Evolution of Galaxies:

Galaxy formation, monolithic evolution

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Galaxy formation

= instability of self-gravitating protogalactic cloud
… like star formation

Dynamics of (isothermal) spherical cloud

$$\frac{\partial \rho}{\partial t} + \nabla(\rho\vec{v}) = 0$$ conserv. of mass

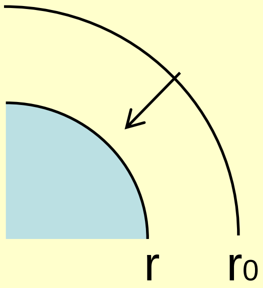
$$\frac{\partial \rho\vec{v}}{\partial t} + \nabla(\rho\vec{v}.\vec{v}) = -\nabla p - \rho\nabla\Phi$$ conserv. of momentum

$$p = p(\rho, T) \propto \rho c^2$$ equation of state

$$\nabla\Phi = 4\pi\rho$$ gravitation

Collapse if $M < M_J \propto T^{3/2}\rho^{-1/2}$ Jeans criterion

Free-fall solution (neglect p, OK for initial phase)



Mass shell initially at r_0

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

$$\frac{\pi}{2}\frac{t}{t_{\rm ff}} = \sqrt{\frac{r}{r_0}(1-\frac{r}{r_0})} + \arcsin\sqrt{1-r/r_0}$$

