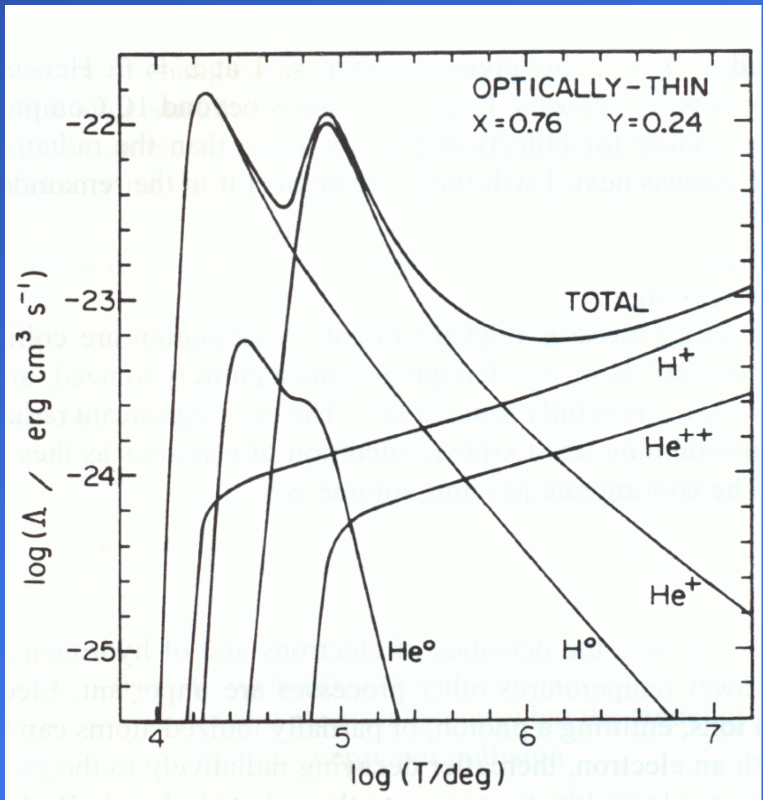
Radiative cooling processes in low-density gas (3)

- Molecular
  - 2-body, $\Lambda \alpha n^2 L(T)$
  - Molecular cooling important at low T, when atoms mostly neutral
  - In primordial gas, H_2 is only coolant for $T < 10^4$ K
  - But H_2 easily photo-dissociated, so expected to be important coolant in galaxy halos only in first generation of objects to form in universe
  - In chemically enriched gas, cooling by other molecules also (e.g. CO)
  - But only in very dense gas which can self-shield against photo-dissociation

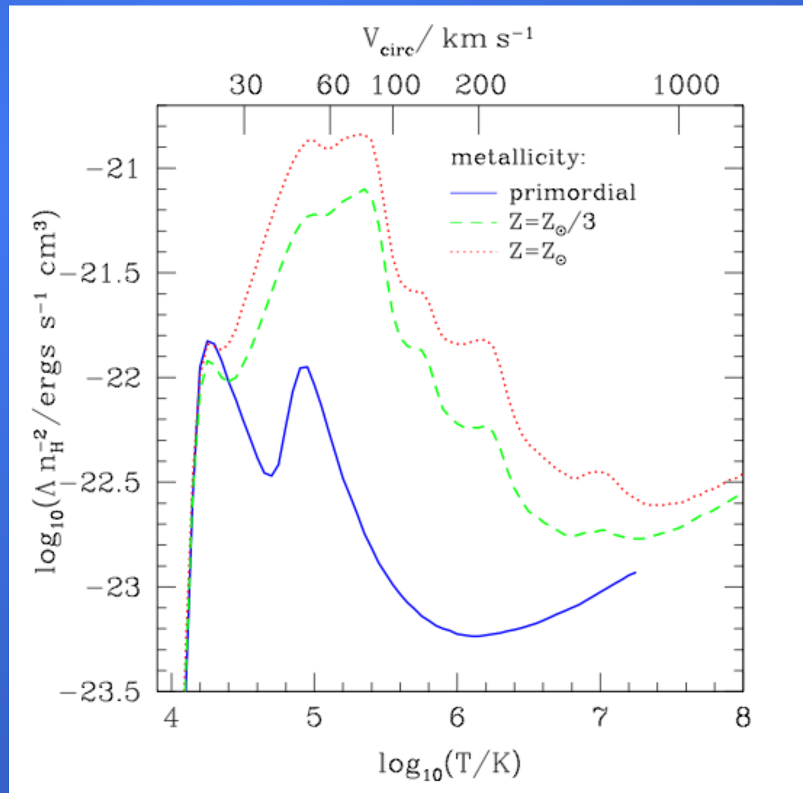
Atomic cooling function

For low-density gas in collisional ionization equilibrium

Primordial gas (H+He)



Metal-enriched gas



General features of cooling

- t_{cool} α $T/(nL(T))$ for atomic & molecular cooling – decreases with increasing n
- Atomic cooling cuts off for $T < 10^4$ K

  => t_{cool} becomes v.long
- For $T>10^6$-10^7 K, dominated by bremsstrahlung, so $L(T)$ α $T^{1/2}$

  $\Rightarrow t_{cool}$ α $T^{1/2}/n$

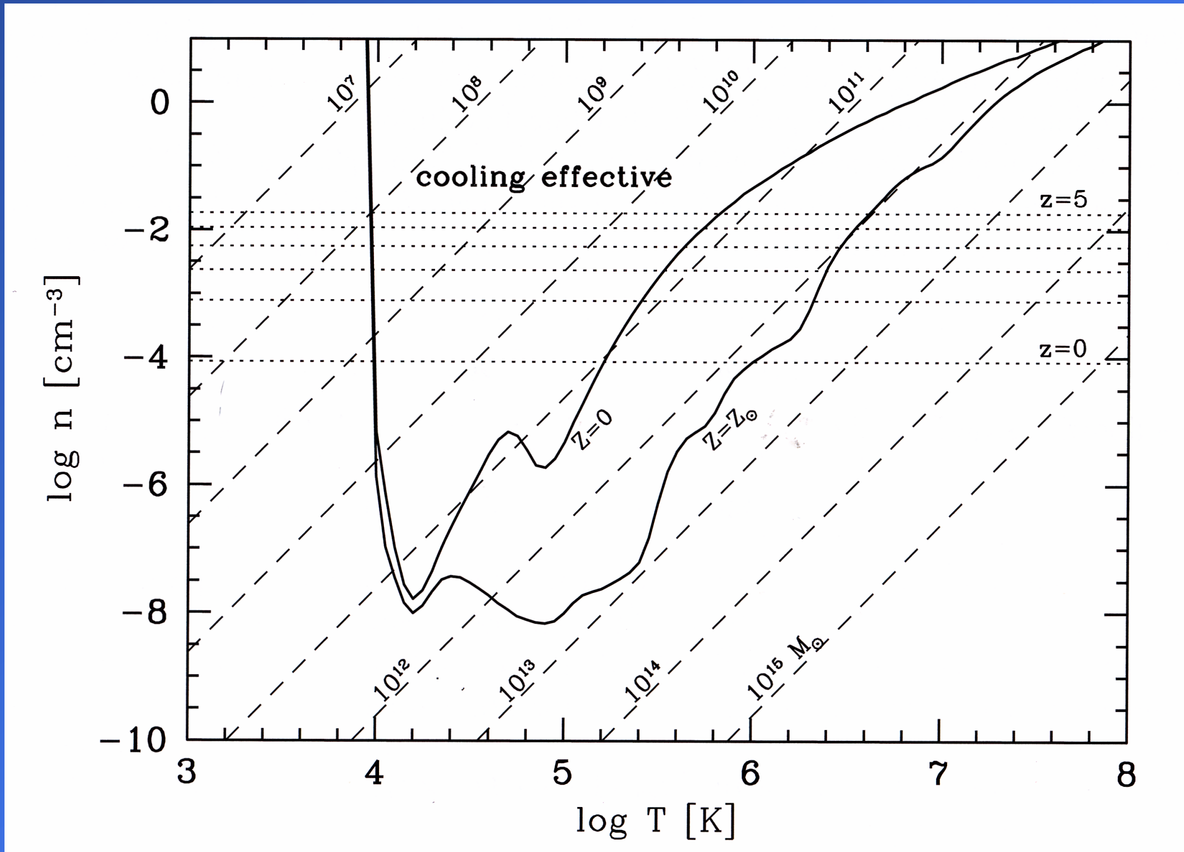
  - increases with T
- So cooling most rapid for intermediate $T \sim 10^4$ - 10^6 K (for fixed n)

Cooling depends on halo M & z

- Halos all have same mean density at given redshift $\rho_{vir} \propto (1+z)^3$
- But temperature increases with mass $T_{vir} \propto V^2_{vir} \sim GM/r \propto M^{2/3} (1+z)$
- So cooling in halos cuts off below $M_{min}(z)$ corresponding to $T_{vir} \sim 10^4$ K, and becomes inefficient for large M
- Since $t_{cool} \propto 1/n \propto 1/(1+z)^3$ while Hubble time $t_H \propto 1/(1+z)^{3/2}$ => $t_{cool}/t_H \propto 1/(1+z)^{3/2}$
- so cooling is more effective at high-z for given T_{vir} & Z