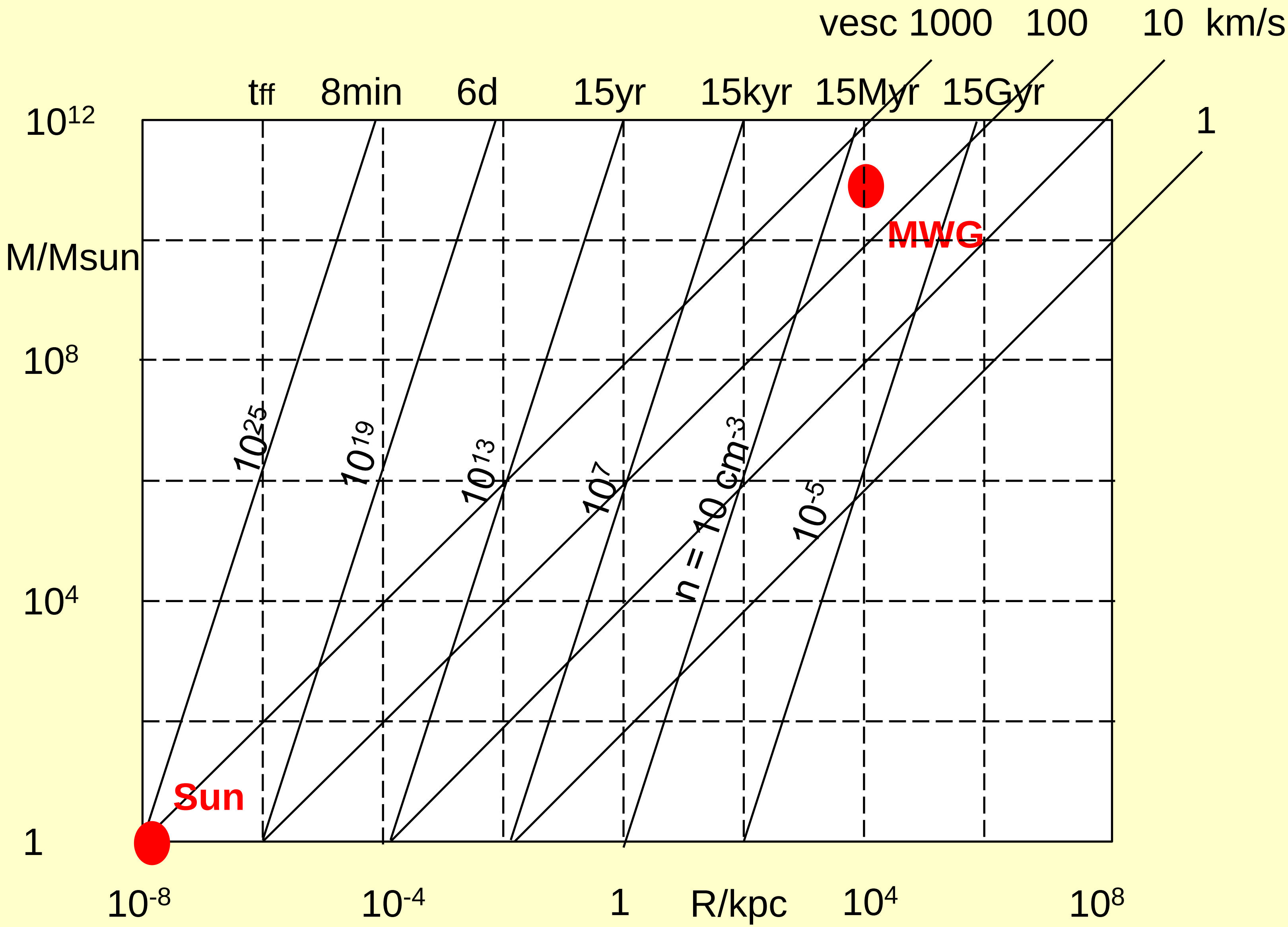
for t << $t_{\rm ff}$

$$r(t) = r_0(1-(\frac{\pi}{4}\frac{t}{t_{\rm ff}})^2)$$

$$v(t) = -\frac{\pi^2}{8}r_0\frac{t}{t_{\rm ff}} \propto -r_0 t$$

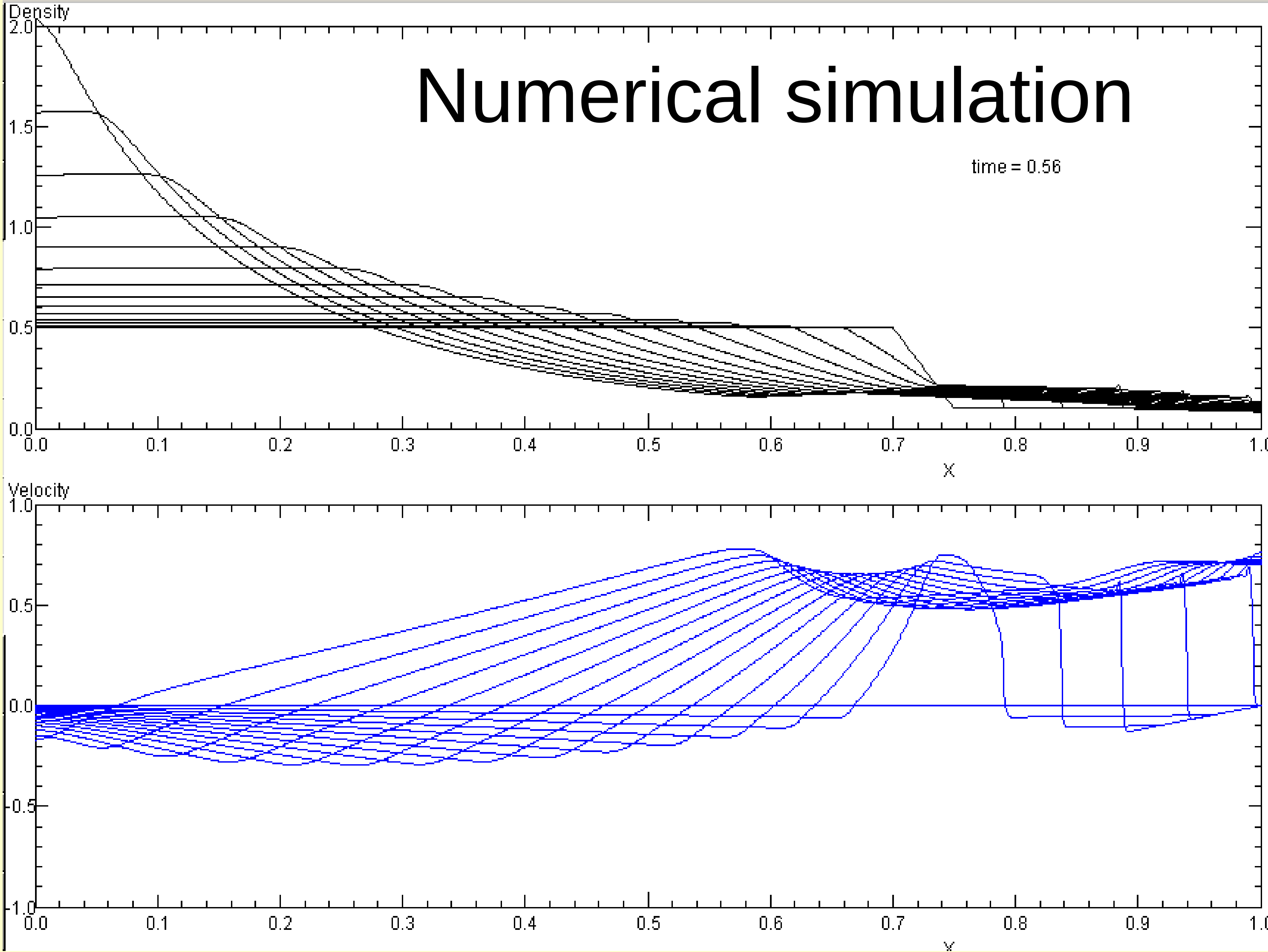
Complete collapse

$$r(t) = r_0(1-\frac{t}{t_{\rm ff}})^2 \to 0 \quad \text{for } t \to t_{\rm ff}$$



vesc 1000
100
10 km/s
1
tff
8min
6d
15yr
15kyr
15Myr
15Gyr
10^12
10^8
10^4
1
M/Msun
MWG
Sun
10^25
10^19
10^13
10^7
n = 10 cm^-3
10^-5
10^-8
10^-4
1
R/kpc
10^4
10^8

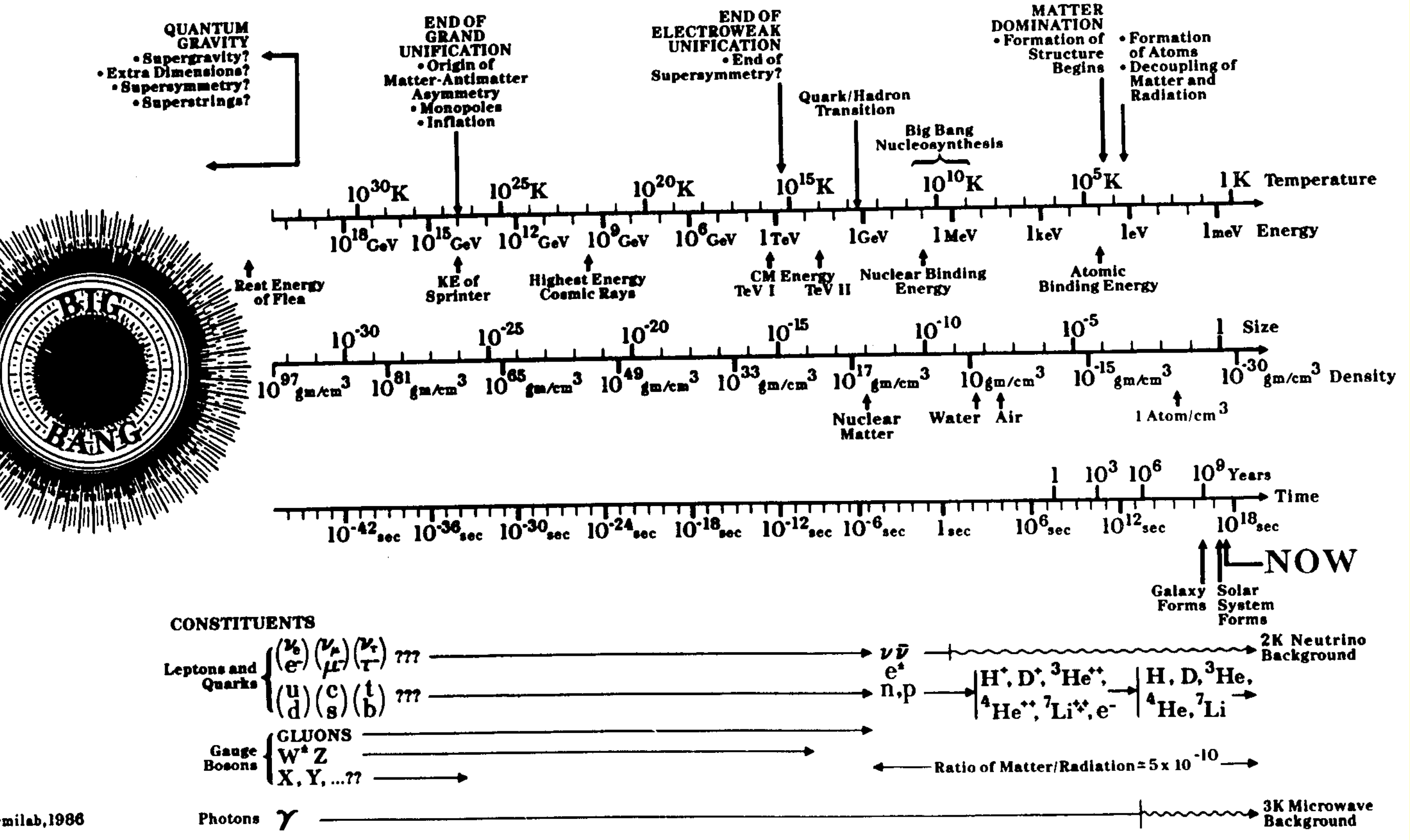
Numerical simulation

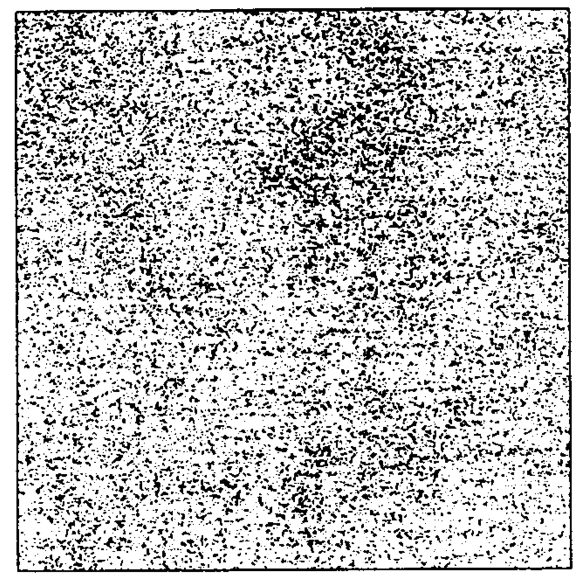


Galaxy formation in the Universe

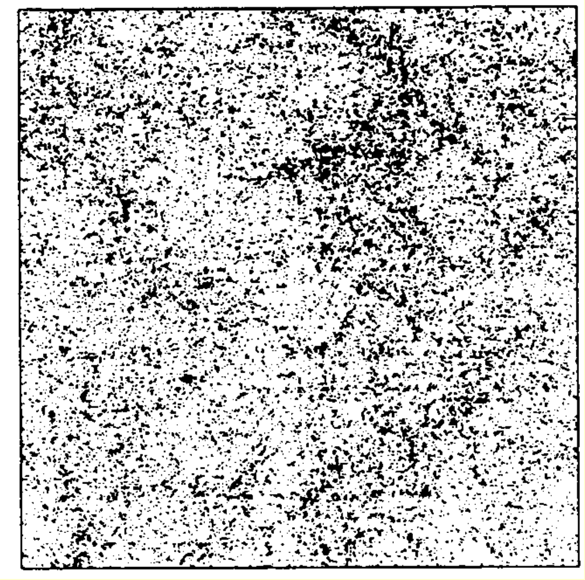
- Big Bang
  - at $T = 10^5$ yrs matter/radiation decoupling
  - Hot gas cools by expansion and radiative cooling
  - Density fluctuations grow if self-gravitation overcomes expansion
    - Condensation can collapse if $M > M_J$
    - cools and forms stars, if cooling time < free fall
  - Cooling curve ➔ $T \sim 10^4$ K ➔ $M_J \sim 10^7 \ldots 10^9$ Msun ➔ size of fragments

History of the Universe

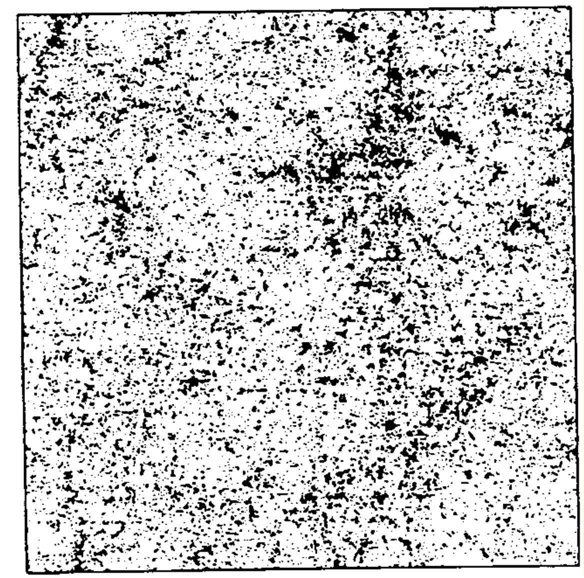




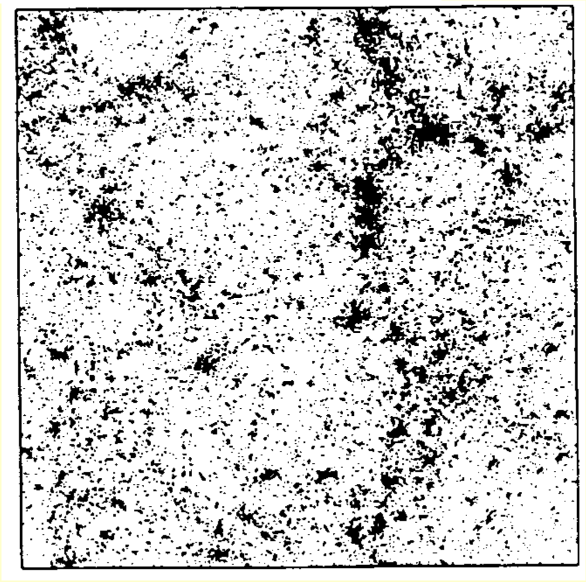
R = 1



R = 1.8



R = 2.4



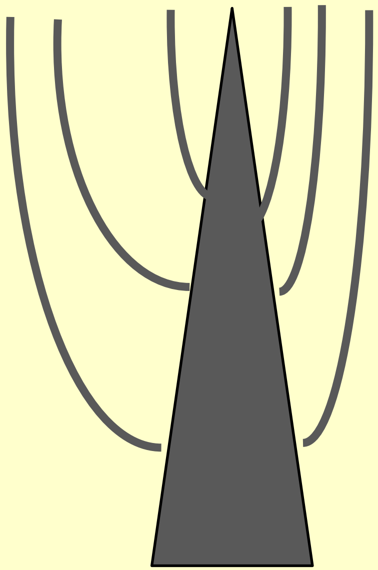
R = 4.5

Formation of (dark matter) structures
By the gravitational instability in
an expanding universe:

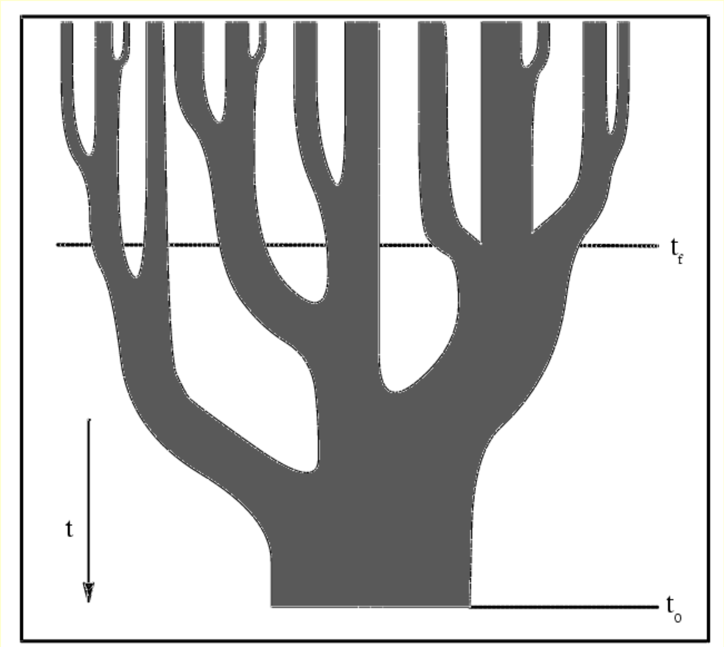
Denser region attracts mass,
becomes denser and attracts
even more mass …

Fate of Fragments

- Fragments are building blocks (~ dwarf galaxies) from which galaxies assemble by merging



Spiral (always prominent.core)



Elliptical (equal mass partners)

Dissipative (Monolithic) Collapse

- Larson (1969ff): protogalaxy consists of Jeans-unstable clouds (‘turbulence elements’) whose population can be treated by the Boltzmann equation (moments $\rightarrow$ fluid equations)
- Let’s consider a spherical protogalactic cloud …