Characteristic mass from radiative cooling in halos

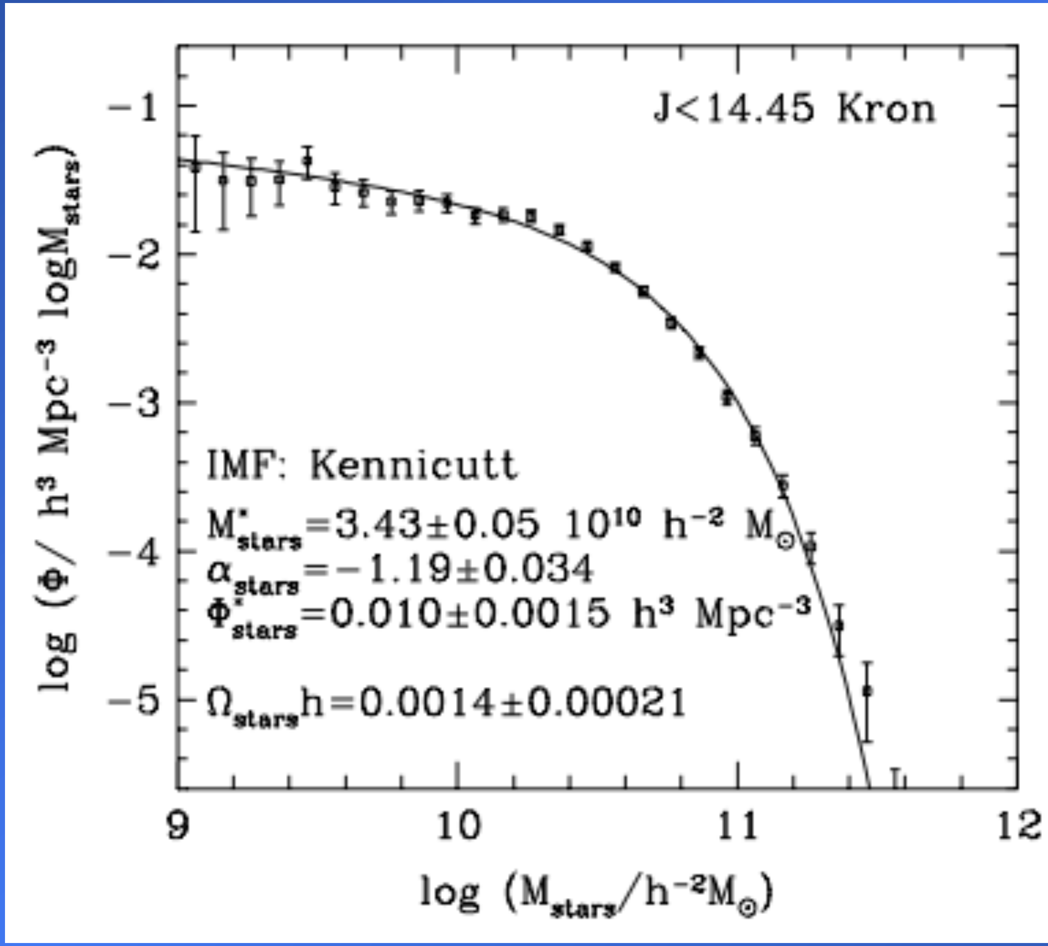
(Rees & Ostriker 1977)



- "efficient cooling" for $t_{cool} < t_{ff}$
- free-fall time $t_{ff} \propto 1/(G\rho)^{1/2} \propto 1/n^{1/2}$
- $n \propto (1+z)^3$ for halos at virial density
- $t_{cool} \propto T/(nL(T))$
- correponds to being above curve in diagram

defines characteristic halo mass $M_{crit} \sim 10^{11}$-10^{12} M_o above which cooling inefficient

c.f. observed galaxy stellar mass function at z=0



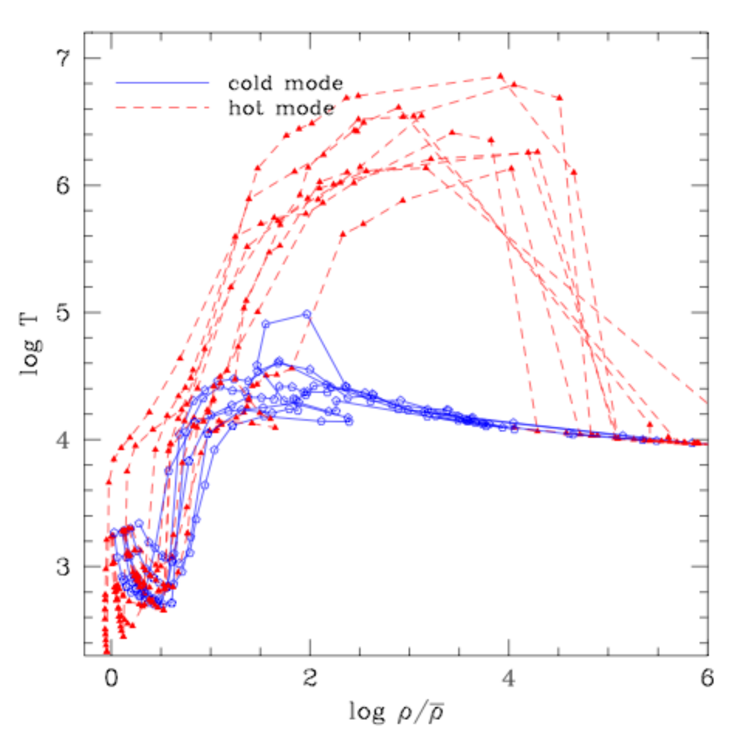
- break in observed galaxy mass function at $M_{gal} \sim 10^{11}M_o$
- corresponds to halo mass $\sim 10^{12}M_o$
- similar to prediction of cooling timescale argument
  - suggests that cooling sets characteristic mass of galaxies