For the gas clouds …

$$e = \frac{1}{2}\rho(\sigma_r^2 + \sigma_\varphi^2 + \sigma_\vartheta^2) = \frac{3}{2}\rho\sigma^2 = \frac{3}{2}p$$

Gas is isotropic

$$\frac{\partial\rho}{\partial t} + \nabla(\rho\vec{v}) = -\Psi$$

$$\frac{\partial\rho\vec{v}}{\partial t} + \nabla(\rho\vec{v}.\vec{v}) = -\vec{v}\Psi - \nabla p - \rho\nabla\Phi$$

$$\frac{\partial e}{\partial t} + \nabla(e\vec{v}) = -\frac{e}{\rho}\Psi - p\nabla\vec{v} - (de/dt)_{diss}$$

Stars (collisionless Boltzmann ➔)

$$\sigma^2_{\rm rad} \neq \sigma^2_{\rm tang} = \frac{1}{2}(\sigma^2_\varphi + \sigma^2_\vartheta)$$

can be anisotropic

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = \Psi$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla(\rho \vec{v}.\vec{v}) = \vec{v_g}\Psi - \rho \nabla \Phi - \frac{\partial \rho \sigma_r^2}{\partial r} - \frac{2\rho}{r}(\sigma_r^2 - \sigma_t^2)$$

$$\frac{\partial \rho \sigma_r^2}{\partial t} + \nabla(\rho \sigma_r^2 \vec{v}) = -(\frac{e}{\rho})_g \Psi - \frac{2\rho\sigma_r^2}{r}\frac{\partial v_r}{\partial r}$$

$$\frac{\partial \rho \sigma_t^2}{\partial t} + \nabla(\rho \sigma_t^2 \vec{v}) = -(\frac{e}{\rho})_g \Psi - \frac{2\rho\sigma_t^2}{r}\frac{v_r}{r}$$

Advection

interaction

Source terms

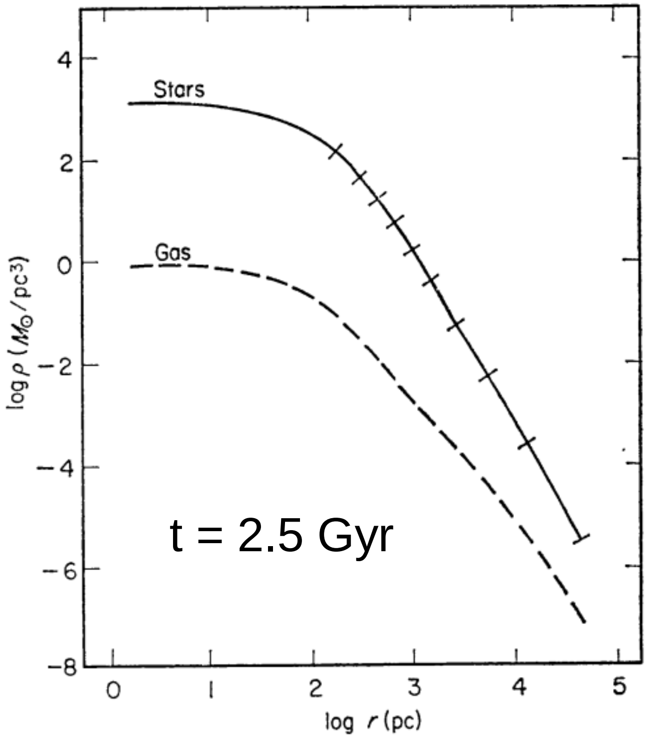
Assumptions (Larson 1969)

- $M = 10^{11}$ Msun, R=50 kpc,
  $\rho = 2\ 10^{-4}$ Msun/pc^3 ➔ t_{ff} = 600 Myr
- $de/dt \propto \rho^{1/2}$ collisions of clouds
- SFR $\Psi \propto \rho^n$ n=2 cloud-cloud collisions (reasonable guess)

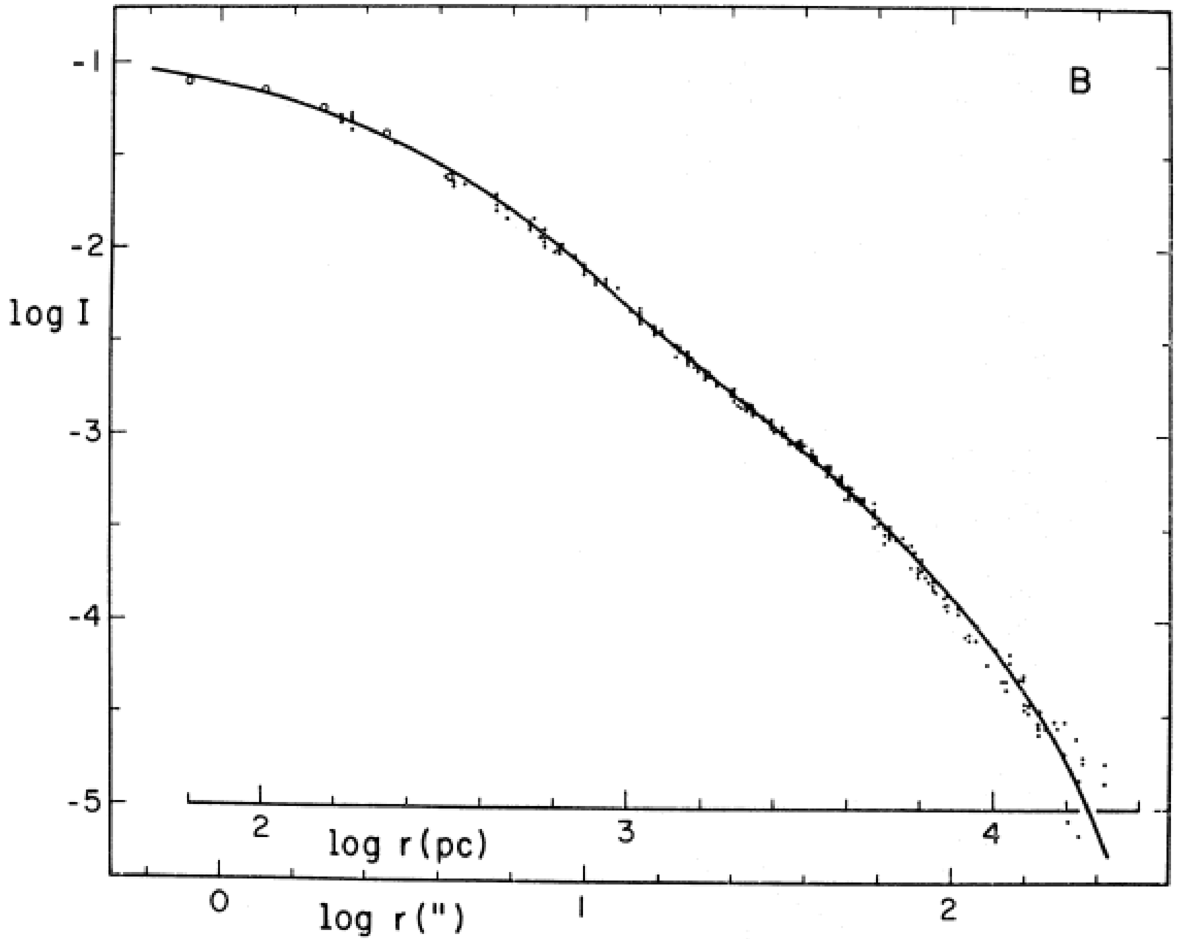
Results (Larson ’69 + ‘74)