Cold vs Hot accretion

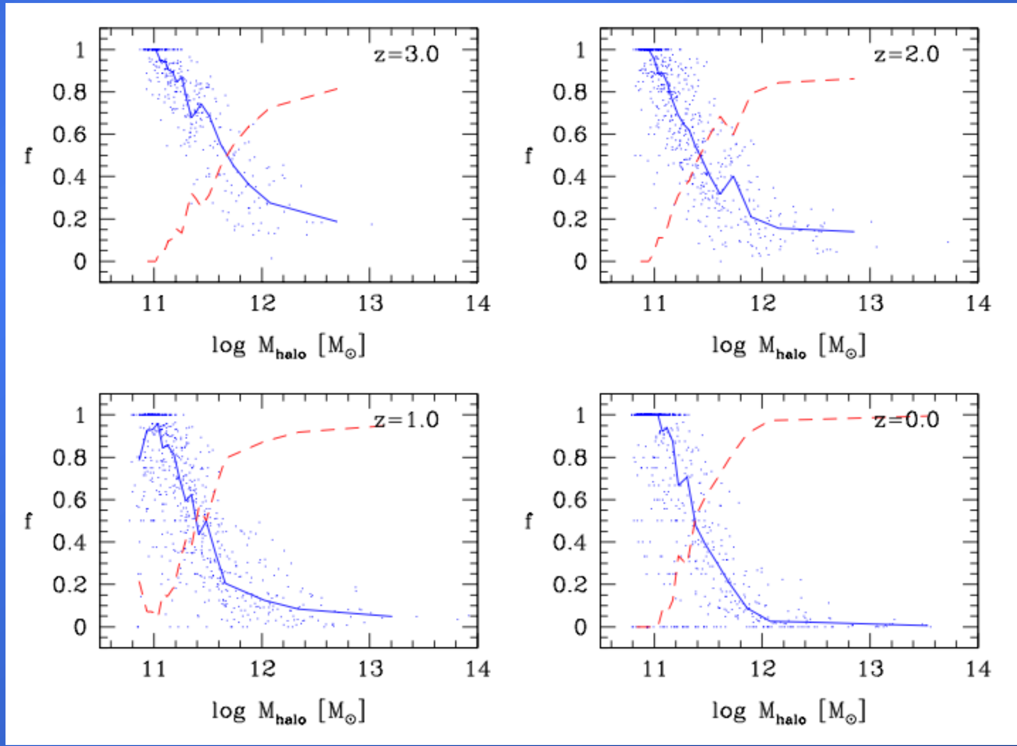
- more recent work (e.g. Birnboim & Dekel 2003, Keres et al 2005) suggests:
  - $t_{cool} < t_{ff}$ gas doesn't shock heat to T_{vir}, cold gas accretes along filaments - "cold accretion"
  - $t_{cool} > t_{ff}$ gas shock-heats to $T \sim T_{vir}$, then cools quasi-statically in halo - "hot accretion"
- however, doesn't affect argument about characteristic galaxy mass scale due to cooling

Cold vs hot accretion of gas in halos

max T of accreted gas

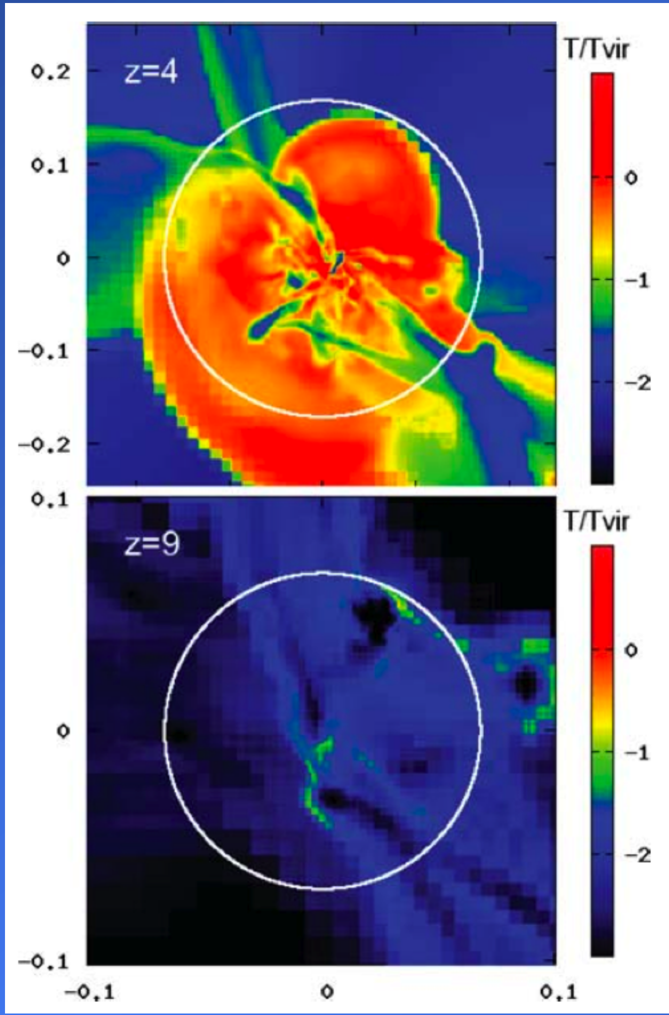


fraction of gas accreted in cold mode

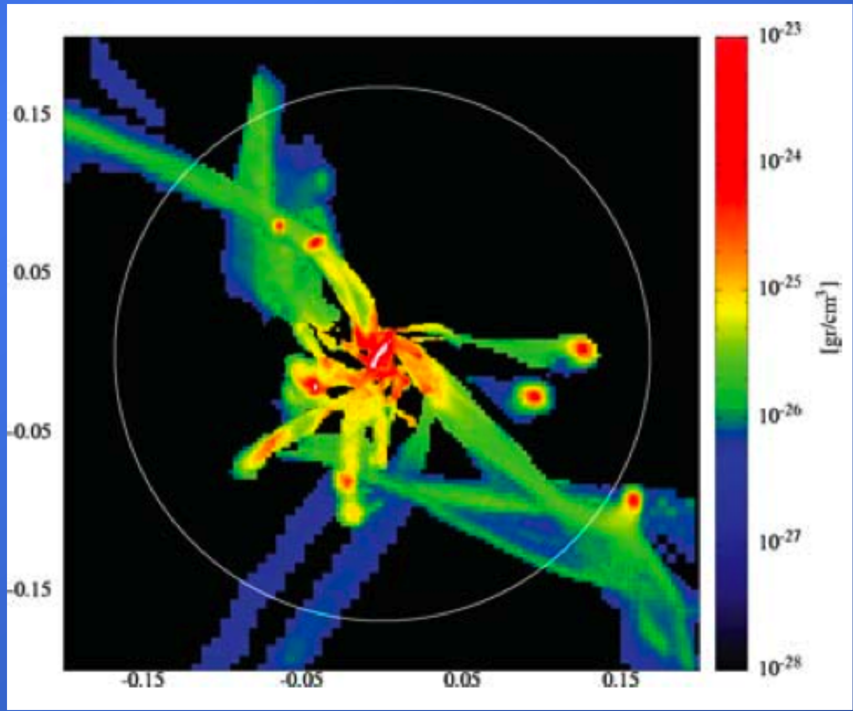


Keres etal 2005

Cold vs hot accretion (3)