- 800 Myrs: $\rho_{gas} = \rho_{stars}$ at centre (1 atom/cm3)
- 1.7 Gyrs: 50 at/cm3; 97% stars
- 2.5 Gyrs: 99.6% stars, stopped (numerics)

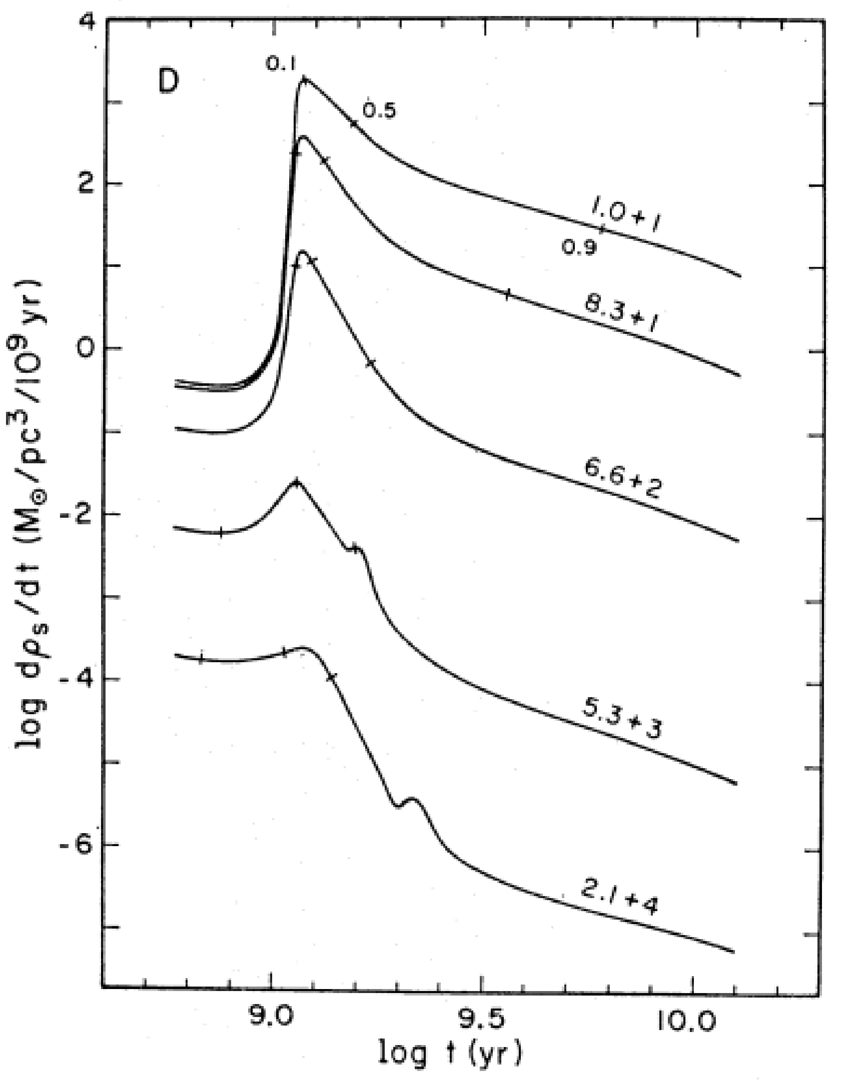
- Stellar density profile $\rho \propto r^{-3}$ OK!
- Stellar velocities nearly isotropic
- Metallicity gradient: negative
- Collapse only if SFR power n > 1.8

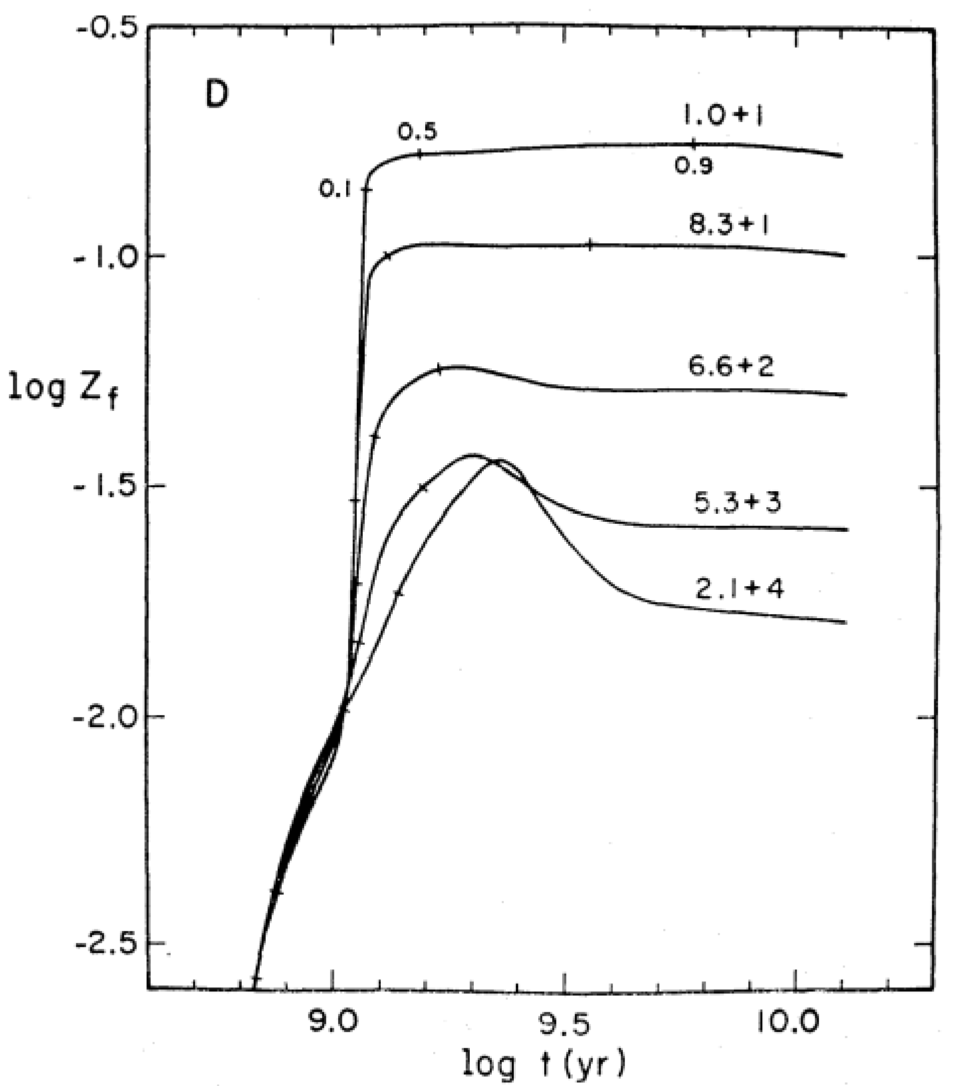


Stellar profile OK with observation!