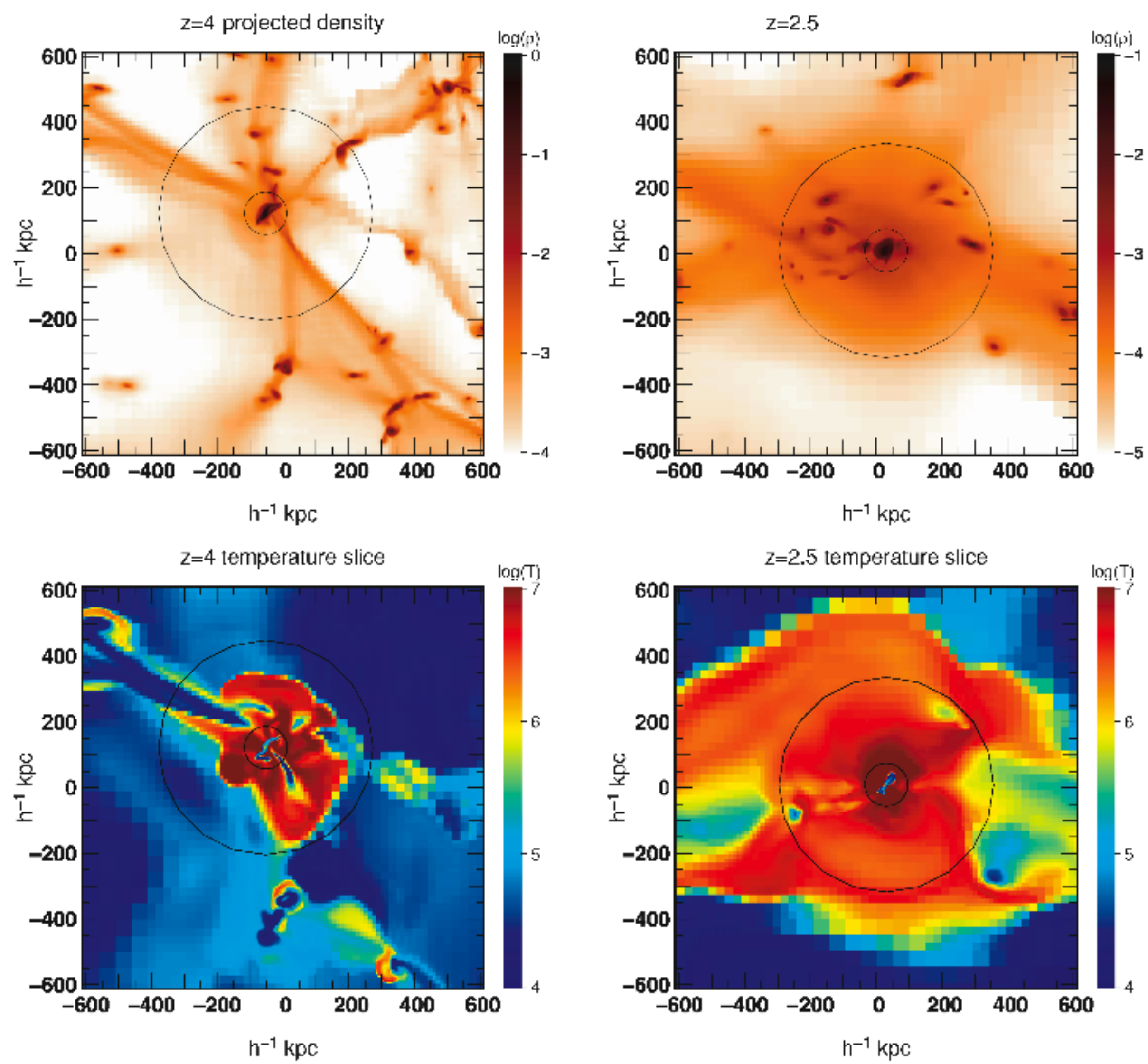


- virial shock forms only for M > M_{crit}
- Cold accretion is along filaments



Dekel & Birnboim 2006

Cold vs hot accretion (3)



- virial shock forms only for M > M_{crit}
- cold accretion is along filaments

Ocvirk et al 2008

Tidal torques & origin of angular momentum

Importance of angular momentum in galaxy formation

- If gas in halo can radiate all of its energy, then what halts its gravitational collapse is angular momentum (assuming cannot transfer all of this to DM halo)
- Stars & gas in galactic disks are on nearly circular orbits - centrifugally supported against gravity
- So sizes of galaxy disks are controlled by how much angular momentum they have

Origin of angular momentum

- Initial density perturbns which seed structure formation through gravitational instability have no angular momentum
- angular momentum actually produced by non-linear evoln of density perturbns
- result of departures from spherical symmetry
  - generate quadrupolar gravitational fields
  - which act on quadrupole moment of mass distribution of density fluctuations
- perturbations gain ang mtm by tidal torques

Generation of angular momentum by tidal torques

- Ang mtm of object changes due to external torques:

$$\dot{\underline{J}} = \int (\underline{r} - \underline{r}_{CM}) \times \nabla \Phi_{ext} \, \rho dV$$

- Expand Φ around centre of mass (CM) of object:

$$\dot{J}_i = -\varepsilon_{ijk} T_{kl} I_{jl}$$

- Where T_{kl} is gravitational tidal field at CM

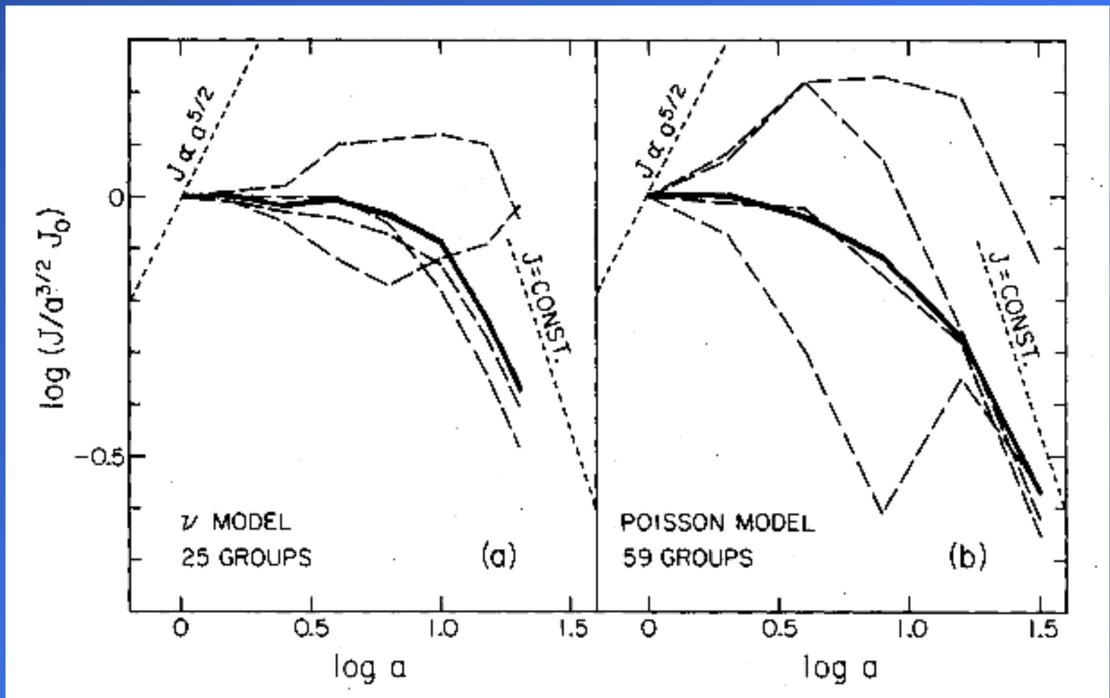
$$T_{kl} = \partial^2 \Phi_{ext} / \partial x_k \partial x_l$$

- And I_{jl} is moment of inertia tensor

$$I_{jl} = \int (x_j - x_j^{CM})(x_l - x_l^{CM}) \rho dV$$

- Thus ang mtm grows due to coupling of external tidal field to quadrupole moment of object

Growth of angular momentum of dark matter



White 1984

- Perturbn theory -> $J \sim t \sim a^{3/2}$
- N-body sims show J roughly follows this until structure turns around and collapses
- J then freezes out

Spin parameter λ

- Dimensionless parameter useful as measure of halo ang mtm

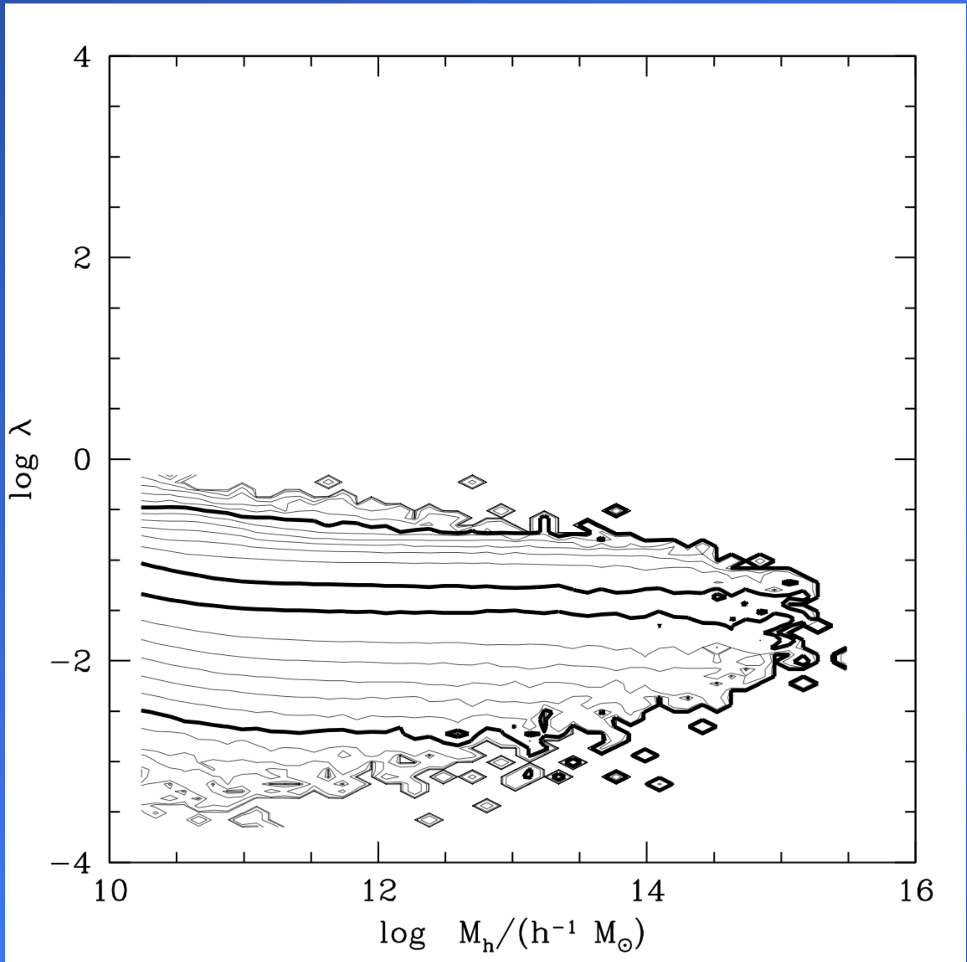
$$\lambda = J|E|^{1/2} / GM^{5/2}$$

- For object in virial equilibrium, with velocity dispersion σ and rotational velocity $V_{rot} < \sigma$ can show