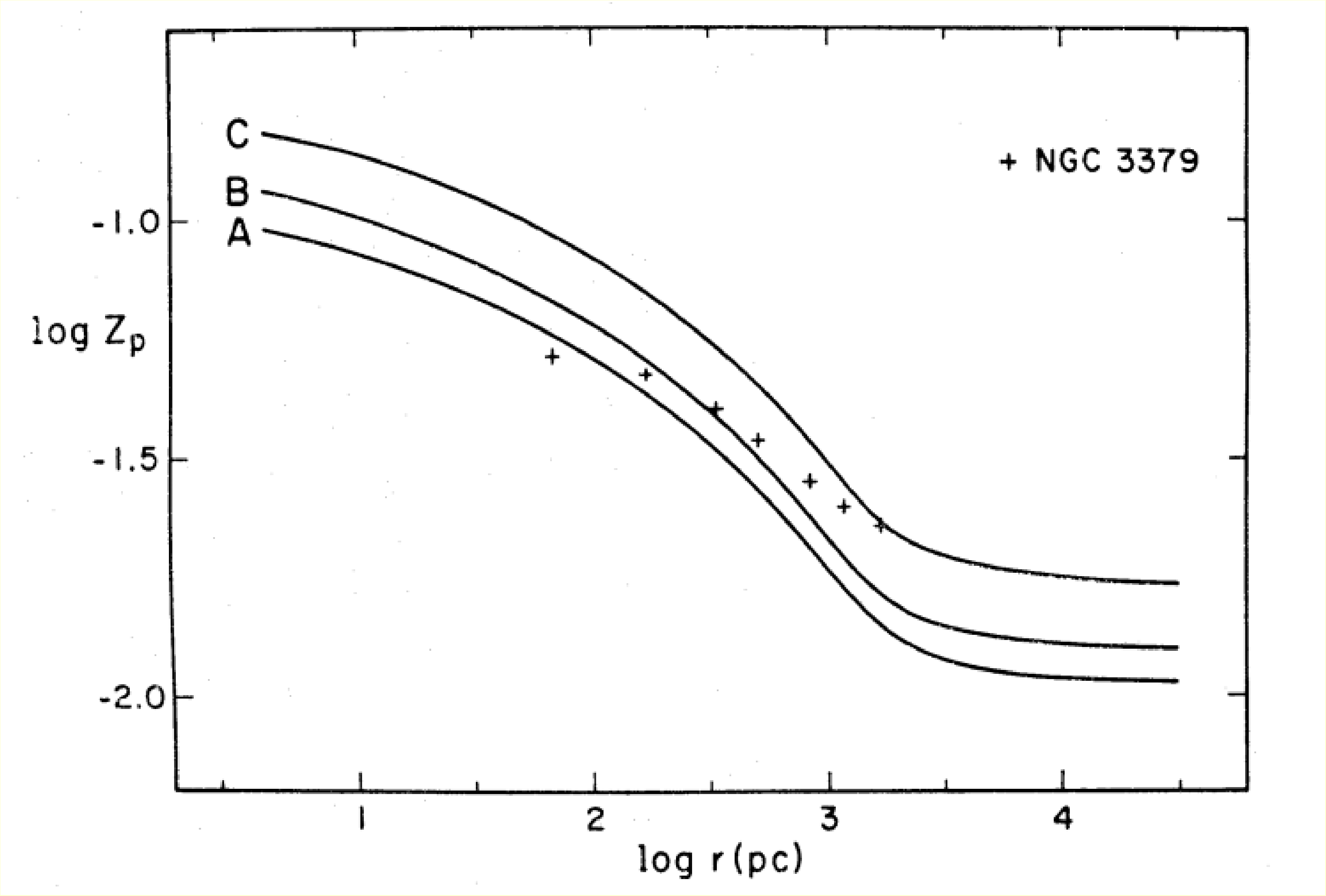


SFR and metallicity (1974)





Projected metallicity profile



However:

- The centre has higher proportion of younger stars → the centre is bluer by about 0.2 mag
- Observations show that centre is redder!

Remedy:

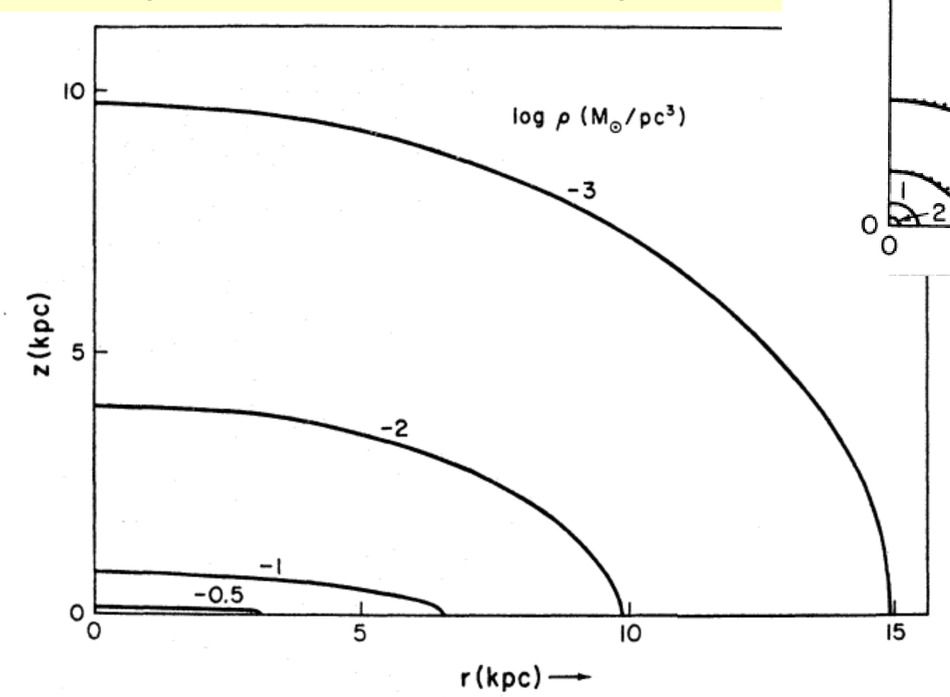
- Expell gas by SN driven terminal wind → cuts star formation → can account for observed photometry and the mass-colour relation

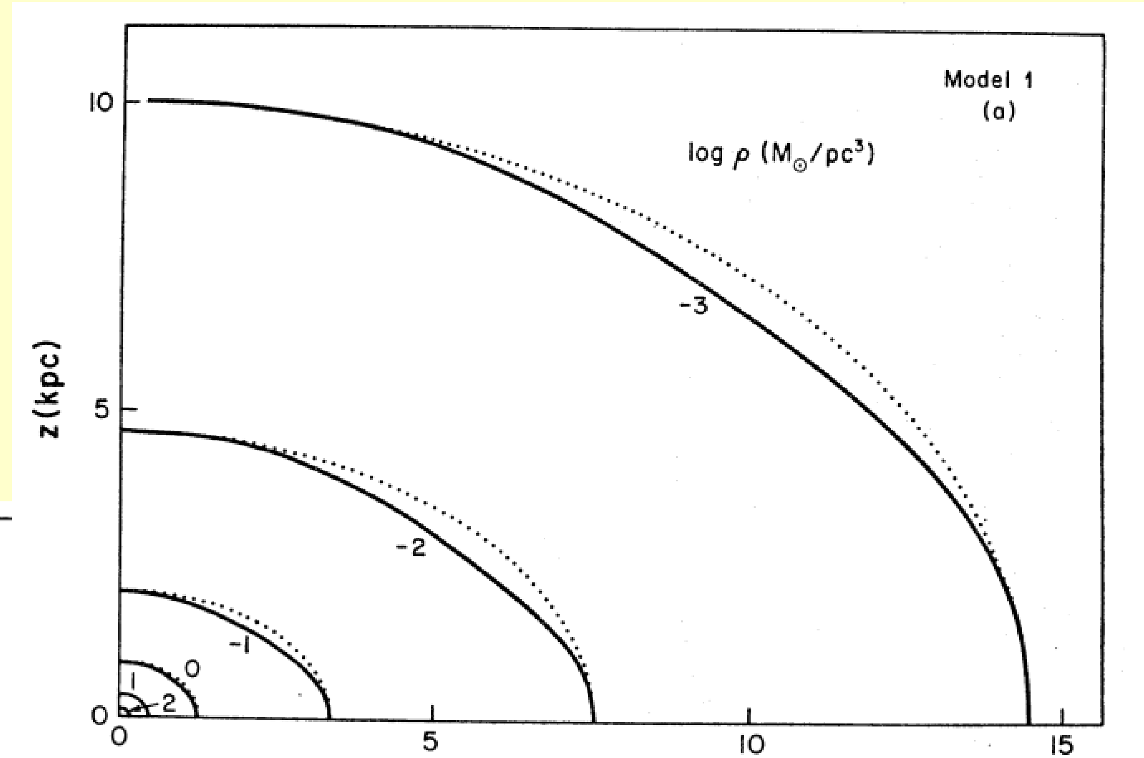
Rotating Ellipticals (1975)

- Not all E are E0
- 2D models
  - Formation of disk in equatorial plane ➔ isophotes would NOT have same ellipticity as it is observed
  - Remedy: postulation of strong viscosity

Rotating Ellipticals (1975)

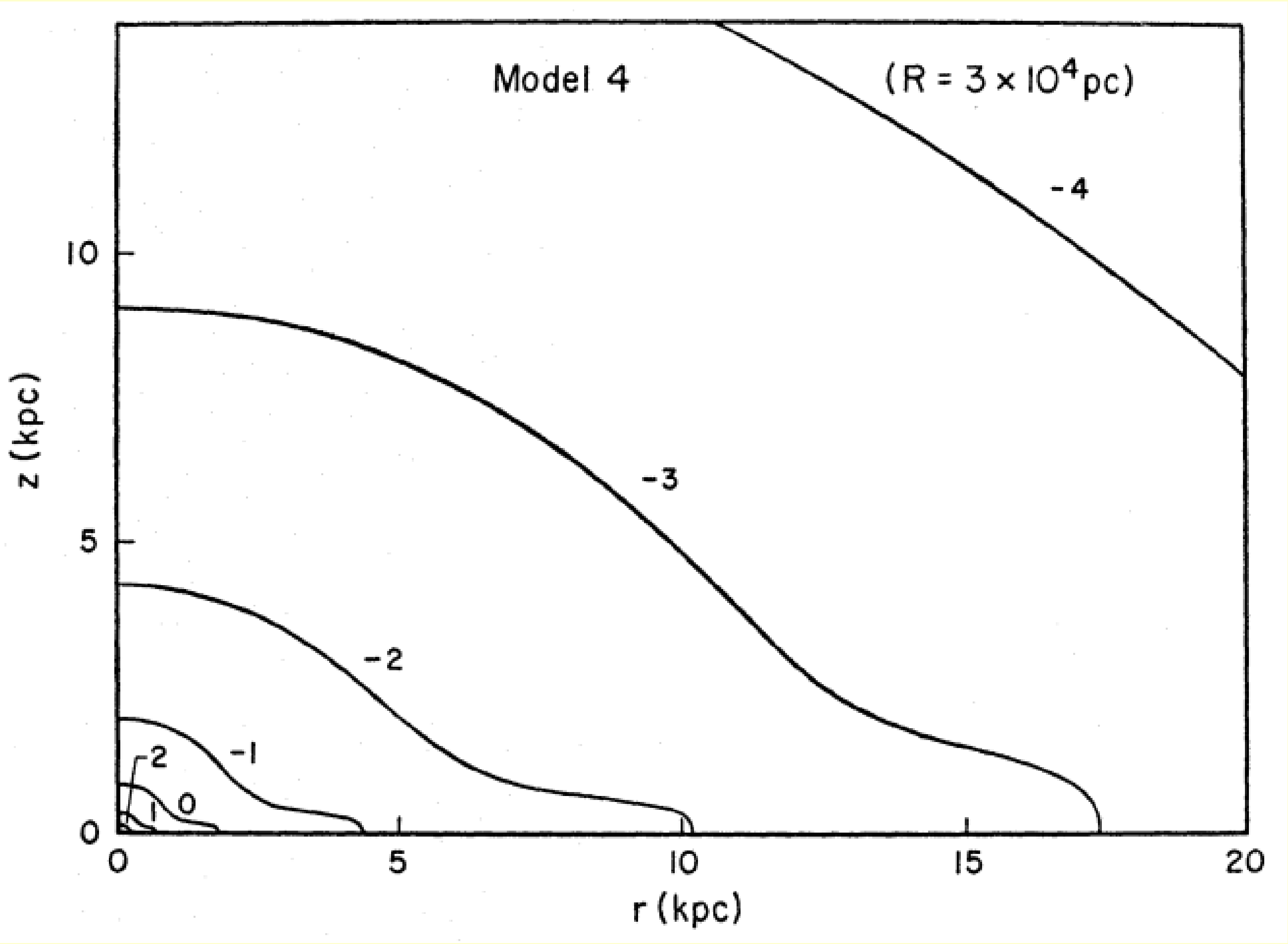
Density contours: no viscosity





With extra viscosity

Disk galaxies (1976)