$$\lambda \approx (1/4)(V_{rot} / \sigma)$$

- So for λ<<1, object is weakly rotating, supported against gravity by random motions
- For λ~1, strongly rotating, supported by rotational motions
- Halos in cosmological sims all have λ<<1, so slowly rotating

Spin parameters of halos in numerical simulations

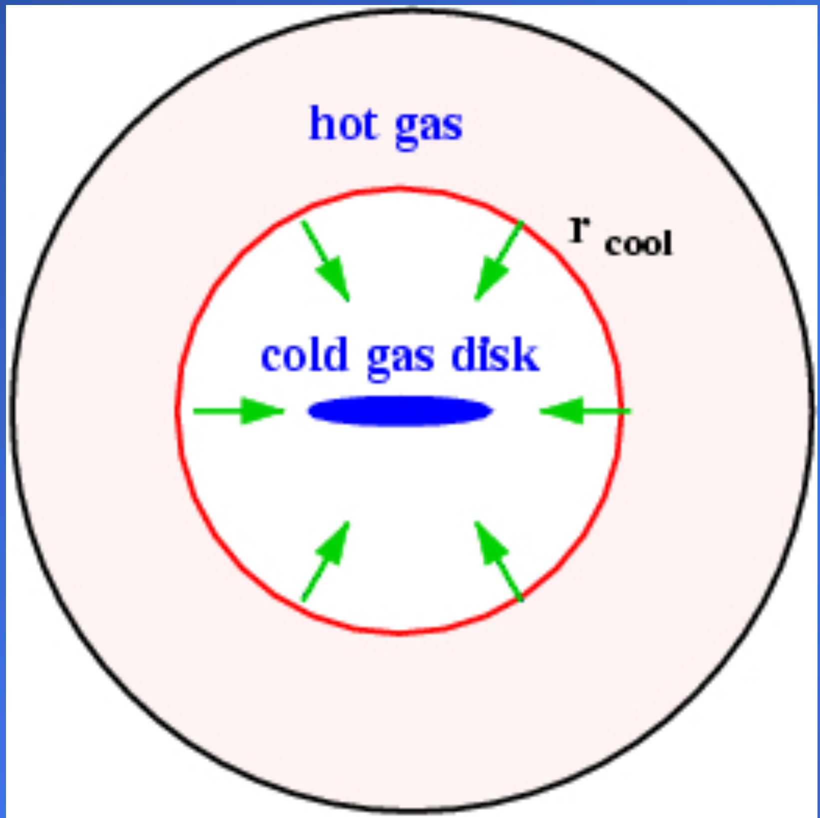


Bett 2006

- median λ ~ 0.05
- almost indept of halo mass
- or redshift
- or cosmology
- or initial spectrum of density fluctuations

Sizes of galaxy disks

Simple model for radii of galaxy disks



Assume:

- gas cools out to radius r_{cool}
- gas in halo initially has same J/M as DM
- gas conserves J as it collapses
- gas collapse stops when it becomes rotationally supported

- To simplify calc, also assume:
  - Ignore self-gravity of baryons
  - Halo has singular isothermal sphere profile

    V_c = const & V_{rot} = const

    $\rho_H = V_c^2 /(4\pi G r^2)$
  - Disk has exponential surface density profile

    $\Sigma_D \sim \exp(- r/h_D)$
- Then

  $J_H/M_H = 2 \lambda_H V_c r_{cool}$ (for DM within $r<r_{cool}$)

  $J_D/M_D = 2 h_D V_c$
- So setting $J_D/M_D = J_H/M_H$ gives

  $h_D = \lambda_H r_{cool}$
- So gas collapses in radius by factor

  $r_{disk}/r_{cool} \sim h_D/r_H \sim \lambda_H \sim 0.1$

Simple model for galaxy disk radii

- thus predict:
  - $r_{disk} \sim \lambda_H \, r_{cool}$ (if gas cools only within radius r_{cool})
  - $r_{disk} \sim \lambda_H \, r_{vir}$ (if all gas in halo cools to form disk)
- in rough agreement with observed sizes of galaxy disks at z~0 (when use distribution of λ_H from sims) (e.g. Fall & Efstathiou 1980, de Jong & Lacey 2000, Shen et al 2003)