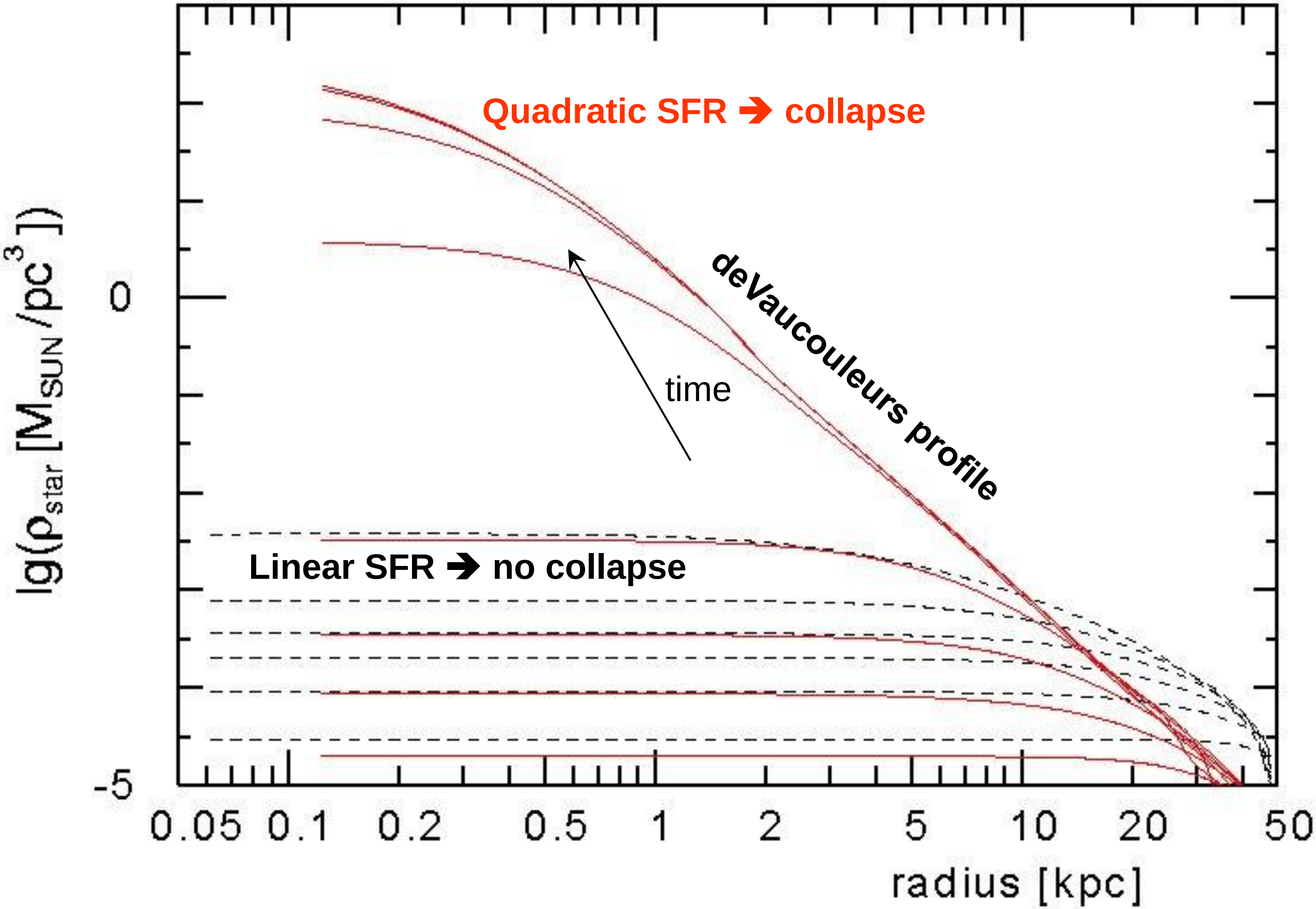
Needs time-dependent viscosity and SFR

☹

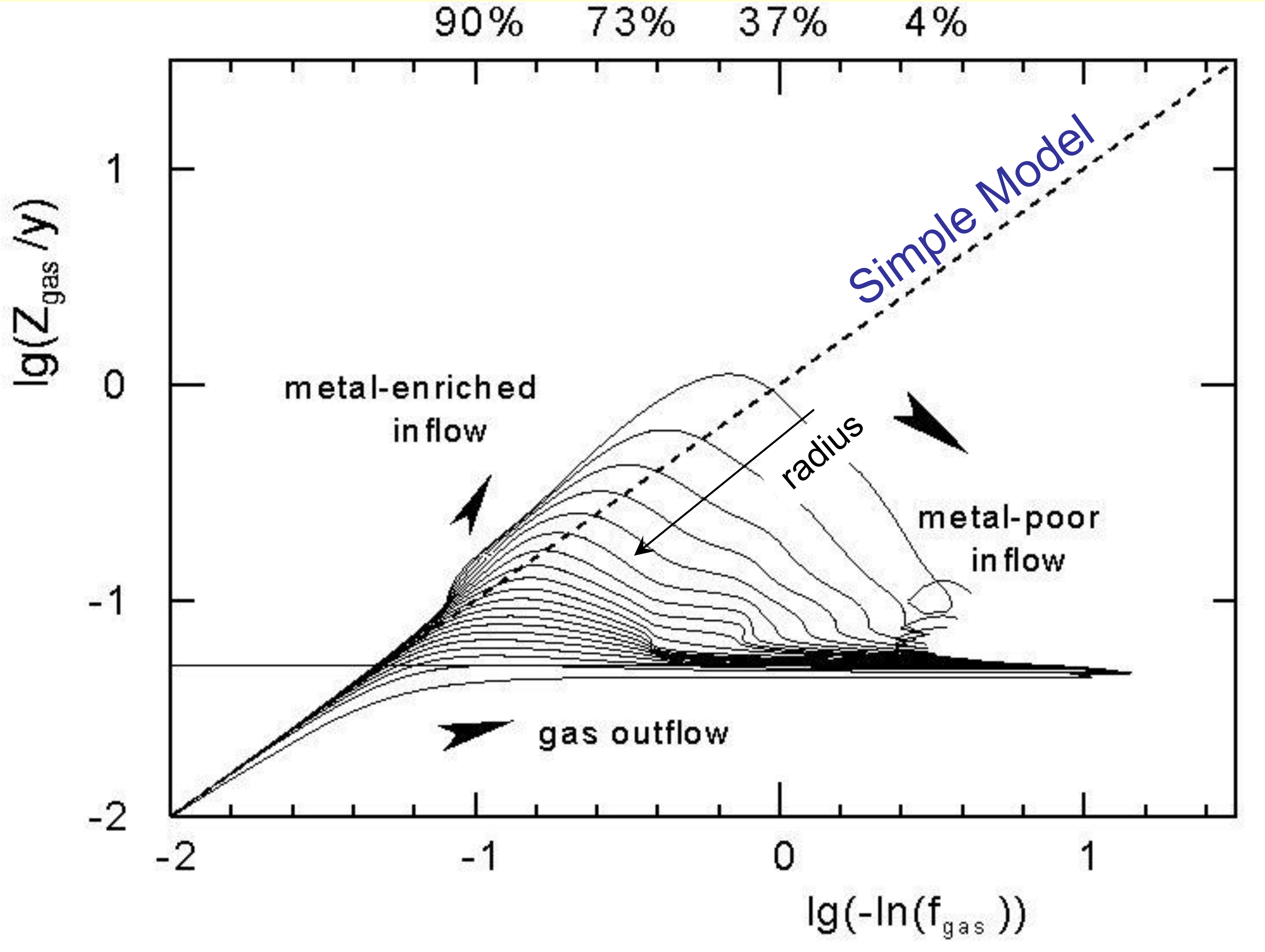
An alternative

- Dissipation-less (stellar dynamical) models of ellipticals:
  - N-body simulations for stellar population (Gunn 1976)
  - Nice density profile is obtained, if a heavy halo (6*Mgal) is assumed
  - does not explain metallicity gradient …

Another look at spherical collapse



Another look at spherical collapse



The G dwarfs …